The *next* next generation of neutrinoless double beta decay searches

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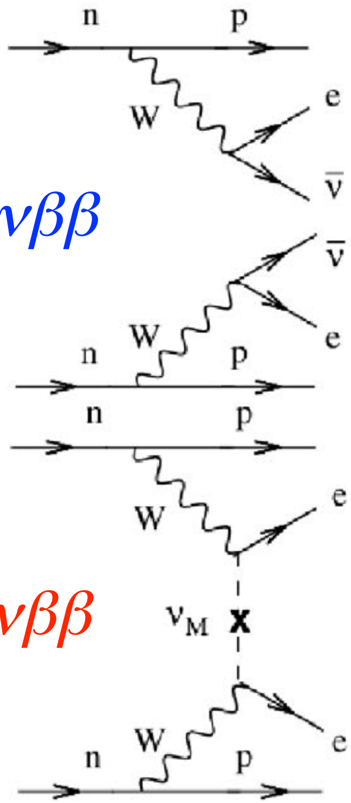
Aspen Winter Workshop
8 February 2013

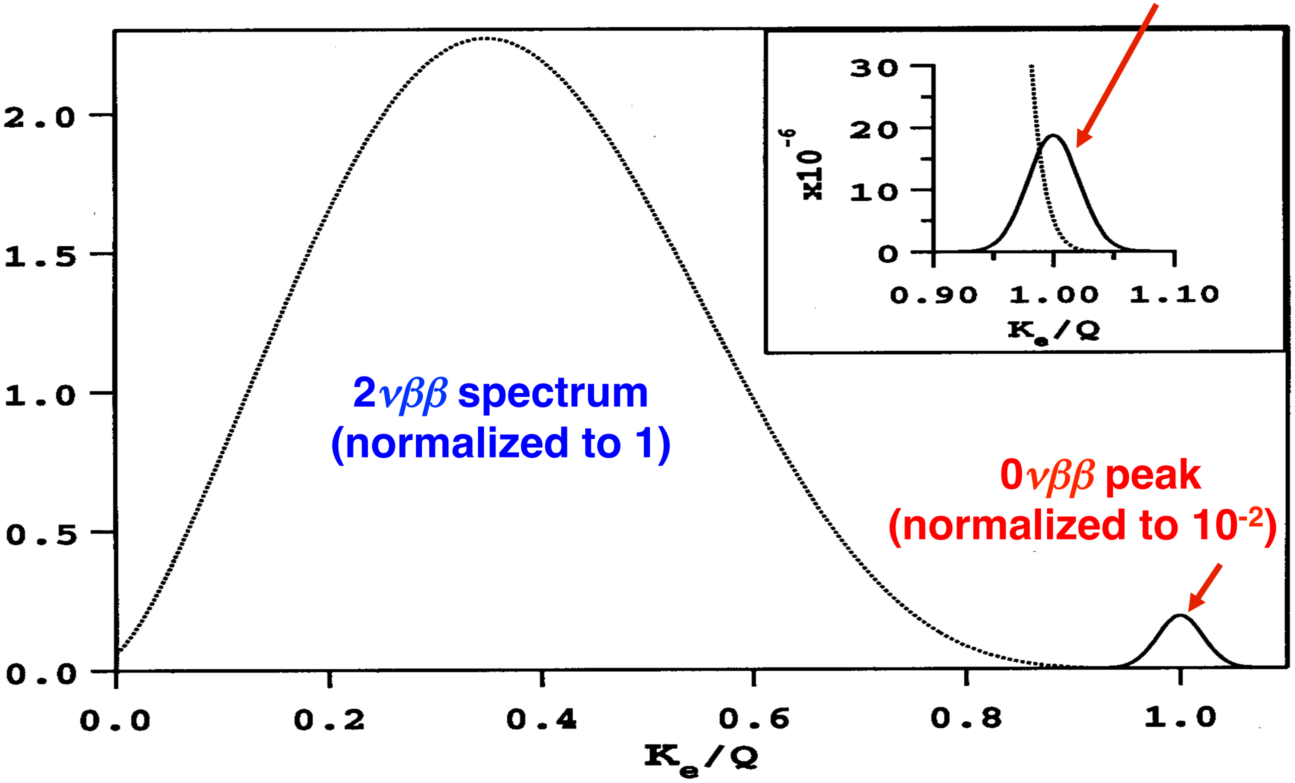
Double beta decay

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



$2\nu\beta\beta$

$0\nu\beta\beta$



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

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

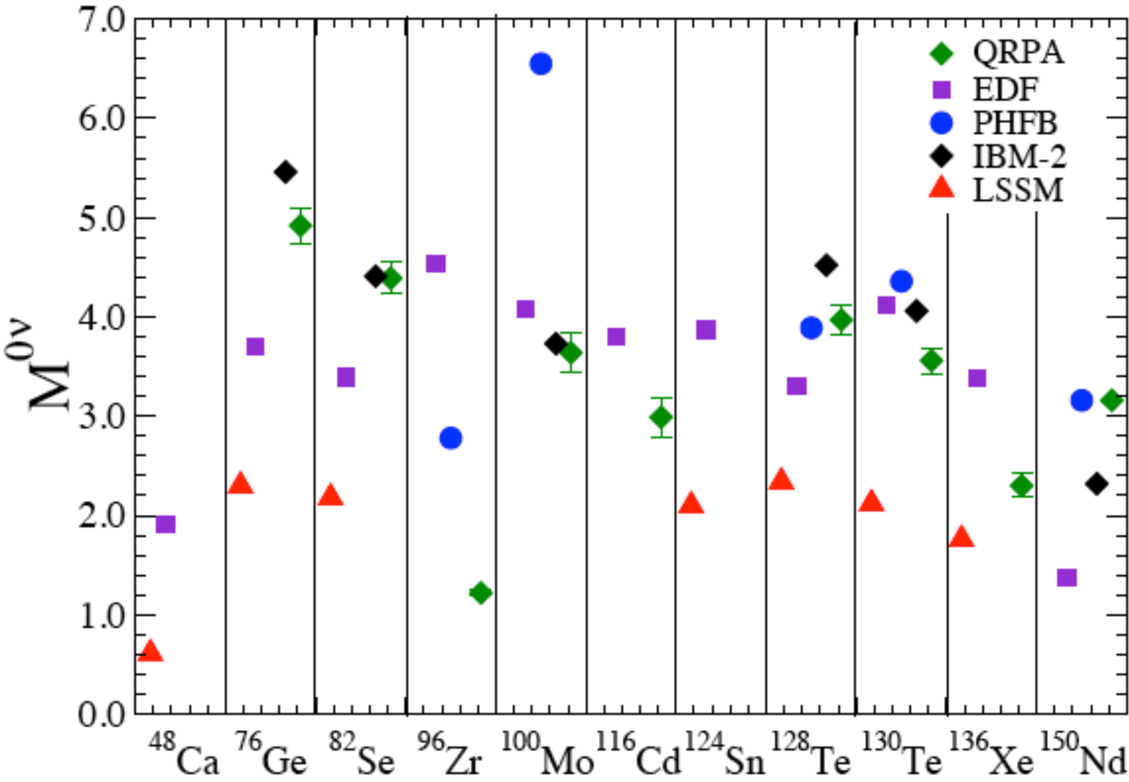
$0\nu\beta\beta$ peak (normalized to 10^{-2})

$0\nu\beta\beta$ can only occur for nonzero Majorana neutrino mass term!

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

$G^{0\nu}$ is a phase space factor $\propto Q^5$
$M^{0\nu}$ is the nuclear matrix element

Nuclear matrix elements



Bilenky and Giunti, arXiv:1203.5250v1

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

Need to observe $0\nu\beta\beta$ in multiple isotopes!

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).

Effective Majorana mass

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

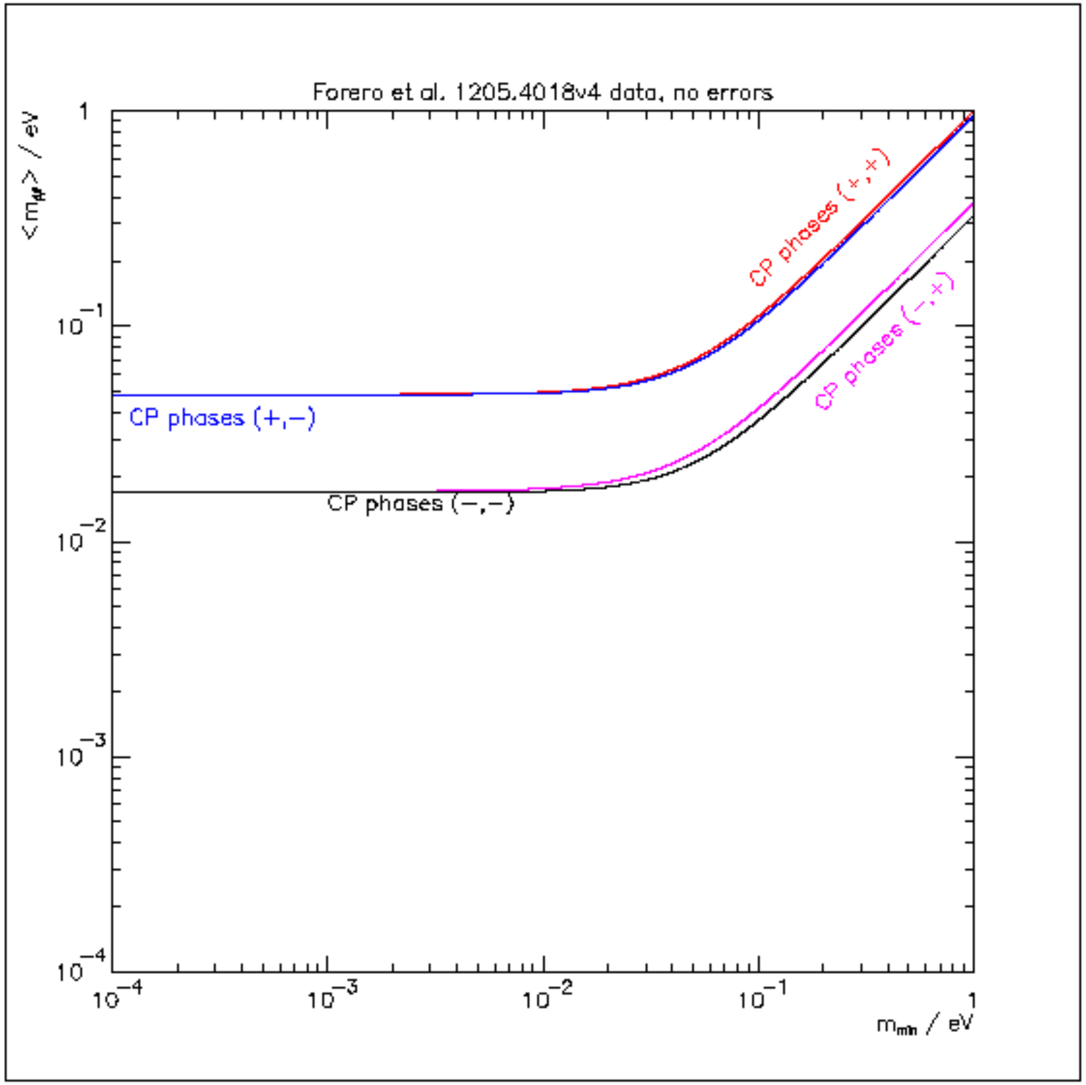
Using the standard representation of the PNMS matrix, the effective Majorana neutrino mass is given as:

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

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

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

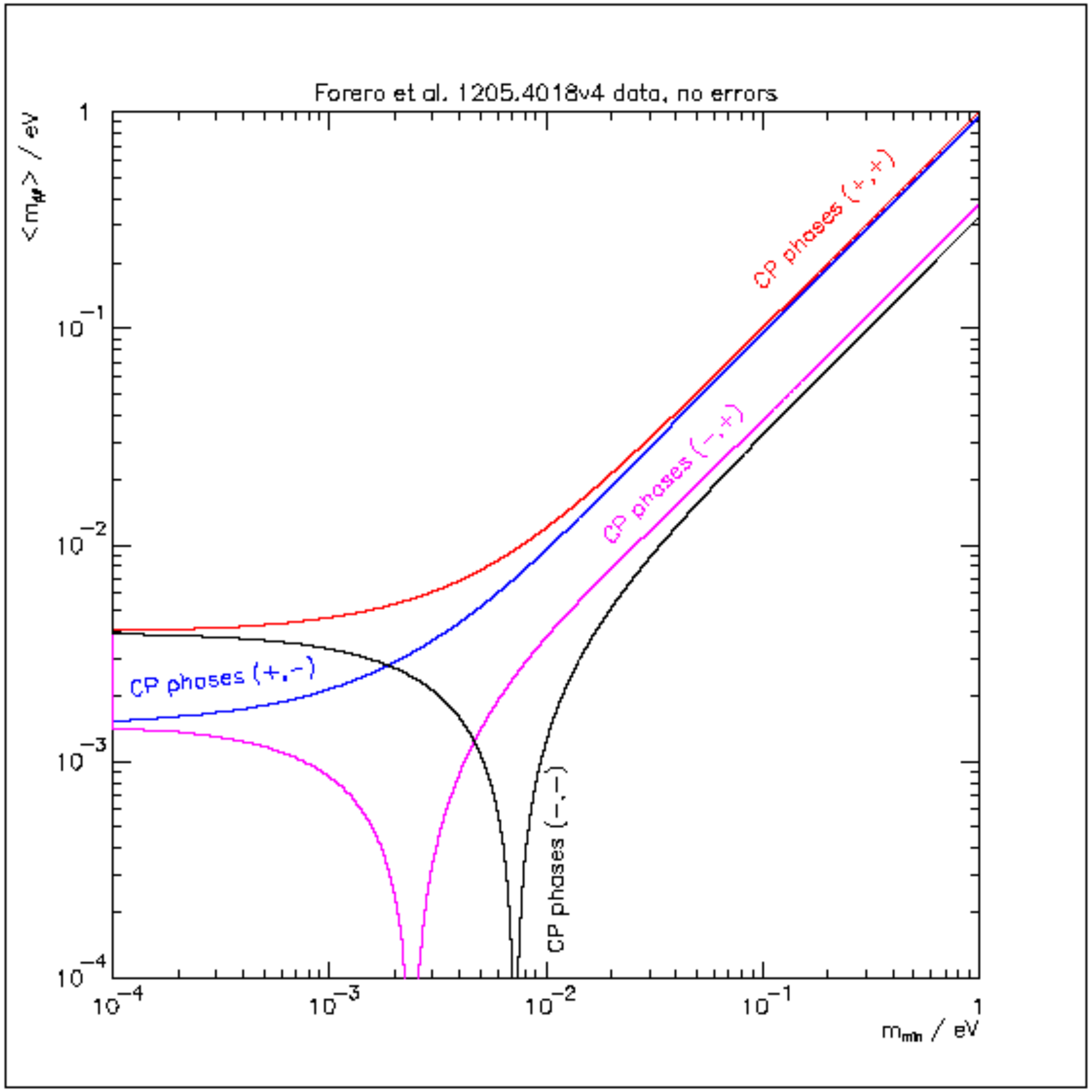
Inverted hierarchy



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

Plots courtesy Andreas Piepke.

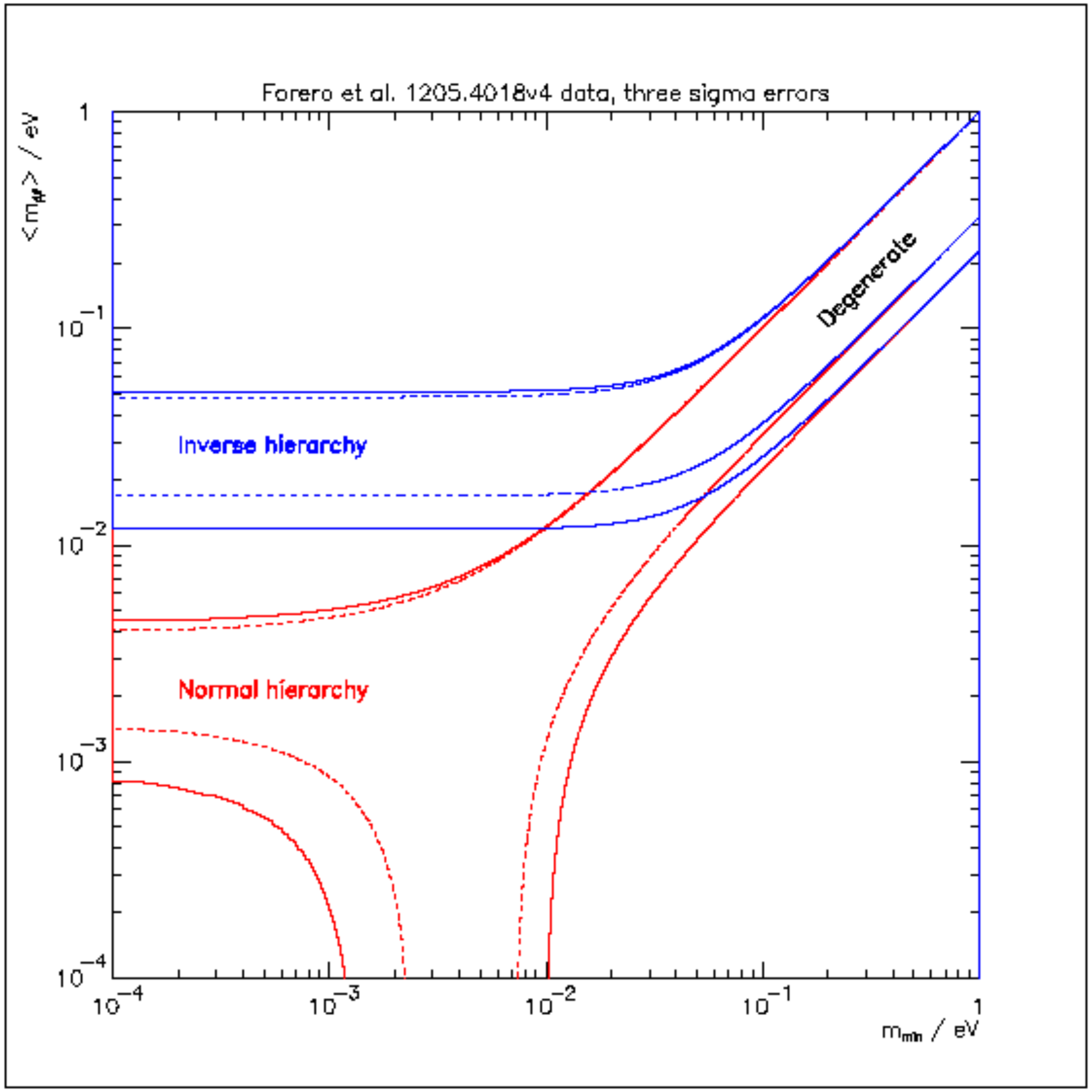
Normal hierarchy



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

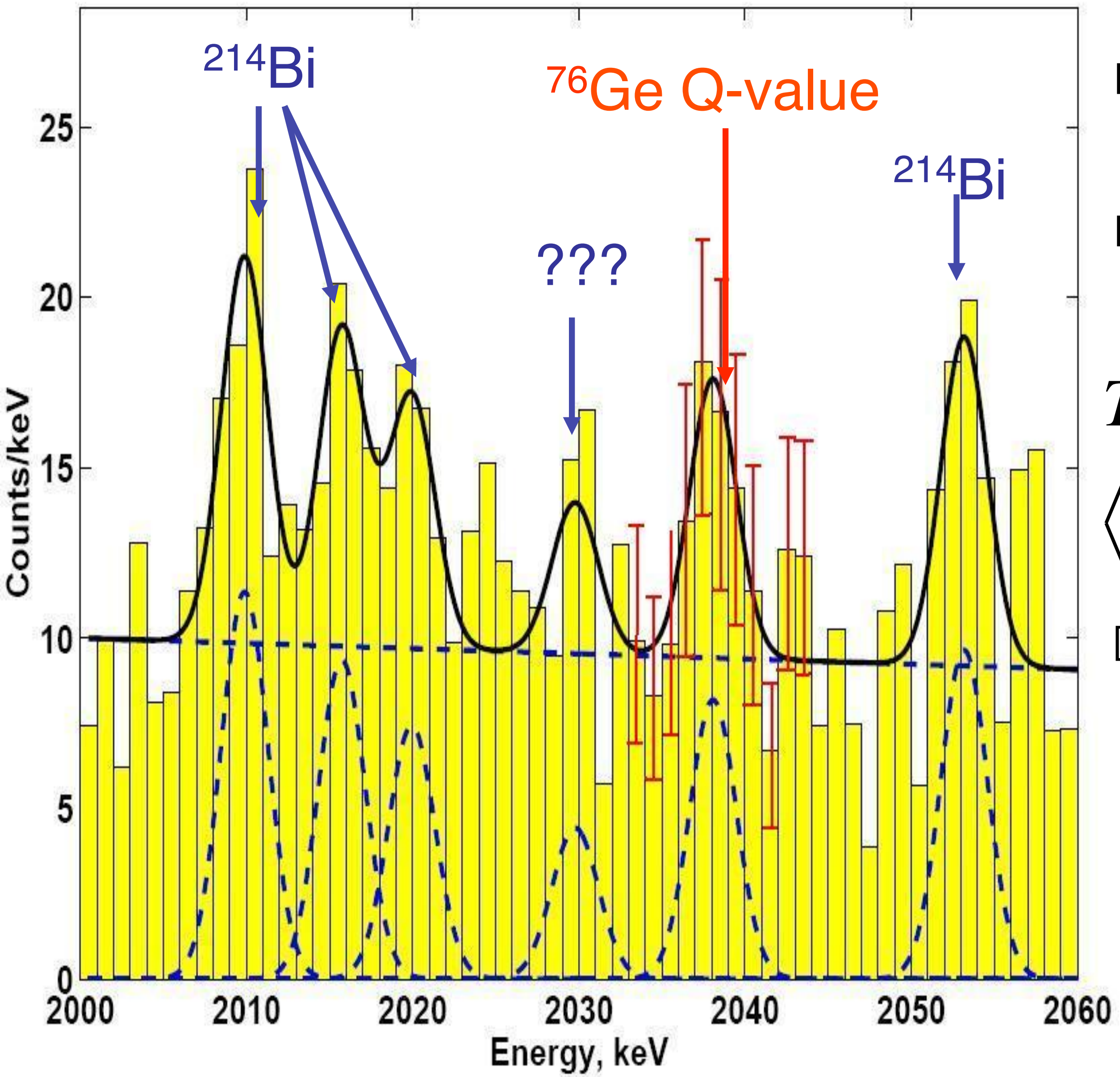
1) considerable variation of the effective mass,
2) allows destructive interference for certain values of m_{min} and choice of phases.

Combined phase space



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

Claim for observation of 0νββ



Fit model:
6 gaussians + linear bknd.

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

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

$$\langle m_{\beta\beta} \rangle = 0.32 \pm 0.03\, eV$$

[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.

Sensitivity of DBD experiments

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

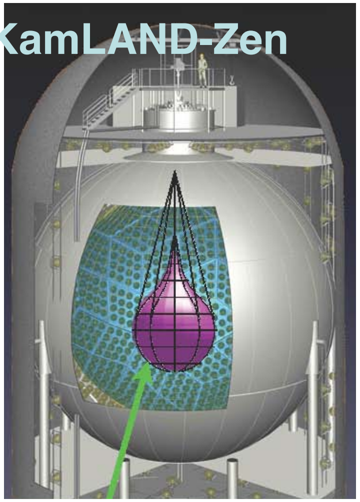
$$F_{0\nu} = \ln 2 \cdot N_A \frac{f}{A}\left(\frac{Mt}{B\Delta E}\right)^{1/2} \varepsilon$$

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

- Large exposure
- High efficiency
- Good energy resolution
- Low background

GERDA

supernemo
collaboration



EXO

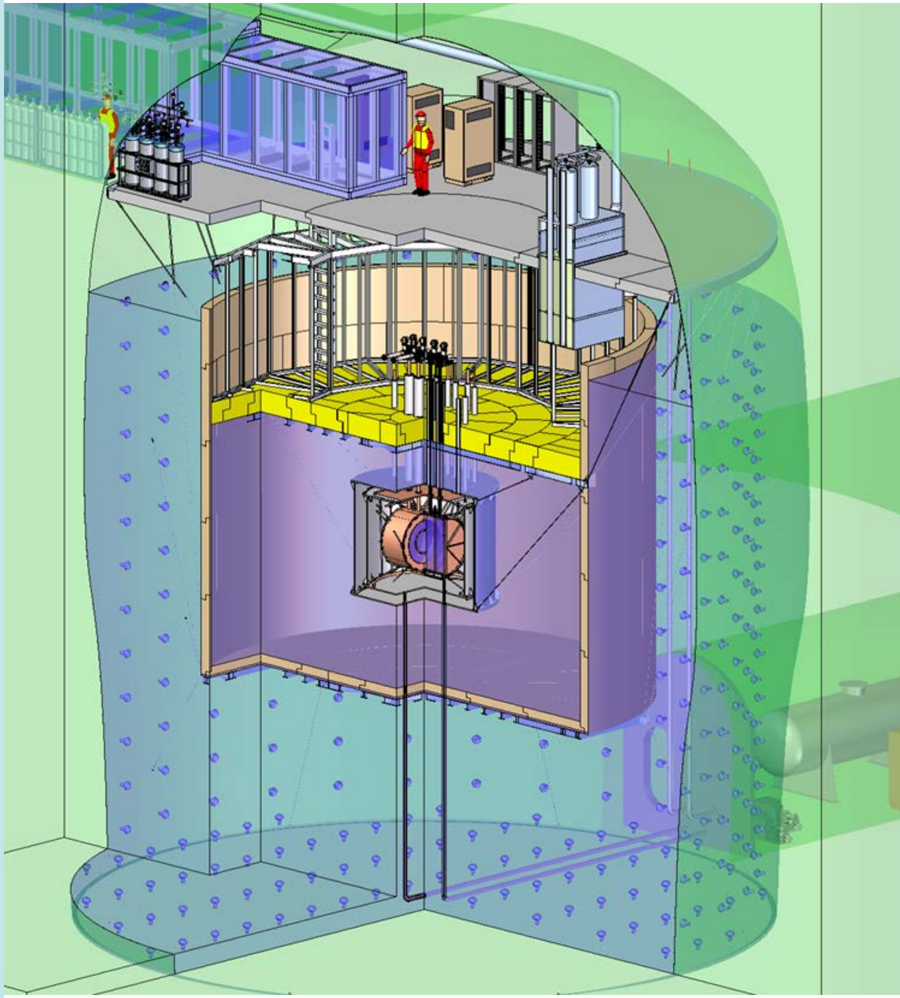
EXO is a program to search for the decay

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

Why Xe?

- Q-value of 2458 keV [Redshaw *et al.*, PRL **98**, 053003 (2007)] gives favorable phase space and a $0\nu\beta\beta$ region of interest above most naturally occurring γ-rays.
- Natural isotopic abundance of 8.9% with inexpensive enrichment.
- Noble gas/liquid detector allows continuous purification.
- Possibility of tagging the Ba^{+} daughter ion.

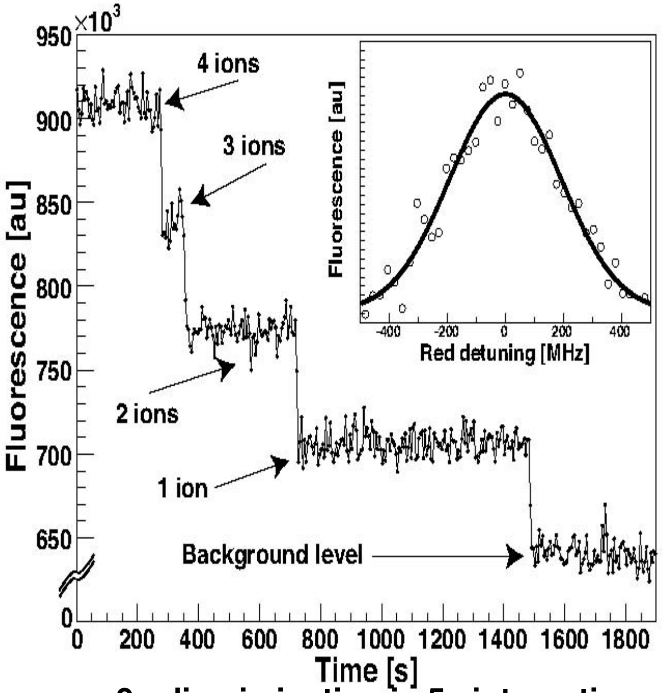
Ultimate goal is a 1-10 ton detector, liquid or gas phase, with real time Ba^{+} tagging. Sensitivity to $m_{\beta\beta}$ of ~10 meV.



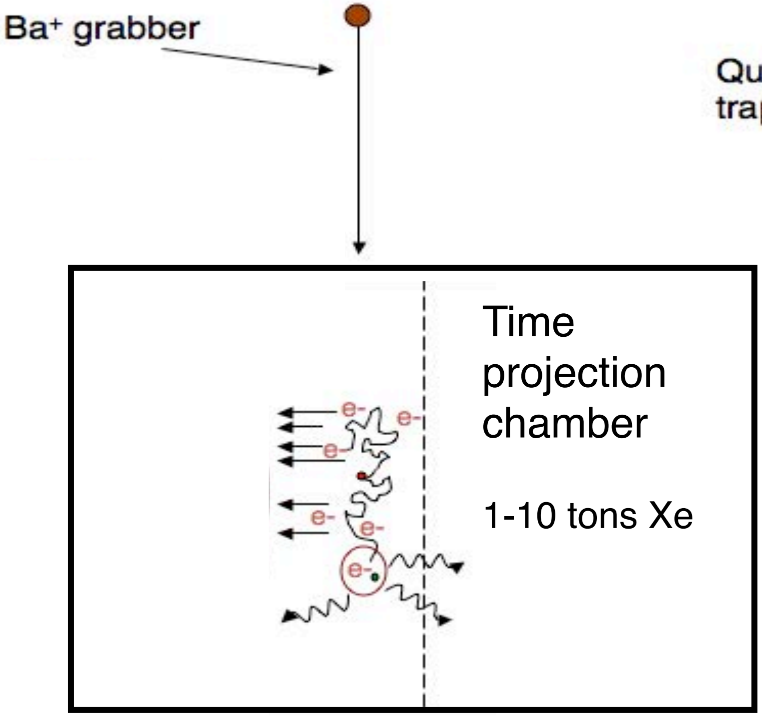
“nEXO” concept

Ba$^+$ tagging

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



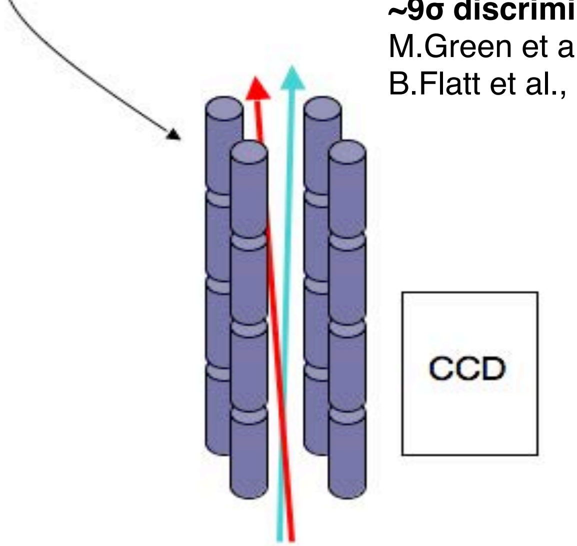
~9σ discrimination in 5s integration
M.Green et al., *Phys Rev* A**76** (2007)
B.Flatt et al., *NIM* A**578** (2007)



Time projection chamber

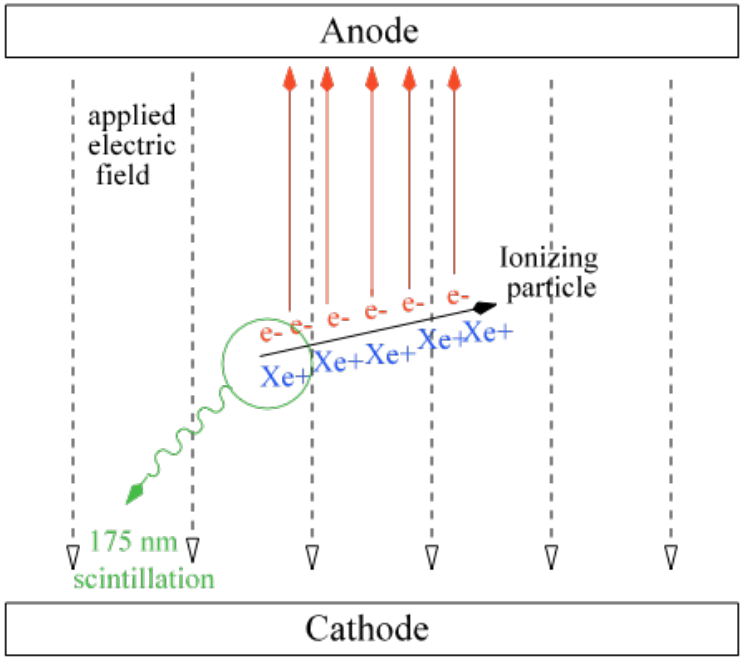
1-10 tons Xe

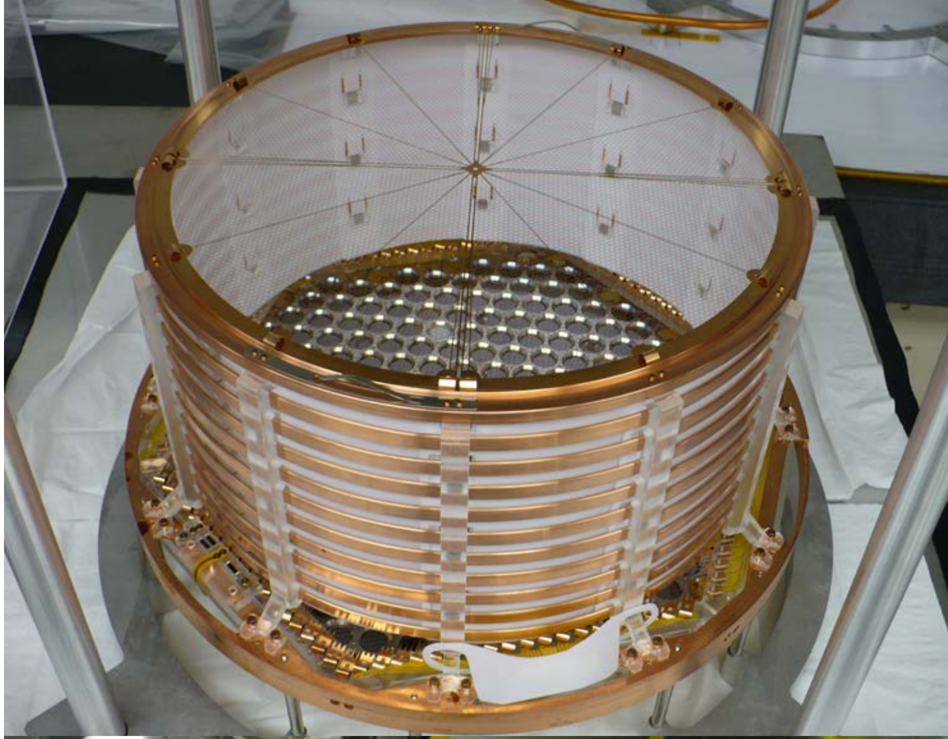
Quadrupole linear ion trap

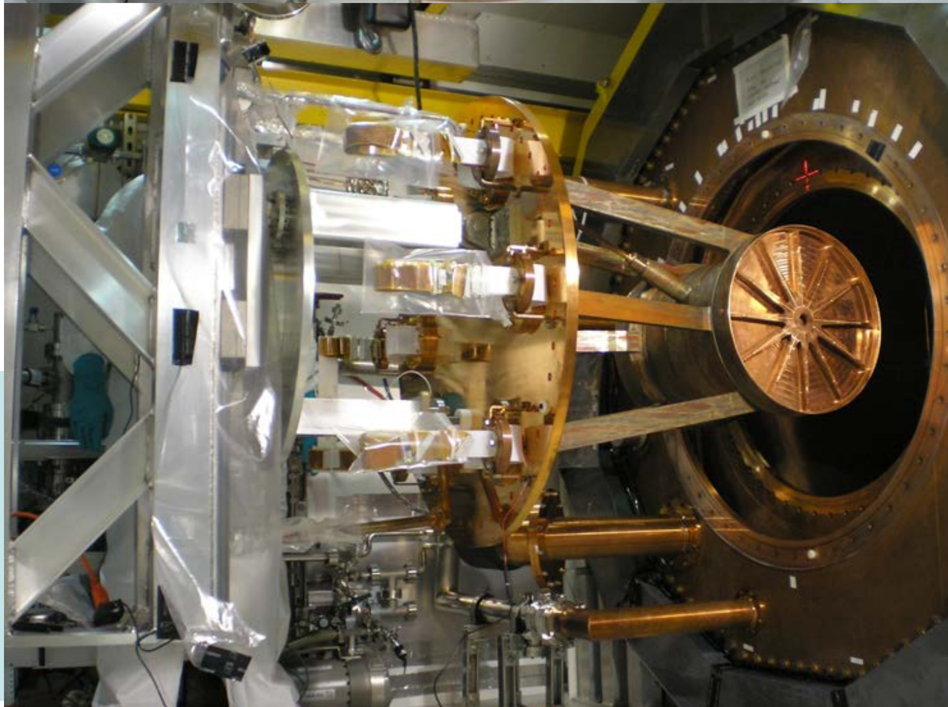


Ba$^+$ tagging would allow for the elimination of all backgrounds other than the background from $2\nu\beta\beta$

EXO-200
Liquid Xe TPC





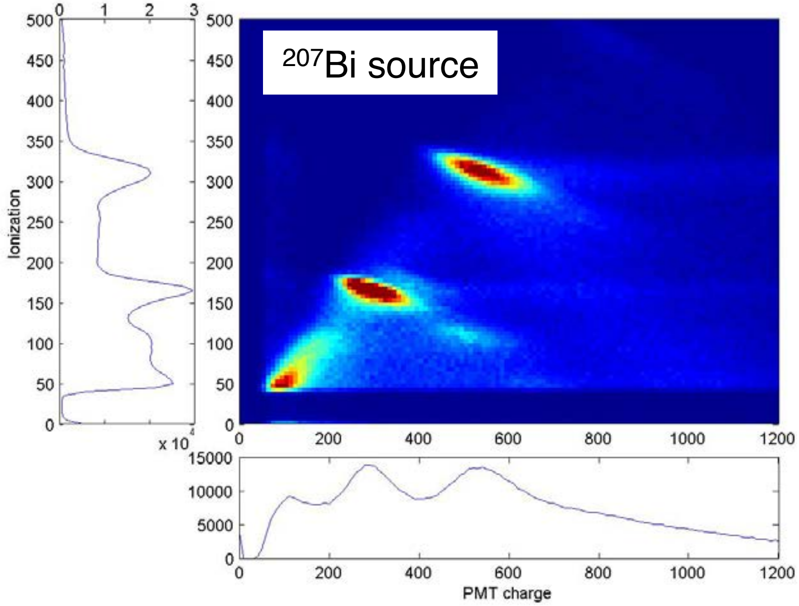


~100 kg fiducial mass Xe enriched to 80% in ^{136}Xe, ultralow background construction.

Readout plane is made up of LAAPDs + crossed wire grid.

Operating at the Waste Isolation Pilot Plant since May 2011.

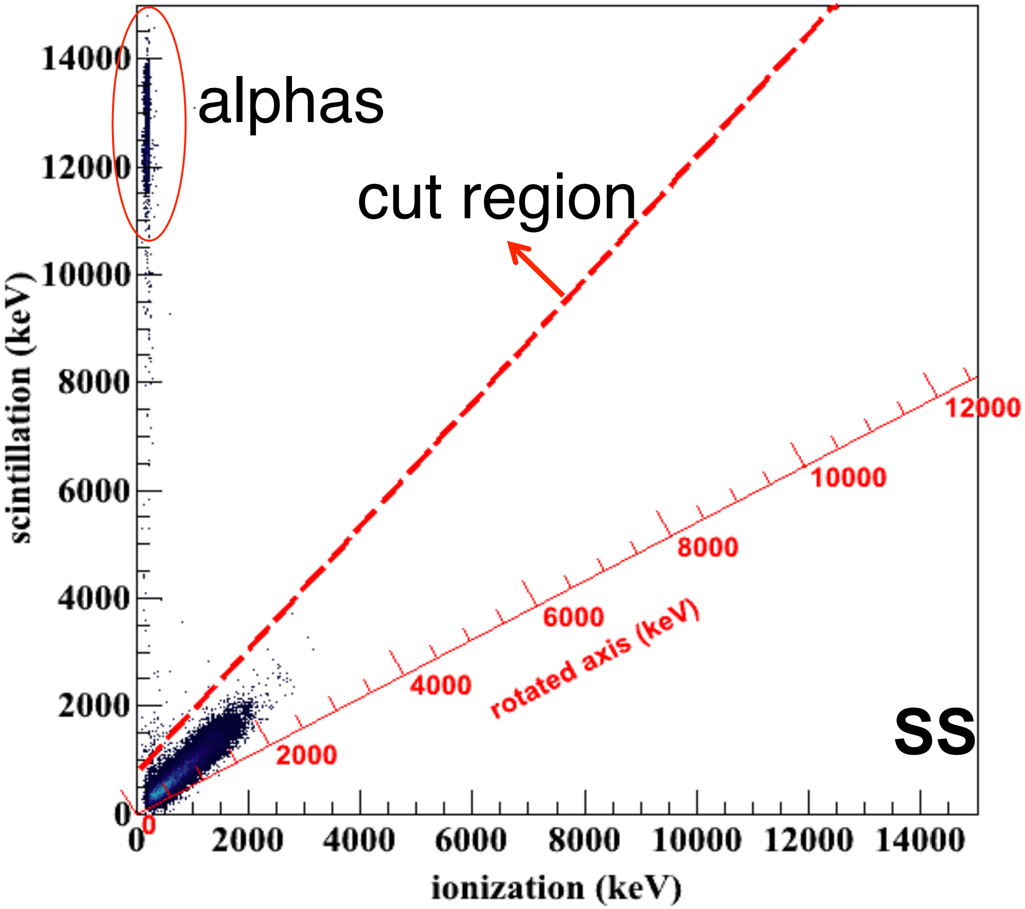
Ionization vs. Scintillation



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

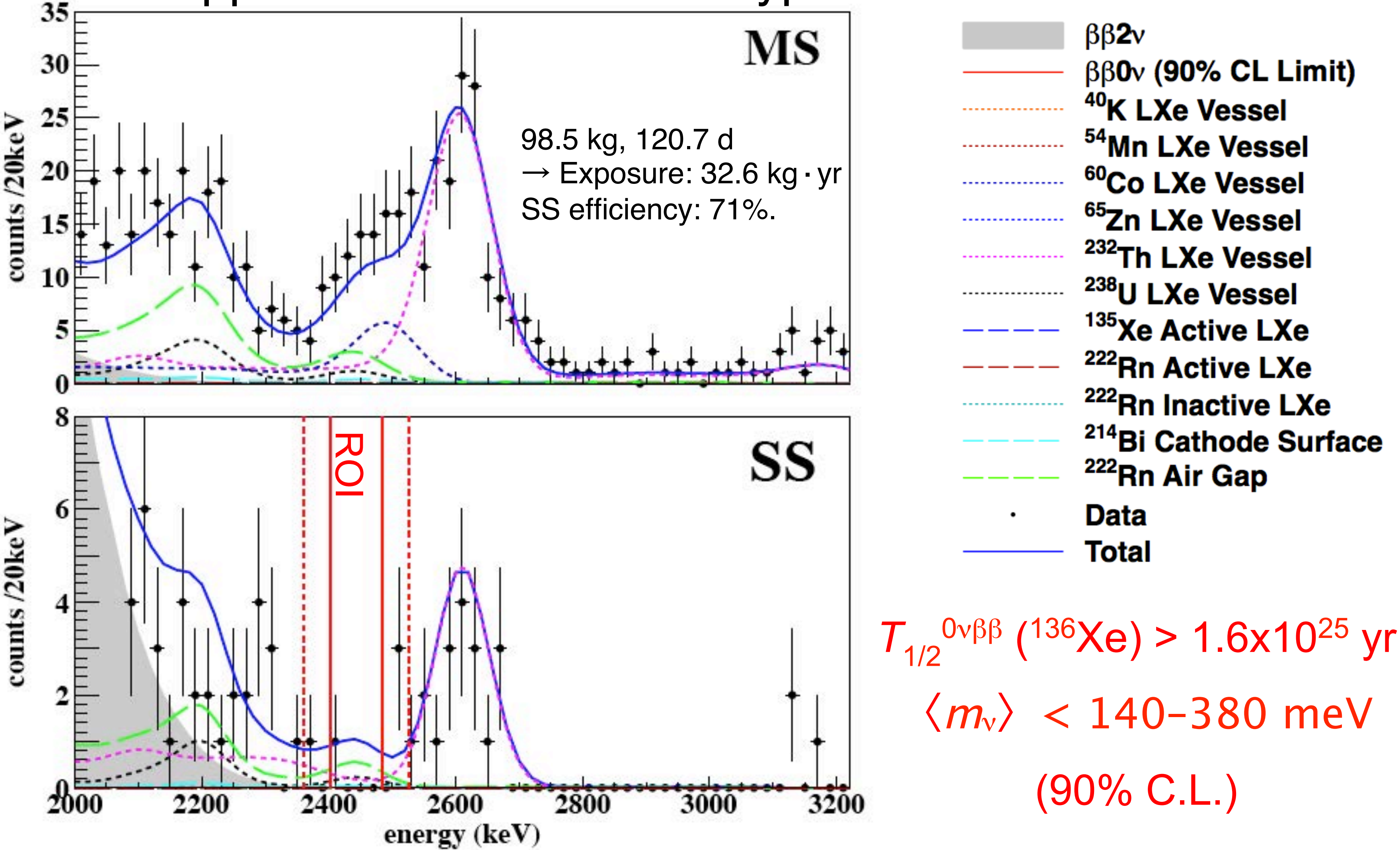
Ionization & Scintillation:
σ(E)/E = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$

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



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%.

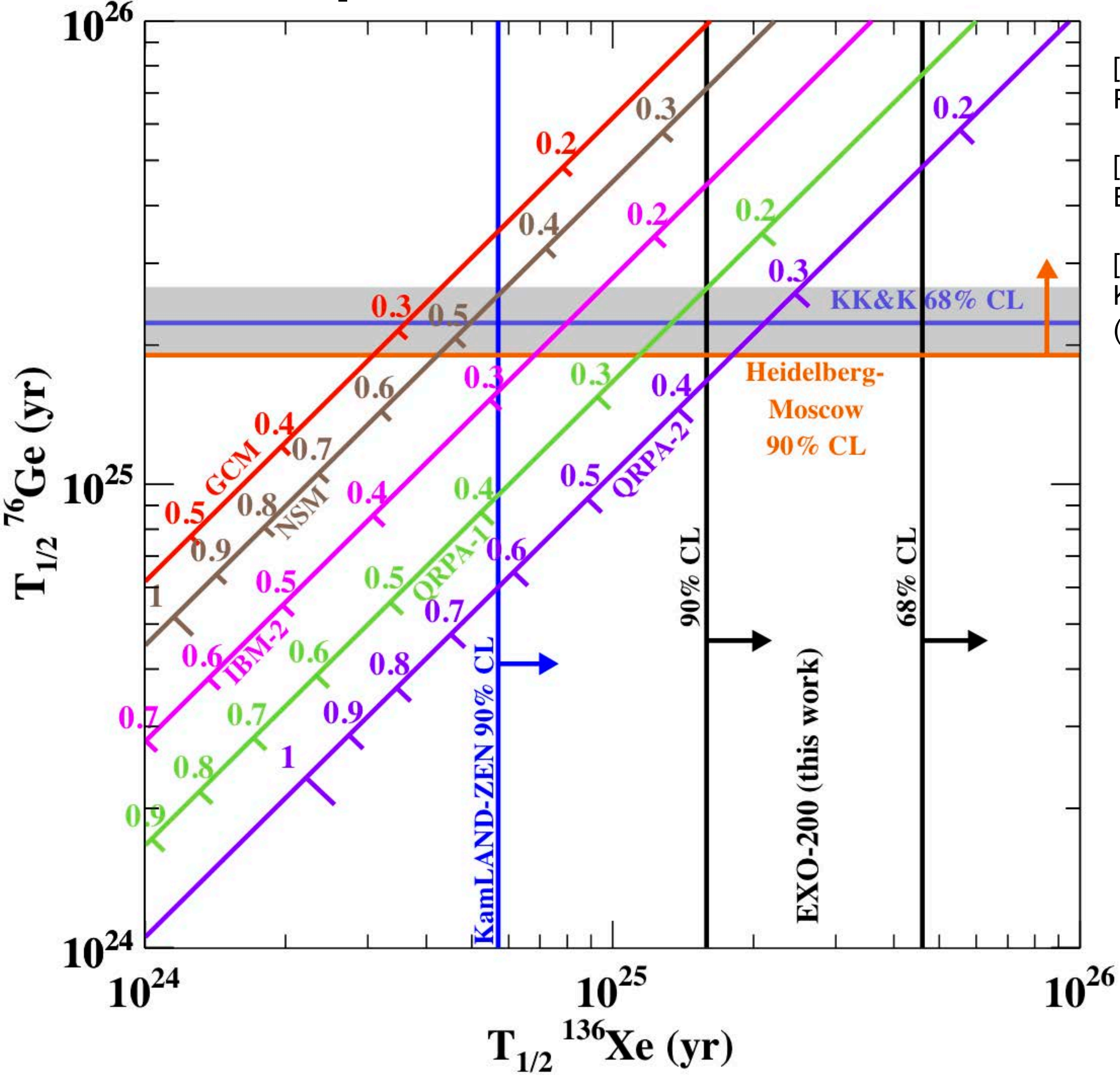
$T_{1/2}^{0\nu\beta\beta}$ (^{136}Xe) > 1.6×10^{25} yr

$\langle m_\nu \rangle$ < 140–380 meV

(90% C.L.)

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

Comparison with existing claim

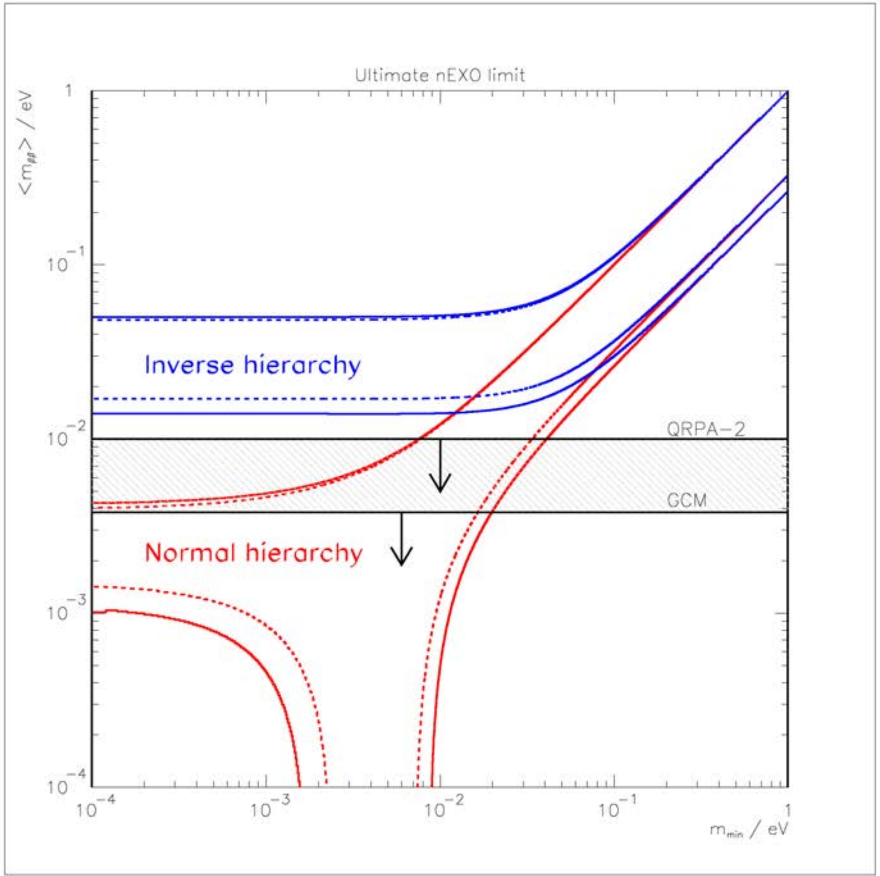


[KamLAND-Zen Collaboration Phys. Rev. C 85 (2012) 045504]

[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]

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.

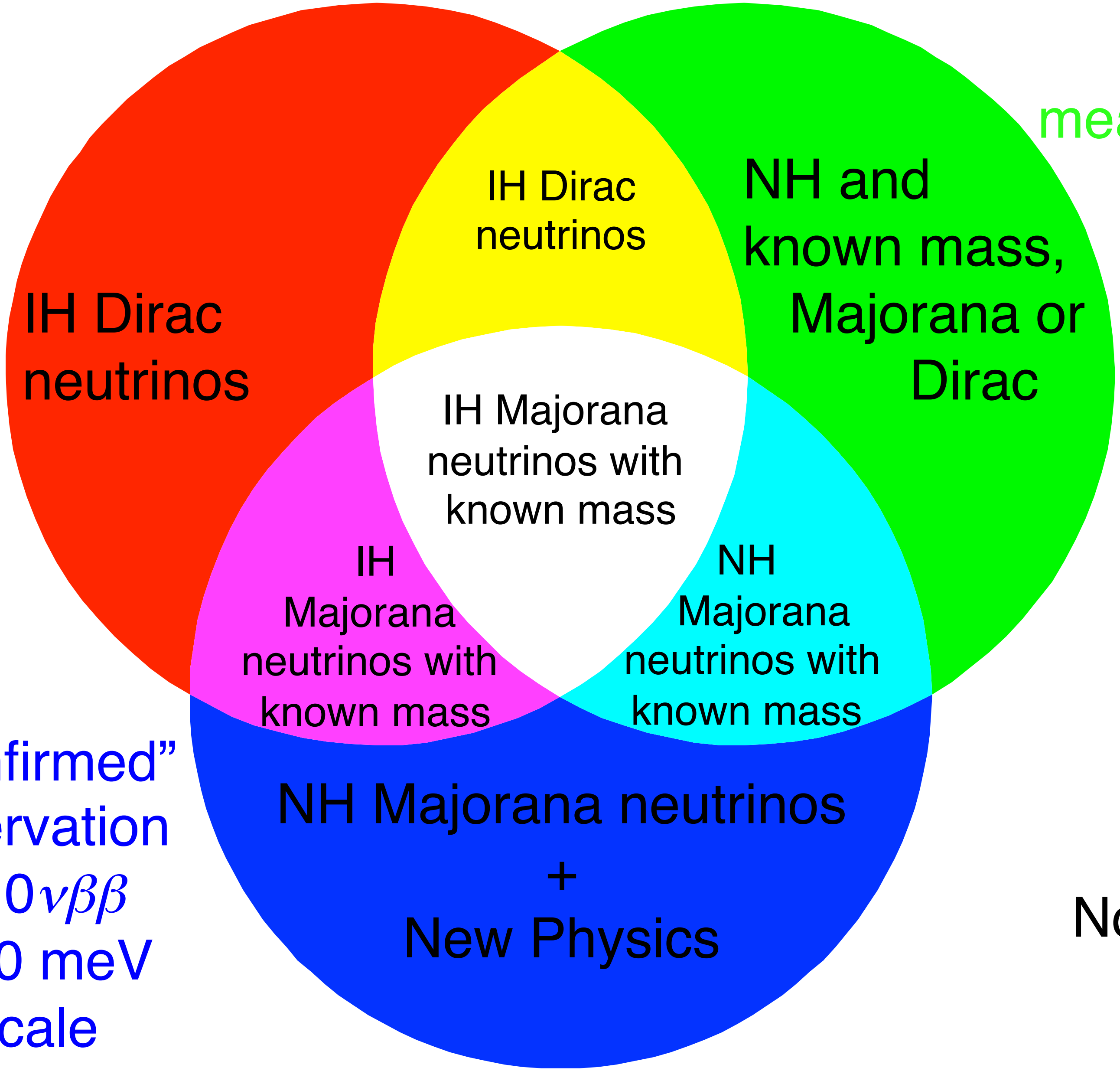
Band	**Fiducial Mass (tonne)**	**Livetime (yr)**	**$T_{1/2}$ sensitivity (yr)**	**Bracketing NMEs (meV)**		**Conditions**
				QRPA-2	**GCM**	
EXO-200 “Ultimate”	**0.1**	**4**	**$5.5 \cdot 10^{25}$**	**200**	**75**	**EXO-200 with Rn removal and new analysis**
Initial nEXO	**4.5**	**10**	**$2.5 \cdot 10^{27}$**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

“Confirmed” observation of $0\nu\beta\beta$ ~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

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??

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

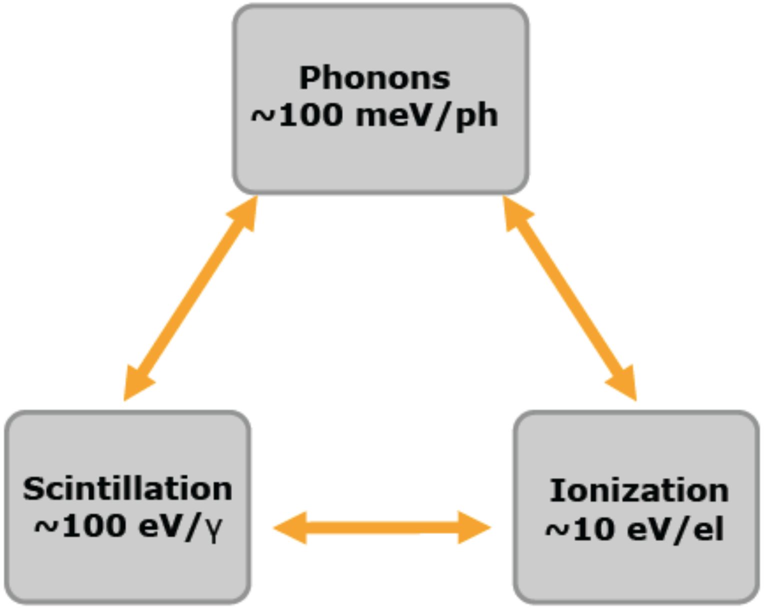
- Basically, the field is still open for new ideas…

What else is out there?

- More EXO? – high pressure gas TPC with Ba^+ tagging (improved energy resolution)
- Quantum dots? - See L. Winslow next!
- LUCIFER? – bolometric experiment + scintillation
- Solid Xe?

Disclaimer:
What I am about to show you is not part of EXO, so please don't hold the rest of my collaborators responsible!

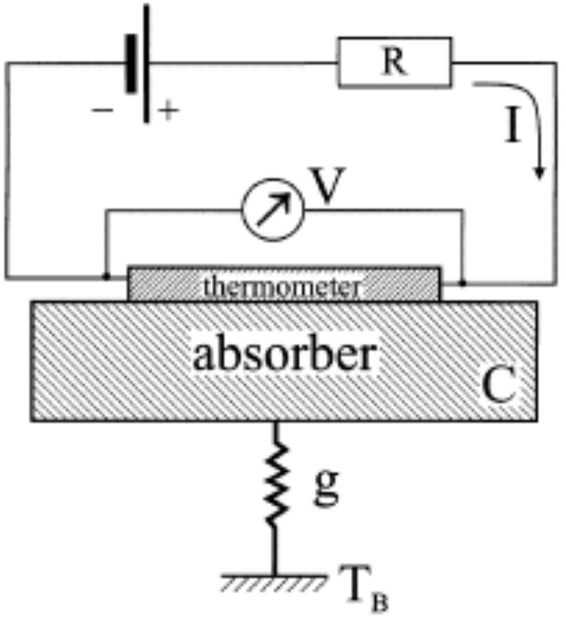
Solid Xe bolometers(+)

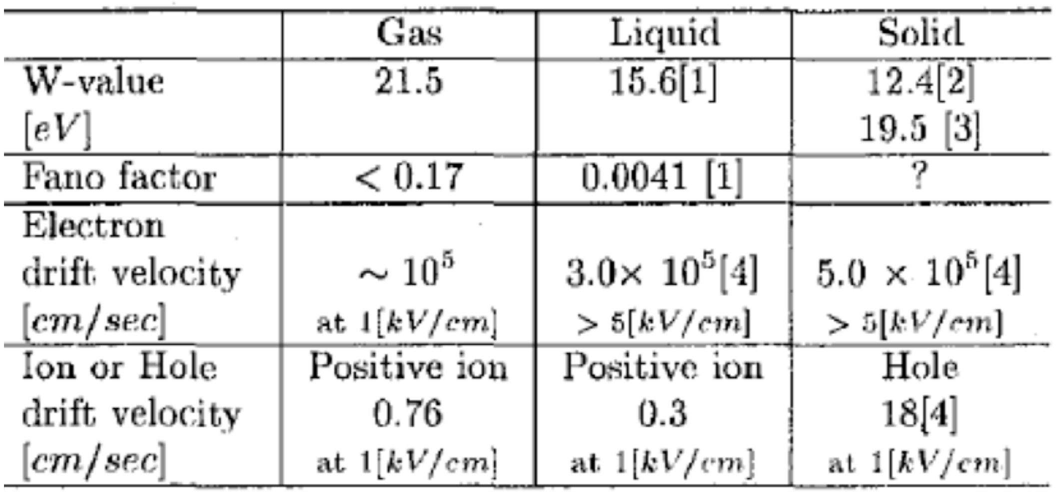


Phonons
~100 meV/ph

Scintillation
~100 eV/γ

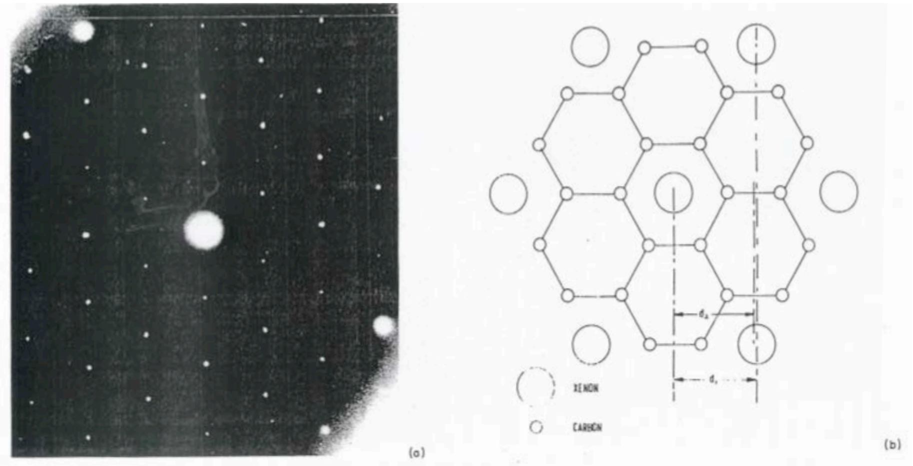
Ionization
~10 eV/el

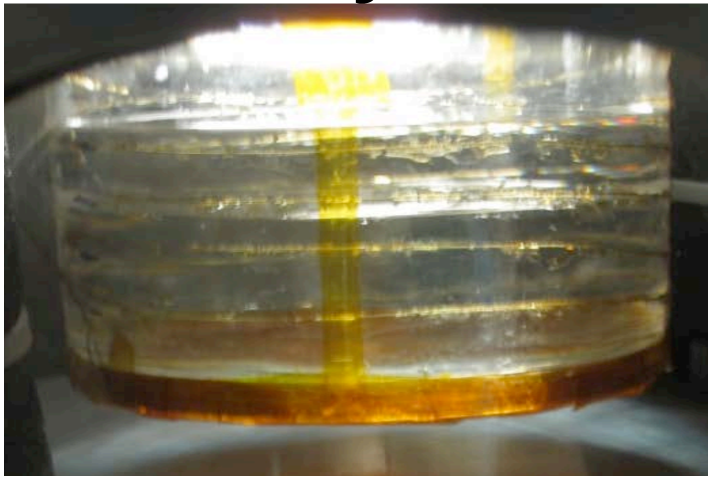




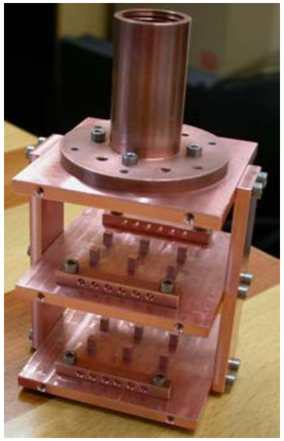
	Gas	Liquid	Solid
W-value $[eV]$	21.5	15.6[1]	12.4[2] 19.5 [3]
Fano factor	< 0.17	0.0041 [1]	?
Electron drift velocity $[cm/sec]$	$\sim 10^5$ at $1[kV/cm]$	3.0×10^5[4] $> 5[kV/cm]$	5.0×10^5[4] $> 5[kV/cm]$
Ion or Hole drift velocity $[cm/sec]$	Positive ion 0.76 at $1[kV/cm]$	Positive ion 0.3 at $1[kV/cm]$	Hole 18[4] at $1[kV/cm]$

Step 1: Grown a Xe crystal





Step 2: Make it a bolometer



Step 3: Instrument other channels?

Conclusions

- Neutrinoless double beta decay is the most practical way to test the Majorana nature of neutrinos.
- The next generation of experiments (including EXO) are poised to test effective Majorana masses down to the ~10 meV scale.
- What comes after that will depend on what they find. We will move on to precision measurements, or we will have to look for new technologies to tackle the remaining normal hierarchy phase space.
- There's still room in double beta decay physics for new ideas!