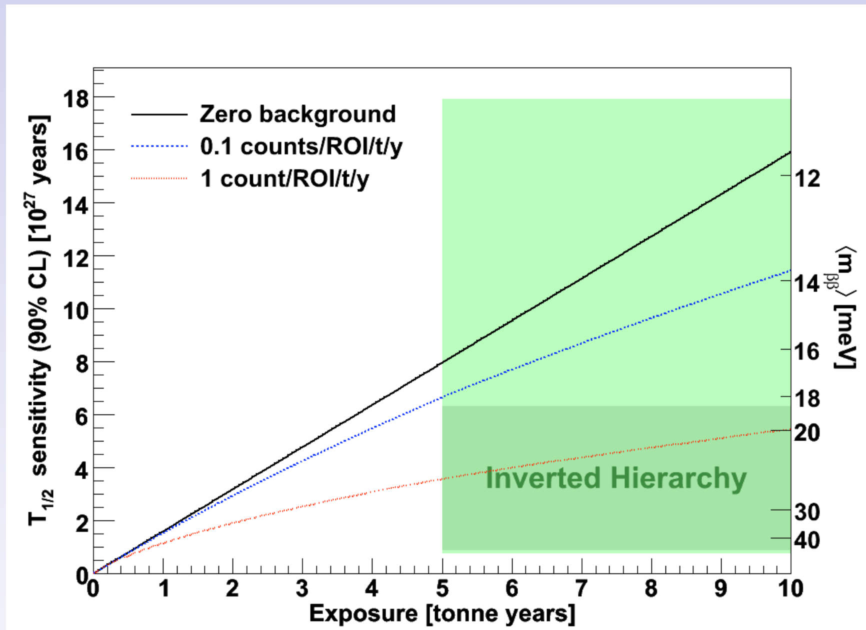
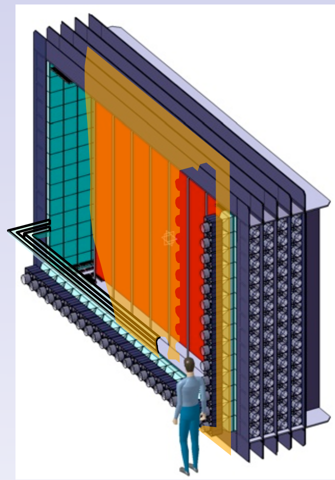
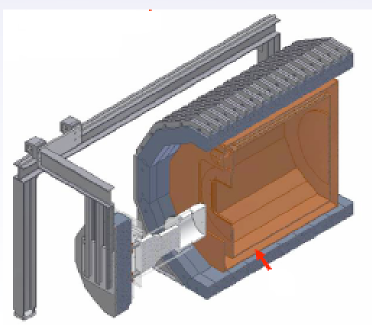
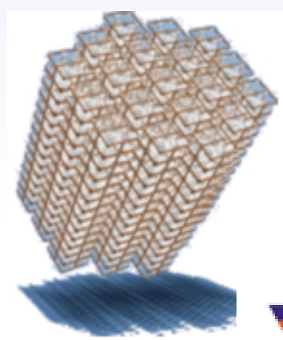
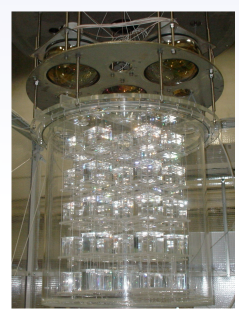
Neutrinoless Double Beta Decay II
Experimental approaches

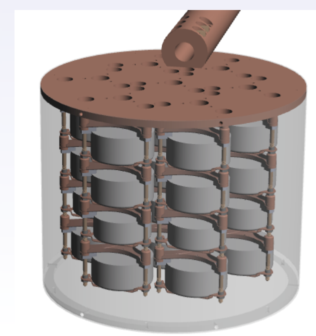












THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

J.F. Wilkerson
International Neutrino Summer School
July 13, 2009

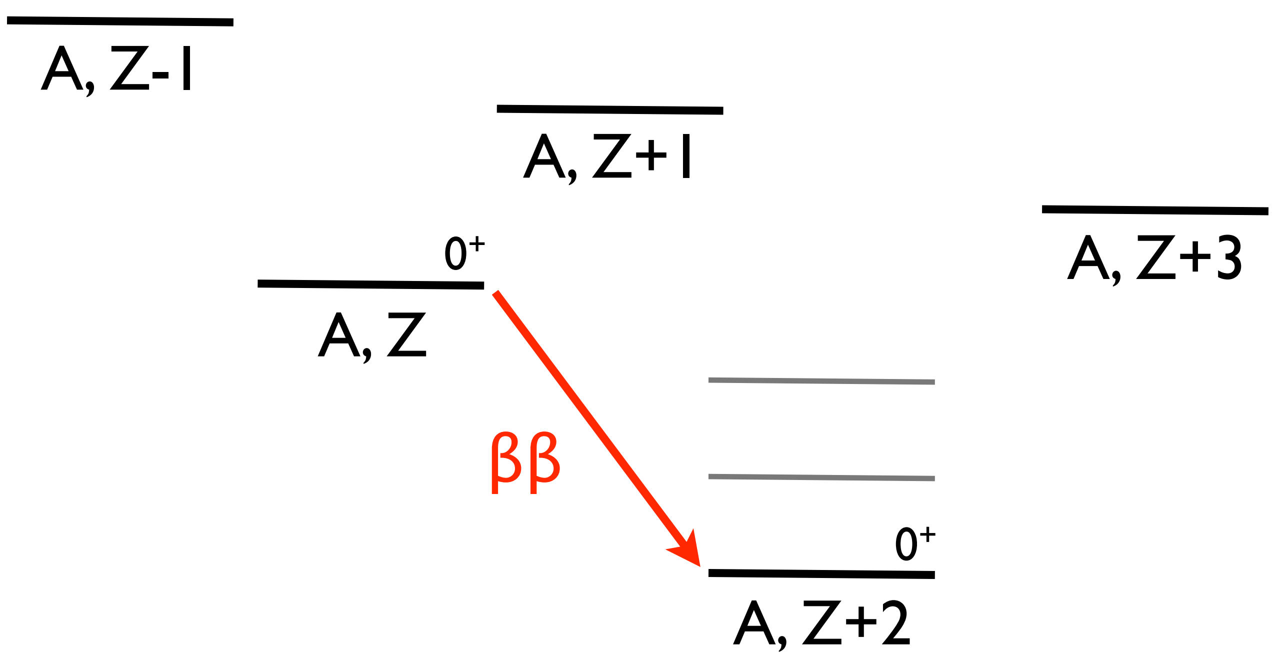
$0\nu\beta\beta$ Decay II

Overview

Review
Early Days
Observables
Rates
Extracting Physics

Double-Beta Decay

In a number of even-even nuclei, β-decay is energetically forbidden or strongly disfavored, while double-beta decay, from a nucleus of (A,Z) to (A,Z+2), is allowed.



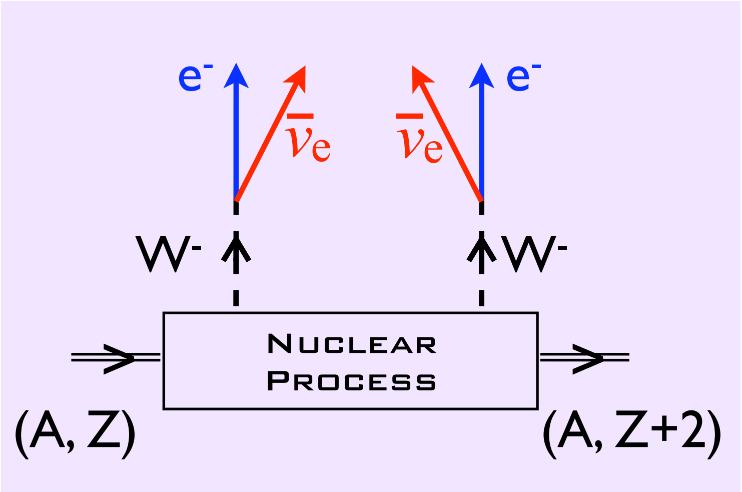
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

Double-Beta Decay Modes

2ν double-beta decay (2νββ): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + $\bar{\nu}_e$ + e^- + $\bar{\nu}_e$

Allowed second-order weak process

Maria Goeppert-Mayer (1935)



0ν double-beta decay (0νββ): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + e^-

Ettore Majorana (1937) realized symmetry properties of Dirac's theory allowed the possibility for electrically neutral spin-1/2 fermions to be their own anti-particle

Double-Beta Decay Modes

2ν double-beta decay (2νββ): **Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + $\bar{\nu}_e$ + e^- + $\bar{\nu}_e$**

Allowed second-order weak process

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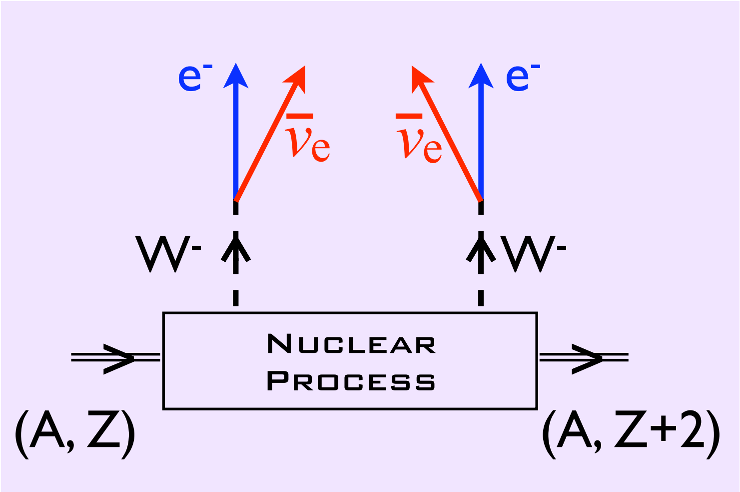
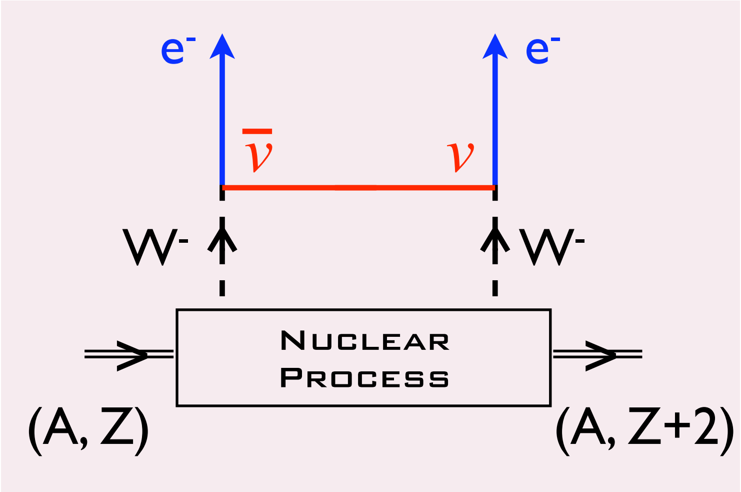


0ν double-beta decay (0νββ): **Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + e^-**

Racah (1937), Furry (1938)

$n \rightarrow p + e^- + \bar{\nu}$

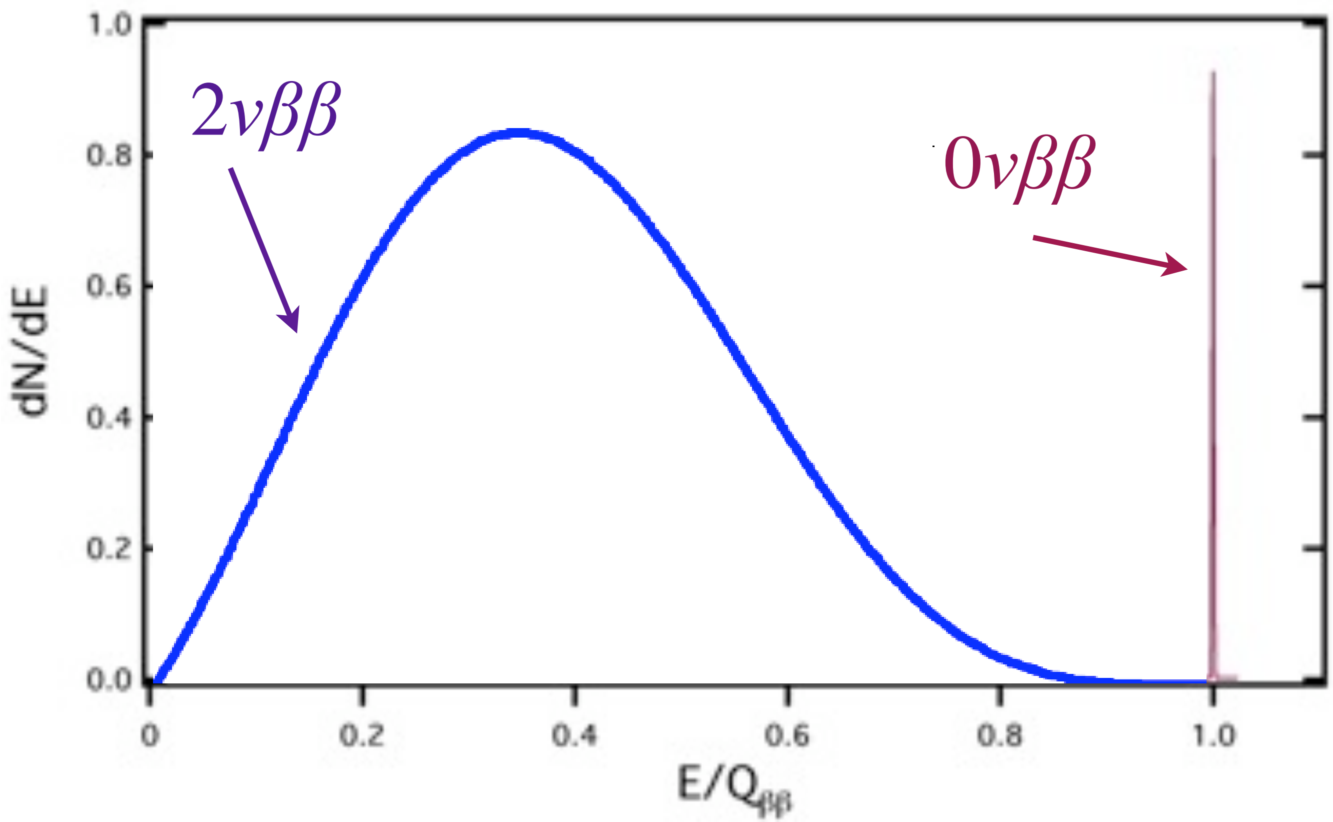
$\nu + n \rightarrow p + e^-$



ββ Observable - electrons

2ν double-beta decay (2νββ)	**0ν double-beta decay (0νββ)**
4-body decay (plus recoil nucleus) - observe the two electrons	2-body decay (plus recoil nucleus) - observe the two electrons

Sum of electrons energy spectrum

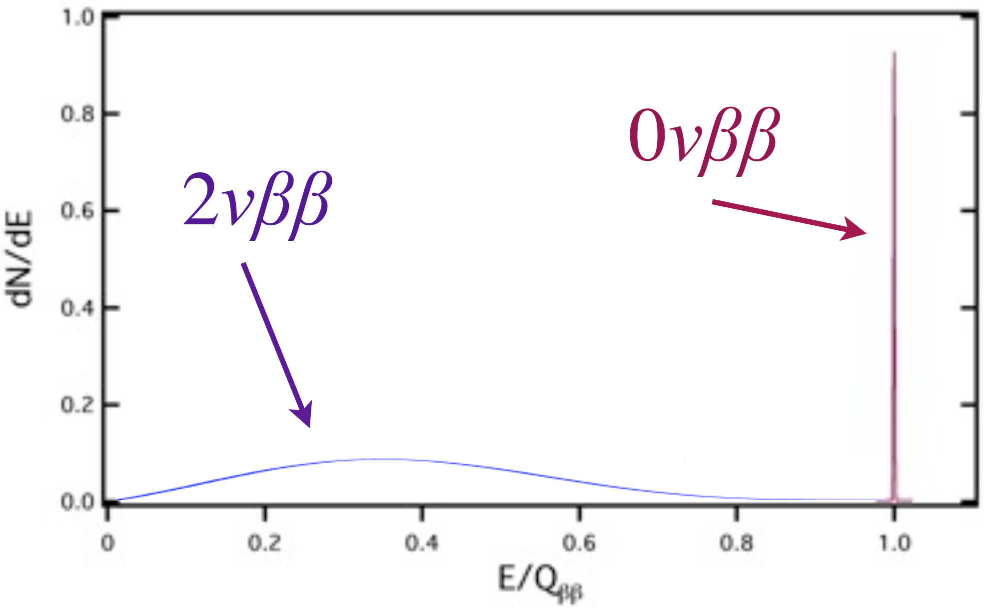


Early Estimates of ββ Decay Rates

2ν double-beta decay (2νββ)	**0ν double-beta decay (0νββ)**
Maria Goeppert-Mayer (1935) using Fermi Theory	Furry (1939), assuming Parity conserved, so no preferential handedness
$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \propto \text{Phase Space (4-body)} \propto Q^{10-12}$	$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} \propto \text{Phase Space (2-body)} \propto (E_\nu Q)^5$
$T_{1/2}^{2\nu\beta\beta} \approx 10^{25}$ years	$T_{1/2}^{0\nu\beta\beta} \approx 10^{19}$ years

$0\nu\beta\beta$ mode highly favored over $2\nu\beta\beta$

If observe $2\nu\beta\beta \Rightarrow$ neutrinos are Dirac

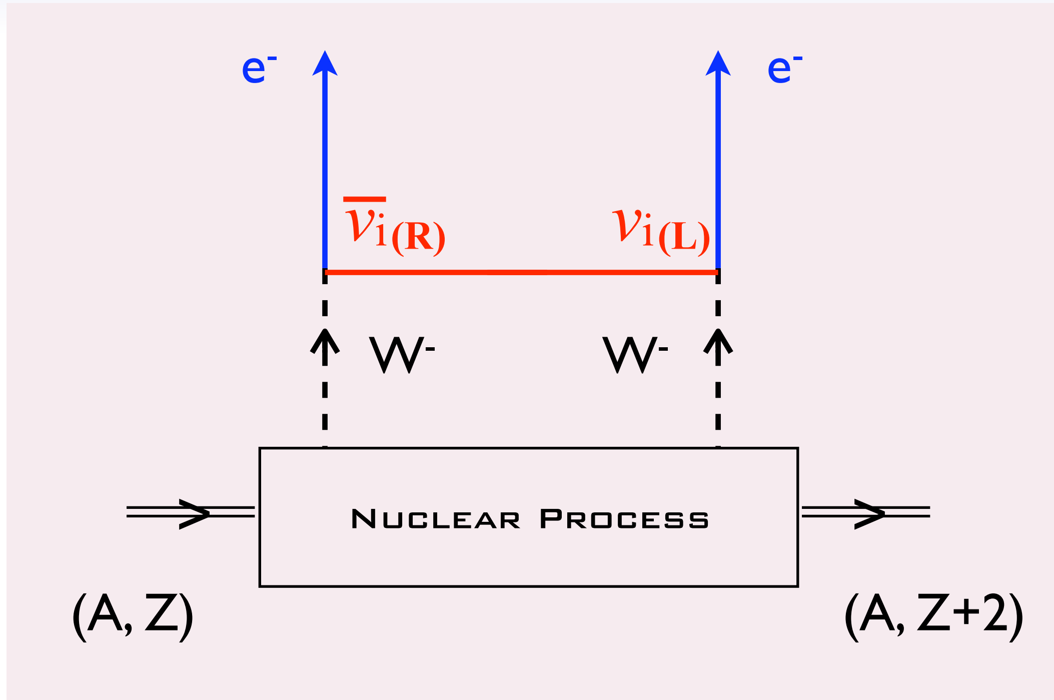


If observe $0\nu\beta\beta \Rightarrow$ neutrinos are Majorana

1956-1958 Parity Violation, ν Helicity and 0νββ-decay

$n \rightarrow p + e^- + \bar{\nu}_{(R)}$

$\nu_{(L)} + n \rightarrow p + e^-$



0νββ requires in addition to Majorana neutrinos and a lepton violating interaction, a mechanism to “flip” from right handed anti-neutrino to left-handed neutrino

The transition can occur if neutrinos have mass
“wrong-handed” helicity admixture ~ m_i/E_{ν_i}

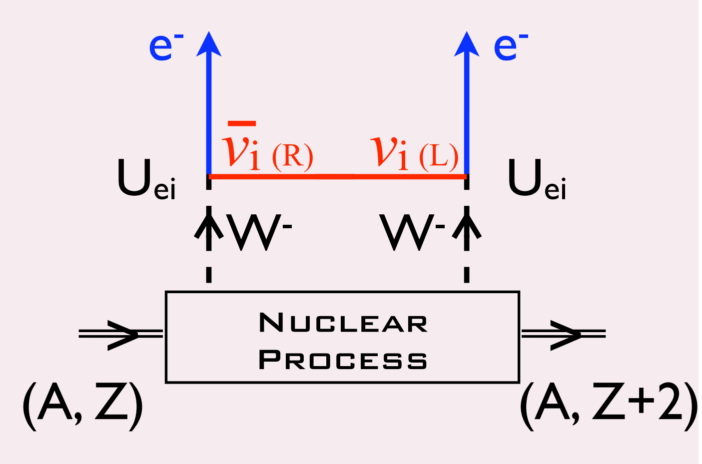
$0\nu\beta\beta$ mode highly suppressed compared to $2\nu\beta\beta$

0νββ Decay - Current Understanding

0νββ Requires:

- neutrino to have non-zero mass
  - "wrong-handed" helicity admixture ~ m_i/E_{ν_i}

Any process that allows 0νββ to occur requires Majorana neutrinos with non-zero mass.
Schechter and Valle, 1982



- Lepton number violation
  - No experimental evidence that Lepton number must be conserved

  (i.e. general SM principles, such as electroweak-isospin conservation and renormalizability)

If 0νββ decay is observed ⇒ neutrinos are Majorana particles

lepton number is violated

ββ Decay Rates (measured)

2ν double-beta decay (2νββ)

Observed for
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo,
^{116}Cd ^{128}Te, ^{130}Te, ^{150}Nd

$T_{1/2}^{2\nu\beta\beta} \approx 10^{19} - 10^{21}$ years

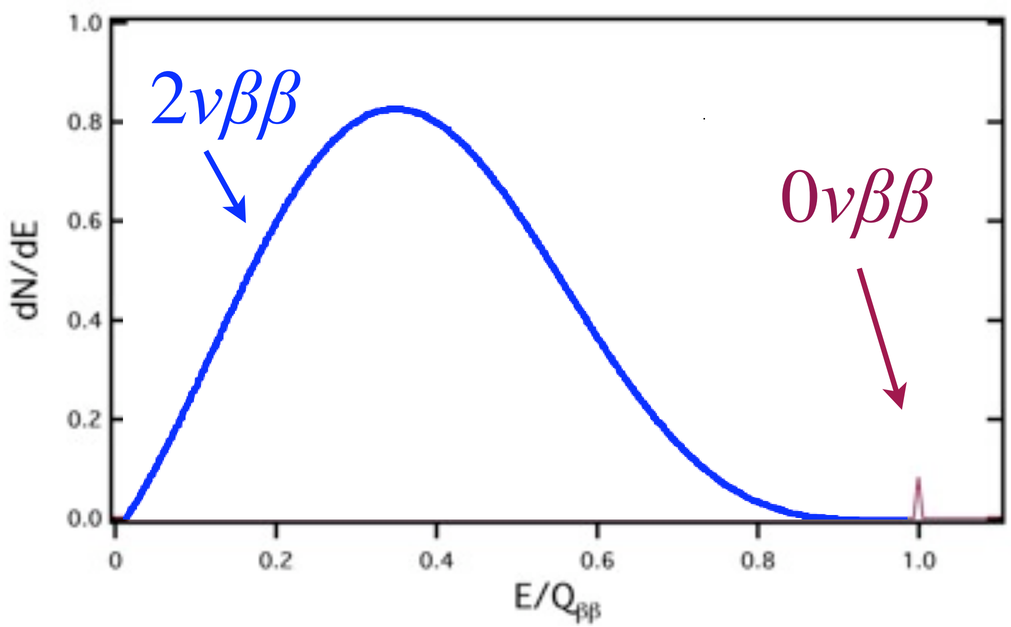
0ν double-beta decay (0νββ)

A claimed observation in ^{76}Ge
$T_{1/2} = (1.19 + 2.99/-0.5) \times 10^{25}$ y

Limits for
^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

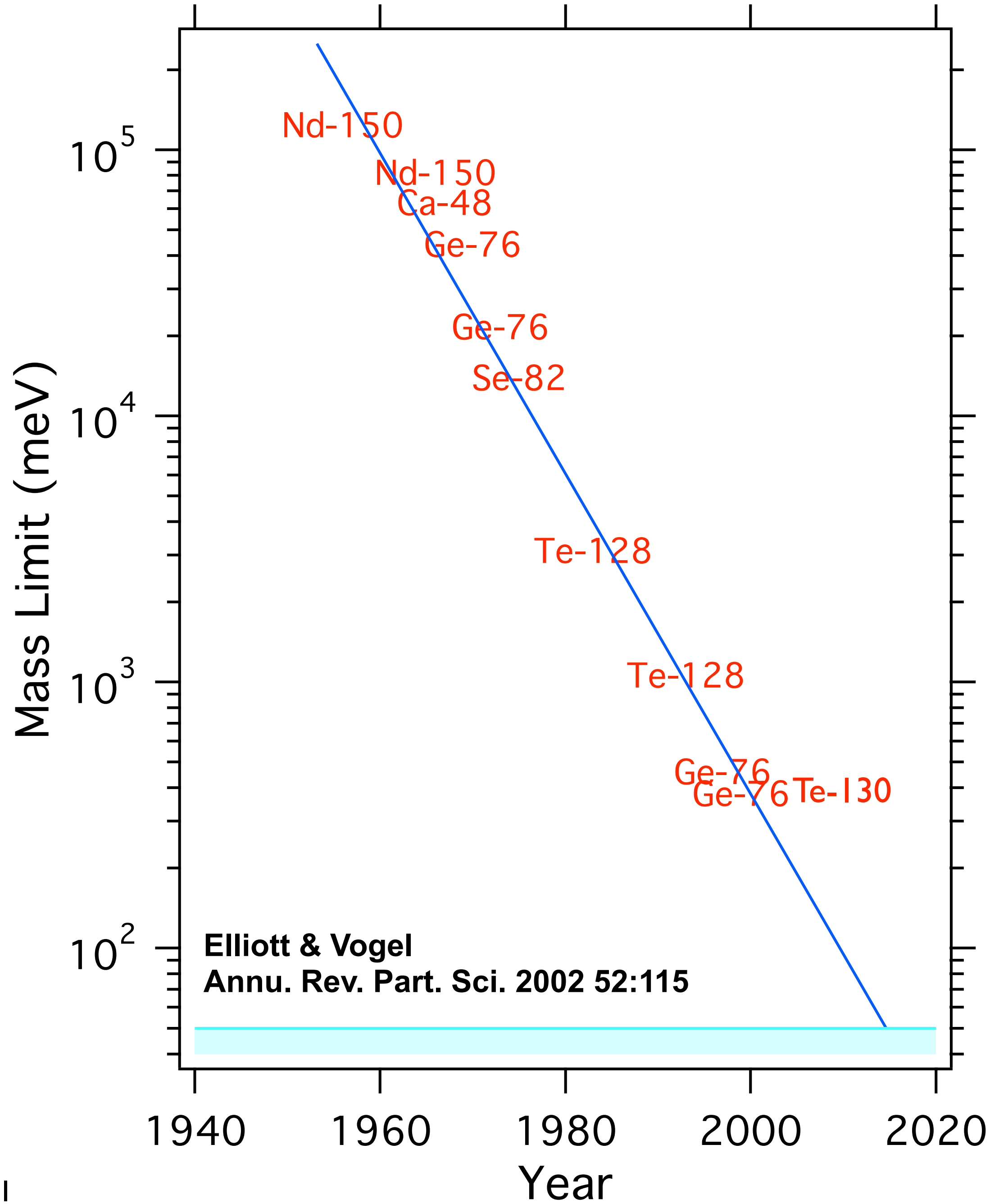
$T_{1/2}^{0\nu\beta\beta} > 10^{25}$ years

0νββ mode highly suppressed compared to 2νββ



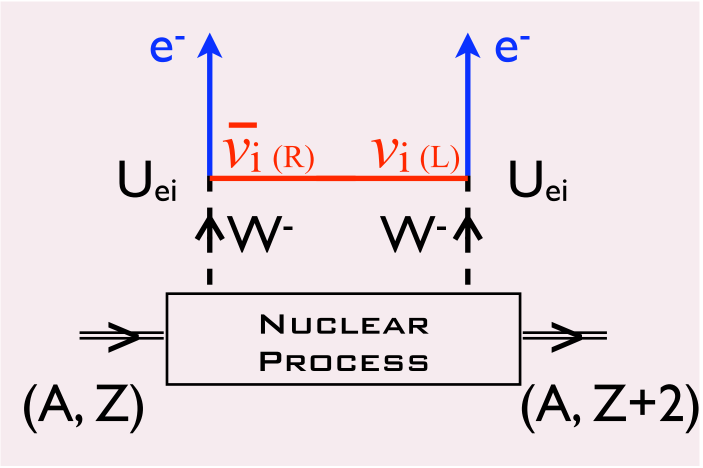
If observe
0νββ ⇒
neutrinos are Majorana

0νββ Progress & Best Limits



Extracting Additional Physics from 0νββ

Neutrino mass & nature of lepton number violating interactions (η)



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}(\eta)\right|^2 \eta^2$$

$$\Downarrow$$

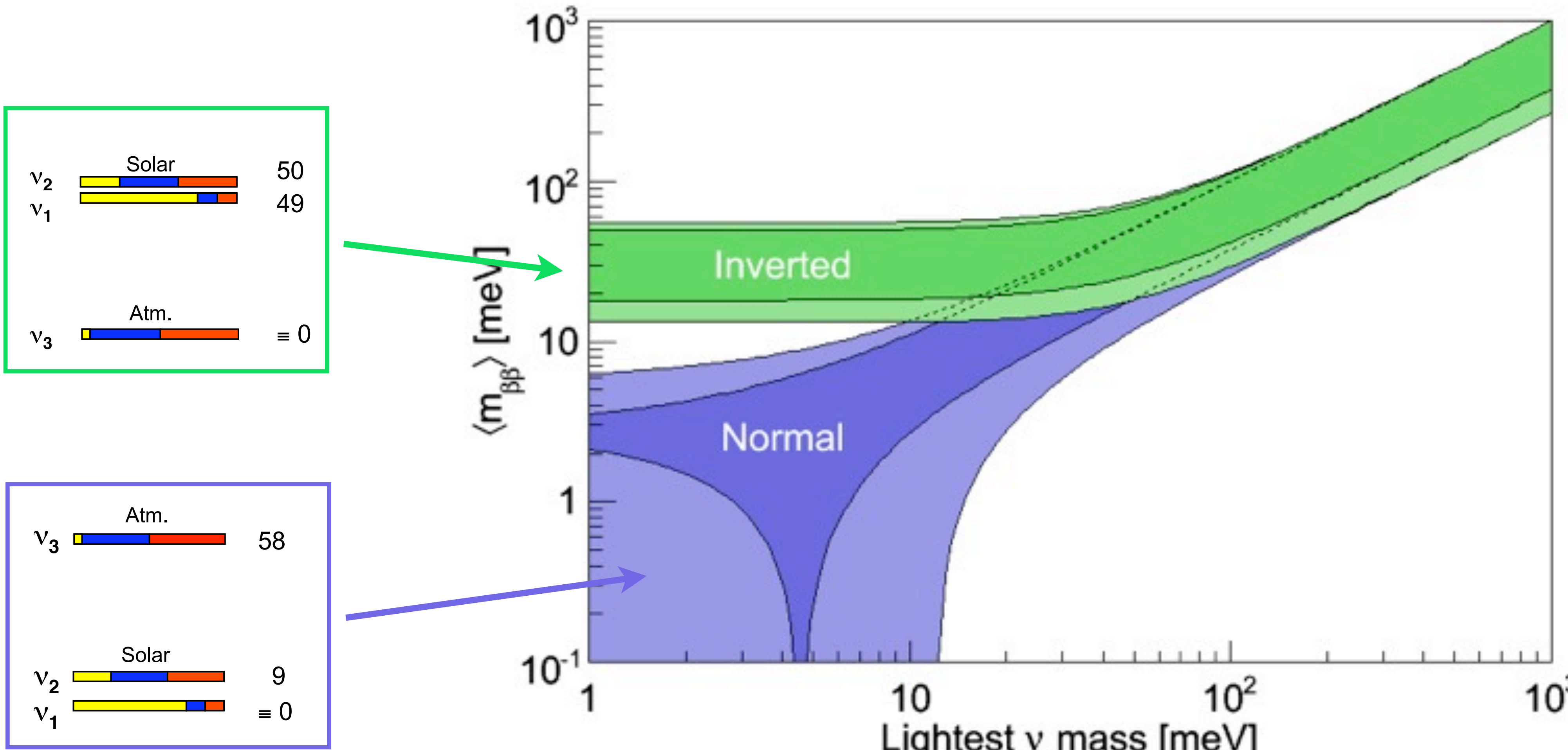
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left\langle m_{\beta\beta}\right\rangle^2$$

- Phase space, $G_{0\nu}$ is exactly calculable.
- Nuclear matrix elements (NME) via theory (Shell Model, Quasi-random phase approximation, interacting boson model).
- Effective neutrino mass, $<m_{\beta\beta}>$, depends directly on the assumed form of lepton number violating (LNV) interactions.
  - simplest, as typically shown (e.g. above): light Majorana neutrino and "standard model" interactions (W^-)

0νββ Decay Sensitivity to <mββ>

Assuming LNV mechanism is light Majorana neutrino exchange

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

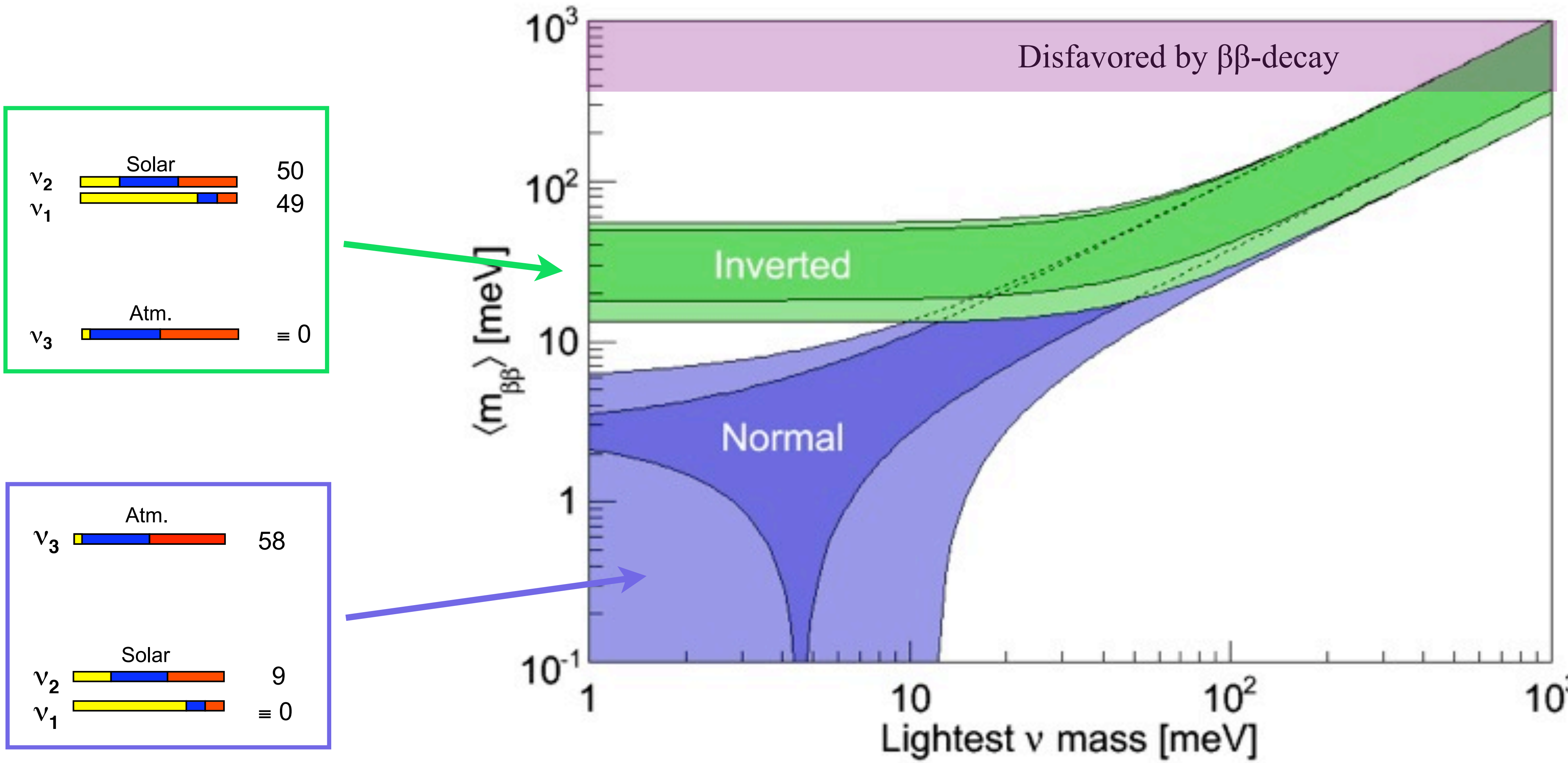


$0\nu\beta\beta$ Decay Sensitivity to $\langle m_{\beta\beta} \rangle$

Assuming LNV mechanism is light Majorana neutrino exchange

$0\nu\beta\beta$ limits for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

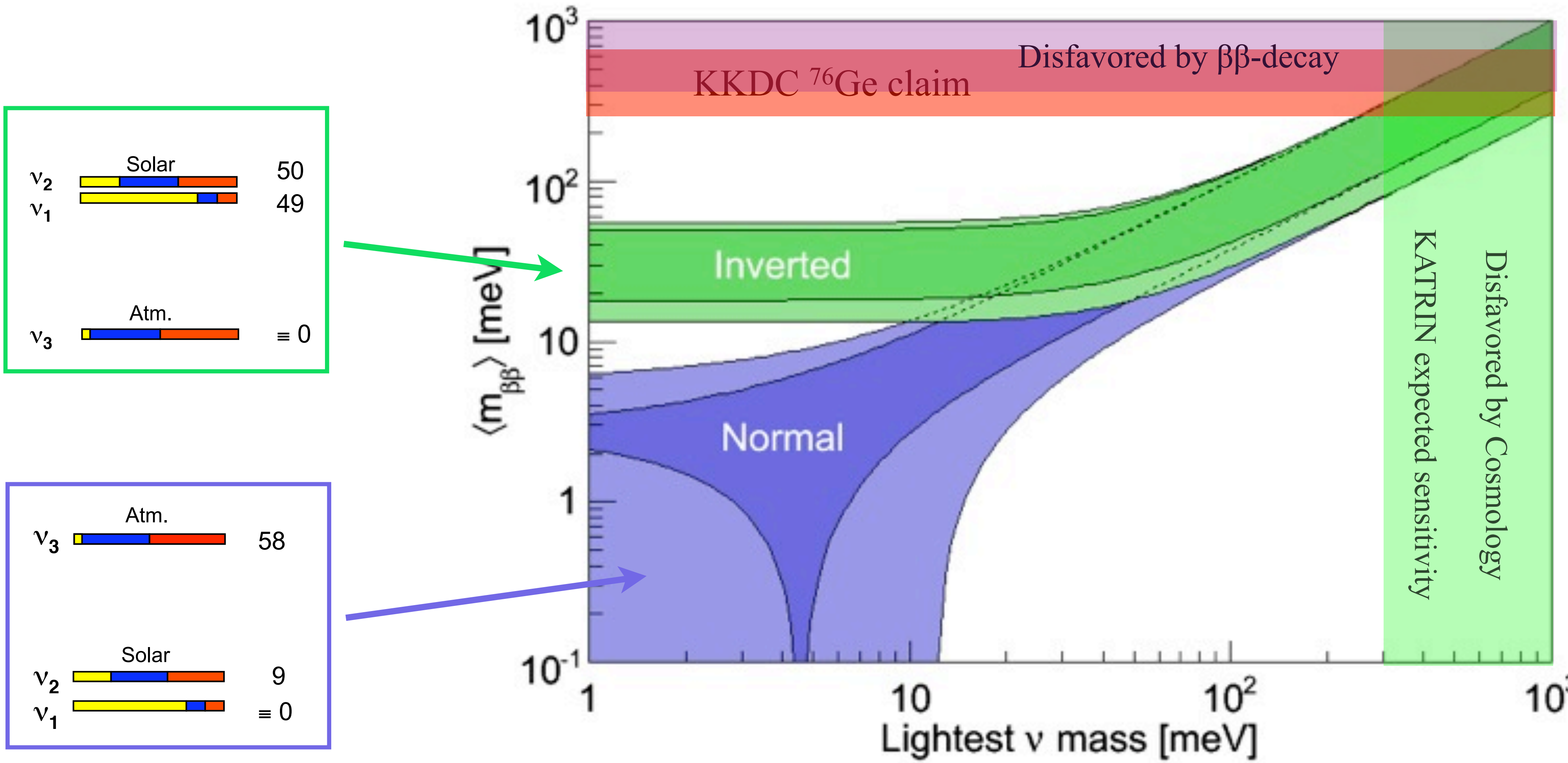


0νββ Decay Sensitivity to <mββ>

Assuming LNV mechanism is light Majorana neutrino exchange

0νββ limits for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



Searches for 0νββ

0νββ decay probes fundamental questions:

- Neutrino properties — the only practical technique to determine if neutrinos are their own anti-particles — Majorana particles.
- Lepton number violation (LNV) — might Leptogenesis be the explanation for the observed matter - antimatter asymmetry?

The observation of 0νββ would demonstrate Majorana nature of ν and LNV

If 0νββ is observed:

- Provides a promising laboratory method for determining the absolute neutrino mass scale that is complementary to other neutrino mass measurement techniques, if calculated NME are reliable.
- Measurements in a series of different isotopes can potentially help reveal the nature of the lepton number violating process(es).

Extraction of ν mass and understanding the LNV process(es) requires significant reliance on both nuclear and particle physics. (See Vogel)

$0\nu\beta\beta$ Decay II

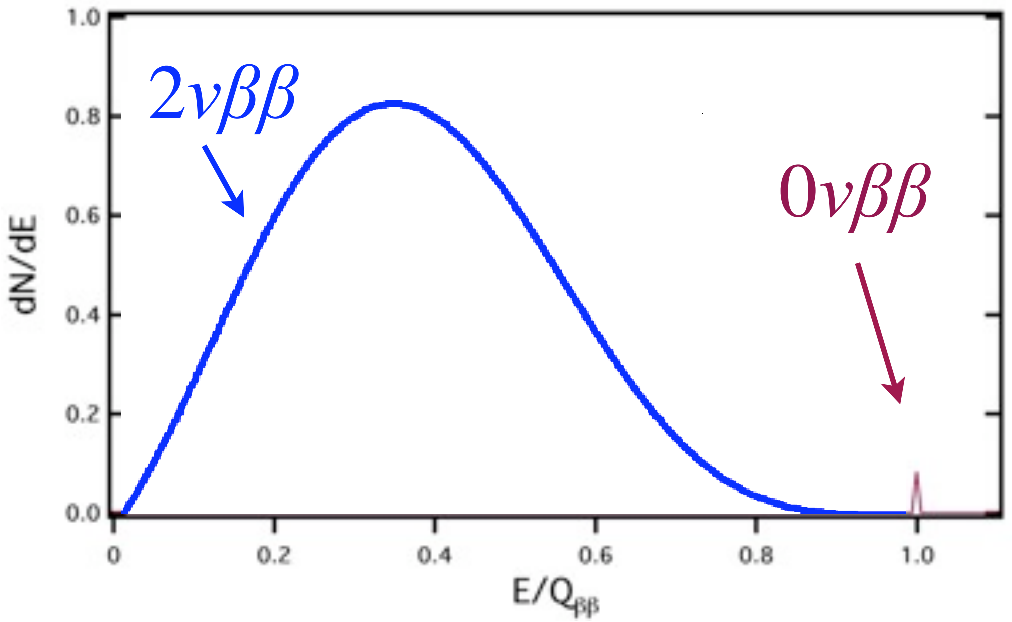
Experimental Considerations & Sensitivity

Basics
Resolution
Backgrounds Overview
Ideal experiment

Basic Considerations

Extremely rare process

$0\nu\beta\beta$ $T_{1/2} \sim 10^{26} - 10^{27}$ years



Large, highly efficient source mass

Best possible energy resolution

Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region

Current sensitivity to $0\nu\beta\beta$-decay

Most sensitive experiments to date (using ^{76}Ge and ^{130}Te) have attained $T_{1/2}$ > 10^{24} - 10^{25} years.

If zero backgrounds, $[T_{1/2}]^{-1} \propto M \bullet t_{exp}$

Typical masses ~ 1-10 kg

Typical exposure times of 5-8 years

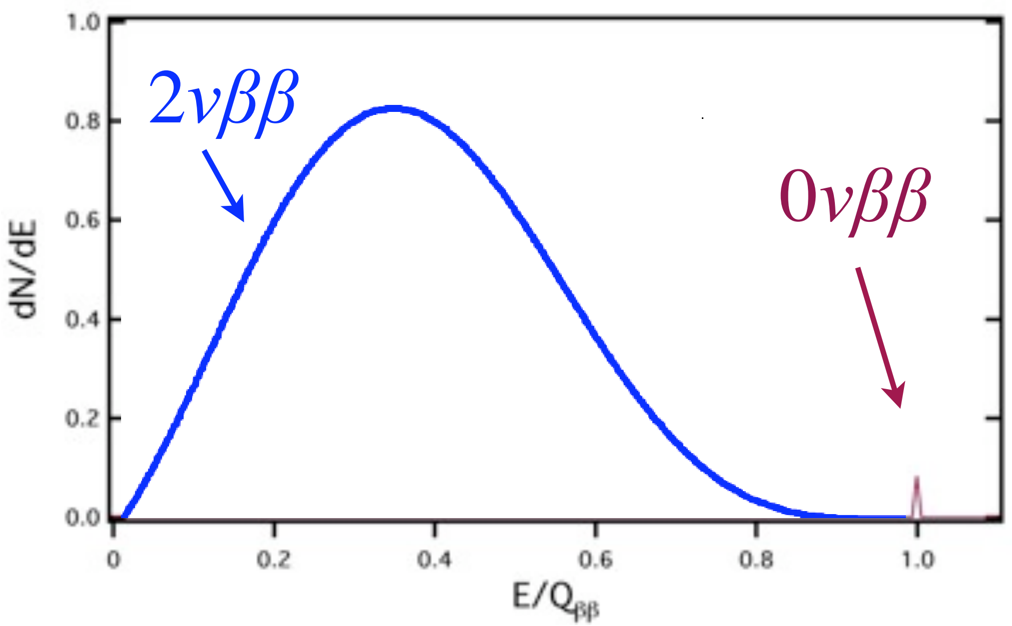
Question 1: What's needed to reach sensitivities of $T_{1/2}$ on the order of 10^{25} - 10^{27} y?

Question 2: What would convince you that $0\nu\beta\beta$ has been discovered?

Basic Considerations

Extremely rare process

$0\nu\beta\beta$ $T_{1/2} \sim 10^{26} - 10^{27}$ years



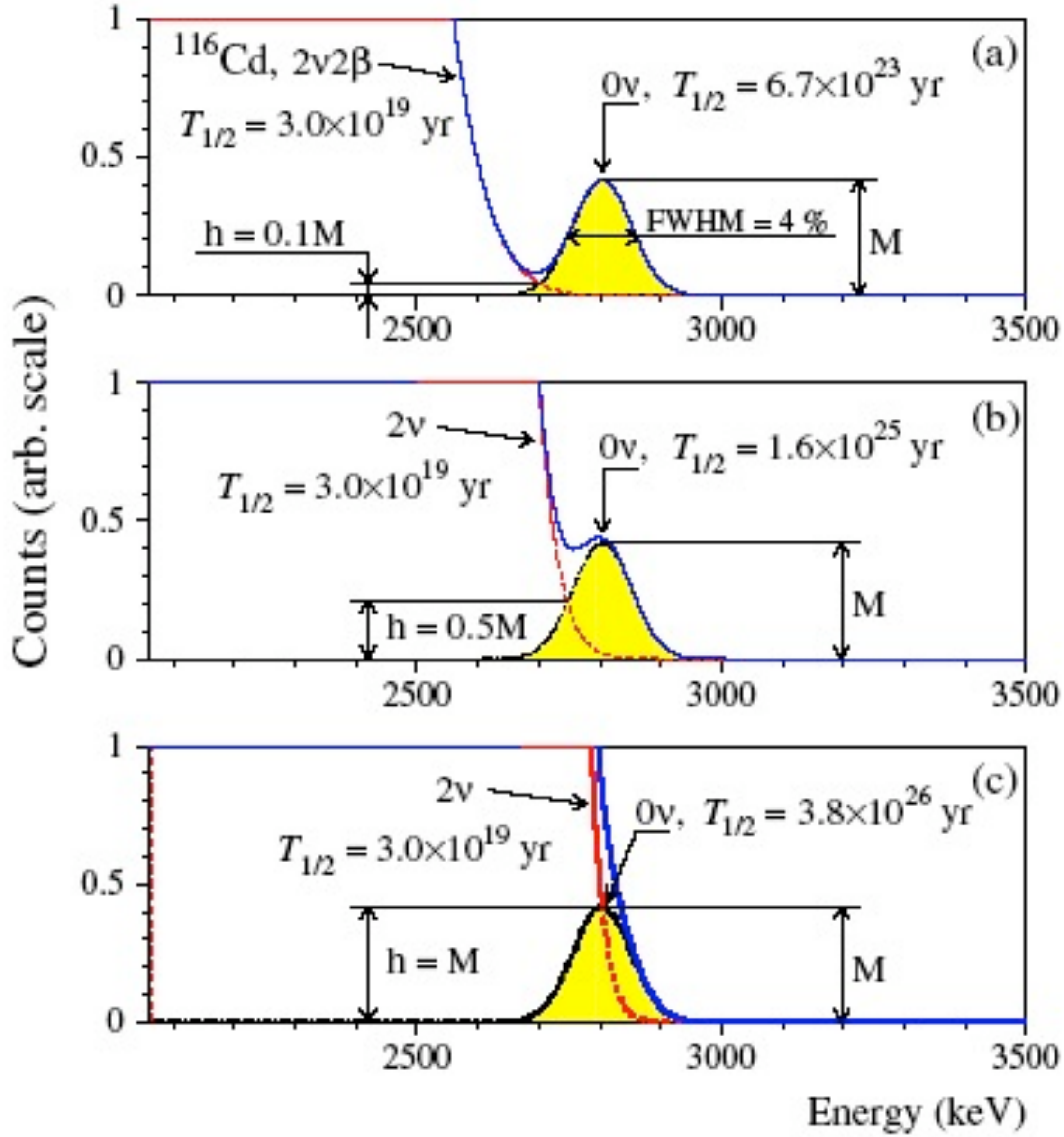
Large, highly efficient source mass
- detector as source

Best possible energy resolution
- minimize $0\nu\beta\beta$ peak ROI to maximize S/B
- separate from $0\nu\beta\beta$ from irreducible $2\nu\beta\beta$ (~ $T_{1/2} \sim 10^{19} - 10^{21}$ years)

Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region
- requires ultra-clean radiopure materials
- the ability to discriminate signal from backgrounds

Energy Resolution & Sensitivity to 0νββ

For ideal case, with only 2νββ background

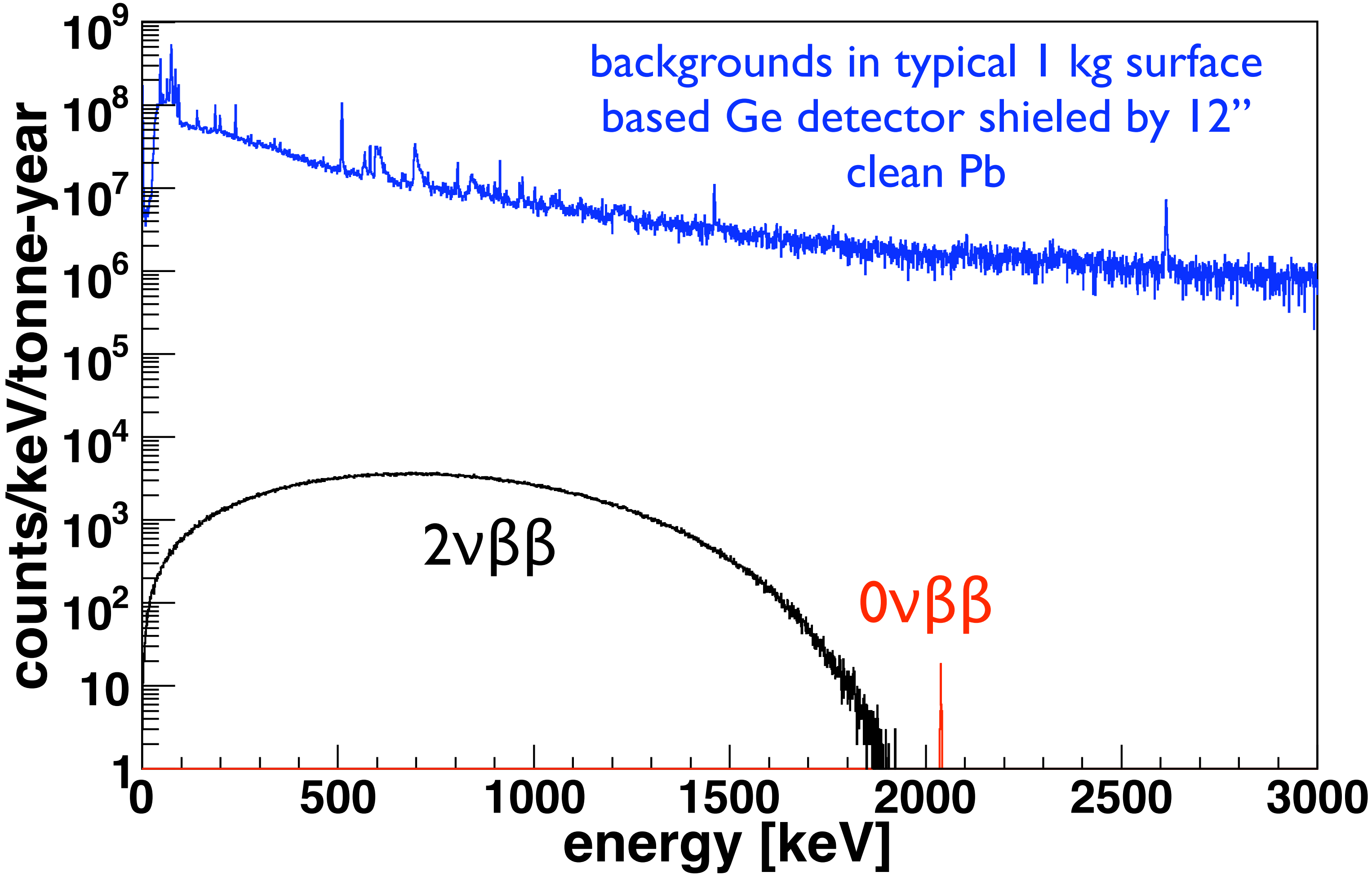


From Zdesenko, Danevich, Tretyak, J. Phys. G 30 (2004) 971

Backgrounds & Sensitivity to 0νββ

- Next generation experiments are striving for backgrounds in the 0νββ region of **counts/tonne-year**.
  - Requires materials with sub μBq/kg level radioimpurities.
    - Very difficult to achieve this sensitivity with direct radioassays
  - Shielding from cosmogenic activation.
  - "New background regimes" -- background sources that could previously be ignored
    - e.g. : very weak (n,n',gamma) lines
- Each experiment's susceptibility to backgrounds depends on a number of factors:
  - Detection technique (Solid state, TPC, bolometer, ...)
  - Detector resolution
  - Detector response function to backgrounds (γ, α, β, neutron, ...)
  - Construction materials and surrounding materials
  - Signal to background discrimination capabilities

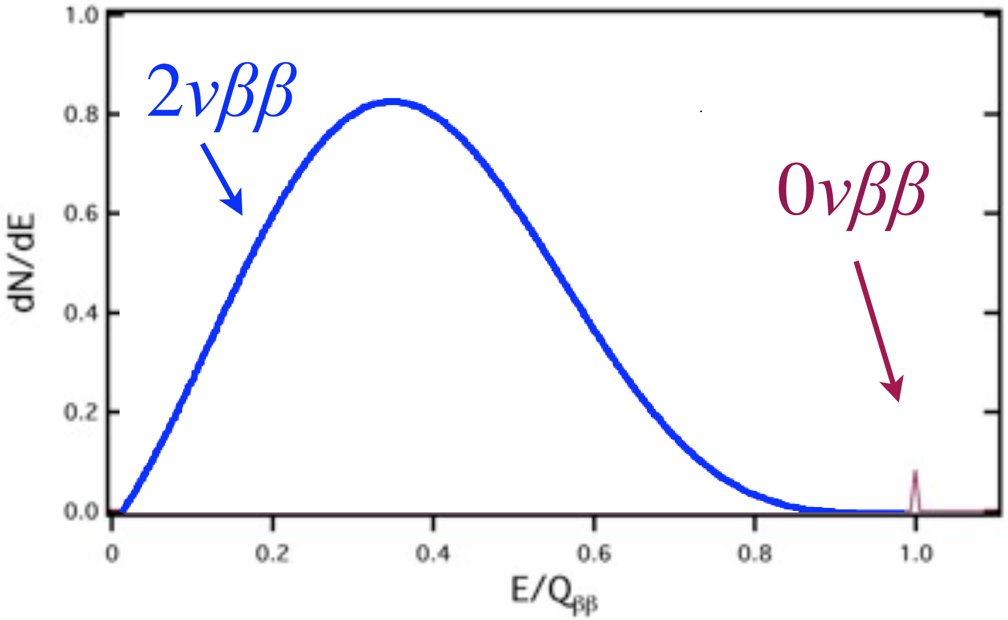
1ct/tonne-year in context - Ge example

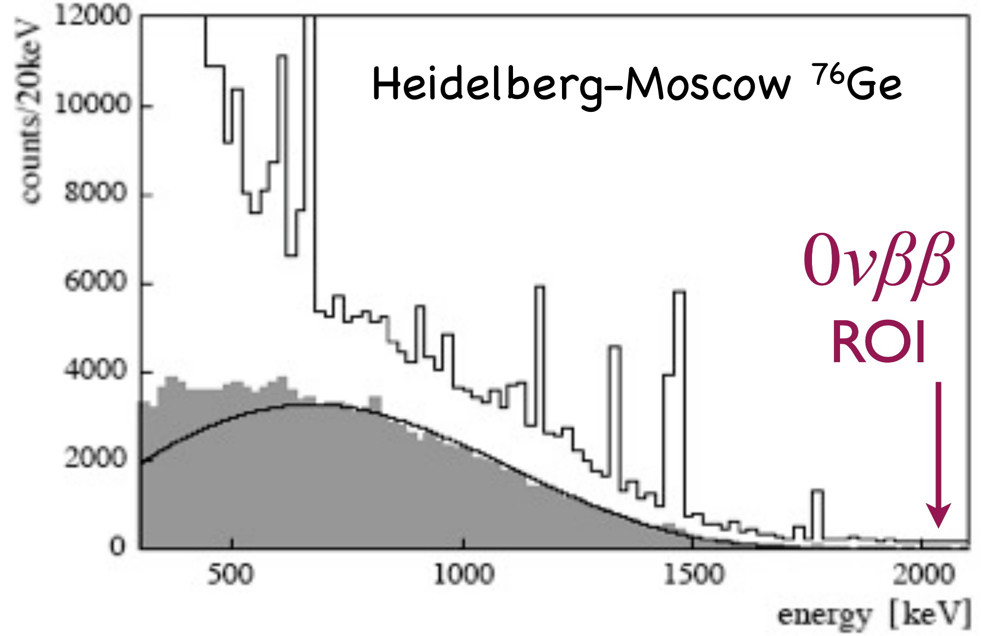


0νββ half-life chosen to be 10x current limit

A. Schubert

Best to date - 100 cnts/tonne-year in ROI





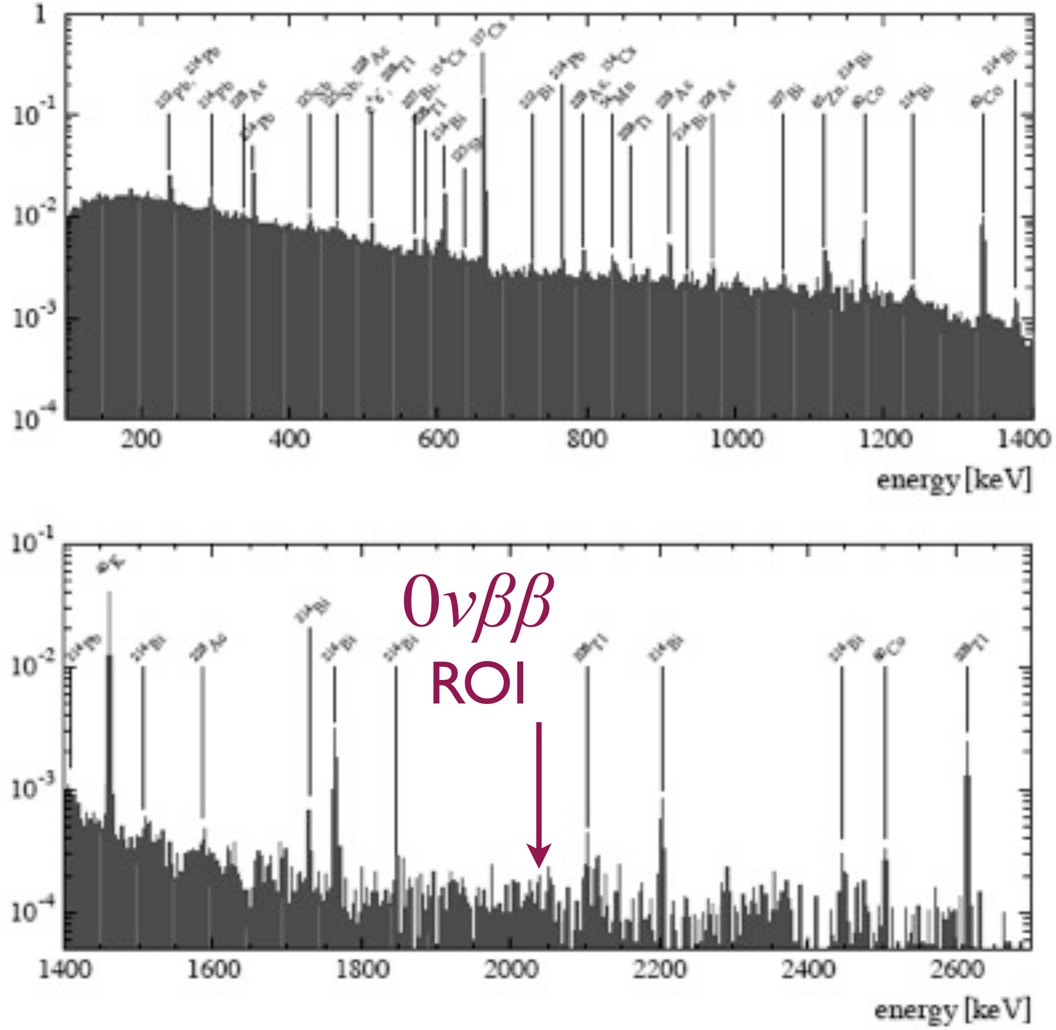
Note ^{76}Ge has best resolution : 0.16%

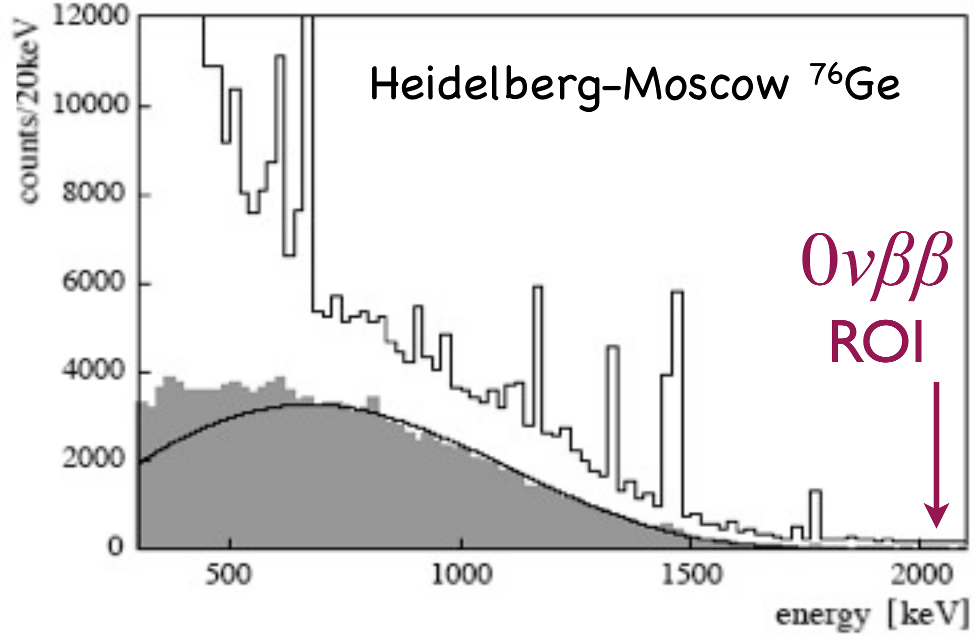
Only 2vββ

2vββ (negligble)
Cosmogenic activity
Natural radioactivity
neutron induced activity

Klapdor-Kleingrothaus et al.,
Eur. Phys. J 12, 147 (2001)

Best to date - 100 cnts/tonne-year in ROI





Note ^{76}Ge has best resolution : 0.16%

2νββ (negligble)
Cosmogenic activity
Natural radioactivity
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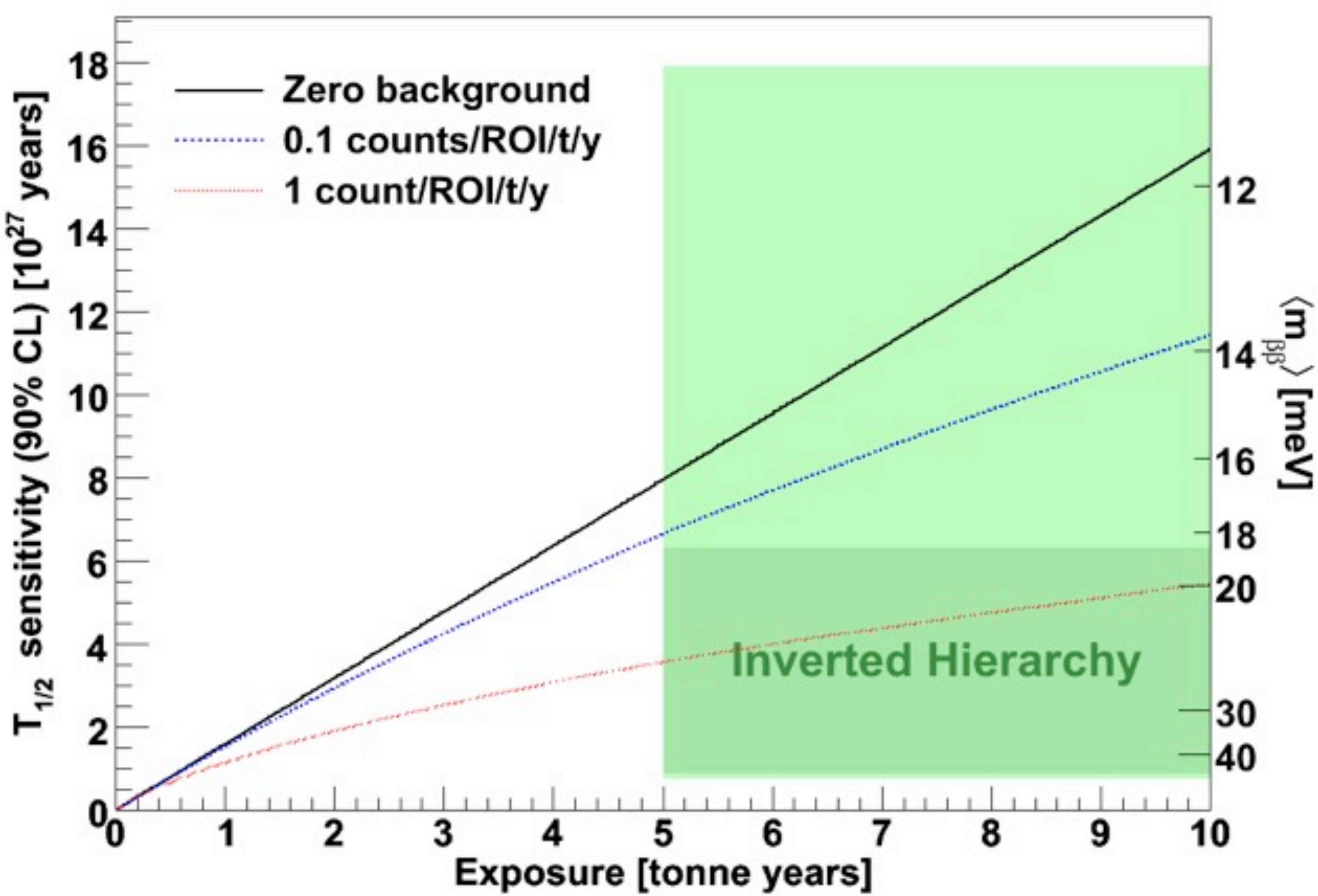
Sensitivity and backgrounds

1-tonne ^{76}Ge Example



"Ideal" Experiment

- Source serves as the detector
- Elemental (enriched) source to minimize active material.
- Large Q value - faster 0 rate and also places the region of interest above many potential backgrounds.
- Relatively slow $2\nu\beta\beta$ rate helps control this irreducible background.
- Direct identification of the decay progeny in coincidence with the $0\nu\beta\beta$ decay eliminates all potential backgrounds except $2\nu\beta\beta$.
- Full Event reconstruction, providing kinematic data such as opening angle and individual electron energy aids in the elimination of backgrounds and demonstration of signal (can possibly use $2\nu\beta\beta$)
- Spatial resolution and timing information to reject background processes.
- Demonstrated technology at the appropriate scale.
- The nuclear theory is better understood in some isotopes than others. The interpretation of limits or signals might be easier to interpret for some isotopes.

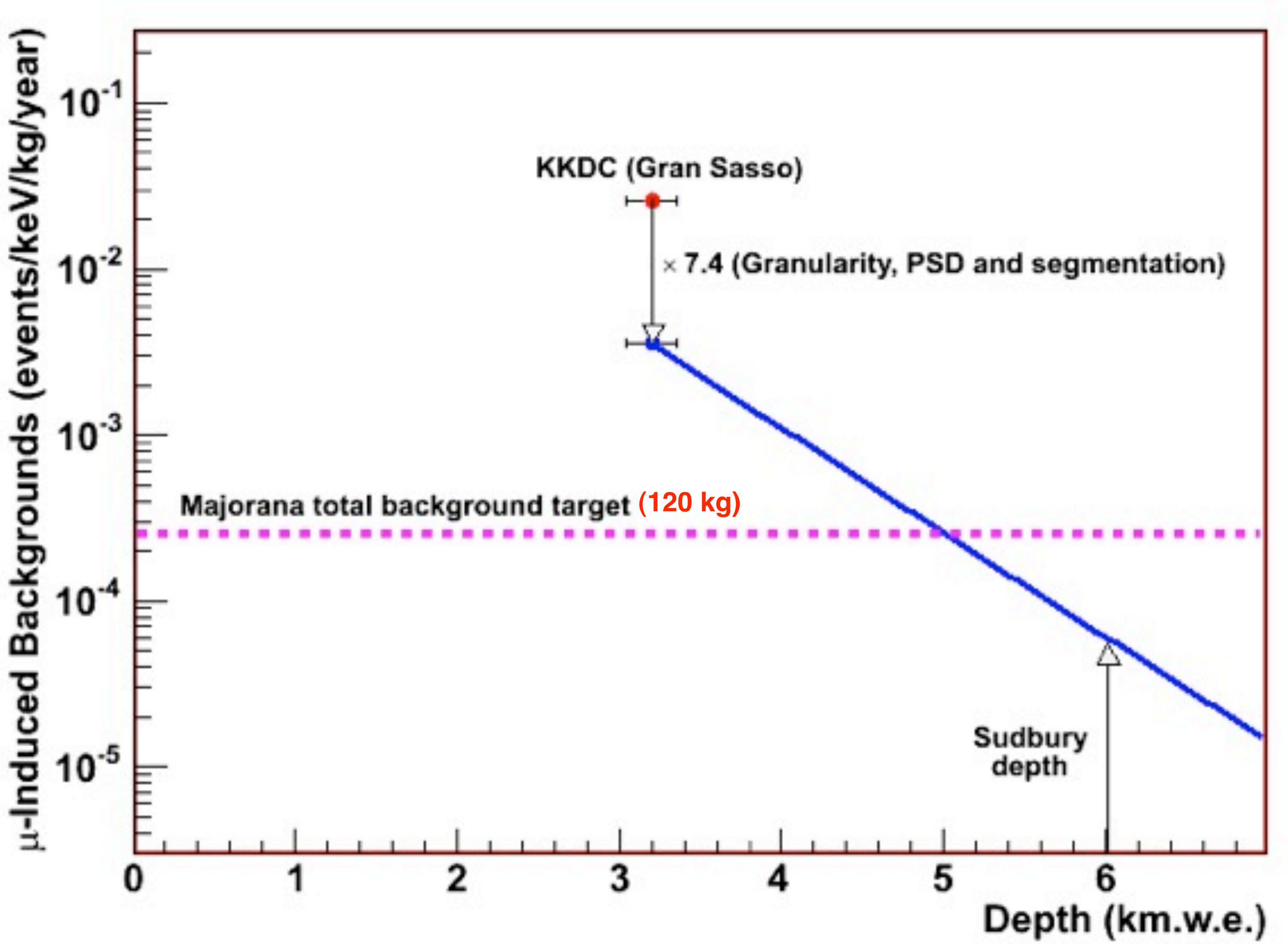
No one ideal isotope or experimental technique

0νββ Decay II

Backgrounds & Discrimination

Cosmogenics
Natural radioactivity
Reducing Backgrounds

Cosmogenic Backgrounds (muons)



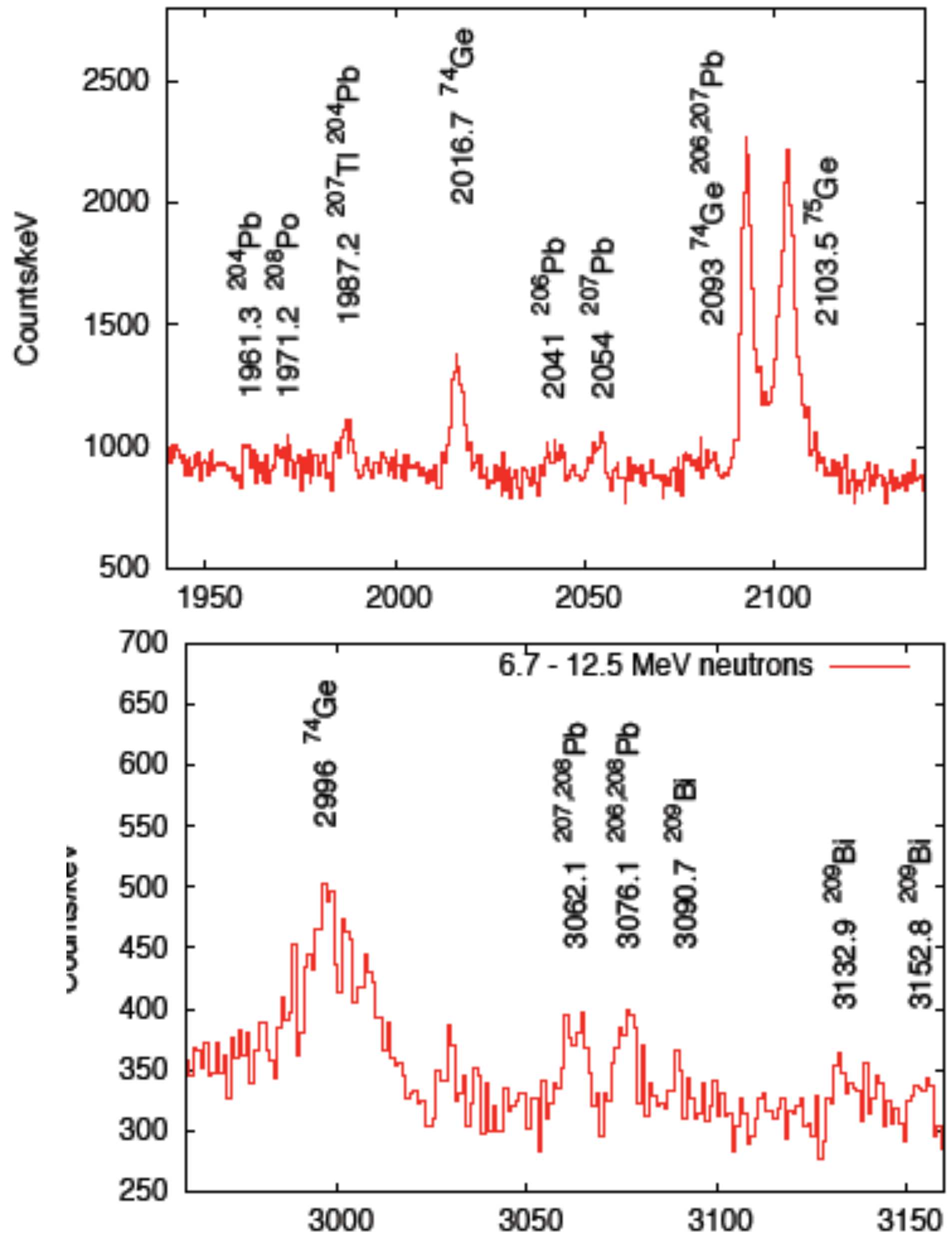
D.-M. Mei and A. Hime, Phys. Rev. D **73**, 053004 (2006).

Pb(n,n'γ) lines

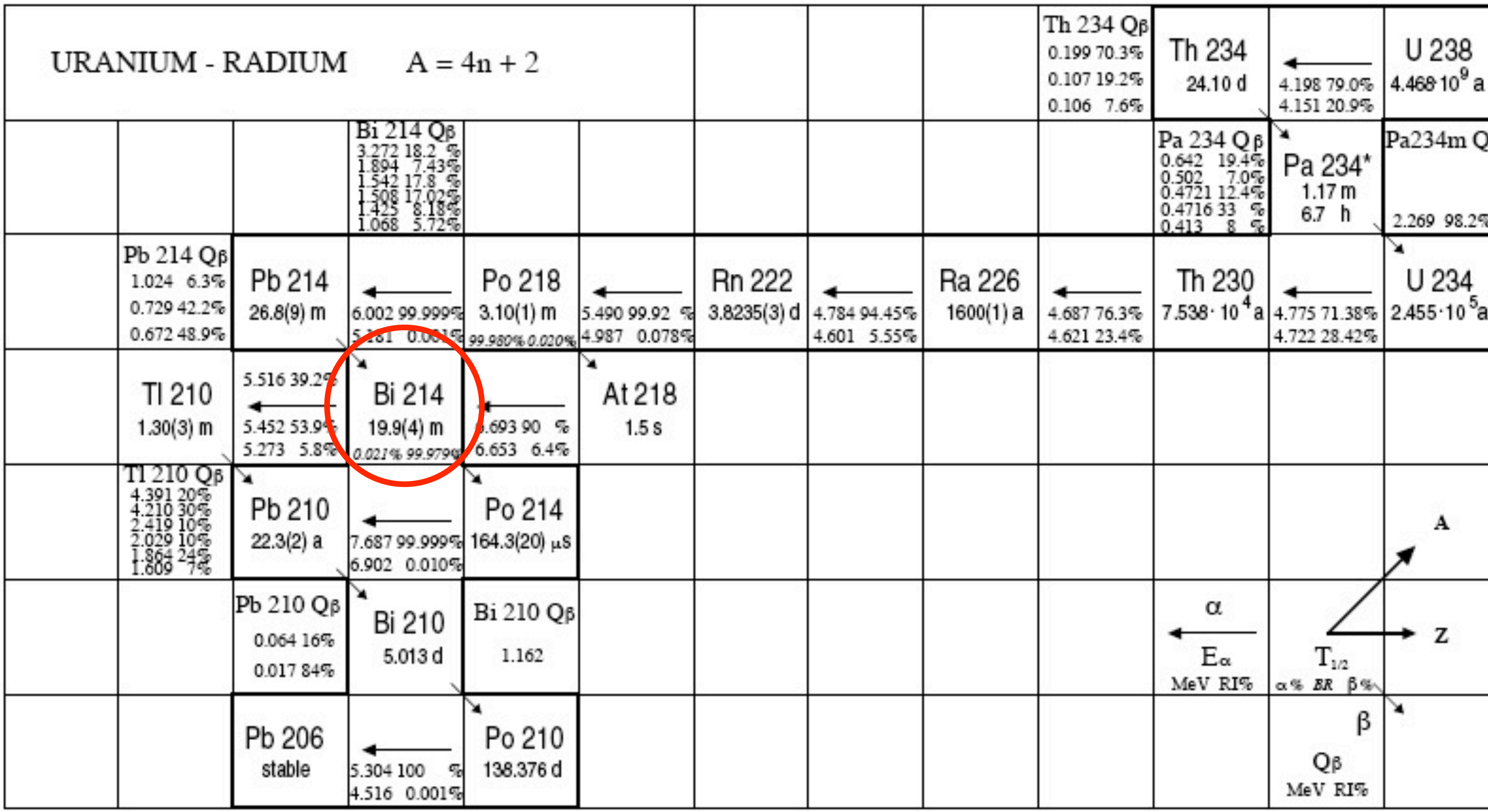
- Specific Pb gamma rays are problematic backgrounds
  - ^{206}Pb has a 2040-keV γ ray
  - ^{207}Pb has a 3062-keV γ ray
  - ^{208}Pb has a 3060-kev γ ray
- Neutron interactions in Pb can excite these levels
- The DEP of the ~3062 keV γ ray is a single site energy deposit at ββ Q-value

V. E. Guiseppe et al.

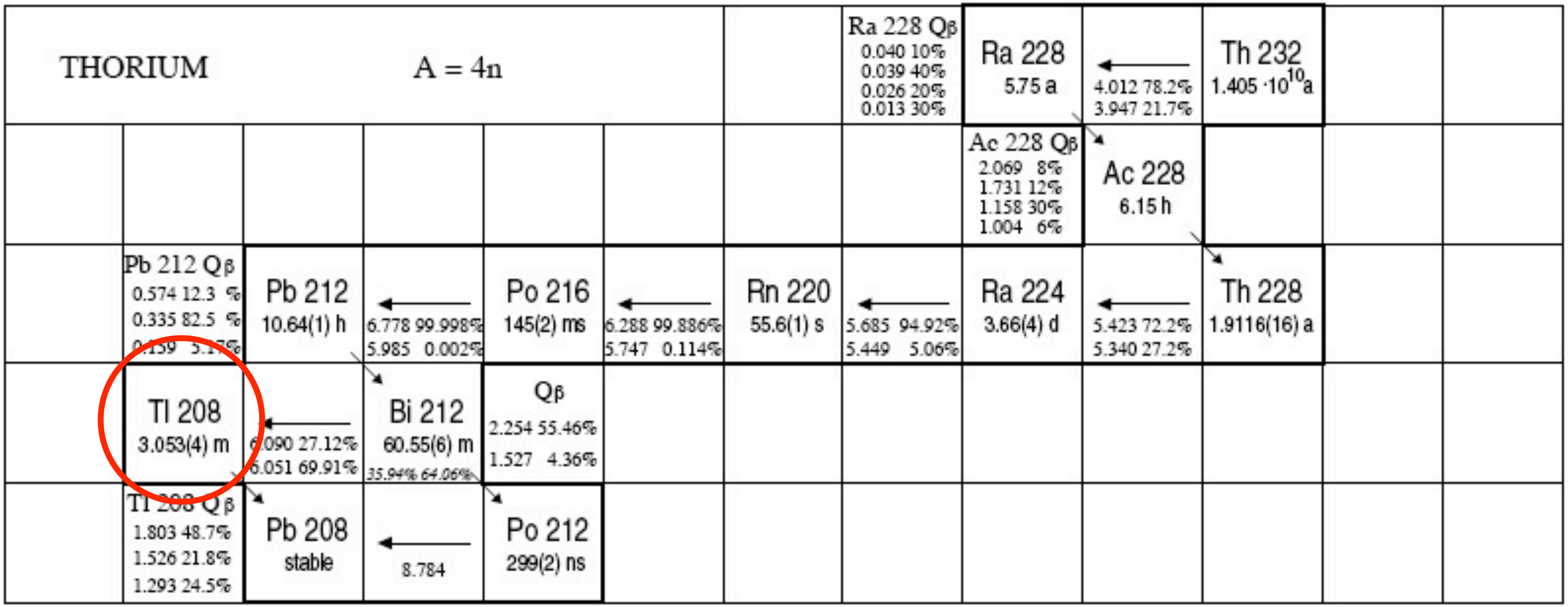
arXiv:0809.5074



Uranium (^{238}U) Decay Chain



Thorium (^{232}Th) Decay Chain



Backgrounds due to natural radioactivity

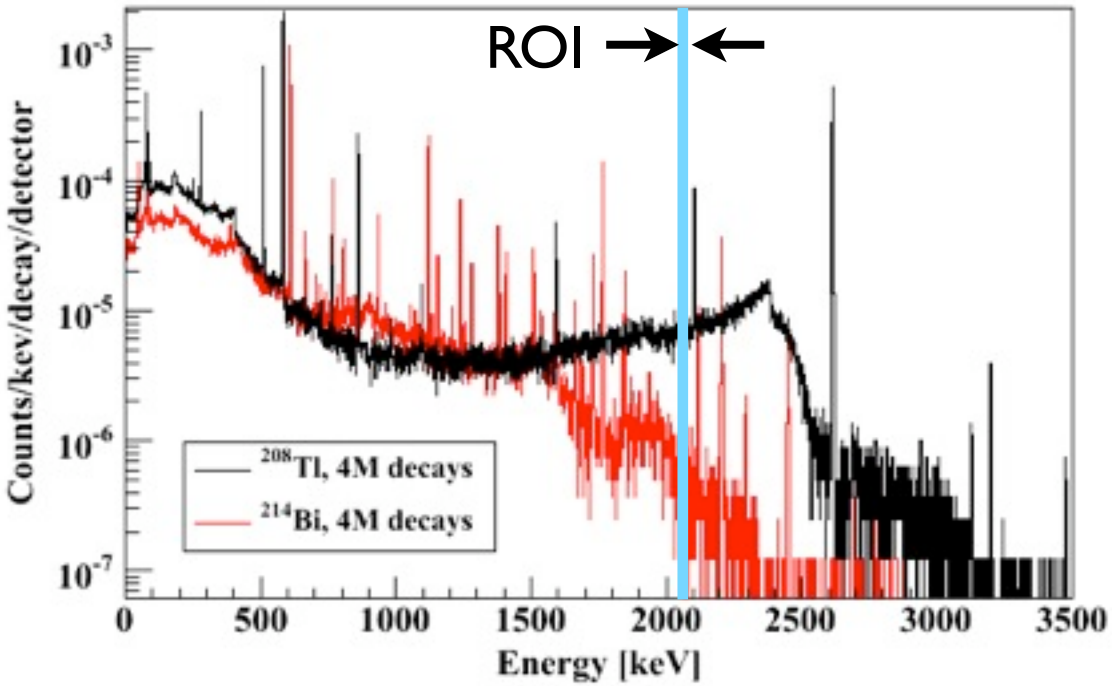
Uranium (^{238}U)

- $T_{1/2} = 4.5 \times 10^9$ years
- decays to ^{206}Pb
- ^{214}Bi produced

Thorium (^{232}Th)

- $T_{1/2} = 1.4 \times 10^{10}$ years
- decays to ^{208}Pb
- ^{208}Tl produced

simulated detector response to ^{208}Tl and ^{214}Bi



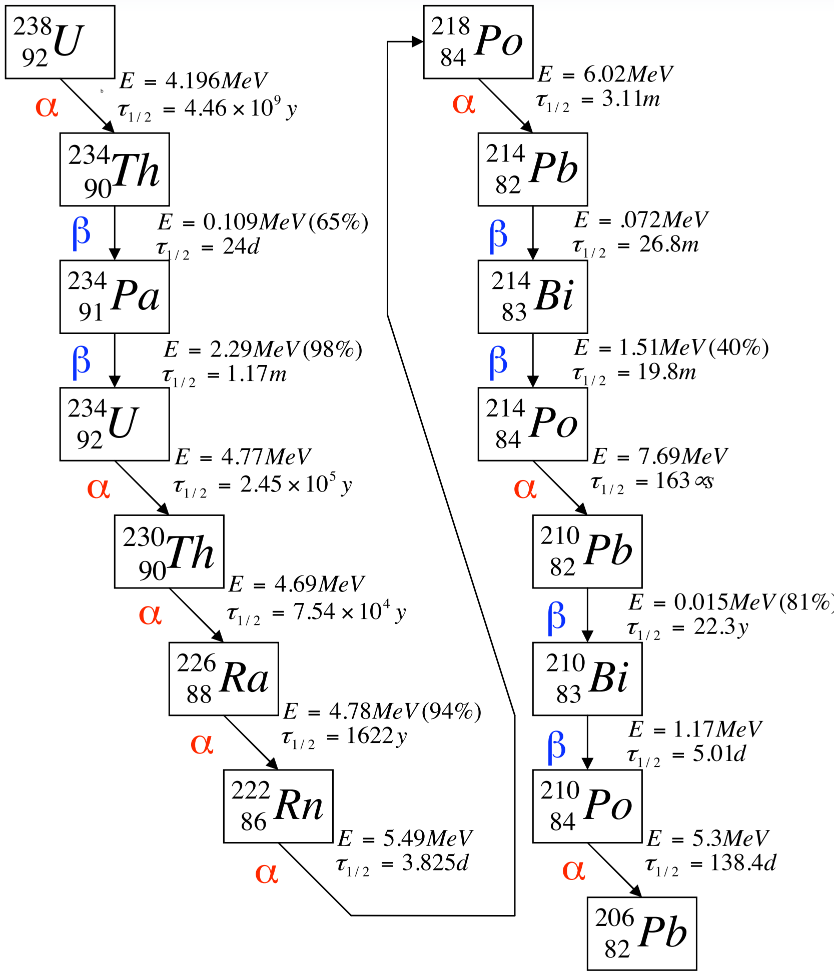
Simulations by A. Schubert

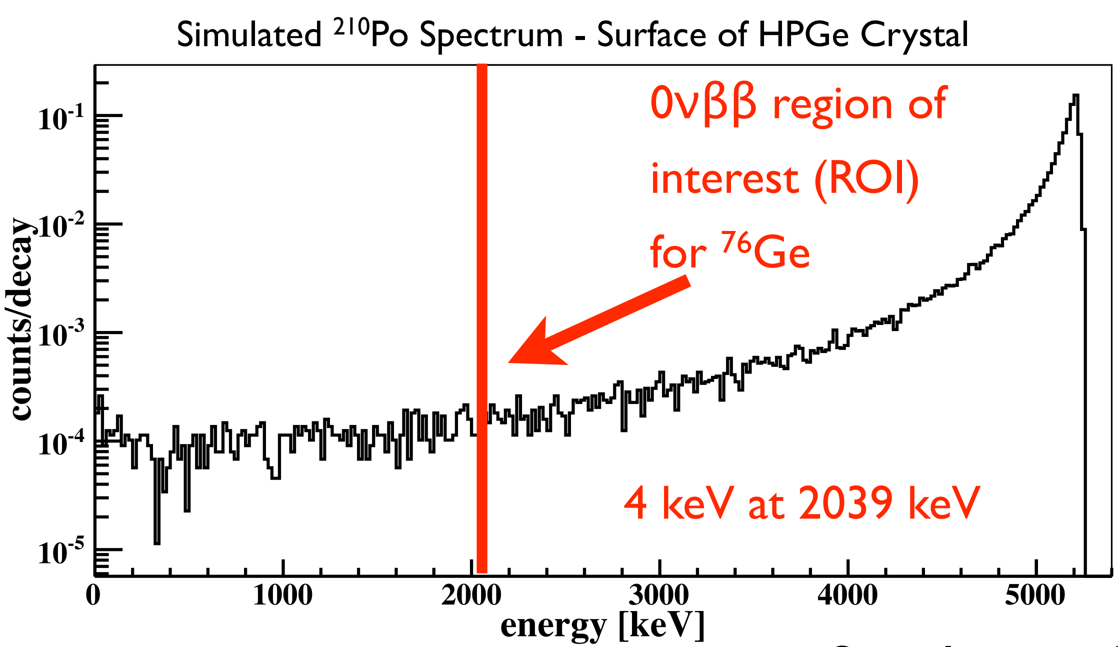
Backgrounds: Alpha Decays

Alphas emitted in decays of ^{232}Th and ^{238}U

Kinetic energies: 4.0-8.8 MeV

Range of alphas in germanium: 13-40 μm





Alphas only a background if

- Decays are near the detector
- The alpha only deposits a fraction of its energy in active region of germanium crystal

Simulations by R. Johnson

Reducing Backgrounds - Two Basic Strategies

- Directly reduce intrinsic, extrinsic, & cosmogenic activities
  - Select and use ultra-pure materials
  - Minimize all non "source" materials
  - Clean passive shield
  - Go deep — reduced μ's & related induced activities

- Utilize background rejection techniques

$0\nu\beta\beta$ is a single site phenomenon, many backgrounds have multiple site interactions

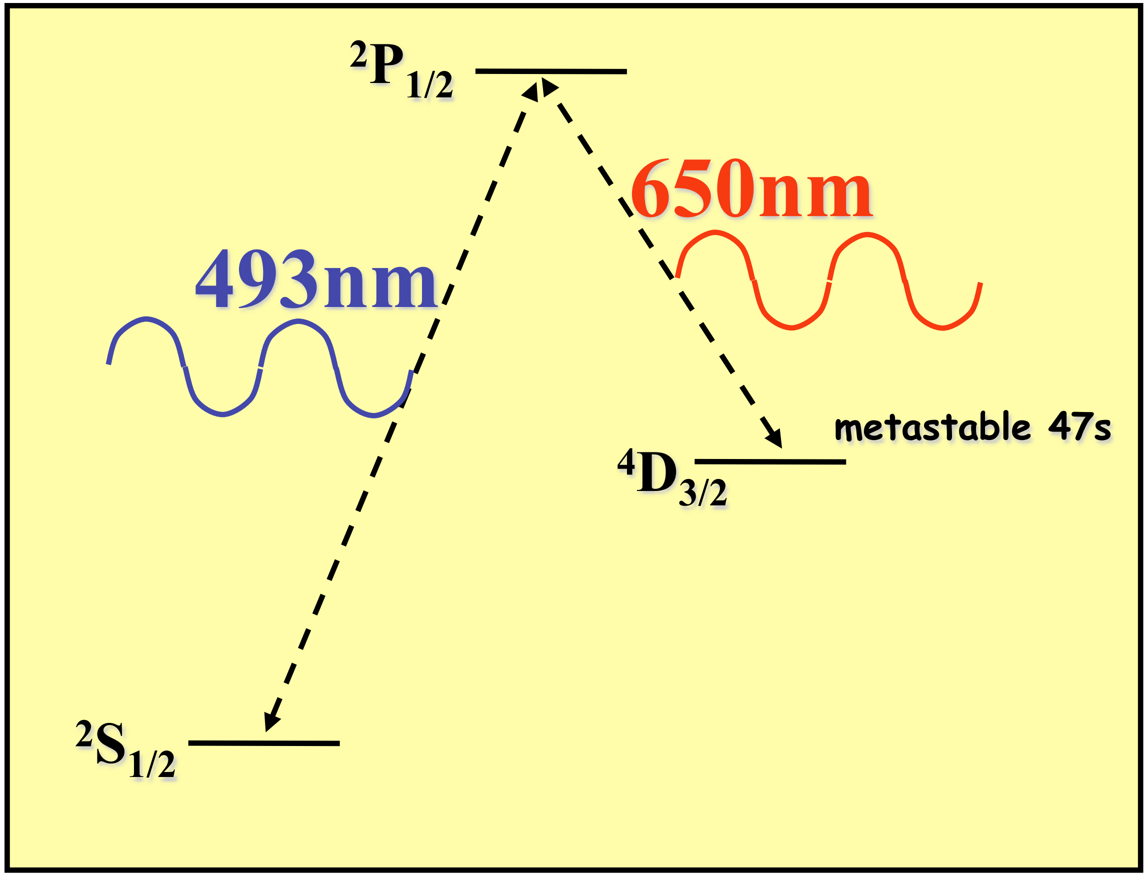
- Energy resolution
- Active veto detector
- Tracking
- Energy & Angular correlations
- Ion Identification
- Granularity [multiple detectors]
- Pulse shape discrimination (PSD)
- Segmentation
- Single Site Time Correlated events (SSTC)

EXO tonne scale with Ba tagging

Xe offers a qualitatively new tool against background:
$^{136}Xe \rightarrow\ ^{136}Ba^{++}\ e^-\ e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

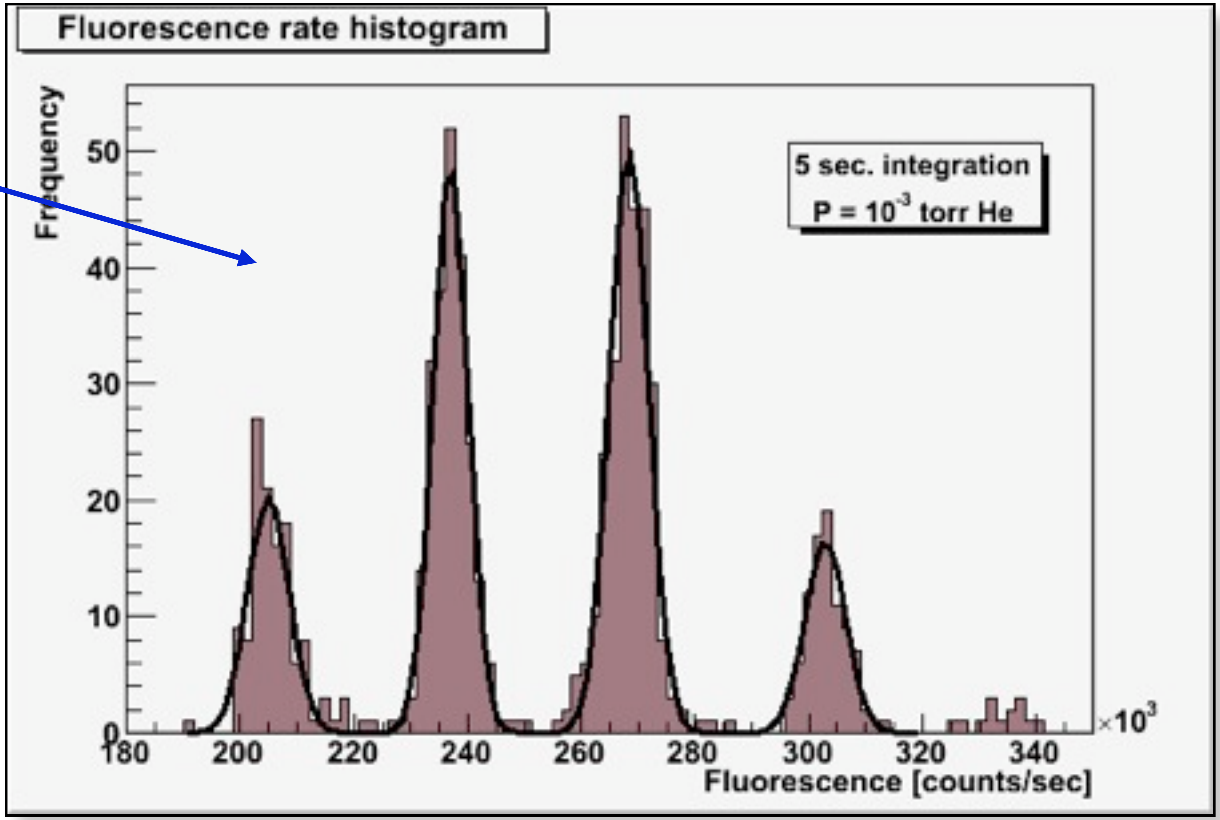
Ba$^+$ system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)
Very specific signature
"shelving"
Single ions can be detected from a photon rate of 10^7/s

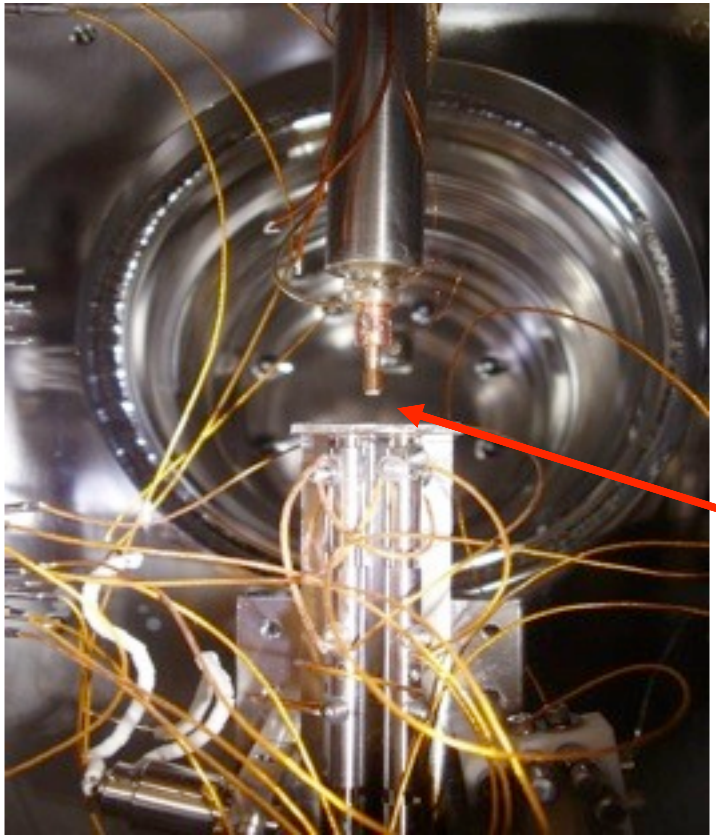
Important additional constraint
Dramatic Background reduction



EXO R&D on ion-tagging

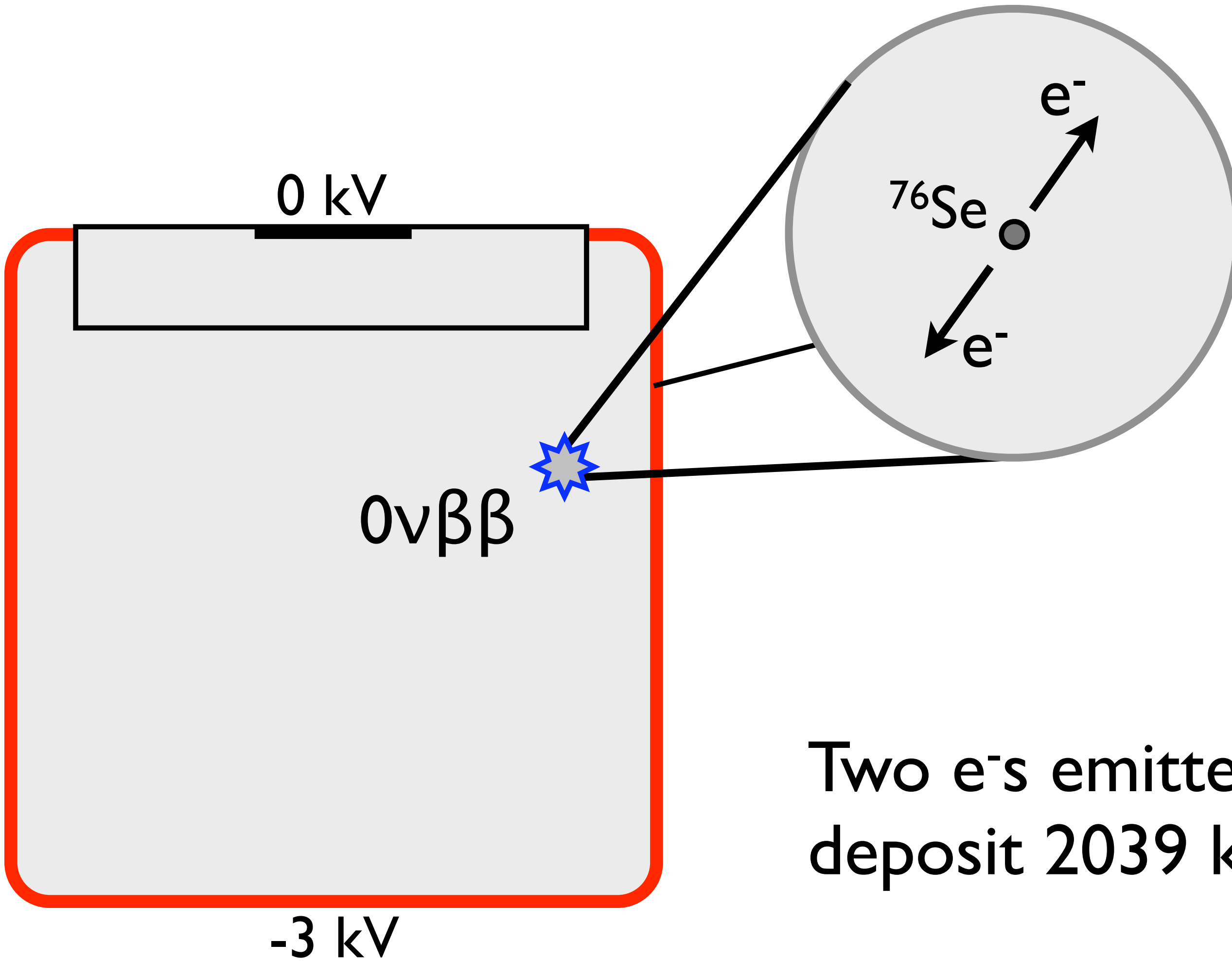
EXO linear trap can see single Ba ions in gas with large S/N ratio





Learning how to transfer single Ba ions from Xe to the ion trap

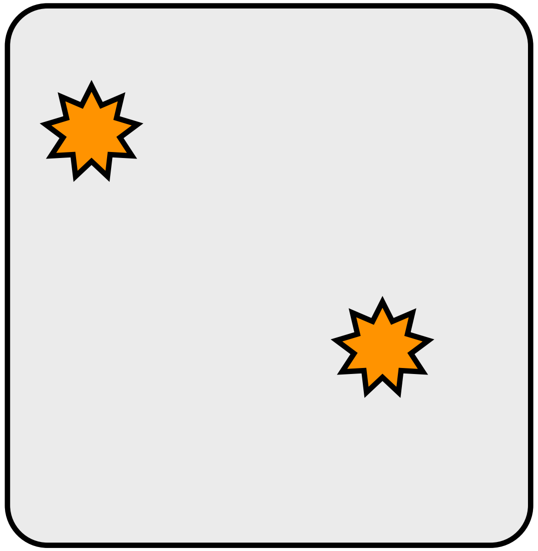
0νββ of ^{76}Ge



Two e^{-}s emitted by ^{76}Ge nucleus deposit 2039 keV in detector

a $0\nu\beta\beta$ event

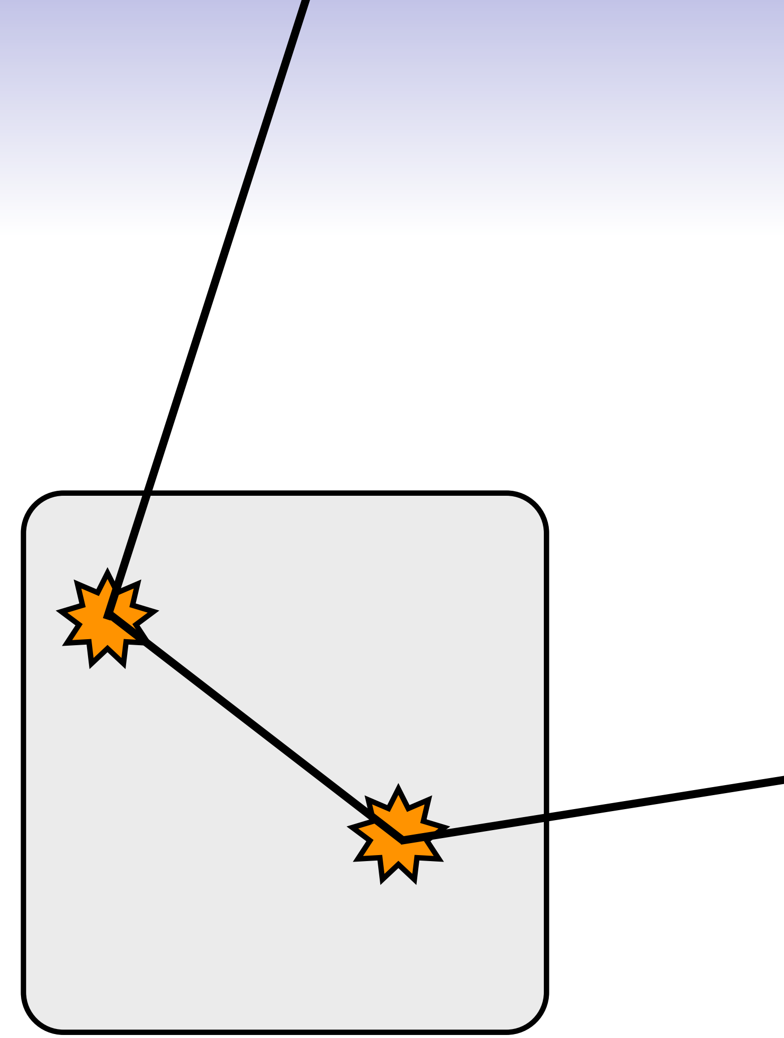
- 2039 keV
- one detector
- one site

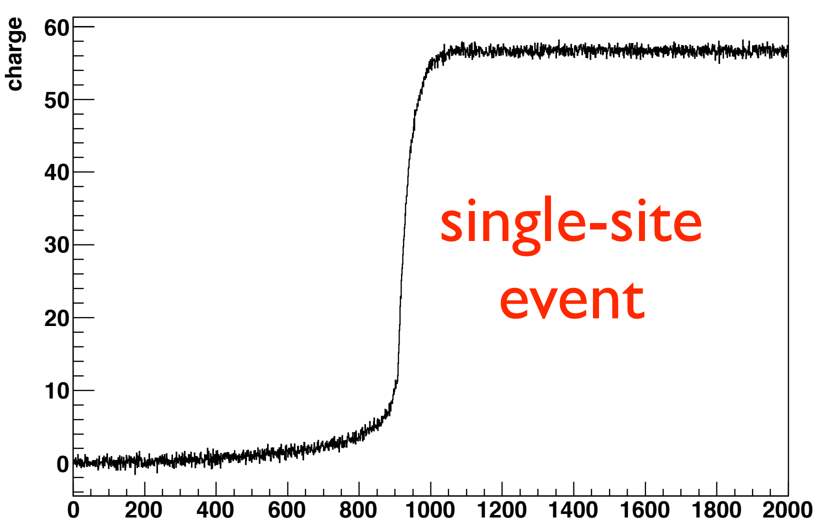


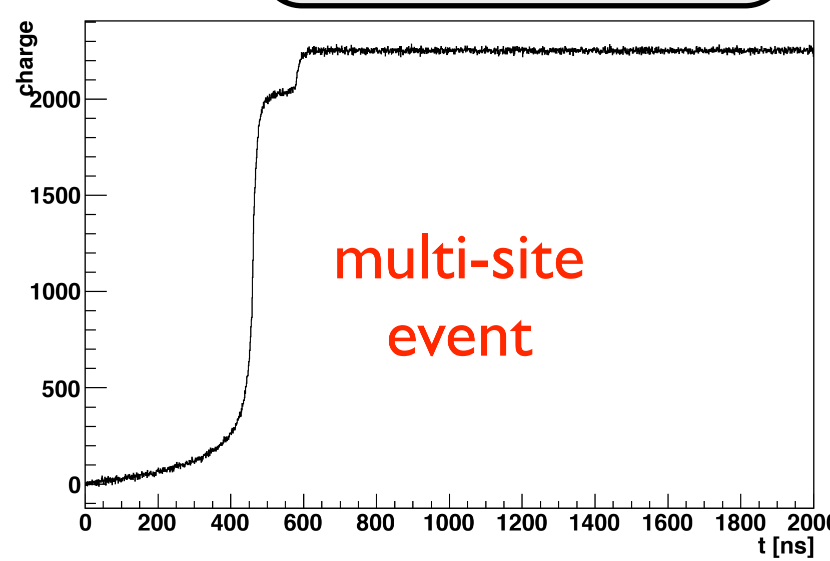
not a 0νββ event

- 2039 keV
- one detector
- one site

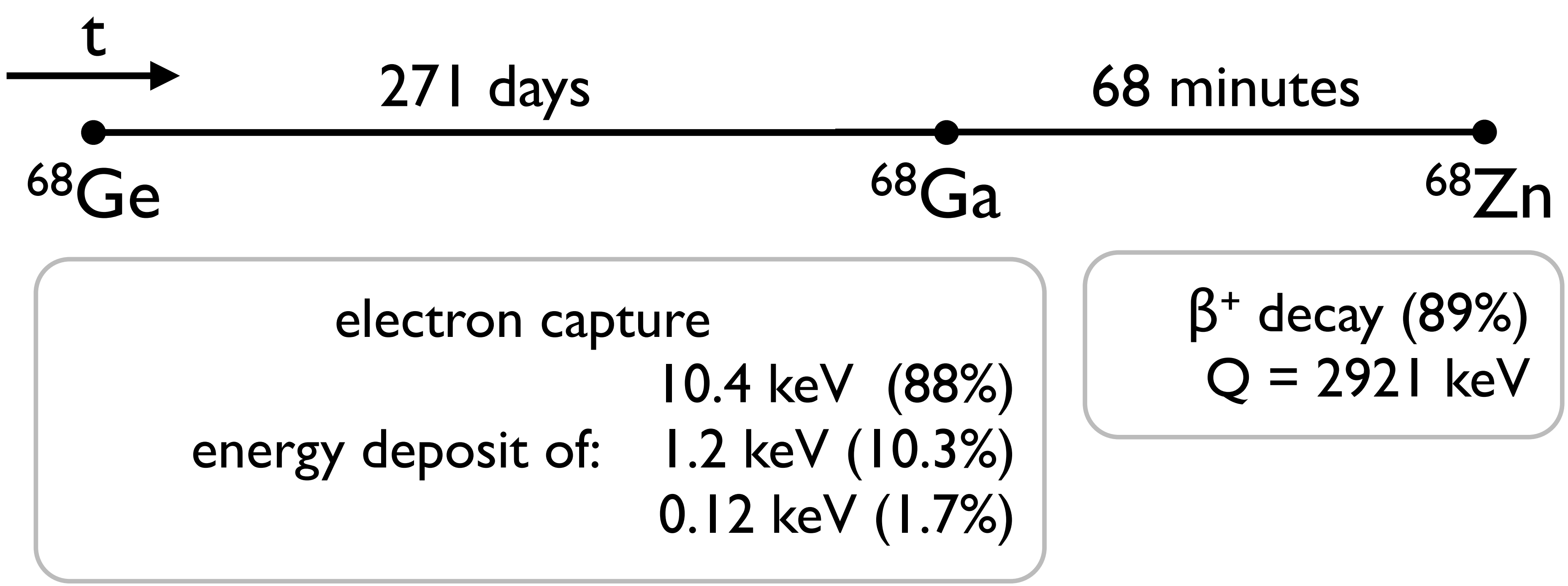
single-site cut







single-site time correlation

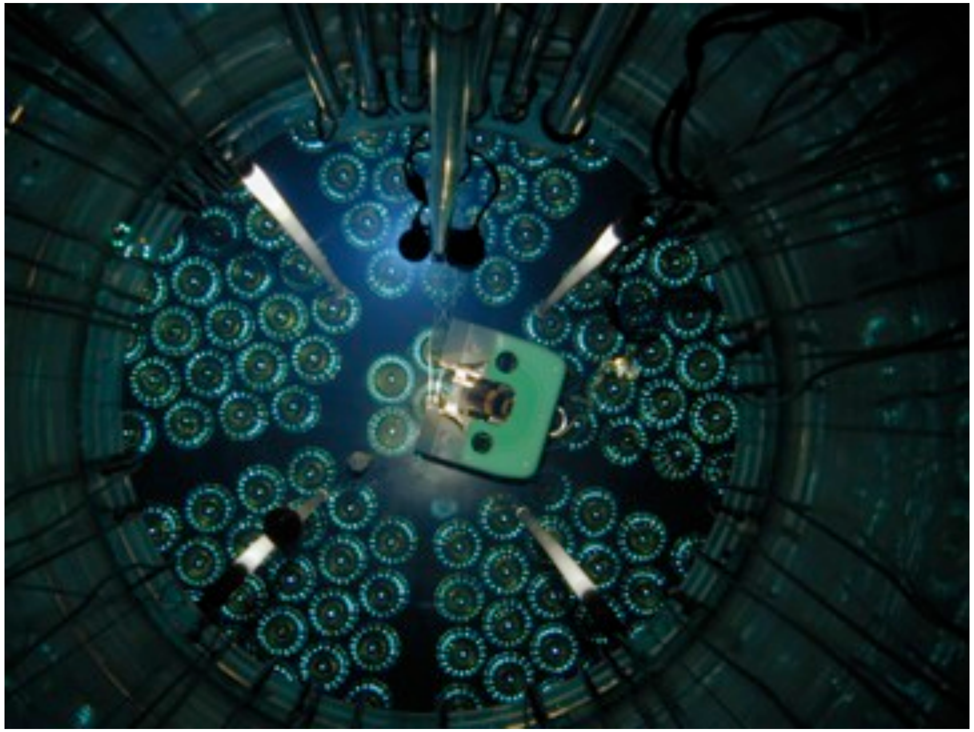


look back in time a few half lives to identify background events

Background reduction at the larger scale

- Many groups have built $0\nu\beta\beta$-decay experiments at the few to 10 kg level. - Need to scale this up to the 100s of kg level.
- Can utilize knowledge from groups that have demonstrated the construction of low-background, large-scale detectors underground: e.g. KamLAND, SNO, SAGE, GNO, Borexino CTF

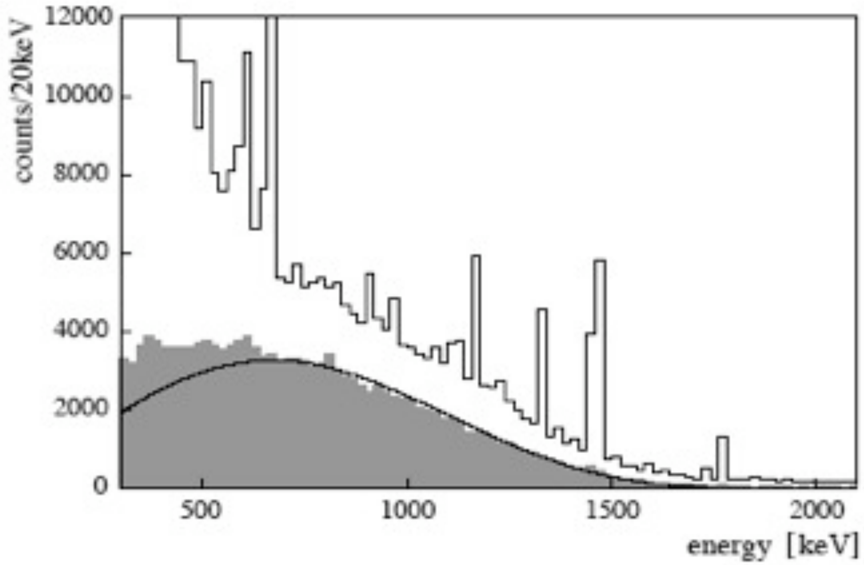
- SNO Neutral Current Detector
  Array of ^{3}He proportional counters
  - 450 kg of material
  - 300 detector segments
  - Activity (Stonehill, 2005)
    23 ± 4 μBq/kg ^{232}Th
    $35\ +8/-10$ μBq/kg ^{238}U



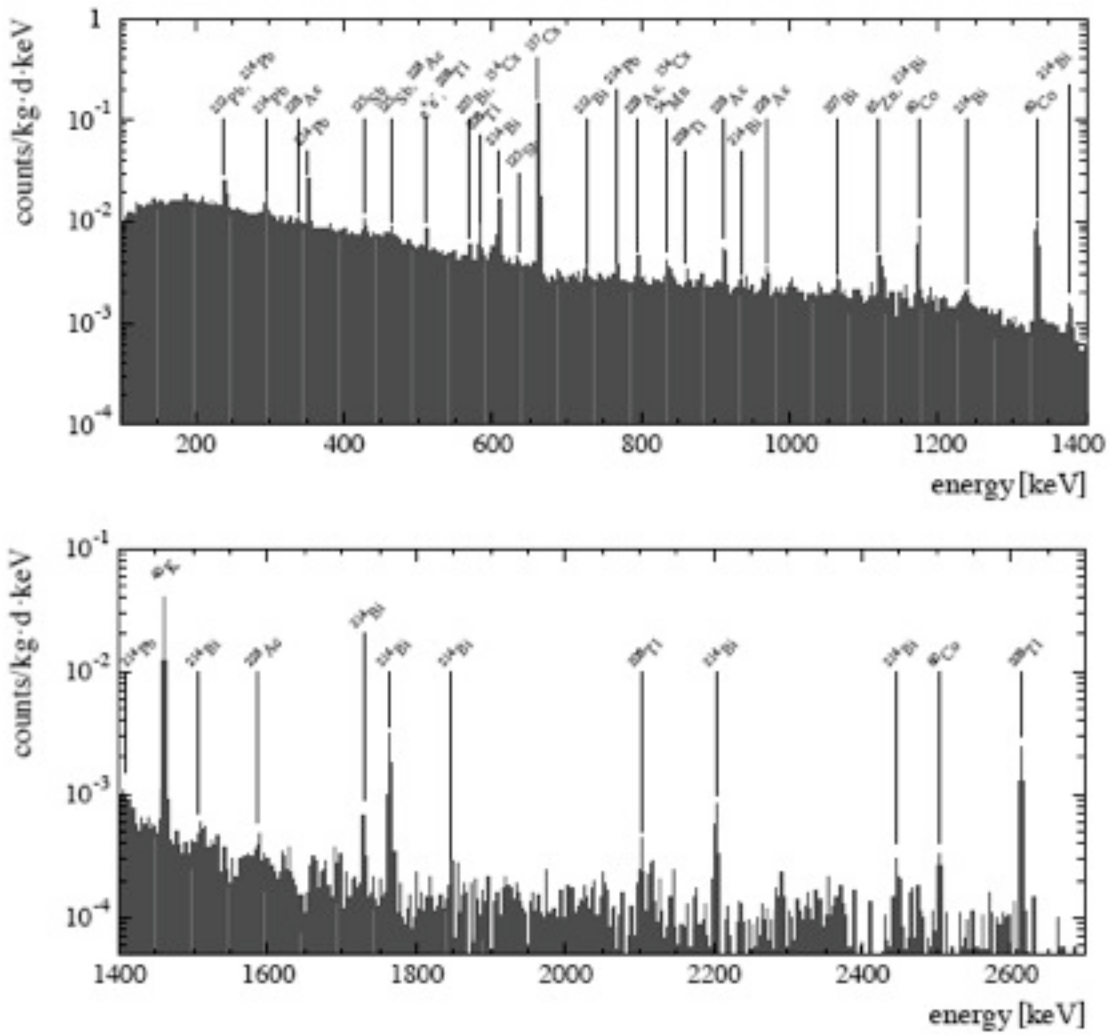
Example: Heidelberg-Moscow ^{76}Ge

Five ^{76}Ge crystals, 11 kg of total mass, ~70 kg-years of data.

- $T_{1/2} > 1.9 \times 10^{25}$ y (90%CL)



Klapdor-Kleingrothaus et al.,
Eur. Phys. J 12, 147 (2001)



The KKDC Result

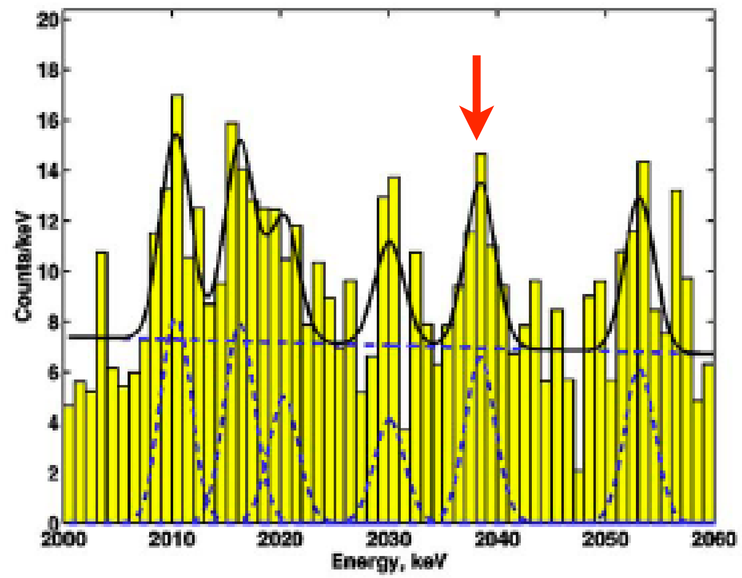
Klapdor-Kleingrothaus, Krivosheina, Dietz and Chkvorets, *Phys. Lett.* B **586** 198 (2004).

Result: Five ^{76}Ge crystals, 10.96 kg of total mass, 71 kg-years of data.

$$T_{1/2} = (1.19 + 2.99/-0.5)\ \mathrm{x}\ 10^{25}\ \mathrm{y}$$
$$0.24 < m_\nu < 0.58\ \mathrm{eV}\quad (3\sigma)$$

Plotted a subset of the data for four of five crystals, 51.4 kg-years of data.

$$T_{1/2} = (1.25 + 6.05/-0.57)\ \mathrm{x}\ 10^{25}\ \mathrm{y}$$



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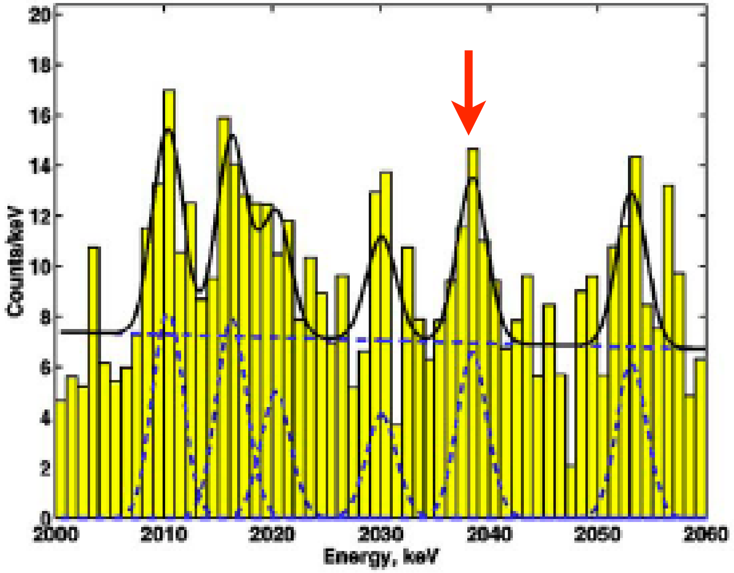
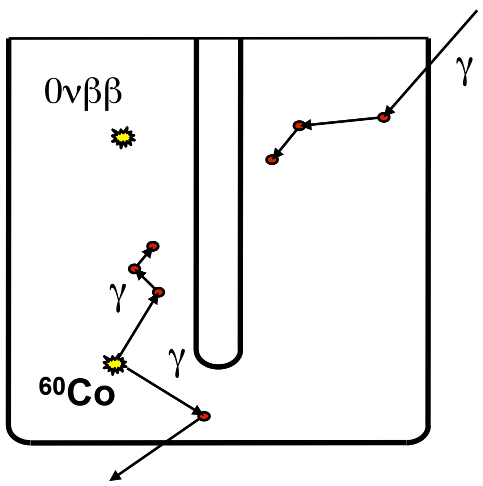
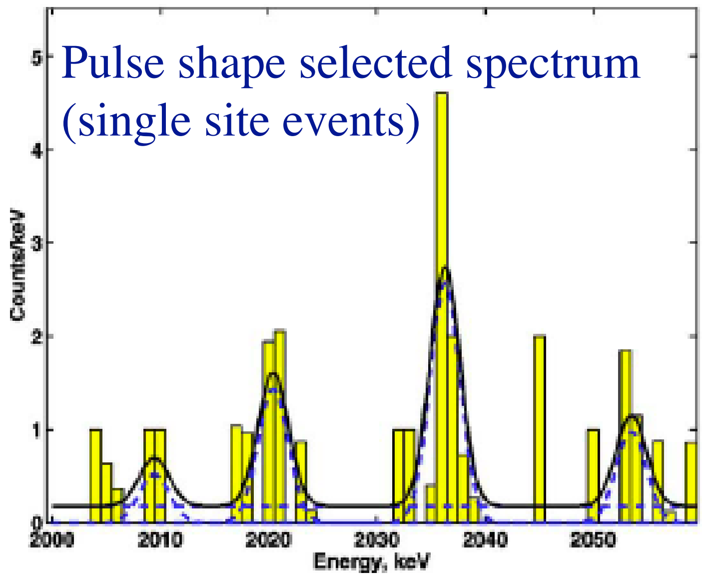
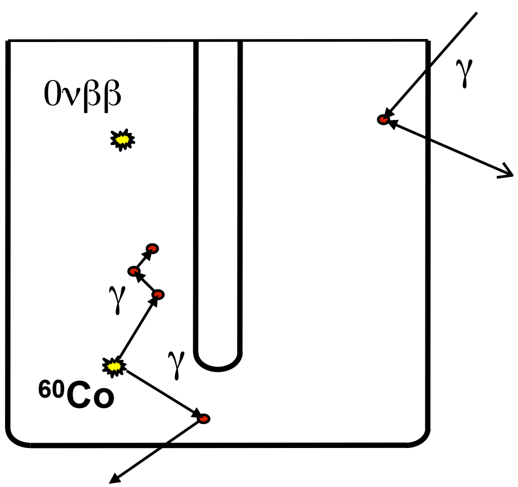




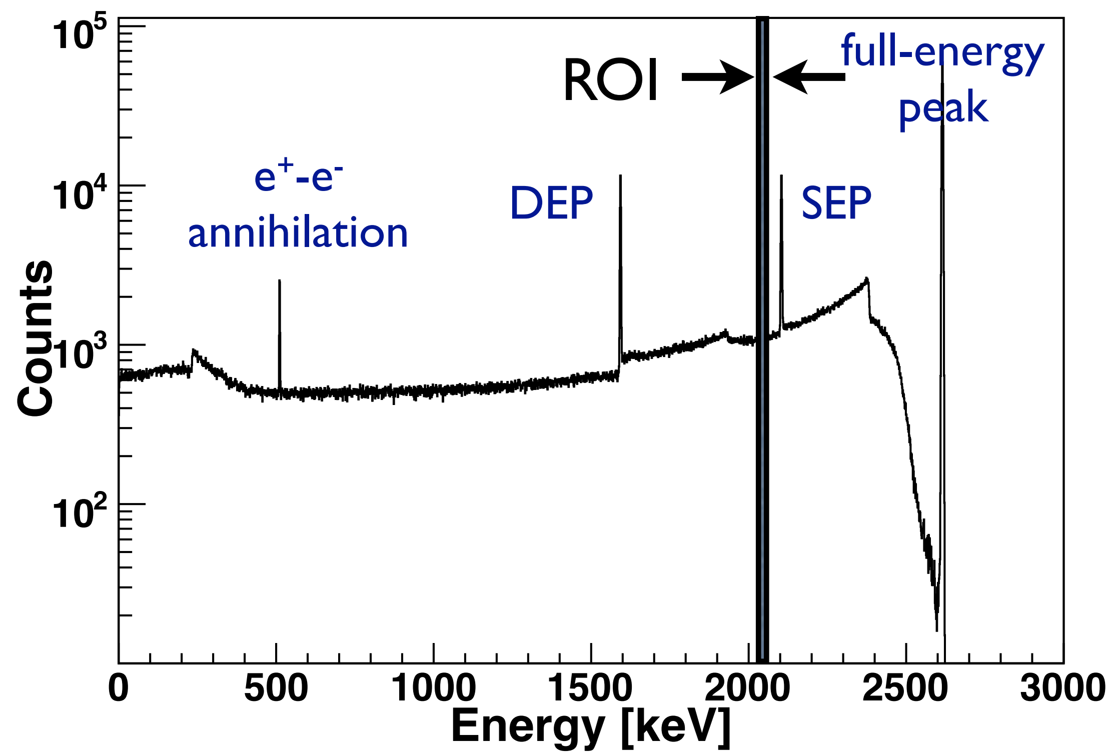


Backgrounds from ^{208}Tl

simulations and measurements show that some ^{208}Tl gammas from outside materials will interact in the detector, and then scatter back out, leaving a continuum of "point like" interactions



simulated response of Ge detector exposed to 2615-keV γs



80-mm diameter, 30-mm tall detector simulated with MaGe

Simulations by A. Schubert

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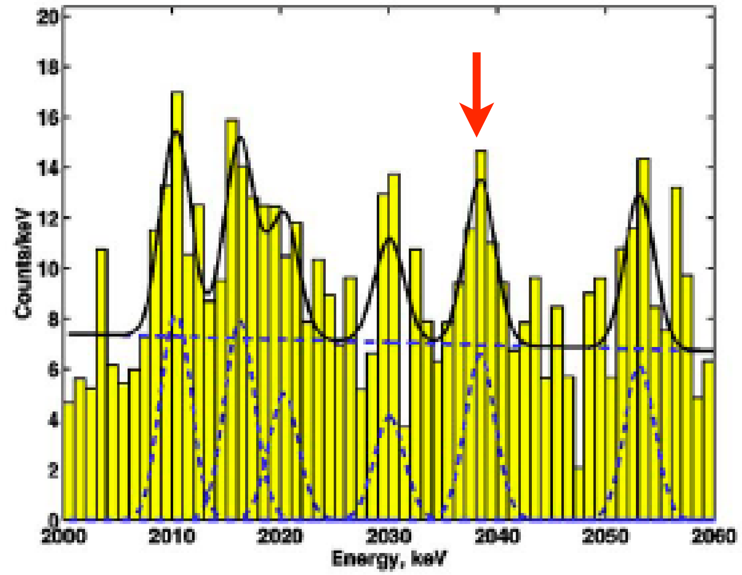
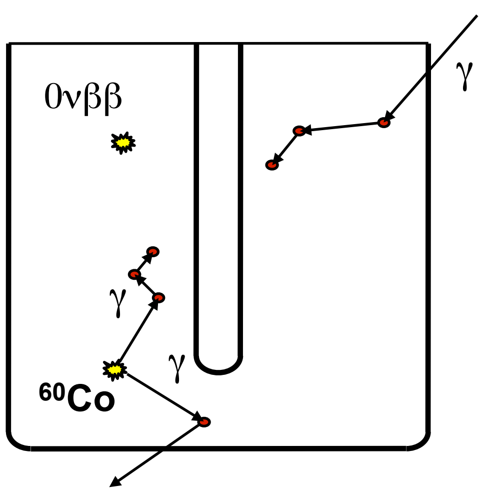
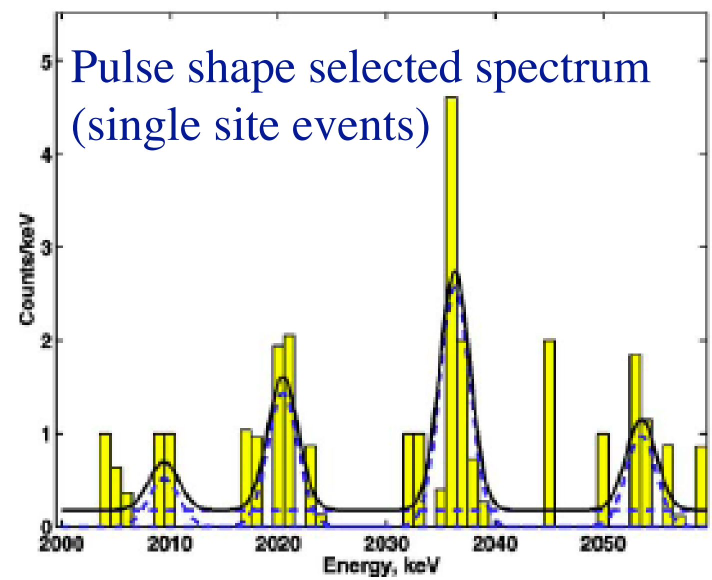






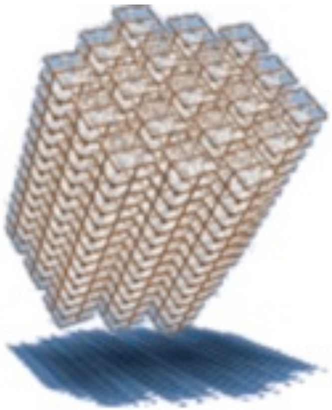
$0\nu\beta\beta$ Decay II

Next Generation Experiments

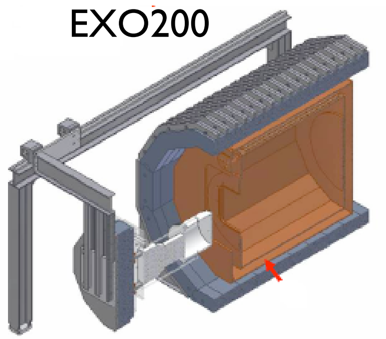
Overview of Experiments
Selected Techniques

0νββ decay Experiments - Efforts Underway

CUORE



EXO200

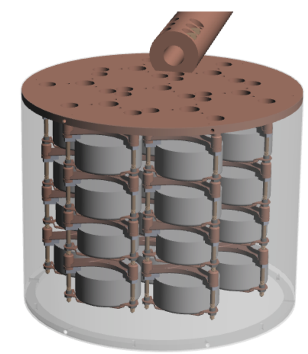


NEMO

Collaboration	Isotope	Technique	Mass	Status
CAMEO	Cd-116	$CdWO_4$ crystals	1 t	
CANDLES	Ca-48	60 CaF_2 crystals in liq. scint	6 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	100 kg	
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUROICINO	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE			206 kg	Construction
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D
EXO200	Xe-136	Xe TPC	200 kg	Construction
EXO		Xe TPC with ion ID		Future
GEM	Ge-76	Ge diodes in LN	1 t	
GERDA	Ge-76	Seg. and UnSeg. Ge in LAr	35-40 kg 1 t	Construction Future
GSO	Gd-160	Gd_2SiO_5:Ce crystal scint. in liquid scint	2t	
KamLAND	Xe-136	Xe in liq. Scint.	200 kg	Construction
MAJORANA	Ge-76	Point Contact Ge	60 kg 1 t	Construction Future
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Operating
SuperNEMO			100 kg	R&D
NEXT	Xe-136	High Pressure TPC	1t	R&D
MOON	Mo-100	Mo sheets	200 kg 1 t	R&D
SNO+	Nd-150	0.1% suspended in Scint.	56 kg	Construction
Xe	Xe-136	Xe in liq. Scint.	1.56 t	

GERDA

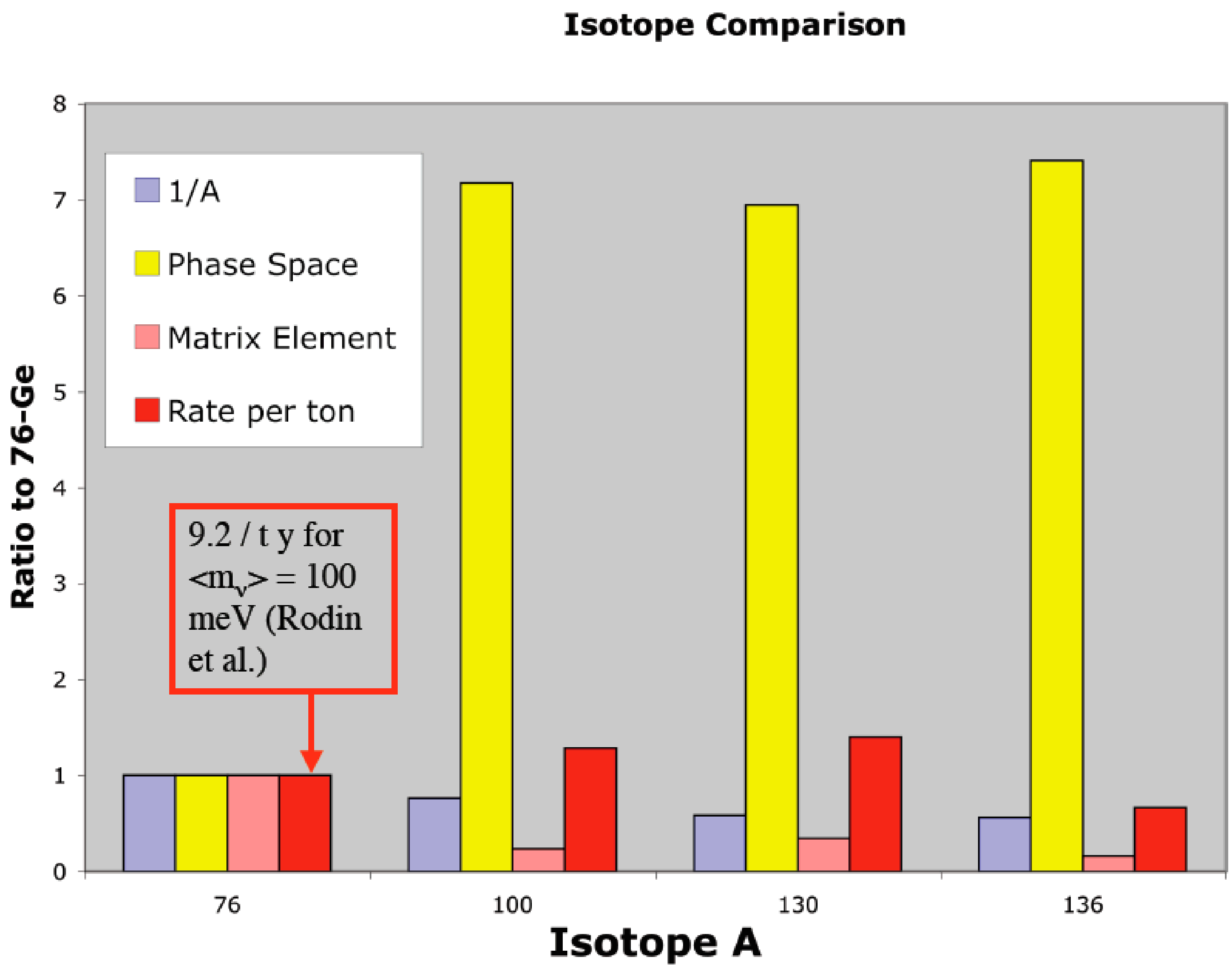
MAJORANA



CANDLES

Operating Construction

“Relative” Sensitivities

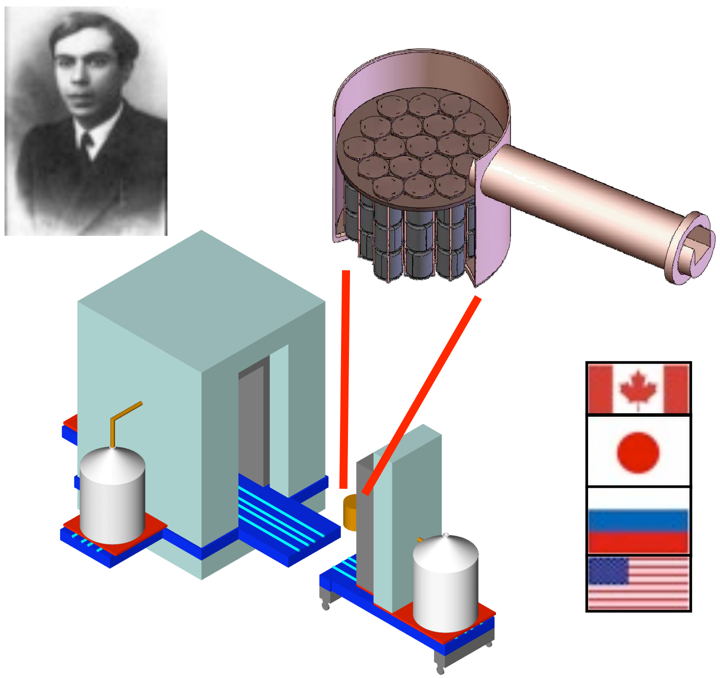


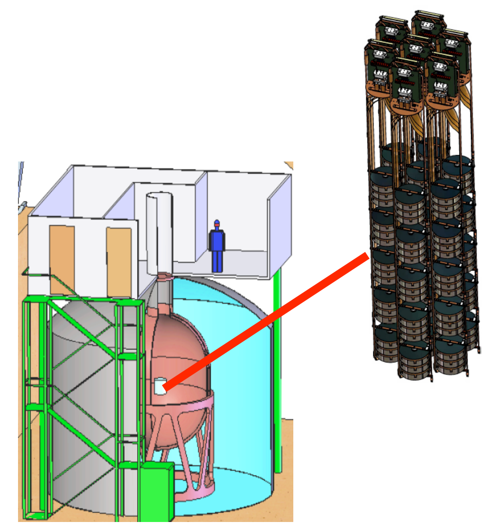
R.G.H. Robertson

Using Rodin et al. Nucl. Matrix elements

^{76}Ge - MAJORANA and GERDA

- 86% enriched Hyper-pure ^{76}Ge crystals
- 0.16 % resolution
- best $0\nu\beta\beta$−decay sensitivity to date





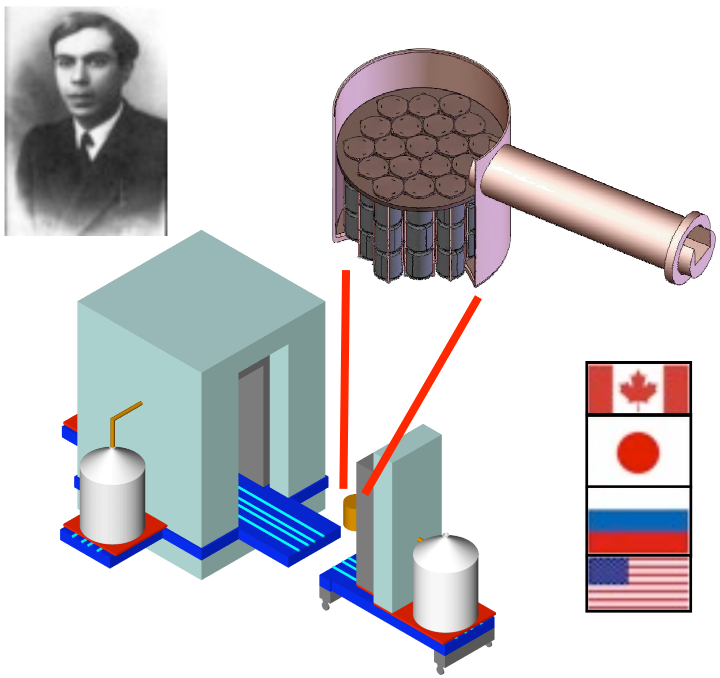
- ^{enr}Ge modules in electroformed Cu cryostat, Cu / Pb passive shield
- 4π plastic scintillator μ veto
- Demonstrator: 30 kg ^{enr}Ge/30 kg ^{nat}Ge

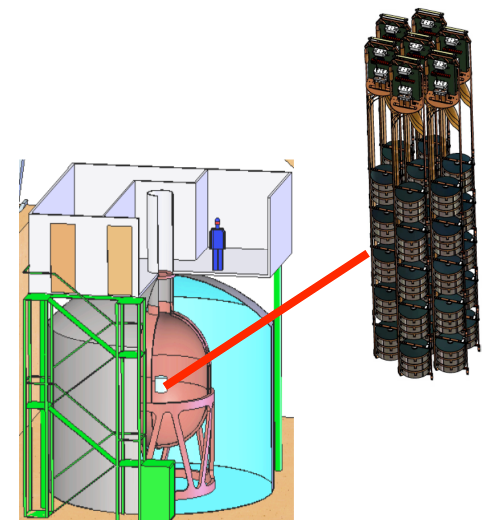
- ^{enr}Ge array submersed in LAr
- Water Cherenkov μ veto
- Phase I: ~18 kg (H-M/IGEX xtals)
- Phase II: +20 kg segmented xtals

^{76}Ge - MAJORANA and GERDA

Joint Cooperative Agreement:

Open exchange of knowledge & technologies (e.g. MaGe, R&D)
Intention to merge for larger scale 1-tonne exp.
Select best techniques developed and tested in GERDA and MAJORANA





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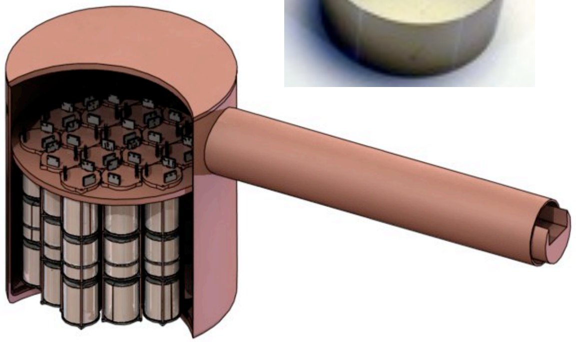
- Water Cherenkov μ veto
- Phase I: ~18 kg (H-M/IGEX xtals)
- Phase II: +20 kg segmented xtals

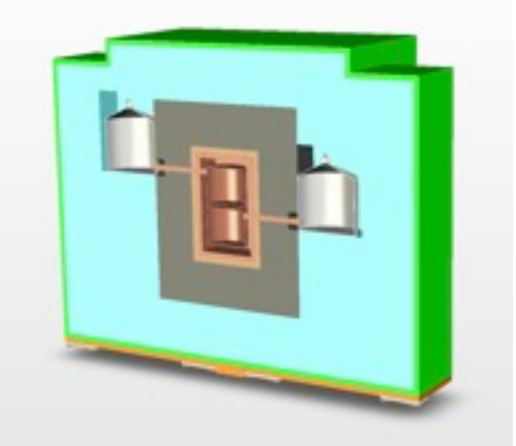
The MAJORANA ^{76}Ge Demonstrator

^{76}Ge offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)



- 60-kg of Ge detectors
  - 30-kg of 86% enriched ^{76}Ge crystals required for science goal; 60-kg for background sensitivity
  - Examine detector technology options p- and n-type, segmentation, point-contact.
- Low-background Cryostats & Shield
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto



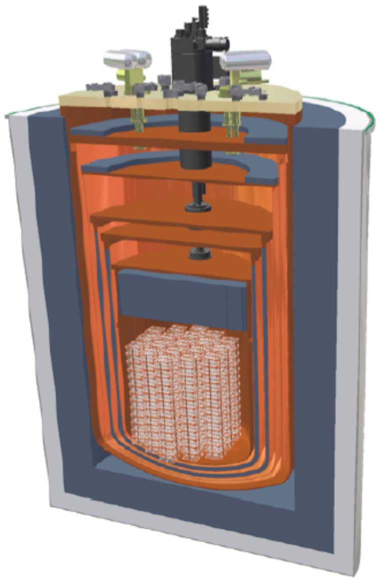
- Located underground 4850' level at Sanford Lab (Homestake)
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV) **~ 1 count/ROI/t-y** (after analysis cuts)

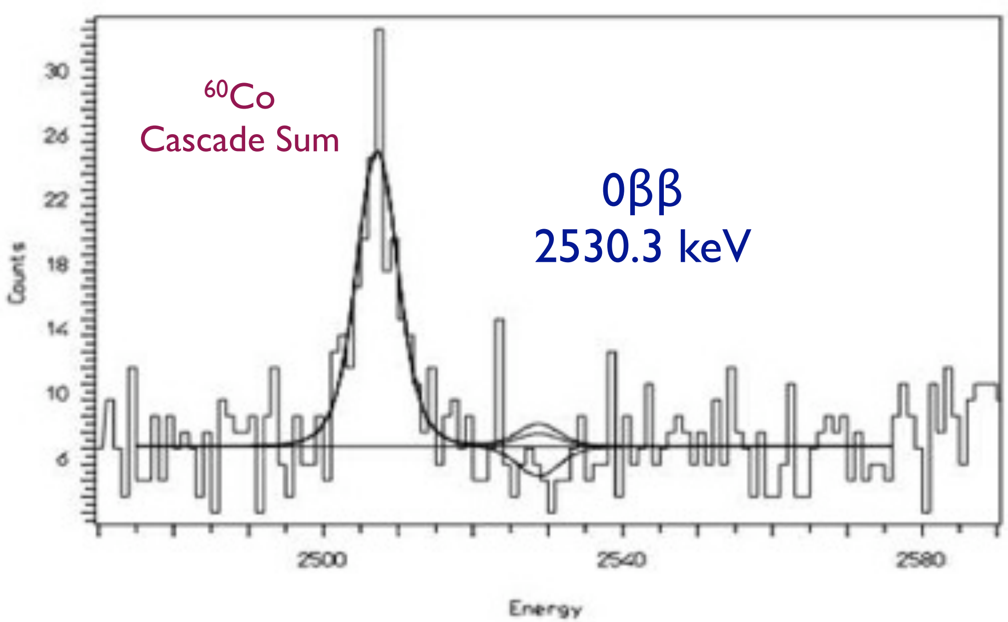
CUORE (Italy - Spain - U.S.)

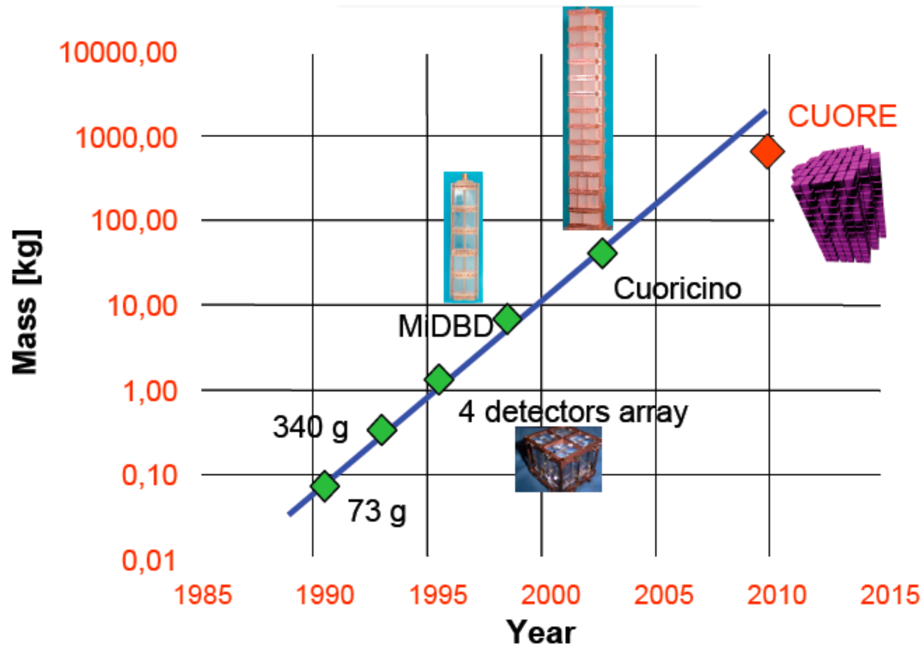
- ^{130}Te (34% abundance) bolometer.
- Array of 988 TeO_2 crystals
- Expects to operate in Gran Sasso by 2012
- Builds upon success of Cuoricino

    11.83 kg of ^{130}Te, April 2003-2006

    $T_{1/2} > 2.94 \times 10^{24}$ y (90% CL)







SuperNEMO

Planar and modular design: ~ 100 kg of enriched isotopes (20 modules × 5 kg)

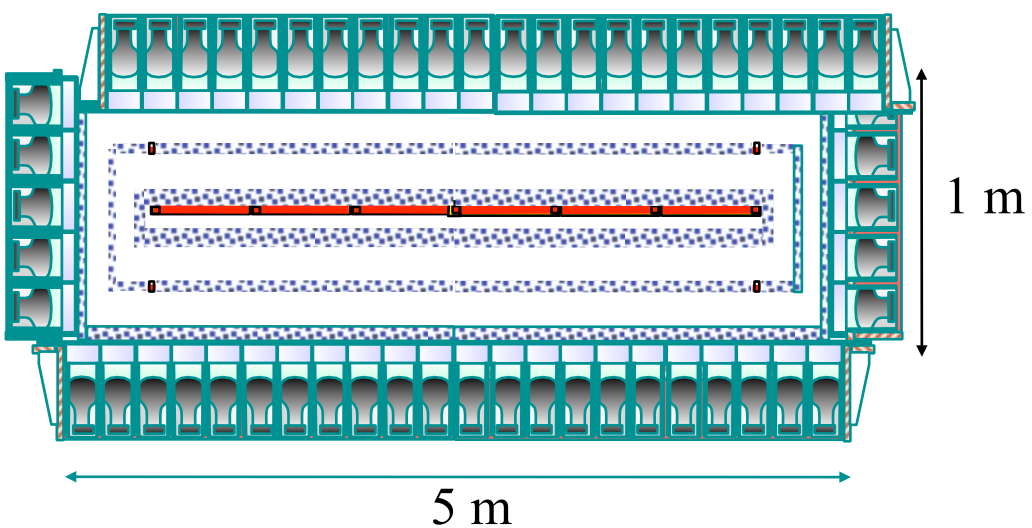
1 module:

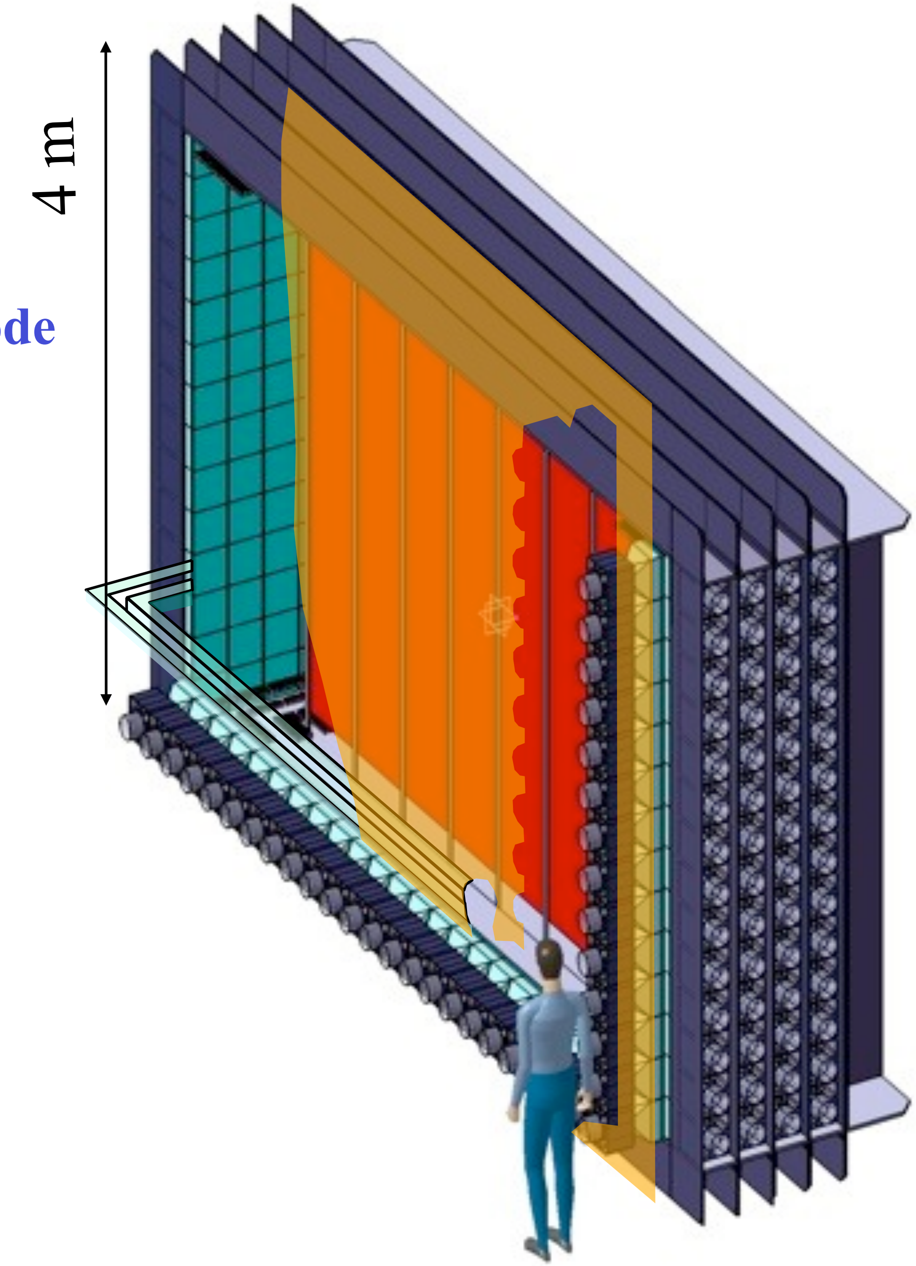
Source (40 mg/cm²)   4 x 3 m²

Tracking : drift chamber ~3000 cells in Geiger mode

Calorimeter: scintillators + PM
~1 000 PM if scint. blocks
~ 100 PM if scint. bars

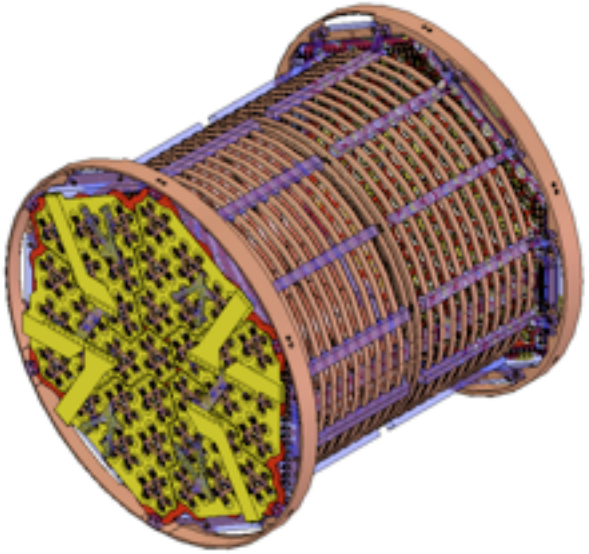
Top view

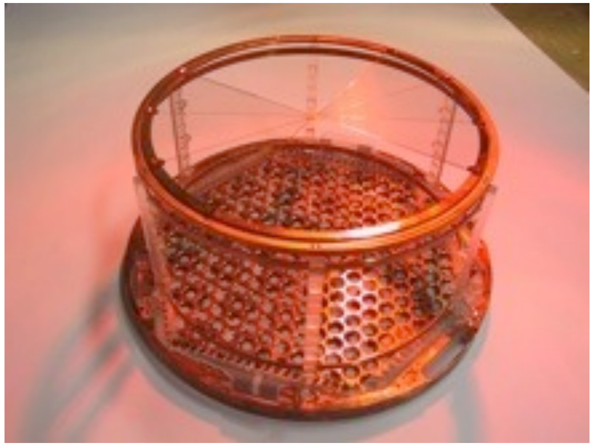




EXO-200 (U.S., Canada, Russia, Switzerland)

- 200 kg of 80% enriched ^{136}Xe
- Liquid time-projection chamber
- Uses charge and light collection 1.6% resolution
- Expects to operate in WIPP by end of 2009
- Aims to measure $2\nu\beta\beta$ mode (not yet observed)



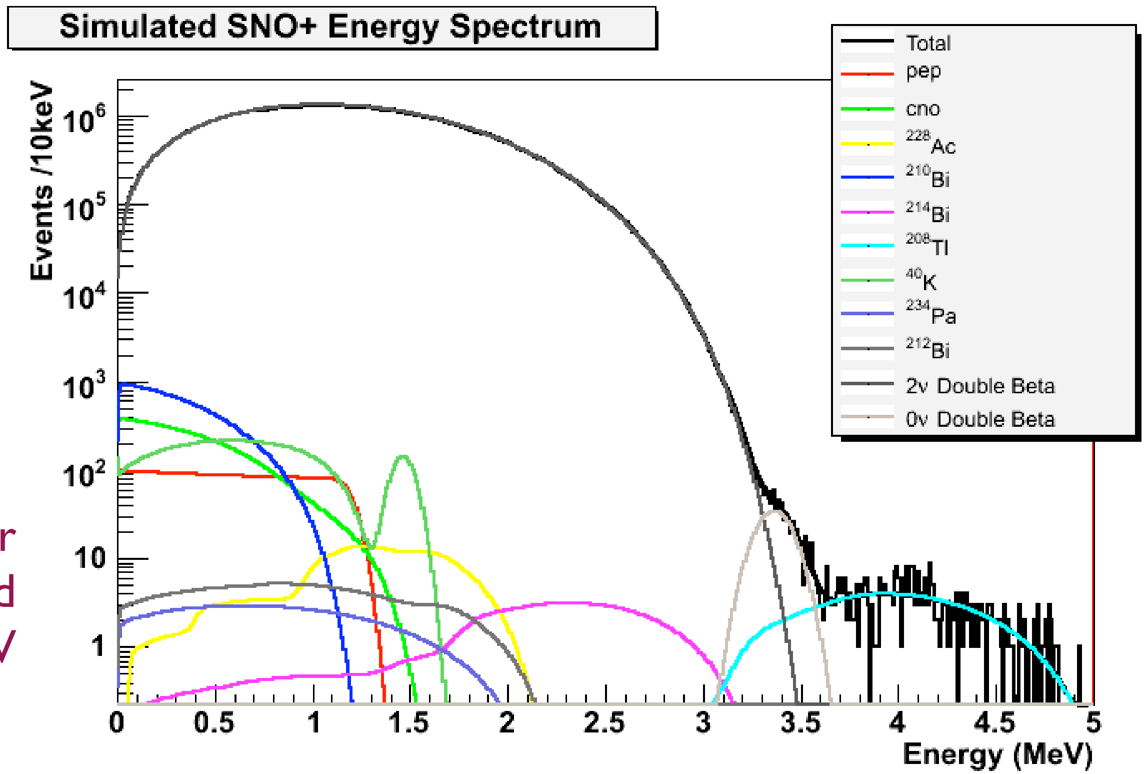


SNO+ (Canada - U.S. - U.K. - Germany -Portugal)

Science : Neutrinoless Double Beta-decay, Geoneutrinos, Solar ν

- ^{150}Nd (5.6% abundance) 0.1% loaded in scintillator.
- Initial plan is to use 1 ton of ^{nat}Nd (56 kg of ^{150}Nd)
- Located at SNOLAB
- Utilizes substantial investment in SNO
- Initial success in loading into pseudocumene and also in linear alkylbenzene
- Technical challenge - available light with loaded scintillator
- Considering enrichment option

1 yr
500 kg of ^{150}Nd
$\langle m_{ee} \rangle$= 150 meV



$0\nu\beta\beta$ Decay II

Future Program

Discovery of 0νββ-decay

- Strong evidence : a combination of
  - Correct peak energy
  - Single-site energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
  - Full energy spectrum understood
- Further confirmation: more difficult
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay
- Irrefutable
  - Observe the process in several isotopes, using a variety of experimental techniques

Experimental Program in 0νββ

Previous
Expts.
~ 1 eV
~kg scale

Quasi-
degenerate
~100's meV
100-200 kg
3-5 Expts

1980 - Present

2007 - 2014

2013 - 2020

Experimental Program in $0\nu\beta\beta$

Previous Expts.
~ 1 eV
~kg scale

Quasi-degenerate
~100's meV
100-200 kg
3-5 Expts

If $0\nu\beta\beta$ Observed

Program to study 8-12 $0\nu\beta\beta$ isotopes, using various techniques

100-200 kg scale

1980 - Present

2007 - 2014

2013 - 2020

Experimental Program in 0νββ

Previous Expts.
~ 1 eV
~kg scale

→

Quasi-degenerate
~100's meV
100-200 kg
3-5 Expts

→

Inverted hierarchy
~30 -40 meV
1 ton scale
at least 2 Expts

→

Normal hierarchy
~5 meV
≥10 ton scale
~2 Expts ?

1980 - Present | 2007 - 2014 | 2013 - 2020

Summary

- The observation of $0\nu\beta\beta$-decay would demonstrate Lepton number violation and indicate that neutrinos are Majorana particles - constituting a major discovery.
  - Discovery needs to be confirmed from independent experiments using different isotopes and measurement techniques.
- If $0\nu\beta\beta$-decay is observed then it opens an exquisitely sensitive window to search for physics beyond the Standard model.
  - Measurement of $\langle m_{\beta\beta} \rangle$ is complementary to direct and cosmological measurements of neutrino mass.
  - Measurements in different isotopes should provide insights into the underlying LNV physics process(es).

Over the past 70 years there have been dramatic changes in our understanding of the of nuclear and particle physics, yet $0\nu\beta\beta$-decay remains relevant as we endeavor to elucidate the underlying framework of our universe.