Double beta decay: an experimental overview

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Invisibles Workshop
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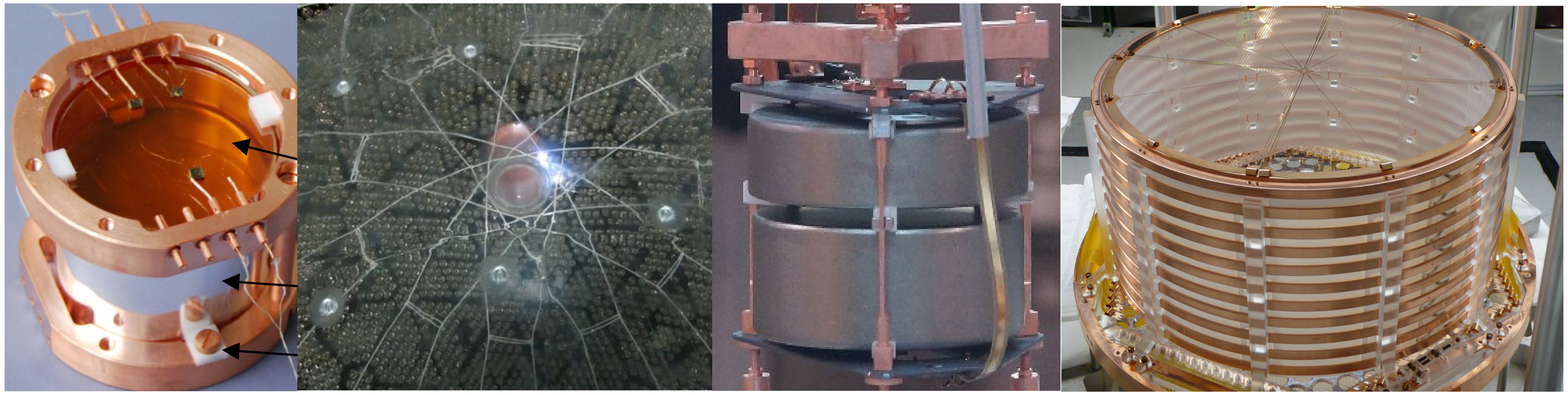
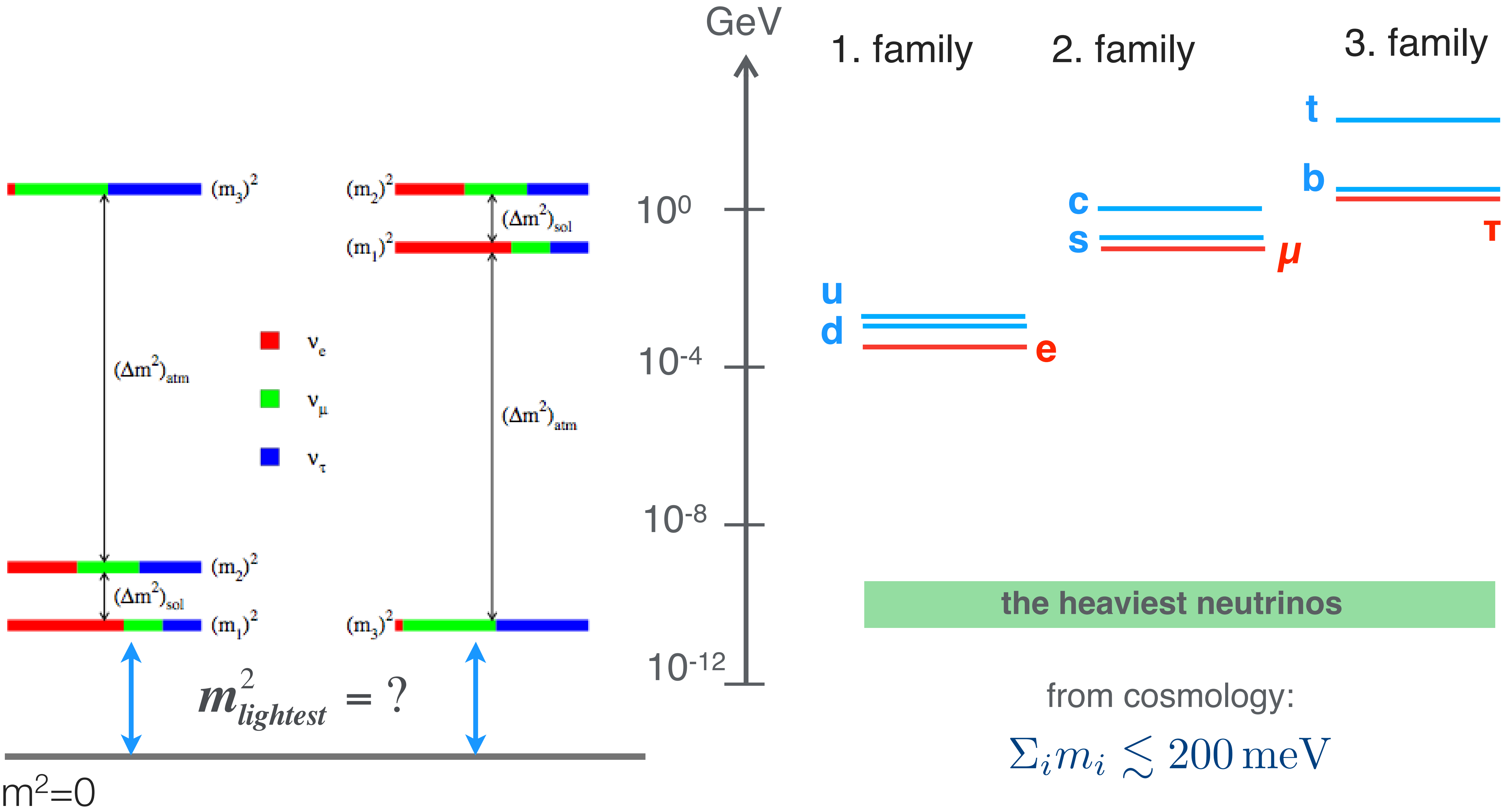


Some open questions in neutrino physics

- What is the nature of neutrinos: Dirac or Majorana particles?
- What are their masses: absolute scale and ordering?

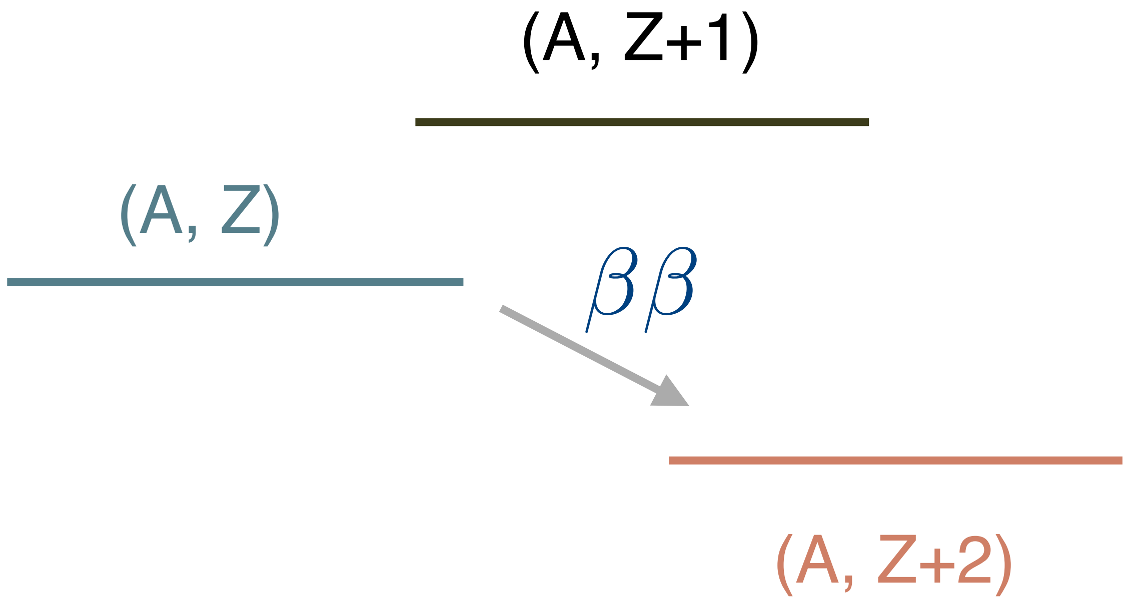


from cosmology:

$$\Sigma_i m_i \lesssim 200\,\mathrm{meV}$$

Double beta decay

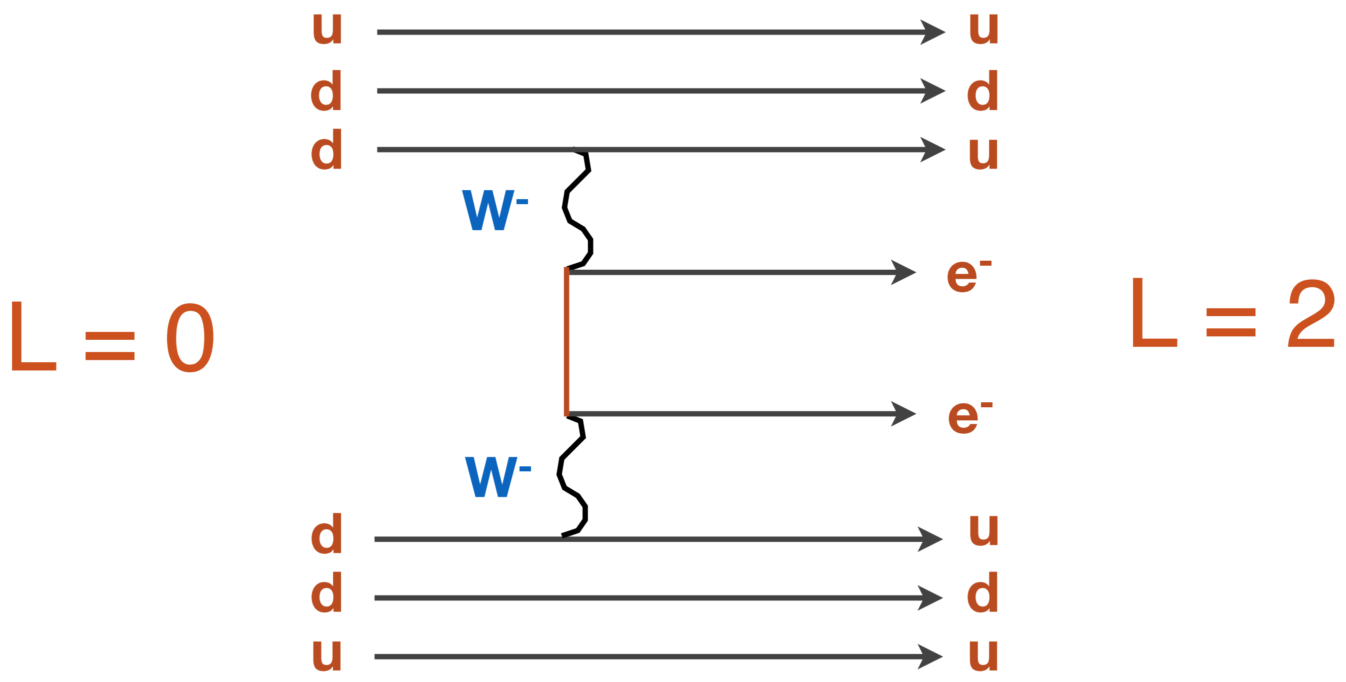
- A second-order process that can only be detected if first order beta decay is energetically forbidden
- Proposed in 1935 by Maria Goeppert-Mayer
- Observed in 11 nuclei, $T_{1/2} > 10^{18}$ y; ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U



Neutrinoless double beta decay

- Extremely rare process, $T_{1/2} > 10^{22}$ y
- Proposed in 1937 by Ettore Majorana; not yet observed
- Requires massive Majorana neutrinos & lepton number violation*

In an atomic nucleus:



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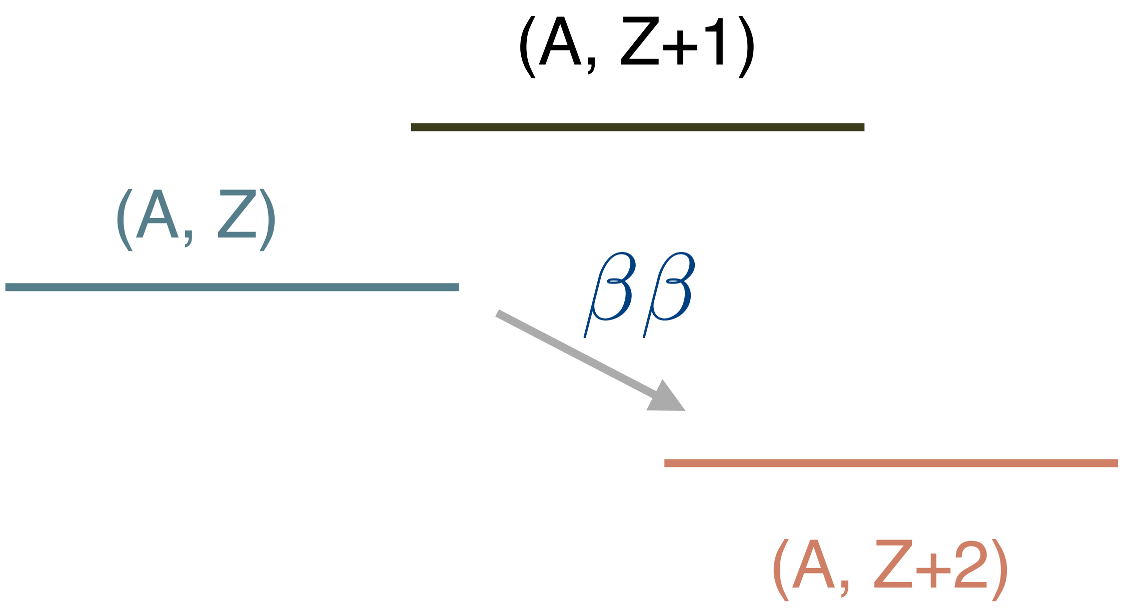
* In the simplest interpretation -> light neutrinos and SM interactions
* New mechanism with heavy particles in general subdominant because of smaller NME

Which nuclei can decay via $0\nu\beta\beta$?

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

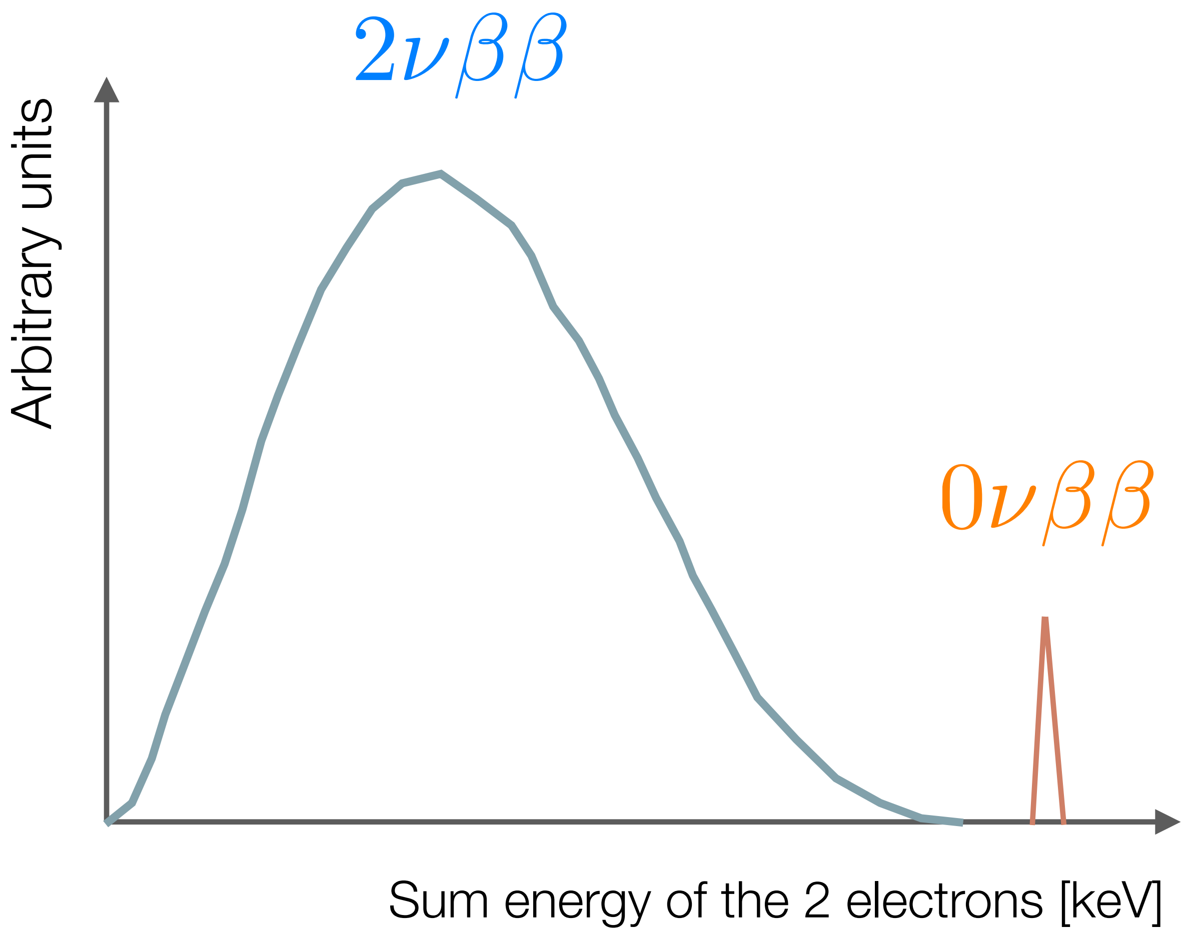


Candidate*	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	2.040	7.8
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	34.5
^{136}Xe -> ^{136}Ba	2.479	8.9
^{150}Nd -> ^{150}Sm	3.367	5.6

* Q-value > 2 MeV

How do we look for the decay?

- Observe the 2 final-state electrons
- Expect a sharp "peak" at the Q-value of the decay
- Excellent energy resolution is essential for a discovery experiment



$$Q = E_{\mathrm{e}1} + E_{\mathrm{e}2} - 2m_{\mathrm{e}}$$

What is the observable decay rate?

Phase space factor

Axial-vector cc

NME

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|m\beta\beta|^2}{m_e^2}$$

Can be calculated: ~ Q^5

Difficult: factor 2-3

- with the **effective Majorana neutrino mass:**

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

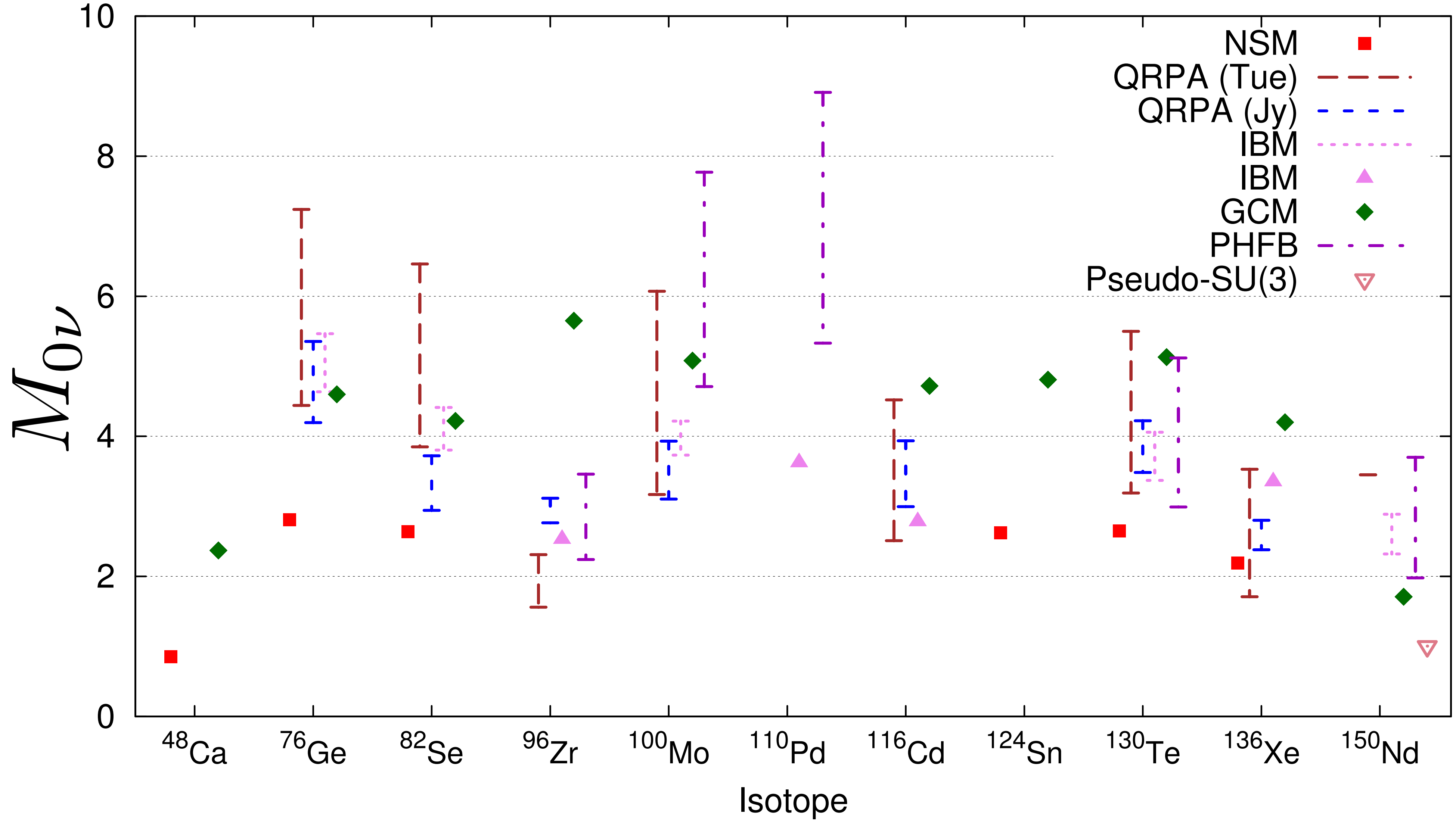
➡ a coherent sum over mass eigenstates with potentially CP violating phases

➡ = a mixture of m_1, m_2, m_3, proportional to the U_{ei}^2, with α_1,α_2 = Majorana CPV phases

- U_{ei} = matrix elements of the PMNS-Matrix, m_i = eigenvalues of the neutrino mass matrix

Matrix elements for $0\nu\beta\beta$

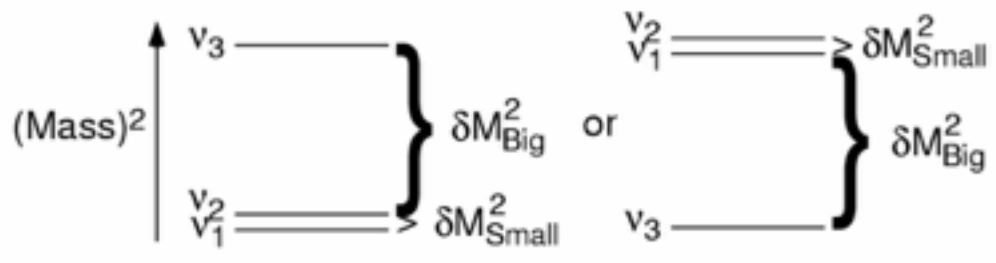
- Past years: improved agreement among the various methods
- Still spread by a factor 2-3 => **uncertainty of ~ 4 - 10 in $T_{1/2}$**



A. Dueck, W. Rodejohann and K.Zuber, Phys.Rev. D83 (2011) 113010

Effective Majorana neutrino mass

normal

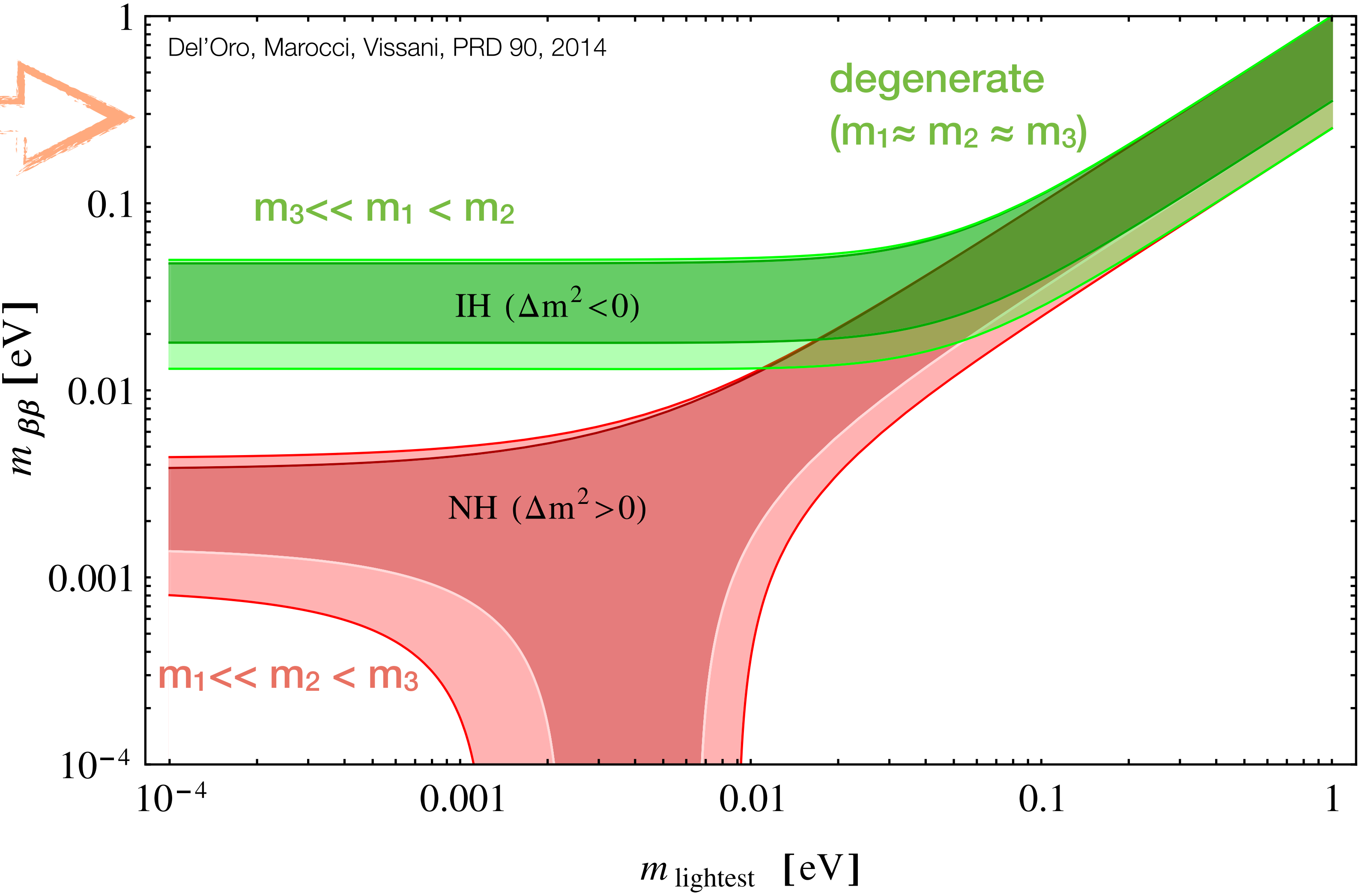


inverted

current sensitivities

$T_{1/2} \sim 10^{27}$ yr

$T_{1/2} \sim 10^{29}$ yr



0.1- 1 counts/(y kg)

0.5 - 5 counts/(y t)

0.1-1 counts/(y 100 t)

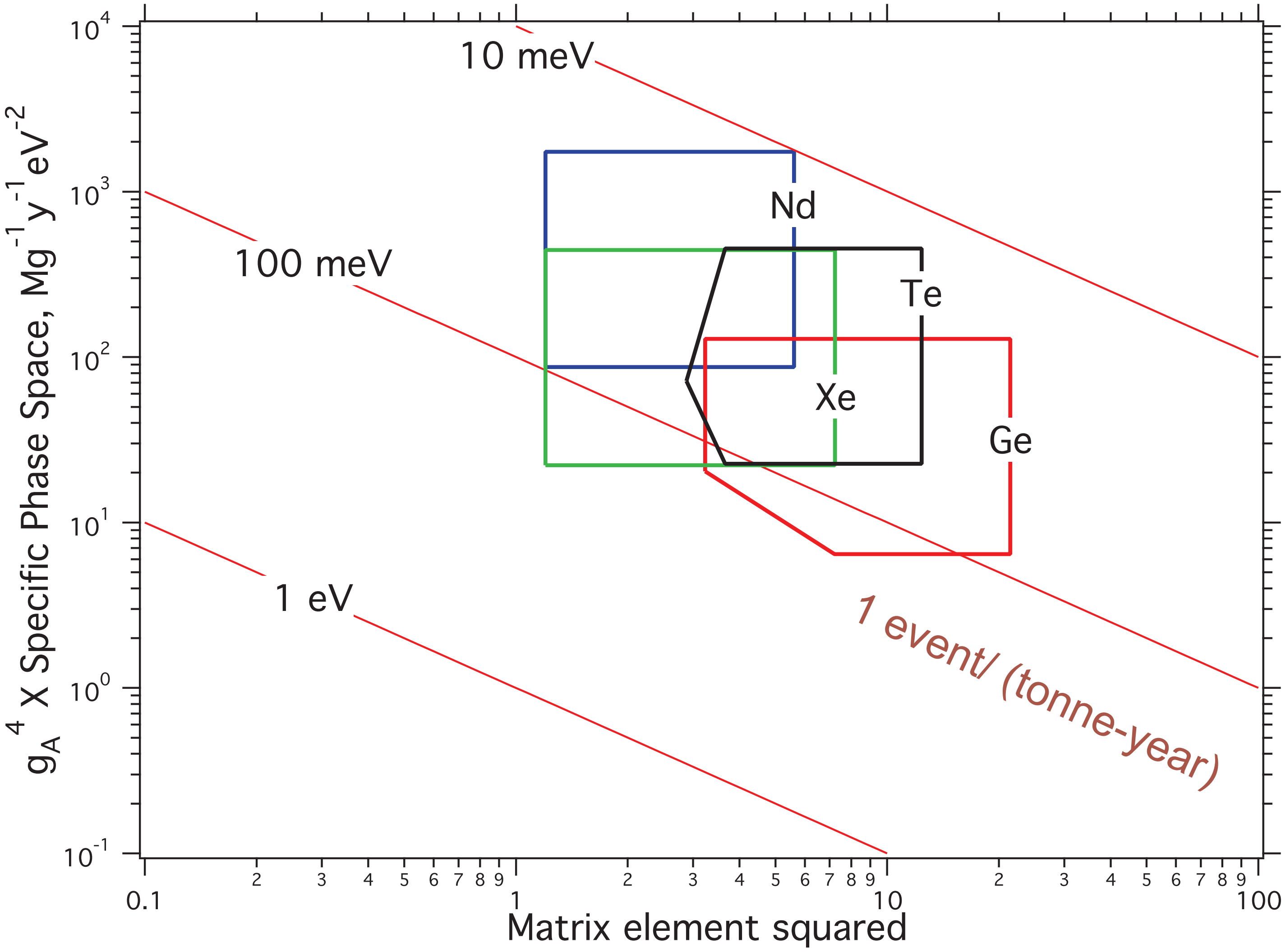
Isotopes and sensitivity to $0\nu\beta\beta$

Isotopes have comparable sensitivities in terms of rates per unit mass

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|m\beta\beta|^2}{m_e^2}$$

$$g_A^4 \ln(2)\frac{N_A}{A m_e^2} G^{0\nu}$$

$|M|^2$ uncertainty



g_A^4 uncertainty

effective value for the axial vector coupling constant g_A: ~ 0.6 - 1.269 (free nucleon value)

R. G. H. Robertson, Mod. Phys. Lett. A28 (2013) 1350021

Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}$ with a sensitivity (for non-zero background)

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

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

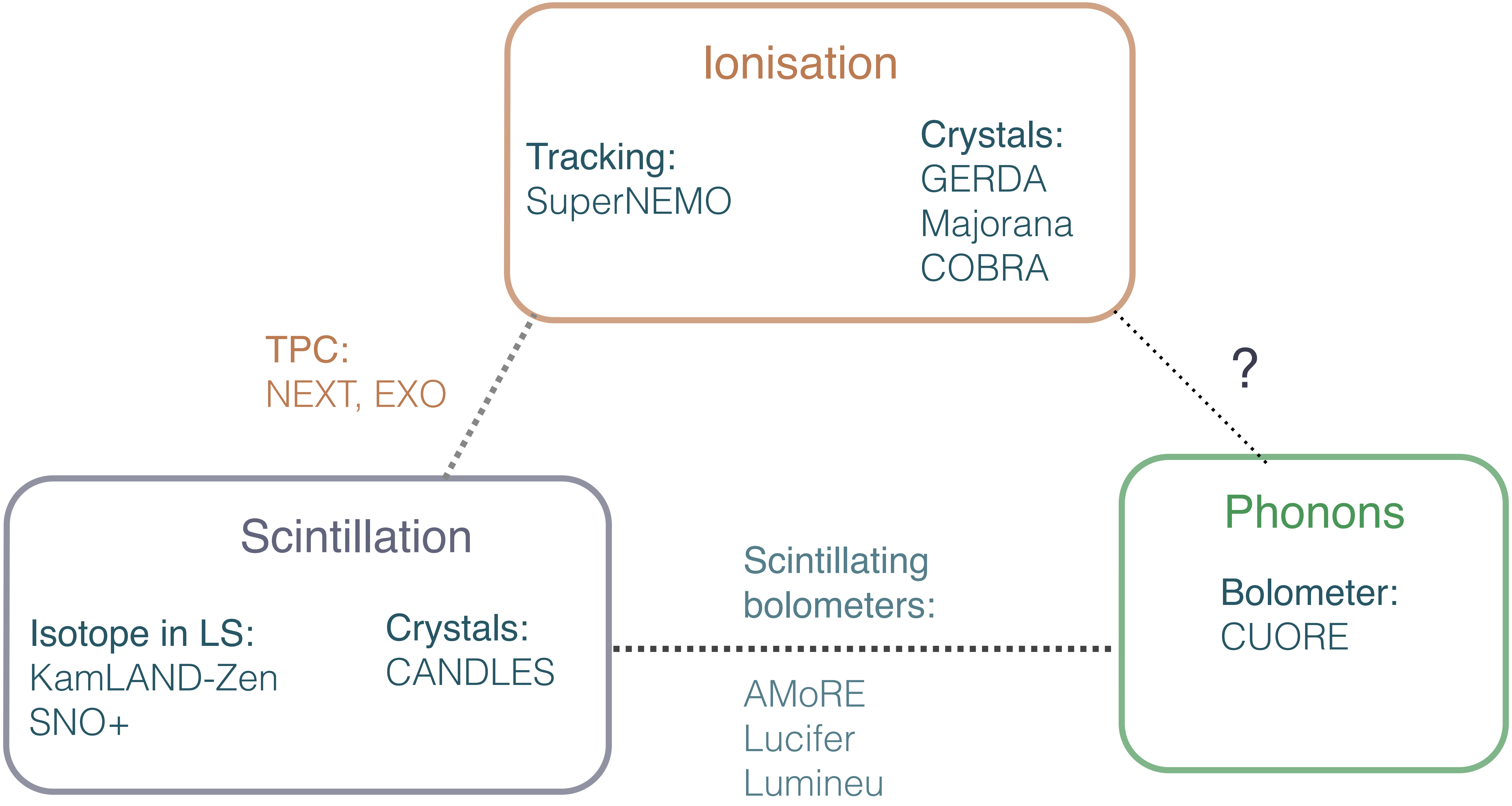
Minimal requirements:

large detector masses
high isotopic abundance
ultra-low background noise
excellent energy resolution

Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification

Experimental techniques



Ionisation

Tracking:
SuperNEMO

Crystals:
GERDA
Majorana
COBRA

TPC:
NEXT, EXO

?

Scintillation

Isotope in LS:
KamLAND-Zen
SNO+

Crystals:
CANDLES

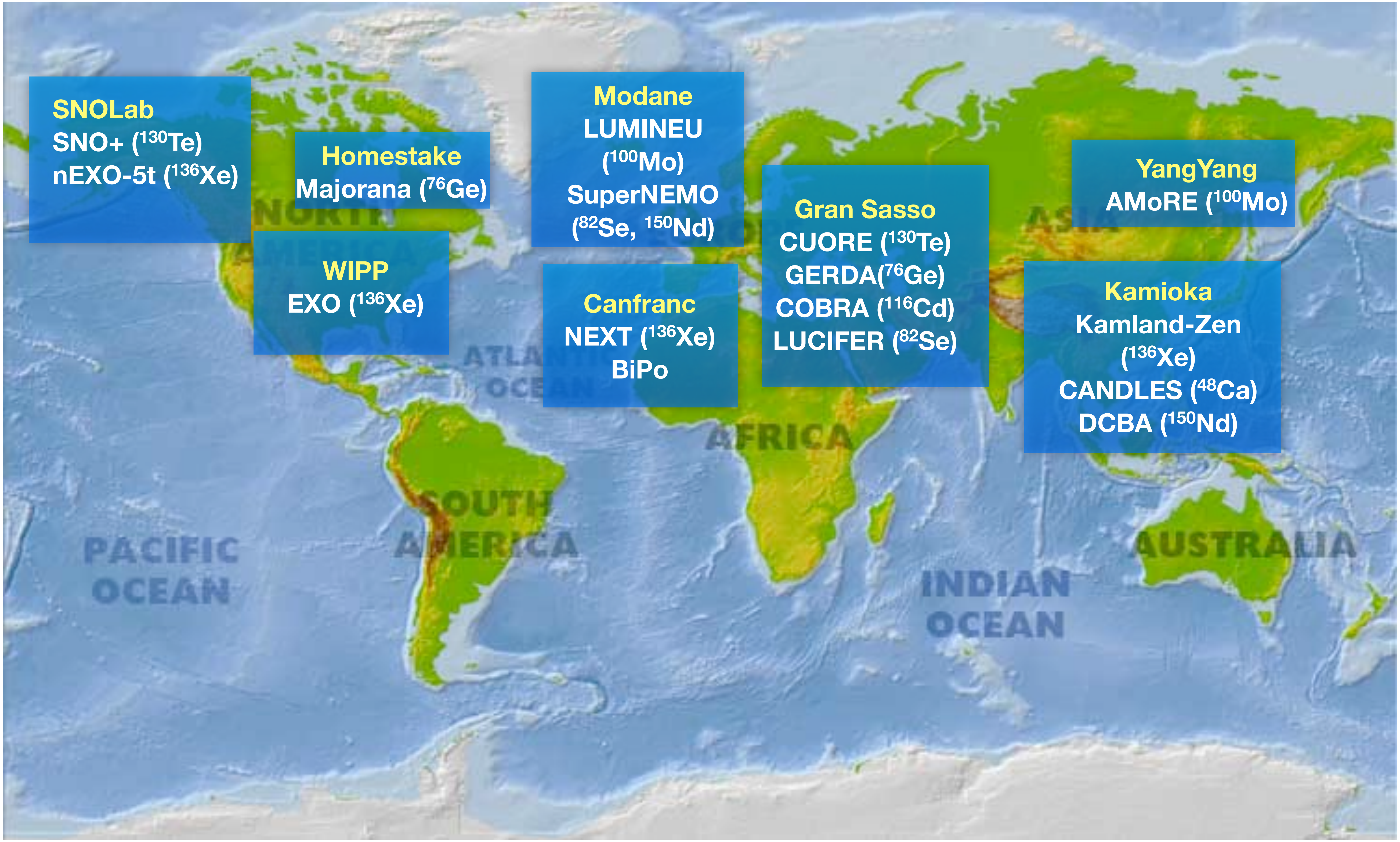
Scintillating bolometers:

AMoRE
Lucifer
Lumineu

Phonons

Bolometer:
CUORE

Double beta experiments in underground labs



SNOLab
SNO+ (^{130}Te)
nEXO-5t (^{136}Xe)

Homestake
Majorana (^{76}Ge)

WIPP
EXO (^{136}Xe)

Modane
LUMINEU (^{100}Mo)
SuperNEMO (^{82}Se, ^{150}Nd)

Canfranc
NEXT (^{136}Xe)
BiPo

Gran Sasso
CUORE (^{130}Te)
GERDA(^{76}Ge)
COBRA (^{116}Cd)
LUCIFER (^{82}Se)

YangYang
AMoRE (^{100}Mo)

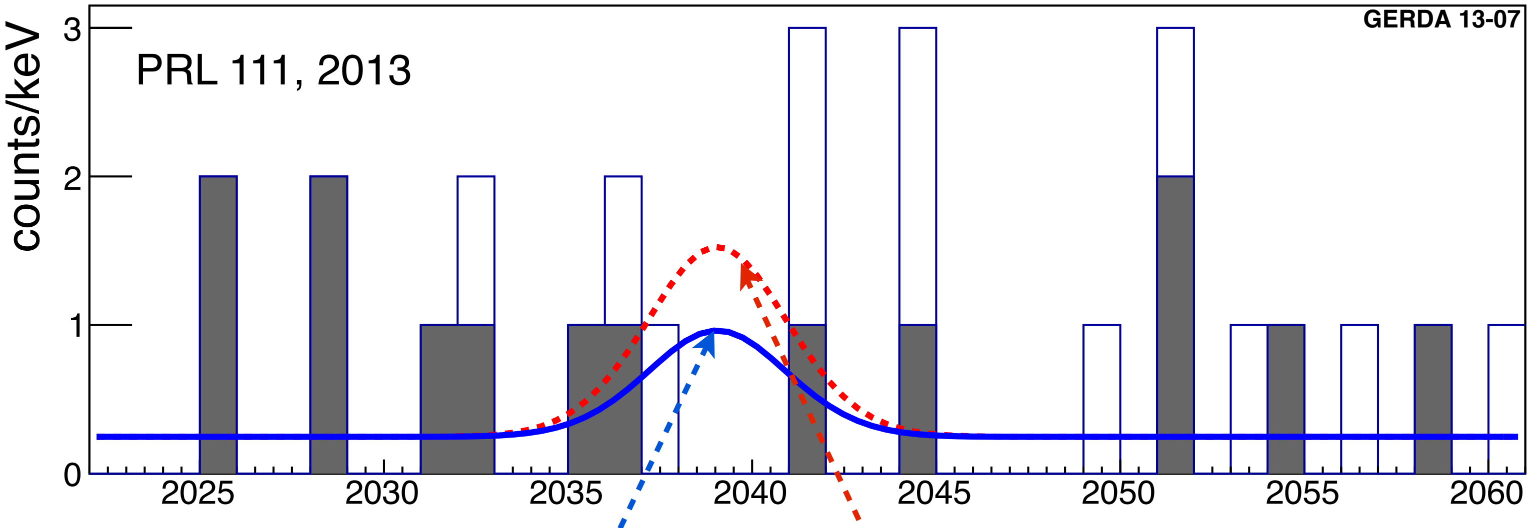
Kamioka
Kamland-Zen (^{136}Xe)
CANDLES (^{48}Ca)
DCBA (^{150}Nd)

Overview of (selected) experiments

Experiment	Isotope	Isotopic mass	Start of operation
CUORE-0 CUORE	^{130}Te	11 kg 210 kg	2013 (running) 2015
EXO-200 nEXO	^{136}Xe	200 kg 5 t	2011 2018 (?)
GERDA phase I GERDA phase II	^{76}Ge	17 kg 40 kg	2011 2015
KamLAND-Zen	^{136}Xe	300 kg	2012 (running)
Majorana	^{76}Ge	30 kg	2015
NEXT	^{136}Xe	100 kg	2016
SNO+	^{130}Te	800 kg	2016
SuperNEMO	^{82}Se	7 kg	2016

HPGe diodes: GERDA

$$m_{\beta\beta} < 0.2 - 0.4\,\mathrm{eV}$$



“Claim”, PLB586 (2004)

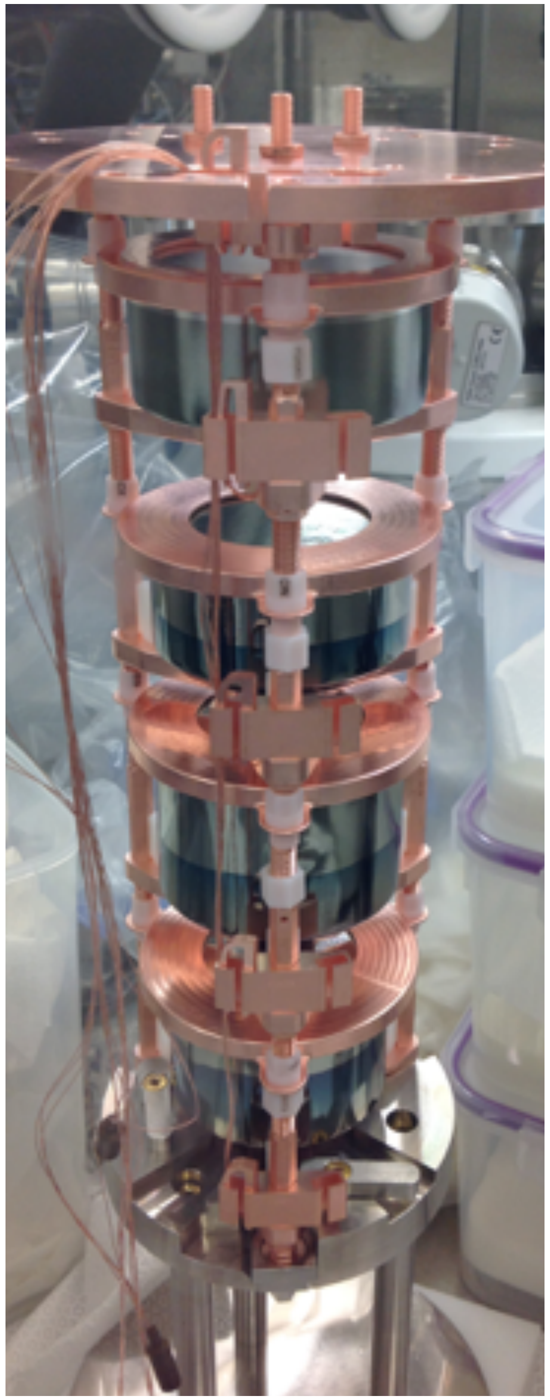
$$T^{0\nu}_{1/2} = 1.19 \times 10^{25}\,\mathrm{yr}$$

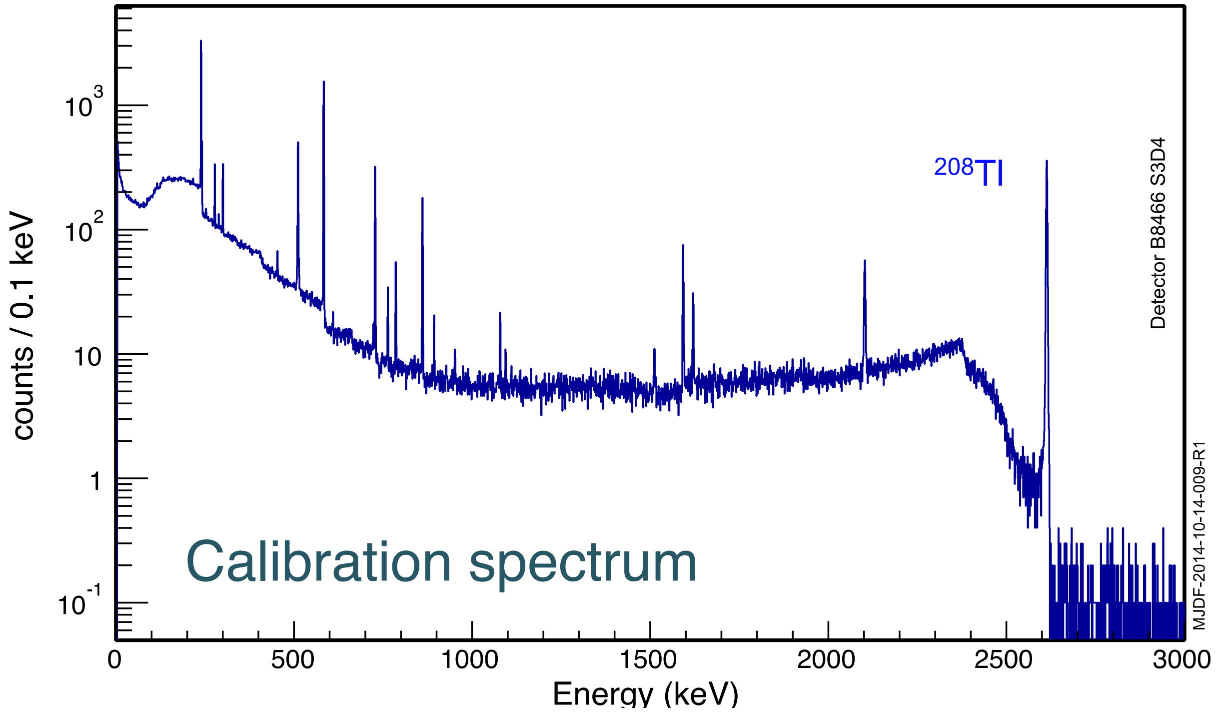
$$T^{0\nu}_{1/2} > \; 2.1 \times 10^{25}\,\mathrm{yr}\;(90\%\,\mathrm{C.L.})$$

- Phase II: 30 (20.5 kg) new $^{\mathrm{enr}}$BEGe detectors at LNGS
- Liquid argon light instrumentation for active veto installed/tested
- New run to start in summer 2015
- Background goal: ≤ 10^{-3} events/(keV kg yr)
- **Explore $T_{1/2}$ values in the 10^{26} yr range**

HPGe diodes: Majorana demonstrator

See talk by C. M. O'Shaughnessy

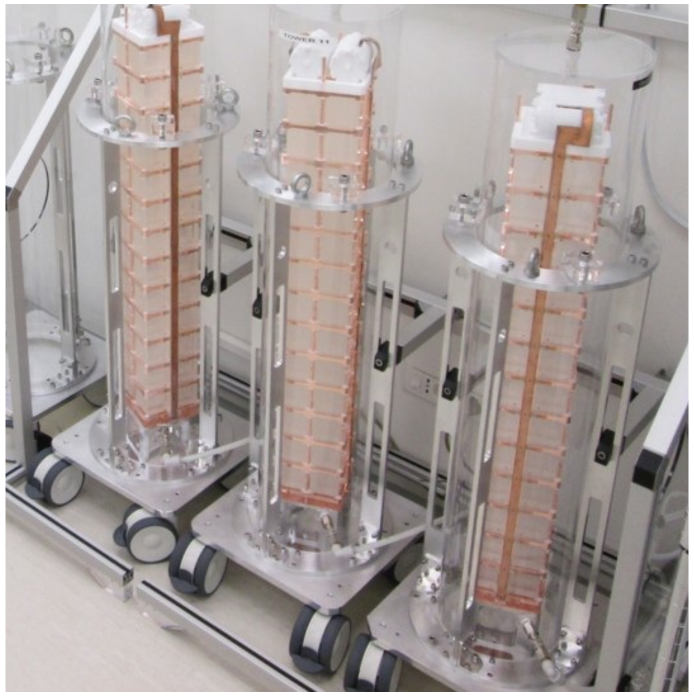




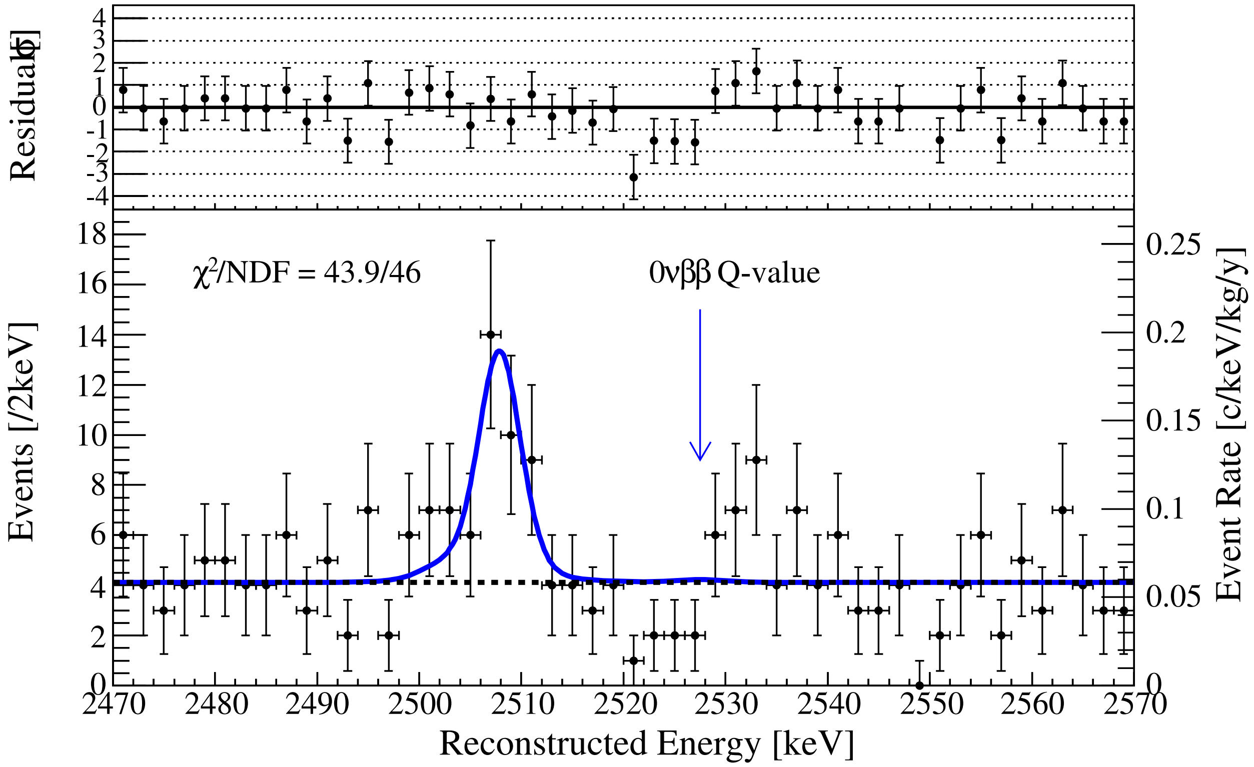
- 29 kg enriched Ge detectors (87%)
- A prototype module was installed and is taking data since July 2014
- Module 1 (~1/2) of enriched detectors to start operation summer 2015
- Assembly of strings for module 2 is proceeding well
- Completion and starting of operation by end of 2015
- **Explore $T_{1/2}$ values in the 10^{26} yr range**

TeO$_2$ bolometers: CUORE

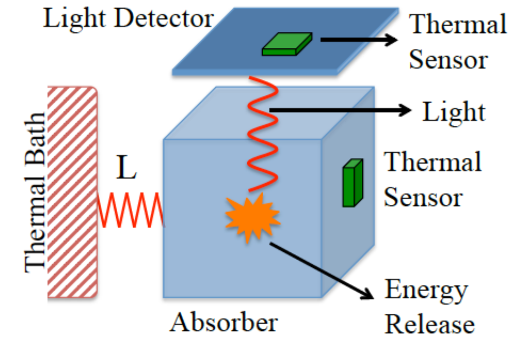
See talk by P. Moistera



arXiv: 1504.2454

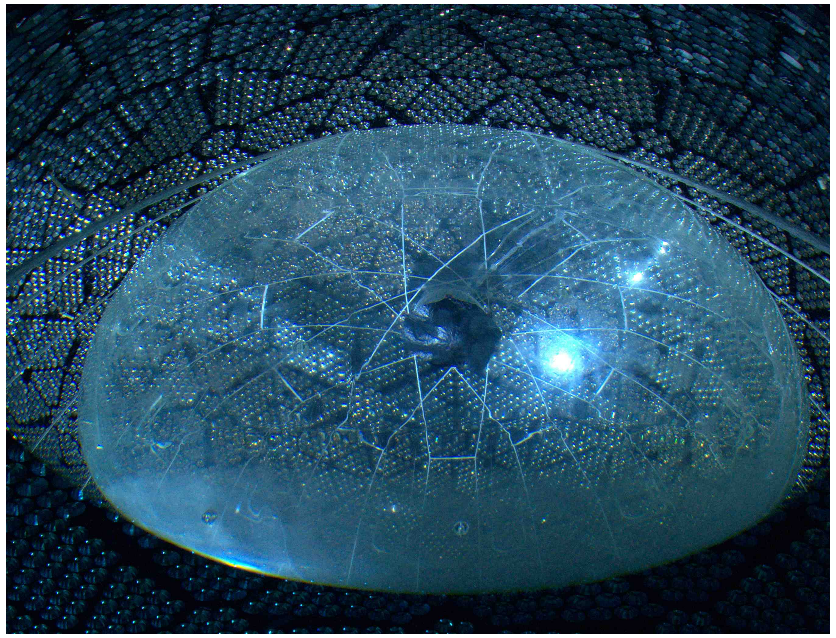


- CUORE-0: array of 52 crystals; 9.8 kg-yr exposure, FWHM = 5.1 keV
- **Recent results: $T_{1/2} > 2.7 \times 10^{24}$ y (90% CL); $T_{1/2} > 2.7 \times 10^{24}$ y (90% CL) combined with Cuoricino**
- CUORE: all 988 crystals (206 kg ^{130}Te) built and assembled in towers
- Cryostat commissioning underway; detector installation in 2015
- Next step: CUPID = CUORE detectors + light read-out for alpha suppression

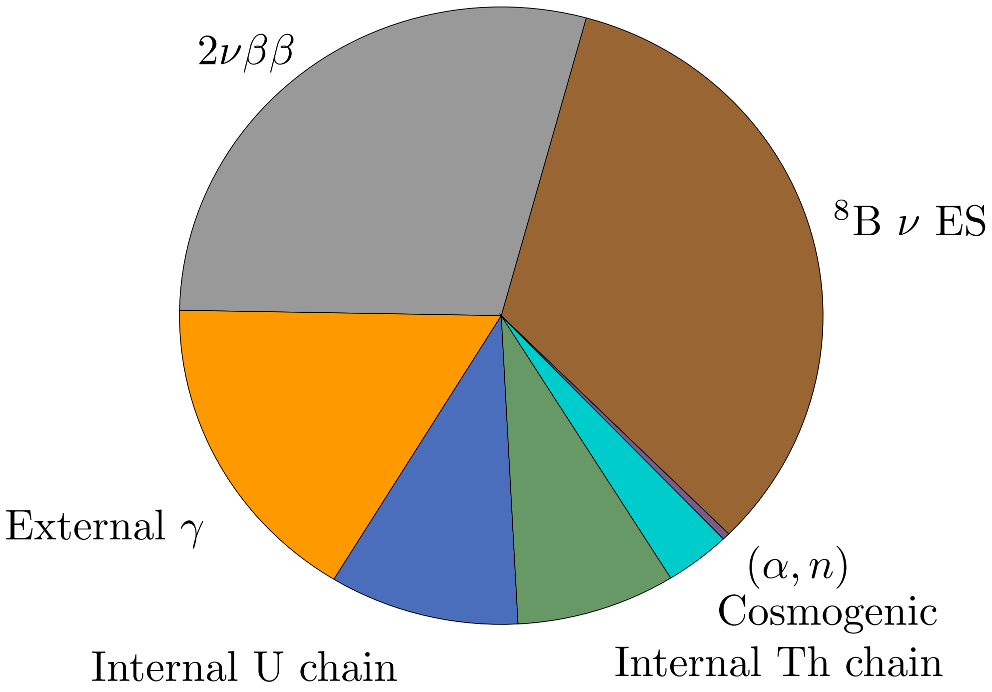


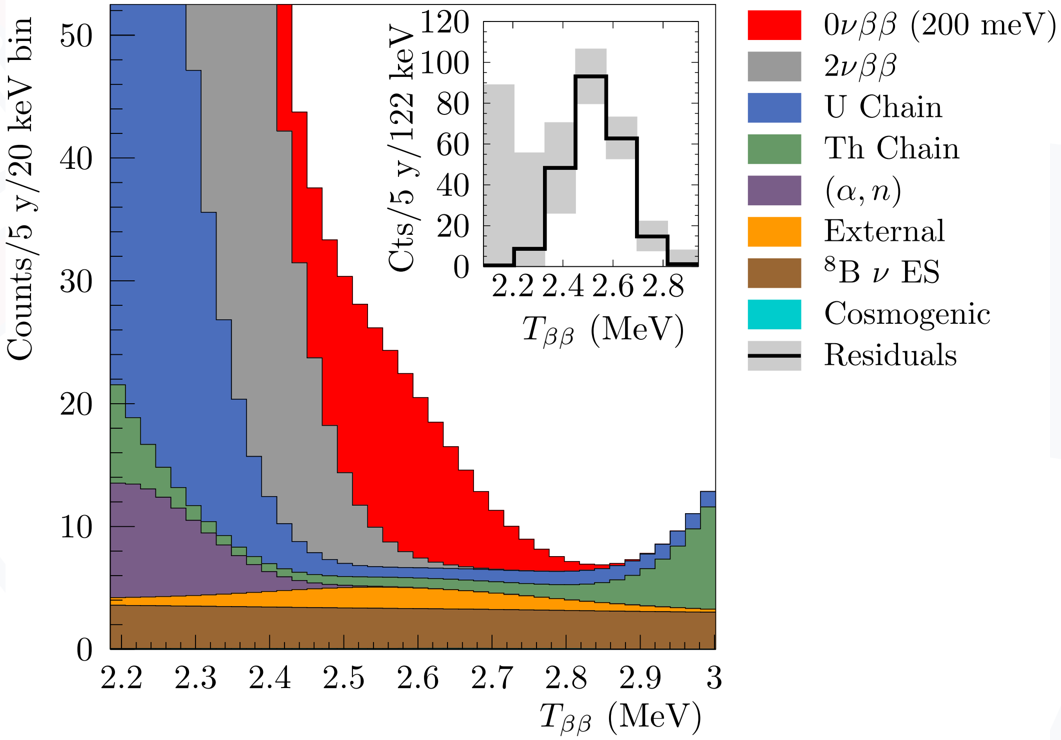
^{130}Te in liquid scintillator: SNO+

- First phase: 0.3% natural Te (~ 800 kg ^{130}Te)
- Detector and cavity being filled with water
- Start LS fill in 2016
- Load 0.3% Te in 2017
- Then upgrade PMTs and 3% load with the goal to cover the inverted hierarchy scenario



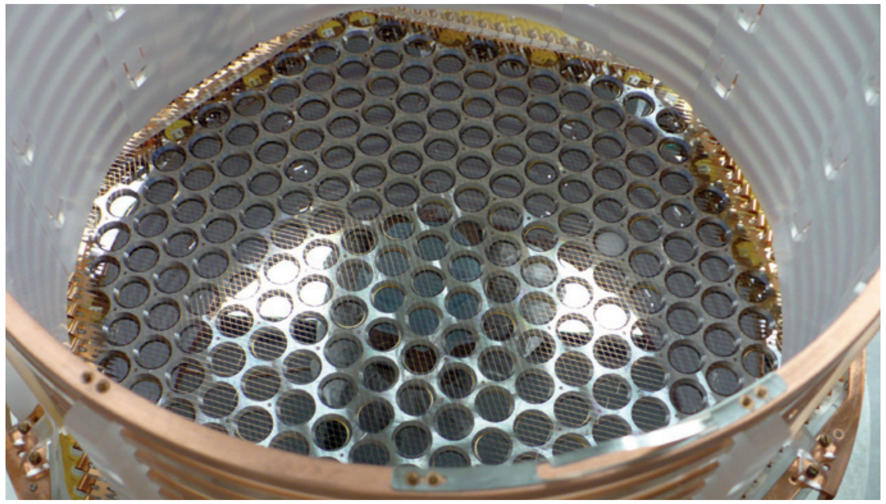
Expected backgrounds in SNO+

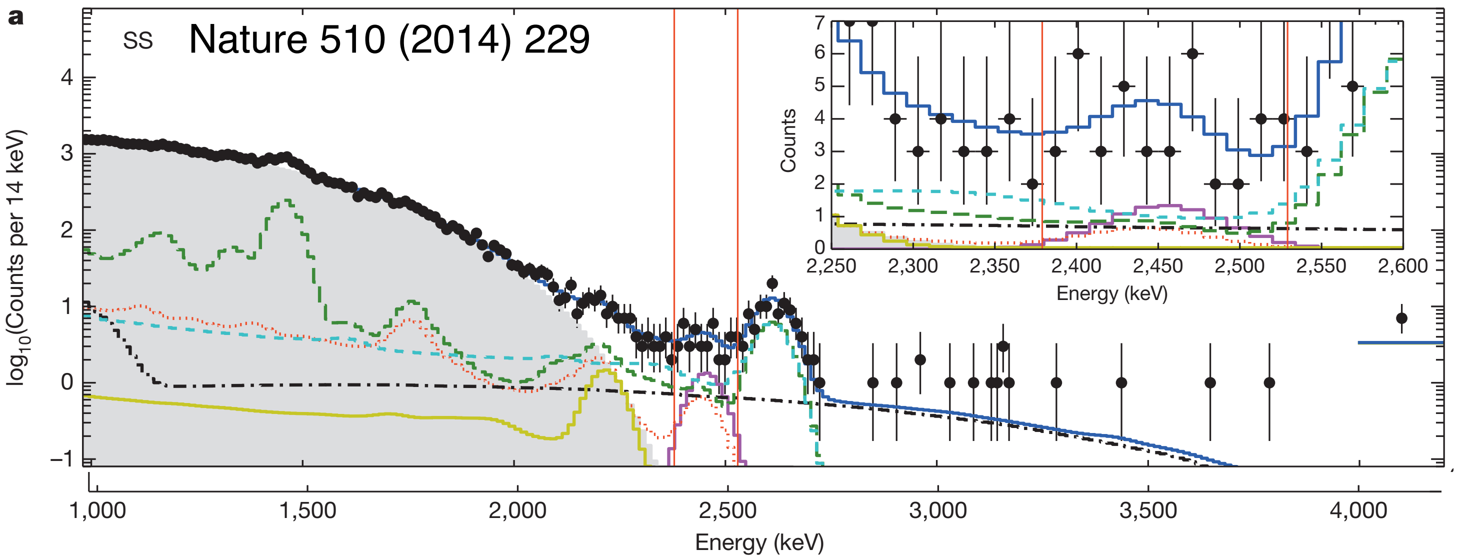




Liquid xenon TPC: EXO and nEXO

- Dual-phase time projection chamber
- 110 kg LXe (80.6% ^{136}Xe) in active volume
- After WIPP accident: ongoing cleanup/repair effort; cooling & filling LXe TPC in summer 2015, data taking in fall 2015
- nEXO: 5 tonnes enriched LXe
- Proposed location SNOLAB cryopit

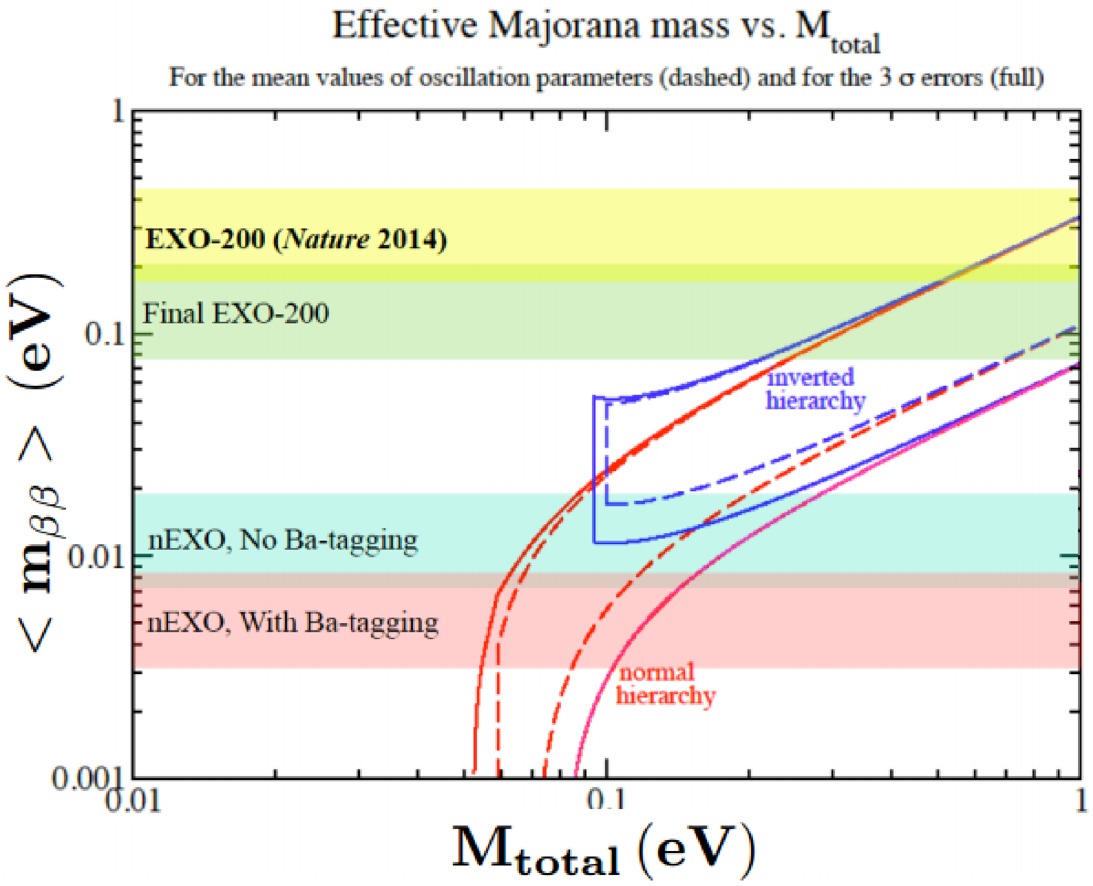




Nature 510 (2014) 229

$$T_{1/2}^{0\nu} > 1.1 \times 10^{25}\,\mathrm{y}\ (90\%\mathrm{C.L.})$$

$$m_{\beta\beta} < 0.19 - 0.45\,\mathrm{eV}$$

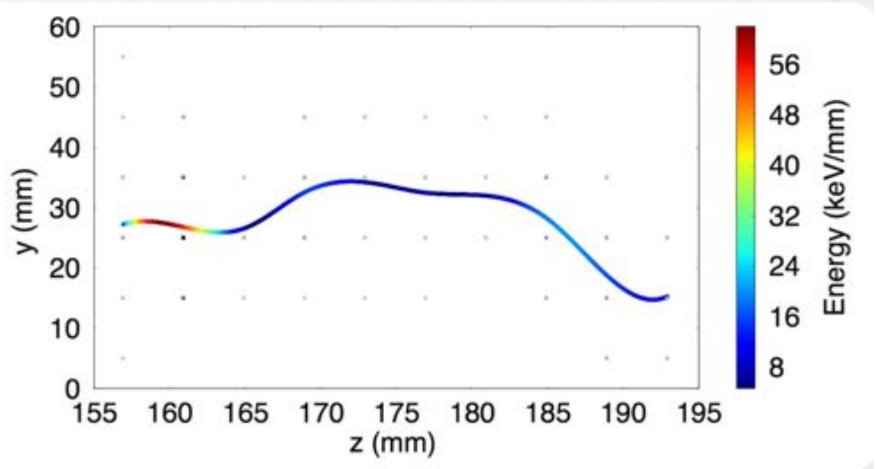


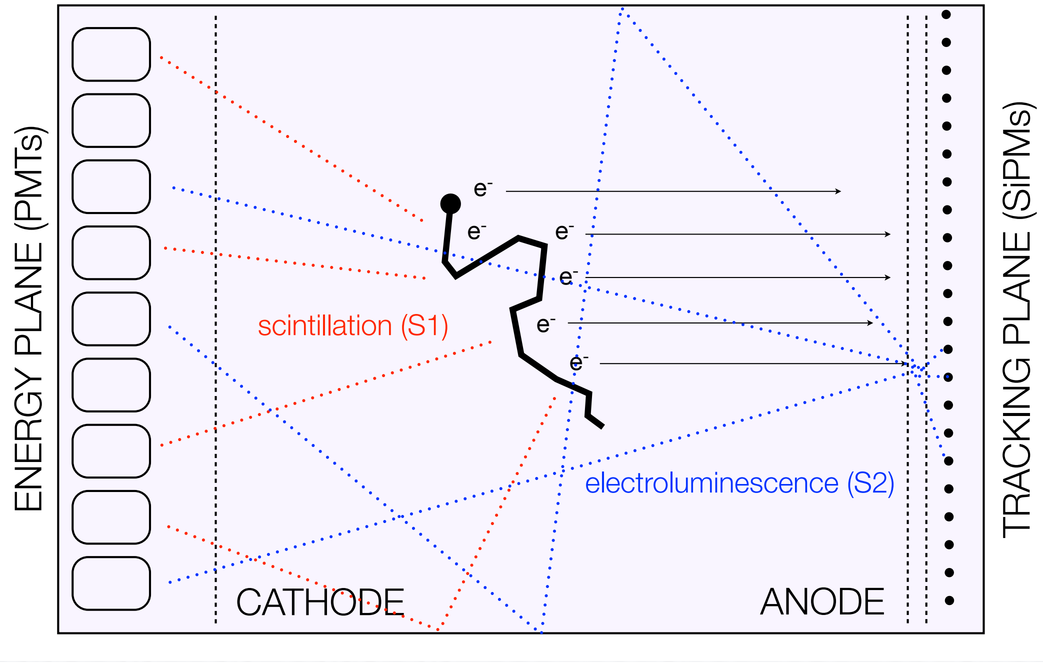
Effective Majorana mass vs. M_{total}

For the mean values of oscillation parameters (dashed) and for the 3 σ errors (full)

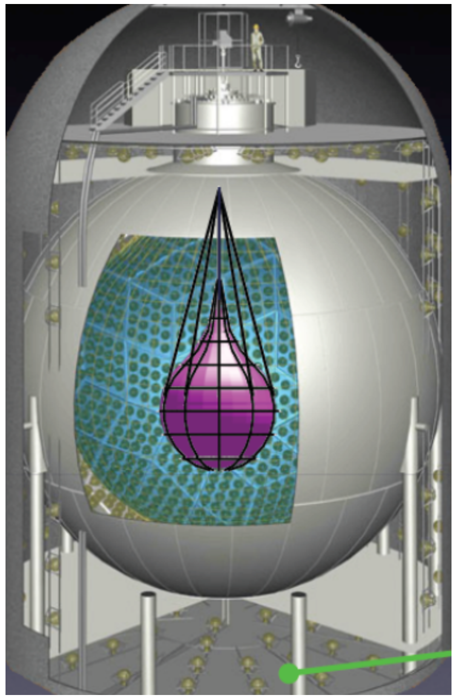
High pressure xenon TPC: NEXT

- NEXT-100: 100 kg ^{136}Xe (90% enriched) HP Xe TPC
- Tracking capabilities and < 1% (FWHM) resolution
- Under construction (vessel, sensors, gas system etc)
- Installation and commissioning at LSC by 2017: **explore the effective Majorana mass to 100 meV**
- 10 kg prototype in deployment at LSC (validate bg model)





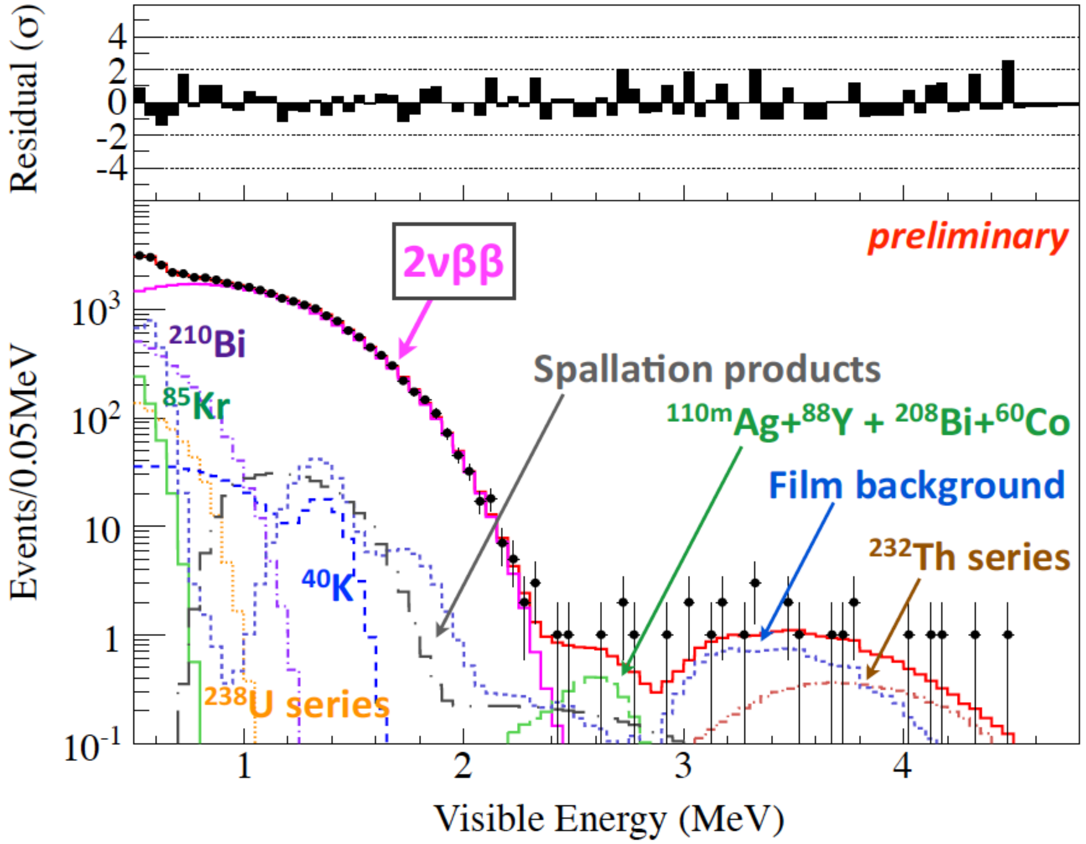
^{136}Xe in liquid scintillator: KamLAND-Zen



- Mini-balloon with ^{136}Xe-loaded LS in KamLAND
- Phase 1+2 (179 kg + 383 kg):
- **$T_{1/2} > 2.6 \times 10^{25}$ y (90% CL)**

$$m_{\beta\beta} < 0.14 - 0.28\,\mathrm{eV}$$

- Next phase: new mini-balloon construction in summer 2015
- Larger LS volume: 600-800 kg ^{136}Xe
- Lower backgrounds
- **Sensitivity: 2×10^{26} yr after 2 years exposure**
- Goal: cover the inverted hierarchy region

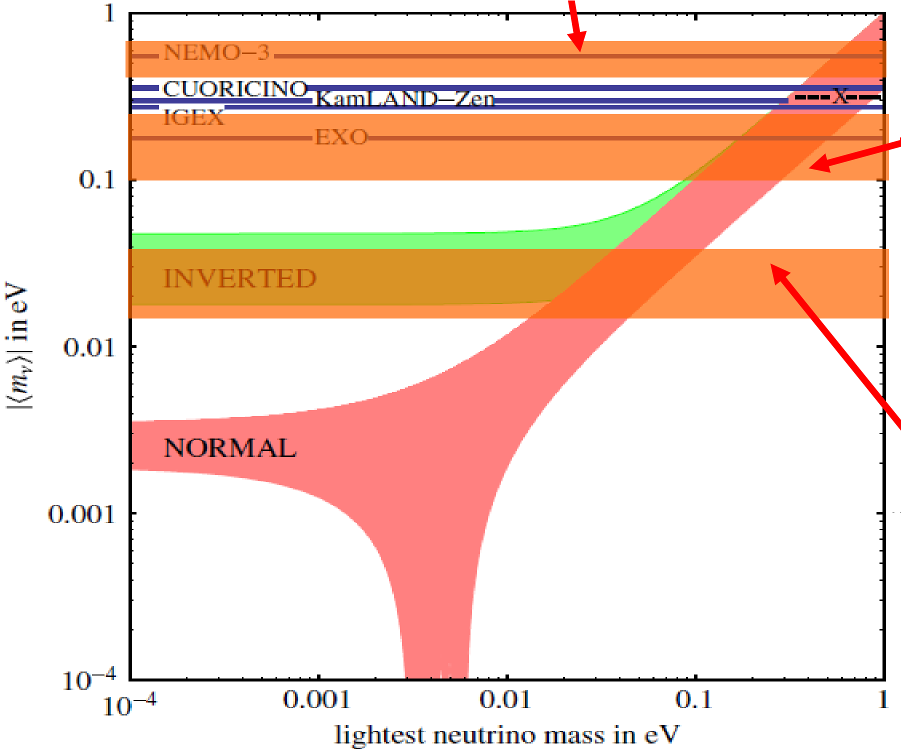


Scintillating bolometers: AMoRE/LUMINEU/LUCIFER

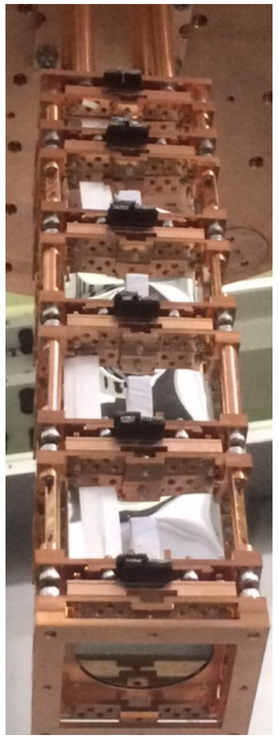
- Measure both heat and light: particle discrimination and background rejection
- AMoRE: $^{40}Ca^{100}MoO_4$ in 3 stages 1.5-10-200 kg of crystals
- LUMINEU: $Zn^{100}MoO_4$ 1 kg - 10 kg (LUCINEU)

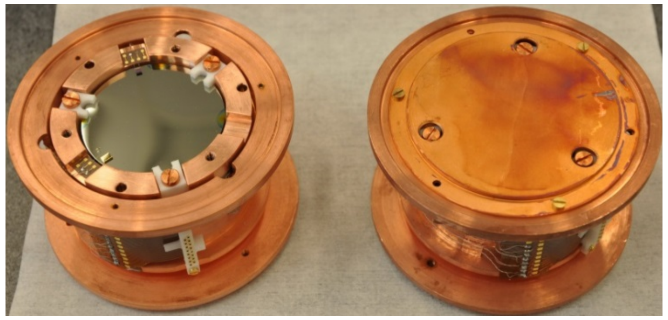
AMoRE-pilot (Now)
1.5 kg of $^{40}Ca^{100}MoO_4$
(2015~)

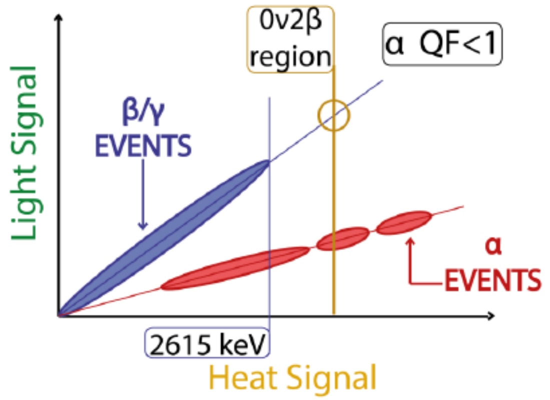
AMoRE-10
10 kg of $^{40}Ca^{100}MoO_4$
(2016~2018)

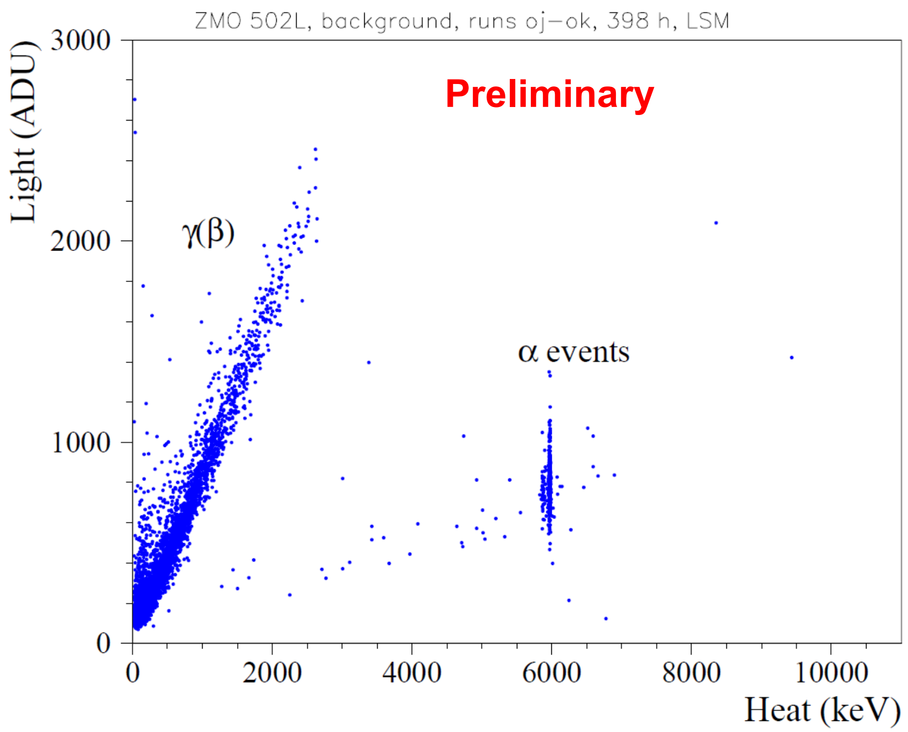


AMoRE-200
(2018~2022)



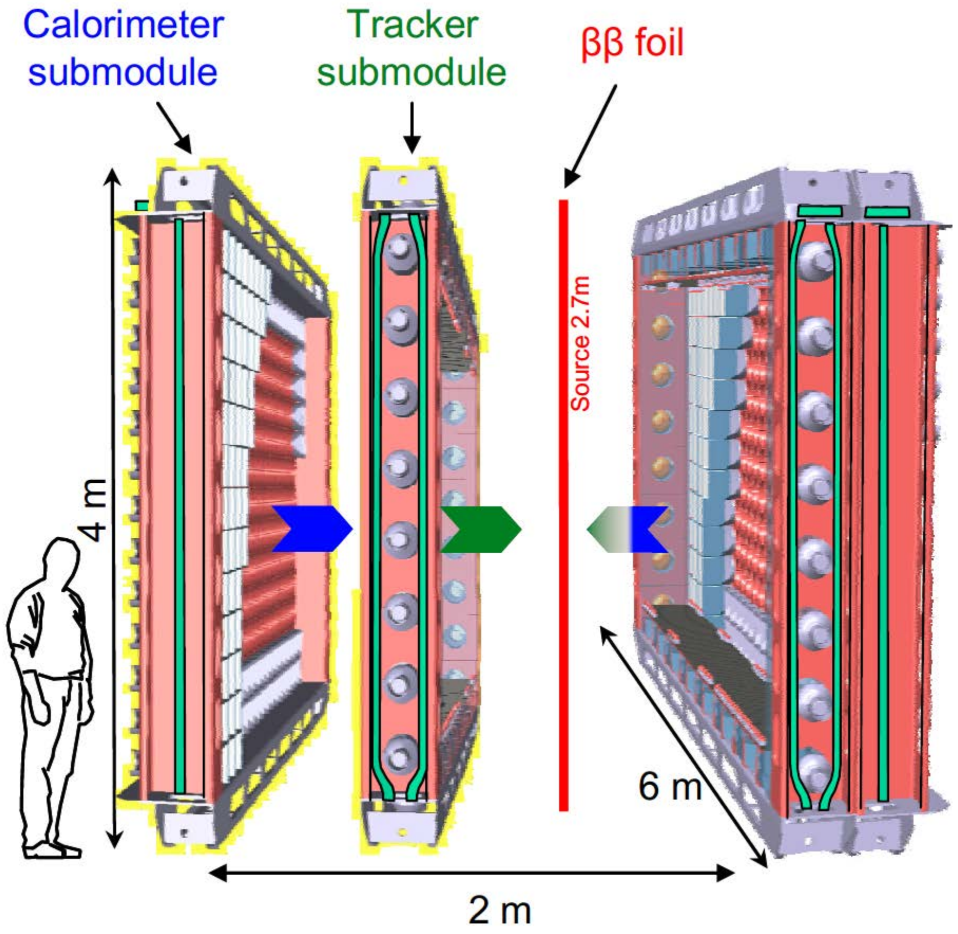


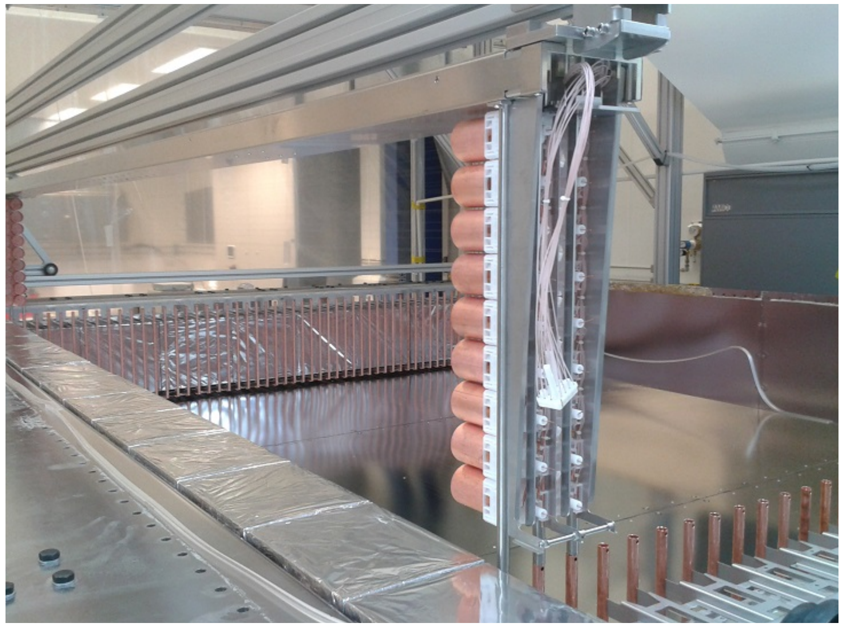




Tracking: SuperNEMO

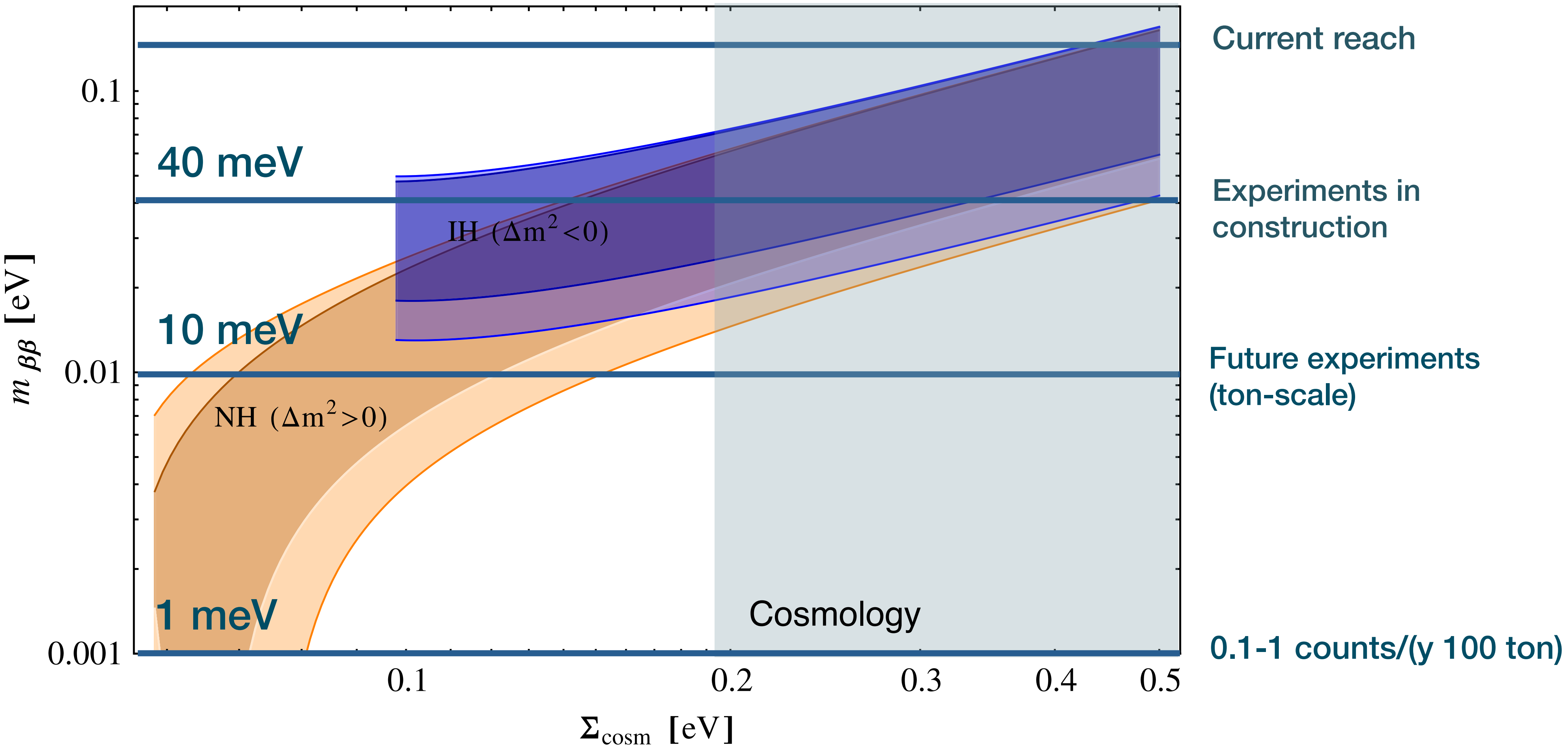
- Separate tracker, calorimeter and source
- Sources: ^{82}Se (^{150}Nd, ^{48}Ca), 100 kg
- **Aim: $T_{1/2} > 10^{26}$ yr**
- Demonstrator: 7 kg ^{82}Se, $T_{1/2} > 6.6 \times 10^{24}$ yr
- Status: in assembly, first demonstrator module in 2016





Outlook: the search continues

- Ton-scale experiments are required to explore the *inverted mass hierarchy* scale
- Several technologies are moving towards this scale with ultra-low backgrounds
- It remains to be seen which ones can be upgraded to 10-100 ton scale and explore the *normal mass hierarchy scale*



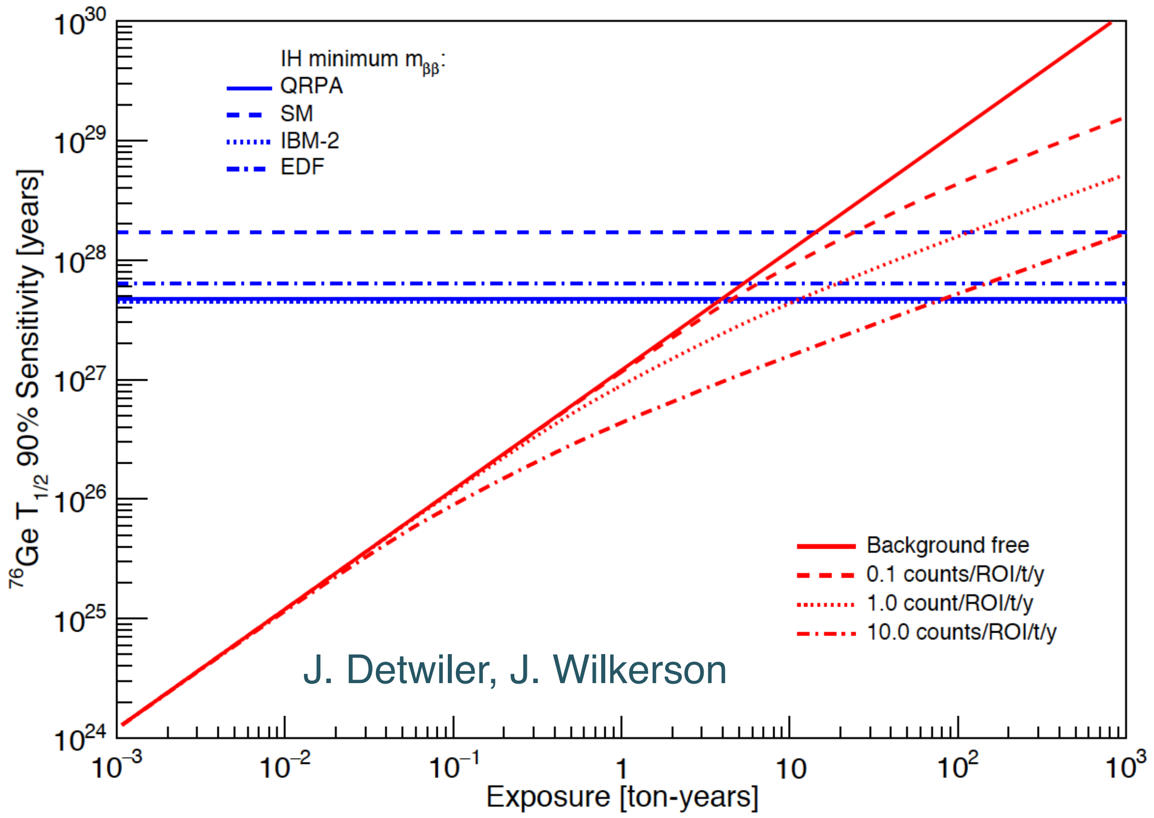
Del’Oro, Marocci, Vissani, PRD 90, 2014

End

Backgrounds

- Muon induced backgrounds
- Natural radioactivity: ^{238}U, ^{232}Th, ^{40}K, Radon, (alpha,n), (n,gamma) etc
- Anthropogenic radioactivity: ^{110m}Ag, ^{207}Bi,
- Cosmogenic activation of detector components: ^{60}Co, ^{42}Ar, ^{68}Ge,
- ^{8}B solar neutrinos
- 2 neutrino double beta decay

Example: Ge sensitivity with/without backgrounds



J. Detwiler, J. Wilkerson

Background reduction

- Ultra-pure materials
- Energy resolution
- Event topology
- Pulse shape discrimination
- Particle identification