Oak Ridge National Laboratory

Realizing The Vision: Science Technologies

TRIUMF Science Week 2021
August 17, 2021

Marcel Demarteau
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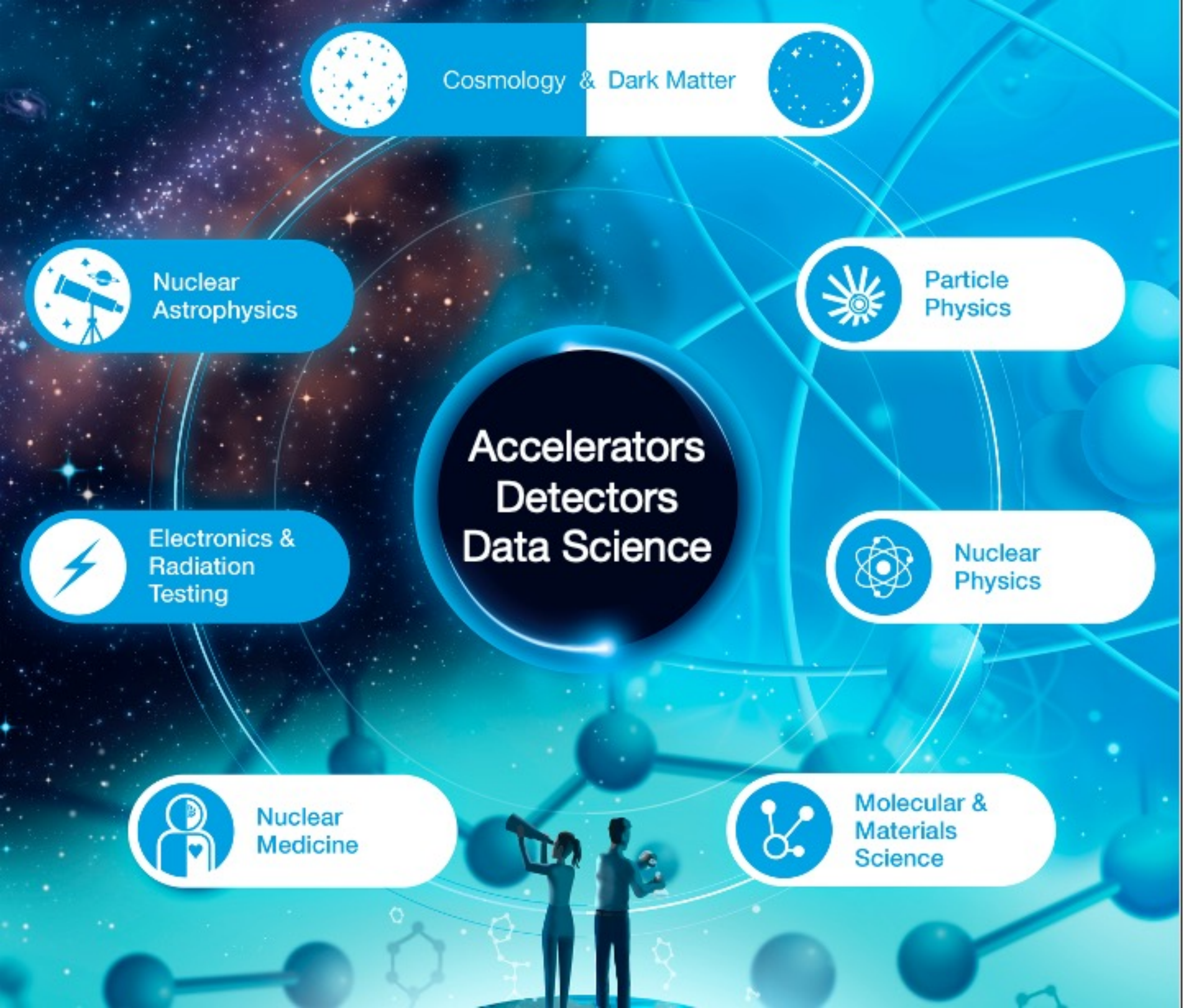
U.S. DEPARTMENT OF ENERGY



TRIUMF's Vision:
To lead in science, discovery, and innovation, improving lives and building a better world.

Science Technologies are foundational to ensure successful realization of the vision

Outline:

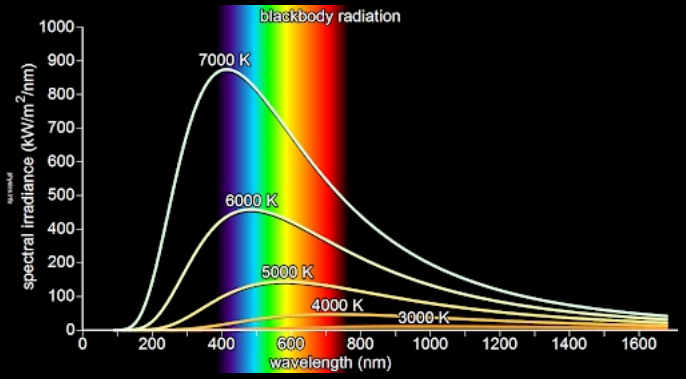
- **Reflection**
- **Research Approaches**
- **The Power of Technology**
- **Outlook**

Our World Today

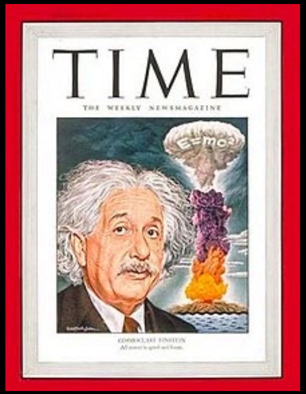
- Amazing understanding of the universe at vastly different scales
  - From Inflation to Cosmic Microwave Background radiation to creation of elements to galaxy formation
  - From the building blocks of matter and their interactions and the generation of mass
- Encapsulated in:
  - Standard Model of Particle Physics
  - Standard Model of Cosmology
- The theories are highly predictive and have been rigorously tested (in QED to 1 part in 10 billion)

Science progresses by experimentation, observation, and theory

- Nobody would have predicted that slight irregularities in black body radiation would have led to the entirely new concept of the quantum world.



- That pondering the constancy of the speed of light would have led to $E= mc^2$



- That special relativity and quantum mechanics would have led to anti-matter

$$(i\gamma^{\mu}\partial_{\mu} - m)\psi = 0$$

- That Noether's theorem would lead to the importance of symmetries and the corresponding conservation laws

Where is True North?

- For the last century or so we have been guided by the development of quantum theories, confirmed by experimental observations, which has been spectacularly successful.

……

- Currently there is no clear roadmap to guide us.
- But, at the same time we find ourselves at arguably the most exciting time in Physics

The Dawn of a New Era ?

- The mystery of the ‘inflaton’
- The mystery of Dark Matter
- The mystery of Dark Energy
- The mystery of the Majorana neutrino
- The mystery of the neutrino mass
- The mystery of the vanishing anti-matter
- The mystery of the hierarchy problem
- The mystery of the quantization of gravity
- The mystery of the proton mass
- The mystery of the proton spin
- The mystery of the Higgs boson
- …..

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We are very much in a data driven era !

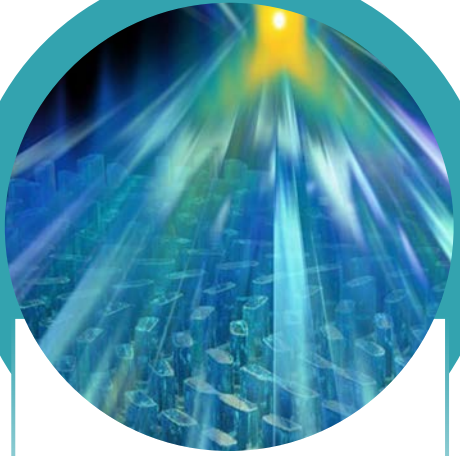
The Enablers !

- The mystery of the ‘inflaton’ .... TES in CMB experiments, …
- The mystery of Dark Matter .... Axion, recoil detectors, …
- The mystery of Dark Energy .... Spectrographic telescopes
- The mystery of the Majorana neutrino .... Neutrinoless double beta decay
- The mystery of the neutrino mass .... Neutrinoless double beta decay
- The mystery of the vanishing anti-matter .... CP-violation, EDMs, ν’s
- The mystery of the hierarchy problem .... Future circular collider
- The mystery of the quantization of gravity .... LIGO, Einstein Telescope, LISA
- The mystery of the proton mass .... Electron Ion Collider
- The mystery of the proton spin .... Electron Ion Collider
- The mystery of the Higgs boson .... Electron Positron colliders
- …..

Science Technologies Will Play a Pivotal Role

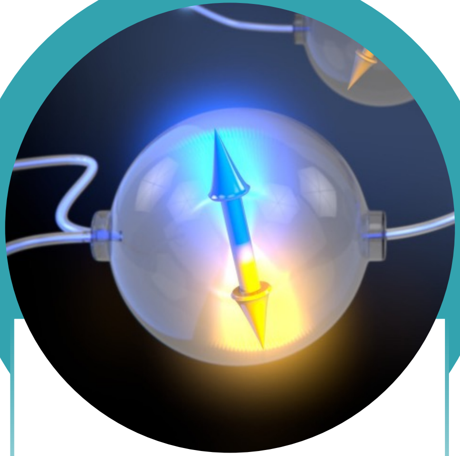
Directed R&D

Aimed at realizing high-priority projects



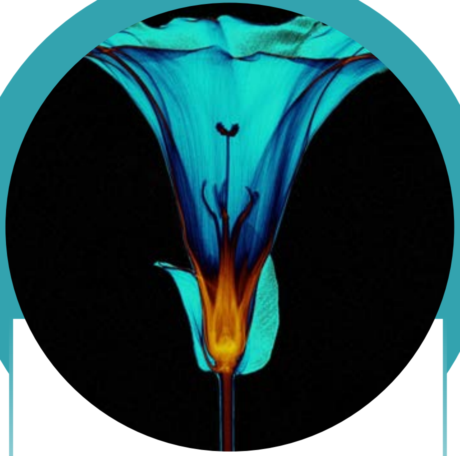
Generic R&D

Aimed at developing new methodologies and techniques, adopting emerging technologies



Inspired R&D

Building on emerging technologies and advances in industry and other science disciplines



R&D That Inspires

Applying the techniques to other areas of science

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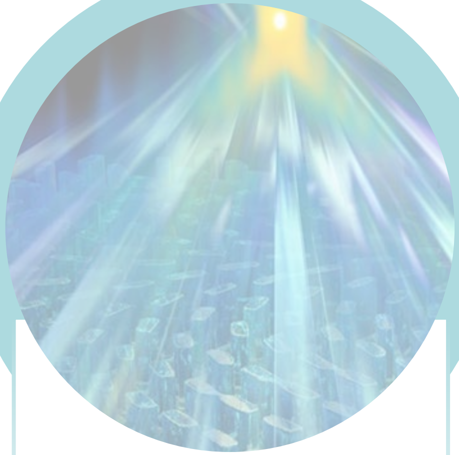

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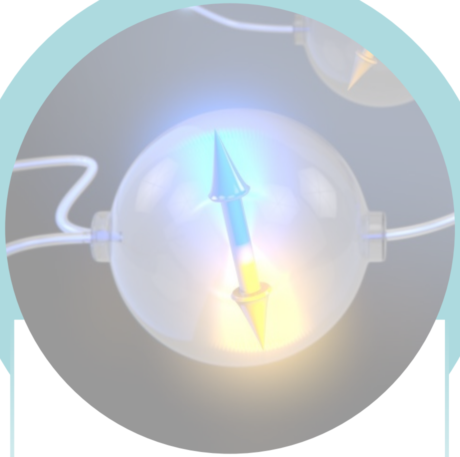

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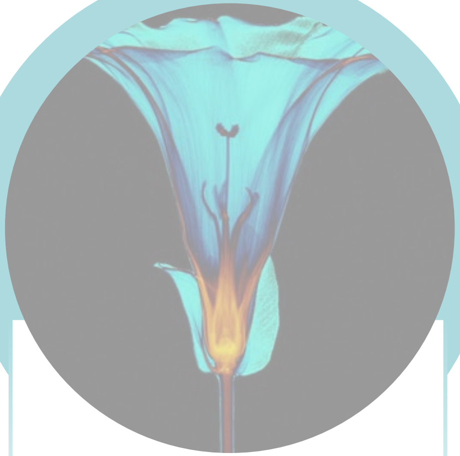


R&D That Inspires

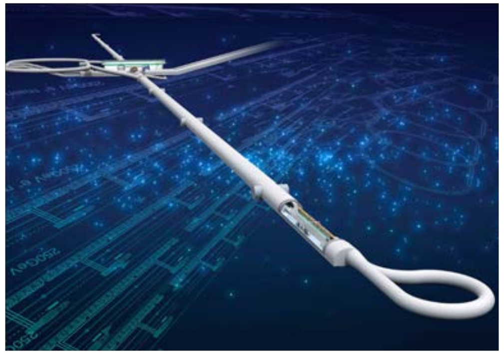
Applying the techniques to other areas of science

Long-Range Strategies

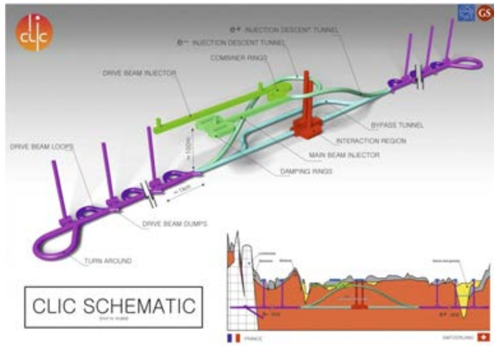
....

Particle Physics Collider Strategy

- P5 has identified five science drivers, one of which is:
  - ***Use the Higgs boson as a new tool for discovery.***
- The unique position of the Higgs boson has recently been confirmed by the 2020 European Strategy Update:
  - ***An electron-positron Higgs factory is the highest-priority next collider.*** *For the longer term, the European particle physics community has the ambition to operate a proton-proton collider …*



International Linear Collider (ILC)
E_{cms} < 1 TeV

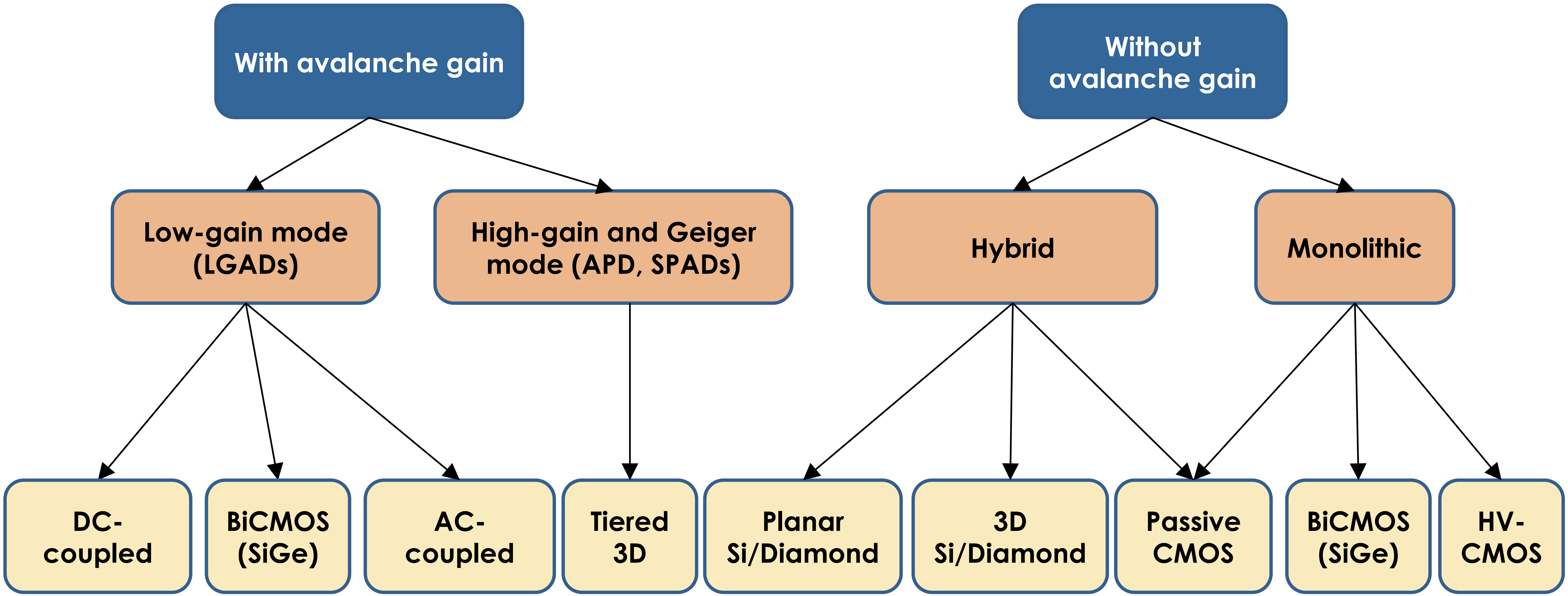


Compact Linear Collider (CLIC)
E_{cms} < 3 TeV

Circular Electron Positron Collider (CepC)
E_{cms} < 250 GeV

FCC-ee
E_{cms} ~365 GeV

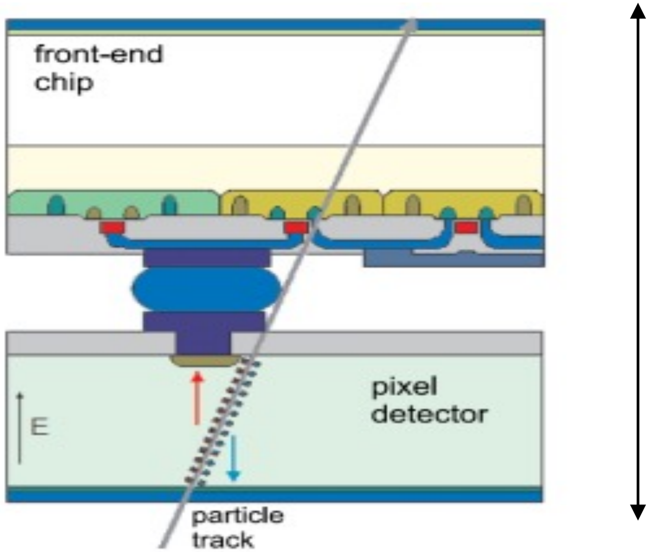
Multi-Dimensional Solid State Tracking Detectors



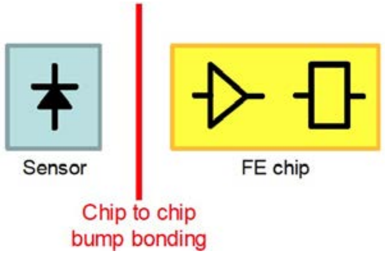
Peric et al., NIM A582 (2007) 876-885 & NIM A765 (2014) 172-176
Mattiazzo, Snoeys et al., NIM A718 (2013) 288-291

Two Pixel Technologies

Hybrid Pixels

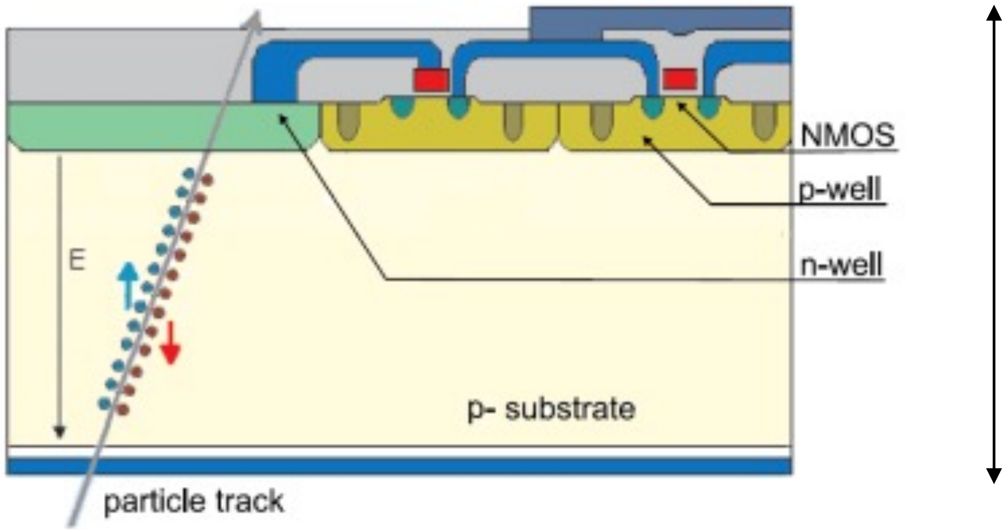


~300 μm

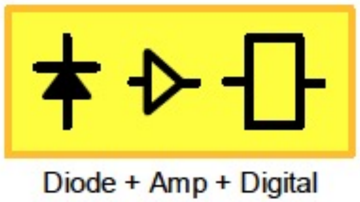


- Workhorse of the field
- Radiation hard
- Flexible (ASIC and sensor separate, 3D sensors)
- Costly

Depleted CMOS MAPS



~100 μm



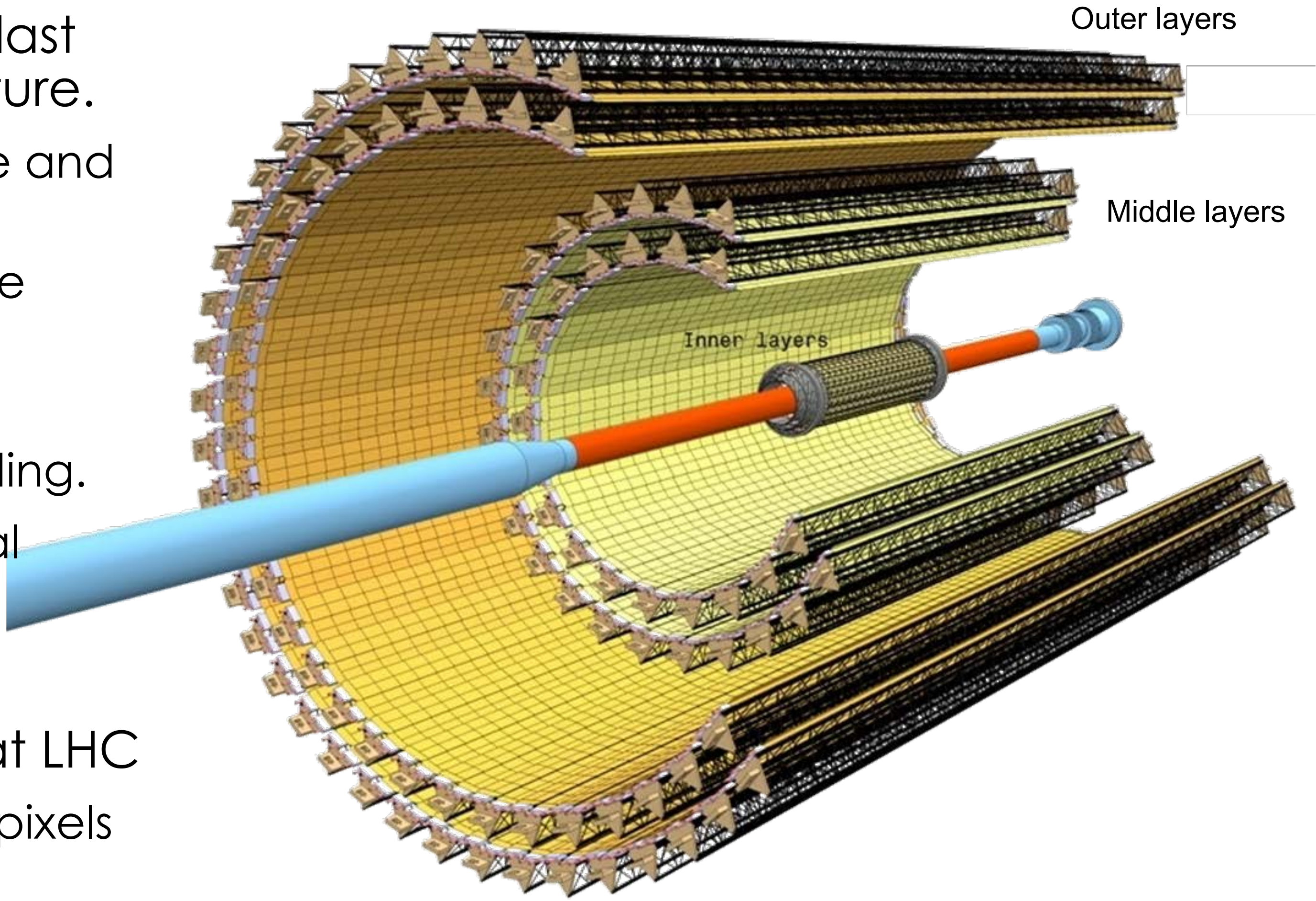
- Integration of Front-End electronics
- Not radiation hard
- Flexible integration
- Commercial process

MAPS = Monolithic Active Pixel Sensor

CMOS Trackers

- CMOS monolithic active pixel trackers have gained **enormous momentum** over the last years and hold great promise for the future.
  - Commercial processes offer high volume and large wafers (cost effective)
  - CMOS sensors can be thinned to achieve ultimate low mass trackers <1%
  - Small pixel sizes (~20 μm), low power
  - No cost (and complexity) of bump-bonding.
  - Highly integrated modules using industrial postprocessing tools.

- ALICE Inner Tracker, first CMOS tracker at LHC
  - 7 layers (R = 21-400 mm), ~ 10 m^2, 12.5 Gpixels
  - 0.35% X_0/layer (Inner)
  - Pixel size: 26.88 x 29.24 μm^2



ALICE Inner Tracker for LHC Run 3

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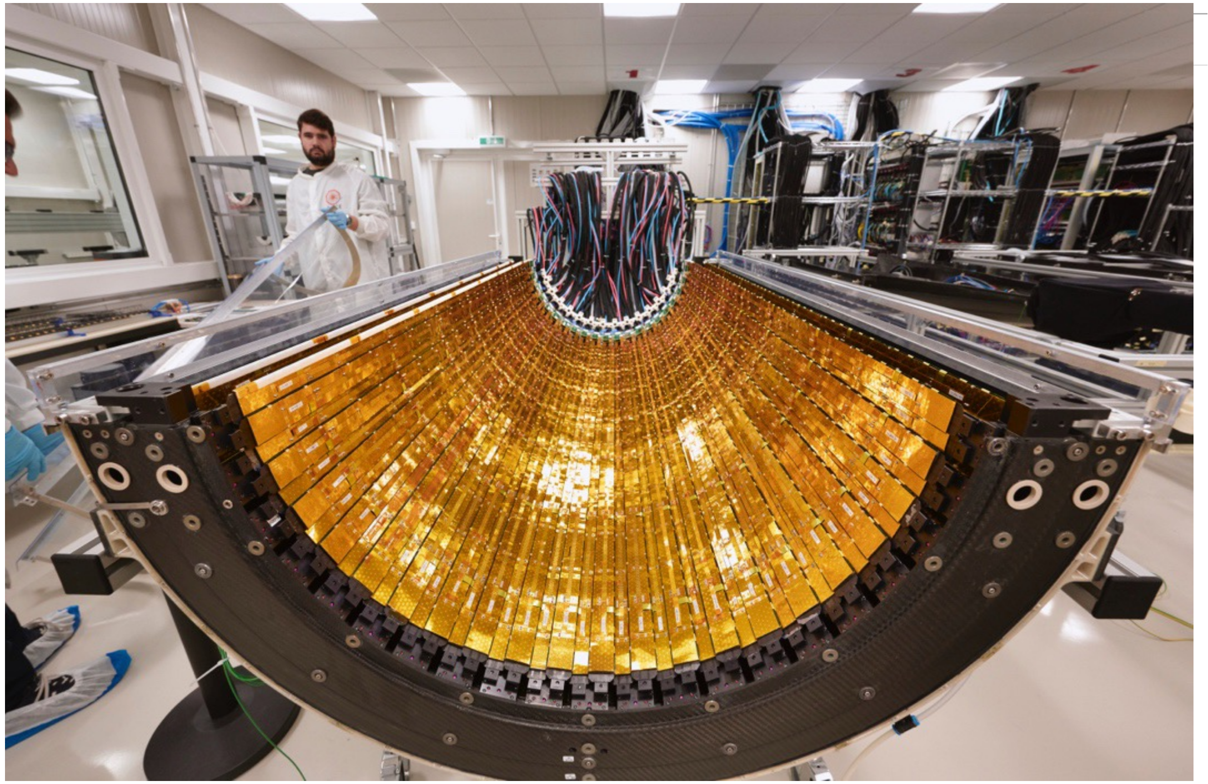
ALICE Inner Tracker System 2



https://home.cern/news/news/experiments/alice-journey-cosmopolitan-detector

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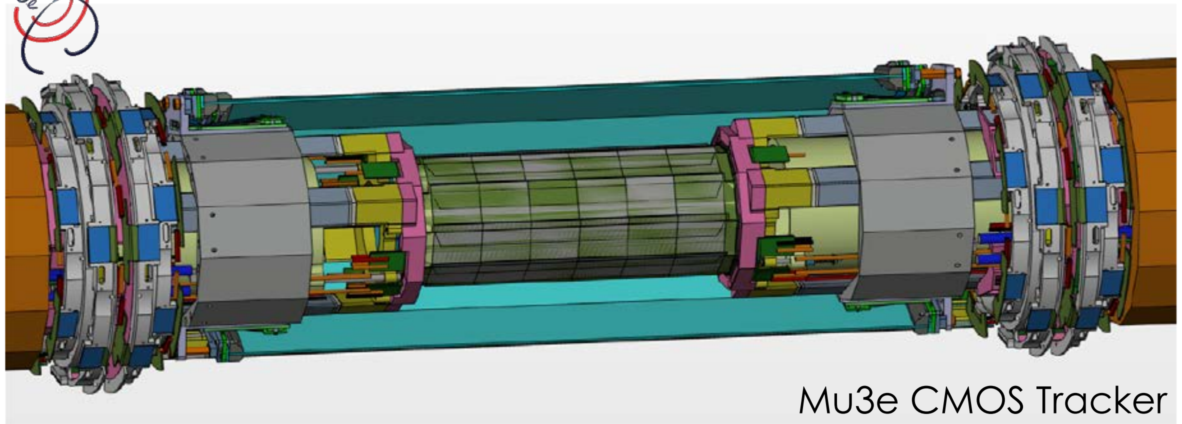
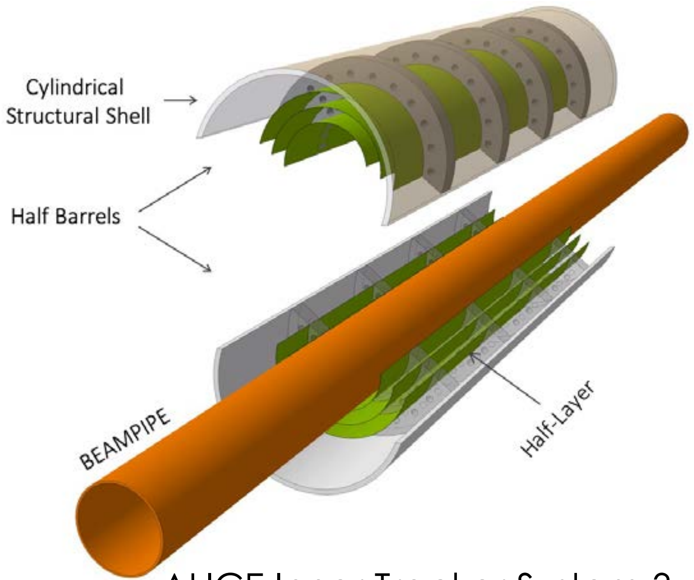
Next Generation CMOS Trackers

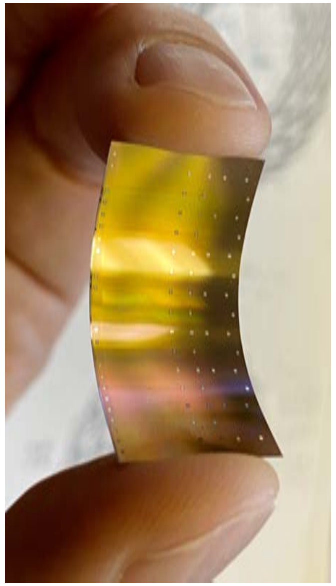


Mu3e CMOS Tracker

- Mu3e:
  - Ultra-thin, 50 μm, wafer-scale HV-CMOS Monolithic Active Pixel Sensor.
  - 180 nm technology, chip size 20.6 x 23.2 mm^2; pixel size 80x80 μm^2
  - **0.5 ‰ X_0** per layer, <30 μm resolution



ALICE Inner Tracker System 3



ALIPIDE thinned readout chip

- ALICE ITS-3:
  - Ultra-thin (20 μm to 40 μm), wafer-scale **HV-CMOS** Monolithic Active Pixel Sensor.
  - 65 nm technology, chip size 280 x 94 mm^2, stitched,
  - 0.5 ‰ X_0 per layer, <5 μm resolution
  - **Flexible!** Bent around beampipe.

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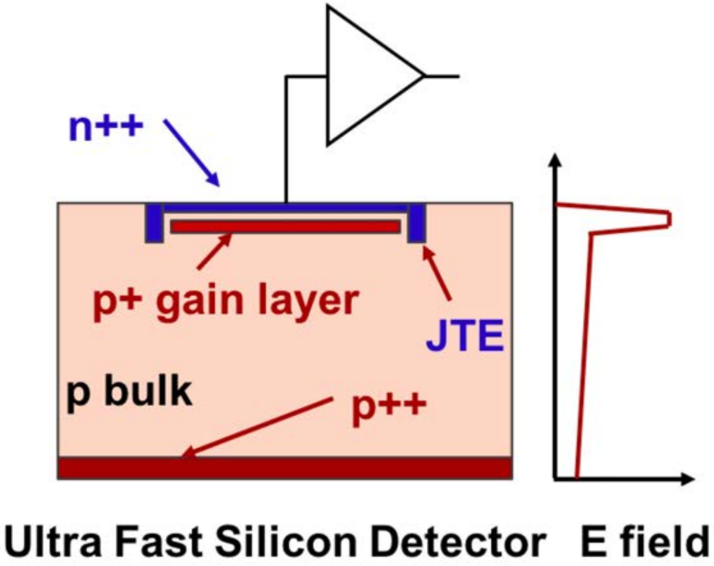
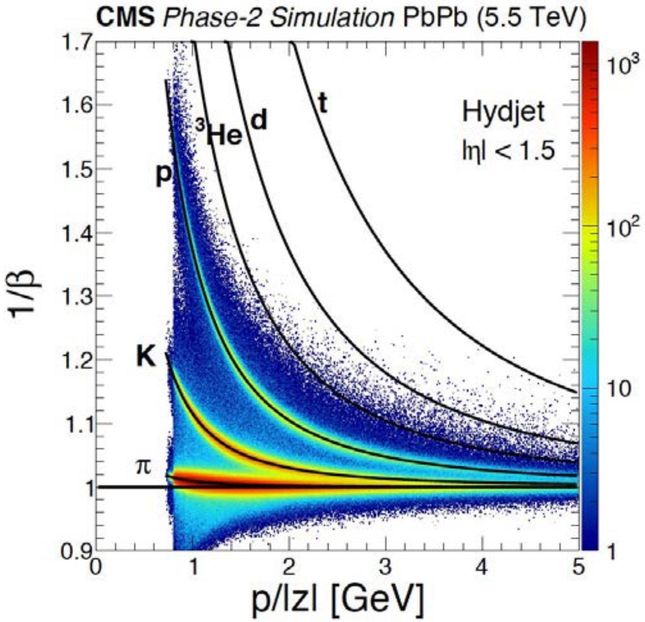
Higher Dimensions

- Increase information output and move functionality as close to sensor

Low-Gain Avalanche Diode **(LGAD)**:

- Silicon-based, with moderately doped p-implant gain layer (~ x20)
- E ~ 300 kV/cm
- Excellent position and timing resolution $\sigma(x) < 5\ \mu m$, **$\sigma(t)$ ~ 30 ps**

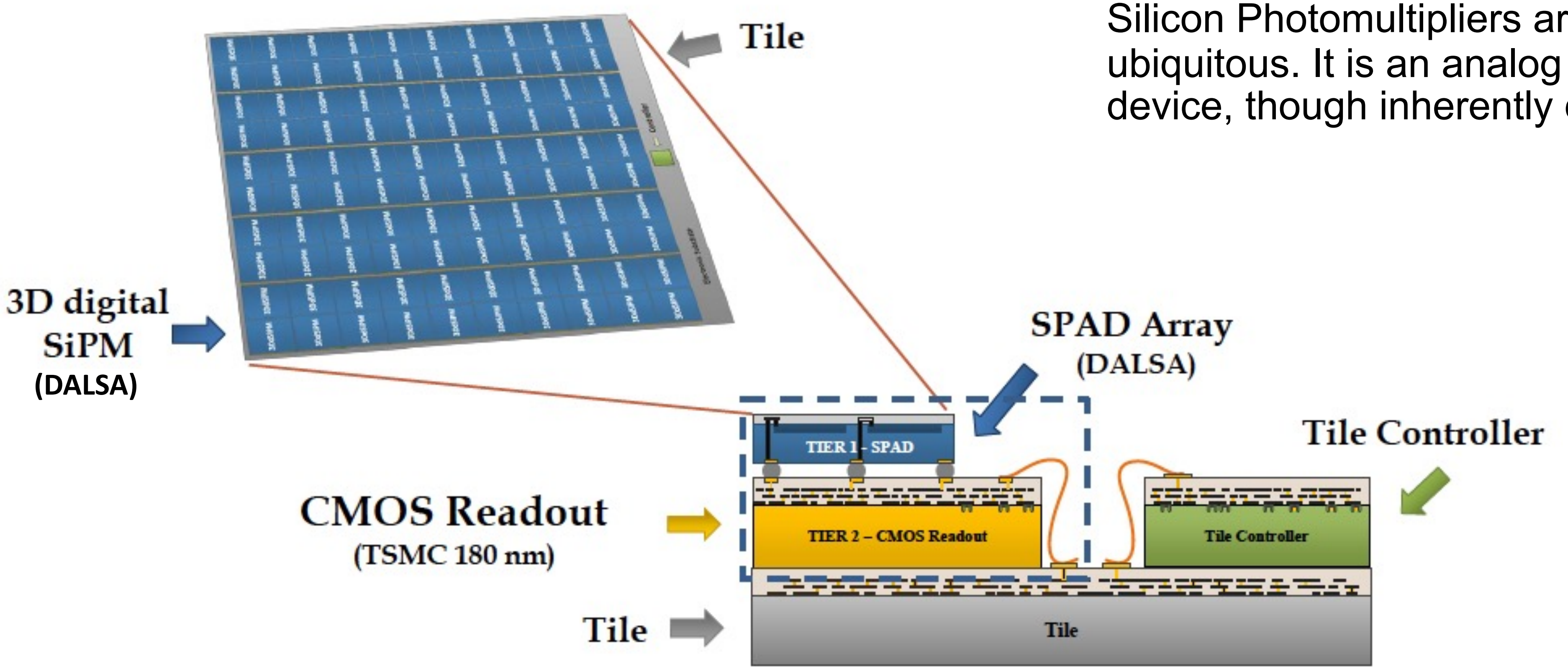




- Timing information for vertex association, particle identification, …
- Increased granularity and complexity demands increased processing power

Higher Dimensions

Silicon Photomultipliers are ubiquitous. It is an analog device, though inherently digital



Sherbrooke

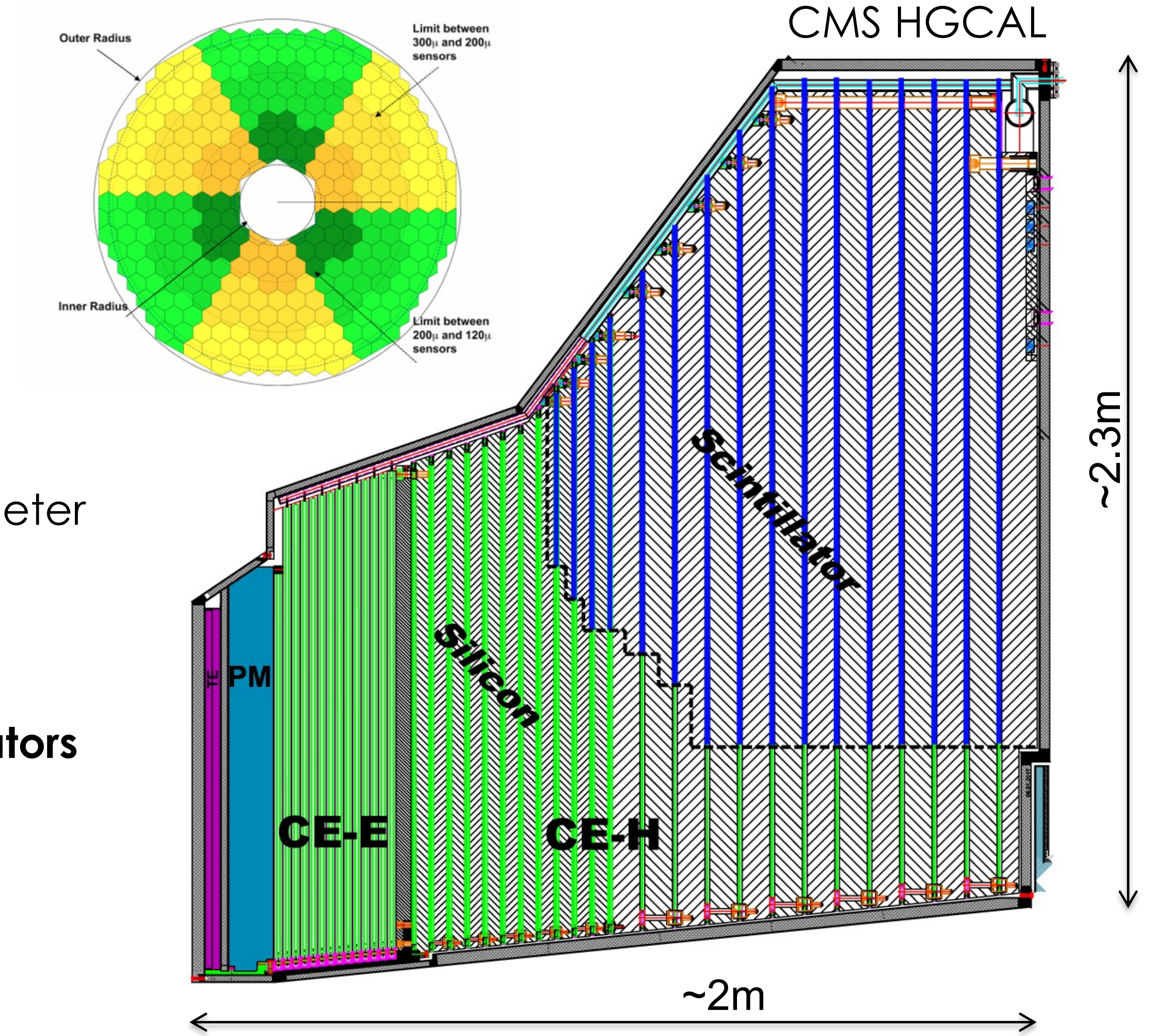
- Integrate the Single-Photon Avalanche Diode (SPAD) array directly to CMOS front-end readout at the wafer level.

Calorimetry

- Obtain the best energy resolution, preferably of all particles separately

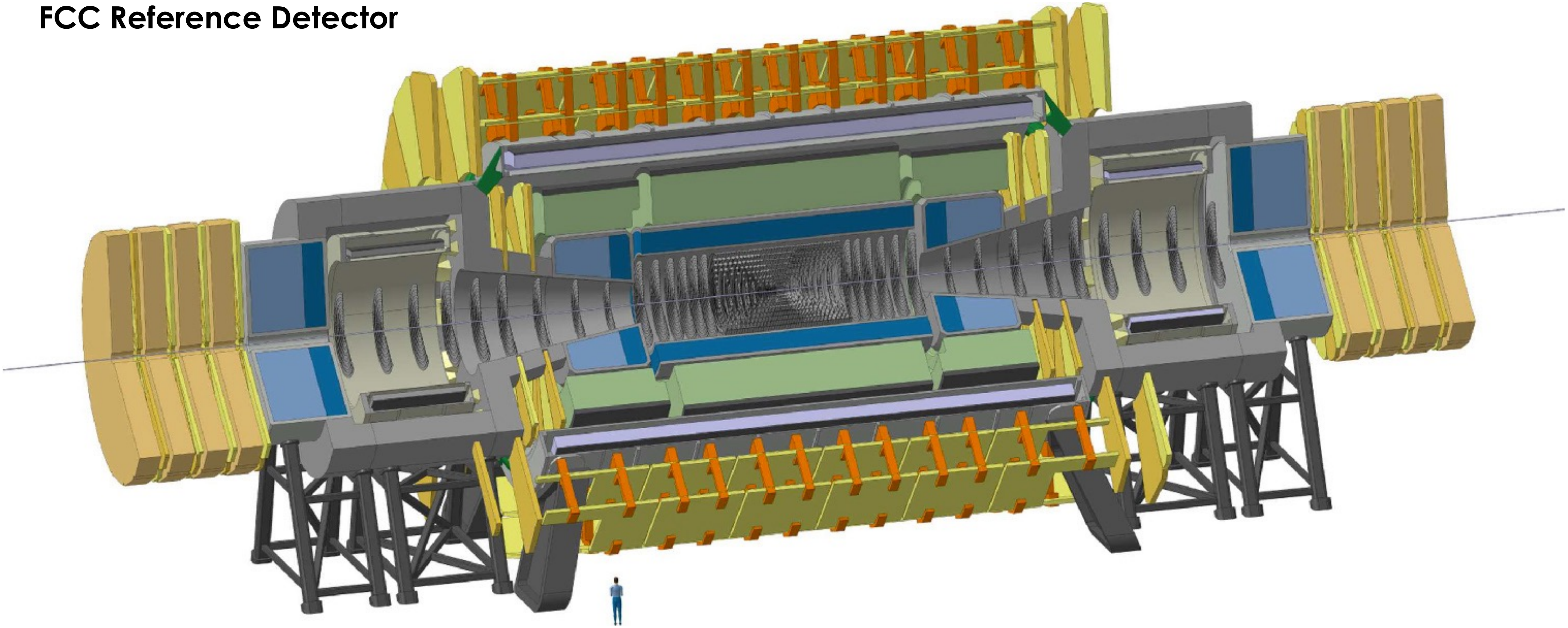
- **Imaging calorimetry**
  - Charged particle measured in tracker
  - γ: by EM Calorimeter
  - Neutral hadron: by EM and Hadron Calorimeter

- CMS High-Grained Calorimeter
  - **~640m² of silicon sensors, ~370m² of scintillators**
  - 6.1M Si channels, 0.5 or 1.1 cm² cell size
  - 240k scintillator tile channels (h-f)
  - Data readout from all layers
  - ~31,000 Si modules (incl. spares)



A Sense of Scale: 100 TeV

FCC Reference Detector



Eur. Phys. J. Special Topics 228, 755{1107 (2019)

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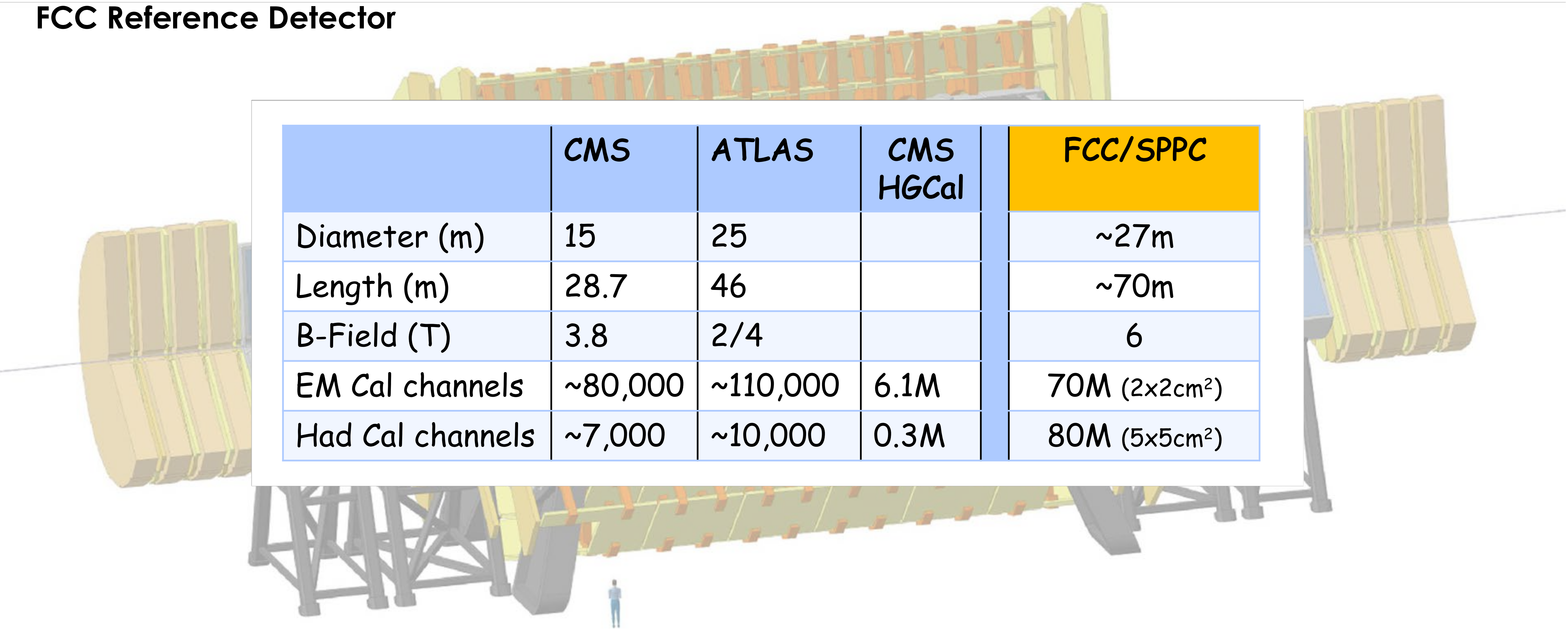

	CMS	ATLAS	CMS HGCal	FCC/SPPC
Diameter (m)	15	25		~27m
Length (m)	28.7	46		~70m
B-Field (T)	3.8	2/4		6
EM Cal channels	~80,000	~110,000	6.1M	70M (2x2cm^2)
Had Cal channels	~7,000	~10,000	0.3M	80M (5x5cm^2)

- Simply scaling CMS High-Grained calorimeter would require >5,000 m^2 of silicon

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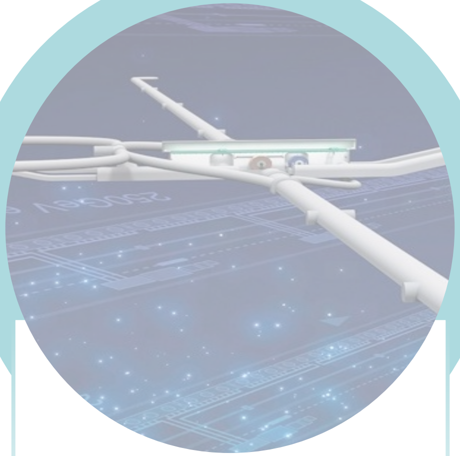
Science Technologies Will Play a Pivotal Role



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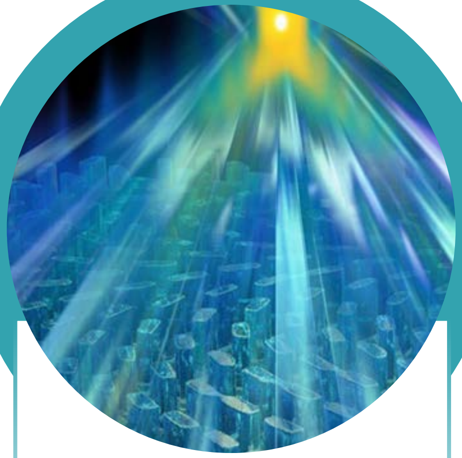

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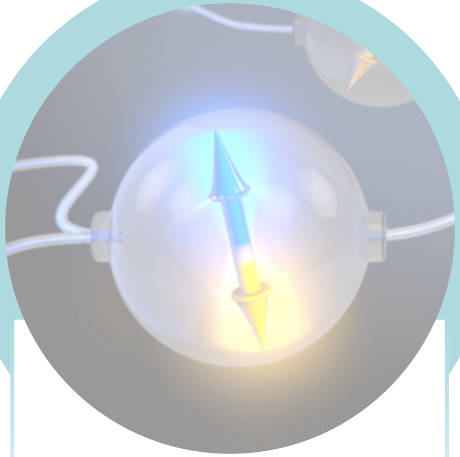

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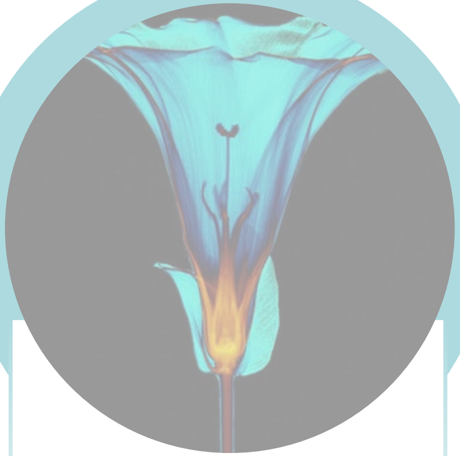

R&D That Inspires

Applying the techniques to other areas of science

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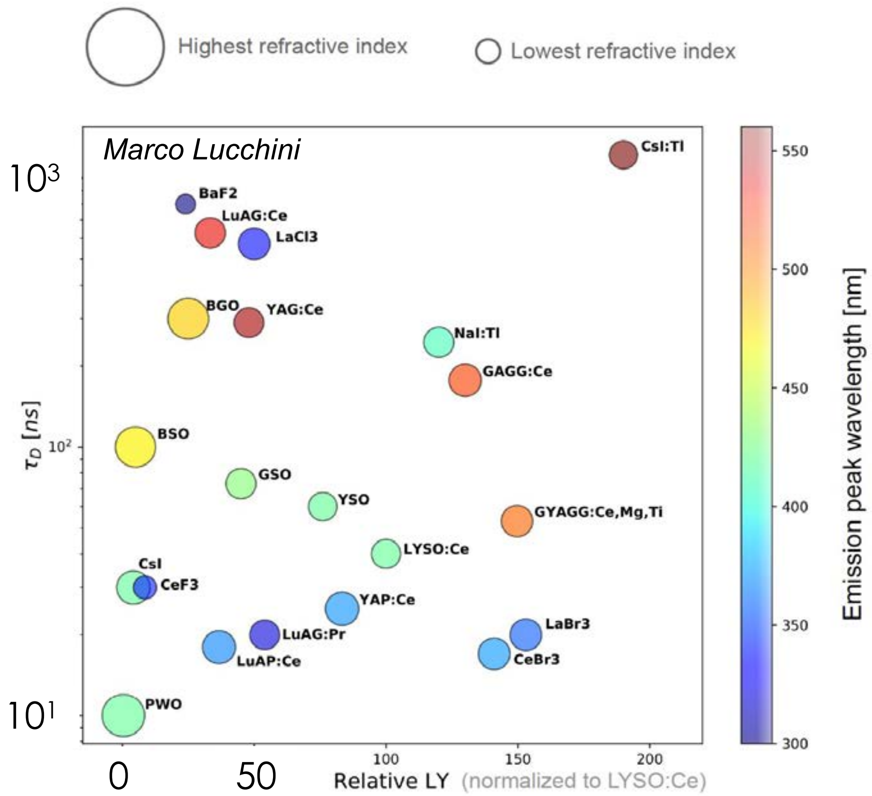
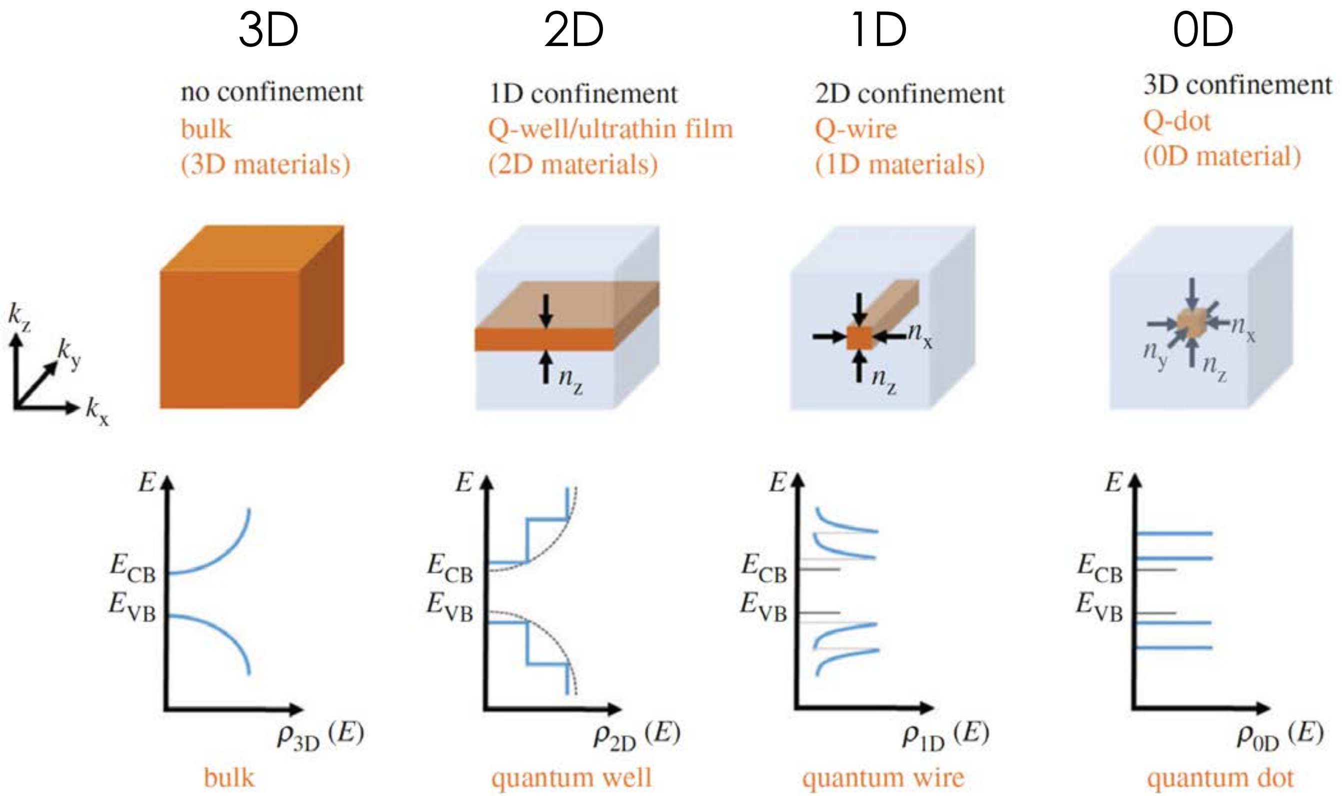
Crystal Calorimetry

- Traditionally, crystal – fully absorbing – calorimetry has obtained the best energy resolution





rsos.royalsocietypublishing.org R. Soc. open sci. 5: 180387

- Huge range of possibilities through **quantum engineering** of materials

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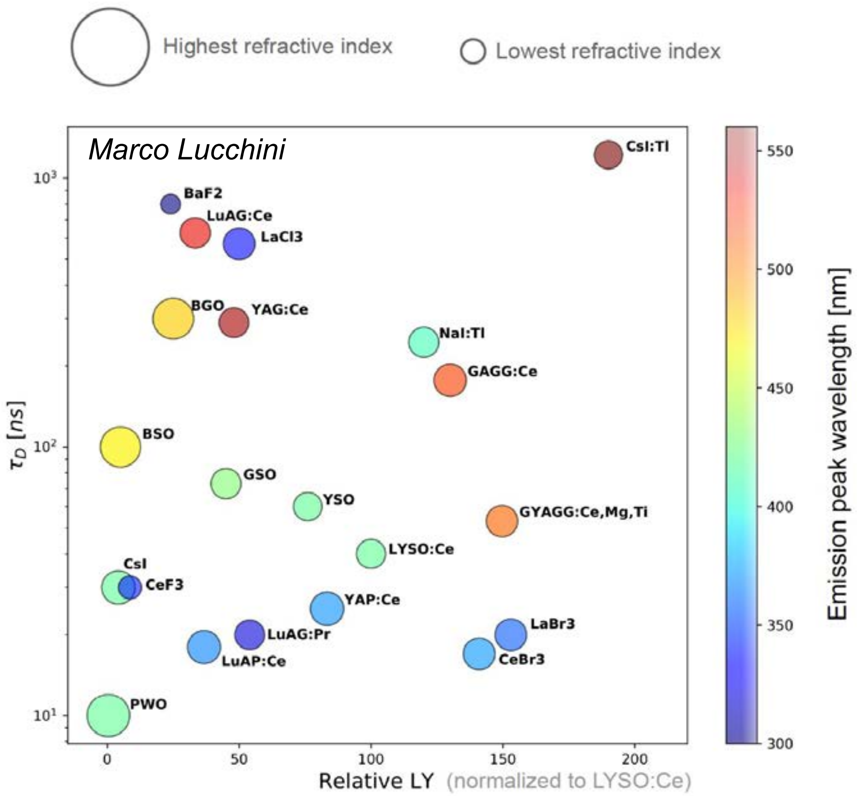
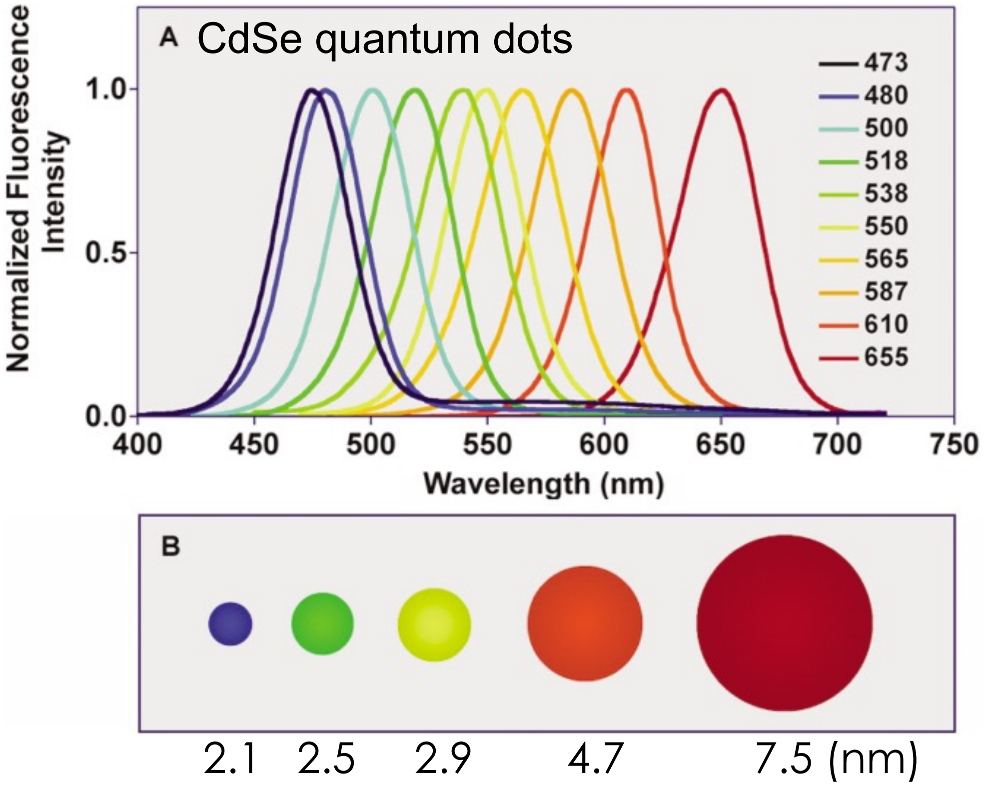


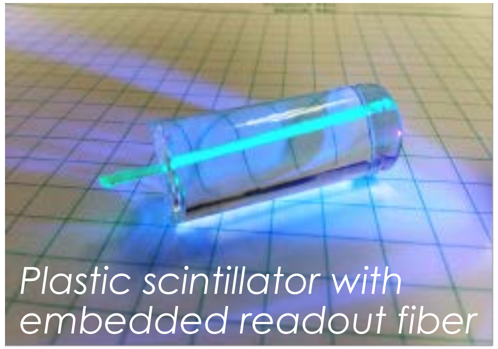


A. Smith, https://doi.org/10.1039/B404498N

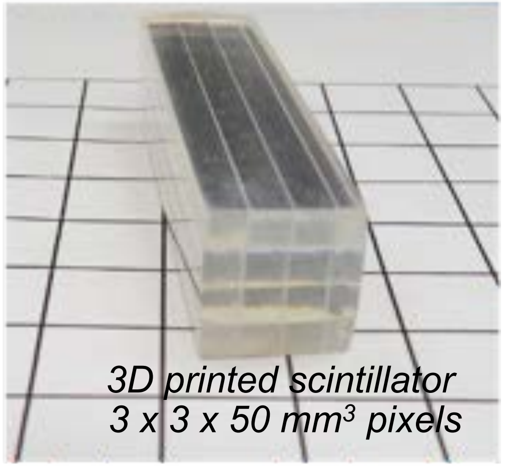
- Huge range of possibilities through **quantum engineering** of materials

Creation of Scintillators with Light

- Light-based **3D Stereolithography** (SLA):
  - Part is produced layer-by-layer from a liquid resin vat using just light
  - Near contactless manufacturing! Background free!
  - Significantly better optical properties than Fused Deposition Modeling
- Photocurable resins allows using UV or visible light:
  - Curing time from seconds to hours; large-scale production
  - Can be performed at room temperature
  - Resin formulations allows for embedding
- Can build **Optically Active** structural materials:
  - Polyethylene naphthalate (PEN) shifts 128 nm LAr scintillation light to ~440 nm and scintillates
  - Yield strength higher than copper at cryogenic temperatures



Plastic scintillator with embedded readout fiber



3D printed scintillator
3 x 3 x 50 mm^3 pixels

Low mass detector holder design under UV illumination (LEGEND)

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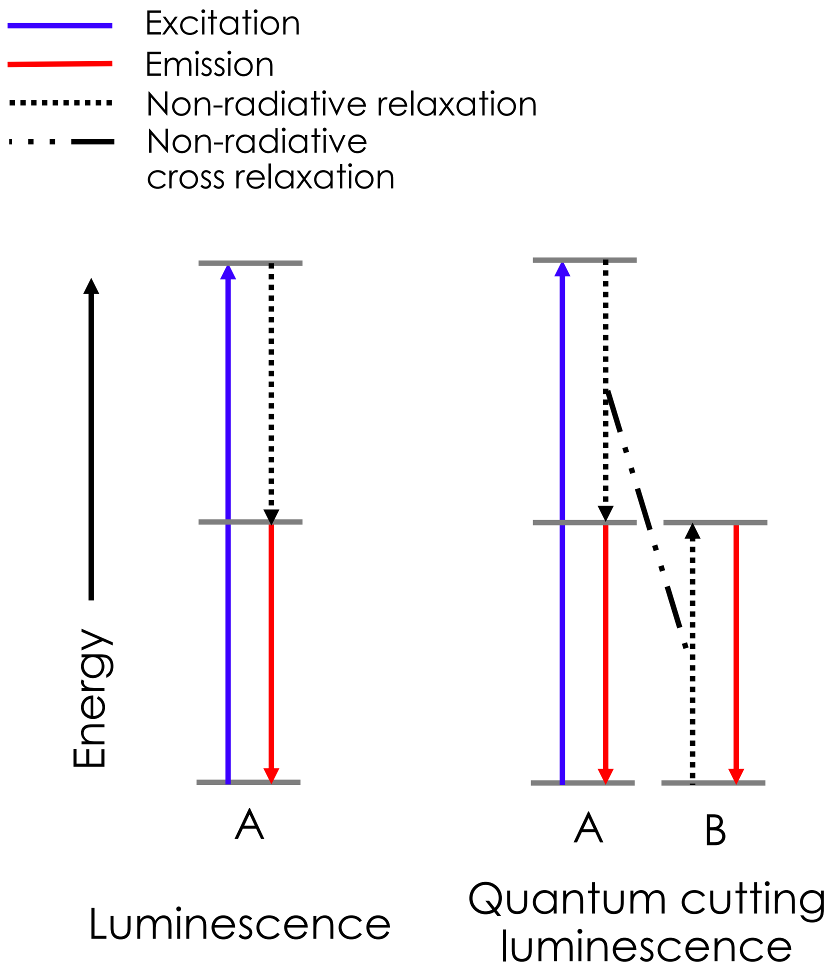
"Quantum amplification" – VUV to VIS



- Quantum Cutting Luminescence (QCL)
  - Two-photon luminescence process
  - Convert high energy photon to two low energy photo
  - Quantum efficiency > 100% possible

Visible Quantum Cutting in $LiGdF_4:Eu^{3+}$ Through Downconversion

René T. Wegh, Harry Donker, Koenraad D. Oskam, Andries Meijerink*
+ See all authors and affiliations

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Vol. 283, Issue 5402, pp. 663-666
DOI: 10.1126/science.283.5402.663

THE JOURNAL OF PHYSICAL CHEMISTRY C Article
pubs.acs.org/JPCC

High Efficiency Green Phosphor $Ba_9Lu_2Si_6O_{24}:Tb^{3+}$: Visible Quantum Cutting via Cross-Relaxation Energy Transfers

Yongfu Liu,[*,†] Jianxin Zhang,[†,‡] Changhua Zhang,[†,§] Jun Jiang,[*,†] and Haochuan Jiang[*,†]
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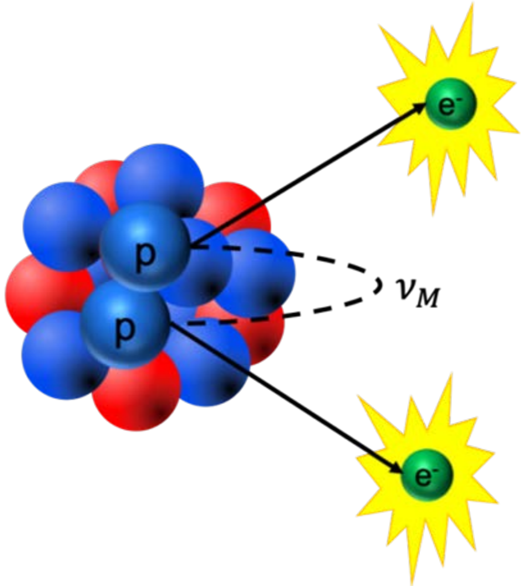
[‡]College of Electronic Information and Engineering, Hangzhou Dianzi University, Hangzhou 310018, China
[§]Department of Chemistry, College of Science, Shanghai University, Shanghai 200444, China

Traditional phosphors	**QE ~90%**
$LiGdF_4:Eu^{3+}$	**QE 190%**
$BaF_2:Gd^{3+},Eu^{3+}$	**QE 194%**

Neutrinoless Double Beta Decay (0νββ)

- The discovery of 0νββ decay would dramatically revise our foundational understanding of physics and the cosmos.



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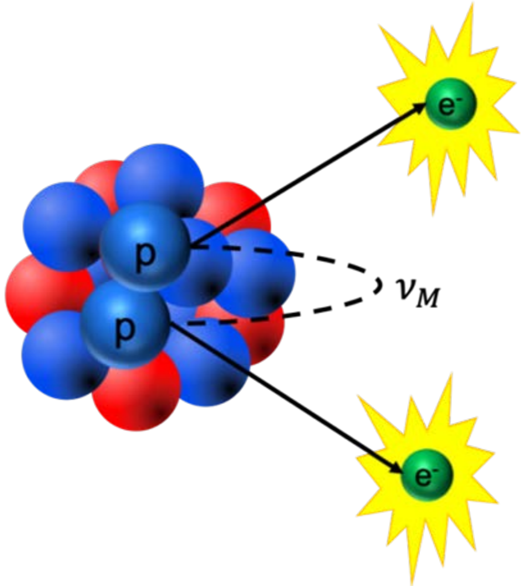


Nuclides

- ^{48}Ca ($Q_{\beta\beta}$ = 4.271 MeV)
- ^{76}Ge ($Q_{\beta\beta}$ = 2.040 MeV)
- ^{82}Se ($Q_{\beta\beta}$ = 2.995 MeV)
- ^{96}Zr ($Q_{\beta\beta}$ = 3.350 MeV)
- ^{100}Mo ($Q_{\beta\beta}$ = 3.034 MeV)
- ^{116}Cd ($Q_{\beta\beta}$ = 2.802MeV)
- ^{130}Te ($Q_{\beta\beta}$ = 2.533 MeV)
- ^{136}Xe ($Q_{\beta\beta}$ = 2.479 MeV)
- ^{150}Nd ($Q_{\beta\beta}$ = 3.667 MeV)

Detector technologies

- (scintillating) crystal at low T
- Semiconductor
- loaded scintillating liquid
- time projection chamber
- tracking detectors
- Solid scintillators

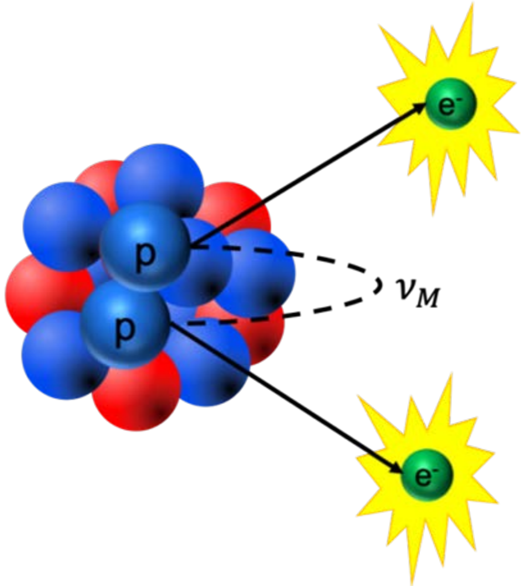
On-going R&D

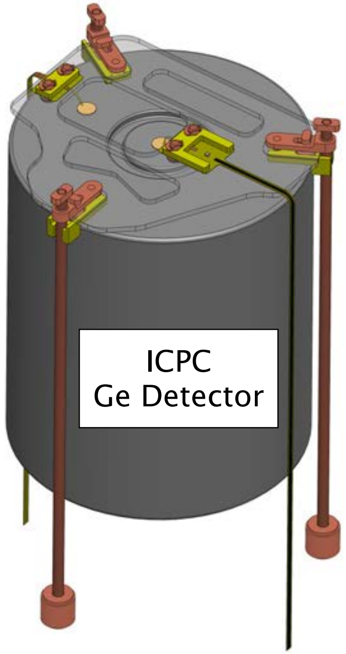
- Isotope enrichment – large active mass
- Increase energy resolution for larger detectors
- background reduction - particle discrimination

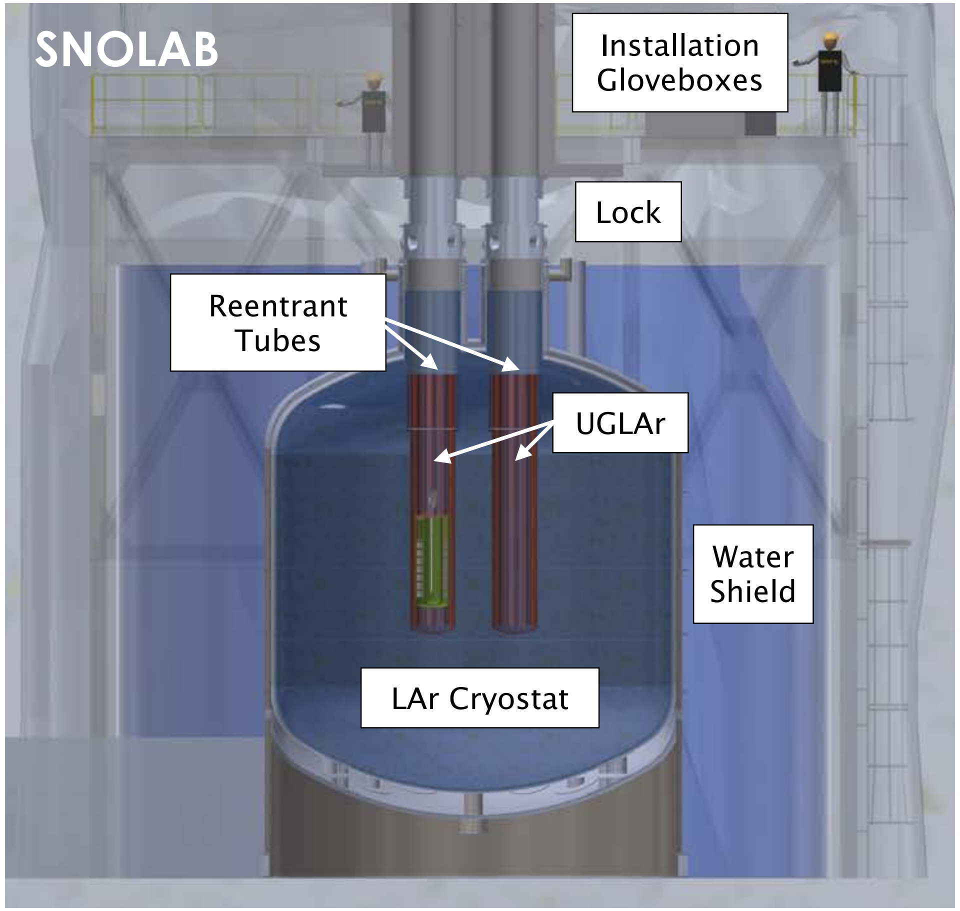
From Loredana Gastaldo

0νββ using ^{76}Ge

- The discovery of 0νββ decay would dramatically revise our foundational understanding of physics and the cosmos.







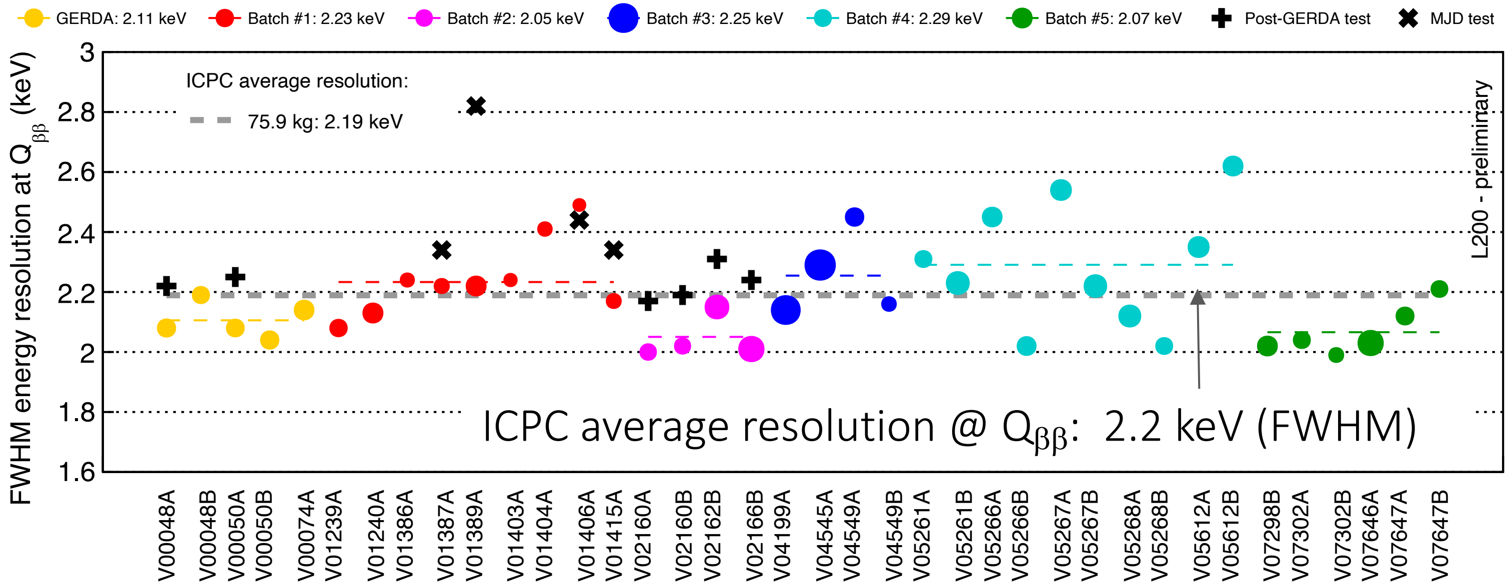
ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar

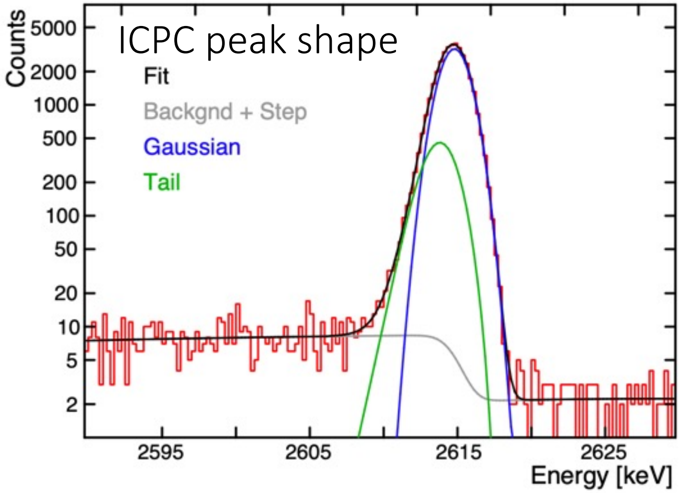
Quasi-background-free[1] search for 0νββ decays of ^{76}Ge at $Q_{\beta\beta}$ = 2039.06 keV

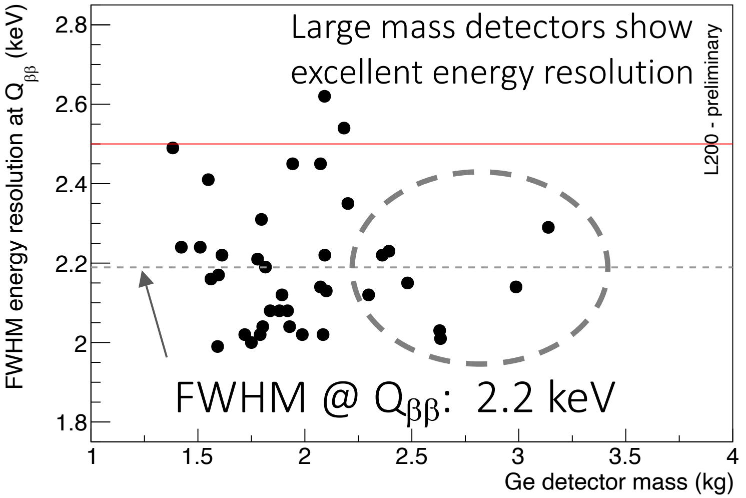
[1] Expected number of background counts is much lower than 1 in the FWHM at full exposure

Germanium Detector Innovation

- Germanium:
  - Superb energy resolution: **σ / $Q_{\beta\beta}$ = 0.05 %**
  - background goal: **0.025 counts/(FWHM t y)**
  - Background Index: < 1×10^{-5} counts/keV kg yr

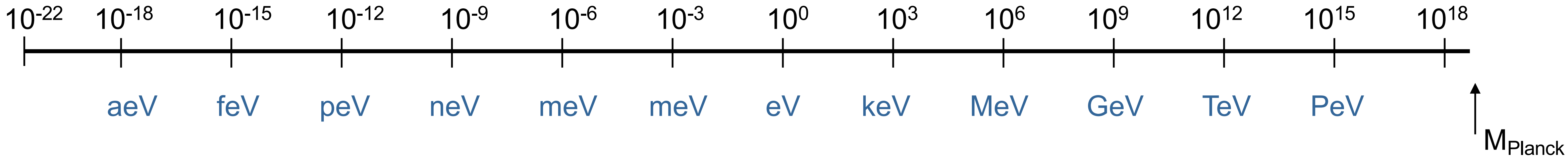






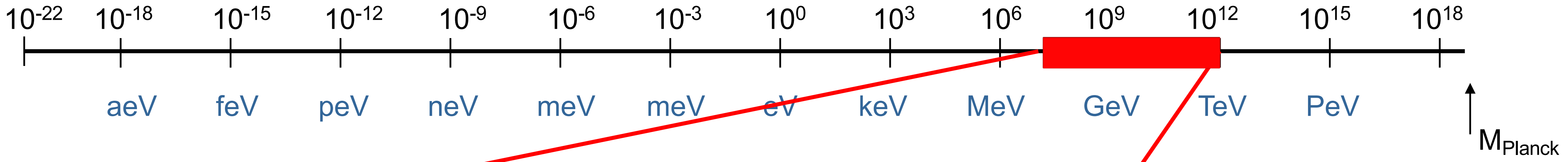
OAK RIDGE National Laboratory

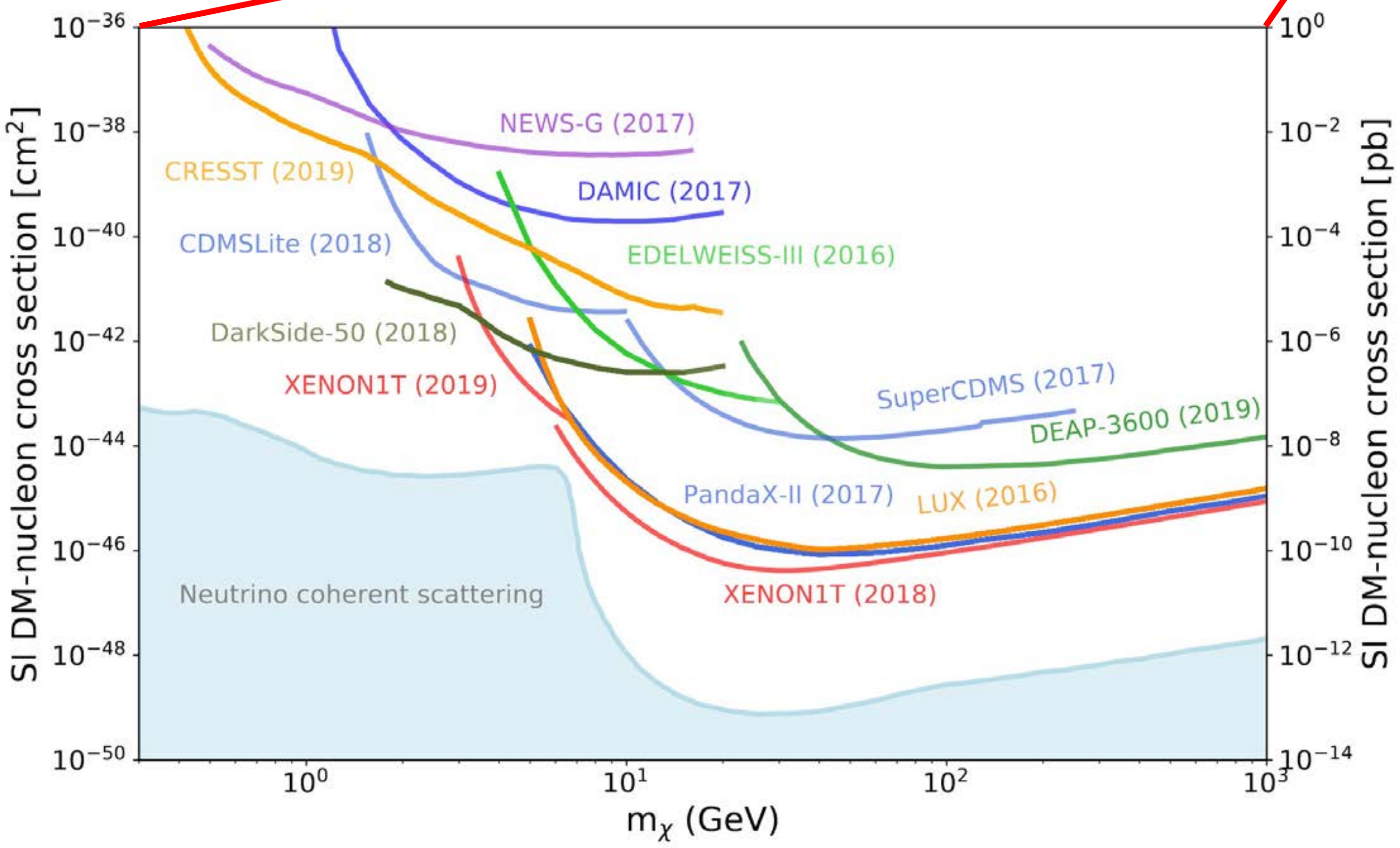
Dark Matter Searches



- The mass range for dark matter is in principle unconstrained
- Weakly Interacting Massive Particles were a favorite model

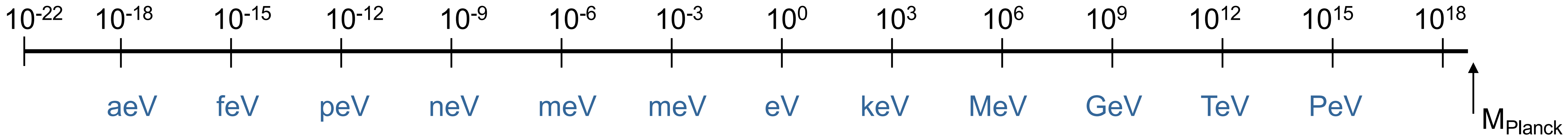
Dark Matter Searches





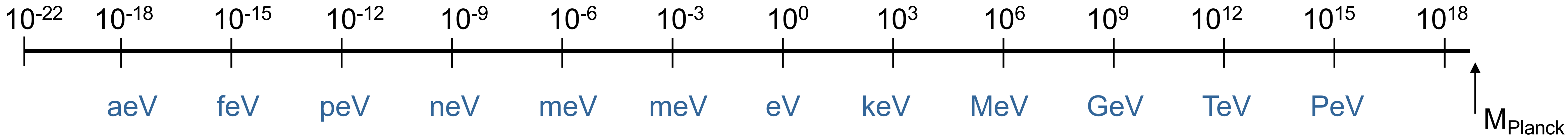
Particle Data Group, 2020
http://pdg.lbl.gov/

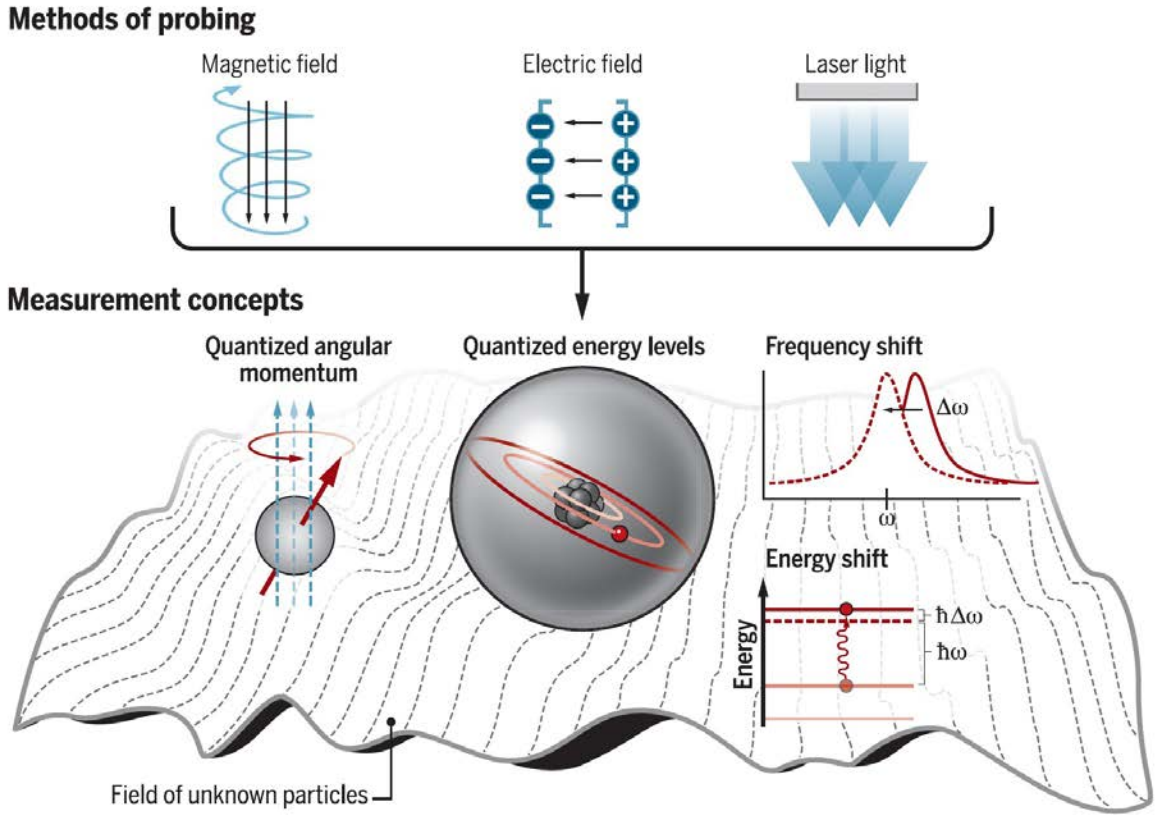
Dark Matter Searches

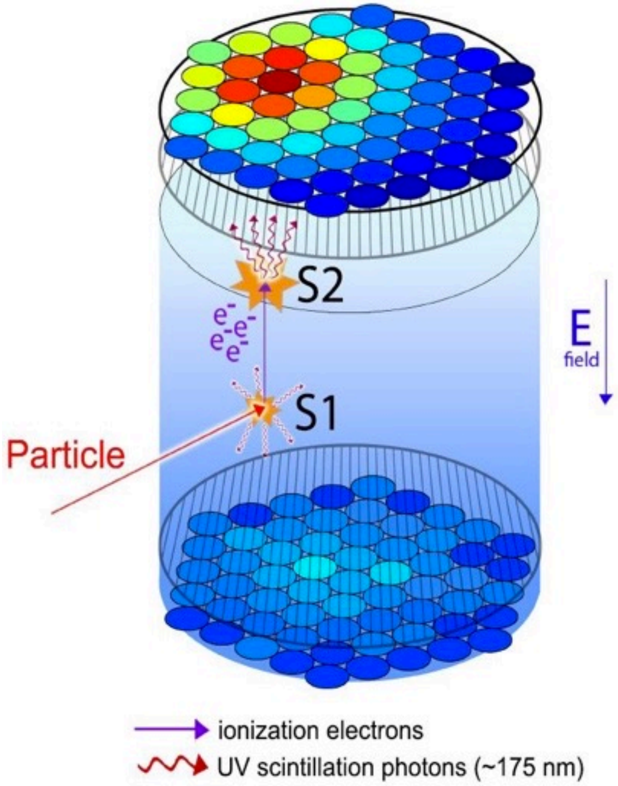


Fields / Bosons	Particles / Fermions	Composite →
Axions Axion Like Particles Fuzzy dark matter	Thermal dark matter WIMPS Dark Sectors	black hole remnants WIMPZillas

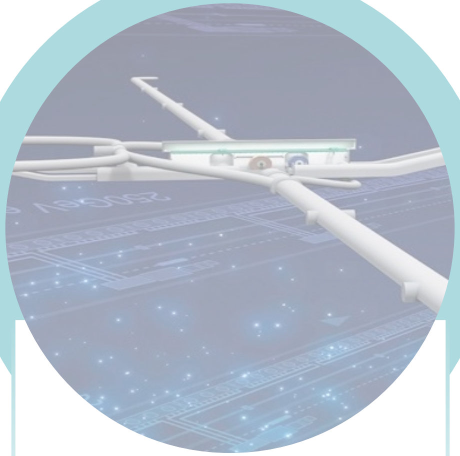
Dark Matter Searches





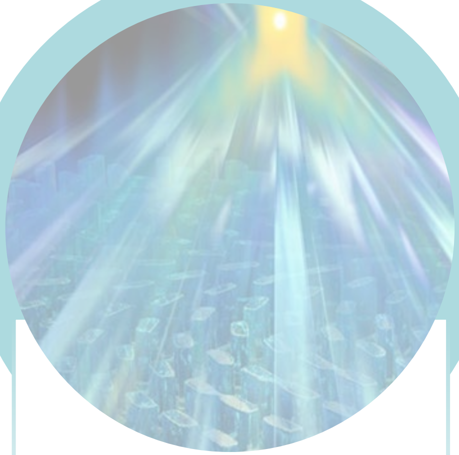


Science Technologies Will Play a Pivotal Role



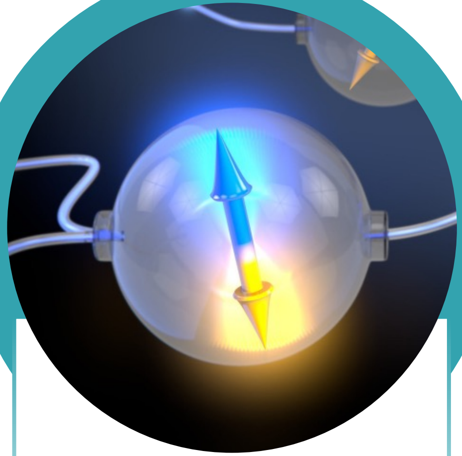
Directed R&D

Aimed at realizing high-priority projects



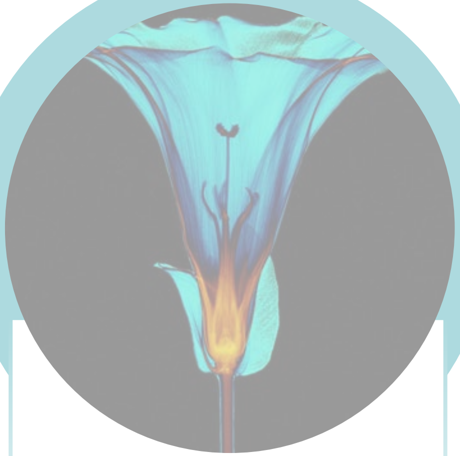
Generic R&D

Aimed at developing new methodologies and techniques, adopting emerging technologies



Inspired R&D

Building on emerging technologies and advances in industry and other science disciplines

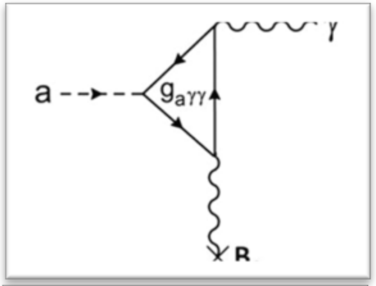


R&D That Inspires

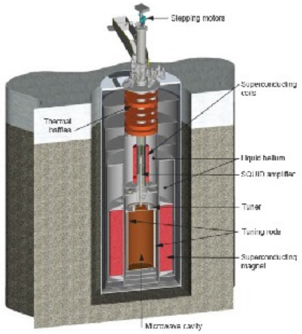
Applying the techniques to other areas of science

Axions or Axion Like Particles

- Coupling to EM Fields: $\frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$



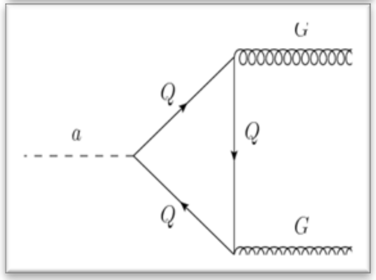
ADMX



Haystac

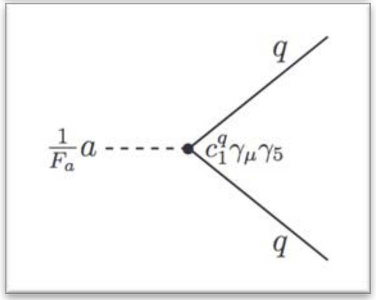
SHAFT,
CAST,
ALPS,
…

- Coupling to gluon fields: $\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$



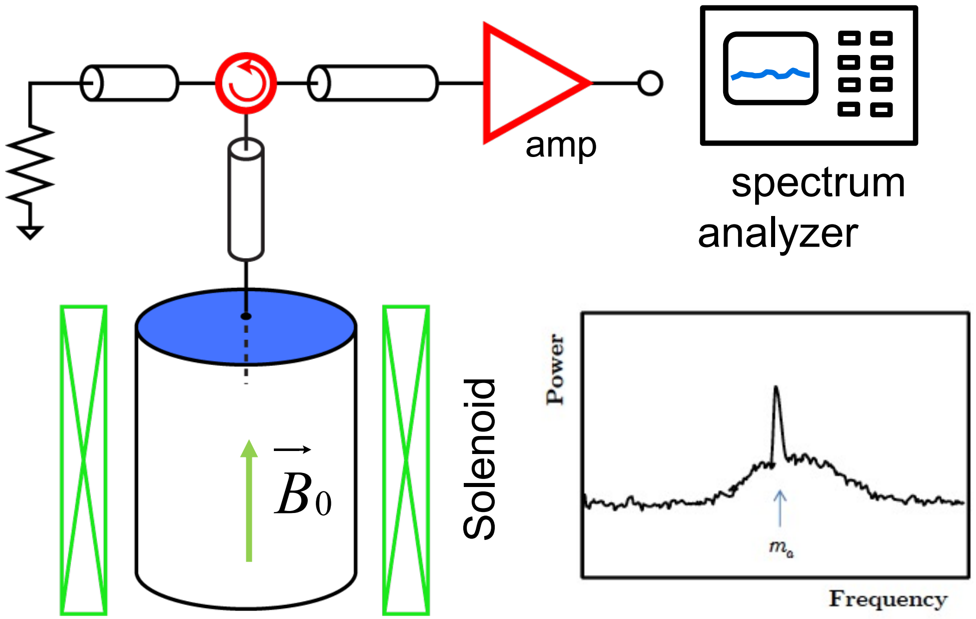
nEDM, CASPEr-electric, …

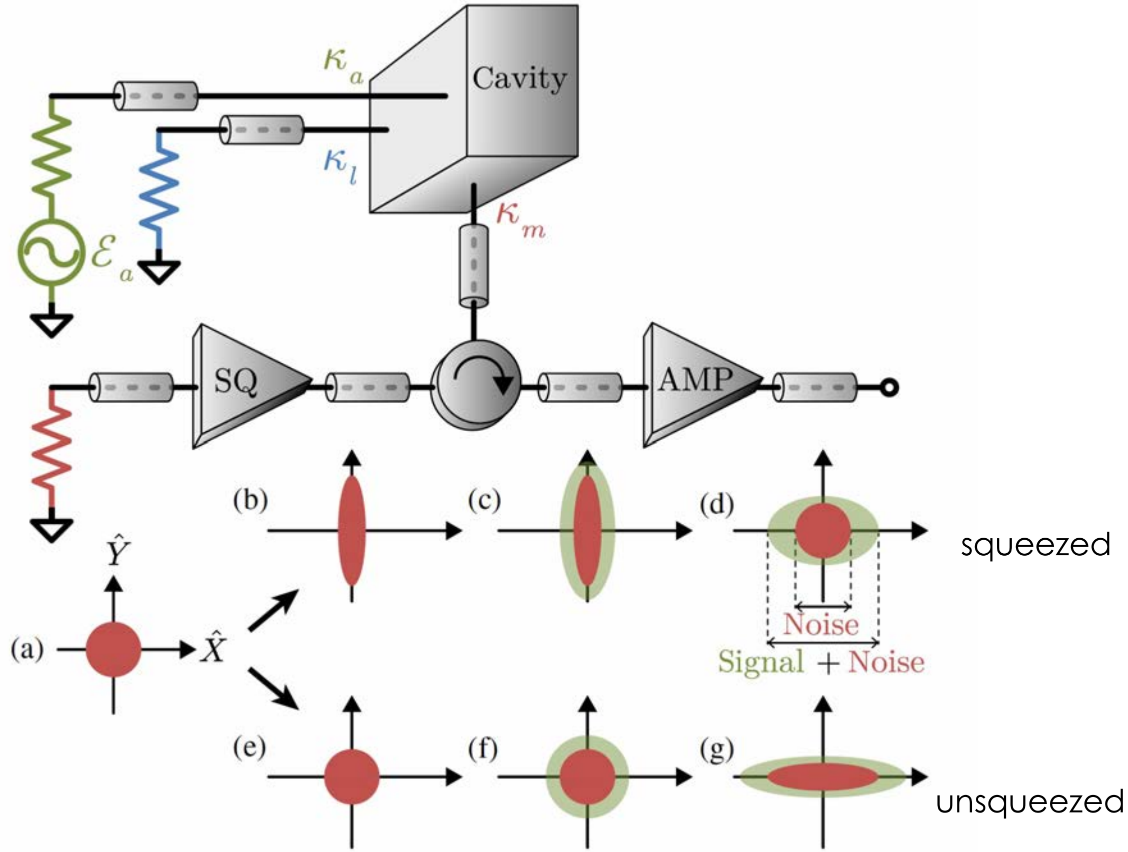
- Coupling to fermions: $\frac{\partial_\mu a}{f_a} \overline{\psi_f} \gamma^\mu \gamma_5 \psi_f$



CASPEr-gradient, ….

Advanced Quantum Techniques

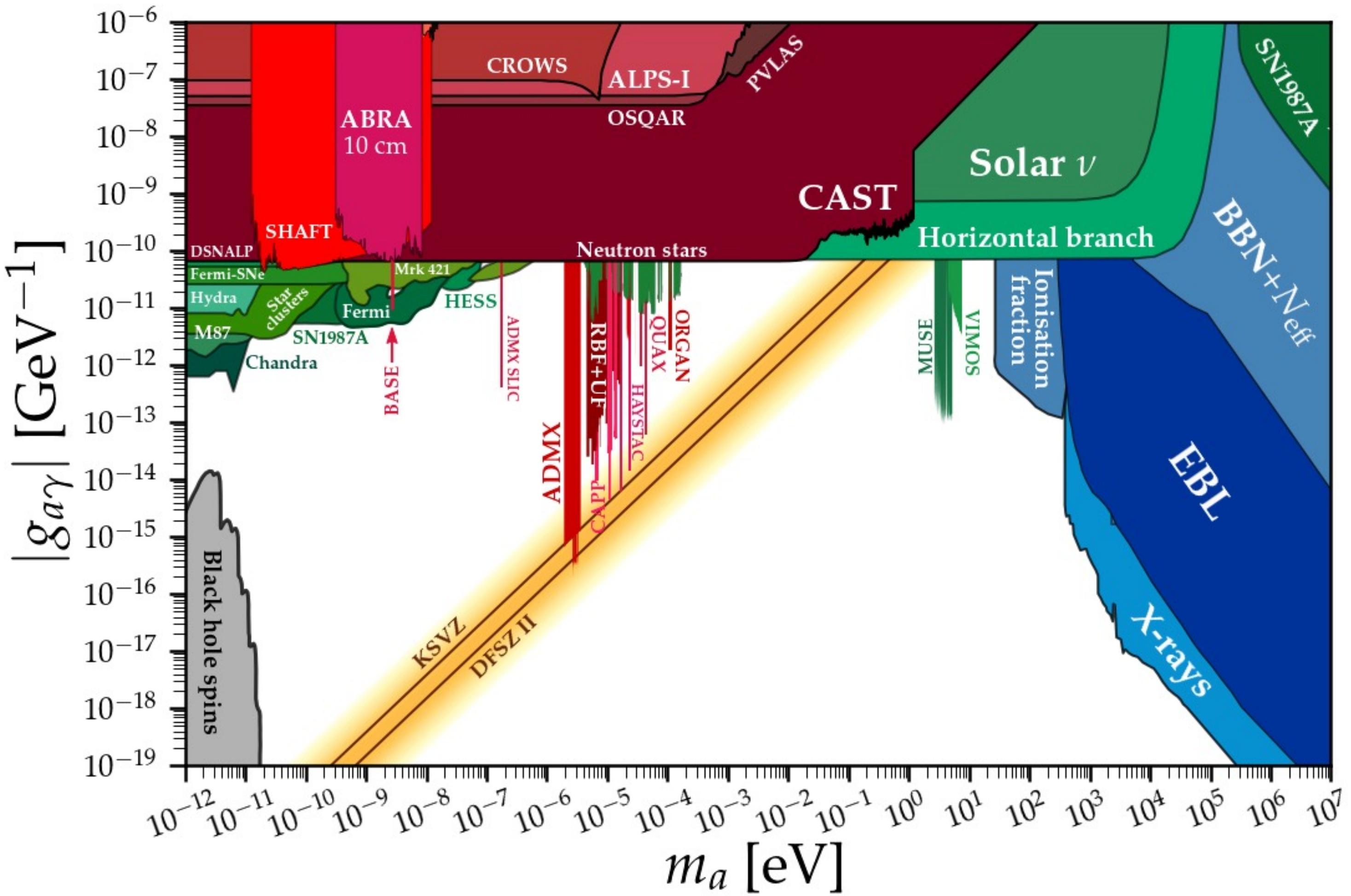




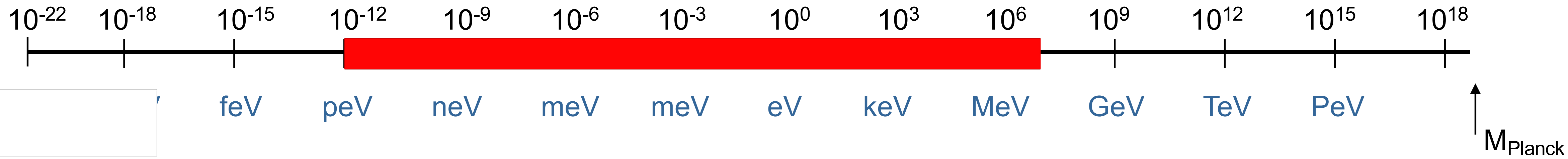
M. Malnou, Phys. Rev. X 10, 039902 (2020)

- By deploying a squeezed state received, comprised of two JPAs, which couple to incoming and outgoing modes at the cavity's measurement port, the spectral scan rate was increased by a factor of >2 !

Axions or Axion Like Particles

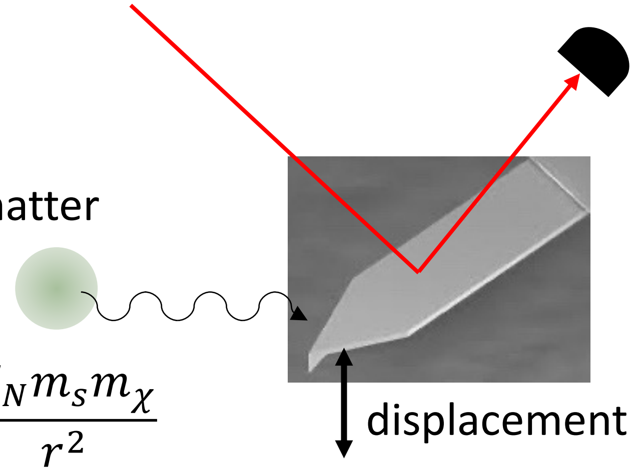


https://cajohare.github.io/AxionLimits/

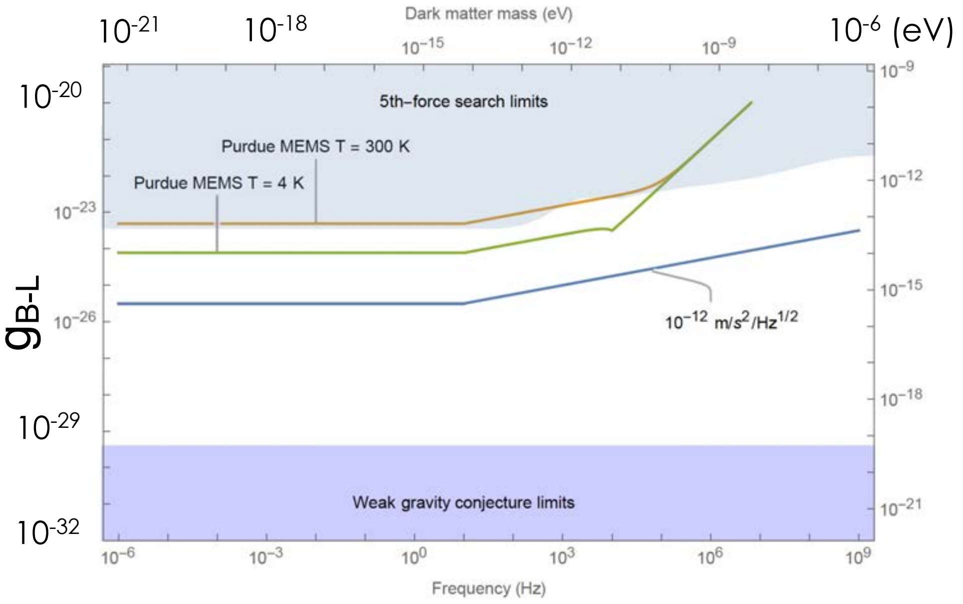


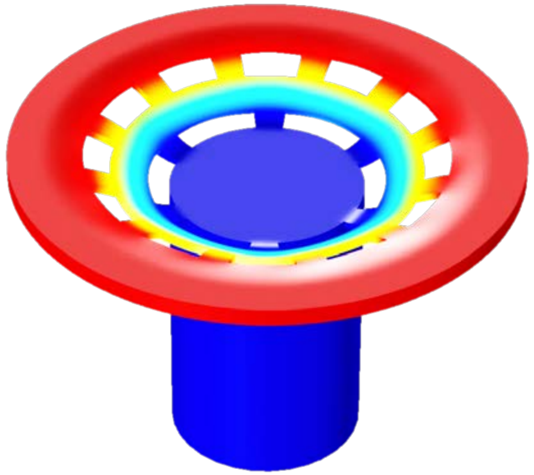
Gravitational Quantum Probe

- Gravitational coupling is the only guaranteed interaction channel for DM!
- Use Micro-electromechanical System (MEMS) technology
  - Bulk Silicon 70 mg accelerometer with soft tethers
  - Readout with dual squeezed light source



$$F = \frac{G_N m_s m_\chi}{r^2}$$





Test mass

Carney et al. 2021 Quantum Sci. Technol. 6 024002

Fundamental Constants and Quantum Sensors

- Clocks (atomic, nuclear, molecular, highly charged ions) measure with extreme precision atomic and molecular spectra

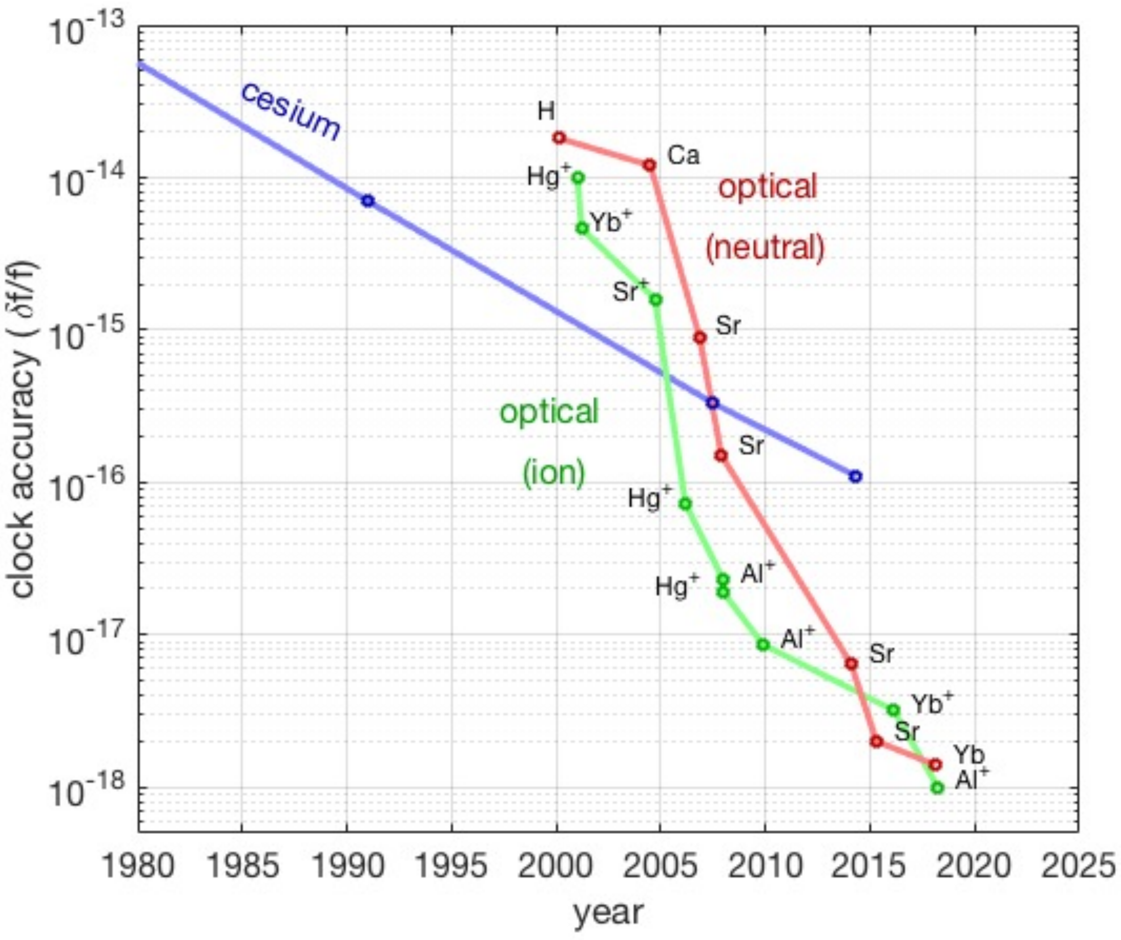
$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

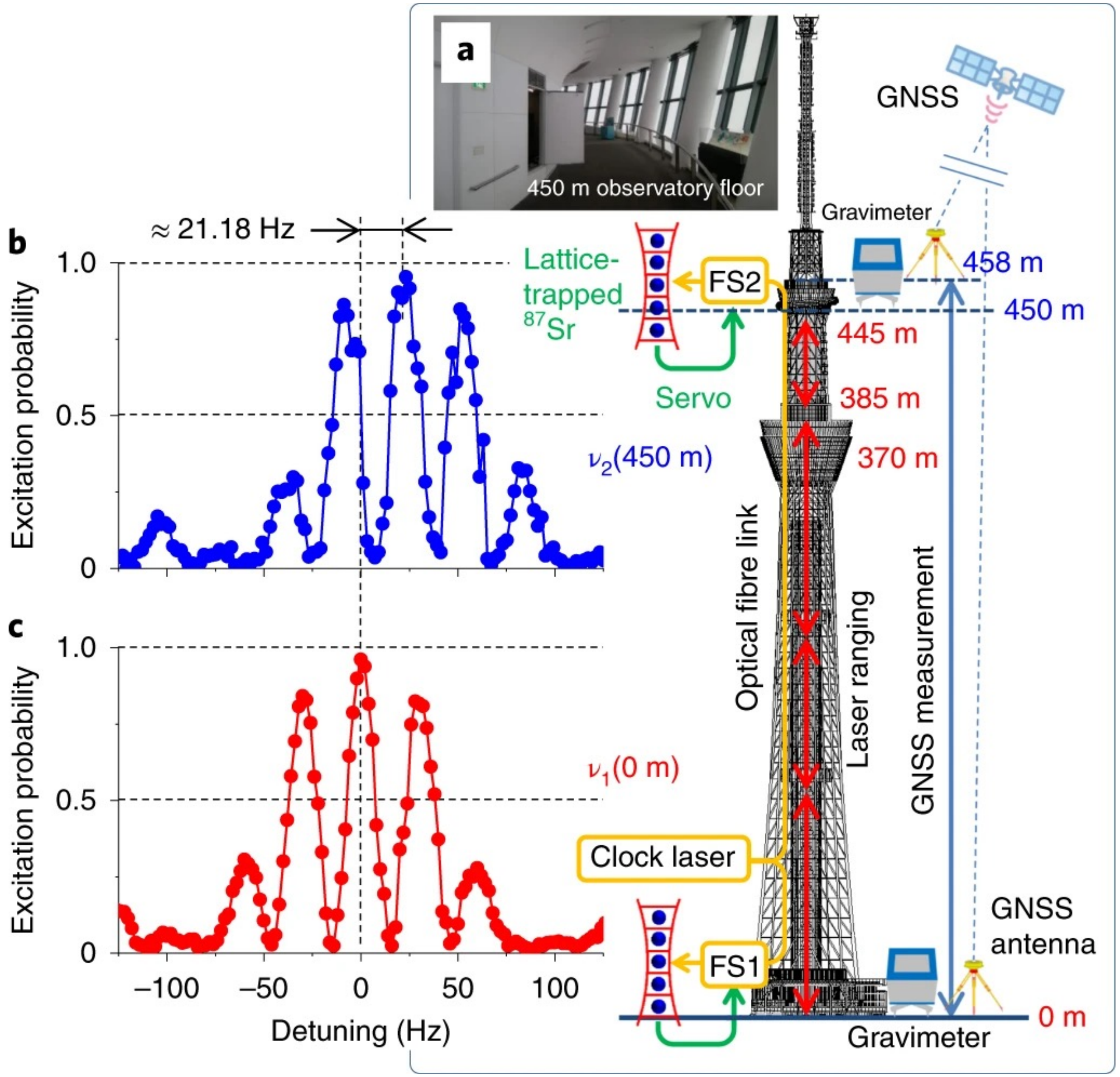
$$\mu = \frac{m_p}{m_e}$$

- Ionic, atomic and molecular systems could hold great promise in the search for new physics that is required to explain the observed universe and tests of fundamental symmetries.

https://www.nationalacademies.org/amo
Search for new physics with atoms and molecules, Rev. Mod. Phys. 90, 025008 (2018)

Gravitational Redshift

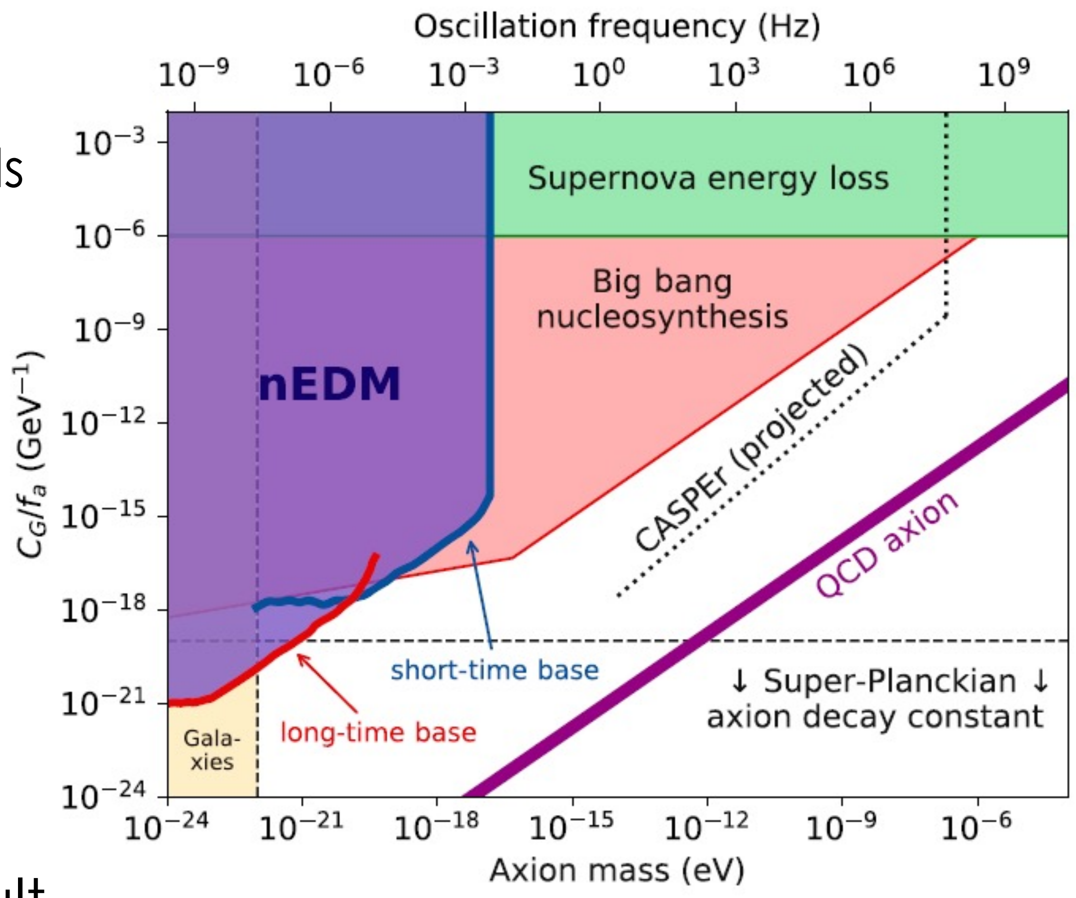




Takamoto et al., Nat. Phot. 14, 411 (2020)

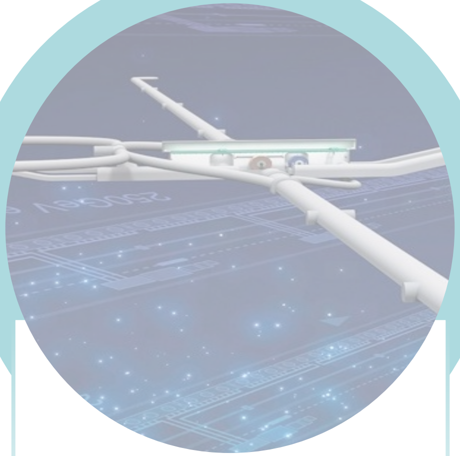
Ultra Cold Neutrons

- Ultra-cold neutrons (UCN) are neutrons, that are totally reflected from surfaces of suitable materials under all angles of incidence, hence storable: material traps, gravity and/or magnetic fields!
- Neutrons are an excellent probe to explore fundamental physics:
  - Neutrons are massive particles with spin
  - Neutrons are electrically neutral.
  - Neutrons only possess a tiny electric polarizability.
  - Neutrons are sufficiently long-lived (minutes)
- UCN Measurements are promising and difficult.



C. Abel, Phys. Rev. X 7, 041034

Science Technologies Will Play a Pivotal Role



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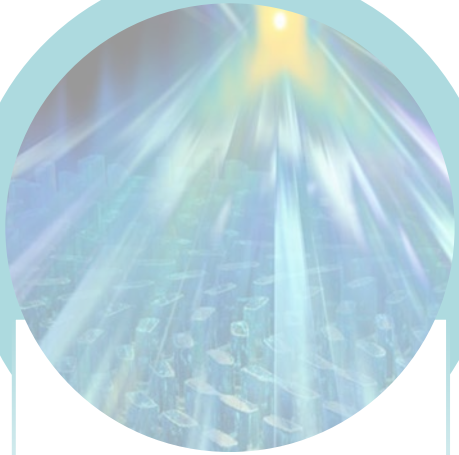

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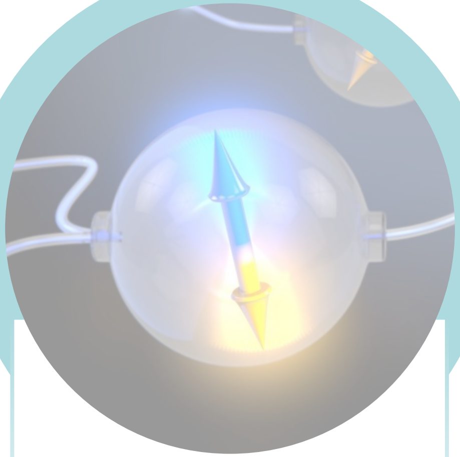
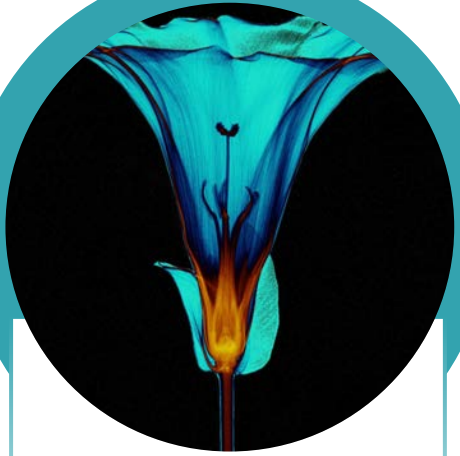


Inspired R&D

Building on emerging technologies and advances in industry and other science disciplines



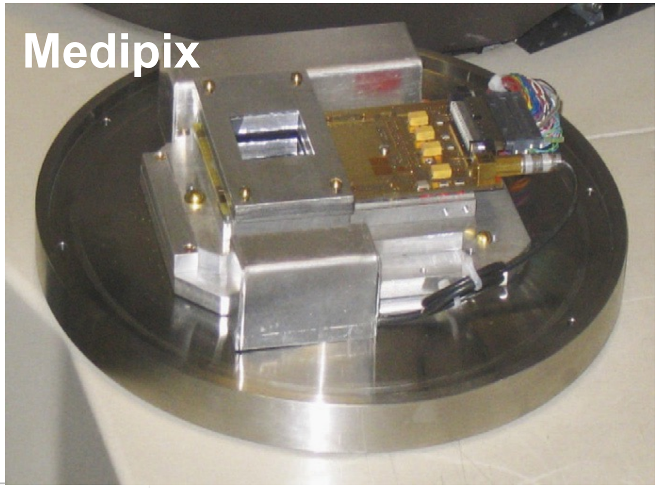
R&D That Inspires

Applying the techniques to other areas of science

R&D That Inspires: Advancing Cryo-Electron Microscopy

- The quest for obtaining the best image resolution of biological material avoiding sample damage and destruction by the electron beam
- Enter the development of the pixel chips for the LHC experiments and their evolution into the Medipix and Timepix families

CMOS node	**250 nm**
Pixel Array	**256 x 256**
Pixel pitch	**55 mm**
ENC	**110 e^{--}**
Minimum detectable charge	**~500 e^{-}**



Noiseless direct detection of electrons in Medipix2 for electron microscopy, *NIM* A546 (2005) 160–163
Direct electron detection methods in electron microscopy, *NIM A*513 (2003) 317-321

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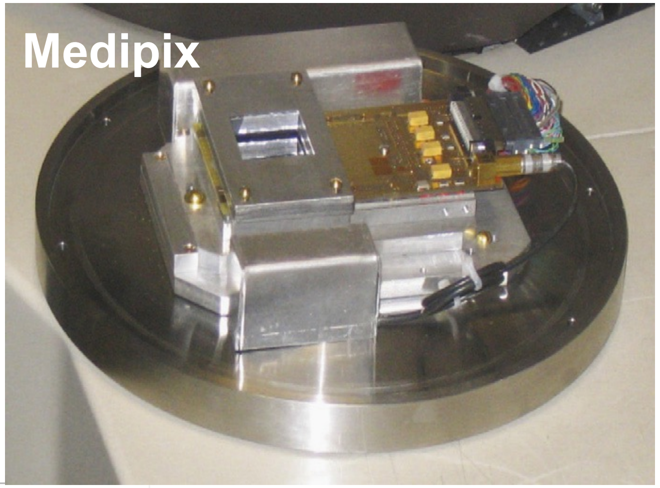
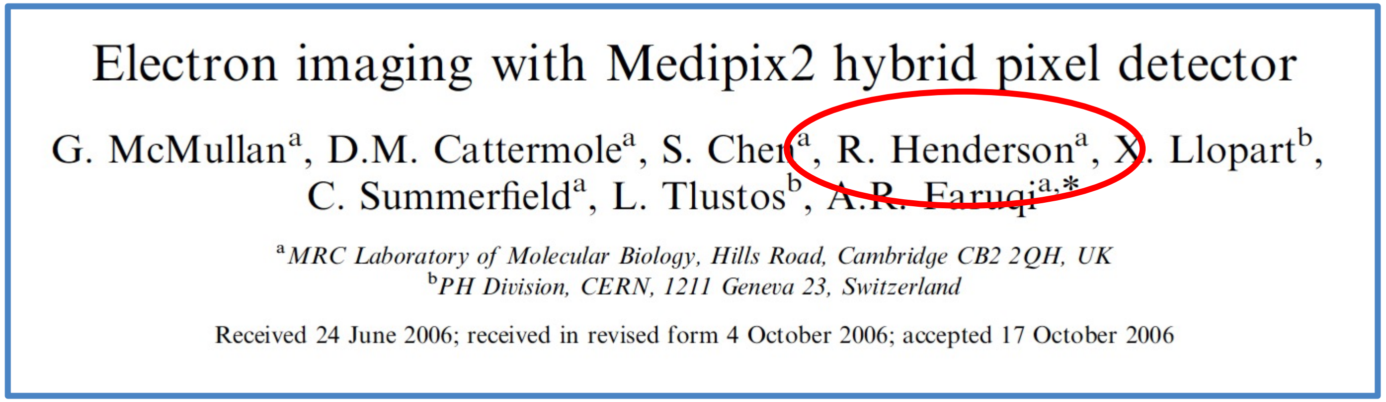



Electron imaging with Medipix2 hybrid pixel detector

G. McMullan[a], D.M. Cattermole[a], S. Chen[a], R. Henderson[a], X. Llopart[b], C. Summerfield[a], L. Tlustos[b], A.R. Faruqi[a,*]

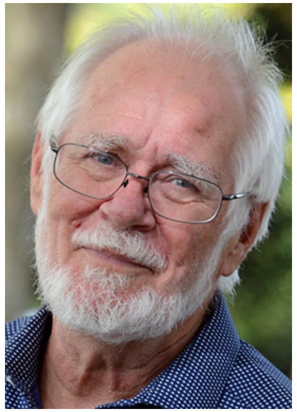
[a] *MRC Laboratory of Molecular Biology, Hills Road, Cambridge CB2 2QH, UK*
[b] *PH Division, CERN, 1211 Geneva 23, Switzerland*

Received 24 June 2006; received in revised form 4 October 2006; accepted 17 October 2006

Ultramicroscopy, **107** (2007) 401-413

Noiseless direct detection of electrons in Medipix2 for electron microscopy, *NIM* A546 (2005) 160–163
Direct electron detection methods in electron microscopy, *NIM A*513 (2003) 317-321

2017 Nobel Prize in Chemistry

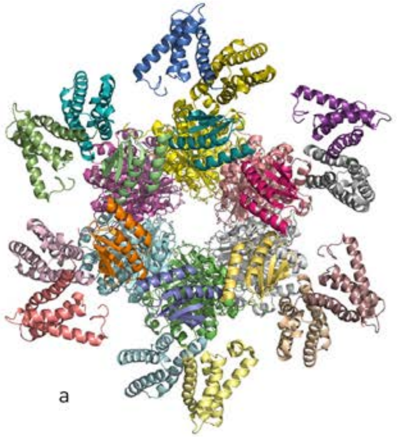


Jacques Dubochet
University of Lausanne

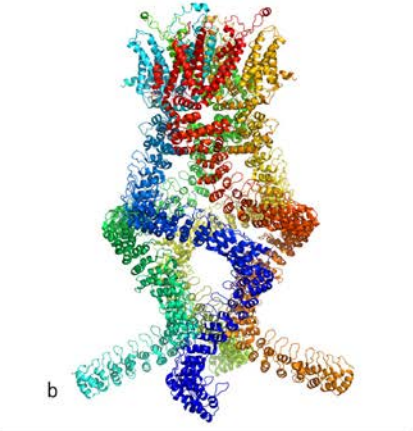
Joachim Frank
Columbia University

Richard Henderson
MRC Lab, Cambridge

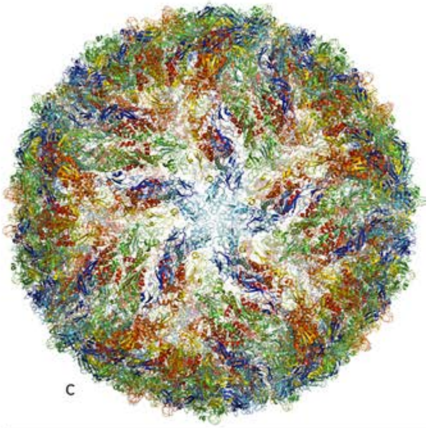
"For developing cryo-electron microscopy for the high-resolution structure determination of biomolecules in solution".



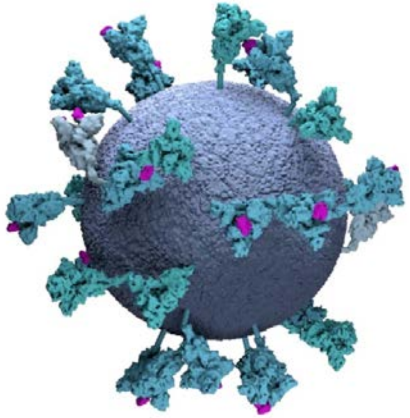
Protein for circadian rhythm

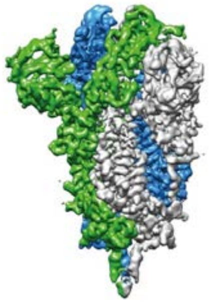


Ear pressure sensor



Zika virus





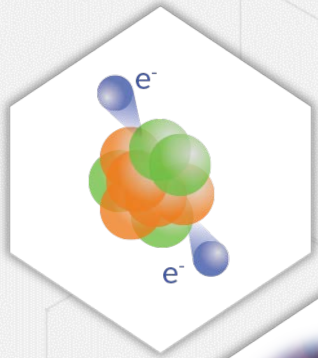
3.5 Å resolution

SARS-CoV-2 virus
Nature volume 588, pg. 498 (2020)

Oak Ridge National Laboratory

Currently use CMOS technology; Medipix helped advance the technology

Looking to the future: Key Elements

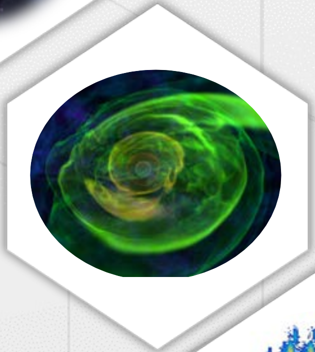


Future looks incredibly bright

- The science questions are **most compelling** and transformational
- Technology Development is happening at breadth taking speed
- The questions are exciting, stimulating and challenging

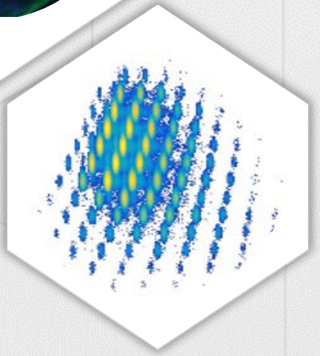
Science Technologies will be crucial

- The effects to fully understand nature are subtle
- Theoretical guidance has no ‘no-lose theorems’
- **Precision**, making measurable what is currently not measurable



Ecosystem that encourages and enables

- A healthy **balance** of traditional and non-traditional approaches
- **Multi-disciplinary** intersects
- Table-top vs large-scale, incremental vs high-risk



Workforce

- Develop and train the **next-generation workforce**
- Provide the necessary facilities

- Backup slides

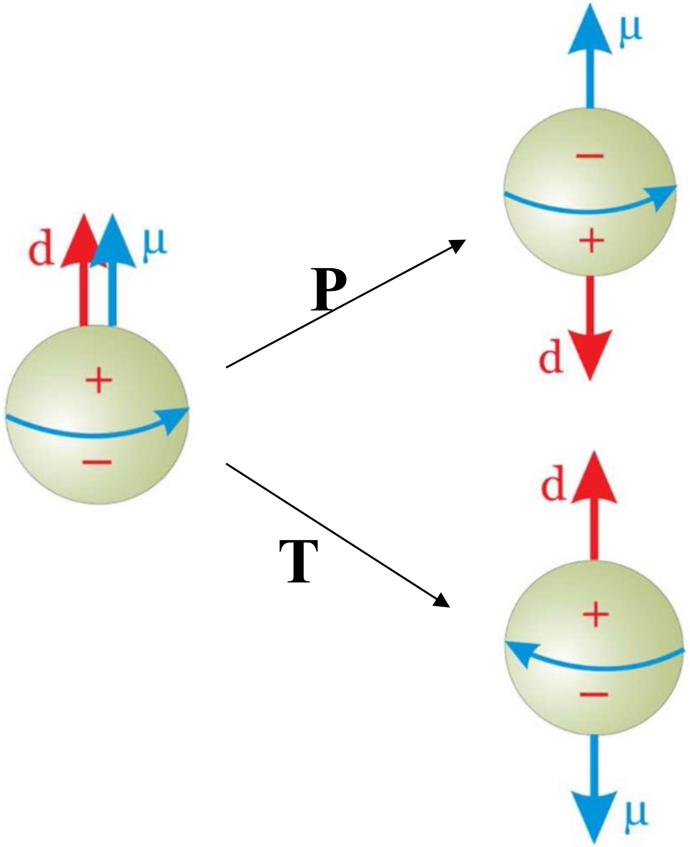
Electric Dipole Moments

Magnetic moment:

$$\vec{\mu} = \mu \frac{\vec{S}}{\hbar / 2}$$

Electric Dipole Moment:

$$\vec{d} = d \frac{\vec{S}}{\hbar / 2}$$



If nature is invariant under parity transformations **P**:

→ **d = 0**

If nature is invariant under time reversal transformations **T**:

→ **d = 0**

An EDM means CP-violation: new physics

Neutrons as a Probe

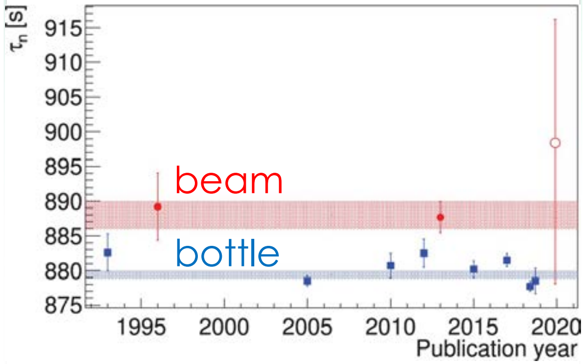
n Lifetime

- What is the lifetime of a free neutron:

$\tau_n^{beam} = 888.0 \ \pm 2.0 \ s$

$\tau_n^{bottle} = 879.4 \ \pm 0.6 \ s$

$\Delta = 8.6 \pm 2.1 \ s \quad (4\sigma)$

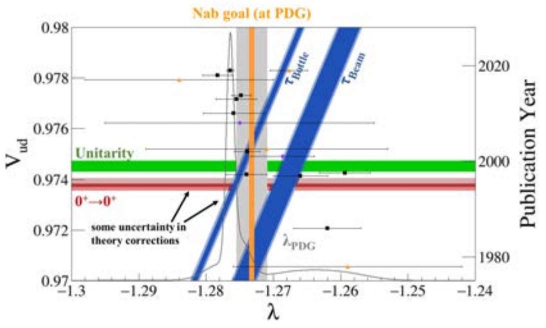


Progress of Th. and Exp. Phys. (2020)12
https://doi.org/10.1093/ptep/ptaa169

Czarnecki, et al., Phys. Rev. Lett. **120**, 202002 (2018)

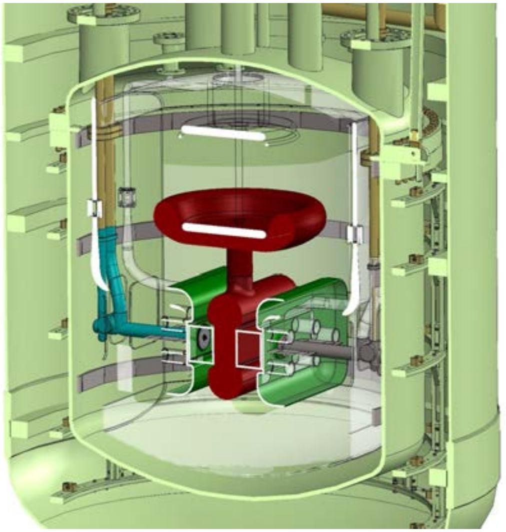
n Weak Decay

- Precise measure of neutron weak decay to address unitarity tension in Standard Model CKM matrix



n EDM

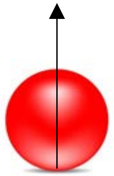
- Measurement of the neutron electric dipole moment by many experiments (TUCAN, PSI, LANL, ORNL)

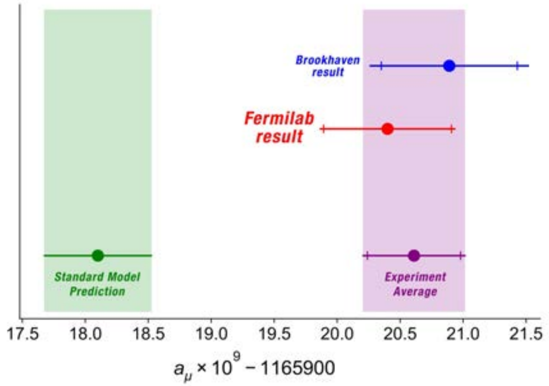


Anomalous Moments

- Magnetic moment of the muon: g-2

muon





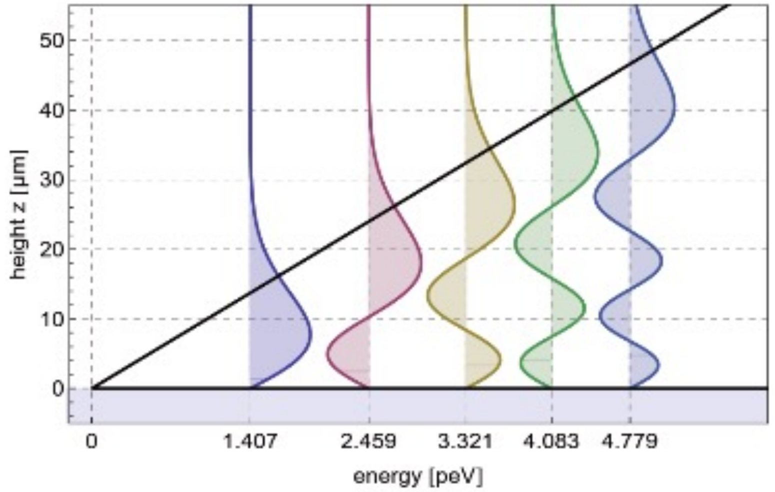
$(a_\mu^{meas} - a_\mu^{th}) = 4.2 \ \sigma$

Phys. Rev. Lett. 126 (2021) 141801
Nature **592**, 17-18 (2021)

Oak Ridge National Laboratory

Neutrons, Gravity and Fundamental Quantum Mechanics

- Schrödinger equation with gravitational potential:

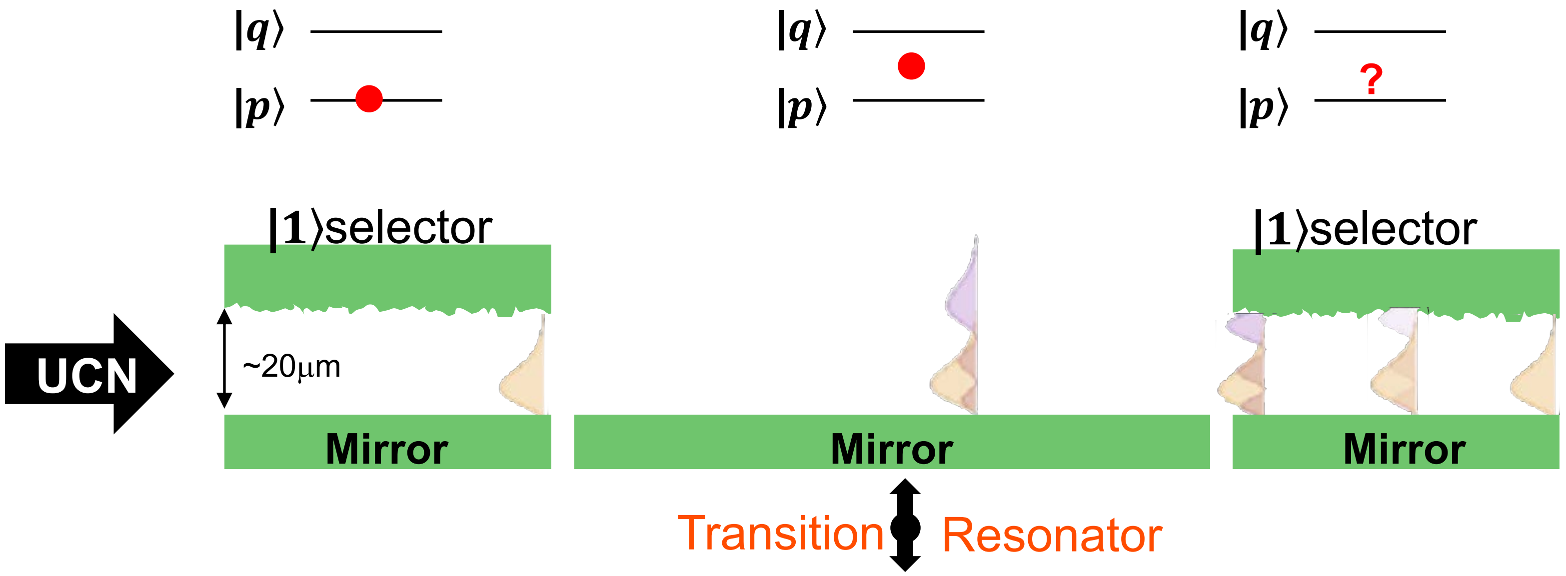


$$\left(-\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial z^2} + m_g g z\right)\varphi_n(z) = E_n\,\varphi_n(z)$$

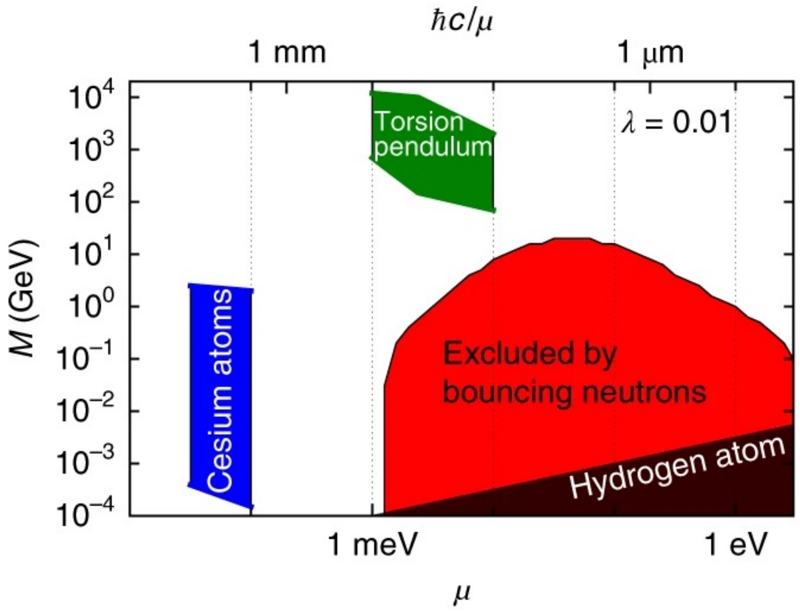
$$\left(-\frac{\hbar^2}{2m_i}\frac{\partial^2}{\partial z^2} + m_g g z + V_{DE}(z) + V_{DM}(z)\right)\psi(z,t) = i\hbar\frac{\partial}{\partial t}\psi(z,t)$$

$V_{DE}(z)$ Parametrized with mass coupling μ, analogous to scalar Higgs field and M, inverse coupling to matter (GeV)

Neutrons, Gravity and Fundamental Quantum Mechanics



- Rabi-type spectroscopy of gravity:
  - Prepare UCN in ground state
  - Coupling through mechanical or magnetic field
  - Ground state selector and measurement of neutron count as function of height



OAK RIDGE National Laboratory

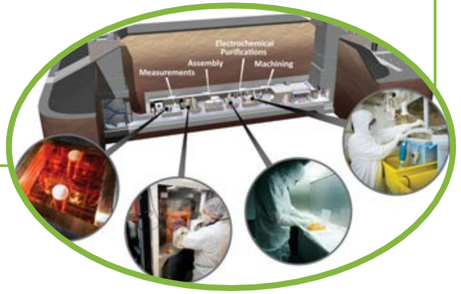
Facilities Support

- To deliver on future science project, a key element has been the availability of test facilities to support instrumentation development.

Low Background Facility

Provides support for low-background experiments in the areas of materials and assay

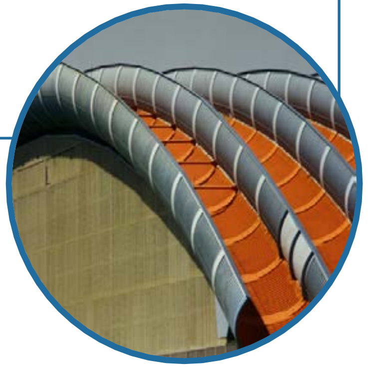
Critical need for low-background experiments



Test Beams

Provides high-quality beams and data taking infrastructure to develop and characterize new detector technologies

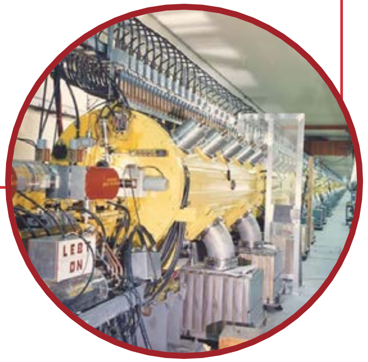
Critical need to explore new technologies



Irradiation Facilities

Provides facilities to validate radiation resistance to extremely high fluences

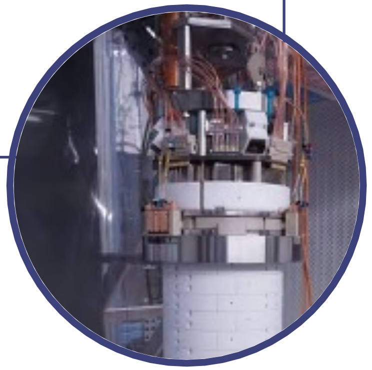
Essential for Energy and Intensity Frontier experiments



Characterization Platforms

Provides platforms for determining fundamental physics of materials

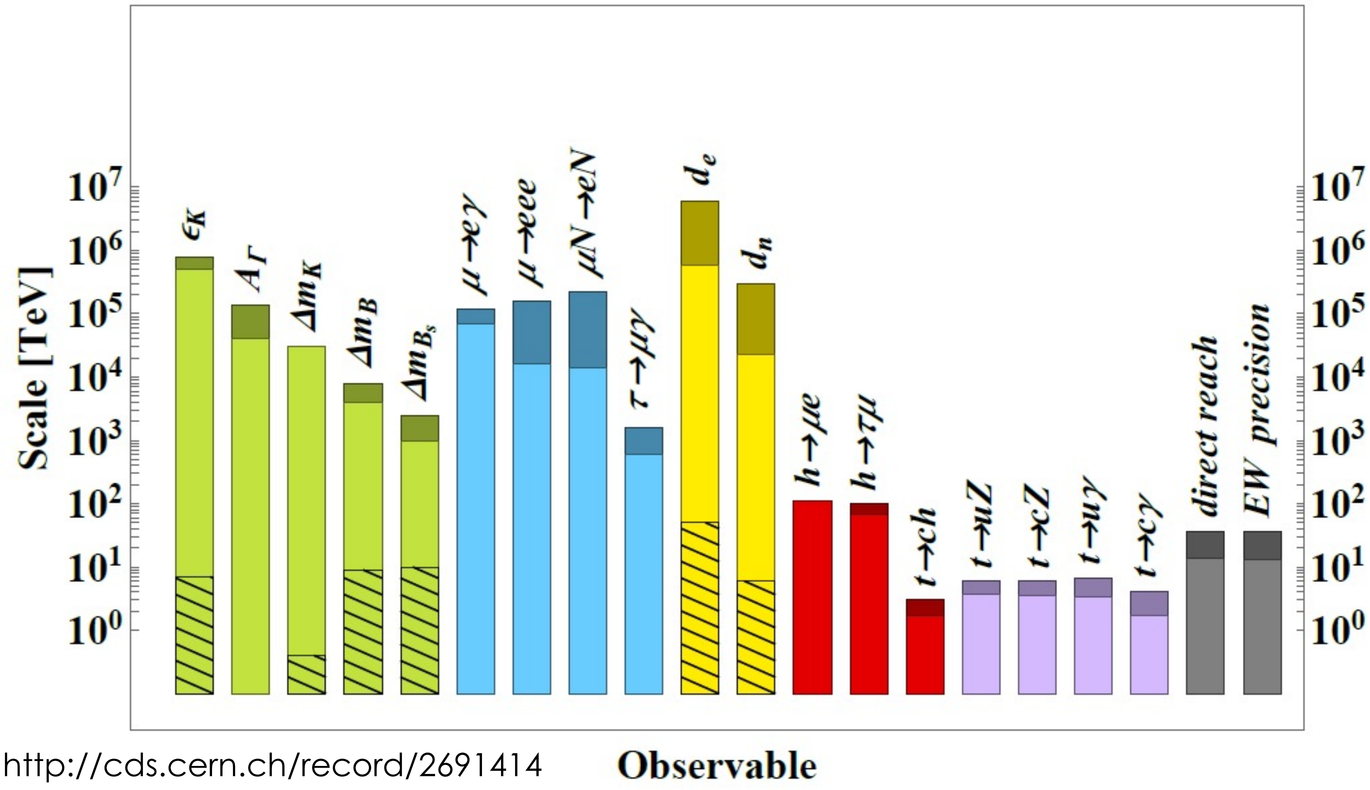
Vital for determining proof of principle and long-term viability of proposed materials and environments



Precision

- Exceeding precision and demanding technology will be required to probe nature

Reach in new physics from Flavor Physics



http://cds.cern.ch/record/2691414

Composite Higgs