Low energy neutrino investigations

J. J. Gomez-Cadenas
Donostia International Physics Center (DIPC),
Fermilab Neutrino University
August, 2018

Low energy neutrino investigations

Sounds too close to
low energy neutrino investigators?

What about...

Get a Nobel Price or set a limit!

Ouch! Too sincere?

.

Survive to discover!

Any Cruises around?

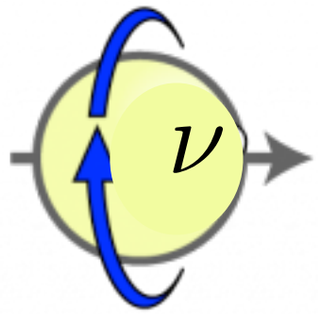
.

Exploring Majorana Landscape

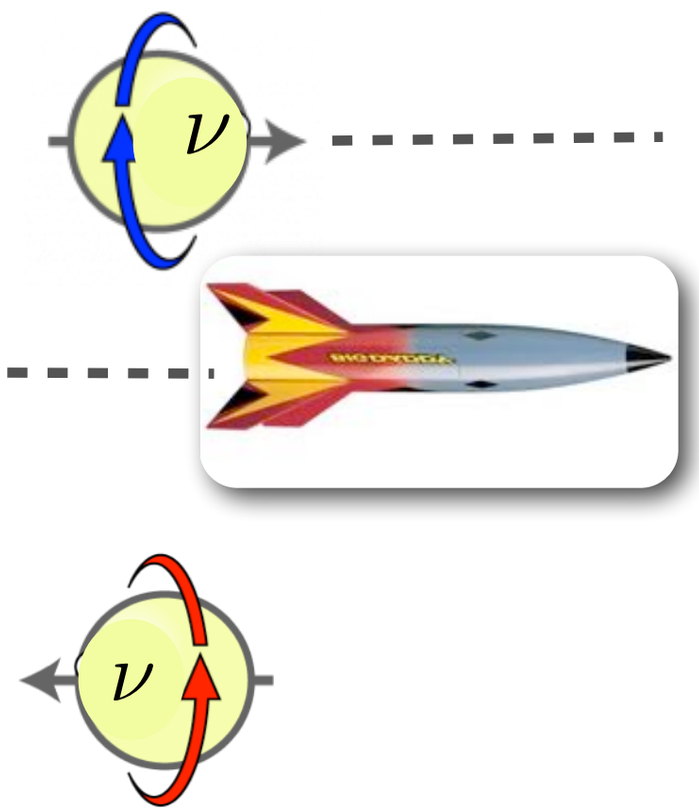
J. J. Gomez-Cadenas
Donostia International Physics Center (DIPC),
Fermilab Neutrino University
August, 2018

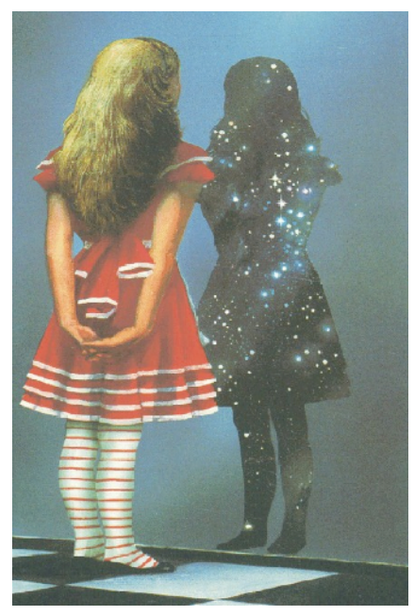
- Experimentalist babbling about neutrino theory follows for the next 16 slides.
- Those of you who have attend the lectures of Boris Kayser and Stephen Parke, can now safely babysit your iphones.

Neutrino through the looking glass



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

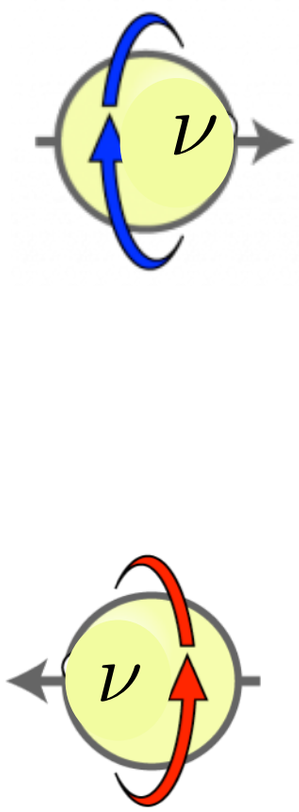




•It would be possible to turn a left handed neutrino into a right handed neutrino by jumping in a reference frame that moves faster than the neutrino. But a massless neutrinos moves at the speed of light and cannot be overtaken

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

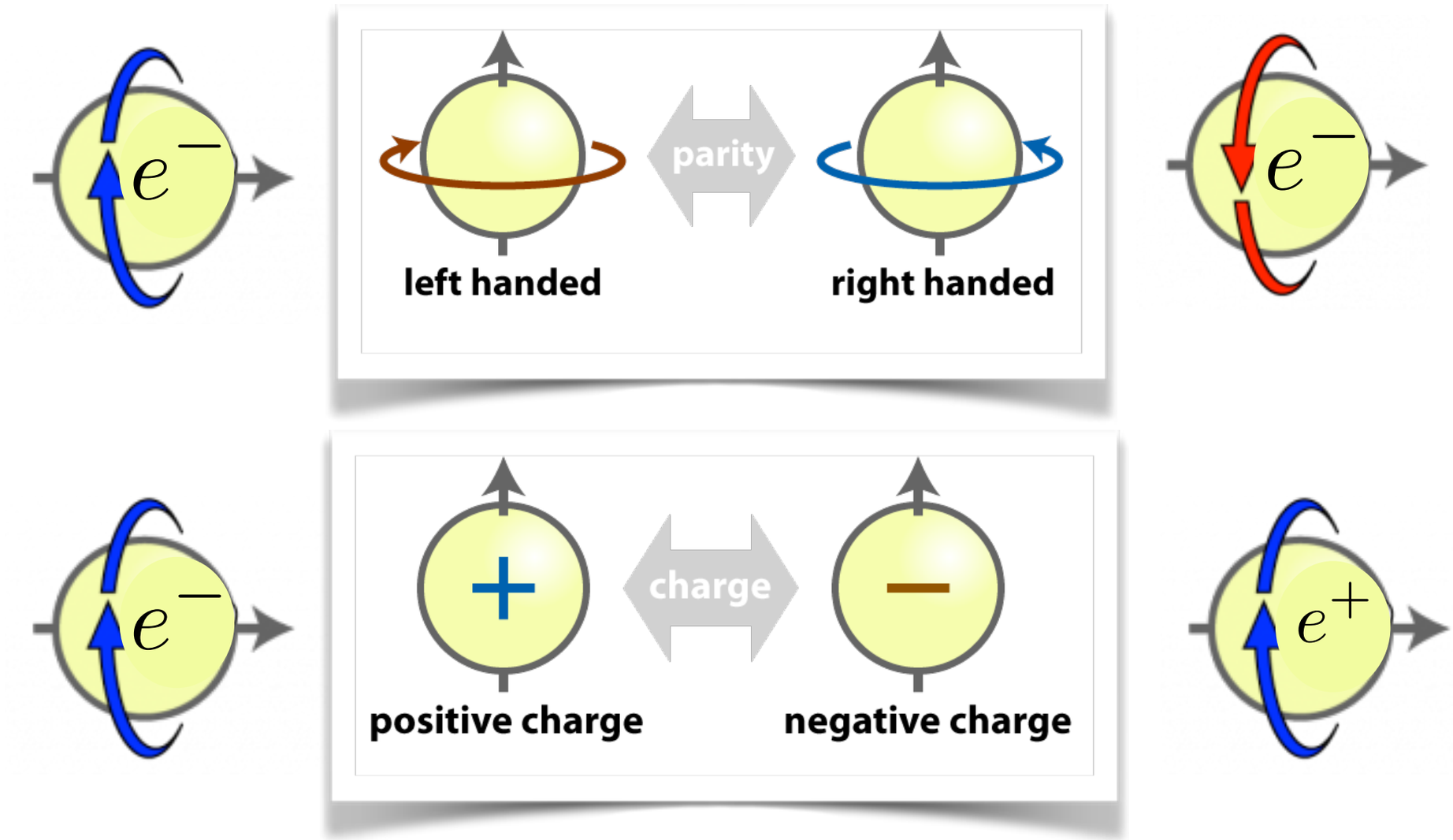
But what if neutrinos are massive?

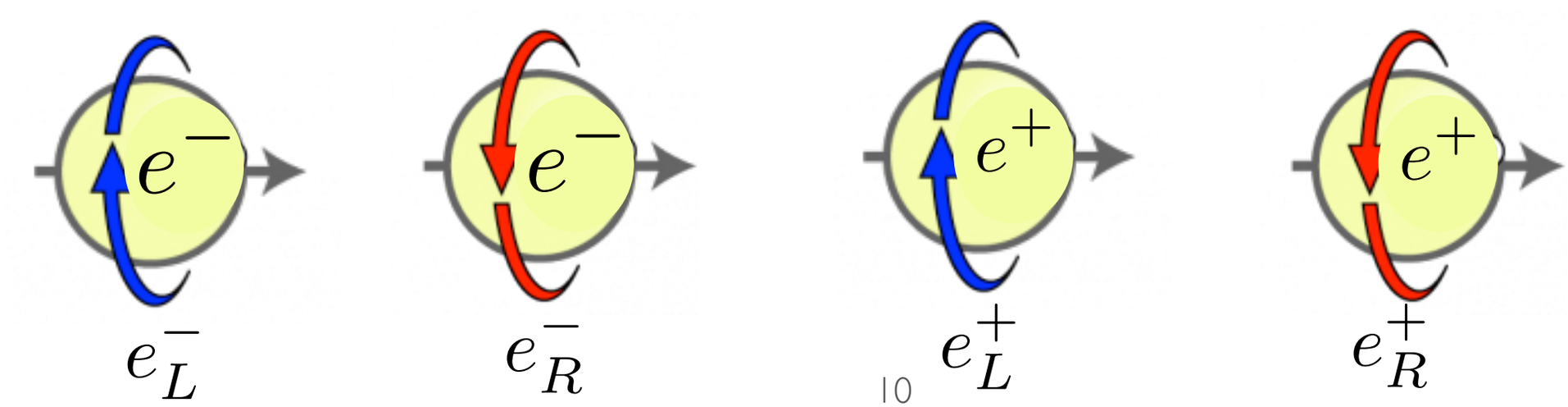


- Reversing the argument, because neutrinos are massive, left-handed and right-handed neutrinos are guaranteed to exist. How does a massive neutrino reflects in the mirror?

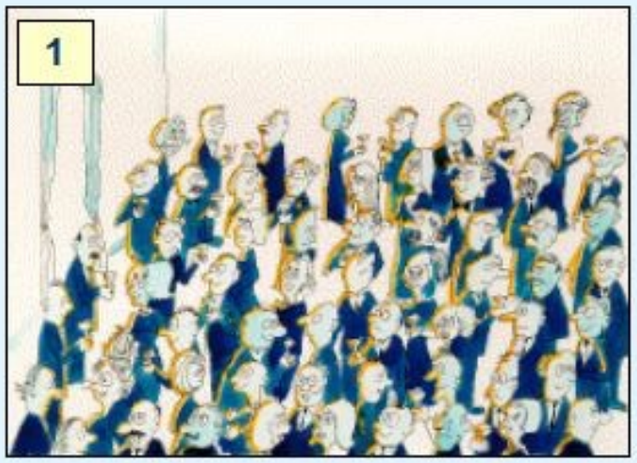
- Who is the right-handed neutrino state ? How do we give neutrinos a mass ?

Electrons through the looking glass





The Higgs mechanism

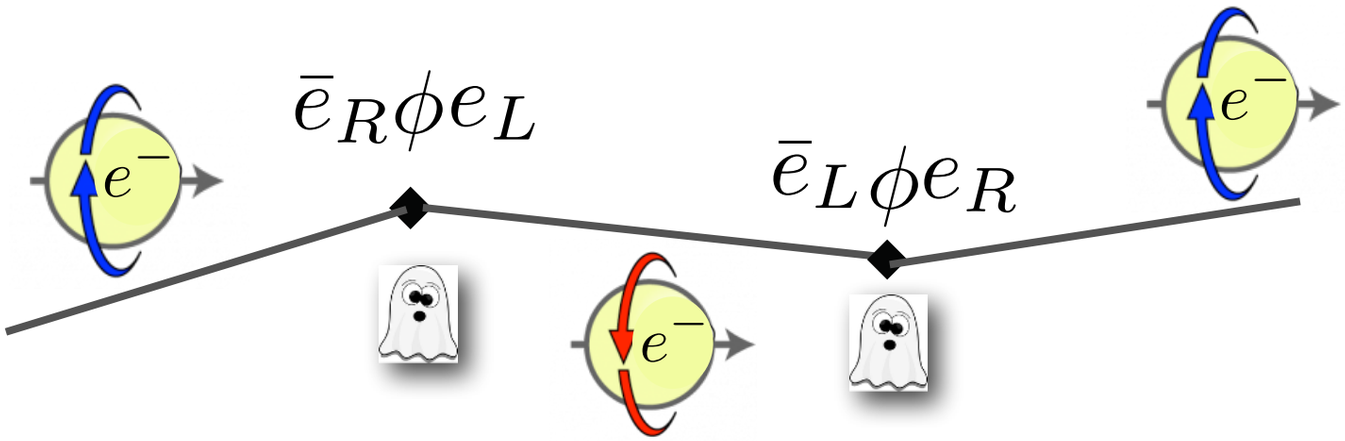


Imagine you're at a Hollywood party. The crowd is evenly distributed around the room, chatting. The room is like space filled with the Higgs Field.

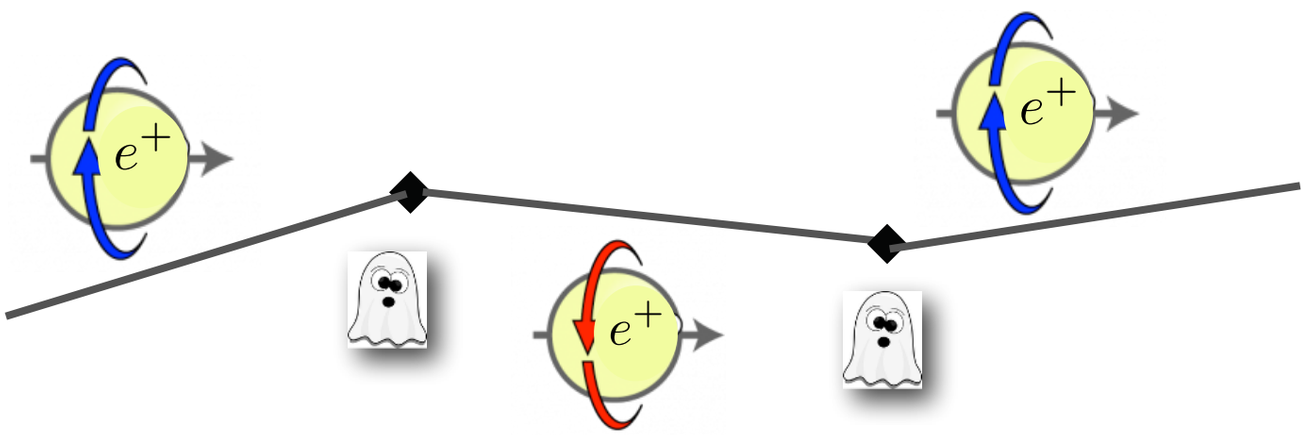
When the big star arrives, the people nearest the door gather around her.

As she moves through the party, she attracts the people closest to her. This increases her resistance to movement. In other words, she acquires mass, just like a particle moving through the Higgs field.

Electron mass



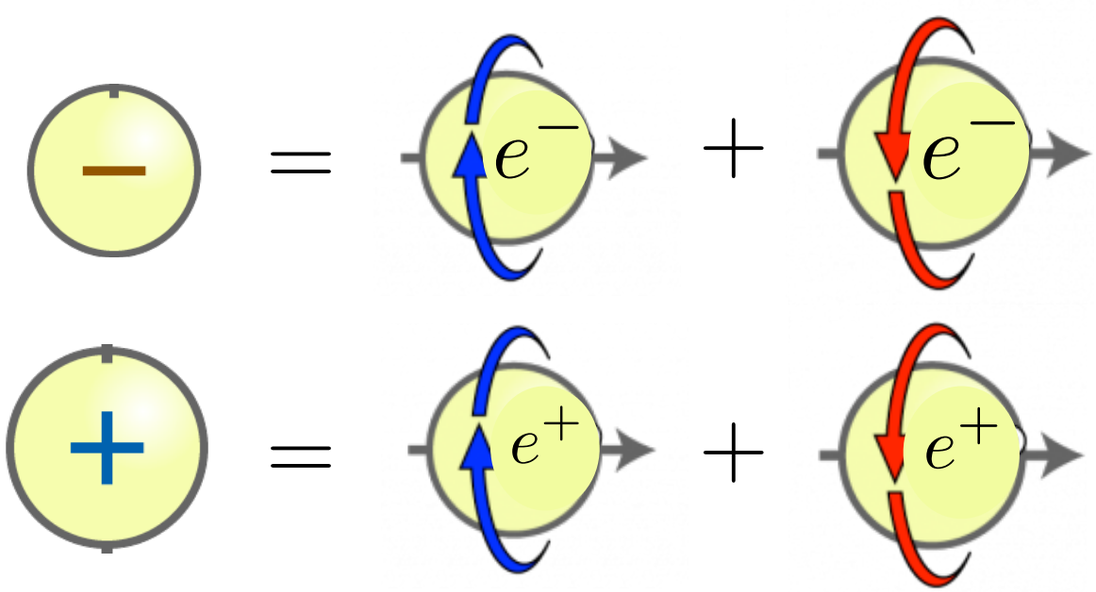
left and right handed states bump against the Higgs field



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

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

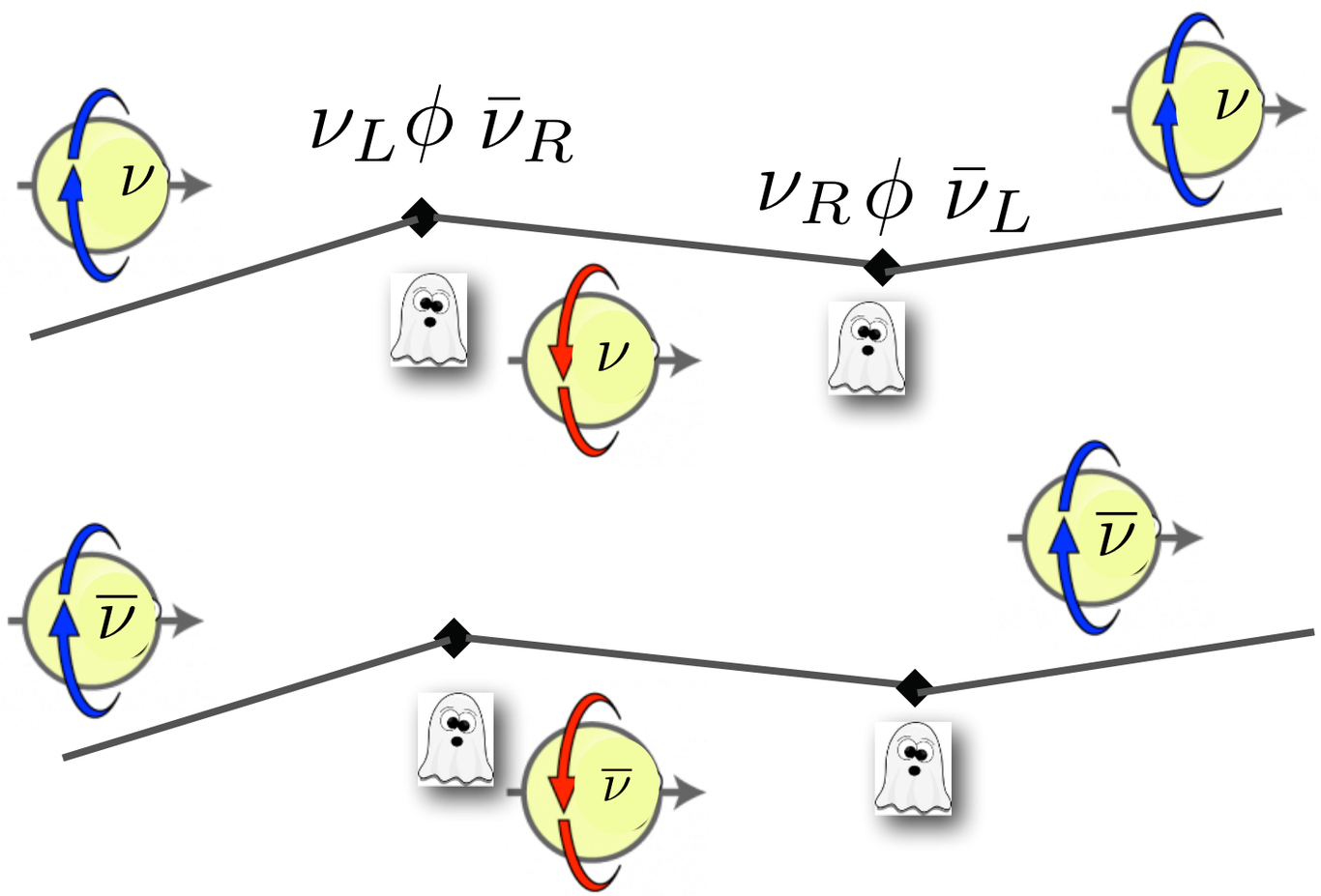
$$m_e = \lambda_e v$$

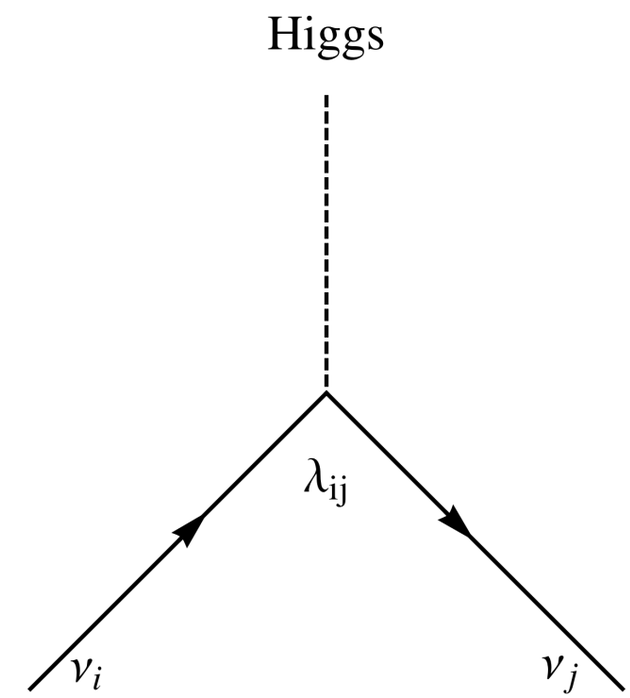


$$e^- = e^-_L + e^-_R$$

$$e^+ = e^+_L + e^+_R$$

Neutrino mass (Dirac recipe)

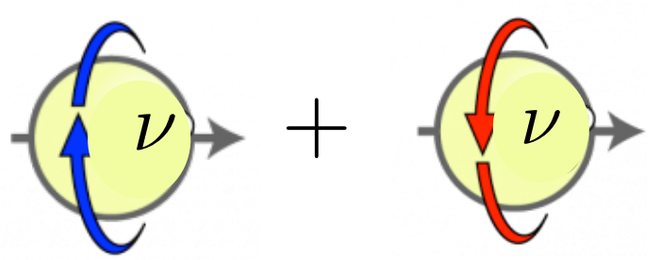




$$-\mathcal{L}_{\text{Dirac}} = \bar{\nu}_L m_\nu \nu_R + h.c.$$

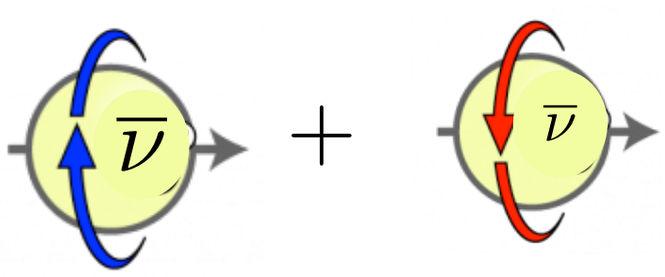
$$m_\nu = \lambda_\nu v$$

ν =



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

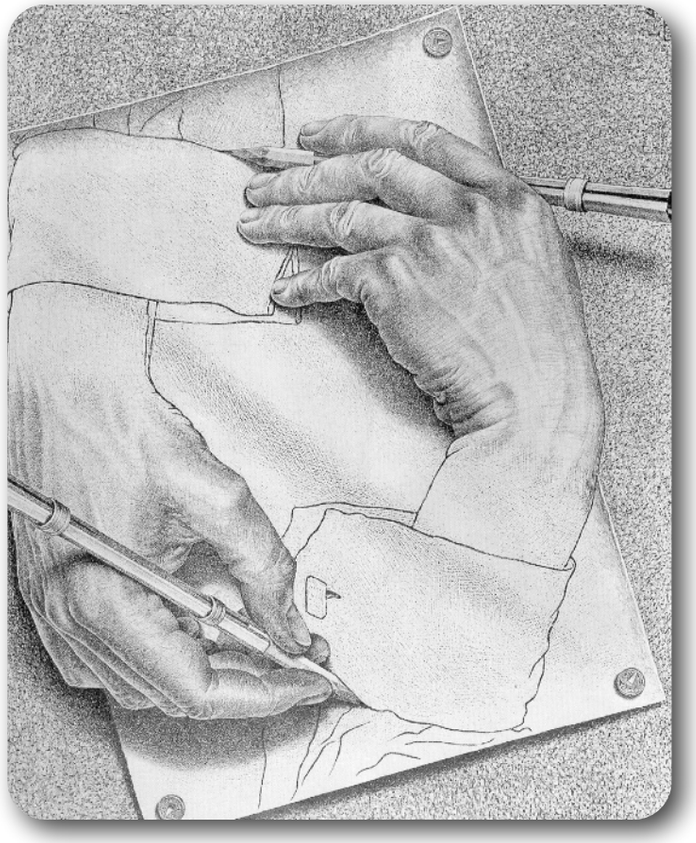
$\bar{\nu}$ =



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

Neutrino charge conjugation

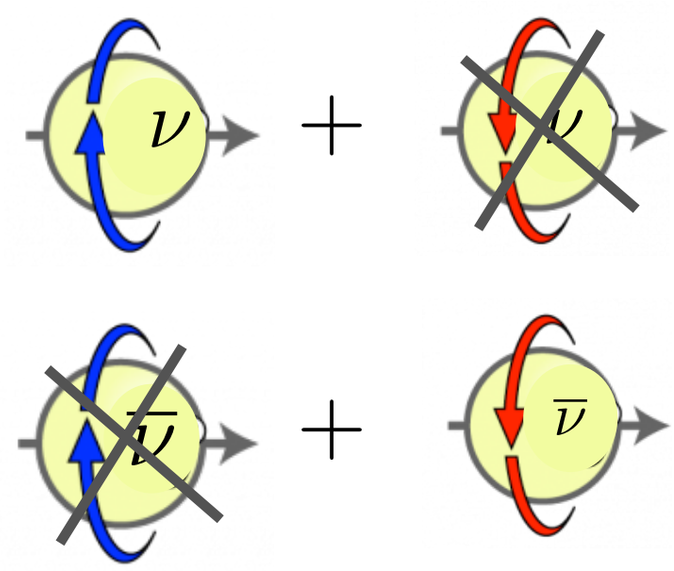
Charge conjugation reverses the electric charge of the electron.



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

Majorana neutrinos

ν =



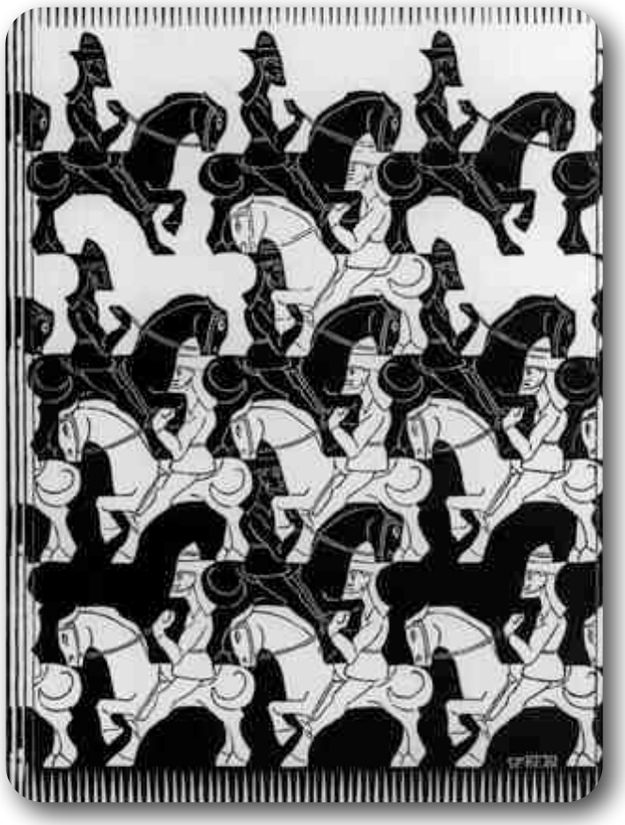
$\nu = \nu_L + \cancel{\nu_R}$

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

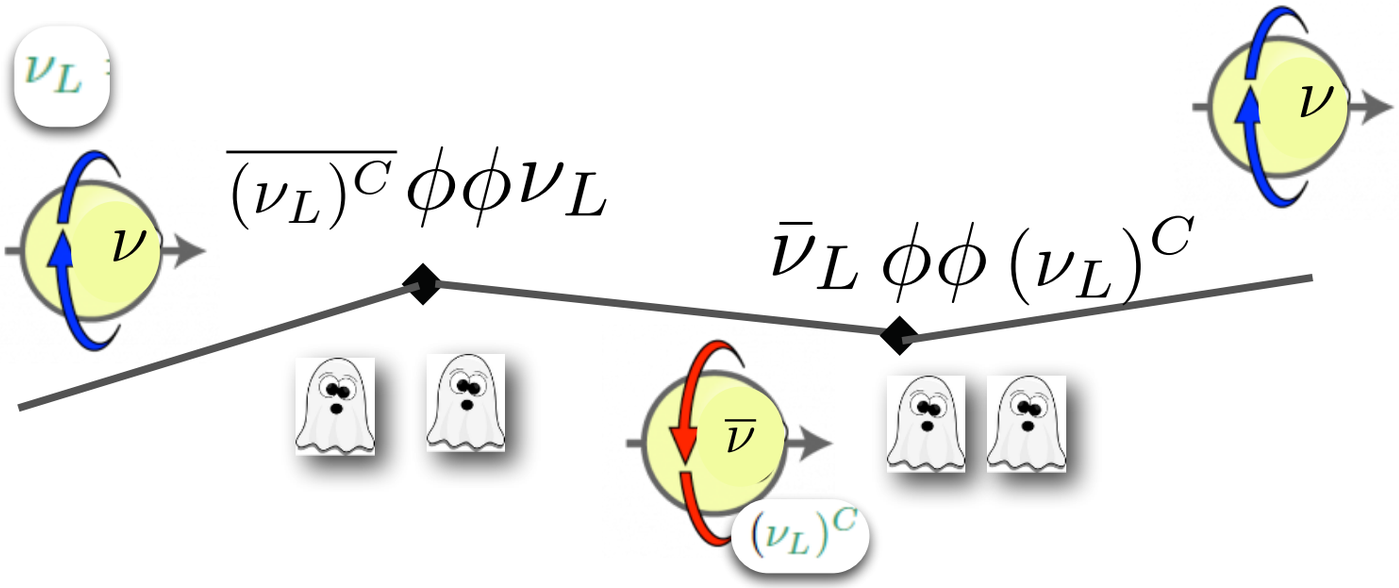
$\nu = \bar{\nu}$

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

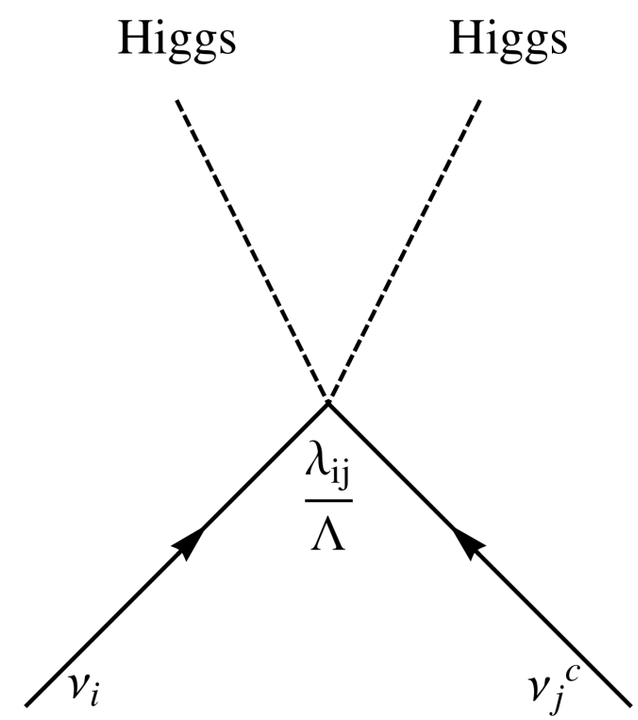
The neutrino is made, like in the Escher's tableau of black and white chevaliers.



Neutrino mass (Majorana recipe)



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



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

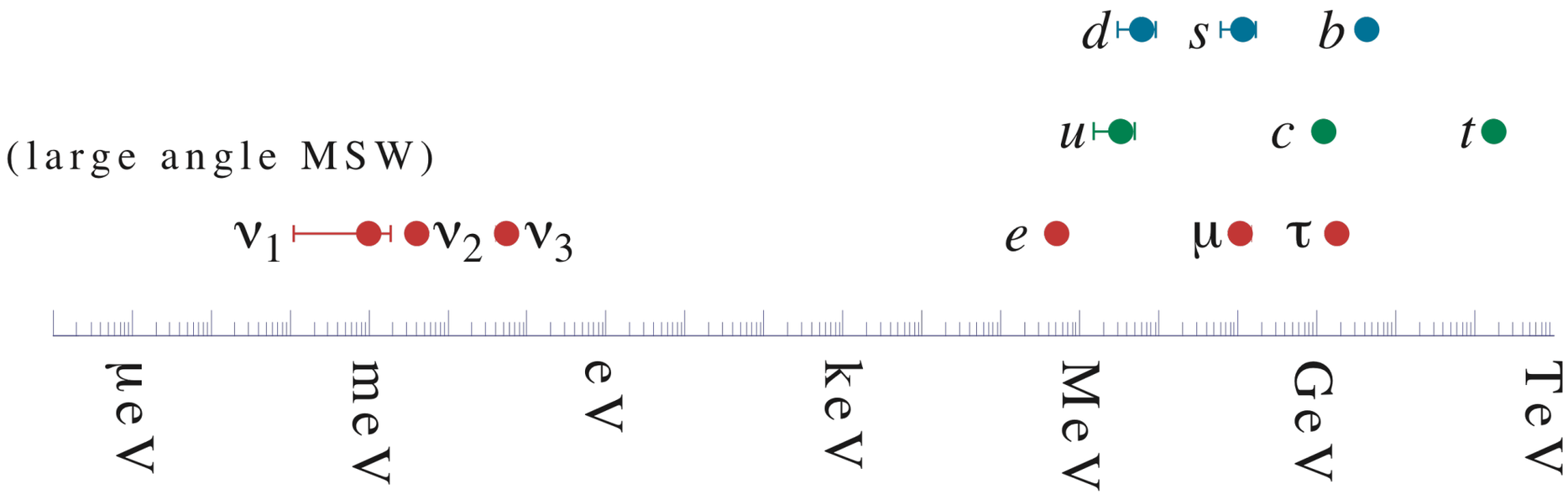
$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$

Λ Scale of new physics

The 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 machine" 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



To explain small neutrino masses with Dirac neutrinos it is necessary arbitrarily small coupling constant… Majorana neutrinos offer a way out of Deus ex machina.

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

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?

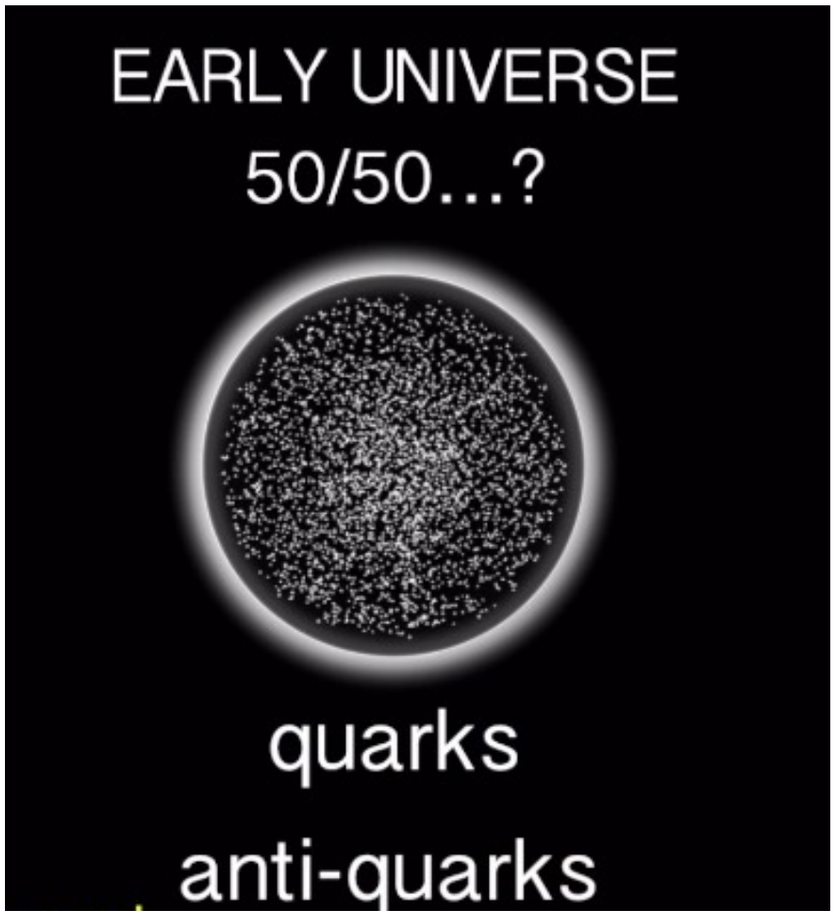
CP violation and Majorana neutrinos

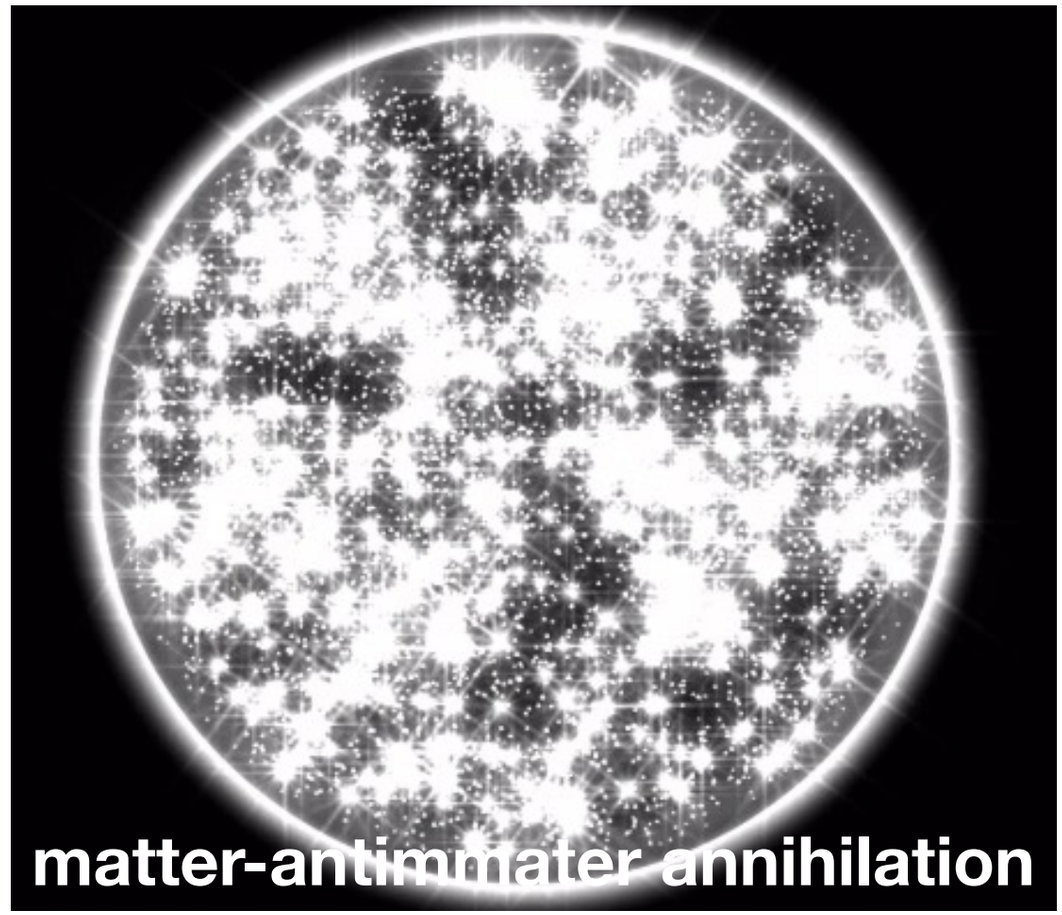
$$N \rightarrow e^- + H^+ \quad \text{and} \quad N \rightarrow e^+ + H^-$$

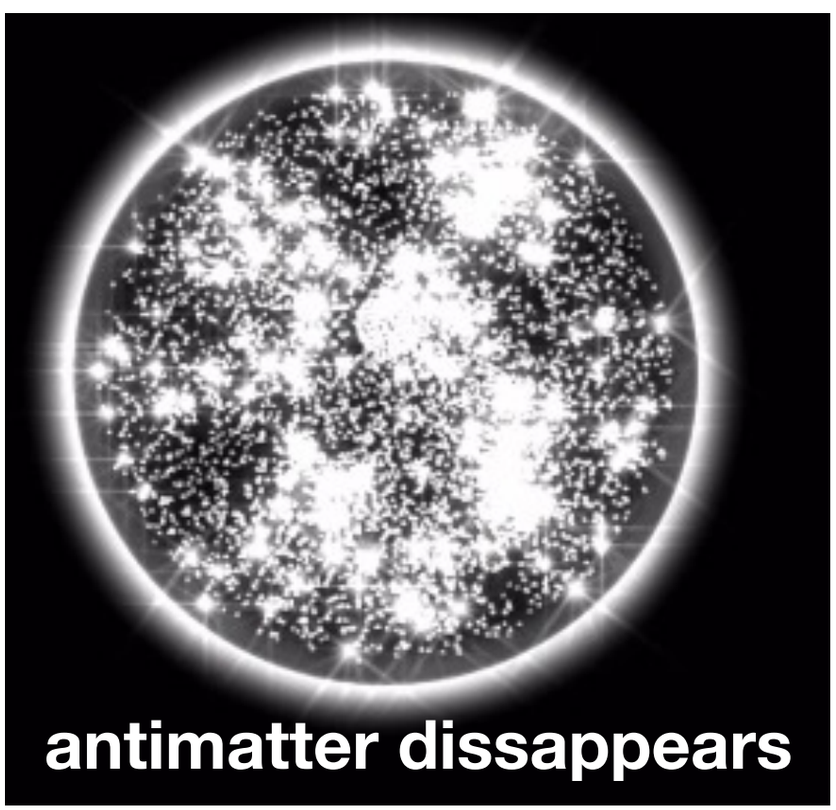
Standard-Model Higgs

- 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...

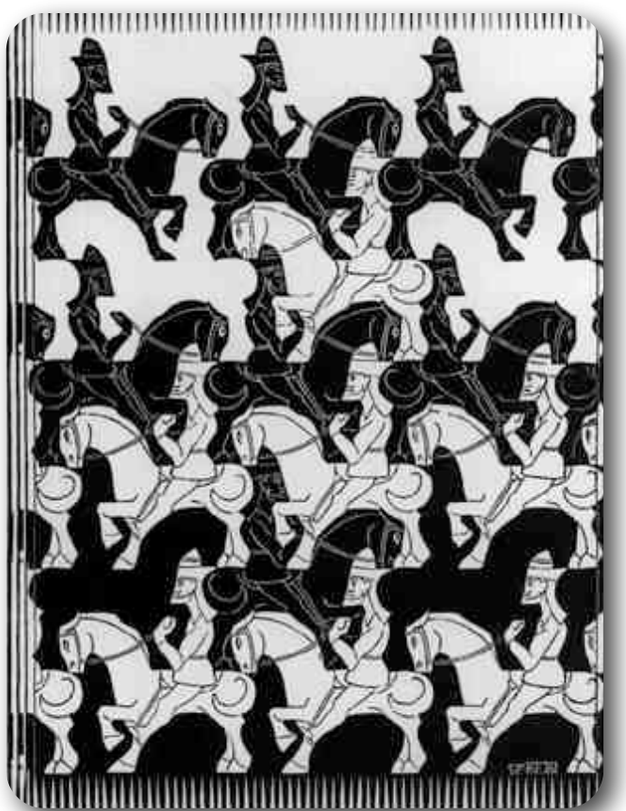

EARLY UNIVERSE
50/50...?
quarks
anti-quarks


matter-antimmater annihilation


antimatter dissappears

The universe today

A recipe for the Universe



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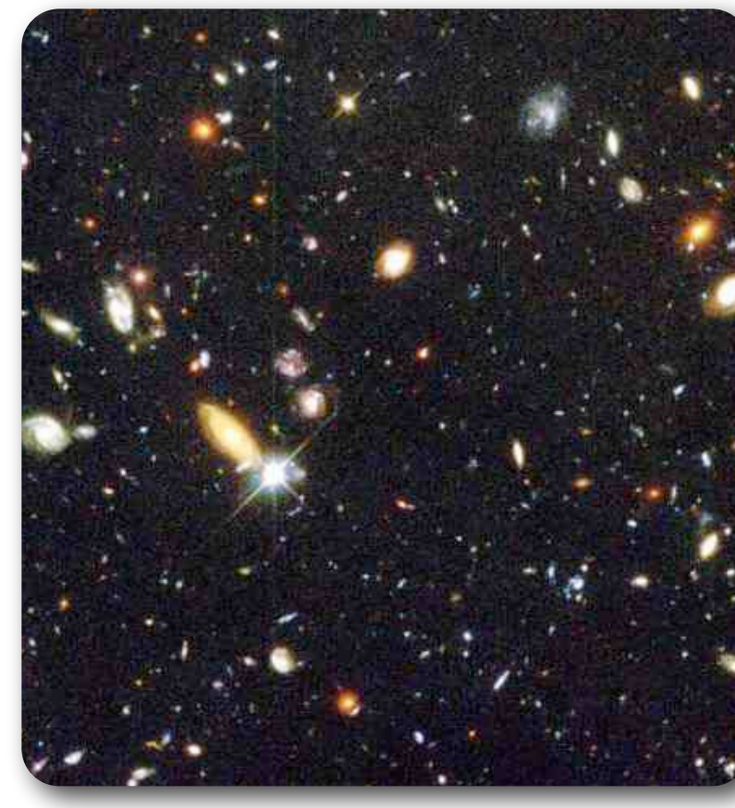
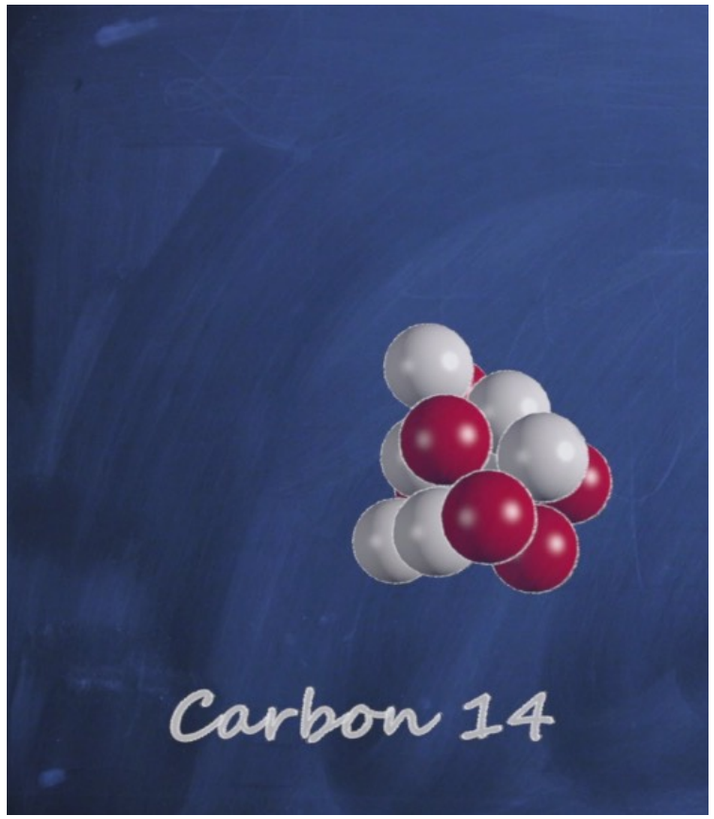
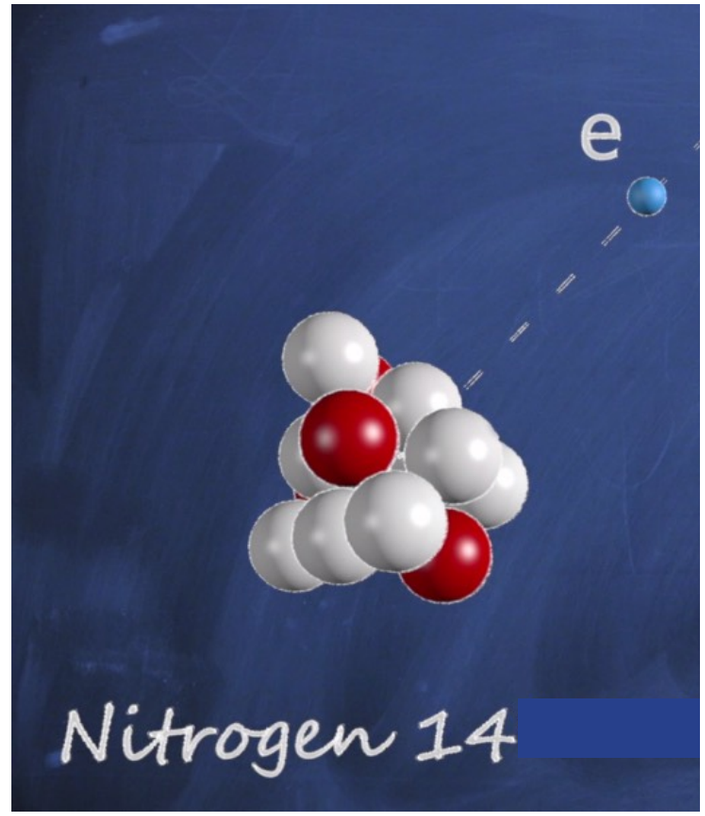


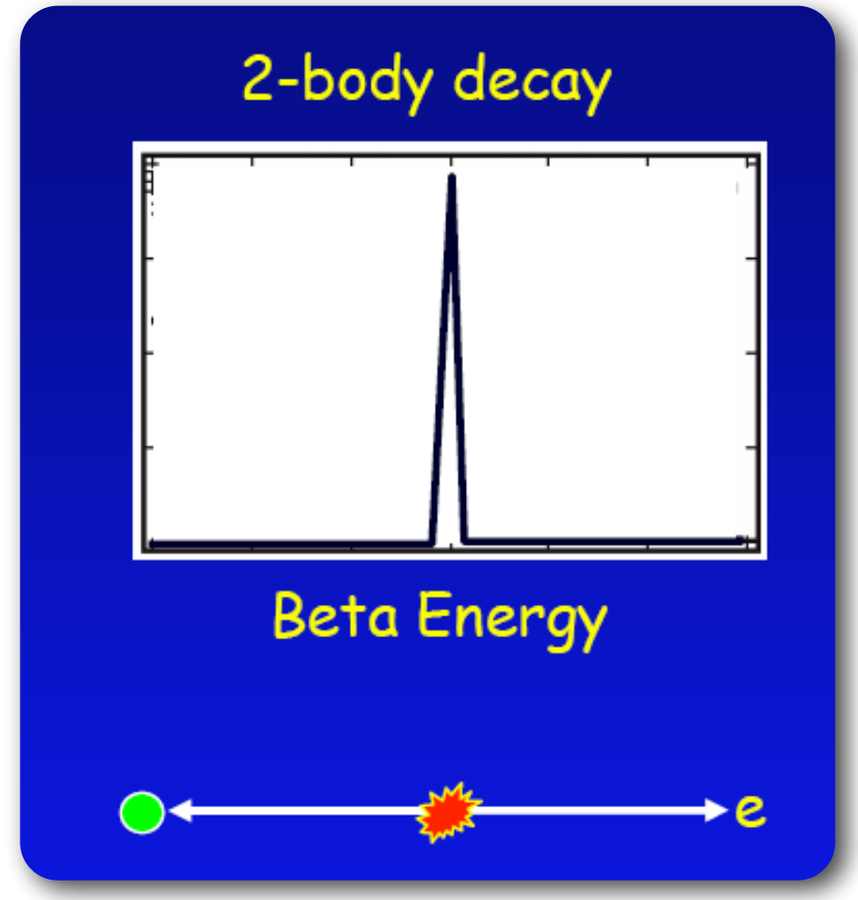
- End of babbling. Please put your iPhones away now…

Are neutrino Majorana particles? To find out play...

Funagain.com

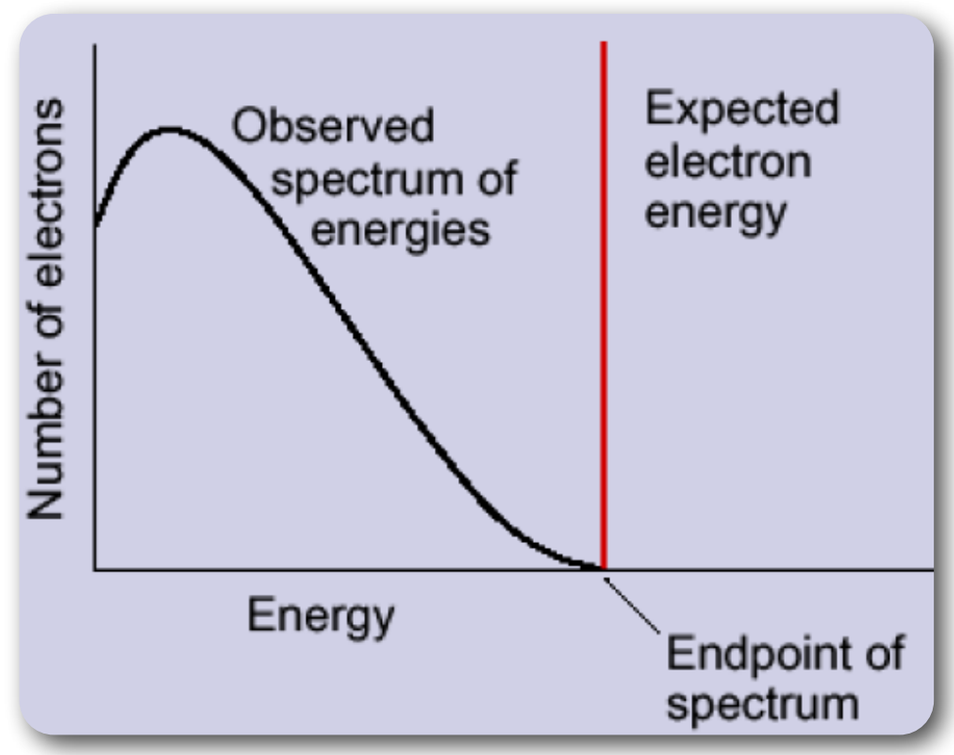




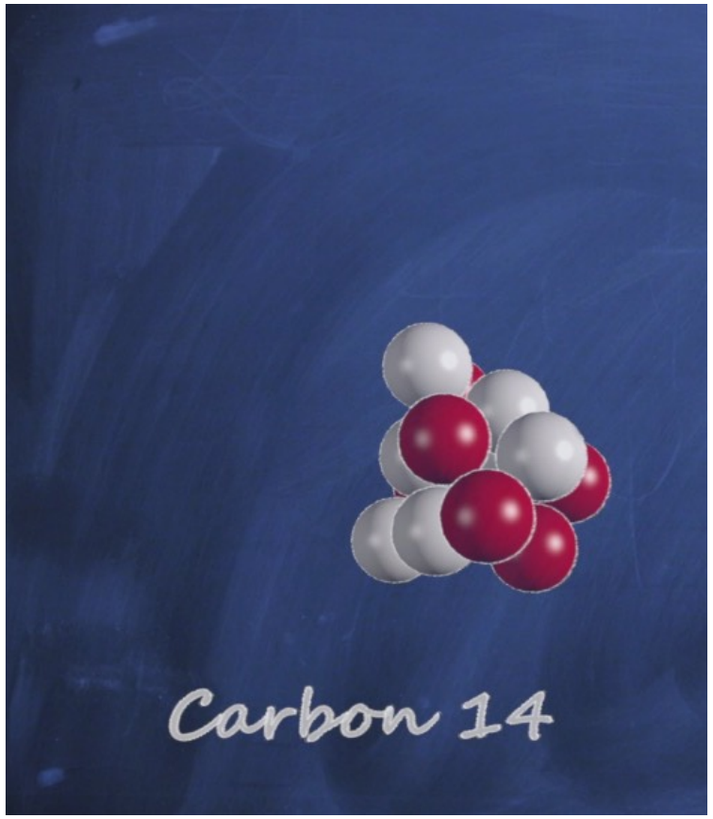


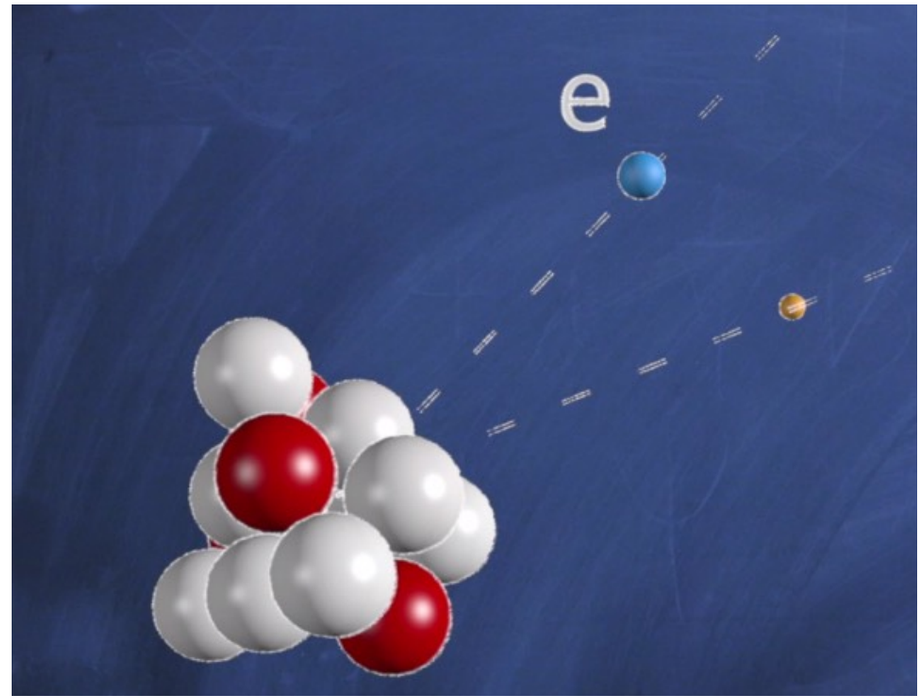
Beta decay

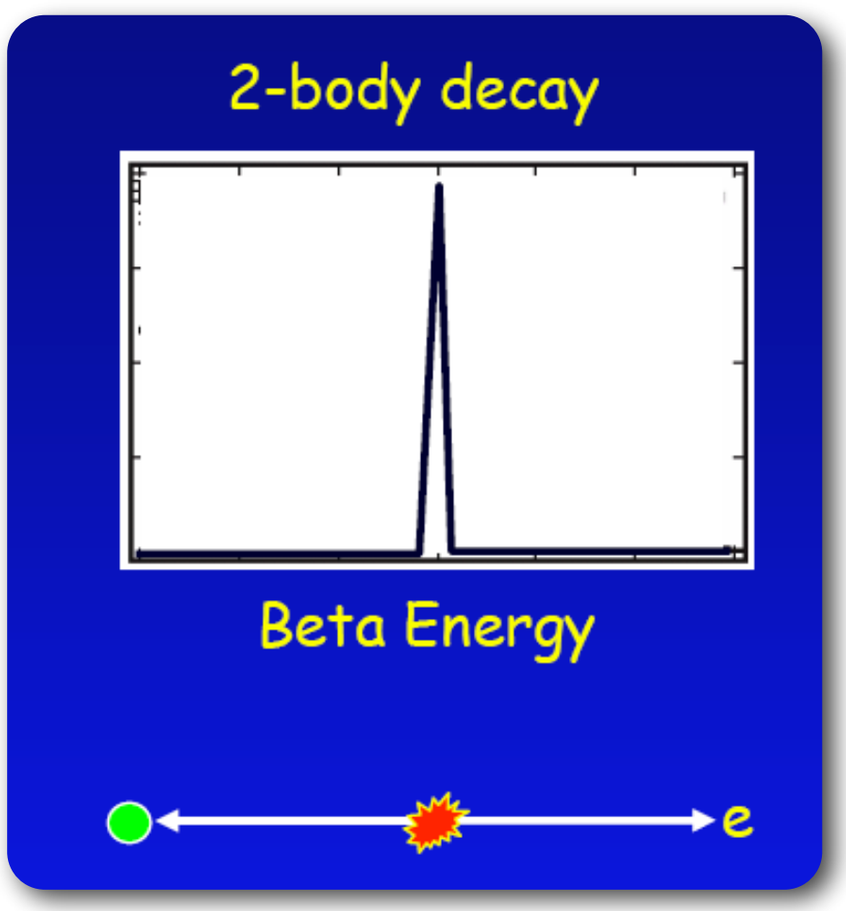
¿Energy conservation?

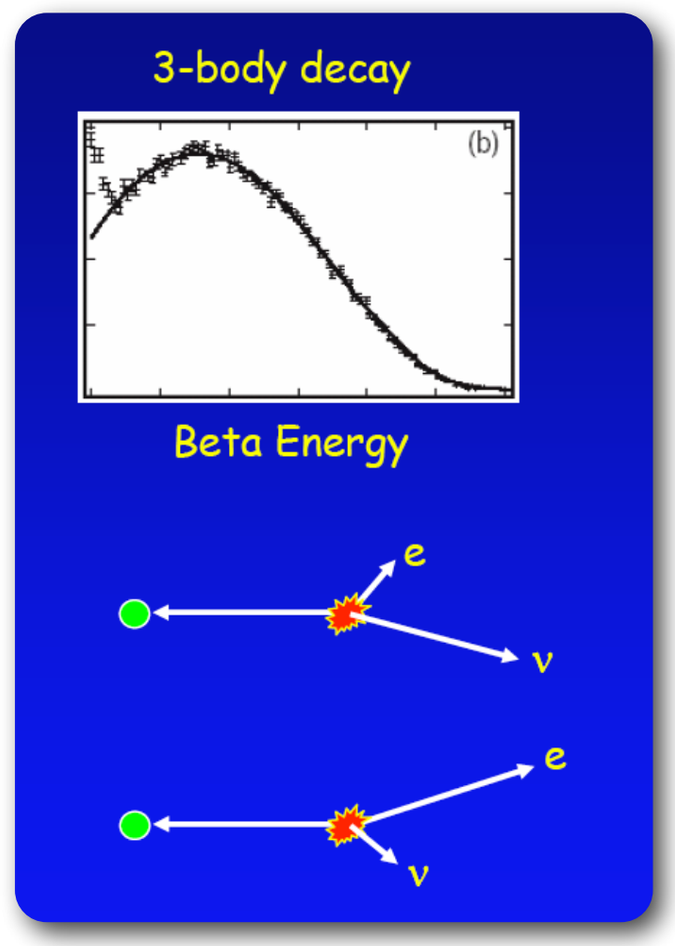


A desperate remedy



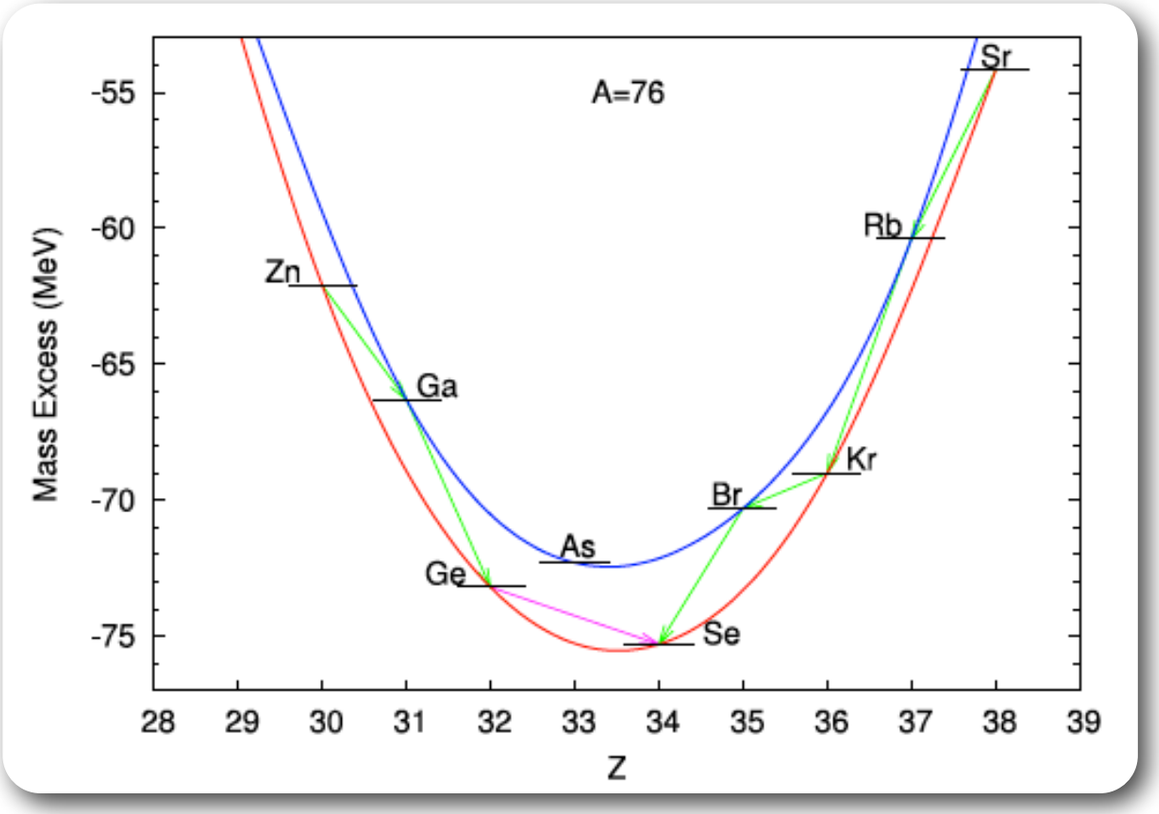


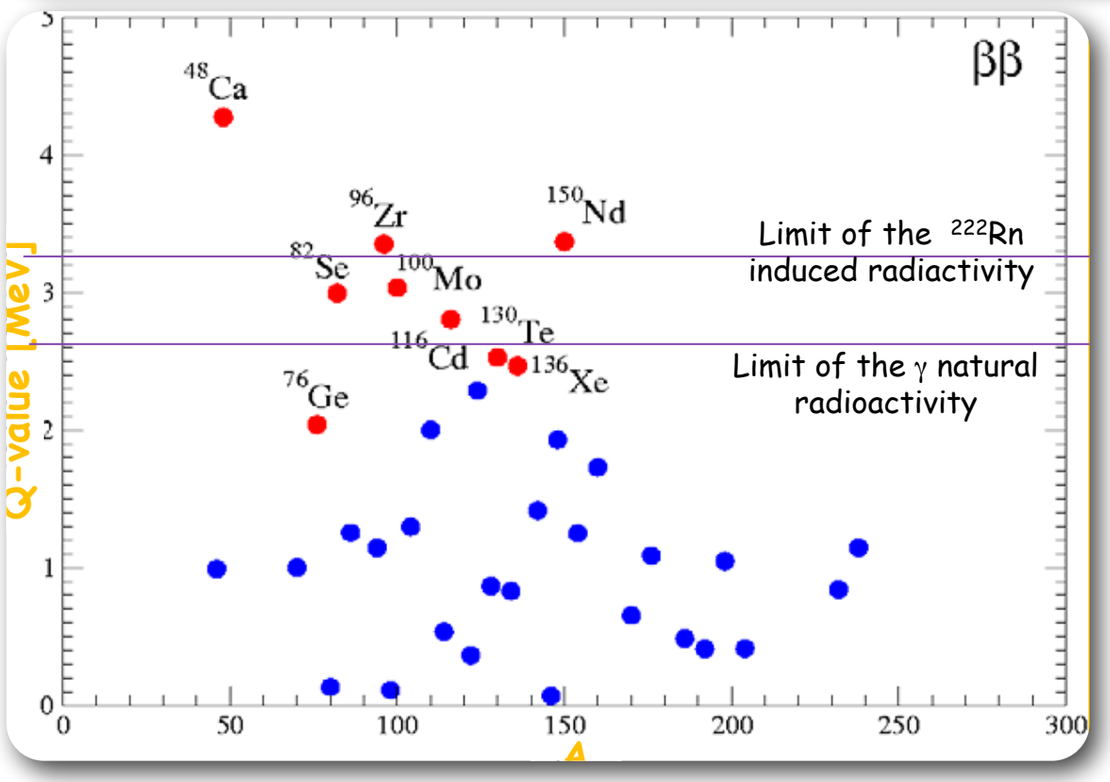




Pauli predicted the existence of a "neutron" (later renames "neutrino" by Fermi) in order to restore our faith in energy conservation.

Double beta decay

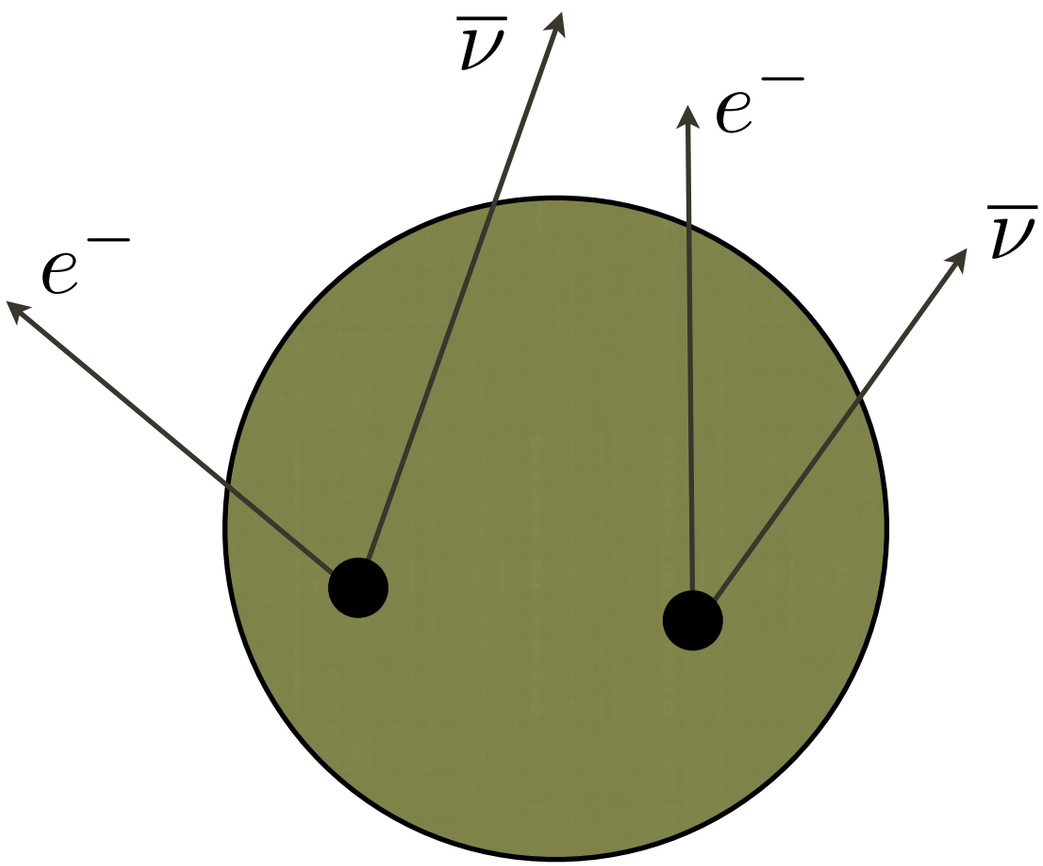




- Some nuclei, otherwise quasi stable can decay by emitting two electrons and two neutrinos by a second order process mediated by the weak interaction.

- This process exists due to nuclear pairing interaction that favours energetically the even-even isobars over the odd-odd ones.

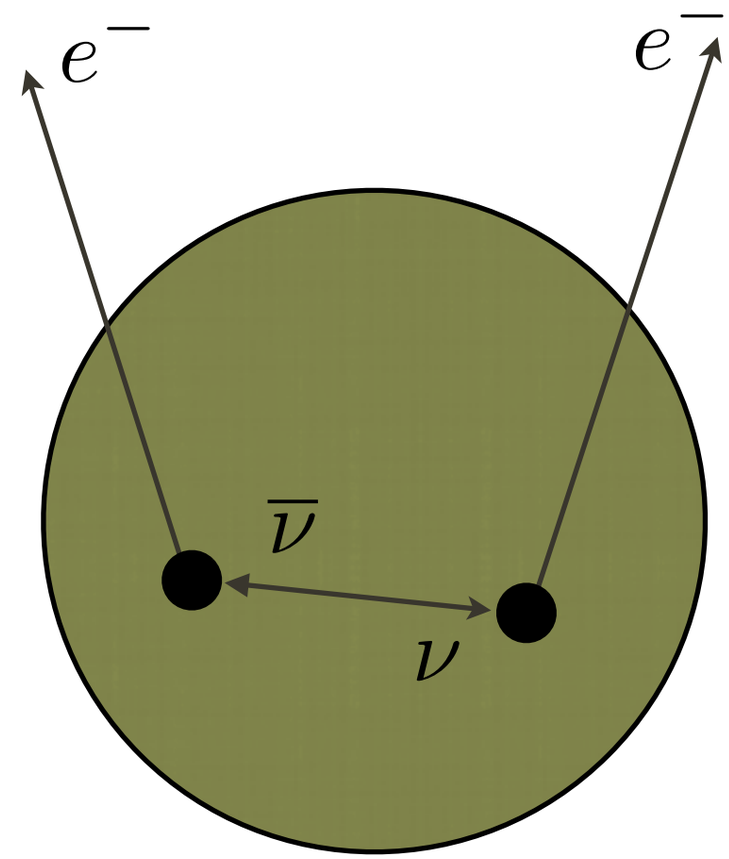
Double beta decay



$\beta\beta 2\nu$

SM-allowed process.
Measured in several nuclei.

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

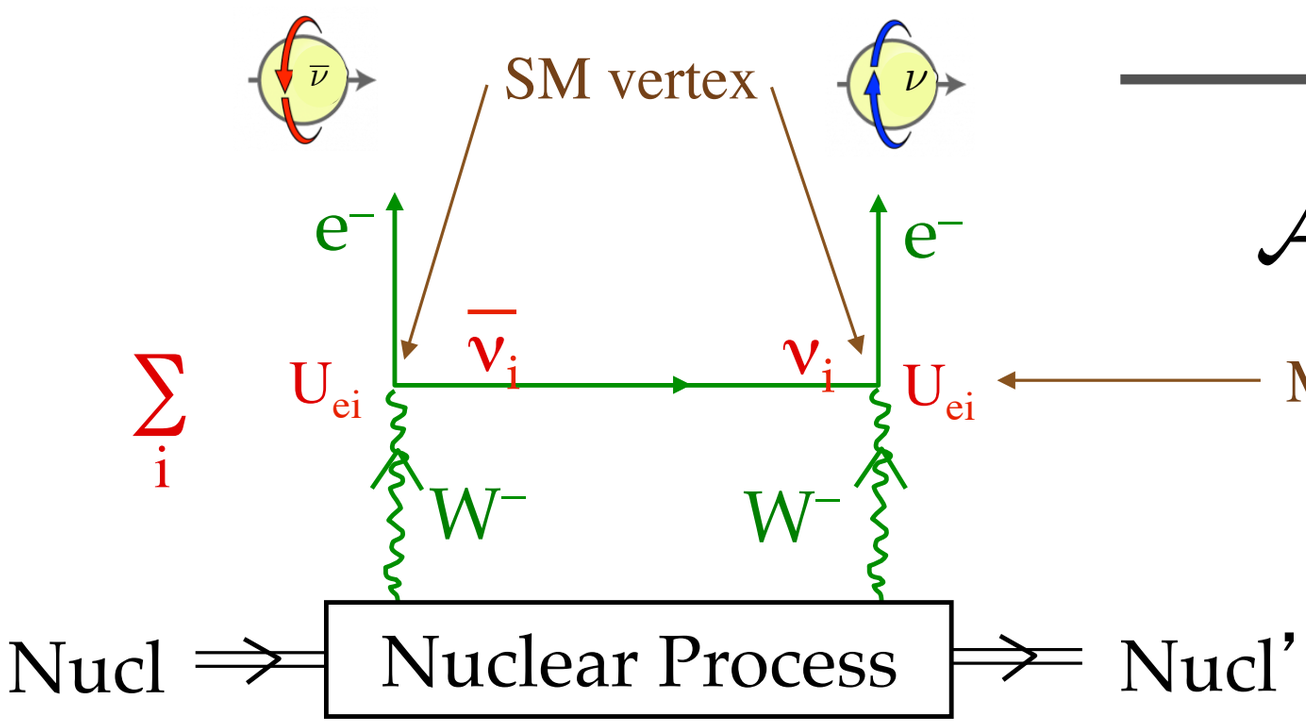


$\beta\beta 0\nu$

Lepton number violating process.
Requires massive, Majorana neutrinos.

$$T_{1/2} > 10^{25}\ \mathrm{y}$$

Majorana mass

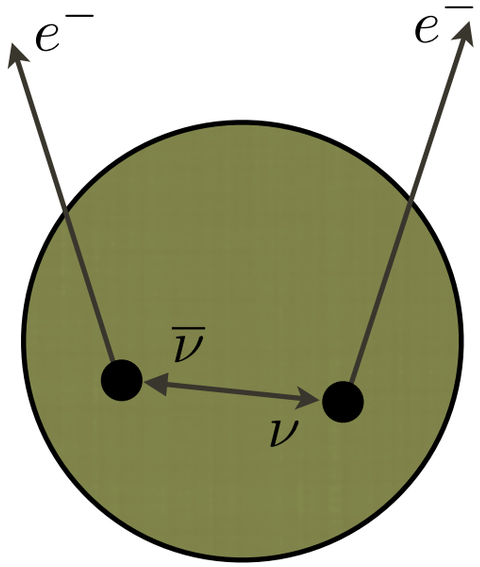


helicity flip $\propto \dfrac{m_i}{E}$

$\mathcal{A} \propto m_i$ **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.



$\beta\beta0\nu$

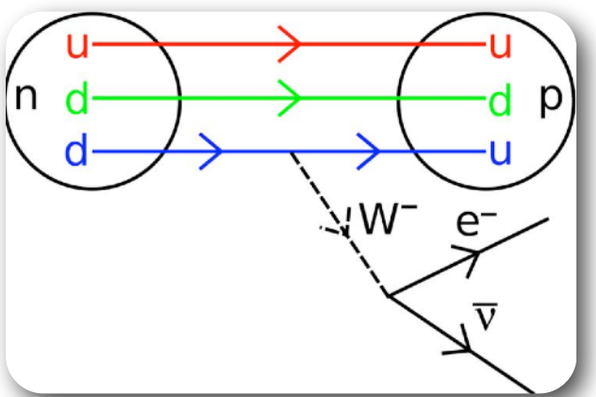
Nuclear physics

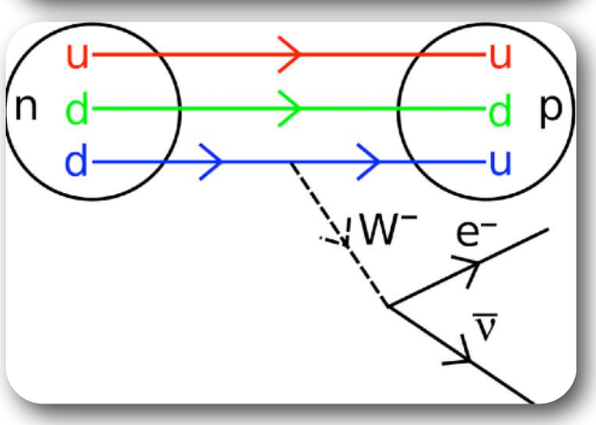
$$(T^{0\nu}_{1/2})^{-1} = \boxed{G^{0\nu}(Q,Z)}\,\boxed{|M^{0\nu}|^2}\,m^2_{\beta\beta}$$

phase-space

nuclear matrix

Majorana neutrino

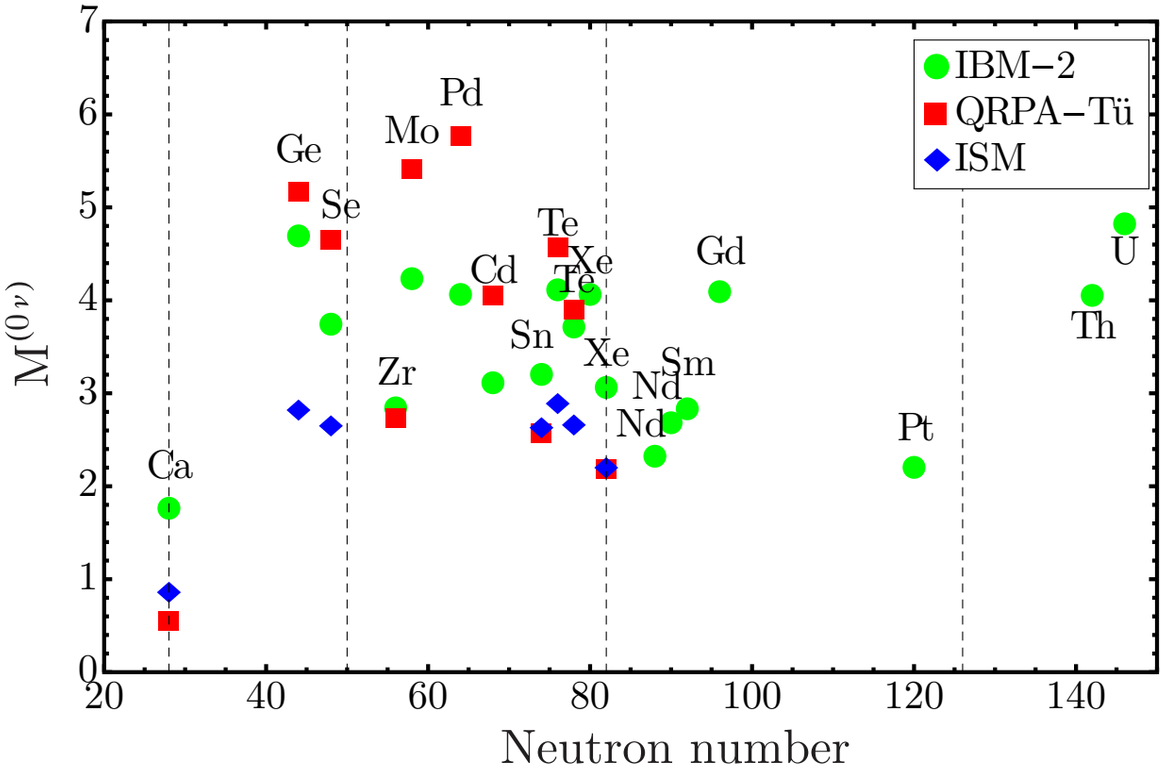


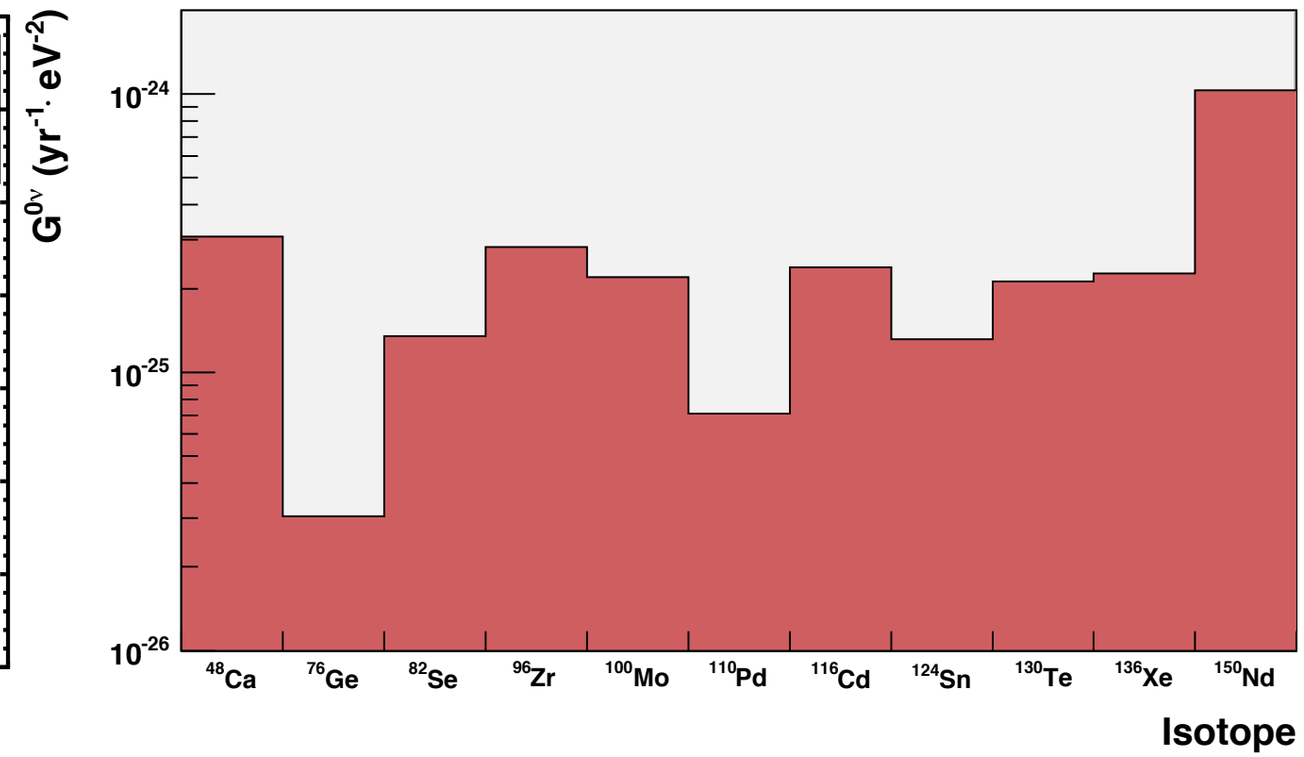


- Two protons decay simultaneously in a heavy isotope
- Nuclear physics results in proportionality constants between period and the inverse of the Majorana mass squared

THE NUCLEAR MATRIX ELEMENT

Phys. Rev. C 91, 034304





- Combination of phase-space, molar weight and uncertainty in NME implies that **no isotope is preferred "a priory" for bb0nu searches**. Quite the contrary, it appears advisable to explore as many isotopes as possible.
- **This implies to plan on at least one experiment per isotope of interest. Practical possibilities include Ge, Te, Se, Mo, and Xe.**

The relation between period and $m_{\beta\beta}$

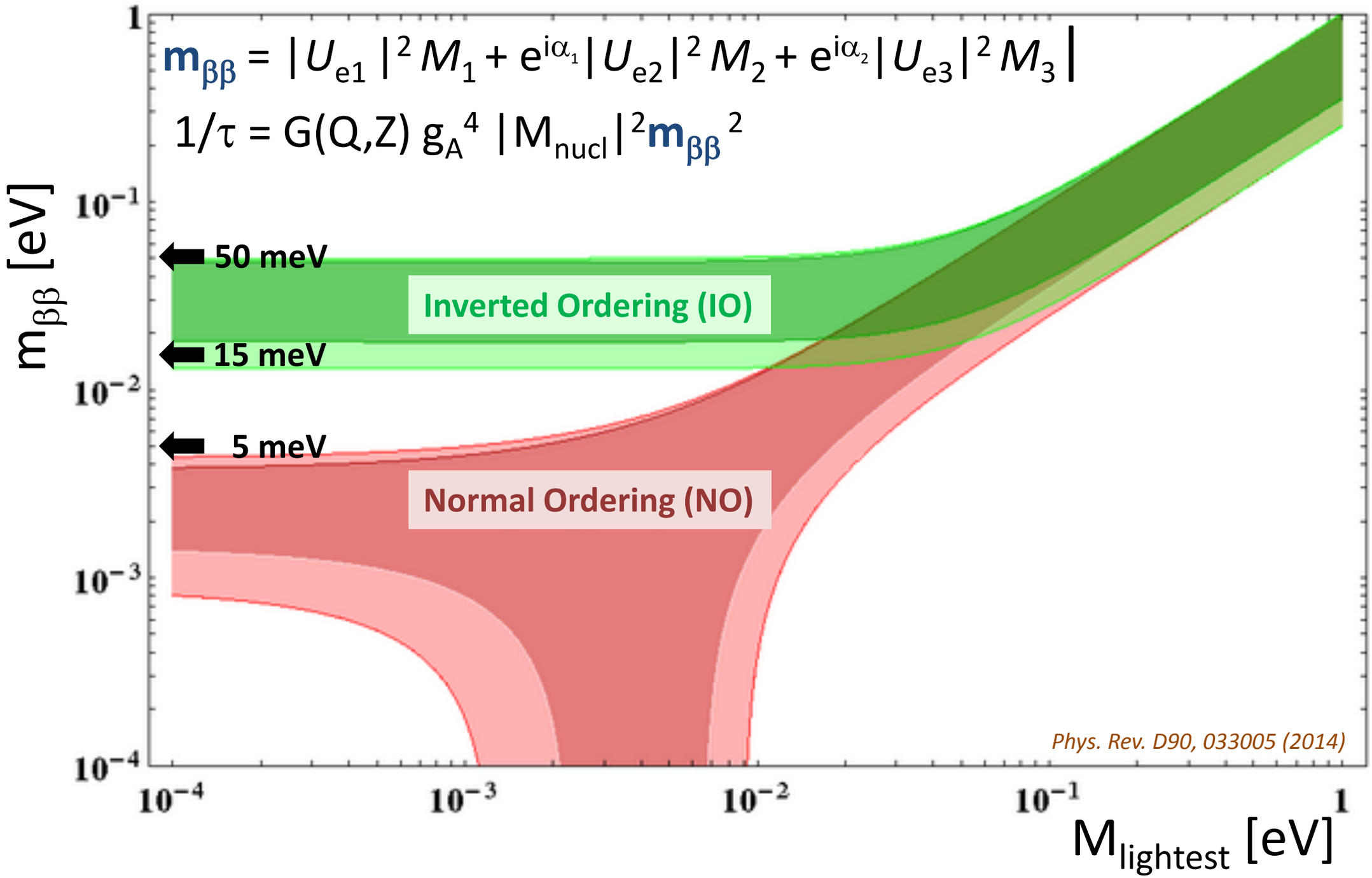
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q, Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

- Given a state of the art in bb0nu searches: Exploring mbb one order of magnitude smaller requires exploring periods two orders of magnitude longer.
- This is turn implies increasing the exposure by two orders of magnitude.
- If one fixes the lifetime of a DBD experiment, each order of magnitude in $m_{\beta\beta}$ requires two orders of magnitude in detector mass… **In the absence of background**

- Following slices show that DBD experiments are hopelessly difficult.
- Those of you looking to a successful and bright career in neutrino physics, can now safely babysit your iPhones again.

A. Giuliani, Neutrino, 2018

Standard mechanism: $m_{\beta\beta}$ vs. lightest ν mass

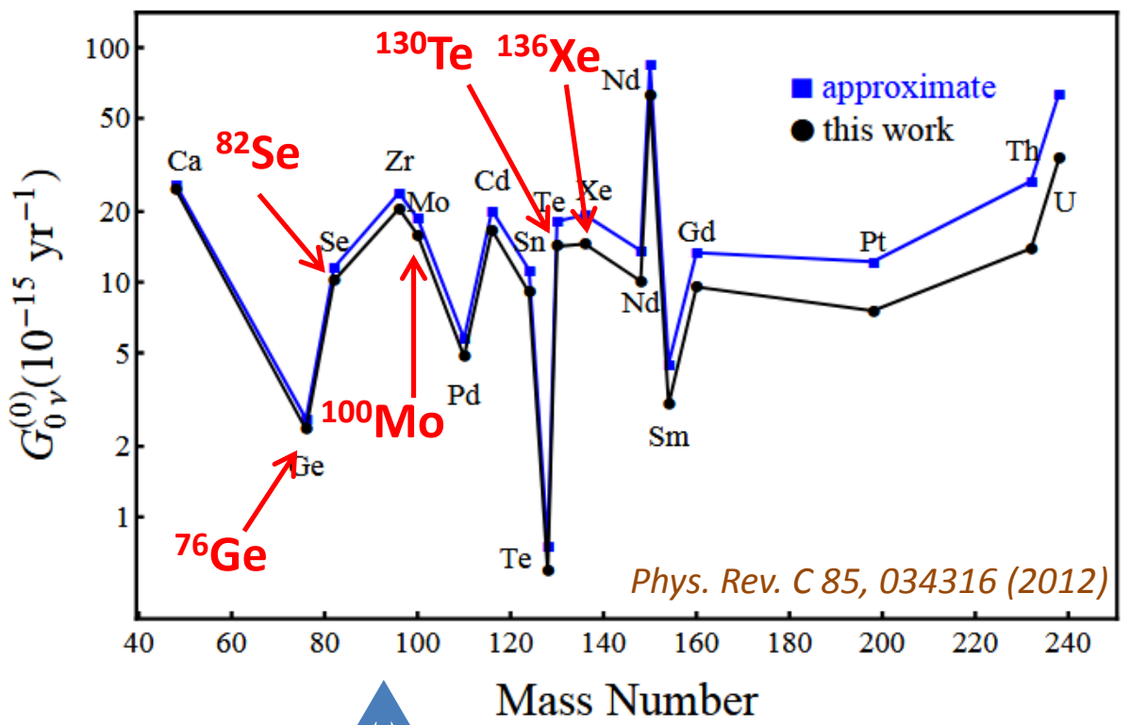


A. Giuliani, Neutrino, 2018

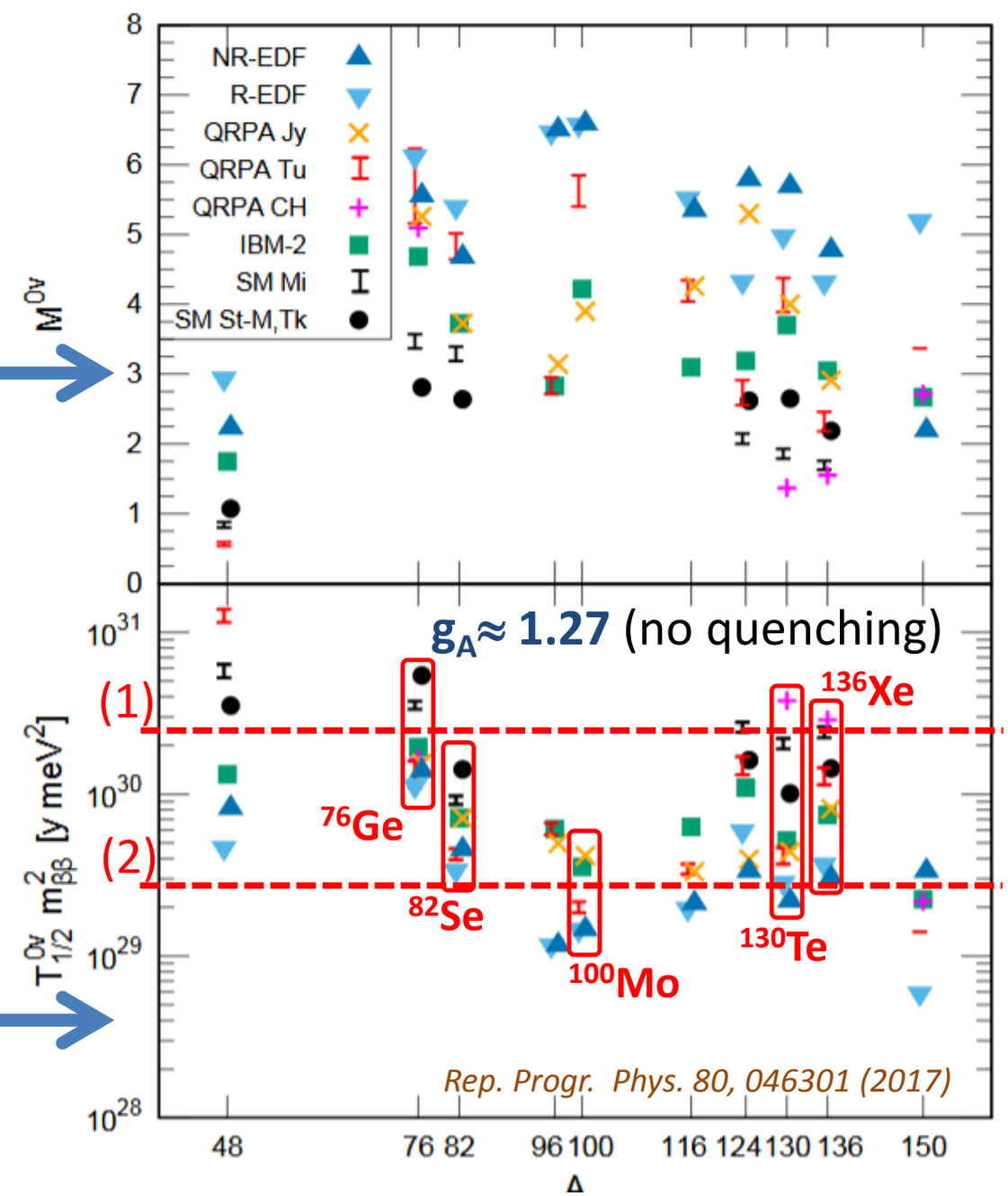
How difficult is it?

*See next talk by **Jouni Suhonen***

Phase space: exactly calculable



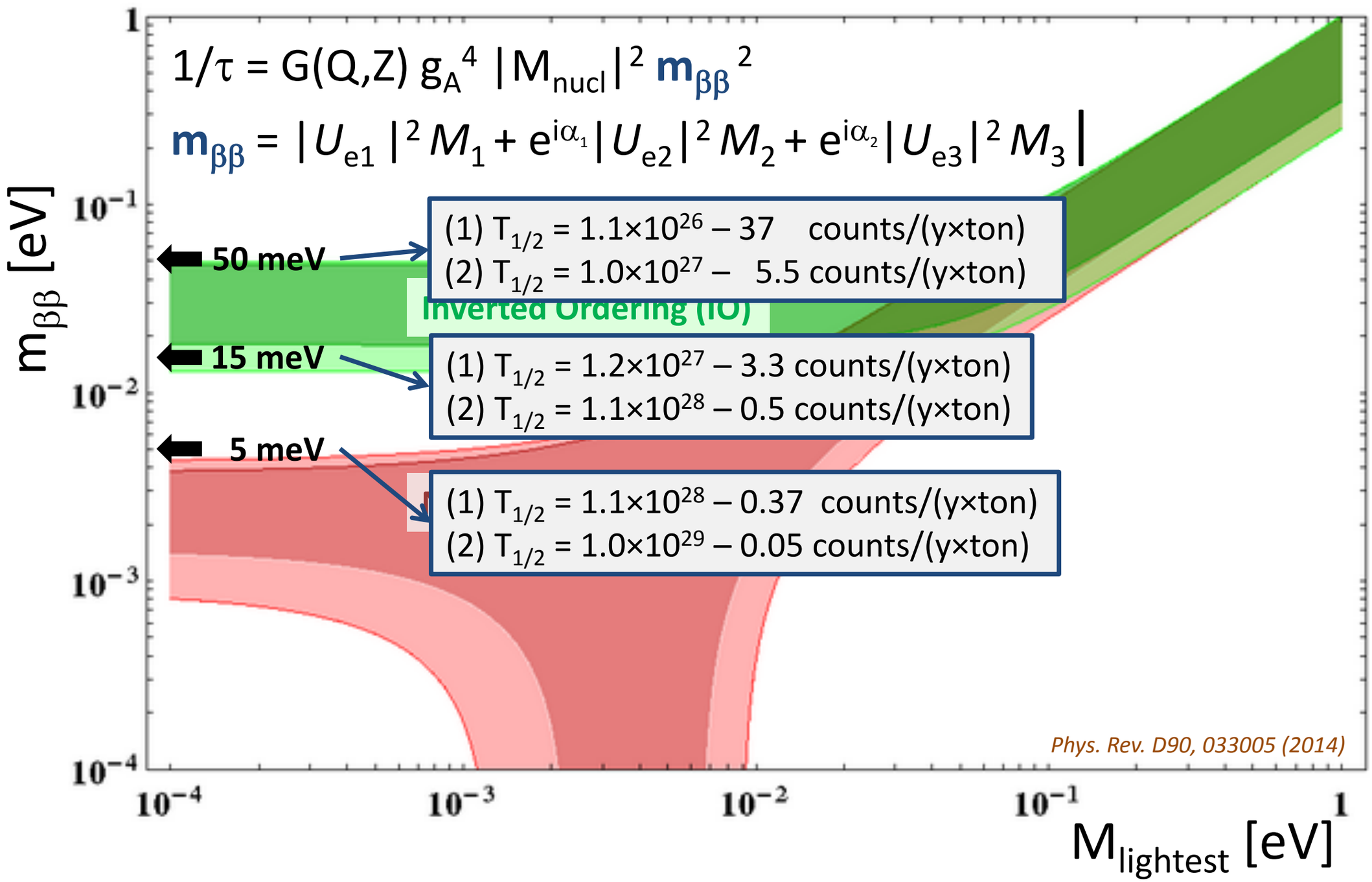
Nuclear matrix elements: several models



$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2\, m_{\beta\beta}^{\,2}$$

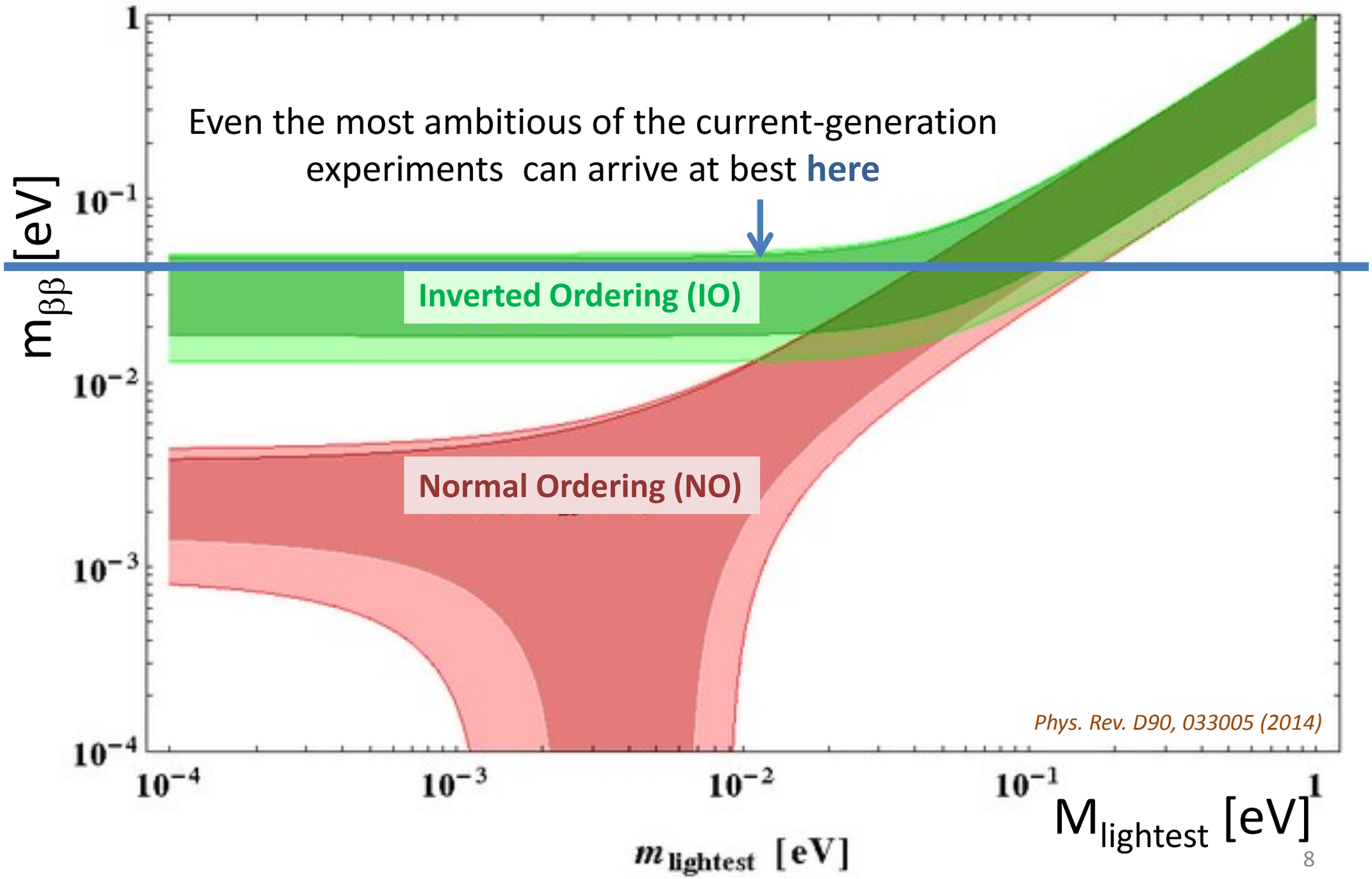
A. Giuliani, Neutrino, 2018

How difficult is it?



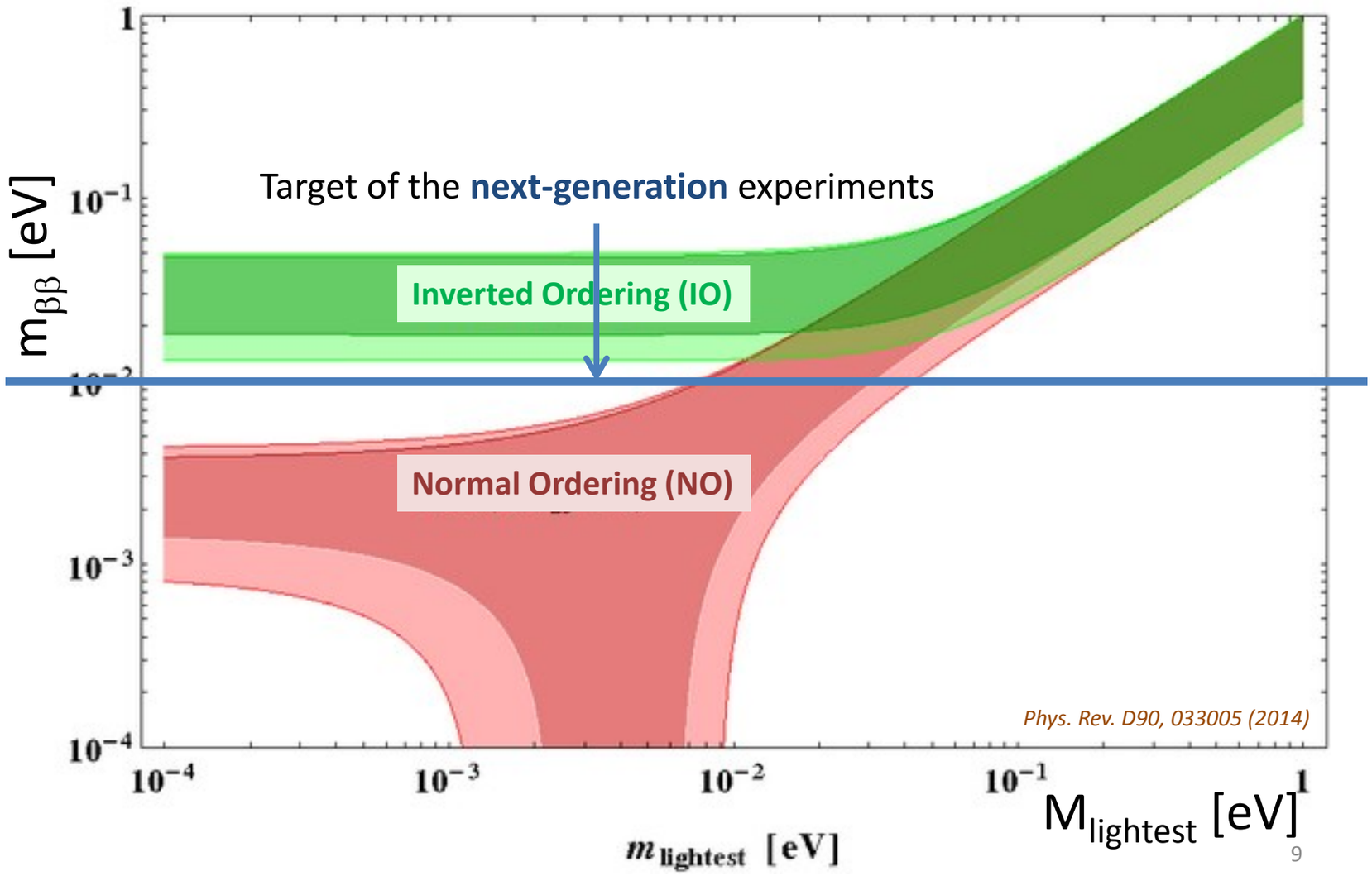
A. Giuliani, Neutrino, 2018

Current-generation experiments



A. Giuliani, Neutrino, 2018

Next-generation experiments

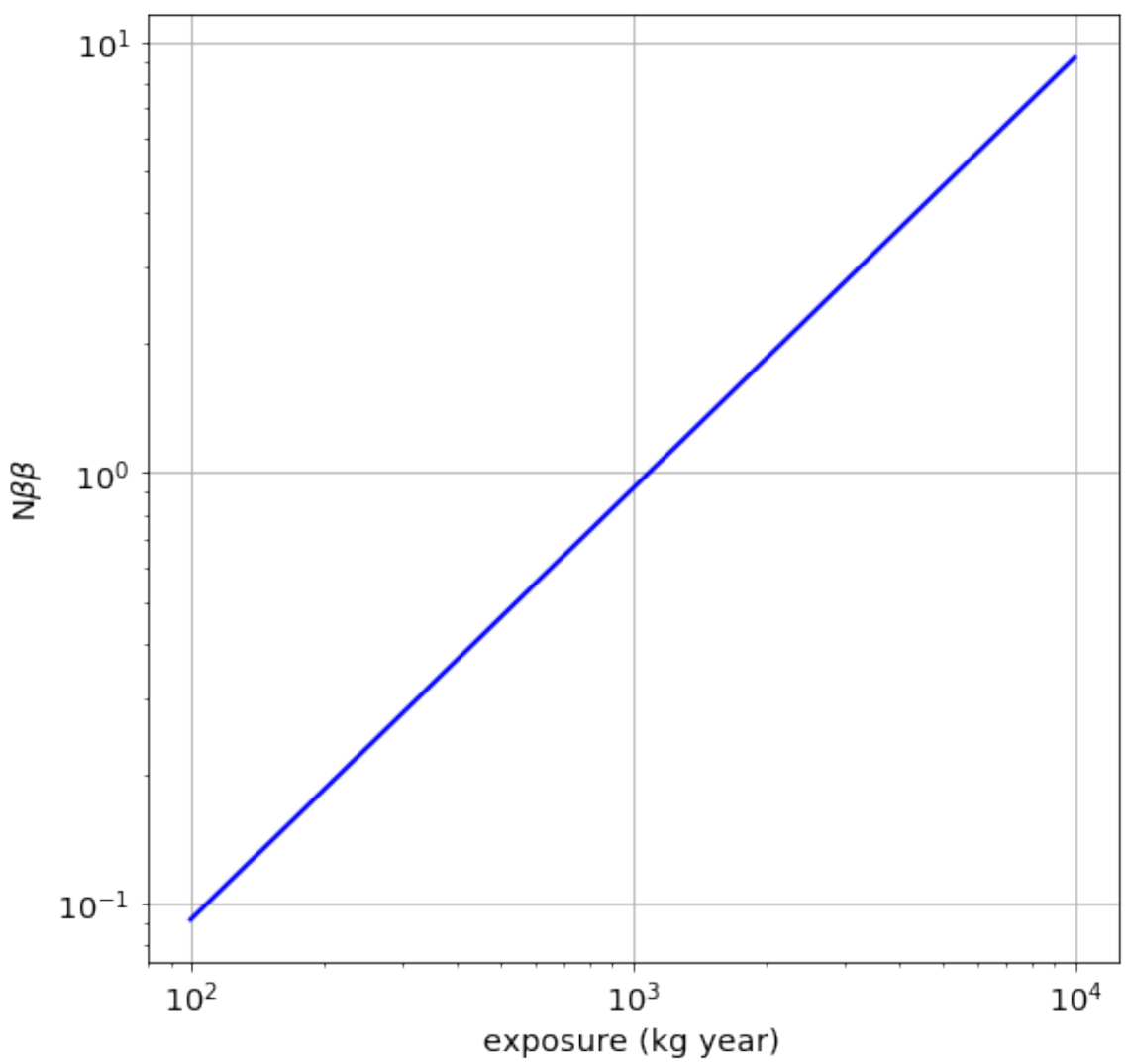


- Next generation DBD experiments aim to see a signal between 0.5 and ~3 counts per ton per year.
- Therefore, next generation DBD experiment must deploy large masses (in the range of several hundred kgs to several tons) and suppress backgrounds to the level that they are small compared with the signal… but the signal is tiny

Experimental aspects

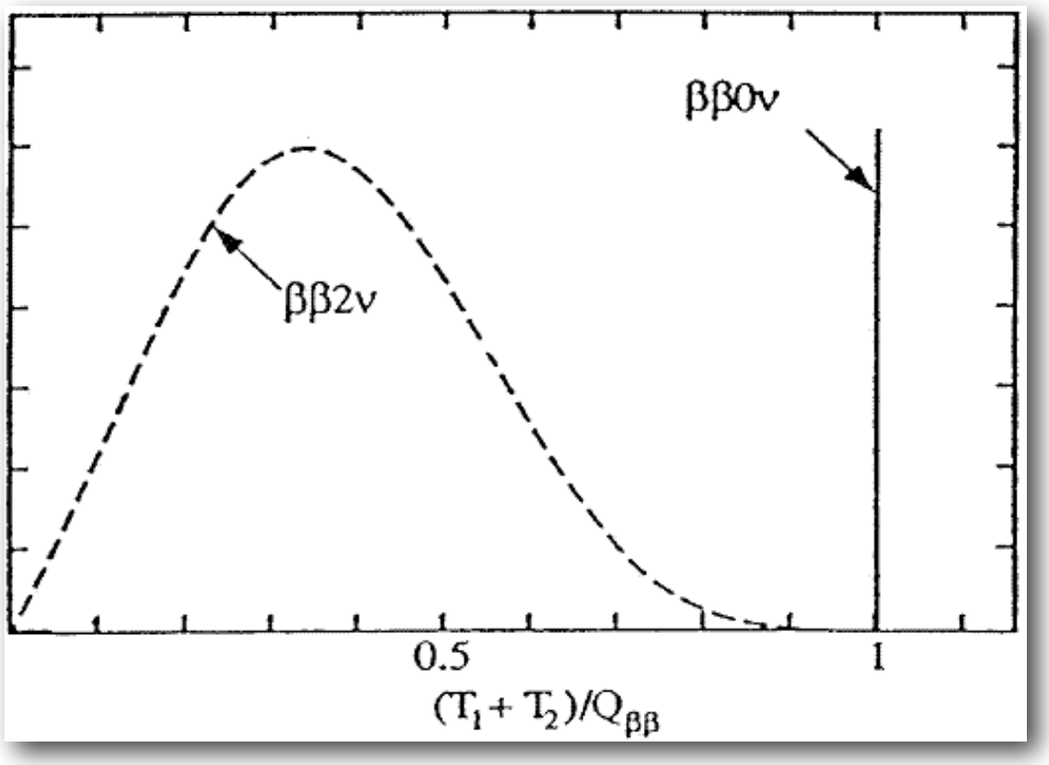
An ideal ββ0ν experiment

$$N = \log 2 \, \frac{\varepsilon \cdot M \cdot N_A}{W} \, \frac{t}{T^{0\nu}_{1/2}}$$



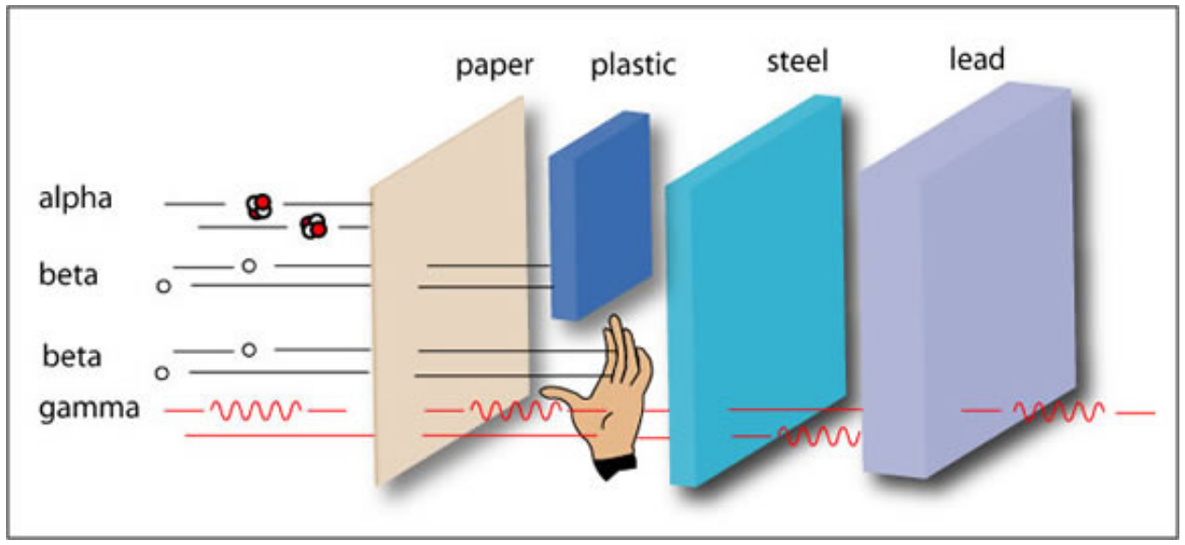
- T1/2 = 10^{27} (10^{29})y
- A = 136 (Xenon)
- efficiency = 30 %
- An exposure of 1 (100) ton year required to observe 1 event (**= discovery, in the absence of background**)
- Assuming a long run, with an integrated lifetime of 10 y, we need:
  - **100 kg of ideal (zero background) detector to cover IH**
  - **10 tons of ideal (zero background) detector to cover IH**

Background free ββ0ν experiment, recipe one



- Get yourself a detector with perfect energy resolution
- Measure the energy of the emitted electrons and select those with (T1+T2)/Qbb = 1 (**notice: background = zero**)
- Count the number of events and calculate the corresponding half-life.

Background free ββ0ν experiment, recipe two



- Get yourself a detector with perfect shielding of all external and internal backgrounds.
- Measure the energy of the emitted electrons and select those with (T1+T2)/Qbb = 1 (**you still need some resolution to separate bb2nu from bb0nu**)
- Count the number of events and calculate the corresponding half-life.

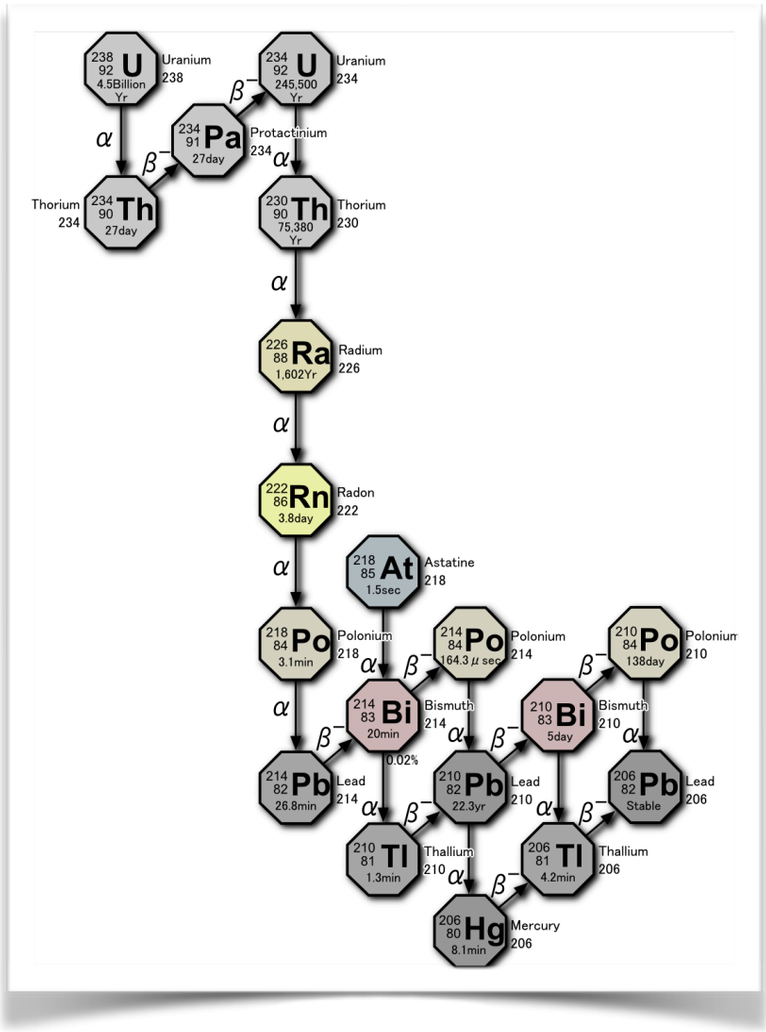
Background free ββ0ν experiment, recipe three

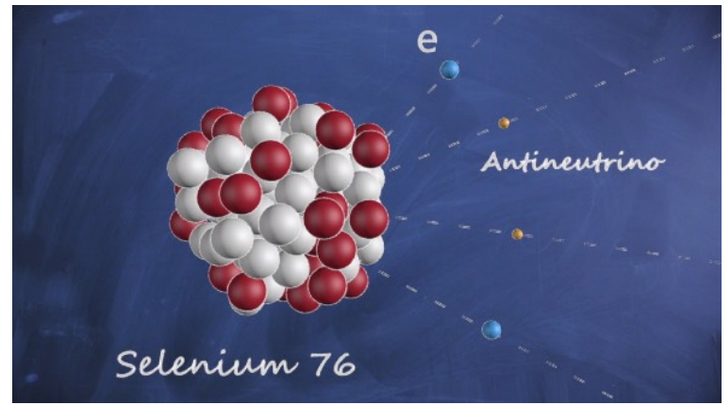
- Build a detector with no radioactive materials.
- You still need to locate it inside a perfect shield for external backgrounds.
- Measure the energy of the emitted electrons and select those with (T1+T2)/Qbb = 1 (**you still need some resolution to separate bb2nu from bb0nu**)
- Count the number of events and calculate the corresponding half-life.

Background free ββ0ν experiment, my favourite recipe

- Get yourself a detector with a holly grail capable to tag and eliminate all external and internal backgrounds.
- Measure the energy of the emitted electrons and select those with (T1+T2)/Qbb = 1 (**you still need some resolution to separate bb2nu from bb0nu**)
- Count the number of events and calculate the corresponding half-life.

Background free bbonu experiments and natural radioactivity





IH: 10^{27} y
NH: 10^{29} y

Lifetime Bkgnd/Signal ~$10^{17(19)}$ y

Earth is a very radioactive planet

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

Majorana’s beach

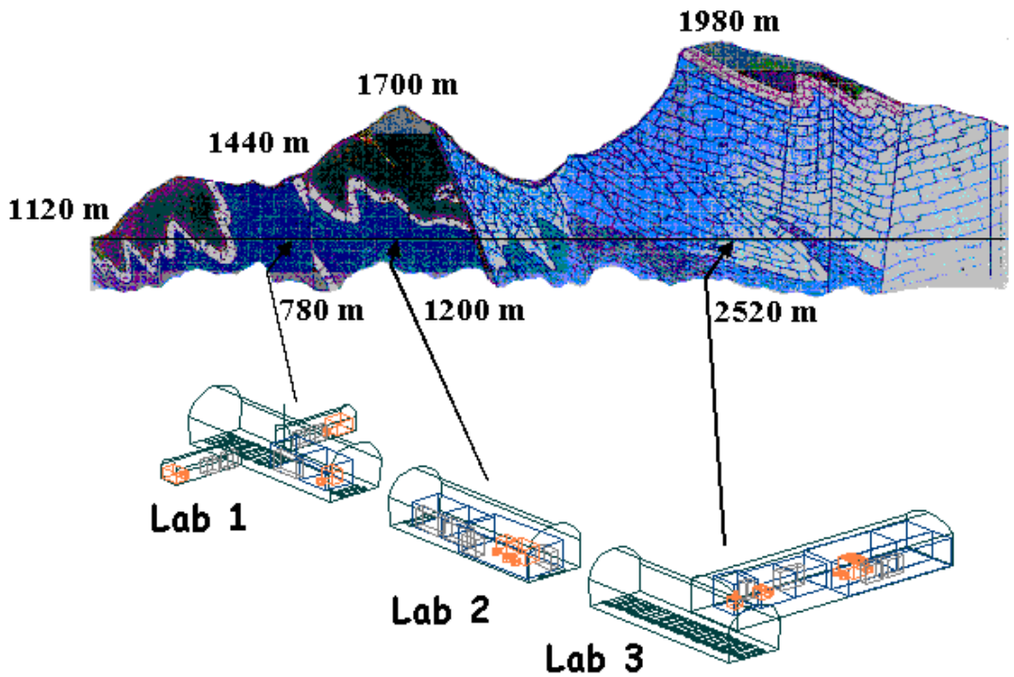
https://www.quora.com/How-many-grains-of-sand-are-there-in-a-given-stretch-of-an-average-beach

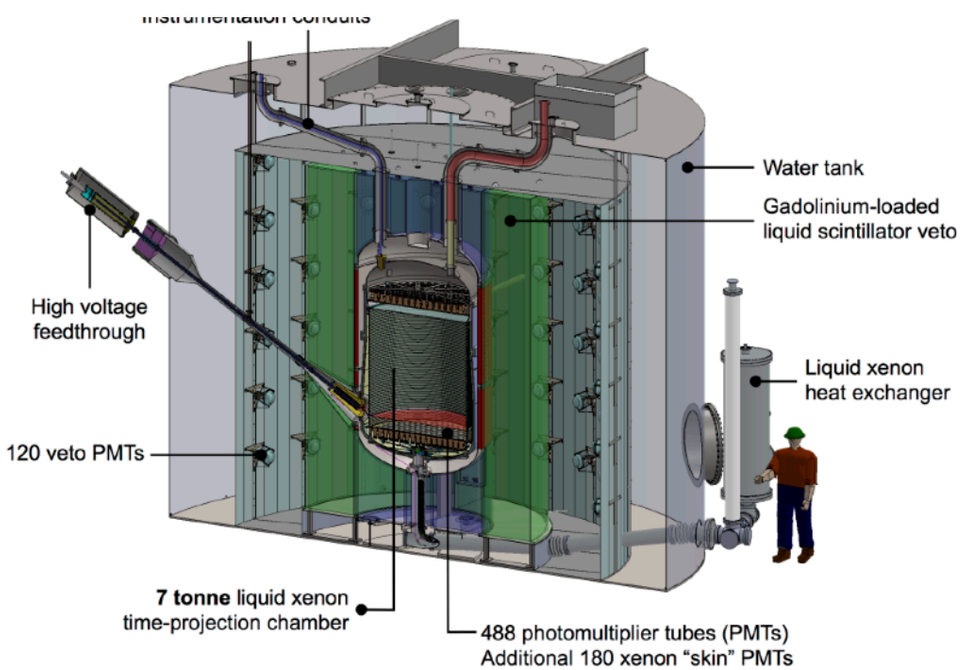
- Definition: A beach with $10^{17(19)}$ grains of sand.
- About 1.5 x 10^{9} per square meter (to a depth of 3 m).
- Thus, Majorana’s beach is:
  - **IH~70 km long and 1 km wide**
  - **NH~70 km long and 100 km wide**

Finding a needle in a haystack?

Rather a grain of sand in a large beach.

Real experiments





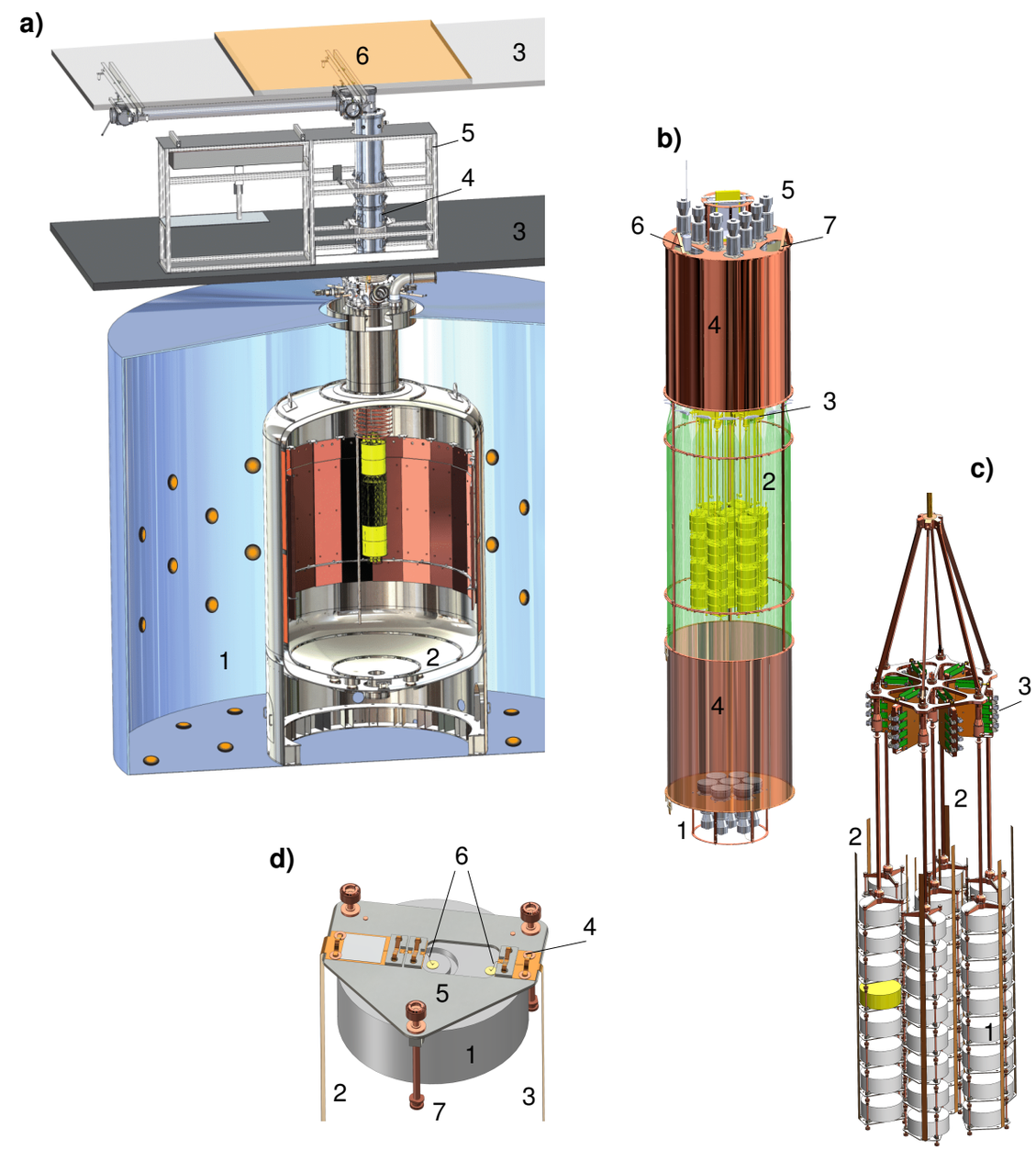
- Underground labs
- External shielding
- Ultra pure materials

Germanium Diodes (Bolometers)

GERDA/LEGEND

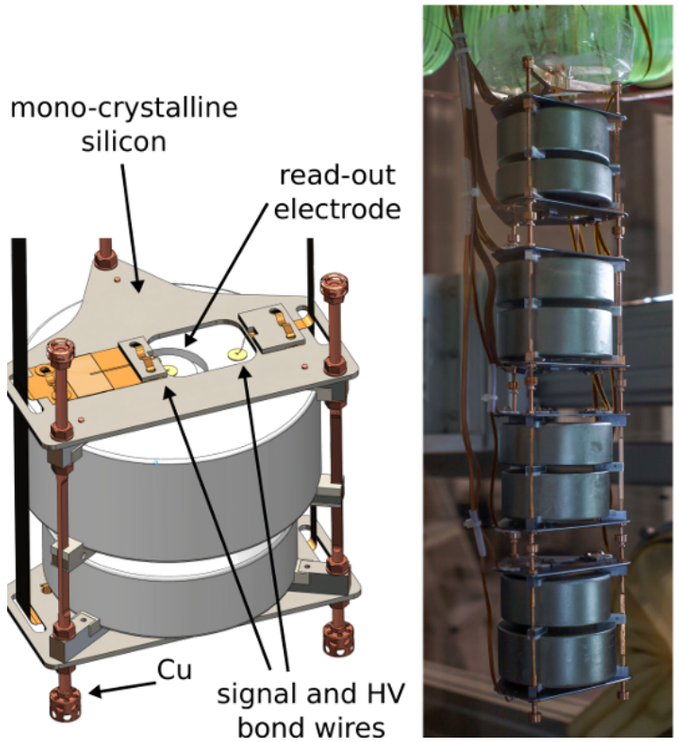
- Isotope: Ge-76, natural abundance 7.8%, mass **35 kg** (**LEGEND -> 200 kg**).
- Technique: diodes.
- **Excellent energy resolution**: 0.1-0.2% FWHM at $Q_{\beta\beta}$.
- **Low background rate**: ~ 10^{-3} counts/(keV kg year): < 1 background event in 100 kg · yr in the ROI: background free at this scale!

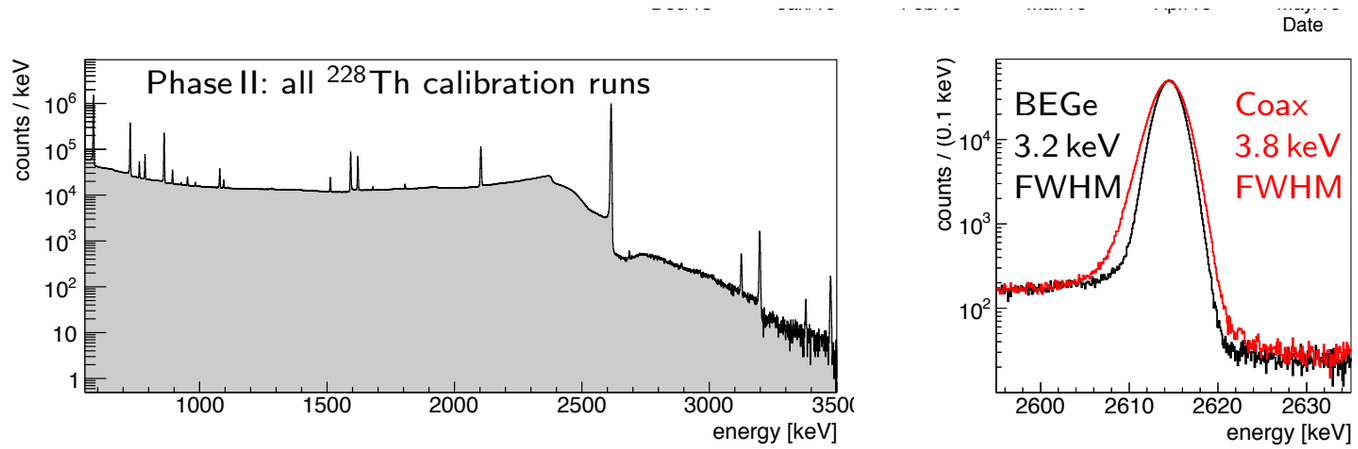
- Cryogenic LAr for cooling and shielding.
- SiPMs and PMTs detect Ar scintillation light produced by background events.
- Pure water tank for shielding.
- Pulse shape discrimination to identify surface background.

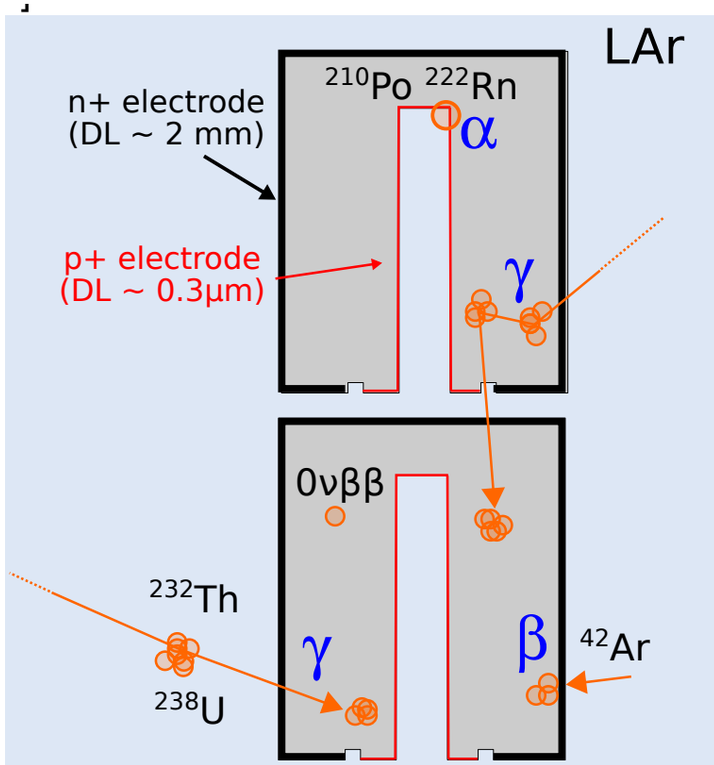


https://arxiv.org/abs/1703.00570

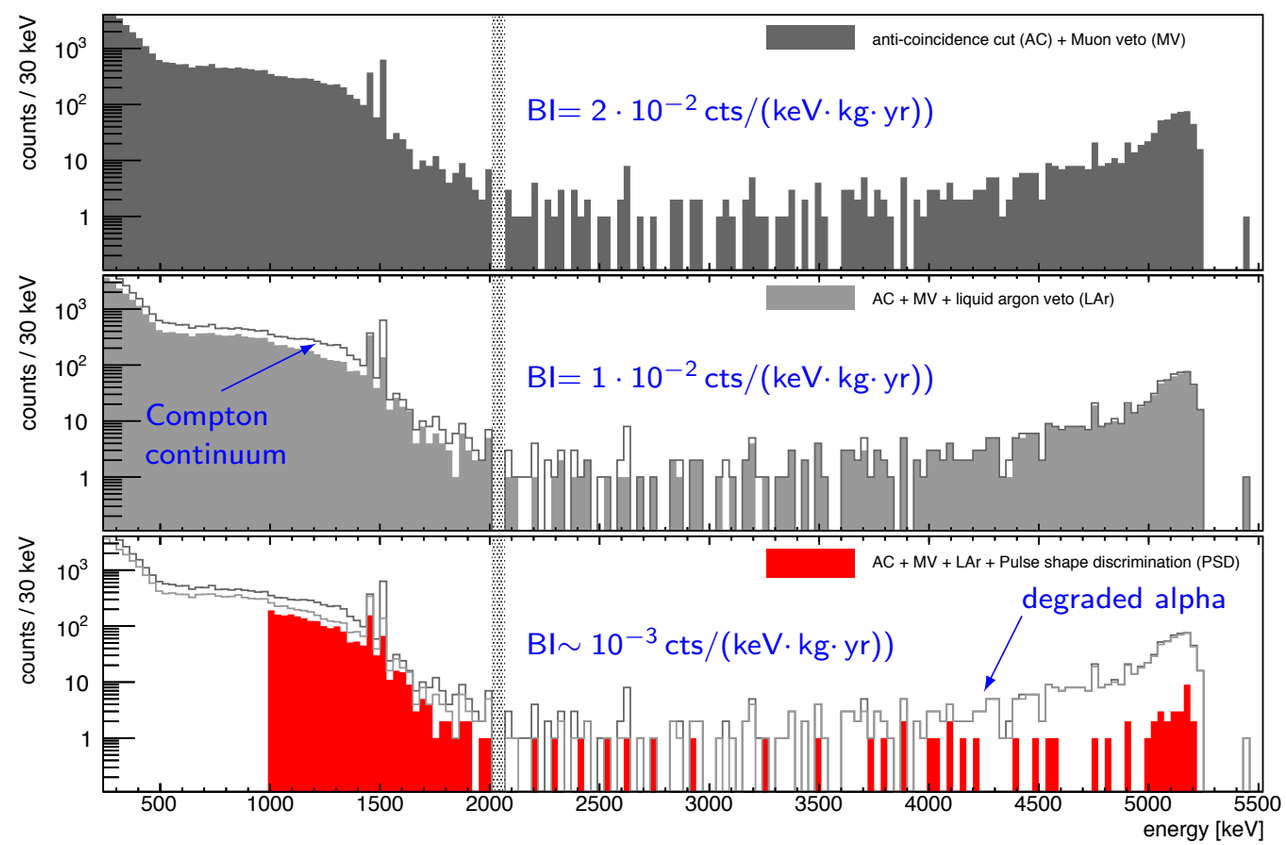
GERDA: resolution and PSD





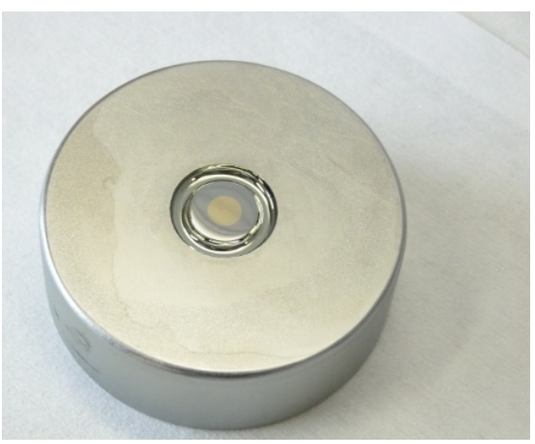


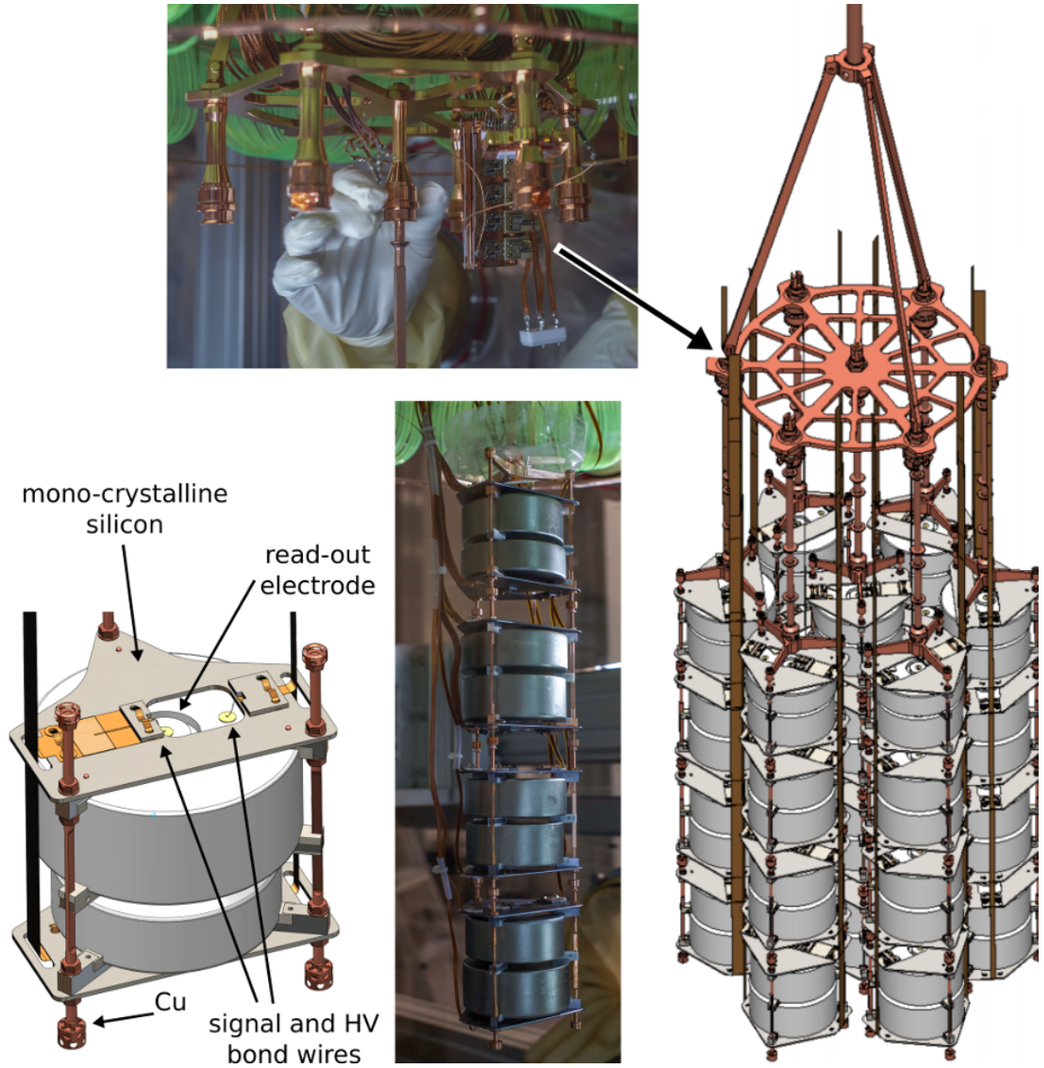
Coaxial detectors: background suppression



Economy of scale

- 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





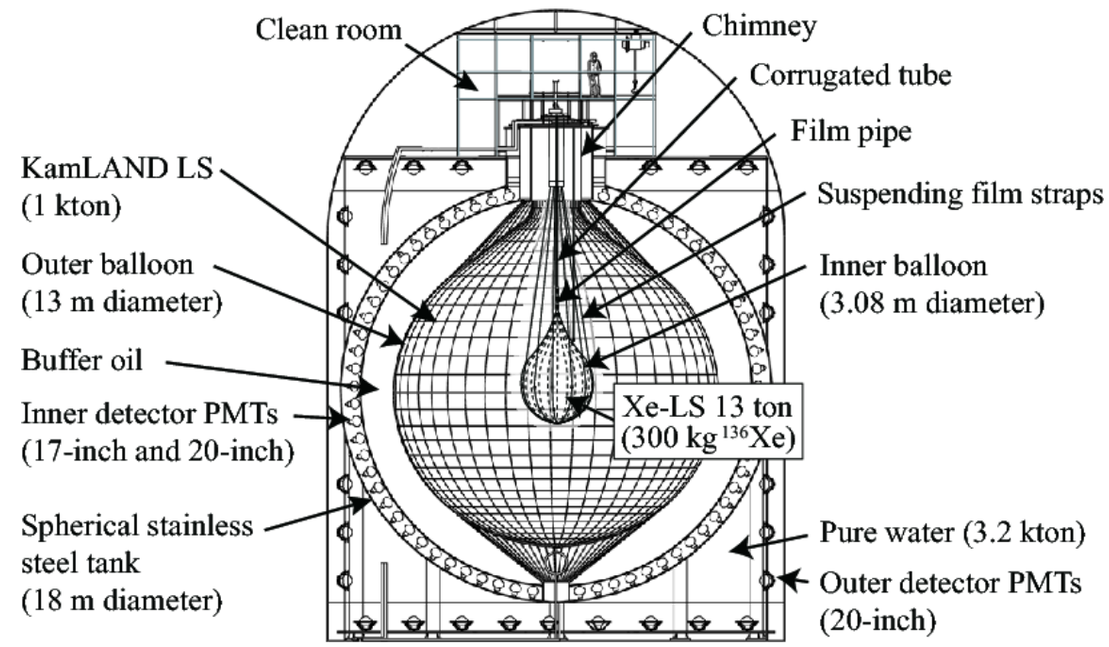
- Detector build by module repetition.
- **Scalability to large masses is difficult (expensive)**
- **No economy of scale**

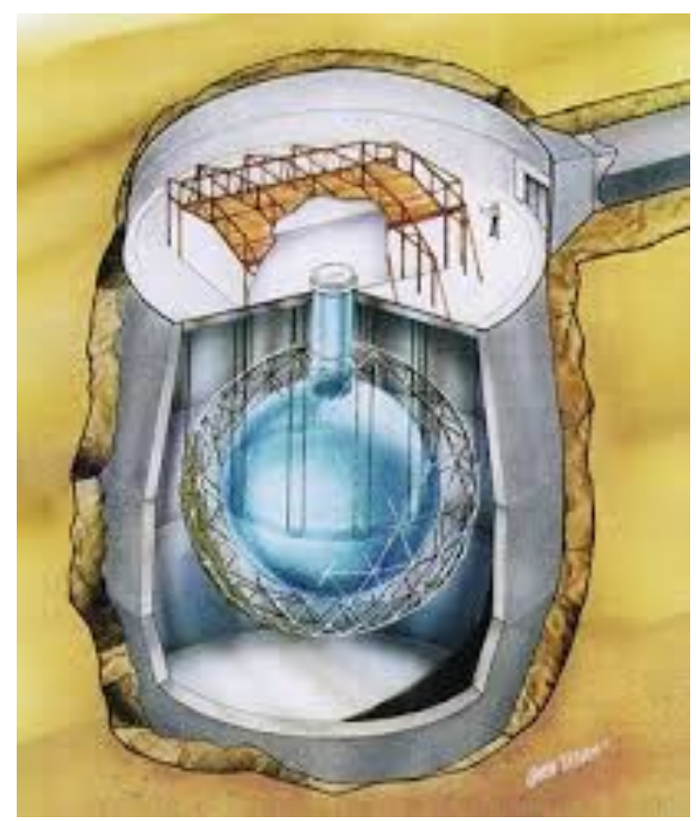
Liquid Scintillator calorimeters

Phys. Rev. Lett. 117, 082503 (2016)

KamLAND-Zen (SNO+)

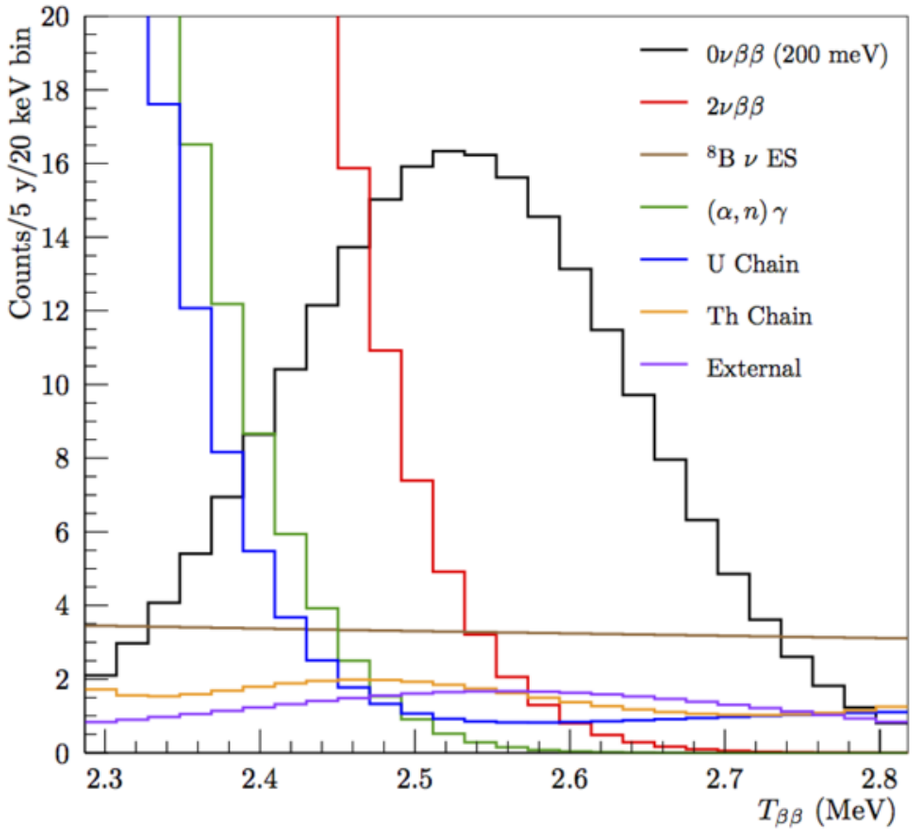
- Isotope: Xe-136, natural abundance 9%, mass 300 kg.
- Technique: Xe dissolved in liquid scintillator.
- **Poor energy resolution:** 11% FWHM at $Q_{\beta\beta}$
- **Extremely low background rate**: 1.6×10^{-4} counts/(keV kg year).
- **Very good self-shielding (virtually no background from outside).**
- Contamination from inner balloon and cosmogenic that activate LS and Xe.
- **Dominated by cosmogenic and ββ2ν.**
- **Very good scalability.**

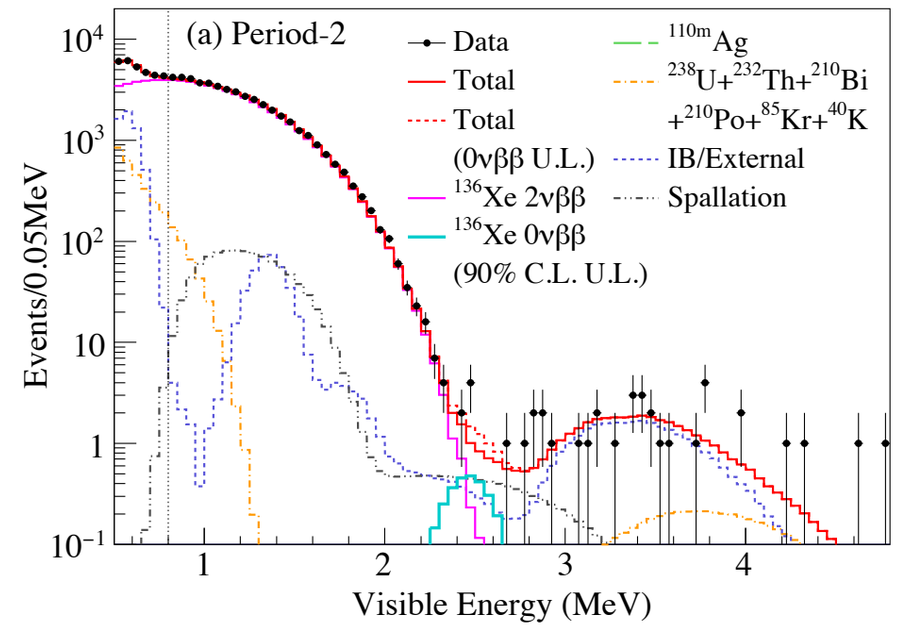


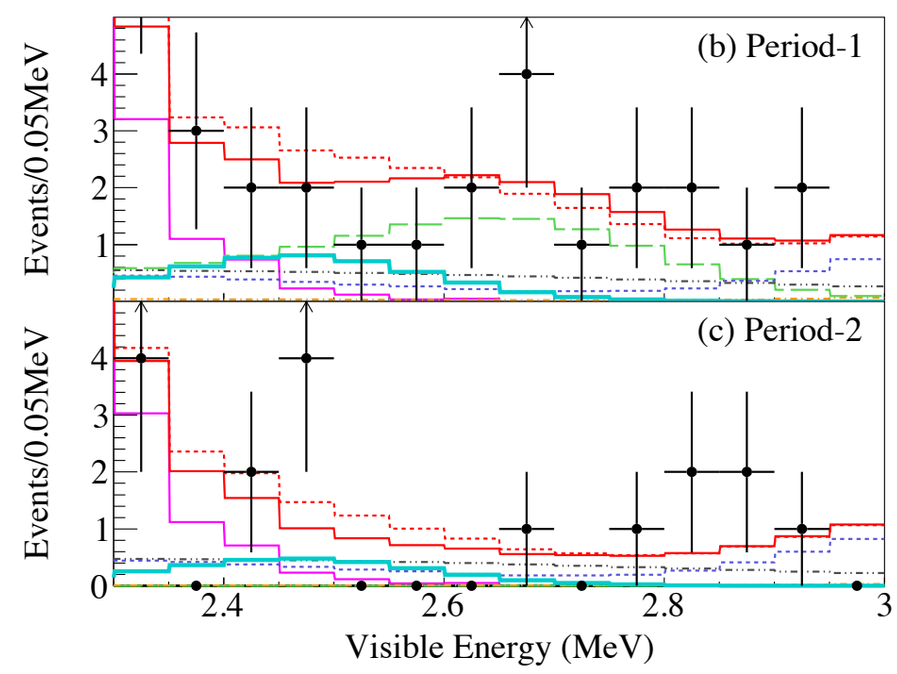


Kamland-Zen: 500 kg (~20 kg fiducial) target mass

Large mass & shielding: KZEN (SNO++)

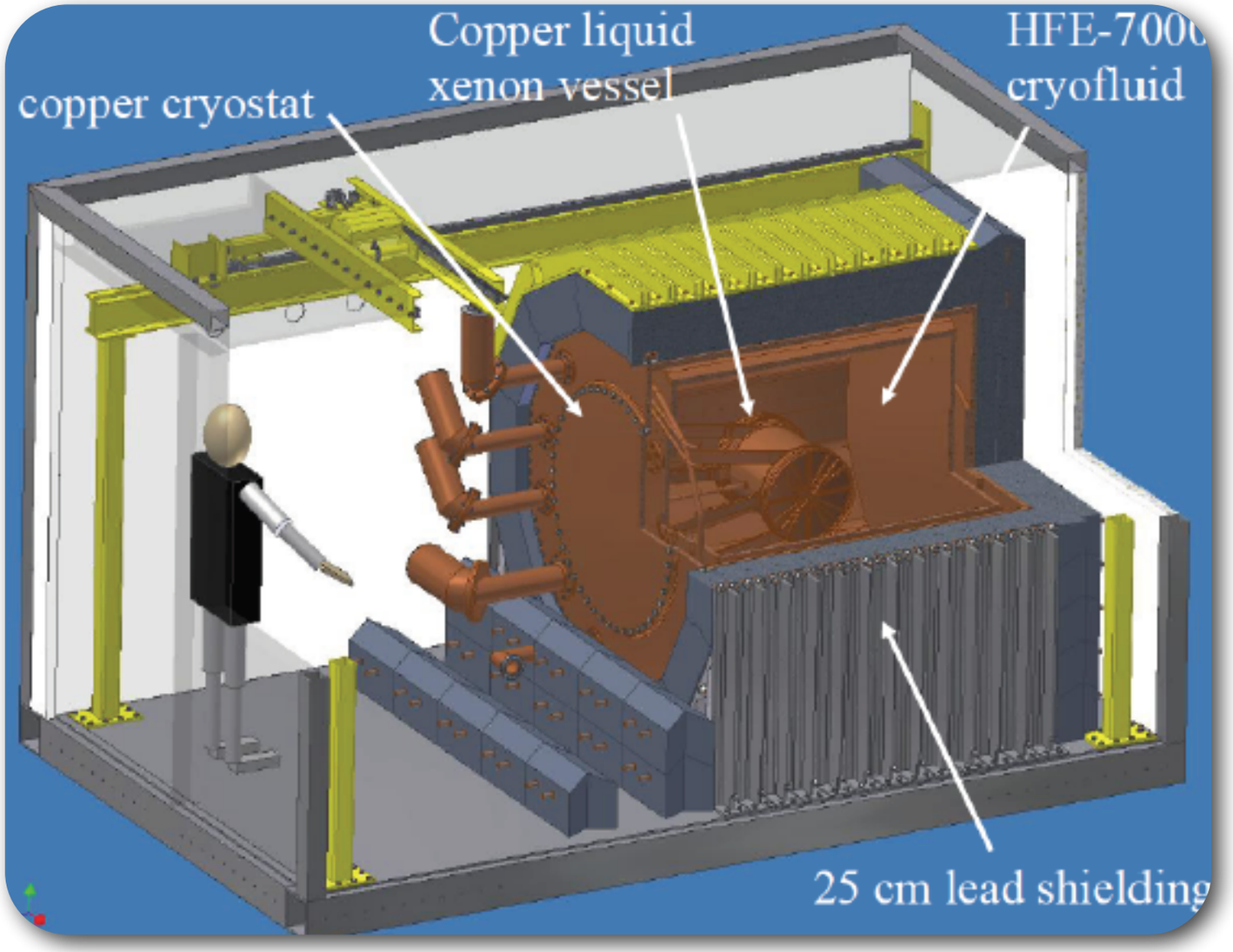




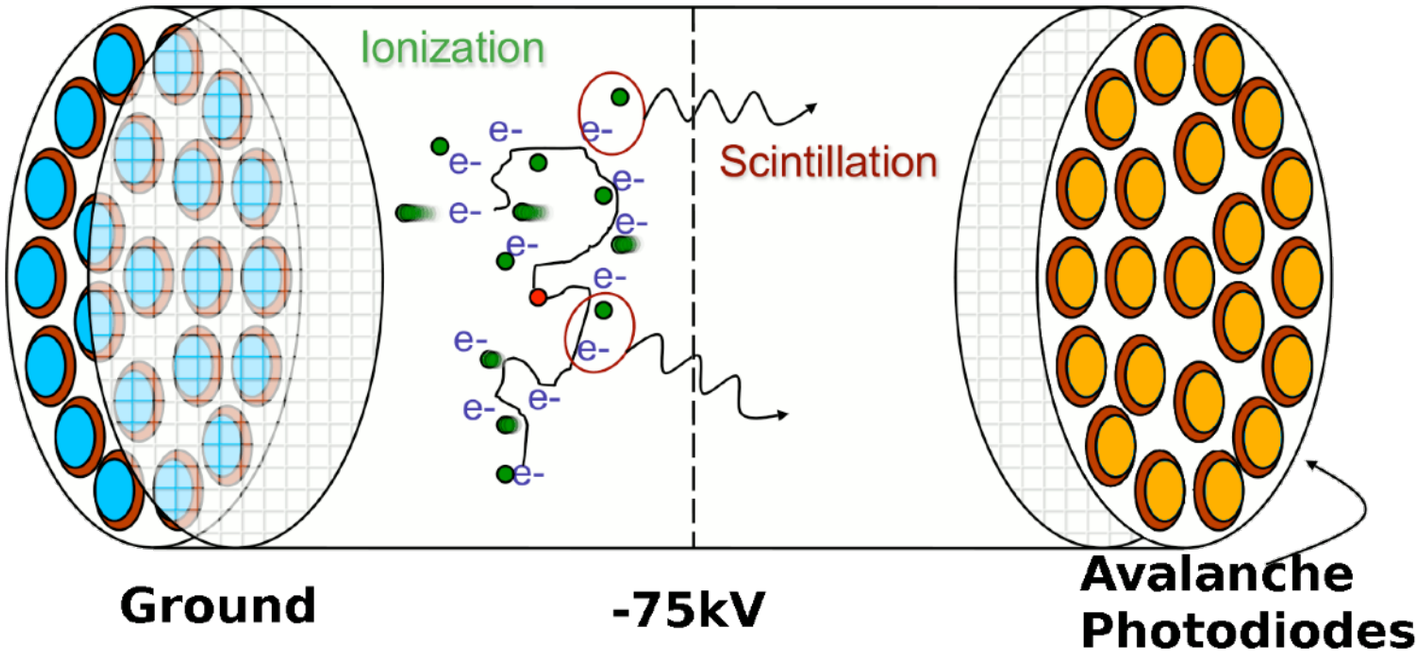


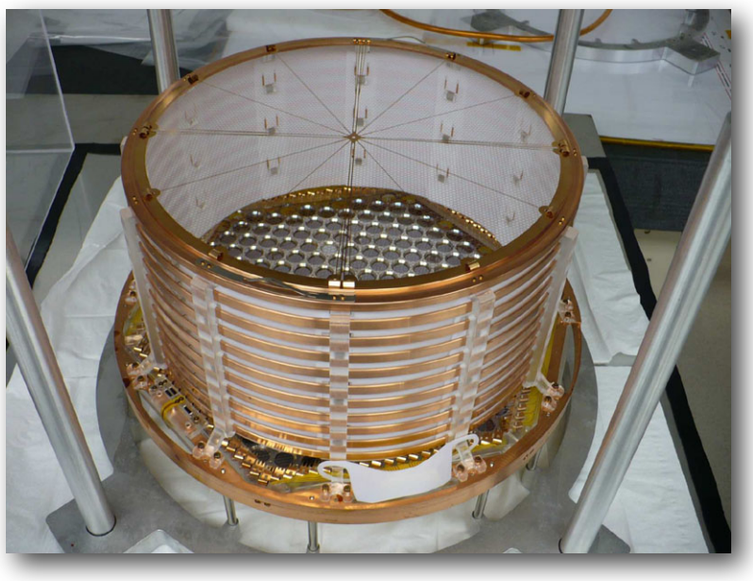
- Excellent self-shielding: LOW BI
- But very poor resolution (compared with GE!)
- Counting experiment (with background subtraction)
- **Ultimately limited by ββ2v**

LXe: EXO



- LXe (single phase) TPC.
- Reads both scintillation and ionization.
- Enriched xenon (80.6 %)
- TPC hosted in a copper vessel and surrounded by active and passive shielding including cry-cooling liquid and 25 cm thick lead castle.

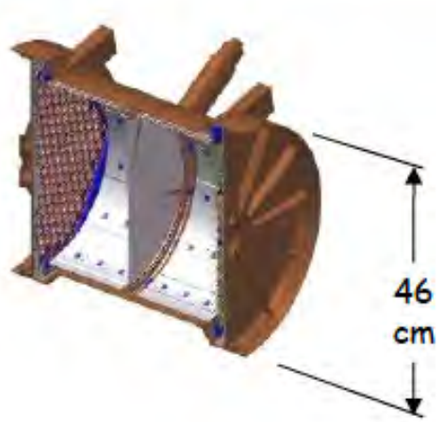


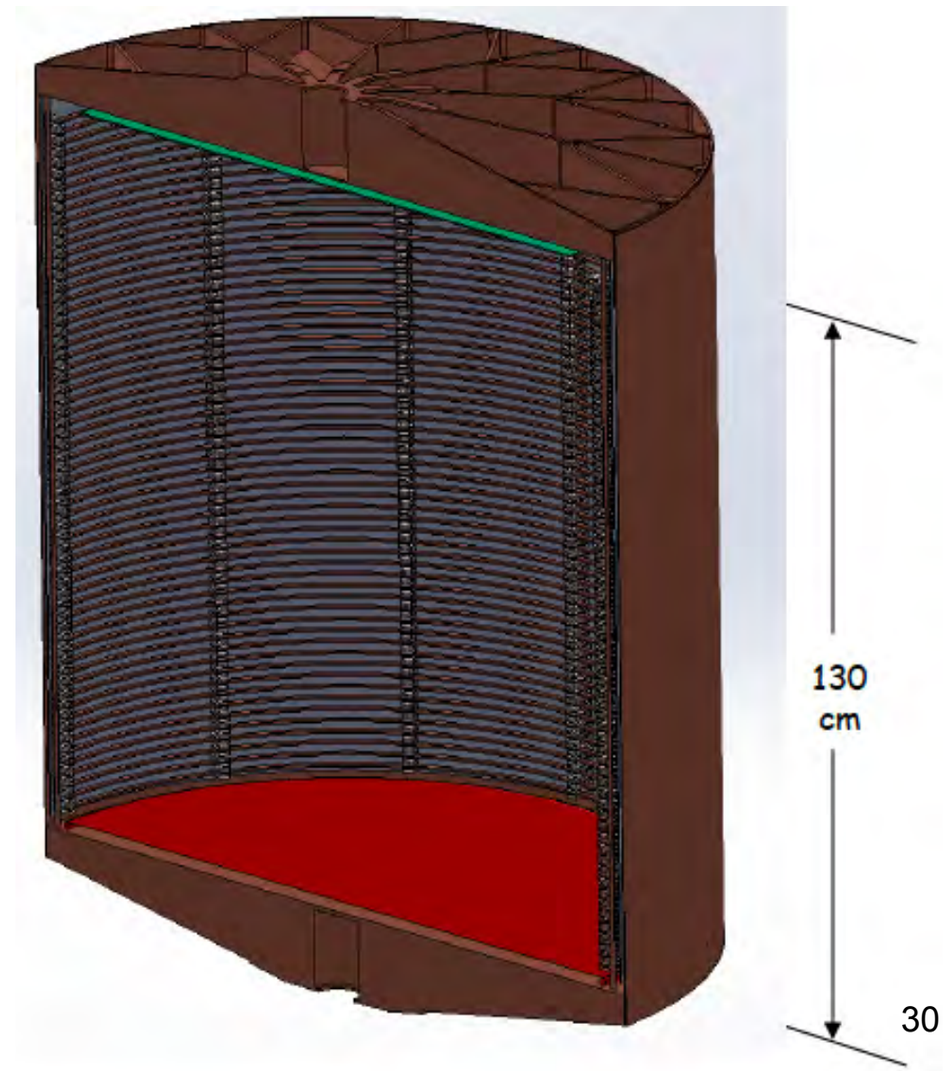


Detail of the LAAPD read-out plane

- Symmetric (small) TPC:
  - R =180 mm and L_d = 200 mm.
- Ionisation read by cross-wires in the anode.
- Scintillation light readout by VUV-sensitive APDs located behind the wires.
- Full XYZ fiducialization of events.

From EXO to nEXO

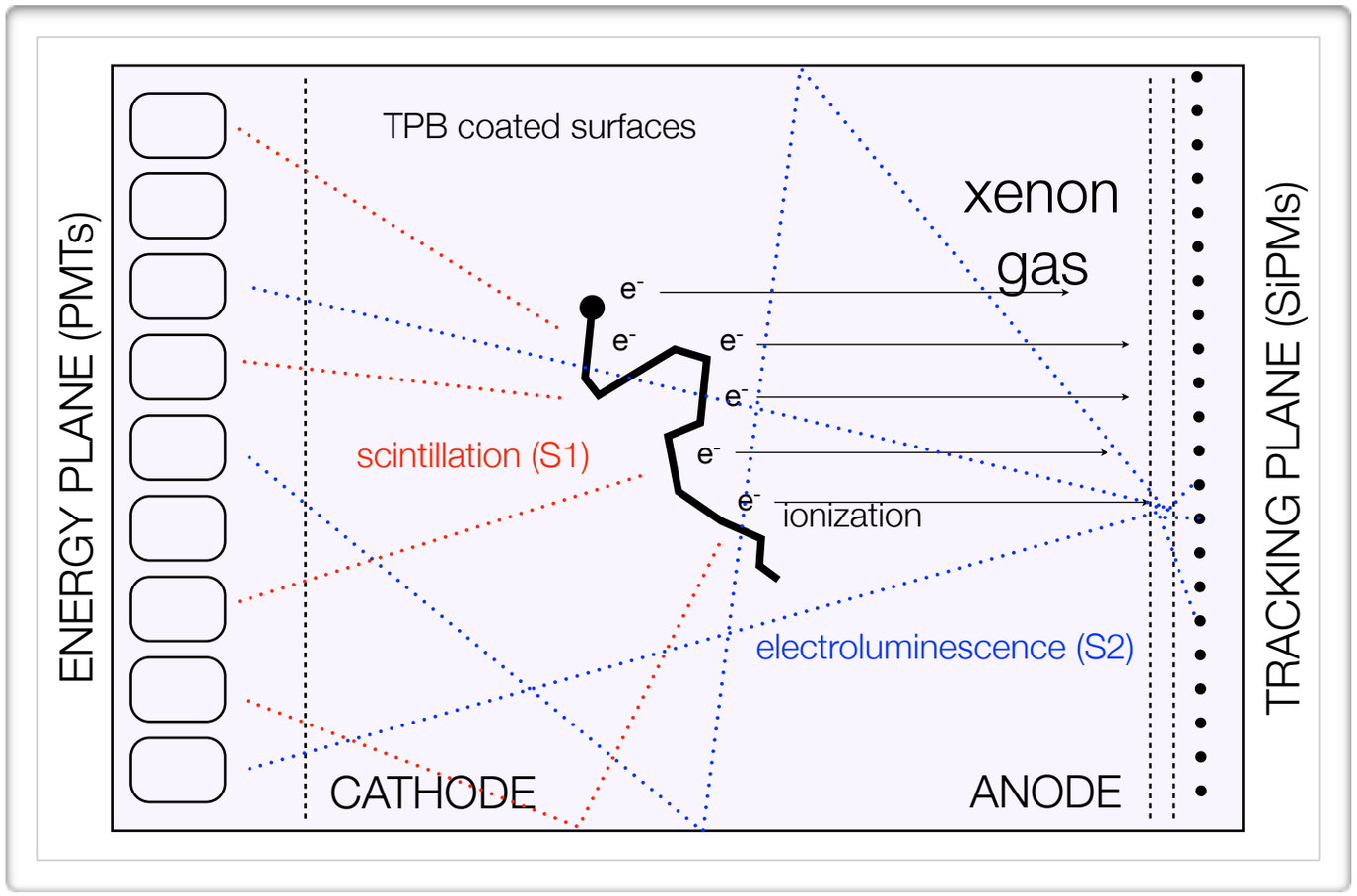




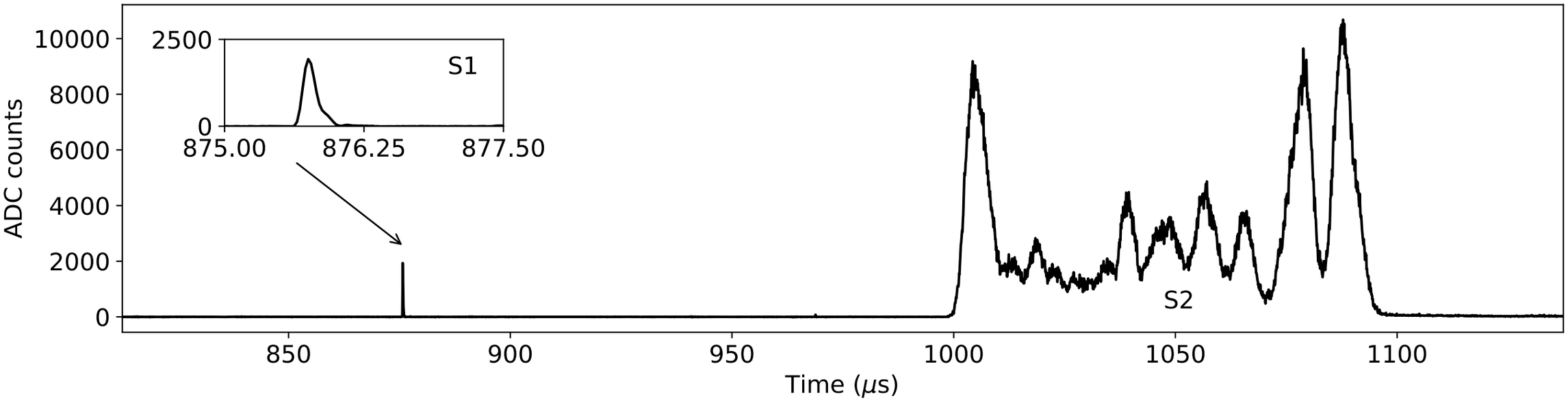
nEXO is a large, homogenous detector that builds on the success of EXO-200.

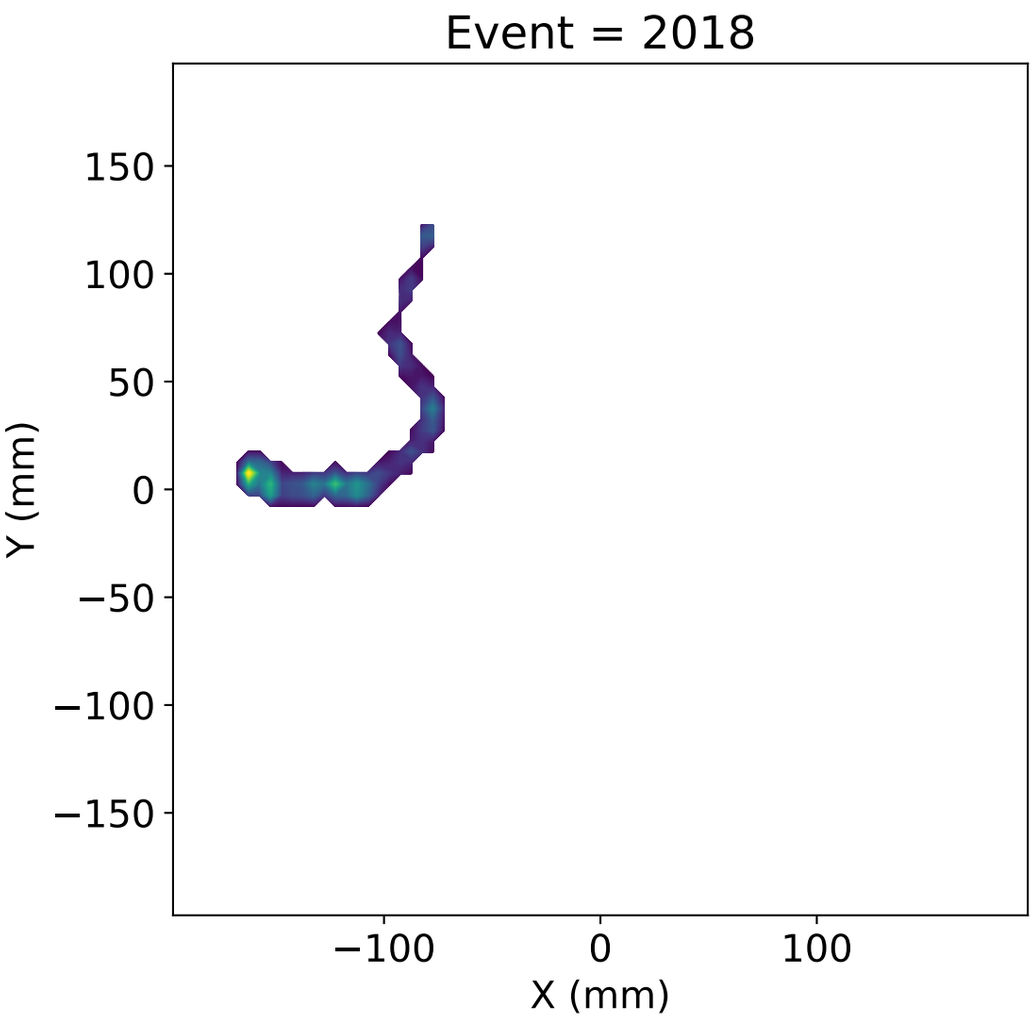
- **Technical issues include:**
  - **Single or double phase?**
  - **Reading charge (wires, MPD, other?)**
  - **Reading light (VUV SiPMs?)**
  - **Self-shielding (fraction of the detector used as target)**

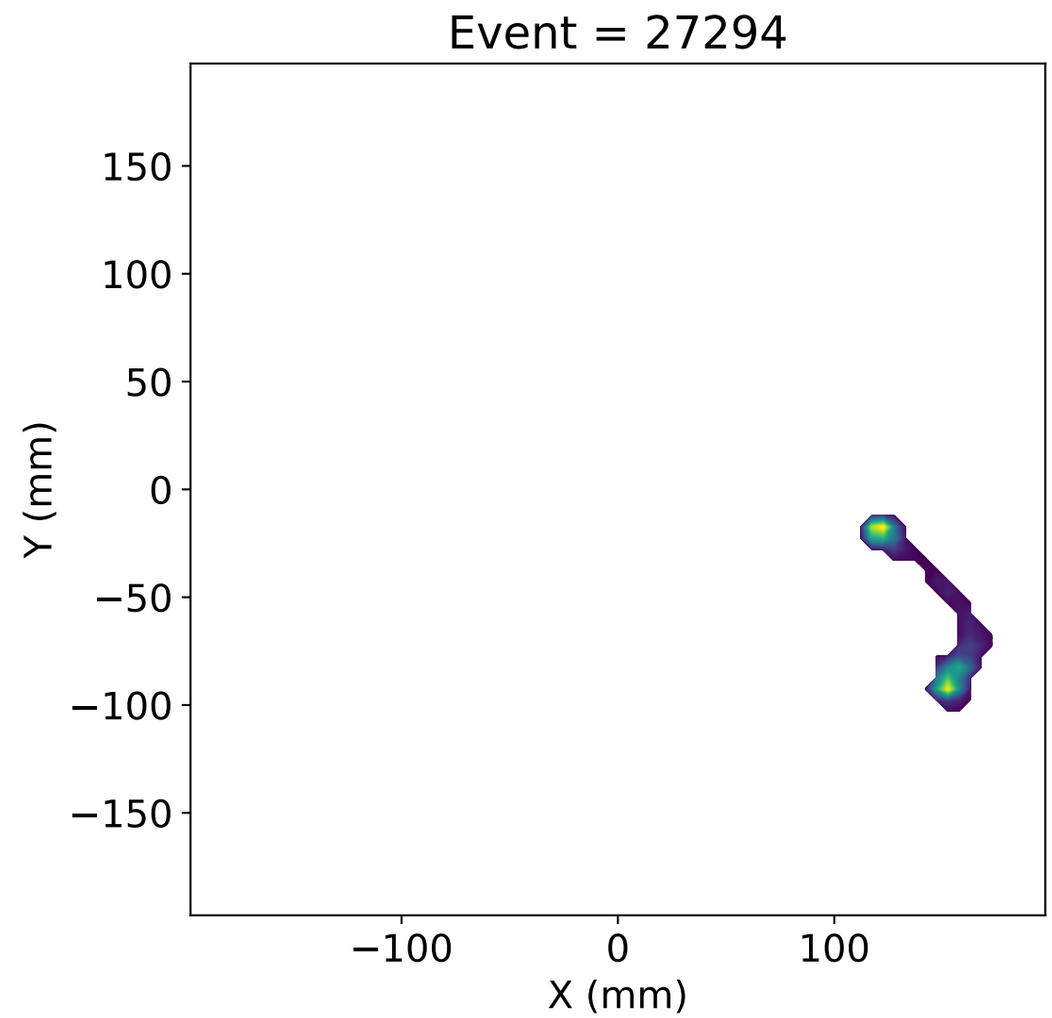
The NEXT concept



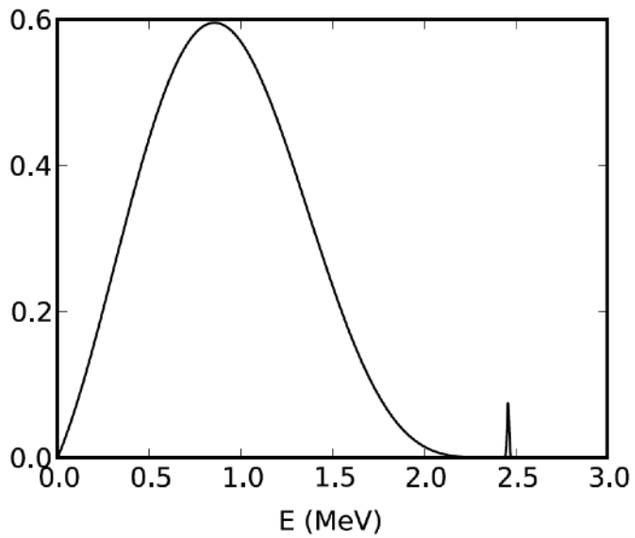
- High Pressure Xenon TPC (operation 10-20 bar)
- EL amplification to achieve excellent energy resolution (~0.5 % FWHM appears possible)
- Adds a topological signature (observation of two electrons) to further suppress the backgrounds.
- Is built with radio pure materials.

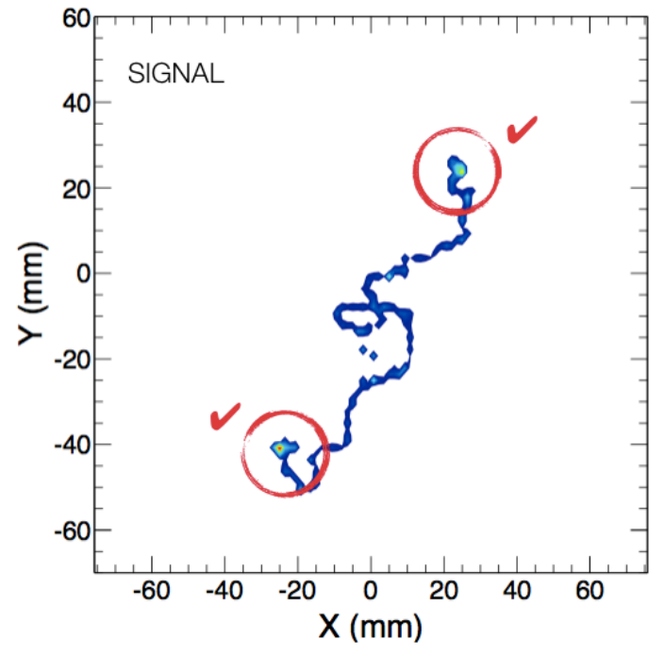

ADC counts
10000
8000
6000
4000
2000
0
2500
0
875.00
876.25
877.50
S1
S2
850
900
950
1000
1050
1100
Time (μs)

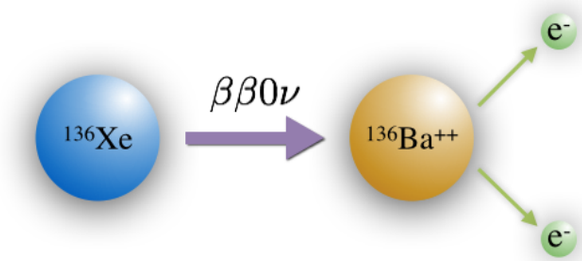

Event = 2018
150
100
50
0
−50
−100
−150
Y (mm)
−100
0
100
X (mm)

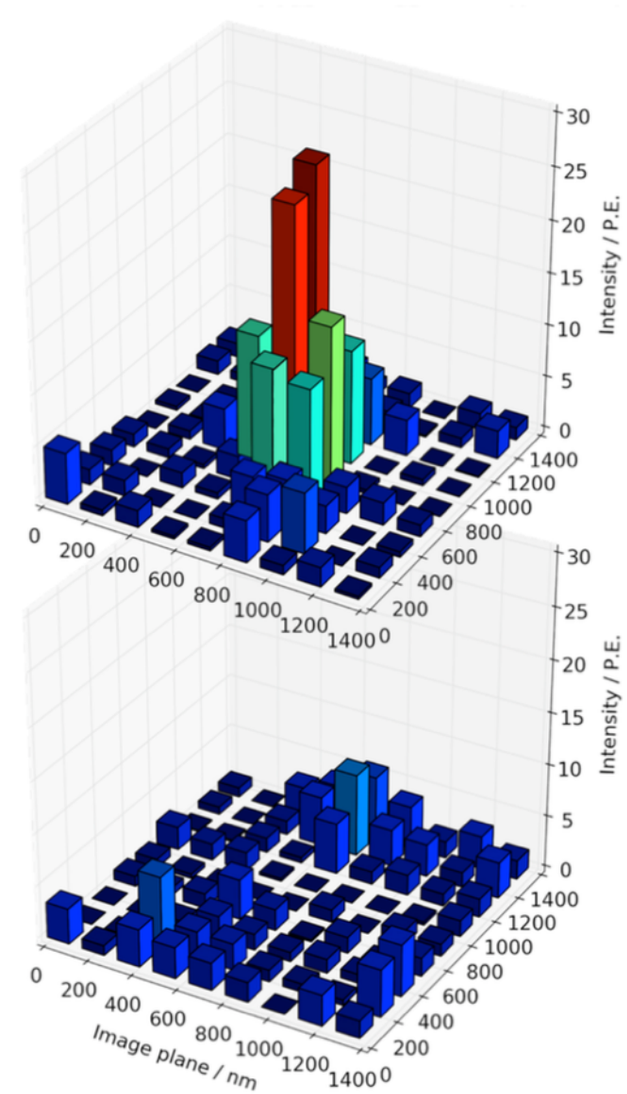

Event = 27294
150
100
50
0
−50
−100
−150
Y (mm)
−100
0
100
X (mm)

Advantages of HPX-EL technology

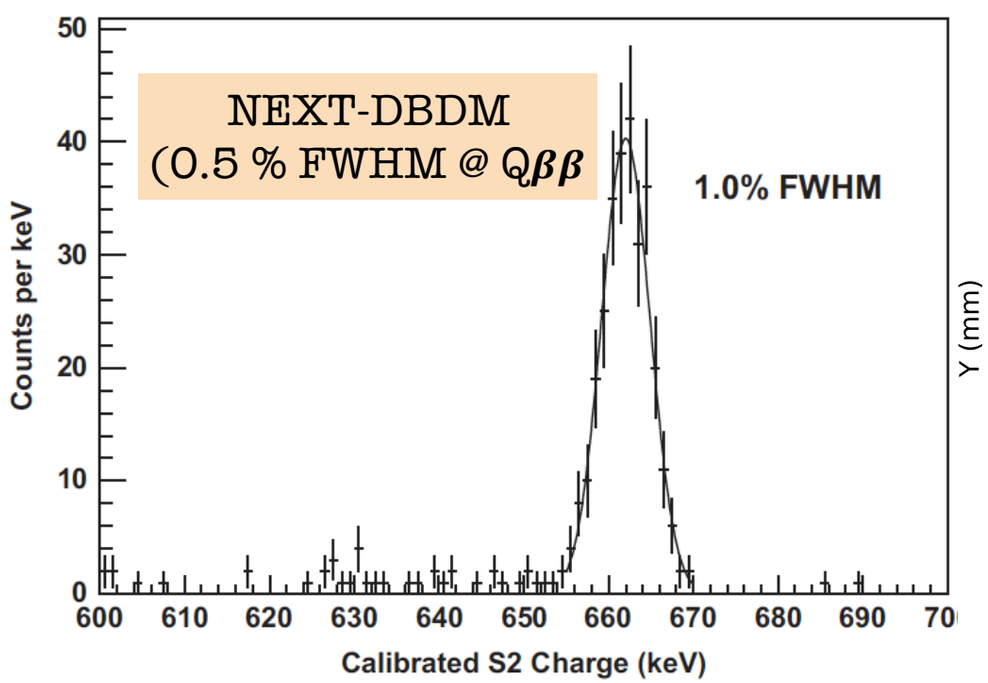


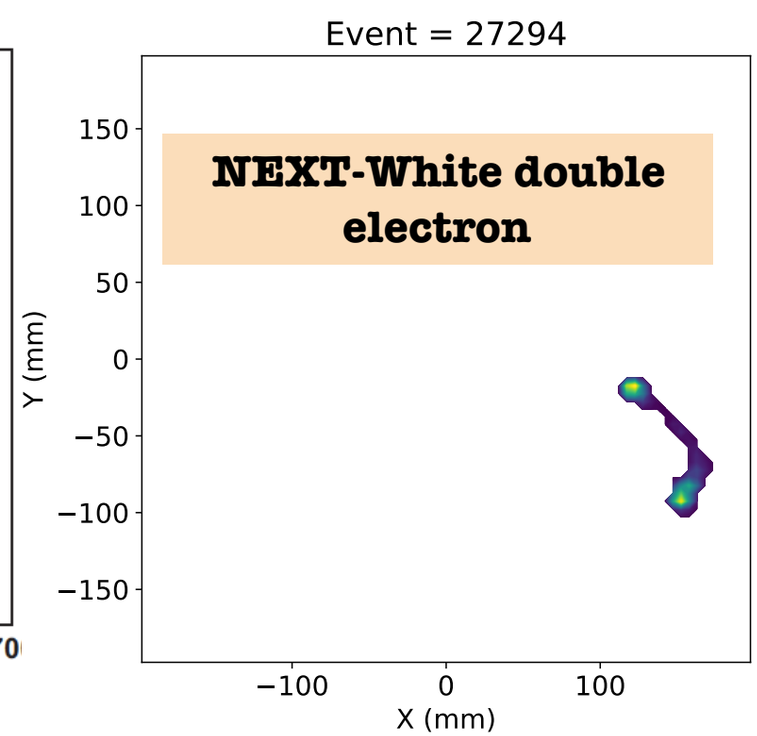






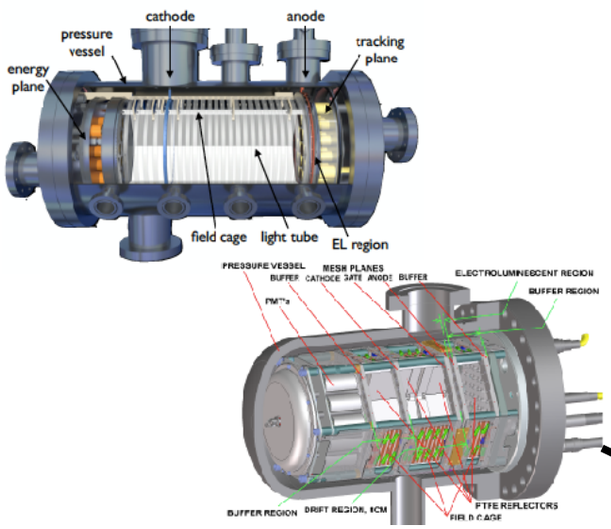
NIM A708. 101 (2014) [arXiv:1211.4474]





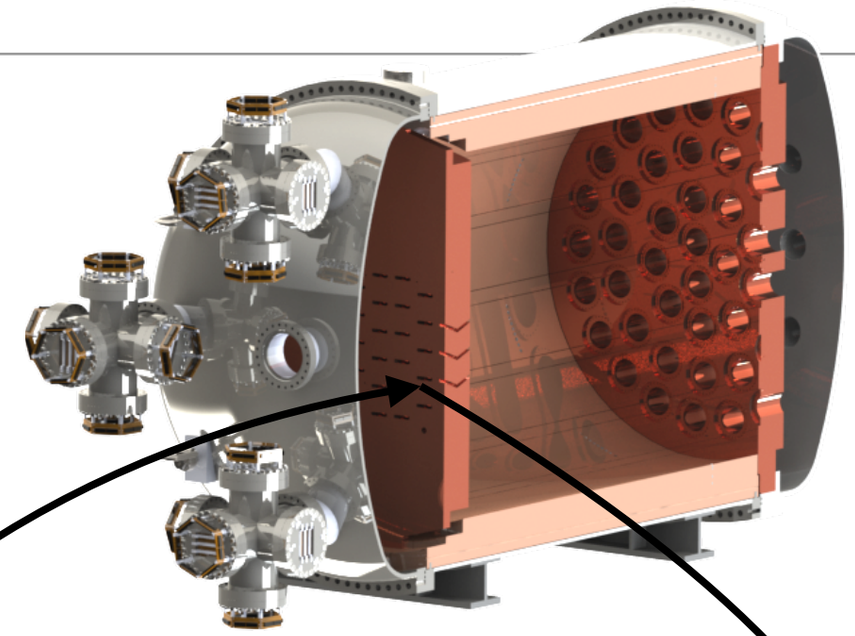
Electroluminescent High pressure Xenon gas optical TPC

NEXT phases



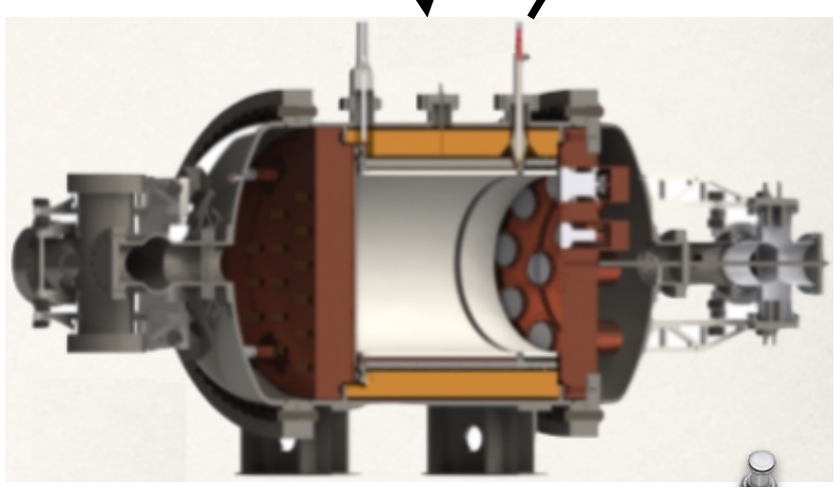
Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept



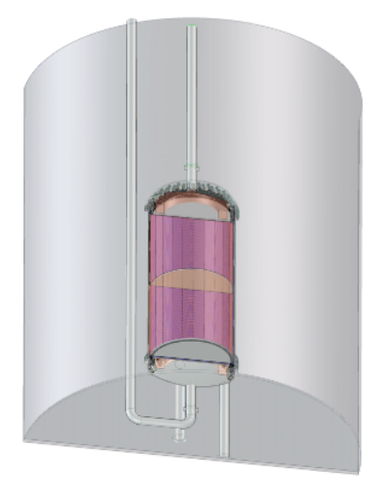
NEXT-100 (~100 kg)
[2019 - 2020's]

??



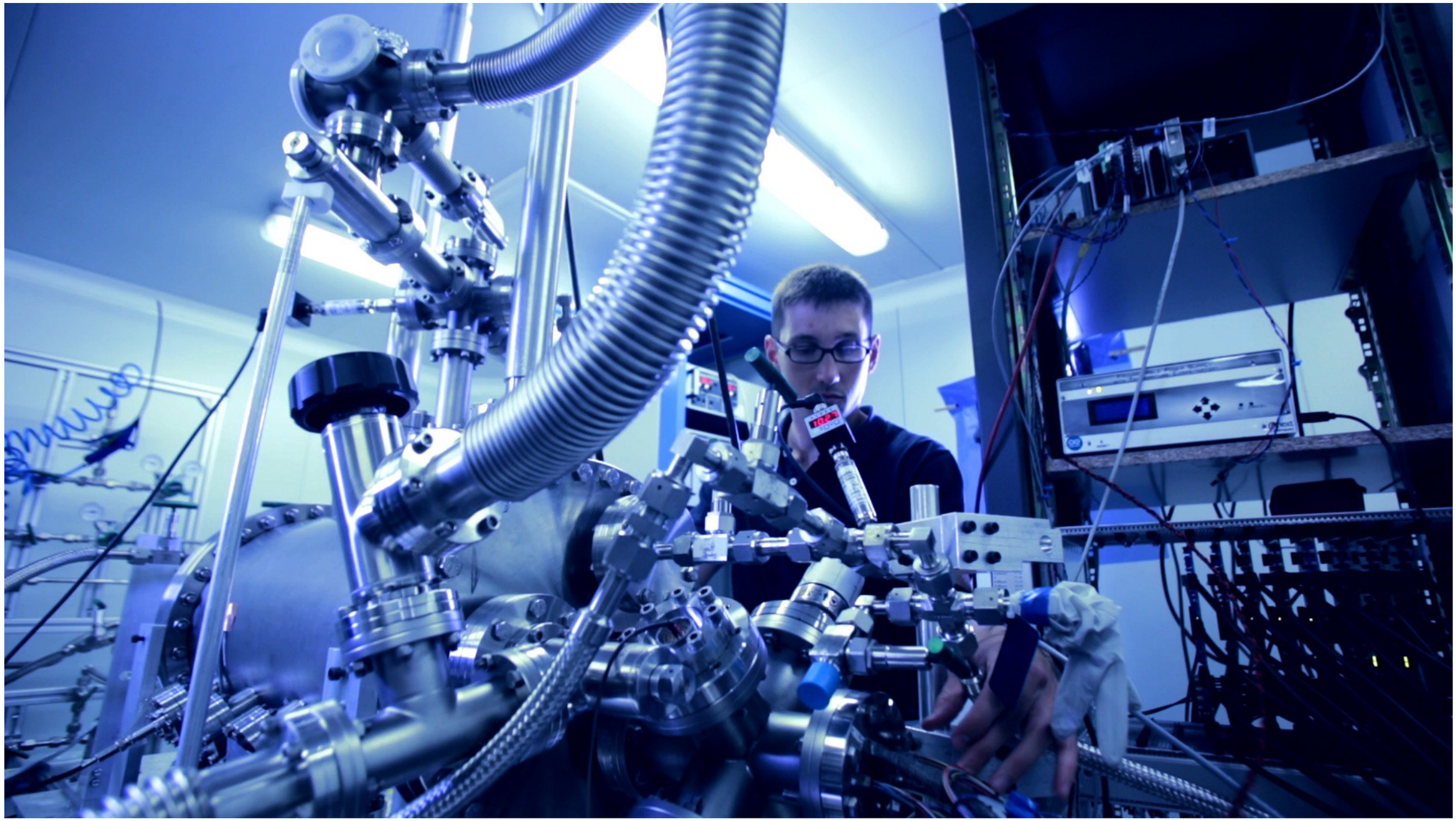
NEXT-NEW (~5 kg)
[2015 - 2018]

Underground and radio-pure operations, background, ββ2ν



- (multi) ton mass
- ββ0ν search

NEXT DEMO



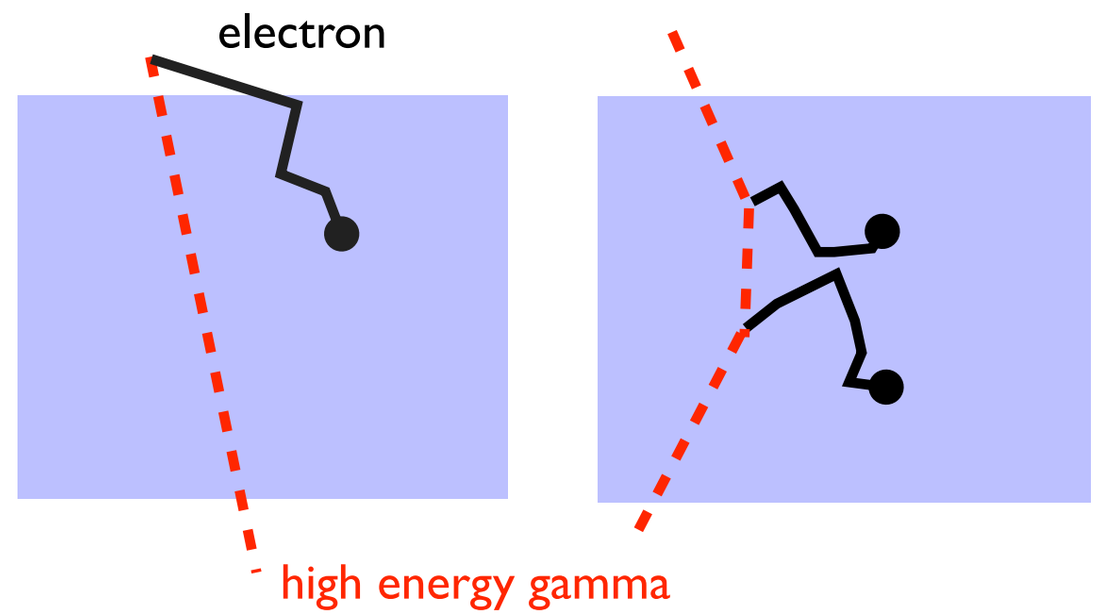
NEXT-DEMO: Started in 2011, first HPXeEL in the World.

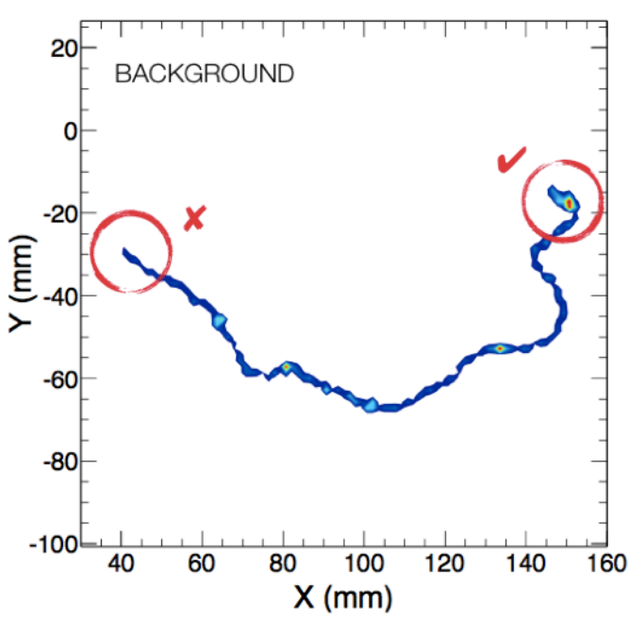
A few years later…

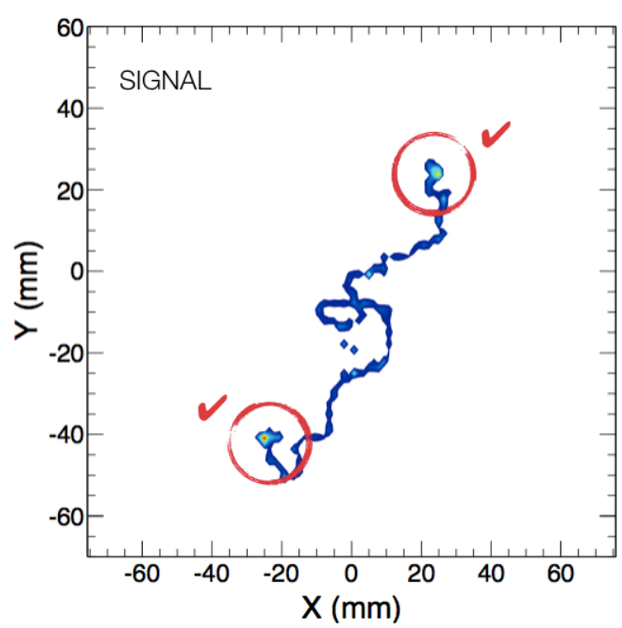
NEXT-White: Already operating at the LSC

TOPOLOGY

- Electrons leave extended tracks in gas, which can be used 1) to veto beta electrons coming from outside, 2) to identify events with more than one track (typically background).

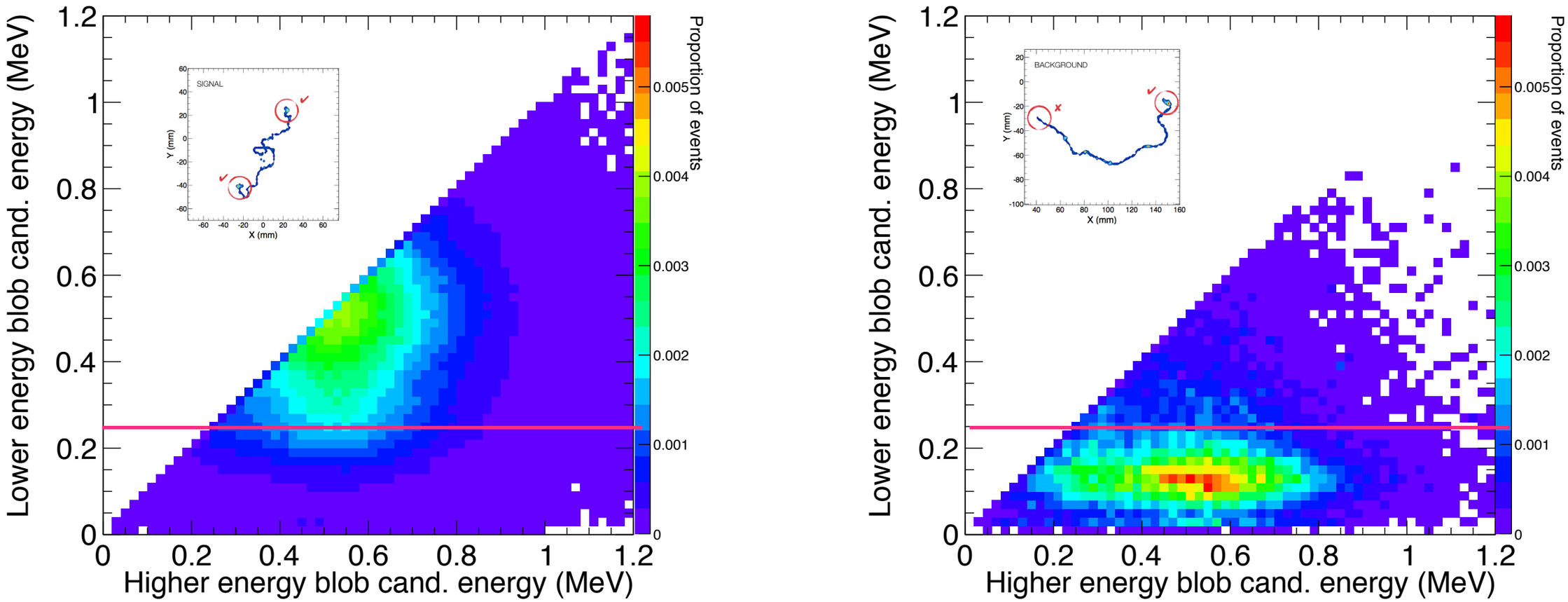






- Electron energy loss in gas is constant until the end of the trajectory (Bragg peak).
- Signal: spaghetti with two "meat balls".
- Background: spaghetti with one "meat ball".

THE POWER OF TOPOLOGY



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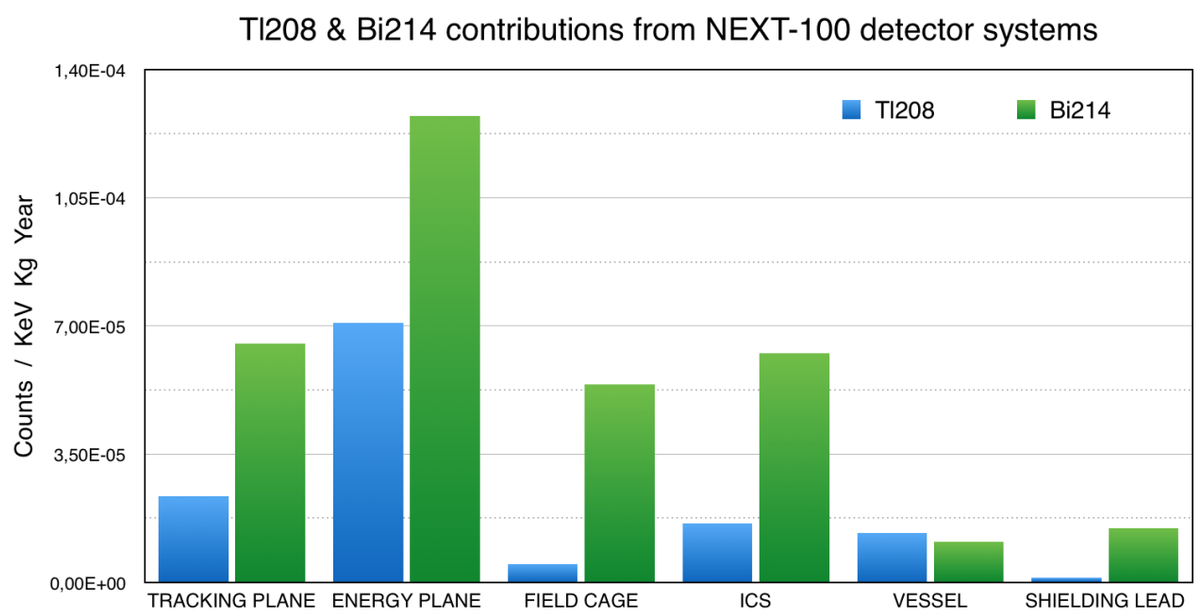
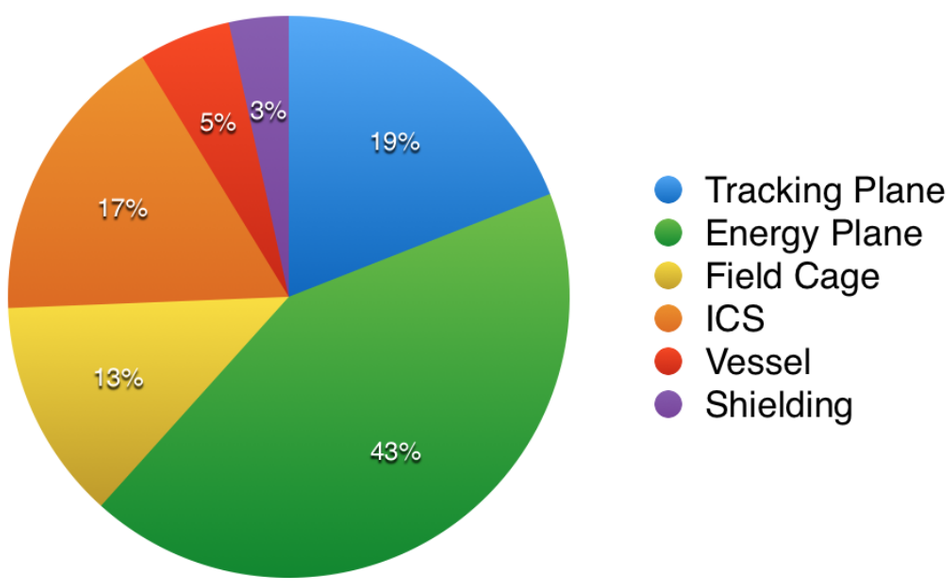
- Distribution of the energy at the end-points of the track.
- High discrimination power.



- Main measured contribution: PMTs (21 and 11 mBq in total) and kapton boards (glue between layers).
- Limits on copper and hdpe.

Relative contributions from NEXT-100 detector systems



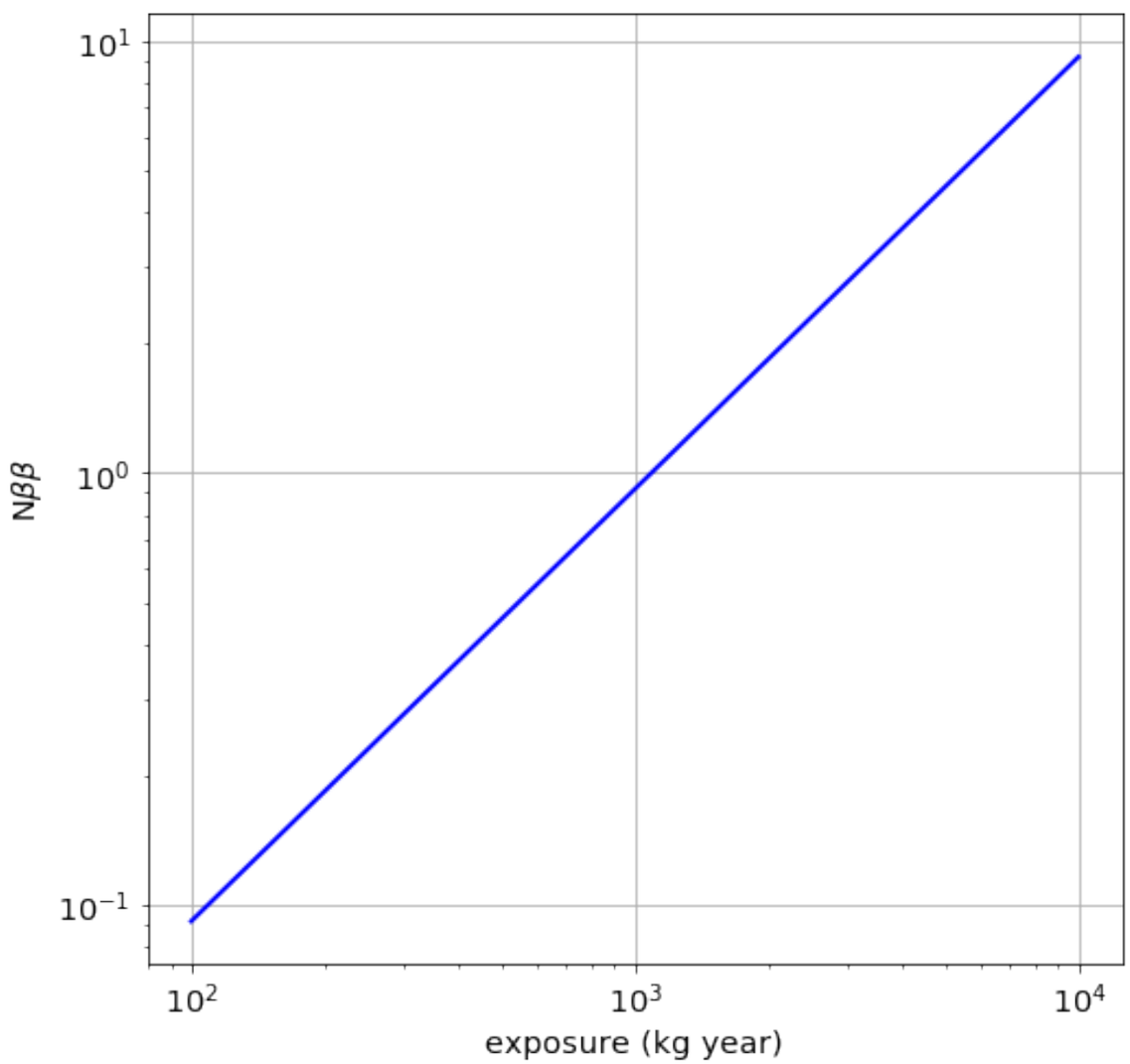
- Expect< 1 count per year in the ROI
- **"Background free" in 100 kg scale**
- **But one needs further reduction to explore the IH and beyond**
- **All DBD experiments are in a similar situation**

Total expected background rate

$< 4 \times 10^{-4}$ cts / (keV kg year)

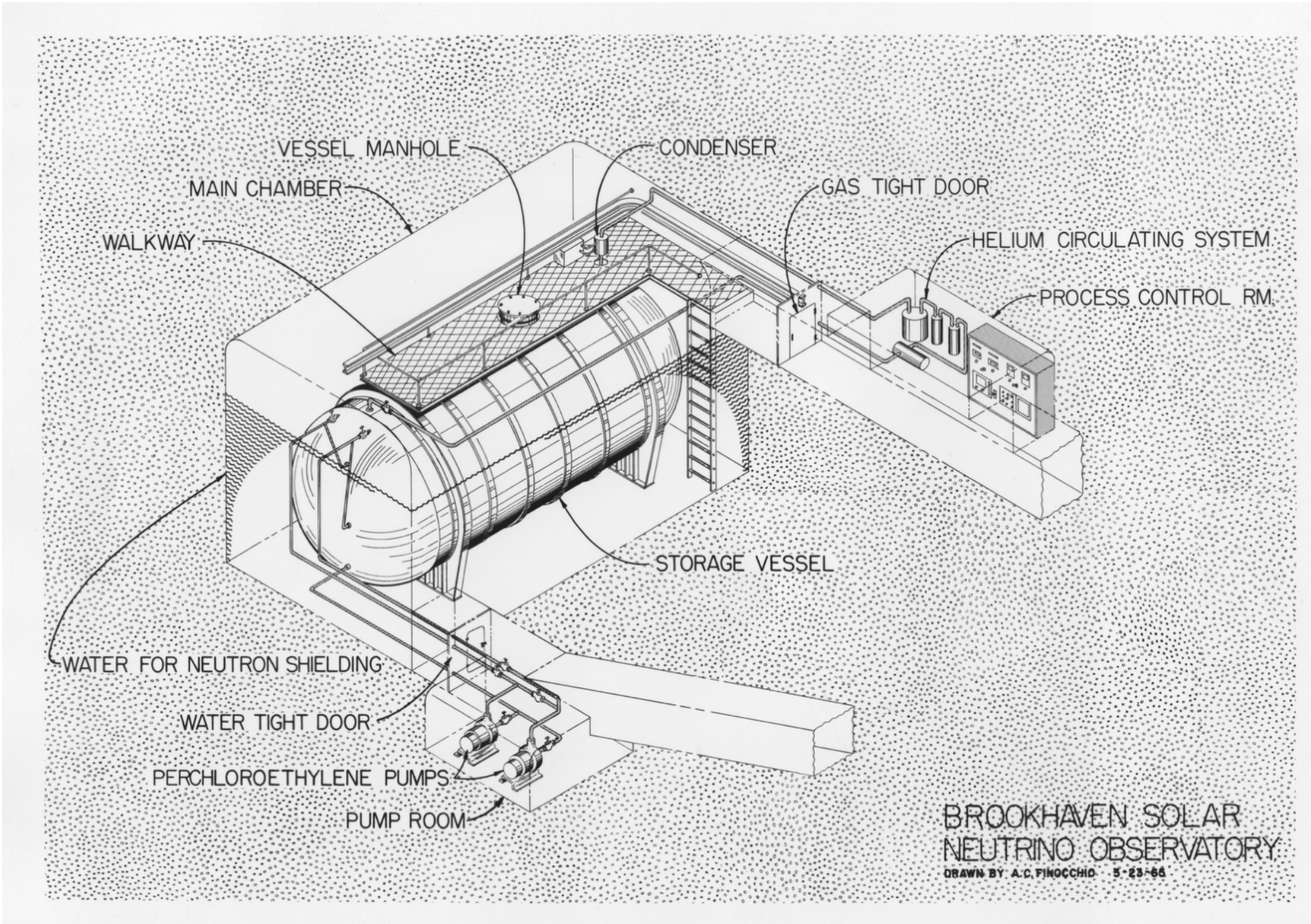
An ideal ββ0ν experiment

- We need to invent an ideal DBD detector
- Make it very massive
- And operate it for decades



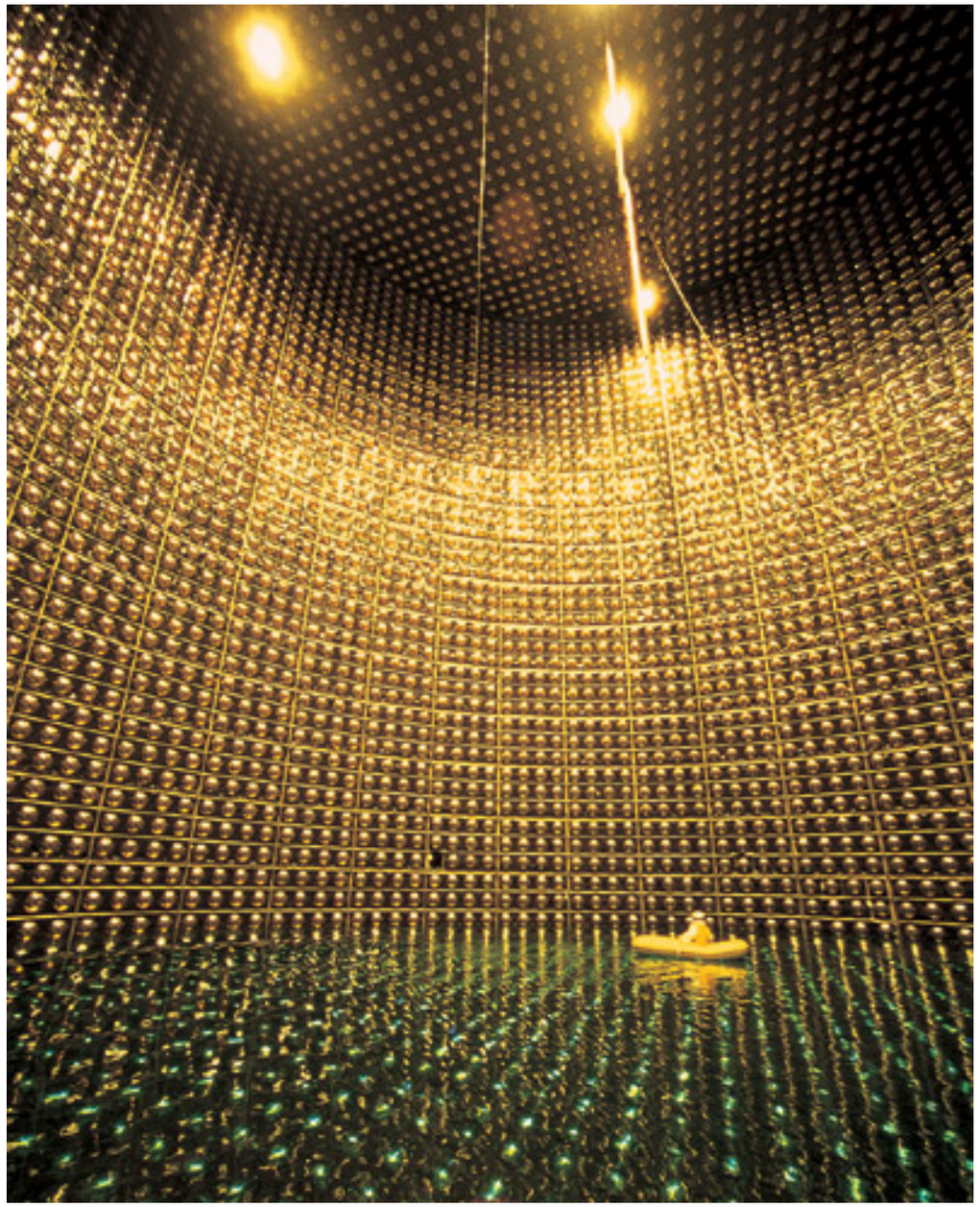
- $T_{1/2} = 10^{27}$ (10^{29})y
- Assuming a long run, with an integrated lifetime of 10 y, we need:
  - **100 kg of ideal (zero background) detector to cover IH**
  - **10 tons of ideal (zero background) detector to cover IH**

So what?



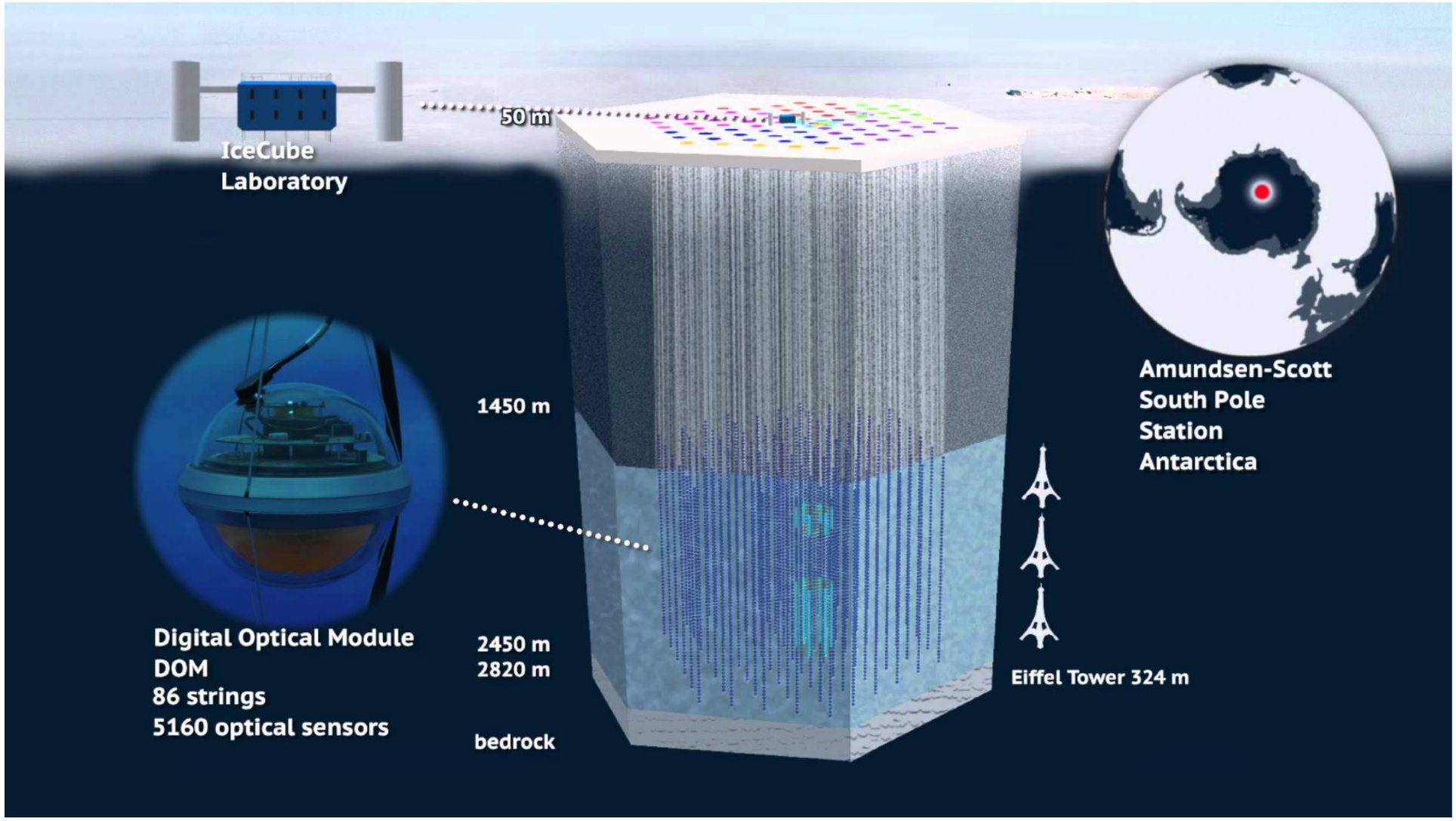
- Davis (solar neutrinos) was not afraid of low background, small rates, large target masses, decade-long runs and gossip from fellow physicists

So What?



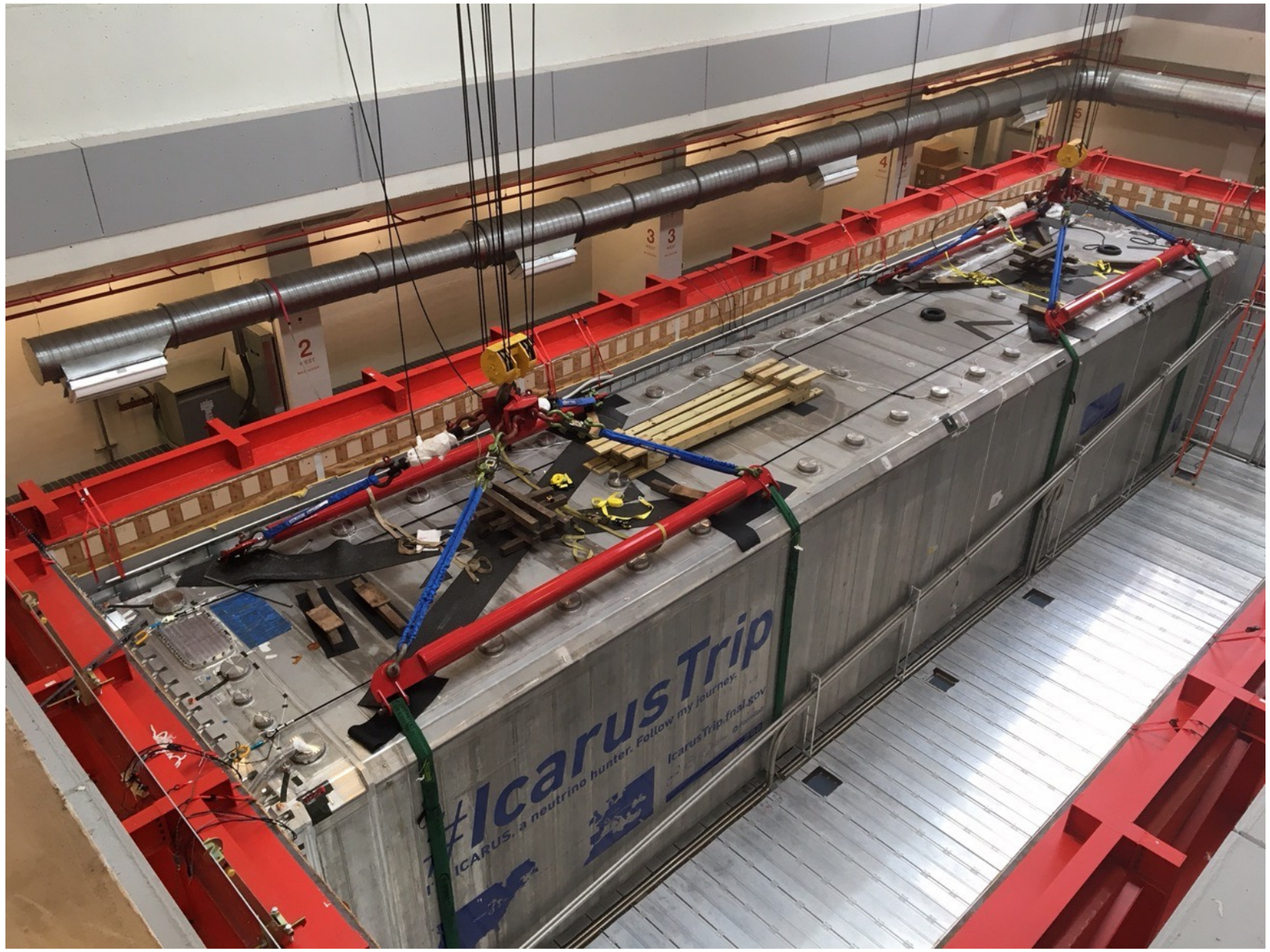
•Kobayashi, Kajita et al., didn’t think that a 50 kilo-ton detector was too large.

So What?



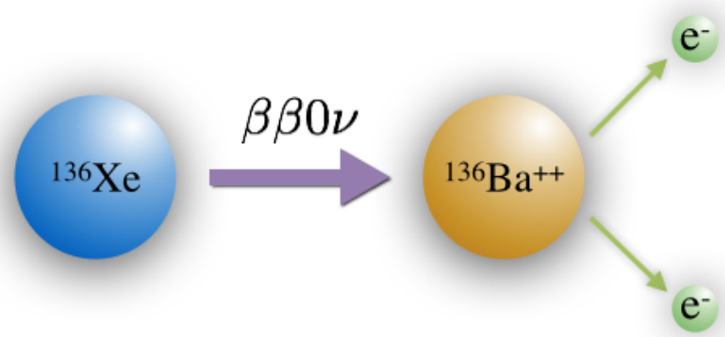
- Francis Halzen et al, thought that Super Kamiokande was just a small toy (compared with Ice Cube)

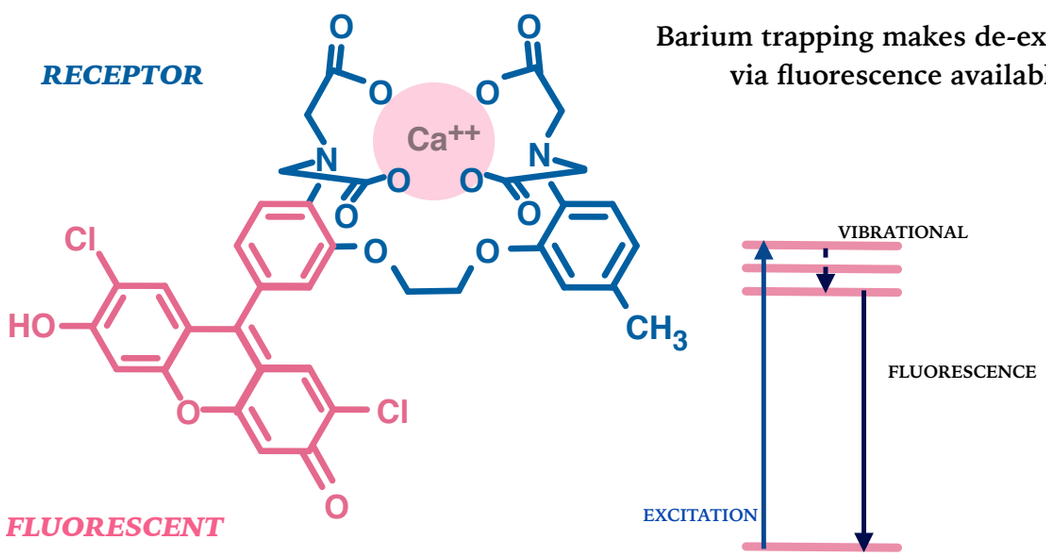
So What?



- A 10 ton noble gas TPC… would not even qualify as a toy for LAr/ICARUS/DUNE experimentalists!

A HOLLY GRIAL FOR NEXT!





- Xe-136 decays produce Ba++
- Ba++ will drift towards cathode (possibly without recombining)
- Coat cathode with suitable molecule, which will capture BA++
- molecule will fluoresce when illuminated with 342 nm light (broad band, 360-430… can design a system to detect blue light. Interrogation rate at ~100 kHz.
- This idea is a new form of Ba-tagging in gas which does not involve extracting the Ba++ ion to vacuum.
- **Potentially: background free experiment.**

•Seminar next week!
(Ben Jones)

Funagain.com