Experimental Overview of Neutrinoless Double Beta Decay

Steve Elliott

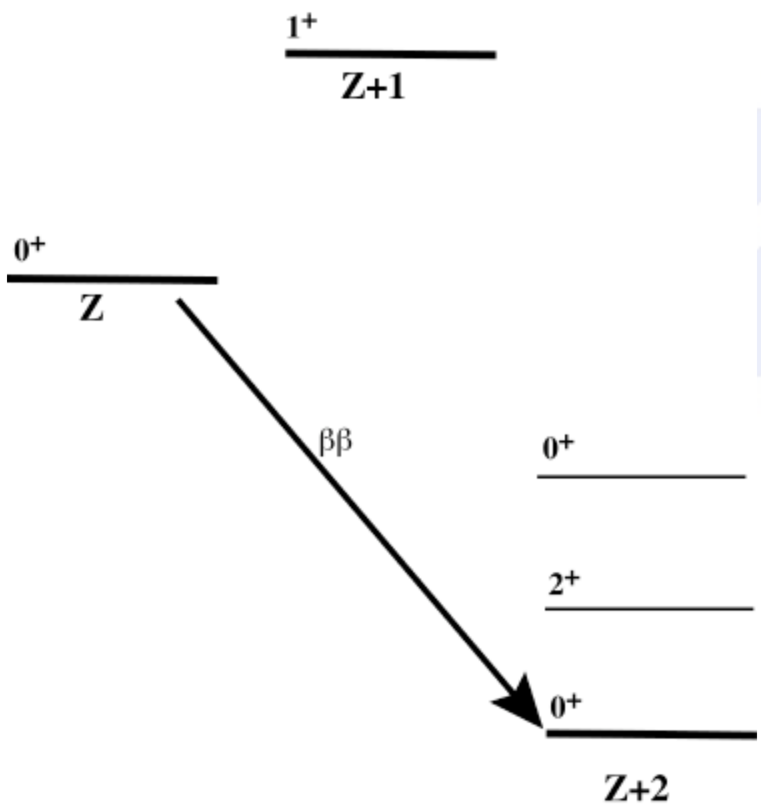
Phenomenology Basics

Background Issues

Auxiliary Measurements

I will avoid talking about the experiments themselves – the experts are here and will speak.

ββ



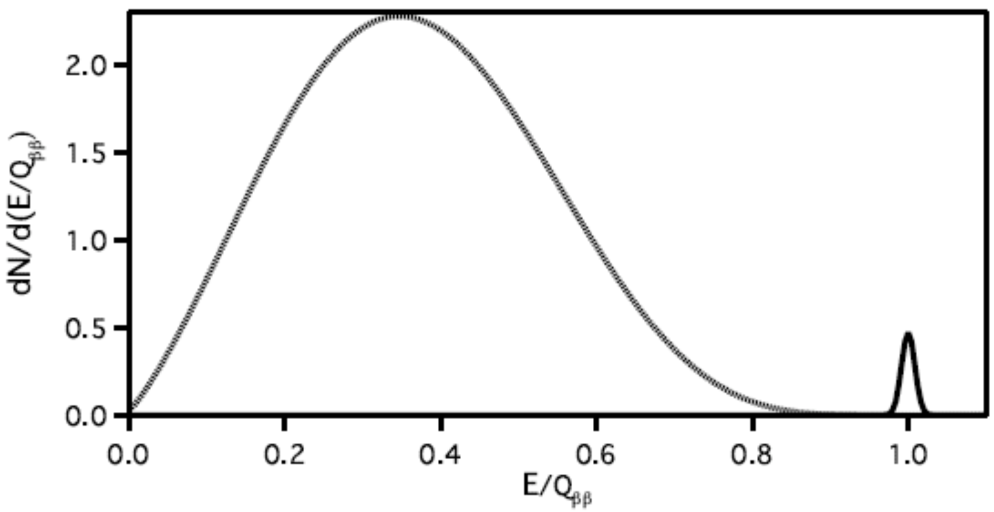


Fig. from arXiv:0708.1033

ββ Decay Rates

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

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

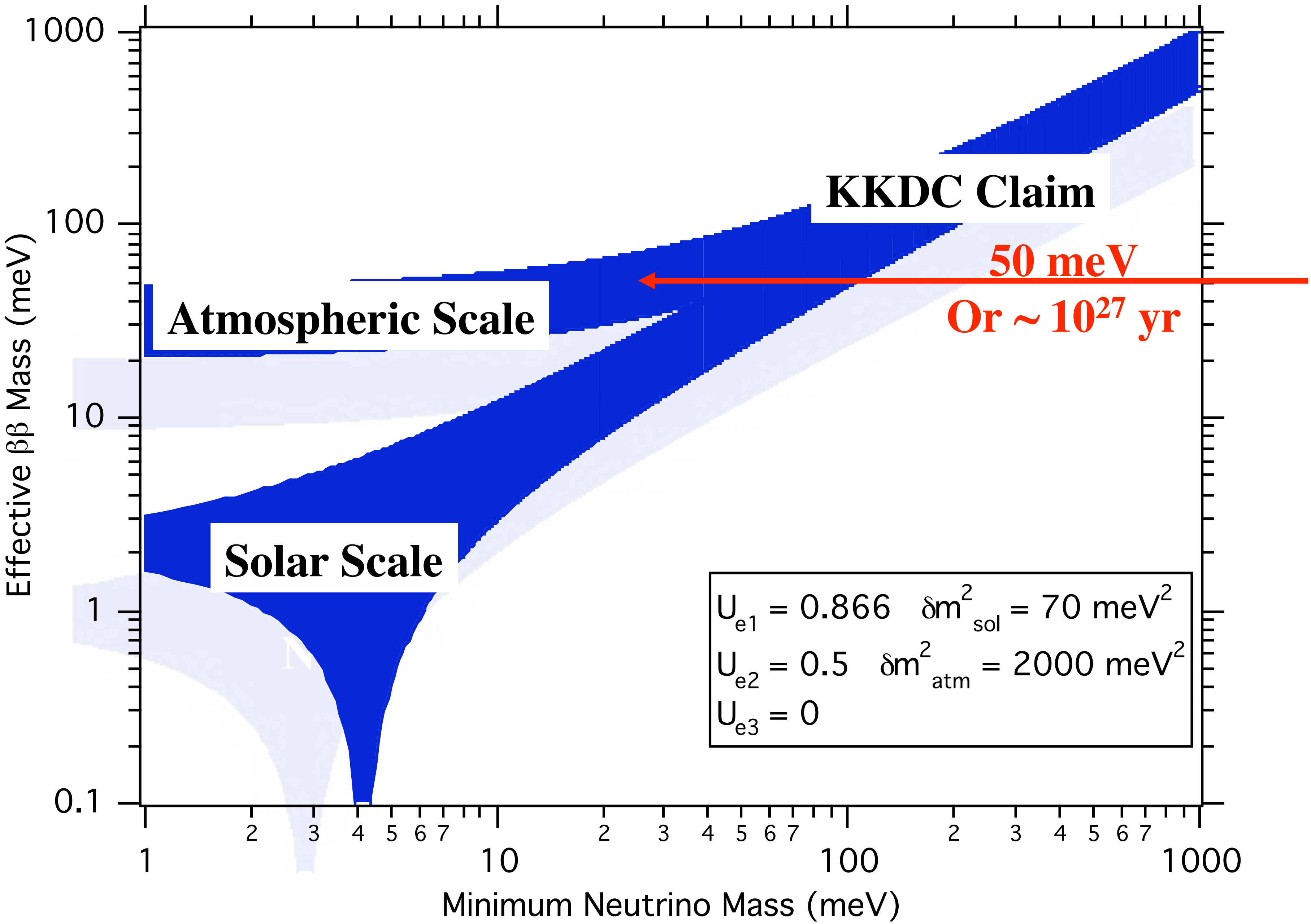
G are calculable phase space factors.

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

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.

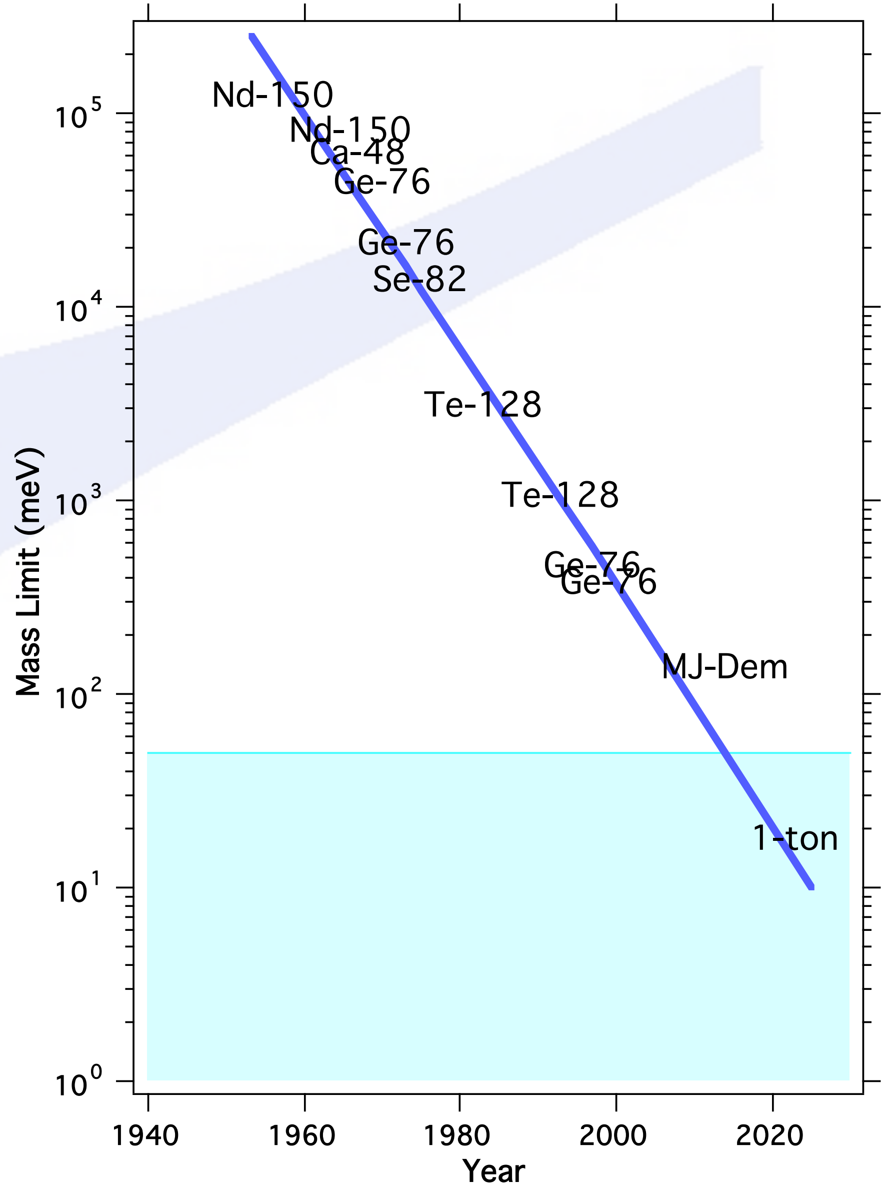


KKDC Claim
50 meV
Or ~ 10^{27} yr
Atmospheric Scale
Solar Scale
$U_{e1} = 0.866$ $\delta m^2_{sol} = 70$ meV^2
$U_{e2} = 0.5$ $\delta m^2_{atm} = 2000$ meV^2
$U_{e3} = 0$
Effective ββ Mass (meV)
Minimum Neutrino Mass (meV)
1000
100
10
1
0.1
1
10
100
1000

Past Results

^{48}Ca CaF_2	>5.8x10^{22} y	<(3.5-22) eV
^{76}Ge H-M	>1.9x10^{25} y	<0.35 eV
^{76}Ge IGEX	>1.6x10^{25} y	<(0.33-1.35) eV
^{76}Ge KDHK	=2.2x10^{25} y	=0.32 eV
^{82}Se NEMO	>3.6x10^{23} y	<(0.89-1.61) eV
^{96}Zr NEMO	>9.2x10^{21} y	<(7.2-19.5) eV
^{100}Mo NEMO	>1.1x10^{24} y	<(0.45-0.93) eV
^{116}Cd Kiev	>1.7x10^{23} y	<1.7 eV
^{128}Te geochem	>7.7x10^{24} y	<(1.1-1.5) eV
^{130}Te (CUORE)	>2.94x10^{24} y	<(0.21-0.70) eV
^{136}Xe Gotthard	>4.4x10^{23} y	<(1.8-5.2) eV
^{150}Nd NEMO	>1.8x10^{22} y	<(1.7-7.6) eV

Elliott & Vogel
Annu. Rev. Part. Sci. 2002 52:115



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
CU…					…asso
C…					…asso
I…					…oka
EX…					…P
					…EL
…					
G…					
G…					…asso
Ka…					…oka
MA…					…L
M…					
N…					…anc
S…					…ab
Sup…					…us
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	

- **Calorimeter**
  - **Semi-conductors**
  - **Bolometers**
  - **Crystals/nanoparticles immersed in scintillator**
- **Tracking**
  - **Liquid or gas TPCs**
  - **Thin source with wire chamber or scintillator**

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

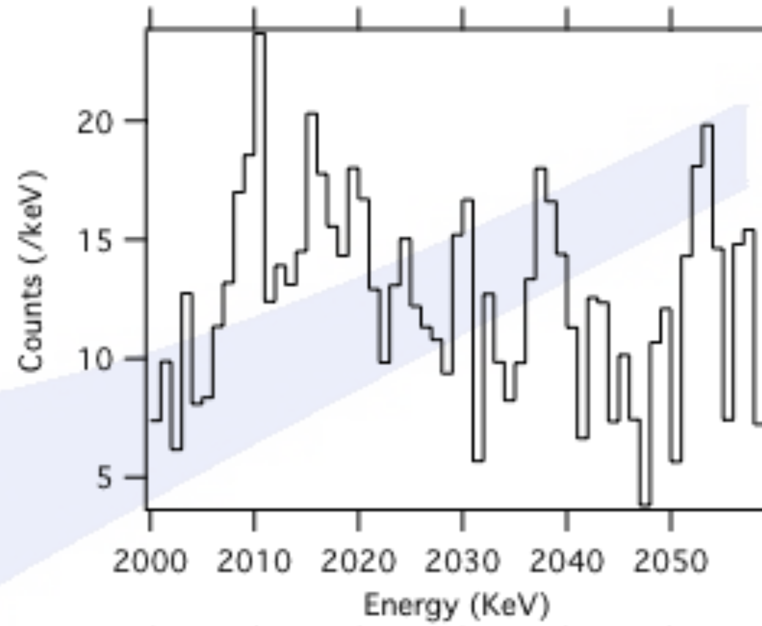
- **Isotope mass**
  - **tens to hundreds of kg**
- **Lower background**
  - **factor of 10-100 better**
- **Resolution**
  - **Critical for signal to noise ratio and the search for a rare peak on a background continuum.**

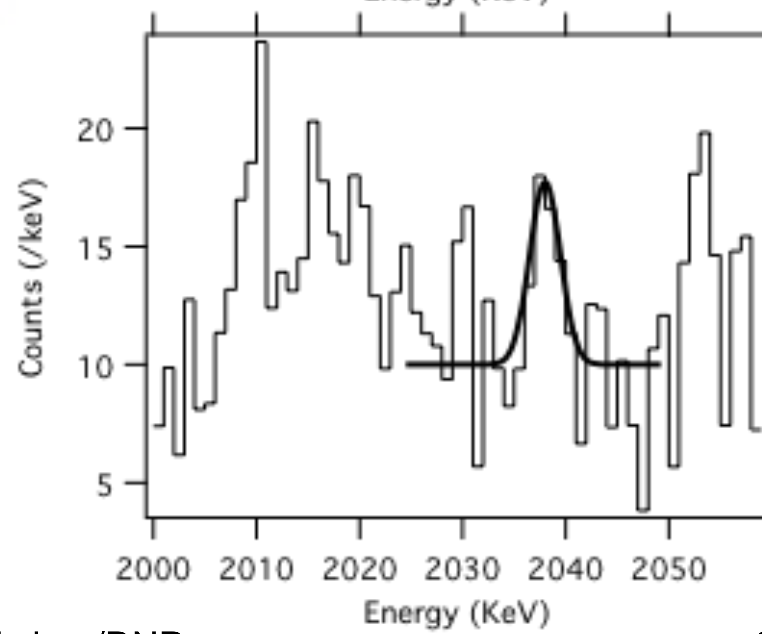
A Recent Claim
has become a litmus test for future efforts

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.





NIM A522, 371 (2004)

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

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	
$5x10^{27}$		40	Atmospheric
$>10^{29}$	<0.05	<10	Solar

To reach atmospheric scale need BG on order 1/t-y.

Background Considerations "the usual suspects"

At atmospheric scale, expect a signal rate on the order of 1 count/tonne-year

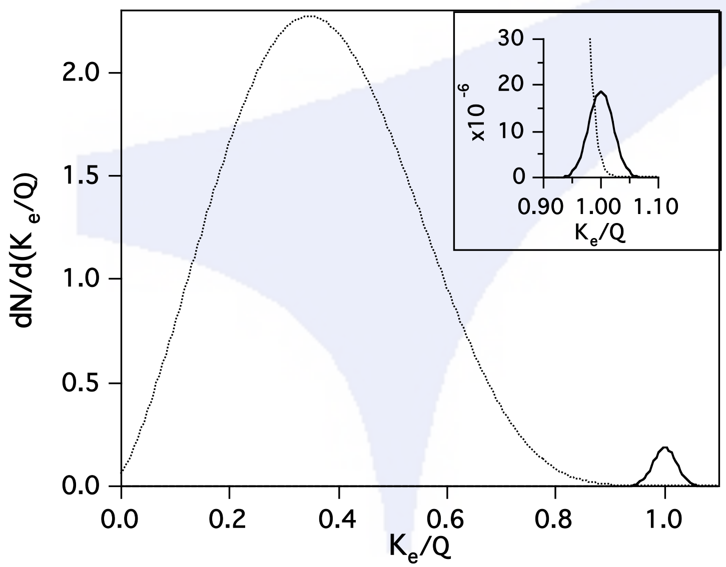
- **$\beta\beta(2\nu)$**
- **natural occurring radioactive materials**
- **long-lived cosmogenics**
- **neutrons**

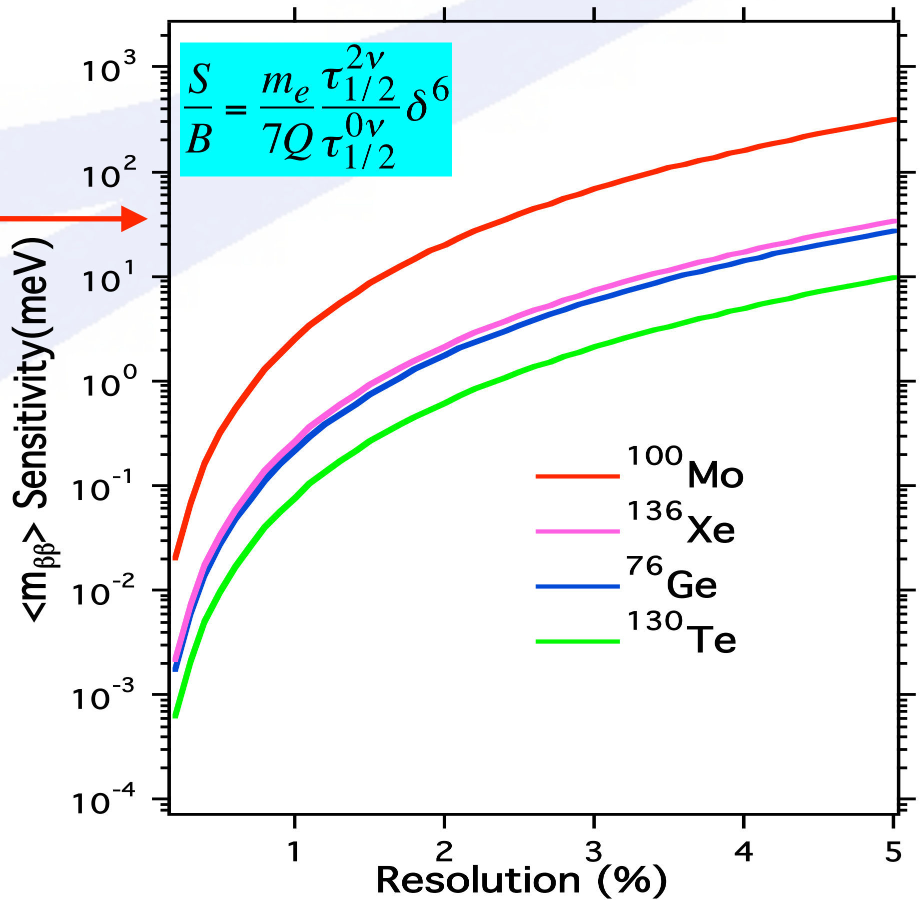
The usual suspects

- $\beta\beta(2\nu)$
  - For the current generation of experiments, resolutions are sufficient to prevent tail from intruding on peak. Becomes a concern as we approach the ton scale
  - Resolution, however, is a very important issue for signal-to-noise

$\beta\beta(2\nu)$ as a Background.
Sum Energy Cut Only

next generation experimental goal





Energy scale for Xe

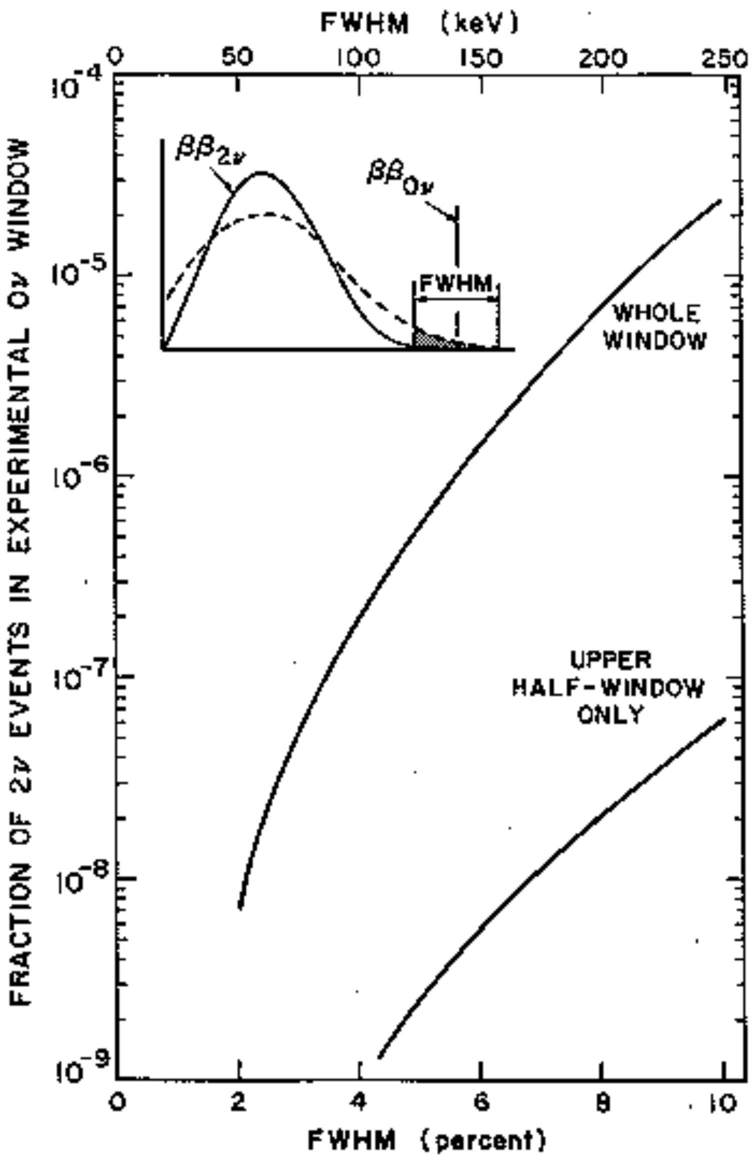
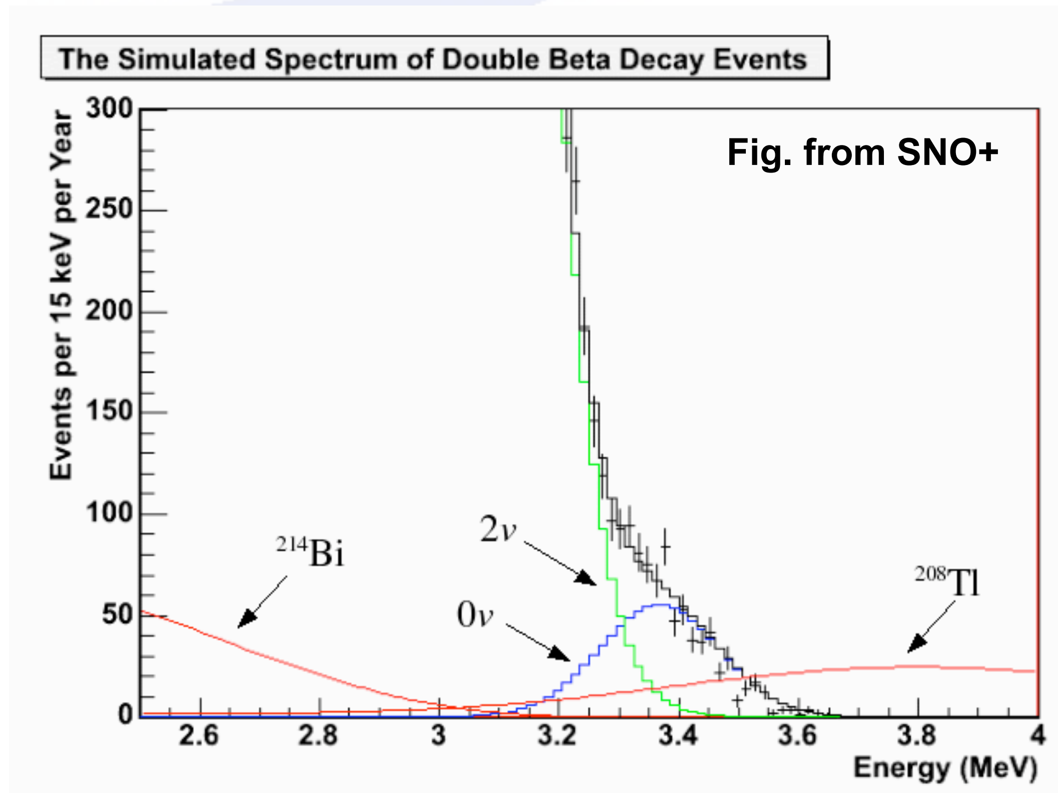


Figure from Mike Moe

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



Resolution and Signal/Noise

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

Background in ROI ~ bΔE

The exposure required for a given sensitivity scales proportionally to the resolution (for a given background level).

The usual suspects

- **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

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

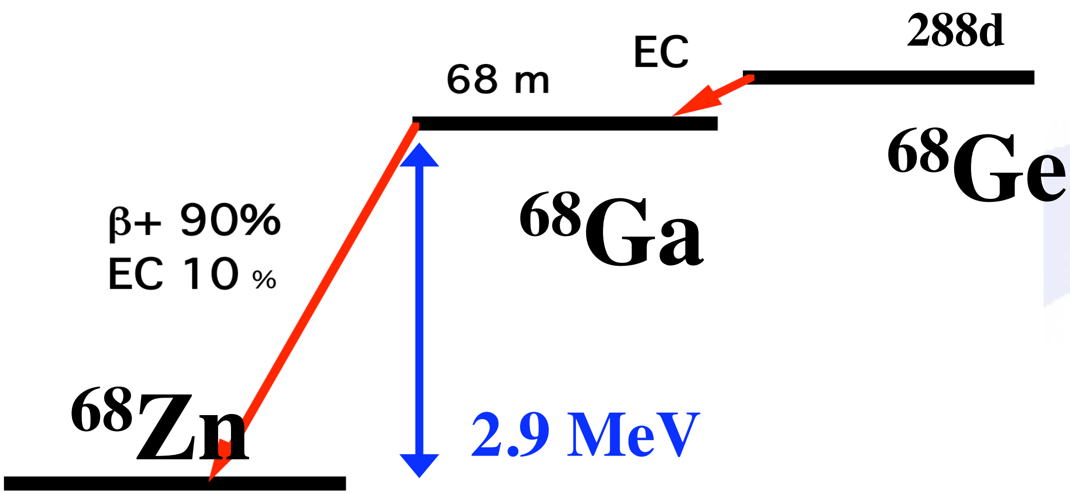
NORM and Assay Techniques

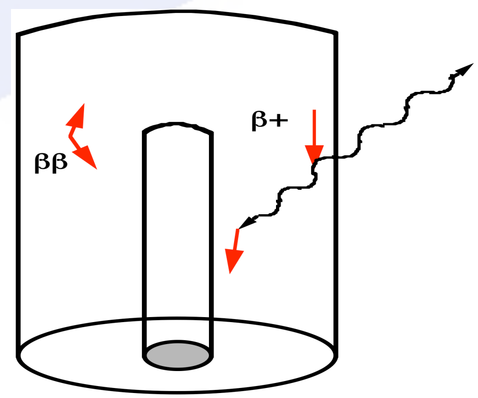
- **Good recent example of survey: EXO, NIM A591:490**
- **Sensitivities of 10^{-10} – 10^{-12} g/g depending on technique and material**
- **ILIAS data base (http://radiopurity.in2p3.fr/)**
- **AARM – New group supported to develop assay support for DUSEL**

The Usual Suspects

- 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





^{68}Ge and ^{60}Co are the dangerous internal backgrounds

For 60-kg enriched detector, initially

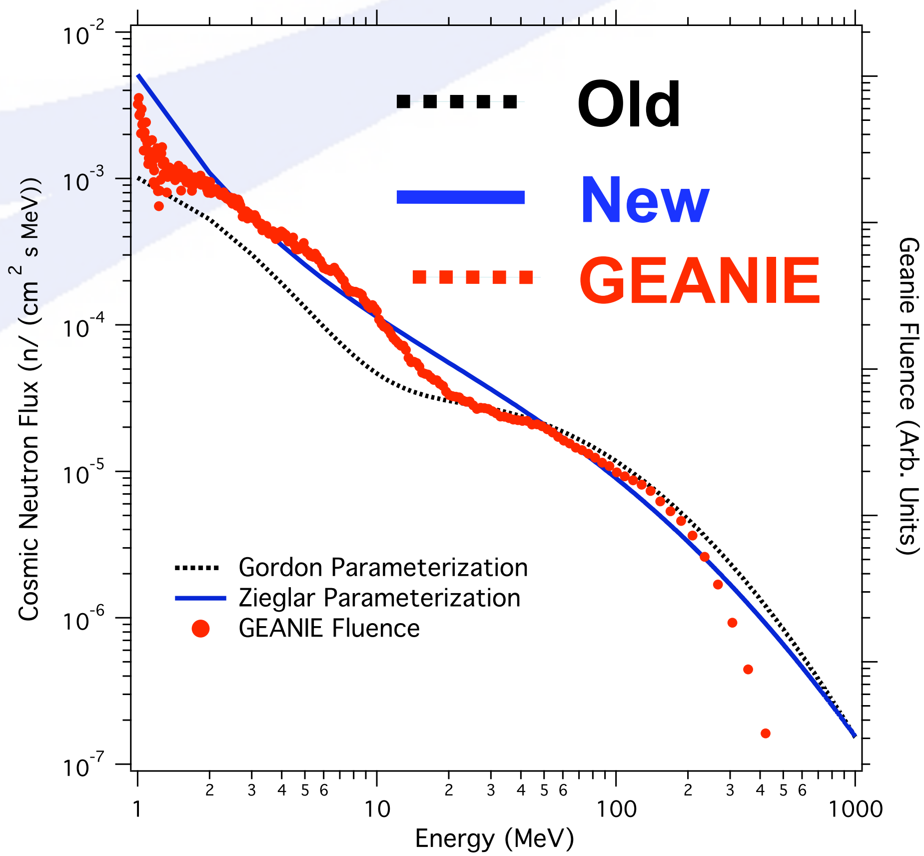
expect ~60 ^{68}Ge decays/day. $\tau_{1\backslash 2}$ = 288 d

Minimize exposure on surface during enrichment and fabrication

PSD, segmentation, time correlation cuts are effective at reducing these

Cosmic Neutron Flux

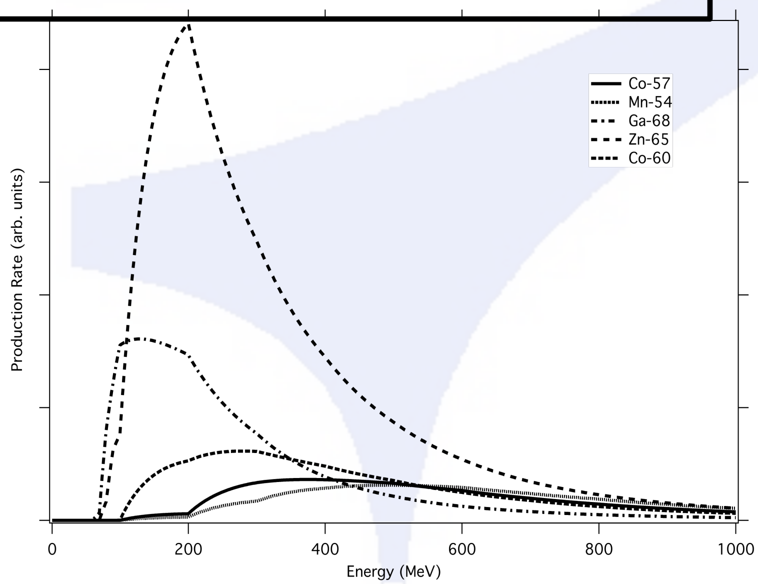
- **Has led to large uncertainties and the "recommended" flux has changed. Astropart. Phys. 31, 417420 (2009)**
- **"Recommended flux": IEEE Trans. on Nucl. Sci. 51, 3427 (2004)**
- **LANSCE neutron beam has similar shape: experimental verification**



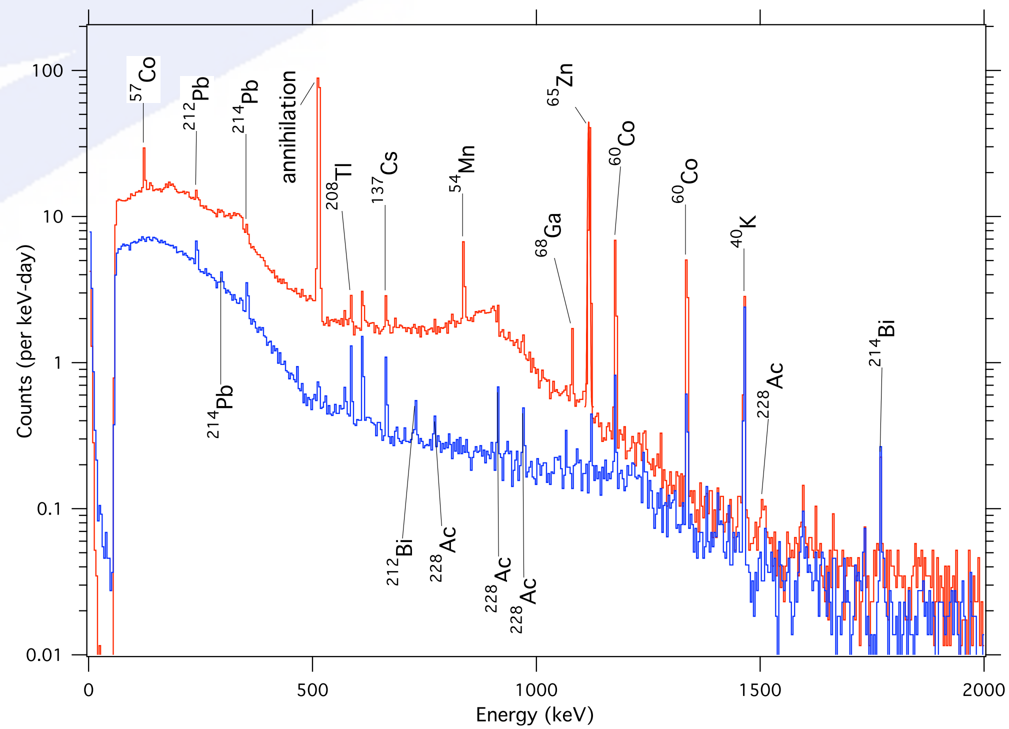
Cosmogenic Production

Some debate about prod. rates - measurement

Production rate dominate between 50-600 MeV.



Irradiated Enriched Sample of Ge



Cross Section Results: LANL measurements

TABLE II: A summary of previous estimates of the production of long-live cosmogenic isotopes in ^{enr}Ge for the isotopes studied in this work. The production rates are given in atoms/(kg d).

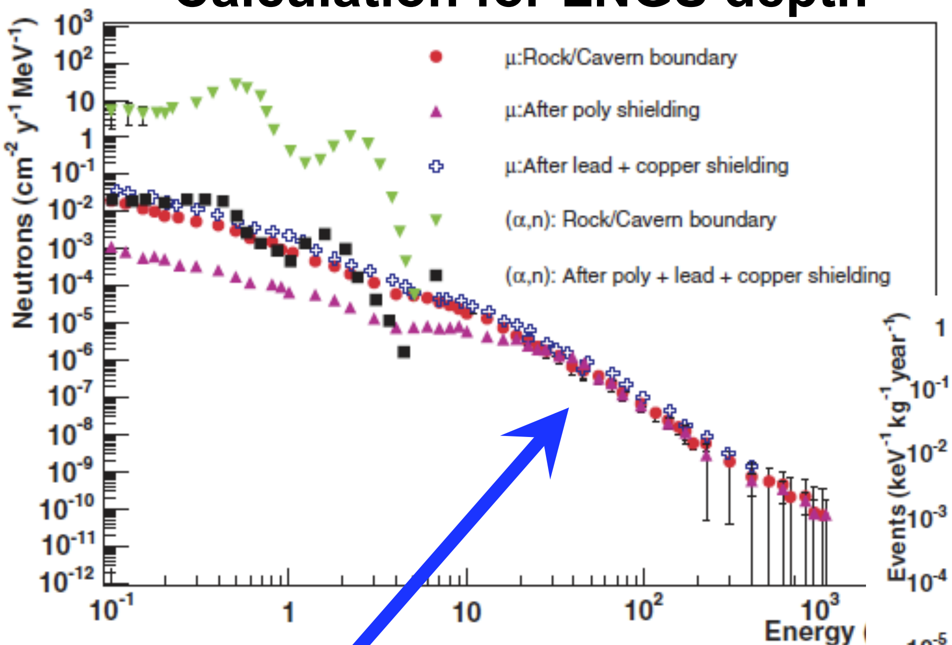
Isotope	Ref. [14]	Ref. [15]	Ref. [20]	Ref. [16]	Ref. [21]	This Work
^{57}Co	0.1	1.0		2.3	6.7	Available soon
^{54}Mn		1.4		5.4	0.87	
^{68}Ge	1.2	1.2	5.7	13	7.2	
^{65}Zn	6.0	6.4		24	20.0	
^{60}Co	3.5		3.3	6.7	1.6	

The Usual Suspects

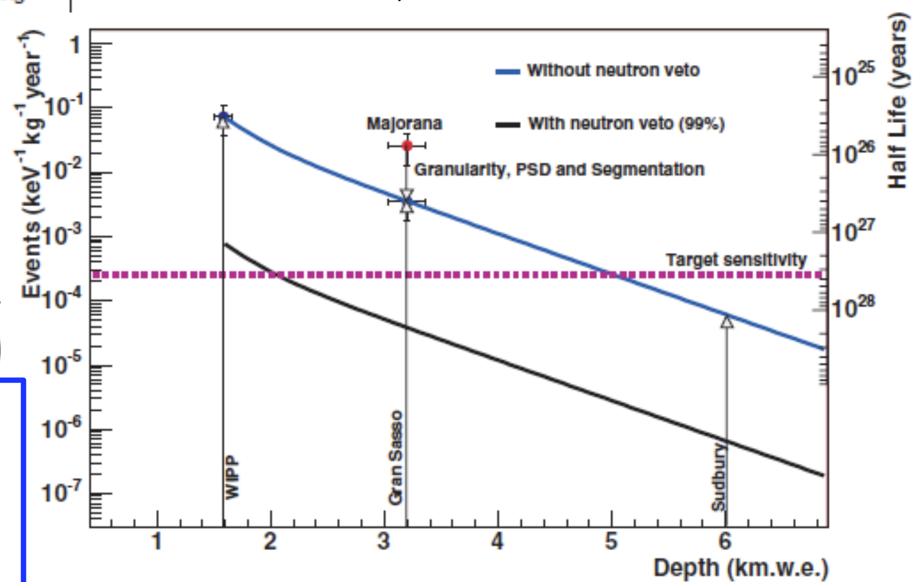
- **As we approach 1 cnt/ton-year, a complicated mix emerges for (n,n'γ).**
- **Neutrons (elastic/inelastic reactions, short-lived isotopes)**
  - **(α,n) up to 10 MeV can be shielded**
  - **High-energy-μ generated n are a more complicated problem**
    - **Depth and/or well understood anti-coincidence 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 are imprecise wrt low-energy nuclear physics**
    - **Low energy nuclear physics is tedious to implement and verify**

μ-generated n's

Calculation for LNGS depth

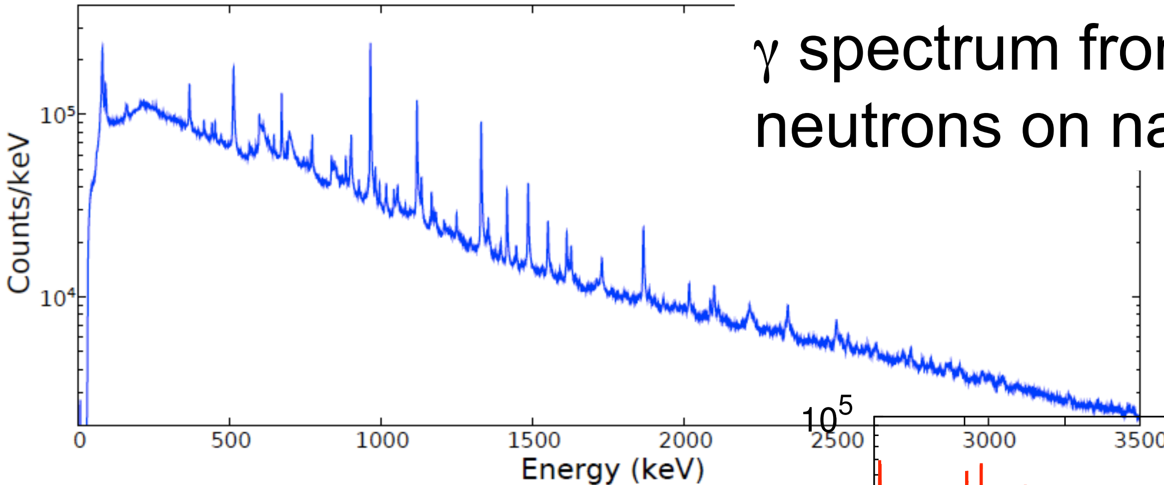


Mei/Hime PRD 73, 053004

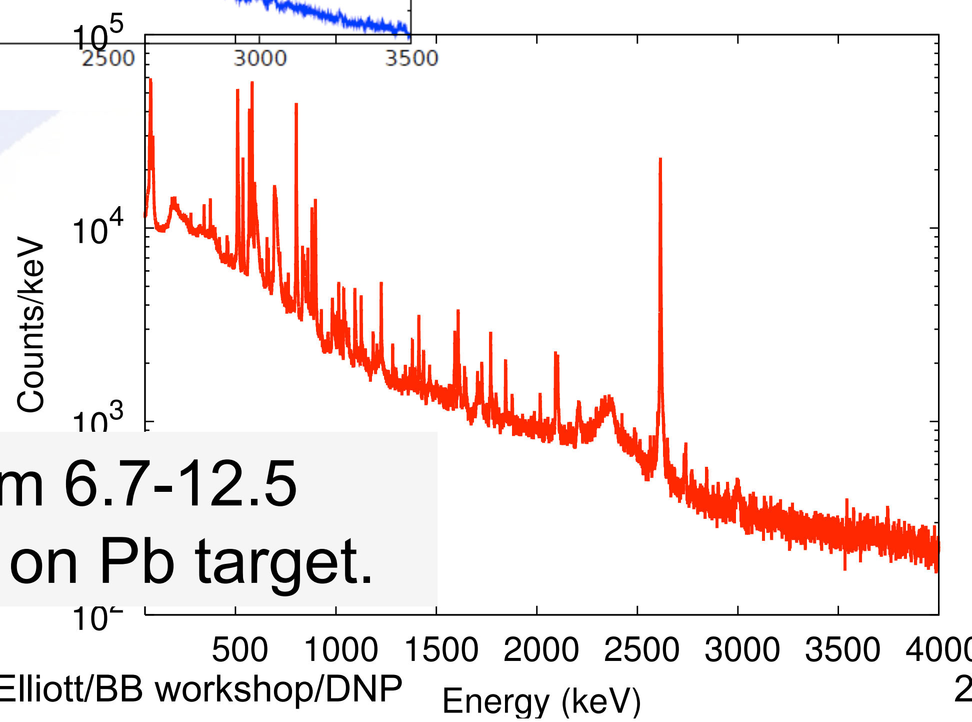


High energy neutrons have low flux but are hard to shield.

(n,n'γ) Spectra are Complicated

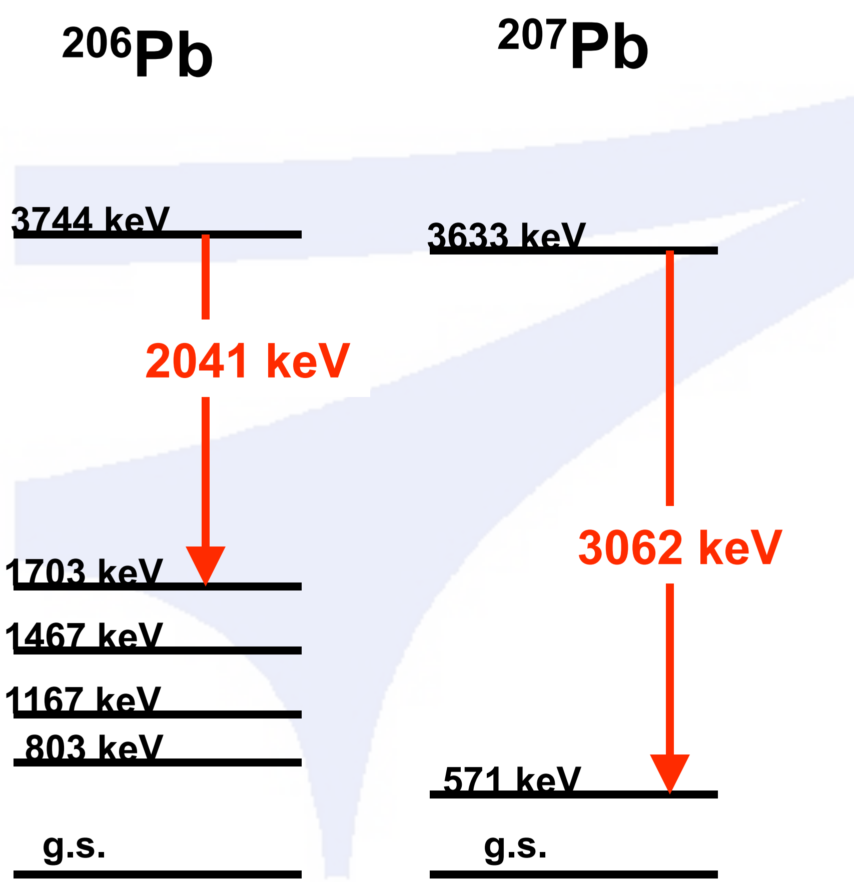


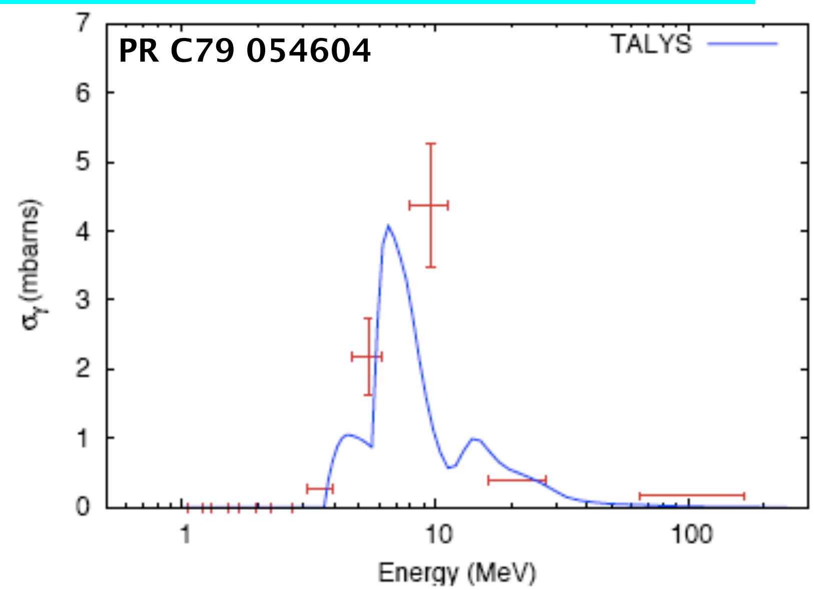
γ spectrum from 3-30 MeV neutrons on natural Cu target.



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

Pb(n,n'γ) and ^{76}Ge (Q=2039 keV)

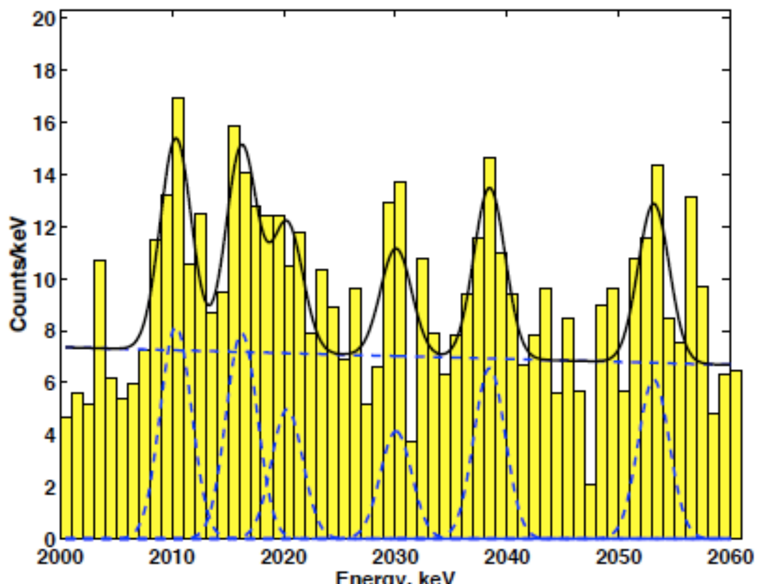




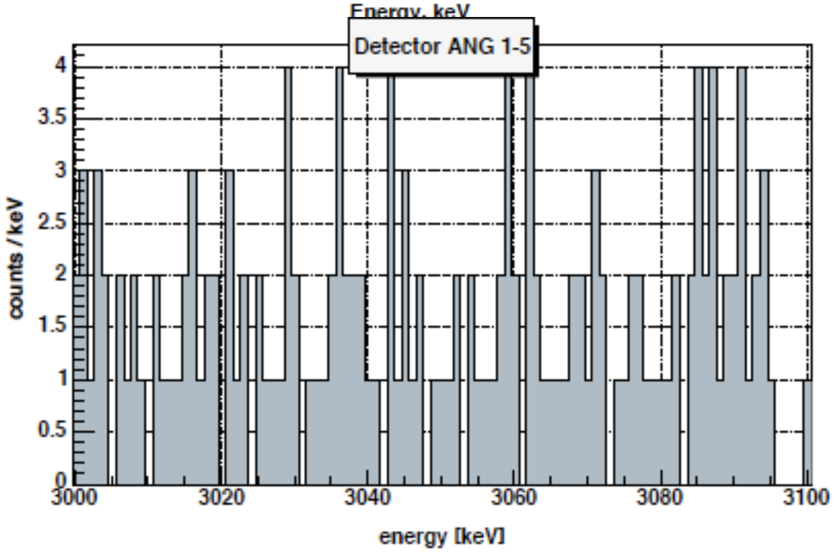
The observed 3062-keV γ-ray production cross section in ^{207,208}Pb.

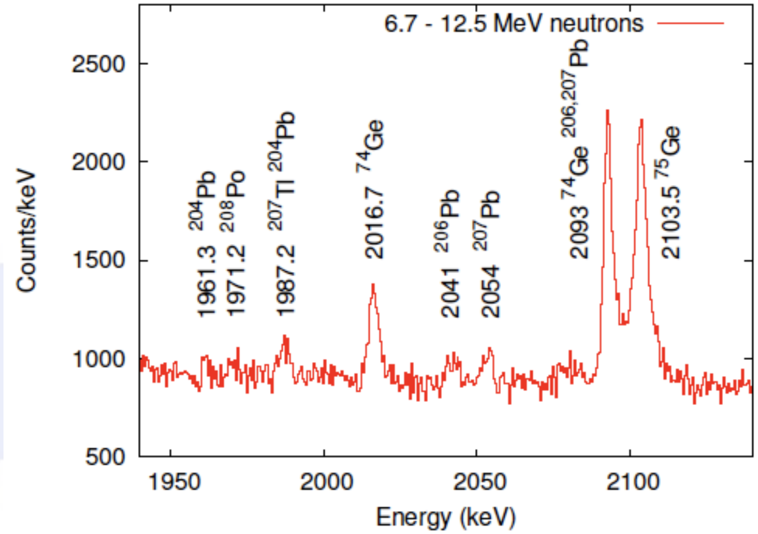
DEP of 3062 line is at 2040 keV!!

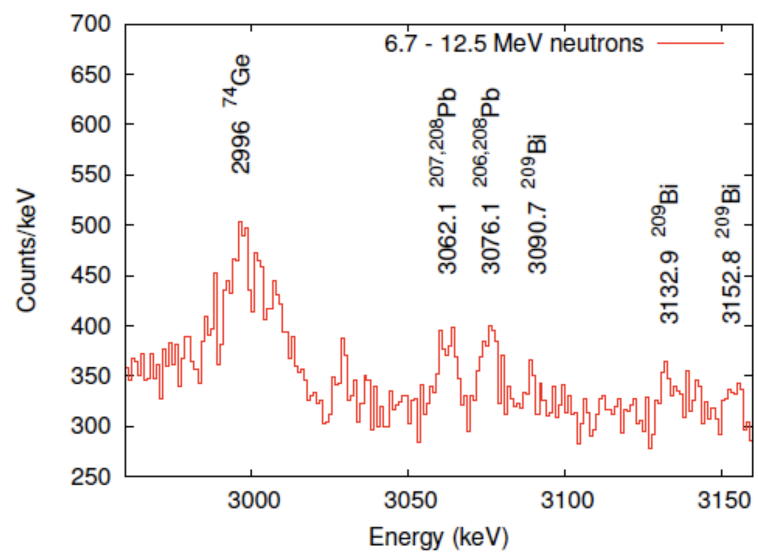
DEP and The Claim: DEP/FEγ ~15%



NIM A 522 (2004) 371







Phys. Rev. C 79, 054604 (2009)

Depth will help these experiments avoid the high energy neutrons

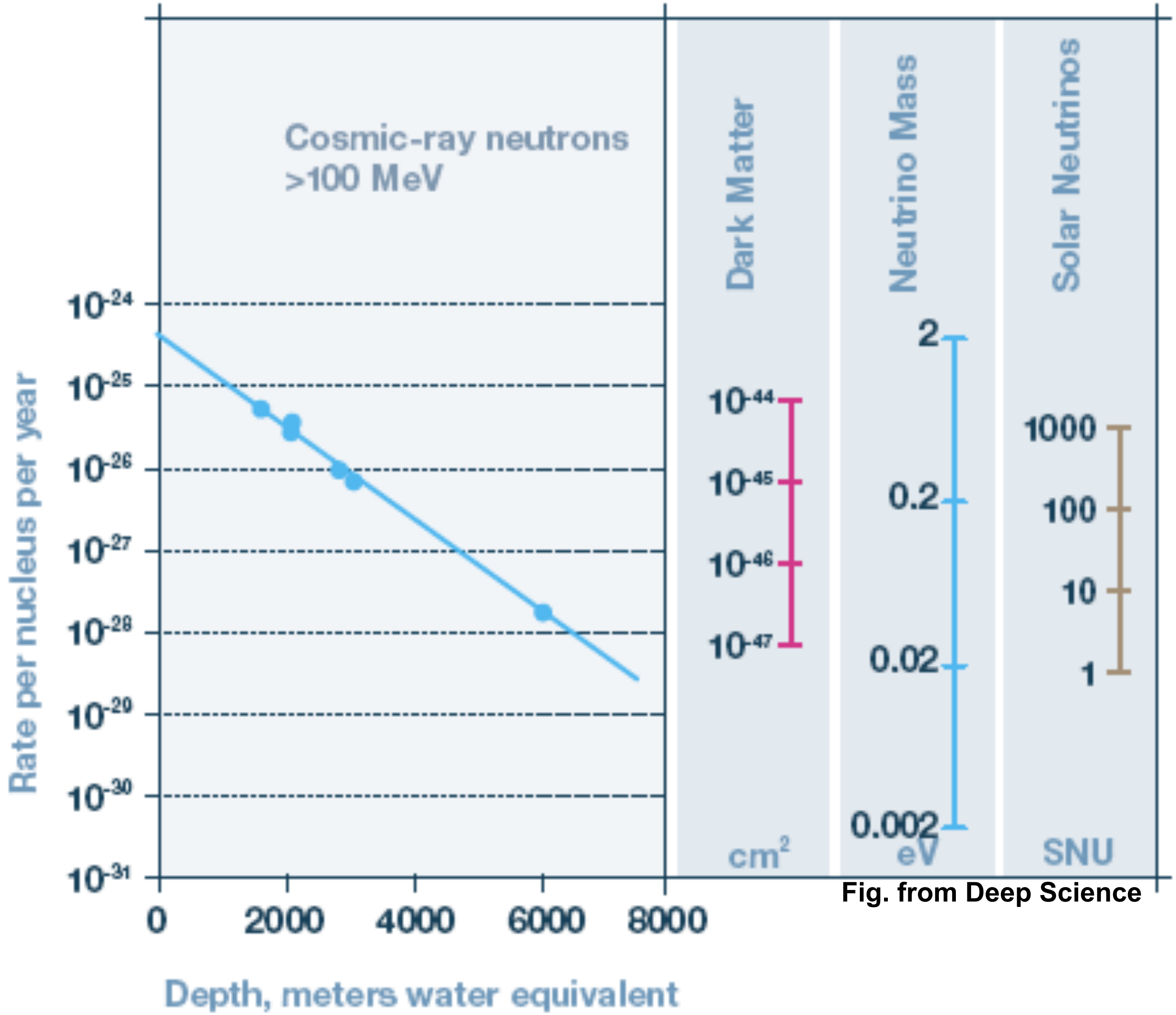


Fig. from Deep Science

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 ββ(0ν) implies massive Majorana neutrinos, but:

- **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.**

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

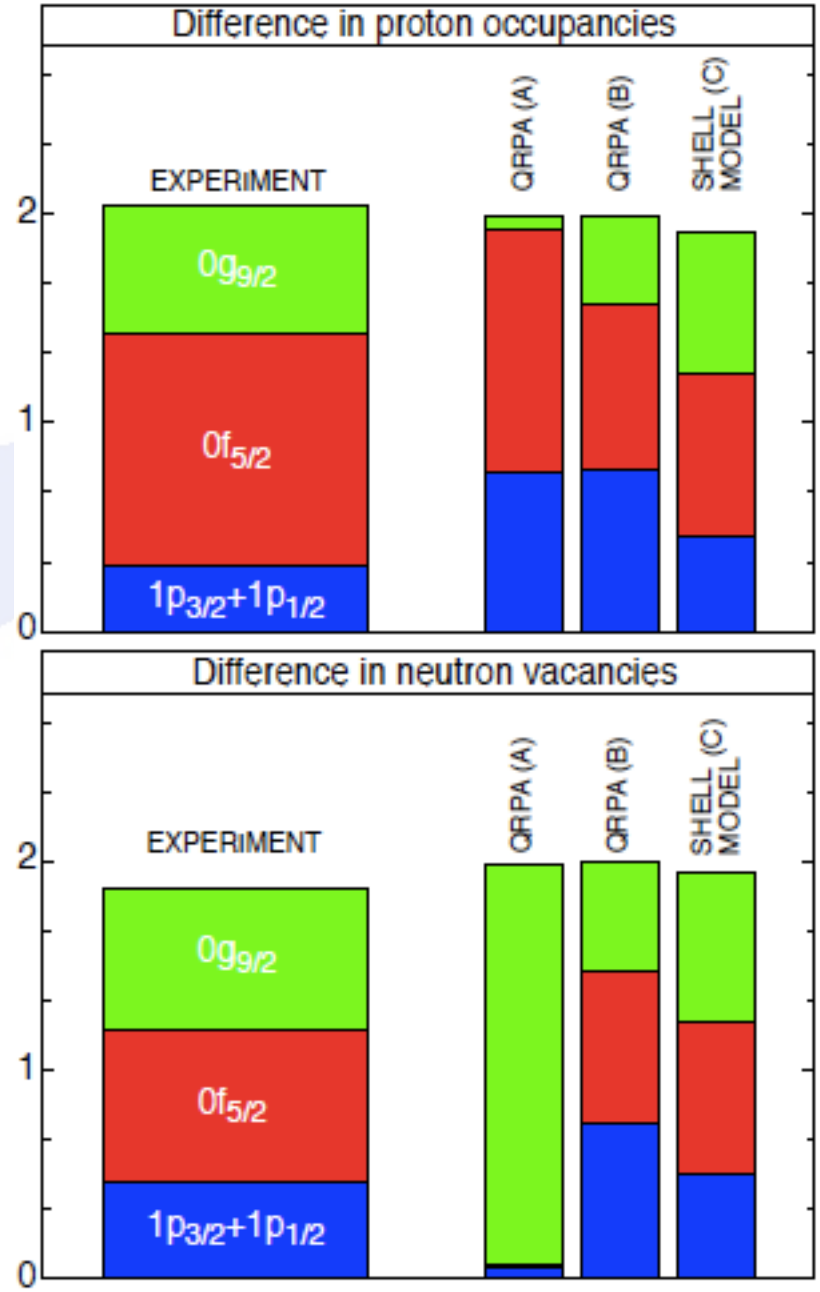
See nucl-ex/0511009

- 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, e.g. pair removal reaction (p,t)
- Pion double-charge exchange
- Electromagnetic transitions to isobaric analogue states

Occupancy Measurements

"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."

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.

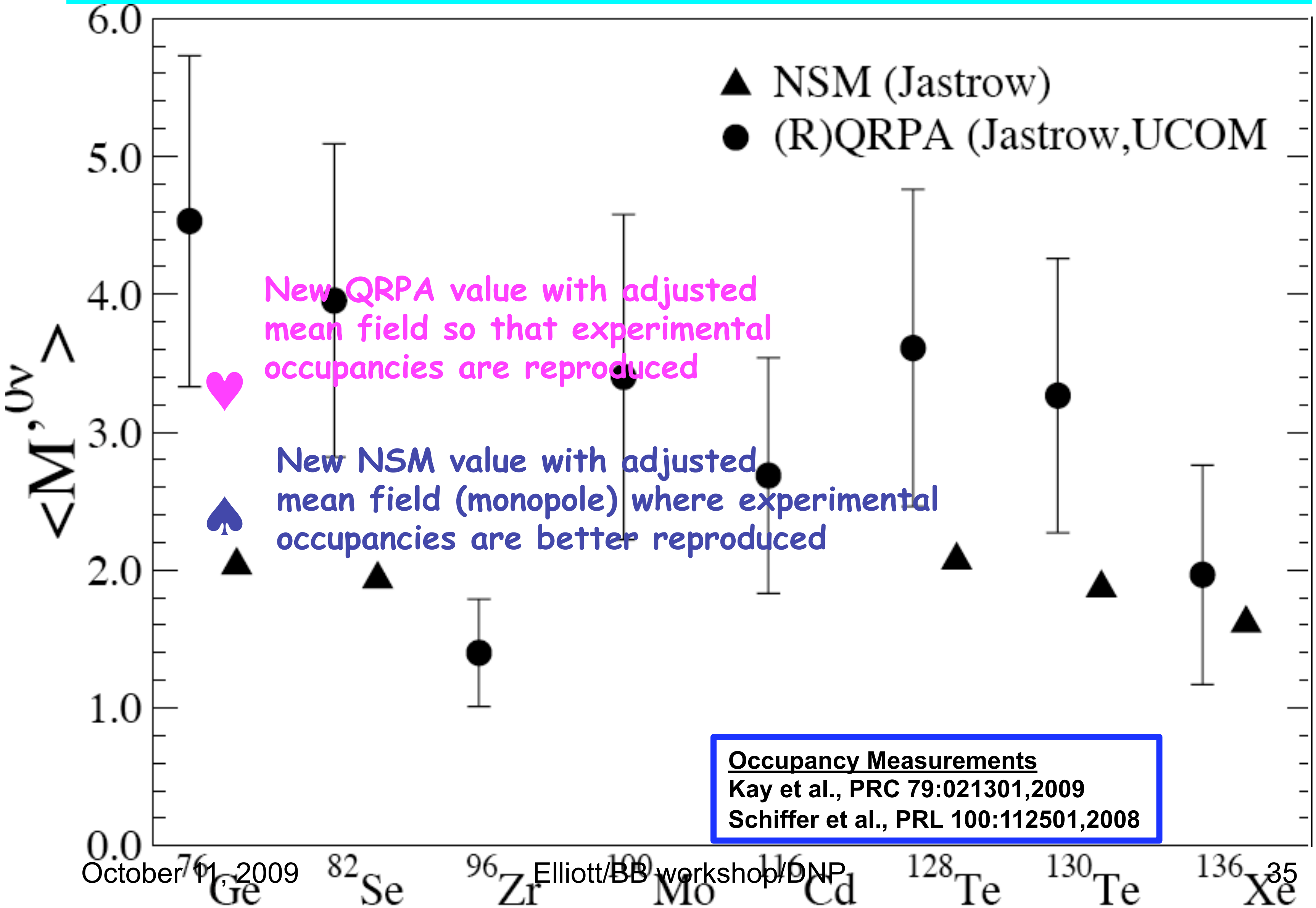


Phys.Rev.C79:021301,2009

After Meas. Calcs.

♥ PRC 79:015502,2009

♠ arXiv:0906.0179



♥ New QRPA value with adjusted mean field so that experimental occupancies are reproduced

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

Occupancy Measurements
Kay et al., PRC 79:021301,2009
Schiffer et al., PRL 100:112501,2008

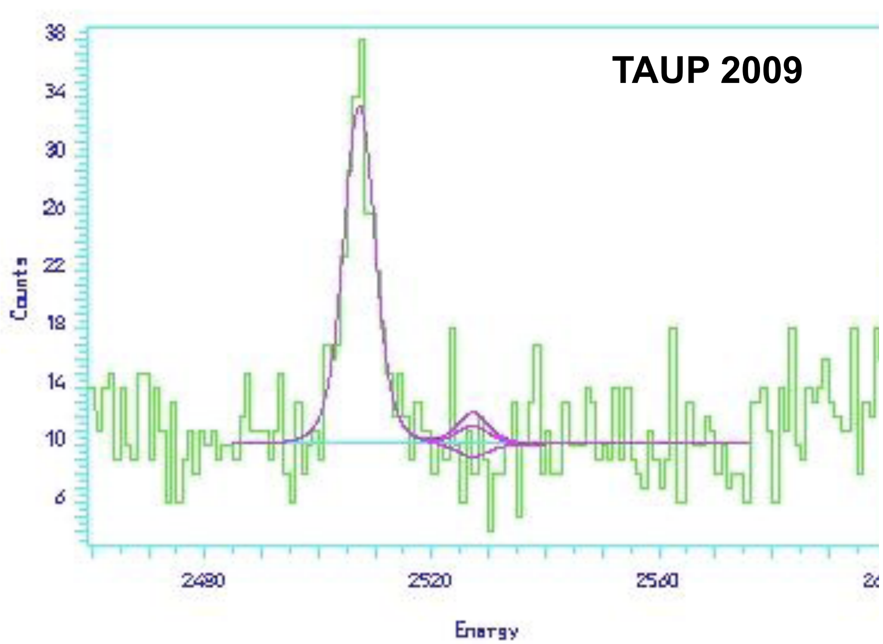
Recent Q-Value Measurements

- $\beta\beta(0\nu)$
  - ^{130}Te, 2527.518(13) keV: PRL 102, 212502 (2009)
    - Previously accepted value: 2530.3±2.0 keV
  - ^{100}Mo, 3034.40(17) keV: Physics Letters B 662 (2008) 111
  - ^{136}Xe, 2457.83(37) keV: PRL 98, 053003 (2007)
  - ^{116}Cd still only known to ~4 keV!

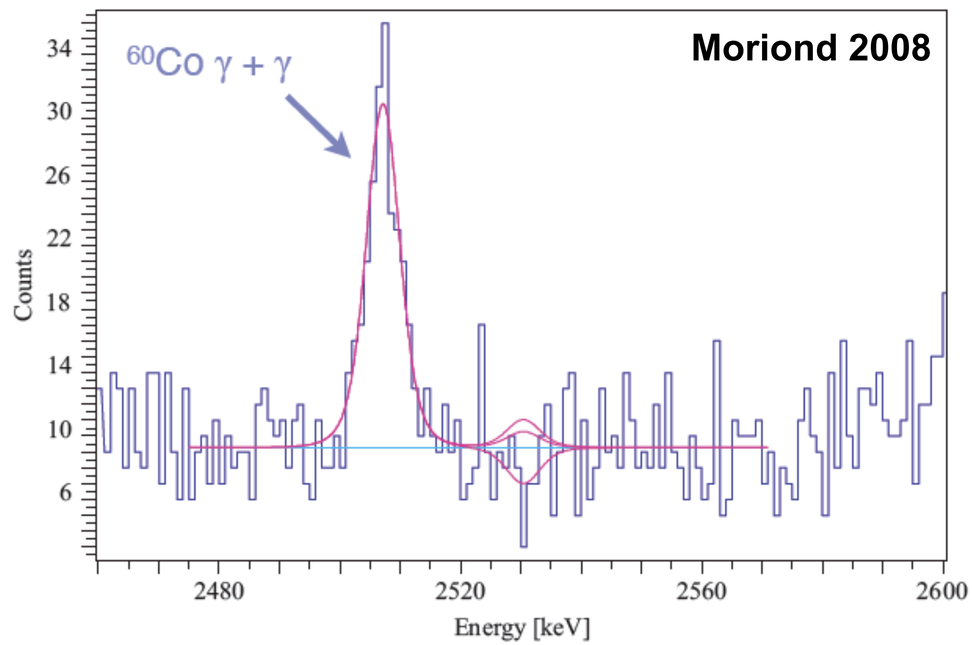
- Radiative EC-EC capture
  - ^{112}Sn and ^{112}Cd of 1919.82(16) keV: PRL 103, 042501 (2009)
    - No longer a good candidate for EC-EC to excited state, 4.6 keV away when <1 keV is required

Q-Value Effect on CUORICINO

$\tau > 2.94 \times 10^{24} y$ *(90% C.L.)*
2527.518 keV



$\tau > 3.1 \times 10^{24} y$ *(90% C.L.)*
2530.3 keV



Enrichment Technologies

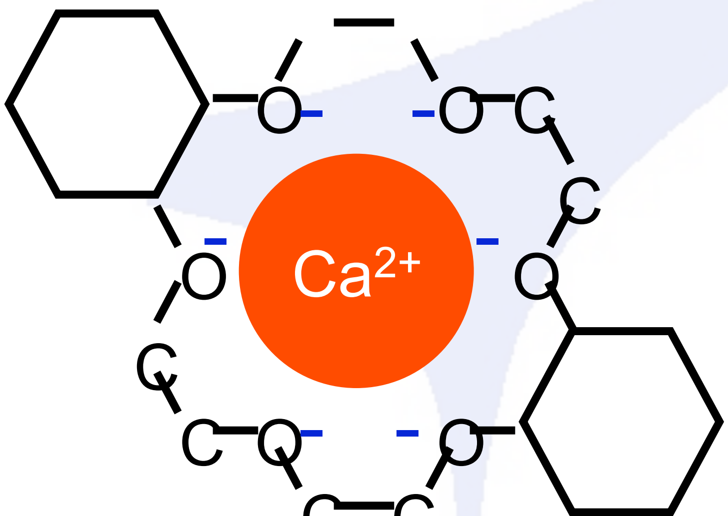
Separation technology	*Field of use*	*Production per year*	*Cost*
Electromagnetic (mass-spectroscopy effect)	**universal**	**tens of grams**	**high**
Chemical & phys. processes (rectification, chem. exchange etc)	**light elements**	**tons**	**low**
Gas diffusion	**elements forming gas compounds**	**thousands 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**	**hundreds of kilograms**	**middle**

Courtesy Lev Inzechik

SVETLANA

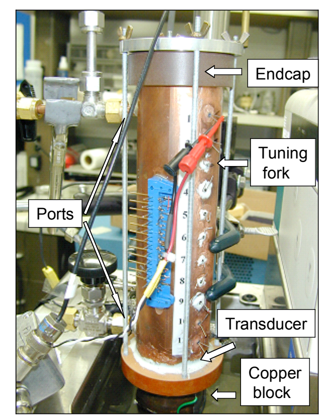
Alternative Technologies

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



Dicyclohexano
18-crown-6

Plasma Separation



Acoustic Separation

Elliott/BB workshop/DNP

Solar Scale: Showstoppers?

- Need 100 tons of isotope
  - Enrichment costs and production rates are not sufficient yet
  - Requires R&D to improve capability
- Need excellent energy resolution
  - Better than 1% FWHM
  - An experiment with 10^6 solid state is possible
    - Cost/detector will need to be greatly reduced
    - Large multi-element detector electronics are improving
  - Metal loaded liquid scintillator or Xe techniques
    - Scales more easily and cost effectively
    - Resolution requires R&D

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.