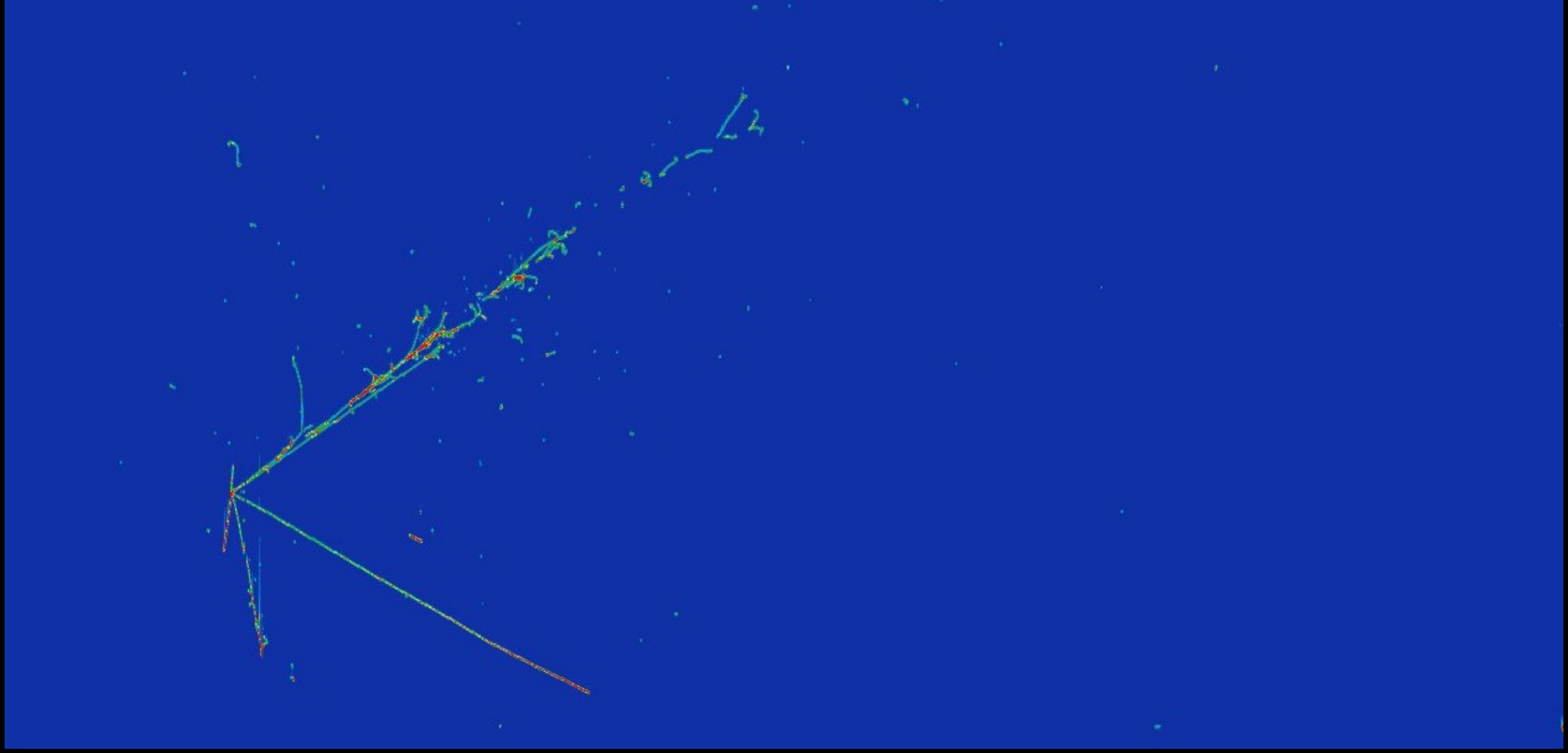
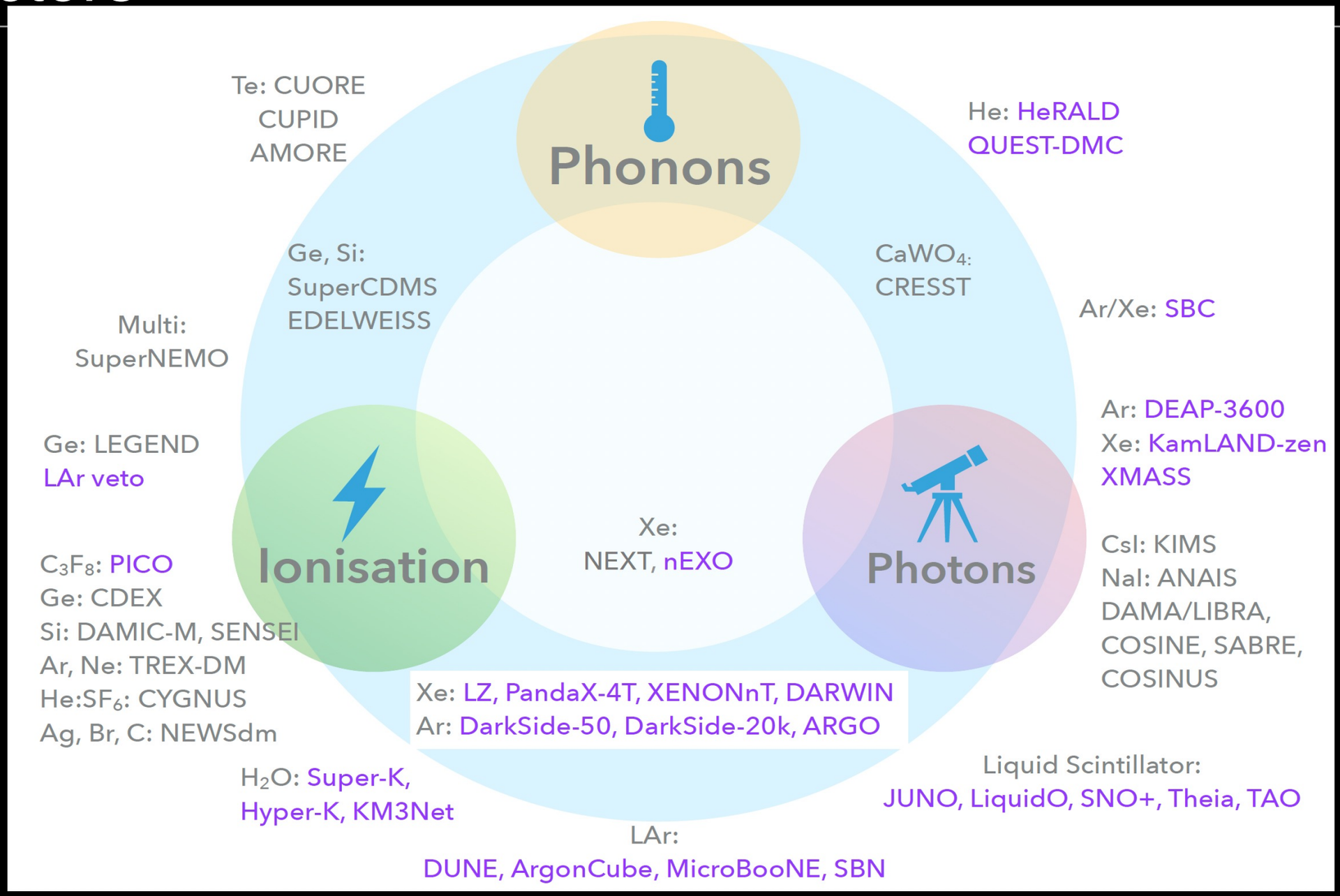


Noble Element Detectors for particle physics

Liquid detectors

- Several large-scale and many small-scale experiments running or foreseen with liquid detectors
- for neutrino oscillation physics @ accelerators
- Neutrino nature Dirac or Majorana?
- Dark matter searches,

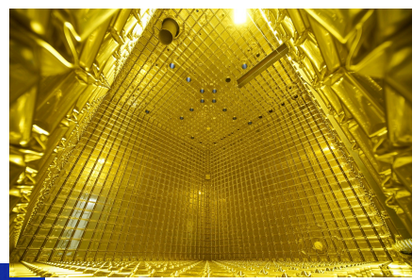


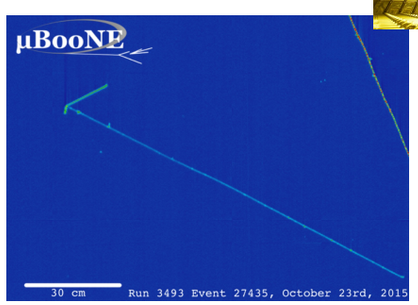
Modified from L. Baudis

Noble Element detectors are now everywhere!

Neutrinos

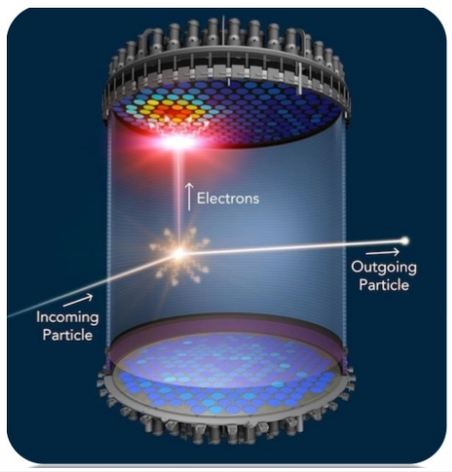
- Oscillation precision measurements (δ_{CP}, mass ordering, θ_{23} octant, sterile νs)
- Neutrino interactions (from CEvNS to DIS)
- Astro neutrinos





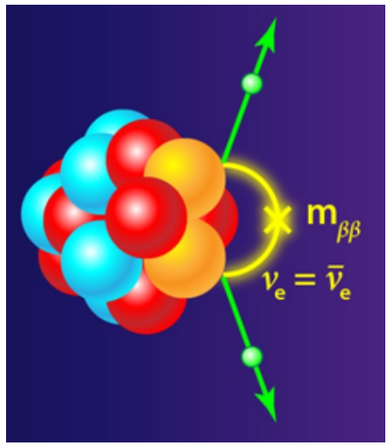
Dark Matter

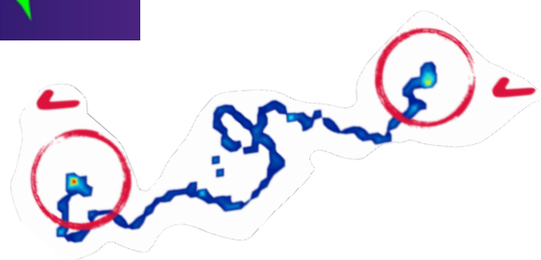
- Direct detection (WIMPs, …)

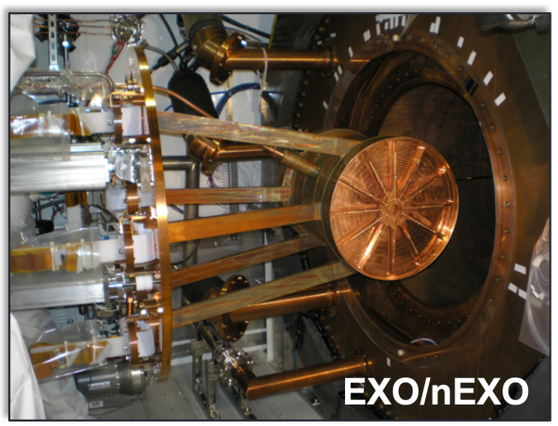


0νββ

- Search for Majorana neutrinos



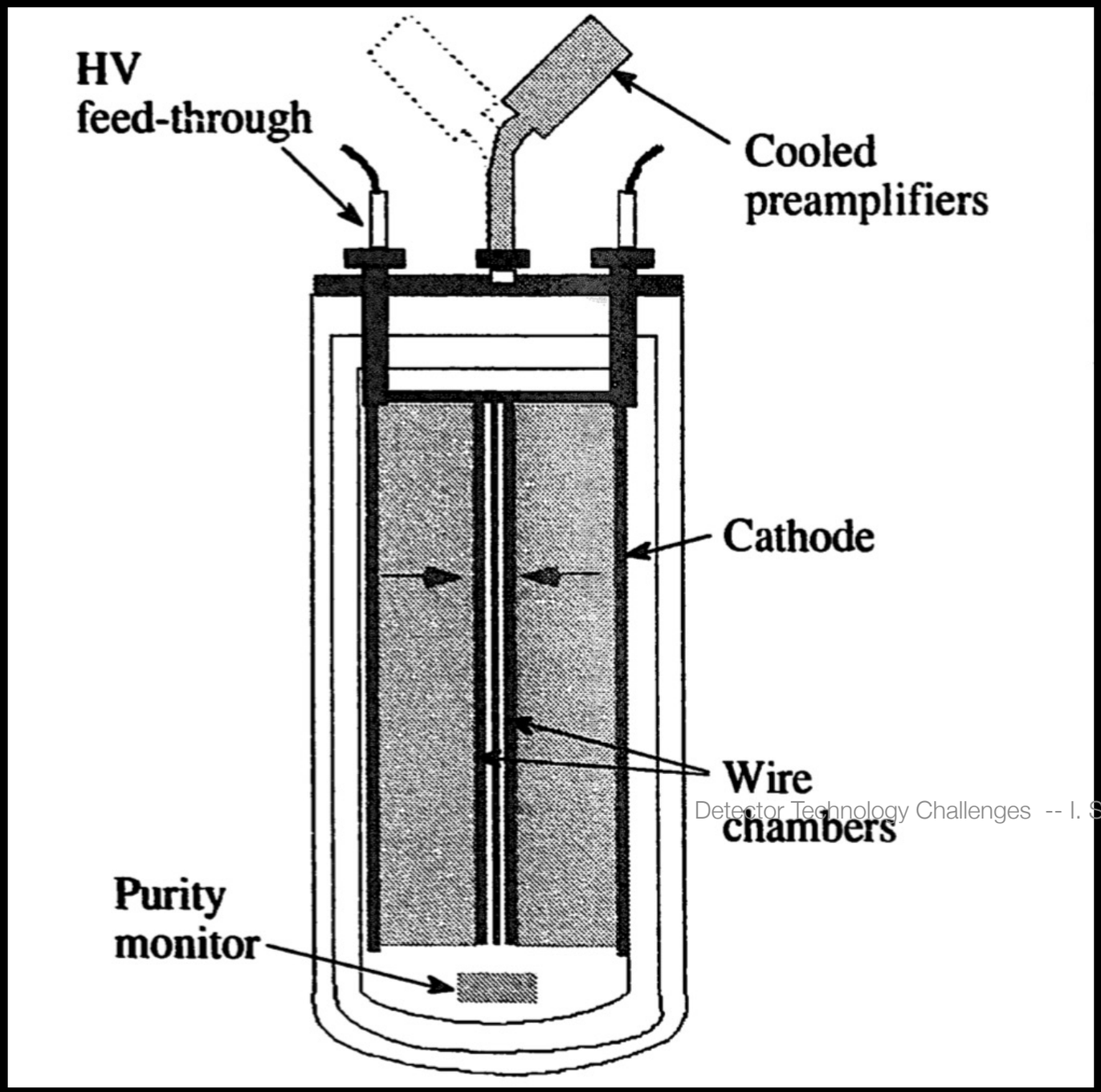


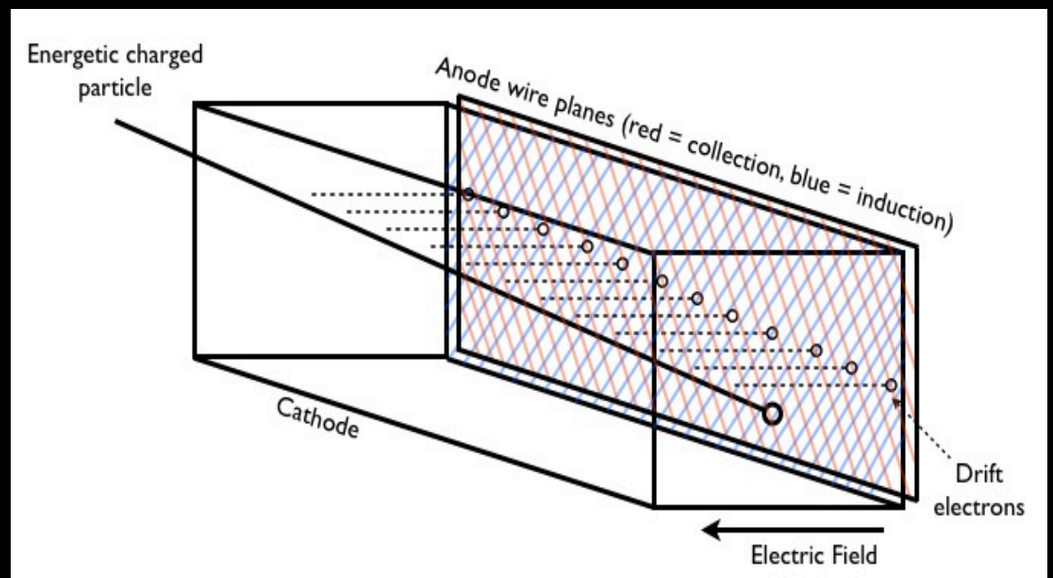


need to develop
new technologies

1970s

TPC

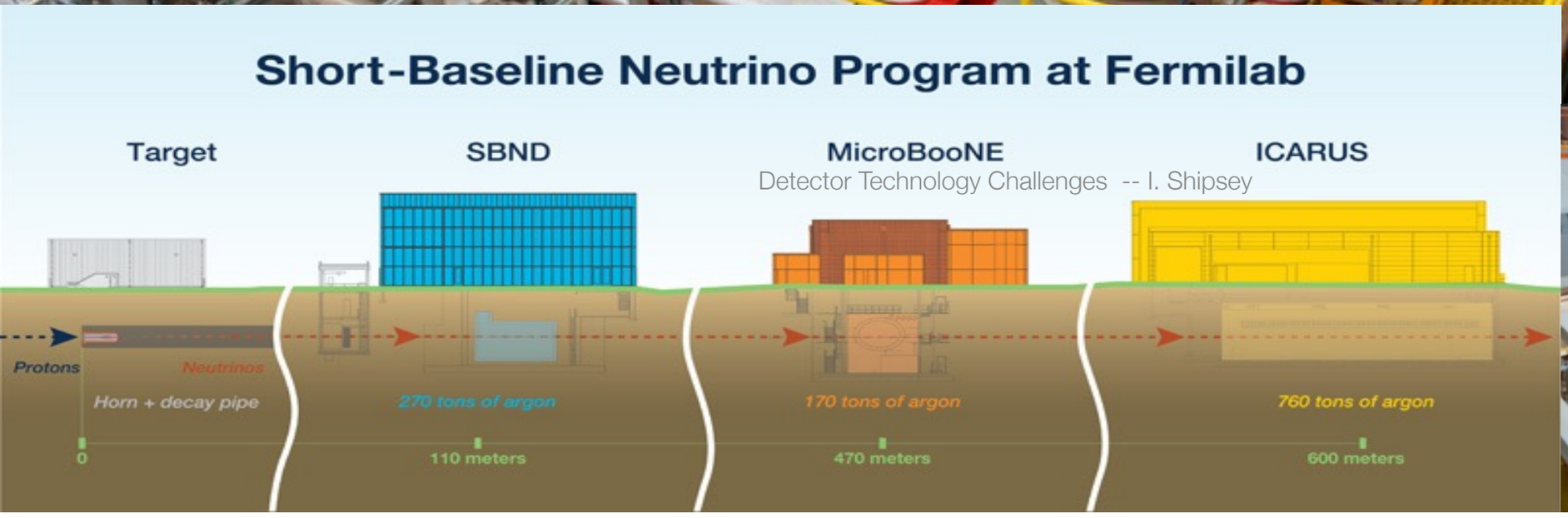


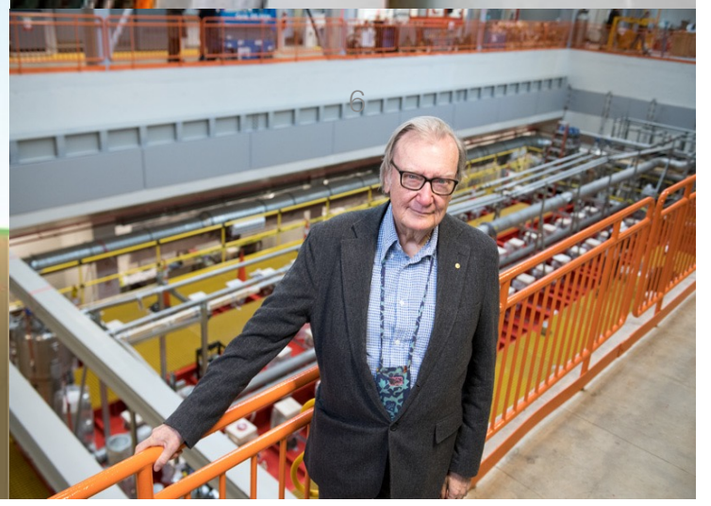


Liquid Argon TPC 1977 Rubbia

Liquid Argon TPC 2021 Rubbia

Credit: FNAL





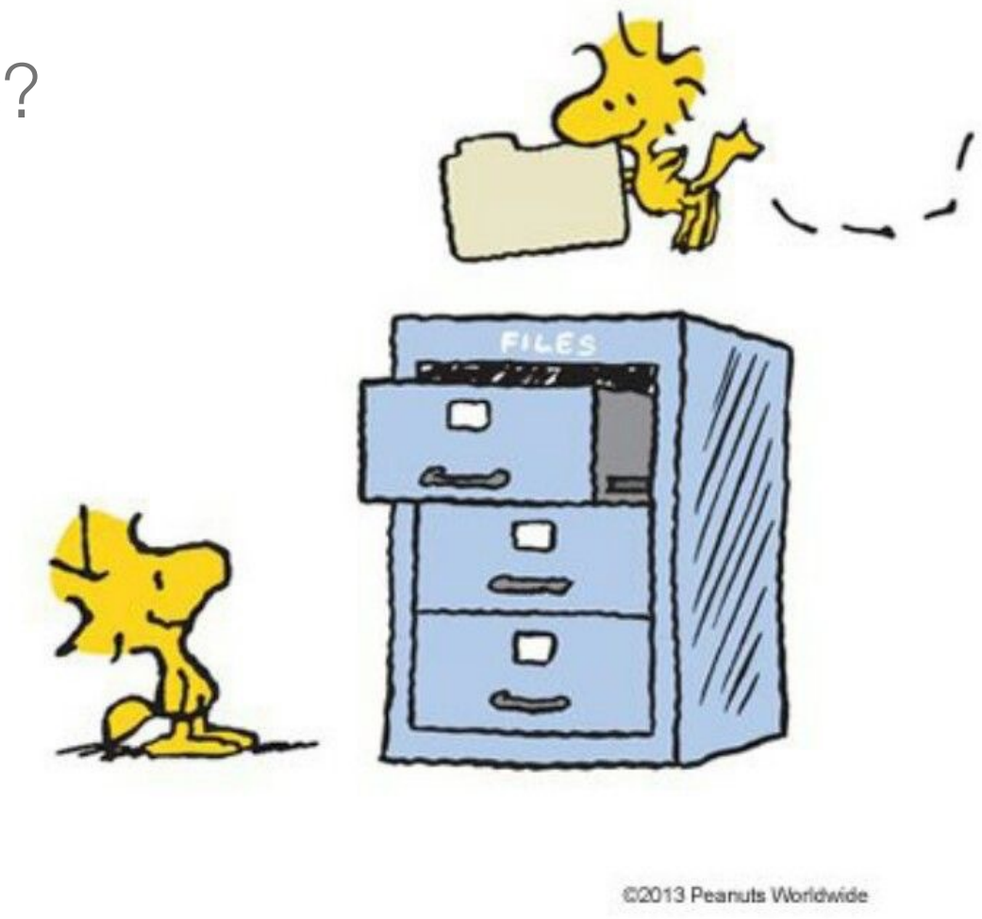
Outline

- What is special about noble elements?
- How does a noble element detector works?
- Application of noble element detectors to:

  ✓ **Neutrino physics**

  ✓ **Dark Matter**

  ✓ **Neutrinoless double beta decay**



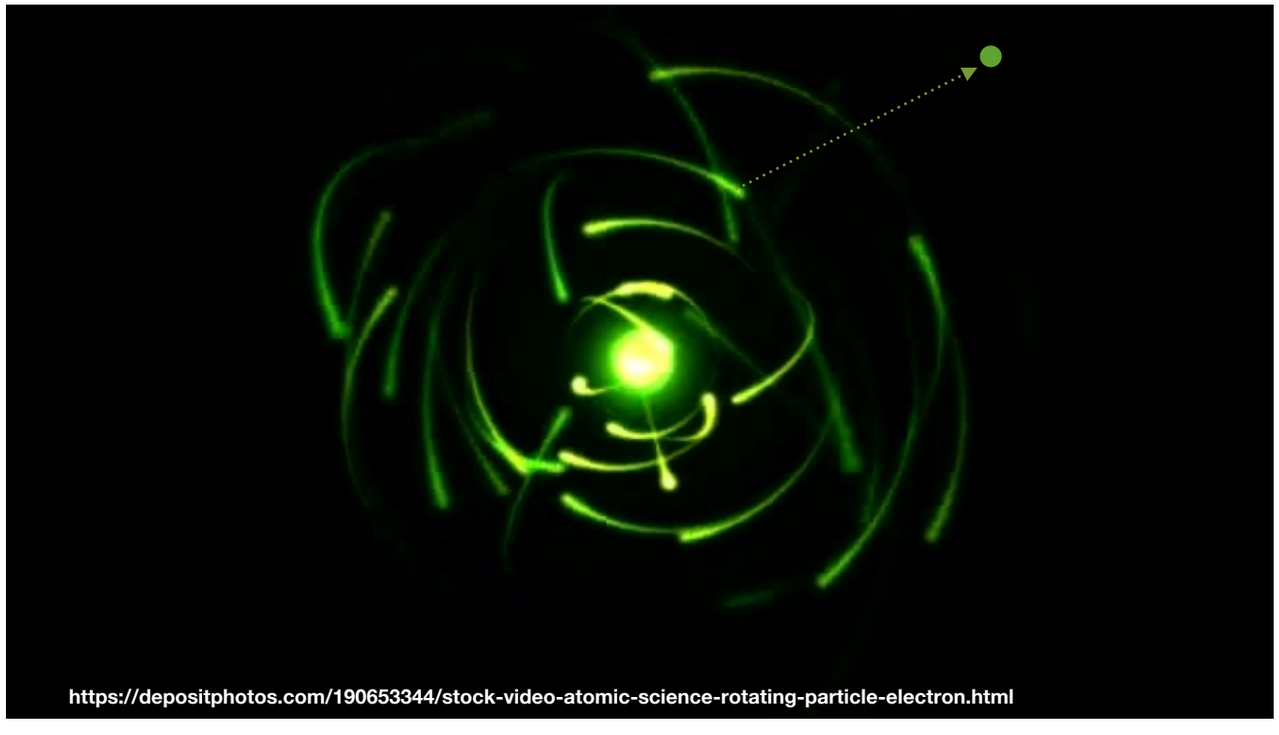
- Novel detection methods and future R&D

The beauty of noble elements

- Two crucial processes happen when charged particles go through a noble medium:

Scintillation

Ionization



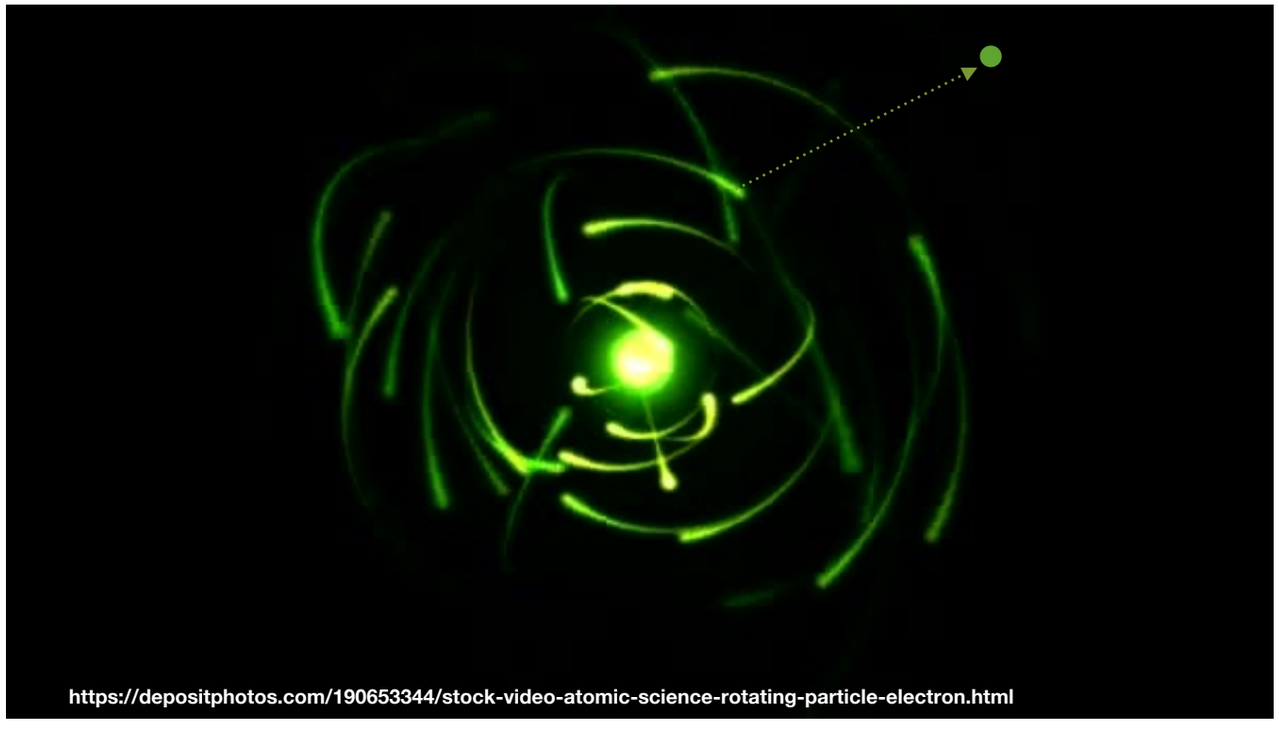
The beauty of noble elements

- Two crucial processes happen when charged particles go through a noble medium:

Scintillation

Noble elements are transparent to their own scintillation light

Ionization



Noble = no e^- attachment, which allows for long drift distance

Good dielectric allows for high voltages to drift over long distances

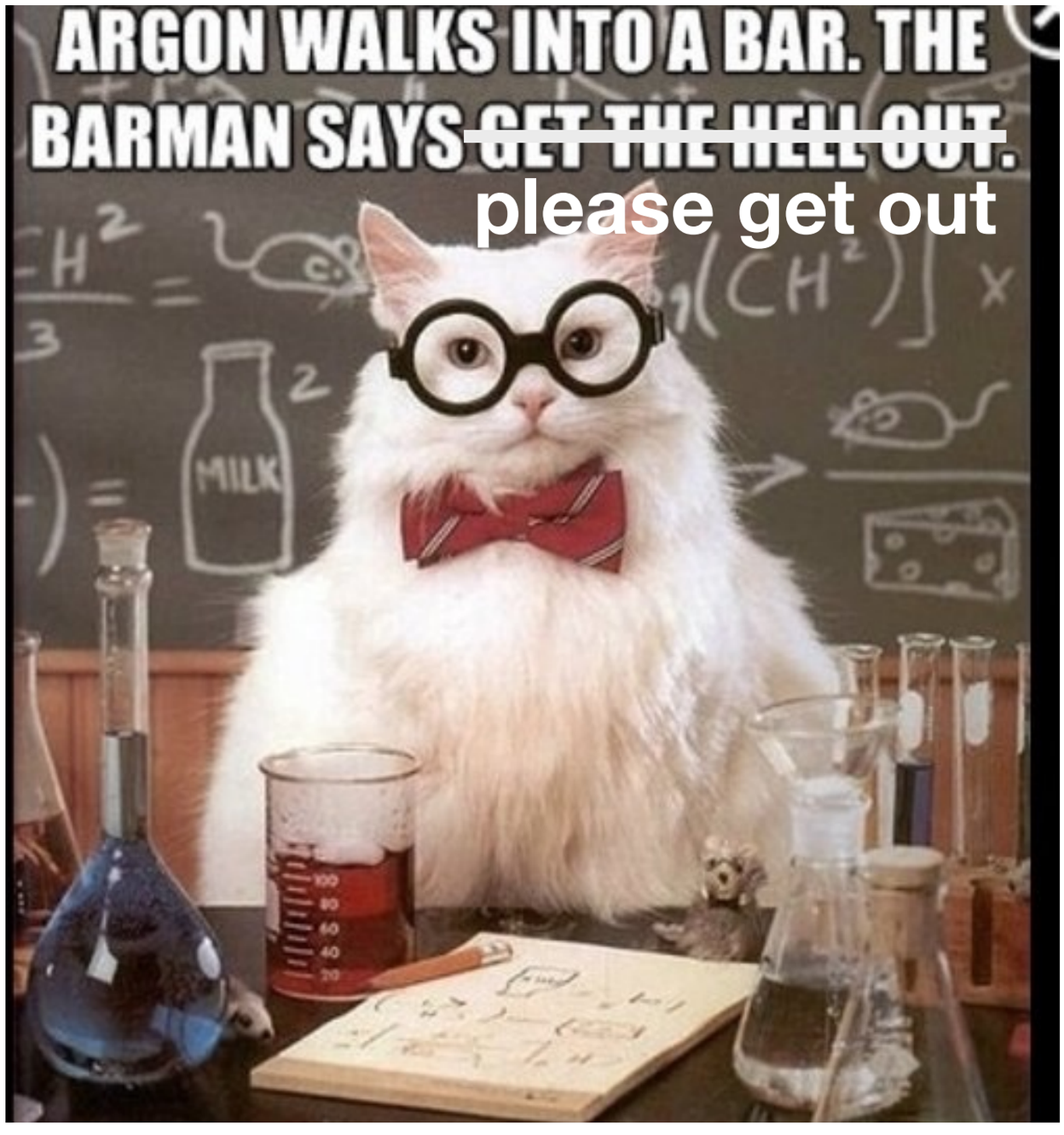
The beauty of noble elements

- All you need for particle detection!

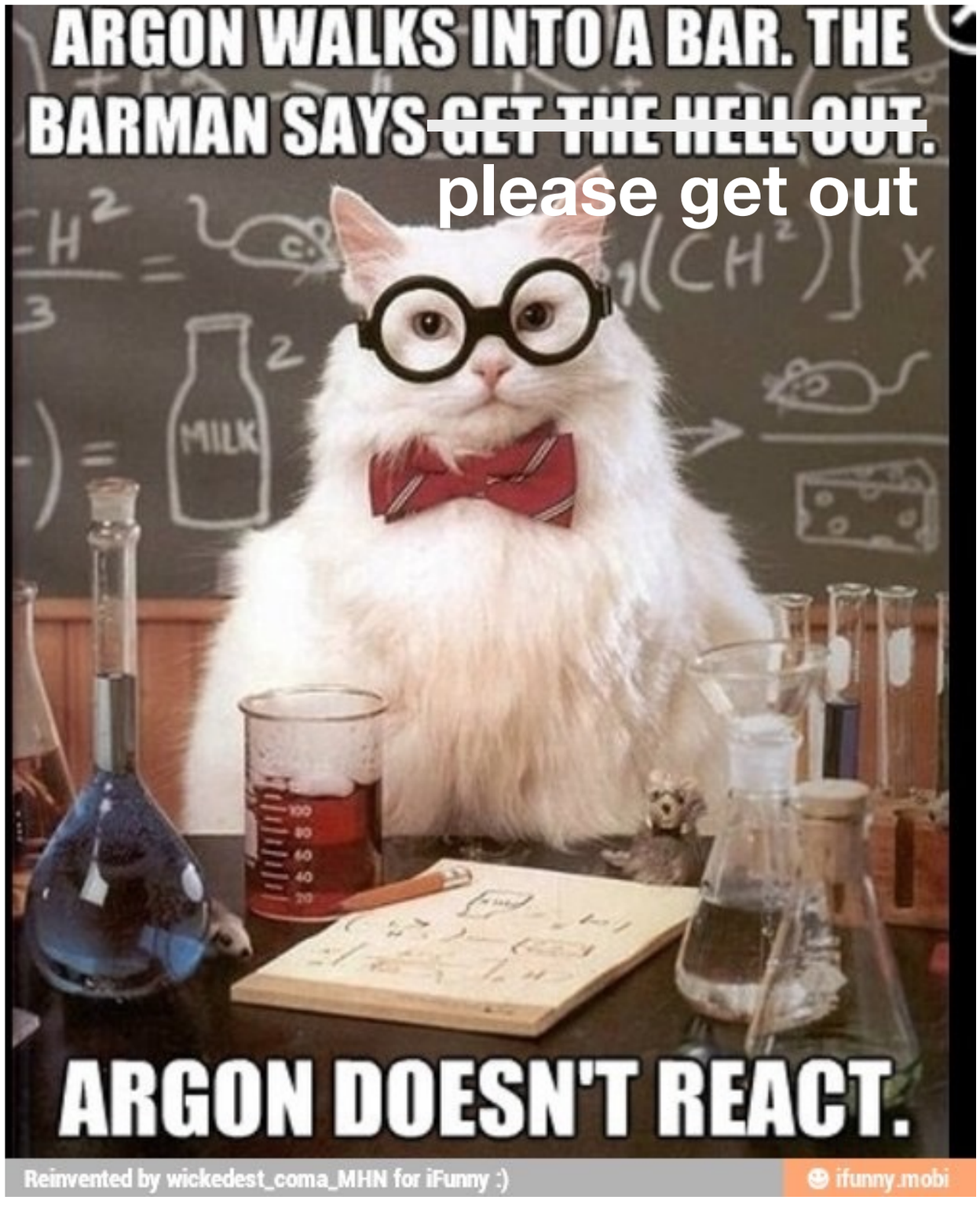
					
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000
Scintillation λ [nm]	80	78	128	150	175

from Mitch Soderberg

The beauty of noble elements



The beauty of noble elements



Not a *one-size-fit-all*

- Dark matter detection requires having detection thresholds as low as keV
- Neutrino oscillation physics needs the study of GeV neutrinos
- Neutrinoless double beta decay searches cannot afford much background and need extraordinary good energy resolution

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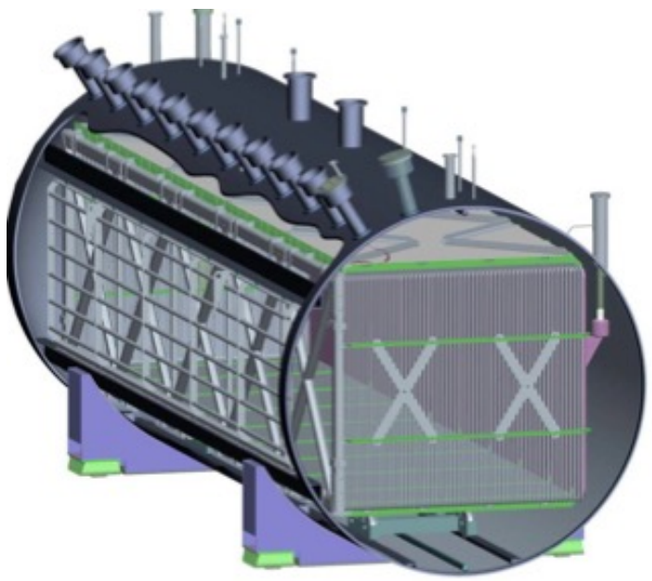
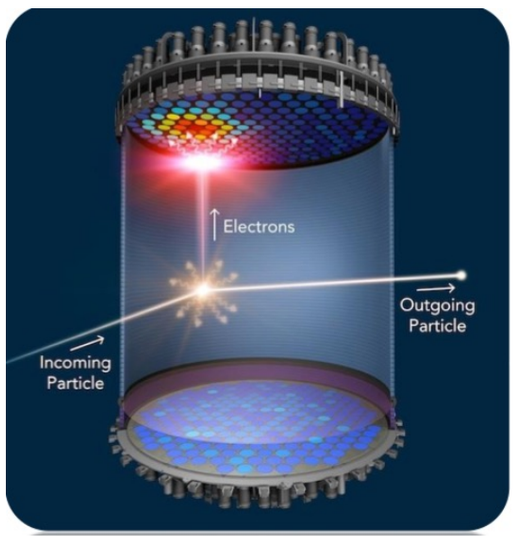
Neutrinos

- Liquid Argon TPCs



Dark Matter

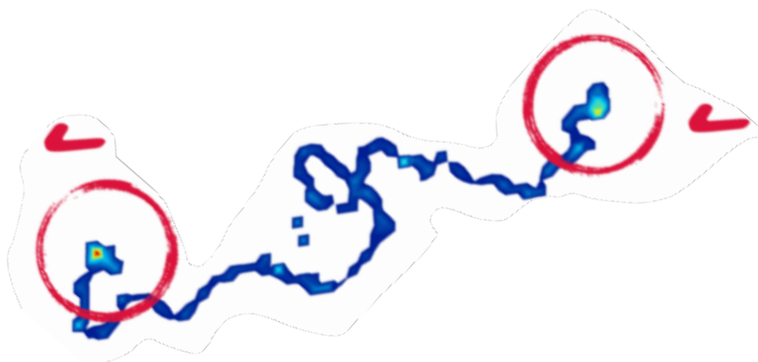
- Liquid Xenon and Liquid Argon TPCs*



*Some are technically not TPCs

0νββ

- Liquid and Gaseous Xenon TPCs



Not a *one-size-fit-all*

- Dark matter detection requires having detection thresholds as low as keV
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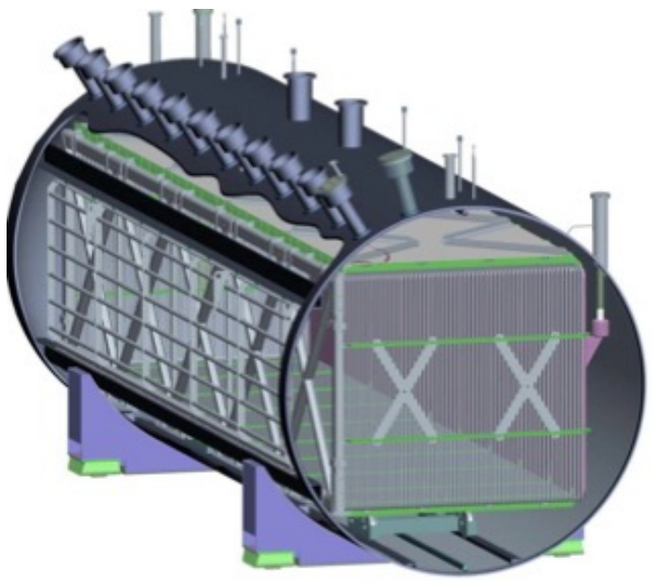
What's a TPC?

Neutrinos

- Liquid Argon TPCs



Dark Matter

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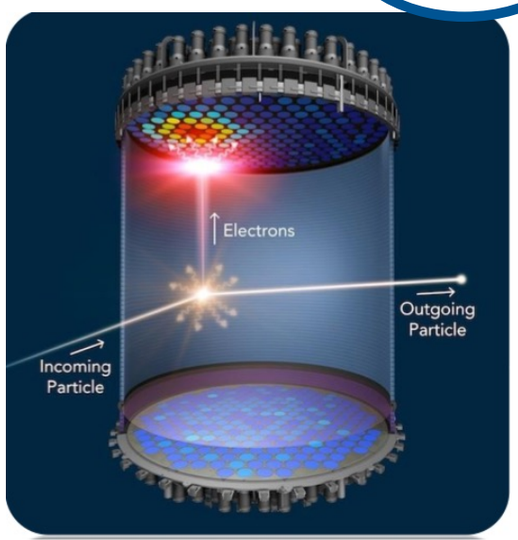

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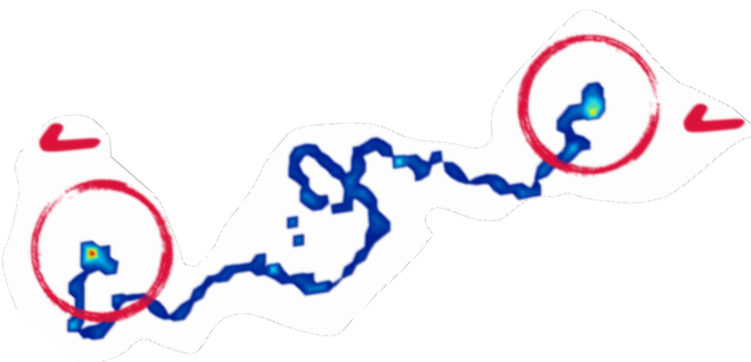
0νββ

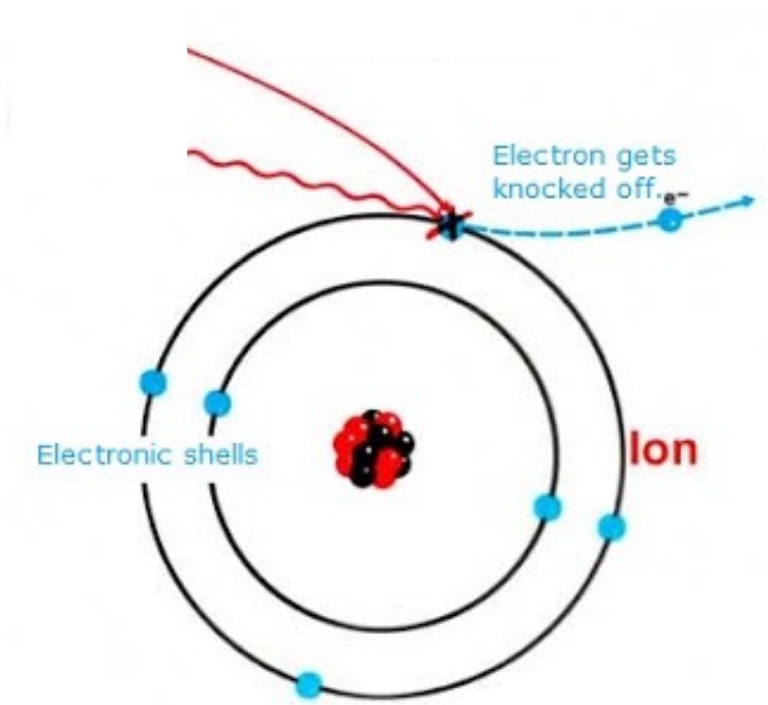
- Liquid and Gaseous Xenon TPCs



What is a TPC?

- Time Projection Chamber uses both ionization and scintillation

Ionization



http://chemistry-alevel.blogspot.com/2010/12/ionic-substances.html

Need $E > E_{binding}$ (e.g. 23.6 eV for Ar)

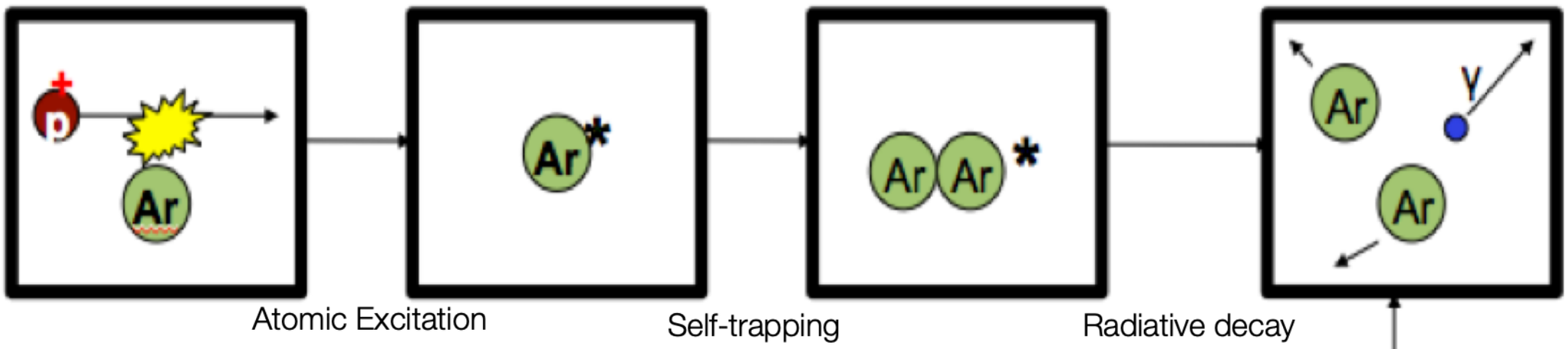
MeV depositions → > 40 000e^-

What is a TPC?

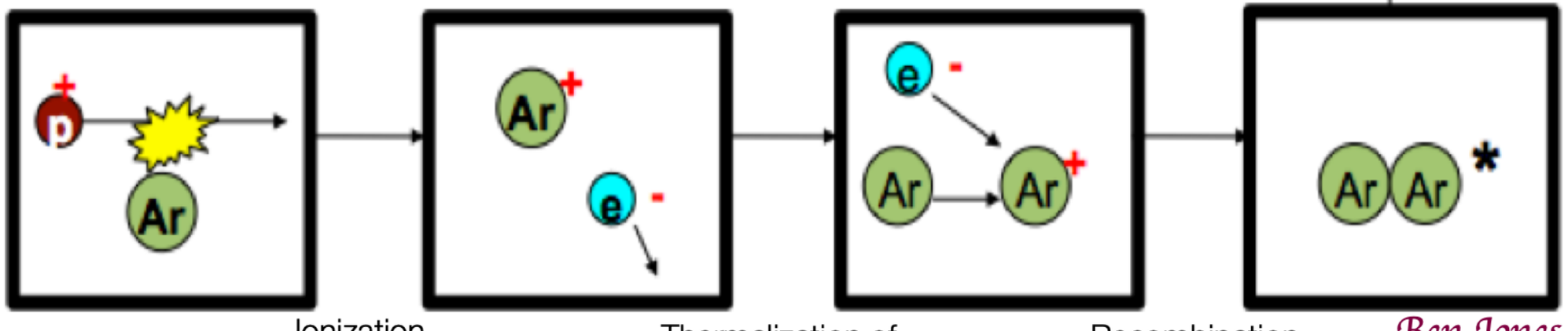
- Time Projection Chamber uses both ionization and scintillation

Scintillation

Self-trapped exciton luminescence



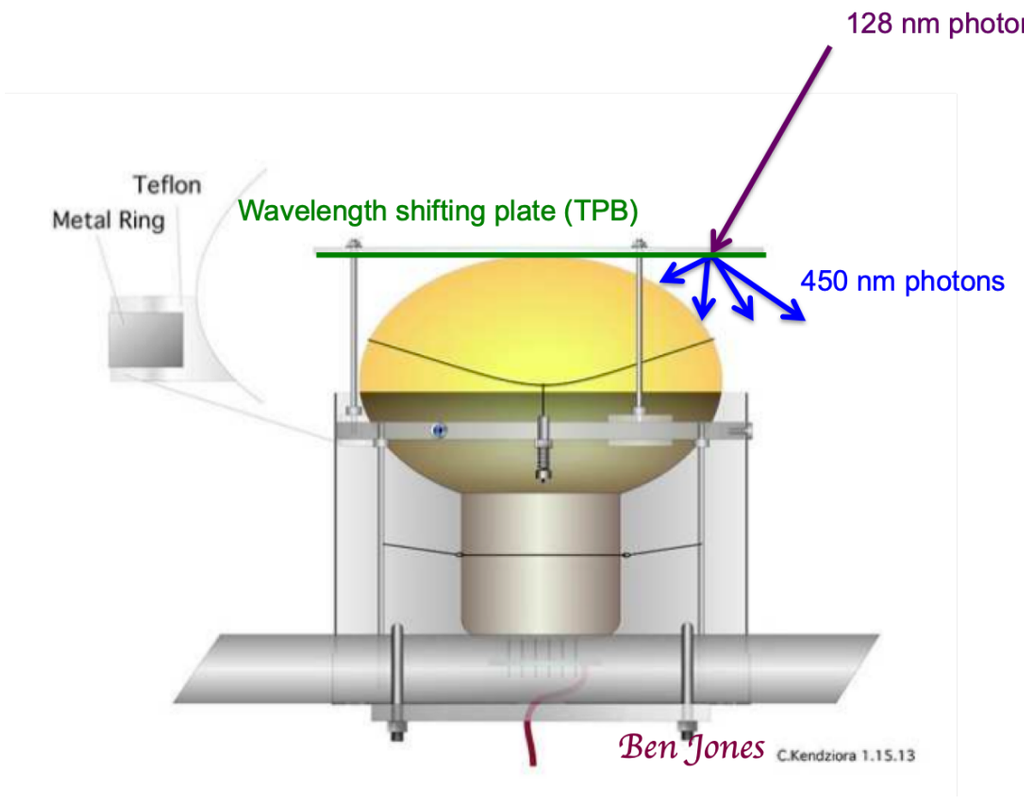
Recombination luminescence



One additional details about scintillation in nobles

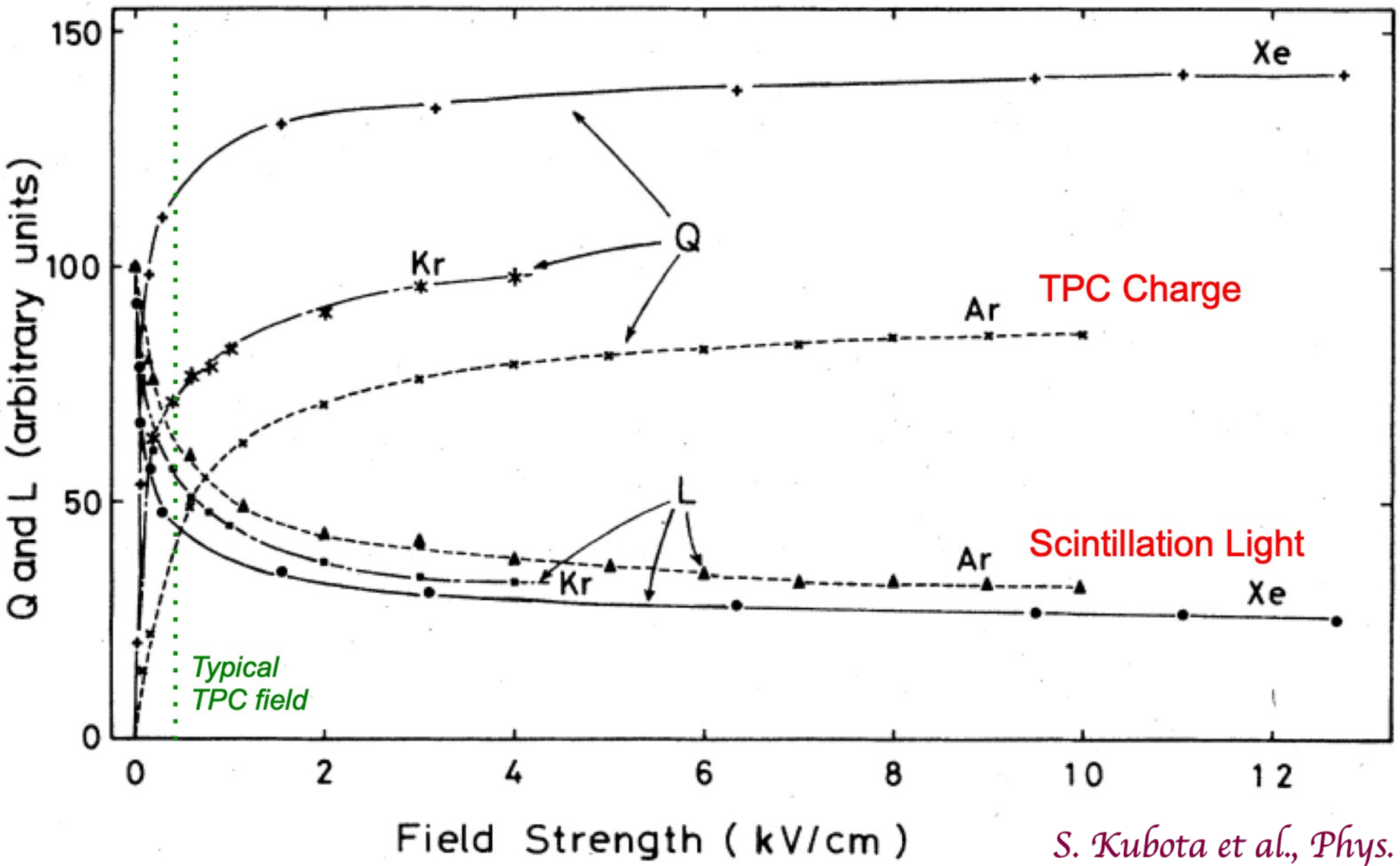
- Each noble has its own scintillation wavelength (not alway compatible with traditional photon detectors)

- Wavelength shifters are often needed to be detect scintillation light



What is a TPC?

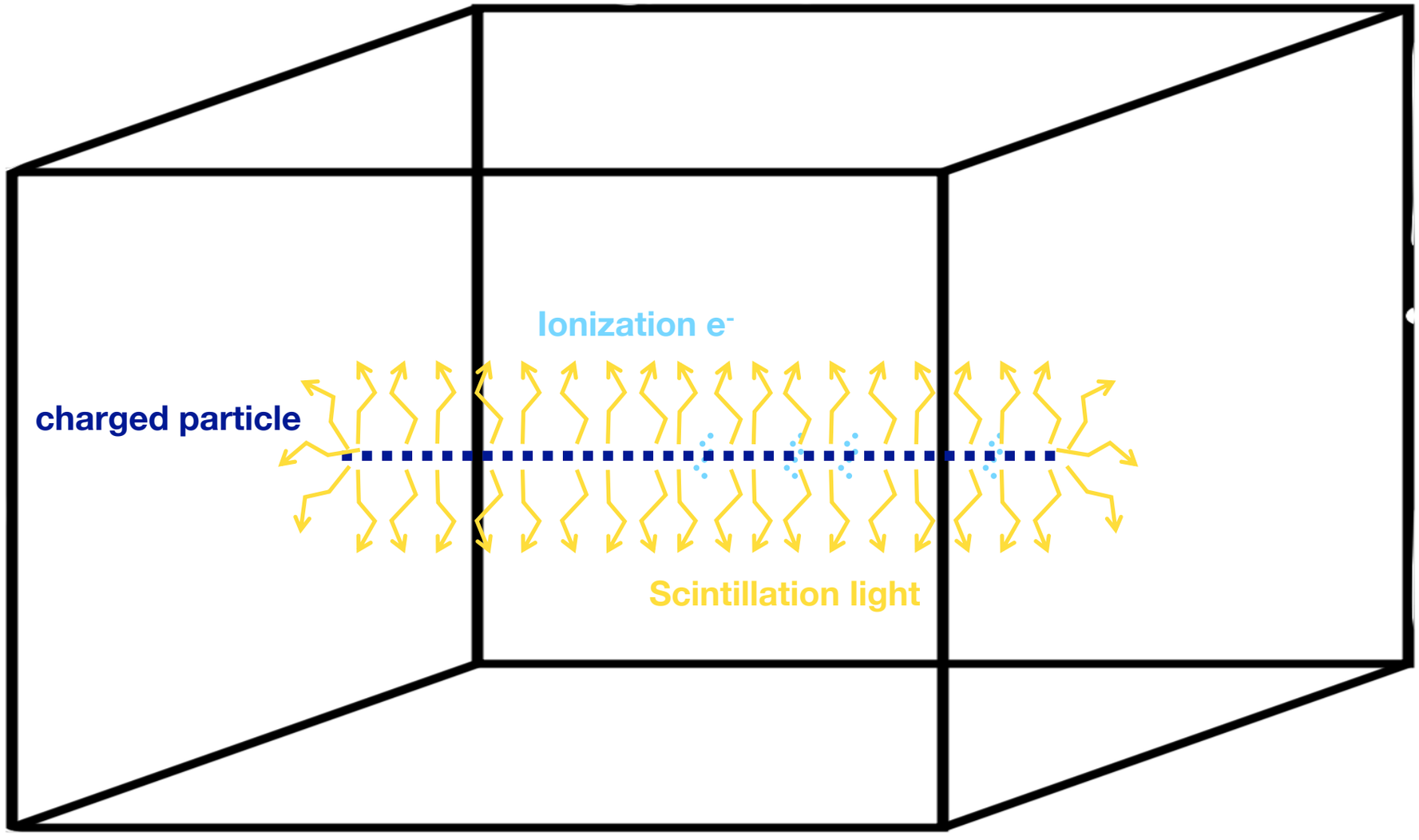
- Time Projection Chamber uses both ionization and scintillation
- **Charge and light are complementary!**



S. Kubota et al., Phys. Rev. B, 20, 8 (1979)

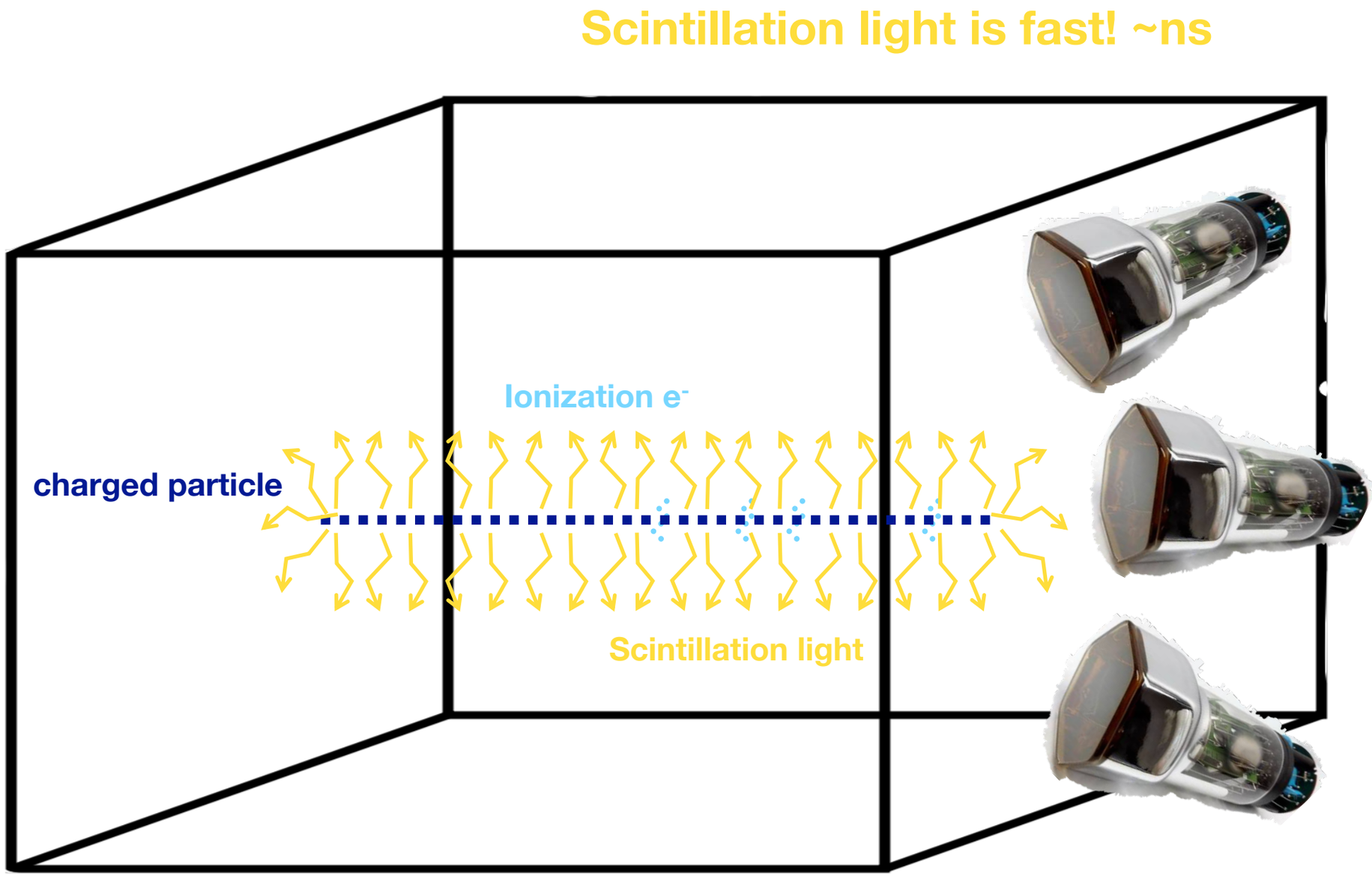
What is a TPC?

- Time Projection Chamber



What is a TPC?

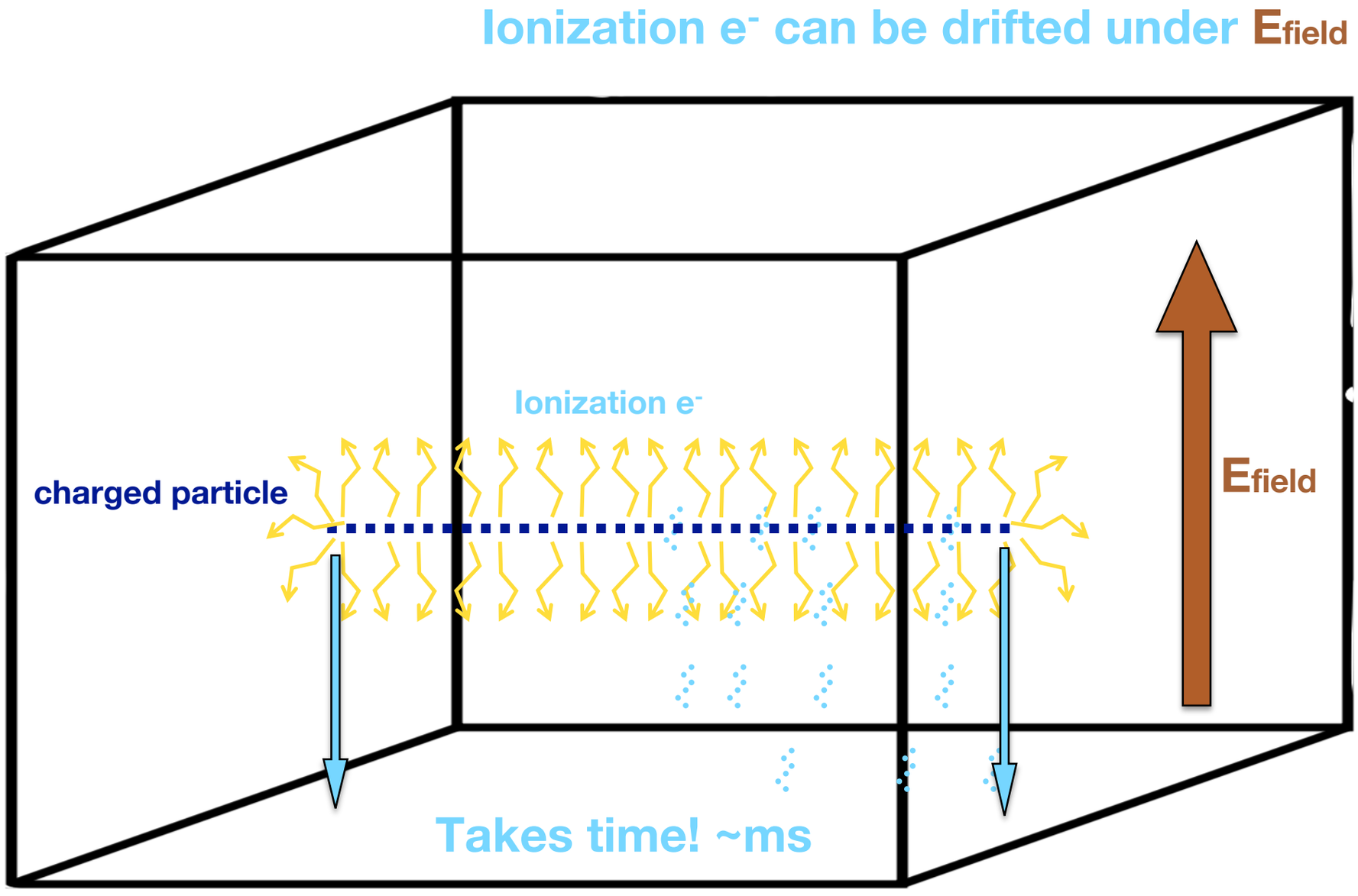
- Time Projection Chamber



Provide t0
Can be used for trigger

What is a TPC?

- Time Projection Chamber



Ionization (or charge) readout is specific to each detector!

What is a TPC?

- Time Projection Chamber

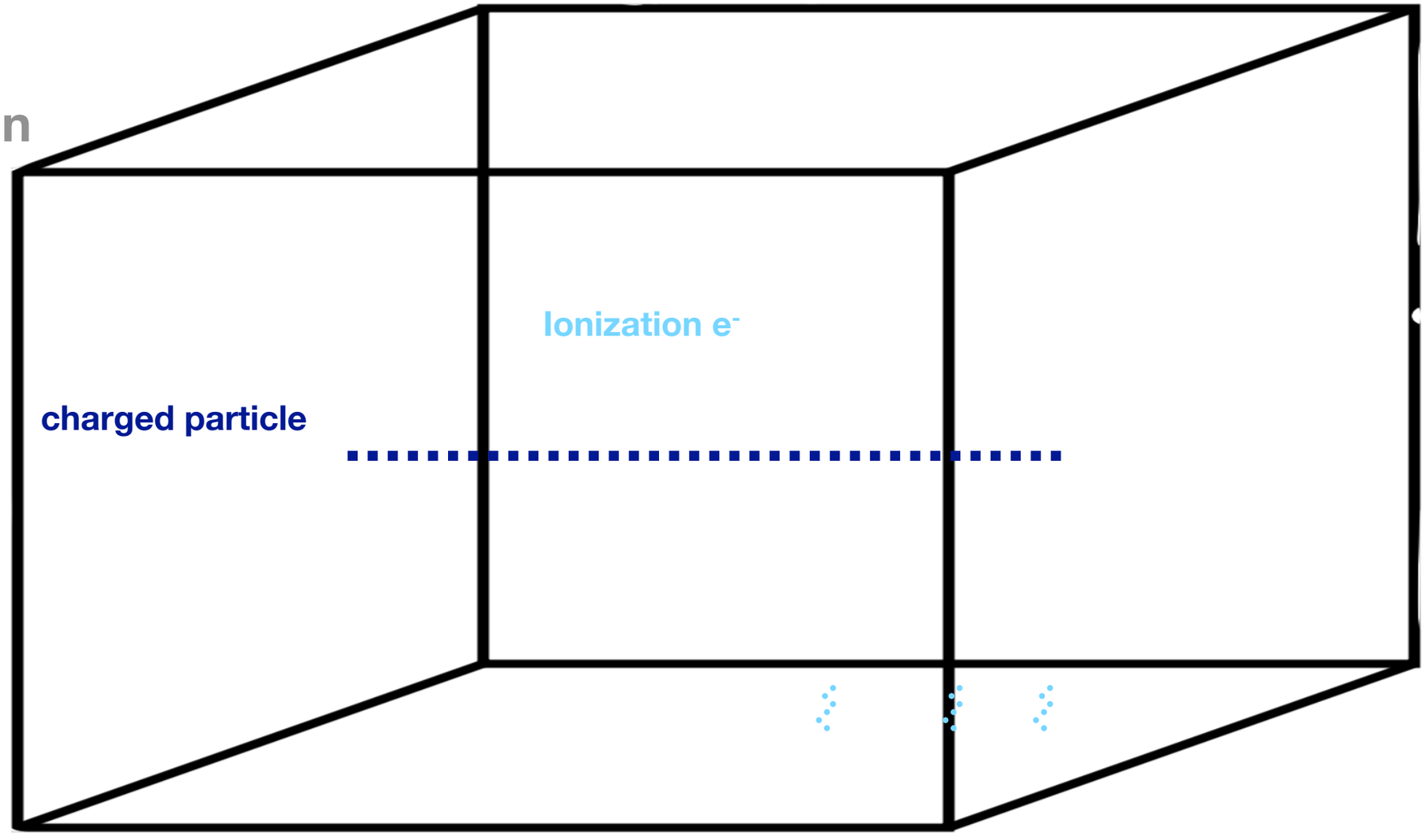
t_0

+

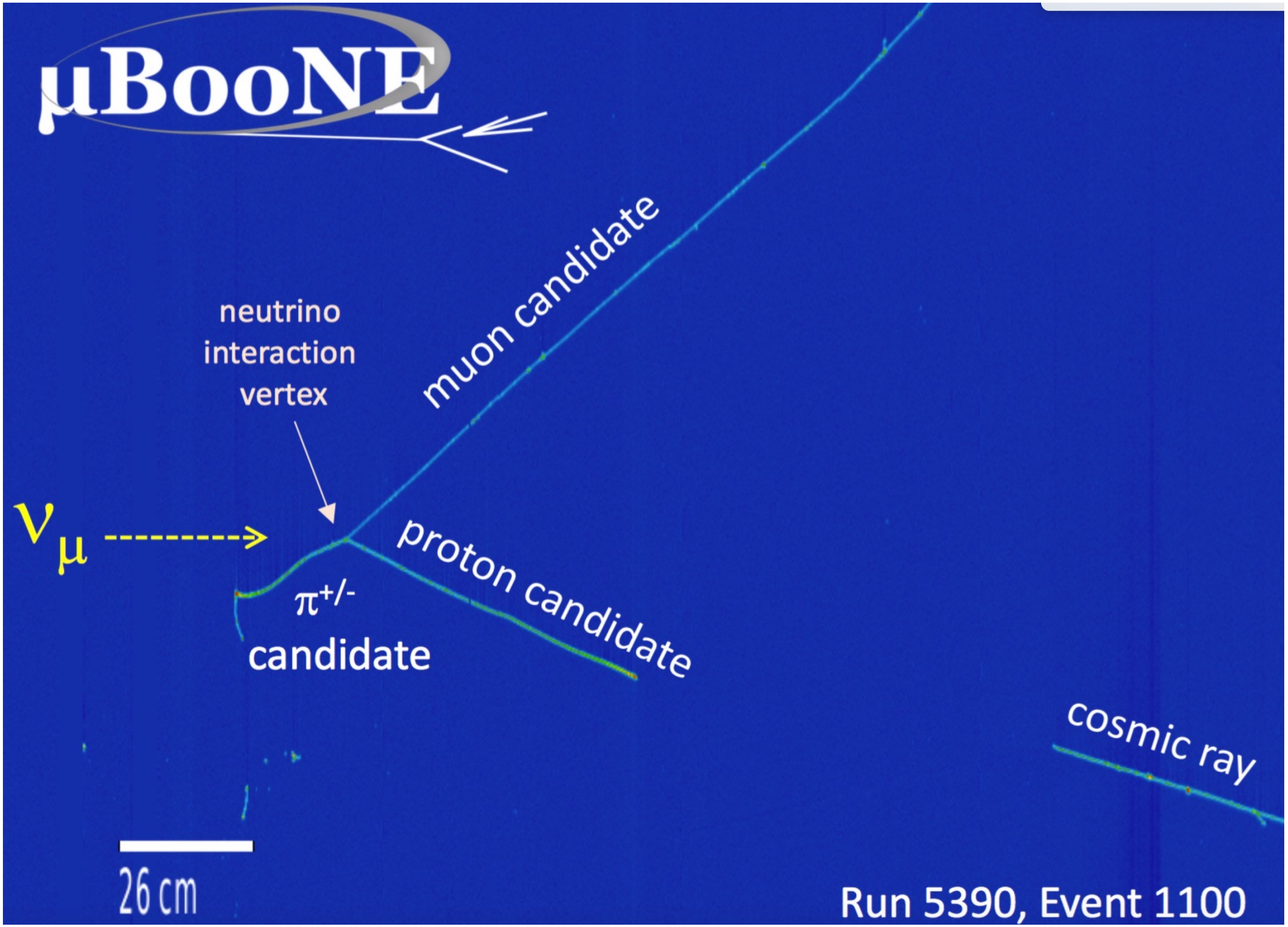
drift time

=

time projection



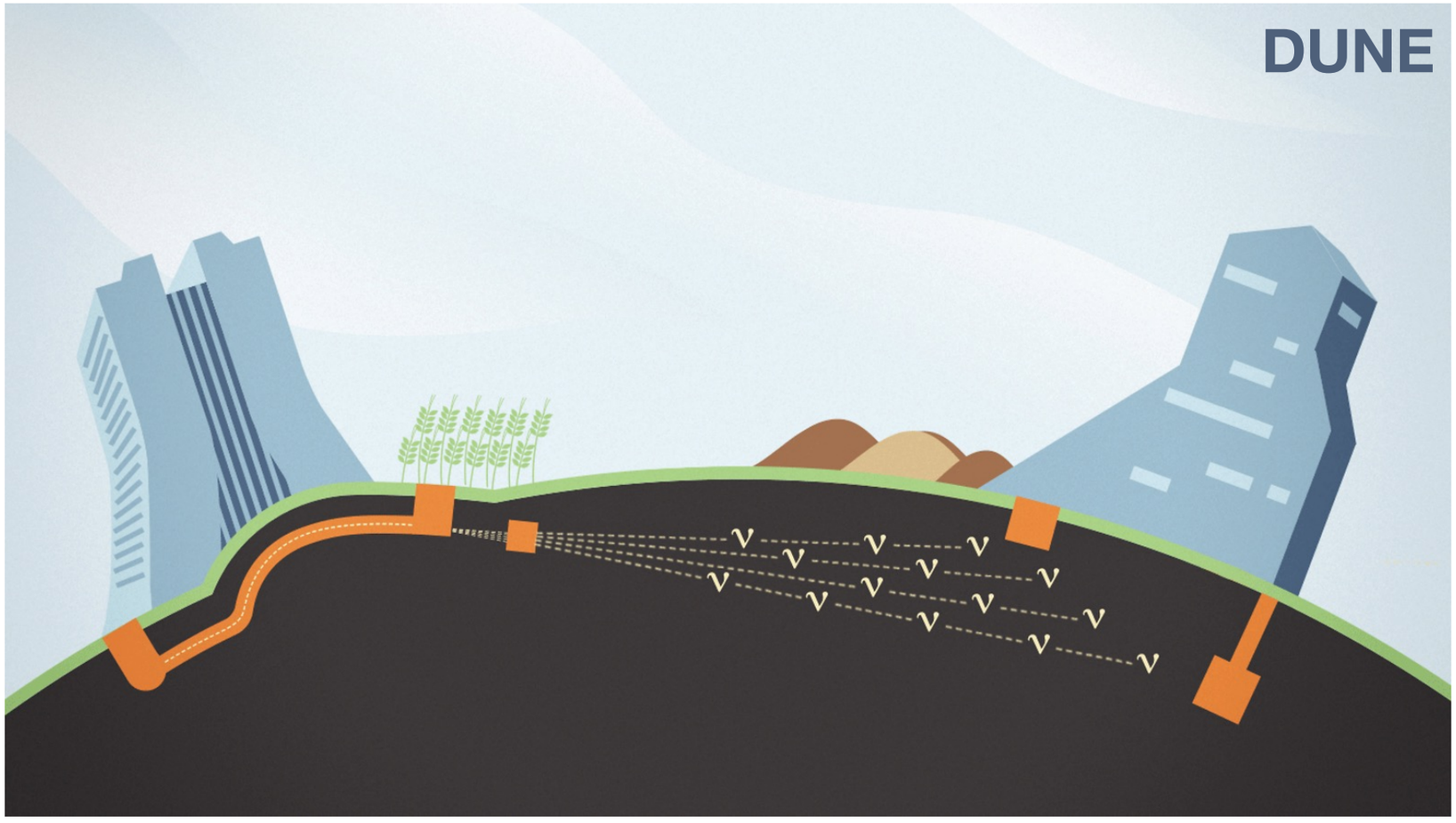
Noble Element Detectors for Neutrino Physics



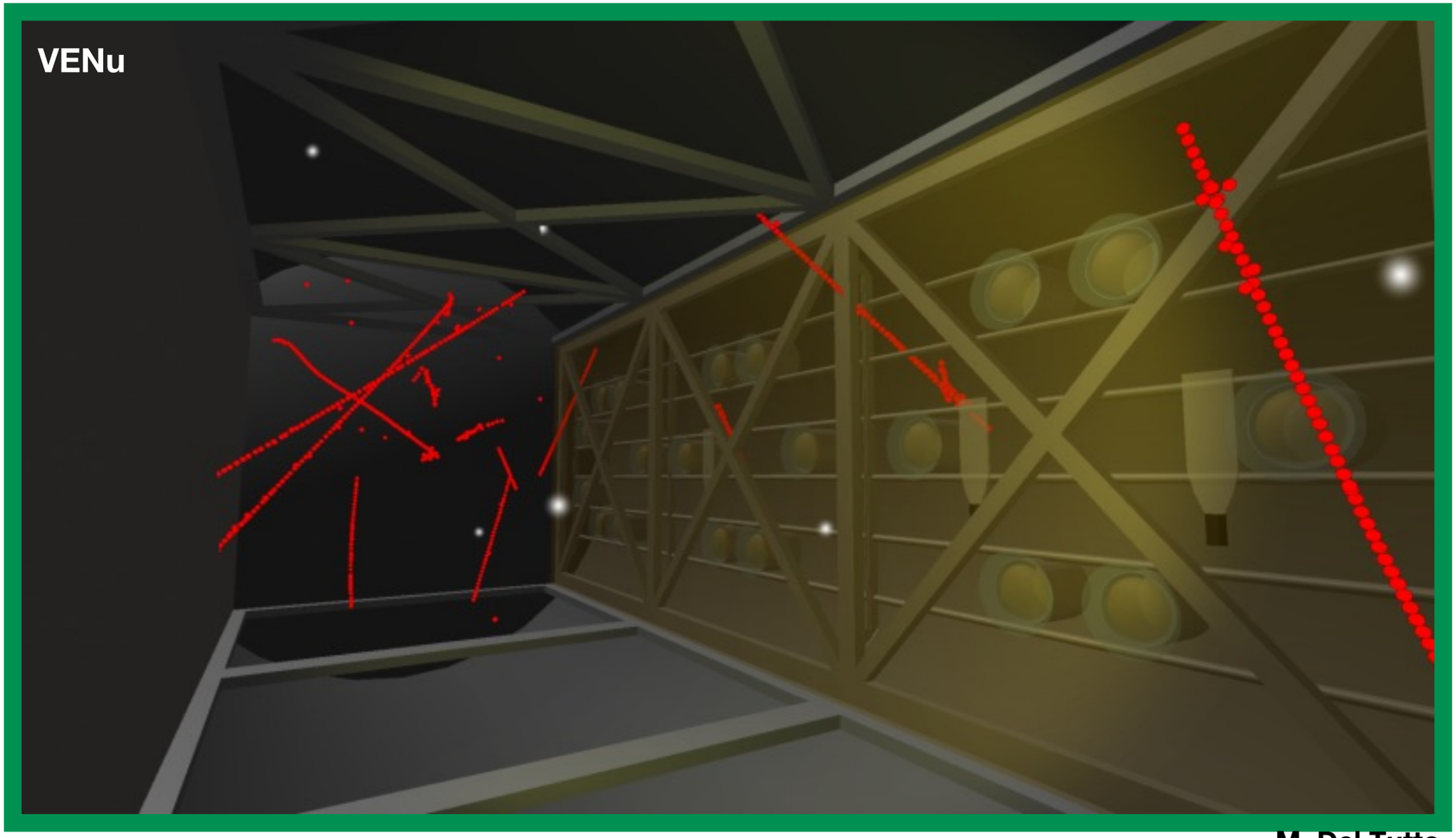
More details on neutrino physics in *Neutrino Theory* and *Neutrino Oscillation Experiments* Lectures

Neutrino physics detector requirements

- Accelerator neutrinos E_ν ~ GeV
- Need high neutrino detection efficiency
- Need good background rejection
- Need extremely large detectors (kilo-ton scale)



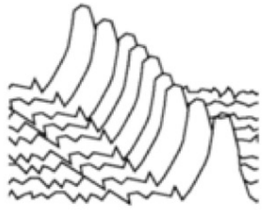
Neutrino physics detector requirements

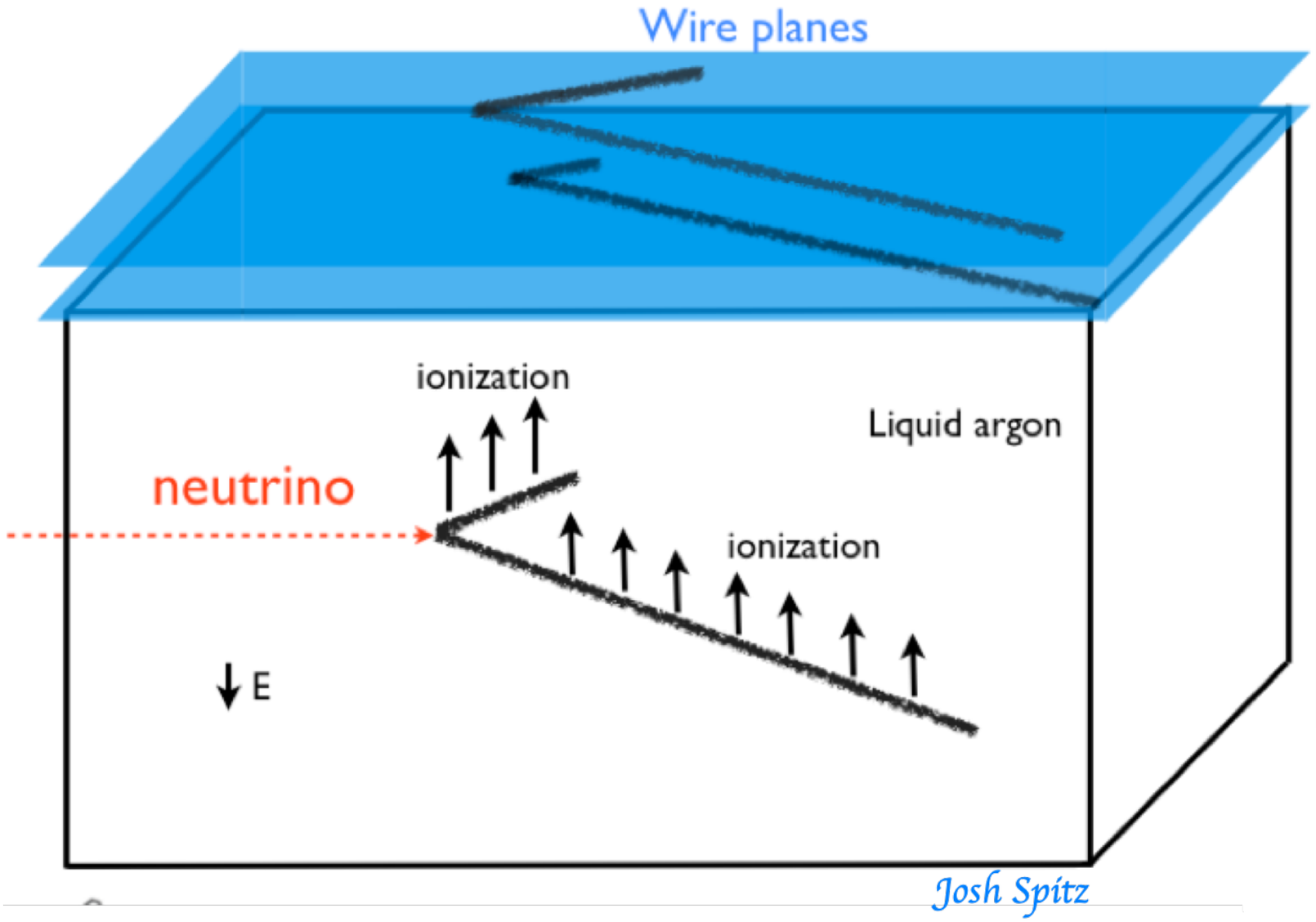


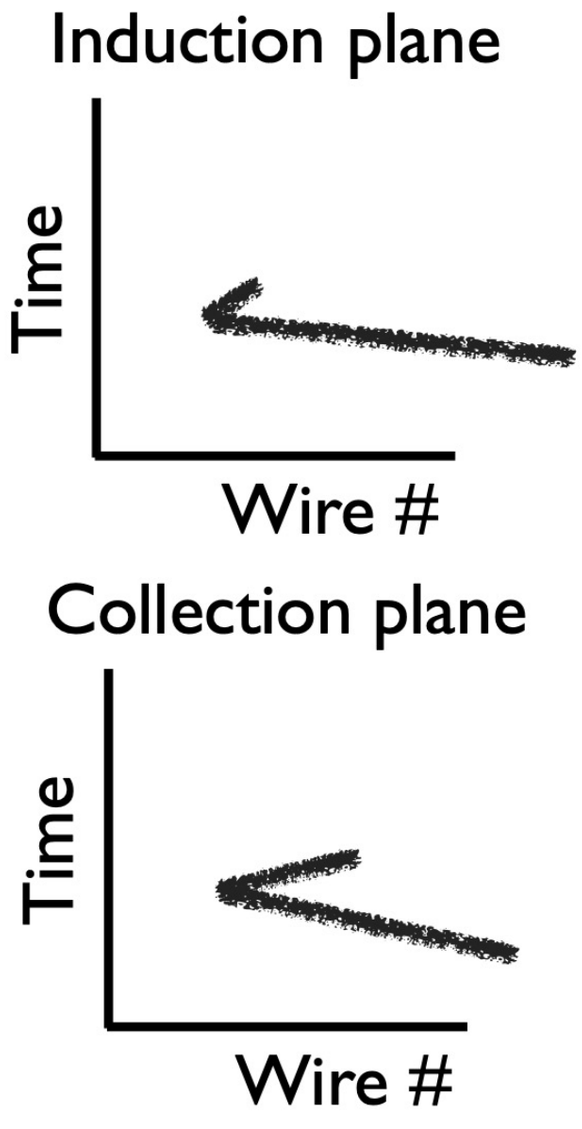
M. Del Tutto

Liquid Argon TPCs are an ideal choice!

LArTPCs for neutrino physics

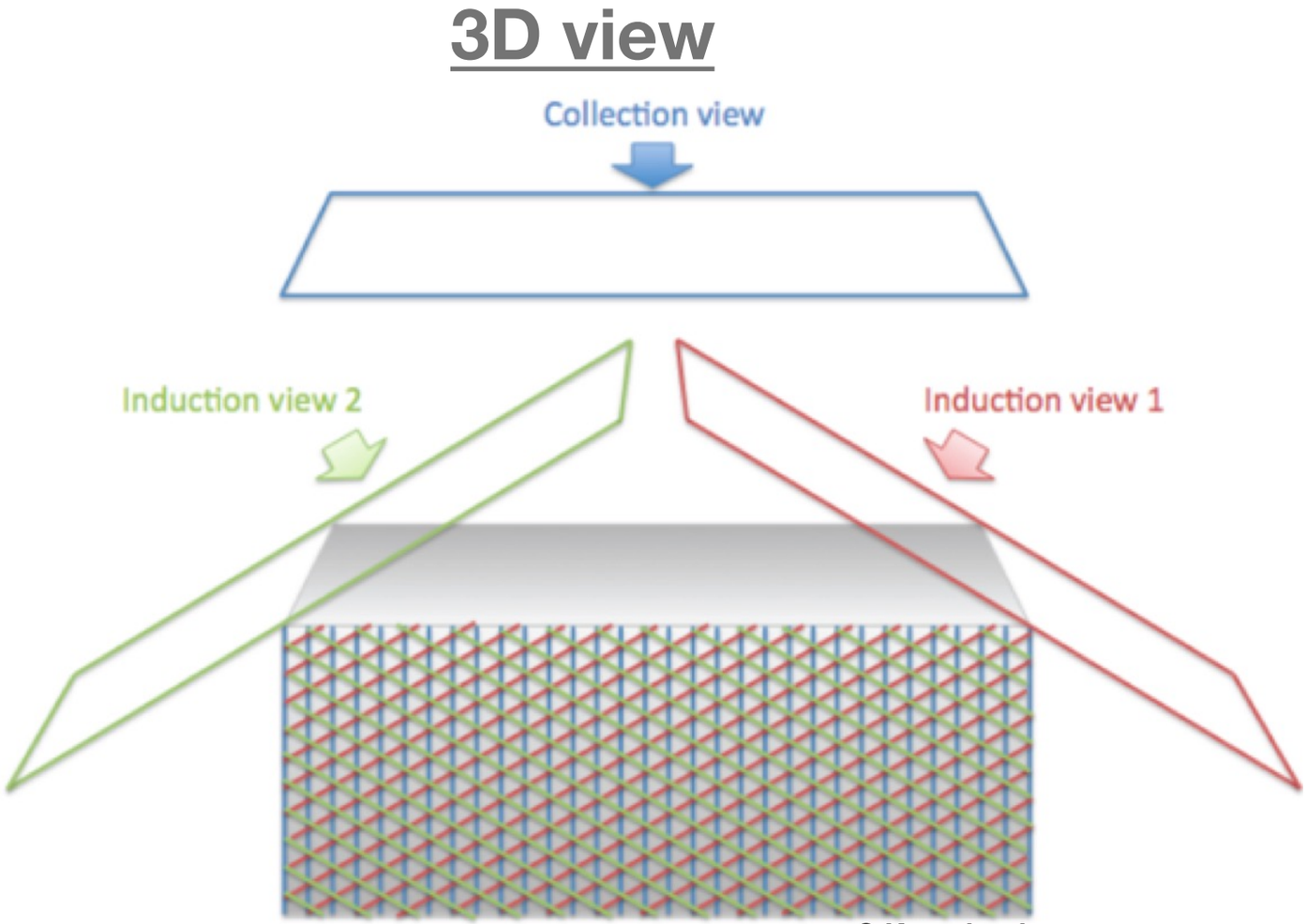




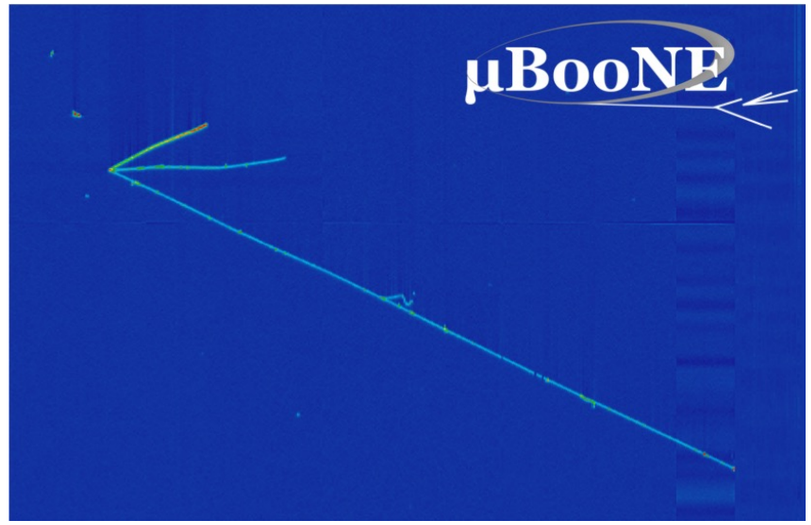


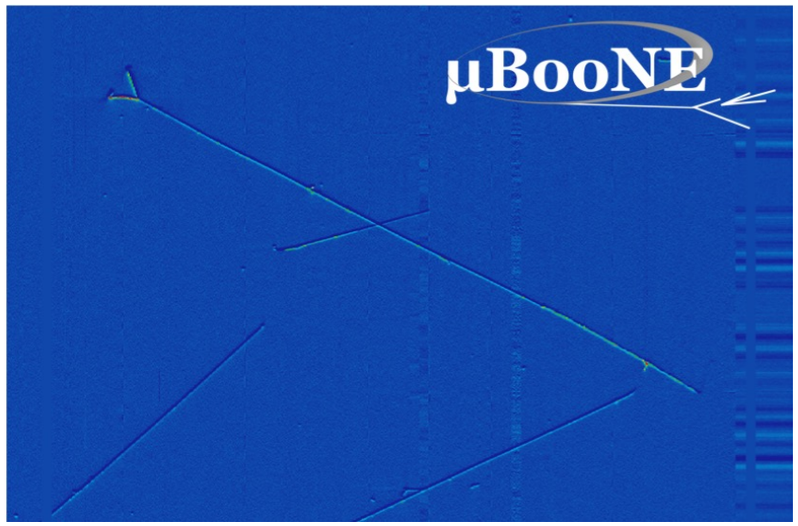
Scintillation light used to trigger and identify neutrino activity
Wire spacing decided based on desired “image resolution”

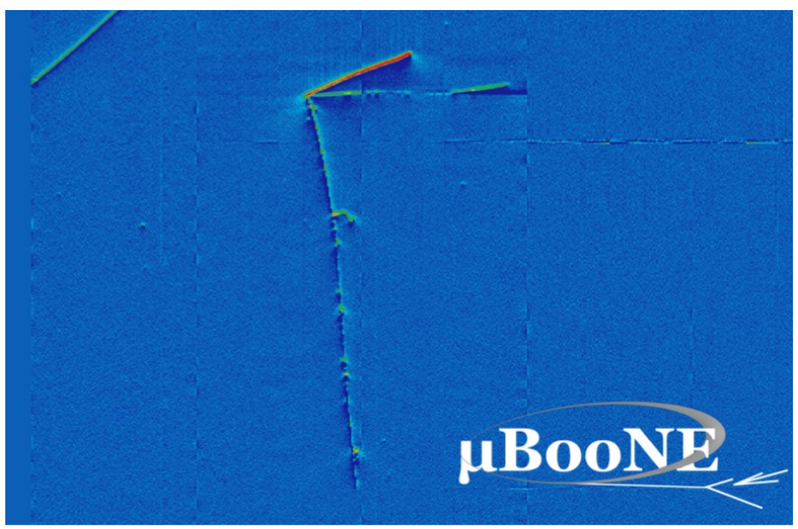
LArTPCs for neutrino physics



G.Karagiorgi

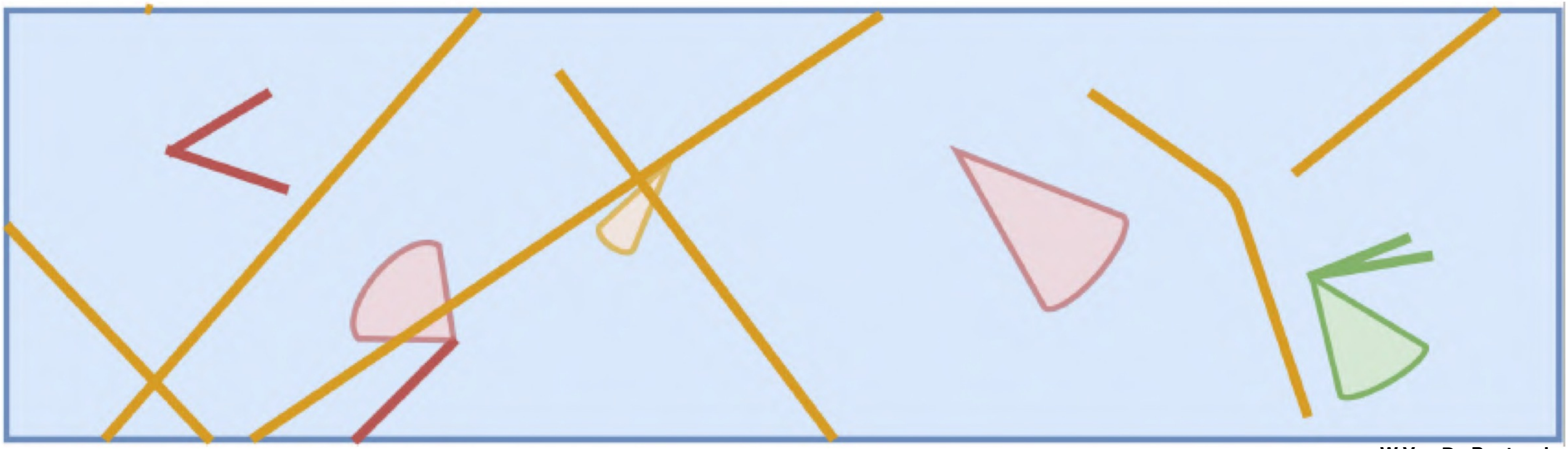






LArTPCs for neutrino physics

- All one have to do is reconstruct these images and compare signal and background events to theoretical predictions!



W.Van De Pontseele

LArTPCs for neutrino physics

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W.Van De Pontseele

LArTPCs for neutrino physics

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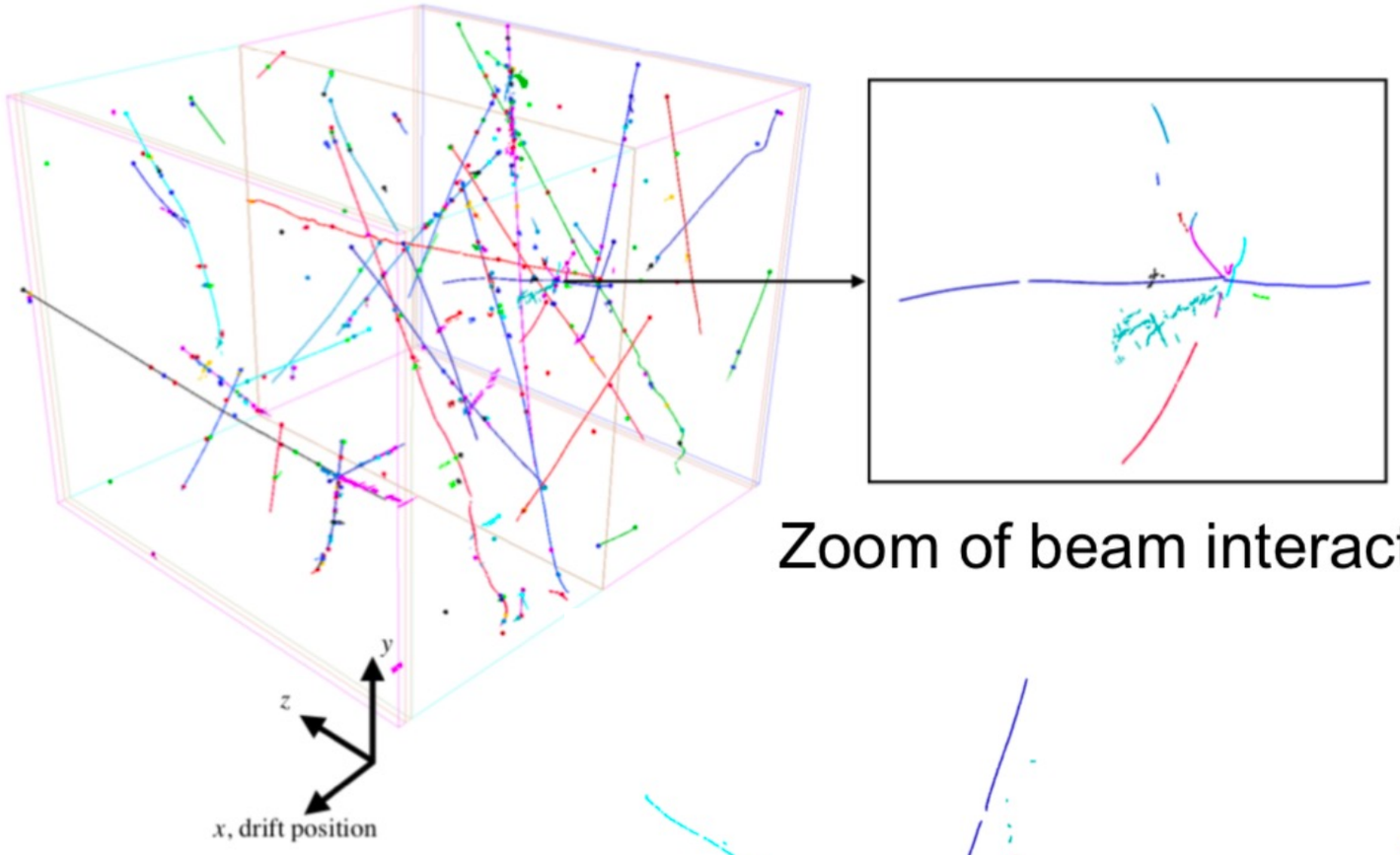
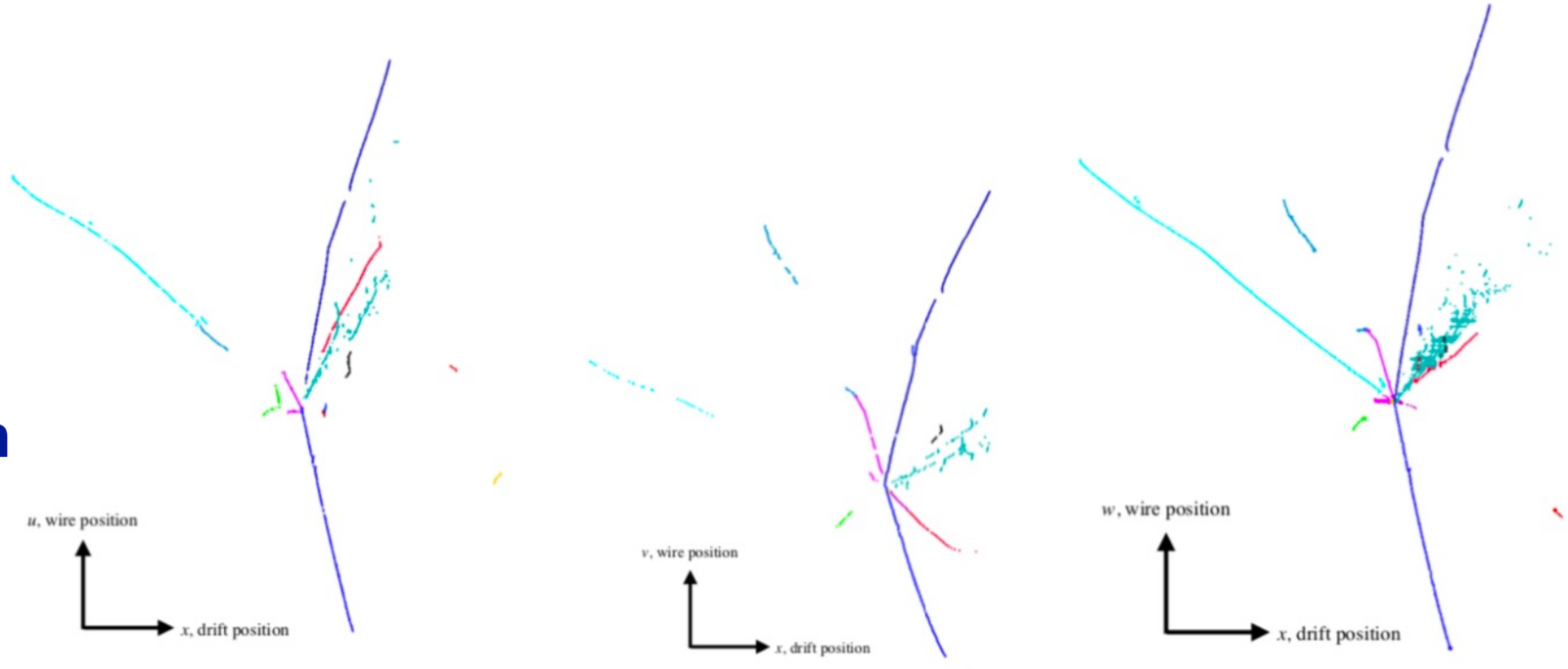


Zoom of beam interaction

L.Whitehead, ICHEP2020

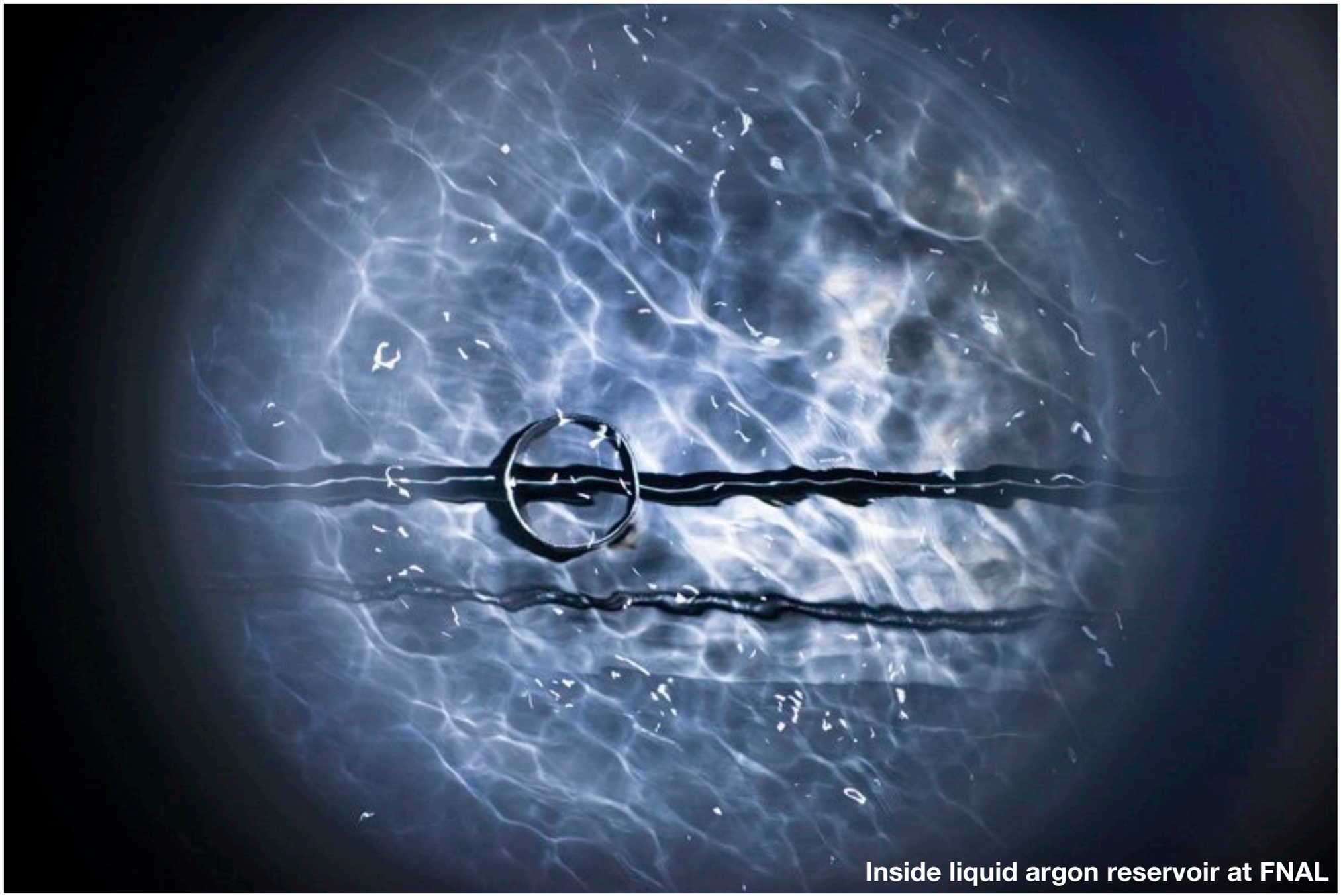
Many methods to reconstruct events

Pandora reconstruction software



Simulated test-beam interaction in ProtoDUNE

But microphysics gets in the way!



Ionization, transport and recombination

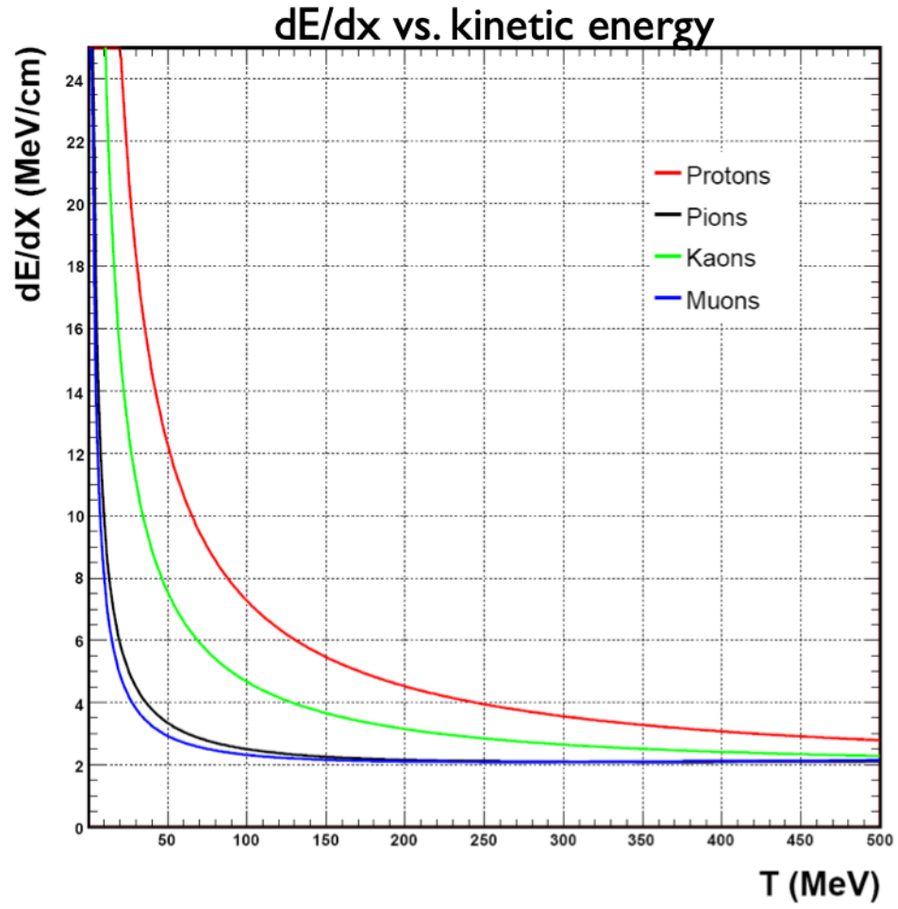
- Charged particles deposit energy (dE/dx) and ionize the element

- Number of ionization e^- depends on energy deposited by particle

***e.g.* for Ar:** $N_e = 42370\ (e^-/\text{MeV}) * E\ (\text{MeV})$

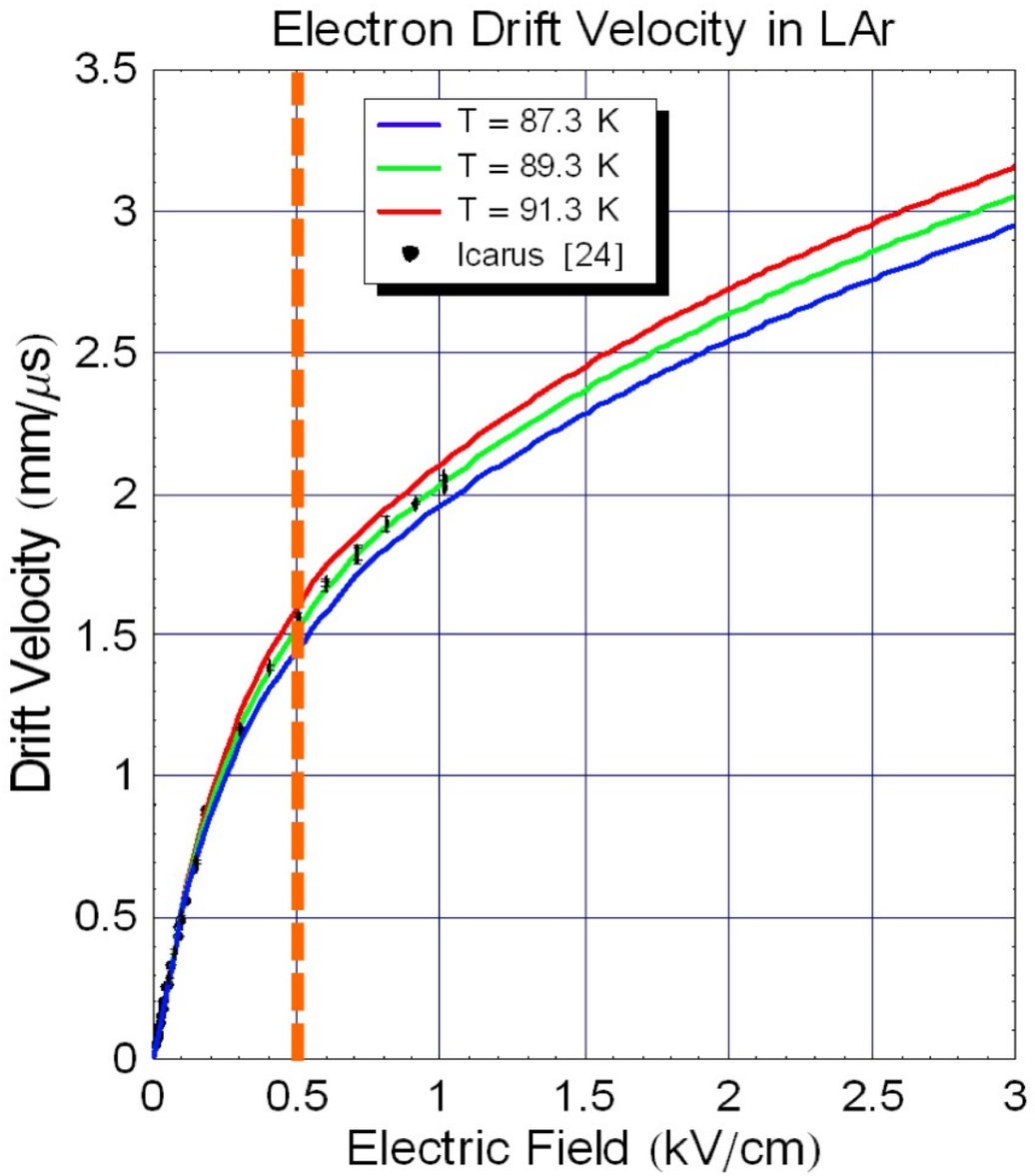
from mean e^-/ion pair production energy for Ar = 23.6 eV

$$W_i = E_i + \frac{N_{ex}}{N_i} E_{ex}$$

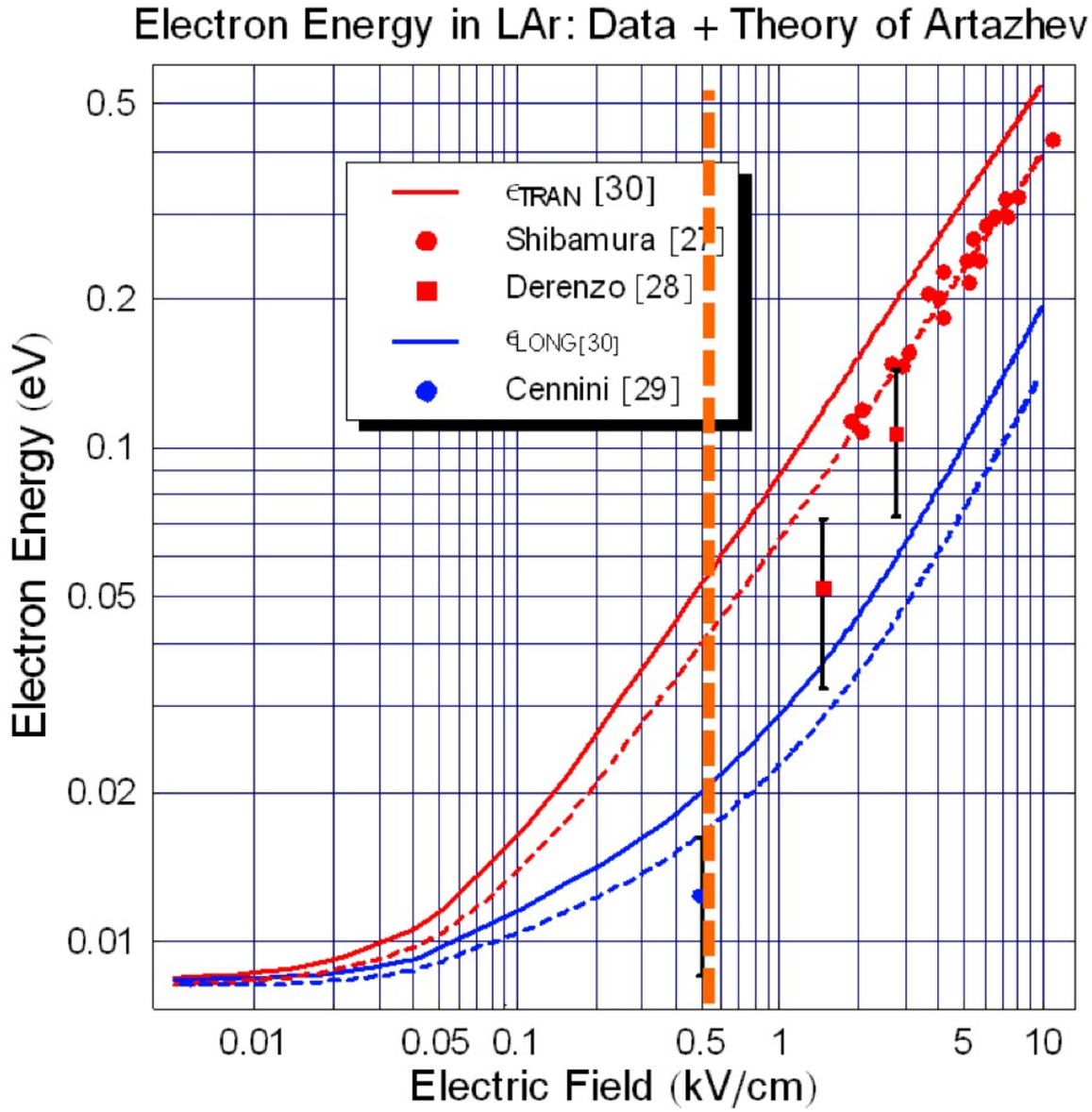


Ionization, **transport** and recombination

- Ionization e^- drift in the electric field



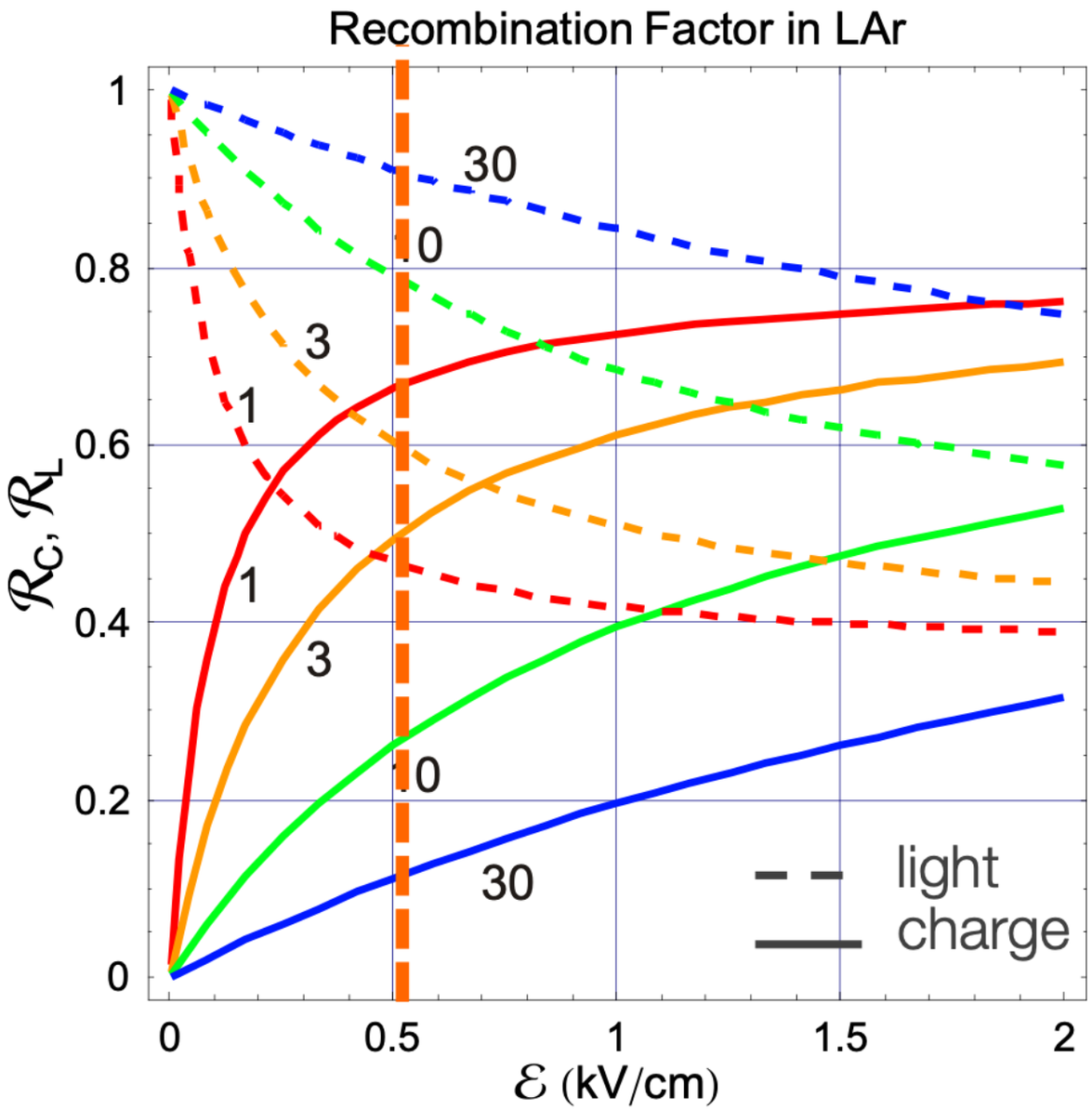
A.M. Kalinin et al., Atlas Internal LARG-NO-058, (1996)



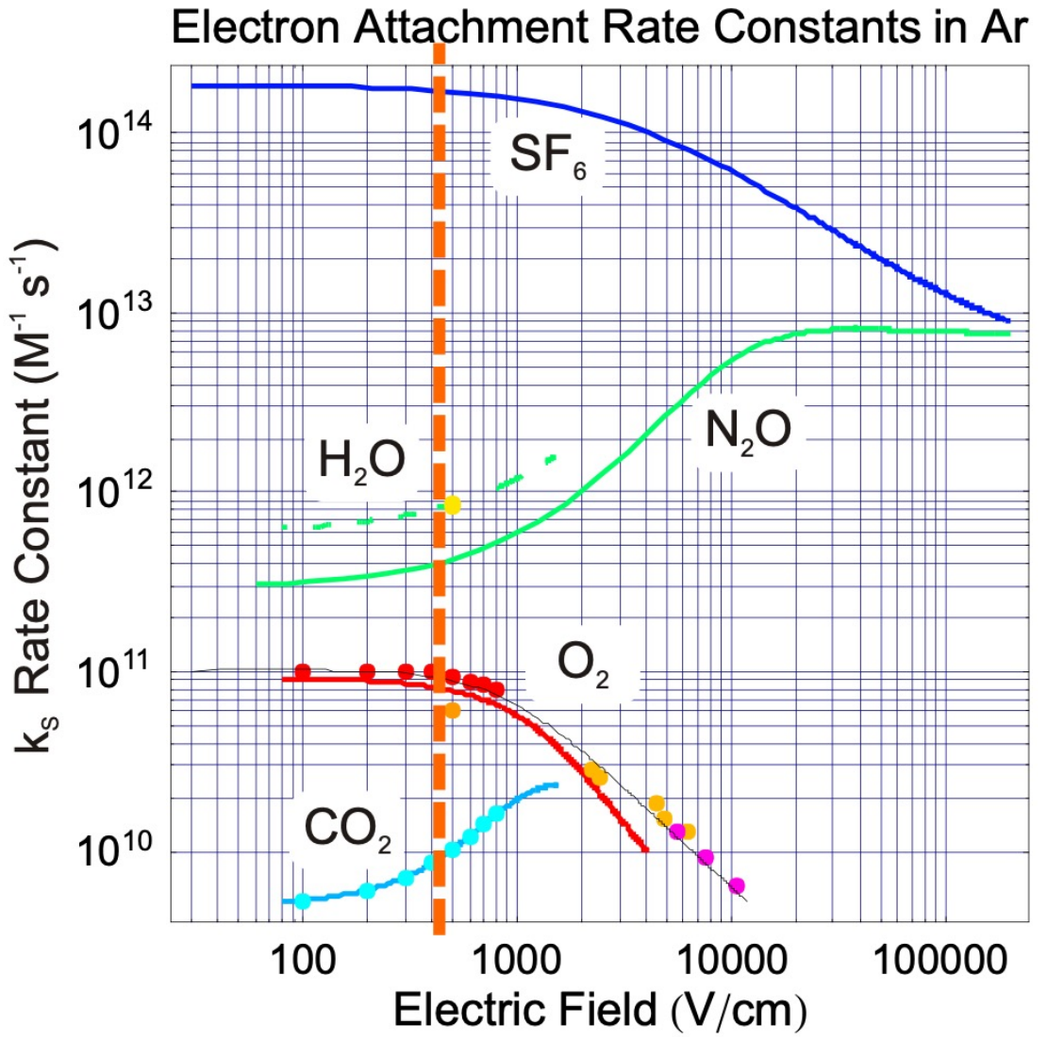
V.M. Atrazhev & I.V. Timoshkin,, IEEE Trans. Dielectrics and Electrical Insulation 5, 450, (1998)

Ionization, transport and **recombination**

- Recombination and impurities can reduce the charge collected



Thomas and Imel., Phys. Rev. A, 36 (1987)



33. G. Bakale, U. Sowada, and W.F. Schmidt, *Effect of electric field on electron attachment to SF_6, N_2O, and O_2 in liquid argon and xenon*, J. Phys. Chem. **80** (1976) 2556.

34. A. Bettini, *et al.*, *A study of the factors affecting the electron lifetime in ultra pure liquid argon*, NIM **A305** (1991) 177.

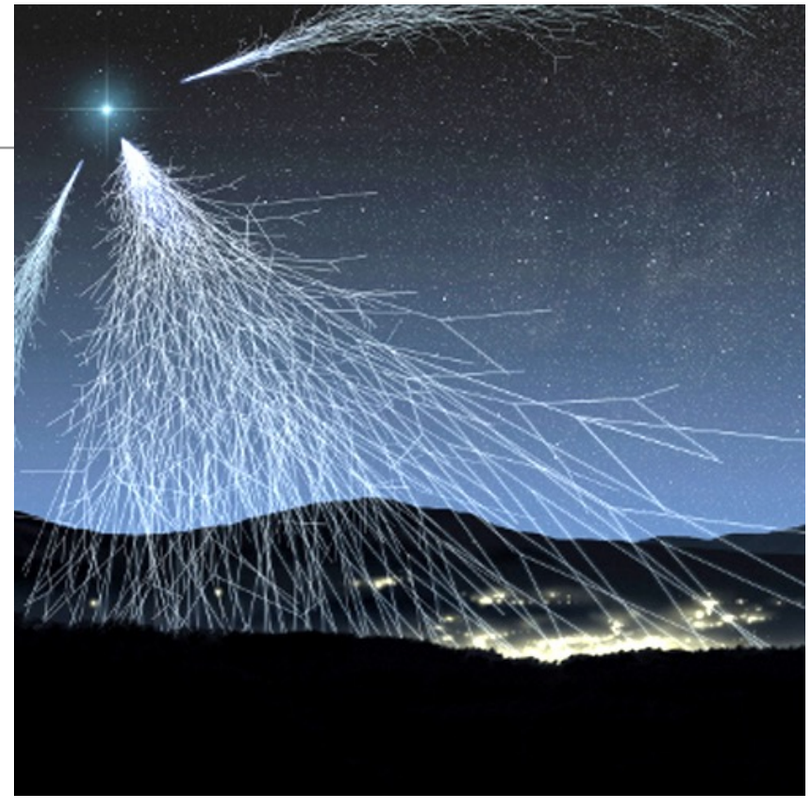
35. E. Aprile, K.L. Giboni, and C. Rubbia, *A study of ionization electrons drifting large distances in liquid and solid argon*, NIM **A241** (1985) 62.

36. M. Adams, *et al.*, *A purity monitoring system for liquid argon calorimeters*, NIM **A545** (2005) 613.

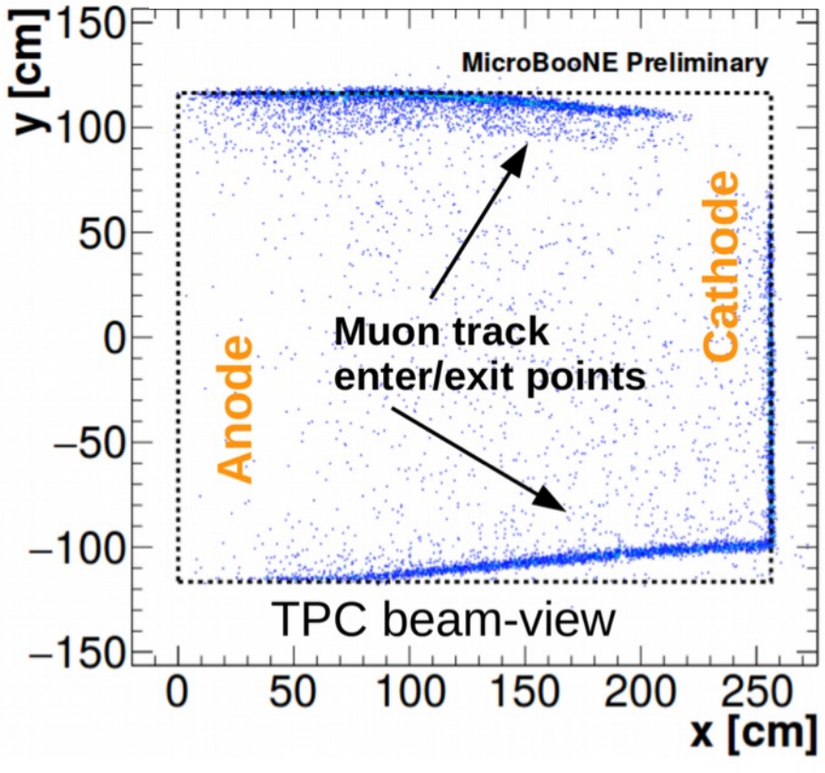
And more…

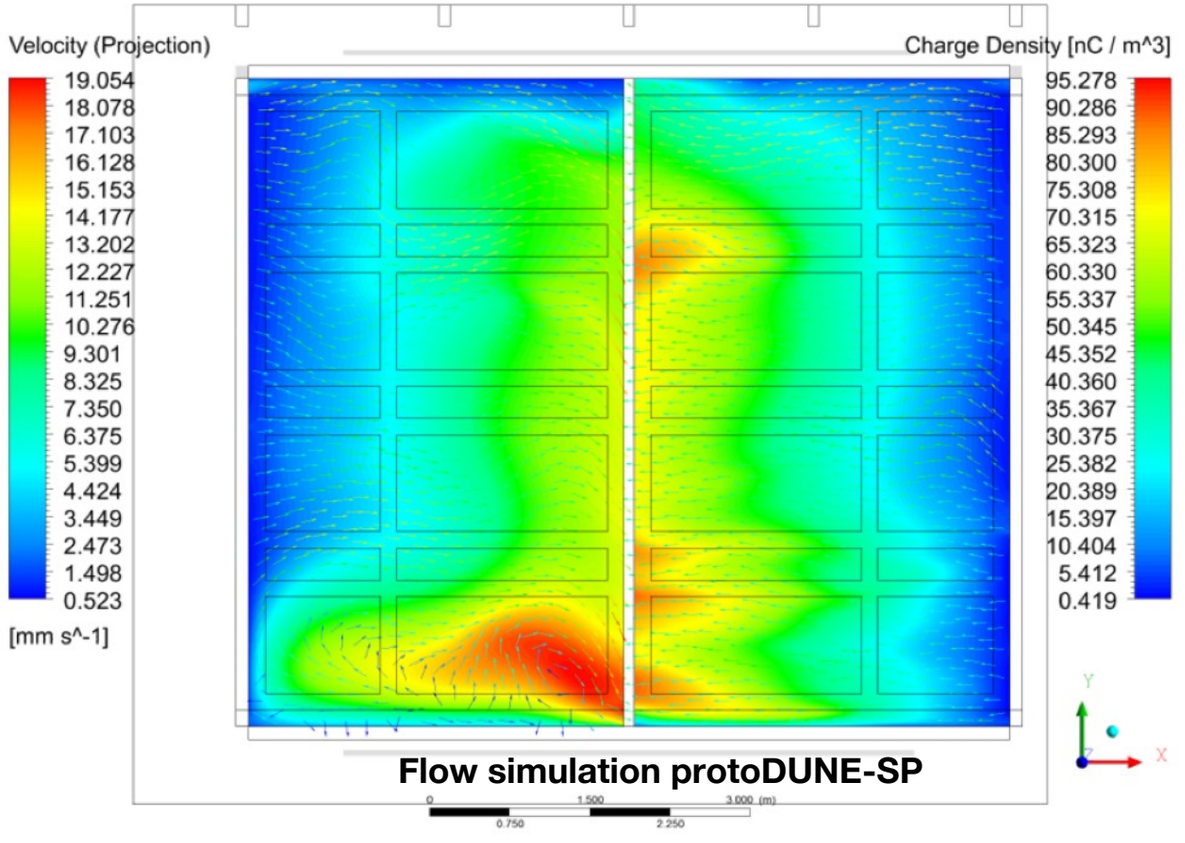
- TPCs rely on uniform E_{field} to drift ionization e^-

- High cosmic-ray rates (creating a lot of slow-moving ions) and non-uniform flows can introduce E_{field} distortions → deforming interactions images

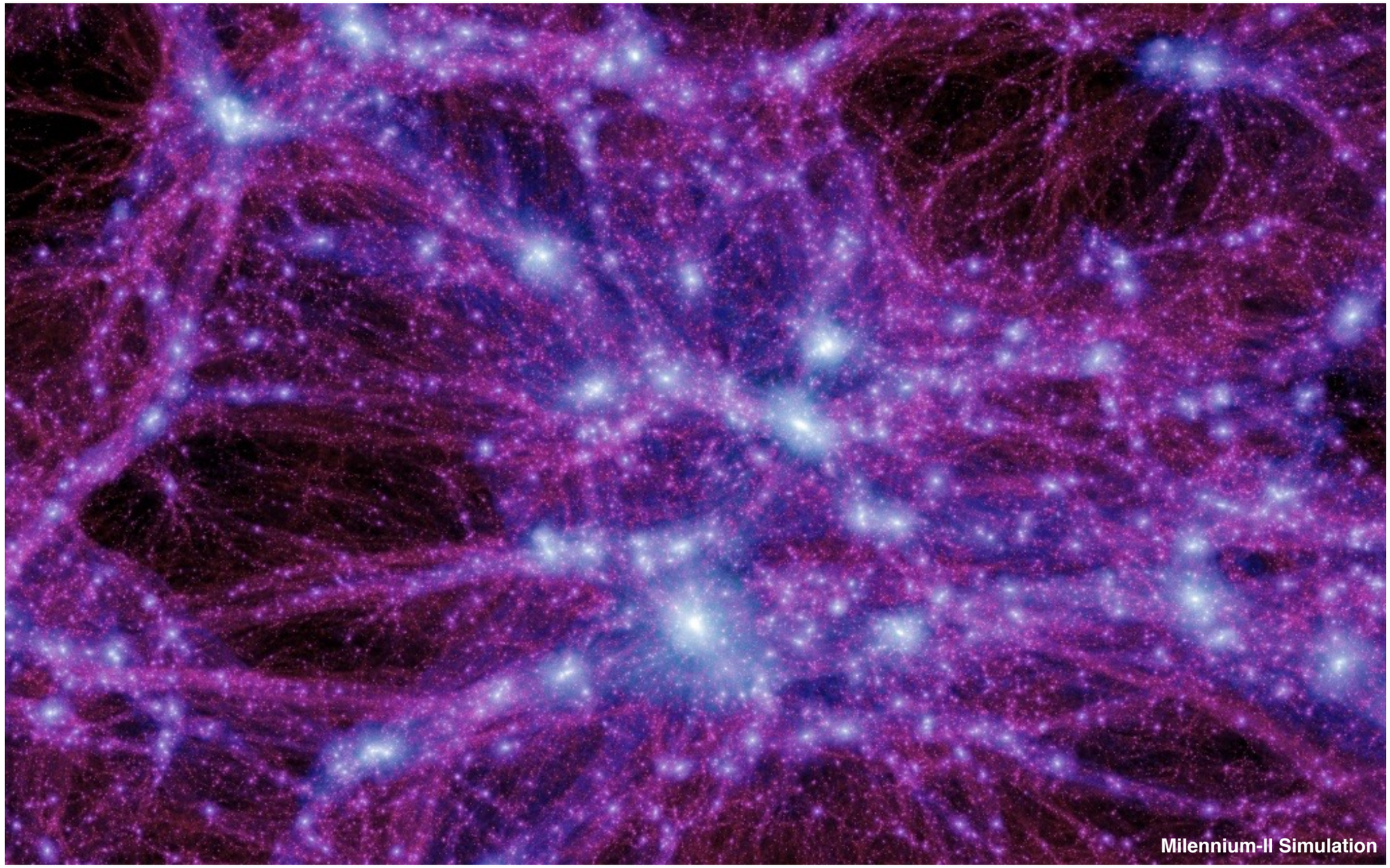


MICROBOONE-NOTE-1018-PUB





Noble Element Detectors for Dark Matter

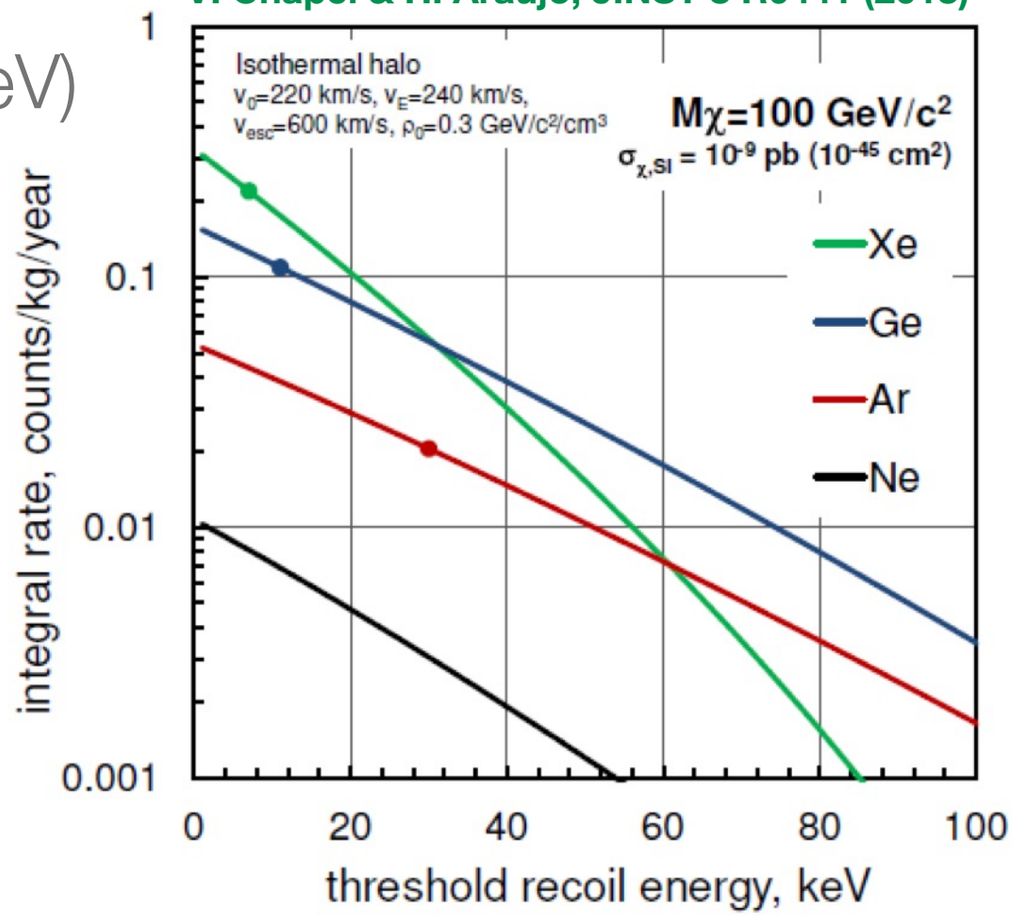


More details on Dark Matter physics in *Direct Dark Matter Searches* Lectures

Noble Element Detectors for Dark Matter

- Need very large detectors (multi ton-scale)
- Need low-energy detection thresholds (keV)
- Need low background

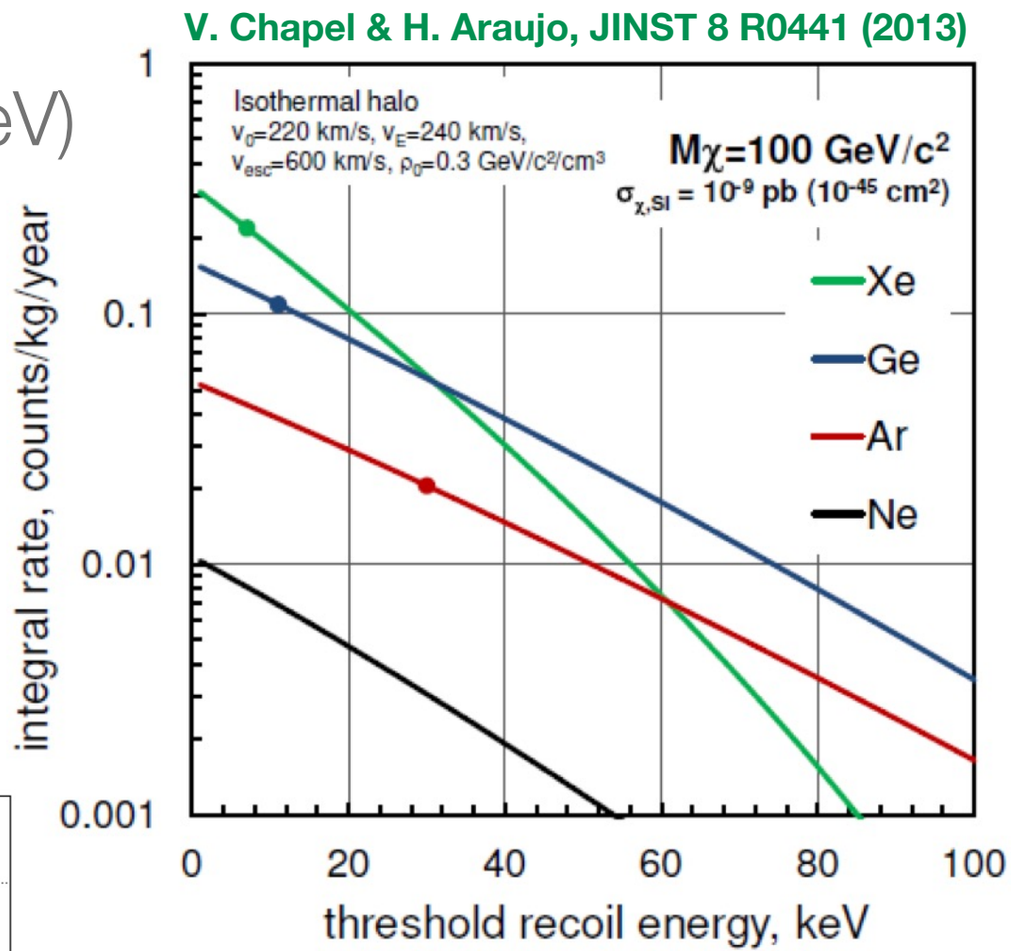
V. Chapel & H. Araujo, JINST 8 R0441 (2013)

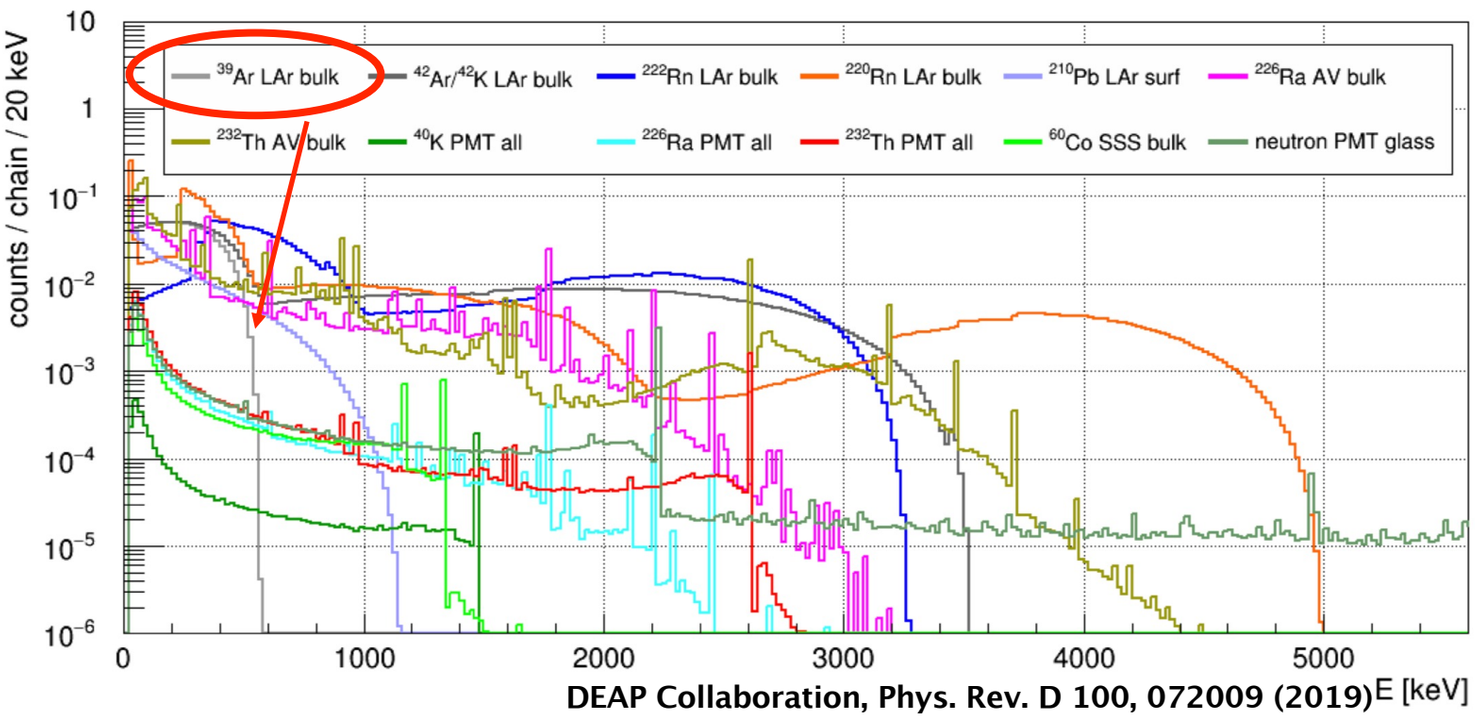


Noble Element Detectors for Dark Matter

- Need very large detectors (ton-scale)
- Need low-energy detection thresholds (keV)
- Need low background

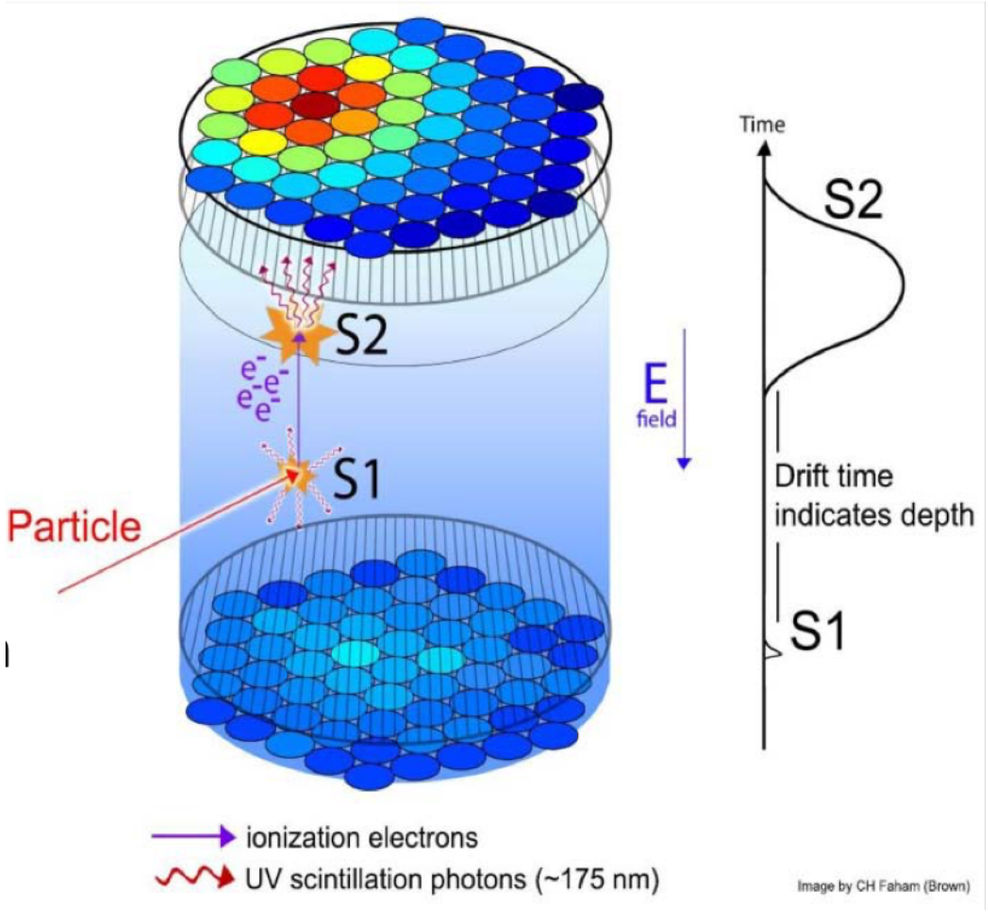
Ar seems a good choice, but ^{39}Ar (≤565 keV) contamination
So Xe became the default (until we found underground Ar)





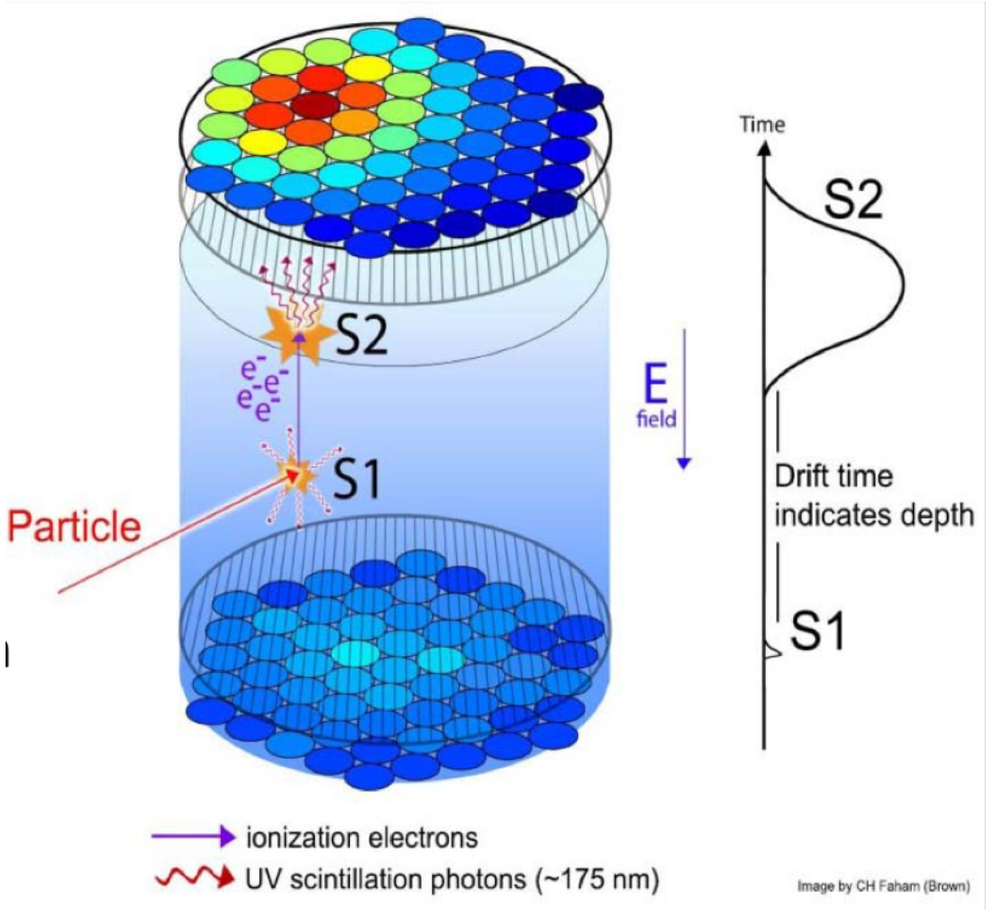
DEAP Collaboration, Phys. Rev. D 100, 072009 (2019)

Liquid Xenon TPCs for dark matter



- Dual-phase TPC
- Amplification (*e.g.*~30ph/e^-) of charge with electroluminescence (S2) in vapor phase
- Self-shielding (attenuation lengths of photons <10 cm for few MeV photons)
- Position identification ~mm level
- Combining S1 (scintillation) and S2 (amplified electroluminescence) allows for Pulse Shape Discrimination

Liquid Xenon TPCs for dark matter



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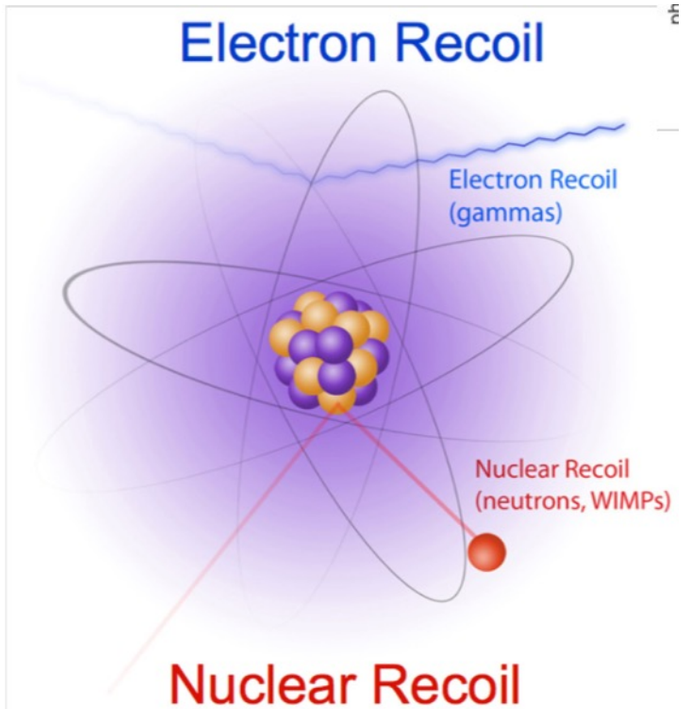
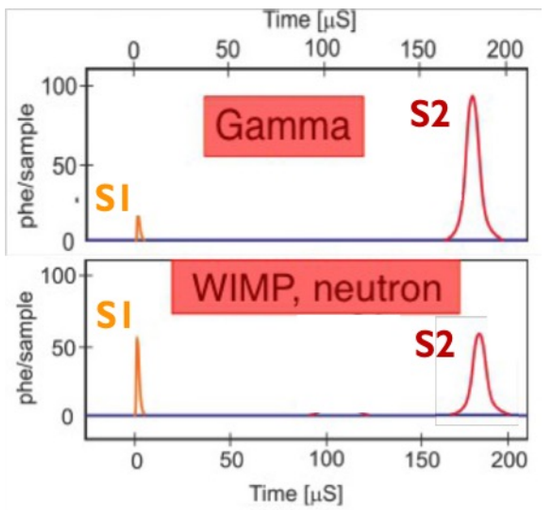
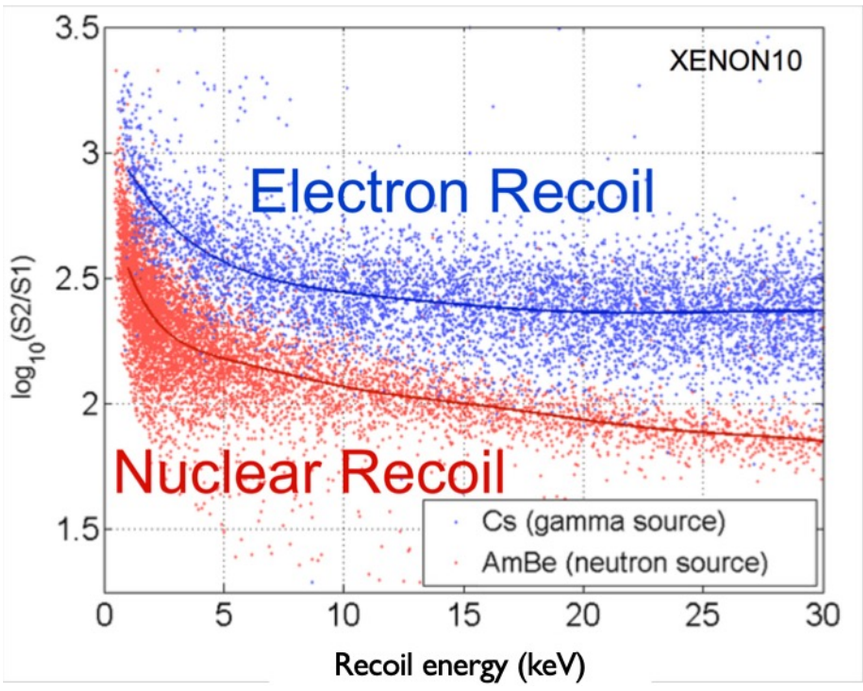
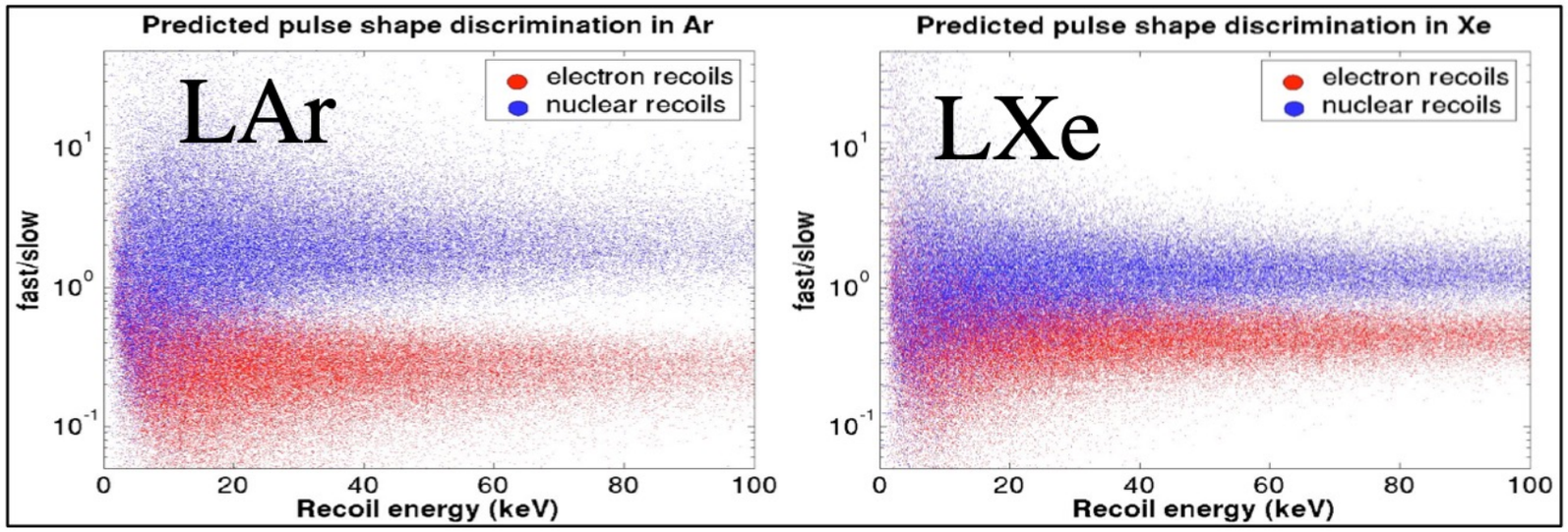






Liquid Argon TPCs for dark matter

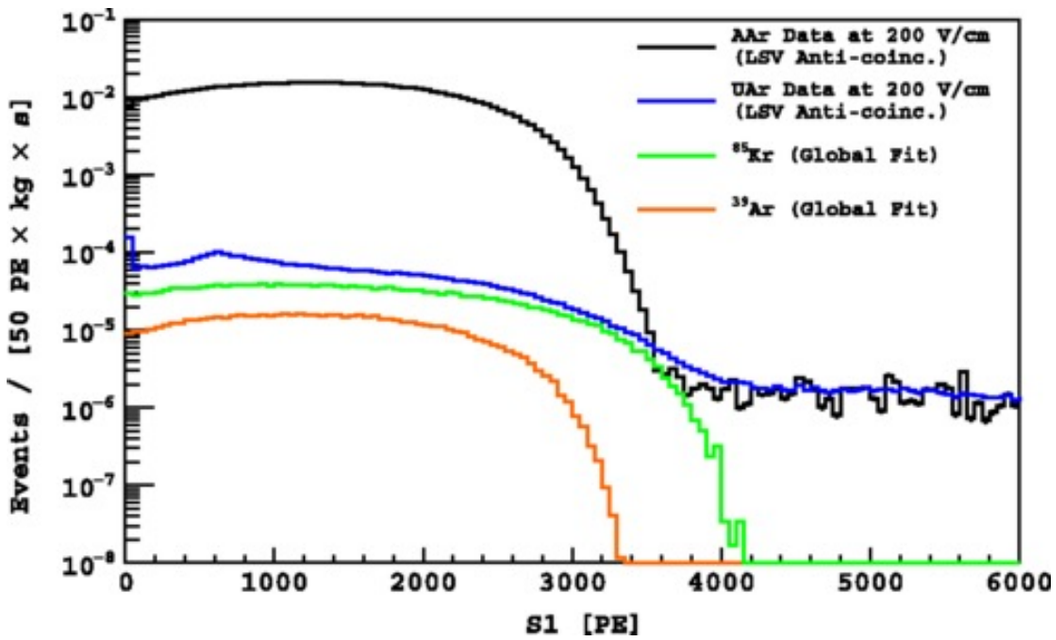
- LAr is also powerful for dark matter search



from T.Shutt

- But ^{39}Ar is a big issue… until now!

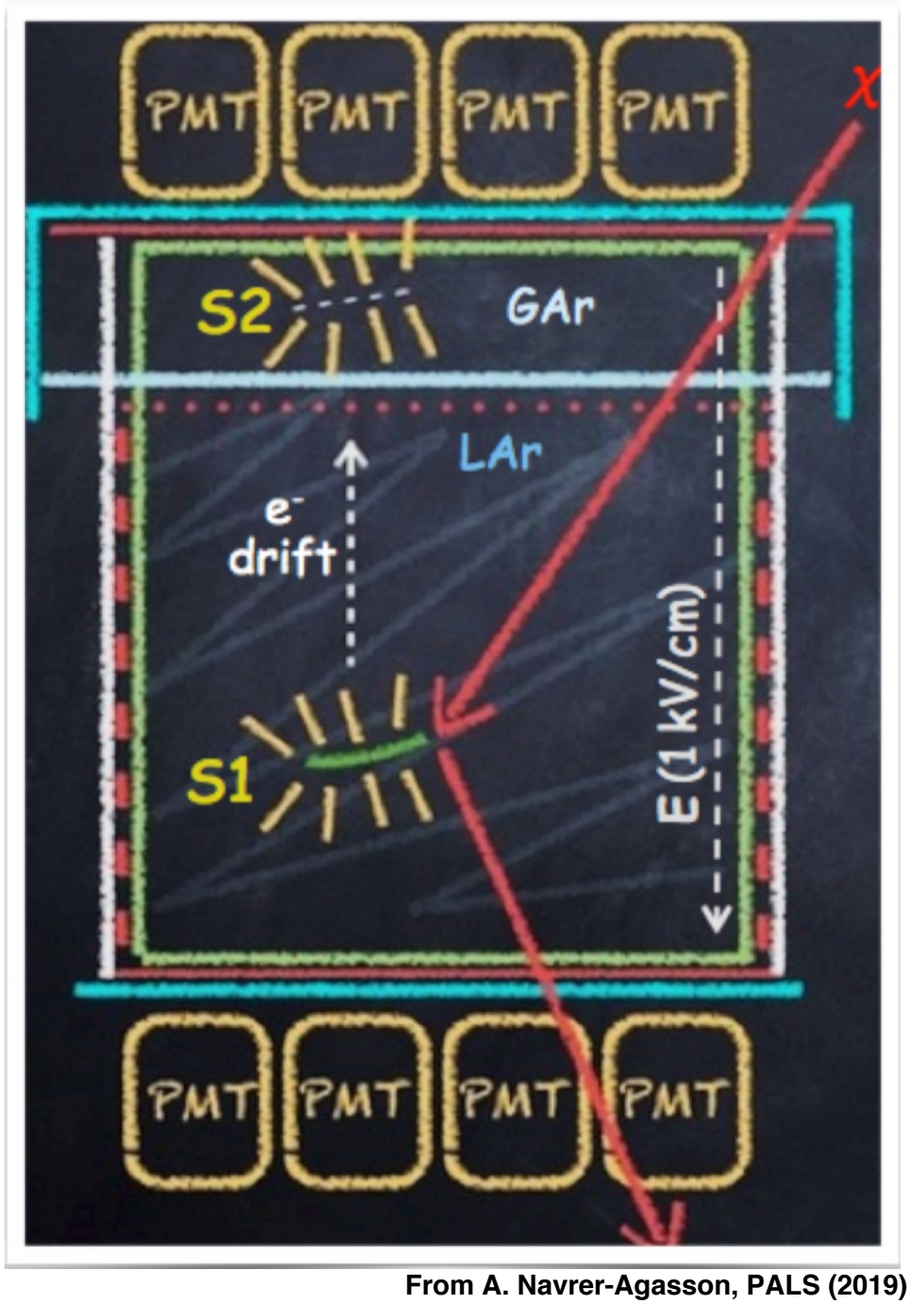
Extraction of Underground Ar (by-product of $C0_2$ facility)



DarkSide Collaboration, Phys. Rev. D 93, 081101(R) 2016

Liquid Argon TPCs for dark matter

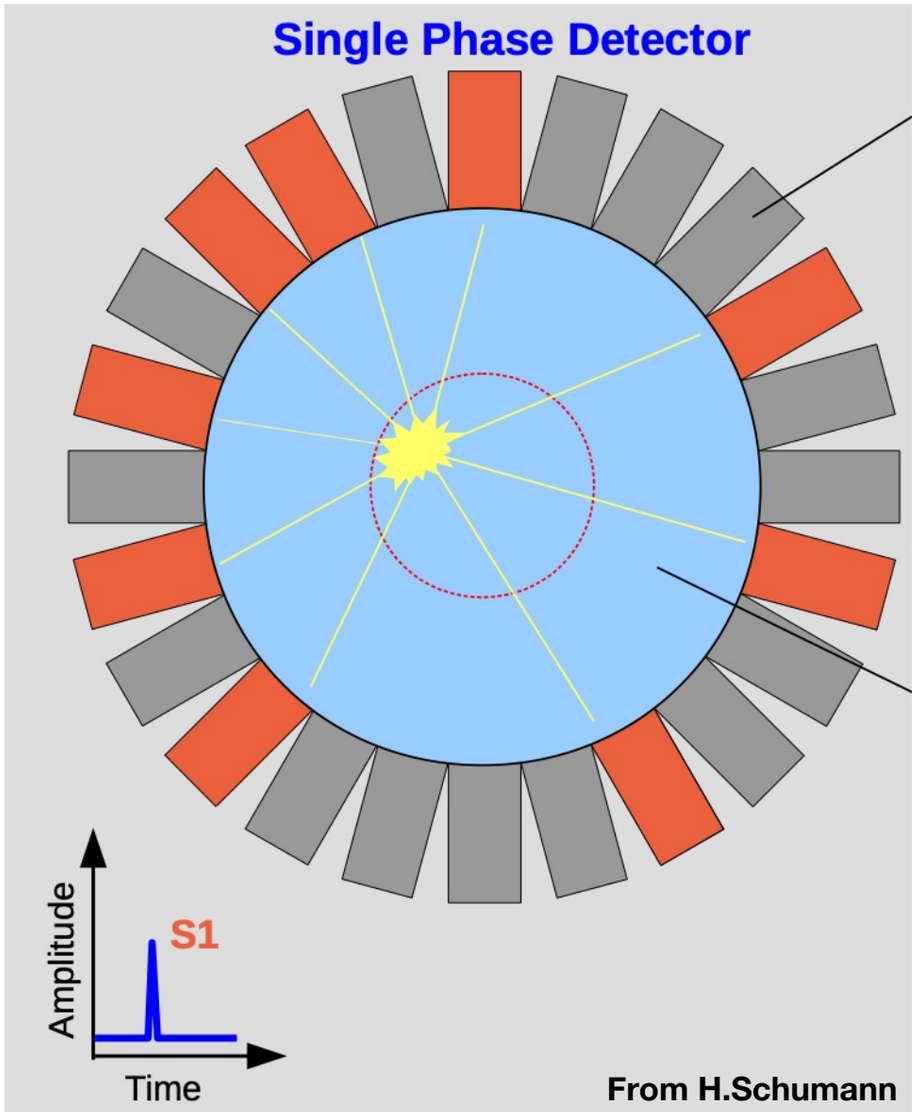
- Dual-phase Ar TPC



From A. Navrer-Agasson, PALS (2019)

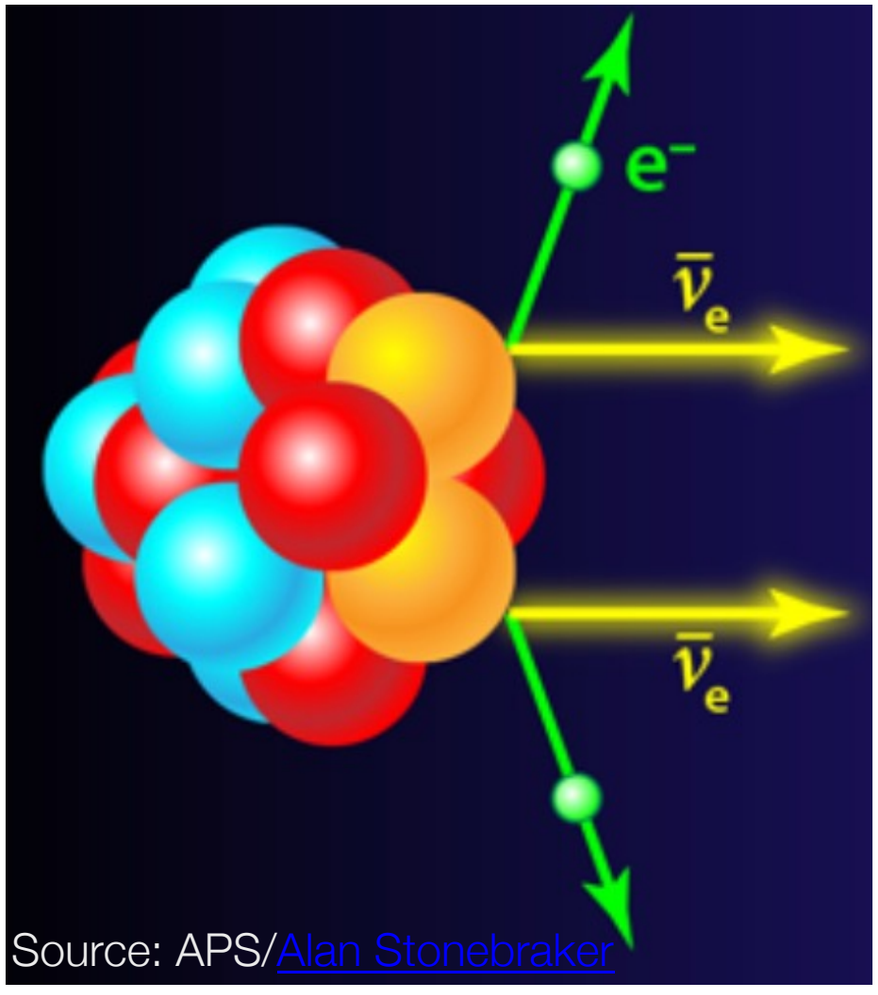
Liquid Argon **detector** for dark matter

- Some dark matter single-phase detectors are not TPCs and they only use the scintillation light



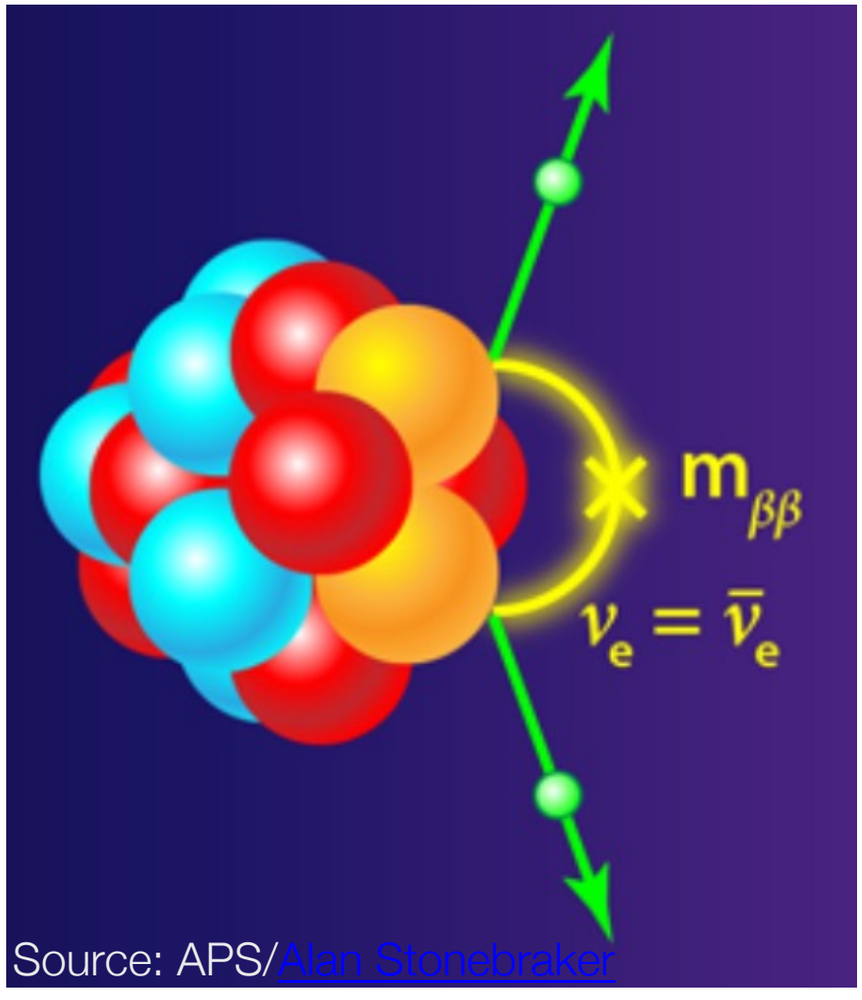
Noble Element Detectors for neutrinoless double beta decay

Allowed regular ββ



Source: APS/Alan Stonebraker

Neutrinoless ββ



Source: APS/Alan Stonebraker

Noble Element Detectors for neutrinoless double beta decay

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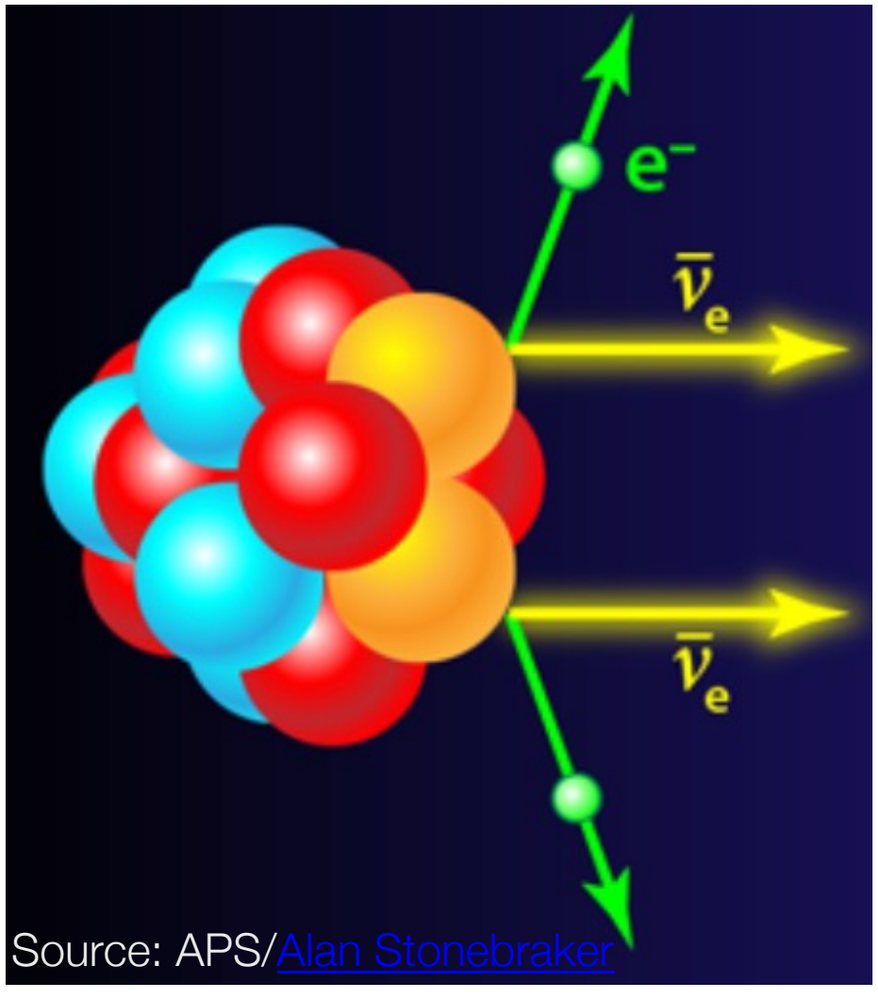
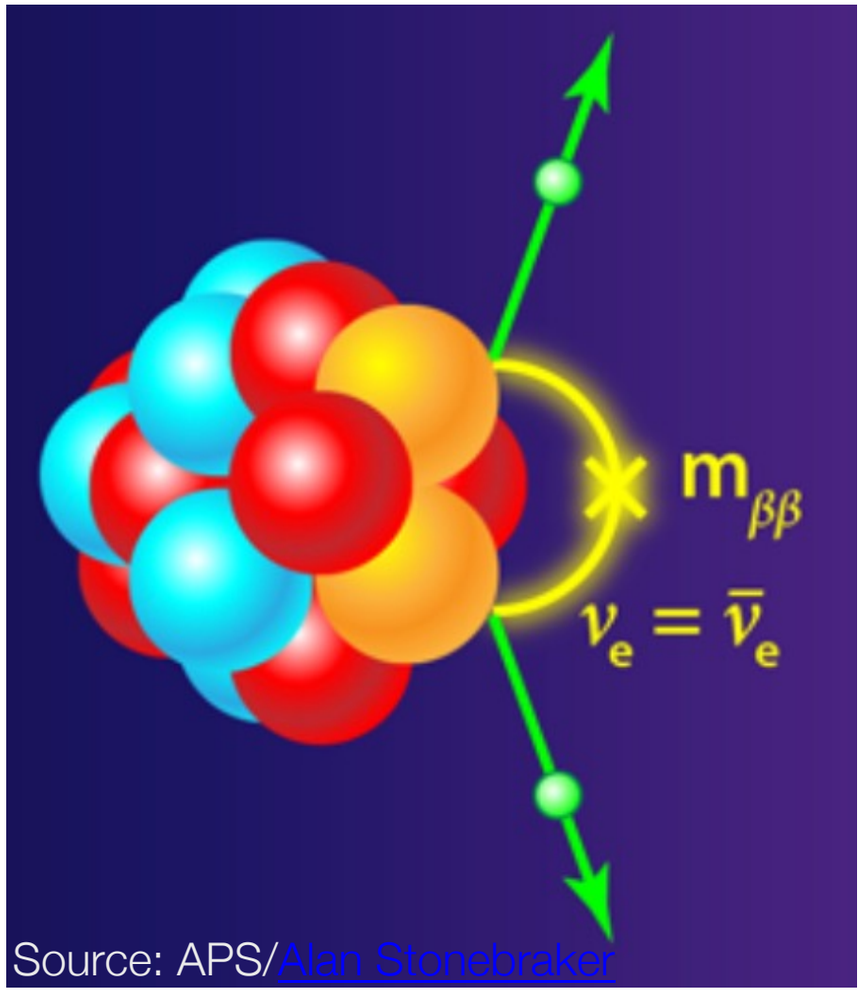


Source: APS/Alan Stonebraker

Neutrinoless ββ

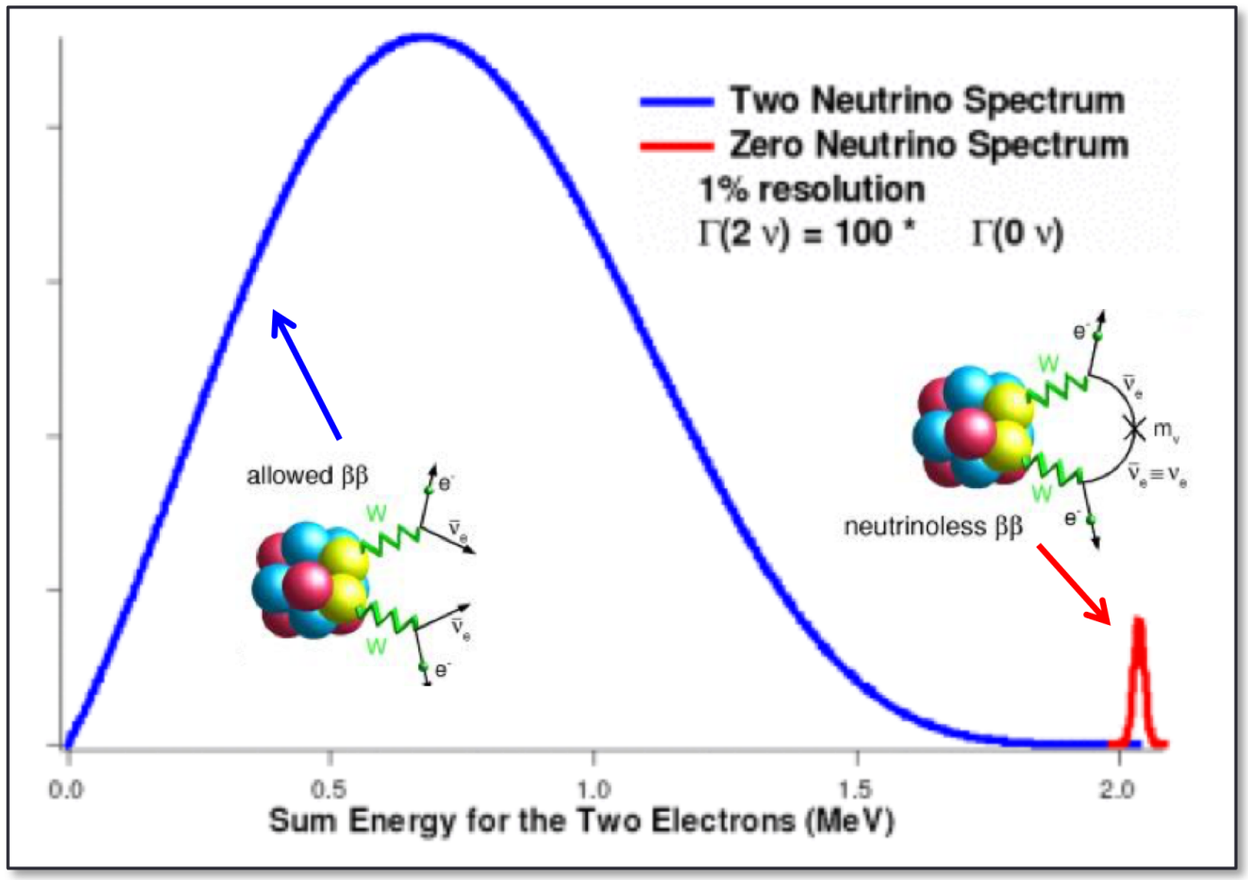


Source: APS/Alan Stonebraker

Here, there is no choice! The only noble element that can undergo double beta decay is ^{136}Xe

Noble Element Detectors for neutrinoless double beta decay

- Need very large detectors (ton-scale)
- Need excellent energy resolution
- Need very low background
- Energy of interest: 2.5 MeV

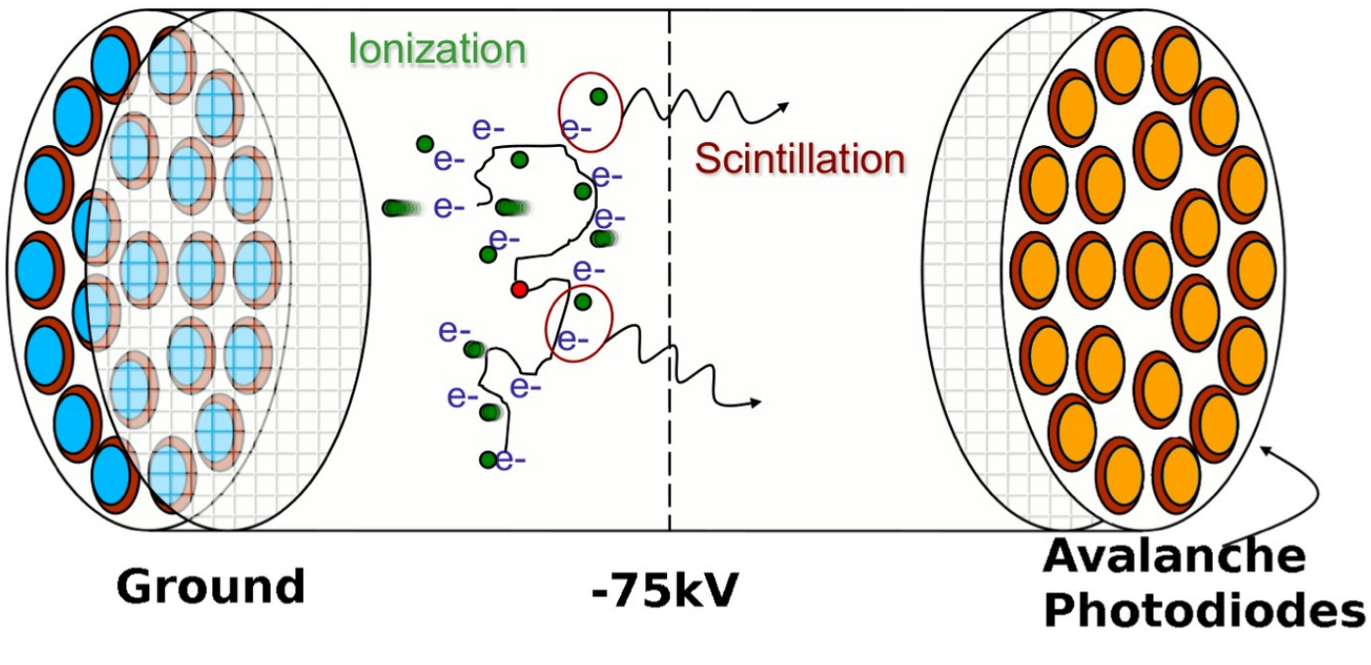


Two choices of technology: Liquid Xe TPC or Gaseous Xe TPC

LXeTPC for neutrinoless double beta decay

- Single-phase TPC (collects both charge and light directly)

EXO-200 schematic



LXeTPC for neutrinoless double beta decay

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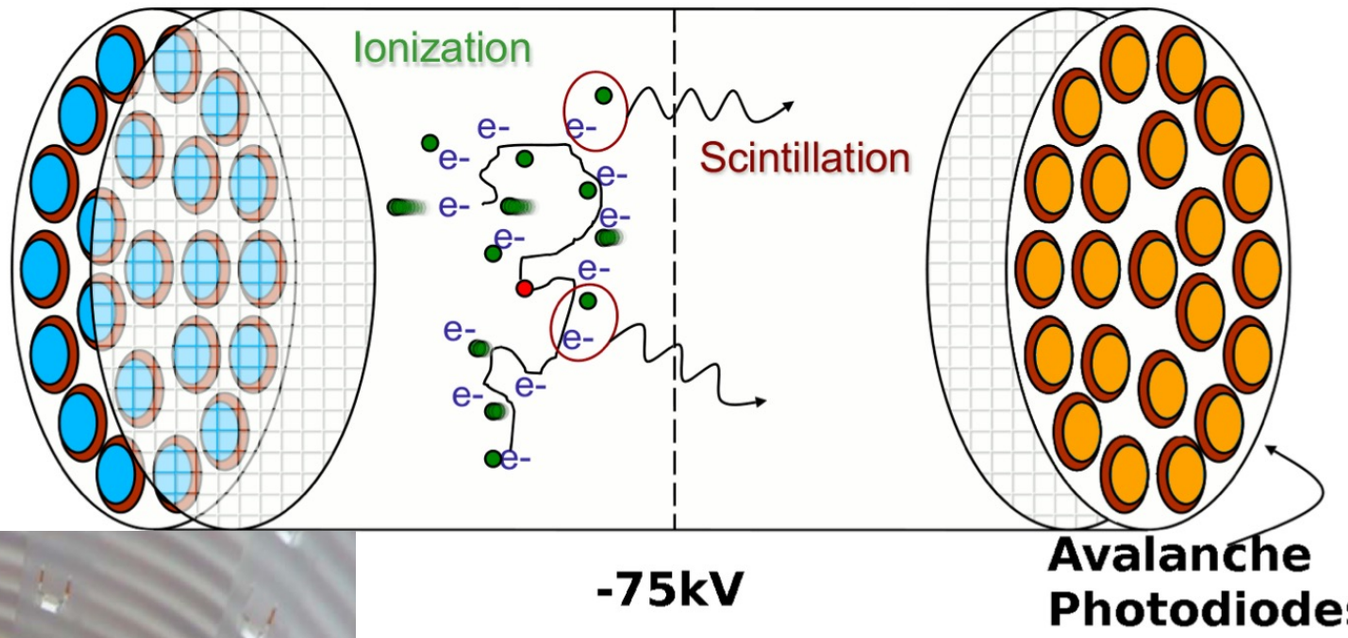
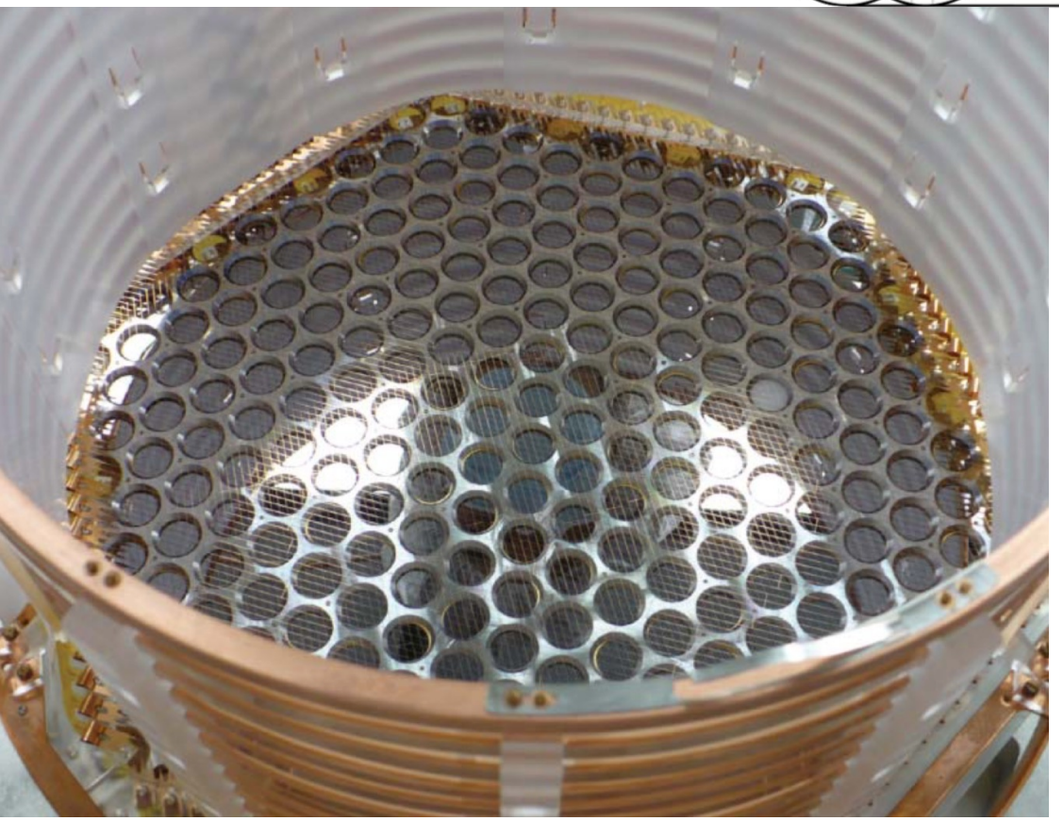
EXO-200 schematic





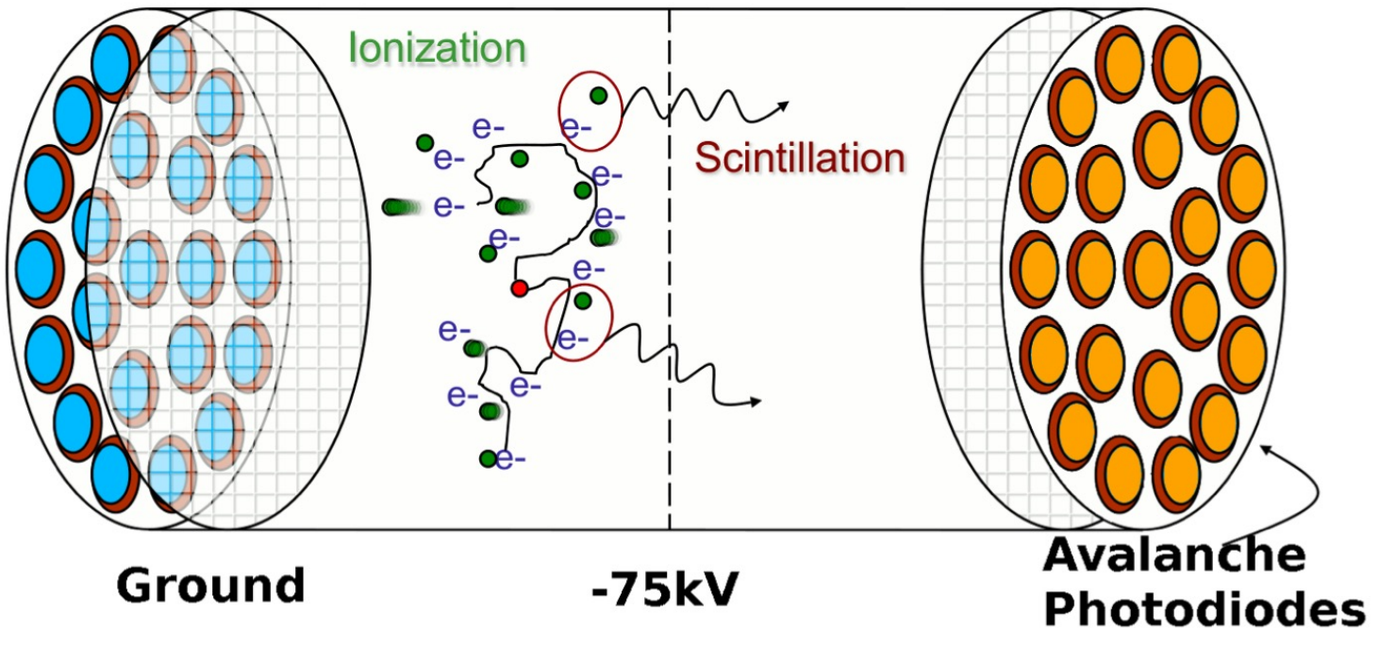
The EXO-200 double-beta-decay detector is a cylinder 40 cm in diameter that will be filled with about 200 kg of xenon enriched to 80% with the isotope ^{136}Xe. Double beta decay reveals itself by producing two electrons, which in turn cause xenon atoms to emit light. The large, silver-coloured avalanche photodiodes detect the "scintillation" photons emitted in this process. Barely visible above the photodiodes is an array of wires that collects the emitted electrons using an electric field, allowing their energy to be accurately measured. The energy spectrum of the two electrons is very different in the case of two-neutrino decay and the much rarer neutrinoless decay that we are after. All r free from radioactive contaminations.

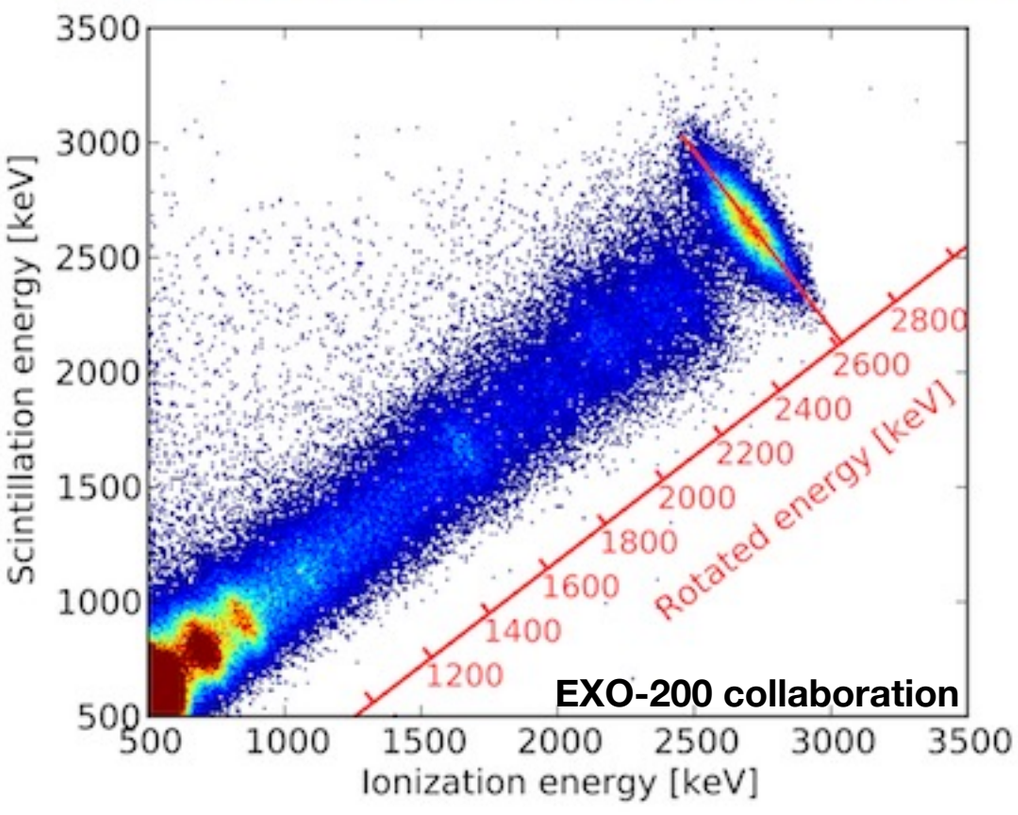
EXO-200 is currently the world's largest double-beta-decay detector and is set to start taking data this summer. The ultimate goal is to search for neutrino-less double beta decay in several tonnes of xenon in a larger-scale experiment planned to follow later this decade. Other major experiments installed in Europe, Japan and North America are using the isotopes ^{130}Te, ^{76}Ge, and ^{150}Nd.

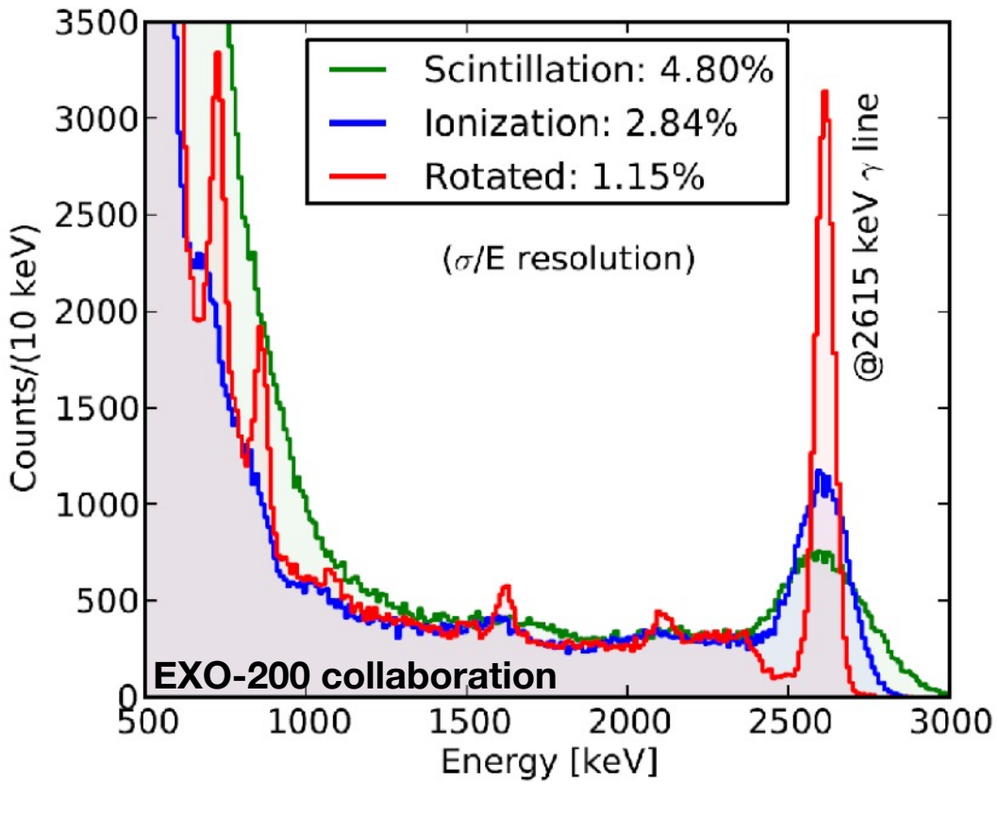
LXeTPC for neutrinoless double beta decay

- Single-phase TPC (collects both charge and light directly)

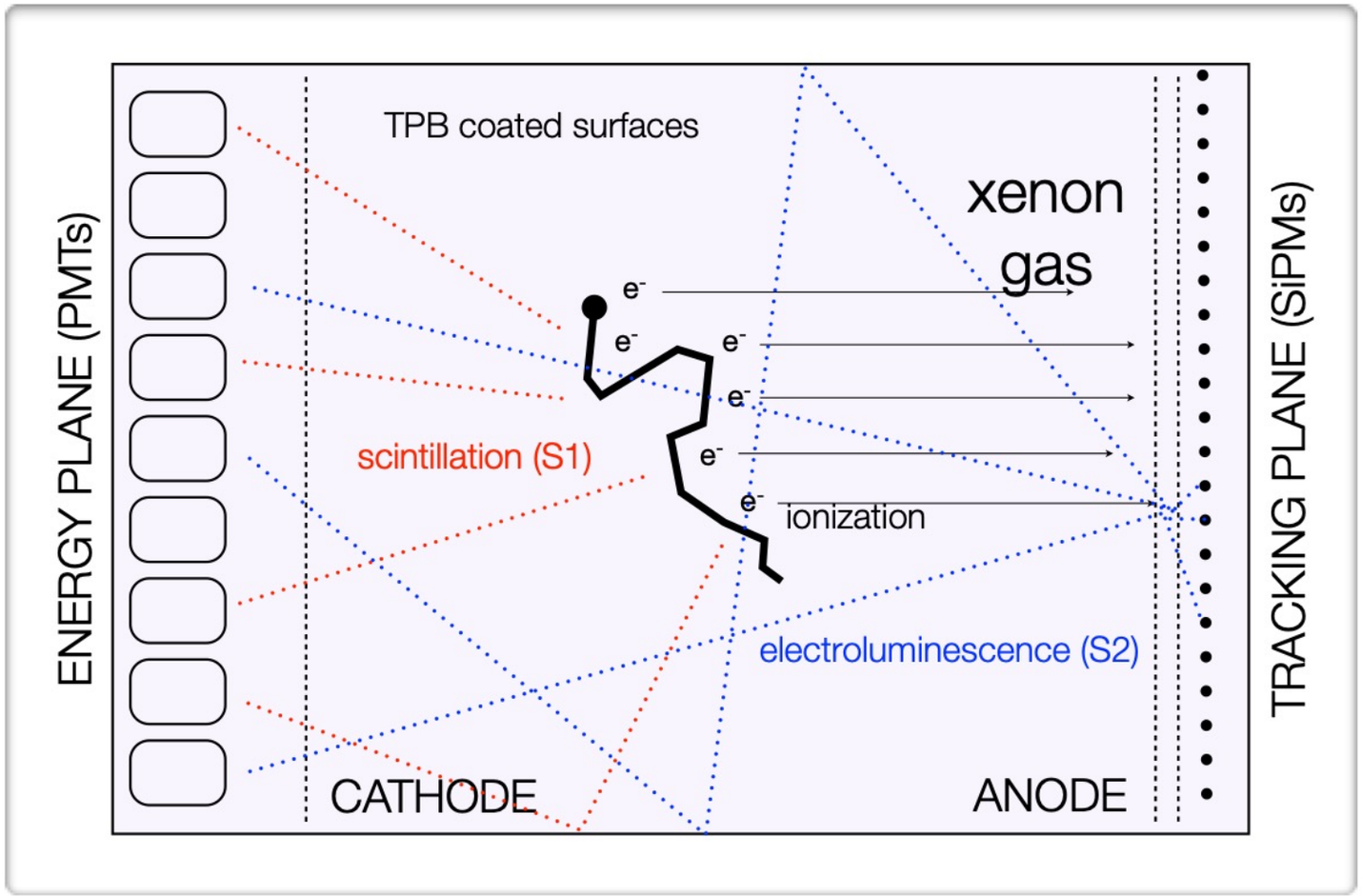
EXO-200 schematic

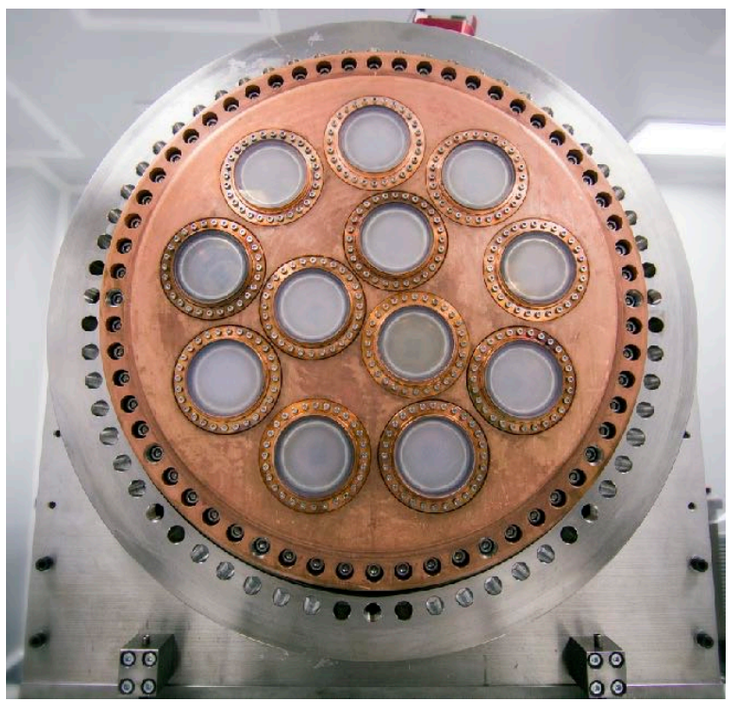


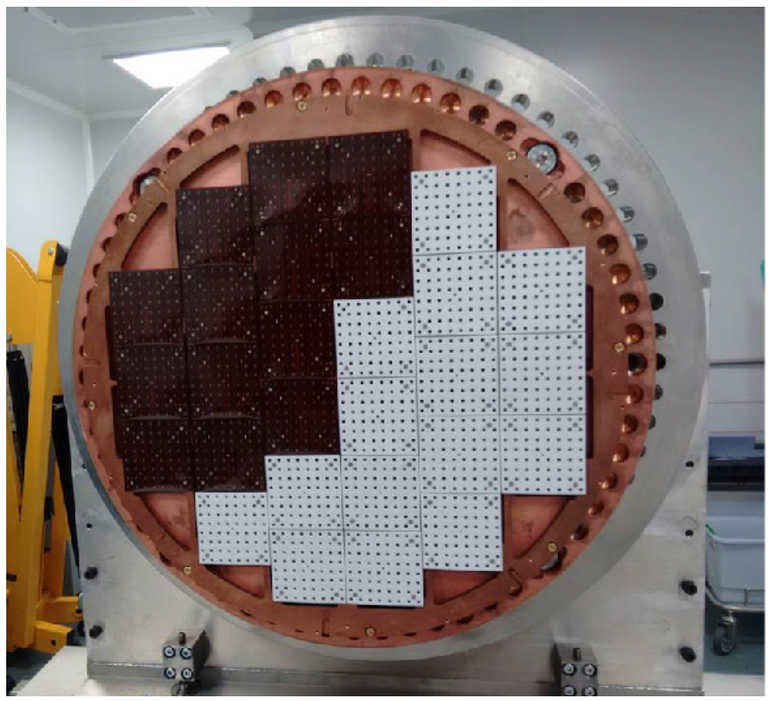




HPgXeTPC for neutrinoless double beta decay

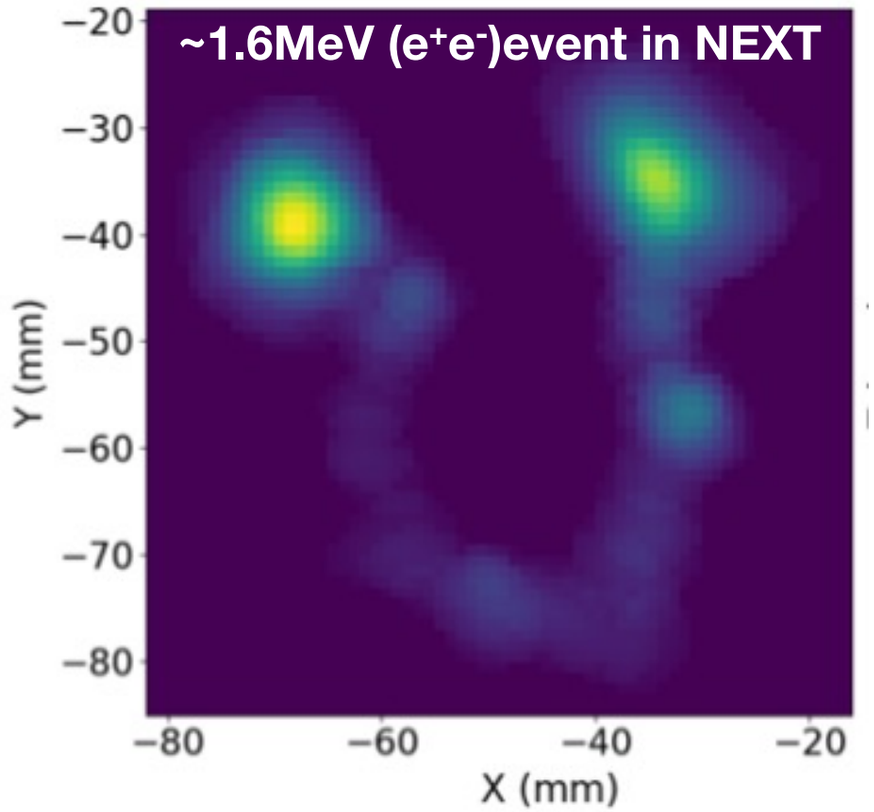


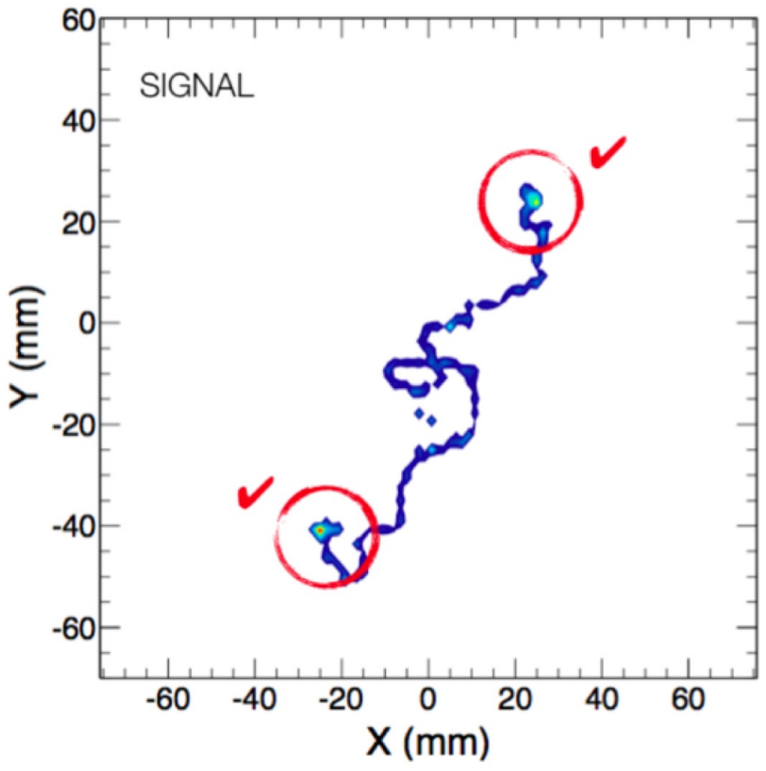


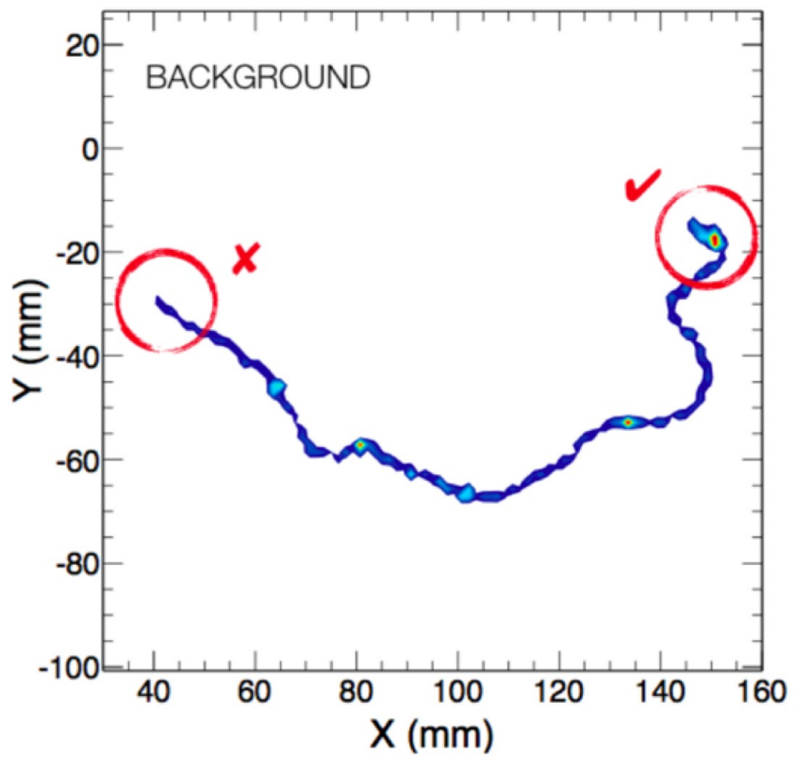


The gas phase

- Density is low → need high pressure
- Better for low-energy (extended tracks)
- Great intrinsic energy resolution
- Easy calibration







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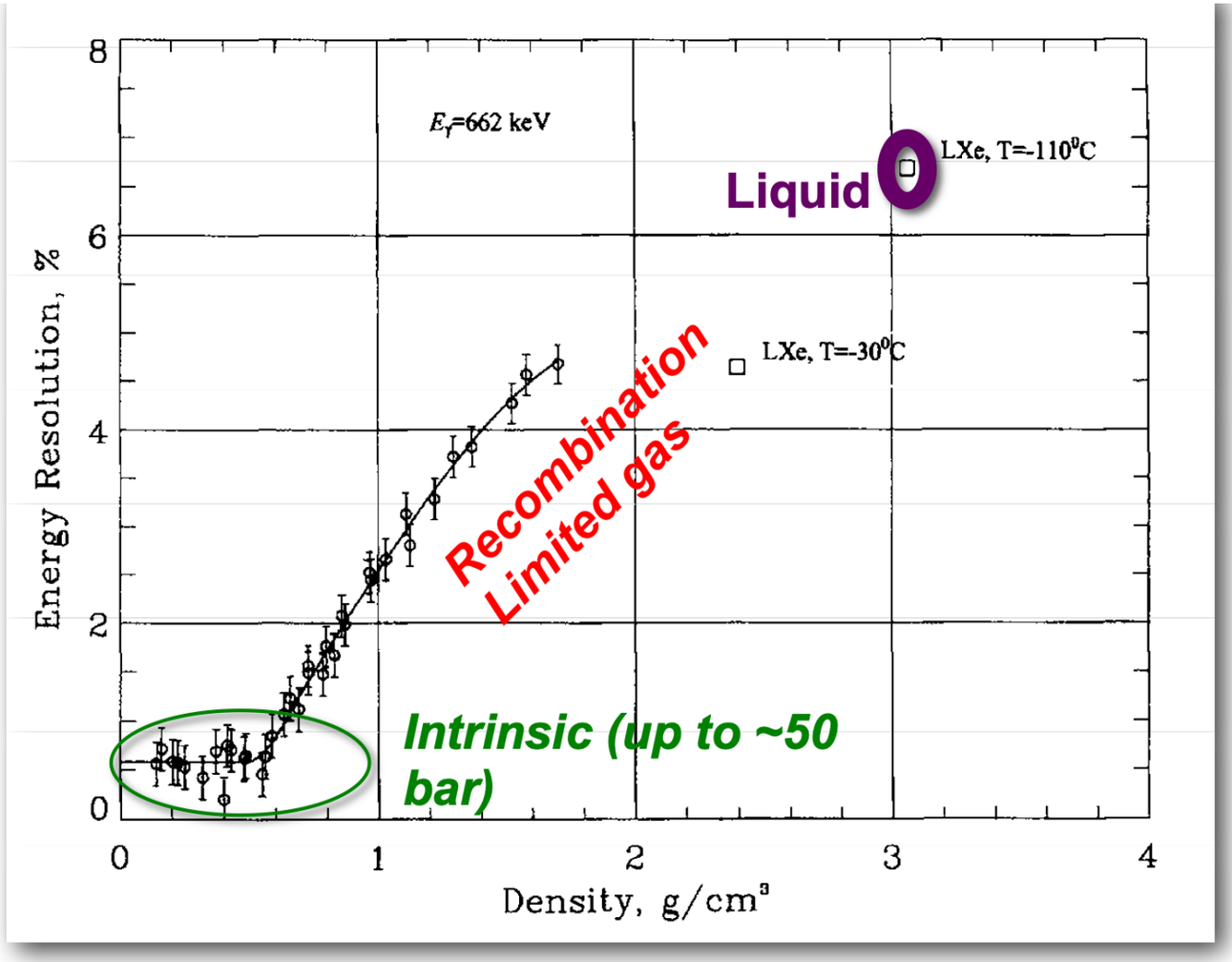
Bolotnikov and Ramsey. "The spectroscopic properties of high-pressure xenon."NIM *A* 396.3 (1997): 360-370



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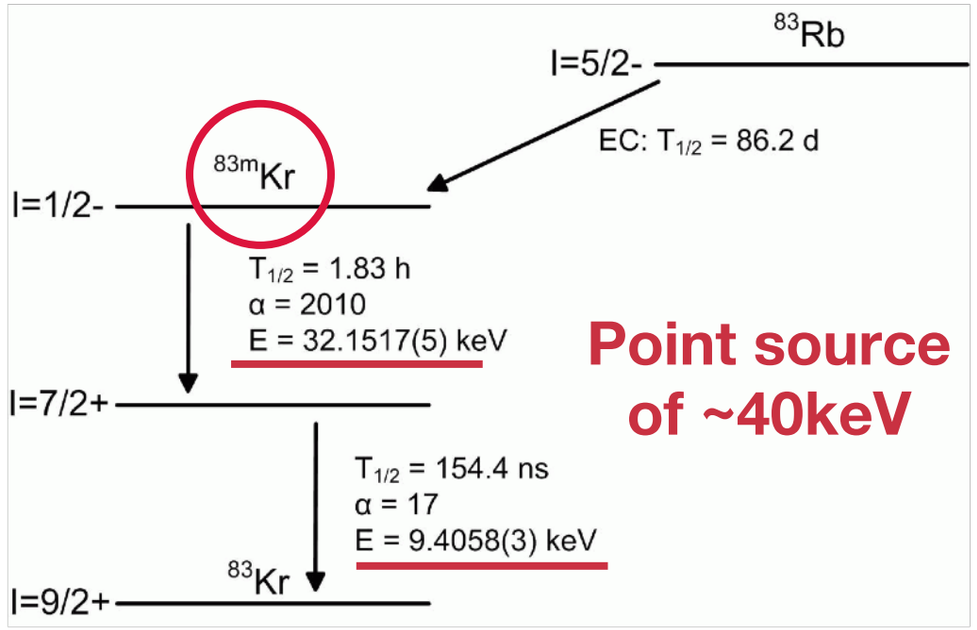
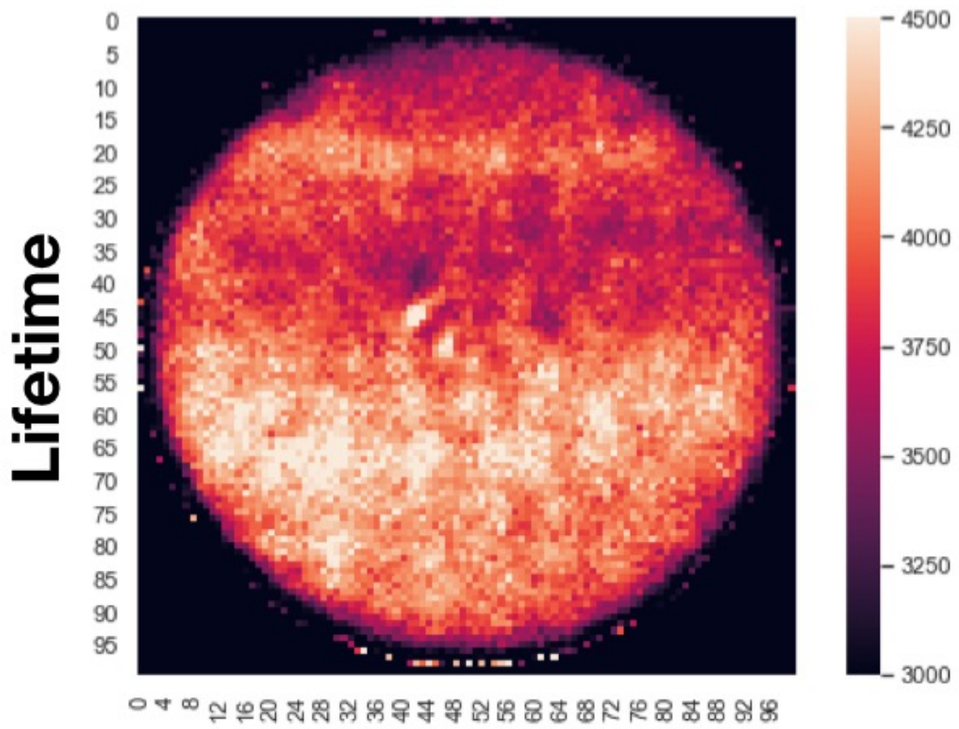
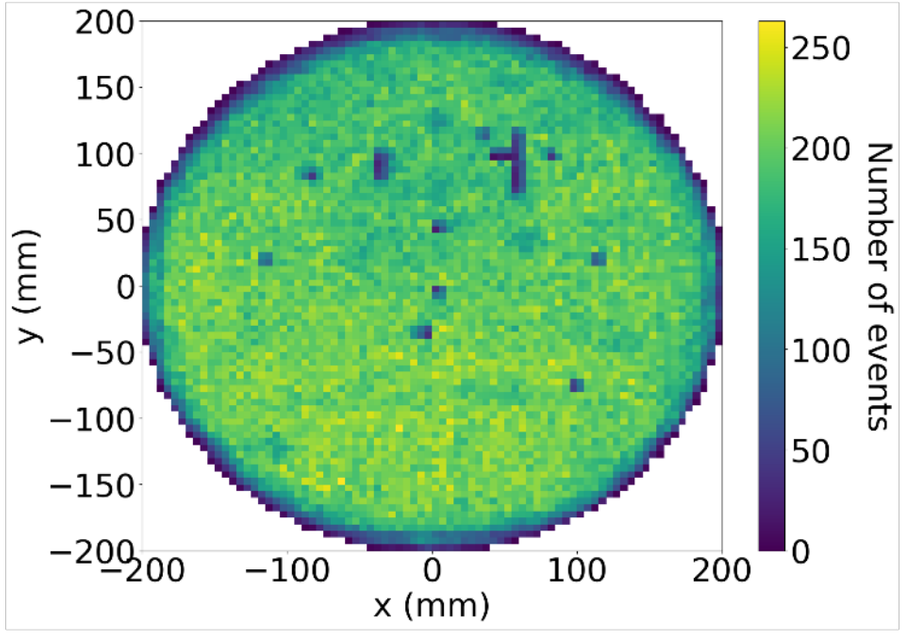


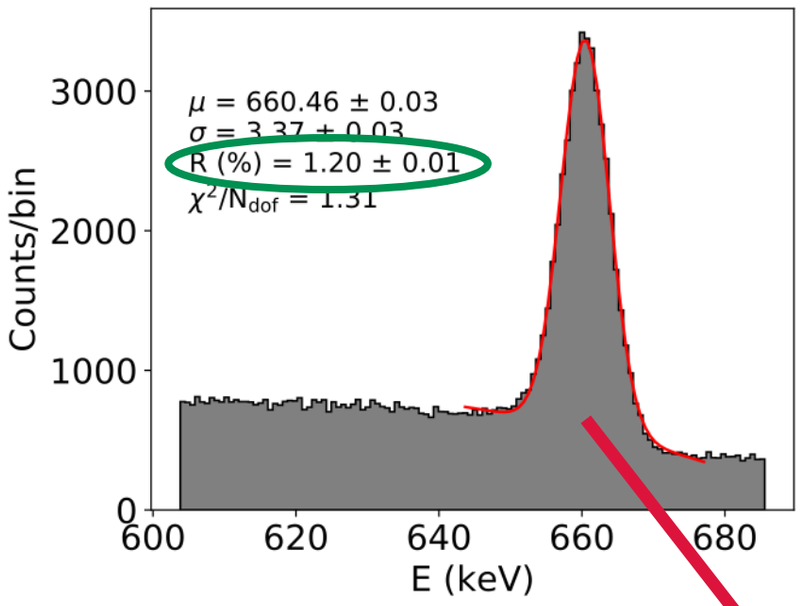


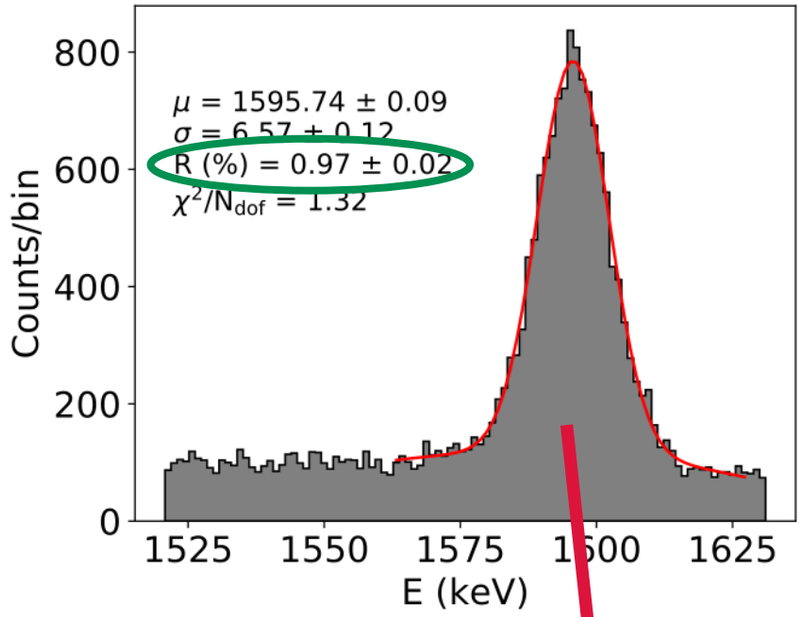


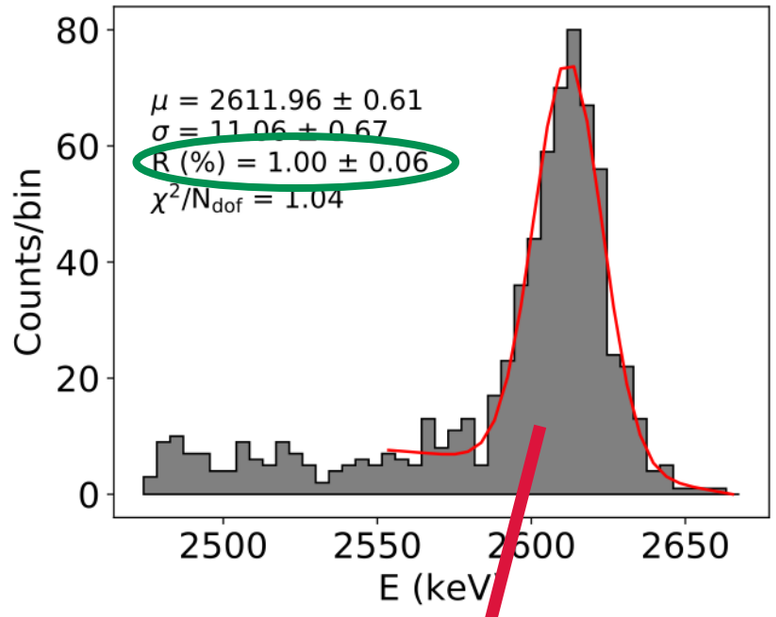
NEXT Collaboration, *JINST* **13** (2018) P10014

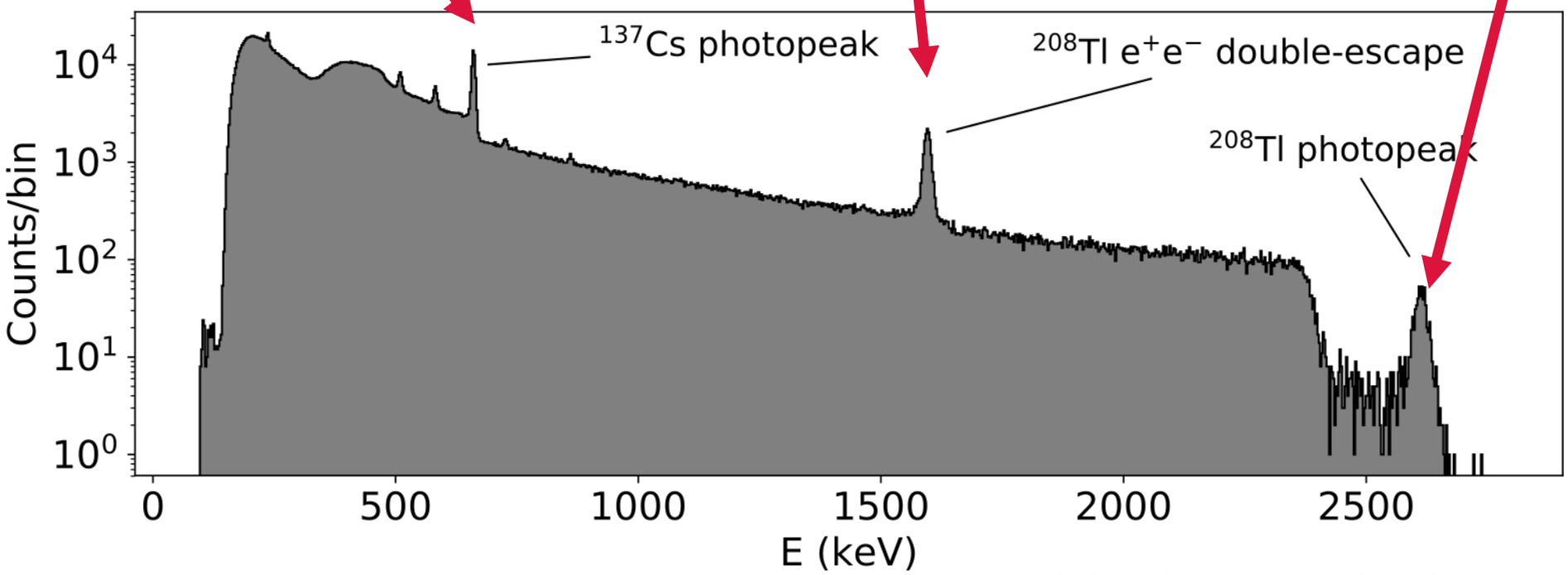
HPgXeTPC for neutrinoless double beta decay

- Energy resolution at the level of sub-percent





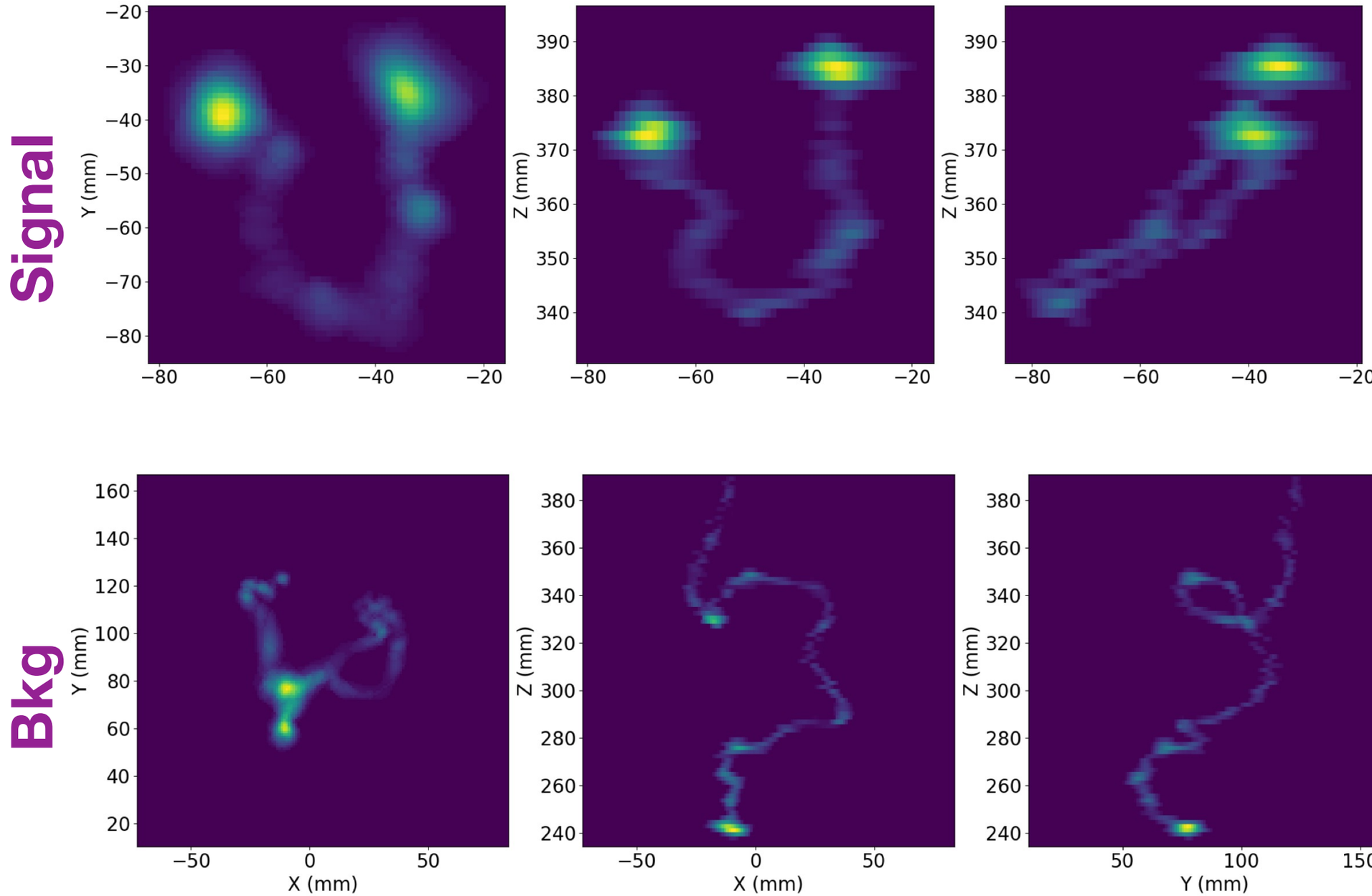




NEXT Collaboration, *JHEP* 10 (2019) 230

HPgXeTPC for neutrinoless double beta decay

- Topologic separation power between signal and background



NEXT Collaboration, *JHEP* 10 (2019) 052

Noble Element Detectors are everywhere

Science

Neutrino oscillation and interactions

Neutrinoless double beta decay searches

Dark Matter searches

Collider physics

Technologies

Liquid Argon

Gaseous Argon

Liquid Xenon

Gaseous Xenon

Solid Xenon

Single-phase TPCs

Dual phase TPCs

Liquid Helium

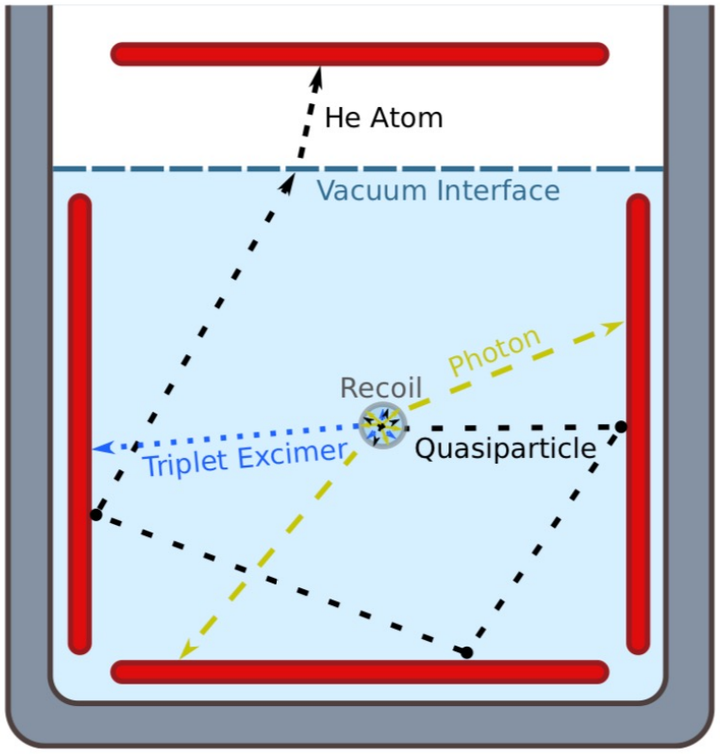
Scintillating bubble chambers

Calorimeters

Thinking outside the box

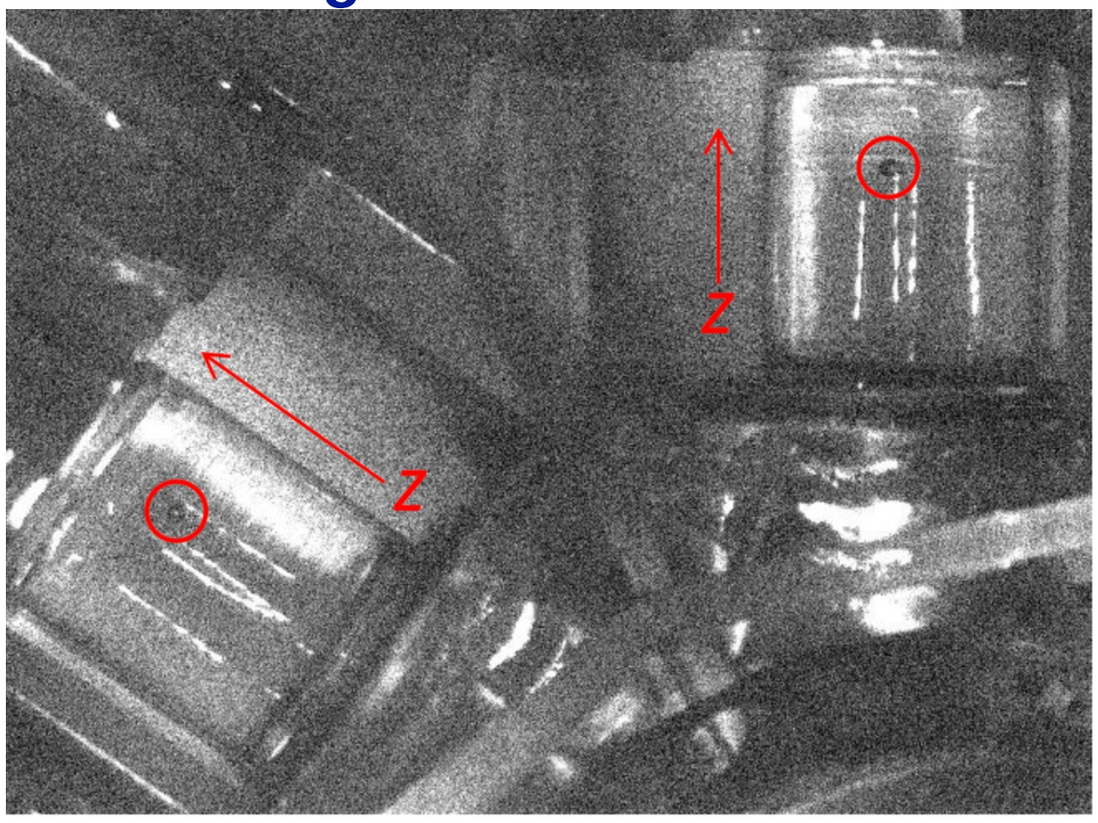
- Using the advantages of noble elements to other cutting-edge detector ideas

Superfluid ^{4}He Detector



Phys. Rev. D 100, 092007 (2019)

Scintillating Xenon Bubble Chamber



Phys. Rev. Lett. 118, 231301 (2017)

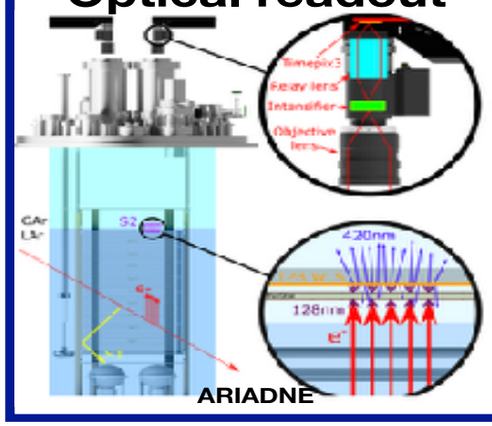
Detector R&D for neutrino experiments

Liquid Argon TPC
(DUNE)

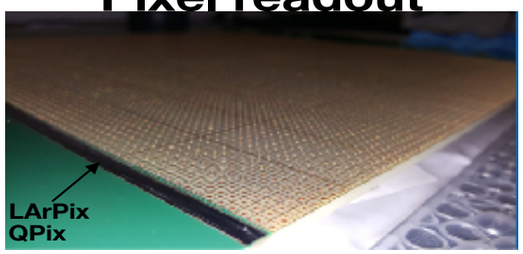
Current:
- ➡ Cryogenics and purification
- ➡ HV and uniform E-field
- ➡ Microphysics and calibration
- ➡ Event reconstruction

Future:
- ➡ Increase charge/light collection
- ➡ Doping (light)
- ➡ …

Optical readout



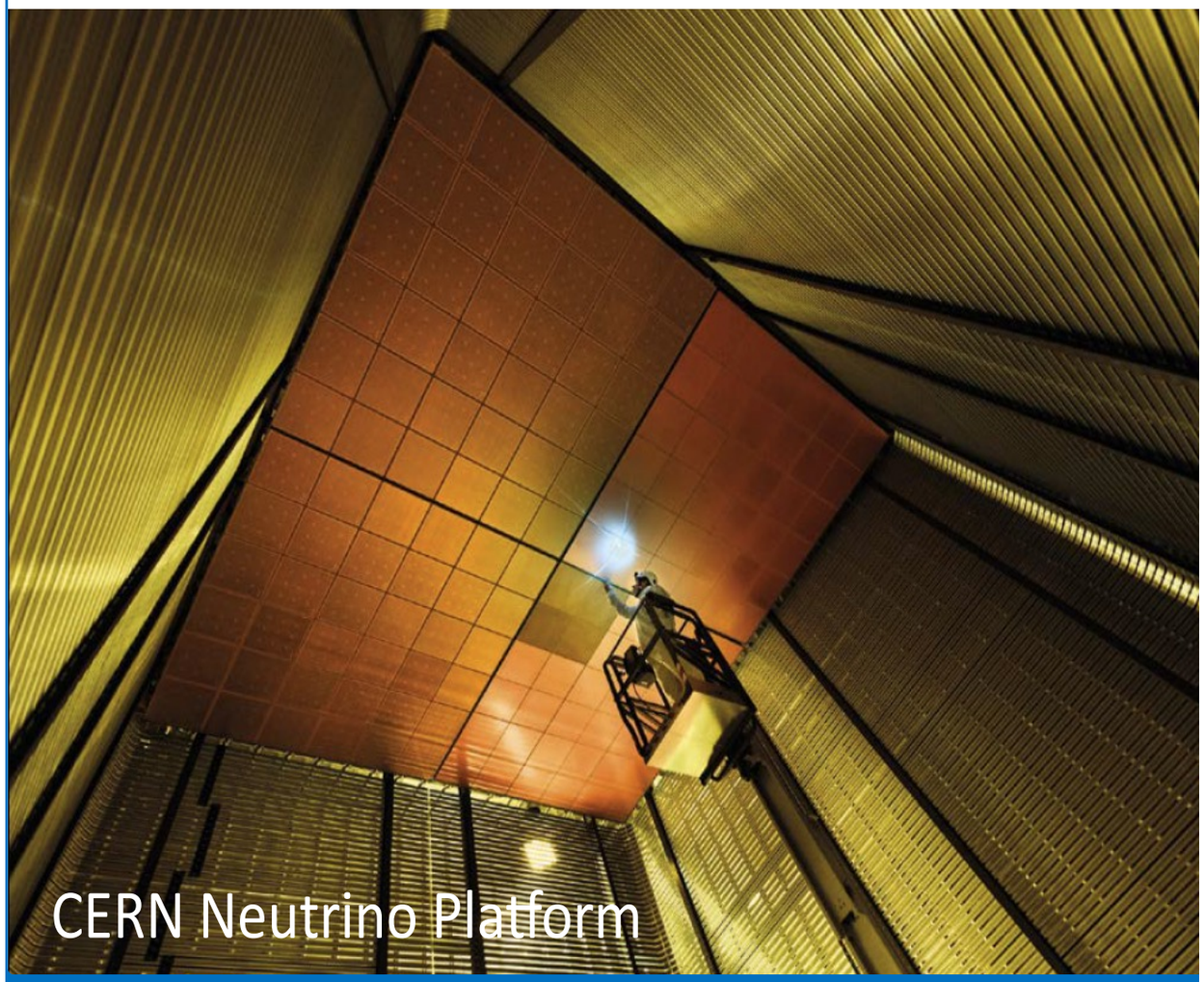
Pixel readout



Dual Q-γ readout

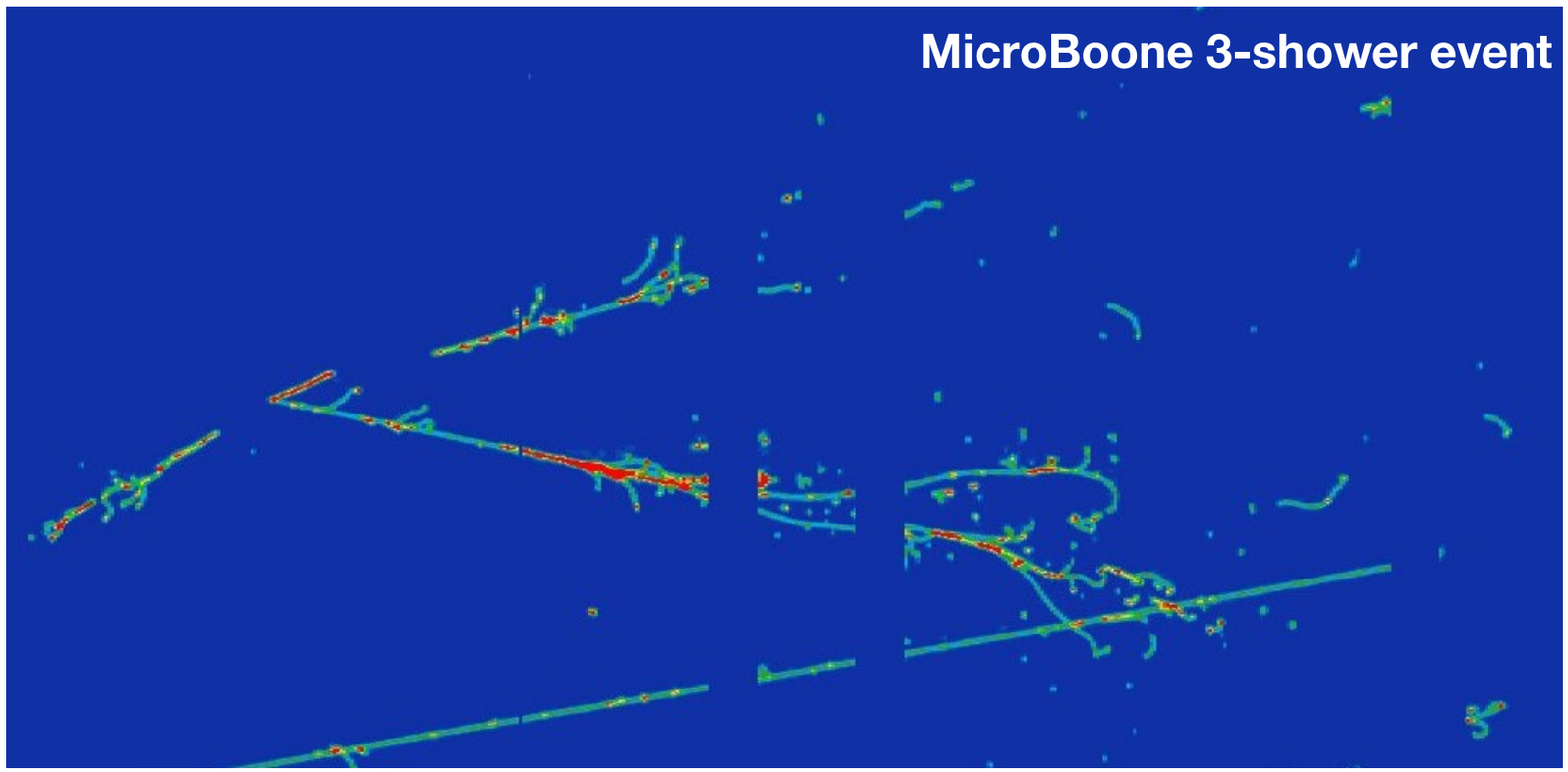
DUNE @ LBNF

Prototype dual-phase Liquid-Argon TPC



Summary

- Noble element detectors have played and are playing a huge role in many areas of particle physics
- These detectors are versatile and scalable
- But a lot of details are important to understand and require particular attention
- A lot of R&D (and fun) remains to do to bring the full potential of these great detectors!



A lot of R&D in noble element detectors!

3D (pixel) readout for TPCs (LArPix, QPix,…)

Ultra-low noise charge detector

Signal amplification in liquid

Integrated readout solutions for light and charge

New and/or improved light detection devices

New wavelength shifting methods (thin films, fluorescent and scintillating material, quantum dots, …)

New highly reflective materials

Target mixture and medium doping

Scintillating bubble chambers (Xe, Ar)

Ion TPCs and ion tagging

Novel detector structures and layouts

Novel purity monitors

Phonons and rotons (direct or indirect) detection

Study of microphysics and calibration for charge, light and heat

…

A lot of R&D in Noble Element Detectors!

- One example: QPix

Dave Nygren (UTA) and Yuan Mei (LBNL): arXiv:1809.10213