Neutrinoless double-beta decay

YETI 2014, IPPP, Durham

Simon JM Peeters

University of Sussex
Physics & Astronomy

During this short hour ...

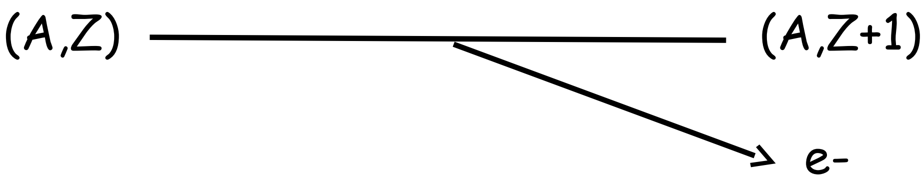
- Introduction
- Experimental aspects
- Current status
- Future experiments
- Further future
- Conclusions

Fact, but also personal view on experimental method and approach for the future

Introduction

Beta decay

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



(view early last century)

Beta decay

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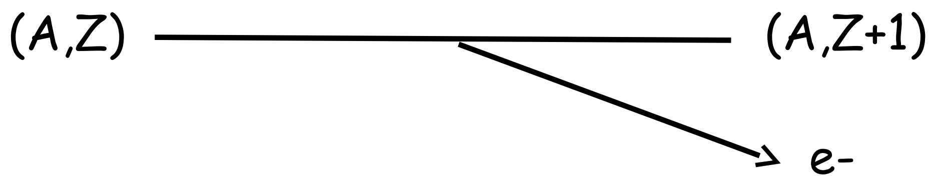
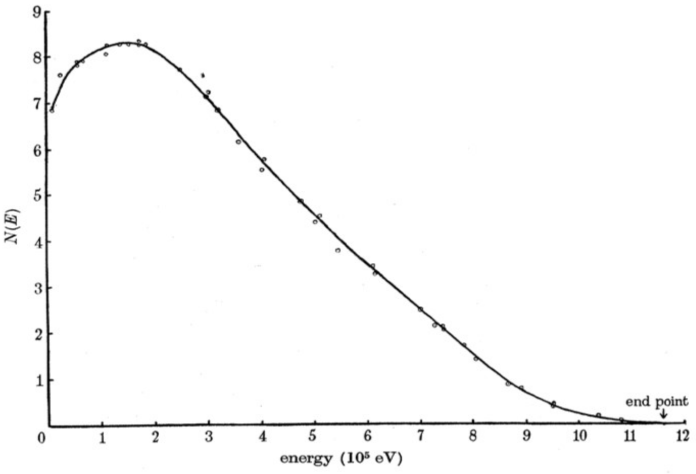


Chadwick 1914:
Beta decay has continuous spectrum (and spin ½ missing)



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Pauli vs ~~Bohr~~:
Missing particle
vs
~~Energy conservation is violated on quantum scale~~

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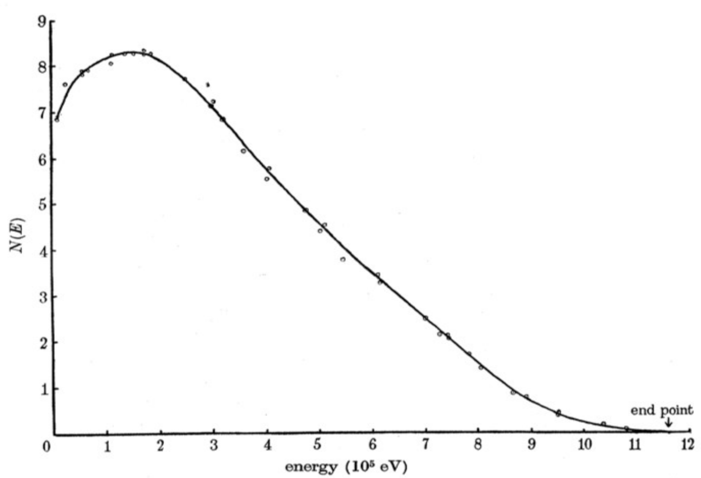

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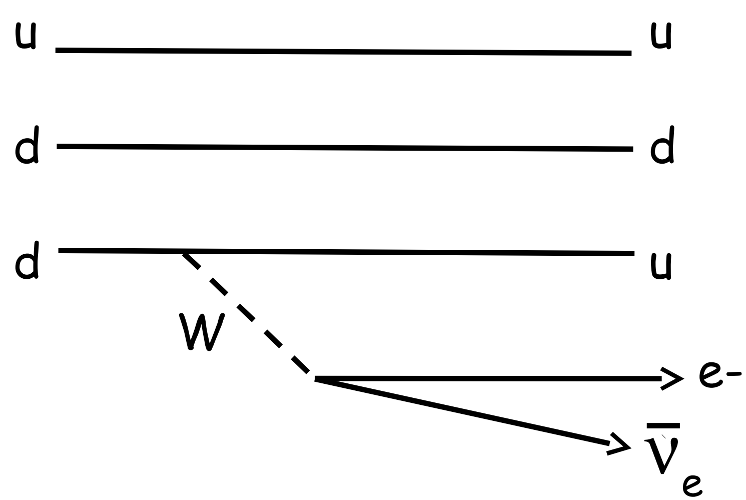

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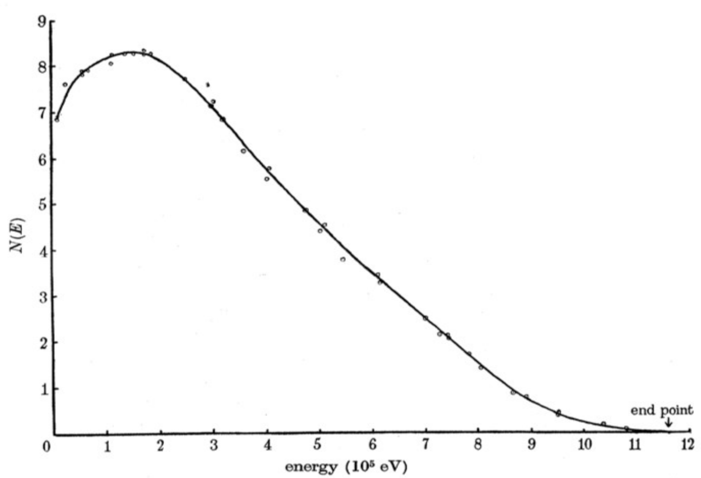
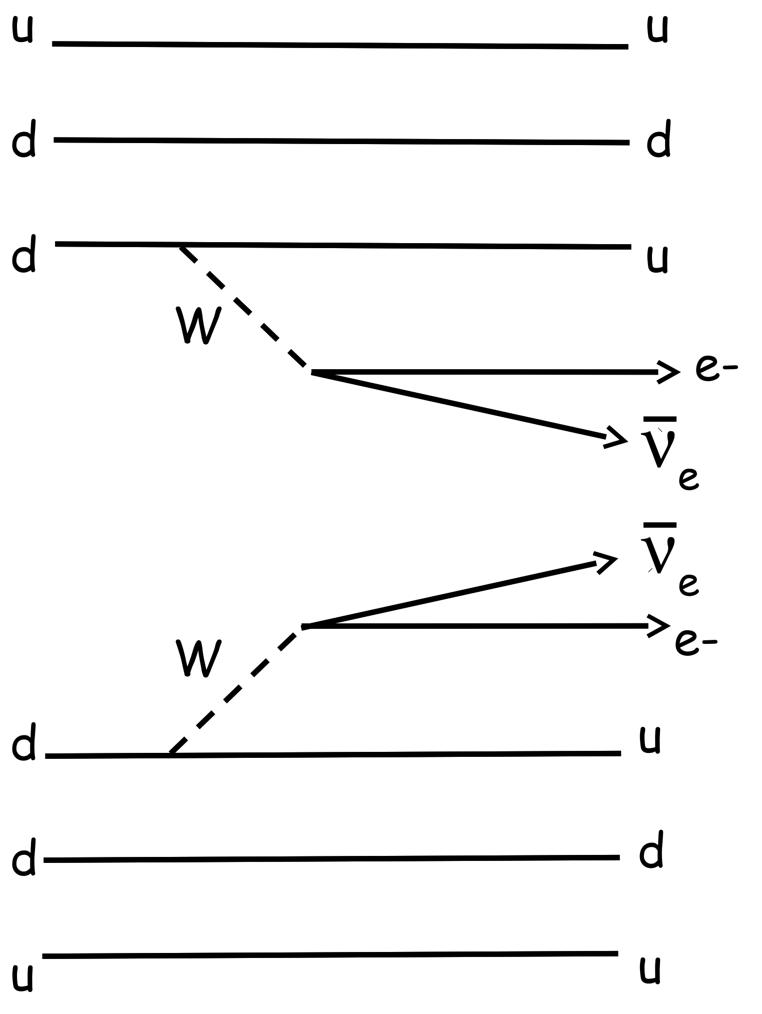
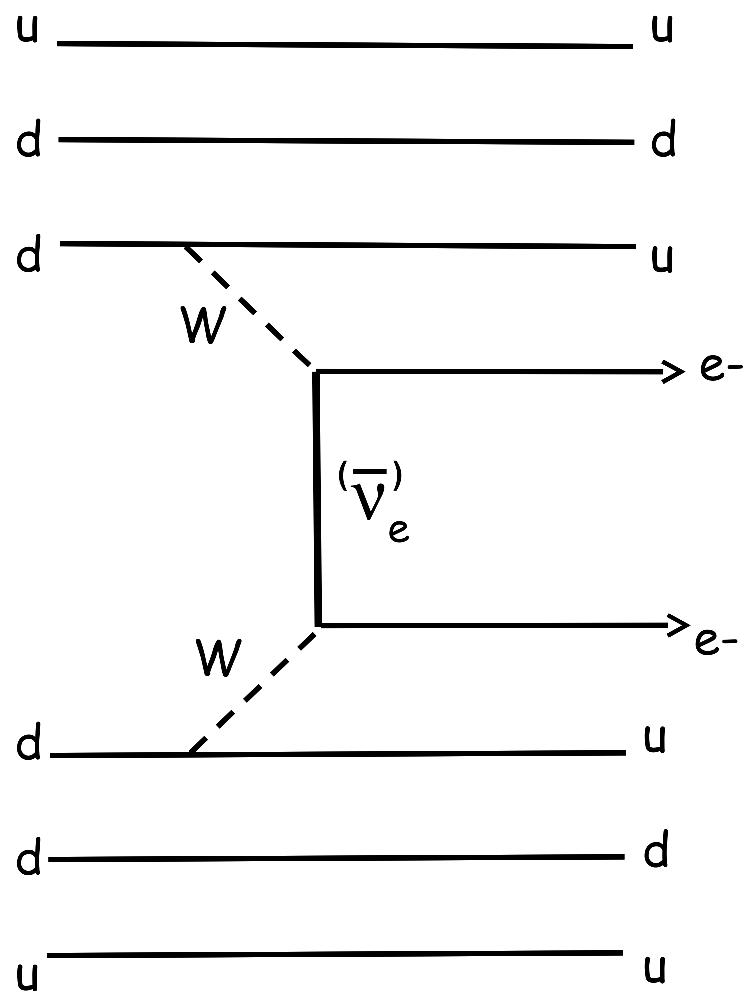


Double beta decay



Maria Goeppert-Mayer
1935

Neutrinoless double-beta decay



Ettore Majorana
1937

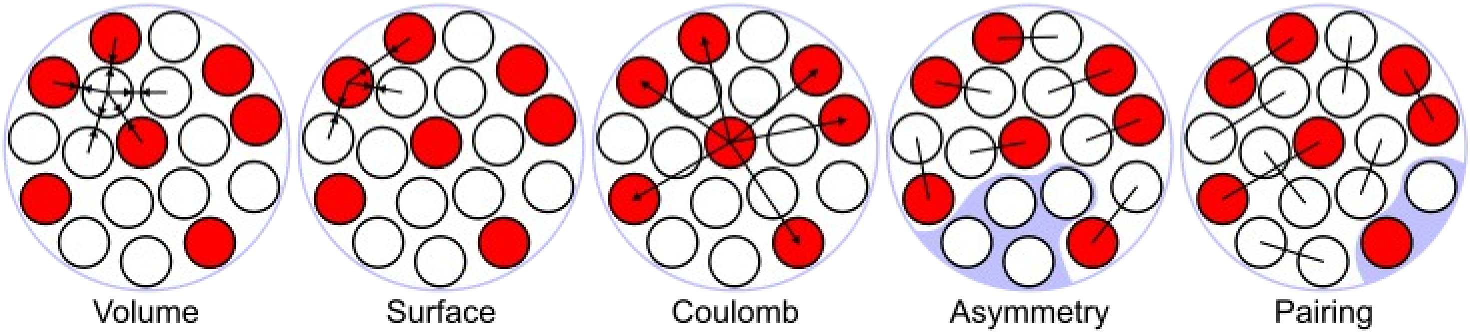
Some (basic) nuclear physics (I/II)

SEMF: Semi Empirical Mass formula

(Bethe-Weizsaecker mass formula)

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} - \delta(A,Z)$$

$$\delta(A,Z) = \begin{cases} -\delta_0 & \text{if (A,Z) even (A even)} \\ 0 & \text{if A odd} \\ +\delta_0 & \text{if (A,Z) odd (A even)} \end{cases}, \text{ where } \delta_0 = \frac{a_P}{A^{1/2}}$$



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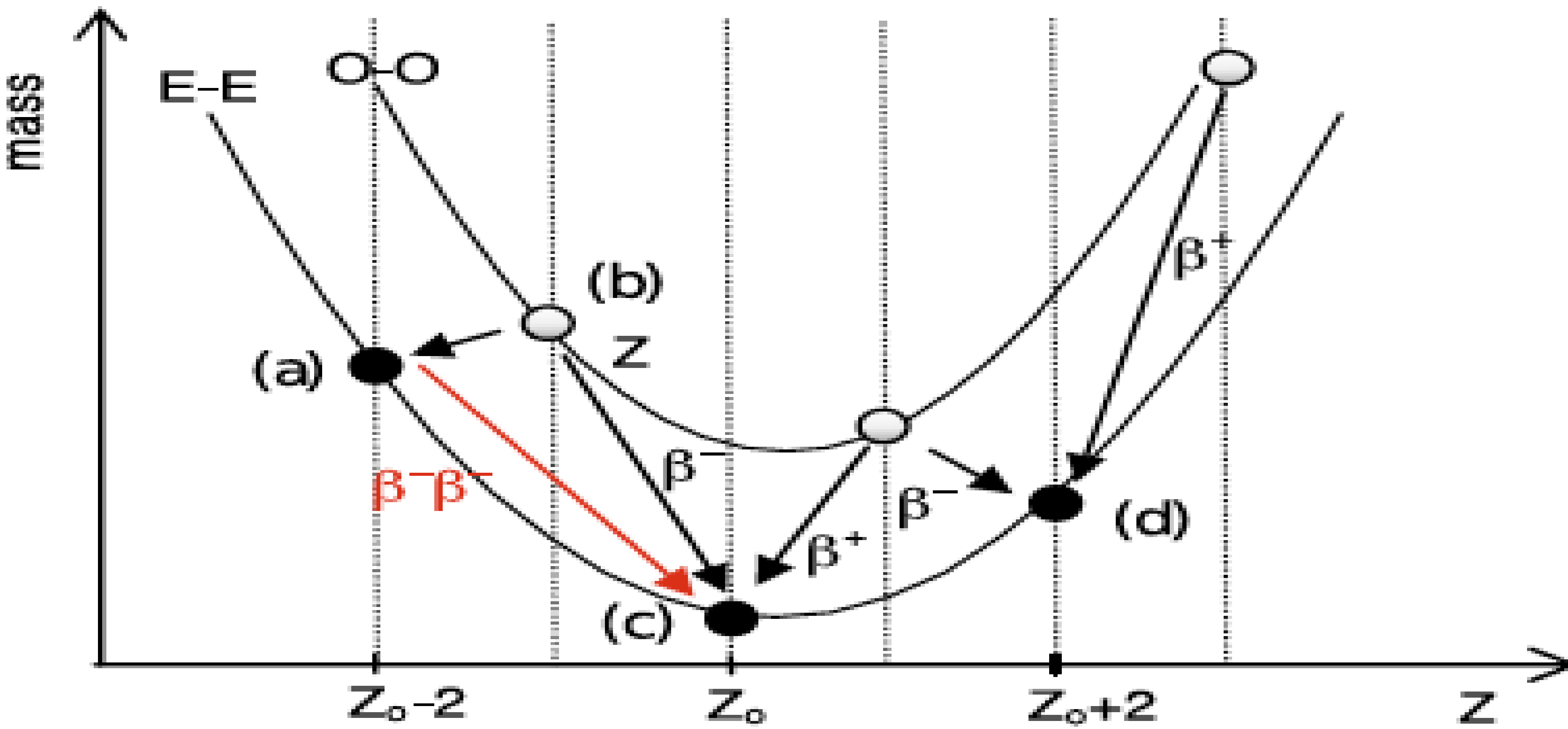

For constant and even A, the SEMF can be written in the form:

$$E_b = aZ^2 - bZ - c \pm \delta_0$$

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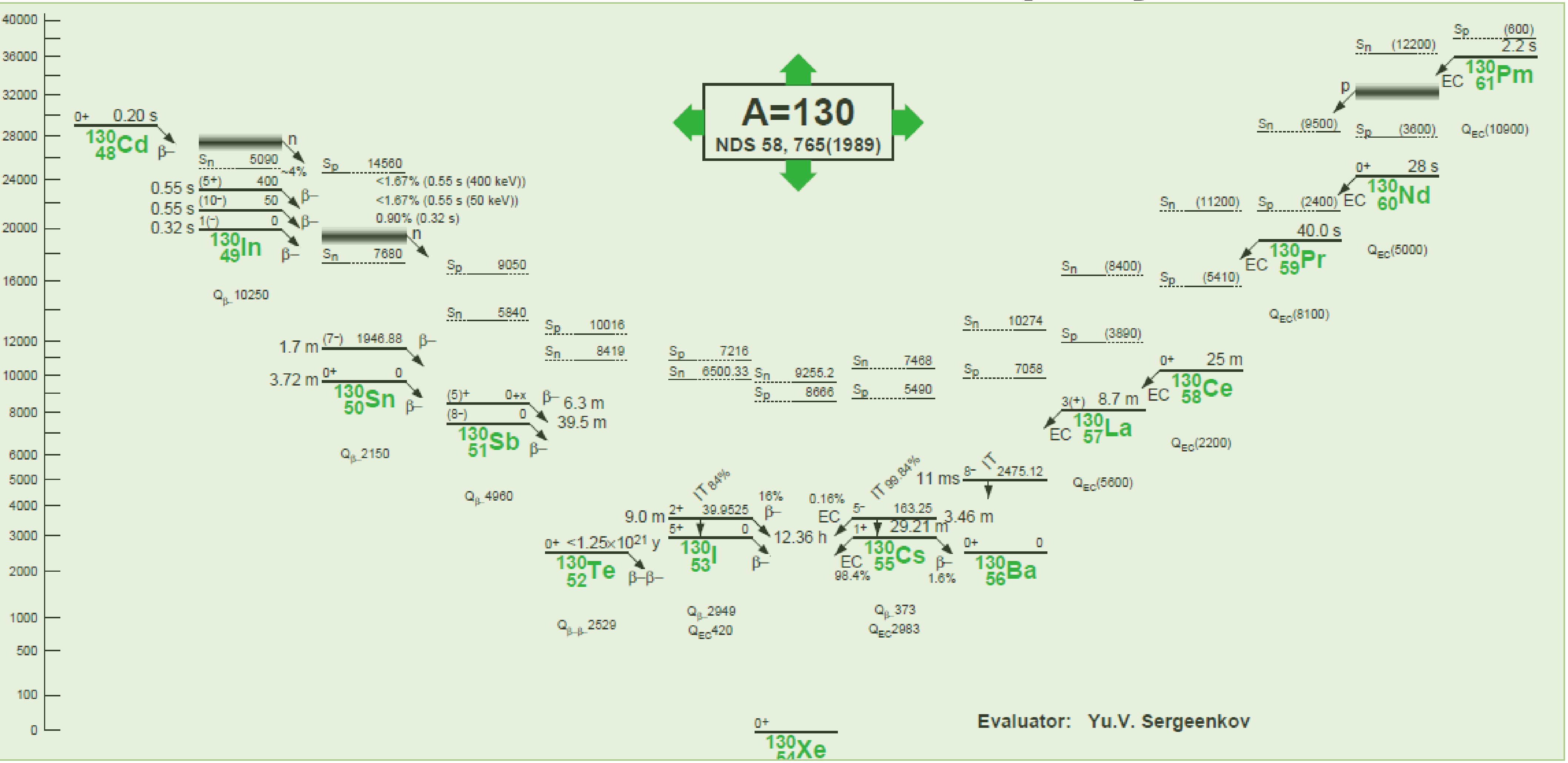

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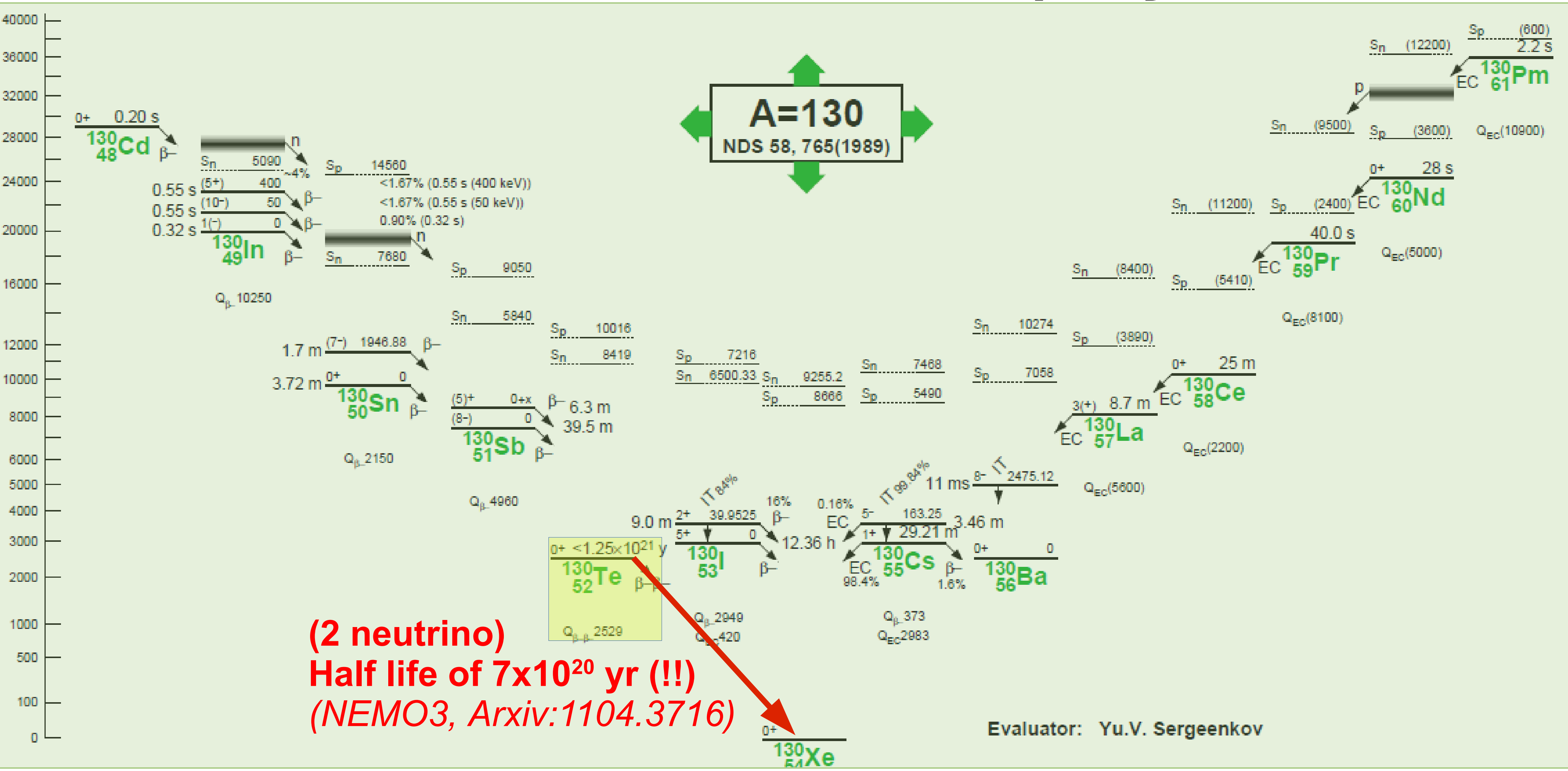

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Observing decays: sketch

$$T_{1/2} = \frac{\ln 2 \cdot a \cdot N_A \cdot M \cdot t}{N_{\beta\beta}}$$

- Assuming $T_{1/2} >> t$
- To measure a half life of $10^{26\text{-}27}$ years, you would want to see at least 1 event/yr

This corresponds to (roughly) 1000 moles, implying order 100 kg

Bringing in realism (nat. ab., eff., backgrounds) makes this only worse ...

NB: common exposure unit used = M t [kg yr]

Double-beta decay isotopes (Q>2 MeV)

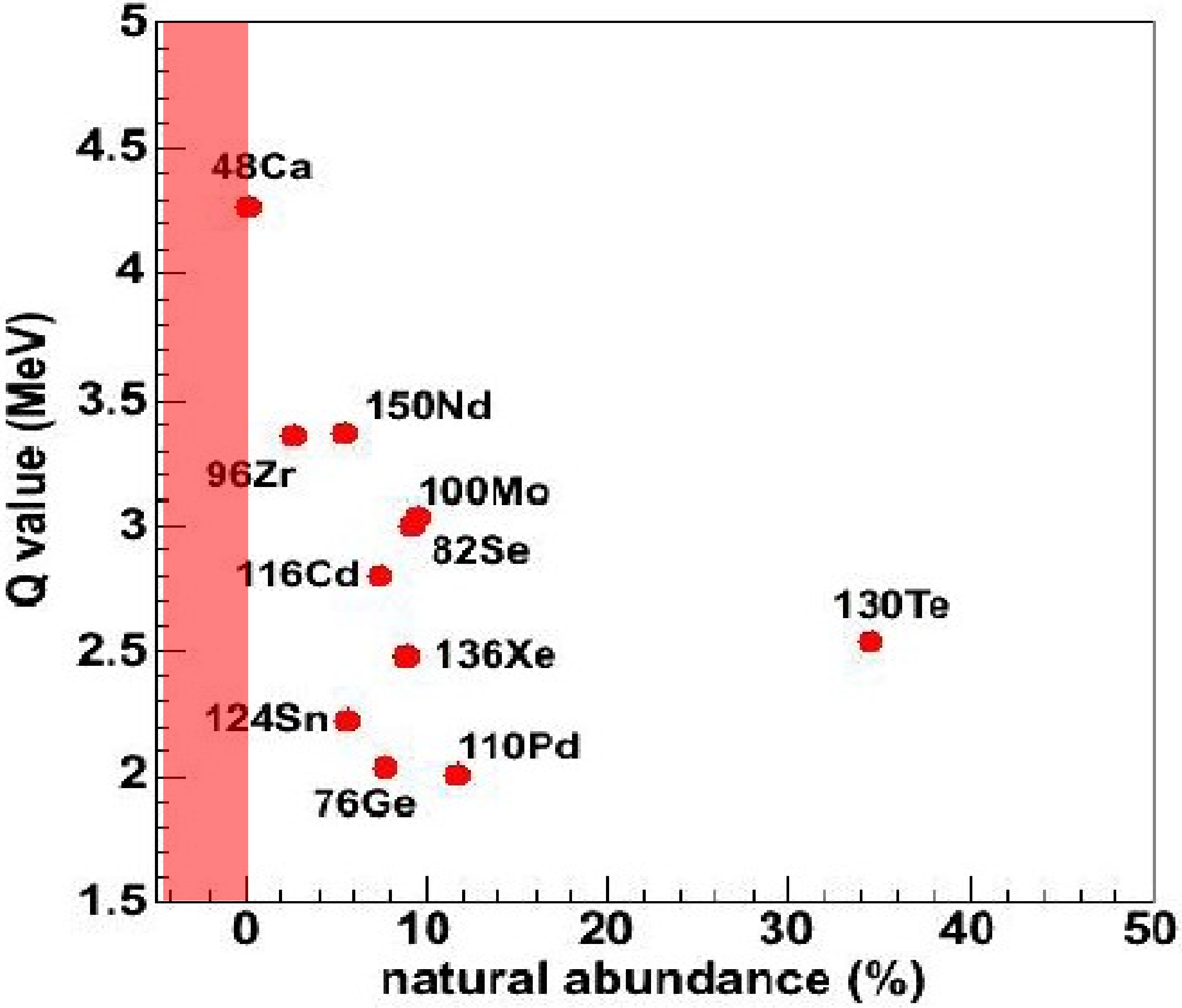
isotope	Q-value [MeV]	natural abundance	
^{48}Ca	4.27	0.19%	
^{150}Nd	3.37	5.6%	CANDLES, AMORE
^{96}Zr	3.35	2.8%	~~SNO+~~, DCBA
^{100}Mo	3.03	9.6%	
^{82}Se	3.00	9.2%	MOON, AMORE
^{116}Cd	2.80	7.5%	COBRA, SuperNEMO, LUCIFER
^{130}Te	2.53	34.5%	COBRA, CUORE, SNO+
^{136}Xe	2.48	8.9%	KamLAND-Zen, EXO, NEXT
^{124}Sn	2.29	5.6%	Sn-loaded scintillator
^{76}Ge	2.04	7.8%	GERDA, MAJORANA
^{110}Pd	2.01	11.8%	

35 naturally occurring double β decay isotopes – 11 are practical (rate μ Q^5!!)

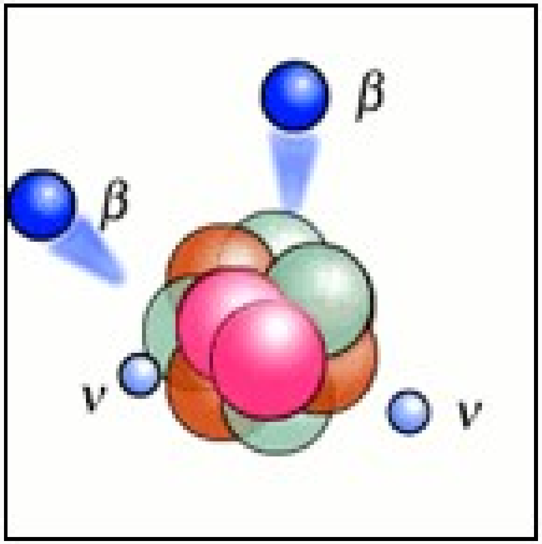
34 naturally occurring EC/EC, EC/β^+, β^+/β^+ isotopes

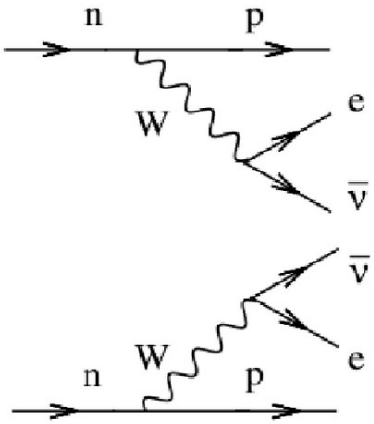
(but only six have enough energy to go $\beta^+\beta^+$)

Double-beta decay isotopes



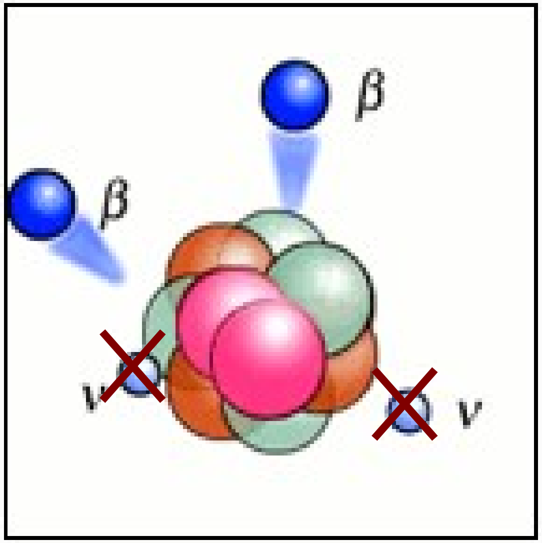
Neutrinoless...

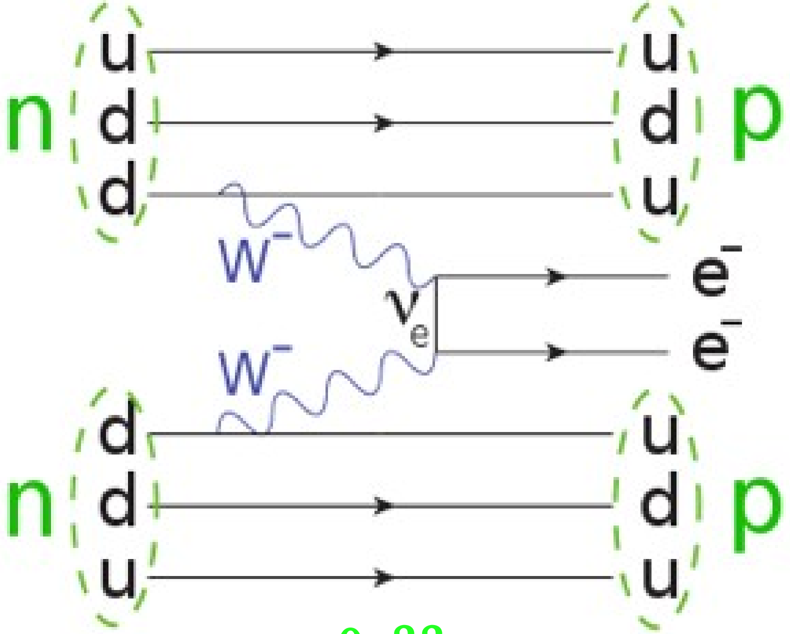




2νββ

Neutrinoless...





0νββ

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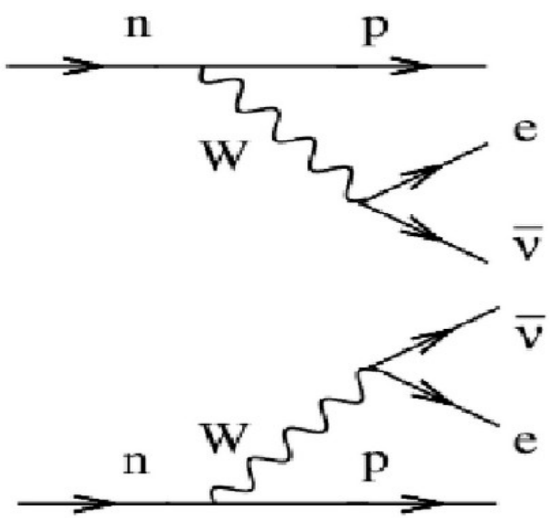

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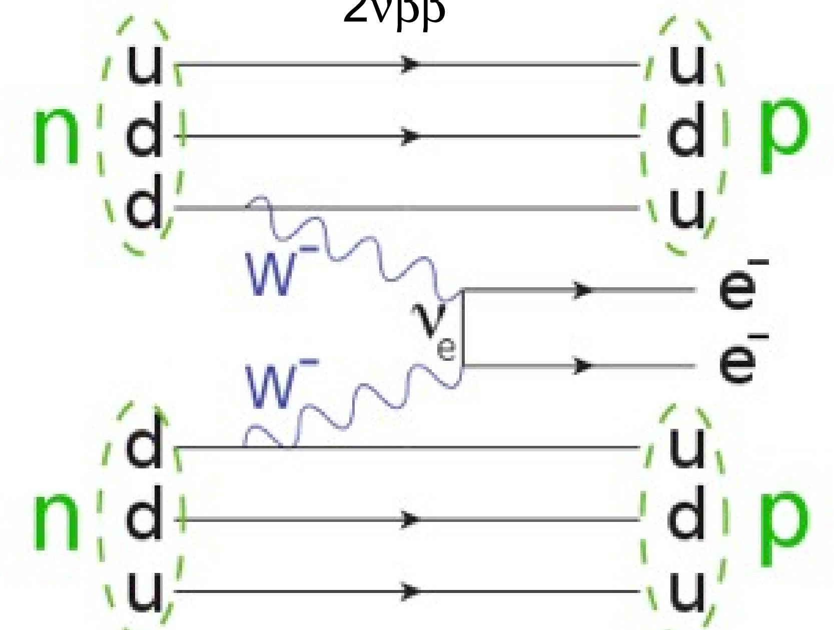
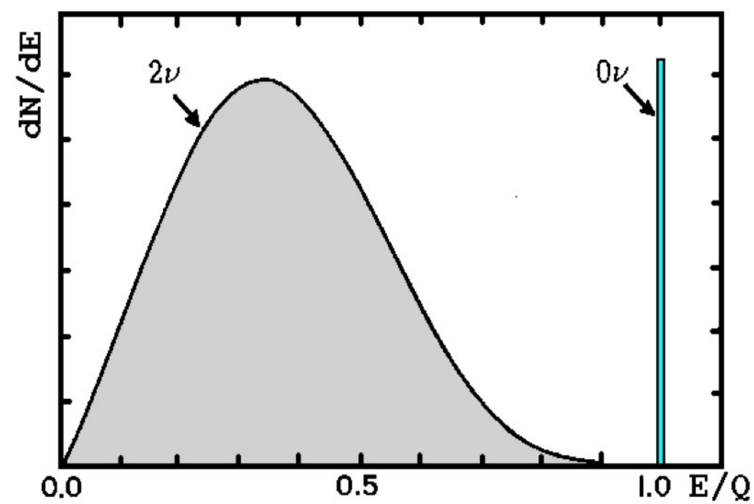


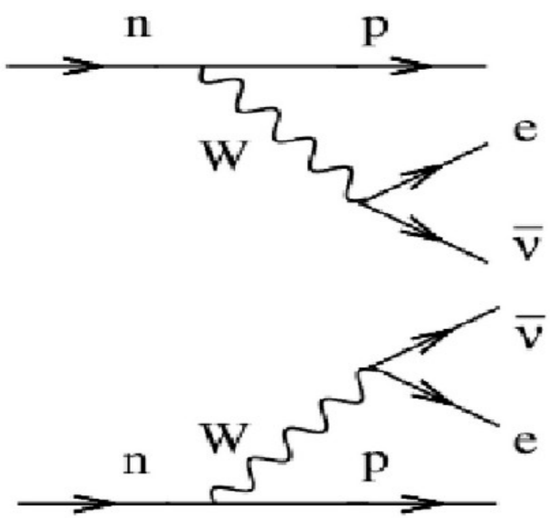
0νββ

$$Q = E_{\text{parent}} - E_{\text{progeny}} - 2m_e$$



Kinetic energy of βs

Neutrinoless...



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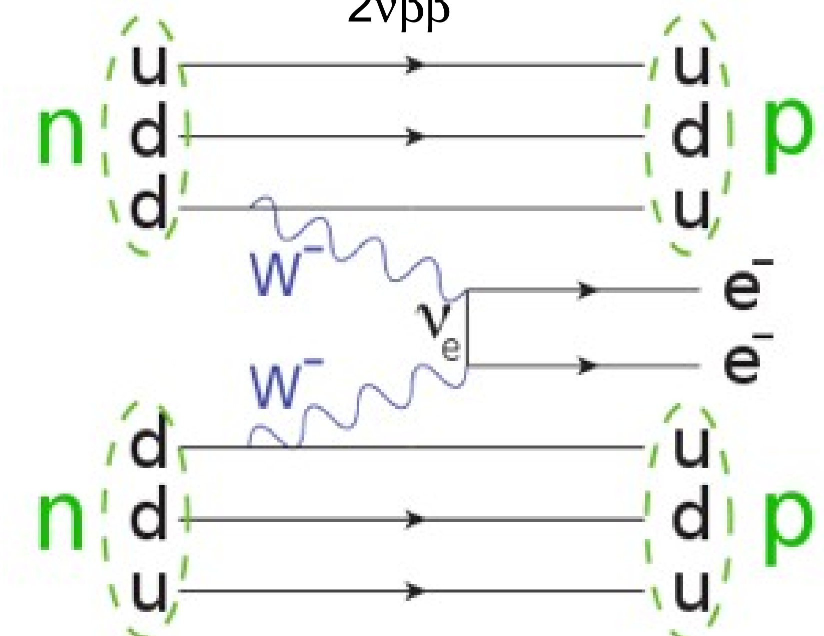

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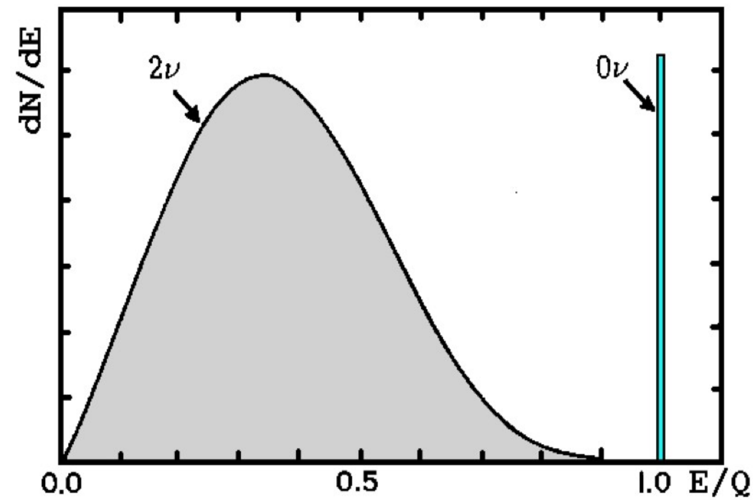

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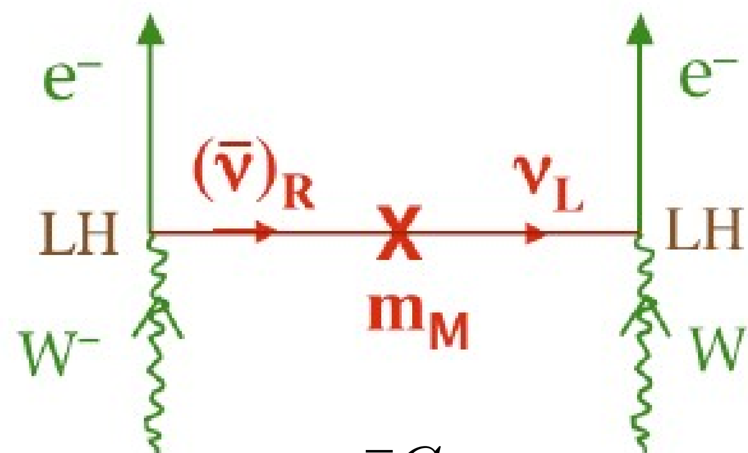

$$m\bar{\psi}_L^C \psi_L$$

Consequences of observing 0νββ

Observation of this process would imply:

- **Violation of lepton number (by 2!)**
- **Majorana nature of light neutrinos (different than quarks and leptons, Schlechter and Valle, 1982)**

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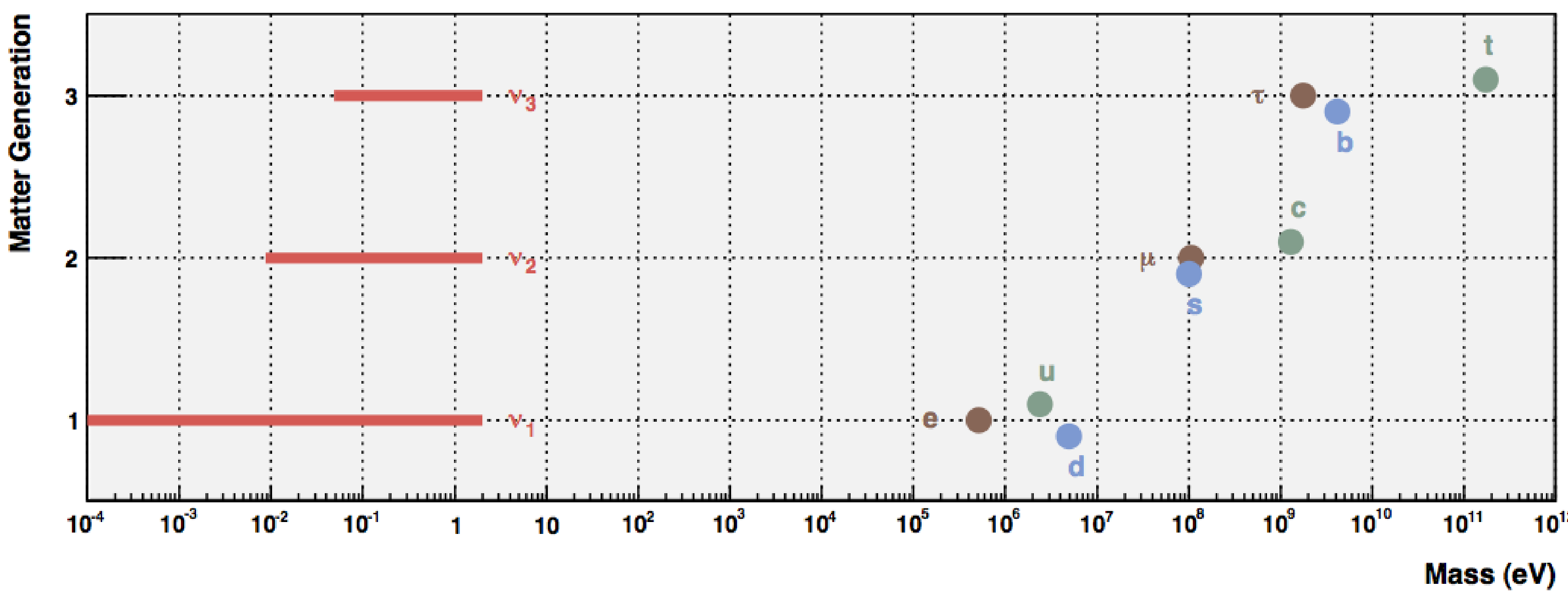
It would tell us something about:

- The seesaw model and why neutrinos are so much lighter than other particles



University of
Physics & Astronoı

See-saw model

$$\mathcal{L} = -m_D \left(\bar{N}_R \nu_L + \bar{\nu}_L N_R \right) - \frac{1}{2} m_M \bar{N}_R N_R + h.c.$$

In matrix form:

$$\mathcal{L} = \frac{1}{2} \left(\bar{\nu}_L, \bar{N}_R \right) \left(\begin{array}{cc} 0 & m_D \\ m_D^T & m_M \end{array} \right) \left(\begin{array}{c} \nu_L \\ N_R \end{array} \right) + h.c.$$

If $m_M >> m_D$, then diagonalising this matrix gives the following eigenvalues:

(Nearly) right-handed neutrino with mass $\sim m_M$

(Nearly) left-handed neutrino with mass $\sim m_D^2/m_M$

See-saw: The heavier m_M is, the lighter the left-handed neutrino is

See Fundamentals of Neutrino Physics, Guinti & Kim, Oxford University Press, 2007 (ISBN 978–0–19–850871–7)

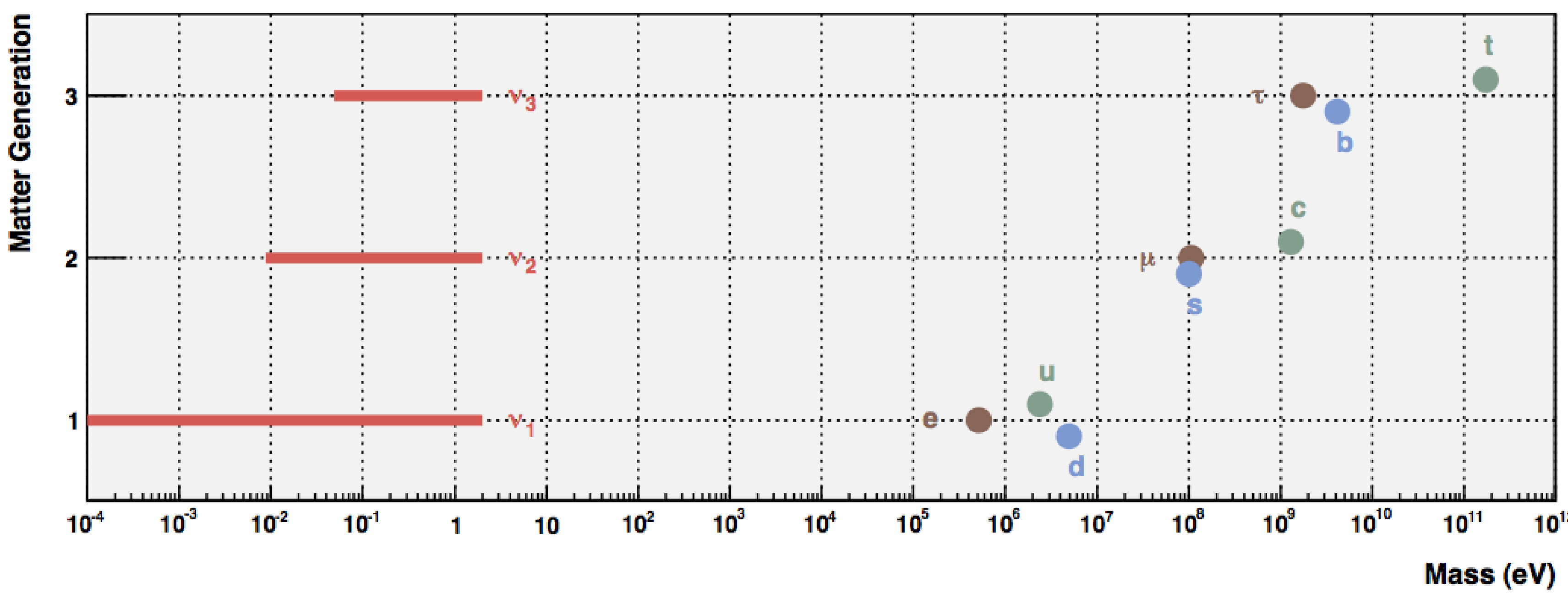
Consequences of observing 0νββ

Observation of this process would imply:

- Violation of lepton number (by 2!)
- Neutrinos have Majorana masses (different than quarks and leptons, Schlechter and Valle, 1982)
- Neutrinos are their own anti-particles

It would tell us something about:

- The seesaw model and why neutrinos are so much lighter than other particles
- Leptogenesis, a possible origin of the baryon-antibaryon assymmetry in the Universe
- Neutrino absolute mass scale
- Neutrino mass hierarchy



0νββ decay rate

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Phase factor
Matrix element
Effective neutrino mass
(more in current status)

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

Neutrino oscillation (PMNS) matrix element

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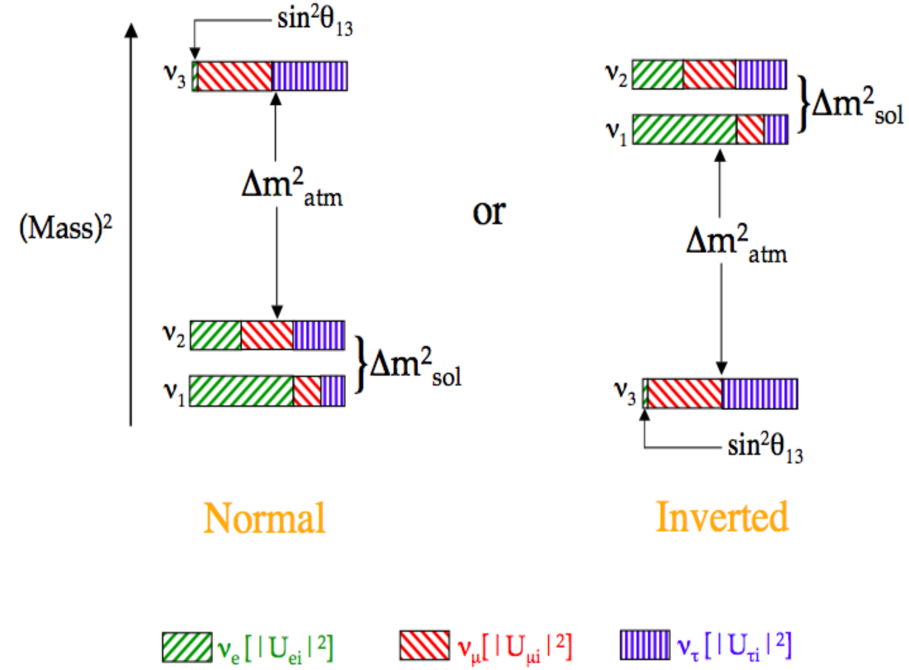

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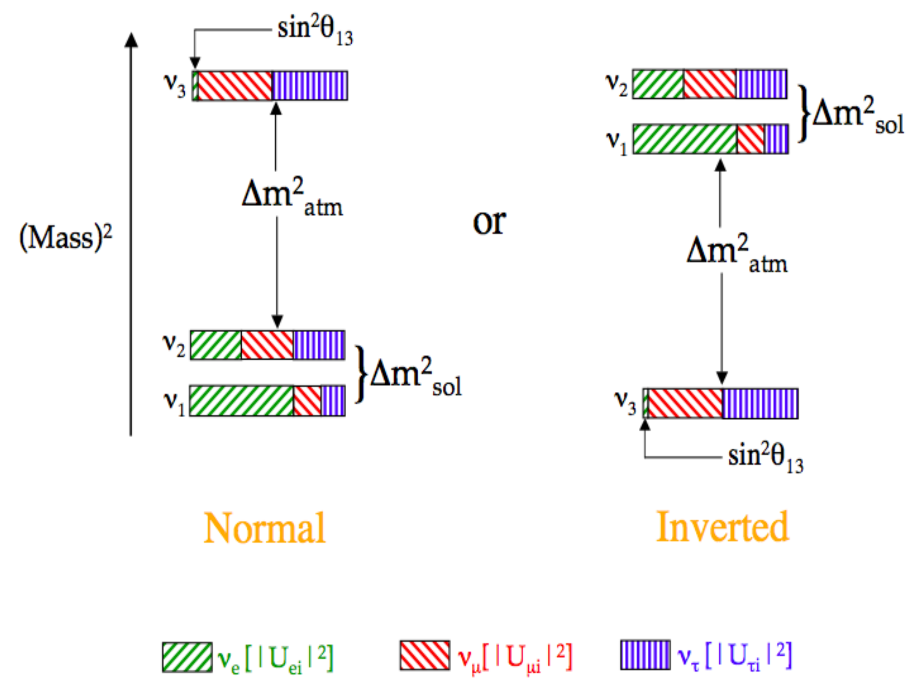

0νββ: electron neutrino component

$$m_{\beta\beta} = \cos^2\theta_{12}\cos^2\theta_{13} m_1 + \sin^2\theta_{12}\cos^2\theta_{13} e^{i\alpha_1} m_2 + \sin^2\theta_{13} e^{i\alpha_2} m_3$$

Neutrino mass

- Cosmological:
  - Planck (95% CL), assuming:
    - ΛCDM
    - 3 massive neutrinos

$$\sum_j m_j \leq 0.66 \ eV$$

  - Planck, combined with BAO (baryon acoustic oscillations)

$$\sum_j m_j \leq 0.23 \ eV$$

(note: taking m_j = 0.5 eV, $m_j/m_{l,q} < 10^{-6}$)

See PDG, Review of Neutrino Mixing

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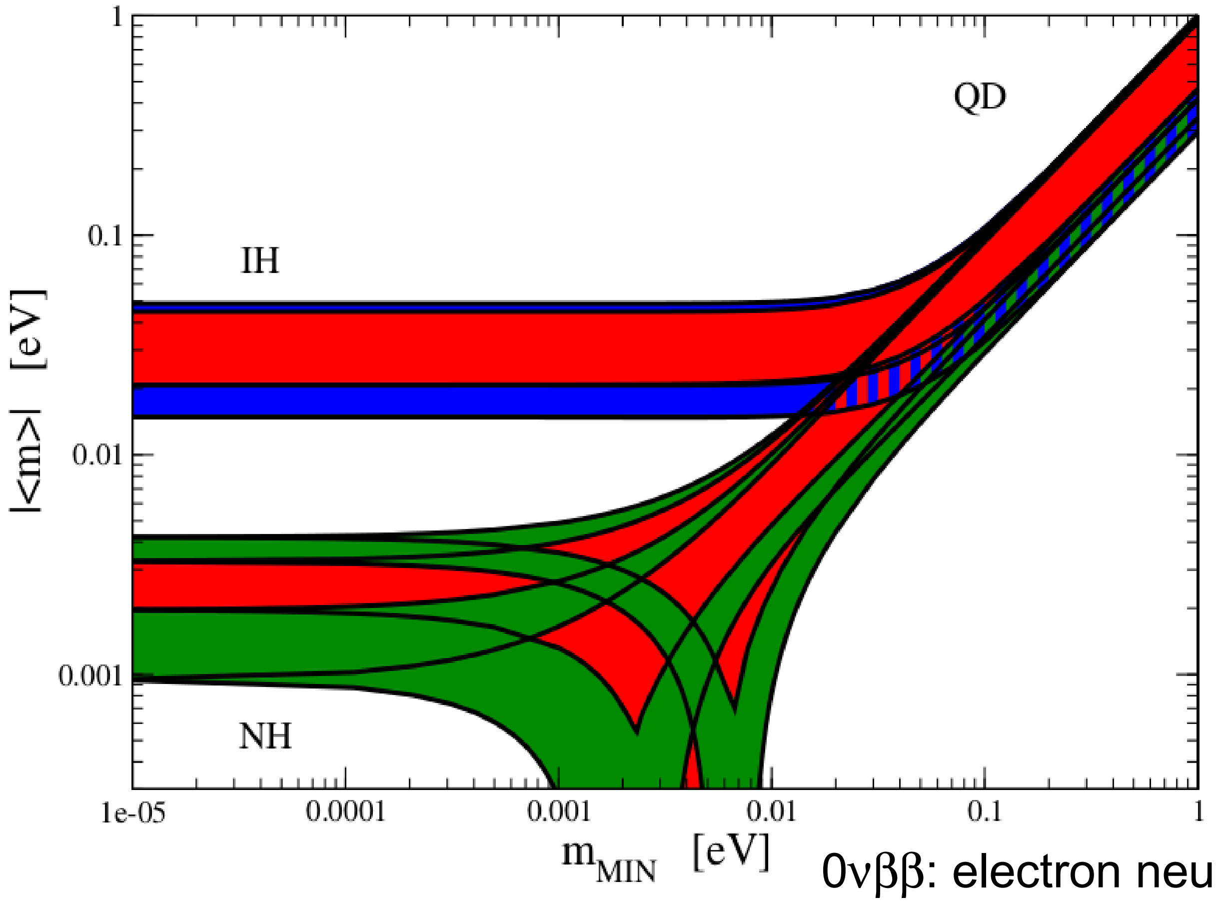
- Tritium beta decay endpoint
  - Troitzk (95% CL) $m_{\nu_e} < 2.05\ \mathrm{eV}$
  - Mainz (95% CL) $m_{\nu_e} < 2.3\ \mathrm{eV}$
  - KATRIN expected $m_{\nu_e} < 0.2\ \mathrm{eV}$

See PDG, Review of Neutrino Mixing

Neutrino mass and 0νββ



From PDG, updated from Phys Rev D 77 113003

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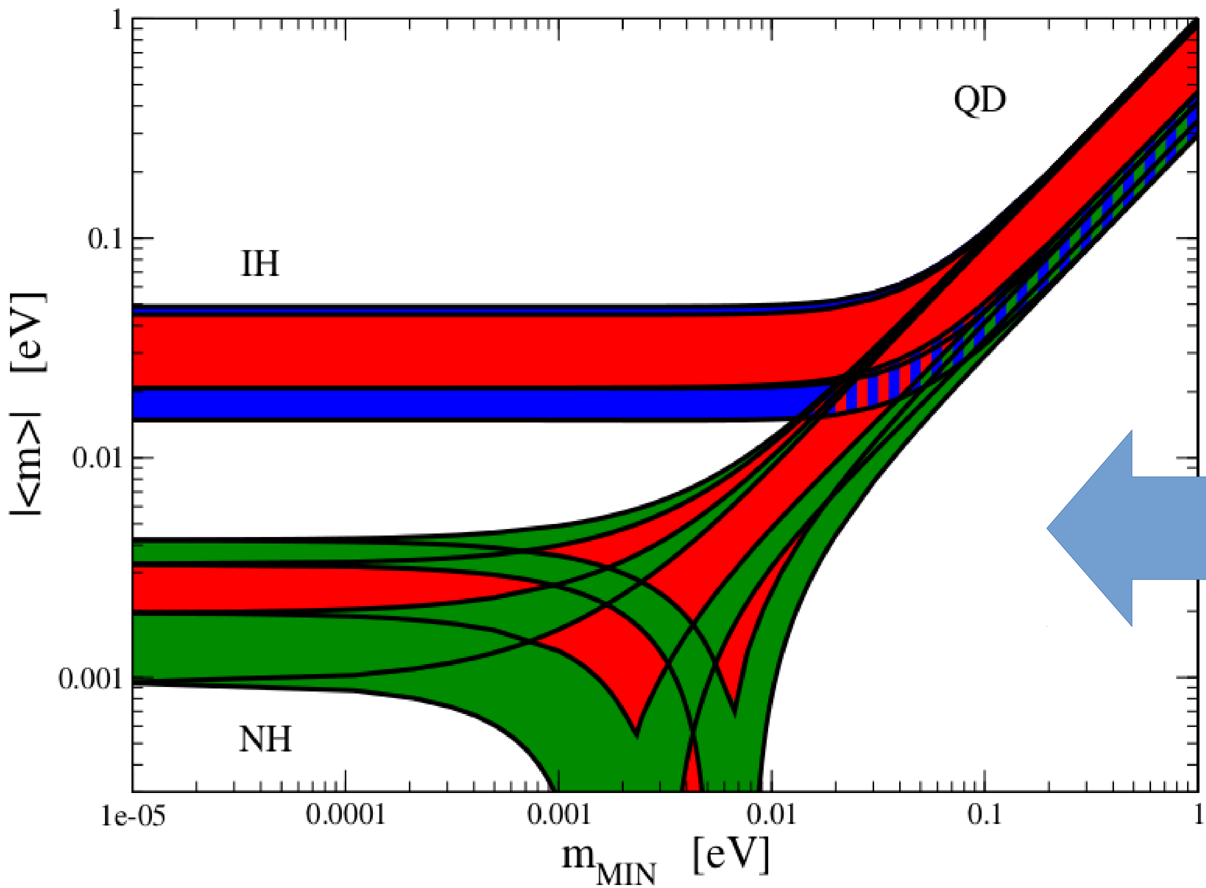

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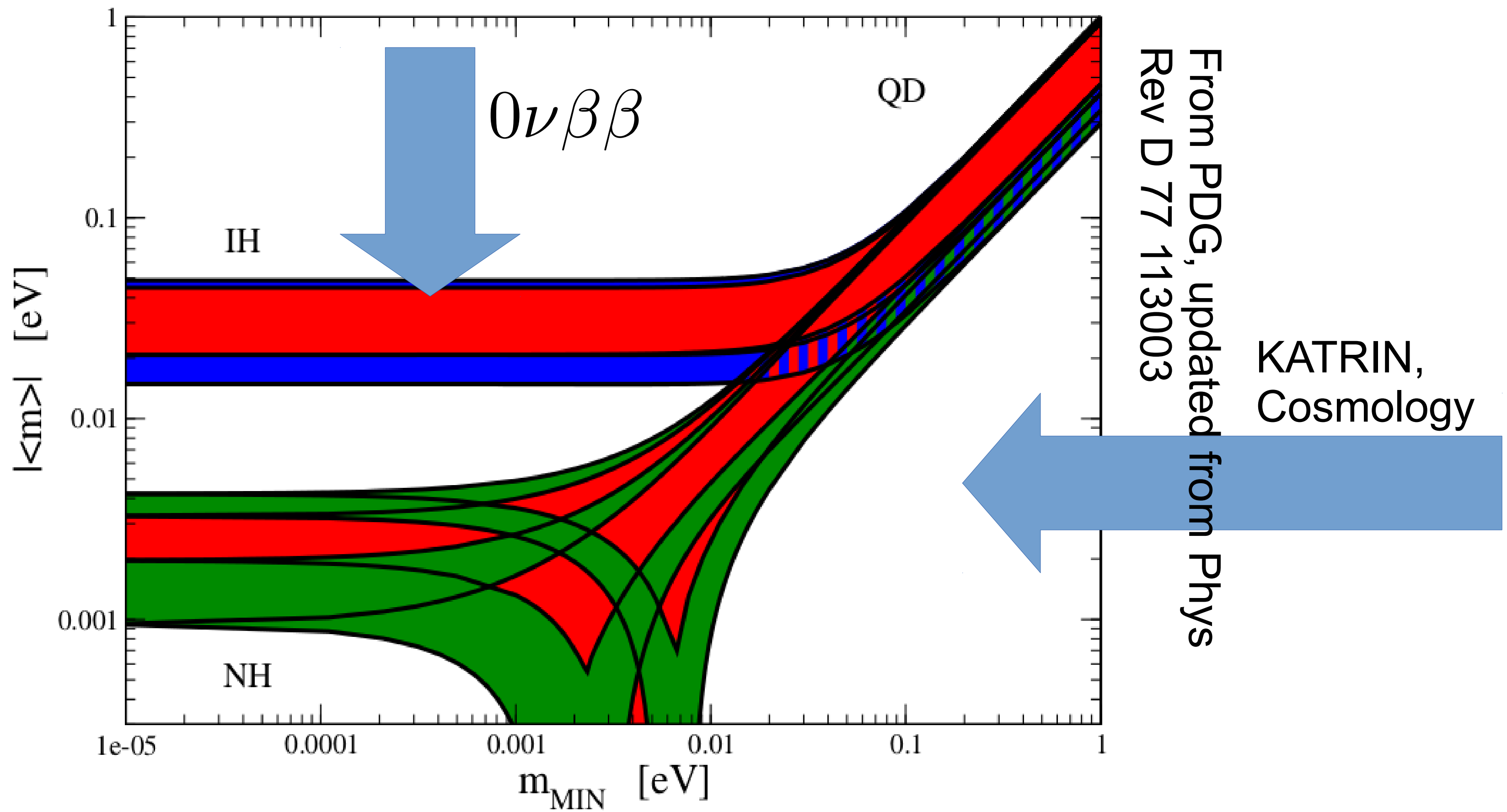
KATRIN, Cosmology

Neutrino mass and 0νββ



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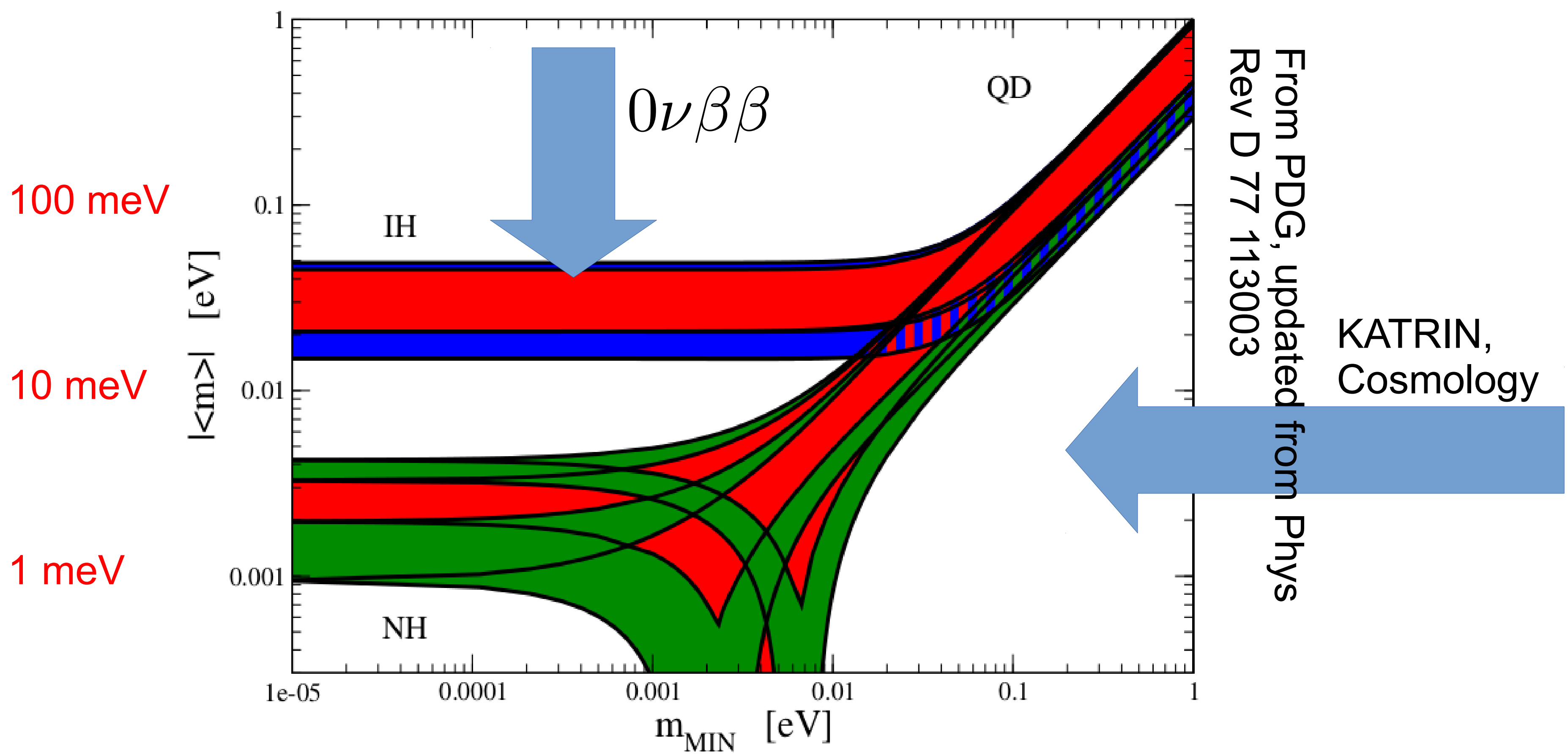
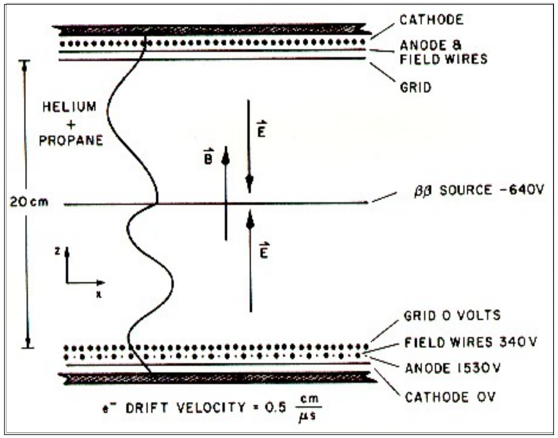


$$\langle m_{\beta\beta}\rangle^{\mathrm{IH}}_{\mathrm{min}} = \left(1-|U_{e3}|^2\right)\sqrt{|\Delta m^2_{\mathrm{atm}}|}\left(1-2\sin^2\theta_{12}\right)$$

The solar mixing angle presents the largest uncertainty (factor 2), equal to the matrix element uncertainties (arXiv:1011.4942)
(RENO50 and JUNO could really improve this)

Elliott, Hahn & Moe
1988
(^{82}Se)



Experimental aspects

Experimental uncertainties

- We measure an inverse half-life by observing a nr of decays:

$$T_{1/2}^{-1} = \frac{\lambda}{\ln 2} \propto \Delta N$$

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

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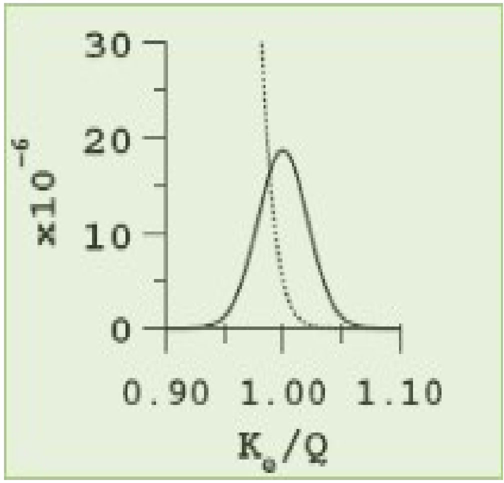
- The uncertainty on the number of decays observed can be expressed as:

$$\sigma_{\Delta \mathrm{N}} = \frac{S}{\sqrt{B}} \propto \frac{aMT}{\sqrt{B\Delta E}} = \frac{aMT}{\sqrt{MT\Delta E}} = a\sqrt{\frac{MT}{\Delta E}}$$



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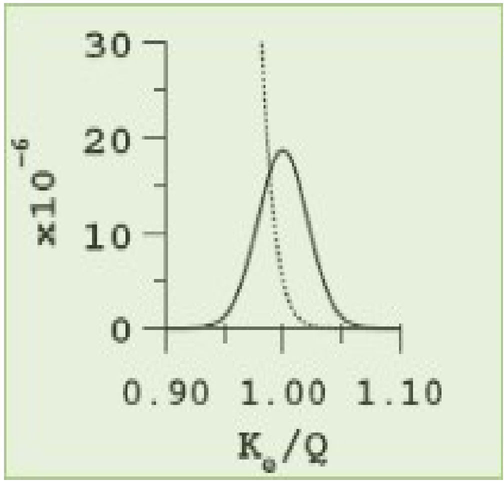

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- With the relation to $m_{\beta\beta}$ this gives:

$$\sigma_{m_{\beta\beta}} \propto \sqrt{a}\left(\frac{MT}{\Delta E}\right)^{1/4}$$

NOTE: this assumes that the backgrounds scale with mass

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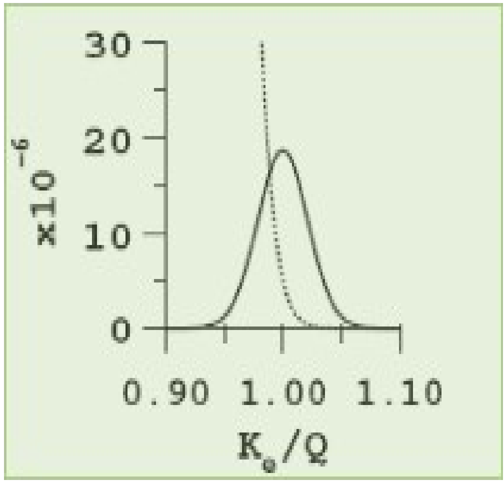

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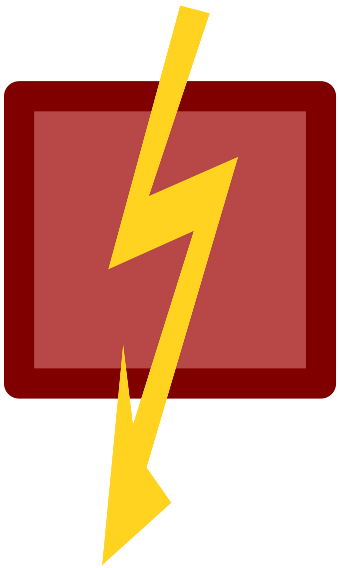
NOTE: that this assumes that the backgrounds DO NOT scale with mass

Backgrounds



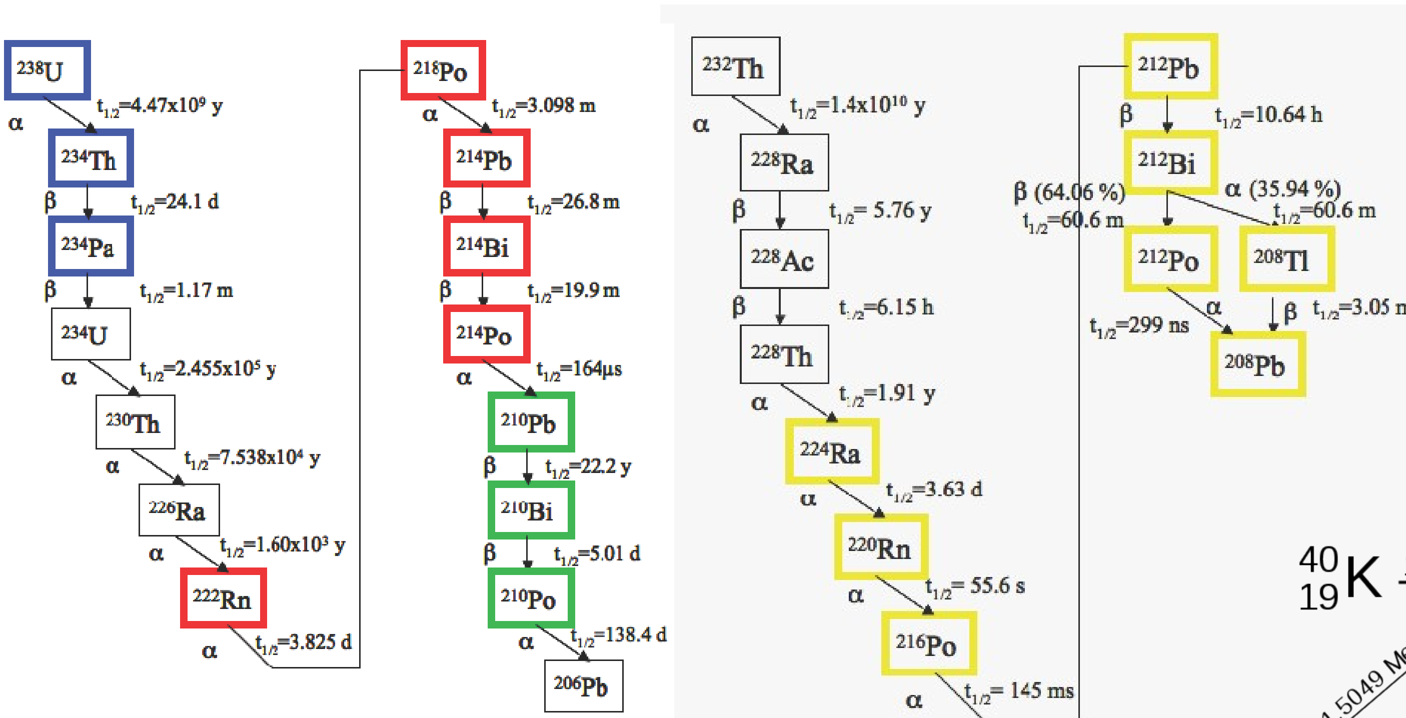
- Internal
  - Clean detector: target and components

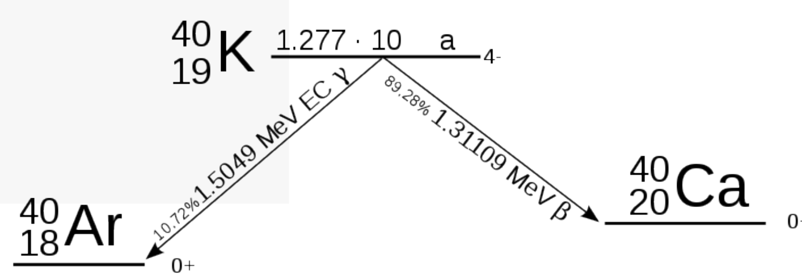
    Bulk material is relatively easier,

    surfaces (and contacts) are problematic
- Cosmogenic activation
  - Bulk material needs to be kept underground: no transport by air, go deep quickly and cool down
- External
  - Use shielding and active veto
  - Go deep (neutrons can still activate)

Internal/external backgrounds

Common radioactive backgrounds in materials





Colours indicate equilibrium that are (generally) assumed

For example, a banana:

0.5 g of ^{40}K, 15 Bq!
(http://anti-proton.com/?p=606)

Cosmogenic activation

- On surface:
  hardronix flux of neutrons (95%), protons (3%) and pions (2%)
- Underground:

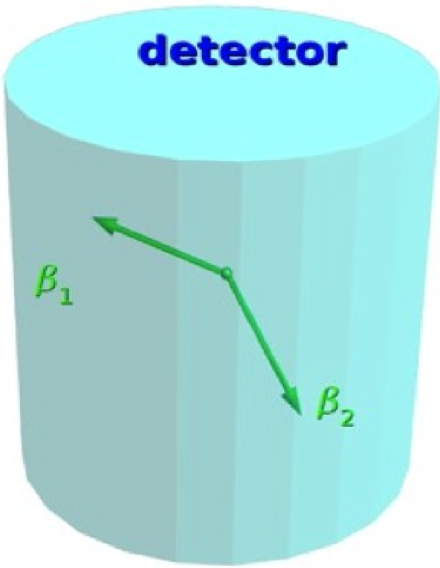
  neutrons: neutrons from (α,n), muon spallation and thermal neutrons from the rock
- Fluxes and cross sections from standard tables, but large uncertainties
- DON'T transport materials via air
  (shipping over sea is slower, but better)
- Clean and quickly move underground
- Store as long as possible before using

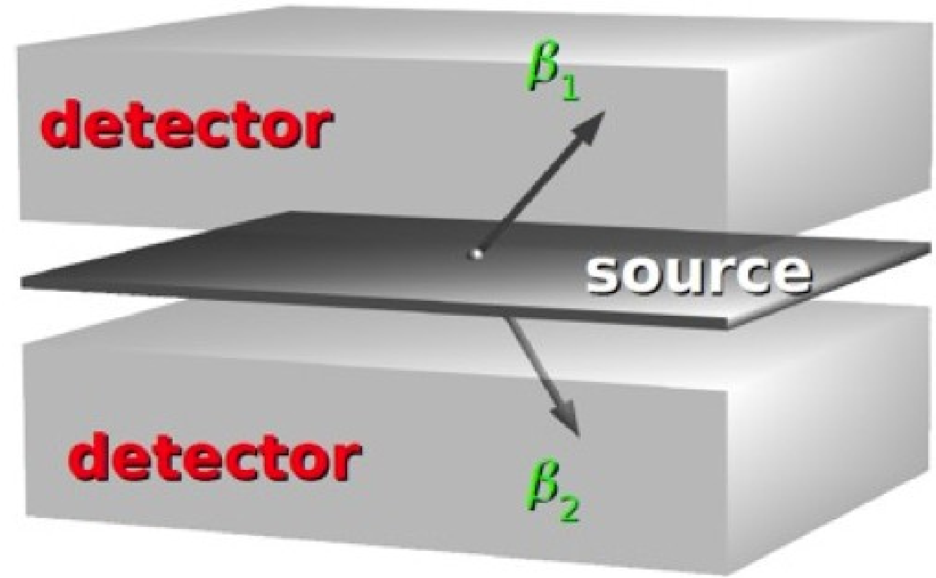
Lozza, Petzholt, Cosmogenic activation of a Tellurium target 2013(Arxiv)

Te example

Isotope	R (ϕ from [10][11]) [μBq/kg]	Events/t in 1 yr			
		t_{exp}=1 yr	PF = 10^{-4}+5h	t_{cool}=6 months	t_{cool}=2 yrs
^{22}Na	1.01	6.54E+3	4.90	4.29	3.84E+3
^{26}Al	0.67	0.02	1.37E-5	1.37E-5	0.02
^{42}K	1.33 (0.24)	85.11+156.25	20.87+0.11	0.10	149.806
^{44}Sc	1.19 (0.052)	24.54+19.02	14.29+0.01	0.01	18.58
^{46}Sc	1.97	1.86E+4	35.56	7.85	44.21
^{56}Co	0.13	1.12E+3	2.29	0.45	1.60
^{58}Co	1.29	1.08E+4	23.62	3.96	8.51
^{60}Co	0.81 (0.367)	2.95E+3	2.09	1.96	2.27E+3
^{68}Ga	3.14 (1.28)	21.17+1.59E+4	17.55+15.58	9.77	2.46E+3
^{82}Rb	(2.44)	7.71E+3	44.58	0.30	1.63E-5
^{84}Rb	1.29	5.06E+3	22.76	0.50	1.00E-3
^{88}Y	3.14 (8.11)	1.67E+5	176.68	99.05	3.19E+3
^{90}Y	2.69 (0.165)	229.22+122.35	12.10+0.08	0.08	116.63
^{102}Rh	11.77 (0.03)	1.18E+5	128.31	89.37	1.03E+4
^{102m}Rh	11.77	5.72E+4	41.46	37.88	3.95E+4
^{106}Rh	(0.06)	655.58	0.58	0.41	167.948
^{110m}Ag	2.34	2.92E+4	29.38	17.70	3.84E+3
^{110}Ag	(0.03)	393.27	0.40	0.24	51.82
^{124}Sb	182.0	1.33E+6	3.36E+3	409.77	294.741
^{126m}Sb	71.42 (7.91)	102.46	101.81	4.32E-4	0.64
^{126}Sb	89.65 (^{126m}Sb)	1.53E+5	1.80E+3	0.06	0.10

Design





Calorimeter design
(source = detector)

- Seminconductors
- Bolometers
- Scintillators

Tracker design
(source ≠ detector)

- Tracker
- TPC

Current status

Current status

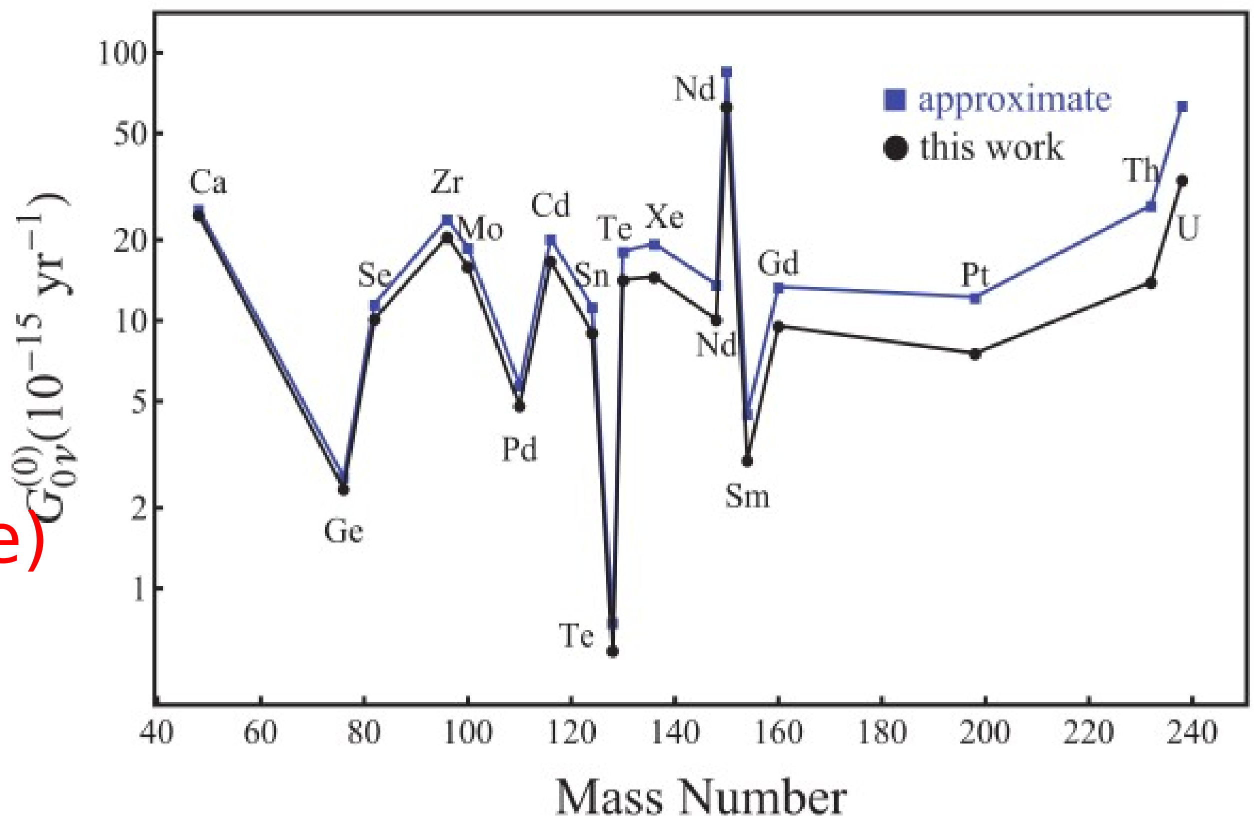
Phase space factor

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

- Calculable
- Thought to be exact ....
  ...but it wasn't
  (now probably is sufficiently accurate)

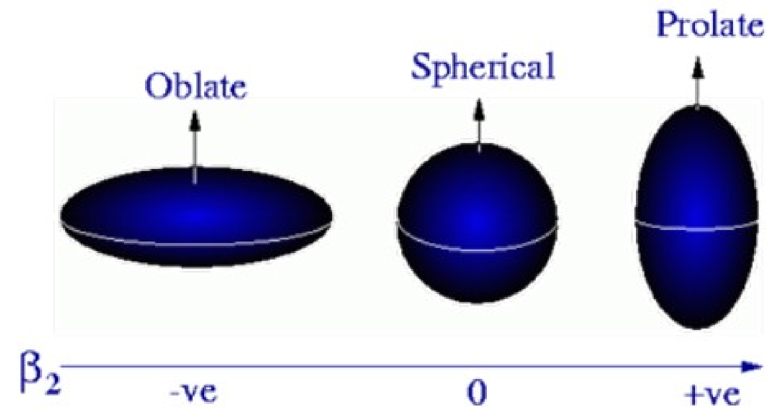
(Improvements:
Exact Dirac wavefunctions and electron screening)

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)

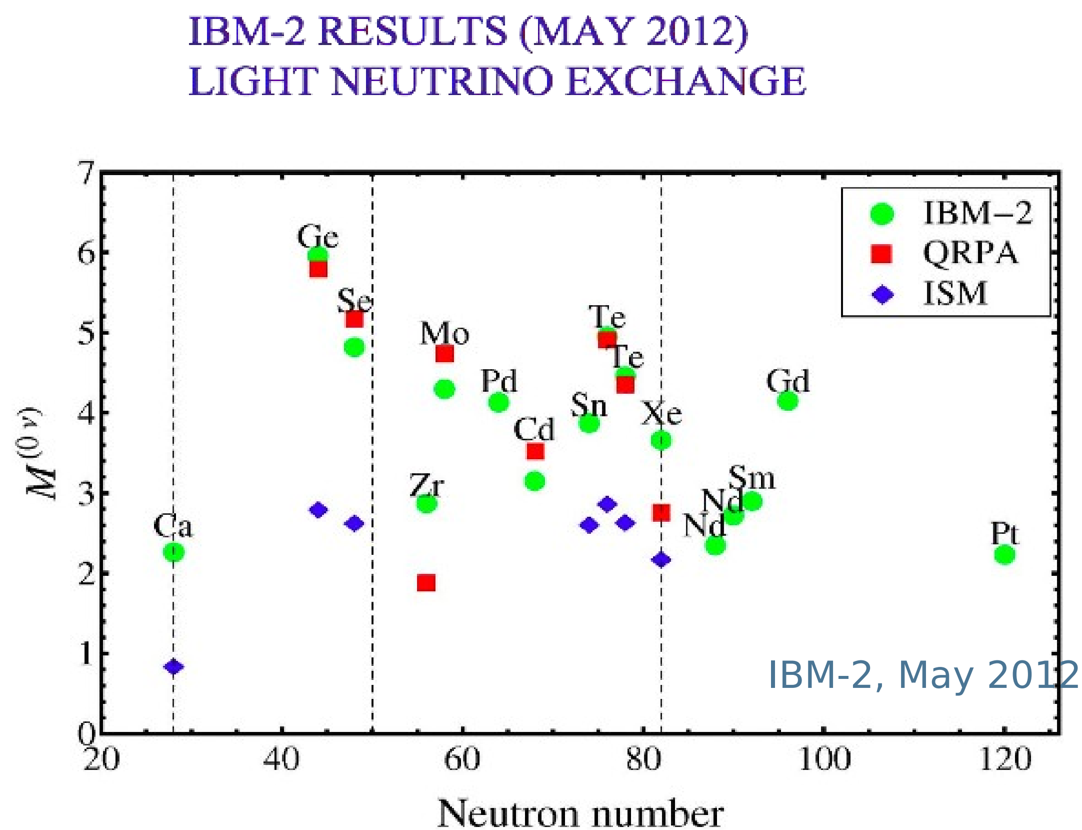


Matrix element

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



- Very difficult to calculate
- Not exact, factor of two uncertainties

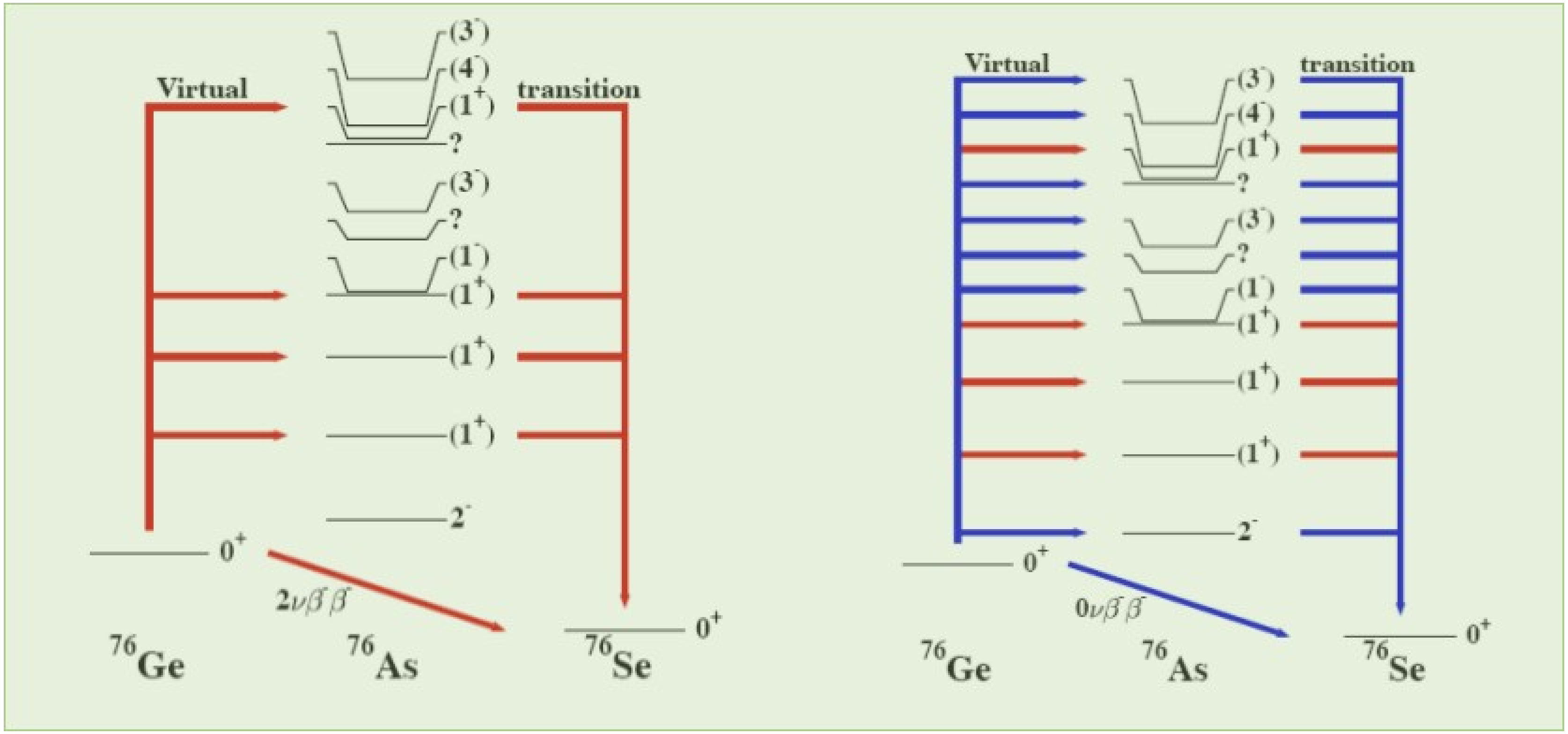


Barea, J., et al. Phys. Rev. Lett. 109, 042501 (2012)

Improving matrix elements

2νββ only via 1^+ states, 0νββ via all virtual states:

straight comparison is not valid



Measure states via exchange reactions

Combining it all

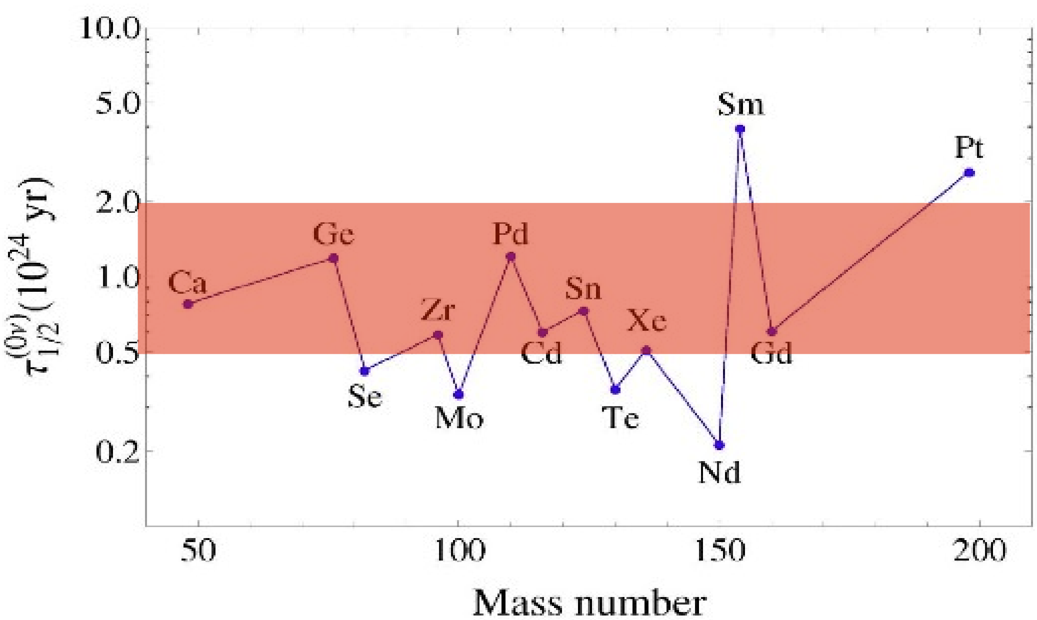
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$$\langle m_{\beta\beta}\rangle = 1 \text{ eV}$$

Factor of 2 difference with similar uncertainties

....

Combining NME with PSF we obtain the expected half-lives



Expected half-lives for light neutrino exchange with $<m_\nu>=1$eV, $g_A=1.269$.
^{128}Te and ^{148}Nd not included in this figure. For other values, scale with $<m_\nu>^2$ and $g_A{}^4$.

By comparing the calculated half-lives with experimental limits we obtain the corresponding limits for masses.

F. Iachello, NOW2012

Combining it all

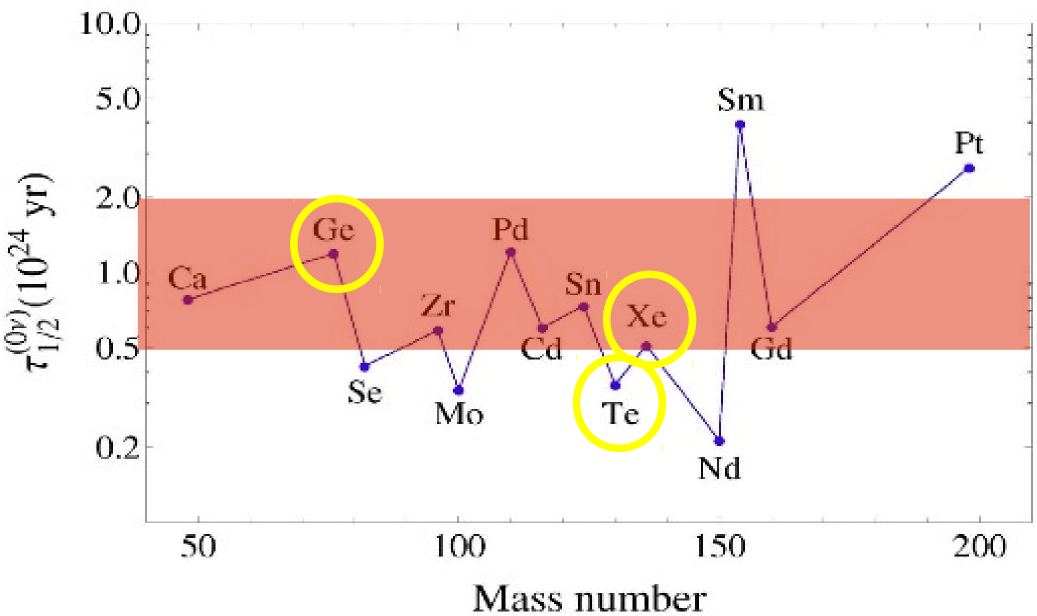
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$$\langle m_{\beta\beta}\rangle = 1 \text{ eV}$$

Factor of 2 difference with similar uncertainties

....

Combining NME with PSF we obtain the expected half-lives

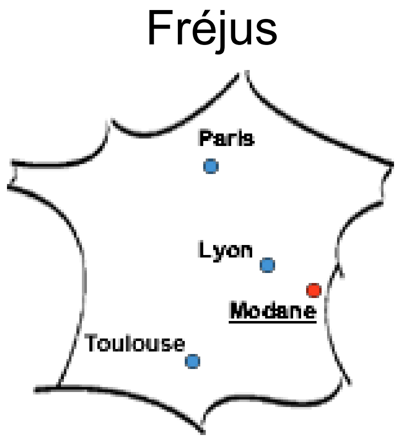


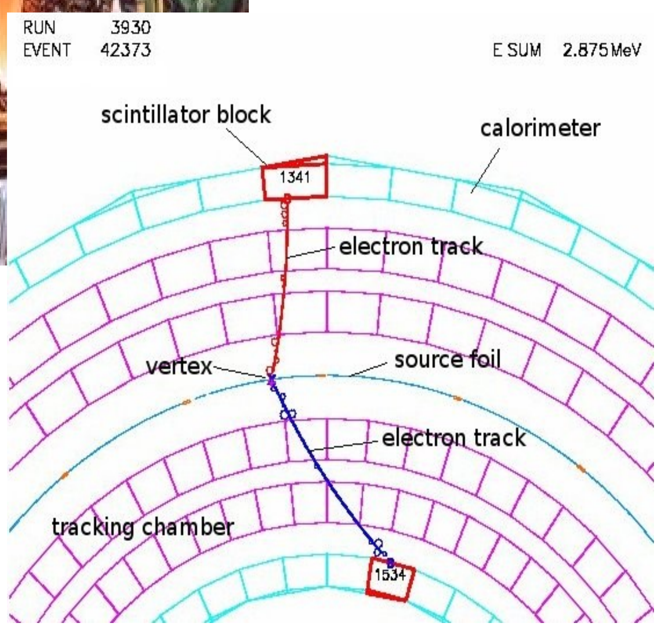
Expected half-lives for light neutrino exchange with $<m_\nu>=1$eV, $g_A=1.269$.
^{128}Te and ^{148}Nd not included in this figure. For other values, scale with $<m_\nu>^2$ and $g_A{}^4$.

By comparing the calculated half-lives with experimental limits we obtain the corresponding limits for masses.

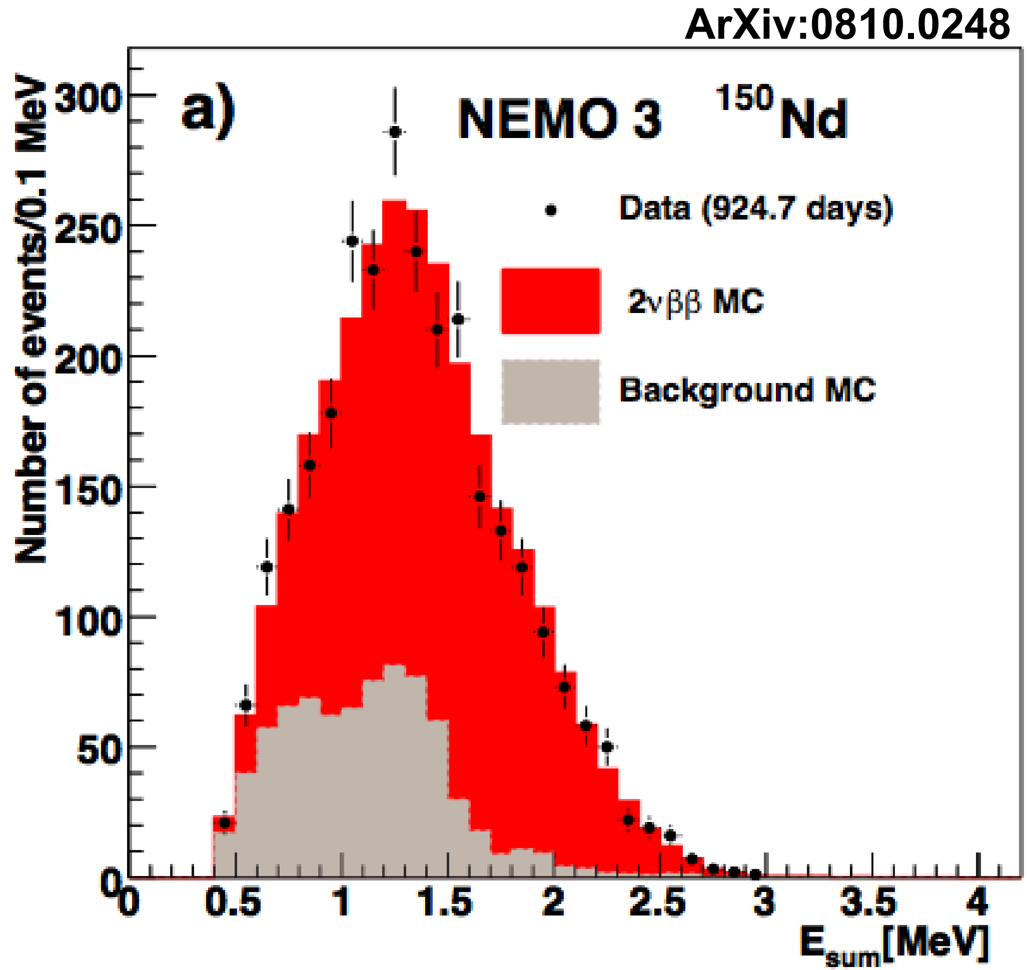
F. Iachello, NOW2012

NEMO-3





^{100}Mo 2νββ candidate



$$T_{1/2}^{2\nu} = (9.11^{+0.25}_{-0.22}(\text{stat.}) \pm 0.63\ (\text{syst.})) \times 10^{18}\ \text{y}$$

Also measured half-lifes for: ^{100}Mo, ^{82}Se, ^{48}Ca, ^{96}Zr, ^{116}Cd, ^{130}Te

^{76}Ge: K^2 *et. al.*: 0νββ found? (No)

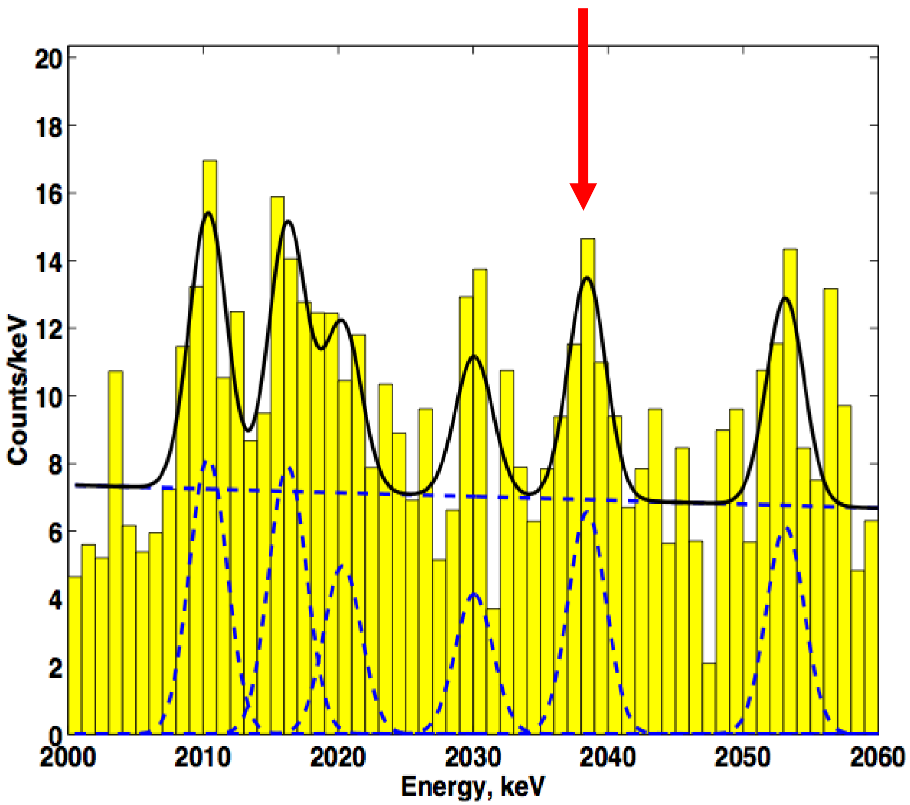
5 isotopically enriched ^{76}Ge detectors, Nov 1995 – May 2000

Published by only a part of the Heidelberg-Moscow collaboration,
H.V. Klapdor-Kleingrothaus et al.,
Phys. Lett. B 586, 198 (2004), Mod.Phys.Lett.A21:1547-1566,2006

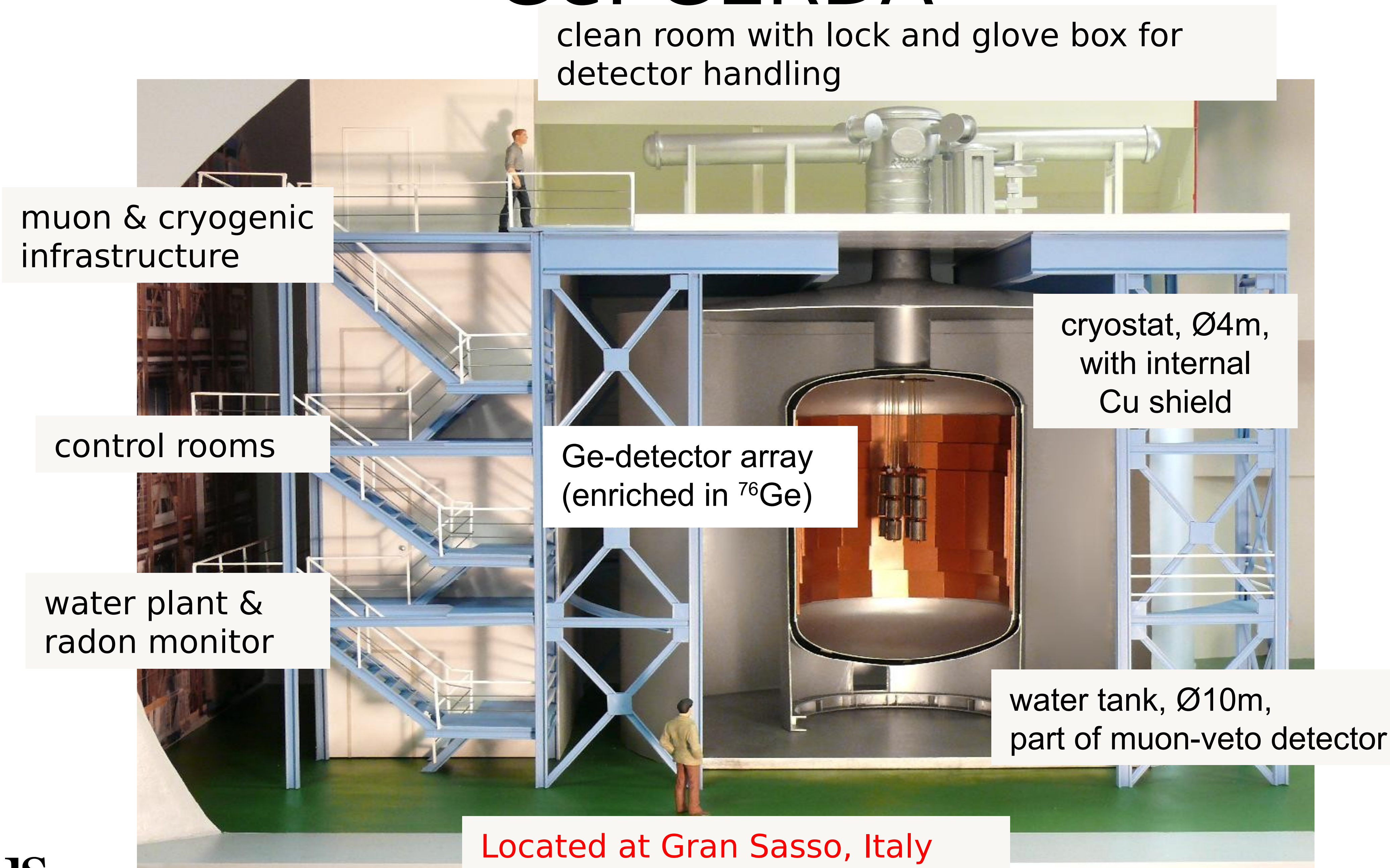
$$T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}\ \mathrm{y}$$

$m_{\beta\beta}$ = 200 – 600 meV

- Inclusion of unidentified (non-existing?) peaks increases the significance
- In tension with astrophysical bounds on the neutrino mass
- Excluded by follow up experiment GERDA



^{76}Ge: GERDA


clean room with lock and glove box for detector handling
muon & cryogenic infrastructure
cryostat, Ø4m, with internal Cu shield
control rooms
Ge-detector array (enriched in ^{76}Ge)
water plant & radon monitor
water tank, Ø10m, part of muon-veto detector
Located at Gran Sasso, Italy

GERDA: Nov 2011, start Phase I

8 refurbished enriched diodes from HdM & IGEX

- 86% isotopically enriched in ^{76}Ge
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

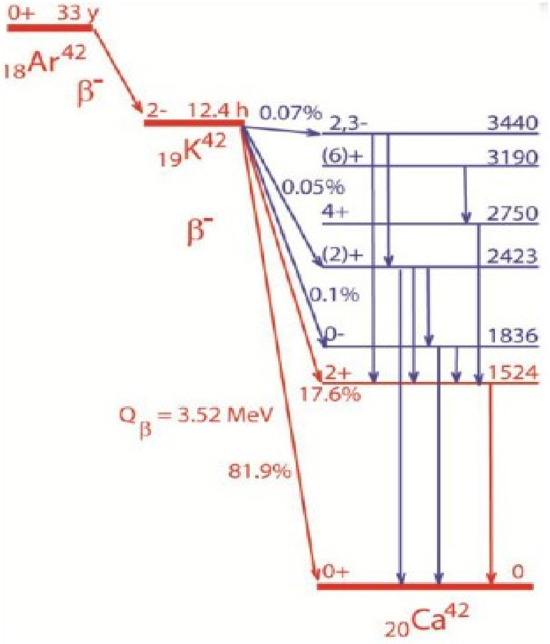
2 diodes shut off because leakage current high:

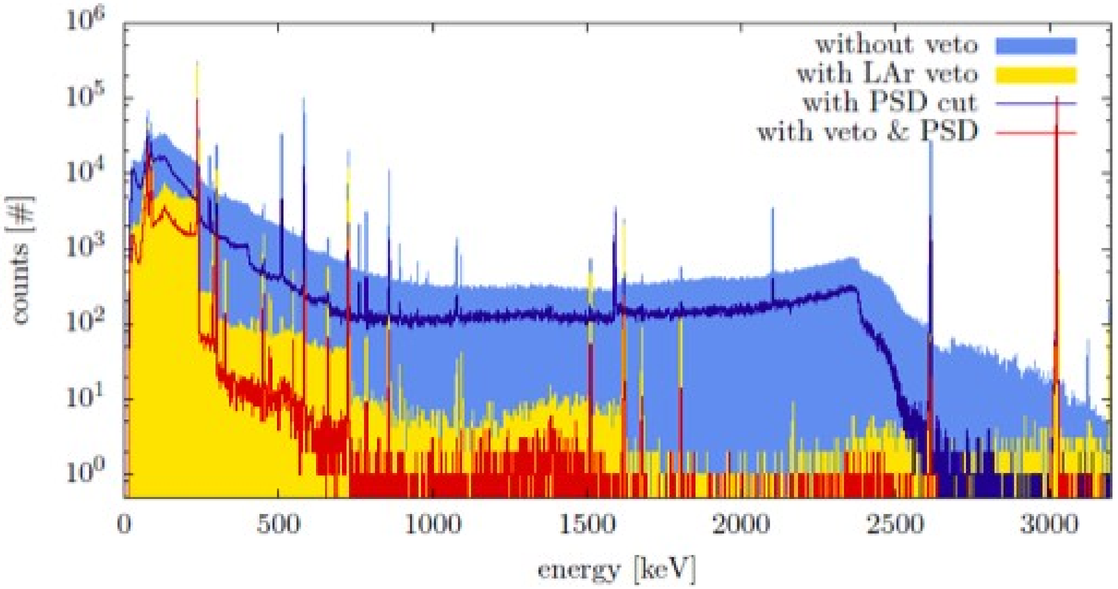
- total enriched enriched detector mass 14.6 kg

GERDA: external backgrounds

Example of problem found and solved:

Add metal shroud in Ar shield, around the detector strings, in order to to avoid drift of ions to detectors





GERDA: Nov 2011, start Phase I

8 refurbished enriched diodes from HdM & IGEX

- 86% isotopically enriched in ^{76}Ge
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

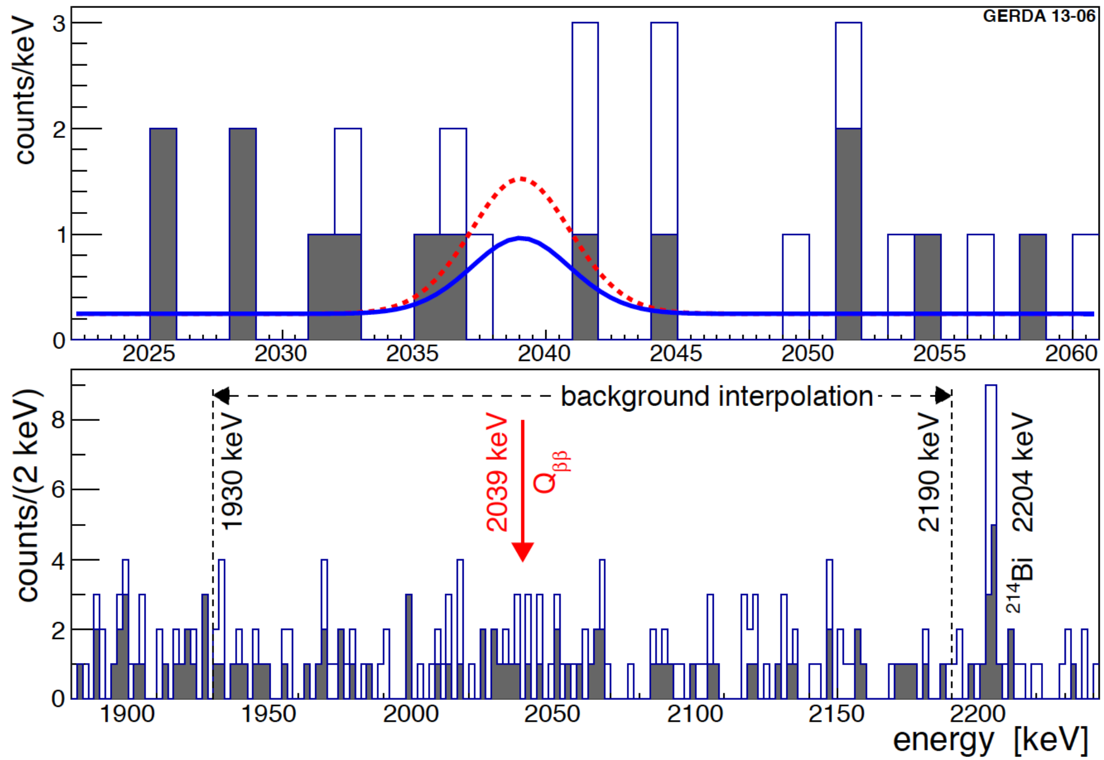
2 diodes shut off because leakage current high:

- total enriched enriched detector mass 14.6 kg

GERDA: Phase I results

Nov 2011 – May 2013: 21.6 kg yr

NO SIGNAL OBSERVED



K2 CLAIM REFUTED WITH HIGH PROBABILITY

GERDA+IGEX+HdM: $T_{1/2}^{0\nu}$ > 3.0×10^{25} yr (90% C.L.)

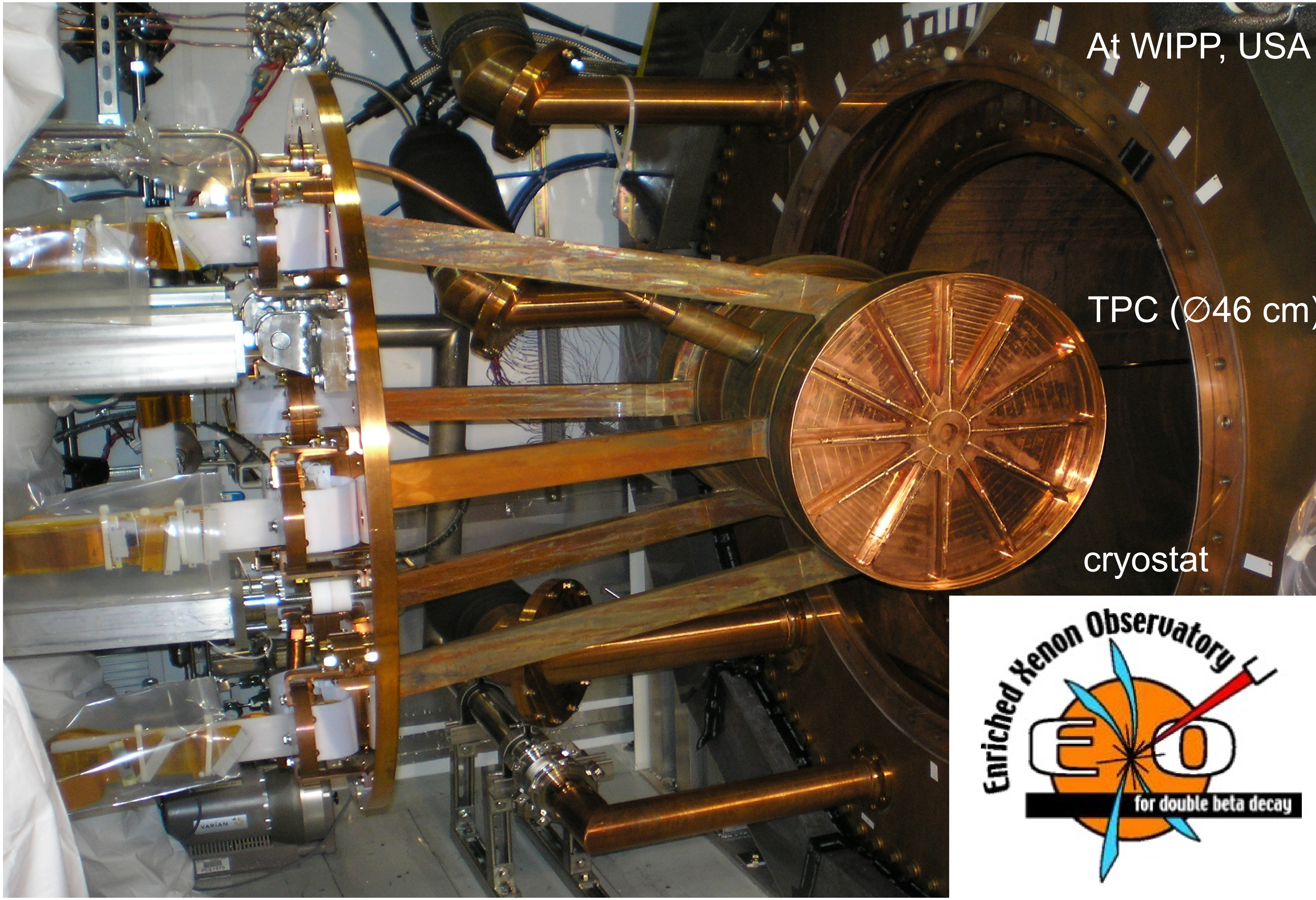
(<$m_{\beta\beta}$> < 0.2-0.4 eV)

ArXiv:1307.2610

Current status

EXO-200

175 kg enriched ^{136}Xe to 80.6% **arXiv:1108.4193**

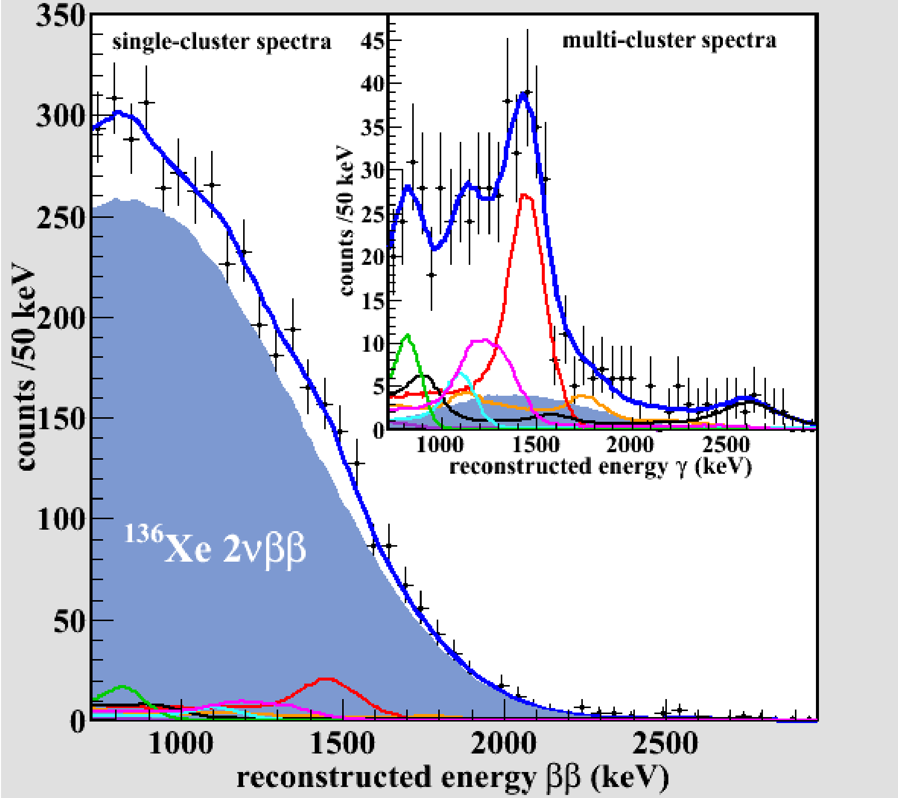


Current status

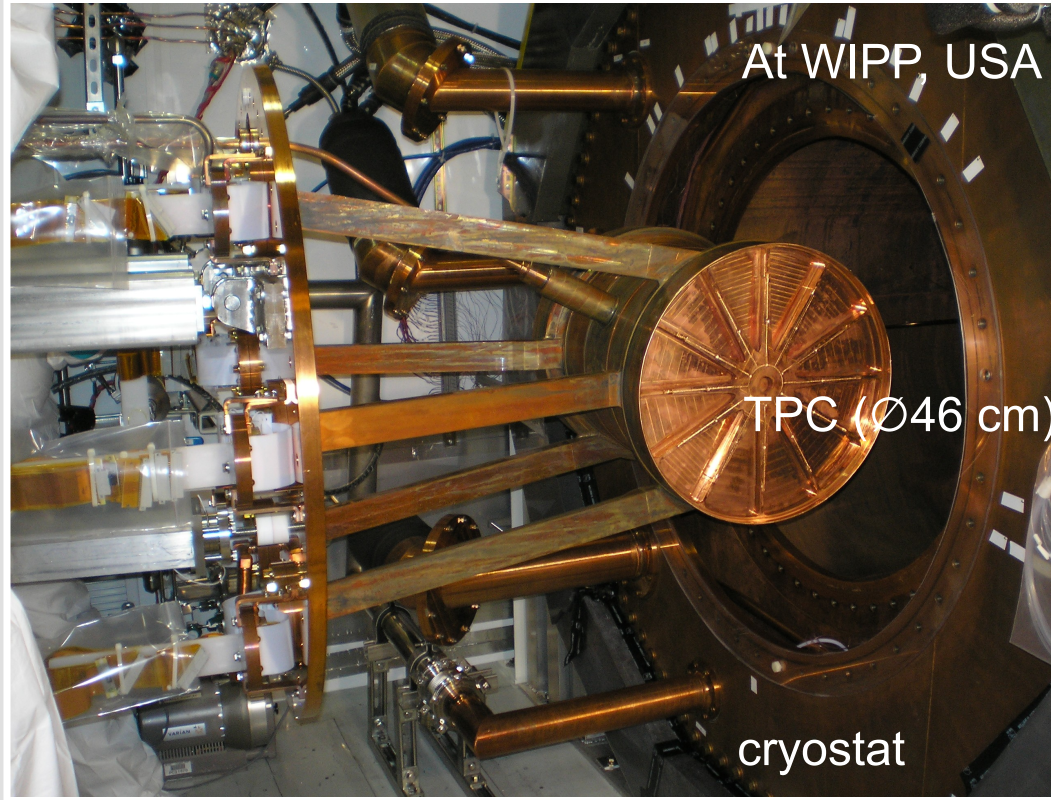
EXO-200

May – Jul 2011, 3.2 kg yr

Phys Rev Lett 107 (2011) 212501



175 kg enriched ^{136}Xe to 80.6%



$$T_{1/2}=2.11\pm0.04(\text{stat.})\pm0.21(\text{sys.})\times10^{21}\ \text{yr}$$

Previous numbers:
2.1 x 10^{22} (Th) Europhys. Lett. 13 (1990) 31
> 1.0 x 10^{22} (Exp) Phys. Let. B 546 (2002) 23–28
> 8.5 x 10^{21} (Exp) Phys. At. Nucl. 69 (12), 2129–2133 (2006)
New result confirmed by KamLAND-Zen

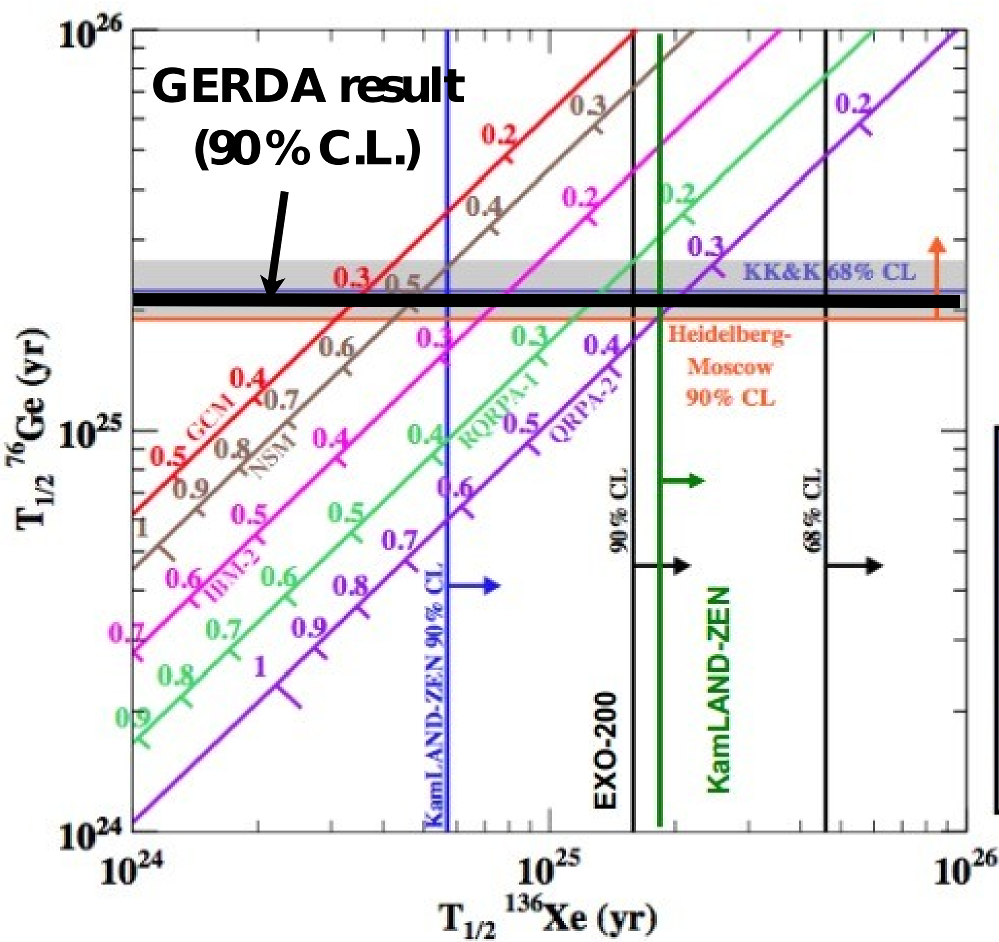
Enriched Xenon Observatory for double beta decay

Current status

EXO-200

Sep 2011– Apr 2012, 26.3 kg yr

Limits on $T_{1/2}^{0\nu\beta\beta}$ and $\langle m_{\beta\beta} \rangle$



Interpret as lepton number violating process with effective Marojana mass ⟨$m_{\beta\beta}$⟩ :

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu} \left|M_{nucl}\right|^2 \langle m_{\beta\beta} \rangle^2$$

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

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

Phys.Rev.Lett 109 (2012) 032505
(arXiv:1205.5608)

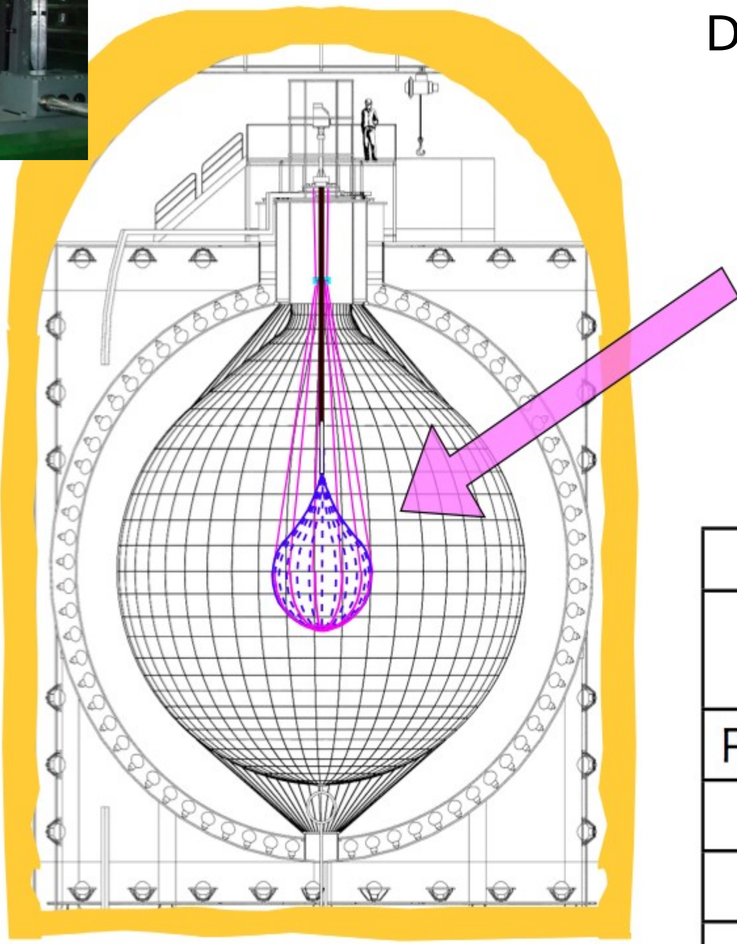
KamLAND-ZEN
Phys.Rev.Lett. 110 (2013) 062502
(arXiv:1211.3863)

More ^{136}Xe: KamLAND-Zen

Kamioka Mine, Japan

Xe system

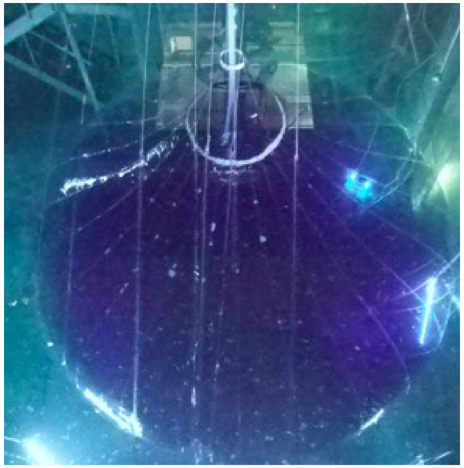
Data taking Oct 2011 – Jan 2012



Mini-balloon : 3.08m ϕ
made of thin (25 μ m) nylon film
filled with Xe-LS containing
330kg 91%-enriched ^{136}Xe.
Special nylon without filler

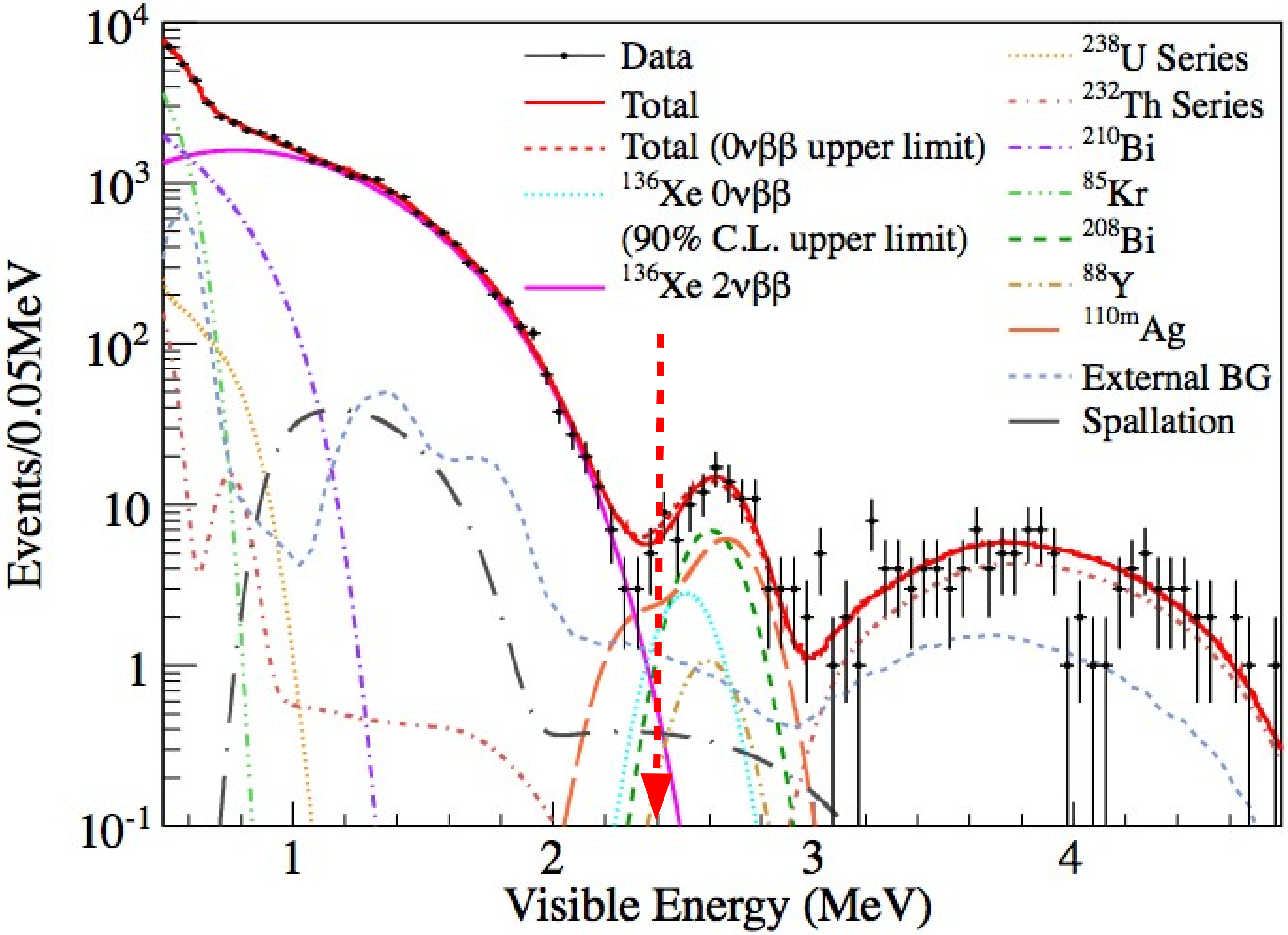
	Xe-LS	KL-LS
Primary oil	Decane 82%	Dodecane 80%
Pseudocumene	18%	20%
PPO (g/ℓ)	2.7	1.36
Rel. Density	+0.1%	1
Rel. Light Y.	-3%	1

balloon



Current status

More ^{136}Xe: KamLAND-Zen



Arxiv:1201.4664

Three candidates for the unexpected background peak:
^{110m}Ag
^{208}Bi
^{88}Y

Cosmogenics are important!

$$T^{0\nu}_{1/2} > 5.7 \times 10^{24} \text{ yr (90\%CL)}$$

$$T^{2\nu}_{1/2} = 2.38 \pm 0.02 \text{ (stat)} \pm 0.14 \text{ (sys)} \times 10^{21} \text{ yr}$$

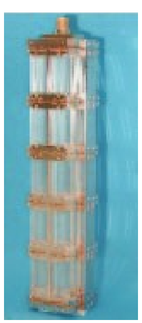
$$\langle m_{\beta\beta} \rangle \leq 160 - 330 \text{ meV}$$

Current efforts:
Filtration, thinner, cleaner balloon
Future plans for 1000 kg experiment

0νββ research with TeO_2

- ^{130}Te is a good DBD candidate ($^{130}Te \rightarrow {}^{130}Xe + 2e^-$) with high natural i.a. (34.2 %) and reasonably high Q-value (Q~2528 keV) leading to high G(Q,Z) and low background
- TeO_2 is a compound with good mechanical and thermal properties containing ^{130}Te
- 5x5x5 cm^3 TeO_2 crystals have a high detection efficiency for 0νββ events: ~87.4%

MiDBD
1.8 kg ^{130}Te



1997-2001

→

Cuoricino
11.3 kg ^{130}Te

2003-2009

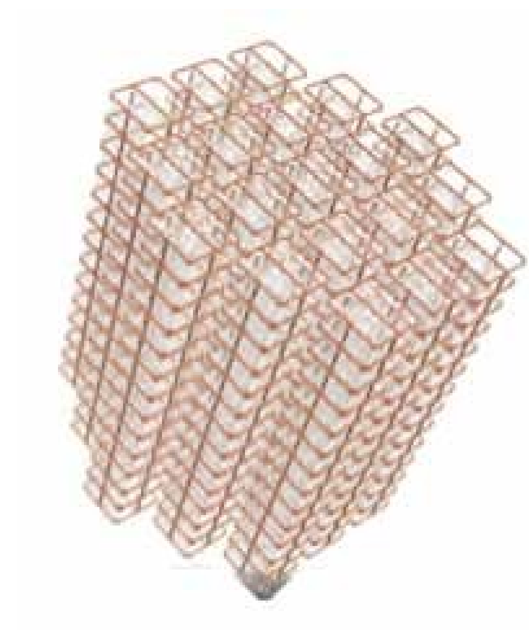
→

CUORE-0
11 kg ^{130}Te

2012...2014

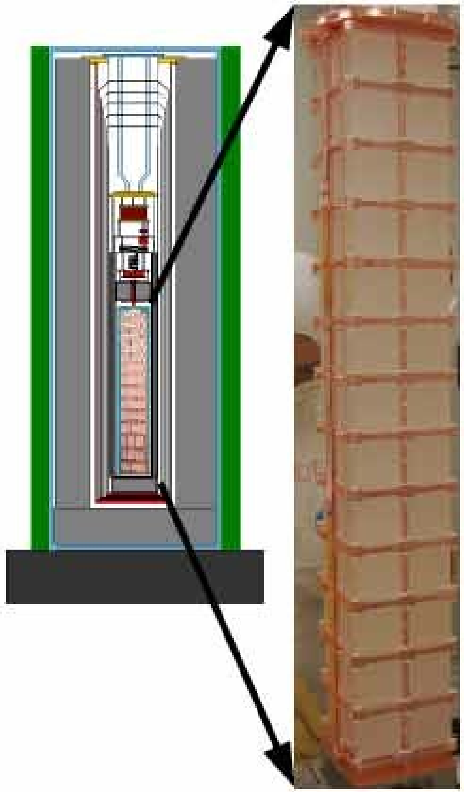
→

CUORE
206 kg ^{130}Te



2014...

CUORE-0: the Demonstrator

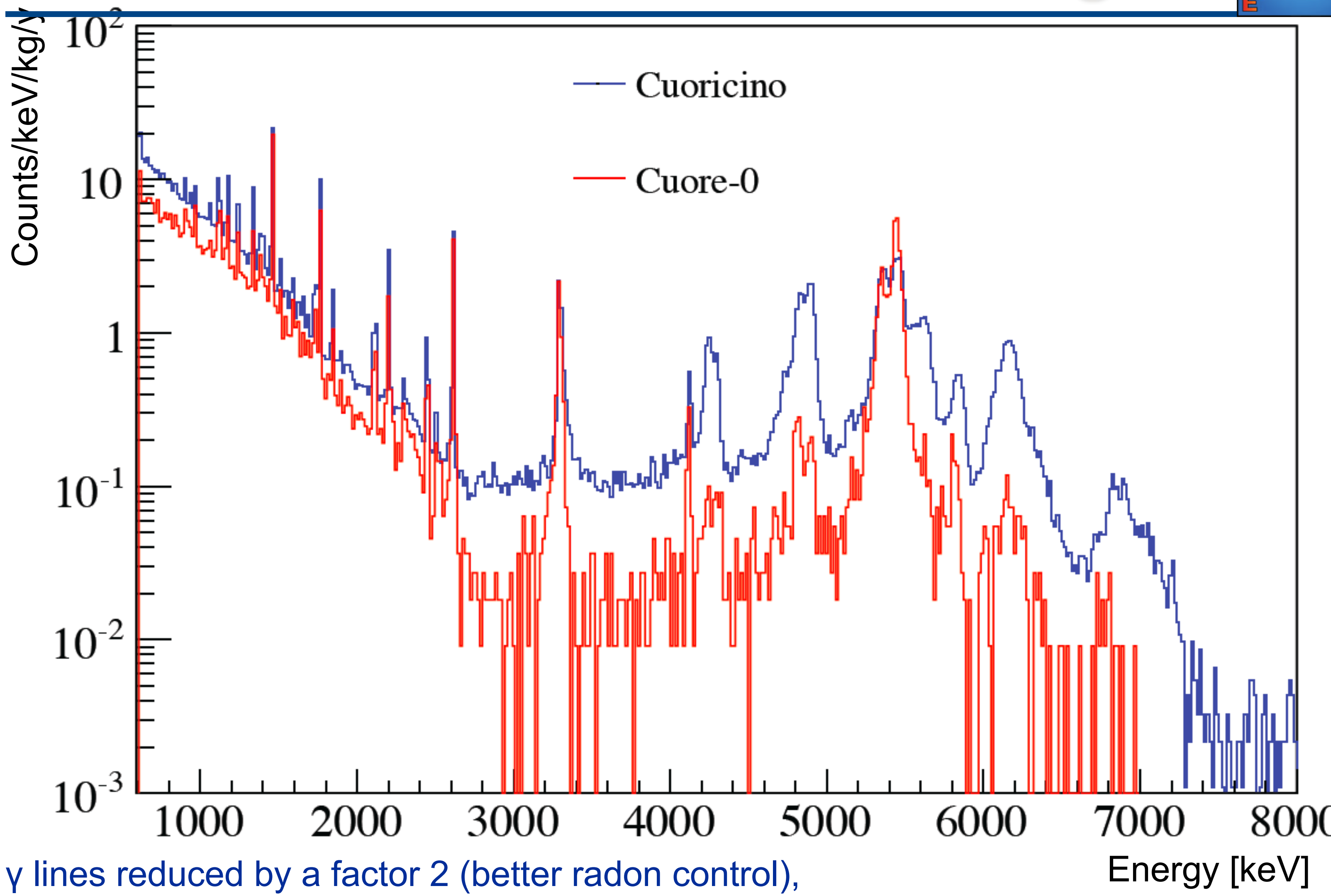


- A single CUORE-like tower:
  - 52 5x5x5 cm^3 TeO_2 bolometers
- Test of the CUORE cleaning procedures
- Test of the CUORE assembly procedures
- A sensitive 0vDBD experiment
- Same detector mass as CUORICINO:
  - TeO2 mass: 39 kg
  - 130Te mass: 11 kg
- Shielding:
  - Internal and external lead shield
  - Borated pohlyethylene shield
  - Anti radon box

Started data taking in March 2013

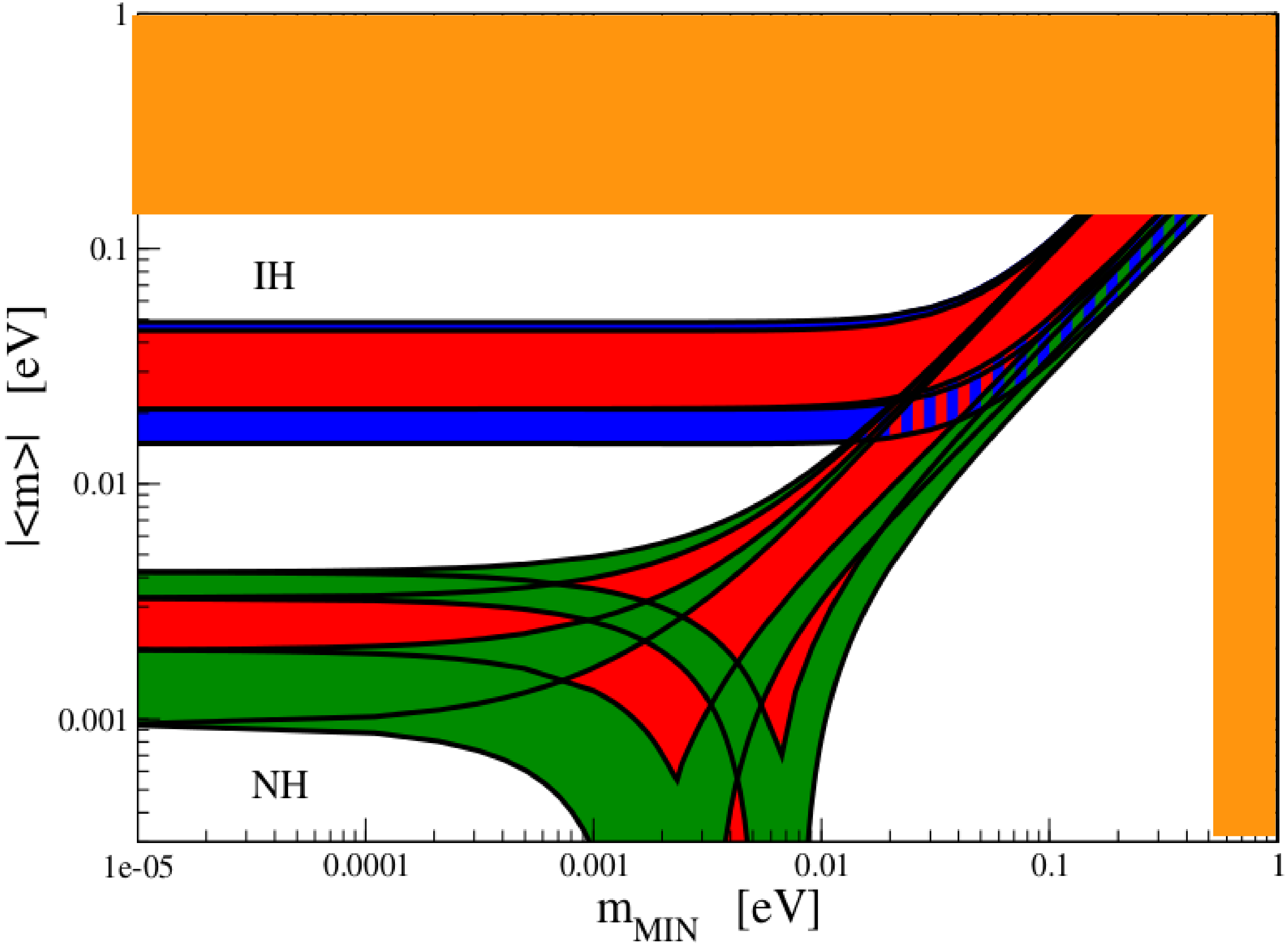
Operated in the CUORICINO cryostat:
γ background not expected to change → study α background

Cuore-0 vs Cuoricino bkg



^{238}U γ lines reduced by a factor 2 (better radon control),
^{232}Th γ lines not reduced (originate from the cryostat).
^{238}U and ^{232}Th α lines reduced thanks to the new detector surface treatment.

Current status



From PDG, updated from Phys Rev D 77 113003

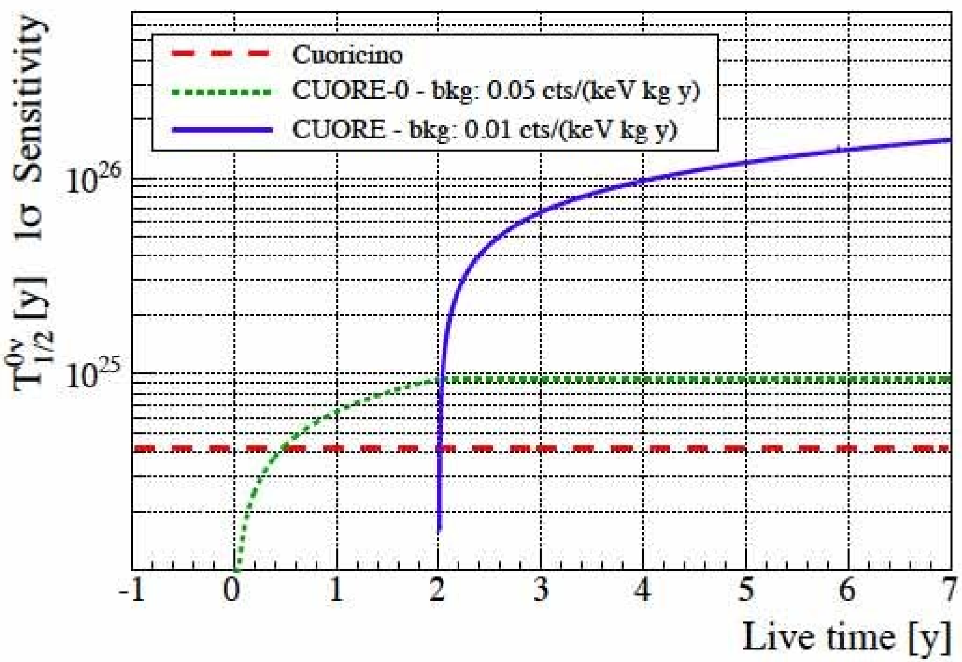
Future experiments

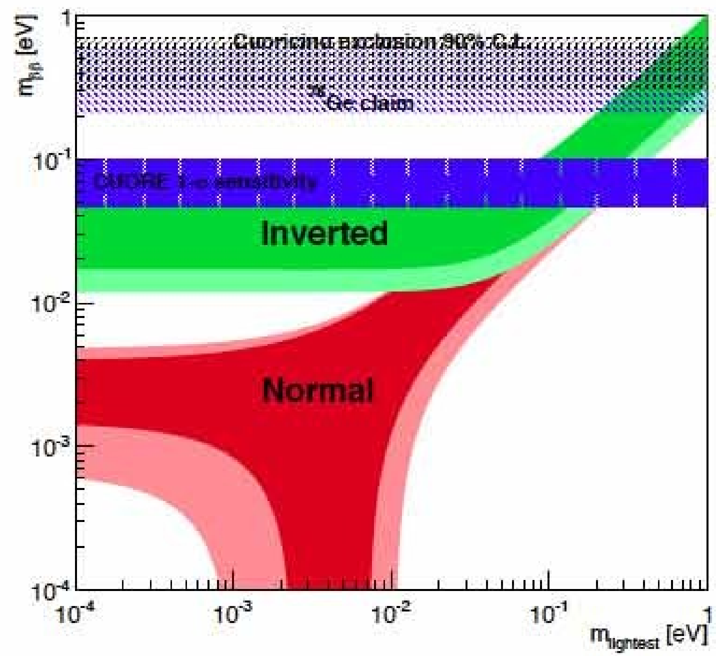
Overview

- Ongoing
  - CUORE
  - KamLAND-Zen – see current
  - GERDA-II
  - nEXO
- Under development with strong UK component
  - SNO+
  - SuperNEMO
- Notable but not mentioned here
  - Candles, NEXT100, Majorana

Cuore-0 and Cuore Sensitivities

- 1σ sensitivity $T_{1/2}^{0\nu\beta\beta} = 1.6 \times 10^{26}$ y; effective Majorana mass down to 47-100 meV.
  - Assuming a background rate of 10^{-2} counts/(keV kg y), and 5 keV FWHM
  - 5 years of live time
- Detector assembly will be finished by June 2014, followed by installation in July and commissioning by the end of 2014.
- Data taking will start in 2015.





GERDA-II

Phase I ended September 30, 2013:
all Phase I detectors dismounted

Phase II: additional 30 enriched BEGe detectors
(adding 20 kg)

already produced by Canberra Olen and completely tested at Hades (Belgium)

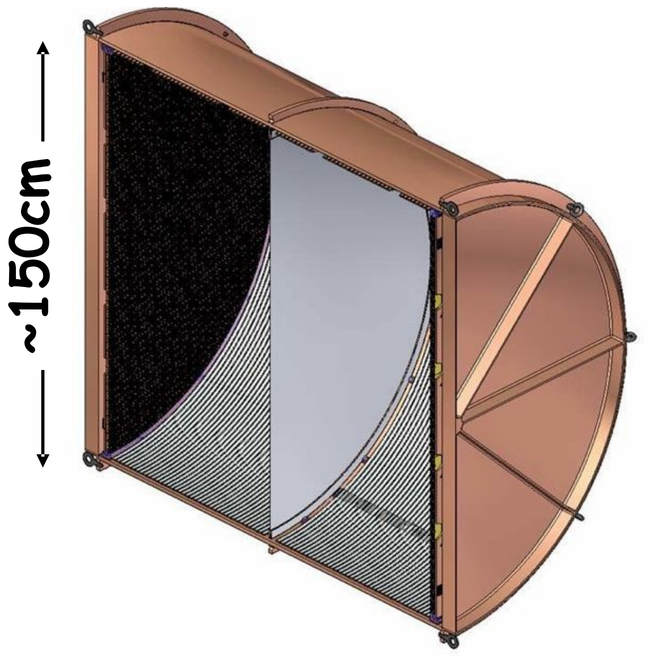
Improvements:

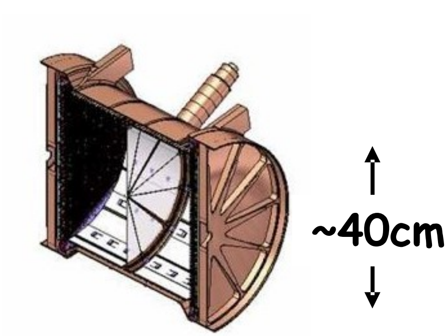
- Suppress background by factor > 10
- new front-end readout in close proximity (2 cm) to detectors
- new front-end, HV and signal cabling
- PSA discrimination with BEGe's
- liquid argon scintillation veto being instrumented

Ready for deployment of Phase II hardware
Spring 2014

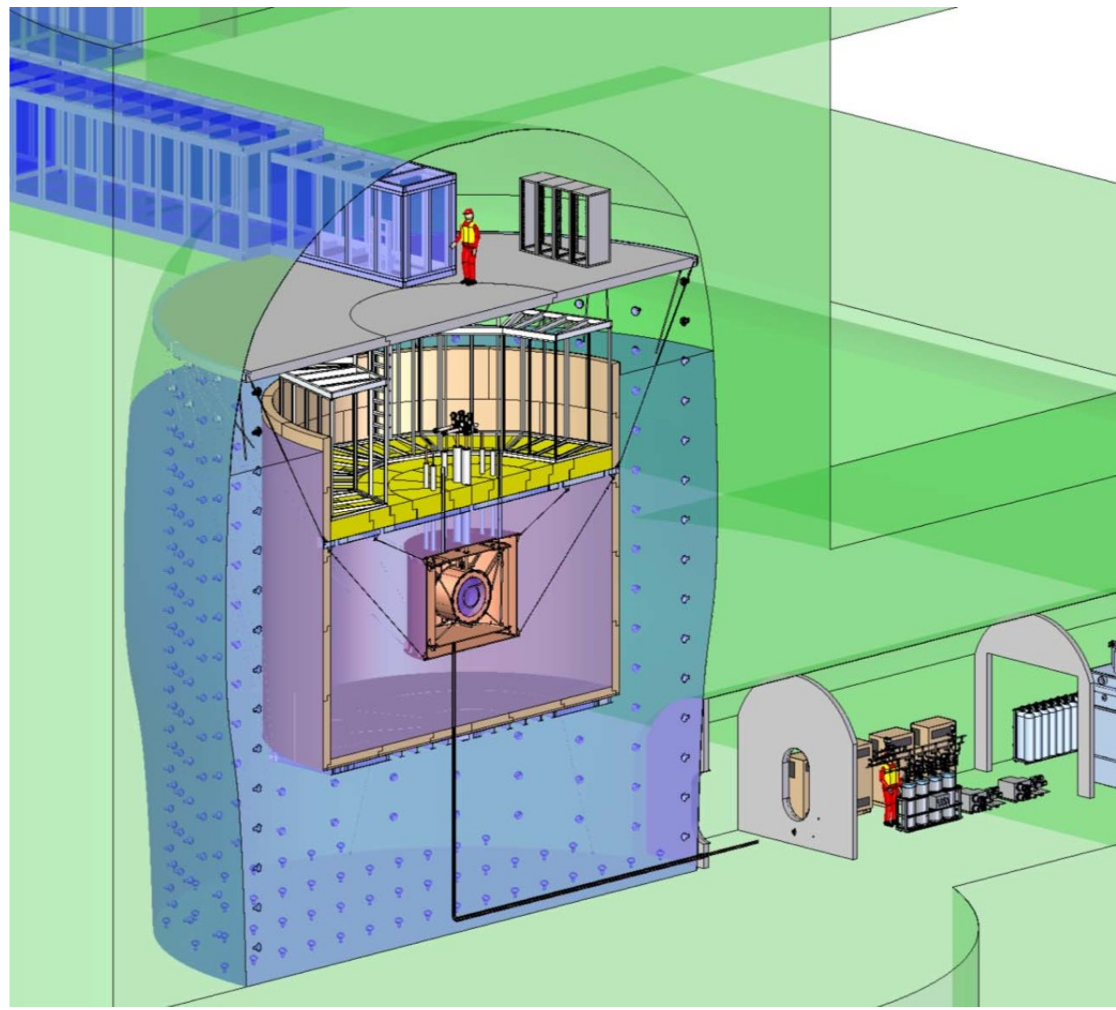
The future of EXO: nEXO

nEXO: 5 tonne LXe TPC "*as similar to EXO-200 as possible*"

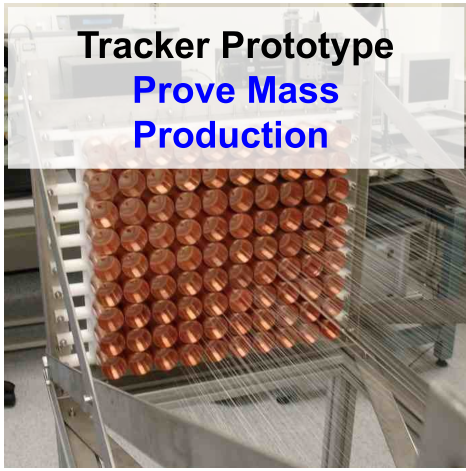




Sketch of nEXO in the SNOlab Cryopit



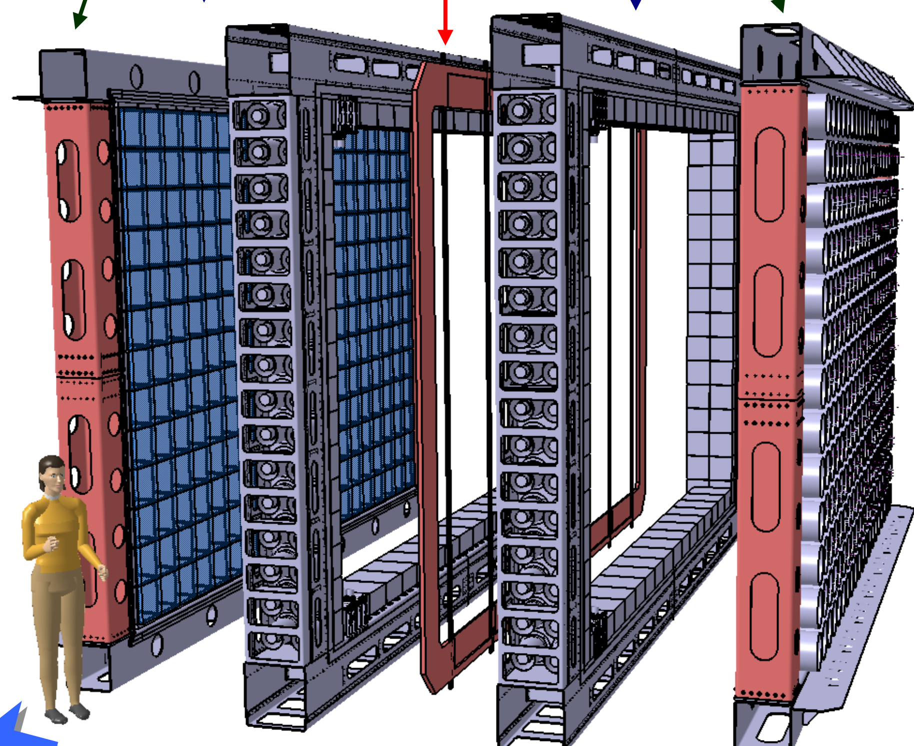
SuperNEMO



~700 calorimeter channels

2000 tracker cells

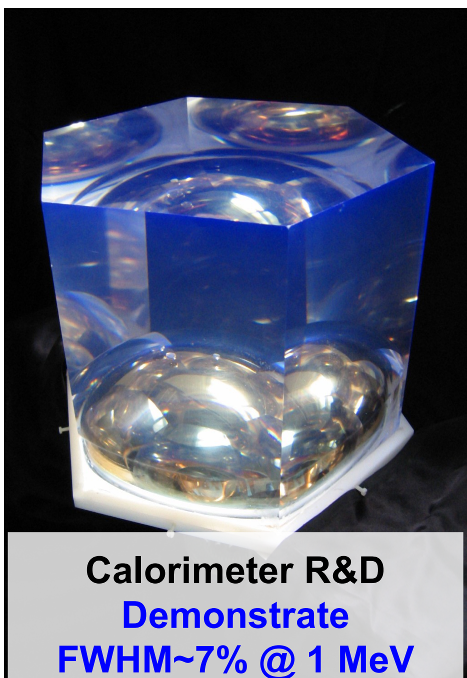
6-7 kg source foil



Demonstrator Module

Also :

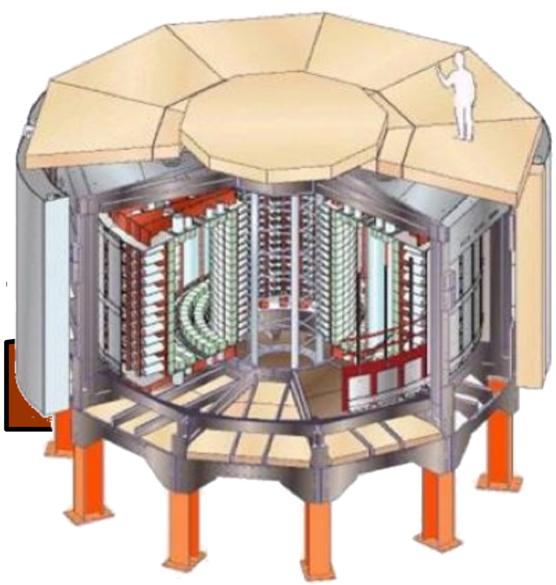
- Change isotope 100Mo -> 82Se
- Reduce radon in gas by factor 30
- Improved efficiency, calibration etc.

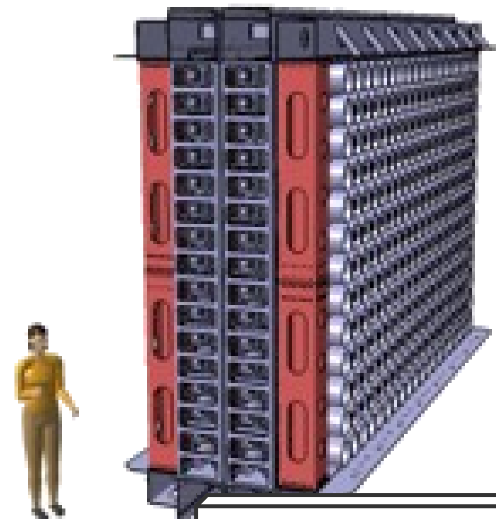


From NEMOIII to SuperNEMO

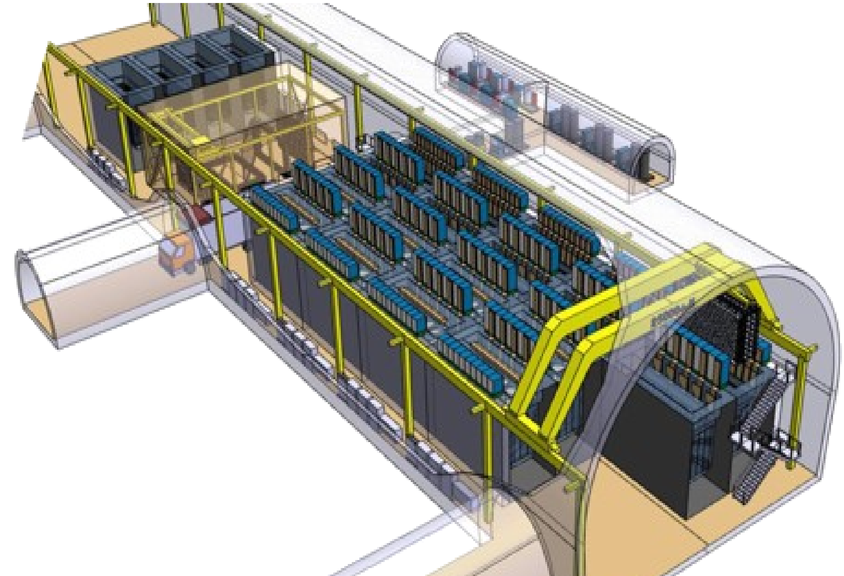
NEMO-3		SuperNEMO
^{100}Mo	isotope	^{82}Se or other
7 kg	isotope mass	100+ kg
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: ~ 300 μBq/kg ^{222}Rn: ~ 5 mBq/m3 222	internal contamination ^{208}Tl ,^{214}Bi in the ββ foil Rn in the tracker	^{208}Tl ≤ 2 μBq/kg ^{214}Bi ≤ 10 μBq/kg ^{222}Rn ≤ 0.15 mBq/m3
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}(0\nu\beta\beta)$> 1-2 x 10^{24} y $\langle m_{\beta\beta}\rangle$ < 0.3 – 0.9 eV		$T_{1/2}(0\nu\beta\beta)$ > 1 x 10^{26} y $\langle m_{\beta\beta}\rangle$ < 0.04-0.11 eV

NEMOIII to SuperNEMO





Demonstrator Module
Prove technology; reach
~200 meV sensitivity



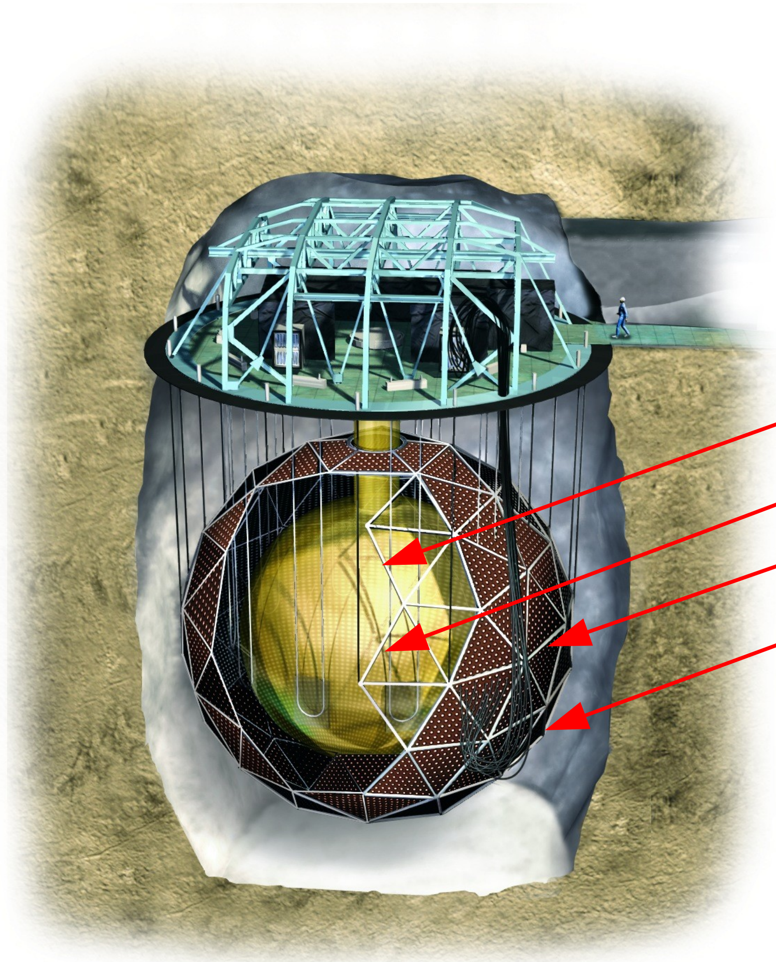
Full SuperNEMO
20 modules : 100 kg
Start to probe I.H.

Demonstrator under construction:
running 2015- 2016

All modules running by 2020:
$T_{1/2} \sim 10^{26}$ y
$\langle m_{\beta\beta} \rangle \sim 40 - 110$ meV

Future experiments

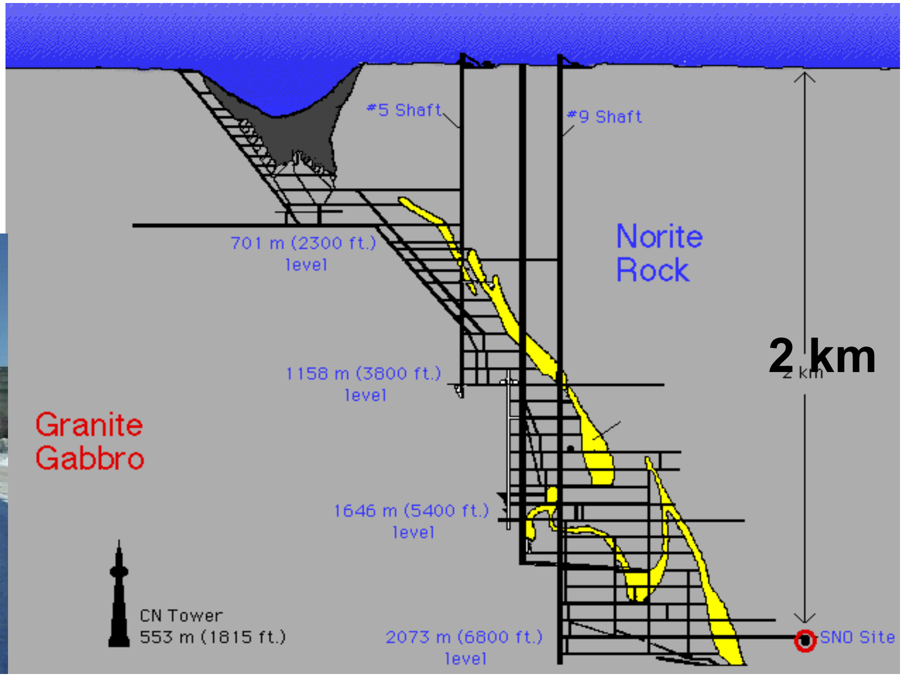
SNO+



Located at 2 km underground @ SNOLAB
Vale nickel mine Sudbury, Ontario, Canada

- 780 tonnes of LS (LAB)
- 12 m diameter acrylic vessel
- 9,500 PMTs with 54% coverage
- 7 ktonne ultapure water shield

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

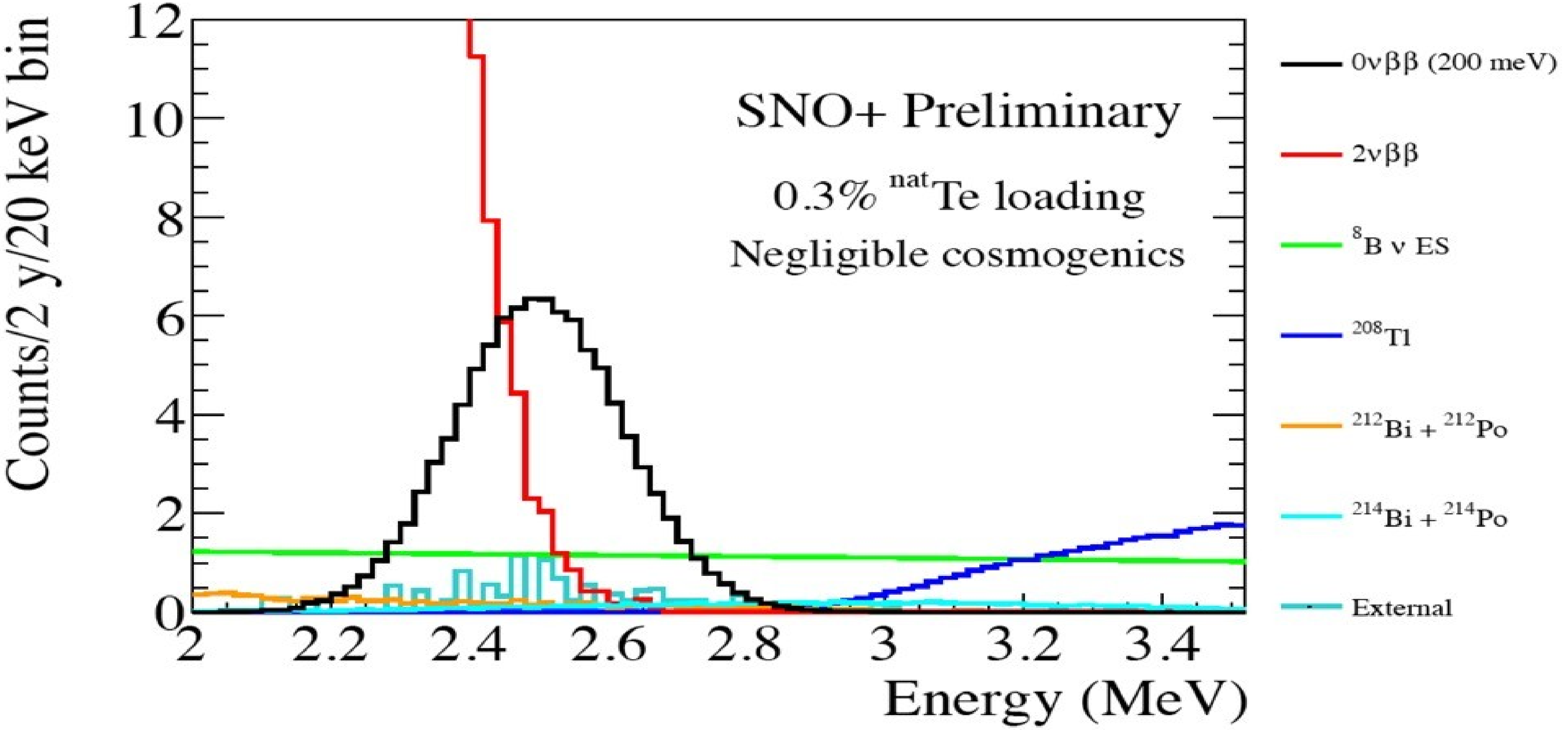


SNO+ with ^{130}Te

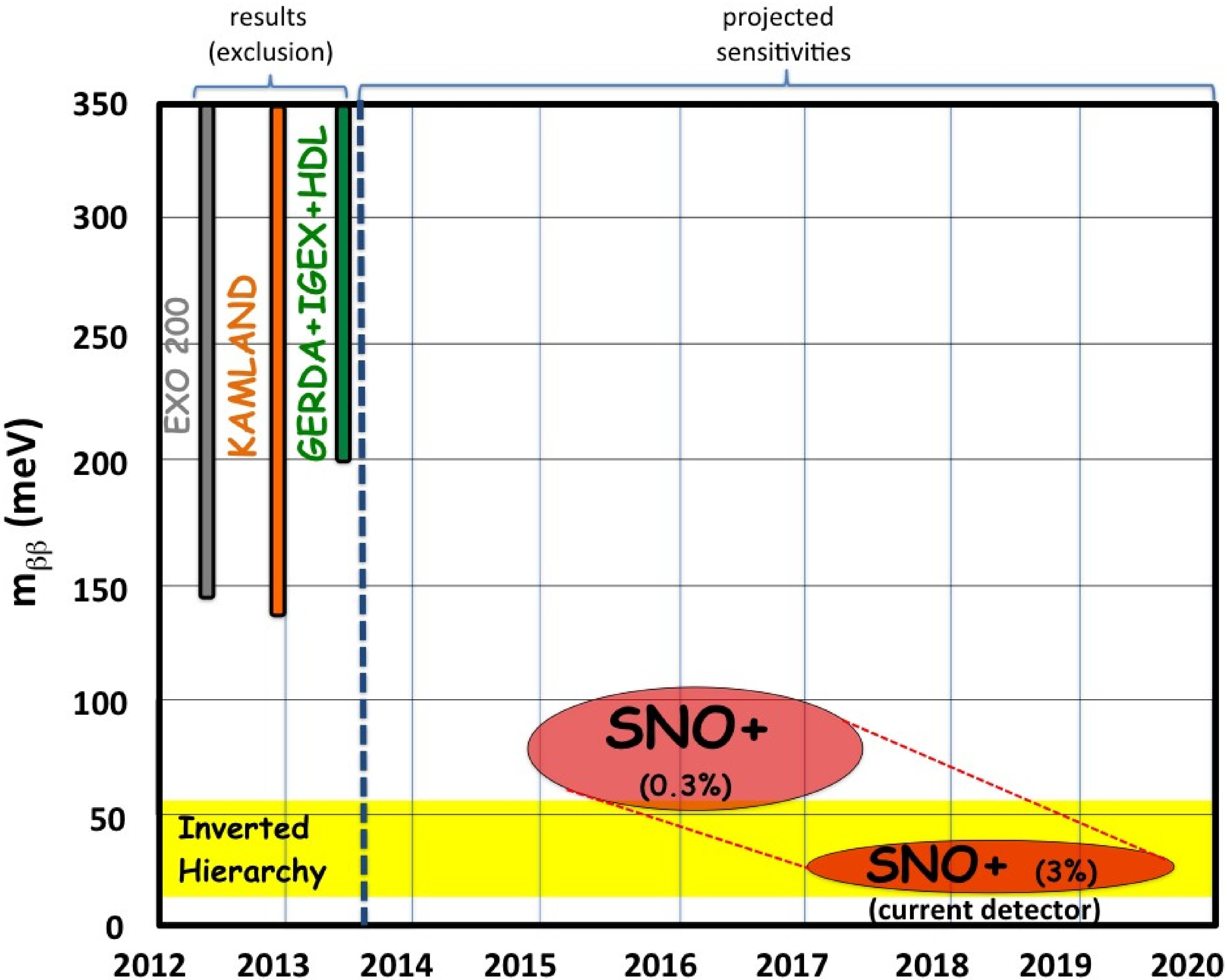
- Large natural isotopic abundance (34%) for ^{130}Te
- tonne scale for ^{130}Te isotope, cost is $1.5 million ***only*** (b/c use natural Te)
- 0.3% Te (by weight) in SNO+ is 2.34 tonnes of Te or **800 kg** of ^{130}Te ***isotope***… (0.3% loading isn't a fundamental loading limit either!)
- In the energy range where the Te endpoint is, the known U chain background (^{214}Bi-^{214}Po) can be rejected by factor >5,000!
  "temporal event topology" for background rejection
- the 2νββ background is relatively small
  (a factor 100 times smaller than in Nd,
  previous isotope considered for SNO+ double beta)
- if the Te LS is otherwise radiopure,
  the dominant background will be ^{8}B solar neutrinos

SNO+ with ^{130}Te

Expected Average Spectra of Contributing Backgrounds for Two Live Years of Data



Future experiments



Further future

Future of $0\nu\beta\beta$ physics

If neutrinoless double-beta is found

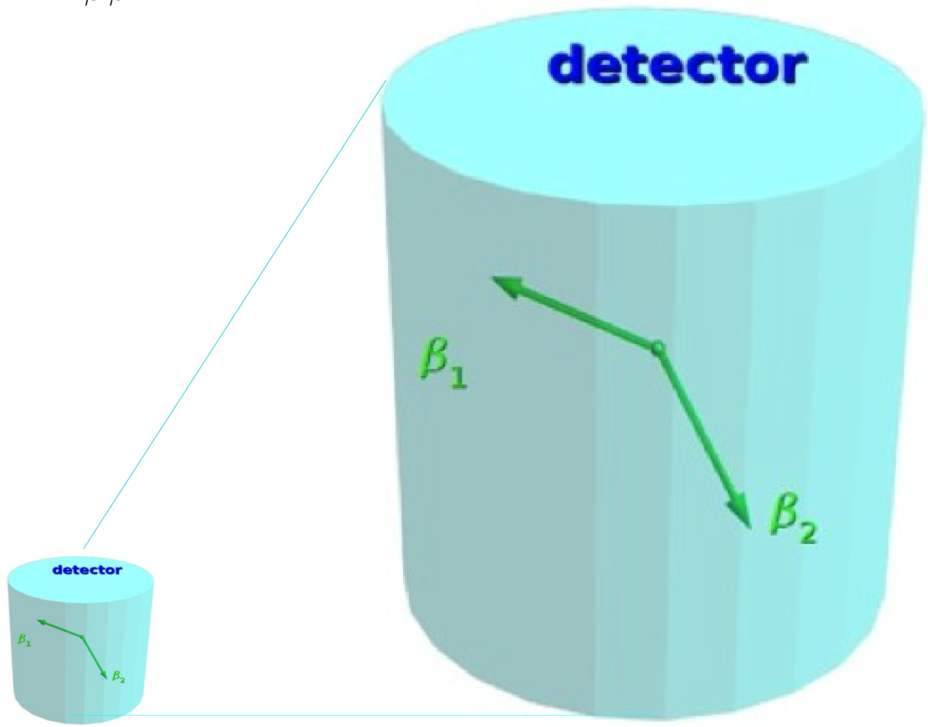
- More focus on matrix elements
- Test multiple isotopes
  - Double-beta decay mechanism
  - Non-standard model interactions

  (any process with L=2 can *contribute* to $0\nu\beta\beta$:
  R_p violating SUSY, V+A interactions, Leptoquarks, Double charged Higgs, Compositeness, Heavy Majorana neutrino exchange …)

Future of experiments

- Scaling $\sigma_{m_{\beta\beta}} \propto \sqrt{a}\left(\frac{MT}{\Delta E}\right)^{1/4} \Rightarrow \sigma_{m_{\beta\beta}} \propto \sqrt{aMT}$
  - remove background scaling
  - Large (efficient) signal detector
  - Limited $$$
    - Scalable technology
    - Deploy multiple isotopes
    - Event topology studies (?)

⇒ Liquid scintillator



- Developments needed
  - Large scale cleaning at very high purity levels
  - Transparent optical mixtures
  - Efficient detection

THE END

Neutrinoless double-beta decay: a

Vibrant

field capable of finding answers to important questions in particle physics and cosmology!