ELUCIDATING THE FUNDAMENTAL NATURE OF NEUTRINOS WITH DOUBLE BETA DECAY

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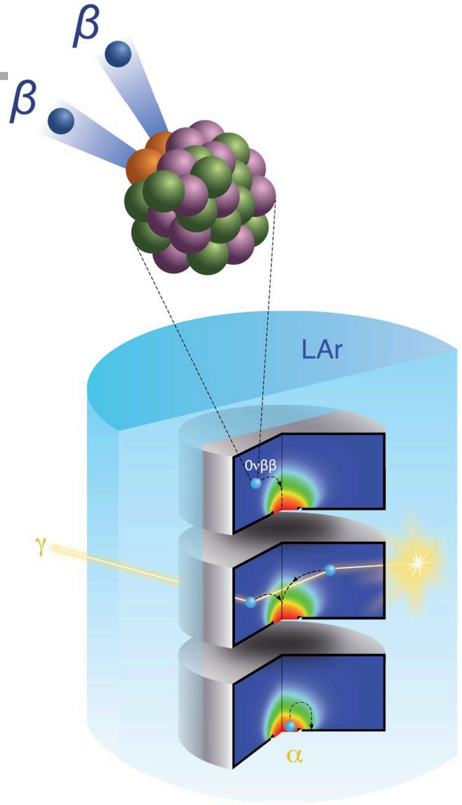
OCTOBER 30, 2020



FIRST, SOME HISTORY

- Zürich, December 4, 1930: Wolfgang Pauli, a 30 years old professor at the ETH (since 1928), writes perhaps one of the most famous letters in modern physics: "Dear radioactive ladies and gentlemen…"
- The letter was addressed mainly to Lise Meitner*, who had been working on radioactivity since 1907 and was attending a meeting in Tübingen (Pauli could not attend, because "a ball which takes place in Zürich the night of the sixth to sevenths of December makes my presence here indispensable")

- Pauli was suggesting "a desperate way out" of some paradox that had arisen in the nascent field of nuclear physics
- He was proposing "a terrible thing" - a new subatomic particle, the neutrino, a particle "which can not be detected"
- In 1930, only the electron, the proton and the photon were known, and Pauli's idea was quite radical

*Lise Meitner had made Pauli aware of the β-decay problem

Original - Photocopie of PLC 039

Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

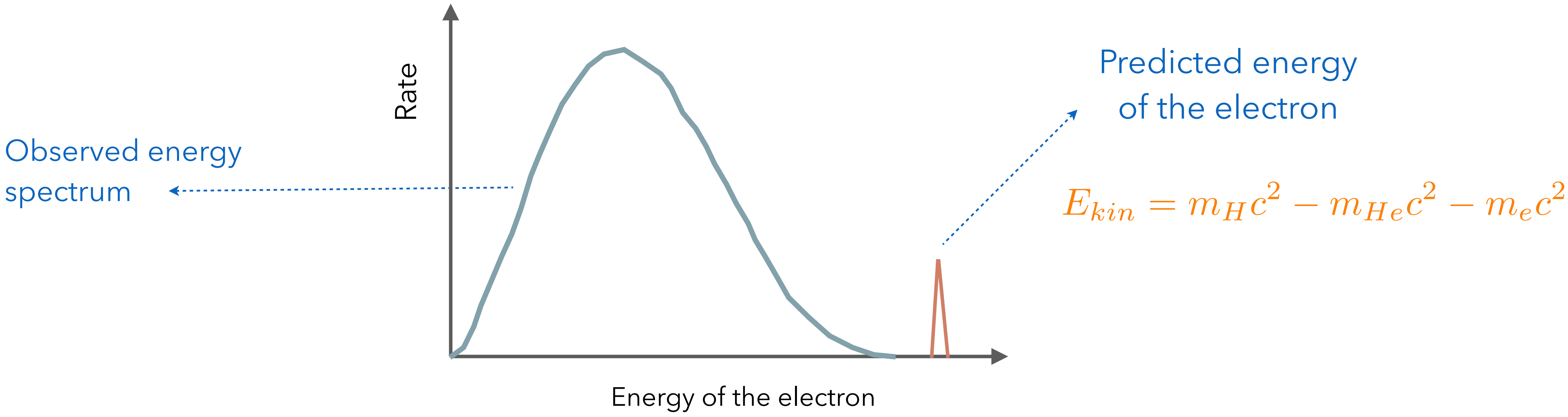
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta-Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

THE PARADOX WAS… "THE ENERGY CRISIS"

- It had been observed by experimental physicists that some nuclei are not stable, but decay under the emission of "beta rays" (electrons)
- The energy of the emitted electrons could be measured - the spectrum was continuous
- This seemed to violate a respected laws in physics: the conservation of energy (and momentum)

$$ {}^{3}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\,\mathrm{He} + e^{-} $$



$$E_{kin} = m_H c^2 - m_{He} c^2 - m_e c^2$$

ONLY ONE REASONABLE WAY OUT…

- A new particle: the neutrino (Pauli: "my foolish child"). It would share the energy with the electron, but would not be observed because of its incredible weak interaction with matter

$$^{3}_{1}\mathrm{H} \longrightarrow ^{3}_{2}\mathrm{He} + e^{-} + \bar{\nu}_e$$

- Niels Bohr, 1934: *"I must confess that I don't really feel fully convinced of the physical existence of the neutrino"*
- Arthur Eddington, 1939: *"I am not much impressed by the neutrino theory…. Dare I say that physicists will not have sufficient ingenuity to make neutrinos?"*
- *Thus,* while the idea was considered by many as a very useful hypothesis, few* believed it is a real particle (or that it can ever be detected**), until…

*Enrico Fermi did take the idea seriously and formulated a theoretical basis for the interaction between a neutrino, an electron, a proton and a neutron (1934, Z. Phys. 88)

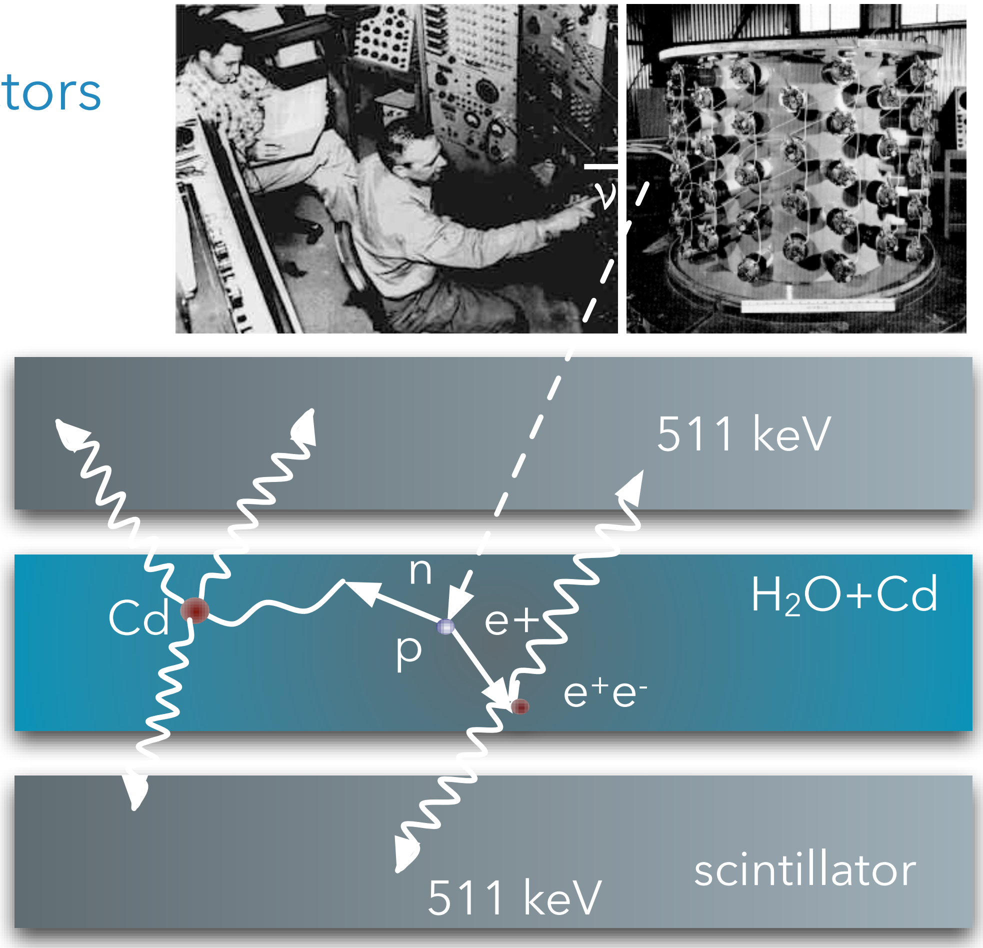
** **Hans Bethe:** "there is a considerable evidence for the neutrino hypothesis. Unfortunately, all this evidence is indirect; and more unfortunately, there seems at present to be no way of getting any direct evidence. "

NEUTRINO DETECTION

- … some 30 years later in 1956, when Clyde Cowan and Frederick Reines started the "Project Poltergeist" and finally detected (anti)neutrinos at the Savannah River Reactor in South Carolina

$$p + \bar{\nu}_e \longrightarrow n + e^+$$

- Detector: 400 l water + $CdCl_2$ seen by 90 photodetectors



Detection via delayed (a few μs) coincidence reaction:

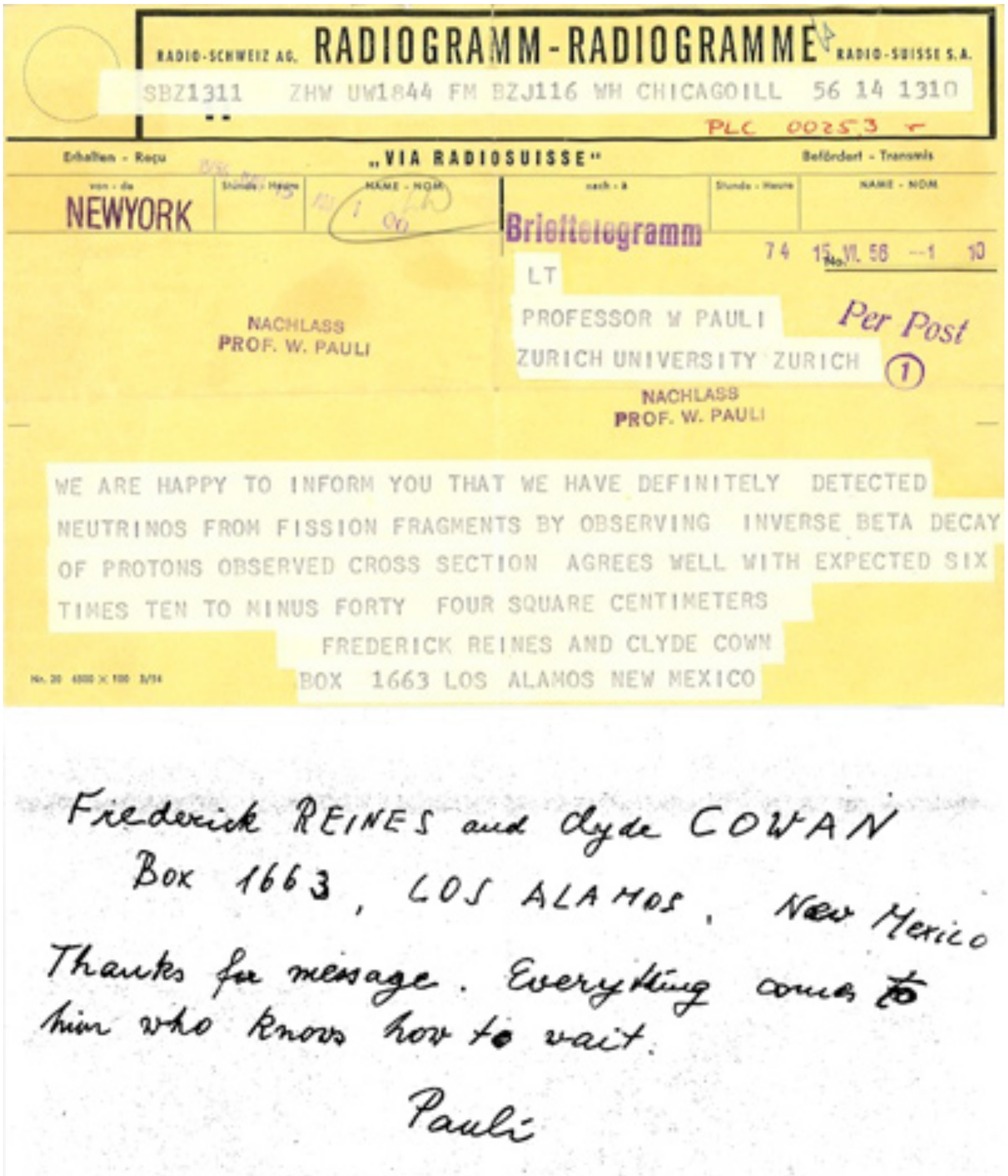
prompt: $e^+ + e^- \rightarrow \gamma + \gamma$

delayed: $n + Cd \rightarrow \gamma' s$

Nobel Prize 1995: (1/2) to Frederick Reines *"for the detection of the neutrino"*

A RADIOGRAMME TO PAULI, A SHORT ANSWER…

- June 1956: Pauli was at a CERN Symposium, and announced the most exciting news of the meeting* - he had just received a telegram from Cowan & Reines
    - "We are happy to inform you that we have definitely detected neutrinos…"
- Pauli's reply: "Thanks for message. Everything comes to him who knows how to wait."



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

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Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

von - de: NEWYORK

Brieftelegramm

74 15.VI.56 --1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post ①

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO NINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

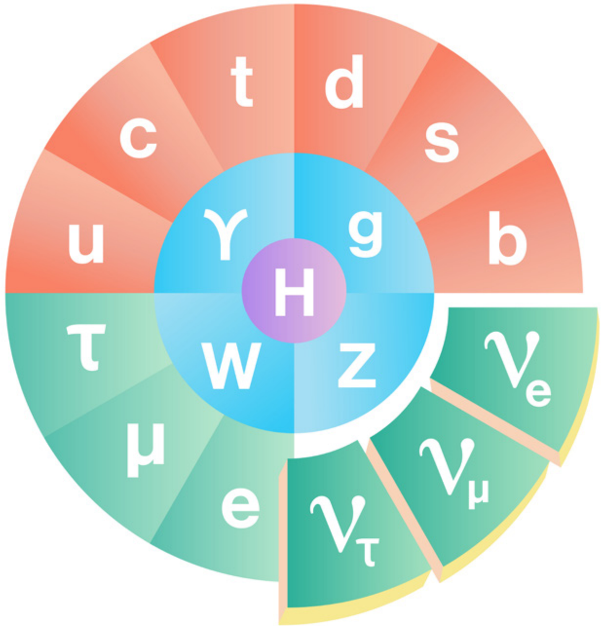
Thanks for message. Everything comes to him who knows how to wait.

Pauli

*See: Cecilia Jarlskog, "Birth of the neutrinos, from Pauli to the Reines-Cowan experiment", 2019 - International Conference of the History of the Neutrino

WHAT ARE NEUTRINOS?

- Elementary particles in the Standard Model which only interact via the weak interaction (they participate in charged current interactions with the corresponding charged lepton)
  - The interactions are of "V-A" type: neutrinos are left-handed, anti-neutrinos are right-handed
- In the SM: flavour lepton number is conserved and neutrinos are exactly massless
  - Today many known sources of neutrinos



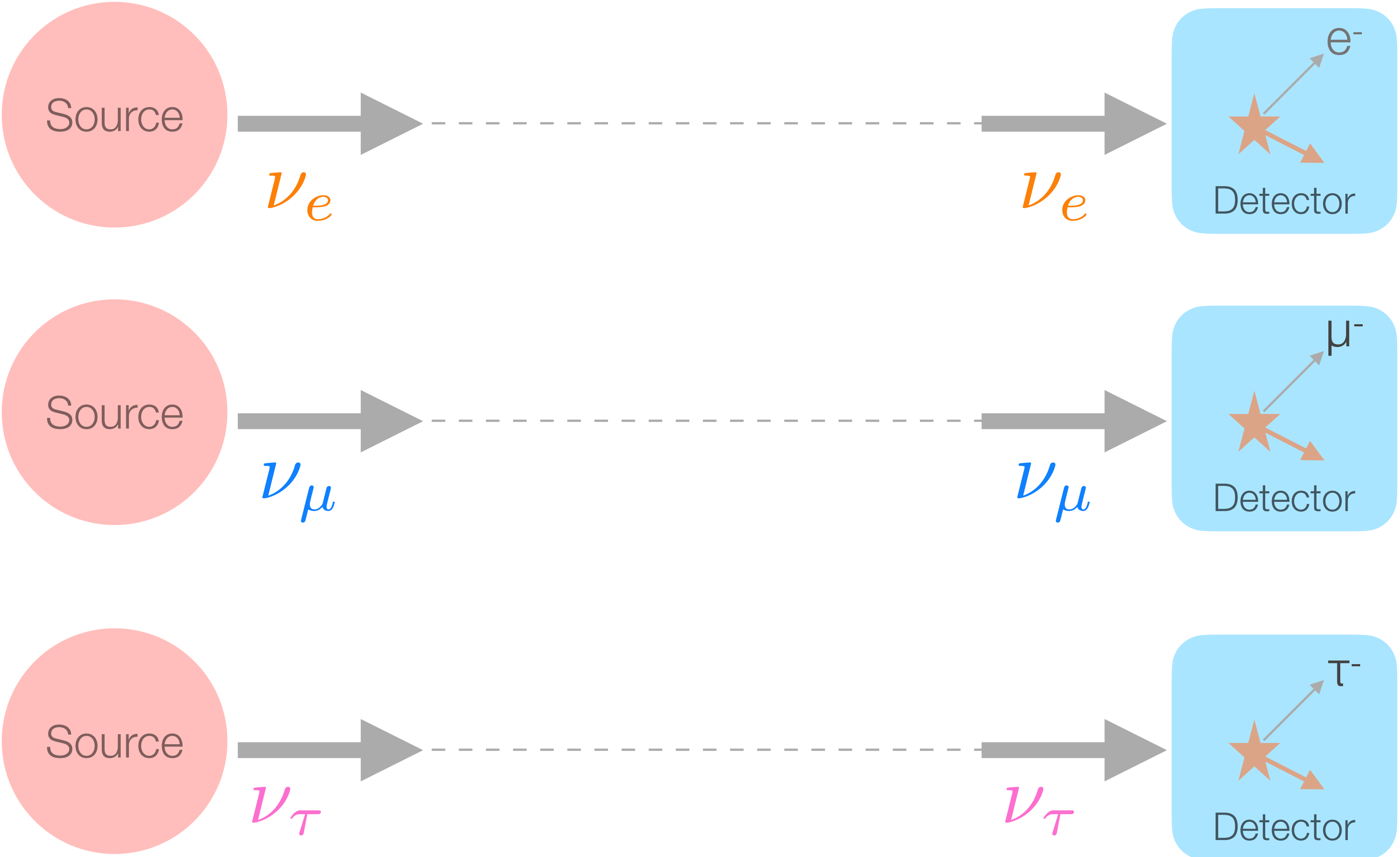
symmetrymagazine.org

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$$

WHAT DO WE KNOW ABOUT NEUTRINOS?

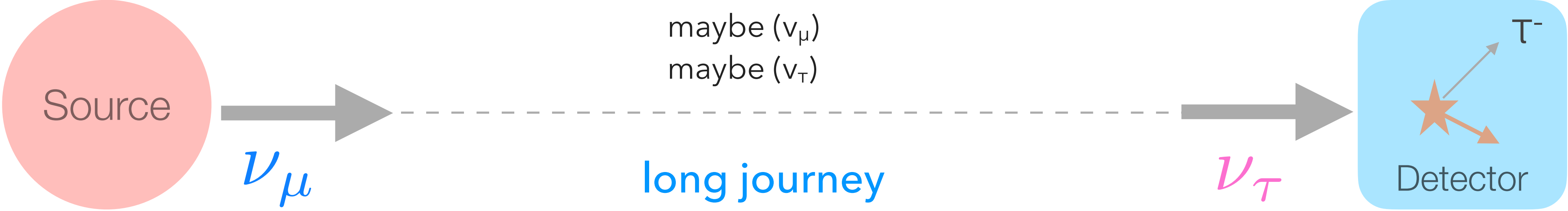
- They come in 3 flavours

ν_e	ν_μ	ν_τ
electron	muon	tau



WHAT DO WE KNOW ABOUT NEUTRINOS?

- However when they propagate over macroscopic distances, they oscillate between flavours



- This is a well-studied effect in quantum mechanics
- It means that flavour is not conserved over macroscopic distances (ν states with different flavours ν_α mix with ν states with different masses ν_i)

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j=1}^{3} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \exp\left(-i \frac{m^2_{\nu_i} - m^2_{\nu_j}}{2E} x\right)$$

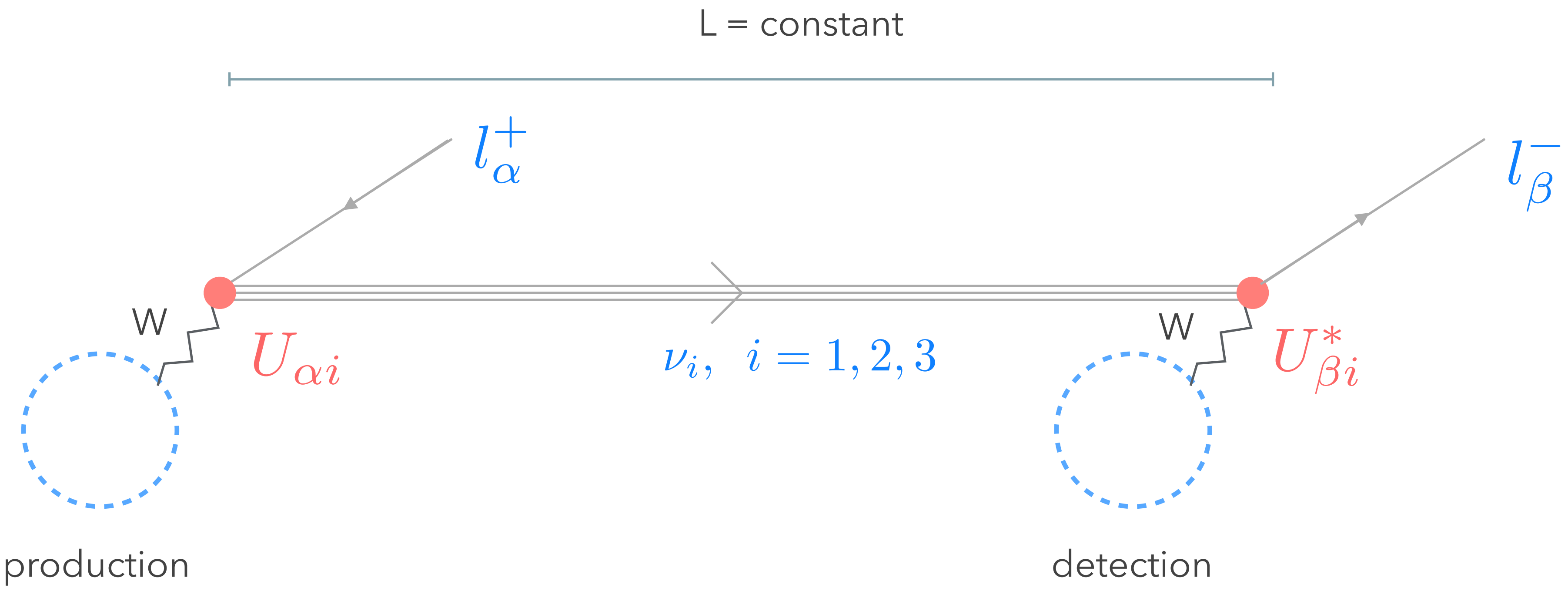
- ◉ the effect of the mass is to generate flavour oscillations as a function of distance

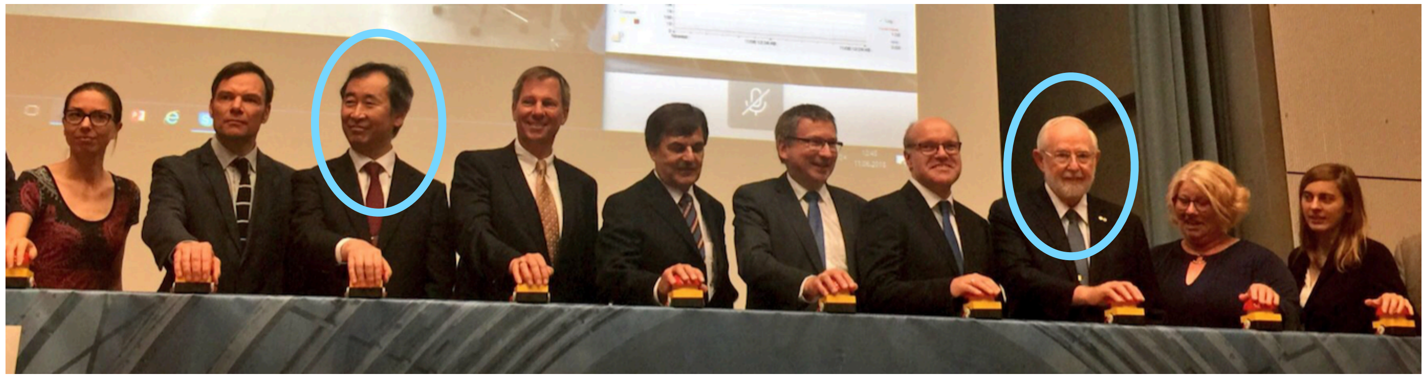
Unitary neutrino mixing matrix (PMNS matrix)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

WHAT DO WE KNOW ABOUT NEUTRINOS?

- From oscillation experiments: non-zero masses and non-trivial mixing





Nobel Prize 2015: Takaaki Kajita and Arthur McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

WHAT DO WE KNOW ABOUT NEUTRINOS?

- In general: 3 mixing angles, 1 CP violating phase, 2 independent Δm^2

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Data from
atmospheric ν's
and accelerators
$\theta_{23} \approx 48$ deg

Data from
reactors and
accelerators
$\theta_{13} \approx 8.6$ deg

Data from solar
and reactor
neutrinos
$\theta_{12} \approx 34$ deg

NuFIT 4.1 2019

$$c_{ij} = cos\theta_{ij}$$

$$s_{ij} = sin\theta_{ij}$$

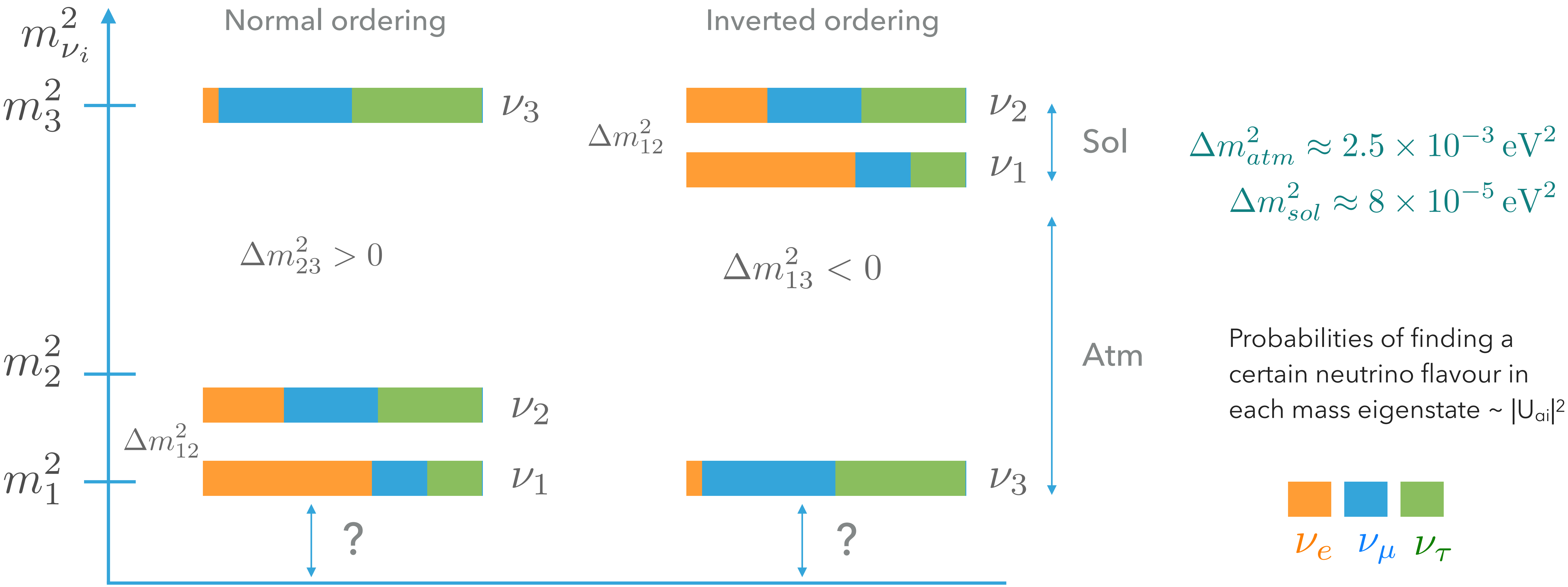
$$0 \leq \delta < 2\pi \qquad \delta \simeq 3\pi/2$$

*Very different than the CKM mixing angles:

$$\theta_{12} \approx 13^\circ, \;\; \theta_{23} \approx 2.4^\circ, \;\; \theta_{13} \approx 0.2^\circ$$

OPEN QUESTIONS IN NEUTRINO PHYSICS

- From oscillation experiments: we know the mixing angles (or the $U_{\alpha i}$) and the Δm^2
- However: 2 possible mass orderings and no information on the mass scale



$$\Delta m^2_{atm} \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$$
$$\Delta m^2_{sol} \approx 8 \times 10^{-5}\,\mathrm{eV}^2$$

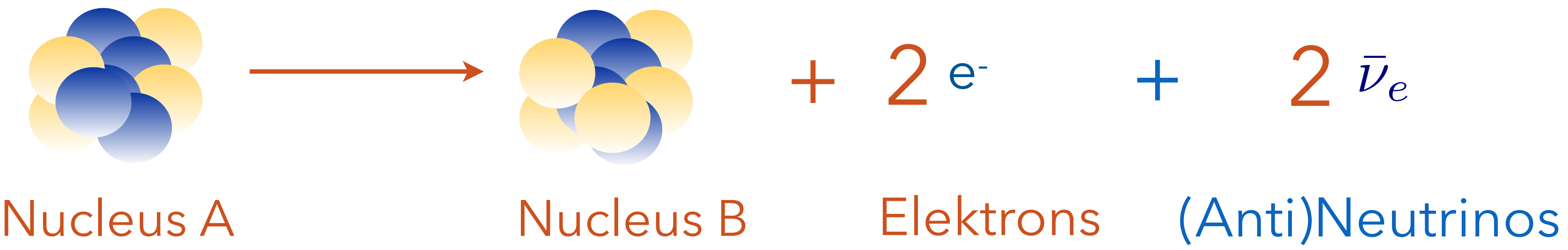
Probabilities of finding a certain neutrino flavour in each mass eigenstate ~ $|U_{\alpha i}|^2$

OPEN QUESTIONS IN NEUTRINO PHYSICS

- What are the absolute values of neutrino masses, and the mass ordering?
- What is the nature of neutrinos? Are they Dirac or Majorana particles?
- What is the origin of small neutrino masses? $\frac{m_{\nu_j}}{m_{l,q}} \lesssim 10^{-6}$ for $m_{\nu_j} \lesssim 0.5\,\mathrm{eV}$
- What are the precise values of the mixing angles, and the origin of the large ν mixing?
- Is the standard three-neutrino picture correct, or do other, sterile neutrinos exist?
- What is the precise value of the CP violating phase δ?
- …

THE DOUBLE BETA DECAY

- Some of these open questions can be addressed with an extremely rare nuclear decay process
  - What are the absolute values of neutrino masses, and the mass ordering?
  - What is the nature of neutrinos? Are they Dirac or Majorana particles?
  - What is the origin of small neutrino masses?



$\longrightarrow \; + \; 2\,e^- \; + \; 2\,\bar{\nu}_e$

Nucleus A Nucleus B Elektrons (Anti)Neutrinos

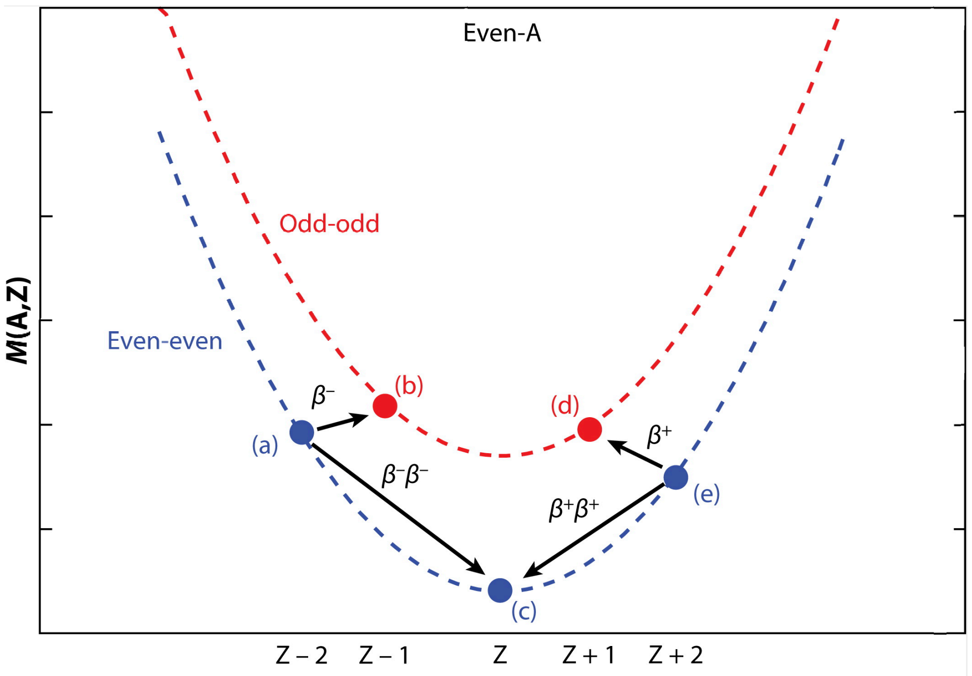
THE DOUBLE BETA DECAY

- If simple β^- or β^+-decay is forbidden on energetic grounds
- Predicted by Maria-Goeppert Mayer in 1935
- The probability for a decay is very small, the mean lifetime of a nucleus is much larger than the age of the universe ($\tau_U \sim 1.4\times10^{10}$ a)

$$\tau_{2\nu} \approx 10^{20} y$$

- Thus: a *very* rare process
- However, if a large amount of nuclei is used, the process can be observed experimentally

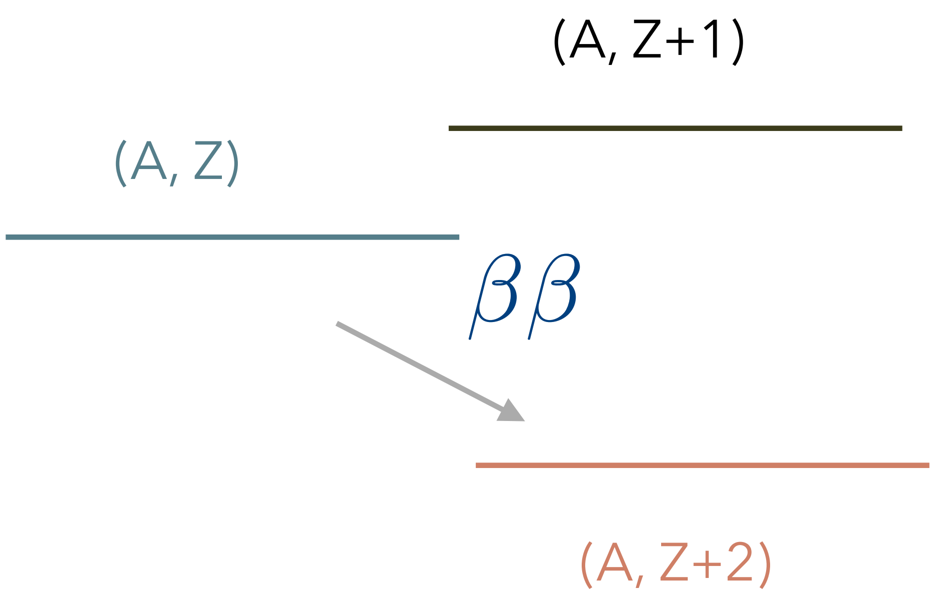
mass parabola of isobars with even A



Ruben Saakyan, Annu. Rev. Nucl. Part. Sci. 63 (2013)

Nobel Prize in physics, 1963 for her discoveries concerning the nuclear shell structure

THE DOUBLE BETA DECAY



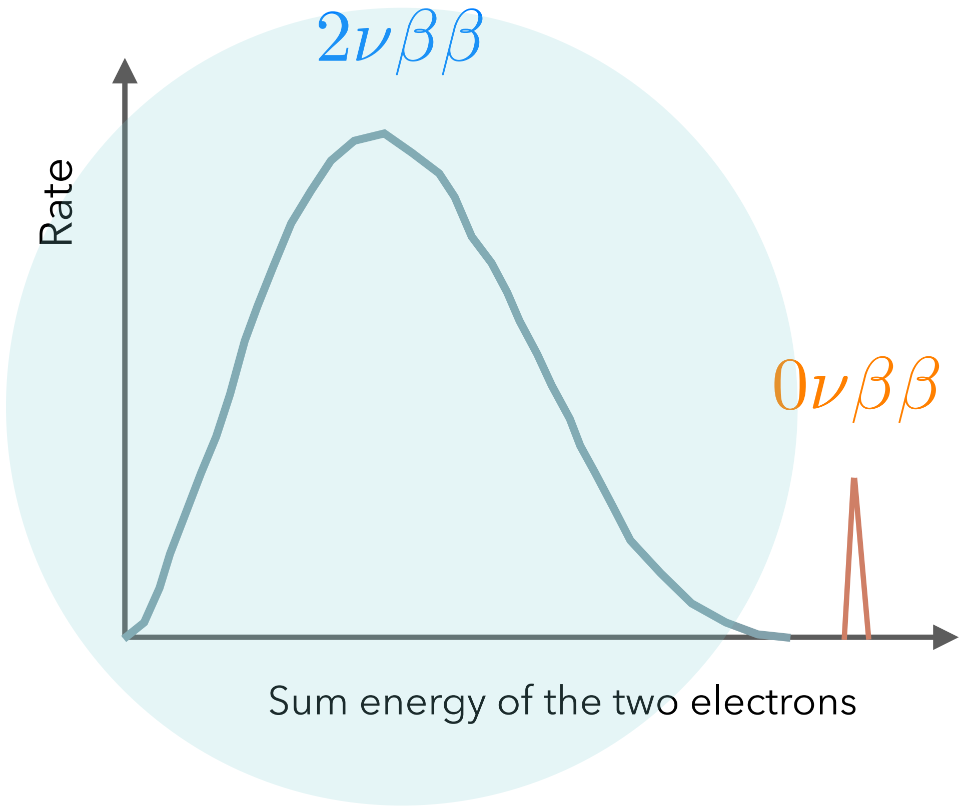
(A, Z+1)

(A, Z)

$\beta\beta$

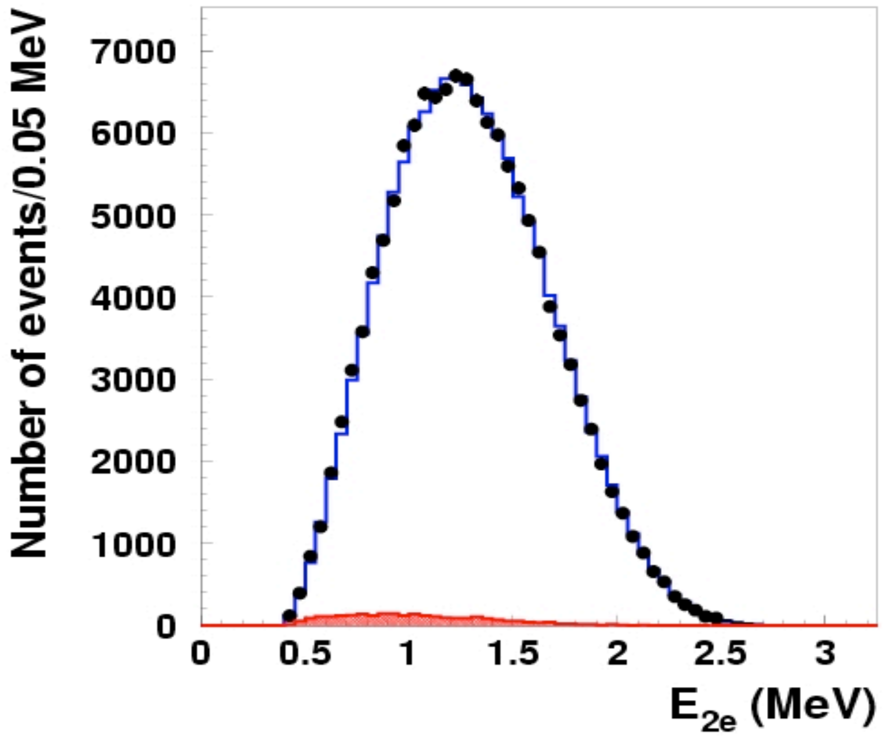
(A, Z+2)

- The Standard Model decay, with 2 neutrinos, was observed in 14 nuclei
- $T_{1/2} > 10^{18}$ y: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U



^{100}Mo: $T_{1/2}=7.15\times10^{18}$ y

NEMO Experiment in Modane/Frejus



THE DOUBLE BETA DECAY

- The decay rate $\Gamma^{2\nu}$ depends on the matrix element $M^{2\nu}$ and on the phase space factor $G^{2\nu}$ (which determines the energy spectrum):

$$\Gamma^{2\nu} = \frac{\ln 2}{T^{2\nu}_{1/2}} = G^{2\nu}(Q, Z)|M^{2\nu}|^2$$

- The phase space factor (Z= charge of daughter nucleus) from the leptonic degrees of freedom:

$$G^{2\nu} \propto (G_F \cos\theta_C)^4 Q^7 \cdot \left(\frac{Q^4}{1980} + \frac{Q^3}{90} + \frac{Q^2}{9} + \frac{Q}{2} + 1\right) \propto (G_F \cos\theta_C)^4 \cdot Q^{11}$$

- The decay rate scales with Q^{11} x $(G_F)^4$ => we expect indeed very long $T_{1/2}$ of ~10^{20} y

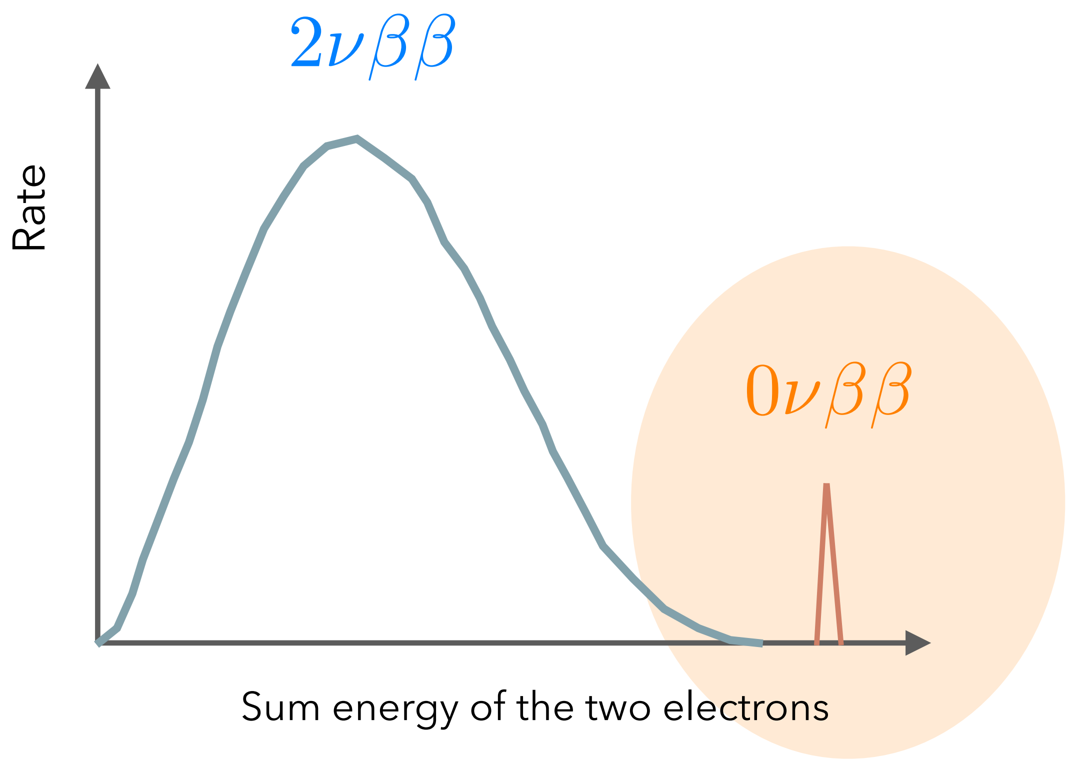
THE NEUTRINOLESS DOUBLE BETA DECAY

- More interesting: the decay *without* emission of neutrinos => ΔL = 2

$$T_{1/2}^{0\nu\beta\beta} > 10^{24}\,\mathrm{y}$$

- Expected signature: *sharp peak at the Q-value of the decay*

$$Q = E_{e1} + E_{e2} - 2m_e$$

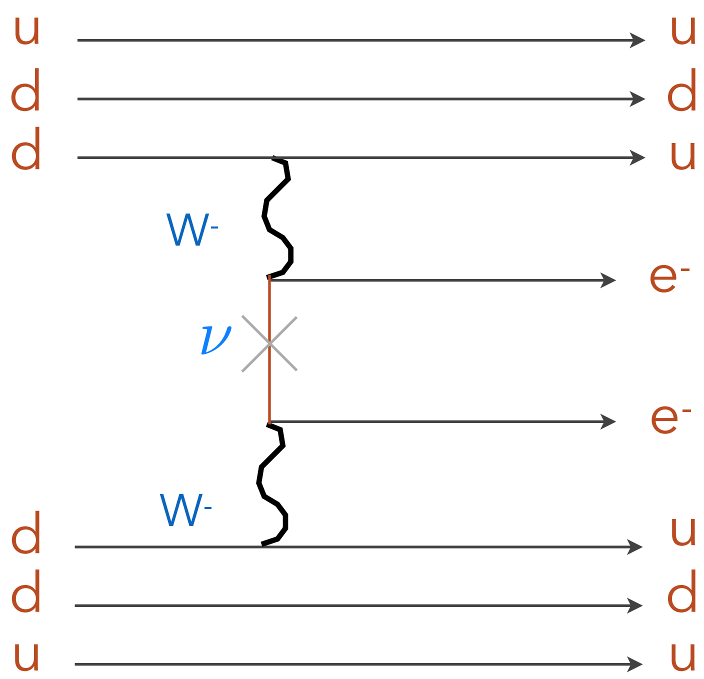


The double beta decay without neutrinos: first discussed by Wendell H. Fury in 1939

Ettore Majorana had proposed in 1937 that neutrinos could be their own antiparticles

THE NEUTRINOLESS DOUBLE BETA DECAY

- In this decay, a light virtual neutrino could be exchanged



Charge conjugate spinor

$$\psi^c = C\bar{\psi}^T$$

A Majorana field

$$\psi = \psi^c$$

$$\psi = \psi_L + \psi_L^c$$

has 2 spin d.o.f.

- The neutron decays under emission of a right handed 'anti-neutrino' ν_L^c
  - the ν_L^c has to be absorbed at the second vertex as left handed 'neutrino' ν_L
  - for the decay to happen: neutrinos and anti-neutrinos must be identical, thus Majorana particles
  - & the helicity must change

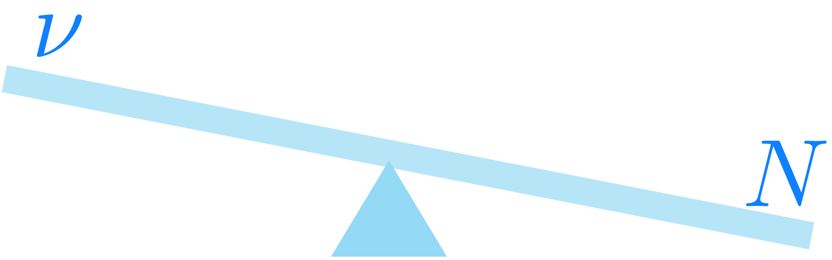
MAJORANA AND DIRAC NEUTRINOS

- Most general Lagrangian: both type of neutrinos masses

$$\mathcal{L}_{\mathcal{M}_\nu} = -\frac{1}{2}\left[m_D(\bar{\psi}_R^c \psi_L^c + \bar{\psi}_R \psi_L) + M \bar{\psi}_L^c \psi_L\right] + h.c.$$

- Dirac term: generated after SSB from Yukawa interactions; Majorana term: singlet of the SM gauge group and can appear as bare mass term
- Masses of physical neutrinos: from the eigenvalues of the mass matrix. In the "see saw" mechanism: M >> m_D => a very light neutrinos state ν and a heavy state N with masses:

$$m_\nu \approx \frac{m_D^2}{M} \qquad m_N \approx M$$



- If Dirac mass term m_D: of similar size as of other fermions & M at the GUT scale (~10^{14} GeV) => explanation of the smallness of neutrino masses

THE NEUTRINOLESS DOUBLE BETA DECAY

- The expected rate can be calculated as:

$$\Gamma^{0\nu} = \frac{\ln 2}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

from the leptonic part of the matrix element

the matrix element of the nuclear transition

- with the phase space integral (now spanned only by 2 electrons):

$$G^{0\nu} \propto (G_F \cos\theta_C)^4 \cdot \left(\frac{Q^5}{30} - \frac{2Q^2}{3} + Q - \frac{2}{5}\right) \propto (G_F \cos\theta_C)^4 \cdot Q^5$$

THE EFFECTIVE MAJORANA NEUTRINO MASS

- The effective Majorana neutrino mass parameter: embeds all the dependance on neutrino quantities

$$|m_{\beta\beta}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2\phi_1} + m_3 U_{e3}^2 e^{2i(\phi_2-\delta)}|$$

- A mixture of m_1, m_2, m_3 ~ to the U_{ei}^2 (the complex entries in the PMNS matrix)

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- φ_1,φ_2 = Majorana phases and $|U_{e1}|^2$ is for instance the probability that ν_e has the mass m_1

◉ fewer phases can be removed by redefining the fields

THE EFFECTIVE MAJORANA NEUTRINO MASS

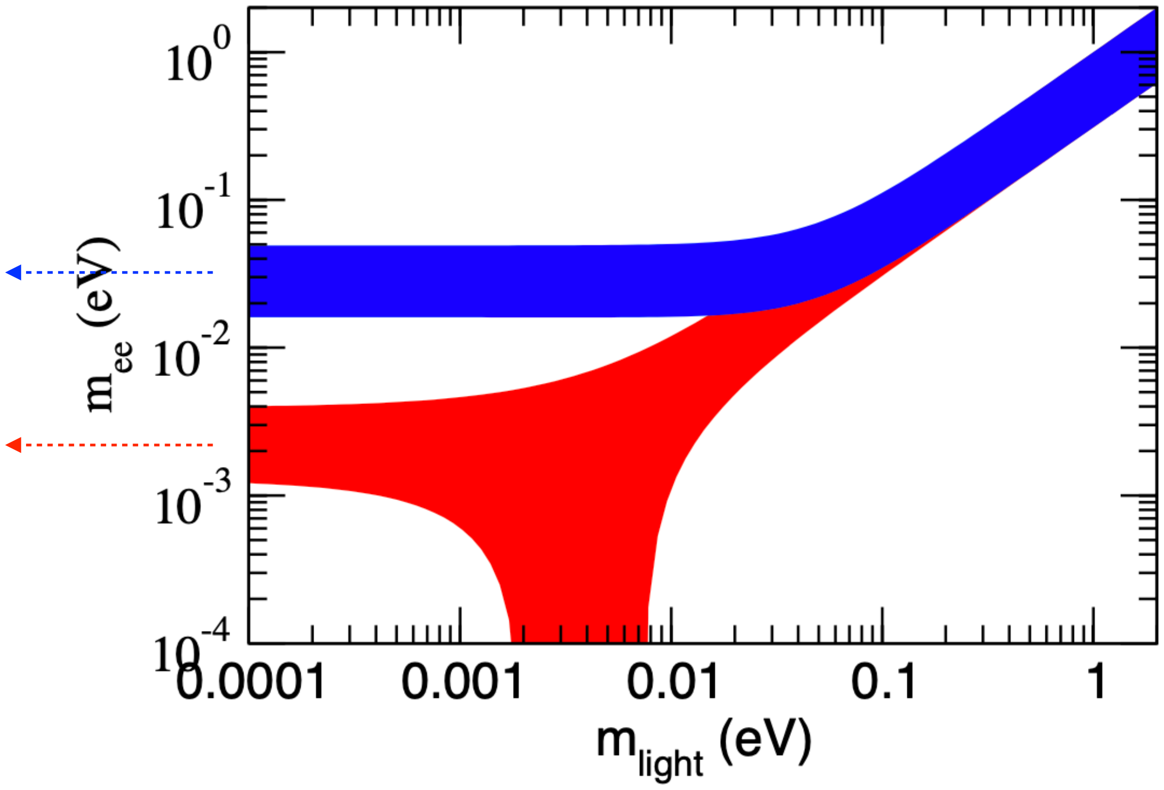
- The values depend critically on the neutrino mass spectrum and on the values of the two Majorana phases in the PMNS matrix
- One can express $m_{\beta\beta}$ as a function of the lightest (m_{light}) mass state for the two mass orderings and obtain the allowed ranges

Inverted mass ordering

$m_3 \ll m_1 < m_2$

Normal mass ordering

$m_1 < m_2 \ll m_3$



PDG Review: PTEP 8, August 2020

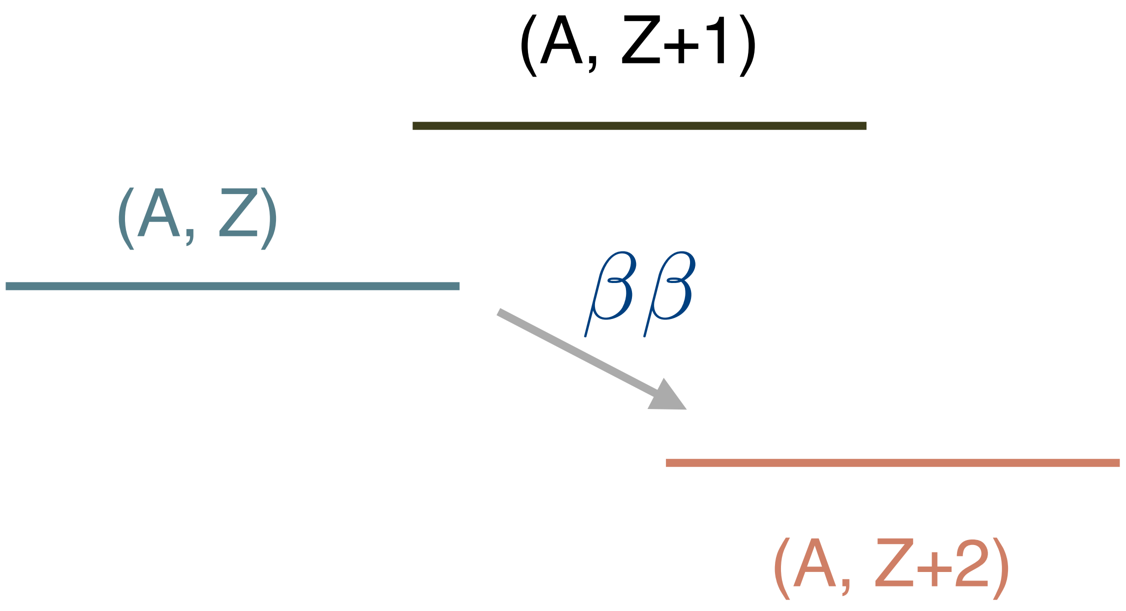
Degenerate region

$m_{\mathrm{lightest}} \simeq m_1 \simeq m_2 \simeq m_3 \gg \sqrt{|\Delta m^2_{32}|}$

Widths: mainly from the unknown Majorana phases φ_1, φ_2

EMPLOYED NUCLEI

- Even-even nuclei
- Natural abundance is low (except ^{130}Te)
- Must use enriched material



Candidate*	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	2.039	7.8
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	**34.5**
^{136}Xe -> ^{136}Ba	2.479	8.9
^{150}Nd -> ^{150}Sm	3.367	5.6

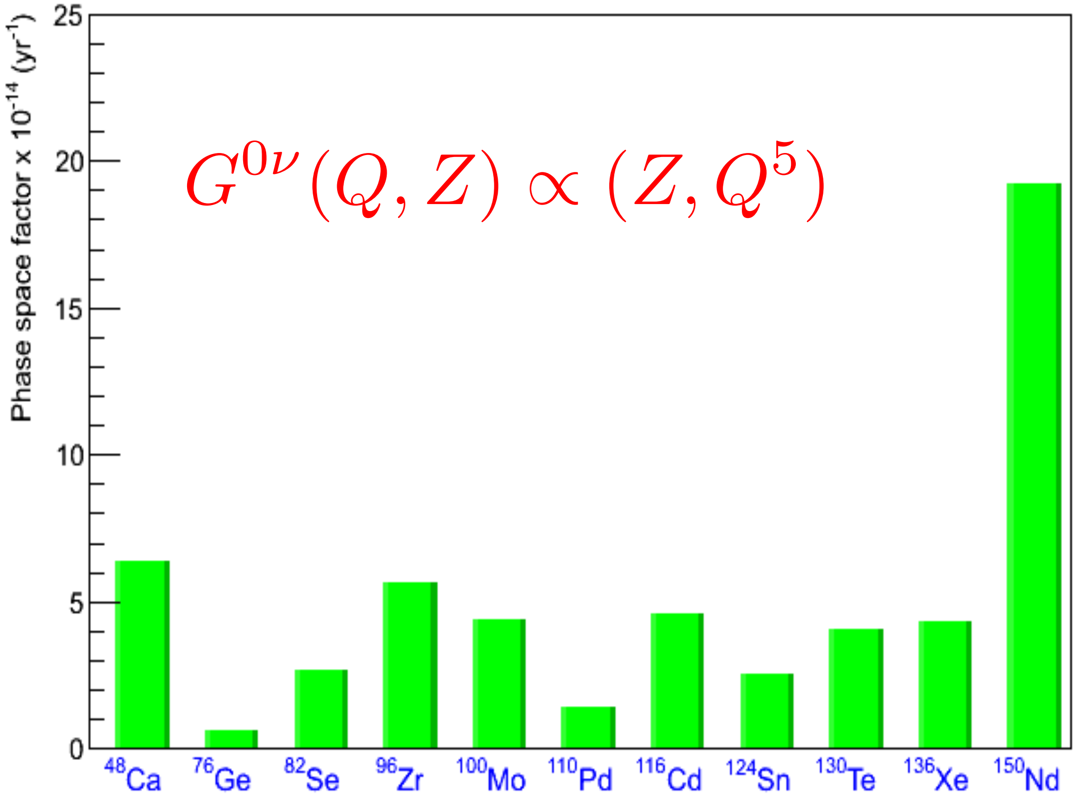
* Q-value > 2 MeV

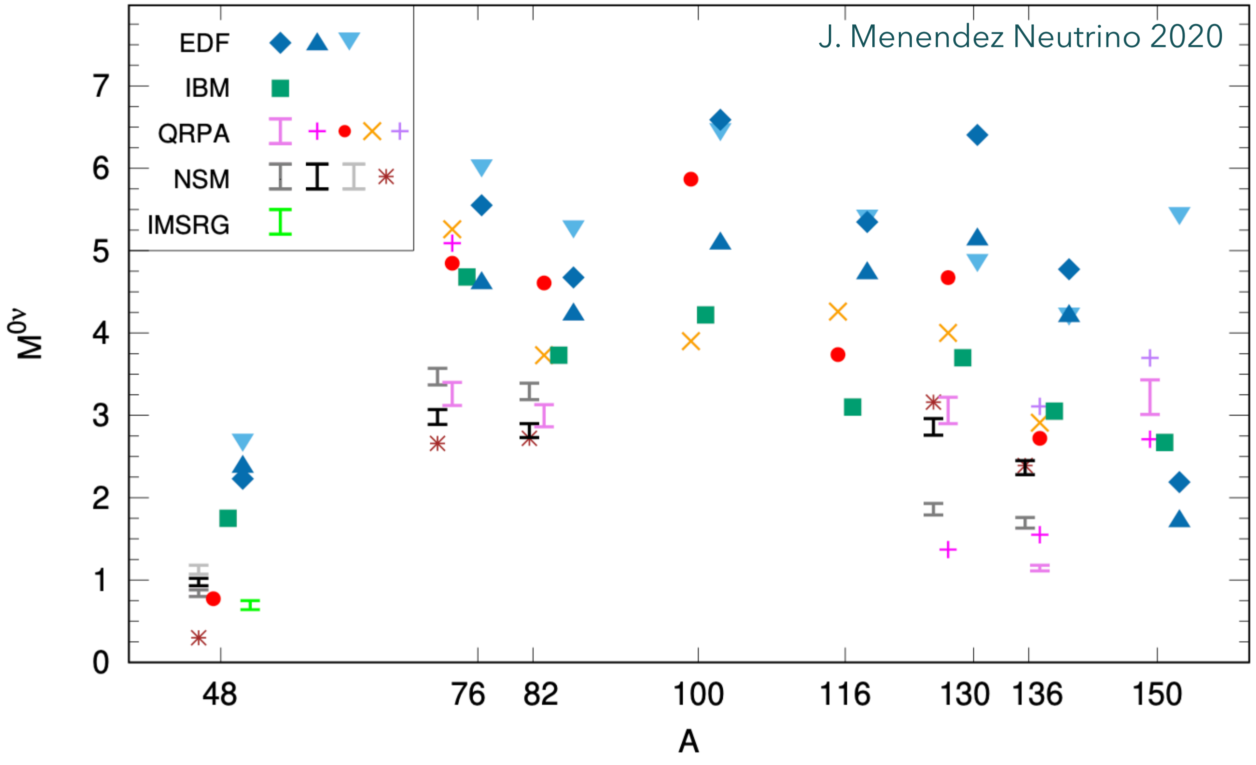
PHASE SPACE AND MATRIX ELEMENTS

Matrix elements: vary by a factor of 2- 3 for a given A

$$\Gamma^{0\nu} = \frac{\ln 2}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

$$\Gamma^{0\nu} = \frac{\ln 2}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$


$$G^{0\nu}(Q,Z) \propto (Z, Q^5)$$



Jonathan Engel and Javier Menéndez 2017 Rep. Prog. Phys. 80 046301

Vergados, Ejiri, Simkovoc, Int. Journal of Modern Physics E, Vol 25 (2016)

EXPRIMENTAL REQUIREMENTS

- Experiments measure the half-life, with a sensitivity (for non-zero background)

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T^{0\nu}_{1/2}}}$$

Minimal requirements:

high isotopic abundance (a)
high efficiency (ε)
large detector masses (M)
ultra-low background noise (B)
good energy resolution (ΔE)

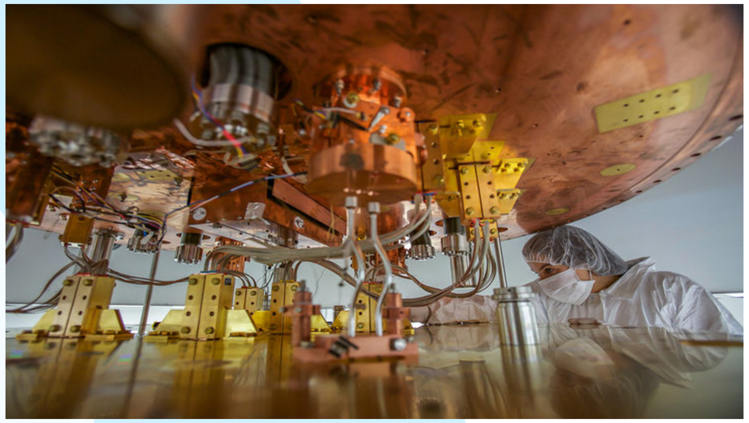
Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification

DOUBLE BETA DECAY: EXPERIMENTAL TECHNIQUES*

Heat

CUORE
CUPID



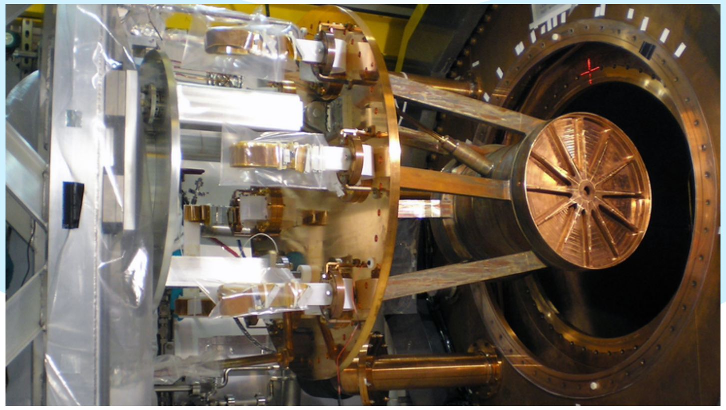
Energy of the two electrons

GERDA
MAJORANA
LEGEND
SuperNEMO
(+tracking)

Charge

Light

KAMLAND-Zen
SNO+



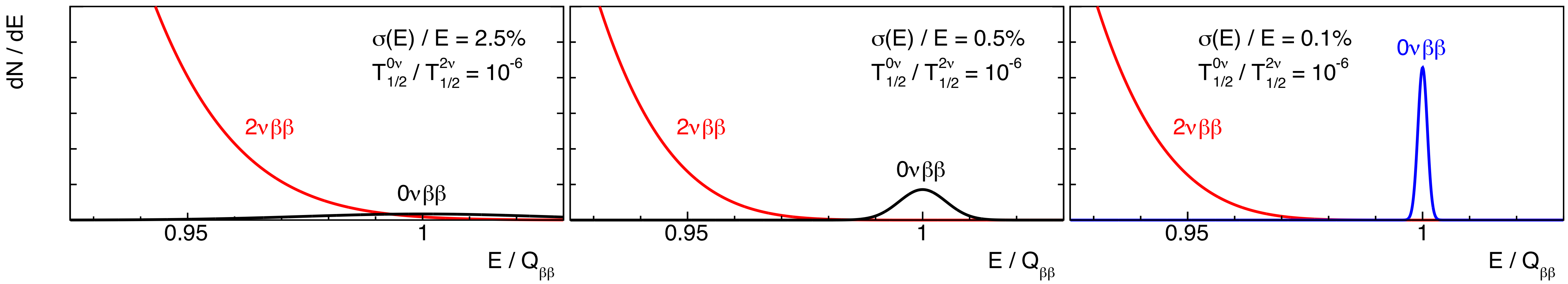
nEXO, NEXT (+tracks)
DARWIN, PandaX-III

(*not a complete list)

MAIN CHALLENGES

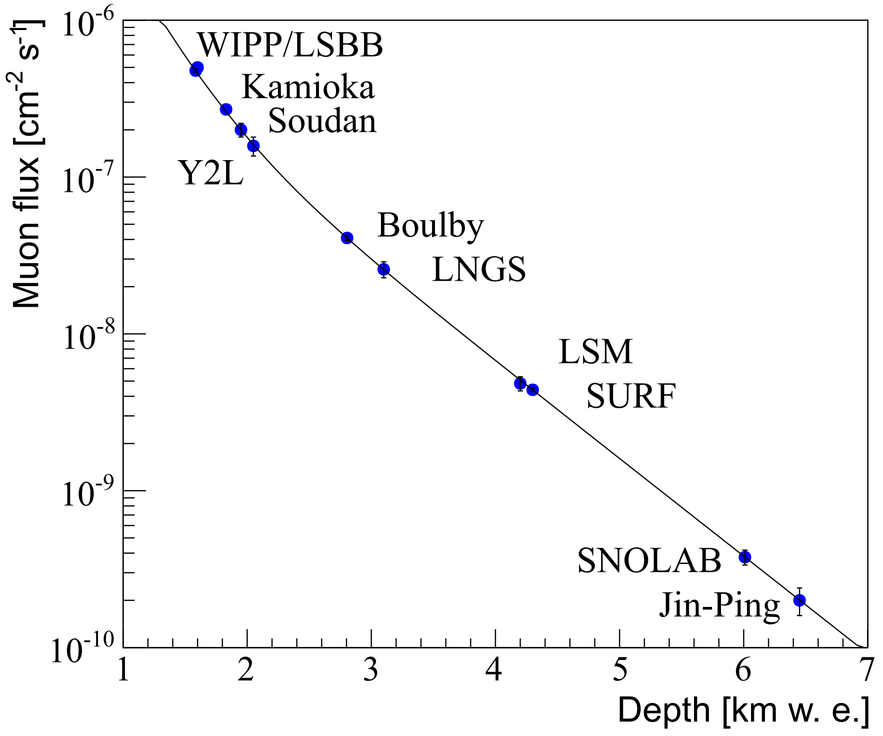
- Energy resolution (ultimate background from 2νββ-decay)
- Backgrounds
  - cosmic rays & cosmogenic activation (including in situ, e.g., ^{77}Ge, ^{137}Xe)
  - radioactivity of detector materials (^{238}U, ^{232}Th, ^{40}K, ^{60}Co, etc: α, β, γ-radiation)
  - anthropogenic (e.g., ^{137}Cs, ^{110m}Ag)
  - neutrinos (e.g., ^{8}B from the Sun): $\nu + e^- \to \nu + e^-$

σ/E = 2.5% σ/E = 0.5% σ/E = 0.1%



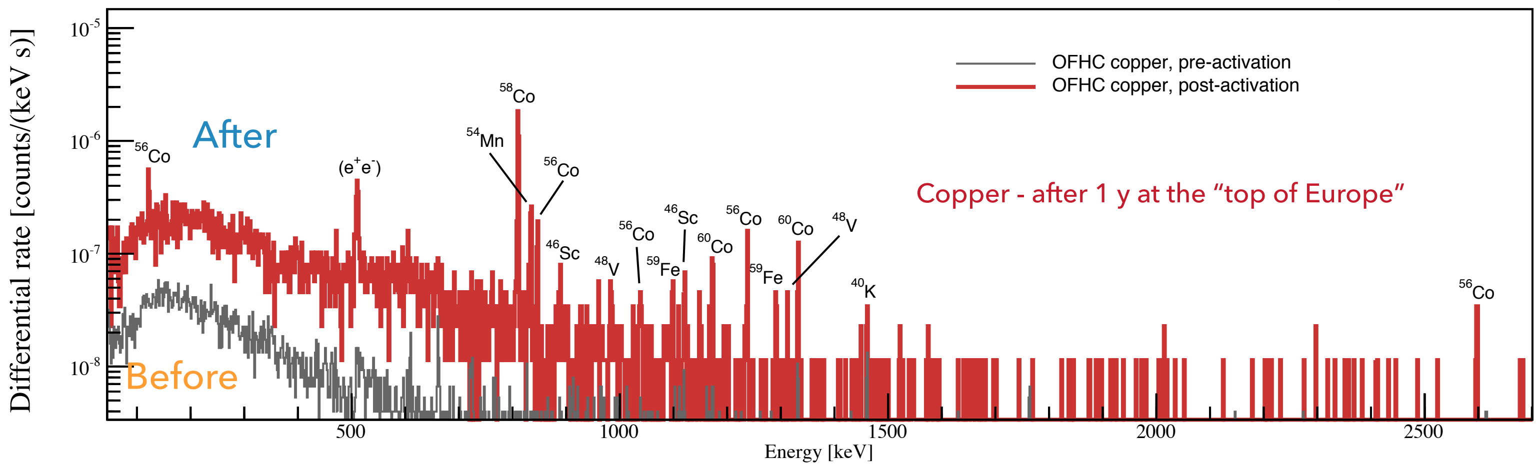
BACKGROUND REDUCTION

- Go deep underground



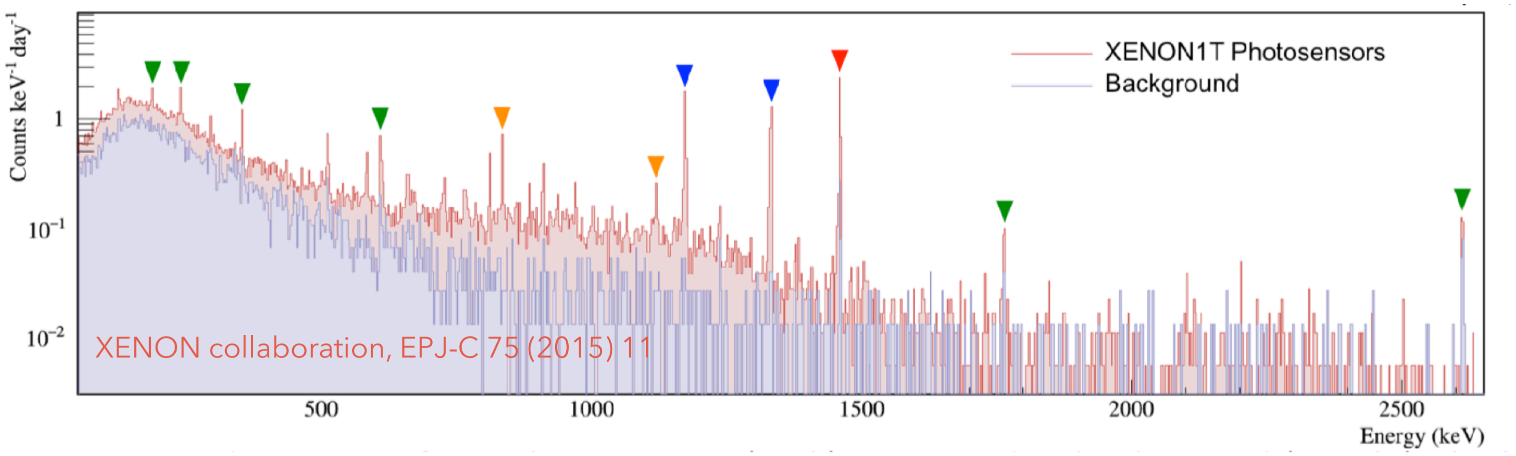
- Avoid cosmic activation

LB et al., Eur. Phys. J. C75 2015



- Use active shields

- Select low-radioactivity materials



XENON collaboration, EPJ-C 75 (2015) 11

VERY BRIEF CURRENT STATUS OF THE FIELD

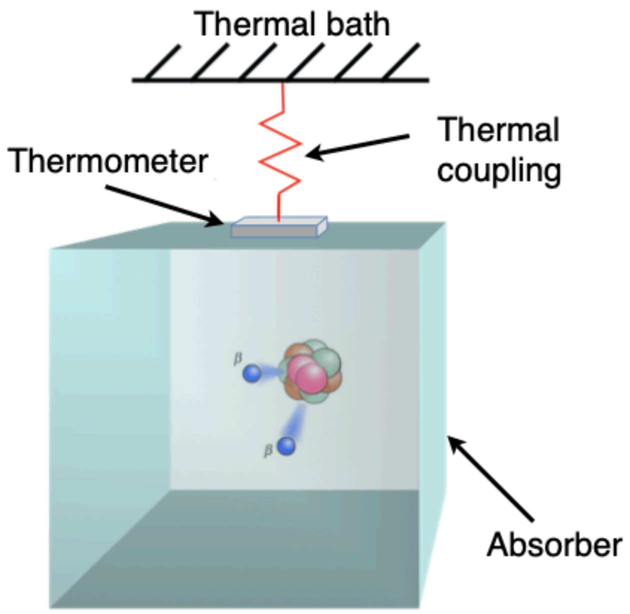
- No observation of this extremely rare nuclear decay (so far)
- Best *lower limits* on $T_{1/2}$: 1.07×10^{26} y (^{136}Xe), 1.8×10^{26} y (^{76}Ge), 3.2×10^{25} y (^{130}Te)

$$m_{\beta\beta} < (0.08 - 0.18)\,\mathrm{eV}\;(90\%\ \mathrm{C.L.})$$

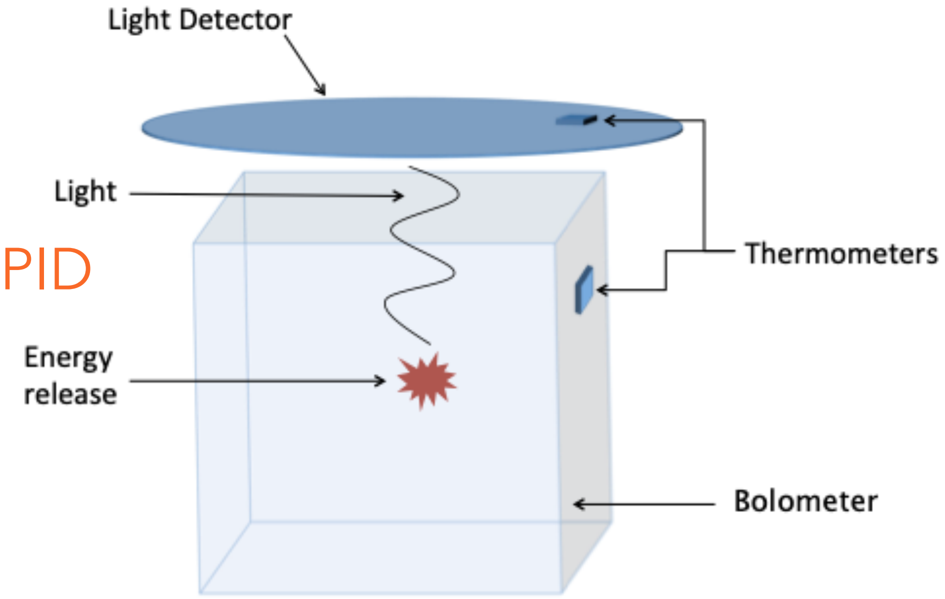
- Running and upcoming experiments (a selection)
  - **^{130}Te:** CUORE, SNO+
  - **^{136}Xe:** KAMLAND-Zen, KAMLAND2-Zen, EXO-200, nEXO, NEXT, DARWIN, PandaX-III
  - **^{76}Ge:** GERDA Phase-II, Majorana, LEGEND (GERDA & Majorana + new groups)
  - **^{82}Se**: CUPID (= CUORE with light read-out)
  - **^{82}Se (^{150}Nd, ^{48}Ca)**: SuperNEMO
  - **^{100}Mo:** NEMO-3, AMoRE, CUPID-Mo

CUORE AND CUPID: BOLOMETRIC TECHNIQUE

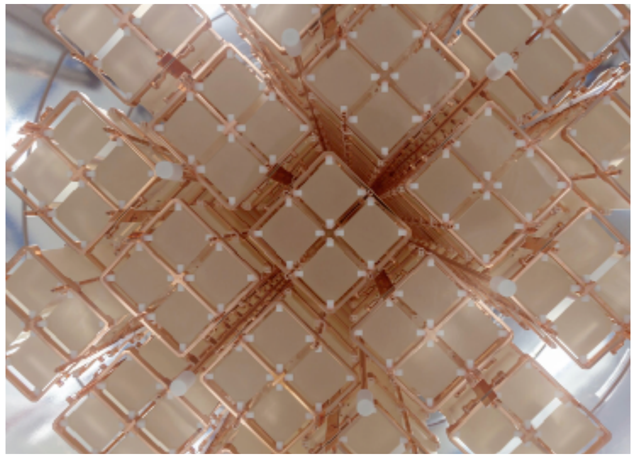
CUORE



CUPID

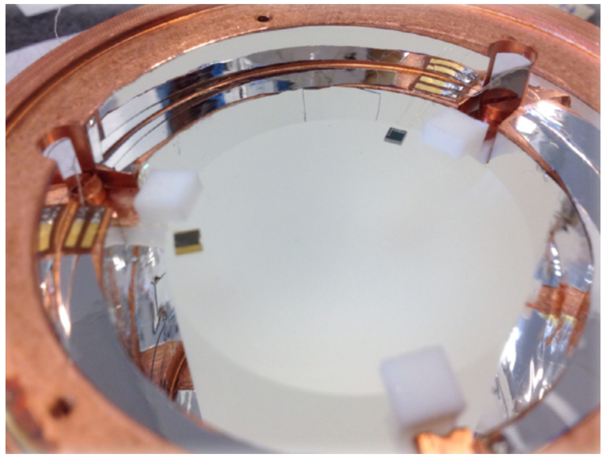


- CUORE: 988 crystals (206 kg ^{130}Te) at LNGS
  - $T_{1/2} > 3.2 \times 10^{25}$ y for ^{130}Te
- CUPID: R&D for ton-scale detector with $Li_2{}^{100}MoO_4$ and $Zn^{82}Se$ crystals as scintillating bolometers (to identify major α-particle background)
- CUPID-0: pilot project at LNGS, 24 $Zn^{82}Se$ crystals



CUORE: PRL 124, 2020

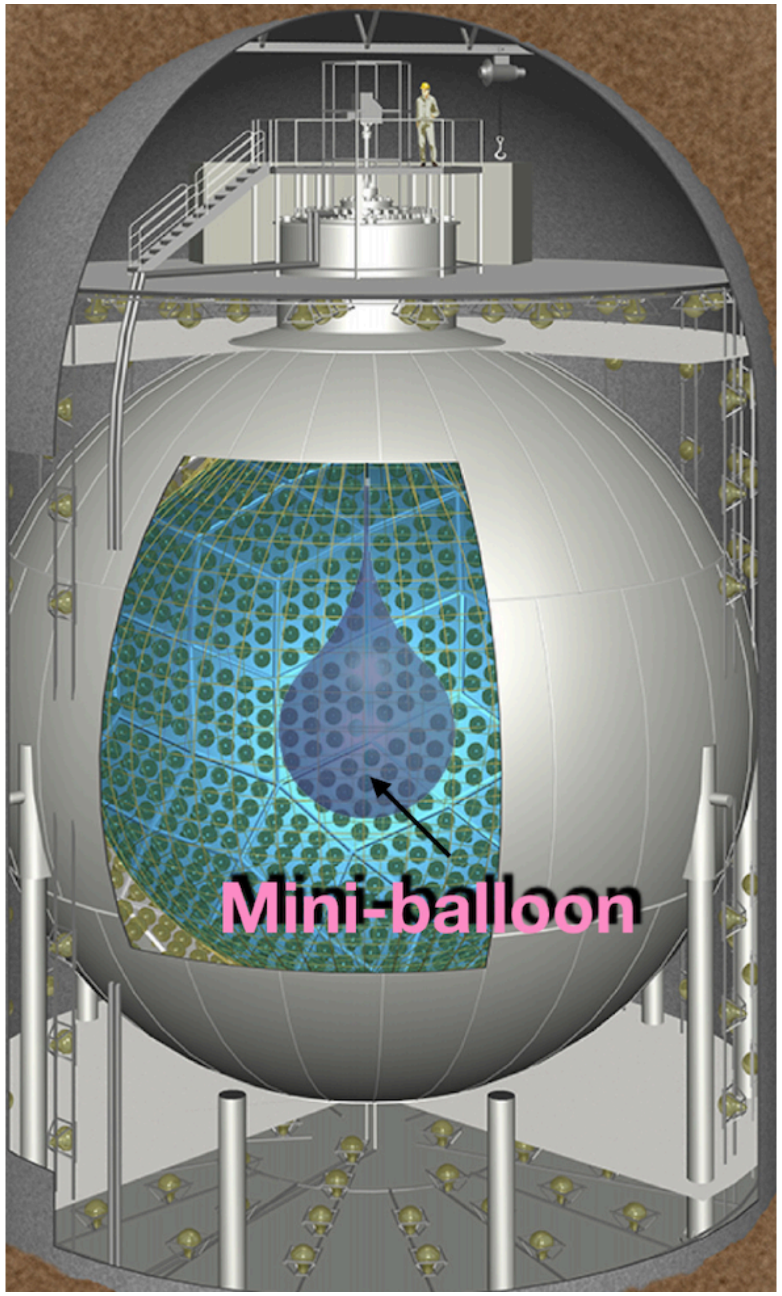
^{82}Se: $T_{1/2} > 3.5 \times 10^{24}$ y



CUPID-0: PRL 123, 2019

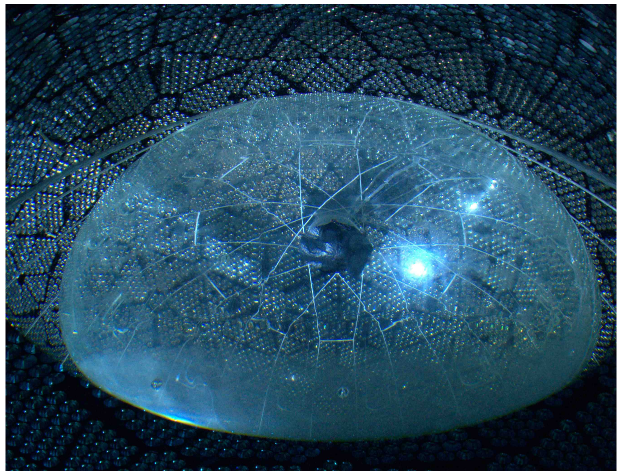
SNO+ AND KAMLAND-ZEN

Kamland-Zen, NIMA 958, 2020

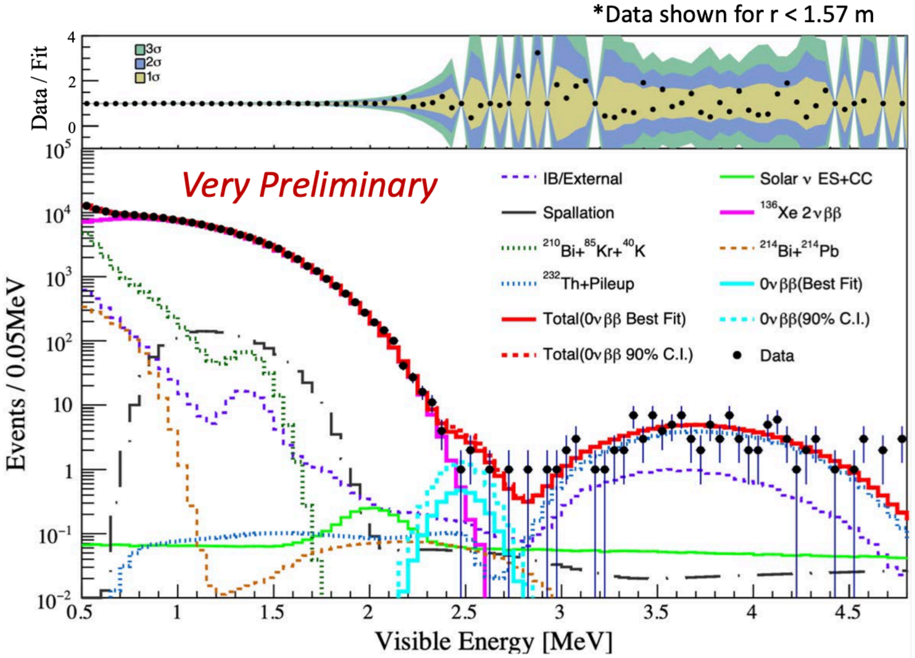


- SNO+: 0.5% ^{nat}Te ~1330 kg ^{130}Te in LS at SNOLAB
  - Fill in 2020, preparing for Te loading and ββ-decay phase to start
- KamLAND-Zen: 745 kg ^{136}Xe in LS at Kamioka since Jan 2019
  - Previous results: **$T_{1/2} > 1.07 \times 10^{26}$ y** (5.6 x 10^{25} y sensitivity)
- KamLAND2-Zen: ~1t ^{136}Xe, higher LCE => improve ΔE

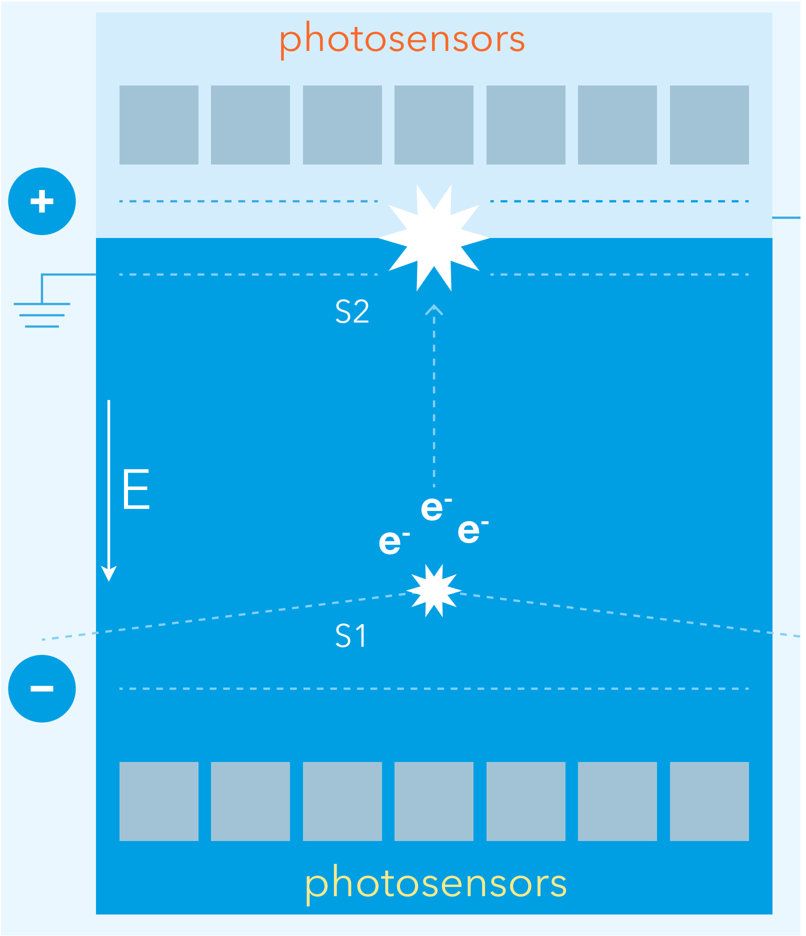
SNO+ J.Phys.Conf.Ser. 1137 (2019)
$T_{1/2} > 1.9 \times 10^{26}$ y, 5 y of data



KamLAND-Zen: Neutrino2020

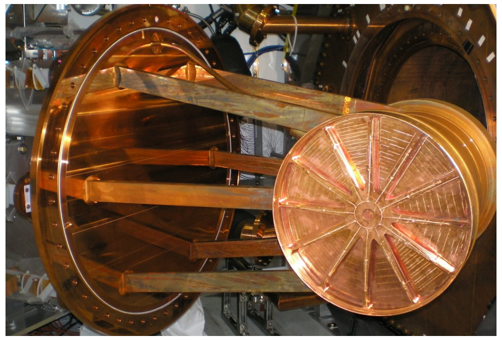


EXO-200, NEXO, NEXT, PANDAX-III

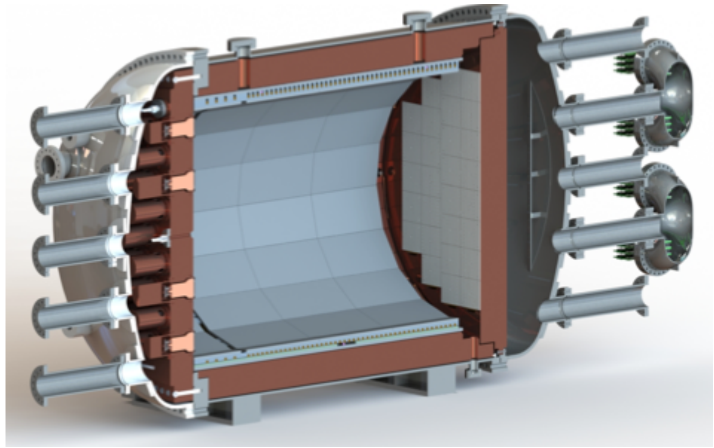


TPC: Detect primary scintillation (S1, t_0), and charge, either directly, or via proportional scintillation (S2)

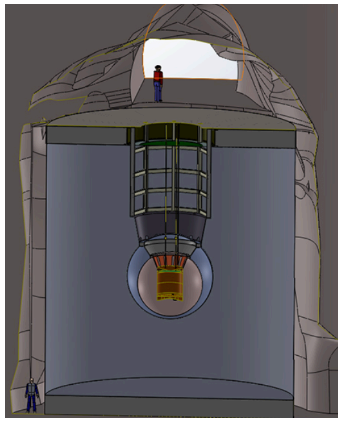
- EXO-200: 75 kg ^{136}Xe, $\sigma/E = 1.1\%$; $T_{1/2} > 3.5 \times 10^{25}$ y
- nEXO: proposal for 5 t of LXe enr. in ^{136}Xe, $T_{1/2} \sim 9.2 \times 10^{27}$ y,10 y
- NEXT: high-pressure (15 bar) ^{136}Xe gas TPC: e$^-$ tracks
  - Demonstrated: $\sigma/E = 0.43\%$; NEXT-100: operation in 2021; R&D on Ba ion tagging ongoing, for ton-scale detector
- PandaX-III: high-pressure (10 bar) ^{136}Xe gas TPC, multiple modules with 200 kg each



EXO-200: PRL 123, 2019



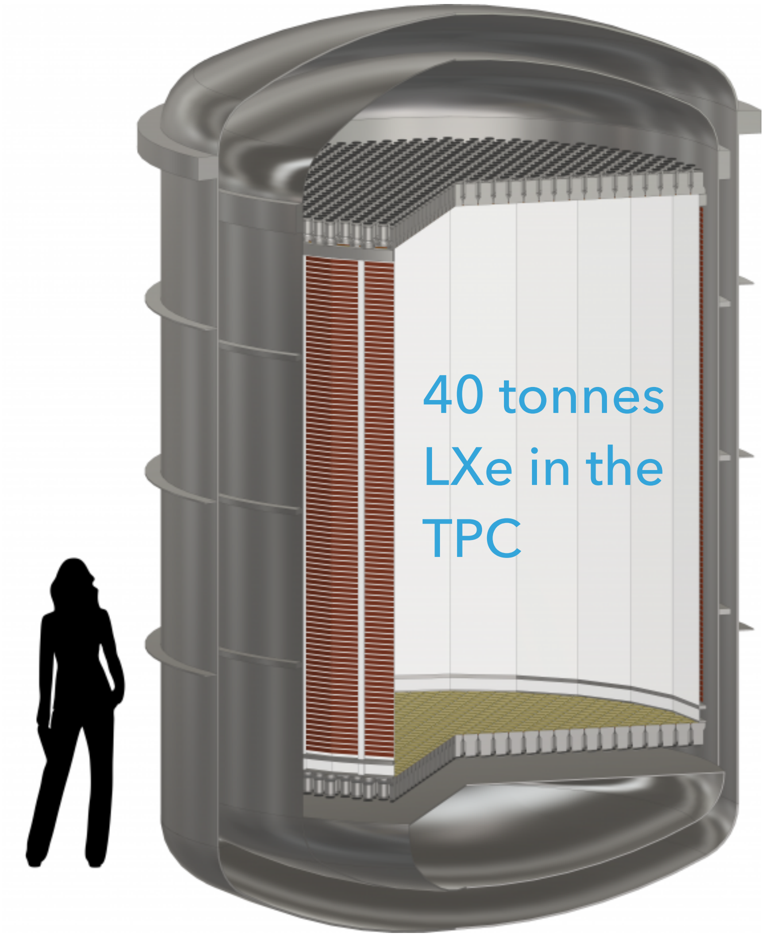
NEXT, 1910.07314



nEXO, 1805.11142

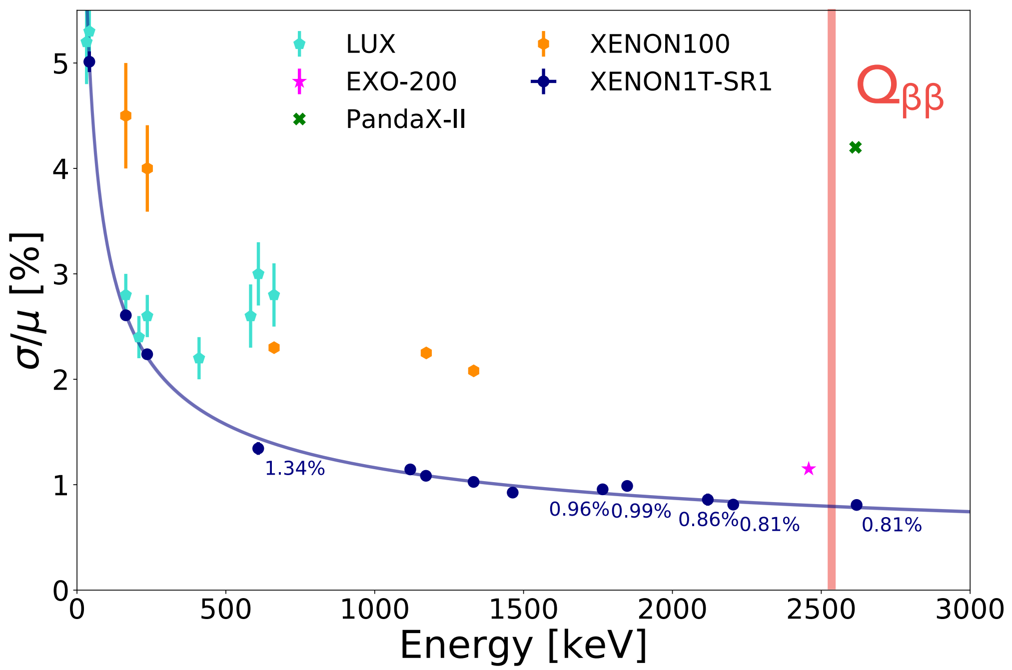
DARWIN

- TPC with 40 t ^{nat}Xe (50 t in total) for DM searches; 8.9% ^{136}Xe ≈ 3.6 t of ^{136}Xe
- Goal: $T_{1/2}$ ~ few x 10^{27} y, with background rate < 0.2 events/(t y) in ROI
- Energy resolution: σ/E = 0.8% (achieved in XENON1T



40 tonnes LXe in the TPC

DARWIN Collaboration, JCAP 1611 (2016) 017
Double beta study: EPJ-C 80, 2020



XENON1T: σ/E=0.8% at 2.5 MeV

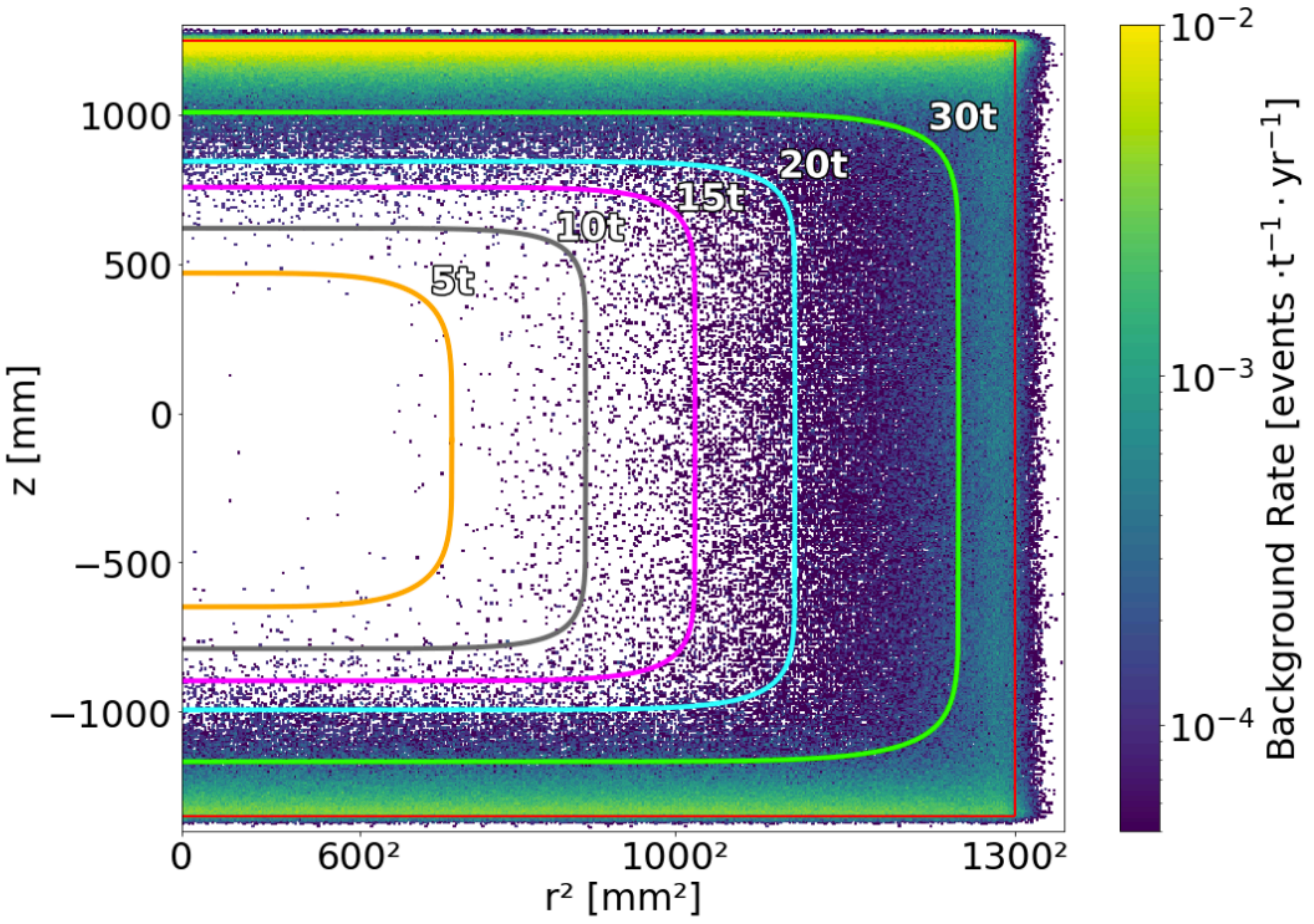
XENON Collaboration, EPJ-C 80, 2020, 8

DARWIN BACKGROUNDS

- Intrinsic:
  - ^{8}B ν's, ^{137}Xe, 2νββ, ^{222}Rn
- Materials:
  - ^{238}U, ^{232}Th, ^{60}Co, ^{44}Ti
- FV cut: super-ellipsoidal

$$\left(\frac{z+z_0}{z_{max}}\right)^t + \left(\frac{r}{r_{max}}\right)^t < 1$$

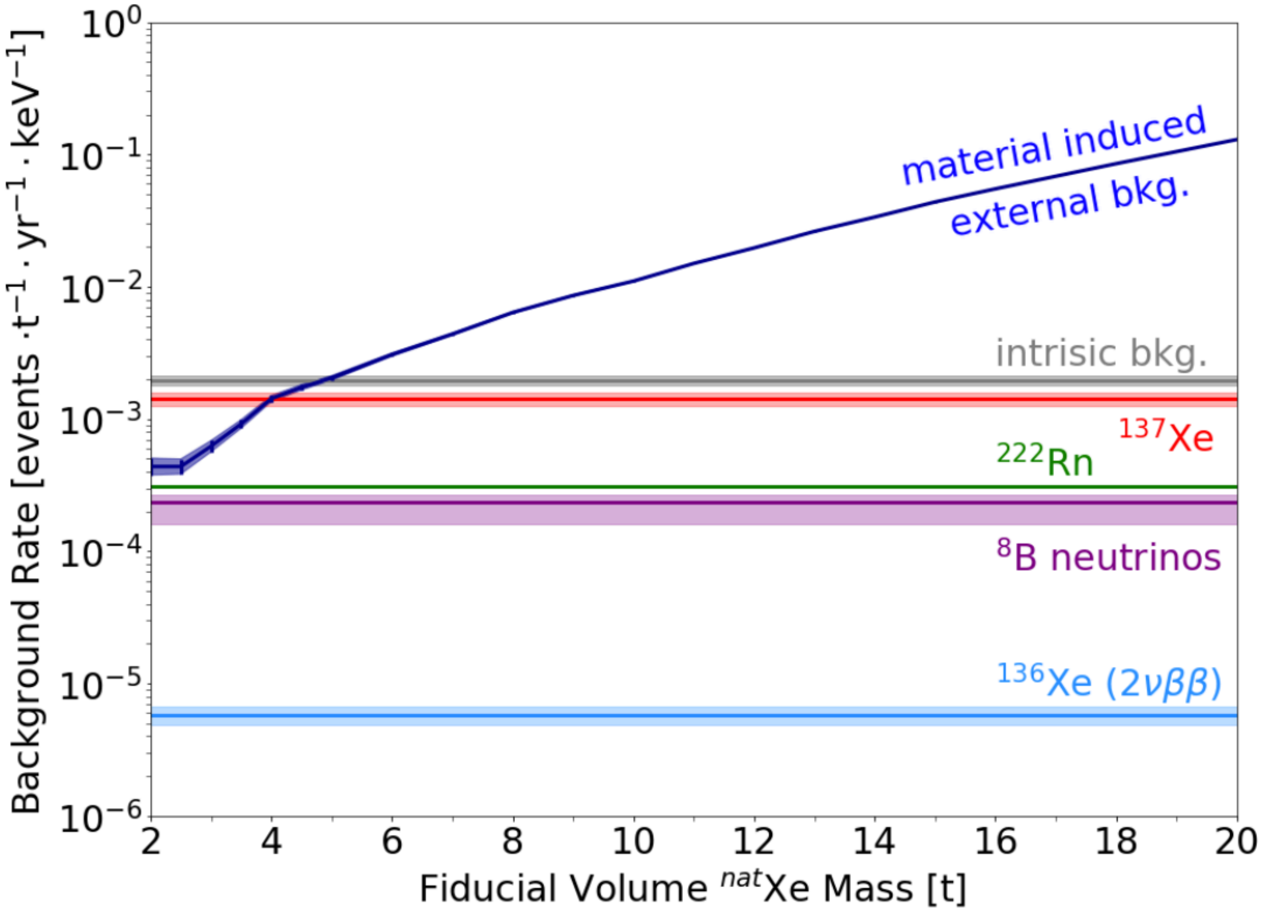
100 y of DARWIN run time, event with energy deposits in the ROI [$Q_{\beta\beta}$± FWHM/2]



DARWIN BACKGROUNDS

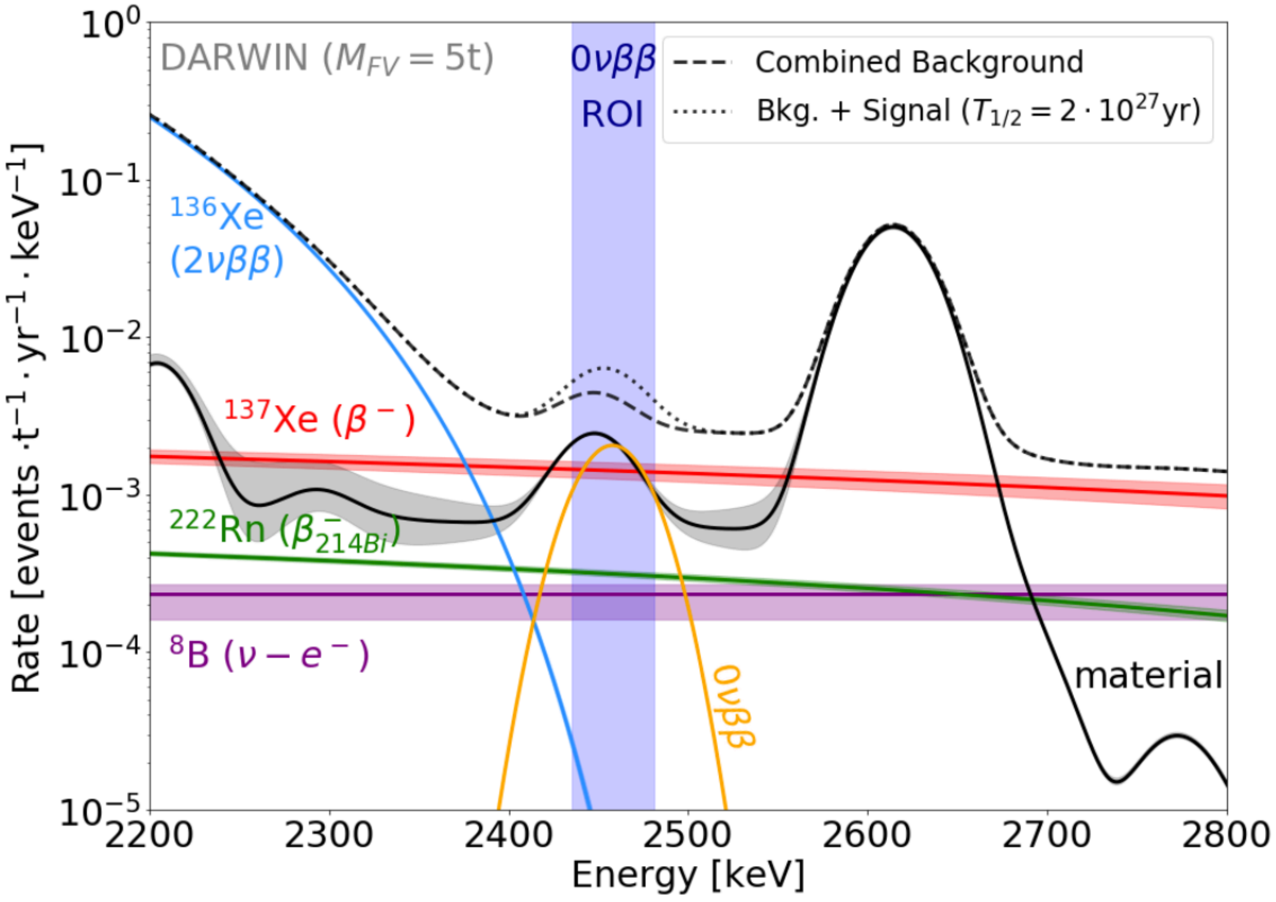
- ROI: [2435-2481] keV = FHWM around $Q_{\beta\beta}$
- ^{137}Xe: β-decay with Q=4173 keV, $T_{1/2}$=3.82 min (via n-capture on ^{136}Xe)

DARWIN collaboration, arXiv:2003.13407



Rate versus fiducial mass

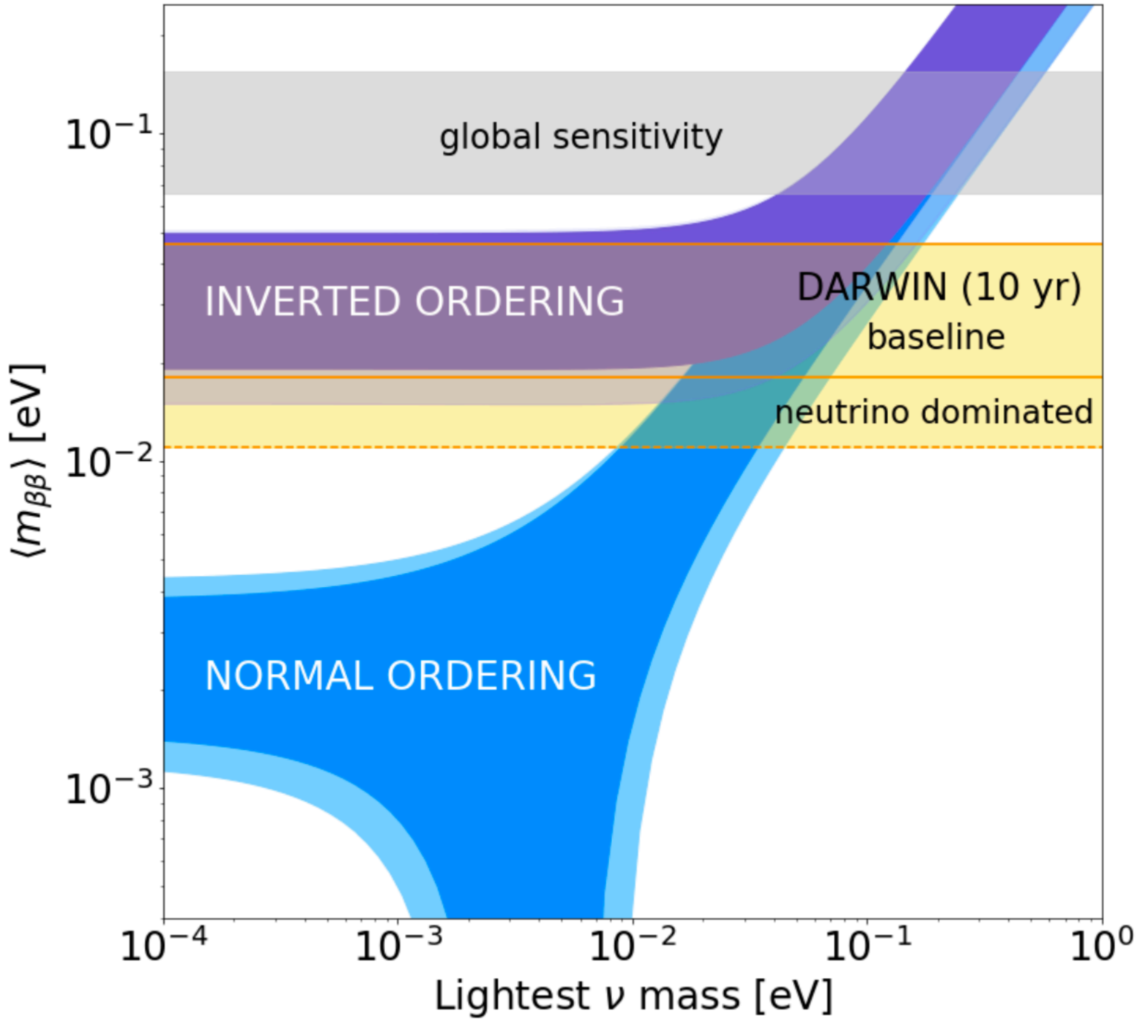
Signal: $T_{1/2}$ = 2 x 10^{27} y



Rate in 5 tonnes fiducial region (0.45 t ^{136}Xe)

DARWIN REACH

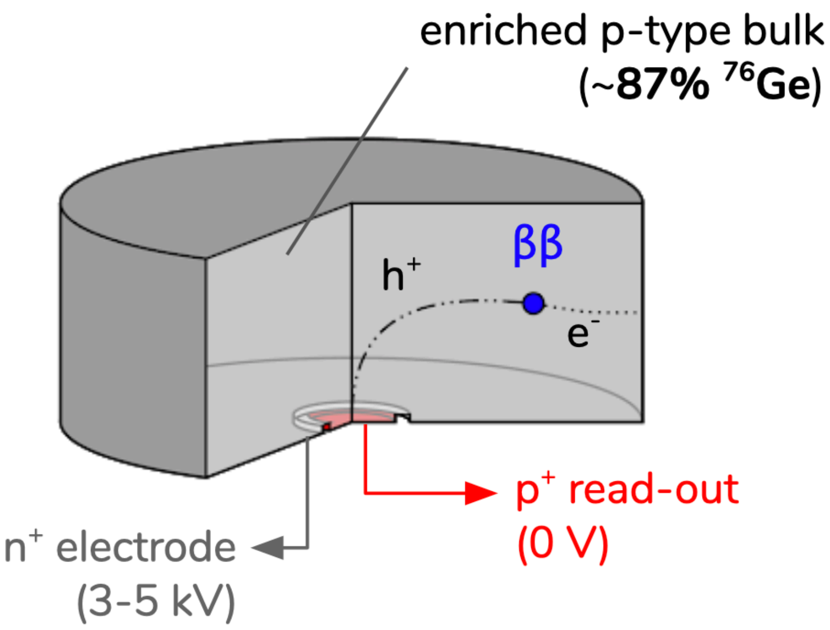
- Reduce external backgrounds
  - SiPMs, cleaner materials & electronics
- Reduce internal background
  - Time veto for ^{137}Xe, deeper lab, BiPo tagging
- Improve signal/background discrimination; resolution…



Baseline: $m_{\beta\beta}$ = (18 – 46) meV

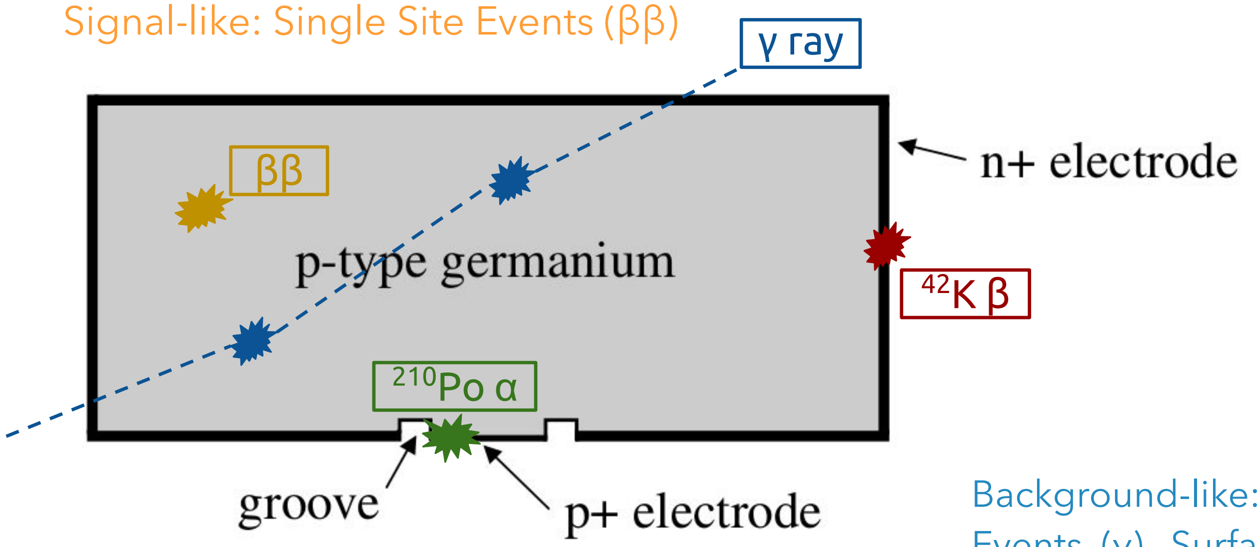
Neutrino dominated: $m_{\beta\beta}$= (11– 28) meV

GERMANIUM IONISATION DETECTORS



- HPGe detectors enriched in ^{76}Ge
  - Source = detector: high detection efficiency
  - High-purity material: no intrinsic backgrounds
  - Semiconductor: $\sigma/E < 0.1\%$ at $Q_{\beta\beta} = 2039.061 \pm 0.007$ keV
  - High stopping power: β absorbed within O(1) mm

Signal-like: Single Site Events (ββ)



Background-like: Multiple Site Events (γ), Surface events (α,β)

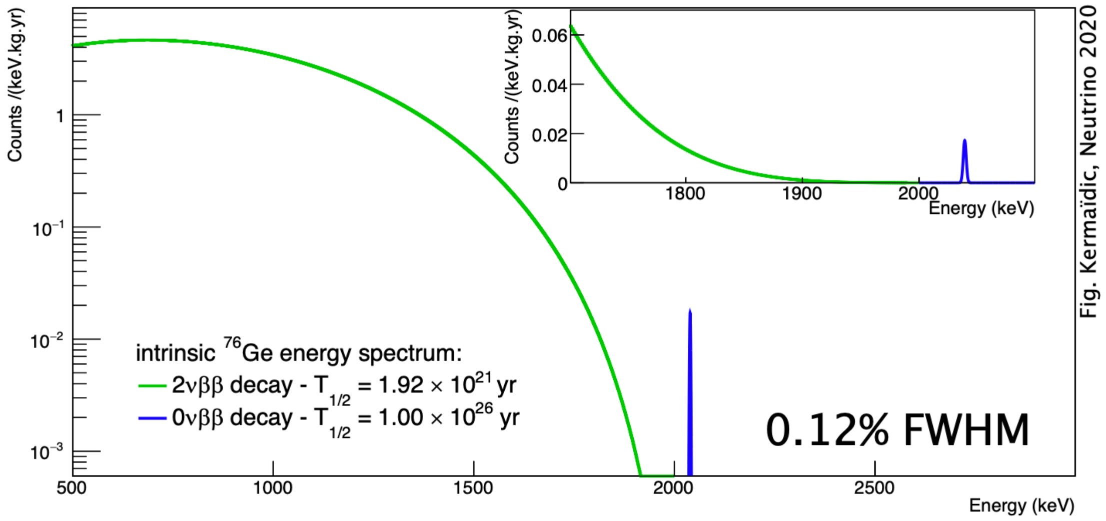
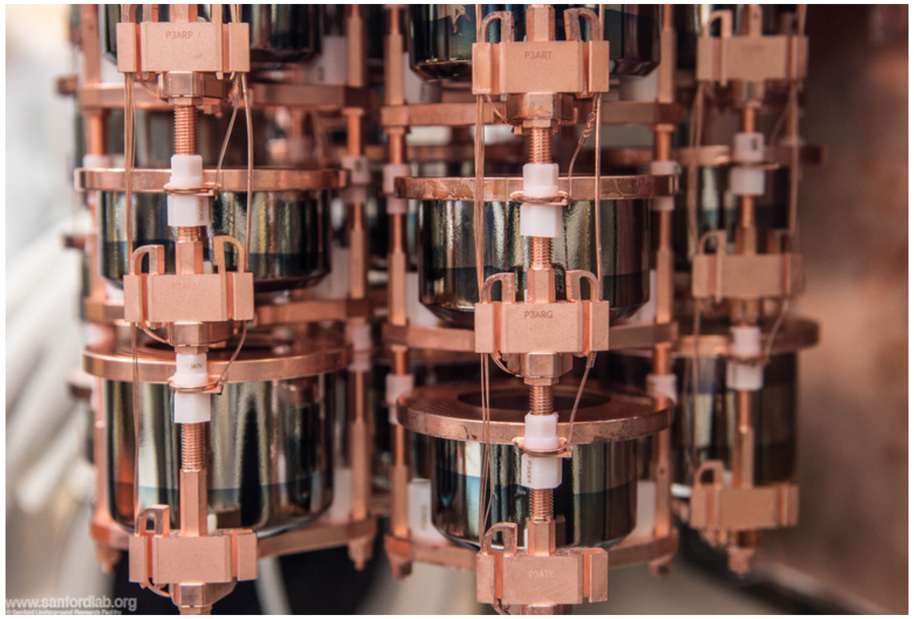
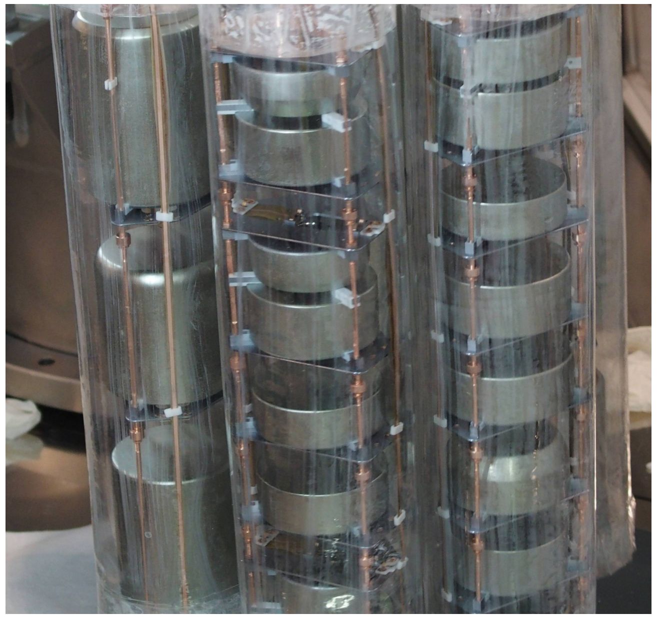


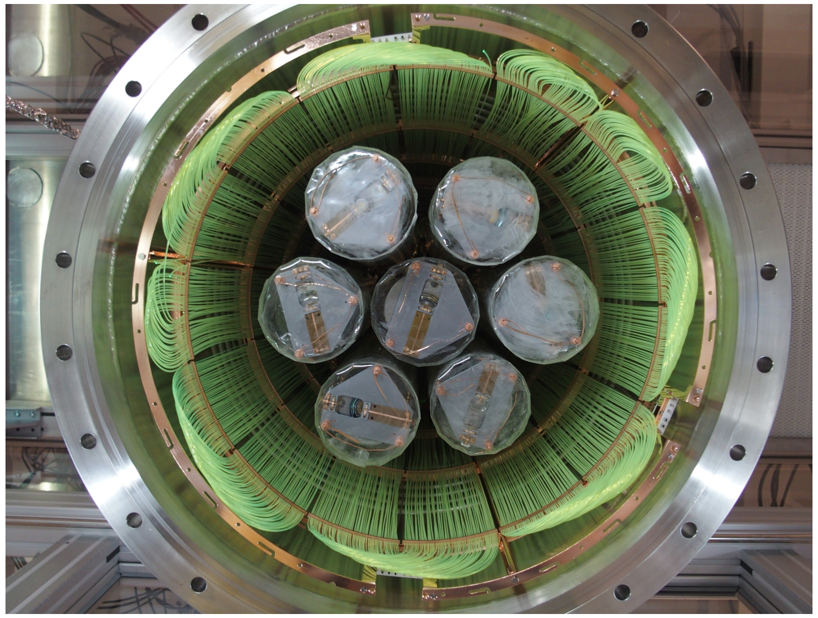
Fig. Kermaïdic, Neutrino 2020

Neutrino 2020

RECENT GERMANIUM EXPERIMENTS







MAJORANA at SURF

29.7 kg of 88% enriched ^{76}Ge crystals

2.5 keV FWHM at 2039 keV

26 kg y exposure; PRL 120 (2018)

$T_{1/2} > 2.7 \times 10^{25}$ y (90% CL)

GERDA at LNGS

35.6 kg of 86% enriched ^{76}Ge crystals in LAr

3.0 keV FWHM at 2039 keV

58.9 kg y exposure; Science 365 (2019), 127.2 kg y exposure: Neutrino 2020 & submitted to PRL

$T_{1/2} > 1.8 \times 10^{26}$ y (90% CL)

$Q_{\beta\beta} = 2039.061 \pm 0.007$ keV

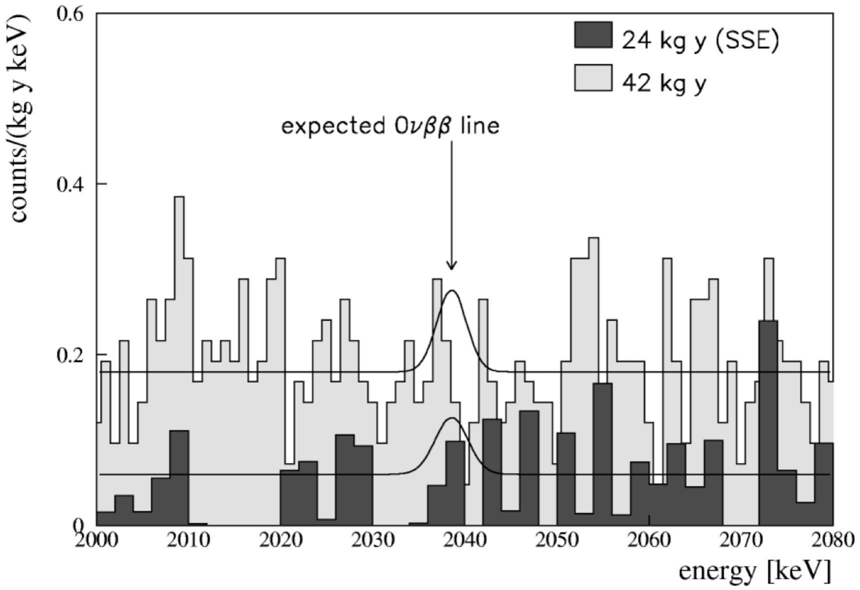
THE HEIDELBERG-MOSCOW EXPERIMENT

- Detectors in conventional shield: five ^{76}Ge detectors, mass 10.96 kg
- Concept to operate directly in cryogenic liquid:
  - Genius -> now GERDA->upcoming LEGEND

A first "bare" HPGe detector

GENIUS background and technical studies:
L. Baudis et al, NIM A 426 (1999)

Heidelberg-Moscow HPGe detector in conventional shield

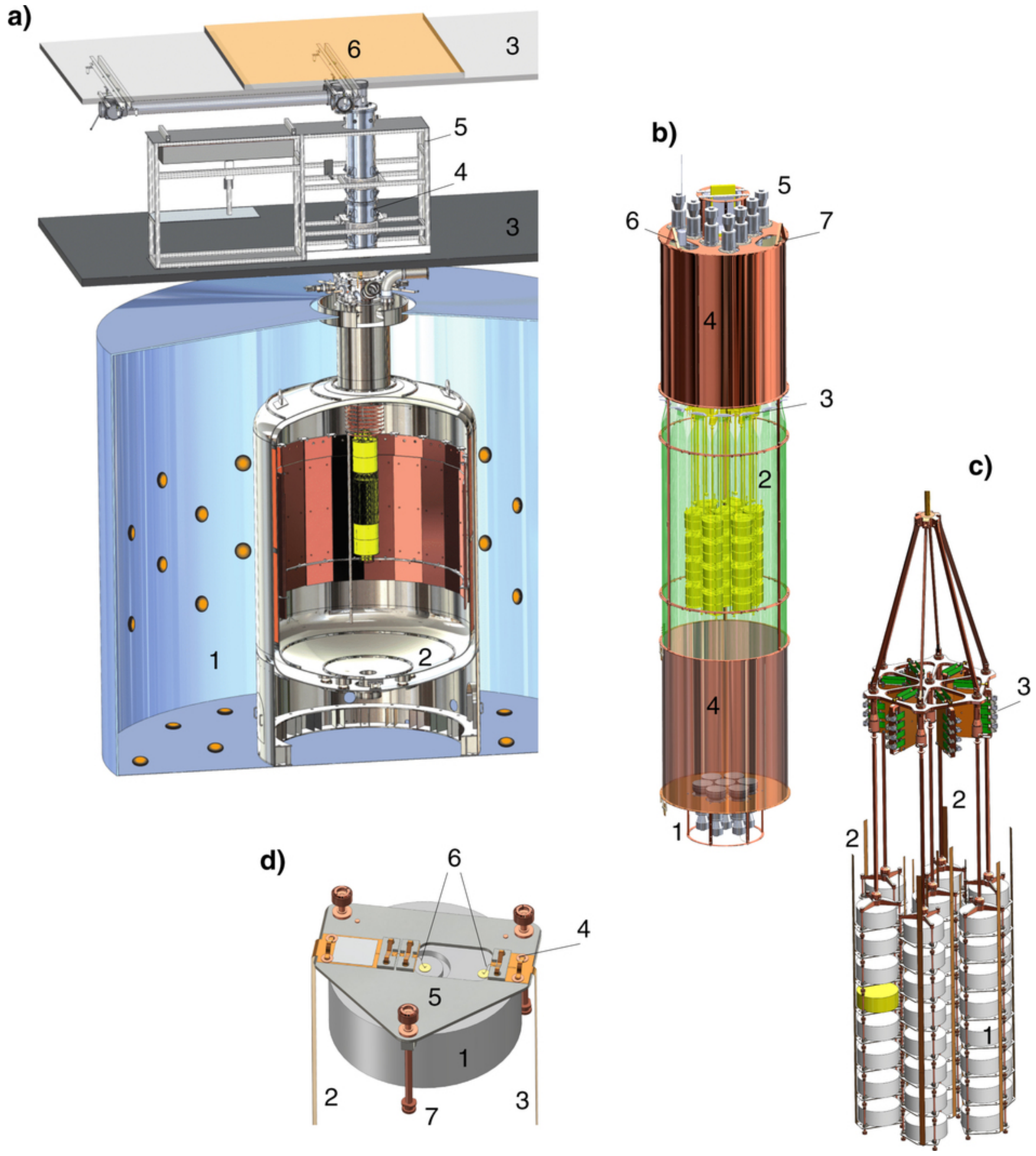


Limits on the Majorana neutrino mass in the 0.1 eV range, L. Baudis et al., Phys. Rev. Lett. 83, 1999

$$T_{1/2} > 1.6 \times 10^{25}\ \mathrm{y}\ \ 90\%\ \mathrm{C.L.}$$

Sensitivity

THE GERDA EXPERIMENT

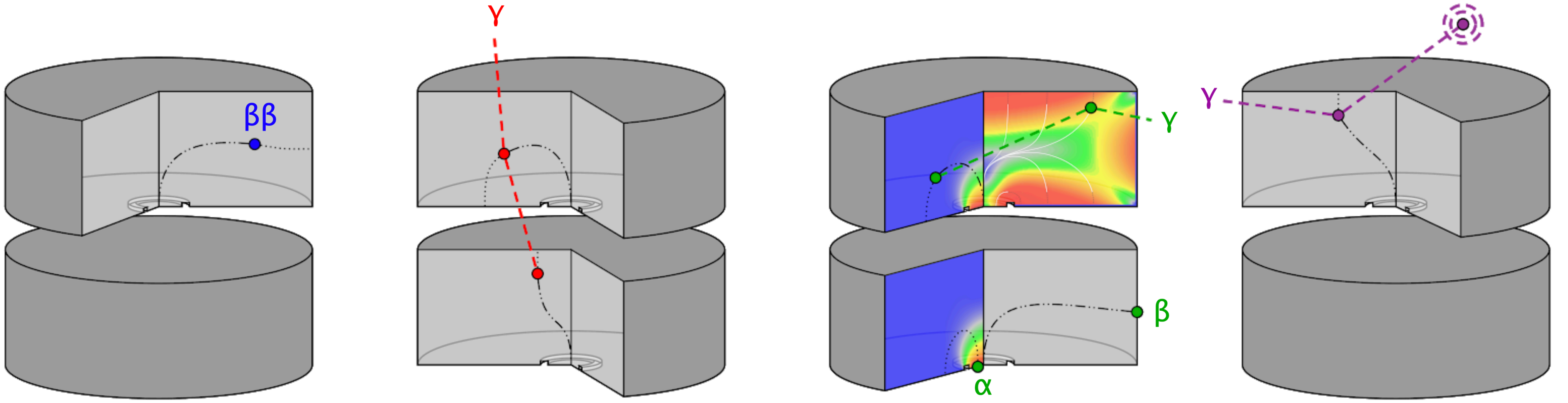


GERDA collaboration, EPJ-C 78 (2018) 5

- Liquid Ar (64 m^3) as cooling medium and shielding
- Surrounded by 590 m^3 of ultra-pure water as muon Cherenkov veto
- U/Th in LAr < 7x10^{-4} µBq/kg
- A minimal amount of surrounding material
- Data taking: 2011-2019

BACKGROUND SUPPRESSION

- Several handles:
  - Event topology + anti-coincidence between HPGe detectors + pulse shape discrimination + liquid argon veto



event topology

differentiate **point-like** (single-detector, single-site) ββ topology from:

detector anti-coincidence

multi-detector interactions

pulse shape discrimination (PSD)

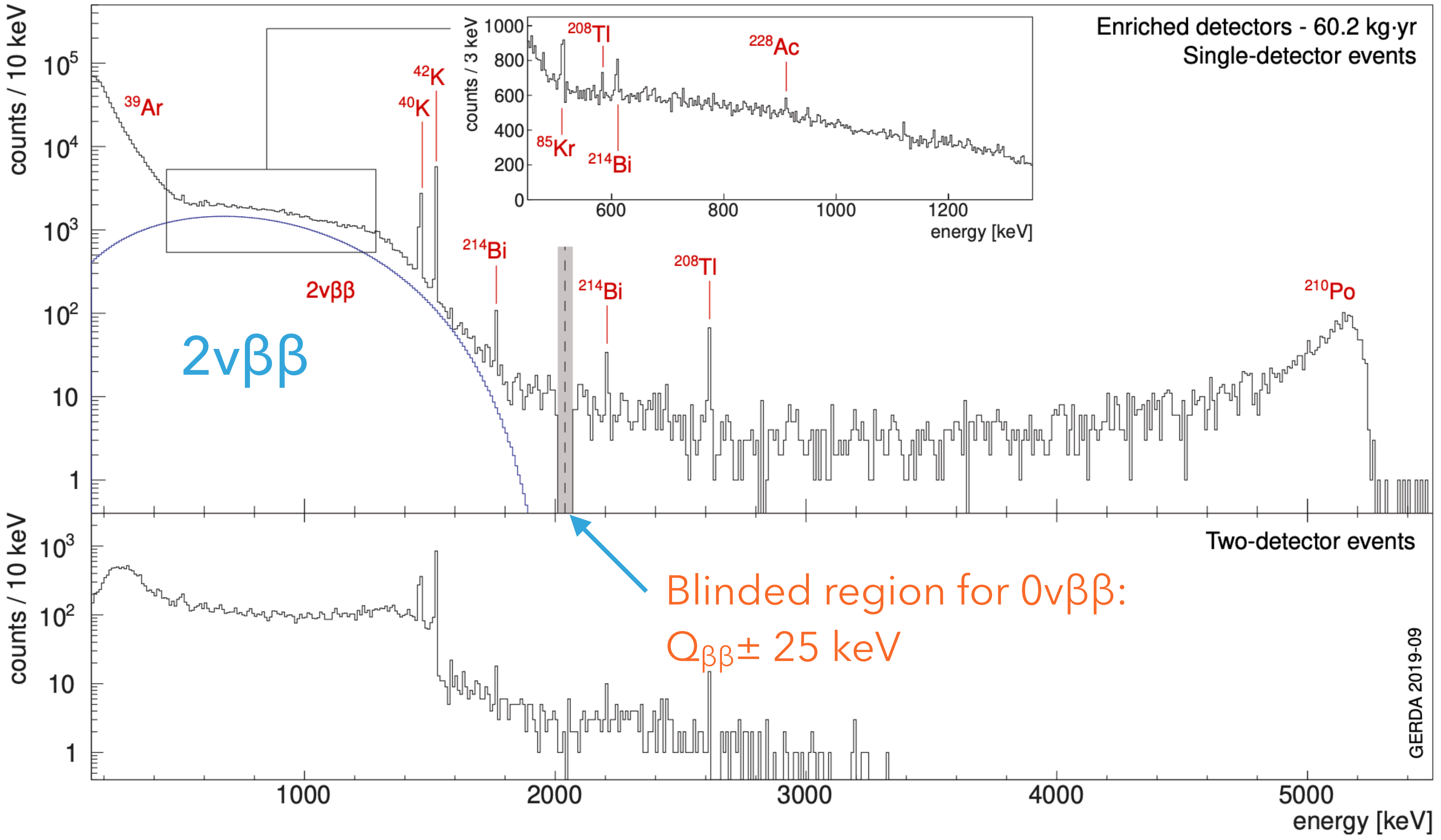
multi-site/surface interactions

detector-LAr anti-coincidence (LAr veto)

interactions with **coincident energy deposition** in surroundings

BACKGROUND MODEL IN GERDA

- Intrinsic 2νββ-events, ^{39}Ar ($T_{1/2}$ = 269 y), ^{42}Ar ($T_{1/2}$ = 33 y) and ^{85}Kr ($T_{1/2}$ = 11 y) in liquid argon
- ^{60}Co, ^{40}K, ^{232}Th, ^{238}U in materials, α-decays (^{210}Po) on the thin p^+ contact



2νββ

Blinded region for 0νββ: $Q_{\beta\beta}$± 25 keV

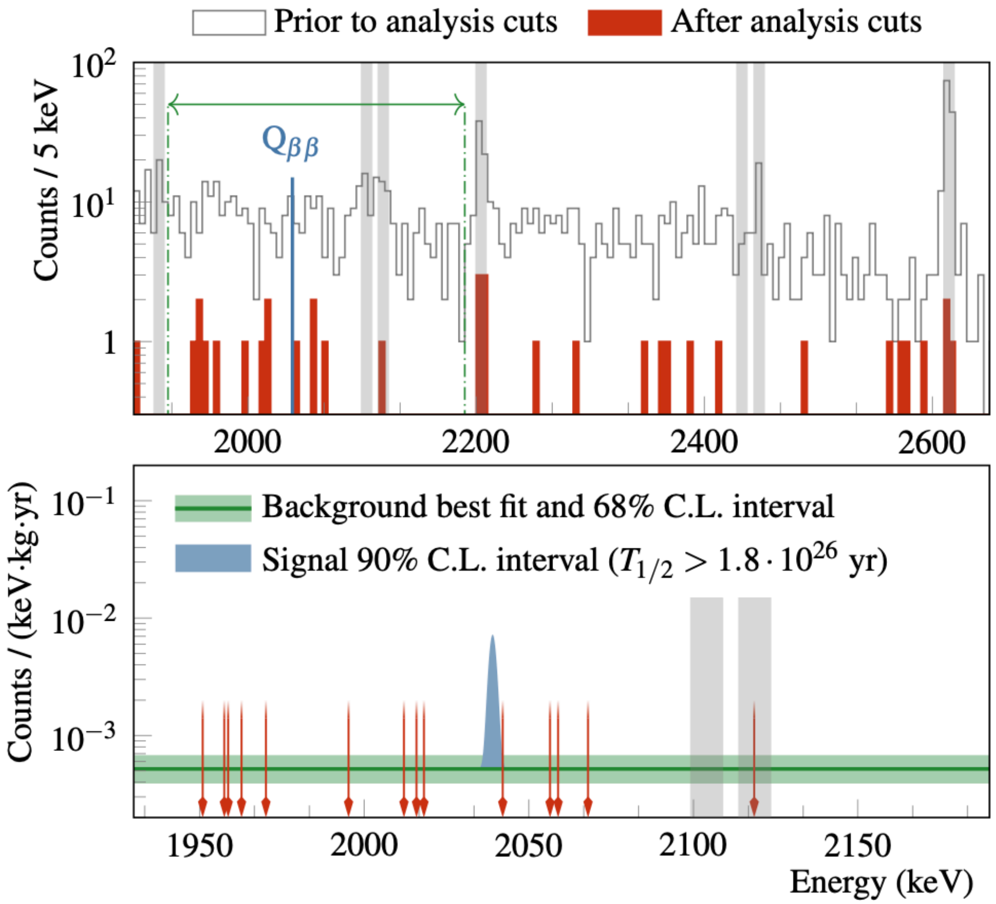
Sum spectrum, single-detector events

Sum spectrum, two-detector events

GERDA collaboration, JHEP 03 (2020)

DOUBLE BETA DECAY FINAL RESULTS

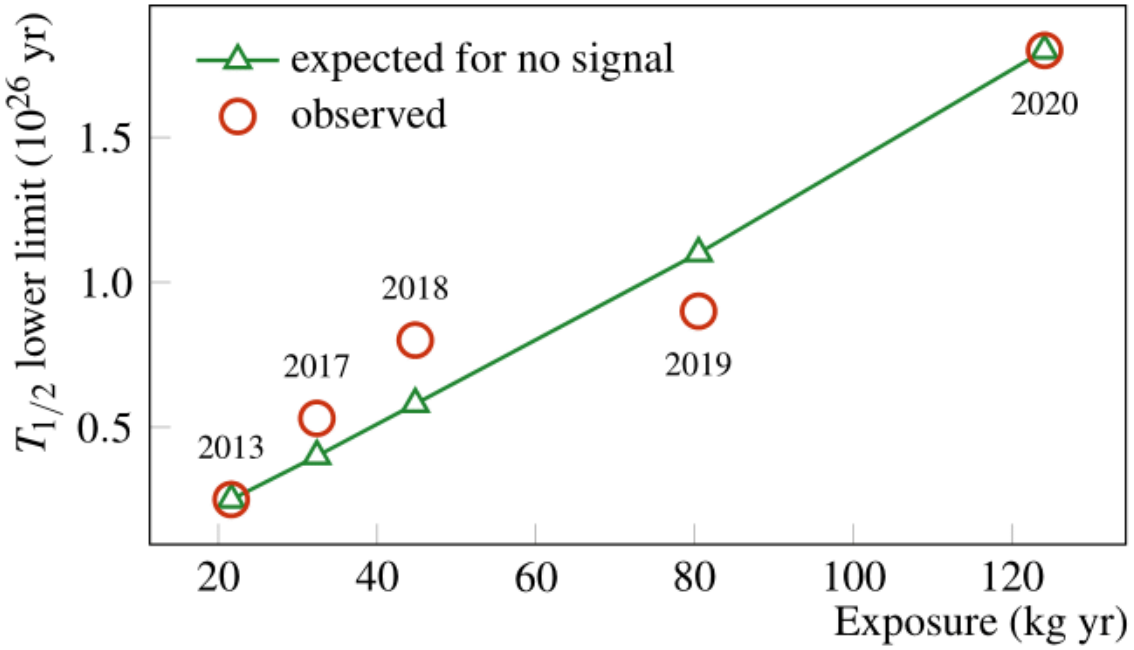
- Measured $T_{1/2}$ of the 2νββ-decay: $(1.926 \pm 0.094) \times 10^{21}$ y
- Background level: 5.2×10^{-4} events/(keV kg y) in 230 keV window around Q-value



GERDA collaboration, arXiv:2009.06079

Constraints on the ^{76}Ge 0νββ-decay

$T_{1/2} > 1.8 \times 10^{26}$ y (90% CL); $m_{\beta\beta} < 80 - 182$ meV

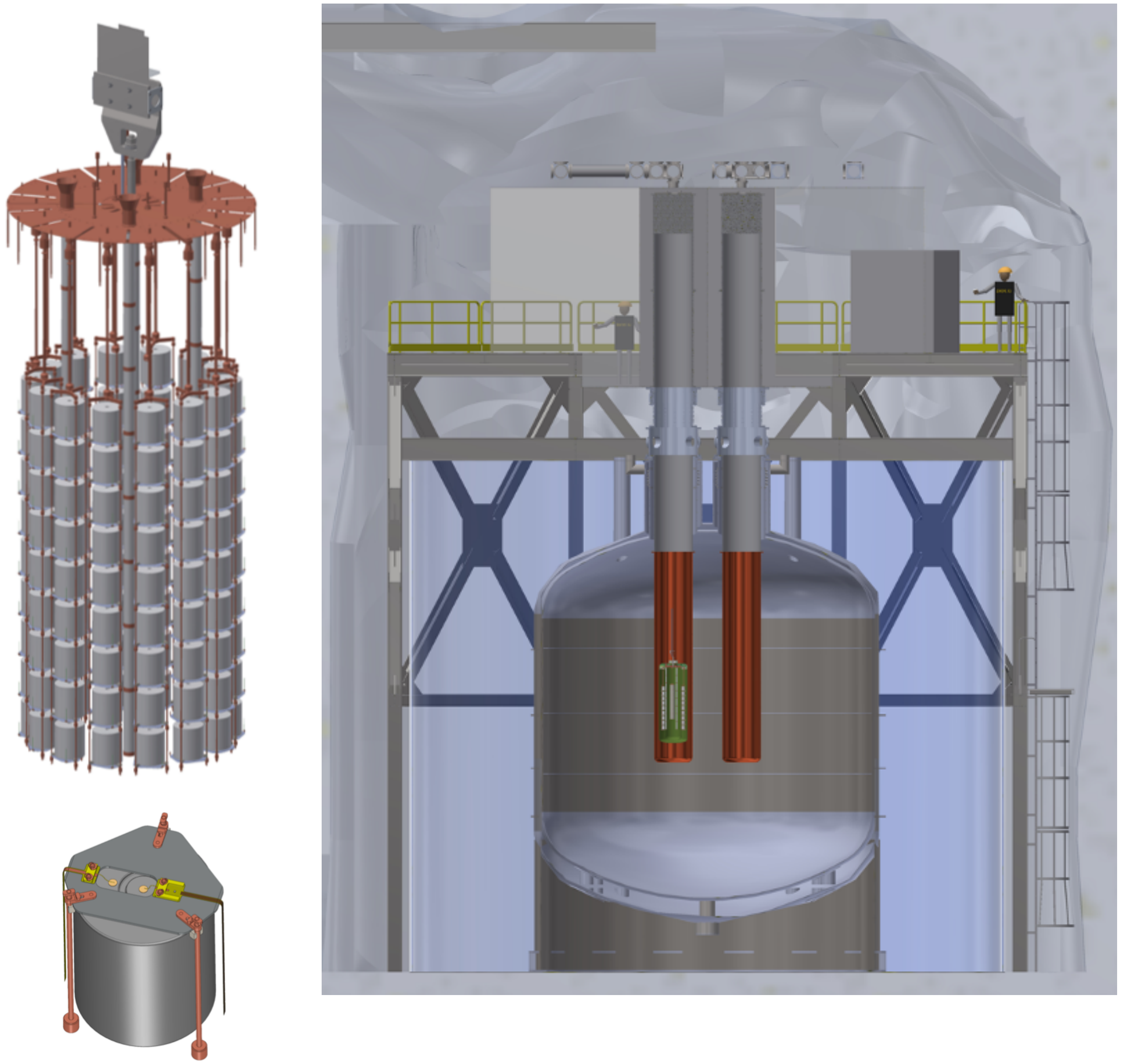


THE FUTURE: LEGEND

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ Decay

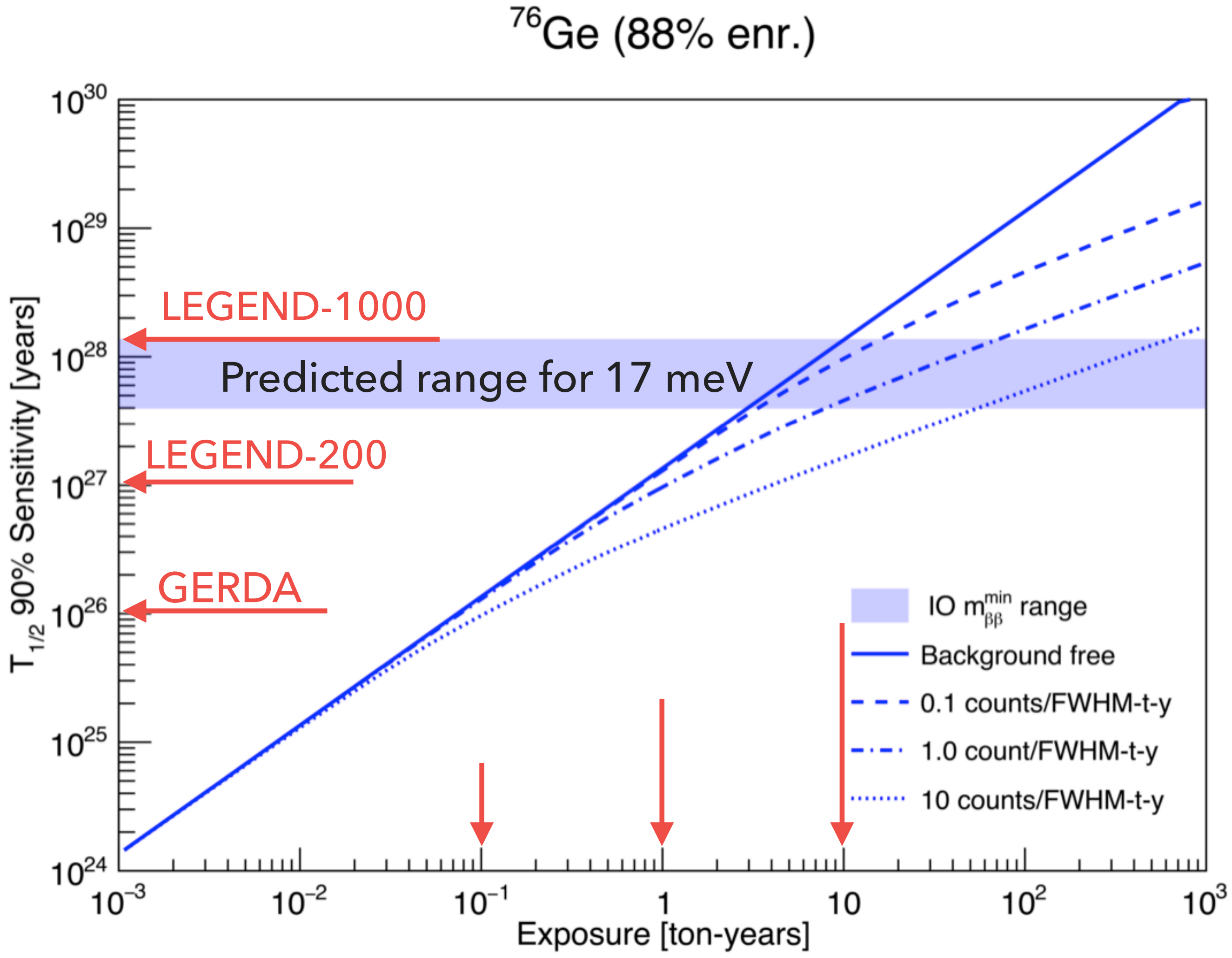
- Large enriched germanium experiment for $0\nu\beta\beta$ decay
- GERDA + Majorana + new groups
  - LEGEND-200: 200 kg in existing (upgraded) GERDA infrastructure at LNGS, to start in 2021
  - Background goal: 0.6 events/(FWHM t y)
  - LEGEND-1000: 1000 kg, staged, 4 modules
  - Background goal: 0.1 events/(FWHM t y)



EXPECTED SENSITIVITY

- LEGEND-200: $T_{1/2} \sim 10^{27}$y
- LEGEND-1000: $T_{1/2} \sim 10^{28}$ y
- $m_{\beta\beta} \sim 17$ meV (for worst case NME)

Post GERDA tests with 20 Majorana, GERDA and new LEGEND detectors completed



Abgrall et al., AIP Conf. Proc. 1894(1), 020027 (2017)

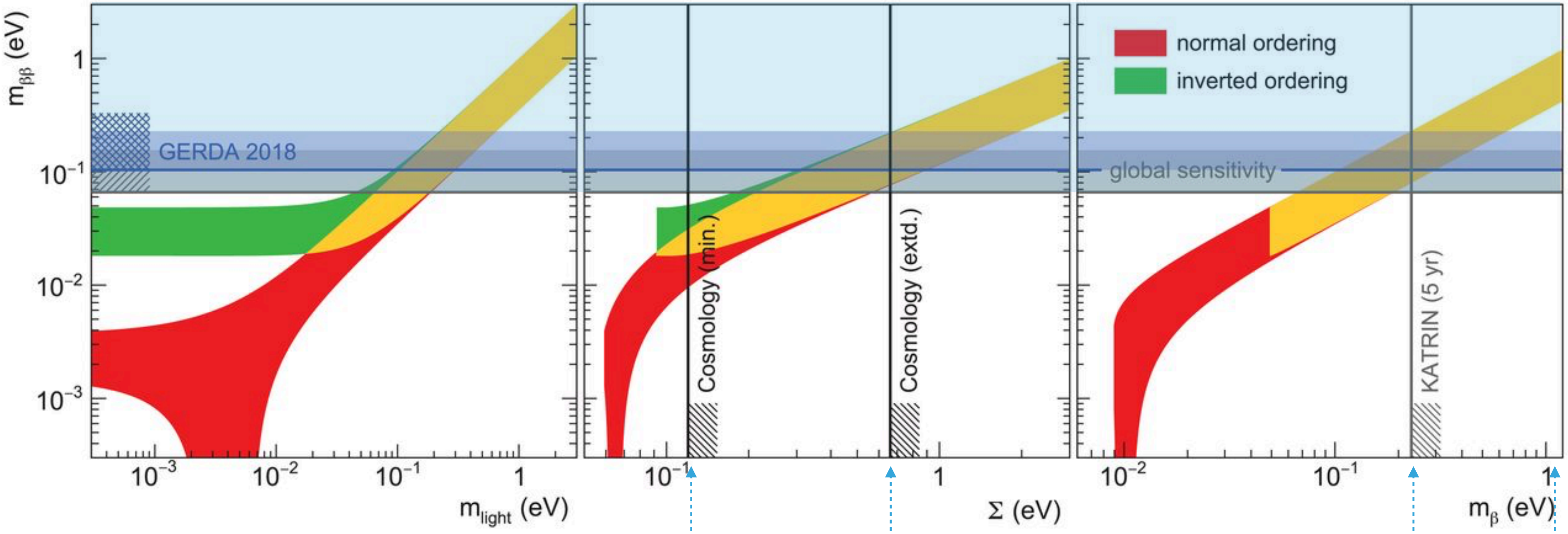
Background

GERDA:	3 events/(ROI t y)
LEGEND-200:	0.6 events/(ROI t y)
LEGEND-1t:	0.1/(ROI t y)

MASS OBSERVABLES

- Constraints in the $m_{\beta\beta}$ parameters space in the 3 light ν scenario
- Global sensitivity from 0νββ-experiments & constraints from direct searches & cosmology

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$



$$\Sigma = \sum_i m_i$$

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

0.11 eV 0.66 eV 0.23 eV 1.1 eV

GERDA collaboration, Science 365, Sept 2019

FUTURE PROJECTS: A SELECTION

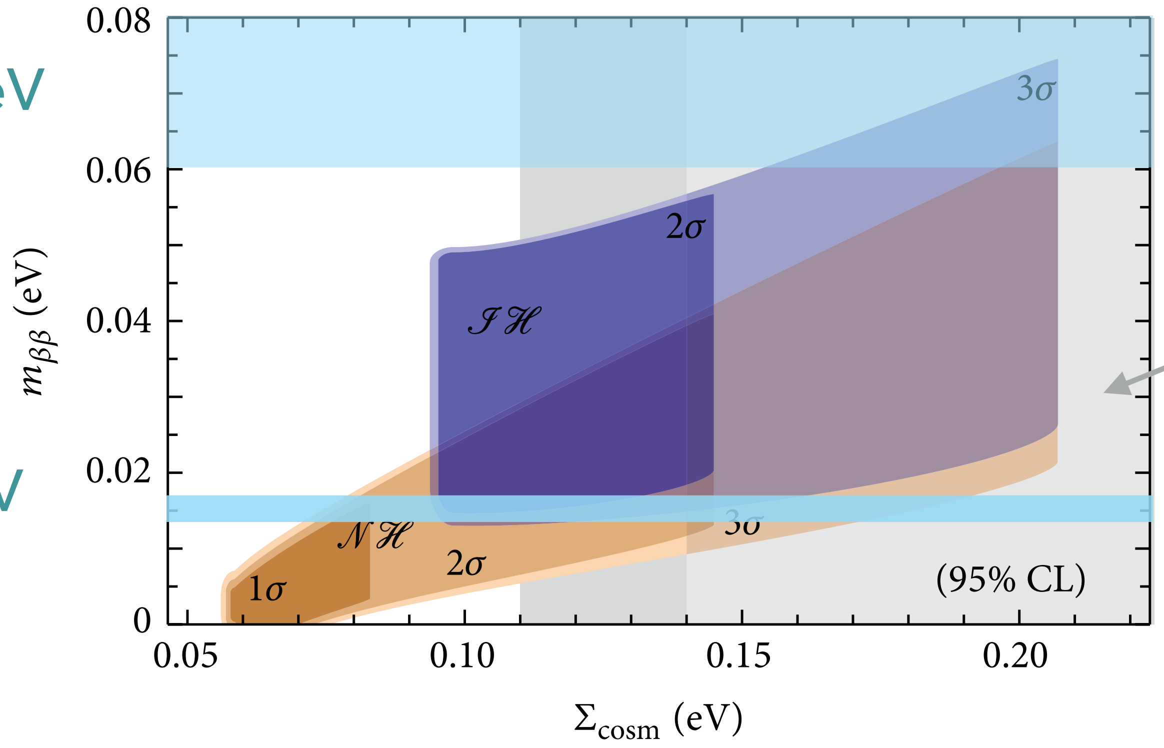
$$|m_{\beta\beta}| \propto \left(\frac{B \cdot \Delta E}{M \cdot t}\right)^{\frac{1}{4}}$$

Experiment	Isotope	Iso mass [kg]	FWHM [keV]	$T_{1/2}$ [10^{27} y]	$m_{\beta\beta}$ [meV]
CUPID	^{130}Te	543	5	2.1	13-31
CUPID	^{82}Se	336	5	2.6	8-38
nEXO	^{136}Xe	4500	59	9	7-21
KamLAND2-Zen	^{136}Xe	1000	141	0.6	25-70
DARWIN	^{136}Xe	1068	20	2.4	11-46
PandaX-III	^{136}Xe	901	24	1.0	20-55
LEGEND-200	^{76}Ge	175	3	1	34-74
LEGEND-1t	^{76}Ge	873	3	6	11-28
SuperNEMO	^{82}Se	100	120	0.1	58-144

- Reminder
  - Large exposures: 10 tonne x year, low background rates < 1 event/(FWHM tonne x year)
  - Good energy resolution, large Q-value, high efficiency, demonstrated technology, etc
- Essential to use multiple isotopes to make a convincing case for **LNV**

SUMMARY AND OUTLOOK

- Ninety years after Pauli postulated his *"silly child"*: many open questions in neutrino physics
- 0νββ-decay: excellent tool to test LNV and the nature of neutrinos (Dirac vs Majorana)
- Existing experiments probe $T_{1/2}$ up to ~ 10^{26} years, with $T_{1/2} \sim (0.1\ \mathrm{eV}/m_\nu)^2 \times 10^{26}$ y
- Ton-scale experiments are required to cover the **inverted mass ordering scenario**
  - Several technologies move into this direction
- Much larger experiments needed to probe the **normal mass ordering**



~70 meV

~10 meV

Current experiments

Cosmology $\sum_i m_i < (0.11 - 0.54)\,\mathrm{eV}$

Future, ton-scale experiments

adapted from Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

THANK YOU

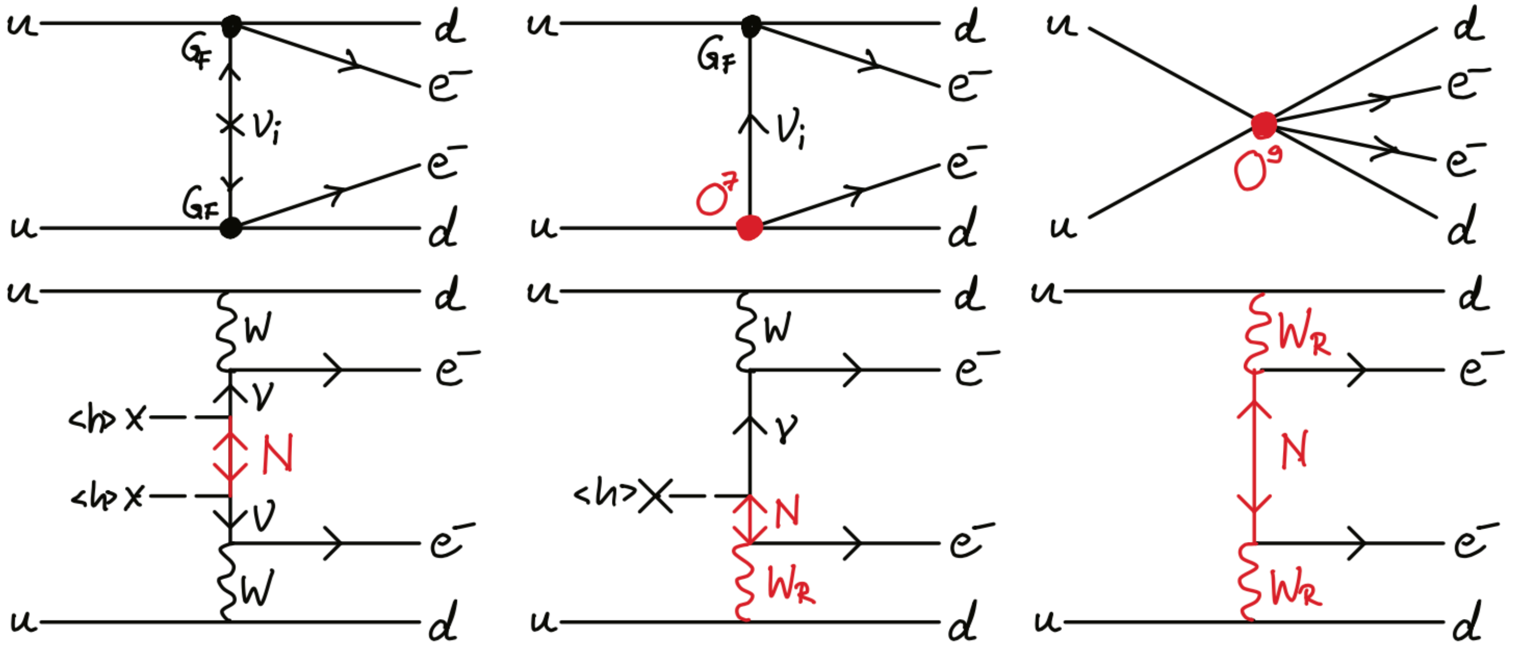
OTHER MECHANISMS FOR DOUBLE BETA DECAY

- LNV processes in extensions of the Standard Model generically contribute to 0νββ-decay (light or heavy sterile neutrinos, LR symmetric models, R-parity violating SUSY, leptoquarks, etc)
- Often classified as short- and long range processes, depending on the mass of the particles mediating the process (whether lighter or heavier than the momentum exchange scale ~ O(100 MeV))
- In the effective Lagrangian picture, the effects at low energies can be summarised in terms of higher order operators, added to the SM Lagrangian

5-dim Weinberg operator, standard mechanism

7-dim operator, long-range contributions

9-dim operator, short-range contributions



Examples from F. Deppisch, A modern introduction to neutrino physics: the lowest-order contributions beyond the standard mechanism

SOME TIME SCALES

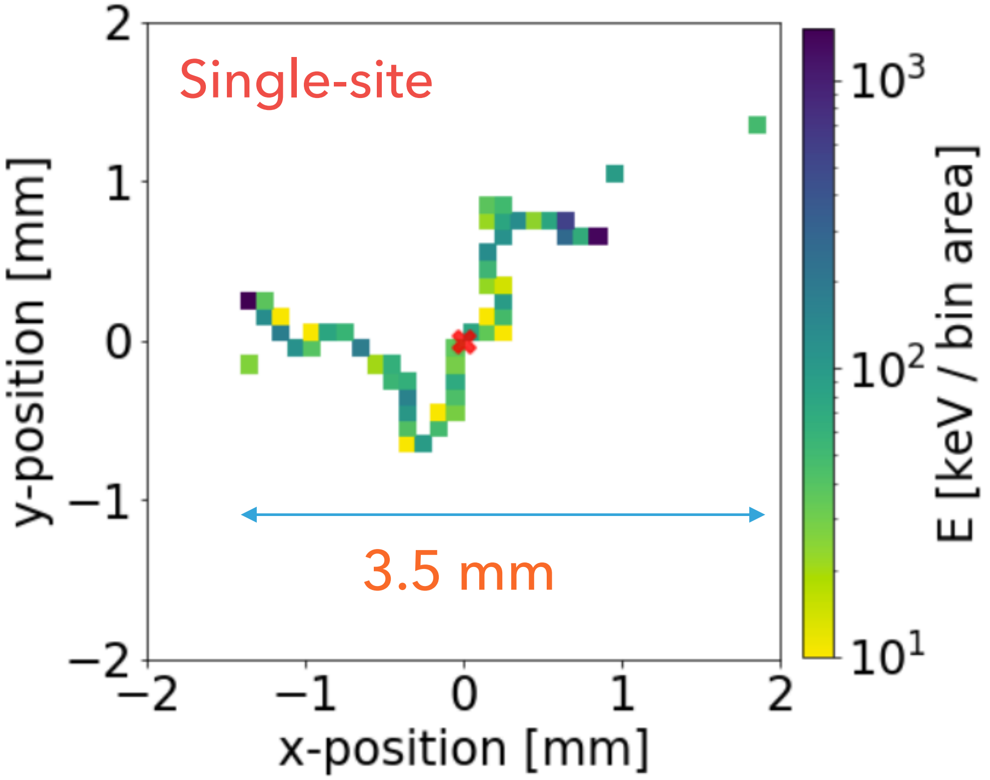
- ^{14}C: $T_{1/2} \sim 5.7 \times 10^4$ y
- ^{40}K: $T_{1/2} \sim 1.3 \times 10^9$ y
- ^{232}Th: $T_{1/2} \sim 1.4 \times 10^{10}$ y
- Age of the universe: $\sim 1.4 \times 10^{10}$ y
- $2\nu\beta\beta$: $T_{1/2} \sim 10^{20}$ y
- $0\nu\beta\beta$: $T_{1/2} > 10^{26}$ y
- Proton decay $> 10^{34}$ y

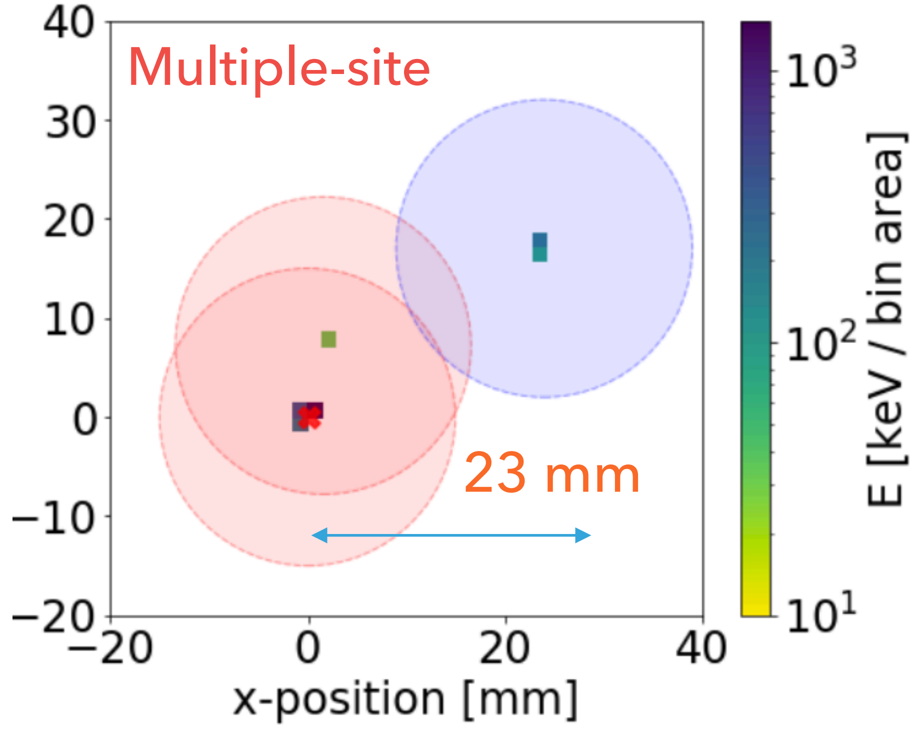
SIGNAL EVENTS IN LIQUID XENON

- Electrons thermalise within O(mm) => single-site topology
- Bremsstrahlung photons: may travel > 15 mm (E>300 keV) => multi-site event
- Energy depositions: spatially grouped using density-based spatial clustering algorithm
    - New cluster, if distance to any previous $E_{dep} > \varepsilon$ (separation threshold)

Assumption: ε = 15 mm; 90% efficiency for ββ-events

2 e^- back-to-back





NEUTRINO MASSES

- Three main methods: direct mass measurements, 0νββ-decay, cosmology
  - the observation of flavour oscillations imply *a lower bound on the mass of the heavier neutrino*
  - depending on the mass ordering, this lower bound is ≈ 0.05 eV

- The most direct probe: precision measurements of β-decays

$$^3_1\mathrm{H} \longrightarrow ^3_2\mathrm{He} + e^- + \bar{\nu}_e$$

- The effect of a non-zero neutrino masses is observed kinematically: when a ν is produced, some of the energy exchanged in the process is spent by the non-zero neutrino mass

- The effects are however very small & difficult to observe

- KATRIN will probe the eff. ν_e mass down to 0.2 eV

Eur. Phys. J. C (2020) 80:264
https://doi.org/10.1140/epjc/s10052-020-7718-z

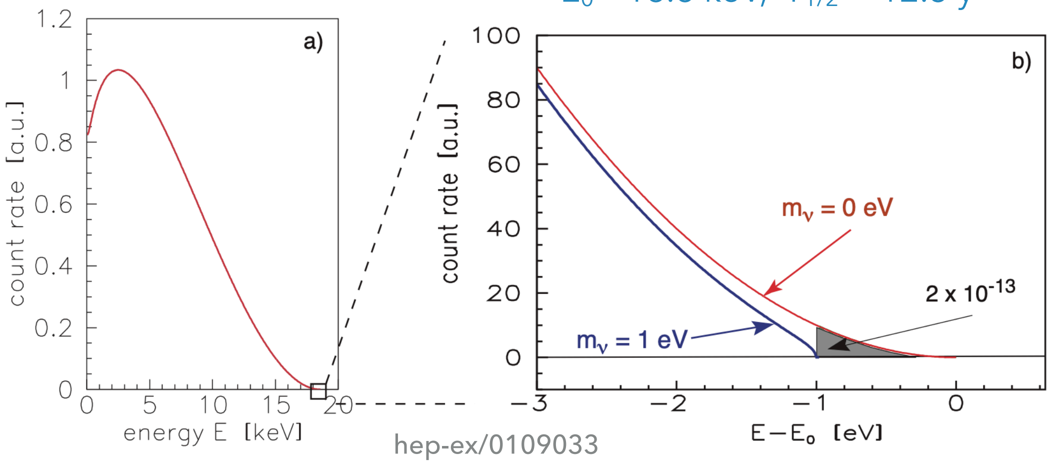
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

First operation of the KATRIN experiment with tritium

$$m^2_{\nu_e} = \sum_i |U_{ei}|^2 m_i^2$$

E_0= 18.6 keV, $T_{1/2}$ = 12.3 y



hep-ex/0109033

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- ◉ Cosmology: neutrinos influence the LSS and the CMB (with the ν density ratio):

$$\frac{\rho_\nu}{\rho_\gamma} = \frac{7}{8} N_{eff} \left(\frac{4}{11}\right)^{4/3}$$

$N_{\mathrm{eff}} = 3$ ~ number of active neutrinos

- ◉ The constraints are on the sum of neutrino masses

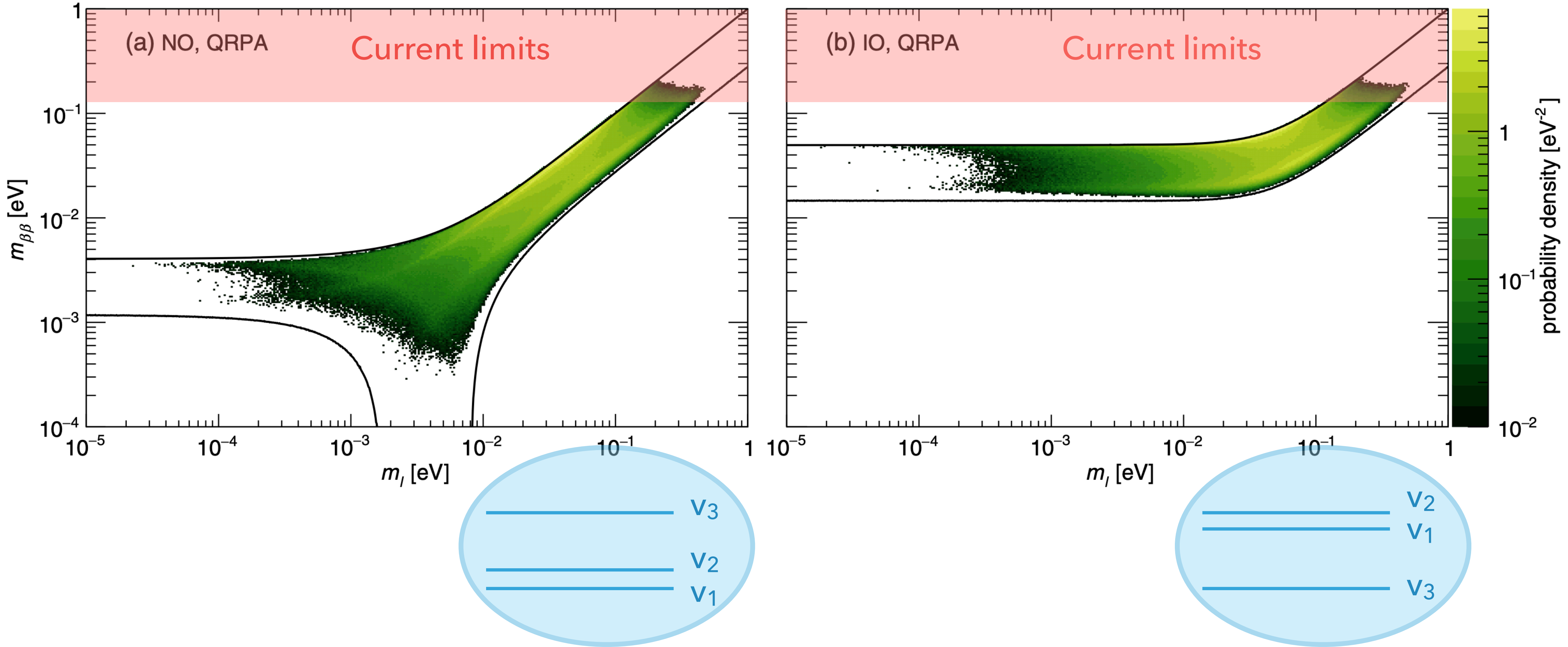
$$\sum_i m_i$$

- ◉ Dependent on the parameters of the cosmological model (ΛCDM)
- ◉ In general, depending on which data is included (see e.g., review in PDG2020)

$$\sum_i m_i < (0.11 - 0.54)\,\mathrm{eV}$$

THE EFFECTIVE MAJORANA NEUTRINO MASS

- Probability distribution of $m_{\beta\beta}$ via random sampling from the distributions of mixing angles and Δm^2
- Flat priors for the Majorana phases



Agostini, Benato, Detwiler, PRD 96, 2017