Why is it natural to think neutrinos to be Majorana particles

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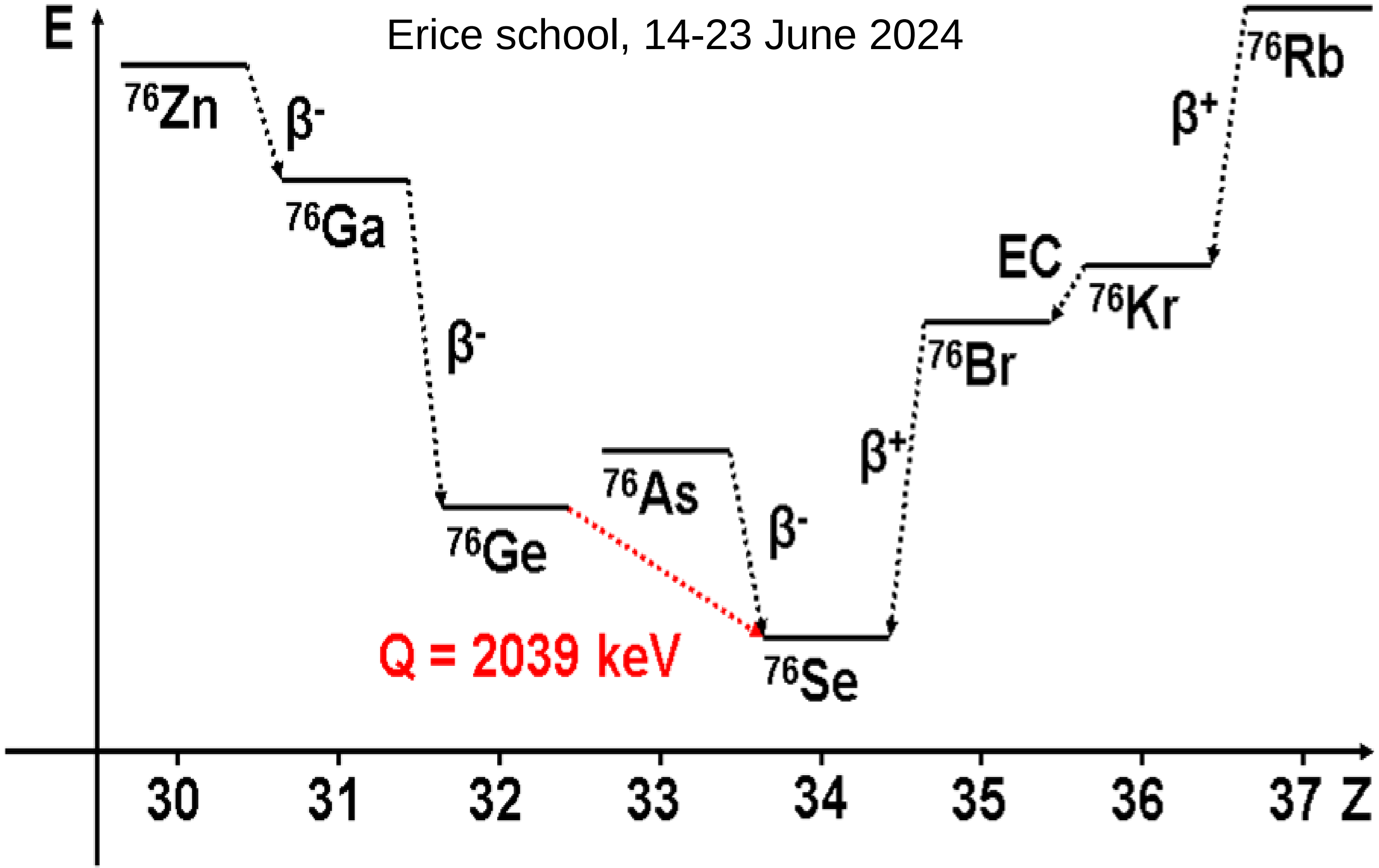


Prologue

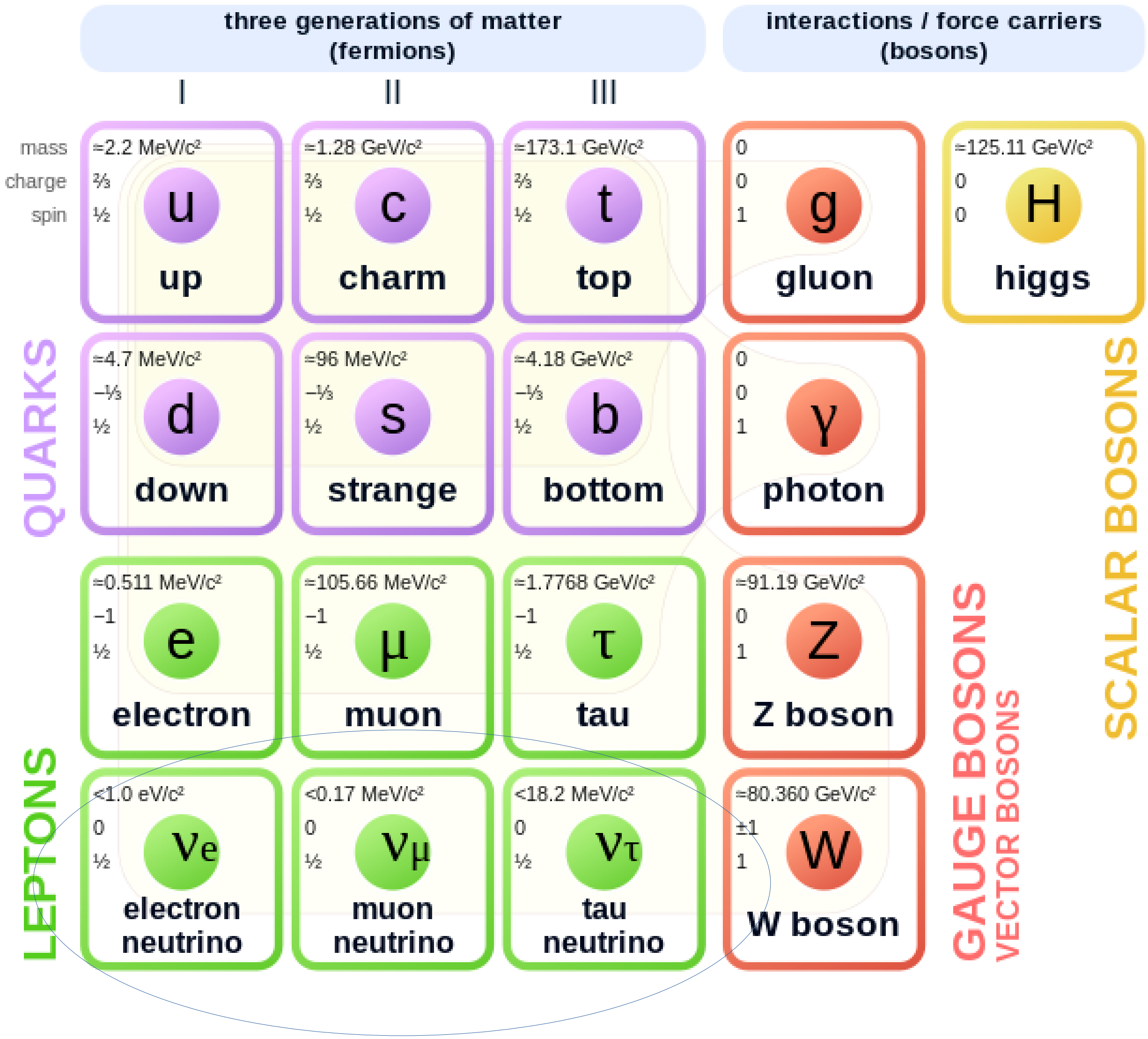
title of the talk is triggered by a comment by a Heidelberg colleague:
why should neutrinos by Majorana particles?
(Majorana means particle = anti-particle)

Early 1990, I would have argued the same way ….
(at that time neutrino mass > 0 (oscillations) was not established,
mass=0 $\rightarrow$ no difference if Majorana or Dirac)

Nowadays, we should know better

Introduction

Standard Model of Elementary Particles



3 neutrino flavors, in SM mass=0

neutrinos are (very) special:

- only SM fermions without charge
  → only weak interactions
  → unclear how to distinguish particle vs antiparticle (1st argument why Majorana)

- mass > 0 !
  only well-established non-SM effect

- most abundant massive particle in universe (we know of)

- 4 Nobel prizes so far

- cross section tiny
  of the 7×10^{10} $\nu/(s\ cm^2)$ from sun
  only O(100) interact in earth

(free) Dirac equation

Dirac equation for fermion: $\left(i\gamma^\mu\partial_\mu - m\right)\Psi = 0$

solution requires 4-dim since $\gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = g^{\mu\nu}$

$$i\partial_0\Psi = H\Psi = \left(-i\partial_k\gamma^0\gamma^k + m\gamma^0\right)\Psi, k=1..3 \quad using \left(\gamma^0\right)^2$$

$$with\ \Psi = u(p)e^{-ip\cdot x}$$

$$\left(\gamma^\mu p_\mu - m\right)\ u(p) = \begin{pmatrix} E-m & -\vec{\sigma}\vec{p} \\ \vec{\sigma}\vec{p} & -E-m \end{pmatrix}\ u(p) = 0$$

$$H = \begin{pmatrix} m & \vec{\sigma}\vec{p} \\ \vec{\sigma}\vec{p} & -m \end{pmatrix}$$

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helicity operator $\vec{\Sigma}\vec{p} = \frac{1}{2}\begin{pmatrix} \vec{\sigma}\vec{\hat{p}} & 0 \\ 0 & \vec{\sigma}\vec{\hat{p}} \end{pmatrix}$ $\quad \vec{\hat{p}}$ = unit vector

$[H, \vec{\Sigma}\vec{p}] = 0$ → helicity is conserved

→ 4 eigenvalues: E, -E (e.g. positron E>0), helicity ±½

in Dirac representation:

$$\gamma^0 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\gamma^1 = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & \sigma^1 \\ -\sigma^1 & 0 \end{pmatrix}$$

$$\gamma^2 = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ -i & 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & \sigma^2 \\ -\sigma^2 & 0 \end{pmatrix}$$

$$\gamma^3 = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & \sigma^3 \\ -\sigma^3 & 0 \end{pmatrix}$$

$$\sigma^i = Pauli\quad spin\quad matrices$$

helicity states

eigenvectors:

$$u^{(1.2)} = N \begin{pmatrix} \chi^{(1,2)} \\ \dfrac{\vec{\sigma}\vec{p}}{E+m}\chi^{(1,2)} \end{pmatrix} \quad \mathit{for}\ E>0\,, \quad \chi^{(1)} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \chi^{(2)} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$u^{(3,4)} = v^{(2,1)} = N \begin{pmatrix} \dfrac{-\vec{\sigma}\vec{p}}{|E|+m}\chi^{(1,2)} \\ \chi^{(1,2)} \end{pmatrix} \quad \mathit{for}\ E<0 \quad \text{(e.g. positron)}$$

$$u_{h=+1} = \vec{\Sigma}\vec{p}\,u^{(1)} = \frac{N}{2}\begin{pmatrix} \sigma^3 & 0 \\ 0 & \sigma^3 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \\ \dfrac{p}{E+m} \\ 0 \end{pmatrix} = \frac{N}{2}\begin{pmatrix} 1 \\ 0 \\ \dfrac{p}{E+m} \\ 0 \end{pmatrix} = \frac{1}{2}u^{(1)} \qquad \mathit{for}\ \vec{p} = p\,\vec{e}_3$$

$$u_{h=-1} = \vec{\Sigma}\vec{p}\,u^{(2)} = -\frac{1}{2}u^{(2)}$$

weak interaction

$$\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$\bar{u}\gamma^\mu u$ vector current (eg. electro-magn. interaction) odd under parity P

$\bar{u}\gamma^5\gamma^\mu u$ axial-vector current space components: even under parity P

weak interaction violate P maximal → V-A current $\frac{1}{2}(1-\gamma^5)$

for relativistic particle E>m $\quad \frac{p}{E+m} = \frac{\sqrt{E^2-m^2}}{E+m} = \sqrt{\frac{E-m}{E+m}} \approx 1 - \frac{m}{E}$

$$\frac{1}{2}(1-\gamma^5)u^{(1)} = \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \frac{N}{2} \begin{pmatrix} 1 \\ 0 \\ \frac{p}{E+m} \\ 0 \end{pmatrix} = \frac{N}{2} \begin{pmatrix} 1-\frac{p}{E+m} \\ 0 \\ -1+\frac{p}{E+m} \\ 0 \end{pmatrix} \approx \frac{m}{E} u_{h=1}$$

$$\frac{1}{2}(1-\gamma^5)u^{(2)} \approx u_{h=-1}$$

weak interaction (II)

$$\frac{1}{2}\left(1-\gamma^5\right)\left(u^{(1)}+u^{(2)}\right)\approx u_{h=-1}+\frac{m}{E}u_{h=1}=u_{LH}$$ left-handed fermion

$$\frac{1}{2}\left(1-\gamma^5\right)\left(v^{(1)}+v^{(2)}\right)\approx v_{h=1}+\frac{m}{E}v_{h=-1}=v_{RH}$$ right-handed anti-fermion

weak interaction (W,Z bosons) couple to LH fermions and RH anti-fermions

in relativistic case E>>m LH has h=-1, RH has h=+1

neutrinos are produced in sun, reactor, supernova, big bang, ... at >MeV energy
mass ~ 10 meV scale → neutrinos are produced h=-1

neutrinos with h=+1 (RH neutrinos) and
anti-neutrinos with h=-1 are not produced
effectively, do no not exist (coupling to Higgs is tiny)

→ only 2 of the 4 (Dirac) states occur in nature??

2nd argument why Majorana

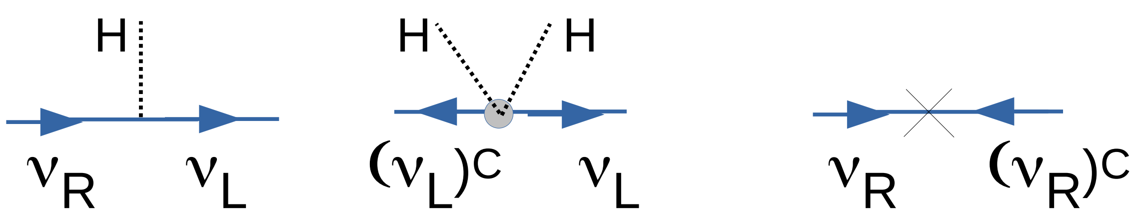
dim 5 operator

operators of SM have dim=4, dim [fermion] = 3/2, dim [boson] = 1
→ coupling = 2 fermions + 1 gauge boson or Higgs (or 4 gauge bosons or ..)

extensions of SM: higher dim operators $\frac{dim\,5}{\Lambda}, \frac{dim\,6}{\Lambda^2}, \ldots$ Λ = energy of new physics, non-renormalizable

$$\mathcal{L}_{\rm Majorana} = -\frac{y_{ij}^{\rm Maj}}{\Lambda}\bar{L}_{Li}^{c}\tilde{\Phi}^{*}\tilde{\Phi}^{\dagger}L_{Lj}\,,$$

ΔL=2
spontaneous sym. breaking → mass



ΔL=0
dim 4

ΔL=2
dim 5

ΔL=2
dim 5

$$L_{Yuk} = m_D\,\bar{\nu}_L\,\nu_R + m_L\,\bar{\nu}_L\,(\nu_L)^C + m_R\,(\bar{\nu}_R)^C\,\nu_R + h.c.$$

dim 5 operator (II)

$$L \sim \begin{pmatrix} \bar{\nu}_L & (\bar{\nu}_R)^C \end{pmatrix} \begin{pmatrix} m_L \sim 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L^C \\ \nu_R \end{pmatrix}$$

eigen vector N $\sim$ $\nu_R + (\nu_R)^C$ $\nu \sim \nu_L + (\nu_L)^C$ Majorana particles

mass ($m_L \sim 0$) m_R m_D^2 / m_R

m_R large $\rightarrow$ m_D^2 / m_R small = see-saw mechanism to explain tiny ν mass

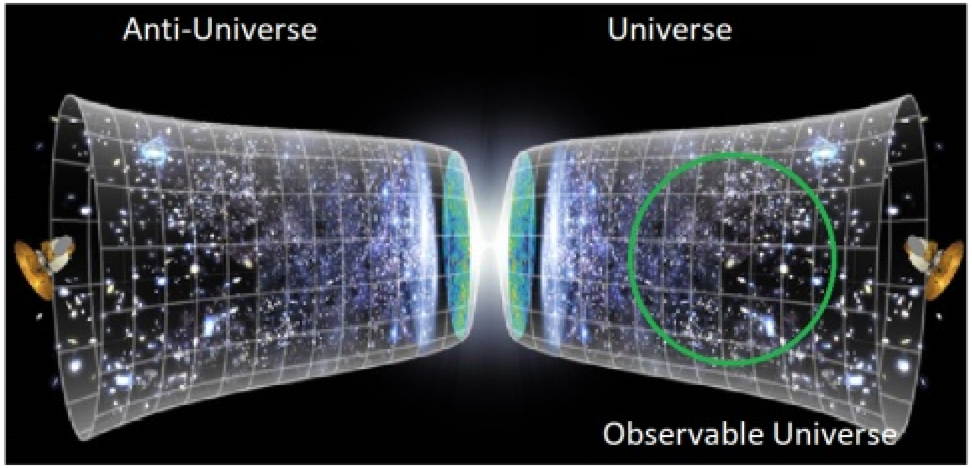
3rd argument for Majorana

"most" extensions of SM predict Majorana neutrinos

4th argument for Majorana

Sakharov conditions

imbalance between matter and
anti-matter in our universe needs:
- C and CP violation
- baryon number B violation
- interaction out of thermal equilibrium



in SM: B is ‘accidentally’ conserved (no global symmetry),
expect also lepton number L violation
CP violation of SM is too small
→ need extension of SM to explain matter asymmetry

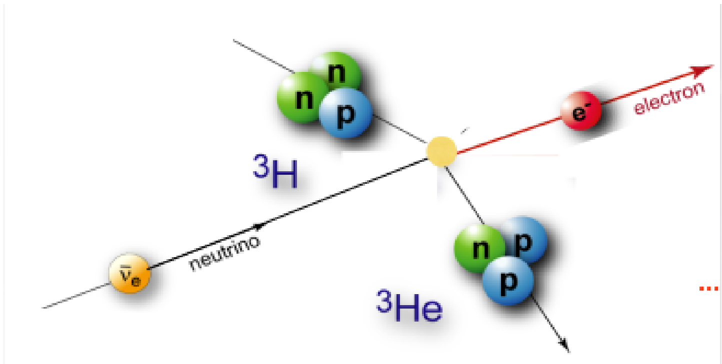
see-saw: lepton asymmetry at high energies, decay of heavy RH neutrinos,
conversion of L asymmetry to B asymmetry via sphaleron
“lepto-genesis”

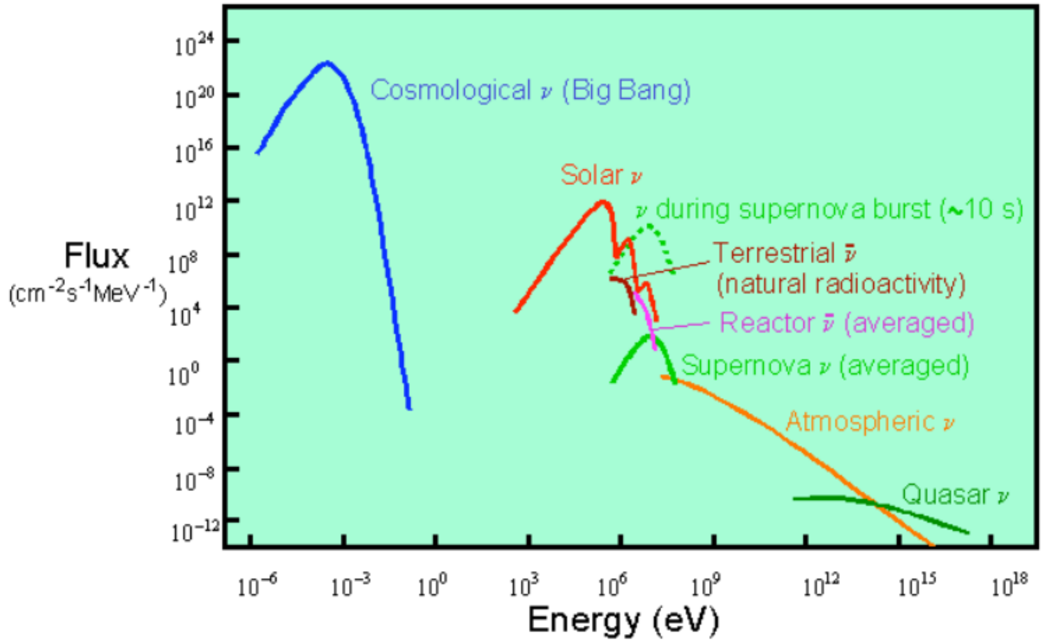
5^{th} argument for Majorana

Primoridal neutrinos

produced at high E → pure h=-1
today $k_B T_\nu$ = 168 μeV → p << m

proposed detection $\nu_e + n \to p + e$





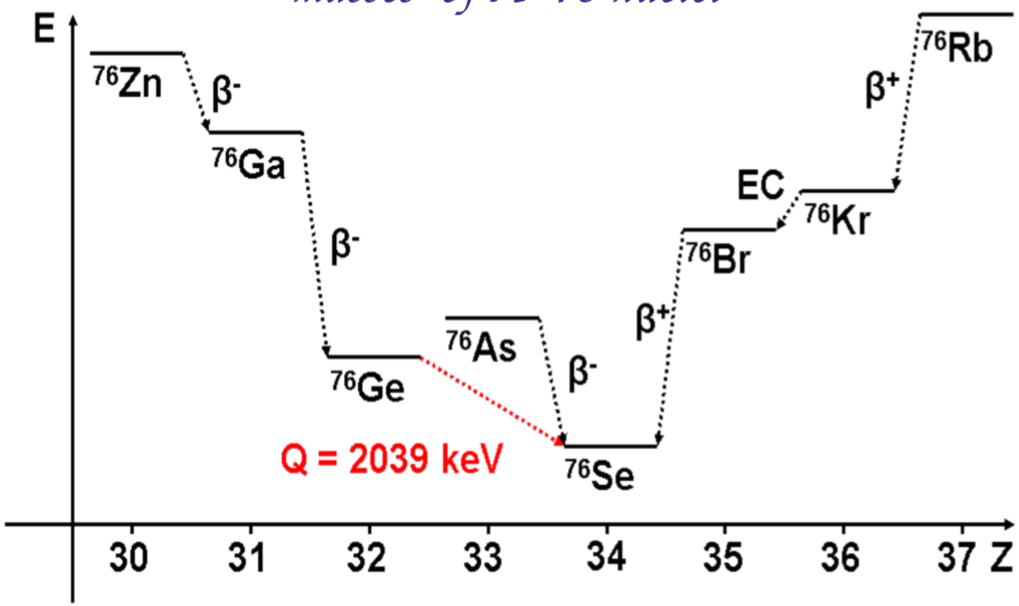
Flux on earth of neutrinos from various sources, in function of energy

non-relativistic → cross section 'same' for h=+1 & h=-1 neutrinos
if ν is Dirac: 50% of 'neutrinos' are anti-neutrinos (h=+1) → no reaction
if ν is Majorana: also the h=+1 ν will react

→ PTOLEMY will see 2x events if ν is Majorana particle
difficult experiment, very far away

Double beta decay

masses of A=76 nuclei



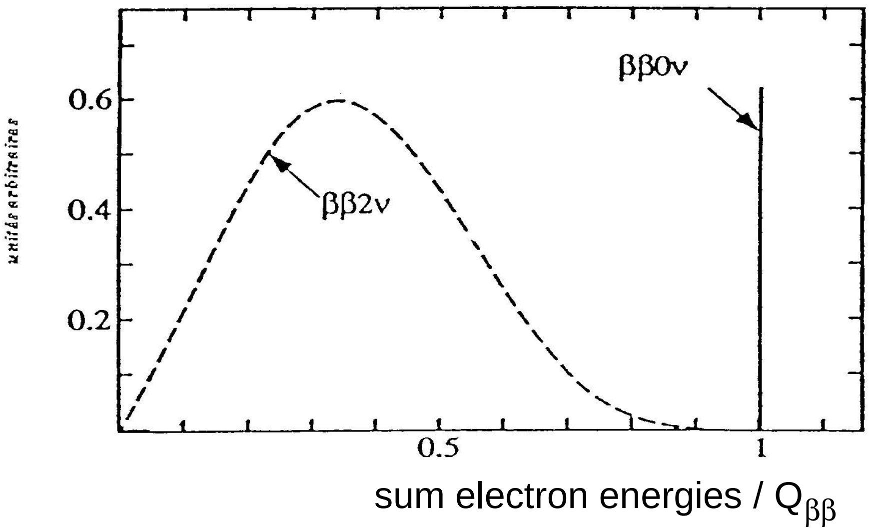
"single" beta decay not allowed

→ only "double beta decay"

$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}$ $\quad \Delta L=0$

$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ $\quad \Delta L=2$

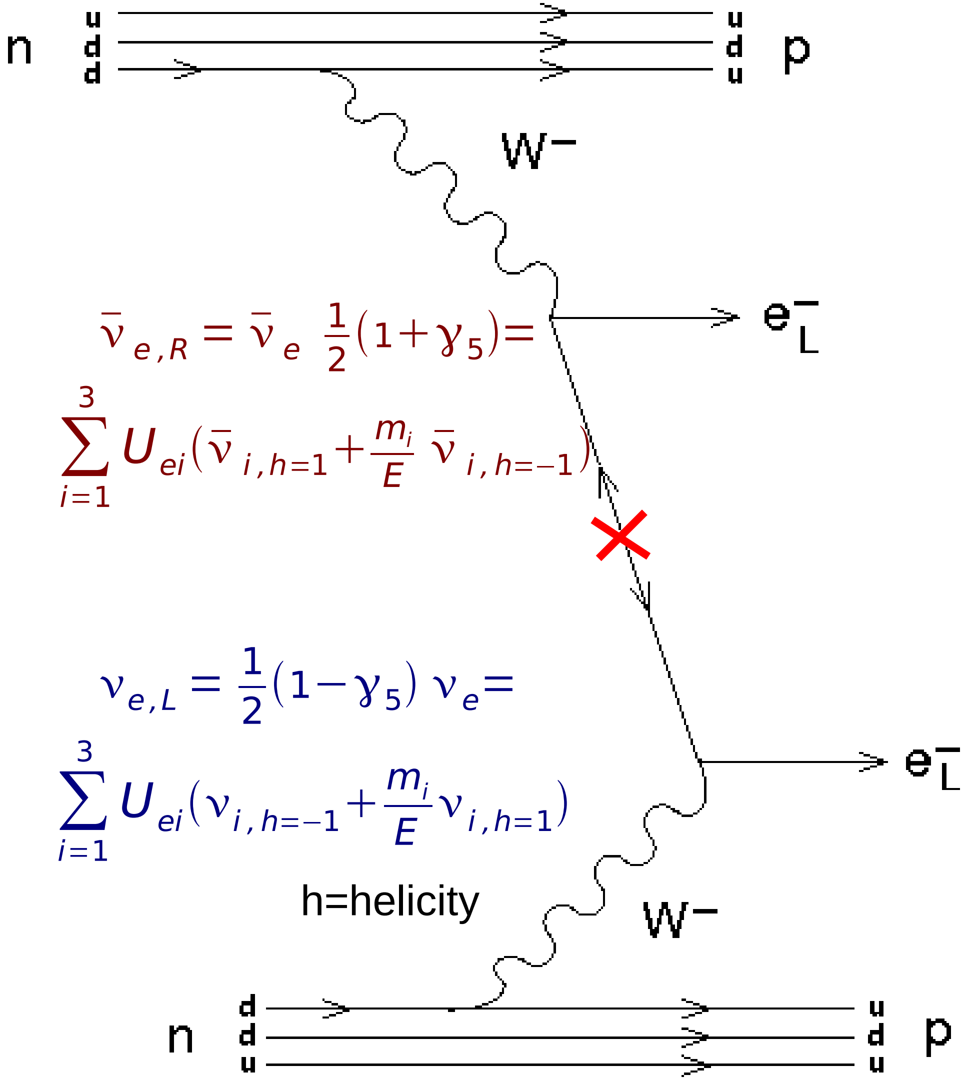
experimental signature for double beta decay



search for a line at Q value of decay → good energy resolution

How to observe Majorana ν?

Look for a process which can only occur if neutrino is Majorana particle



$$\bar{\nu}_{e,R} = \bar{\nu}_e \, \frac{1}{2}(1+\gamma_5) = \sum_{i=1}^{3} U_{ei}\left(\bar{\nu}_{i,h=1} + \frac{m_i}{E}\,\bar{\nu}_{i,h=-1}\right)$$

$$\nu_{e,L} = \frac{1}{2}(1-\gamma_5)\,\nu_e = \sum_{i=1}^{3} U_{ei}\left(\nu_{i,h=-1} + \frac{m_i}{E}\nu_{i,h=1}\right)$$

h=helicity

coupling strength ~ $m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_i$

function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

→ coupling strength ~ $\sum_{i=1}^{3} V_{ei}^2 / M_i$

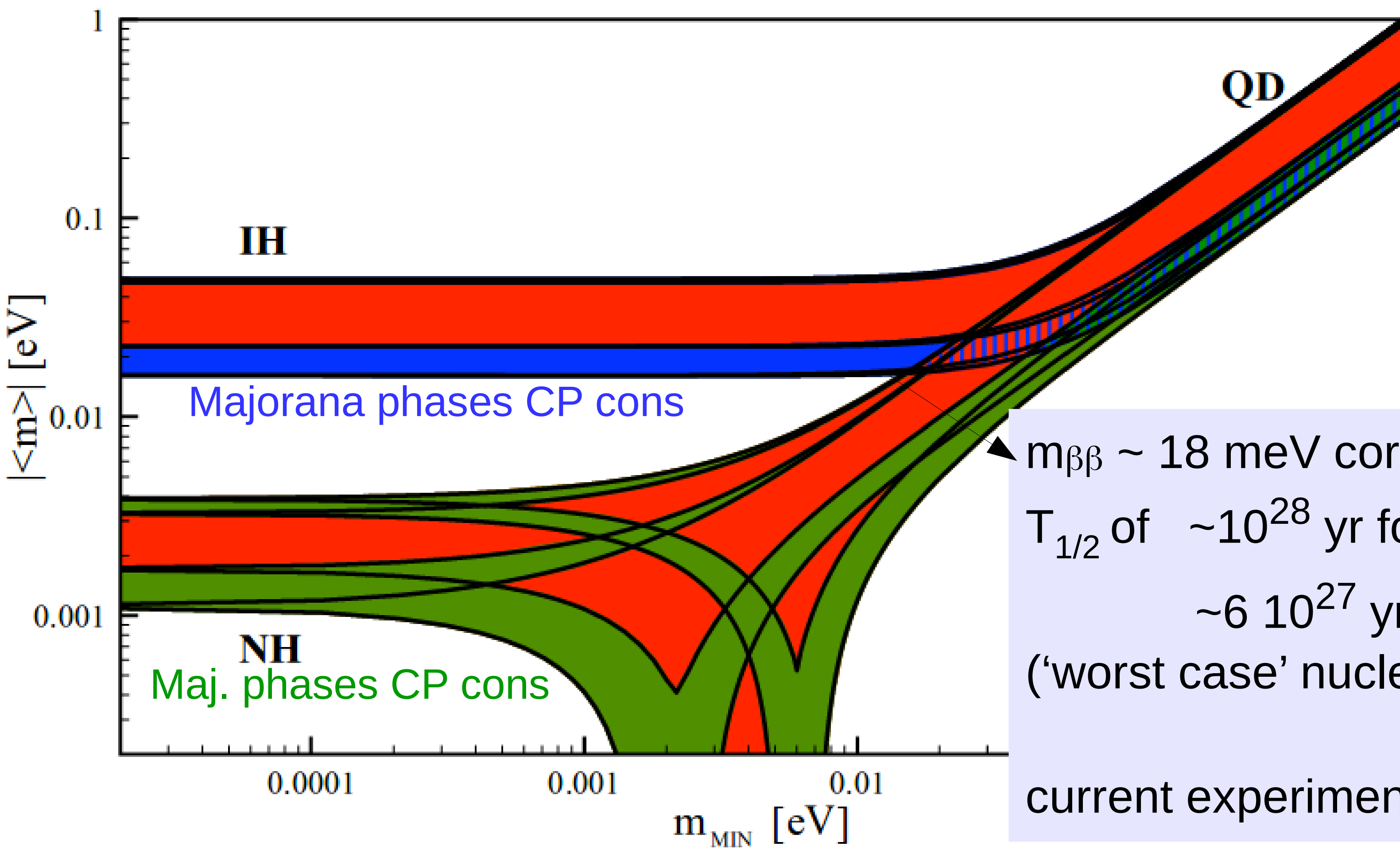
strength ~ $(m/E)^2$ ~ $(10\text{ meV}/1\text{ MeV})^2$ ~ 10^{-16}

$N_A = 6\ 10^{23}$ helps to compensate helicity suppression

Expected Majorana mass range

scan of $m_{\beta\beta}$ (Δm_{atm}^2, Δm_{sol}^2, m_{min}, θ_{atm}, θ_{sol}, θ_{13}, 2 Majorana phases)

according to measurements (2 σ range) or random (2 Maj. phases)



$m_{\beta\beta}$ ~ 18 meV correspond to

$T_{1/2}$ of ~10^{28} yr for ^{76}Ge

~6 10^{27} yr for ^{136}Xe

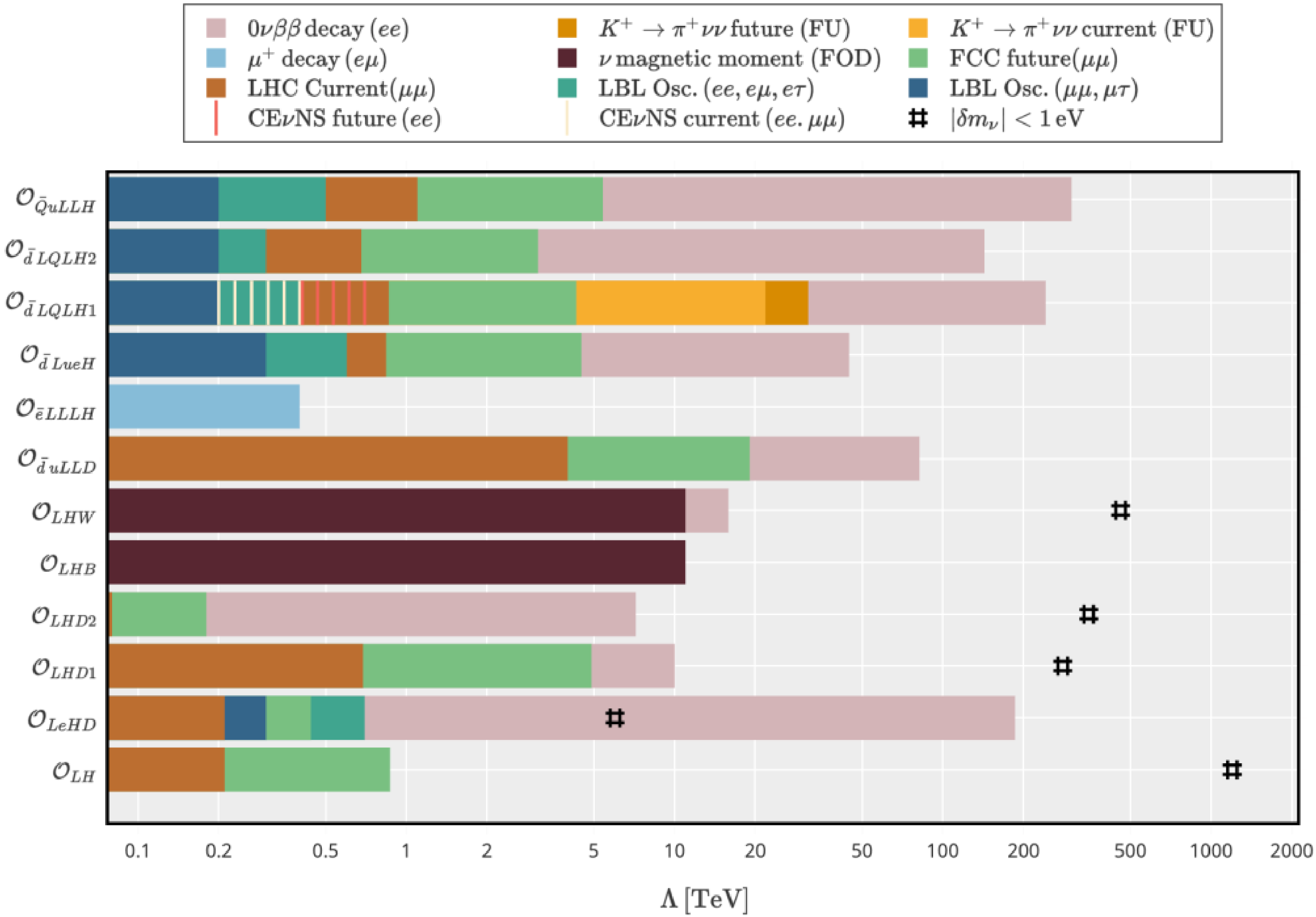
('worst case' nuclear matrix element)

current experiments 10^{25} - 10^{26} yr

PDG 2016

Higher dim operators

L violating dim=7 operators: limit for scale Λ of new physics for several discovery channels



arXiv:2306.08709

$0\nu\beta\beta$ most sensitive except for 2 operators

From $T_{1/2}$ to $m_{\beta\beta}$

$$\frac{1}{T^{0\nu}_{1/2}} = g_A^4 G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$T^{0\nu}_{1/2}$ = measured experimentally

g_A = axial vector coupl. (= 1.27)

$G^{0\nu}$ = phase space factor ~ Q^5

$M^{0\nu}$ = nuclear matrix element

m_e = electron mass

selected $0\nu\beta\beta$ isotopes from PRD 83 (2011) 113010

Isotope	$G^{0\nu}$ [10^{-14}y]	Q[keV]	nat. abund.[%]
^{48}Ca	2.5	4273.7	0.187
^{76}Ge	0.23	2039.1	7.8
^{82}Se	1.0	2995.5	9.2
^{100}Mo	1.6	3035.0	9.6
^{130}Te	1.4	2530.3	34.5
^{136}Xe	1.5	2461.9	8.9
^{150}Nd	6.6	3367.3	5.6

enrichment required (except ^{130}Te), cost differs

need $M^{0\nu}$ to understand physics mechanism

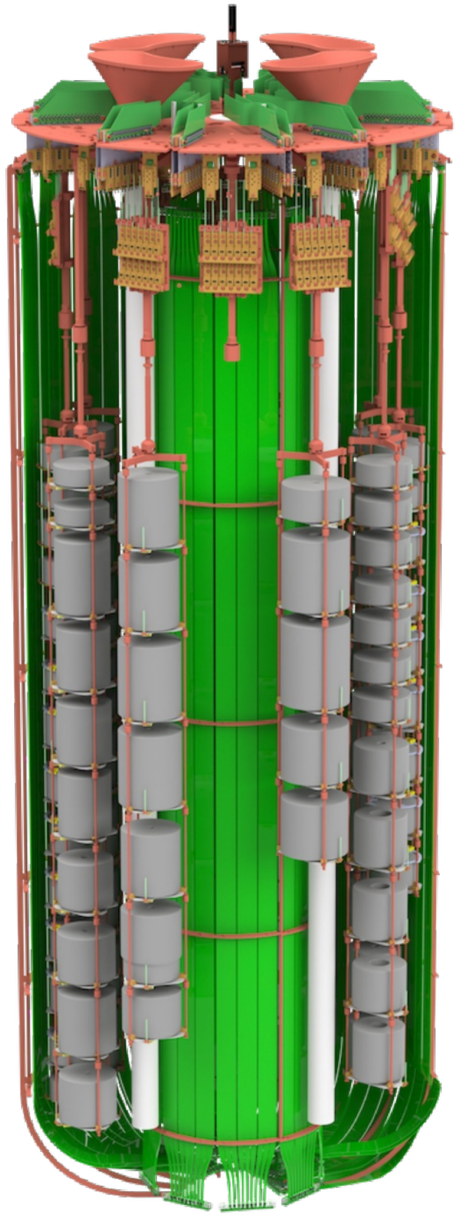
Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

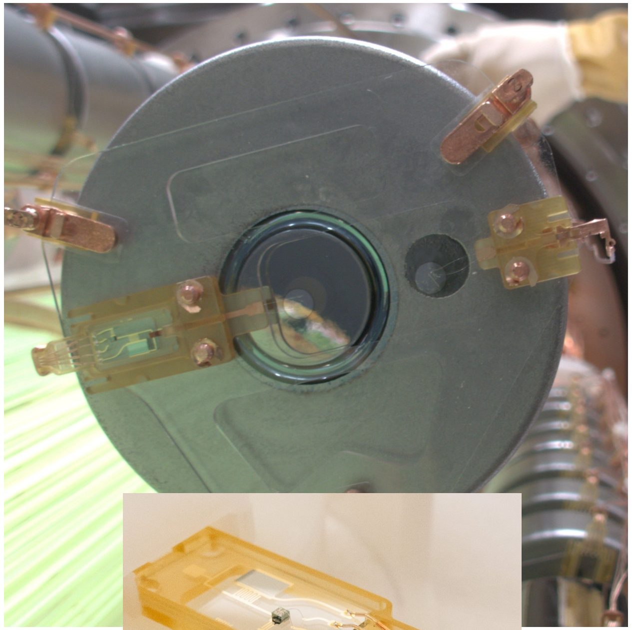
M = mass of detector
t = measurement time
A = isotope mass per mole
N_A = Avogadro constant
a = fraction of $0\nu\beta\beta$ isotope
ε = detection efficiency
B = background index in units cnt/(keV kg y)
ΔE = energy resolution = energy window size

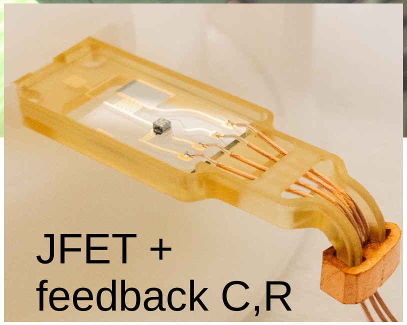
Experimental sensitivity

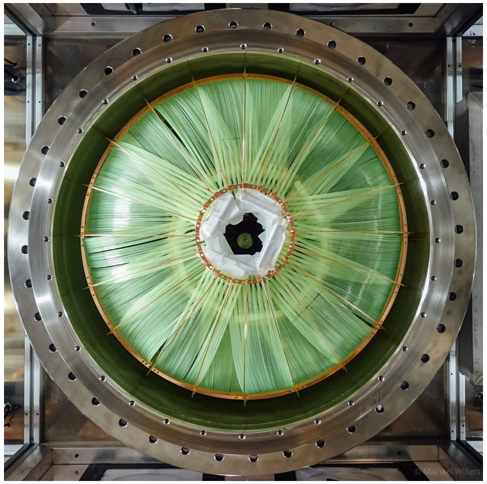
$$T_{1/2}(90\%\,CL) > \begin{cases} \frac{\ln 2}{2.3} \frac{N_A}{A} a \cdot \epsilon \cdot M \cdot t & \text{for } N^{bkg} = 0 \\ \frac{\ln 2}{1.64} \frac{N_A}{A} a \cdot \epsilon \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

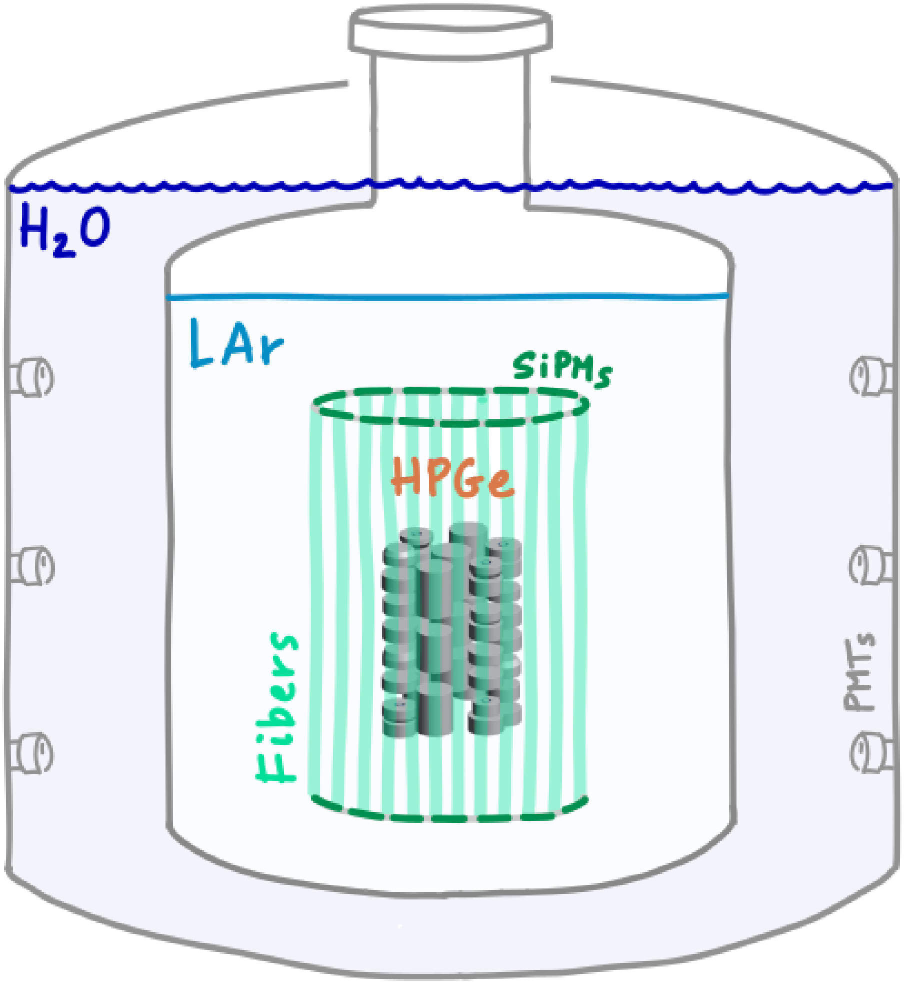
LEGEND@LNGS: search for $0\nu\beta\beta$ of ^{76}Ge





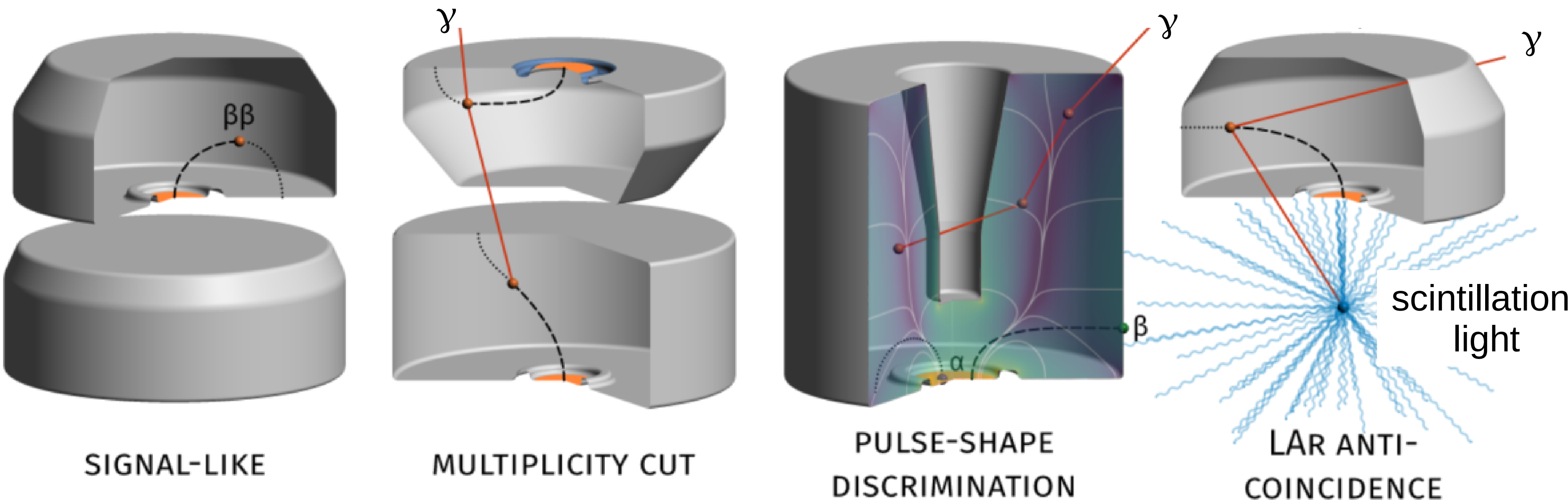


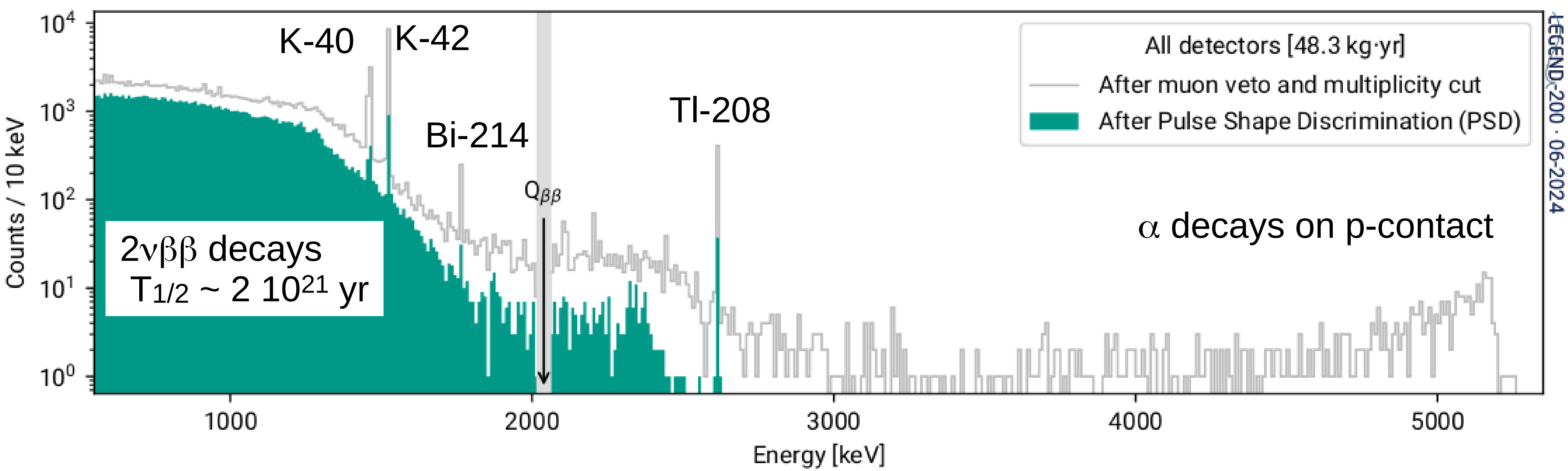




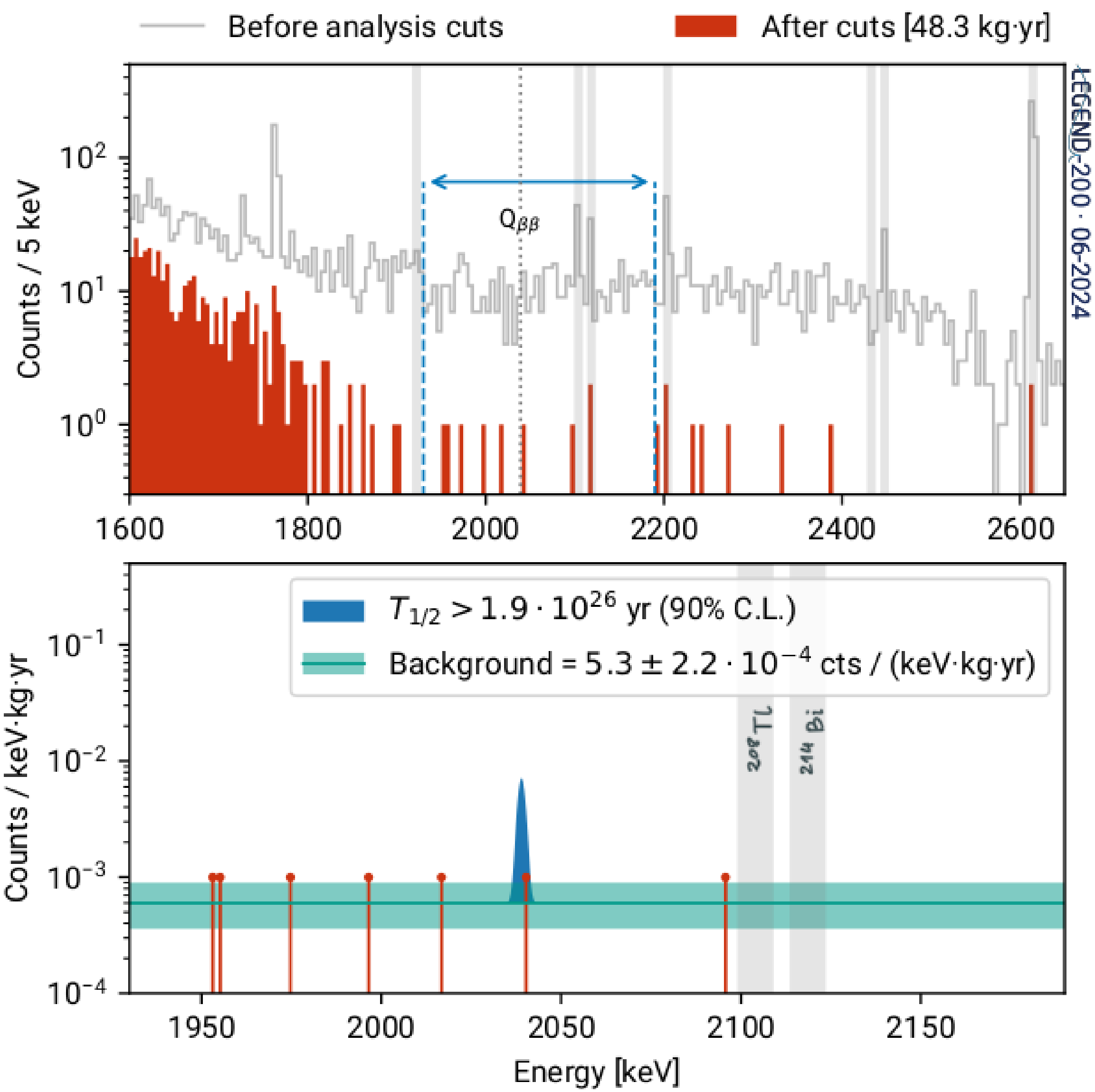
^{76}Ge enriched from 8% to ~90%
LEGEND-200: taking data since 2023,
up to 200 kg of Ge (now 140 kg)
LEGEND-1000: in planning

Background rejection in LEGEND





First LEGEND-200 result: next Tuesday



blind analysis:

events close to $Q_{\beta\beta}$ are hidden
fix all procedures & cuts
open the box and apply analysis
(happened last Friday, results next Tuesday @ Neutrino)

Background $(6\pm2.5)\times10^{-3}$ cnt/(keV kg yr)

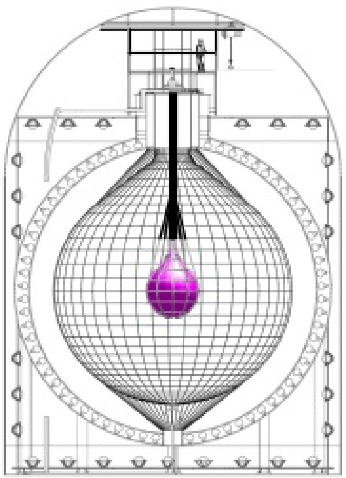
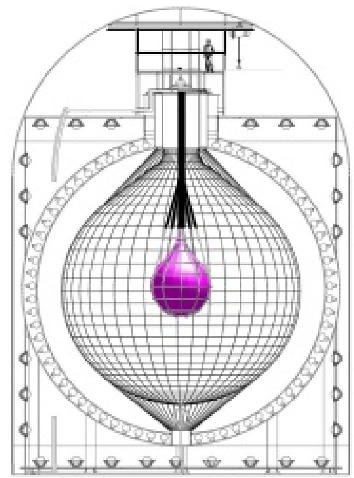
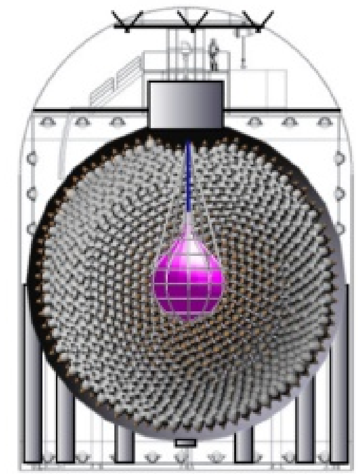
same as for GERDA
3x our goal → investigating origin

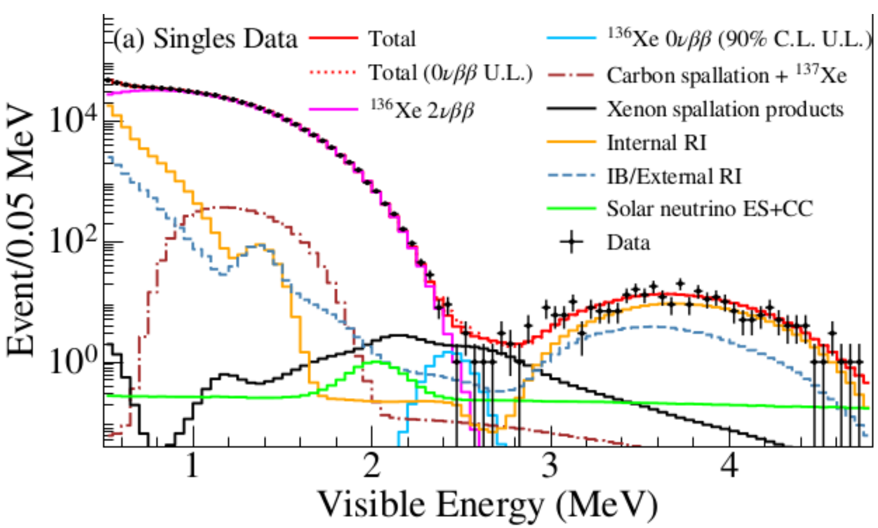
Sensitivity for 90% C.L. $T_{1/2}$ limit combined w. GERDA + Majorana Dem. 2.8×10^{26} yr

limit 1.9×10^{26} yr

Kamland-Zen-800: Xe-136 in scint.

Past	Present	Future
KamLAND-Zen 400	**KamLAND-Zen 800**	**KamLAND2-Zen**
320-380 kg of Xenon	~750 kg of Xenon	~1 ton of Xe
Data taking in 2011 - 2015	DAQ started in 2019	Better energy resolution

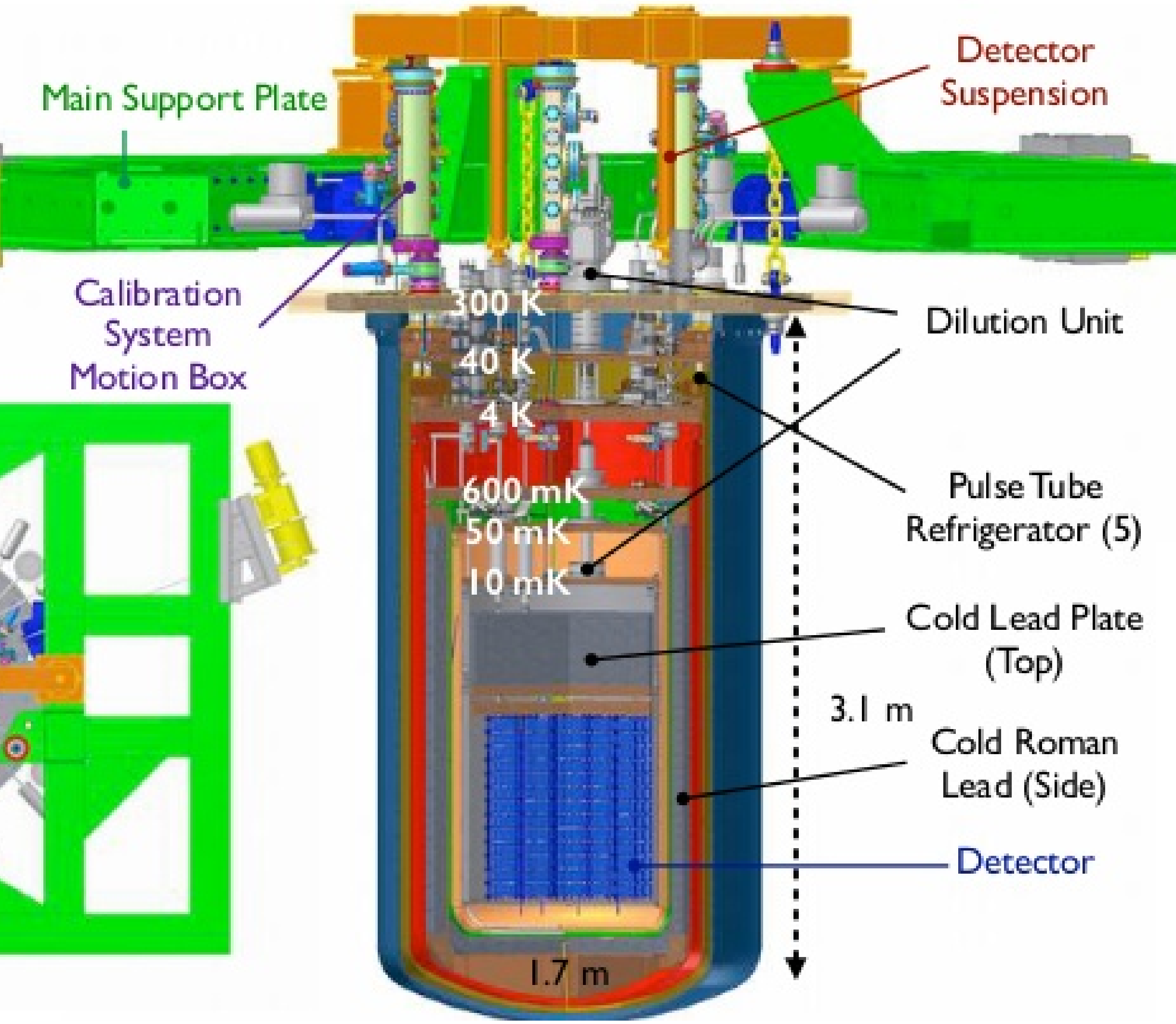


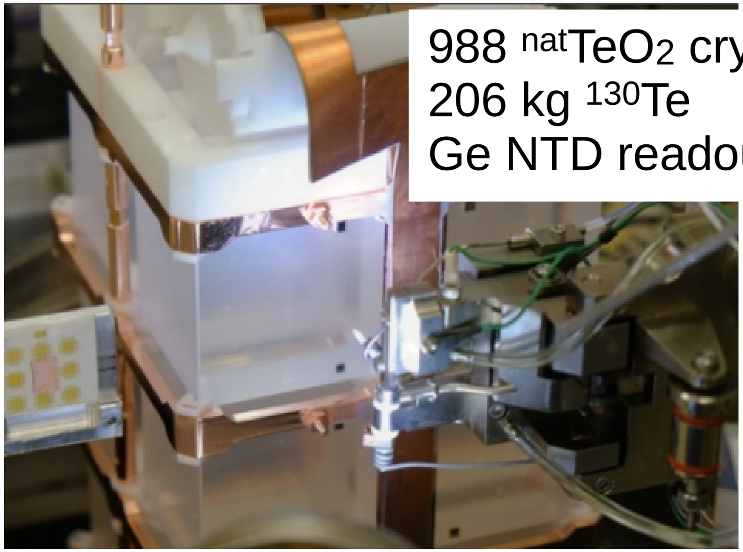
1000 t liquid scintillator,
6.5 m Ø inner balloon (25 μm thick)
with 3% Xe doping (91% ^{136}Xe)

energy resolution FWHM ~10% at $Q_{\beta\beta}$ (Ge 0.15%)

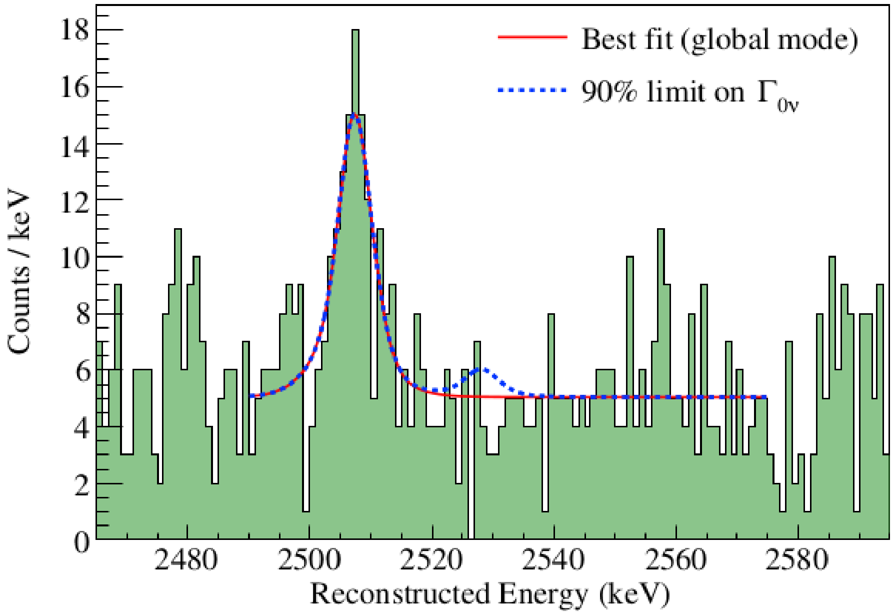
$T_{1/2}$ > 2.3 10^{26} yr (90% C.L.) PRL 130, 051801
best current limit

CUORE: TeO_2 bolometer





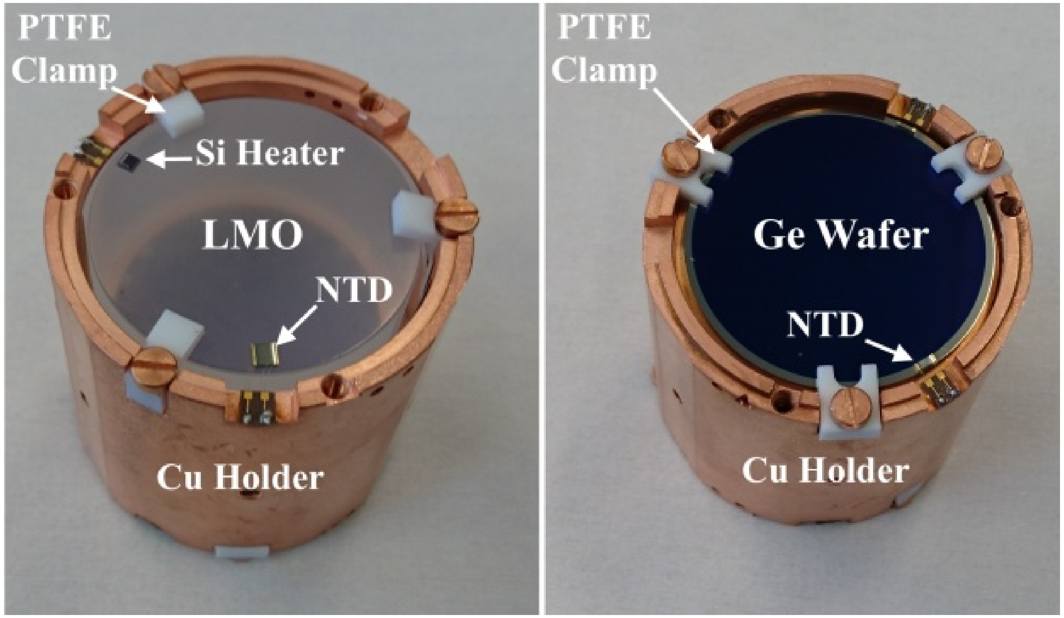
988 $^{nat}TeO_2$ crystals
206 kg ^{130}Te
Ge NTD readout



PRL 124, 122501(2020)

data taking since 2017
FWHM ~0.28% at $Q_{\beta\beta}$ bkg ~ 0.01 cnt/(keV kg yr)
$T_{1/2}$ > 3.2 10^{25} yr (90% C.I.)

CUPID: scintil. bolometer in CUORE cryost.

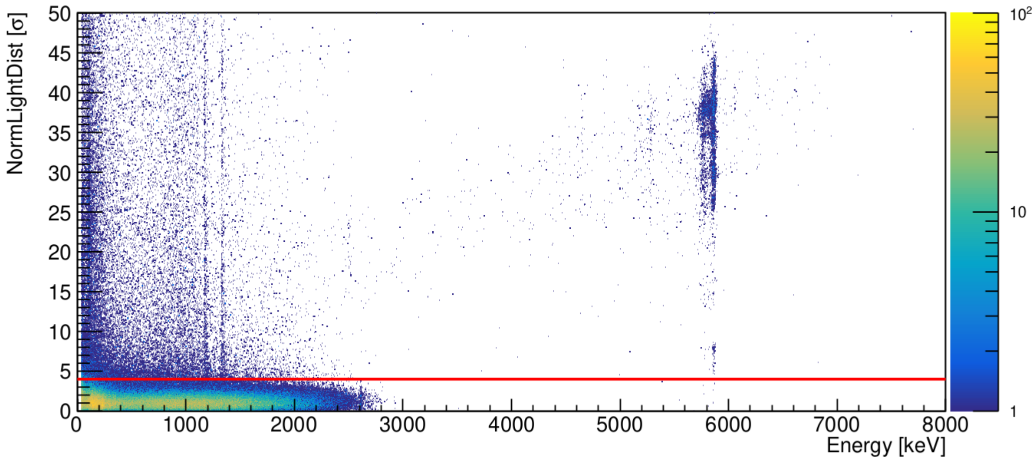


1534 Li_2MoO_4 crystals with
Ge wafer as light detectors

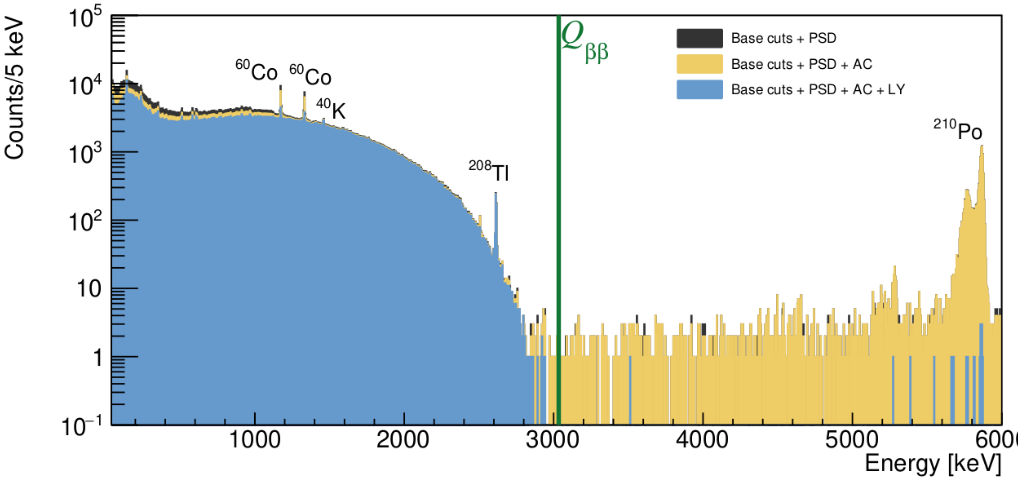
253 kg ^{100}Mo (472 kg crystals)
background 10^{-4} cnt/(keV kg yr)
FWHM ~ 0.2% at $Q_{\beta\beta}$

sensitivity $T_{1/2}$ ~ 1.5 10^{27} yr (limit)
1.1 10^{27} yr (discov)

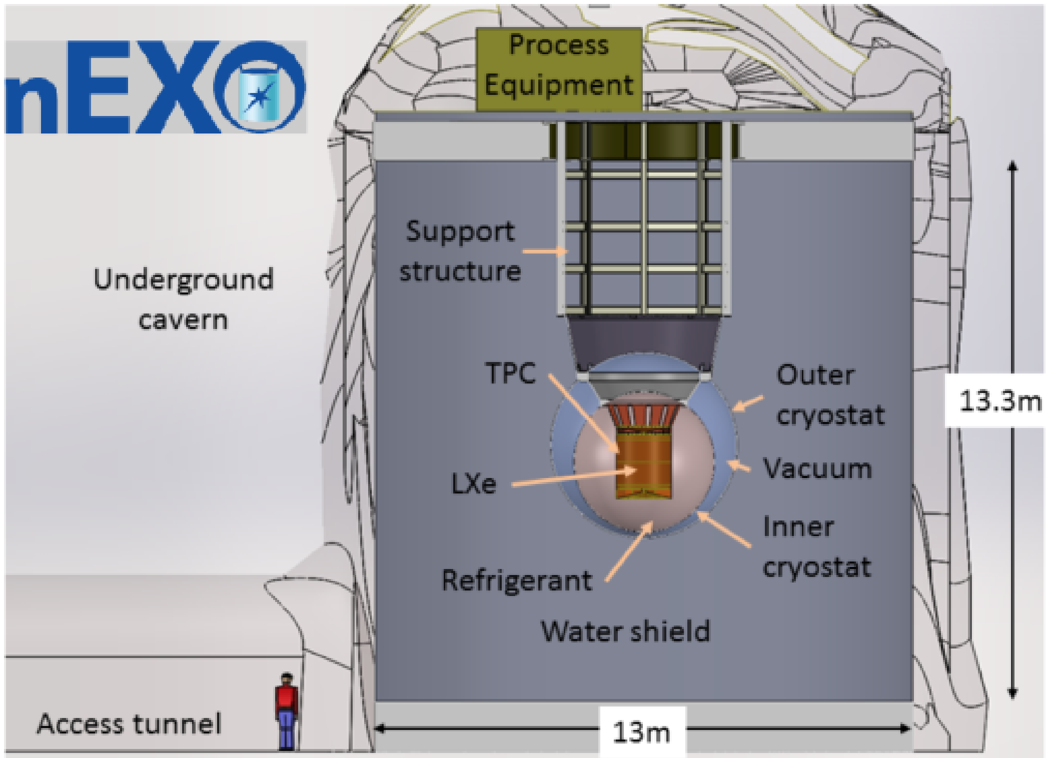
background suppression by light readout

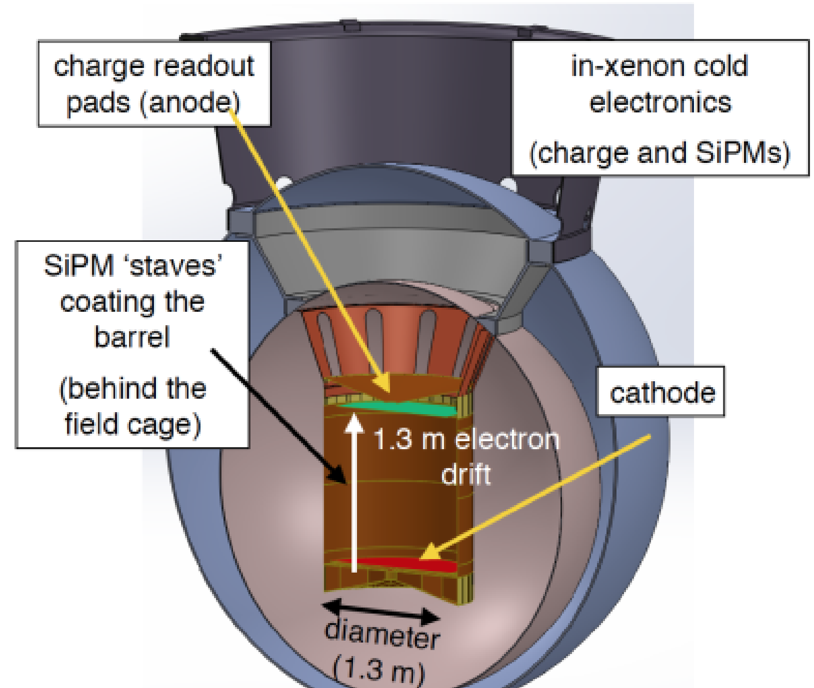


spectrum in Edelweiss cryostat: 4 kg, 3 kg yr exp

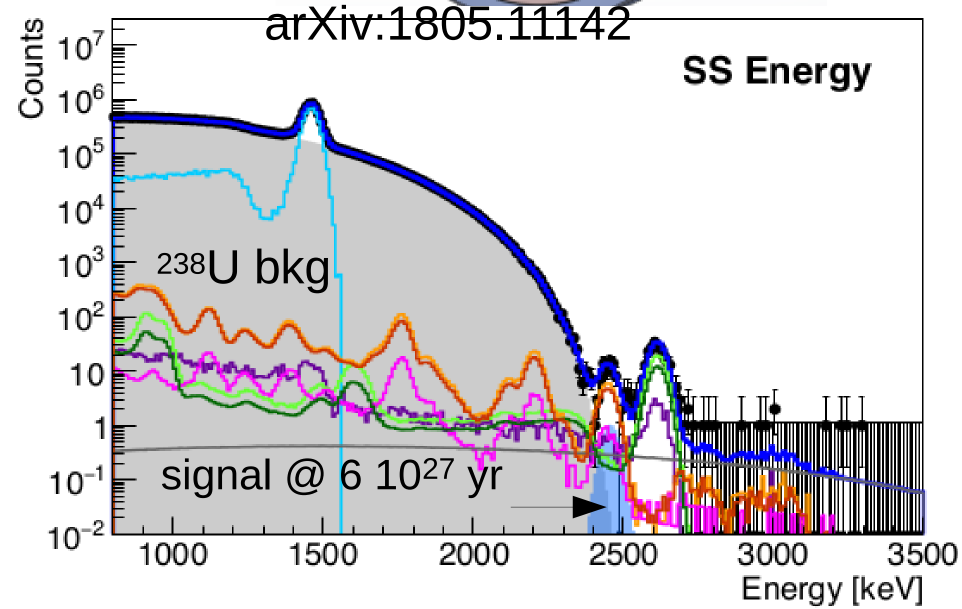


nEXO: liquid Xe TPC





arXiv:1805.11142



5100 kg of Xe (90% ^{136}Xe)

FWHM ~2.3% at $Q_{\beta\beta}$

bkg inner 1000 kg   1.4 10^{-4} cnt/(FWHM kg yr)

(L1000: 2.5 10^{-5} cnt/(FWHM kg yr)

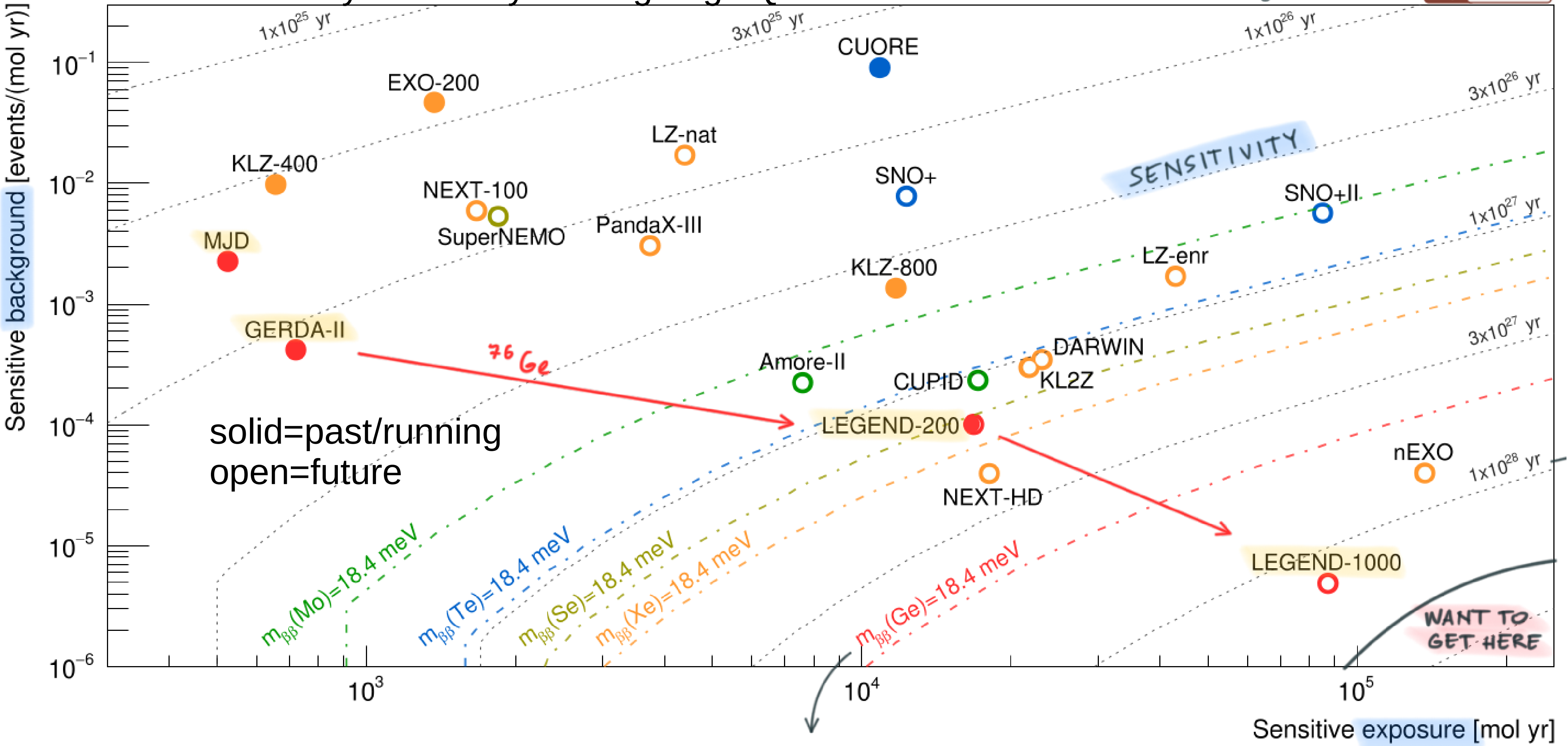
bkg inner 2000 kg   3.6 10^{-4} cnt/(FWHM kg yr)

$T_{1/2}$ sensitivity (discovery) ~6 10^{27} yr

Future experiments - overview

discovery sensitivity = using large QRPA nuclear matrix element

Agostini *et al.* 2022 arXiv 2202.01787



Ge detectors have best energy resolution (& lowest bkg) → easy identification of a peak

Summary

>5 good reasons why we should assume neutrinos are Majorana particles

most sensitive test is search for $0\nu\beta\beta$ decay

when $0\nu\beta\beta$ is found $\rightarrow$ strong impact on particle physics and cosmology

LNGS is front-runner with LEGEND and CUORE/CUPID

"After all, the idea of Majorana fermions is so elegant and attractive that Nature just could not have missed the opportunity to create them." Evgeny Akmedov (arXiv:1412.3320v1)