Invisibles Workshop, July 17, 2013

Status of Neutrinoless Double Beta Decay Experiments

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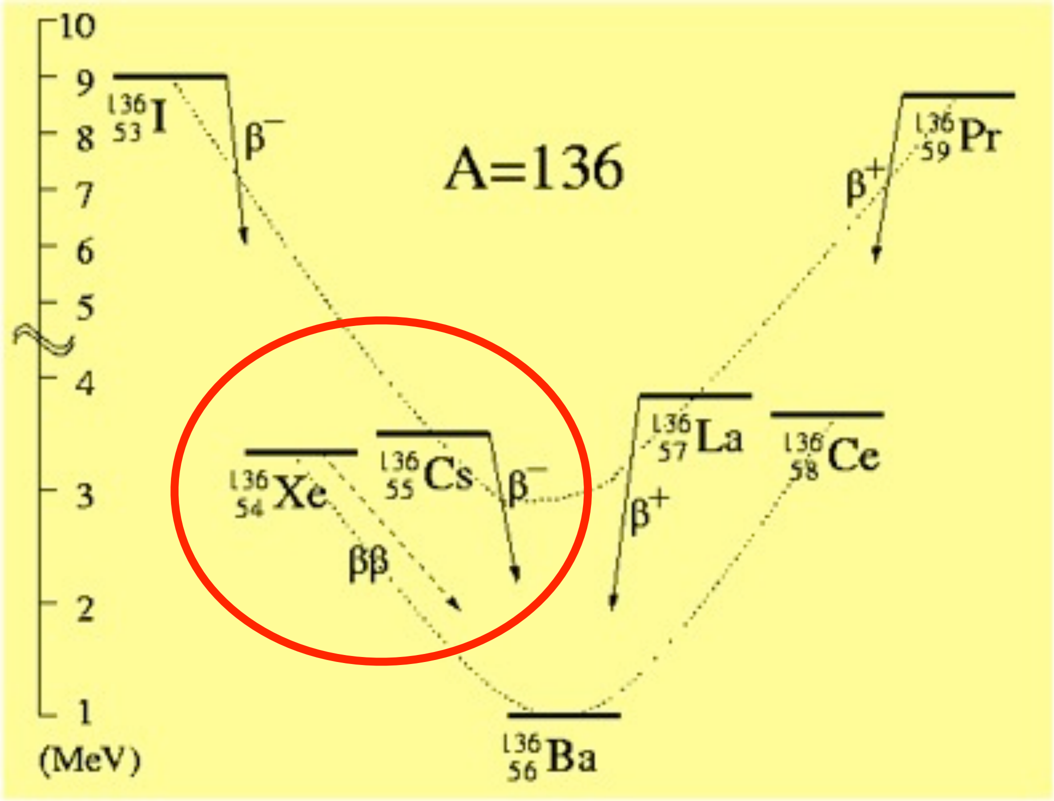
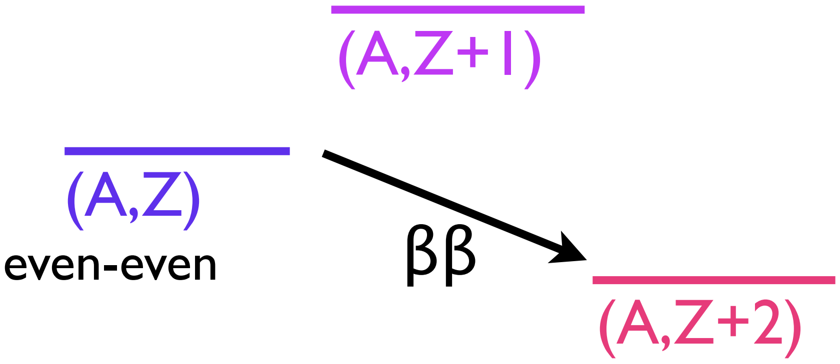
NIKHEF

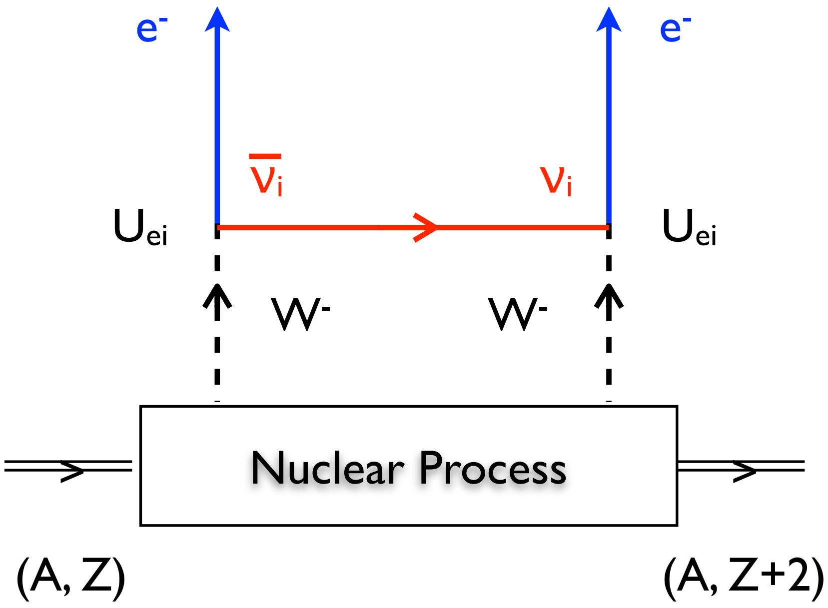
Double beta decay Isotopes





A second-order process only detectable if first-order beta decay is energetically forbidden

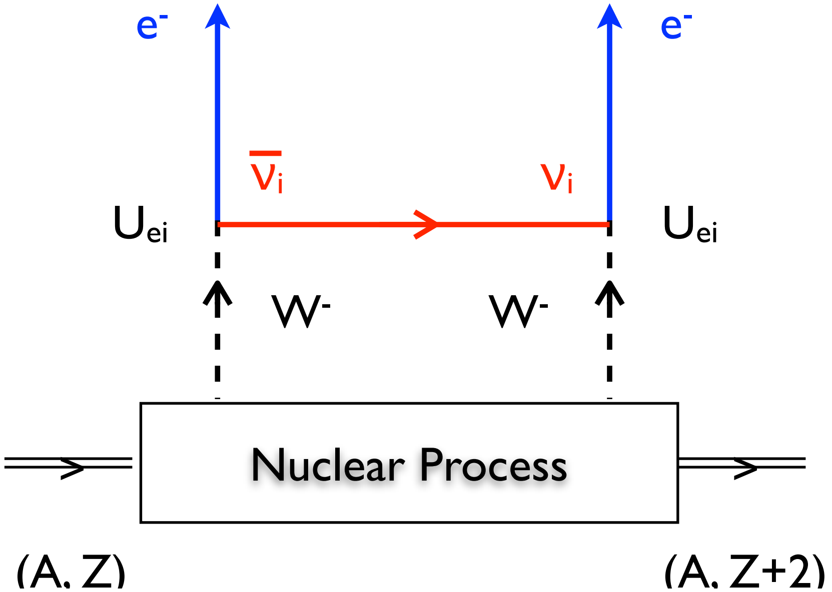
Neutrinoless Double Beta Decay



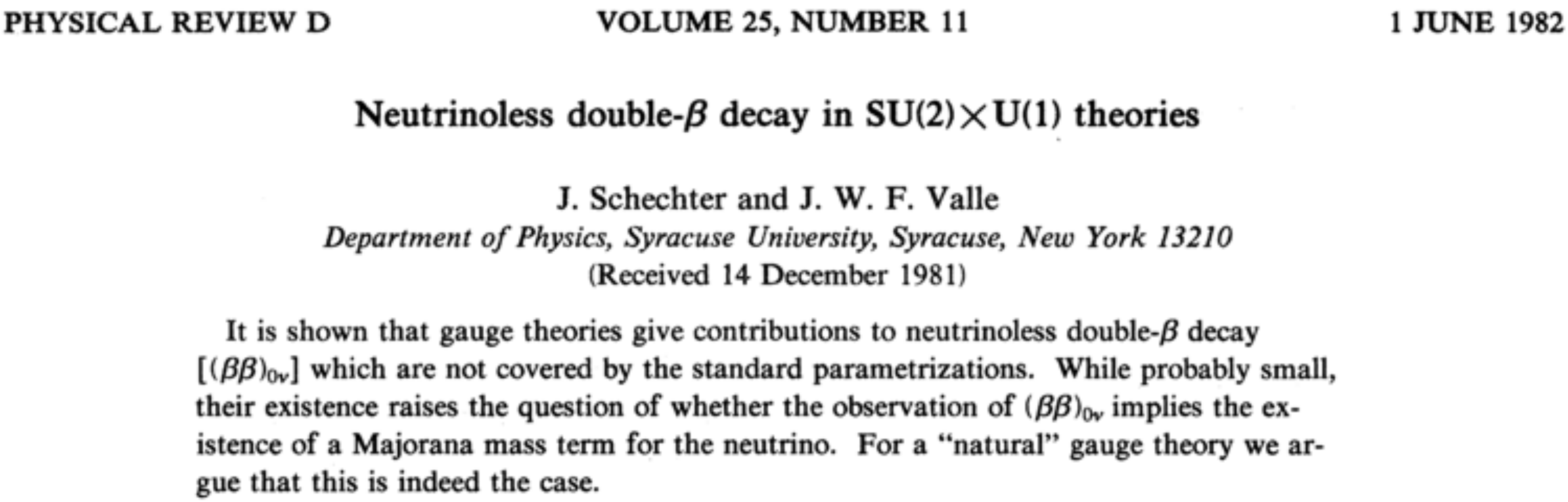
$$
\begin{aligned}
M_\nu &\neq 0 \\
|\Delta L| &= 2
\end{aligned}
$$

- Extremely rare process [W.H. Furry (1939): $T_{1/2} > 10^{16}$ yr]
- Requires massive Majorana neutrino
- Lepton Number Violation
    - Model dependent - Standard interpretation: light Majorana ν + SM interactions

Neutrinoless Double Beta Decay



$$\begin{aligned} M_\nu &\neq 0 \\ |\Delta L| &= 2 \end{aligned}$$



PHYSICAL REVIEW D VOLUME 25, NUMBER 11 1 JUNE 1982

Neutrinoless double-β decay in SU(2)$\times$U(1) theories

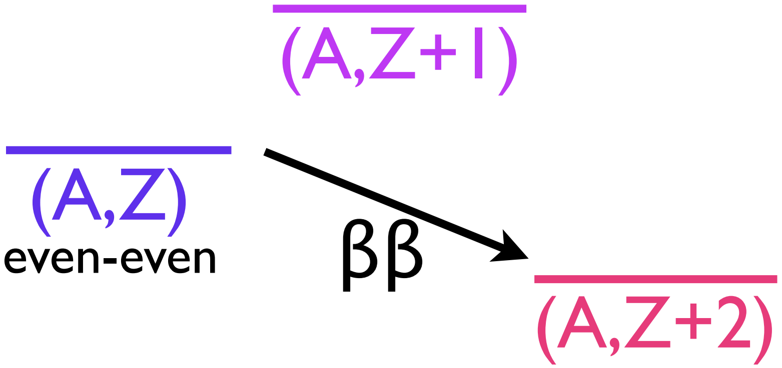
J. Schechter and J. W. F. Valle
Department of Physics, Syracuse University, Syracuse, New York 13210

(Received 14 December 1981)

It is shown that gauge theories give contributions to neutrinoless double-β decay [$(\beta\beta)_{0\nu}$] which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of $(\beta\beta)_{0\nu}$ implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed the case.

Candidate 0ν2β Nuclei

Candidates are even-even nuclei

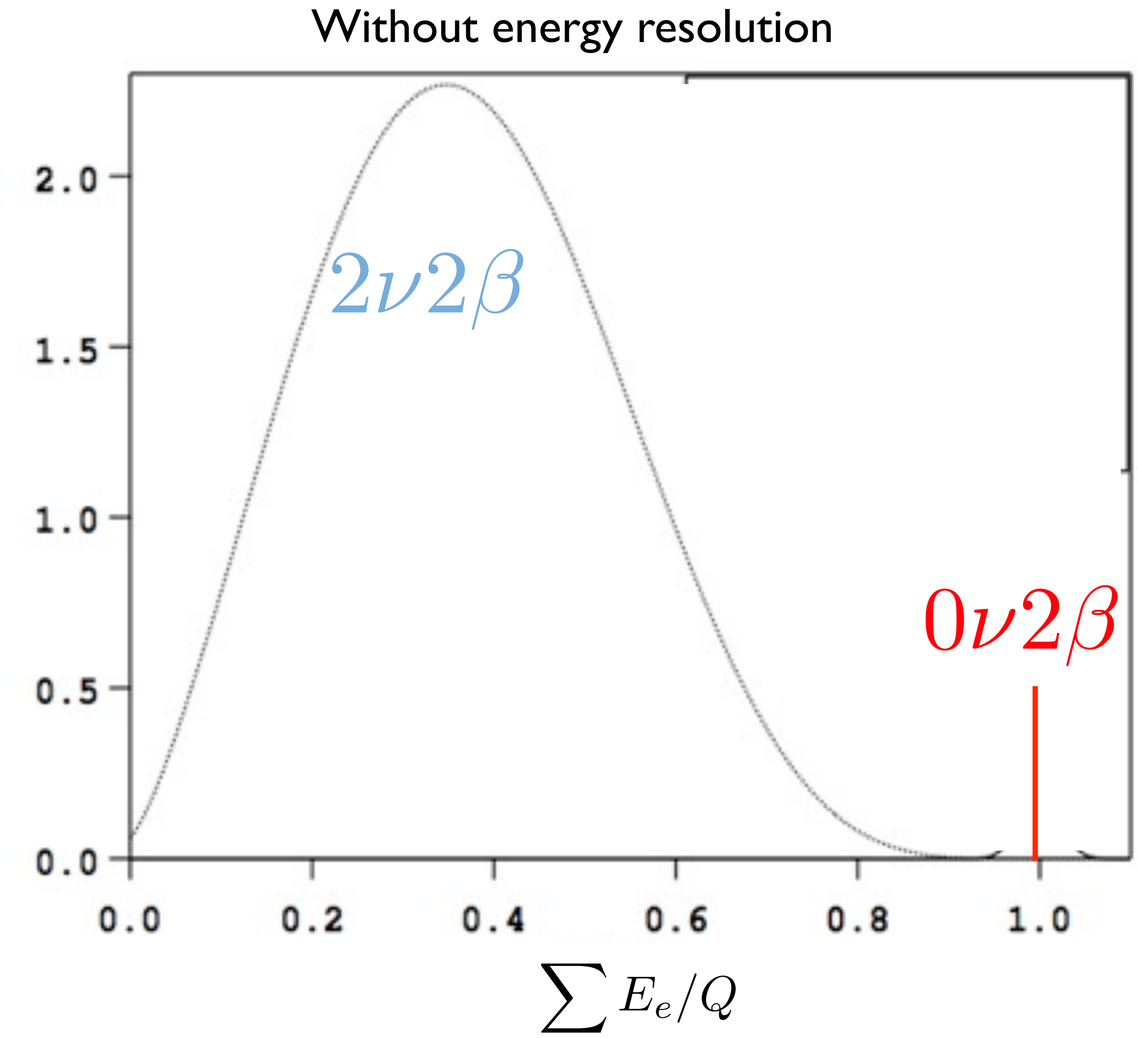


[Candidates with Q>2 MeV]

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

Natural abundance of 0ν2β candidates is low
→ enrichment necessary

Detecting 0ν2β Decay

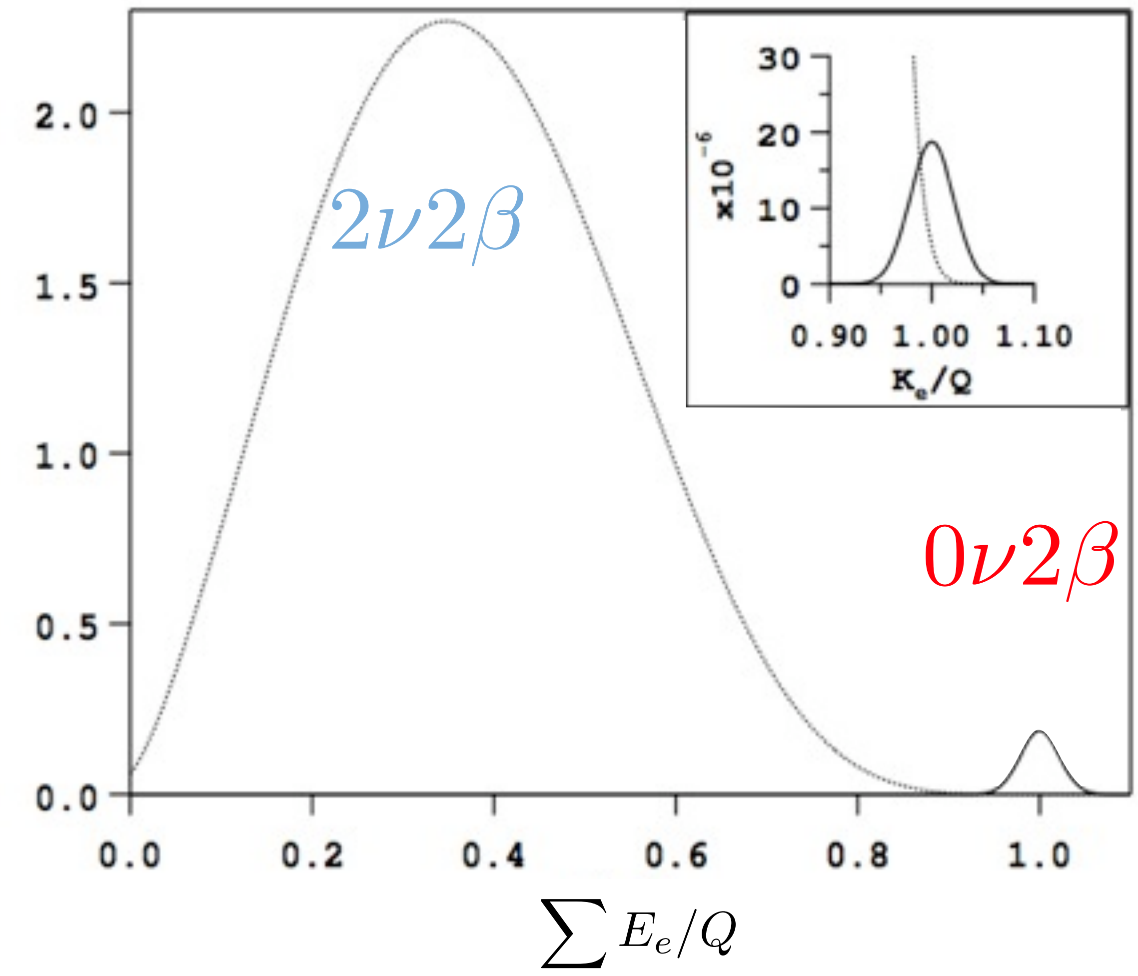


- General approach: detect the two final-state electrons

- Signature: Two simultaneous electrons with summed energy $Q_{\beta\beta}$, the Q-value for the ββ decay in the isotope of study

Detecting 0ν2β Decay

With energy resolution



- <u>General approach</u>: detect the two final-state electrons
- <u>Signature</u>: Two simultaneous electrons with summed energy $Q_{\beta\beta}$, the Q-value for the ββ decay in the isotope of study

2ν2β has been measured

$$(T^{2\nu}_{1/2})^{-1} = \underset{\substack{\uparrow \\ \text{Phase Space} \\ \text{factor}}}{G_{2\nu}}(Q,Z)|\underset{\substack{\nwarrow \\ \text{Nuclear} \\ \text{Matrix Element}}}{M_{2\nu}}|^2$$

- Conserves lepton number
- Does not discriminate between Dirac and Majorana neutrinos
- Not sensitive to neutrino mass scale
- Nevertheless: slow process!

Isotope	$T_{1/2}^{2\nu}$ [yr]
^{48}Ca	4.2±1.0 x 10^{19}
^{76}Ge	1.5±0.1 x 10^{21}
^{82}Se	0.92±0.07 x 10^{20}
^{96}Zr	2.0±0.3 x 10^{19}
^{100}Mo	7.1±0.4 x 10^{18}
^{116}Cd	3.0±0.2 x 10^{19}
^{128}Te	2.5±0.3 x 10^{24}
^{130}Te	0.9±0.1 x 10^{21}
^{136}Xe	**2.172±0.062 x 10^{21}**
^{150}Nd	7.8±0.8 x 10^{18}
^{238}U	2.0±0.6 x 10^{21}

What mass does 0ν2β measure?

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase Space factor:
Calculable

Nuclear Matrix Element:
Hard to calculate

Effective Majorana mass:

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

[coherent sum]

Where U_{ei} elements from the Lepton Mixing Matrix

$$U = \begin{array}{cc} & \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} & \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \end{array}$$

$$\times \operatorname{diag}\left(e^{i\alpha_1/2},\ e^{i\,\alpha_2/2},\ 1\right) .$$

What mass does 0ν2β measure?

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2 \boxed{\langle m_{\beta\beta}\rangle^2}$$

Phase Space factor:
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Nuclear Matrix Element:
Hard to calculate

Interesting physics

Effective Majorana mass:

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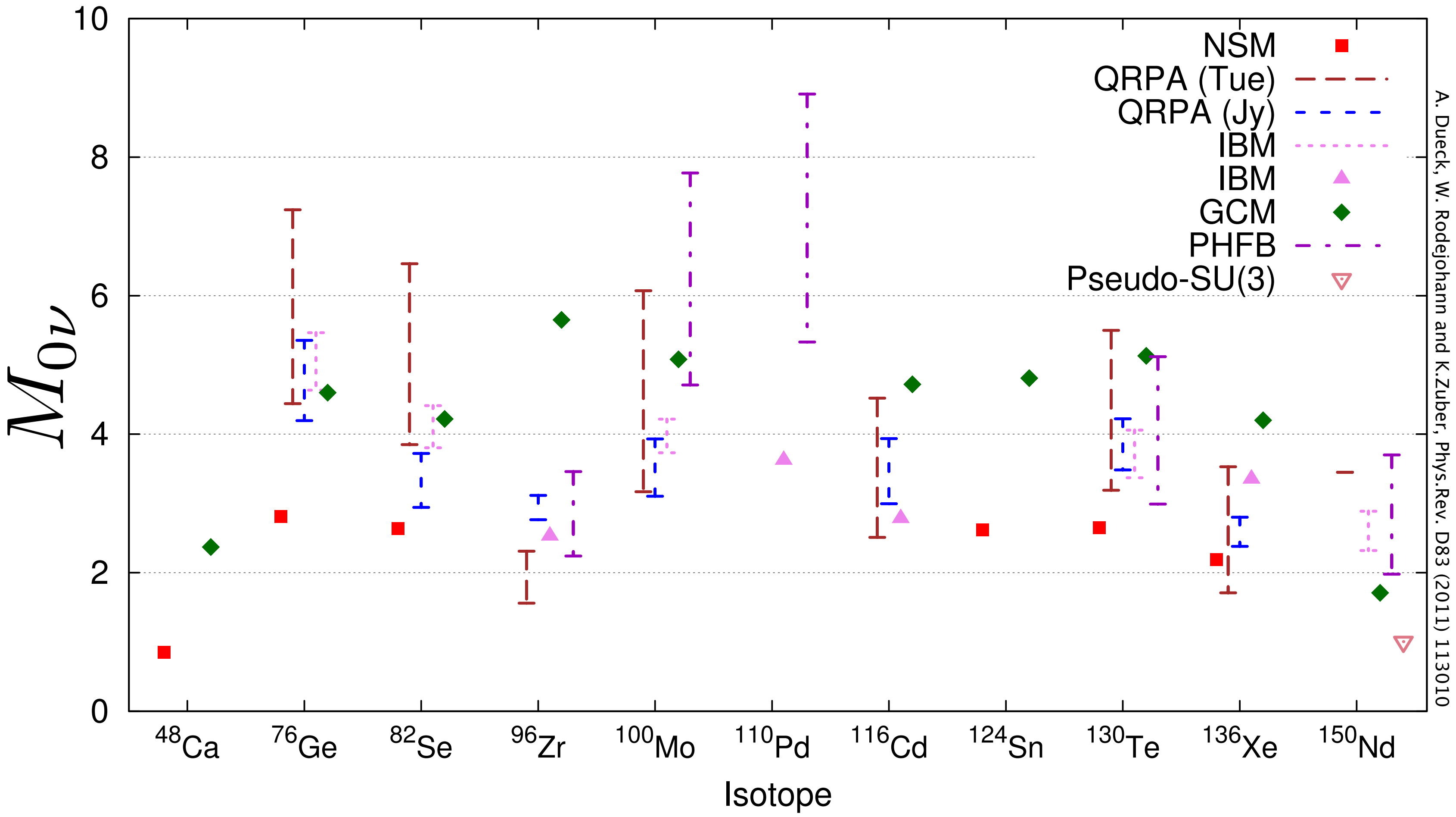
Nuclear Matrix Elements



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

Past 7-8 years: much better agreements between various models (e.g. NSM and QRPA)

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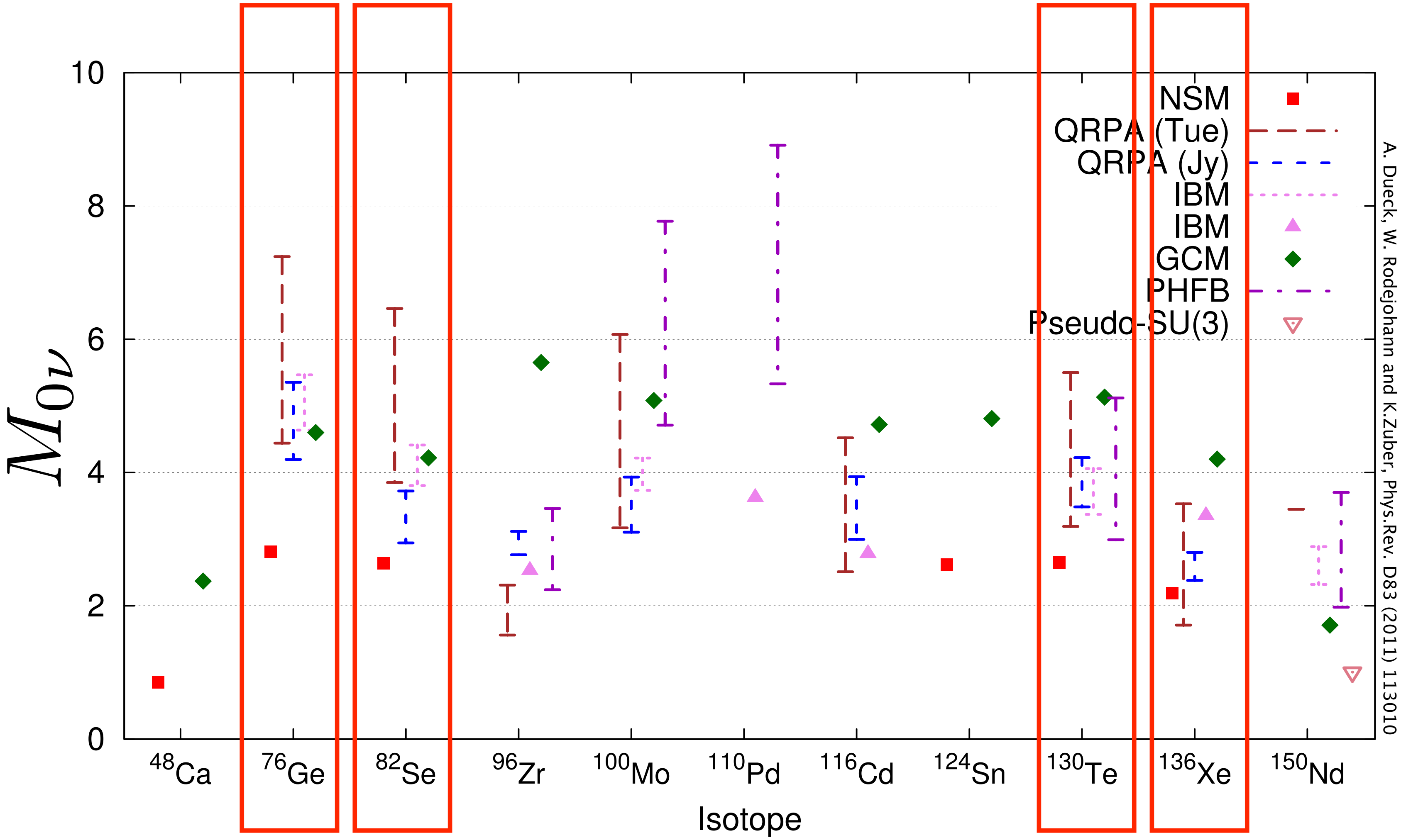

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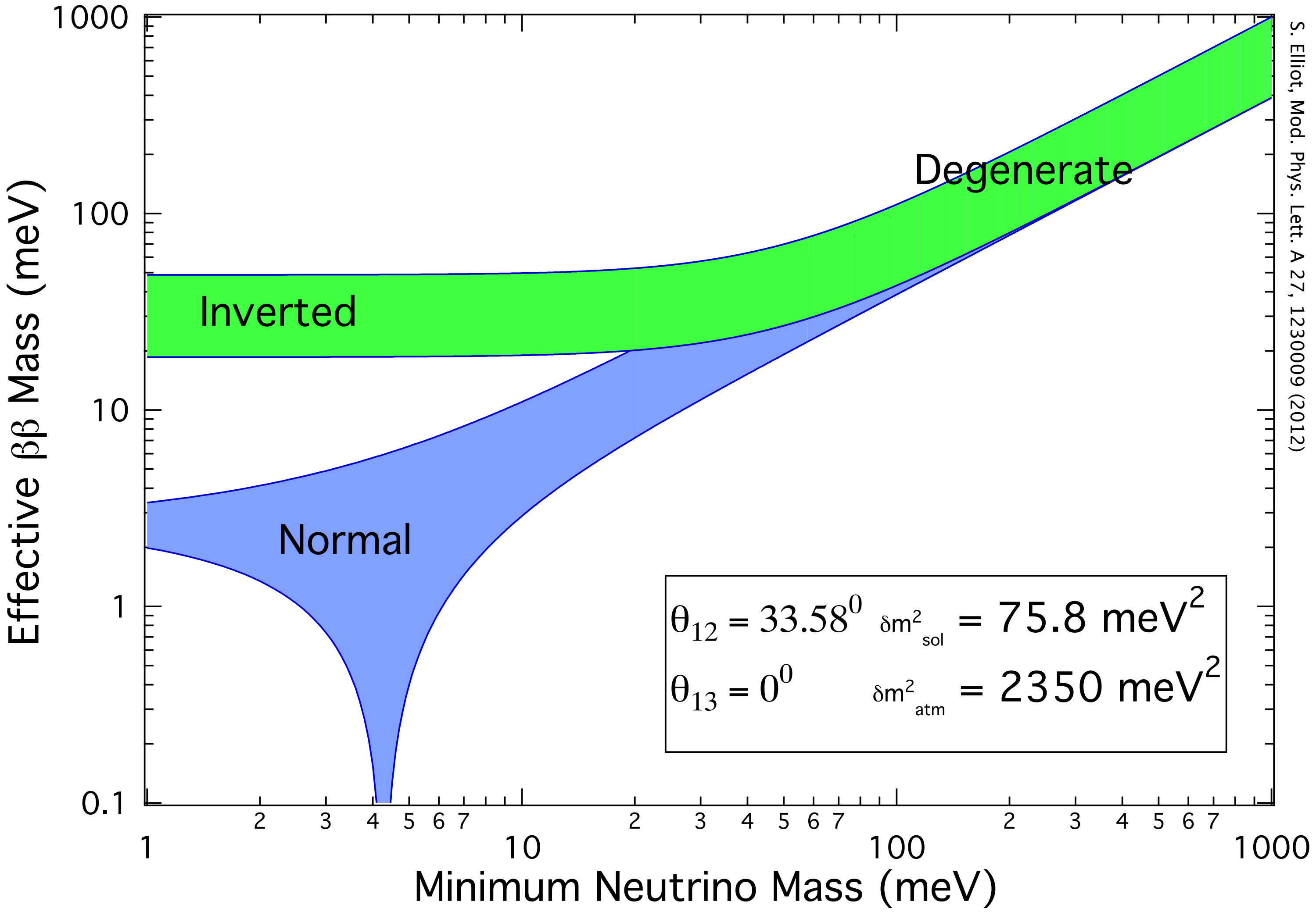
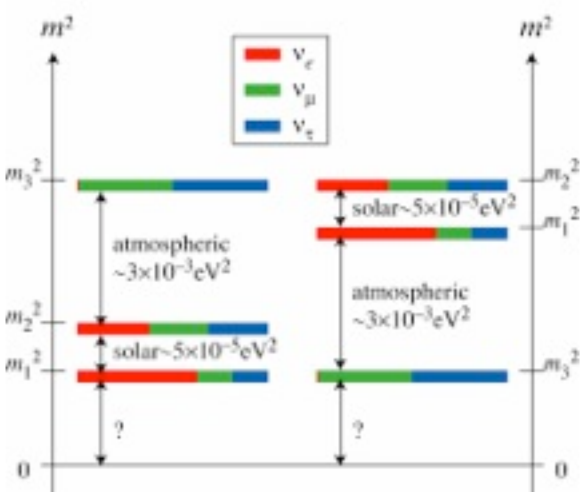
Effective Majorana Mass

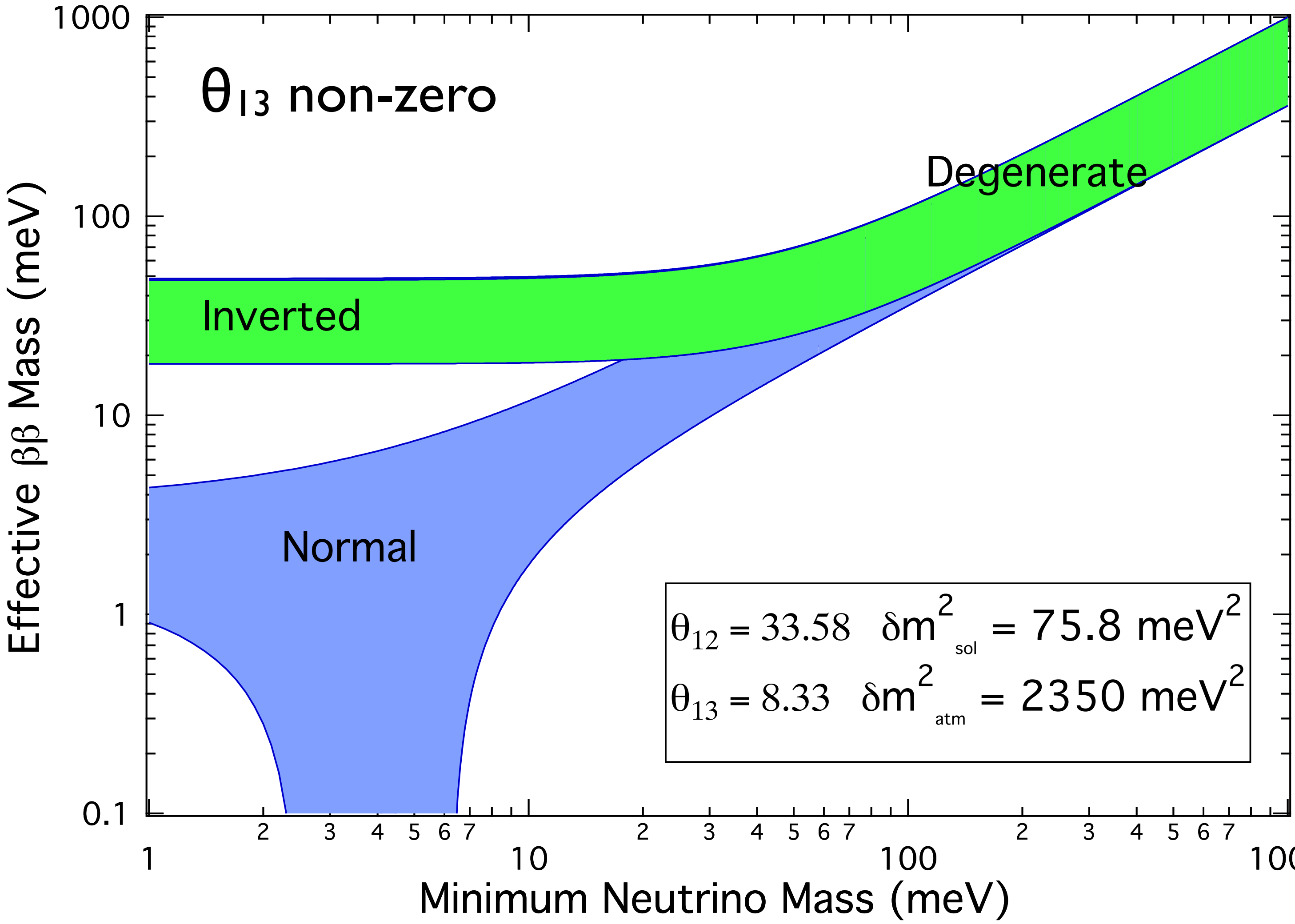


S. Elliot, Mod. Phys. Lett. A 27, 1230009 (2012)



Normal Inverted

Effective Majorana Mass



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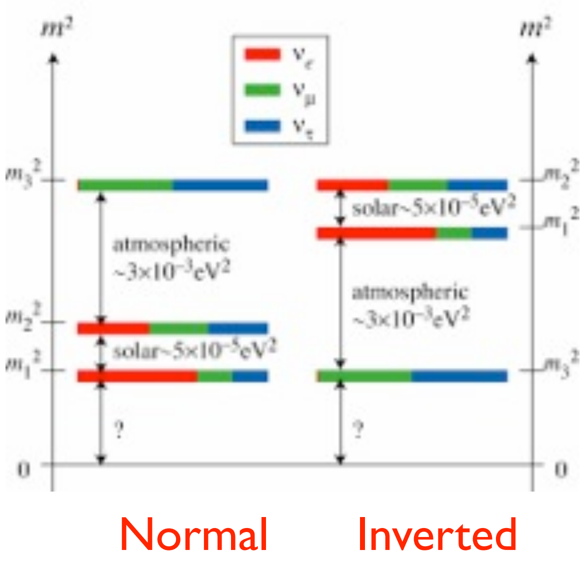

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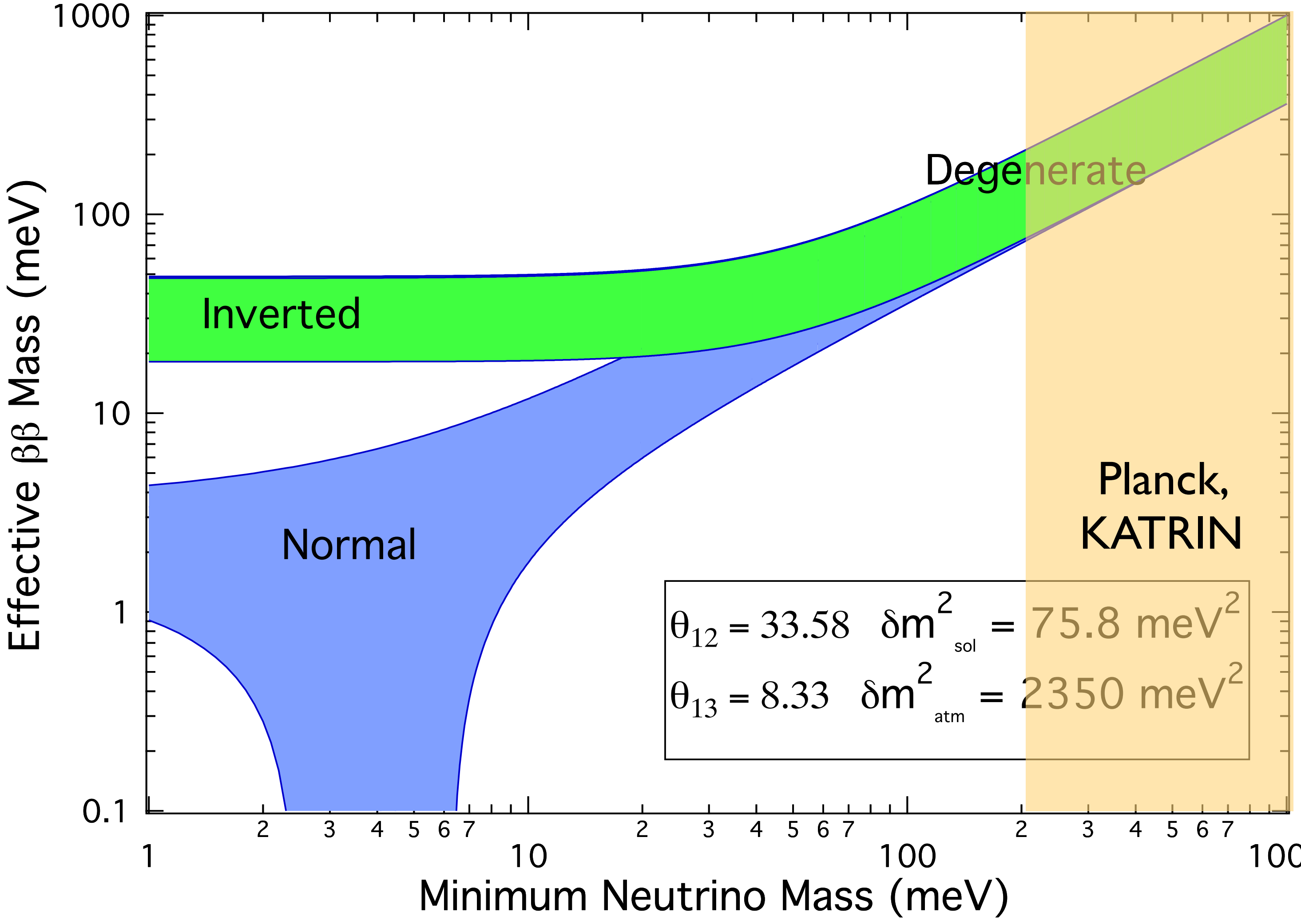

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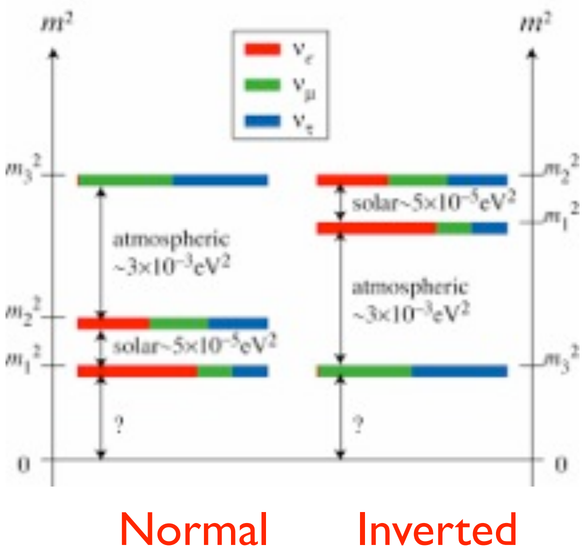

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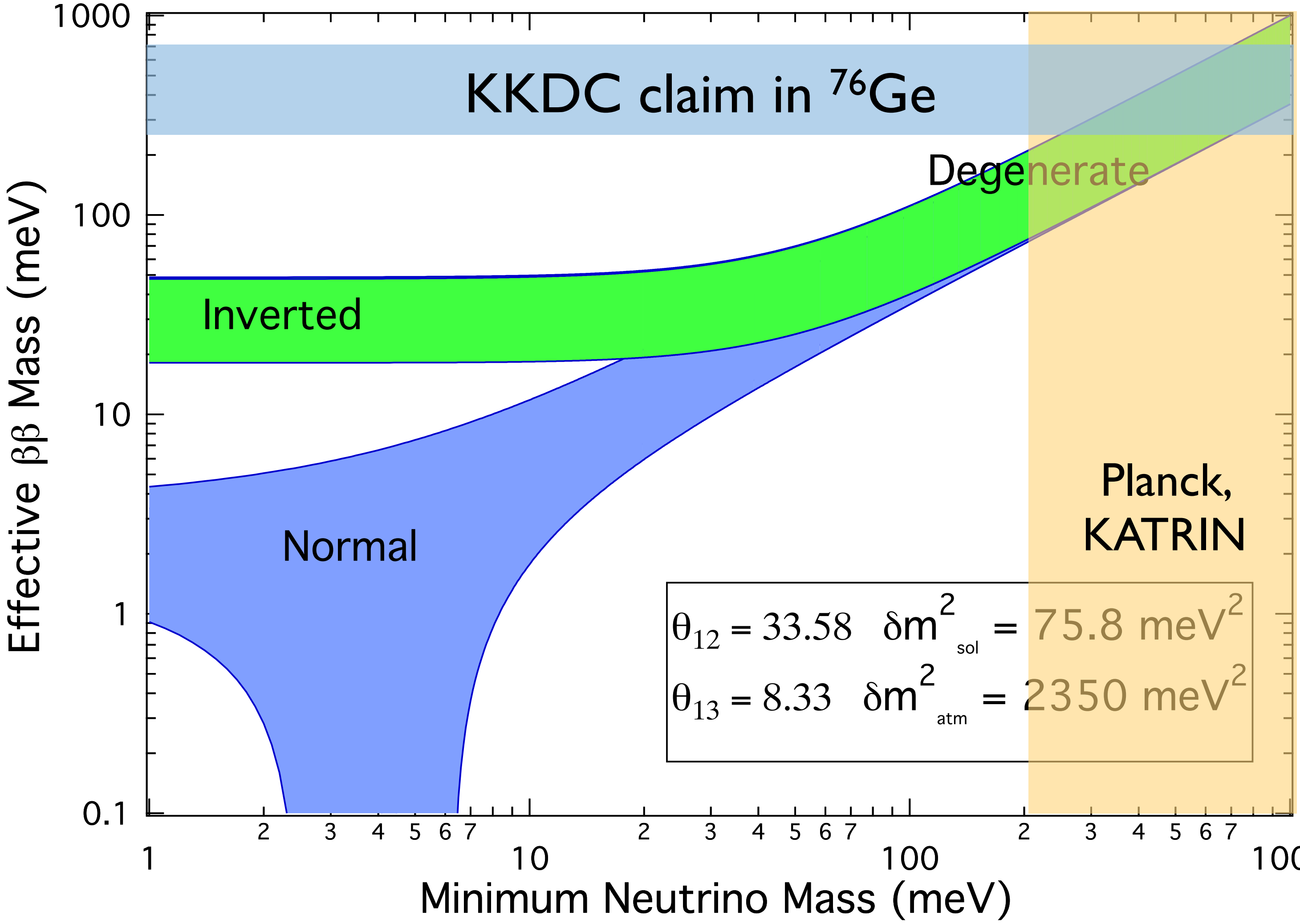

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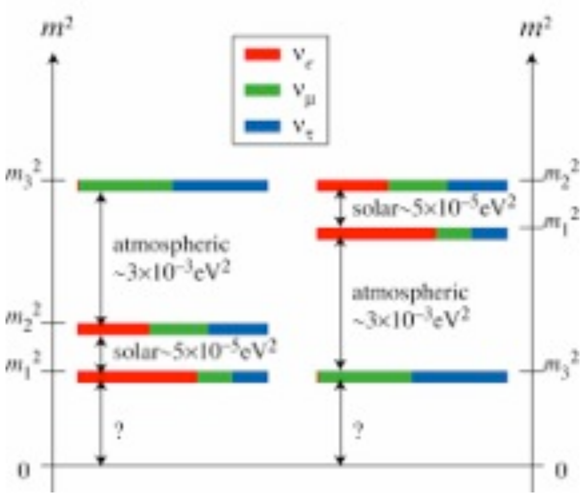

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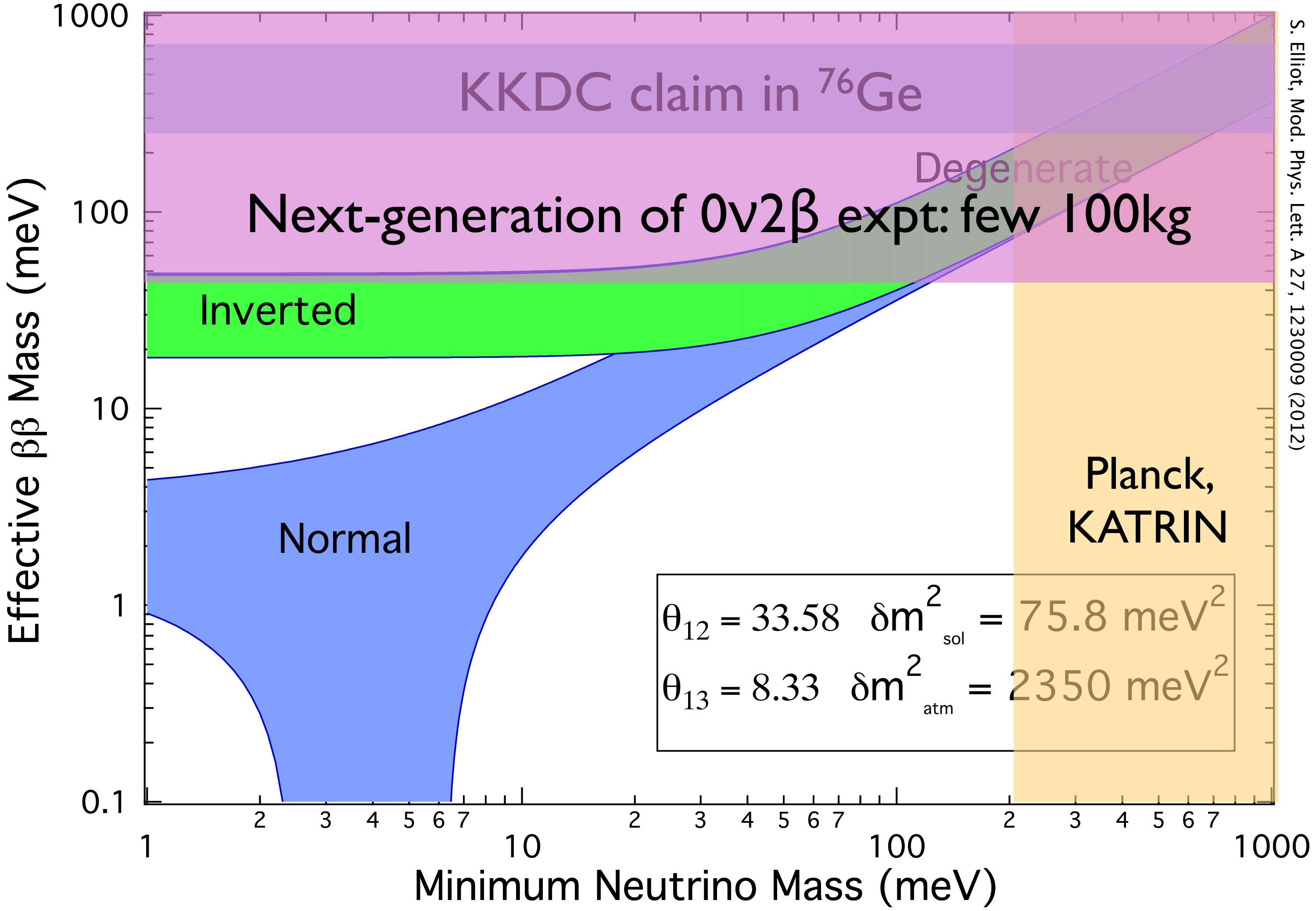

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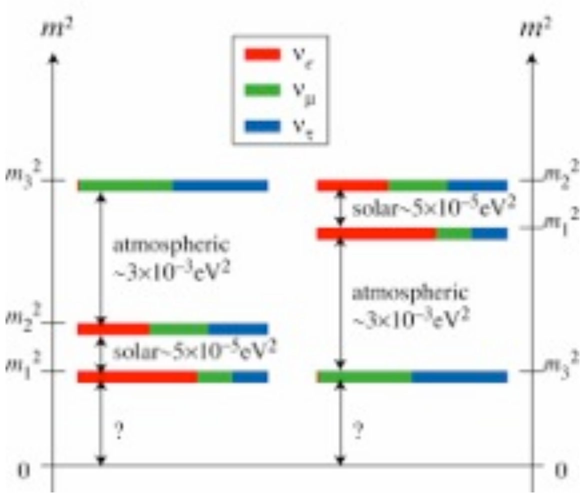

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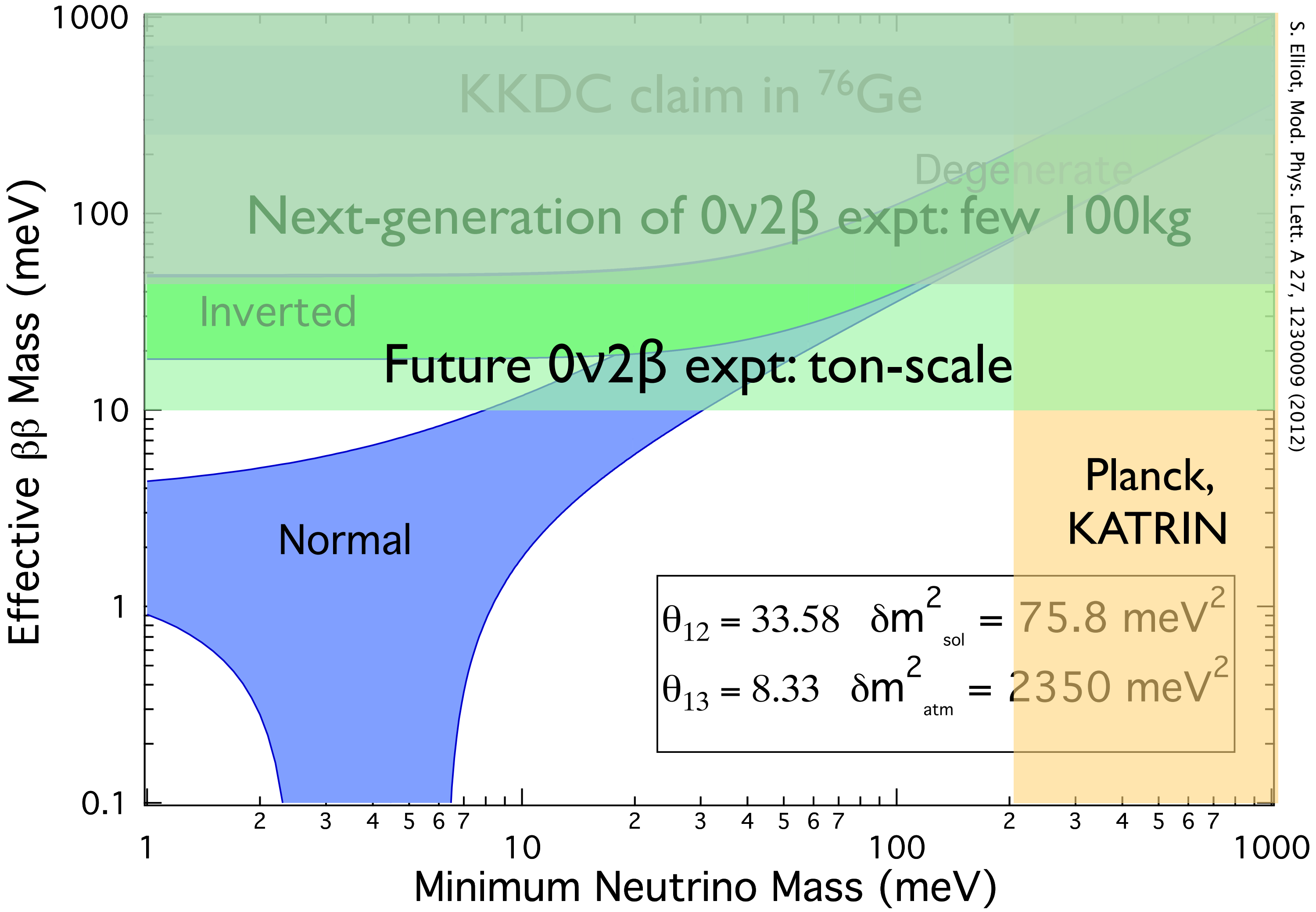

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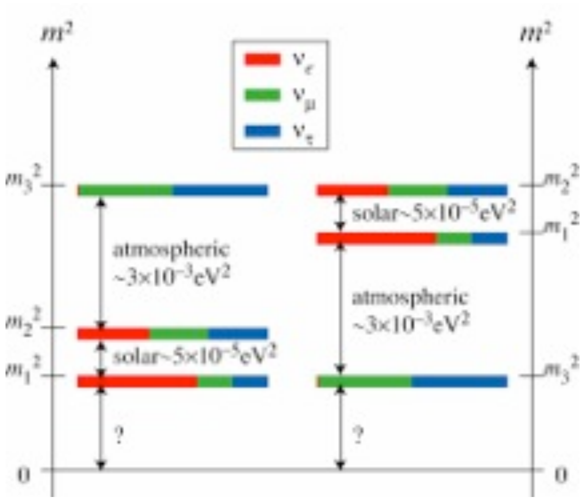
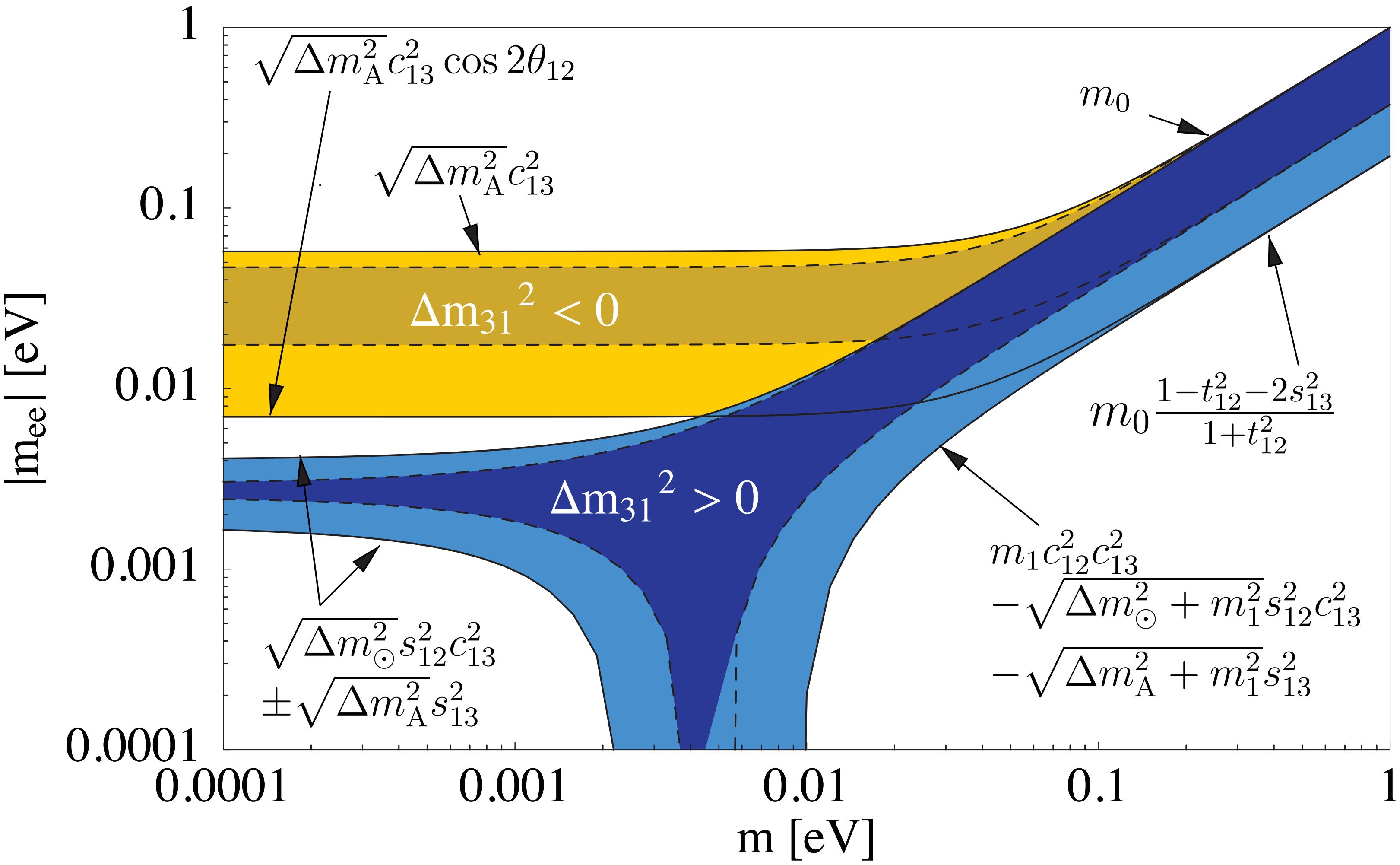


Normal Inverted

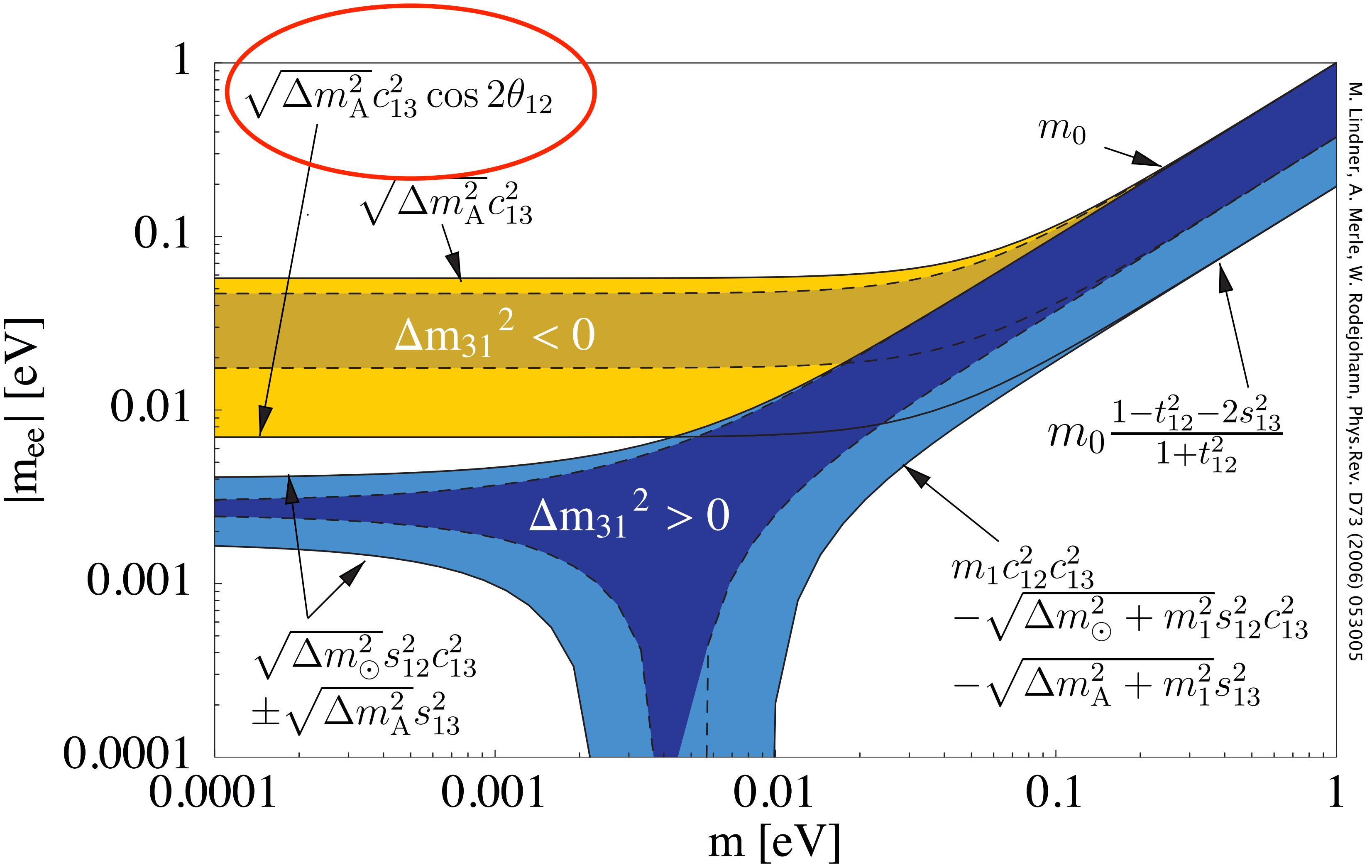
Osc Params in ⟨mββ⟩ determination



M. Lindner, A. Merle, W. Rodejohann, Phys.Rev. D73 (2006) 053005

[And, if sterile νs exist, this diagram is no longer correct!]

Osc Params in ⟨mββ⟩ determination



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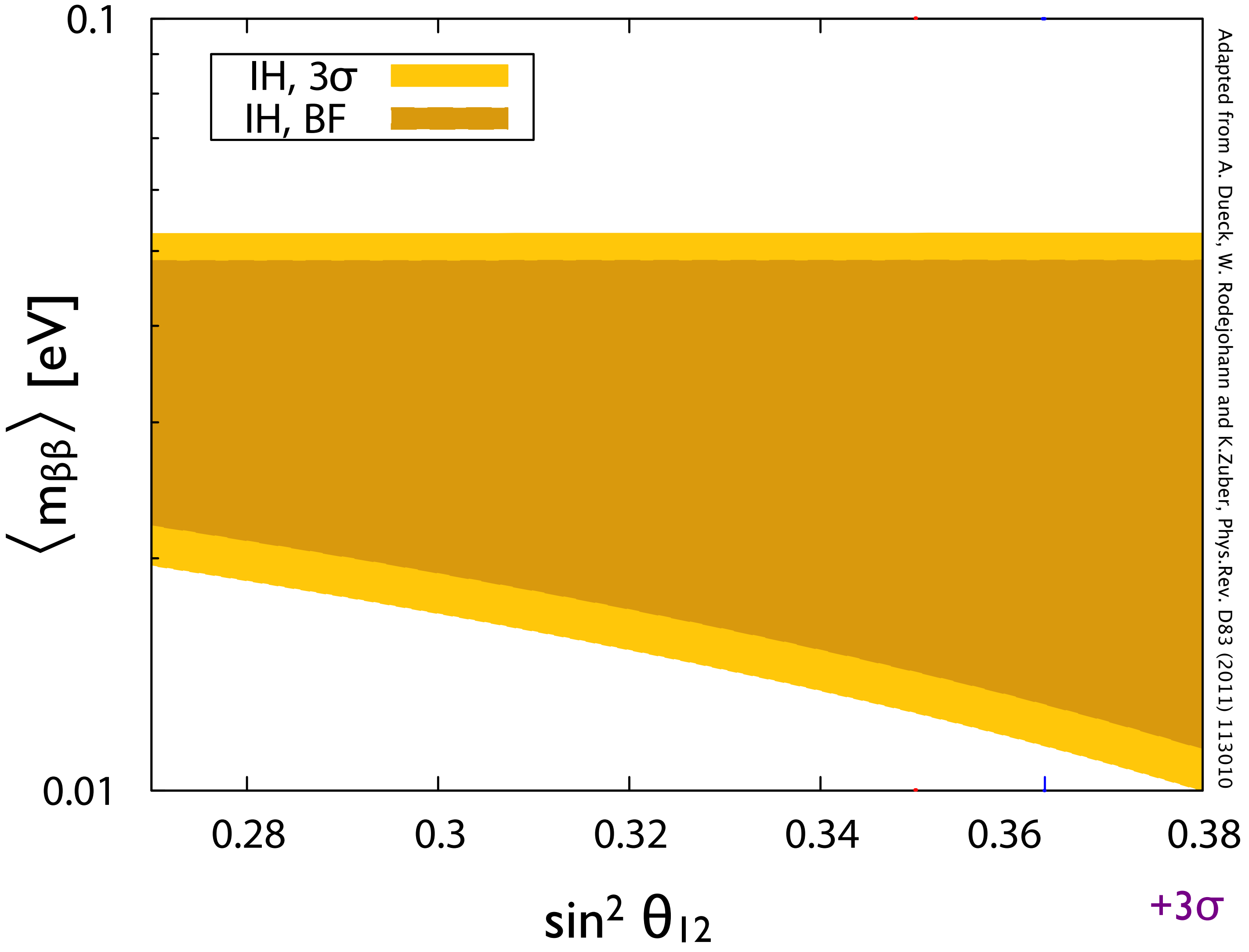
θ_{12} Matters!

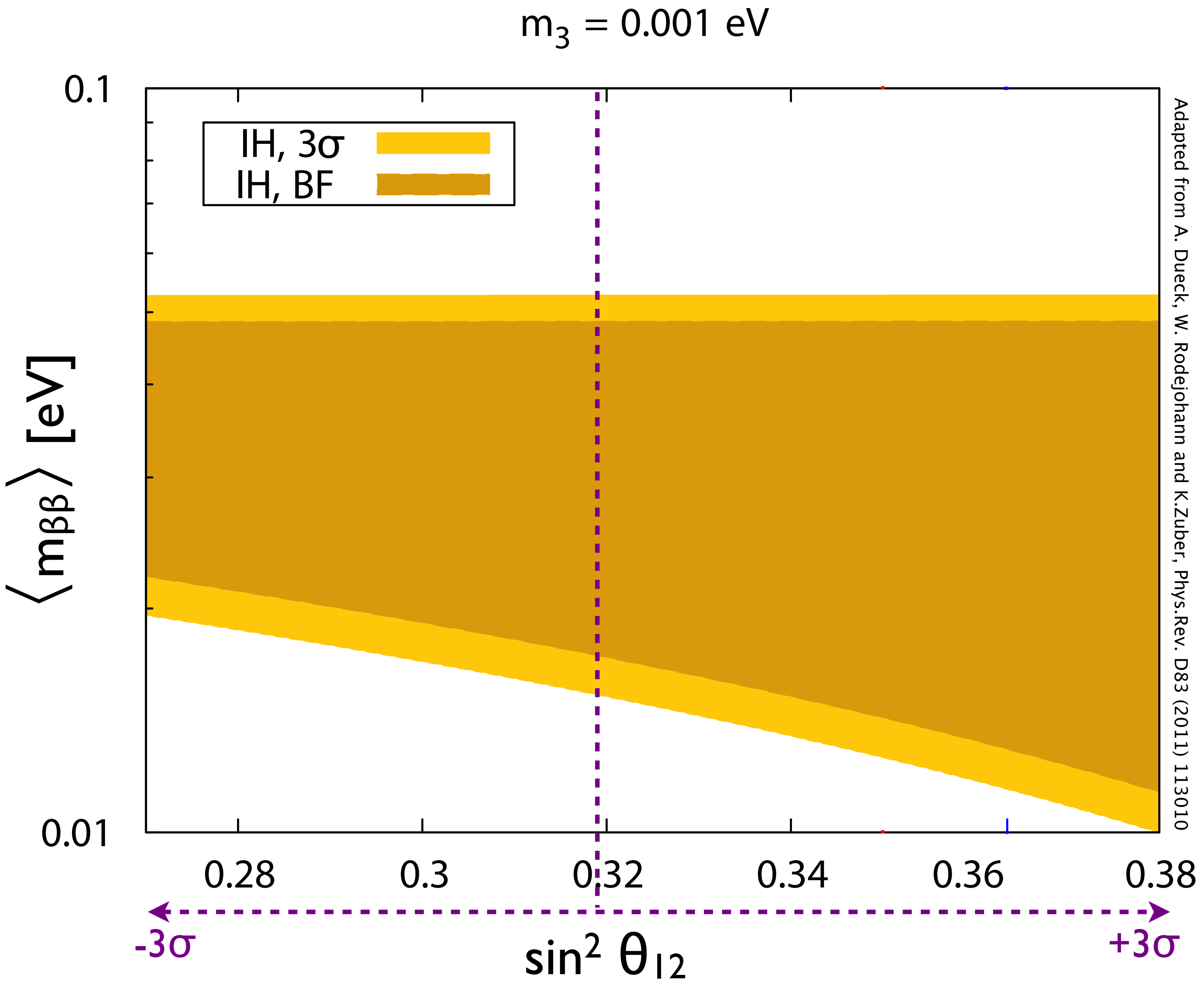
$m_3 = 0.001$ eV



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

+3σ

θ$_{12}$ Matters!



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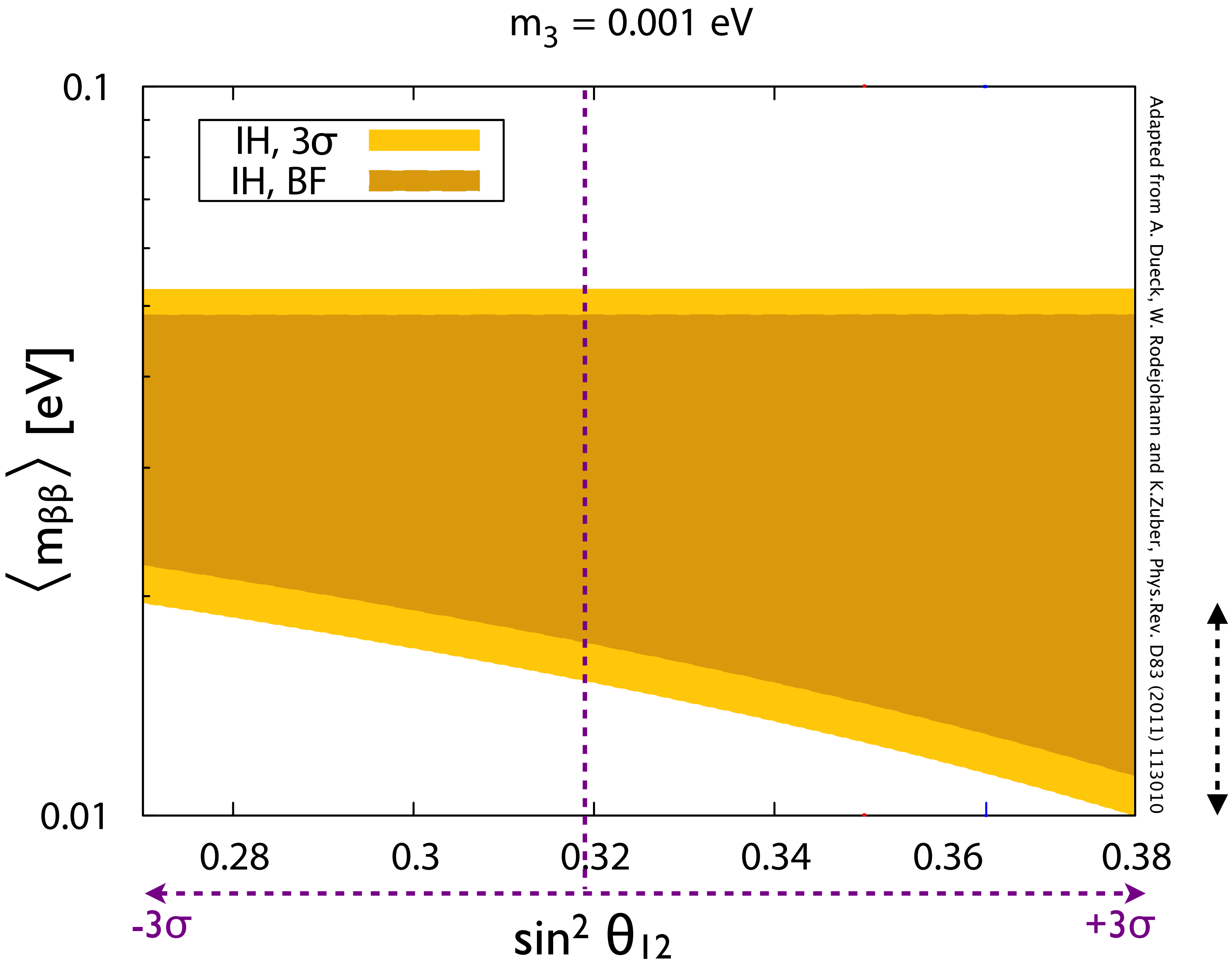

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Factor 2!

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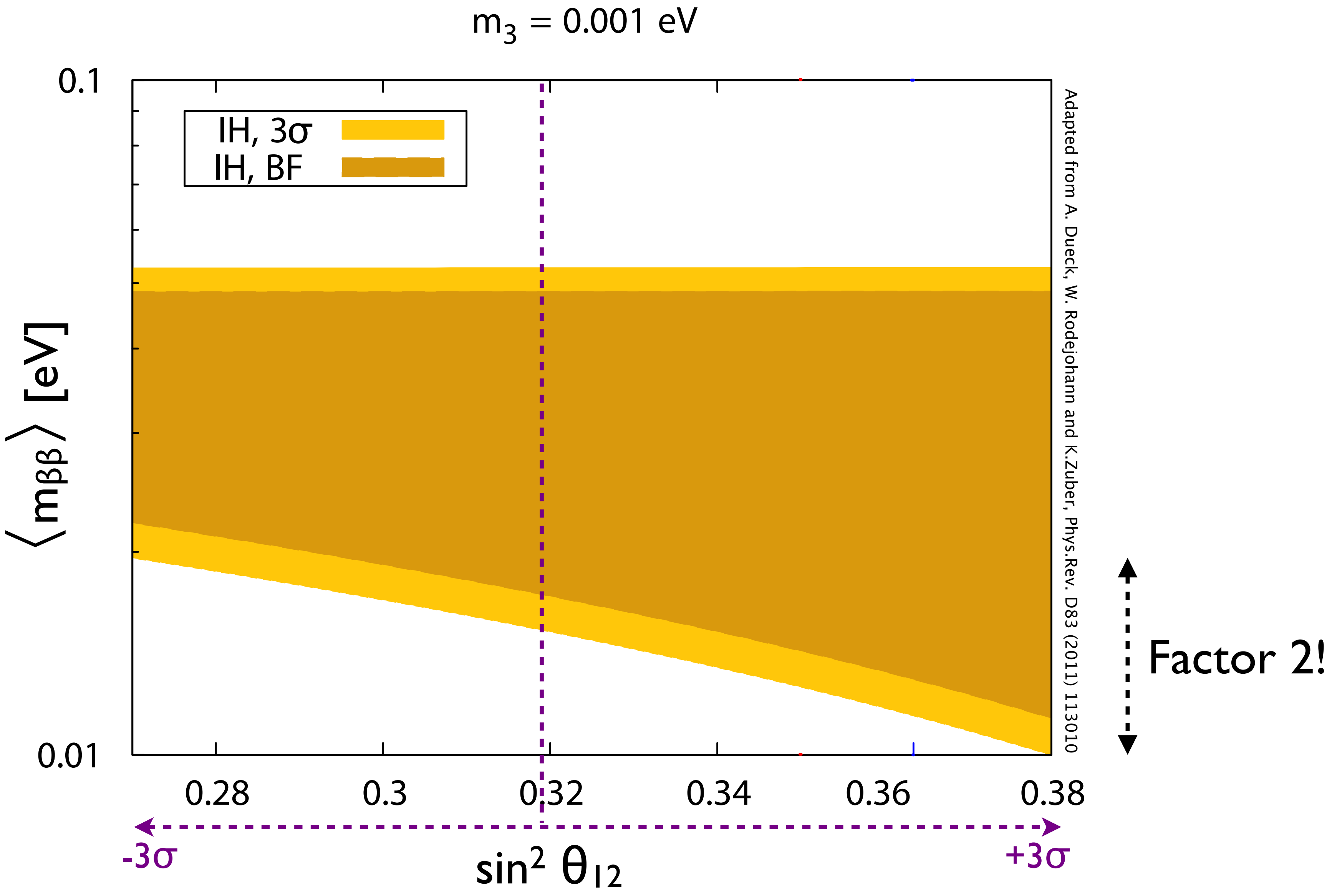

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Factor 2!

Better measurement of θ_{12} required: similar impact as NME uncertainty for a given isotope

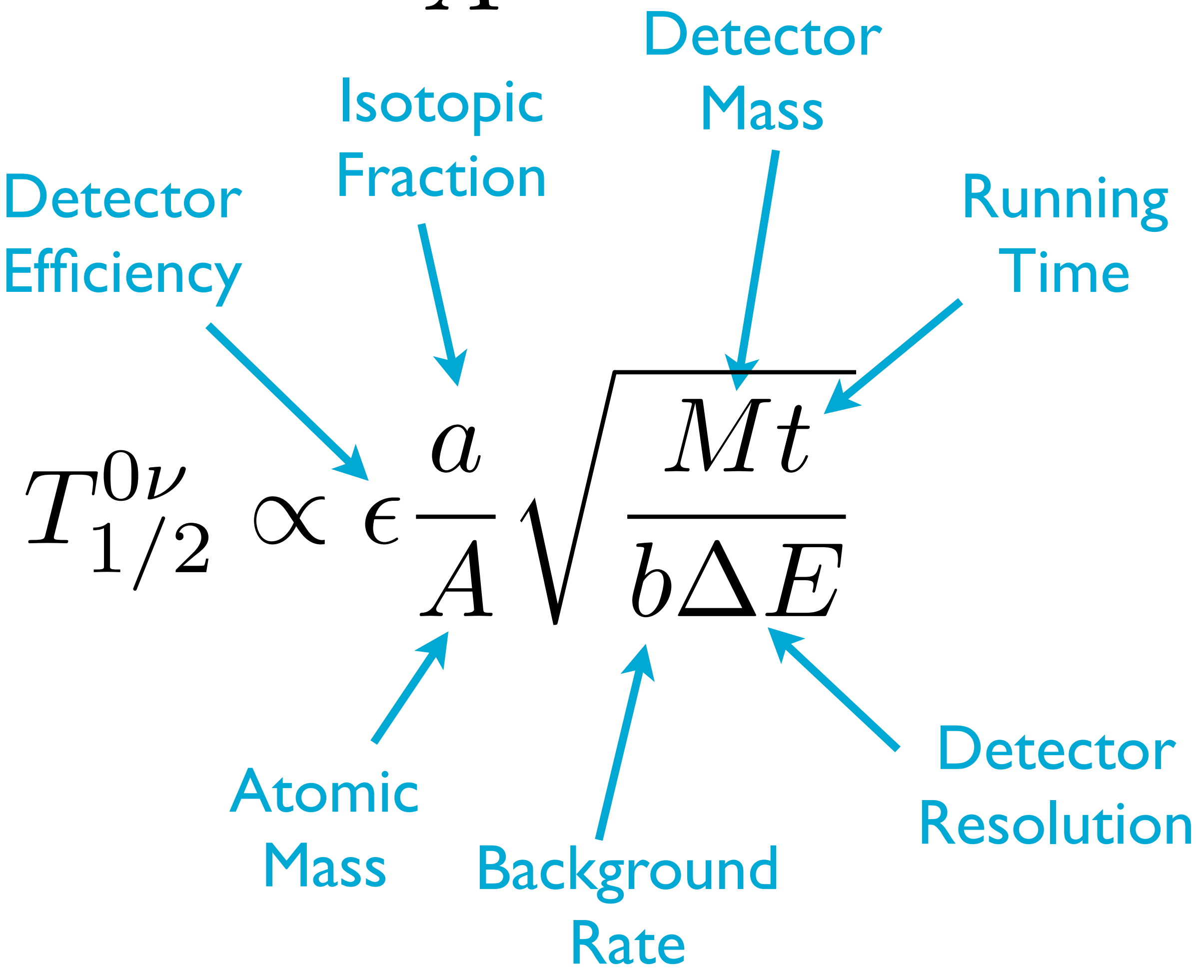
Experimental sensitivity

No experimental background:

$$T^{0\nu}_{1/2} \propto \epsilon \frac{a}{A} M t$$

With experimental background:

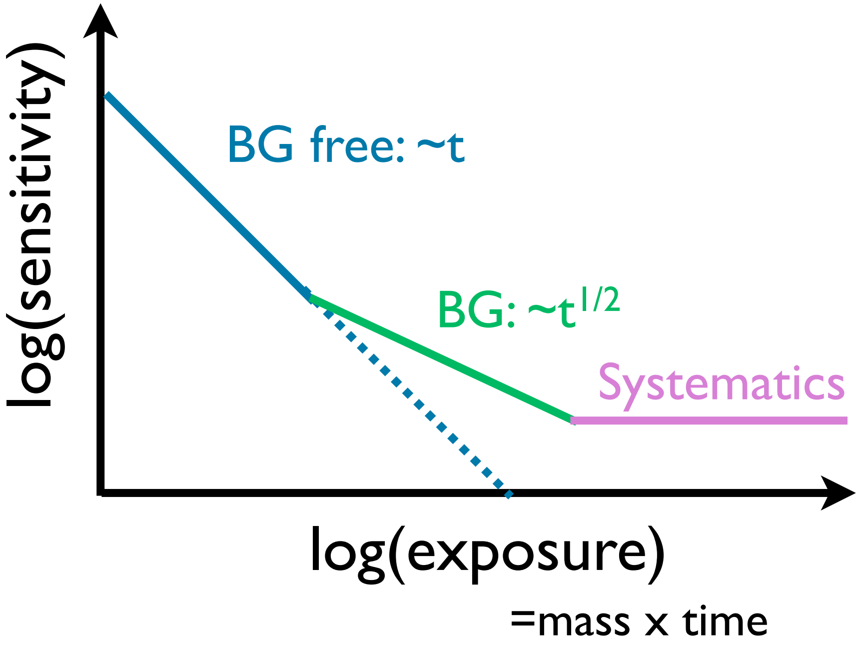
$$T^{0\nu}_{1/2} \propto \epsilon \frac{a}{A} \sqrt{\frac{Mt}{b\Delta E}}$$



Backgrounds

- The signal level of the experiments is few cnts/(ton-year)
  - Background control critical
- Typical backgrounds involved
  - Contamination from U and Th decay-chain isotopes
    - Compton-scattered ɣ rays, β and α particles
  - Cosmogenic muon induced backgrounds
    - Activation of shielding, source material etc.

For any rare event expt:



0ν2β experiments are ultra-clean and conducted deep under ground

Q and Background

Natural radioactivity (^{40}K, ^{60}Co, ^{234m}Pa, external ^{214}Bi and ^{208}Tl…)

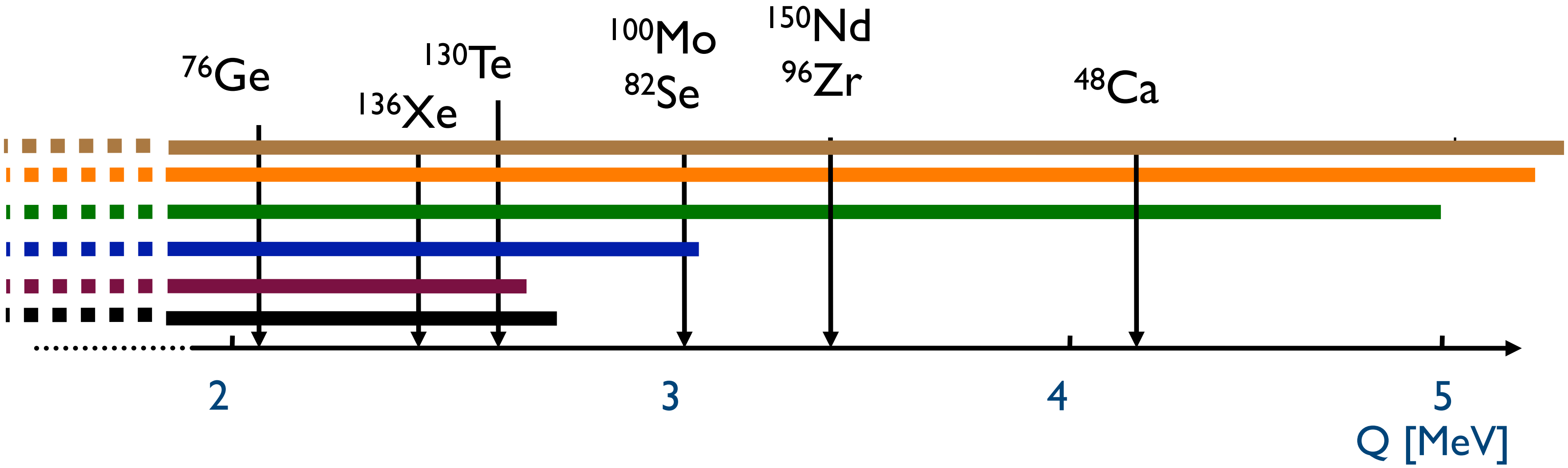
^{214}Bi and Radon

^{208}Tl (2.6 MeV γ line) and Thorium

γ from (n,γ) reactions

Surface or bulk contamination in α emitters

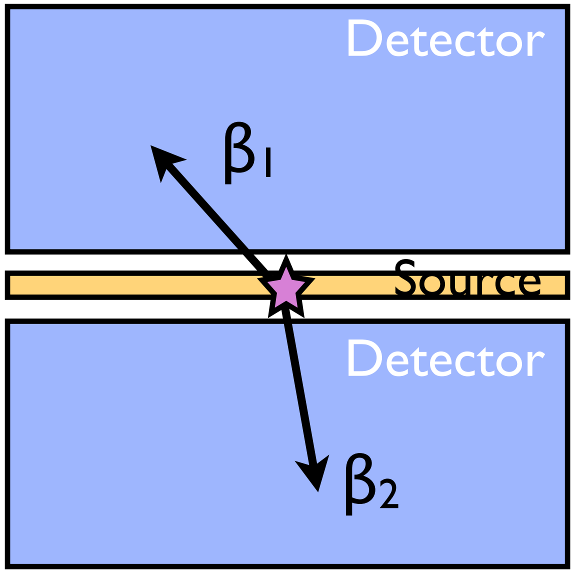
Cosmogenic production



Patrick Decowski/University of Amsterdam

Generally Two Techniques

Source ≠ Detector



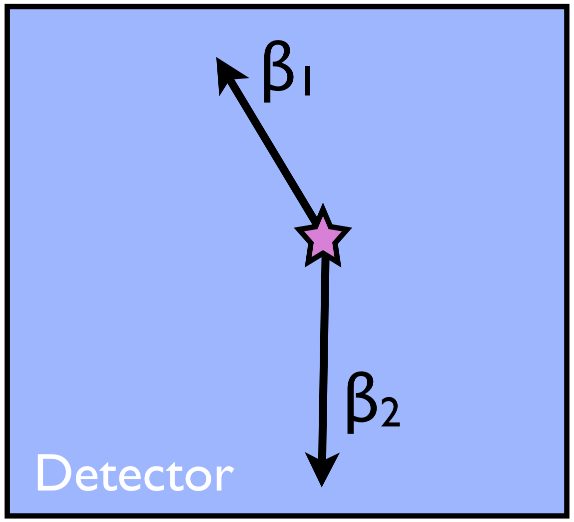
Pros:

- +Easy to change source isotope
- +Background mitigation
- +Topology

Cons:

- -Mass
- -Detection Efficiency

Source = Detector



Pros:

- +Energy resolution
- +Mass
- +Detection Efficiency

Cons:

- -Background mitigation
- -Topology

Incomplete overview of experiments

Isotope	Experiment	Technique	Mass	Enriched	$Q_{\beta\beta}$ [MeV]	Start/Stage
^{130}Te	Cuoricino	TeO_2 bolometers	40.7kg	No	2.6	Done
^{82}Se, ^{100}Mo	NEMO-3	tracko-calo	0.9kg/6.9kg	Yes	3.37	Done
^{76}Ge	GERDA Phase I/II	Ge diodes in LAr	18kg/40kg	86%	2.04	2011/2013
^{136}Xe	EXO	LXe [tracking]	200kg/1t	80%	2.458	2011/2017?
^{136}Xe	KamLAND-Zen	Isotope in LS	400kg	90%	2.458	2011
^{130}Te	CUORE	TeO_2 bolometers	11kg/204kg	No	2.53	2013/2015
^{130}Te(^{150}Nd)	SNO+	Isotope in LS	750kg	No	3.37/2.53	2014
^{76}Ge	Majorana	Ge diodes	30kg	86%	2.04	2015
^{82}Se, ^{150}Nd	SuperNEMO	tracko-calo	7kg/100kg	Yes	3.37	2014
^{136}Xe	NEXT	GXe	100kg	yes	2.458	2013
^{116}Cd	COBRA	CdZnTe semicond		No	2.80	Prototype
^{48}Ca	CANDLES	CaF_2 cryst in LS	0.35kg	No	4.27	Prototype
^{82}Se	Lucifer	bolom+scintill				
^{136}Xe	XMASS	LXe				
^{100}Mo	MOON	tracking	1t	No	3.03	Prototype

Incomplete overview of experiments

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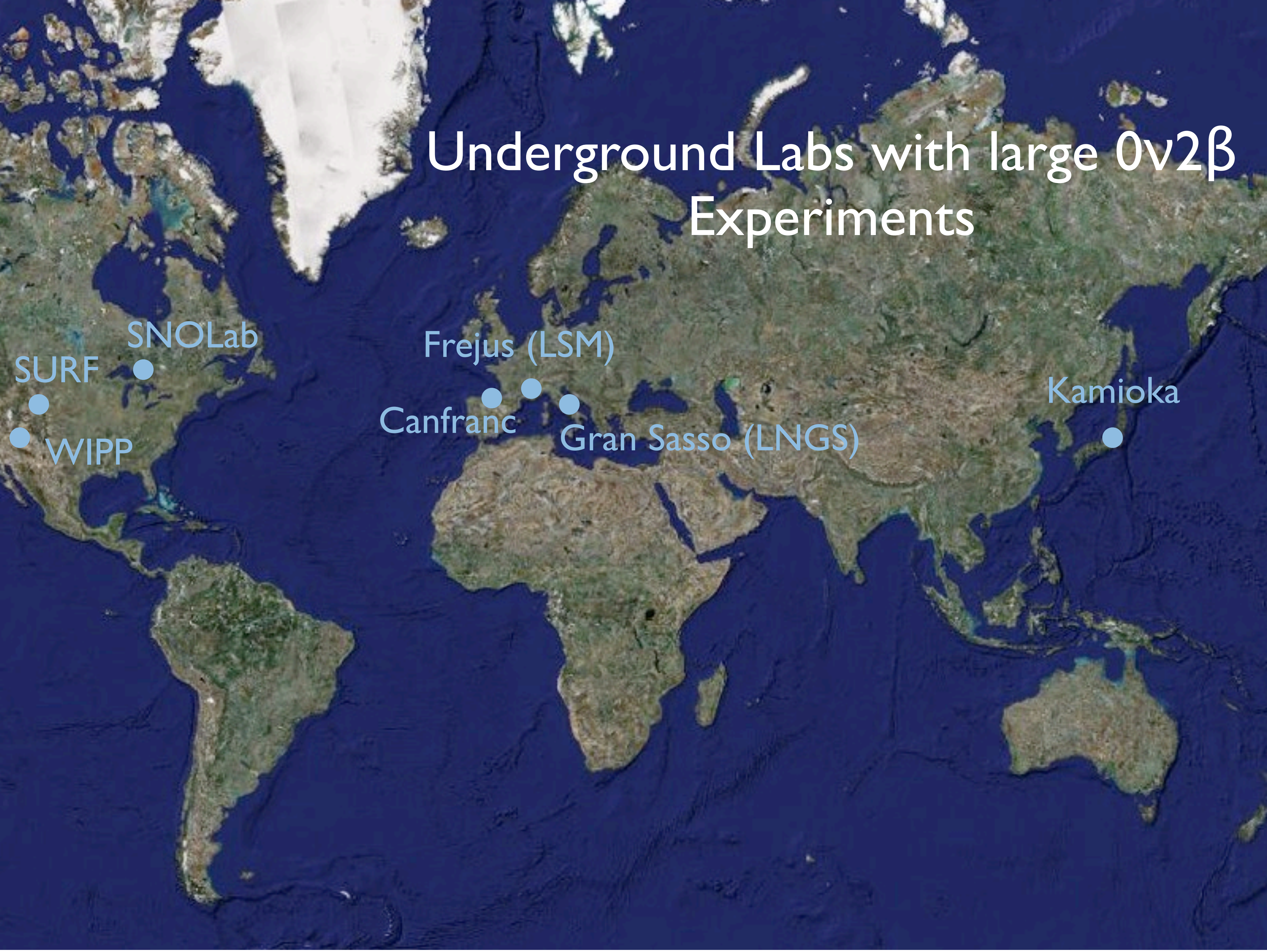
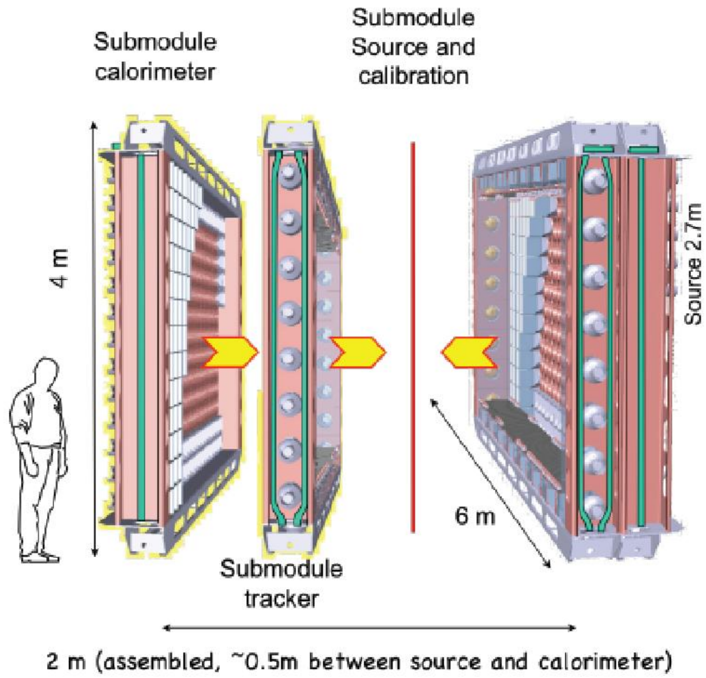
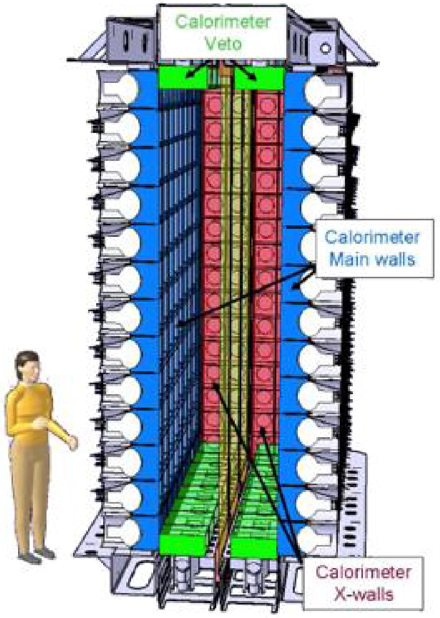
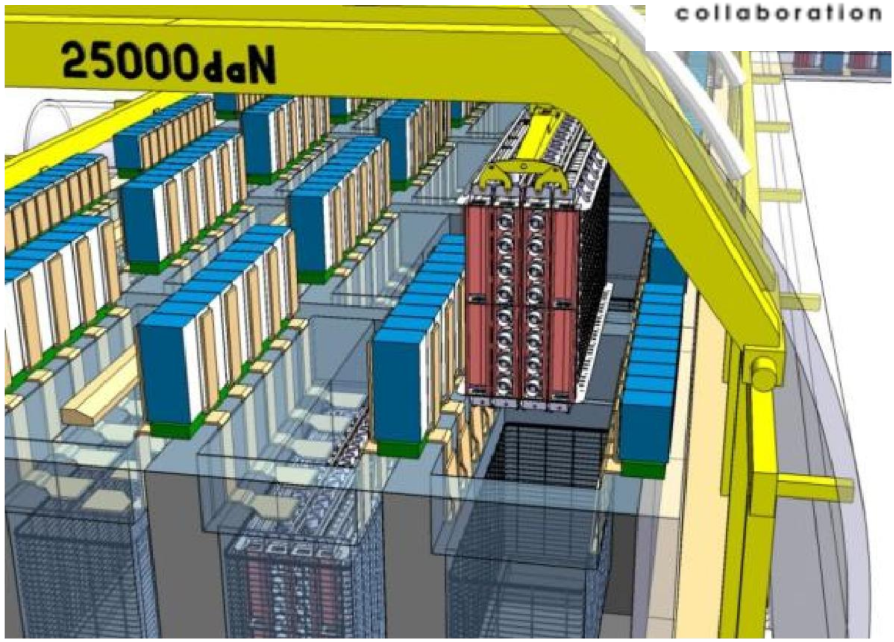
Underground Labs with large $0\nu2\beta$ Experiments



SuperNEMO







- 7kg ^{82}Se demonstrator operational 2014-2015
  - Tracking: No background
  - Goal: $T_{1/2} > 6.6 \times 10^{24}$yr → 200 - 400 meV @ 2yrs data
- Ultimately 20 modules, 100 kg. Both ^{82}Se and ^{150}Nd
  - Goal: $T_{1/2} > 1 \times 10^{26}$ yr → 40 - 100 meV

CUORE Program

Cuoricino

2003–2008

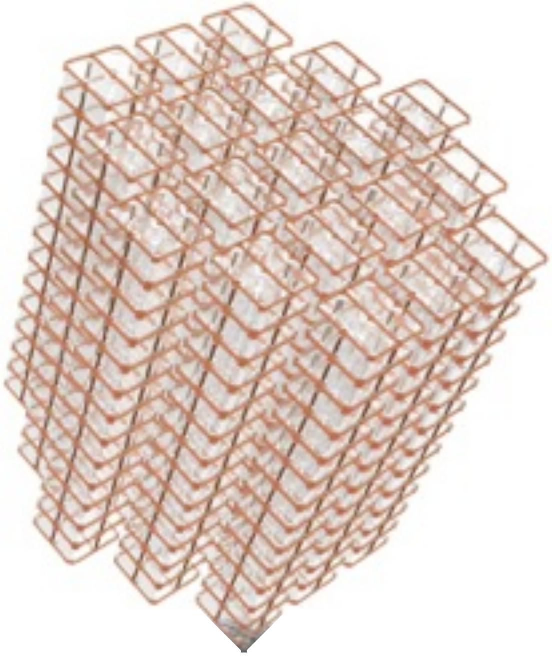
11 kg ^{130}Te

COMPLETE

CUORE-0

2013–2015

11 kg ^{130}Te

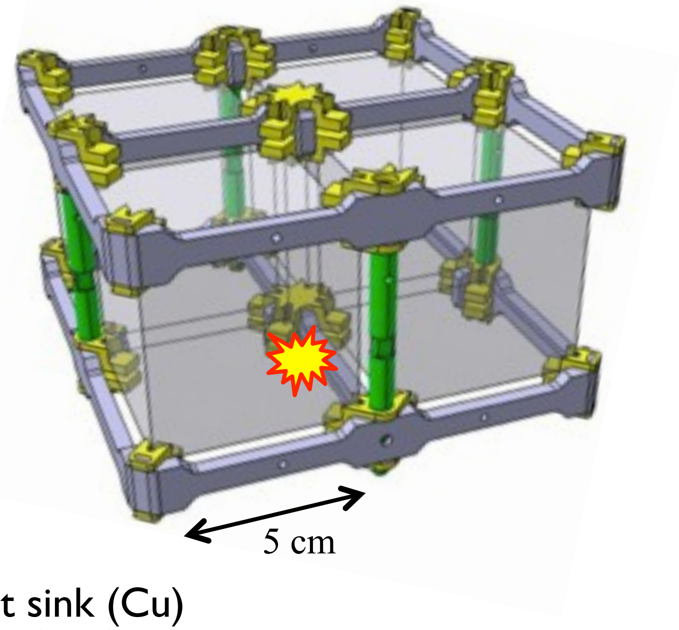


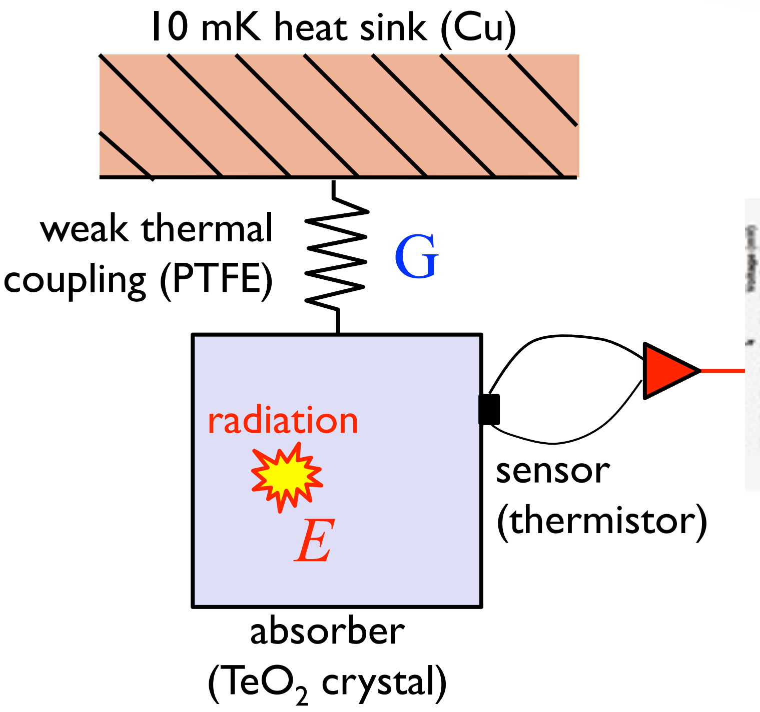
CUORE

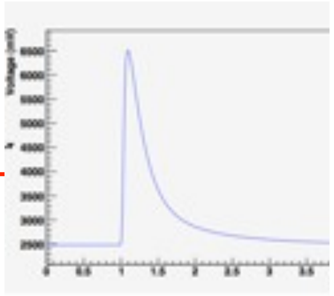
2014–2019

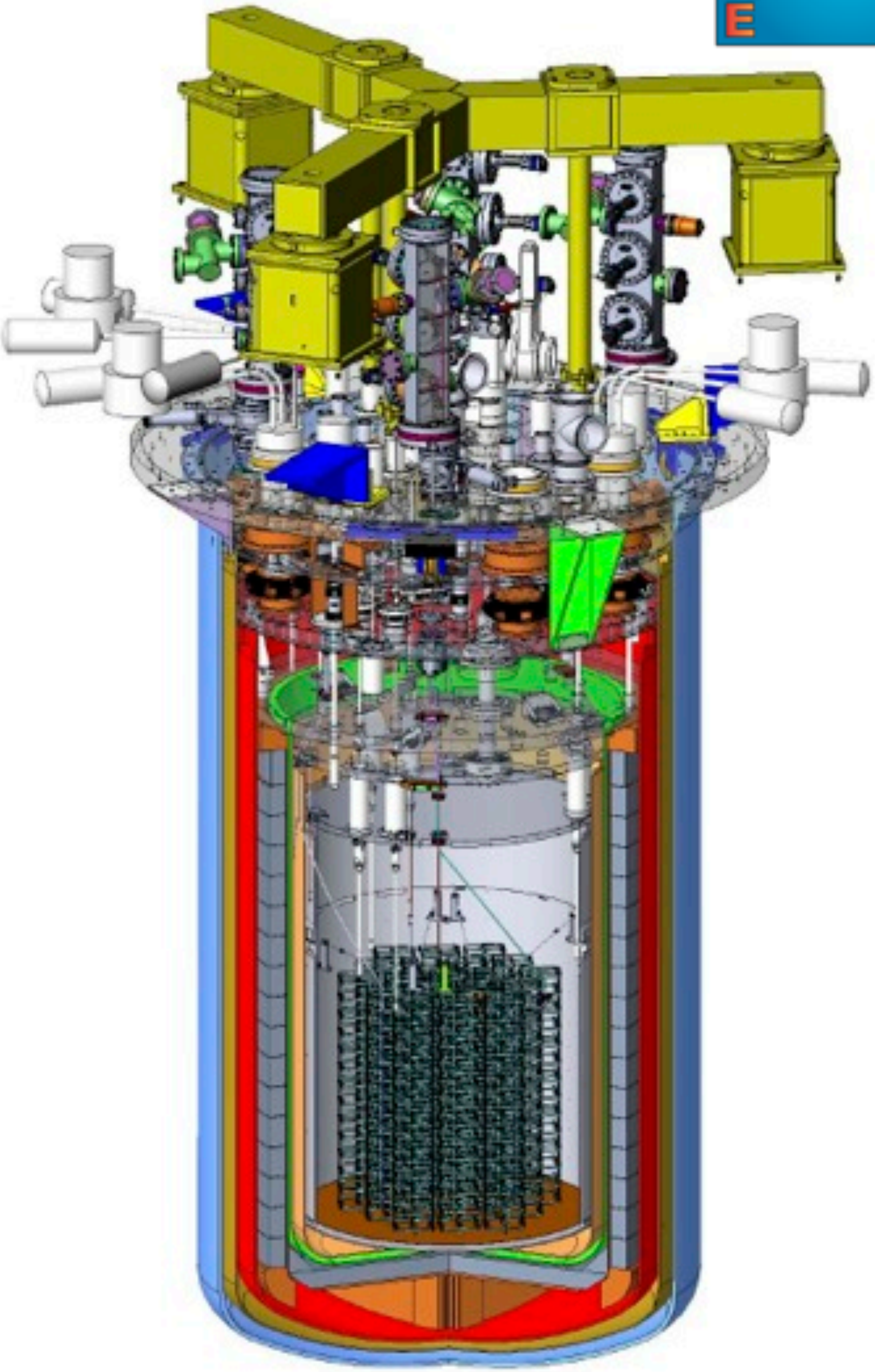
206 kg ^{130}Te

CUORE Design



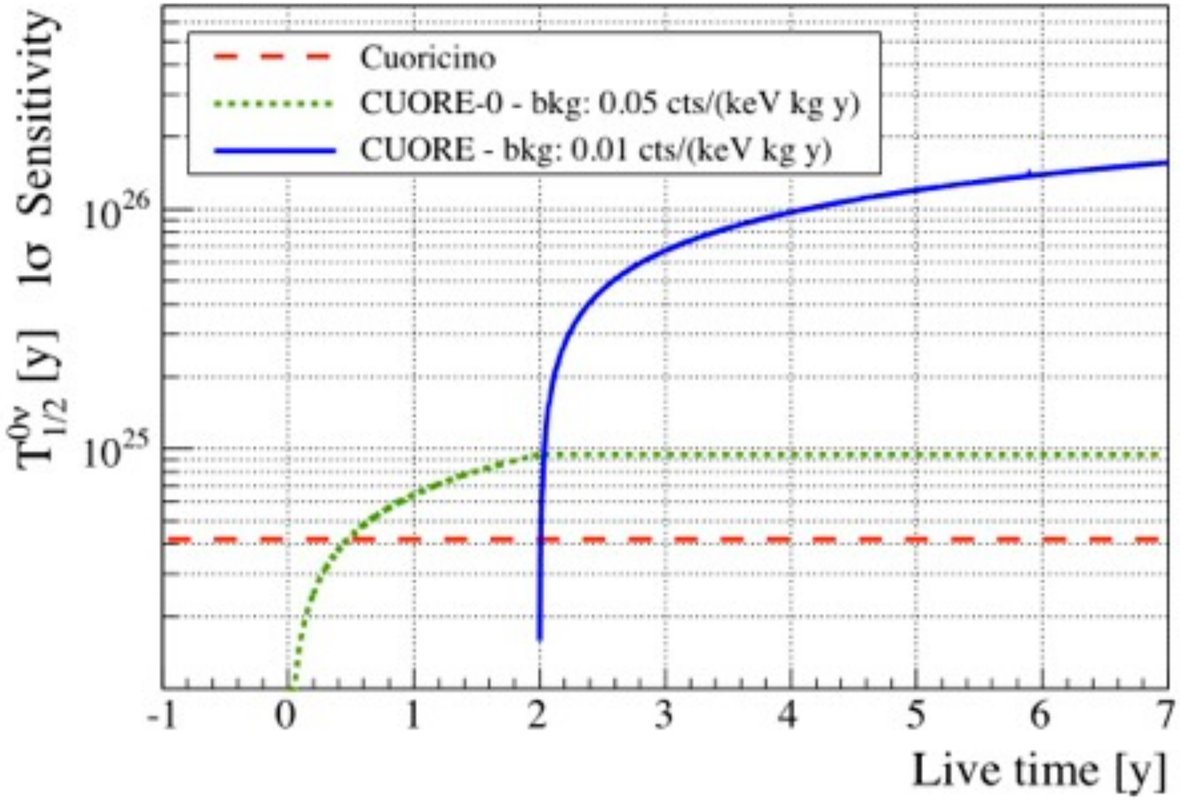






$C \sim 10$ MeV/mK

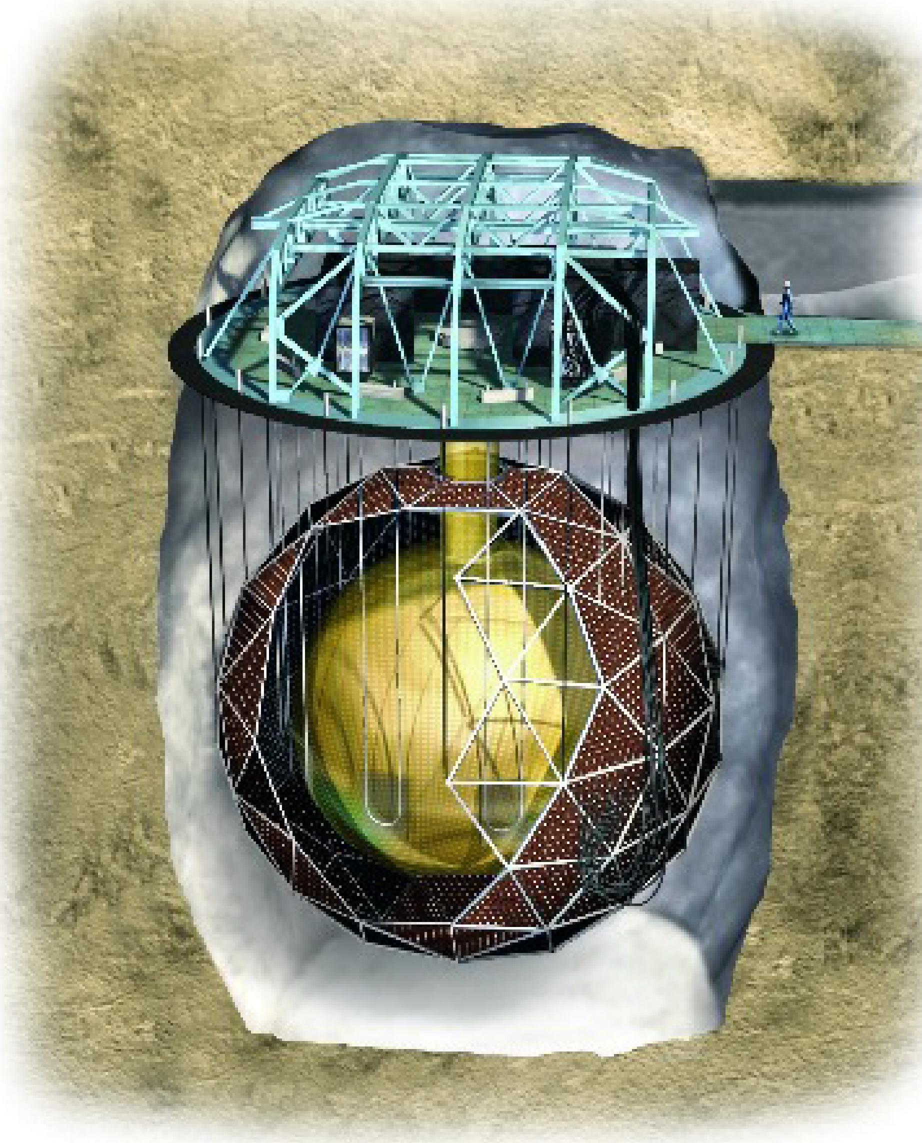
CUORE Reach



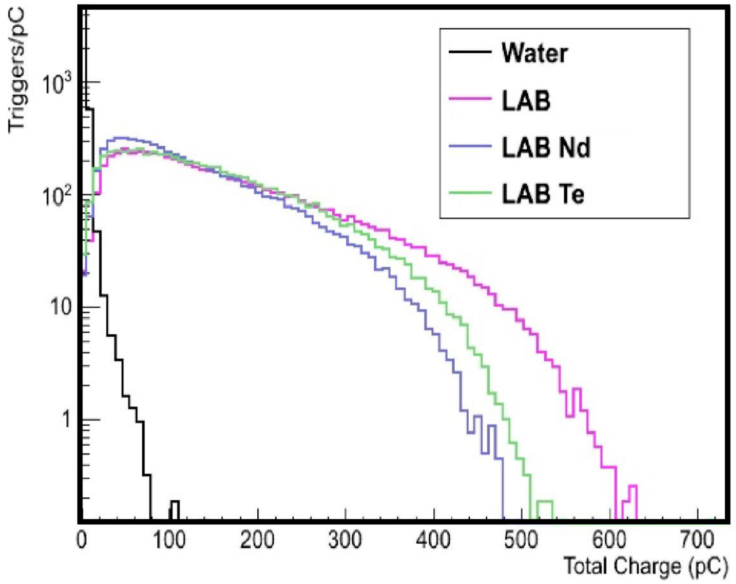
	Cuoricino	CUORE-0	CUORE
^{130}Te mass (kg)	11	11	206
Background (c/keV/kg/y) @ 2528 keV	0.17	0.05	0.01
E resolution (keV) FWHM @ 2615 keV	7	5–6	5
$\langle m_{\beta\beta} \rangle$ (meV) @ 90% C.L.	300–710	200–500	40–90
Science Start	Done	2013	2015

SNO+

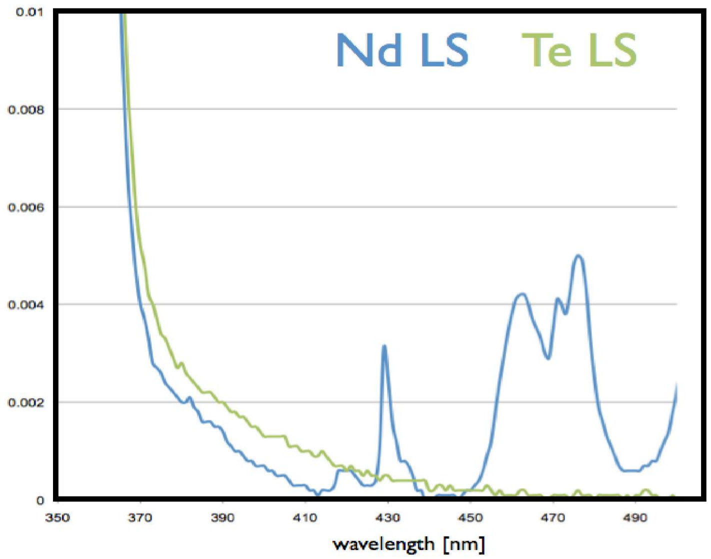
- Reuse of SNO equipment with Liquid Scintillator in the Acrylic Vessel
- Physics priority: 0ν2β over solar, geo
- Original plan: ^{150}Nd
- Current plan: **^{130}Te**
  - ^{130}Te solubility in LAB demonstrated
  - 34.5% vs 5.6% natural abundance
- Scintillator fill in 2014



Te-LS over Nd-LS



Te-loaded LAB better light yield than Nd-loaded LAB



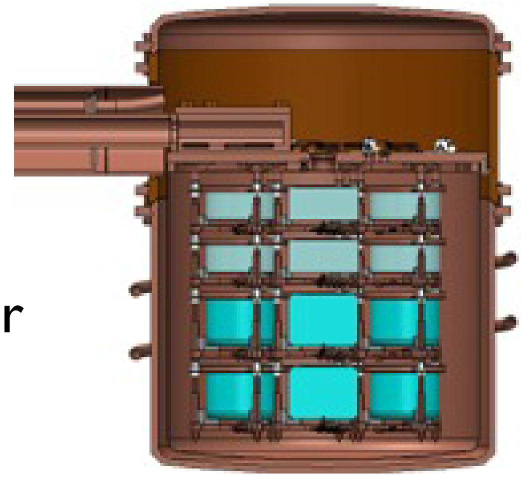
Te-LS has no absorption lines

Initially 0.3% loading (~800kg)
maybe increased

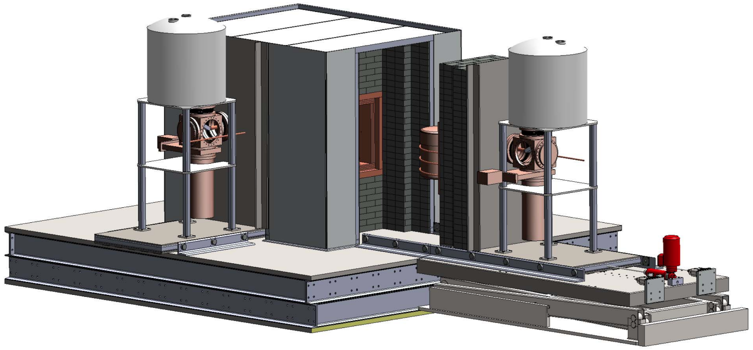
K. Zuber, SNO+

Majorana Demonstrator

- Goals:
  - Technical: demonstrate feasibility of a tonne-scale detector
  - Physics: test KKDC claim
  - Community: work with GERDA towards tonne-scale detector



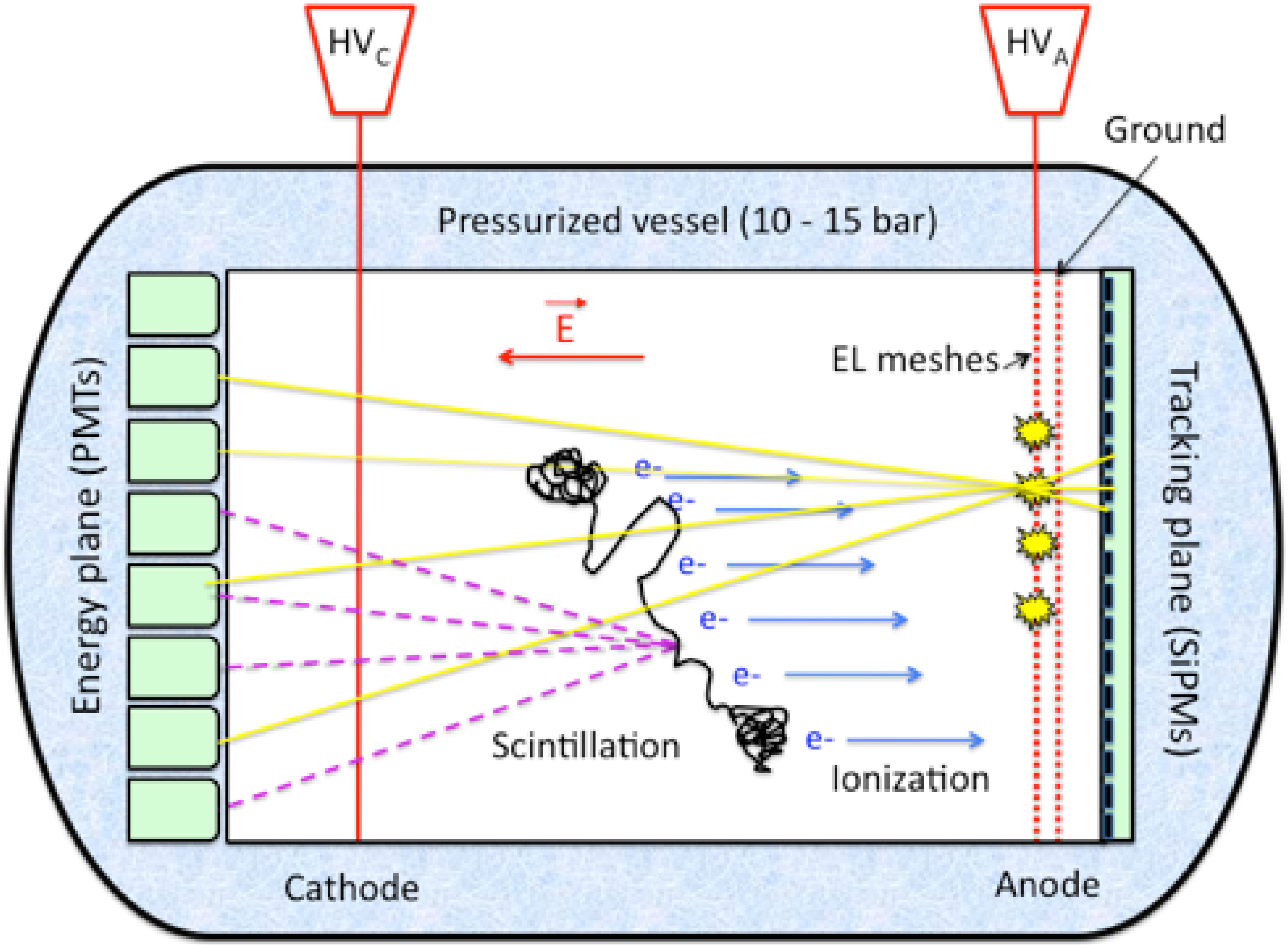
- 40 kg of Ge:
  - 30kg 86% enr ^{76}Ge & 10 kg ^{nat}Ge crystals
  - P-type, point-contact diodes



- Backgrounds: ultra clean, electroformed Cu

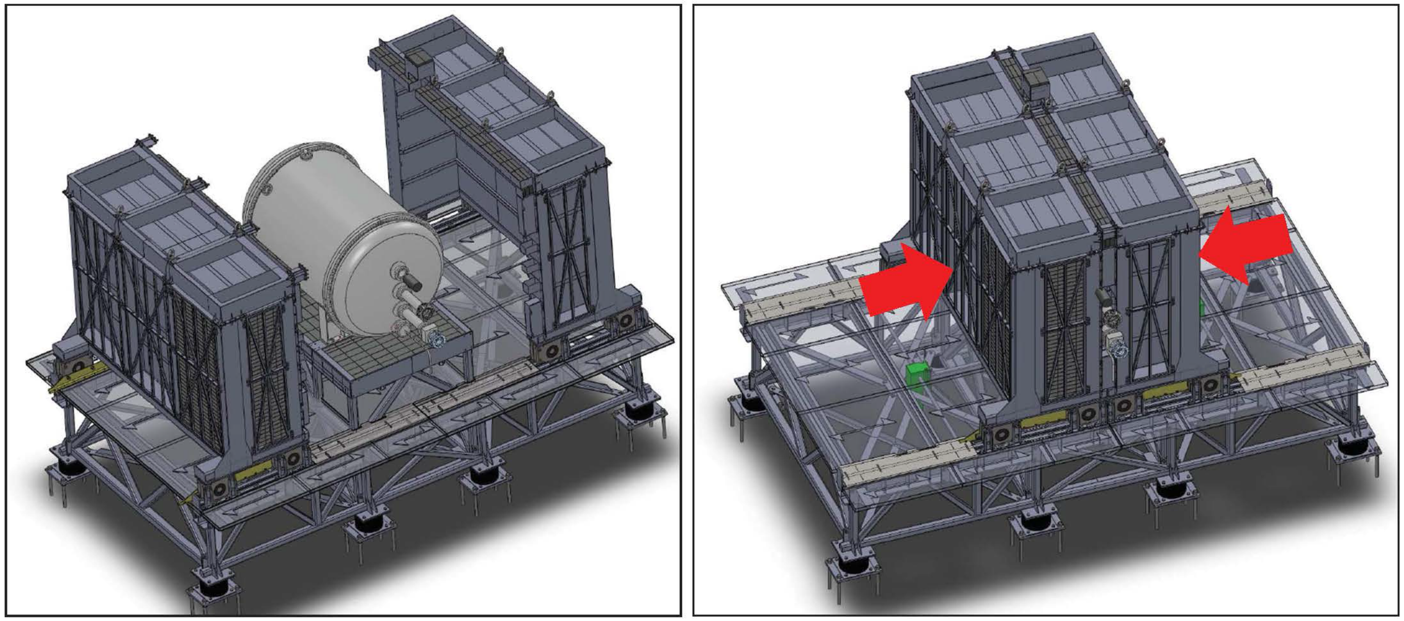
Proto. Cryostat	2 ^{nat}Ge strings	Summer 2013
Cryostat 1	3 ^{enr}Ge & 4 ^{nat}Ge	Late 2013
Cryostat 2	7 ^{enr}Ge strings	Fall 2014

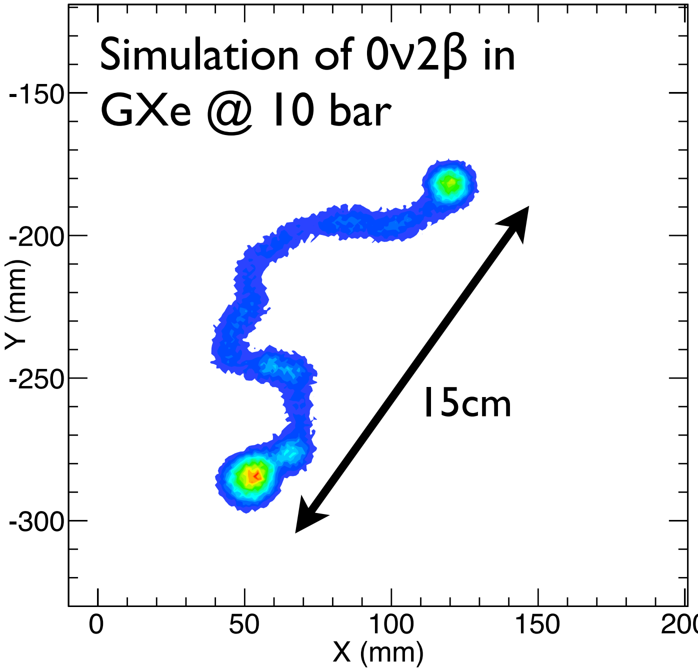
NEXT-100



- High pressure gas TPC with 100kg of enriched Xe
- Electroluminescence amplifies ionization signal
- Separate energy and tracking planes

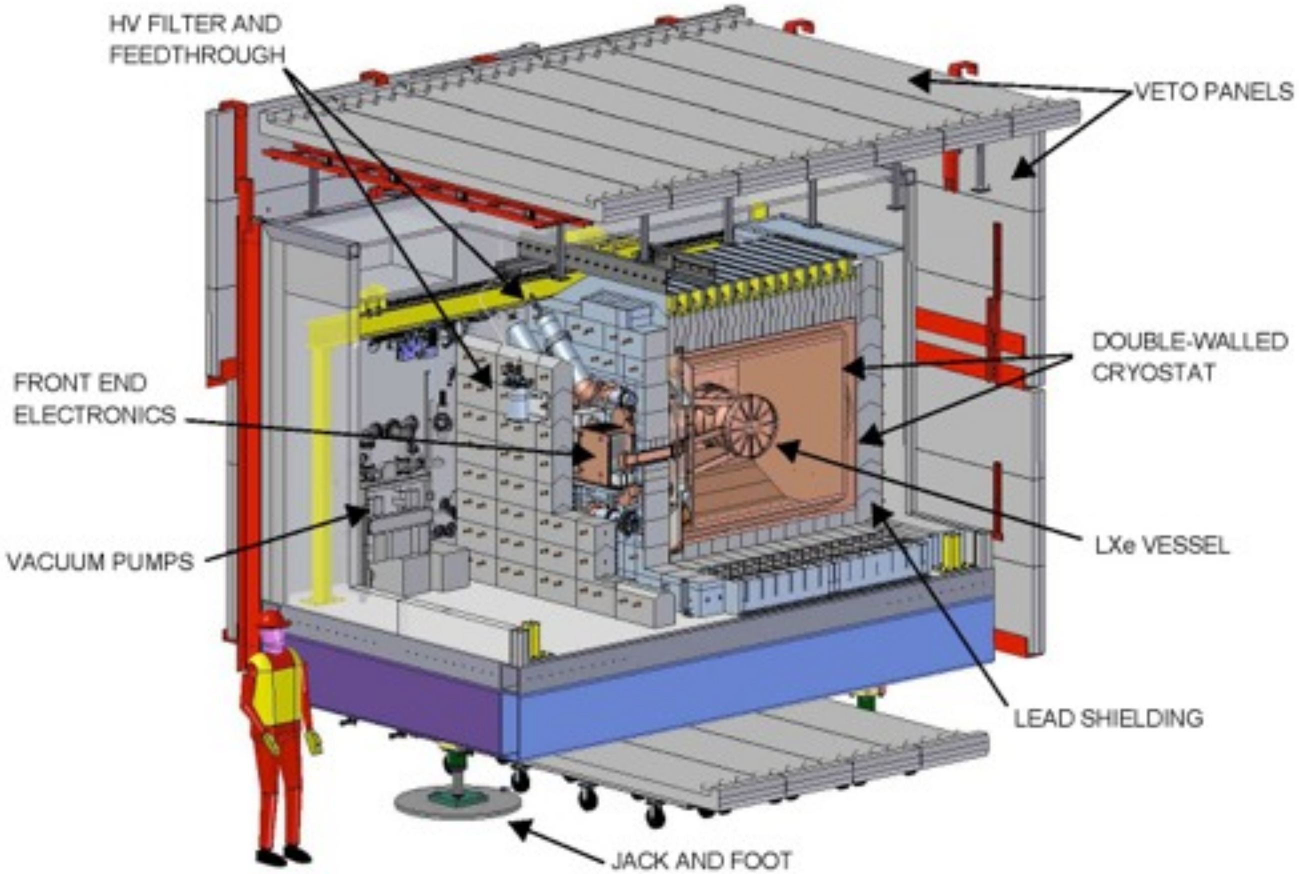
NEXT-100

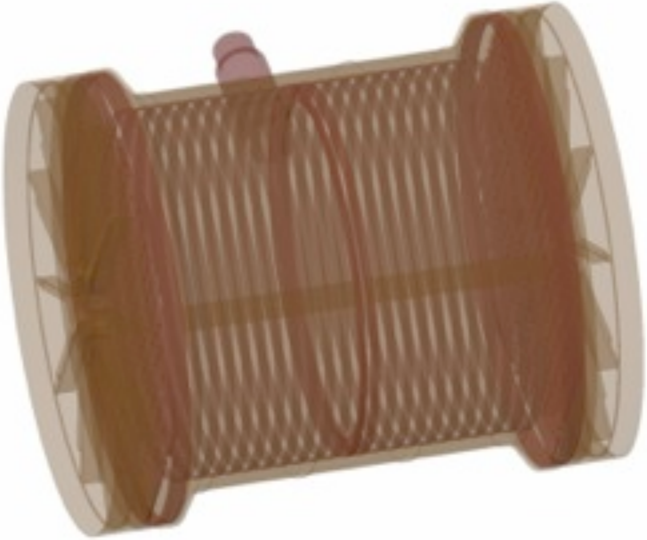




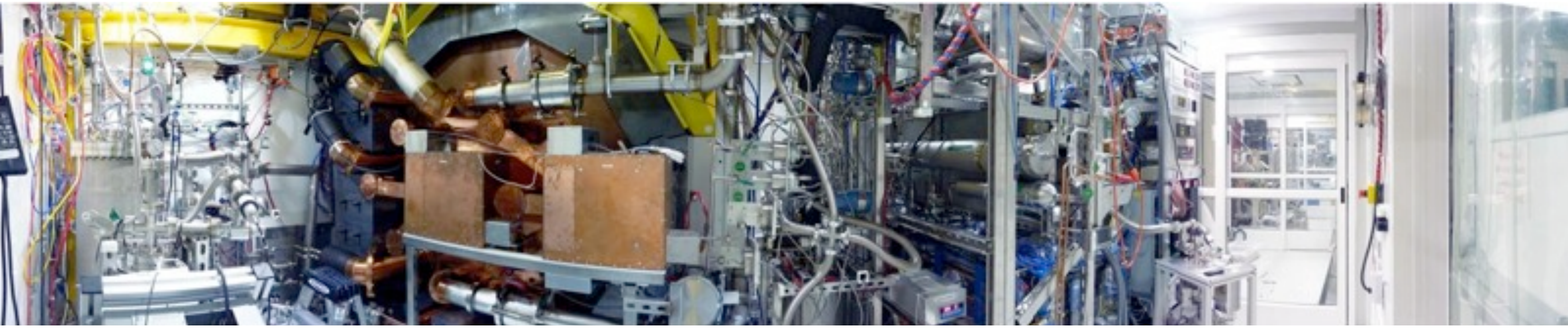
- Very good energy resolution and topology info
- R&D phase now being completed
- NEXT-100 under construction
- Commissioning in 2014, physics in 2015
- Plans for tonne-scale detector for full IH exploration

EXO-200

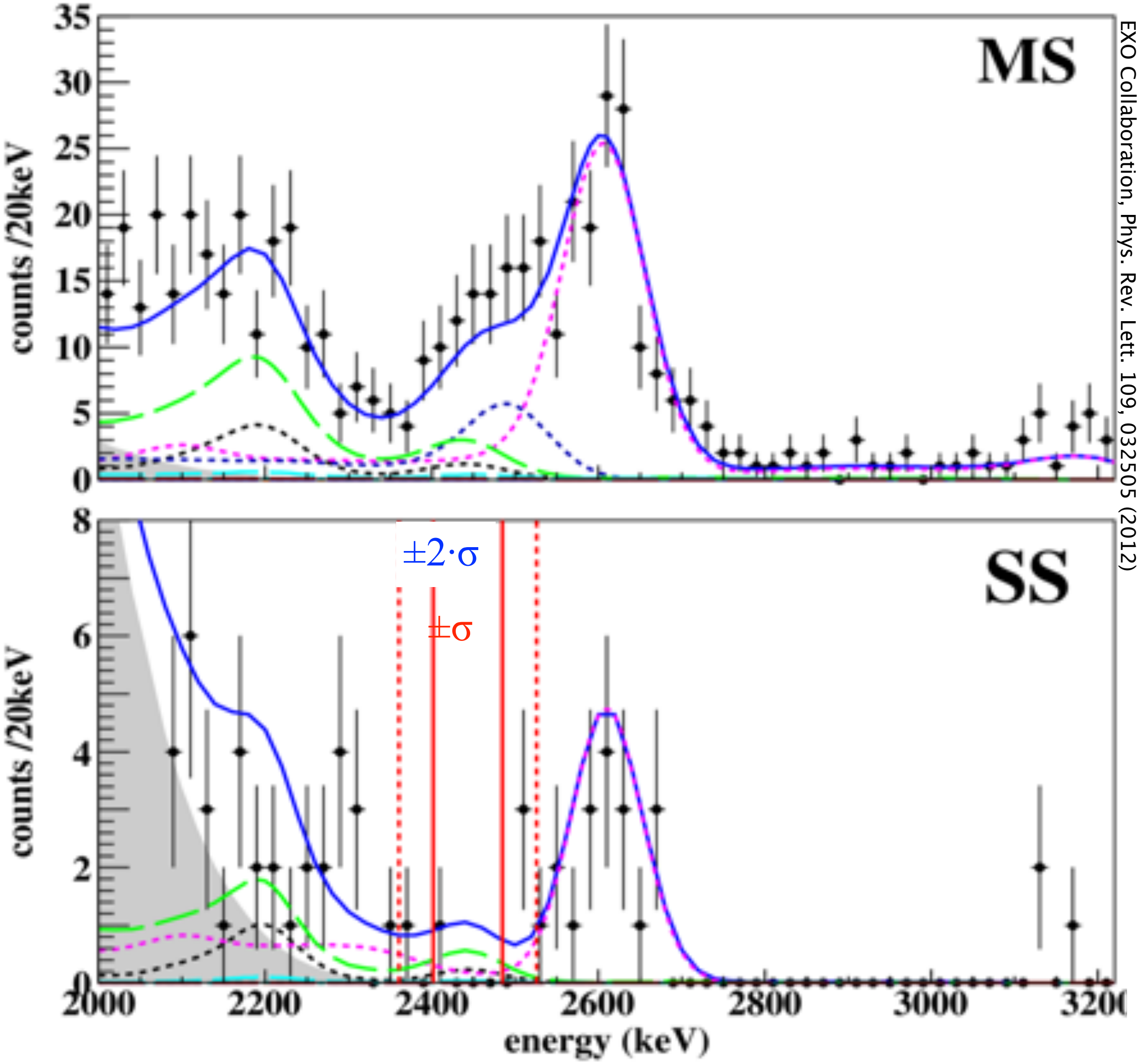




Liquid Xe TPC



Last 0ν2β results



EXO Collaboration, Phys. Rev. Lett. 109, 032505 (2012)

98.5 kg Xe, 120.7 d, 32.6 kg-yr,
by now 3x more data

$T_{1/2} > 1.6\times10^{25}$ yr (90% CL)

$\langle m_{\beta\beta} \rangle < 140 - 380$ meV

Multi-site (MS) vs Single-Site (SS):
powerful background discrimination

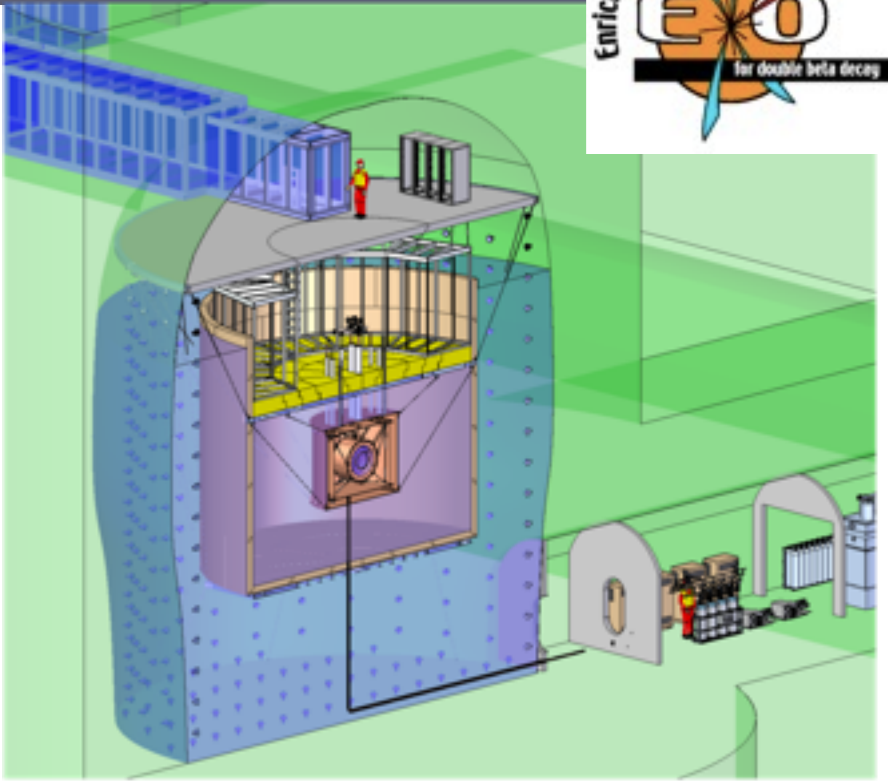
EXO-200 Plans / Goals

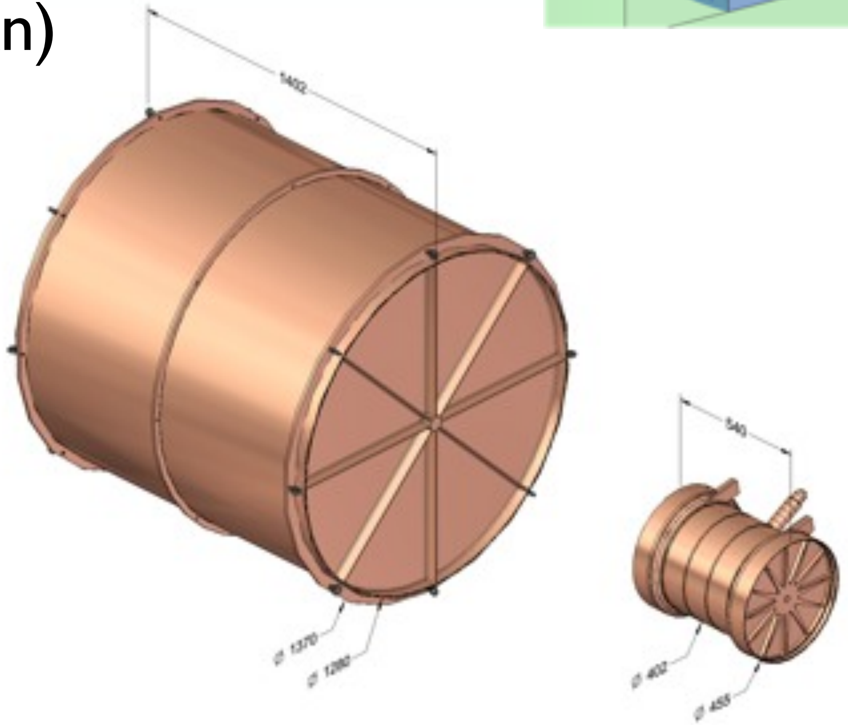
- Plans
  - Improve E-reconstruction efficiency and resolution (e.g. 1.67% → 1.4%)
  - Improve fiducial volume uncertainty from 9% → 4% (1.6% for $2\nu2\beta$)
  - Reduce background by perhaps 2x (Rn trapped in shield)
- Goals
  - Sensitivity of (3 - 5.5) x 10^{25}yr (90% CL) → $\langle m_{\beta\beta} \rangle < 75 - 270$ meV
  - Demonstrator for next generation EXO

A. Piepke, EXO

nEXO

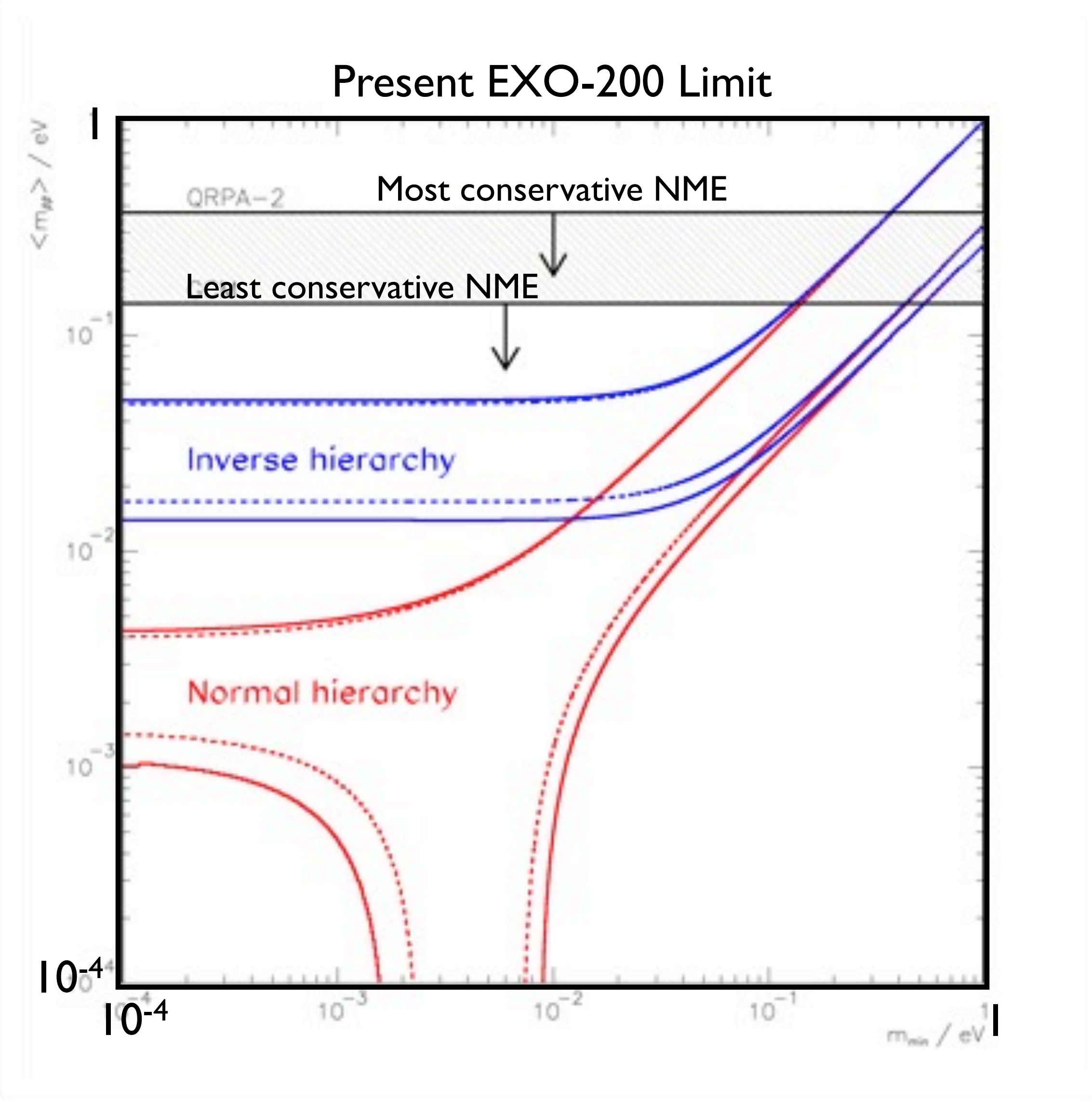
- 5 ton ^{enr}Xe (~4.5 ton fid) initially without Ba-tagging
    - Ba-tagging an option, R&D continuing
- 1.4% (σ) E-reso
- Move from WIPP to SNOLab
- Assume backgrounds similar to EXO-200 (but no Rn)





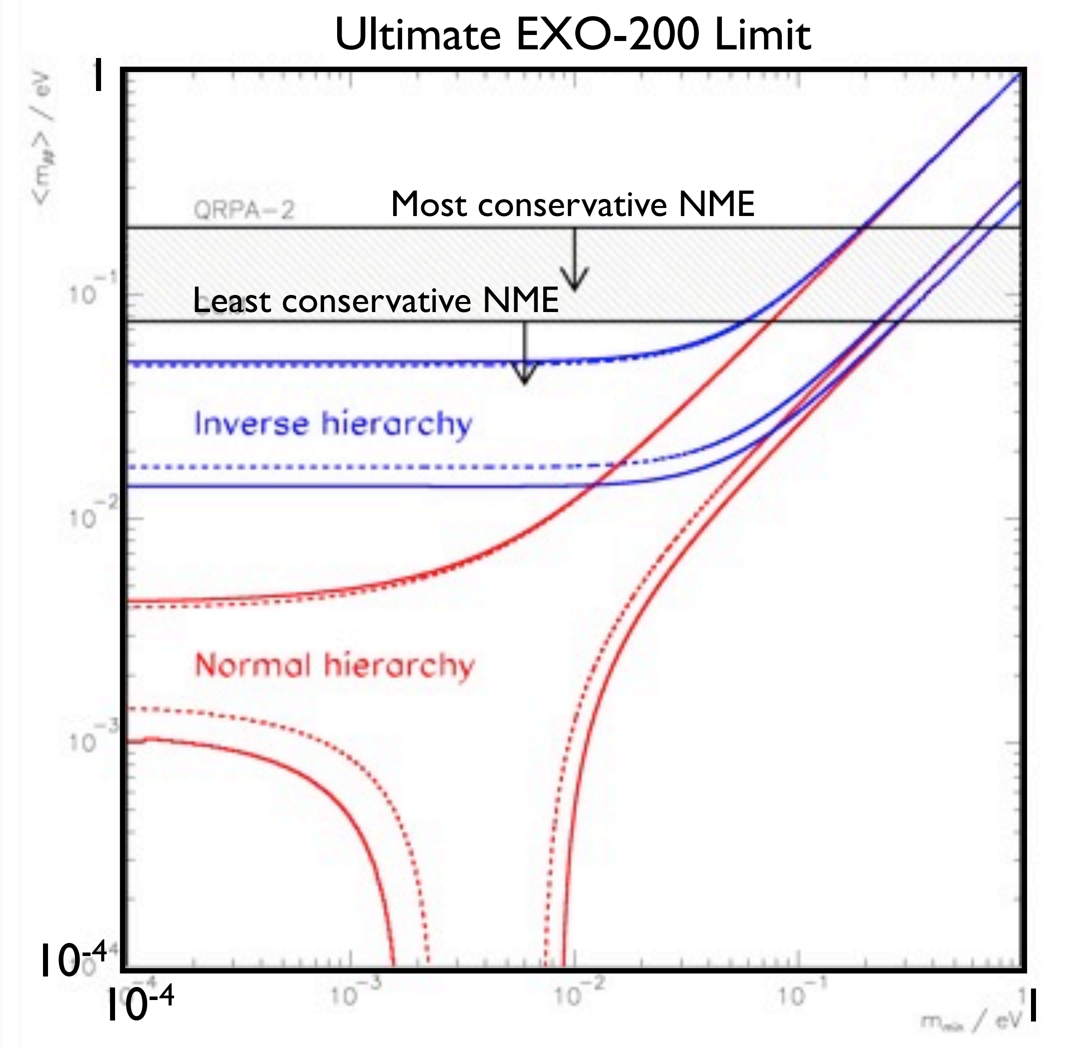
A. Piepke, EXO

nEXO limits



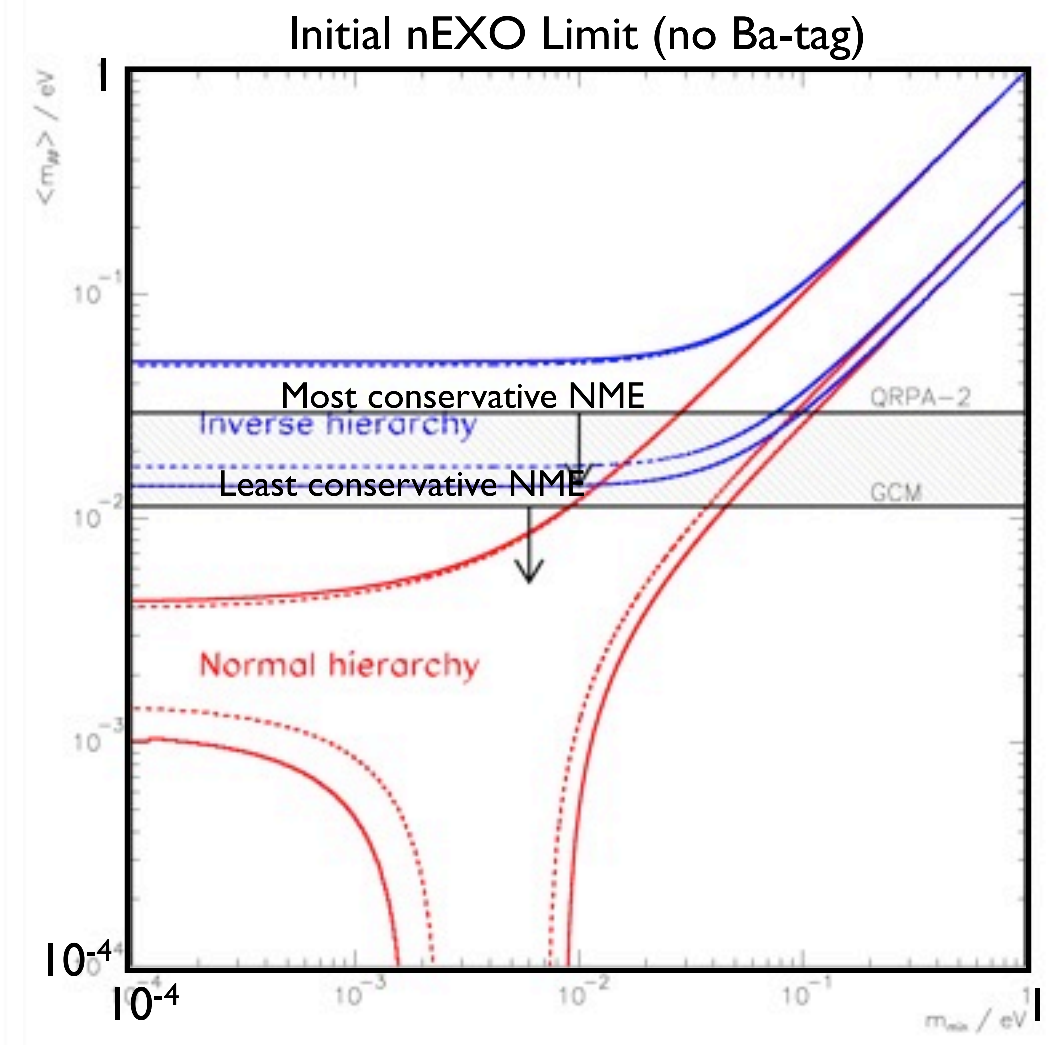
A. Piepke, EXO

nEXO limits



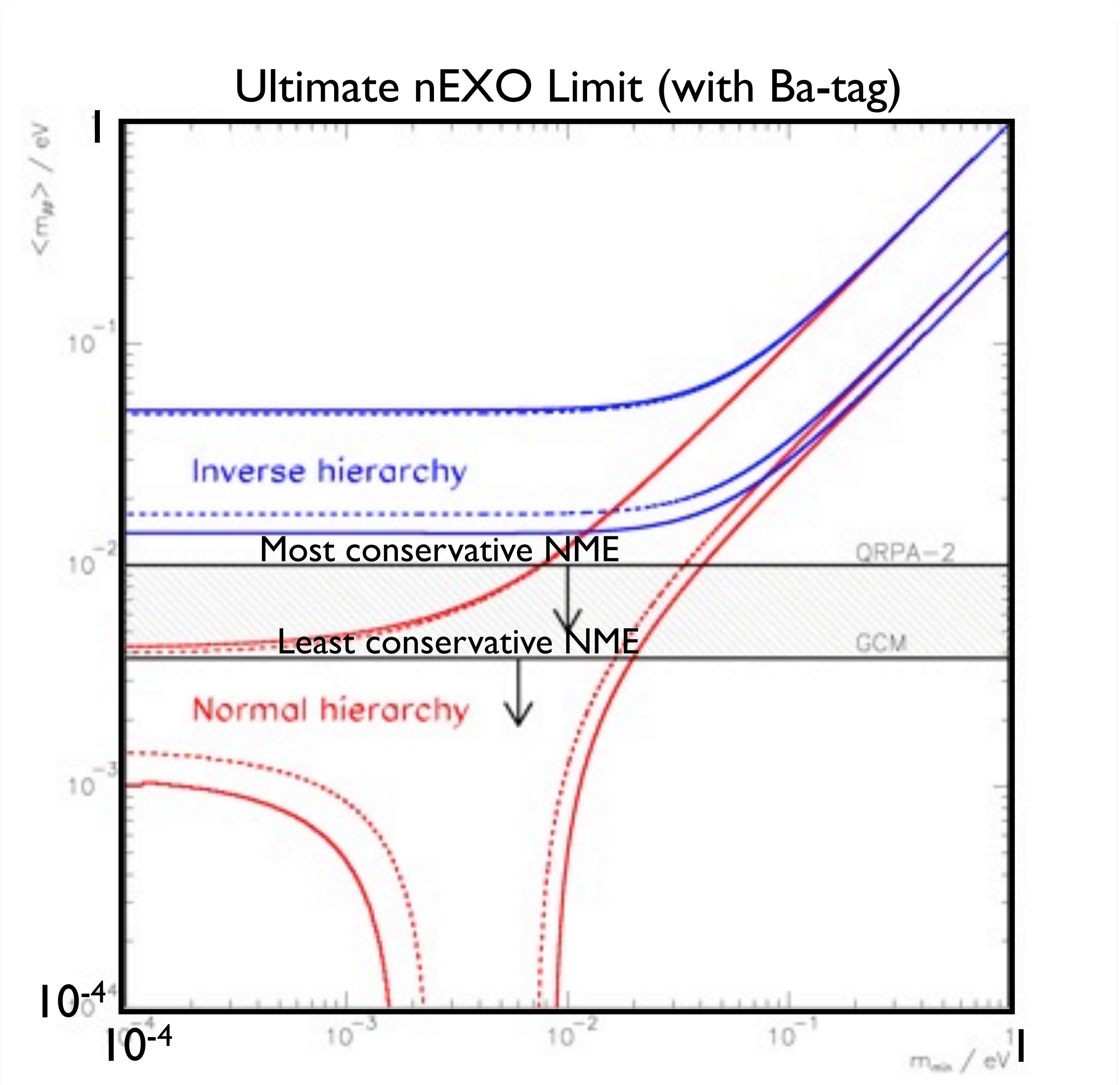
Ultimate EXO-200: 4yrs, with Rn removal

nEXO limits


Initial nEXO Limit (no Ba-tag)

Initial nEXO: scale up of EXO-200, no Ba-tagging

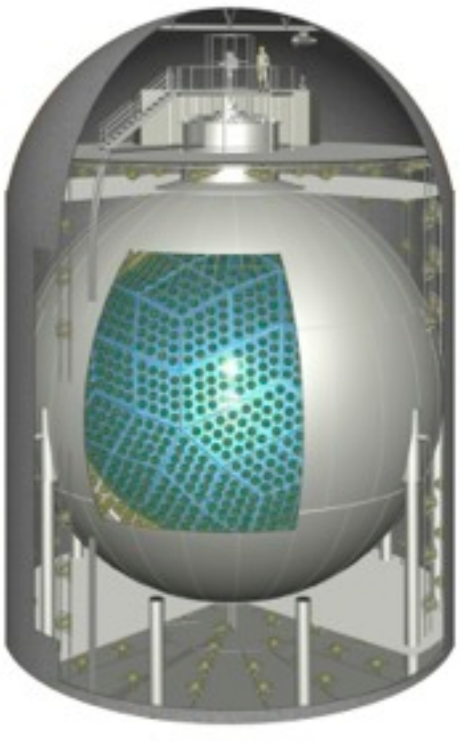
nEXO limits


Ultimate nEXO Limit (with Ba-tag)

Final nEXO: Ba-tagging, no BG besides $2\nu\beta\beta$

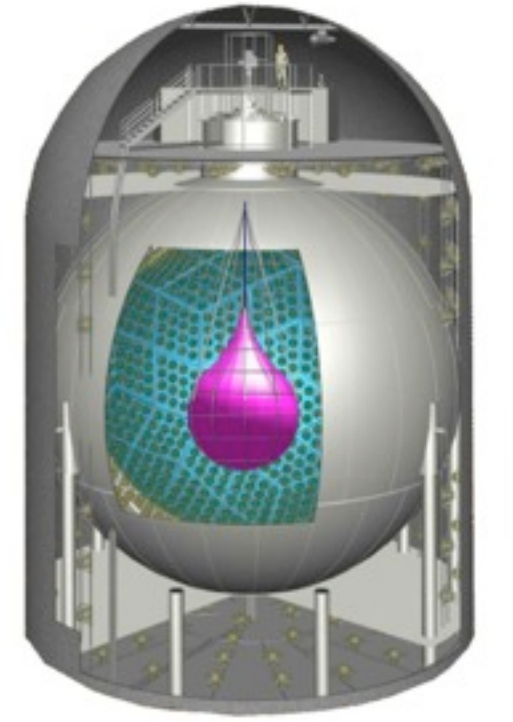
A. Piepke, EXO

Towards the KamLAND-Zen detector



KamLAND

2002-2011



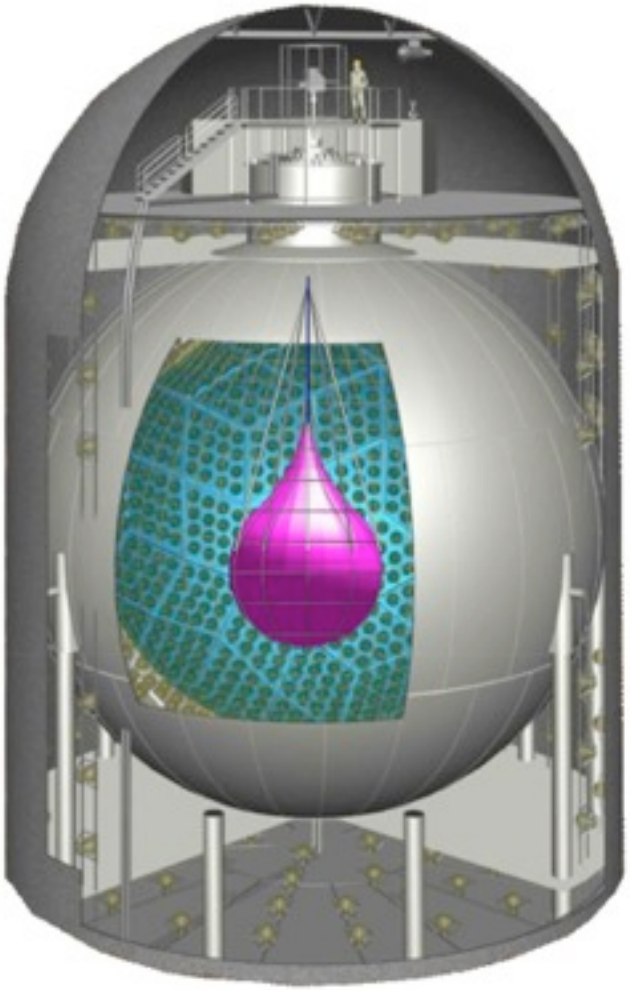
KamLAND-Zen

2011-

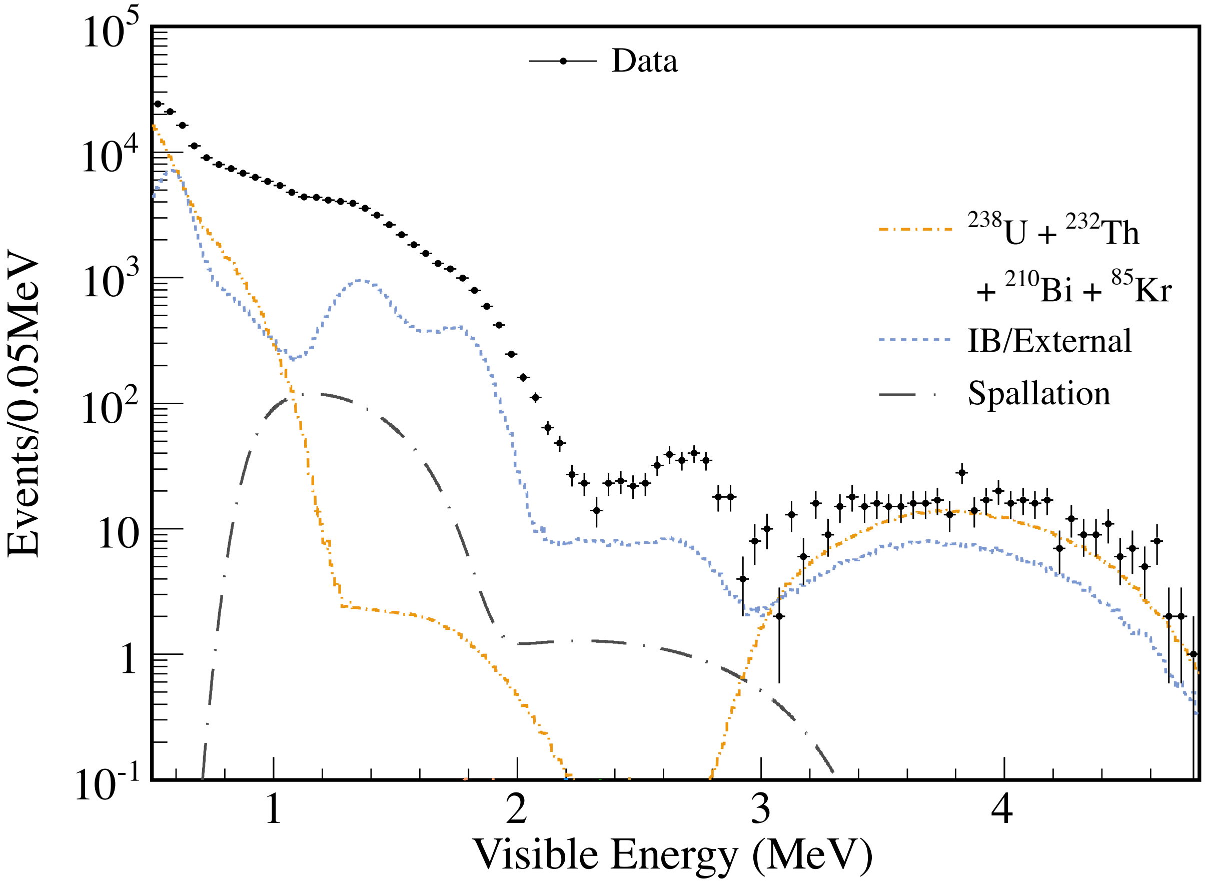
KamLAND-Zen advantages & disadvantages

- +Well-understood detector
- +Highly pure, self-shielding environment
- +Large ββ source mass, scalable
- -Relatively poor energy resolution
- -No particle identification

[And similar arguments apply to SNO+!]



Latest 0ν2β results



KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

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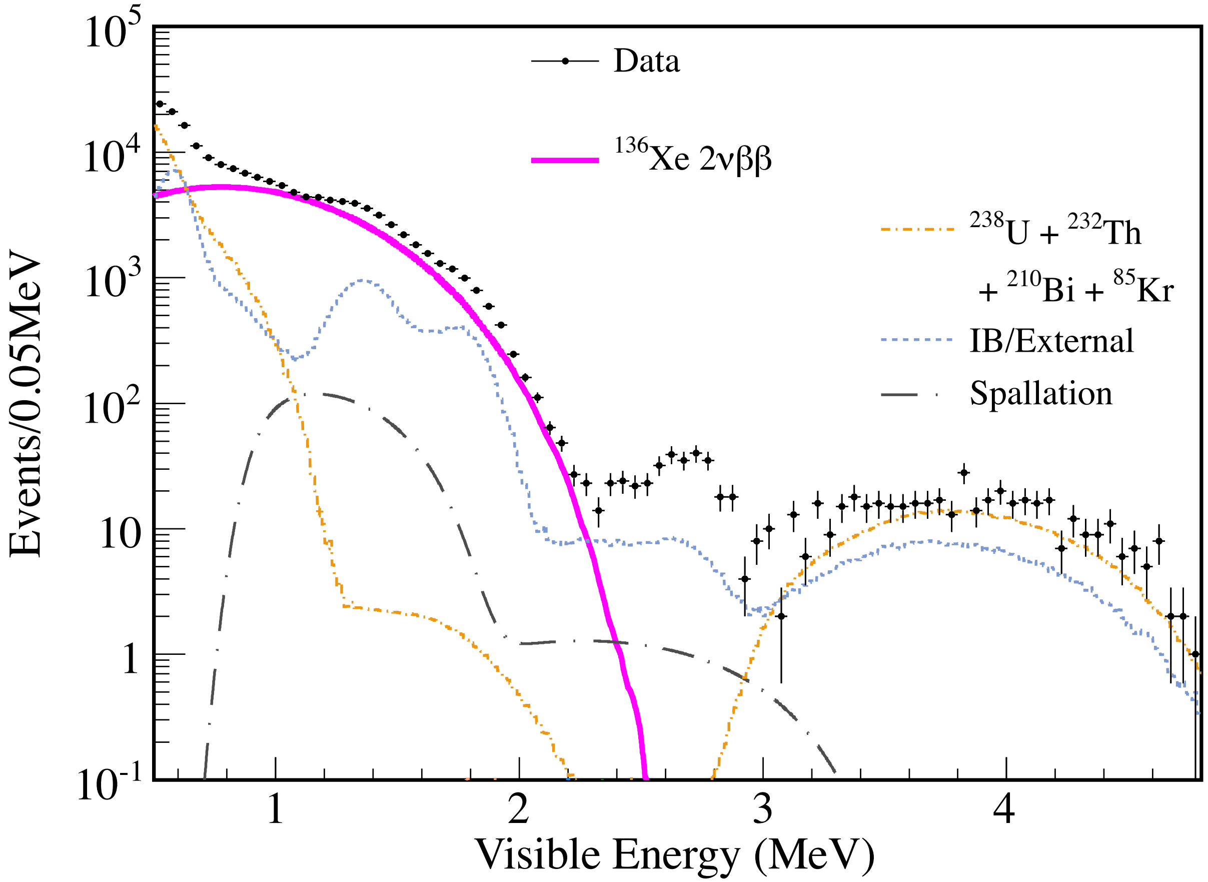

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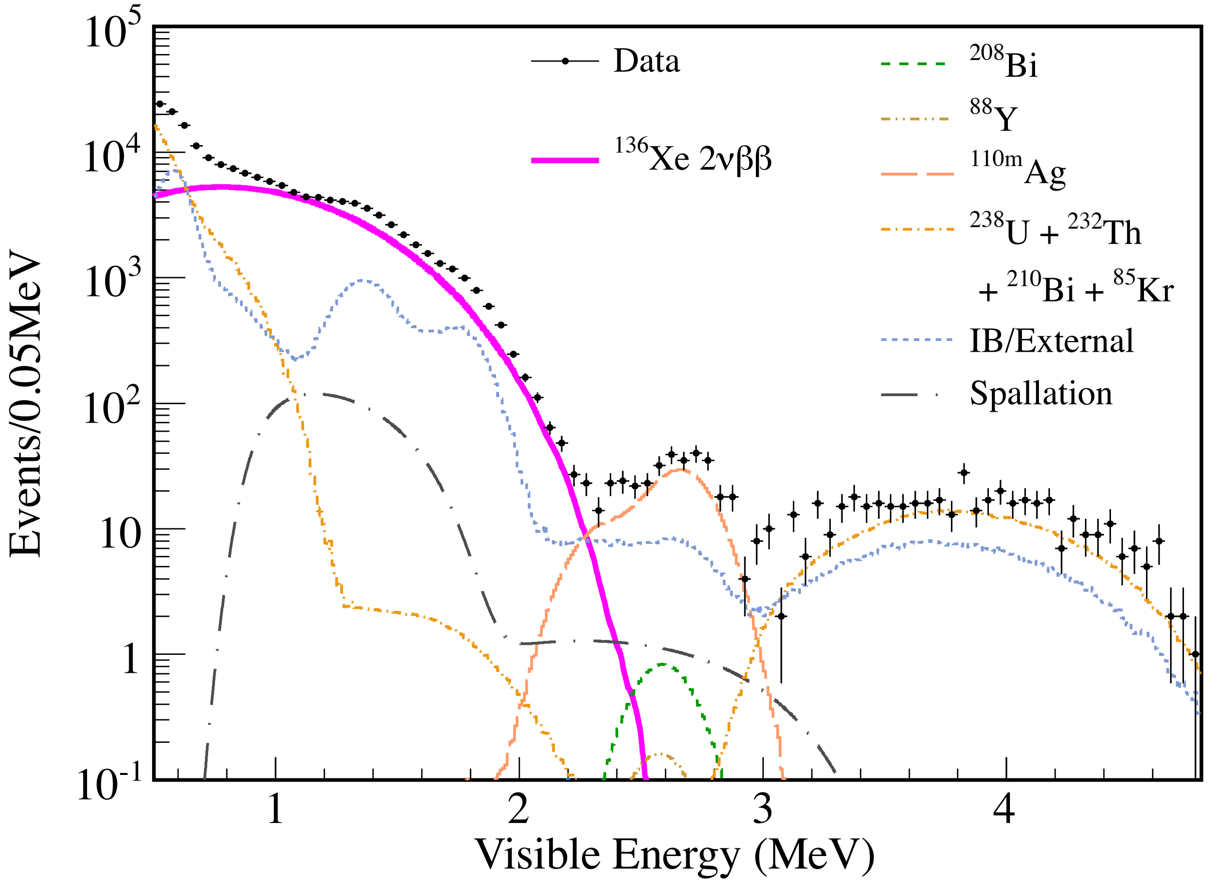

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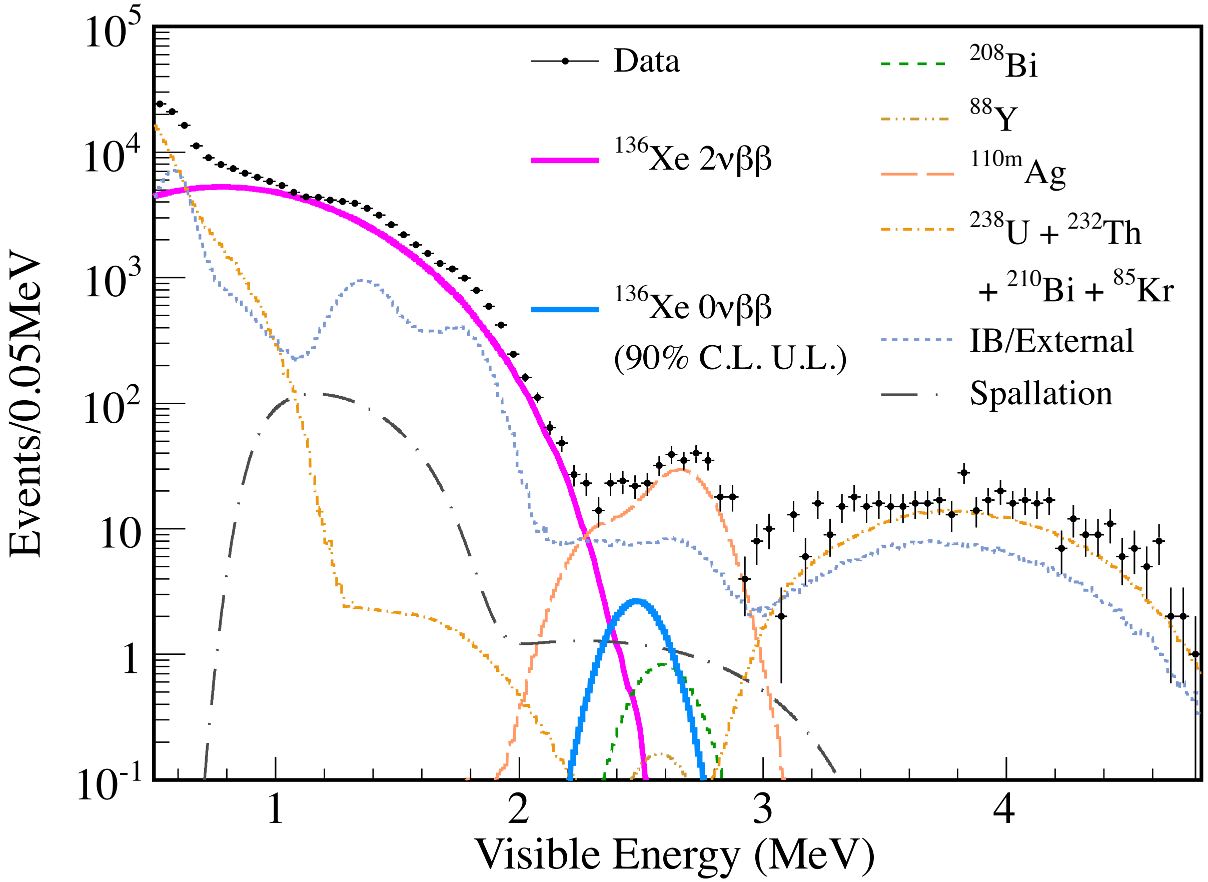

KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

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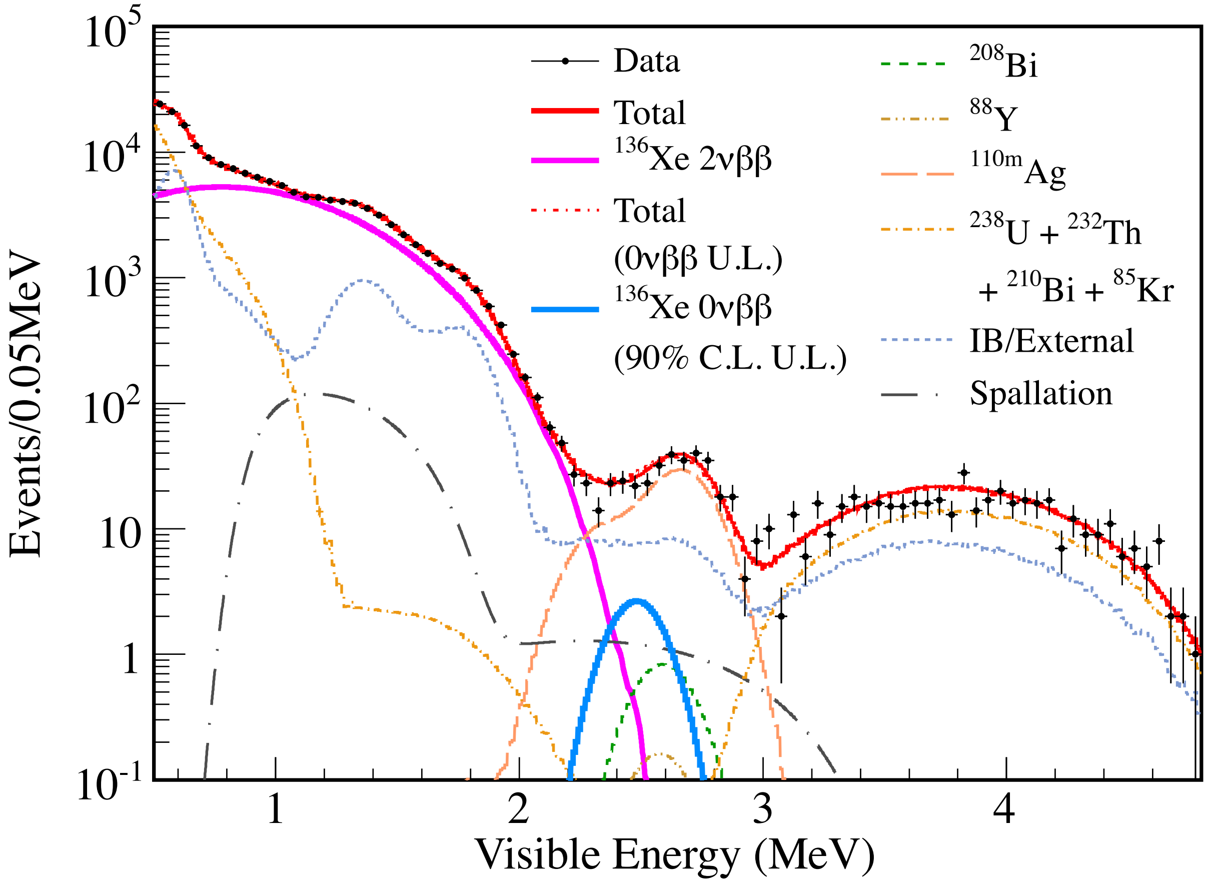
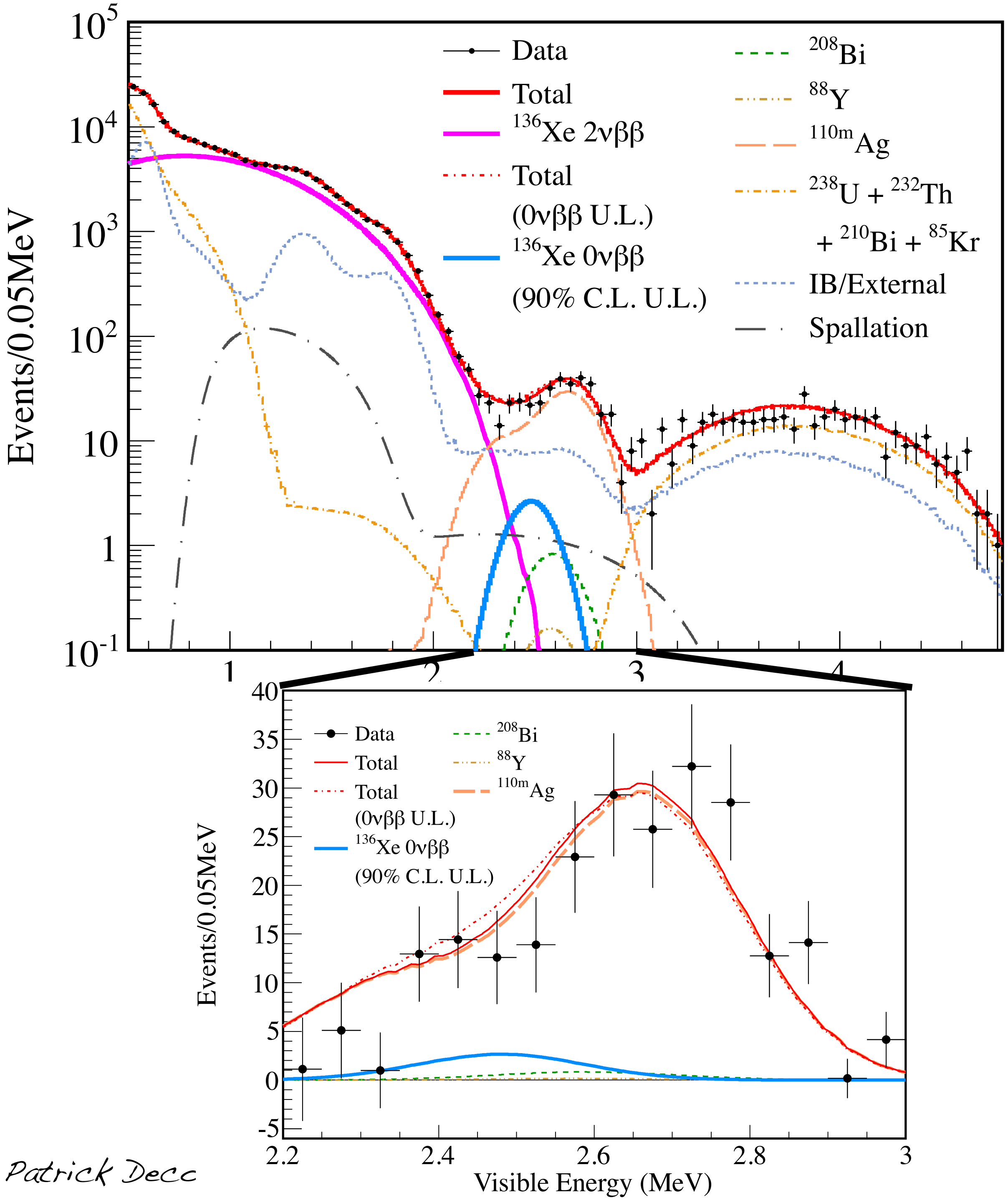


KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

Patrick Decowski / Nikhef

Latest 0ν2β results



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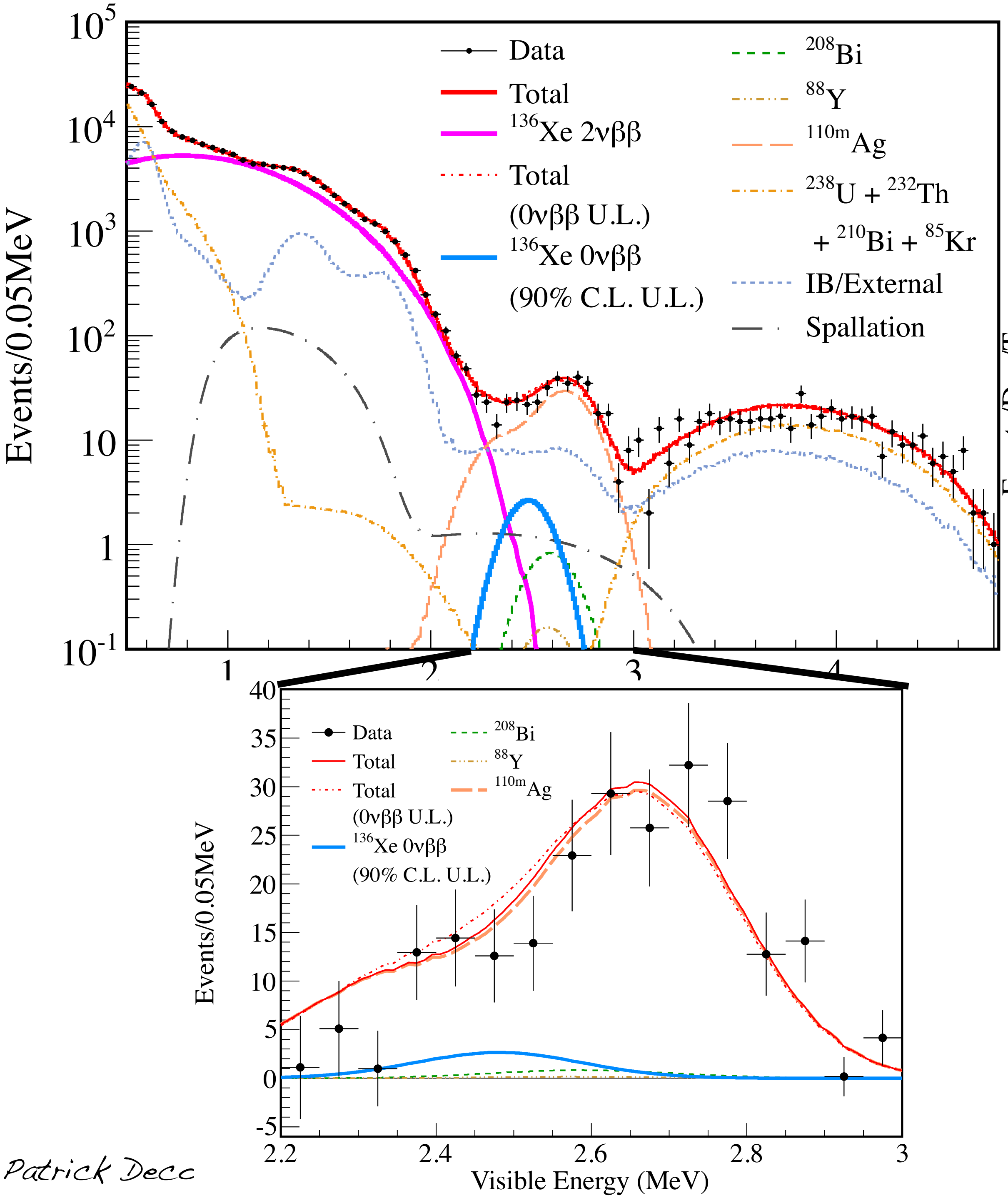

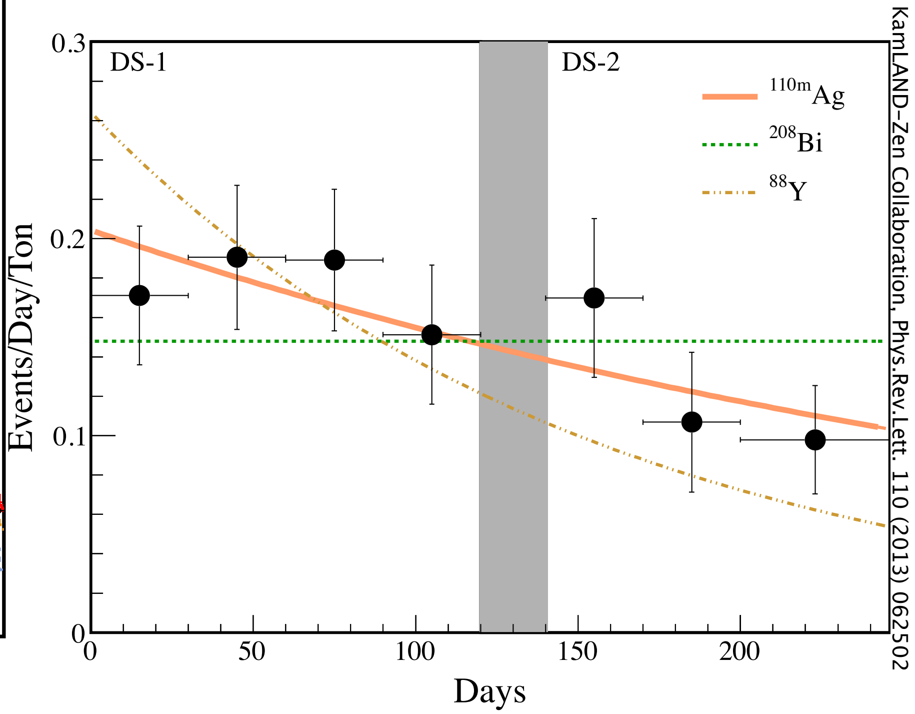

KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

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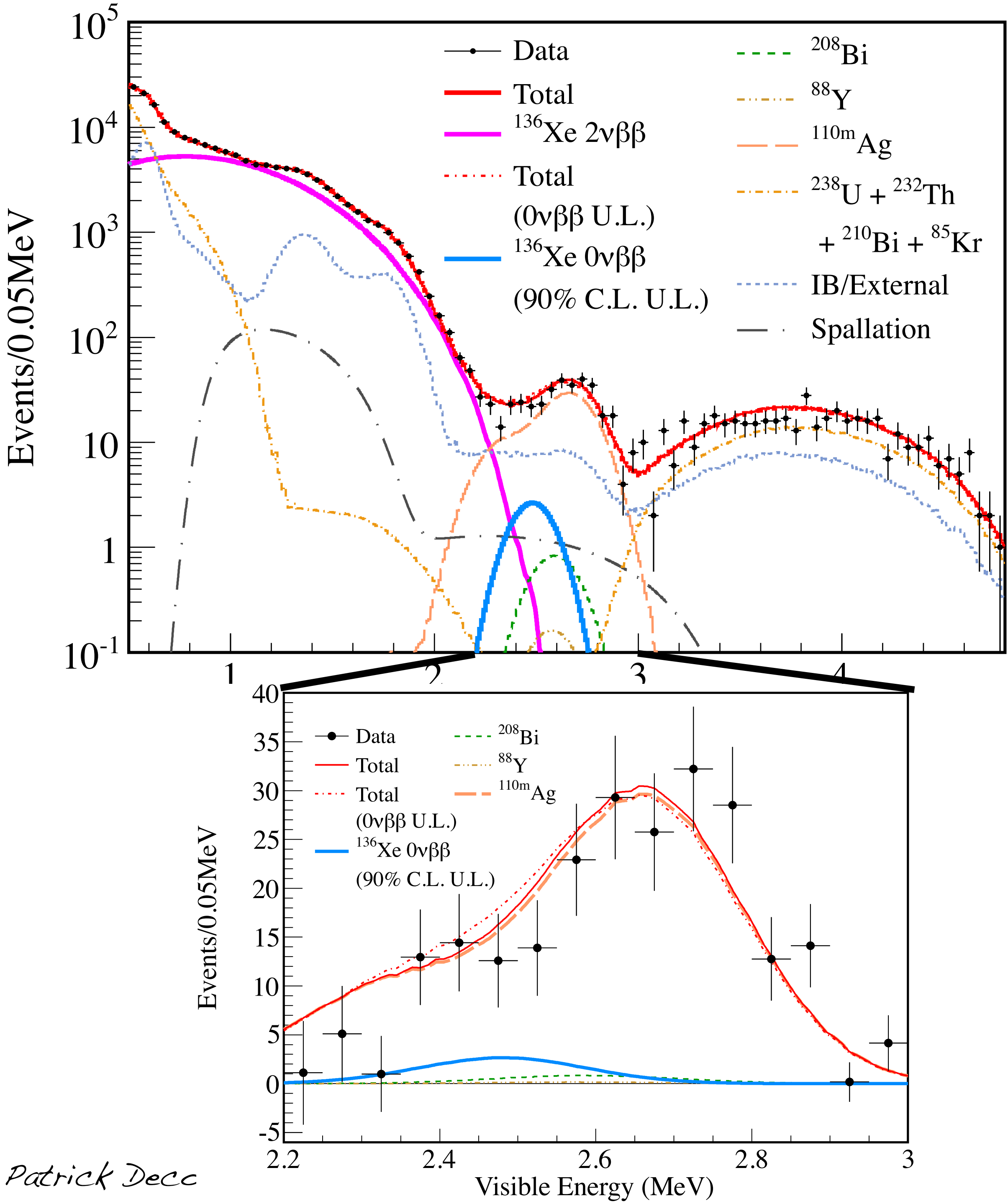
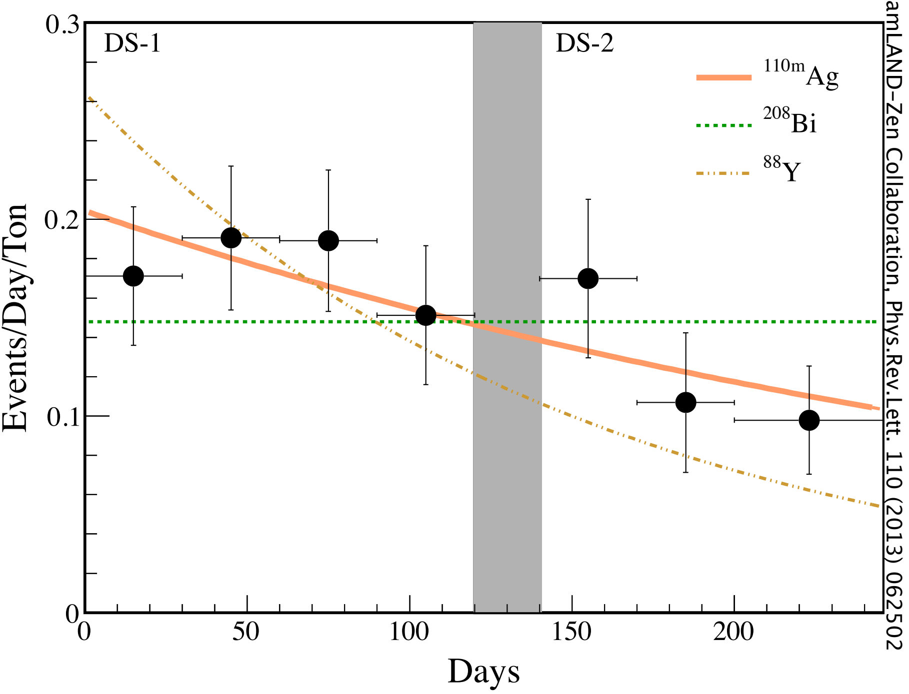
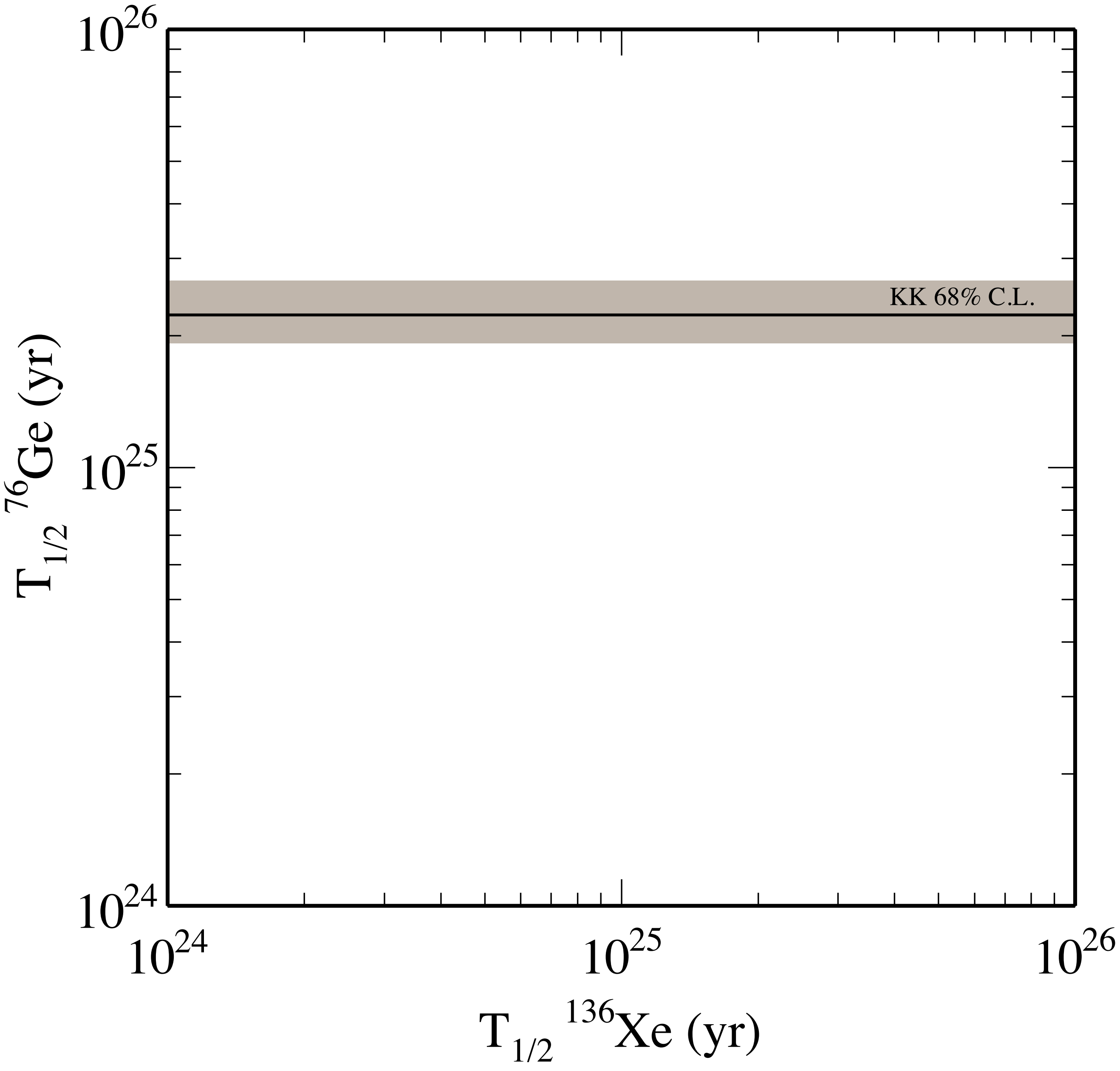




KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

- Current status: destillation of LS and Xe separately
- New 0ν2β run starting in Aug 2013

The positive claim in ^{76}Ge…



KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

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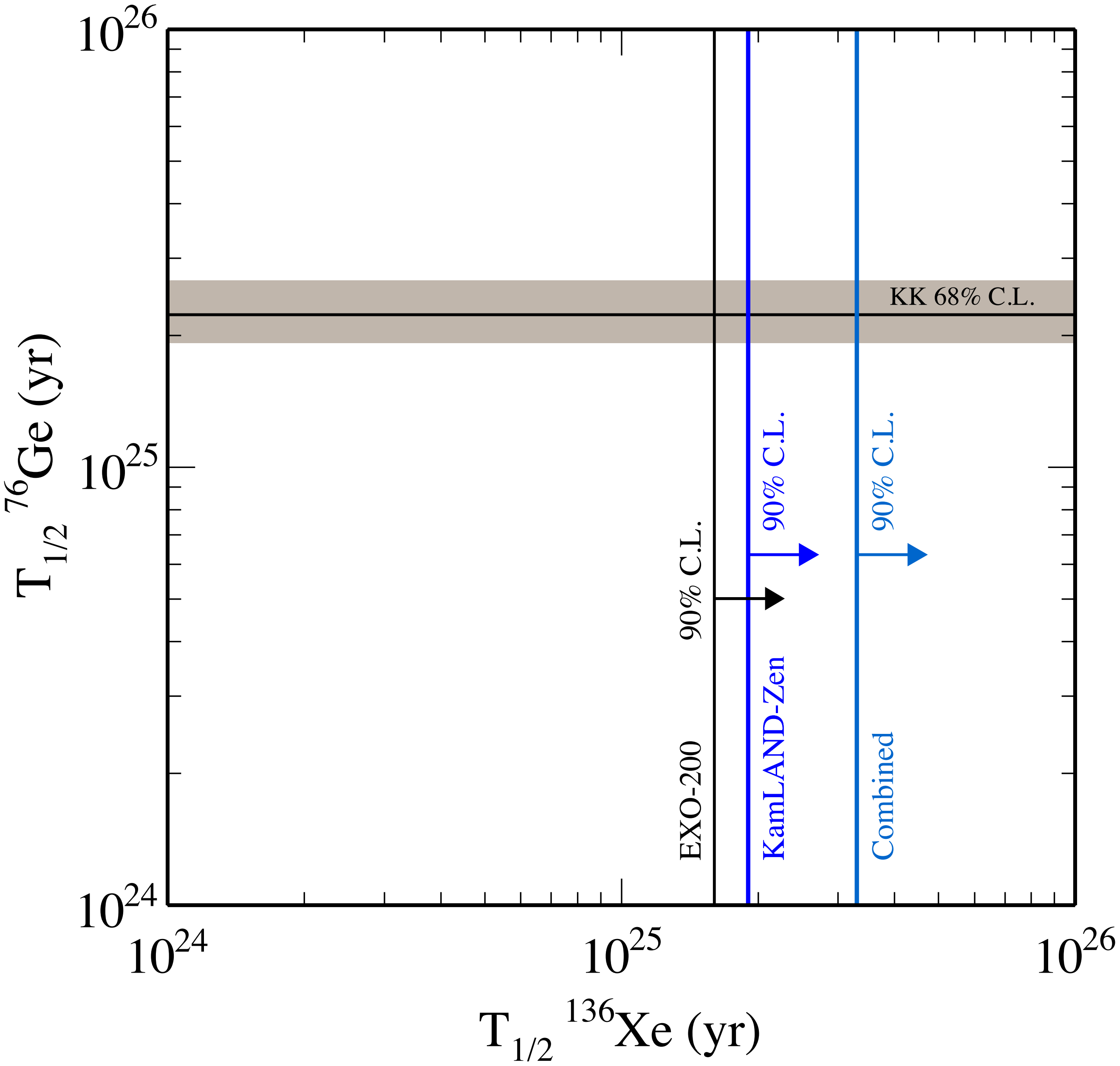

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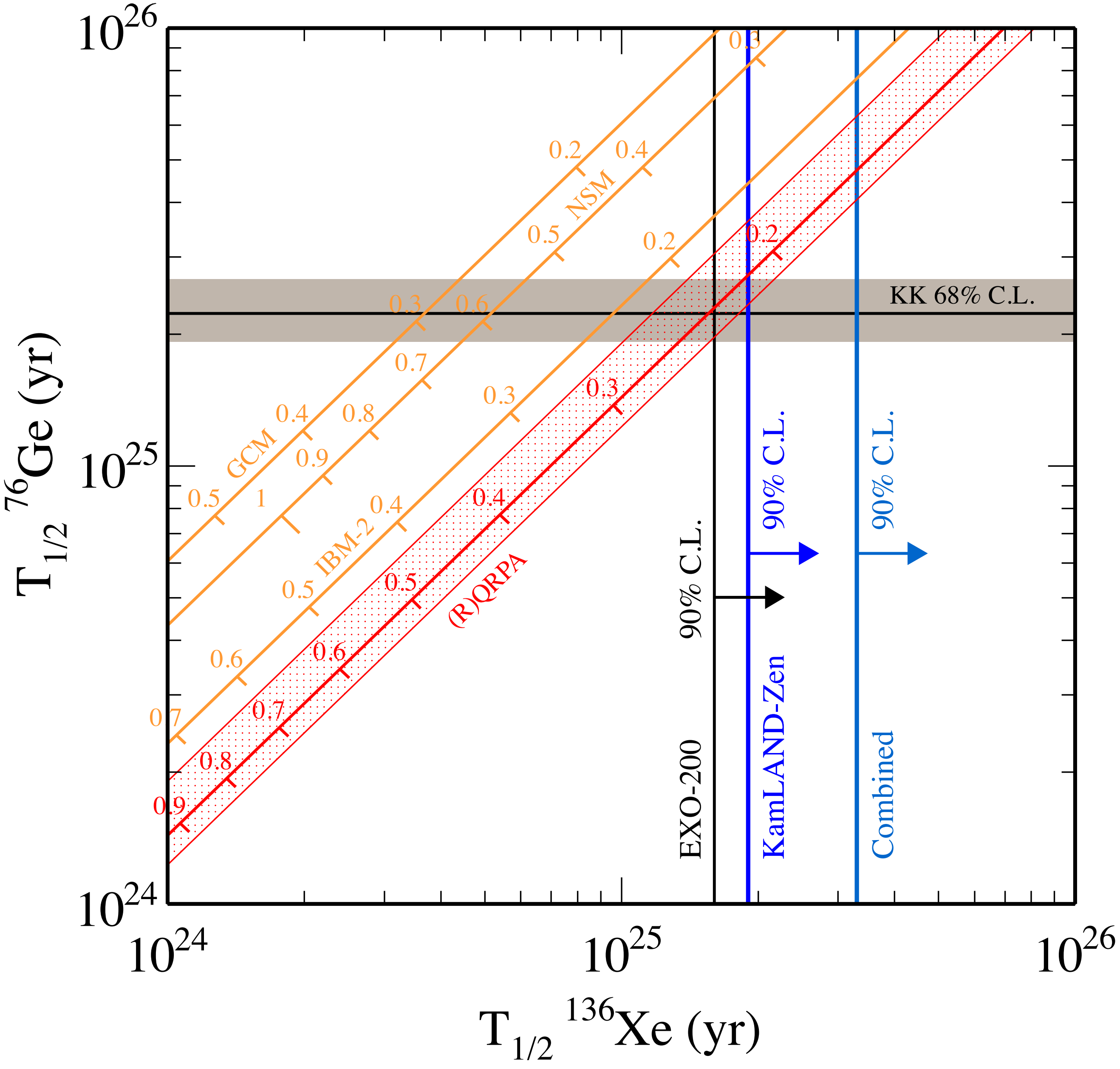

KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

Combined limit from EXO-200 + KLZ: KKDC claim is excluded at >97.5% C.L.

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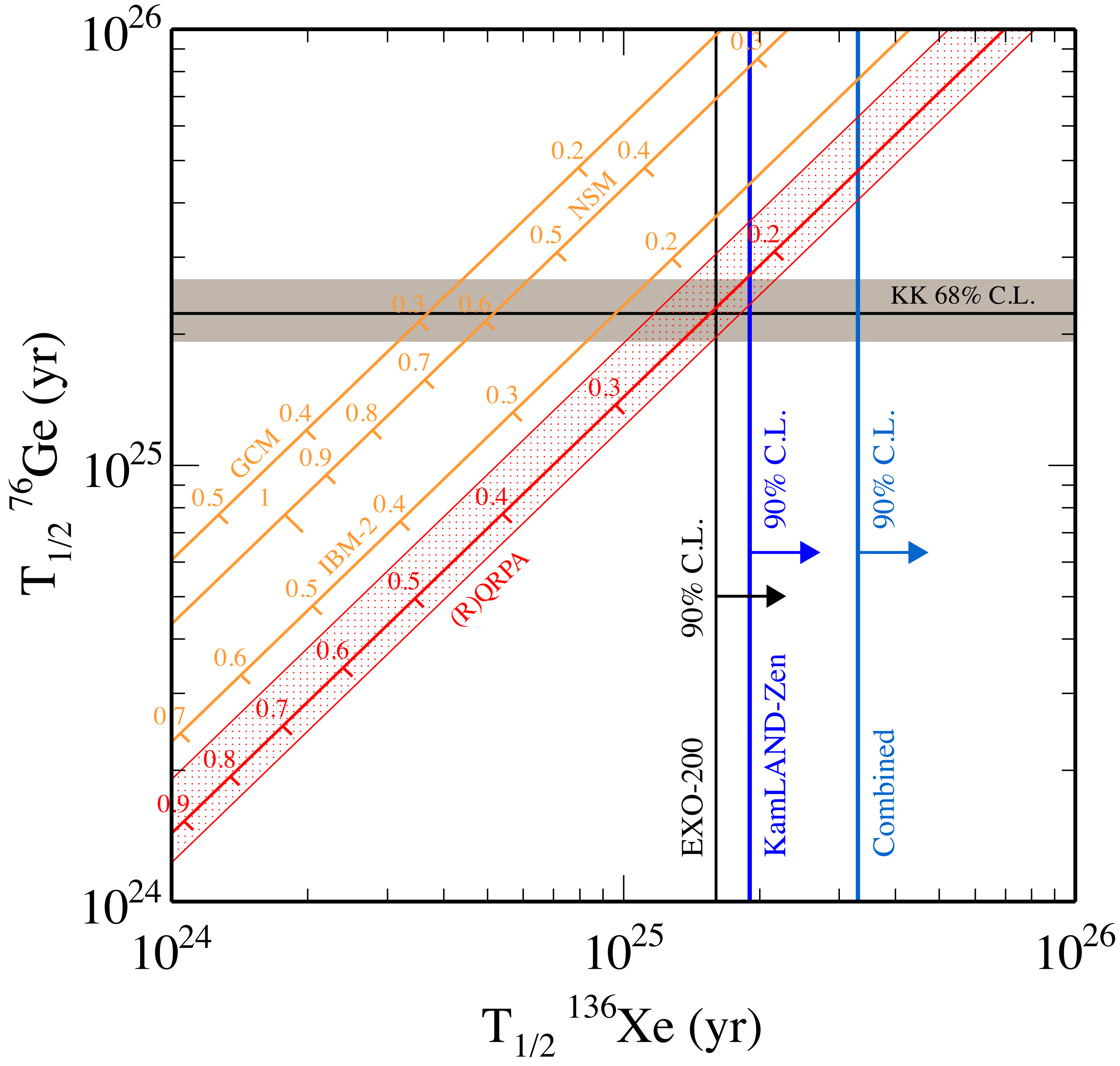


KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

$\langle m_{\beta\beta} \rangle < 120 - 250$ meV

Combined limit from EXO-200 + KLZ: KKDC claim is excluded at >97.5% C.L.

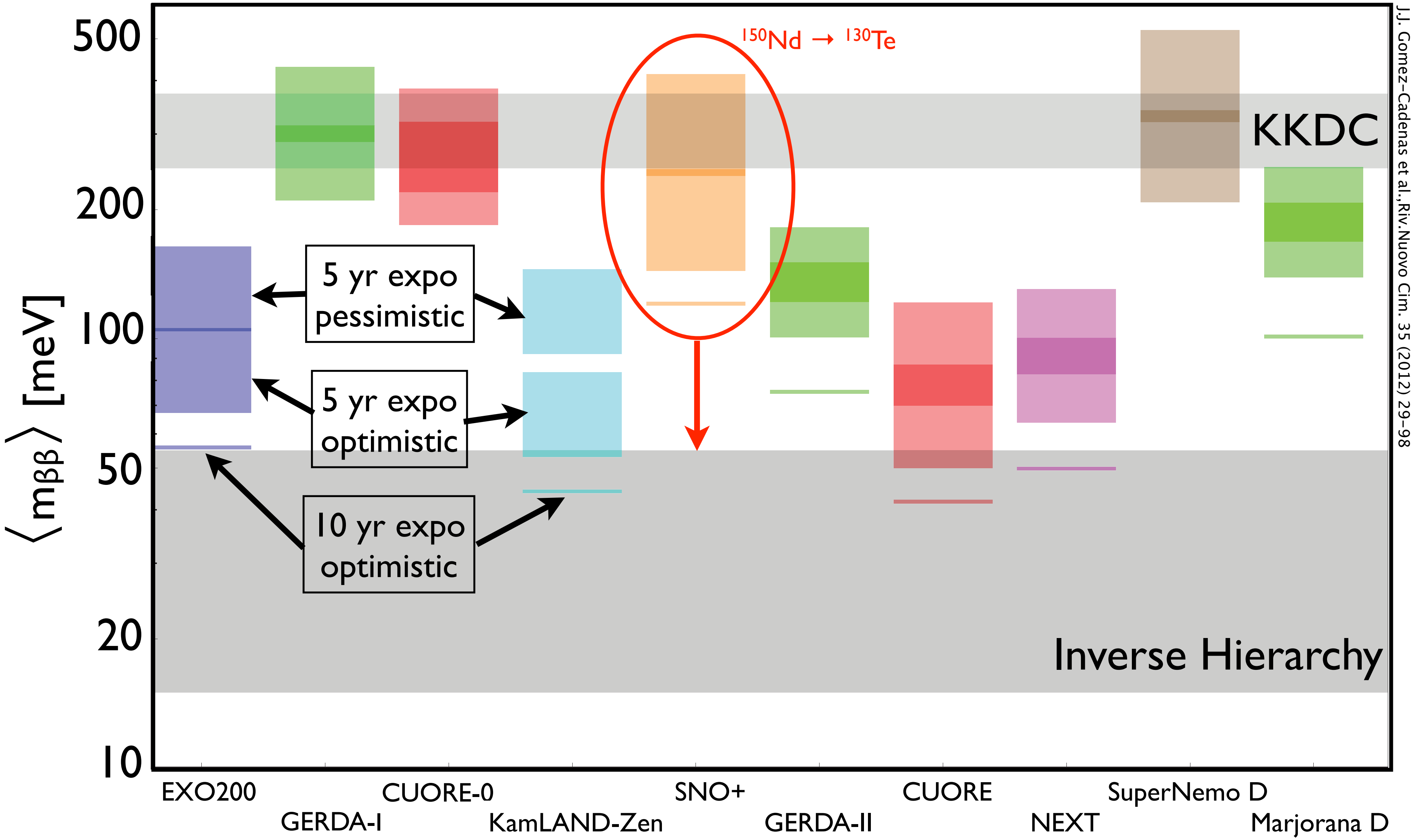
Other Experiments

AMoRE	^{100}Mo	Good energy reso
CANDLES	^{48}Ca	High Q-value
COBRA	^{116}Cd, ^{130}Te	Topology
DCBA	^{82}Se, ^{150}Nd	Topology
LUCIFER	^{82}Se, ^{100}Mo, ^{116}Cd	Good energy reso
MOON	^{82}Se, ^{100}Mo, ^{150}Nd	Topology
XMASS	^{136}Xe	Large Mass

A.Giuliani

Experimental Summary of Current Gen

Current Gen: ~100kg mass



J.J. Gomez-Cadenas et al.,Riv.Nuovo Cim. 35 (2012) 29-98

Summary

- Observation of 0ν2β would be a major discovery
  - Majorana nature of neutrinos
  - Lepton Number Violation
  - Needs verification with different techniques and isotopes
- Many experiments are running or will be commissioned in the next few years at a few 100kg scale
  - Exploration of inverted hierarchy feasible
  - Normal hierarchy will remain difficult (>10 ton scale expts)
  - Not just NME, but also new measurements (e.g. θ_{12}) necessary

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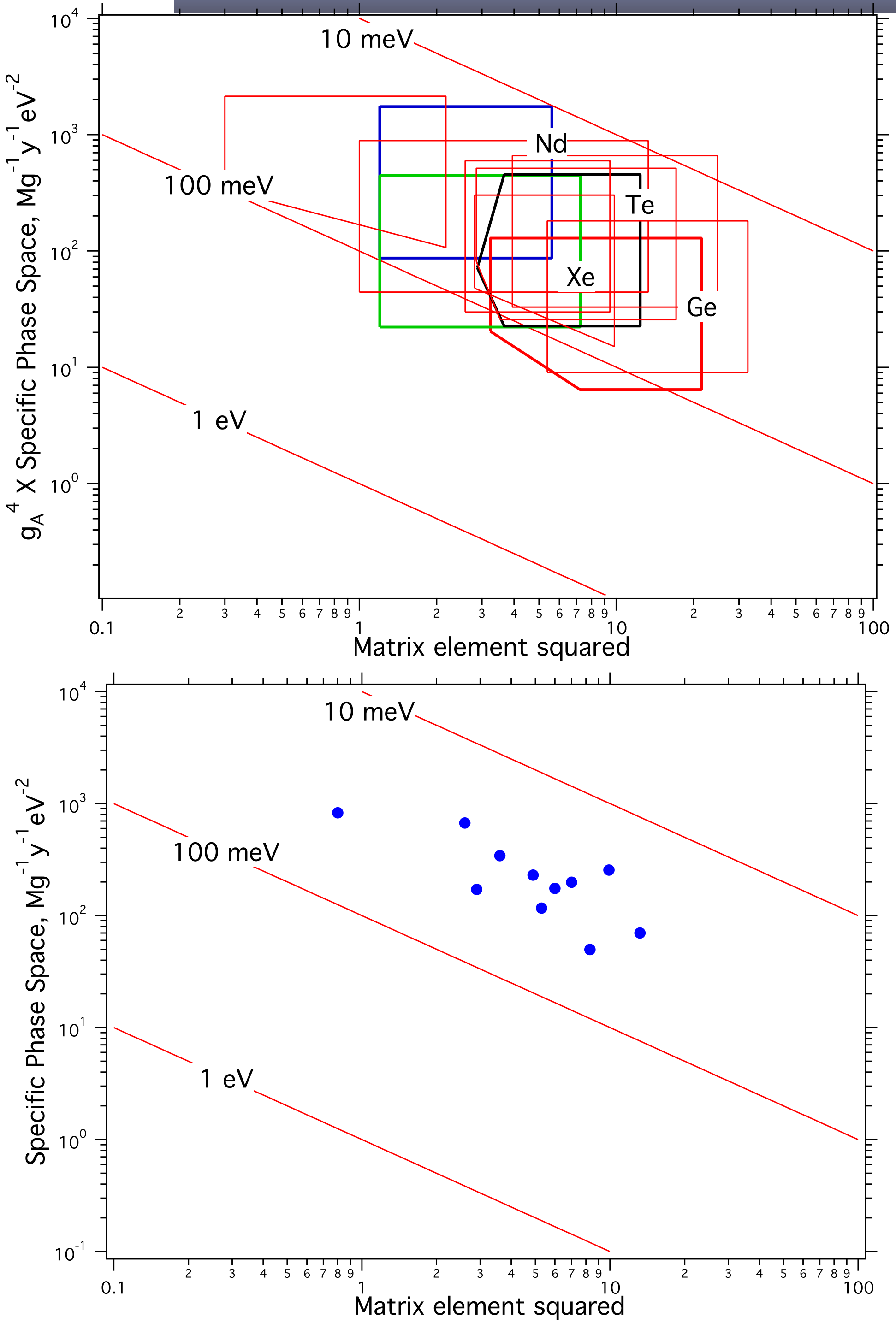
I expect EXO-200 results soon, but there will be limited new data coming for 1-2 years after that…

Correlations?



The phase space $G_{0\nu}$: activity per atom

Specific phase space: activity per unit mass

$$(T_{1/2}^{0\nu})^{-1} = g_A^4 G'_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Setting g_A = 1.0 for all isotopes

→ Unexpected inverse relationship

H. Robertson, arXiv: 1301.1323