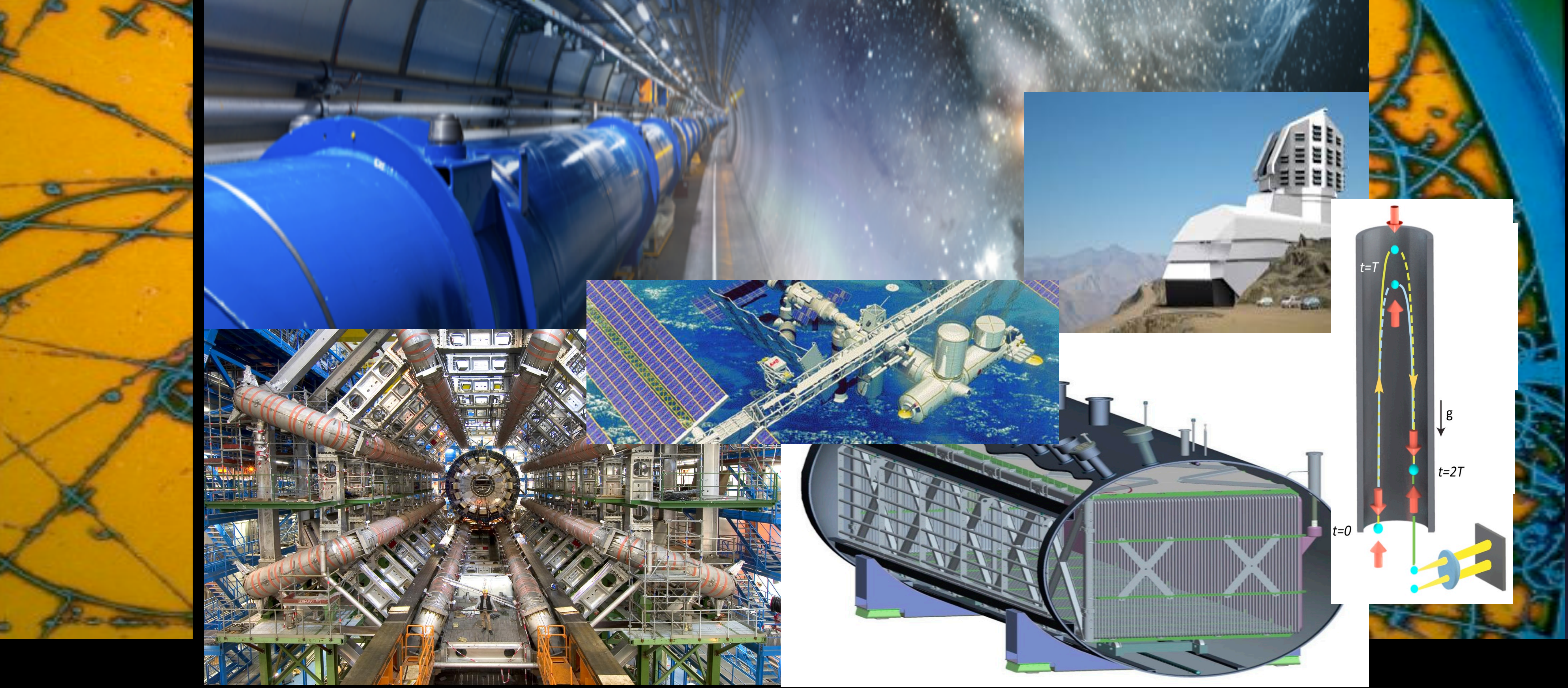


Instrumentation – The Great Enabler

Ian Shipsey

Outline

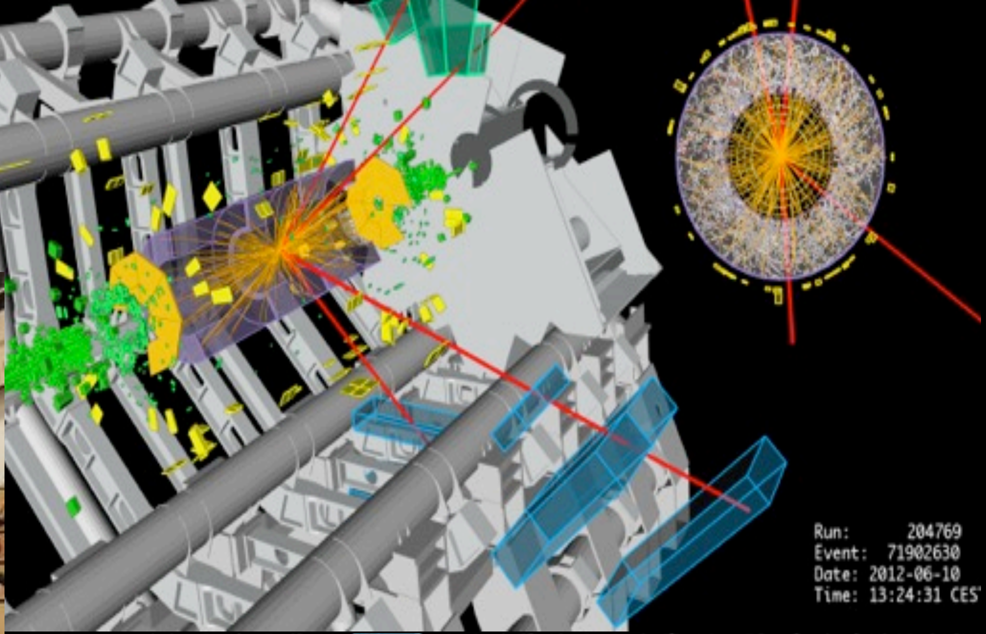
Lecture 1 & 2

Instrumentation the Great Enabler
Instrumentation Roadmaps
The basics of the interactions of radiation
and matter
Gas Detectors
Liquid Detectors
Solid State Detectors

Lecture 3 & 4
Quantum Sensing
Photon Detectors and PID
Calorimetry
TDAQ
Integration
Facilities
Instrumentation Community Development/Workforce
Development/ Schools/Training

2012.7.4

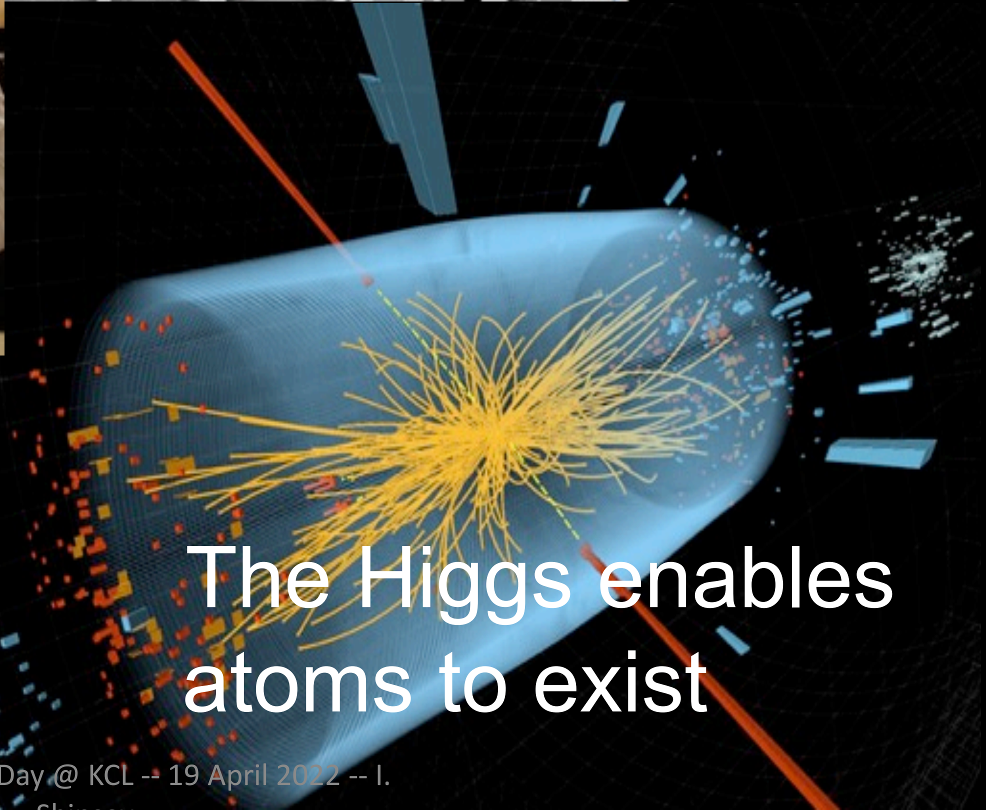
discovery of Higgs boson



theory : 1964

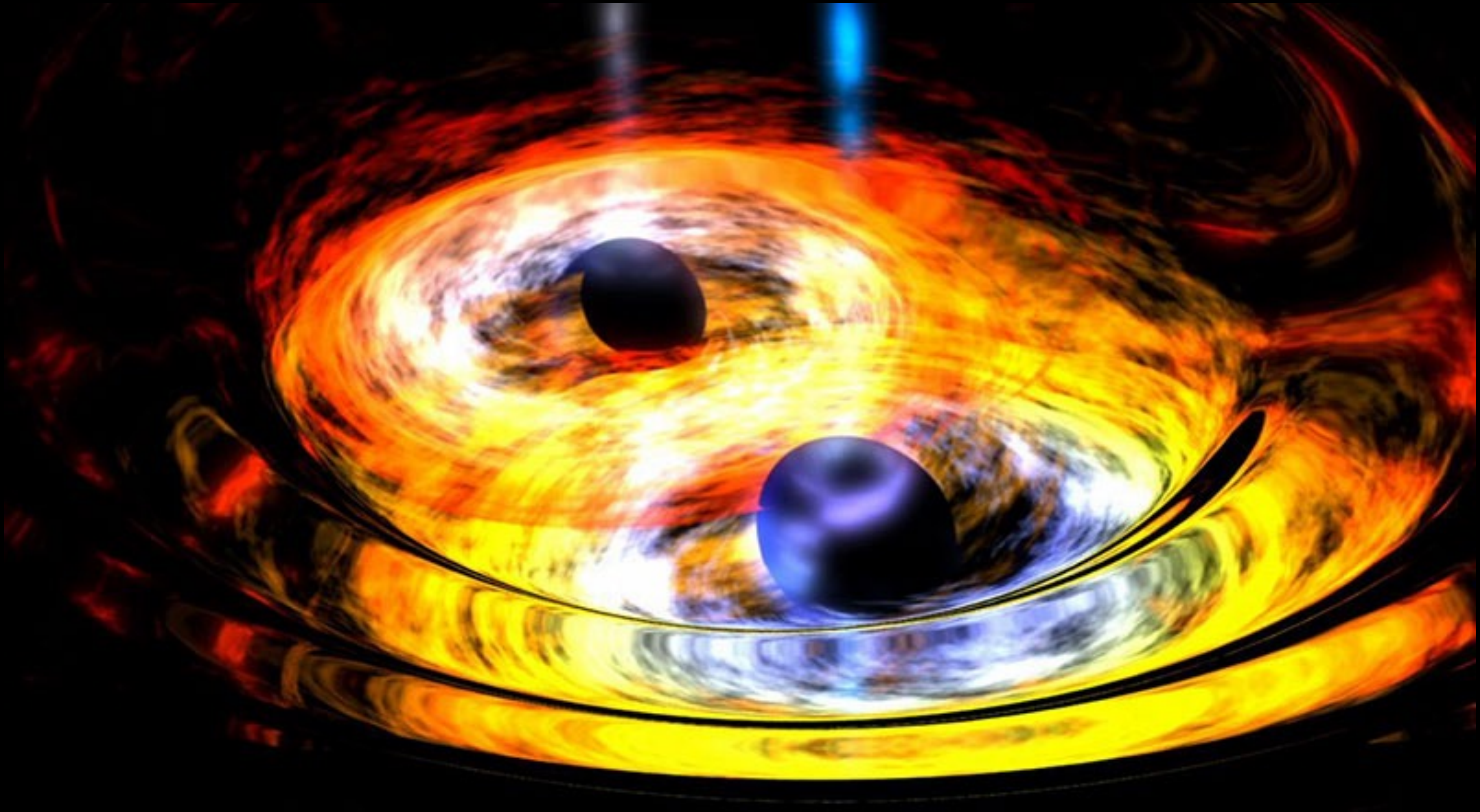
design : 1984

construction : 1998

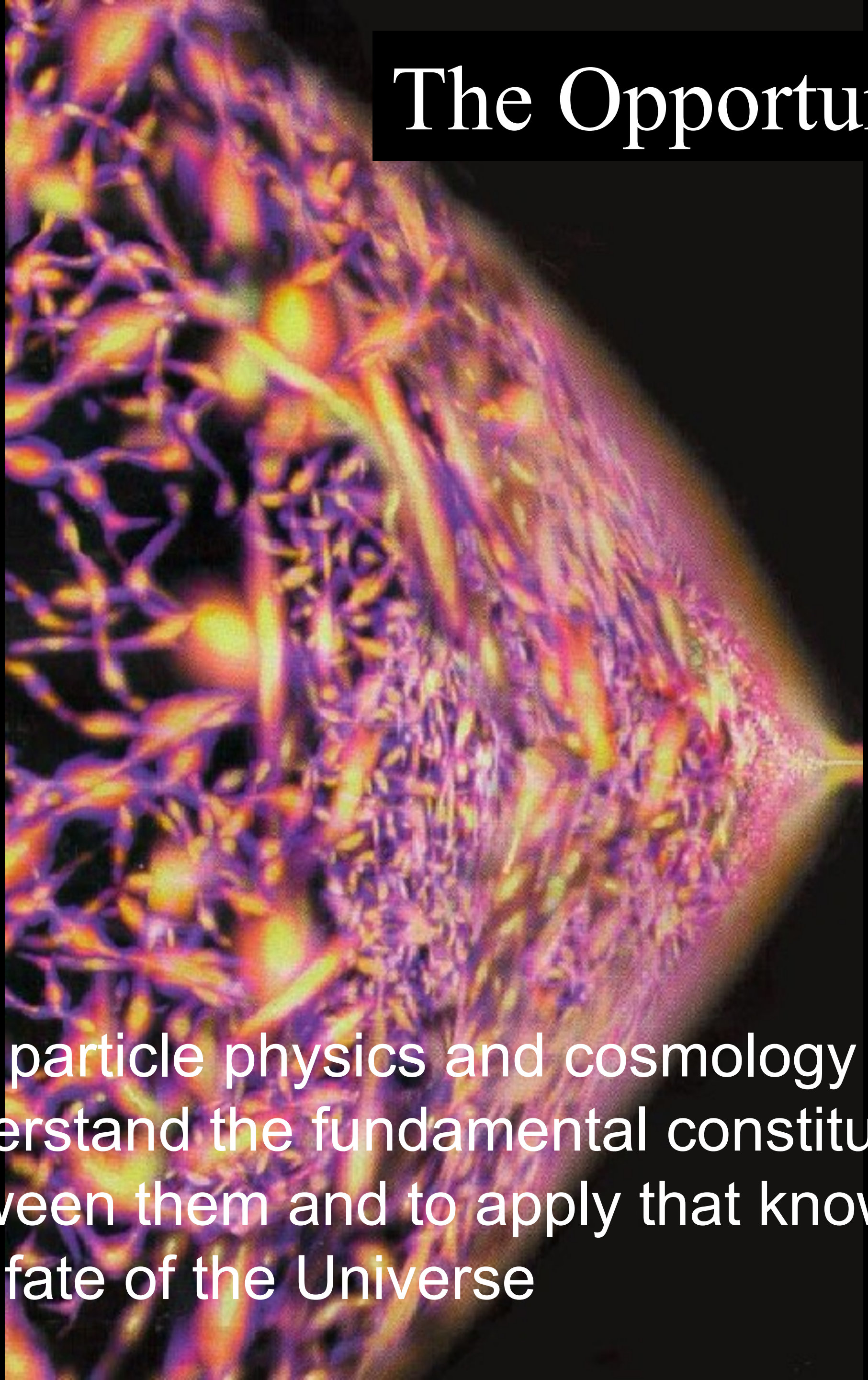


The Higgs enables atoms to exist

Detection of gravitational waves
LIGO February, 2016



The Opportunities for Discovery



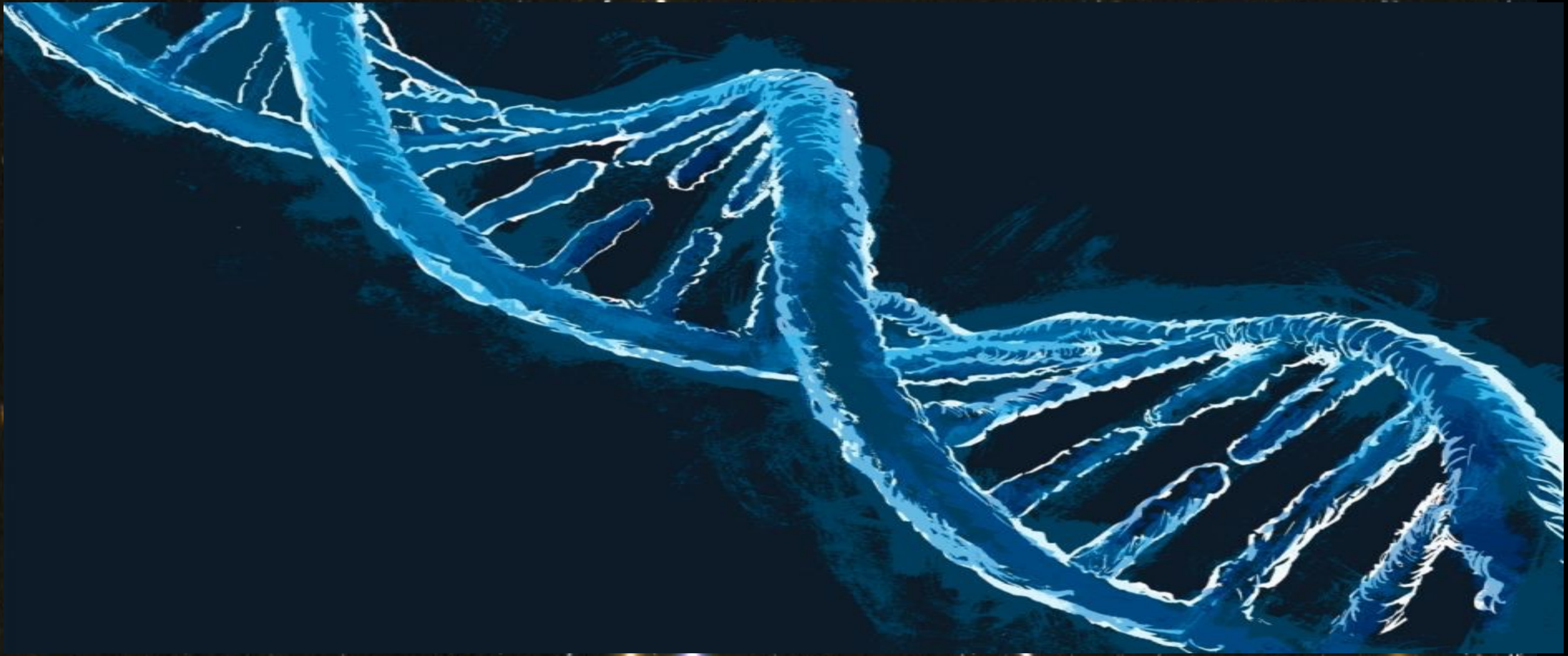
The particle physics and cosmology communities are united in seeking to understand the fundamental constituents of the Universe and the forces between them and to apply that knowledge to understand the birth, evolution and fate of the Universe

The Opportunities for Discovery

The particle phyiscs and cosmology communities are united in seeking to understand the fundamental constituents of the Universe and the forces between them and to apply that knowledge to understand the birth, evolution and fate of the universe

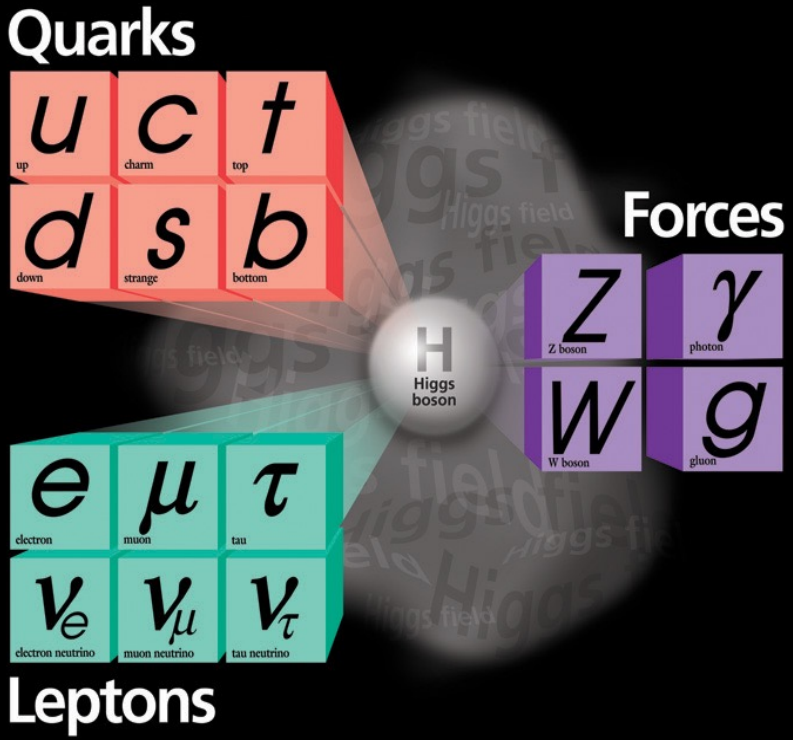
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Our communities have revolutionized human understanding of the Universe – its underlying code, structure and evolution

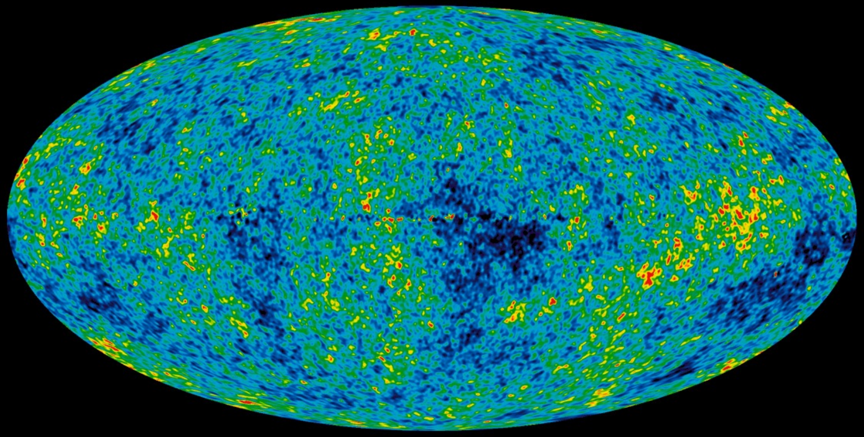


BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Particle Standard Model

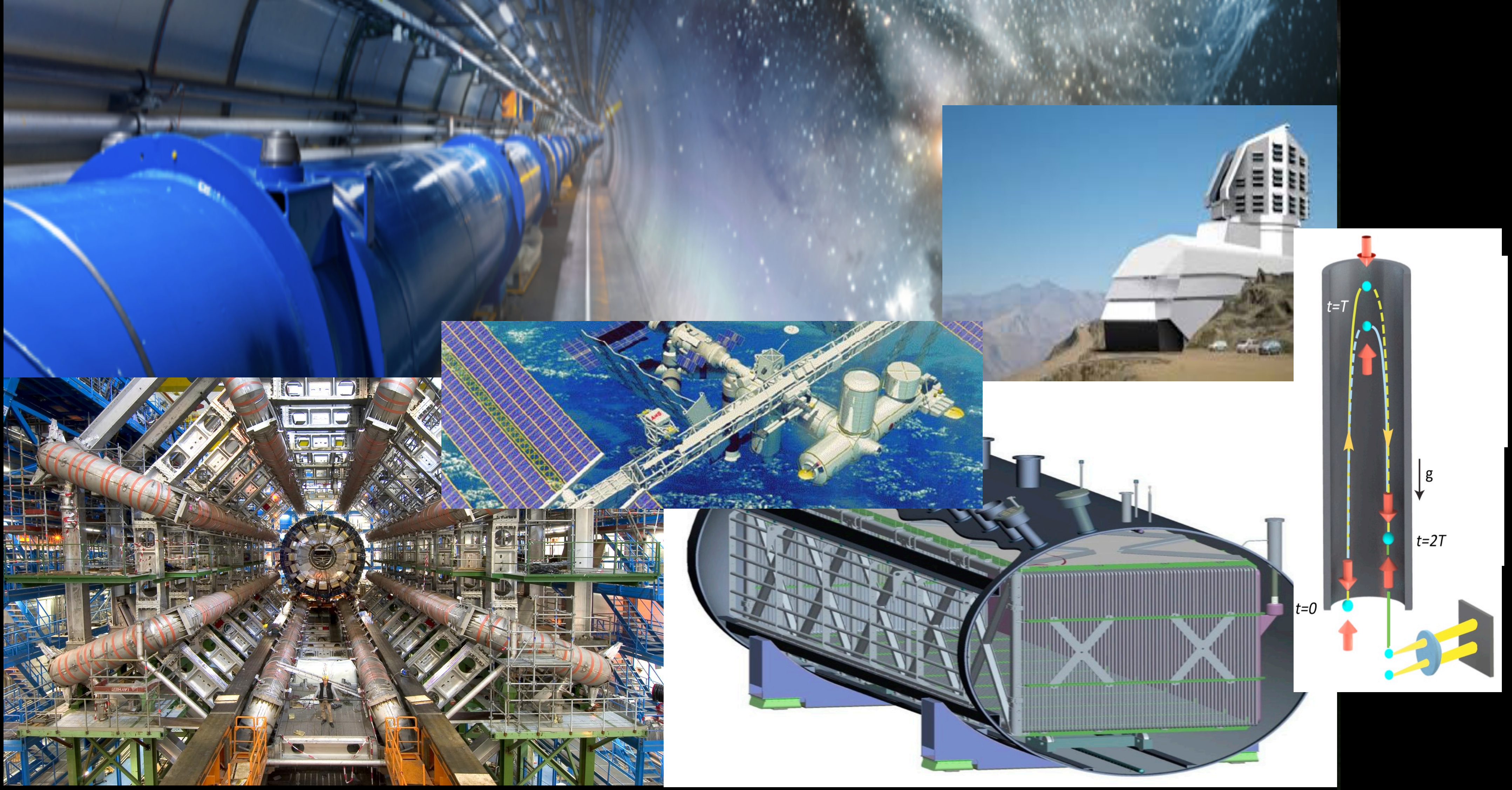


Cosmology Standard Model



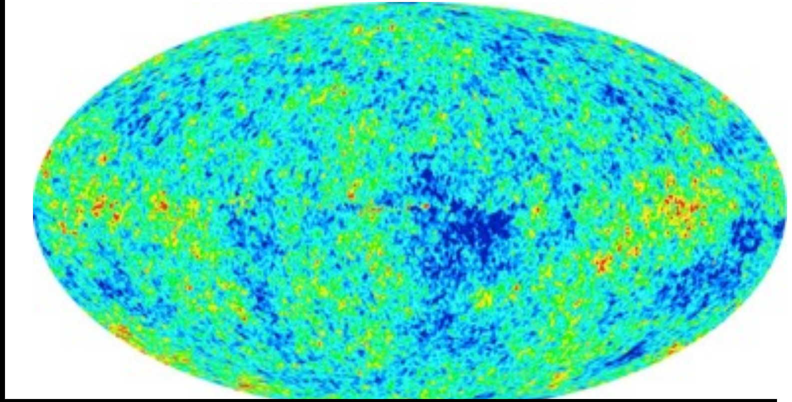
Λ_{CDM}

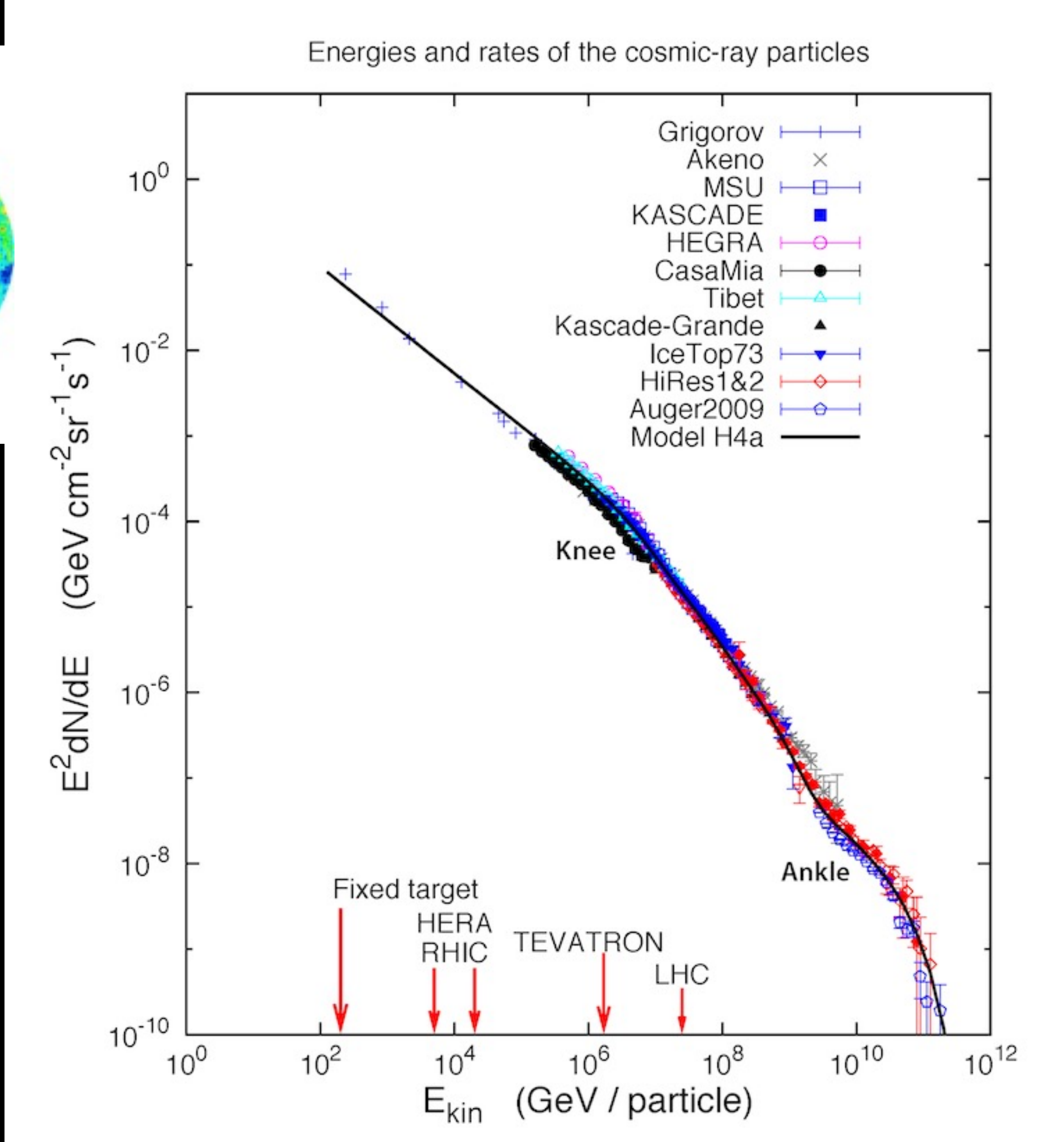
……enabled by instrumentation



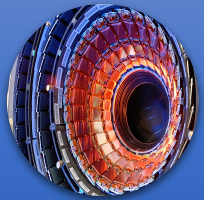
Our scope is broad and we deploy many tools; accelerator, non-accelerator, astrophysical & cosmological observations all have a critical role to play

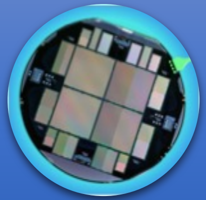
Detect & Measure over 24 orders of magnitude

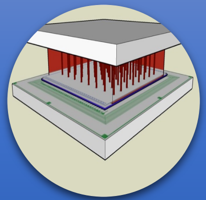


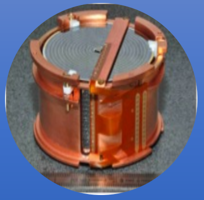


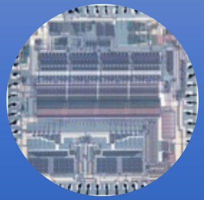
A Rich Spectrum of Technologies Developed by our Community

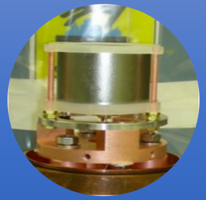

Silicon

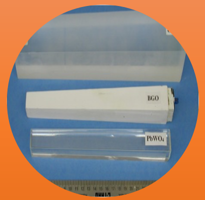

CCD


3D Si

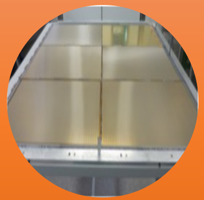

Germanium

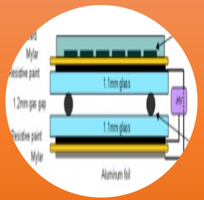

ASIC


HPGe

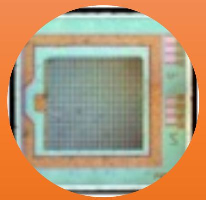

Crystals


LAPPD

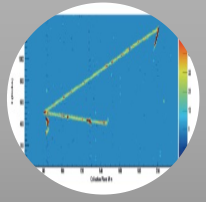

MicroMegas

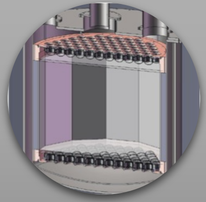

RPC

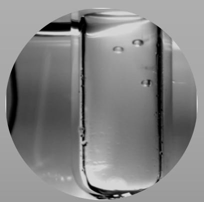

GEM

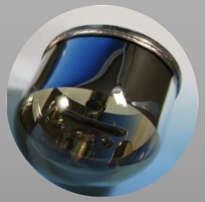

SiPM

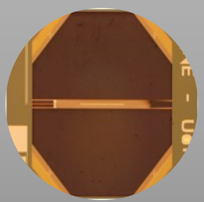

H_2O Ckov


LAr TPC

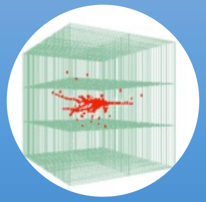

Noble Liquids


Bubbles

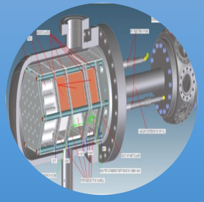

Phototubes

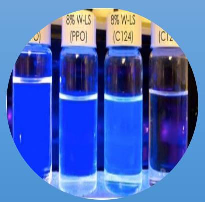

TES


HS-DAQ


Imag. Calor.

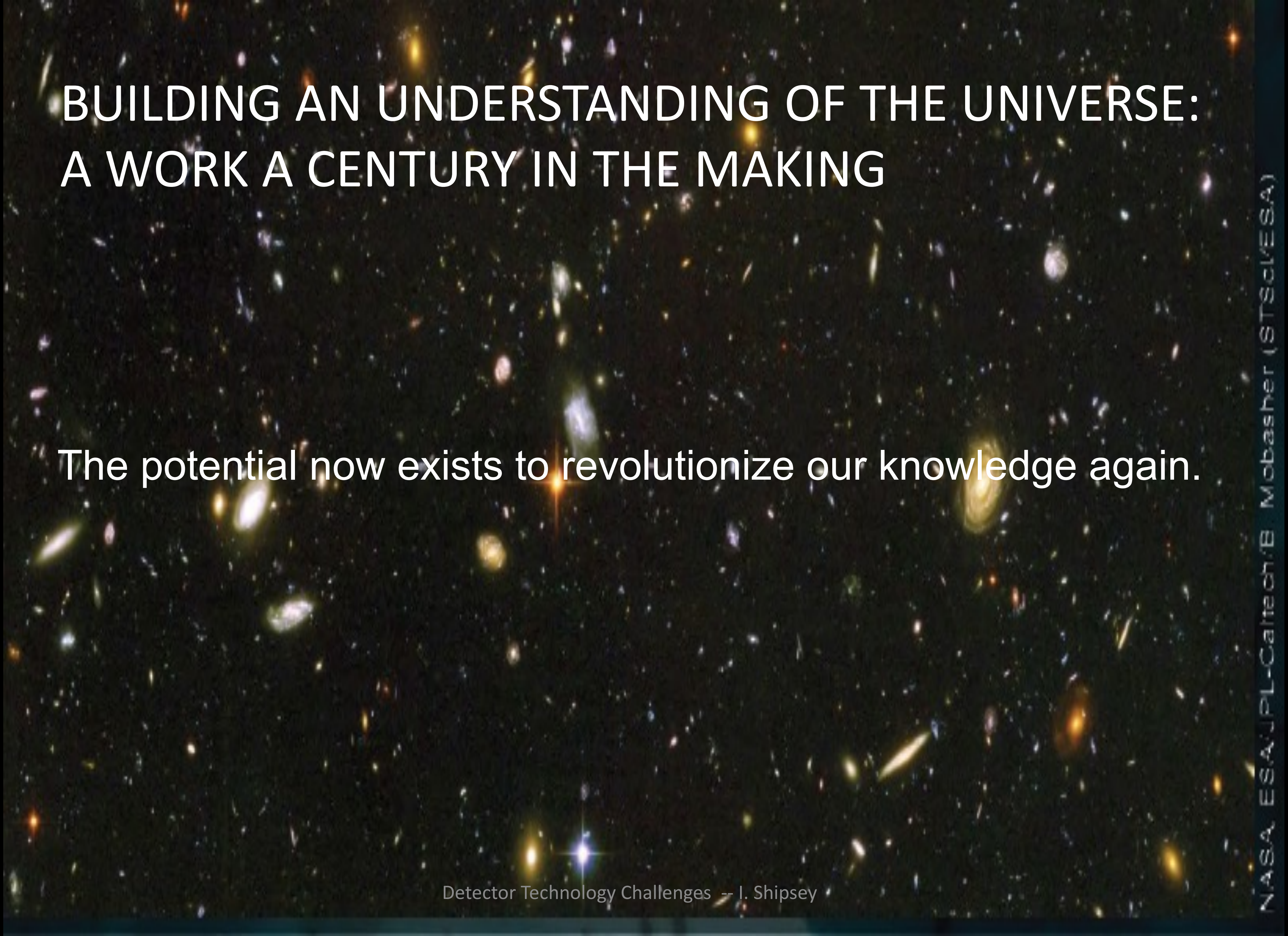

Materials


Noble Gases


WbLS


Power

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING



NASA, ESA/JPL-Caltech/B. Mobasher (STScI/ESA)

The potential now exists to revolutionize our knowledge again.

Opportunities for Discovery

Many mysteries to date go unanswered including:

The mystery of the Higgs boson

The mystery of Neutrinos

The mystery of Dark Matter

The mystery of Dark Energy

The mystery of quarks and charged leptons

The mystery of Matter – anti-Matter asymmetry

The mystery of the Hierarchy Problem

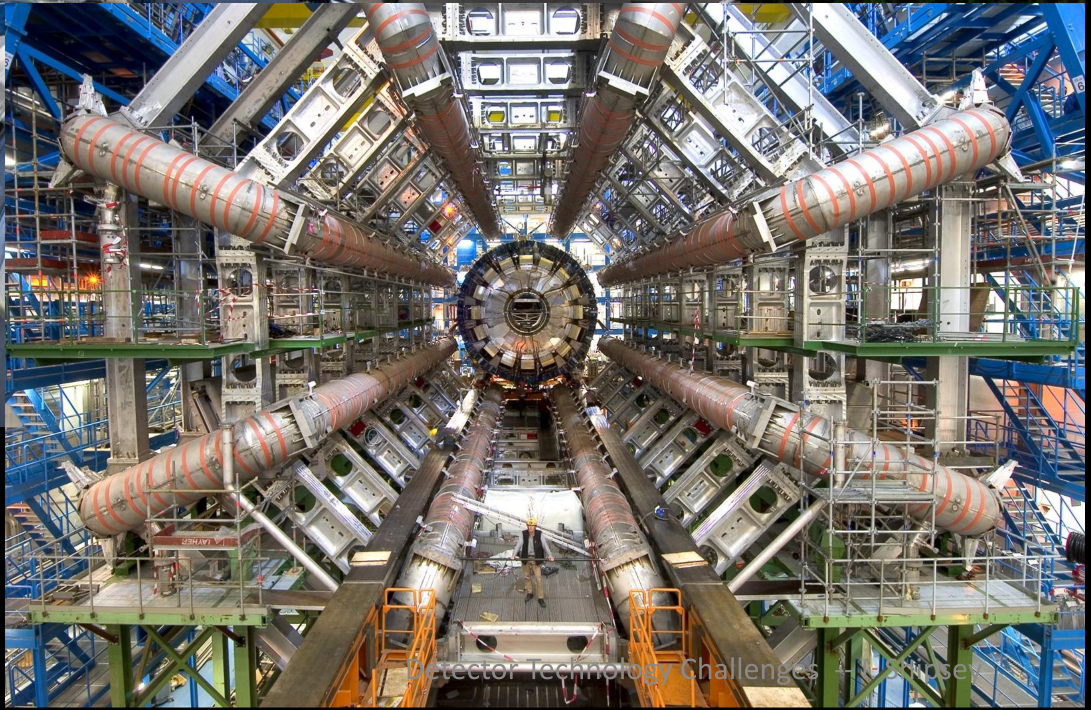
The mystery of the Families of Particles

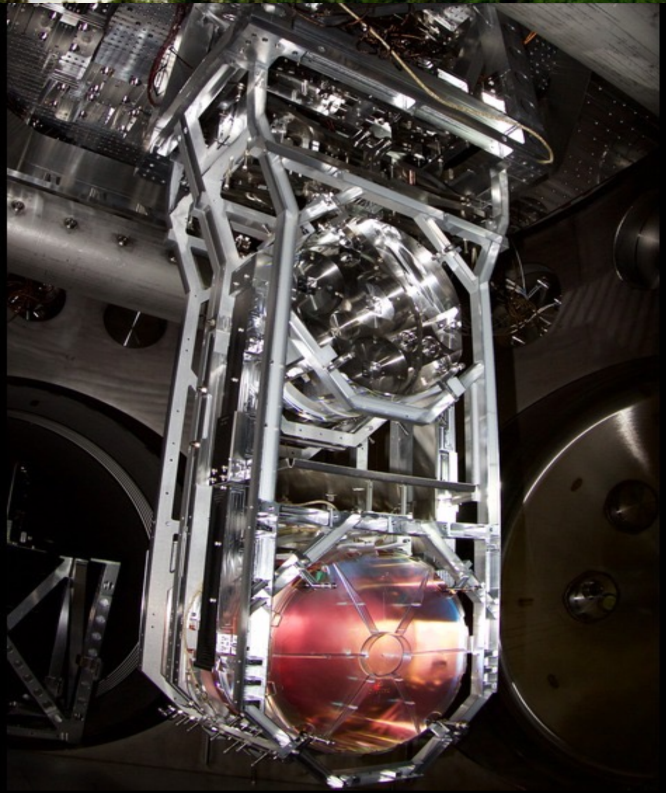
The mystery of Inflation

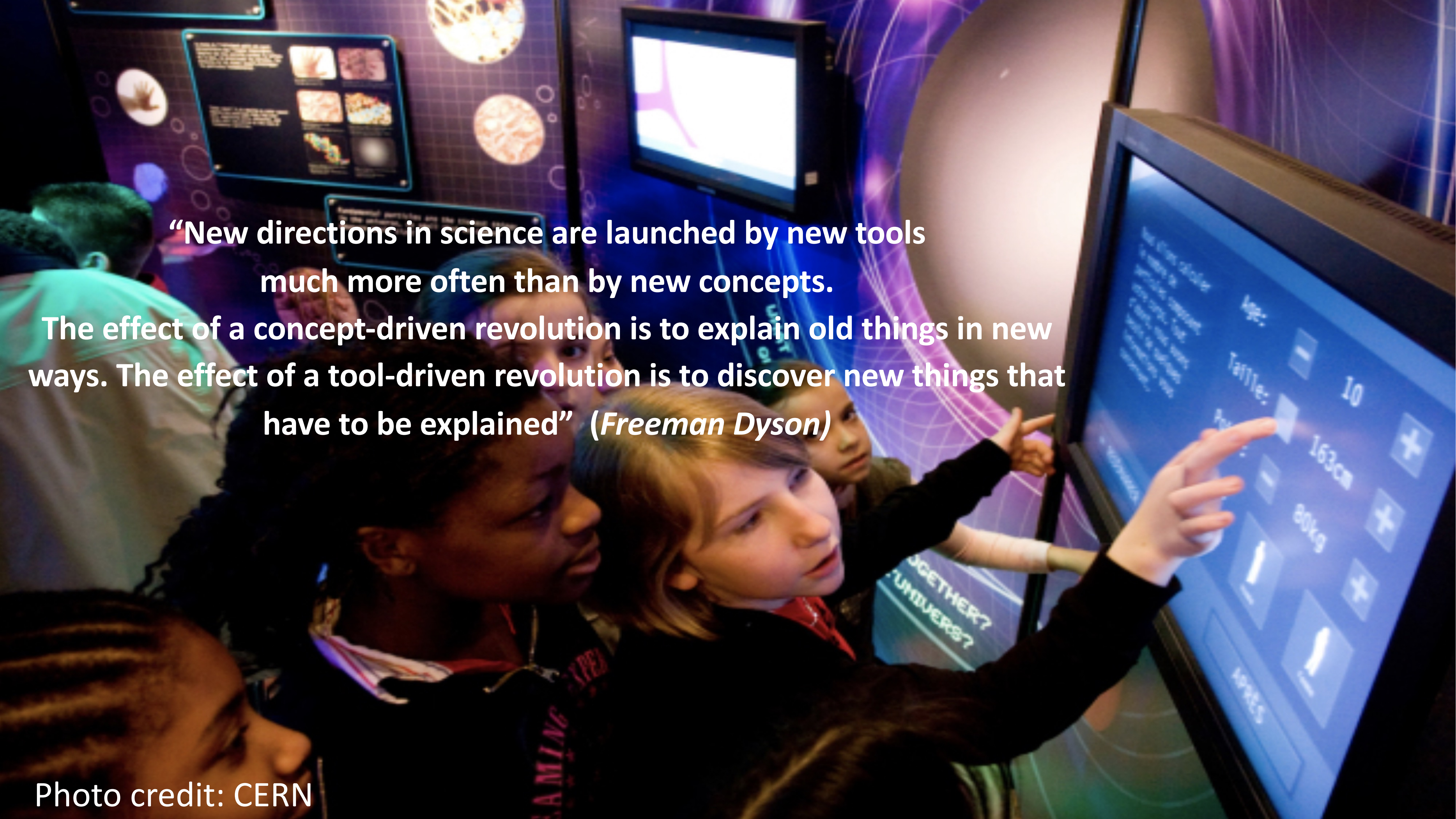
The mystery of Gravity

We are very much in a data driven era !

The gestation time to realize the tools and the experiments e.g. LHC & LIGO are decades long! For the most ambitious future experiments e.g FCCee/hh & Einstein Telescope to take the data and seize the opportunities for discovery, we must develop the tools (instrumentation and facilities) we need NOW.







“New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained” (*Freeman Dyson)*

Photo credit: CERN

“Measure what is measurable, and
make measurable what is not so” (*Galileo Galilei)*

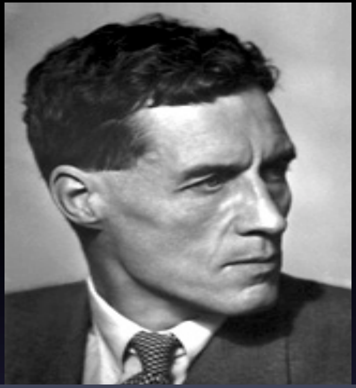
Photo credit: CERN

NOBEL PRIZES FOR INSTRUMENTATION

http://www.lhc-closer.es/php/index.php?i=1&s=9&p=2&e=0

1927: C.T.R. Wilson, Cloud Chamber

1939: E. O. Lawrence, Cyclotron



1948: P.M.S. Blacket, Cloud Chamber

1950: C. Powell Photographic Method

1954: W. Bothe Coincidence method

1960: Donald Glaser, Bubble Chamber

1968: L. Alvarez Hydrogen Bubble Chamber

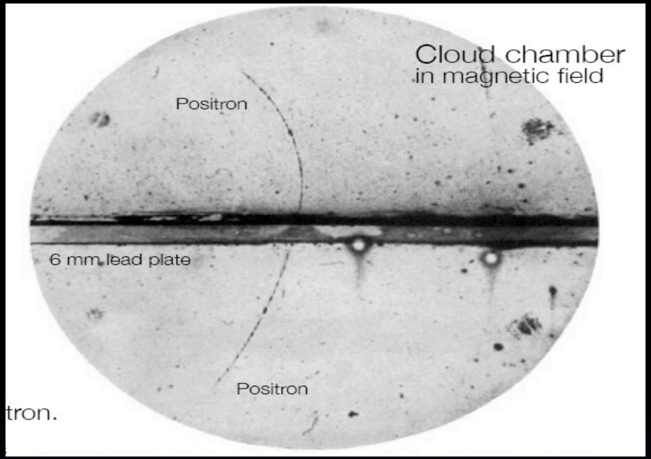
1992: G. Charpak Multi Wire Prop. Chamber

2009: W. S. Boyle & G. E. Smith
CCD sensors

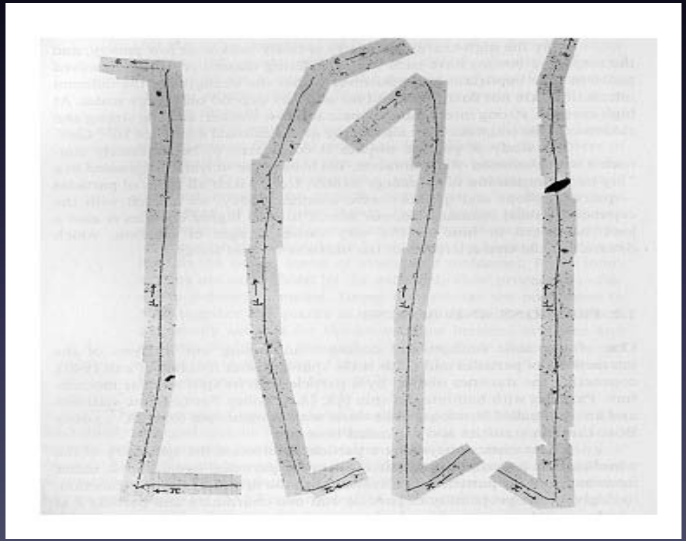
Instrumentation & the building of the SM

- Fluorescent screen: e^-
- Ionization chamber: n
- Cloud chamber: e^+, μ^+, μ^-, K^0, Λ^0, Ξ^-, Σ^-
- Nuclear emulsions: π^+, π^-, Σ^+, K^+, K^-
- Bubble chamber: Ξ^-, Σ^-, Ω^-, neutral currents, ..
- Electronic techniques: anti-n, anti-p, π^0

Positron



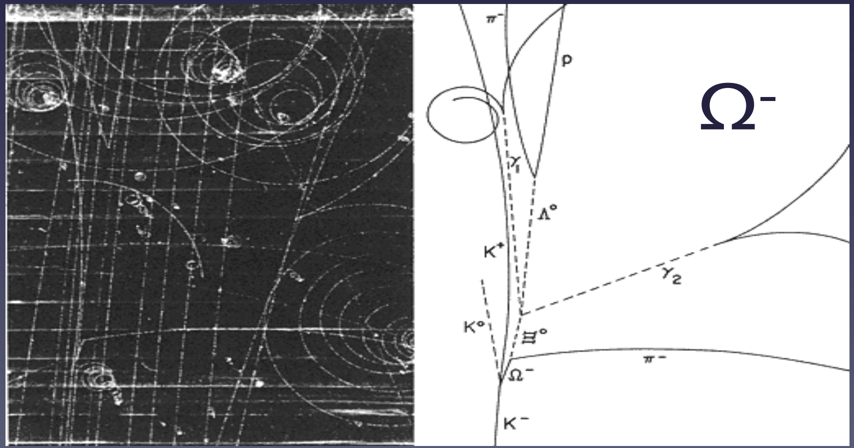
Pion



$$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu$$

$$\mu^- \longrightarrow e^- \bar{\nu}_e \nu_\mu$$

Neutral currents



Imaging Detectors: Cloud Chamber

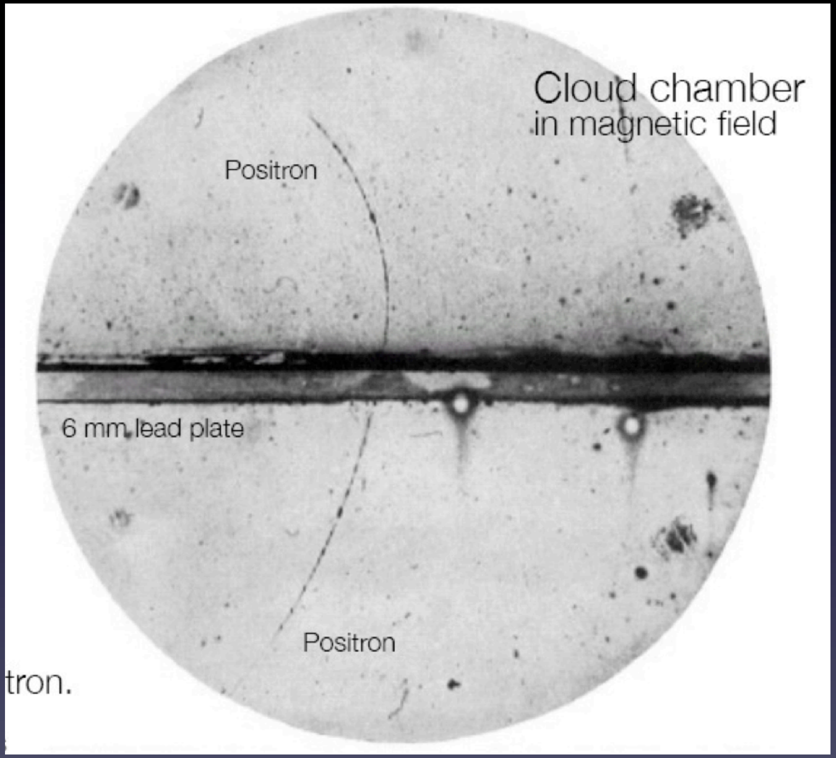
- The **cloud chamber** contains a supersaturated vapor of water or alcohol.
  - A charged particle interacting with the mixture, creates ions.
  - Ions act as condensation nuclei around which a mist will form
- If a magnetic field is applied positively and negatively charged particles curve in opposite directions.

- High energy α and β particles leave a track due to the ions they produce along their path

The positron

Positron discovery, Carl Andersen 1933 [Nobel price 1936]

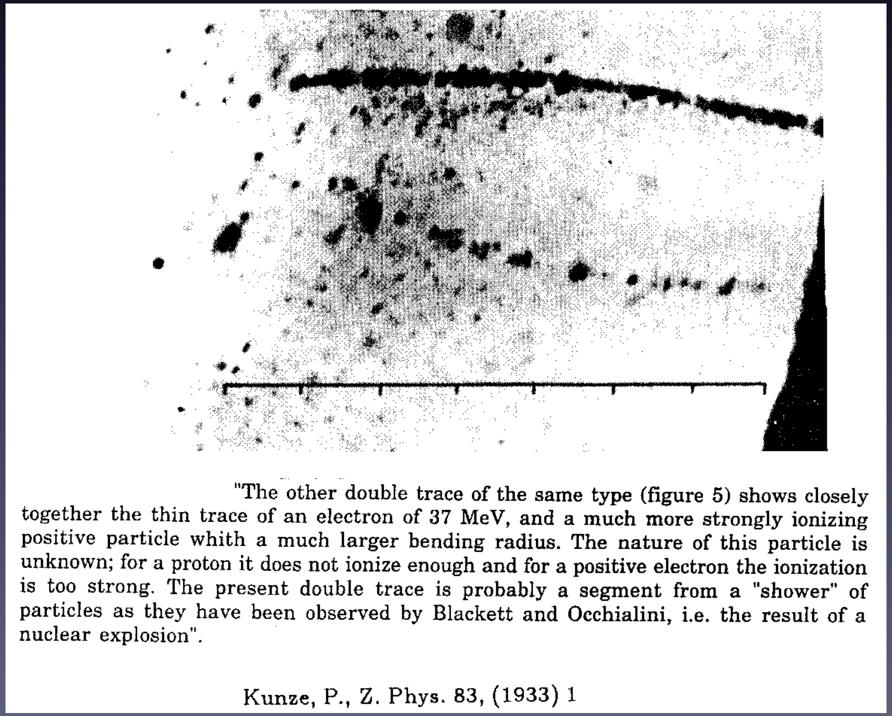
- Magnetic field 15000 Gauss, chamber diameter 15cm.
- A 63 MeV positron passes through a 6mm lead leaving the plate with energy 23MeV.
- The ionization of the particle, and its behavior in passing through the foil was the same as those of an electron but with positive charge



Confirmation of antiparticles

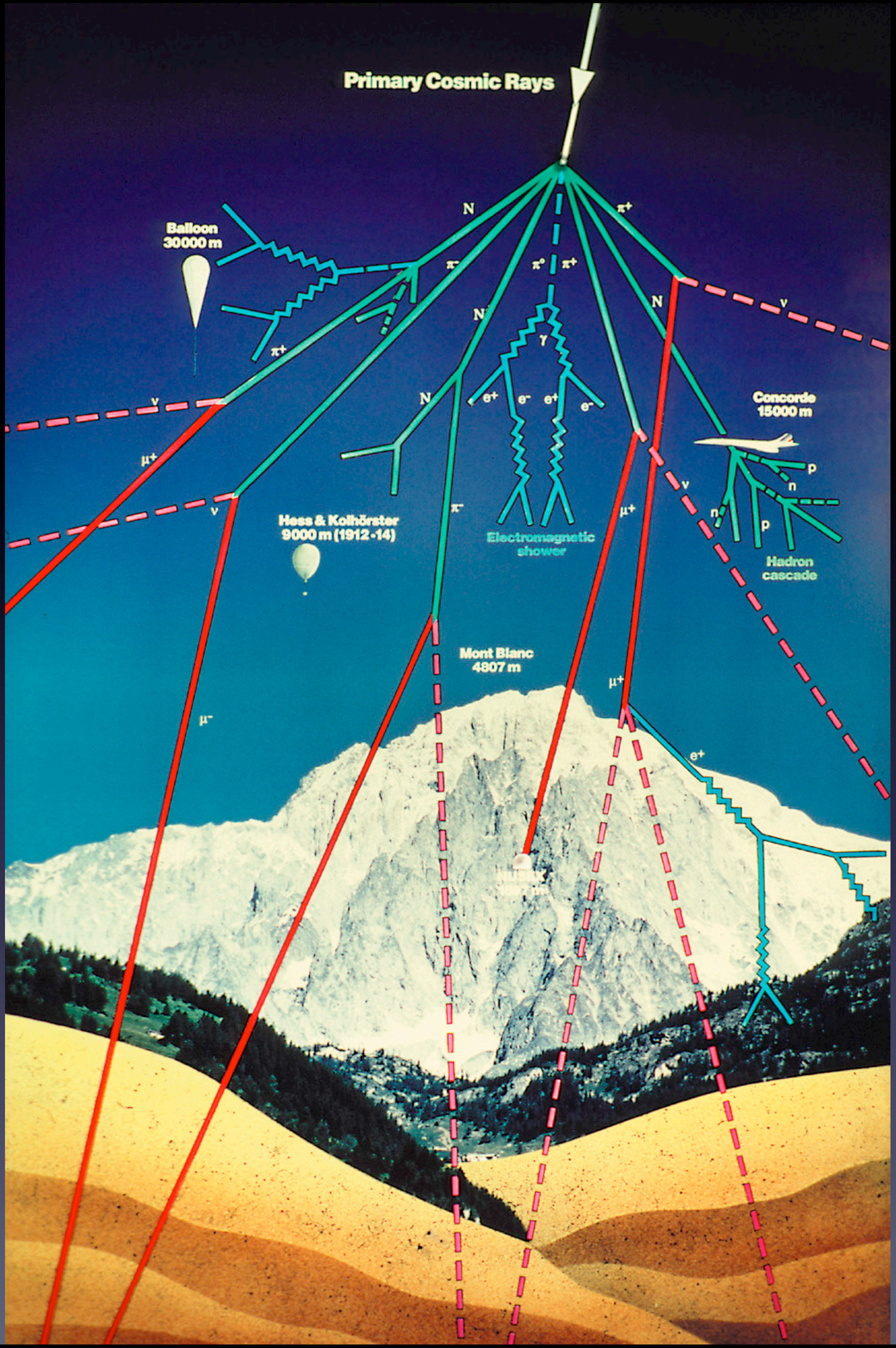
The muon

- Muons were discovered by Carl D. Anderson and Seth Neddermeyer at Caltech in 1936 with a cloud chamber while studying cosmic radiation



"The other double trace of the same type (figure 5) shows closely together the thin trace of an electron of 37 MeV, and a much more strongly ionizing positive particle whith a much larger bending radius. The nature of this particle is unknown; for a proton it does not ionize enough and for a positive electron the ionization is too strong. The present double trace is probably a segment from a "shower" of particles as they have been observed by Blackett and Occhialini, i.e. the result of a nuclear explosion".

Kunze, P., Z. Phys. 83, (1933) 1



Existence of generations

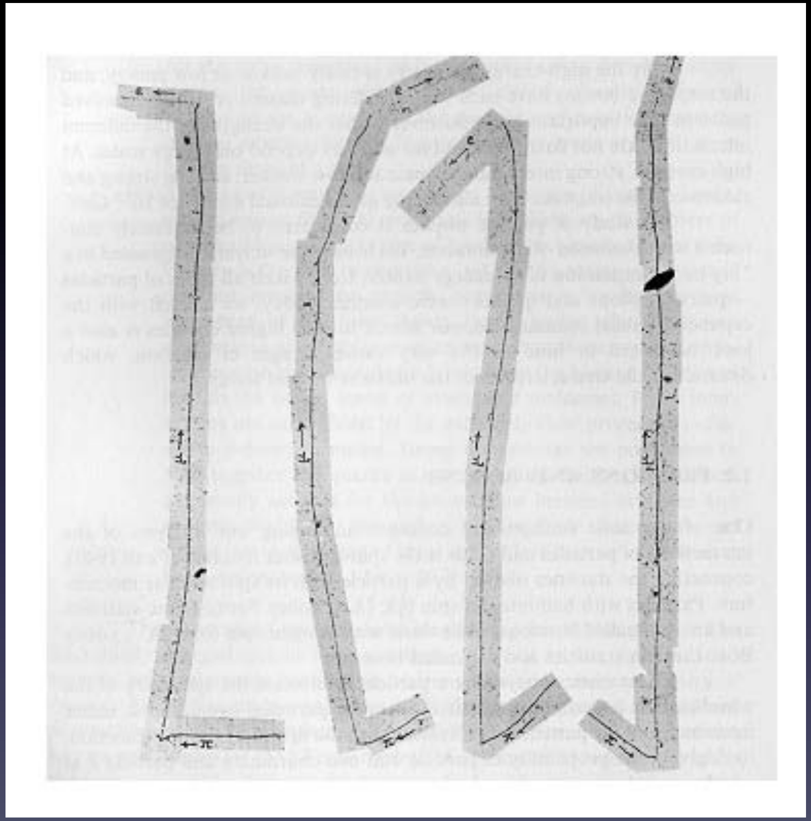
The Pion

The pion was discovered in Nuclear emulsion techniques, Powell 1947; Nobel Prize 1950

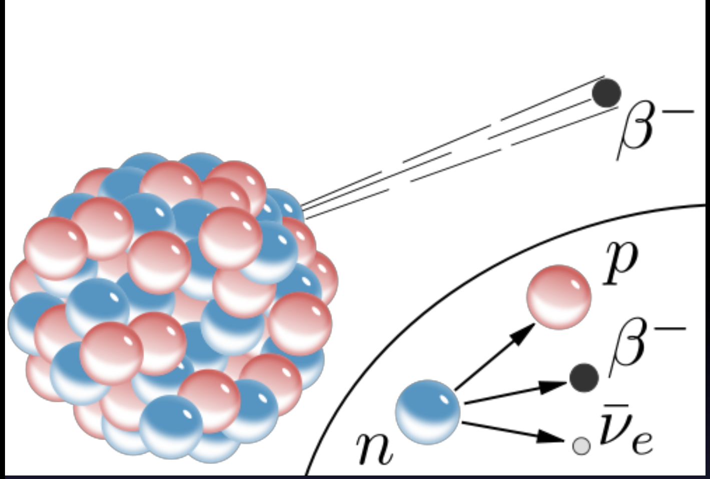
- Discovered in 1947 in nuclear emulsions exposed to cosmic rays, and they showed that it decay to a muon and an unseen partner.
- The constant range of the decay muon from the pion decay indicate that this is a two body decay

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

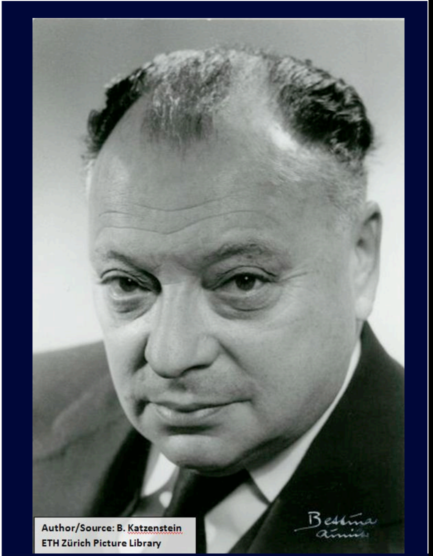
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



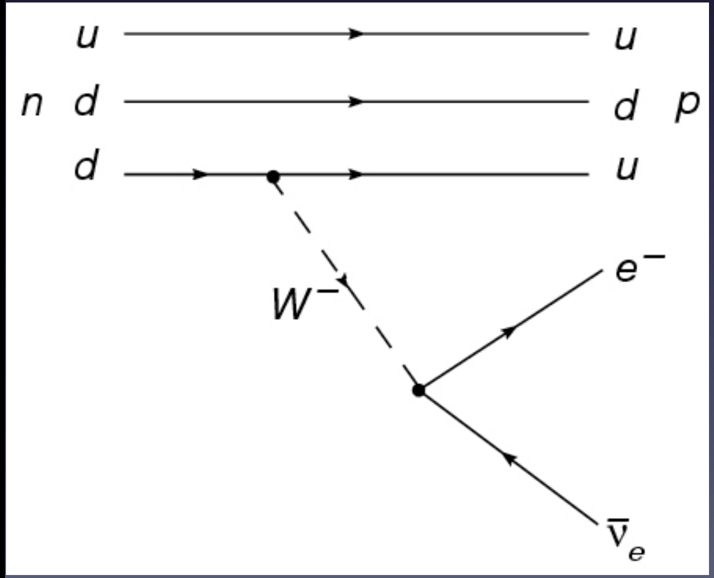
3-body kinematics: the neutrino

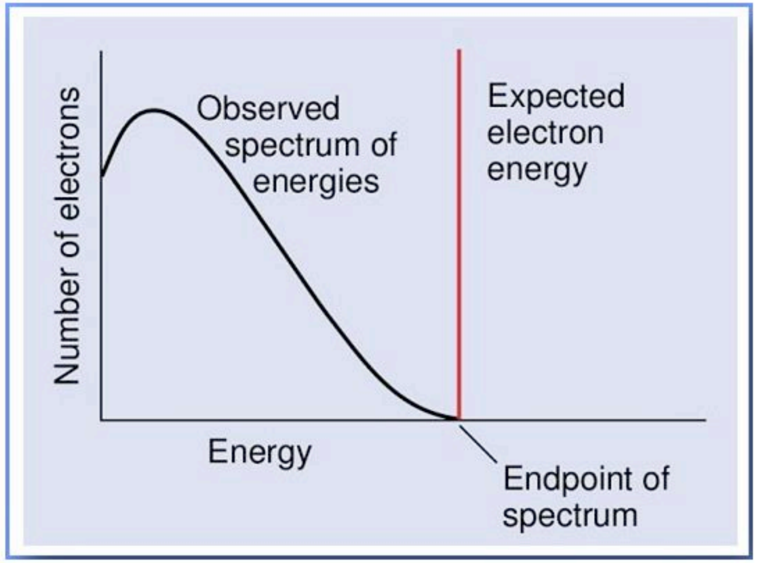


- Neutrinos do not carry any charge → take part in the electroweak and gravitational interaction → neutrinos hardly interact with matter
- Existence of neutrinos was inferred from studies of the lepton spectrum in beta decays.

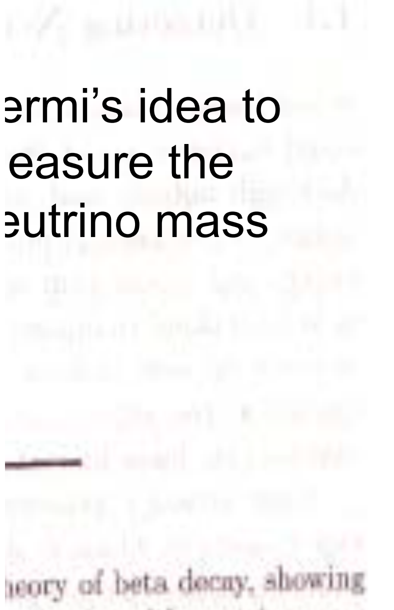


"I have done a terrible thing.





Single beta decay energy spectrum. The observed spectrum is continuous and not at a constant energy as was initially expected. [D. Stewart]

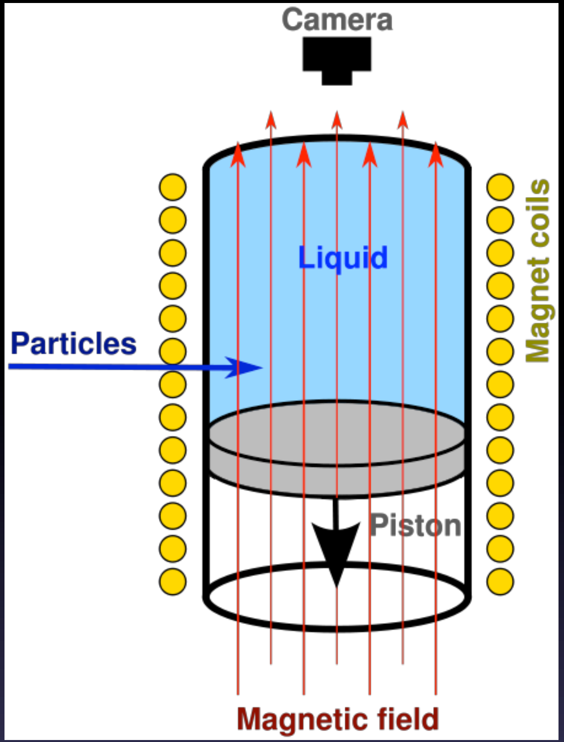


ermi's idea to
easure the
eutrino mass

ieory of beta decay, showing
im varies with neutrino mass

Imaging Detectors: the Bubble chamber

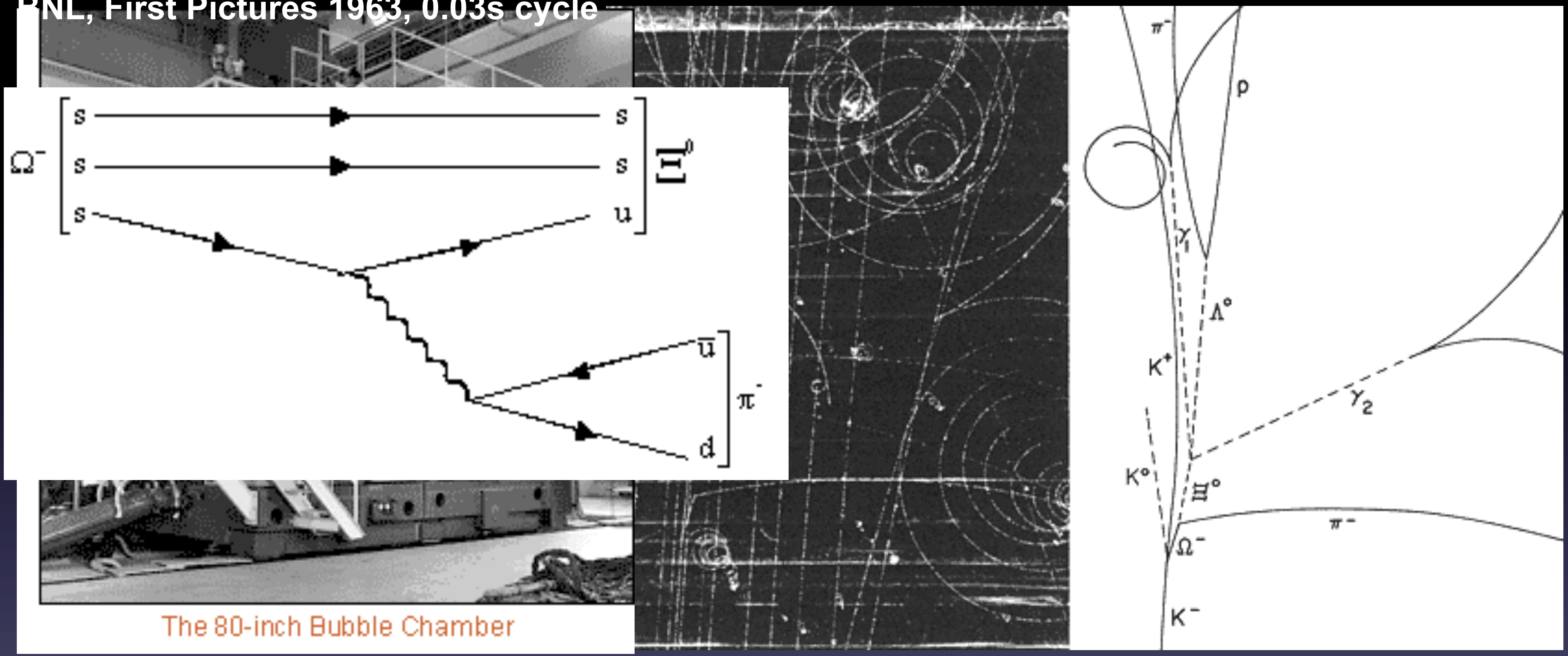
Invented in 1952 by Glaser
(1960 Nobel Prize in Physics)



- A **bubble chamber** is a vessel filled with a superheated transparent liquid (for ex. Hydrogen at T=30K). A charge particle initiate boiling.
- The size of chambers grew quickly:
  - 1954: 2.5''(6.4 cm)
  - 1954: 4''   (10 cm)
  - 1956: 10'' (25 cm)
  - 1959: 72'' (183 cm)
  - 1963: 80'' (203 cm)
  - 1973: 370 cm
- Some disadvantages:
  - It cannot be triggered
  - Low rate capability
  - The photographic readout: for data analysis one had to look through millions of photos

- Urban history: Glaser was inspired by the bubbles in a glass of beer
- In a 2006 talk he said that he did experiments using beer to fill early prototypes.

Discovery of the Omega



BNL, First Pictures 1963, 0.03s cycle

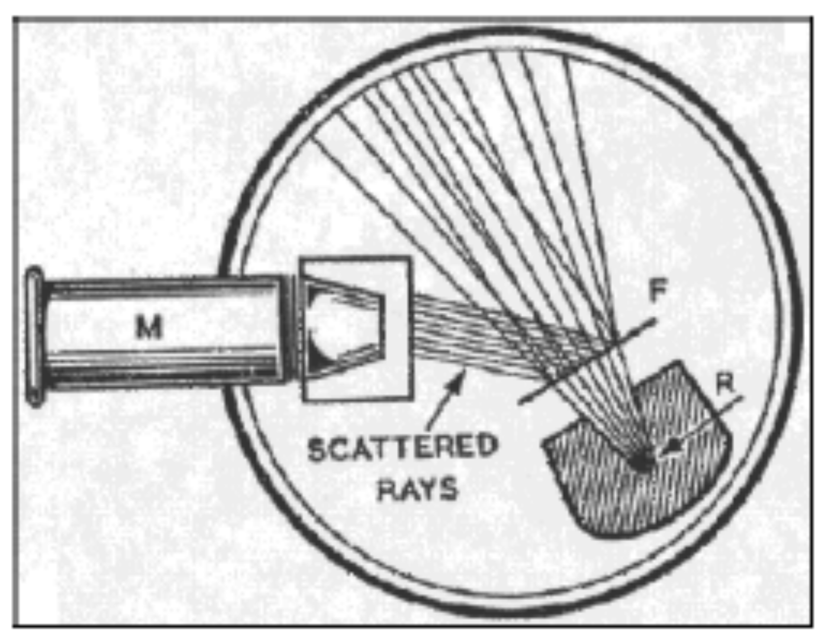
The 80-inch Bubble Chamber

Ω^- = sss   Confirmation of the quark model and color

Bubble chambers are now used to search for WIMPs

Electronics detectors

- In the 70ies the logic (electronic) detectors took over
  - Geiger counters
  - Scintillator + photomultipliers
  - Spark counters
- The particle is not "seen" but its nature and existence "deduced" via a logic experiment (coincidences, triggers, detection of decay products ...)

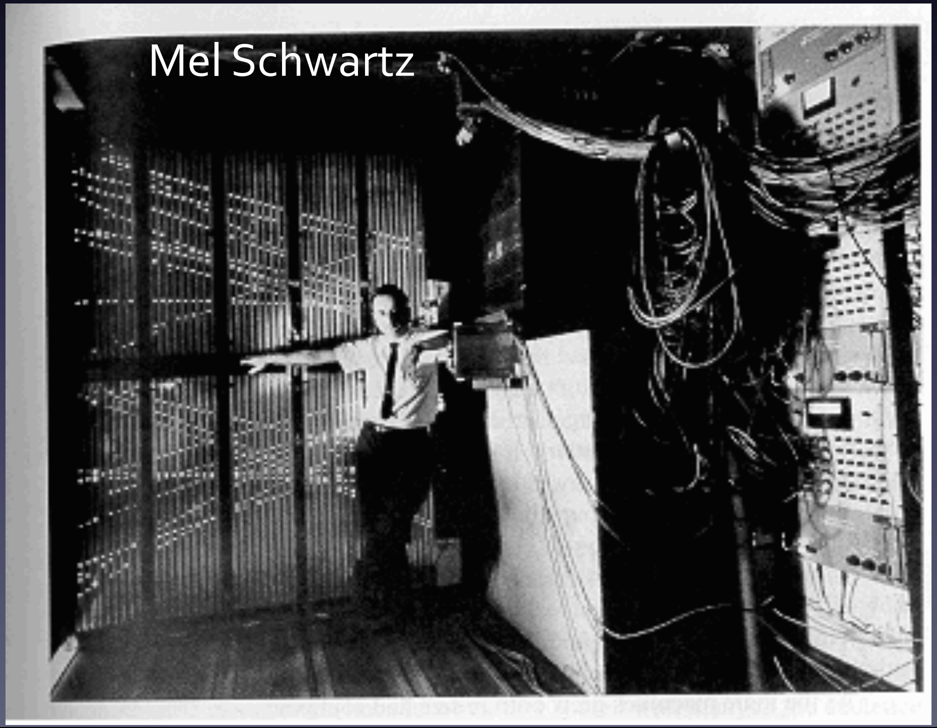


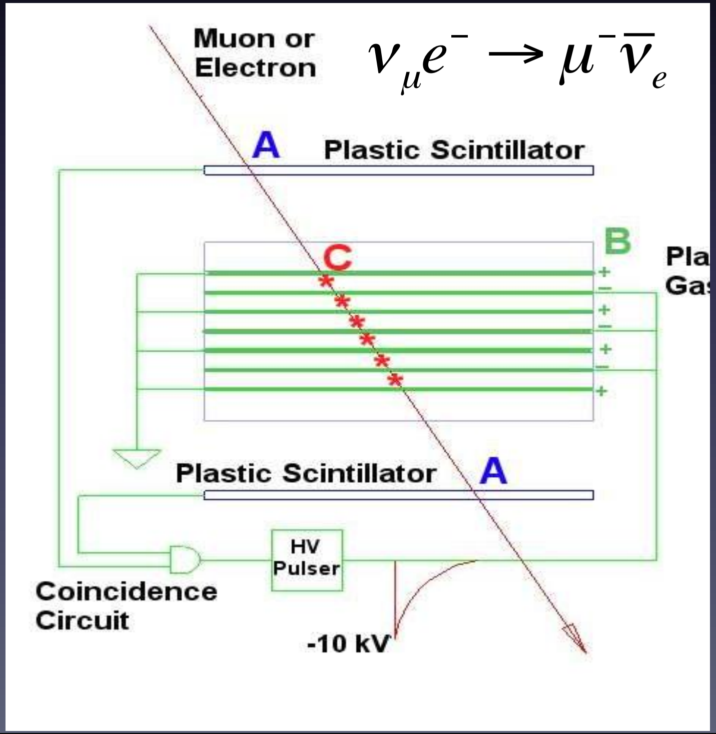
Scintillating Screen:

- Rutherford Experiment 1911:
  - Zinc Sulfide screen used as detector.
  - If an alpha particle hits the screen, a flash could be detected

The discovery of the ν_μ

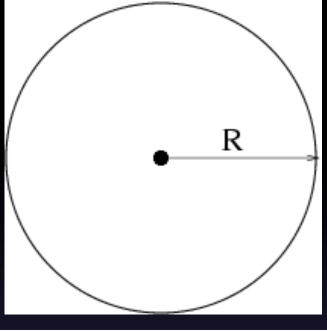
- A newly completed accelerator, the alternating Gradient SynChrotron (AGS) @ BNL was used to create a neutrino beam
  - Protons →Beryllium target→ $\pi\rightarrow\mu\nu_\mu$
  - Create neutrino beam by eliminating other particle with a 13.5-metre-thick steel wall (scrapped warships)
- Detect neutrinos with a newly invented 10-ton spark chamber



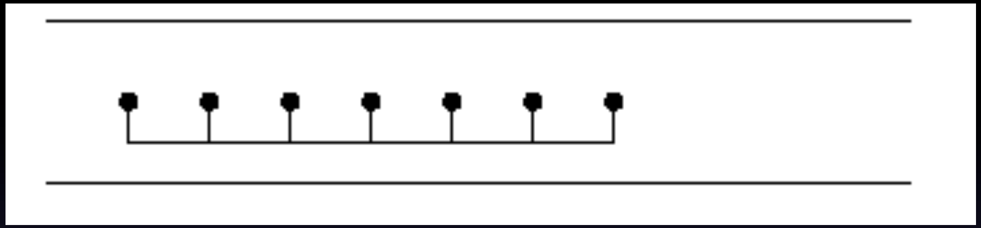


Multi-wire proportional chambers

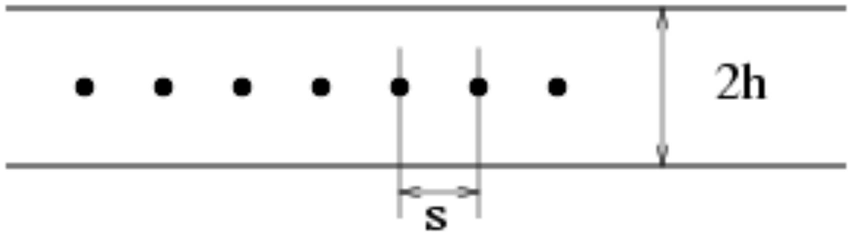
Tube, Geiger- Müller, 1928



Multi Wire Geometry, in H. Friedmann 1949

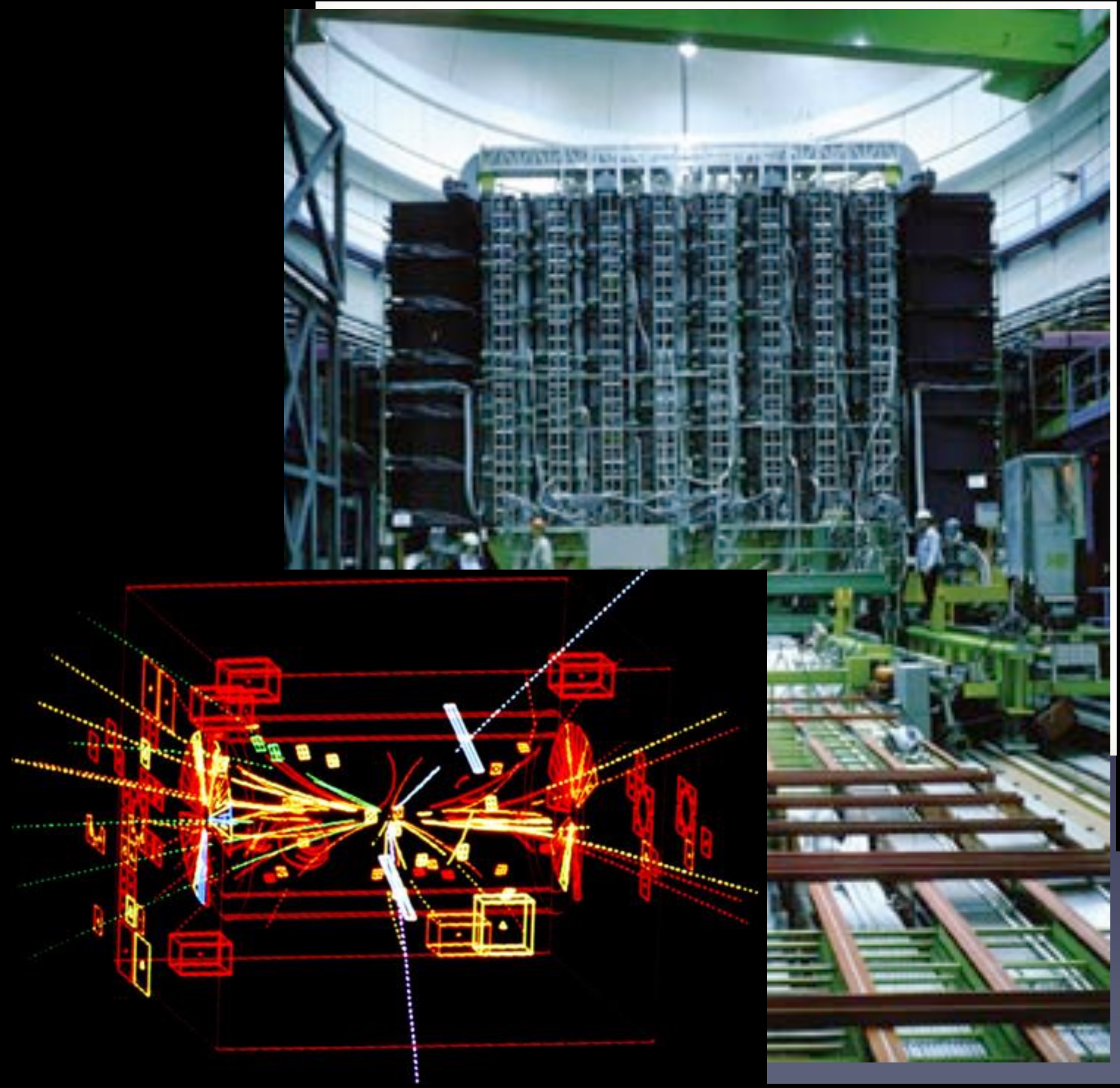


G. Charpak 1968, Multi Wire Proportional Chamber,
readout of individual wires and proportional mode working point.

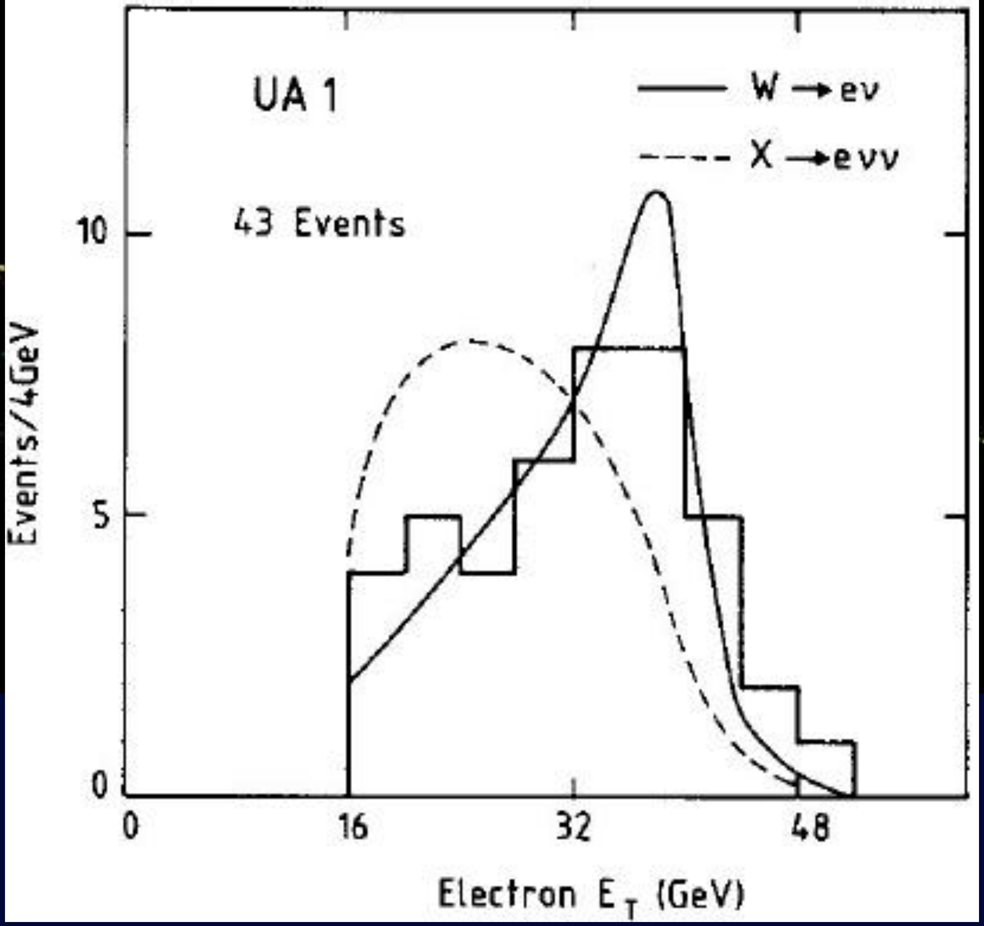


- A charged particle traversing the detector leaves a trail of electrons and ions.
- Wires are kept at positive HV.
- Electrons drift to the wires in the E field and form an avalanche close to the wire.
- This induces a signal on the wire which can be read out by an amplifier.

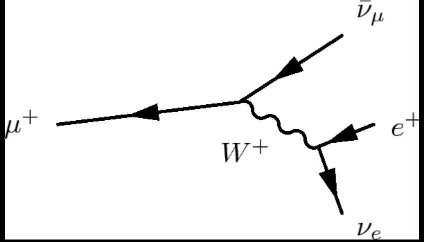
Discovery of W & Z captured in electronic photo-like images



W and Z (1983)
Rubbia & Van der Meer, Nobel Prize 1984

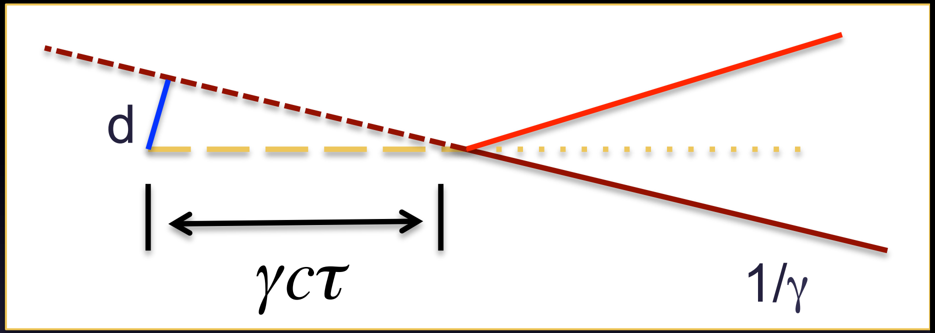


Charm and Beauty



- Lifetime of heavy quarks expected to be of the order of ~ 10^{-12} and 10^{-13} seconds

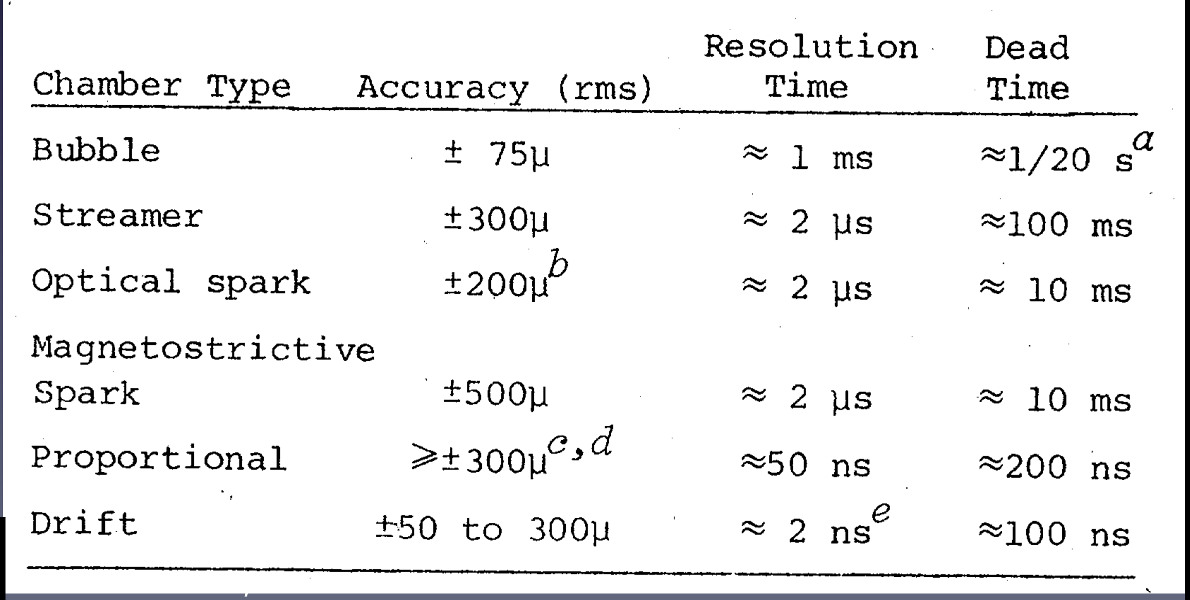
$$\Gamma \cong \frac{m_c^5 (G_F \cos\theta_c)^2}{192\pi^3} \cong \left(\frac{m_c}{m_\mu}\right)^5 \times 10^7 \sec^{-1}$$



$$d = \gamma c\tau \times \frac{1}{\gamma} \approx c\tau$$

$$\approx 30 - 300\ microns$$

Review of Particle Properties (1978)

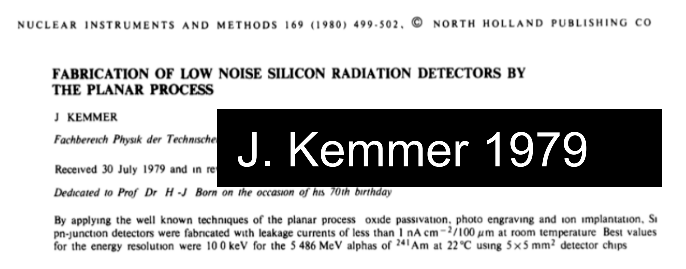


Chamber Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble	± 75μ	≈ 1 ms	≈1/20 s[a]
Streamer	±300μ	≈ 2 μs	≈100 ms
Optical spark	±200μ[b]	≈ 2 μs	≈ 10 ms
Magnetostrictive Spark	±500μ	≈ 2 μs	≈ 10 ms
Proportional	≥±300μ[c,d]	≈50 ns	≈200 ns
Drift	±50 to 300μ	≈ 2 ns[e]	≈100 ns

- Technologies in the 70s could not provide the combination of accuracy, position resolution and time resolution to identify study charm ot beauty decays.

The silicon revolution

- Game changing development: Planar technology silicon strip detectors.
  - Fast, good resolution, low dead time, radiation hardness



NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502, © NORTH HOLLAND PUBLISHING CO

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

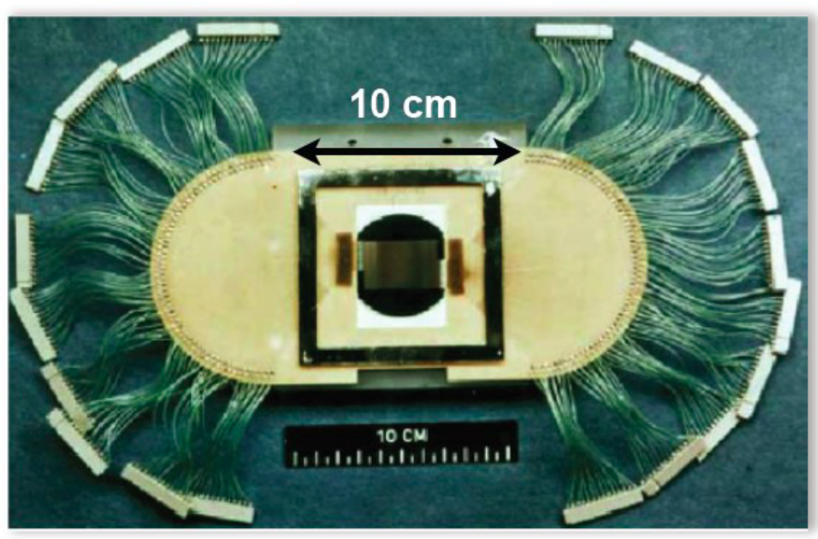
Fachbereich Physik der Technische

Received 30 July 1979 and in re

Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday

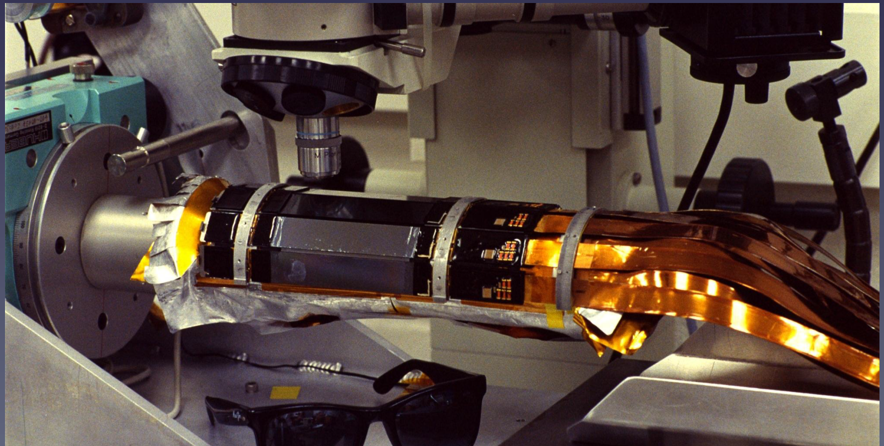
By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 μm at room temperature Best values for the energy resolution were 10 0 keV for the 5 486 MeV alphas of ^{241}Am at 22 °C using 5×5 mm^2 detector chips

J. Kemmer 1979

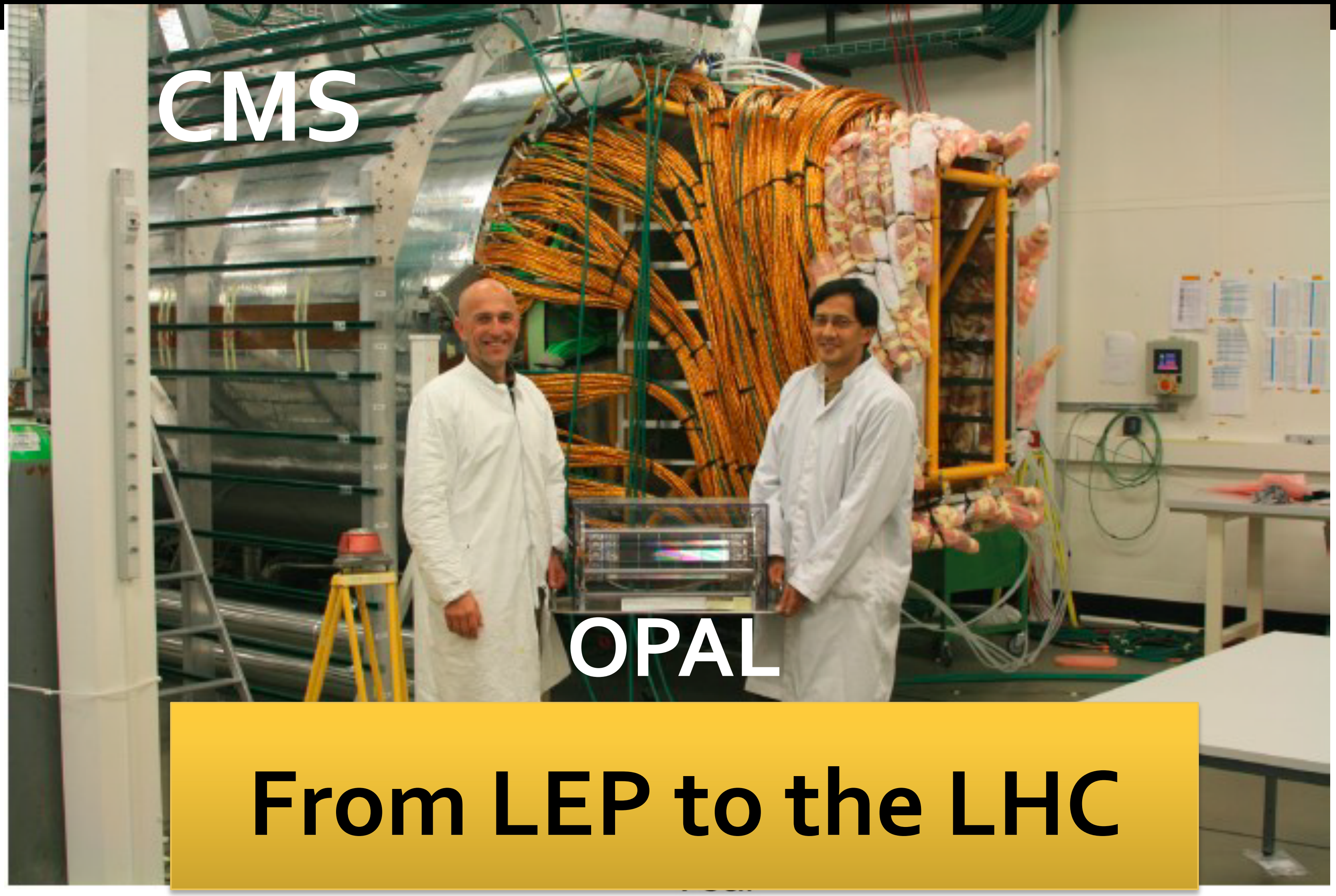


- NA 11- NA32 (1981-1984)
  - First position-sensitive silicon detector in HEP
  - Measurement of charm quark lifetimes
  - 1200 diode strips on 24x 36 mm^2
  - 4.5 μm resolution

- MARK II silicon Vertex Detector
- Proposed in 1985

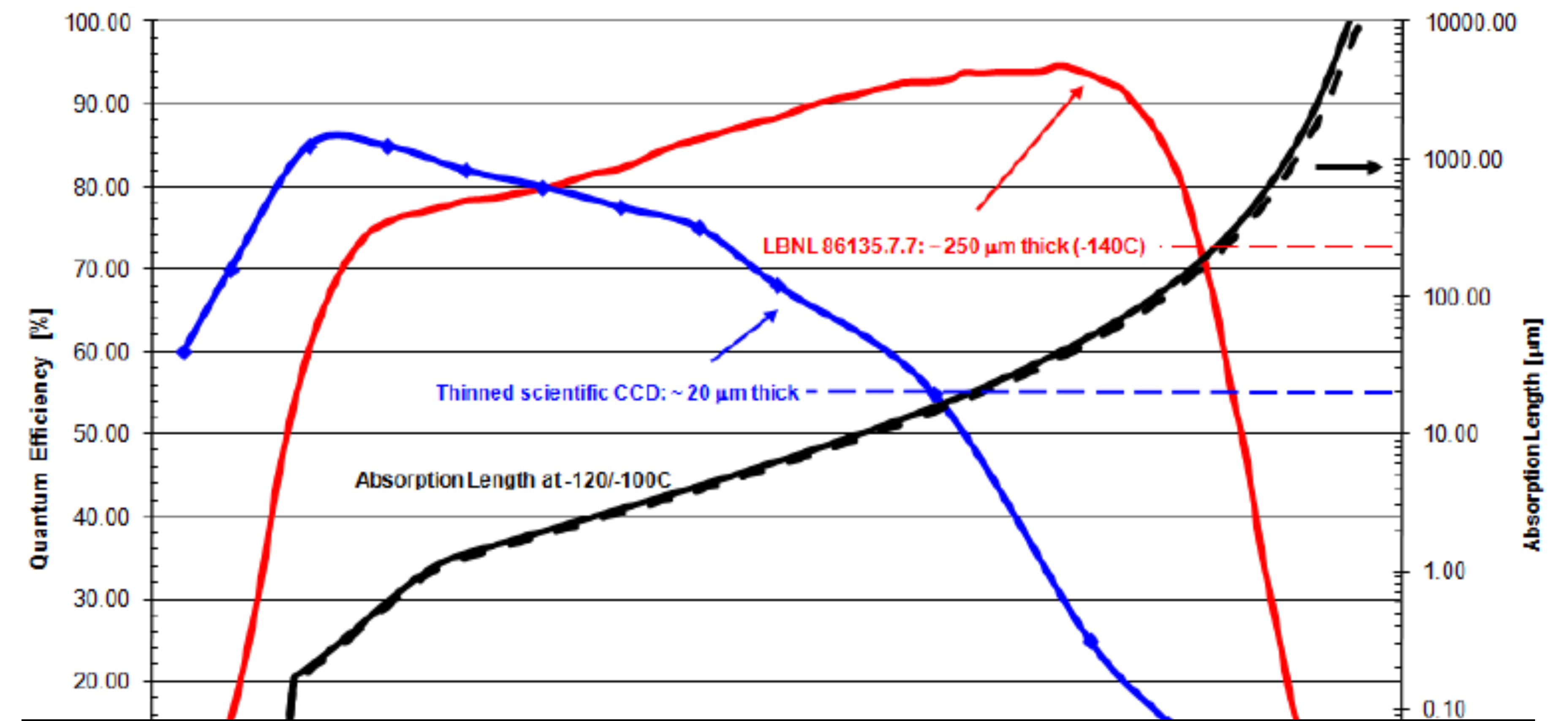


Silicon detectors evolution



From LEP to the LHC

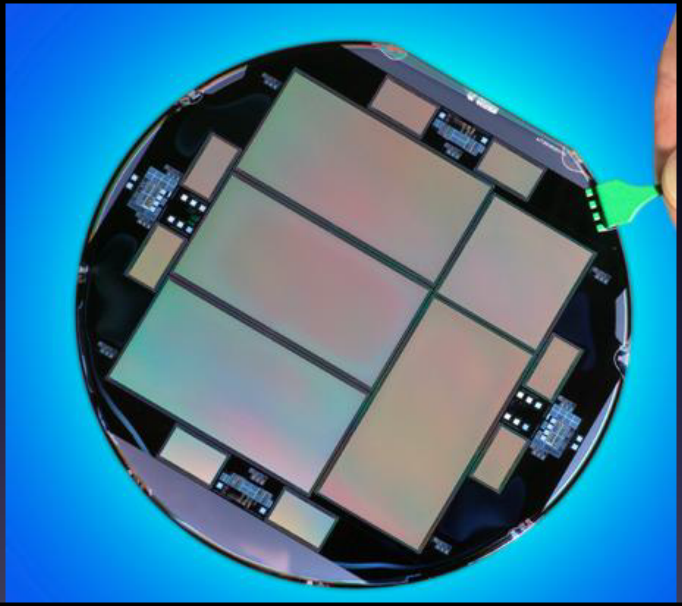
CCD and Thick CCD



Factor of 5 improvement in the detection efficiency around 900nm. Critical for the study of dark energy

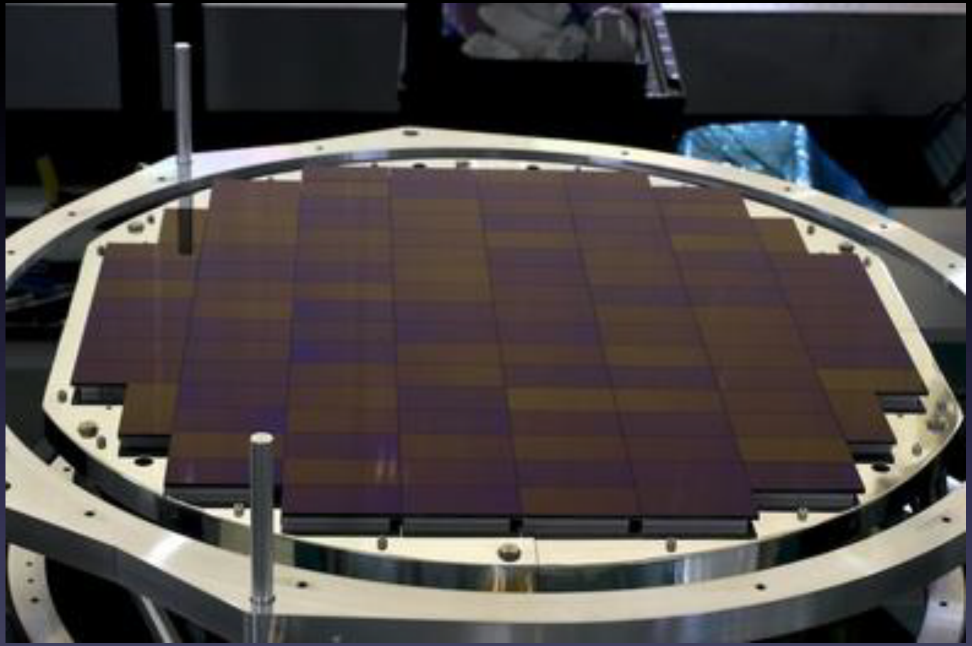
Thick CCD

- Initially all fabrication steps were done in the LBNL MicroSystems Laboratory Class 10 cleanroom



Dark Energy Survey Camera (DECam) – 62 2k x 4k, (15 µm)2-pixel CCDs *NOAO Cerro Tololo Blanco 4-m Telescope*

LBNL/DALSA: 250μm thick fully depleted CCD

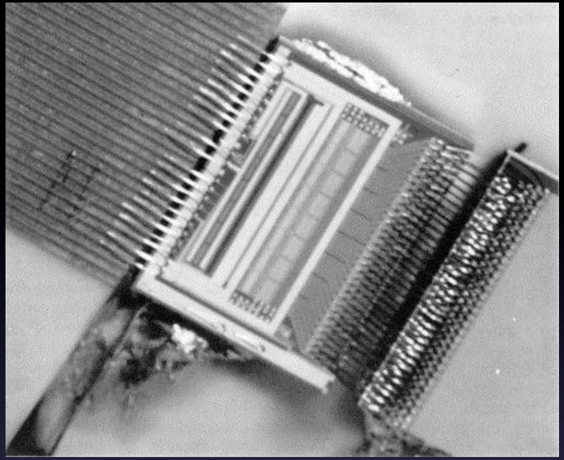


HyperSuprimeCam – 116 2k x 4k, (15 µm)^2-pixel CCDs *Subaru 8-m Telescope*

Hamamatsu: 200μm thick fully depleted CCD

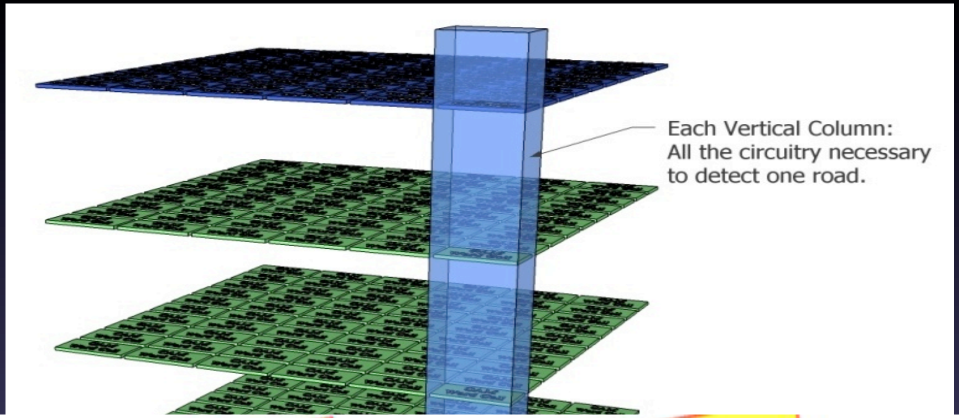
ASIC Revolution

- Microplex CHIP:128 channels on a 4.7 by 6.4 mm chip (5μm CMOS)



ATLAS FE-I4: 26,880 pixel in a 20 mm x 19 mm chip (130 nm CMOS)

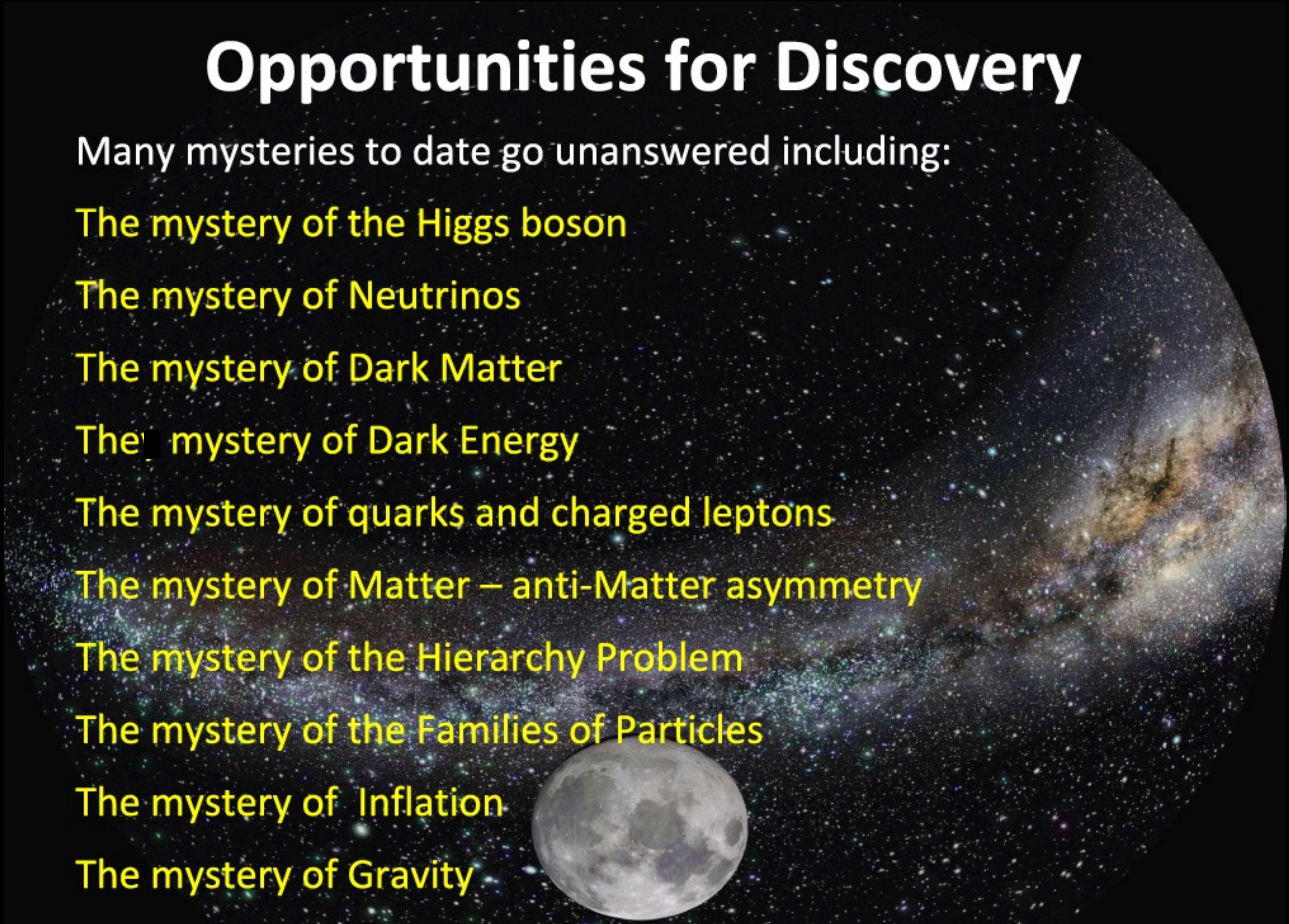
- Use emergent 3D electronics for intelligent trackers selecting high p_T event of interest in high rate environments



G. Deptuch
HEPIC2013

new "Moore's Law" on documentation volume
seen from the 14th floor at Fermilab perspective

Opportunities for Discovery



Many mysteries to date go unanswered including:

The mystery of the Higgs boson

The mystery of Neutrinos

The mystery of Dark Matter

The[redacted] mystery of Dark Energy

The mystery of quarks and charged leptons

The mystery of Matter – anti-Matter asymmetry

The mystery of the Hierarchy Problem

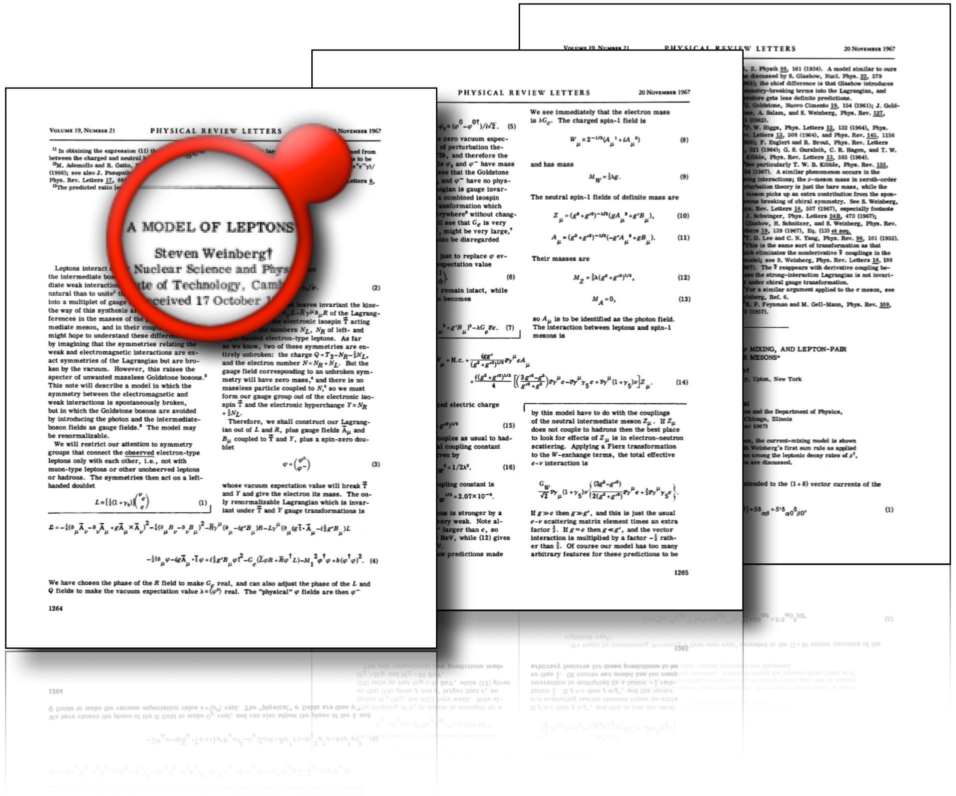
The mystery of the Families of Particles

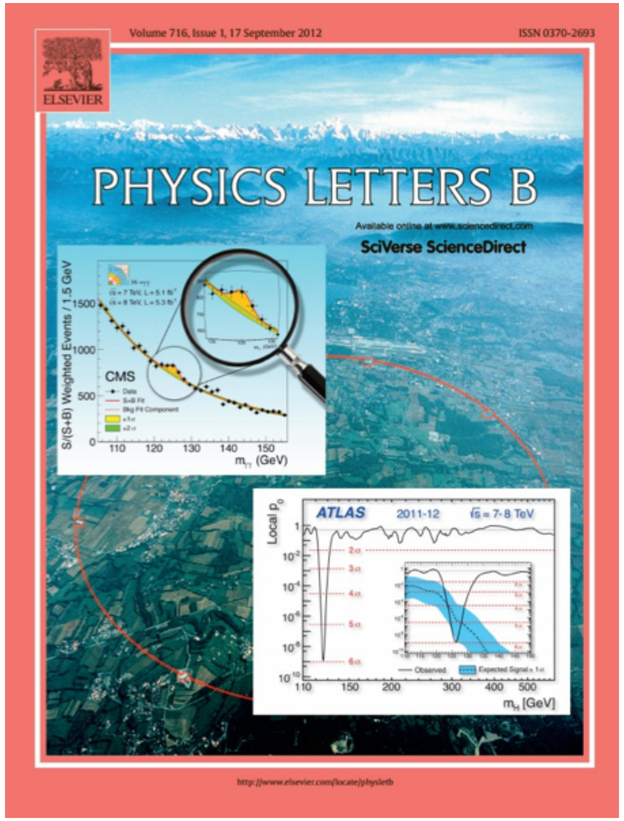
The mystery of Inflation

The mystery of Gravity

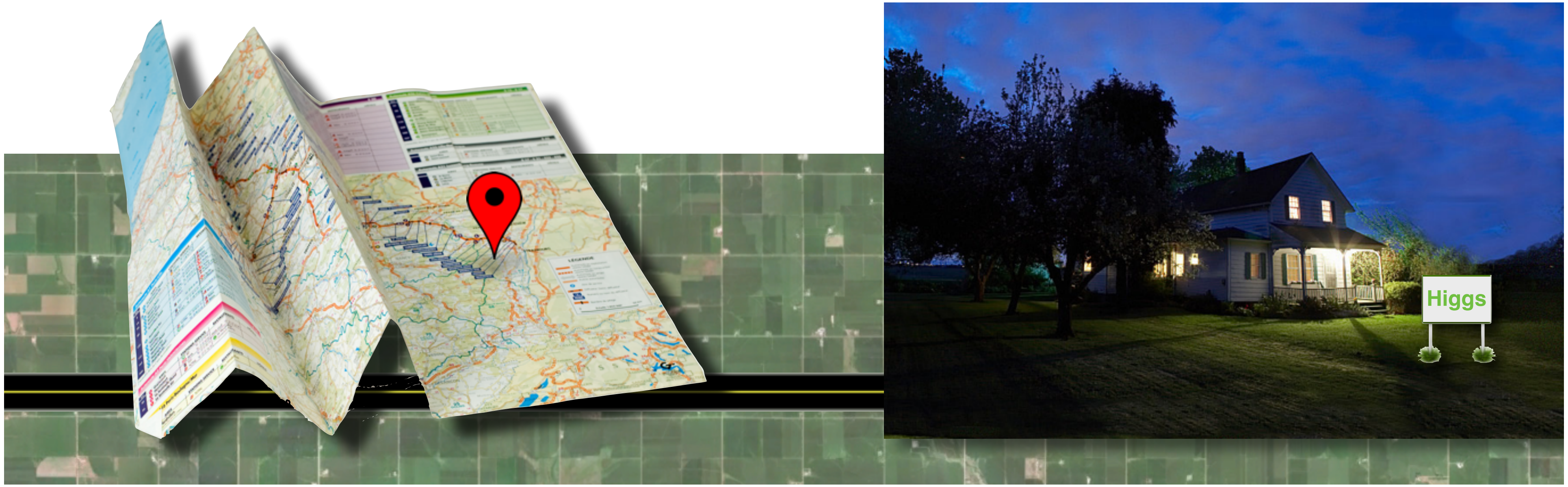
We are very much in a data driven era !

between **1967 - 2012**





The Standard Model Guided Research



No-lose completion of the Standard Model

Guaranteed discoveries

W & Z	CERN SppS
Top quark	Tevatron
Higgs	LHC

No-lose completion of the Standard Model

Now that the Standard Model is complete,
there are no further no-lose theorems
In principle, the Standard Model could be
valid to the Planck scale

No guaranteed
discoveries

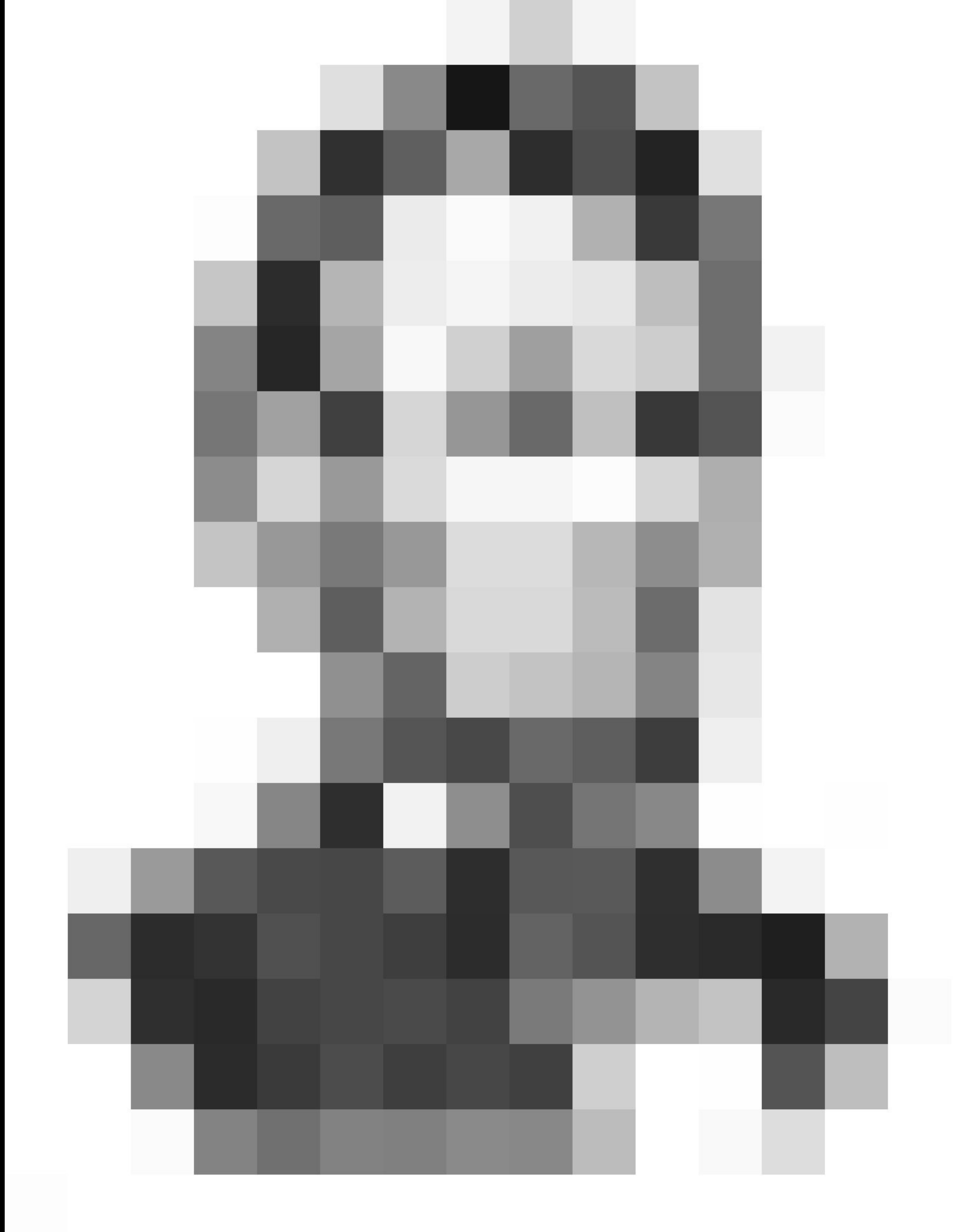
Perception & understanding *with a roadmap*

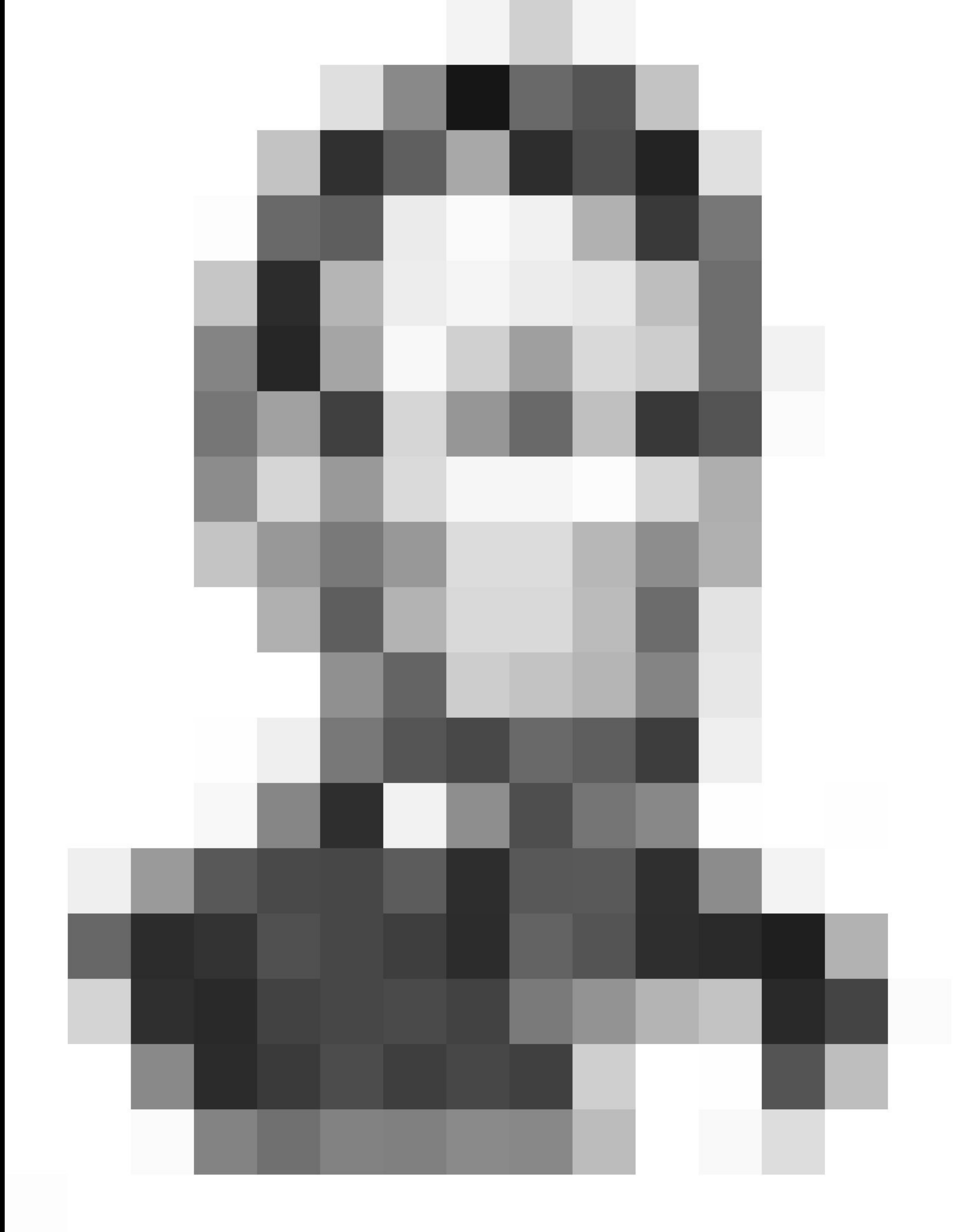
Perception is a dynamic combination of top-down (theory) and bottom-up (data driven) processing

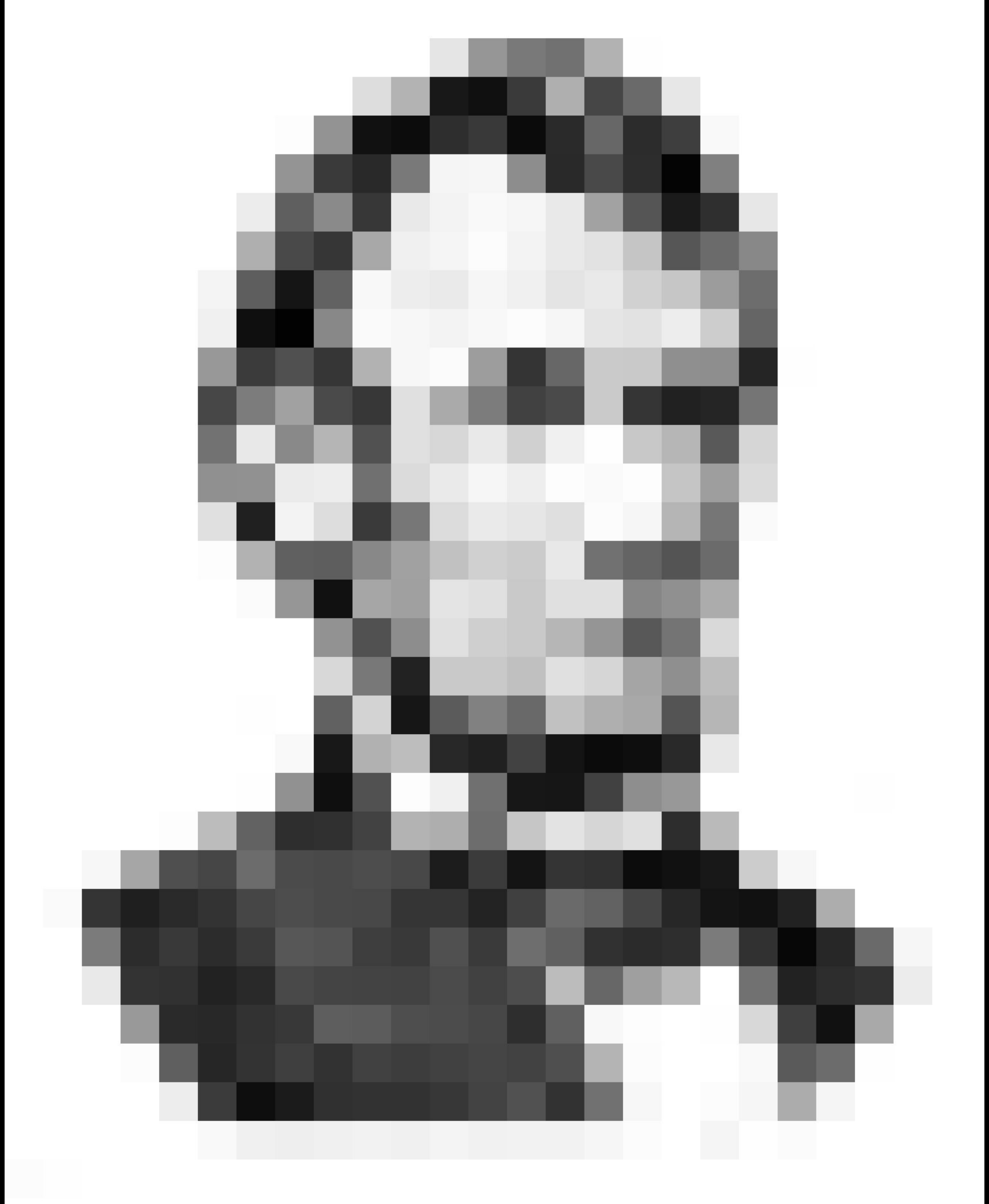
- The need for detail (quality and quantity of the data) depends on the *distinctiveness* of the object and the *level of familiarity*

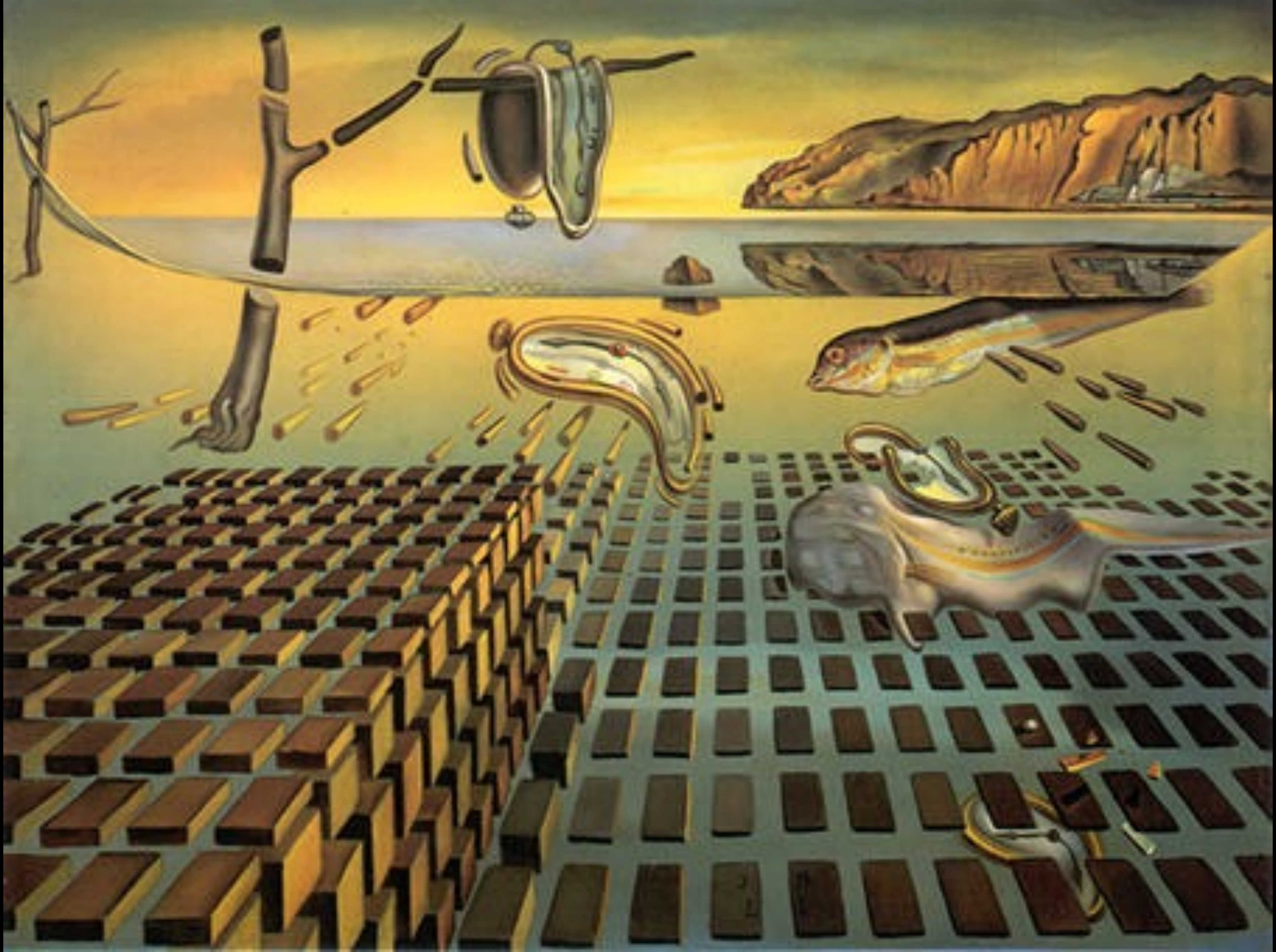
When we know the characteristics and context of what to expect (W,t,H) a little data goes a long way (top-down dominates)

Visual examples…



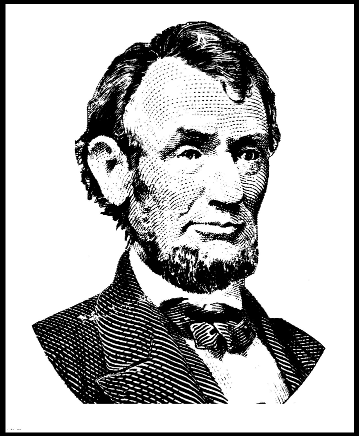






Perception & understanding

With a roadmap (theory)



(W,t,H) a little data goes a long way (top-down dominates)

w/o a roadmap (data driven)

New physics need lots of data
(bottom up dominates)

Discoveries in particle physics

Based on an original
slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	
AGS BNL (1960)	π N interactions	
FNAL Batavia (1970)	Neutrino Physics	
SLAC Spear (1970)	ep, QED	
ISR CERN (1980)	pp	
PETRA DESY (1980)	top quark	
Super Kamiokande (2000)	Proton Decay	
Telescopes (2000)	SN Cosmology	

Discoveries in particle physics

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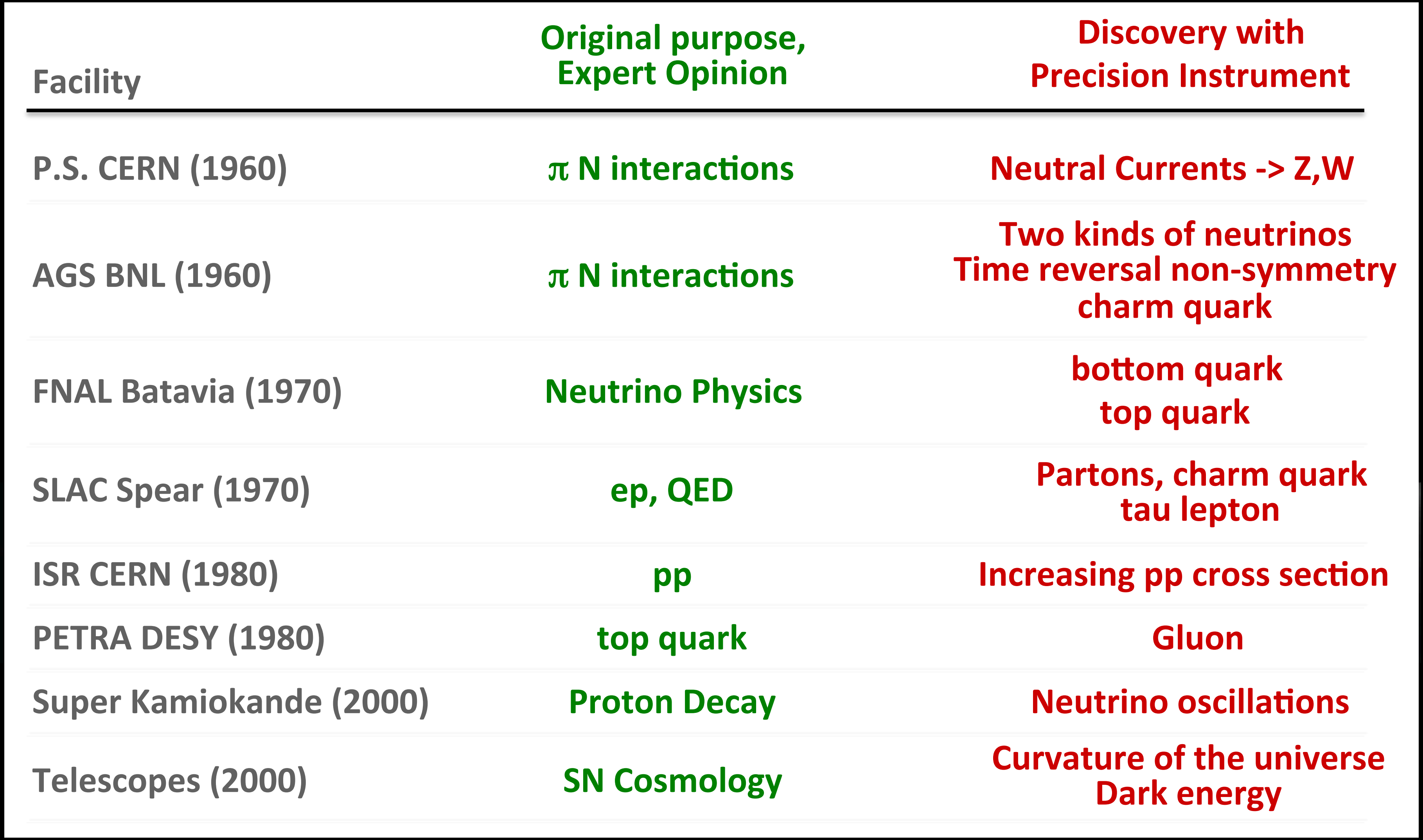

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FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
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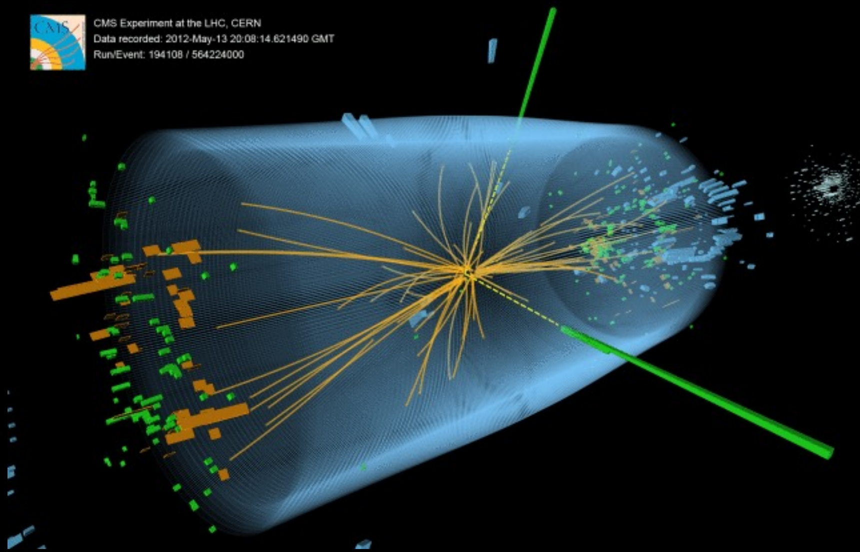
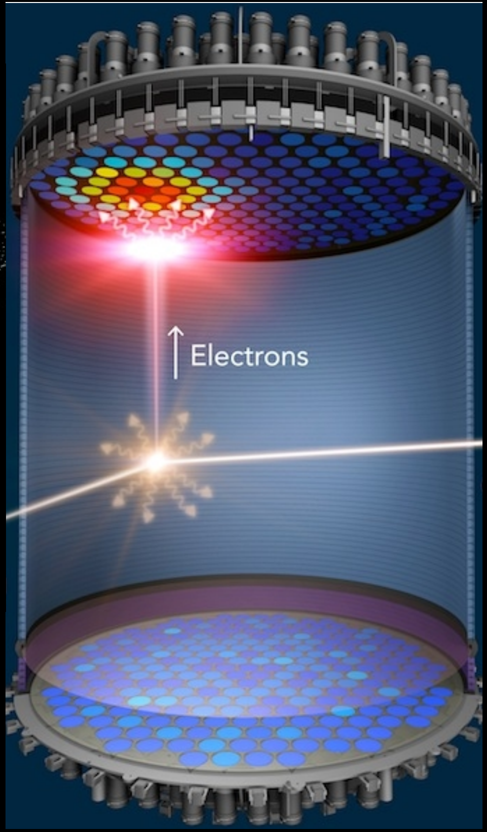
precision instruments are key to discovery when exploring new territory

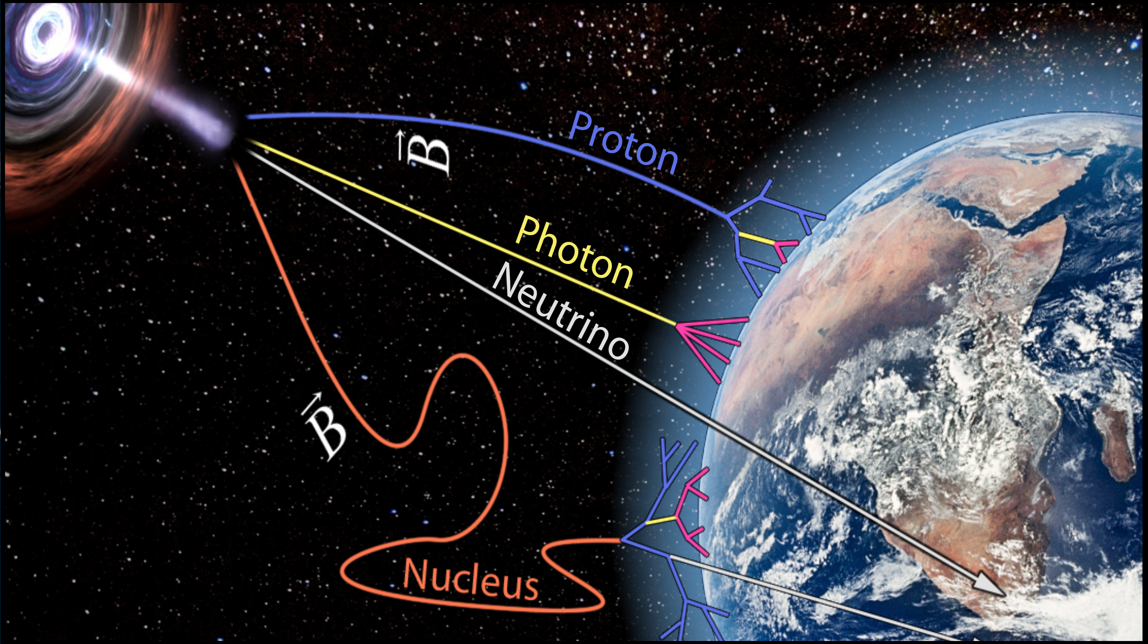
Our Technologies: synergy & broad applicability

- The particles the technologies detect, whether produced in accelerator collisions, in non-accelerator experiments, in cosmic rays or space are: photons, electrons, protons, neutrons, neutrinos, pions and kaons

- Therefore the technologies that detect these particles are broadly applicable across PP NP and APP & synergistically developed



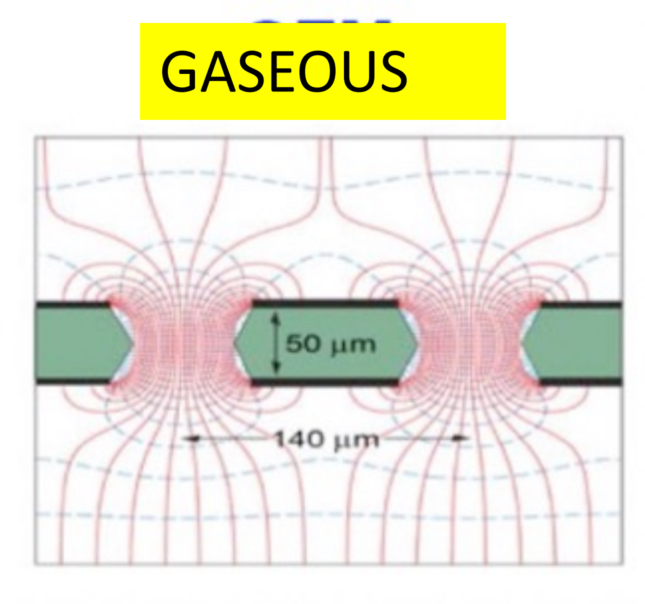




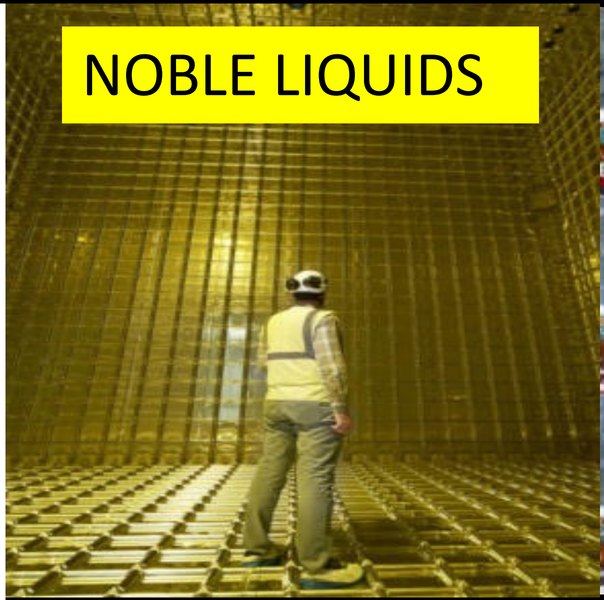
- In addition LIGO detects gravitational waves & certain quantum technologies are sensitive to dark matter waves

Technology Classification for the ECFA R&D Roadmap

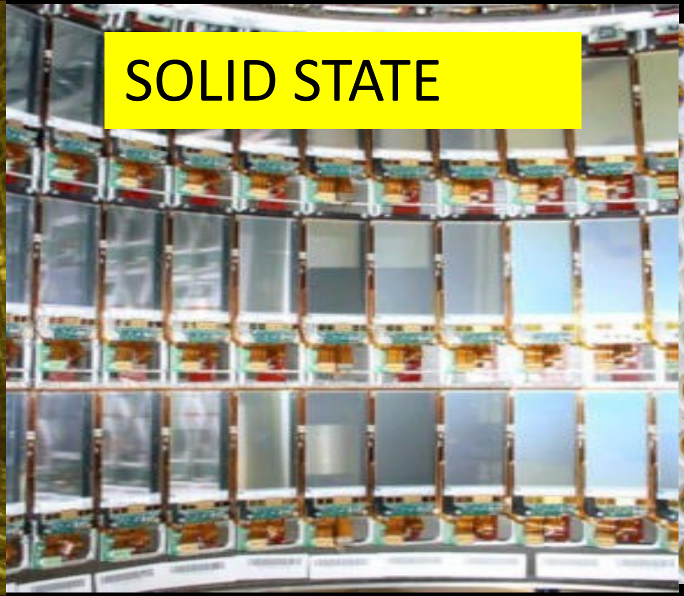
GASEOUS



NOBLE LIQUIDS

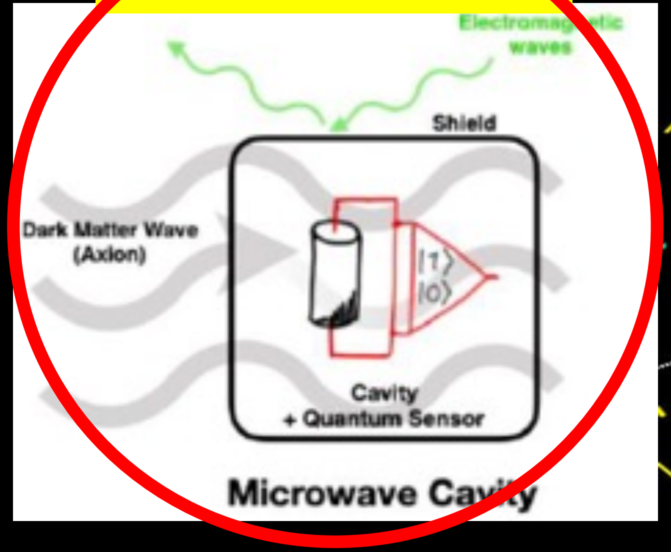


SOLID STATE

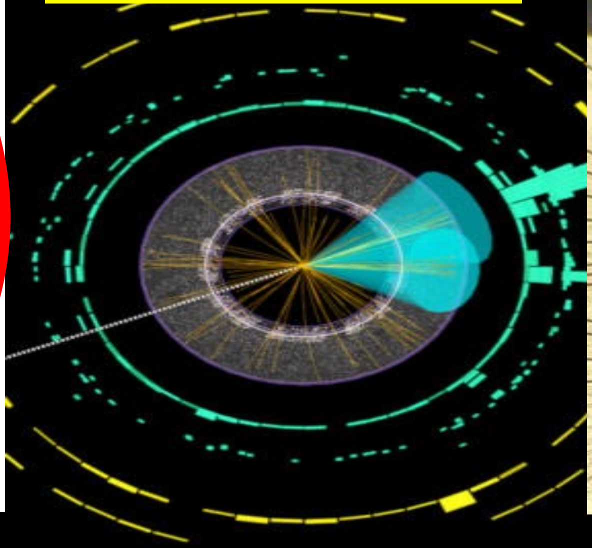


PHOTODETECTORS

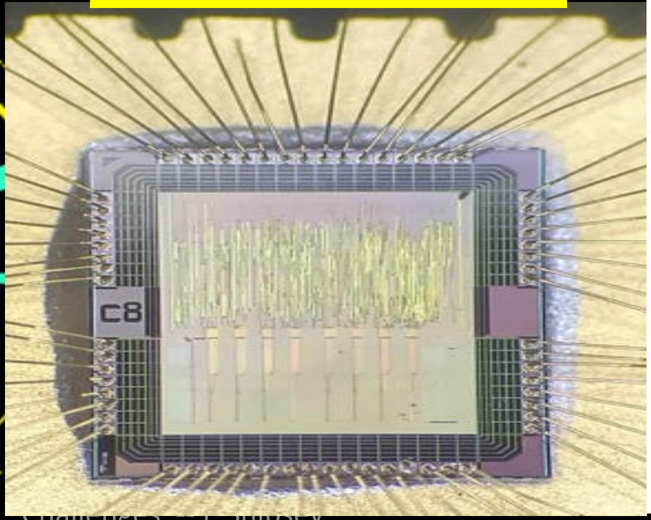
QUANTUM



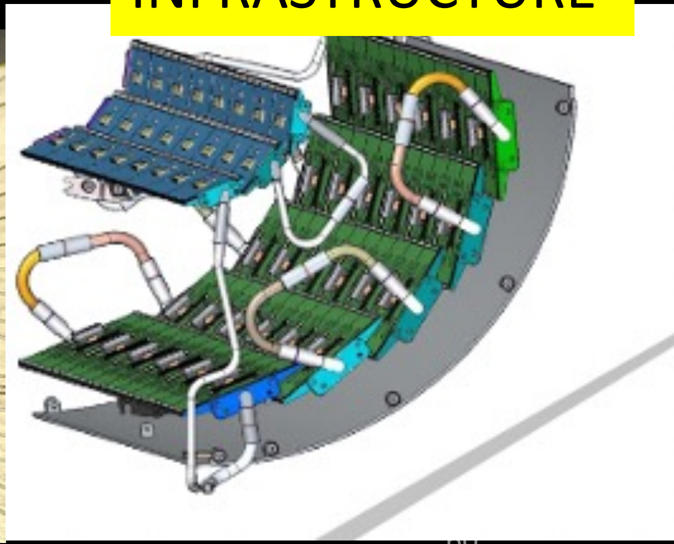
CALORIMETER



ELECTRONICS



INFRASTRUCTURE

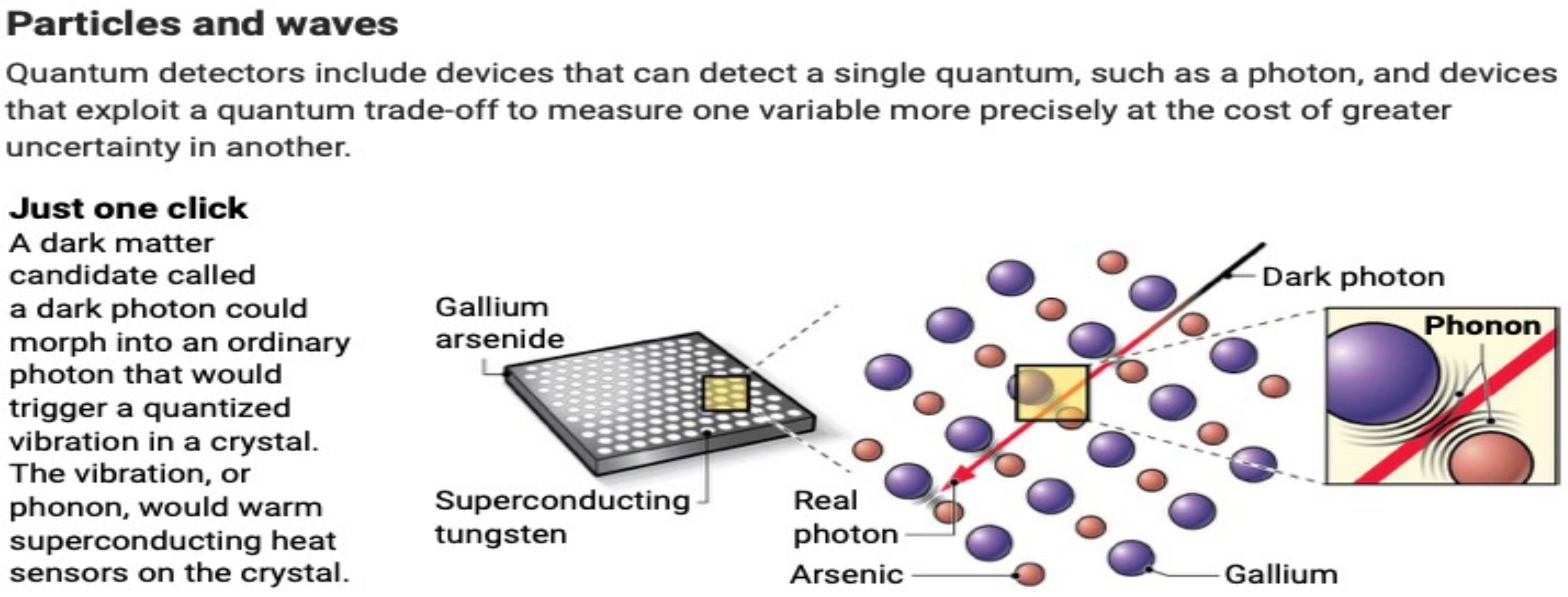


quantum sensors register a change of quantum state caused by the interaction with an external system:

- transition between superconducting and normal-conducting
- transition of an atom from one state to another
- change of resonant frequency of a system (quantized)

Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***.

and because the commensurate energies are very low, unsurprisingly, quantum sensors are ideally matched to low energy (particle) physics;



Particles and waves

Quantum detectors include devices that can detect a single quantum, such as a photon, and devices that exploit a quantum trade-off to measure one variable more precisely at the cost of greater uncertainty in another.

Just one click

A dark matter candidate called a dark photon could morph into an ordinary photon that would trigger a quantized vibration in a crystal. The vibration, or phonon, would warm superconducting heat sensors on the crystal.

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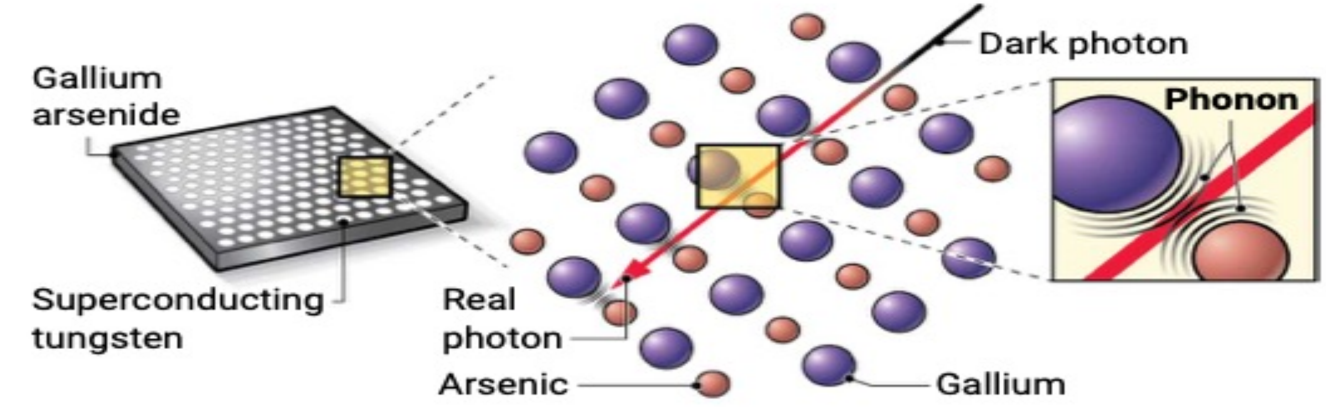
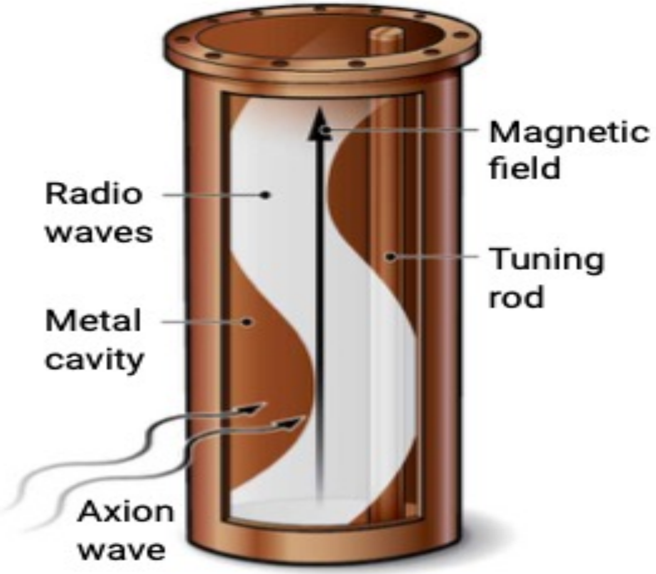


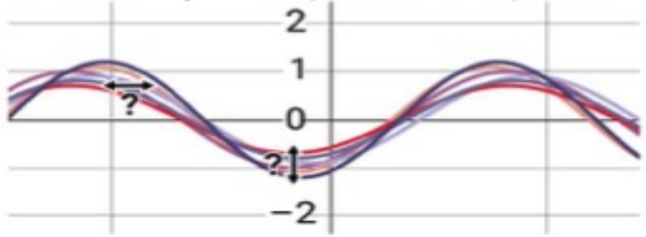
Quantum trade-off

Within a resonating cavity, a wave of hypothetical axions could transform into faint radio waves, uncertain in both amplitude and phase. Quantum techniques could reduce the uncertainty in the amplitude while increasing that in the wave's irrelevant phase.

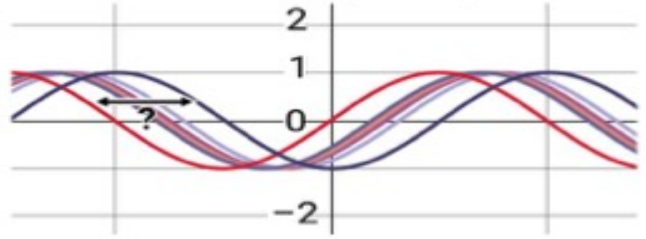


Radio signals

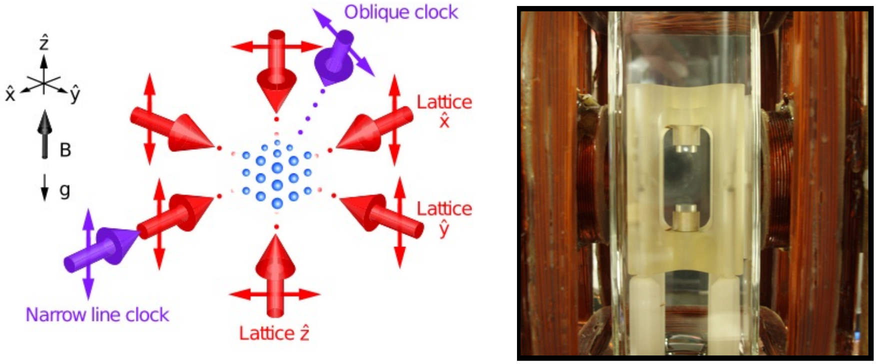
Uncertainty in amplitude and phase



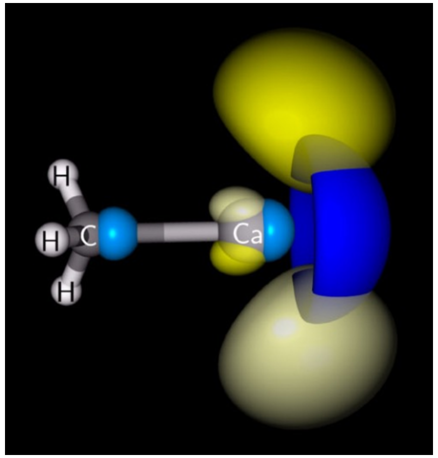
Increase phase uncertainty to decrease uncertainty in amplitude



Experimental Systems

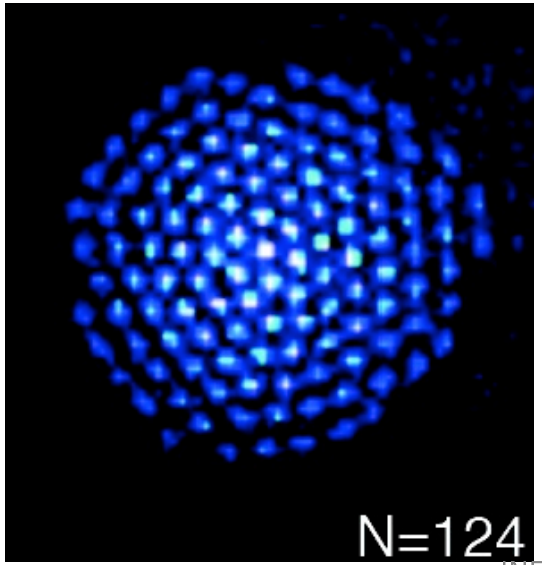


Atoms in an Optical Lattice/Cavity

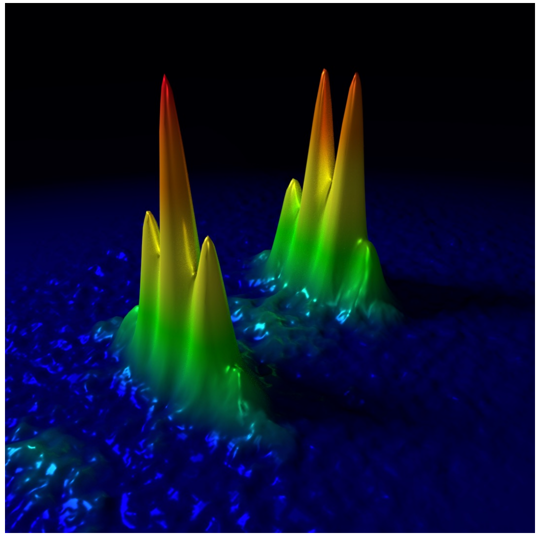


Molecules

QUANTUM
A broad range of different experimental methodologies

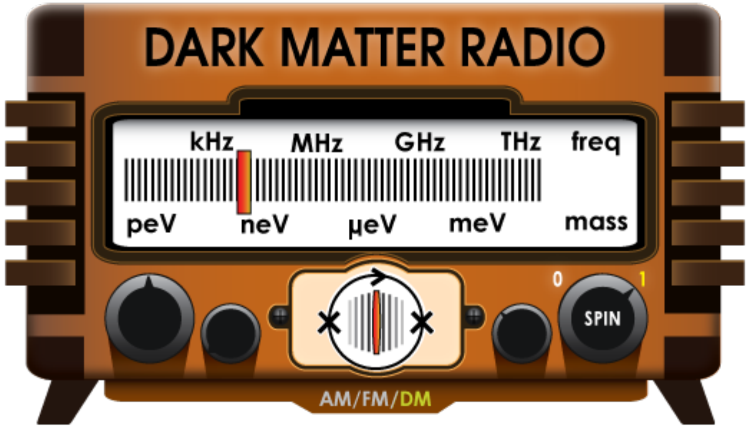


Trapped Ions

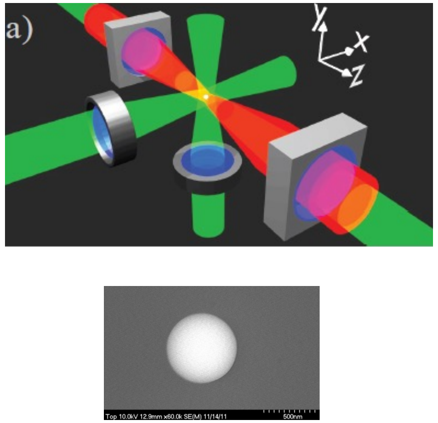


Atom Interferometers

Experimental Systems, continued…

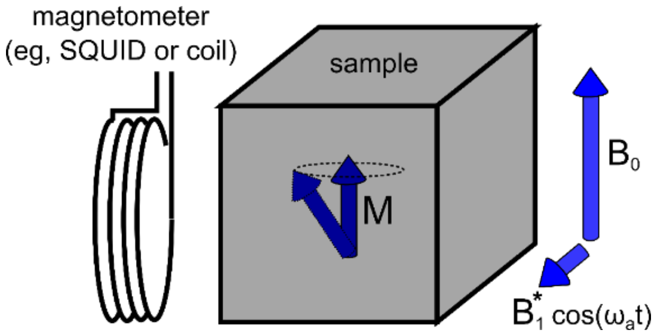


Superconducting Circuits



Nanomechanical Resonators

QUANTUM
A broad range of different experimental methodologies



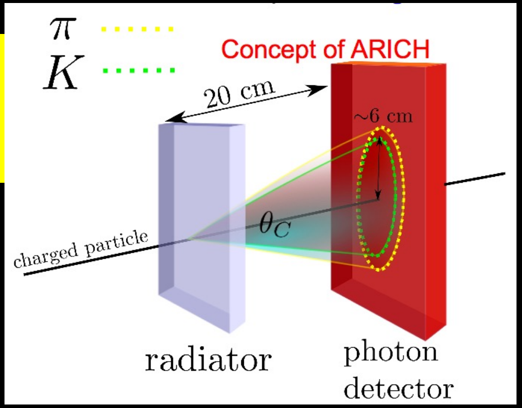
NMR

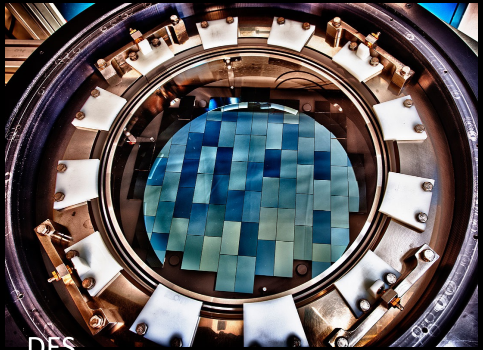
Commercial Quantum Annealer

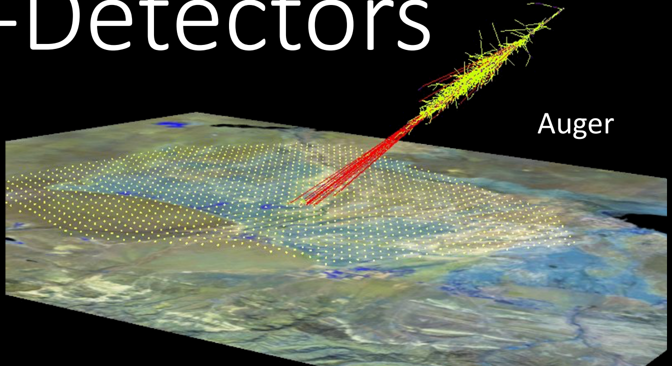
The Broad Reach of Photo-Detectors

Example: Photodetectors

BELLE-II

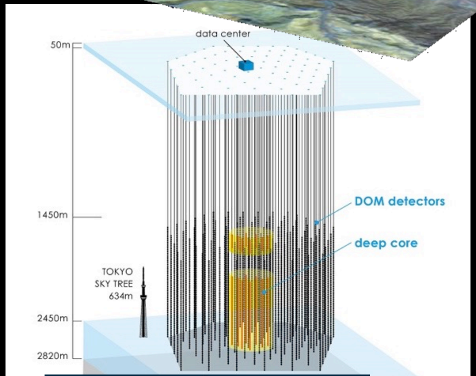


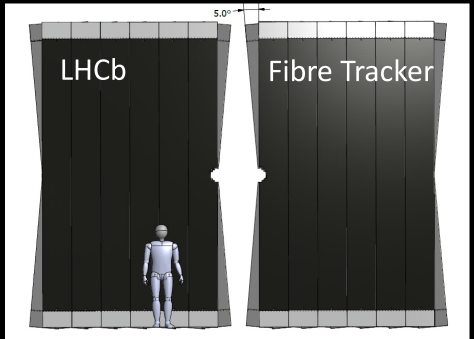


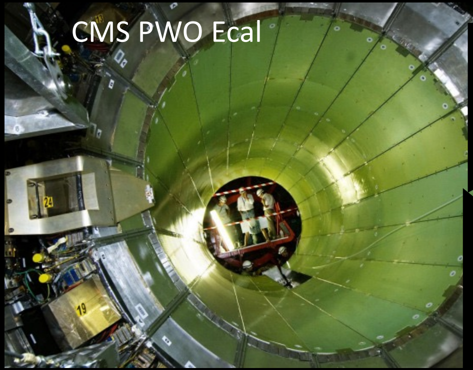


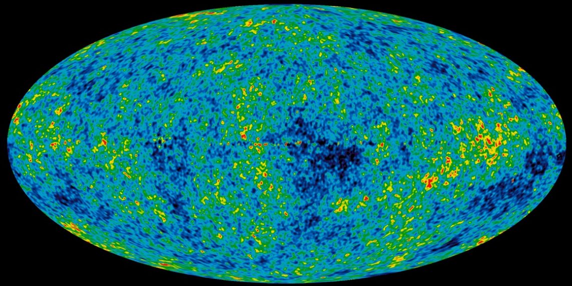
Photon detection is ubiquitous over wide range of wavelengths & signal times

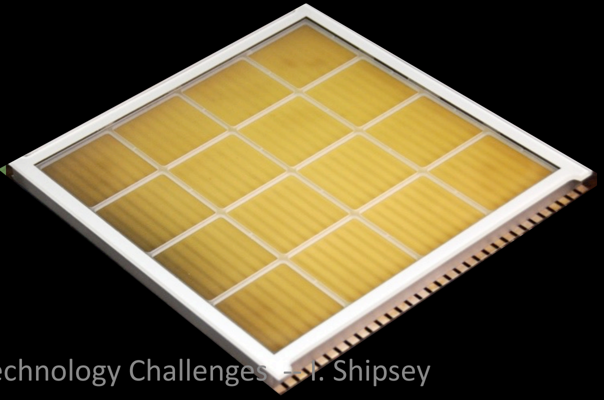
Challenge: Development of large-area devices, radiopure, cryogenic stability and high QE within appropriate wavelength sensitive window

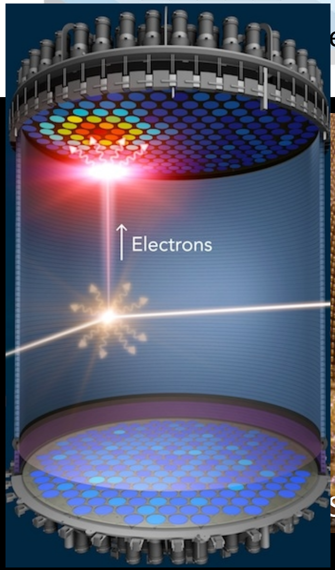


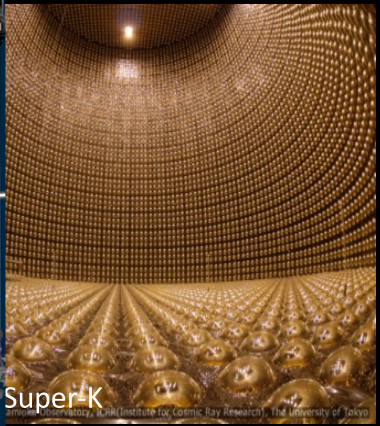










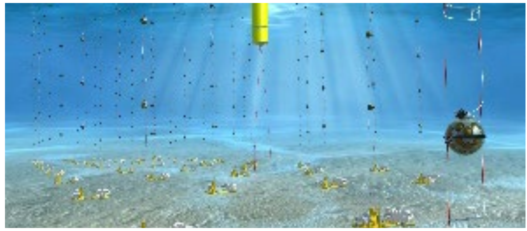


APPEC Flagship Research Infrastructures

This is not a closed, but dynamic list…

(APPEC is the European Astro Particle Physics Community)

[construction KM3NeT 2020-2026]



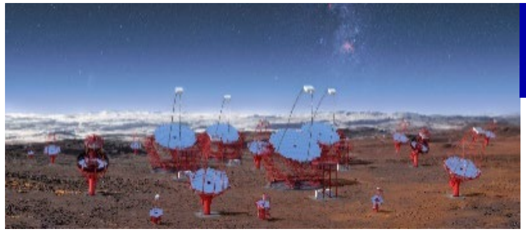
ESFRI

HE Neutrinos

[construction AugerPrime 2019-2023]

HE Cosmic Rays

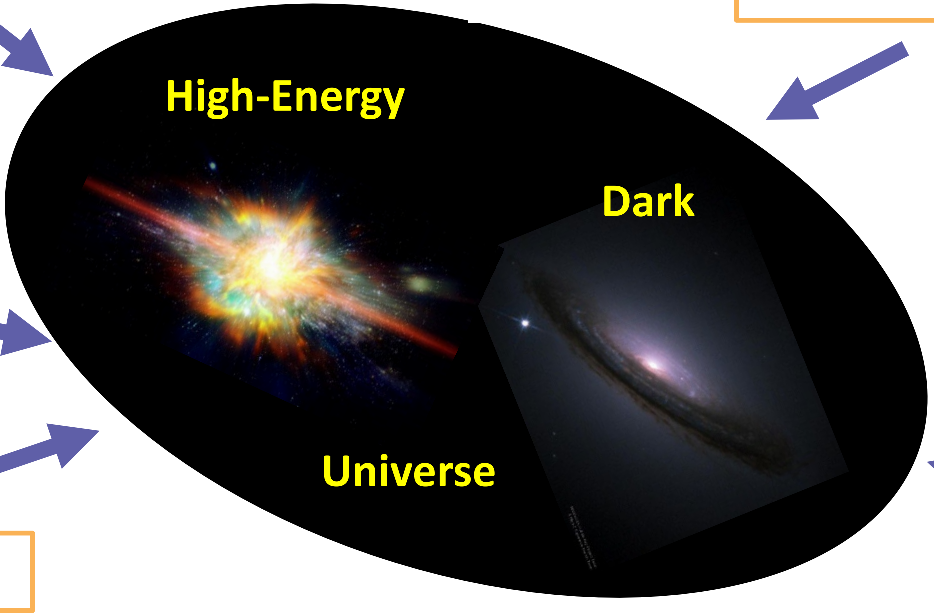
[construction CTA 2021-



ESFRI

HE Gamma rays

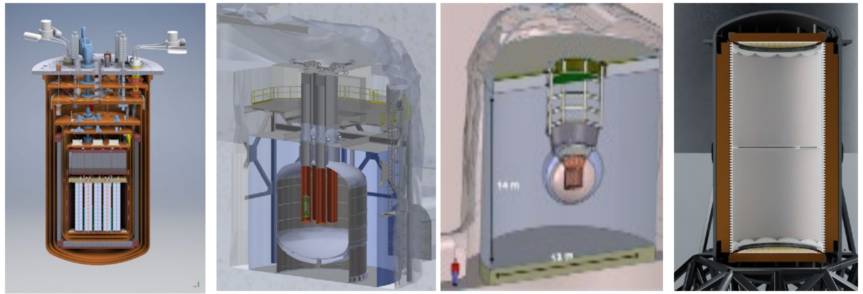
Photo-sensors play a crucial role in enabling the science objectives in each of these infrastructures



High-Energy

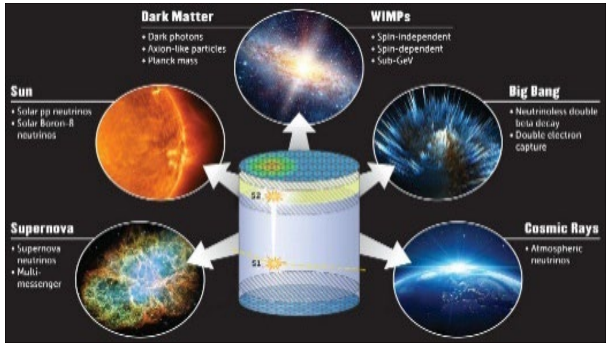
Dark

Universe



[construction LEGEND-1000 2023-

Neutrino Properties



[construction DARWIN 2024-

Now XLZD

Dark Matter

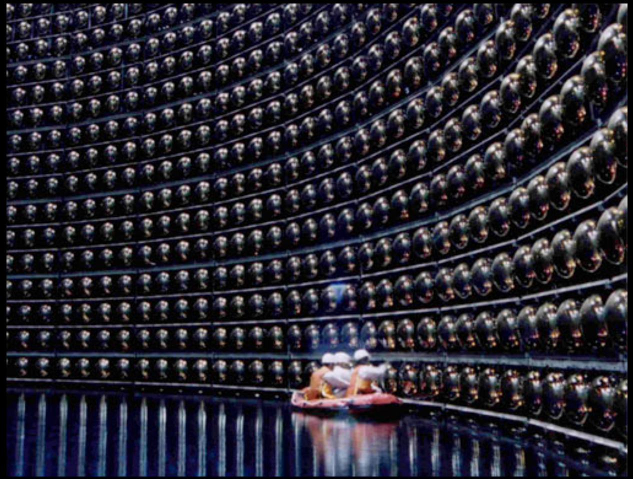
Modified from a slide by Andreas Haungs

Themes of detector development

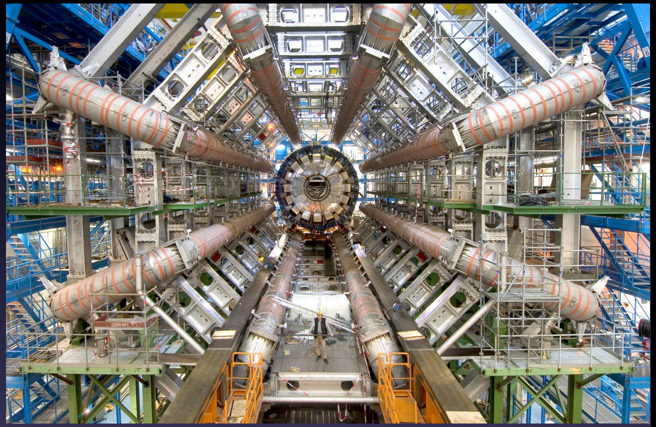
- Continue improvement
  - Incremental changes
  - Improve efficiency
  - Reduce costs
  - Safe

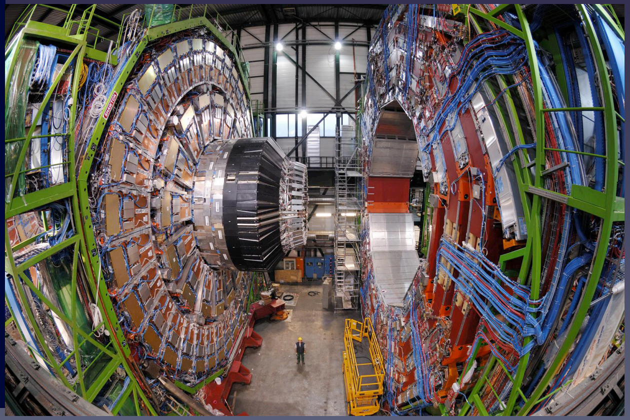
- Disruptive Innovation
  - Introduction of new technologies
  - Risky
  - Requires investments
  - Creates new market opportunities

Detector Optimization

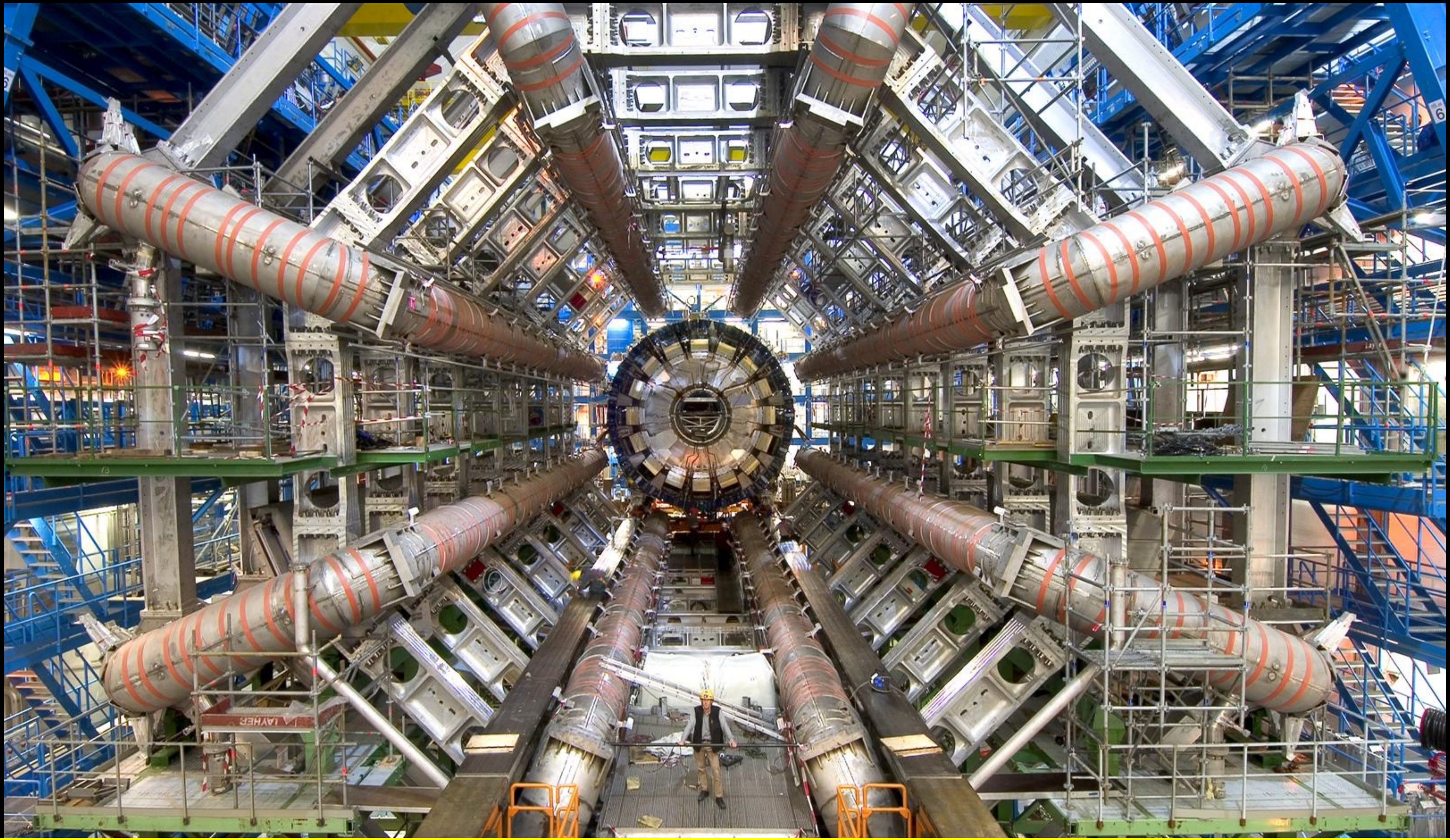


- Which kind of “particle” we have to detect?
- What is the required dimension of the detector?
- Which “property” of the particle we have to know?
  - Position
  - Lifetime
  - Quantum numbers
  - Energy
  - Charge
- What is the maximum count rate?
- What is the “time distribution” of the events?
- What is the required resolution ?
- What is the dead time?
- What is the occupancy ?



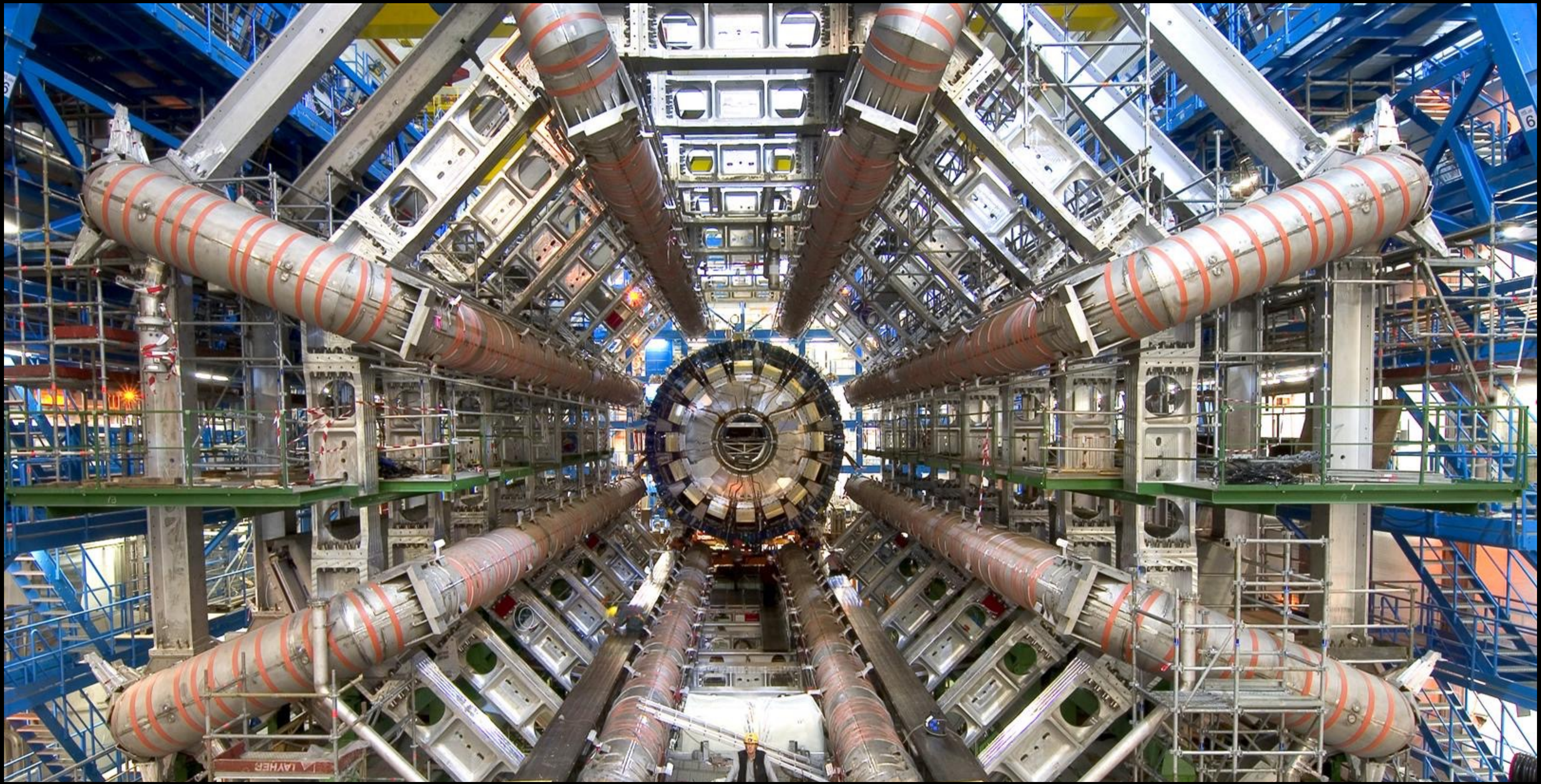


Instrumentation is the great enabler of science……..

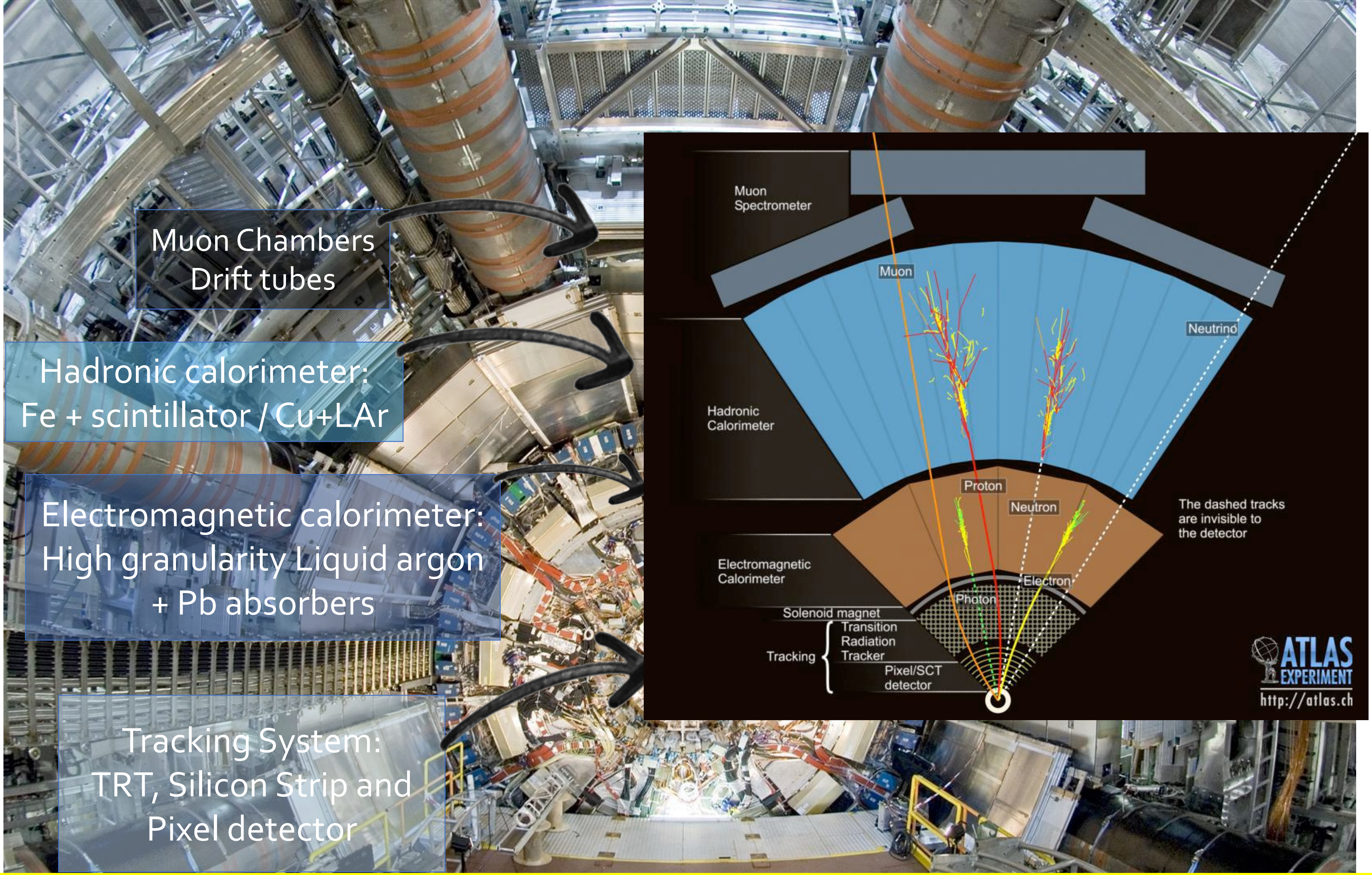


In many experiments many classes of detector technology are necessary working in synchronous harmony to reveal the mysteries of nature

Instrumentation is the great enabler of science……..



CMS and ATLAS are digital cameras designed to completely surround the collision point which is at the centre of the camera so that all the of particles produced can be imaged. A variety of detector types are used nested one inside the other like layers of an onion.



Muon Chambers
Drift tubes

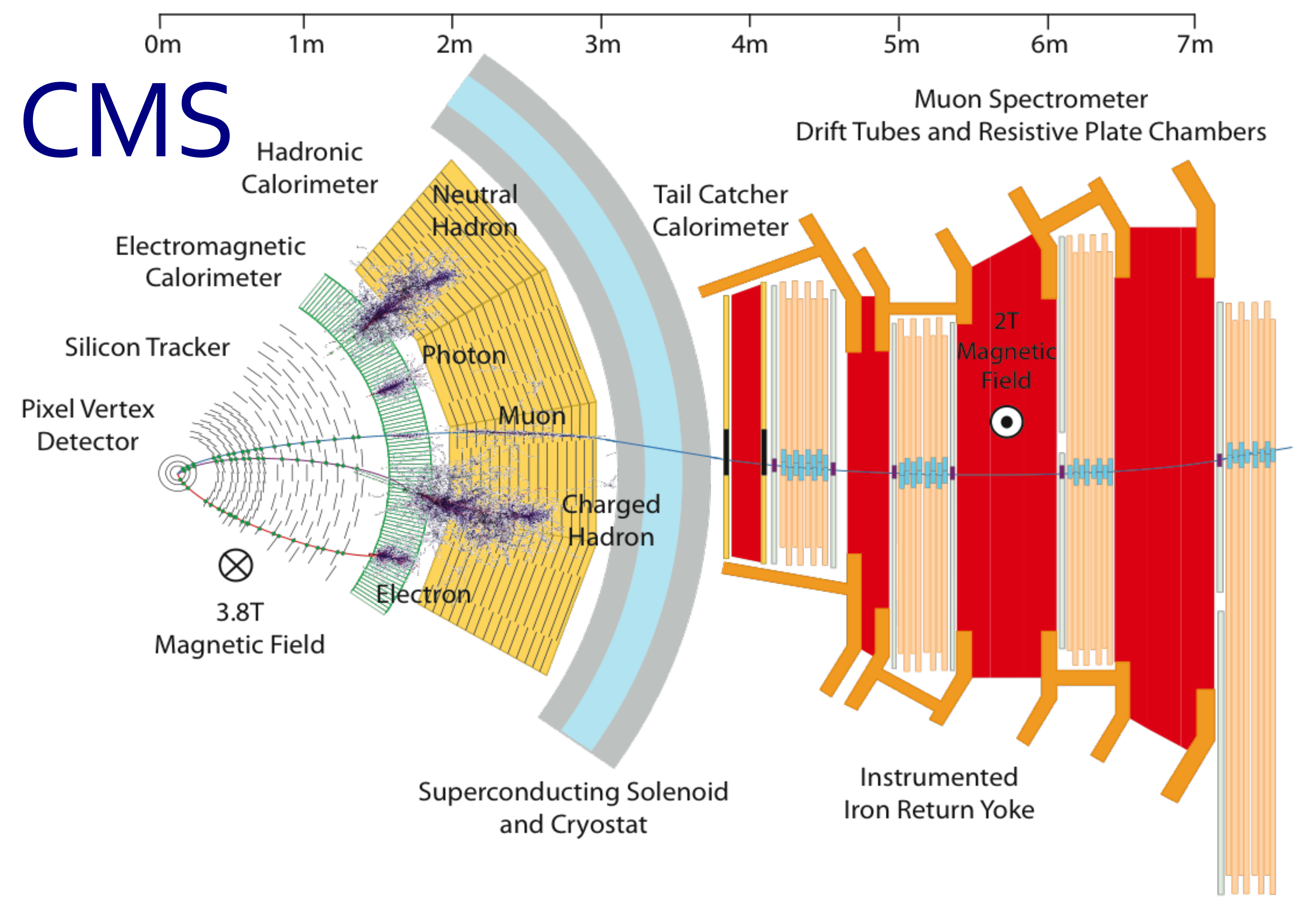
Hadronic calorimeter:
Fe + scintillator / Cu+LAr

Electromagnetic calorimeter:
High granularity Liquid argon
+ Pb absorbers

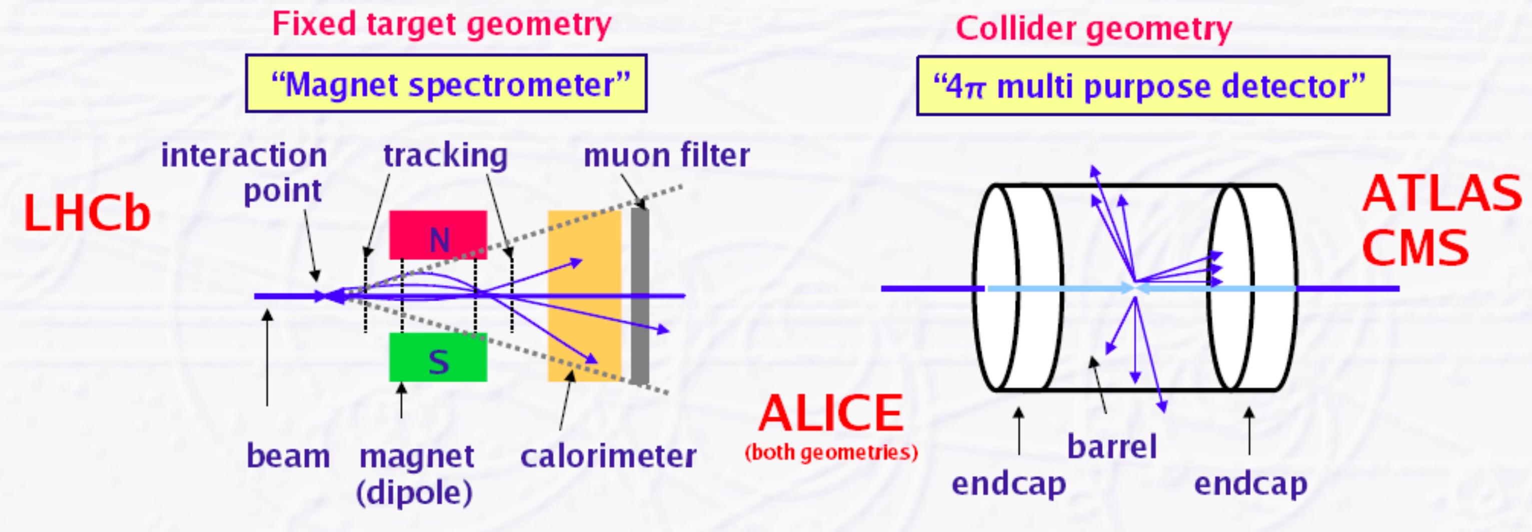
Tracking System:
TRT, Silicon Strip and
Pixel detector

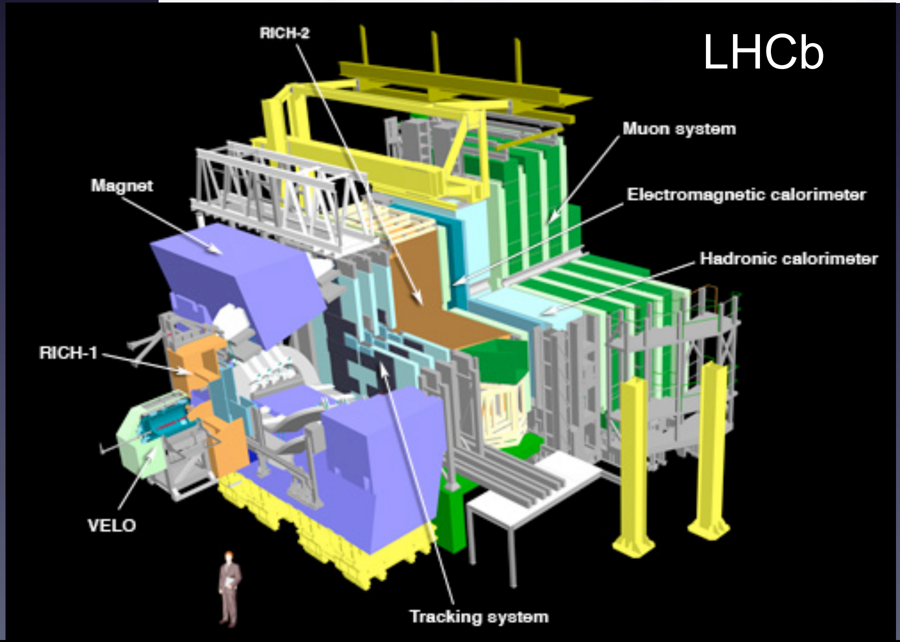
Experiments at accelerators are generally comprised of many detector subsystems

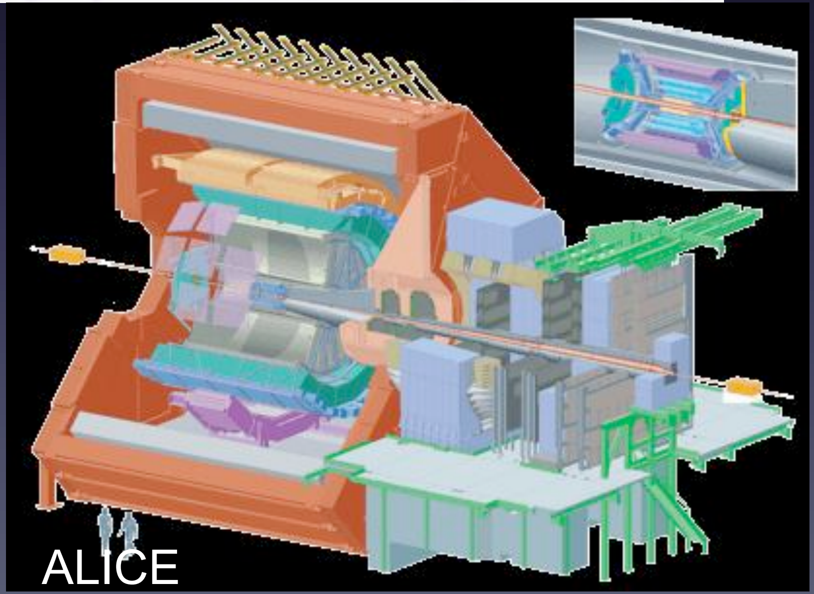
Multipurpose Detectors



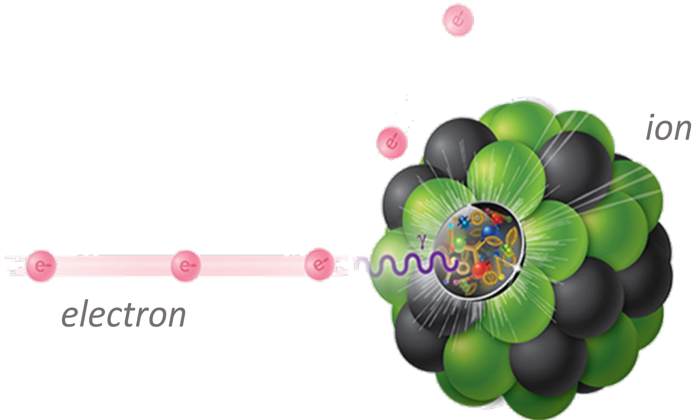
Configuration of HEP Detectors



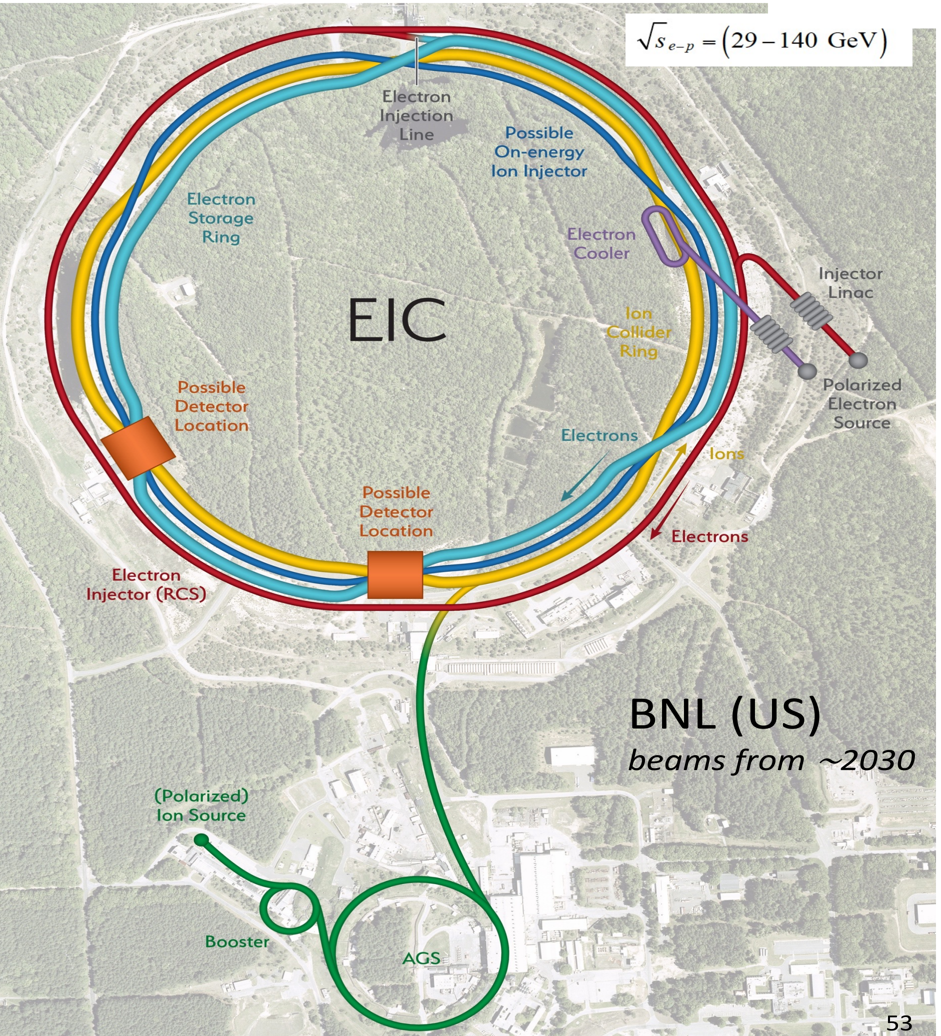


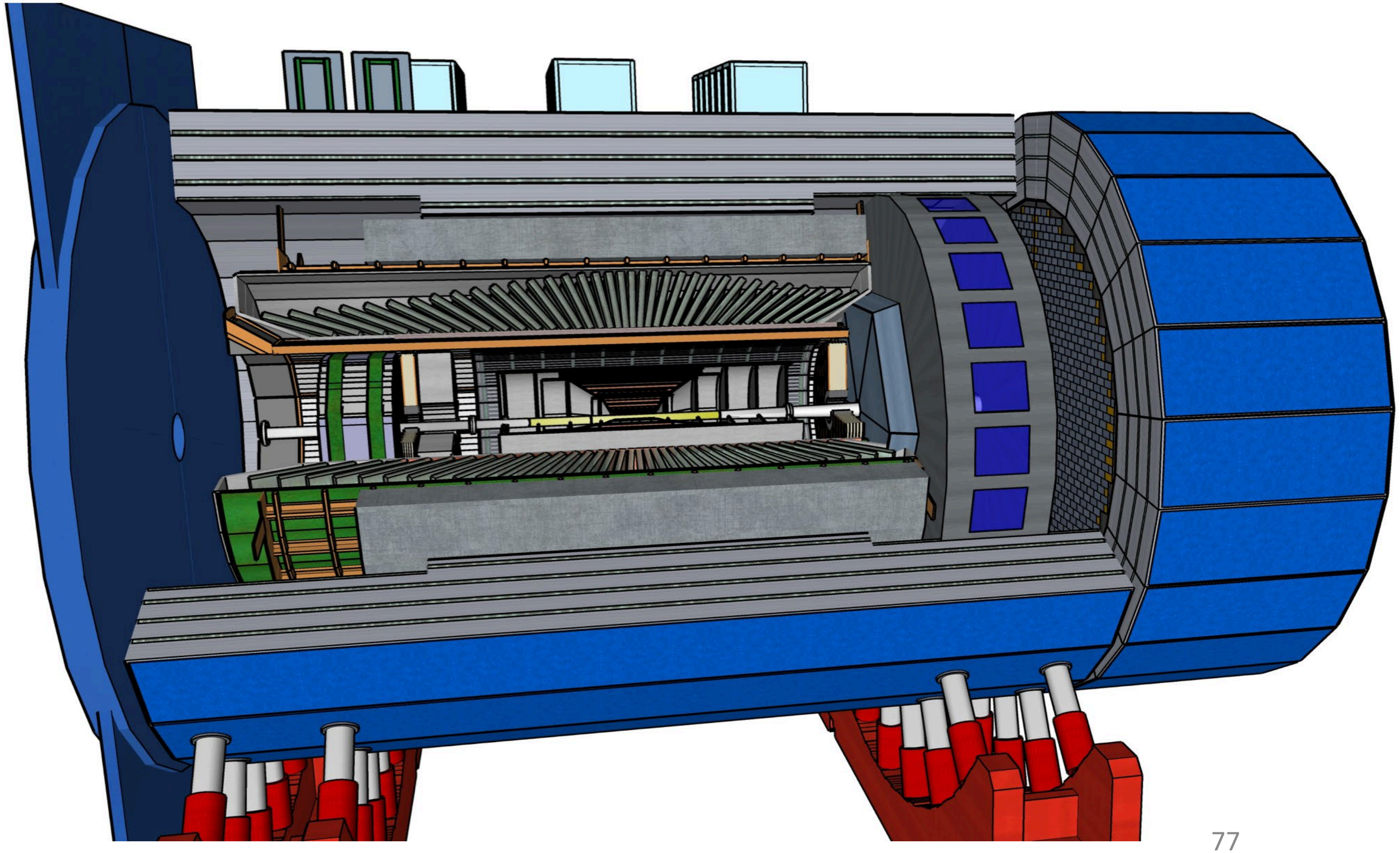


Electron Ion Collider @ BNL beams from ~2030 concurrent operations with HL-LHC for a decade & mutual interest to NP & PP



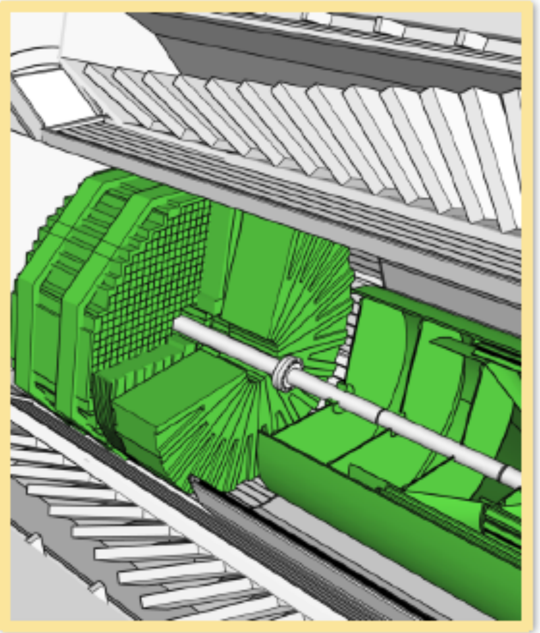
EIC Comprehensive Chromodynamics Experiment





The ECCE Reference Technologies

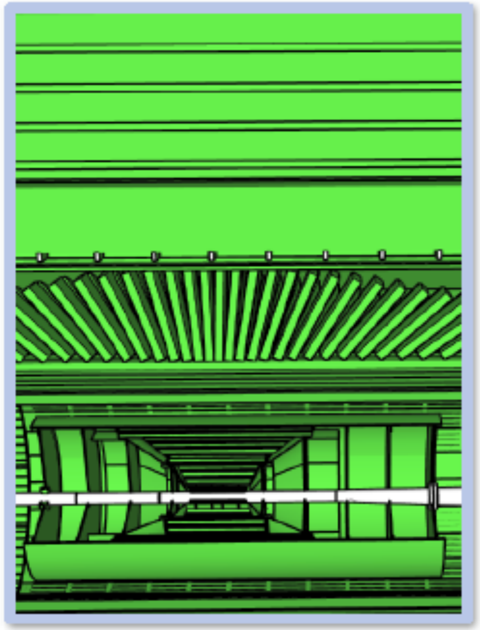
Most technologies in common with the LHC/HL-LHC & RHIC:
silicon, gaseous, photo, particle identification, calorimetry



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)



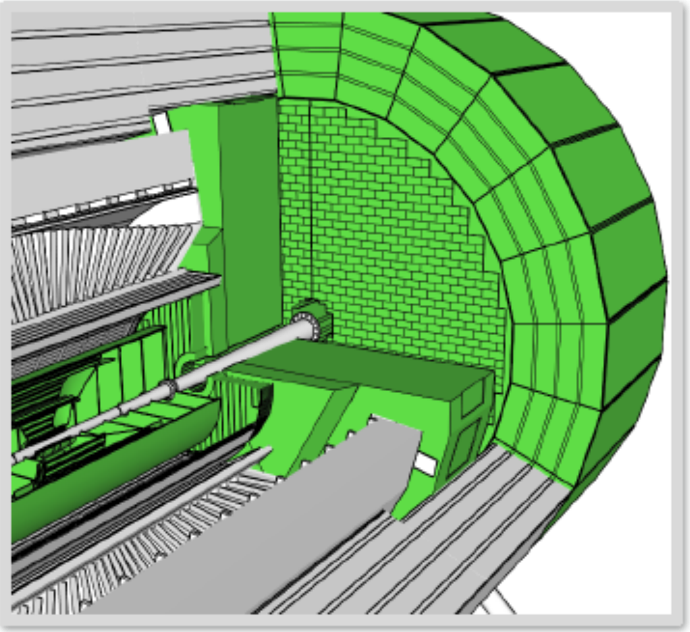
Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

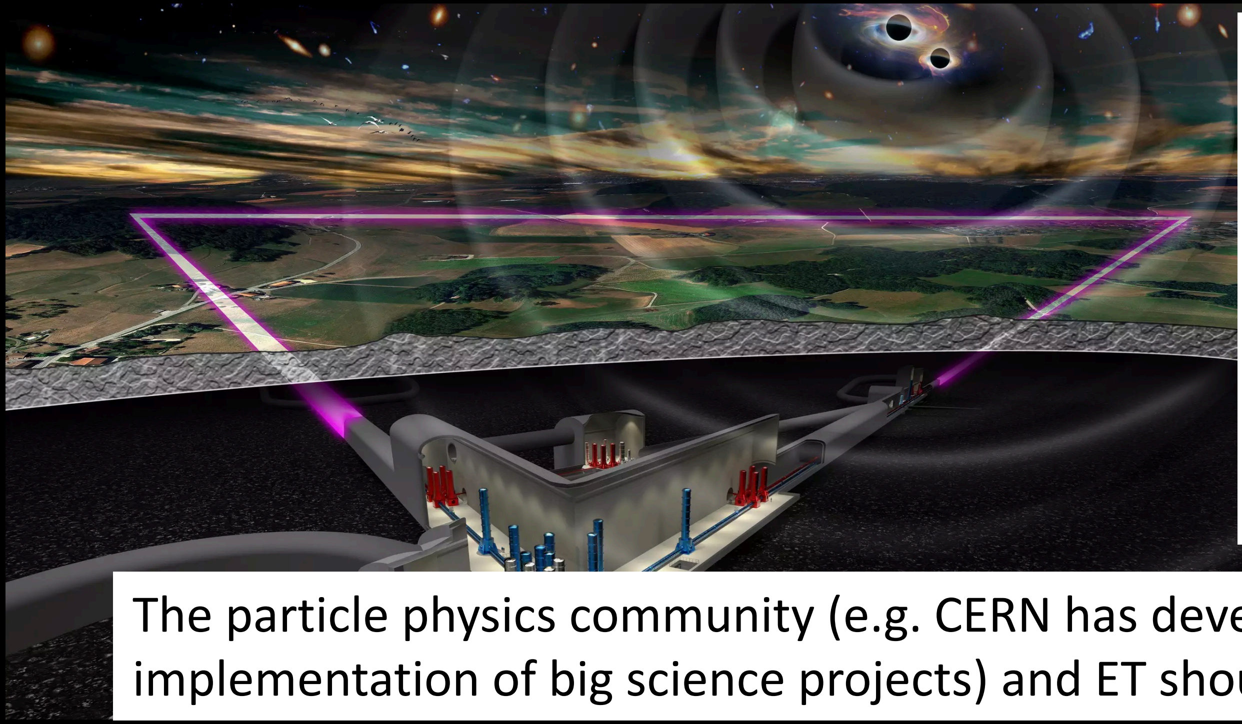
Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

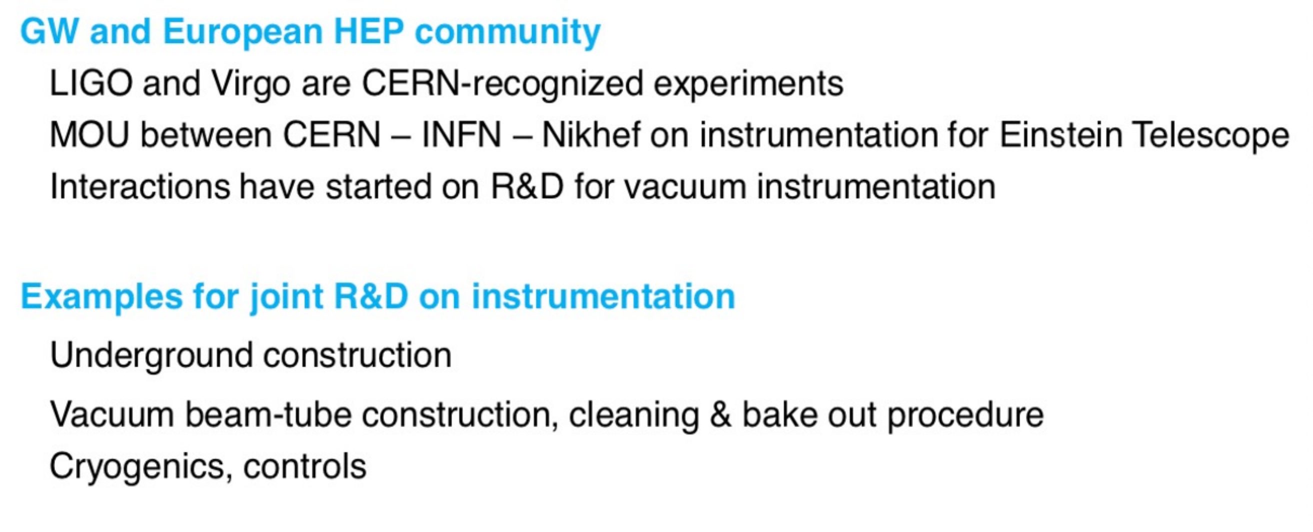
PID:
- dRICH
- AC-LGAD TOF

Calorimetry:

NP & PP working side by side immensely synergistic

Gravitational Waves / Future Einstein Telescope





GW and European HEP community

LIGO and Virgo are CERN-recognized experiments

MOU between CERN – INFN – Nikhef on instrumentation for Einstein Telescope

Interactions have started on R&D for vacuum instrumentation

Examples for joint R&D on instrumentation

Underground construction

Vacuum beam-tube construction, cleaning & bake out procedure

Cryogenics, controls

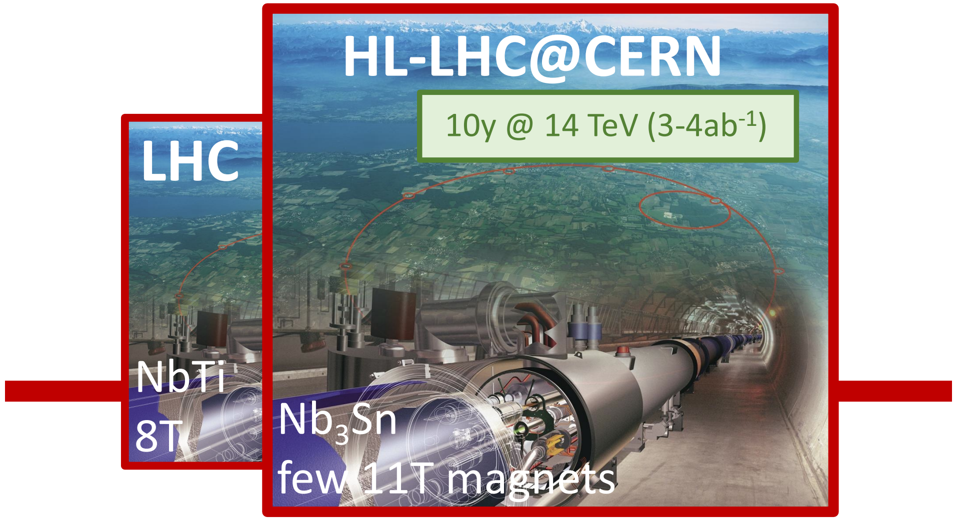
The particle physics community (e.g. CERN has developed vast experience in governance and implementation of big science projects) and ET should build on this.

Technology:
Laser power and squeezed states
Reduce Seismic (Newtonian) noise ➔ underground; long tunnels
Reduce thermal noise in suspension and test masses
➔ cryogenics to cool the mirrors

ET Pathfinder

Current flagship (27km)

impressive programme up to 2040



LHC

NbTi
8T

HL-LHC@CERN

10y @ 14 TeV (3-4ab^{-1})

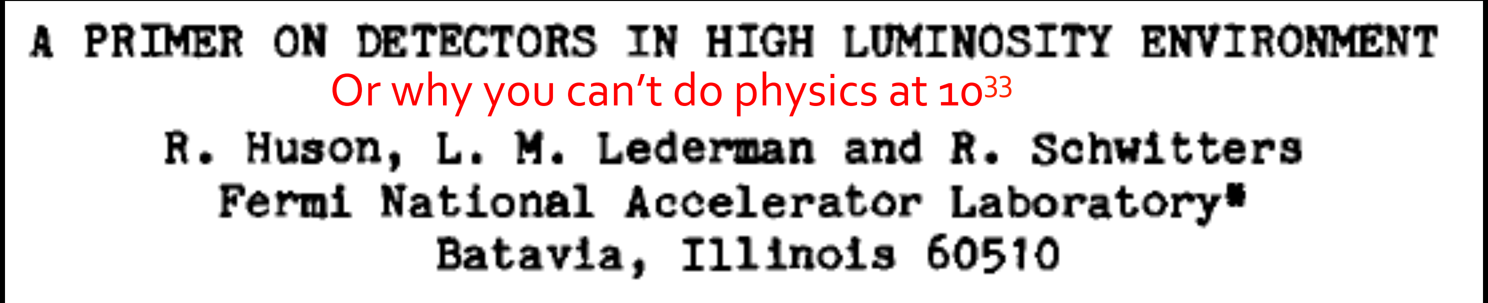
Nb$_3$Sn
few 11T magnets

ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

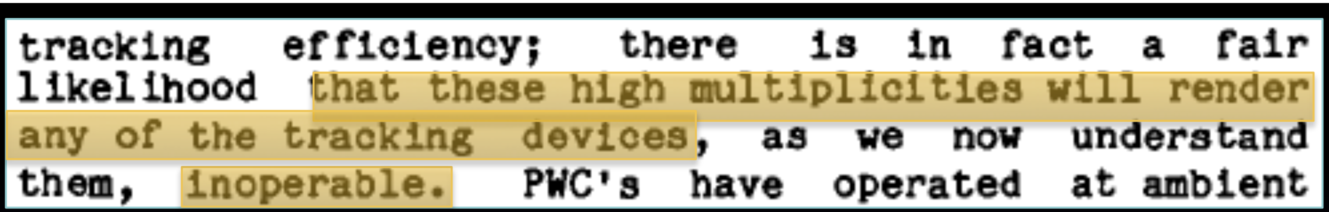
Only 4% of the collisions that we plan to collect at the LHC have so far been recorded LHC Run 3 then HL-LHC will be immensely exciting enabled by an ambitious accelerator and detector upgrade program that is very far advanced. A discovery at any moment!



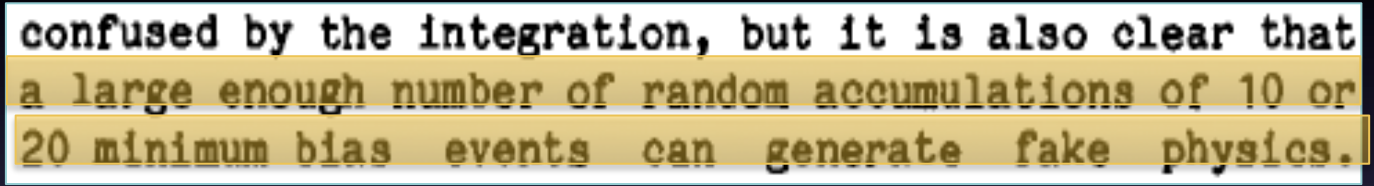
A PRIMER ON DETECTORS IN HIGH LUMINOSITY ENVIRONMENT

Or why you can't do physics at 10^{33}

R. Huson, L. M. Lederman and R. Schwitters
Fermi National Accelerator Laboratory*
Batavia, Illinois 60510

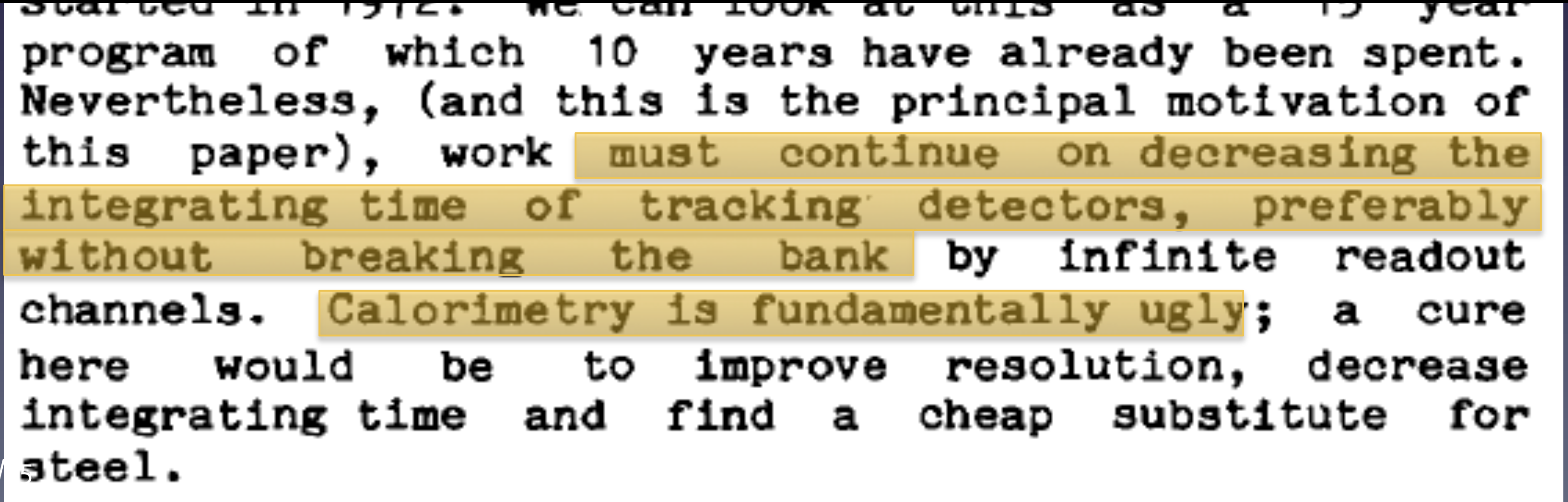


tracking efficiency; there is in fact a fair likelihood that these high multiplicities will render any of the tracking devices, as we now understand them, inoperable. PWC's have operated at ambient



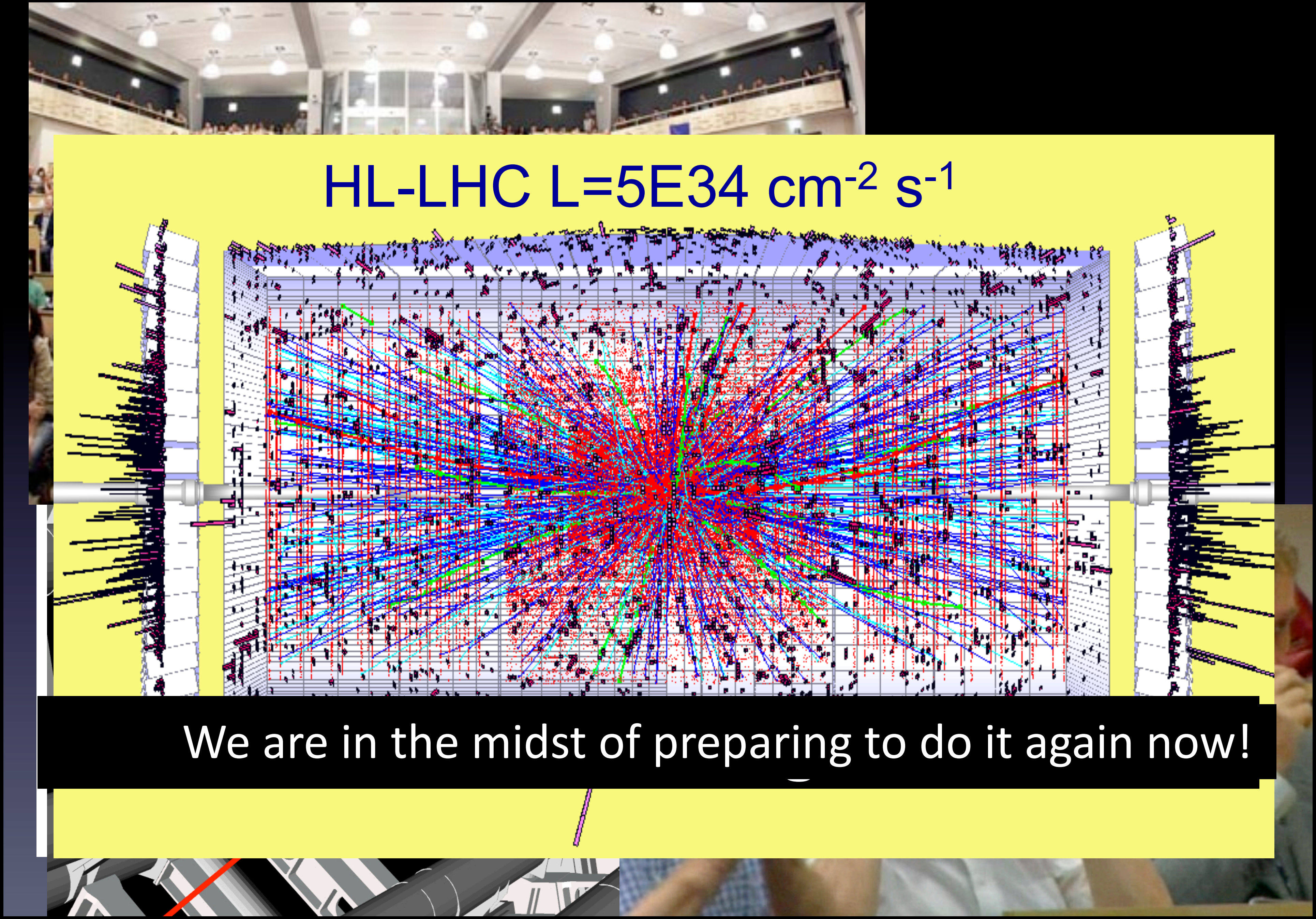
confused by the integration, but it is also clear that a large enough number of random accumulations of 10 or 20 minimum bias events can generate fake physics.

1982 SNOWMASS



started in 1972. We can look at this as a 15 year program of which 10 years have already been spent. Nevertheless, (and this is the principal motivation of this paper), work must continue on decreasing the integrating time of tracking detectors, preferably without breaking the bank by infinite readout channels. Calorimetry is fundamentally ugly; a cure here would be to improve resolution, decrease integrating time and find a cheap substitute for steel.

HL-LHC L=5E34 cm^{-2} s^{-1}



We are in the midst of preparing to do it again now!

We need to be preparing to do it again further into the future!

Future flagship at the energy & precision frontier

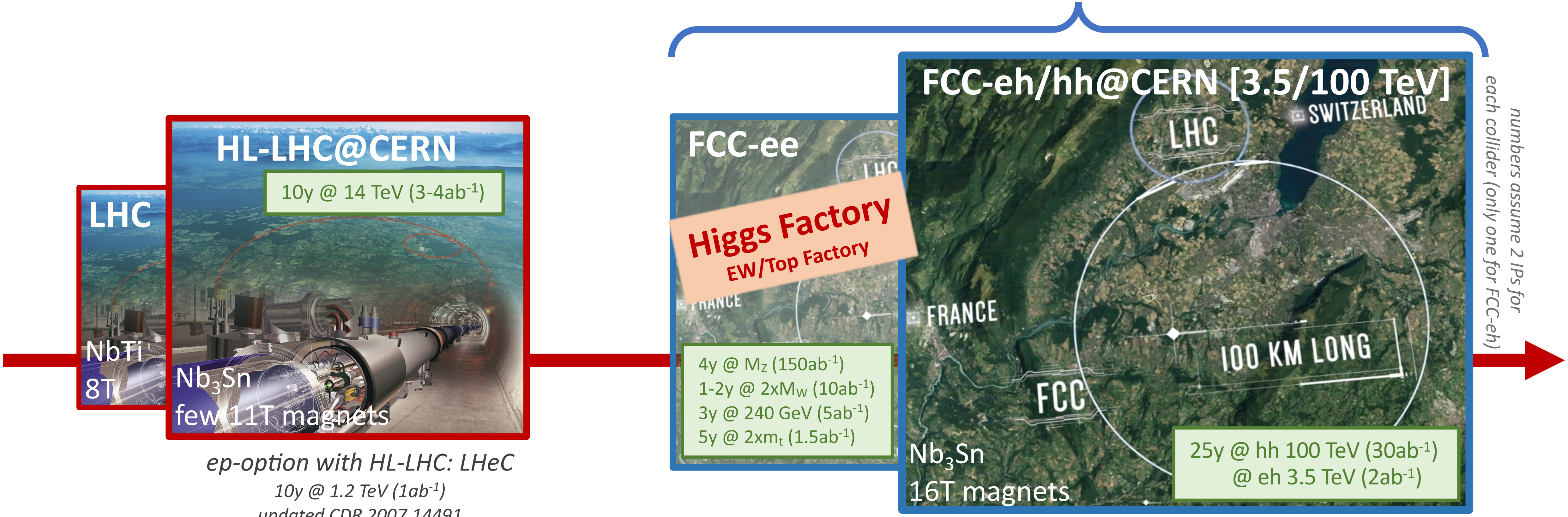
Current flagship (27km)

impressive programme up to 2040

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier



LHC

NbTi 8T

HL-LHC@CERN

10y @ 14 TeV (3-4ab^{-1})

Nb_3Sn few 11T magnets

FCC-ee

Higgs Factory

EW/Top Factory

4y @ M_Z (150ab^{-1})

1-2y @ $2xM_W$ (10ab^{-1})

3y @ 240 GeV (5ab^{-1})

5y @ $2xm_t$ (1.5ab^{-1})

FCC-eh/hh@CERN [3.5/100 TeV]

Nb_3Sn 16T magnets

25y @ hh 100 TeV (30ab^{-1})
@ eh 3.5 TeV (2ab^{-1})

numbers assume 2 IPs for each collider (only one for FCC-eh)

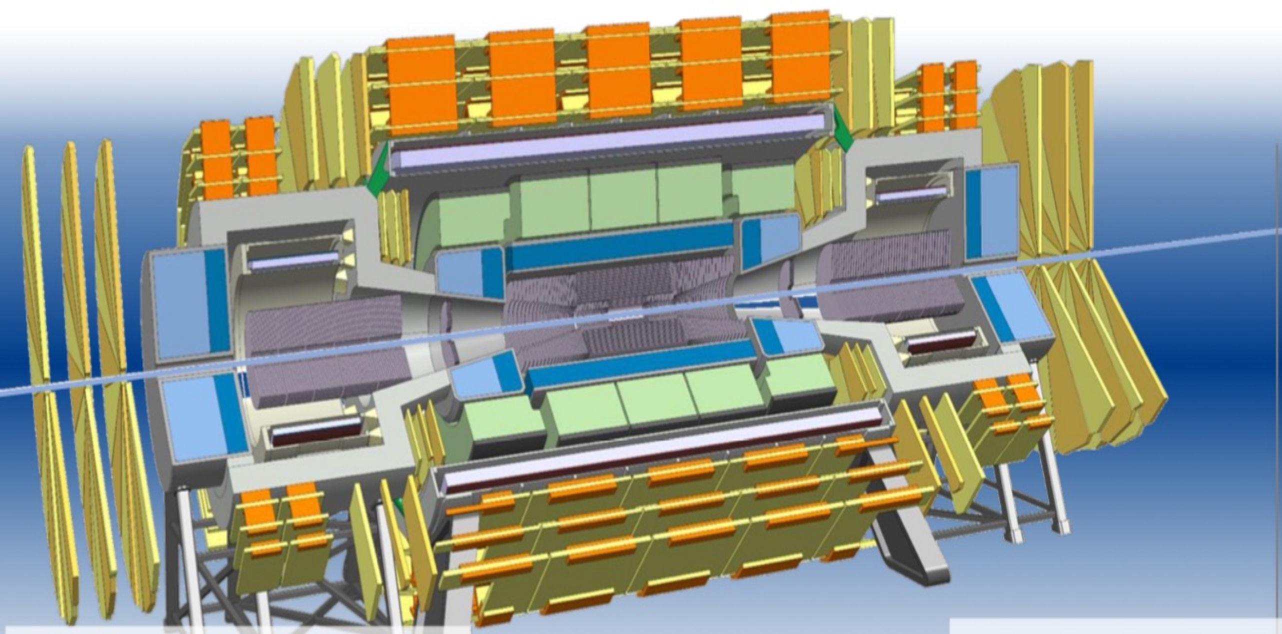
ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

by around 2026, verify if it is feasible to plan for success (techn. & adm. & financially & global governance)

potential alternatives pursued @ CERN: CLIC & muon collider



FCChh, HE-LHC, …

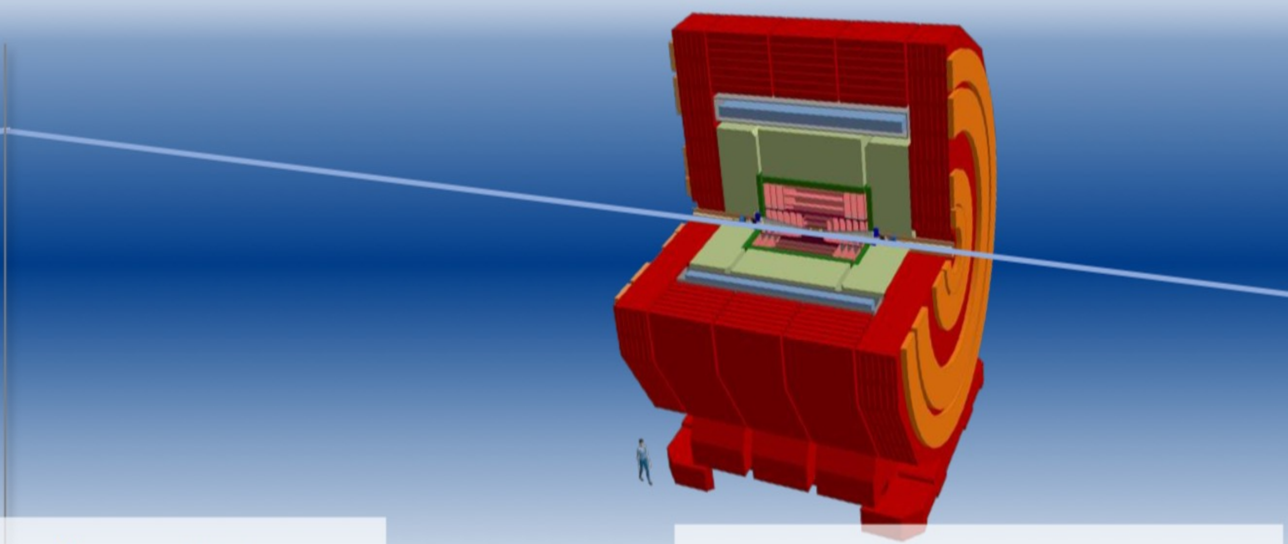
hh collisions

- **Large dimensions (50m)**
- **High radiation Level (up to 2.8 x10^{17}neq/cm2; 90MGy @10 year)**
- Central solenoid (10m) 4T, Forward solenoids 4T
- Silicon tracker **Tracker Radius 1.6m, Length 32m**

  radiation damage is a concern

One of the many challenges: radiation hardness. Radiation levels go well beyond what any currently available microelectronics can survive (≲ MGy) and few sensor technologies can cope beyond $\sim 10^{16}$ n_{eq}/cm^2

➔ Detector R&D essential



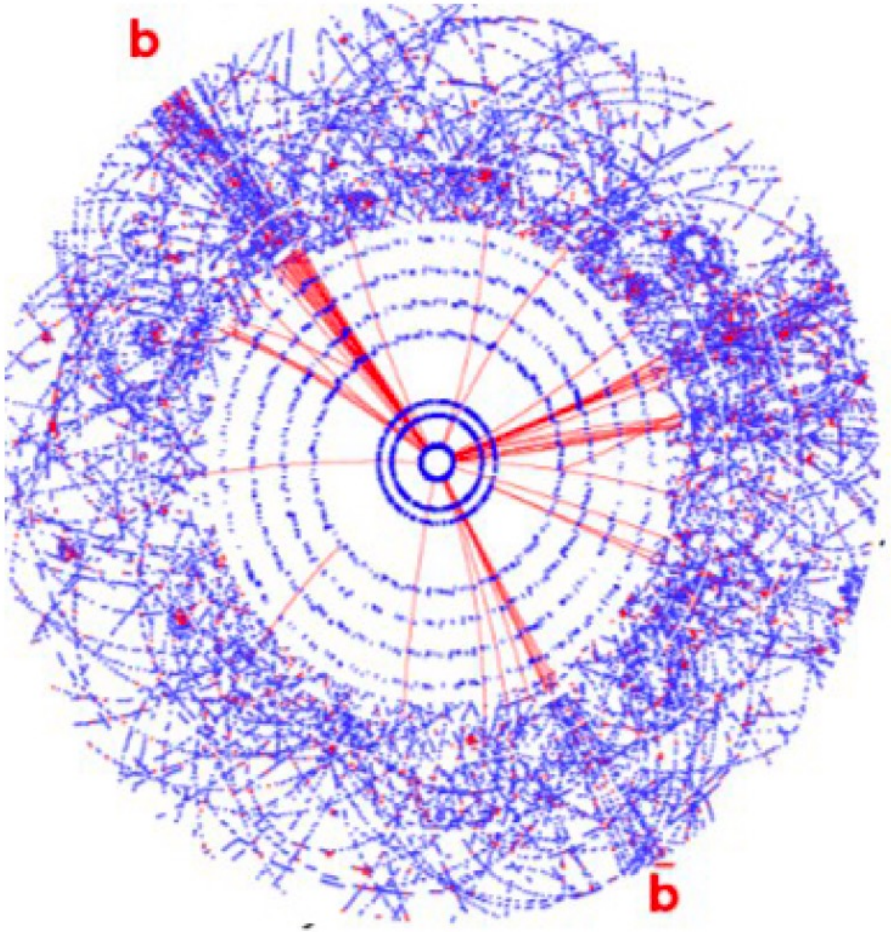
e$^+$e$^-$ collisions

CLIC, FCCee, ILC, CEPC,…

- Standard dimensions
- Low radiation Level, Radiation level NIEL (<4×10^{10} neq cm^{-2}/yr); TID (<200Gy/yr)
- Magnet 4T, 2T
- Silicon tracker
  - **unprecedented spatial resolution (1-5 µm point resolution)**
  - **very low material budget (0.1X%)** Dissipated power (vertex) (<50mW/cm^2)
- Barrel fine grained calorimeter
- Compact Forward calorimeter

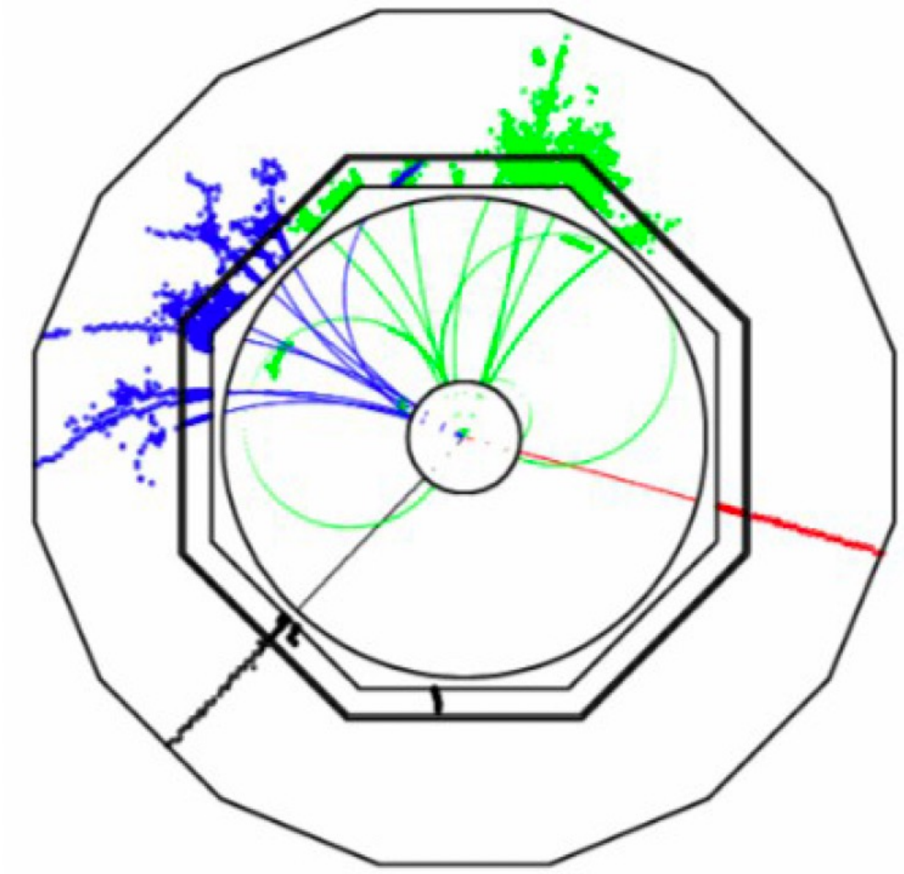
➔ Detector R&D essential

Hadron –hadron collisions LH/HL-LHC➔ FCC-hh



- Busy events
- Require hardware and software triggers
- High radiation levels

Electron-positron collisions LEP ➔ FCC-ee



- Simple Events
- No trigger
- Full event reconstruction
- Modest radiation levels

20 Years

- The technologies developed for the LHC took >20 years to research, develop and build
- These grew out of technologies developed for earlier rounds of experiments at earlier accelerators SppbarS, SPS, & LEP @ CERN, the Tevatron @ Fermilab and other facilities worldwide in the 1960-1990s.
- The technologies for the HL- LHC began to be developed around 2008, the R&D, build, install and commission will be completed in 2029
- The technology R&D for experiments that commence operation in the 2030s, 2040s & 2050s and beyond e.g. FCC-ee/FCC-hh is either underway already or must begin now

20 Years

- The technologies developed for the LHC took >20 years to research, develop and build

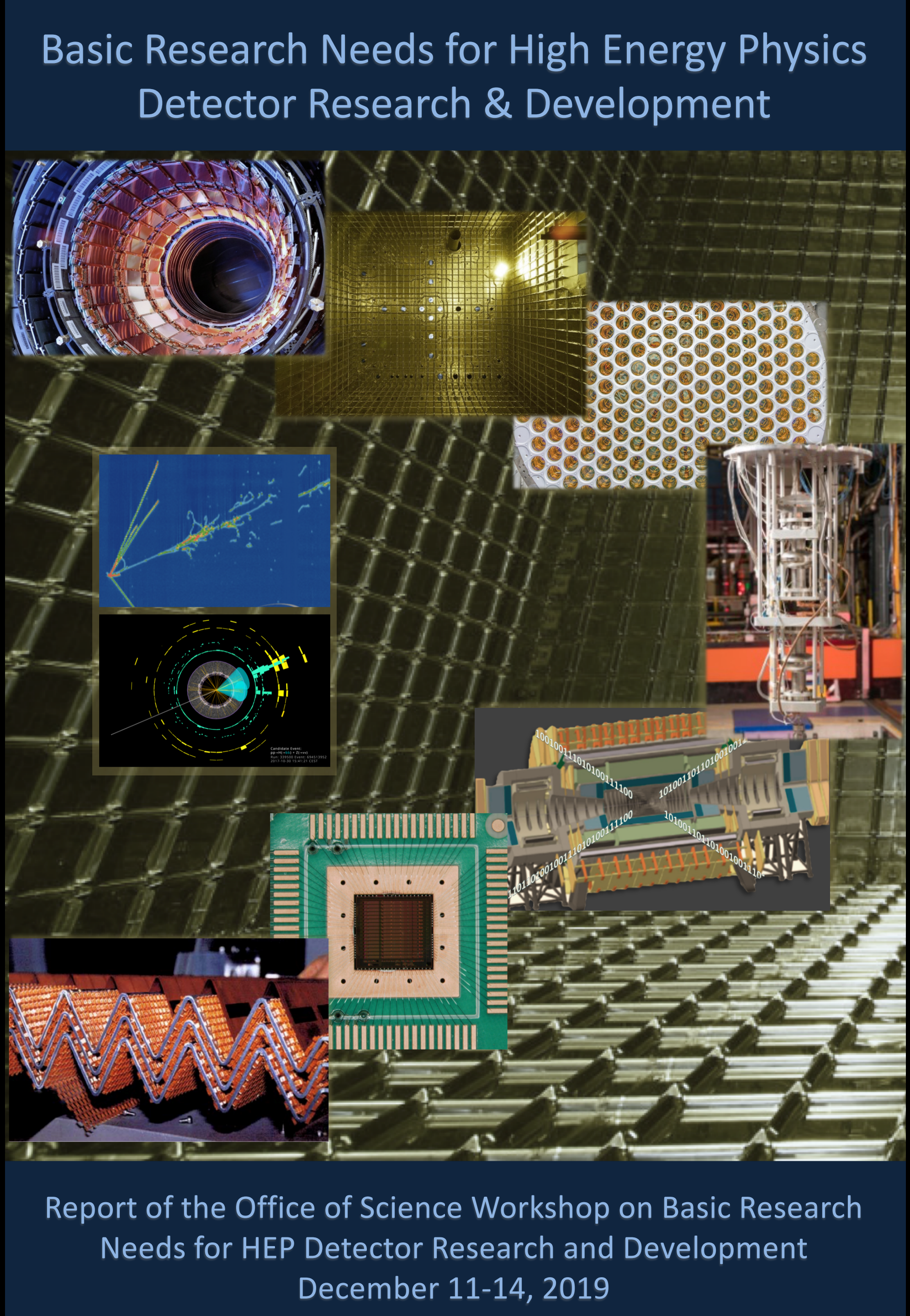
- These grew out of technologies developed for earlier rounds of experiments at earlier accelerators SppbarS, SPS, & LEP @ CERN, the Tevatron @ Fermilab and other facilities worldwide in the 1960-1990s.

- The technologies for the HL- LHC began to be developed around 2008, the R&D, build, install and commission will be completed in 2029

- The technology R&D for experiments that commence operation in the 2030s, 2040s & 2050s and beyond e.g. FCC-ee/FCC-hh is either underway already or must begin now

- And this applies not only to the energy frontier, but also to the intensity and cosmic frontiers

Starting from the 2014 P5 vision:



Basic Research Needs for High Energy Physics
Detector Research & Development

Report of the Office of Science Workshop on Basic Research
Needs for HEP Detector Research and Development
December 11-14, 2019

Most recent European Strategies

the large …

weblink

APPEC

European Astroparticle Physics Strategy 2017-2026

2017-2026 European Astroparticle Physics Strategy

… the connection …

weblink

NuPECC

NuPECC
Long Range Plan 2017
Perspectives
in Nuclear Physics

European Science Foundation

Long Range Plan 2017 Perspectives in Nuclear Physics

… the small

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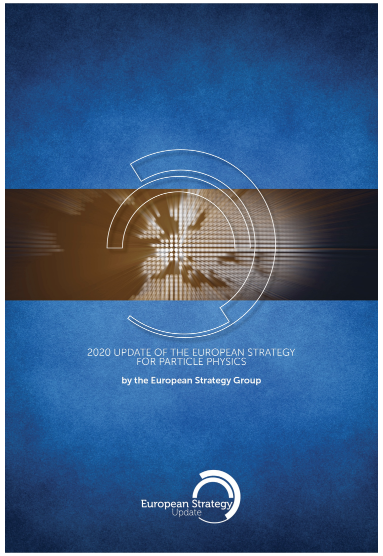

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

2020 Update of the European Particle Physics Strategy

Are community driven strategies outlining our ambition to address compelling open questions

Guidance for funding authorities to develop resource-loaded research programmes

Most recent European Strategies

the large …

weblink

European Astroparticle
Physics Strategy
APPEC 2017-2026

2017-2026 European
Astroparticle Physics Strategy

… the connection …

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NuPECC
Long Range Plan 2017
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European Science Foundation

Long Range Plan 2017
Perspectives in Nuclear Physics

… the small

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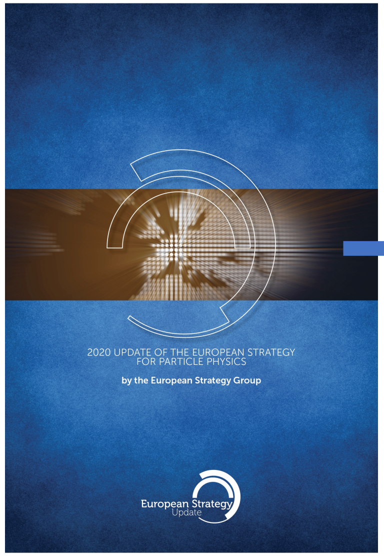


2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy
Update

2020 Update of the European
Particle Physics Strategy

THE 2021 ECFA DETECTOR
RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators
Detector R&D Roadmap Process Group

European Strategy
Update

ECFA

ECFA Detector R&D Roadmap

ECFA Detector R&D Roadmap

- Given the future physics programme, identify **the main technology R&D to be met so that detectors ar not the limiting factor for the timeline.**
- Detector context considered:

- Full exploitation of LHC
- Long baseline neutrinos
- Detectors for future Higgs-EW-Top factories (in all manifestations)
- Long term vision for 100 TeV hadron collider

- Future muon colliders
- Accelerator setup for rare decays/dark matter
- Experiments for precision QCD
- Non accelerator experiments (reactor neutrinos, double beta decay, dark matter)

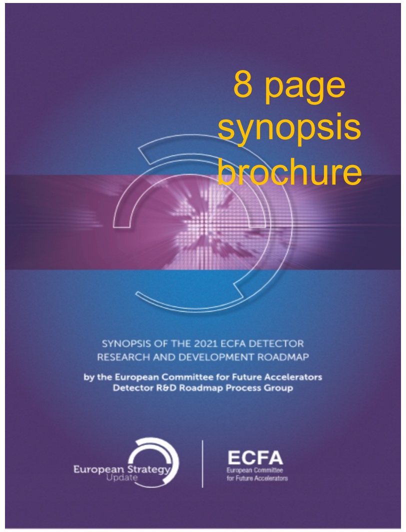
Process organised by Panel and nine Task Forces with input sessions and open symposia with wide community consultation (1359 registrants)

Main Document published (approval by RECFA at 19/11/21) and 8 page synopsis brochure prepared for less specialised audience


250 pages main

THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators Detector R&D Roadmap Process Group


8 page synopsis brochure

SYNOPSIS OF THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

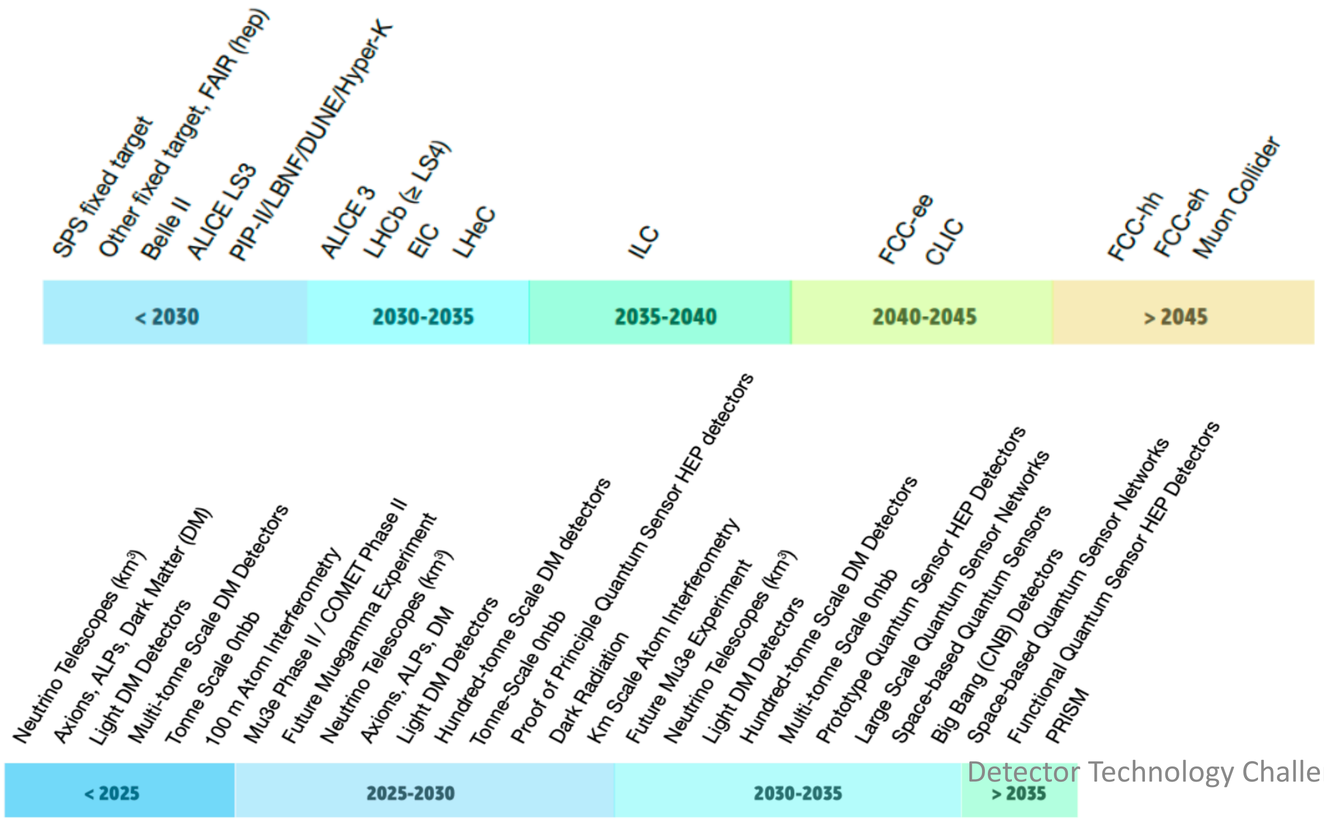
by the European Committee for Future Accelerators Detector R&D Roadmap Process Group

ECFA Detector R&D Roadmap Panel web pages at: https://indico.cern.ch/e/ECFADetectorRDRoadmap

Documents CERN-ESU-017: 10.17181/CERN.XDPL.W2EX

Roadmap Document Structure

Within each Task Force (one for each technology area + training) the aim is to propose a time ordered detector R&D programme by Detector Research and Development Themes (DRDT) in terms of **capabilities not currently achievable**.



DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

DRDT 1.1 Improve time and spatial resolution for gaseous detectors with long-term stability
DRDT 1.2 Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
DRDT 1.3 Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
DRDT 1.4 Achieve high sensitivity in both low and high-pressure TPCs
DRDT 2.1 Develop readout technology to increase spatial and energy resolution for liquid detectors
DRDT 2.2 Advance noise reduction in liquid detectors to lower signal energy thresholds
DRDT 2.3 Improve the material properties of target and detector components in liquid detectors
DRDT 2.4 Realise liquid detector technologies scalable for integration in large systems
DRDT 3.1 Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
DRDT 3.2 Develop solid state sensors with 4D-capabilities for tracking and calorimetry
DRDT 3.3 Extend capabilities of solid state sensors to operate at extreme fluences
DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics
DRDT 4.1 Enhance the timing resolution and spectral range of photon detectors
DRDT 4.2 Develop photosensors for extreme environments
DRDT 4.3 Develop RICH and imaging detectors with low mass and high resolution timing
DRDT 4.4 Develop compact high performance time-of-flight detectors
DRDT 5.1 Promote the development of advanced quantum sensing technologies
DRDT 5.2 Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
DRDT 5.3 Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
DRDT 5.4 Develop and provide advanced enabling capabilities and infrastructure
DRDT 6.1 Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments
DRDT 7.1 Advance technologies to deal with greatly increased data density
DRDT 7.2 Develop technologies for increased intelligence on the detector
D
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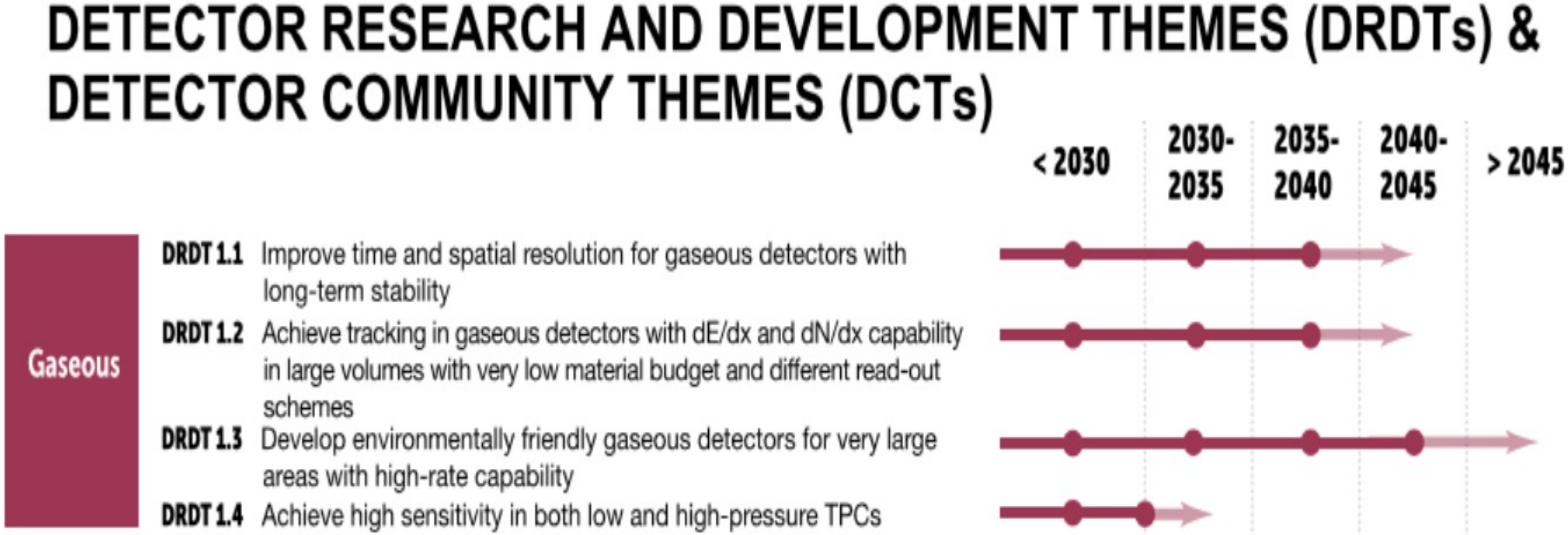
technologies
DRDT 8.1 Develop novel magnet systems
DRDT 8.2 Develop improved technologies and systems for cooling
DRDT 8.3 Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
DRDT 8.4 Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects
DCT 1 Establish and maintain a European coordinated programme for training in instrumentation
DCT 2 Develop a master's degree programme in instrumentation

Many themes so much too small to read!

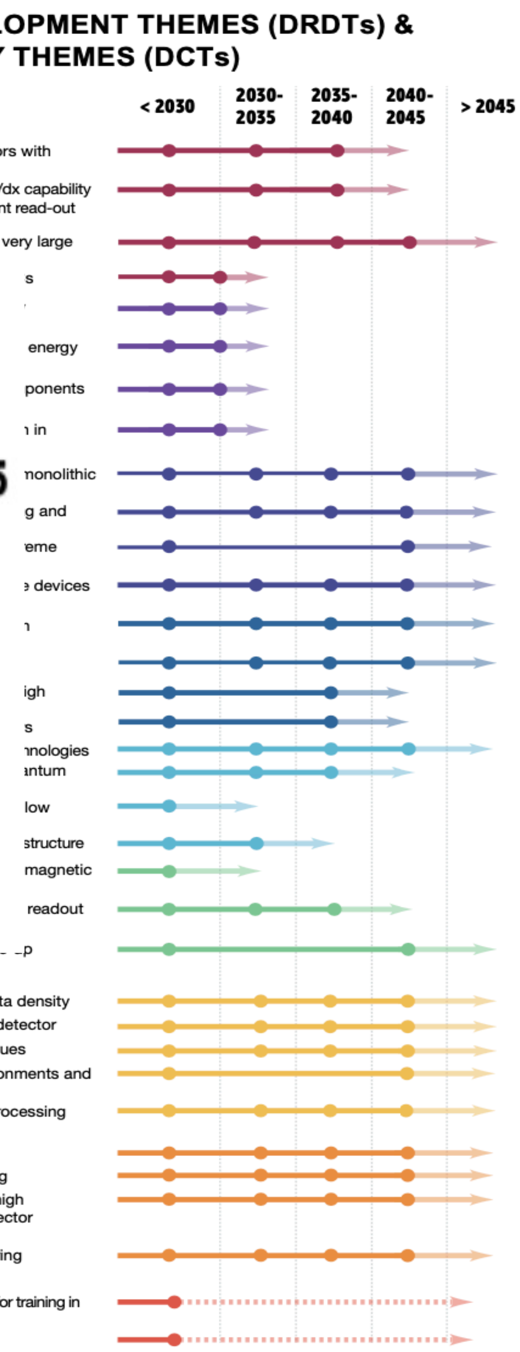
Roadmap Document Structure

Within each Task Force the aim is to propose a time ordered detector R&D programme by



DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

		< 2030	2030-2035	2035-2040	2040-2045	> 2045
Gaseous	**DRDT 1.1** Improve time and spatial resolution for gaseous detectors with long-term stability	●	●	●	→	
	DRDT 1.2 Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes	●	●	●	→	
	DRDT 1.3 Develop environmentally friendly gaseous detectors for very large areas with high-rate capability	●	●	●	●	→
	DRDT 1.4 Achieve high sensitivity in both low and high-pressure TPCs	●	●	→		



DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

< 2030 | 2030-2035 | 2035-2040 | 2040-2045 | > 2045

Gaseous

DRDT 1.1 Improve time and spatial resolution for gaseous detectors with long-term stability

DRDT 1.2 Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes

DRDT 1.3 Develop environmentally friendly gaseous detectors for very large

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Electronics

DRDT 7.1 Advance technologies to deal with greatly increased data density

DRDT 7.2 Develop technologies for increased intelligence on the detector

DRDT 7.3 Develop technologies in support of 4D- and 5D-techniques

DRDT 7.4 Develop novel technologies to cope with extreme environments and required longevity

DRDT 7.5 Evaluate and adapt to emerging electronics and data processing technologies

Integration

DRDT 8.1 Develop novel magnet systems

DRDT 8.2 Develop improved technologies and systems for cooling

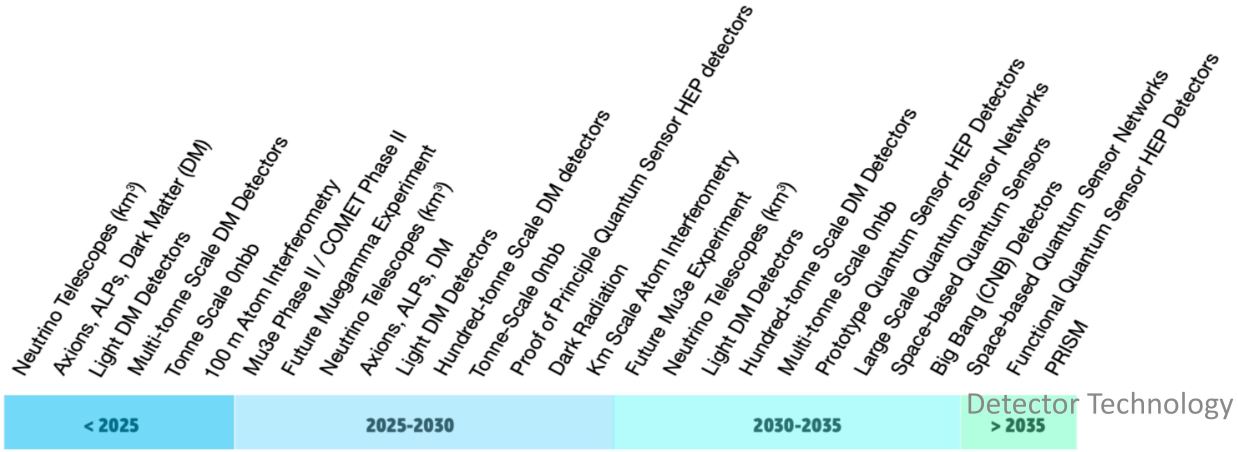
DRDT 8.3 Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.

DRDT 8.4 Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects

Training

DCT 1 Establish and maintain a European coordinated programme for training in instrumentation

DCT 2 Develop a master's degree programme in instrumentation



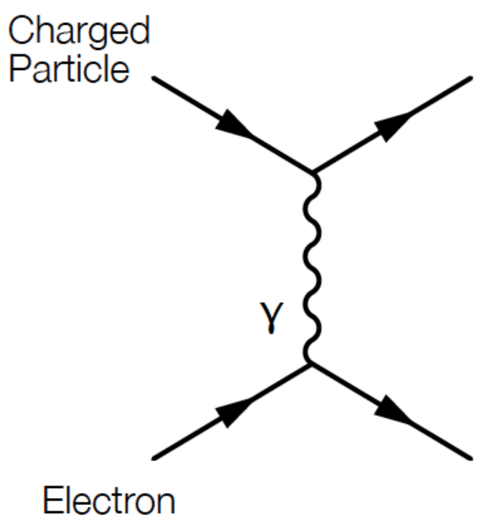
Detecting particles

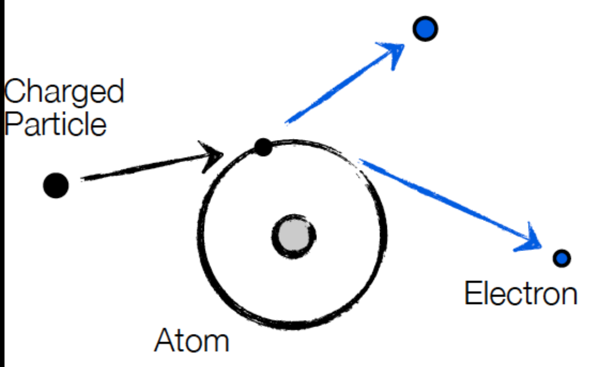
- Every effect of particles or radiation can be used as a working principle for a particle detector.

Claus Grupen

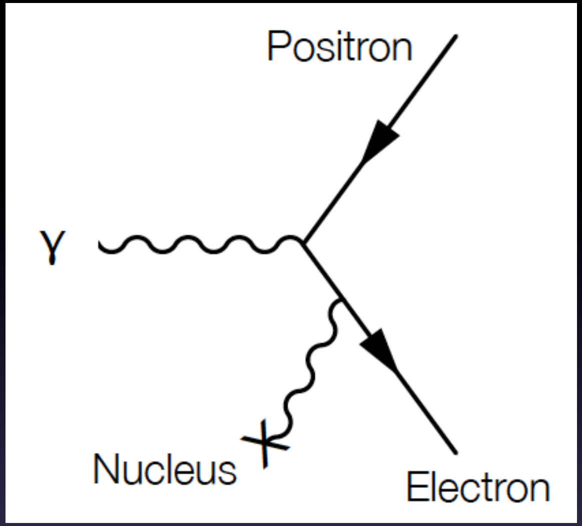
Example of particle interactions

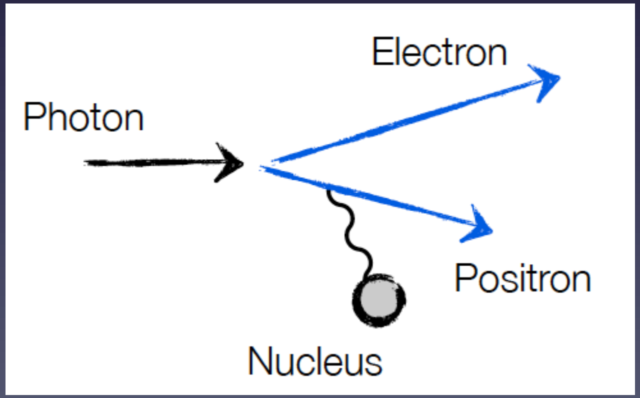
- Ionization



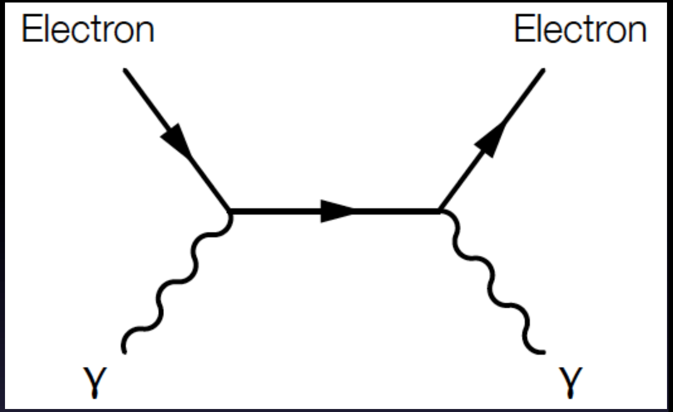


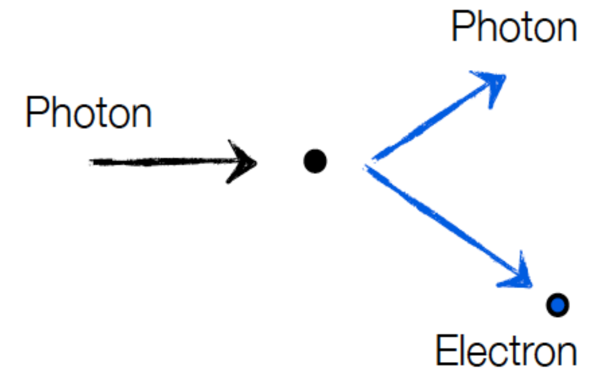
- Pair production



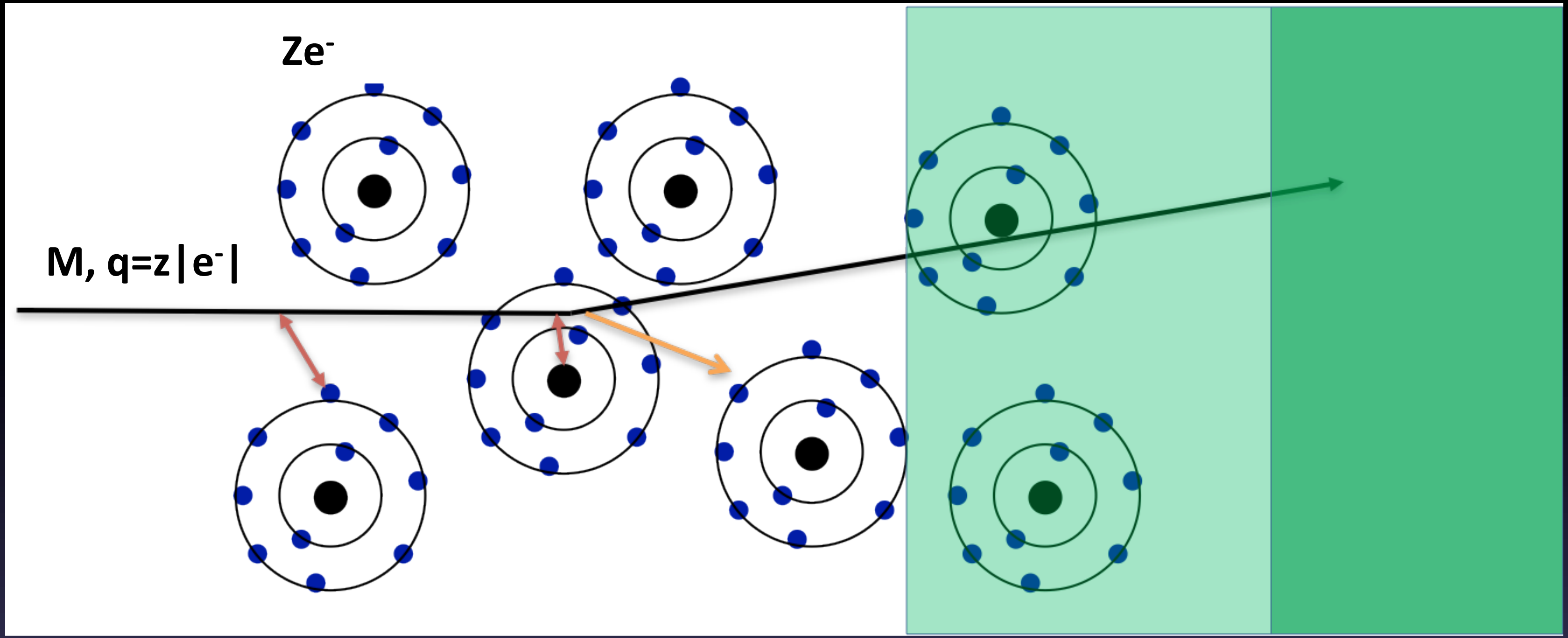


- Compton scattering





EM interaction of charged particles with matter



Interaction with the atomic electrons. Incoming particles lose energy and atoms are excited or ionized.

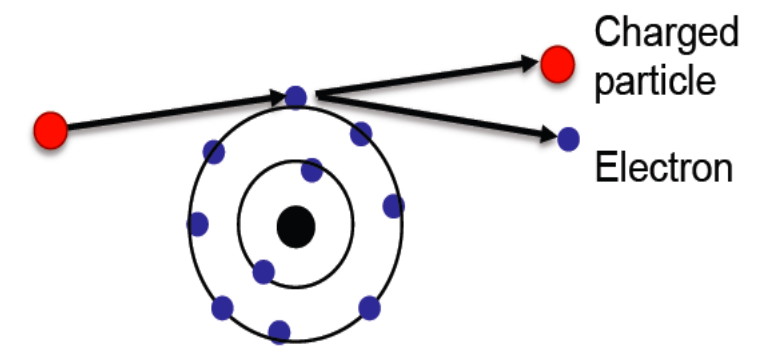
Interaction with the atomic nucleus. Particles are deflected and a Bremsstrahlung photon can be emitted.

If the particle's velocity is > the velocity of light in the medium → Cherenkov Radiation.

When a particle crosses the boundary between two media, there is a probability ≈1% to produce an X ray photon Transition radiation.

Energy Loss by Ionization

- Assume: $Mc^2 \gg m_e c^2$ (calculation for electrons and muons are more complex)
- Interaction is dominated by elastic collisions with electrons
  - The trajectory of the charged particle is unchanged after scattering
- Energy is transferred to the electrons



Energy loss (- sign)

Bethe-Bloch Formula

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Classical derivation in backup slides agrees with QM within a factor of 2

$\propto 1/\beta^2 \cdot \ln(\mathrm{const} \cdot \beta^2\gamma^2)$

Energy loss by ionization

- The Bethe-Bloch equation for energy loss

Valid for heavy charged particles ($m_{incident} >> m_e$), e.g. proton, k, π, μ

$$-\left\langle \frac{dE}{dx} \right\rangle = \boxed{2\pi N_a r_e^2 m_e c^2}\, \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I^2}W_{max}\right) - 2\beta^2 - \delta(\beta\gamma) - \frac{C}{Z}\right]$$

=0.1535 MeV cm^2/g

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2}\ln\left(a\beta^2\gamma^2\right)$$

Fundamental constants

r_e=classical radius of electron

m_e=mass of electron

N_a=Avogadro's number

c =speed of light

$$r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}$$

Absorber medium

I = mean ionization potential

Z = atomic number of absorber

A = atomic weight of absorber

ρ = density of absorber

δ = density correction

C = shell correction

Incident particle

z = charge of incident particle

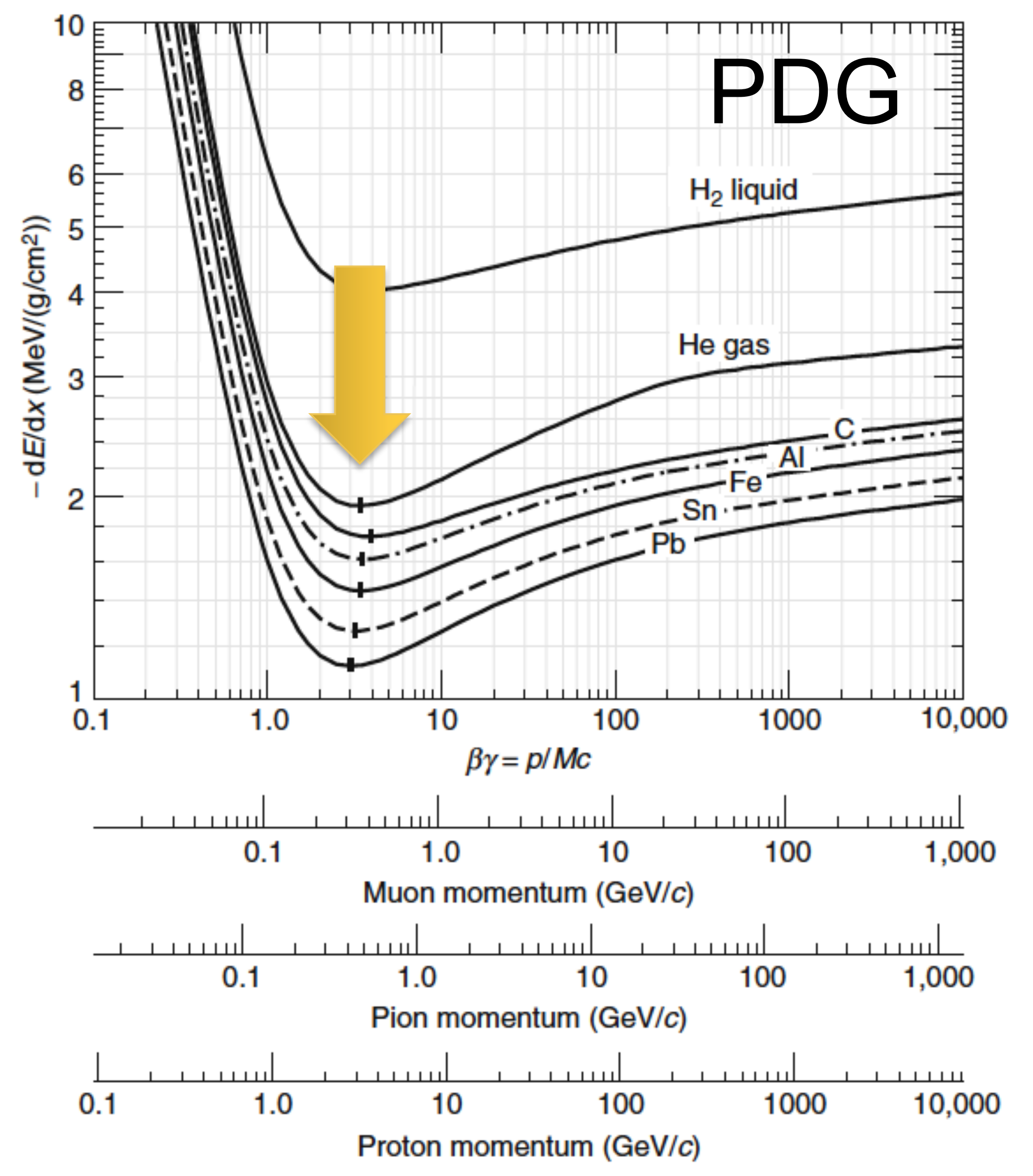
β = v/c of incident particle

γ = $(1-\beta^2)^{-1/2}$

W_{max}= max. energy transfer in one collision

The Bethe-Bloch Formula

- Common features:
  - fast growth, as **1**/β², at low energy
  - wide minimum in the range 3 ≤ βγ ≤ 4,
  - slow increase at high βγ.
- A particle with d**E**/d**x** near the minimum is a minimum-ionizing particle or mip.
- The mip's ionization losses for all materials except hydrogen are in the range 1-2 MeV/(g/cm²)
  - increasing from large to low Z of the absorber.

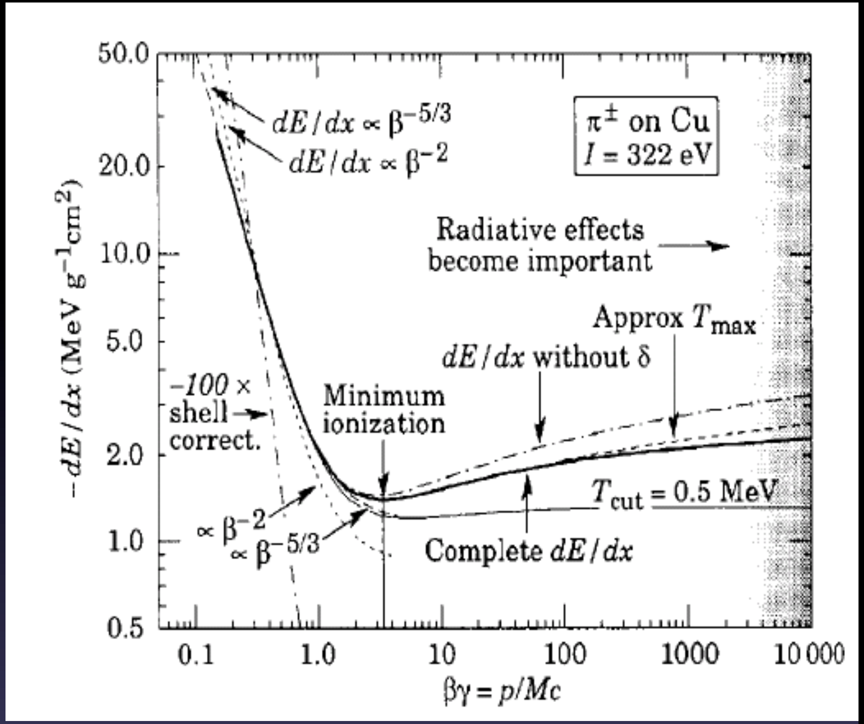


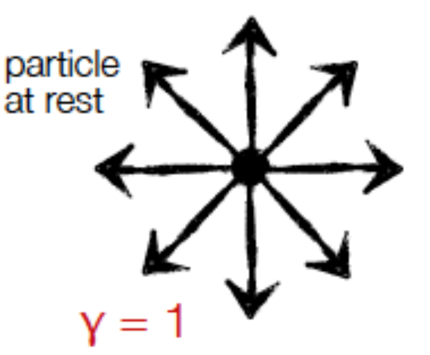
Understanding Bethe-Bloch

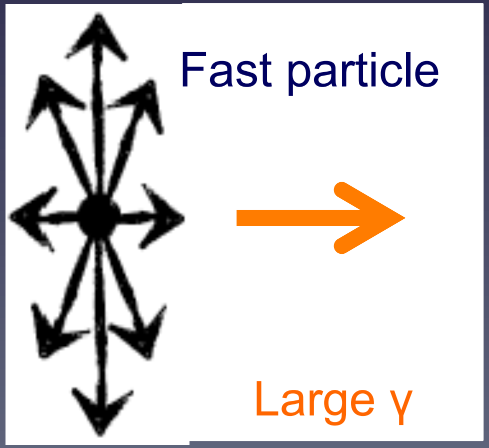
- dE/dx falls like $1/\beta^2$
  [exact dependence $\beta^{-5/3}$]
  - Classical physics: slower particles "feel" the electric force from the atomic electron more

$$\Delta p_{\perp} = \int F_{\perp} dt = \int F_{\perp} \frac{dt}{dx} dx = \int F_{\perp} \frac{dx}{v}$$

- Relativistic rise as $\beta\gamma > 4$
  - Transversal electric field increases due to Lorentz boost



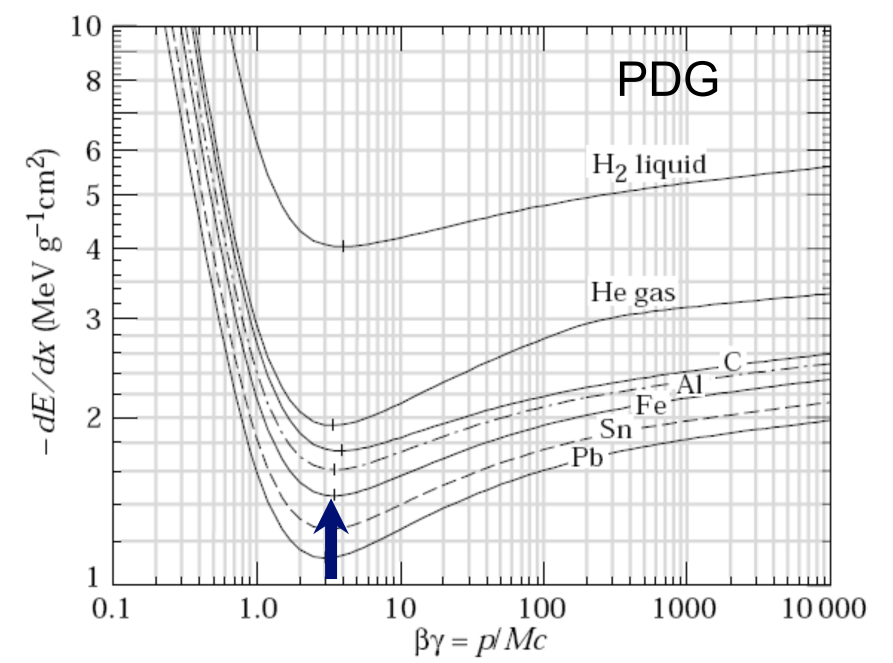




- Shell corrections
  - if particle v ≈ orbital velocity of electrons, i.e. $\beta c \sim v_e$. Assumption that electron is at rest breaks down → capture process is possible .
- Density effects due to medium polarization (shielding) increases at high γ

Bethe-Bloch: Order of magnitude

- For Z ≈ 0.5 A
  - $1/\rho\, dE/dx \approx 1.4$ MeV cm ^{2}/g for $\beta\gamma \approx 3$
- Can a 1 GeV muon traverse 1 m of iron ?
  - Iron: Thickness = 100 cm; $\rho = 7.87$ g/cm^3
  - $dE \approx 1.4$ MeV cm ^{2}/g × 100 cm ×7.87g/cm^3= 1102 MeV
  - This is only an average value
- dE/dx must be taken in consideration when you are designing an experiment

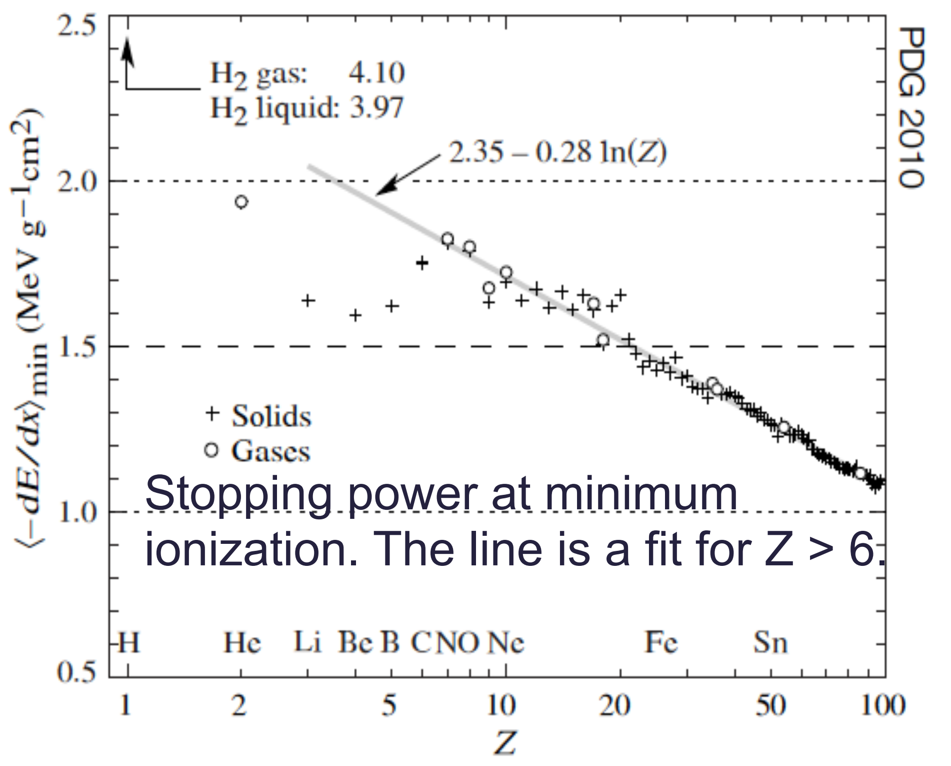


This number must be multiplied with ρ [g/cm^3] of the Material → dE/dx [MeV/cm]

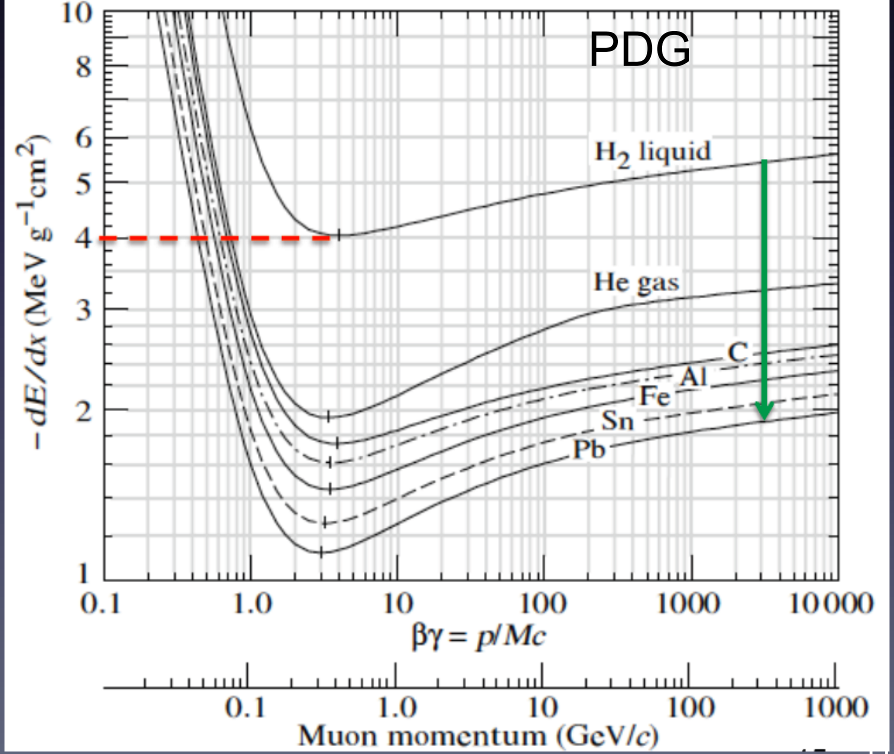
Bethe-Bloch dependence on Z/A

$$-\left\langle \frac{dE}{dx} \right\rangle = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I^2} W_{\max}\right) - 2\beta^2 - \delta(\beta\gamma) - \frac{C}{Z} \right]$$

- Minimum ionization ≈ 1 - 2 MeV/g $\mathrm{cm}^{-2.}$ For H_2: 4 MeV/g cm^{-2}
- Linear decrease as a function of Z of the absorber



Stopping power at minimum ionization. The line is a fit for Z > 6.

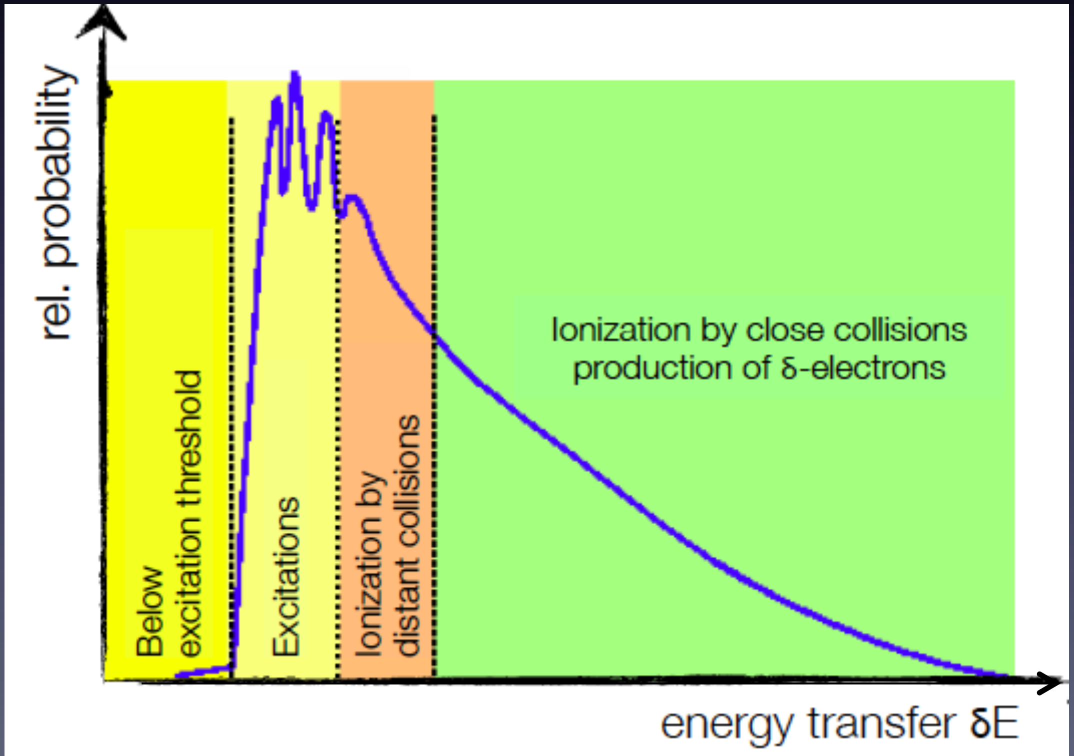


dE/dx Fluctuations

- The statistical nature of the ionizing process results in large fluctuations of energy loss (Δ) in absorbers which are thin compared with the particle range.

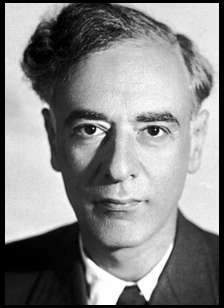
$$\Delta E = \sum_{n=1}^{N} \delta E_n$$

N= number of collisions
δE=energy loss in a single collision



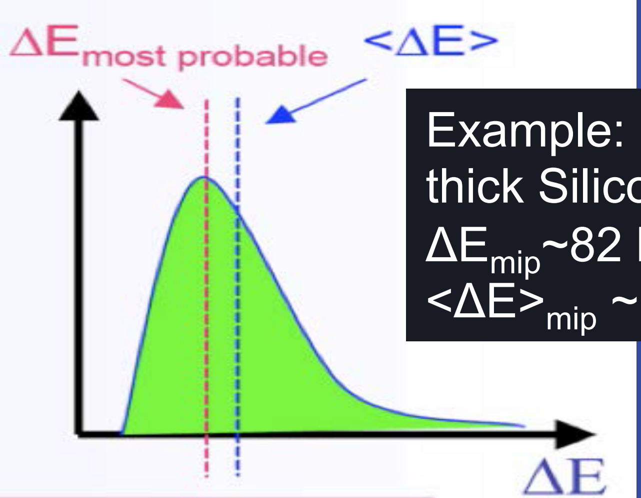
- Ionization loss is distributed statistically
- Small probability to have very high energy delta-rays (or knock-on electrons)

dE/dx Fluctuations

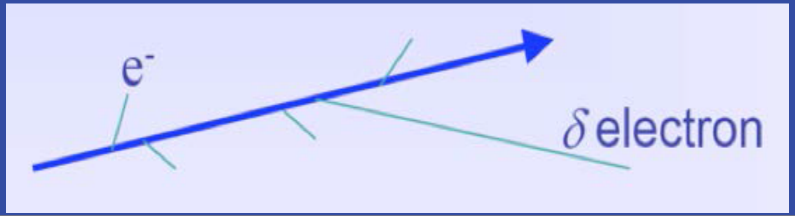


- A real detector (limited granularity) cannot measure <dE/dx>
  - It measures the energy ΔE deposited in layers of finite thickness Δx
  - Repeated measurements are needed

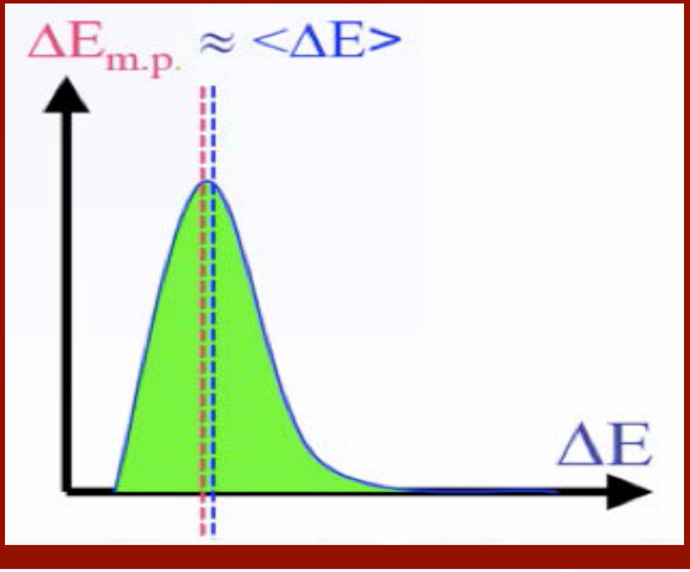
- Thin layers or low density materials: dE/dx has large fluctuations towards high losses (Landau)

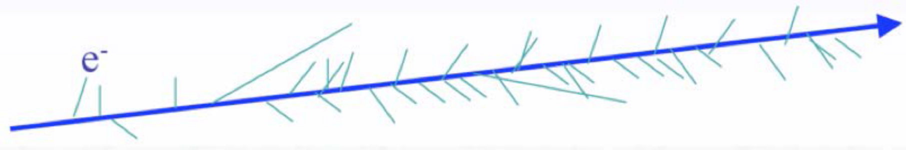


Example: 300 µm thick Silicon
ΔE_{mip}~82 keV,
$<\Delta E>_{mip}$ ~115 keV



- Thick layers and high density materials: the dE/dx is a more Gaussian-like (many collisions



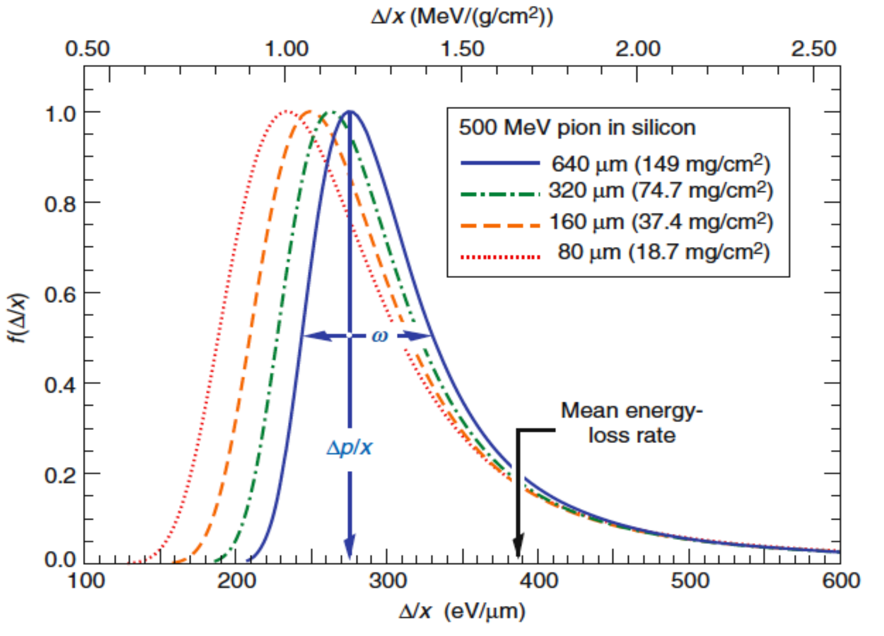


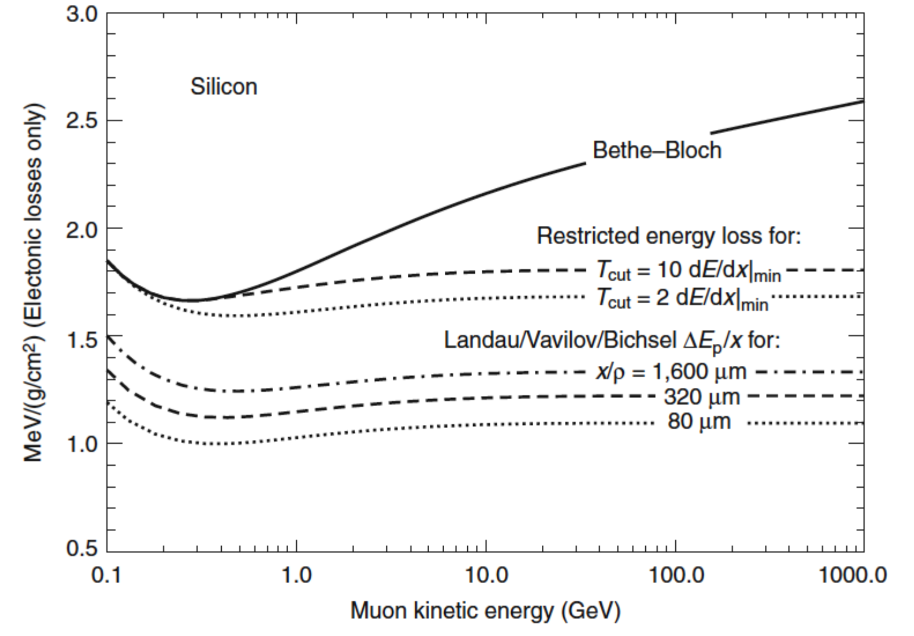
Landau Distribution

- For thin (not too thin) absorbers the Landau distribution offers a good approximation of the energy loss (Gaussian-like + tail due to high energy delta-rays which might leave the detector)

Landau distribution- Most Probable Value (MPV) dE/dx ≠ average dE/dx

Normalized energy loss probability





- An approximation of the Landau distribution:

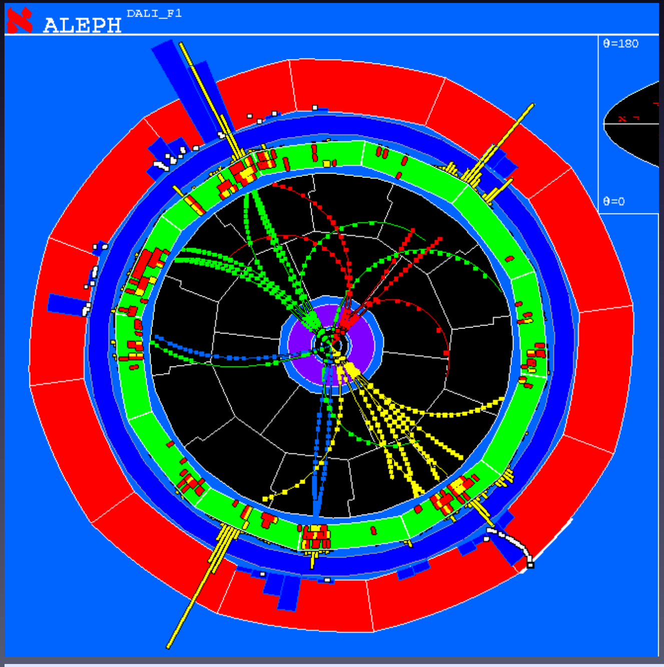
$$L(\lambda)=\frac{1}{\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\lambda+e^{-\lambda}\right)\right]$$

$$\lambda=\frac{\Delta E-\Delta E^{MP}}{\xi}$$

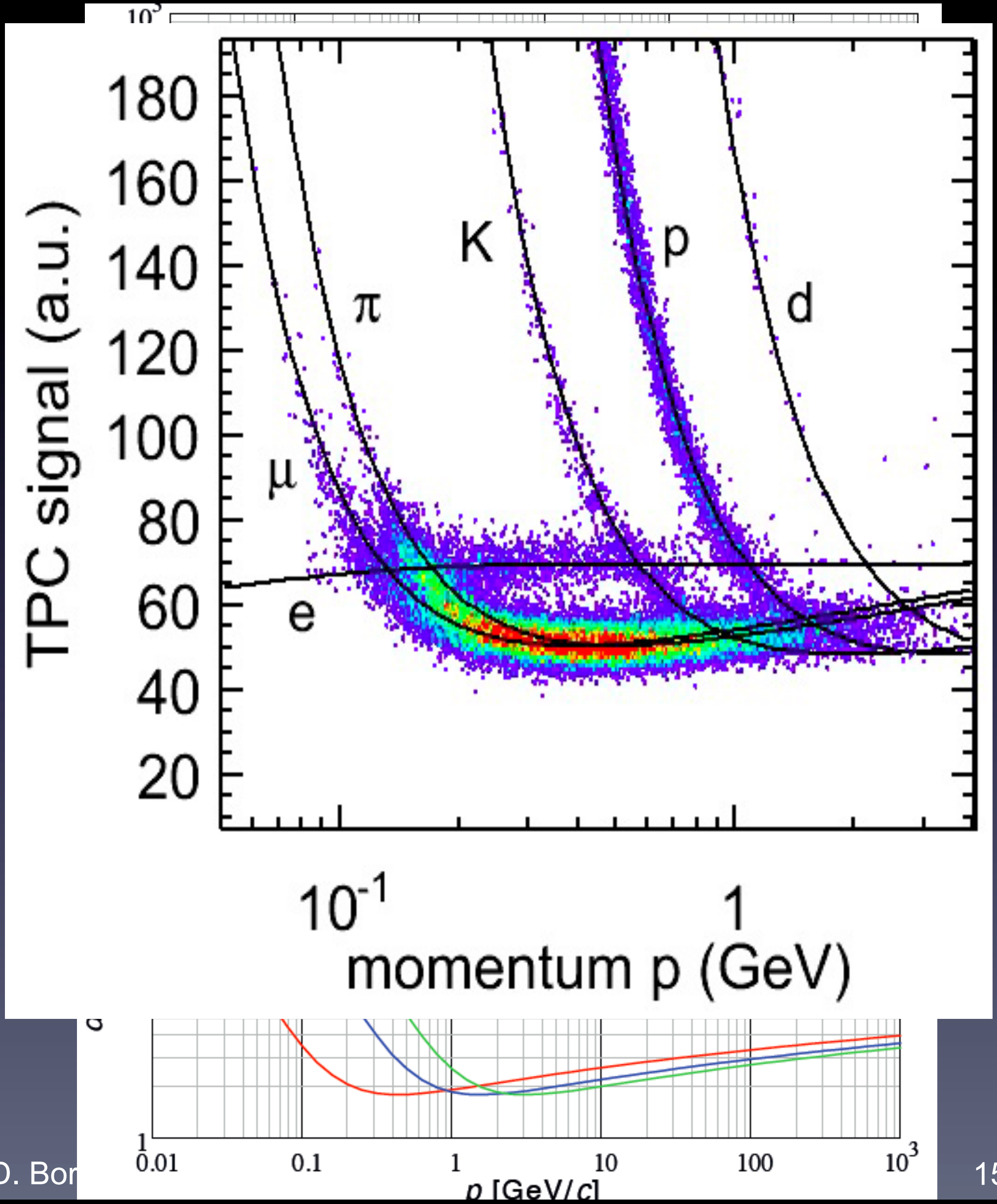
ξ Is material dependent

dE/dx and particle ID

- dE/dx is a function of $\beta\gamma = P/Mc$ and it is independent of M.
- By measuring P and the energy loss independently → Particle ID in certain momentum regions

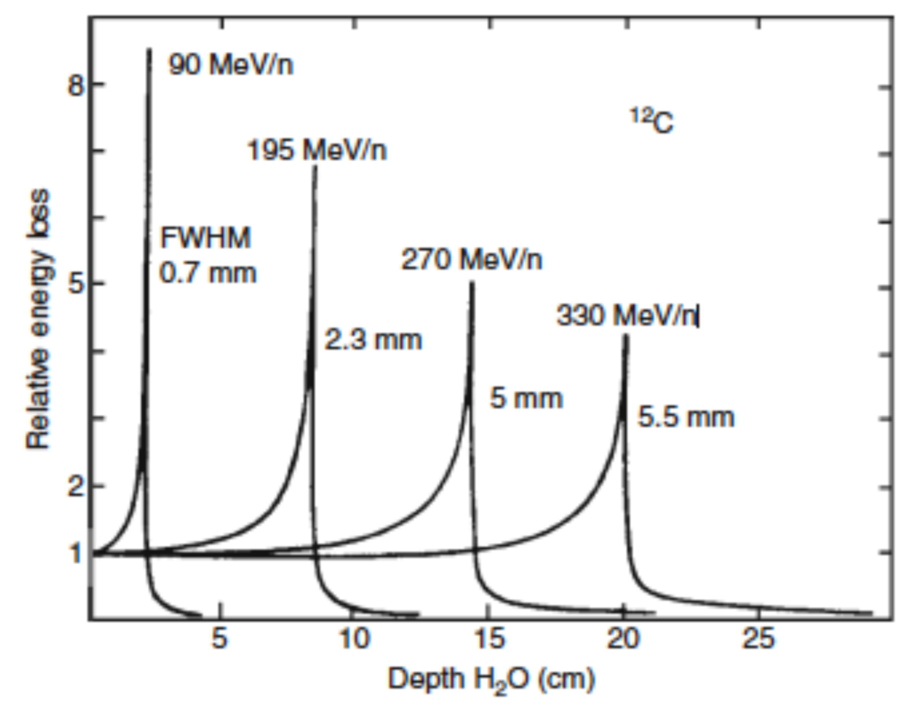


$$P_T\left[GeV/c\right] = 0.3B[T]\rho[m]$$



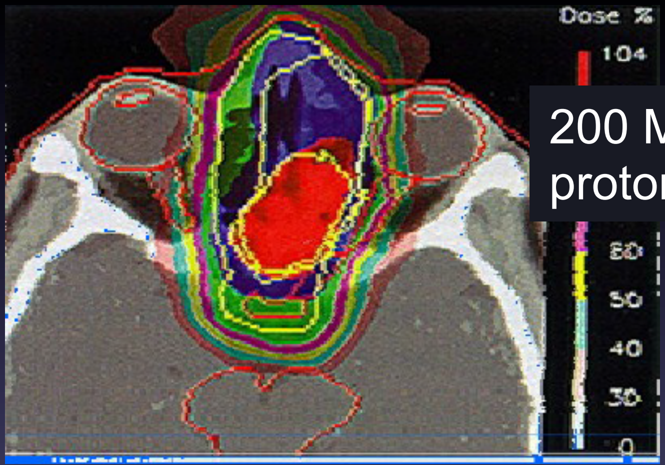
Energy loss at small momenta

- If the energy of the particle falls below $\beta\gamma=3$ the energy loss rises as $1/\beta^2$ → Particles deposit most of their energy at the end of their track → Bragg peak

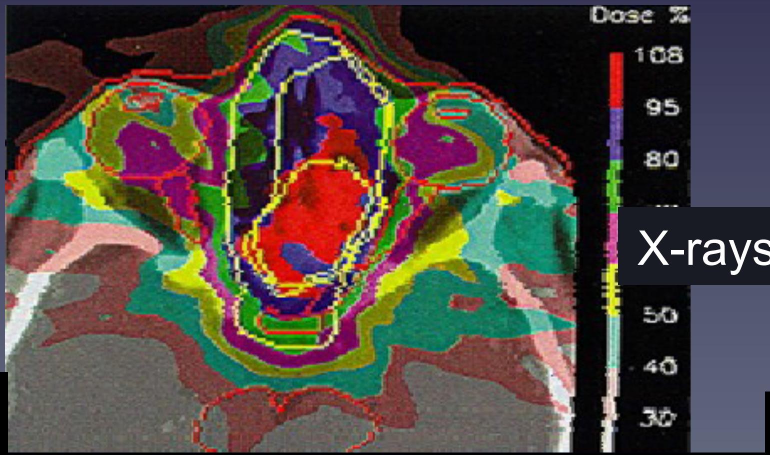


Critical for radiation therapy

Hadron therapy: Protons 200 MeV 1 nA
Carbon ions 4800 MeV 0.1 nA



200 MeV proton beam



X-rays

Range of particles in matter

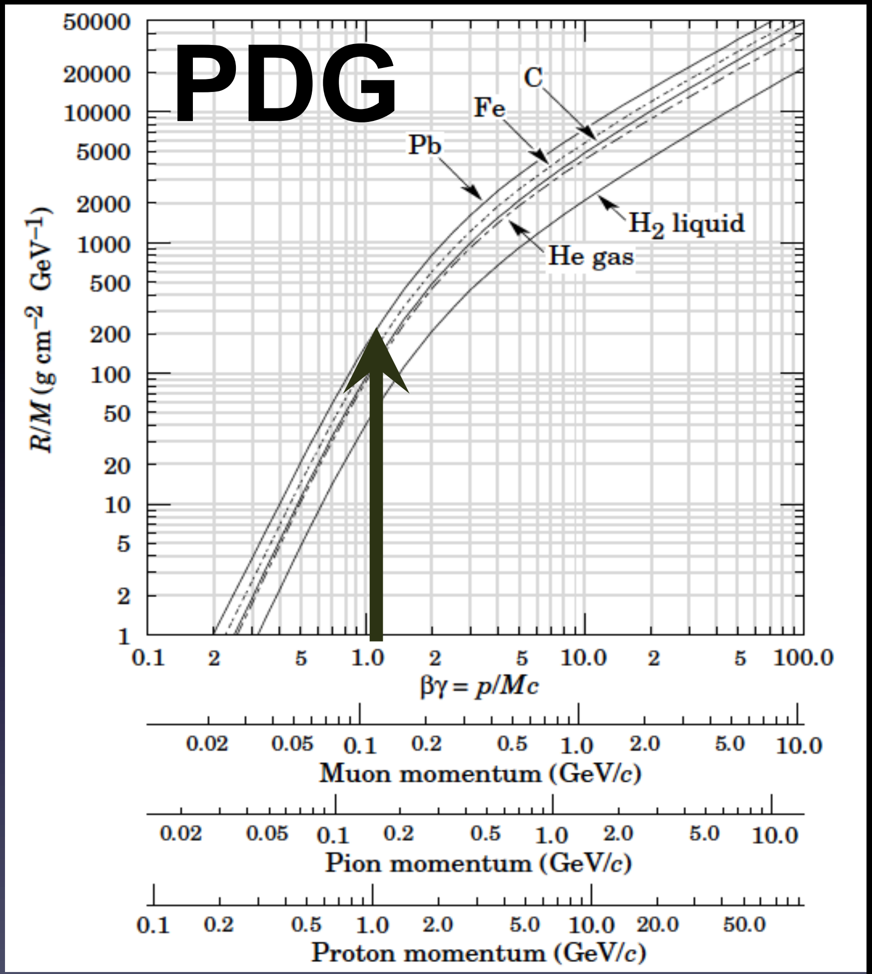
- A particle of mass M and kinetic Energy E_0 enters matter and looses energy until it comes to rest at a distance R.

$$R(E_0) = \int_{E_0}^{0} \frac{1}{dE/dx}\, dE$$

$$R(\beta_0\gamma_0) = \frac{Mc^2}{\rho}\frac{1}{z^2}\frac{A}{Z} f(\beta_0\gamma_0)$$

$$\frac{\rho R(\beta_0\gamma_0)}{Mc^2} = \frac{1}{z^2}\frac{A}{Z} f(\beta_0\gamma_0)$$

- R/M is ≈ independent of the material
- R is a useful concept only for low-energy hadrons (R <λ_I =the nuclear interaction length)



1GeV p in Pb ρ(Pb)= 11.34 g/cm^3

R/M(Pb)=200 g cm^{-2} GeV^{-1}

R=(200/11.34) cm ≈ 20 cm

Range of particles in matter

- A particle of mass M and kinetic Energy E_0 enters matter and looses energy until it comes to rest at a distance R.

$$R(E_0) = \int_{E_0}^{0} \frac{1}{dE/dx}\, dE$$

$$R(\beta_0\gamma_0) = \frac{Mc^2}{\rho}\frac{1}{z^2}\frac{A}{Z} f\left(\beta_0\gamma_0\right)$$

$$\frac{\rho R(\beta_0\gamma_0)}{Mc^2} = \frac{1}{z^2}\frac{A}{Z} f\left(\beta_0\gamma_0\right)$$

- R/M is ≈ independent of the material
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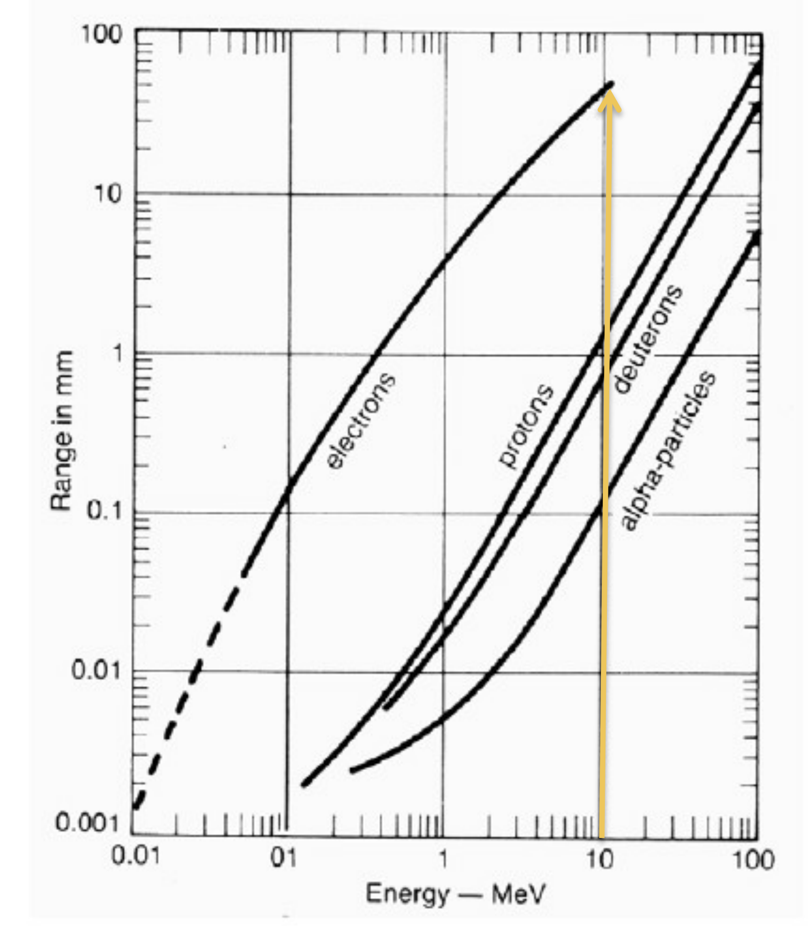
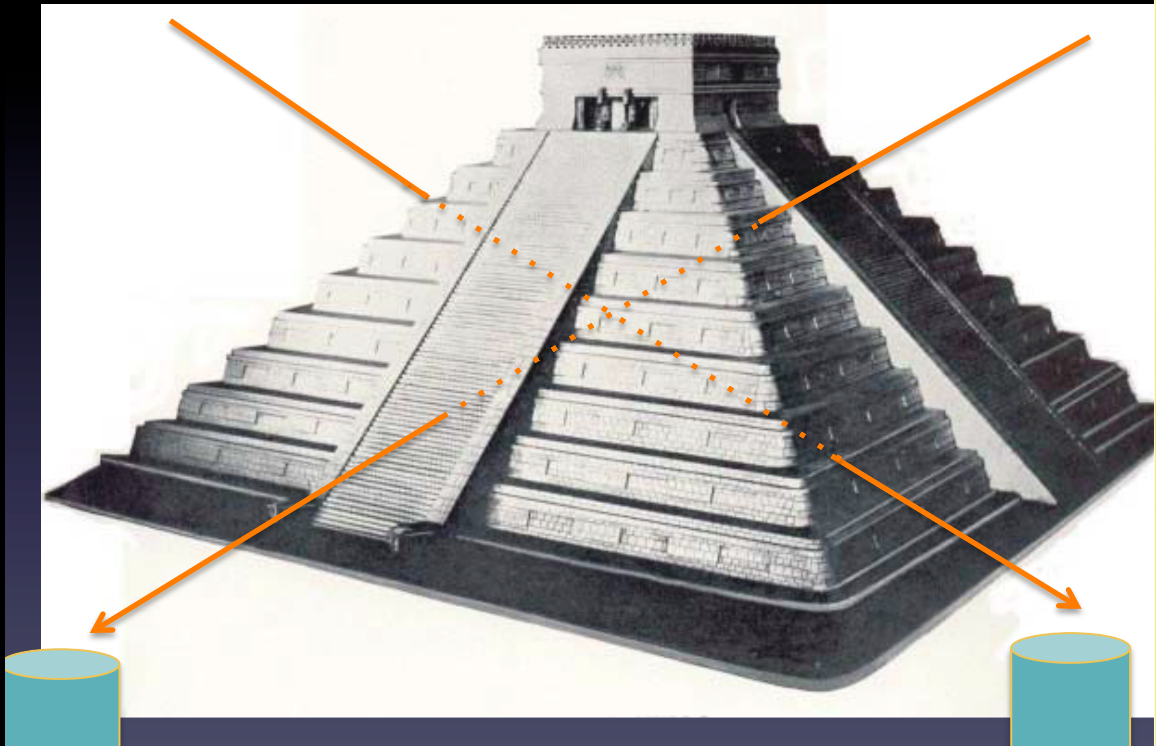
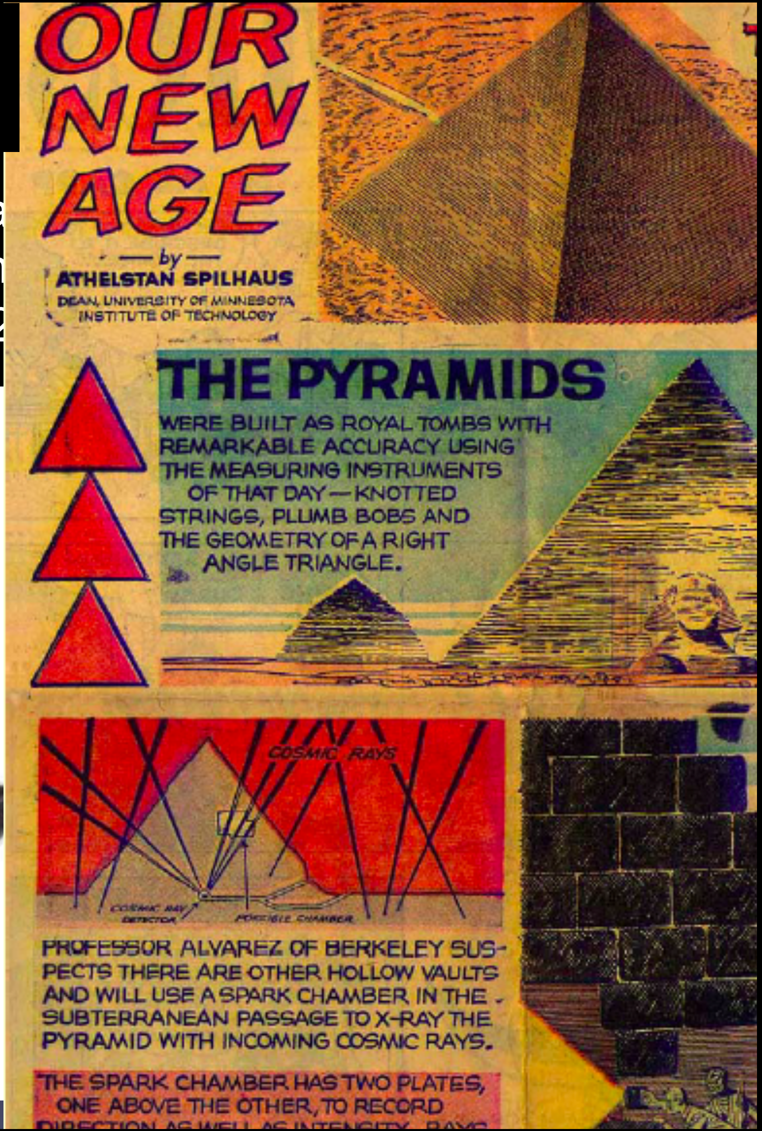


Mean free path in plastic scintillator for various charged particle

Muon Tomography

- L. Alvarez in the 60s used the measurement of a
  cosmic ray muons to look for hidden chambers in
  Pyramid → Muon Tomography (Science 167, 832





OUR NEW AGE

— by —

ATHELSTAN SPILHAUS

DEAN, UNIVERSITY OF MINNESOTA INSTITUTE OF TECHNOLOGY

THE PYRAMIDS

WERE BUILT AS ROYAL TOMBS WITH REMARKABLE ACCURACY USING THE MEASURING INSTRUMENTS OF THAT DAY — KNOTTED STRINGS, PLUMB BOBS AND THE GEOMETRY OF A RIGHT ANGLE TRIANGLE.

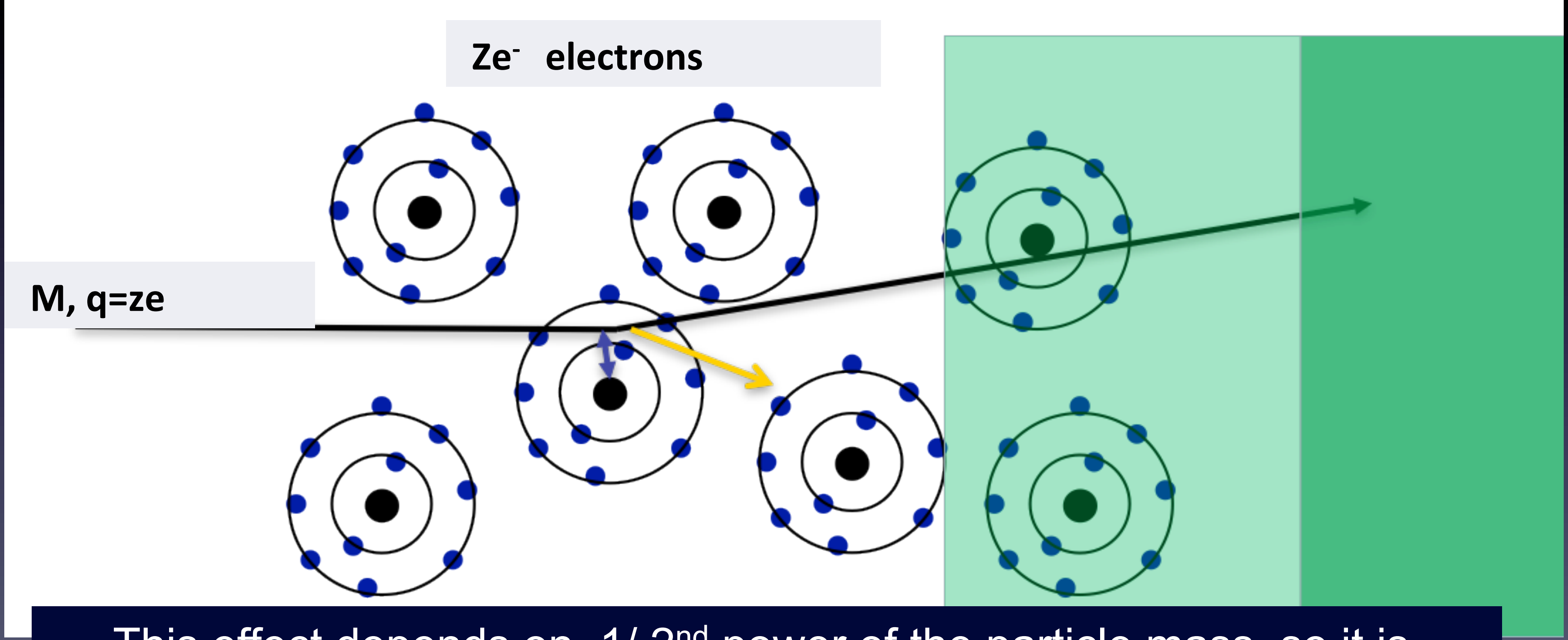
PROFESSOR ALVAREZ OF BERKELEY SUSPECTS THERE ARE OTHER HOLLOW VAULTS AND WILL USE A SPARK CHAMBER IN THE SUBTERRANEAN PASSAGE TO X-RAY THE PYRAMID WITH INCOMING COSMIC RAYS.

THE SPARK CHAMBER HAS TWO PLATES, ONE ABOVE THE OTHER, TO RECORD DIRECTION AS WELL AS INTENSITY. RAYS

- No hidden chambers
- Now used for archeology in the Yucatan, detection of illicitly trafficked Special Nuclear Material etc.

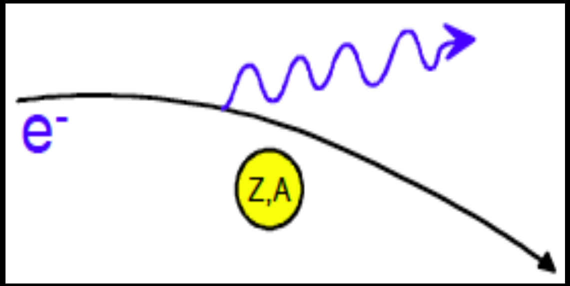
Bremsstrahlung

A charged particle of mass M and charge q=ze is deflected by a nucleus of charge Ze which is partially ‘shielded’ by the electrons. During this deflection the charge is ‘accelerated’ and therefore it can radiate a photon → Bremsstrahlung.



This effect depends on 1/ 2nd power of the particle mass, so it is relevant for electrons and very high energy muons

Energy loss for electrons and muons



- Bremsstrahlung=photon emission by an electron accelerated in Coulomb field of nucleus

$$\frac{dE}{dx} = 4\alpha N_A \frac{z^2 Z^2}{A}\left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}}$$

- Dominant process for E_e > 10-30 MeV
  - energy loss proportional to $1/m^2$
  - Important mainly for electrons and h.e. muons

$$\Rightarrow \quad -\left\langle \frac{dE}{dx} \right\rangle_{brem} \propto \frac{E}{m^2}$$

- For electrons

$$\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}}$$

$$\text{If} \quad X_0 \approx \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}} \quad \Rightarrow \quad \frac{dE}{dx} = \frac{E}{X_0} \quad \Rightarrow \quad E = E_0 e^{-x/X_0}$$

X_0 = radiation length in [g/cm^2]

After passing a layer of material of thickness **X_0** the electron has 1/e of its initial energy.

Total energy loss and critical energy

$$\left(\frac{dE}{dx}\right)_{\text{Tot}} = \left(\frac{dE}{dx}\right)_{\text{Ion}} + \left(\frac{dE}{dx}\right)_{\text{Brems}}$$

- Critical energy

$$\left.\frac{dE}{dx}(E_c)\right|_{brems} = \left.\frac{dE}{dx}(E_c)\right|_{ion}$$

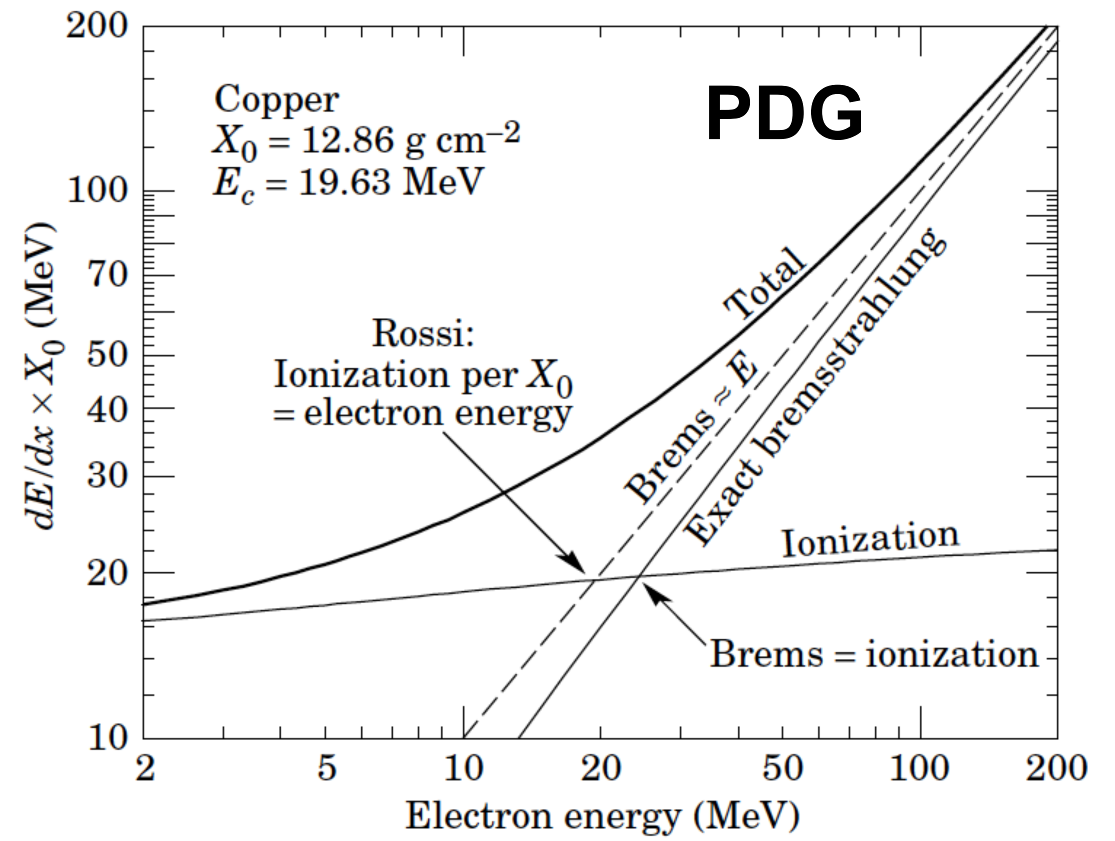
For solid and liquids

$$E_c = \frac{610\ \text{MeV}}{Z+1.24}$$

For gasses

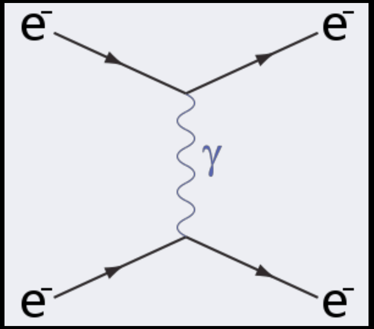
$$E_c = \frac{710\ \text{MeV}}{Z+0.92}$$

Example Copper:
$E_c \approx 610/30$ MeV ≈ 20 MeV

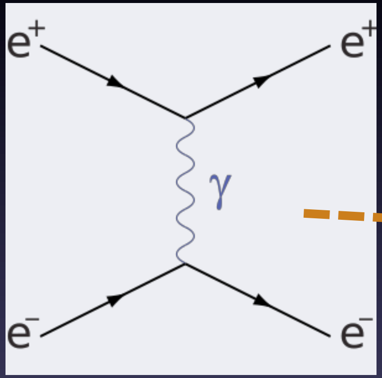


Electron energy loss

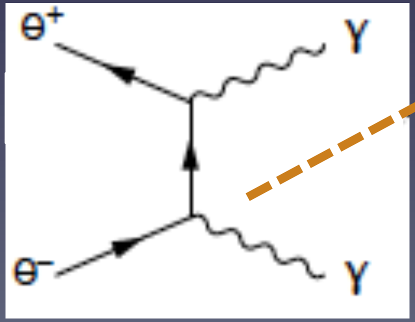
- Møller scattering

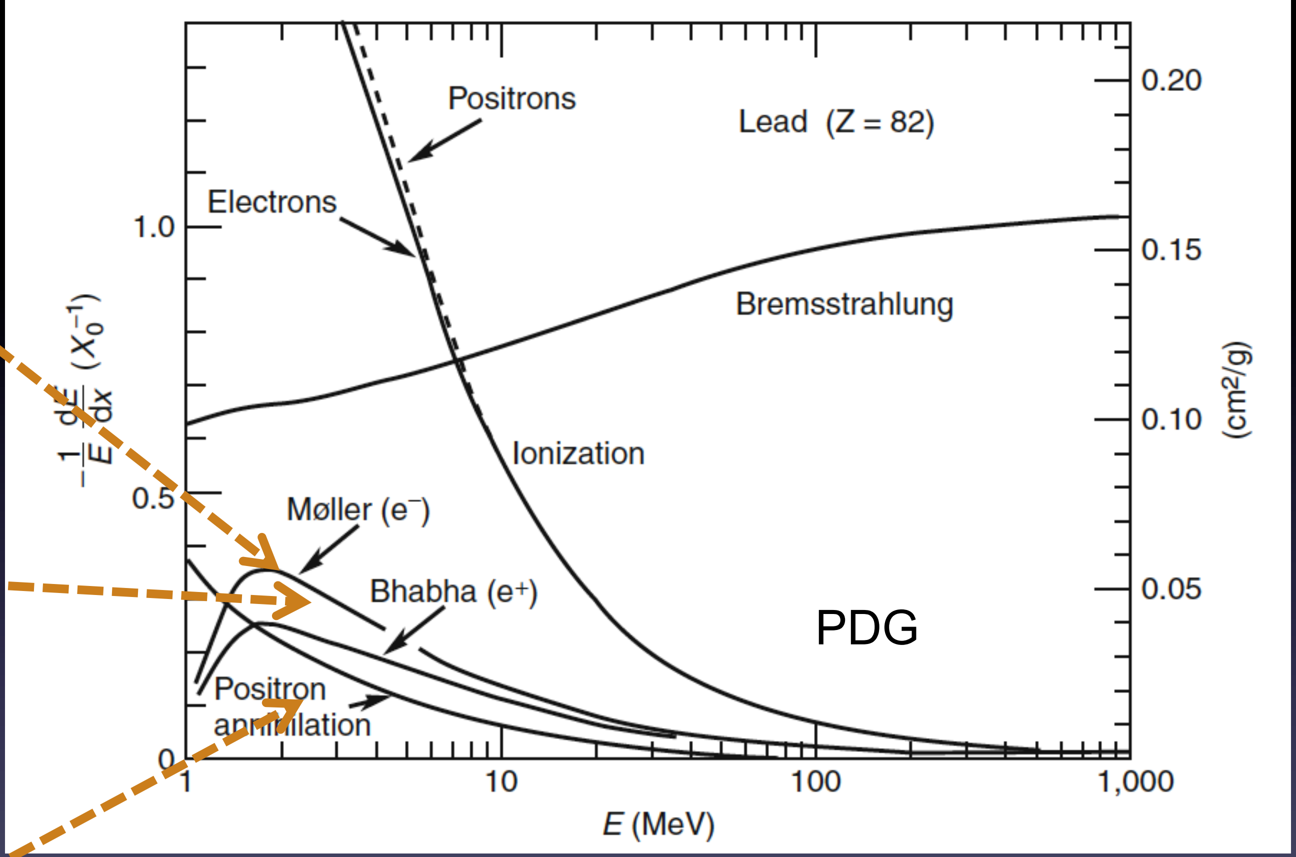


- Bhabha scattering



- Positron annihilation





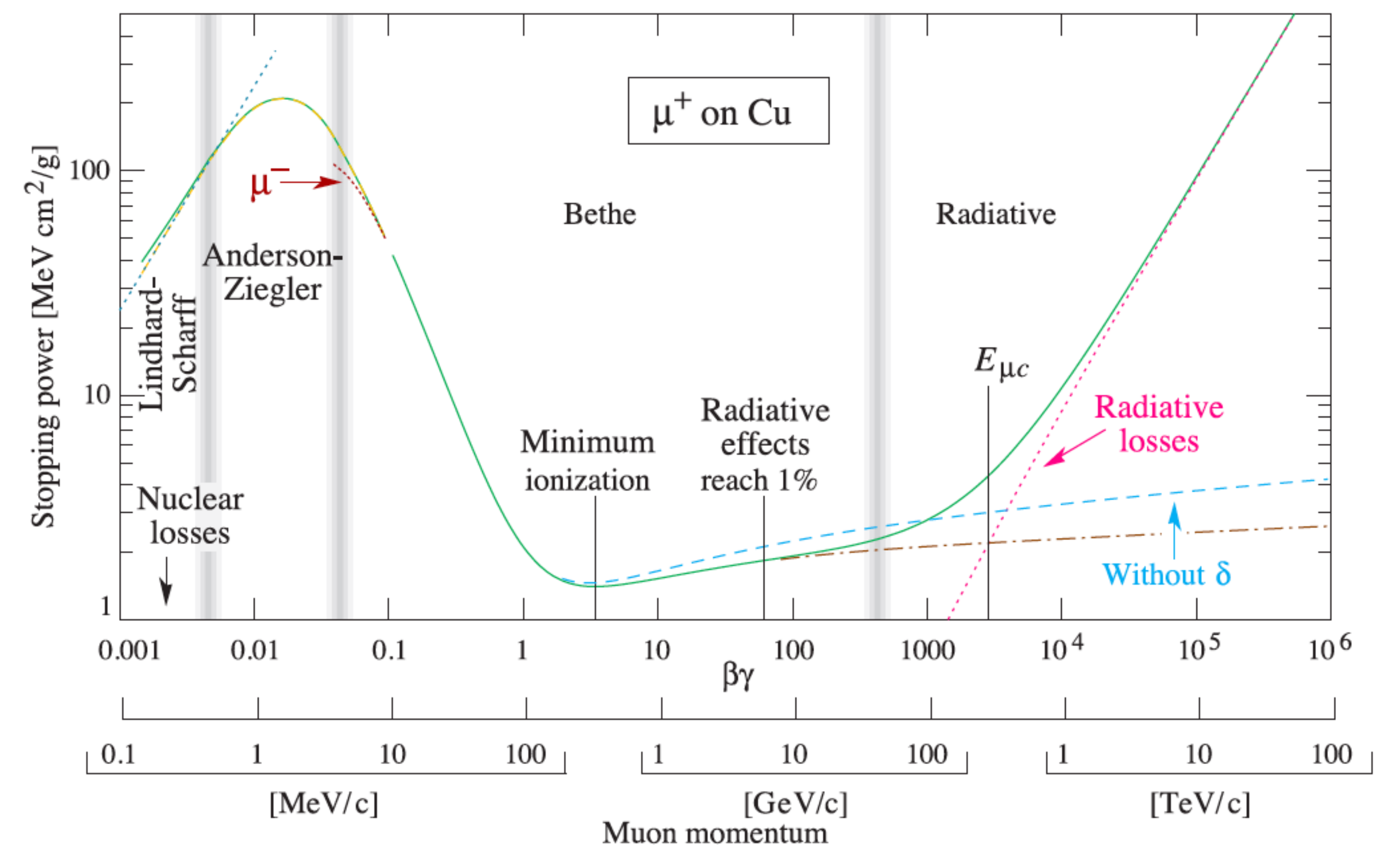
- Fractional energy loss per radiation length in lead as a function of the electron or positron energy

Energy loss summary

Since $m_\mu/m_e \approx 200$ E_c for muons ≈ 400 GeV.

$$-\left\langle \frac{dE}{dx} \right\rangle_{brem} \propto \frac{E}{m^2}$$

$$\left\langle \frac{dE}{dx} \right\rangle_{brem,\mu} \propto \frac{1}{40,000} \left\langle \frac{dE}{dx} \right\rangle_{brem,2}$$



- Muons with energies > ~10 GeV can penetrate thick layers of matter
- This is the key signature for muon identification

Interaction of photons with matter

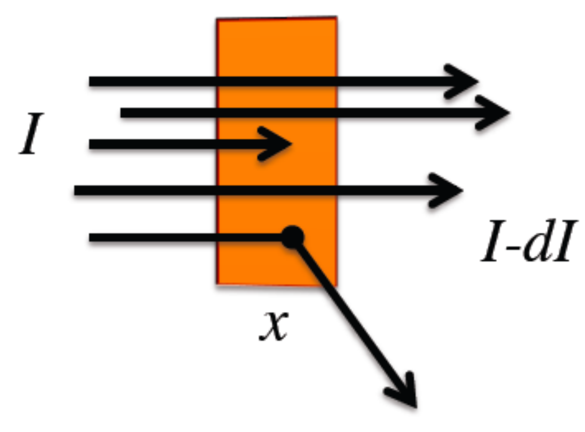
- A photon can disappear or its energy can change dramatically at every interaction

$$I(x) = I_0 e^{-\mu x} \qquad \mu = \frac{N_A}{A}\sum_{i=1}^{3}\sigma_i$$

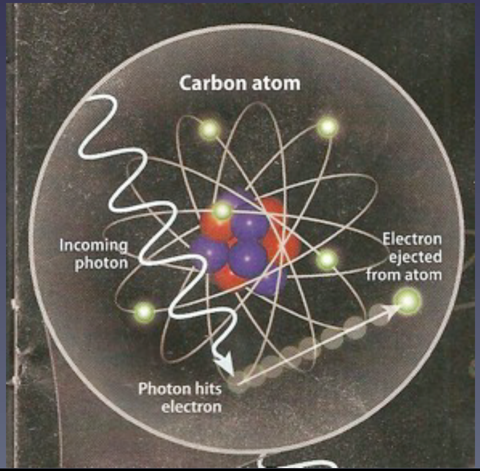
$$\lambda = \frac{1}{\mu}$$

μ=total attenuation coefficient

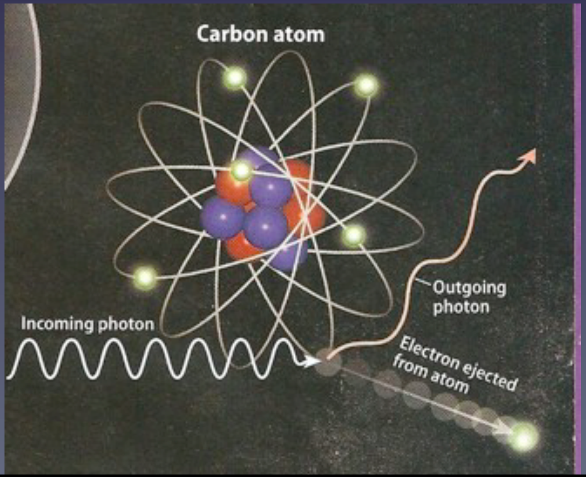
σ_i=cross section for each process



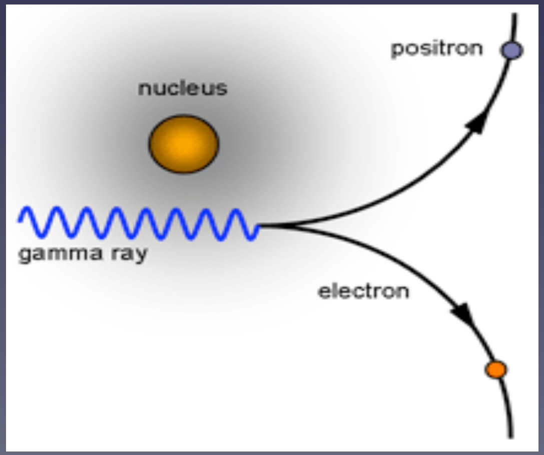
Photoelectric Effect



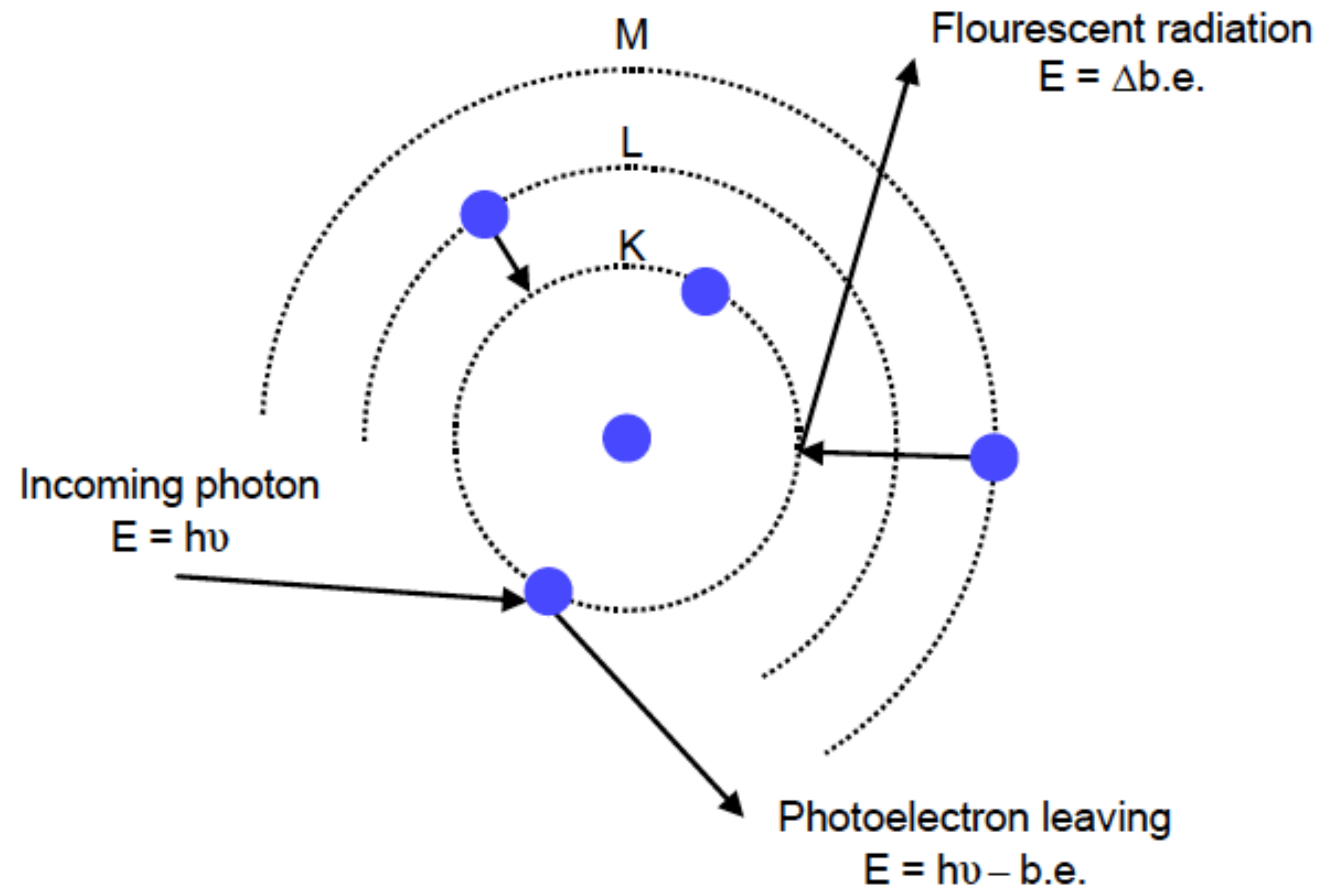
Compton Scattering



Pair production



Photoelectric effect



Compton scattering

- Best known electromagnetic process (Klein–Nishina formula)
  - for $\mathbf{E_\lambda} \ll \mathbf{m_e c^2}$

$$\sigma_c \propto \sigma_{Th}(1-\varepsilon)$$

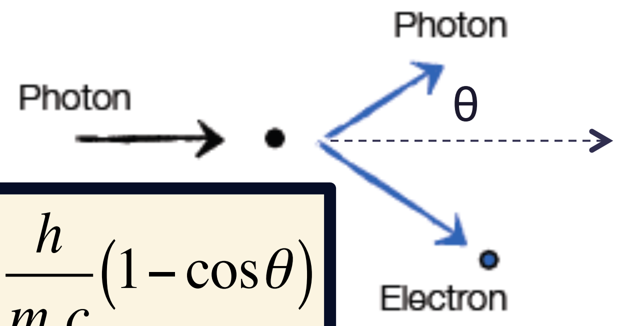
  - for $\mathbf{E_\lambda} \gg \mathbf{m_e c^2}$

$$\sigma_c \propto \frac{\ln \varepsilon}{\varepsilon} Z$$

where

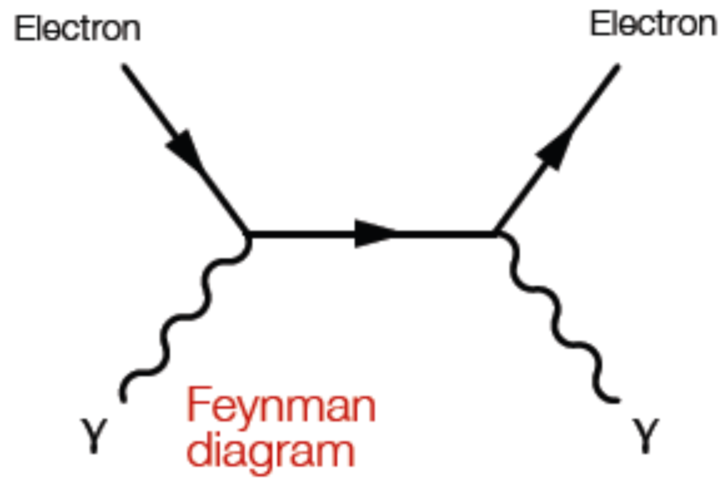
$$\sigma_{Th} = \frac{8\pi}{3r_e^2} = 0.66\ barn$$

$$\varepsilon = \frac{E_\lambda}{m_e c^2}$$



$$\lambda' - \lambda = \frac{h}{m_e c}(1-\cos\theta)$$

$$\gamma + e^- \rightarrow (\gamma)' + (e^-)'$$



Compton scattering

- From E and p conservation yields the energy of the scattered photon

$$E'_\gamma = \frac{E_\gamma}{1+\varepsilon(1-\cos\theta)} \qquad \varepsilon = \frac{E_\lambda}{m_e c^2}$$

- Kinetic energy of the outgoing electron:

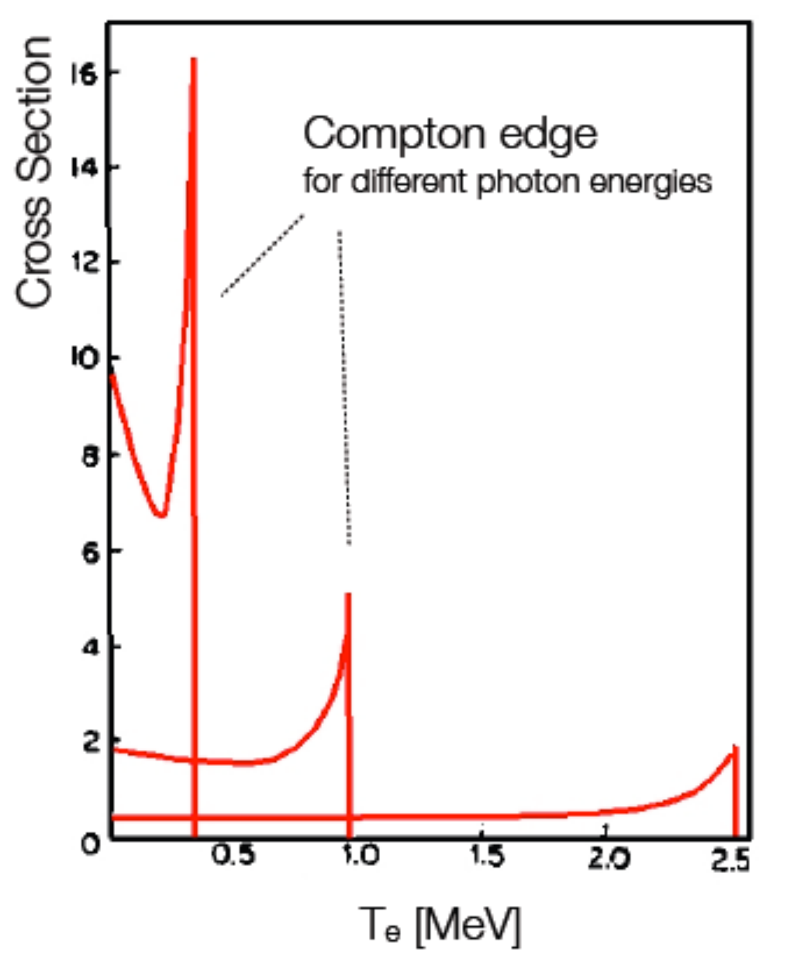
$$T_e = E_\gamma - E'_\gamma = E_\gamma \frac{\varepsilon(1-\cos\theta)}{1+2\varepsilon}$$

- The max. electron recoil is for θ=π

$$T_{\max} = E_\gamma \frac{2\varepsilon}{1+2\varepsilon}$$

$$\Delta E = E_\gamma - T_{\max} = E_\gamma \frac{1}{1+2\varepsilon}$$

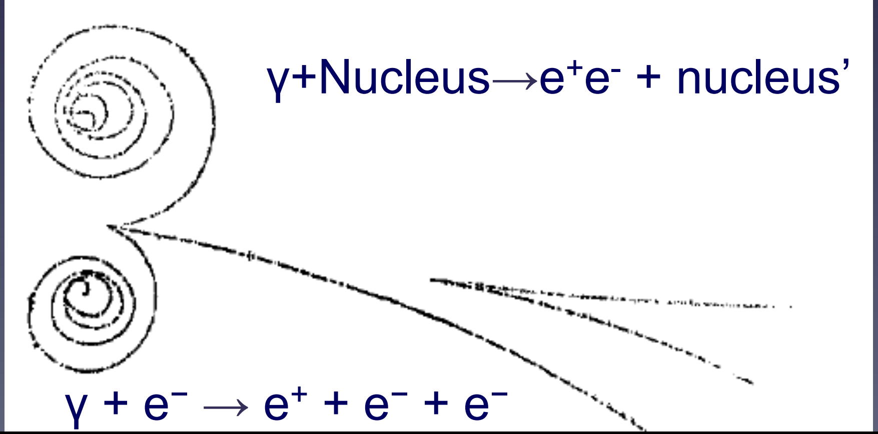
- Transfer of complete γ-energy via Compton scattering not possible

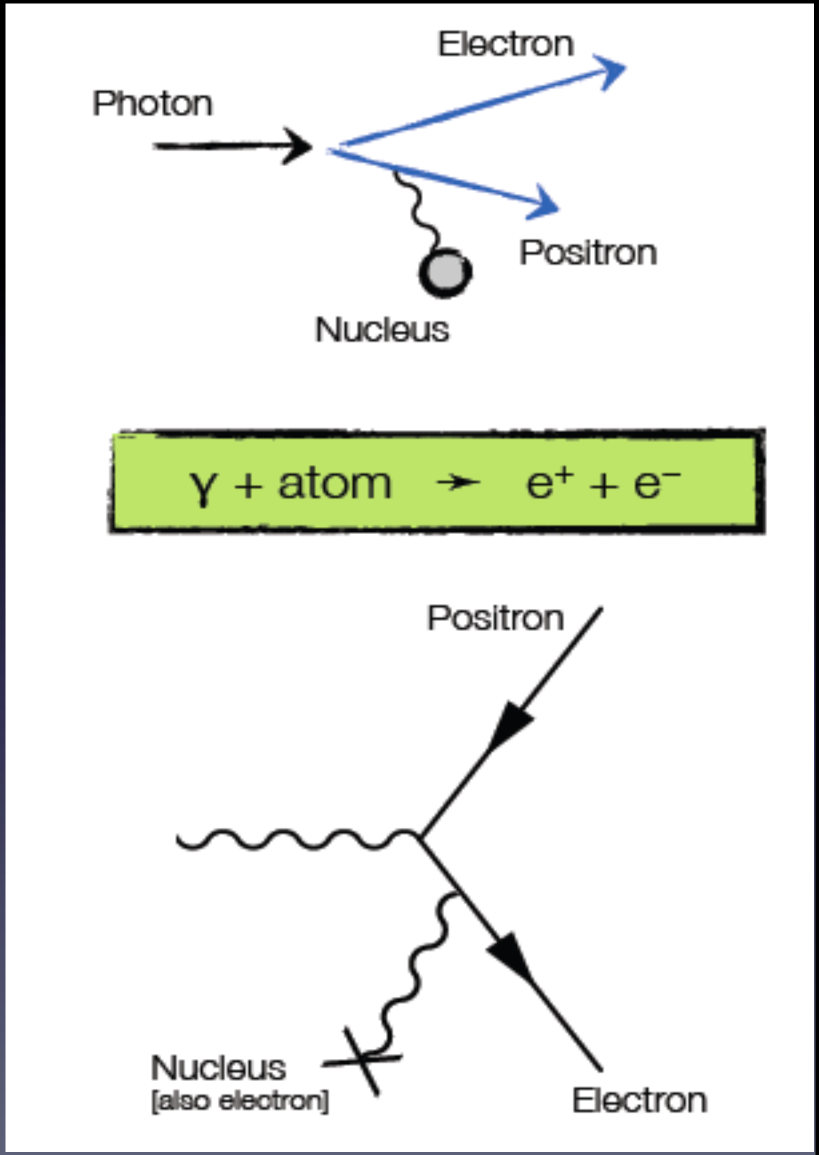


Pair production

- At E>100 MeV, electrons lose their energy almost exclusively by bremsstrahlung while the main interaction process for photons is electron–positron pair production.
- Minimum energy required for this process 2 m_e + Energy transferred to the nucleus

$$E_\gamma \geq 2m_e c^2 + \frac{2m_e c^2}{m_{Nuleus}} \geq 2m_e c^2$$





Pair production

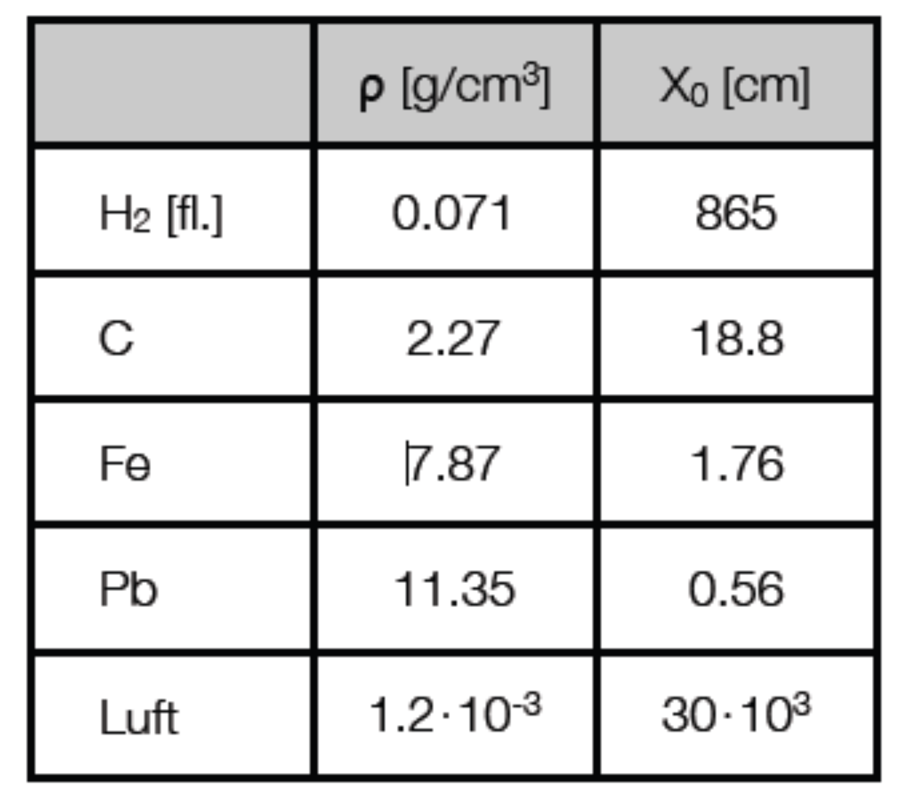
- If $E_\lambda >> m_e c^2$

$$\sigma_{pair} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \ [\mathrm{cm}^2/\mathrm{atom}]$$

- Using as for Bremsstrahlung the radiation length and neglecting the small 1/54 term

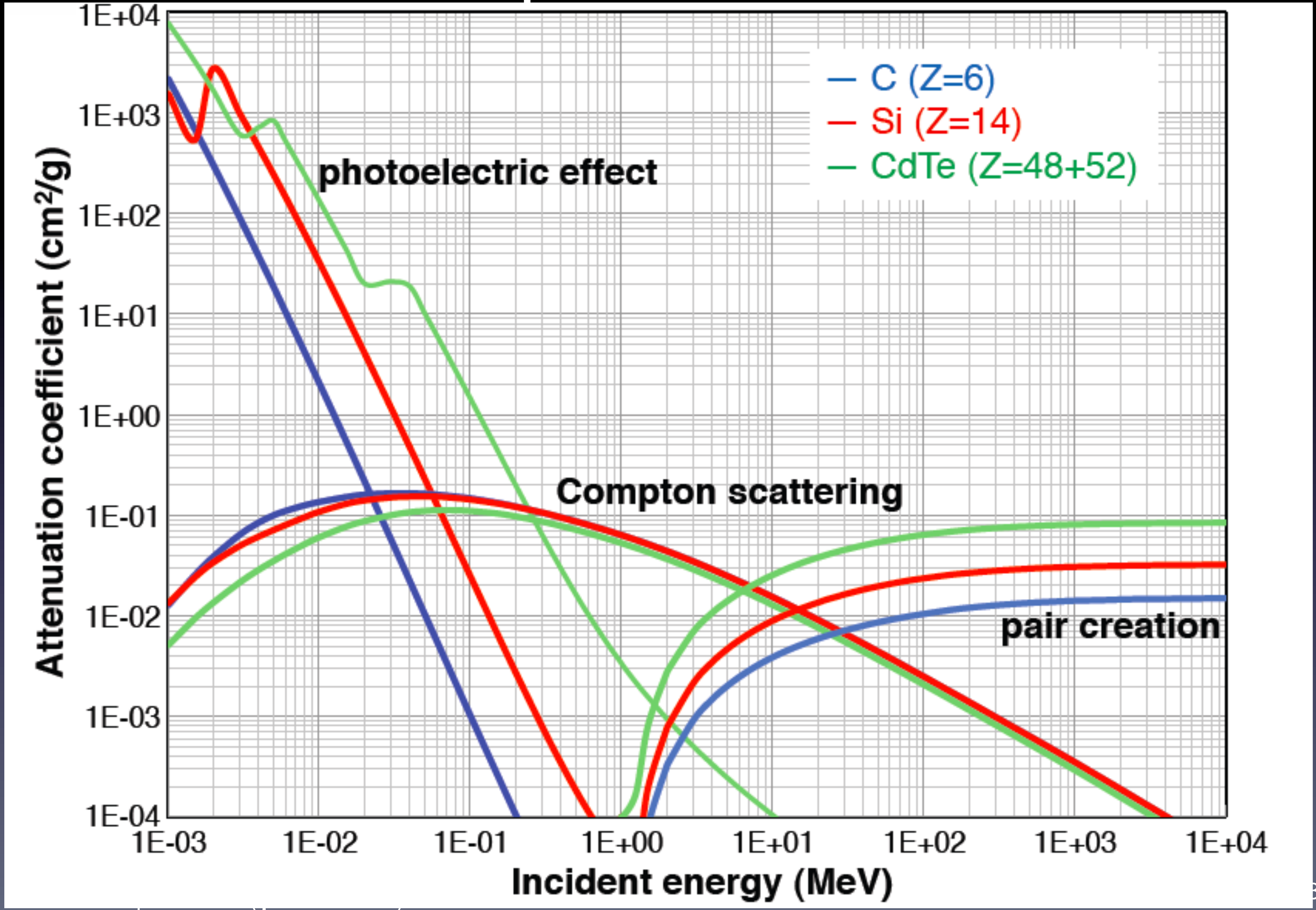
$$X_0 = \frac{A}{4\pi N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$

$$\sigma_{pair} = \frac{7}{9} \frac{N_A}{A} \frac{1}{X_0}$$



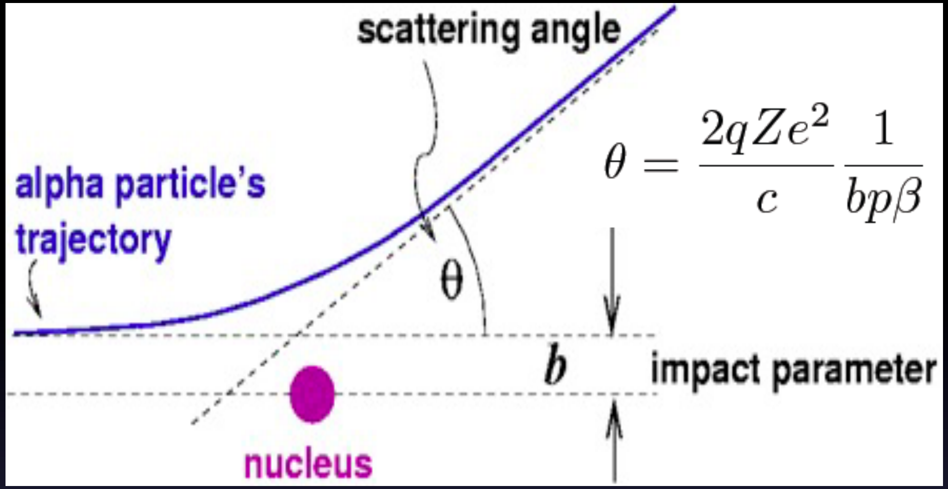
	ρ [g/cm³]	X_0 [cm]
H_2 [fl.]	0.071	865
C	2.27	18.8
Fe	7.87	1.76
Pb	11.35	0.56
Luft	$1.2 \cdot 10^{-3}$	$30 \cdot 10^{3}$

Interaction of photons with matter



Multiple scattering

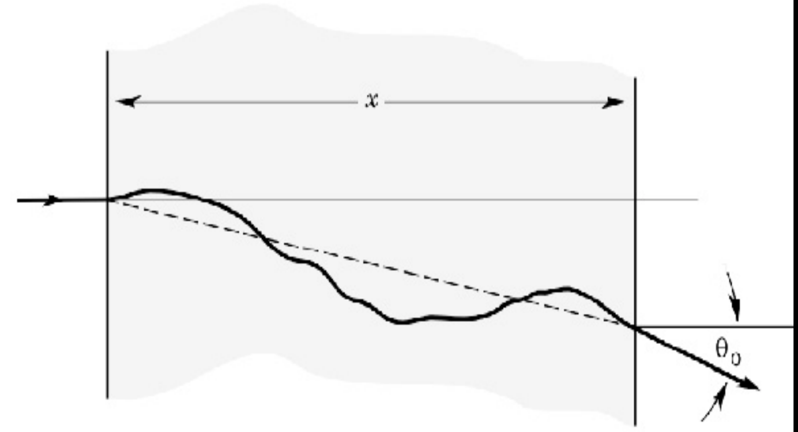
- A particle passing through material undergoes also multiple deflections due to Coulomb scattering with the nuclei



  - The scattering angle as a function of the thickness x is

$$\theta_{\rm rms}^{\rm proj} = \sqrt{\langle\theta^2\rangle} = \frac{13.6\,{\rm MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}}\left[1 + 0.038\ln(x/X_0)\right]$$

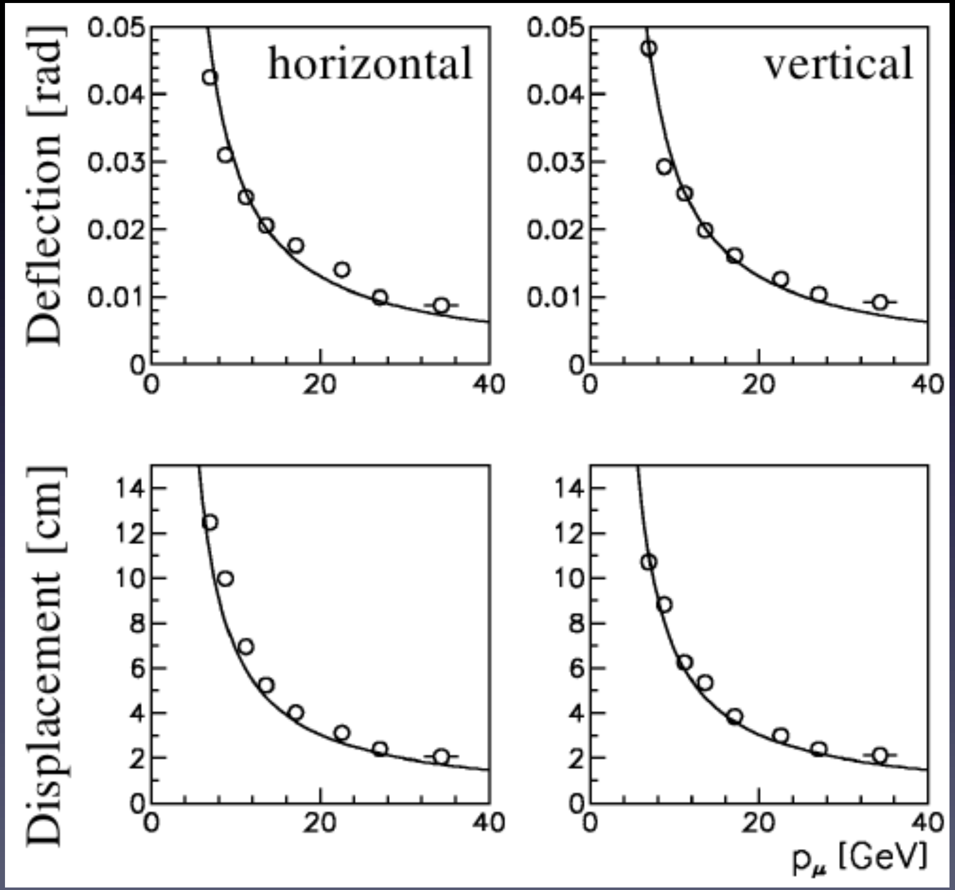
  - Where:
    - p (in MeV/c) is the momentum,
    - βc the velocity,
    - z the charge of the scattered particle
    - x/X_0 is the thickness of the medium in units of radiation length (X_0).



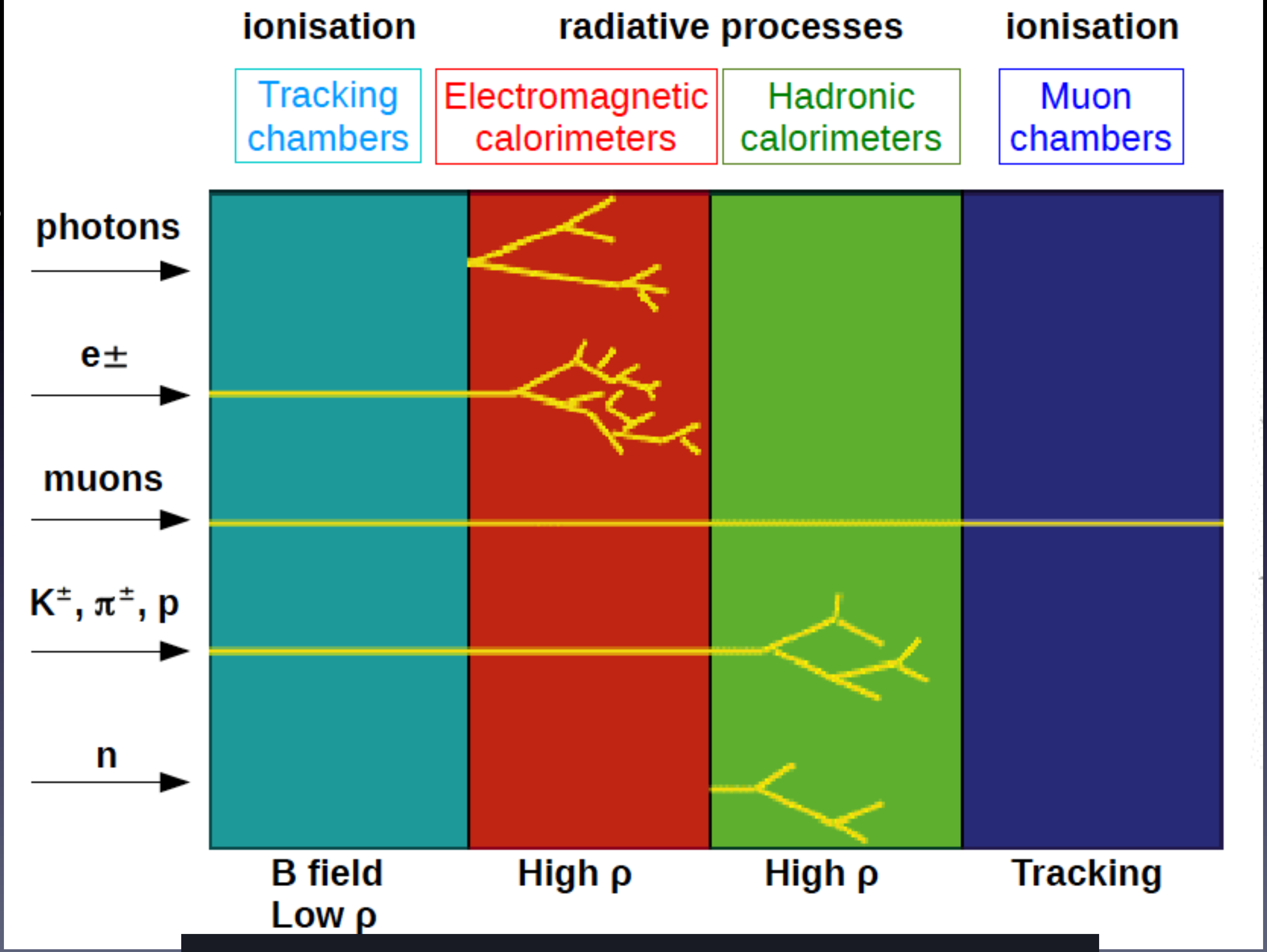
Multiple scattering

- Particularly relevant for μ in high-energy physics, but also common for low-energy e
- Hadrons generally undergo nuclear interactions before multiple scattering and energy loss become significant.
- Example: muon with E=14 GeV
  $\theta_0 \sim 13.6 / 14\text{x}10^3 \ \sqrt{(x / x_0)}$
  ~ 1 mRad $\sqrt{(x / x_0)}$
  Iron $X_0 = 1.8$ cm ; μ at E=10 GeV after 100 cm Fe :
  $\theta_0 \sim 13.6 / 10^4 \sqrt{(100/1.8)} \sim 10$ mRad

Example of Multiple scattering: Muons before and after 320 radiation lengths



Building your detector



ionisation

radiative processes

ionisation

Tracking chambers

Electromagnetic calorimeters

Hadronic calorimeters

Muon chambers

photons

e±

muons

$K^{\pm}$, $\pi^{\pm}$, p

n

B field
Low ρ

High ρ

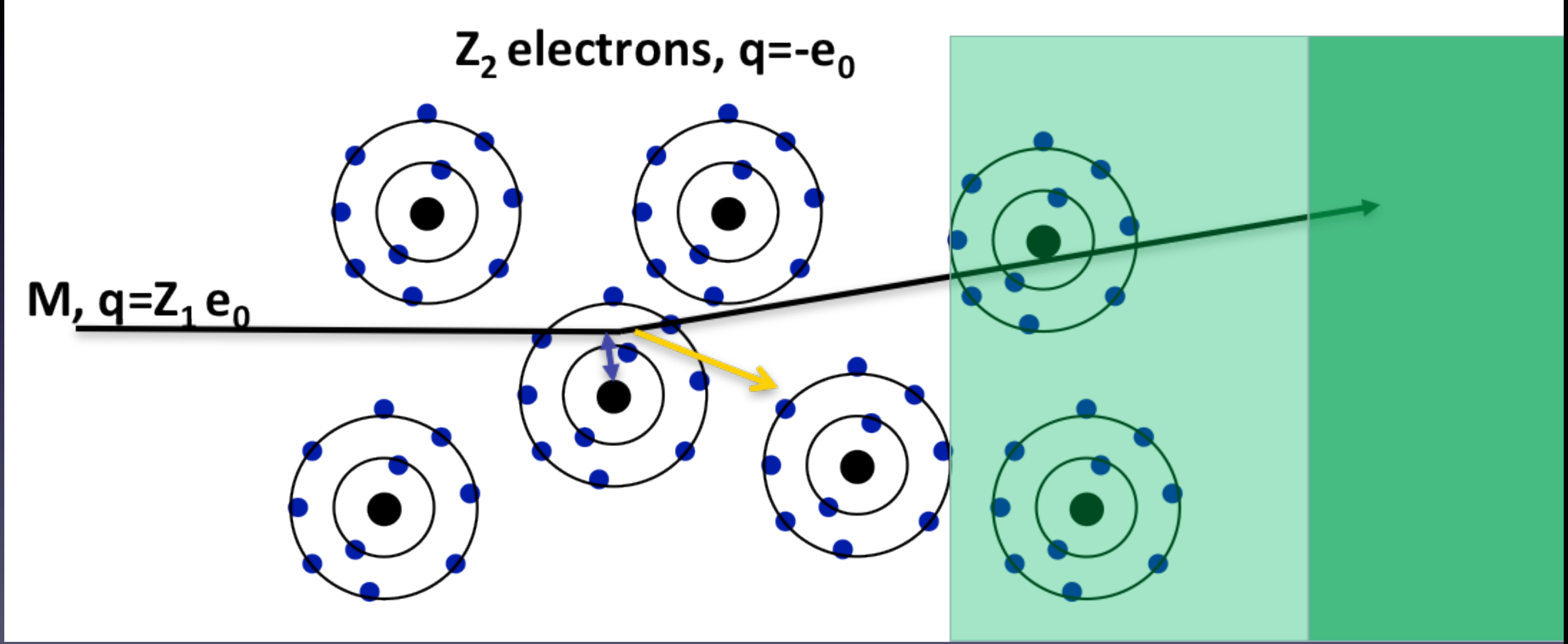
High ρ

Tracking

http://pdg.lbl.gov/2014/AtomicNuclearProperties/

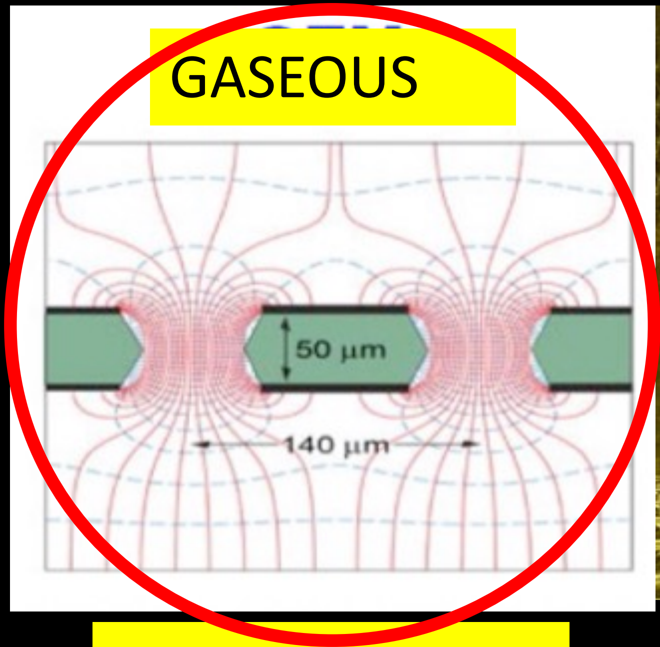
Energy loss by photon emission

- Emission of Cherenkov light
- Emission of transition radiation

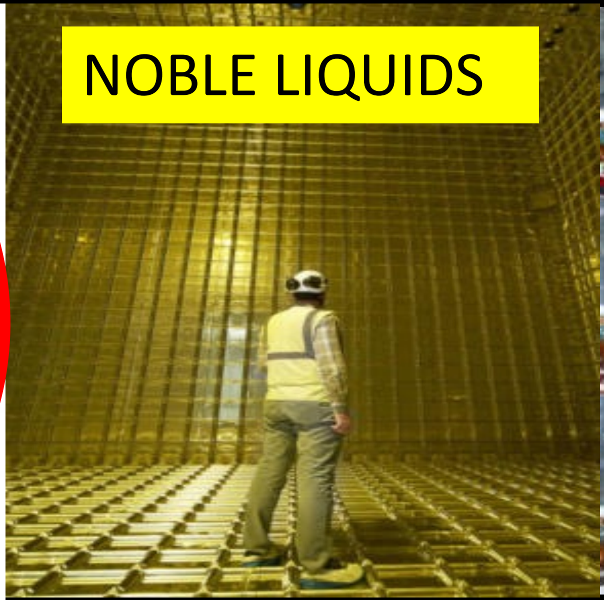


Technology Classification for the ECFA R&D Roadmap

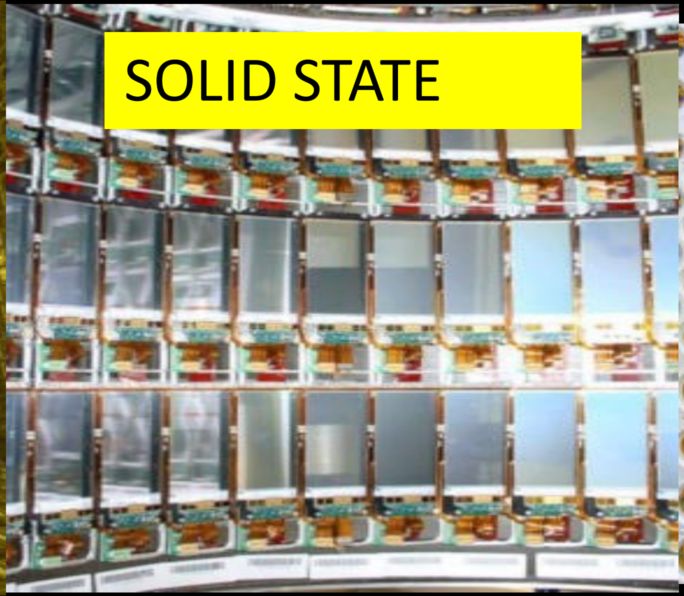
GASEOUS



NOBLE LIQUIDS

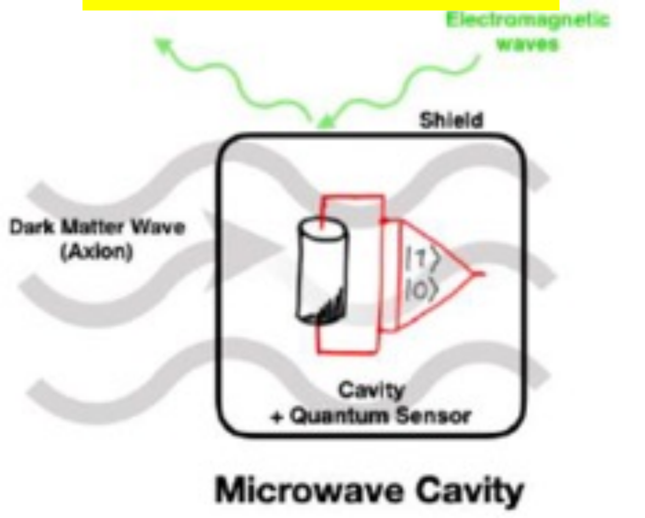


SOLID STATE

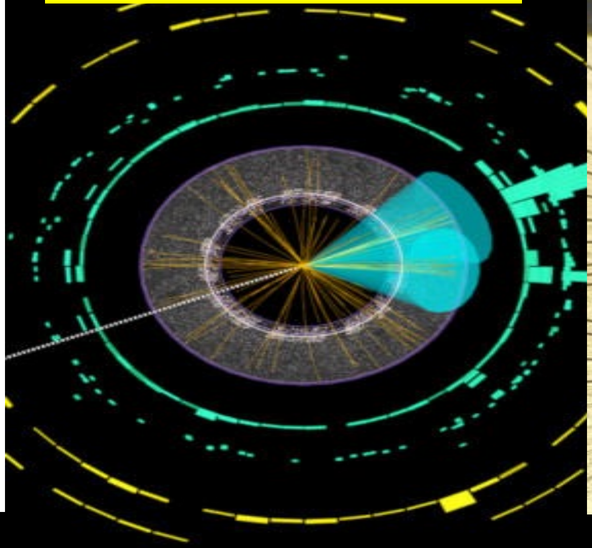


PHOTODETECTORS

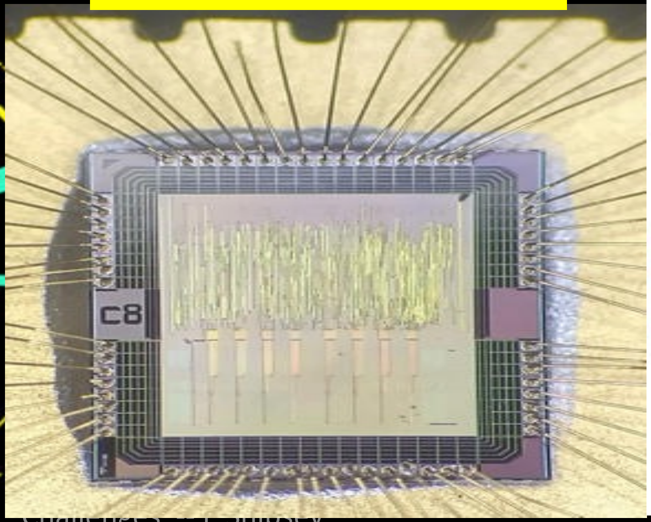
QUANTUM



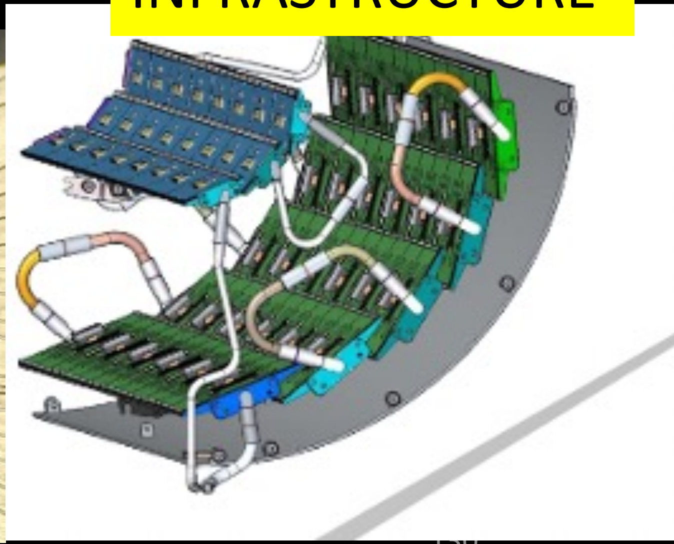
CALORIMETER



ELECTRONICS



INFRASTRUCTURE



Gaseous Detectors

Coaxial Cylindrical Proportional Counter

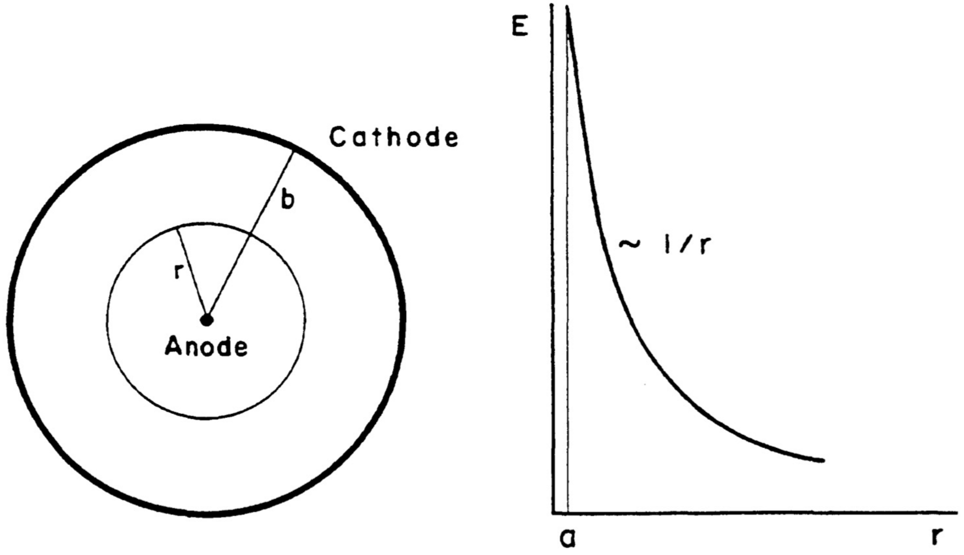


Fig. 48 The coaxial cylindrical proportional counter, and the shape of the electric field around the thin anode. Only very close to the anode the field grows high enough to allow avalanche multiplication.

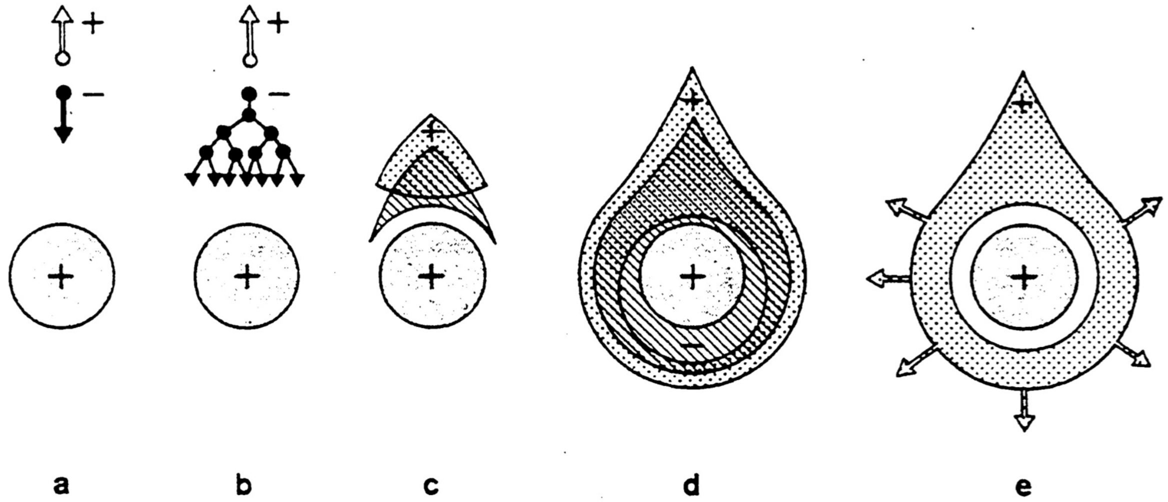
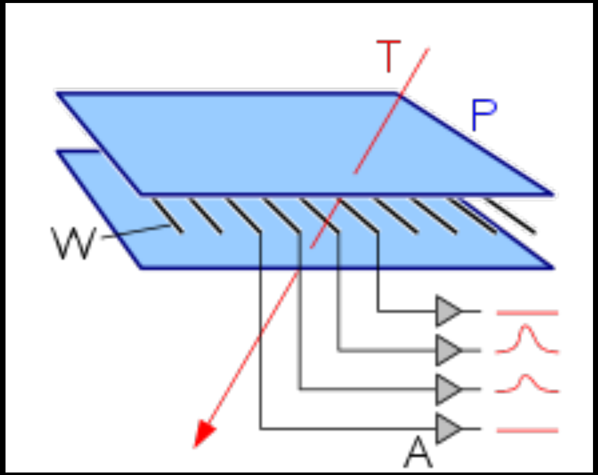
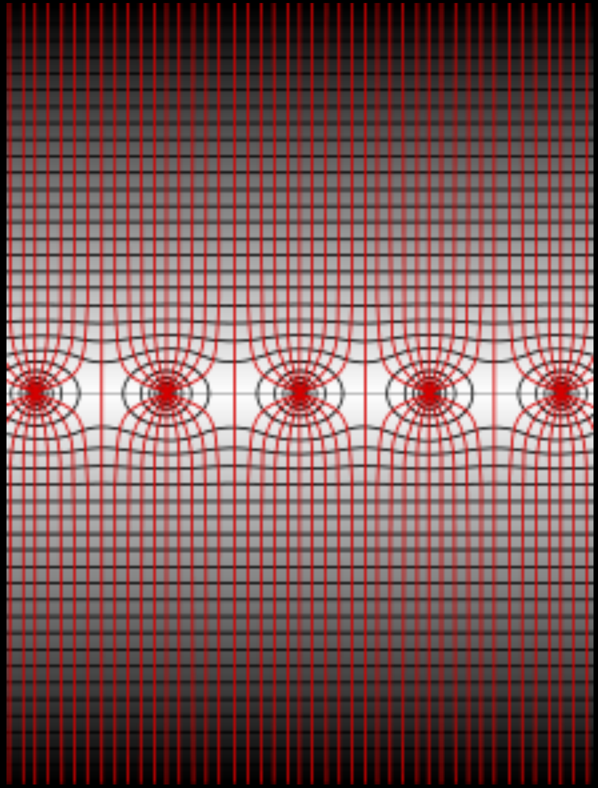
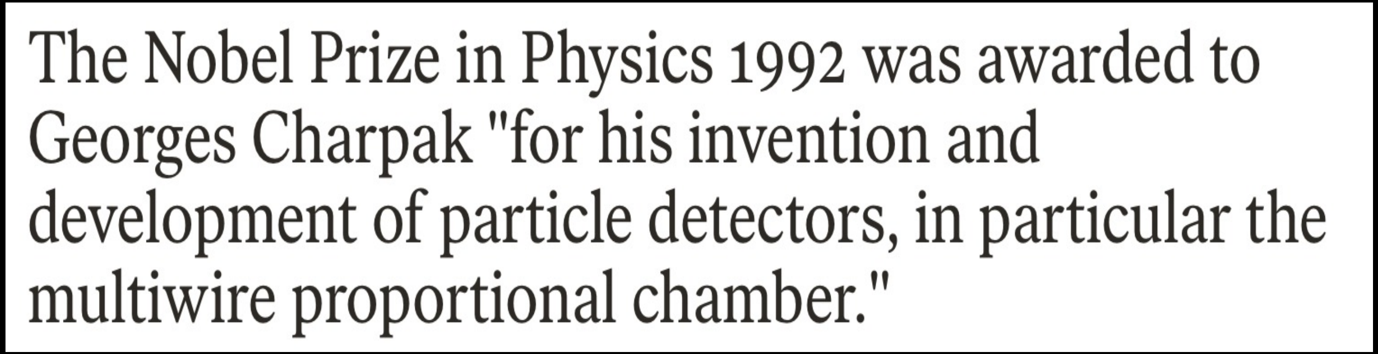


Fig. 49 Time development of an avalanche in a proportional counter30). A single primary electron proceeds towards the anode, in regions of increasingly high fields, experiencing ionizing collisions; due to the lateral diffusion, a drop-like avalanche, surrounding the wire, develops. Electrons are collected in a very short time (1 nsec or so) and a cloud of positive ions is left, slowly migrating towards the cathode.

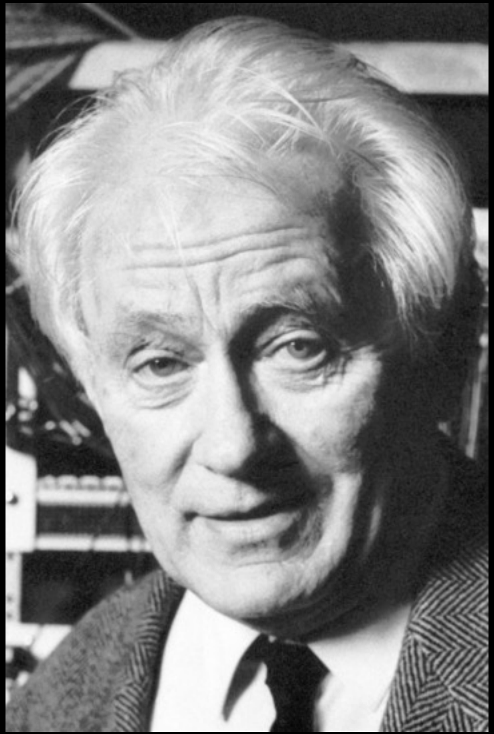
Gaseous Detectors
Multiwire Proportional Chamber
1960’s





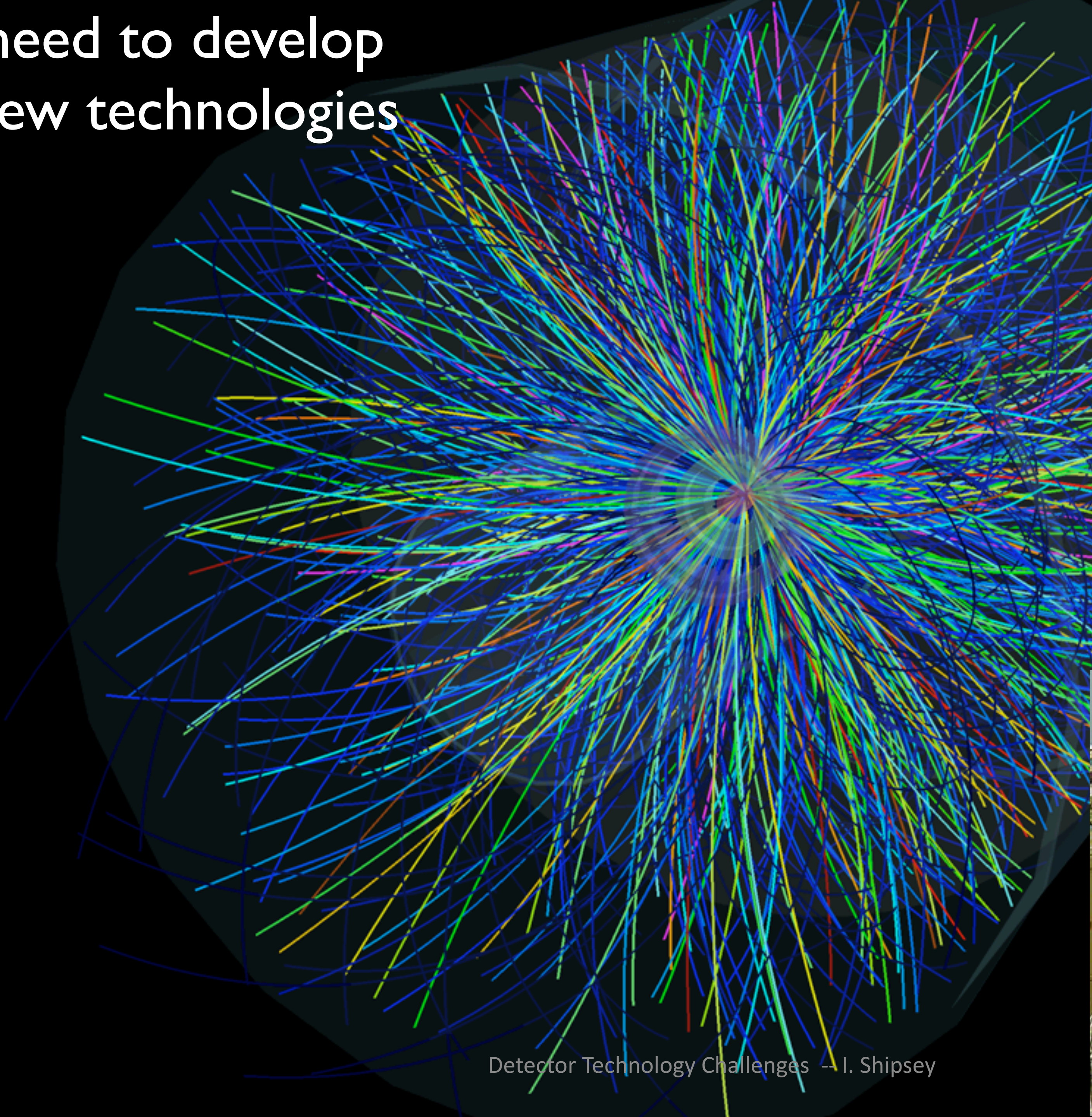


The Nobel Prize in Physics 1992 was awarded to Georges Charpak "for his invention and development of particle detectors, in particular the multiwire proportional chamber."



need to develop new technologies

1970s



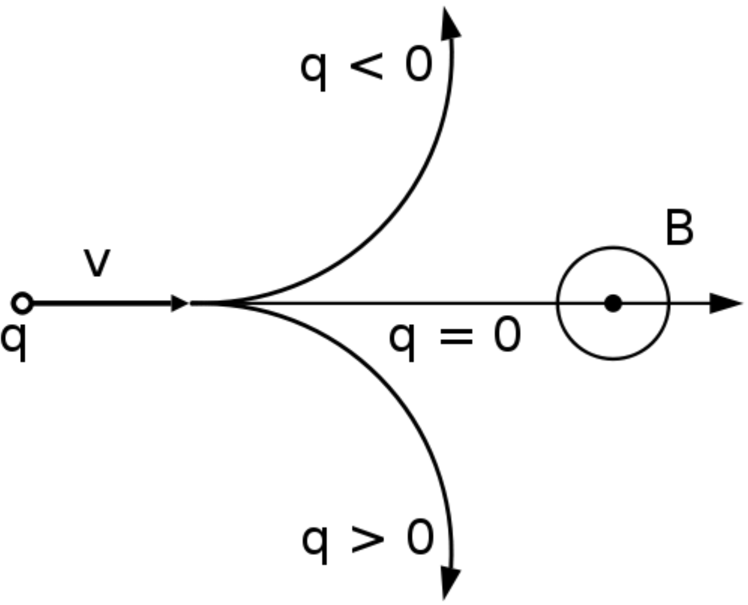
TPC

Tracking


© Rolf Hicker

- Particle detection has many aspects:
  - Particle counting
  - Particle Identification = measurement of mass and charge of the particle
  - Tracking
- Charged particles are deflected by B fields:

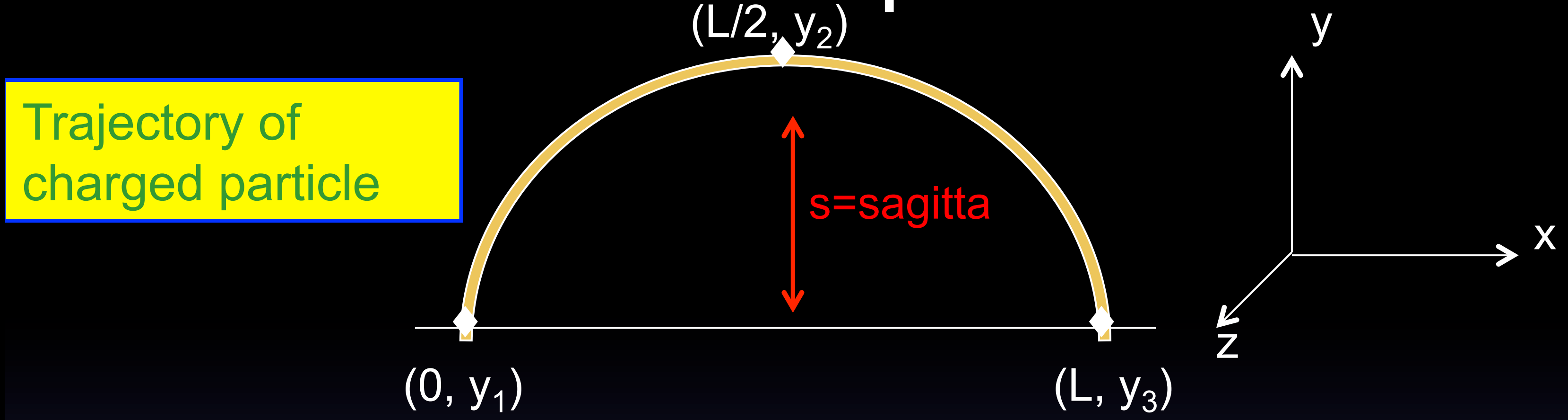
$$\vec{F} = q\vec{v} \times \vec{B}$$



$$\rho = \frac{p_T}{q|B|} = \frac{\gamma m_0 \beta c}{q|B|}$$

- By measuring the radius of curvature we can determine the momentum of a particle
- If we can measure also β independently we can determine the particle mass.

Momentum and position resolution



Trajectory of charged particle

Assume: we measure y at 3 points in (x, y) plane (z=0) with precision σ_y and a constant B field in z direction so $p_\perp = 0.3Br$.

$$s = y_2 - \frac{y_1 + y_3}{2} \approx \frac{L^2}{8r} = \frac{L^2}{8p_\perp/(0.3B)} = \frac{0.3BL^2}{8p_\perp}$$

The exact expression is

$$s = r - \sqrt{r^2 - \frac{L^2}{4}}$$

The error on the sagitta, σ_s, due to measurement error is (using propagation of errors):

$$\sigma_s = \sqrt{3/2}\,\sigma_y$$

Thus the momentum ($\perp$ to B) resolution due to position measurement error is:

$$\frac{\sigma_{p_\perp}}{p_\perp} = \frac{\sigma_s}{s} = \frac{\sqrt{3/2}\,\sigma_y}{(0.3L^2B)/(8p_\perp)} = \frac{8p_\perp\sqrt{3/2}\,\sigma_y}{0.3L^2B} = 32.6\frac{p_\perp\sigma_y}{L^2B}\ \textbf{(m, GeV/c, T)}$$

Momentum and Position Measurement

- The momentum resolution expression can be generalized for the case of n measurements, each with a different σ_y (Gluckstern's classic article, NIM, 24, P381, 1963).

$$\frac{\sigma_{p_\perp}}{p_\perp} = \sqrt{\frac{720}{n+4}}\,\frac{\sigma_y p_\perp}{(0.3BL^2)} \quad \textbf{(m, GeV/c, T)}$$

You can improve this component of momentum resolution by:

- Increasing B
- Increasing L
- Increasing n
- Decreasing σ_y

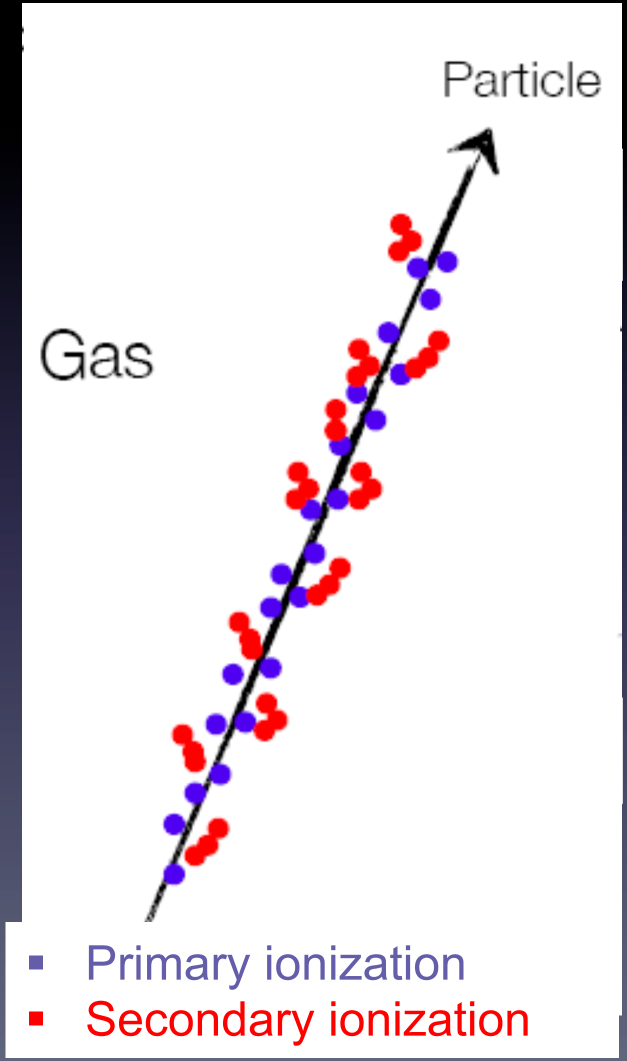
If we assume L=4m, B=1T and p=1TeV then:

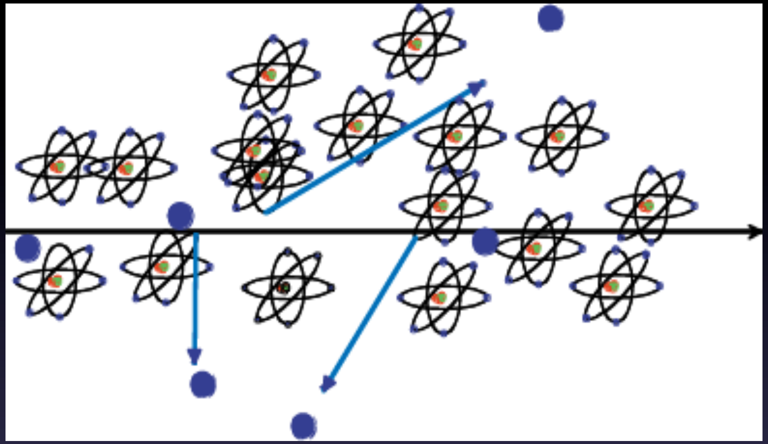
- R = p/(0.3 B) = 1000 / 0.3 = 3300 m
- s ≈ 16/(8*3300) ≈ 0.6 mm

If we want to measure the momentum With $\sigma_p/p \approx \Delta s/s \approx 10\%$ (at p = 1 TeV) we need: $(\sigma_s/s) \approx 60\ \mu\text{m}$

Signal creation

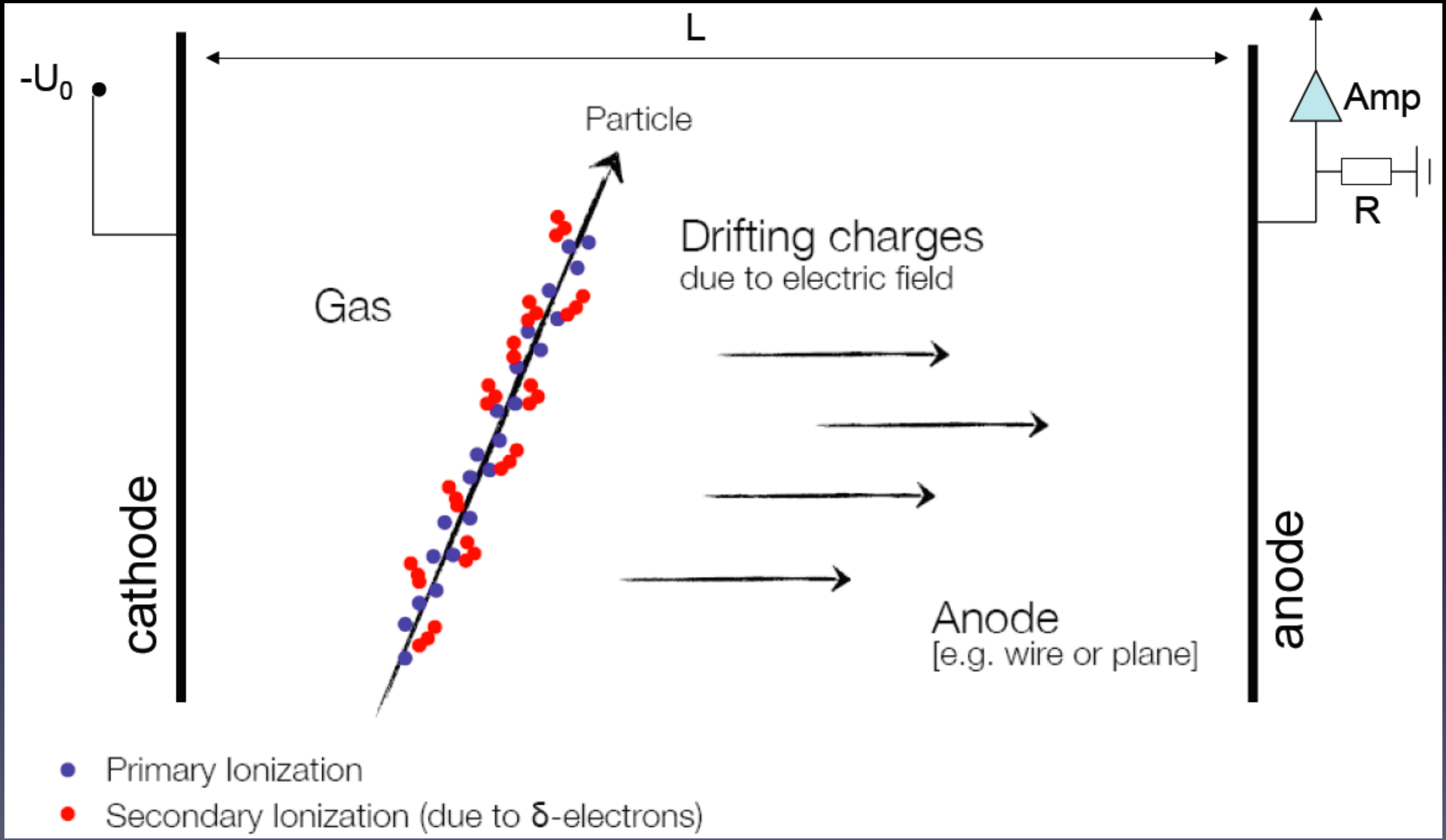
- Charged particle traversing matter leave excited atoms, electron-ion pairs (gases) and electrons-hole pairs (solids)





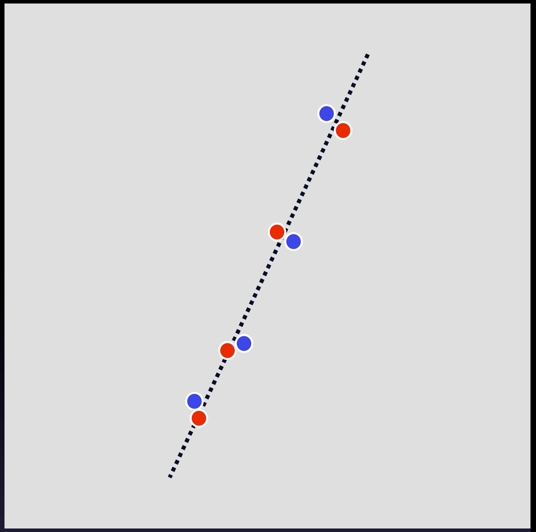
- Excitation: Photons emitted by the excited atoms in transparent materials can be detected with photon detectors
- Ionization: By applying an electric field in the detector volume, the ionization electrons and ions can be collected on electrodes and readout

Gas Detectors: primary



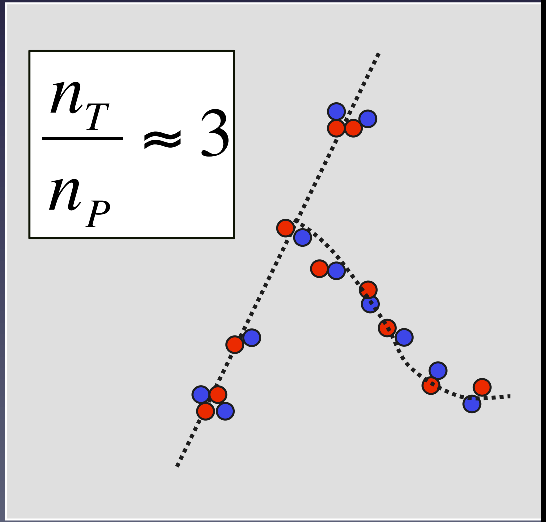
Primary and secondary ionization

- Coulomb interactions between E field of the particle and of the molecules of the medium produce electron-ion pairs.

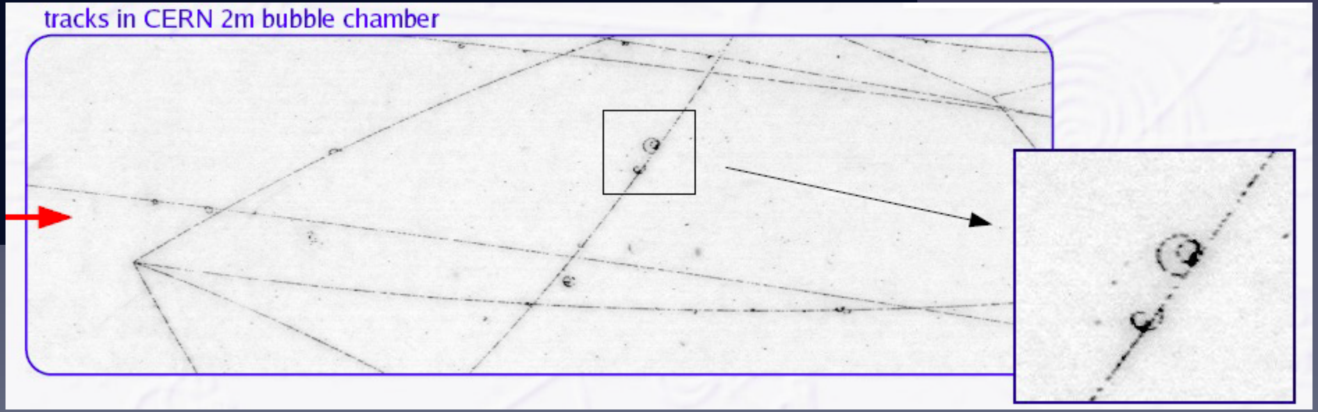


- Minimum ionizing particles in argon NTP
  - $\langle n_P \rangle$: 25 cm^{-1}
- Primary electrons can ionize the medium producing local e-ion clusters. Electron can have energy to produce a long trail (delta electron).
- Total number of ion pairs n_T:
  - *E:* energy loss
  - w_i : average energy per ion pair

$$n_T = \frac{\Delta E}{w_i}$$

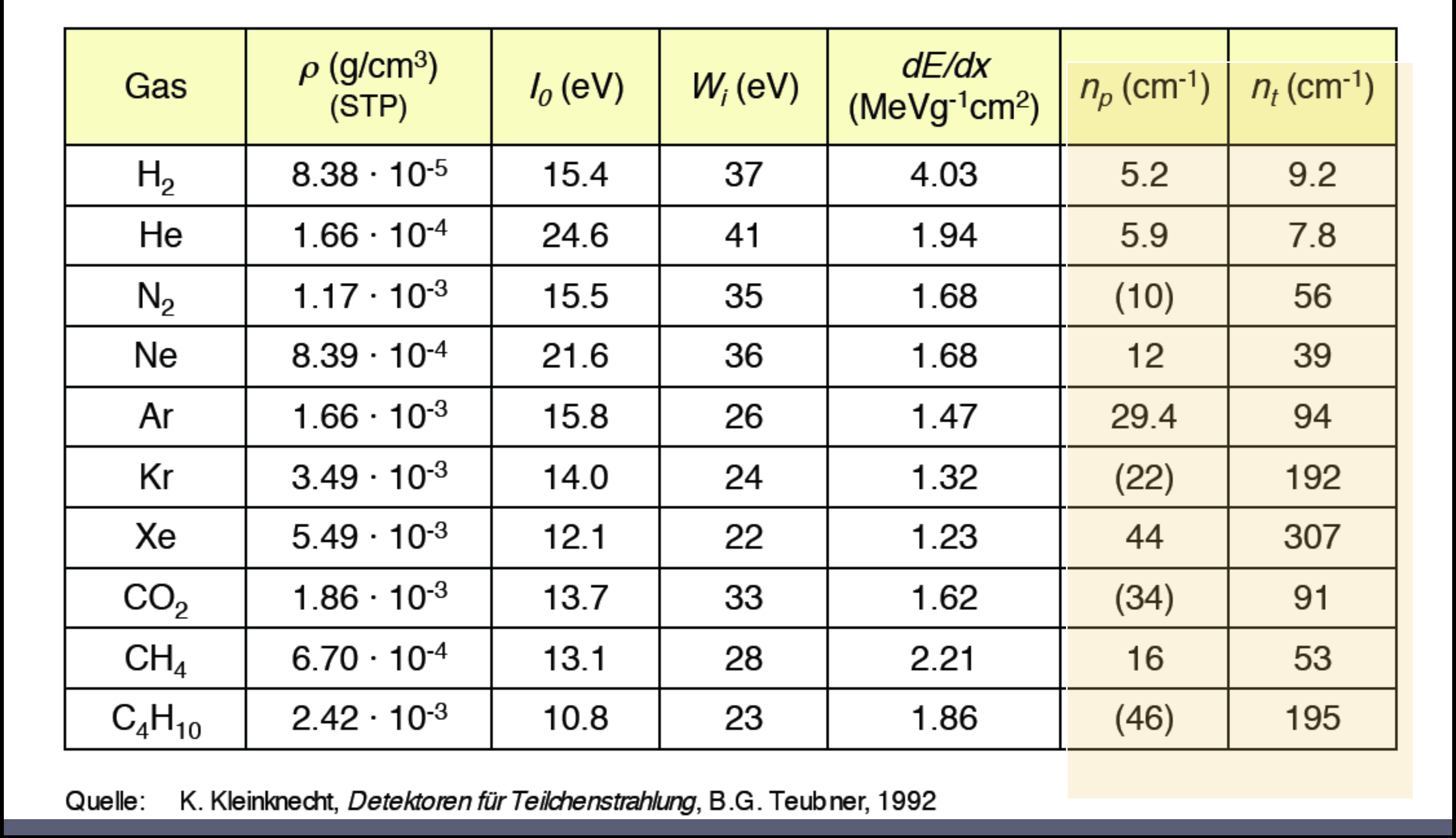


$$\frac{n_T}{n_P} \approx 3$$



tracks in CERN 2m bubble chamber

Most common gases



Gas	ρ (g/cm^3) (STP)	I_0 (eV)	W_i (eV)	dE/dx (MeVg^{-1}cm^2)	n_p (cm^{-1})	n_t (cm^{-1})
H_2	$8.38 \cdot 10^{-5}$	15.4	37	4.03	5.2	9.2
He	$1.66 \cdot 10^{-4}$	24.6	41	1.94	5.9	7.8
N_2	$1.17 \cdot 10^{-3}$	15.5	35	1.68	(10)	56
Ne	$8.39 \cdot 10^{-4}$	21.6	36	1.68	12	39
Ar	$1.66 \cdot 10^{-3}$	15.8	26	1.47	29.4	94
Kr	$3.49 \cdot 10^{-3}$	14.0	24	1.32	(22)	192
Xe	$5.49 \cdot 10^{-3}$	12.1	22	1.23	44	307
CO_2	$1.86 \cdot 10^{-3}$	13.7	33	1.62	(34)	91
CH_4	$6.70 \cdot 10^{-4}$	13.1	28	2.21	16	53
C_4H_{10}	$2.42 \cdot 10^{-3}$	10.8	23	1.86	(46)	195

Quelle: K. Kleinknecht, *Detektoren für Teilchenstrahlung*, B.G. Teubner, 1992

Ionization statistics

- Multiple ionizing collisions follow Poisson's statistics:

$$\langle n_p \rangle = \frac{L}{\lambda}$$

$$\lambda = \frac{1}{n_e \sigma_I}$$

$$P_{n_P}^{\langle n_P \rangle} = \frac{\langle n_p \rangle^{n_p} e^{-\langle n_p \rangle}}{n_p!}$$

σ_I: Ionization x-section
n_e: Electron density
L: Thickness

Typical values of the mean free path **λ**

- He 0.25 cm
- Air 0.052 cm
- Xe 0.023 cm

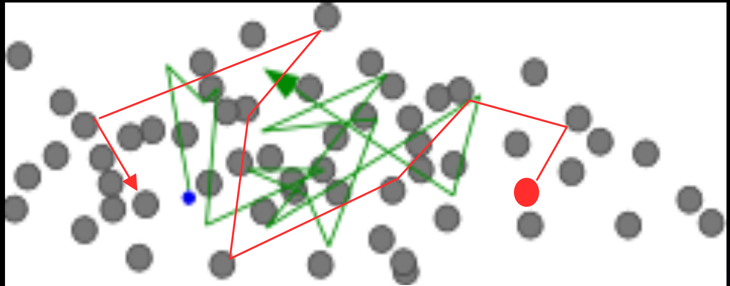
GAS (STP)	*thickness*	*ε (%)*
Helium	1 mm	45
	2 mm	70
Argon	1 mm	91.8
	2 mm	99.3

- Efficiency: $\varepsilon = 1 - P_0^{\langle n_p \rangle} = 1 - e^{-\langle n_p \rangle}$

- Other important parameters are:
  - Recombination and electron attachment due to Electro-negative gases which bind electrons; e.g.: O_2, Freon, Cl_2, SF_6 ... →influences detection efficiency
  - Diffusion→ Influences the spatial resolution
  - Mobility of charges → Influences the timing behavior of gas detectors
  - Electronic noise in amplifier is typically 1000 e- (ENC)→Amplification is needed → Important for the gain factor of the gas detector ...

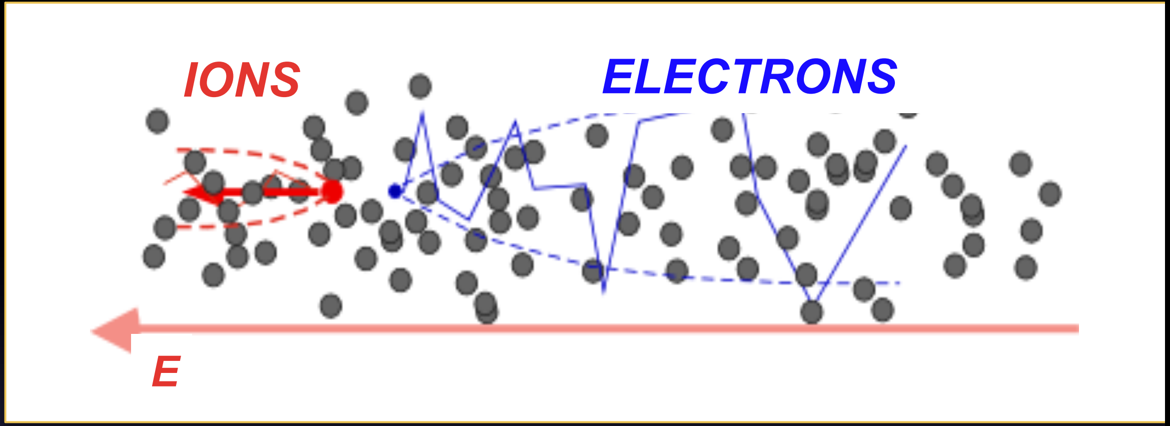
Diffusion & Drift

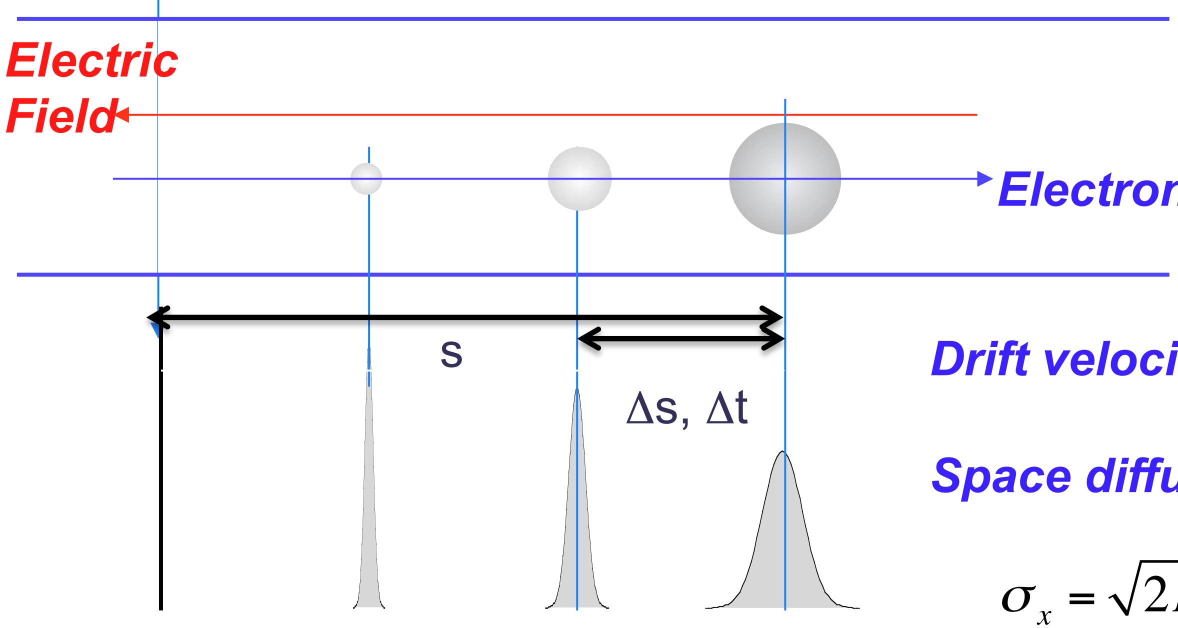
E = 0: Thermal diffusion



$$D = \frac{1}{3} v\lambda = \frac{2}{3\sqrt{\pi}} \frac{1}{P\sigma_0} \sqrt{\frac{(kT)^3}{m}}$$

E >0: Charge Transport and Thermal diffusion





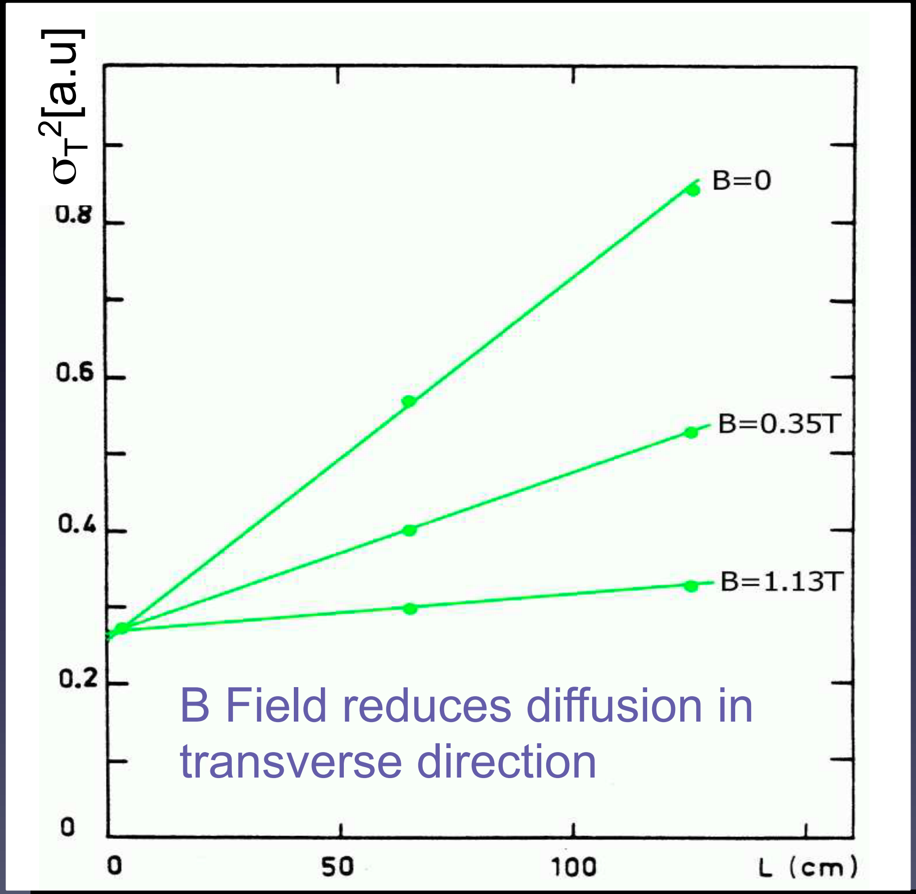
Drift velocity: $v_D = \frac{\Delta s}{\Delta t}$

Space diffusion rms:

$$\sigma_x = \sqrt{2Dt} = \sqrt{2D\frac{s}{v_D}}$$

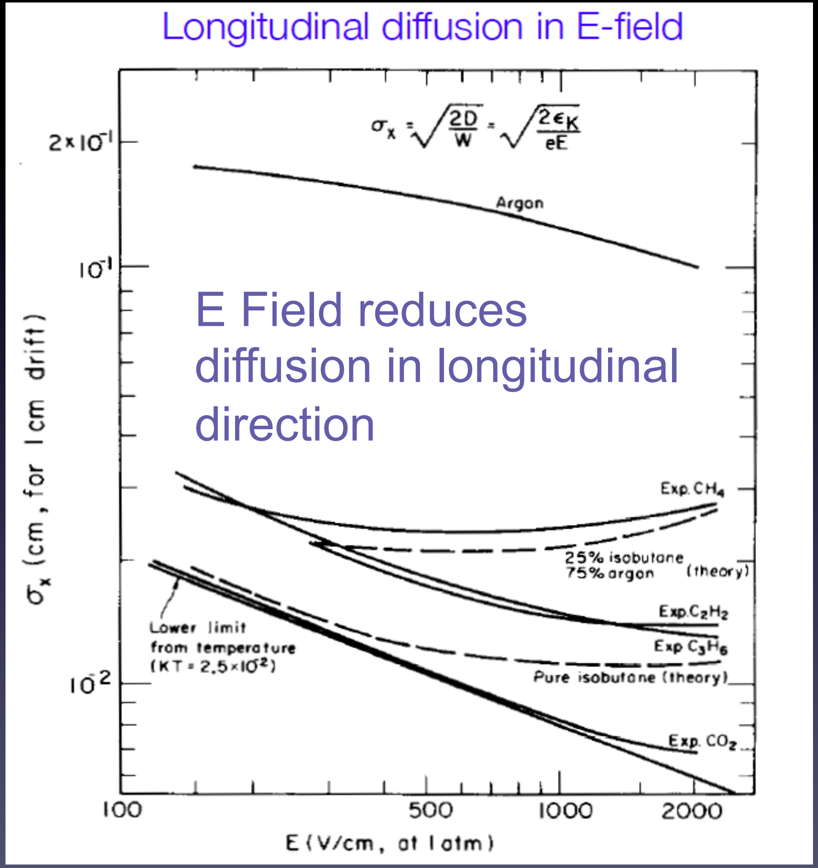
Drift and diffusion in E and B fields

- Transverse diffusion as function of drift length for different B fields



B Field reduces diffusion in transverse direction

- Longitudinal diffusion as function of E field

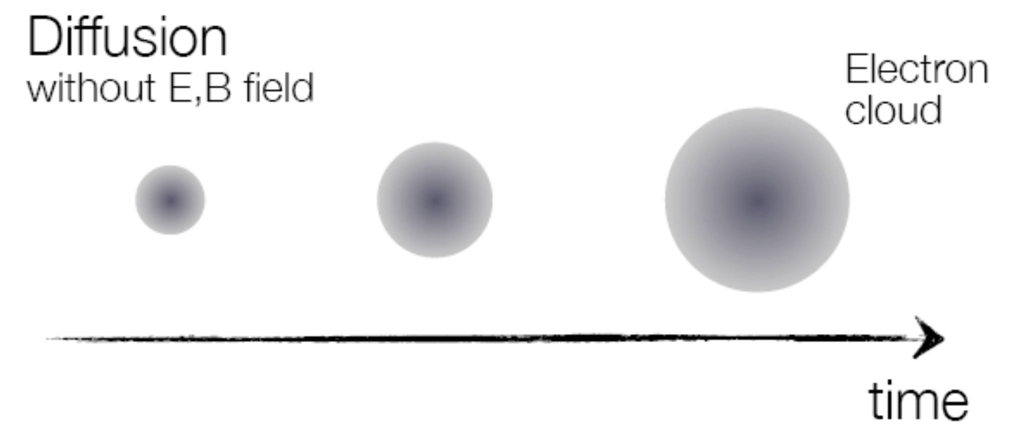

Longitudinal diffusion in E-field

E Field reduces diffusion in longitudinal direction

Transport equation is usually solved numerically using programs like Magboltz and Garfield

Diffusion in a gas

- Diffusion is evaluated using the classical theory of gases.
- Due to multiple collisions the distribution of charge at time t in a length dx after a distance x is given by a Gaussian



$$\frac{dN}{dx} = \frac{N_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$

- Linear diffusion

$$\sigma_x = \sqrt{2Dt}$$

D=diffusion coefficient depends on the pressure P and the temperature T

$$D = \frac{1}{3} v\lambda = \frac{2}{3\sqrt{\pi}} \frac{1}{P\sigma_0} \sqrt{\frac{(kT)^3}{m}}$$

- The Mean-free path of electrons/ions in the path

$$\lambda = \frac{1}{\sqrt{2}} \frac{kT}{\sigma_0 P}$$

- The mean velocity is given by the Maxwell distribution where m is the mass of the particle

$$v = \sqrt{\frac{8kT}{\pi m}}$$

Drift and mobility

- In an external E-field e^-/ions obtain velocity $\mathbf{v}_D$ in addition to thermal motion; on average e^-/ions move along field lines of electric field E

$$\vec{v}_D = \mu_\pm \left|\vec{E}\right|$$

Typical values of v_D

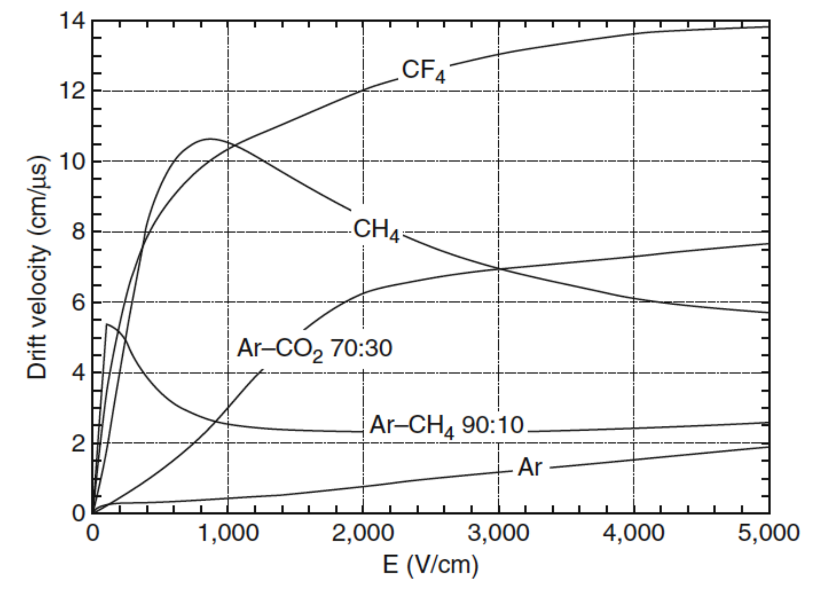
- E ~ 1 kV / cm
- v_D ≈cm/ms for ions
- v_D≈cm/μs for e-

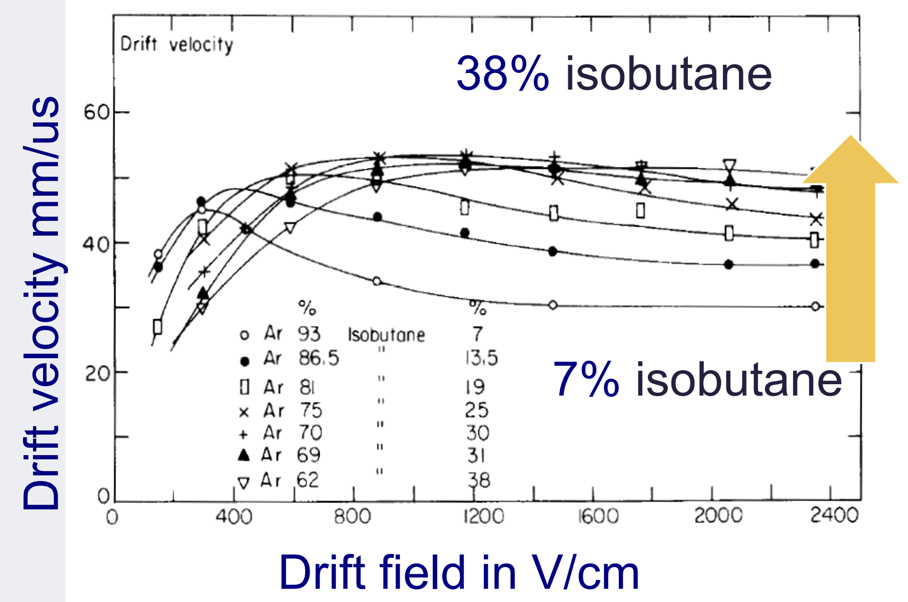
MWPC: 1 cm gap, Ar-CH_4, 5 kV/cm

Total ions drift time τ^+ ~ 120 μs

TPC: 1 m drift, Ar-CH4, 200 V/cm

Total ions drift time τ^+ ~ 300 ms





Drift velocity in several argon-isobutane (C_4H_{10}) mixtures

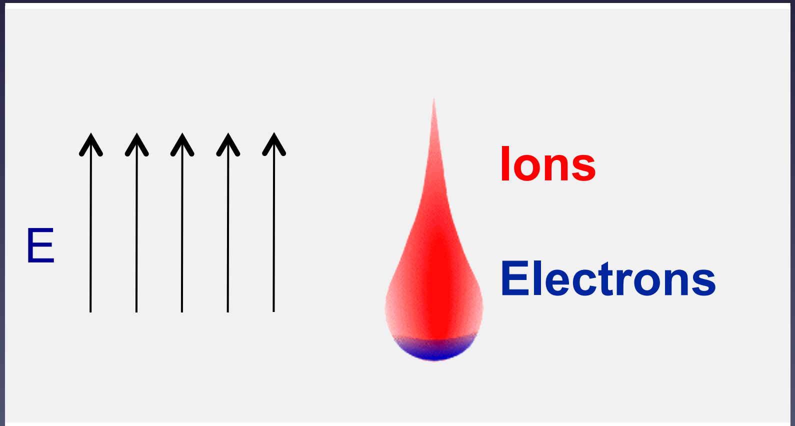
- τ(collection) ≈1/v_d → diffusion effects are reduced in gases such as CF_4 that have high drift

Avalanche Multiplication

- The primary ionization signal is very small in a gas layer: in 1 cm of Ar/CO_2 (70:30) at NTP only ~**100** electron–ion pairs are created →use an “internal gas amplification” mechanism to increase signal
- Large E fields →large electron kinetic energy →avalanche formation
  - **$dn = n\,\alpha\,dx$** **α=Townsend Coefficient**
  - **$n(x) = n_0\, e^{\alpha x}$** $n(x)$=electrons at location x
- Gain or Amplification is:

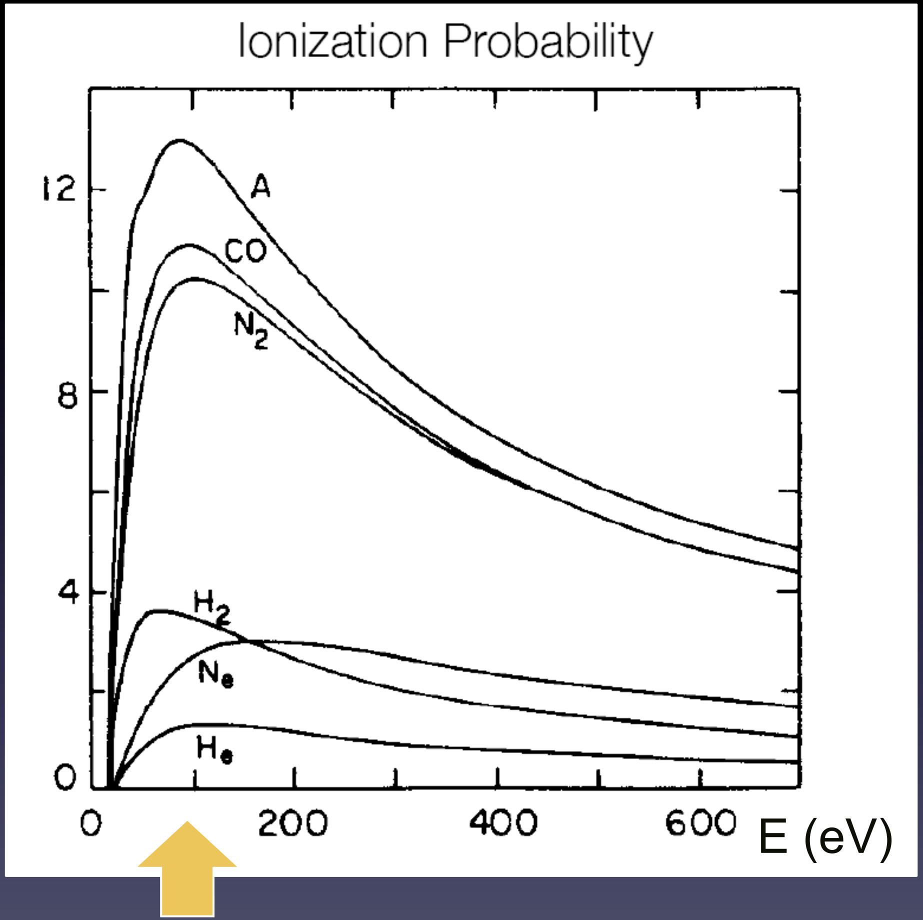
$$G = \frac{n}{n_0} = e^{\alpha x}$$

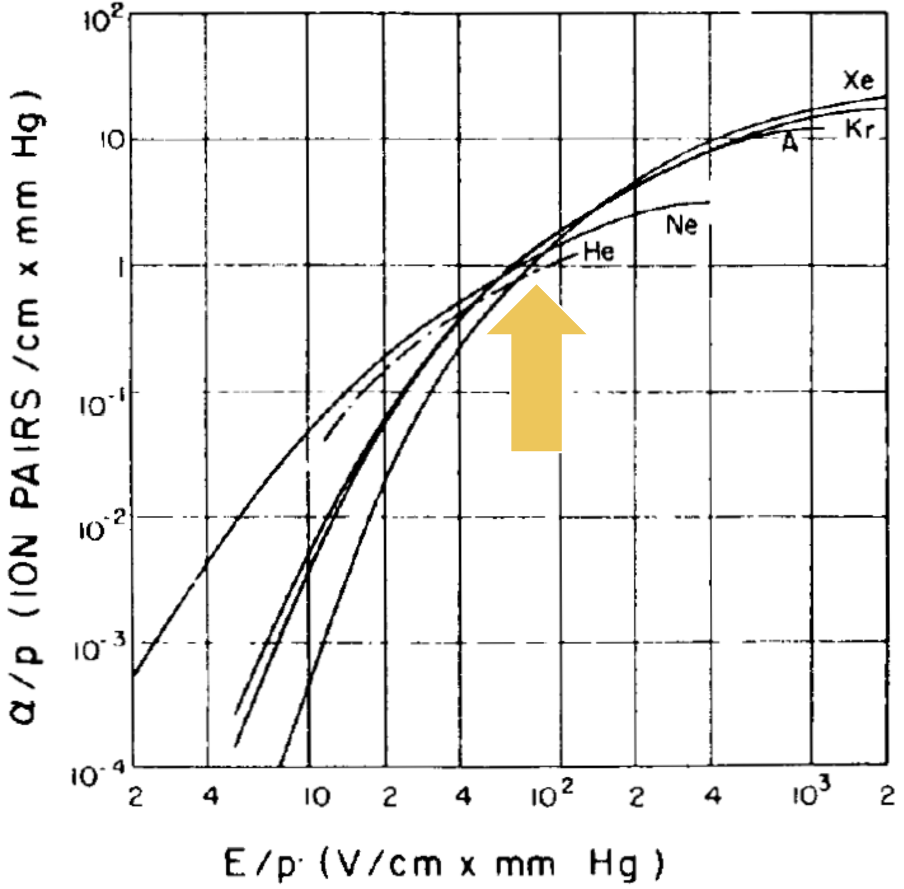
- Raether’s limit $G \approx 10^8$, since after that sparking can occur



Drop-like shape of an avalanche

Avalanche multiplication

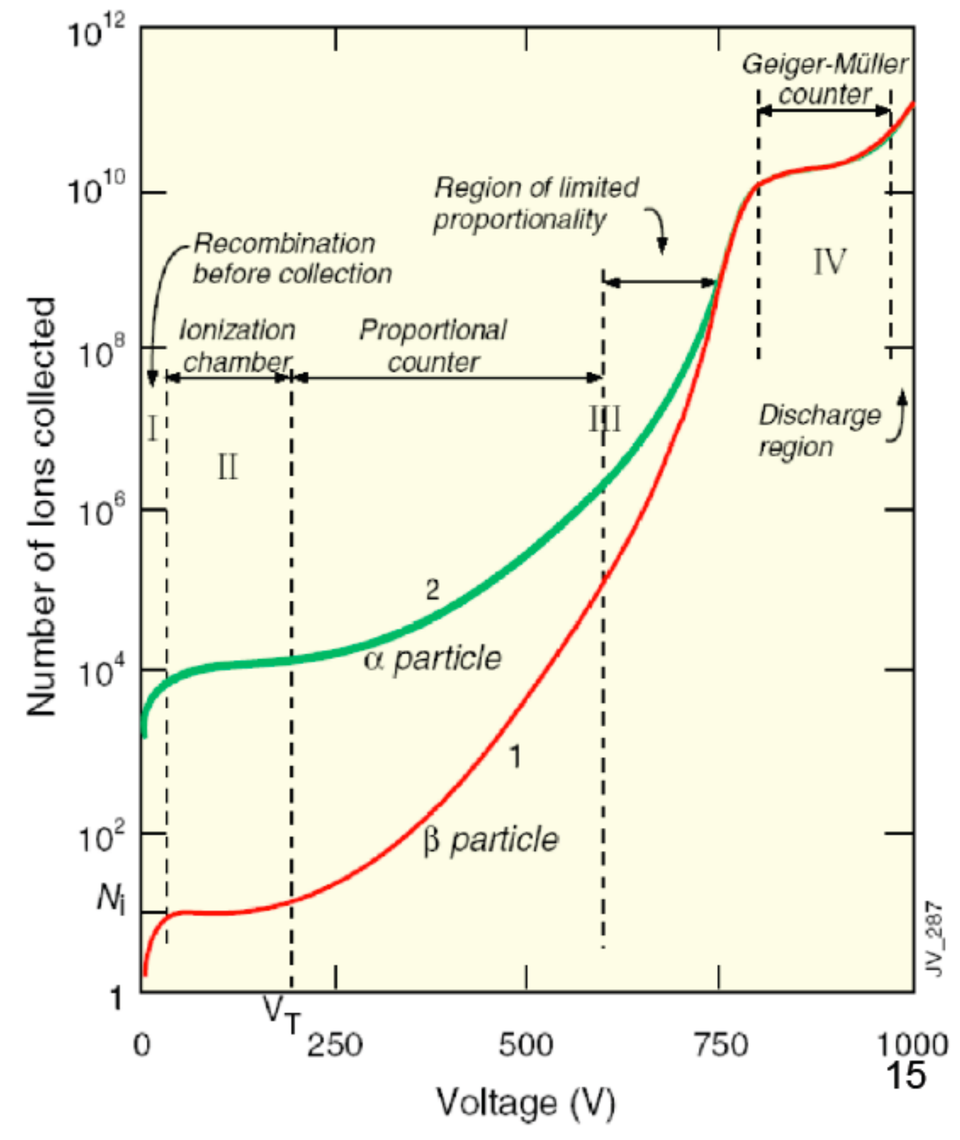




- Need an energy of 75-100 eV for High ionization probability (and need to gain it in a few μm)
- E=75 kV/cm to reach α=1

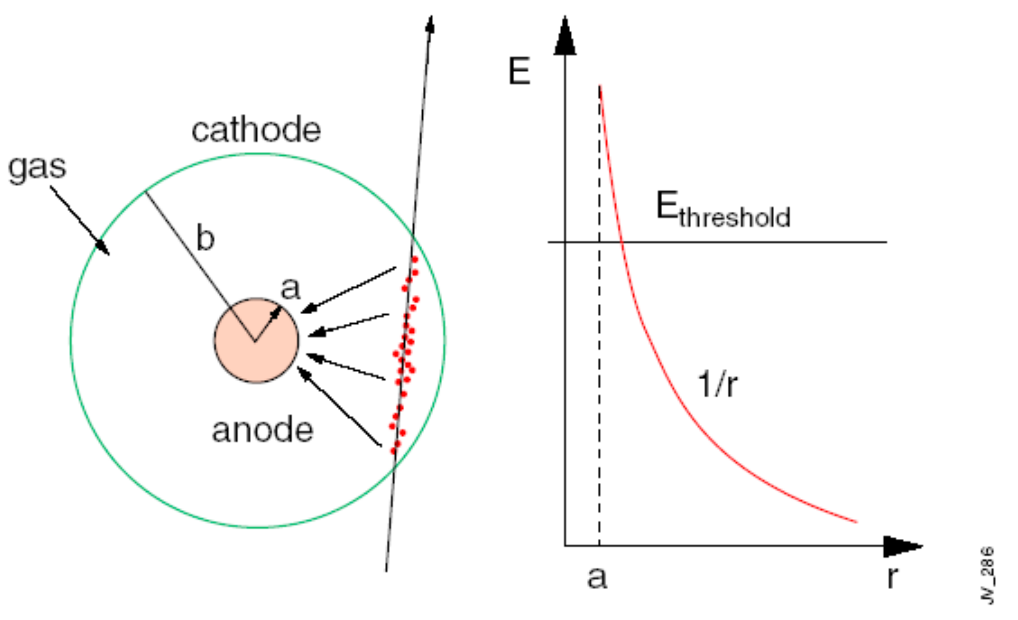
Gas amplification factor

- Ionization mode: full charge collection; no amplification; G=1
- Proportional mode: multiplication; signal proportional to original ionization ⇒ measurement of dE/dx. Secondary avalanches needs quenching; G $\approx 10^4$-10^5
- Limited Proportional (Saturated, Streamer mode): strong photo-emission; Require strong quenchers. High gain 10^{10} ⇒ large signal, simple electronics
- Geiger mode: Massive photo emission. Full length of anode affected. Discharge stopped by HV cut



Proportional counter

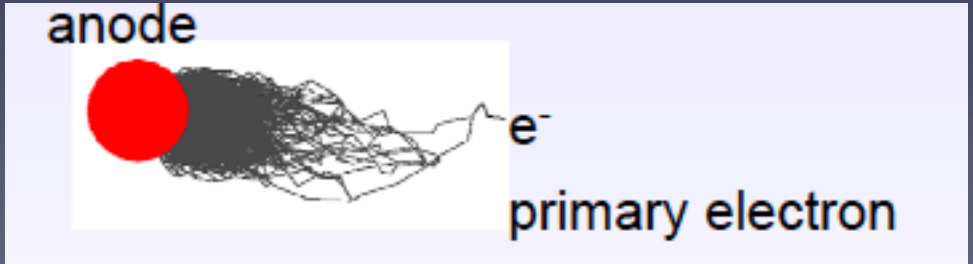
- Cylindrical proportional counter:
  - Single anode wire in a cylindrical cathode
  - e^-/ions drift in the volume



$$E = \frac{V_0}{r \ln(a/b)}$$

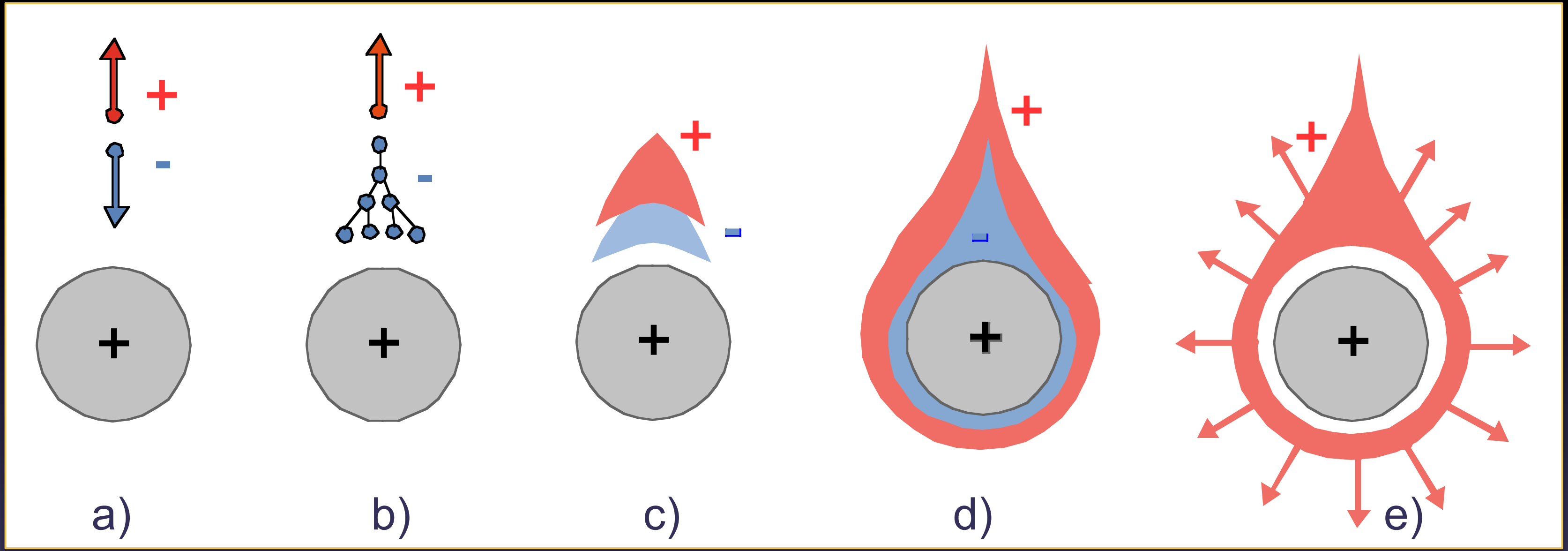
- V_0= potential between anode and cathode
- Close to wire (diameter 10 μm) E-field very large (> 10 kV/cm) kinetic energy of the electrons becomes very large → can produce secondary ionization

$$\Delta T_{kin} = e\Delta U$$



Avalanche development

- Time development of avalanche near the wire of a proportional counter

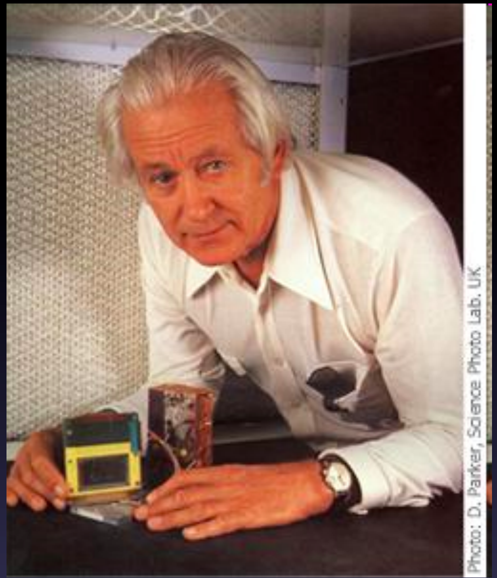


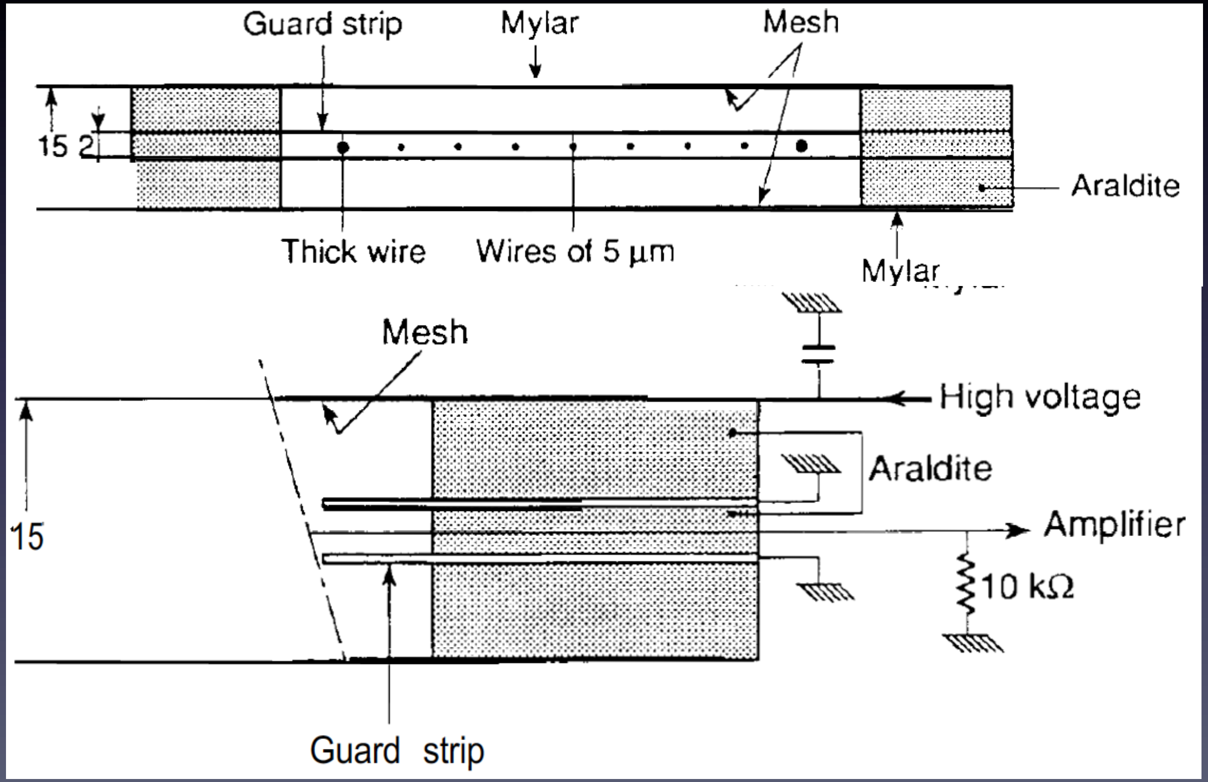
a) single primary electron proceeds towards the wire anode,
b) In the region of increasingly high field avalanche multiplication starts
c) electrons and ions are subject to lateral diffusion,
d) a drop-like avalanche develops which surrounds the anode wire,
e) the electrons are quickly collected (~1ns) while the ions begin drifting towards the cathode generating the signal at the electrodes

Multiwire proportional chambers

- A proportional counter does not provide the position of the incident particle
- Charpak developed of multi-wire proportional chamber

G. Charpak Nobel price (‘92)





Construction details of the original design
of Charpak’s multi-wire chambers (from Nobel lecture)

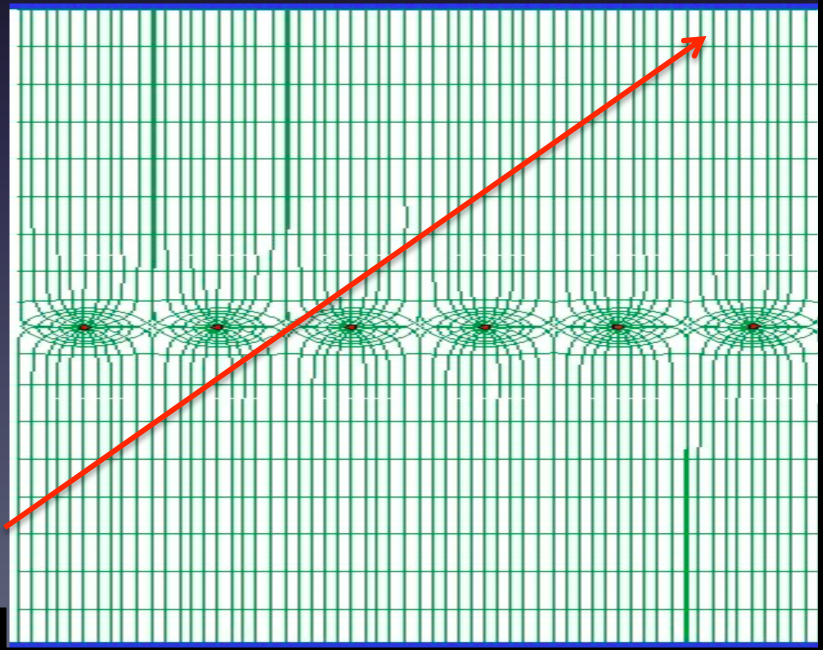
Anode wire =20μ diameter
d=2 mm

MWPC

- First large area MWPC
- First electronic device allowing high rate experiments
- PID capabilities through dE/dx

- Resolution
  - Wire spacing 1 mm
  - Wire diameter 20μm
  - Digital readout
  - $\sigma_x \approx 300\ \mu\text{m}$

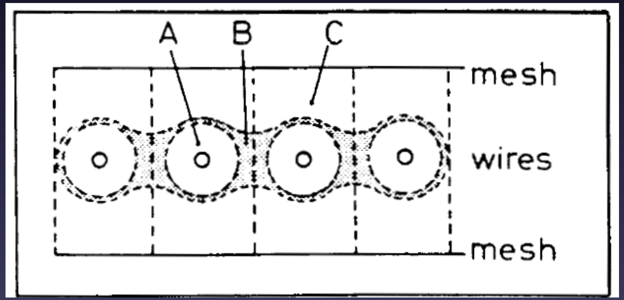
$$\langle x^2 \rangle = \frac{\int_0^{d/2} x^2 dx}{\int_0^{d/2} dx} = \frac{2}{d}\frac{x^3}{3}\Big|_0^{d/2} = \frac{d^2}{12}$$

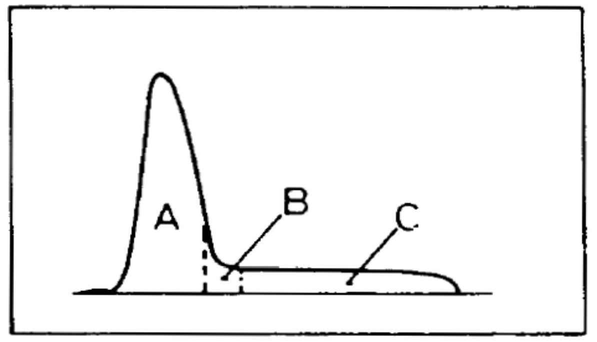


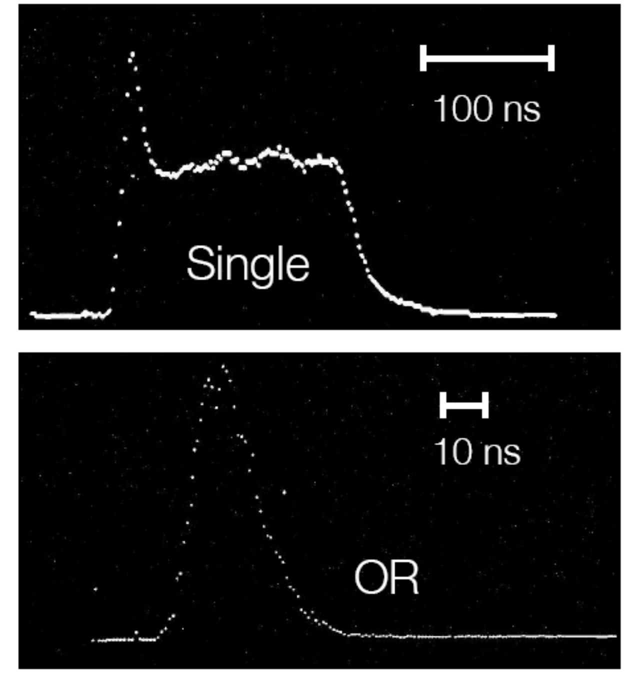
MWPC performance

- Signal generation:
  - Electrons drift to closest wire. Gas amplification near wire ➛ avalanche
    Signal generation due to electrons and slow ions (mainly slow ions, Ramo Theorem)

- Timing resolution:
  - Depends on location of particle
  - For fast response: OR of all channels …[Typical: $\boldsymbol{\sigma}_t$ = 10 ns]

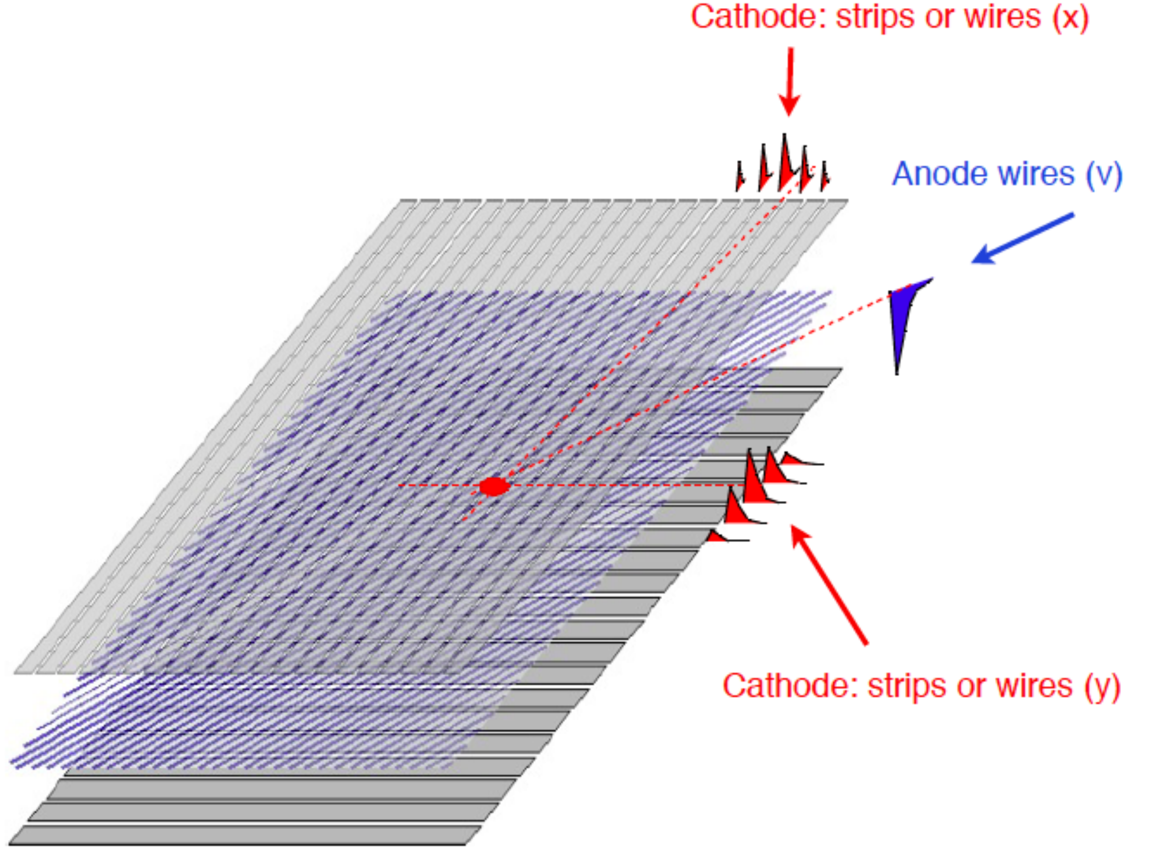






2D MWPC

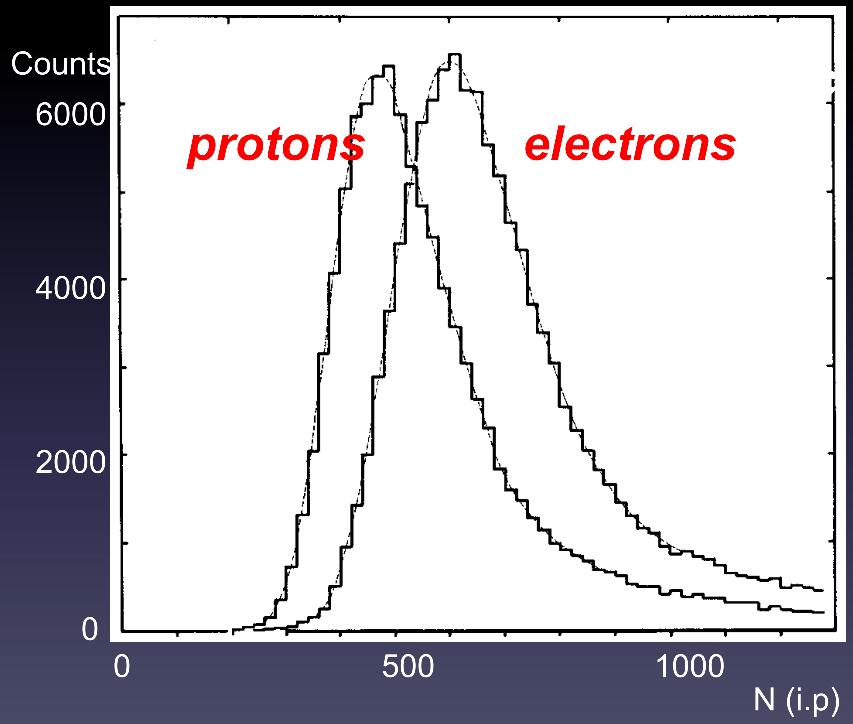
- Two coordinates (x,y) of the track hit can be determined from the position of the anode wire and the signal induced on the cathode strips (or wires)
  - High spatial resolutions due to center of gravity
  - Resolve ambiguities using strip pattern



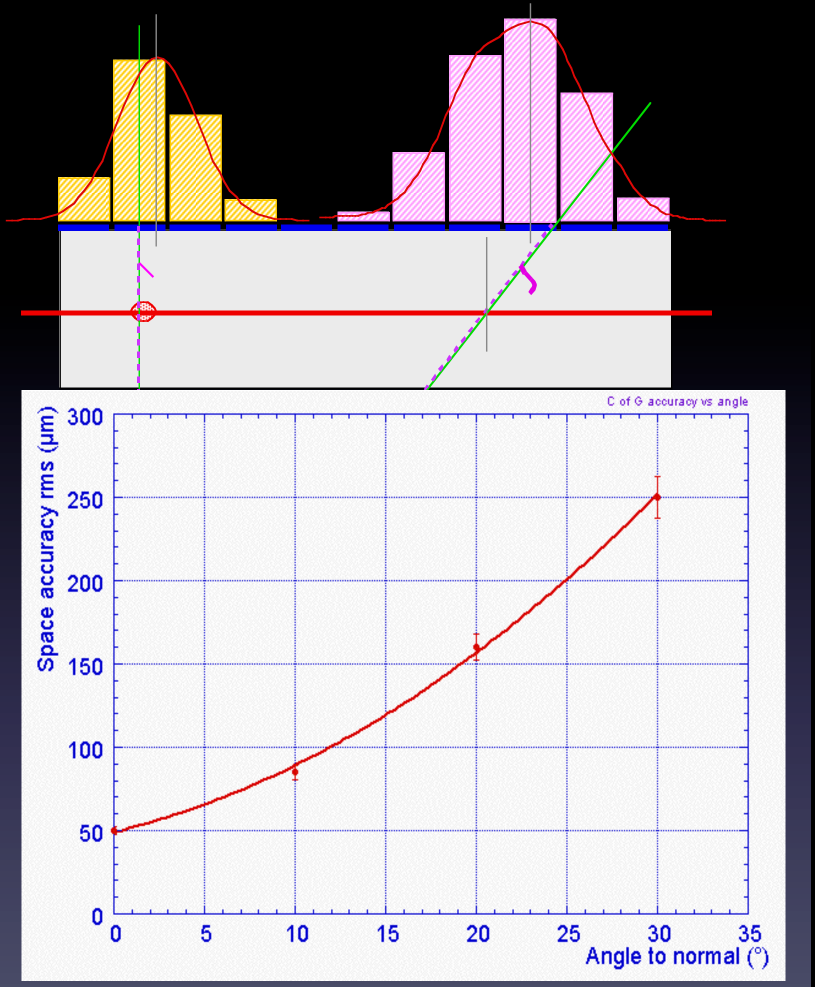
Particle ID & space accuracy

Particle identification

- **Requires statistical analysis of hundreds of samples**



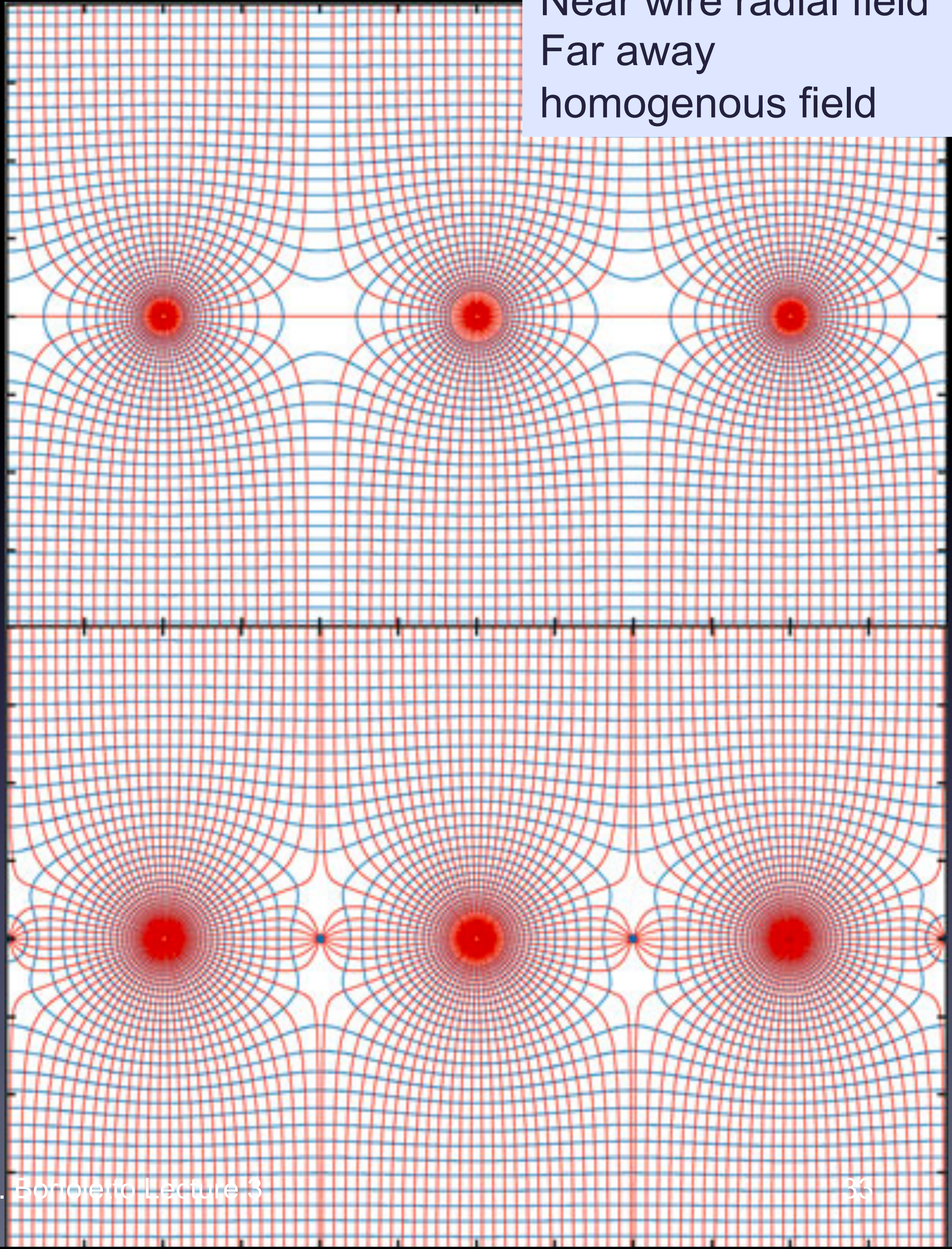
I. Lehraus et al, Phys. Scripta 23(1981)727



Position accuracy as a function of the track angle to the normal to the chamber

Field distribution

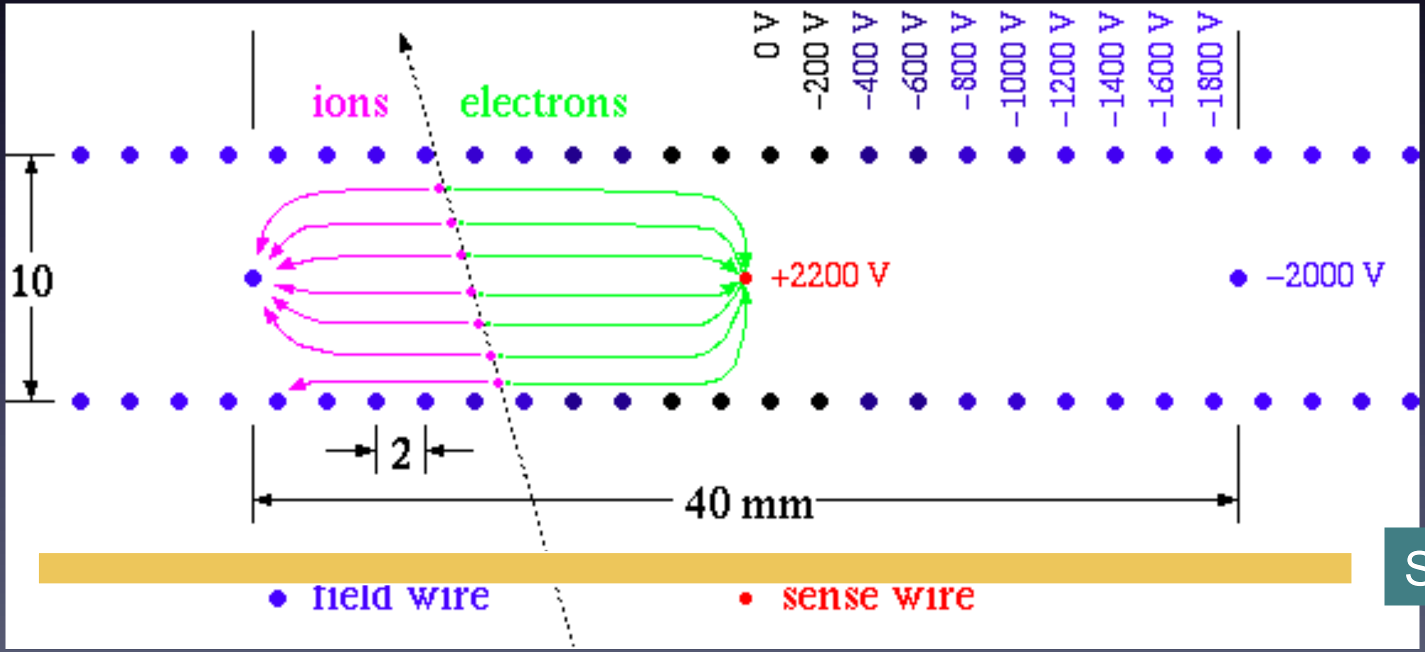
- MWPC: Operation is difficult at smaller wire spacings.
    - The electrostatic repulsion for thin (10 μm) anode wires causes mechanical instability above a critical wire length of less than 25 cm for 1-mm
- Drift chambers
    - a thicker wire at proper voltage between anodes (field wire) reduces the field inhomogeneity at the middle point between anodes and improves charge collection
    - Linearity of the space-to-drift-time relation→ resulting in better spatial resolution



Near wire radial field
Far away homogenous field

Drift chambers

- Obtain spatial information by measuring the electrons drift time
  - time measurement started by an external (fast) detector, i.e. scintillator counter
  - electrons drift to the anode (sense wire), in the field created by the cathodes
  - the electron arrival at the anode stops the time measurement



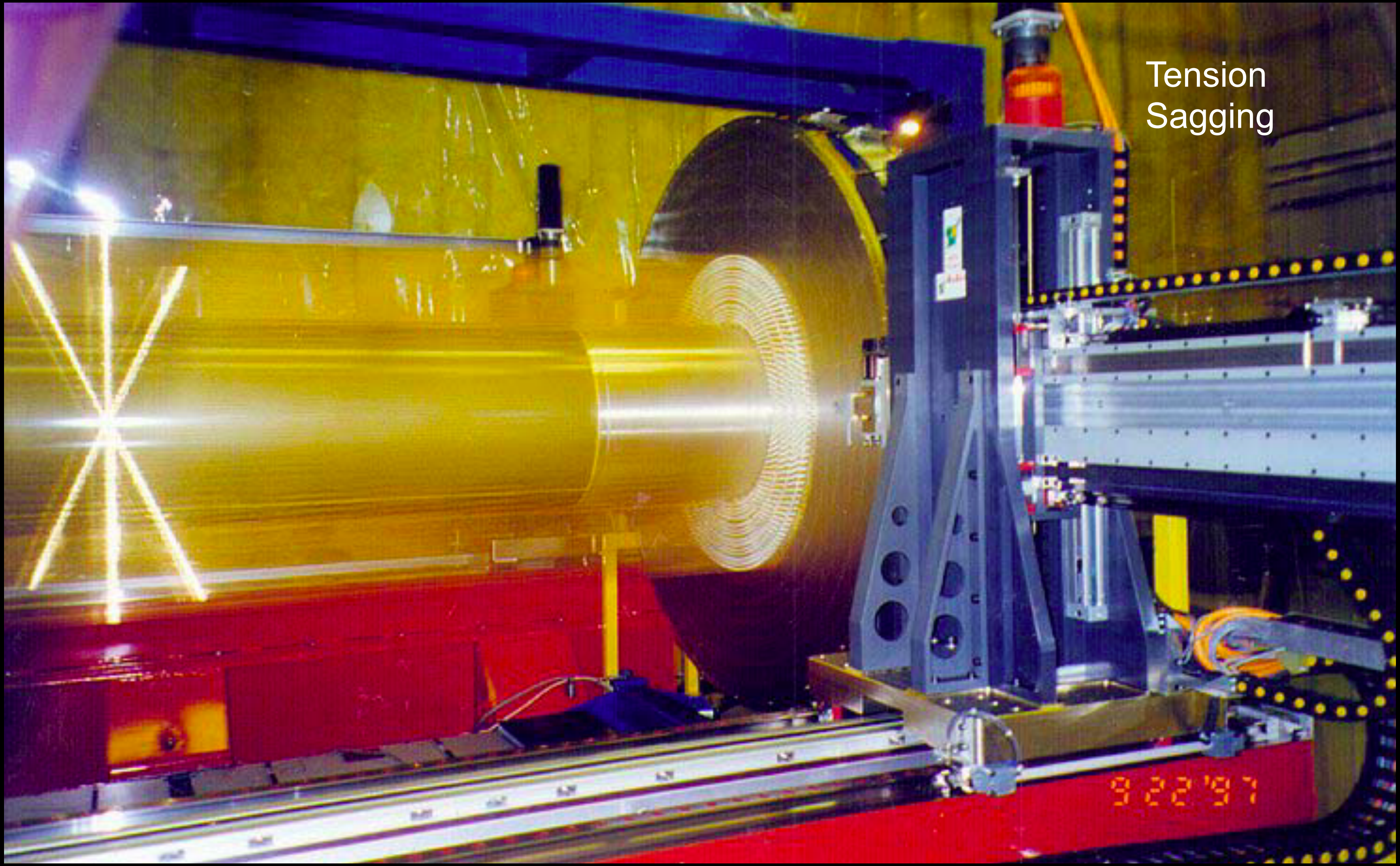
Scintillator counter

$$x = \int_0^{t_D} v_D \, dt$$

Need well-defined drift field

J. Heintze, 1971

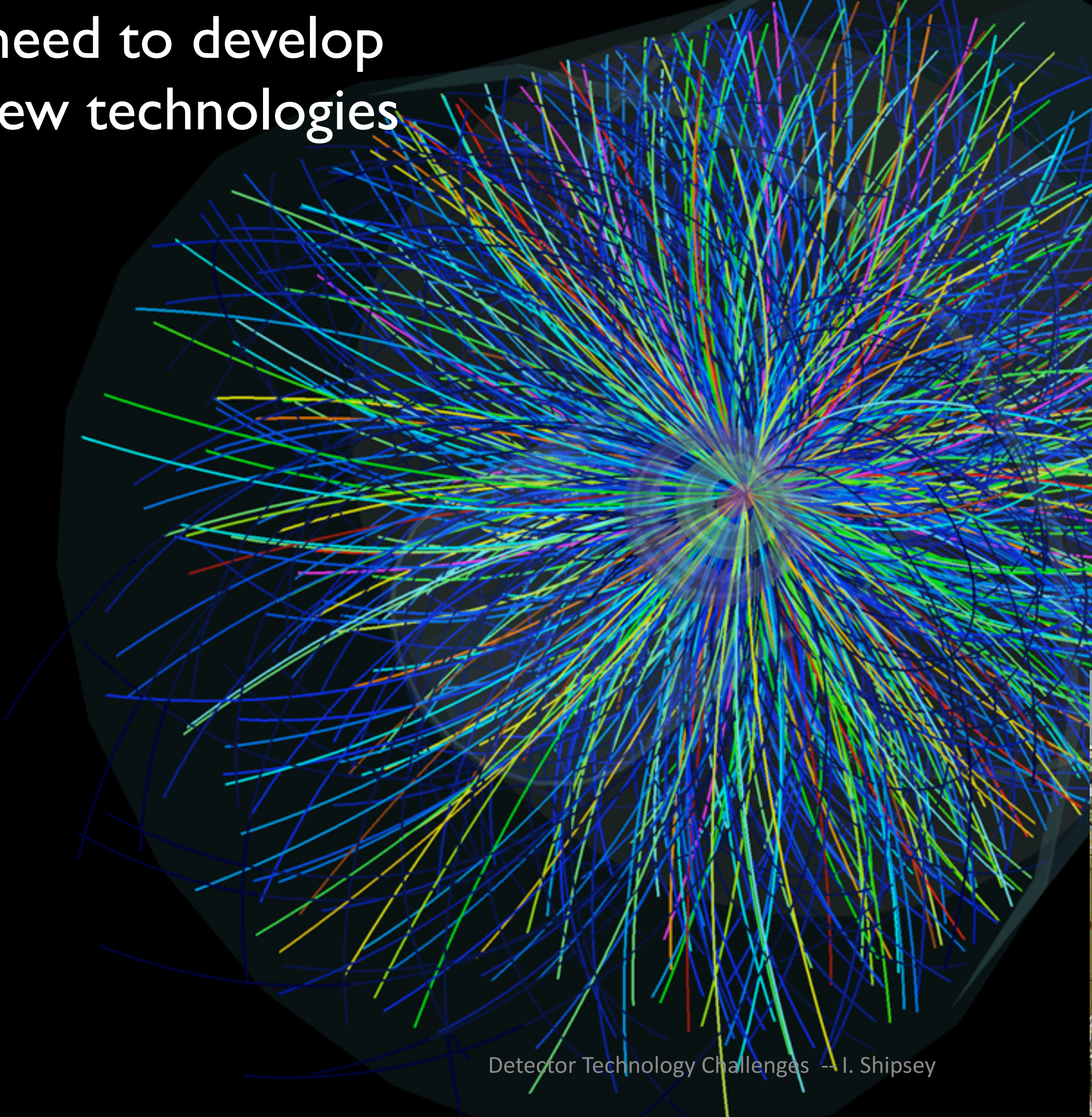
Wire stringing



Tension
Sagging

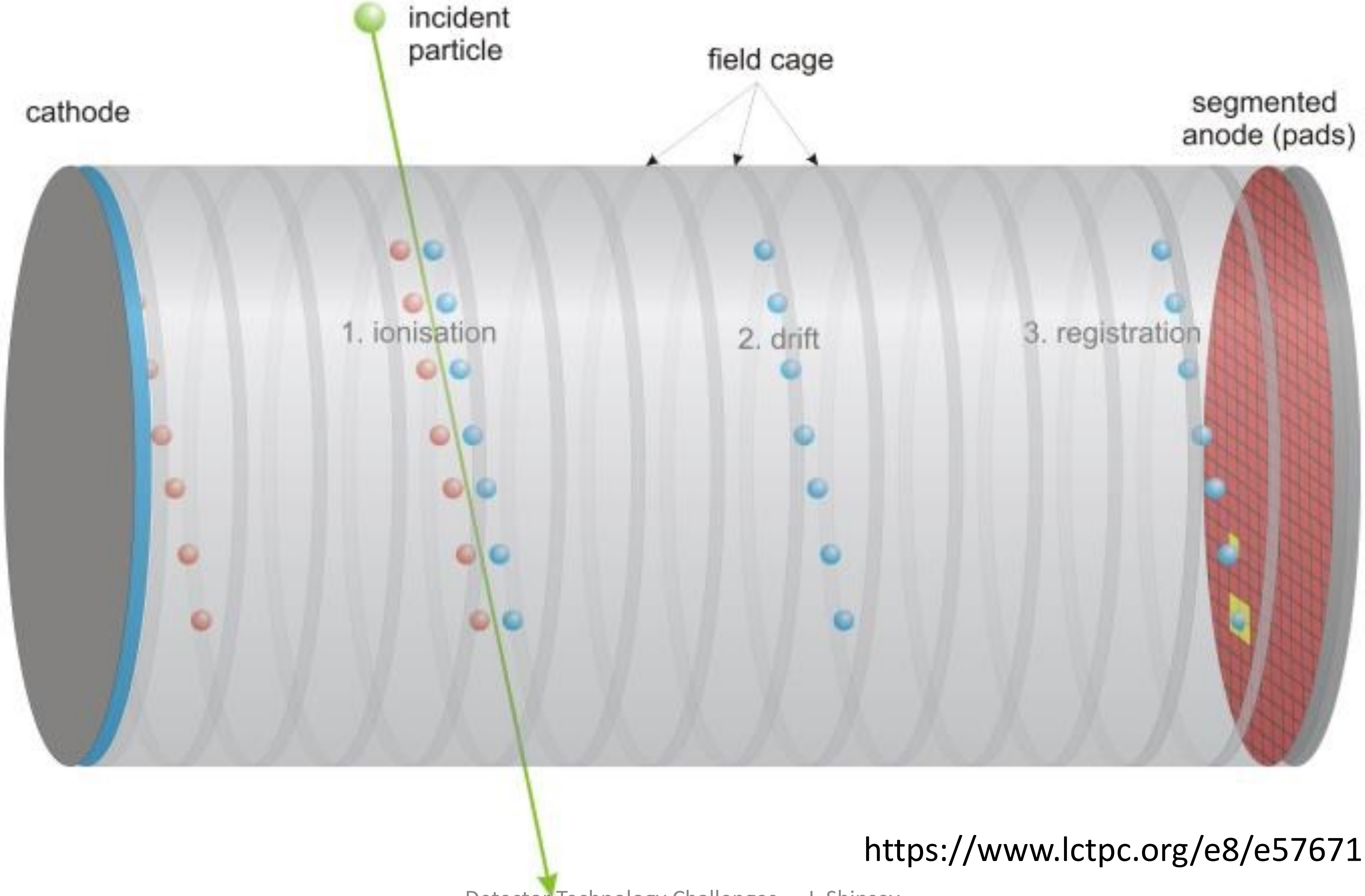
need to develop
new technologies

1970s



TPC

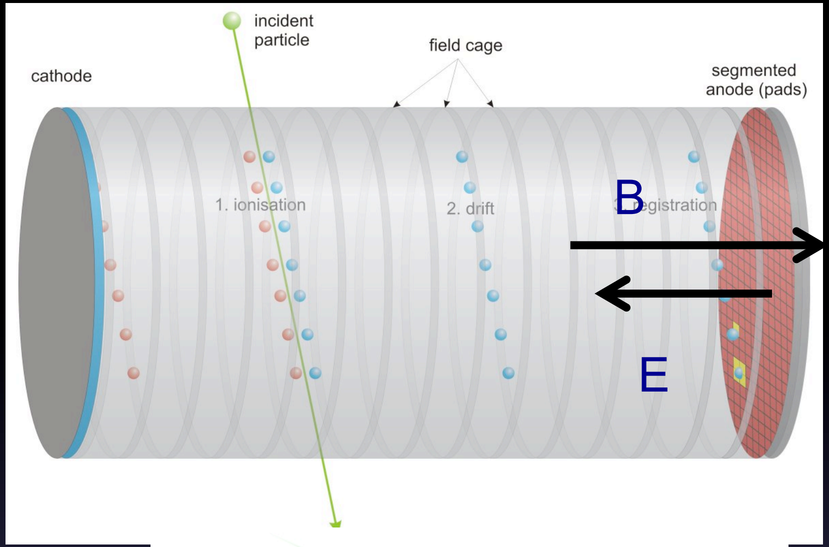
David Nygren

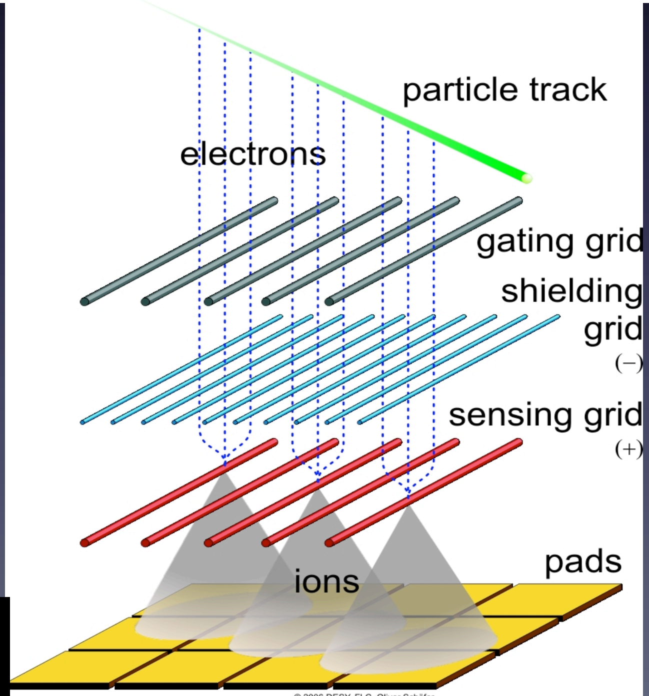


https://www.lctpc.org/e8/e57671

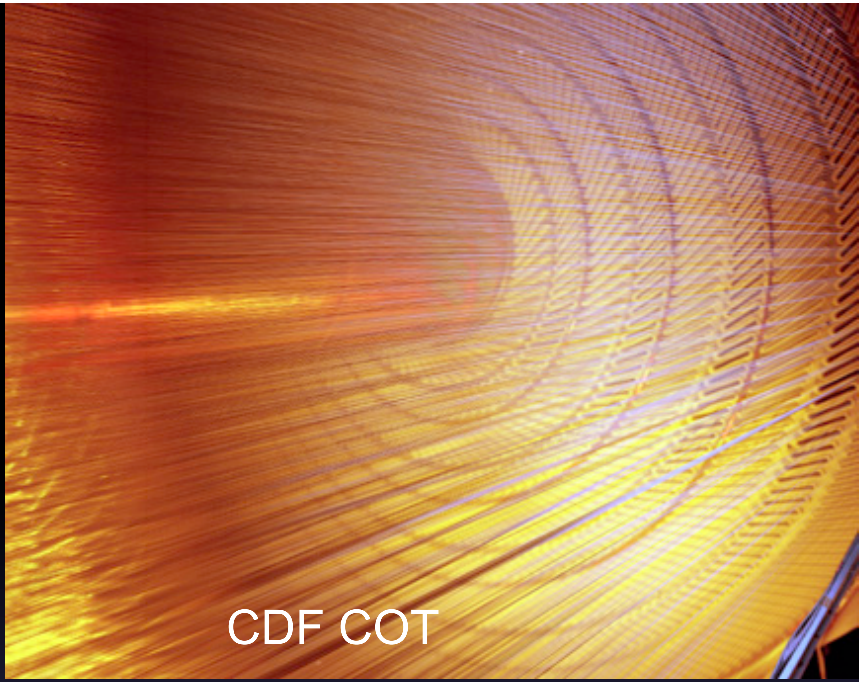
Time Projection chamber (TPC)

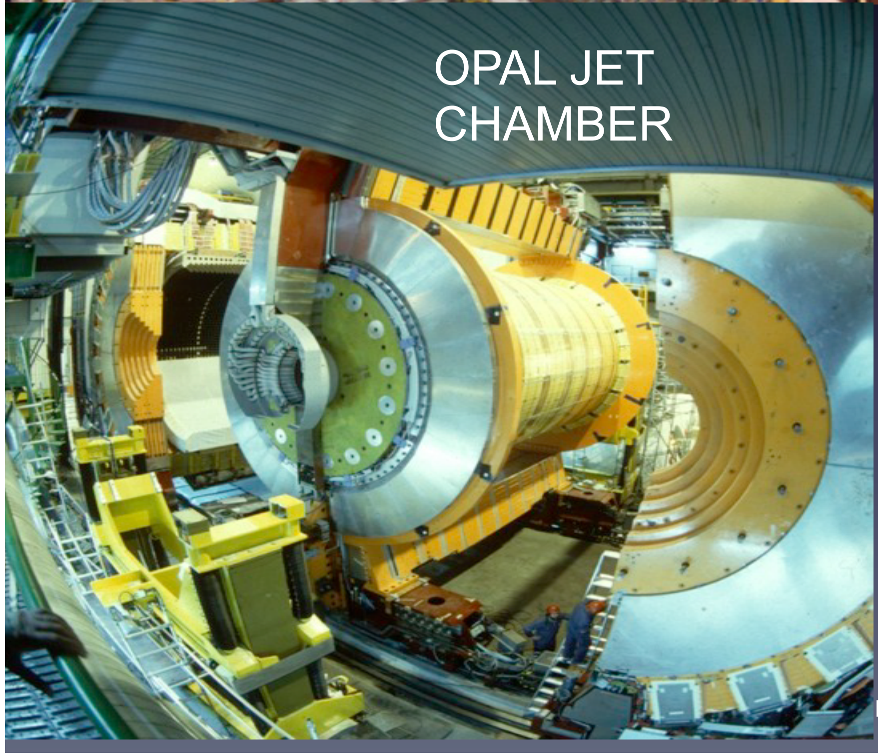
- D.R. Nygren in 1976
- Full 3-D reconstruction
  - XY: MWPC and pads of MWPC at the endcap
  - Z: from drift time measurement (several meters)
    - Field cage for very homogenous electric field
- Typical resolution
  - z and y ≈mm, x=150-300 μm
  - dE/dx ≈5-10%
- Advantages:
  - Complete track information → good momentum resolution
  - Good particle ID by dE/dx
- Challenges
  - Long drift time limited rate
  - Large volume (precision)
  - Large voltages (discharges)
  - Large data volume
  - Difficult operation at high rate

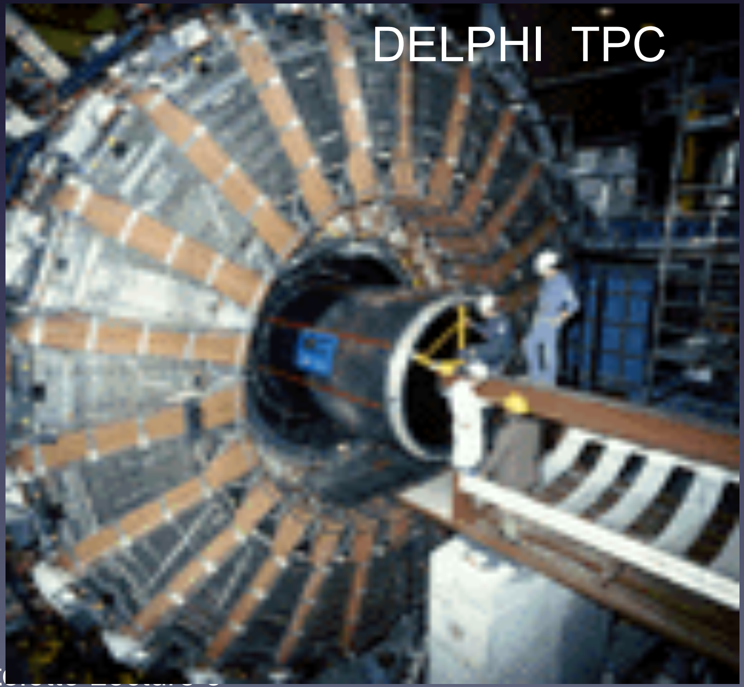


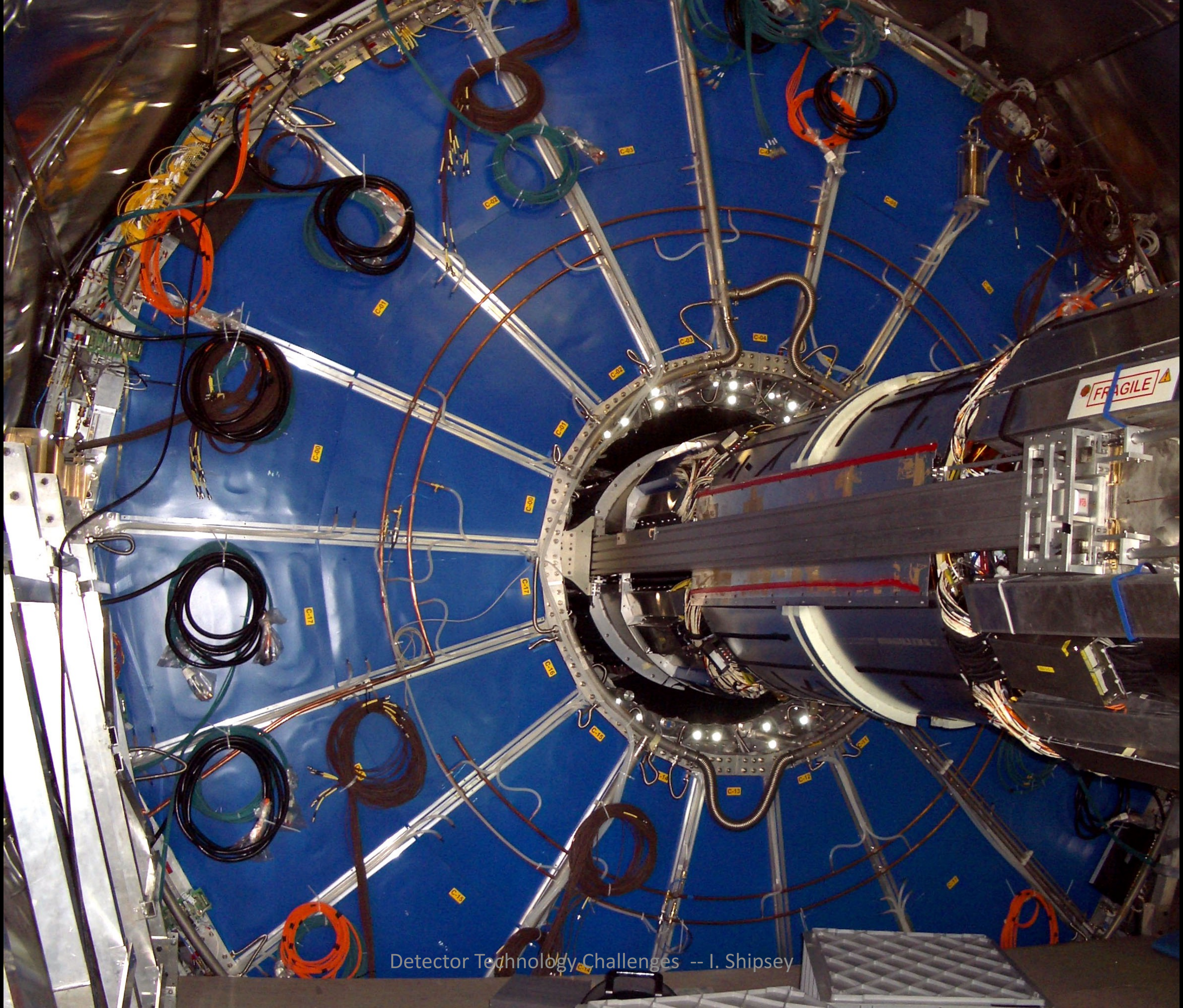



ALEPH TPC


CDF COT


OPAL JET
CHAMBER

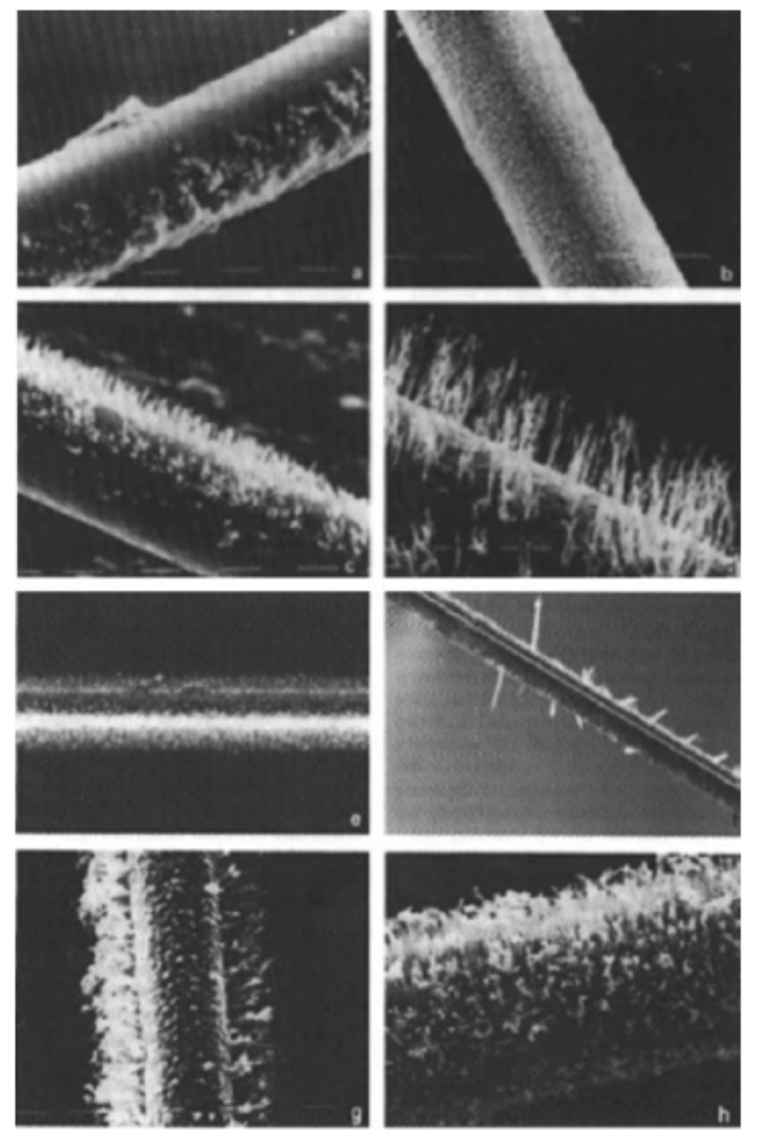

DELPHI TPC



ALICE
TPC
2010

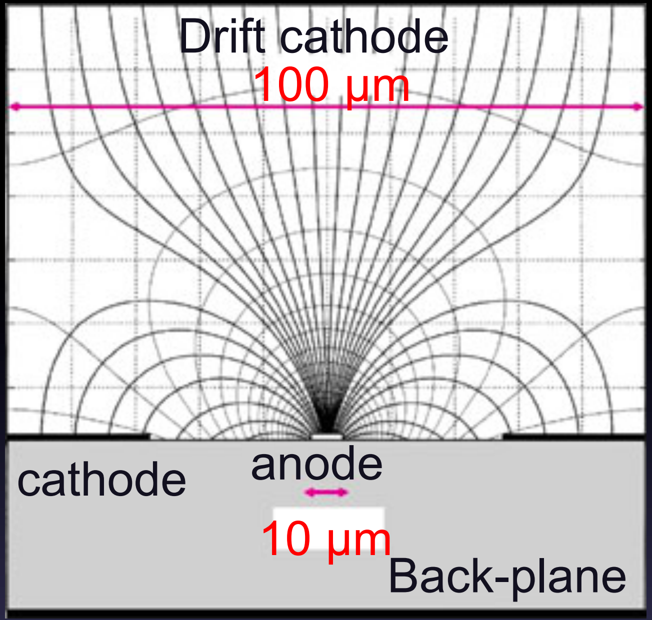
Aging in wire chambers

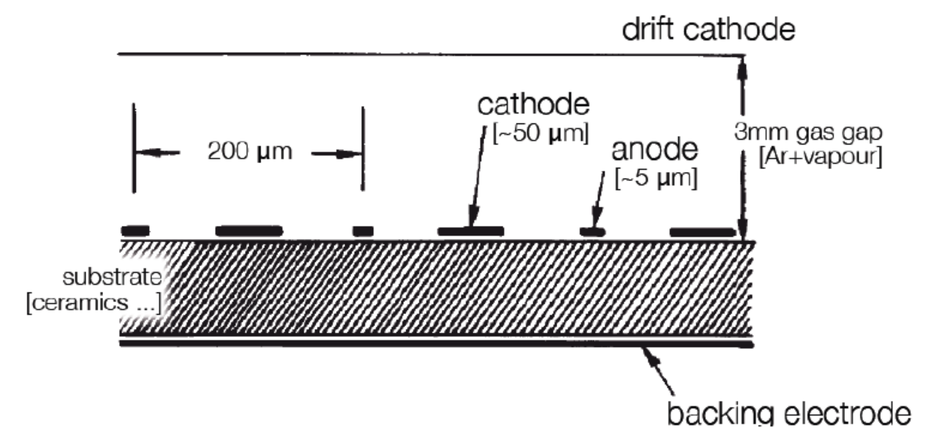
- Consequences of avalanche
  - Formation of radicals i.e. molecule fragments
  - Polymerization yield long chains of molecules
  - Polymers may be attached to the electrodes
  - Reduction of gas amplification
- Important to avoid contamination

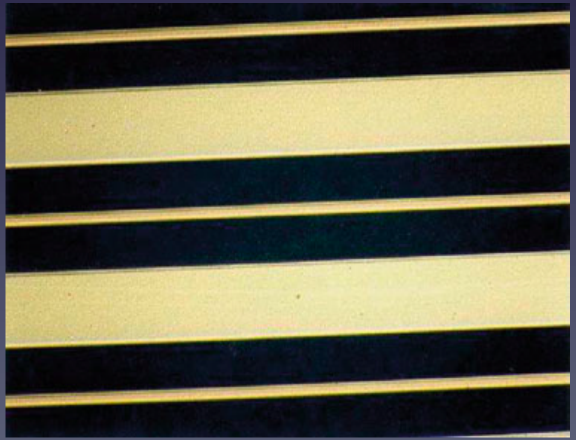


Micro-strip gas chambers (MSGC)

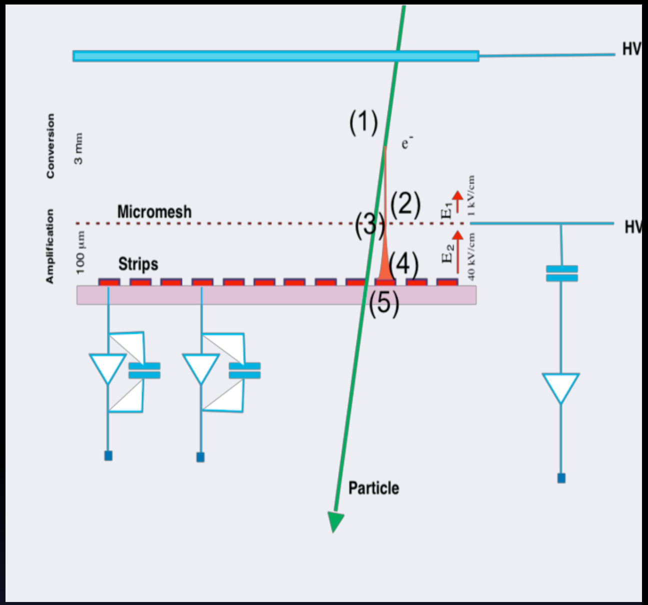
- Replace wires with electrodes on printed circuit board
- Photolithography techniques allow 100 **µm** pitch
  - Higher granularity over wire chambers
  - High-rate capability **>10⁶** Hz/mm²
  - Excellent spatial resolution (~30**µm**)
  - Time resolution in the ns range.
- MSGC were first developed in 1990s
  - Initial problems sparks and anode destruction



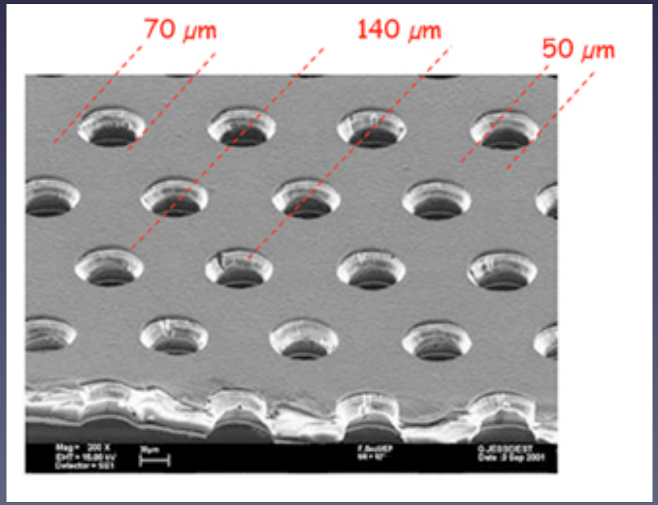


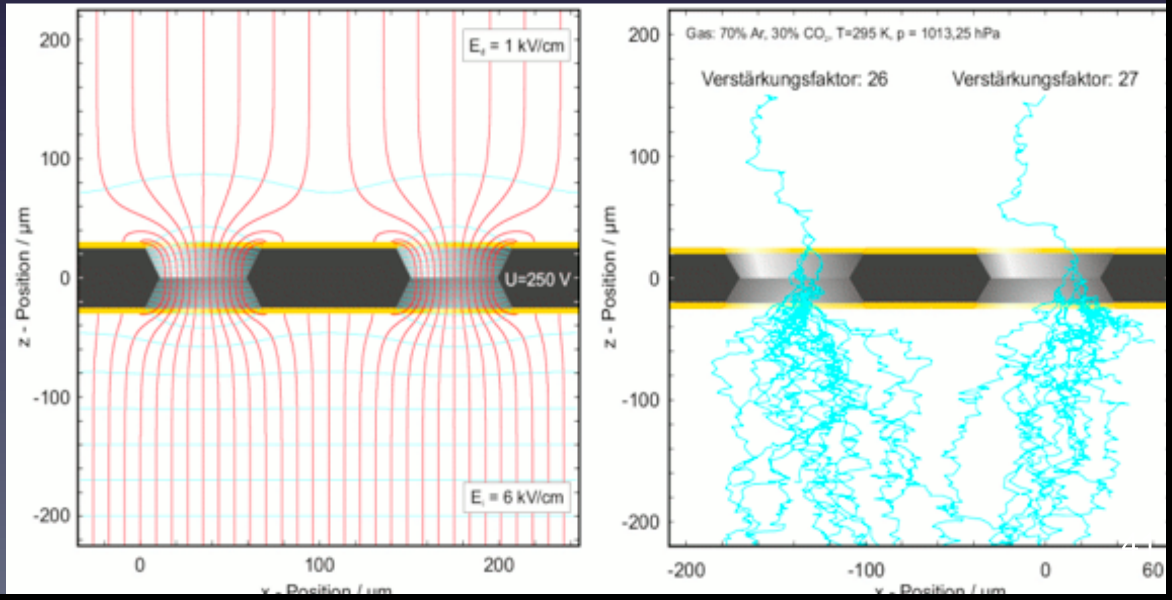


Micromegas and GEM



- Micromegas
  - Gas volume divided in two by metallic micro-mesh
  - Gain = 10^4 and a fast signal of 100ns.
- GEM (Gas Electron Multipliers, Sauli 1996)
  - Thin insulating Kapton foil coated with metal film
  - Chemically produced holes pitch ≈100 µm
  - Electrons are guided by high drift field of GEM which generates avalanche
    - Electric field strength is in the order of some 10 kV/cm
    - Avalanche gain of 100 – 1000



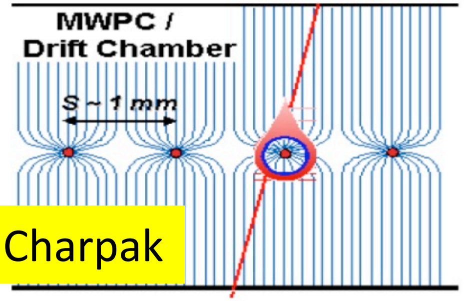


- **Gaseous detectors:** from Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors

Evolution over 50 years

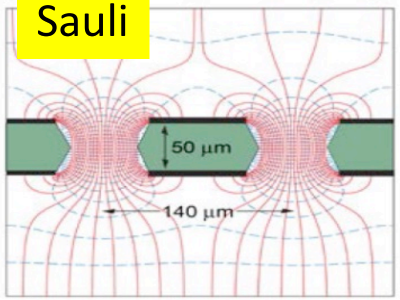
- Primary choice for large-area coverage with low material budget

MWPC / DC



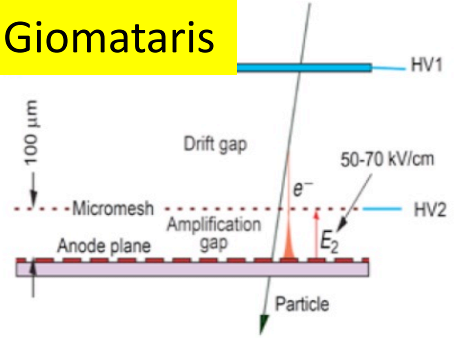
Charpak

GEM



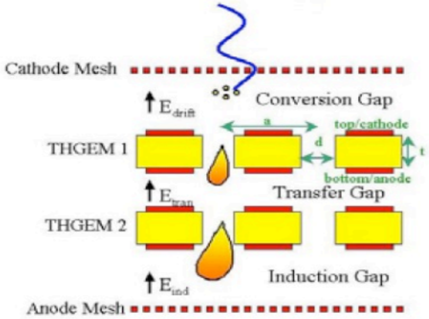
Sauli

MICROMEGAS

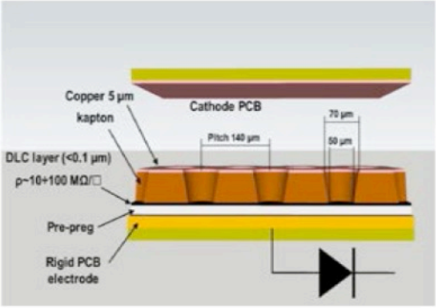


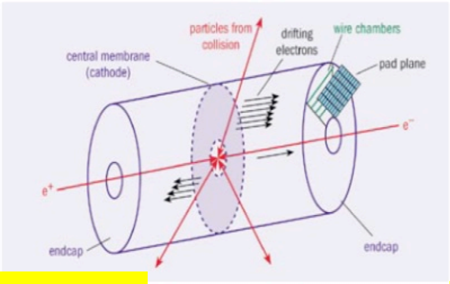
Giomataris

THGEM



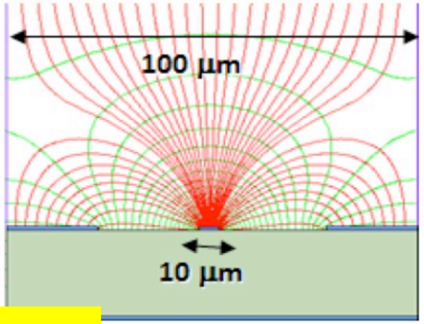
µ-RWELL





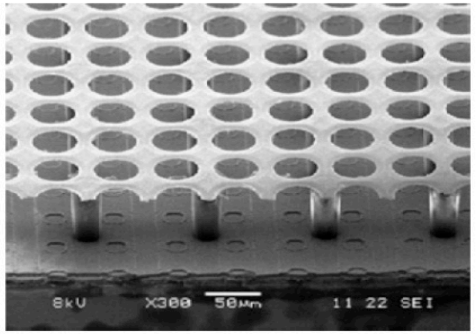
Nygren

TPC

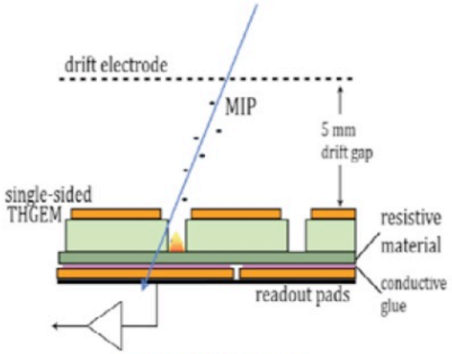


Oed

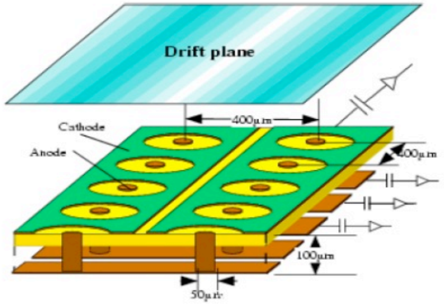
MSGC



INGRID



RPWELL



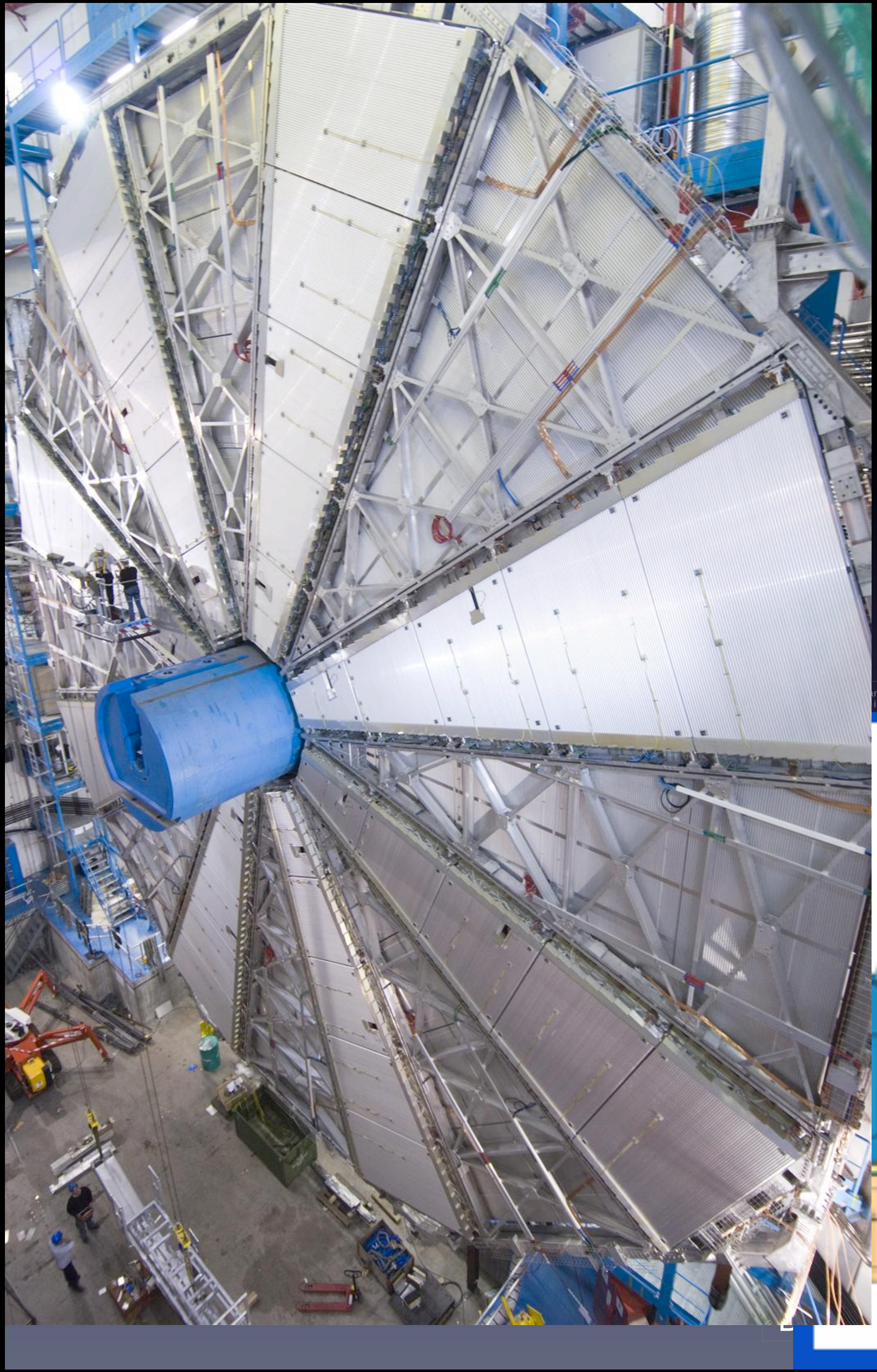
µ–PIC

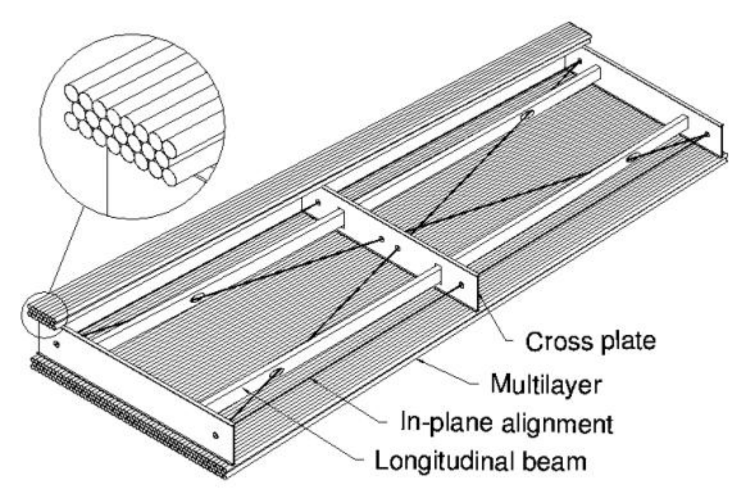
GAS detectors at the LHC

- ALICE: TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)
- ATLAS: TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)
- CMS: Muon detector (drift tubes, CSC), RPC (muon trigger)
- LHCb: Tracker (straw tubes), Muon detector (MWPC, GEM)
- TOTEM: Tracker & trigger (CSC , GEM)

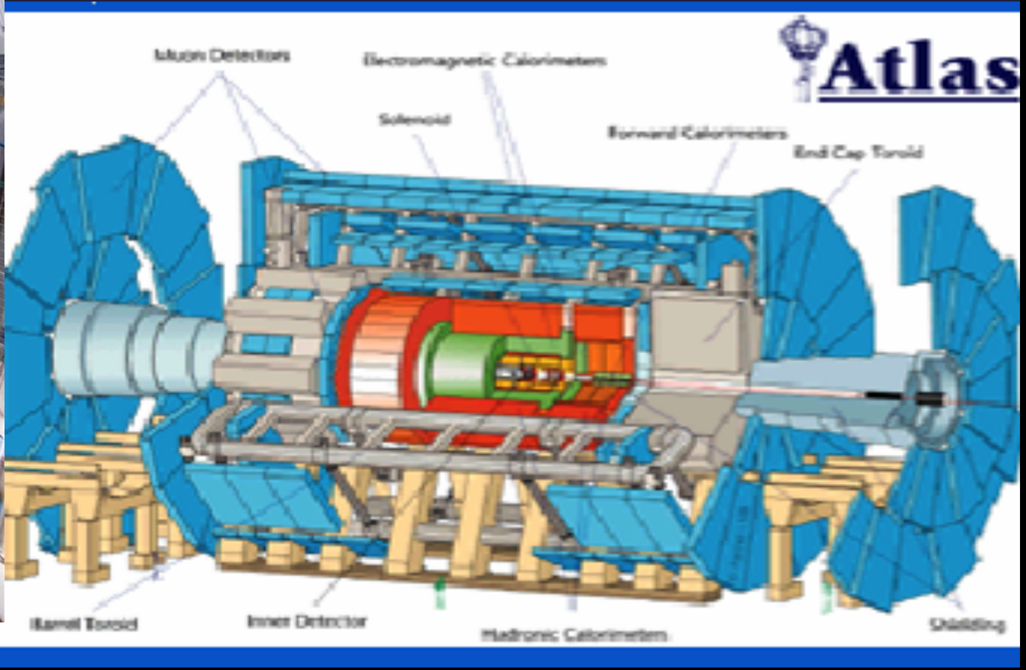
- The LHC experiments use gas detectors mainly for large scale muons detectors
- While the principle detecting elements are quit traditional many aspects have improved dramatically:
  - Readout electronics (integration, radiation resistance)
  - Excellent understanding and optimization of detector physics effects (HEED, MAGBOLTZ, GARFIELD)
  - Improvement in ageing characteristics due to special gases
- The principles are traditional but all other aspects are 100% state of the art.

ATLAS drift tubes



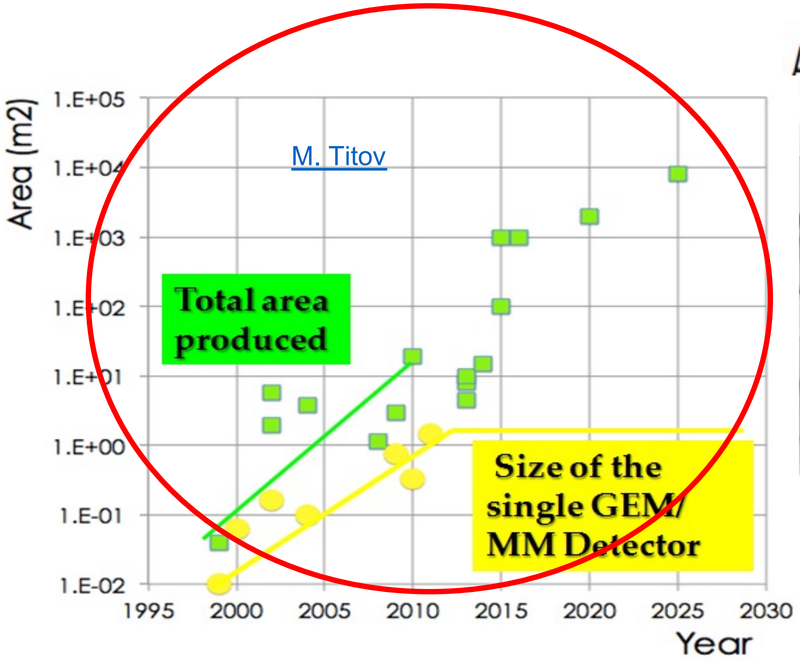


nnot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have image and then insert it again.

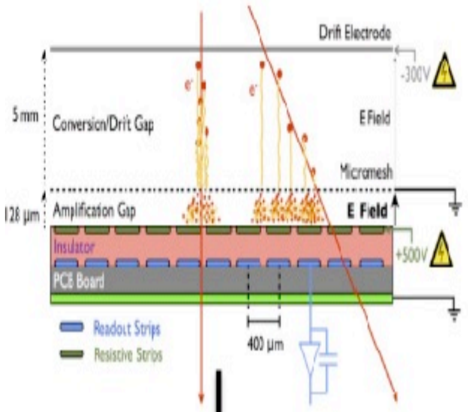


Gaseous detectors: MPGD area increasing dramatically

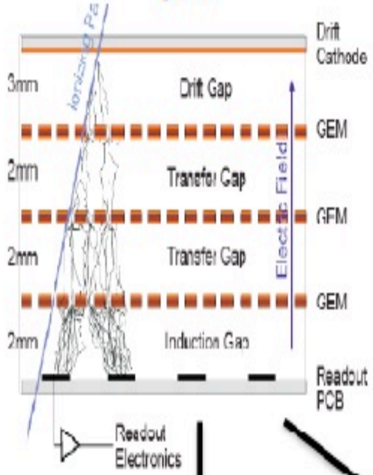
- **Upgrades to a number of systems used at the LHC** for tracking, muon spectroscopy and triggering have **taken advantage of the renaissance in gaseous detectors** (*esp* MPGDs)
- **New generation of TPCs use MPGD-based readout**: e.g. ALICE Upgrade, T2K, ILC, CepC



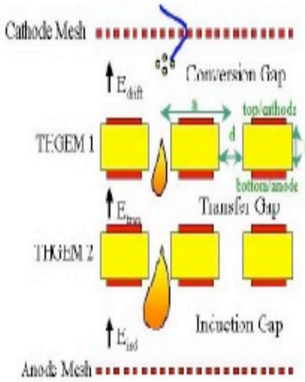
MicroMegas (MM)



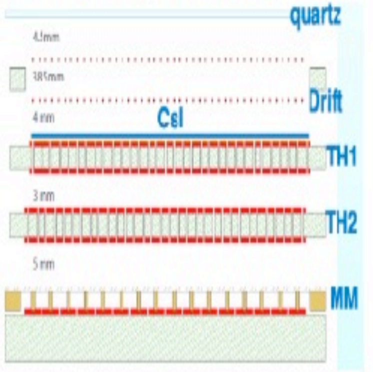
GEM



THGEM



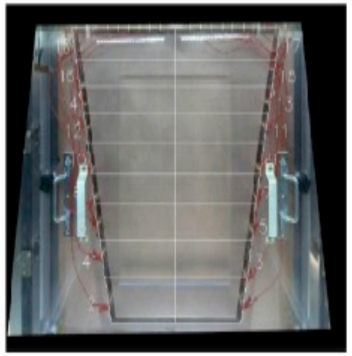
Hybrid design THGEM + MM



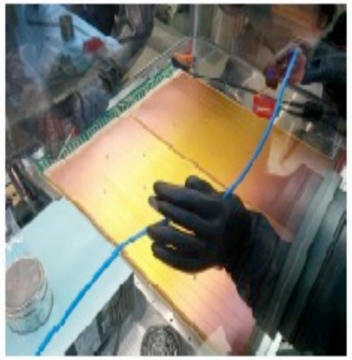
ATLAS new small wheels

CMS GEM

ALICE TPC upgrade



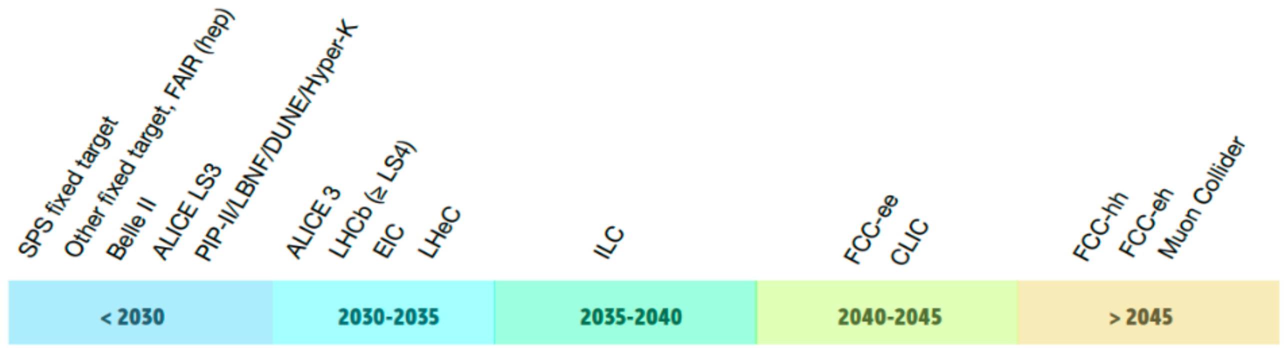
COMPASS RICH

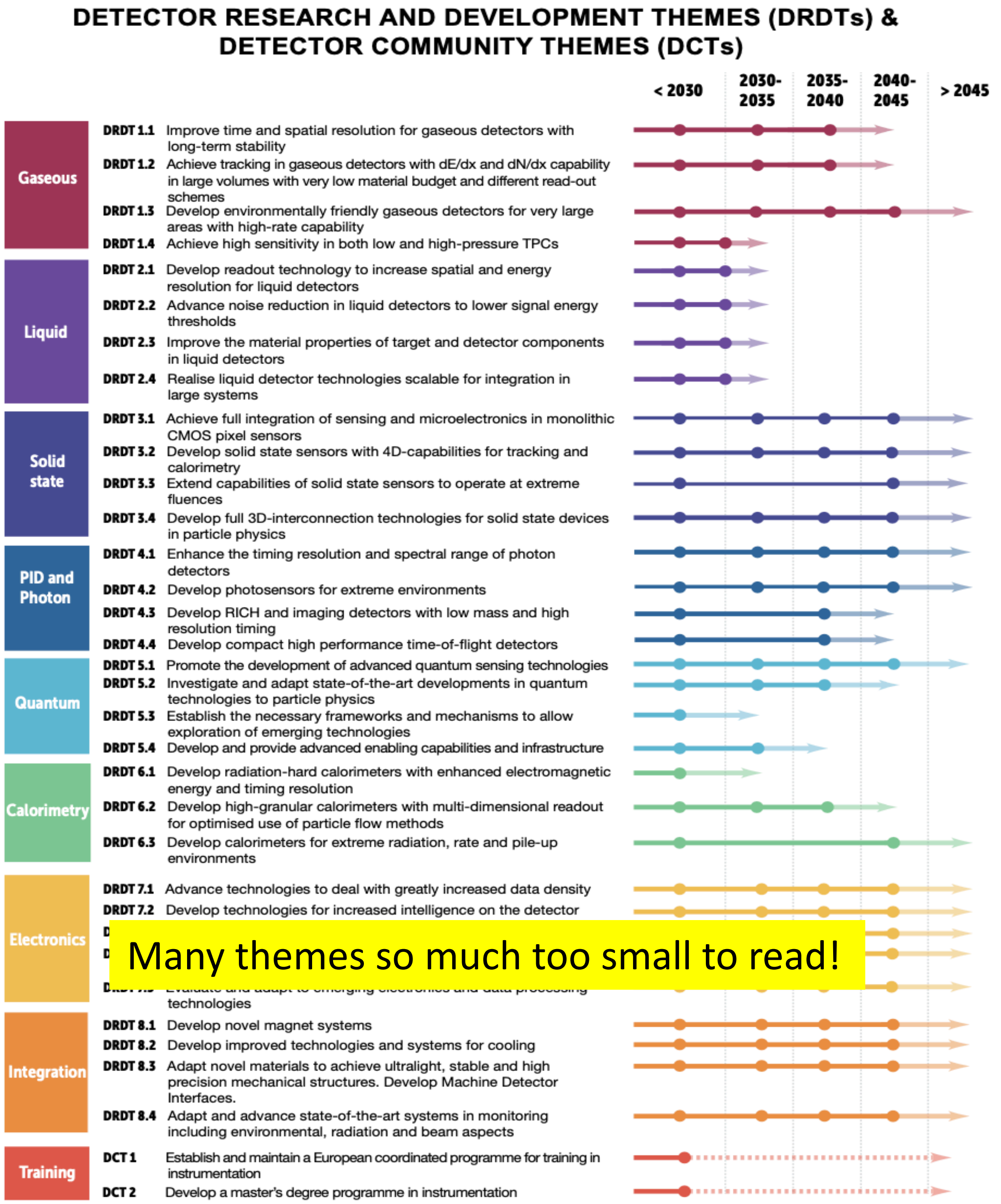


From widely used MWPC to widely used MPGD has taken 50 years

Roadmap Document Structure

Within each Task Force (one for each technology area + training) the aim is to propose a time ordered detector R&D programme by Detector Research and Development Themes (DRDT) in terms of **capabilities not currently achievable**.





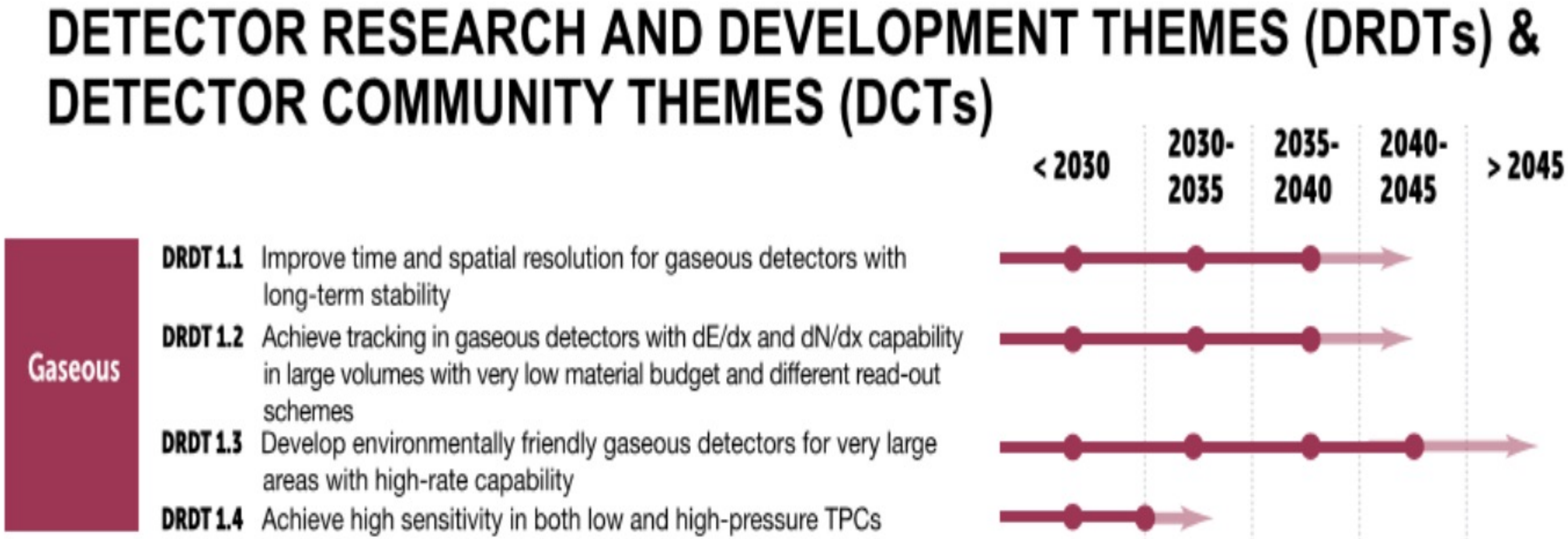
DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

DRDT 1.1 Improve time and spatial resolution for gaseous detectors with long-term stability
DRDT 1.2 Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
DRDT 1.3 Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
DRDT 1.4 Achieve high sensitivity in both low and high-pressure TPCs
DRDT 2.1 Develop readout technology to increase spatial and energy resolution for liquid detectors
DRDT 2.2 Advance noise reduction in liquid detectors to lower signal energy thresholds
DRDT 2.3 Improve the material properties of target and detector components in liquid detectors
DRDT 2.4 Realise liquid detector technologies scalable for integration in large systems
DRDT 3.1 Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
DRDT 3.2 Develop solid state sensors with 4D-capabilities for tracking and calorimetry
DRDT 3.3 Extend capabilities of solid state sensors to operate at extreme fluences
DRDT 3.4 Develop full 3D-interconnection technologies for solid state devices in particle physics
DRDT 4.1 Enhance the timing resolution and spectral range of photon detectors
DRDT 4.2 Develop photosensors for extreme environments
DRDT 4.3 Develop RICH and imaging detectors with low mass and high resolution timing
DRDT 4.4 Develop compact high performance time-of-flight detectors
DRDT 5.1 Promote the development of advanced quantum sensing technologies
DRDT 5.2 Investigate and adapt state-of-the-art developments in quantum technologies to particle physics
DRDT 5.3 Establish the necessary frameworks and mechanisms to allow exploration of emerging technologies
DRDT 5.4 Develop and provide advanced enabling capabilities and infrastructure
DRDT 6.1 Develop radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution
DRDT 6.2 Develop high-granular calorimeters with multi-dimensional readout for optimised use of particle flow methods
DRDT 6.3 Develop calorimeters for extreme radiation, rate and pile-up environments
DRDT 7.1 Advance technologies to deal with greatly increased data density
DRDT 7.2 Develop technologies for increased intelligence on the detector
technologies
DRDT 8.1 Develop novel magnet systems
DRDT 8.2 Develop improved technologies and systems for cooling
DRDT 8.3 Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
DRDT 8.4 Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects
DCT 1 Establish and maintain a European coordinated programme for training in instrumentation
DCT 2 Develop a master's degree programme in instrumentation

Many themes so much too small to read!

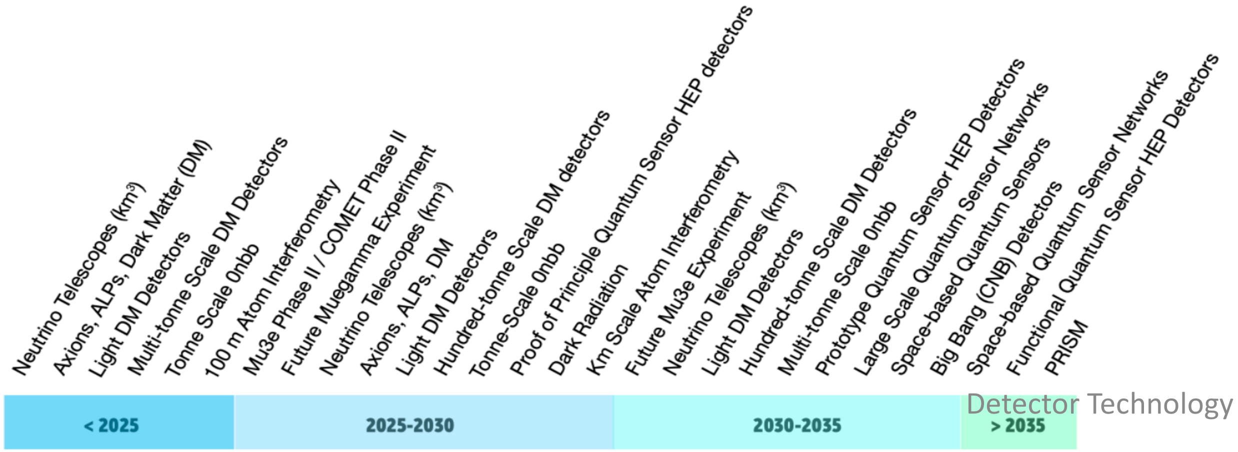
Roadmap Document Structure

Within each Task Force the aim is to propose a time ordered detector R&D programme by



DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

			< 2030	2030-2035	2035-2040	2040-2045	> 2045
Gaseous	**DRDT 1.1**	Improve time and spatial resolution for gaseous detectors with long-term stability					
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes					
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability					
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs					



DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

< 2030 | 2030-2035 | 2035-2040 | 2040-2045 | > 2045

Gaseous
DRDT 1.1 Improve time and spatial resolution for gaseous detectors with long-term stability
DRDT 1.2 Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
DRDT 1.3 Develop environmentally friendly gaseous detectors for very large areas with high-rate capability

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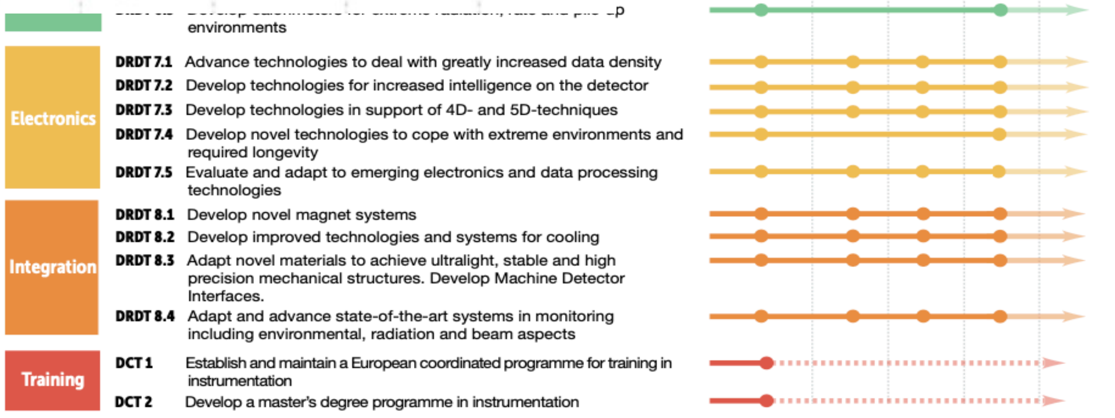
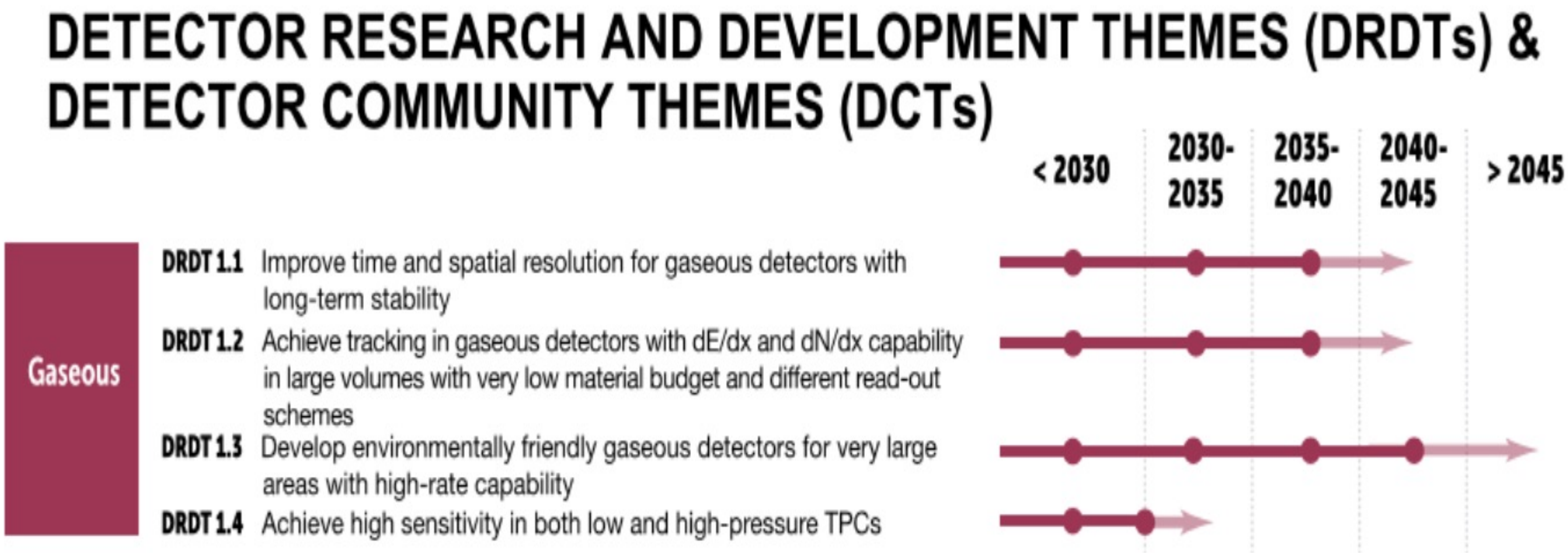


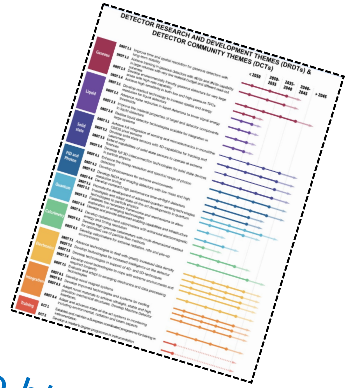
Electronics	**DRDT 7.1**	Advance technologies to deal with greatly increased data density
	DRDT 7.2	Develop technologies for increased intelligence on the detector
	DRDT 7.3	Develop technologies in support of 4D- and 5D-techniques
	DRDT 7.4	Develop novel technologies to cope with extreme environments and required longevity
	DRDT 7.5	Evaluate and adapt to emerging electronics and data processing technologies
Integration	**DRDT 8.1**	Develop novel magnet systems
	DRDT 8.2	Develop improved technologies and systems for cooling
	DRDT 8.3	Adapt novel materials to achieve ultralight, stable and high precision mechanical structures. Develop Machine Detector Interfaces.
	DRDT 8.4	Adapt and advance state-of-the-art systems in monitoring including environmental, radiation and beam aspects
Training	**DCT 1**	Establish and maintain a European coordinated programme for training in instrumentation
	DCT 2	Develop a master's degree programme in instrumentation

Gaseous detectors



DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

			< 2030	2030-2035	2035-2040	2040-2045	> 2045
Gaseous	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability	●	●	●	→	
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes	●	●	●	→	
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability	●	●	●	●	→
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs	● ●	→			



To highlight the most important drivers for research in each technology area

To not limit a feasible start date of a future facility

- The faded region indicates the typical time needed between the completion of the R&D phase and the readiness of an experiment at a given facility.
- Stepping stones are shown to represent the R&D needs of facilities intermediate in time.
- It should be emphasised that the future beyond the end of the arrows is simply not yet defined, not that there is an expectation that R&D for the further future beyond that point will not be needed.

Gaseous detectors

Are ubiquitous

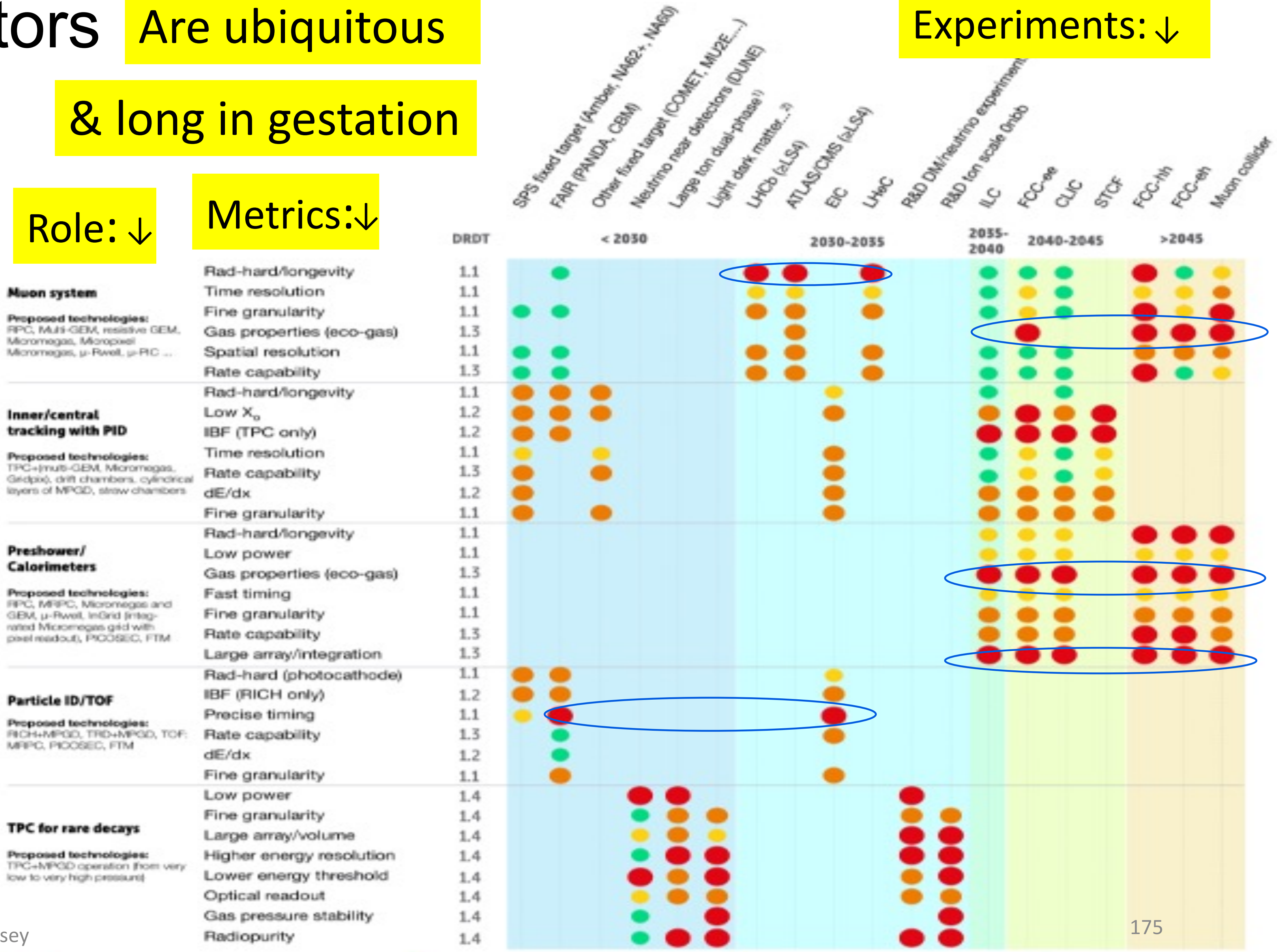
& long in gestation

- **Detector Readiness Matrices of each Task Force chapter** focus on the extent to which the R&D topic is *mission critical* to the programme rather than the intensity of R&D required
  - Must happen or main physics goals cannot be met
  - Important to meet physics goals
  - Desirable to enhance physics reach
  - R&D need being met

Role: ↓

Metrics:↓

Experiments:↓



Role	Metrics	DRDT	SPS fixed target (Amber, NA62+, NA60)	FAIR (PANDA, CBM)	Other fixed target (COMET, MU2E...)	Neutrino near detectors (DUNE)	Large ton dual-phase	Light dark matter	LHCb (≥LS4)	ATLAS/CMS (≥LS4)	EIC	LHeC	R&D DM/neutrino experiment	R&D ton scale 0nbb	ILC	FCC-ee	CLIC	STCF	FCC-hh	FCC-eh	Muon collider
			< 2030								2030-2035				2035-2040	2040-2045			>2045		
Muon system **Proposed technologies:** RPC, Multi-GEM, resistive GEM, Micromegas, Micropixel Micromegas, μ-Rwell, μ-PIC ...	Rad-hard/longevity	1.1		🟢					🔴	🔴		🔴			🟢	🟢	🟢		🔴	🟢	🟡
	Time resolution	1.1							🟡	🟡		🟡			🟢	🟡	🟢		🟡	🟡	🟠
	Fine granularity	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟡	🟢		🔴	🟡	🔴
	Gas properties (eco-gas)	1.3								🟠						🔴			🔴	🔴	🔴
	Spatial resolution	1.1	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🟠	🟠	🟠
	Rate capability	1.3	🟢	🟢					🟠	🟠		🟠			🟢	🟢	🟢		🔴	🟢	🟡
Inner/central tracking with PID **Proposed technologies:** TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers	Rad-hard/longevity	1.1	🟠	🟠	🟠						🟡				🟢		🟢				
	Low X_0	1.2	🟠	🟠	🟠						🟠				🟠	🔴	🟠	🔴			
	IBF (TPC only)	1.2	🟠	🟠											🔴	🔴	🔴	🔴			
	Time resolution	1.1	🟡		🟡						🟠				🟢	🟡	🟢	🟡			
	Rate capability	1.3	🟠		🟠						🟠				🟢	🟡	🟢	🟡			
	dE/dx	1.2	🟠								🟠				🟠	🟠	🟠	🟠			
	Fine granularity	1.1	🟠		🟠						🟠				🟠	🟠	🟠	🟠			
Preshower/ Calorimeters **Proposed technologies:** RPC, MRPC, Micromegas and GEM, μ-Rwell, InGrid (integrated Micromegas grid with pixel readout), PICOSEC, FTM	Rad-hard/longevity	1.1													🟡	🟡	🟡		🔴	🔴	🔴
	Low power	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Gas properties (eco-gas)	1.3													🔴	🔴	🔴		🔴	🔴	🔴
	Fast timing	1.1													🟡	🟡	🟡		🟡	🟡	🟡
	Fine granularity	1.1													🟠	🟠	🟠		🟠	🟠	🟠
	Rate capability	1.3													🟠	🟠	🟠		🔴	🔴	🟠
	Large array/integration	1.3													🔴	🔴	🔴		🔴	🔴	🔴
Particle ID/TOF **Proposed technologies:** RICH+MPGD, TRD+MPGD, TOF: MRPC, PICOSEC, FTM	Rad-hard (photocathode)	1.1	🟠	🟠							🟡										
	IBF (RICH only)	1.2	🟠	🟠							🟠										
	Precise timing	1.1	🟡	🔴							🔴										
	Rate capability	1.3		🟢							🟠										
	dE/dx	1.2		🟢																	
	Fine granularity	1.1		🟠							🟠										
TPC for rare decays **Proposed technologies:** TPC+MPGD operation (from very low to very high pressure)	Low power	1.4				🔴	🔴						🔴								
	Fine granularity	1.4				🟢	🟠	🟠					🟠	🟠							
	Large array/volume	1.4				🟡	🟠	🟡					🔴	🔴							
	Higher energy resolution	1.4				🟢	🔴	🔴					🔴	🔴							
	Lower energy threshold	1.4				🔴	🟠	🔴					🟠	🔴							
	Optical readout	1.4				🟡	🟠	🟠					🟠	🟠							
	Gas pressure stability	1.4				🟢		🔴						🔴							
	Radiopurity	1.4				🟢	🔴	🔴					🔴	🔴							

Literature

- D.H. Wilkinson: *Ionization Chambers and Counters* (Cambridge Univ. Press, 1950)
- S.A. Korff: *Electron and Nuclear Counters* (Van Nostrand, 1955)
- P. Rice-Evans: *Spark, Streamer, Proportional and Drift Chambers* (Richelieu, 1974)
- F. Sauli: *Principles of Operation of Multiwire Proportional and Drift Chambers* (CERN 77-09, 1977)
- Th. Ferbel, Editor: *Techniques and Concepts of High-energy Physics* (Plenum, 1983)
- R.C. Fernow: *Introduction to Experimental Particle Physics* (Cambridge Univ. Press, 1986)
- W.R. Leo: *Techniques for Nuclear and Particle Physics Experiments* (Springer, 1987)
- C. Fabjan and J. Pilcher, ed.: *Instrumentation in Elementary Particle Physics* (World Scientific, 1988)
- C.F.G. Delaney and E.C. Finch: *Radiation Detectors* (Clarendon Press, 1992)
- R. Gilmore: *Single Particle Detection and Measurement* (Taylor and Francis, 1992)
- F. Sauli, ed.: *Instrumentation in High Energy Physics* (World Scientific, 1992)
- K. Grupen: *Particle Detectors* (Cambridge Monographs on Part. Phys. 1996)
- K. Kleinknecht: *Detectors for Particle Radiation* (Cambridge Univ. Press 1998)
- G.F. Knoll: *Radiation Detection and Measurements, 3d Ed.* (Wiley, 2000)
- W. Blum, W. Riegler and L. Rolandi: *Particle Detection with Drift Chambers, 2d Ed.* (Springer 2008)