Neutrinoless Double Beta Decay: Technology

Los Alamos NATIONAL LABORATORY

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PHYSICS SINCE 1943

TRI-INSTITUTE SUMMER SCHOOL ON ELEMENTARY PARTICLES
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Background Issues
Related Physics Measurements
Some Recent Technical Progress

Experimental Parameters

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

All isotopes are roughly comparable.

Robertson Mod. Phys. Lett. A, **28** (2013) 1350021

- W – molecular weight of source
- f – isotopic abundance
- x – number of $\beta\beta$ isotopes per molecule
- ε – detector efficiency
- $G_{0\nu}$ – decay phase space
- $|M_{0\nu}|$ - matrix element
- b – background in counts/keV-kg-y
- 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)

Toward an Ideal Future Experiment

Maximize Rate/Minimize Background

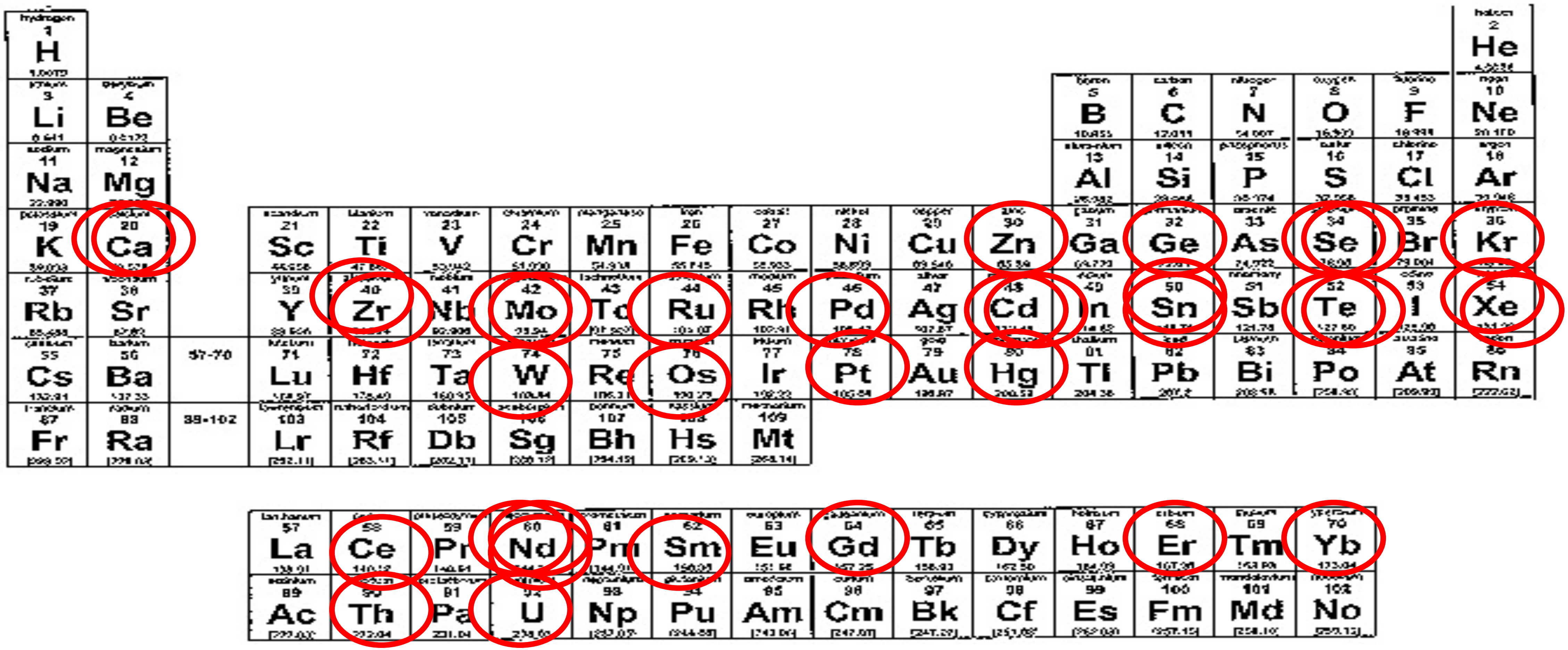
Experiment Designs are Advanced

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

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 $\beta\beta(0\nu)$	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 $\beta\beta(2\nu)$ rate	$\beta\beta(2\nu)$ 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

ββ Candidate Isotopes

There are a lot of them!

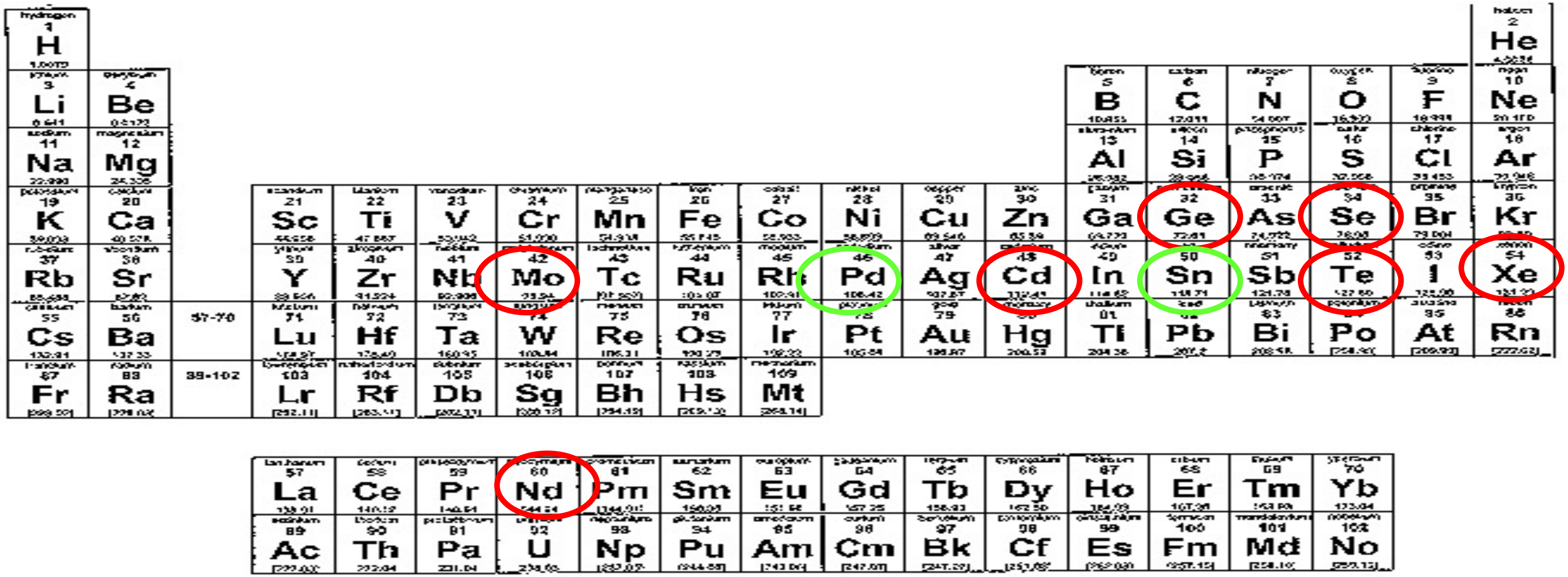


So, How do we choose a $\beta\beta$ isotope?

- Detector technology exists
- High isotopic abundance or an enriched source exists.
- High energy = fast rate, above background

ββ Candidates

Abundance > 5%,Trans. Energy > 2 MeV



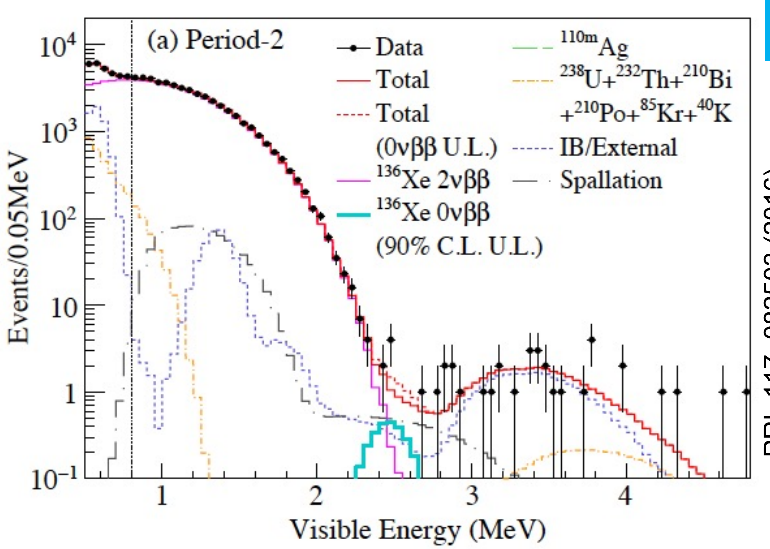
Frequently studied isotope.

Signal:Background
Background is a key issue in ββ

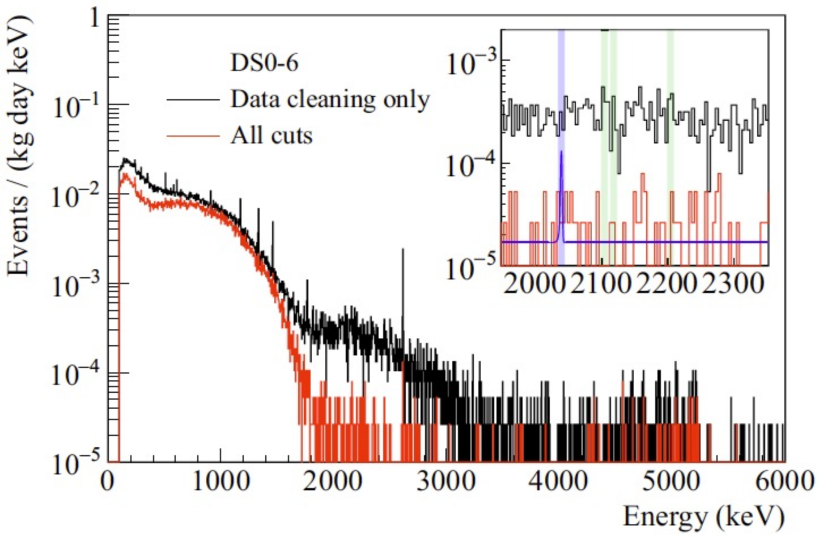
Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
$5x10^{26}$	10	100	
$5x10^{27}$		40	Atmospheric, IO
$>10^{29}$	<0.05	<10	Solar, NO

To reach atmospheric scale need BG better than 1/t-y.

Background in Recent Experiments



PRL 117, 082503 (2016)



PRC 100 (2019) 025501

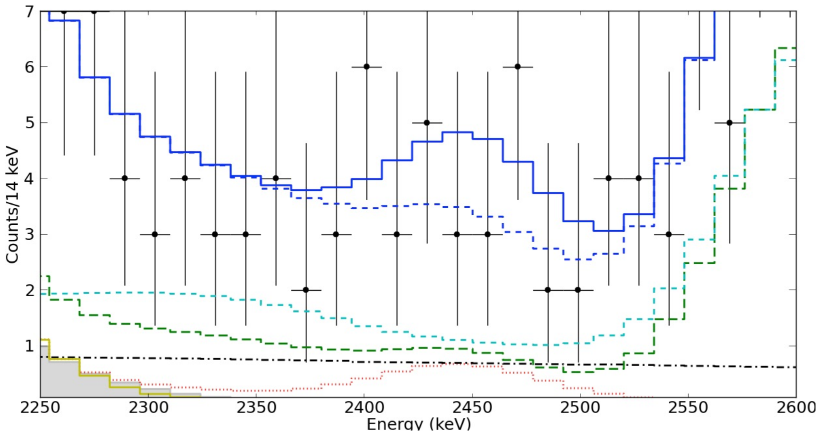
KamLAND-Zen: 120 c/(FWHM t(Xe) y)

Note KZ quotes ROI 400 keV, not FWHM

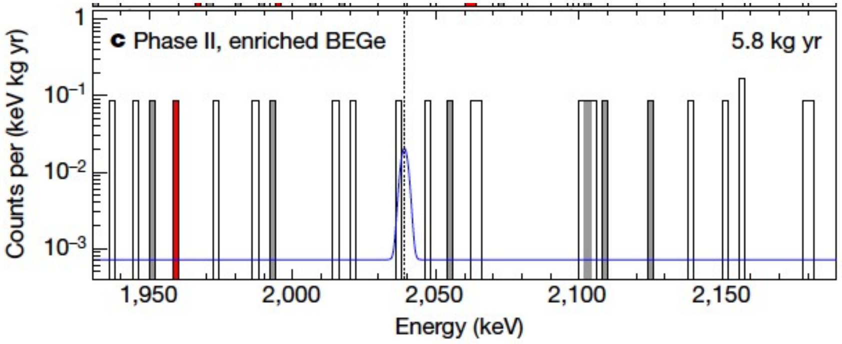
MAJORANA: 11.9 c/(FWHM t y)

GERDA: 2.1 c/(FWHM t y)

EXO-200: 150 c/(FWHM t y)



Nature 510, 229-234



Nature 544, 47 (2017)

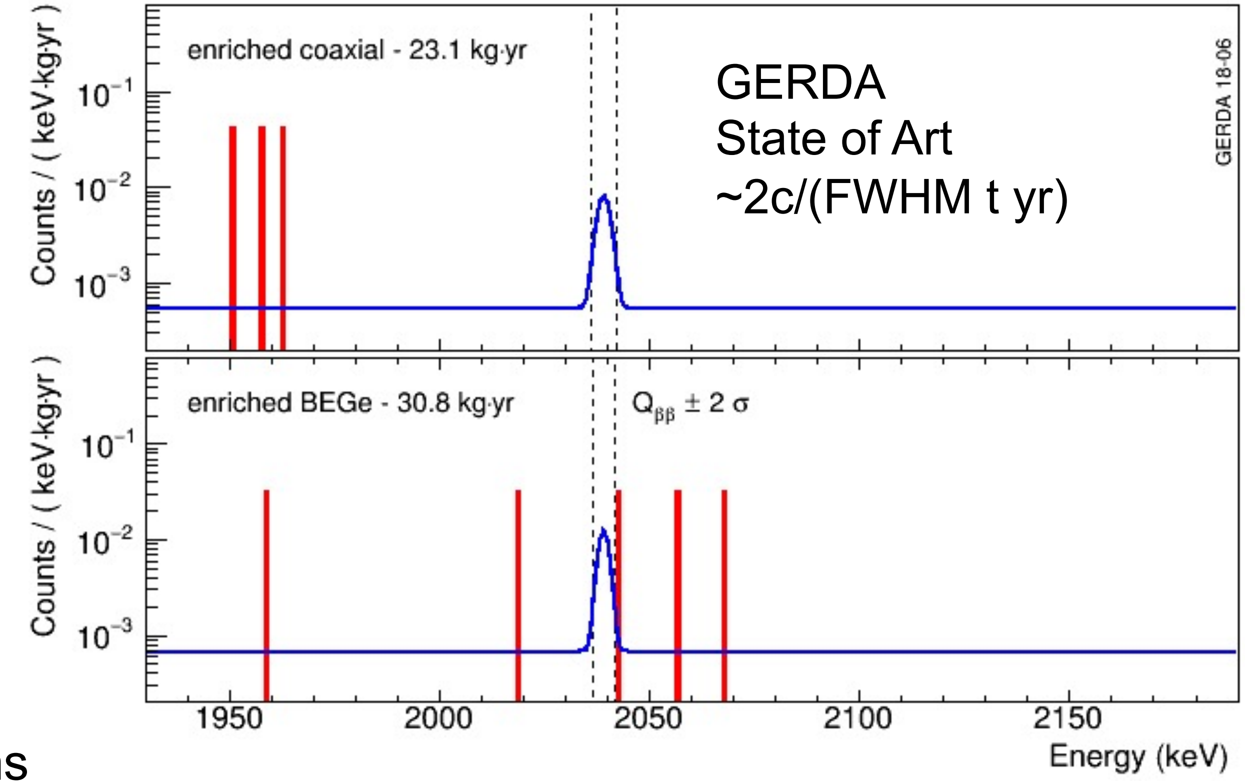
The background is never zero, but can be 'nearly' background free.

We will come back to this.

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
- $2\nu\beta\beta$
  - 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

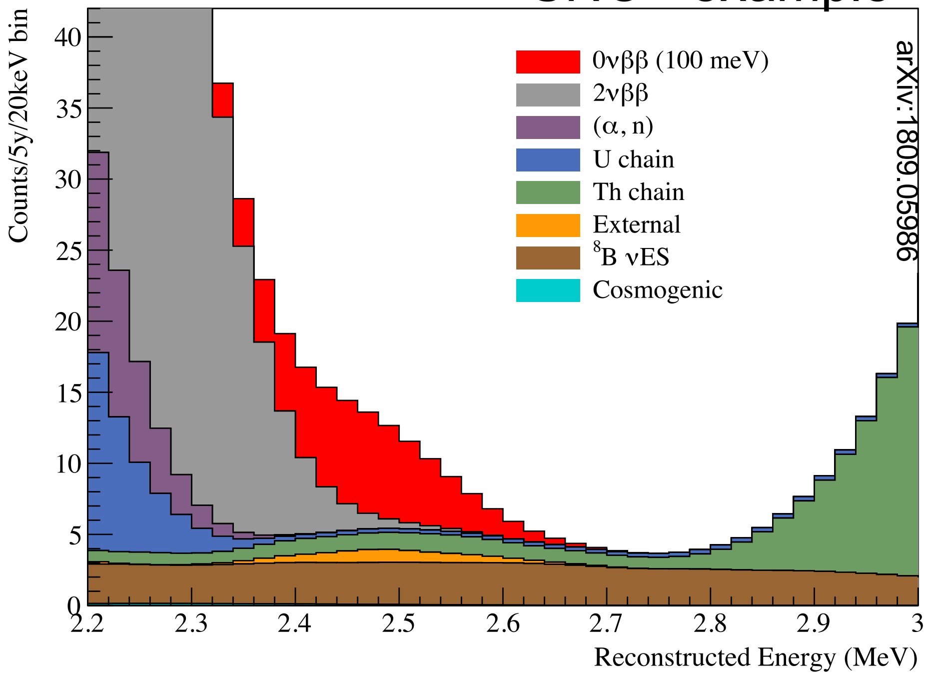


GERDA
State of Art
~2c/(FWHM t yr)

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

SNO+ example



Resolution and Signal/Noise

- $0\nu\beta\beta$ is a single-site, mono-energetic deposit uniform in time.
- Most backgrounds deposit energy in multiple locations and many have time correlated features.
- Experiments are designed to exploit these features.

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

- Background in ROI ~ $b\Delta E$
- Getting a large Mt is typically in tension with good ΔE.
- The Mt required for a given sensitivity scales proportionally to the ΔE (for a given b).
- Nearby background lines can be resolved by resolution.

The Usual Suspects - NORM

- Natural Occurring Radioactive Materials - NORM
  - 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 1μBq/kg or less for ton scale expts.
    - Sensitivity improvements required for ICPMS, direct counting, NAA

NORM Assay Techniques/Sensitivities

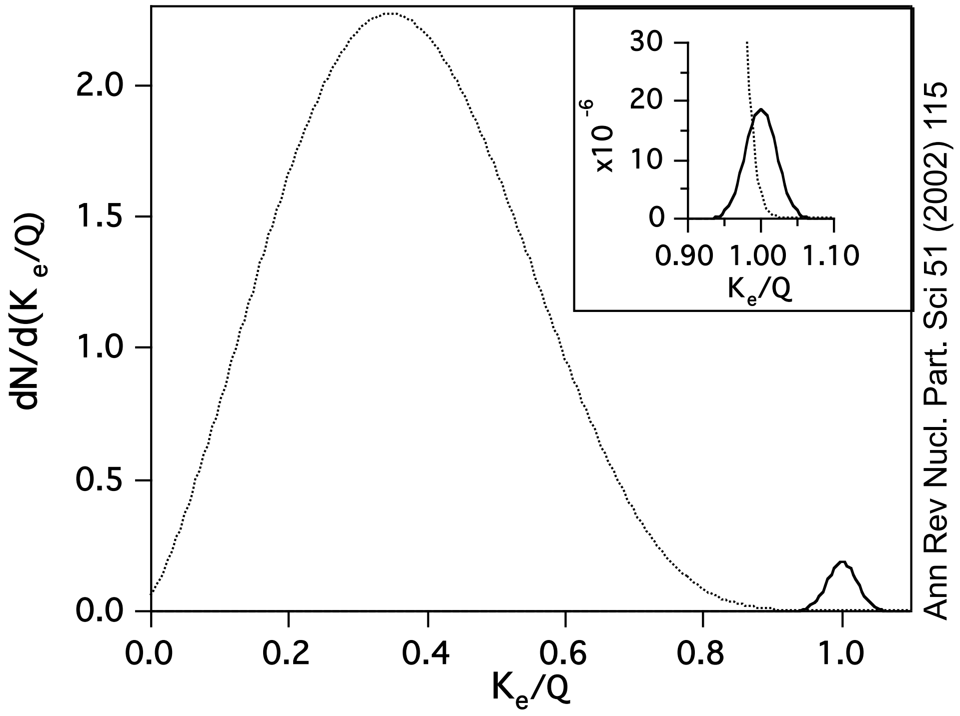
adapted from: Laubenstein/ILIAS

Method	Application	Sensitivity U/Th
Ge Spectroscopy	γ emitting nuclides	10-100 μBq/kg
Rn Emanation	^{226}Ra, ^{228}Th	0.1-10 μBq/kg
Neutron Activation Analysis	Primordial Parents	0.01 μBq/kg
Liquid Scint. Counting	α,β Emitting Nuclides	1 mBq/kg
Mass Spectroscopy	Primordial Parents	1-100 μBq/kg
AFS and AAS analysis	Primordial Parents	1-1000 μBq/kg
X-Ray Fluorescence	Primordial Parents	10 mBq/kg
Alpha Spectroscopy	α Emitting Nuclides	1 mBq/kg

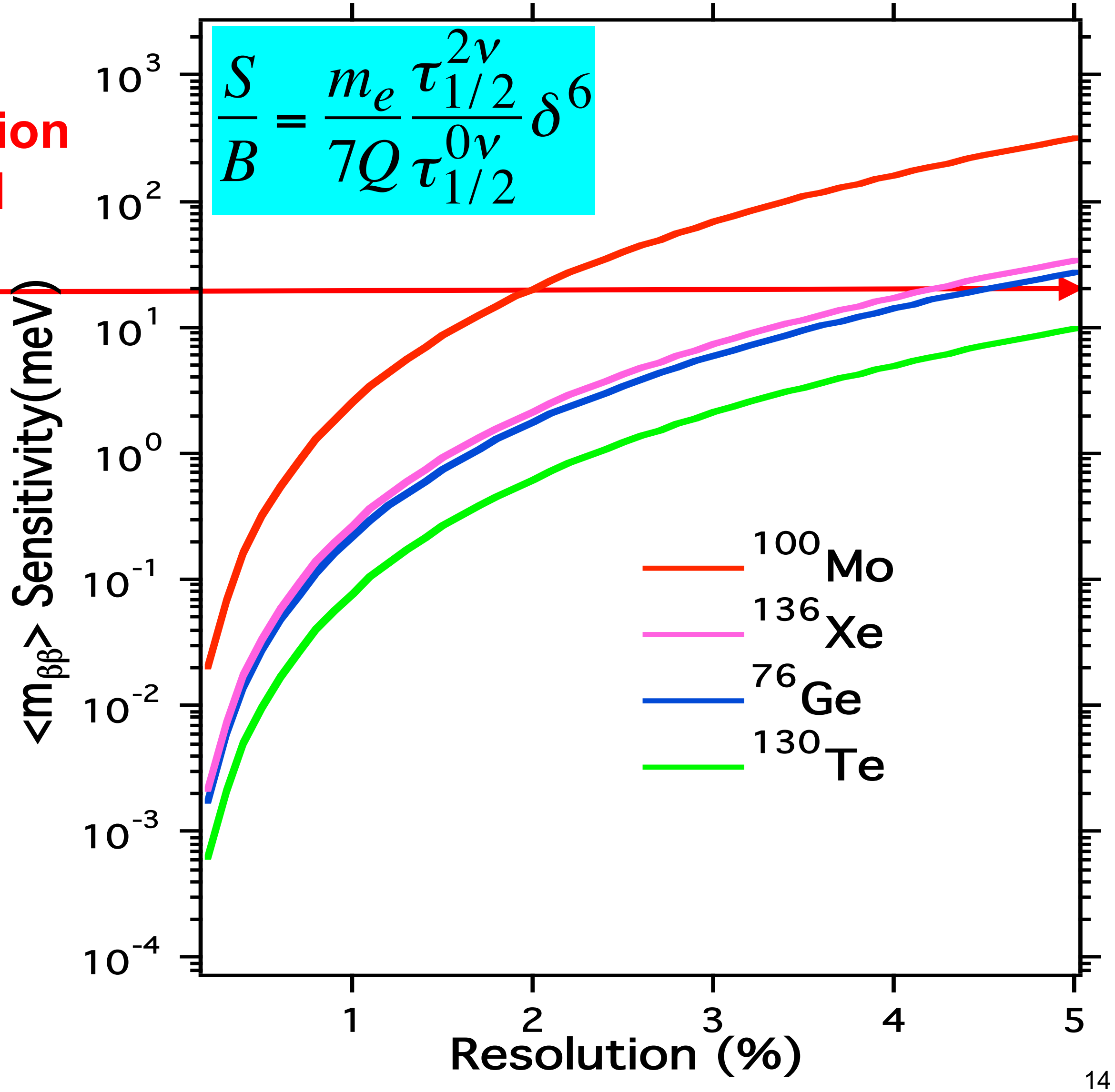
Sensitivity comparisons are difficult: each method has it special applications. These are best possible values that can’t usually be reached for a given sample.

ββ(2ν) as a Background.

Sum Energy Cut Only



next generation experimental goal



Splitting the window, or in the case of high-event rates, fitting the spectrum.

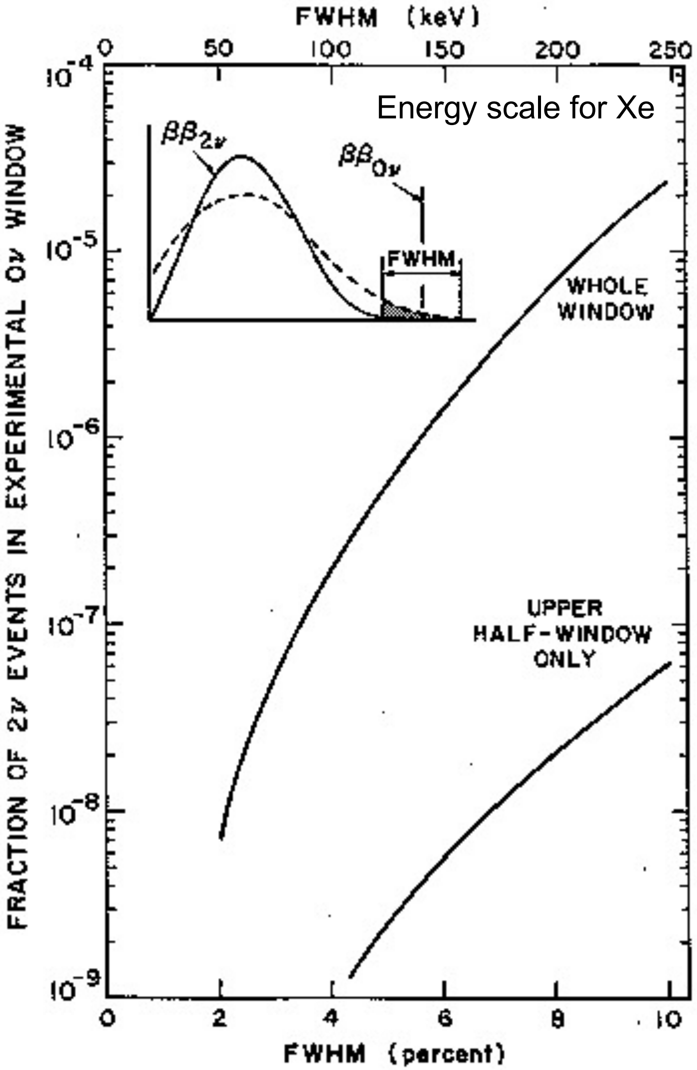
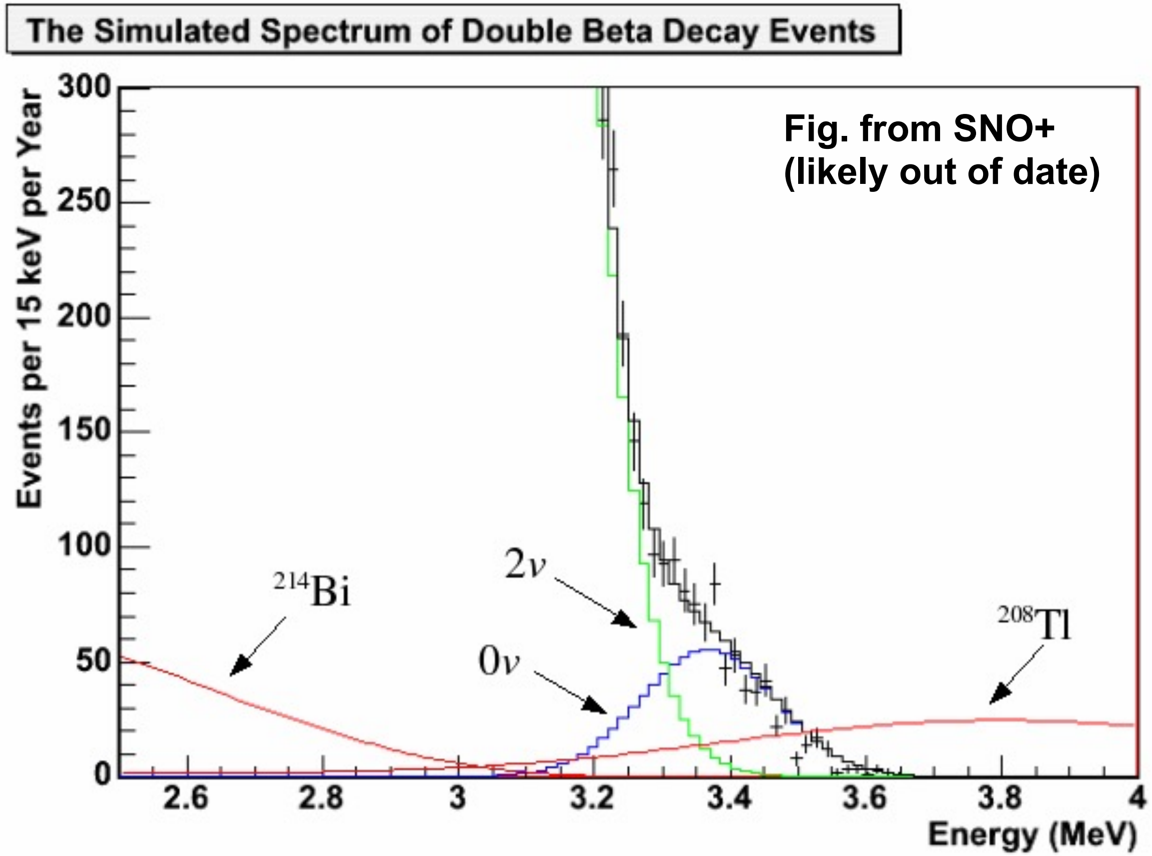


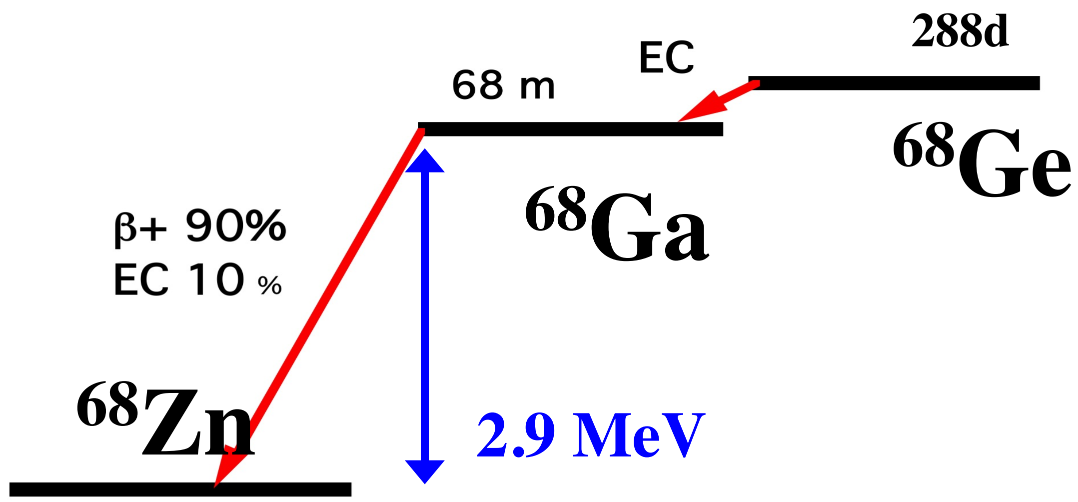
Figure from Mike Moe

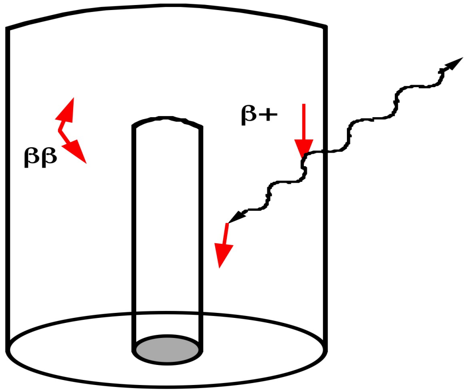


The Usual Suspects - Cosmogenics

- Long-lived cosmogenics
  - –material and experimental design dependent
  - –Minimize exposure on surface of problematic materials
  - –Development of underground fabrication
- Required inputs to calculations
  - –N flux
  - –Cross sections
  - –Measured vs. calculated

Cosmogenic ^{68}Ge and ^{60}Co
Ge detector example





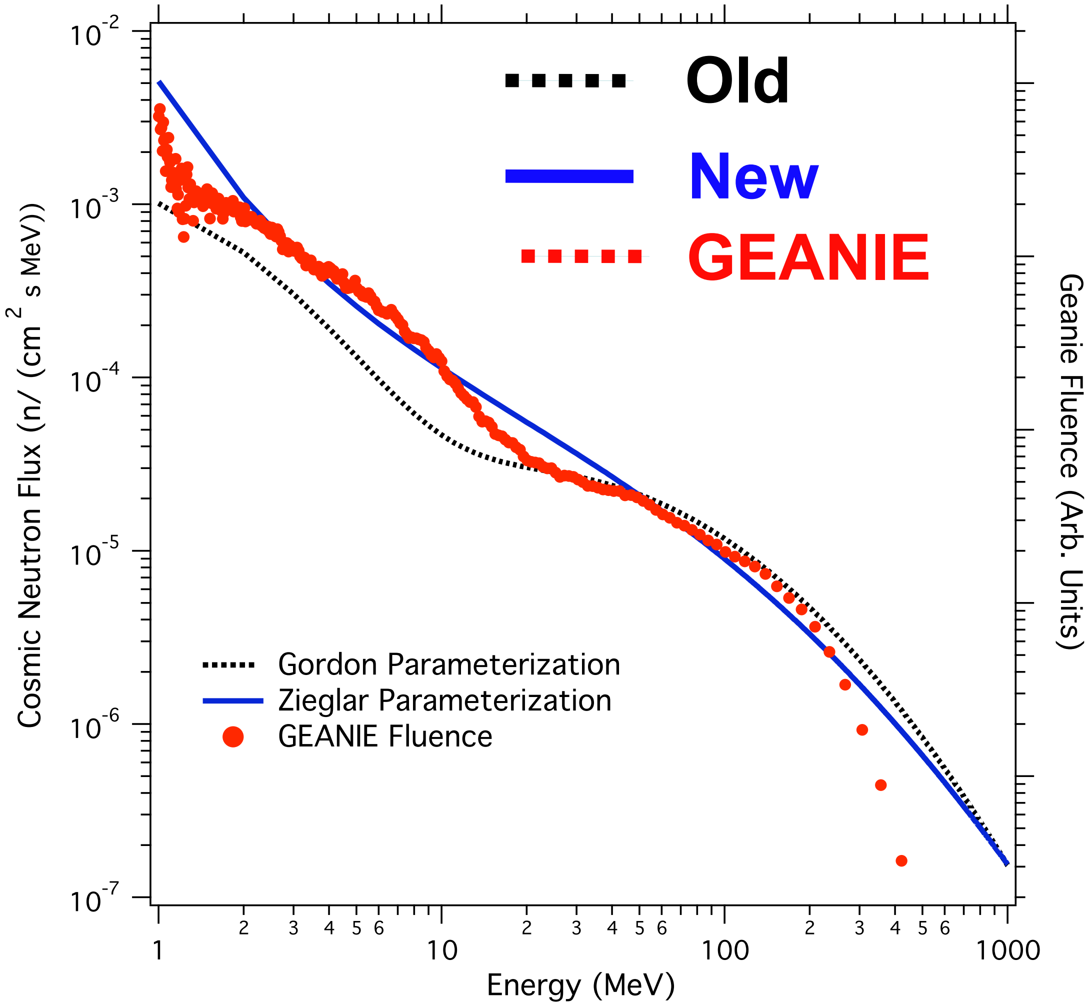
For a human, the ^{40}K activity is about 70 Bq/kg ~6x10^{6}/(kg d).

^{68}Ge and ^{60}Co are the dangerous internal backgrounds for Ge-based experiments.
For enriched Ge, initially expect ~2 ^{68}Ge decays/(kg day) at saturation. $\tau_{1\backslash 2}$ = 288 d
Minimize exposure on surface during enrichment and fabrication
PSD, segmentation, time correlation cuts are effective at reducing these

Cosmic Neutron Flux

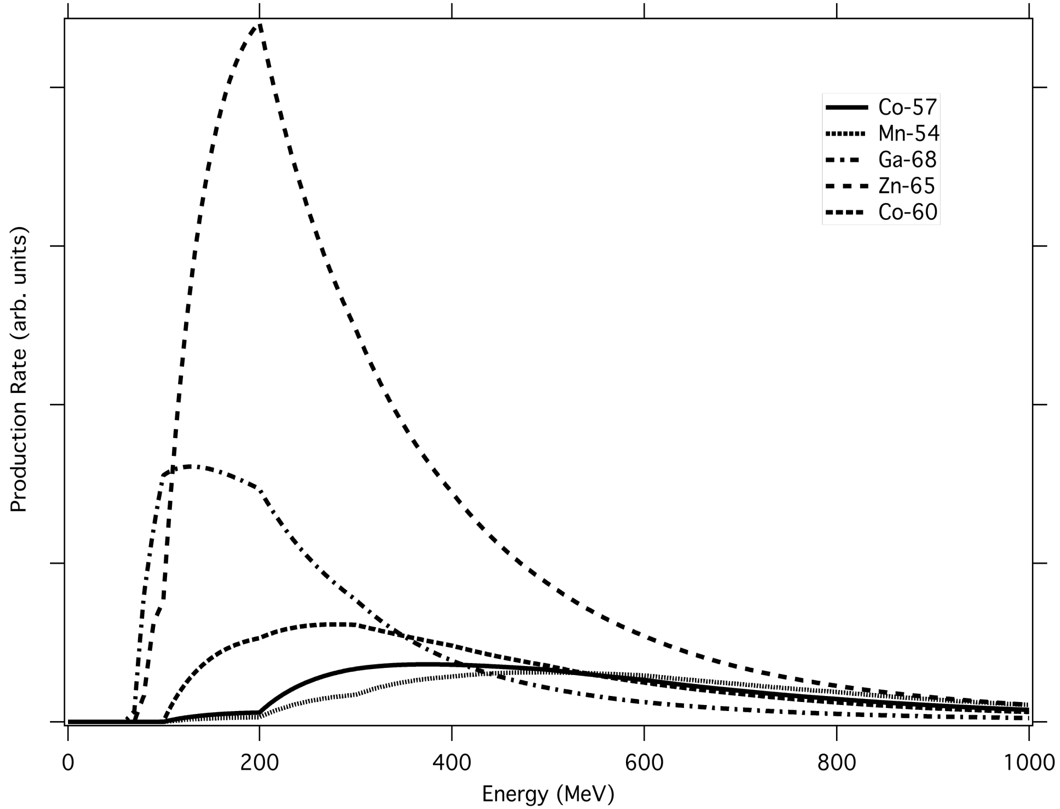
- Has led to large uncertainties and the “recommended” flux has changed. Astropart. Phys. 31, 417420 (2009)
- “Recommended flux”: Gordon et al., IEEE Trans. on Nucl. Sci. 51, 3427 (2004)
- LANSCE neutron beam has similar shape: experimental studies of many isotopes
- Nice review of topic:

Cebrian Universe 6 (2020) 162

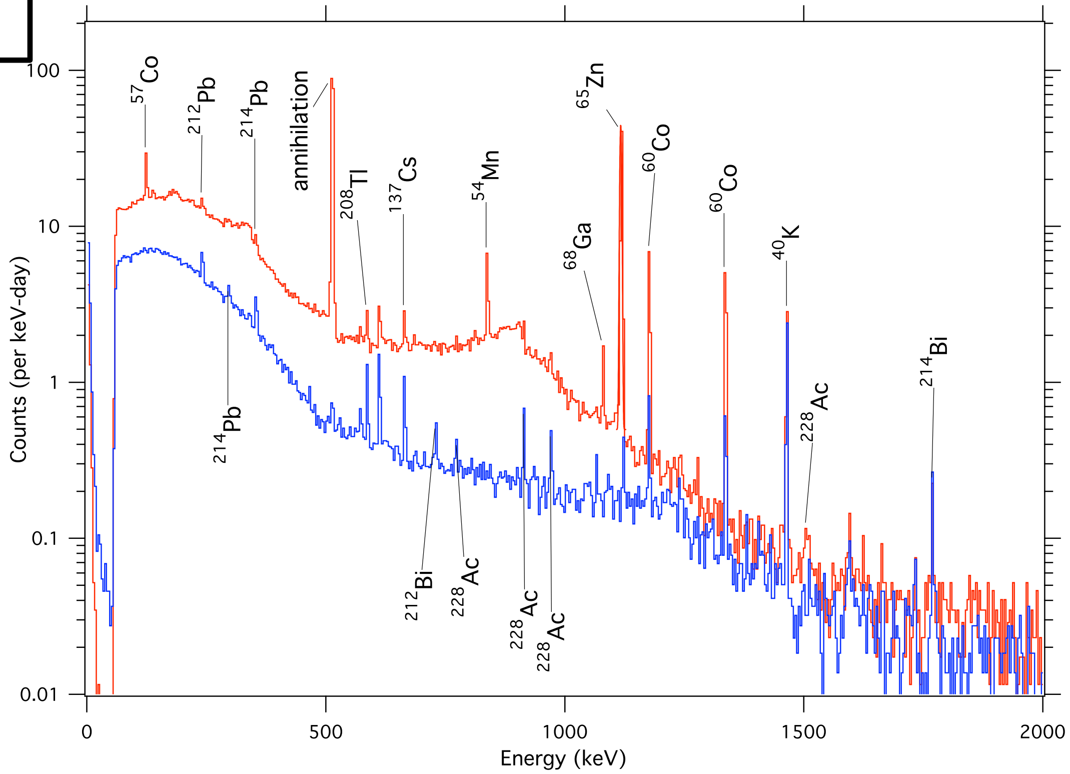


Cosmogenic Production
Some debate about prod. rates - measurement

Production rate dominate between 50-600 MeV.
  Requires high energy n, cosmic ray induced for example.
Large ΔA transitions have very small cross sections.
Example for ^{76}Ge(n,xn yp) trans.



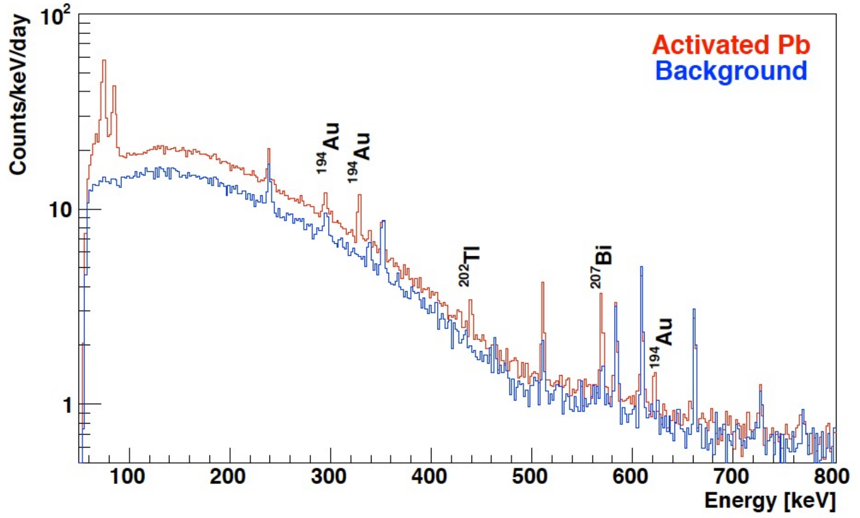
Irradiated Enriched Sample of Ge



Some Other Cosmogenic Examples

Sample	^{26}Al	^{22}Na
Kryal, Hydro Aluminium, UTH 1	0.6±0.3	0.7±0.3
Kryal, VAW, UTH 0.25	< 0.15	< 0.26
Highpural, VAW	< 0.45	< 0.37
ULB I [6]	0.2±0.1	< 0.32
ULB II [5]	$0.38^{+0.19}_{-0.14}$	< 0.18

Al cosmogenics
Majorvites et al. NIM A



^{194}Au, ^{202}Tl, ^{207}Bi prod in Lead
Guiseppe et al, PRC 79 (2009) 054604

^{60}Co in Copper
270 d expos: 2100 μBq/kg
Laubenstein/Heusser
48.3/(kg d)
arXiv:2106.01685

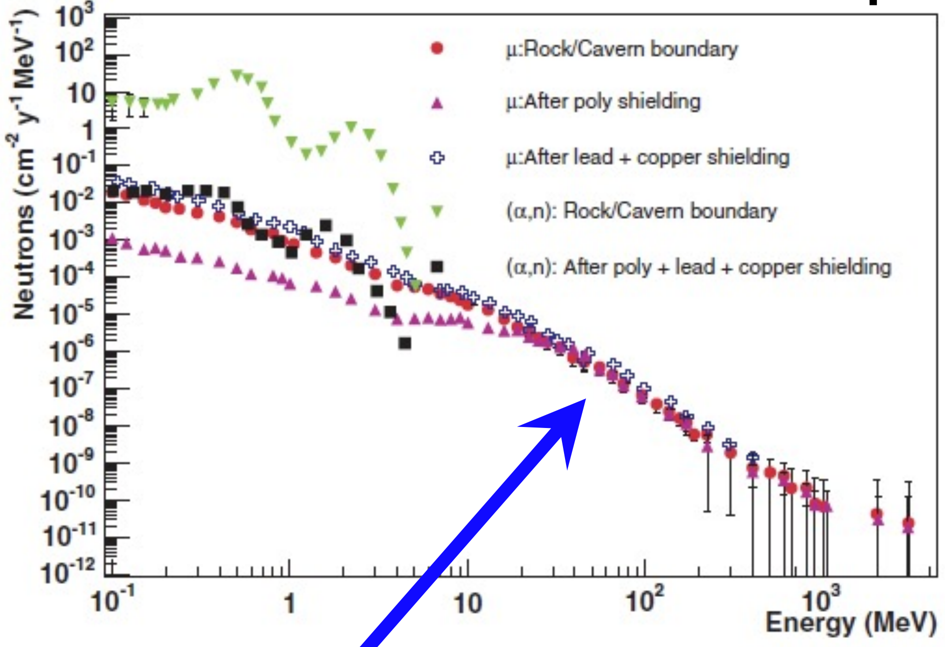
^{110m}Ag in Xe from reactor accident
KamLAND-Zen (not cosmogenic)

New worries - Neutrons

- As we approach 1 cnt/ton-year, a complicated mix emerges for (n,n'γ).
- Neutrons (elastic/inelastic reactions, short-lived isotopes)
  - (α,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 and hence difficult at these low rates to discern actual process, e.g. (n,n'γ) reactions - which isotope/level
    - Simulation codes were imprecise wrt low-energy nuclear physics, but improving
    - Low energy nuclear physics is tedious to implement and verify

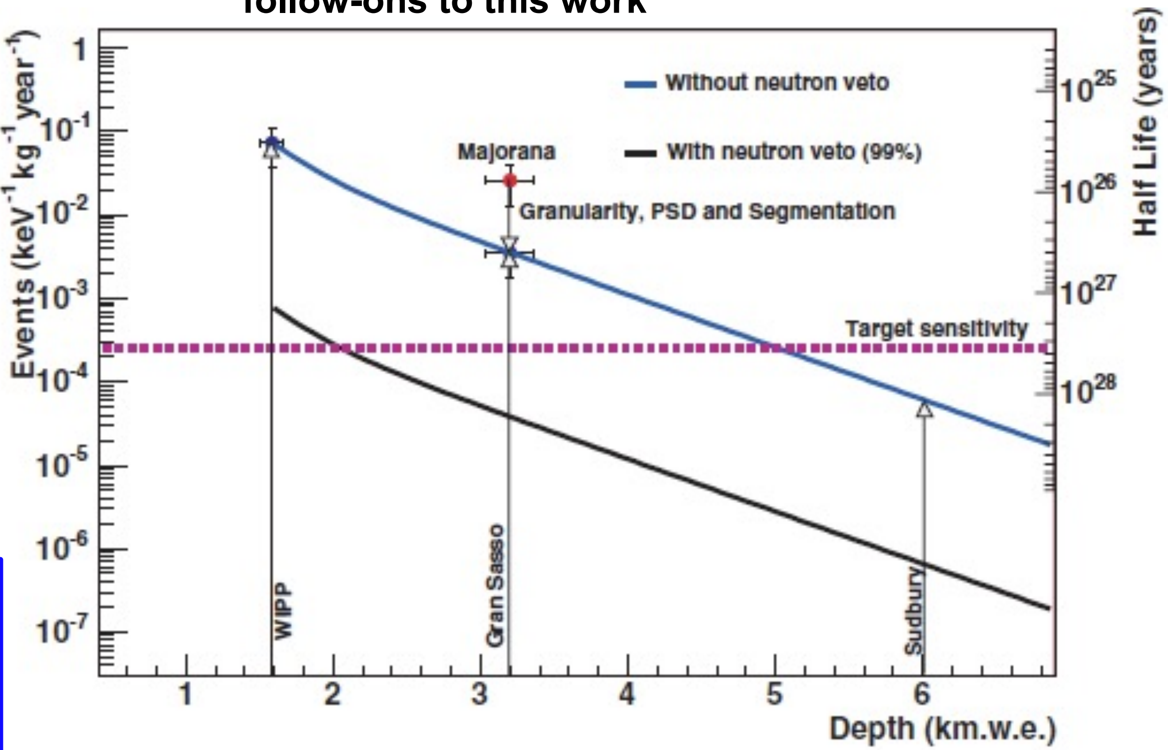
μ-generated n's

Calculation for LNGS depth



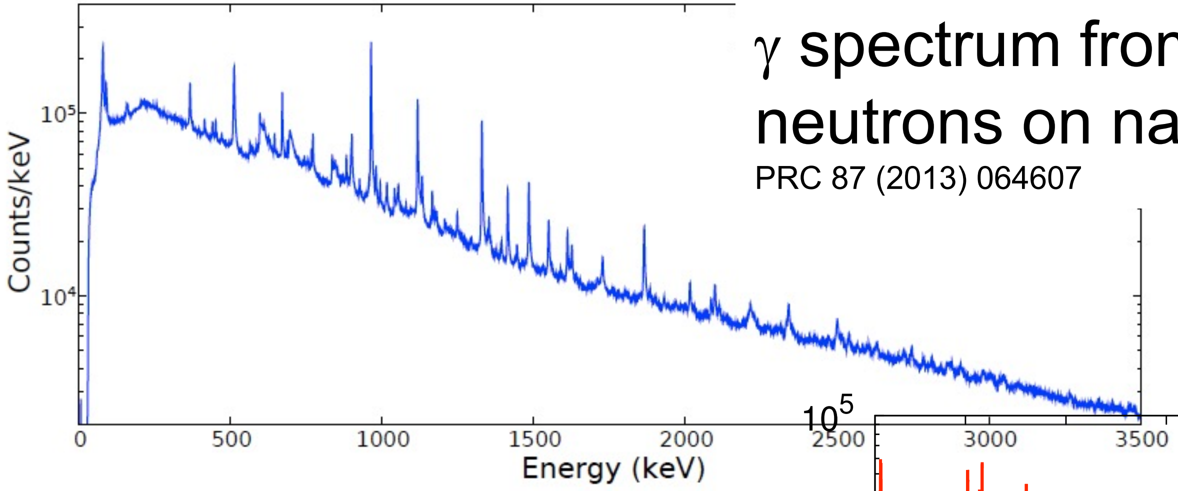
High energy neutrons have low flux but are hard to shield.

Mei/Hime PRD 73, 053004
there are many experiment-specific follow-ons to this work



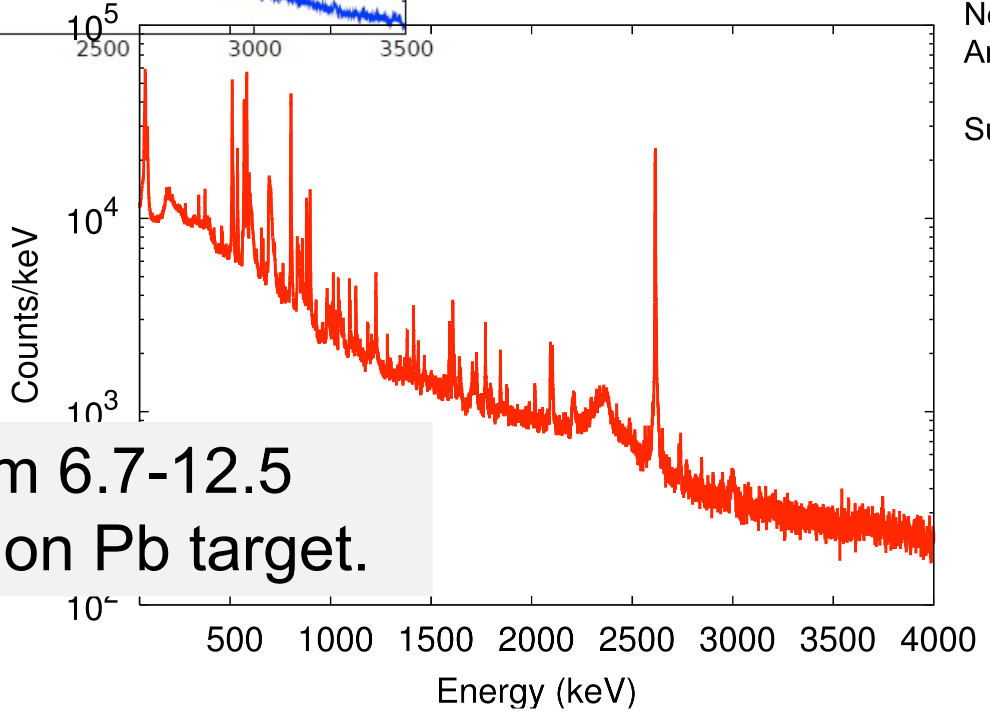
(n,n'γ) Spectra are Complicated

There are so many peaks that at low rates, the spectrum is basically a continuum.



γ spectrum from 3-30 MeV neutrons on natural Cu target.

PRC 87 (2013) 064607

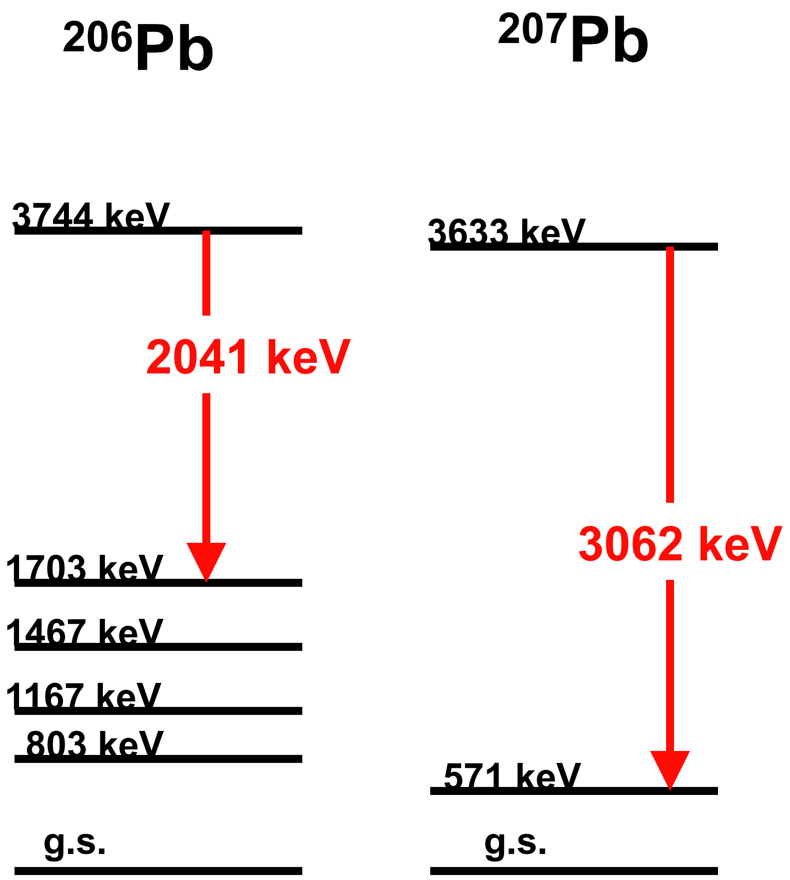


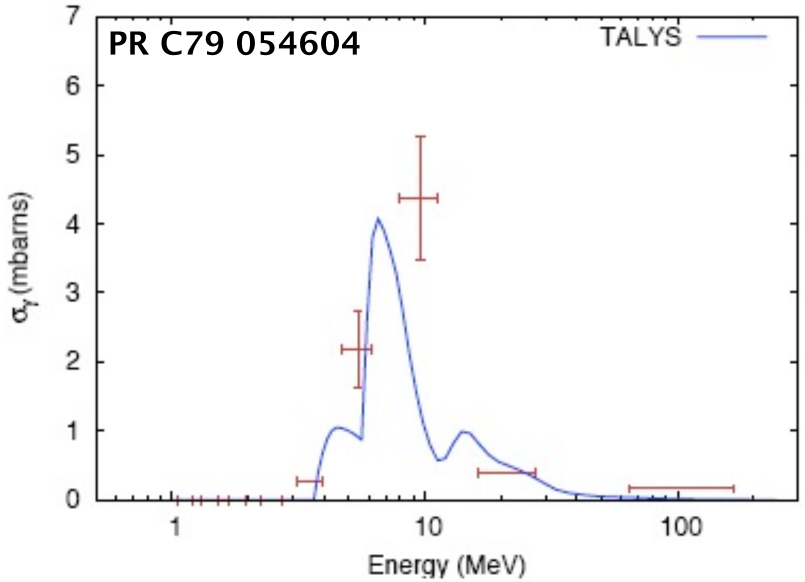
γ spectrum from 6.7-12.5 MeV neutrons on Pb target.

Ne: PRC 86 (2012) 067601
Ar: PRC 85 (2012) 064614

Sure there are other references

Pb(n,n'γ) and ^{76}Ge (Q=2039 keV)



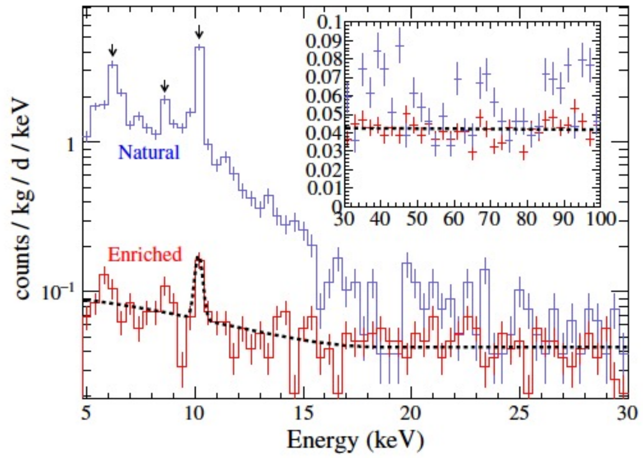


The observed 3062-keV γ-ray production cross section in ^{207,208}Pb.

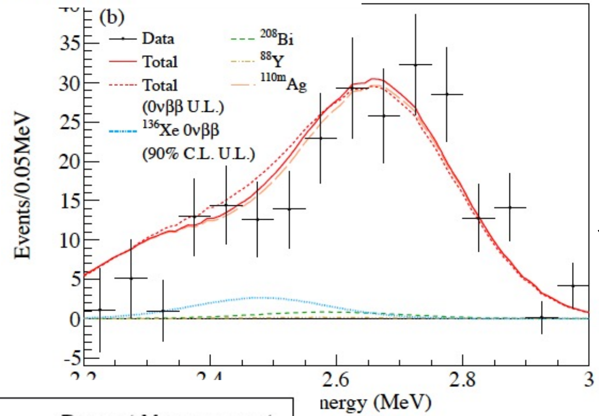
DEP of 3062 line is at 2040 keV!!

Summary: as we approach 1 cnt/ton-year, other complications emerge.

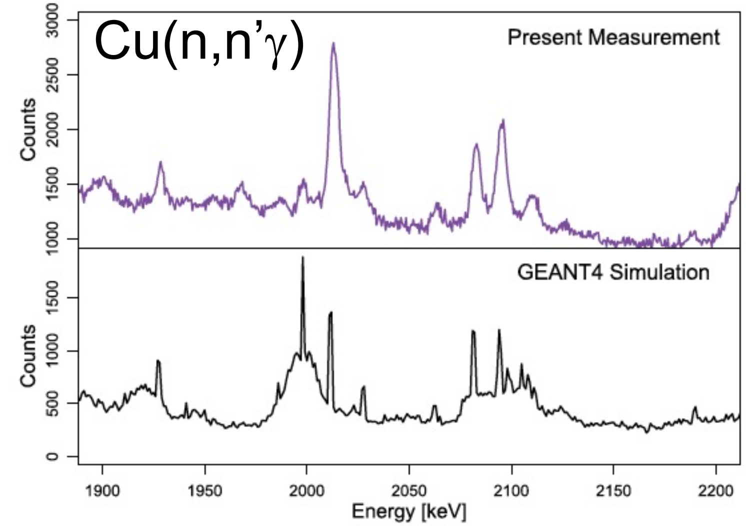
- Long-lived Cosmogenic Isotopes
  - –Material and experimental design dependent
  - –Minimize surface exposure for problematic materials
  - –Development of underground fabrication
- Anthropomorphic Activities
  - –Frequently related to notable events, precautions usually can be implemented
- Neutrons (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

Critical Physics Parameters for Sensitivity

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

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

- Neutrino mixing parameter uncertainties
  - θ_{12}: $\pm$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 $\Gamma_{0\nu}$), theory is addressing.
- Phase space uncertainty: small, 5-10% in $\Gamma_{0\nu}$
- Lepton Number Violation mechanisms or sterile ν: can significantly alter $m_{\beta\beta}$ plots

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)
- g_A: Theory efforts making progress, ab initio calculations
- Interpretation: of course neutrino oscillation experiments play an important role in understanding $\beta\beta$

Occupancy Measurements
Useful to complete other systems

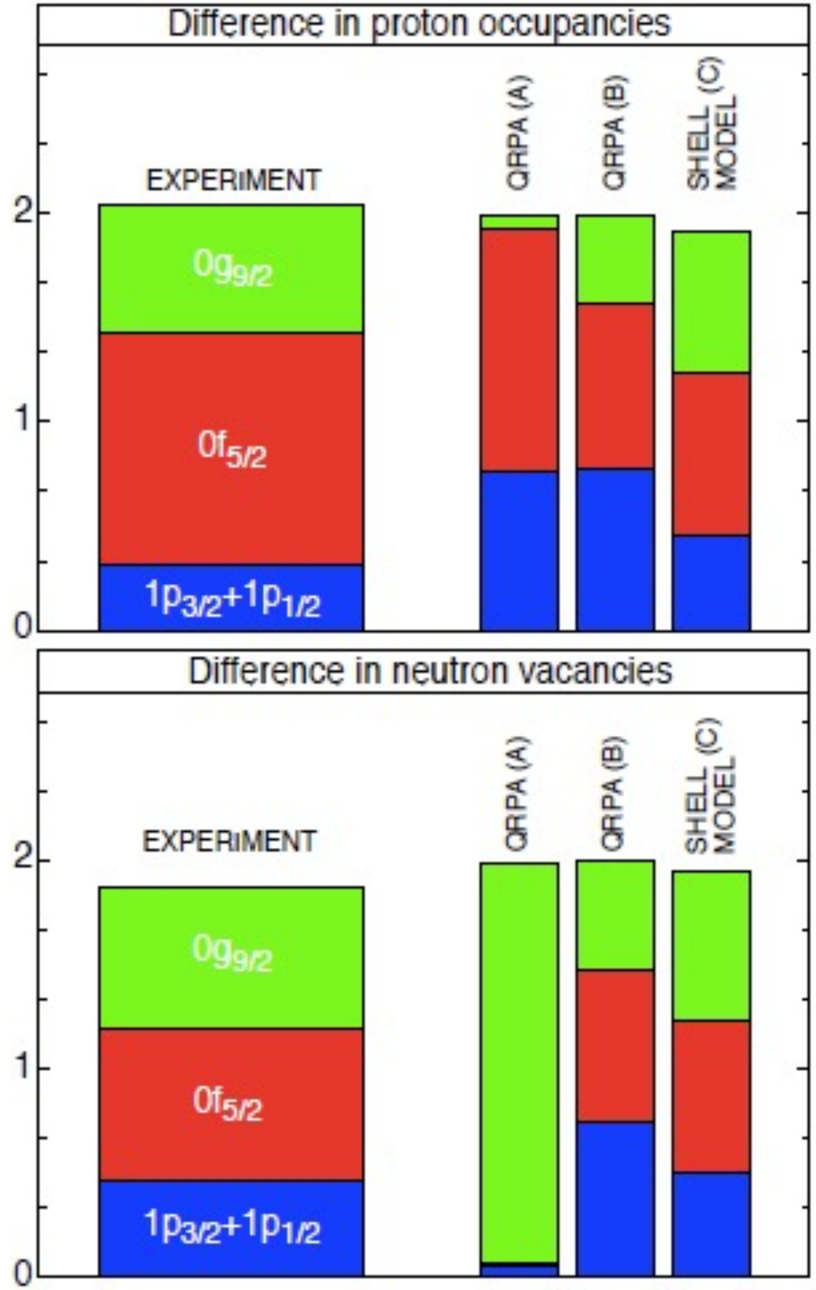
"The difference in the configuration of nucleons between the initial and final states (the 0^+ ground states of ^{76}Ge and ^{76}Se) is a major ingredient in the matrix element."

<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

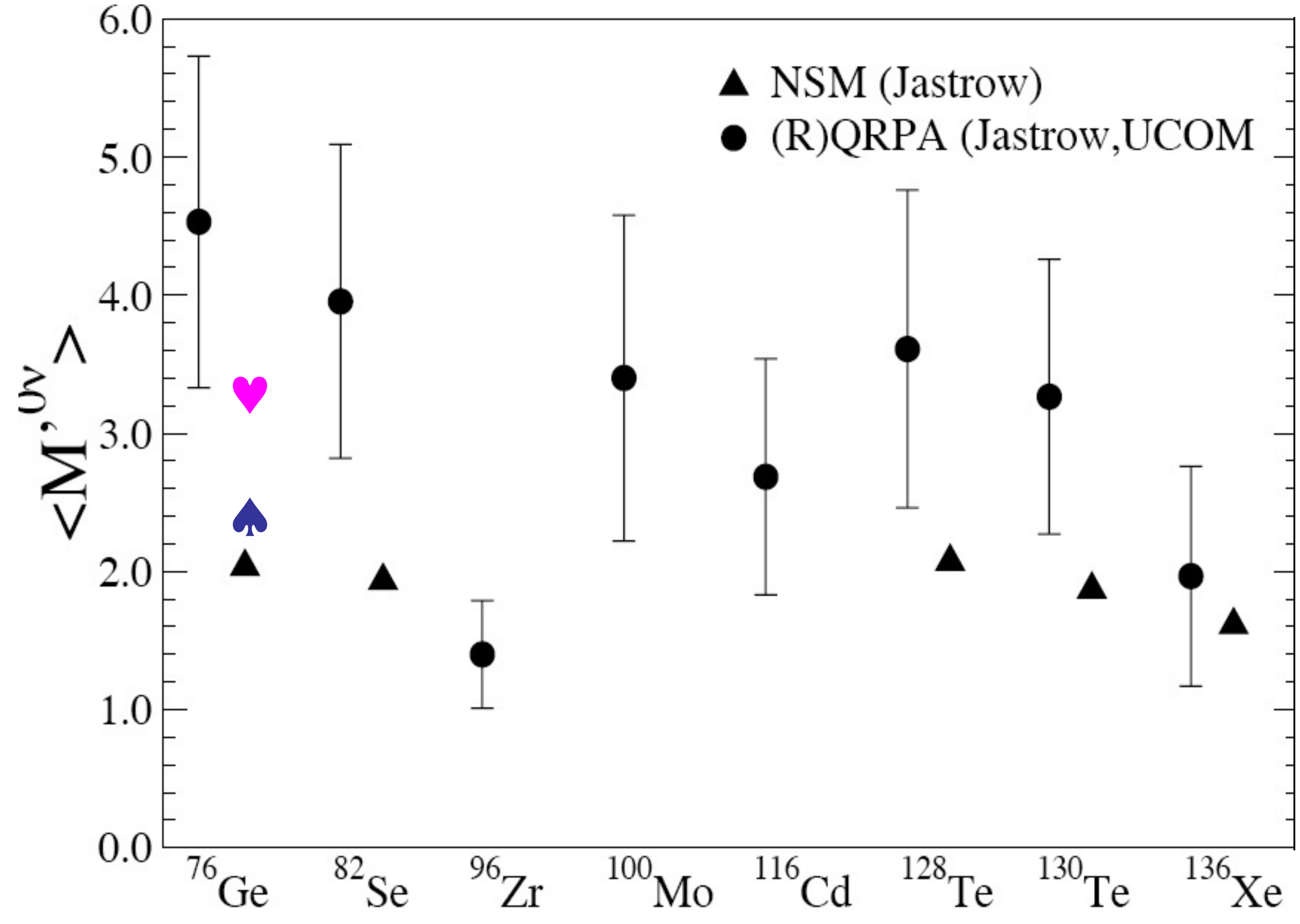
<u>Occupancy Measurements Xe</u>
Szwec et al., PRC 94 (2016) 054314

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.



Phys.Rev.C79:021301,2009

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

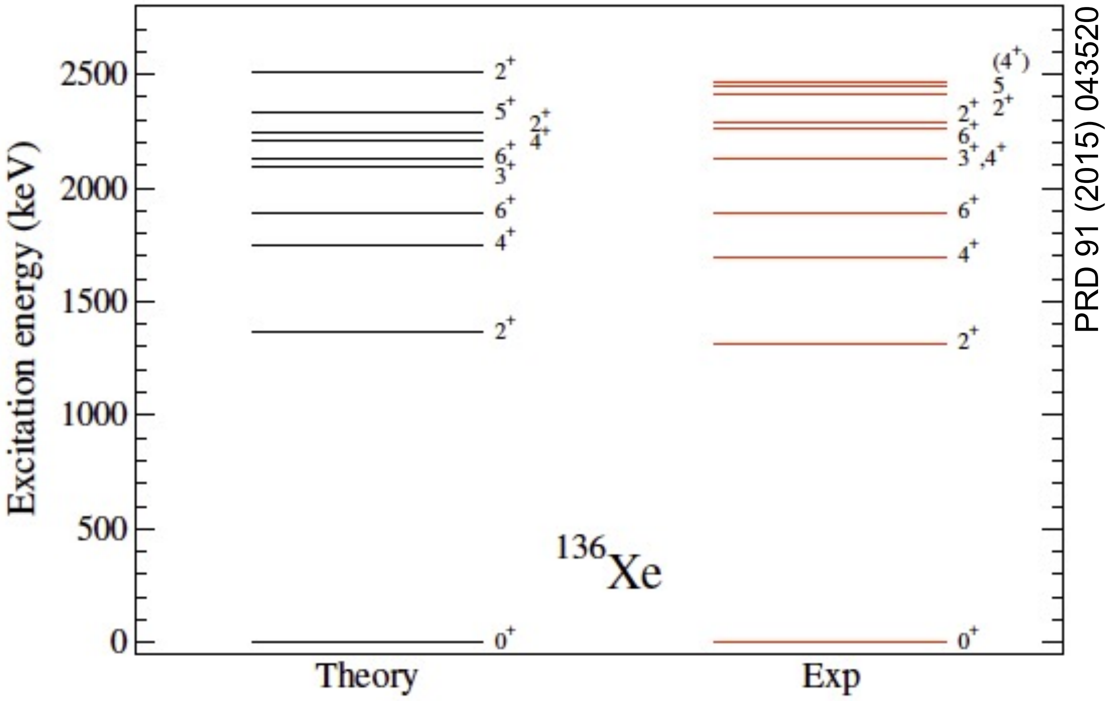


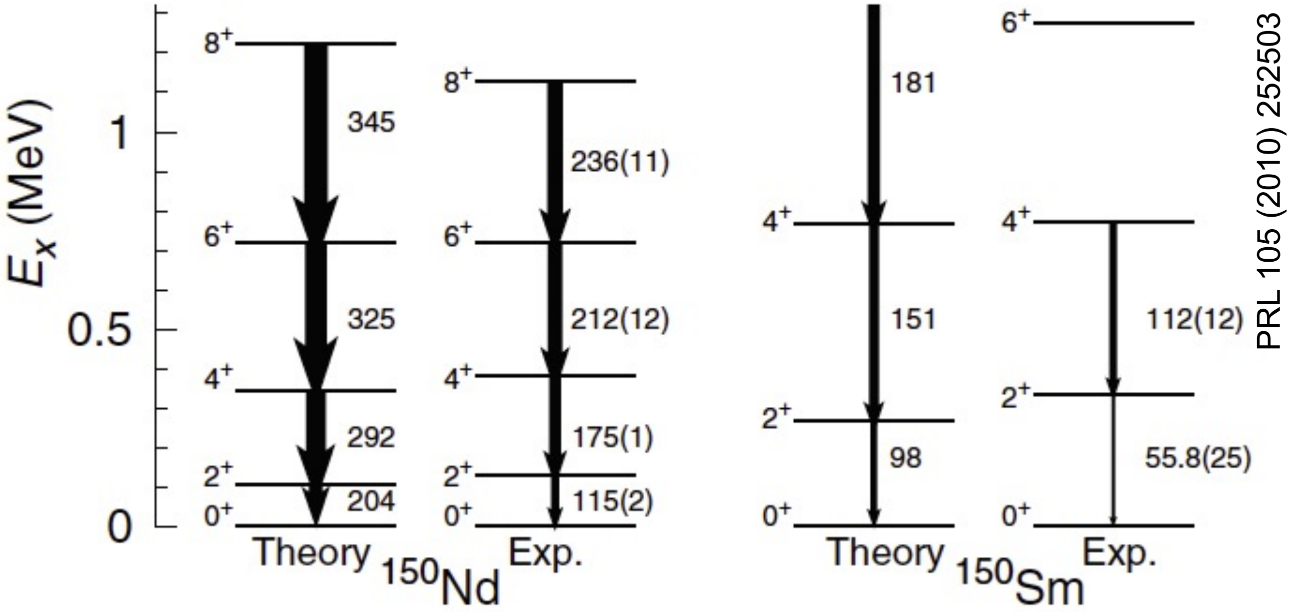
♥ New QRPA value with adjusted mean field so that experimental occupancies are reproduced
PRC 79 (2009) 015502

♠ 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.

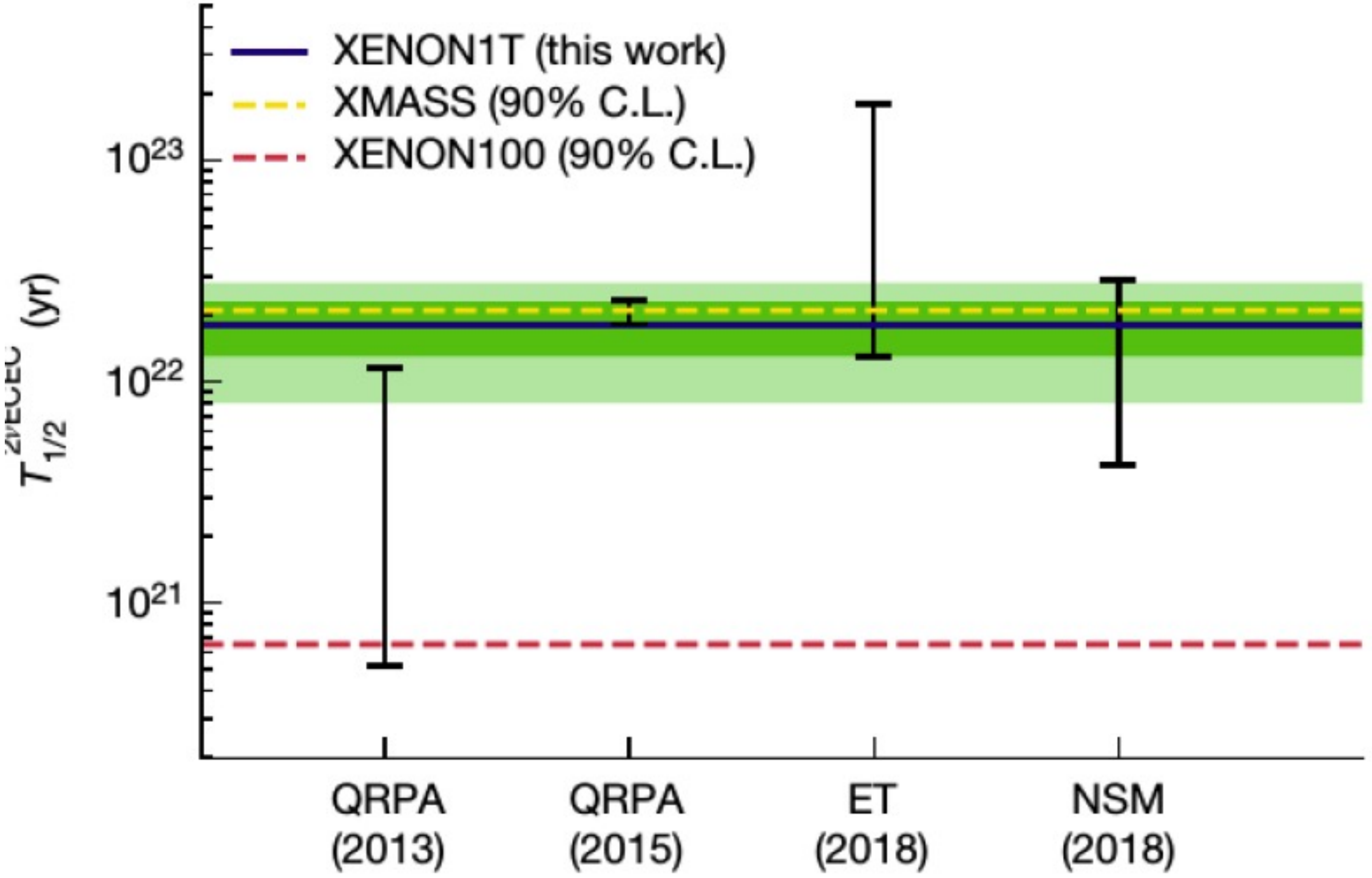
Nuclear Structure Tests - Spectroscopy





Theory and Experiment agree well, or at least well enough.

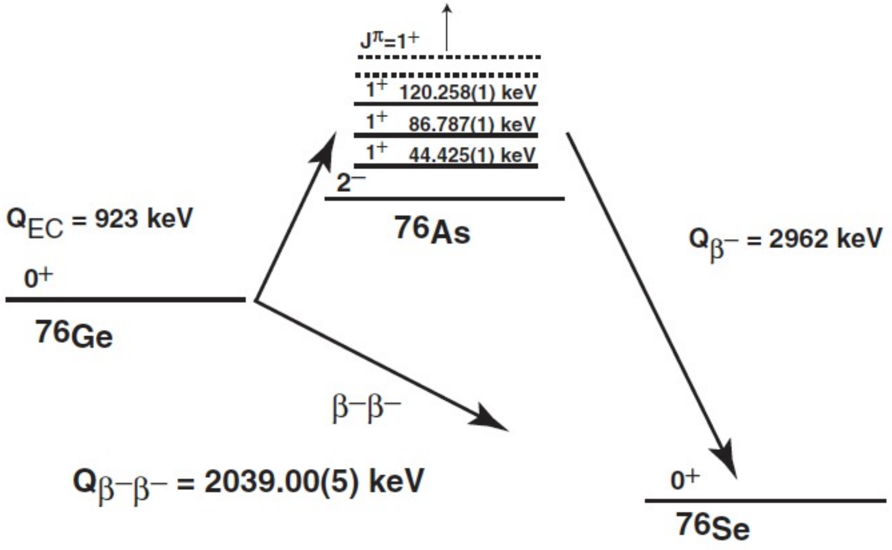
2ν ECEC Predicted Half Life

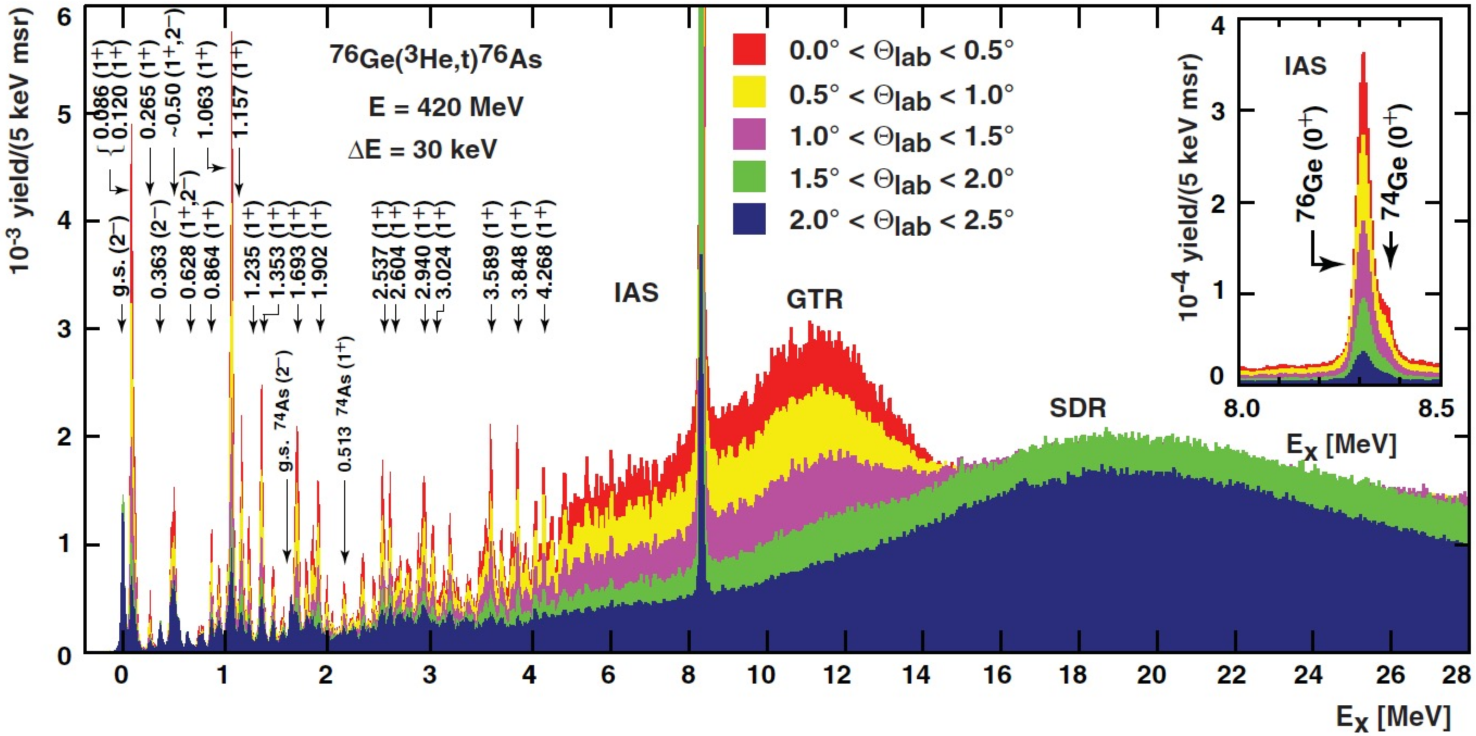


XENON1T: Nat 568 (2019) 532

QRPA: JPG 40 (2013) 075102
QRPA: PRC 91 (2015) 054309
Effective Theory &Shell Model: PLB 797 (2019) 134885

Charge Exchange Reactions have been done on the key ββ isotopes





PRC 86 (2012) 014304

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

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

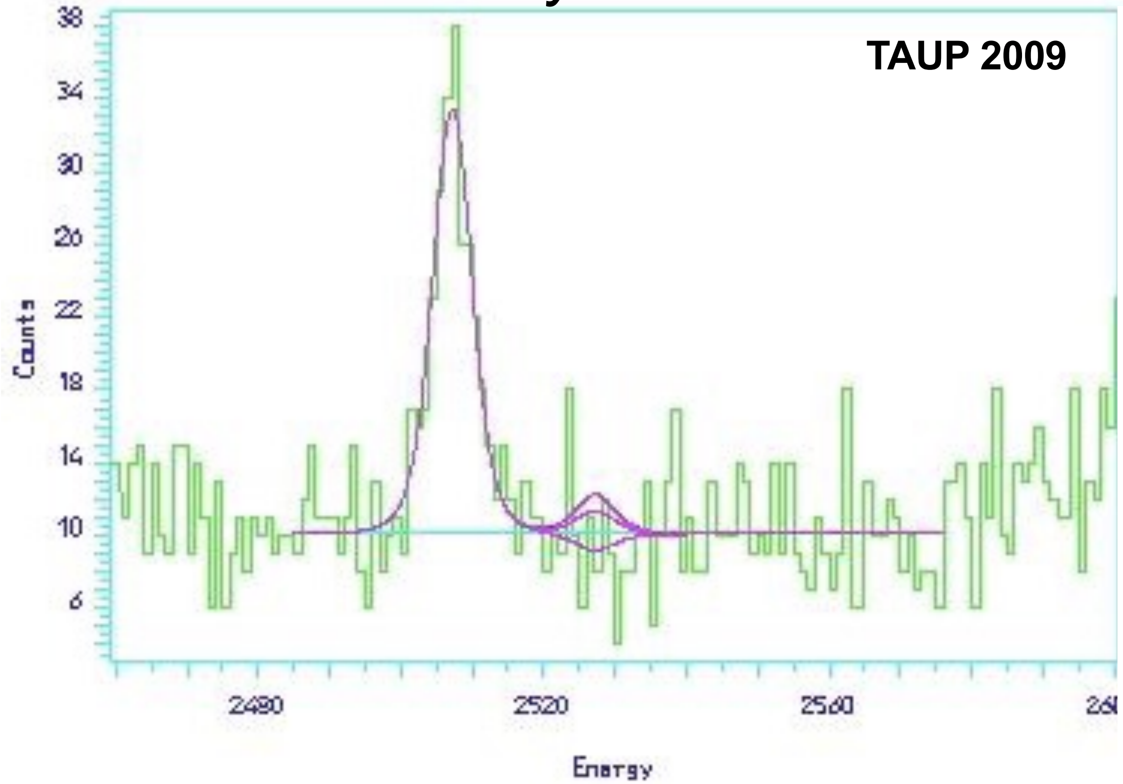
Double charge experiments planned
NURE, e.g. (18O,18Ne) reactions.
arXiv:2002.02761, J Phys: conf. ser 996 (2018) 012021

^{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)

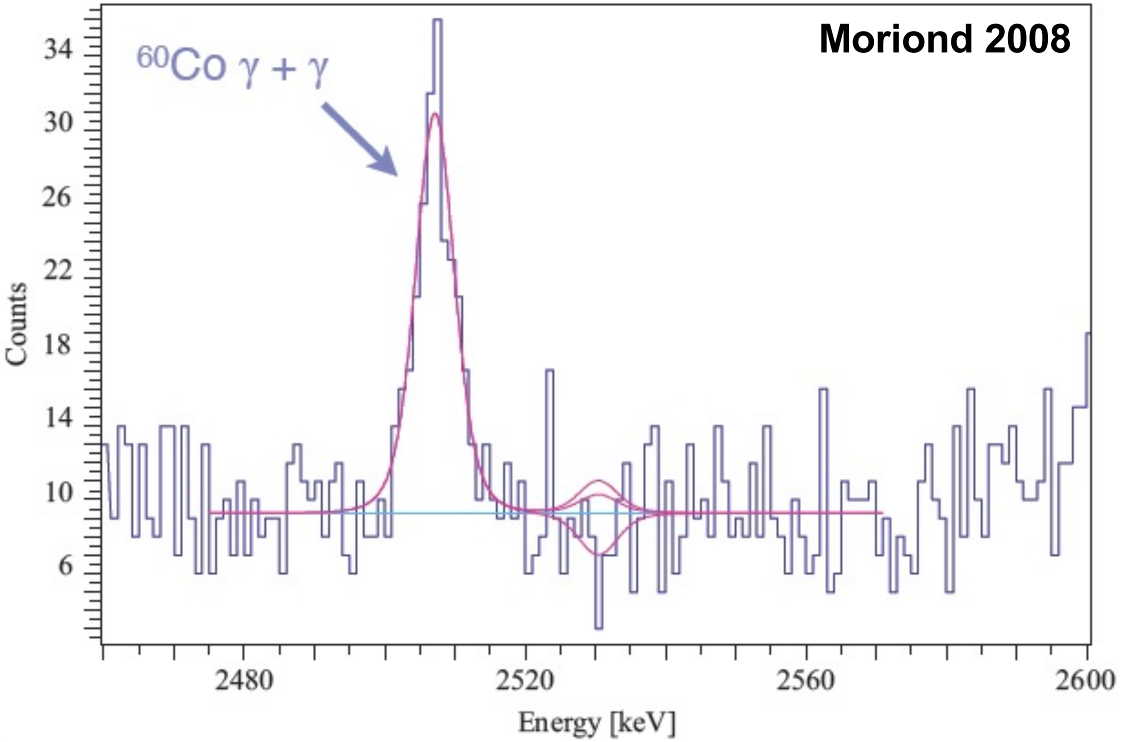
Q-Value Effect Measurements: Very Successful

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.

$\tau > 2.94 \times 10^{24} y$ 2527.518 keV



$\tau > 3.1 \times 10^{24} y$ 2530.3 keV



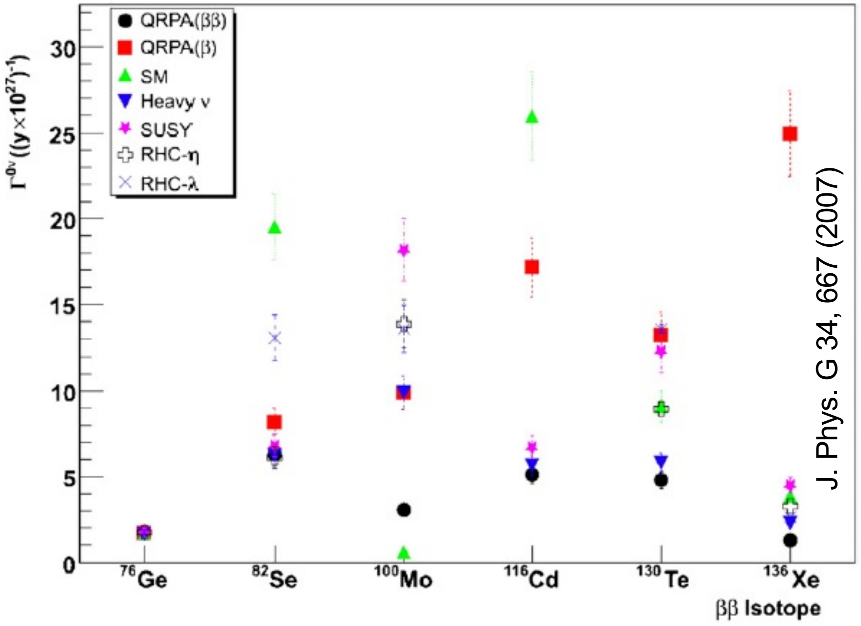
^{76}Ge PRC 81 (2010) 032501(R), ^{82}Se PRL 110 (2013) 012501, ^{100}Mo PLB 662 (2008) 111, ^{116}Cd/^{130}Te PLB (2011) 412, ^{150}Nd PRC 82 (2010) 022501(R), ^{136}Xe PRL 98 (2007) 053003

Need several ββ(0ν) 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 ββ 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.

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.



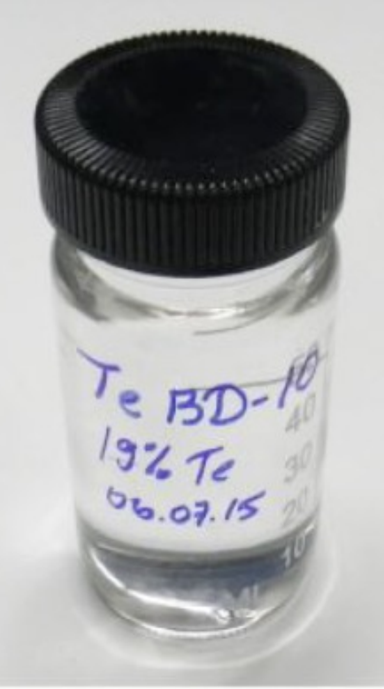
J. Phys. G 34, 667 (2007)

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

Recent R&D Successes For Ton-Scale

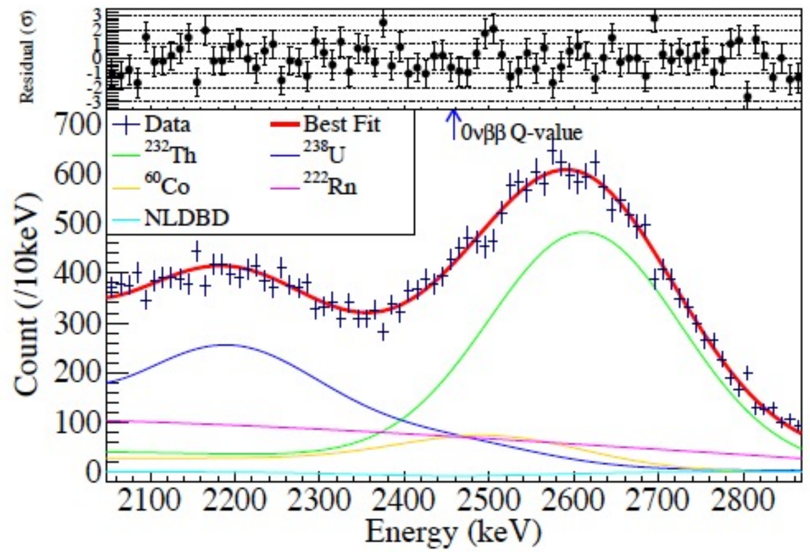
Source-Loaded Scintillator

- 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)



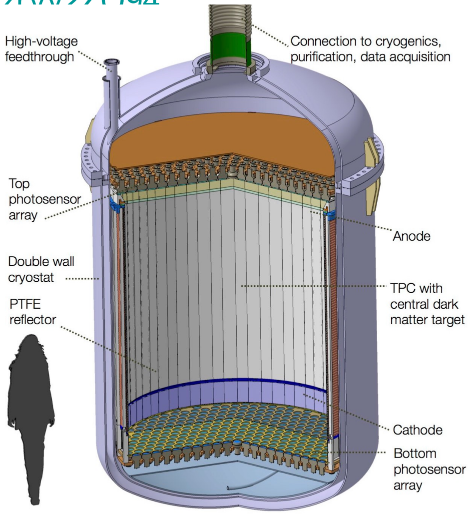
- SNO+, Te
  - Metal loading with good transparency
  - arXiv:1904.01418
  - Scintillator cocktail, Linear alkyl benzene (LAB) + 2,5-diphenyloxazole (PPO)
  - Organo-metallic compound from telluric acid and butanediol
  - High fractions of isotope
  - 0.5% loading leads to over a ton of isotope

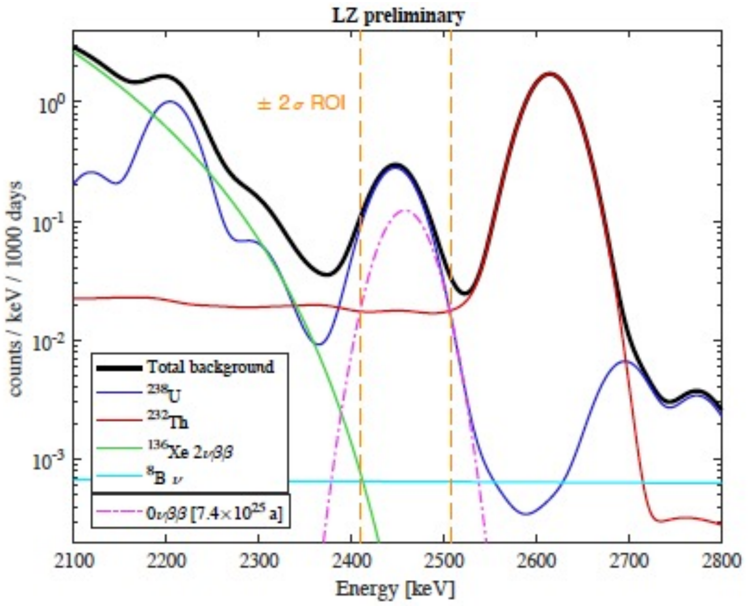
Recent R&D Successes For Ton-Scale



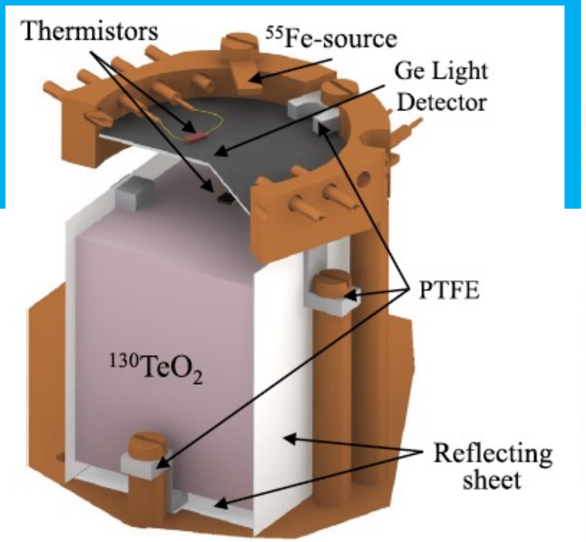
[Dual Phase TPCs for Dark Matter]

- Large detectors planned to come on line in next few years.
- Natural Xe, but many tons of it.
- PANDAX-II, first limit on 0νββ from dual phase detector.
  - 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#.XRzrVv2ZO94
  - arXiv:1509.02910
  - Proposal stage
- XENON-1T, DARWIN
  - JCAP11 (2016) 017
  - Very large detector, 40 tons
  - Already observed 2νECEC
  - Better energy resolution



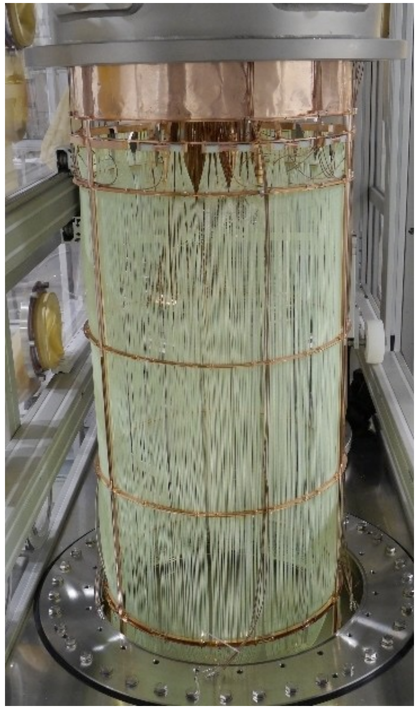


Recent R&D Successes
Crystal Calorimetry



Reduced surface sensitivity with Bolometry

- Bolometers have no dead layer, no natural immunity against surface background. Success reducing this background
- AMoRE, scintillation, arXiv:1903.09483
- CUPID, scintillation, arXiv:1906.05001
- LUMINEU, scintillation, arXiv:1709.07846, Eur Phys J C77 (2017) 785
- CROSS, superconductive Al coating and PSD, arXiv:1906.10233

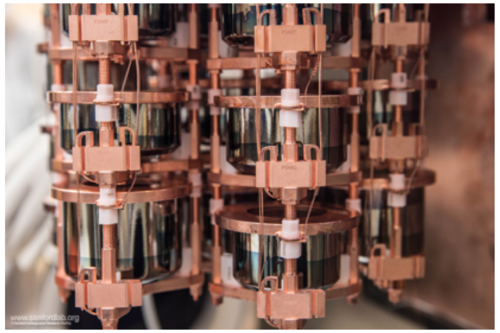


Large point-contact Ge detectors

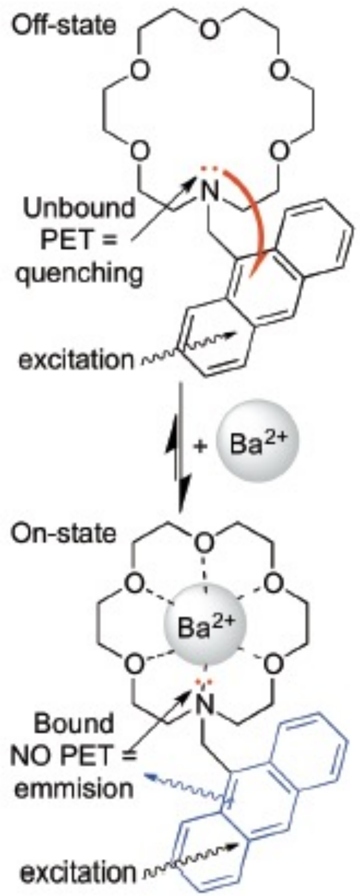
- MAJORANA, PRL 120 (2018) 132502/arXiv:1902.02299
- GERDA, PRL 120 (2018) 132503
- Good multiple site rejection/resolution, 2 kg and getting larger
- Inverted semi-coax, NIM A665, (2011) 25, NIM A891 (2018) 106

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
Daughter Detection

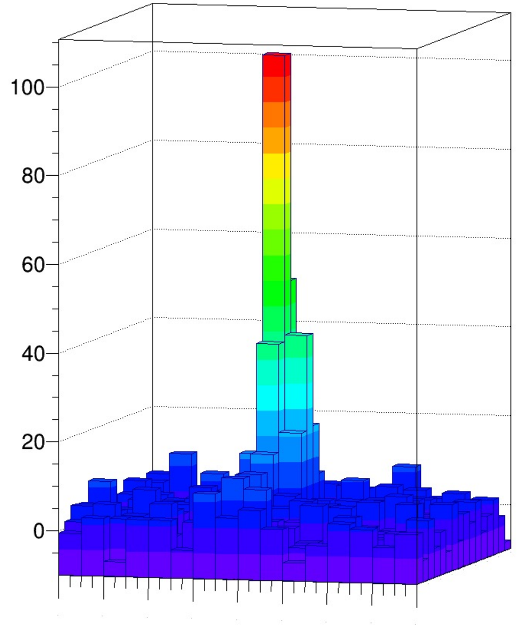


High Pressure Xe Gas TPCs

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

Liquid Xe TPCs

- nEXO, PRC 97 (2018) 065503, arXiv:1906.02723
- Good energy resolution in LXe, PRL 109 (2012) 032505
- Detection of Ba in solid Xe, Nature 569 (2019) 203

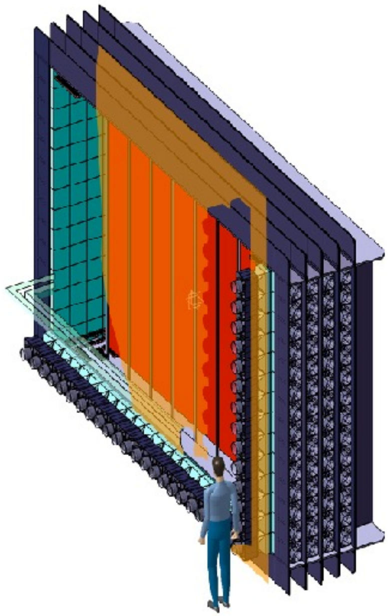


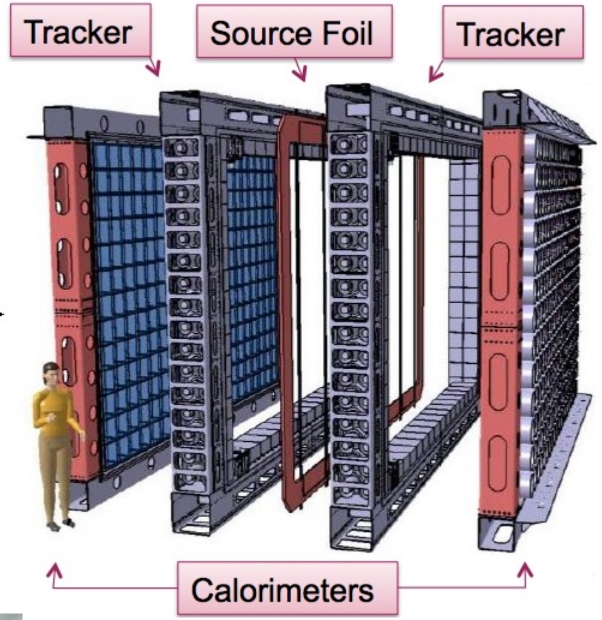
Exciting progress toward detecting the daughter, but there is still a ways to go. Technique could remove all background except that due to $2\nu\beta\beta$ and neutrino CC scattering.

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.



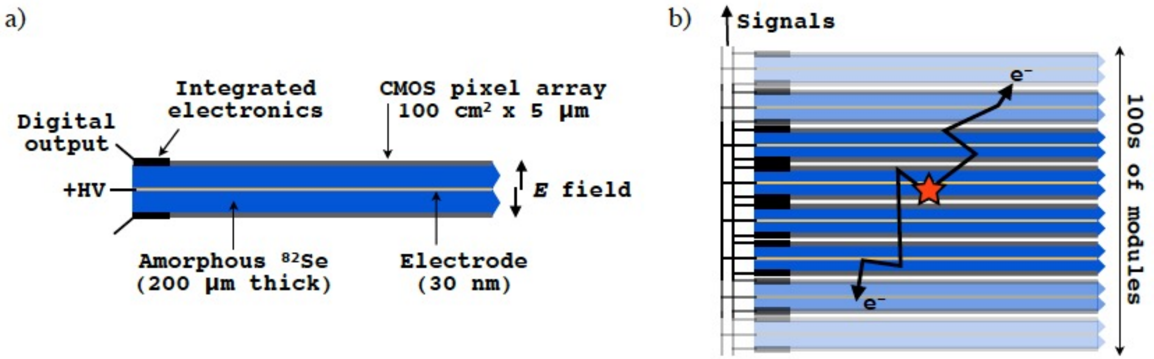


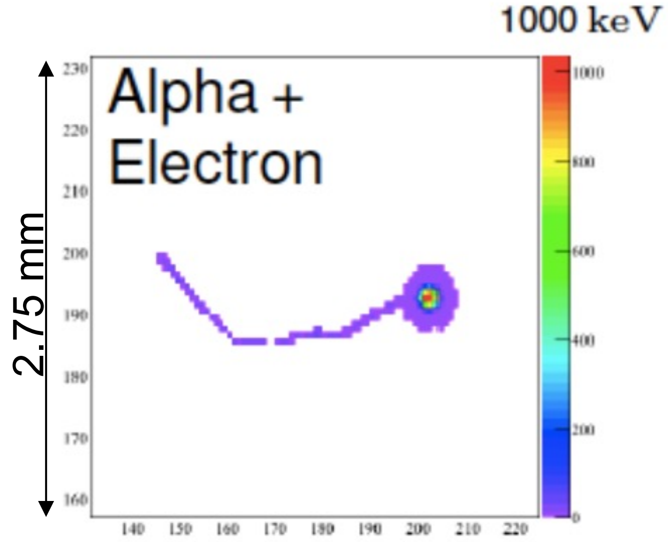
R&D Concepts for Advanced Projects
Longer term development and more speculative

Tracking in high density detectors

- Might address the disadvantage of thin sources required for tracking experiments.
- Electron scattering is significant.
- Xe TPCs have possibilities 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.

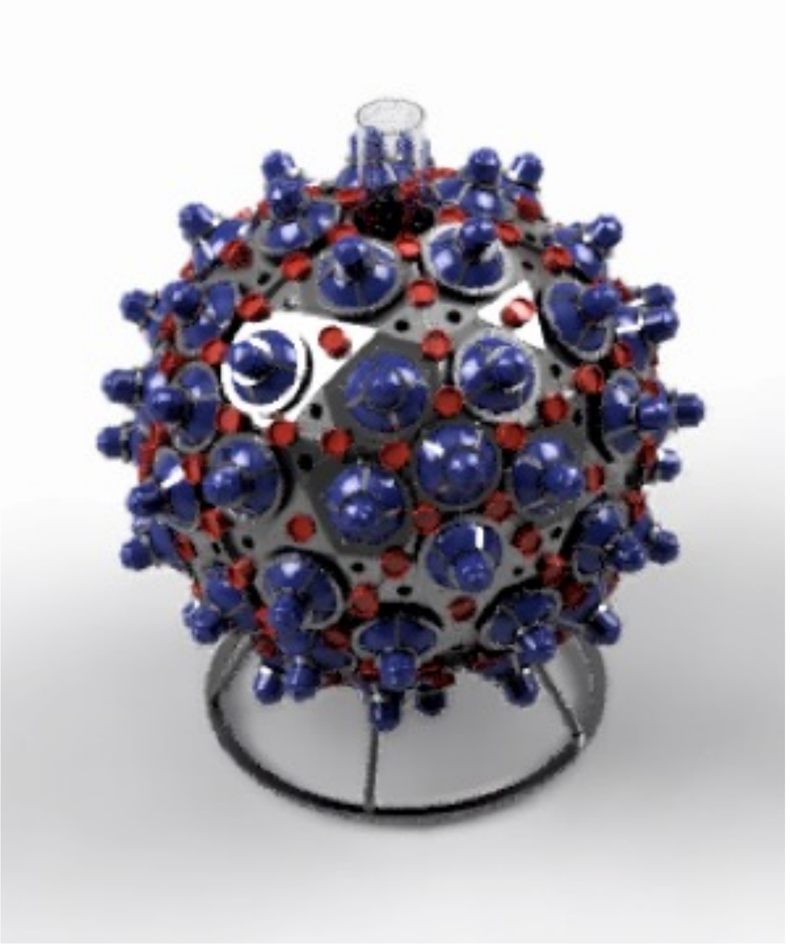




Solid state tracking detectors are still small and require a lot of electronics and cables.

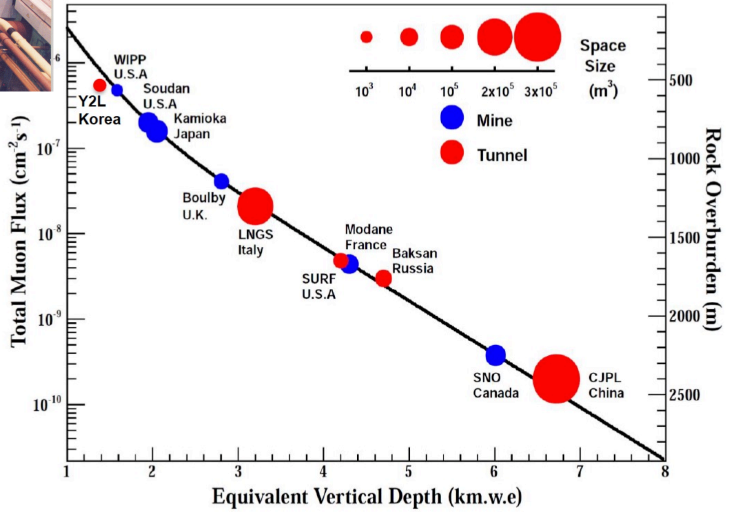
R&D Concepts for Advanced Projects
Longer term development and more speculative

- 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, will test $\beta\beta$ 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)



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Key R&D Challenges: Great Progress

This is a generic summary. This is an idea of the work being done.

- Source Loaded Scintillator
  - Largest quantity of source
  - Modest energy resolution
  - Key R&D
    - Improved light collection
    - Source loading
- Crystal Calorimetry
  - Less source
  - Best energy resolution
  - Lowest backgrounds to date
  - Key R&D
    - Surface alphas
    - U/Th in nearby parts
    - Cable connections
- High Pressure Gas/Liquid TPC
  - Good amount of source
  - Modest energy resolution
  - Key R&D
    - Improved light collection
    - High electric fields
    - Electronic readout
    - Daughter identification
- Tracking
  - Least amount of source
  - Low efficiency, Very low background
  - Best meas. of kinematic parameters
  - Key R&D
    - Source purity
    - Energy resolution
    - Improved light collection from scintillator
    - U/Th in nearby parts

Enrichment Technologies

Cost, Throughput, World Production of Source Material

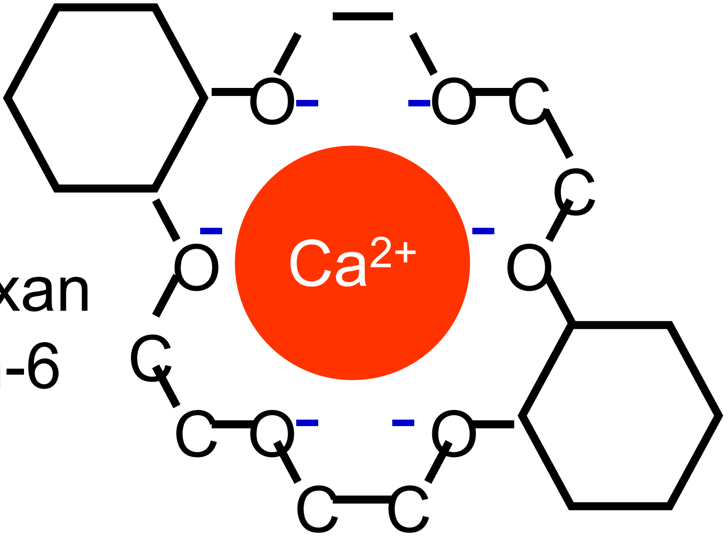
Separation technology	*Field of use*	*Production per year*	*Cost*
Electromagnetic (mass-spectroscopy effect)	universal	tens of grams	high
Chemical & phys. processes (rectification, chem. exchange etc)	light elements	tons	low
Gas diffusion	elements forming gas compounds	thousands of tons	middle
Gas centrifuge	elements forming gas compounds	thousands of tons	low
Laser (optical) separation	elements having isotope shift of spectrum lines	kilograms	middle
Plasma ion-cyclotron effect (under developing – the USA, Russia)	universal	R&D	middle

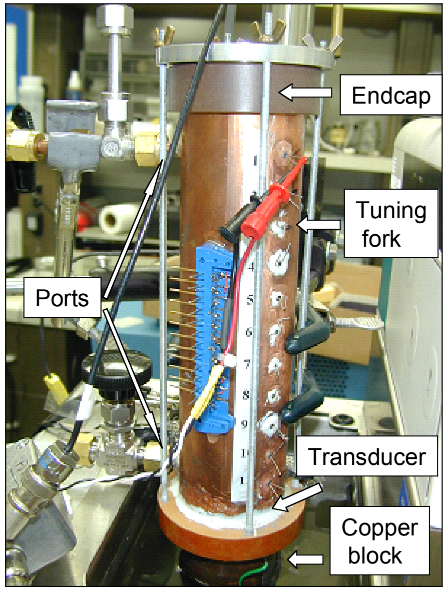
Courtesy Lev Inzechik

Alternative Technologies

- Gas Centrifuge
- Plasma Separation
- Acoustic Barodiffusion
- Cryogenic/Fractional Thermal Distillation/Diffusion
- Crown Ether

Dicyclohexan
18-crown-6





Acoustic Separation