The Path to Large-Mass Double Beta Decay Experiments

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Phenomenology Basics

Background Issues

Future Program

ββ and the neutrino

- **The ββ(0ν) decay rate is proportional to neutrino mass**
- **Decay only occurs if neutrinos are massive Majorana particles**
  - **Critical for understanding incorporation of mass into standard model**
  - **Violates Lepton number conservation**
    - **Leptogenesis?**
  - **ββ is only practical experimental technique to answer this question**
- **Fundamental nuclear/particle physics process**

What is ββ?

$$n \Rightarrow p + e^- + \bar{\nu}_e \qquad \nu_e + n \Rightarrow p + e^-$$

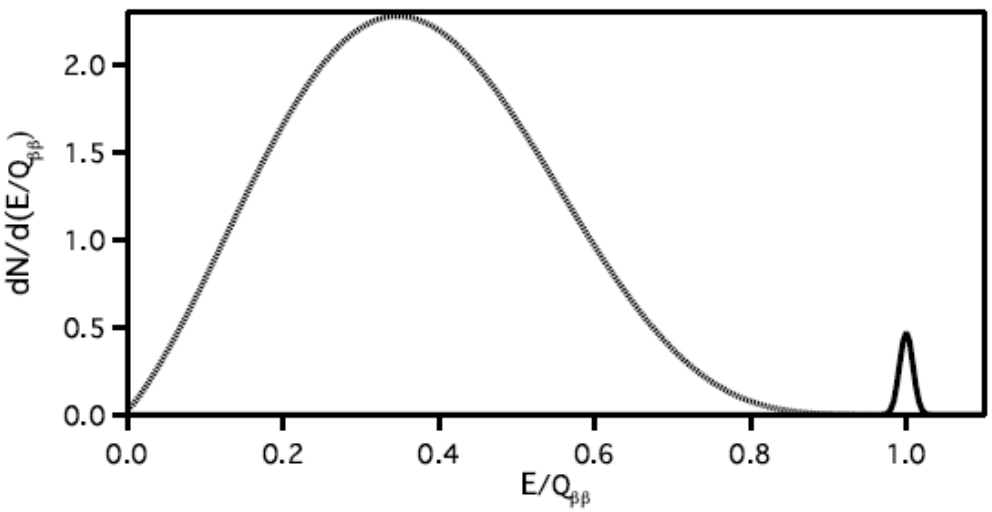


Fig. from arXiv:0708.1033

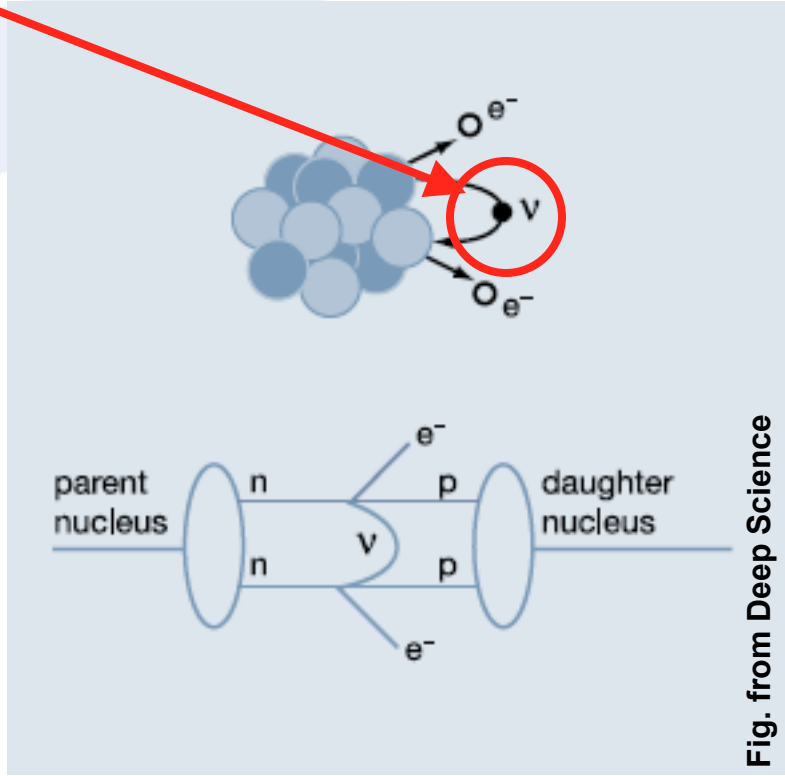


Fig. from Deep Science

ββ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

$$\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_{\beta\beta}^2$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.

The Effective Neutrino Mass

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

virtual ν exchange

Oscillation experiments indicate at least 1 of the m_i > 50 meV.
Sets target for upcoming projects.

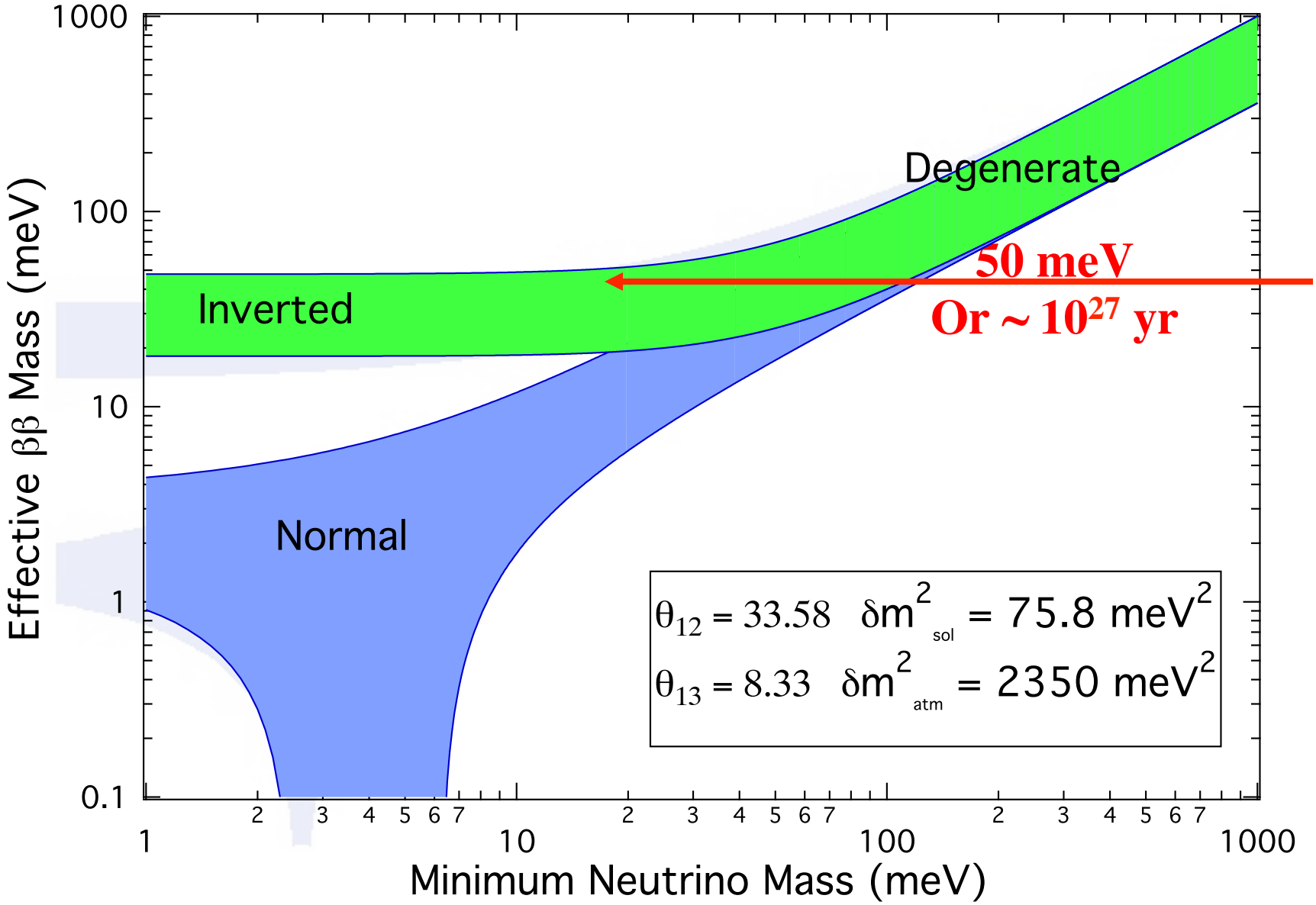
Compare to β decay result:

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

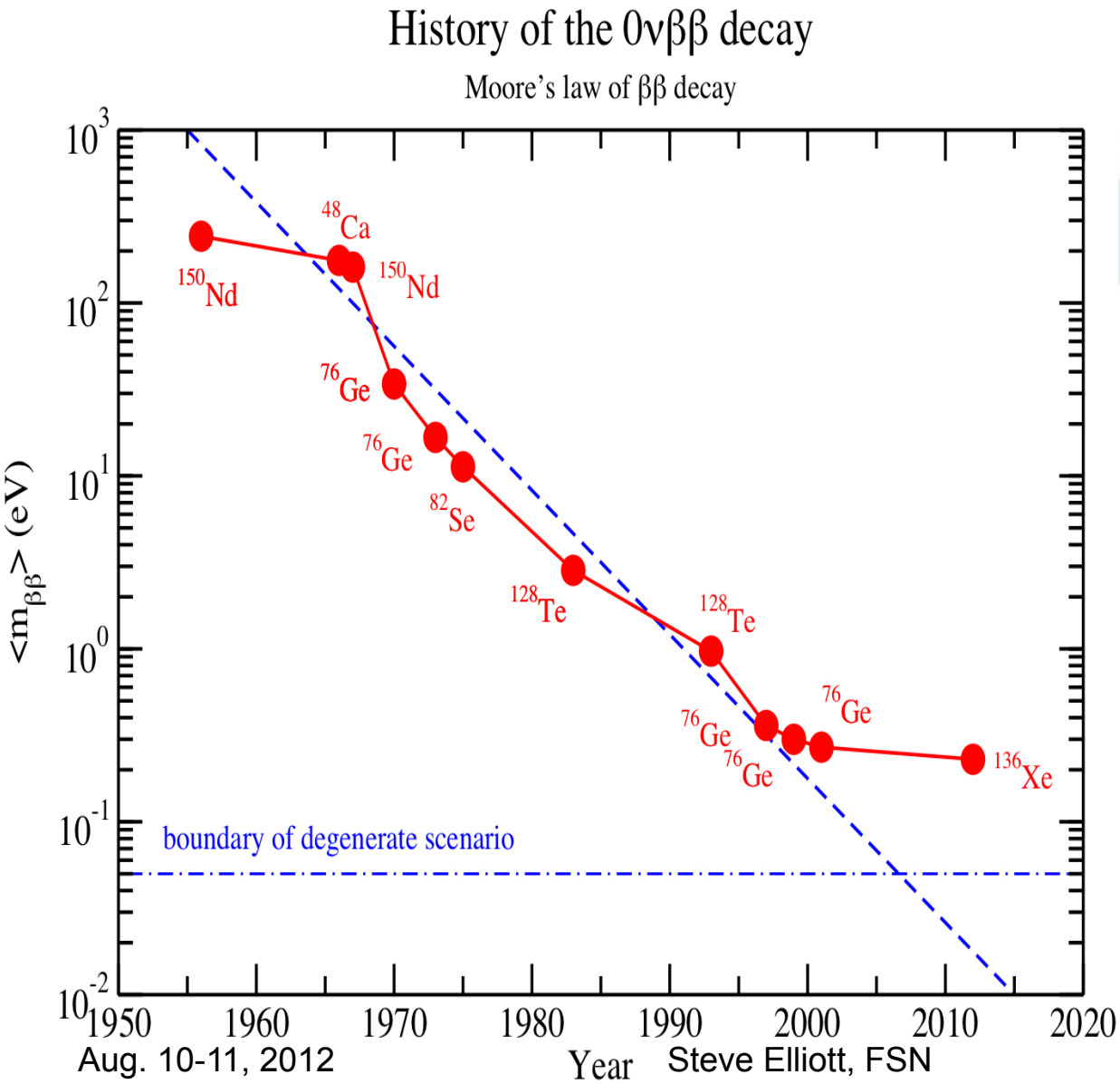
real ν emission

Compare to cosmology:

$$\sum = \sum m_i$$


Effective ββ Mass (meV)
1000
100
10
1
0.1
Minimum Neutrino Mass (meV)
1
10
100
1000
Degenerate
Inverted
Normal
50 meV
Or ~ 10^27 yr
θ12 = 33.58 δm²sol = 75.8 meV²
θ13 = 8.33 δm²atm = 2350 meV²

ββ trends (updated Elliott/Vogel plot by Vogel)



Historically, there are > 100 experimental limits on $T_{1/2}$ of the 0νββ decay. Here are the deduced mass limits using one set of nuclear matrix elements (RQRPA of Simkovic et al. 2009.)

Note the approximate linear slope vs time on such semilog plot.

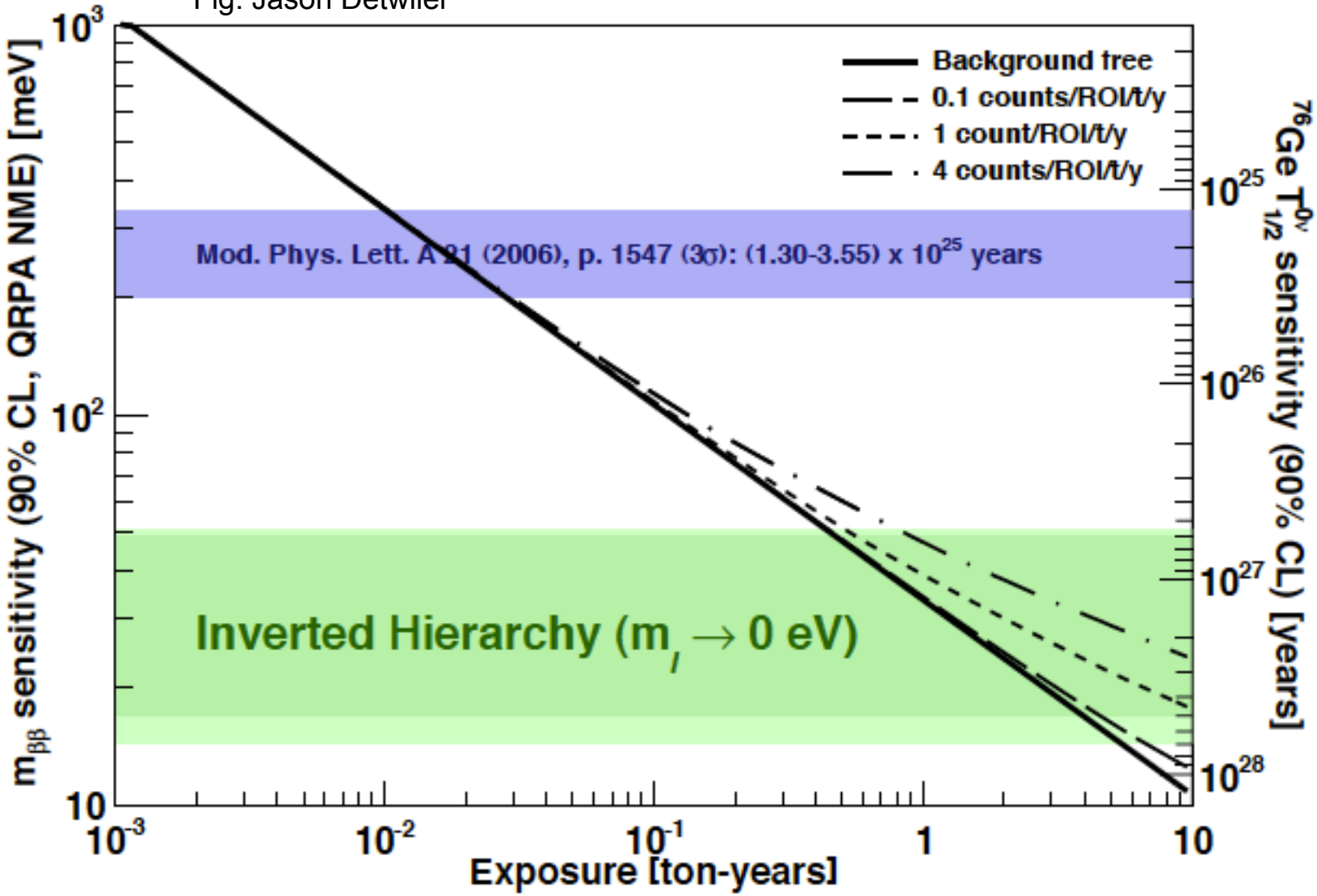
However, during the last decade the Complexity of such experiments has increased dramatically. The slope has changed.

Signal:Background ~ 1:1
Its all about the background

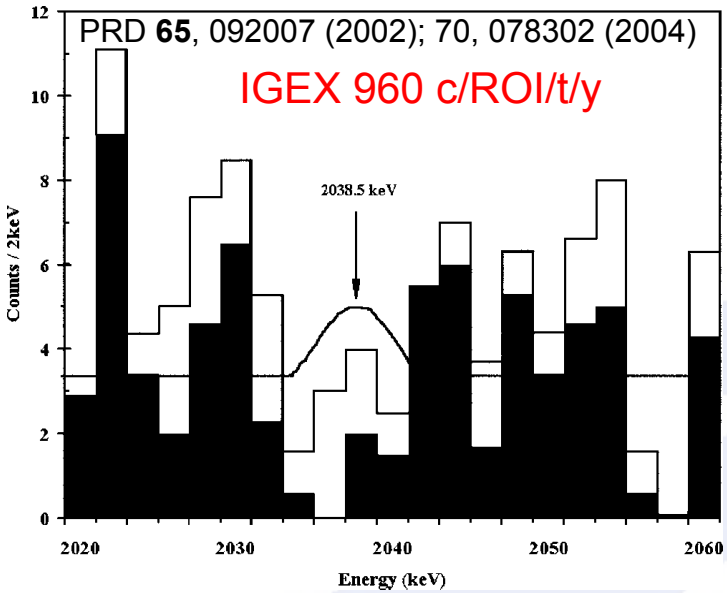
Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
$5x10^{26}$	10	100	
$5x10^{27}$	**To reach atmospheric scale need BG on order 1/t-y.**	40	Atmospheric
$>10^{29}$	<0.05	<10	Solar

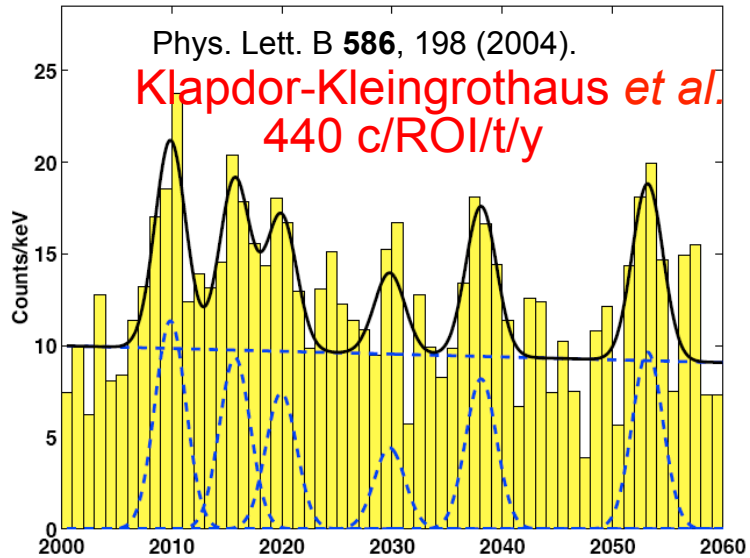
Sensitivity, Background and Exposure

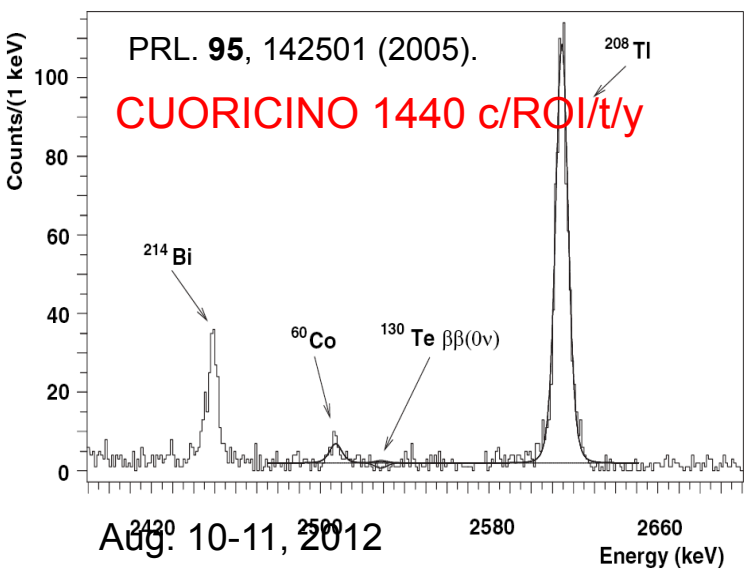
Fig: Jason Detwiler

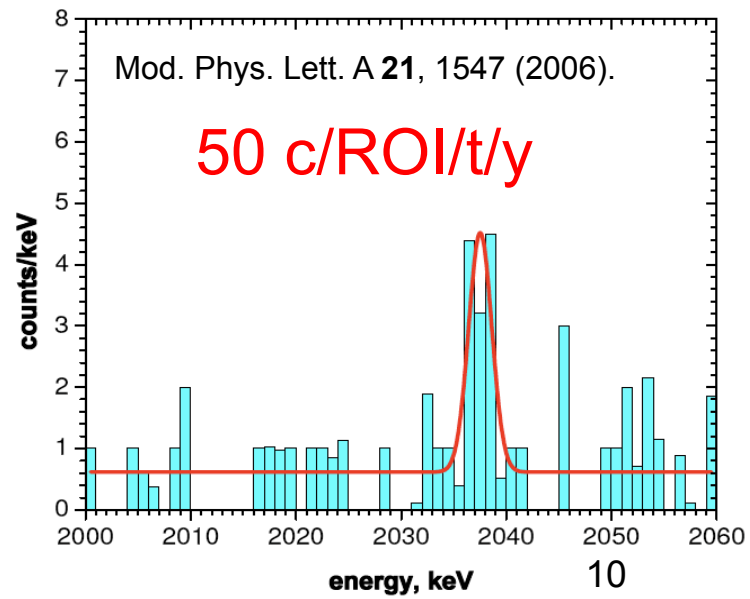


Background in Pre-2007 Experiments

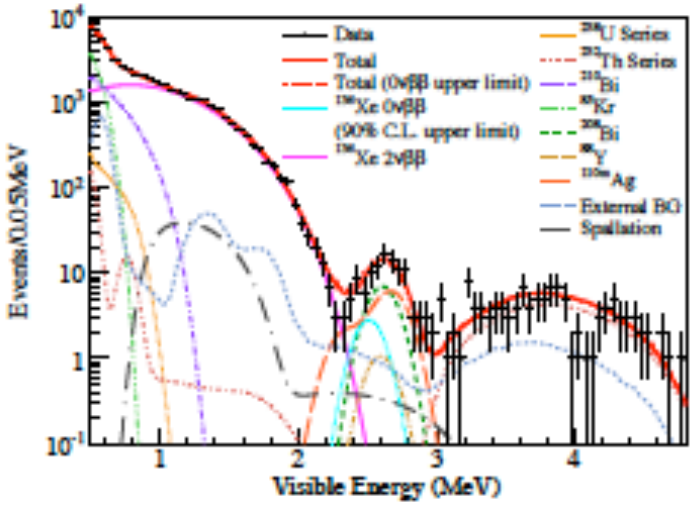




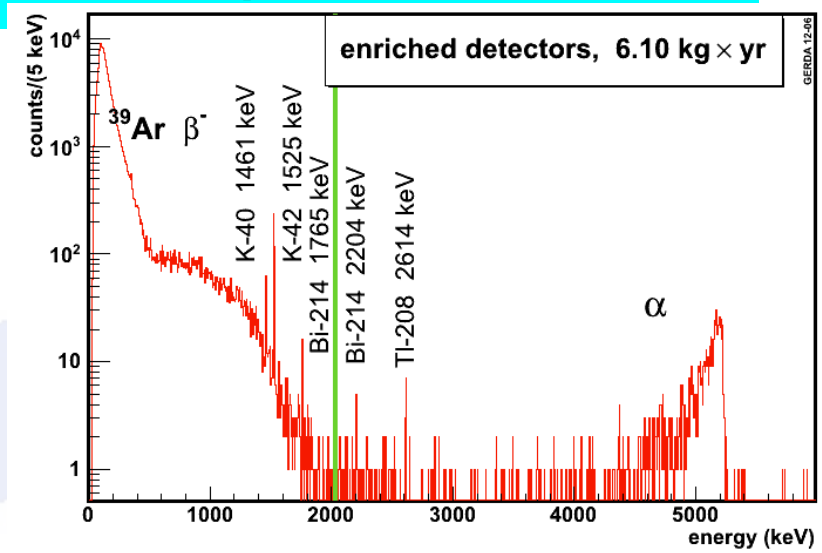




Background in Recent Experiments



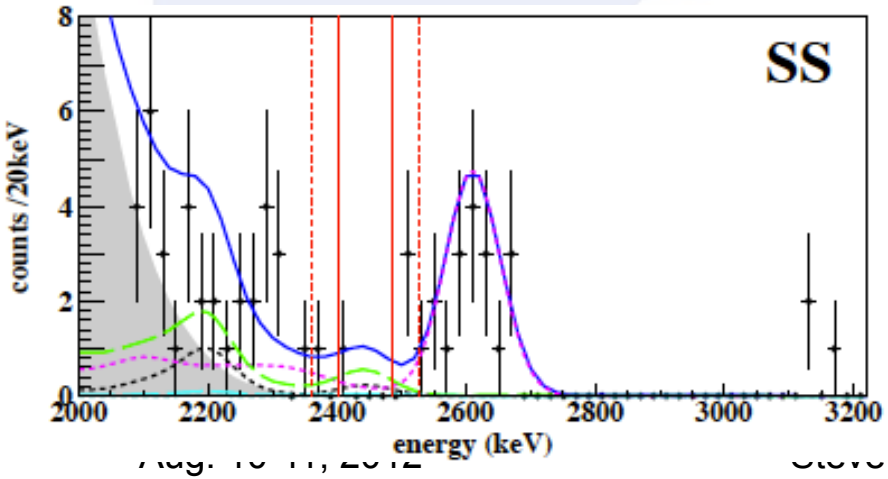
arXiv:1201.4664



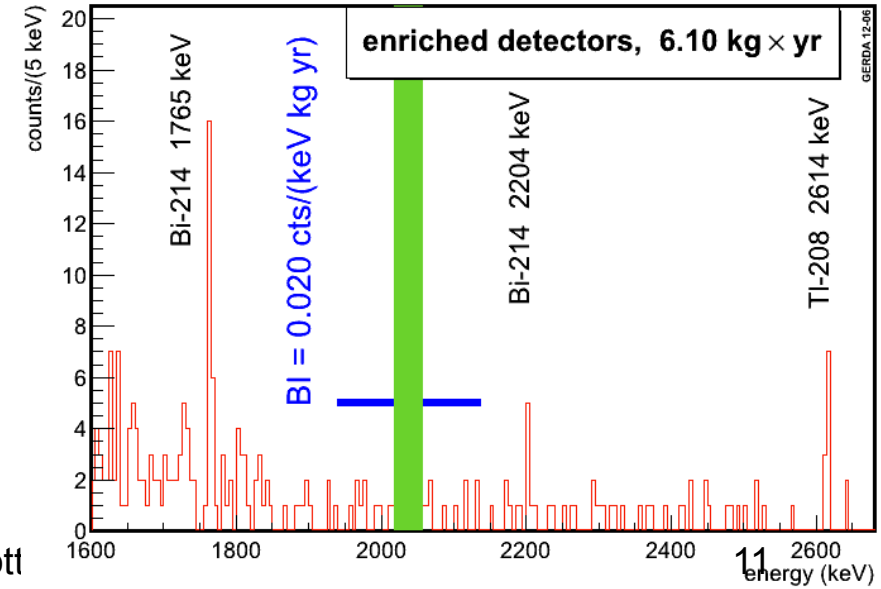
Neutrino 2012

KamLAND-Zen 2000 c/ROI/t(Xe)/y
EXO-200 123 c/ROI/t/y

GERDA – init. enr. 80 c/ROI/t/y



arXiv:1205.5608



Summary

Experiment	Background (cnts/ ROI-t-y)	Width (1 FWHM)
IGEX	960 (400 with PSD)	4 keV ROI
Heid-Moscow	440 (50 with PSD)	4 keV ROI
CUORICINO	1440	8 keV ROI
GERDA	80	4 keV ROI
EXO-200	123	82 keV ROI (1.7% ±1 sig resol.)
KamLAND-Zen	~50(~2000per t(Xe))	Width not explicitly given

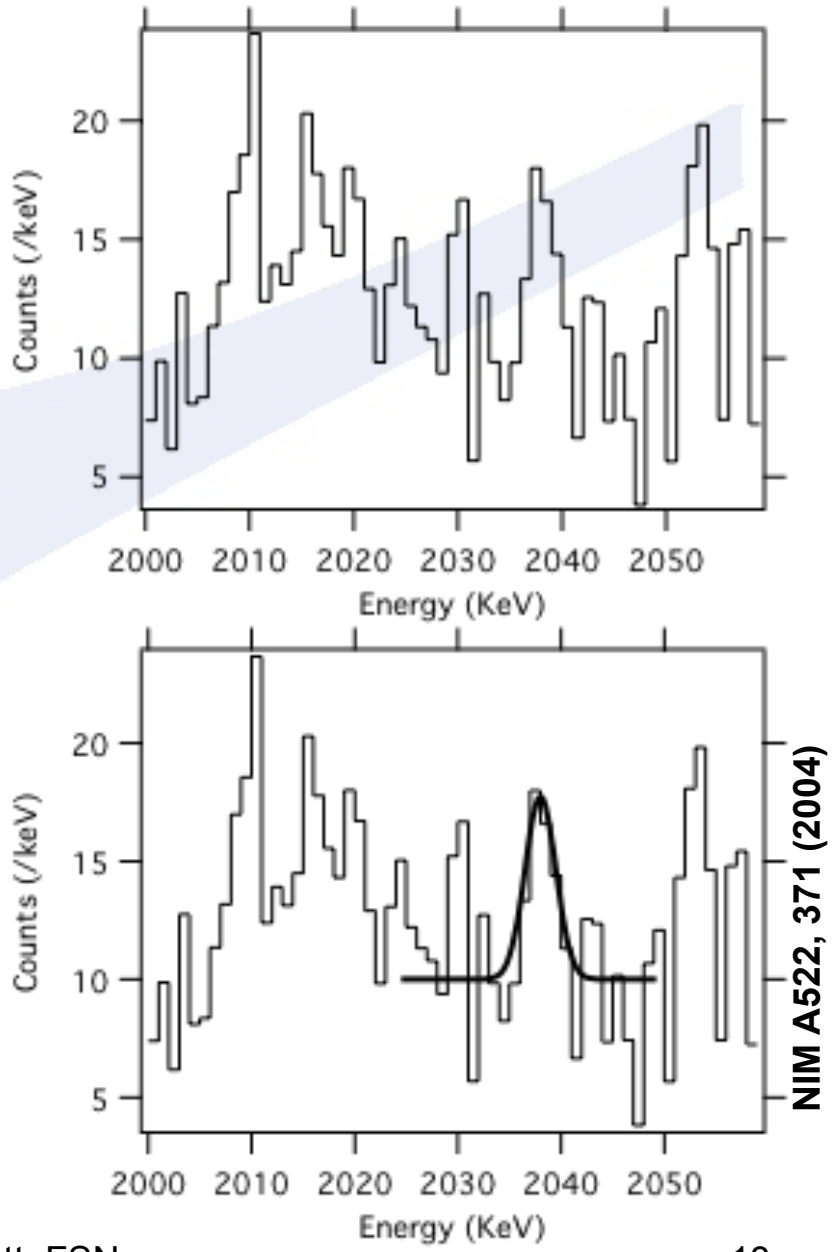
Background is per tonne of material – big difference for KamLAND-Zen

A Claim for ββ
has become a litmus test for future efforts

ββ is the search for a *very* rare peak on a continuum of background.

~70 kg-years of data
13 years

The "feature" at 2039 keV is arguably present.



Future Data Requirements

Why wasn't this claim sufficient to avoid controversy?

- **Low statistics of claimed signal - hard to repeat measurement**
- **Background model uncertainty**
- **Unidentified lines**
- **Insufficient auxiliary handles**

Result needs confirmation or repudiation

Key Past Experimental Limitations

- **Scintillators: Resolution and internal radioactivity**
- **Tracking Detectors: Source mass**
- **Calorimeters: External background**
  - **Most sensitive techniques to date**

Key Ingredients of Next Experiments

- **Isotope mass**
  - **tens to hundreds of kg**
- **Lower background**
  - **factor of 10-100 better**
- **Resolution**
  - **Critical for signal to noise ratio and the search for a rare peak on a background continuum.**

Great Number of Proposed Experiments

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype - 2009	Kamioka
CARVEL	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
COBRA	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORICINO	^{130}Te	11 kg	TeO_2 bolometers	Complete - 2008	Gran Sasso
CUORE	^{130}Te	200 kg	TeO_2 bolometers	Construction - 2012	Gran Sasso
DCBA	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
EXO-200	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Construction - 2009	WIPP
EXO	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	DUSEL
GEM	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive	
GENIUS	^{76}Ge	1 ton	^{enr}Ge det. in liq. nitrogen	Inactive	
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Construction - 2009	Gran Sasso
GSO	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
KamLAND	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Contruction - 2012?	Kamioka
MAJORANA	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2011	SUL
MOON	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
NEXT	^{136}Xe	80 kg	gas TPC	Development	Canfranc
SNO+	^{150}Nd	55 kg	Nd loaded liq. scint.	Construction - 2011	SNOLab
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Frejus
Xe	^{136}Xe	1.56 t	^{enr}Xe in liq. scint.	Development	
XMASS	^{136}Xe	10 ton	liquid Xe	Inactive for $\beta\beta$	Kamioka
HPXe	^{136}Xe	tons	High Pressure Xe gas	Development	

Experiments that will test claim in coming few years.

	Mass	Run Plan
CUORE	~200 kg	2014
EXO-200	~200 kg	2011
GERDA I/II	~34 kg	2011/2013
KamLAND-Zen	~300 kg	2012
MAJORANA	~30 kg	2013
NEXT	~100 kg	2014
SNO+	~60 kg	2013
SuperNEMO Dem.	~7 kg	2013

Good guess that we'll reach about 100 meV in the 2012-2015 time frame.

1-ton projects might be starting by 2020.

Various Levels of Confidence in a Result

- **Preponderance of the evidence: a combination of**
  - **Correct peak energy**
  - **Single-site energy deposit**
  - **Proper detector distributions (spatial, temporal)**
  - **Rate scales with isotope fraction**
- **Beyond a reasonable doubt: include the following**
  - **Observe the two-electron nature of the event**
  - **Measure kinematic dist. (energy sharing, opening angle)**
  - **Observe the daughter**
  - **Observe the excited state decay**
- **Smoking Gun**
  - **See the process in several isotopes**

Need Several Experiments to Fully Deduce Underlying Physics

If $\Gamma^{0\nu}$ is non-zero, ν's are massive Majorana particles, but…

$$\Gamma^{0\nu} = G^{0\nu}\left|M_{0\nu}\eta\right|^2 \quad \text{or} \quad G^{0\nu}\left|M_{0\nu}\right|^2\left\langle m_{\beta\beta}\right\rangle^2$$

- **There are many physics models that lead to Lepton Number Violation (η), |M| can change with the model**
  - **Light neutrino exchange**
  - **Heavy neutrino exchange**
  - **R-parity violating supersymmetry**
  - **RHC**
  - **etc.**

Observation of $\beta\beta(0\nu)$ implies massive Majorana neutrinos, but:

- **Relative rates between isotopes might discern light neutrino exchange and heavy particle exchange as the $\beta\beta$ mechanism.**
- **Relative rates between the ground and excited states might discern light neutrino exchange and right handed current mechanisms.**

Effective comparisons require experimental uncertainties to be small wrt theoretical uncertainties. Correlations between |M| calculations are important.

Deppish/Pas Phys. Rev. Lett. 98, 232501 (2007)
Gehman/Elliott J. Phys. G 34, 667 (2007) [Erratum G35, 029701 (2008)
Fogli/Lisi/Rotunno Phys. Rev. D 80, 015024 (2009)

Input Needed from Auxiliary Measurements

See nucl-ex/0511009

- **Atomic masses (Cd, Te & radiative EC-EC candidates - better Q values)**
- **Precise $\beta\beta(2\nu)$ data; β^-, β^+ data on intermediate-state isotopes - g_{pp}**
- **Charge exchange reactions on parent & daughter (p,n), (n,p), (^{3}He,t), (d,^{2}He), etc. - charge-changing weak currents**
- **Muon capture - all multipoles populated**
- **Pair correlation studies and nucleon configuration studies using transfer reactions on parent & daughter (p,t), (d,p), (p,d), (a,3He), and (3He, a)**
- **Pion double-charge exchange**
- **Neutrino cross sections**
- **Electromagnetic transitions to isobaric analogue states**

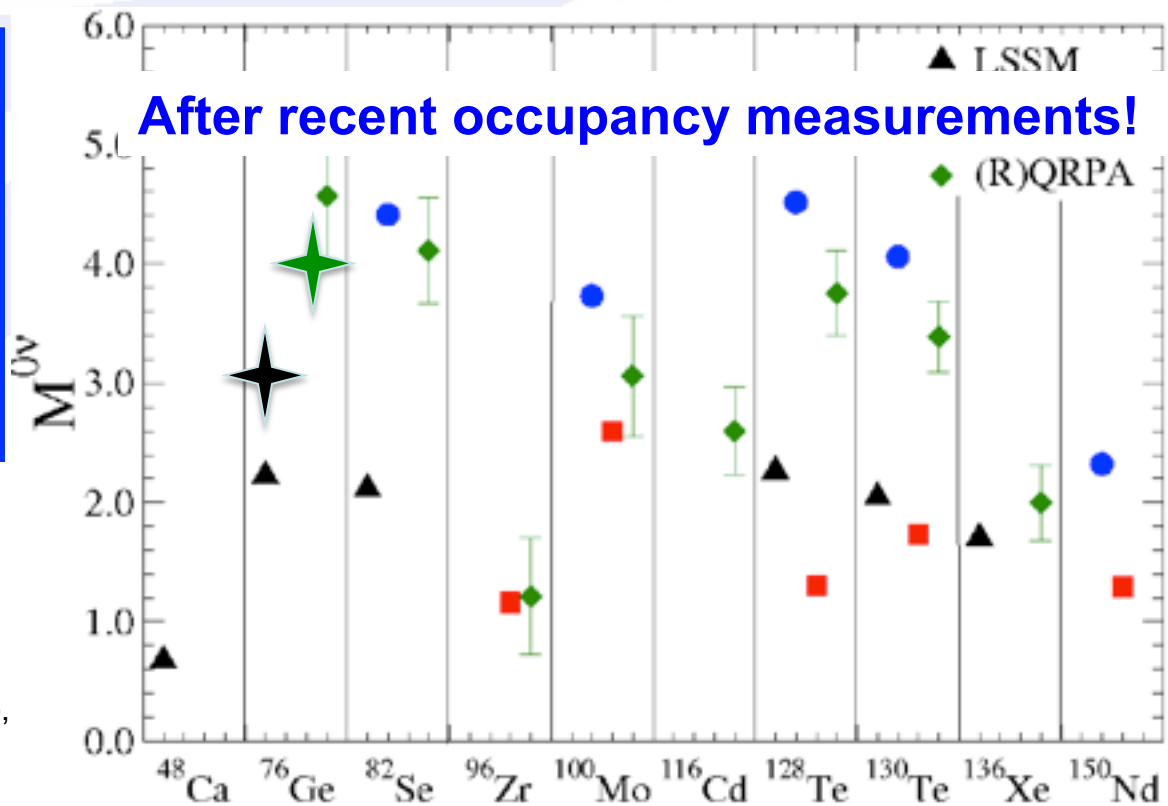
Nuclear Matrix Elements

$$\Gamma_{0\nu} = G_{0\nu} \left| M_{0\nu} \right|^2 m_{\beta\beta}^2$$

NME are calculated using different approximate methods:
Shell Model; Quasi-random phase approximation (QRPA);
Interacting Boson Model; Projected Hartree-Fock-Bogoliubov

Recent progress NSM-QRPA:
2005 within x5
2010 agree within x2

Does agreement between methods provide an estimate of theoretical uncertainty?



Barea and Iachello, PRC 79 (2009), IBM
Menedez, Poves, Caurier, Nowacki NPA 818 (2009), NSM
K. Chaturvedi et al, PRC 78 (2008), PHFB
Rodin, Faesler, Šimkovic, Vogel, NPA 766 (2006), spherical QRPA

Discovery vs. Measurement

a future decision point

Expt. Size: up to 10 kg
Sensitivity: ~1 eV
~10 $\beta\beta(2\nu)$ measurements

Expt. Size: 30-200 kg
Sensitivity: ~100 meV
Quasi-degenerate
~8-10 expts. worldwide

If $\beta\beta$ obs.

Expt. Size: 100-200 kg
Several experiments
Program to measure rate in several isotopes

Expt. Size: ~1T
~3 expts.
Sensitivity: 50 meV
Atmos. scale

If $\beta\beta$ obs.

Expt. Size: few T
>3 experiments
Program to measure rate in several isotopes
Kinematic meas.

Expt. Size: > 10T
~3 expts.
Sens.: 5 meV
Solar scale

1985- Present | 2007-2015 | 2015- 2025 | Future

Questions from the NSAC Subcommittee

1. **What major scientific discoveries have occurred in your research area since the 2007 LRP was drafted?**
   1. **The EXO-200 limit on $0\nu\beta\beta$ in Xe.**
   2. **The KamLAND and EXO-200 measurements of $2\nu\beta\beta$ in Xe.**
   3. **CUORICINO final result**
   4. **Significant progress on matrix elements. New theoretical approaches and input from transfer reaction studies.**
2. **What compelling and unique science is to be done in the next 5 years?**
   1. **Numerous experiments will approach and perhaps surpass the 100 meV scale. At least some should get there. Most collaborations have large US participation.**
   2. **Further experimental and theoretical progress on matrix elements.**
3. **What science would you expect to pursue in the program in 2020 and beyond?**
   1. **Large $\beta\beta$ experiments aimed at covering the inverted hierarchy scale (that is 20 meV) should be pursued.**
4. **What is the international context, and how does it affect your vision?**
   1. **Many projects and R&D programs worldwide are proceeding.**
   2. **US led efforts seem well situated to reach inverted hierarchy scale.**
   3. **There is a shortage of deep underground lab space worldwide.**
   4. **Tonne-scale experiments will require large international collaborations.**

Conclusions

- **The technology is ready for atmospheric scale sensitivity and we can at least discuss it for the solar scale.**
- **Even null results will be interesting.**
- **Supporting measurements are important and have an impact.**
- **Need several measurements with a total uncertainty (experiment & theory) of ~50% or less, and eventually even better.**

If we see ββ, the qualitative physics results are profound, but next we'll want to quantify the underlying physics.