Update on Double Beta Decay Experiments

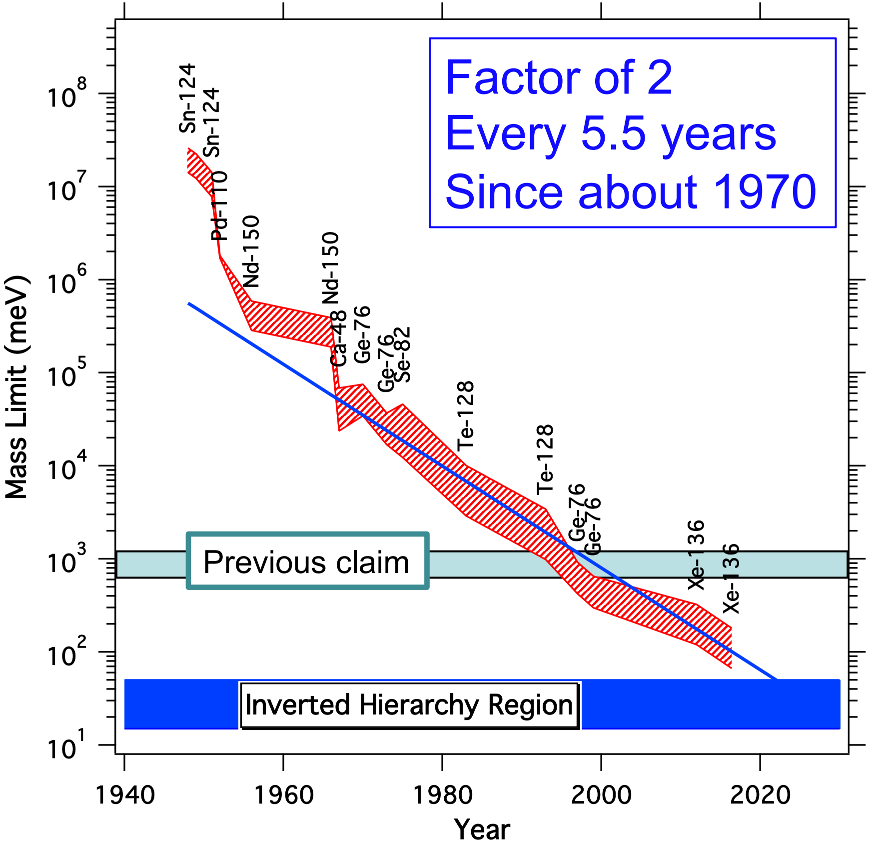
DBD Topical Nuclear Theory Collaboration Spring 2020 Meeting

Los Alamos

Steve Elliott

Physics Goals
Some soap box messaging
Exciting R&D Results
Outlook

ββ History

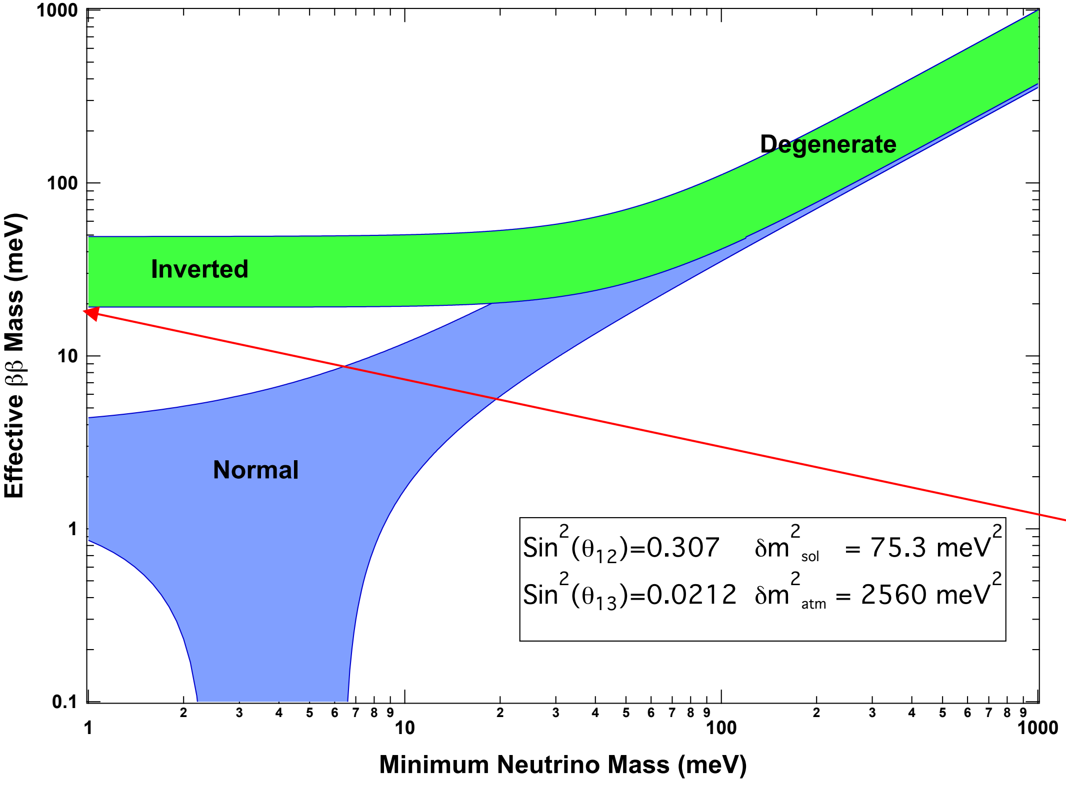


Historically, there are > 100 experimental limits on the $T_{1/2}$ of $0\nu\beta\beta$. Here are the best constraints expressed as limits on $\langle m_{\beta\beta}\rangle$ using a range of nuclear matrix elements. Note the approximate linear slope vs. time on a semi-log plot.

In 2019, Xe and Ge have comparable exclusion levels. Ge is more direct at excluding claim, which is now discredited.

$0\nu\beta\beta$ Sensitivity

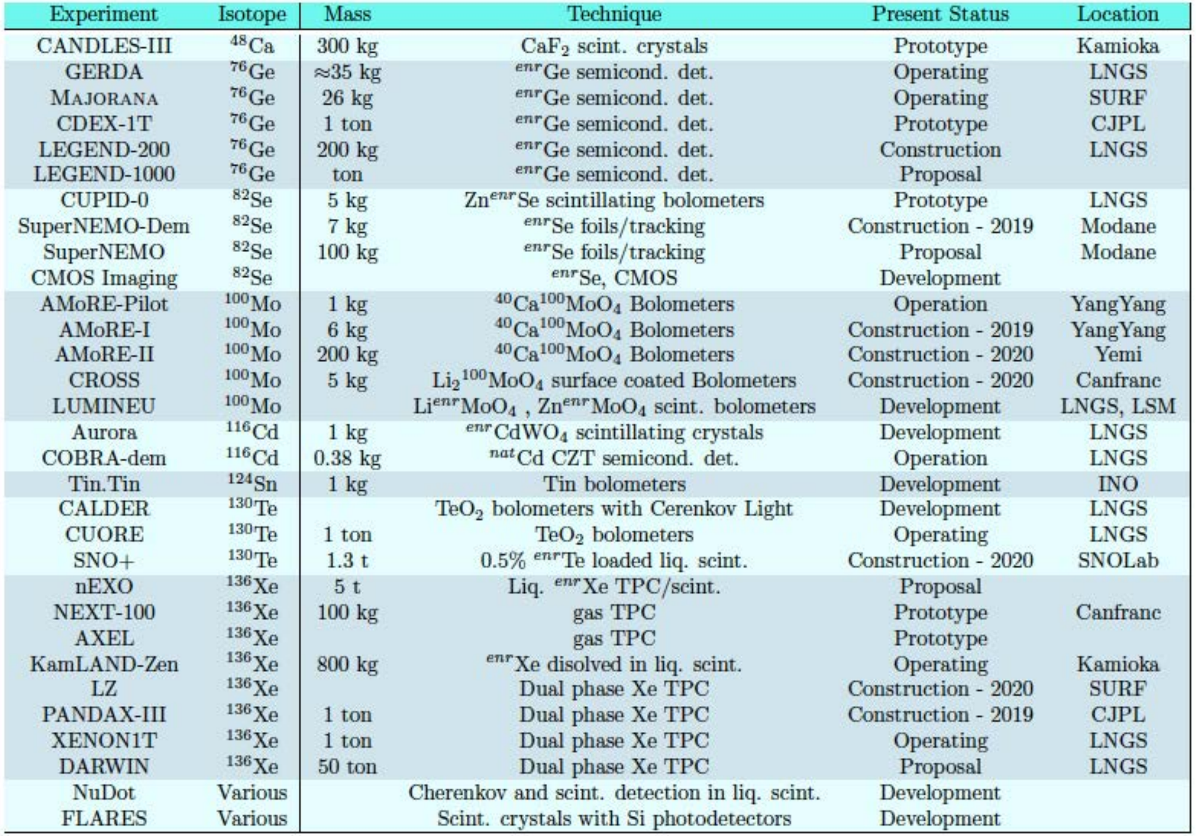
(mixing parameters from PDB-2018, without uncertainties)



Even a null result will constrain the possible mass spectrum possibilities!

A $m_{\beta\beta}$ limit of ~17 meV would exclude Majorana neutrinos in an inverted hierarchy 3-ν model.

Lots of R&D Efforts Based on Many Isotopes



Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III	^{48}Ca	300 kg	CaF$_2$ scint. crystals	Prototype	Kamioka
GERDA	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Operating	LNGS
Majorana	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Operating	SURF
CDEX-1T	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Prototype	CJPL
LEGEND-200	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Construction	LNGS
LEGEND-1000	^{76}Ge	ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0	^{82}Se	5 kg	Zn^{enr}Se scintillating bolometers	Prototype	LNGS
SuperNEMO-Dem	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2019	Modane
SuperNEMO	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal	Modane
CMOS Imaging	^{82}Se		^{enr}Se, CMOS	Development	
AMoRE-Pilot	^{100}Mo	1 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Operation	YangYang
AMoRE-I	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Construction - 2019	YangYang
AMoRE-II	^{100}Mo	200 kg	^{40}Ca^{100}MoO$_4$ Bolometers	Construction - 2020	Yemi
CROSS	^{100}Mo	5 kg	Li$_2$^{100}MoO$_4$ surface coated Bolometers	Construction - 2020	Canfranc
LUMINEU	^{100}Mo		Li^{enr}MoO$_4$, Zn^{enr}MoO$_4$ scint. bolometers	Development	LNGS, LSM
Aurora	^{116}Cd	1 kg	^{enr}CdWO$_4$ scintillating crystals	Development	LNGS
COBRA-dem	^{116}Cd	0.38 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Tin.Tin	^{124}Sn	1 kg	Tin bolometers	Development	INO
CALDER	^{130}Te		TeO$_2$ bolometers with Cerenkov Light	Development	LNGS
CUORE	^{130}Te	1 ton	TeO$_2$ bolometers	Operating	LNGS
SNO+	^{130}Te	1.3 t	0.5% ^{enr}Te loaded liq. scint.	Construction - 2020	SNOLab
nEXO	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100	^{136}Xe	100 kg	gas TPC	Prototype	Canfranc
AXEL	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen	^{136}Xe	800 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
LZ	^{136}Xe		Dual phase Xe TPC	Construction - 2020	SURF
PANDAX-III	^{136}Xe	1 ton	Dual phase Xe TPC	Construction - 2019	CJPL
XENON1T	^{136}Xe	1 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
NuDot	Various		Cherenkov and scint. detection in liq. scint.	Development	
FLARES	Various		Scint. crystals with Si photodetectors	Development	

- **Signal near the inverted ordering scale is about 1/(t yr) or less.**
- **To reach IO scale need background much lower than that.**

Near-Term Upcoming Results – some COVID impacts

	Mass	Status
AMoRE-I	~3 kg	Installation-2019
CUORE	~200 kg	Running
EXO-200	~100 kg	Complete
GERDA I/II	~36 kg	Running
KamLAND-Zen800	~750 kg	Running
MAJORANA	~30 kg	Running
LEGEND-200	~200 kg	Construction-2021
NEXT	~100 kg	Construction-2021
SNO+	~120 kg	Installation-2021
SuperNEMO Dem.	~7 kg	Installation-2020

Experiments are beginning to reach below 100 meV.

ββ technology is ready for detectors at the ton scale. At the ton scale, the IO is a convenient goalpost.

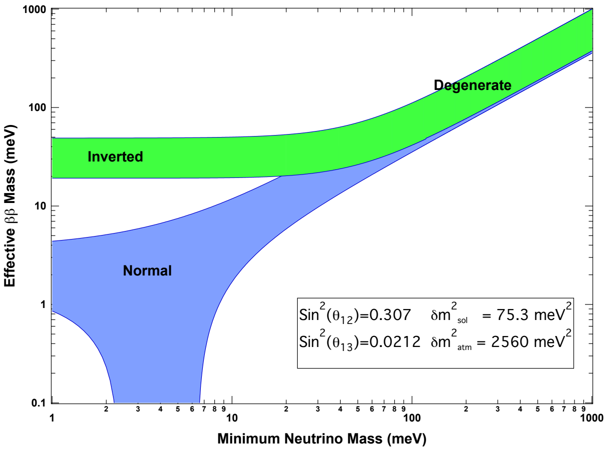
The double-edged sword

Double beta decay can have contributions from a large variety of underlying physics. This is both good and bad news.

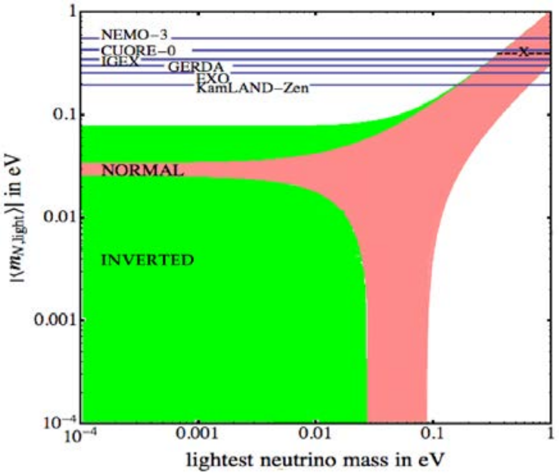
- It enriches the science and makes ββ results complementary to many other BSM studies. ββ has provided constraints on many BSM extensions.

- It makes interpretation open to many caveats.

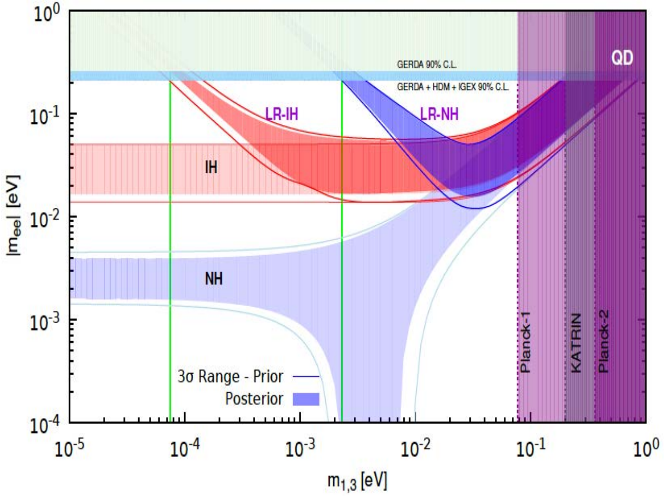
ββ Addresses Key Physics, Regardless of Mass Ordering



3 neutrino paradigm



Light sterile neutrino contribution
An example: PRD92, 093001 (2015)
Many papers on this topic.



Left-Right symm., Type II contributions
From J. HEP 10, 077 (2015)
Also many papers on this topic.

If ββ is seen, the qualitative conclusions are profound, but observations in several nuclei will be required to fully understand the underlying physics.

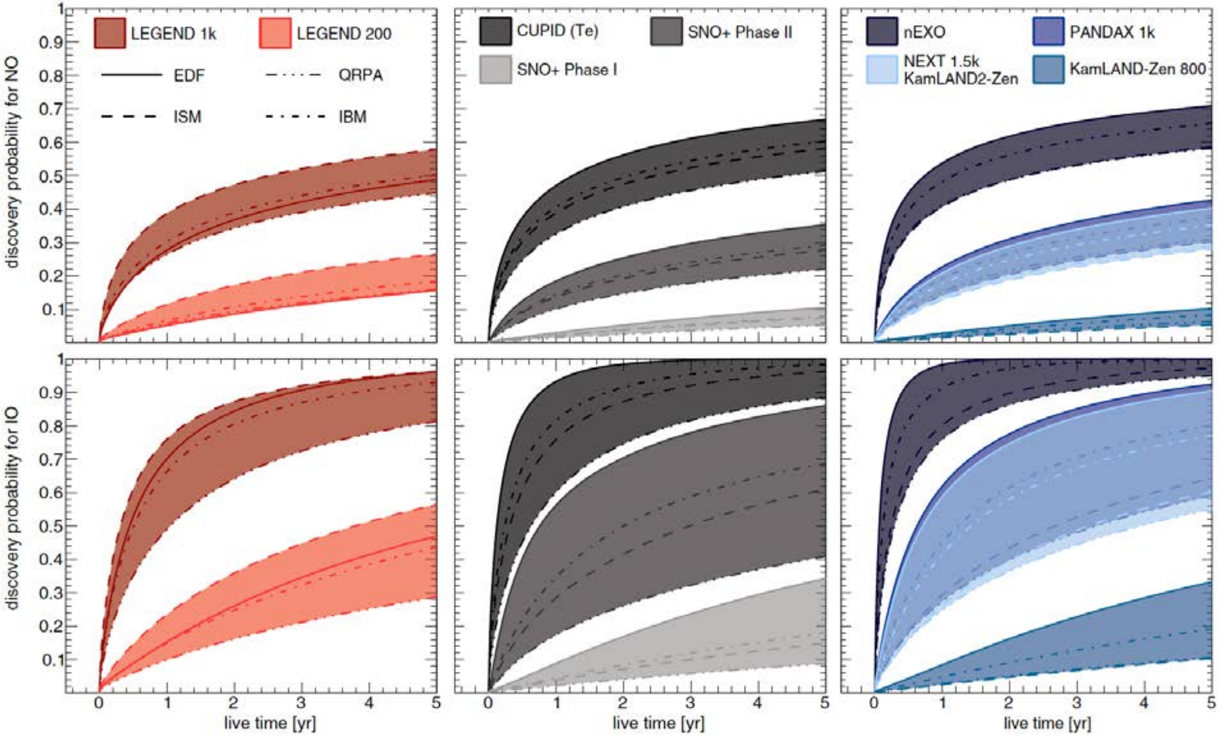
Complementarity of ββ and Cosmology

- The ΛCDM model has become a ‘standard model’ for cosmology. Within the next decade, observations will have sensitivity to neutrino mass below the IO boundary. However, ΛCDM has components that are not fully understood.
  - What mechanism leads to inflation?
  - What components comprise the dark matter?
  - What is dark energy?
- As a standard model with significant unknowns, ΛCDM must be well tested.
- Neutrino mass is one parameter of ΛCDM that can be measured in the laboratory and hence provides a crucial test of ΛCDM.
- ββ and direct neutrino mass experiments must be pursued as a component of cosmology.
- Additionally, cosmology measurements do not test lepton number violation or the Majorana/Dirac character of neutrinos.

ββ discovery potential high, even for NO

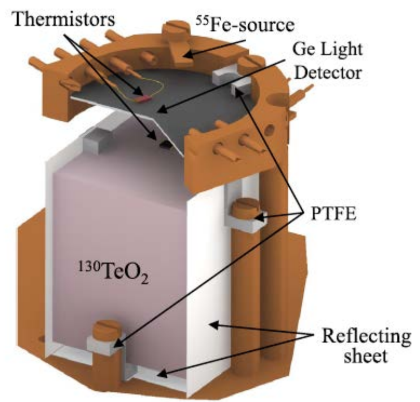
Even for the case of normal ordering of neutrino masses in a 3-ν paradigm, the discovery potential is high because the phases and lightest neutrino mass value have no a priori preferred values.

This qualitative conclusion is not changed due to cosmological constraints or if g_A quenching is included.



Example analysis from PRD 96, 053001 (2017)

Recent R&D Successes
Crystal Calorimetry



Reduced surface sensitivity with Bolometry

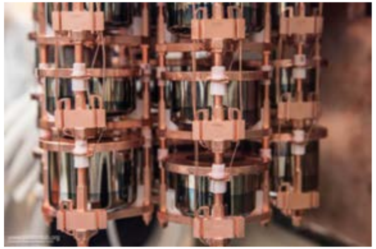
- Bolometers have no dead layer, no natural immunity against surface background. Success reducing this background
- AMoRE, scintillation, Eur Phys J C 79 (2019) 791
- CUPID, scintillation, PRL 123 (2019) 032501
- LUMINEU, scintillation, Eur Phys J C77 (2017) 785
- CROSS, superconductive Al coating and PSD, JHEP 2020 (2020) 18

Large point-contact Ge detectors

- MAJORANA, PRL 120 (2018) 132502, PRC 100 (2019) 025501
- GERDA, PRL 120 (2018) 132503
- Good multiple site rejection/resolution, 2 kg and getting larger
- Inverted semi-coax, NIM A665, (2011) 25, NIM A891 (2018) 106

Ge detector operation in LAr and with LAr veto

- GERDA, Eur Phys J 78 (2018) 388
- Avoids high Z shielding
- Reduces background from detector mounting material



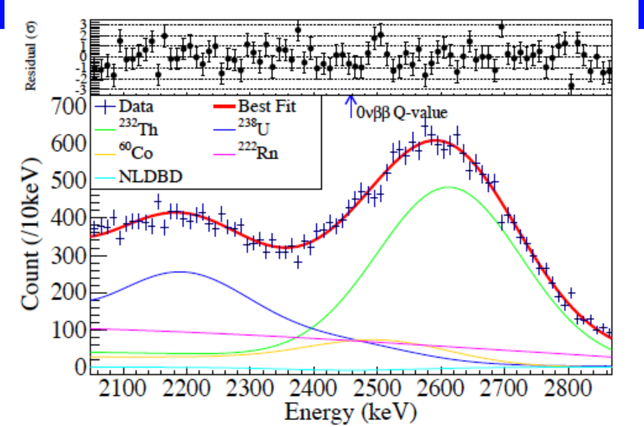
Recent R&D Successes For Ton-Scale

Source-Loaded Scintillator

- KamLAND-Zen, Xe
  - Isotope Segregation - Clean transparent balloon: KamLAND-Zen
  - PRL 117 (2016) 082503
  - Reduces fiducialization or using isotope as side-band analysis
  - Permits use of very pure scintillator as shield/veto
  - KamLAND-Zen 800 now in operation (745 kg Xe)

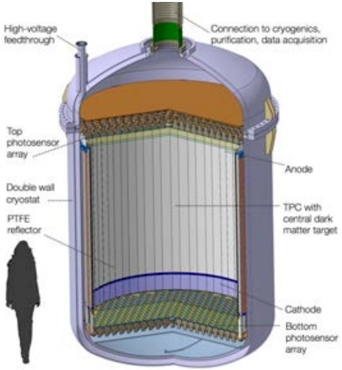
- SNO+, Te
  - Metal loading with good transparency
  - arXiv:1904.01418
  - Scintillator cocktail, Linear alkyl benzene (LAB) + 2,5-diphenyloxazole (PPO)
  - Organo-metallic compound from telluric acid and butanediol
  - High fractions of isotope
  - 0.5% loading leads to over a ton of isotope

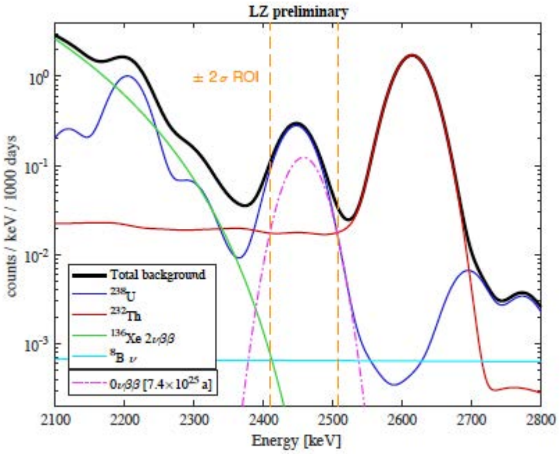
Recent R&D Successes For Ton-Scale



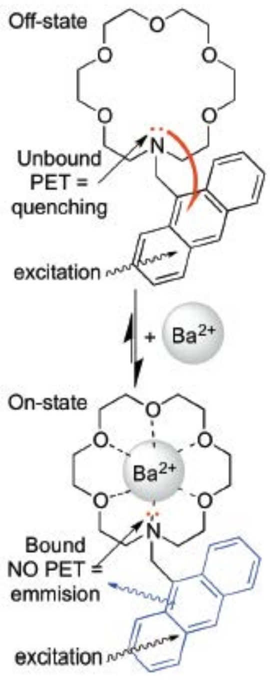
Dual Phase TPCs for Dark Matter

- Large detectors planned to come on line in next few years.
- Natural Xe, but many tons of it.
- PANDAX-II, first limit on $0\nu\beta\beta$ from dual phase detector.
  - Chin. Phys. C 11 (2019) 113001, (arXiv:1906.11457), 219 kg
  - presently small exposure, poor energy resolution, ROI 200 keV wide.
  - high background index ~ 400 cnts/(10 keV 242 kg yr) = 0.17/(keV kg yr).
- LZ, 7 tons
  - https://zenodo.org/record/1300887#.XRzrVy2ZO94
  - arXiv:1509.02910
  - Under construction
- XENON-1T, DARWIN
  - JCAP11 (2016) 017
  - arXiv:2003.13407
  - Very large detector, 40 tons
  - Already observed 2νECEC
  - Better energy resolution





Recent R&D Successes
Daughter Detection

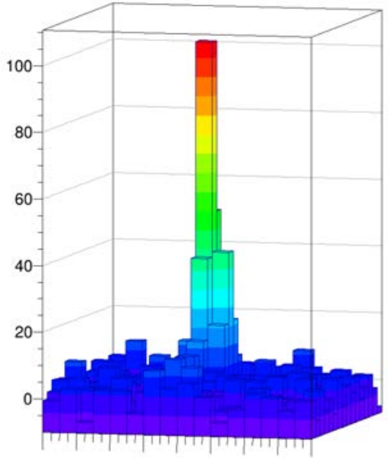


High Pressure Xe Gas TPCs

- NEXT, arXiv:1906.01743
  - – Daughter Ba identification with chemosensor molecules
    - arXiv:1904.05901

Liquid Xe TPCs

- – nEXO, PRC 97 (2018) 065503, PRL 123 (2019) 161802
- – Good energy resolution in LXe, PRL 109 (2012) 032505
- – Detection of Ba in solid Xe, Nature 569 (2019) 203

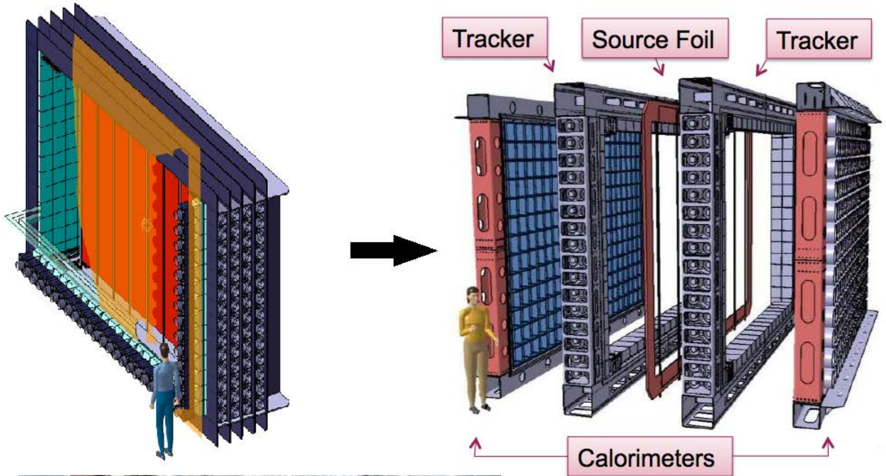


Exciting progress toward detecting the daughter, but there is still a ways to go. Technique could remove all background except that due to $2\nu\beta\beta$ and neutrino CC scattering.

R&D Concepts for Advanced Projects

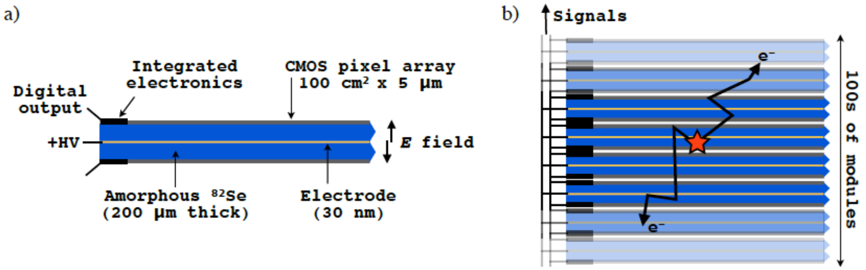
Longer term development and more speculative

- Tracking – will be important if ββ is observed.
  - NEMO has provided best 2νββ opening angle and lone electron spectra to date. PRD 92 (2015) 072011
  - NEMO3 is still providing ββ information
    - Eur Phys. J. C78 (2018) 821, Eur. Phys. J C79 (2019) 440
  - Can establish that event is two electrons
  - SuperNEMO, arXiv:1704.06670
  - Energy resolution improving with R&D (~8%/√E)
    - NIM A868 (2017) 98
  - But the requirement for a thin source to minimize scattering still limits mass
  - SuperNEMO Demonstrator is in final stages of commissioning and should be running this year



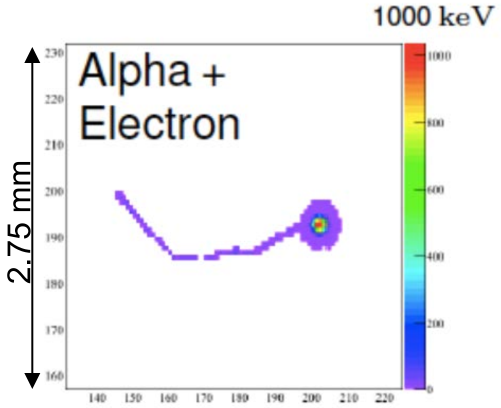
R&D Concepts for Advanced Projects

Longer term development and more speculative



Tracking in high density detectors

- Might address the disadvantage of thin sources required for tracking experiments
- Electron scattering is significant
- Xe TPCs have possibility to provide tracks
- CMOS imaging, JINST 12 P03022
  - pixel array sandwich with thin source
  - hence doesn't solve source-scattering problem
- CZT: COBRE, PRC 94 (2016) 024603
  - nice tracks but requires a lot of readout infrastructure

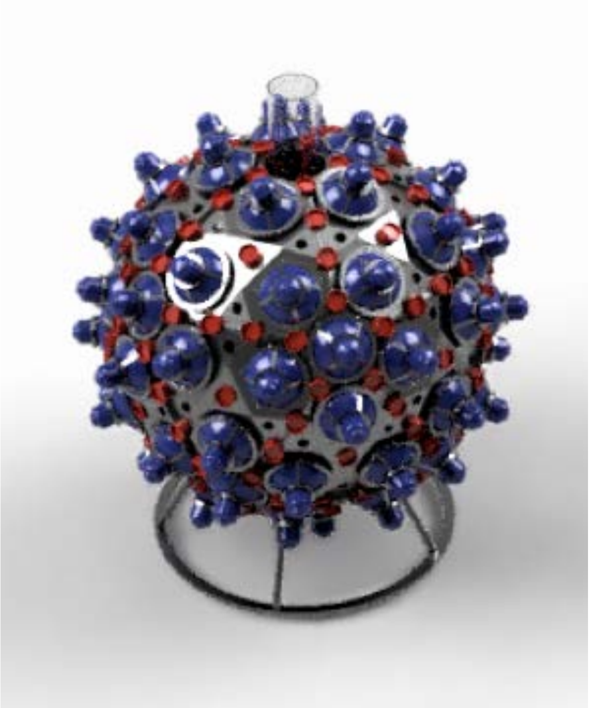


Solid state tracking detectors are still small and require a lot of electronics and cables

R&D Concepts for Advanced Projects

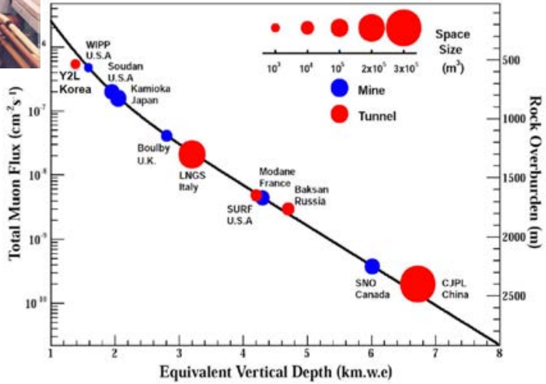
Longer term development and more speculative

- Quantum Dots, JINST 7 (2012) P07010
  - –Technique for loading a lot of isotope and fine-tuning the optical emission parameters
  - –Absorption and emission spectra can be ‘engineered’ by the size of the QD (few nm)
  - –Including Cherenkov light with scintillation, now observed in FlatDot. JINST 14 (2019) P02005
    - Can reduce directional solar-neutrino elastic-scatter background in liquid scintillator targets
  - –NuDot, presently under construction for above-ground testing, will test ββ application



Common Development Challenges for all Experiments

- Isotope enrichment
  - – Limited number of production facilities (2)
  - – Cost, typically in the range $10-60/g
  - – Quantity of required natural isotope
    - In some cases it approaches world yearly production
- Underground facilities
  - – Depth requirement
    - Muon-induced in-situ backgrounds, e.g. C-10, Ar-42, Ge-77, Xe-137, etc.
  - – Collaboration building and need to work in “home” lab
  - – Radon control
- Radio-assay capability
  - – Sensitivity requirements are becoming stricter
  - – Limited throughput
  - – Most sensitive techniques are pricey (~$1k/sample)



Discovery Sensitivity

Spread in $M_{0\nu}$ a large uncertainty.

Xe experiments are proposing large exposure.

Crystal experiments are proposing good energy resolution.

Ge detectors are very competitive even with small exposure because of resolution and background.

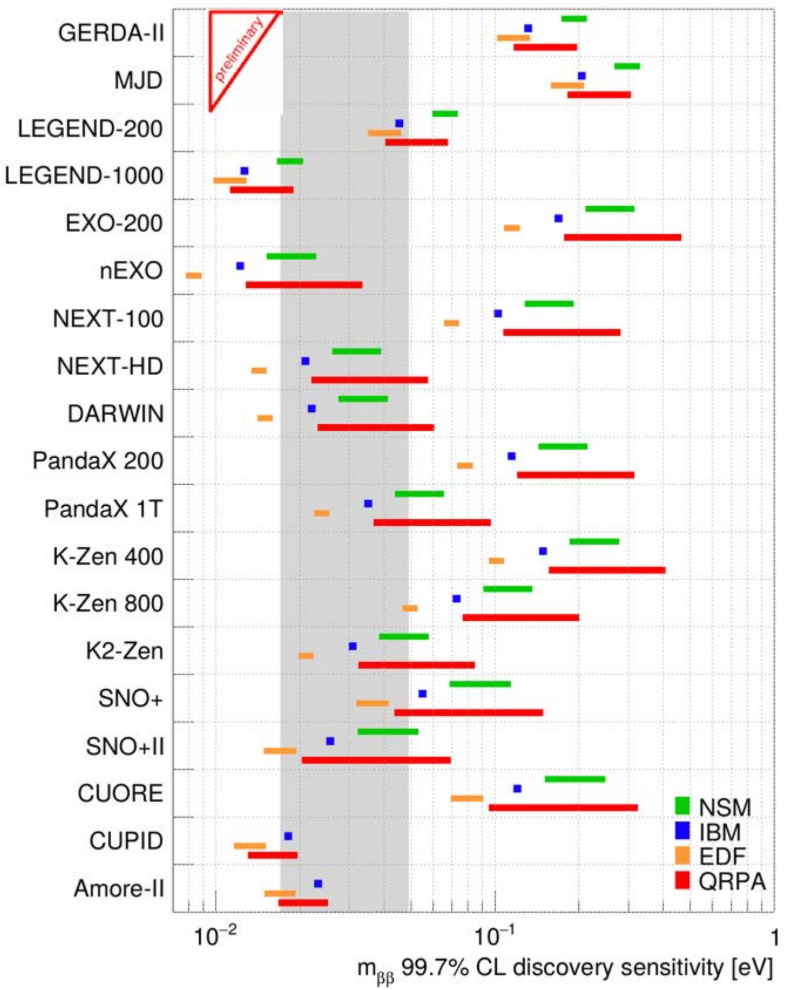


Figure from Detwiler APS 2020 talk

An Experimentalist’s View of Key Theory Elements

Nothing you don’t already know, but these form key questions experimentalists face during reviews.

- g_A
- Contact term and its associated uncertainty
- Uncertainty estimate for $M_{0\nu}$
- 0νECEC has uncertain matrix elements
  - –Probably not competitive, but should not be overlooked
  - –See backup slides for my view

Take Away Message

- The search for $0\nu\beta\beta$ is exciting regardless of other neutrino physics results.
- The recent progress has been impressive. Including:
  - the sensitivity of $0\nu\beta\beta$ searches,
  - the variety of studies to understand matrix elements, backgrounds and relevant nuclear physics,
  - the matrix element theory.
- Several technologies are ready for ton-scale projects with background projections below 1 cnt/(FWHM t yr). Will cover IO region.
- The next decade will be very interesting.

Backup Slides

Is 0νECEC an Alternative to 0νββ?

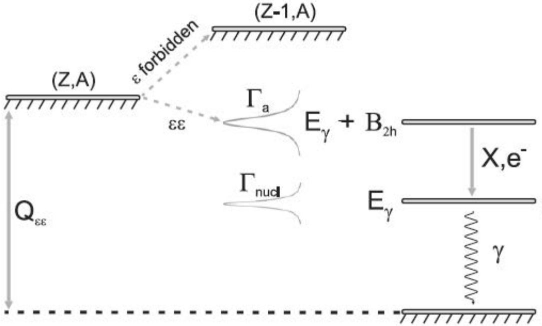
PRC89, 064319 (2014)

$$[\tau_{1/2}^{ECEC}]^{-1} = G_{0\nu}^{EC} M_{0\nu,EC}^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2 mc^2 R$$

$$[\tau_{1/2}^{0\nu}]^{-1} = G_{0\nu} M_{0\nu}^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

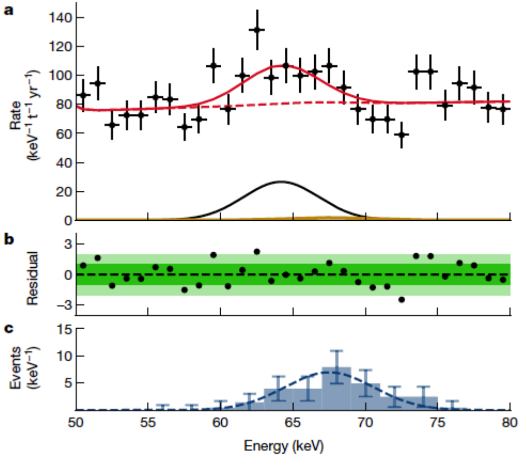
$$R = \frac{\Gamma}{\Delta^2 + 0.25\Gamma^2}$$

$$\Delta = Q - B_{2h} - E^*$$



J.Phys.G:NPP 39(2012) 124003

Compare ^{124}Xe to ^{136}Xe. Recent 2νECEC measurement.
Not a good resonance(Δ~1.9 keV). R_{exp} ~5.7x10^{-6}/eV, $R_{\Delta=0}$ ~ 0.2/eV.
But 2γ emission from 2790 keV is similar to 2450 keV ββ peak.
Similar technologies, so it's a good hypothetical comparison.
Define r as the ratio of the expected half lives.
ECEC half-life x32 longer than 0νββ, even if Δ=0.



Nature 568 (2019) 532

$$\tau_{1/2}^{ECEC} = \frac{8.7\times10^{24}\, yr\, eV}{R}\left(\frac{1\, eV}{m_{\beta\beta}}\right)^2$$

$$\tau_{1/2}^{0\nu} = 1.3\times10^{24} yr \left(\frac{1\, eV}{m_{\beta\beta}}\right)^2$$

$$r = \frac{\tau_{1/2}^{ECEC}}{\tau_{1/2}^{0\nu}} = \frac{6.7/eV}{R}$$

$r_{\Delta=0} \sim 32$, $r_{exp} \sim 10^6$

0νECEC – ^{156}Dy

Some more theory and Penning work useful

$$R = \frac{\Gamma}{\Delta^2 + 0.25\Gamma^2}$$

- ^{156}Dy ⟹ ^{156}Gd*(1988 keV) may have optimum overlap.
  - Δ = 0.54±0.24 keV.
  - It has a small $M_{0\nu,EC}$~0.3. With R_{Best} = 0.53/eV, r_{Best} is 120 meaning for the same $m_{\beta\beta}$, the half life is x120 longer compared to ^{136}Xe. Not all that encouraging.
- Penning trap measurements have done a great job looking for overlaps with a precision of a few hundred eV. Not many possibilities remain.
  - Γ values are 10-100 eV, so some improvement in precision for the still-interesting cases would be helpful.
- There are few careful $M_{0\nu,EC}$ calculations. This is a significant caveat. If $M_{0\nu,EC}$ is x10 larger, 0νECEC could be competitive. Additional effort on any key isotope would be good.

Toward an Ideal Future Experiment

Maximize Rate/Minimize Background

Experiment Designs are Advanced

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\Delta E}{MT_{live}} \right)^{\frac{1}{4}}$$

Experimental Parameter	Status
Large Exposure(~10 t-y)	Designs exist
Low Background (<1cnt/FWHM t-y)	Best so far is ~2, future extrapolation claims vary widely
Good energy resolution	Varies by tech., discovery potential sensitive to resol. & backgnd
Large Q value, fast ββ(0ν)	Ca, Ge, Se, Mo, Cd, Te, Xe
Enriched isotope	Costs & world production of raw material vary
Demonstrated technology	‘Prototypes’ in operation
Ease of operation	Demonstrated high duty cycles
High efficiency	True for most technologies
Slow ββ(2ν) rate	ββ(2ν) rate is slow for key isotopes and present resolutions
Identify daughter in real time	Not yet demonstrated, but some nice progress
Event reconstruction	Very nice, but detector mass is limited

Critical Physics Parameters for Sensitivity

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

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

- Neutrino mixing parameter uncertainties
  - θ_{12}: ±5 meV effect for IO lower border (3σ), x2 in $\Gamma_{0\nu}$
  - absolute mass, NO top (~5 meV) vs. IO bottom (~17 meV): factor of ~4 in $m_{\beta\beta}$, x16 in $\Gamma_{0\nu}$
  - Majorana phases. Completely unknown: factor of ~3 in IO $m_{\beta\beta}$, x10 in $\Gamma_{0\nu}$
- Matrix element uncertainty: factor of ~2, x4 in $\Gamma_{0\nu}$
- How large is quenching in $\beta\beta$? (g_A): may be large (x10 in $\Gamma_{0\nu}$)
- How large is the contact term?: another factor 2 in the matrix element?
- Phase space uncertainty: small, 5-10% in $\Gamma_{0\nu}$
- Lepton Number Violation (LNV) mech. or sterile ν: could significantly change $m_{\beta\beta}$

Experimental Parameters

$$m_{\beta\beta} \leq \left(2.50x10^{-5}\,meV\right)\sqrt{\frac{W}{fx\varepsilon G_{0\nu}\left|M_{0\nu}\right|^{2}}}\left[\frac{b\Delta E}{MT}\right]^{\frac{1}{4}}$$

All isotopes are roughly comparable.
Robertson Mod. Phys. Lett. A, **28** (2013) 1350021

- W – molecular weight of source
- f – isotopic abundance
- x – number of ββ isotopes per molecule
- ε – detector efficiency
- $G_{0\nu}$ – decay phase space
- $|M_{0\nu}|$ - matrix element
- b – background in counts/(keV kg yr)
- ΔE – energy window in keV
- M – mass of source in kg
- T – counting time in years

- When comparing isotopes, don't forget W, favors low A. $G_{0\nu}$ favors high A.
- QRPA |M| has more A dependence than SM.

Isotope	**$\sqrt{(W/(G_{0\nu}\|M_{0\nu}\|^2))}$ x10^7**
Ge	2.4(QRPA) 4.7(SM)
TeO_2	1.9(QRPA) 3.1(SM)
Xe	2.4(QRPA) 3.3(SM)

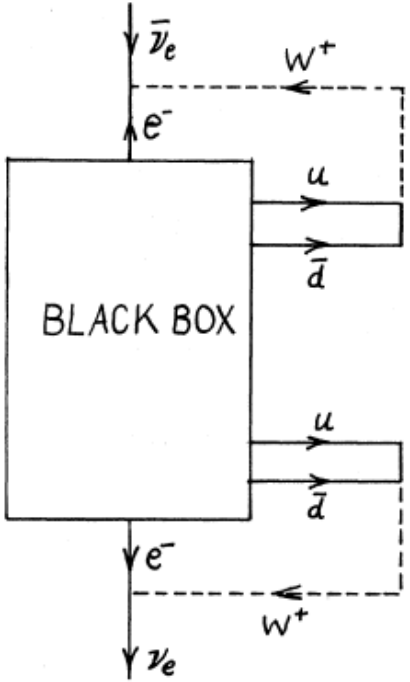
Input from Auxiliary Studies

reference lists are not comprehensive, just some important examples

- $M_{0\nu}$: Pair correlation studies and nucleon configuration studies using transfer reactions
  - (p,t), (d,p), (p,d), (α,^{3}He), and (^{3}He, α). PRC 75 (2007) 051301; PRC 79 (2009) 021301(R); PLB 668 (2008) 277
- $M_{0\nu}$: NUMEN project: Heavy ion double charge exchange measurements.
  - Eur. Phys. J. A54 (2018) 72; PRC 98 (2018) 061601, PRL 122 (2019) 192501
- $M_{0\nu}$: Precise $2\nu\beta\beta$, 2νECEC half-lives, β^-, β^+ data for intermediate-state isotopes – g_{pp}, g_A
  - PRC 68 (2003) 044302; PLB 607, (2005) 87
- $M_{0\nu}$: Precise $2\nu\beta\beta$ spectral shapes, PRL 122 (2019) 192501
- $M_{0\nu}$: Charge exchange reactions (p,n), (n,p), (^{3}He,t), (d,^{2}He), etc. - charge-changing weak currents
  - PRC 76 (2007) 014604, PRC 94 (2016) 014614; NPA 916 (2013) 219, J. Phys. G 42 (2015) 055201
- $M_{0\nu}$: Muon capture - all multipoles populated- Czech J. Phys. 56 (2006) 459
- $M_{0\nu}$: Electromagnetic transitions to isobaric analogue states- PRC 88 (2013) 045610
- $M_{0\nu}$, Background: Neutrino interactions- J. Phys. G 31 (2005) 903; PRC 89 (2014) 055501; PRC 95 (2017) 055501
- Background: Cosmogenic production- PRC 82 (2010) 054610; NPB (proc. supp.) 143 (2005) 508; Astrop. Phys. 64 (2015) 34
- Background: (n,n’) cross sections and excitation- PRC 87 (2013) 064607; PRC 79 (2009) 054604; PRC 98 (2018) 064606
- Q value: Atomic masses (EC-EC candidates - better Q values)
  - PRL 98 (2007) 053003; PRL 110 (2013) 012501; PRC 89 (2014) 045502; PLB 703 (2011) 412; PRC 81 (2010) 032501(R)
- gA: Theory efforts making progress, ab initio calculations
- Interpretation: of course neutrino oscillation experiments play an important role in understanding $\beta\beta$

ββ implies LNV and Majorana ν, but…

- The Schechter-Valle theorem states there must be a Majorana component to the neutrino mass term if ββ exists.
- However, the S-V “black-box” operator contribution to m_ν is very small. Other leading contributions from BSM physics are required to explain an observable decay rate.
- Its possible to have a significant ββ rate with negligible ν mass. (See JHEP 1106:091,2011)
- Still we know there are light, massive νs.
- They may get their mass from a Majorana term in the $\mathcal{L}_\nu$.
- The simplest hypothesis to test is three light neutrinos, either Majorana or Dirac. This hypothesis has the least new physics.
- ββ is the best way to explore this hypothesis. This ansatz is also the usual basis to compare techniques.

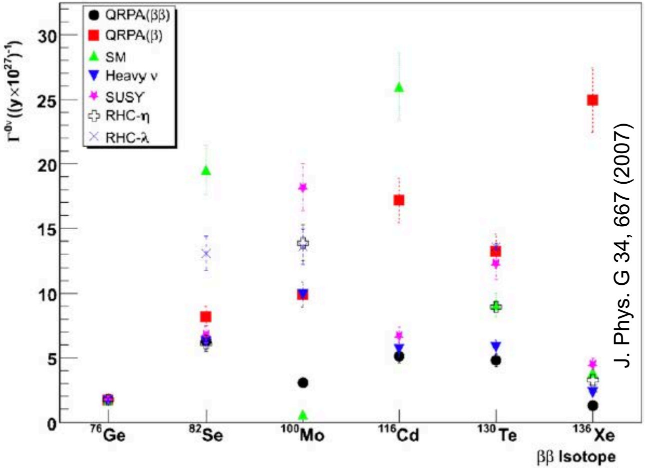


PRD 25 (1982) 2951

Need several $\beta\beta(0\nu)$ measurements to fully exploit physics and matrix element theoretical studies

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

- 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.
- Kinematic distributions of energy and opening angle might discern mechanisms.



J. Phys. G 34, 667 (2007)

PRL 98, 232501 (2007)
J. Phys. G 34, 667 (2007) [Erratum G35, 029701 (2008)
PRD 80, 015024 (2009)
Many other papers address similar issues.

Effective comparisons require experimental uncertainties to be small wrt theoretical uncertainties. Correlations between |M| calculations are important. m_ν mechanism more fully studied than other BSM.

Potential Future Experimental Results
ββ will still be a critical program, no matter the answers

Double beta decay is a test of lepton number conservation.

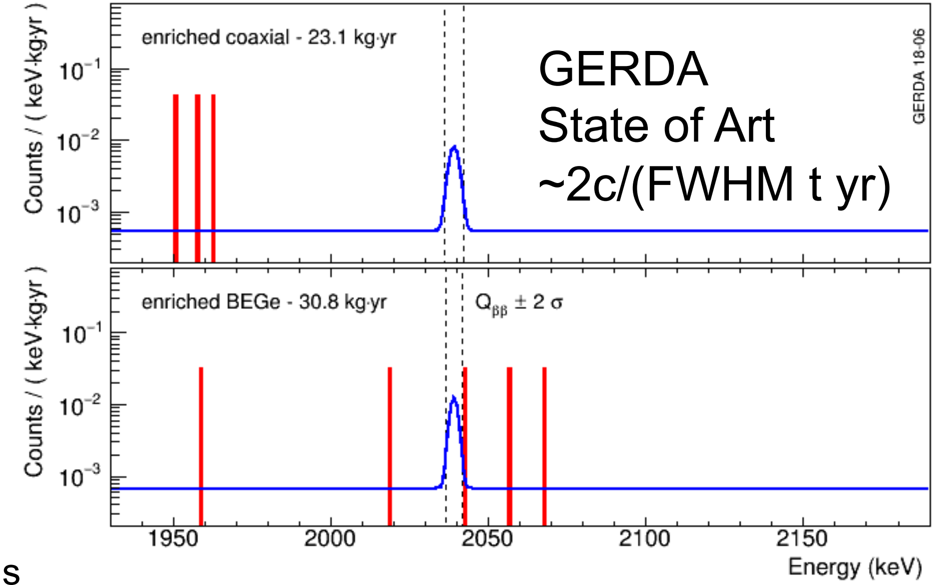
Technique	Result	ββ Influence
Oscillations	Θ_{12} Measured	Would better define boundaries of IO/NO bands. That would be good for ββ.
Oscillations	Mass ordering determined	Inverted order with 3 ν's might become irrelevant. Even so, the NO branch still extends to high $m_{\beta\beta}$ values. LNV processes other than light ν aren't constrained by oscillations. Presently, significance of IO exclusion still rather low.
LHC	Heavy ν or LR symmetry found	The result would be complementary to ββ. It would be an interesting test of the underlying physics if both techniques saw an effect.
Cosmology	Σm_ν constrained <100 meV	Cosmology does not discern Majorana/Dirac character. A 3ν NO scenario with Σ near its minimum would not constrain other potential LNV processes that might contribute to ββ. Importantly, laboratory measurements will help resolve tensions/degeneracies in cosmology.
Short Baseline Oscillation	Sterile ν discovered	If a 4th ν is seen, it fits the Majorana ν paradigm, increasing ββ interest. The new ν might contribute to ββ and significantly alter predicted $m_{\beta\beta}$ curves. The accessible sensitivity regions remain.
β decay	m_β measured	Would make the observation/non-observation of ββ even more exciting. Null ββ result might indicate Dirac ν.

Background Considerations

“the Usual Suspects” but also some new players

Always an issue
Mostly solved
Upcoming concerns

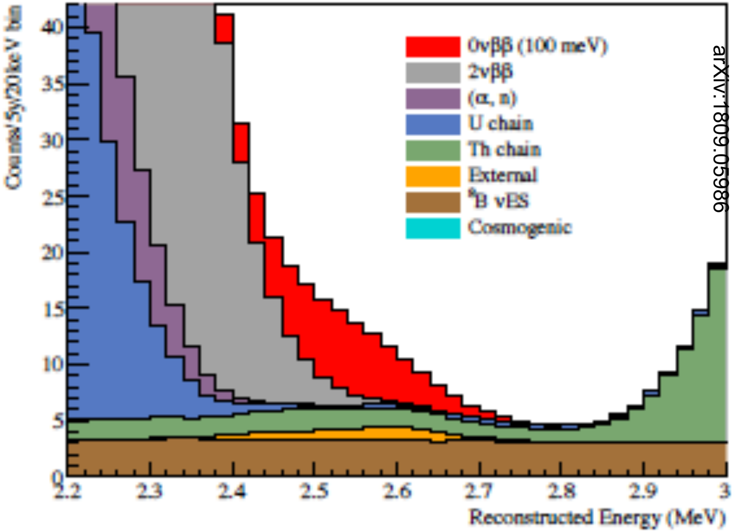
- Natural occurring radioactive materials in detector apparatus
  - U/Th/K in detector materials or from contamination, radon daughter plate-out
- Environmental γs
  - The lab environment, radon
- Prompt μ
- 2νββ
  - need energy resolution
- Long-lived cosmogenics
  - Exposure on Earth’s surface
- Anthropomorphic activities
  - Fallout
- Neutrons from (α,n), fission, or μ interactions
  - in situ produced activation products, (n,n’) emissions
- Solar Neutrino Interactions



GERDA
State of Art
~2c/(FWHM t yr)

The usual suspects

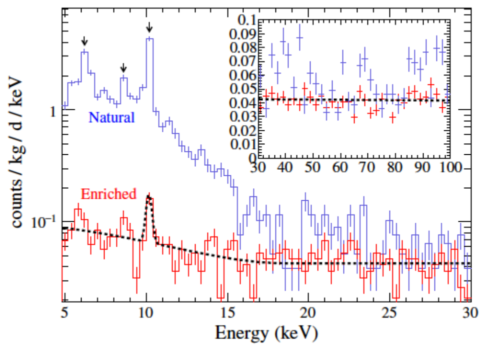
- Natural Occurring Radioactive Materials
  - –Solution mostly understood, but hard to implement
    - Great progress has been made understanding materials and the U/Th contamination, purification
    - Elaborate QA/QC requirements
  - –Future purity levels greatly challenge assay capabilities
    - Some materials require levels of 1 μBq/kg or less
    - Sensitivity improvements required for ICPMS, γ counting, NAA
    - Assay techniques have equilibrium assumptions
    - Sample testing doesn’t always reflect installed materials
- Prompt μ and environmental γ
  - – Shielding and veto solutions are rather robust these days
- ββ(2ν)
  - –For most present experiments, resolutions are sufficient to prevent tail from intruding on peak
  - –Becomes a concern as exposures get larger
  - –Note, resolution, at any experiment scale, is an important issue for signal-to-noise and discovery potential



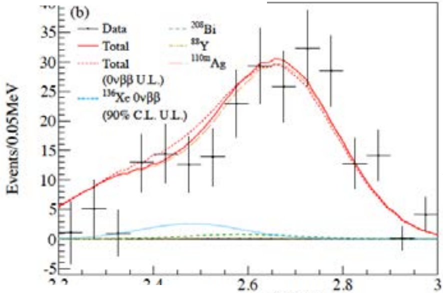
arXiv:1809.05986

As we approach 1 cnt/ton-year, other complications emerge.

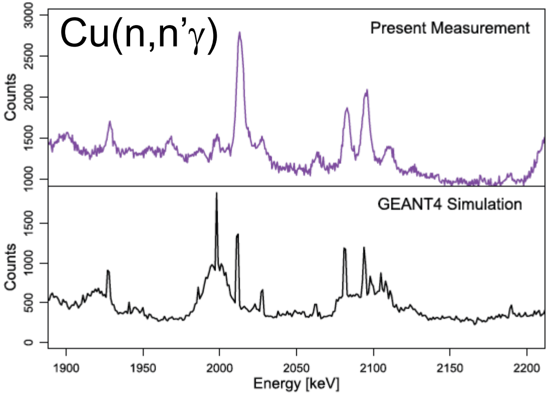
- Long-lived Cosmogenic Isotopes
  - –Material and experimental design dependent
  - –Minimize surface exposure for problematic materials
  - –Development of underground fabrication
- Anthropomorphic Activities
  - –Frequently related to notable events, precautions usually can be implemented
- Neutrons (elastic/inelastic reactions, short-lived isotopes)
  - –(α,n) and fission n up to 10 MeV can be shielded
  - –High-energy-μ generated n are a more complicated problem
    - Depth and/or well understood anti-coincidence techniques
    - Rich spectrum, but at low rates it is difficult to discern the actual process, e.g. (n,n'γ) reactions - which isotope/level
    - Simulation codes still have a lot of uncertainty
- Neutrinos (elastic or charge-current interactions)
  - –Must be considered as detectors get big



PRL 118, 161801 (2017)

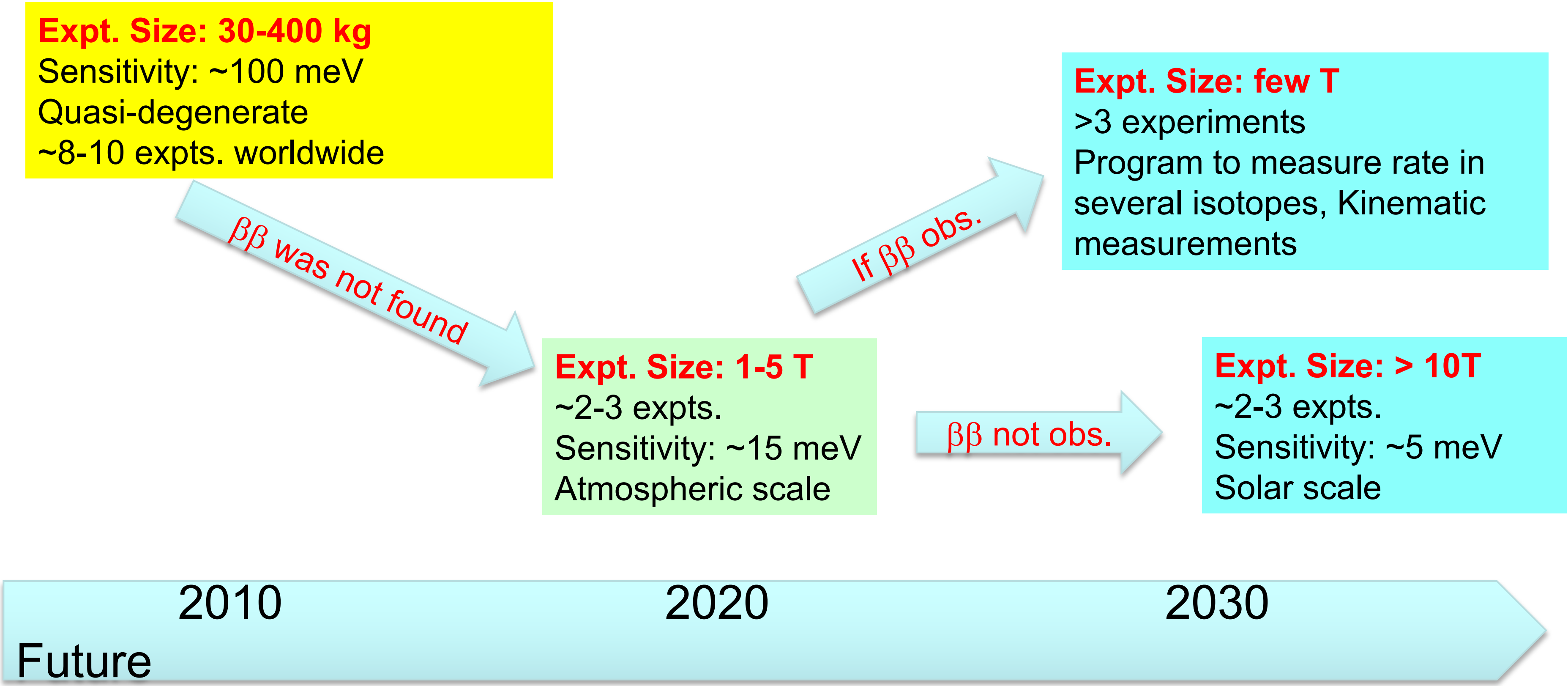


PRL **110**, 062502



PRC 87 (2013) 064607

Discovery Leading to Measurement



Expt. Size: 30-400 kg
Sensitivity: ~100 meV
Quasi-degenerate
~8-10 expts. worldwide

ββ was not found

Expt. Size: 1-5 T
~2-3 expts.
Sensitivity: ~15 meV
Atmospheric scale

If ββ obs.

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

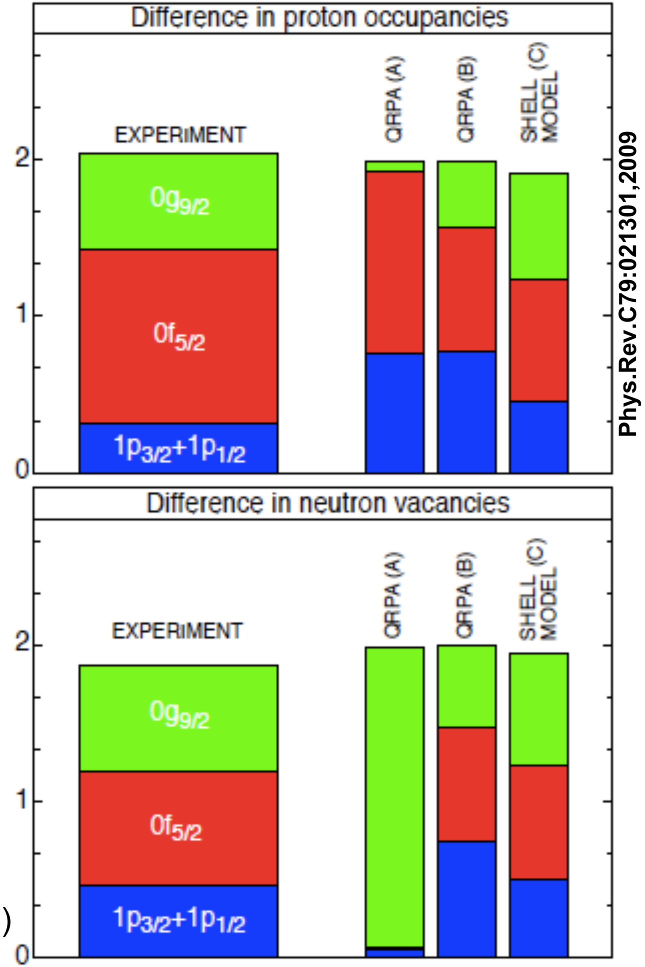
ββ not obs.

Expt. Size: > 10T
~2-3 expts.
Sensitivity: ~5 meV
Solar scale

Occupancy Measurements

Useful to complete other systems

"The difference in the configuration of nucleons between the initial and final states (the 0^+ ground states of ^{76}Ge and ^{76}Se) is a major ingredient in the matrix element."



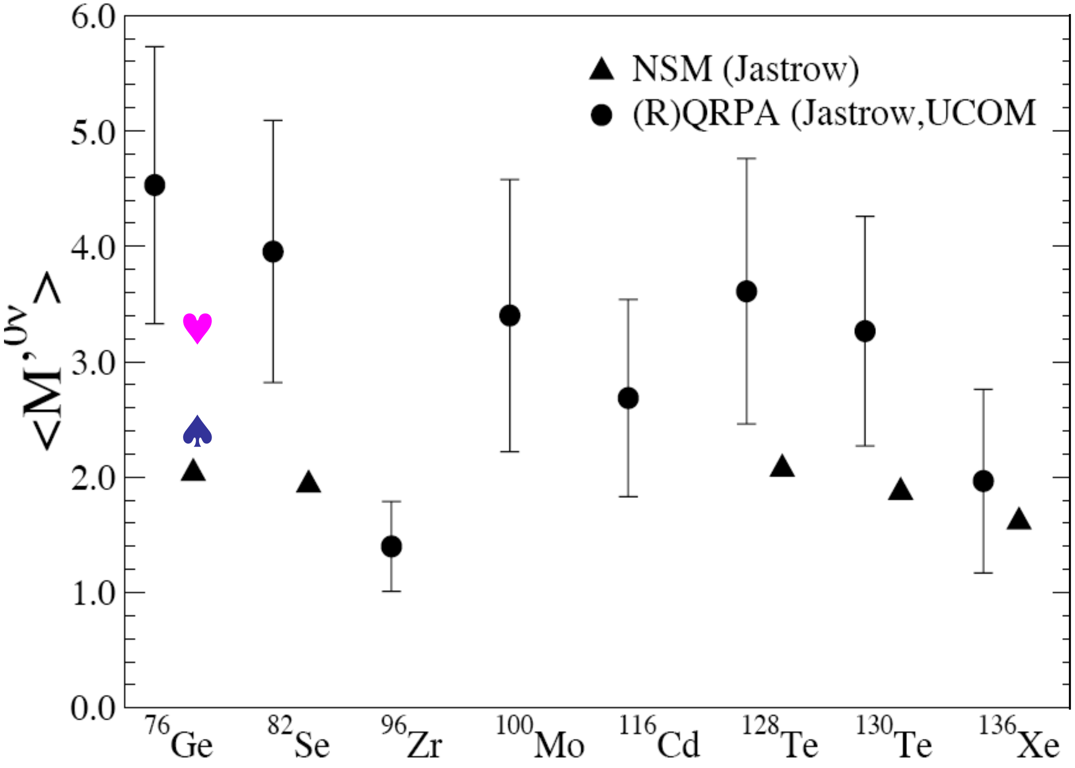
Phys.Rev.C79:021301,2009

<u>Occupancy Measurements Ge</u>
Kay et al., PRC 79:021301,2009
Schiffer et al., PRL 100:112501,2008

<u>Occupancy Measurements Te</u>
Kay et al., PRC 87 (2013) 011302(R)
Entwisle et al., PRC 93 (2016) 064312

QRPA (PRC 68, 044302 (2003), NPA 766, 107 (2006), PLB 668, 277 (2008)) and Shell model (PRL 100, 052503 (2008)) estimates are from before measurements.

After Measurement Calculations – Narrowed Difference More study along this lines might be useful

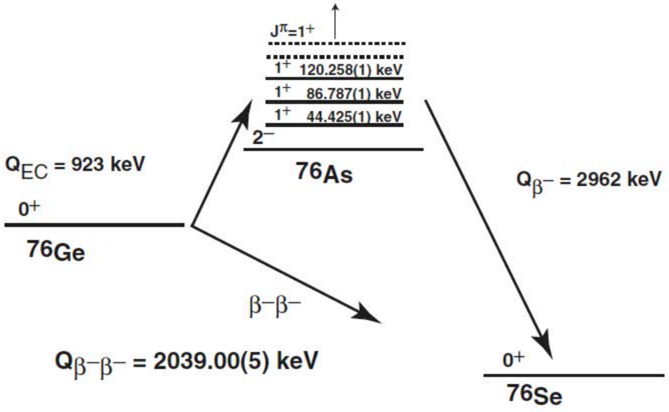


♥ New QRPA value with adjusted mean field so that experimental occupancies are reproduced
PRC 79 (2009) 015502

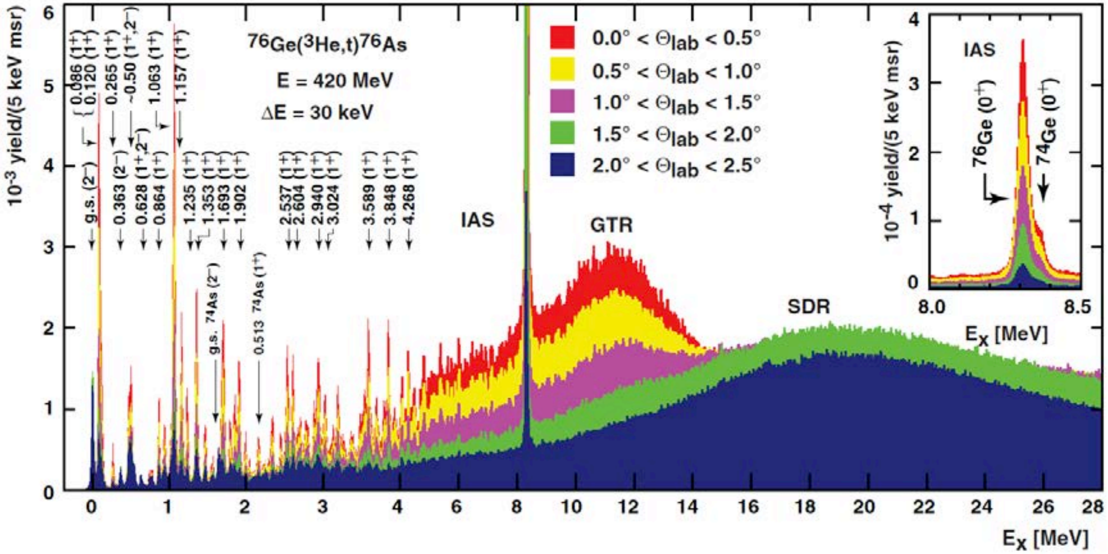
♠ New NSM value with adjusted mean field (monopole) where experimental occupancies are better reproduced
PRC 80 (2009) 048501

Useful to compare predictions of occupancy to measurements.

Charge Exchange Reactions have been done on the key ββ isotopes



^{76}Ge(^{3}He,t)^{76}As
^{75}Se(d,^{2}He)^{76}As
Can deduce 2νββ matrix element
PRC 86 (2012) 014304



PRC 86 (2012) 014304

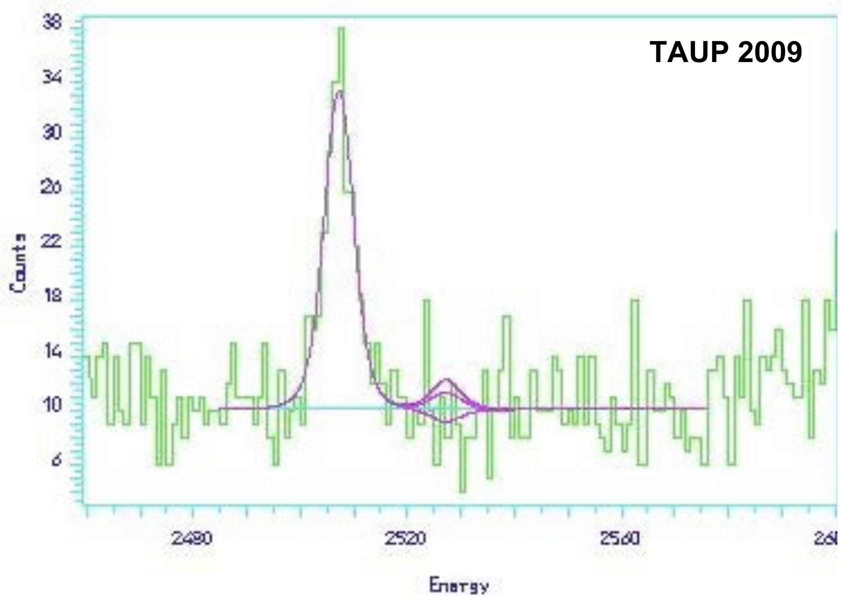
Can also deduce neutrino cross section to quantify potential background from solar neutrinos.

^{82}Se PRC 94 (2016) 014614, ^{100}Mo PRC 86 (2012) 044309, ^{128,130}Te PRC 86 (2012) 044603, ^{150}Nd PRC 83 (2011) 064318, ^{136}Xe PRC 84 (2011) 051305(R)

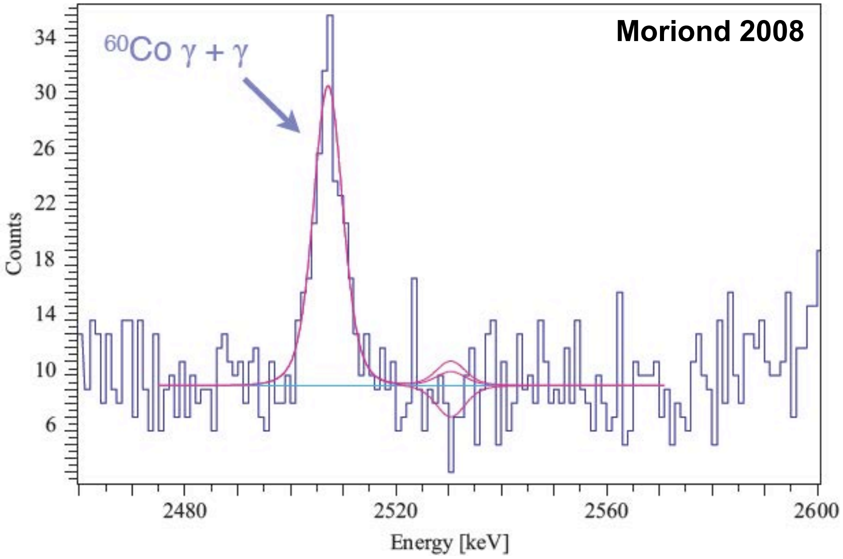
Q-Value Effect Measurements: Very Successful

For key $0\nu\beta\beta$ isotopes, the Q value has been measured much better than any anticipated resolution. Significant impact on CUORICINO, e.g.

$\tau > 2.94\times10^{24} y$ 2527.518 keV



$\tau > 3.1\times10^{24} y$ 2530.3 keV



^{76}Ge PRC 81 (2010) 032501(R), ^{82}Se PRL 110 (2013) 012501, ^{100}Mo PLB 662 (2008) 111, ^{116}Cd/^{130}Te PLB (2011) 412, ^{150}Nd PRC 82 (2010) 022501(R), ^{136}Xe PRL 98 (2007) 053003