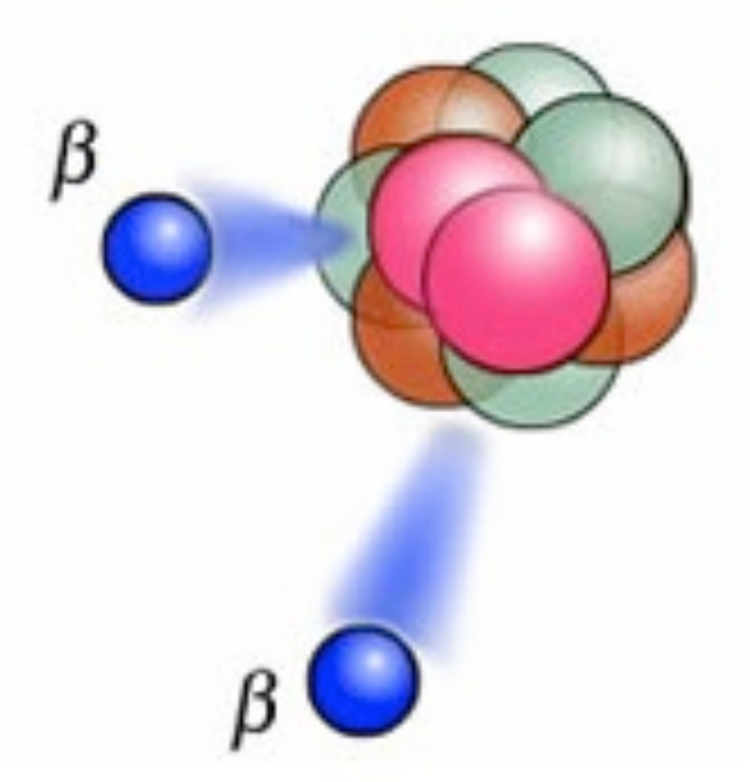
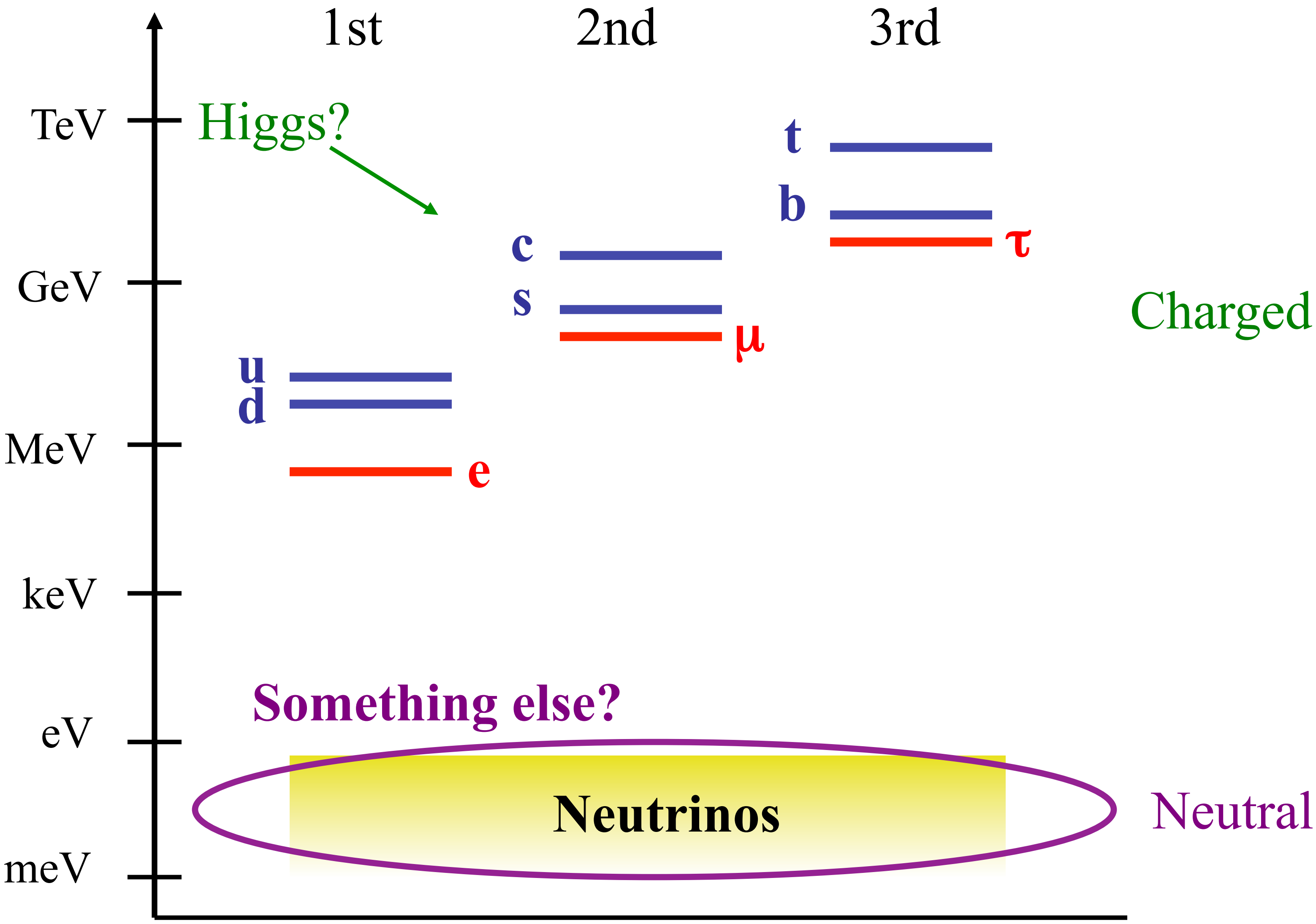
Neutrinoless Double Beta Decay



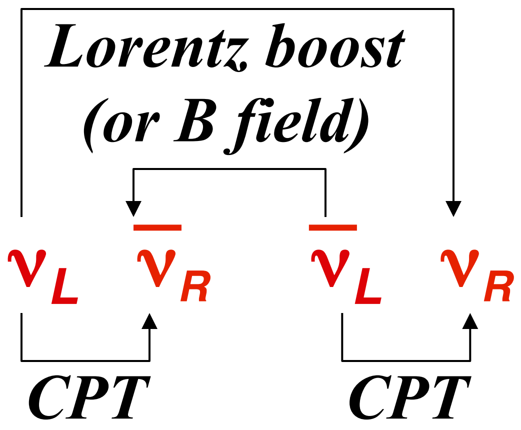
Michelle Dolinski
Drexel University
SSI, 16 July 2013

Neutrino mass puzzle



Massive neutrinos

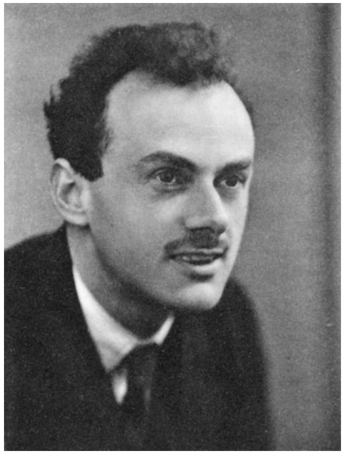
“Dirac” neutrinos



Lorentz boost (or B field)

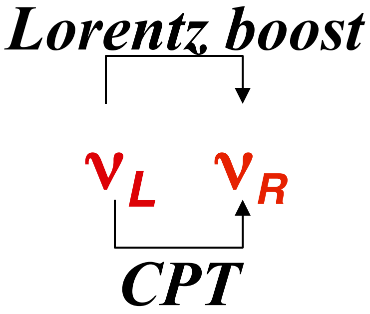
ν_L $\bar{\nu}_R$ $\bar{\nu}_L$ ν_R

CPT *CPT*



“Majorana” neutrinos

No lepton number conservation!



Lorentz boost

ν_L ν_R

CPT

The two descriptions are distinct and distinguishable only if $m_\nu \neq 0$.

Seesaw mechanism

Experimentally, it is an open question whether neutrinos are their own anti-particles (Majorana type) or not (Dirac type).

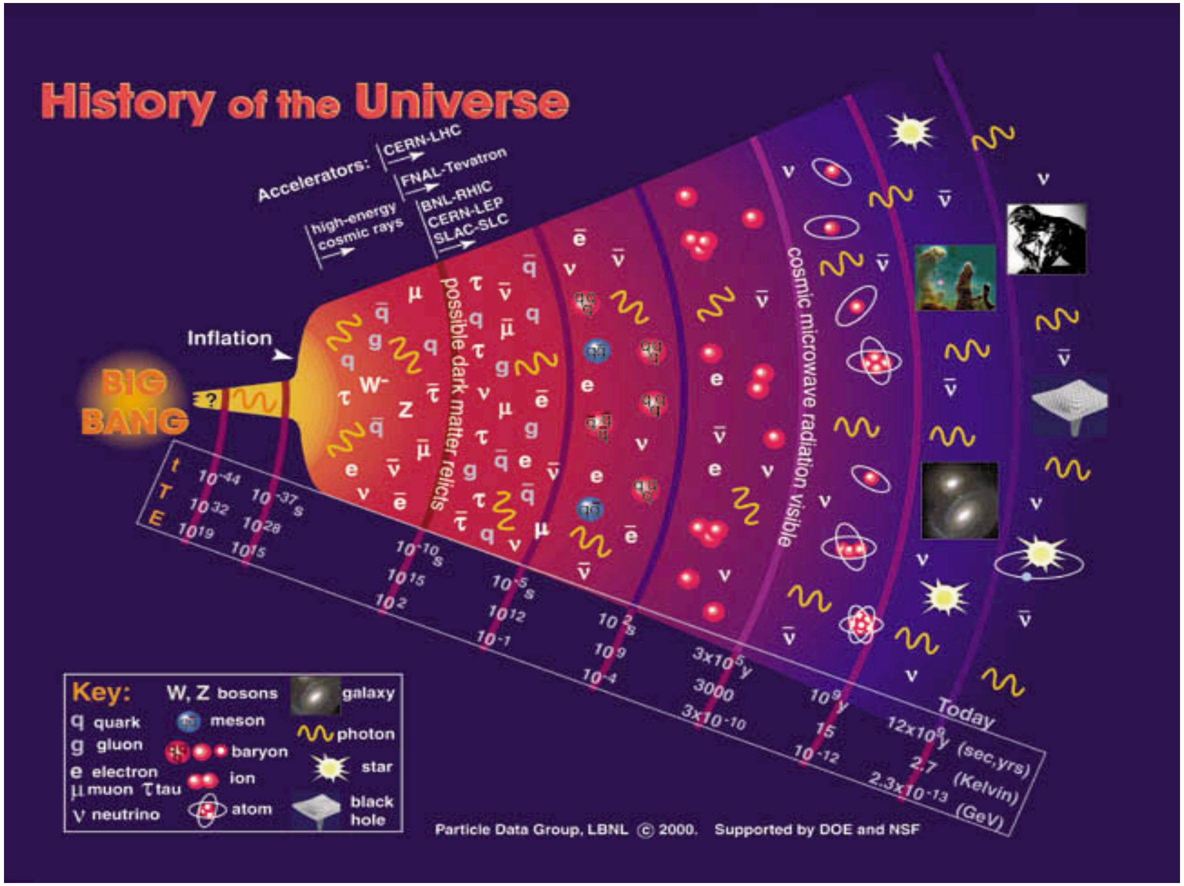
Majorana neutrinos are preferred by theorists. Seesaw mechanism can be used to explain small neutrino masses.

Seesaw mechanism (Gell-Mann, Ramond, Slansky and Yanagida, 1979):

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix}$$

$$Z^T M_\nu Z = D_\nu = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \approx \begin{bmatrix} m_D^2 / m_R & 0 \\ 0 & m_R \end{bmatrix}$$

Leptogenesis



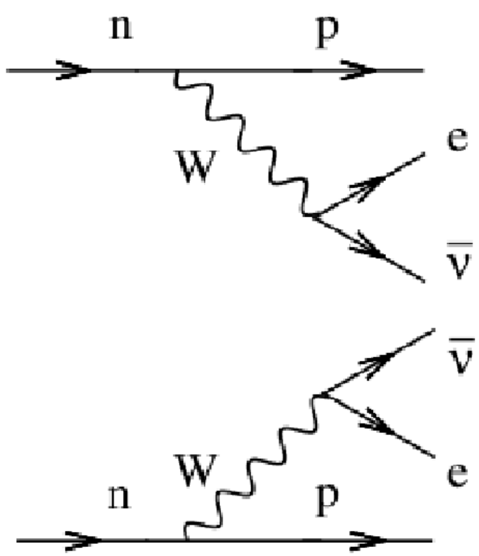
"Sakharov conditions" for leptogenesis:

- *B-L* violation
- *CP* violation
- Out of thermal equilibrium

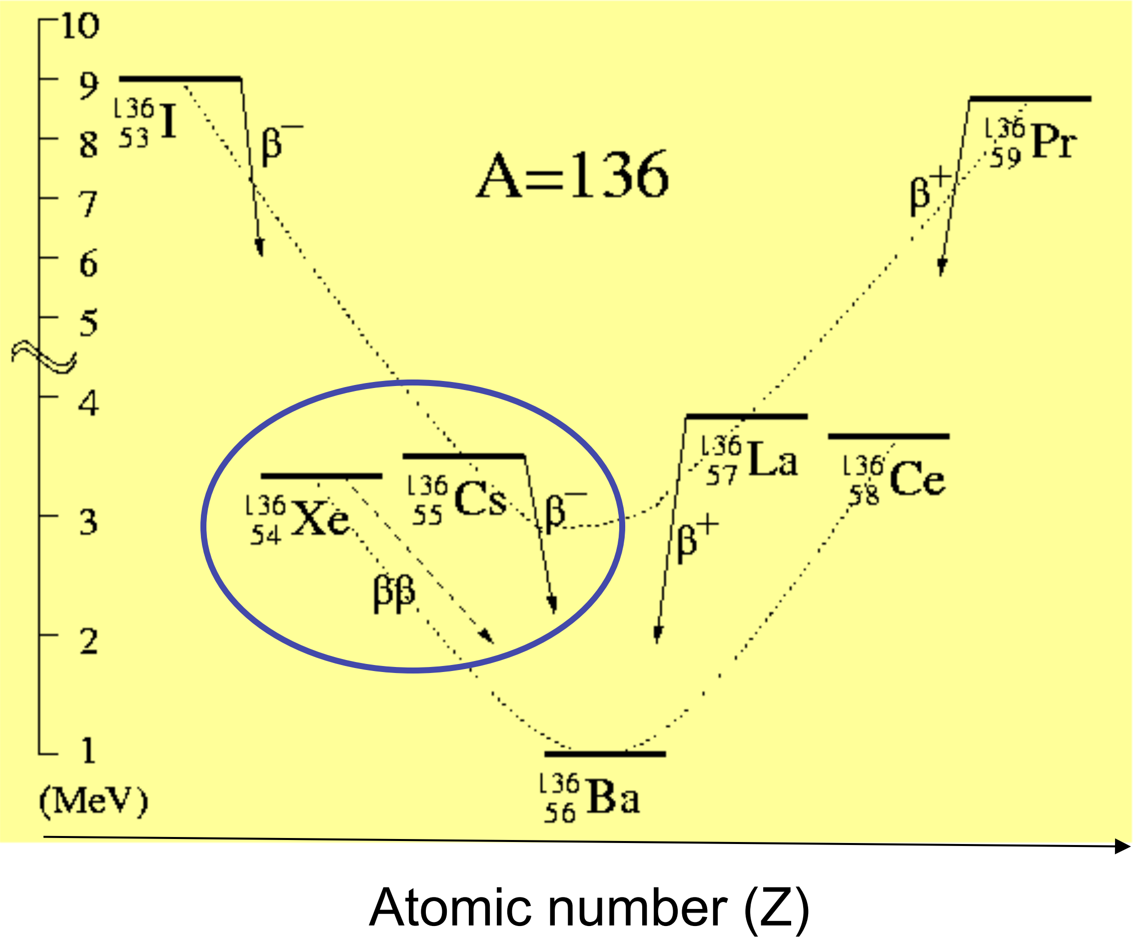
Double beta decay

Double beta decay

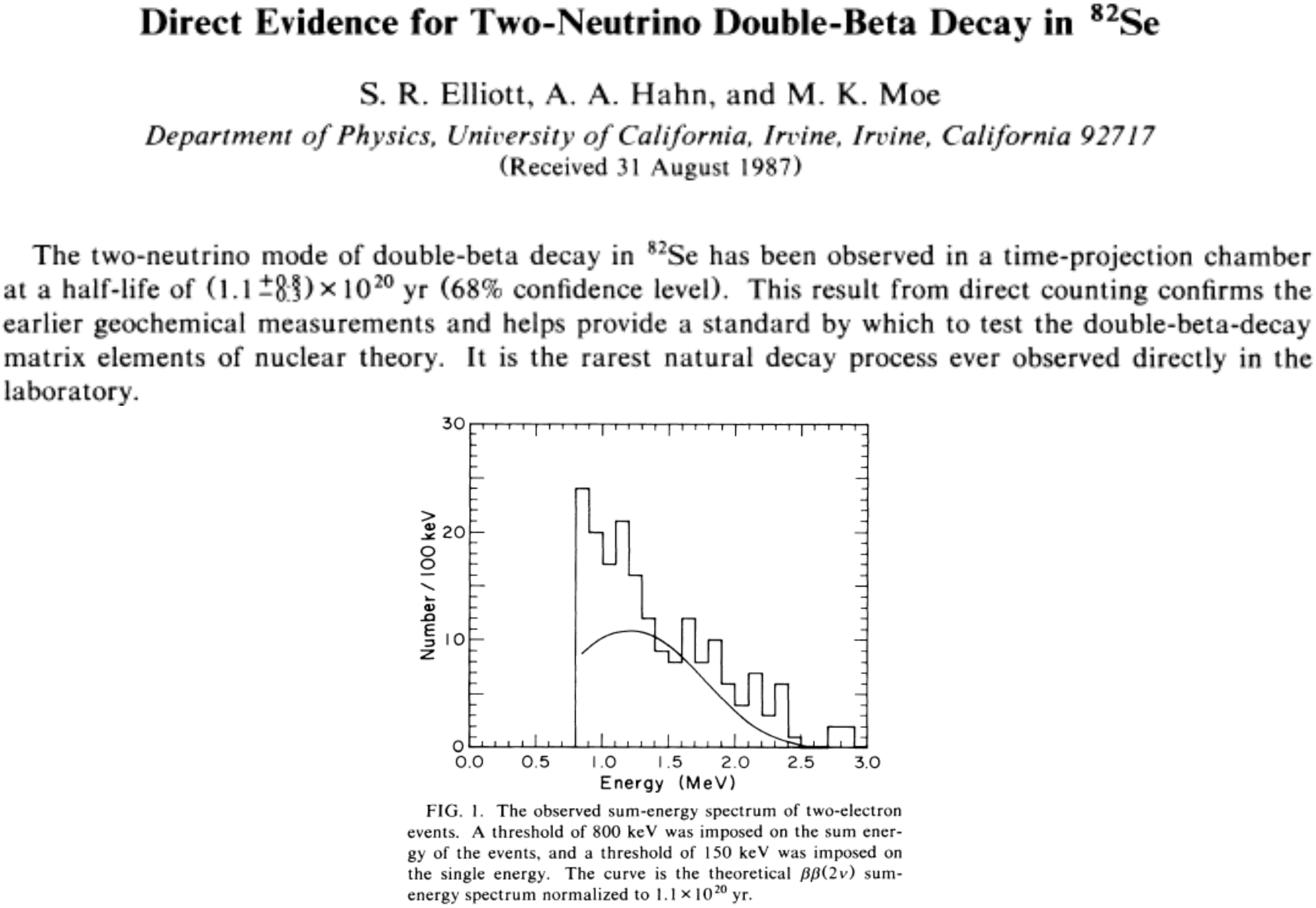
M.Goeppert-Mayer,
Phys. Rev. 48
(1935) 512



2νββ



Some candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe



Direct Evidence for Two-Neutrino Double-Beta Decay in ^{82}Se

S. R. Elliott, A. A. Hahn, and M. K. Moe
Department of Physics, University of California, Irvine, Irvine, California 92717

(Received 31 August 1987)

The two-neutrino mode of double-beta decay in ^{82}Se has been observed in a time-projection chamber at a half-life of $(1.1^{+0.8}_{-0.3})\times 10^{20}$ yr (68% confidence level). This result from direct counting confirms the earlier geochemical measurements and helps provide a standard by which to test the double-beta-decay matrix elements of nuclear theory. It is the rarest natural decay process ever observed directly in the laboratory.

FIG. 1. The observed sum-energy spectrum of two-electron events. A threshold of 800 keV was imposed on the sum energy of the events, and a threshold of 150 keV was imposed on the single energy. The curve is the theoretical $\beta\beta(2\nu)$ sum-energy spectrum normalized to 1.1×10^{20} yr.

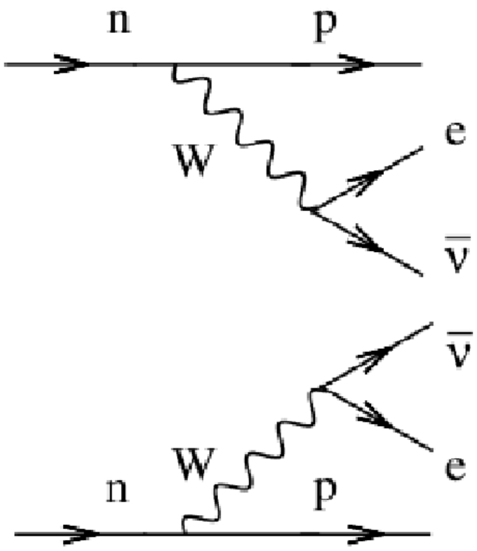
S.R. Elliott, A.A. Hahn, M.K. Moe *Phys. Rev. Lett.* **59** (1987) 2020-2023

Measured $2\nu\beta\beta$ half-lives

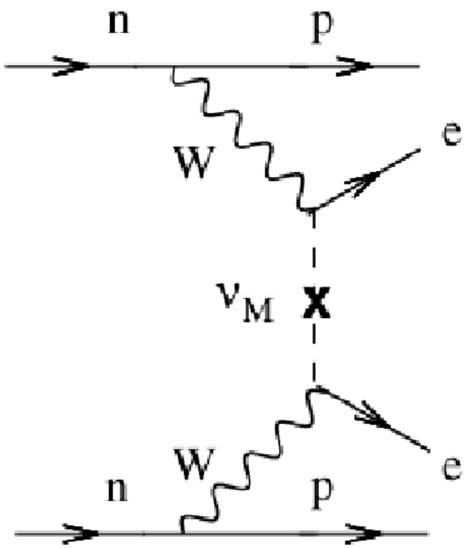
	$T_{1/2}$ (y)	$M^{2\nu}$ (MeV^{-1})	
^{48}Ca	$(4.3\ ^{+2.4}_{-1.1} \pm 1.4)$E19	0.05 ± 0.02	Balysh,PRL**77**,5186(1996)
^{76}Ge	$(1.74 \pm 0.01\ ^{+0.18}_{-0.16})$E21	0.13 ± 0.01	Doerr,NIMA**513**,596(2003)
^{82}Se	(9.6 ± 0.3 ± 1.0)E19	0.10 ± 0.01	Arnold,PRL**95**,182302(2005)
^{96}Zr	(2.35 ± 0.14 ± 0.16)E19	0.12 ± 0.01	Argyriades,NPA**847**,168(2010)
^{100}Mo	(7.11 ± 0.02 ± 0.54)E18	0.23 ± 0.01	Arnold,PRL**95**,182302(2005)
^{116}Cd	$(2.9^{+0.4}_{-0.3})$E19	0.13 ± 0.01	Danevich,PRC**68**,035501(2003)
^{128}Te*	(1.9 ± 0.1 ± 0.3)E24	0.05 ± 0.005	Lin,NPA**481**,477(1988)
^{130}Te	(7.0 ± 0.9 ± 1.1)E20	0.033 ± 0.003	Arnold,PRL**107**,062504(2011)
^{136}Xe	**(2.1 ± 0.04 ± 0.21)E21**	**0.019 ± 0.001**	**Ackerman,arXiv:1108.4193(2011)**
^{150}Nd	$(9.11^{+0.25}_{-0.22} \pm 0.63)$E18	0.06 ± 0.003	Argyriades,PRC**80**,032501R(2009)
^{238}U**	(2.2 ± 0.6)E21	0.05 ± 0.01	Turkevich,PRL**67**,3211(1991)

*From geochemical ratio ^{128}Te/^{130}Te.
**Radiochemical result.

Neutrinoless double beta decay



$2\nu\beta\beta$

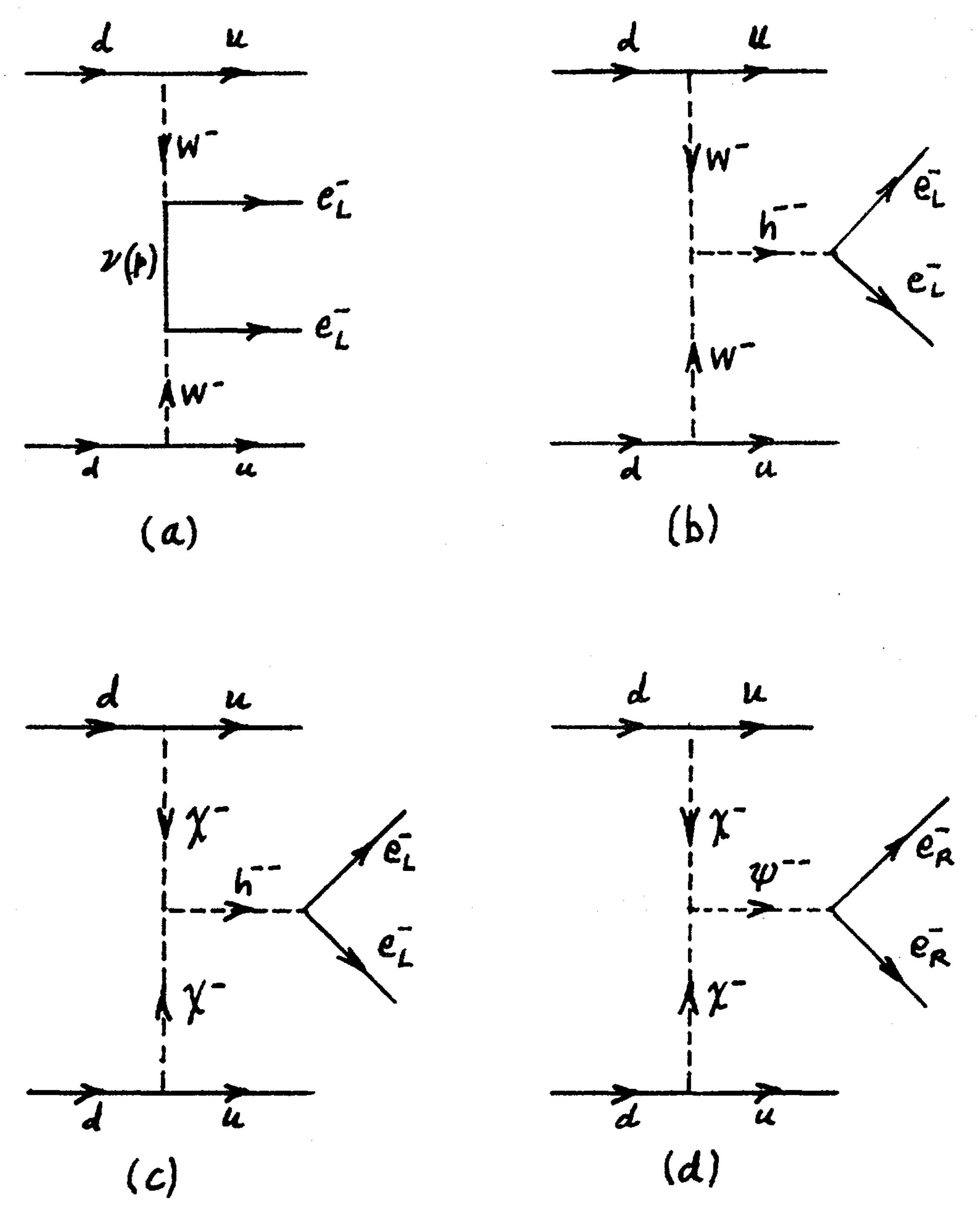


$0\nu\beta\beta$

This process can only occur for a Majorana neutrino!

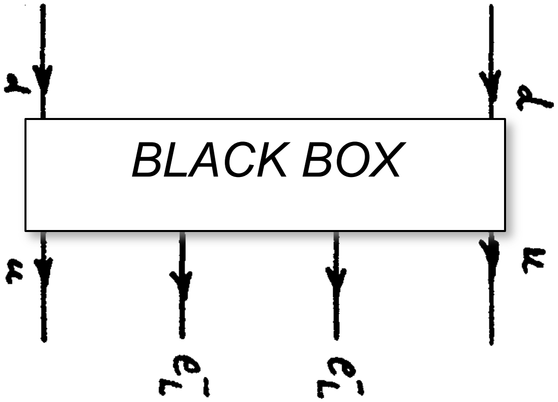
Same candidate nuclei: ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe

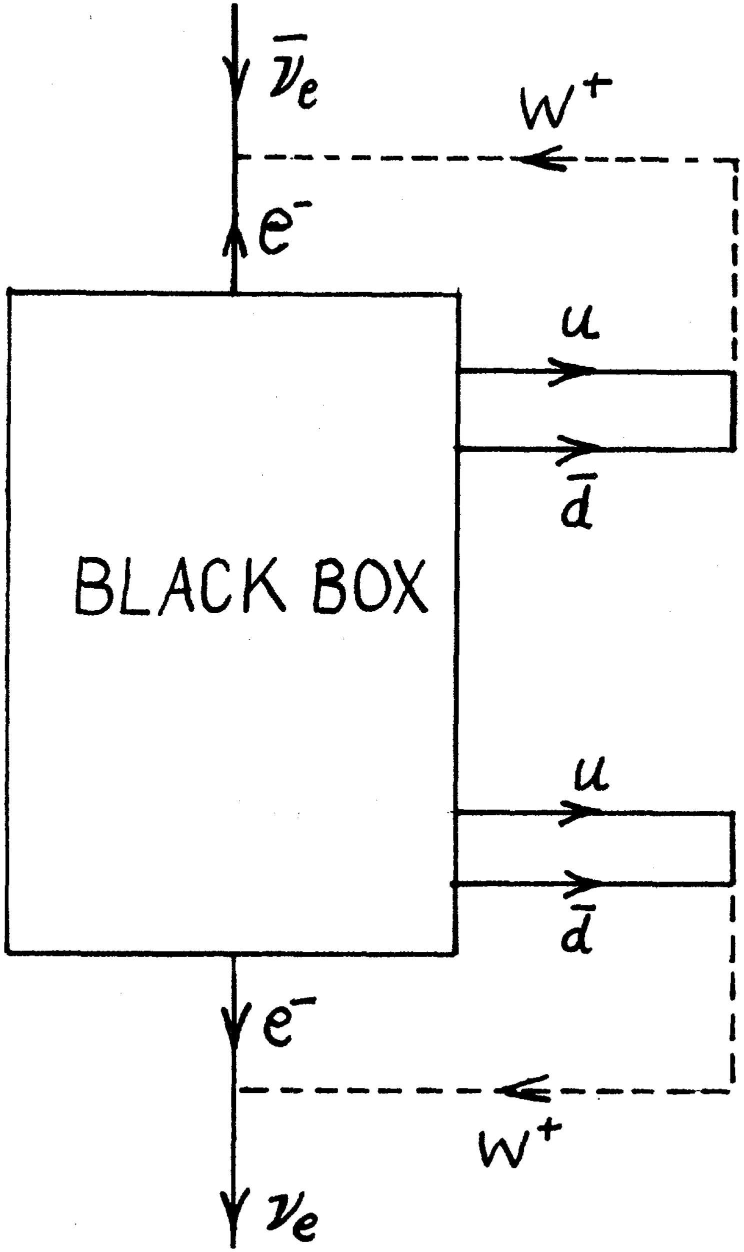
Mechanism?



In some cases, it’s possible to determine the mechanism by measuring the opening angle between the electrons.

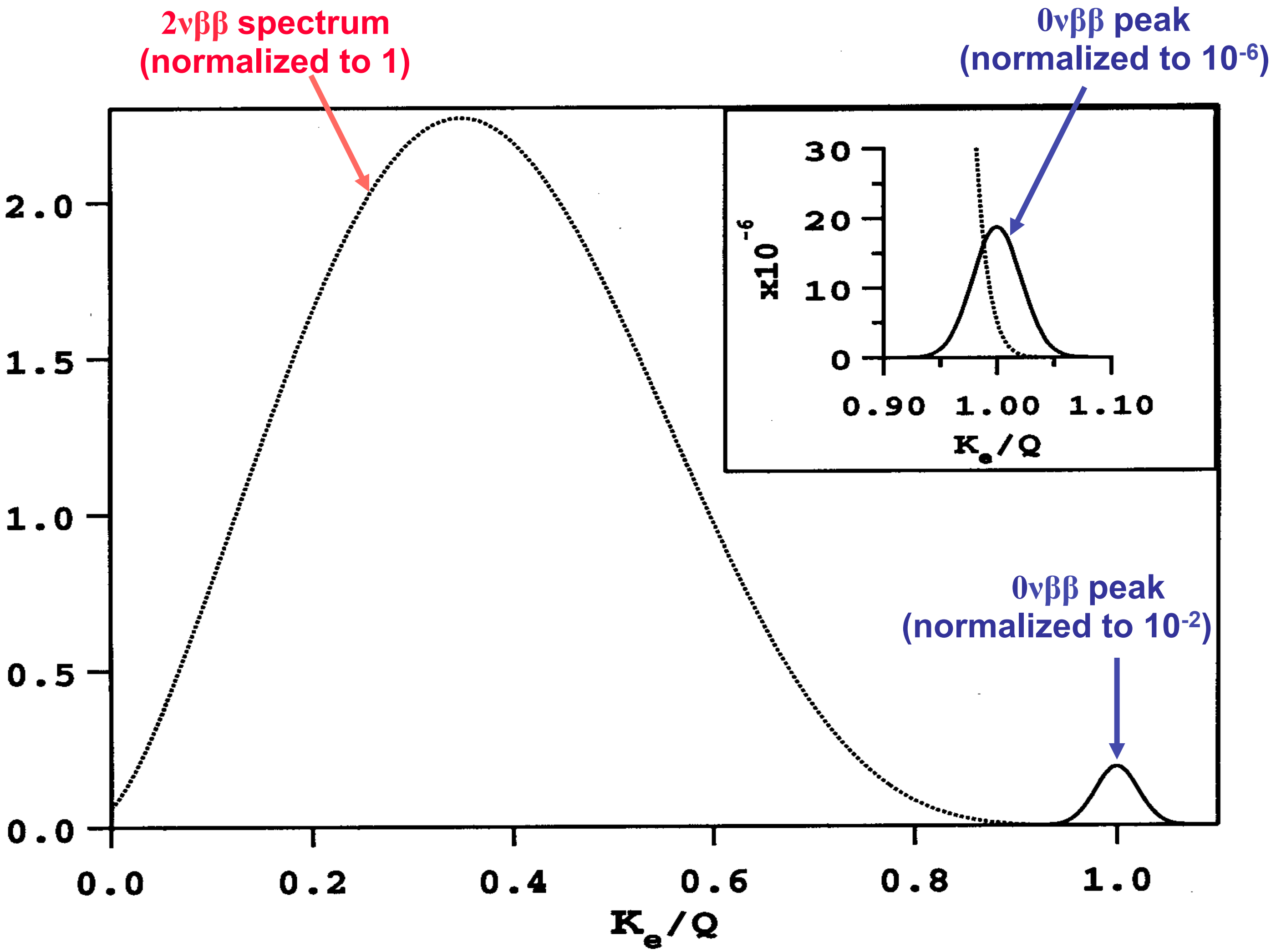
“Black box” theorem





“Neutrino Masses in SU(2) x U(1) Theories“ J. Schechter and J.W.F. Valle, *Phys.Rev. D* **22** (1980) 2227

Double beta decay spectrum

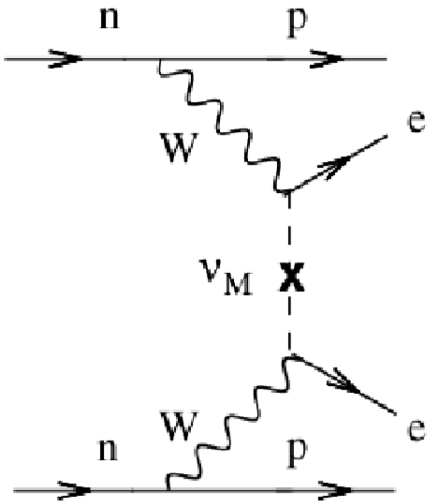


2νββ spectrum (normalized to 1)

0νββ peak (normalized to 10^{-6})

0νββ peak (normalized to 10^{-2})

$0\nu\beta\beta$ rate



If we assume that the mechanism is light neutrino exchange, we can write the rate for $0\nu\beta\beta$:

Phase space factor ~Q^5

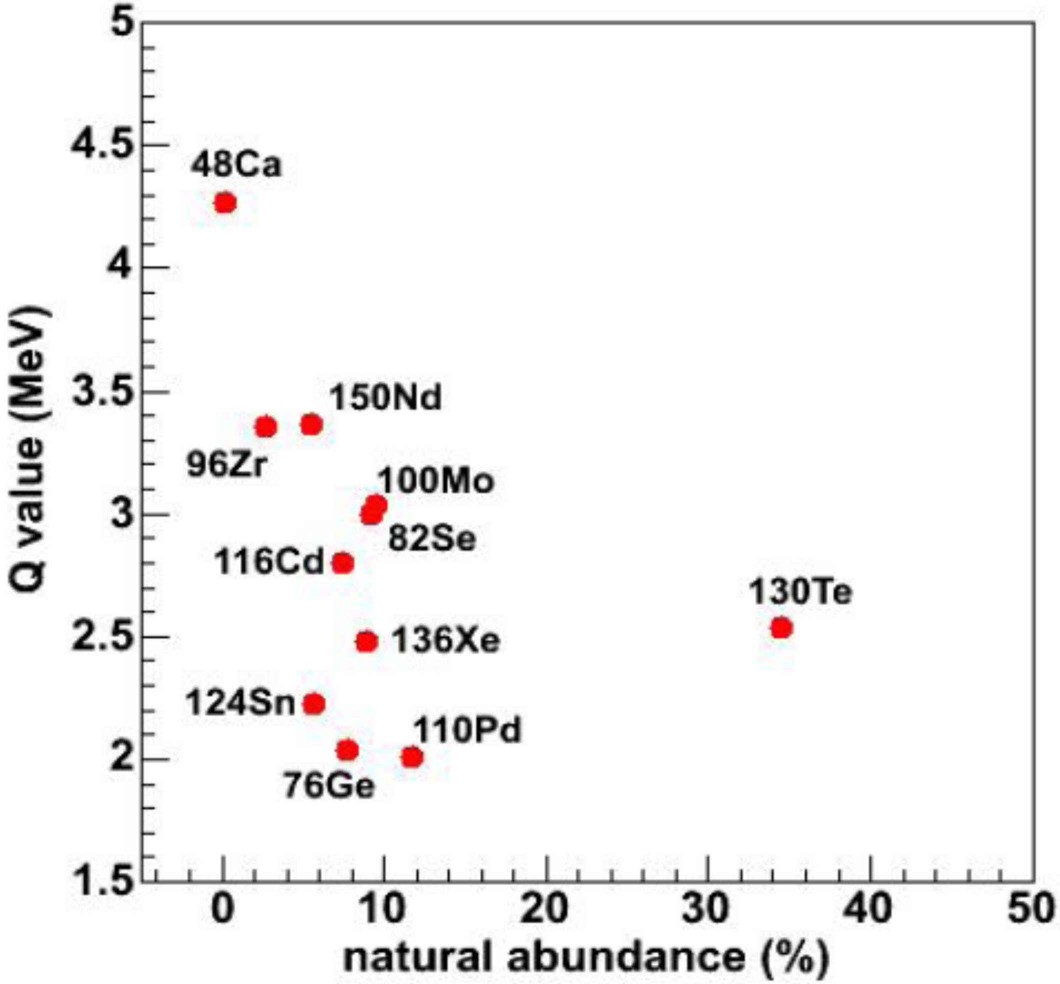
Effective Majorana mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \langle m_\nu \rangle^2$$

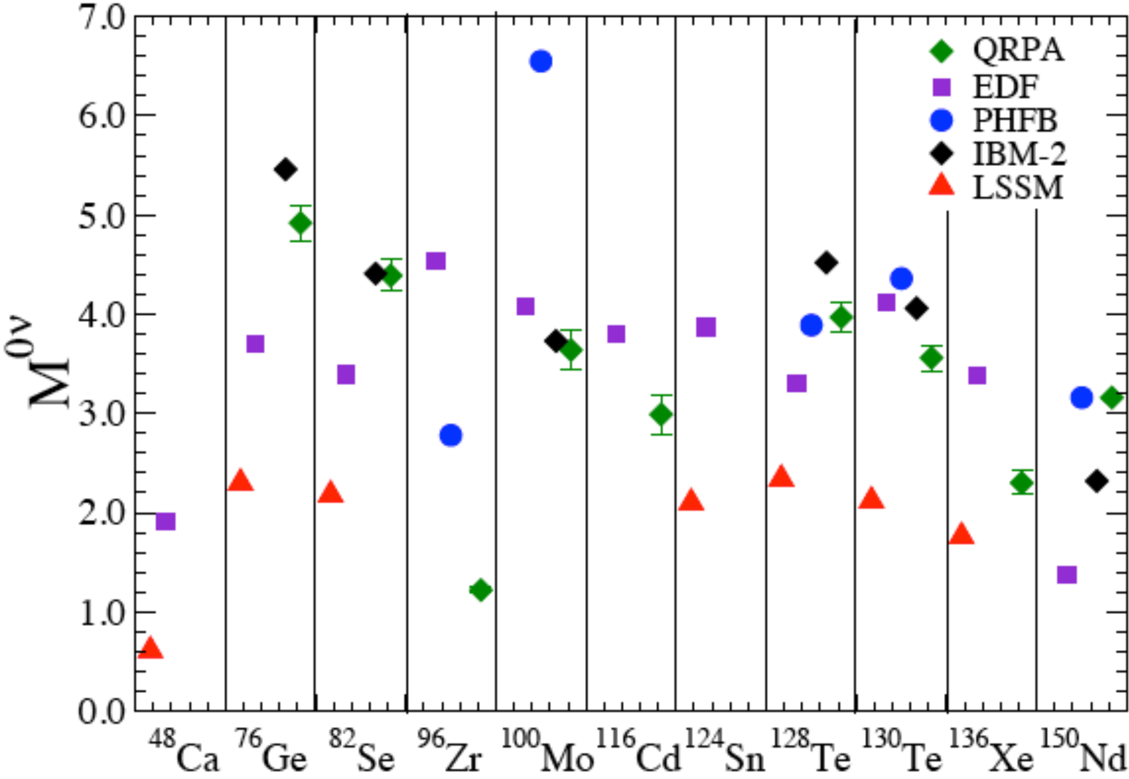
Nuclear matrix element

Isotopes of interest

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^2 * \left\langle m_{\beta\beta}\right\rangle^2$$



NME calculations



Bilenky and Giunti, arXiv:1203.5250v1

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu} * \boxed{\left|M^{0\nu}\right|^{2}} * \left\langle m_{\beta\beta}\right\rangle^{2}$$

V.A. Rodin, A. Faessler, F. Simkovic, and P. Vogel, Phys. Rev. C 68, 044302 (2003);
V.A. Rodin, A. Faessler, F. Simkovic, and P. Vogel, Nucl. Phys. A 793, 213 (2007), and erratum A 793, 213 (2007).
Dong-Liang Fang, A. Faessler, V. Rodin, F. Simkovic, Phys. Rev. C 82, 051301 (2010);.
F. Simkovic Phys.Part.Nucl. 42 (2011) 598.
T.R. Rodriguez, G. Martinez-Pinedo, Prog.Part.Nucl.Phys. 66 (2011) 436.
T.R. Rodr+gez and G. Martinez-Pinedo, Phys. Rev. Lett. 105, 252503 (2010).
P.K. Rath, R. Chandra, K. Chaturvedi, P.K. Raina, J.G. Hirsch, Phys. Rev. C 82, 064310 (2010);
P.K. Rath J.Phys.Conf.Ser. 322 (2011) 012019.
J. Barea, F. Iachello, Phys. Rev. C 79, 044301 (2009);
F. Iachello, J. Barea, Nucl.Phys.Proc.Suppl. 217 (2011) 5;
F. Iachello, J. Barea, AIP Conf.Proc. 1355 (2011) 7.
J. Menendez, A. Poves E. Caurier, F. Nowacki J.Phys.Conf.Ser. 312 (2011) 072005;
J. Menendez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A 818, 139 (2009).

Differences in the models include:

- Mean field
- Residual interaction
- Size of the model space
- Many-body approximation

F. Simkovic, Neutrino 2010

Effective Majorana mass

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu} * \left|M^{0\nu}\right|^{2} * \boxed{\left\langle m_{\beta\beta}\right\rangle}^{2}$$

Using the standard representation of the PNMS matrix, the effective Majorana neutrino mass is given as:

$$\begin{aligned}\left\langle \mathrm{m}_{\beta\beta}\right\rangle = \Big|\,& \mathrm{m}_1 \cdot \left(1-\sin^2\theta_{12}\right)\cdot\left(1-\sin^2\theta_{13}\right) + \\ & \mathrm{m}_2 \cdot \sin^2\theta_{12} \cdot \left(1-\sin^2\theta_{13}\right)\cdot \mathrm{e}^{\mathrm{i}\cdot\left(\alpha_2-\alpha_1\right)} + \\ & \mathrm{m}_3 \cdot \sin^2\theta_{13} \cdot \mathrm{e}^{-\mathrm{i}\cdot\alpha_3}\,\Big|\end{aligned}$$

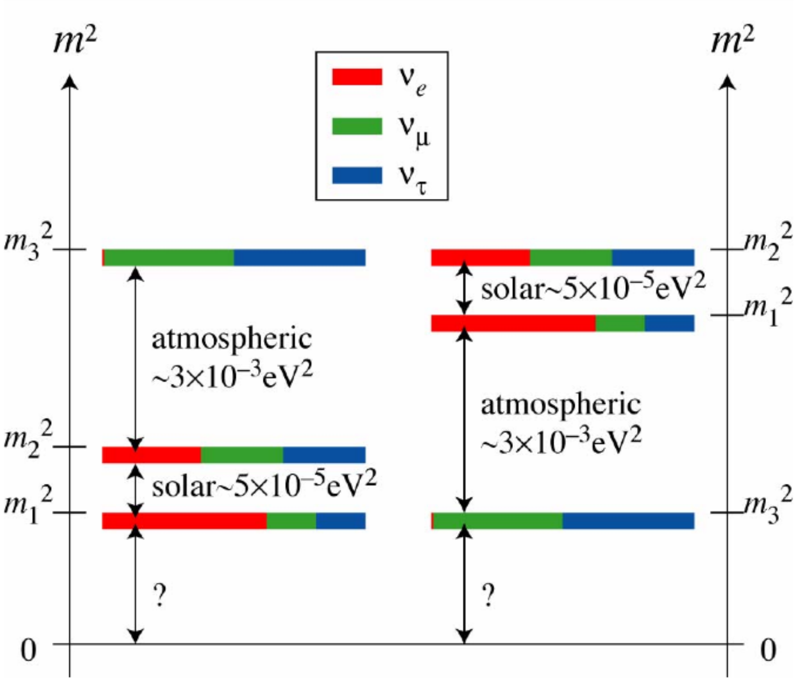
The three CP phases α_1, α_2, and α_3 are unknown. This uncertainty is expressed by varying:

$$\begin{aligned}\left\langle \mathrm{m}_{\beta\beta}\right\rangle = \Big|\,& \mathrm{m}_1 \cdot \left(1-\sin^2\theta_{12}\right)\cdot\left(1-\sin^2\theta_{13}\right) \pm_{(1)} \mathrm{m}_2 \cdot \sin^2\theta_{12} \cdot \left(1-\sin^2\theta_{13}\right) \\ & \pm_{(2)} \mathrm{m}_3 \cdot \sin^2\theta_{13}\,\Big|\end{aligned}$$

Neutrino mixing matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

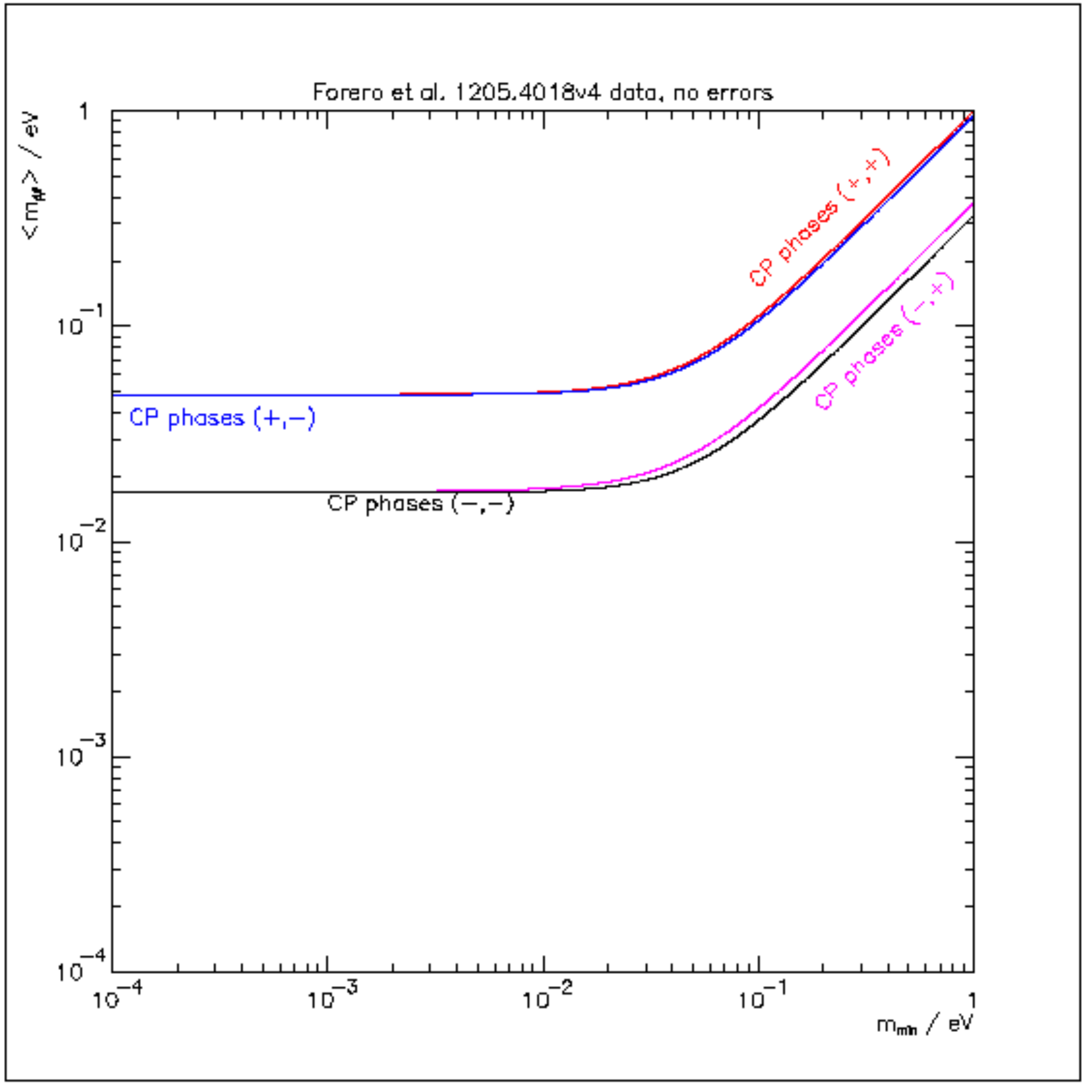
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Measured oscillation parameters:

- $\sin^2(2\boldsymbol{\theta}_{13}) = 0.092 \pm 0.017$
- $\tan^2(\boldsymbol{\theta}_{12}) = 0.457{+}0.040{-}0.029$
- $\sin^2(2\boldsymbol{\theta}_{23}) > 0.92$ at 90% confidence level
- $\Delta \boldsymbol{m}^2_{21} = (7.59{+}0.20{-}0.21) \times 10^{-5}$ eV^2
- $|\Delta \boldsymbol{m}^2_{31}| \approx |\Delta \boldsymbol{m}^2_{32}| = (2.43{+}0.13{-}0.13) \times 10^{-3}$ eV^2

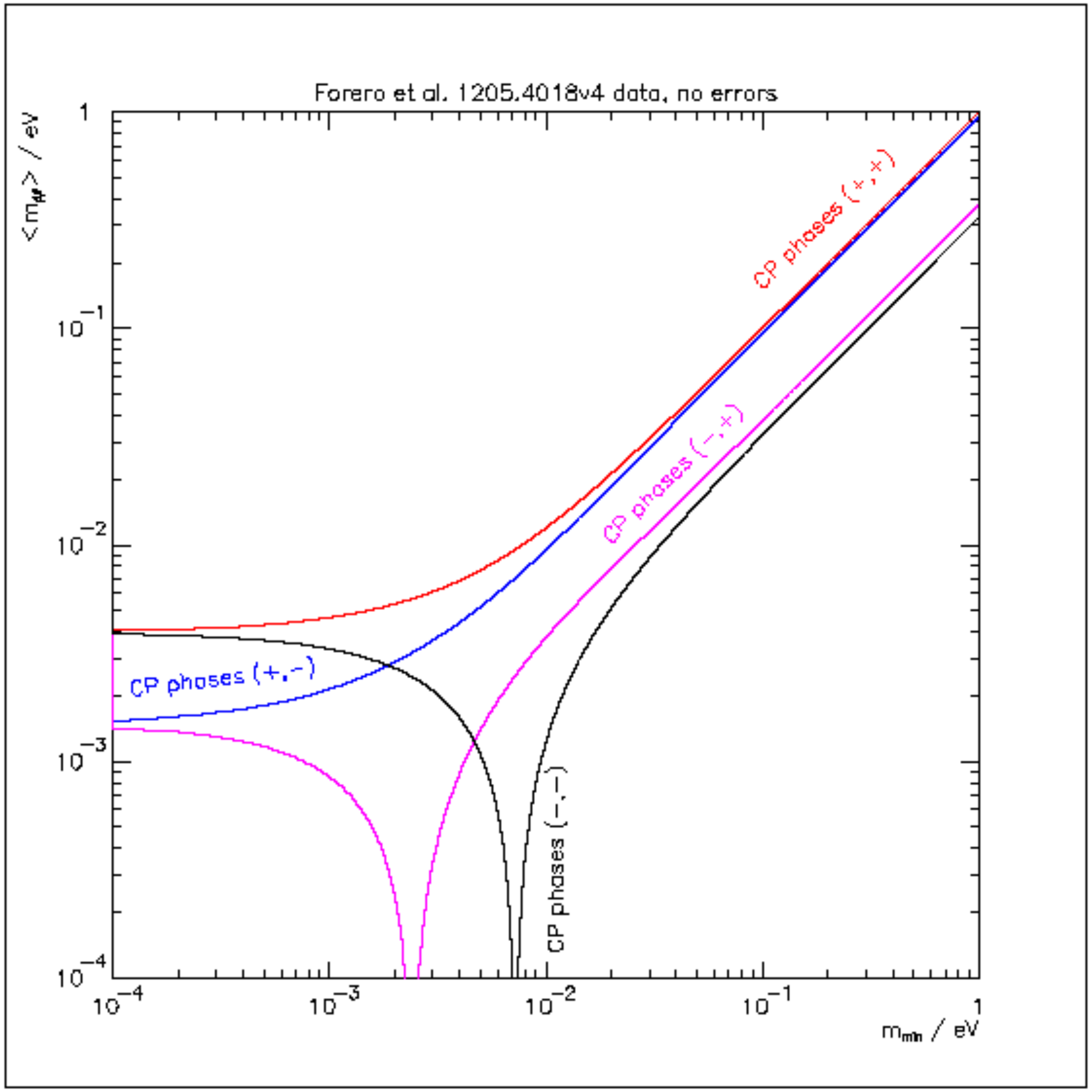
Inverted hierarchy



Now we insert the standard neutrino oscillation parameters (central values). No total cancellation is possible for the inverted hierarchy.

Plots courtesy Andreas Piepke.

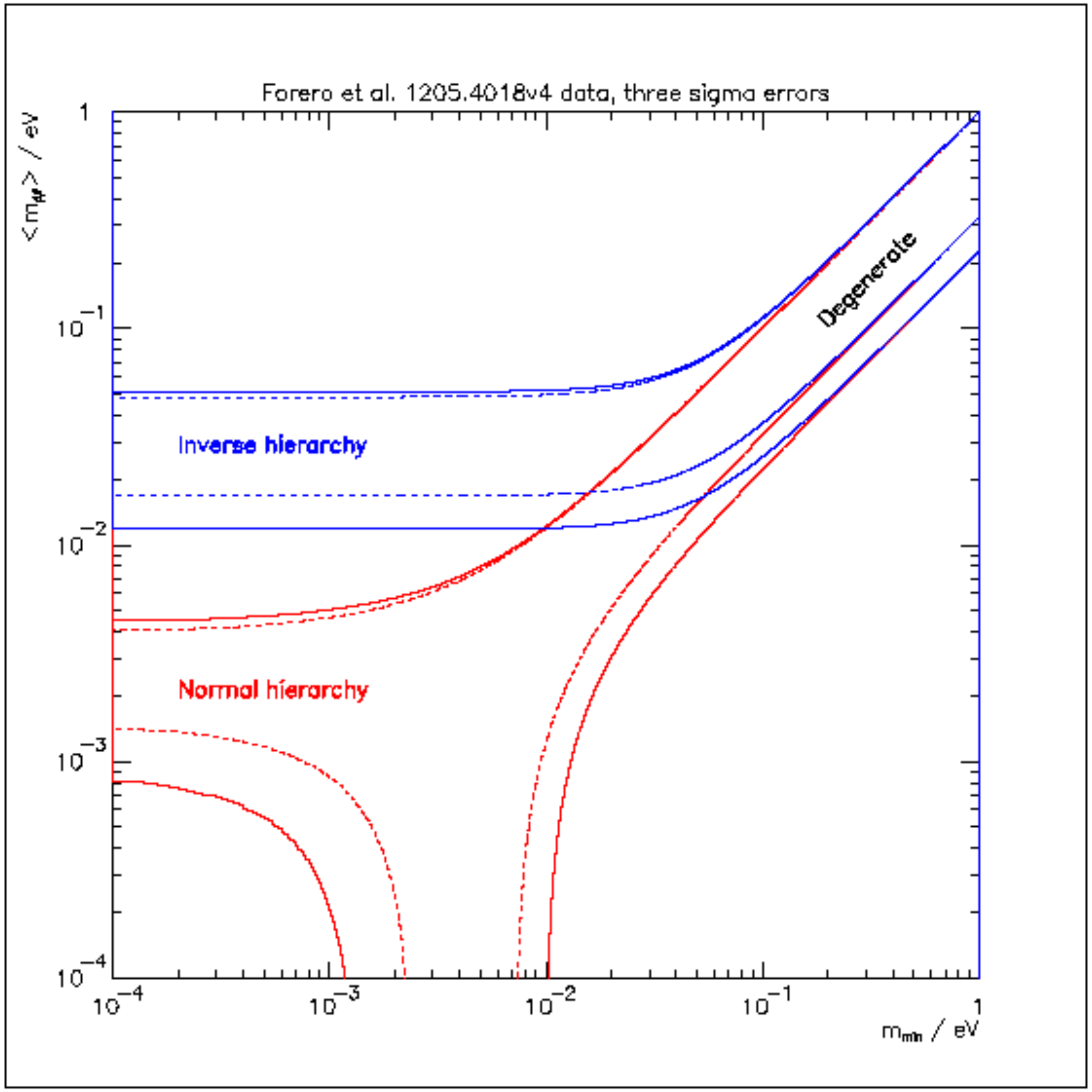
Normal hierarchy



For the normal hierarchy variation of the unknown CP-phases introduces:

1) considerable variation of the effective mass,
2) allows destructive interference for certain values of m_{min} and choice of phases.

Combined phase space

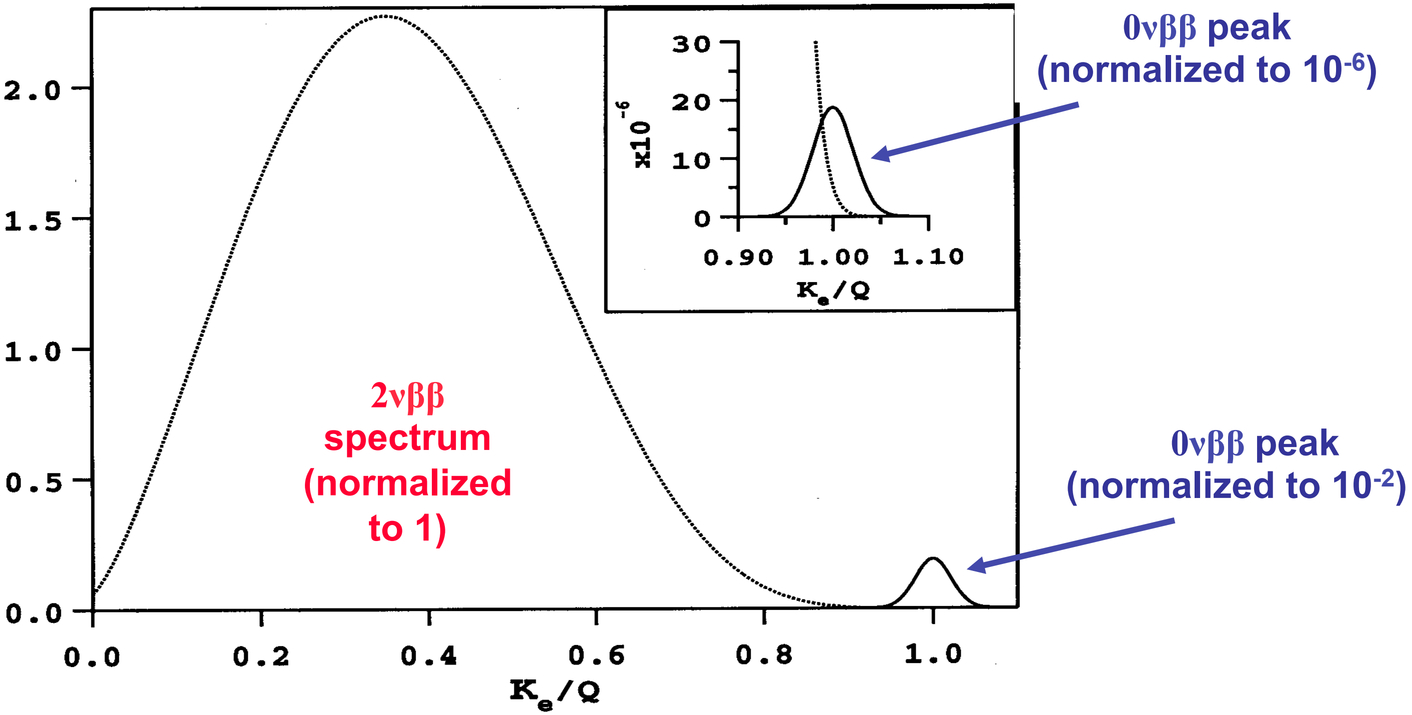


Inverted and normal hierarchy including 3σ errors on oscillation parameters.

Experimental search

- Energy resolution
- Low background
- Large mass
- Some other handle?
  - Multiple isotopes
  - Event topology
  - “Tagging”

Energy resolution



$0\nu\beta\beta$ peak (normalized to 10^{-6})

$2\nu\beta\beta$ spectrum (normalized to 1)

$0\nu\beta\beta$ peak (normalized to 10^{-2})

Superior energy resolution:

^{76}Ge (diode): 0.2% FWHM

^{130}Te (bolometer): 0.4% FWHM

Intermediate energy resolution:

^{136}Xe (liquid TPC): 3.3% FWHM

Modest energy resolution:

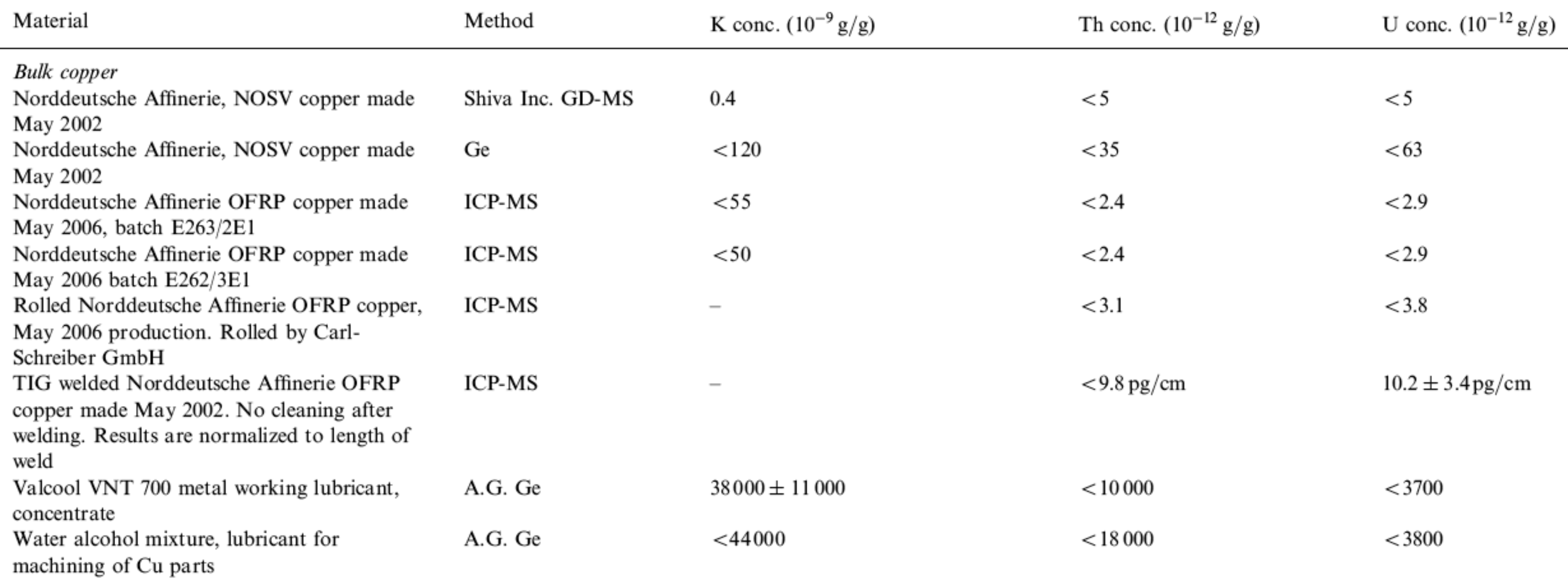
^{100}Mo, ^{136}Xe, ^{150}Nd (scintillators): 10%-15% FWHM

Low background

Massive effort on material radioactive qualification using:

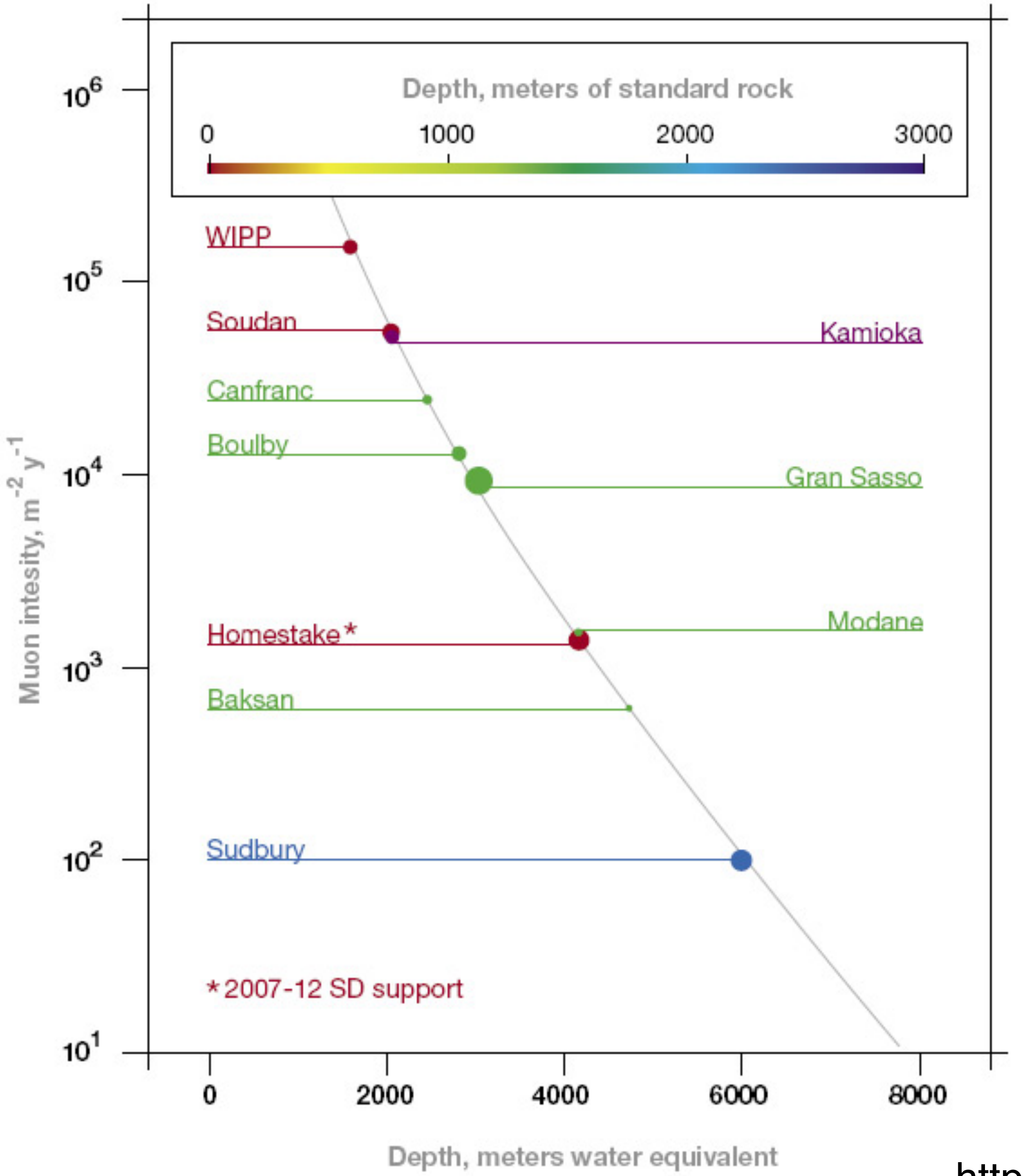
- Neutron activation analysis
- Low background γ-ray spectroscopy
- α-counting and radon counting
- High sensitivity GD-MS and ICP-MS

At present the database of characterized materials includes over 300 entries. See D.Leonard et al., *Nucl. Instr. Meth*. A**591**, 490 (2008).



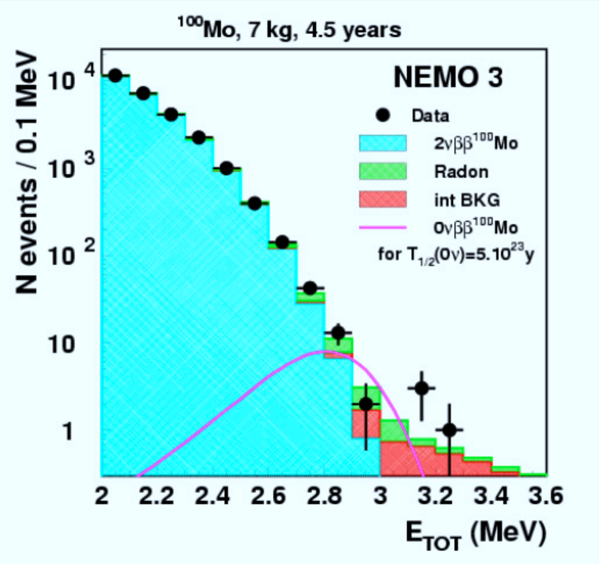
Material	Method	K conc. (10^{-9} g/g)	Th conc. (10^{-12} g/g)	U conc. (10^{-12} g/g)
Bulk copper				
Norddeutsche Affinerie, NOSV copper made May 2002	Shiva Inc. GD-MS	0.4	<5	<5
Norddeutsche Affinerie, NOSV copper made May 2002	Ge	<120	<35	<63
Norddeutsche Affinerie OFRP copper made May 2006, batch E263/2E1	ICP-MS	<55	<2.4	<2.9
Norddeutsche Affinerie OFRP copper made May 2006 batch E262/3E1	ICP-MS	<50	<2.4	<2.9
Rolled Norddeutsche Affinerie OFRP copper, May 2006 production. Rolled by Carl-Schreiber GmbH	ICP-MS	–	<3.1	<3.8
TIG welded Norddeutsche Affinerie OFRP copper made May 2002. No cleaning after welding. Results are normalized to length of weld	ICP-MS	–	<9.8 pg/cm	10.2 ± 3.4 pg/cm
Valcool VNT 700 metal working lubricant, concentrate	A.G. Ge	38 000 ± 11 000	<10 000	<3700
Water alcohol mixture, lubricant for machining of Cu parts	A.G. Ge	<44 000	<18 000	<3800

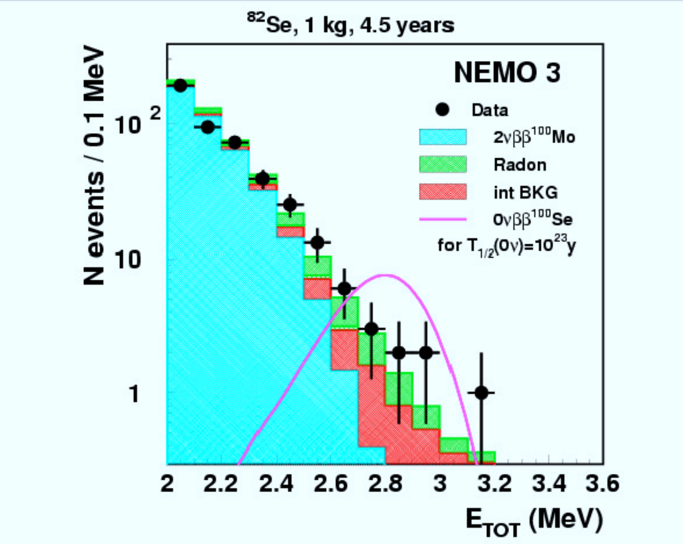
Underground physics



http://www.deepscience.org/

NEMO-3 to SuperNEMO





[2.8–3.2] MeV: DATA = 18; MC = 16.4±1.4

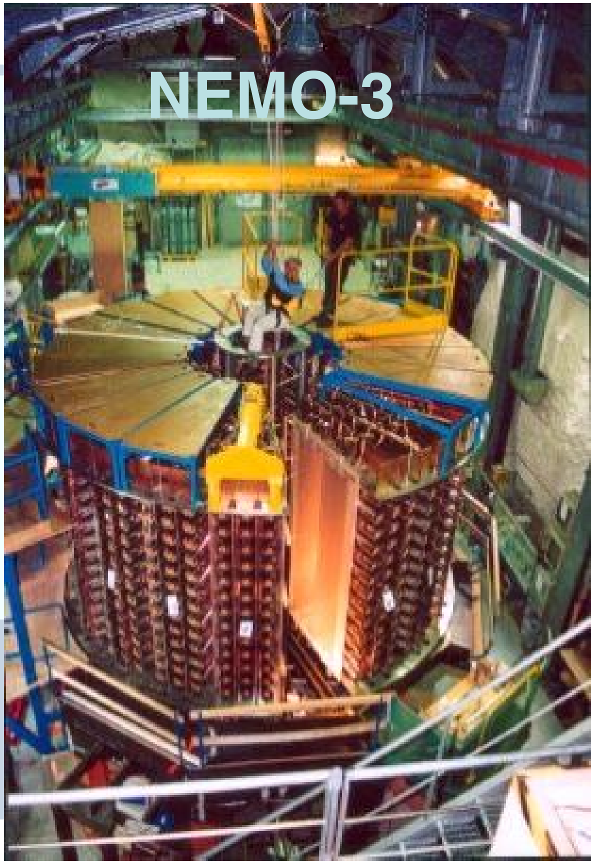
$T_{1/2}(0\nu) > 1.0\times10^{24}$ yr at 90%CL

$\langle m_\nu \rangle < (0.47 - 0.96)$ eV

[2.6–3.2] MeV: DATA = 14; MC = 10.9±1.3

$T_{1/2}(0\nu) > 3.2\times10^{23}$ yr at 90%CL

$\langle m_\nu \rangle < (0.94 - 2.5)$ eV



supernemo
collaboration

Like the first observation of $2\nu\beta\beta$ in the laboratory,
NEMO uses source foils in a gas TPC.
SuperNEMO will scale up to ~100 kg.

Source = detector

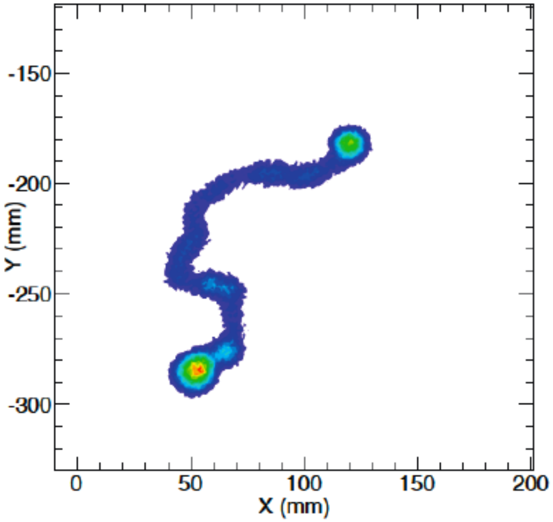
For source = detector configuration, the figure of merit $F_{0\nu}$:

$$F_{0\nu} = \ln 2 \cdot N_A \frac{f}{A}\left(\frac{Mt}{B\Delta E}\right)^{1/2} \varepsilon$$

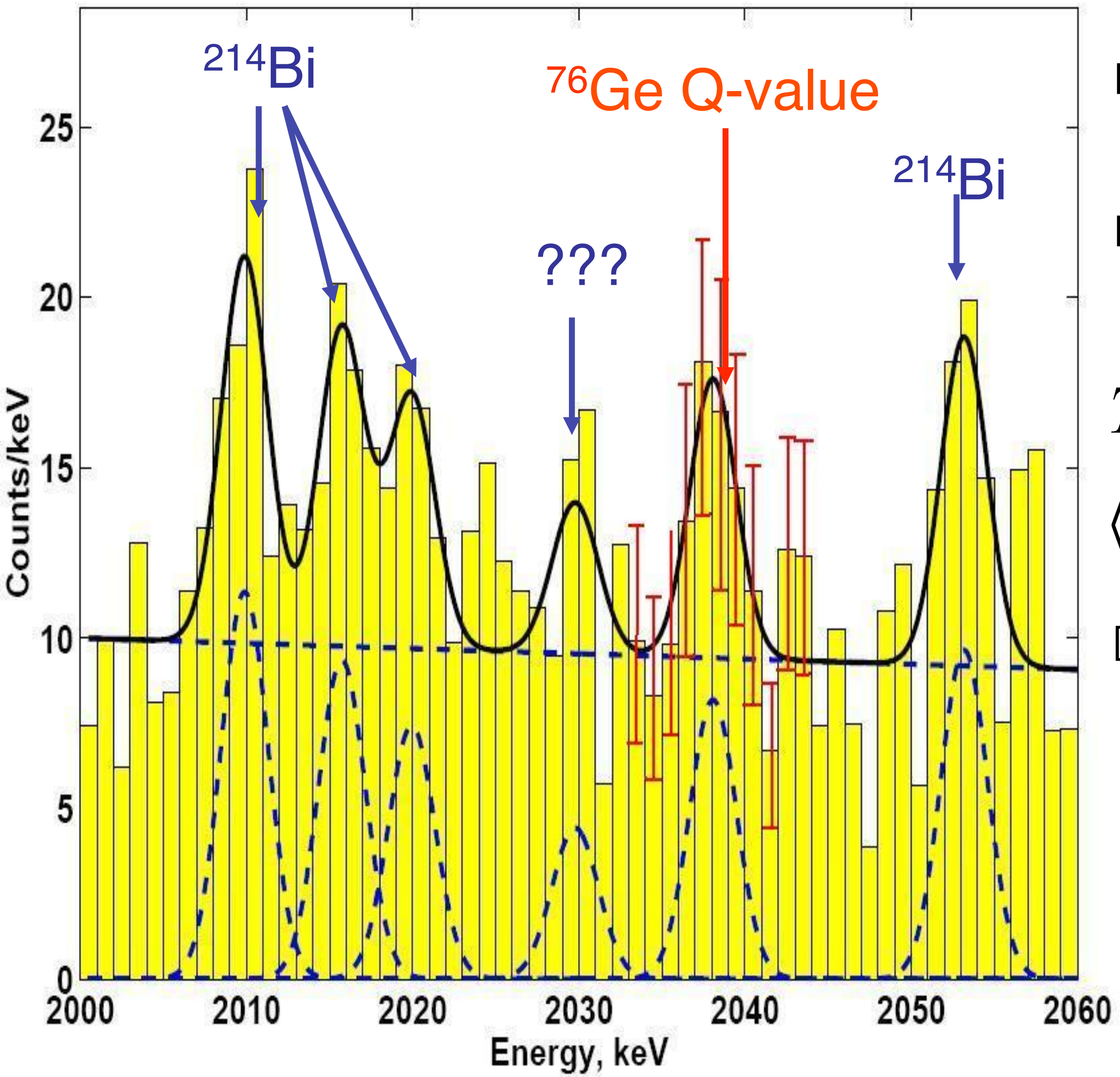
f is the number of atoms of the $\beta\beta$ isotope/molecule;
A is the molecular mass;
M is the mass;
t is the running time;
B is the number of background counts/keV/kg/year;
ΔE is the energy resolution of the detector in keV;
ε is the detector efficiency in the $\beta\beta$ region

NEXT

- 15 bar high pressure gas Xe time projection chamber (TPC) with ~100 kg fiducial mass. SiPMs (MPPCs) for tracking and PMTs for energy.
- Proportional electroluminescent amplification for large photon yield.
- Tracking and event topology reconstruction.
- Good energy resolution. Demonstrated <0.9% energy resolution achievable at $0\nu\beta\beta$ Q-value.
- Will be sited at the Canfranc laboratory (LSC).



Claim for observation of 0νββ



Fit model:
6 gaussians + linear bknd.

Fitted excess @ $Q_{\beta\beta}$
28.75 ± 6.86 → 4.2 σ

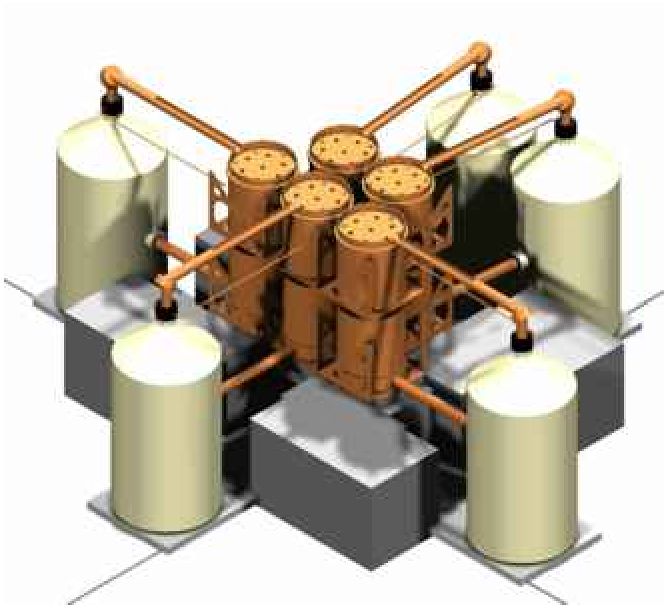
$$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24}\, yr$$

$$\langle m_\nu \rangle = 0.32 \pm 0.03\ eV$$

[H.V.Klapdor-Kleingrothaus and I.Krivosheina, Mod.Phys.Lett. A21 (2006) 1547]

Heidelberg-Moscow Collaboration split over this result, and it is still controversial.

^{76}Ge diode experiments



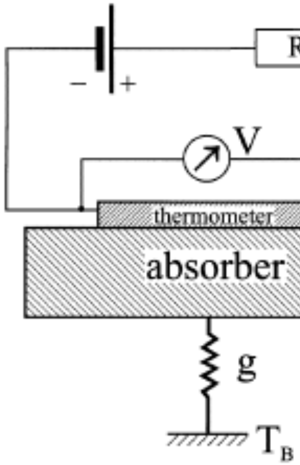
Majorana

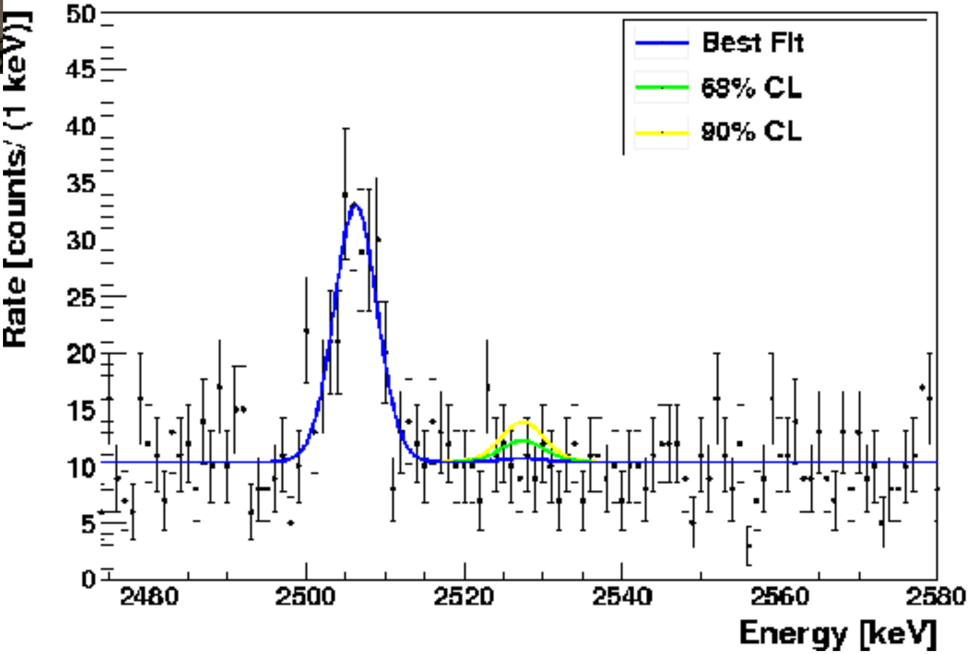
Brand new result as of 0530 am PDT:

$T_{1/2}^{0\nu\beta\beta}$ (^{76}Ge) > 2.1x10^{25} yr @ 90% C.L.

Current best limit!

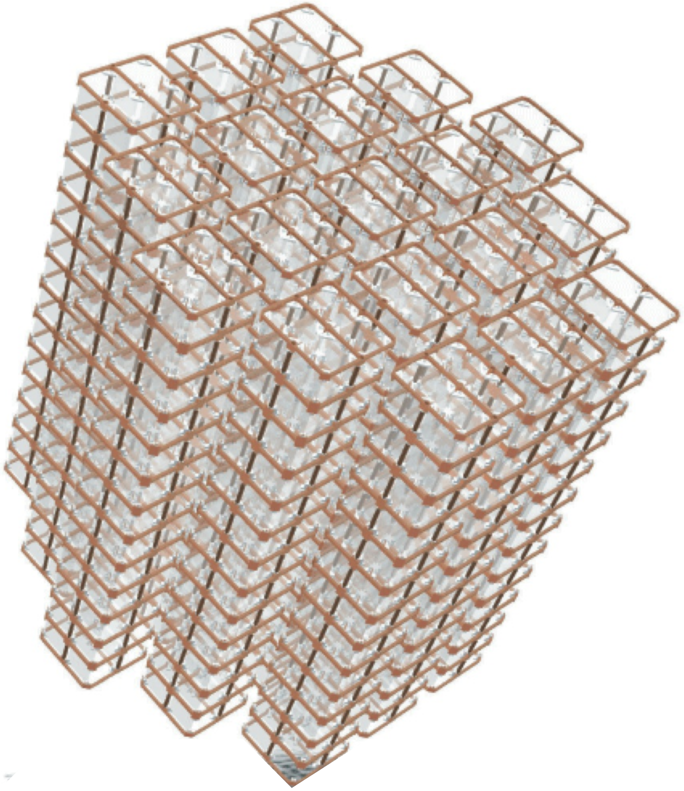
Cuoricino and CUORE





$T_{1/2}^{0\nu\beta\beta}$ (^{130}Te) > 2.8x10^{24} yr

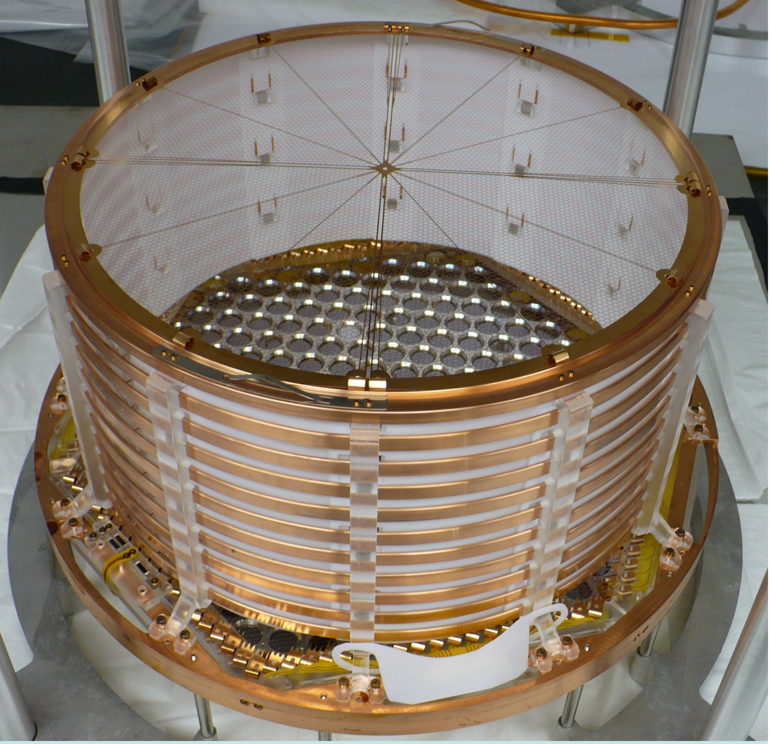
[*Astropart.Phys.* **34** (2011) 822-831]

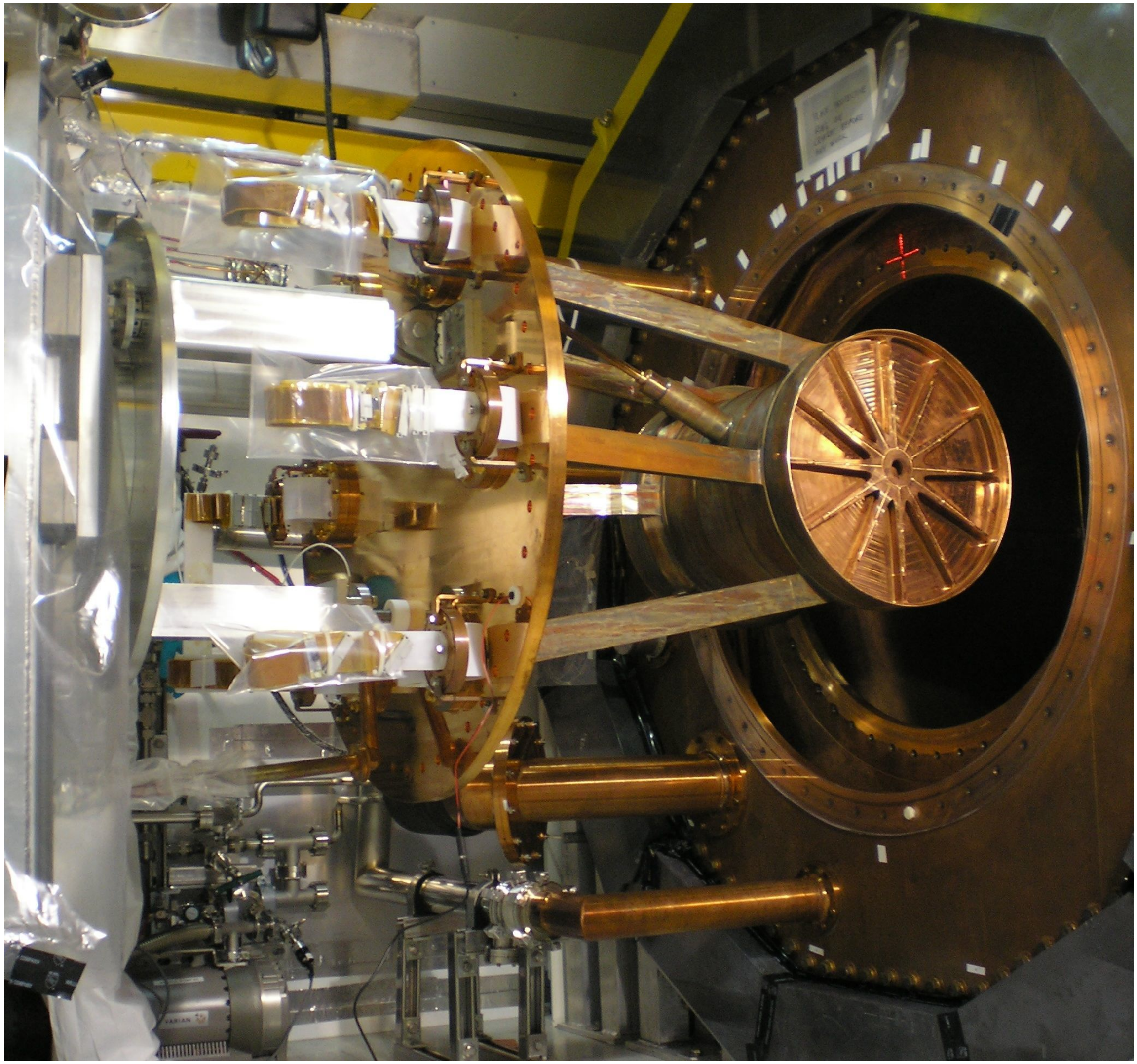


CUORE - 200 kg

^{130}Te, online ~2014

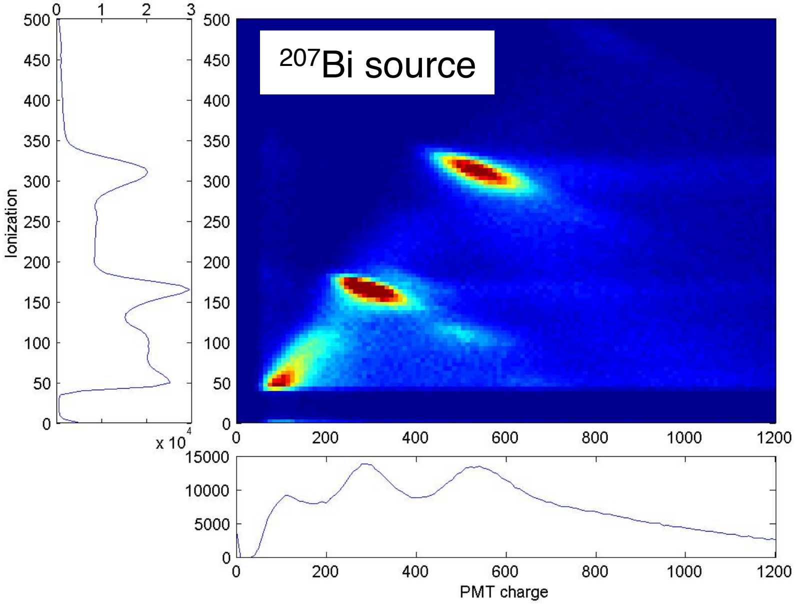
EXO-200





- LXe TPC with ~100 kg fiducial mass Xe enriched to 80% in ^{136}Xe, ultralow background construction.
- Central cathode with readout planes up of LAAPDs + wires planes.
- Operating with enriched Xe at the Waste Isolation Pilot Plant since May 2011.

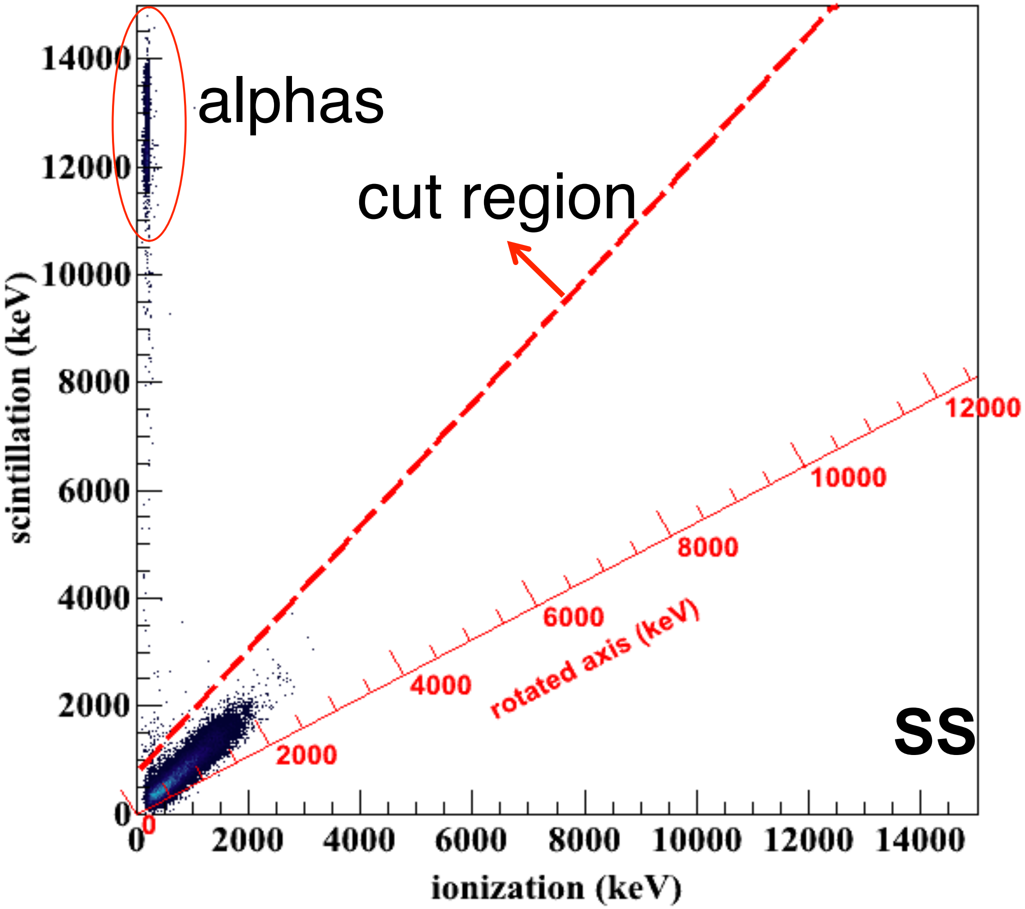
Ionization vs. Scintillation



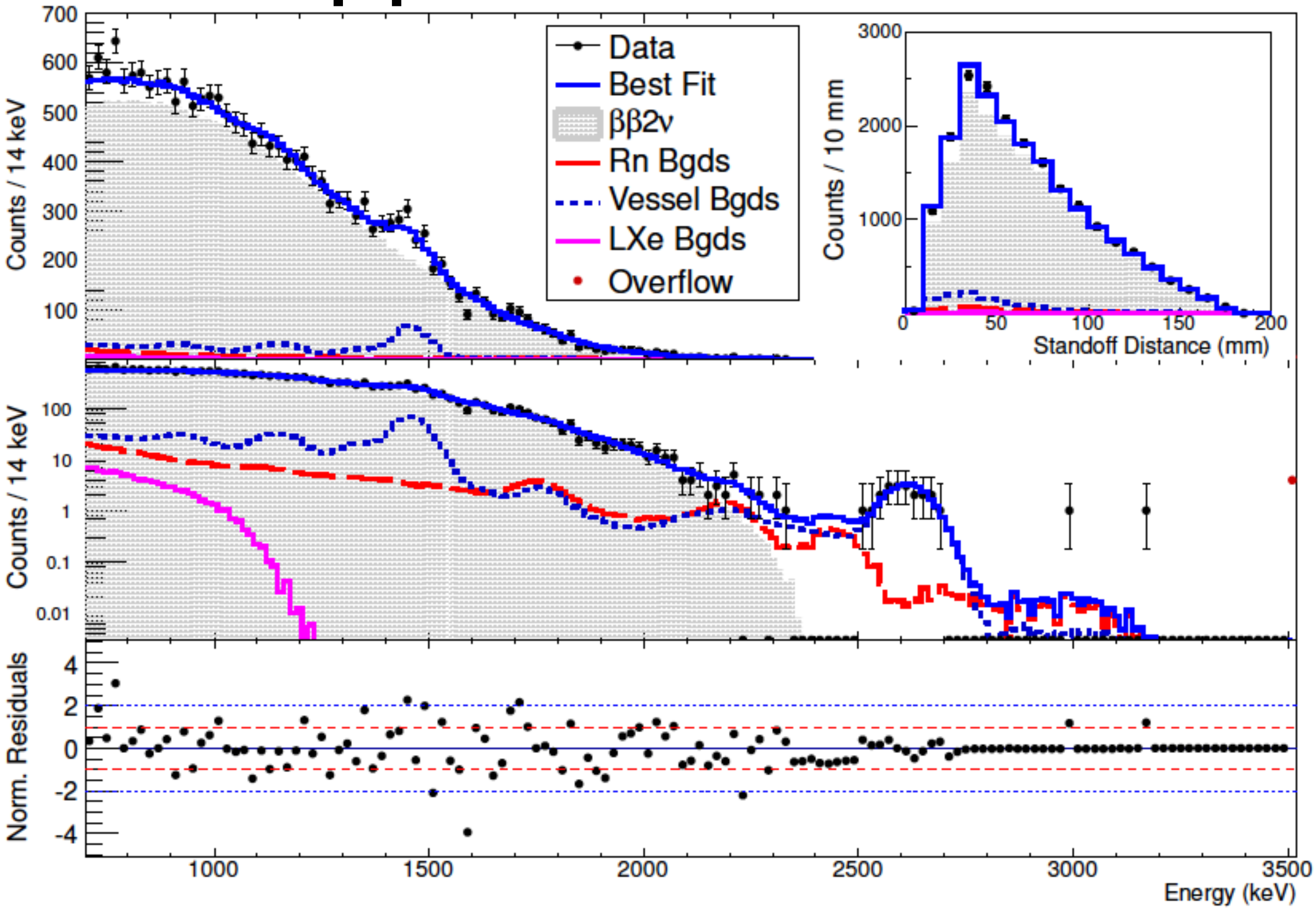
Ionization alone:
$\sigma(E)/E$ = 3.8% @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

Ionization & Scintillation:
$\sigma(E)/E$ = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$

E.Conti et al., *Phys. Rev.* B **68** 054201 (2003)



2νββ measurement

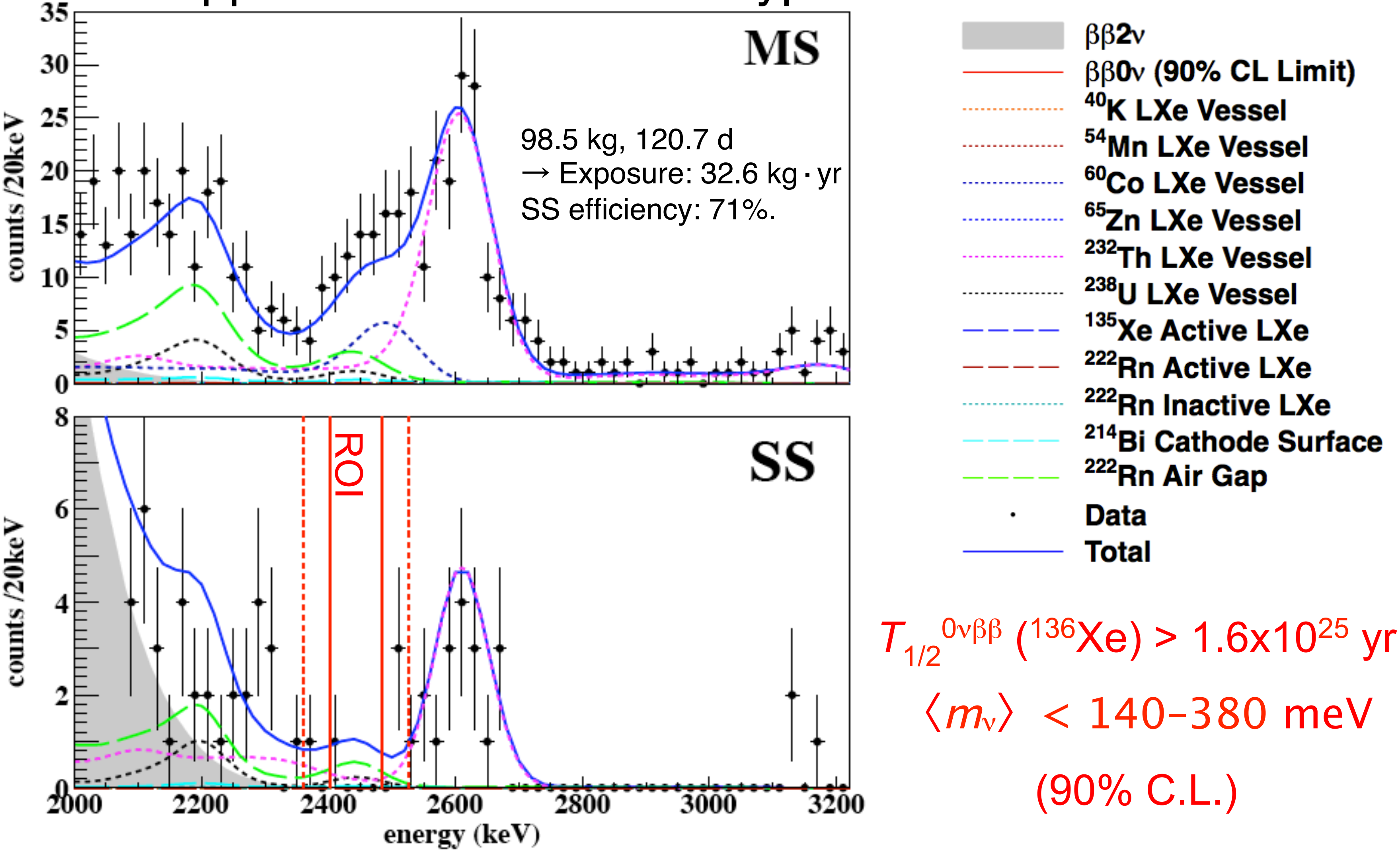


$T_{1/2}^{2\nu\beta\beta}$ (^{136}Xe) =(2.172 ± 0.017^{stat} ± 0.060^{sys}) x 10^{21} yr

EXO-200 new precision measurement paper [arXiv:1306.6106v1]
Agrees with EXO-200 first observation [Phys. Rev. Lett. **107** 212501 (2011)] and KamLAND-ZEN [Phys. Rev. C**85**, 045504 (2012)].

Low background spectrum

No peak observed at $Q_{\beta\beta}$. Use the background model to construct a limit $0\nu\beta\beta$ via a likelihood ratio hypothesis test.



98.5 kg, 120.7 d
→ Exposure: 32.6 kg · yr
SS efficiency: 71%.

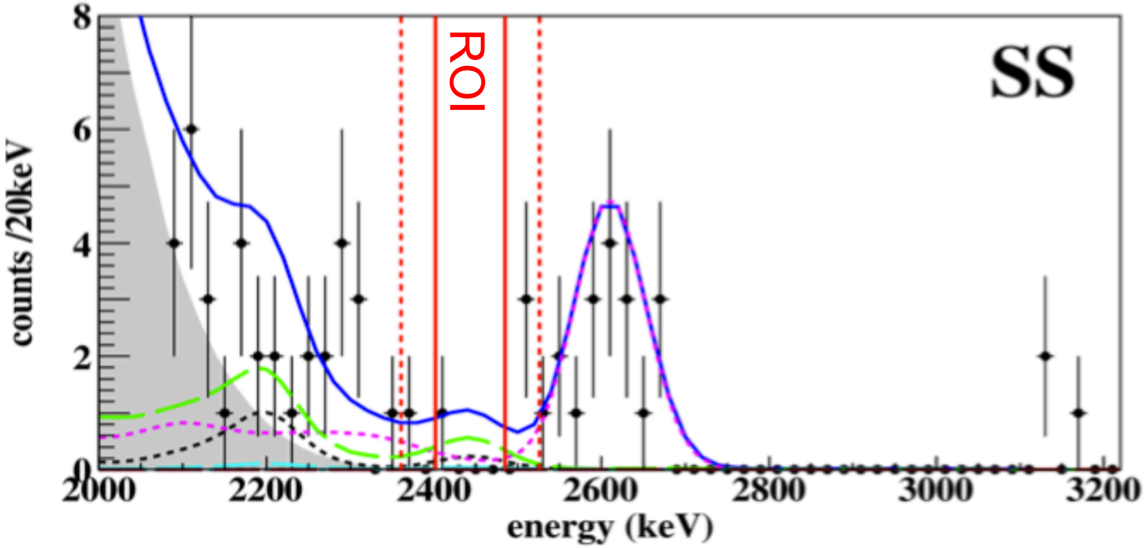
$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > $1.6\text{x}10^{25}$ yr

$\langle m_\nu \rangle < 140\text{–}380$ meV

(90% C.L.)

[Phys. Rev. Lett. 109, 032505 (2012)]

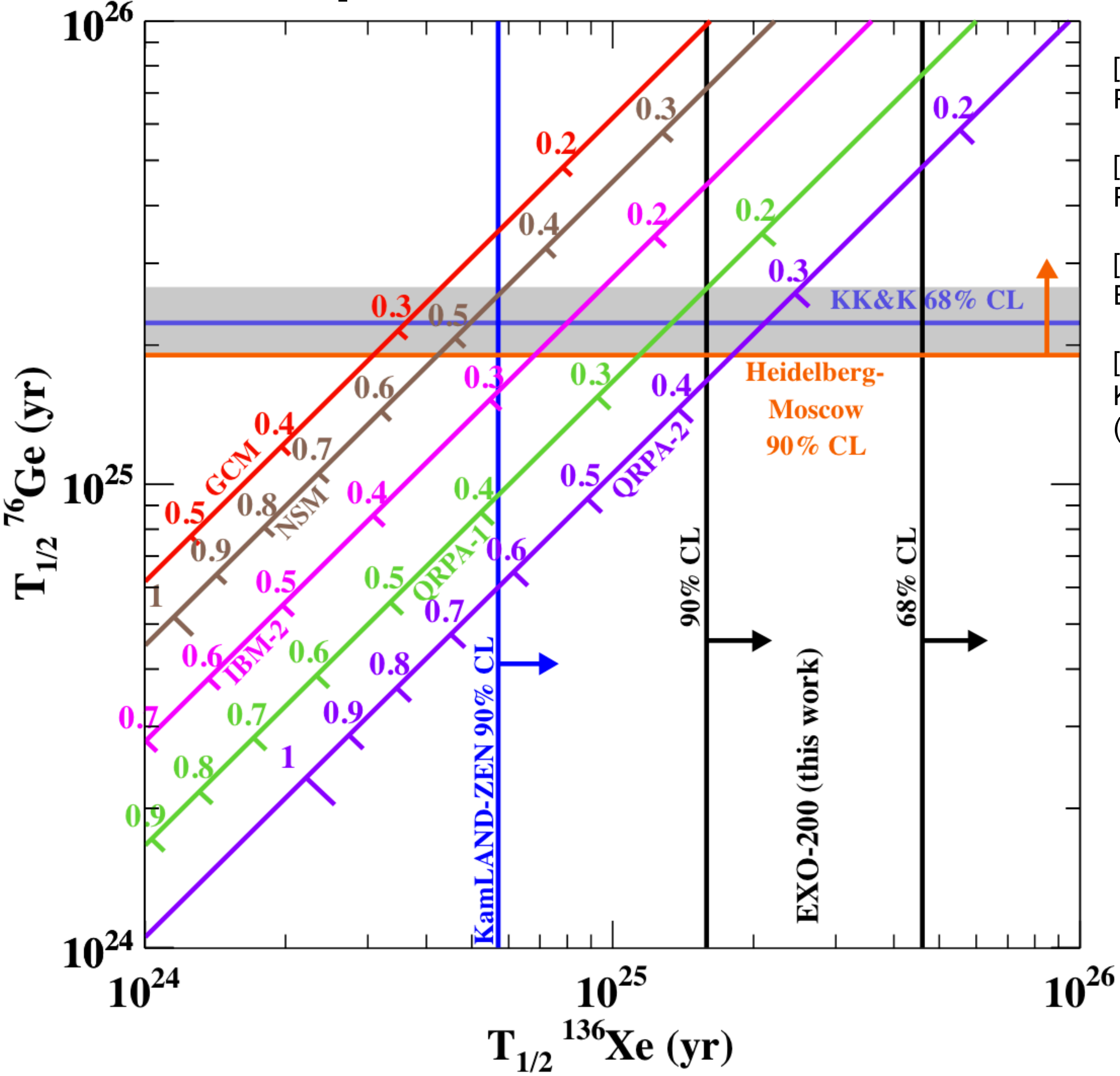
Background contributions



Background goal for this exposure was 4.6 counts in ±2σ ROI

	Expected events from fit			
	±1 σ		±2 σ	
^{222}Rn in cryostat air-gap	1.9	±0.2	2.9	±0.3
^{238}U in LXe Vessel	0.9	±0.2	1.3	±0.3
^{232}Th in LXe Vessel	0.9	±0.1	2.9	±0.3
^{214}Bi on Cathode	0.2	±0.01	0.3	±0.02
All Others	~0.2		~0.2	
Total	4.1	±0.3	7.5	±0.5
Observed	1		5	
Background rate (kg^{-1}yr^{-1}keV^{-1})	1.5 x 10^{-3} ± 0.1		1.4 x 10^{-3} ± 0.1	

Comparison with existing claim



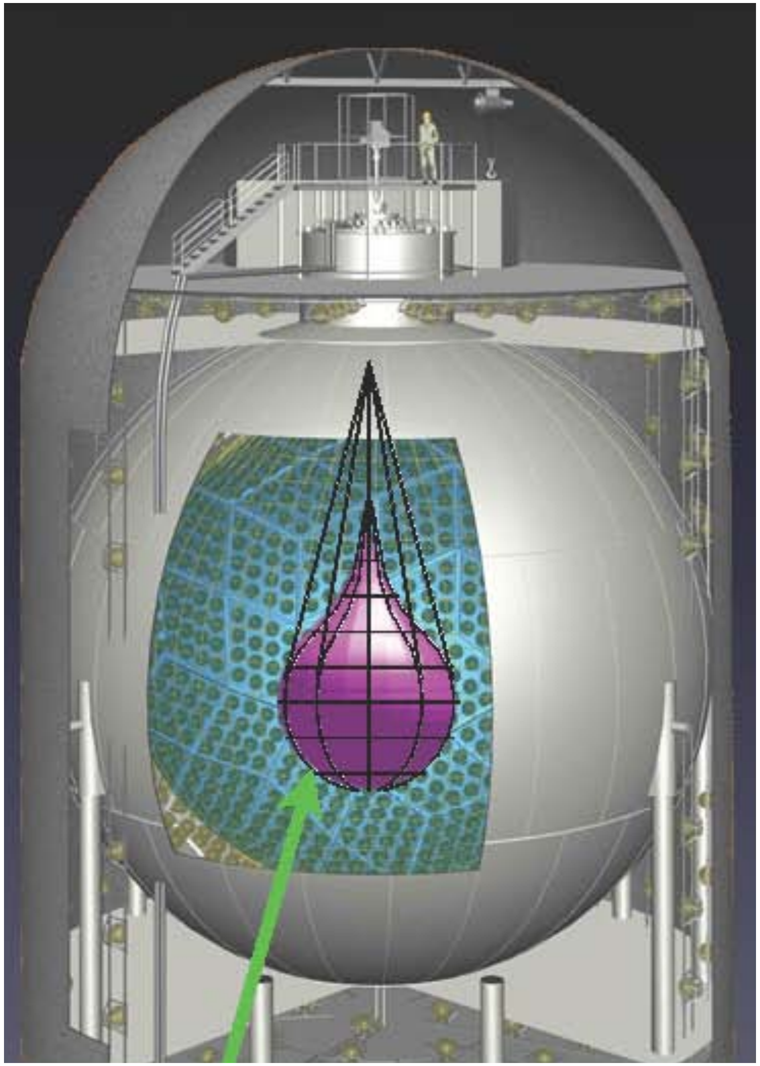
[EXO-200 Collaboration
Phys. Rev. Lett. 109 (2012) 032505]

[KamLAND-Zen Collaboration
Phys. Rev. C 85 (2012) 045504]

[H.V. Klapdor-Kleingrothaus et al.
Eur. Phys. J. A12 (2001) 147]

[H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Mod. Phys. Lett., A21 (2006) 1547]

Scintillator-based detectors



KamLAND-Zen uses the existing KamLAND detector with the addition an inner balloon of liquid scintillator with dissolved Xe.

$T_{1/2}$ = (2.38 ± 0.02 stat ± 0.14 sys) x 10^{21} yr
Consistent with EXO-200

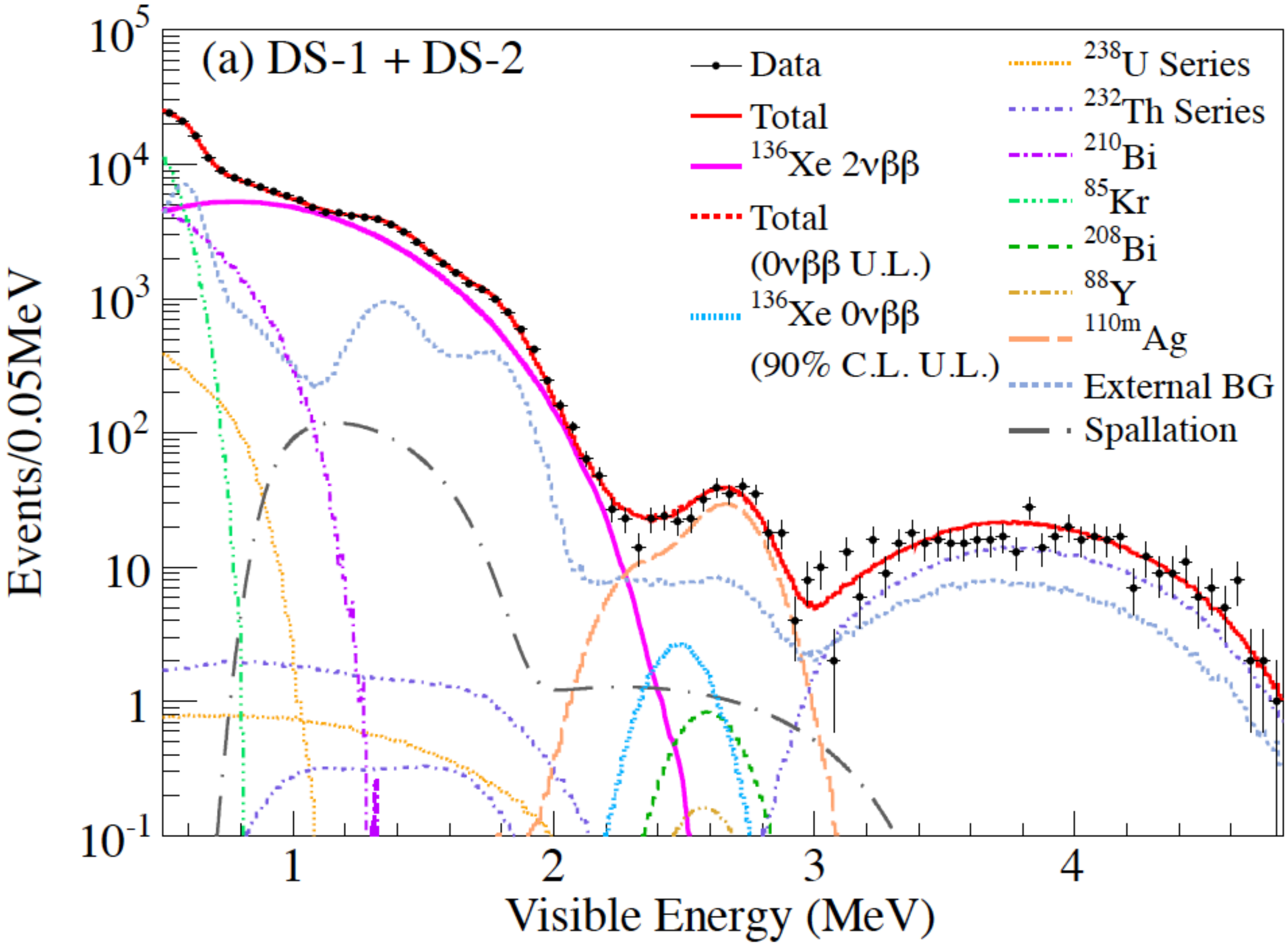
[*Phys. Rev. C* **85** (2012) 045504]

$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ y at 90% C.L.

[*Phys. Rev. Lett.* **110** (2013) 062502]

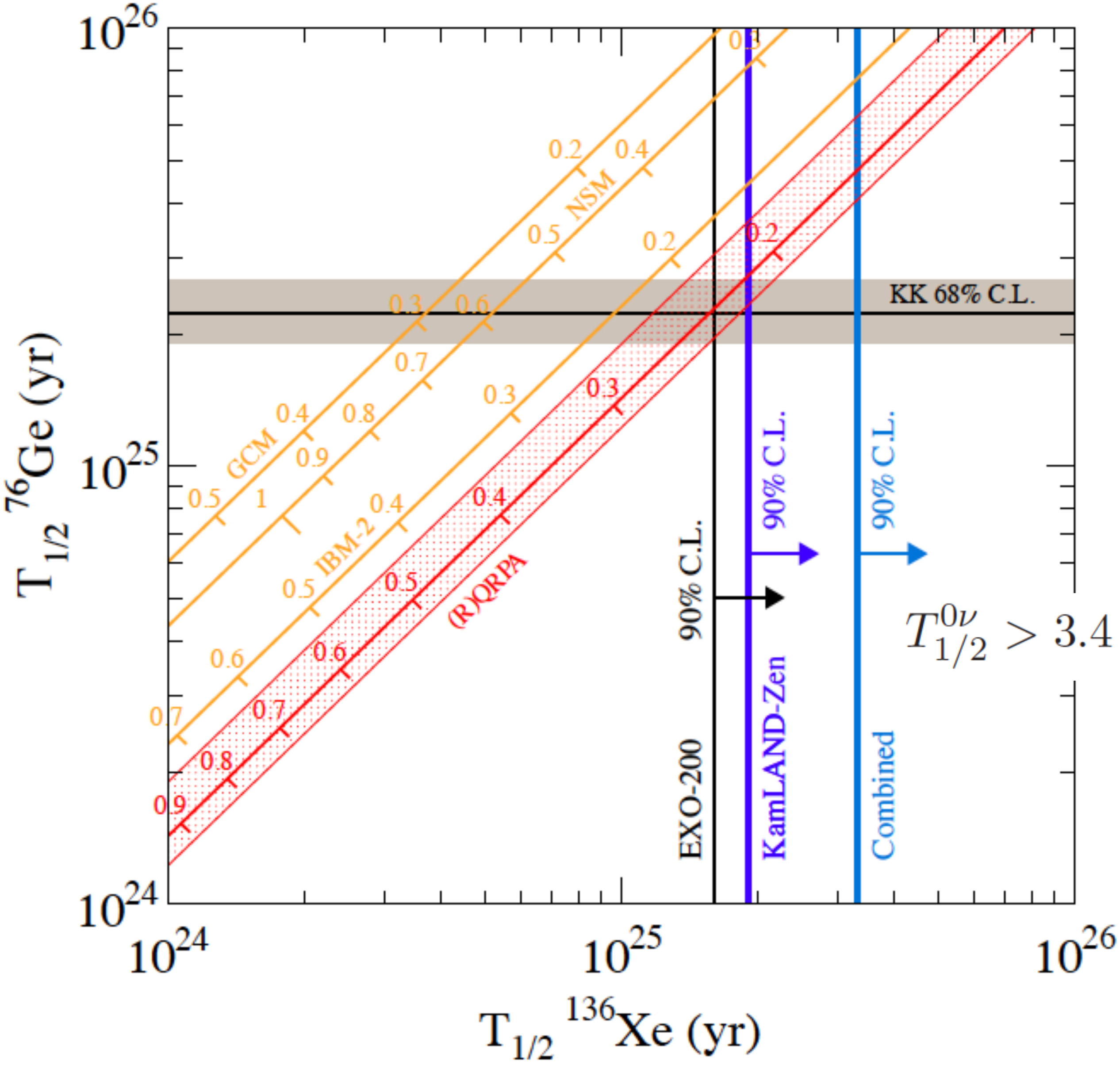
SNO+ is a similar idea for the SNO detector. Current plans to convert to a scintillator detector with dissolved ^{130}Te.

KamLAND-Zen



$$T^{0\nu}_{1/2} > 1.9 \times 10^{25}\,\text{yr} \quad (90\%\ \text{C.L})$$

Combined analysis



[EXO-200 Collaboration
Phys. Rev. Lett. 109 (2012) 032505]

[KamLAND-Zen Collaboration
Phys. Rev. C 85 (2012) 045504]

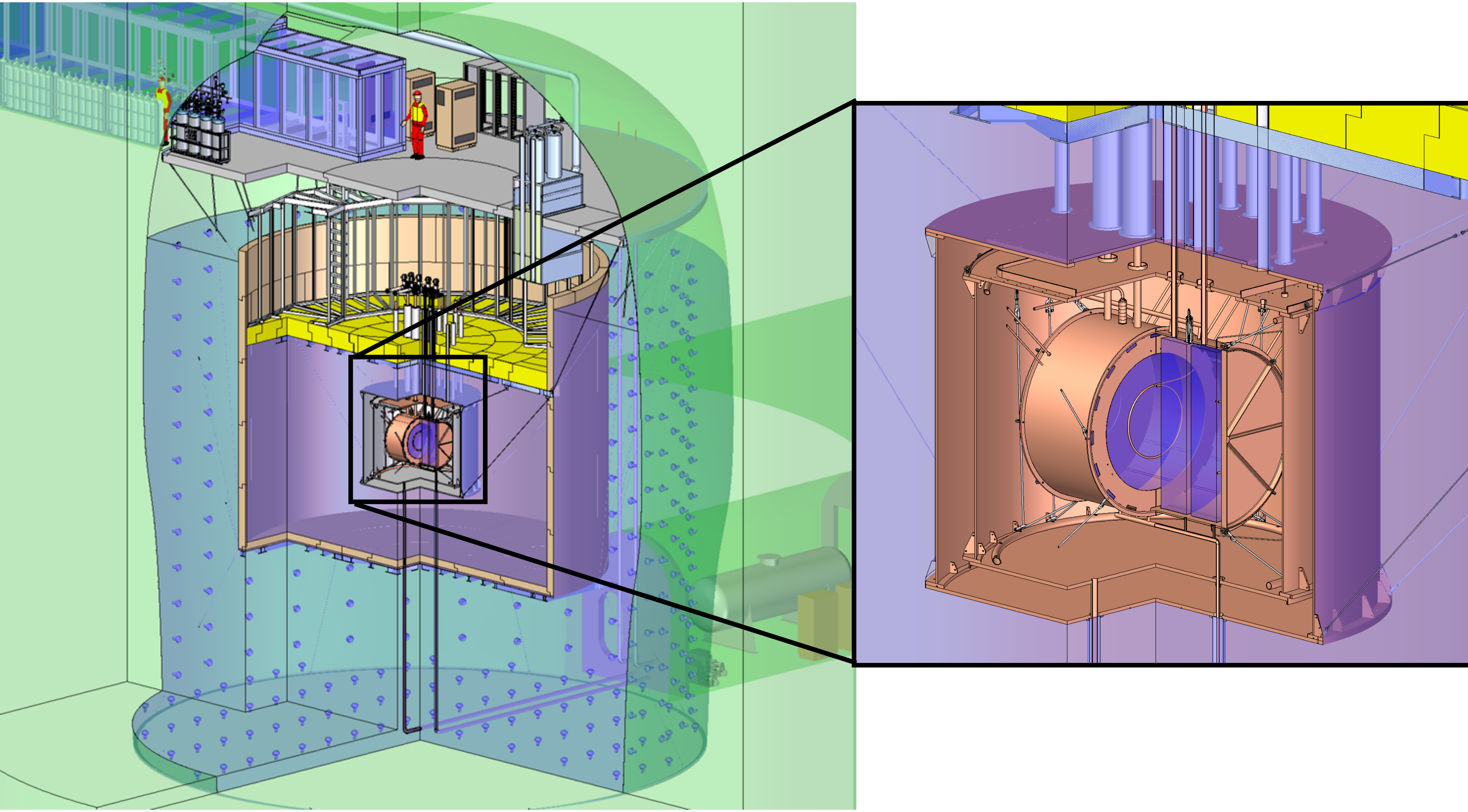
[H.V. Klapdor-Kleingrothaus et al.
Eur. Phys. J. A12 (2001) 147]

[H.V. Klapdor-Kleingrothaus and I.V. Krivosheina, Mod. Phys. Lett., A21 (2006) 1547]

$$T^{0\nu}_{1/2} > 3.4 \times 10^{25}\,\mathrm{yr} \quad (90\%\ \mathrm{C.L})$$

The future?

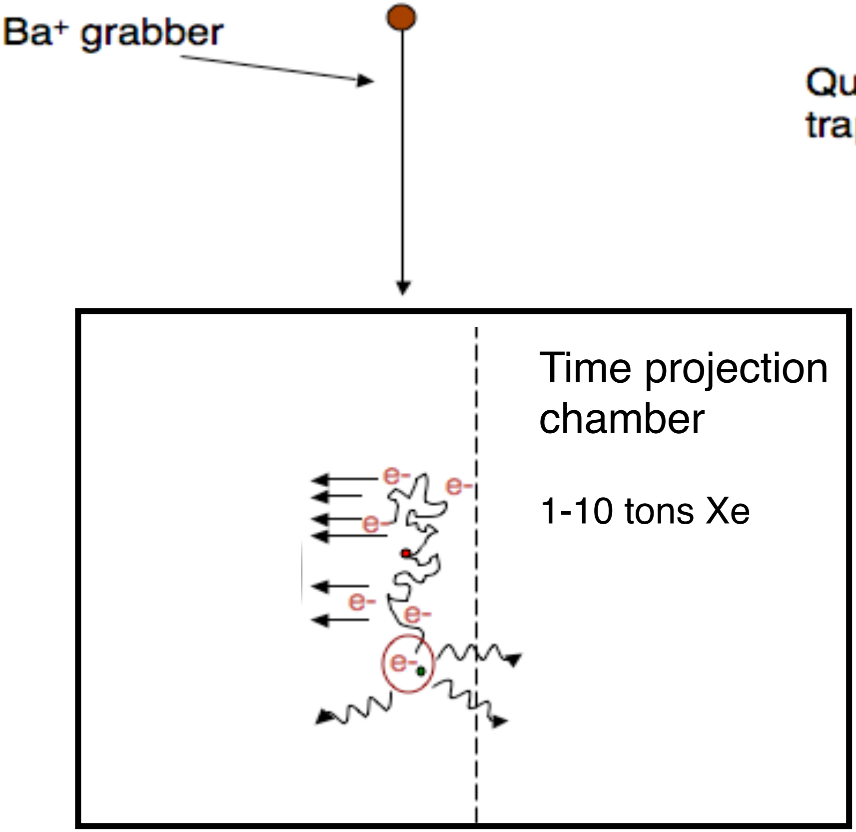
nEXO detector

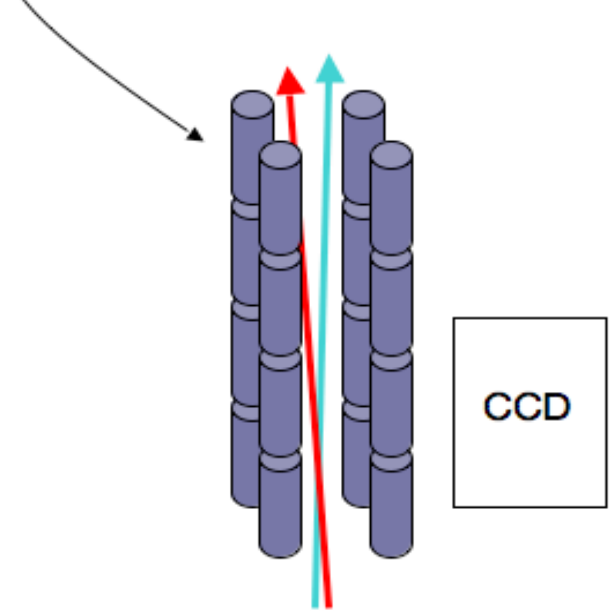


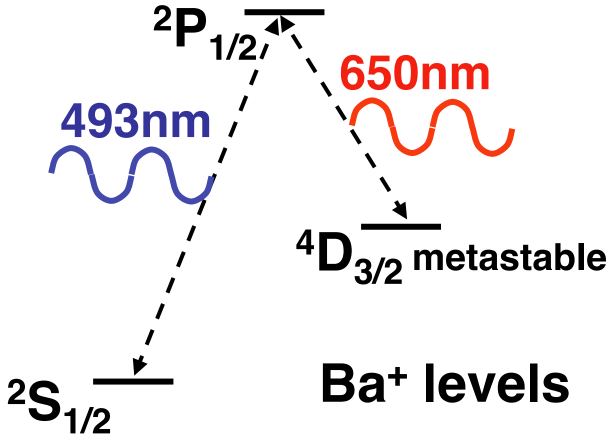
1-5 T “conventional” low background LXe detector, possibly sited at SNOLAB.
Option to include Ba^+ tagging…

Ba^+ tagging: Overview

$$^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Ba}^{++} + 2e^-$$



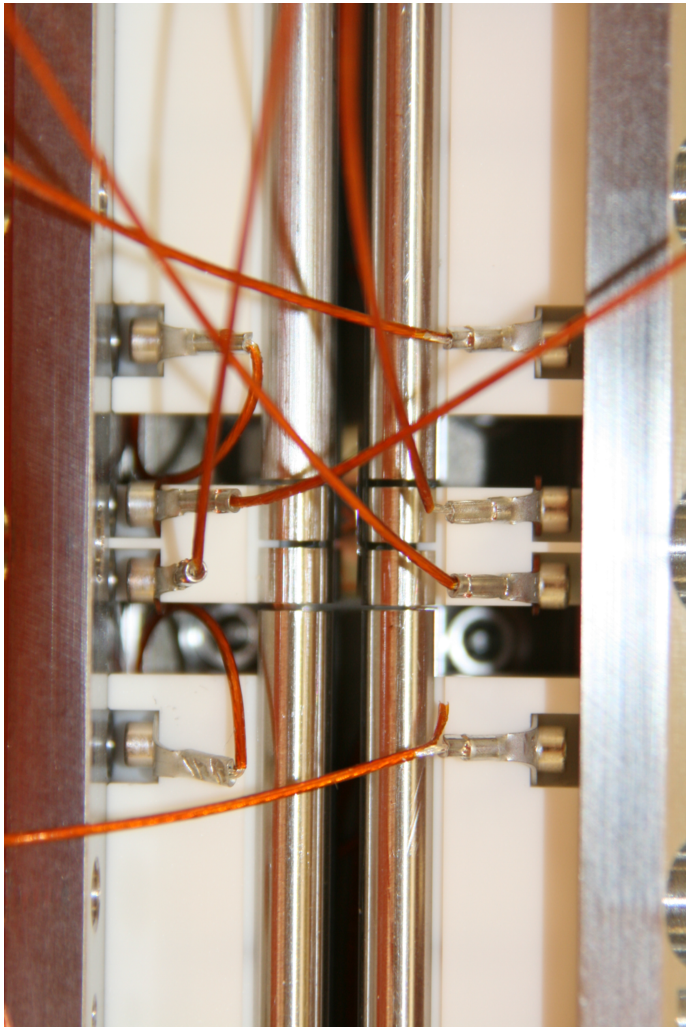


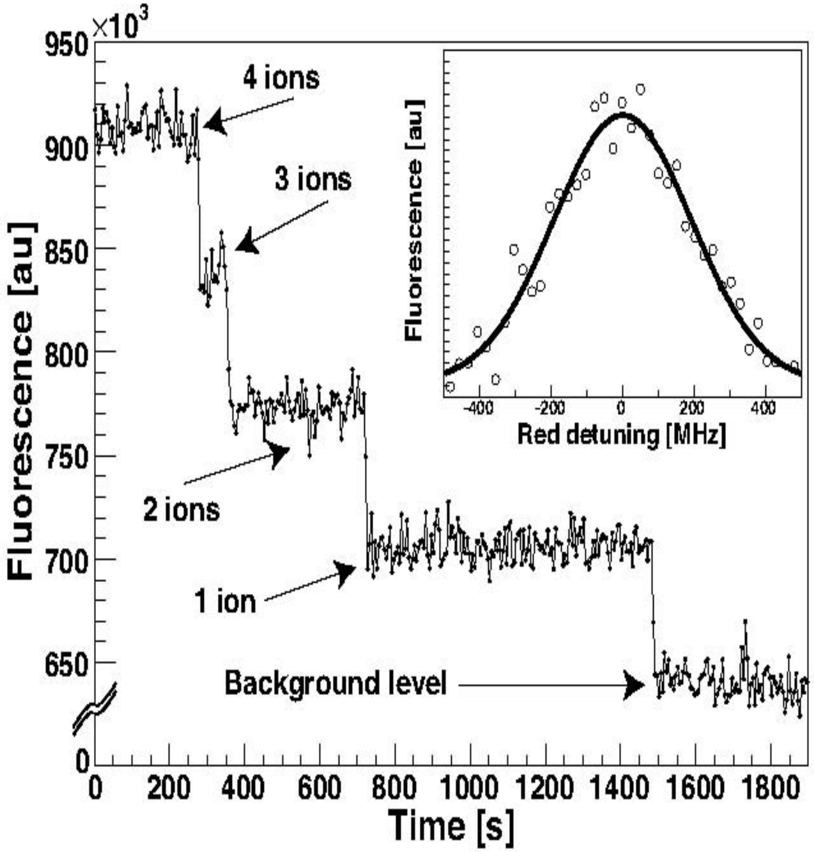


Ba^+ levels

Ba^+ tagging would allow for the elimination of all backgrounds other than the background from $2\nu\beta\beta$

Ba$^+$ tagging: Trap

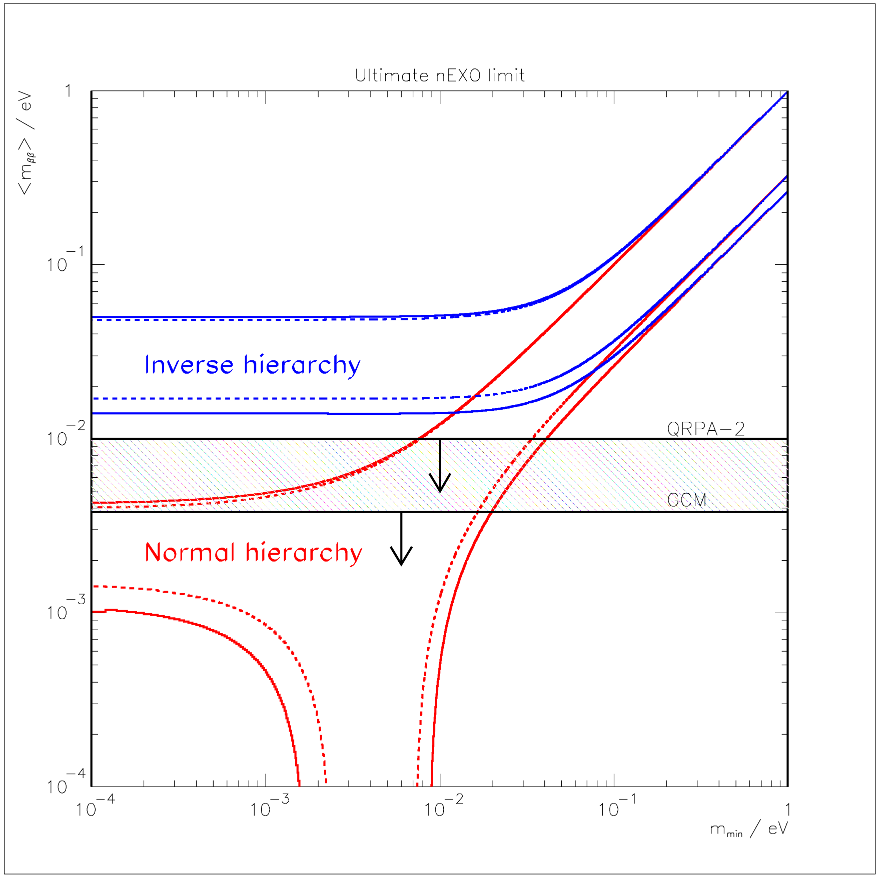




~9σ discrimination in 5s integration

M.Green et al., *Phys Rev* A**76** (2007) 023404
B.Flatt et al., *NIM* A**578** (2007) 409

Ultimate EXO sensitivity



Neutrino parameters: Forero et al. 1205.5254, 95%CL.

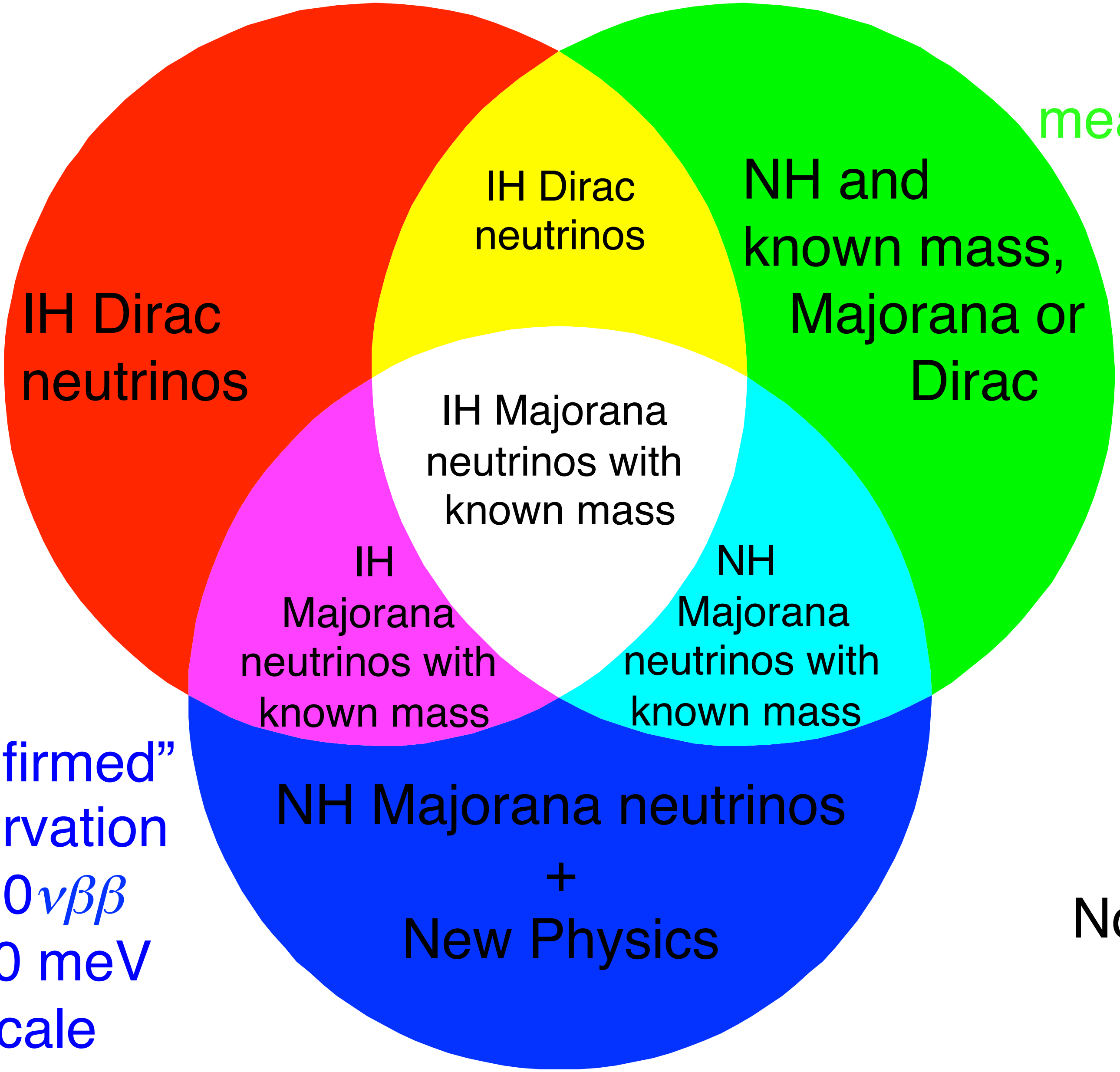
GCM: T.R. Rodriguez and G. Martinez-Pinedo, Phys. Rev. Lett. 105 (2010) 252503.;
QRPA-2: A. Staudt, K. Muto and H. V. Klapdor-Kleingrothaus, Europhys. Lett. 13 (1990) 31.

Band	**Fiducial Mass (tonne)**	**Livetime (yr)**	**$T_{1/2}$ sensitivity (yr)**	**Bracketing NMEs (meV)**		**Conditions**
				QRPA-2	**GCM**	
EXO-200 "Ultimate"	**0.1**	**4**	**$5.5\cdot10^{25}$**	**200**	**75**	**EXO-200 with Rn removal and new analysis**
Initial nEXO	**4.5**	**10**	**$2.5\cdot10^{27}$**	**30**	**11**	**Extrapolation from EXO-200 using EXO-200 backgrounds**
Final nEXO	**4.5**	**5+5**	**$2.2\cdot10^{28}$**	**10**	**4**	**Second 5 yr background-free (e.g. Ba tagging)**

Experimental neutrino program, circa 2030?

Inverted
hierarchy
verified

Direct
measurement
of ν mass
~100 meV
scale



IH Dirac
neutrinos

IH Dirac
neutrinos

NH and
known mass,
Majorana or
Dirac

IH Majorana
neutrinos with
known mass

IH
Majorana
neutrinos with
known mass

NH
Majorana
neutrinos with
known mass

NH Majorana neutrinos
+
New Physics

“Confirmed”
observation
of $0\nu\beta\beta$
~100 meV
scale

Now what??

What does come next?
Let’s assume we see it…

- The next generation of neutrinoless double beta decay experiments may detect $0\nu\beta\beta$ at mass scales of $m_{\beta\beta}$ ~100 meV.
- If they do, precision experiments to nail down the nuclear physics and the mechanism!
  - First, precision measurements in multiple isotopes to nail down the nuclear physics.
  - Angular correlations to try to understand the mechanism.
    - Low pressure gas TPC or NEMO-like experiment to study angular correlations. Need lots of decays, so this is really hard.
  - Mechanism would be further constrained by observation of neutrinoless EC/β+ or double EC.
  - Finally, Majorana phases?? (Not likely!)

But if we rule out the IH…

Accessing the normal hierarchy is really tough!

- Need excellent energy resolution.
- Need heroic background rejection.
- Need ~10 tons or more of enriched isotope.

All of the front runners run into limitations

- GERDA/Majorana Ge – 10 meV (10 t-y)
- EXO liquid with Ba tagging – 10 meV
- CUORE – backgrounds
- SNO+ and KamLAND-Zen – energy resolution
- SuperNEMO – hard to get a lot of mass

Basically, the field is still open for new ideas…

(Scintillating bolometers, quantum dots, etc.)

Summary

- Neutrino masses are an open window into physics beyond the Standard Model.
- Majorana neutrino masses may be the key to understanding the matter-antimatter asymmetry of the universe.
- Neutrinoless double beta decay is the most sensitive experimental probe of whether neutrinos have Majorana masses.
- There is a varied experimental program to search for neutrinoless double beta decay.
- We need theorists, too!
- The reach of next generation experiments complements other parts of the experimental neutrino program.