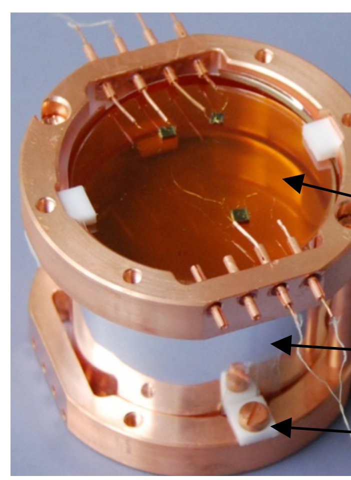
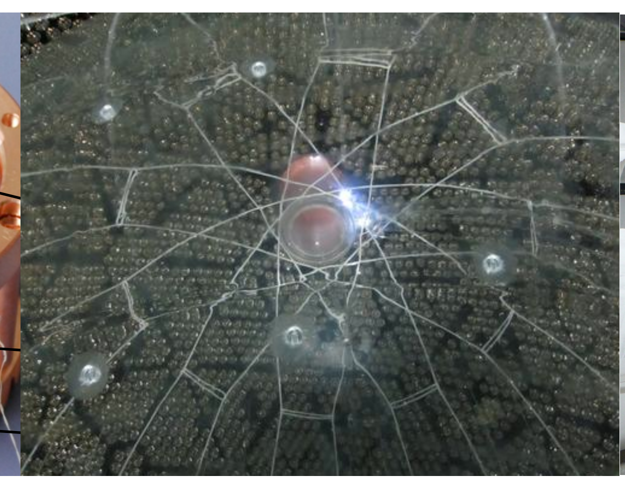
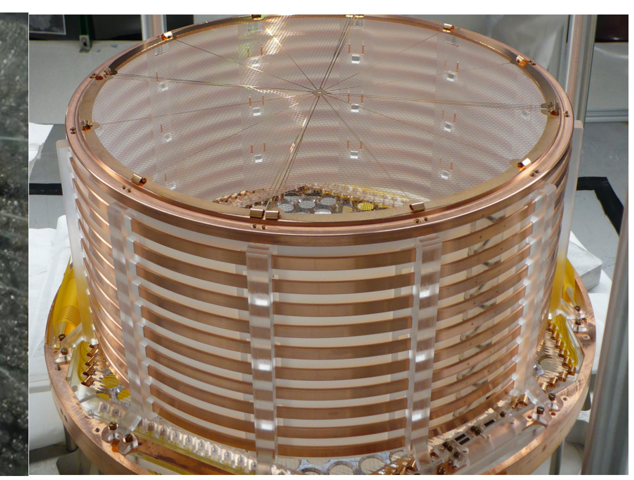
Double beta decay:
non-Ge experimental programmes

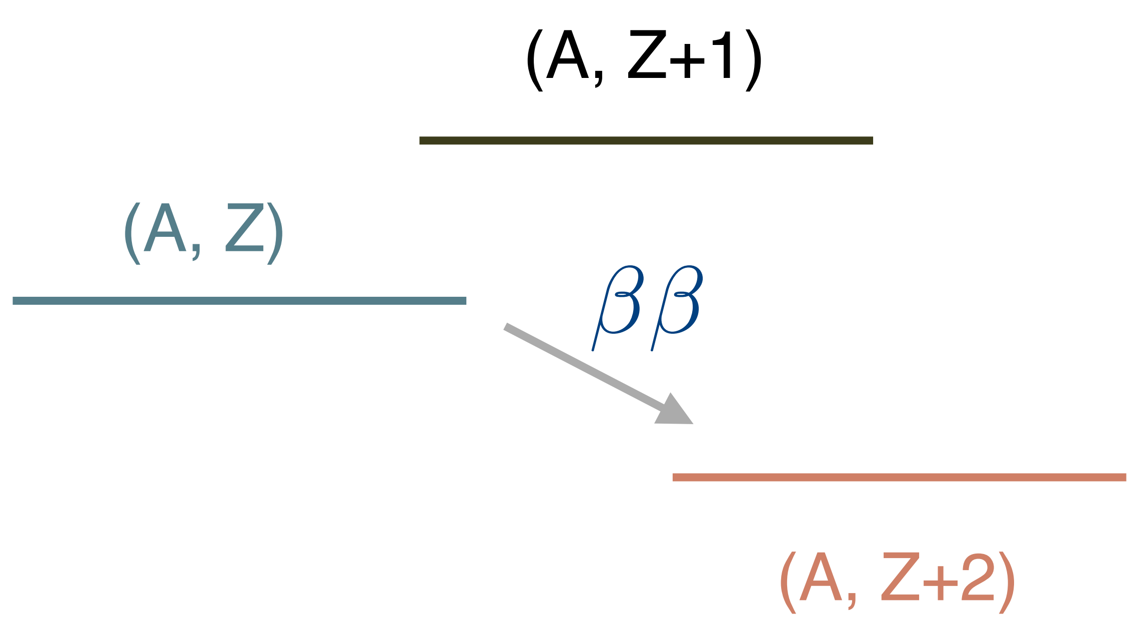




Laura Baudis
University of Zurich

Meeting on the Next Generation ^{76}Ge experiment
Munich, April 25, 2016

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

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:**

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

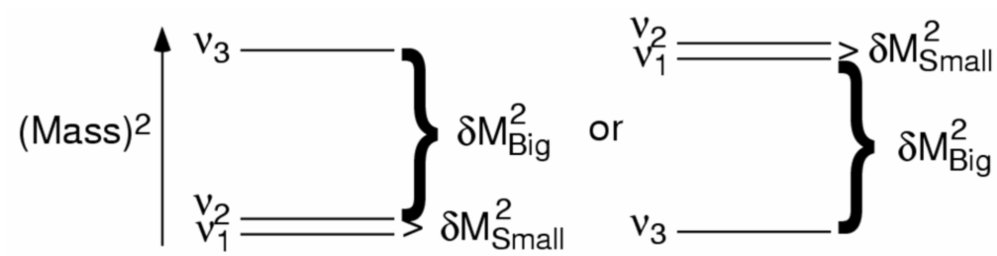
➡ a coherent sum over mass eigenstates with potentially CP violating phases

➡ = 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

Effective Majorana neutrino mass

normal

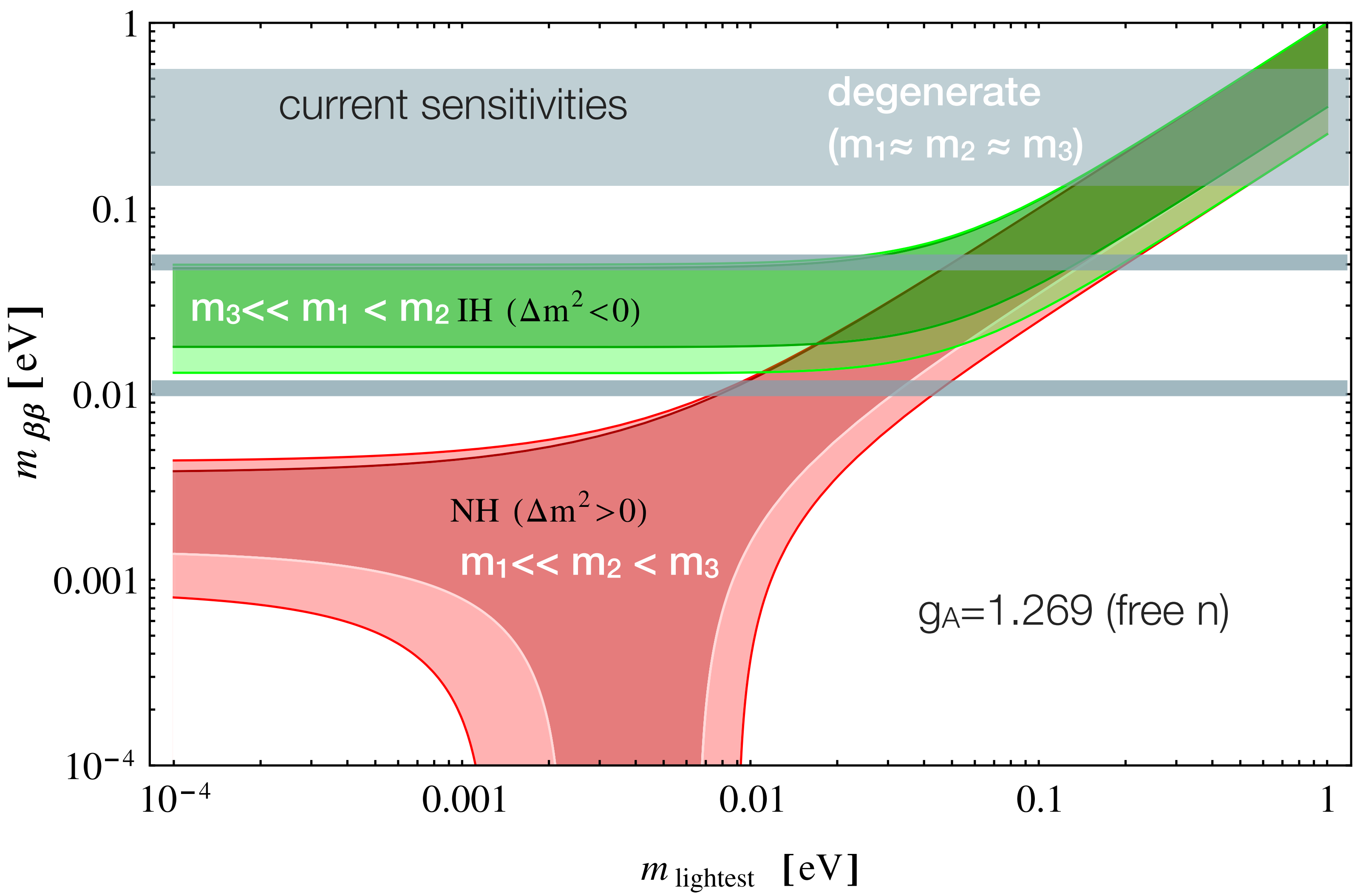


inverted

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

$T_{1/2} \sim 10^{26} y$

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



0.1- 1 counts/(y kg)

0.5 - 5 counts/(y t)

0.1-1 counts/(y 100 t)

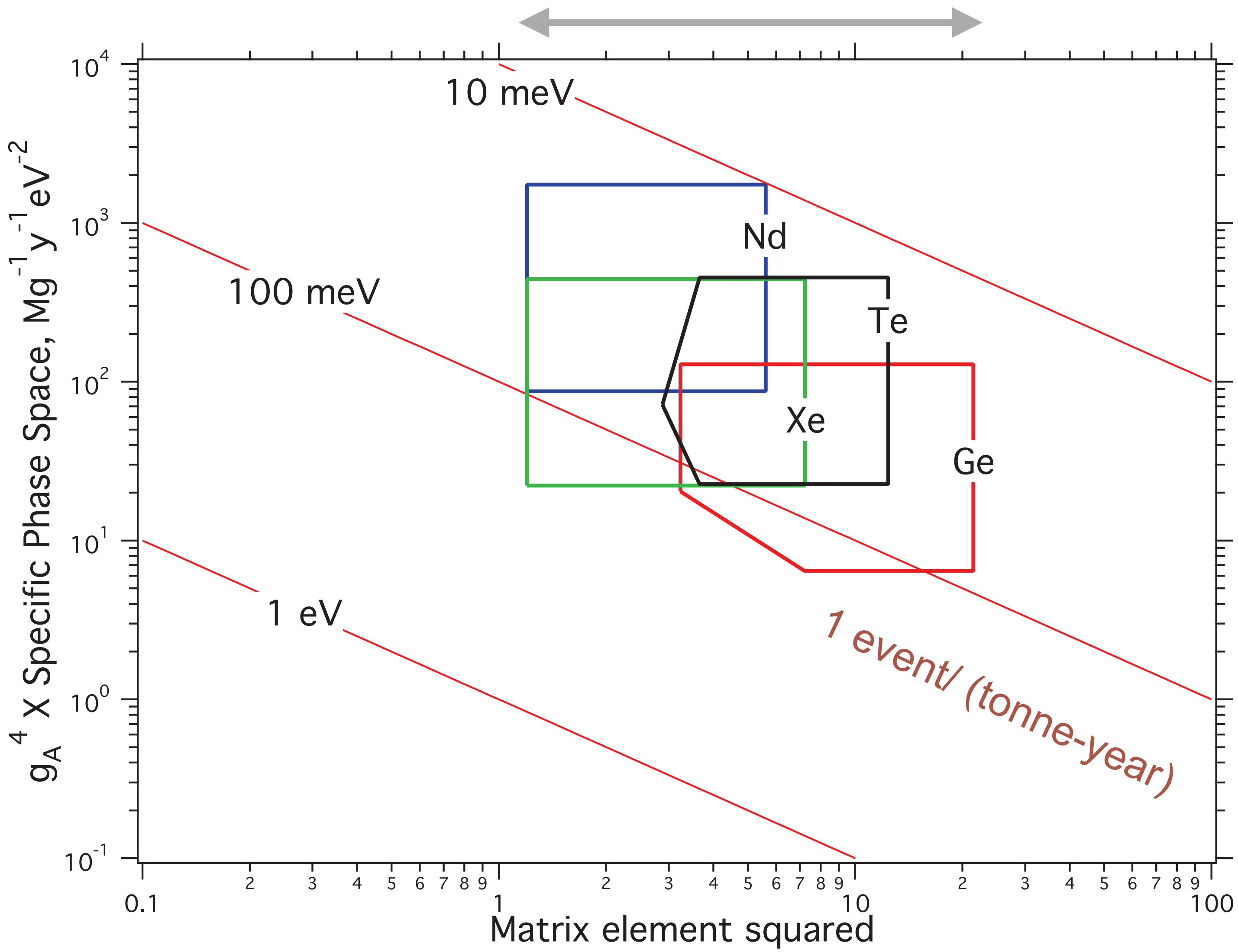
Isotopes and sensitivity to $0\nu\beta\beta$

Isotopes have comparable sensitivities in terms of rates per unit mass

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

$|M|^2$ uncertainty

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



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)**

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

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

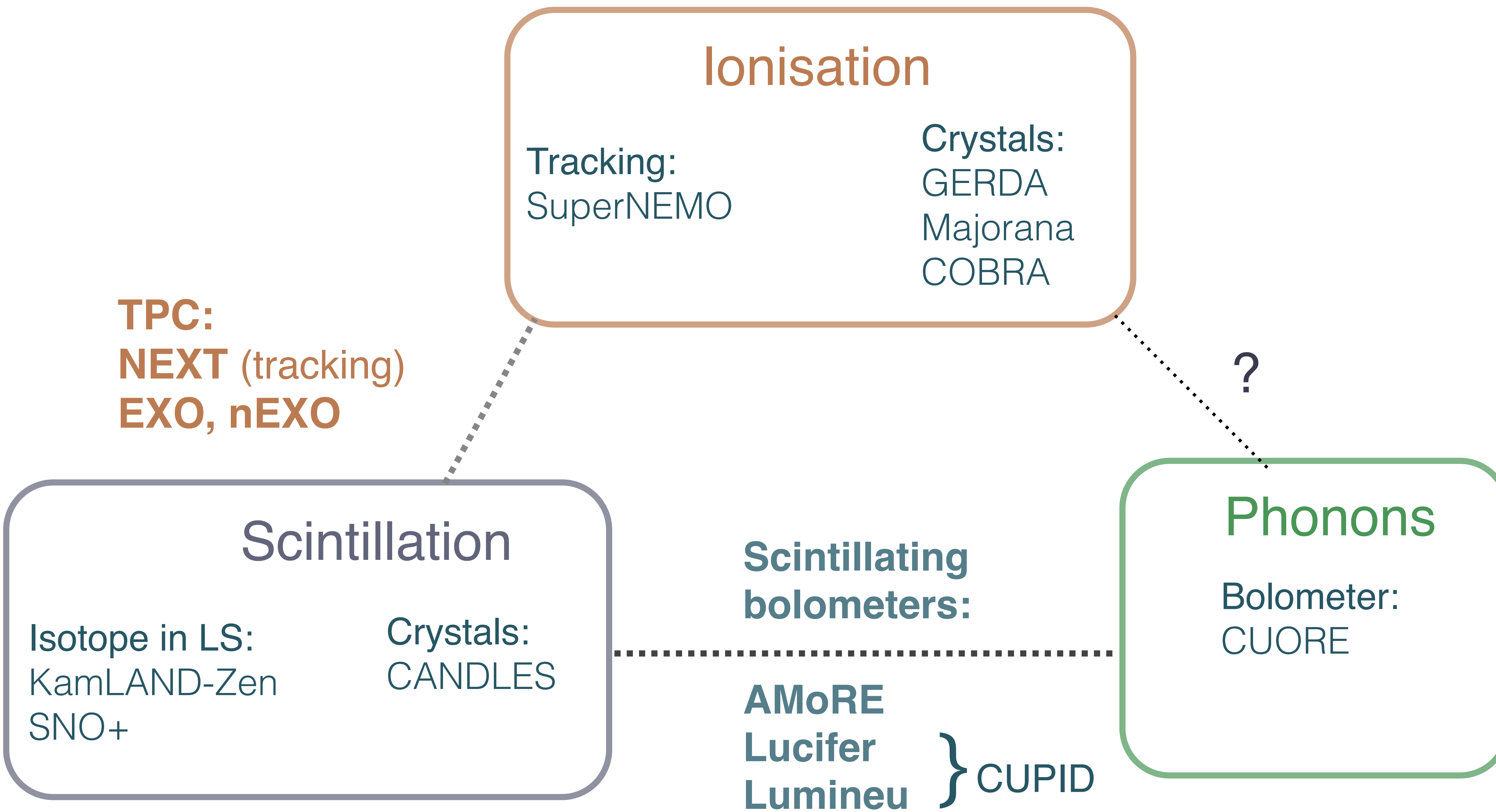
Minimal requirements:

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

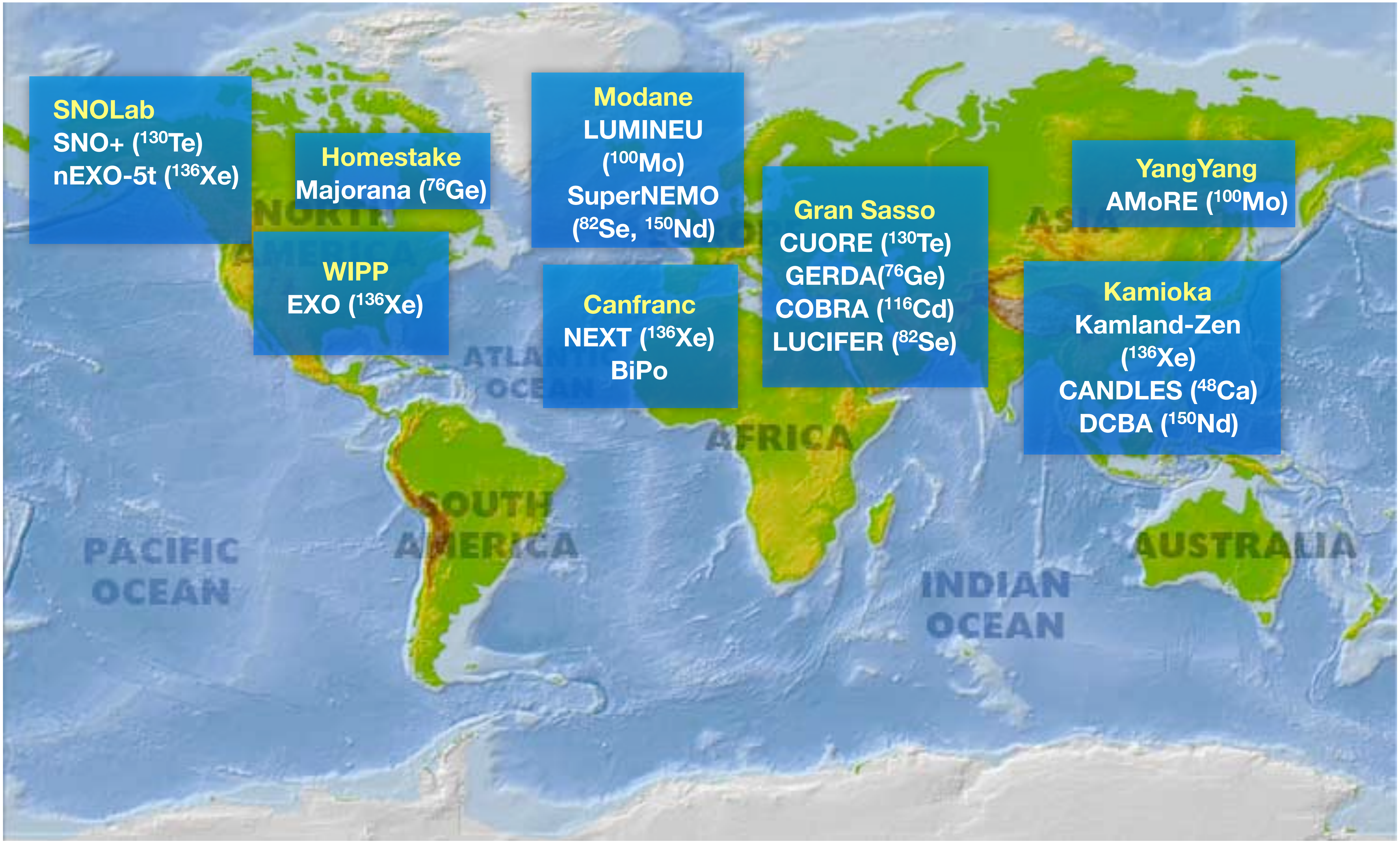
Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification

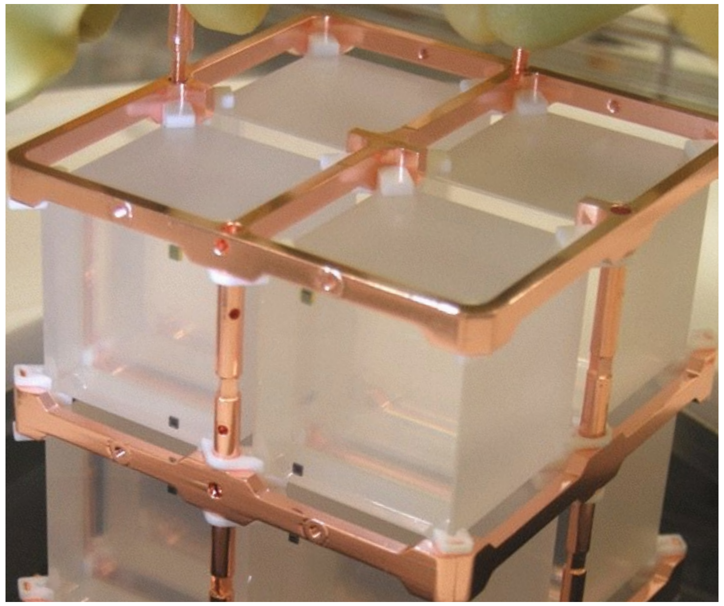
Experimental techniques

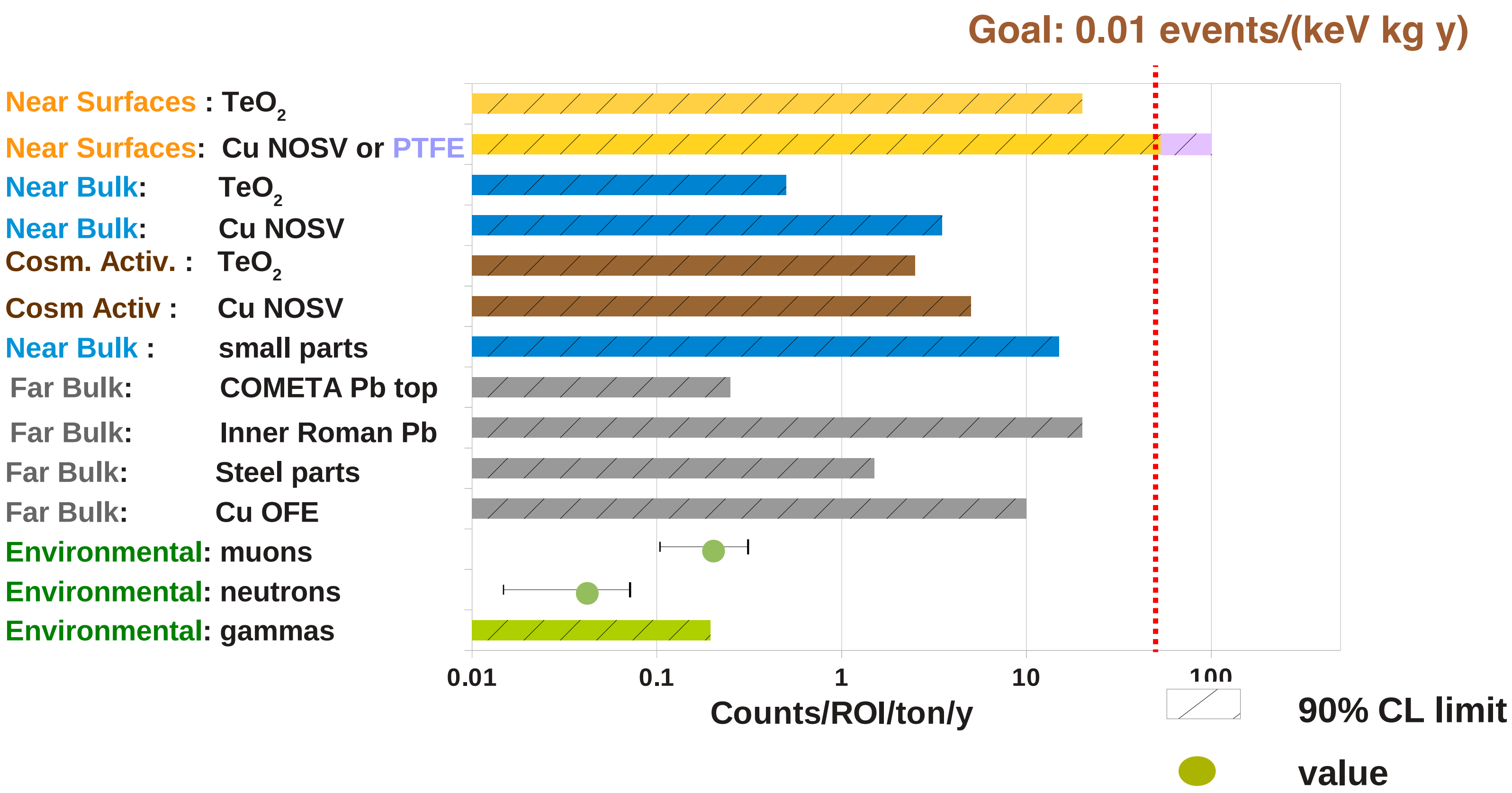


Double beta experiments in underground labs



TeO_2 bolometers: CUORE-0





- Array of 52 5 x 5 x 5 cm^3 crystals (~ 750 g each), total mass: 39 kg TeO_2 (10.9 kg ^{130}Te)
- 9.8 kg-yr exposure, **FWHM = 4.9 keV at 2.6 MeV**
- Background index: **0.058 events/(kg keV y)**
- **Results (combined with Cuoricino, 90% CL):**

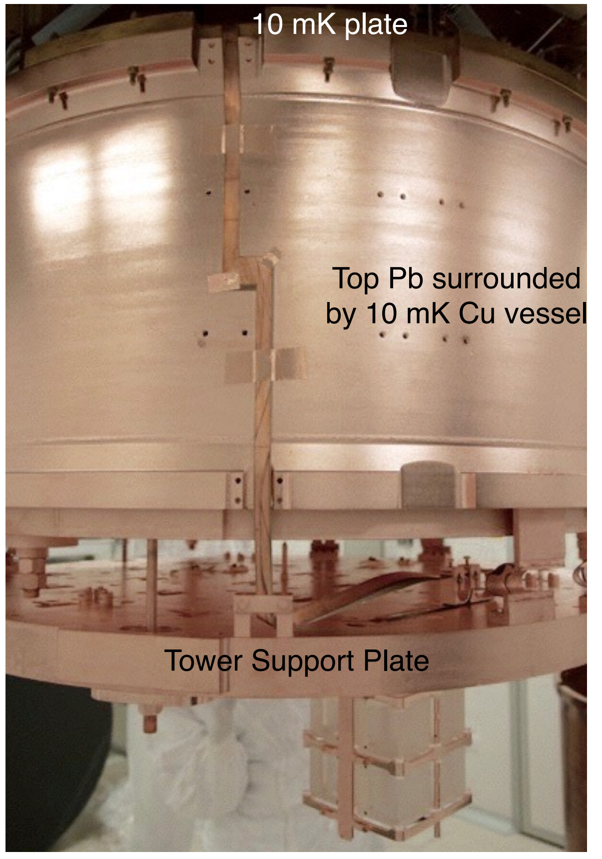
$$T_{1/2} > 2.7 \times 10^{24} y$$

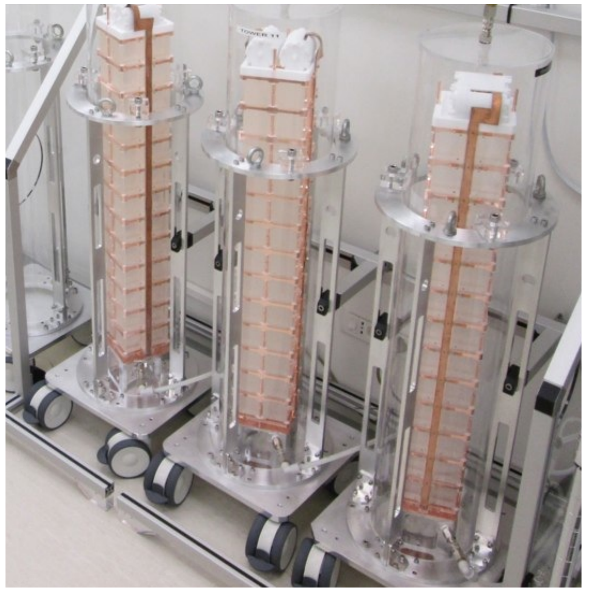
TeO_2 bolometers: CUORE

- All 988 crystals (206 kg ^{130}Te) built and assembled in towers
- Cryostat commissioning complete: stable base temperature, allows operation of bolometers at 6.3 mK
- Detector installation in spring 2016, data taking starts summer 2016
- Presently: bolometers and readout commissioning

- Background goal: 0.01 events/(kg keV y)
- Energy resolution goal: 5 keV at 2.6 MeV [FWHM]
- **Sensitivity aim:**

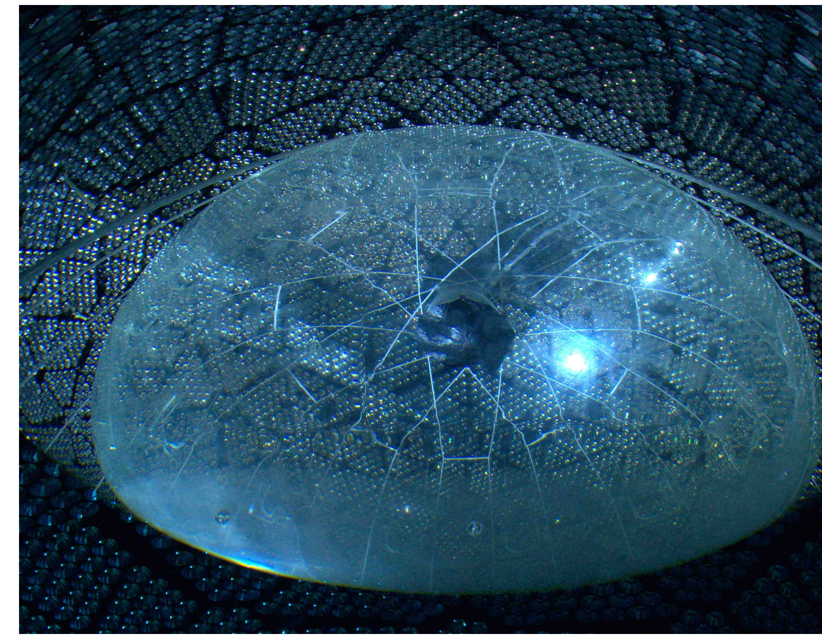
$$T_{1/2} \sim 9.5 \times 10^{25} y$$



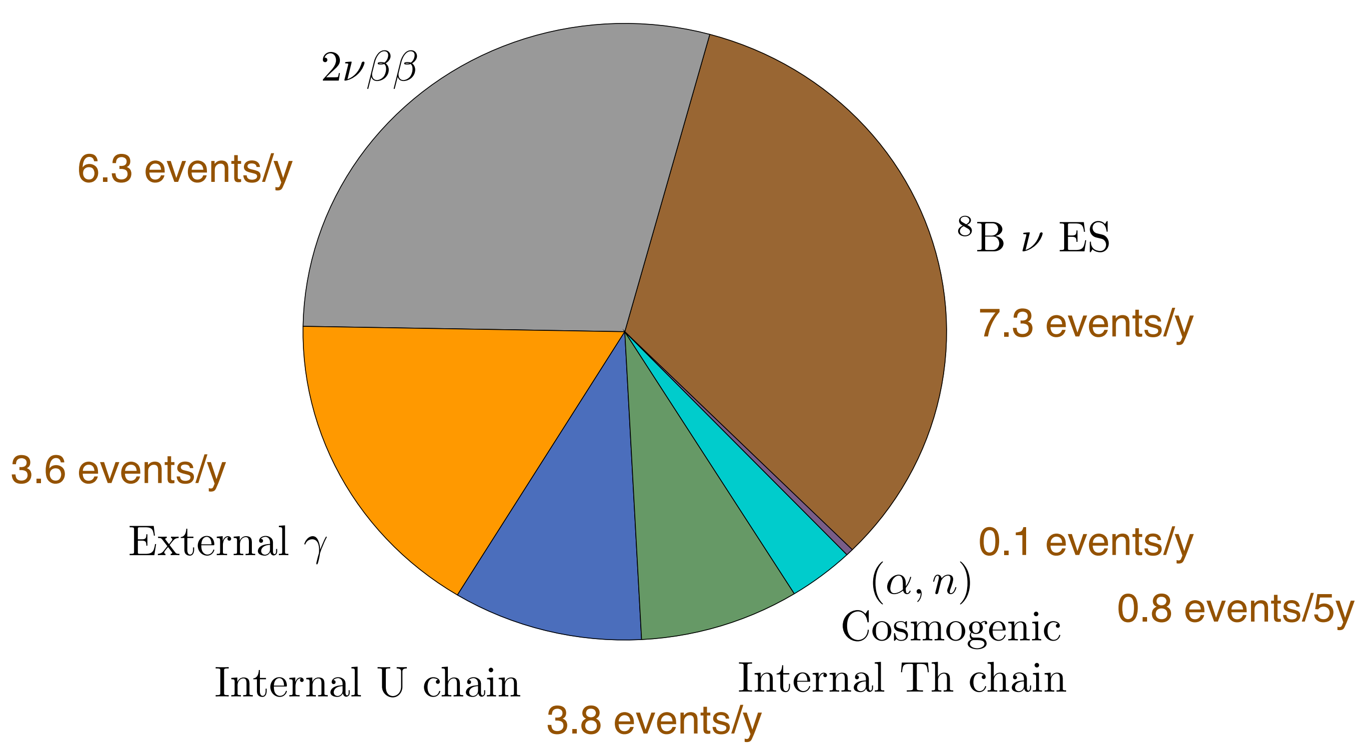


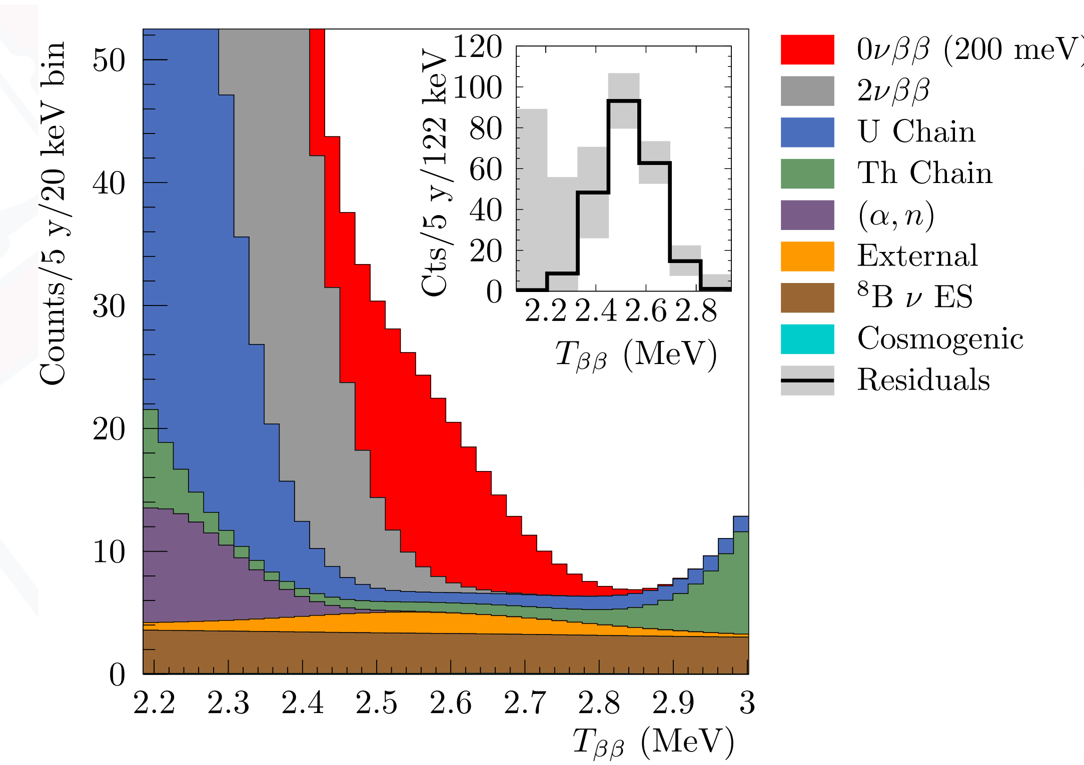
^{130}Te in liquid scintillator: SNO+

- First phase: 0.3% natural Te (~ 800 kg ^{130}Te)
- Detector and cavity being filled with light water, full water in summer 2016 & run with water
- Fill LS in late 2016, load 0.3-0.5% Te in 2017
- Future: upgrade PMTs and 3% load -> to cover inverted hierarchy scenario



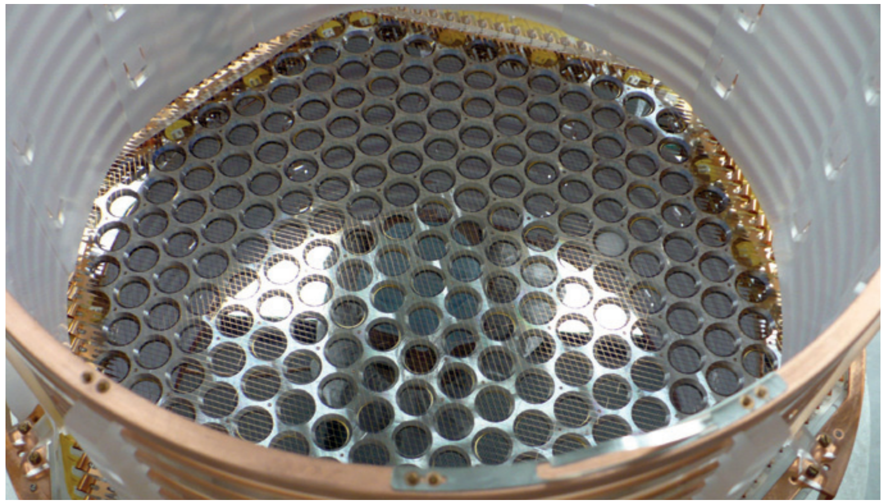
Expected backgrounds in SNO+

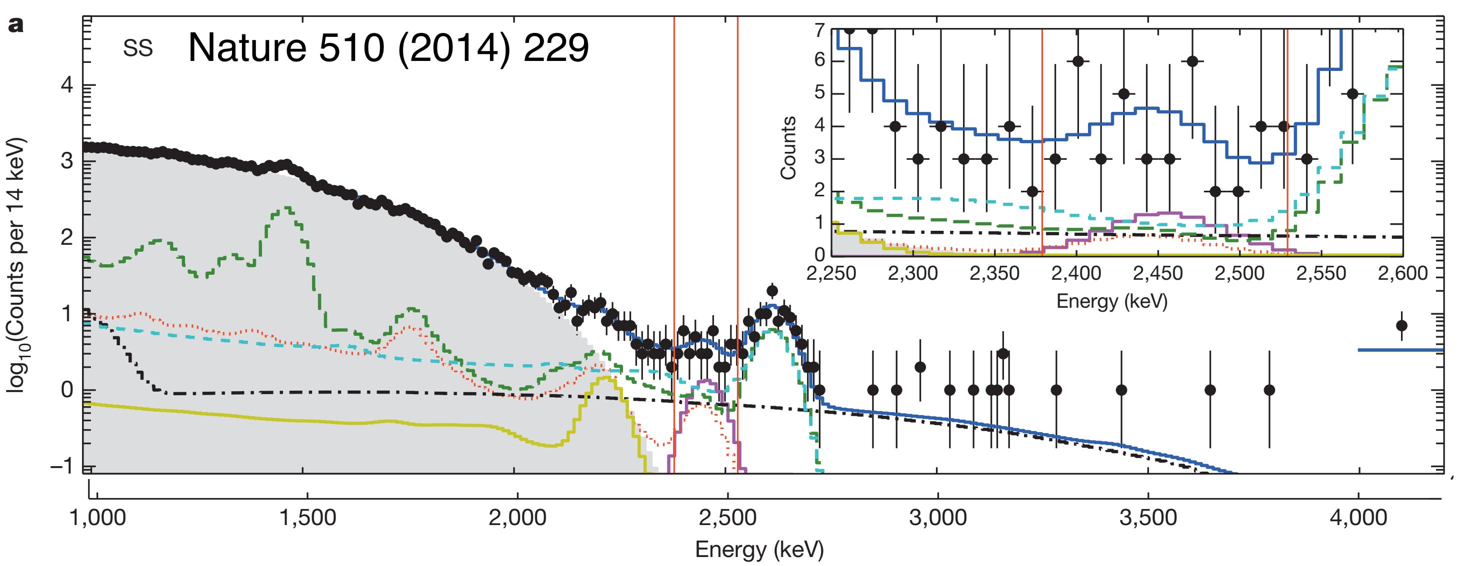




Liquid xenon TPC: EXO-200

- 110 kg LXe (80.6% ^{136}Xe) in active volume
- After WIPP accident: cleanup/repair effort; cooling & filling LXe TPC in winter 2015/16
- Data taking since Jan 31, 2016
- Hardware improvement to achieve 1% energy resolution at Q-value (minimise APD noise)
- Deradonator to reduce backgrounds in ROI

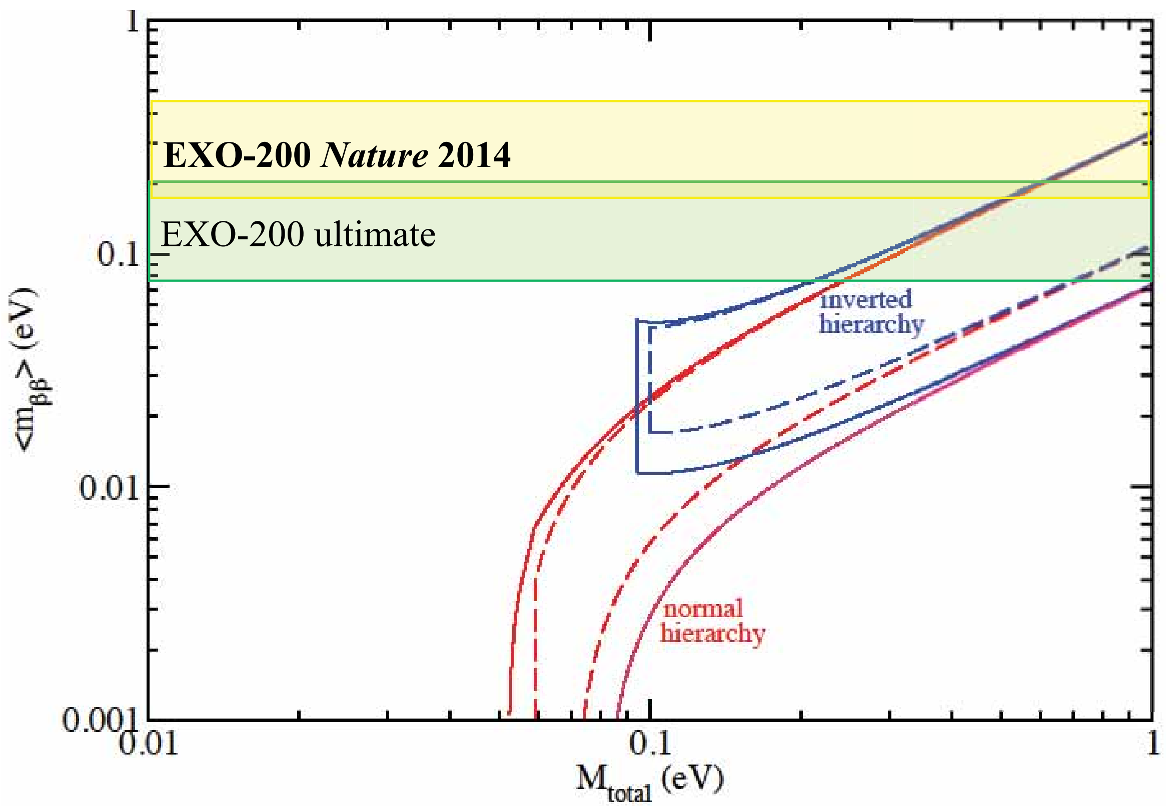




$$T^{0\nu}_{1/2} > 1.1 \times 10^{25}\,\mathrm{y}\,(90\%\mathrm{C.L.})$$

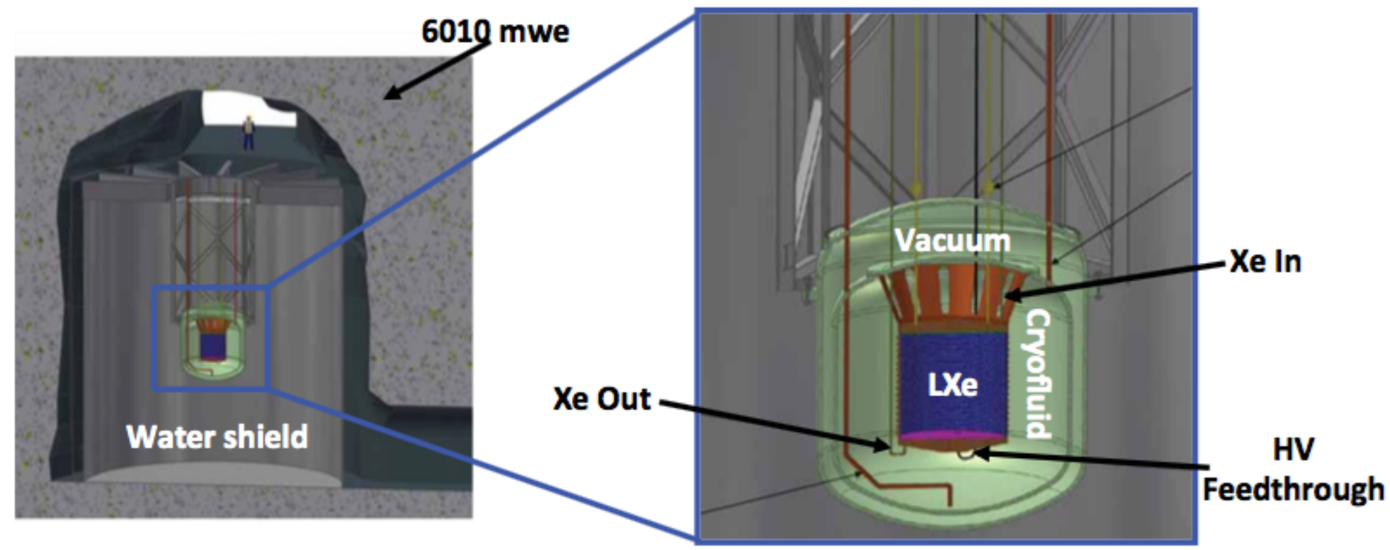
$$m_{\beta\beta} < 0.19 - 0.45\,\mathrm{eV}$$

Moriond, March 2016

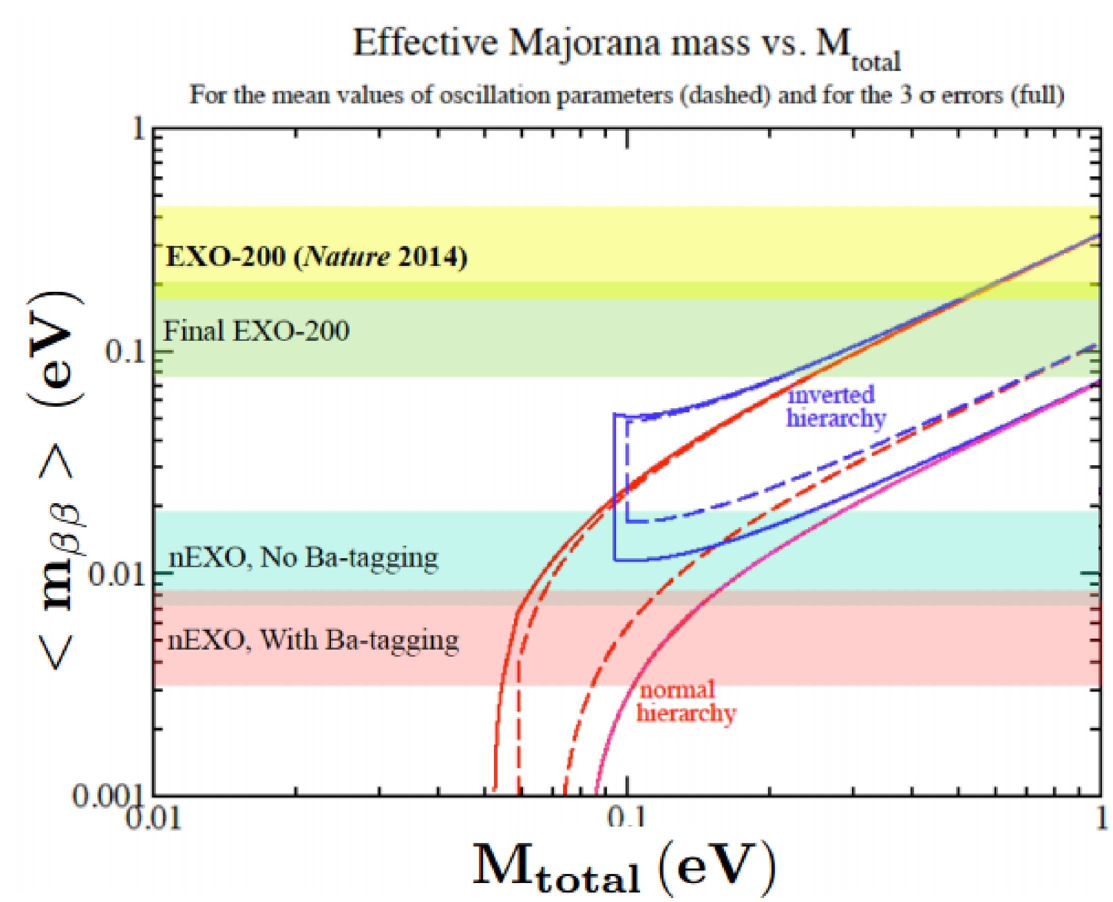


Liquid xenon TPC: nEXO

- Detector 50 x size of EXO
- 5 tonnes enriched LXe
- Proposed location SNOLAB cryopit
- R&D in progress



Parameter	nEXO	EXO-200
Fiducial mass (kg)	4780	98.5
Enrichment (%)	80-90	80
Data taking time (yr)	5	5
Energy resolution @ $Q_{\beta\beta}$ (keV)	58	88 (58)
Depth (m.w.e)	6010	1500
Background within FWHM of endpoint (events/yr/mol_{136})	6.1×10^{-4}	0.022 (0.0073)
Background within FWHM of endpoint inner 3000kg (events/yr/mol_{136})	1.6×10^{-4}	



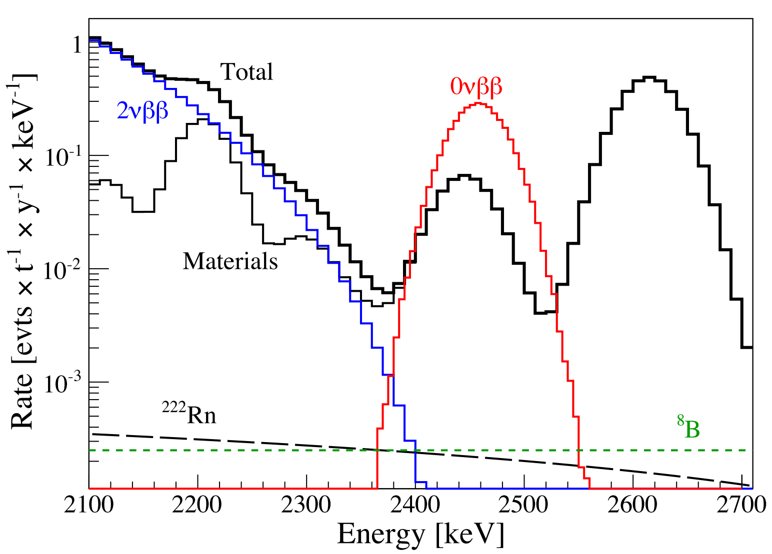
$$T_{1/2} \sim 6.6 \times 10^{27} y$$

Liquid xenon TPC: DARWIN

- **50 tonnes ^{nat}Xe, 8.9% ^{136}Xe,**
- **Sensitivity (140 t y exposure, ^{nat}Xe)**

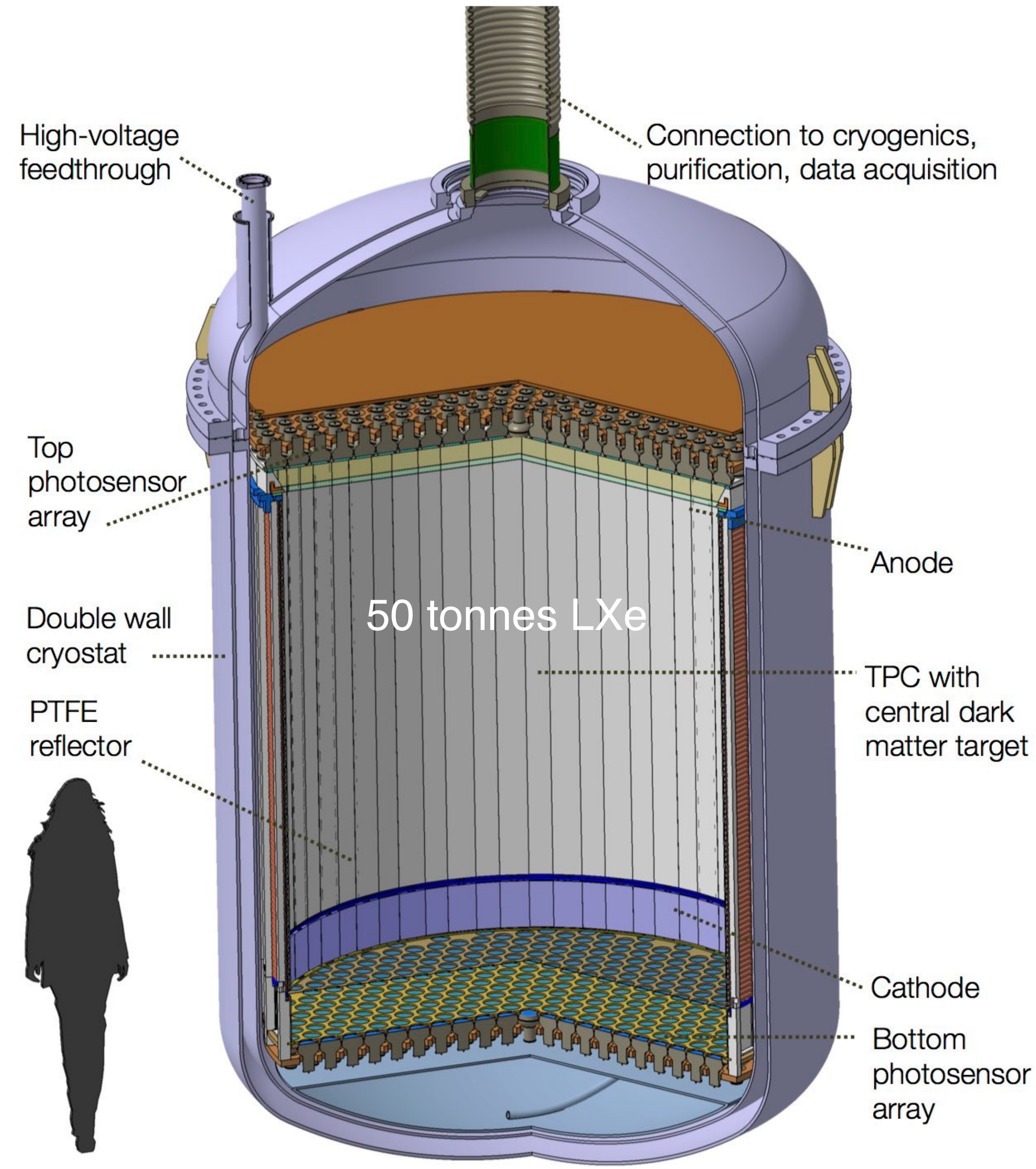
$$T_{1/2} \sim 8.5 \times 10^{27} y$$

- Assumptions:
  - ^{222}Rn: 0.1 μBq/kg (~ 0.036 events/(t y))
  - (^{8}B rate is ~ 0.036 events/(t y))
  - sigma/E = 1% at Q-value
  - materials BG: sub-dominant



MC simulation of 20 t LXe detector, here 6 t ^{nat}Xe fiducial mass

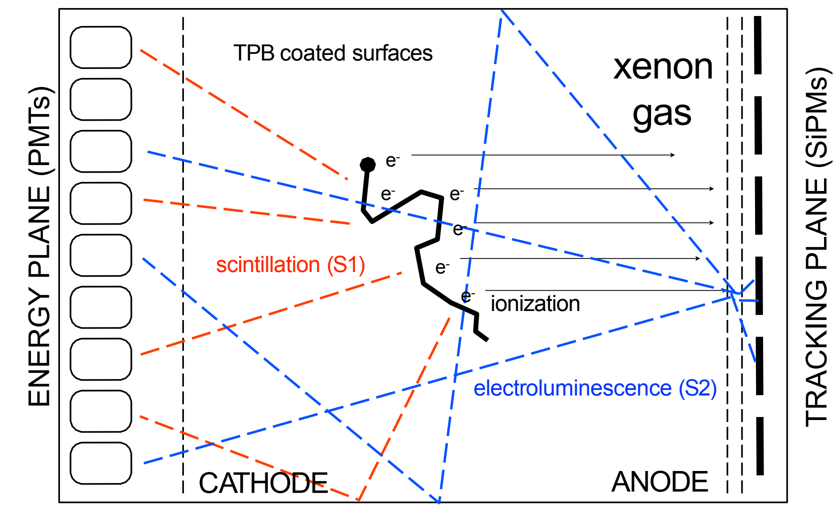
LB et al., JCAP 1401, 2014

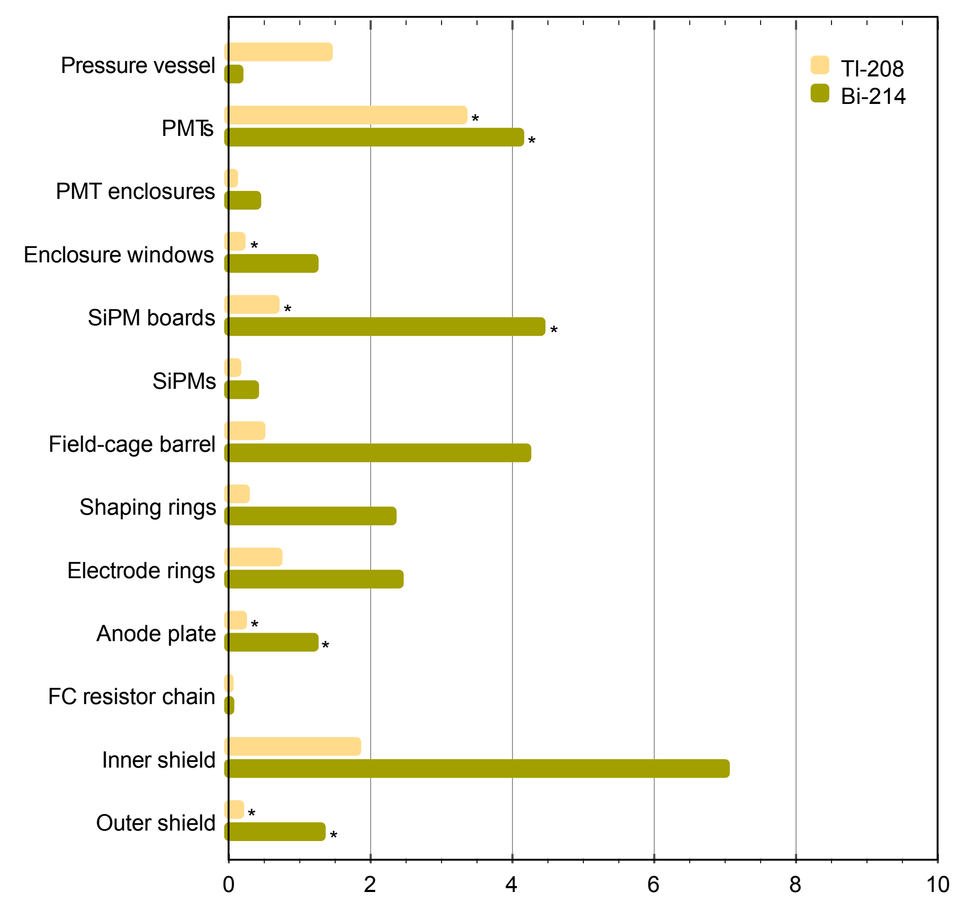


High pressure xenon TPC: NEXT

- Goal: 100 kg ^{136}Xe (90% enriched) HP (15 bar) Xe TPC
- **Tracking capabilities and < 1% (FWHM) resolution**
- NEW: 10 kg, 2015-2017, now commissioning run at LSC
- NEXT-100: 100 kg, 2018-2020
- Background: 4 x 10^{-4} events/(kg keV y)
- **Sensitivity aim:**

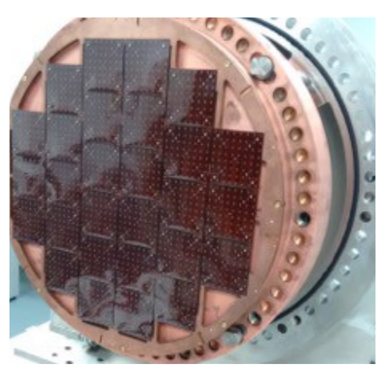
$$T_{1/2} \sim 5 \times 10^{25} y$$





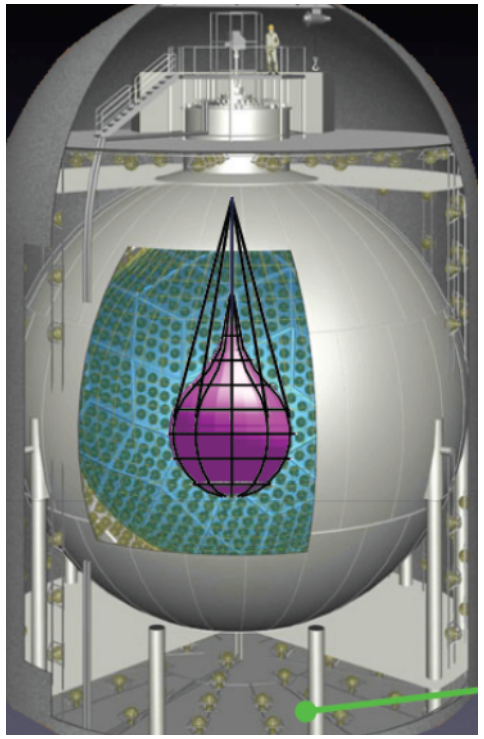
UCLA DM February 2016


NEW at Canfranc


Tracking plane


Energy plane

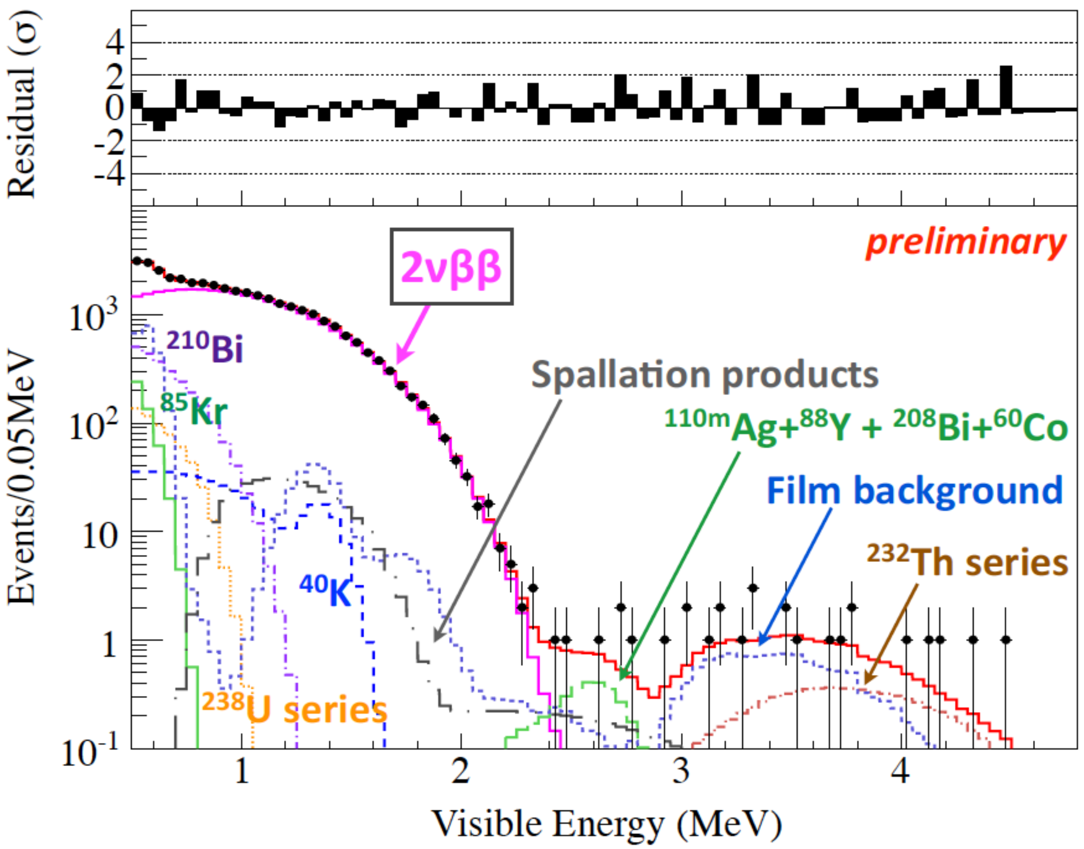
^{136}Xe in liquid scintillator: KamLAND-Zen



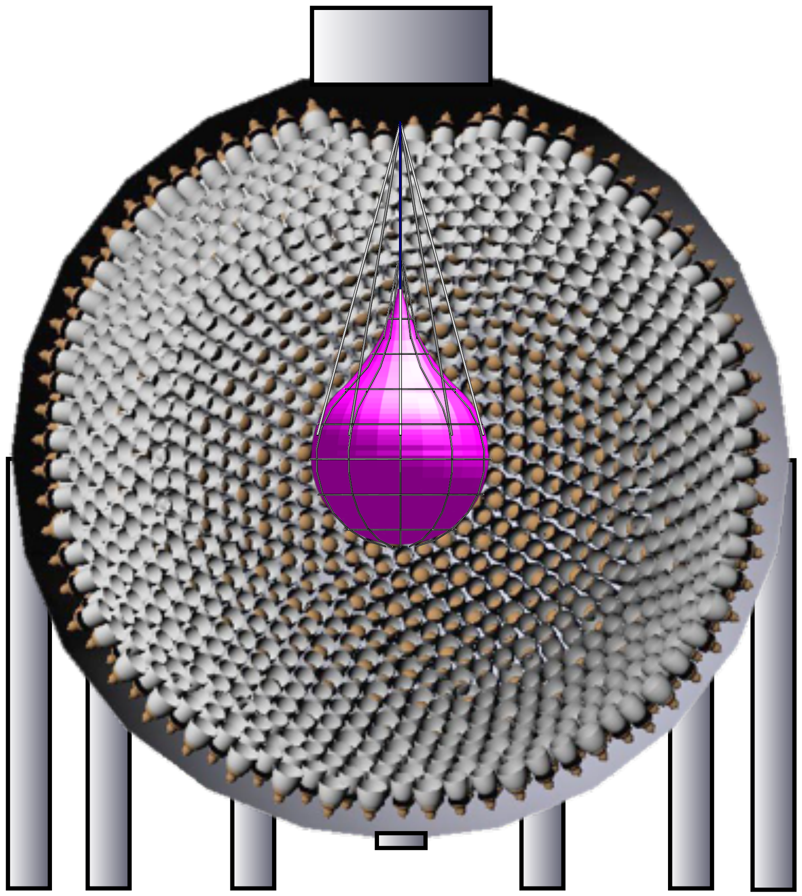
- Mini-balloon with ^{136}Xe-loaded LS in KamLAND
- Phase 1+2 (179 kg + 383 kg):
- **$T_{1/2} > 2.6 \times 10^{25}$ y (90% CL)**

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

- New mini-balloon construction in summer 2015
- Larger LS volume: 800 kg ^{136}Xe, lower backgrounds
- Start 800 kg phase in summer 2016
- **Sensitivity: 2×10^{26} yr after 2 years exposure**



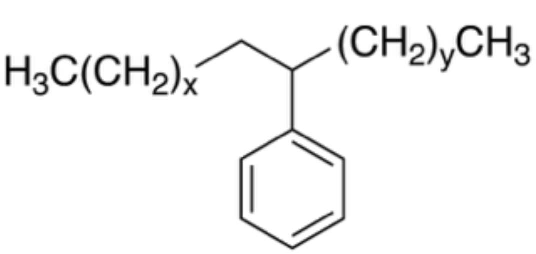
^{136}Xe in liquid scintillator: KamLAND2-Zen



FroST, March 2016

- 1000 kg enriched Xe
- Photo-coverage: > x 2
- Light collection efficiency: > x 1.8
- New liquid scintillator: x 1.4 (12 photons/keV)

$$\sigma(2.6\,\mathrm{MeV}) = 4\% \longrightarrow < 2.5\%$$

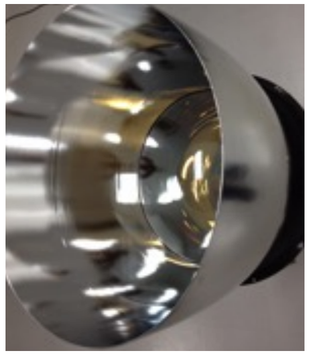


n = x + y = 10–13

Linear alkylbenzene

Goal for 5 years of data:

$$\langle m_{\beta\beta} \rangle \sim 20\,\mathrm{meV}$$

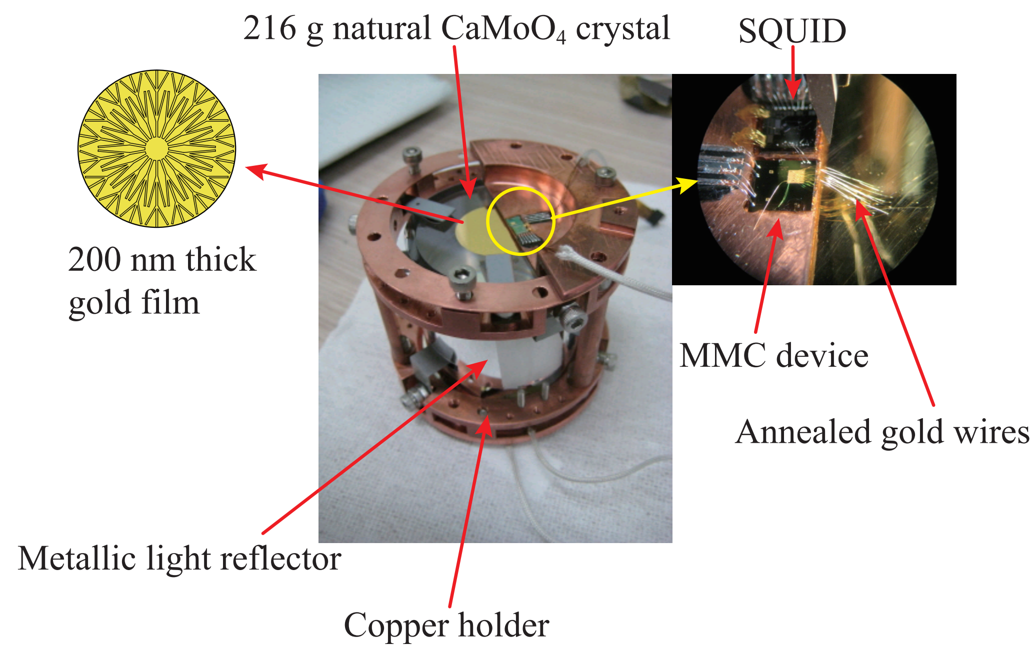


Winstone cone

High QE PMTs

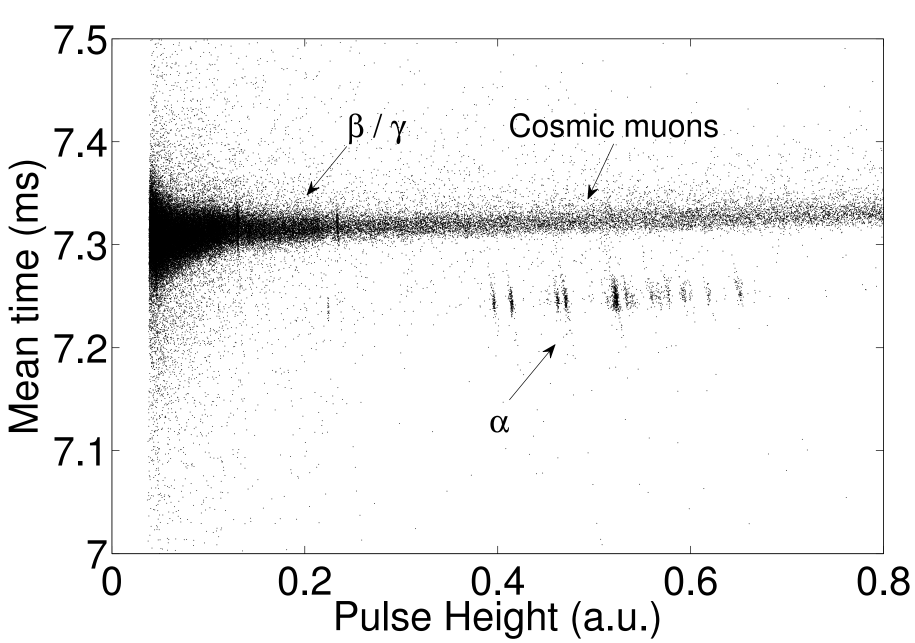
Scintillating bolometers: AMoRE

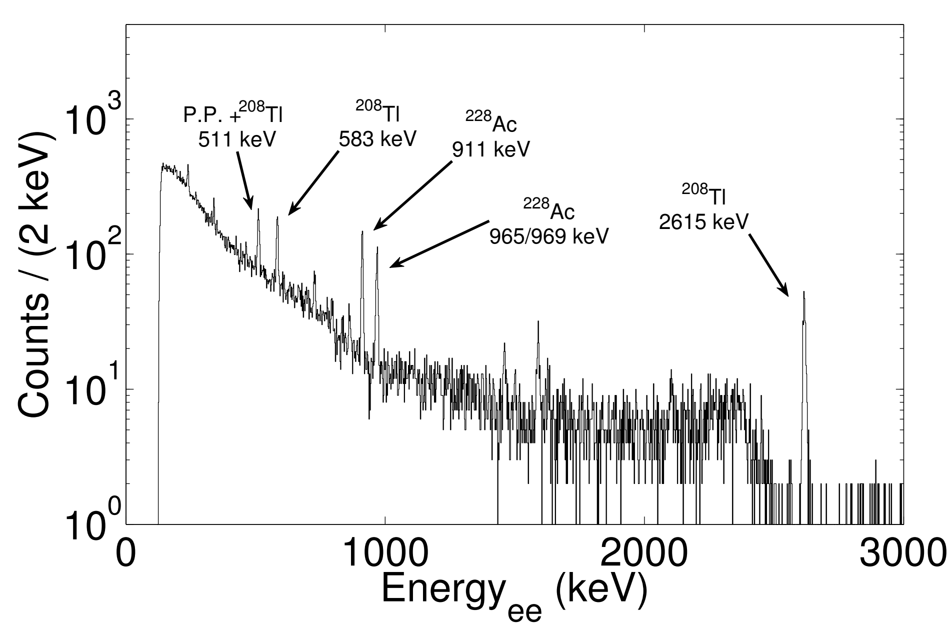
- Measure both heat and light: particle discrimination and background rejection
- $^{40}Ca^{100}MoO_4$ in 2 stages:
- 10 kg (2016) —> 200 kg of crystals (2018-2022)
- Resolution (now): 11 keV at 2.6 MeV [FWHM]



$$\langle m_{\beta\beta} \rangle \sim 20 - 50\,\mathrm{meV}$$

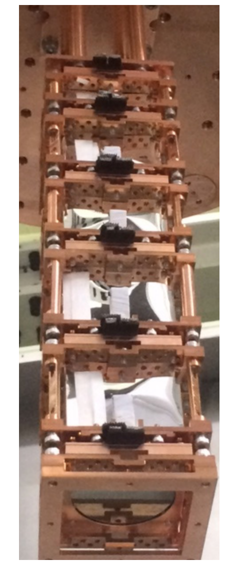
G.B. Kim et al., arXiv:1602.07401

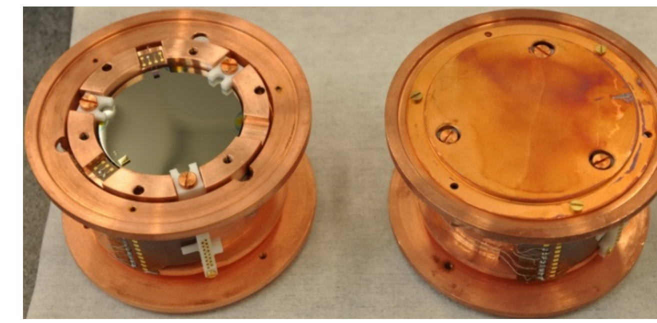




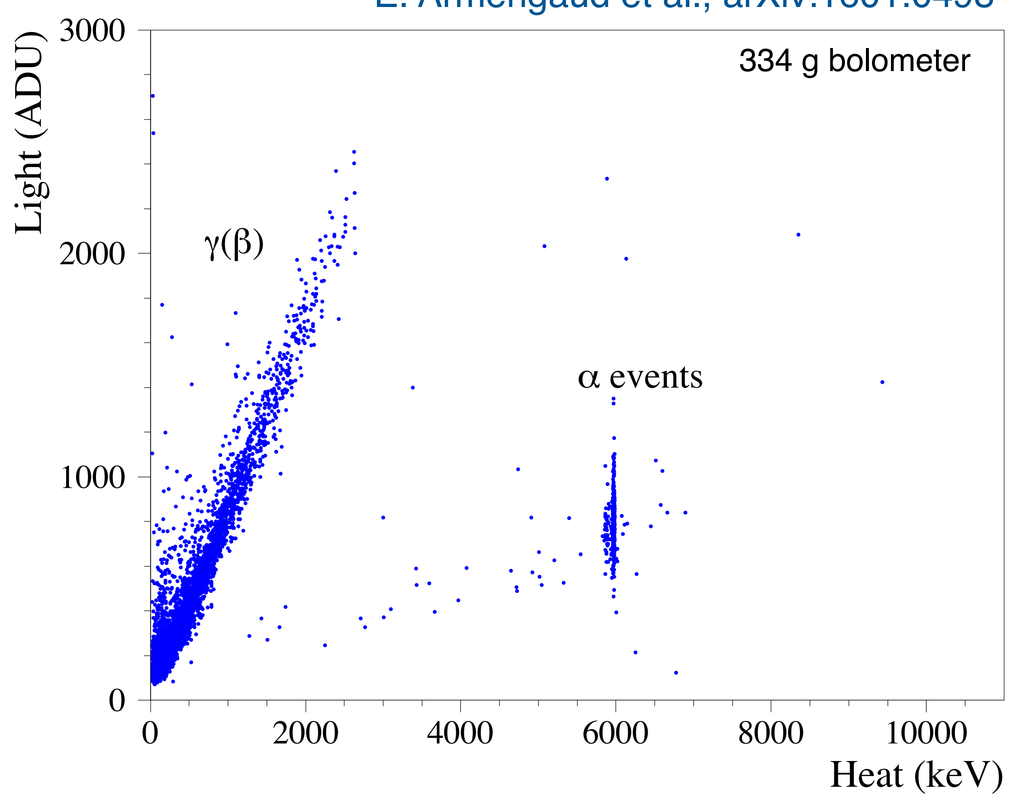
Scintillating bolometers: LUMINEU & LUCIFER

- LUMINEU: $Zn^{100}MoO_4$ scintillating bolometers
- ~ few keV resolution, initially 1 kg - 10 kg
- Background goal: 0.5 events/(ton keV y) in ROI
- LUCIFER: enriched $Zn^{82}Se$ bolometers, 15 kg
- CUPID: ton-scale bolometric experiment with light readout

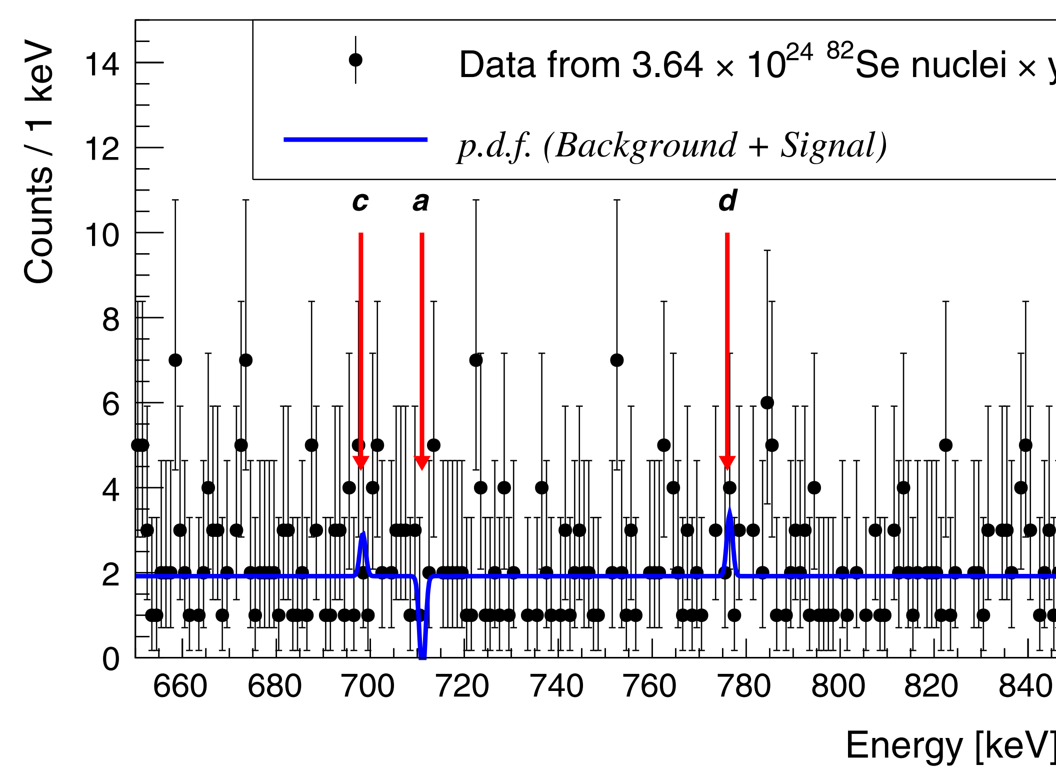




E. Armengaud et al., arXiv:1601.0498



J.W. Beeman et al., EPJ-C (2015) 75

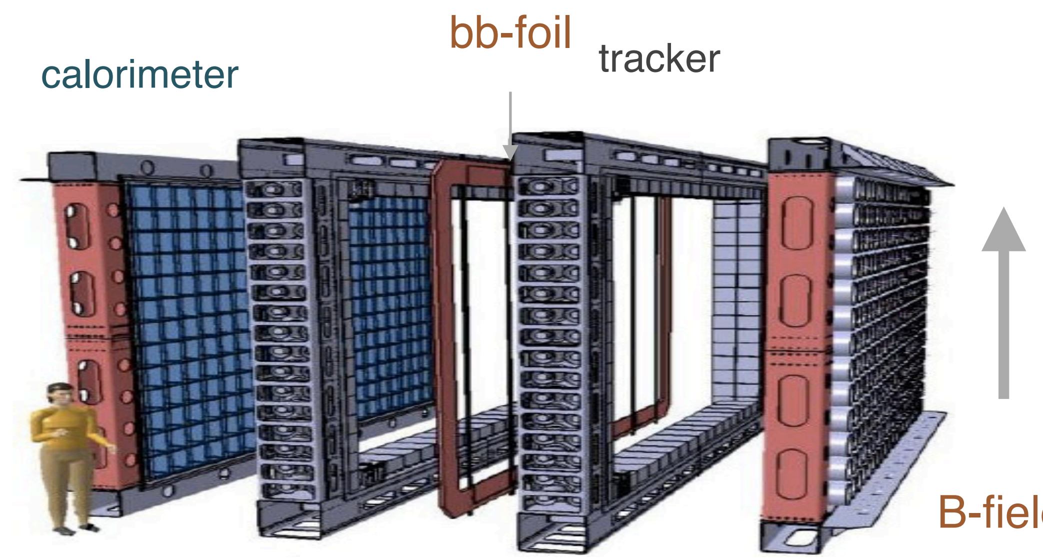


Tracking: SuperNEMO

- Separate tracker, calorimeter and source
- Source foil: ^{82}Se (^{150}Nd, ^{48}Ca), 100 kg
- **Aim:** $T_{1/2} > 1 \times 10^{26} y$
- **Demonstrator: 7 kg ^{82}Se, 20 kg y exposure:**

$$T_{1/2} > 6.6 \times 10^{24} y$$

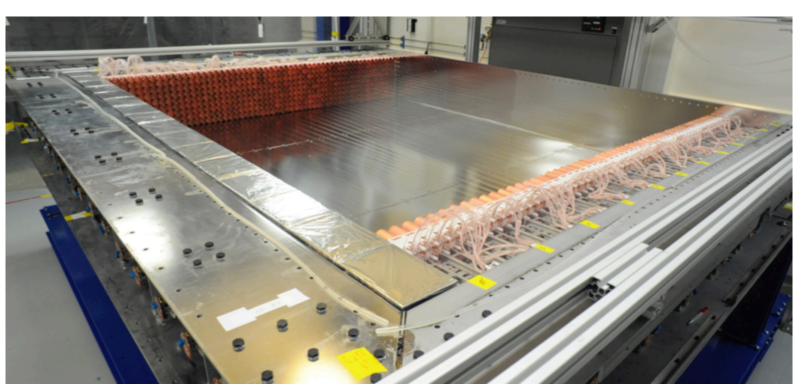
- **Status:** in assembly, first demonstrator module installed and commissioned in 2016
  - 19 additional modules in 2017



demonstrator module

	NEMO-3	SuperNEMO
Mass (kg)	7	100
Energy resolution @ 3 MeV (%)	8	4
^{222}Rn in tracker (mBq/m^3)	~5	<0.15
^{214}Bi (nBq/g)	60-300	<10
^{208}Tl (nBq/g)	~100	<2
Tracking cells	6180	20x2034
Calorimeter blocks	1940	20x712
Total background (counts/keV/kg/yr)	$1.3 \cdot 10^{-3}$	$5 \cdot 10^{-5}$
$T_{1/2}^{0\nu\beta\beta}$ @ 90% C.L. (yr)	$>1.1 \cdot 10^{24}$	$>1 \cdot 10^{26}$
$\lvert m_{\beta\beta}\rvert$ (eV)	<0.33-0.87	<0.04-0.10

Vienna Conference of Instrumentation, 2016


tracker section

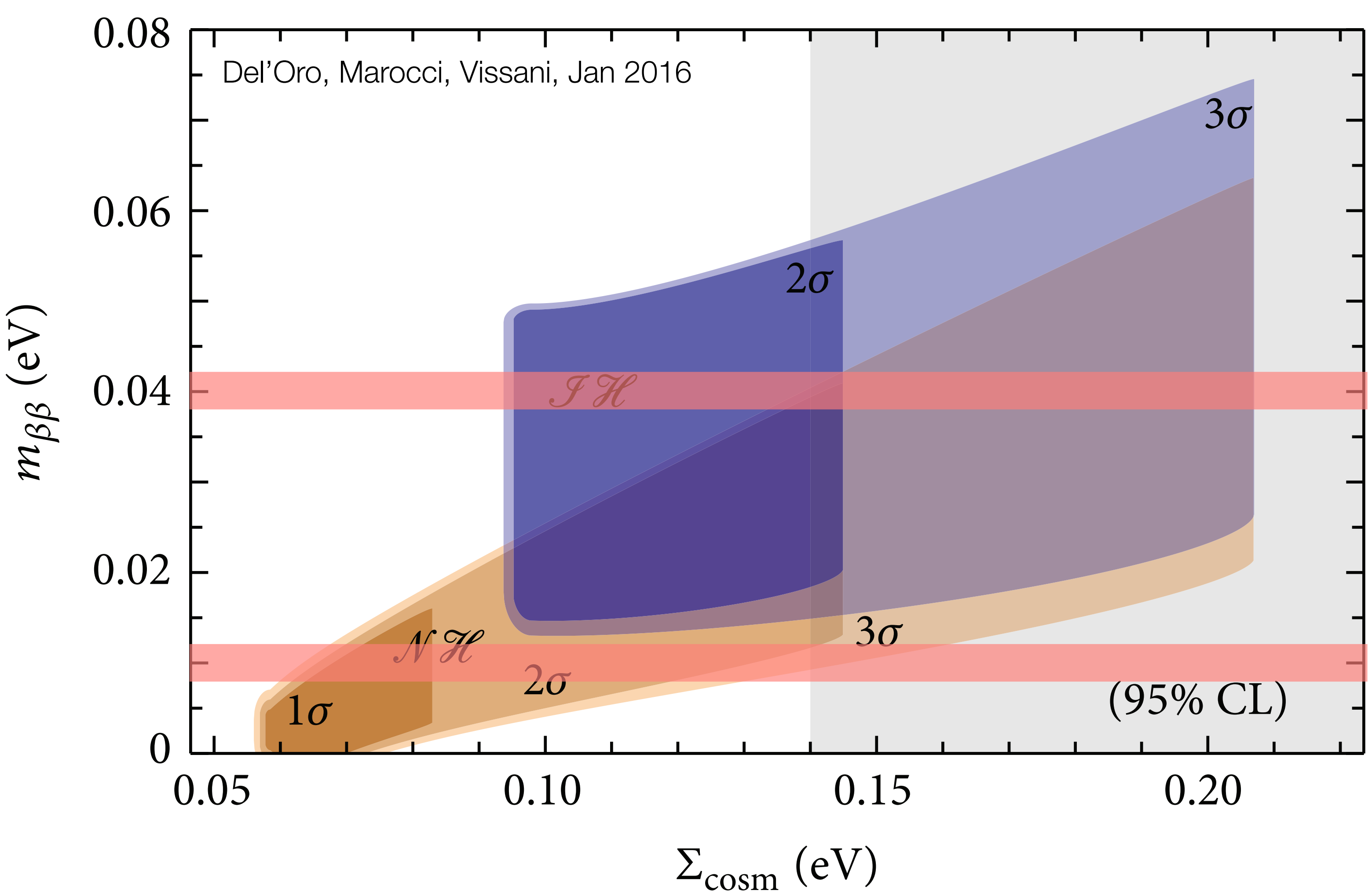

calorimeter

Outlook: the search continues

- Ton-scale experiments are required to explore the *inverted mass hierarchy* scale
- Several technologies (apart from HPGe) 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*

40 meV

10 meV



Experiments in construction

Future experiments (ton-scale)

The End