Searching for the Grail

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physics colloquium GSSI, May, 2021

Searching for the holly grail

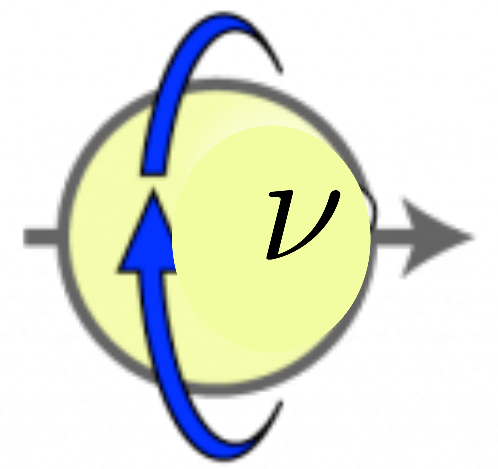
- The Grail was the holiest of all the holly relics in the middle ages.
- The search for the grail is one of the main cycles of the Arthur’s sagas.
- It involved uncountable perils with very low probability of success.
- Only the strongest, smartest, bravest and noblest knights were fit to try.

Neutrinos

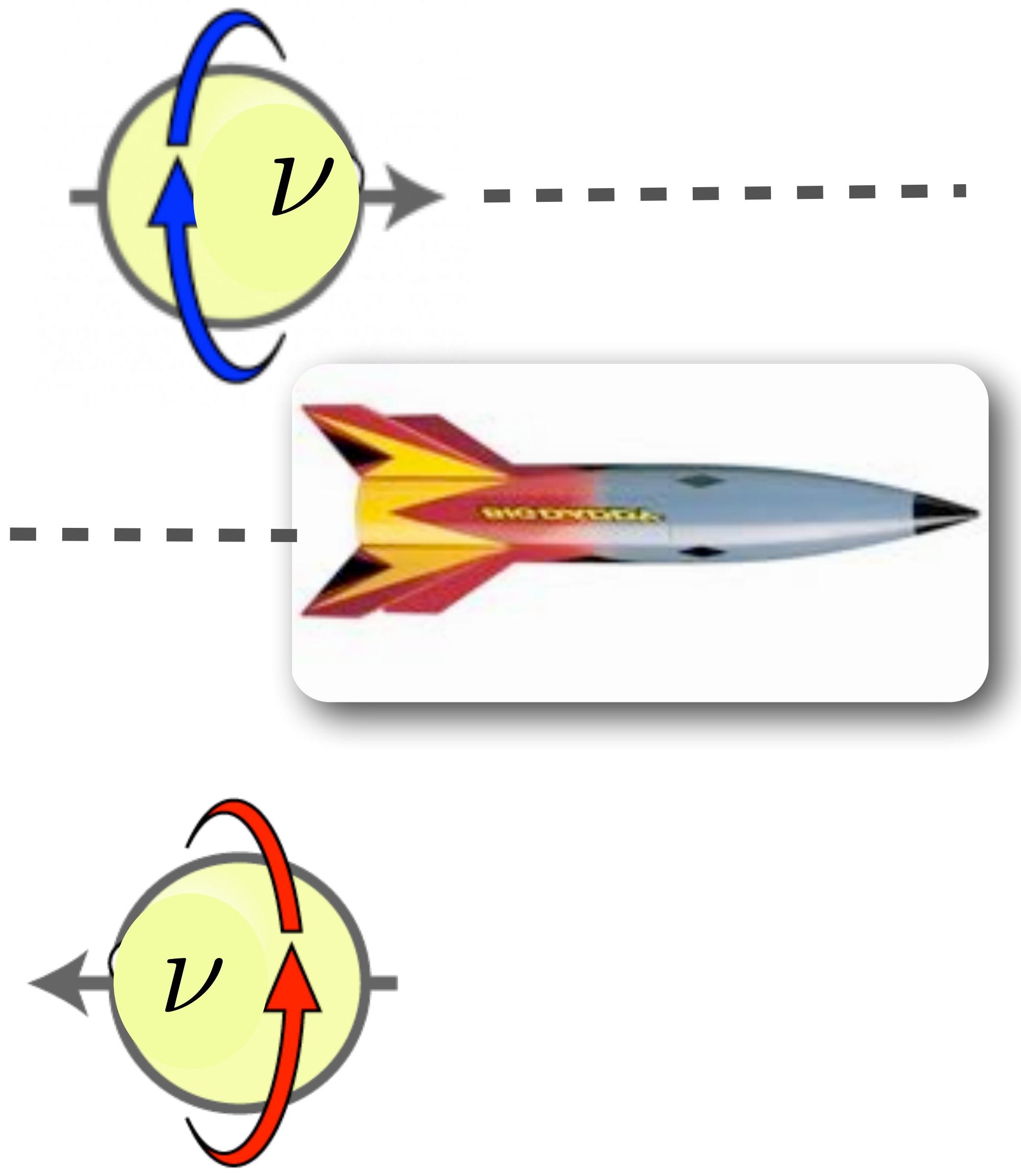
I have done a terrible thing, I have postulated a particle that cannot be detected.

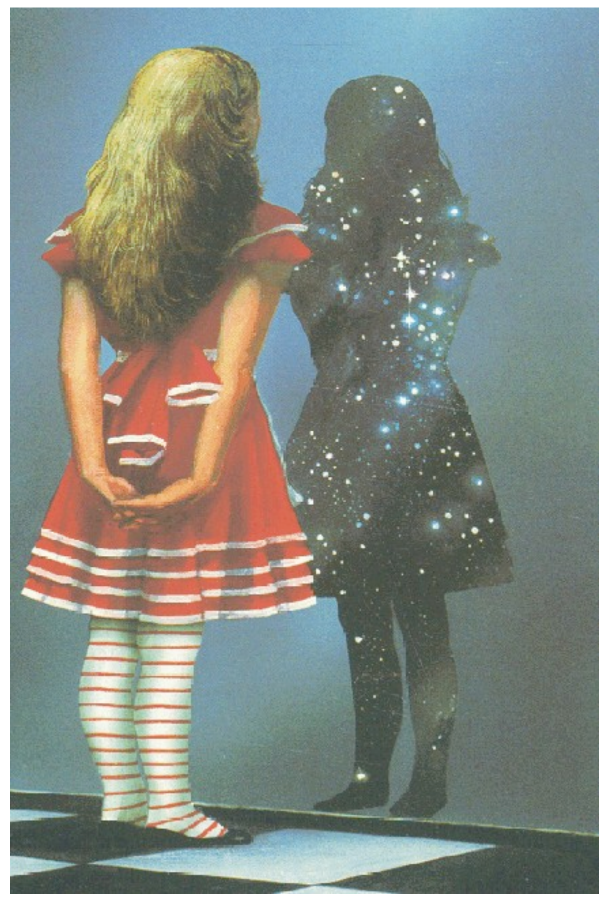
Just now nuclear physicists are writing a great deal about hypothetical particles called neutrinos supposed to account for certain peculiar facts observed in ß-ray disintegration. **We can perhaps best describe the neutrinos as little bits of spin-energy… I am not much impressed by the neutrino theory. In an ordinary way I might say that I do not believe in neutrinos... Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos?**

Neutrino through the looking glass



•In the Standard Model neutrinos are massless and left handed (antineutrinos are right handed)

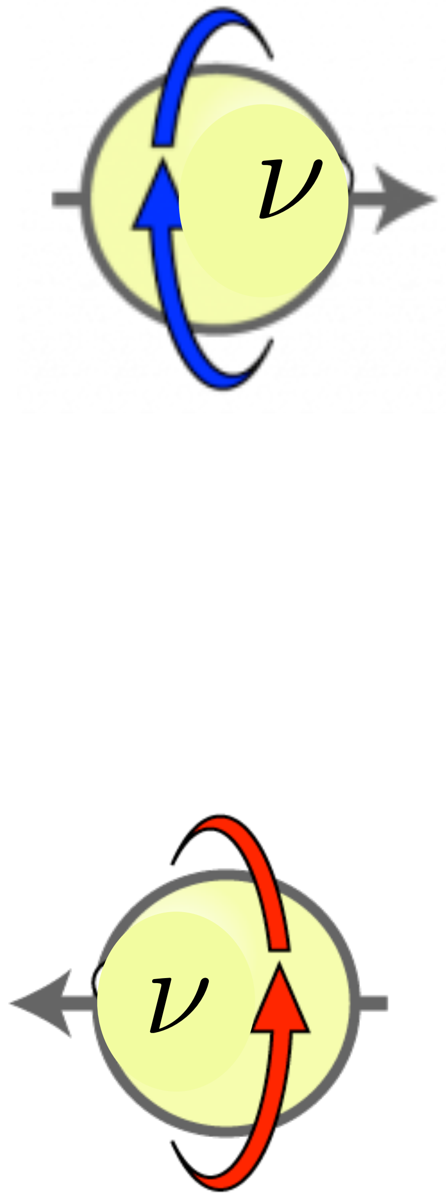


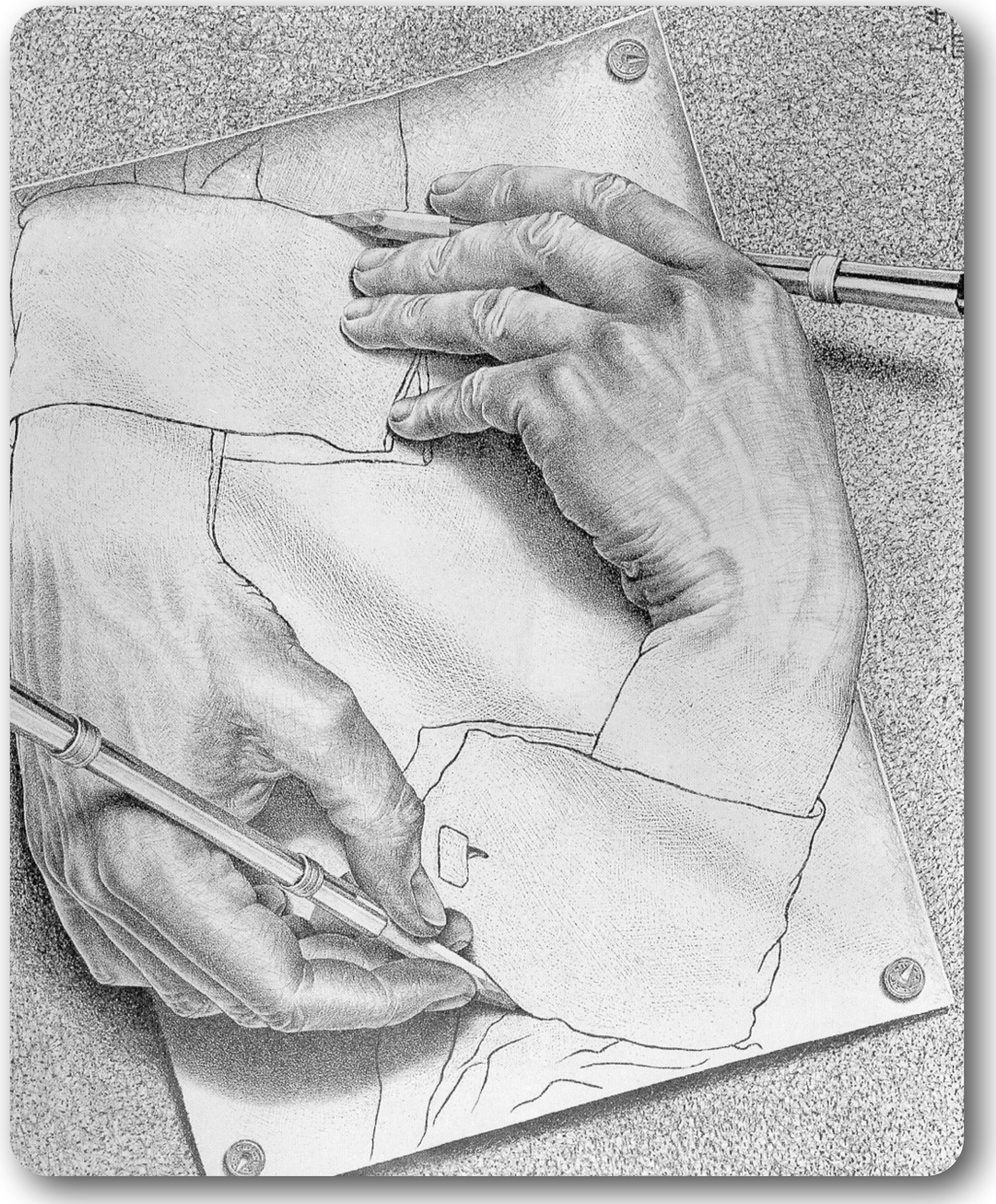


•It would be possible to turn a left handed neutrino into a right handed neutrino by jumping in a reference frame that moves faster than the neutrino. But a massless neutrinos moves at the speed of light and cannot be overtaken

•Therefore we could live without right handed neutrinos and without left-handed antineutrinos. **Standard model neutrinos do not reflect in the mirror!**

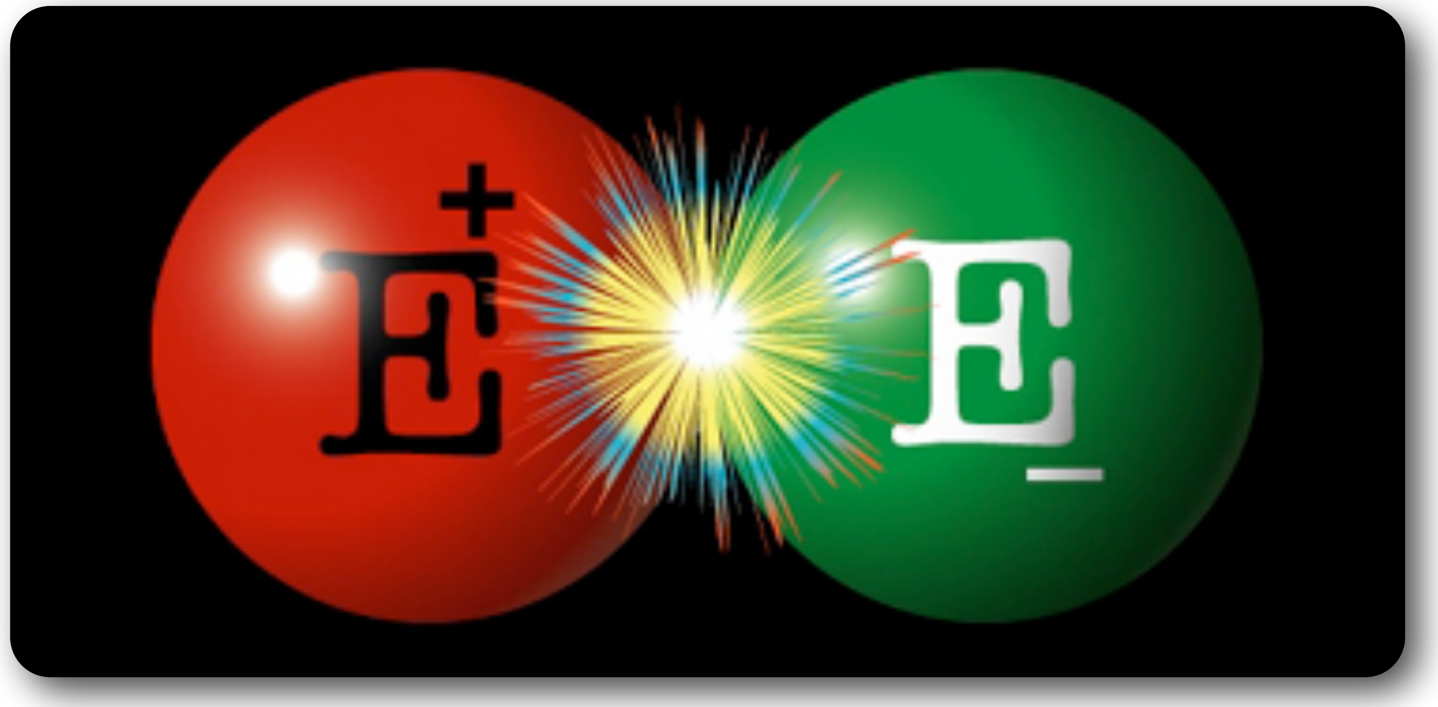
But what if neutrinos are massive?



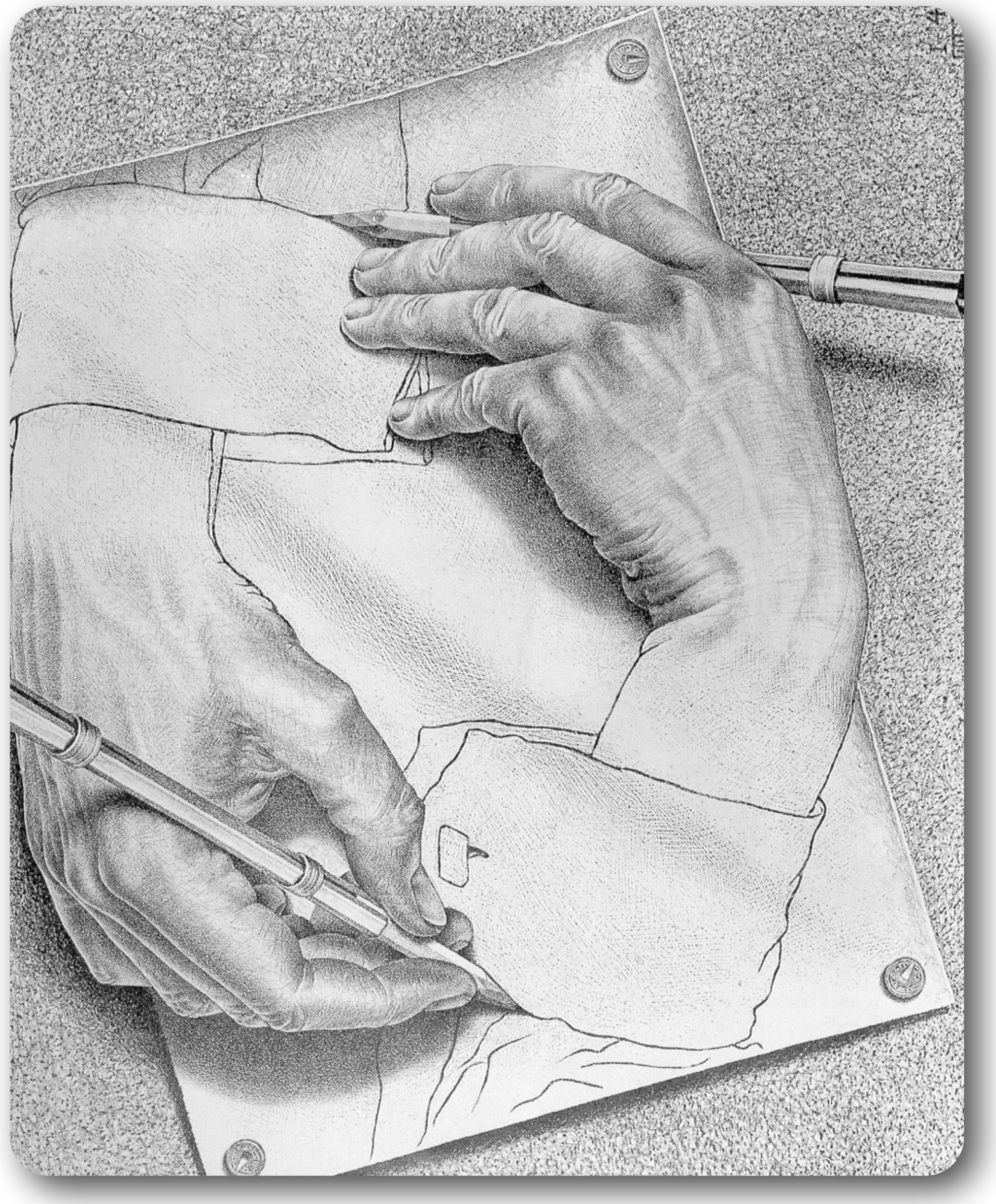


- Reversing the argument, left-handed and right-handed neutrinos are guaranteed to exist. How does a massive neutrino reflects in the mirror?

Neutrino’s charge conjugation

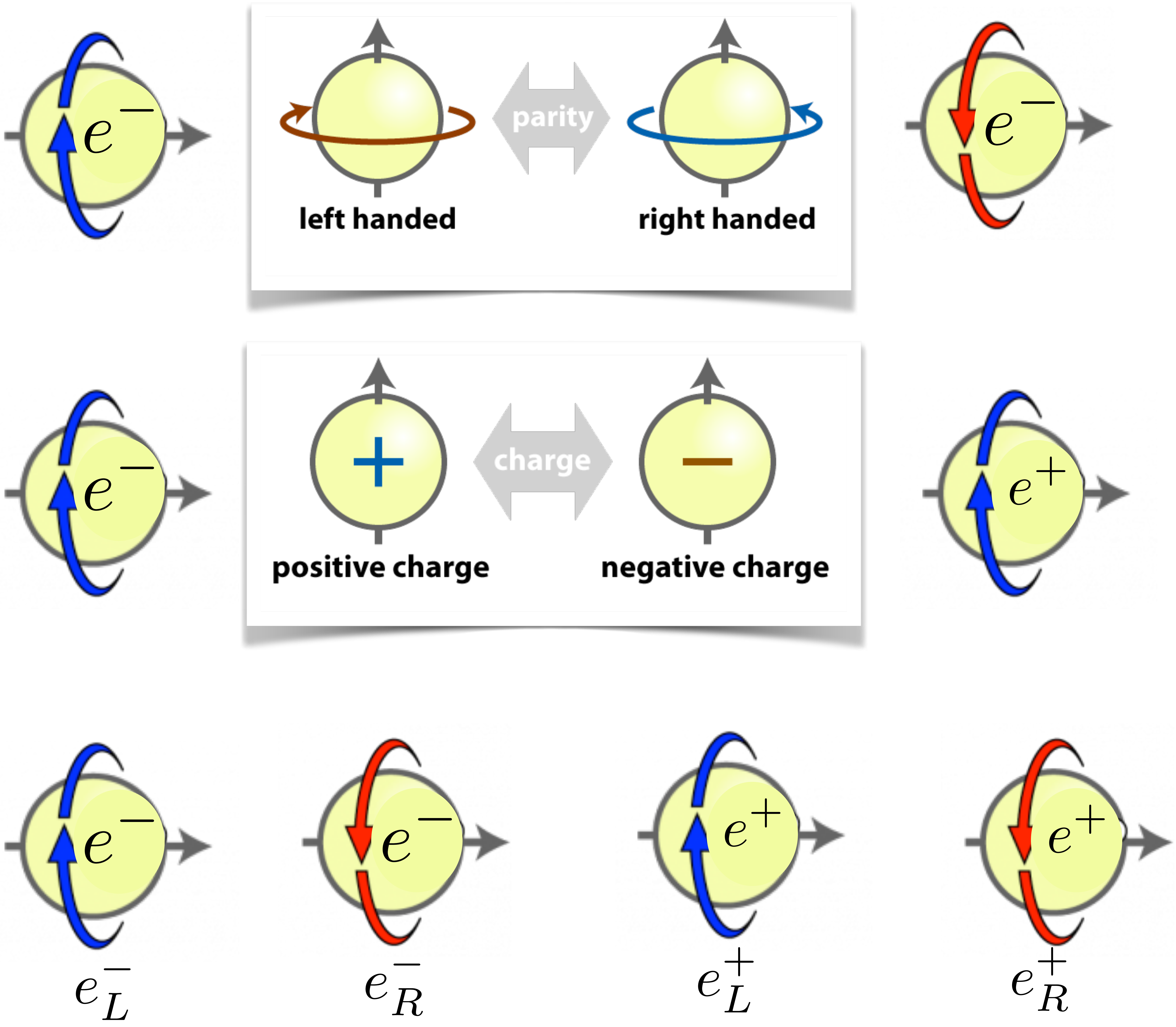


Charge conjugation reverses the electric charge of the electron (and all other elementary particles).

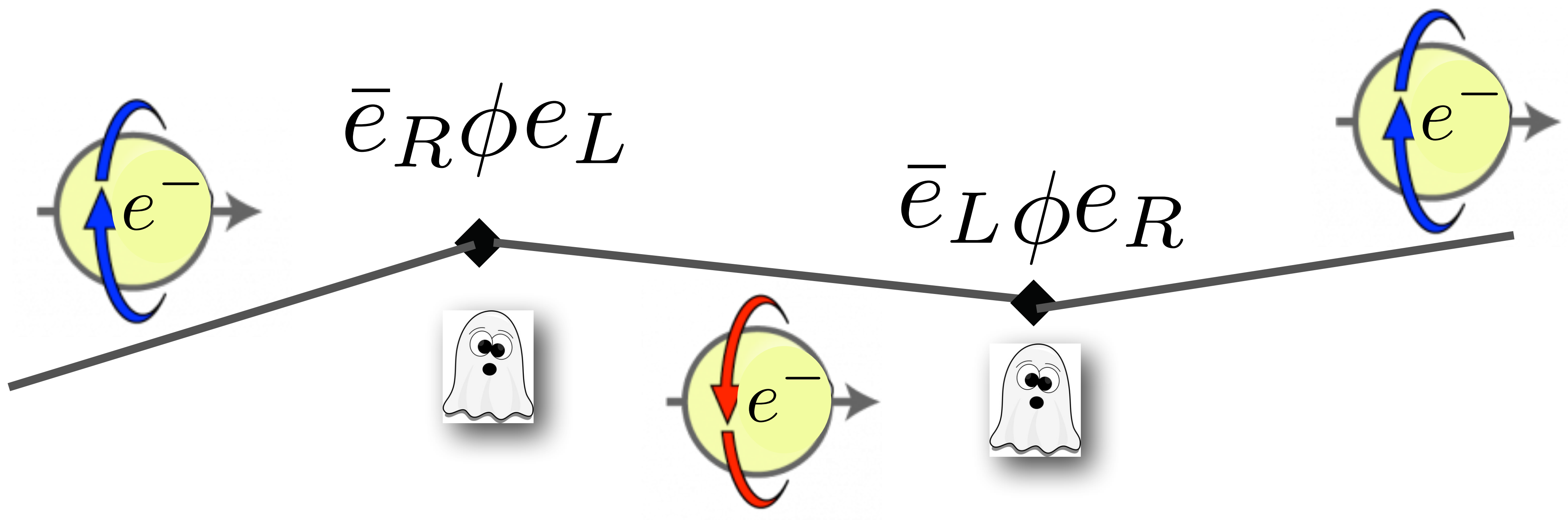


But the neutrino has no electric charge that needs to be conserved.

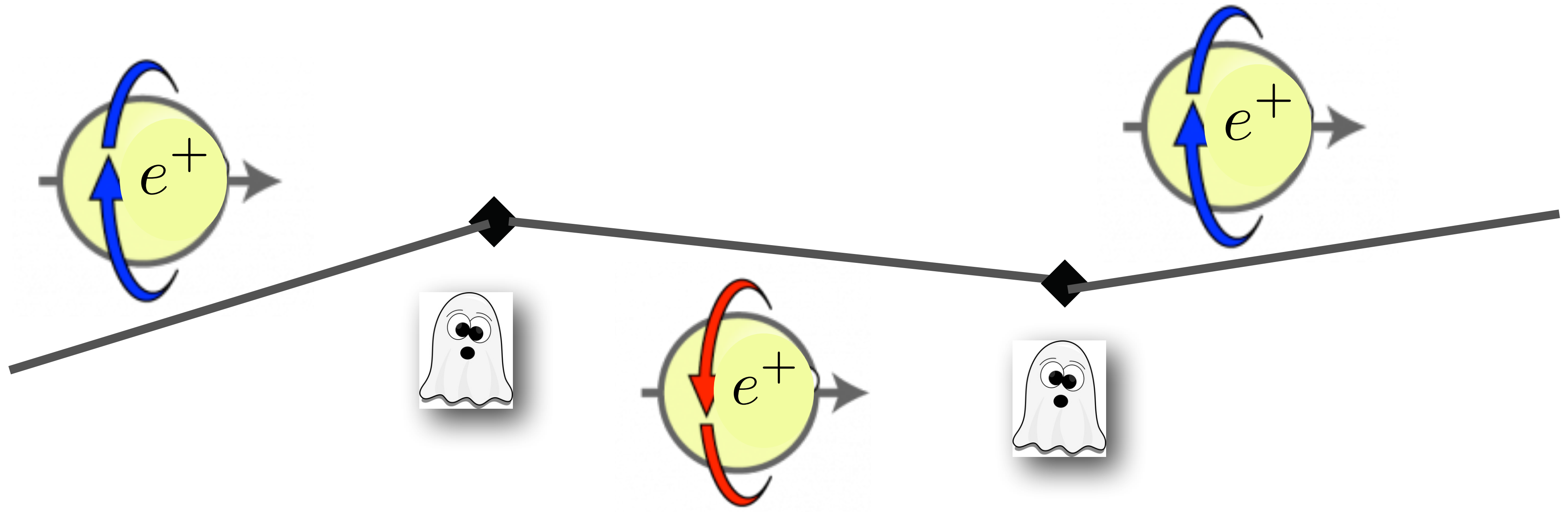
Electrons through the looking glass



Electron mass



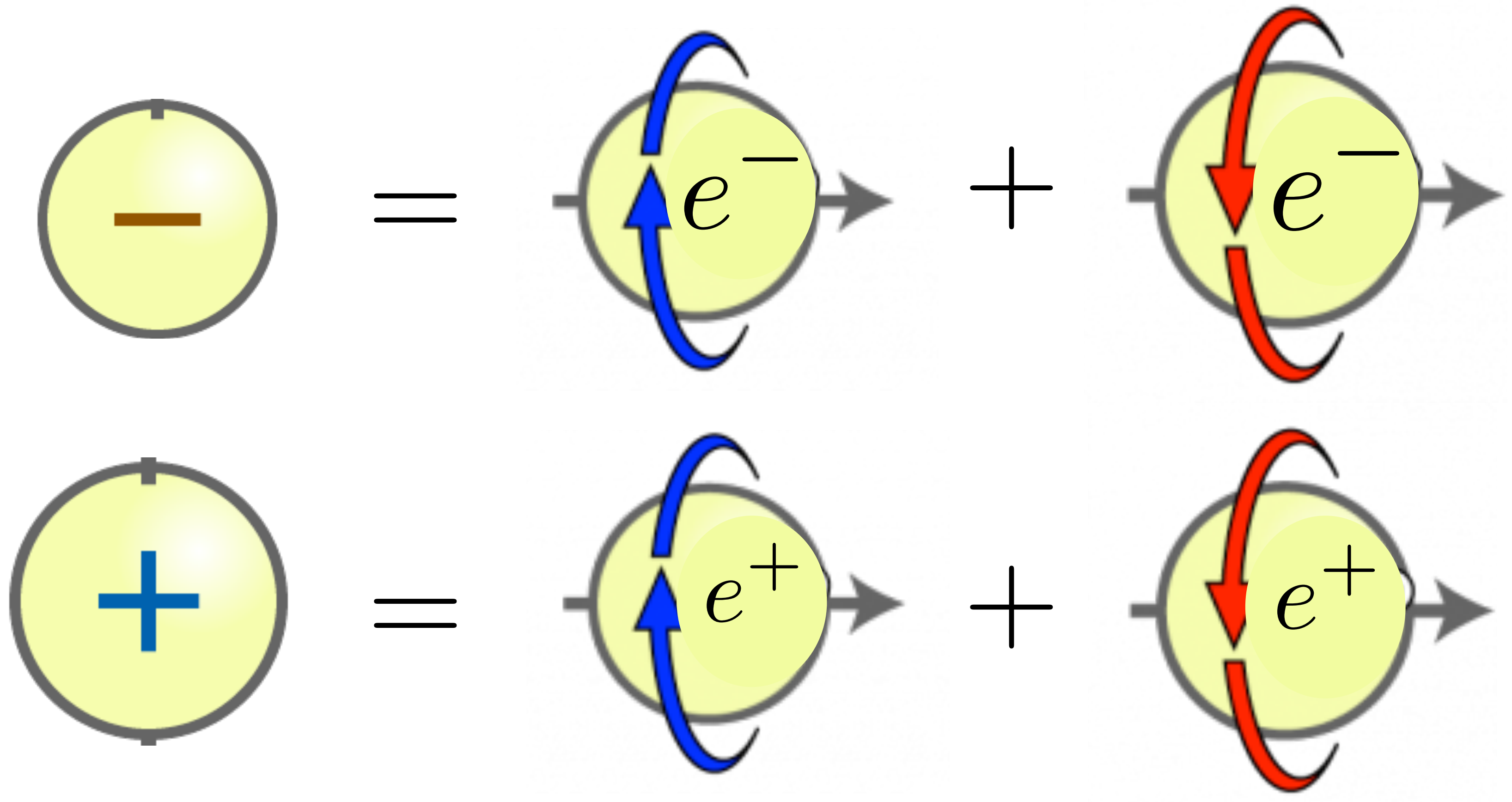
left and right handed states bump against the Higgs field



$$\mathcal{L}_D = \bar{e}_L m_e e_R + h.c.$$

$$\lambda\bar{e}_R\phi e_L \to \lambda v\bar{e}_R e_L$$

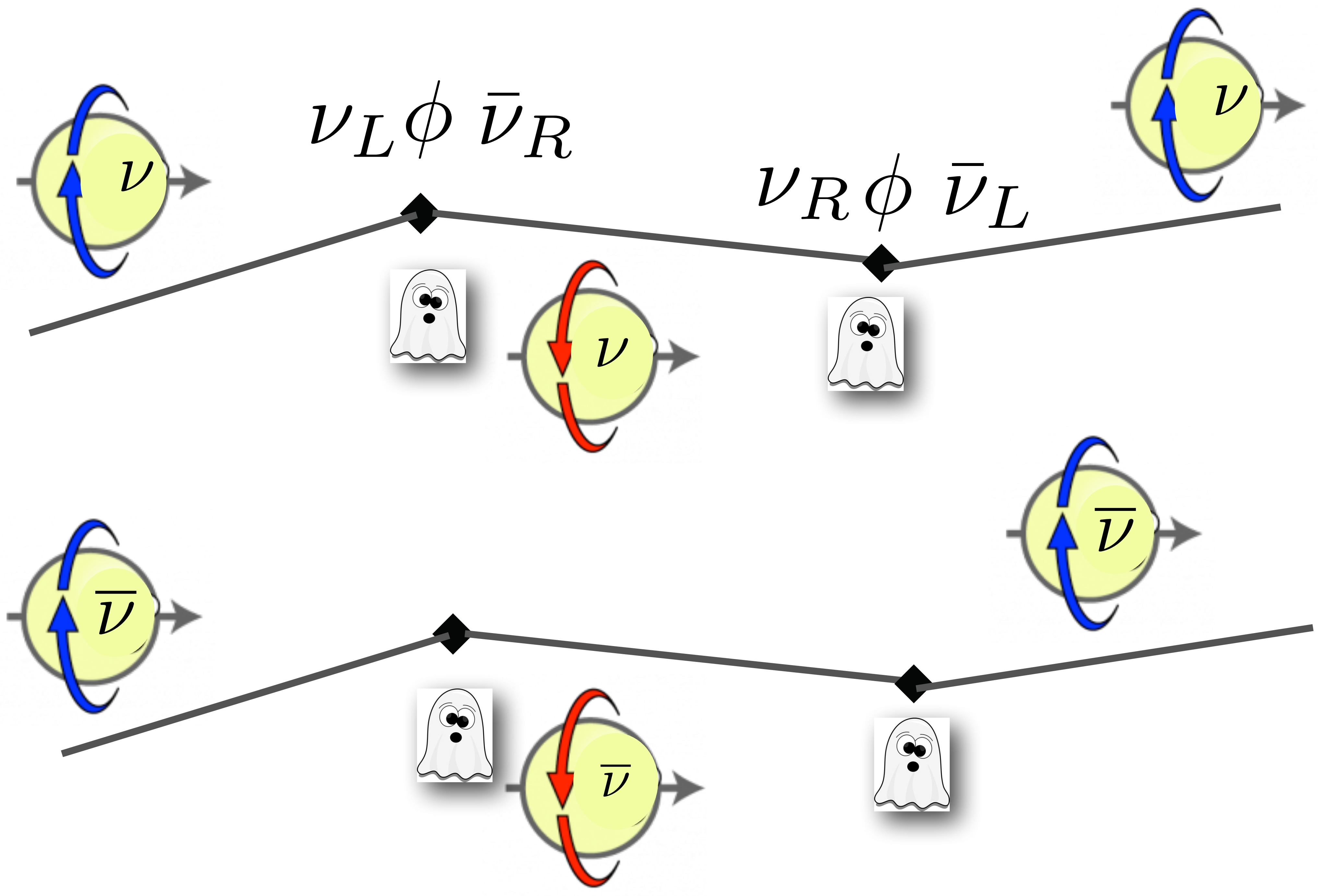
$$m_e = \lambda_e v$$

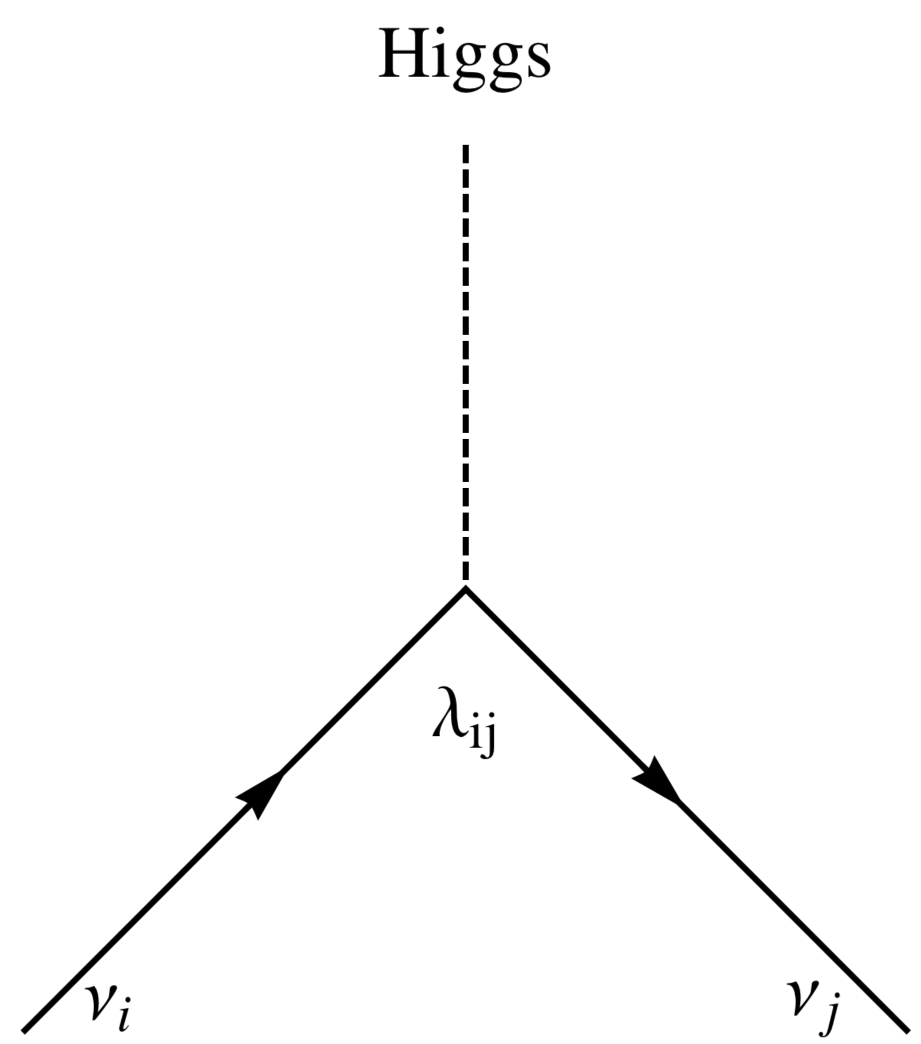


$$e^- = e_L^- + e_R^-$$

$$e^+ = e_L^+ + e_R^+$$

Neutrino mass (Dirac recipe)

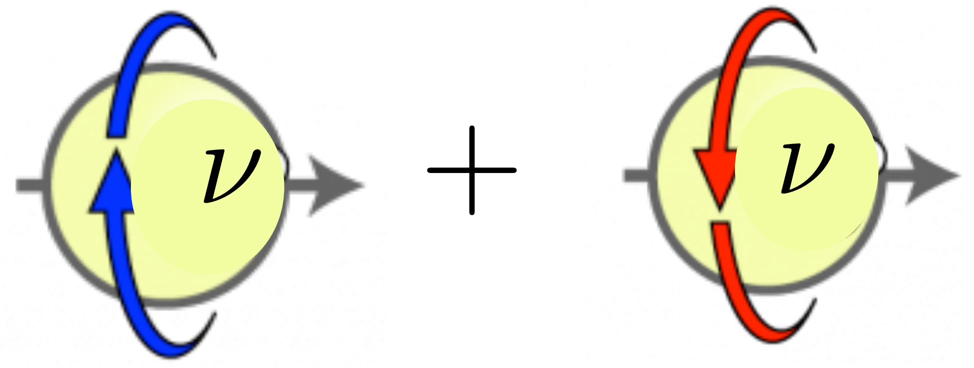




$$-\mathcal{L}_{\text{Dirac}} = \bar{\nu}_L m_\nu \nu_R + h.c.$$

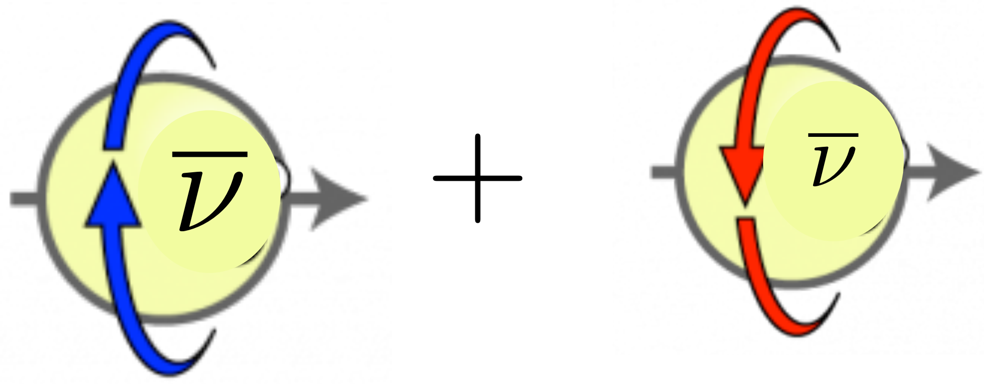
$$m_\nu = \lambda_\nu v$$

ν =



$$\nu = \nu_L + \nu_R$$

$\overline{\nu}$ =



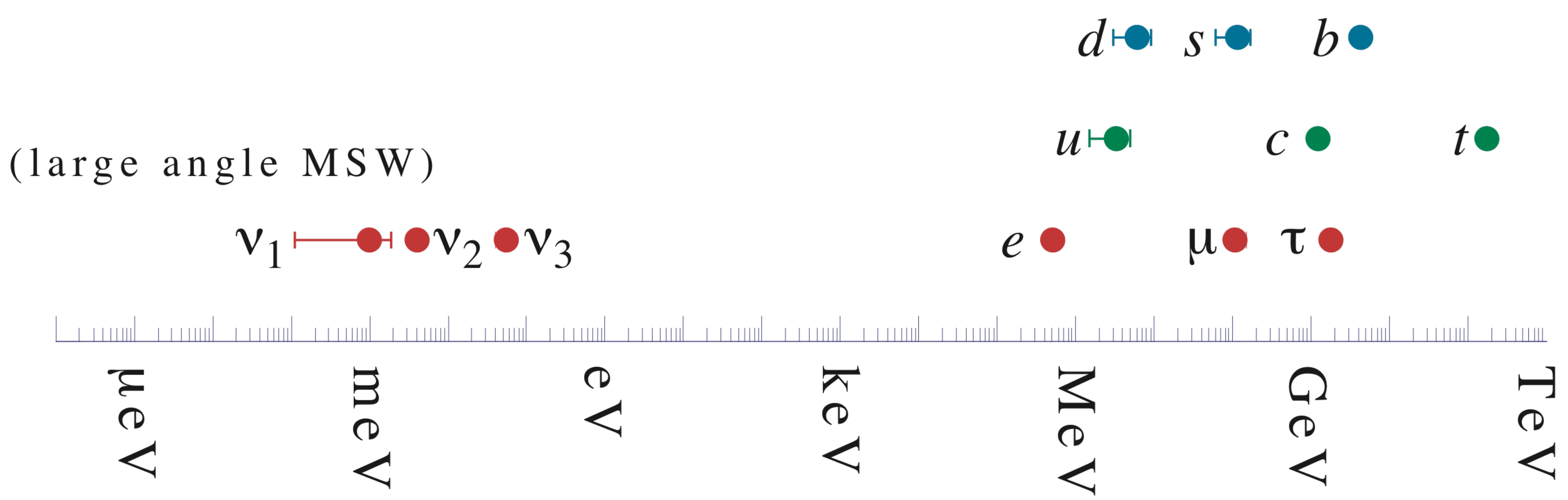
$$\nu^C = (\nu_L)^C + (\nu_R)^C$$

Deus ex machina

The phrase comes from Horace's where he instructs poets that they must never resort to a god from the machine (mekhane) to solve their plots.

A deus ex machina Latin: "god from the crane" is a plot device whereby a seemingly unsolvable problem is suddenly and abruptly solved with the contrived and unexpected intervention of some new event, character, ability, or object. Depending on usage, it can be used to move the story forward when the writer has "painted themselves into a corner" and sees no other way out, to surprise the audience, or to bring a happy ending into the tale.

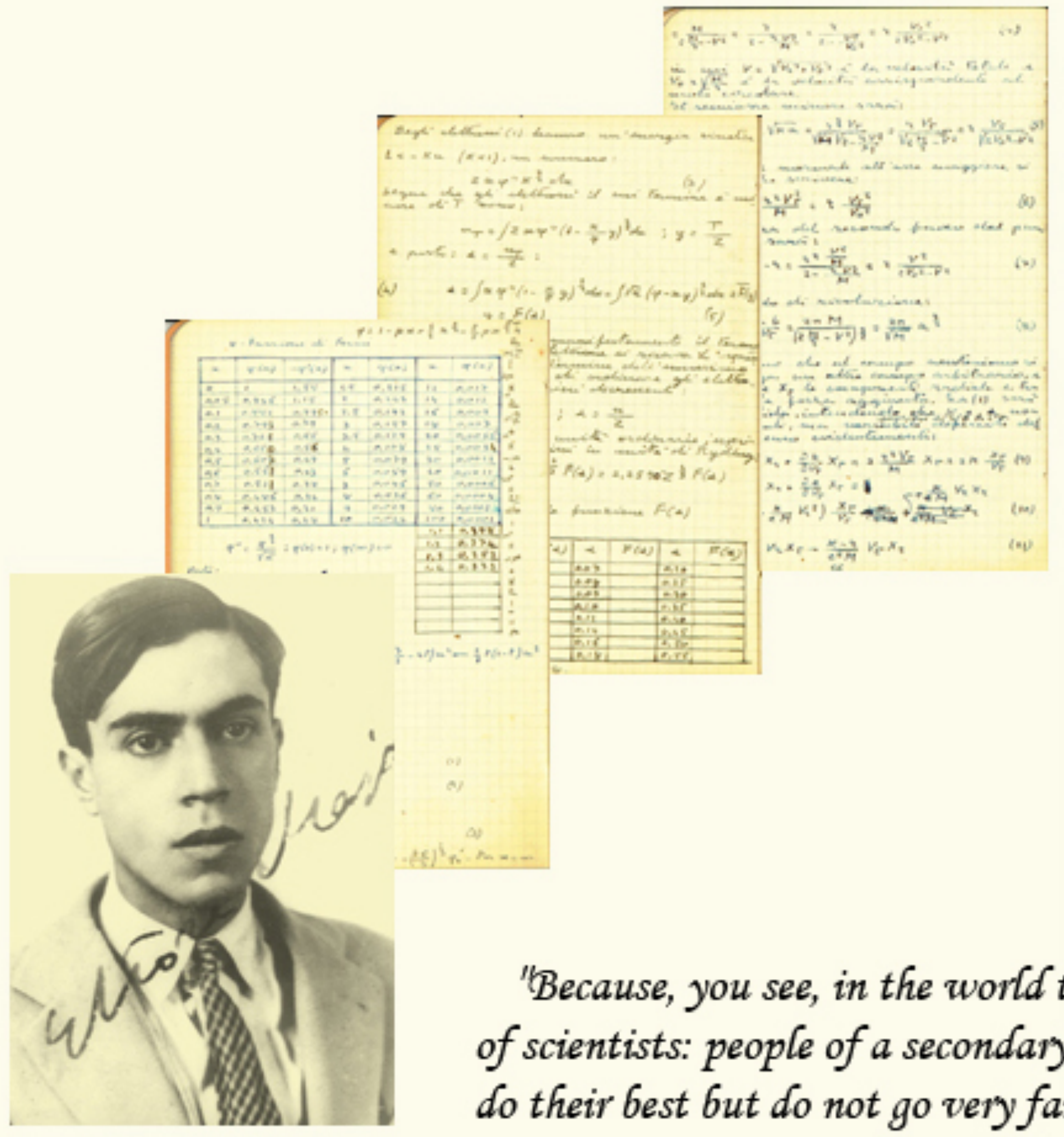
Dirac neutrinos: Deus ex machina



Nature has painted herself into a corner and sees no other way out to explain small neutrino masses than to resort to arbitrarily small coupling constant, that she lowers from the machine...

$$\lambda_\nu << \lambda_e?$$

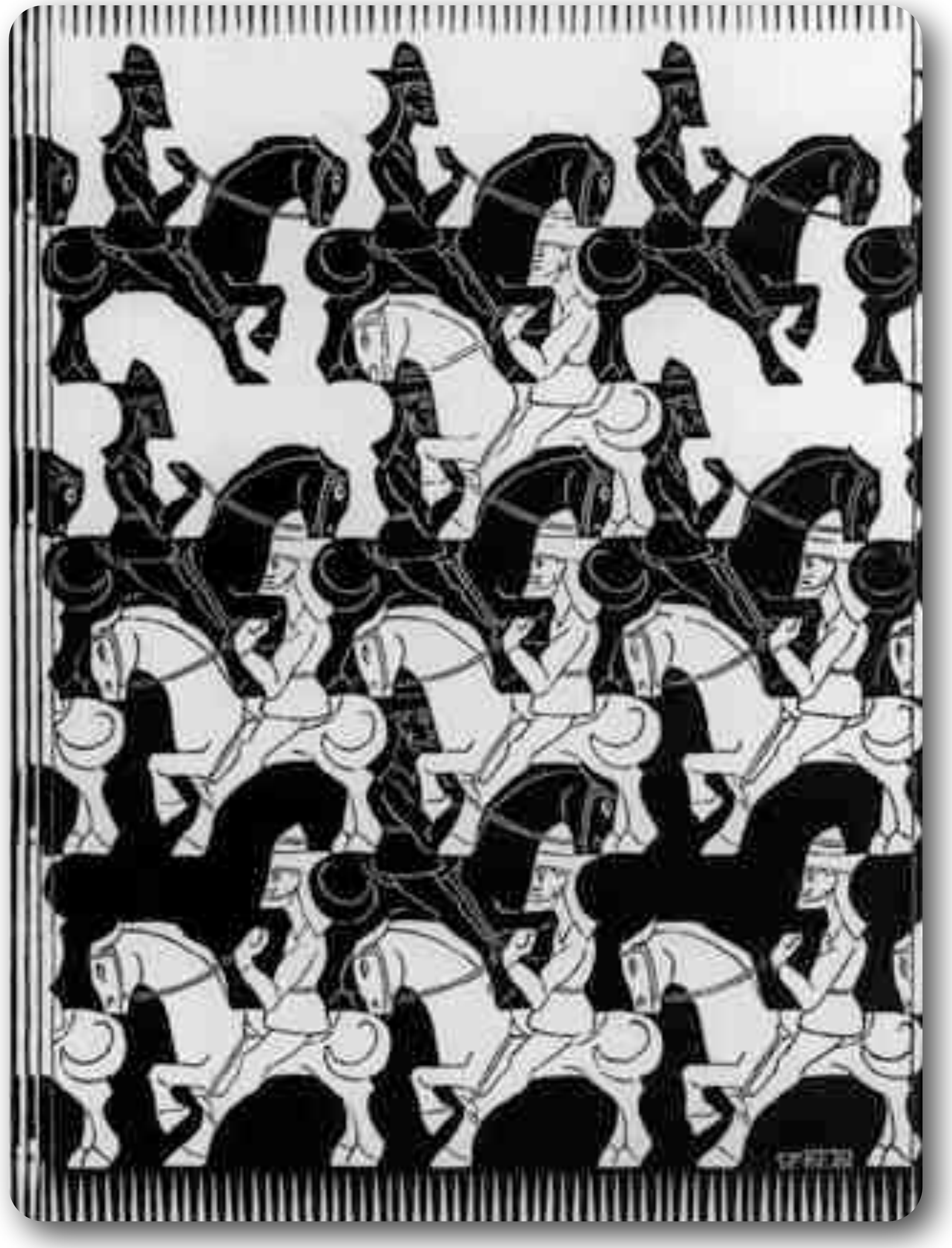
Majorana’s idea



"Because, you see, in the world there are various categories of scientists: people of a secondary or tertiary standing, who do their best but do not go very far. There are also those of high standing, who come to discoveries of great importance, fundamental for the development of science.

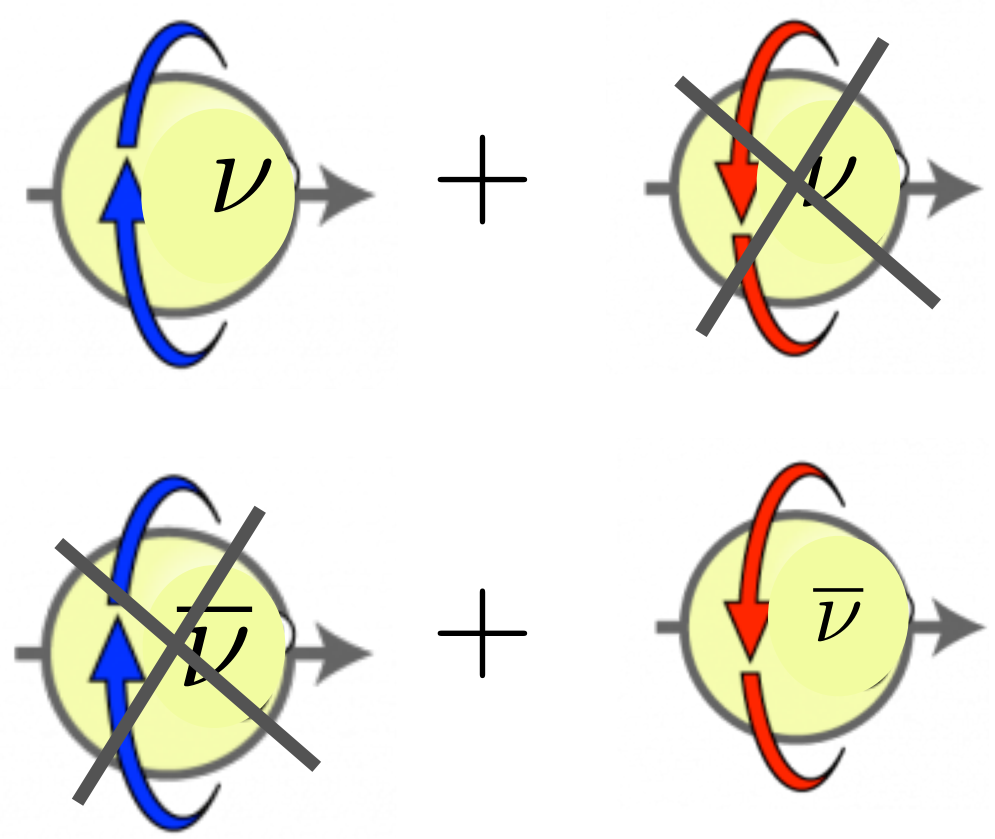
But then there are geniuses like Galileo and Newton. Well, Ettore was one of them. Majorana had what no one else in the world had".

E. Fermi



Majorana neutrinos

$$\nu =$$



$$\nu = \nu_L + \cancel{\nu_R}$$

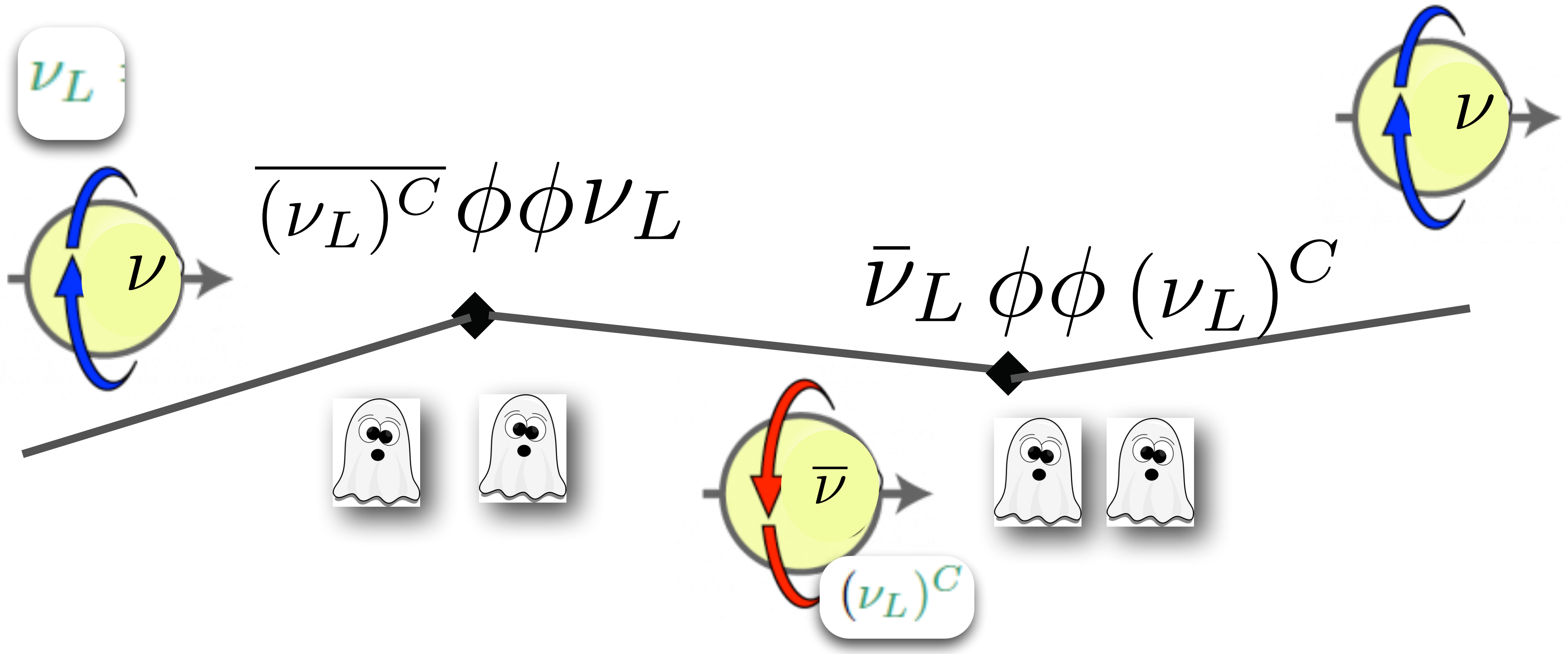
$$\nu^C = (\nu_L)^C + (\cancel{\nu_R})^C$$

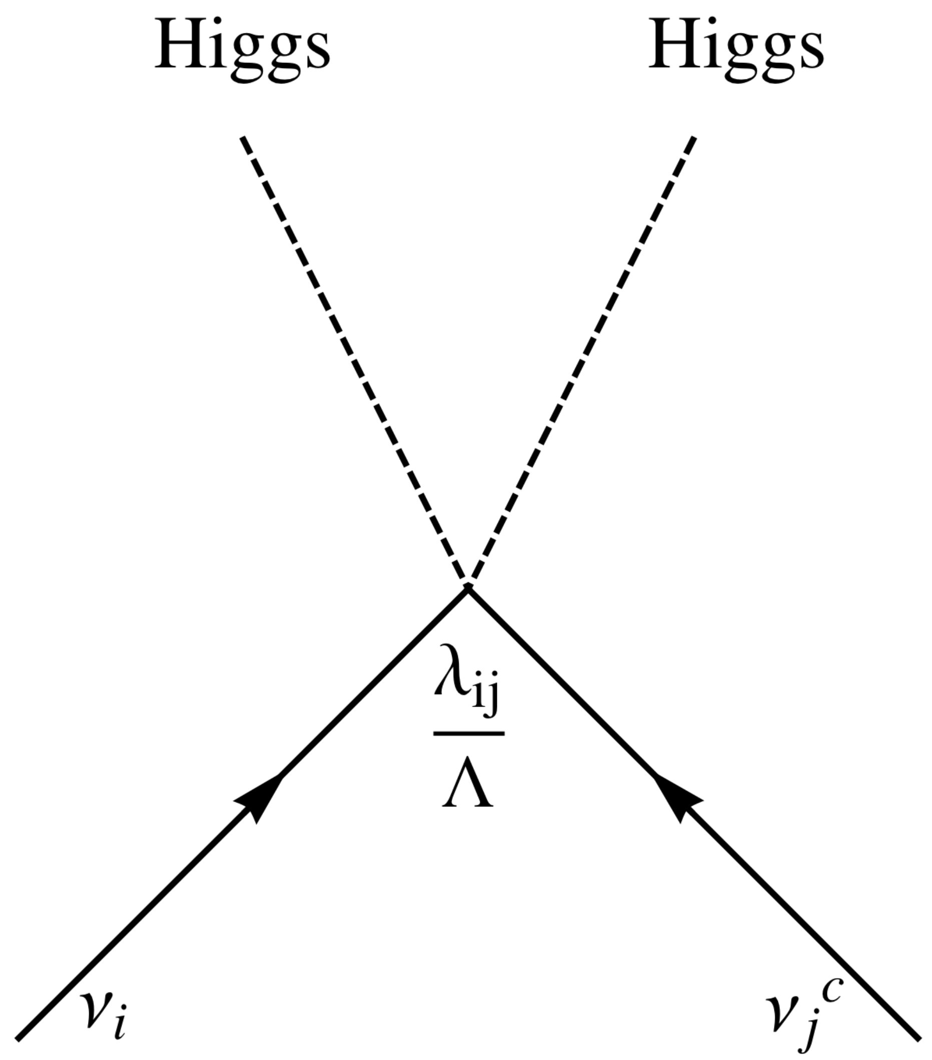
$$\nu = \bar{\nu}$$

$$\nu = \nu_L + \nu_L^C \qquad \nu^c = \nu$$

The neutrino is made, like in the Escher's tableau of black and white chevaliers.

Neutrino mass (Majorana recipe)





$$\nu_L = (\nu_R)^C \qquad (\nu_L)^C = \nu_R$$

$$-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c.$$

$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$

Λ Scale of new physics

The mystery of the missing antimatter

- The Big-Bang theory of the origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning
- Collider experiments confirm that matter and antimatter are produced in equal amounts in elementary particle collisions.
- But out universe appears to be made only of matter.
- Where did all the antimatter go?

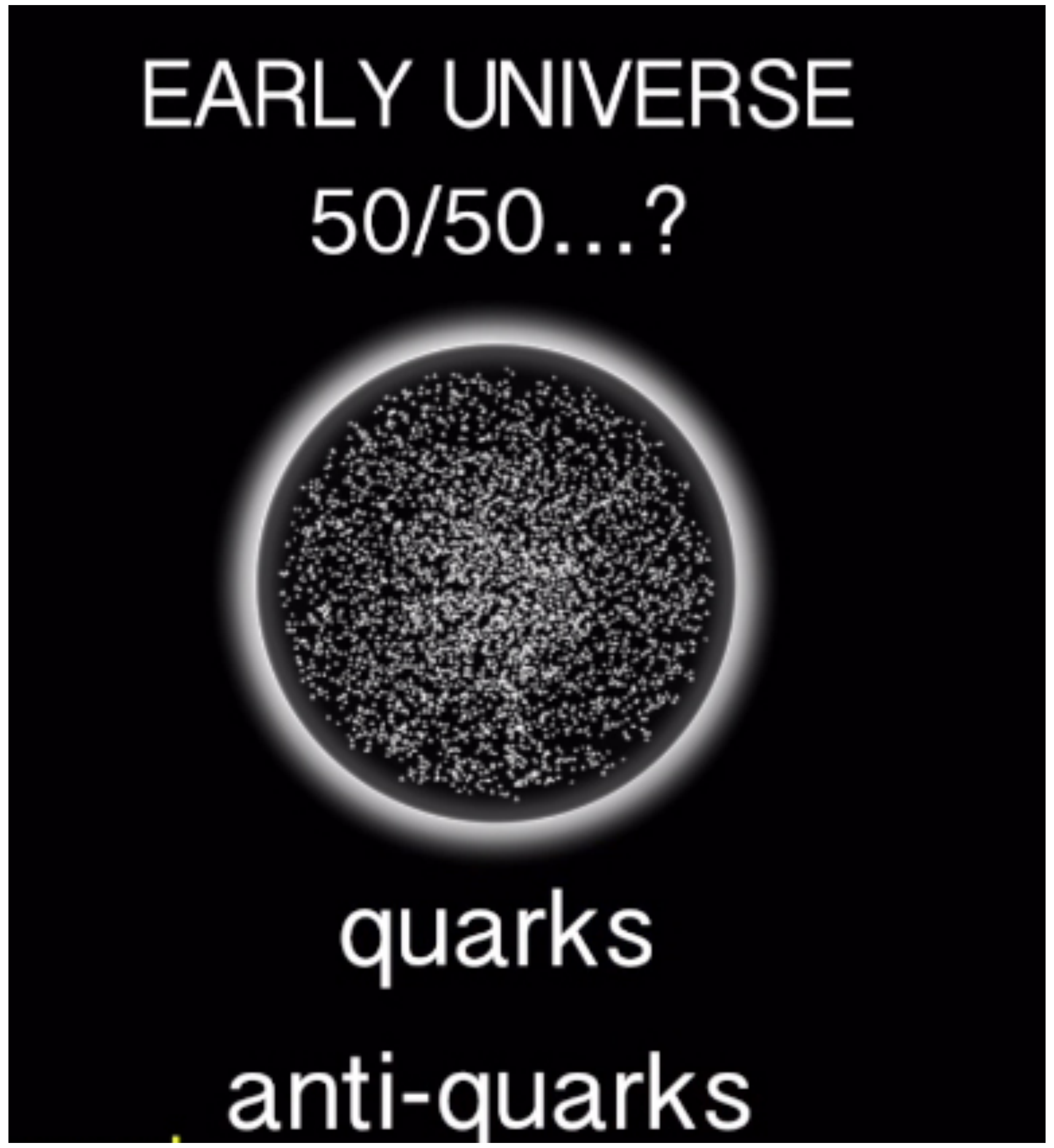
CP violation and Majorana neutrinos

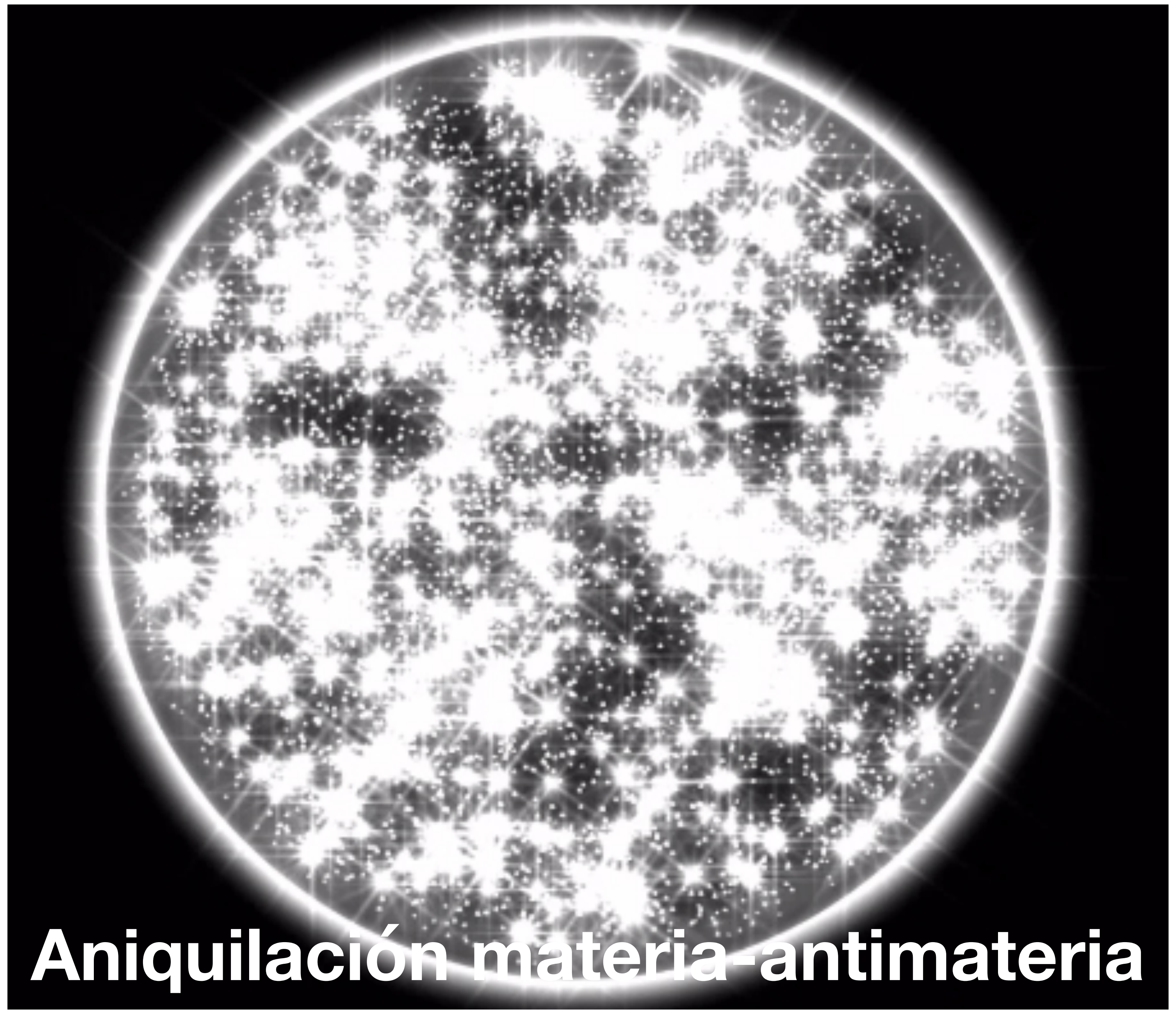
$$N \to e^- + H^+ \quad \text{and} \quad N \to e^+ + H^-$$

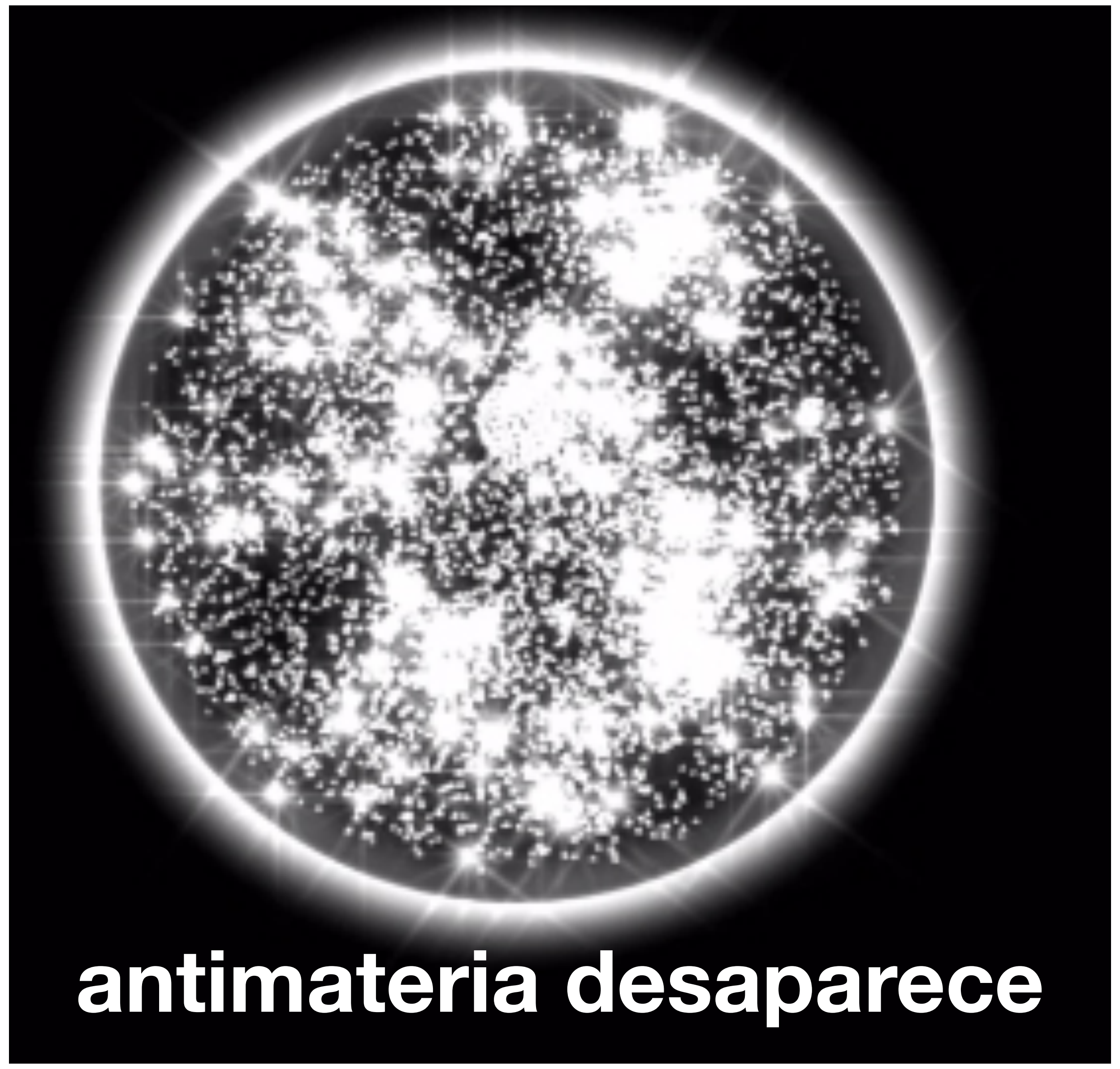
Standard-Model Higgs

- If there is CP violation in the lepton sector, the heavy Majorana neutrino N can violate CP too and decay with different rates to electrons and positrons. This results in an unequal number of leptons and antileptons in the early universe

- Leptonic asymmetry is later transferred to baryons, resulting in...

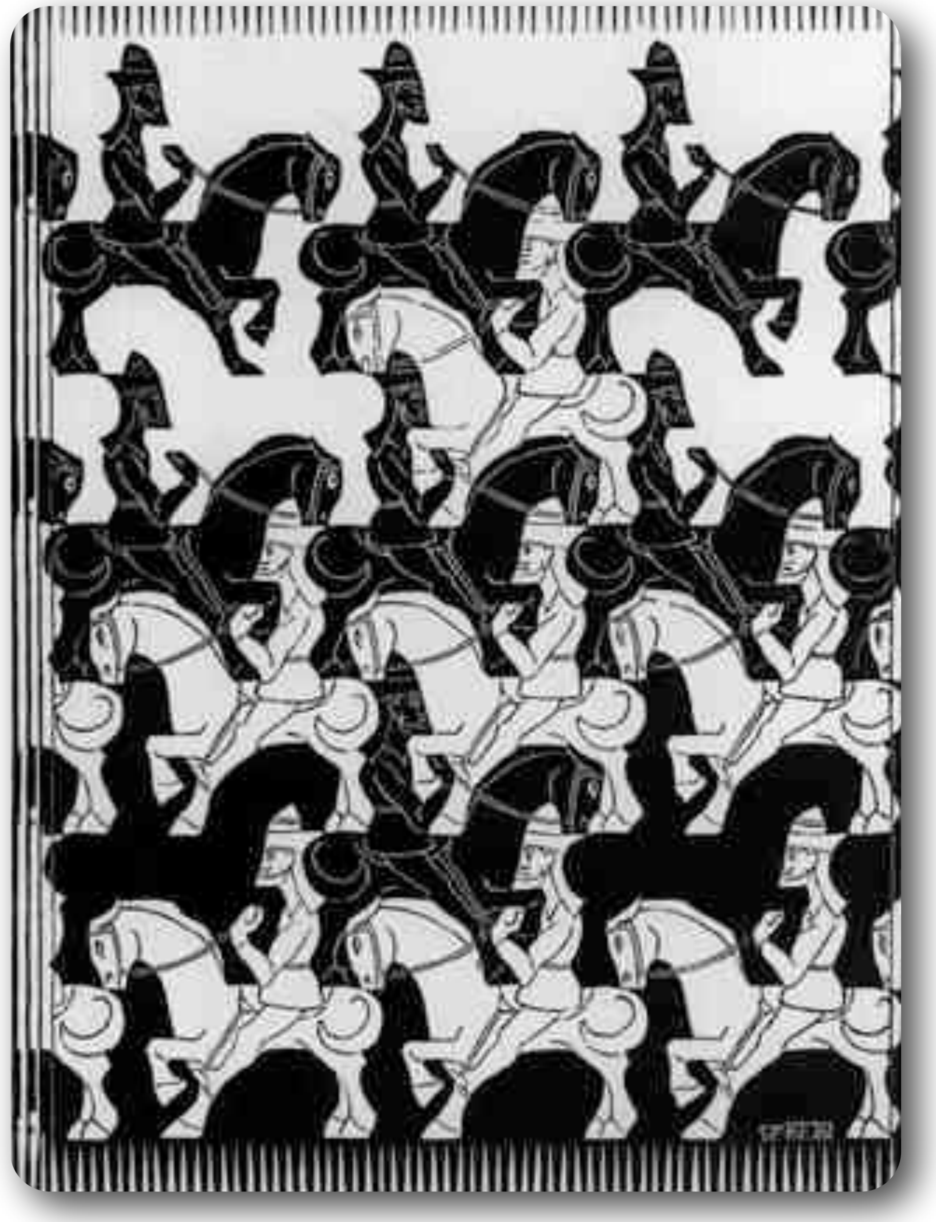

EARLY UNIVERSE
50/50...?
quarks
anti-quarks


Aniquilación materia-antimateria


antimateria desaparece


el universo, hoy

A recipe for the Universe



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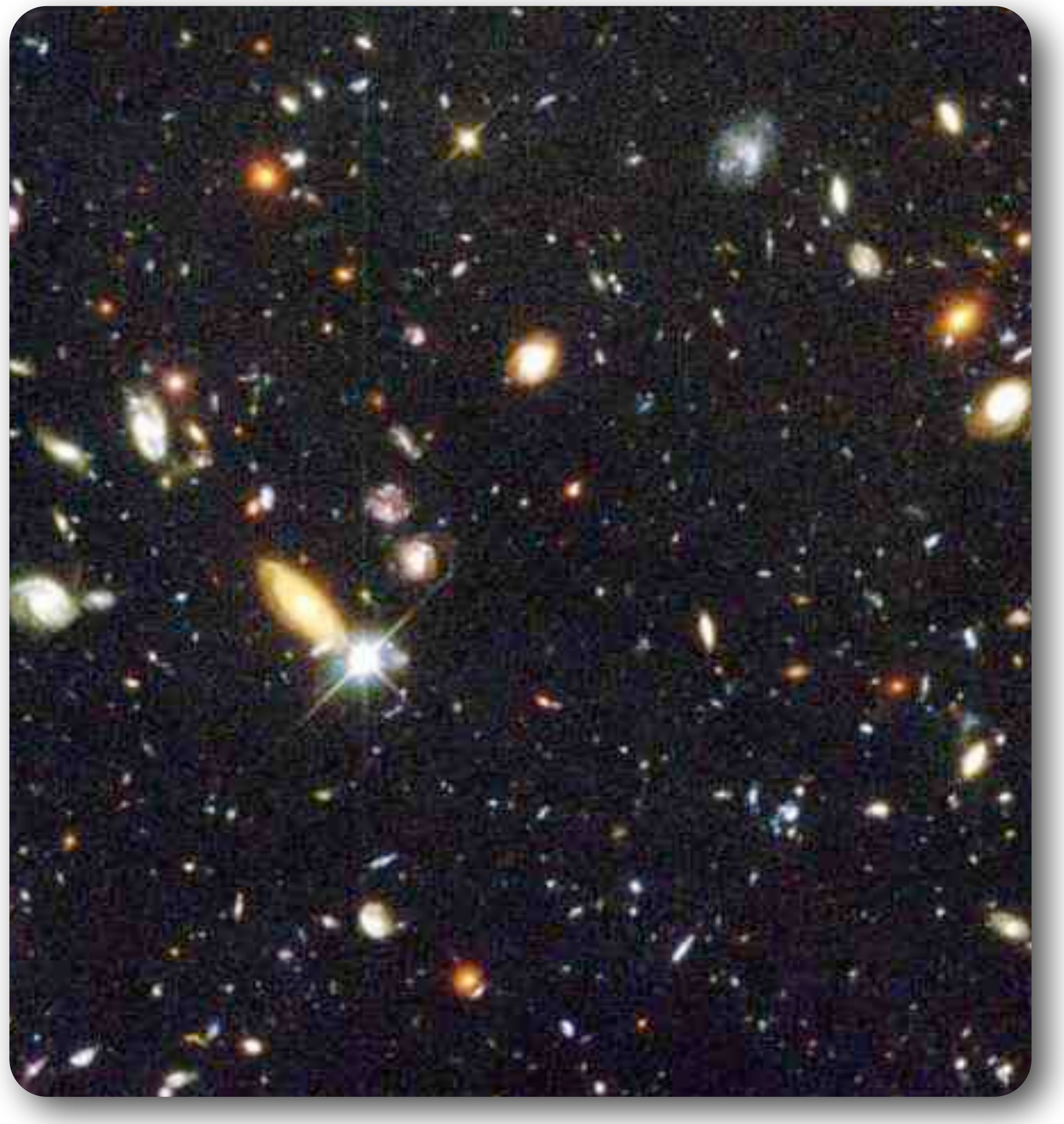
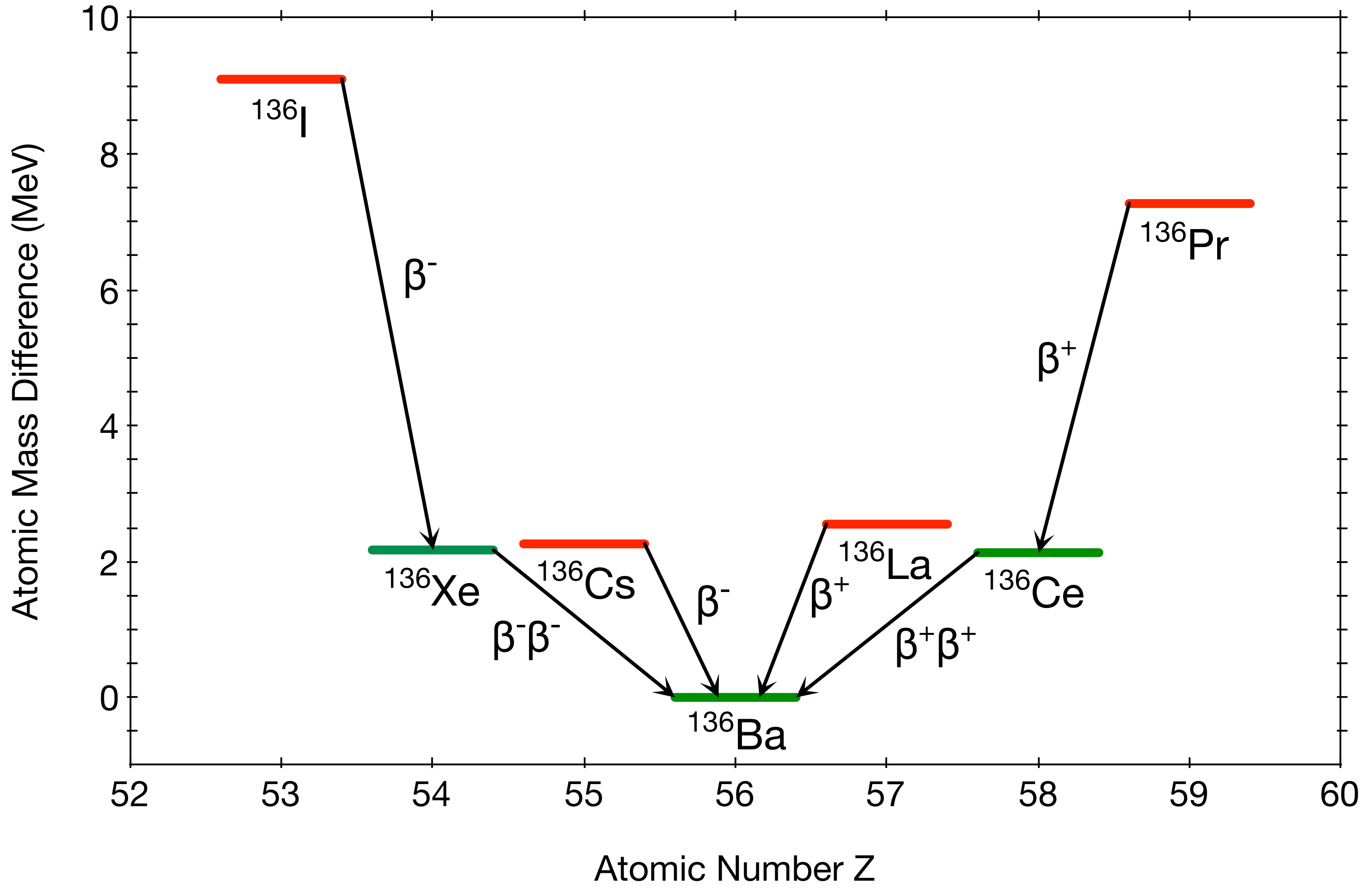
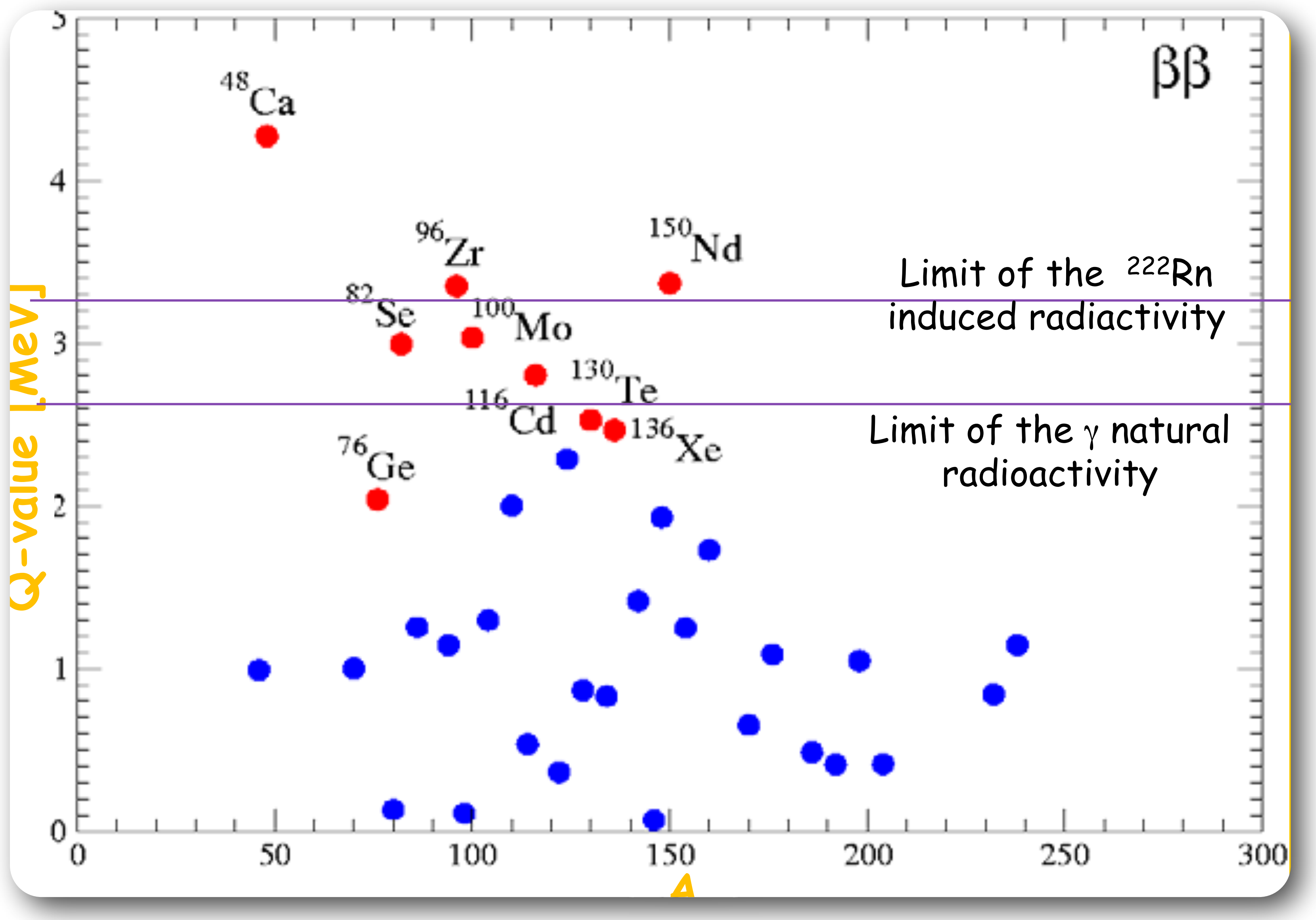


Majorana neutrinos and neutrinoless double beta decay

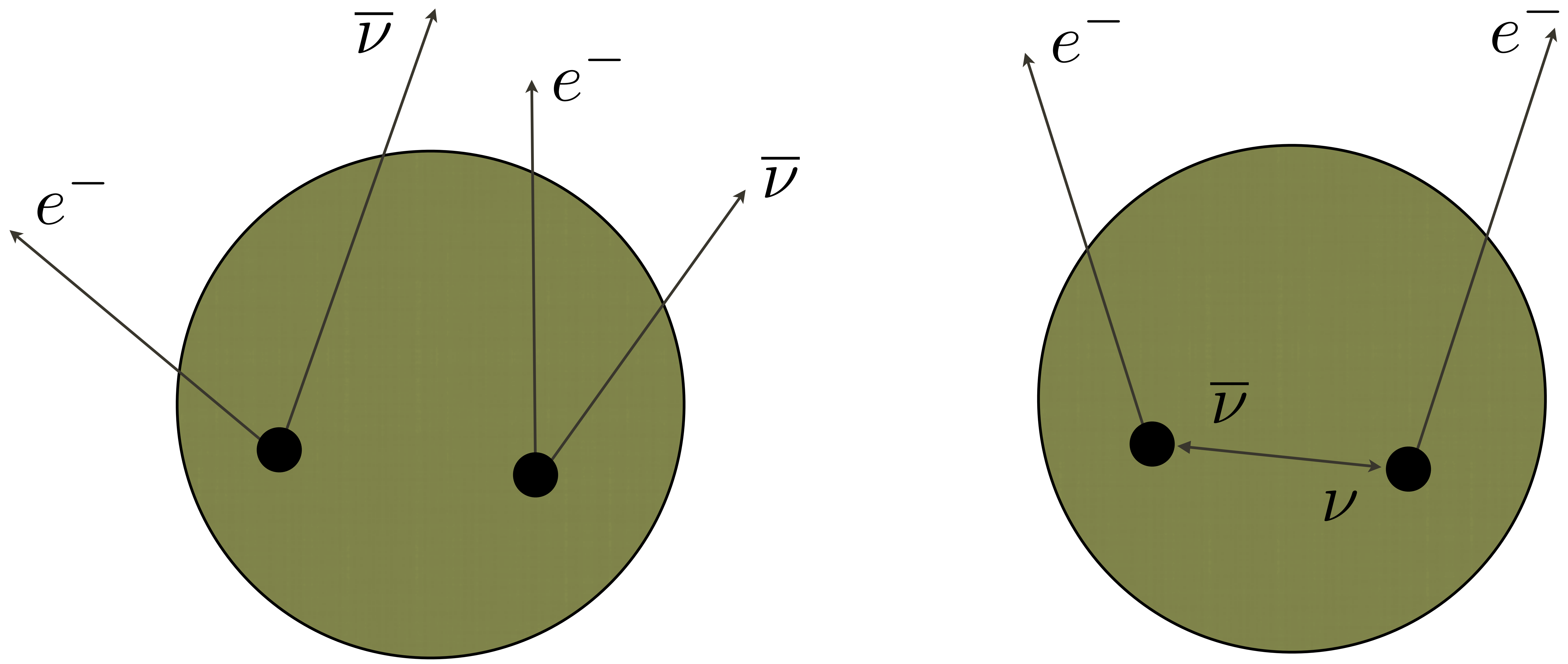
Double beta decay





- Some nuclei, otherwise quasi stable can decay by emitting two electrons and two neutrinos by a second order process mediated by the weak interaction.
- This process exists due to nuclear pairing interaction that favours energetically the even-even isobars over the odd-odd ones.

Double beta decay



$\beta\beta 2\nu$

SM-allowed process.
Measured in several nuclei.

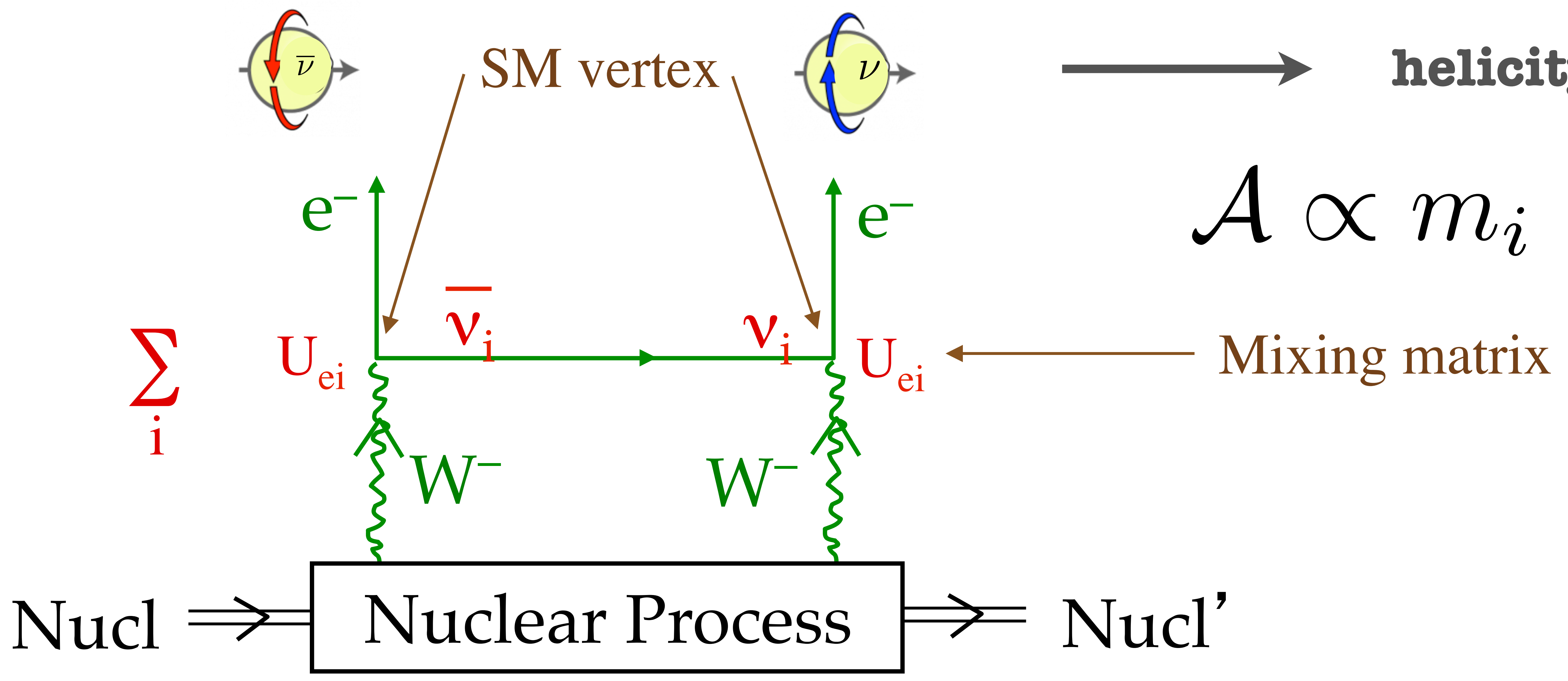
$$T_{1/2} \sim 10^{18} - 10^{20} \text{ y}$$

$\beta\beta 0\nu$

Lepton number violating process.
Requires massive, Majorana neutrinos.

$$T_{1/2} > 10^{26} y$$

Majorana mass



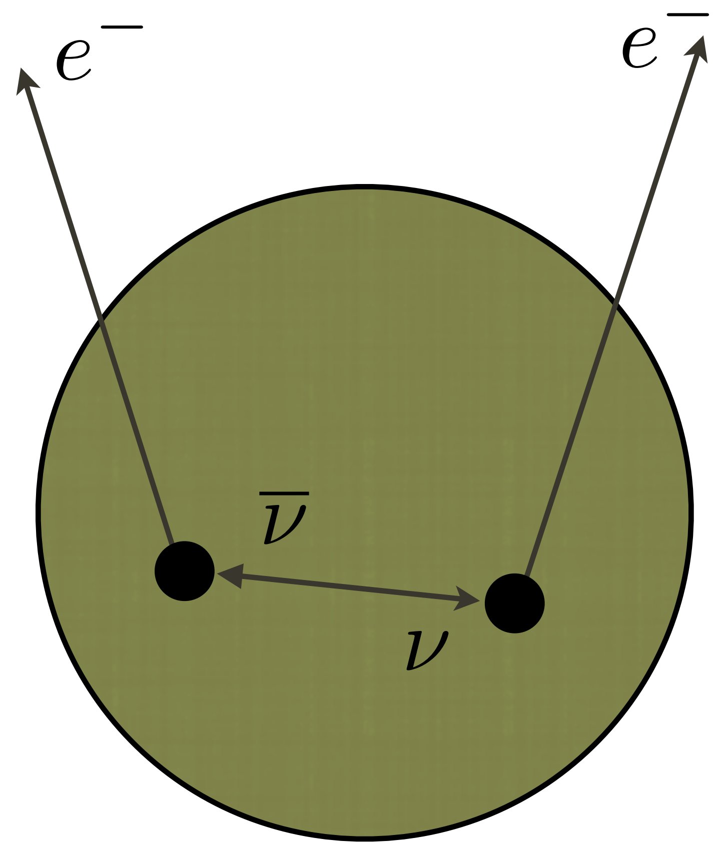
→ **helicity flip** $\propto \dfrac{m_i}{E}$

$\mathcal{A} \propto m_i$ **for each** ν_i

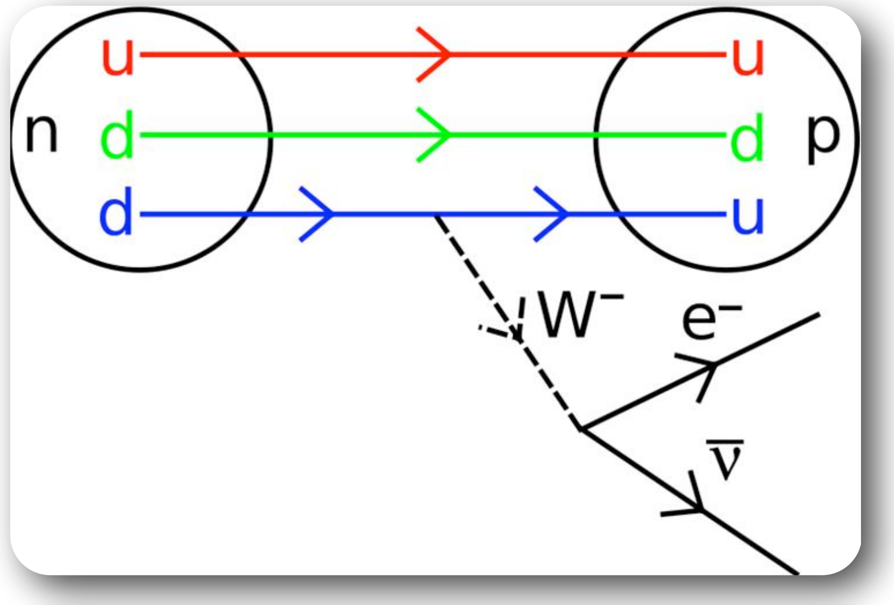
$$m_{\beta\beta} = ||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3|$$

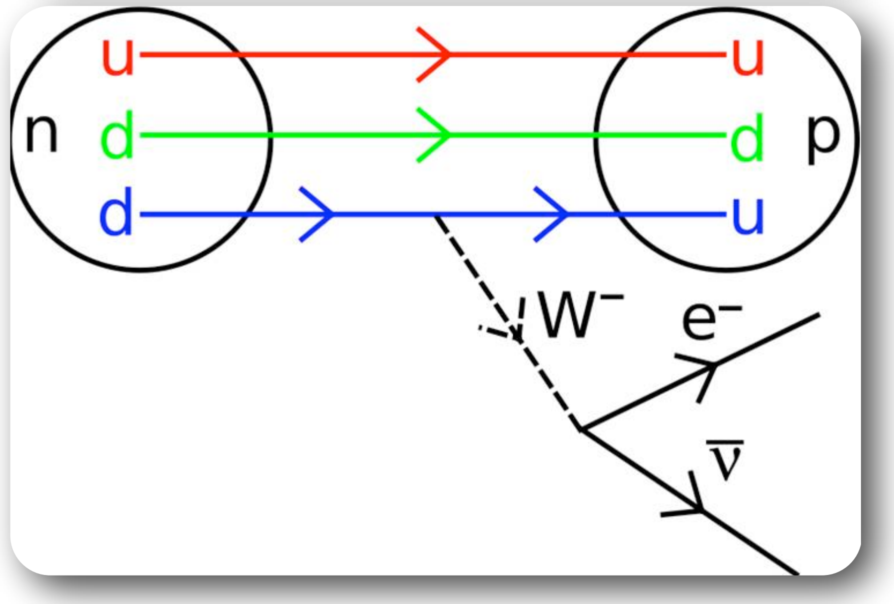
The U_{ei} terms are measured by neutrino oscillation experiments. Nothing is known about the two Majorana phases.

Nuclear physics



$\beta\beta0\nu$





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

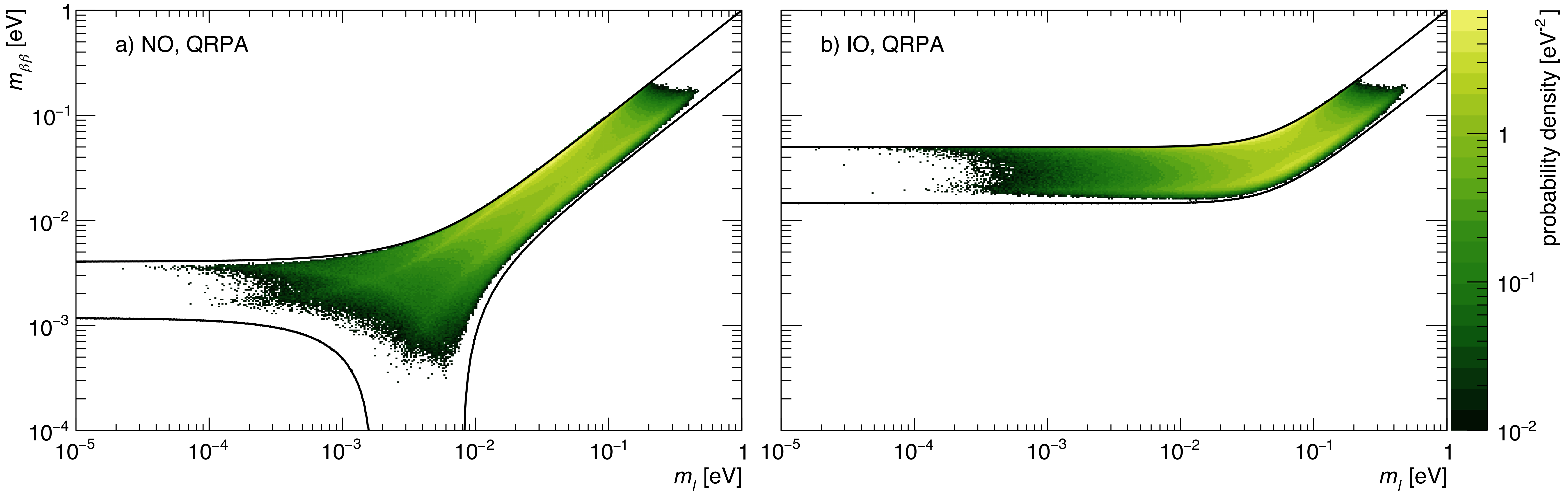
phase-space

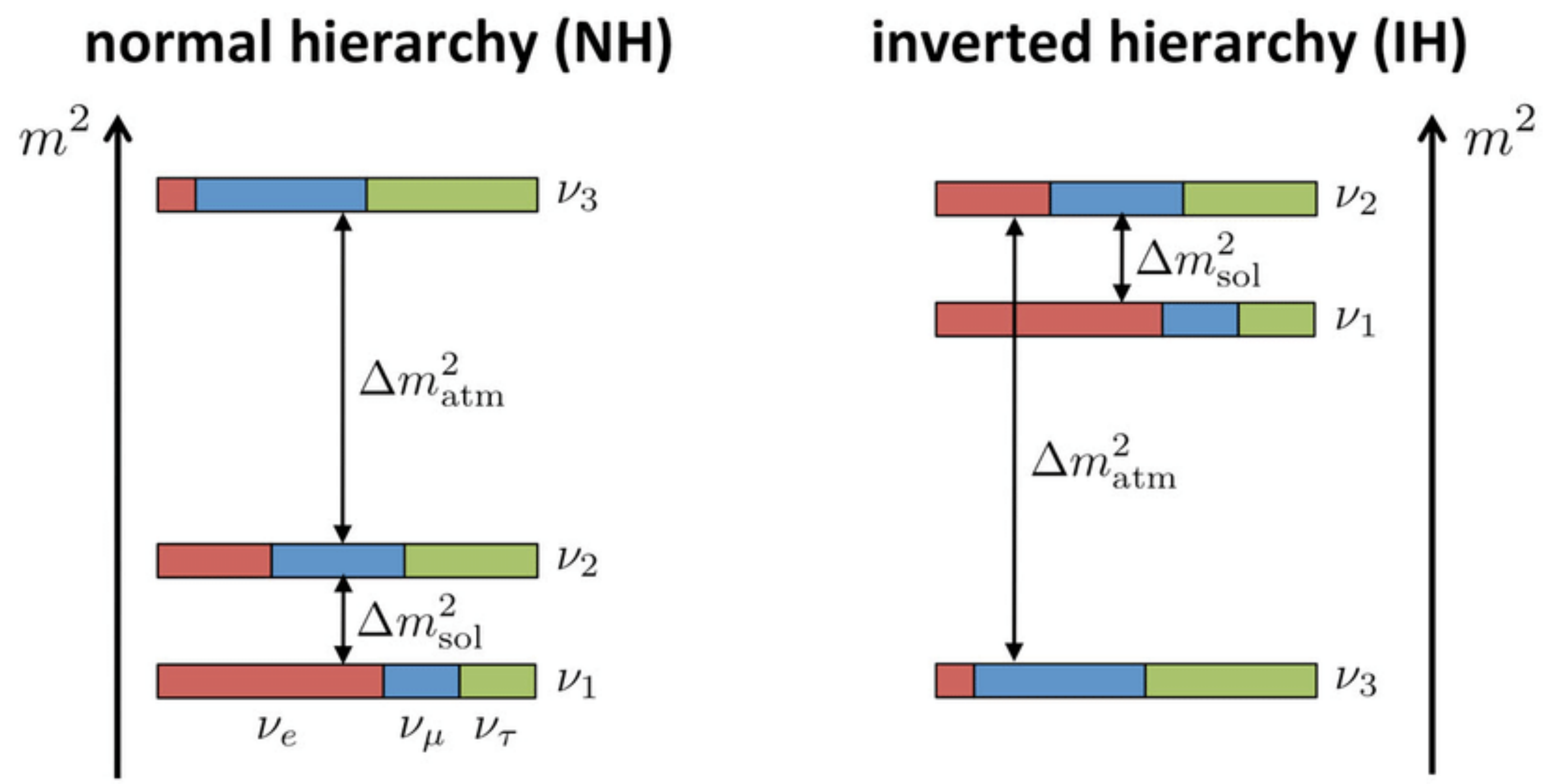
nuclear matrix

Majorana neutrino

Two protons decay simultaneously in a heavy isotope
Nuclear physics results in proportionality constants between period and the inverse of the Majorana mass squared

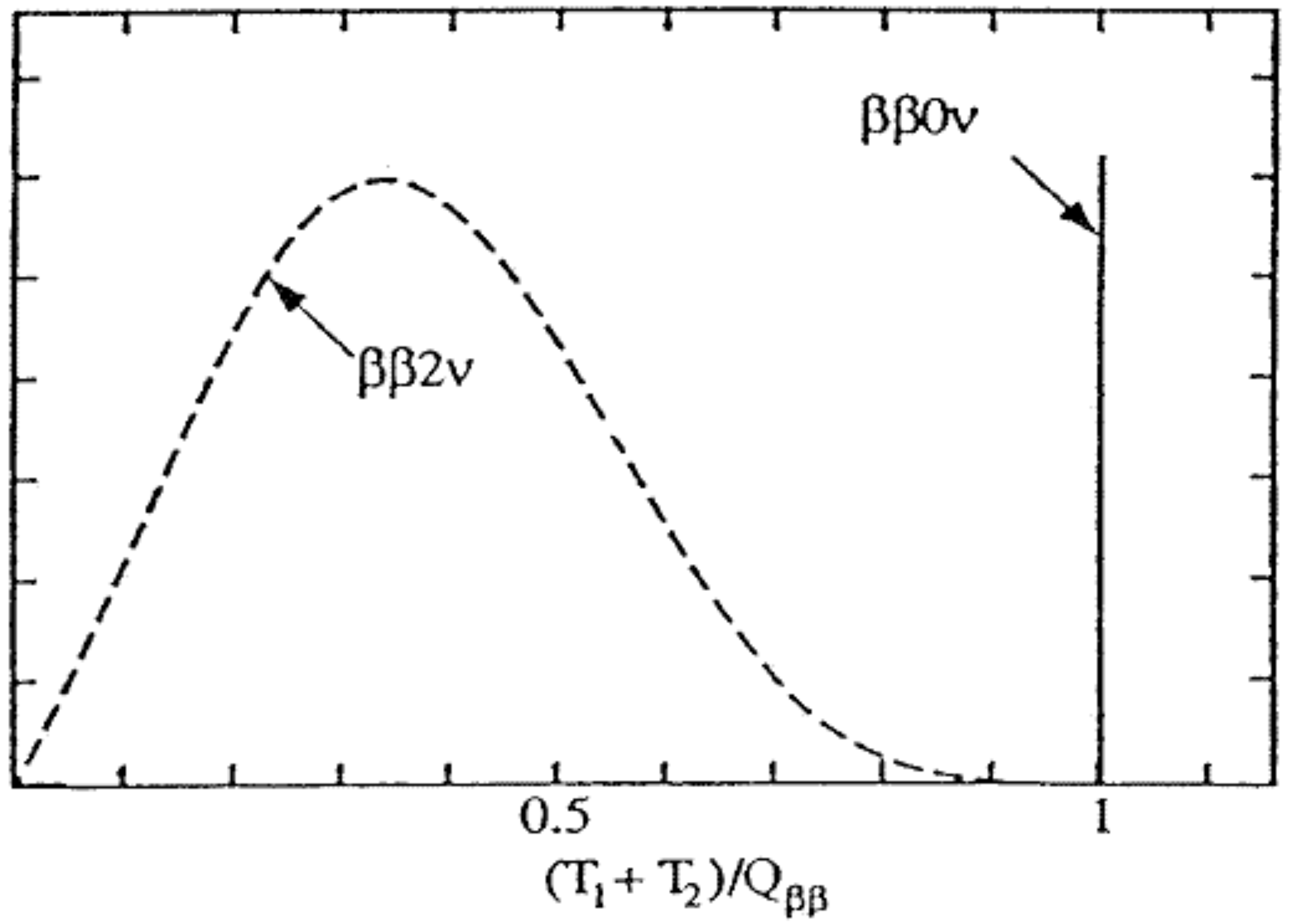
The Majorana landscape





A Most Difficult Quest

An ideal ββ0ν experiment



- Get yourself a detector with perfect energy resolution
- Measure the energy of the emitted electrons and select those with (T1+T2)/Qbb = 1
- Count the number of events and calculate the corresponding half-life.
- In Xe-136, a perfect detector of 100 kg observes 3 events for a lifetime of 10^{26} y (or about 1 event for 30 % efficiency)

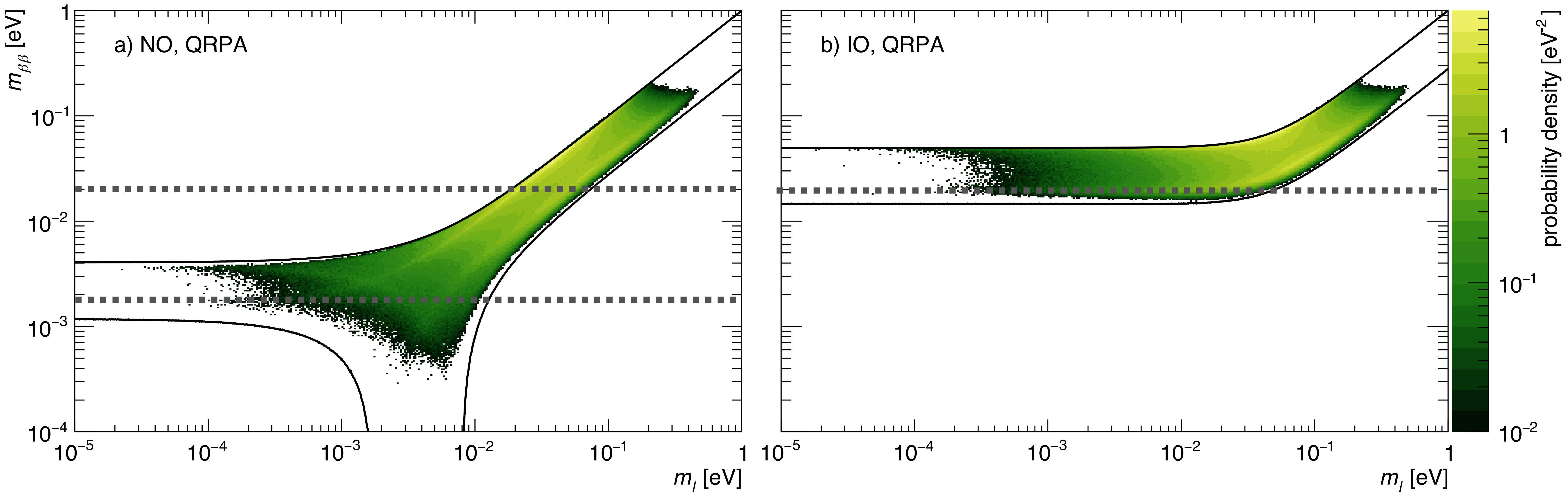
$$T_{1/2} = \log 2 \; \frac{N_A \; Mt}{A \; N_{\beta\beta}}$$

$$M = 100 \; kg, \; A = 136, \; T_{1/2} = 10^{26} y \; N_{\beta\beta} \sim 3$$

- A perfect detector makes a discovery (1 event) with an exposure of 1 ton year for 10^{27} y
- A perfect detector makes a discovery (1 event) with an exposure of 10 ton year for 10^{28} y

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

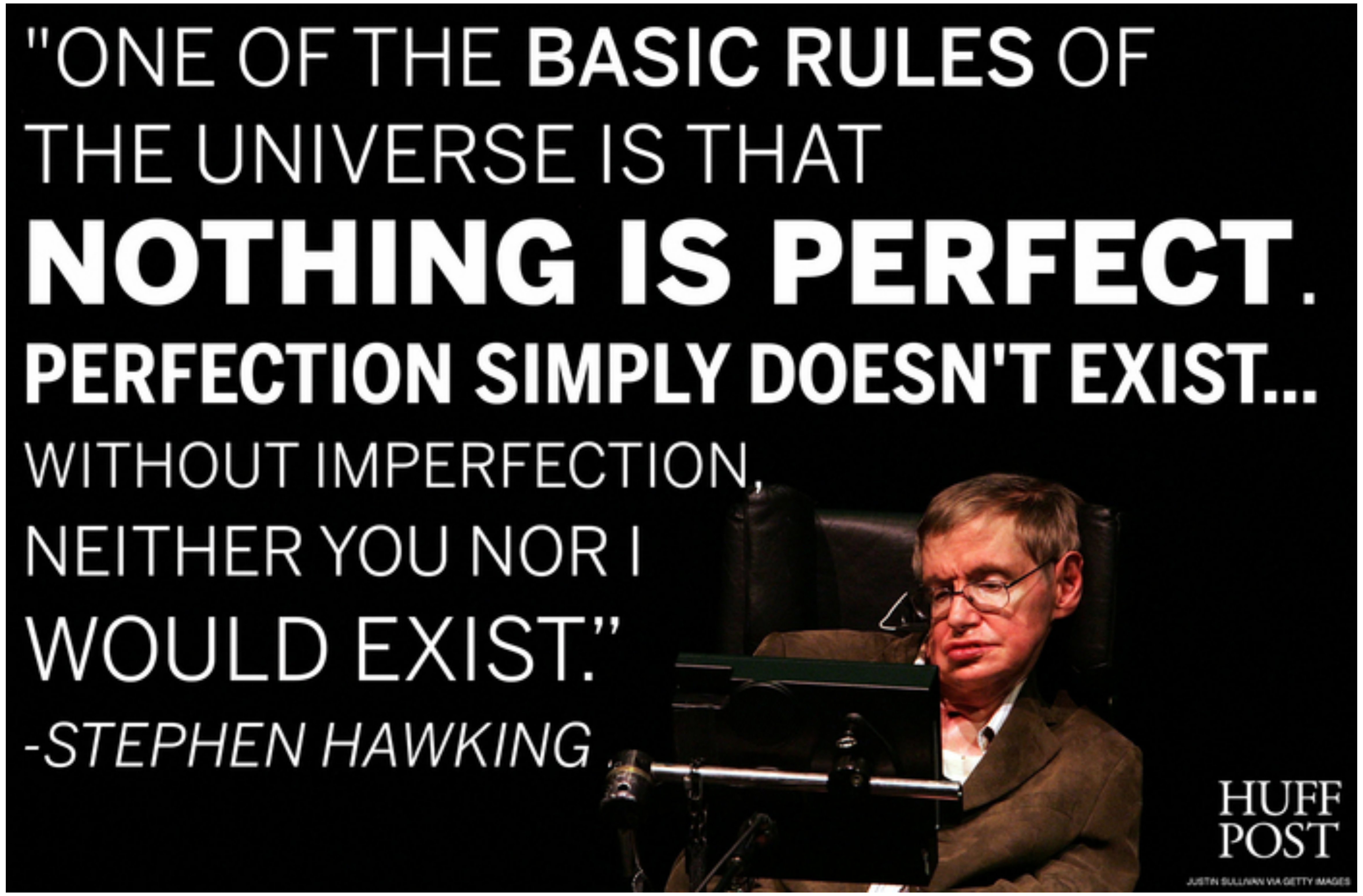
•Will not discuss here “details” like phase space (which favours some isotopes over others) or the uncertainties in nuclear matrix elements (which introduce huge uncertainties).

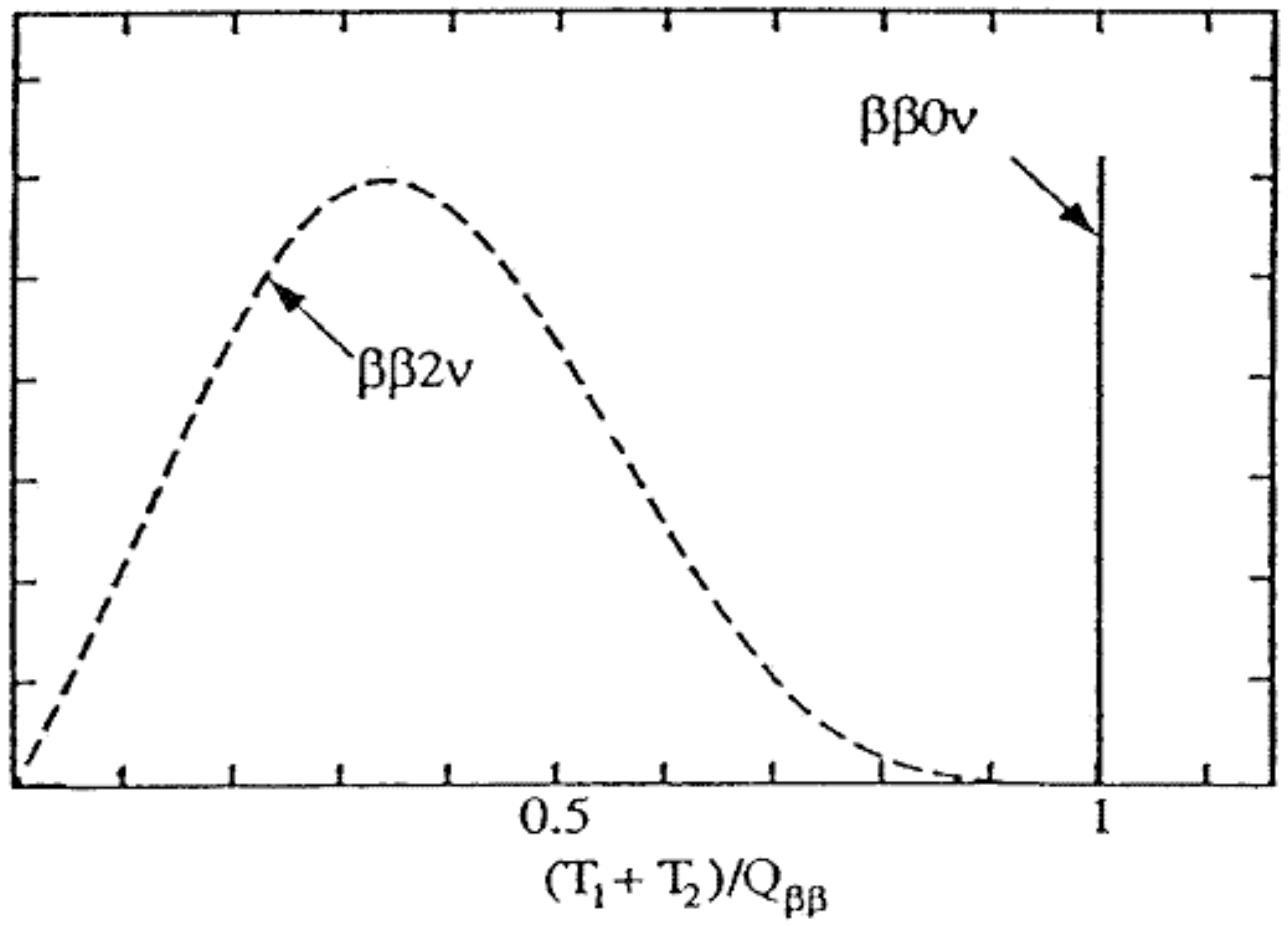


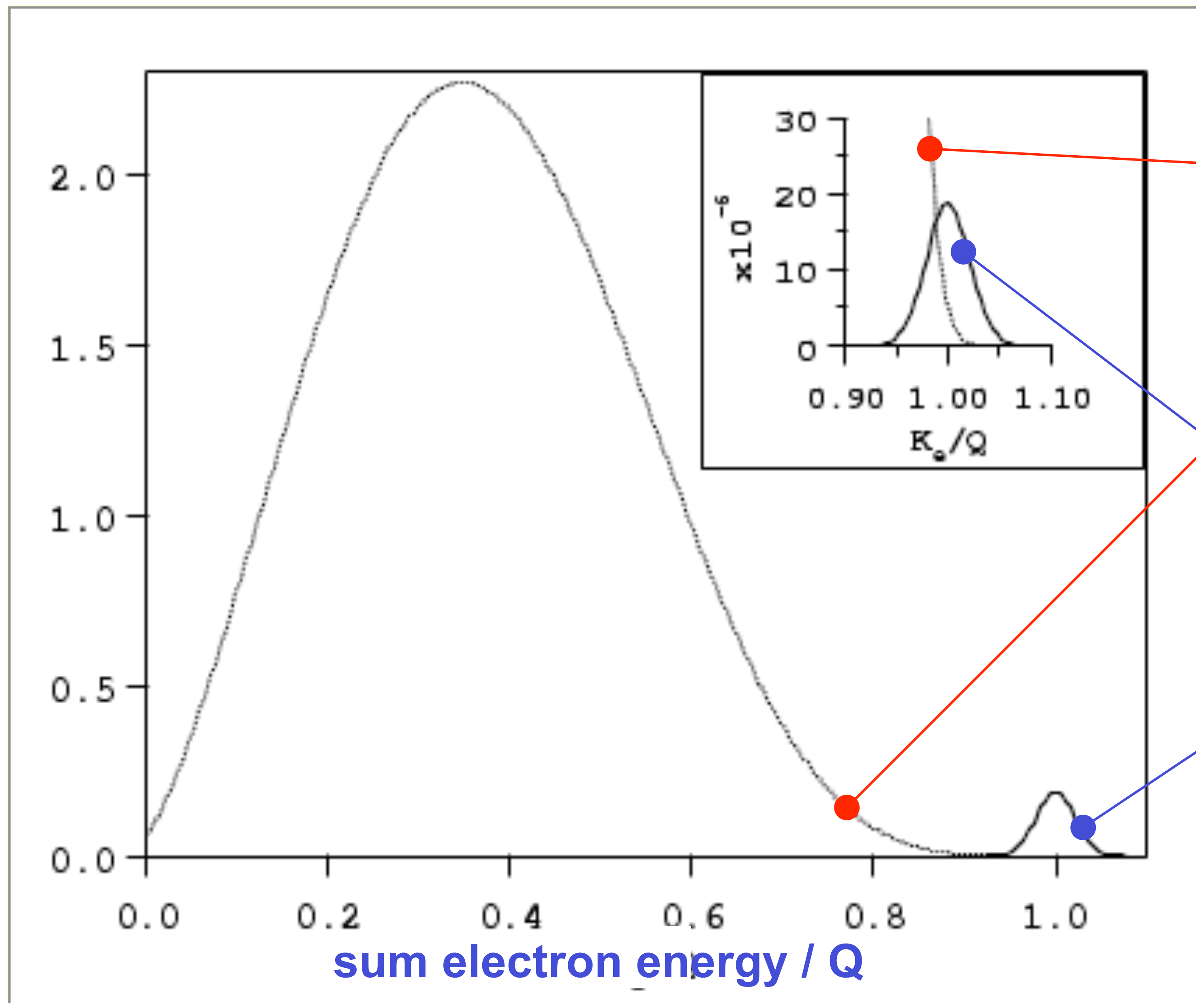
•A perfect detector makes a discovery (1 event) with an exposure of 1 ton year for 10^{27} if neutrinos are Majorana particles, the bb0nu is mediated by light neutrinos and Nature has chosen IO (IH)

•A perfect detector has a large chance of making a discovery (1 event) with an exposure of 1 ton year for 10^{28} if neutrinos are Majorana particles, the bb0nu is mediated by light neutrinos and Nature has chosen NO (NH)

Result 1: **even with a perfect detector**, searching for $\beta\beta0\nu$ events is extremely difficult **if nature has chosen** (as it appears very likely) **NH**

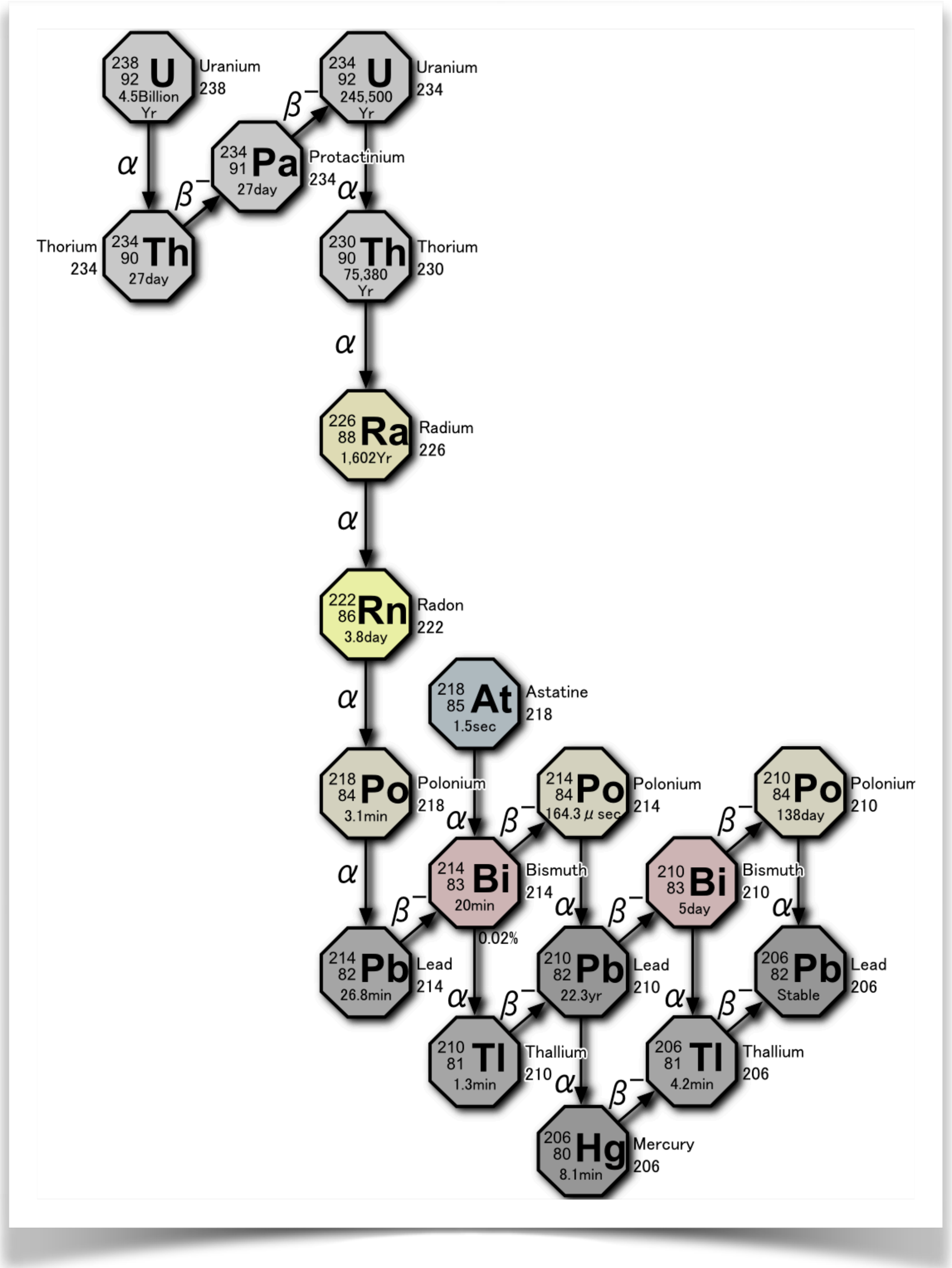


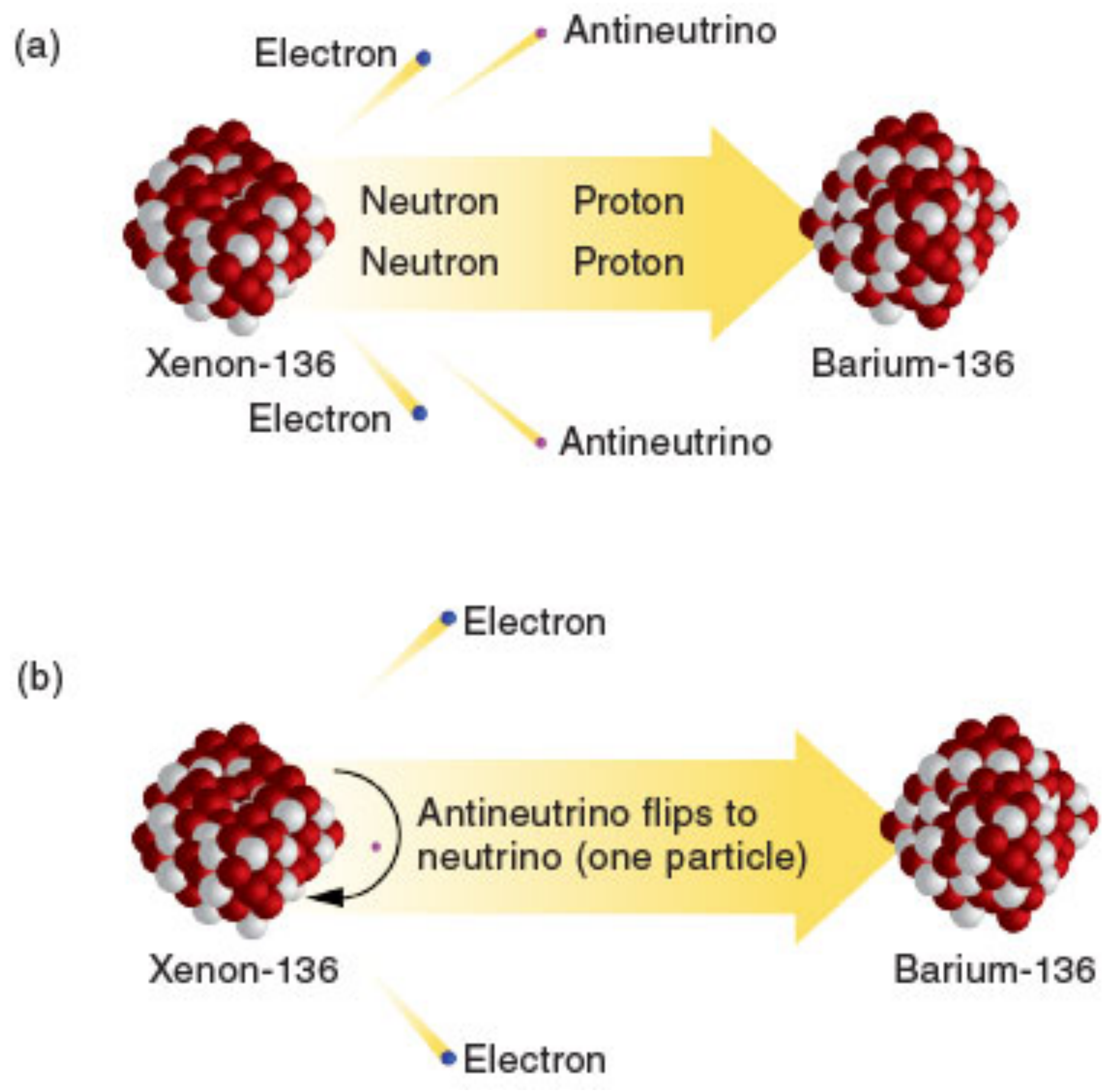




- But perfect detectors do not exist.
- Best energy resolution (GERDA/LEGEND): few keV
- Still, a narrow energy window results in enormous background reduction
- But how large is the background to our searches?

Background to $\beta\beta0\nu$ searches





ββ0ν experiments aim to observe a signal whose lifetime is 10^{27} (10^{28}) y

Lifetime Bkgnd/Signal ~10^{17} (10^{18})

Earth is a very radioactive planet

Lifetime of Th-232 is of the oder of the age of the Universe (~1.4 10^{10} y)

Majorana’s beach

https://www.quora.com/How-many-grains-of-sand-are-there-in-a-given-stretch-of-an-average-beach

- Majorana’s beach: A beach with 10^{17} grains of sand.
- About 1.5×10^9 per square meter (to a depth of 3 m).
- Thus, Majorana’s beach is 70 km long and 1 km wide.

Background ruins the sensitivity

DBD experimental rate

number of nuclides under control

live time

number of detected decays

$$\tau = \frac{N_N \bullet T}{N_S}$$

If no decay is observed in presence of N_B background events in an energy window ΔE:

detector energy resolution

$$N_S < (N_B)^{1/2} \Rightarrow \tau > \frac{N_N \bullet T}{(N_B)^{1/2}}$$

sensitivity F: lifetime corresponding to the minimum detectable number of events over background at a given (1 σ) confidence level

in the calorimetric approach $N_B = b\,M\,T\,\Delta E \qquad N_N \propto M$

background level

$$F \propto (MT / b\Delta E)^{1/2}$$

importance of the nuclide choice
(but large uncertainty due to nuclear physics)

$$\text{sensitivity to } m_{ee} \propto (F/Q\,|M_{nucl}|^2)^{1/2} \propto \frac{1}{Q^{1/2}\;|M_{nucl}|}\left[\frac{b\Delta E}{MT}\right]^{1/4}$$

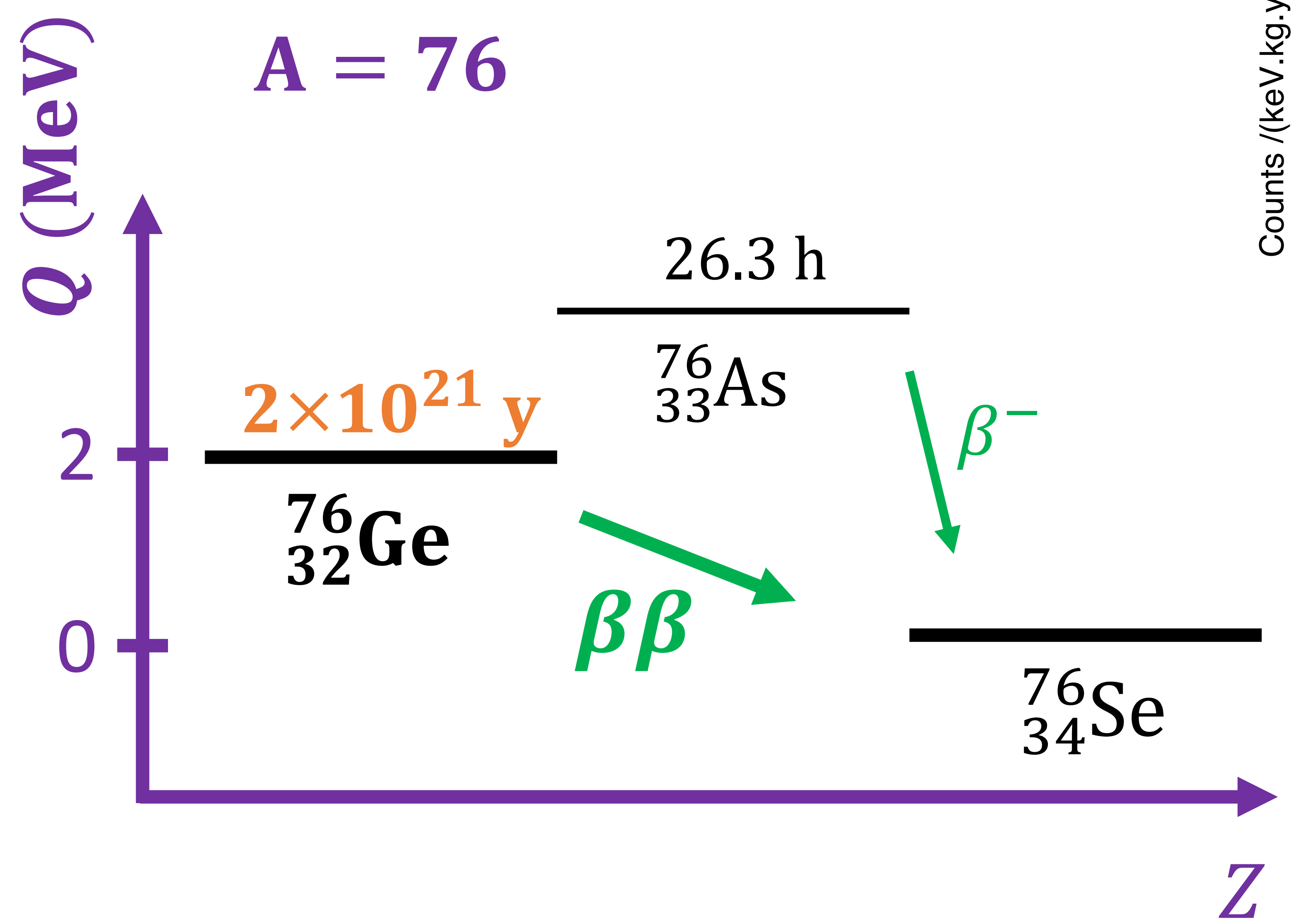
To find the grial **one must kill the dragon** (in practice, **reaching 10^{27}-10^{28} y requires large exposures and zero background**)

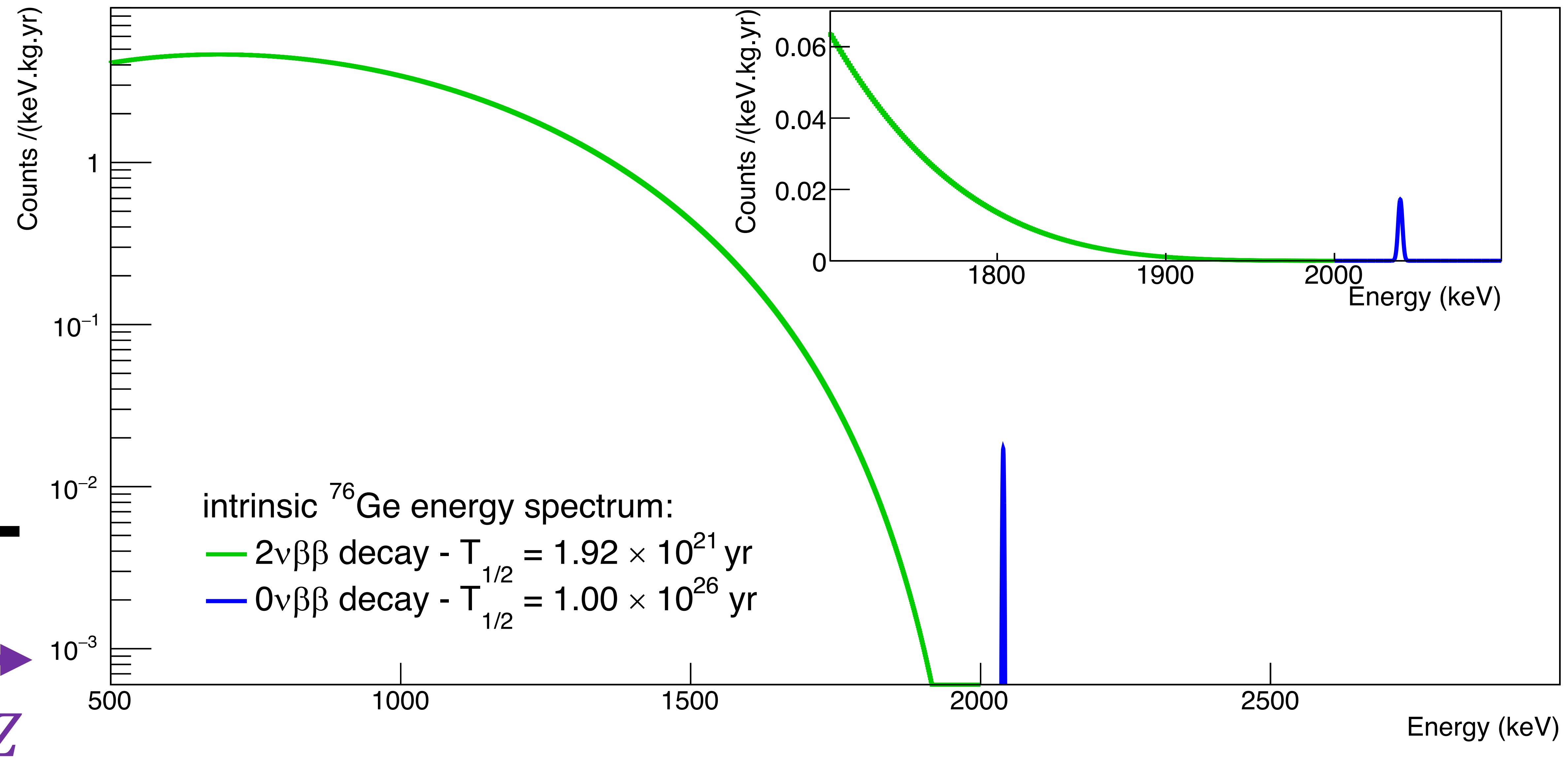
Knights of the round table

Main characters looking for the grail. Each of them have unique abilities (and weaknesses)

Germanium Diodes
(Gwenivere)

Ge-76 diodes are “near-perfect resolution detectors



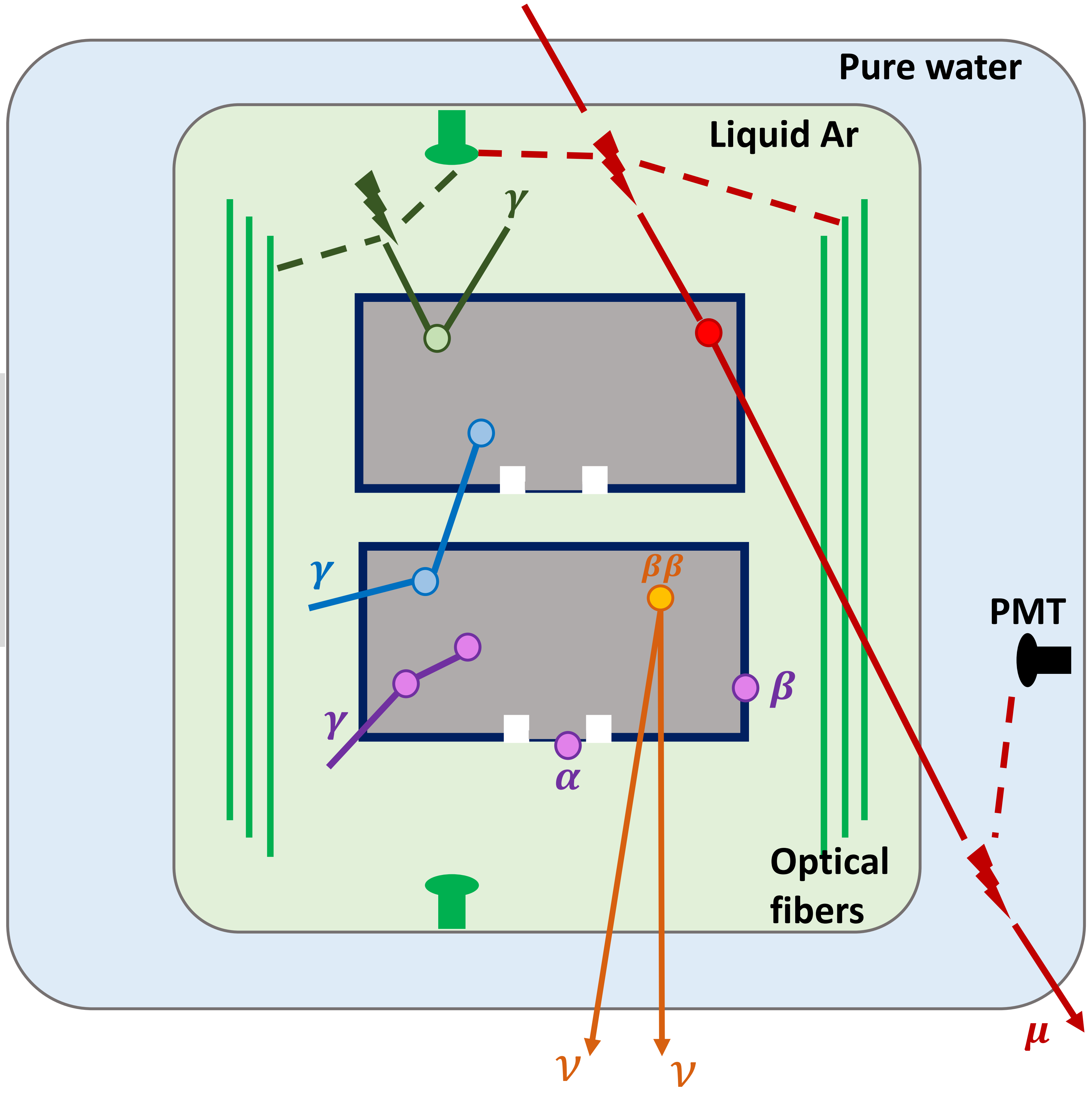


Signature: Expected **line at the ^{76}Ge Q-value** (2039.061 ± 0.007 keV) for a given decay half-life $T^{0\nu}_{1/2}$ above measured $2\nu\beta\beta$ continuum

But they have also many extra handles

- background mitigation

$\beta\beta$ decay signal: single-site event energy deposition in a 1 mm^3 volume



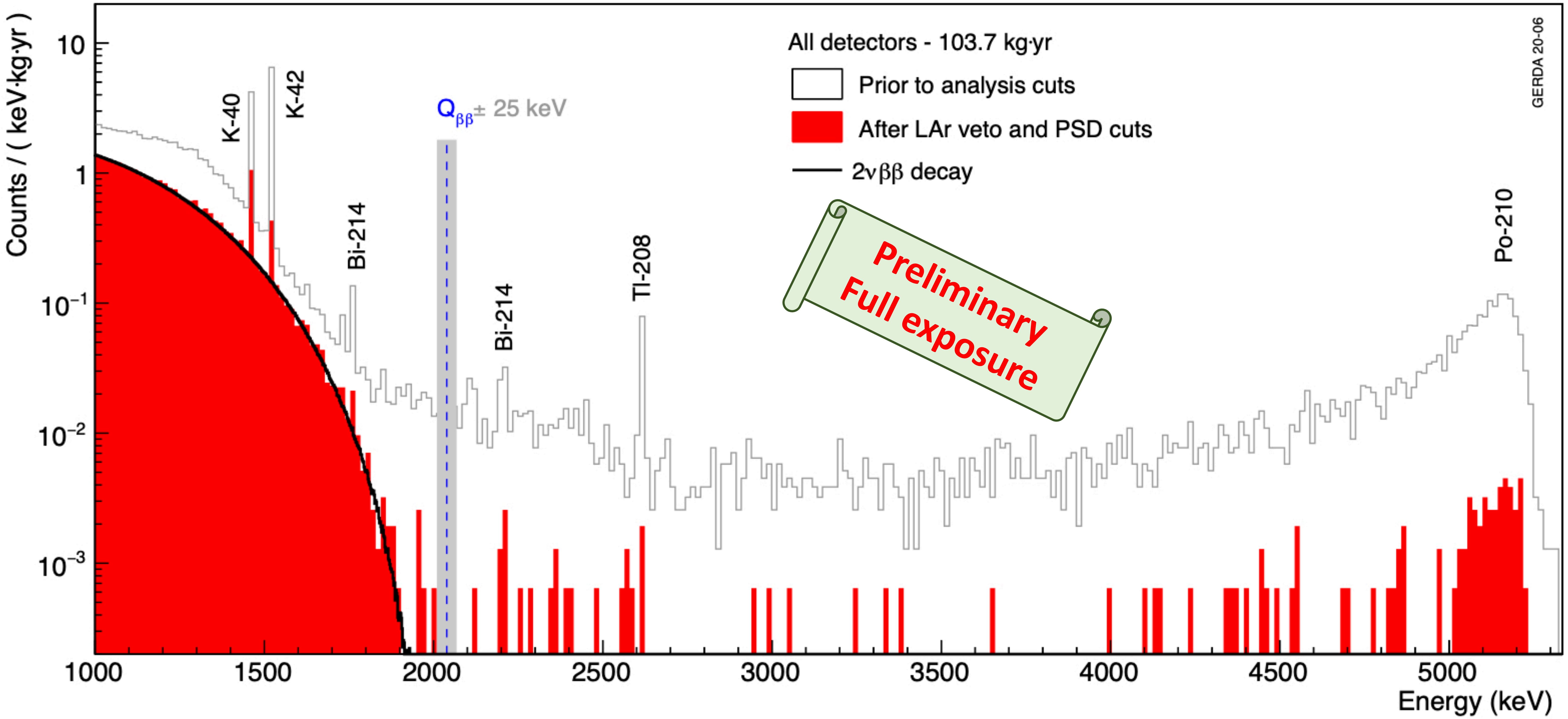
Pulse shape discrimination (PSD) for multi-site and surface α, β events

Ge detector anti-coincidence

LAr veto based on Ar scintillation light read by fibers and PMT

Muon veto based on Cherenkov light and plastic scintillator

Phase II physics spectra after all analysis cuts

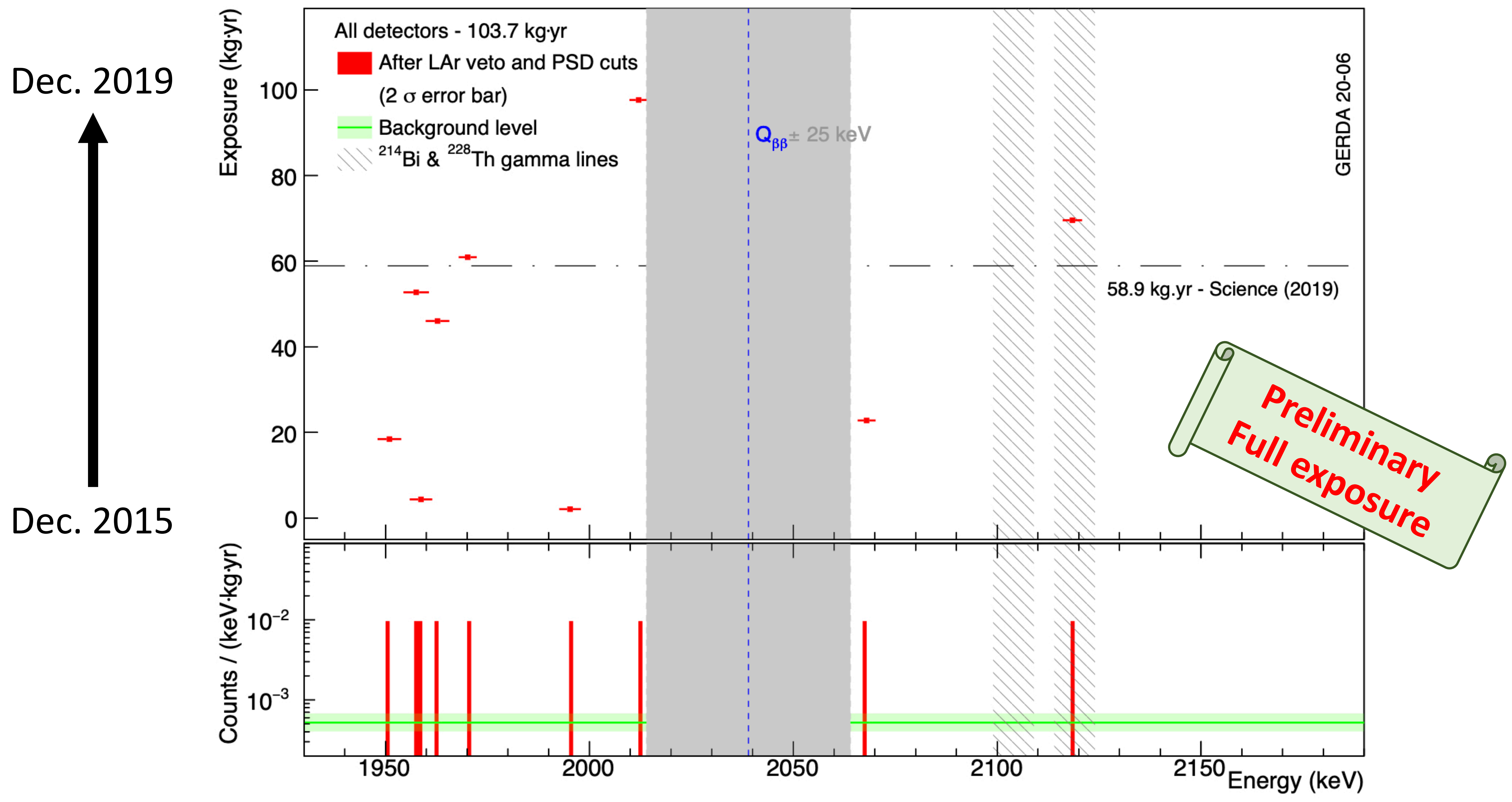


- [600 - 1900] keV – Almost pure $2\nu\beta\beta$ **decays** sample
- [1450 - 1530] keV – Strong suppression of **^{40}K and ^{42}K gamma lines** (LAr veto + MSE)
- [1900 - 2620] keV – Strong suppression of **^{214}Bi and ^{228}Th gamma lines** + Compton
- > 3500 keV – Suppression of almost all α **events** (p+ contact)

- **Extremely powerful complementarity between LAr veto and PSD cuts!**

Zoom around the region of interest

GERDA



- Bkg index (BI) analysis window: [1930-2190] keV with the exclusion of ^{208}Tl SEP and ^{214}Bi FEP lines and $Q_{\beta\beta} \pm 25$ keV
- Prior to analysis cuts, $\mathrm{BI} = 143^{+9}_{-8} \times 10^{-4}\ \mathrm{cts/(keV \cdot kg \cdot yr)}$ $\div$ **30!**
- **After all cuts:** $\mathbf{BI = 5.2^{+1.6}_{-1.3} \times 10^{-4}\ cts/(keV \cdot kg \cdot yr)}$ at the final exposure of $\mathbf{103.7\ kg \cdot yr}$

- **100 kg -> ~10^{26} y, "background free" in the 100 kg scale.**
- **How to keep BF when scaling one (two) orders of magnitude?**
- **e.g., how to reduce the background by two additional orders of magnitude?**

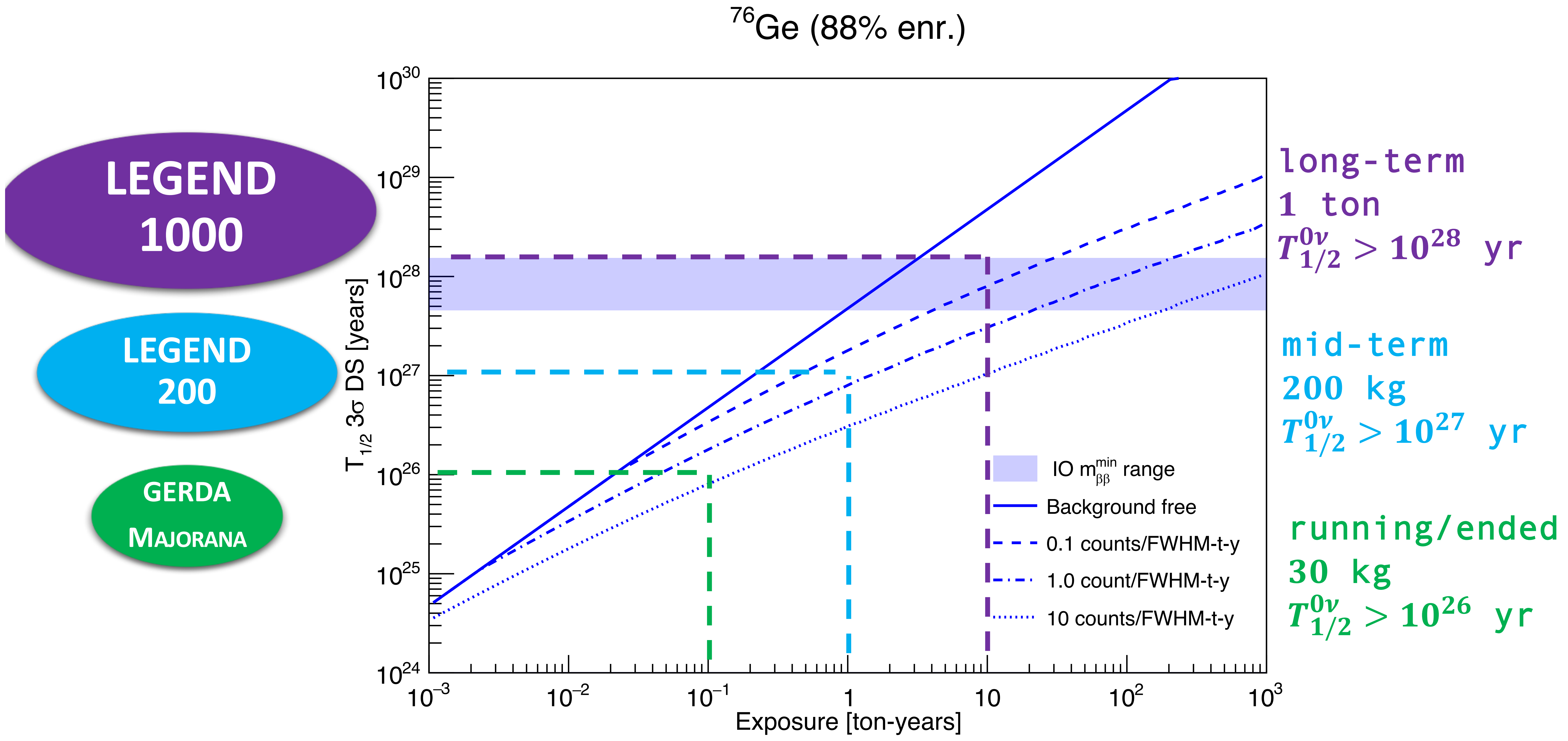
Frequentist analysis*:

- Median sensitivity for limit setting:
  $\mathbf{1.8 \times 10^{26}\ yr\ (90\%\ C.L.)}$
  - Best fit → no signal

Bayesian analysis with uniform prior*:

- Median sensitivity for limit setting:
  $1.4 \times 10^{26}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$
- $T^{0\nu}_{1/2} > 1.4 \times 10^{26}\ \mathrm{yr}\ (90\%\ \mathrm{C.I.})$

Exploring IH(NH) is very difficult



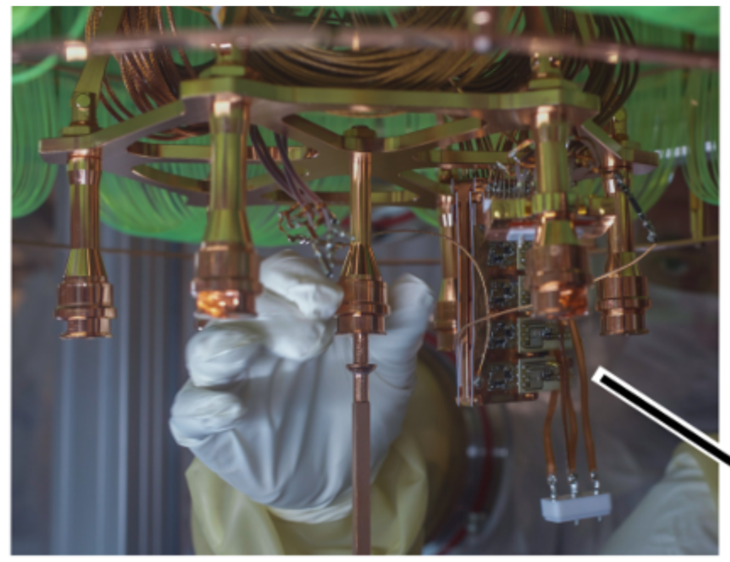
- **Huge challenge! And this is one of the leading experiment of the field, combining the best resolution and the best BI of the current generation.**

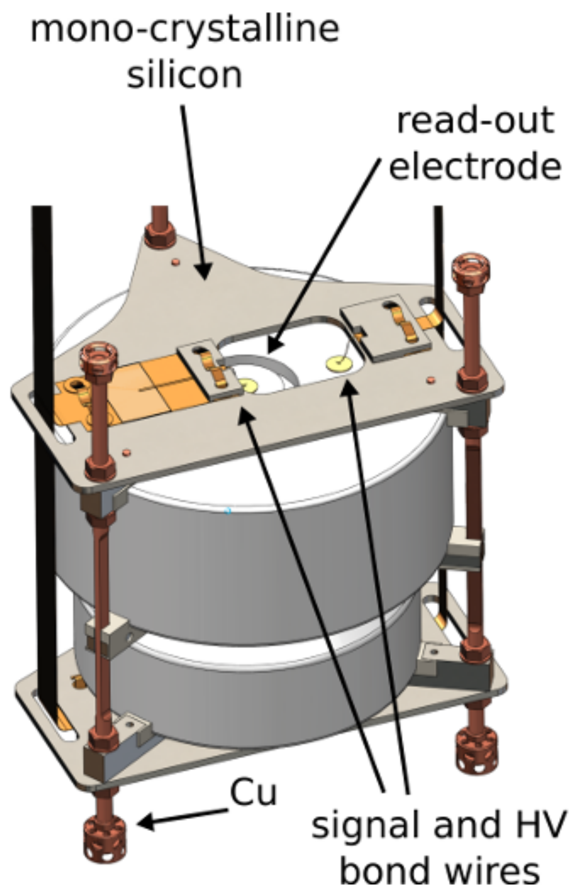
- **Notice brutal dependence with bkgnd.**
- **“BF” requires “only” 2 ton year to reach 10^{28} y and opens the possibility or reaching further.**
- **0.1 c/FWHM-t-y implies that 20 tons year are needed to reach 10^{28} y and makes very hard further progress**
- **1 c/FWHM-t-y implies 200 tons year to reach 10^{28} y (making it unrealistic)**

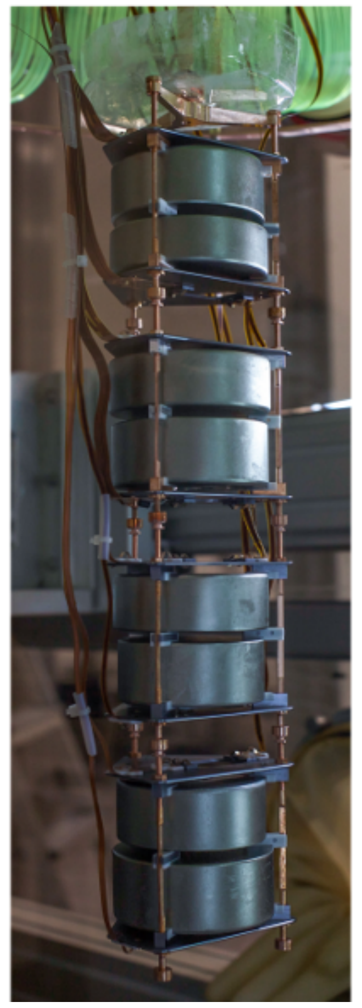
Result 2: **Background rate near zero is required to reach 10^{28} y** in a reasonable time (with large fiducial mass). But even if you achieve such stupendous result: **¿How will you quantify your error in the background?**

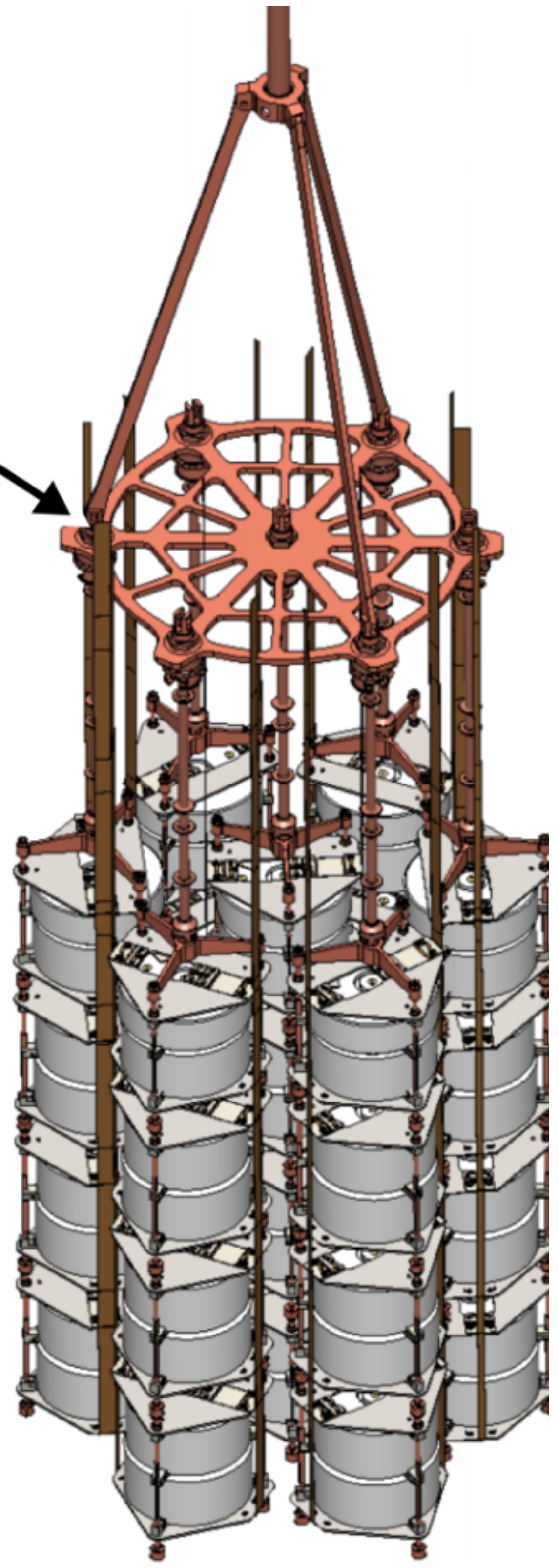
The scaling problem in Ge diodes

- produced 30 custom-designed BEGe-type detectors in collaboration with Canberra [EPJC 75 (2015) 39]
- new lower mass holders and contacting solution (wire bonding)
- all BEGe installed in the array (20 kg of target mass)
- new low-mass low-activity electronics and detector-to-FE contacts







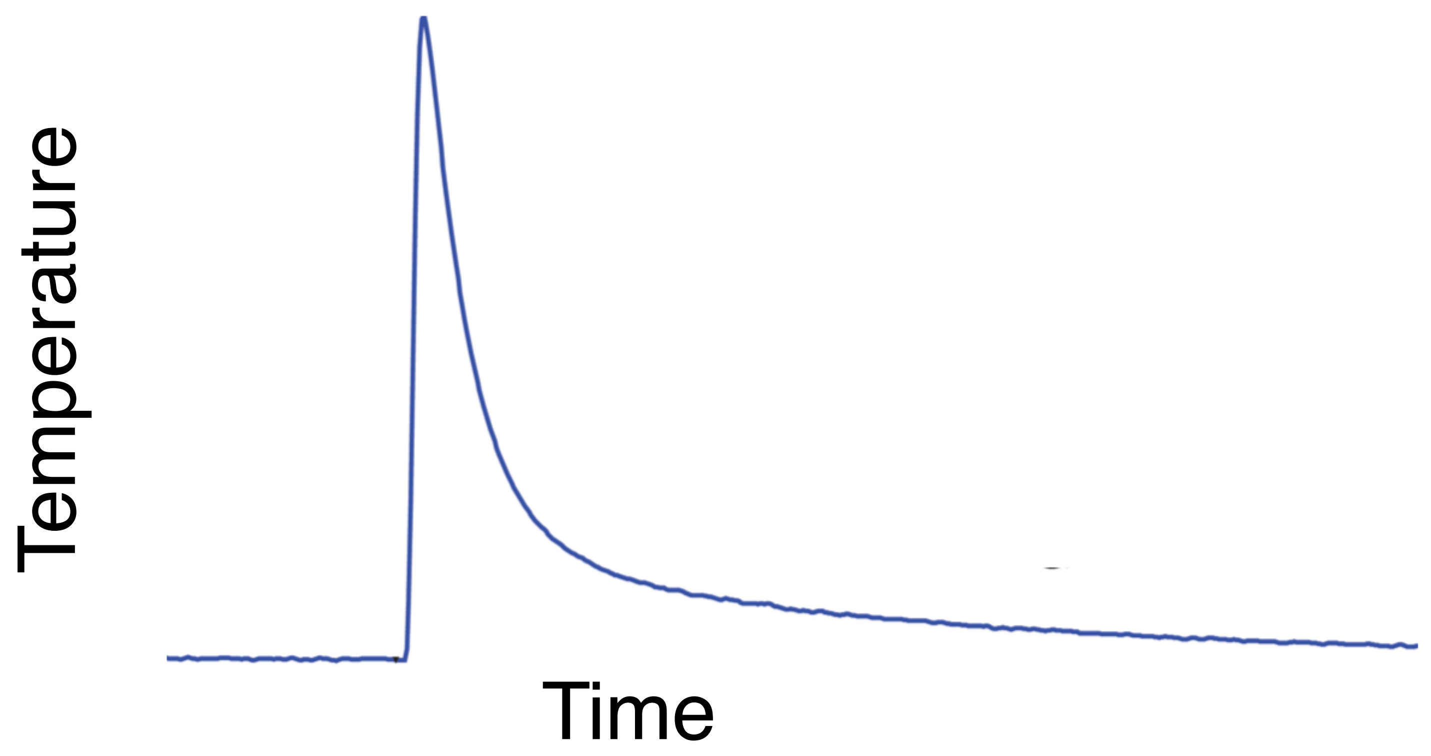


- **Detector build by module repetition.**
- **Scalability to large masses is difficult (also expensive because of enrichment)**
- **Is there a high-resolution technique that permits easier scaling?**
- **An additional motivation to search for another high-resolution technique is to explore different isotopes.**

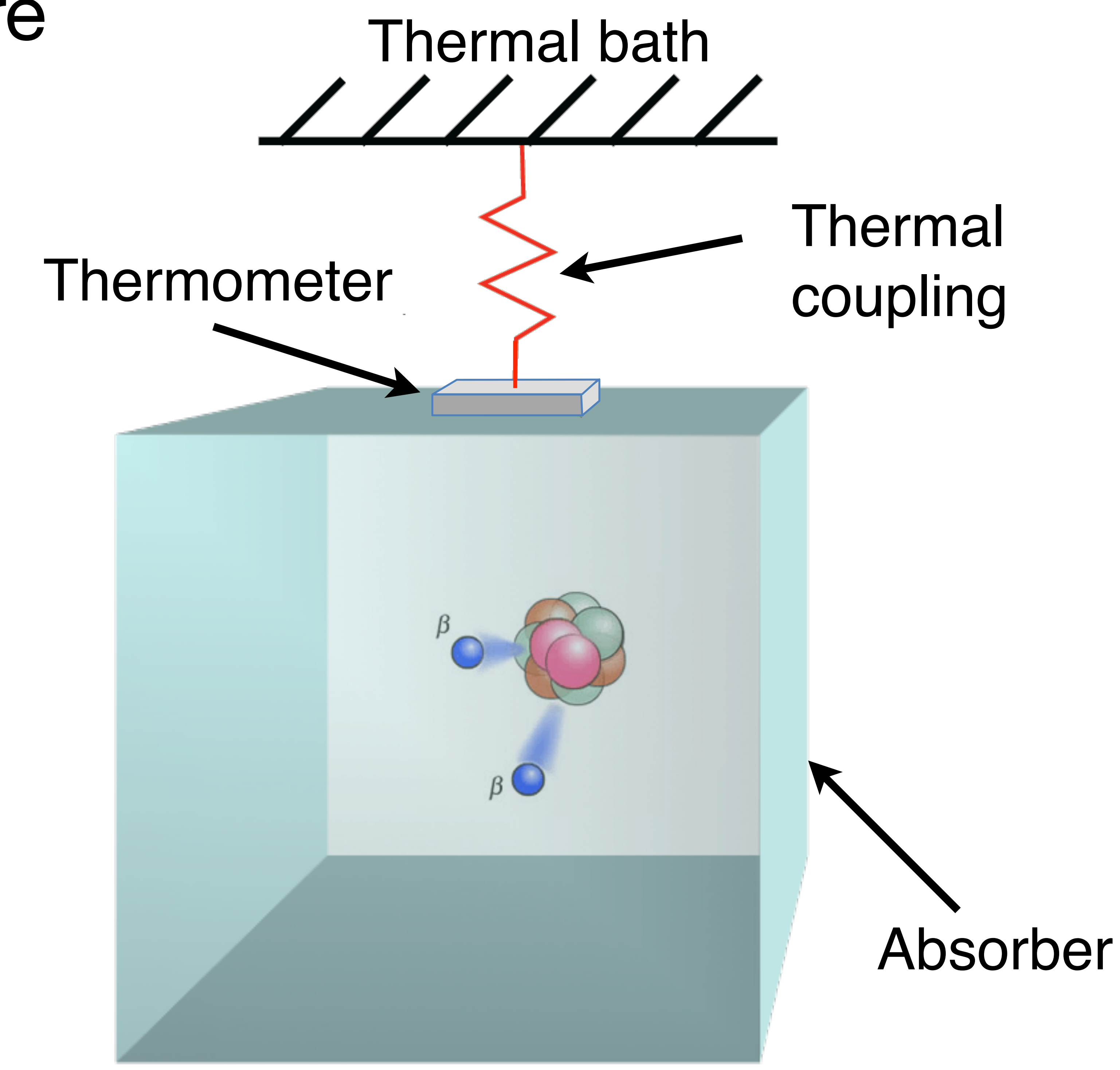
Bolometers
(Gallahad)

Macro Bolometer Technique

- The absorbed energy causes an increase in absorber temperature
- Use temperature change to measure energy absorbed

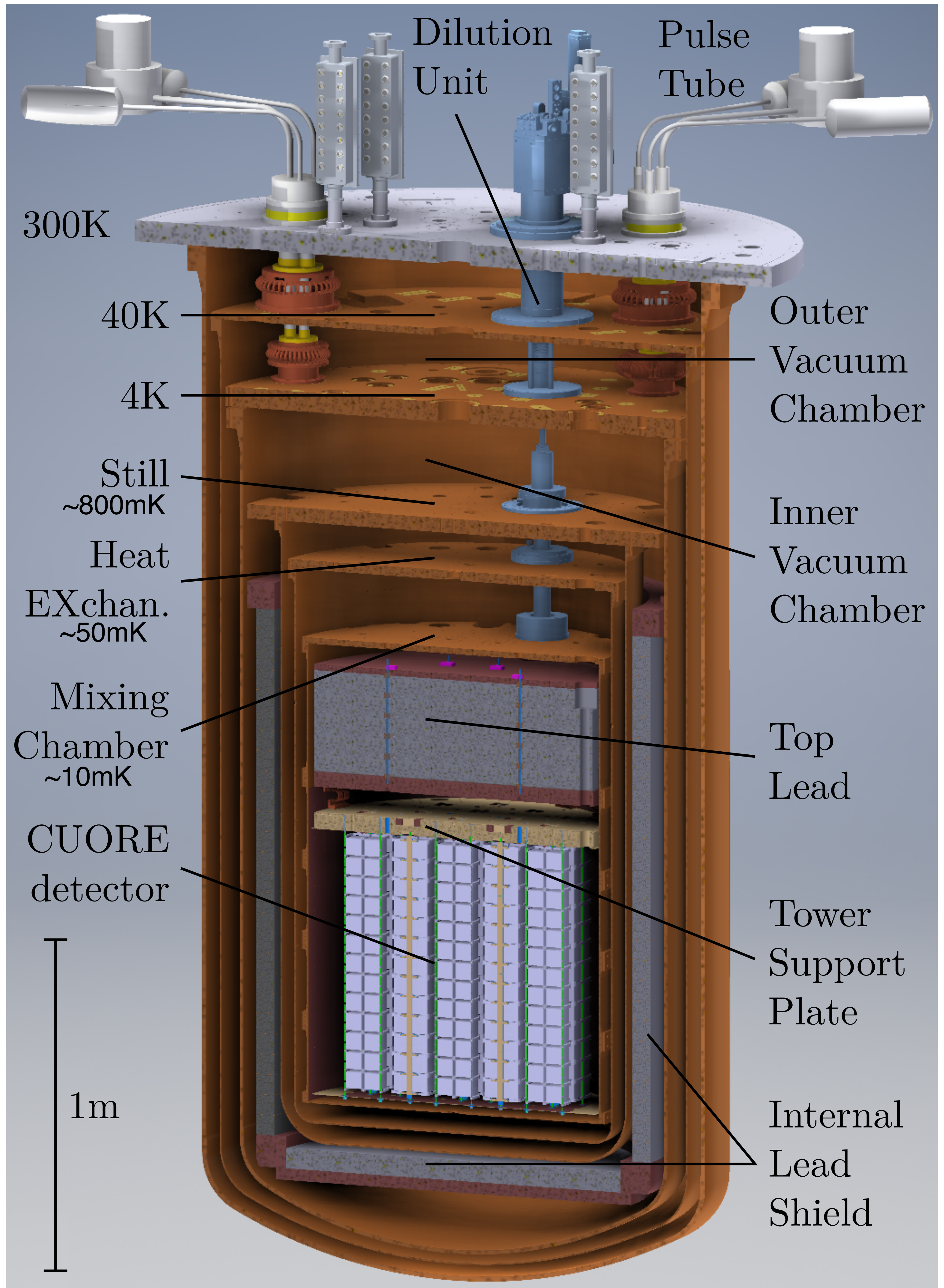


- For dielectric crystal absorbers, heat capacity $\sim T^3$
- Typically operated at ~10mK
- Relative energy resolution of 0.2~0.3% FWHM routinely achieved

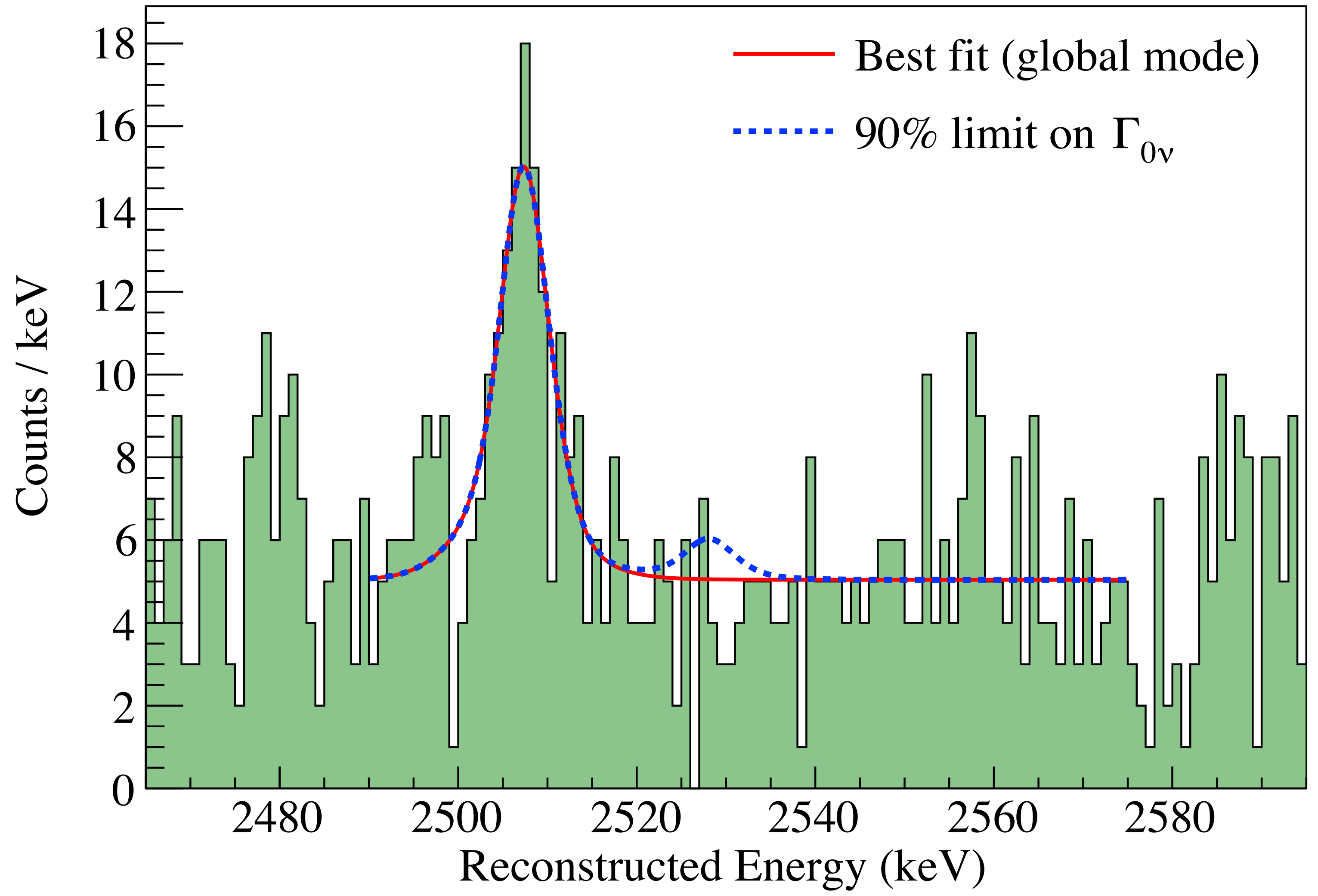


CUORE uses this technique

Cuore: the coldest m³ of the known universe



CUORE ROI Spectrum



Detector Performance Parameters

Background Index

$$(1.38 \pm 0.07) \times 10^{-2} \text{cnts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$$

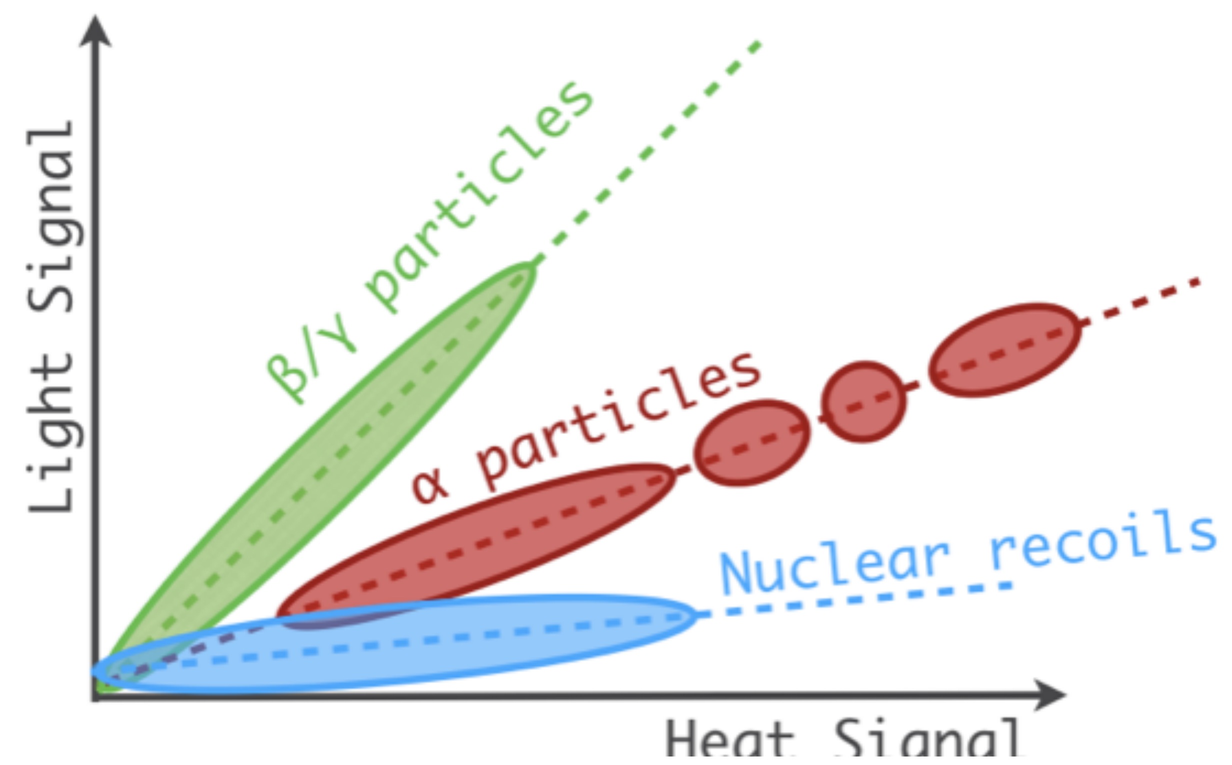
Characteristic FWHM ΔE at $Q_{\beta\beta}$

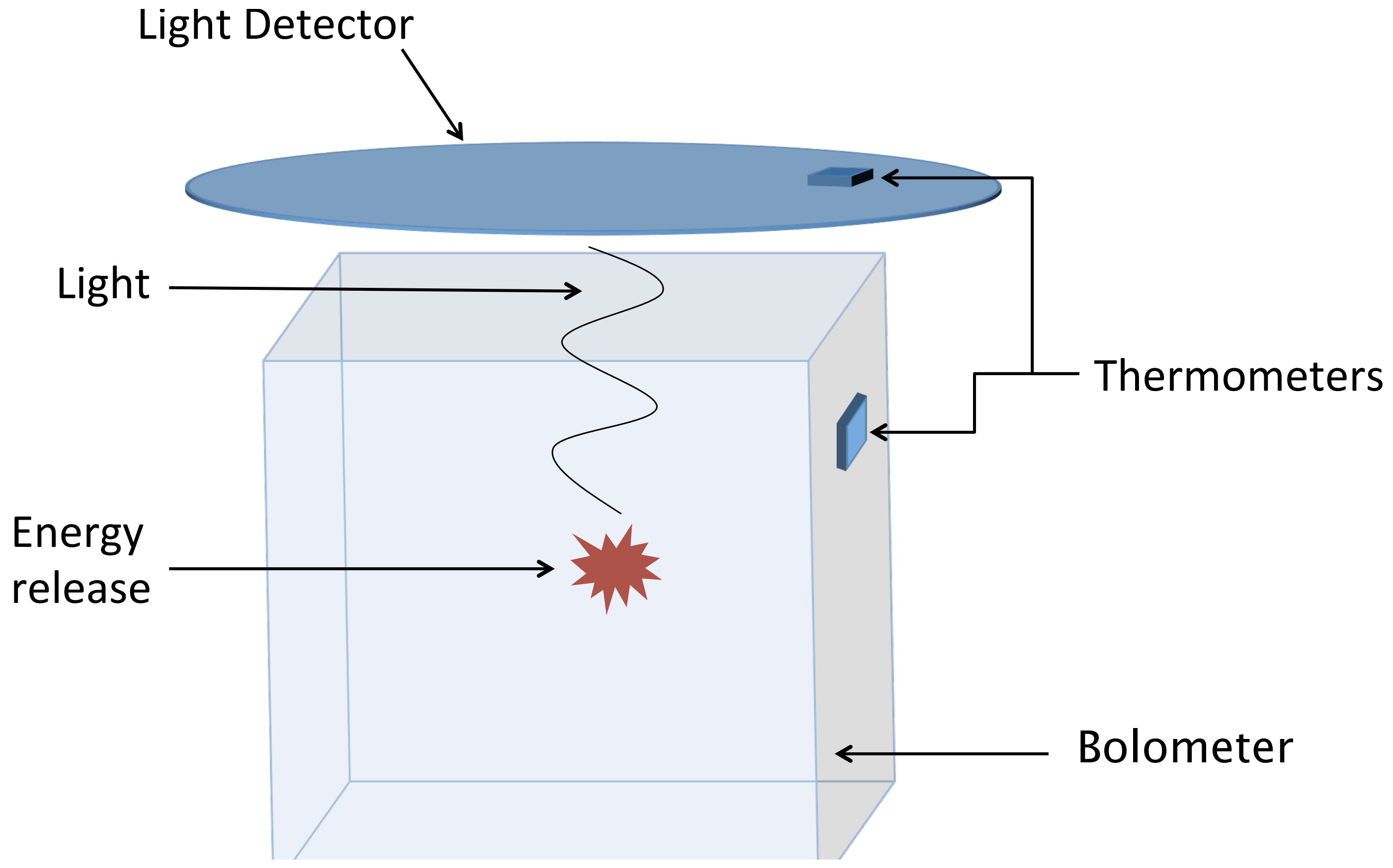
$$7.0 \pm 0.3 \text{ keV}$$

$$T^{0\nu}_{1/2} > 3.2 \times 10^{25} \text{ yr } (90\% \text{ C.I.})$$

- **Cuore has deployed a larger mass than GERDA.**
- **But BI is a factor 30 worse, limited by surface alphas.**
- **Resolution is also a factor 2/3 worse than Ge76 diodes.**
- **The “straight” technique does not extrapolate easily to large masses.**

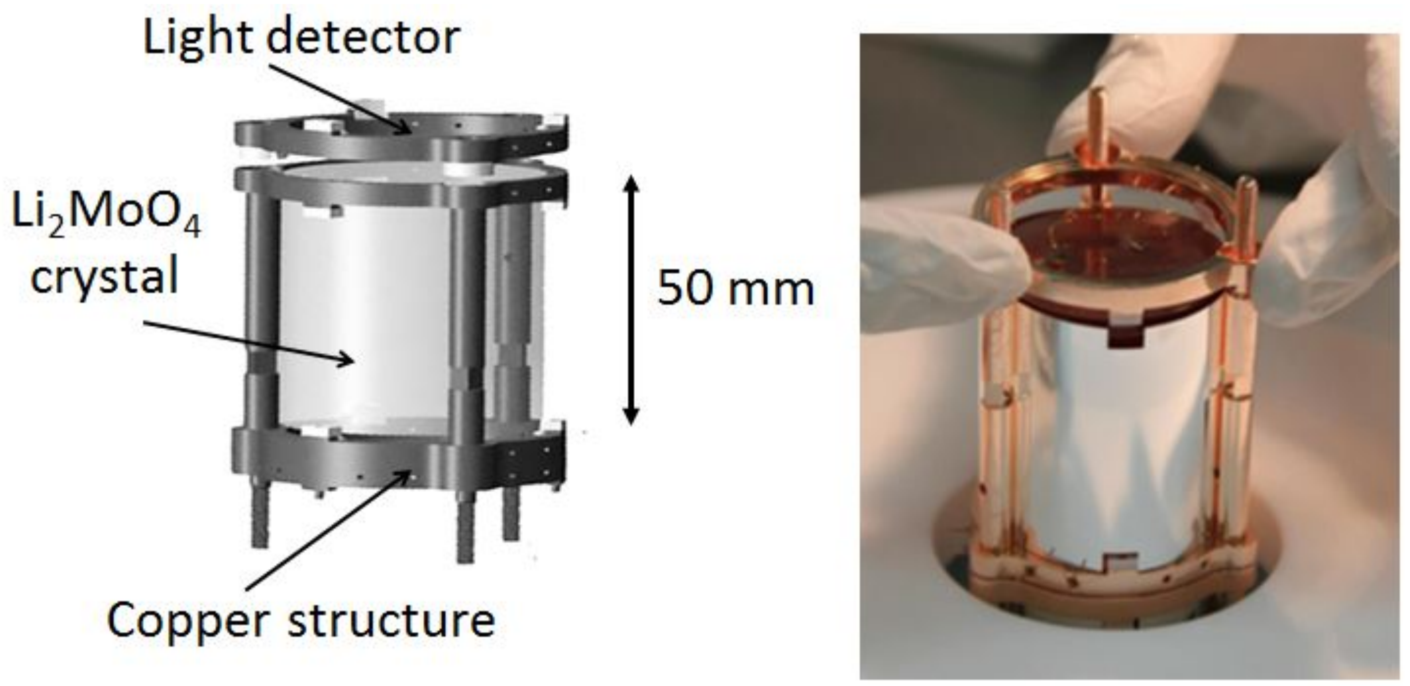
Cupid: scintillating bolometers





CUPID preCDR
https://arxiv.org/abs/1907.09376

Parameter	CUPID Baseline
Crystal	$Li_2{}^{100}MoO_4$
Detector mass (kg)	472
^{100}Mo mass (kg)	253
Energy resolution FWHM (keV)	5
Background index (counts/(keV·kg·yr))	10^{-4}
Containment efficiency	79%
Selection efficiency	90%
Livetime (years)	10
Half-life exclusion sensitivity (90% C.L.)	1.5×10^{27} y
Half-life discovery sensitivity (3σ)	1.1×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV



- **Expected BI is 10^{-4} ckky, with a resolution of 5 keV.**
- **Need enriched material.**
- **Similar (excellent) performance than Ge76 diodes (including very high efficiency) but also similar scaling problems.**
- **Re-use know-how (cryogenics at 10 mK)**
- **Explore Mo100.**

KamLAND-Zen & SNO+
(Gareth)

KamLAND-Zen

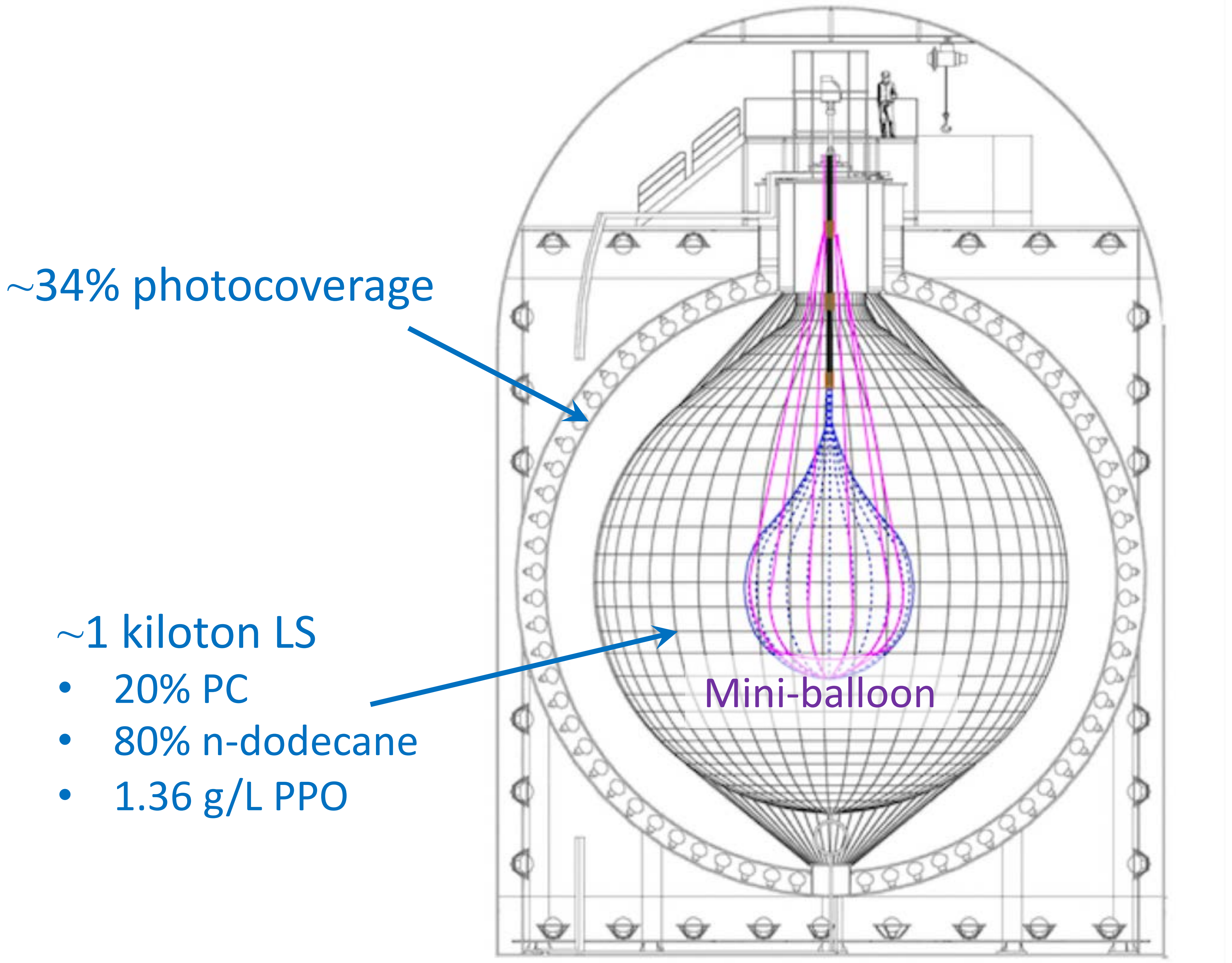
Mini-balloon:

- 25-μm-thick nylon film (durable)
- Fabricated in class-1 clean room
- Highly transparent (~99% at 400 nm)

Xenon loading:

- Chemically stable (noble gas)
- Good solubility (3.2% wt in LS)
- Removable from LS
- Purification is well-established

Located in Kamioka Mine at 2700 m.w.e.

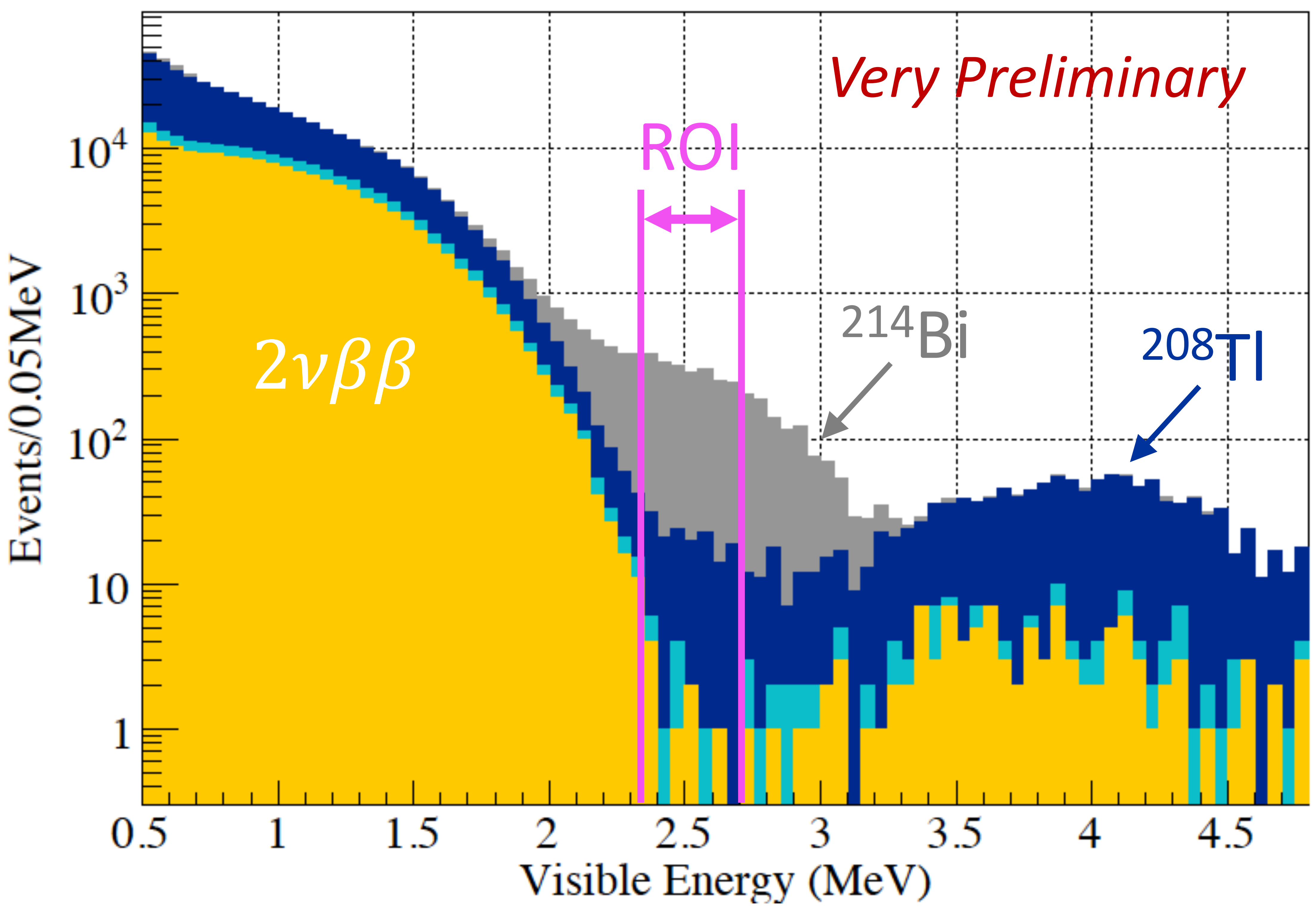


91% enriched ^{136}Xe loaded in LS inside mini-balloon (Q value = 2.4578 MeV)

- **Idea: Give up on energy resolution, control background by self-shielding and other handles.**
- **Advantage: It is possible to deploy large (very large) masses, addressing the scalability problem.**

No energy resolution

Total livetime of 132.7 days



Cuts used to reduce backgrounds:

r < 240 cm

Select events inside and just outside of the mini-balloon

Rn cut

Delayed coincidence cut for ^{214}Bi – ^{214}Po and ^{212}Bi – ^{212}Po

Fiducial volume cut

Further reduce backgrounds going from r < 240 cm to r < 157 cm

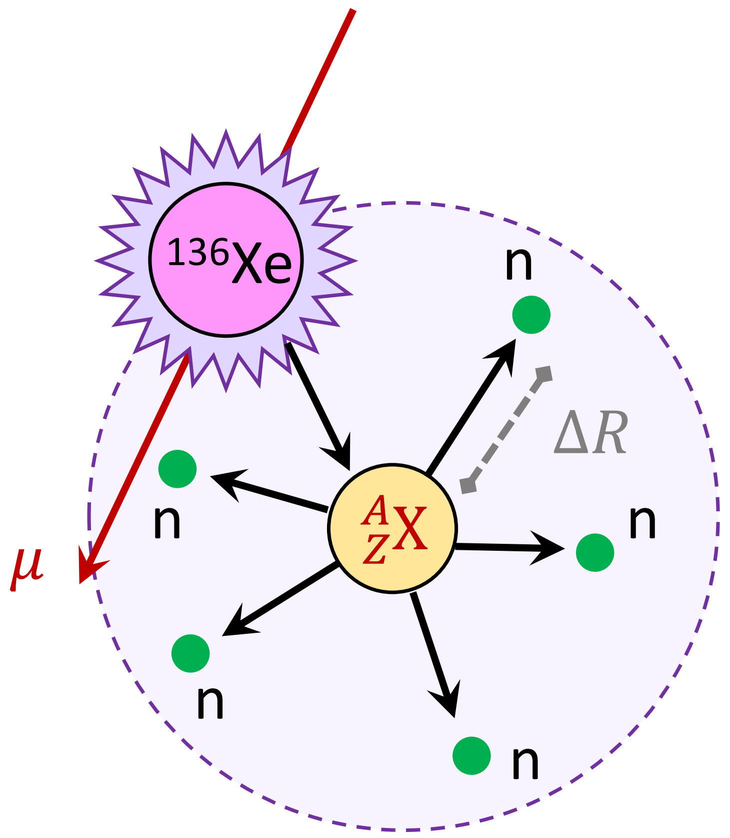
Spallation Cut

Remove events correlated with muons

Self-shielding and vetoes

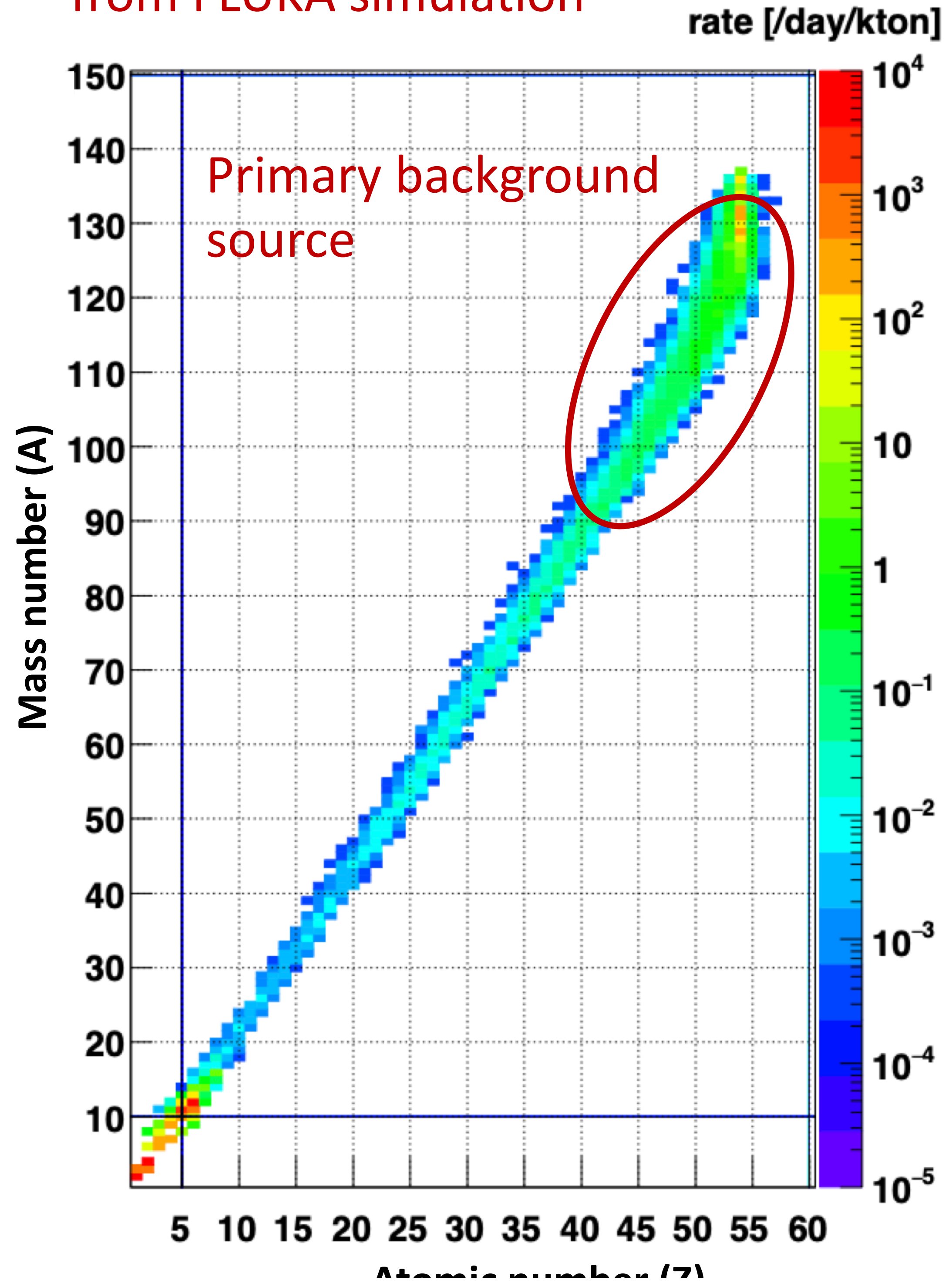
is being studied extensively

(NEW) Spallation on ^{136}Xe

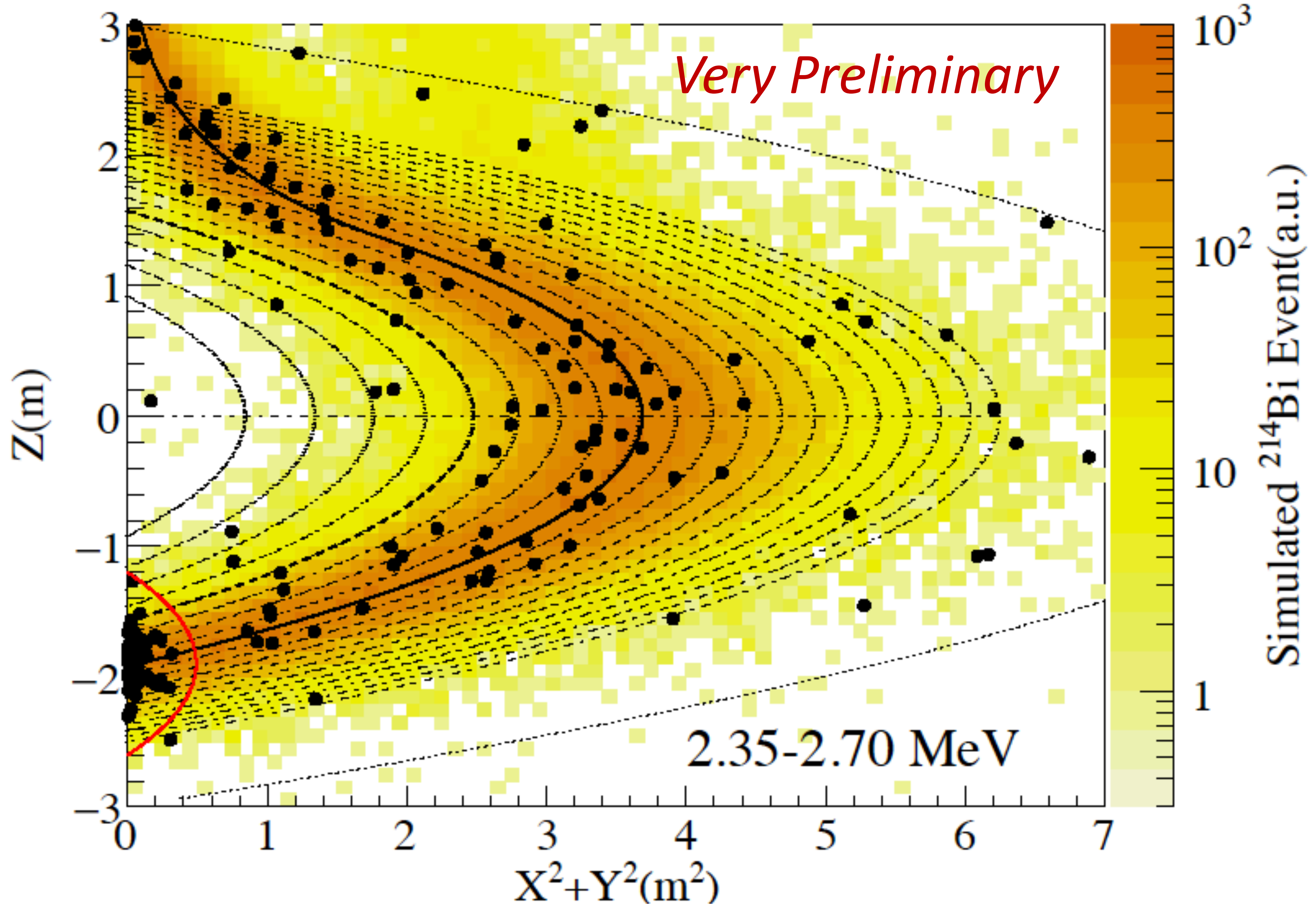


Can a similar technique be applied to high A isotopes with high neutron multiplicity?

μ + ^{136}Xe spallation byproducts from FLUKA simulation



Vertex distribution of events in the ROI overlayed on ^{214}Bi MC

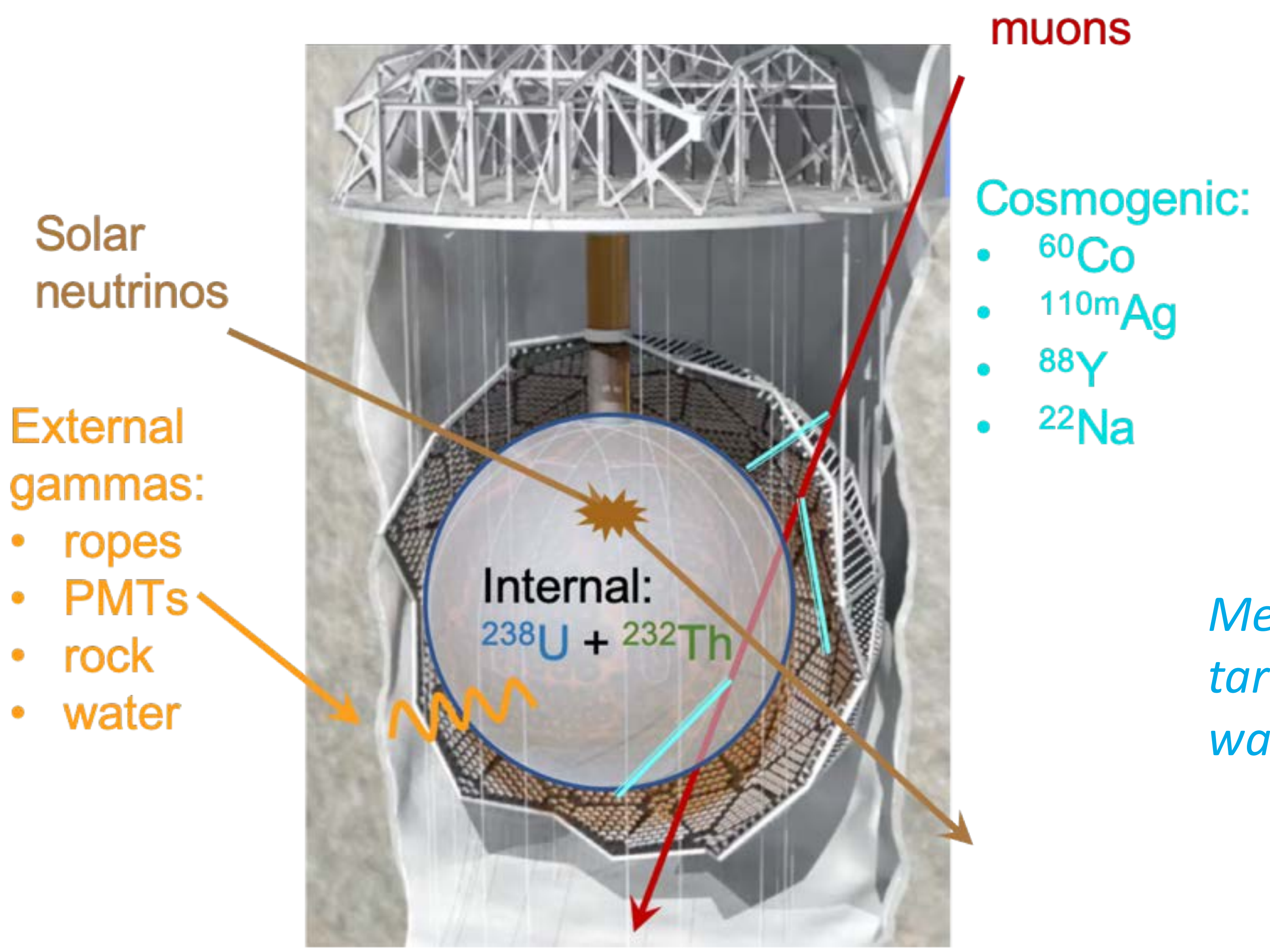


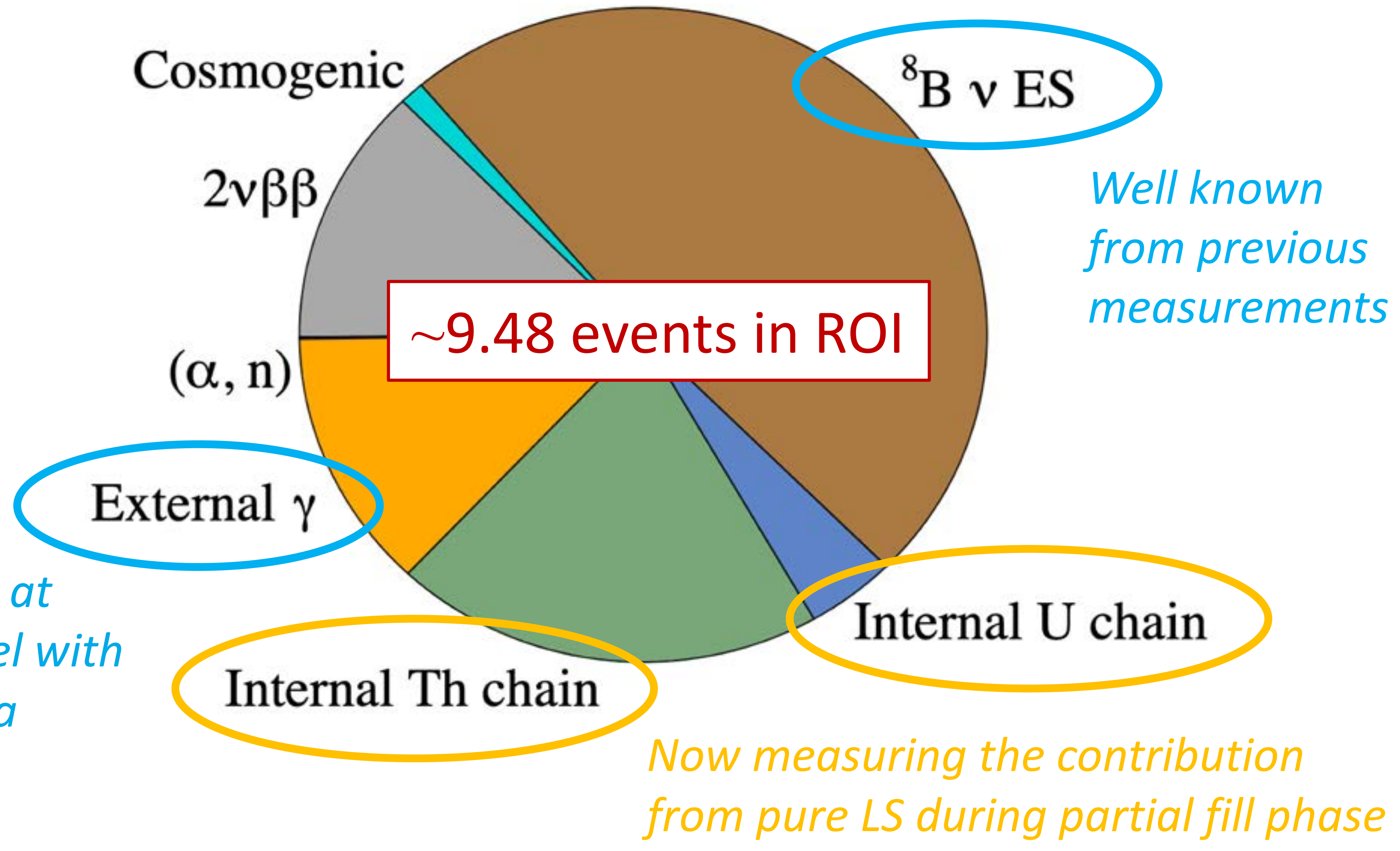
- **Issues: effective self-shielding requires very harsh fiducial cuts (giving up most of the fiducial mass)**
- **Spallation background (Xe-136) may be very hard to control (can be reduced at higher depth, thus SNO may be better than KZEN).**

Background zoo (SNO+)

$0\nu\beta\beta$ Background Predictions

ROI: 2.42 – 2.56 MeV [-0.5σ - 1.5σ]





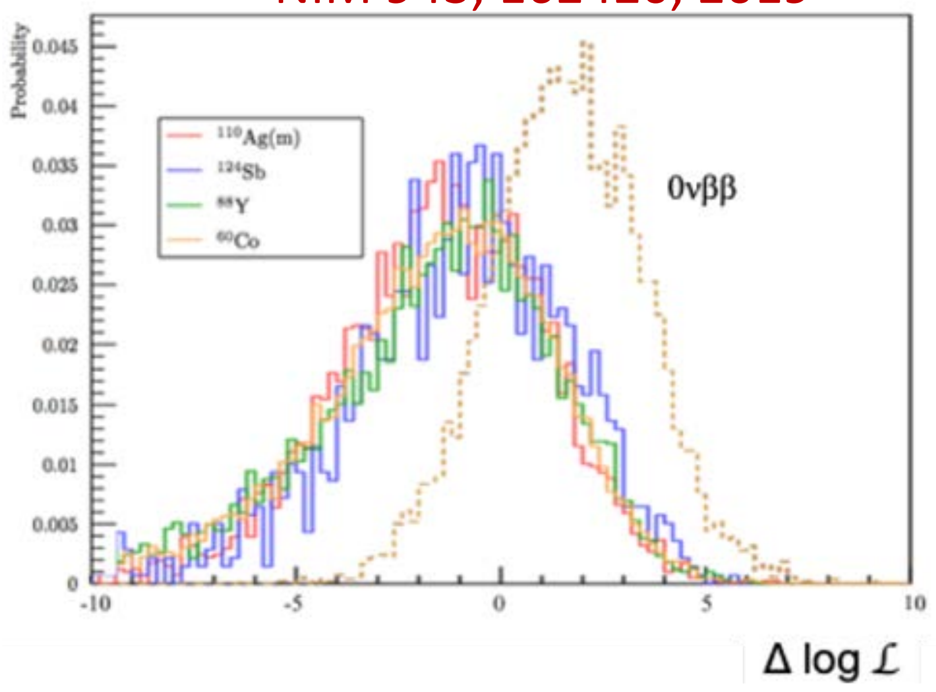
Target concentrations of less than 10^{-15} g/g U and 10^{-16} g/g Th in pure LS are required for $0\nu\beta\beta$ decay.

We're currently below our targets for U and Th in the partial LS phase.

Remaining backgrounds will be measured during Te-loading!

Cosmogenic backgrounds will be verified by multi-site analysis

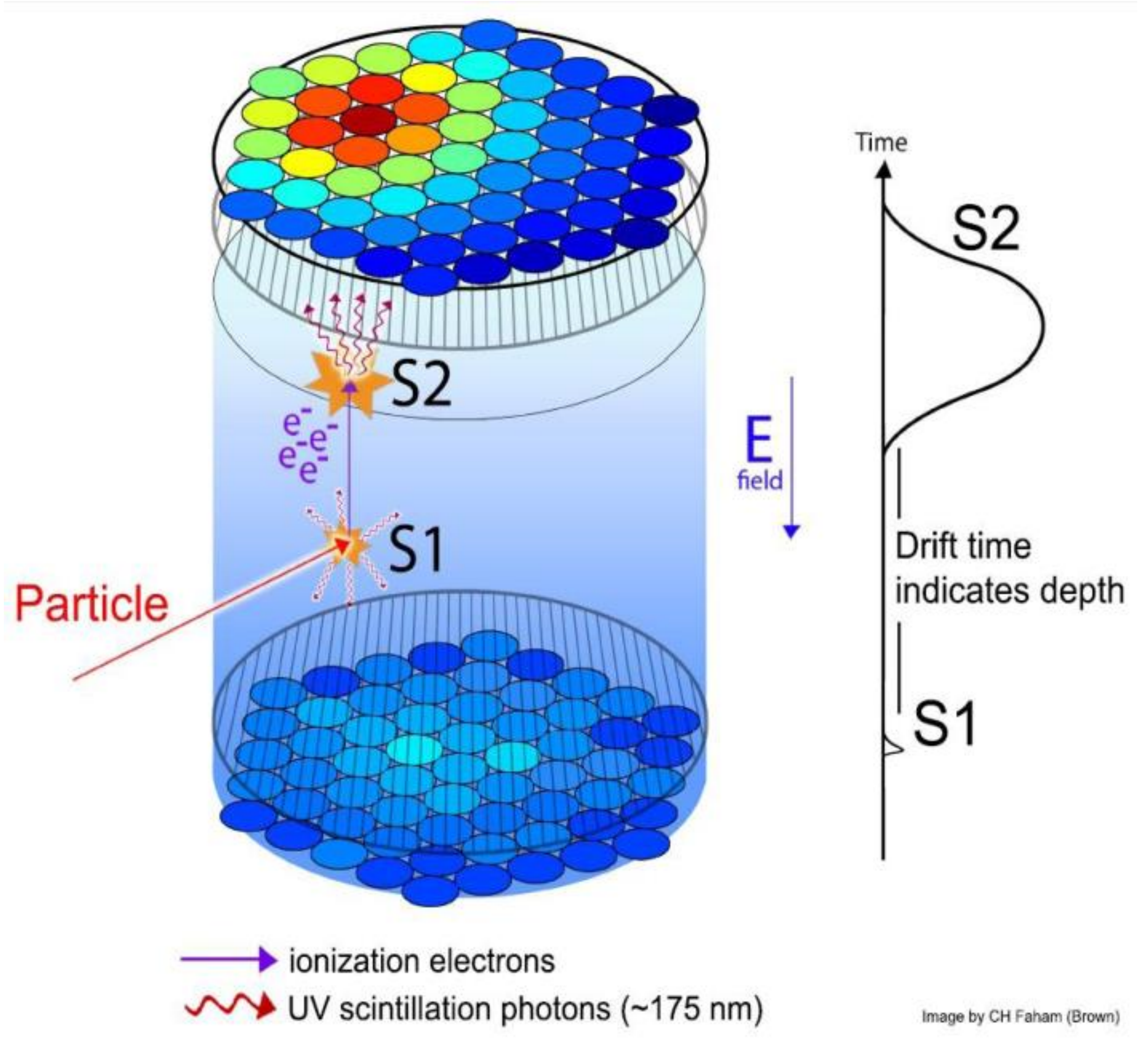
NIM 943, 162420, 2019

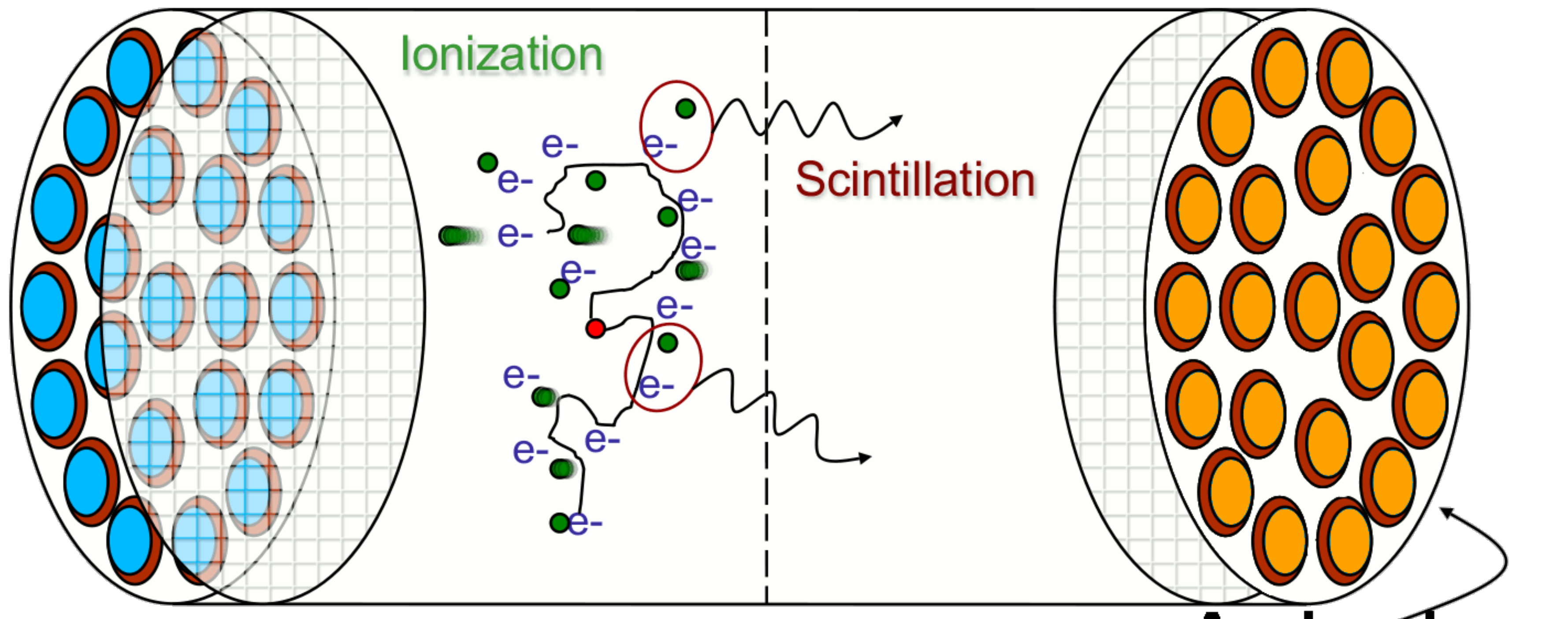


LXe (Merlin)

Xenon TPCs

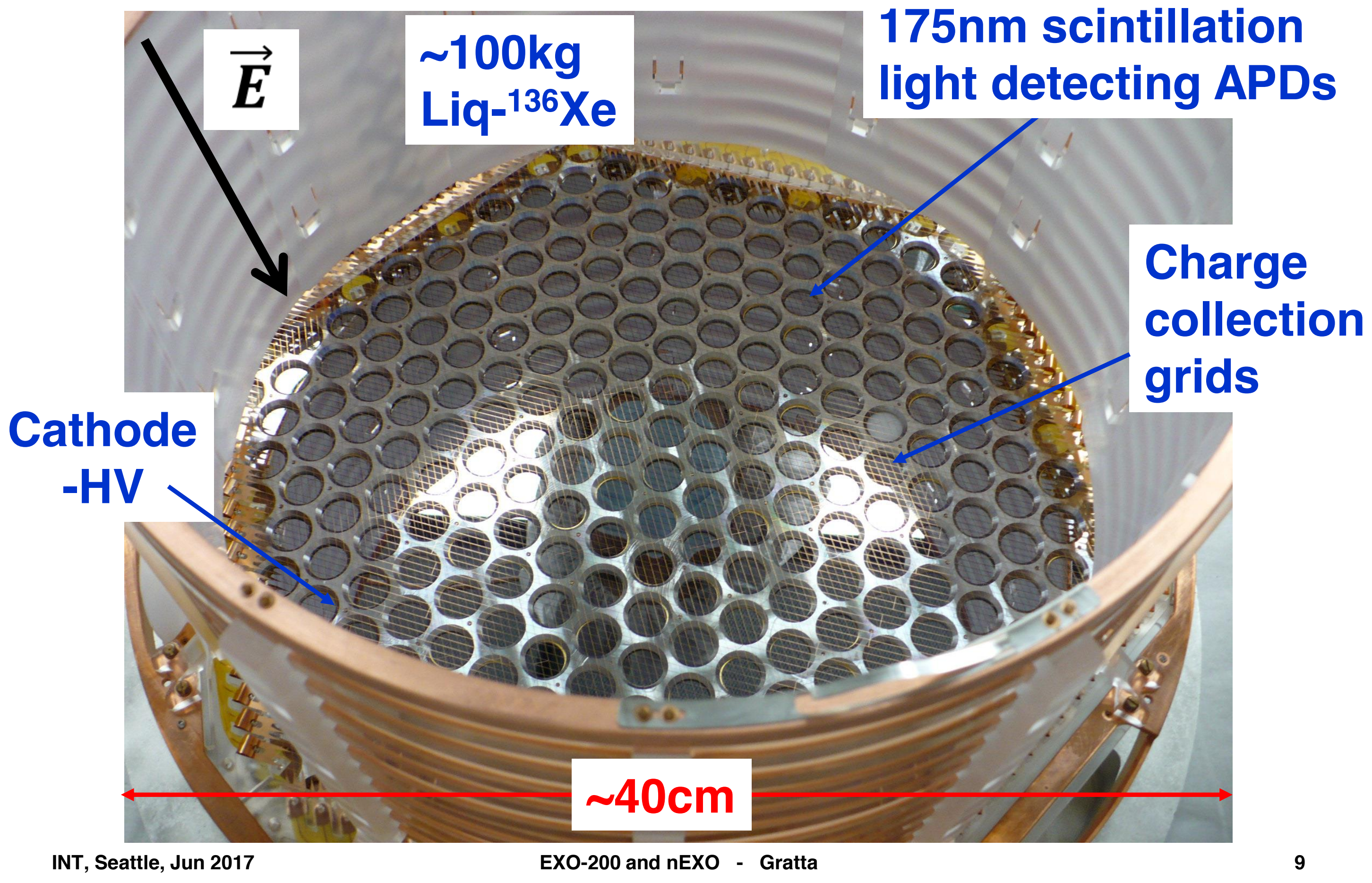
- Detection exploits scintillation (S1) and ionisation (S2) signals in xenon.
- S1 provides t_0, essential for fiducial definition.
- EL TPCs (, XENON, LZ, LUX, DARWIN) detect only light (S2 converted via electroluminescence in photons)
- EXO/nEXO detect charge (without/with) amplification
- Large masses (compact detector) and acceptable resolution

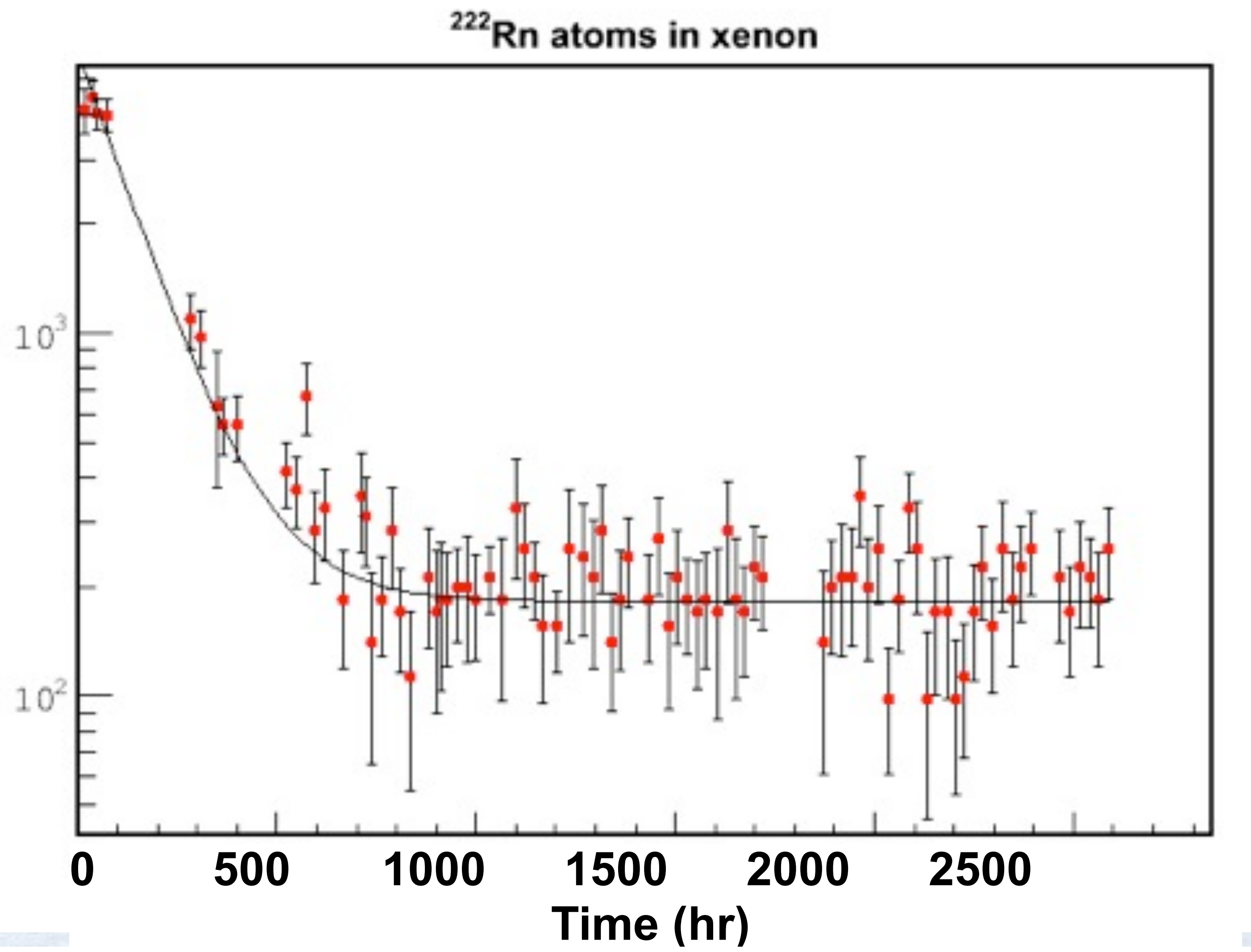


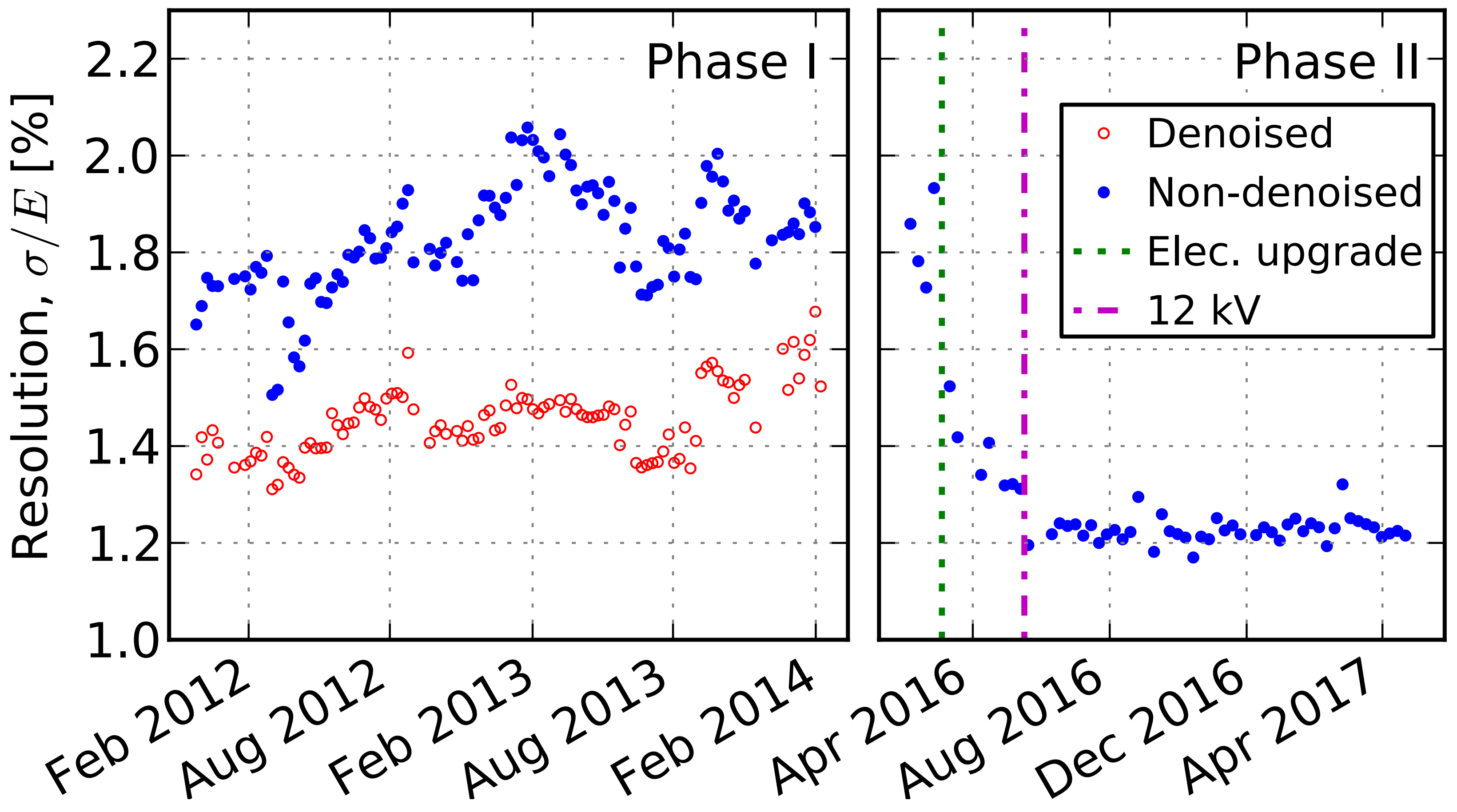


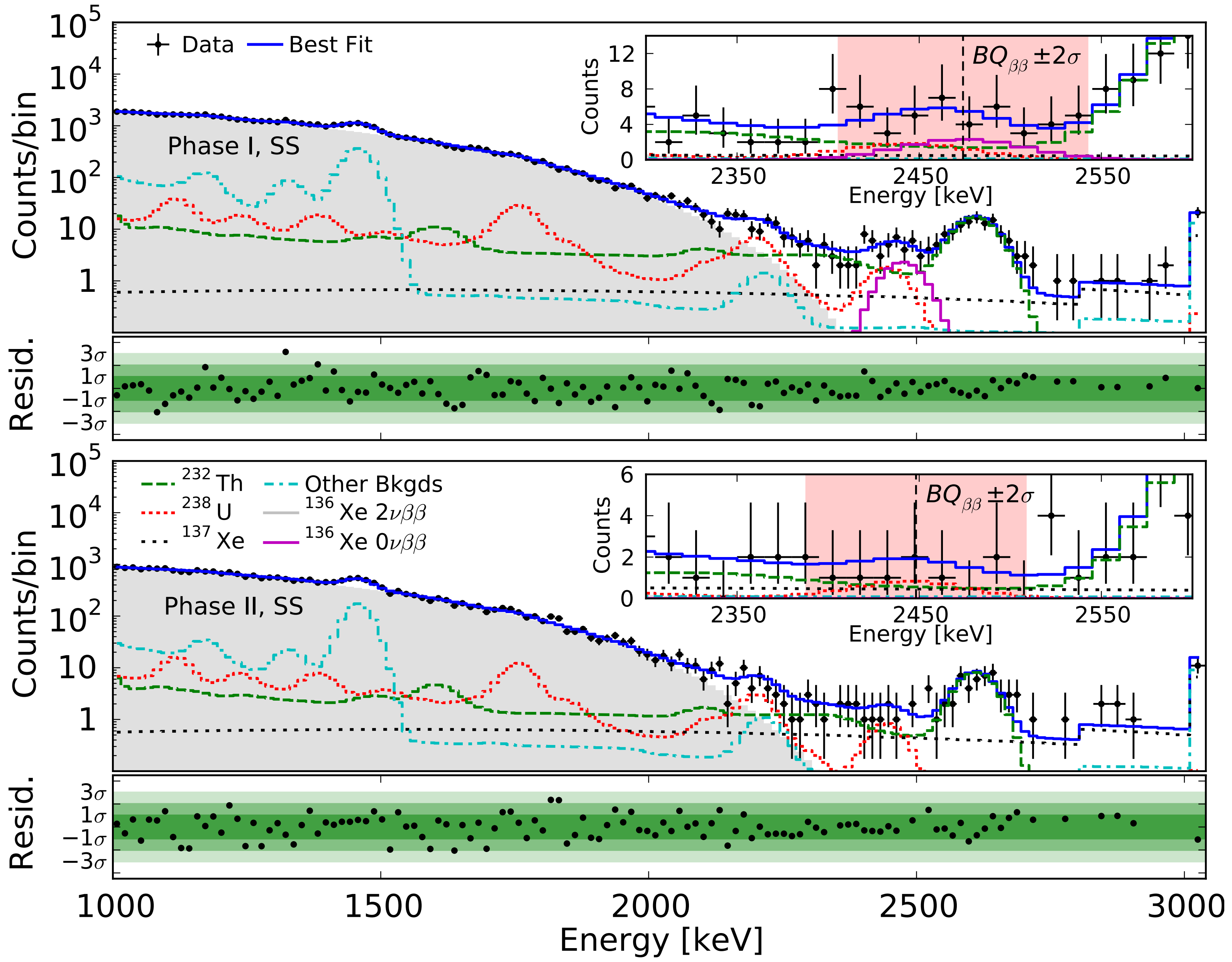
EXO-200

- *Phys.Rev.Lett.* **123 (2019) 16, 161802**









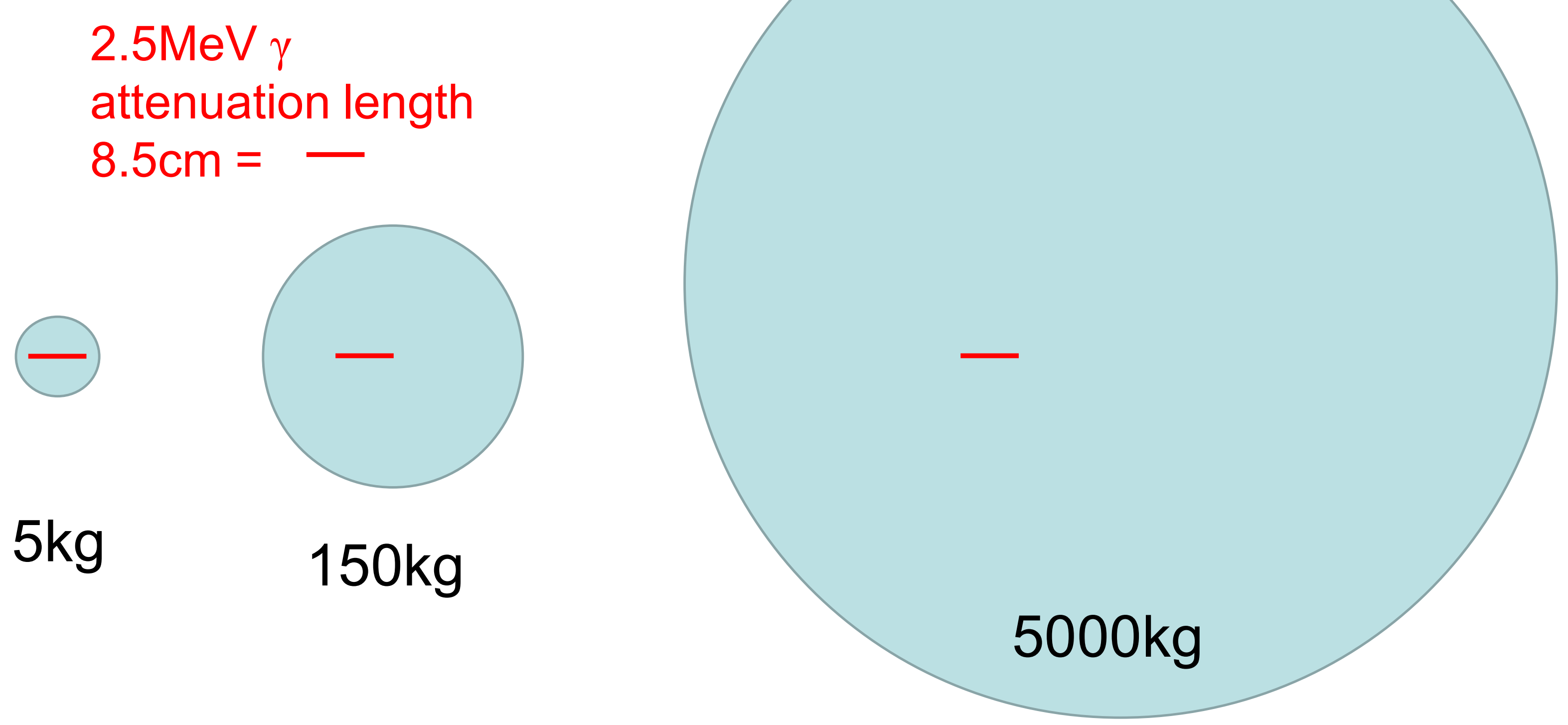
- **Demonstrated single phase LXe TPC technology. Energy measured using scintillation (APDs) and ionisation (wires). Anticorrelation allows a measurement with a resolution of 2.8 % FWHM at $Q_{\beta\beta}$**

- **Searched for $\beta\beta0\nu$: sensitivity T ~3.7 10^{25} y. Limit T >5 10^{25} y at 90 % CL.**

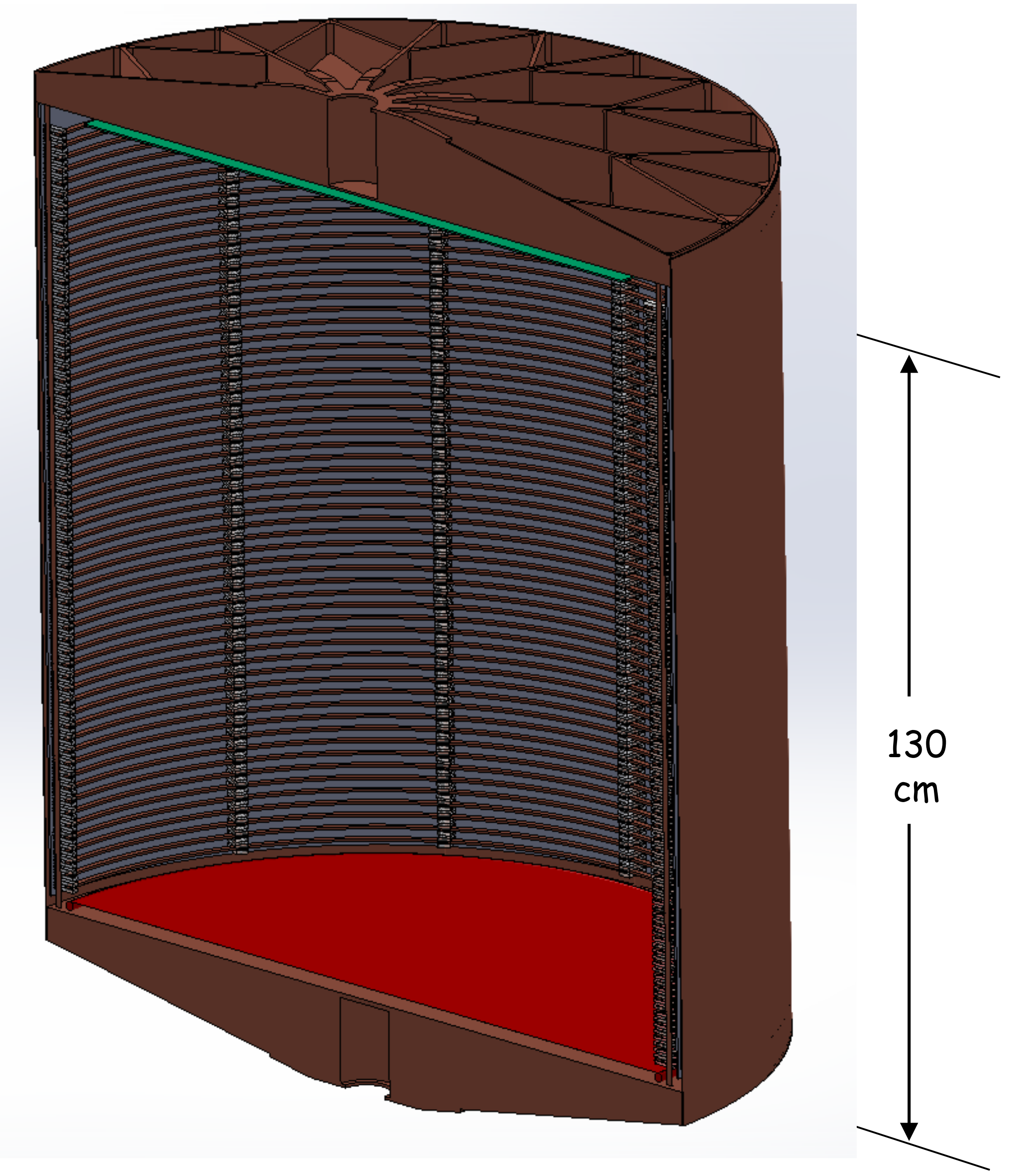
- **Background Index (B):**
$(1.5 \pm 0.3) \times 10^{-3}\ \mathrm{kg}^{-1}\ \mathrm{yr}^{-1}\ \mathrm{kev}^{-1}$

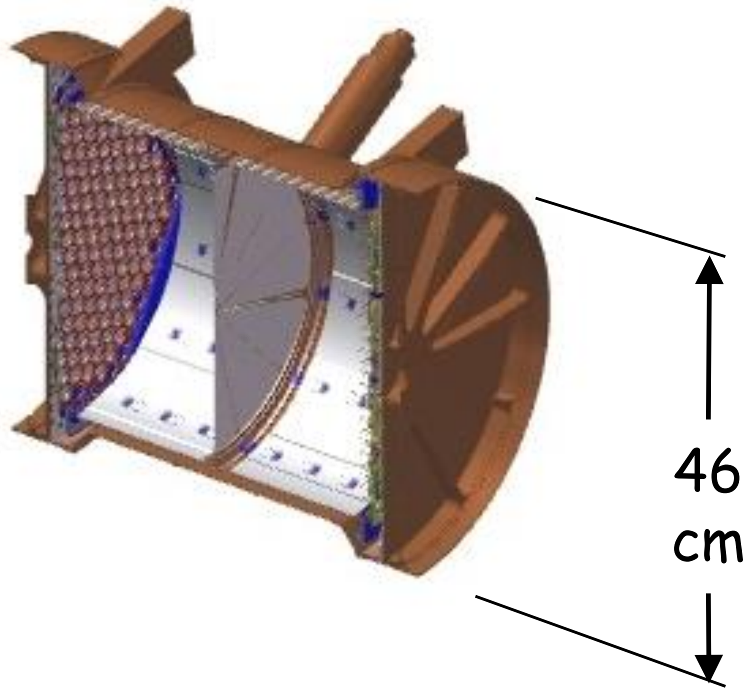
nEXO

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13



This works best for a monolithic detector



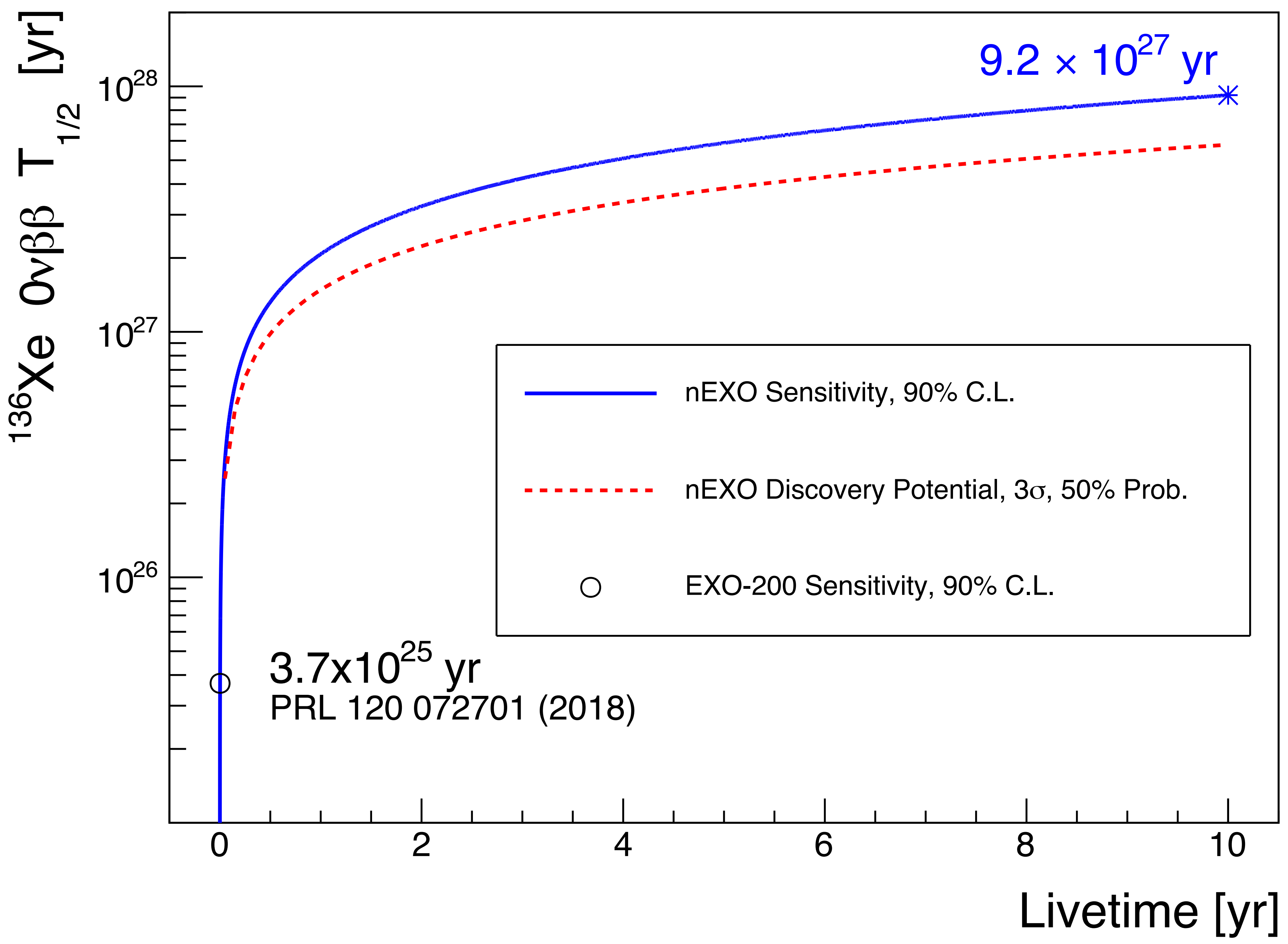


- Monolithic single phase detector with 5 ton enriched xenon total mass (~4 ton fiducial mass). Principle of operation like EXO-200, but asymmetric TPC to minimise impact of Rn-222 daughters. Underground must be deep to minimise Xe^{137} background (SNOLAB assumed)
- S2 measured from charge (no amplification, silica tiles patterned with crossed metal strips at the anode).
- S1 measured covering the barrel with VUV SiPMs (4.5 m^2 of them).
- Combines low background budget, self-shielding, good energy resolution.

nEXO performance

https://arxiv.org/ftp/arxiv/papers/1805/1805.11142.pdf

- LXe proses a compromise between ultra-high resolution experiments (e.g, Ge-Diodes, scintillation bolometers) and very-large mass experiments (KamLAND-Zen, SNO+).
- Resolution is worse than GERDA/CUPID (NEXT) but much better than KZ/SNO+
- Fiducialization is excellent, and strict self-shielding possible.
- Cosmogenics (Xe-137) still a background.



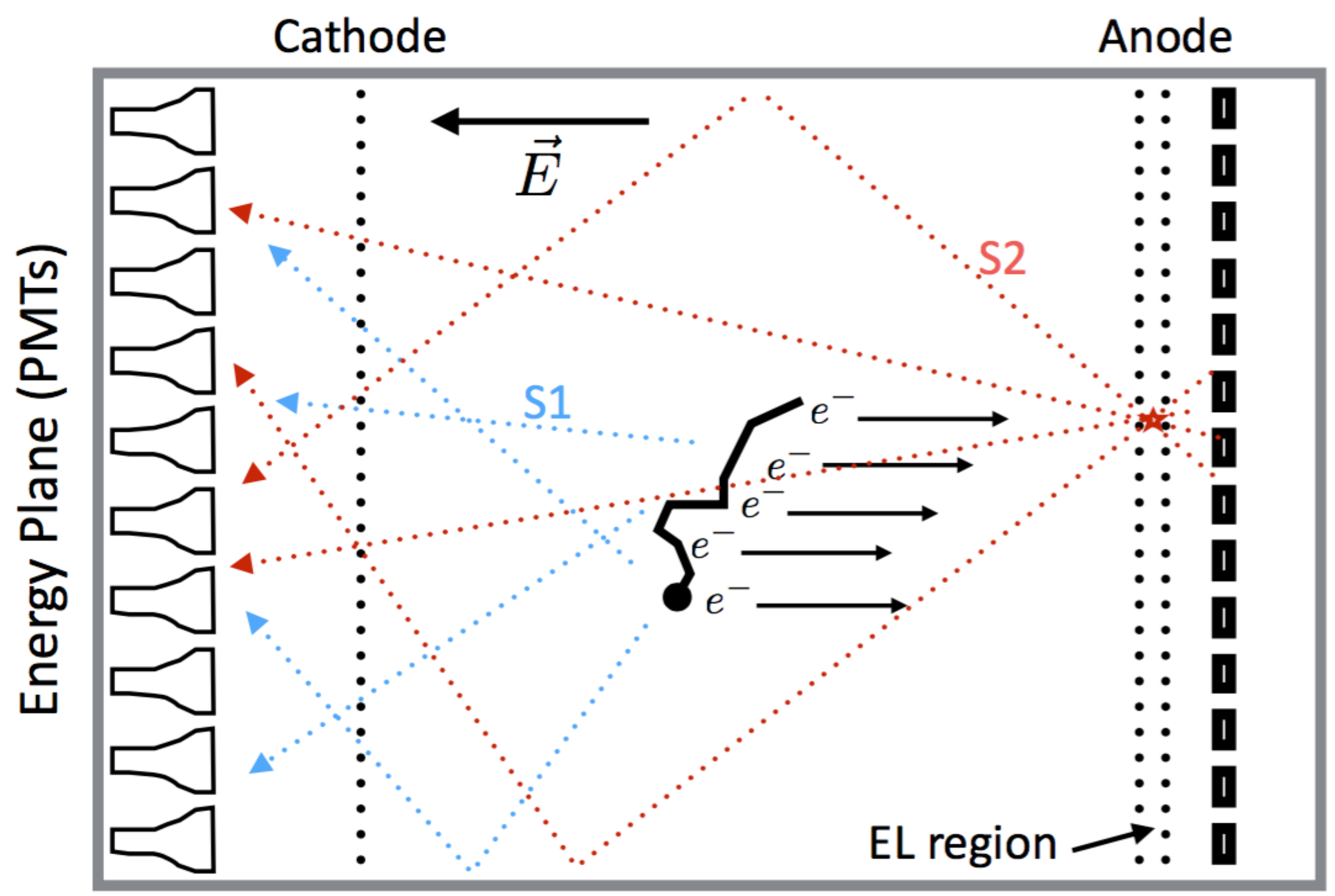
In inner 2 ton: $B(\mathrm{nEXO}) \sim 3.6 \times 10^{-4}/(\mathrm{FWHM} \cdot \mathrm{kg} \cdot \mathrm{year}) = 5.3 \times 10^{-6}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{year})$

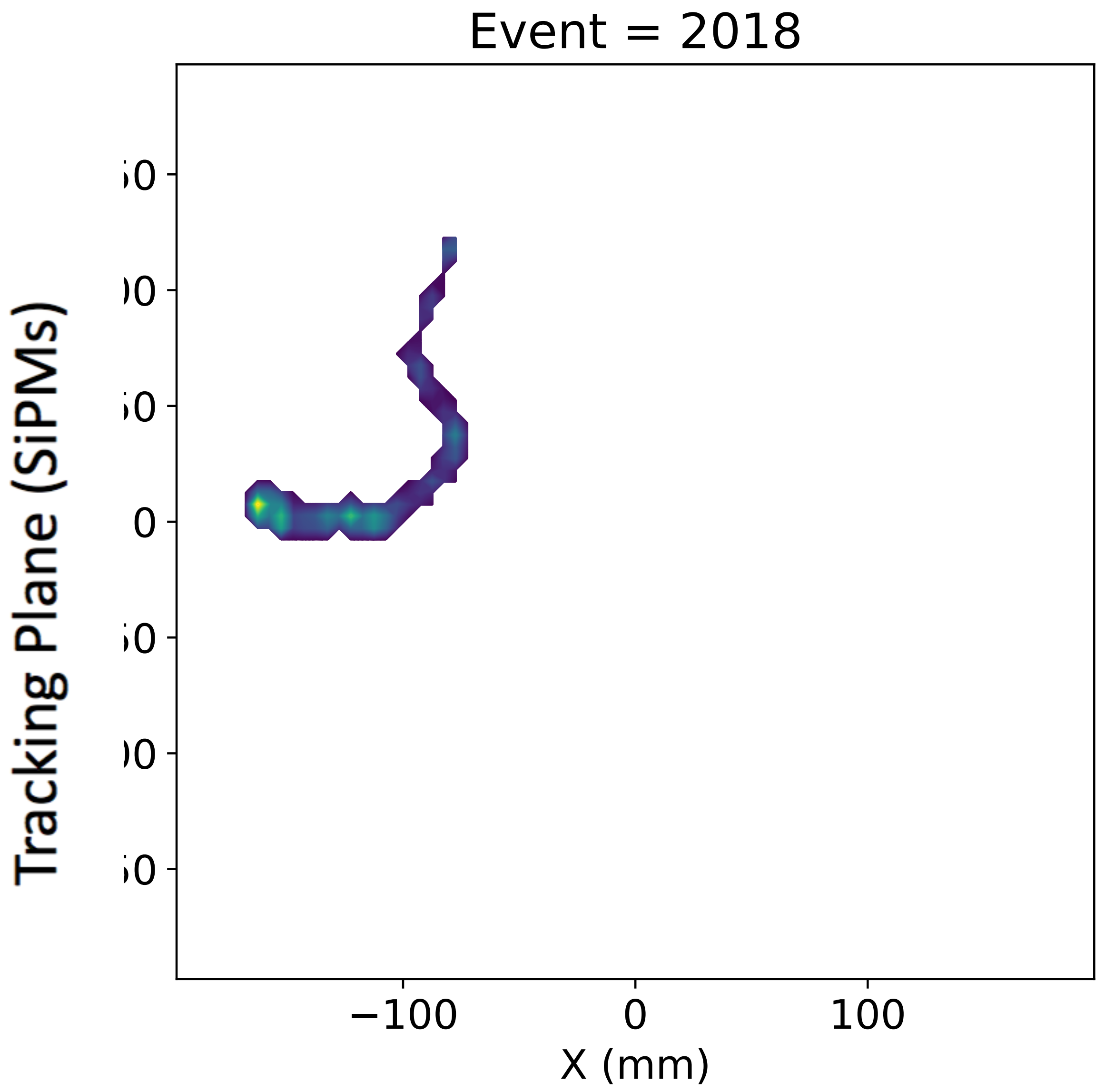
$B(\mathrm{EXO}) \sim = 1.5 \times 10^{-3}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{year})$

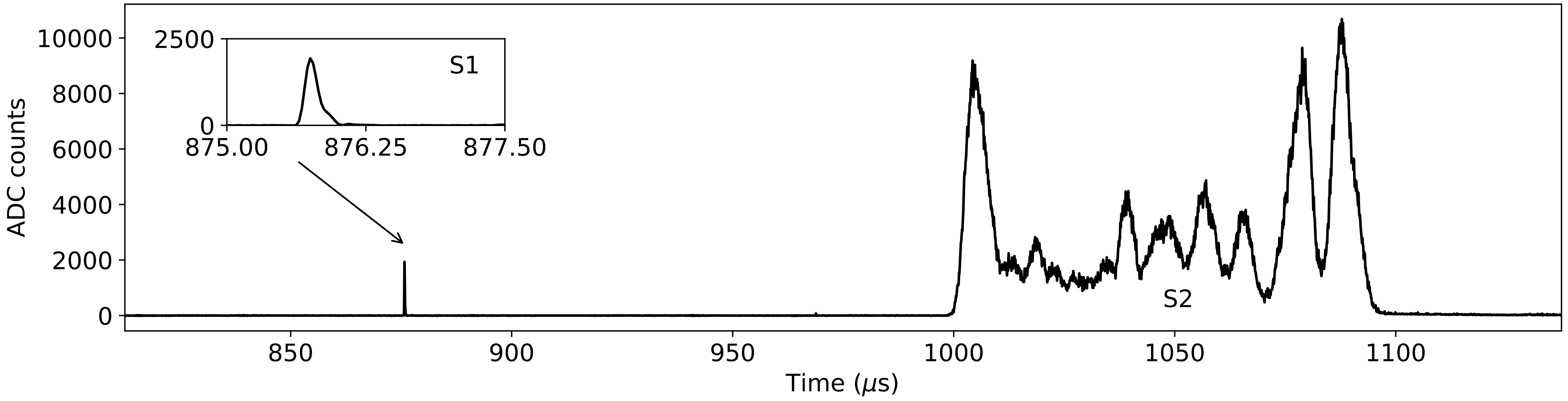
HPXe (Percival)

https://arxiv.org/pdf/1906.01743.pdf

NEXT

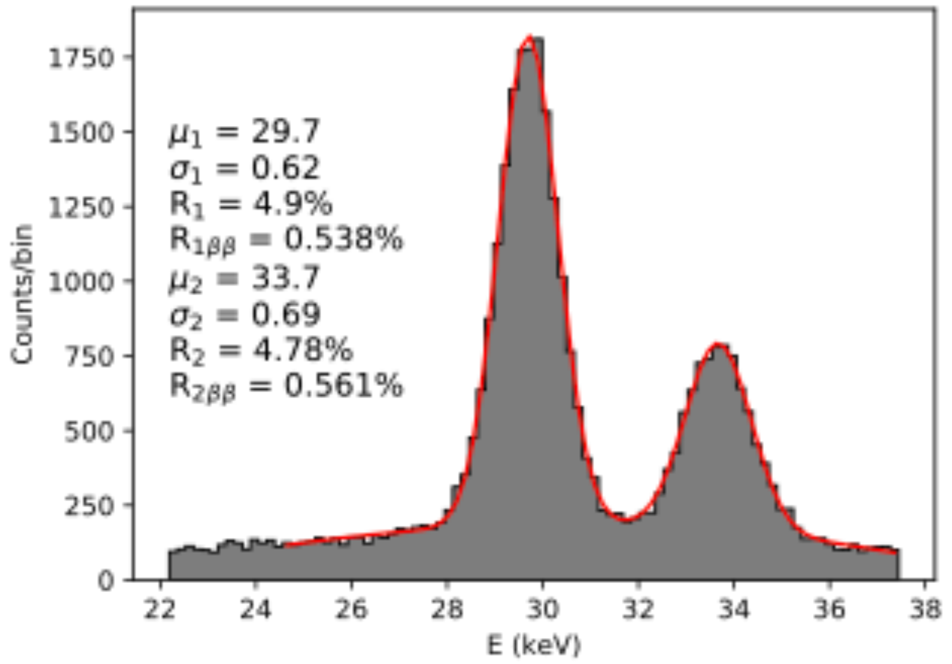


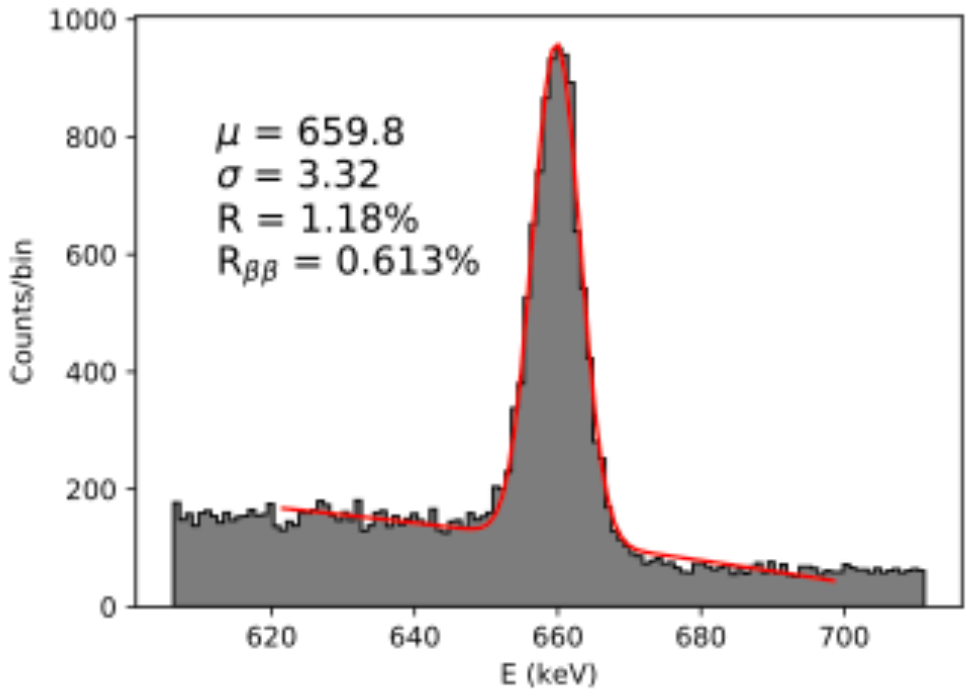


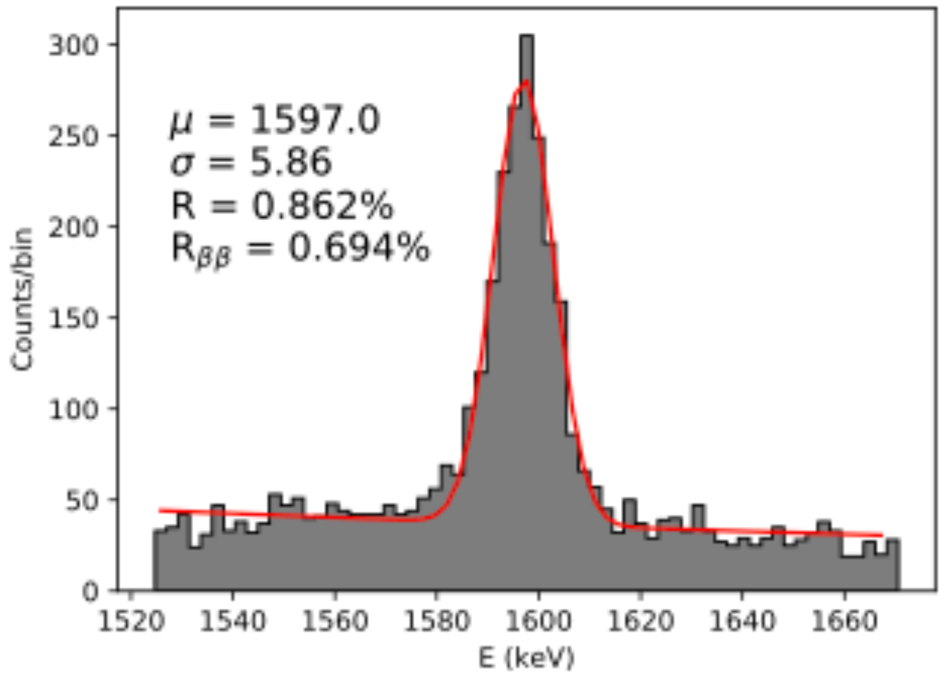


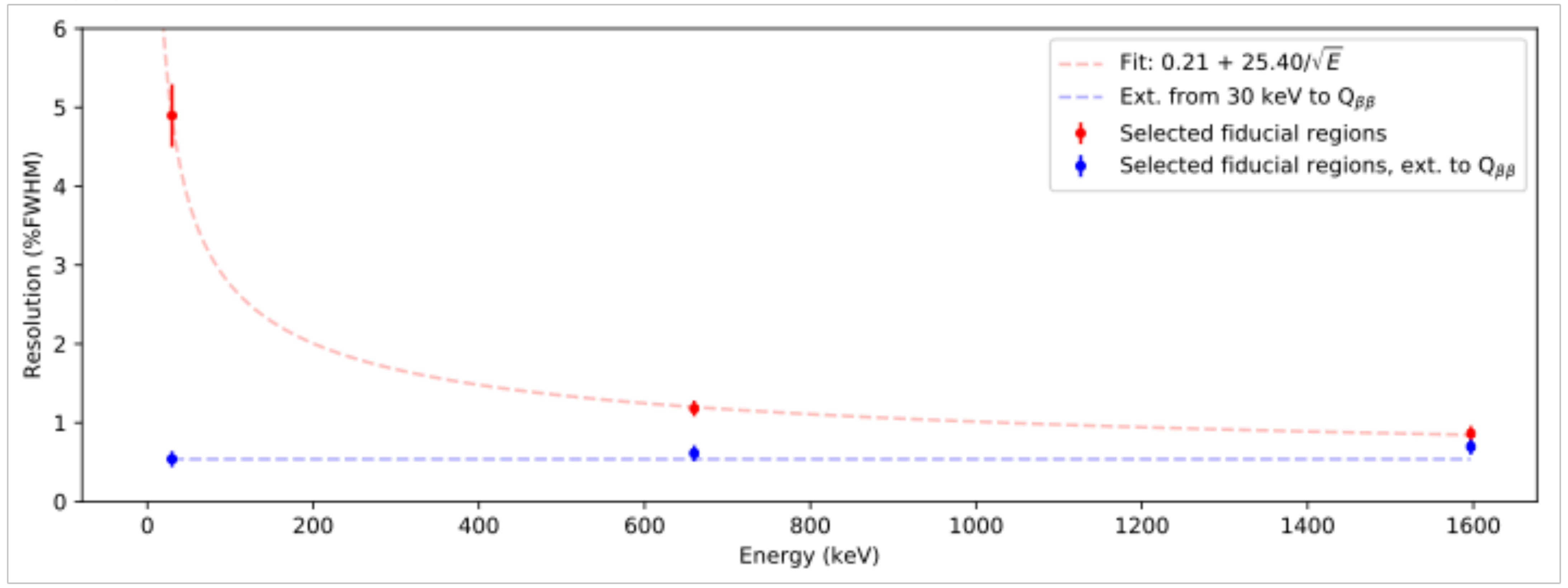
- HPXeEL TPC
- Good energy resolution (measured ~0.8 % FWHM, feasible 0.5-0.7 % FWHM).
- Topological signature (reconstruction of electrons in event). Measured 70 % efficiency for 95 % background suppression
- Radiopure detector, along the lines of all other Xe TPCs
- Moderately high masses.

NEXT: Resolution

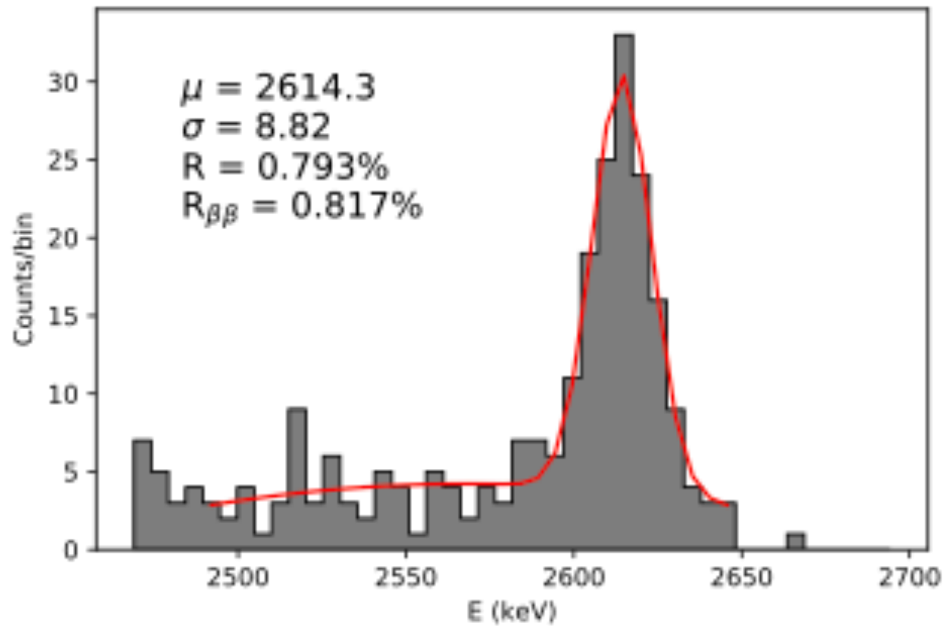








Energy resolution



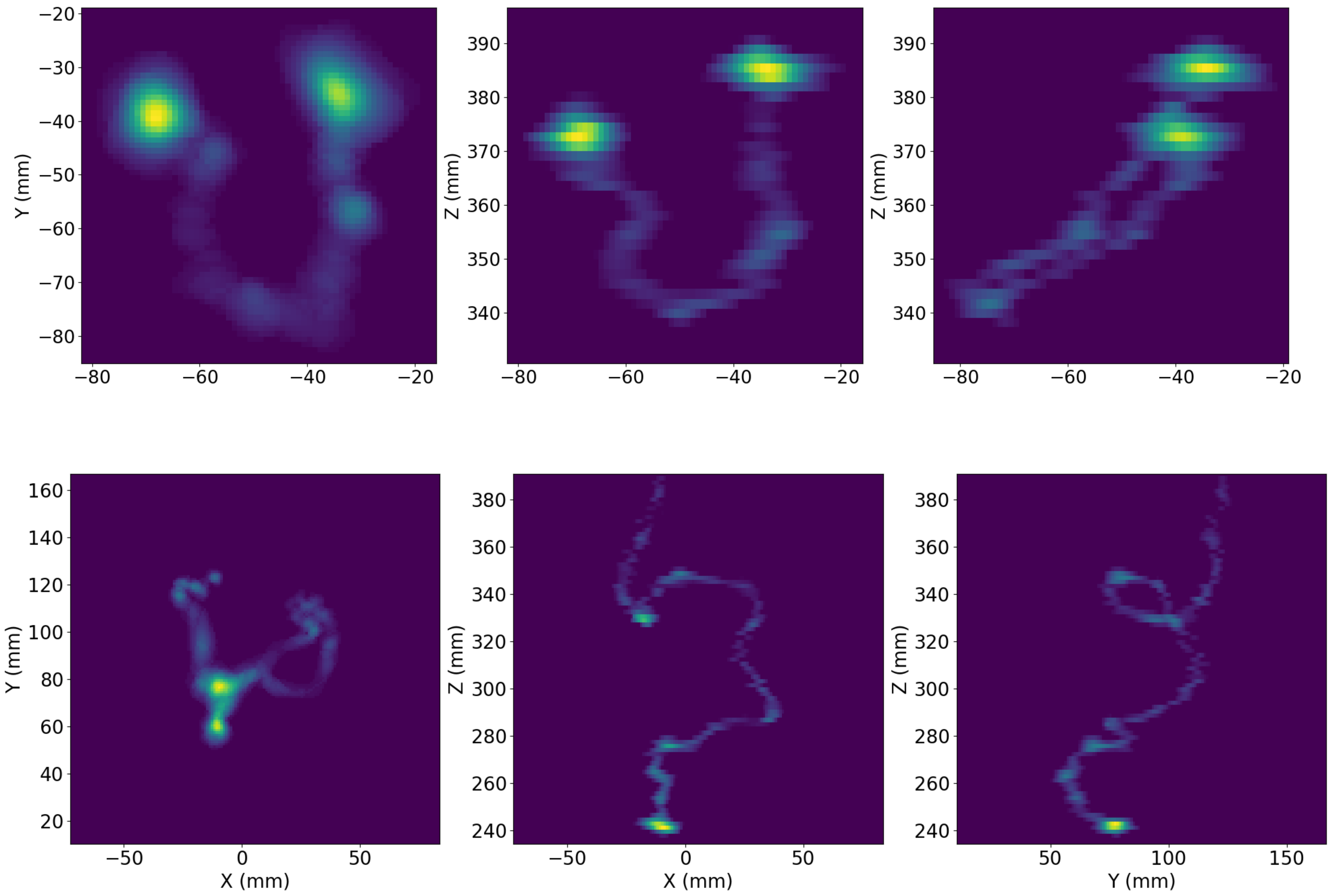
Energy resolution at $Q_{\beta\beta} \sim 0.8\,\%\, FWHM$ dominated by track corrections (0.5 % FWHM por point-like tracks). Room for improvement.

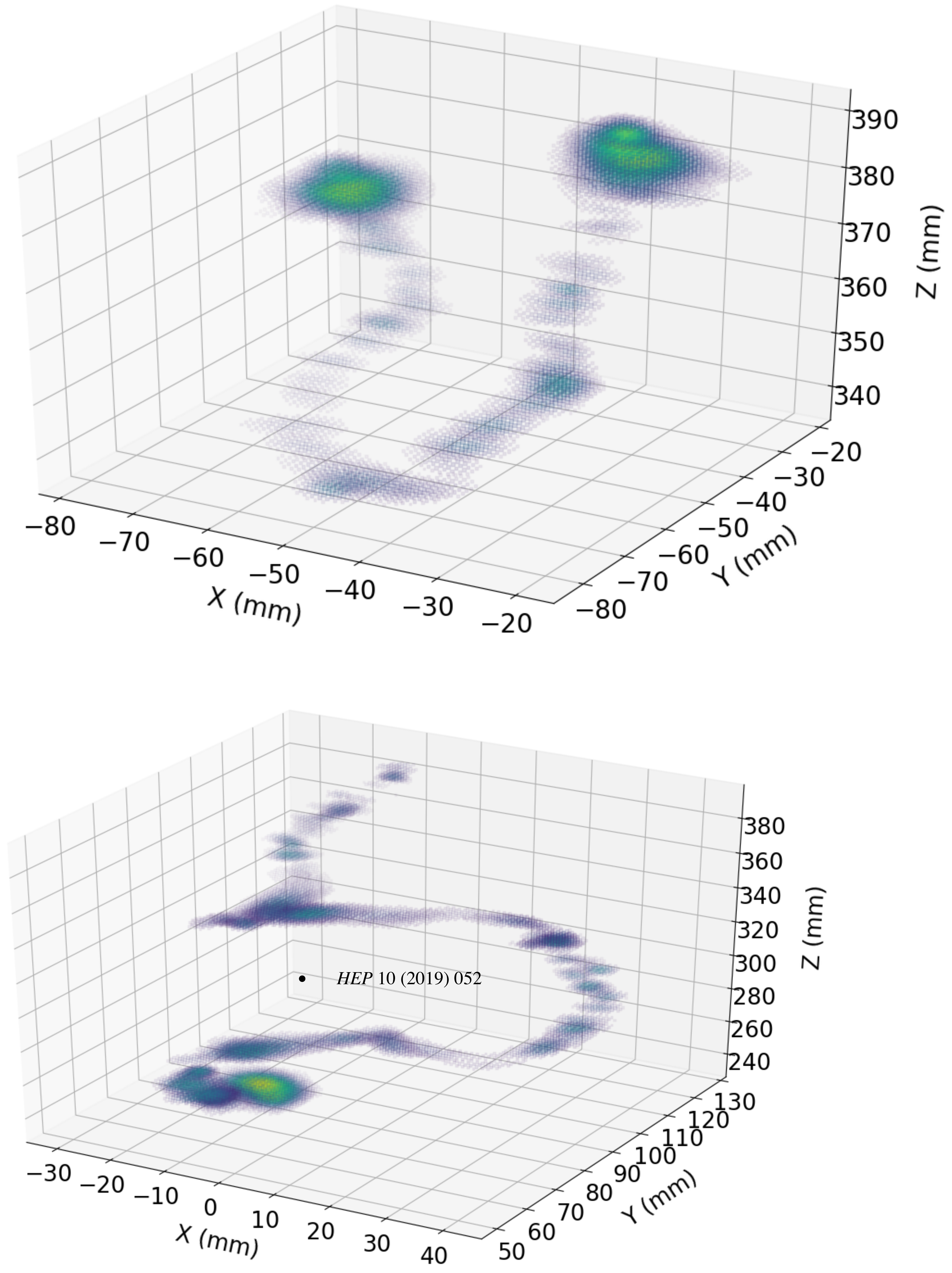
- ***JHEP* 10 (2019) 230**

Topological signature

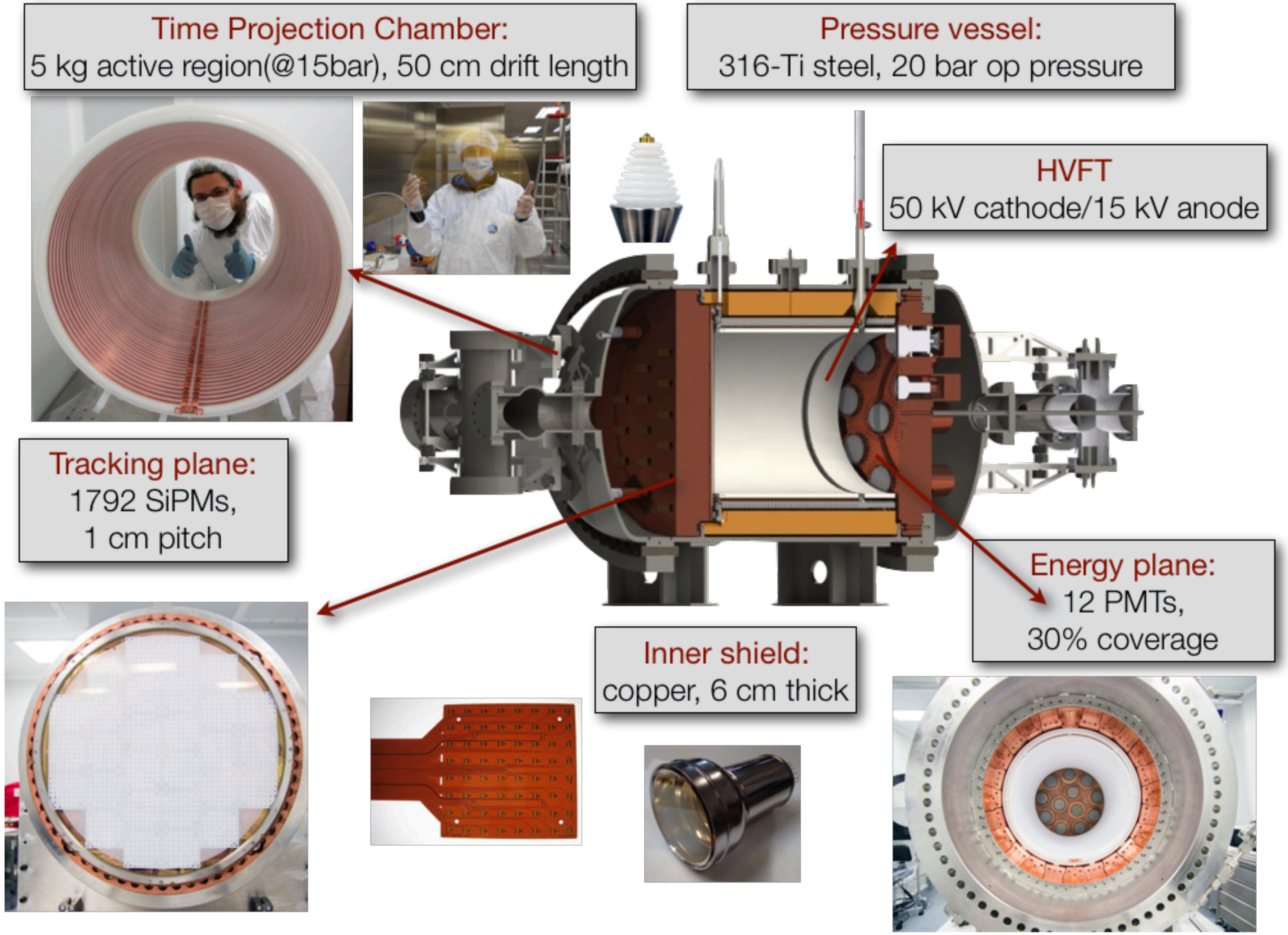
- ***JHEP* 10 (2019) 052**

Single and double electrons from $\beta\beta 2\nu$ analysis with energies near $Q_{\beta\beta}$

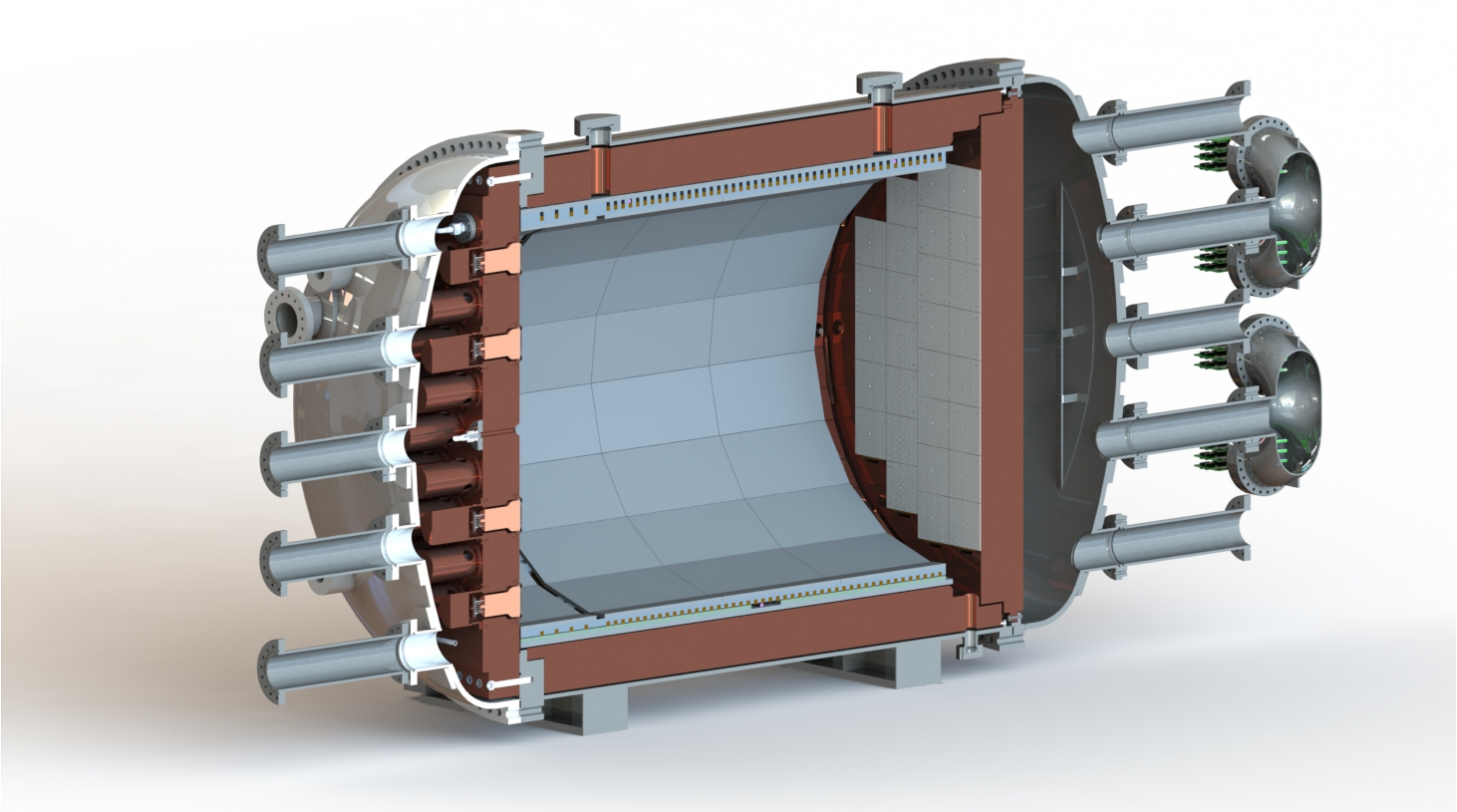




NEXT-White and NEXT-100

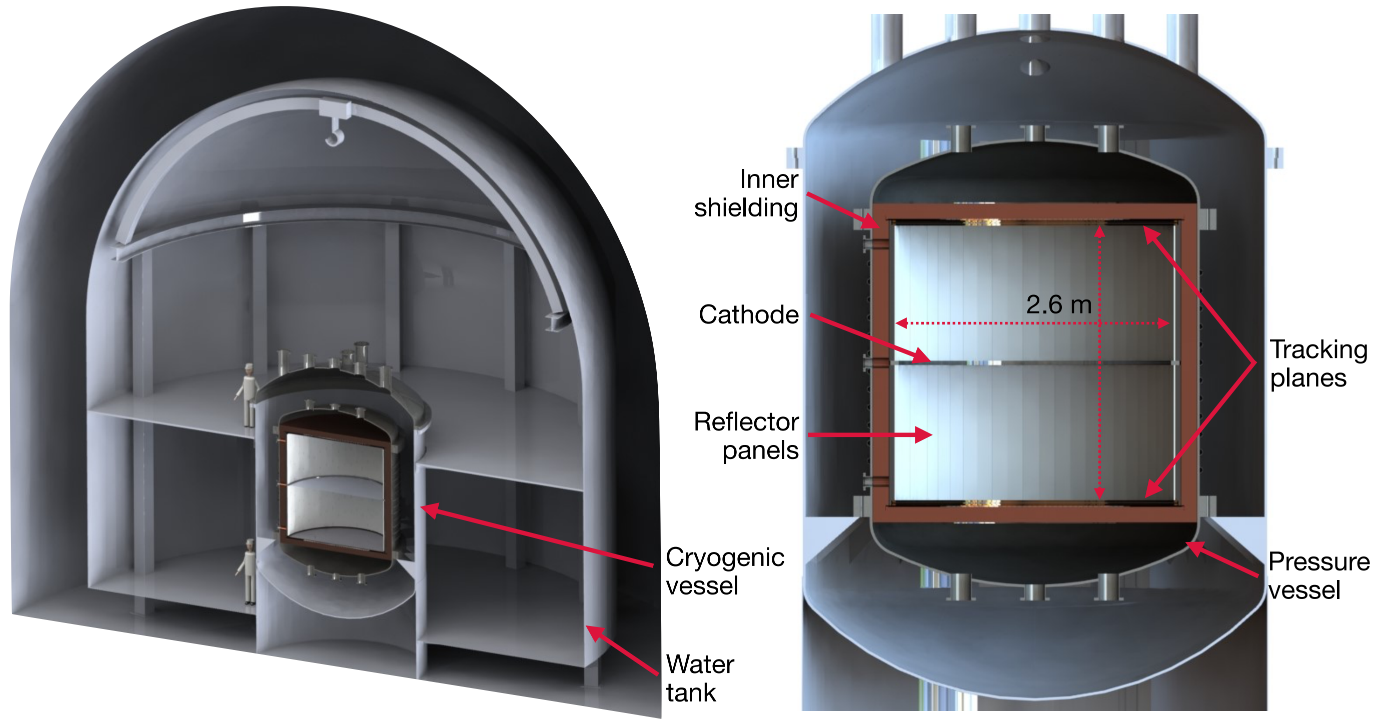


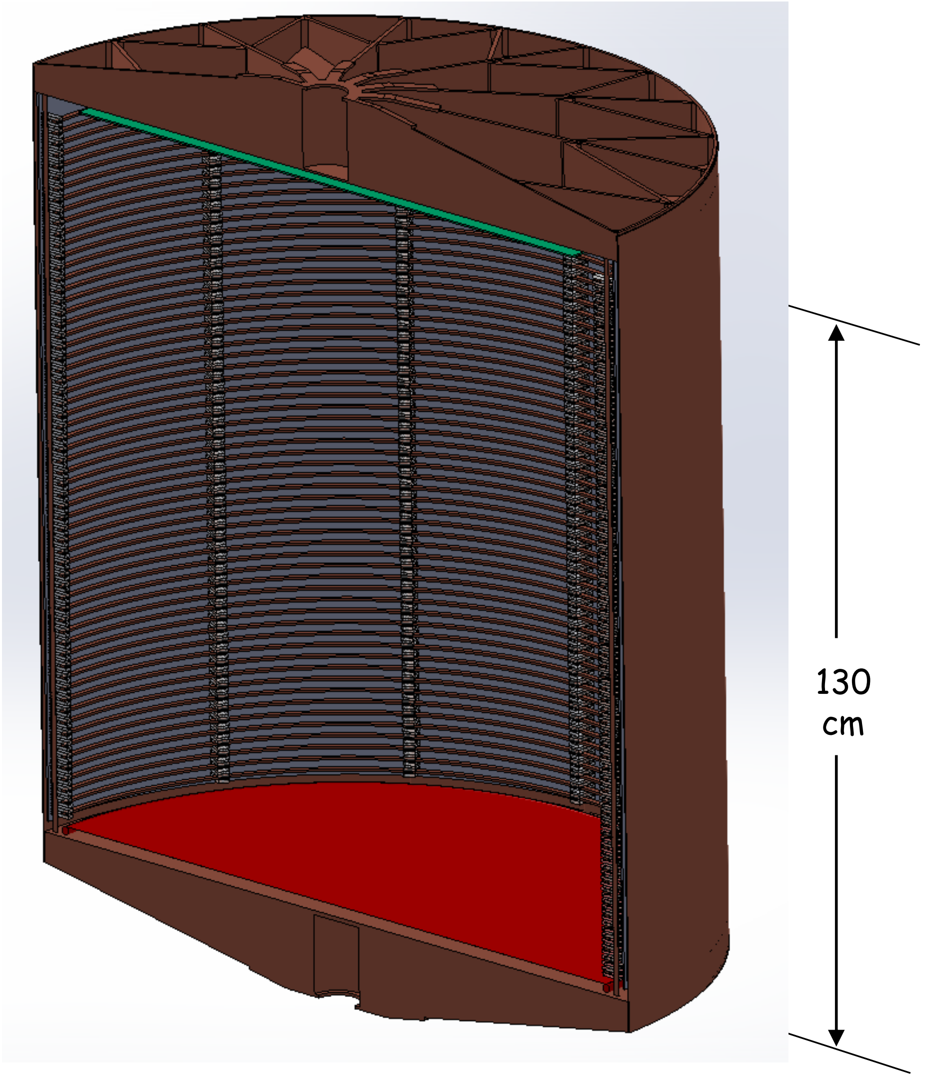
$$B \sim 4 \times 10^{-4}\ \mathrm{kg}^{-1}\ \mathrm{yr}^{-1}\ \mathrm{kev}^{-1}$$



- ***JINST*** **13 (2018) 12, P12010**

Percival vs Merlin



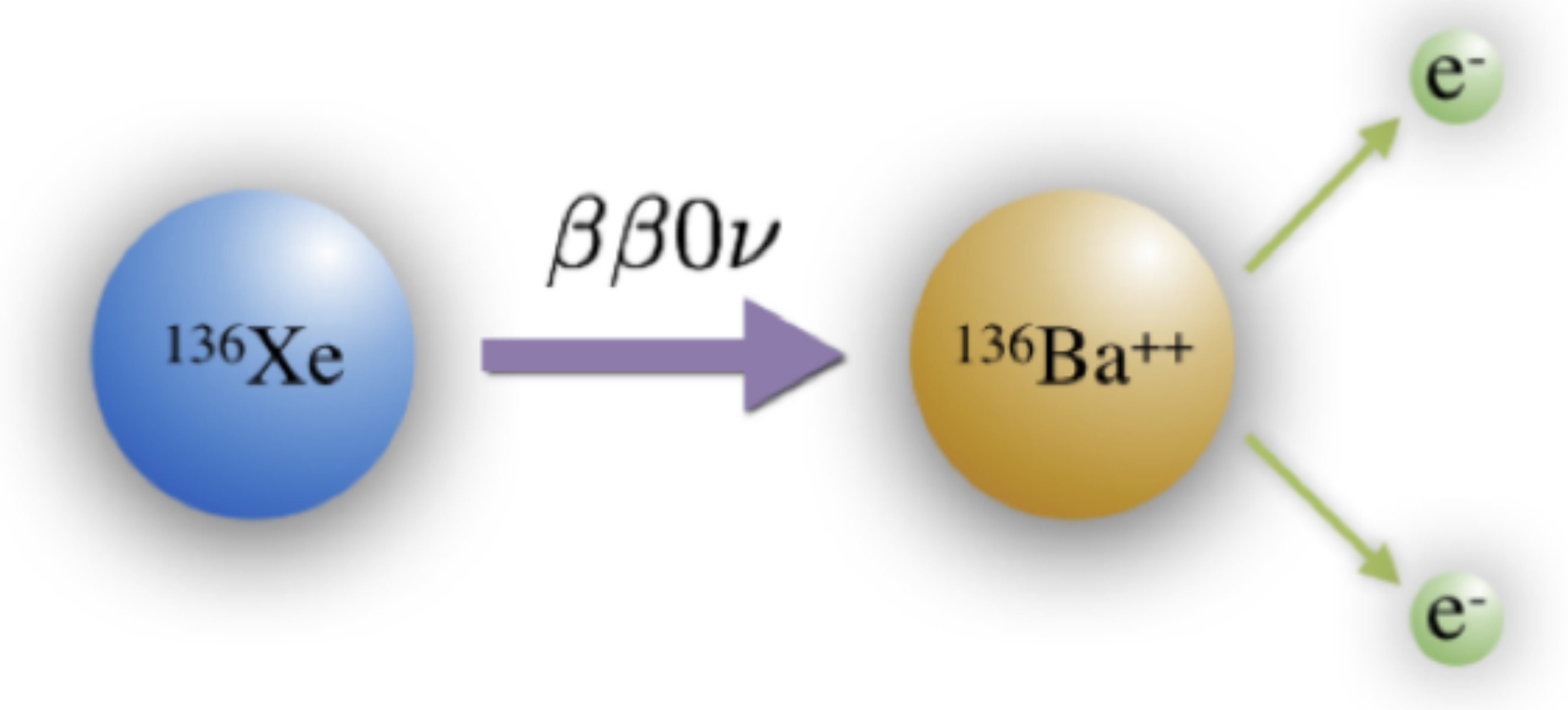


- $\Delta E/E \sim 0.5\,\%\ FWHM$
- $BI = 3 \times 10^{-6} ckky$ (Topology radio purity)
- $\epsilon \sim 25\,\%$
- Mass ~1-2 ton
- Xe-136 spallation not dominant

- $\Delta E/E \sim 2\,\%\ FWHM$
- $BI = 6 \times 10^{-6} ckky$ (self-shielding, radiopurity)
- $\epsilon \sim 80\,\%$
- Mass (fiducial) ~1-2 ton
- Xe-136 spallation may be a problem (mitigated by depth)

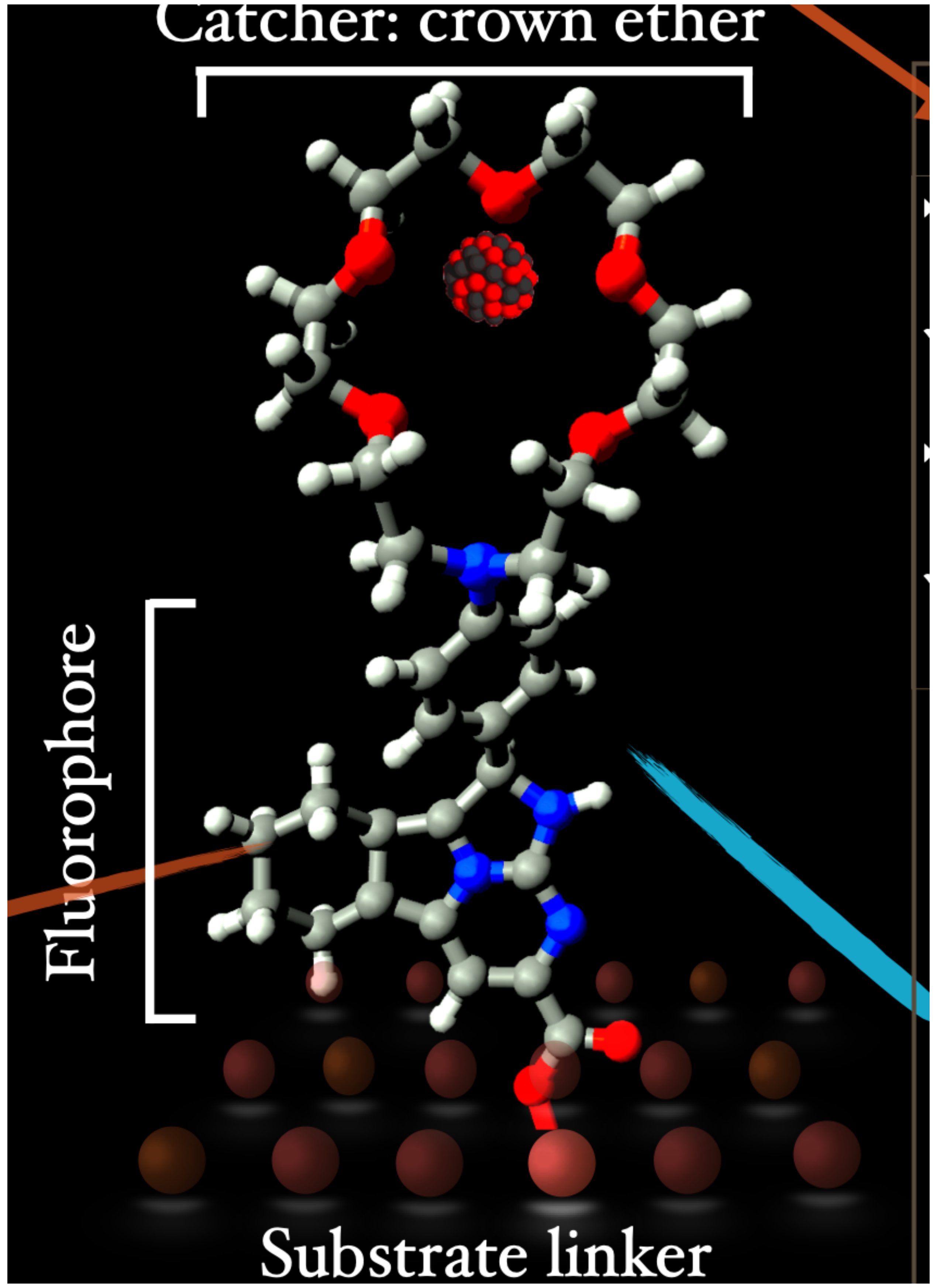
BOLD (Lancelot)

NEXT-BOLD



Detecting “tagging” the Ba++ signaling a ββ0v process has been a long sought holy grail of xenon chambers.

Ba2+ detection using molecular indicators



D. Nygren , J.Phys.Conf.Ser. 650 (2015) no.1, 012002

A.D. McDonald *et al.* (NEXT Collaboration)
Phys. Rev. Lett. 120, 132504 (2017)

Nature Sci Rep 9, 15097 (2019)

Nature 583, 48–54 (2020)

ACS Sens. 2021, 6, 1, 192–202 (2021)

- **Idea (Nygren)**: Exploit single molecule fluorescent imaging (SFMF) to visualise ("tag") a single Ba2+ ion as it arrives at the TPC cathode
- **Ba2+ sensor**: Based on molecular indicators, able to change luminous response after chelating Ba2+ cations.
- **Apparatus**: Must be able to detect in delayed coincidence the electron signal (in anode) and the cation signal in cathode.
- **Crucial bonus** : delayed coincidence pushes estimated background (and error) to very small numbers (ultimately limited by $\beta\beta2\nu$ at levels near 10^{-9} ckky). Efficiency of delayed coincidence can be measured (calibration with Ra2+ source).

Ba2+ expected to chelated indicators in high pressure gas

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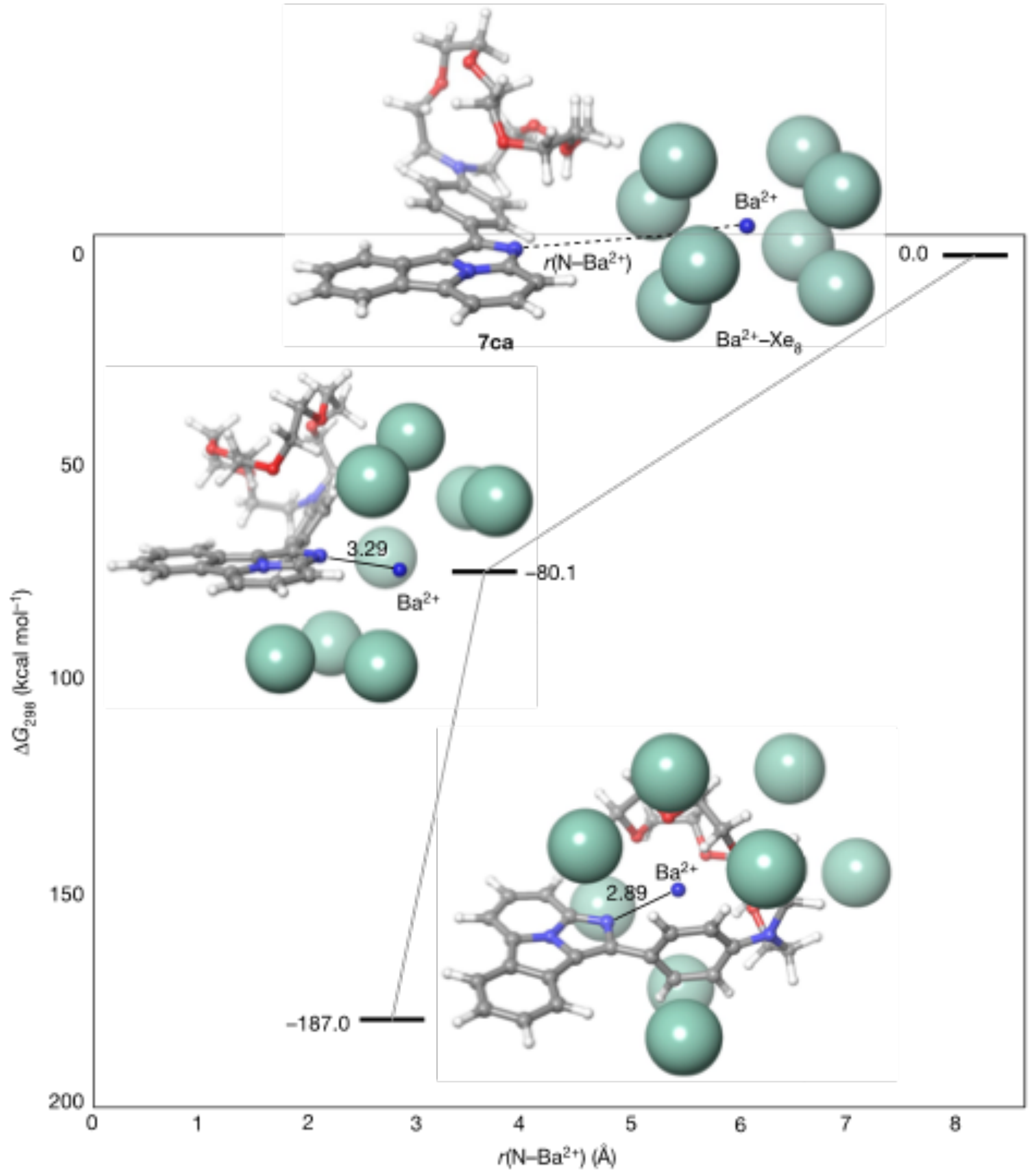
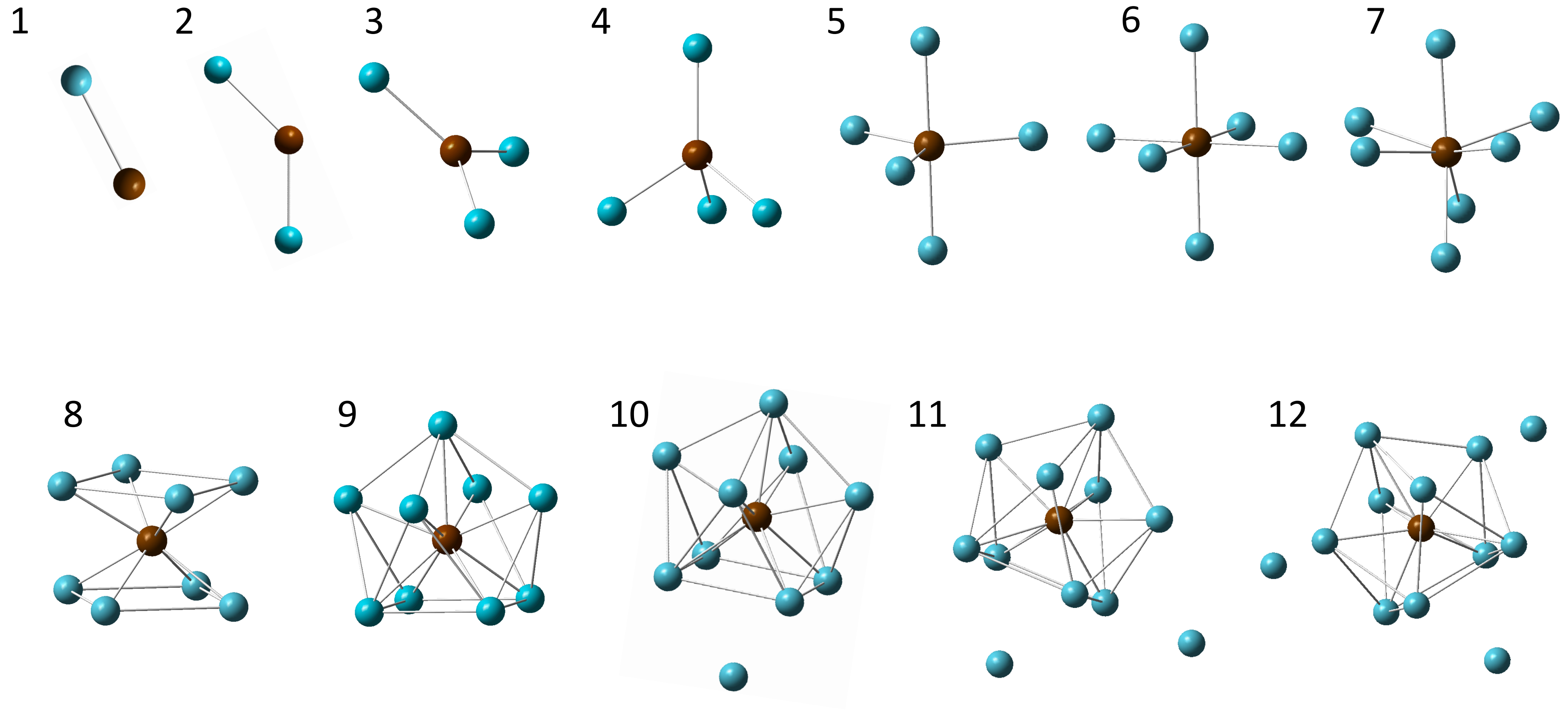
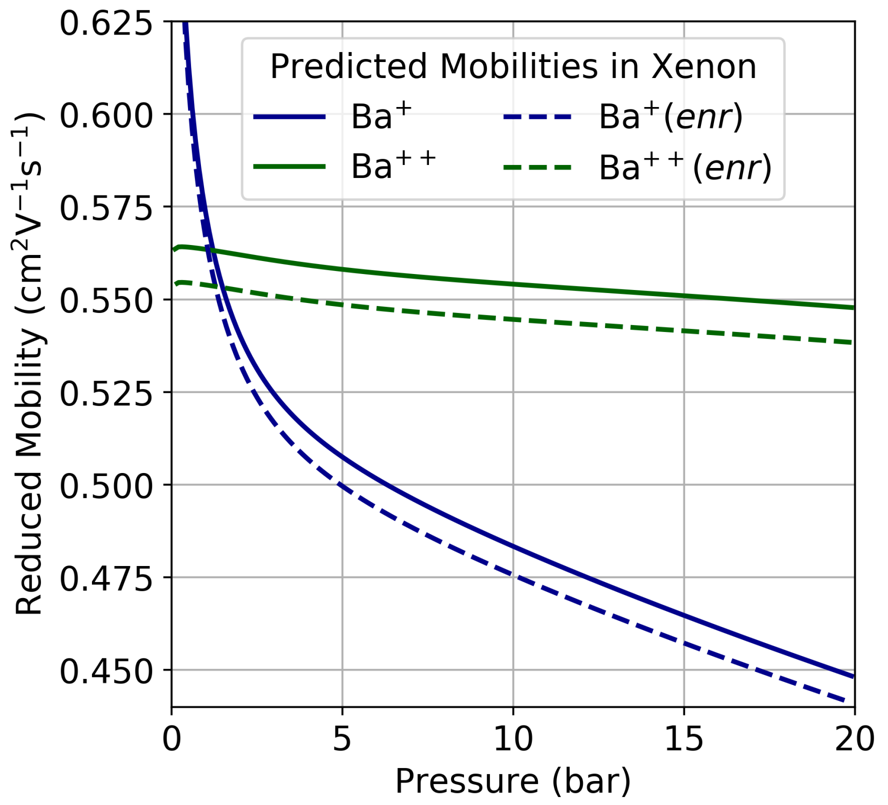


Fig. 4 | Computed structures of FBI (7ca) and a Ba^{2+}Xe$_8$ cluster at different N–Ba^{2+} distances. The geometries and energies shown were computed using DFT (see Methods for further details). Xenon atoms are represented using the Corey–Pauling–Koltun (CPK) space-filling model. The remaining atoms are represented using a ball-and-stick model and the CPK colouring code. Relative free energies (ΔG_{298}), have been computed at 25 °C (298 K).

Phys. Rev. A **97**, 062509





New Chemistry

- Conventional ion chemosensors are not suitable for solventless (dry) imaging.
- NEXT has developed selective, dry-phase imaging of barium ions using crown ether derivatives.
- Ring receptor can be tuned to bind efficiently and selectively to barium.
- Computational chemistry is predictive for molecular fluorescence and binding.
- Two types have been developed: **on-off**, and **bi-color.**

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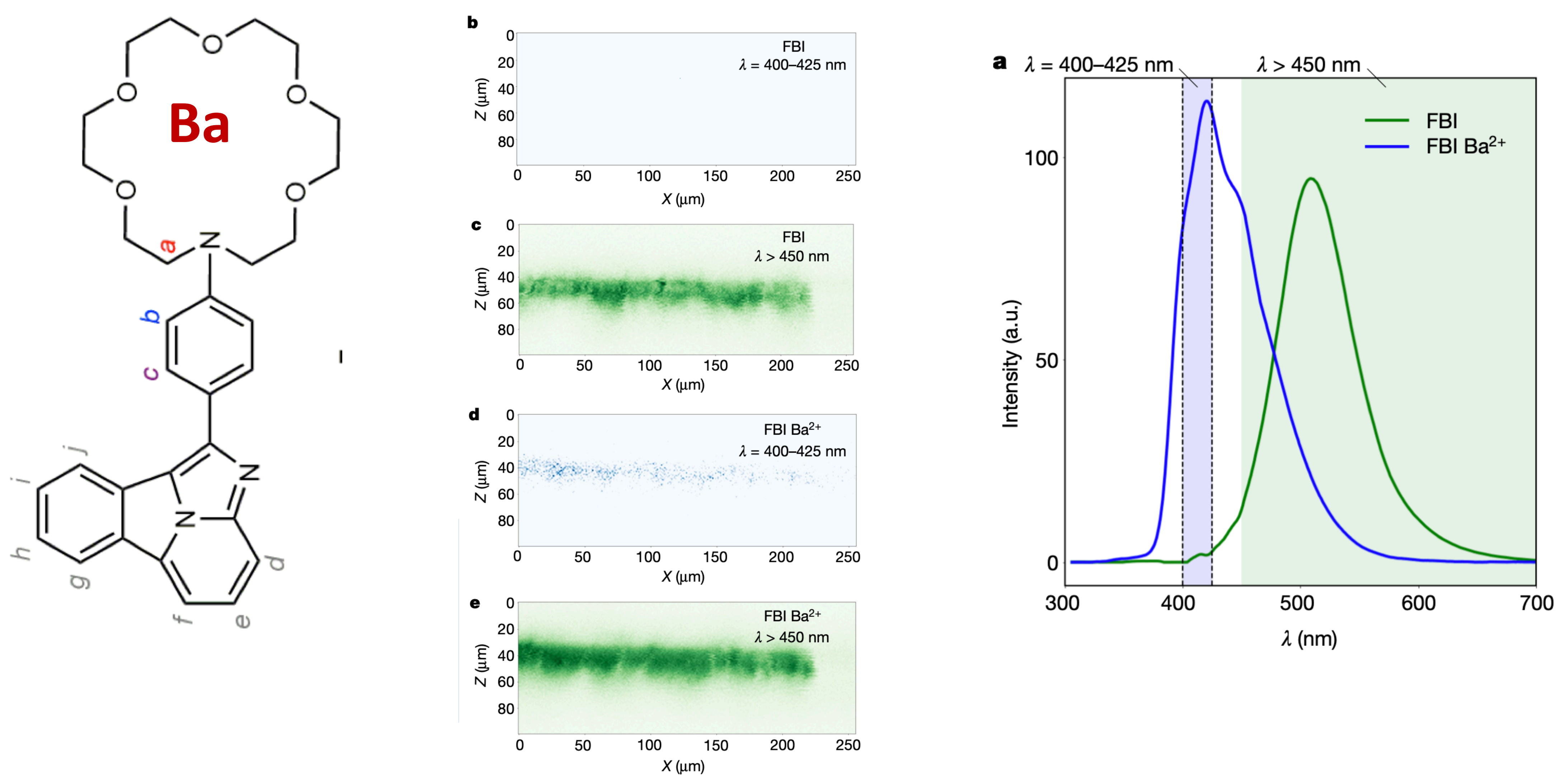
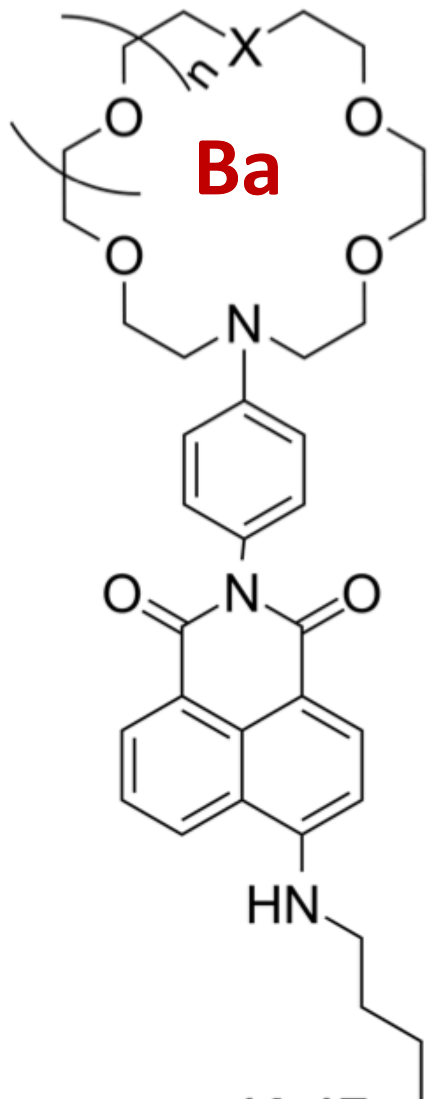
arXiv: 2006.09494 (submitted to JACS)

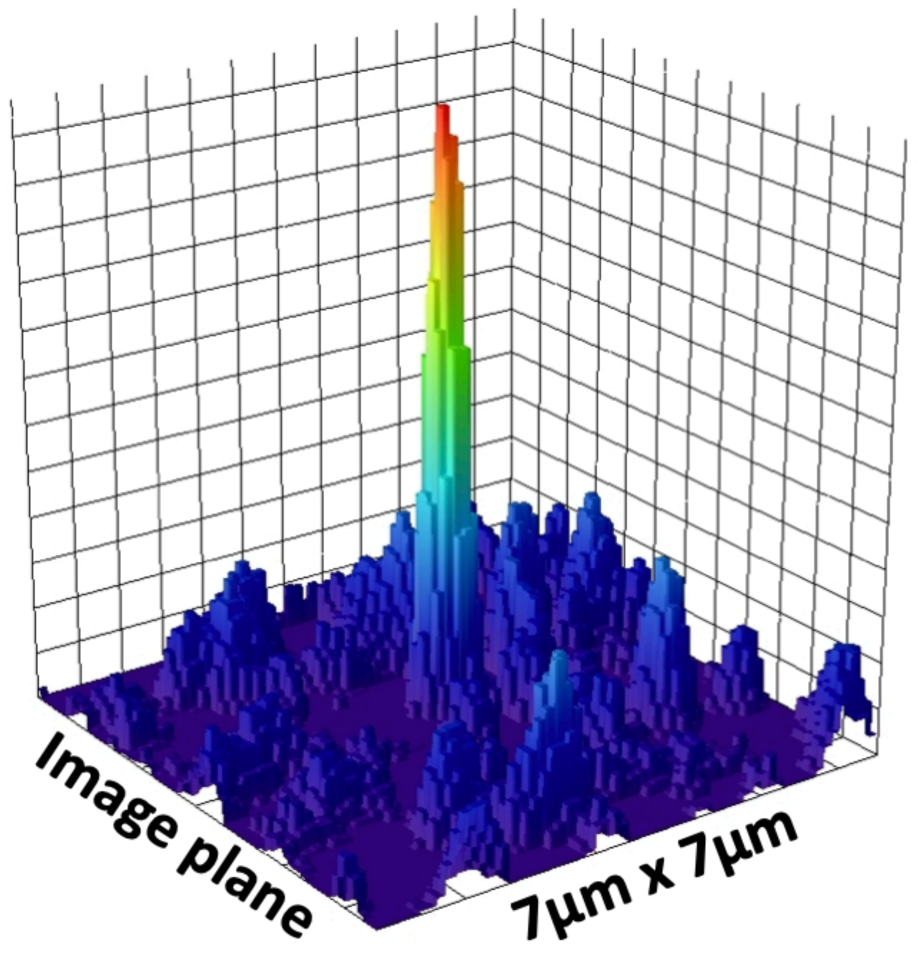
In-vacuo capture from $Ba(ClO_4)_2$ with bi-color response

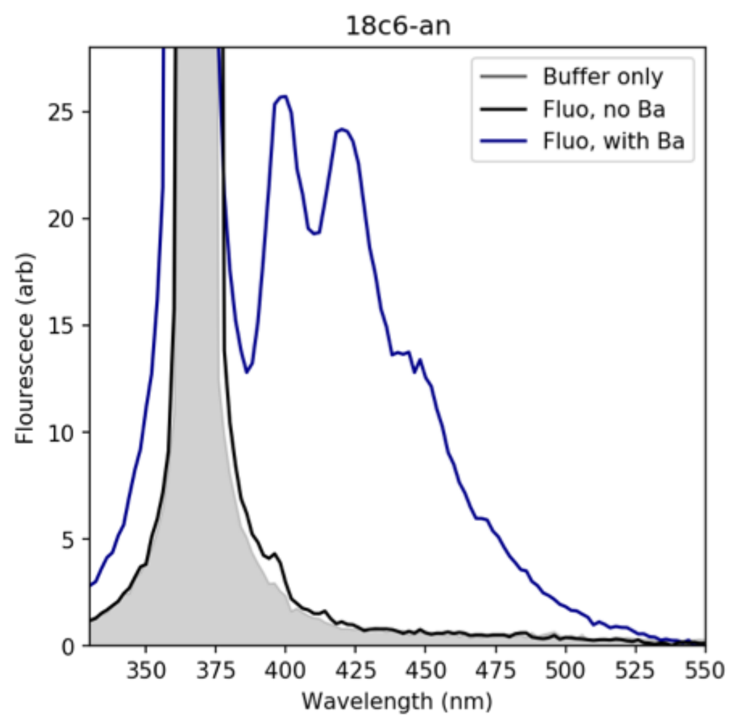


Dry single Ba++ ion detection with on-off fluorescence



1A-1E





First demonstration of Ba2+ chelation in dry medium

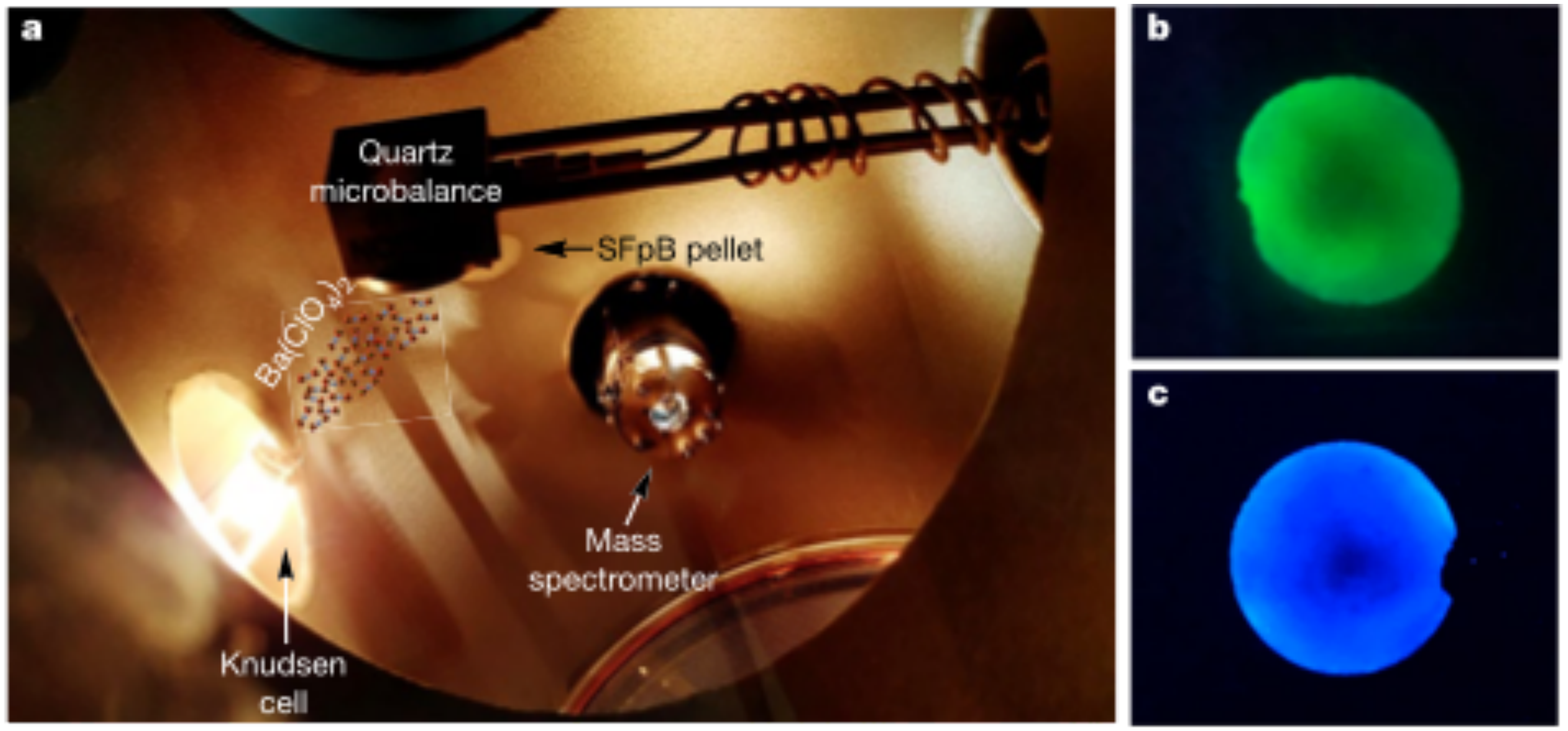


Fig. 3 | Sublimation of $Ba(ClO_4)_2$ on the FBI. a, Experimental setup. Photograph of the interior of the UHV chamber used for sublimation. The positions of the pellet, evaporator, quartz microbalance and mass spectrometer are indicated. **b**, **c**, Photographs of the pellet before (**b**) and after (**c**) the sublimation. In both cases, the excitation light is 365 nm. We note the characteristic green colour of unchelated FBI before the sublimation and the blue shift after the sublimation, which shows a large density of chelated molecules.

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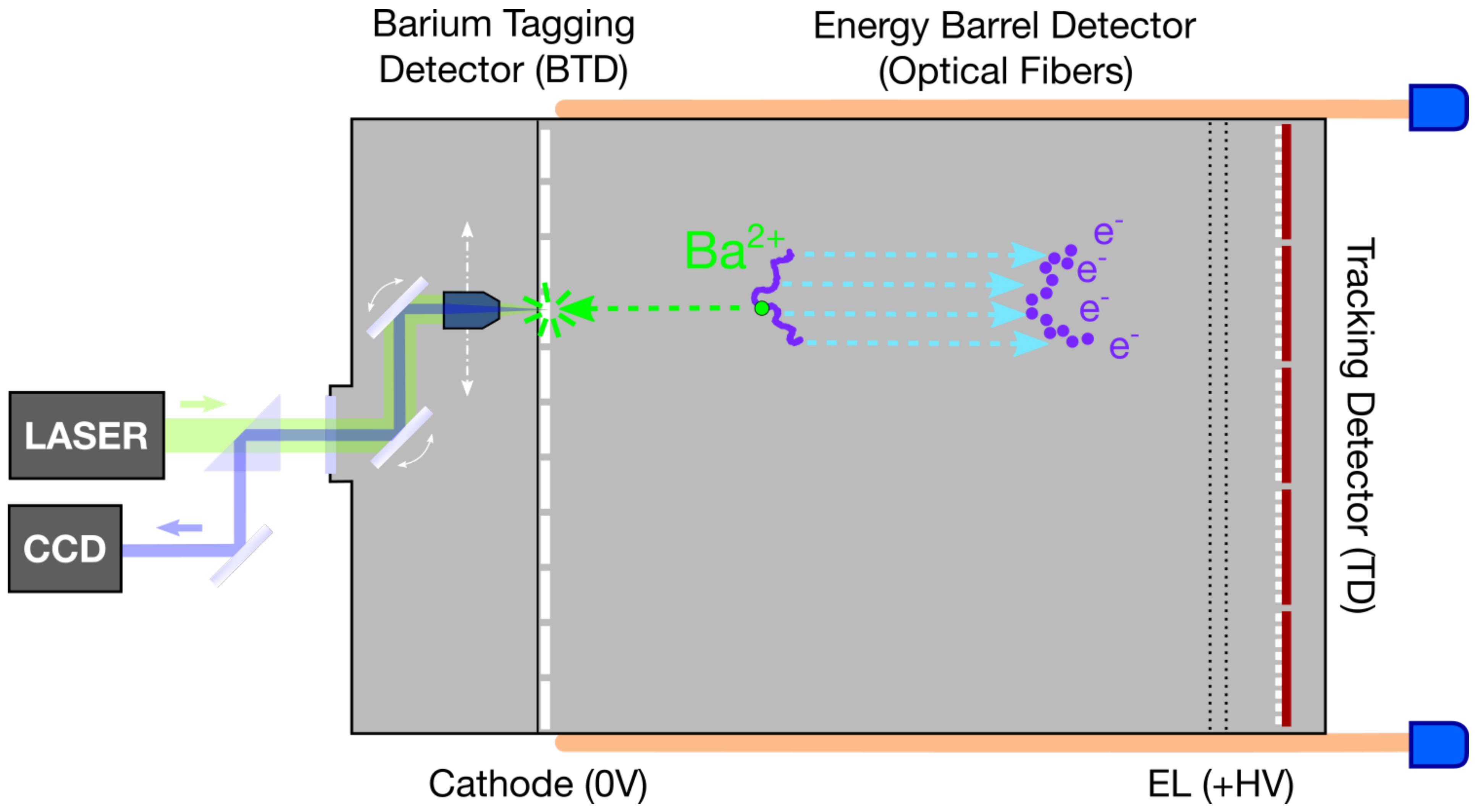
NEXT-BOLD concept

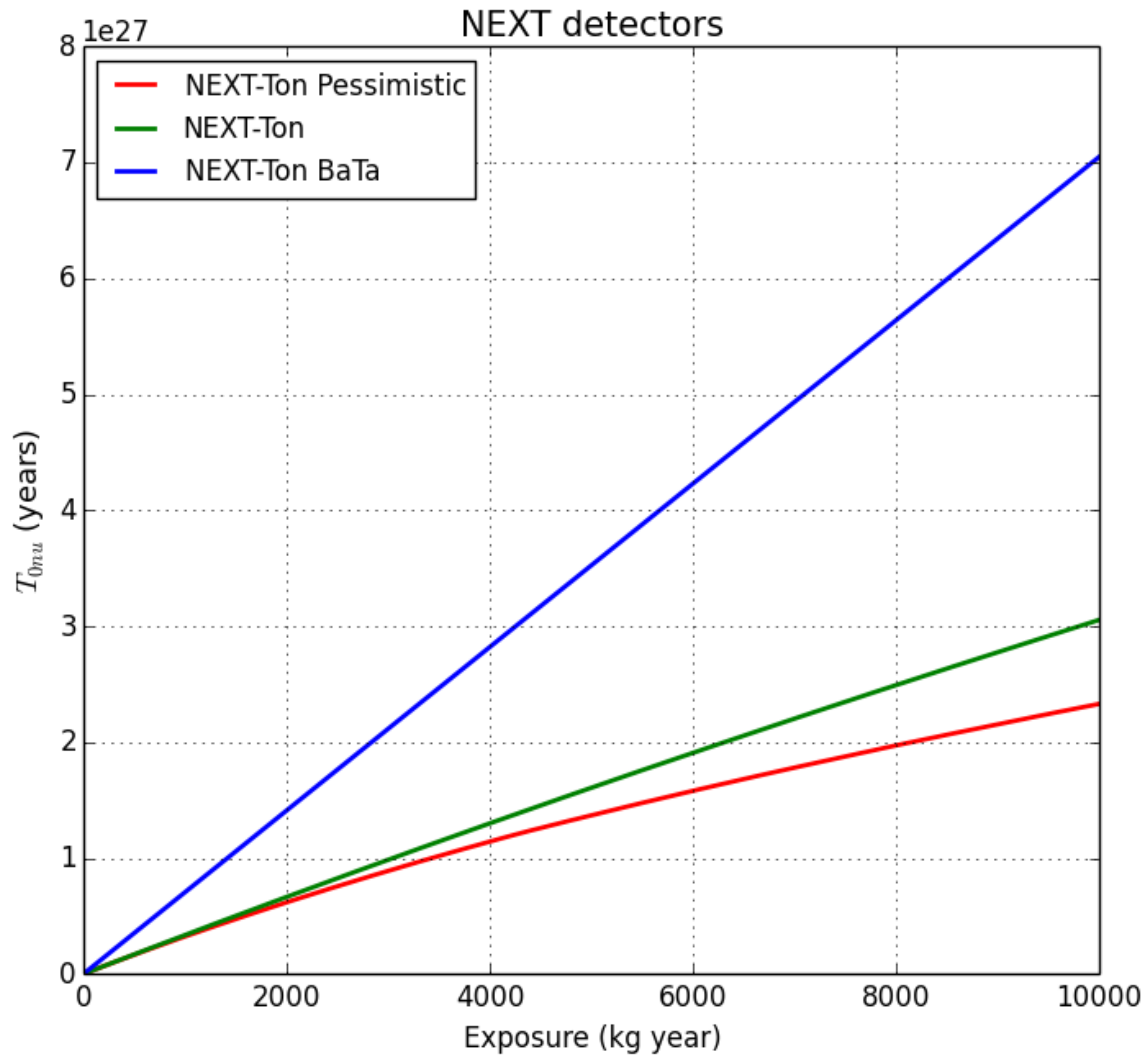


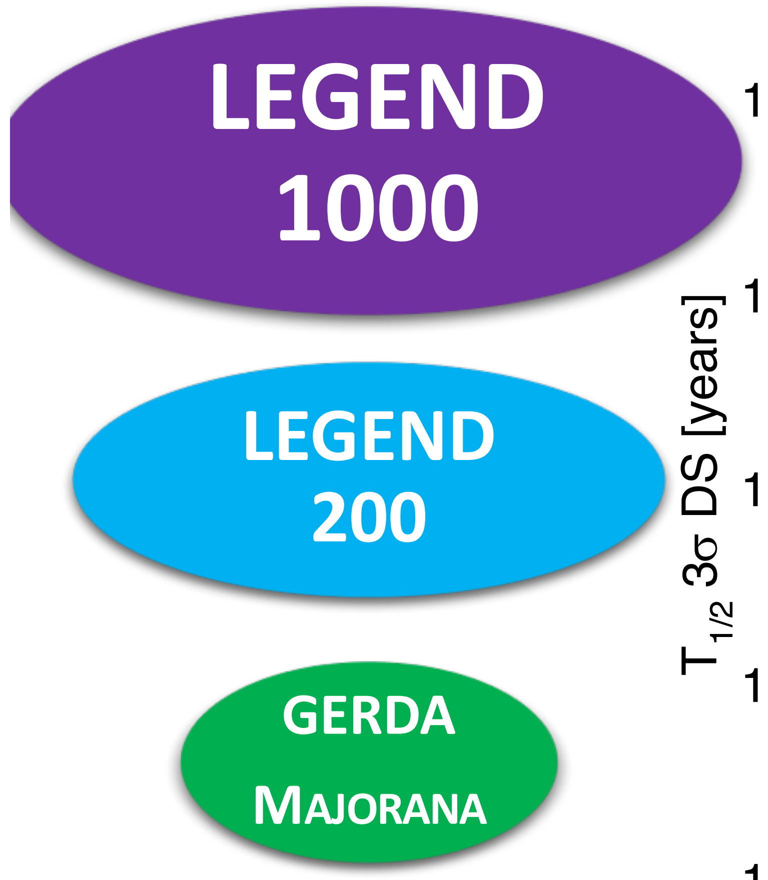
- Delayed trigger:
- Single deposition with energy in ROI
- Opens gate at predicted arrival time
- Scans ~1cm around predicted arrival point

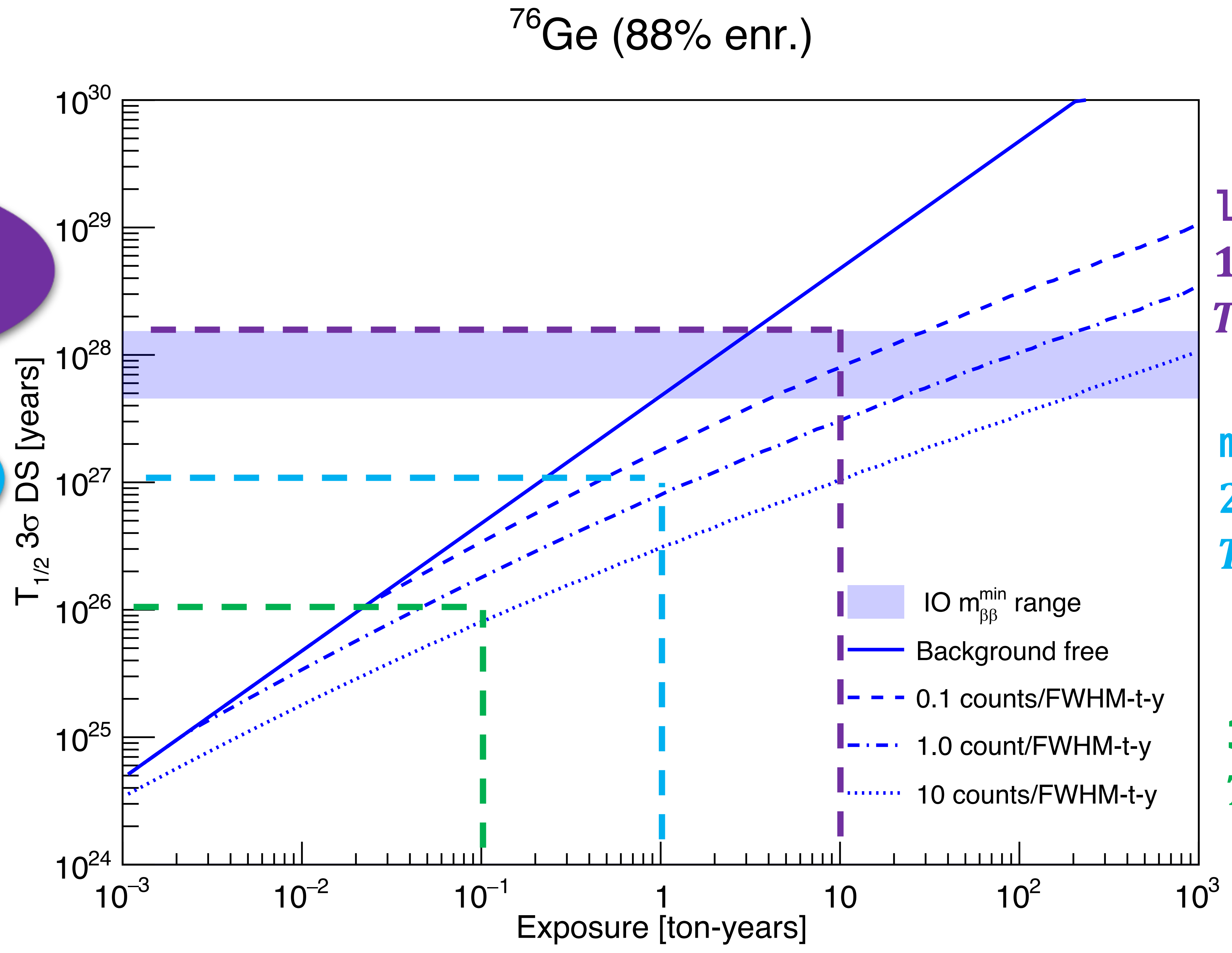
- Asymmetric detector.
- Energy measured by Barrel Detector (fibres).
- Topology reconstruction with SiPMs.
- High pressure to increase mass and decrease size of track (40 bars)
- Scanning region selected by predicted impact point.
- Cathode at V+ opens gate only on delayed bbonu trigger.
- Fast, high-pressure microscopy.
- Prototype: NEXT-White or NEXT-100

Funding for BOLD granted through an ERC Synergy Grant.

A background free experiment?







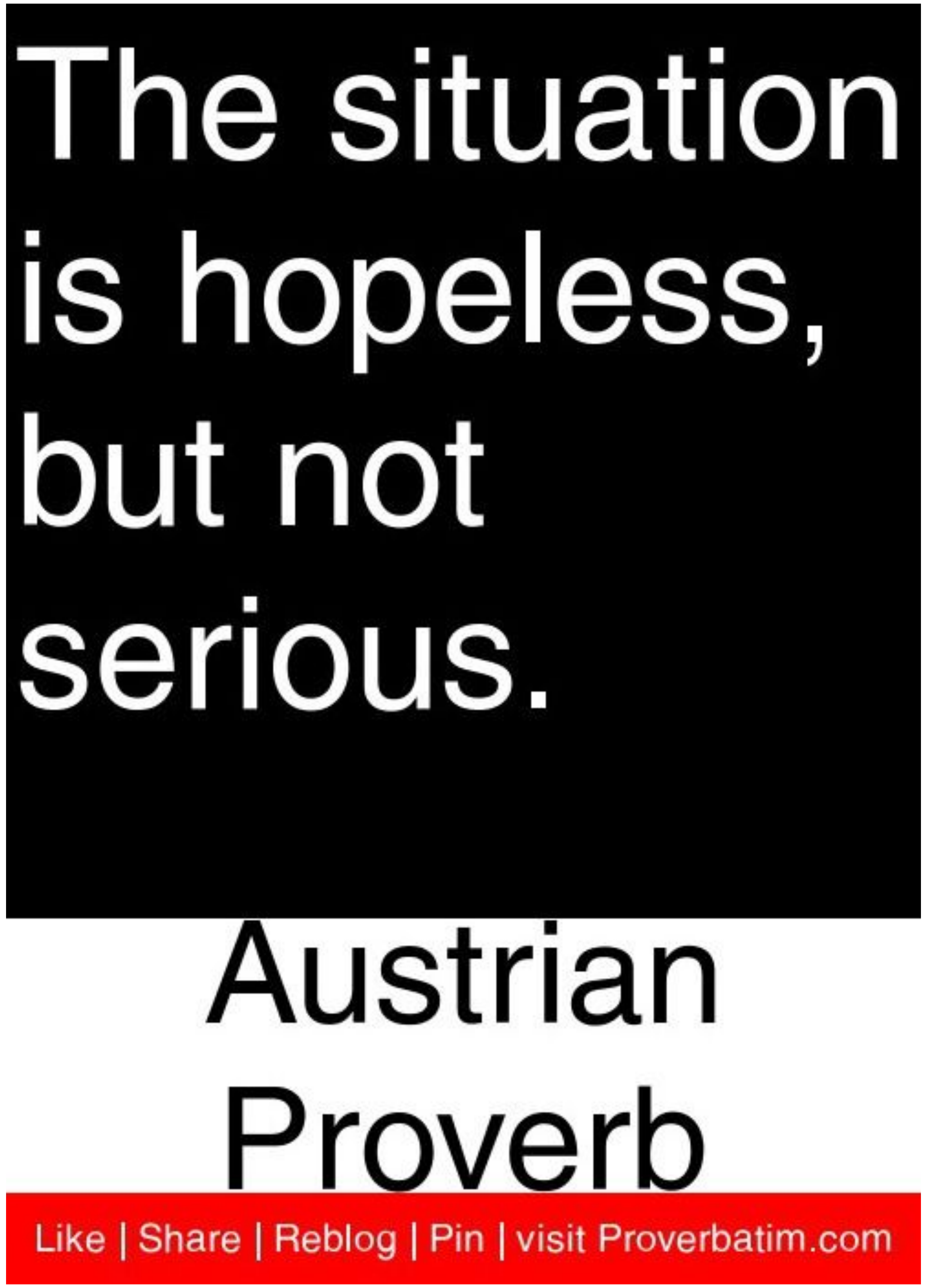
long-term
1 ton
$T_{1/2}^{0\nu} > 10^{28}$ yr

mid-term
200 kg
$T_{1/2}^{0\nu} > 10^{27}$ yr

running/ended
30 kg
$T_{1/2}^{0\nu} > 10^{26}$ yr

- **IF barium tagging is possible AND efficient, the BOLD technique is essentially background free** (equally important: **background model free**)
- At higher pressure and not using topological signature, selection efficiency is larger and fiducial mass is also larger.

Finding the grail requires a pure heart



- We don’t know yet if single-atom barium tagging can be implemented in a large detector with sufficiently high efficiency.
- But we have a road map to do it (6-7 years) and the funding to go.
- The essential point to keep in mind is: reaching 1027 y is within the range of next-generation experiments (with a lot of work). But reaching 1028 appears hopeless (control of backgrounds to virtually zero while increasing the mass, cosmogonies, neutrino floor).
- And yet, we believe that the situation is hopeless but not serious. There are plenty of knights with pure hearts ready to try.
- Ultimately we will have the technology and the wits to find the Grail

Thanks for your attention