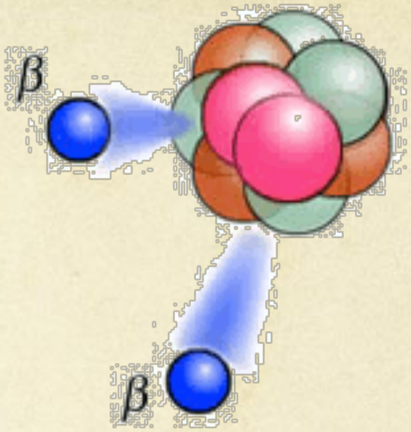
Double Beta Decay



Lisa Kaufman

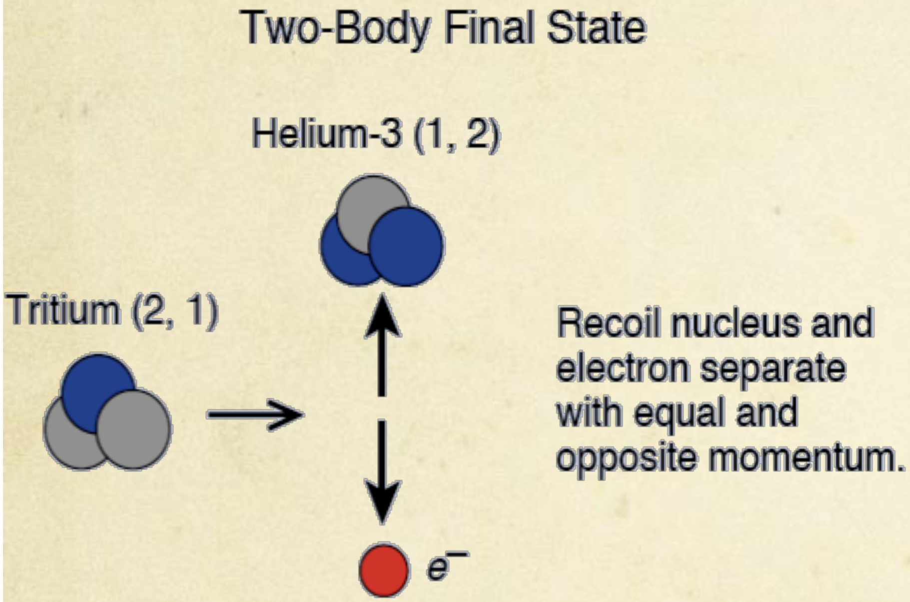
Indiana University

September 13, 2012

Physics in Collision 2012

Beta (β) Decay, at the beginning

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



Two-Body Final State

Helium-3 (1, 2)

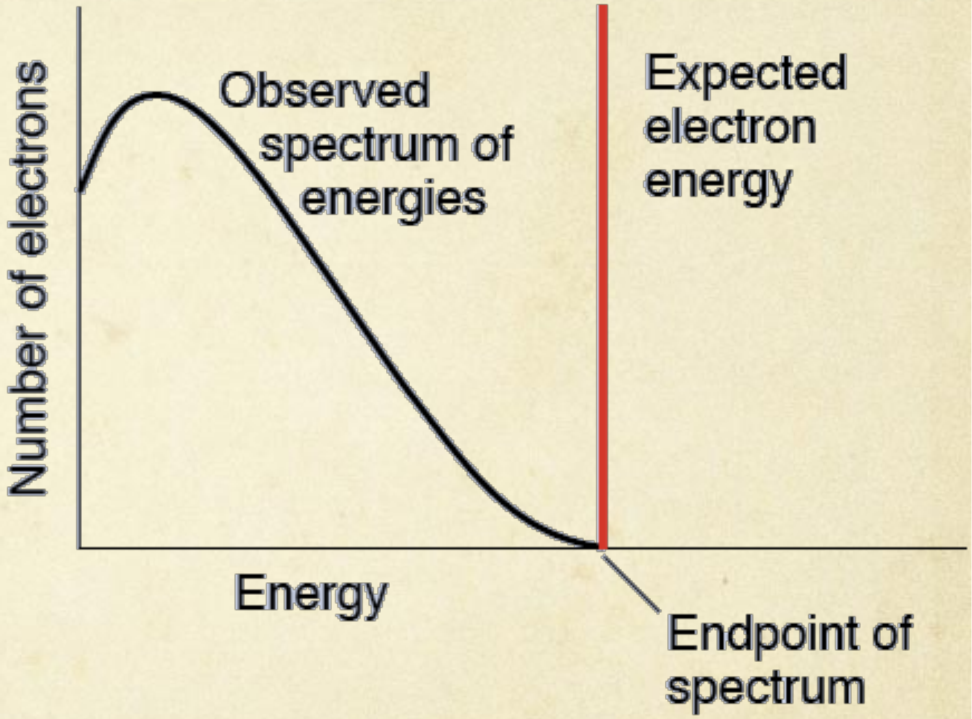
Tritium (2, 1)

Recoil nucleus and electron separate with equal and opposite momentum.

e^-

$(N, Z) \rightarrow (N-1, Z+1) + e^-$,

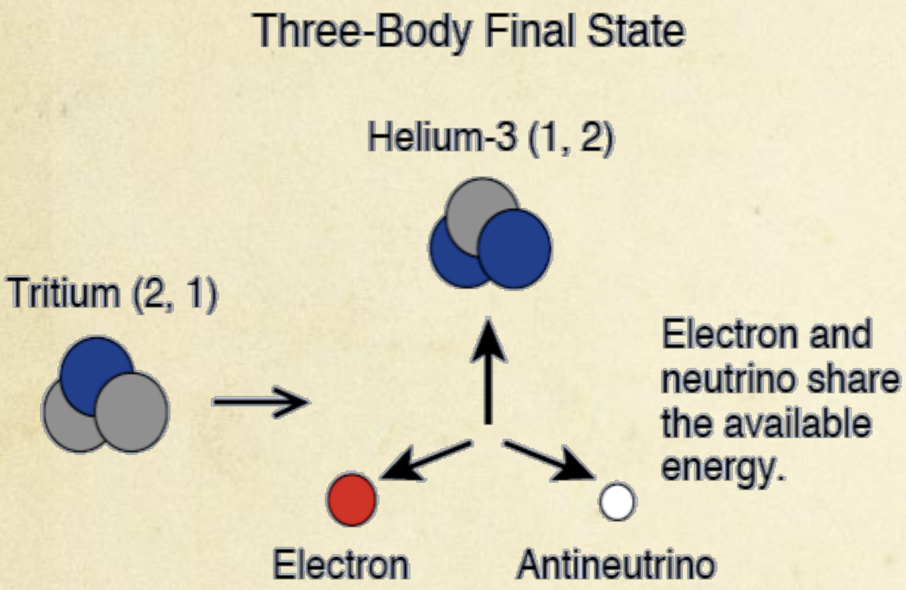
where N = number of neutrons, and
Z = number of protons.



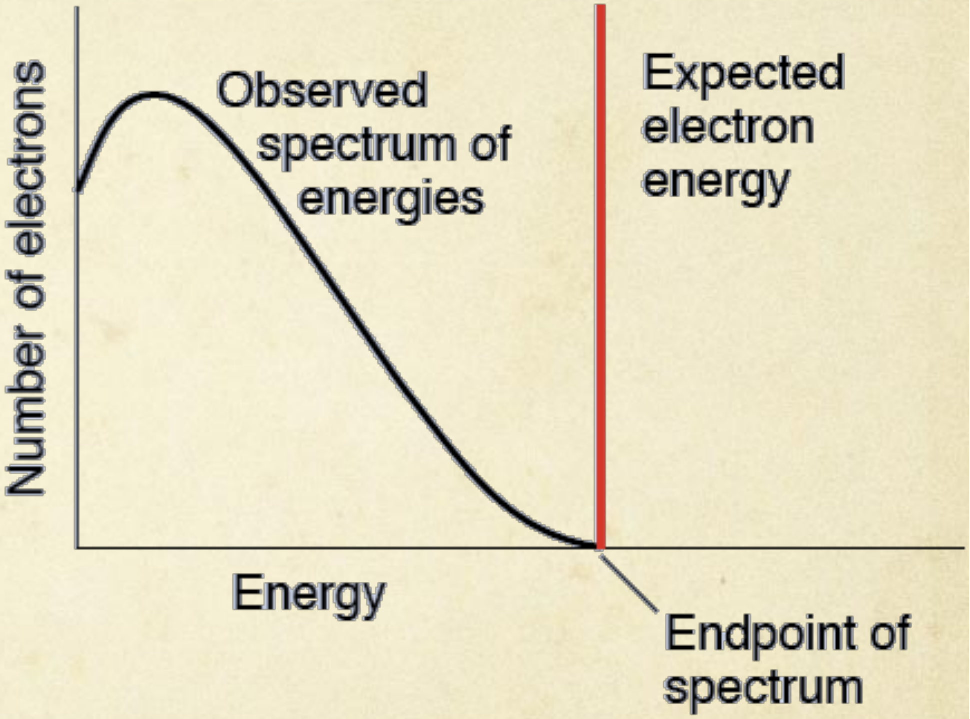
From Los Alamos Science No. 25, 1997.

Beta (β) Decay, at the beginning

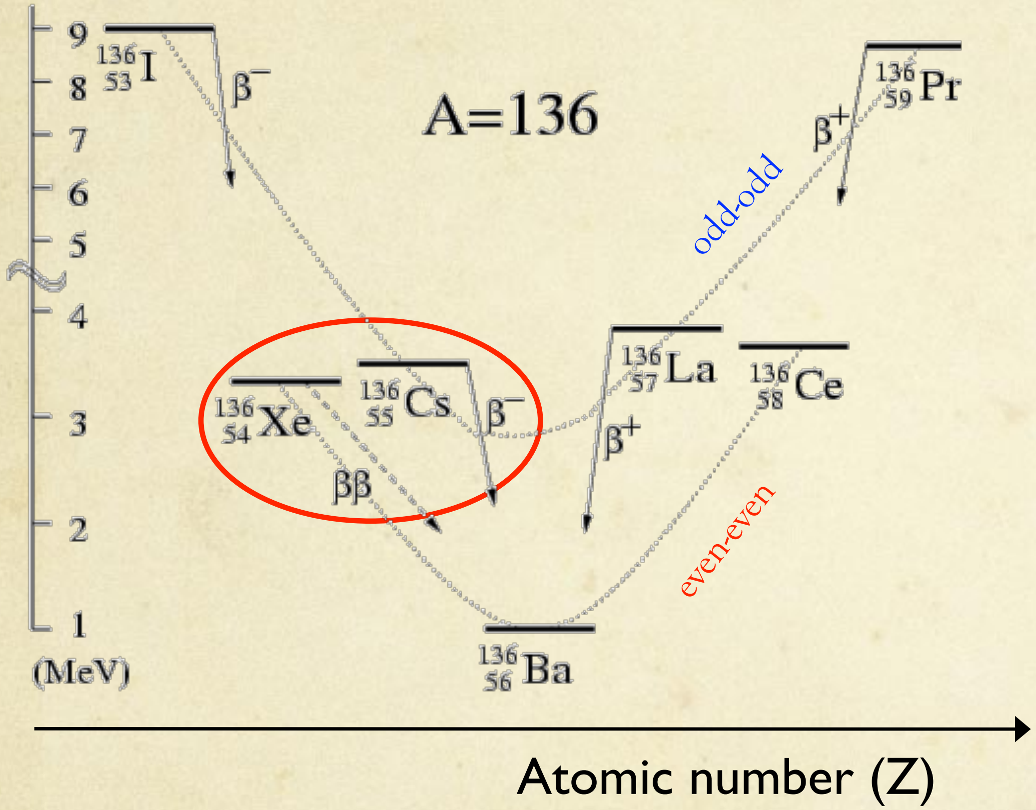
$$n \to p + e^- + \overline{\nu}_e$$



$(N, Z) \to (N-1, Z+1) + e^- + \overline{\nu}$.



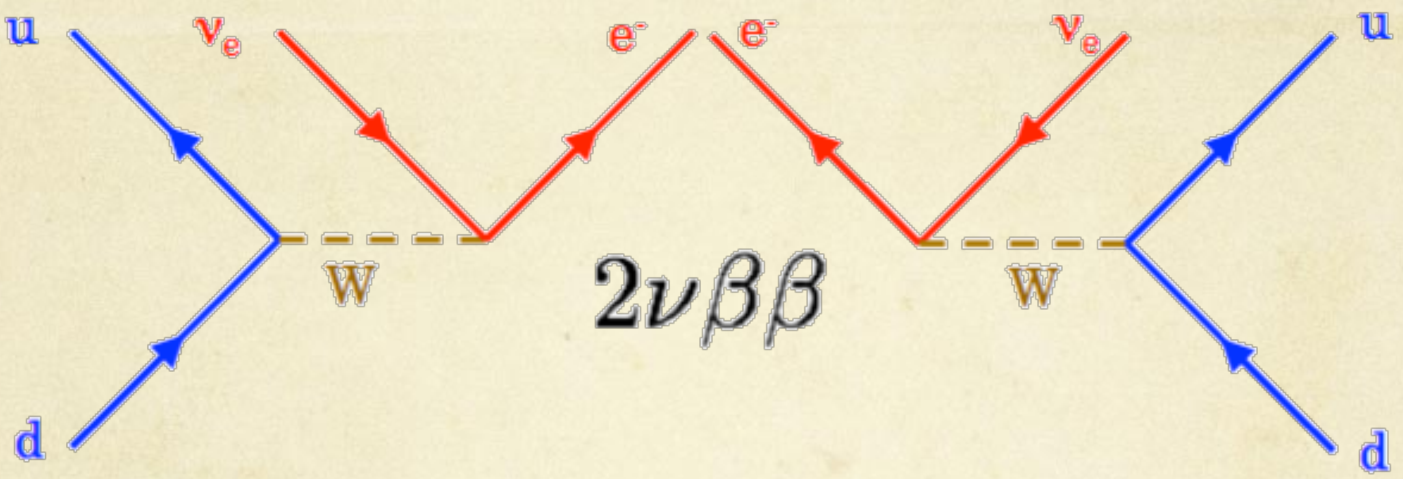
What is $\beta\beta$ decay?



Second-order weak process by which two neutrons decay to two protons

Only allowed for nuclei where beta decay is energetically forbidden or highly suppressed due to a large angular momentum difference

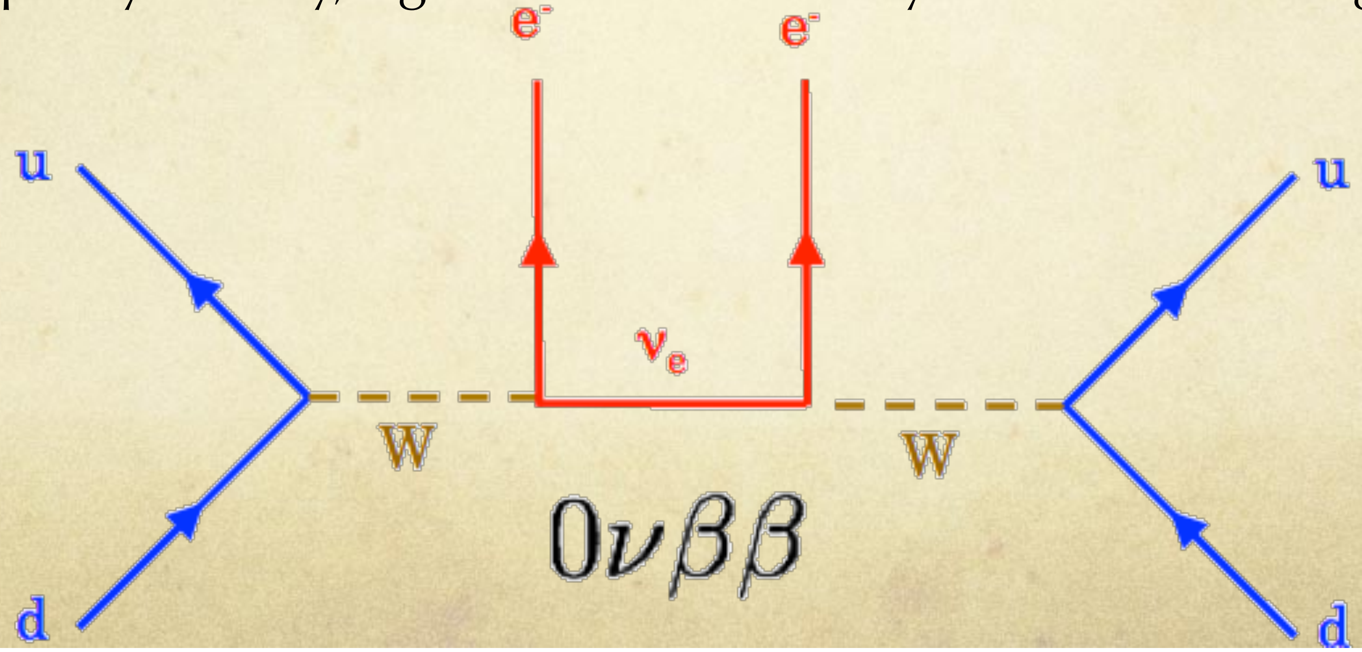
Two Way for Double Beta Decay to Occur



- $2\nu\beta\beta$ has been observed in several nuclides: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, and recently, ^{136}Xe
- Half lives are 10^{18}-10^{21} years
- Standard Model process: decay rates are used to compare nuclear models
- First direct observation by Elliot, Hahn, and Moe in ^{82}Se (1987).

Two Ways for Double Beta Decay to Occur

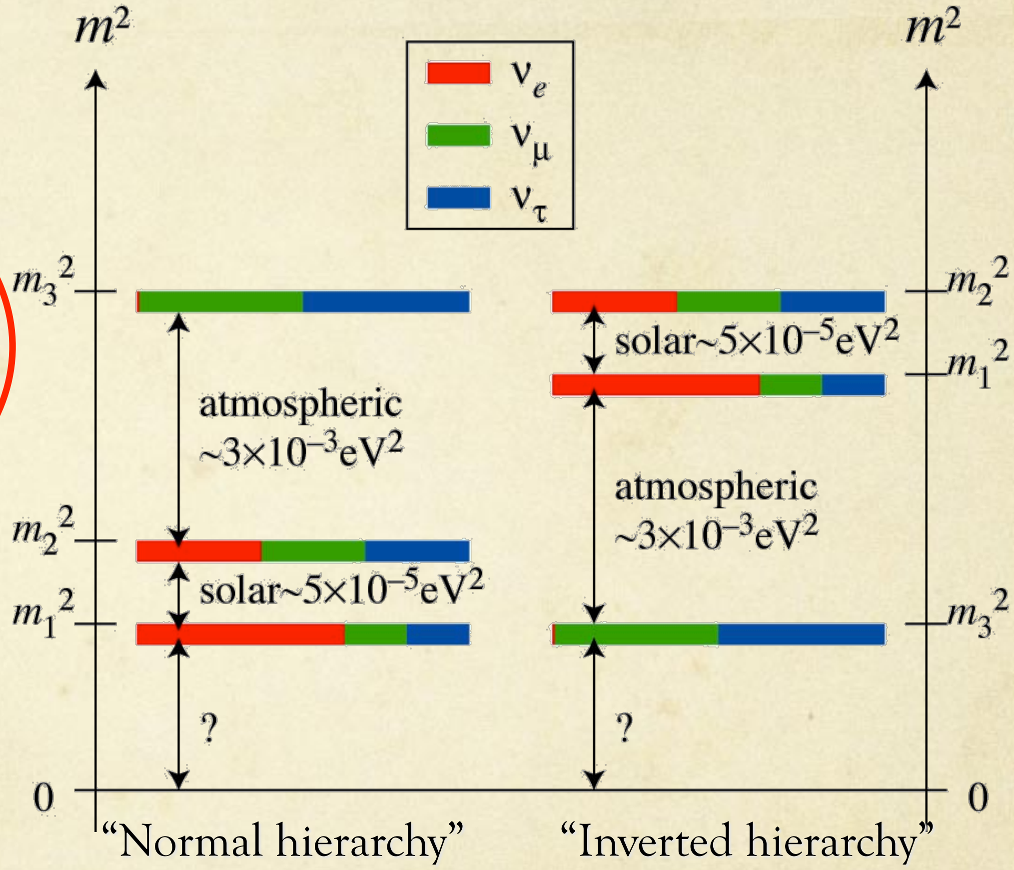
- $0\nu\beta\beta$ can only occur if neutrinos have mass and are their own antiparticle (Majorana)
- Process violates lepton number conservation (by 2!)
- New Physics!
- Several theories for the mechanism: right-handed currents, super-symmetry, light neutrino or heavy neutrino exchange



Unknown properties of the neutrino

Major Questions in Neutrino Physics

- Is the neutrino a Dirac or Majorana particle, (i.e. is it its own antiparticle?)
- Absolute mass scale of neutrinos.
- Mass hierarchy
- ✔Mixing angle, θ_{13}
- CP violation phase



The search for neutrinoless double beta decay can shed light on the first three questions.

We Measure the Decay Half-life

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2\left|f_b\left(m_i,U_{ei}\right)\right|^2$$

$G^{0\nu}(Q,Z)$ Calculable phase space factor $\sim Q^5$

$\left|M^{0\nu}\right|^2$ Nuclear matrix elements are difficult to calculate

$\left|f_b\left(m_i,U_{ei}\right)\right|^2$ New Physics: lepton-number violating term

We Measure the Decay Half-life

Assuming light Majorana neutrinos:

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

$G^{0\nu}(Q,Z)$ Calculable phase space factor $\sim Q^5$

$\left|M^{0\nu}\right|^2$ Nuclear matrix elements are difficult to calculate

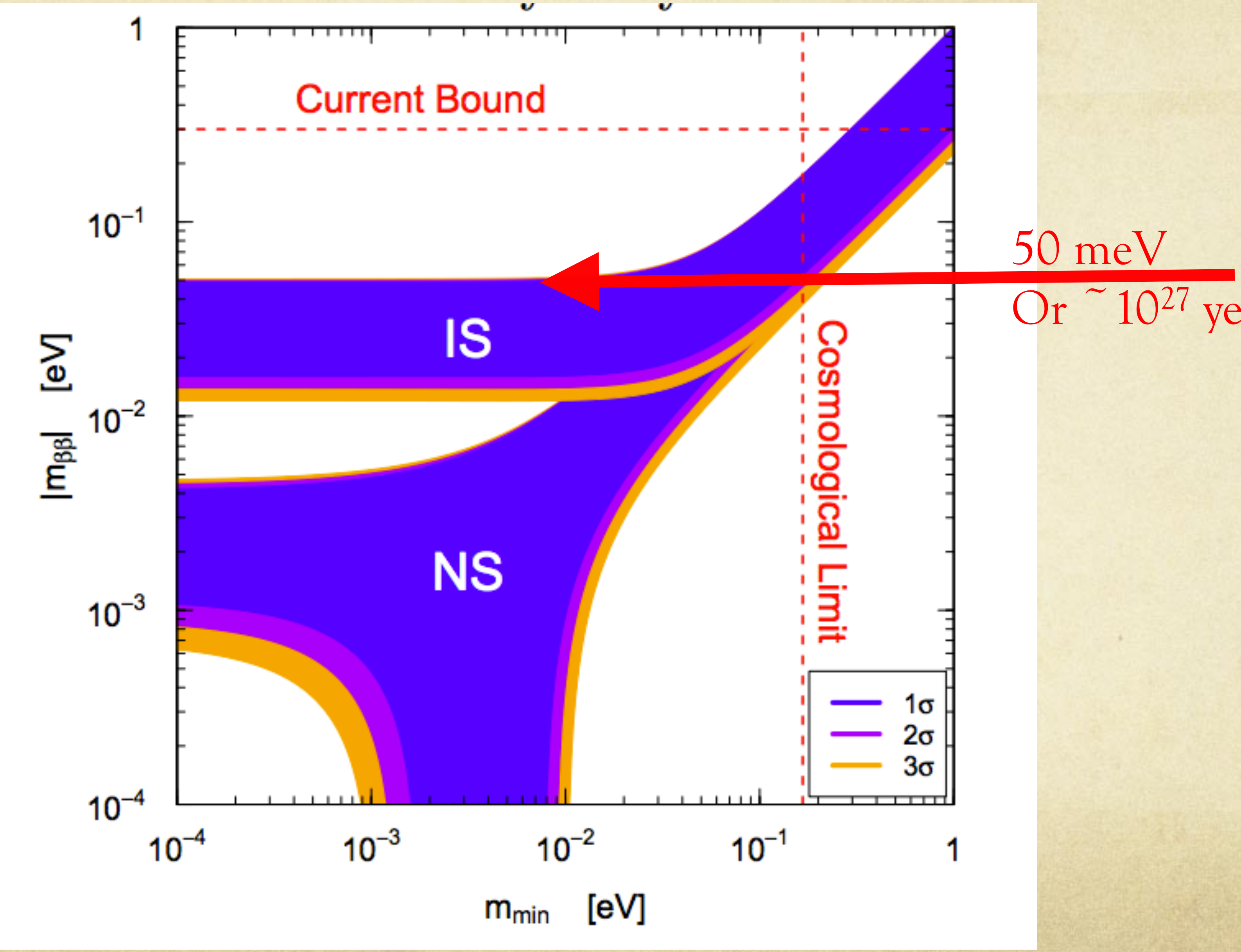
Neutrino masses

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

CP phases

Neutrino mixing matrix

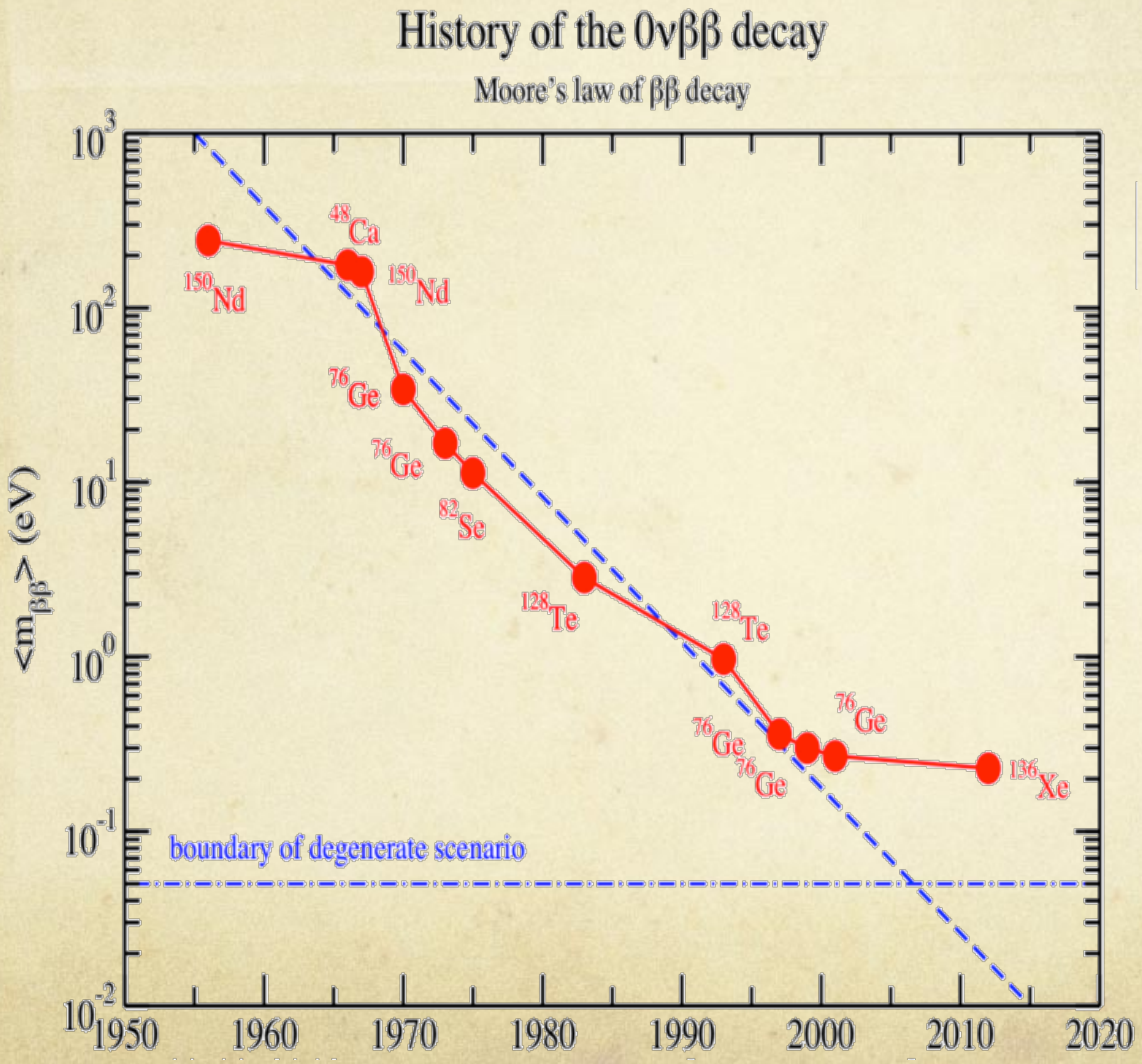
Neutrino Mass Scale



50 meV

Or ~10^{27} years

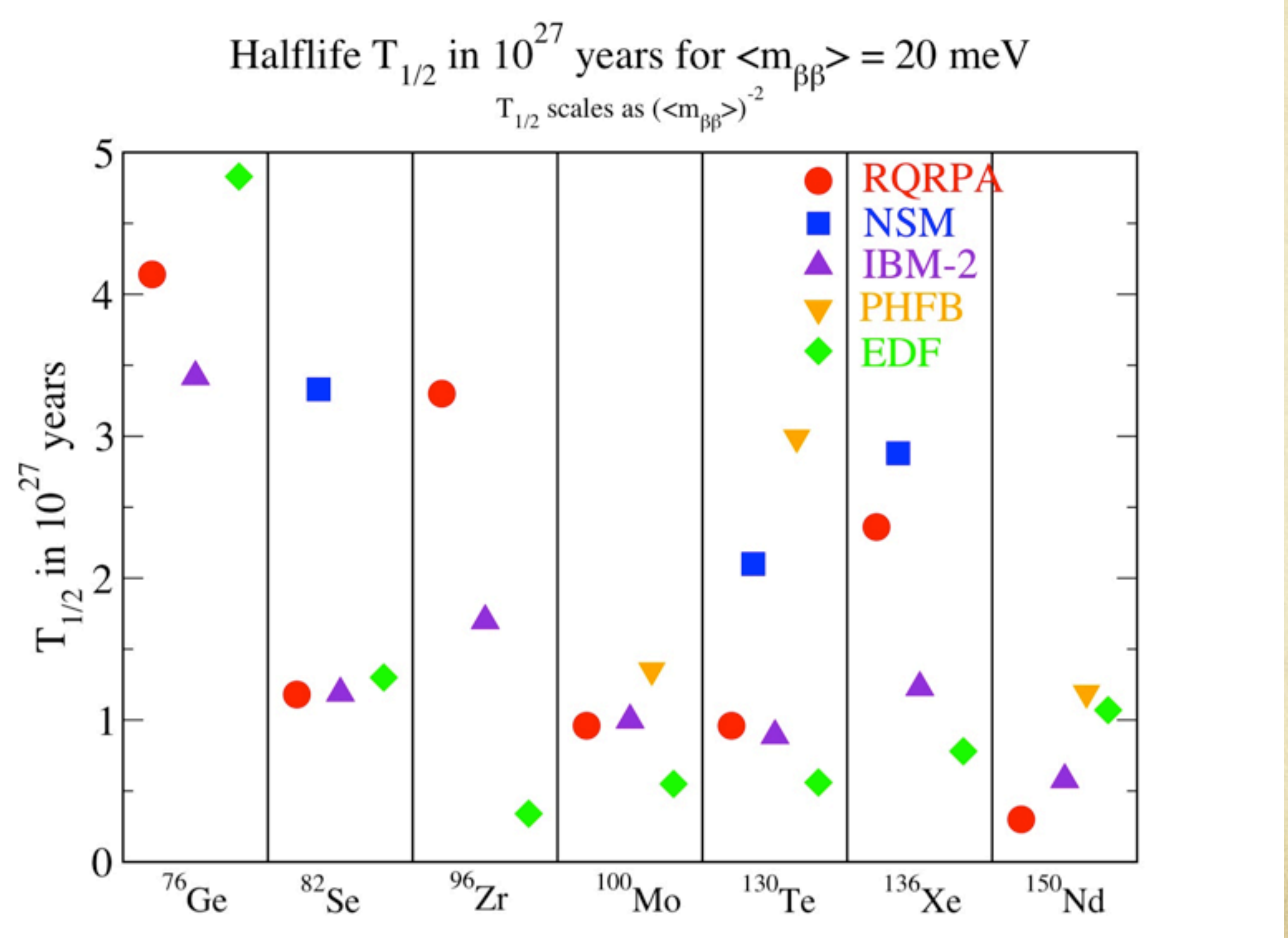
Double Beta Decay Through the years



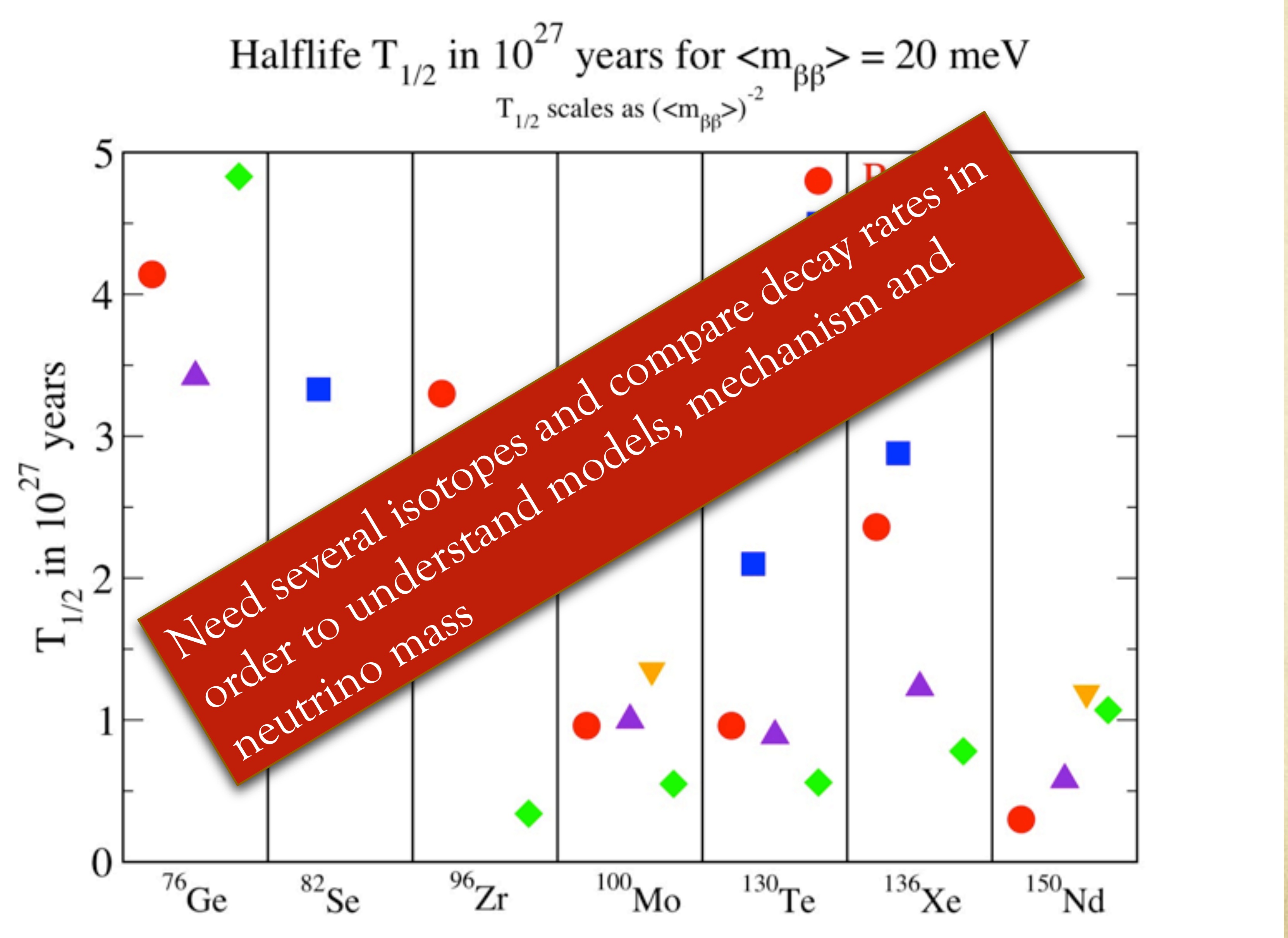
Mass limits for several iostopes using the matrix elements from RQRPA (Simkovic *et al*. 2009)

There is an approximate linear slope vs time on this semilog plot – however, the complexity of experiments has increased in the last decade and the slope has changed – hopefully not forever.

Is there a Smoking-Gun Isotope?

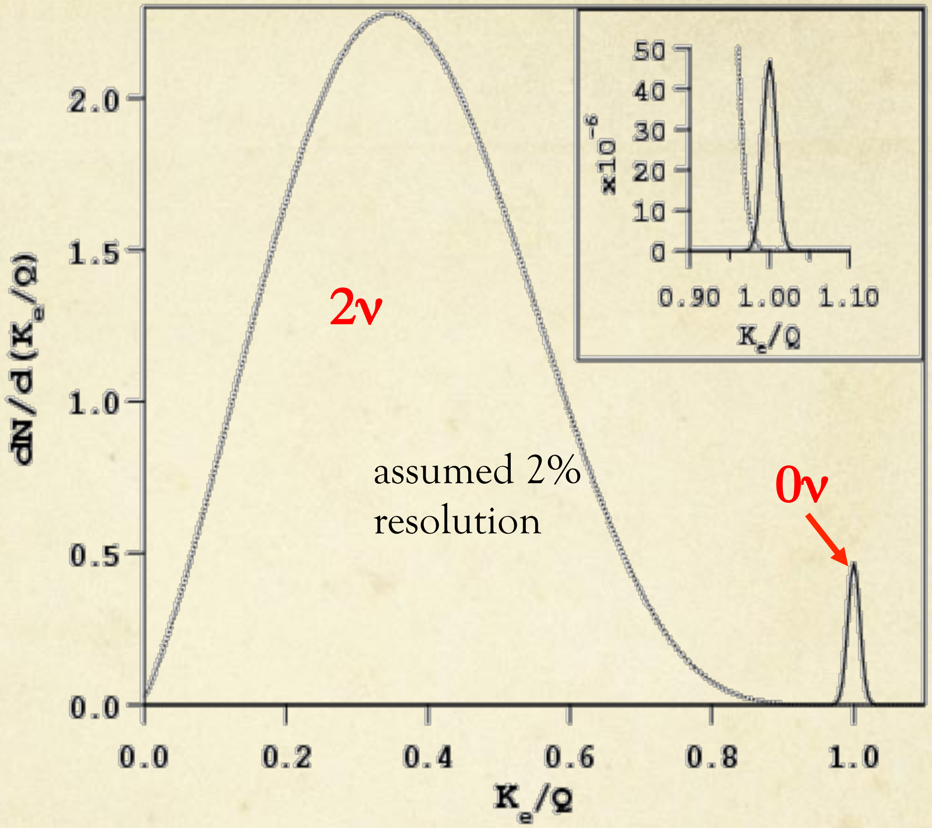


Is there a Smoking-Gun Isotope?



Need several isotopes and compare decay rates in order to understand models, mechanism and neutrino mass

How do we Measure the Rate?



2ν

assumed 2% resolution

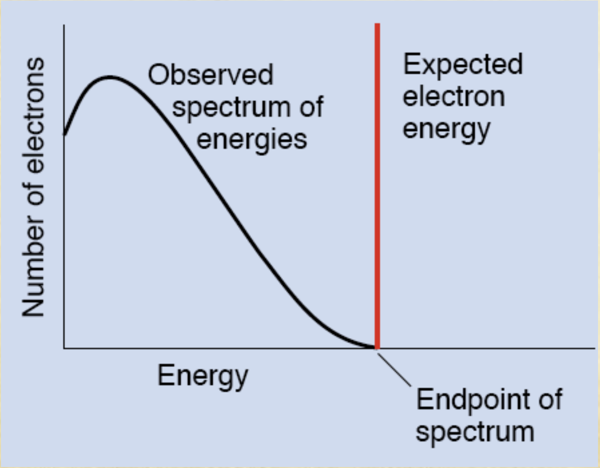
0ν

assumed rate ratio 1:10^6

assumed rate ratio 1:10^2

Elliot, S. et al., Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

Summed electron energy in units of the kinematic endpoint (Q)



Sensitivity

$$S^{0\nu}_{1/2} \propto \varepsilon \frac{a}{A}\left[\frac{MT}{B\Gamma}\right]^{1/2}$$

ε is efficiency
a is isotopic abundance
A is atomic mass
M is source mass
T is time
B is background
Γ is resolution

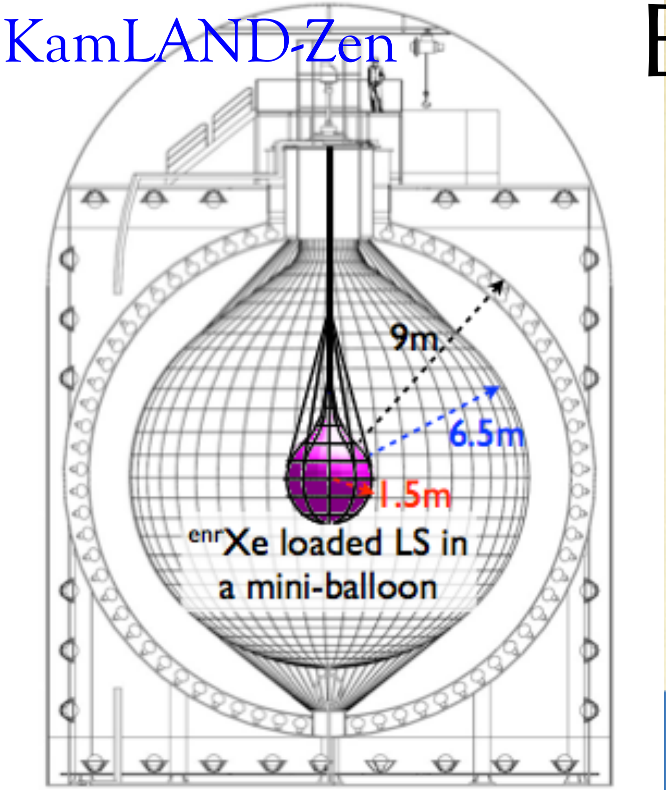
To maximize sensitivity:

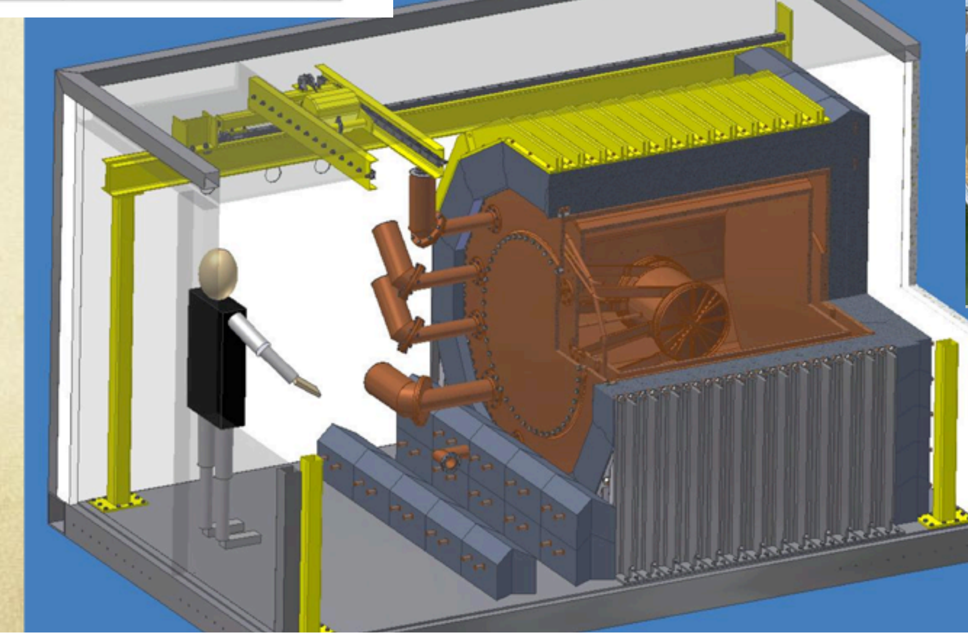
- Large mass
- Low background
- High detection efficiency
- Good energy resolution

Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
^{48}Ca→^{48}Ti	4.271	0.187
^{76}Ge→^{76}Se	2.040	7.8
^{82}Se→^{82}Kr	2.995	9.2
^{96}Zr→^{96}Mo	3.350	2.8
^{100}Mo→^{100}Ru	3.034	9.6
^{110}Pd→^{110}Cd	2.013	11.8
^{116}Cd→^{116}Sn	2.802	7.5
^{124}Sn→^{124}Te	2.228	5.64
^{130}Te→^{130}Xe	2.533	34.5
^{136}Xe→^{136}Ba	2.458	8.9
^{150}Nd→^{150}Sm	3.367	5.6

Experimental Technique





Current $2\nu\beta\beta$ Results

	$T_{1/2}$ (y)	$M^{2\nu}$ (MeV^{-1})	
^{48}Ca	$(4.3\ ^{+2.4}_{-1.1} \pm 1.4)$E19	0.05 ± 0.02	Balysh,PRL**77**,5186 (1996)
^{76}Ge	$(1.74 \pm 0.01\ ^{+0.18}_{-0.16})$E21	0.13 ± 0.01	Doerr,NIMA**513**,596 (2003)
^{82}Se	(9.6 ± 0.3 ± 1.0)E19	0.10 ± 0.01	Arnold,PRL**95**,182302 (2005)
^{96}Zr	(2.35 ± 0.14 ± 0.16)E19	0.12 ± 0.01	Argyriades,NPA**847**,168 (2010)
^{100}Mo	(7.11 ± 0.02 ± 0.54)E18	0.23 ± 0.01	Arnold,PRL**95**,182302 (2005)
^{116}Cd	$(2.9^{+0.4}_{-0.3})$E19	0.13 ± 0.01	Danevich,PRC**68**,035501 (2003)
^{128}Te*	(1.9 ± 0.1 ± 0.3)E24	0.05 ± 0.005	Lin,NPA**481**,477 (1988)
^{130}Te	(7.0 ± 0.9 ± 1.1)E20	0.033 ± 0.003	Arnold,PRL**107**,062504 (2011)
^{136}Xe	**(2.23 ± 0.017 ± 0.22)E21** **(2.30 ± 0.02 ± 0.12)E21**	**0.018 ± 0.001**	**Auger,PRL109, 032505 (2012)** **Gando, PRC86, 021601 (2012)**
^{150}Nd	$(9.11^{+0.25}_{-0.22} \pm 0.63)$E18	0.06 ± 0.003	Argyriades,PRC**80**,032501R (2009)
^{238}U**	(2.2 ± 0.6)E21	0.05 ± 0.01	Turkevich,PRL**67**,3211(1991)

*From geochemical ratio ^{128}Te/^{130}Te.

**Radiochemical result.

$0\nu\beta\beta$ Results Before Neutrino 2012

Experiment	Isotope	0ν Half-life (yr)	$\langle m_\nu \rangle$ (eV)
HM	^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
HM Partial	^{76}Ge	$= 2.23^{+0.44}_{-0.31} \times 10^{25}$	0.32 ± 0.03
This is a controversial claim of discovery			
IGEX	^{76}Ge	$> 1.6 \times 10^{25}$	$< (0.24\text{-}0.75)$
NEMO-3	^{82}Se	$> 3.6 \times 10^{23}$	$< (0.89\text{-}2.3)$
NEMO-3	^{100}Mo	$> 1.1 \times 10^{24}$	$< (0.45\text{-}0.93)$
SOLOTVINO	^{116}Cd	$> 1.7 \times 10^{23}$	$< (1.4\text{-}2.76)$
Cuoricino	^{130}Te	$> 2.8 \times 10^{24}$	$< (0.29\text{-}0.77)$
KamLAND-Zen	^{136}Xe	$> 5.7 \times 10^{24}$	$< (0.3\text{-}0.6)$
New results from EXO-200 and KamLAND-Zen are shown later in this talk			

arXiv:1107.5663 and arXiv:1201.4664

	Nuclide	Q [MeV]	Principle	Det mass [kg]	Decay mass [kg]	Site
CANDLES	^{48}Ca (0.19%)	4.271	CaF$_2$ scint.	305	0.3	Kamioka
Cobra	^{116}Cd (90%)	2.802	CdZnTe semicond.	420	142	Gran Sasso
CUORE	^{130}Te (34%)	2.527	Bolometer	741	206	Gran Sasso
EXO-200	^{136}Xe (80%)	2.458	Liquid TPC	120	96	WIPP
EXO	^{136}Xe (80%)	2.458	Liquid/gas TPC final state tag	$10^3 - 10^4$	800-8000	Homestake?
GERDA	^{76}Ge (86%)	2.039	Ge semicond.	40	35	Gran Sasso
KamLAND-Zen	^{136}Xe (90%)	2.458	Liquid. scint.	400	360	Kamioka
MAJORANA	^{76}Ge (86%)	2.039	Ge semicond.	60-1000	52-860	Homestake?
MOON	^{100}Mo (90%)	3.034	Source foil plastic scint.	480	430	Oto
SNO+	^{150}Nd (5.6%)	3.367	Liquid. scint.	780	44	SNOLab
Super NEMO	^{82}Se (95%)	2.995	Source foil tracking & scint	100+		Frejus
NEXT	^{136}Xe (90%)	2.458	Gas TPC	100-150	90-135	Canfranc

Under construction

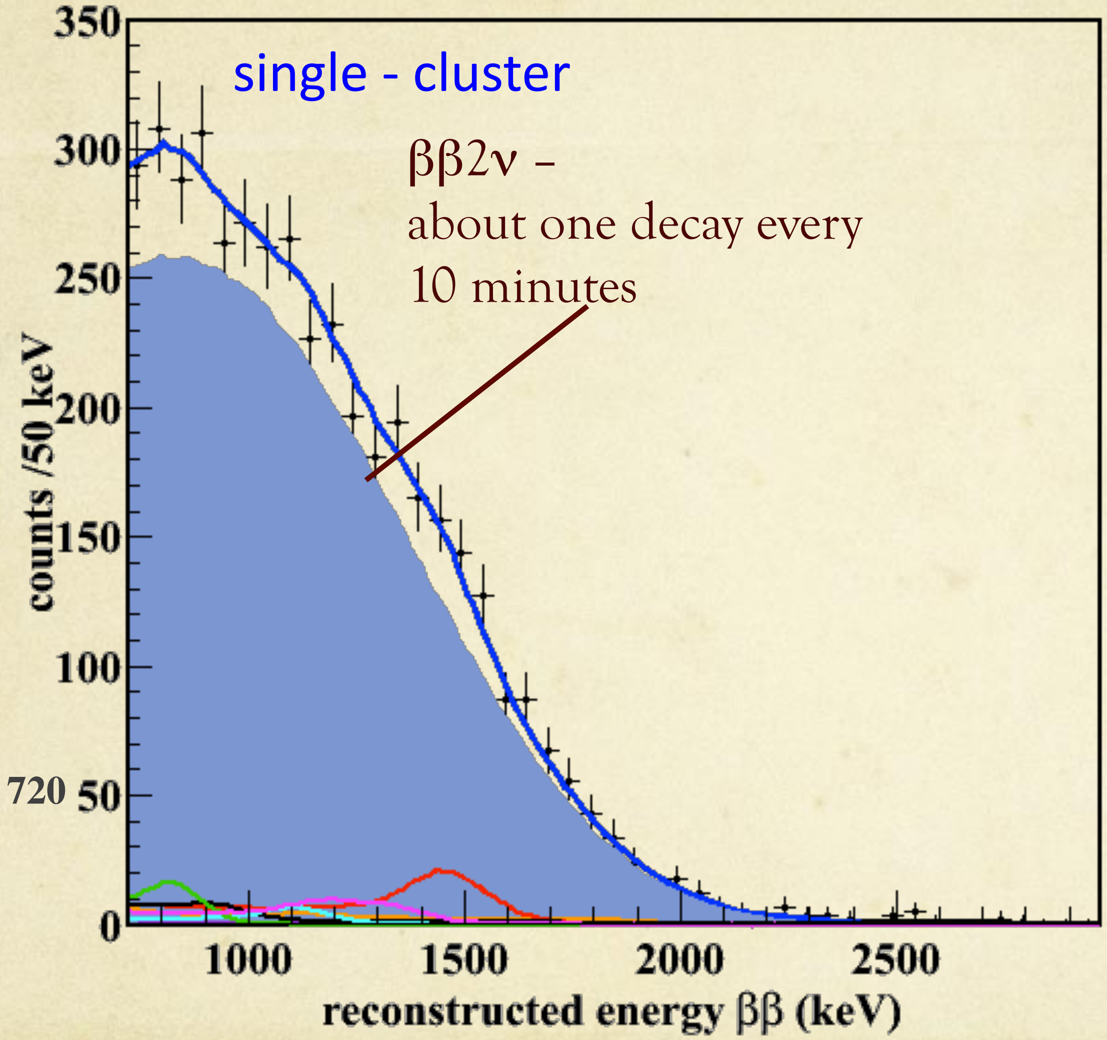
The rest have substantial R&D funding

In blue: passive source

Taking Data

	Nuc-lide	Backgr [1/ keV·y·kg]	Res. σ [keV]	Active background tag	$\langle m_{\beta\beta}\rangle$ [meV]	Data
CANDLES	^{48}Ca	$4\cdot10^{-6}$	170	Active LS shield	500 (5 yr)	2011
Cobra	^{116}Cd	$10^{-3} - 5\cdot10^{-4}$	4.8	Fine pixelation	50 (3-4 y)	?
CUORE	^{130}Te	$10^{-2} - 10^{-3}$	2.0	Heat/light, anti-coinc	40-100 (5 y)	2014
EXO-200	^{136}Xe	10^{-3}	37	3d tracking, ion/scint	130–190 (2 y)	2011
EXO	^{136}Xe	$2\cdot10^{-7}$	25	3d tracking, Ba tag	5 (10 y)	?
GERDA	^{76}Ge	$10^{-3} - 10^{-4}$	1.5	Pulse shape, anti-coinc	75–130 (3 y)	2011
KamLAND	^{136}Xe	$6\cdot10^{-5}$	107	BiPo, anti-coinc	50 (3 y)	2011
MAJORANA	^{76}Ge	10^{-3}	1.5	Pulse shape, anti-coinc	100 (3 y)	2014
MOON	^{100}Mo	$5\cdot10^{-5}$	67	Tracking, 1e/2e discrim	30–45 (4 y)	?
SNO+	^{150}Nd		216	BiPo, anti-coinc	150 (1 y)	2012
Super NEMO	^{82}Se		51	Tracking, 1e/2e discrim	50-110	2016
NEXT	^{136}Xe		10.5	3d tracking,ion	100	2016

FIRST OBSERVATION OF ββ2ν IN ^{136}XE



ββ2ν –
about one decay every
10 minutes

^{136}Xe⟶^{136}Ba ββ2ν

First observation
of ββ2ν in this isotope!

Longest half-life ever
directly observed.

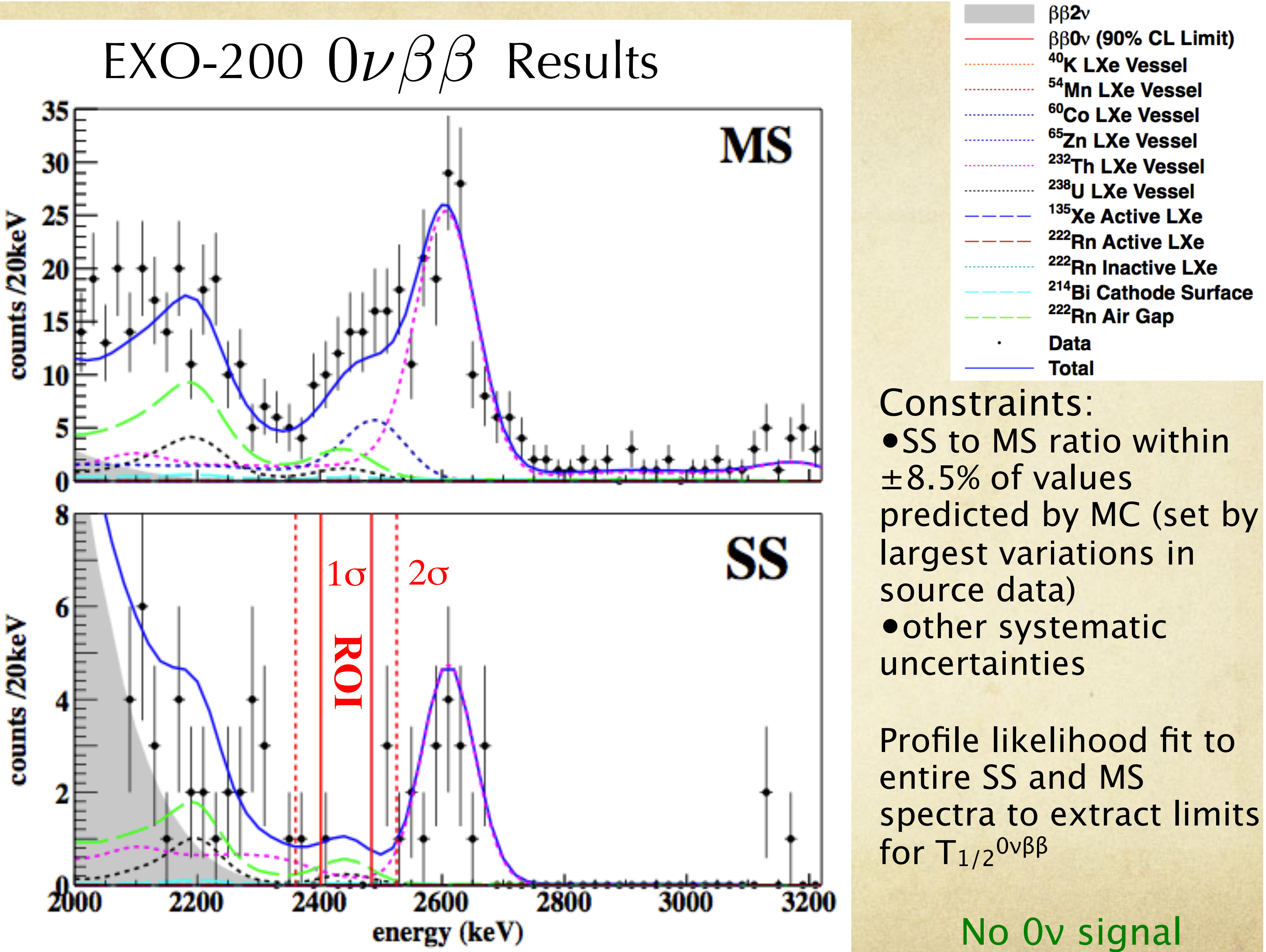
Only 31 days of data.

Signal-to-background
ratio 10:1

$T_{1/2}$ = **2.11·10^{21} yr (± 0.04 stat) yr (± 0.21 syst)**

N. Ackerman *et al.*, PRL **107**, 212501 (2011).

EXO-200 $0\nu\beta\beta$ Results



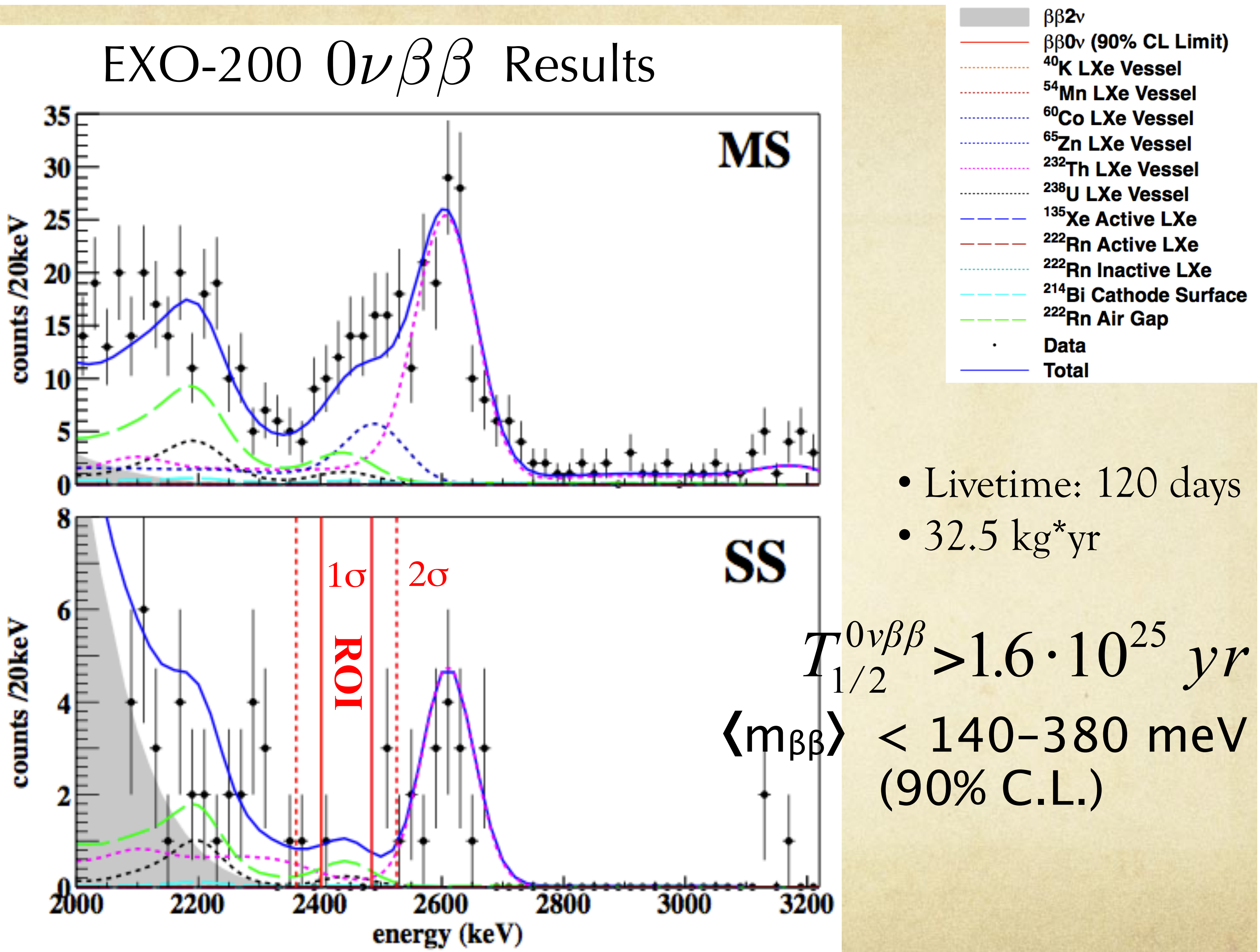
Constraints:

- SS to MS ratio within ±8.5% of values predicted by MC (set by largest variations in source data)
- other systematic uncertainties

Profile likelihood fit to entire SS and MS spectra to extract limits for $T_{1/2}^{0\nu\beta\beta}$

No 0ν signal observed

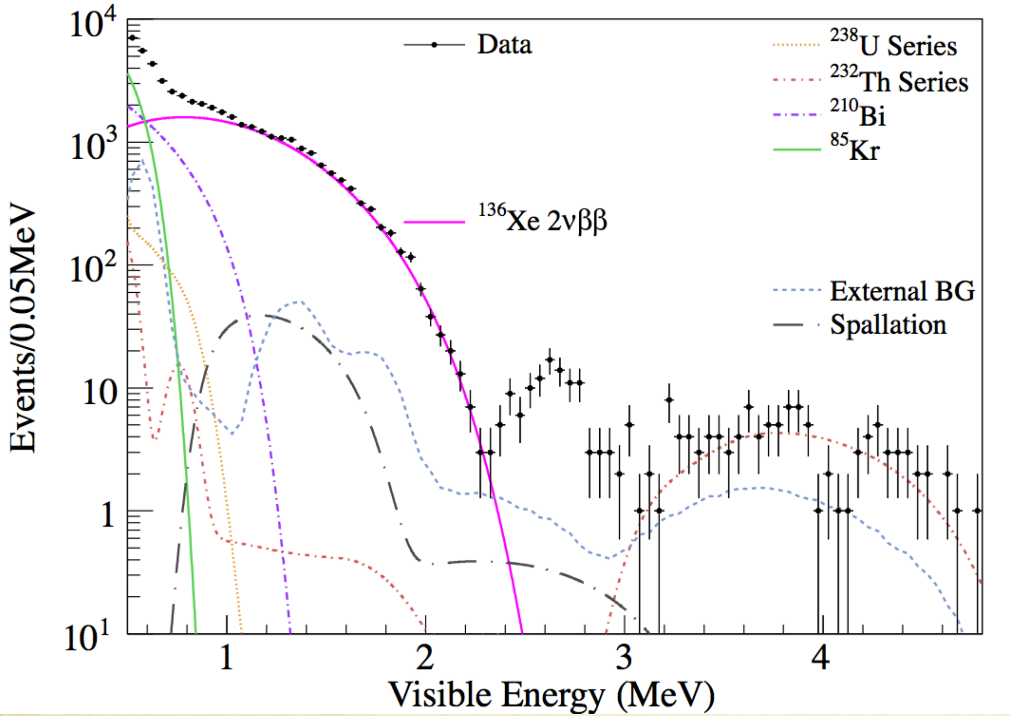
EXO-200 $0\nu\beta\beta$ Results



- Livetime: 120 days
- 32.5 kg*yr

$$T_{1/2}^{0\nu\beta\beta} > 1.6 \cdot 10^{25}\ yr$$

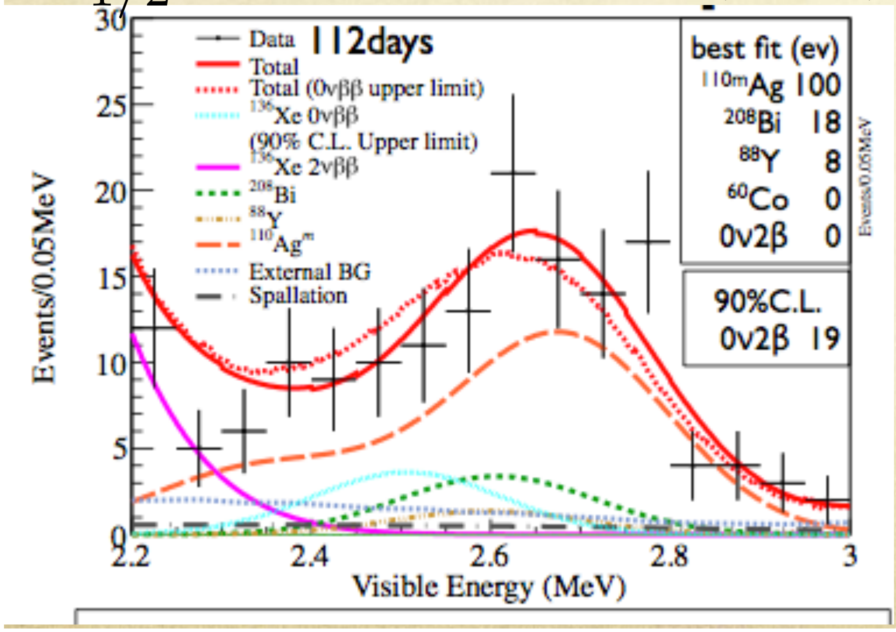
$\langle m_{\beta\beta} \rangle$ < 140–380 meV
(90% C.L.)



KamLAND-Zen

- Livetime 112 days
- 38.6 kg*yr

$$T^{2\nu}_{1/2} = \mathbf{2.30 \pm 0.02\ (stat) \pm 0.012\ (syst) \times 10^{21}\ years}$$



$$T^{0\nu}_{1/2} = \mathbf{6.2 \times 10^{24}\ years}$$

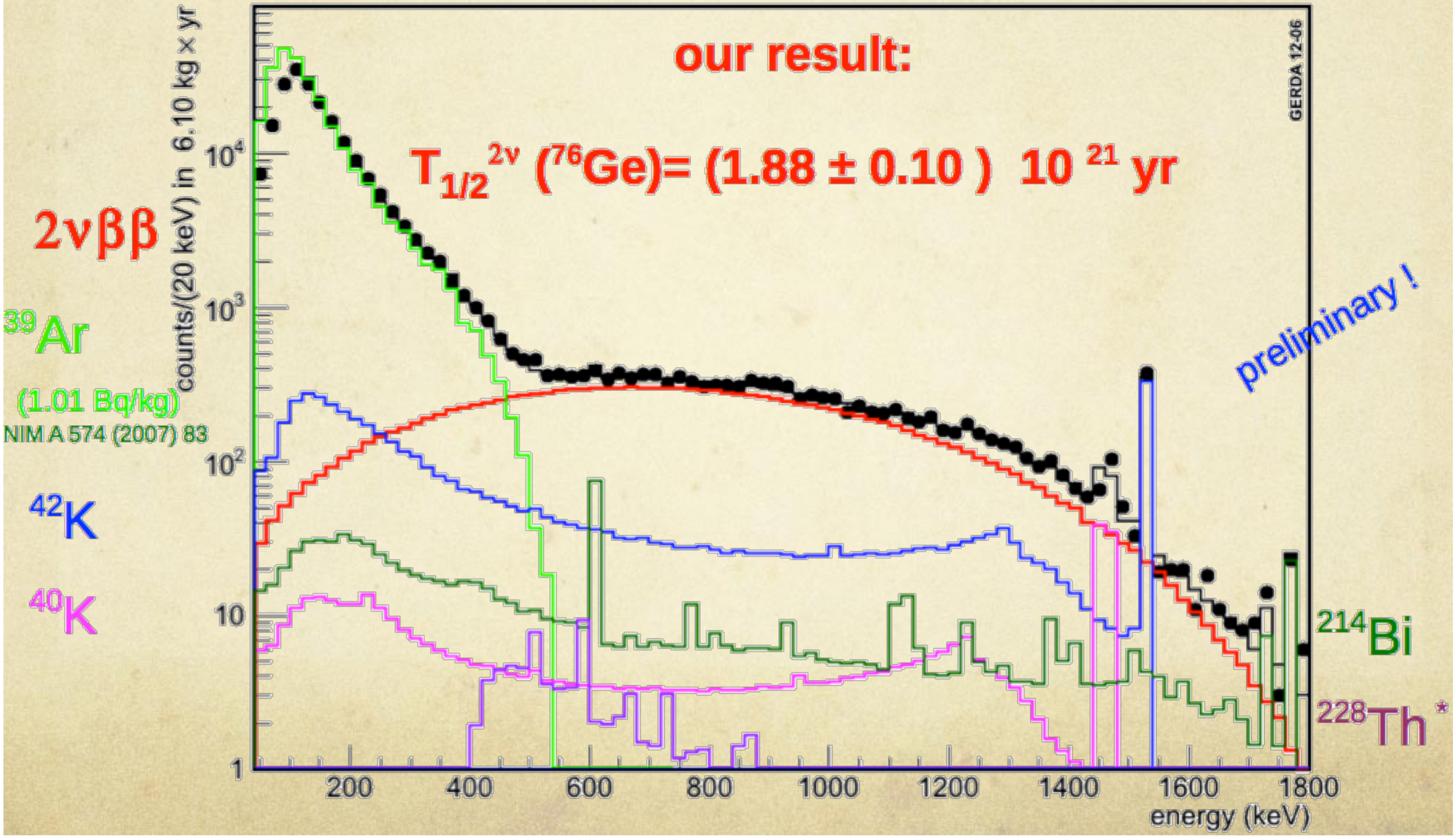
$$\langle m_{\beta\beta} \rangle \leq \mathbf{260\text{-}540\ eV}$$

$$\mathbf{(90\%\ C.L.)}$$

GERDA Phase I:
Measurement of 2νββ spectrum

summed electron energy spectrum in GERDA

exposure : 6.1 kg yr



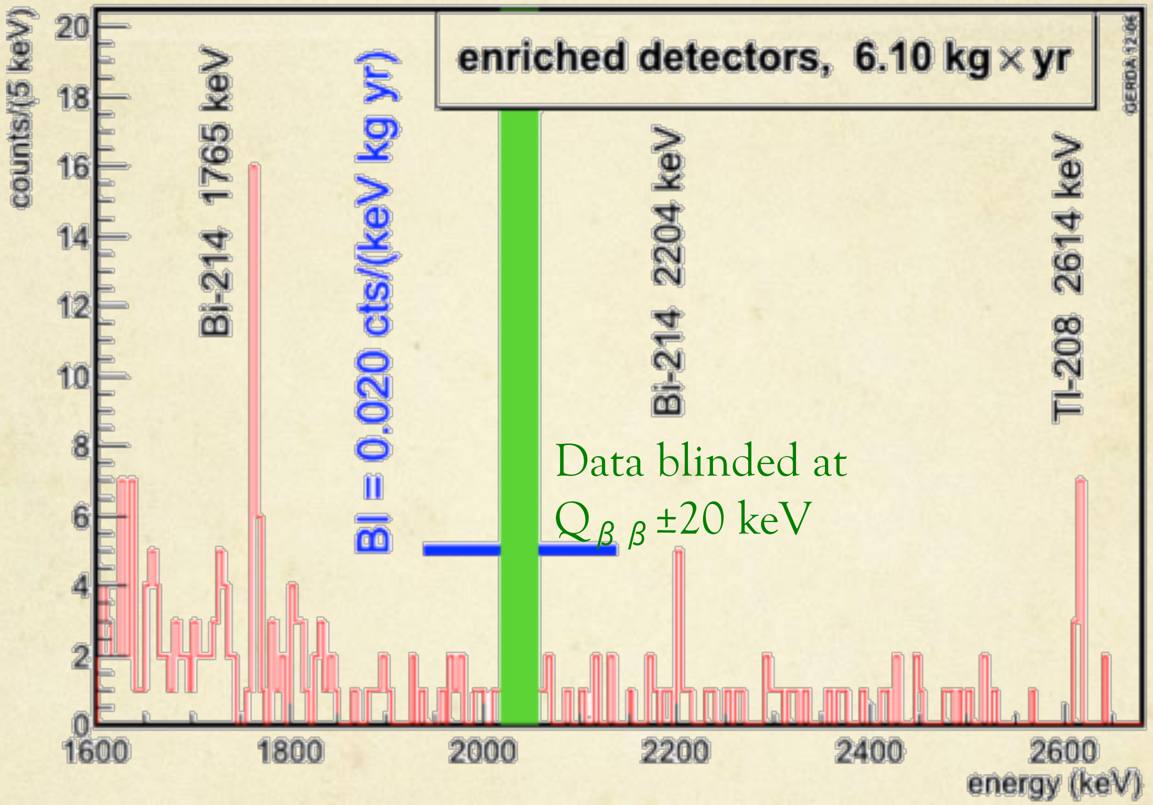
our result:

$T_{1/2}^{2\nu}$ (^{76}Ge)= (1.88 ± 0.10) 10 ^{21} yr

preliminary !

Phase I data taking started November 2011

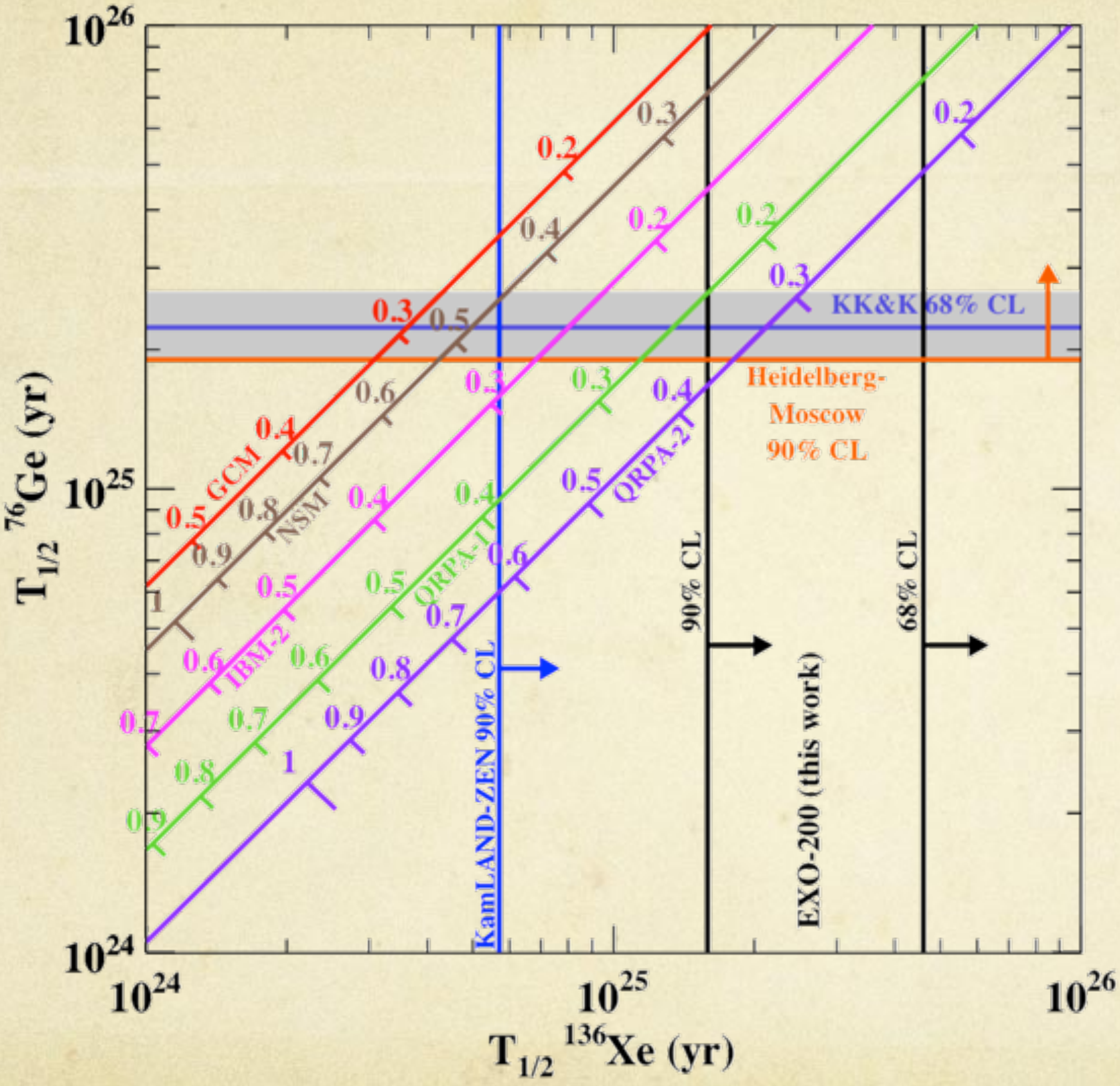
The GERDA background index (BI)



Data blinded at $Q_{\beta\beta}$ ±20 keV

Energy Window: 200 – 40 (blinded region) = 160 keV

Background Index = 0.020 + 0.006 – 0.004 cts/keV kg yr

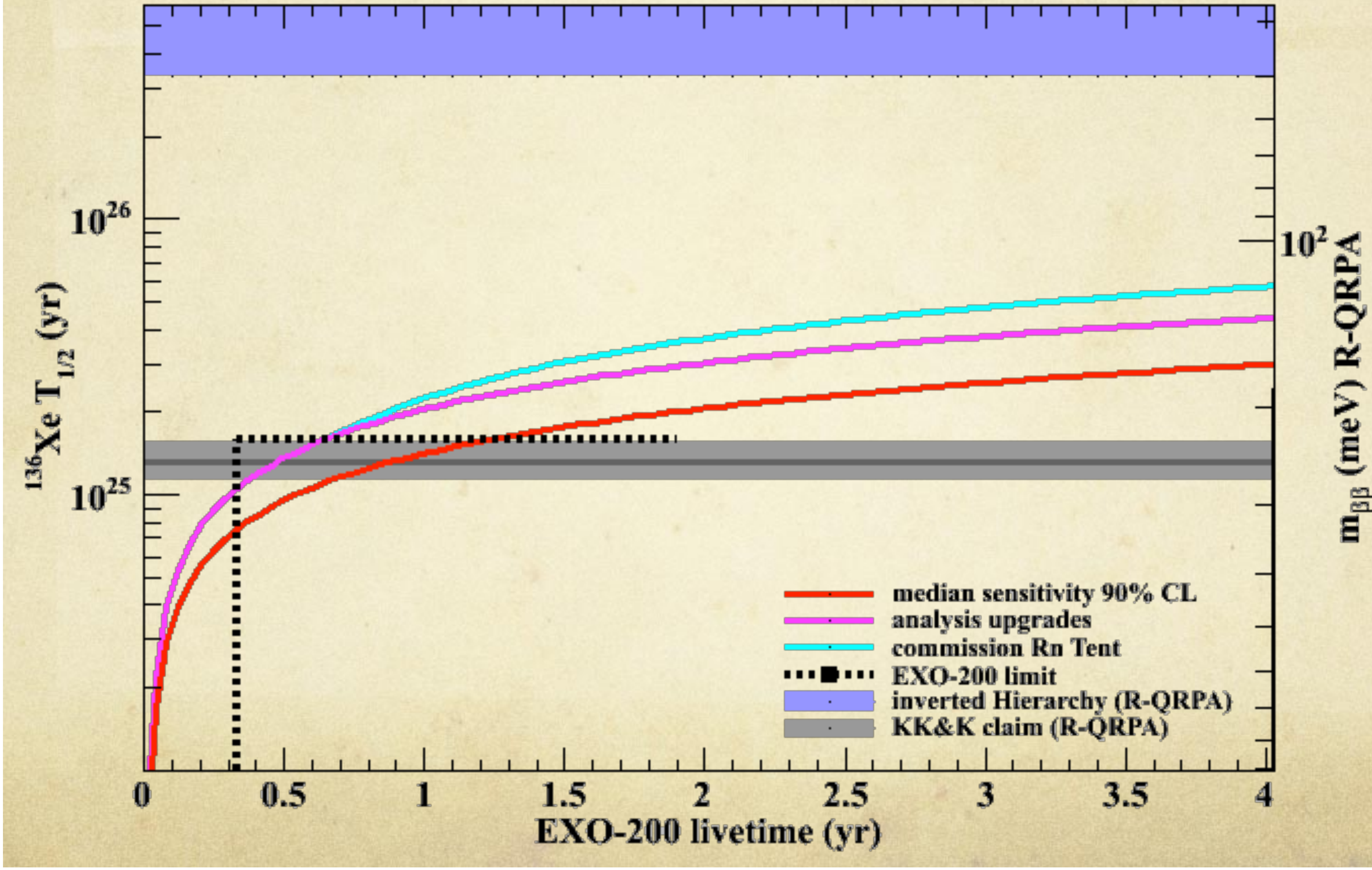


Using different nuclear matrix elements the absence of a 0νββ-peak in EXO-200 is compared to the evidence published for ^{76}Ge.

For most matrix element calculations there seems to be tension between these two experiments.

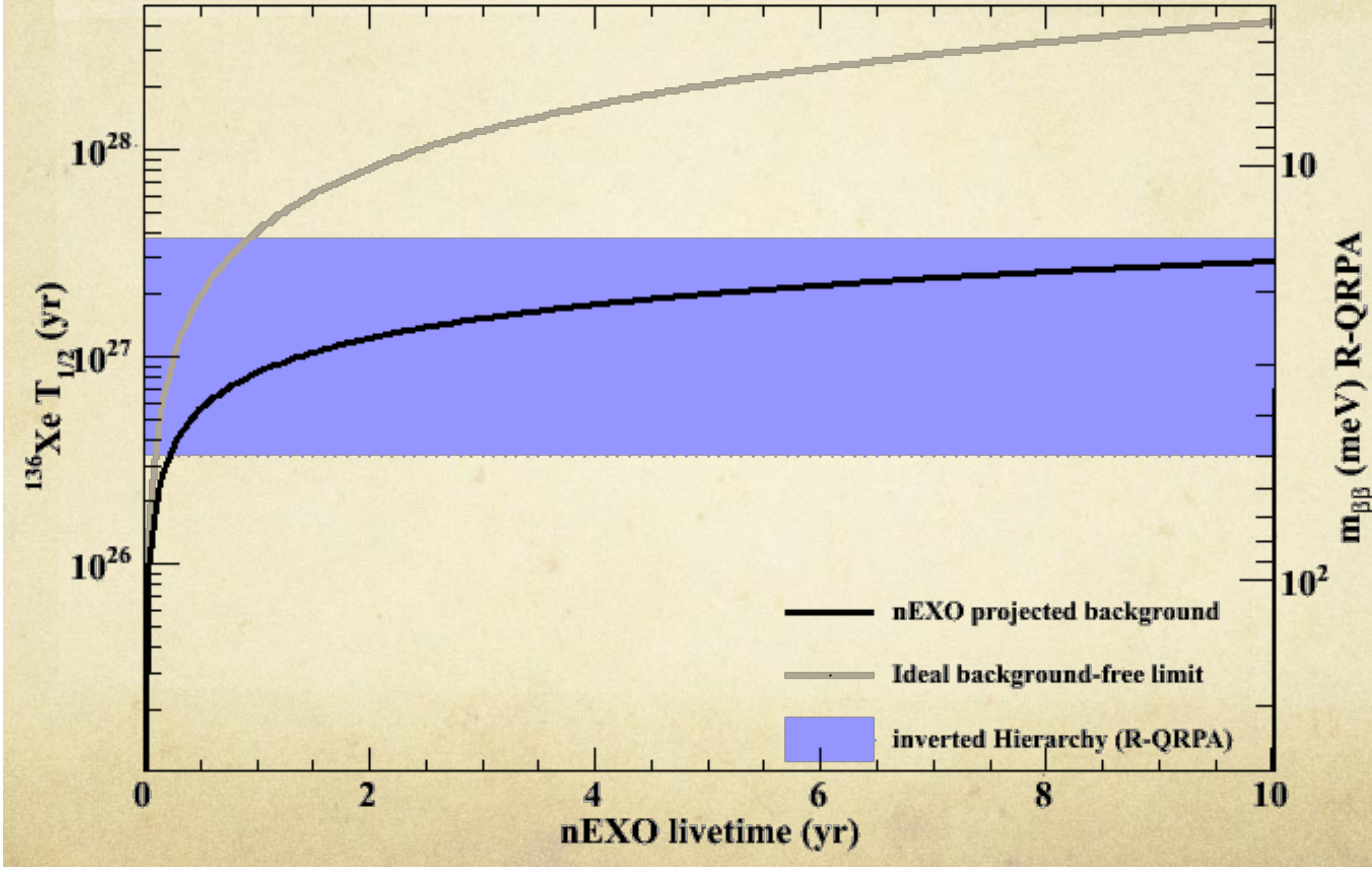
EXO-200 Sensitivity

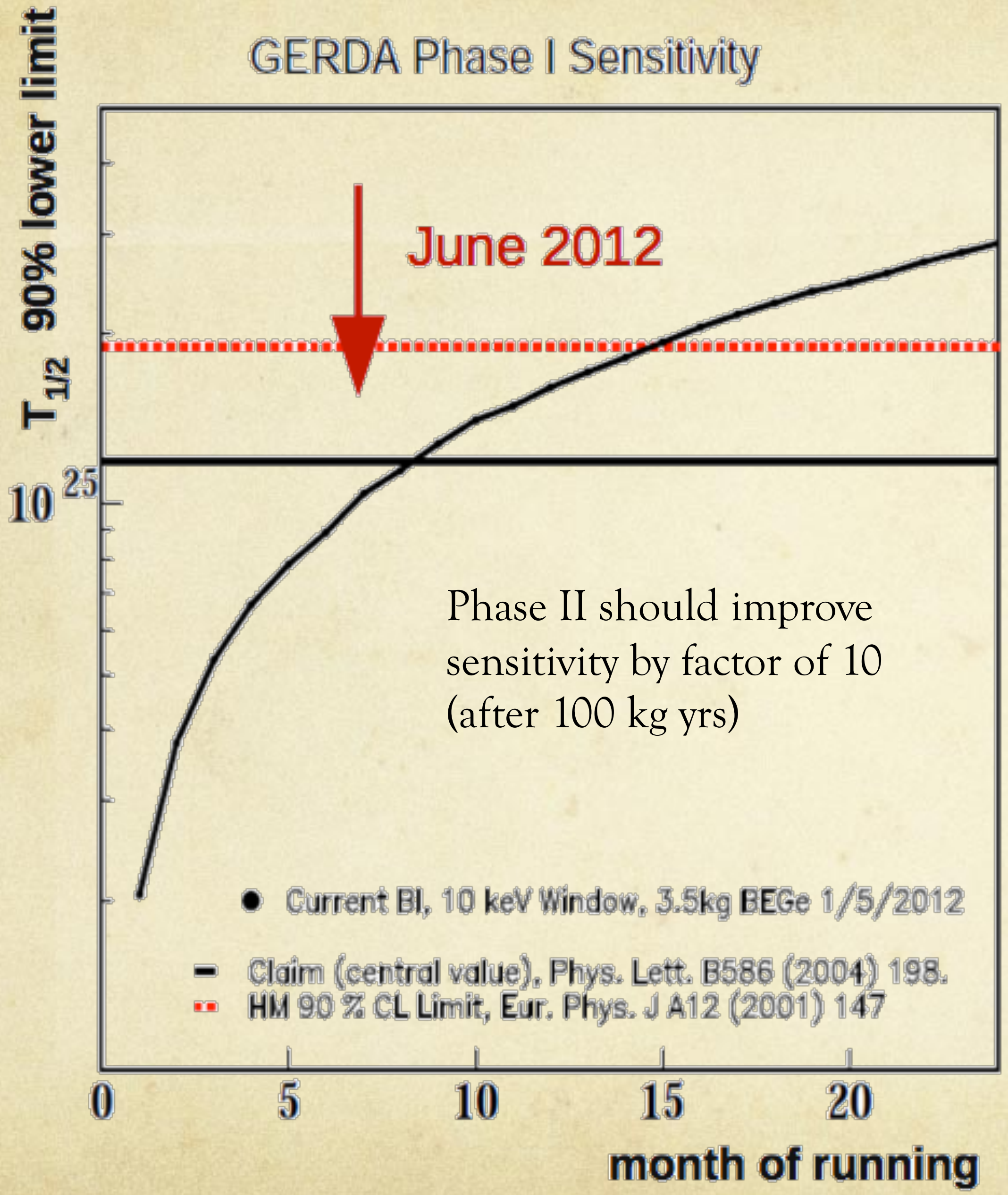
for R-QRPA matrix element calculation (2009)



nEXO Sensitivity

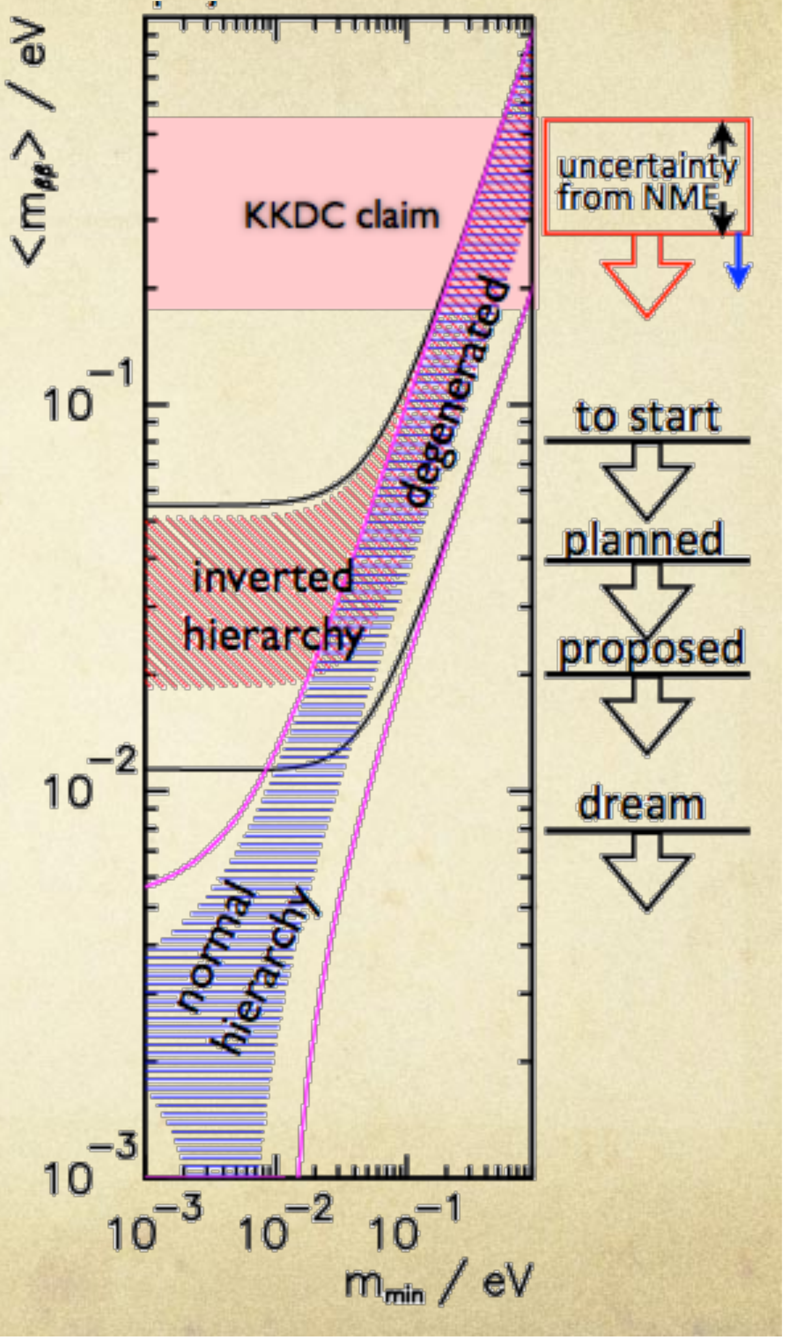
for R-QRPA matrix element calculation (2009)





Phase II should improve sensitivity by factor of 10 (after 100 kg yrs)

KamLAND-Zen Sensitivity



Summary

Majorana neutrino mass limit range:

^{136}Xe (EXO-200): <140-380 meV
[Auger et al., PRL 109 (2012) 032505]

^{136}Xe (KamLAND-ZEN): <240-620 meV
[Gando et al., PRC85 (2012) 045504]

^{130}Te (Cuoricino): < 270 – 660 meV
[Arnaboldi et al. PRC 78 (2008) 035502]

^{76}Ge (HD-Mo): < 270 – 640 meV
[H.V. Klapdor-Kleingrothaus, EJP A12 (2001) 147]

^{76}Ge (IGEX): < 295 – 700 meV
[Aalseth et al., PRD 65 (2002) 092007]

^{100}Mo (NEMO-3): < 450 – 1070 meV
[Barabash et al., PAN 74 (2011) 312]

- Previous claim of $0\nu\beta\beta$ observation almost ruled out by EXO-200 results.
- Extremely active and aggressive field of study – need several isotopes to disentangle physics.
- The next generation experiments should be able to access the inverted hierarchy scale.
- These measurements will put stringent limits on (or observe) lepton number violation
- Experiments are big and challenging, but physics payoff is also big – observation means new physics!

Back-up Slides

References for nuclear matrix elements:

RQRPA (Renormalized Quasiparticle Random Phase Approximation): from Table II, column 6, Simkovic *et al.,* Phys. Rev.C**79,** 055501 (2009). For ^{150}Nd D.L. Fang, ArXiv:1009.5260

NSM (Nuclear Shell Model): J. Menendez *et al.,* Nucl. Phys.**A818**, 139 (2009).

IBM-2 (Interacting Boson Model -2): J. Barea and F. Iachell, Phys. Rev. C**79**, 044301 (2009) and private communication.

PHFB (Projected Hartree-Fock Bogoljubov): K. Chatuverdi *et al.,* Phys. Rev. C**78**, 054302 (2008).

EDF (Energy Density Functional): T. R. Rodriguez and

G. Martinez-Pinedo, ArXiv:1008.5260

Phase space factors for the $0\nu\beta\beta$ decay from F. Boehm and P. Vogel, Physics of Massive Neutrinos, Table 6.1

Vogel, 9/2010

Future Data Requirements

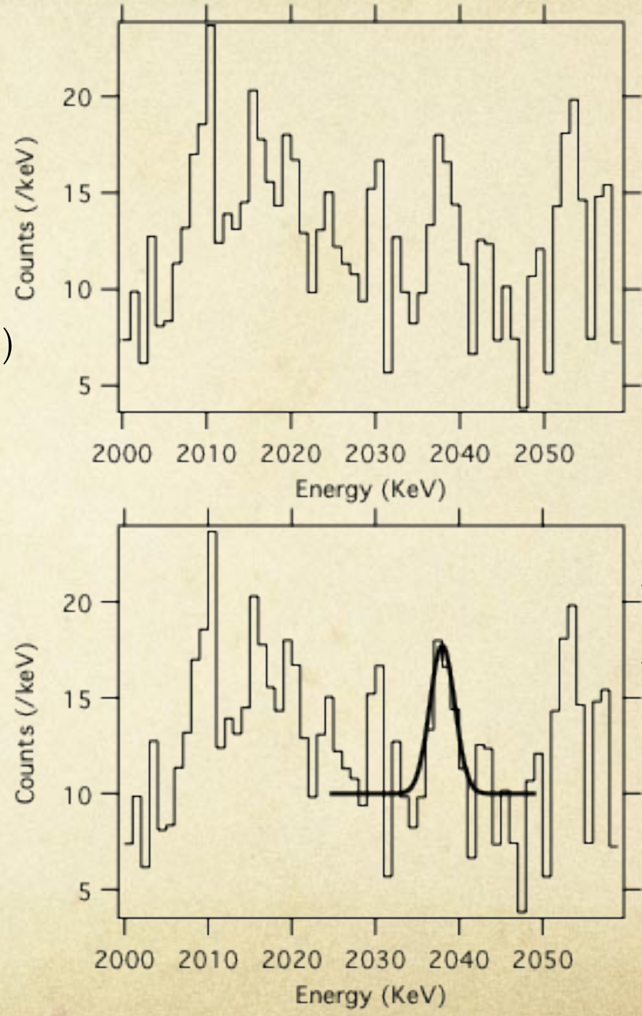
Why isn't the current claim sufficient to avoid controversy?

- Low statistics of claimed signal - hard to repeat measurement
- Background model uncertainty
- Unidentified lines
- Insufficient auxiliary handles (e.g. better known Q values)

Result needs confirmation or repudiation

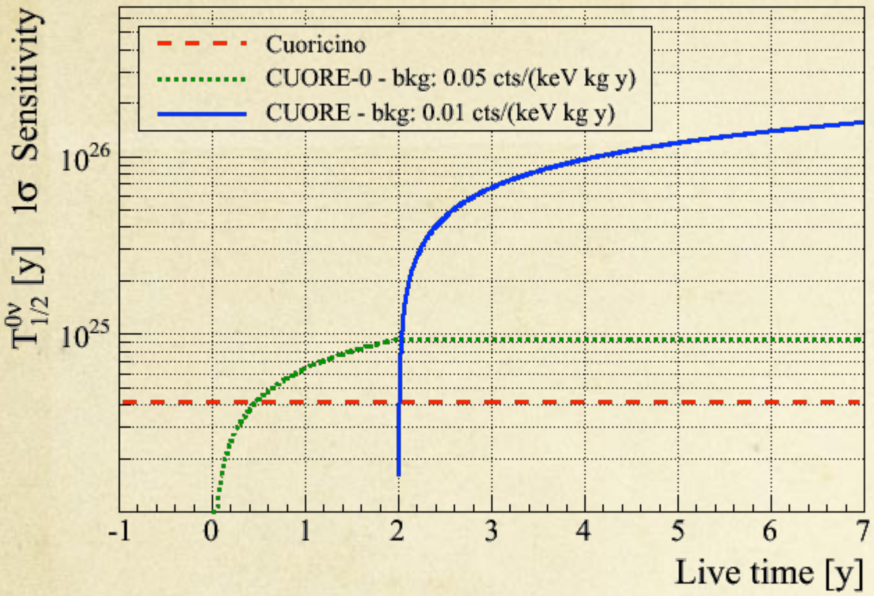
Background considerations: looking for a rare peak on a continuum:

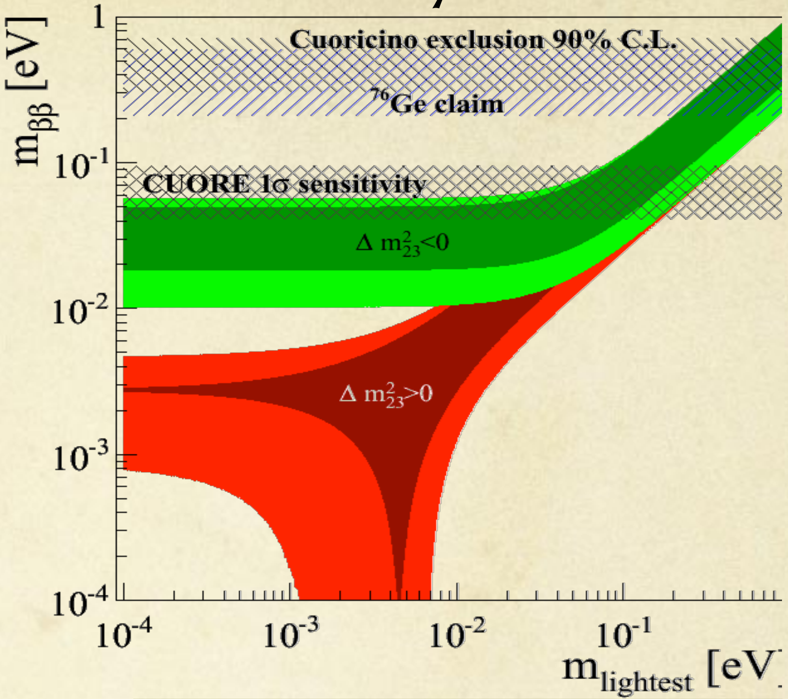
- ββ(2ν)
- natural occurring radioactive materials
- neutrons
- long-lived cosmogenics



NIM A522, 371 (2004)

CUORE Sensitivity





In CUORE, we expect to achieve

5 keV RESOLUTION @ 2528-keV Q-value

0.01 counts/(keV kg y) BACKGROUND

5 years LIVE TIME

Expected 1 σ sensitivity:

$T_{1/2}^{0\nu}(^{130}Te) > 1.6 \times 10^{26}$ y

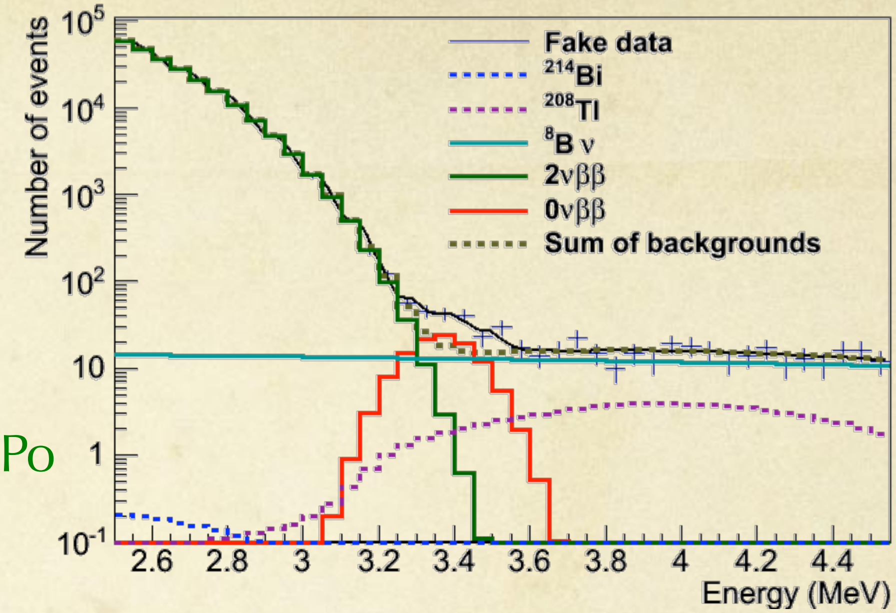
$m_{\beta\beta} < 41 – 95$ meV

Now	Crystal production ongoing since 2008 (~30 per month) CUORE hut and clean room are ready and cryostat being manufactured Installation of CUORE-0 in Cuoricino cryostat
2012-2014	Data-taking with CUORE-0 Assembly of cryostat, detector, Faraday cage, and electronics
2014	Start of data-taking with CUORE

Neutrinoless $\beta\beta$-decay

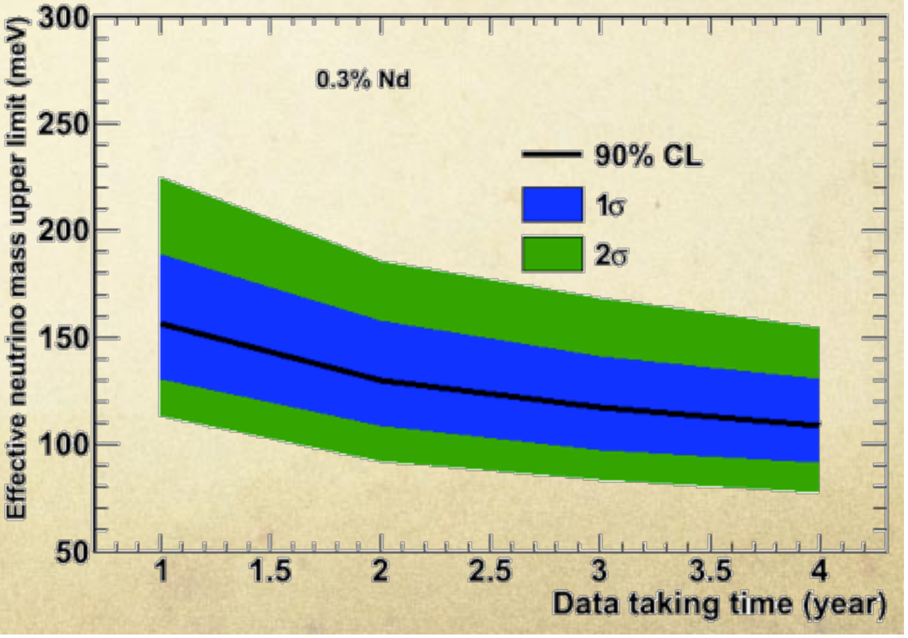
$\beta\beta$-decay signal for 0.1% Nd loaded scintillator

- signal at the level of Klapdor [Phys. Lett. B 586 (2004) 198]
- 2.4 live-years data simulated
- ^{214}Bi tagged and removed with ^{214}Bi-Po
- ^{208}Tl constrained with ^{212}Bi-Po delayed coincidence
- $t_{1/2}$ 3 min alpha tag of ^{208}Tl rejects 90%



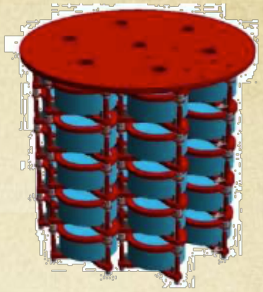
Neutrino mass sensitivity for 0.3% Nd loading.

- IBM-2 [Phys. Rev. C 79 (2009) 044301] NME values were used (includes deformation)
- radioactivity backgrounds at the levels achieved by Borexino



From M. Chen

MAJORANA DEMONSTRATOR IMPLEMENTATION AND MAJORANA SENSITIVITY



- Three Phases
  - Prototype cryostat (2-3 strings, ^{nat}Ge) **(Fall 2012)**
    - **Same design as C1 and C2 but fabricated with OFHC Cu instead of electroformed Cu**
  - Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge) **(Fall 2013)**
  - Cryostat 2 (up to 7 strings ^{enr}Ge) **(Fall 2014)**