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Basque Foundation for Science

DIPC
Donostia International Physics Center

High pressure gaseous TPCs for neutrino physics

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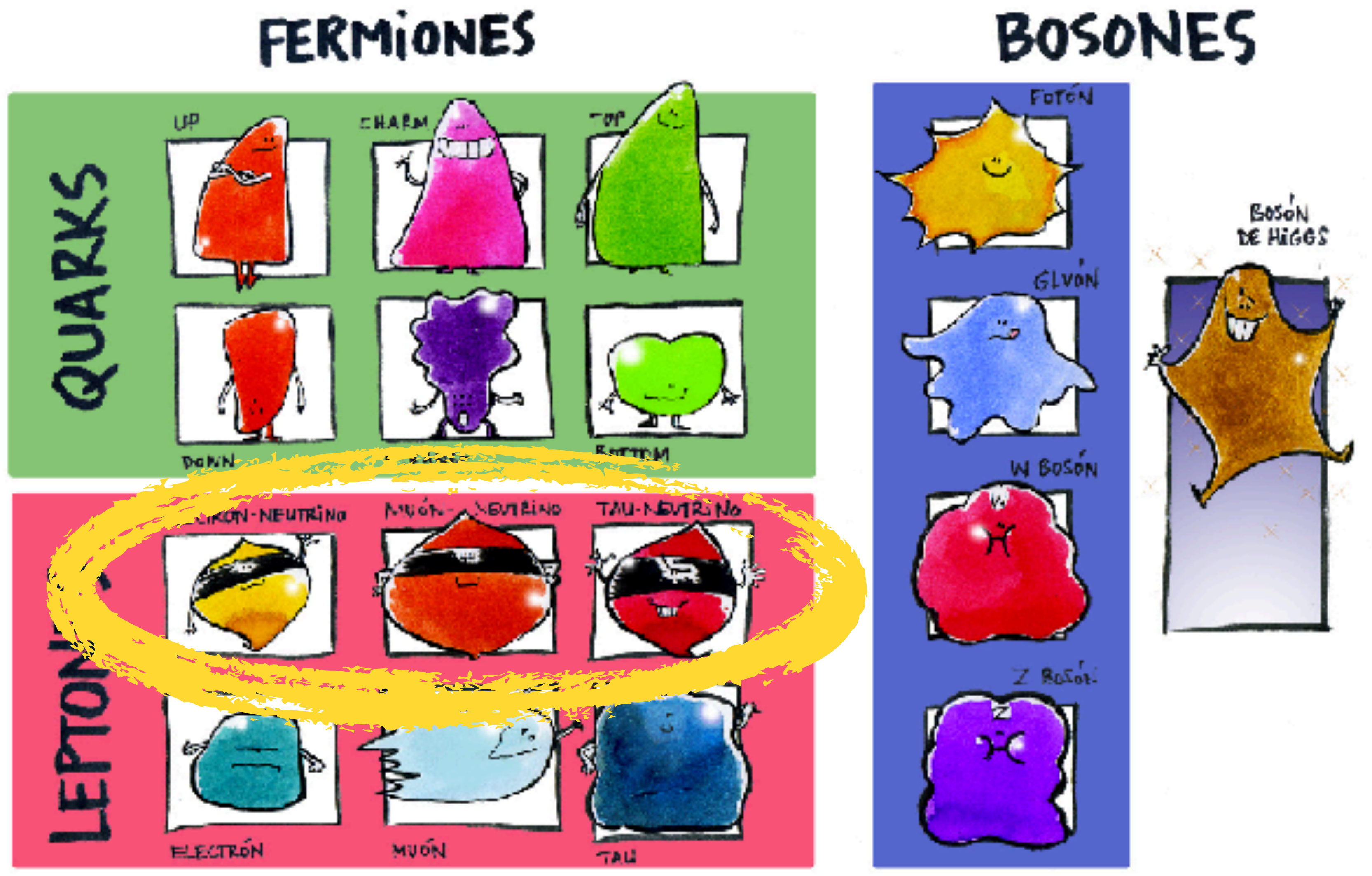
Rutherford Appleton Laboratory
23th March 2022

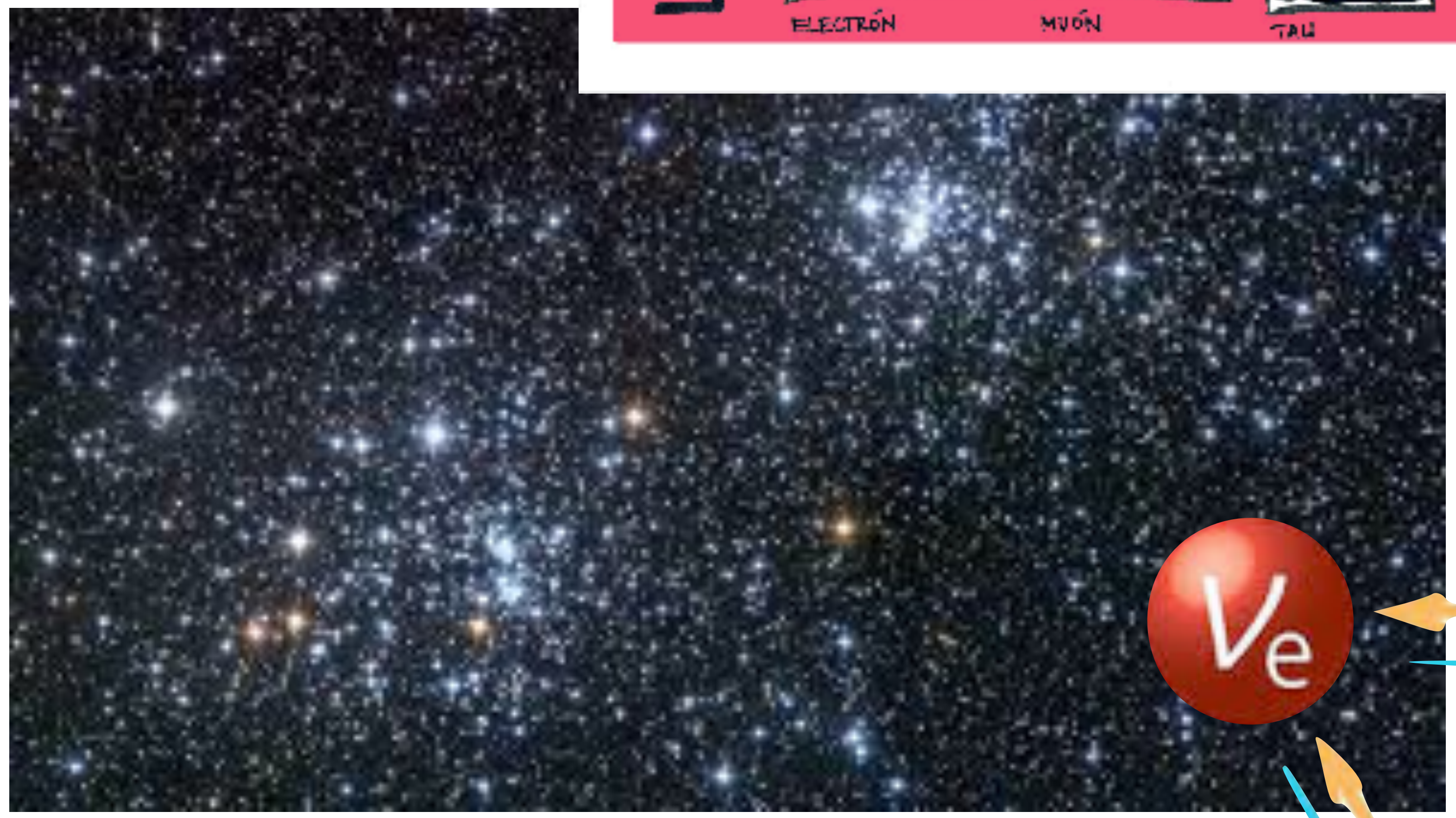
Science & Technology Facilities Council
Rutherford Appleton Laboratory

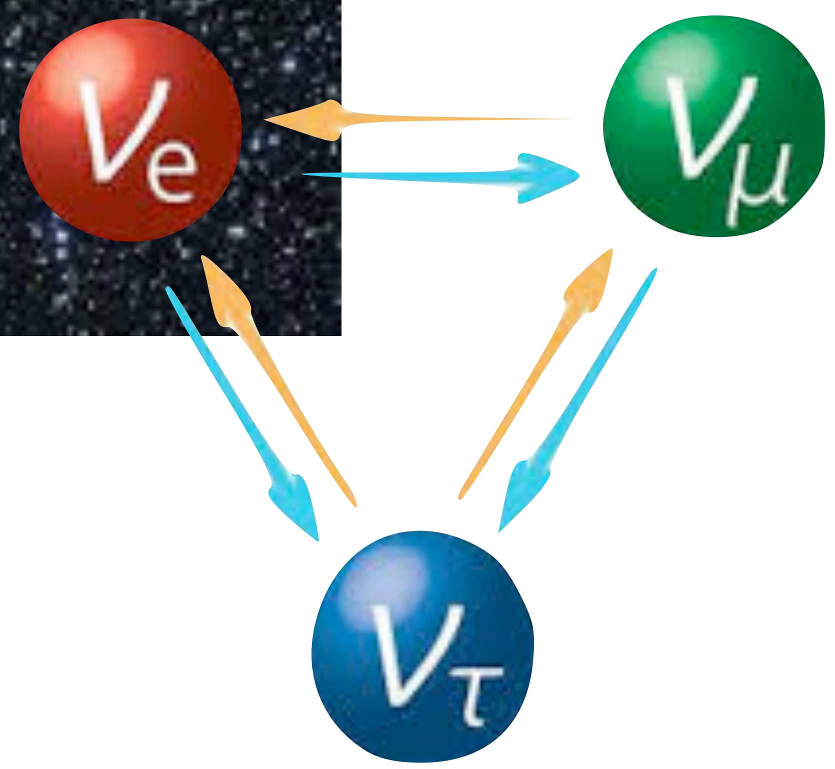
NEUTRINOS

Neutrinos: what we know



@raquelberryfinn





Interact only weakly

No color, no electric charge

Three light ($<m_Z/2$) neutrino states

ν_e, ν_μ, ν_τ flavors

Neutrino number density in Universe only outnumbered by photons

$n(\nu+\bar{\nu}) \approx 100\ \mathrm{cm}^{-3}$ per flavor

From neutrino oscillations:

Neutrinos are massive (lightest known fermions)

Large flavor mixing

Outstanding Questions in Neutrino Physics

Identity: Dirac or Majorana fermion? — $\nu = \overline{\nu}$

Mass scale: Absolute mass value — m_ν

Mass ordering: Normal/inverted — $m_1 > m_3$, $m_1 < m_3$

CP phase: is CP violated?

Species: Are there sterile neutrinos?

Neutrino detectors

Neutrino detectors

Most elusive particles ever detected

First demonstration of Physics beyond the Standard Model

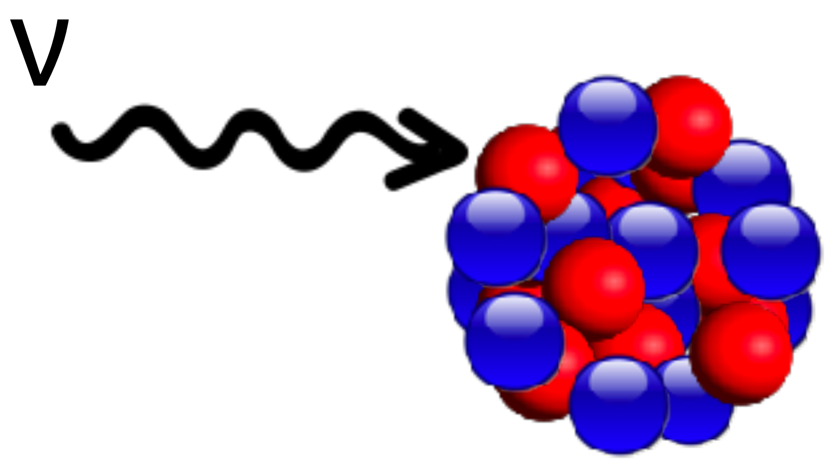
Nobel Prize in Physics in 1988, 1995, 2002, 2015,…

Astrophysics neutrinos have opened a new window to the universe

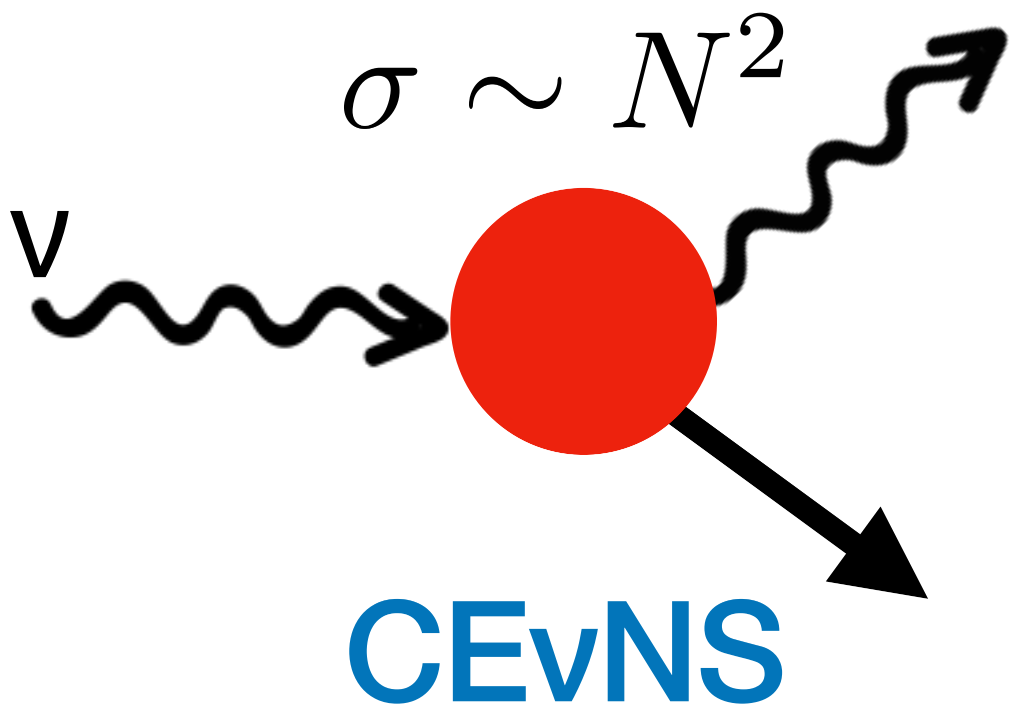
Detecting neutrinos requires very large detectors with tons of active material. Right?

COHERENT NEUTRINO NUCLEUS SCATTERING

Coherent Elastic Neutrino-nucleus scattering



Long wavelength,
“sees” all nucleons
simultaneously



Cross section increases as N^2.
Four orders of magnitude
increase for large nucleus!

First observation published only
4 years ago.

Coherent Elastic Neutrino-nucleus scattering

Very rich physics

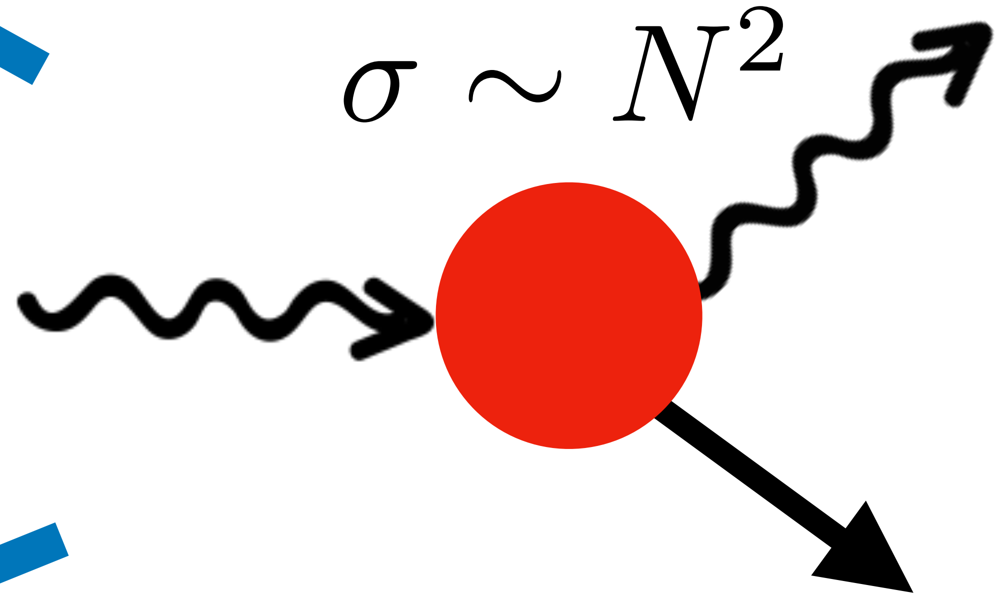
Complementary to oscillation experiments

Sensitivity to Non-Standard Interactions

Study of Neutral Currents

Study of the Nuclear structure

$\sigma \sim N^2$



Sterile neutrinos

Effective neutrino charge radius

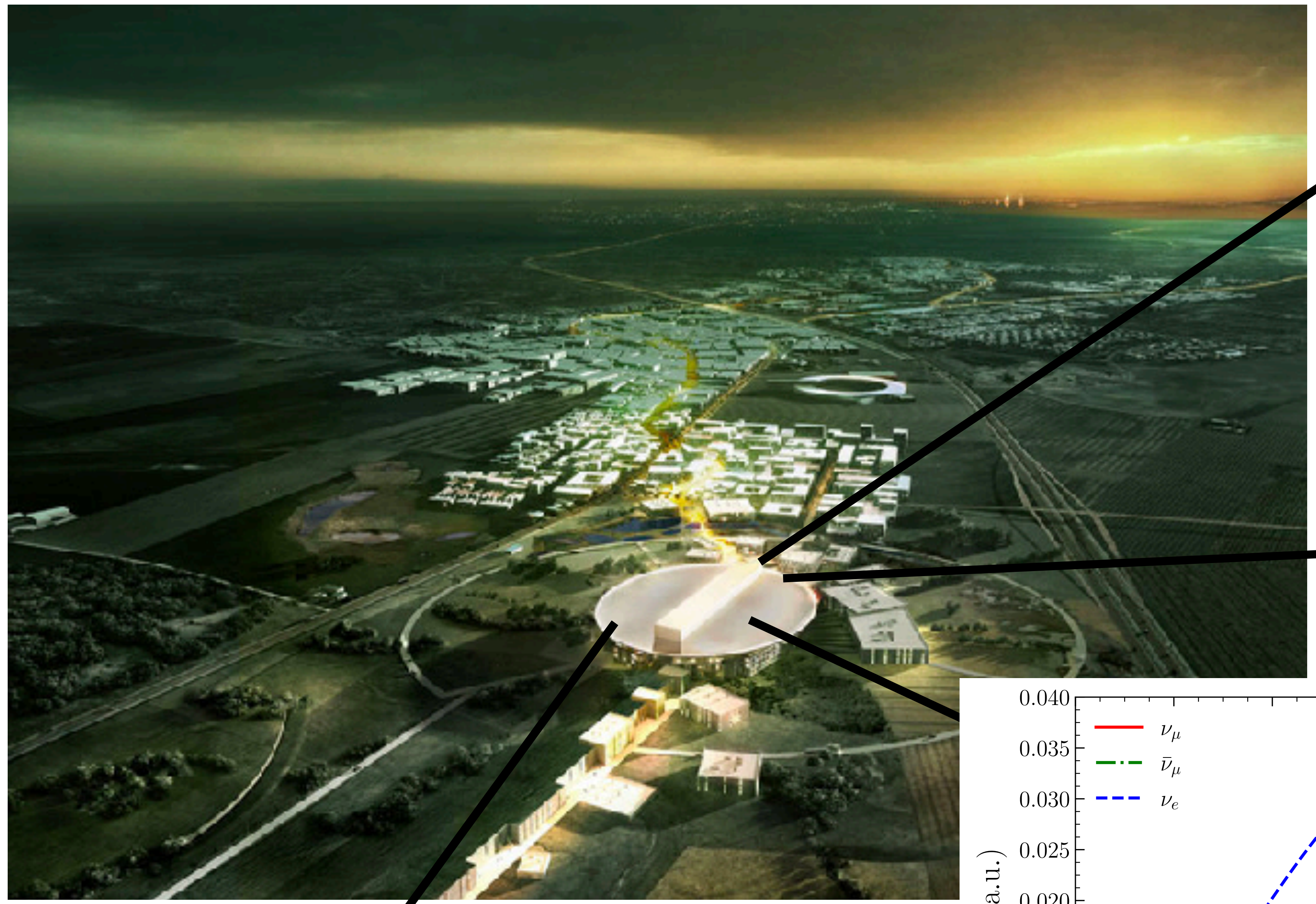
Neutrino magnetic moment

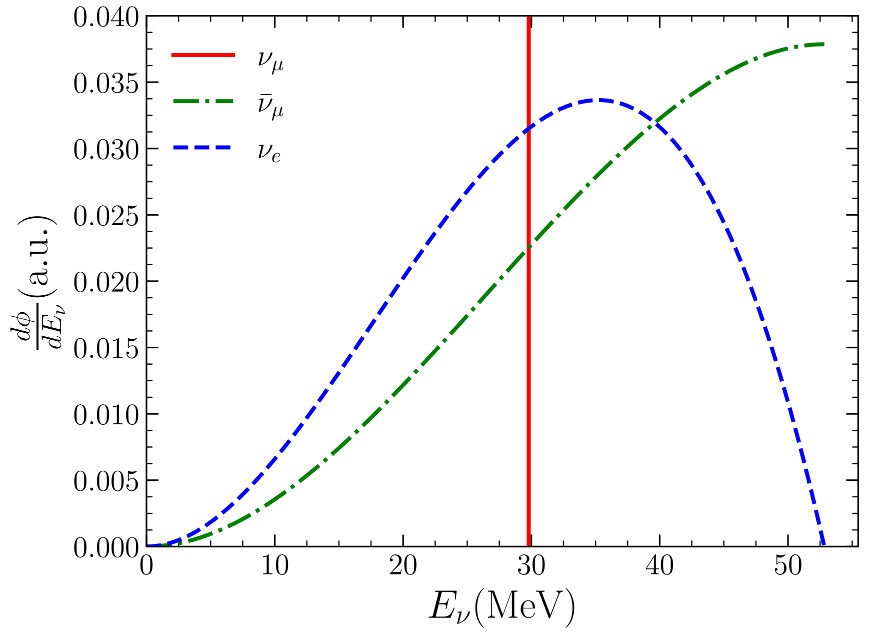
...

New types of dark matter particles

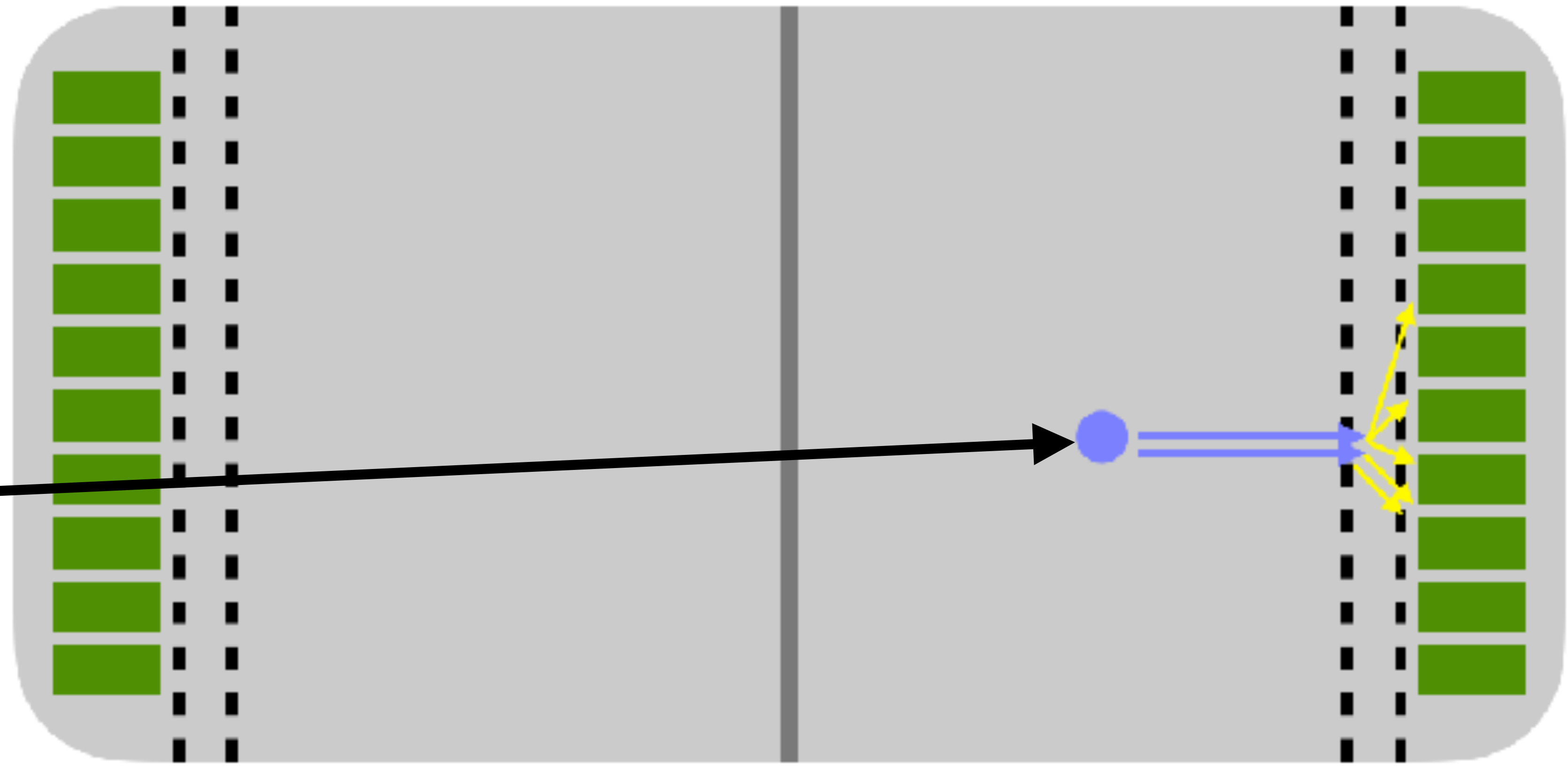
Detecting CEvNS

CEvNS sources, must be sufficiently intense in yield, and low enough in neutrino energy so the coherence condition can be satisfied.



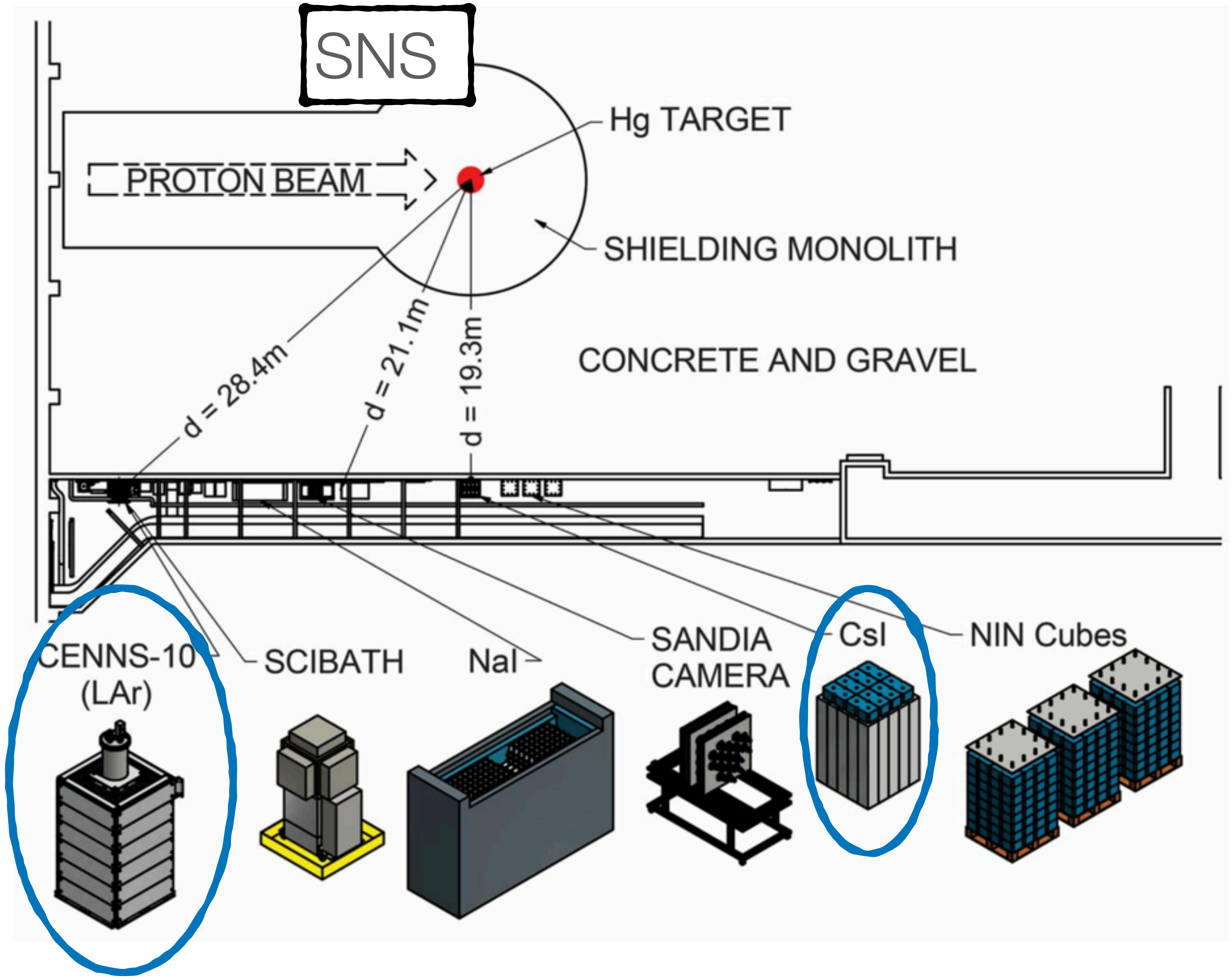


ν

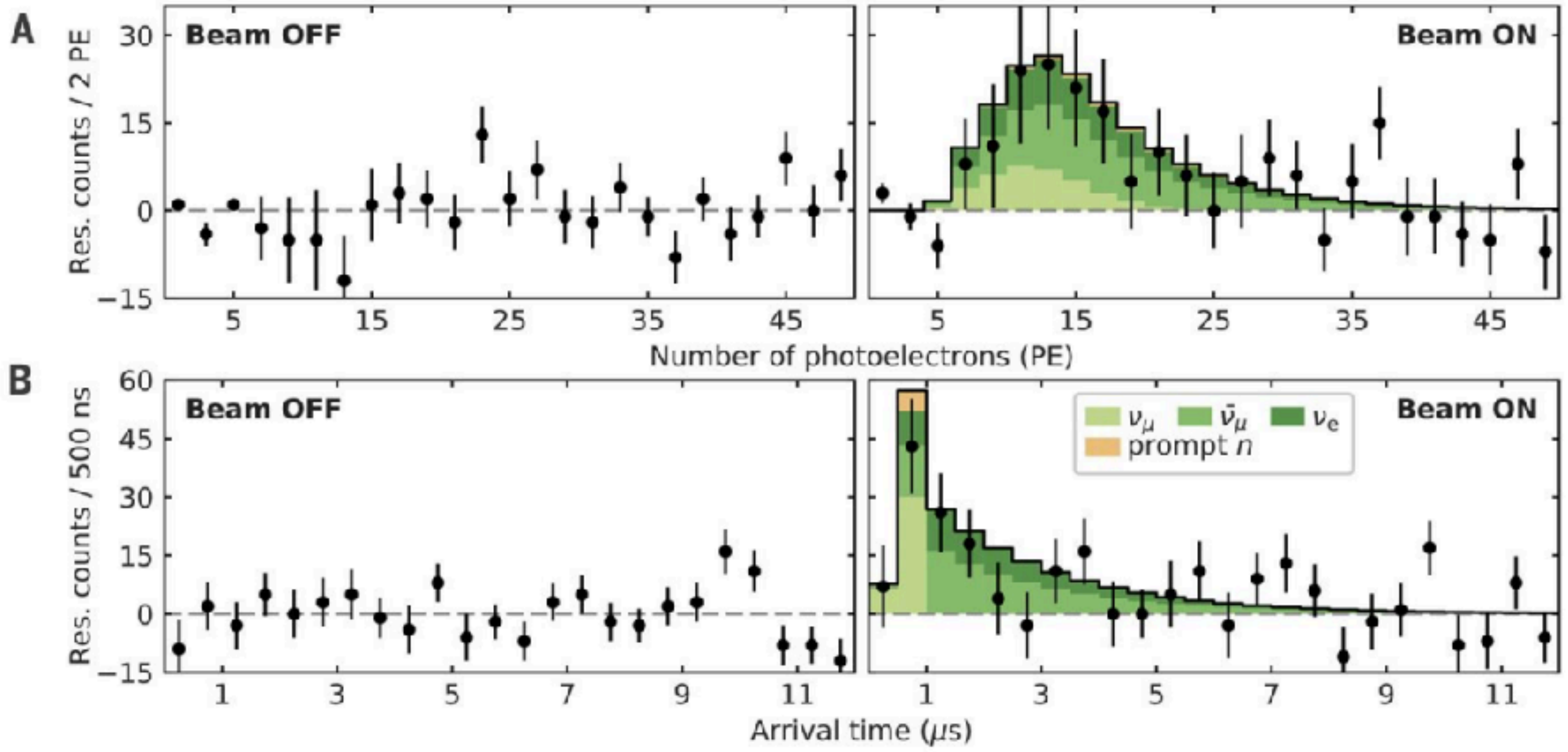


~10 kg size detectors.

Detecting CEvNS: First observation



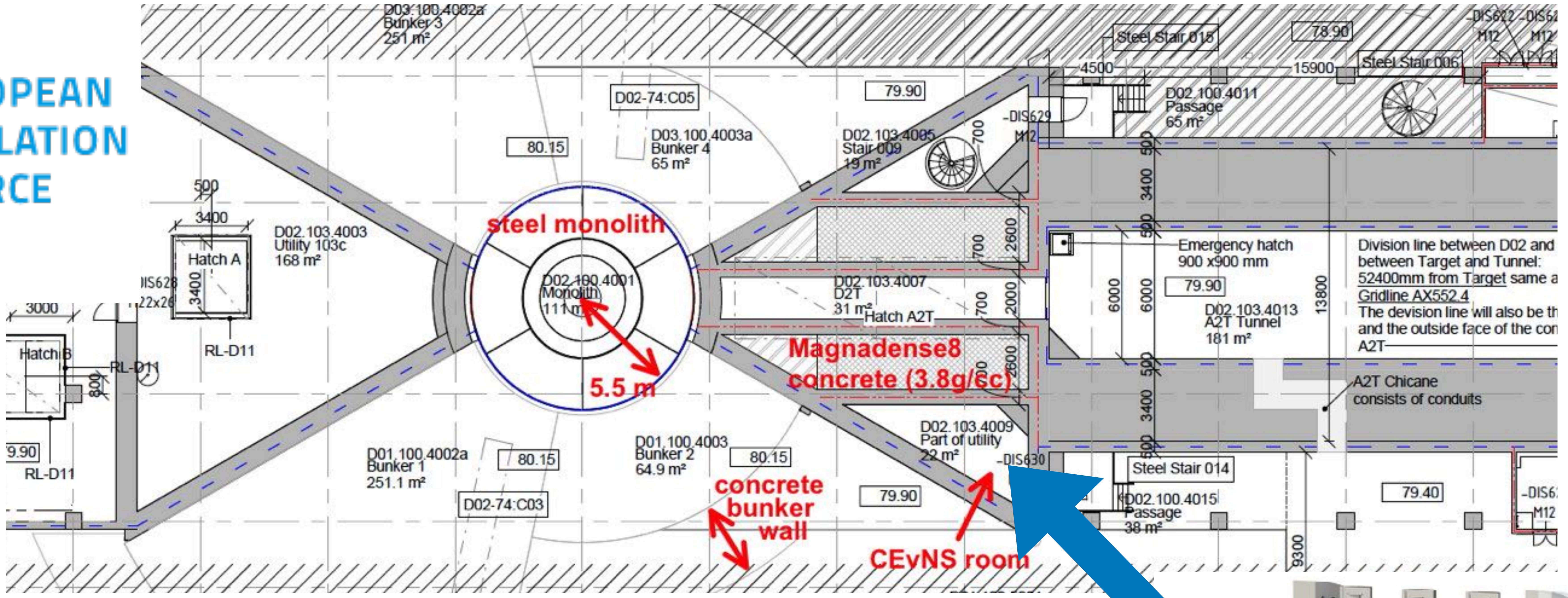
Science 357, 1123–1126 (2017)

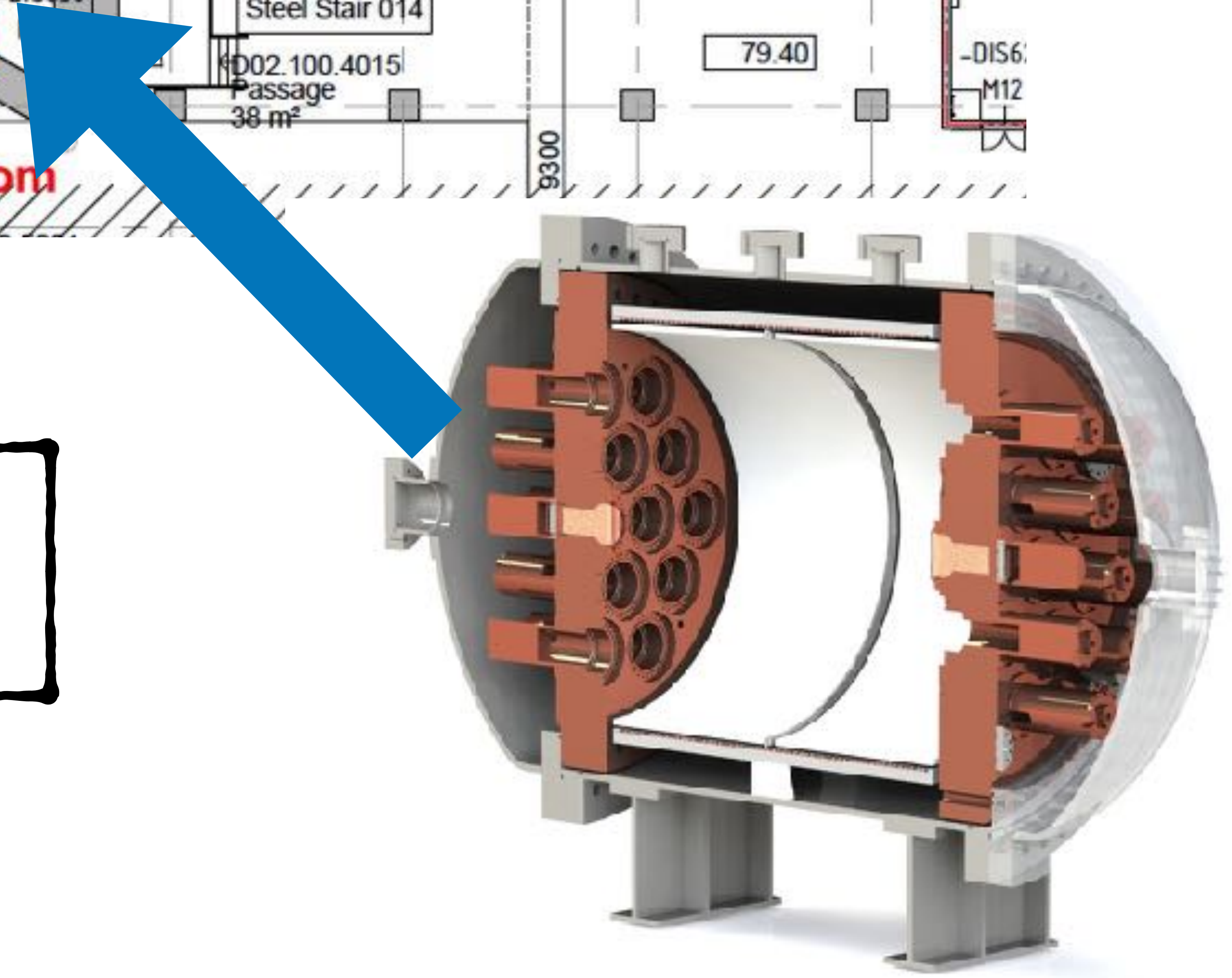


Detection of the coherent scattering less than 5 years ago demonstrates a new mechanism to observe neutrinos.

Detecting CEvNS: Future observations

ess
EUROPEAN
SPALLATION
SOURCE





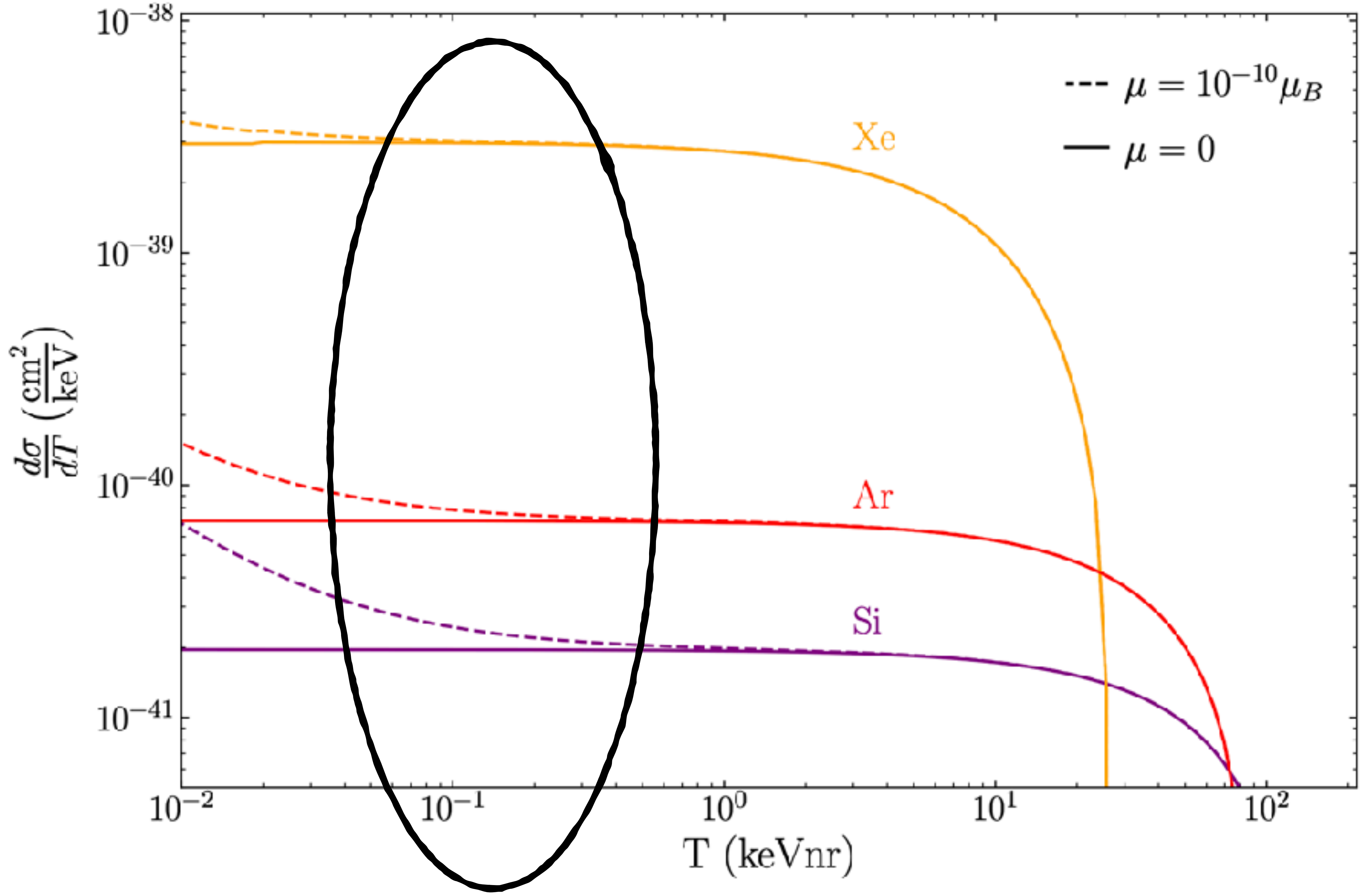
ESS will produce the largest low energy neutrino flux of the next generation facilities.

Detecting CEvNS

Detectors

Neutrino magnetic moment, new physics!

Ultra low energy threshold is crucial



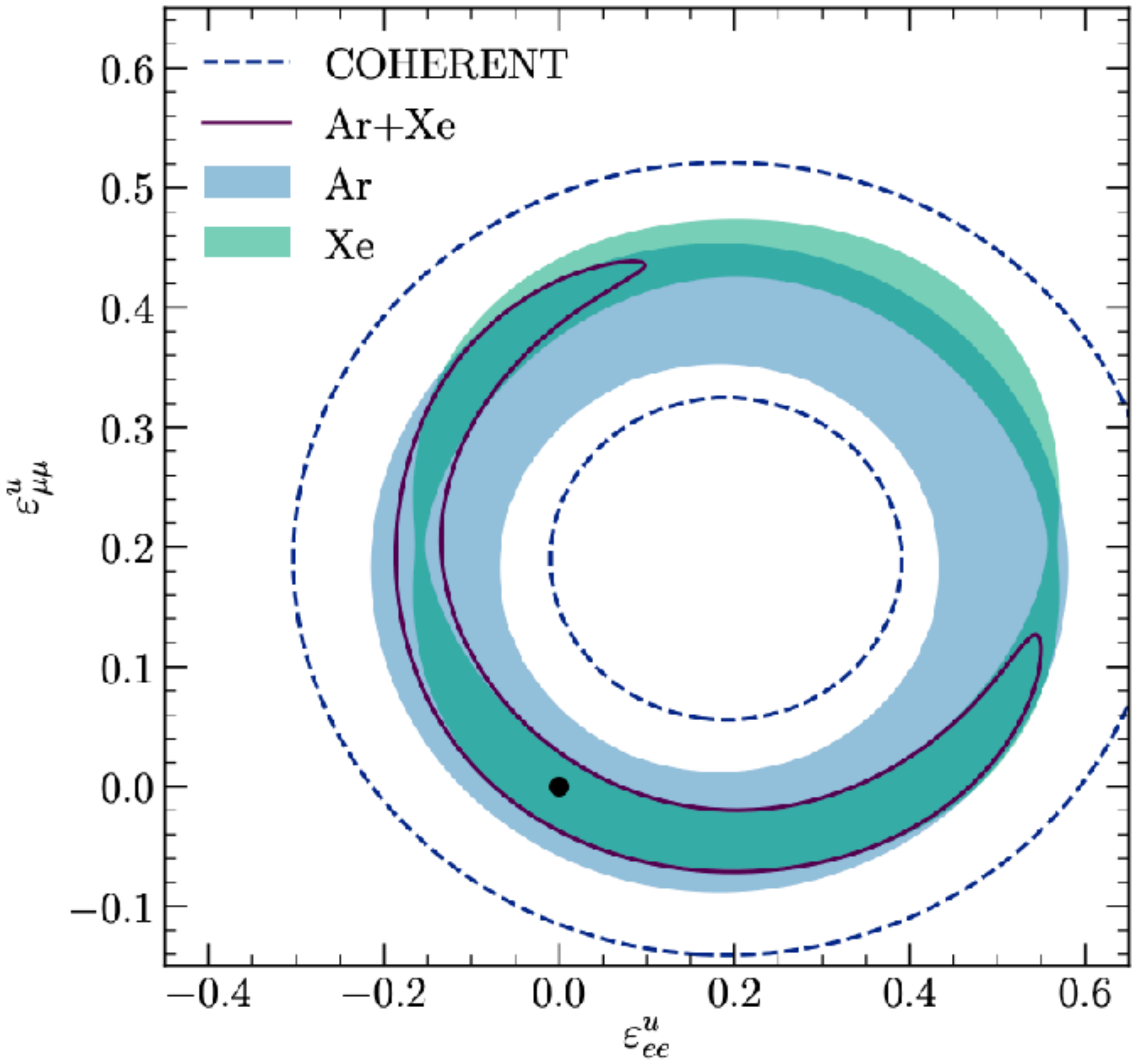
Interesting physics concentrates at low energies

Detecting CEvNS

Detectors

Non-Standard neutrino-quarks interactions

Operation with different nuclei helps breaking degeneracies

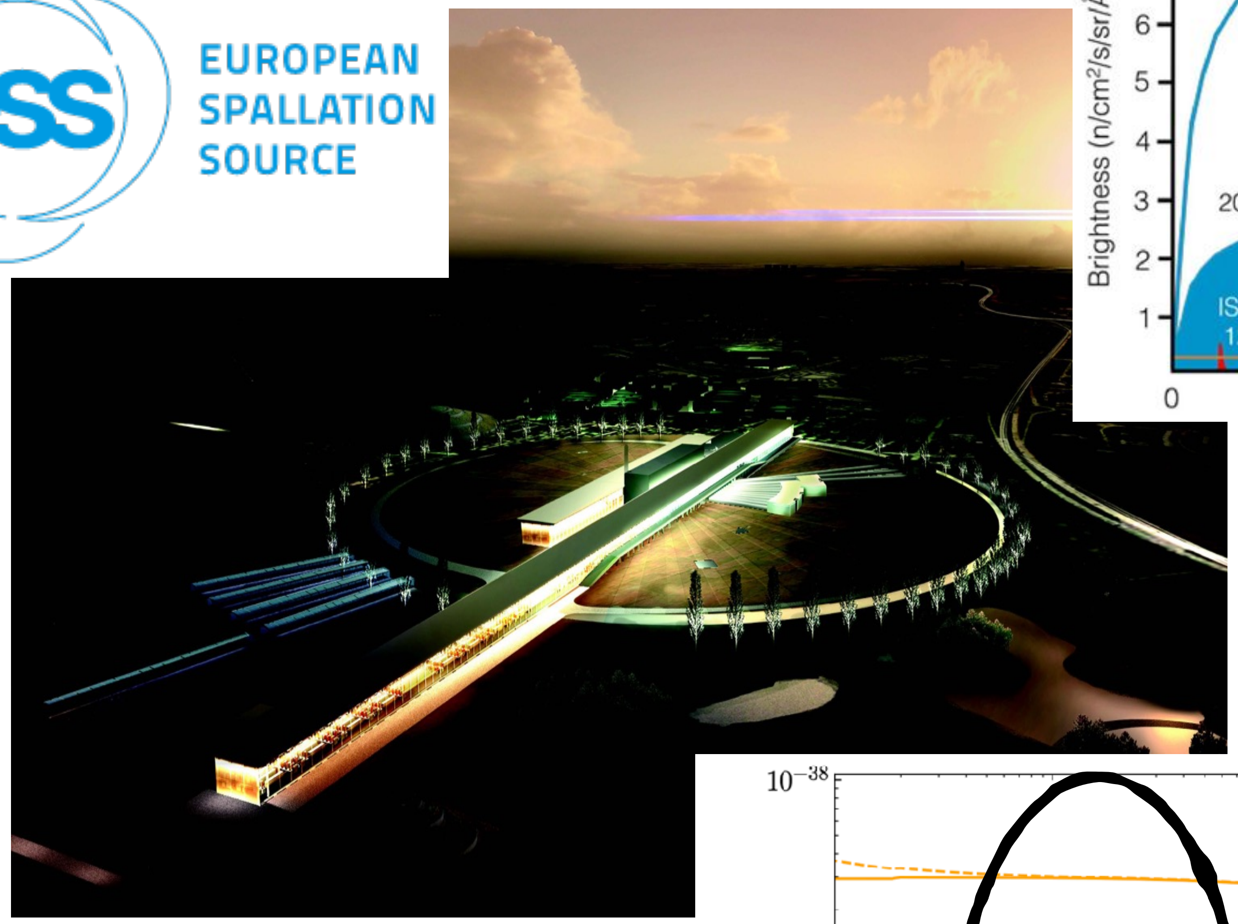


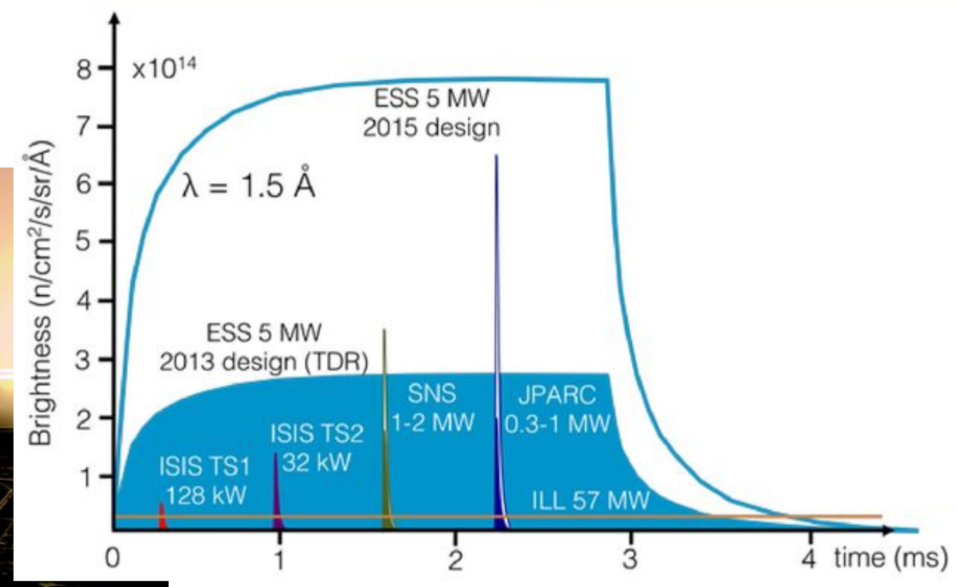
A full experimental program must allow for operation with different targets.

Detecting CEvNS

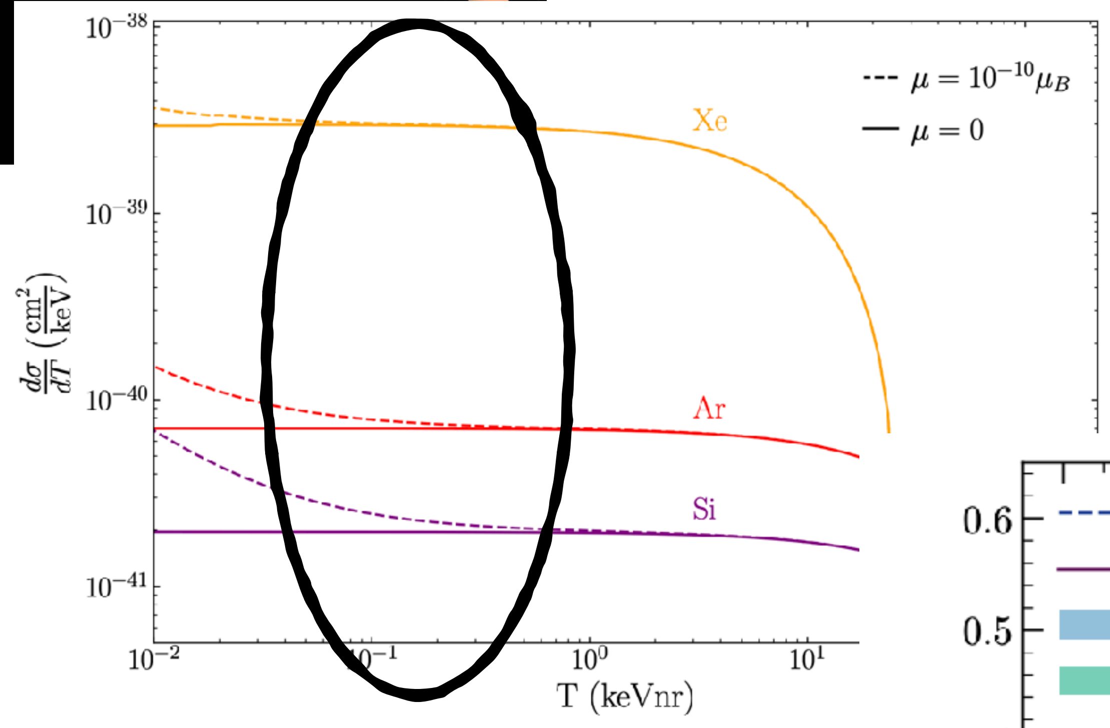
Specs.

EUROPEAN SPALLATION SOURCE

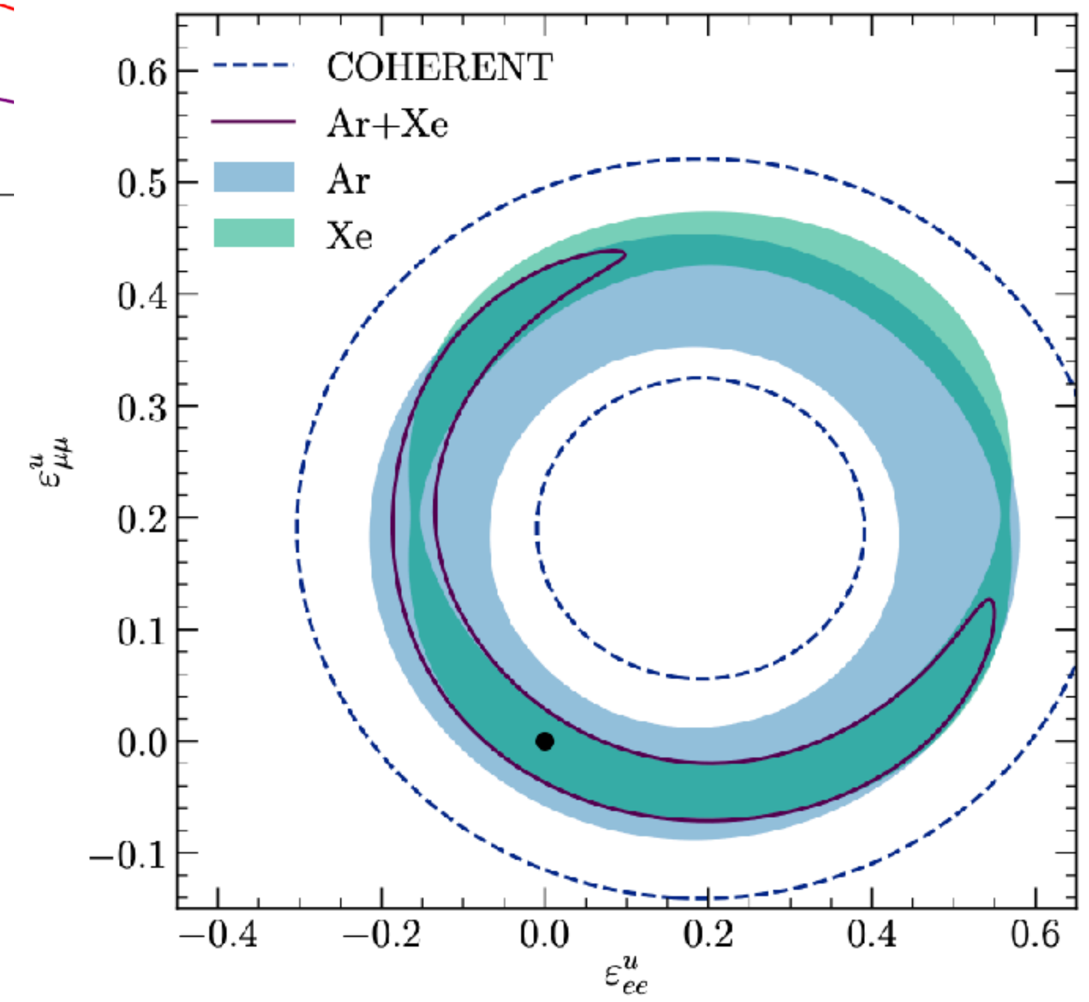




- Large flux of MeV neutrinos



- Detectors with low energy threshold

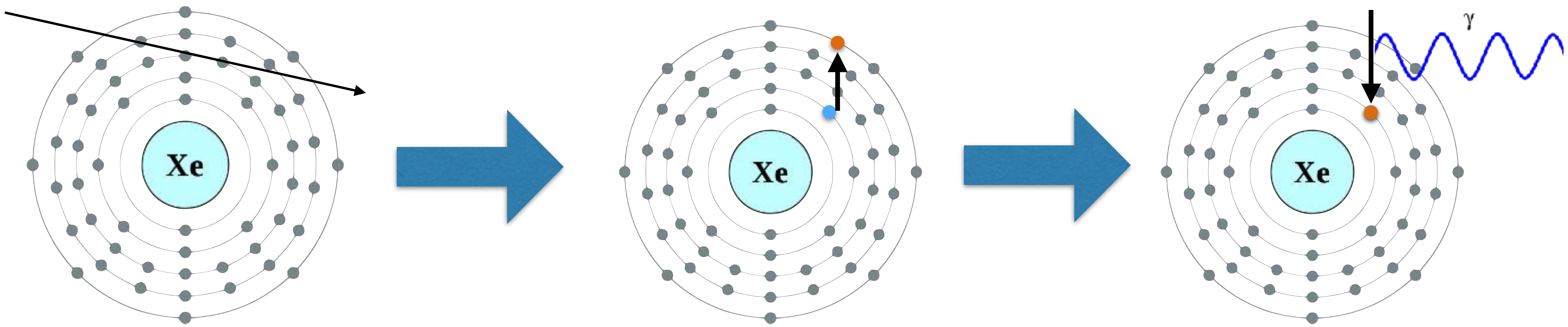


- Operation with different nuclei

GASEOUS DETECTORS

Ionization and scintillation in Xe

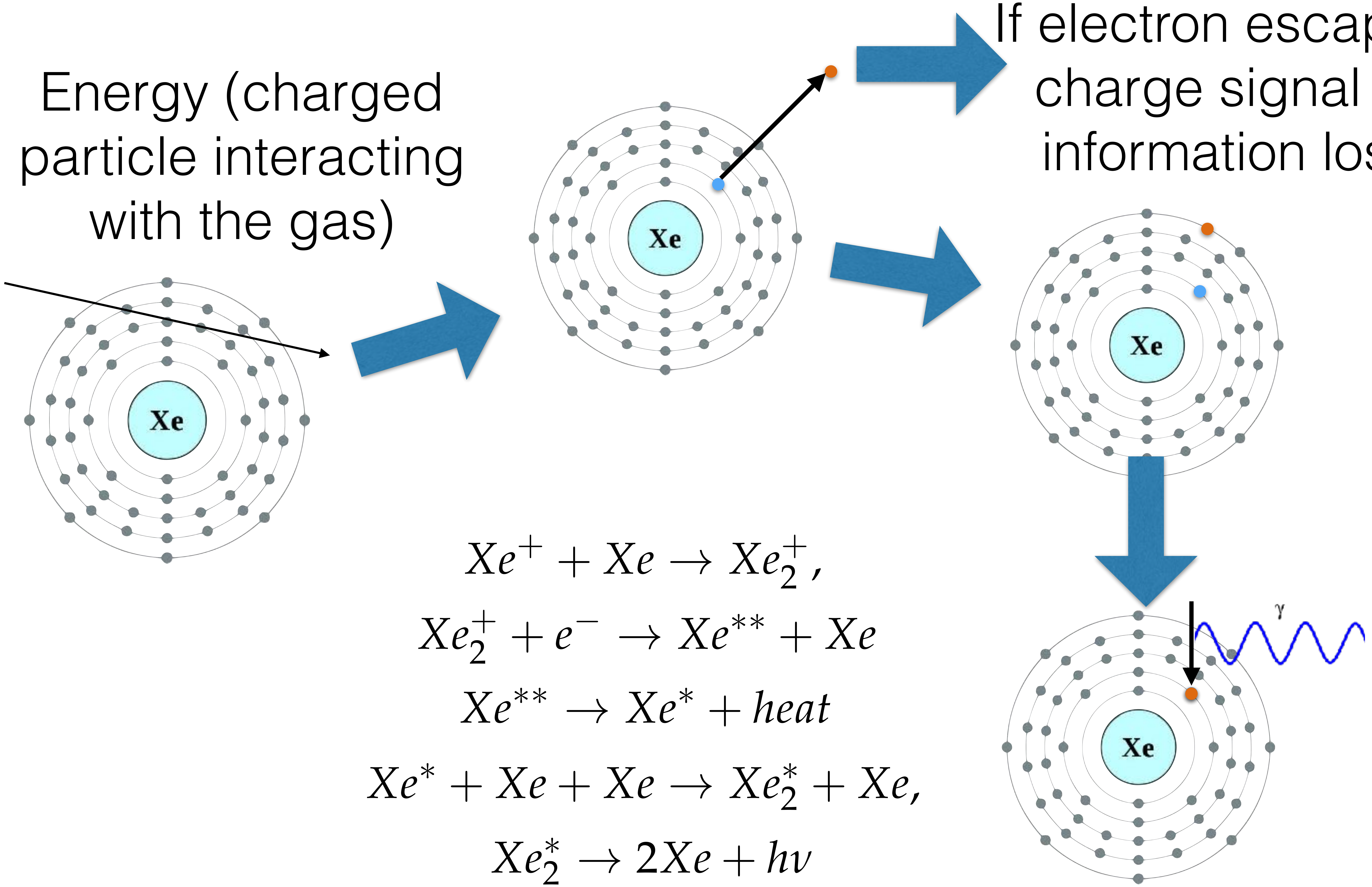
Energy (charged particle interacting with the gas)



$$Xe^* + Xe + Xe \rightarrow Xe_2^* + Xe,$$

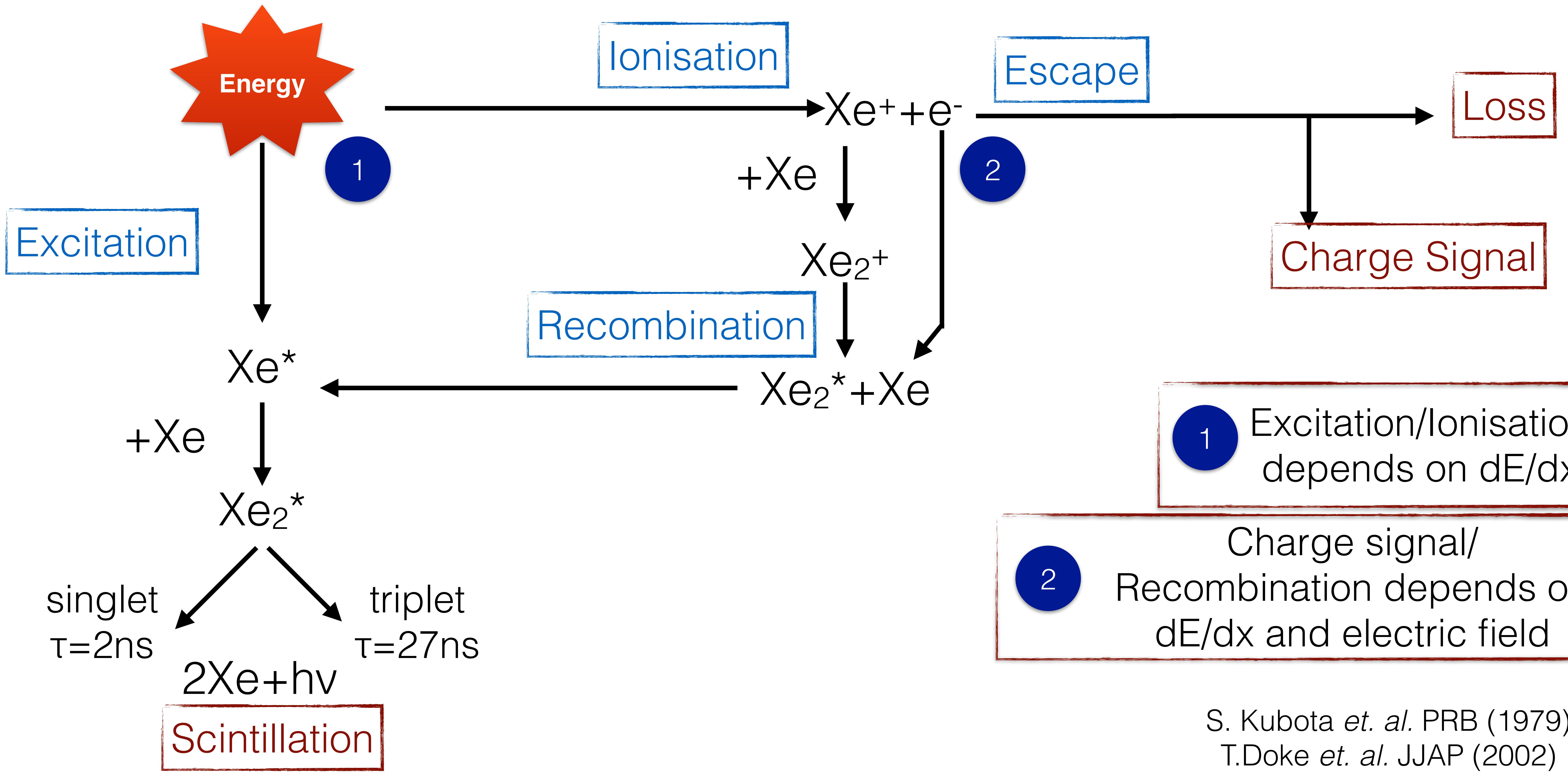
$$Xe_2^* \rightarrow 2Xe + h\nu$$

Ionization and scintillation in Xe



$$Xe^{+} + Xe \rightarrow Xe_2^{+},$$
$$Xe_2^{+} + e^{-} \rightarrow Xe^{**} + Xe$$
$$Xe^{**} \rightarrow Xe^{*} + heat$$
$$Xe^{*} + Xe + Xe \rightarrow Xe_2^{*} + Xe,$$
$$Xe_2^{*} \rightarrow 2Xe + h\nu$$

Ionization and scintillation in Xe



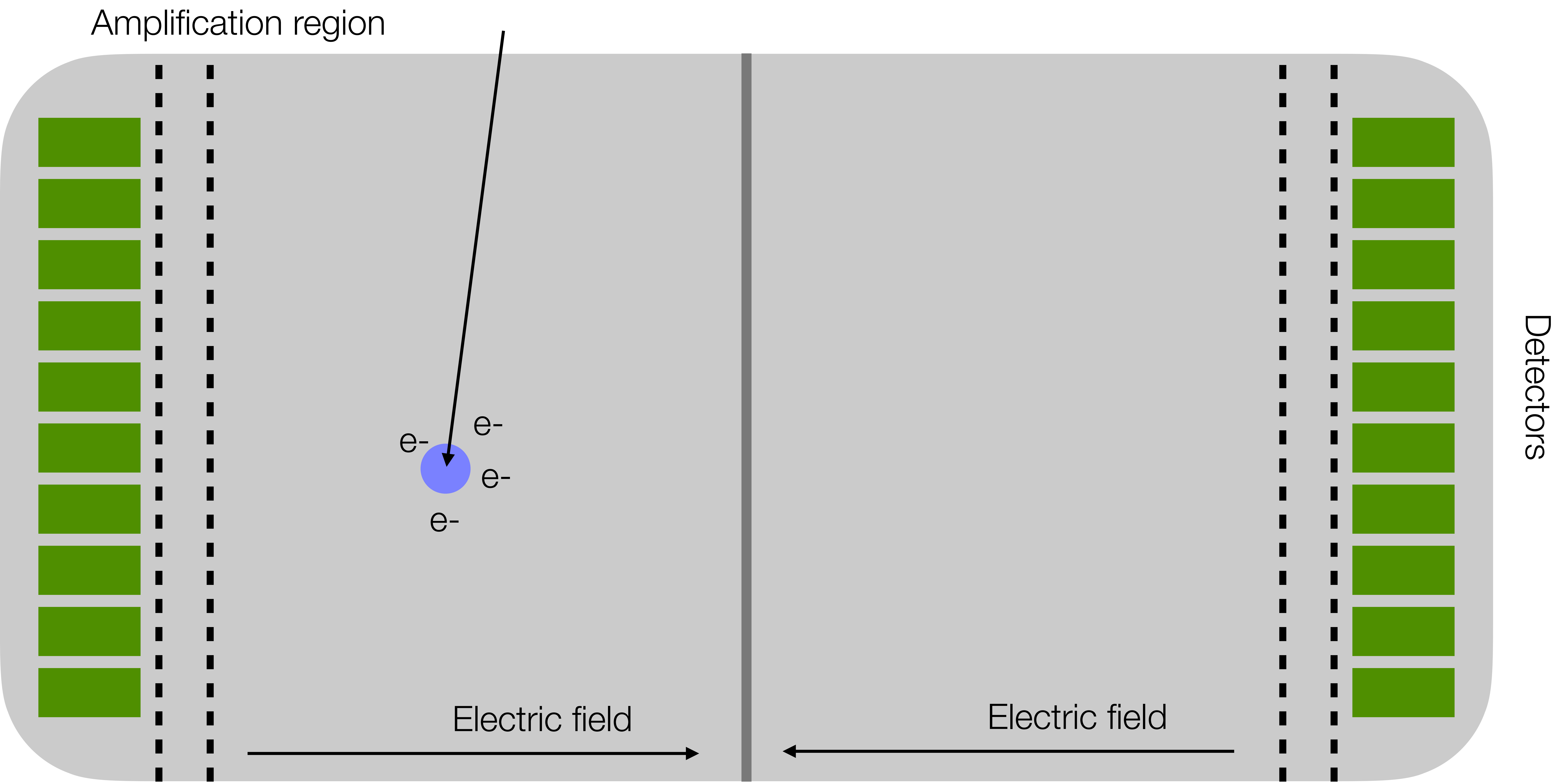
1 Excitation/Ionisation depends on dE/dx

2 Charge signal/ Recombination depends on dE/dx and electric field

S. Kubota *et. al.* PRB (1979)
T.Doke *et. al.* JJAP (2002)

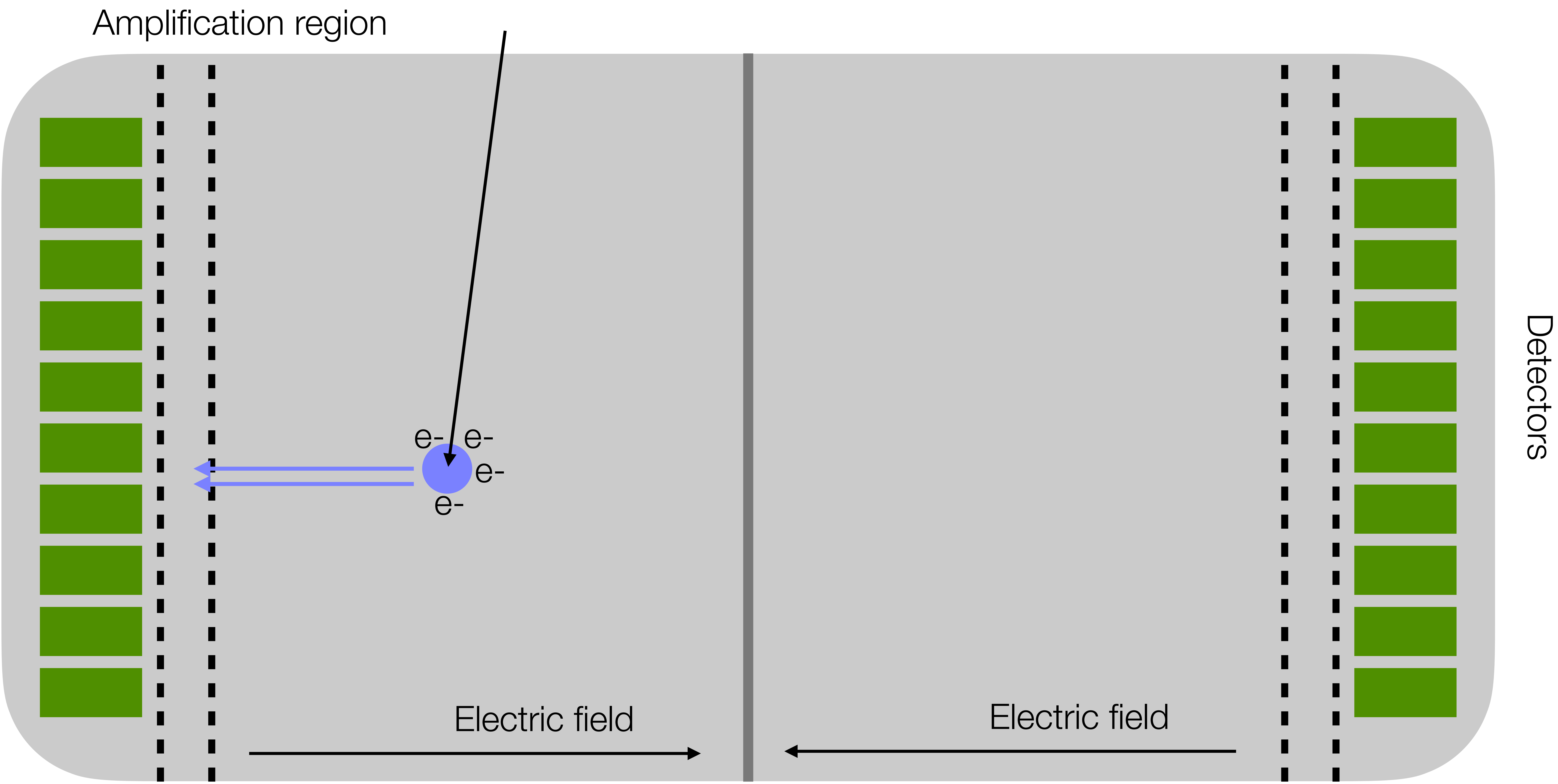
TPC

TPC concept



Amplification region
e-
e-
e-
e-
Electric field
Electric field
Detectors

TPC concept



Amplification region
e-
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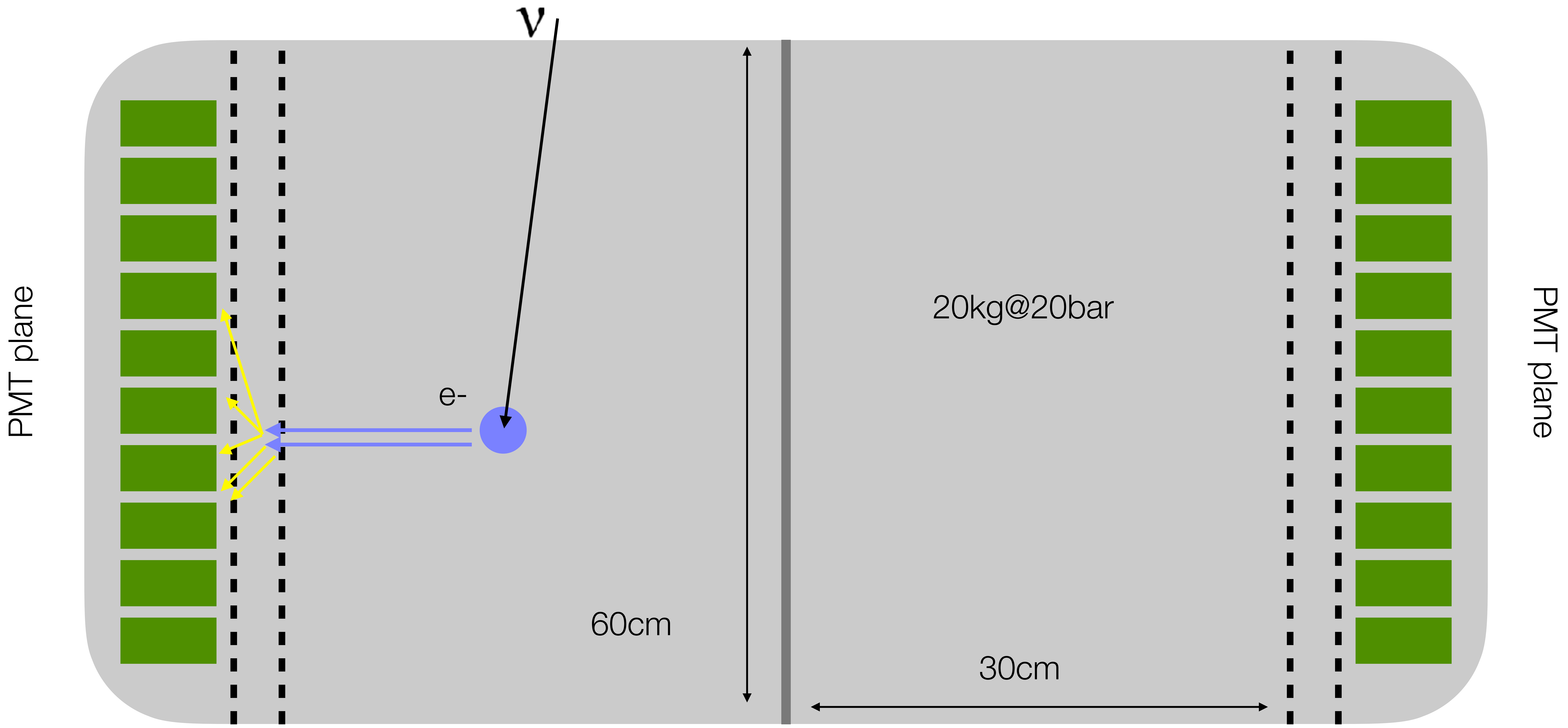
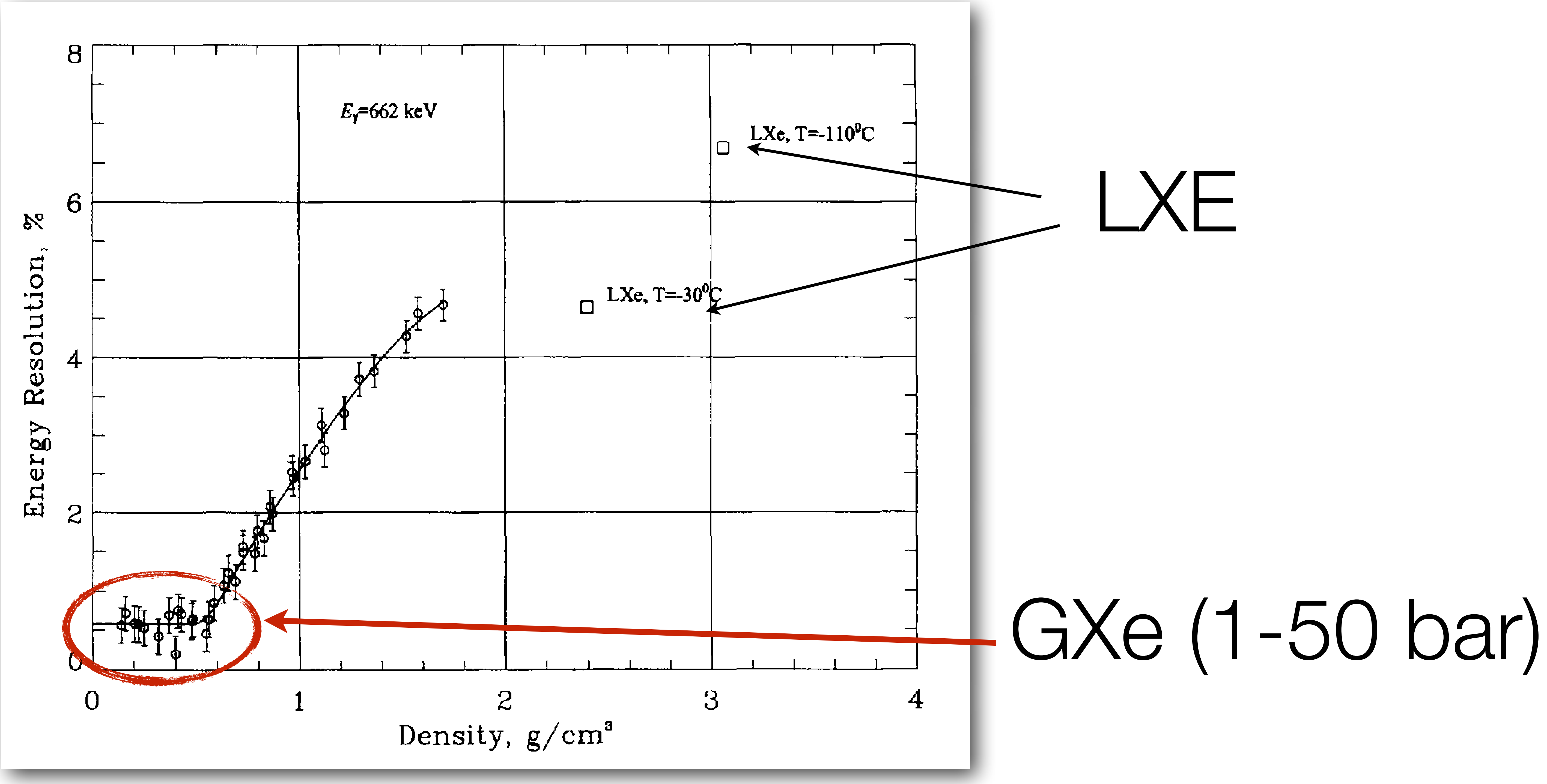
Electric field
Electric field
Detectors

TPC concept



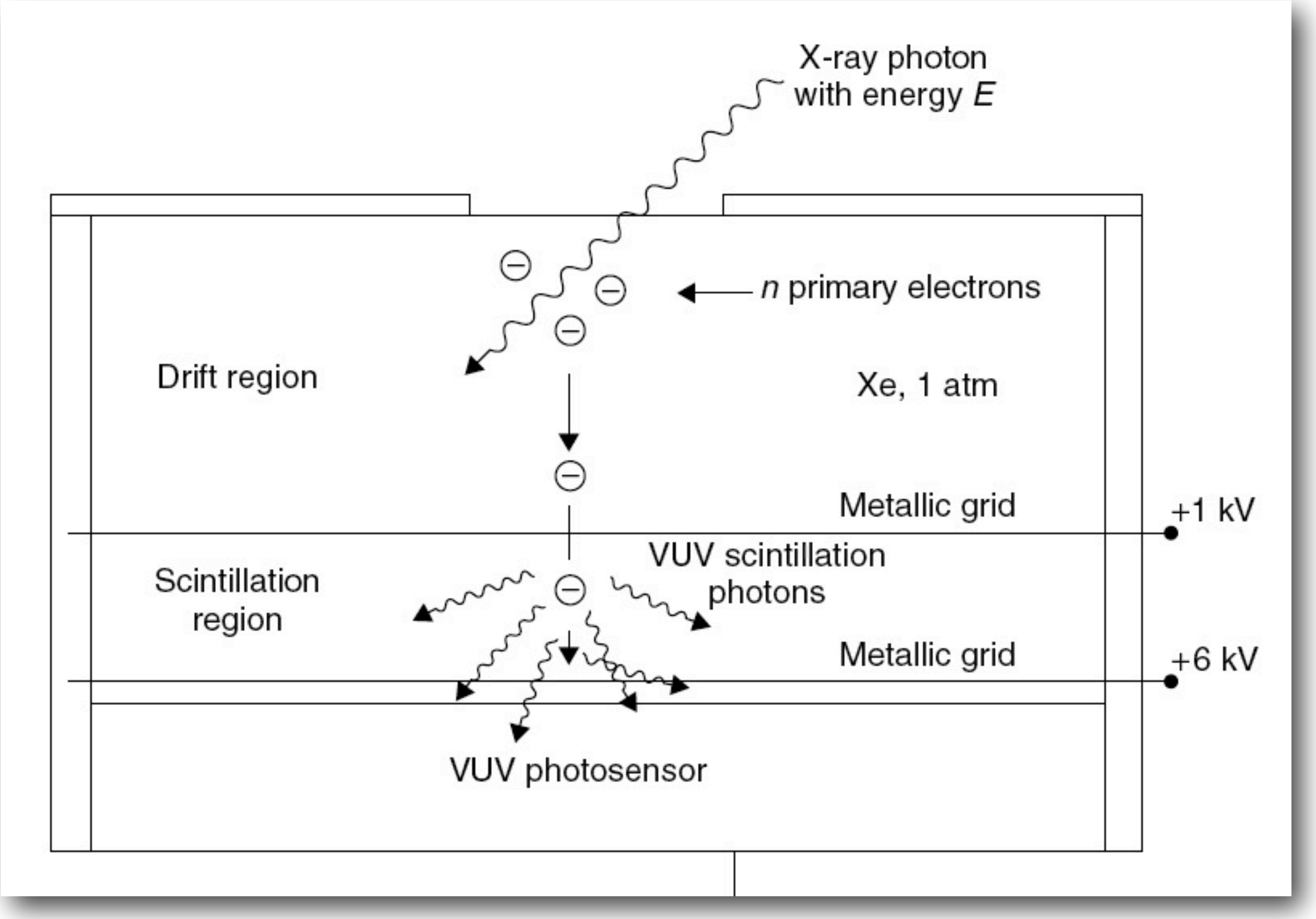
Energy resolution in HPXe

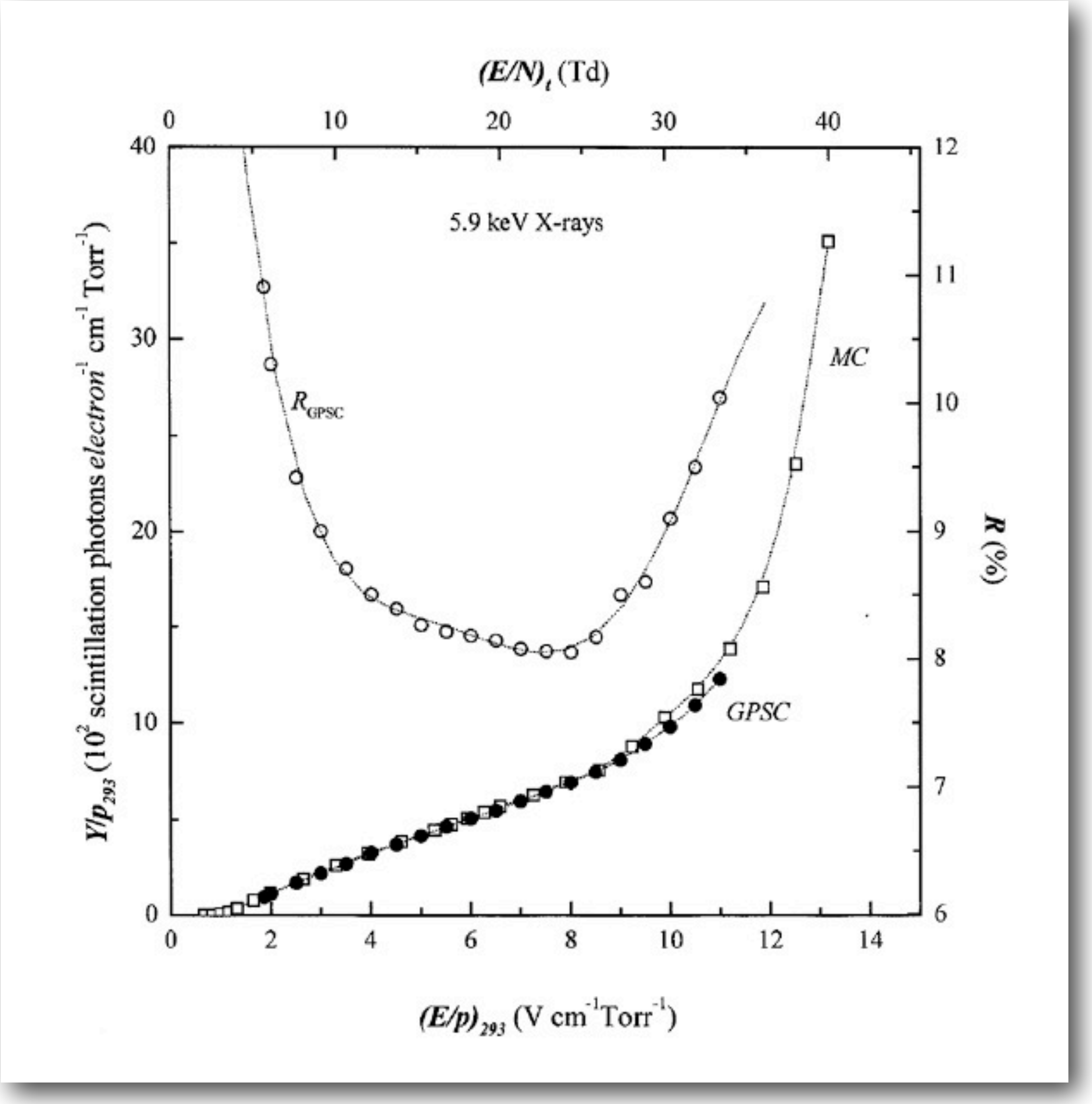
Bolotnikov and Ramsey, NIM A 396 (1997)



- Intrinsic resolution (Fano factor) 0.15.
- Extremely good intrinsic resolution.
- We need an amplification method to maintain it.

Amplification preserving resolution: Electroluminescence



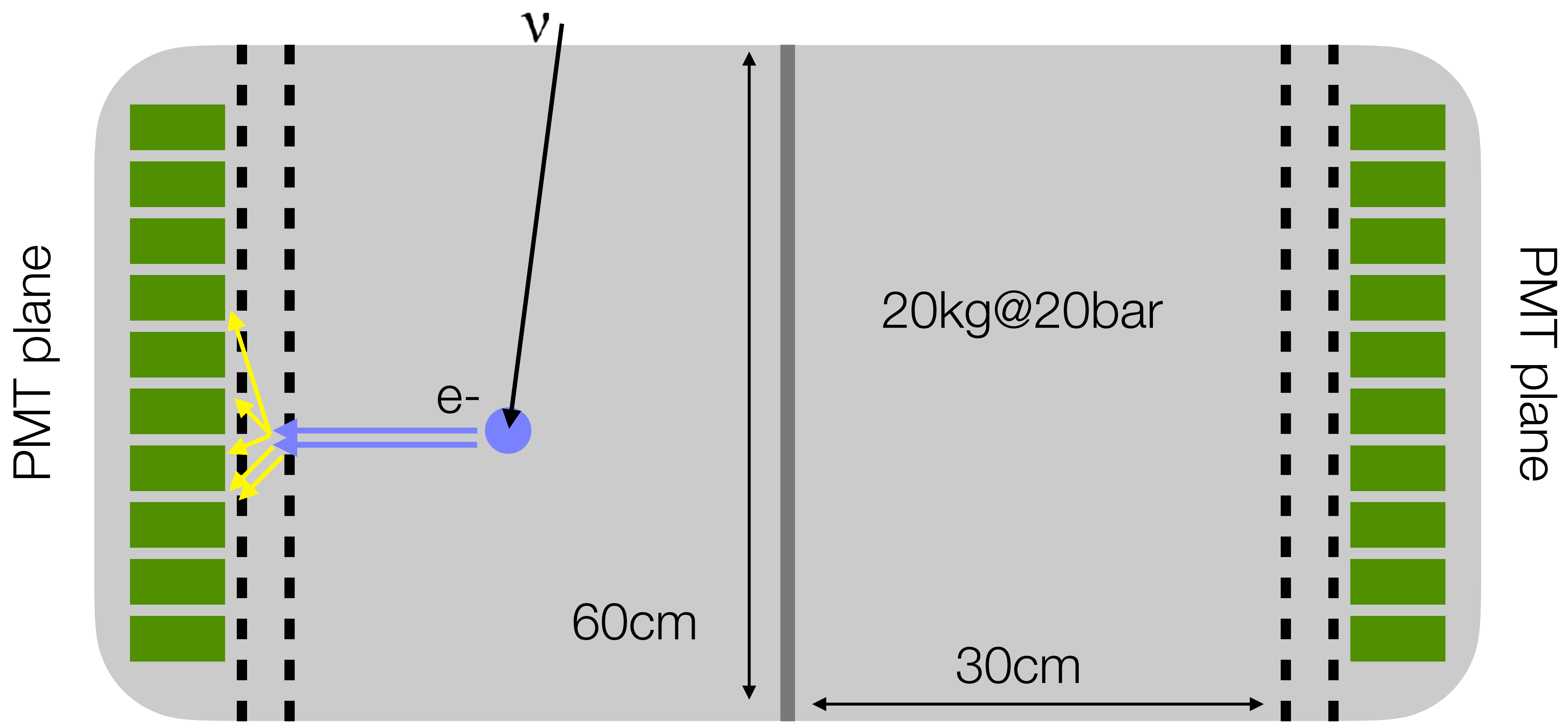


- Emission of scintillation light after atom excitation by a charge accelerated by a moderately large (no charge gain) electric field.
- Linear process, huge gain (1500 ph./e-) at 3 < E/p < 6 kV/cm/bar.
- Sub-poisson fluctuations in the process allows to maintain the intrinsic resolution

GaNESS project

The GanESS detector

- Optimised for **reduced threshold**.
- Operation with **different gases**.

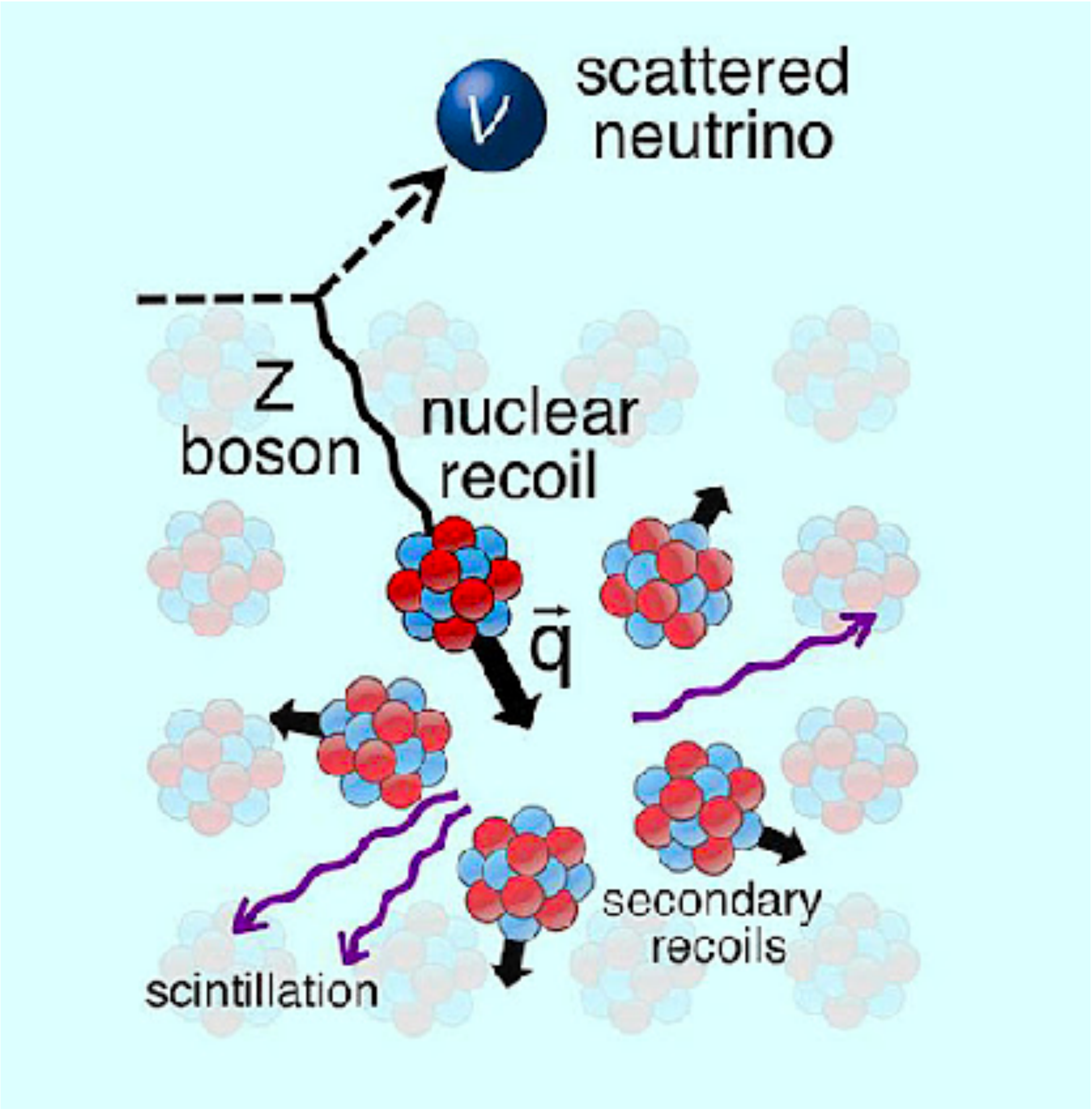


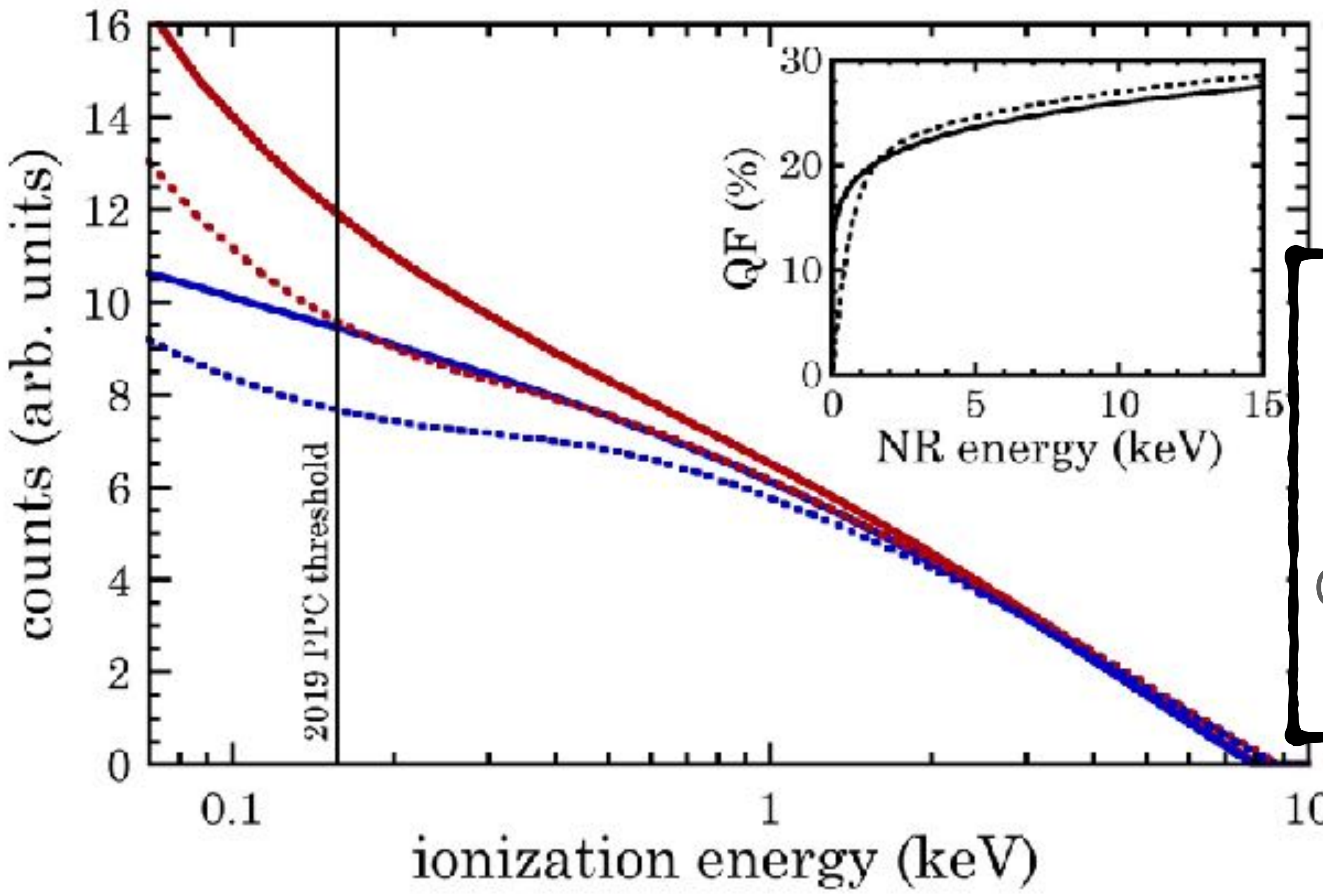
GaNESS project

The Gaseous Prototype (GaP) system

- Test for high pressure (up to 50 bar) and operation with different gases.

- Characterisation of the **response to nuclear recoil** (QF) at low energies.



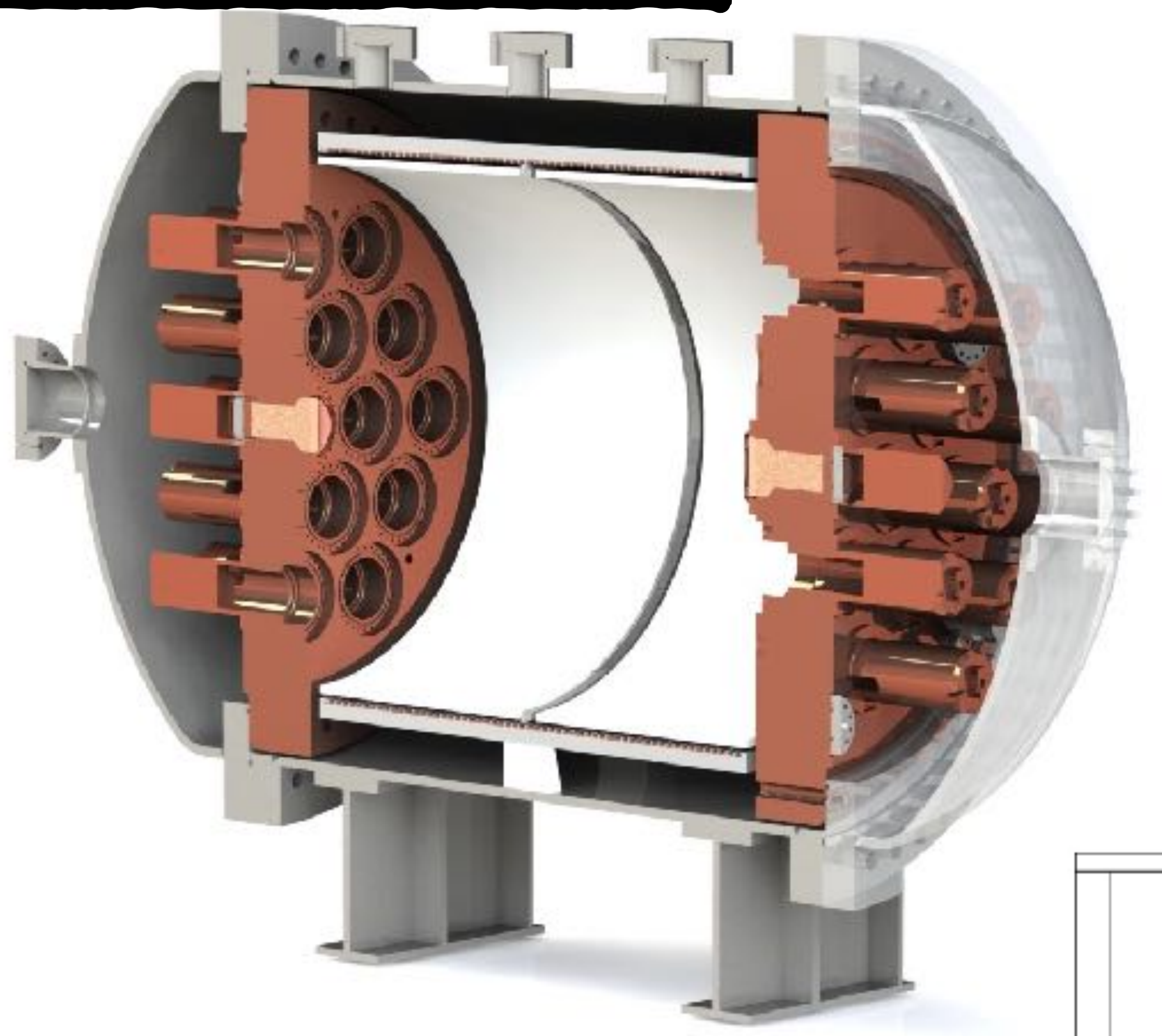


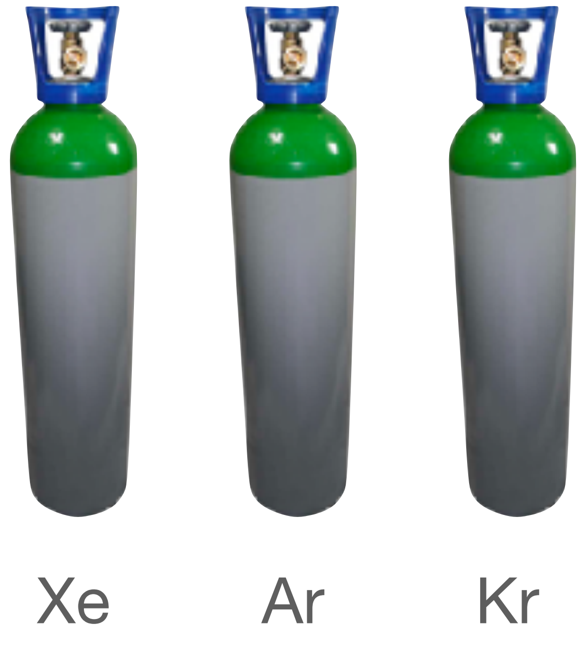
Expected number of events for different values of the neutrino magnetic moment (blue-red) and different models of the quenching factor (solid-dashed)

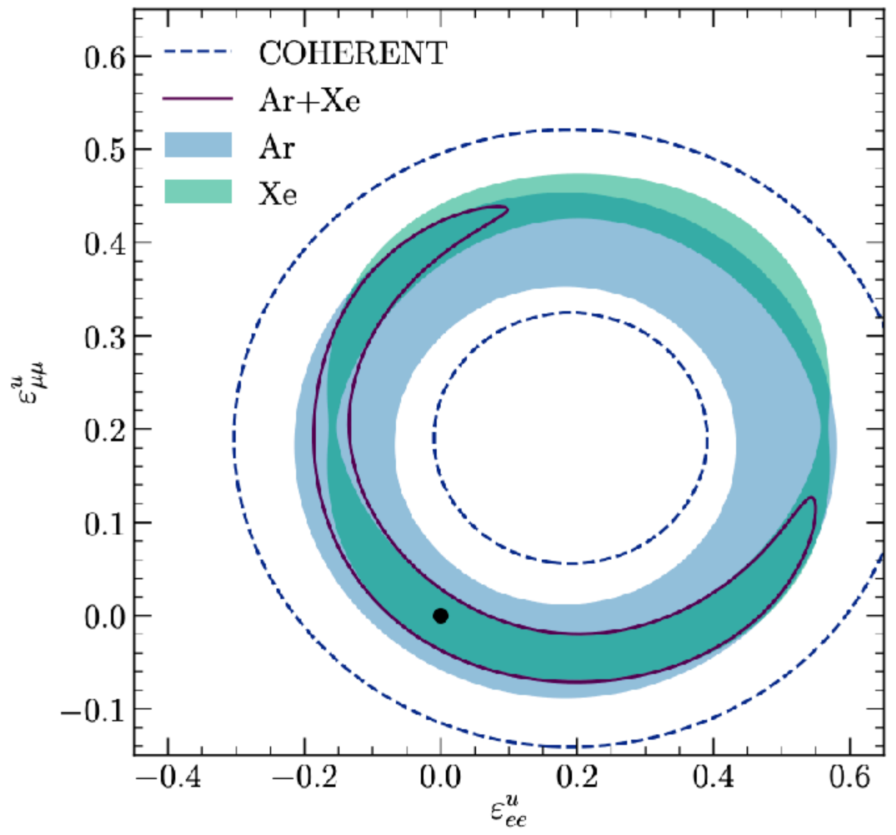
GaNESS project

Gaseous TPC

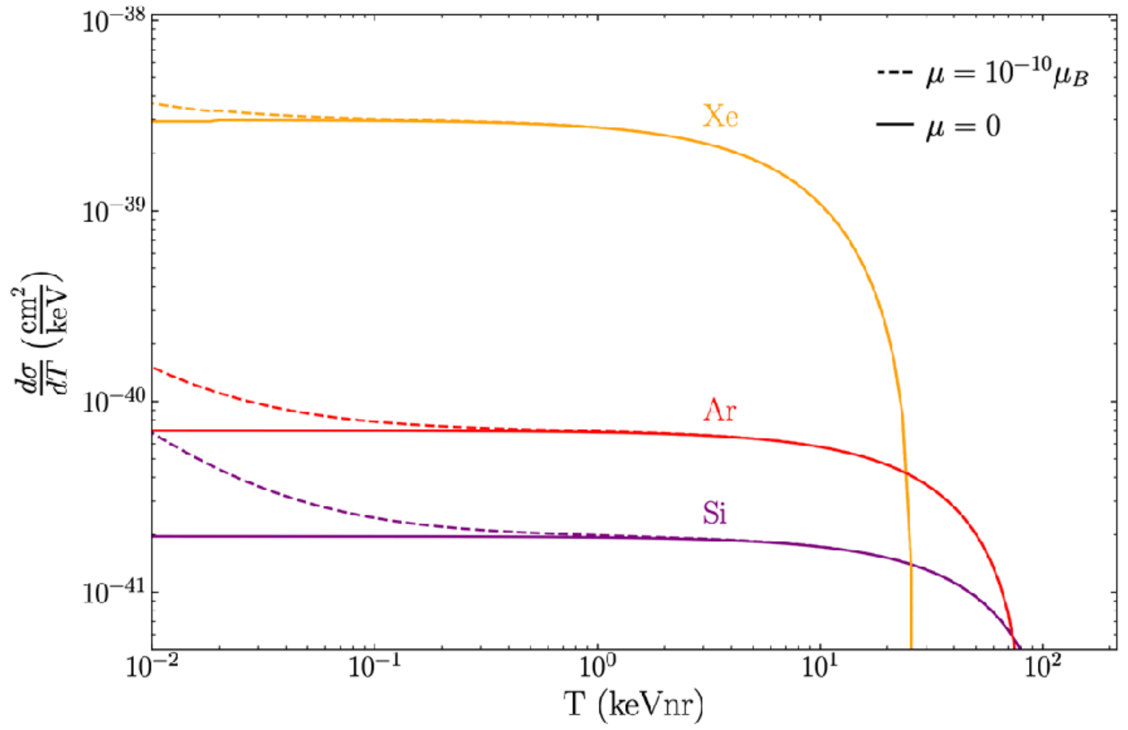
Detector construction

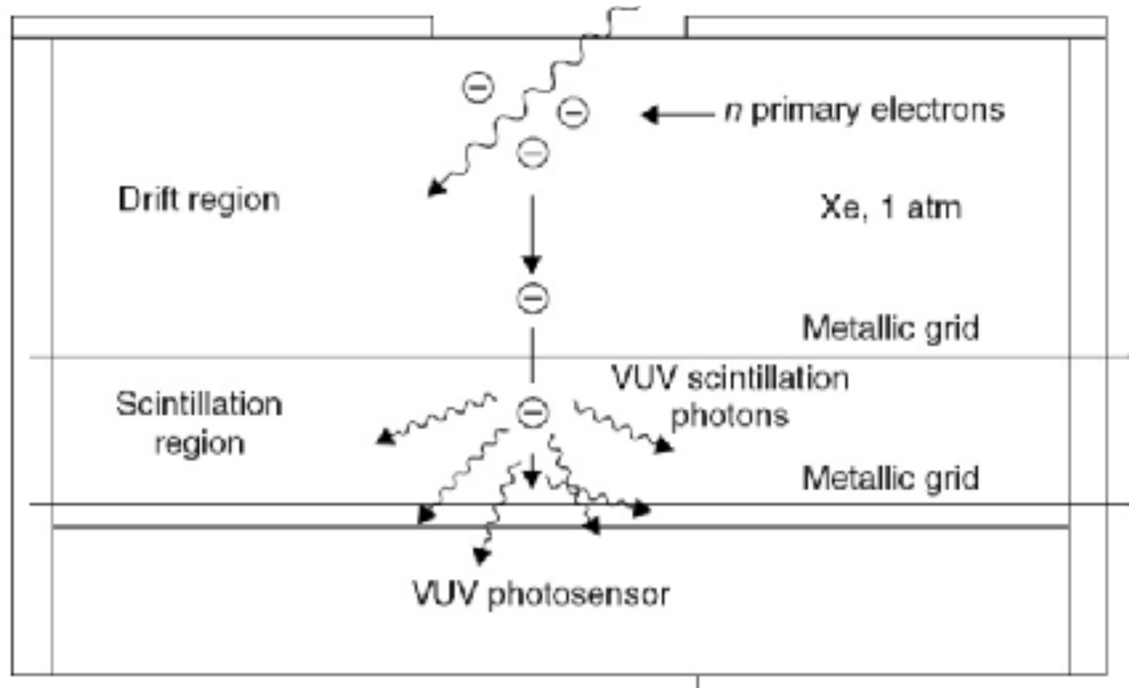


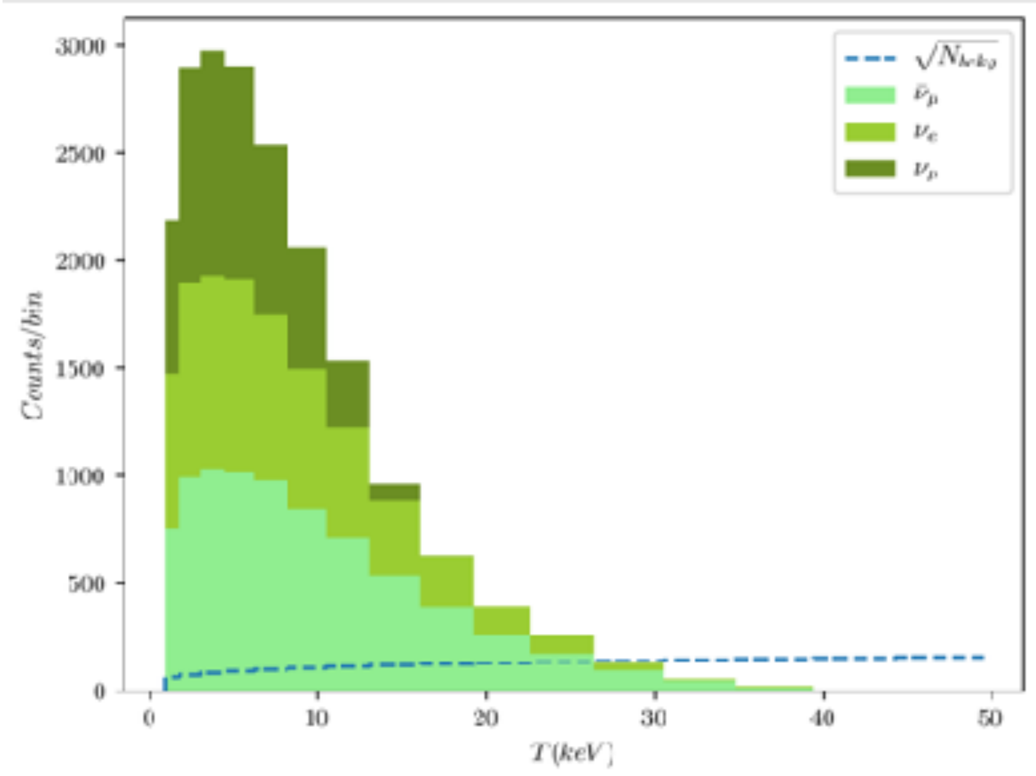




Physics exploitation

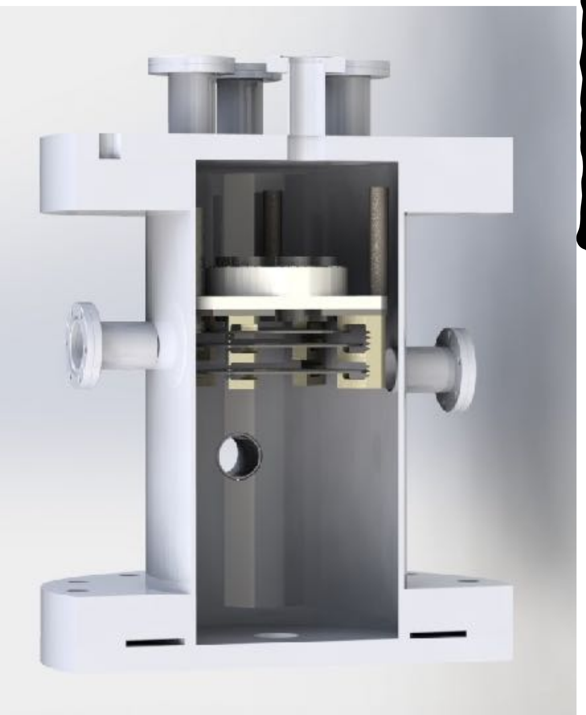






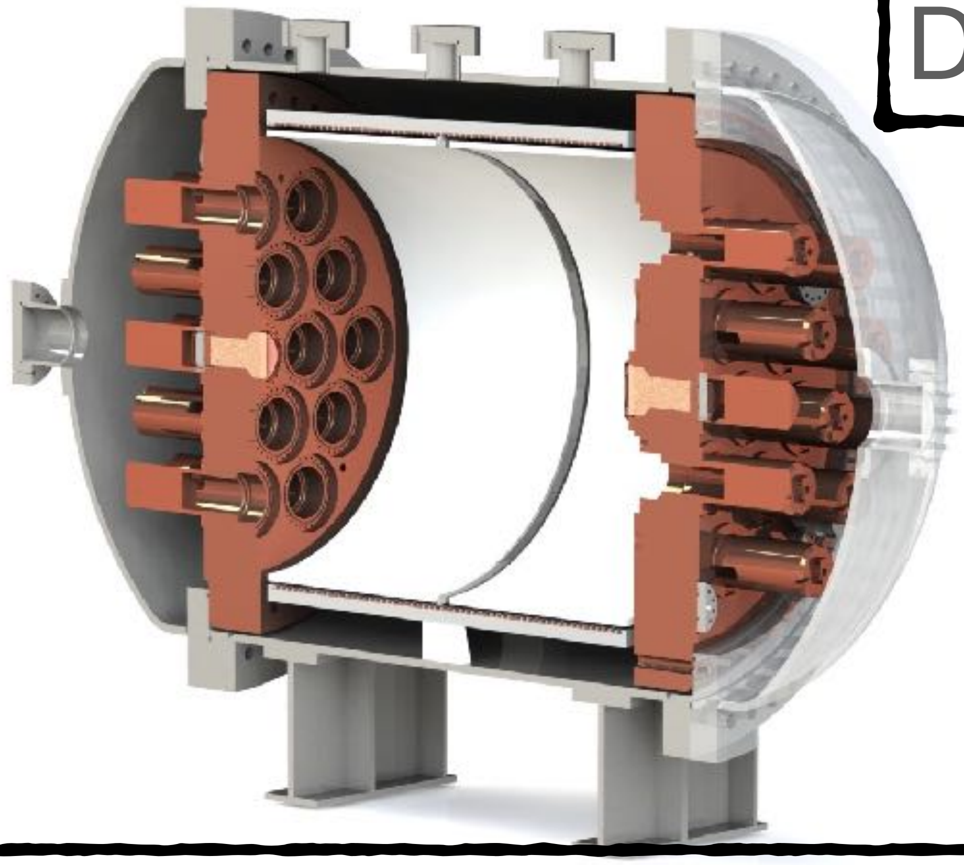
GaNESS project

Initial steps



Gaseous Prototype (GaP)

R&D, Study of nuclear recoils



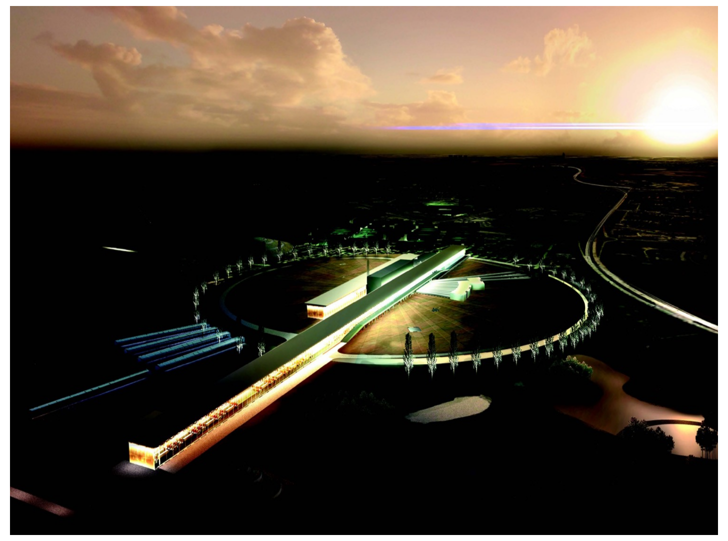
Detector construction, GanESS@DIPC

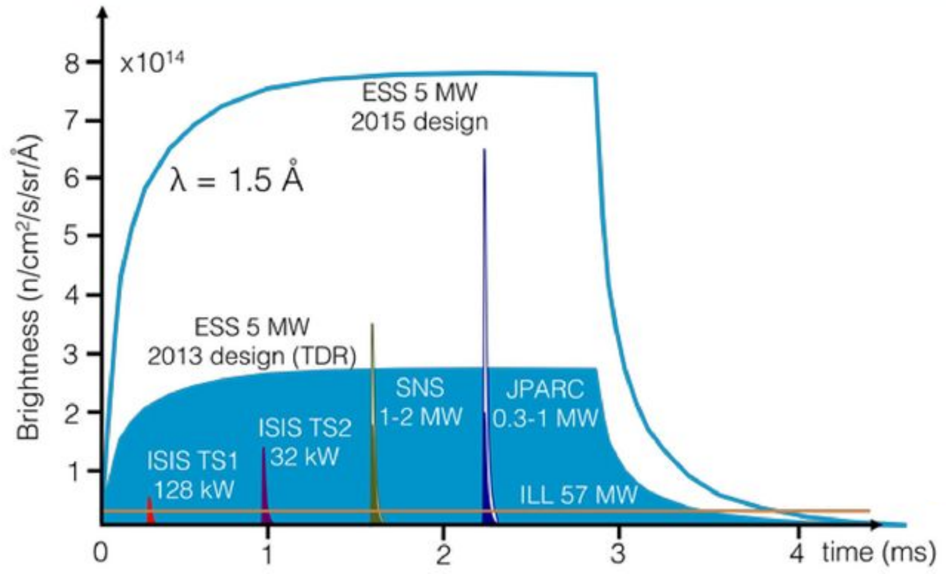
High pressure technology developed within the NEXT experiment

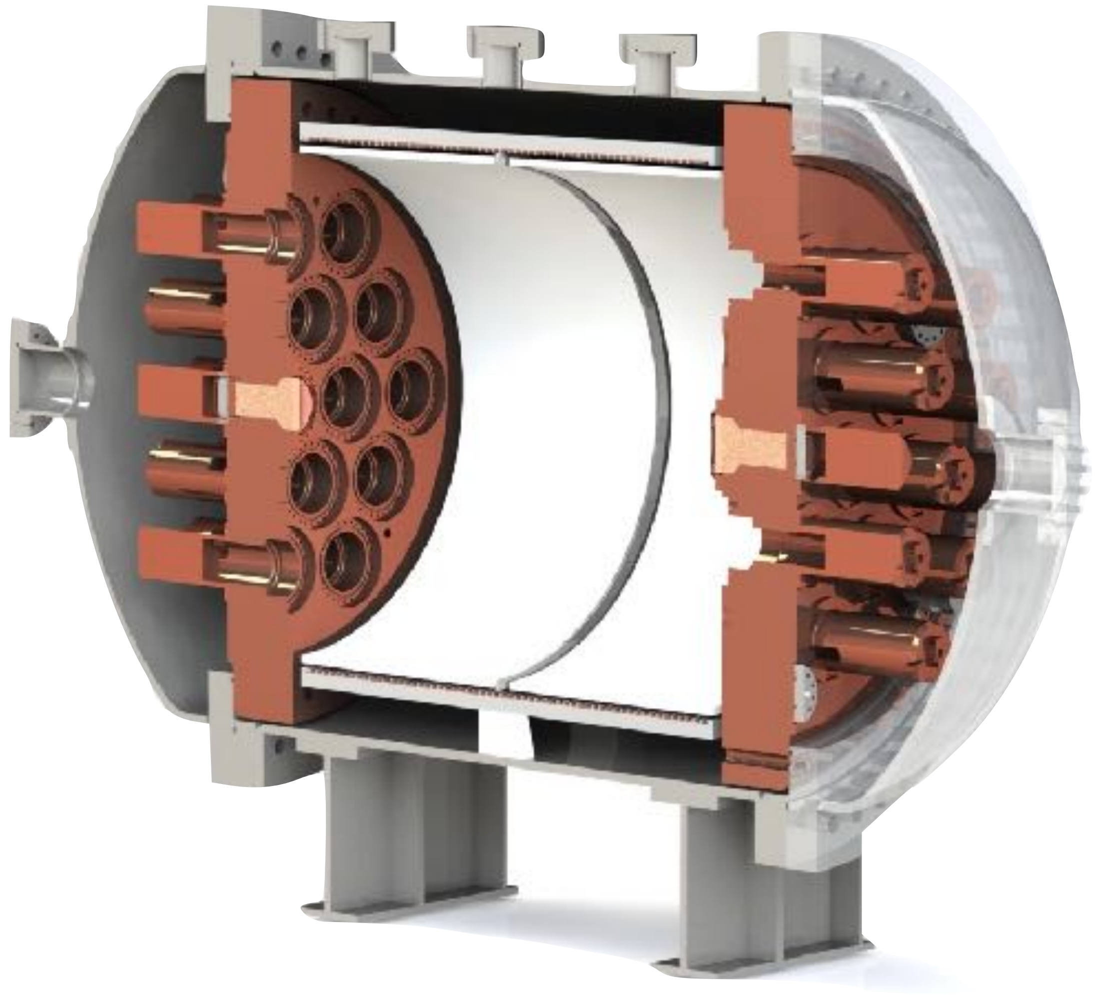
Operation GanESS@ ESS

GanESS Summary

- CEvNS detection opens a **new avenues in the search of physics beyond the Standard Model**.
- **ESS** will become the largest low-energy neutrino source. Perfect facility to study this process.
- The **GanESS project**, with the ERC support, will produce a detector to observe the process at the ESS with a variety of nuclei.
- **GanESS** offers an opportunity to **lead a world-class neutrino program** in the coming years with a **large discovery potential**.







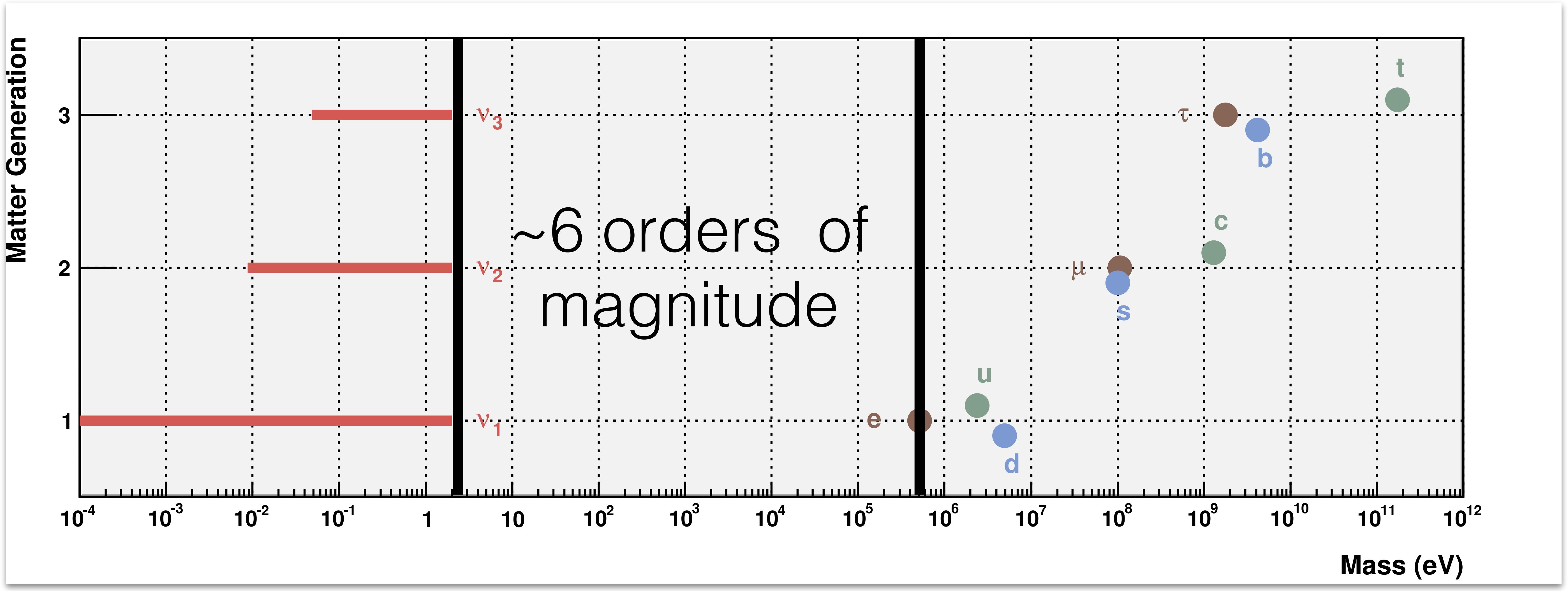
ARE NEUTRINOS MAJORANA PARTICLES?

“NOT DETECTING NEUTRINOS”

Majorana neutrinos

Neutrino masses much smaller than the other fermions masses

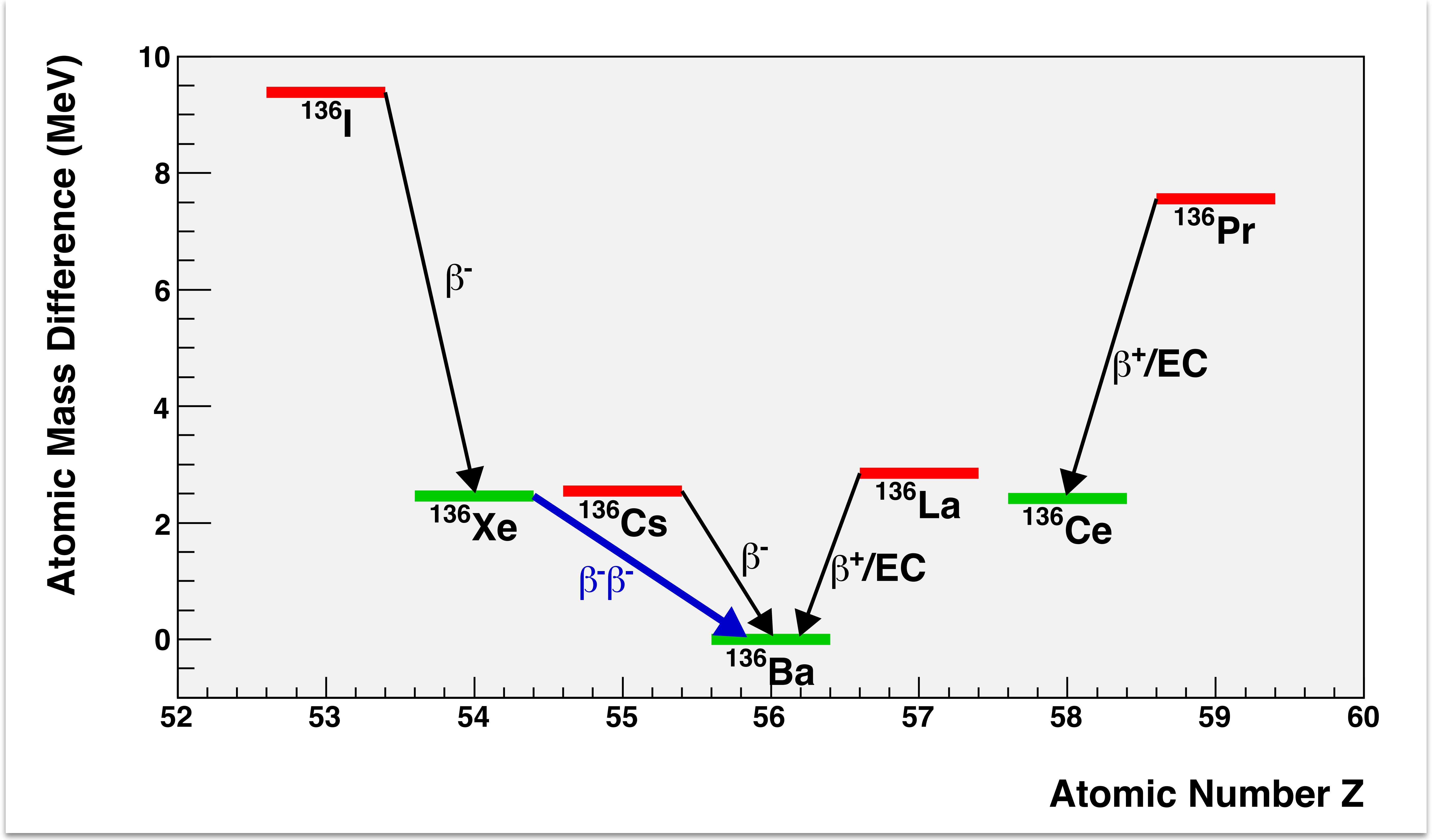
Neutrinos are the only chargeless fermions, the only that could be Majorana particles



Majorana neutrinos allow for simple explanation of this gap. At the same time, will prove the existence of physics at different scale

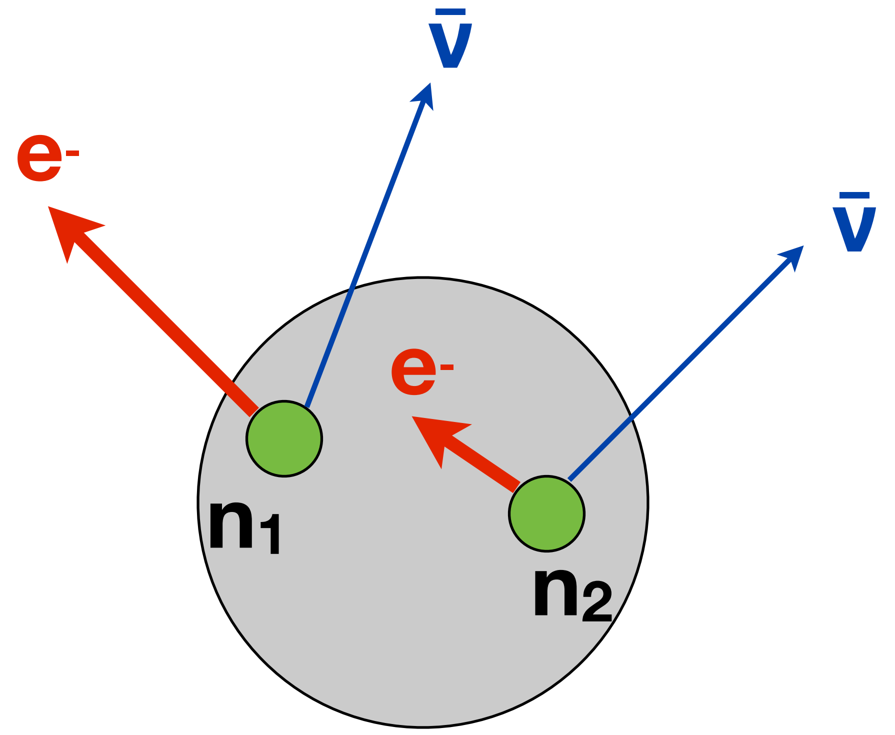
Double beta decay

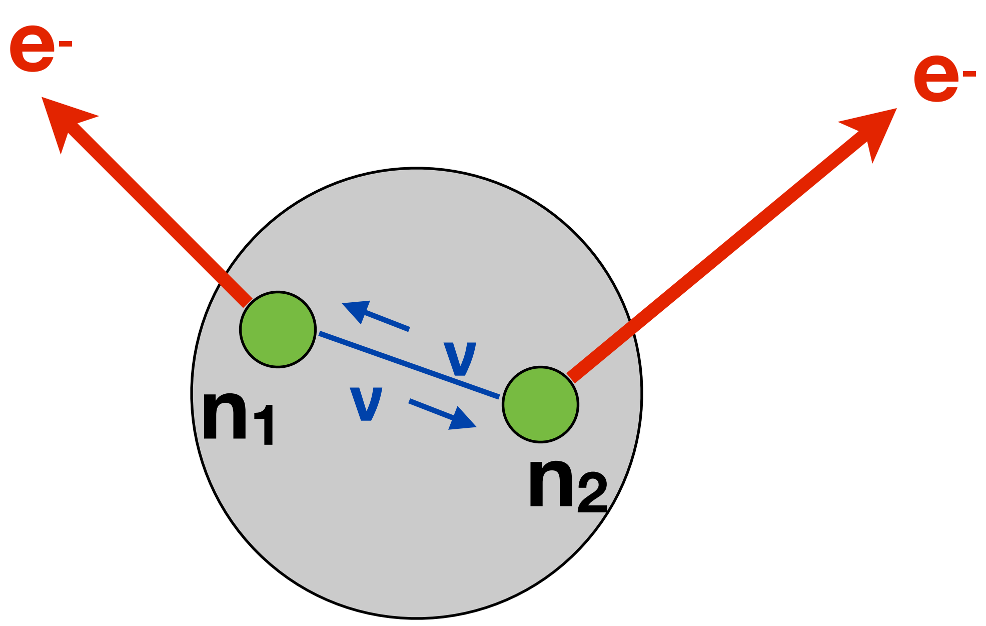
- Rare (Z,A)→(Z+2,A) nuclear transition, with emission of two electrons



Double beta decay

- Rare (Z,A)→(Z+2,A) nuclear transition, with emission of two electrons
- Two basic decay modes





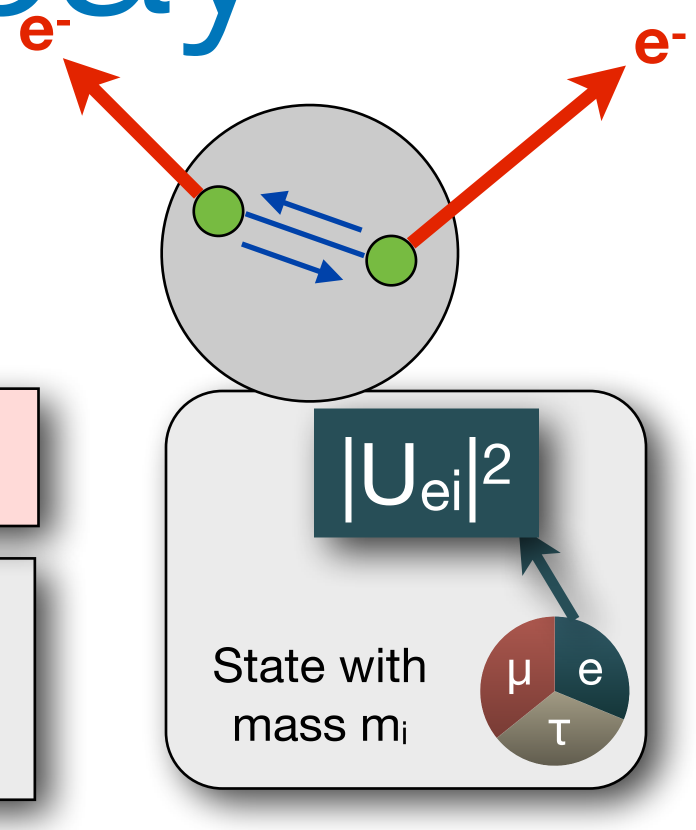
Two neutrino mode

- Observed in several nuclei
- 10^{19}-10^{21} yr half-lives
- Standard Model allowed

Neutrinoless mode

- Not observed yet in Nature
- >10^{26} yr half-lives
- Would signal Beyond-SM physics

Neutrinoless double beta decay and the neutrino questions

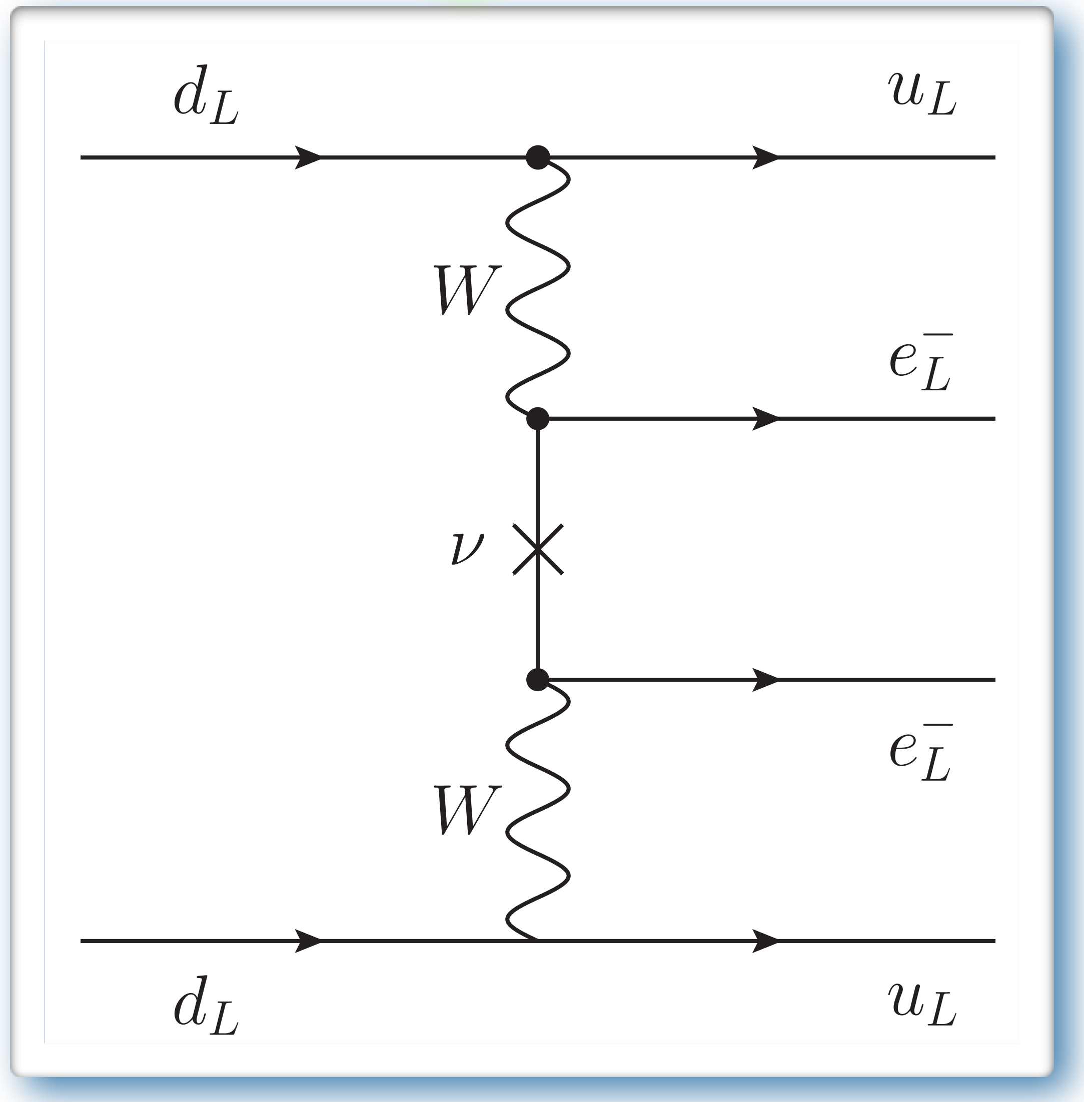


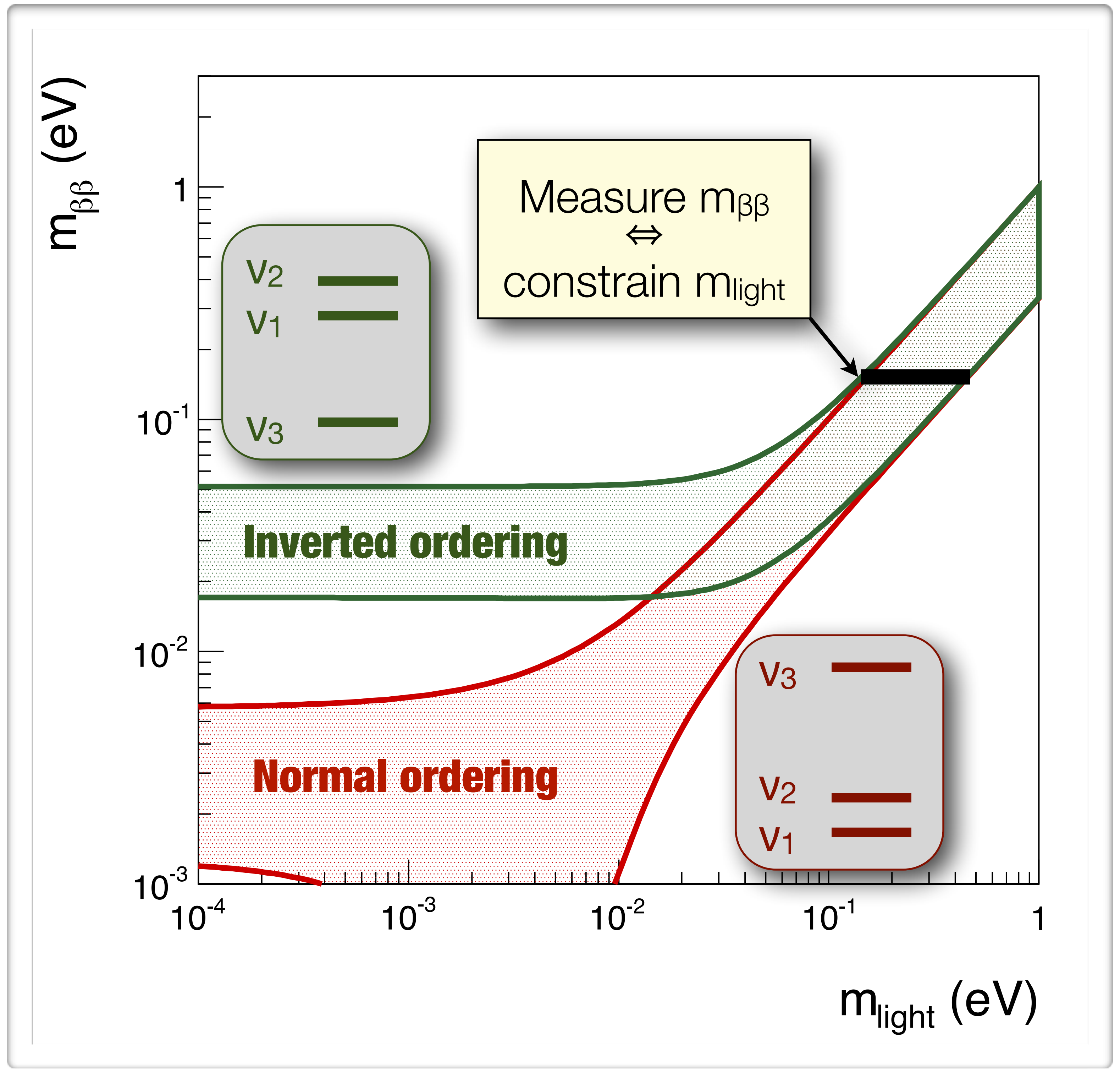
$(\text{Rate})_{\beta\beta0\nu} \propto m_{\beta\beta}^2$

Majorana ν mass:
$m_{\beta\beta} \equiv \left| \sum_i m_i U_{ei}^2 \right|$

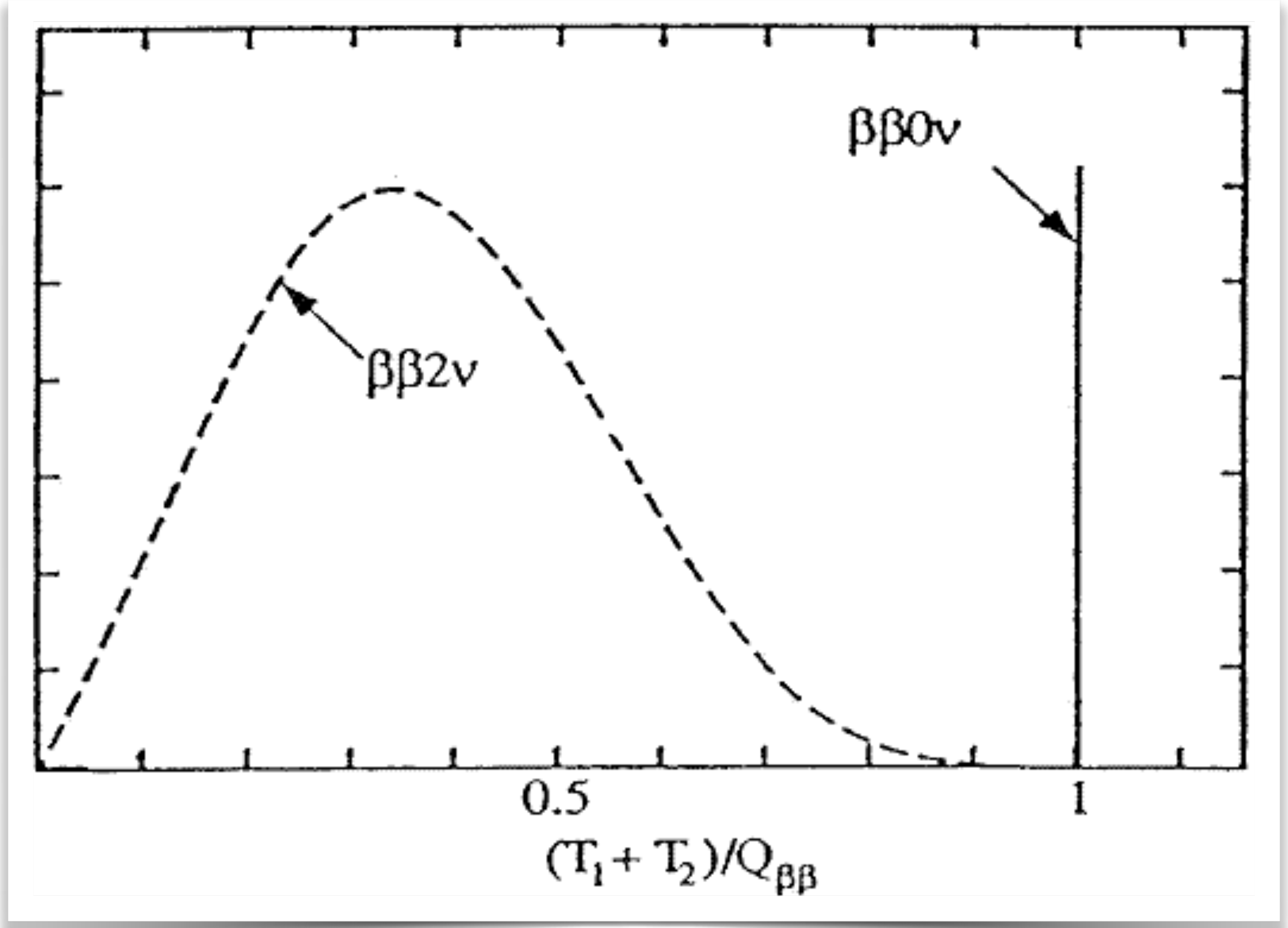
Lepton number violating process implying massive Majorana neutrinos

- Identity
- Mass scale
- Mass ordering
- Mixing
- Species





Measuring ββ0ν

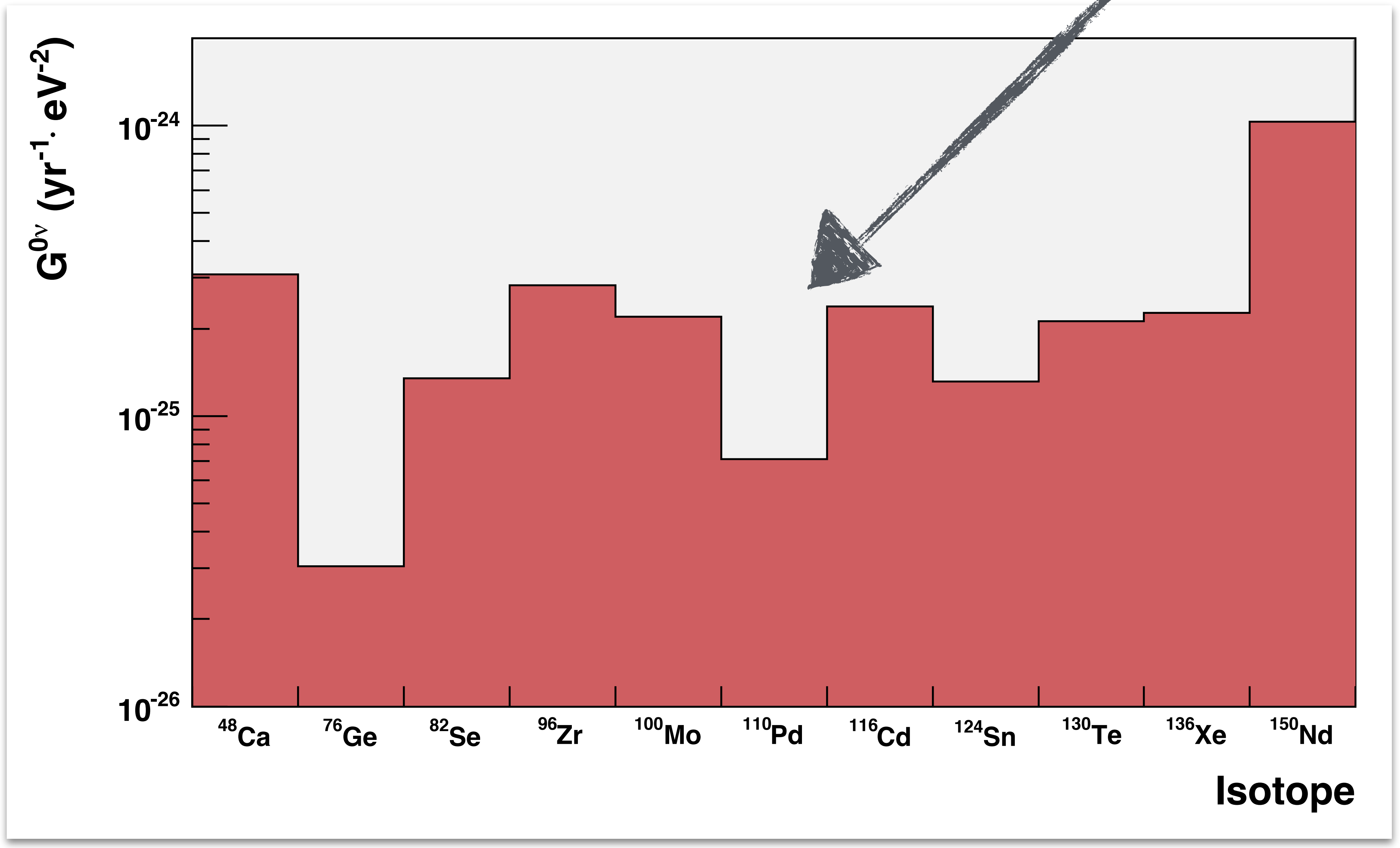


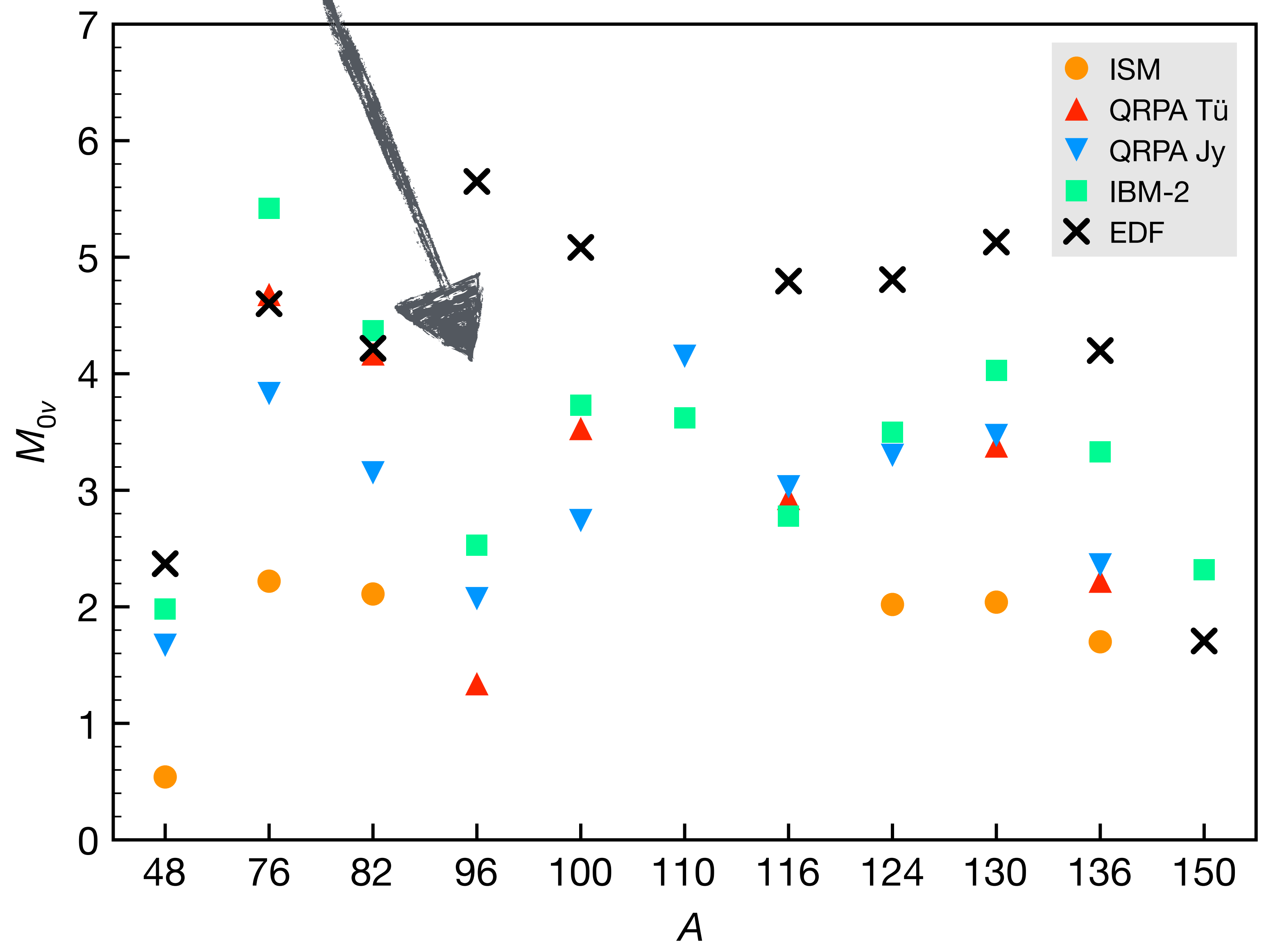
- Get yourself a detector with perfect energy resolution
- Measure the energy of the emitted electrons and select those with (T1+T2)/Q = 1
- Count the number of events and calculate the corresponding half-life.
- Obtain $m_{\beta\beta}$ from $T_{1/2}$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 m^2_{\beta\beta}$$

From lifetime to $m_{\beta\beta}$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 m^2_{\beta\beta}$$

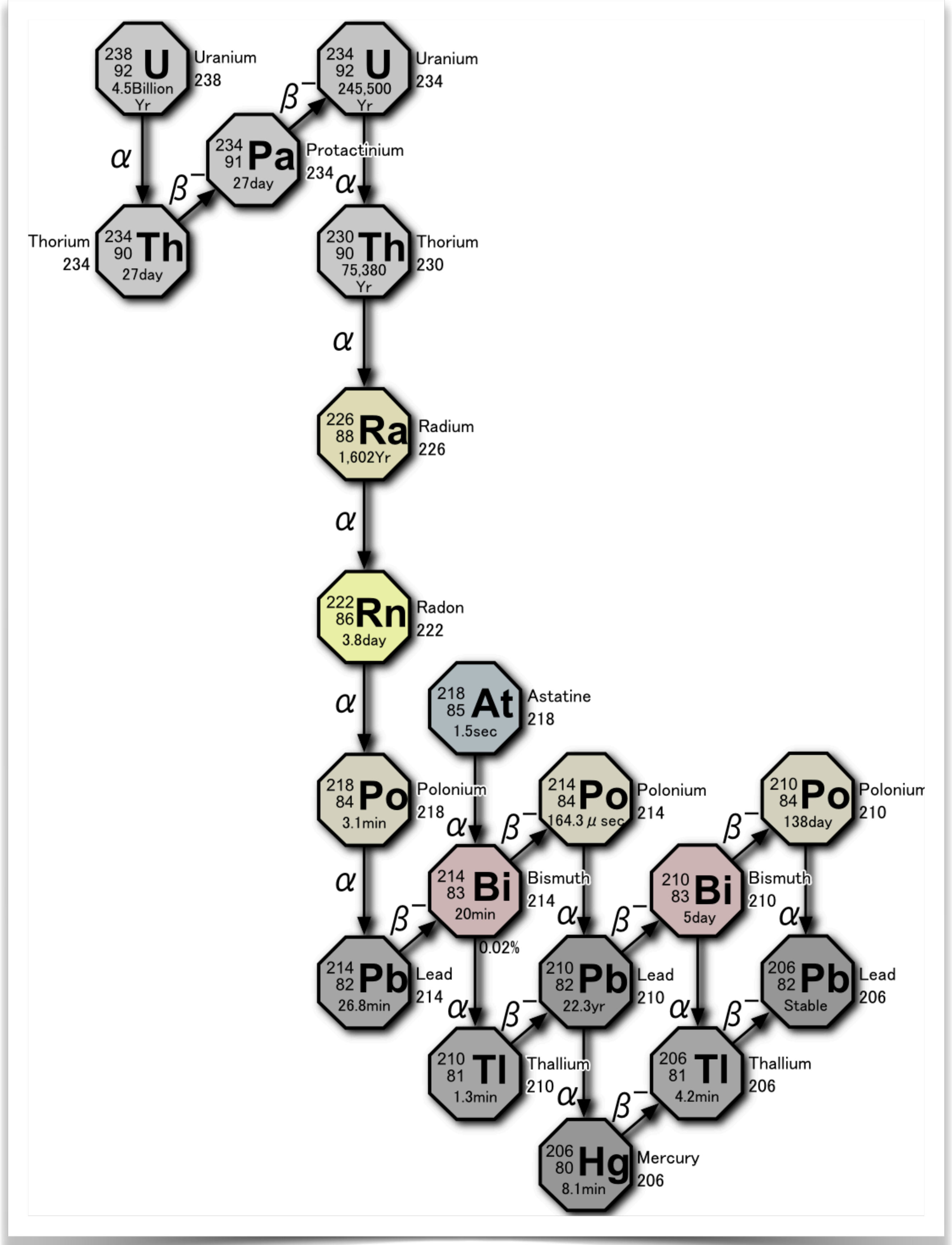




Phase space is rather democratic for interesting isotopes, with the notable exception of Ge-76 (lower) and Nd-150 (higher).

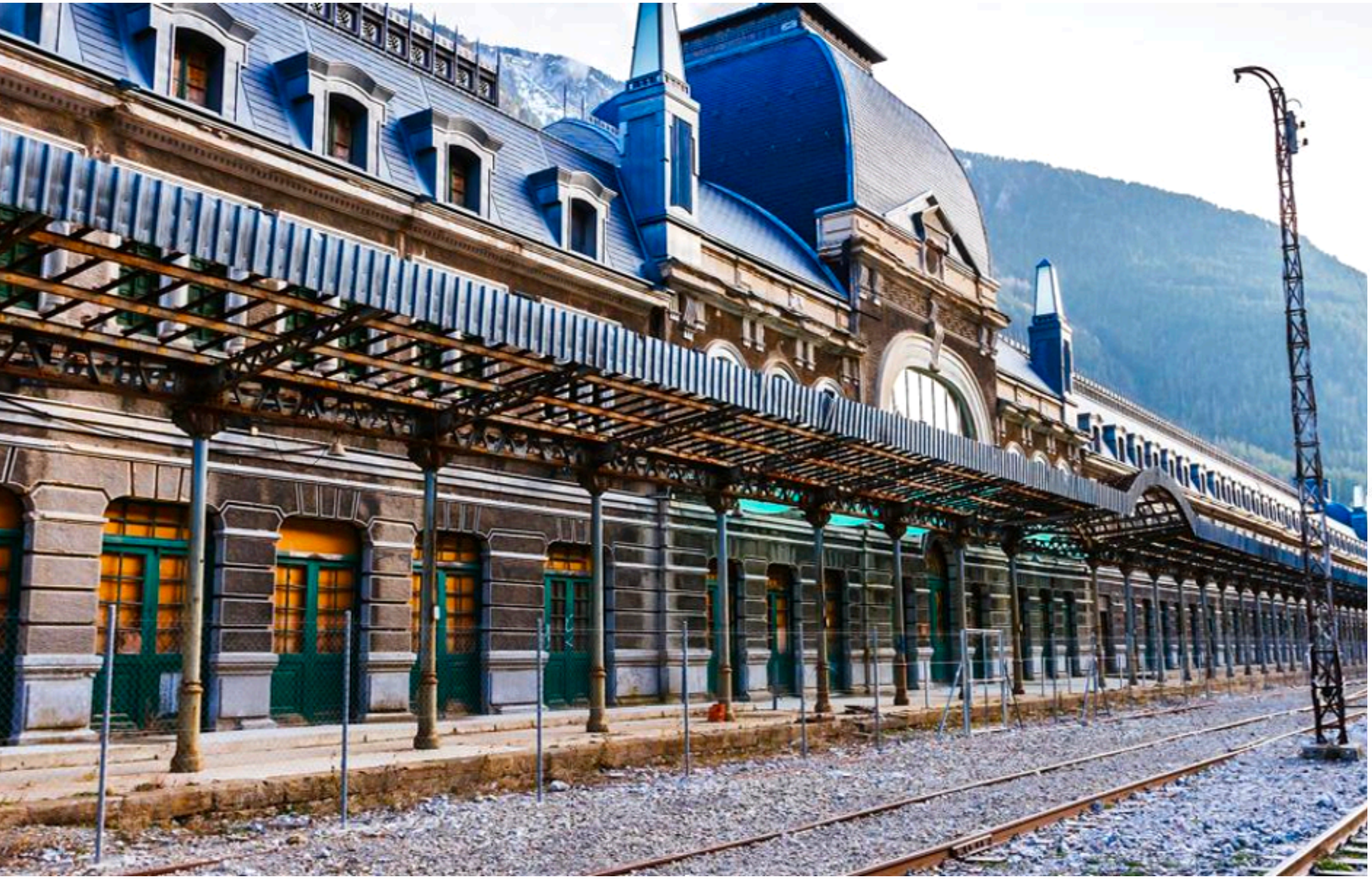
The discrepancy in NME is a major source of uncertainty (in particular if no discovery is made)

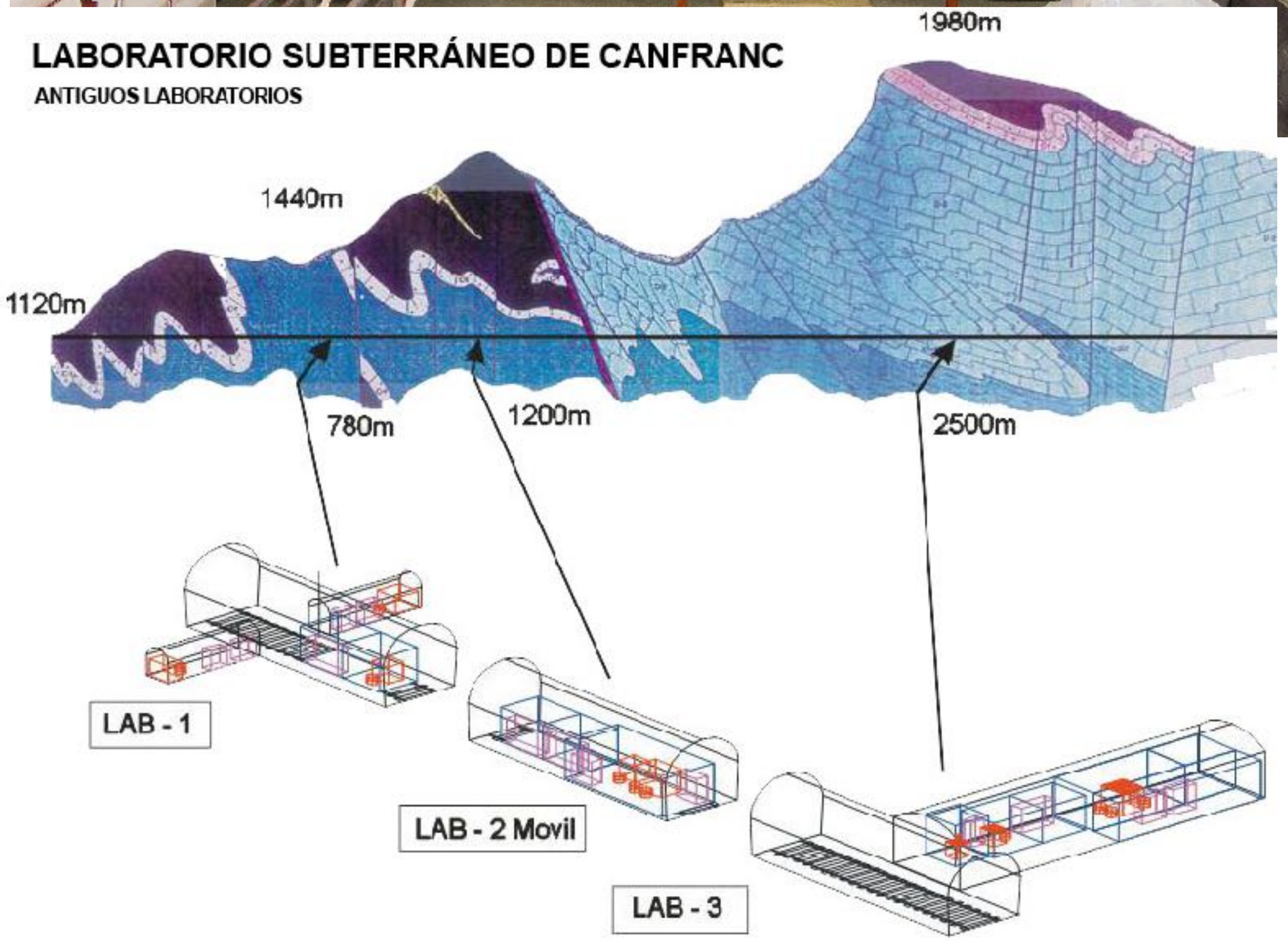
Why ββ0ν experiments are difficult



- Earth is a very radioactive planet. There are about 3 grams o U-238 and 9 grams of Th-232 per ton of rock around us.
- This is an intrinsic activity of the order of 60 Bq/kg of U-238 and 90 Bq/kg of Th-232.
- The lifetime of U-238 is of the order of 10^9 y and that of Th-232 10^{10} y. We want to explore lifetimes of of the order of 10^{26} -10^{27} y.
- The problem is much harder than finding a needle in a haystack

Canfranc Underground Lab (LSC)



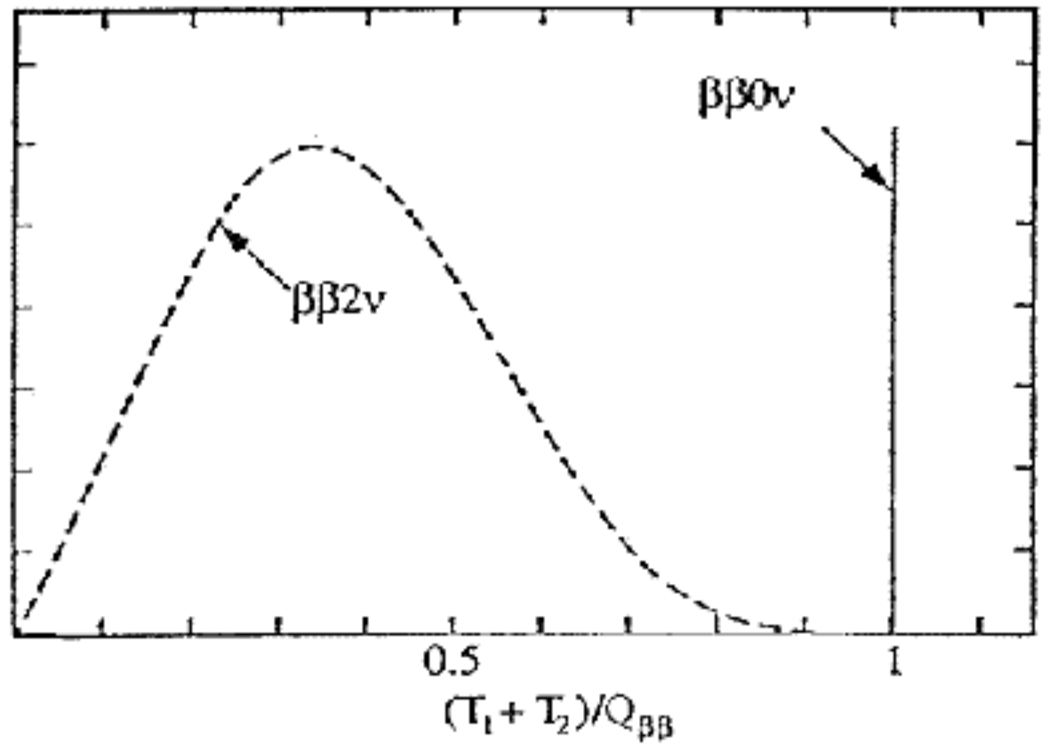


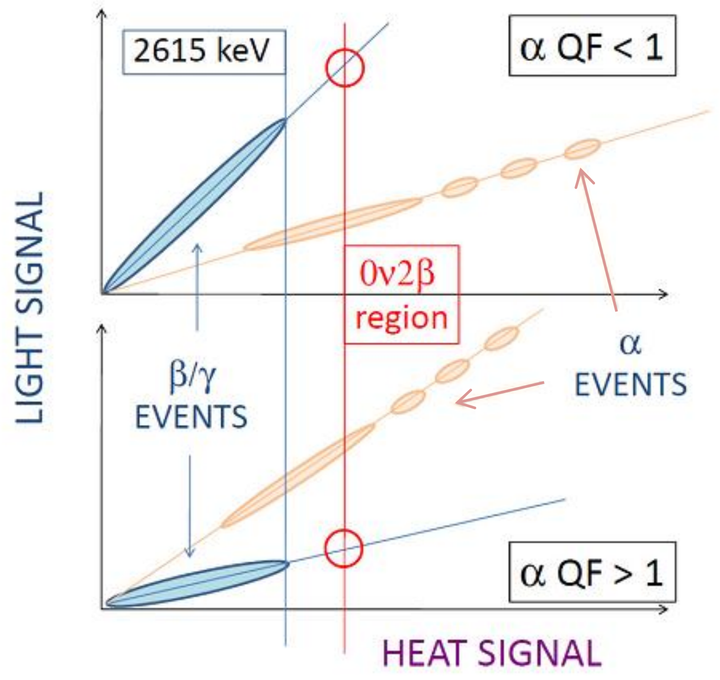
Detector in the Canfranc Underground Laboratory

Experimental signature

Rare signature to be isolated in radio-pure detector underground:

1. Calorimetry *(A MUST)*:
   - 2ν mode: continuous spectrum for sum electron kinetic energy T_1+T_2
   - 0ν mode: mono-energetic line at $Q_{\beta\beta}$ for T_1+T_2 spectrum





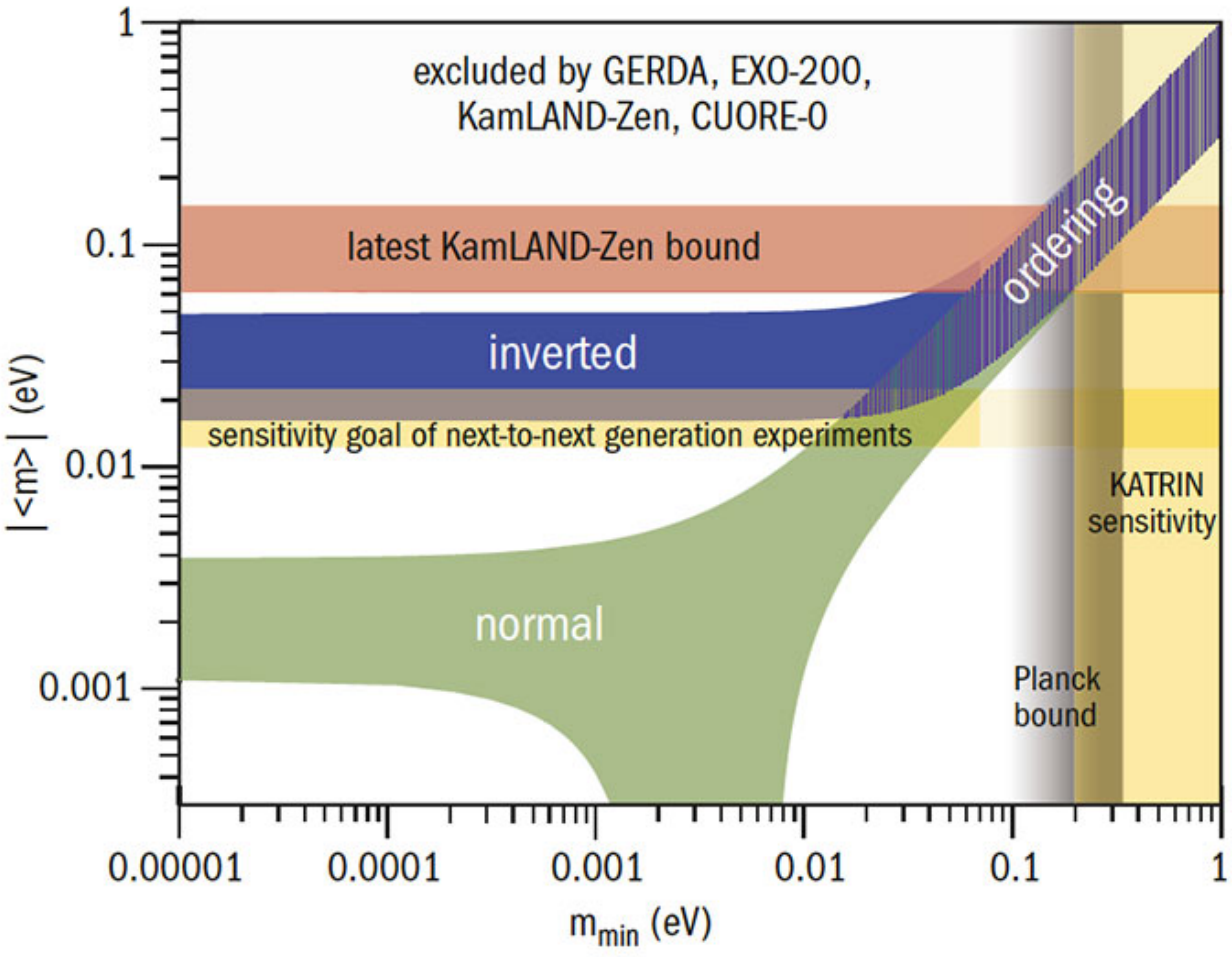
Research Proposal (B1) LUCIFER 2009

2. *Additional Handles*:
   - Observe two electrons emitted from a common vertex
   - Different signals for different interactions in the detector

3. Daughter ion tagging *(A long shot…)*:
   - Observe nucleus produced in the decay

4. Build a radiopure detector.
   - Reduce the number of background events in your detector

The Majorana landscape

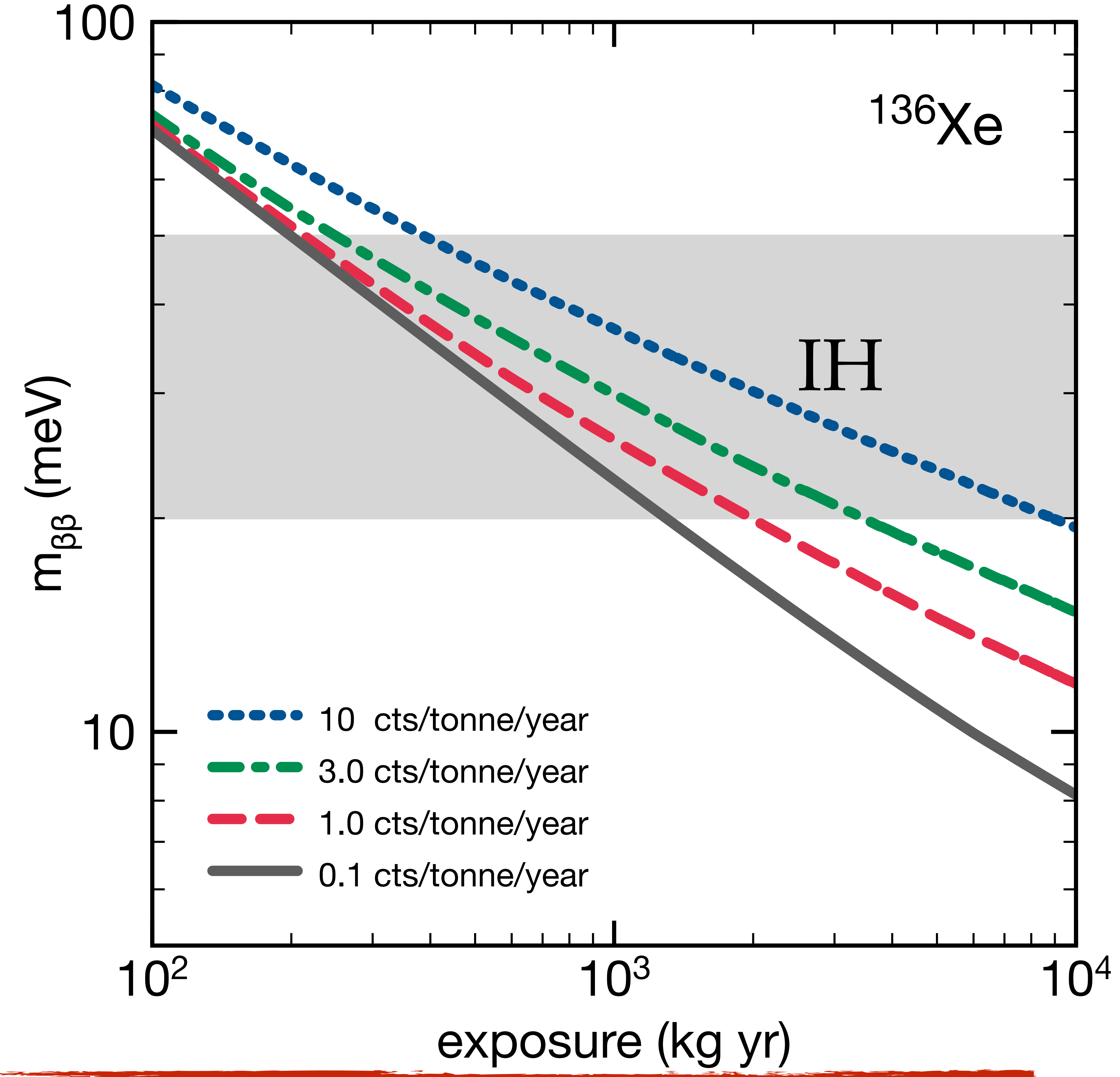


Results from GERDA, CUORE KamLAND-ZEN, EXO barely scratching IH

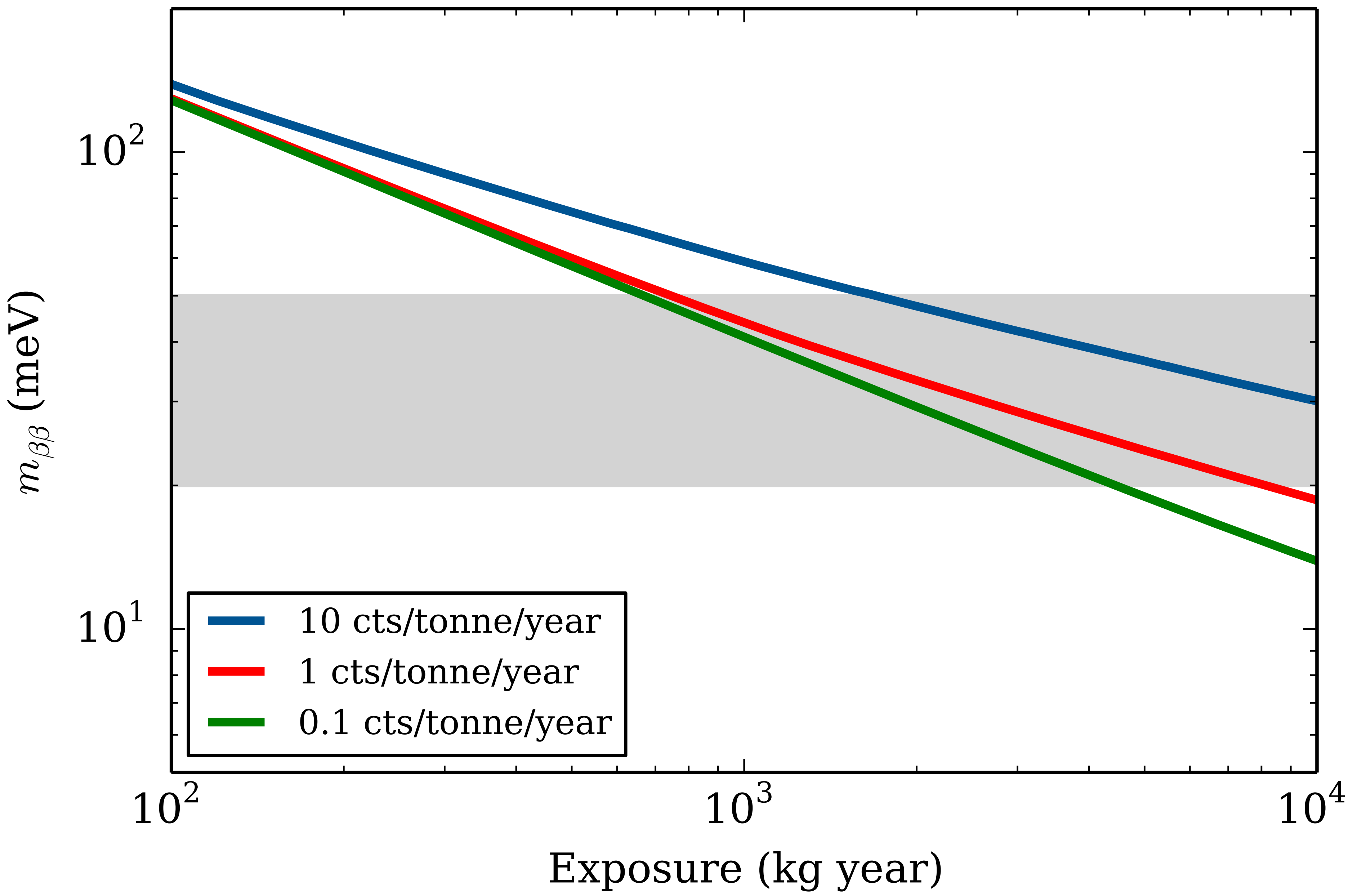
exploring IH : T~ 10^{27}y

"Background free" experiments

Exploring the IH



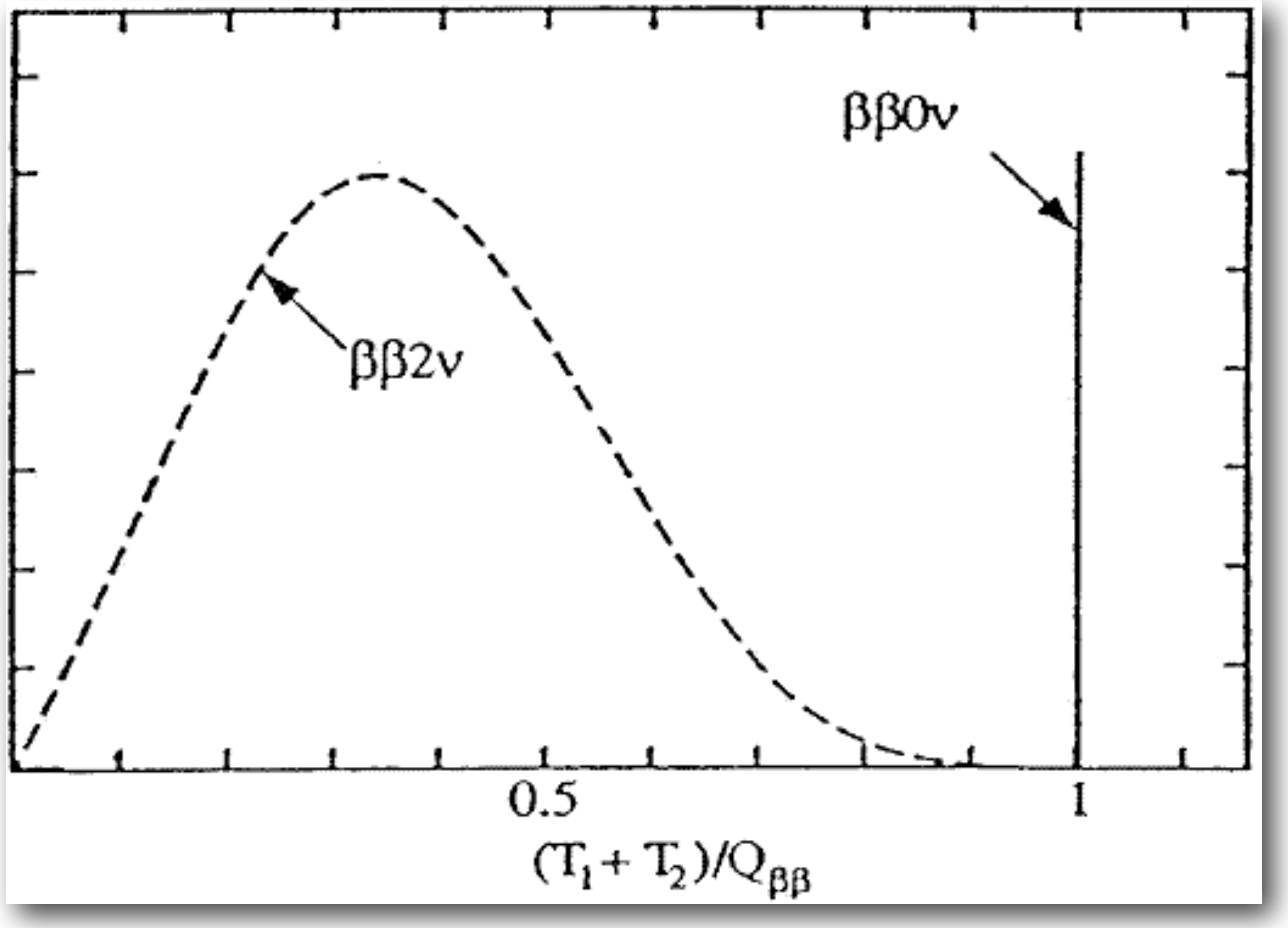
100 % efficient Xe experiment
(using a "reasonable NME set")
2 ton year to explore IH with 1 background event per ton per year

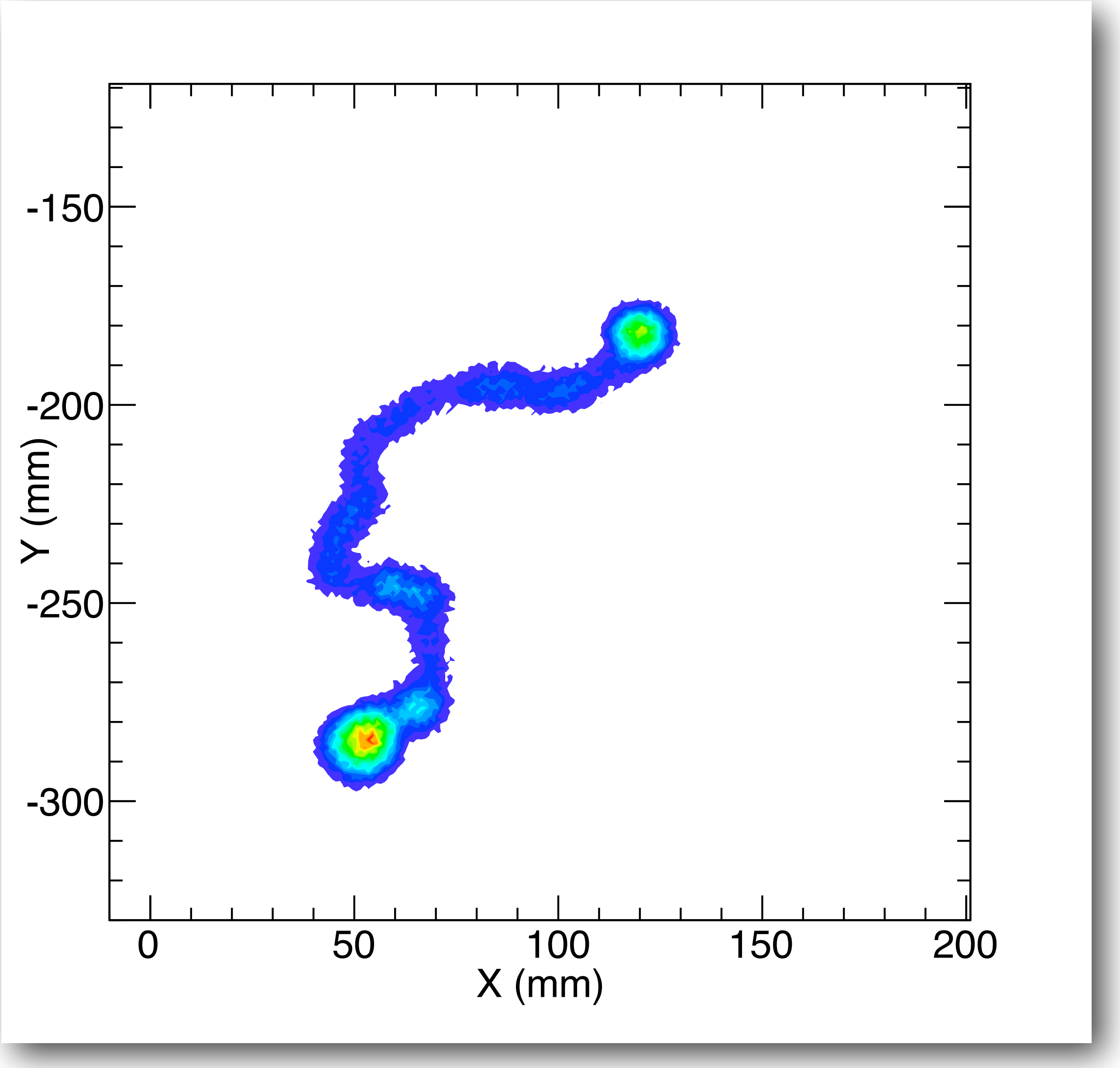


30 % efficient Xe experiment
(using a "reasonable NME set")
6 ton year to explore IH with 1 background event per ton per year

THE NEXT EXPERIMENT FOR NEUTRINOLESS DOUBLE BETA DECAY SEARCHES

The experimental signature of double beta decay

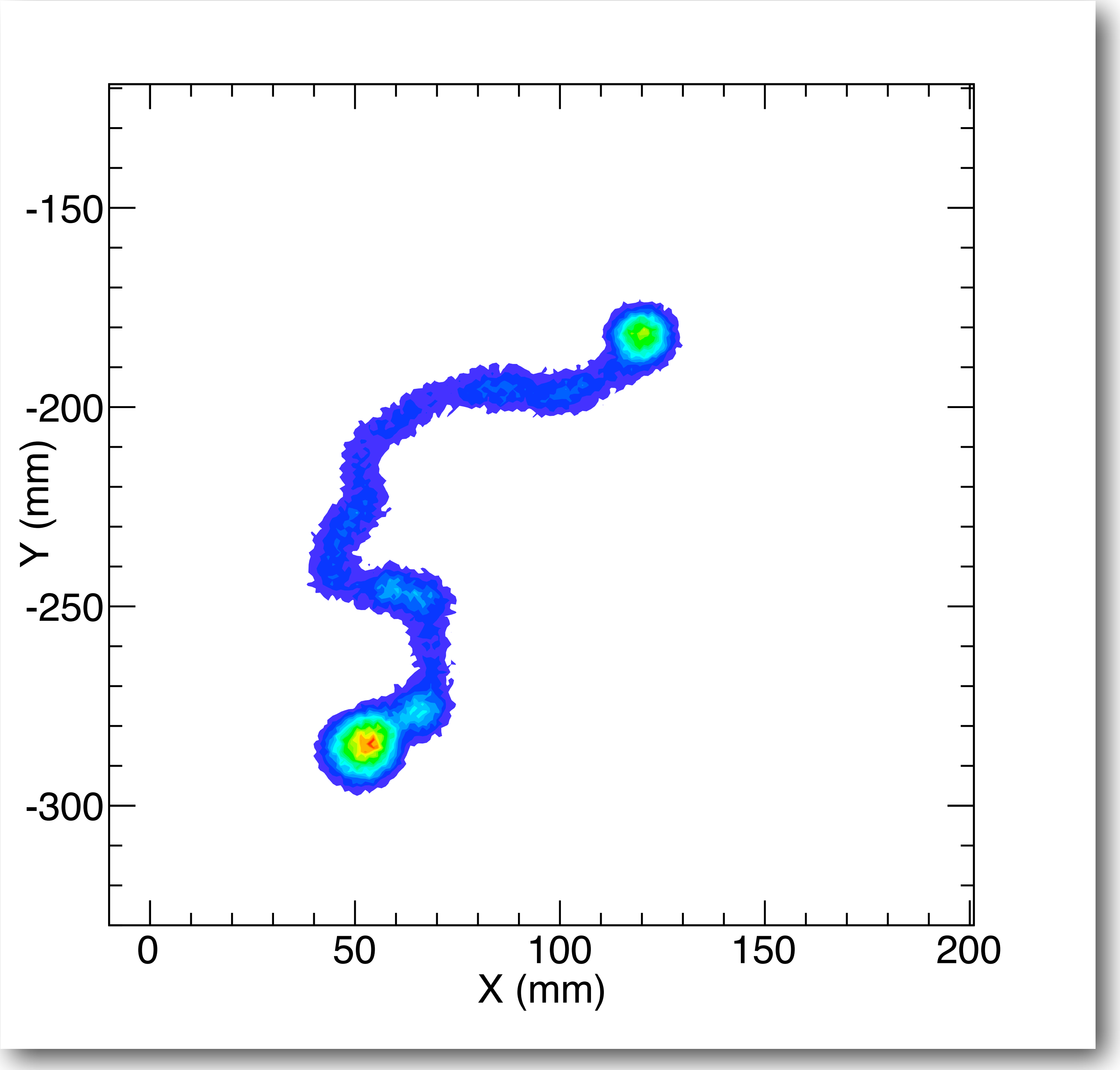




$$T_{1/2} = ln(2)\frac{N_A M t}{A N_{\beta\beta}}$$

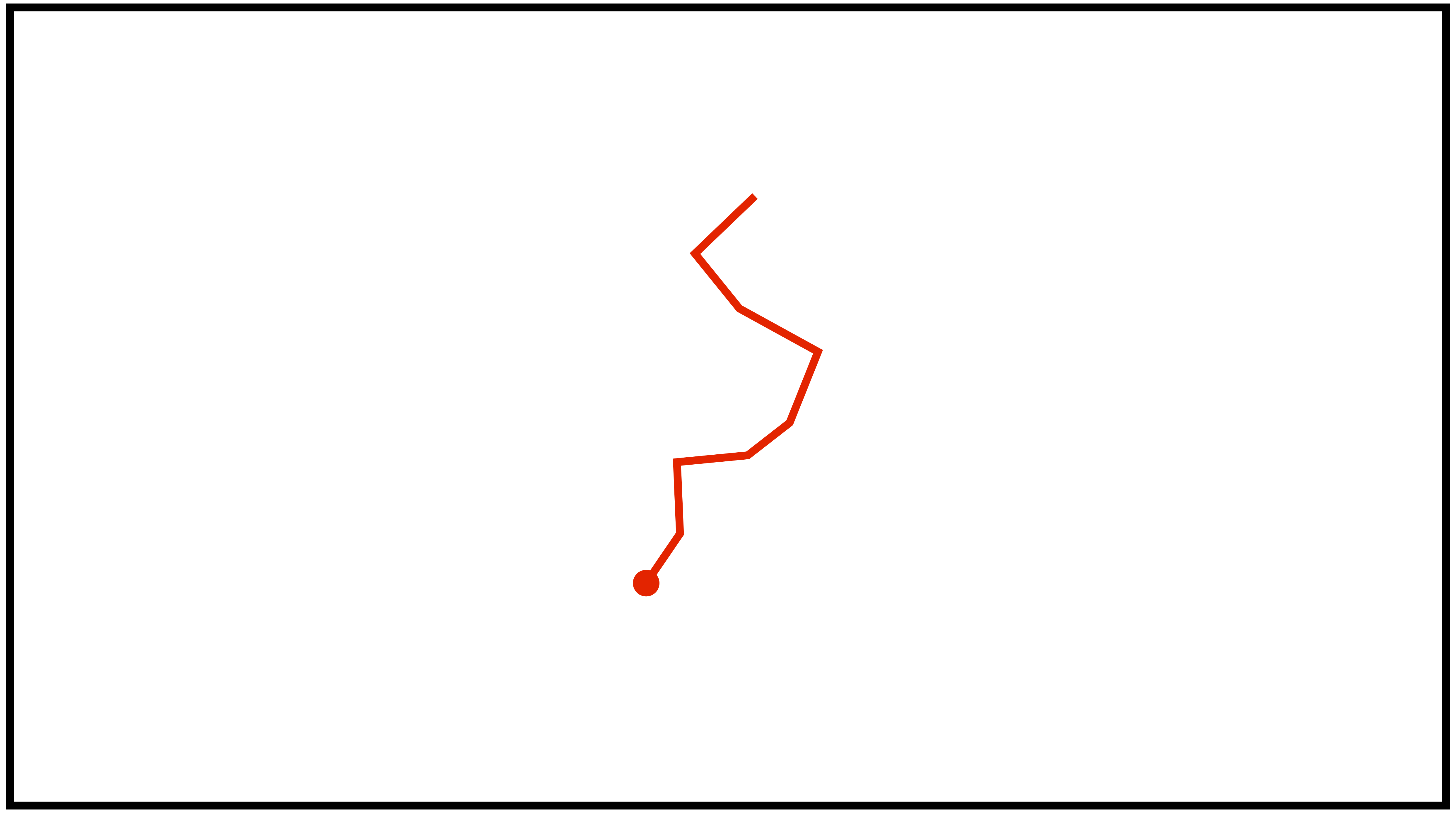
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 m\beta\beta^2$$

Tracking in HPXe



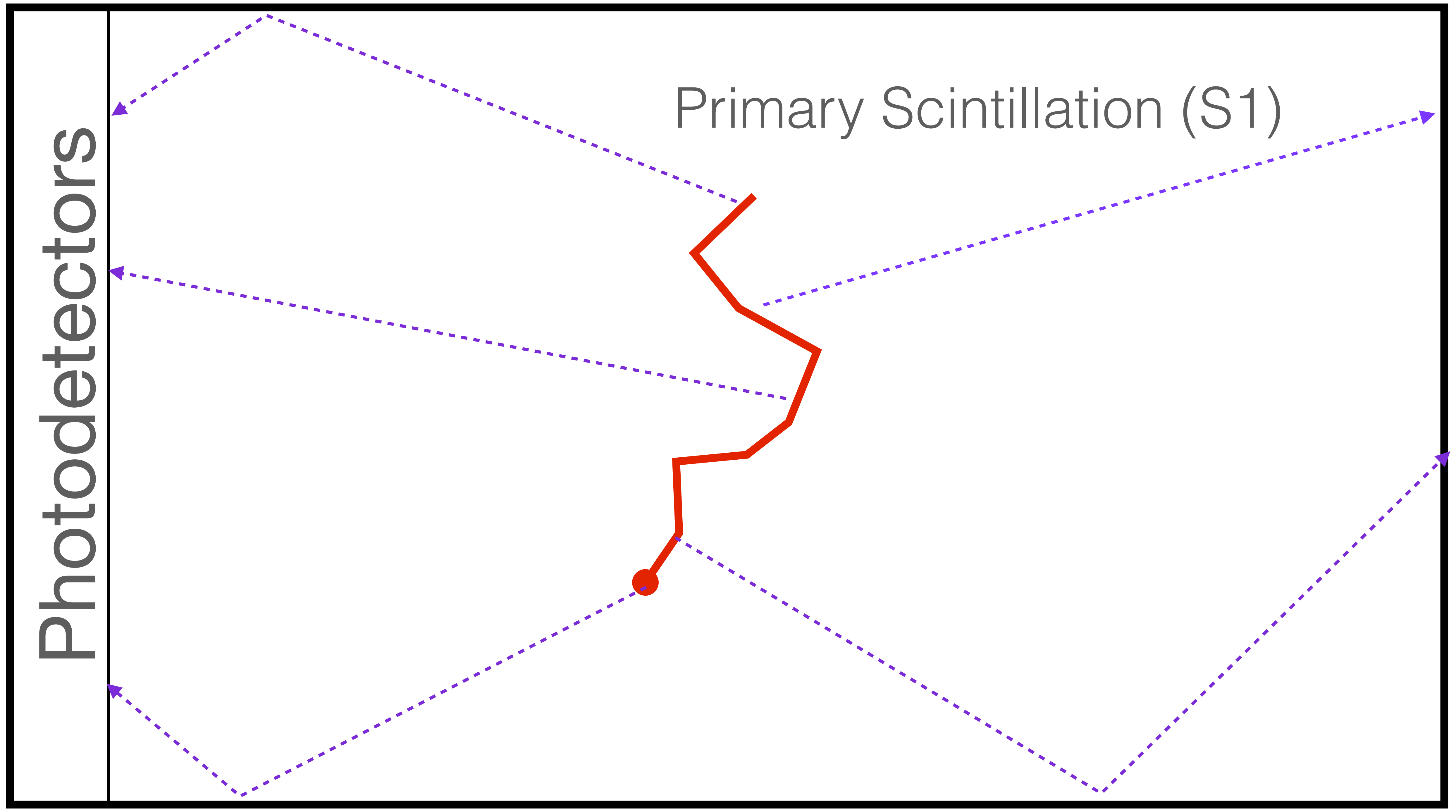
- Electrons travel on average ~10 cm (15 bar) each.
- Trajectories highly affected by multiple scattering.
- Electrons travel with almost constant dE/dx but at the end-points where they generate “blobs”.

Detection concept



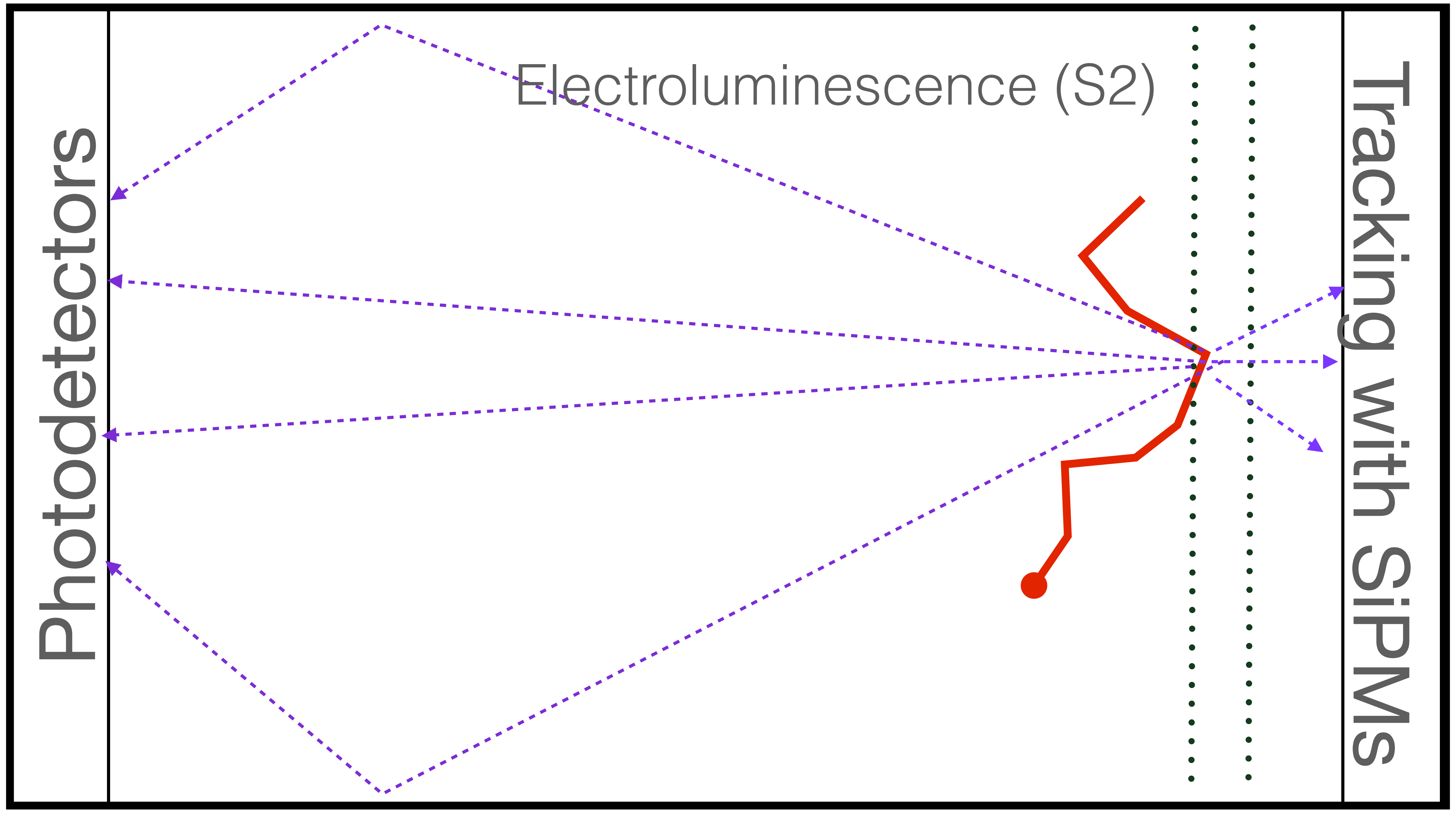
- It is a High Pressure Xenon (**HPXe**) TPC operating in EL mode.
- It is filled with Xe enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.

Detection concept



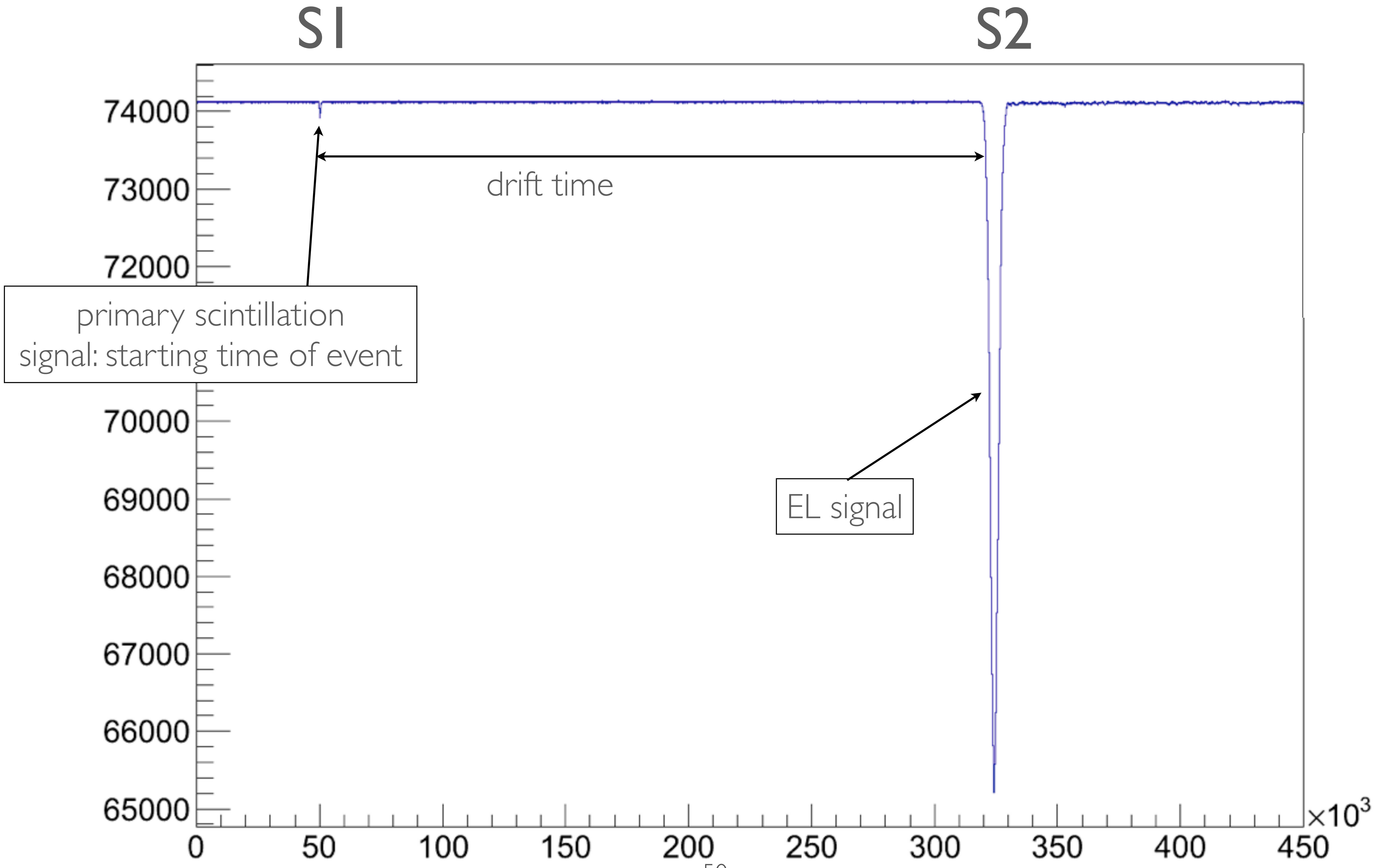
Primary Scintillation light is detected by a plane of photosensors. It gives t_0 of the event and the z position.

Detection concept



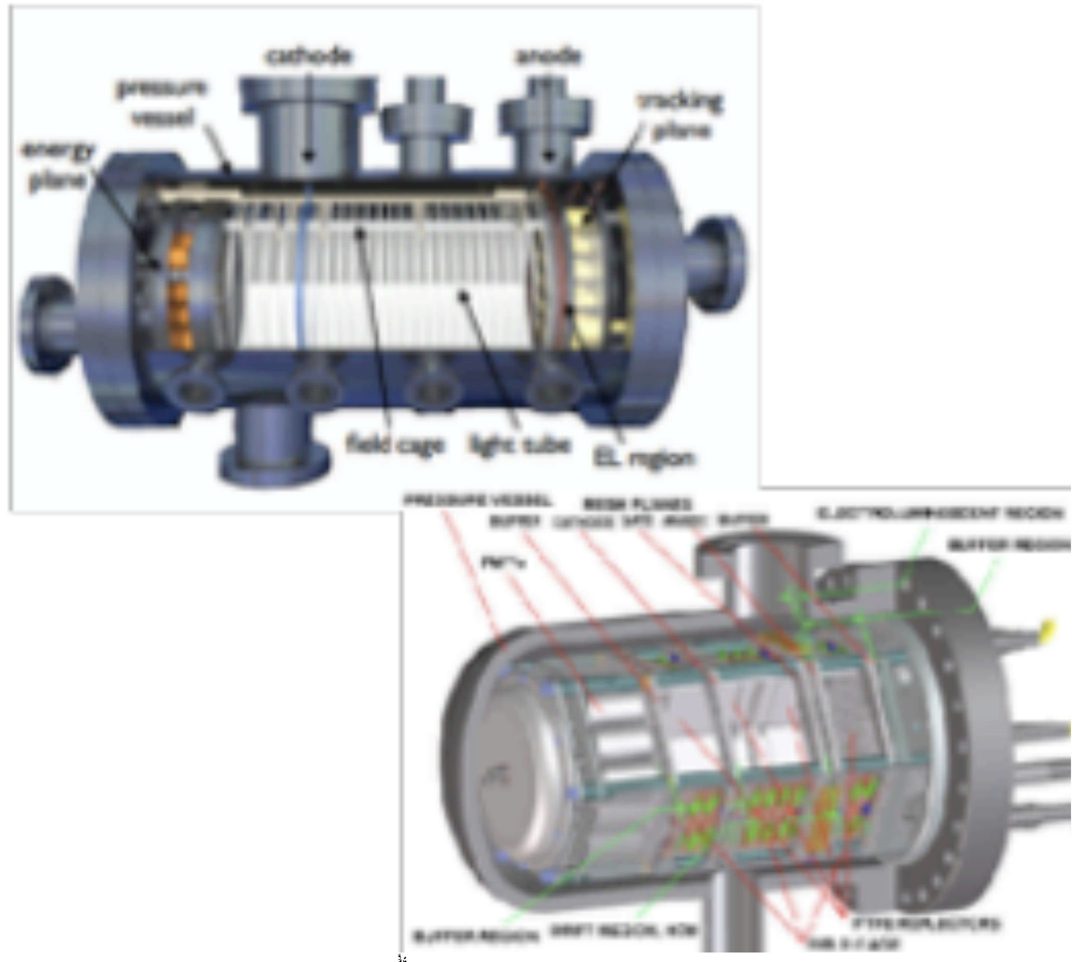
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (**energy plane**), which also provide t0.
- The event topology is reconstructed by a plane of radiopure silicon pixels (SiPMs) (**tracking plane**).

waveforms in next



NEXT Programm

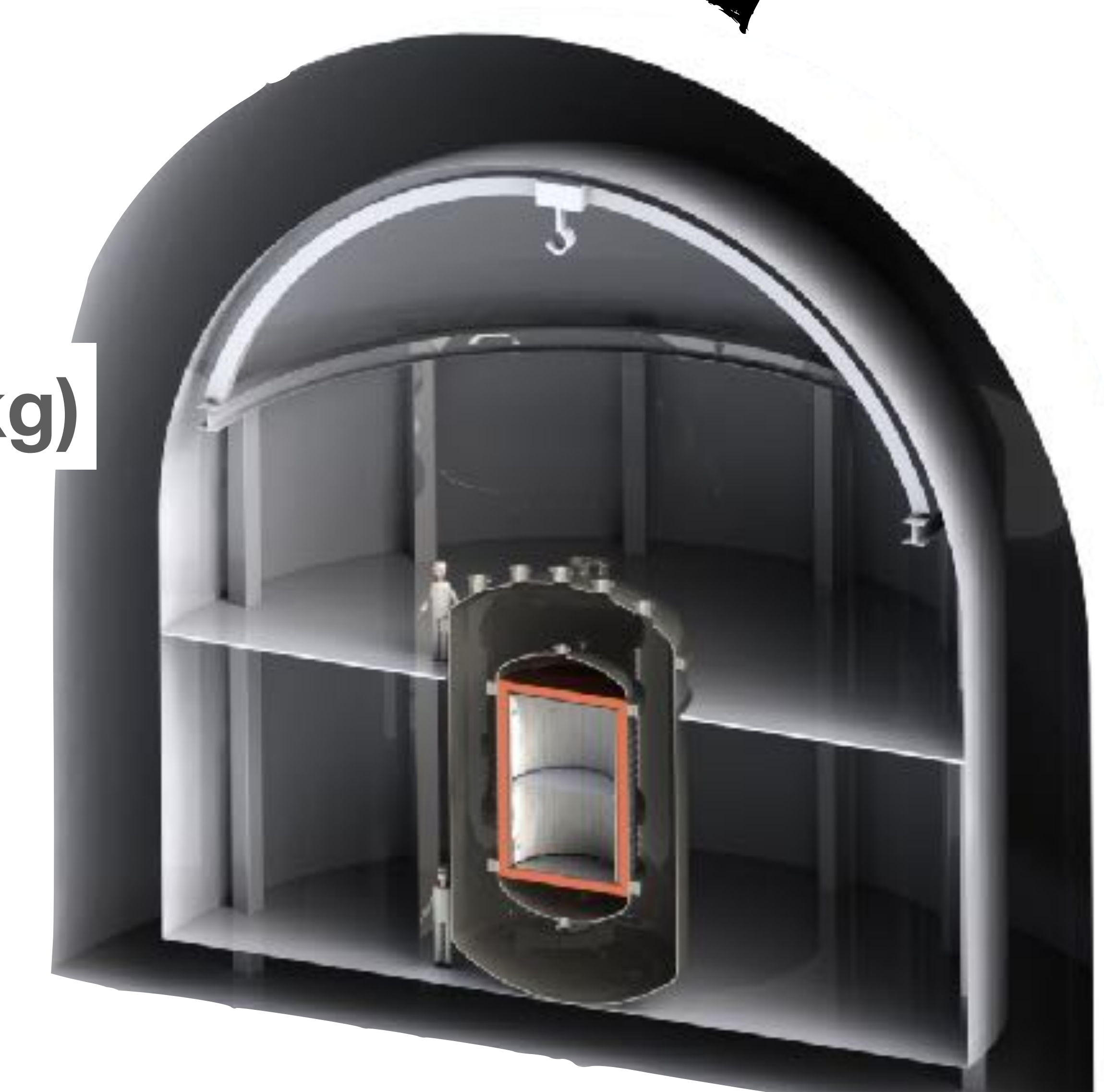
NEXT-DEMO



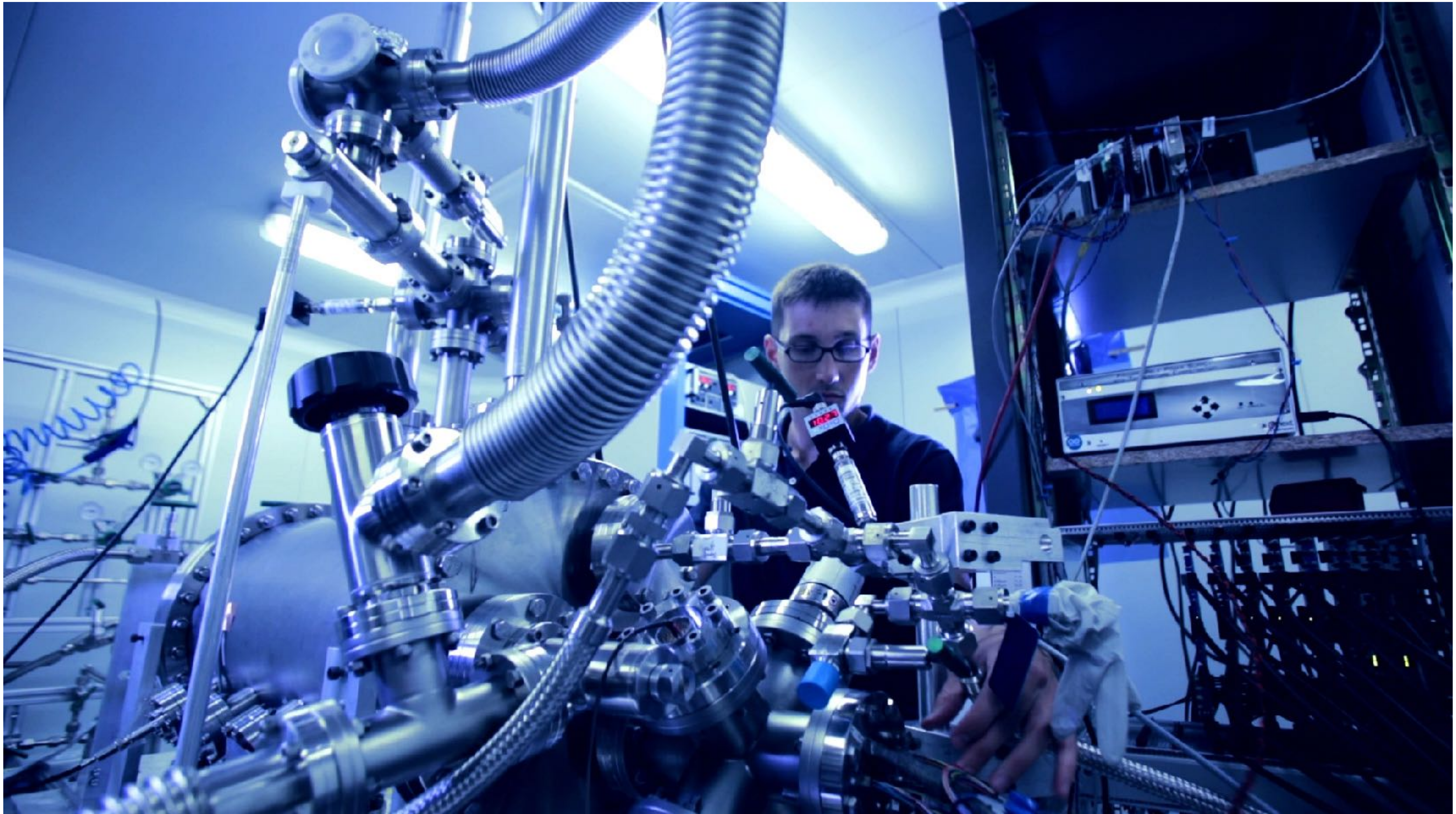
NEXT-White (~10kg)

NEXT-100 (100 kg)

NEXT-HD (~1000 kg)



NEXT-DEMO (2011-2014)




SiPM Plane
Anode
0.5 cm EL gap
Gate
30 cm drift field
Cathode
10 cm buffer region
PMT Shield
PMT Plane

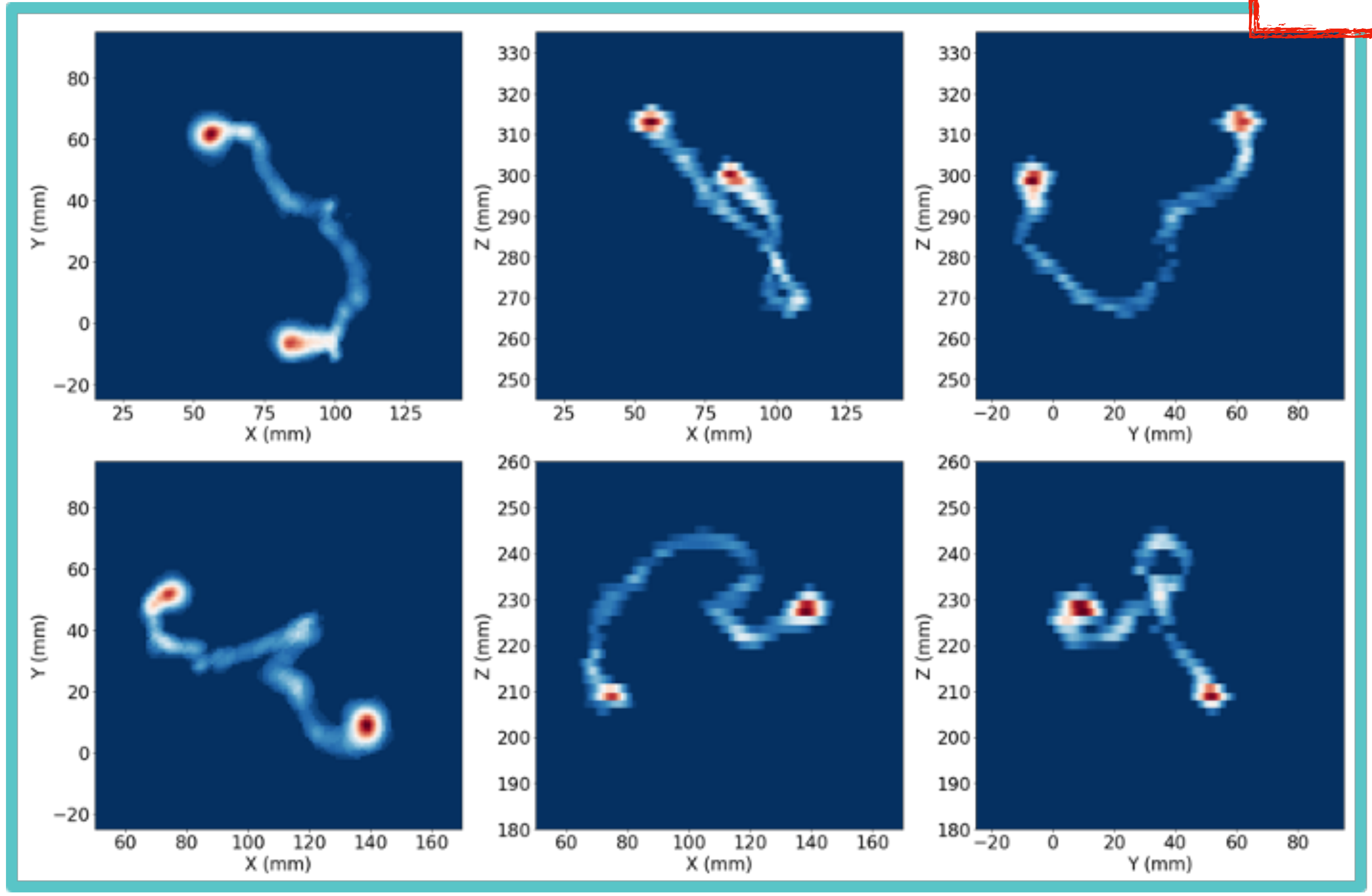
NEXT-White (NEW)

NEXT-White (NEW)

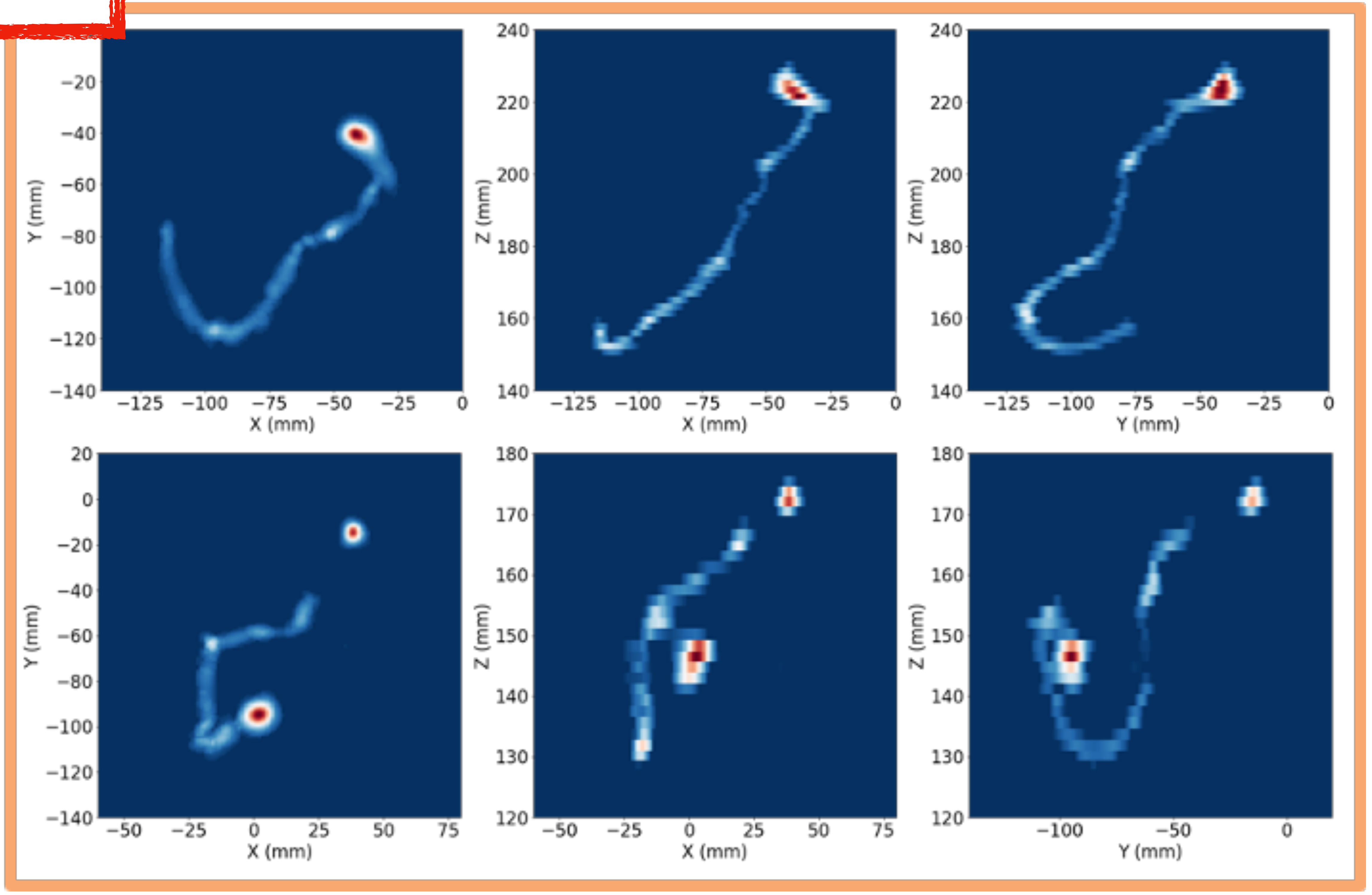
NEXT-White (NEW): Tracking capabilities

Signal

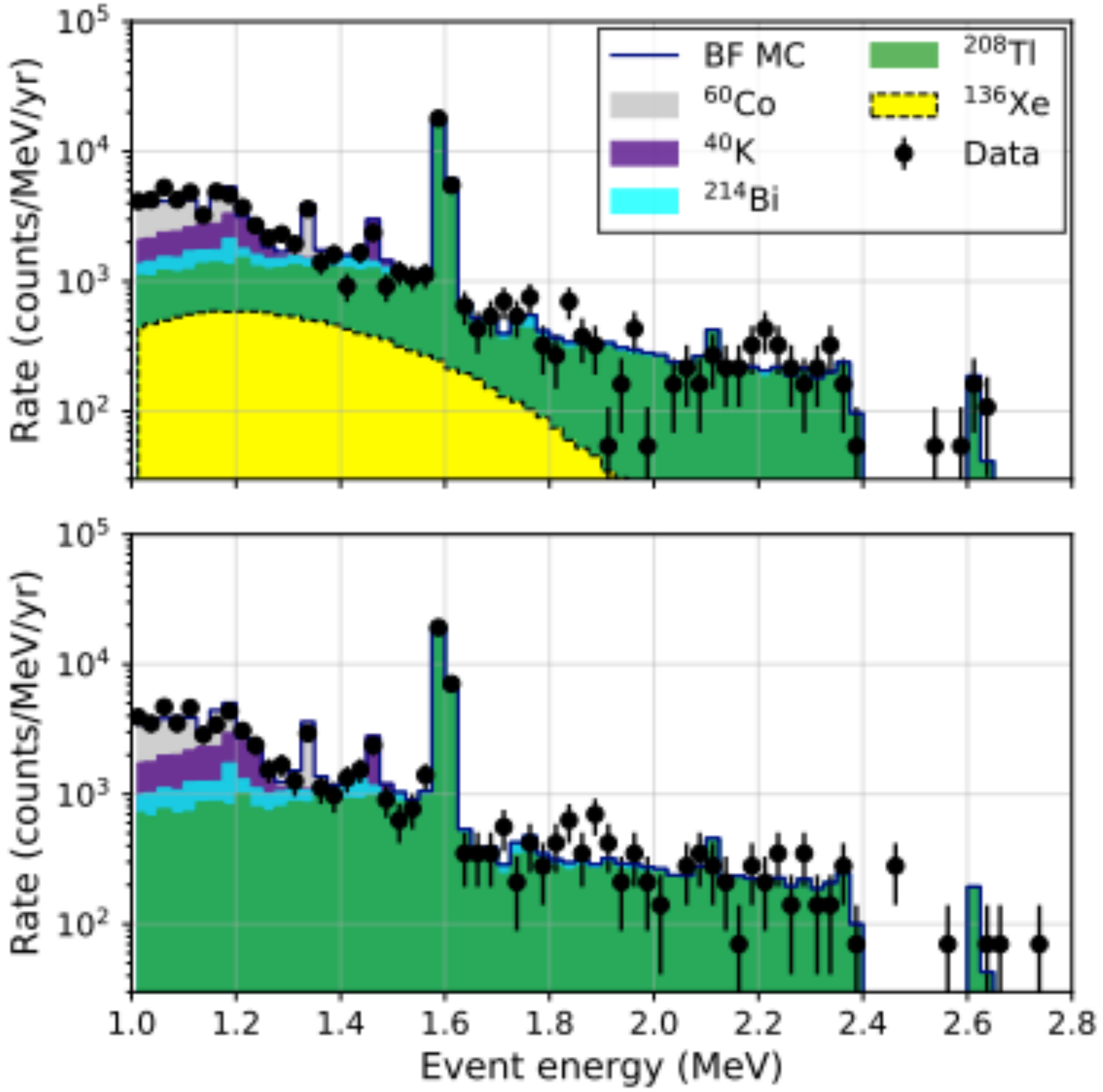
DATA!!!



Background



NEXT-White (NEW): Measuring bb with neutrinos



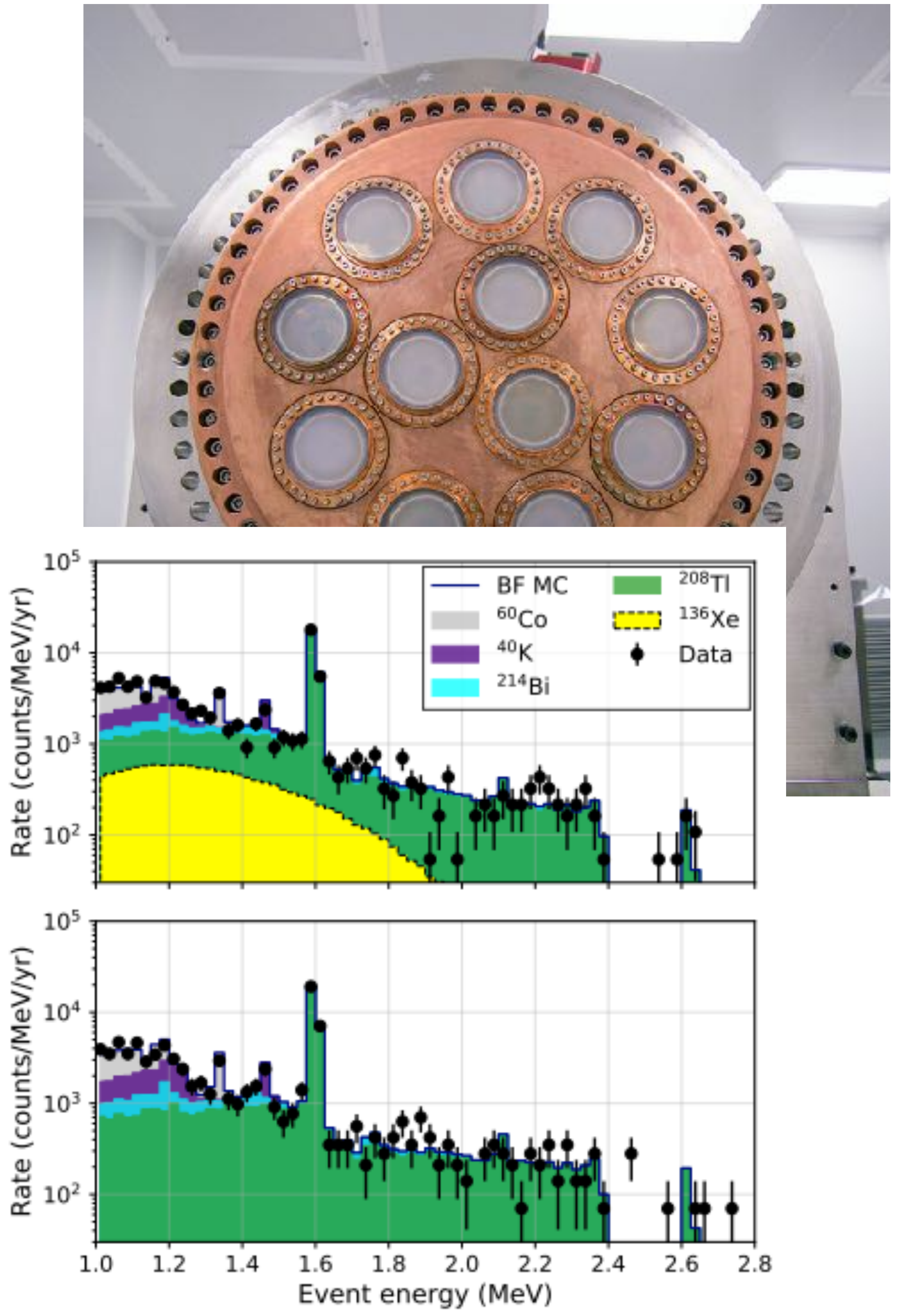
ββ-like sample: fiducial containment + single track + blob cut. Joint ML fit to energy distributions of enriched and depleted Xe data.

- ^{136}Xe rate: 334±78(stat)±54(sys) yr^{-1}

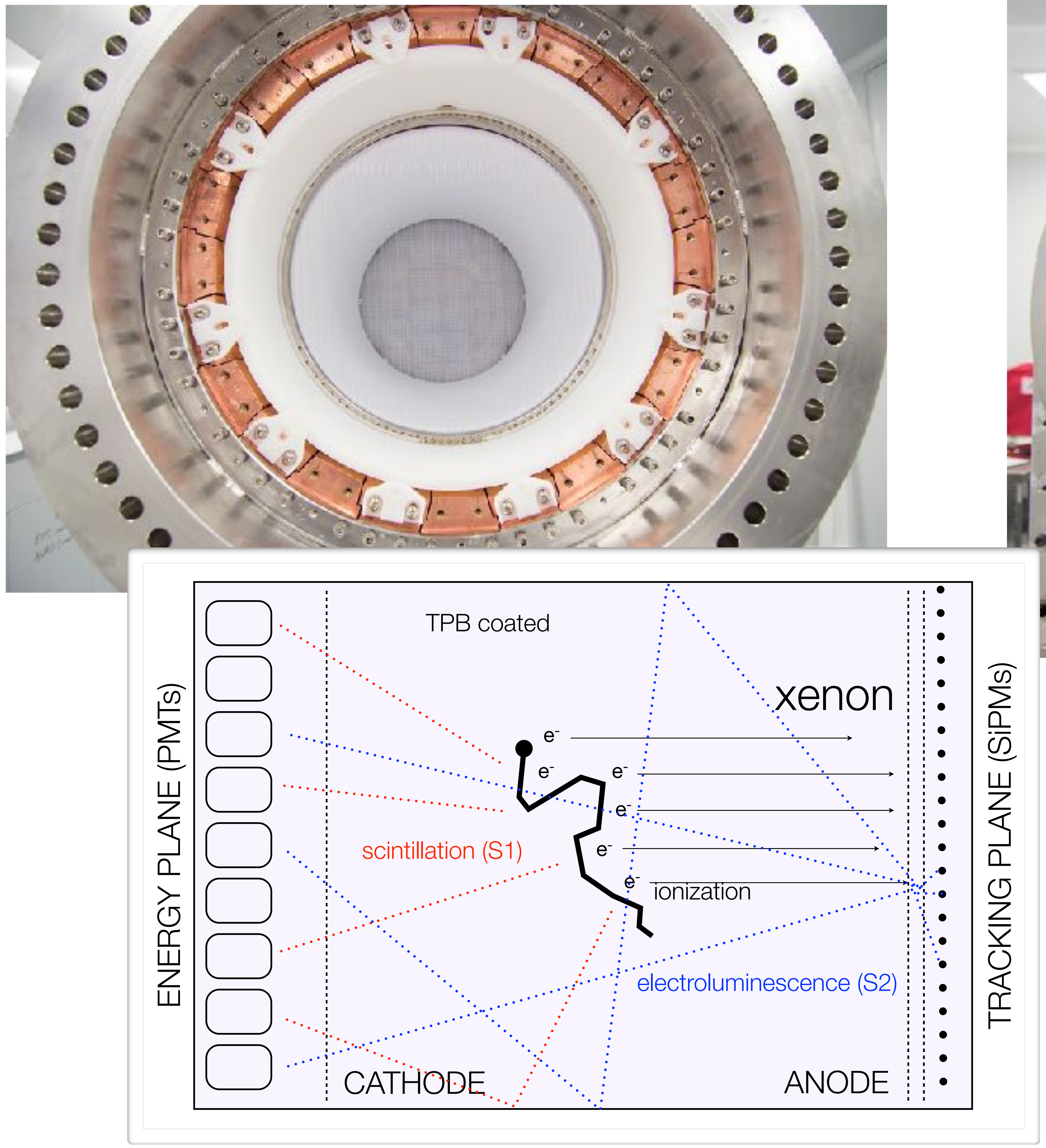
$$T^{2\nu}_{1/2} = 2.14^{+0.65}_{-0.38}(stat)^{+0.46}_{-0.26}(syst) \times 10^{21}$$

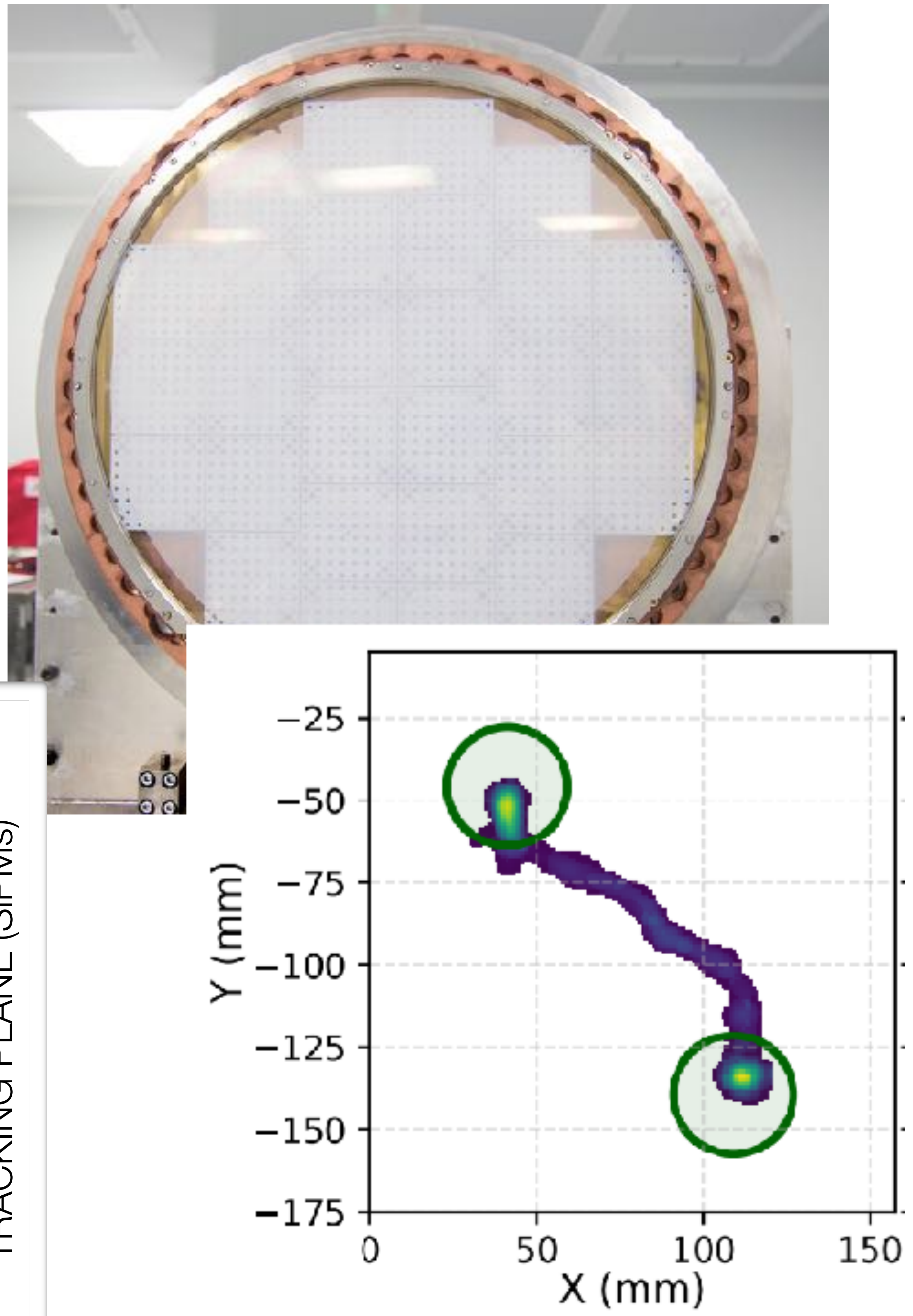
- Background rates:
  - ^{40}K: 10±2 μHz
  - ^{60}Co: 14±2 μHz
  - ^{214}Bi: 6±2 μHz
  - ^{208}Tl: 40±2 μHz

NEXT-White (NEW)



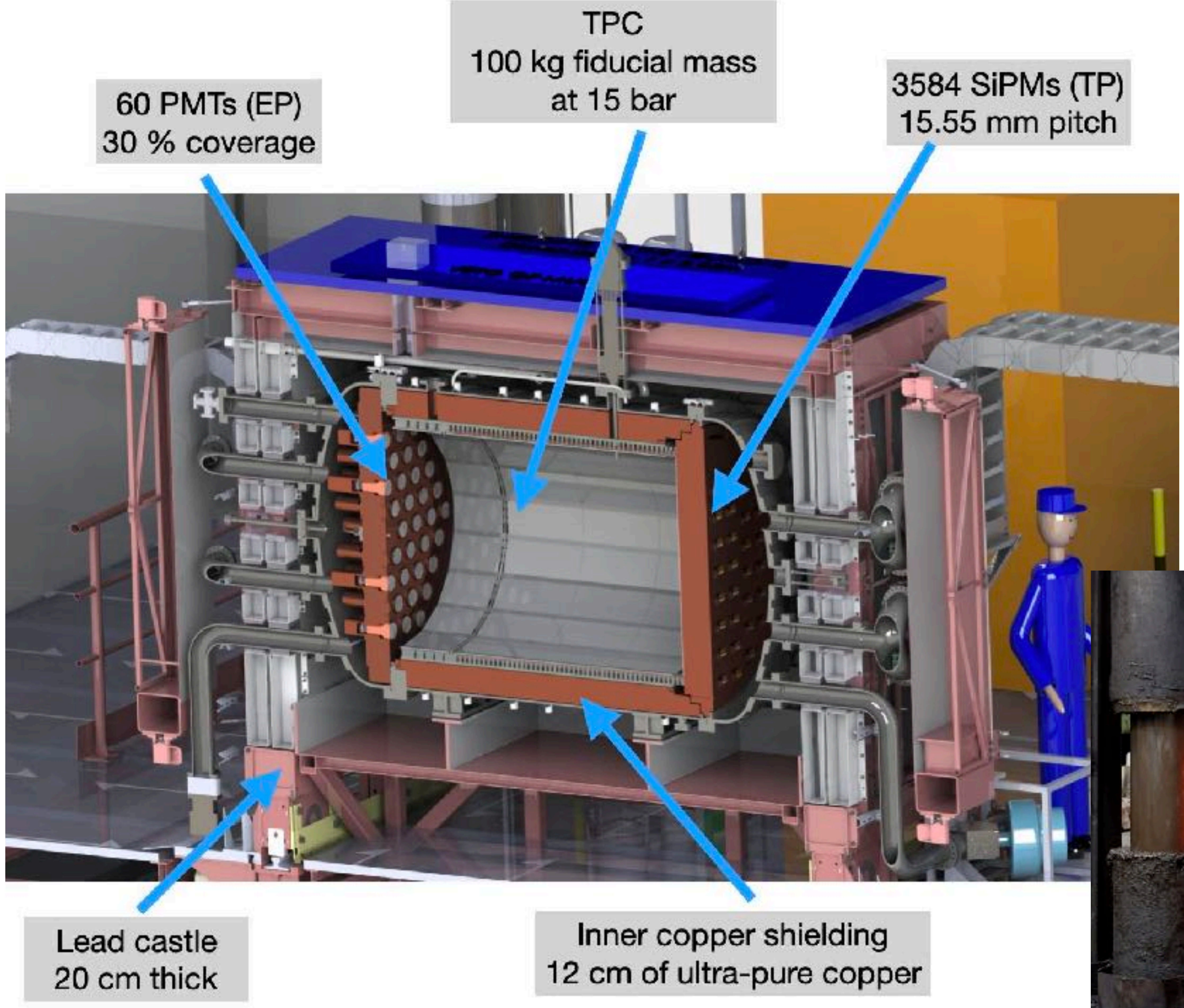
Measurement of the two neutrino mode.
Use of depleted xenon for a good background measurement
arXiv:2111.11091

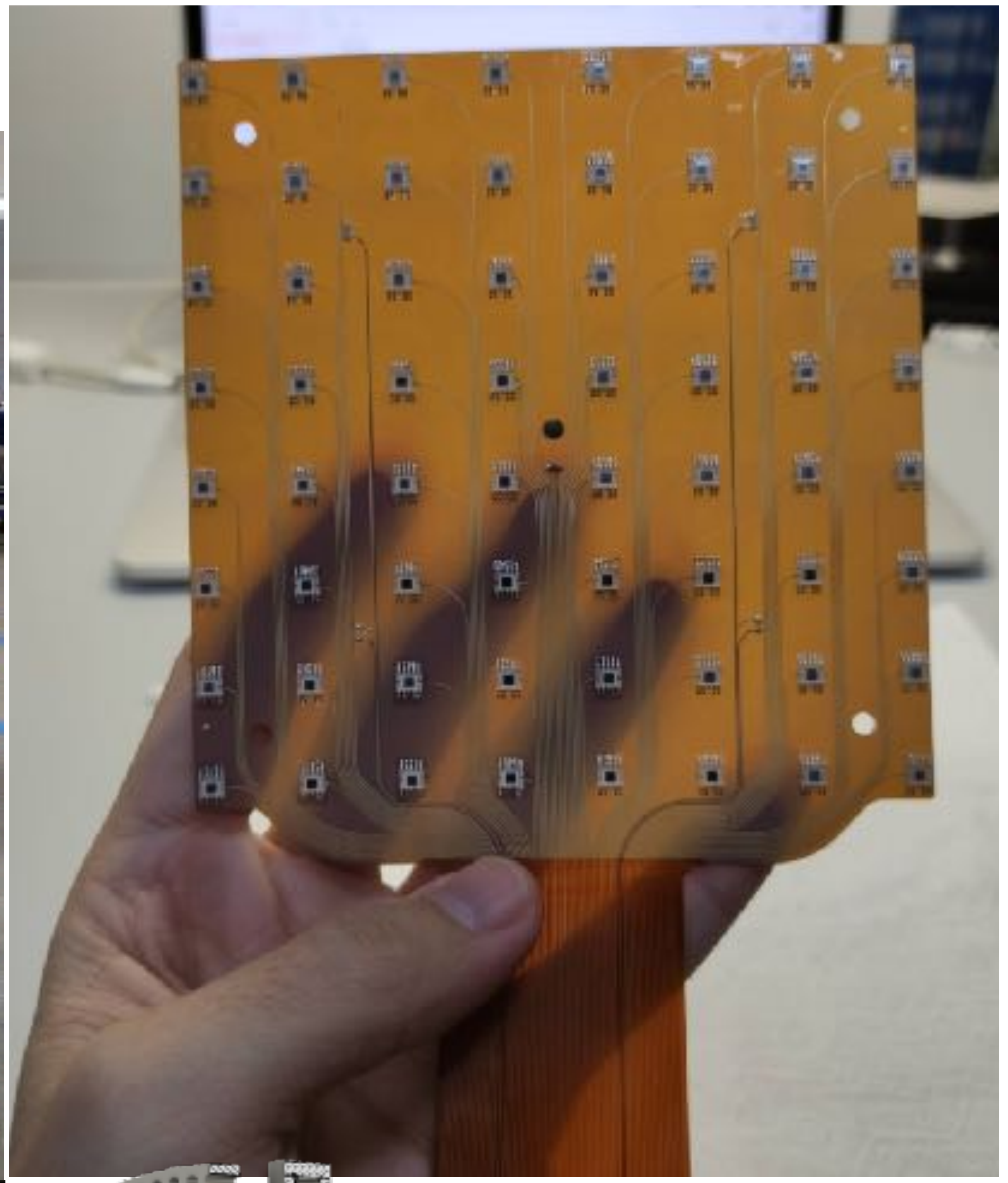


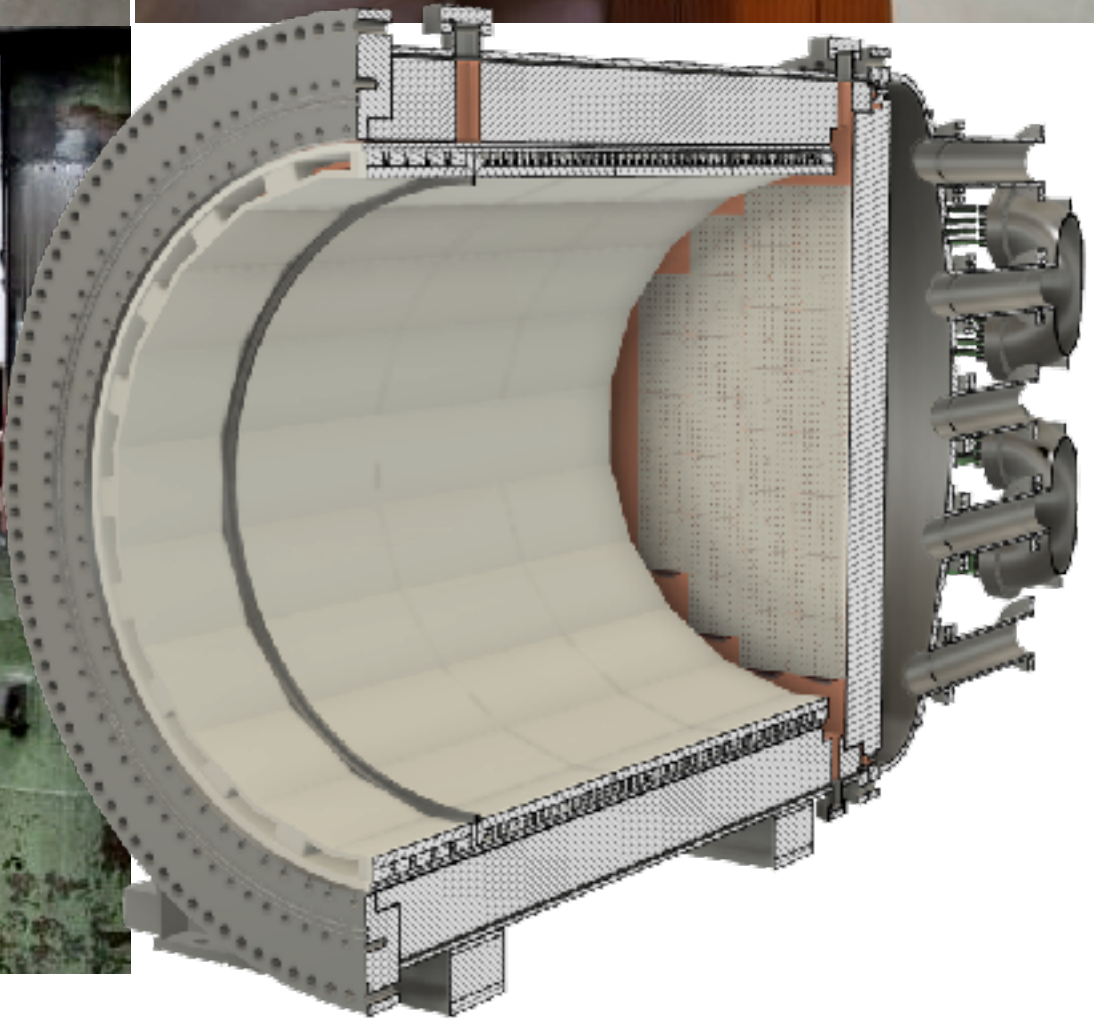


Use of deconvolution algorithms
to improve topological signature
arXiv:2102.11931

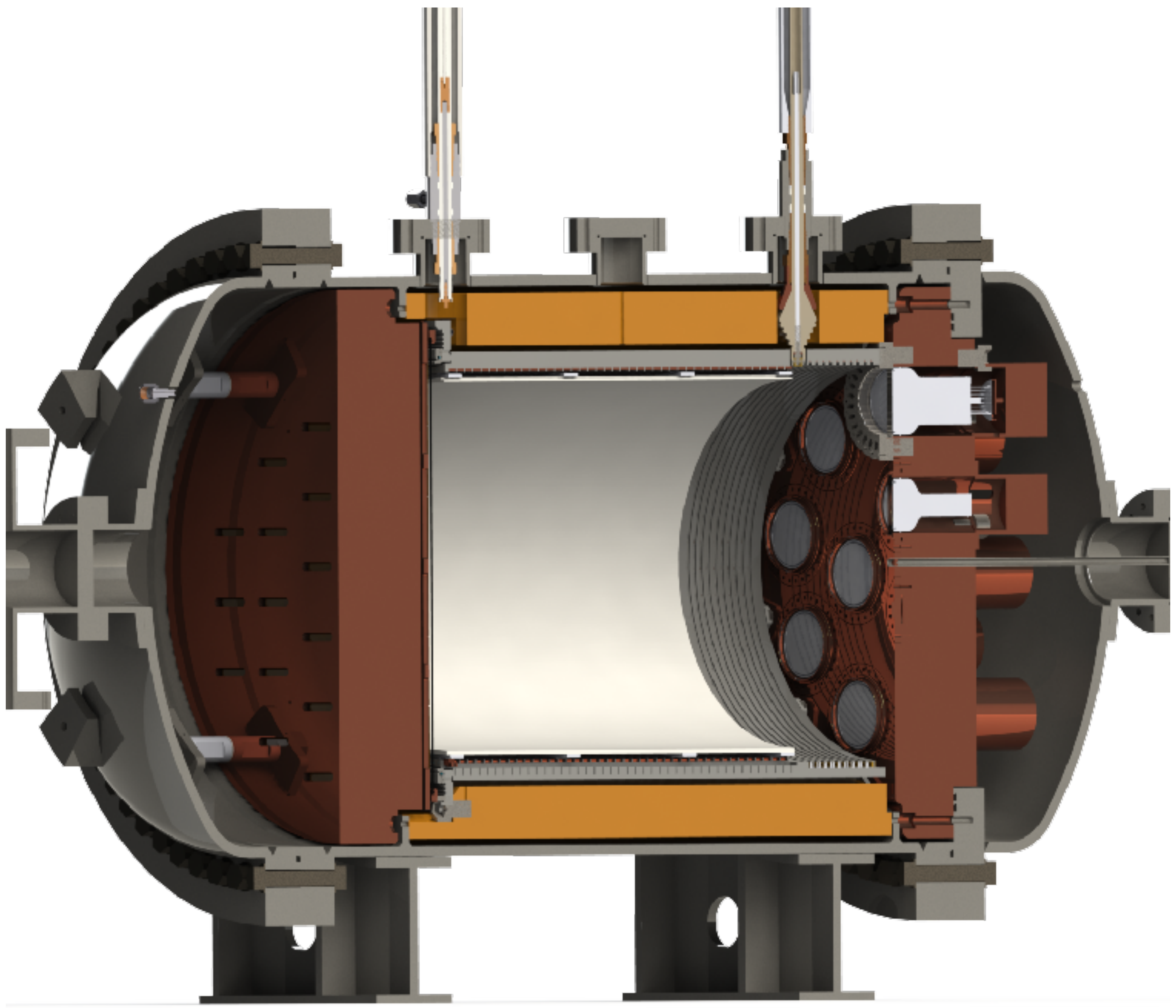
NEXT-100

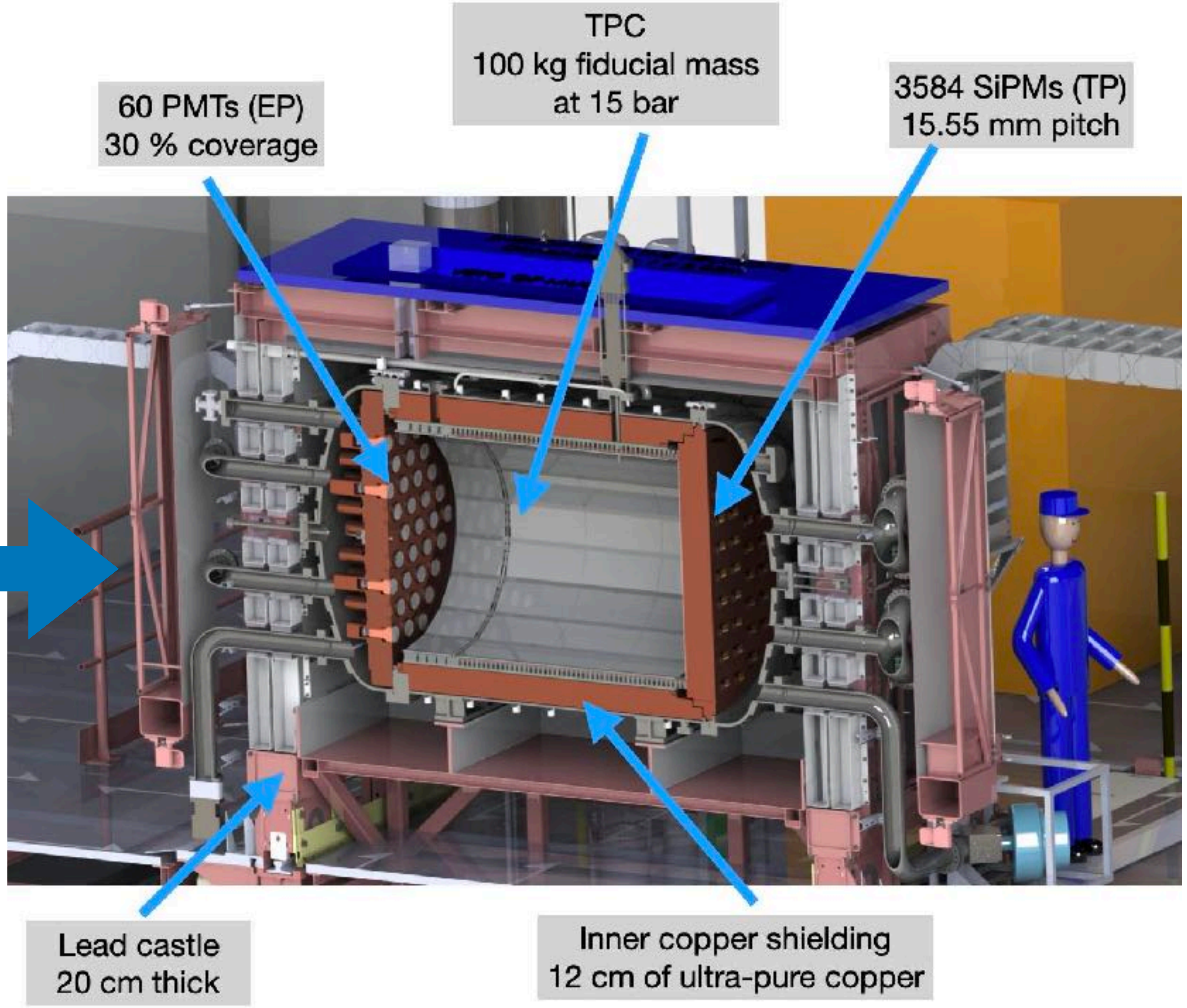

60 PMTs (EP)
30 % coverage
TPC
100 kg fiducial mass
at 15 bar
3584 SiPMs (TP)
15.55 mm pitch
Lead castle
20 cm thick
Inner copper shielding
12 cm of ultra-pure copper



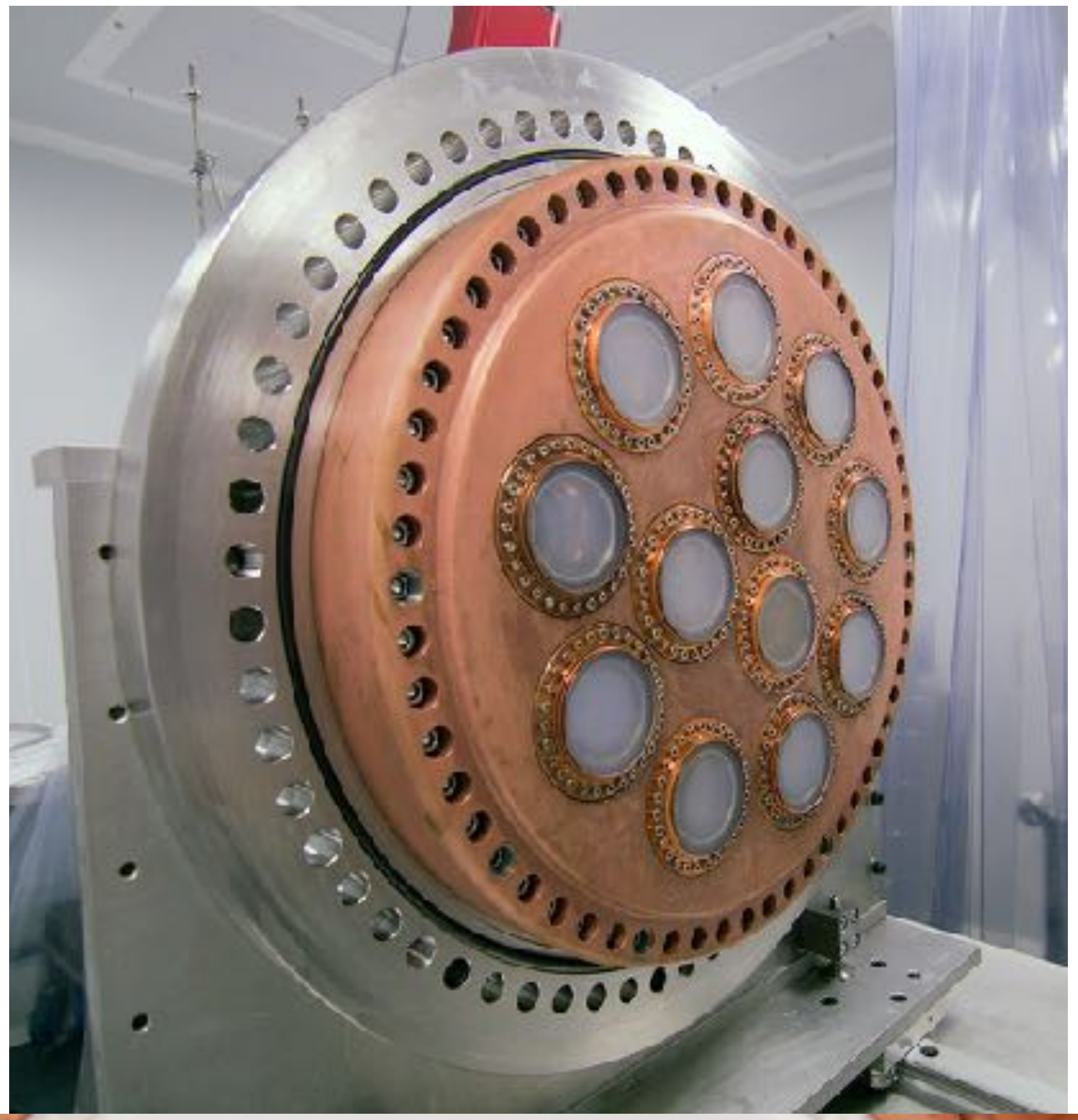


From NEW to NEXT-100





NEXT-100: Inner copper shielding



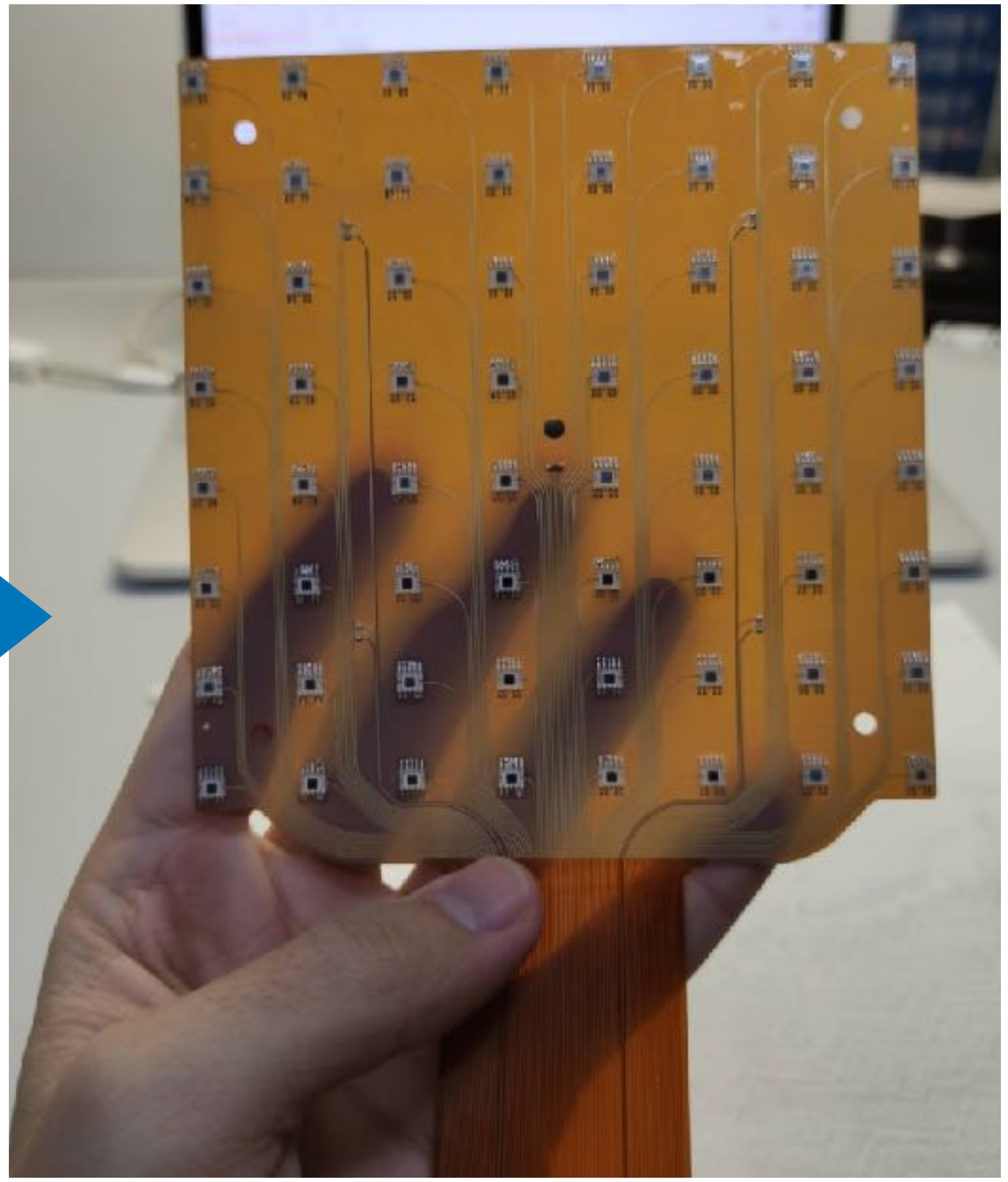
- The size and amount of copper needed for NEXT-100 has forced us to change our purchase and fabrication protocols.
- Direct contact with all the companies involved, mine, foundry, machining,… maintaining radiopurity!

- Fundamental development for larger detectors

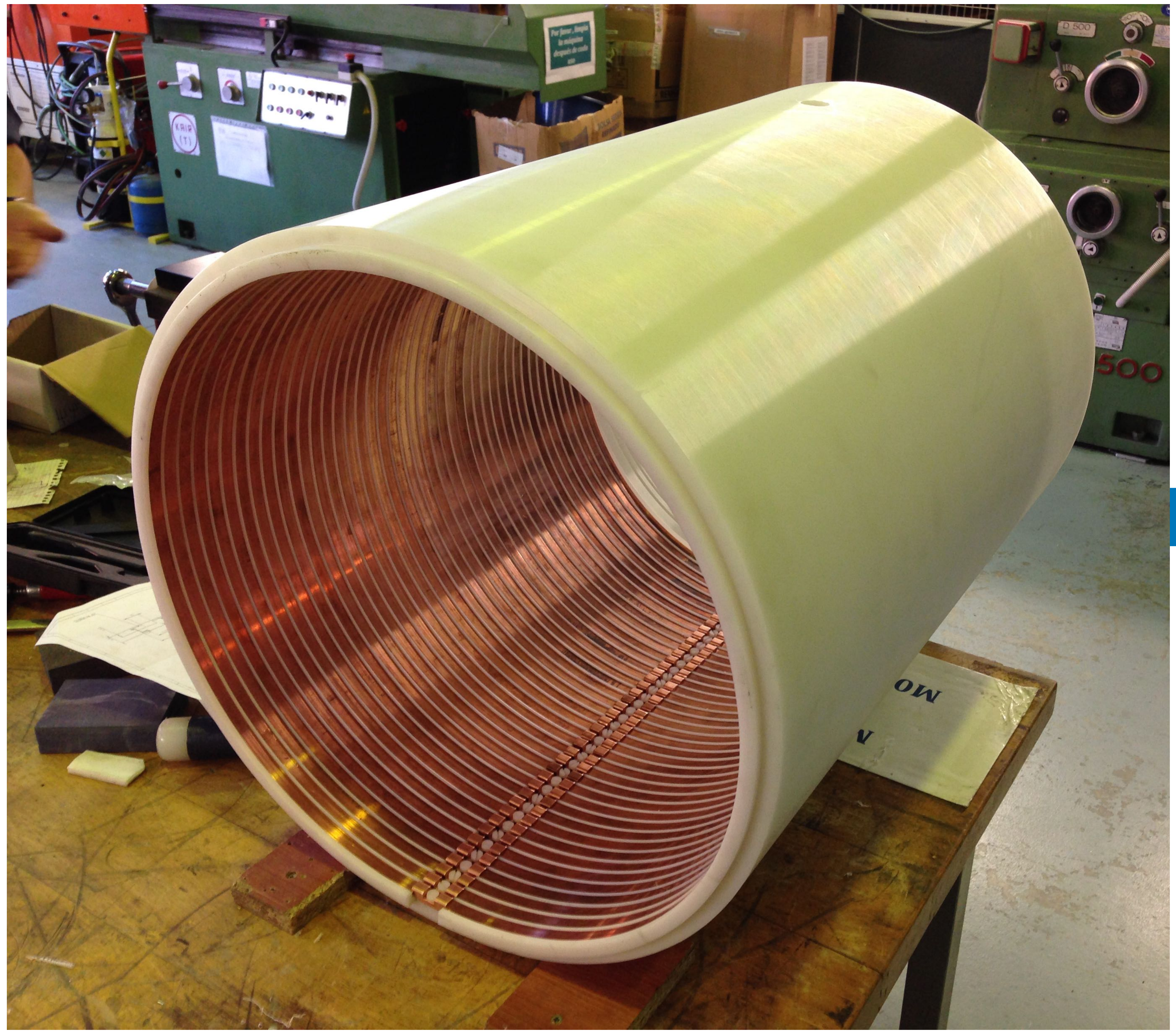
NEXT-100: Tracking plane

- Kapton flexible circuits with a single Kapton layer and no-glue in the front side. Reduction of radioactivity.

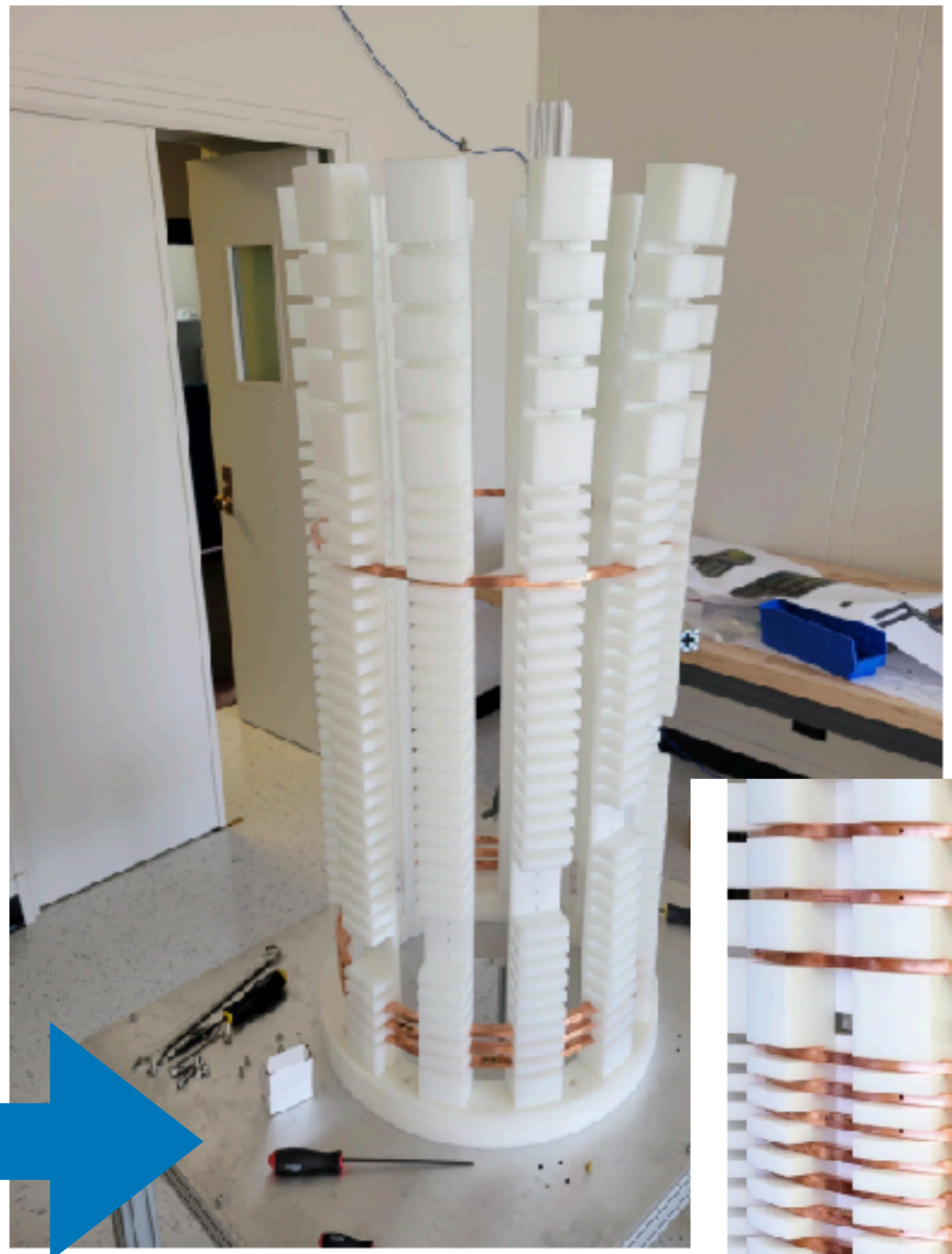
- From SensL to Hamamatsu SiPMs: Easier to mount, more robust, larger area.
- Better for dynamic range.



NEXT-100: Field cage



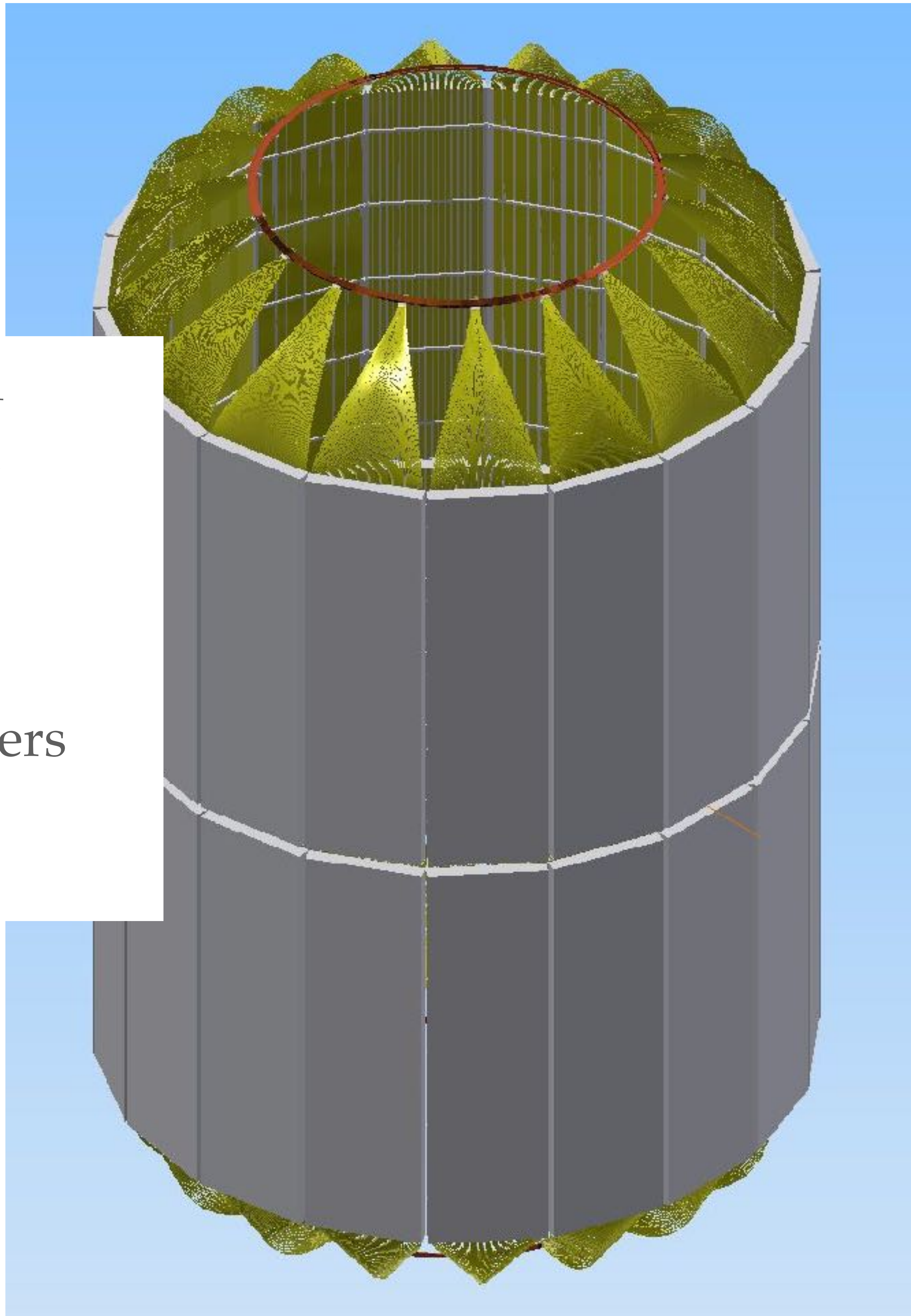
- Abandon solid HDPE structure: Reduction of outgassing.



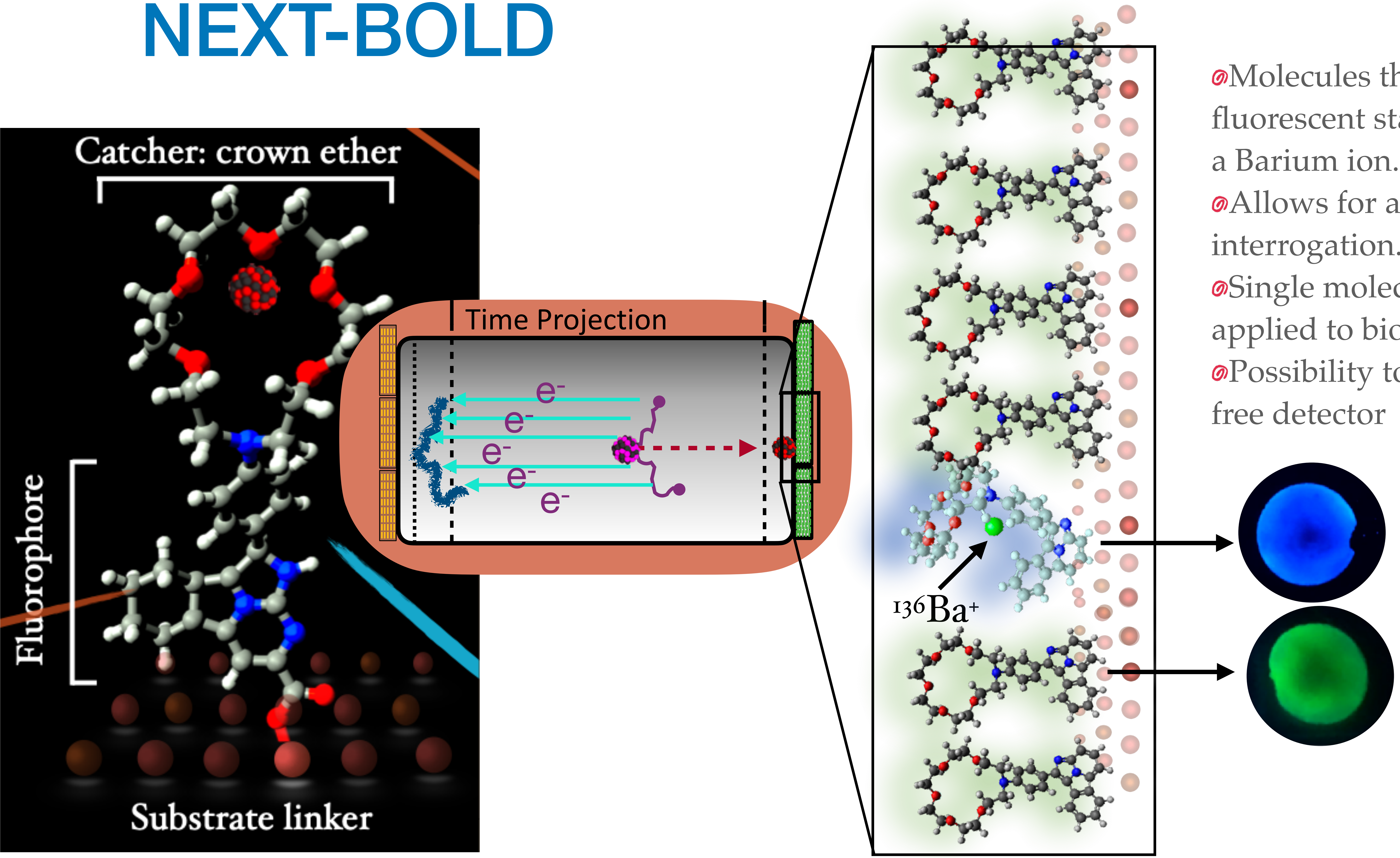
- Larger separation among rings for an easier assembly and more robust resistor chain.

NEXT-HD (2025–)

- Move to a symmetric TPC, central cathode, two amplification regions.
- Denser SiPM pitch.
- Read S1 by using WLS fibers surrounding the volume.
- Read S2 with a combination of fibers and SiPMs.
- Water tank shielding.



NEXT-BOLD



- Molecules that change their fluorescent states when capturing a Barium ion.
- Allows for a multiple "on-line" interrogation.
- Single molecule capabilities applied to biology and medicine.
- Possibility to build a true bckg-free detector

Thanks!