

**Advances in
neutrinoless double beta decay**

**Ralph Massarczyk
Los Alamos National Laboratory**

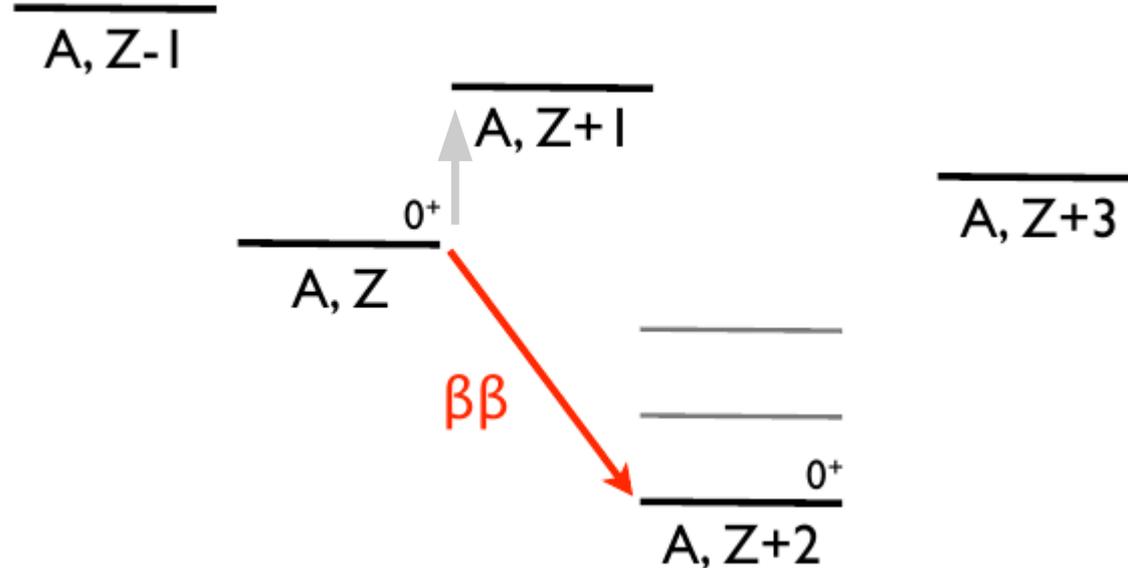
LA-UR-16-26536

Introduction



In a number of even-even nuclei, the beta decay is energetically forbidden.

A double-beta decay from (A, Z) to $(A, Z+2)$, is energetically allowed.



Introduction



SEPTEMBER 15, 1935

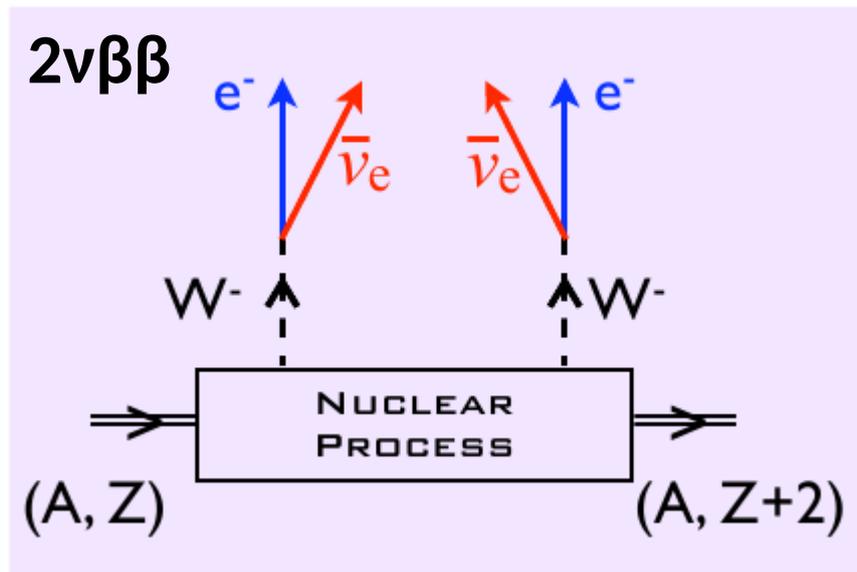
PHYSICAL REVIEW

VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935)



Introduction



SEPTEMBER 15, 1935

PHYSICAL REVIEW

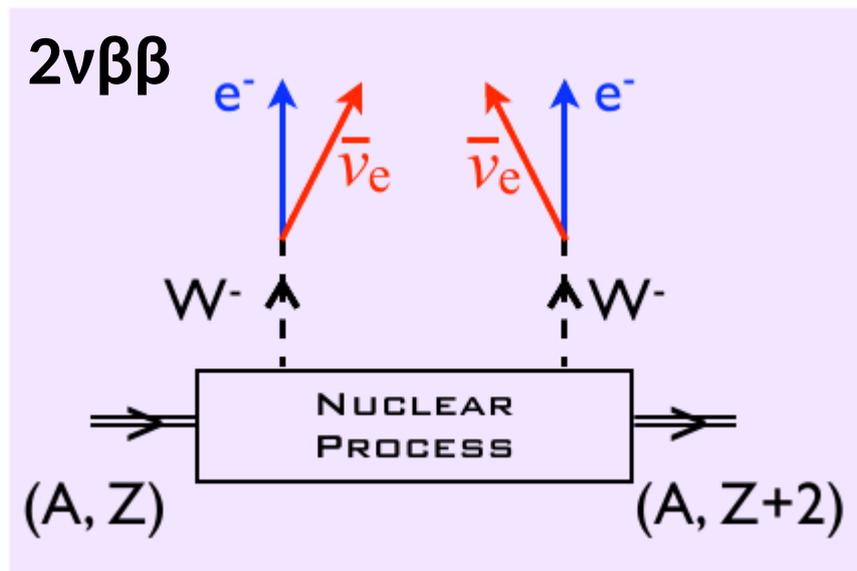
VOLUME 48

Double Beta-Disintegration

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

1937



Introduction



SEPTEMBER 15, 1935

PHYSICAL REVIEW

VOLUME 48

Double Beta-Disintegration

TEORIA SIMMETRICA DELL' ELETTRONE

DECEMBER 15, 1939

PHYSICAL REVIEW

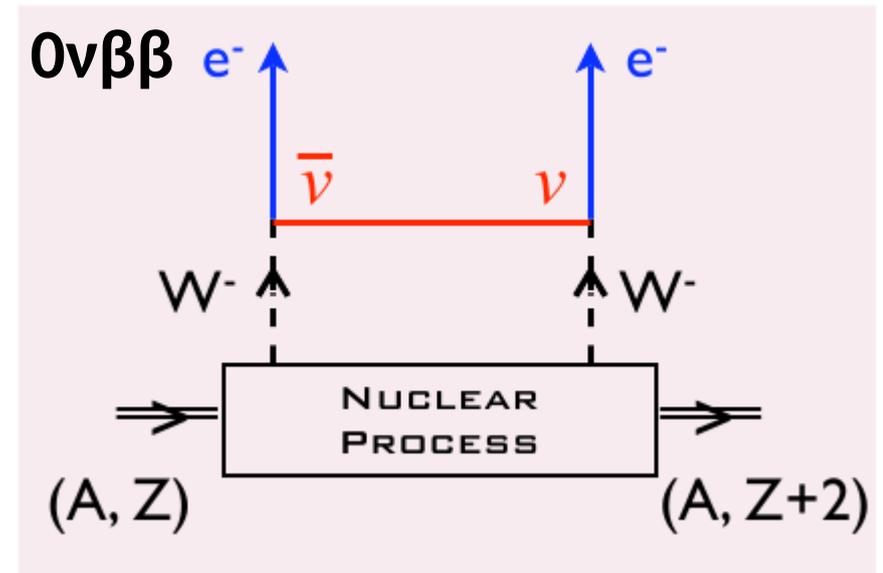
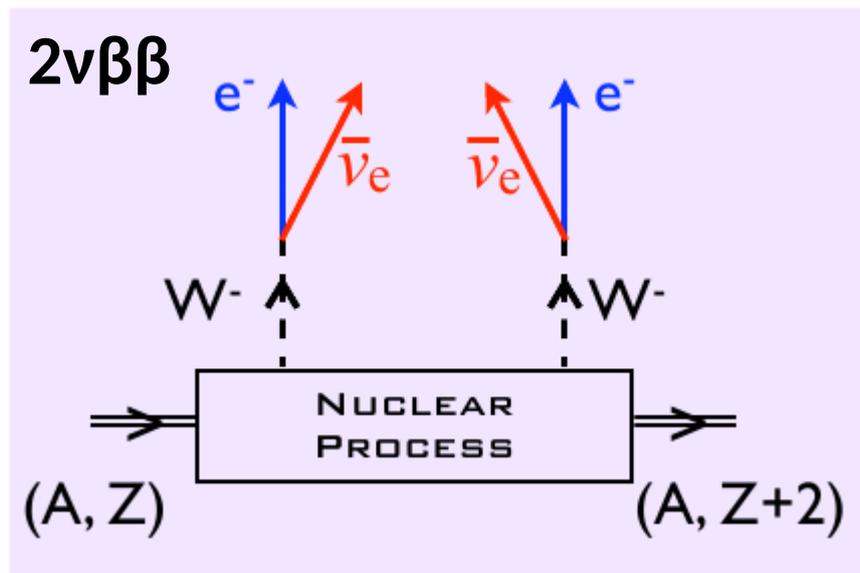
VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY

Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)



Introduction



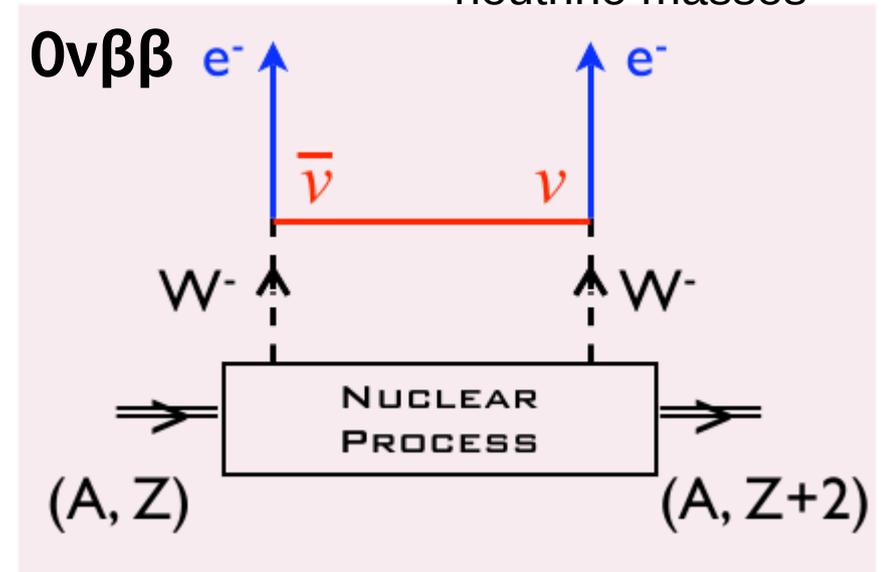
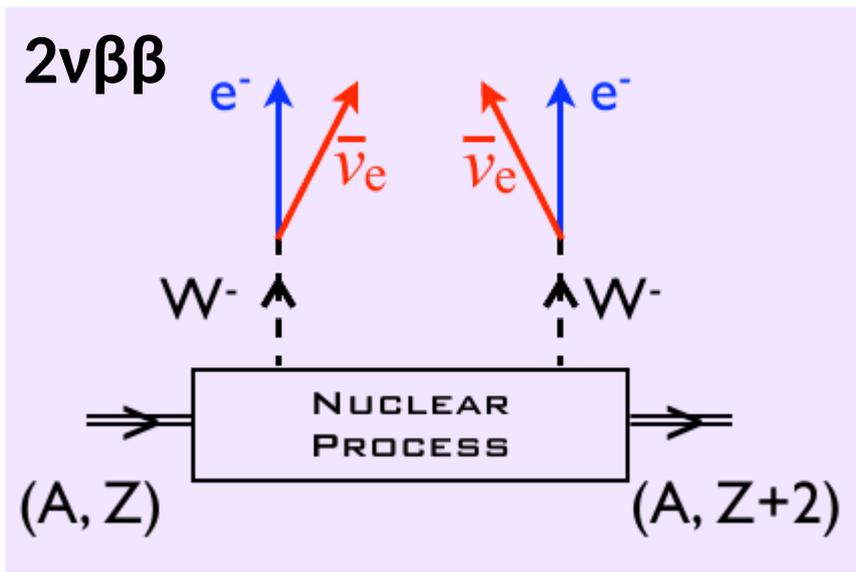
nuclear matrix element

$$\left[\mathbf{T}_{1/2}^{2\nu} \right]^{-1} = G_{2\nu} \left| M_{2\nu} \right|^2$$

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

Phase space

neutrino masses



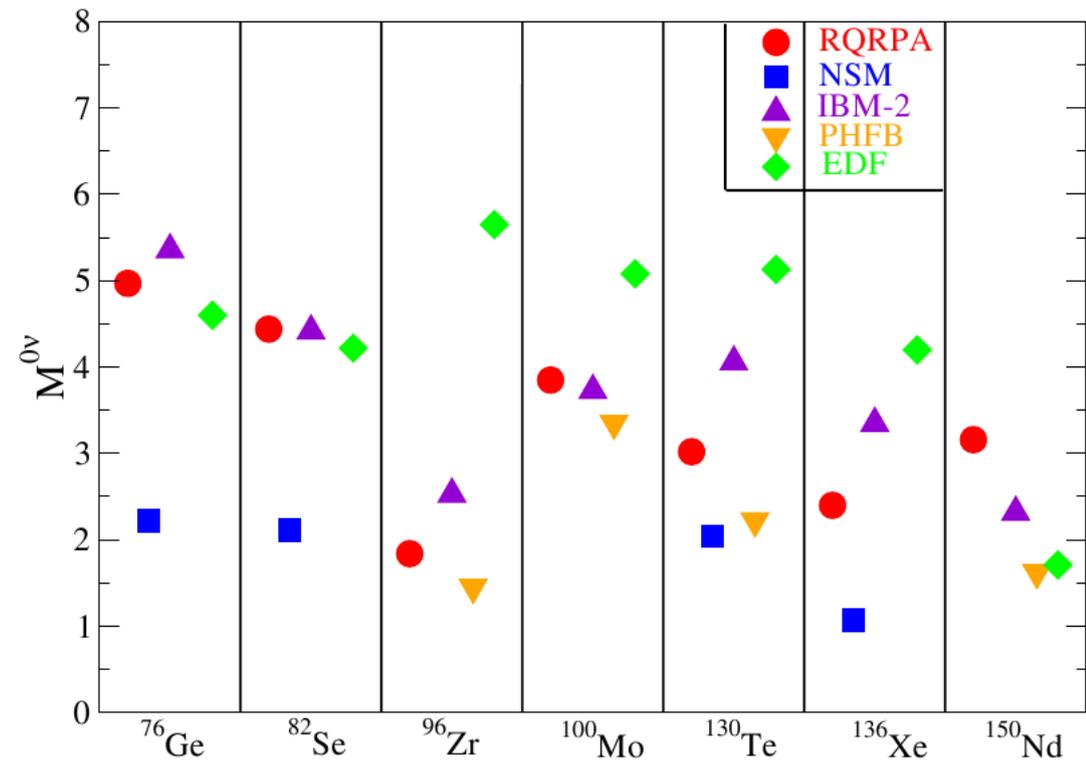
Introduction - matrix element



- candidates

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

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



P. Vogel, J. Phys. G 39, 124002 (2012).

Introduction - matrix element



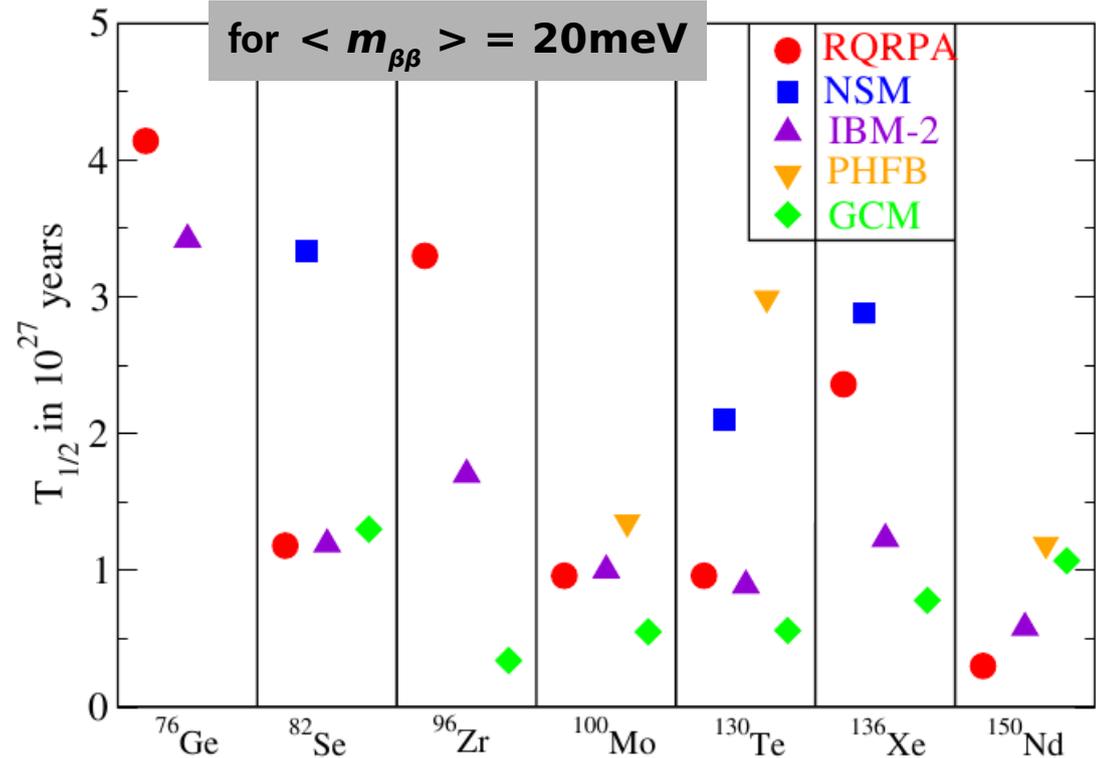
- **candidates**

^{48}Ca , ^{76}Ge , ^{82}Se , ^{96}Zr ,
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- uncertainties in matrix element have direct on

- $T_{1/2}$
 (theory predicts $\langle m_{\beta\beta} \rangle$)

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Introduction - neutrino masses / hierarchy

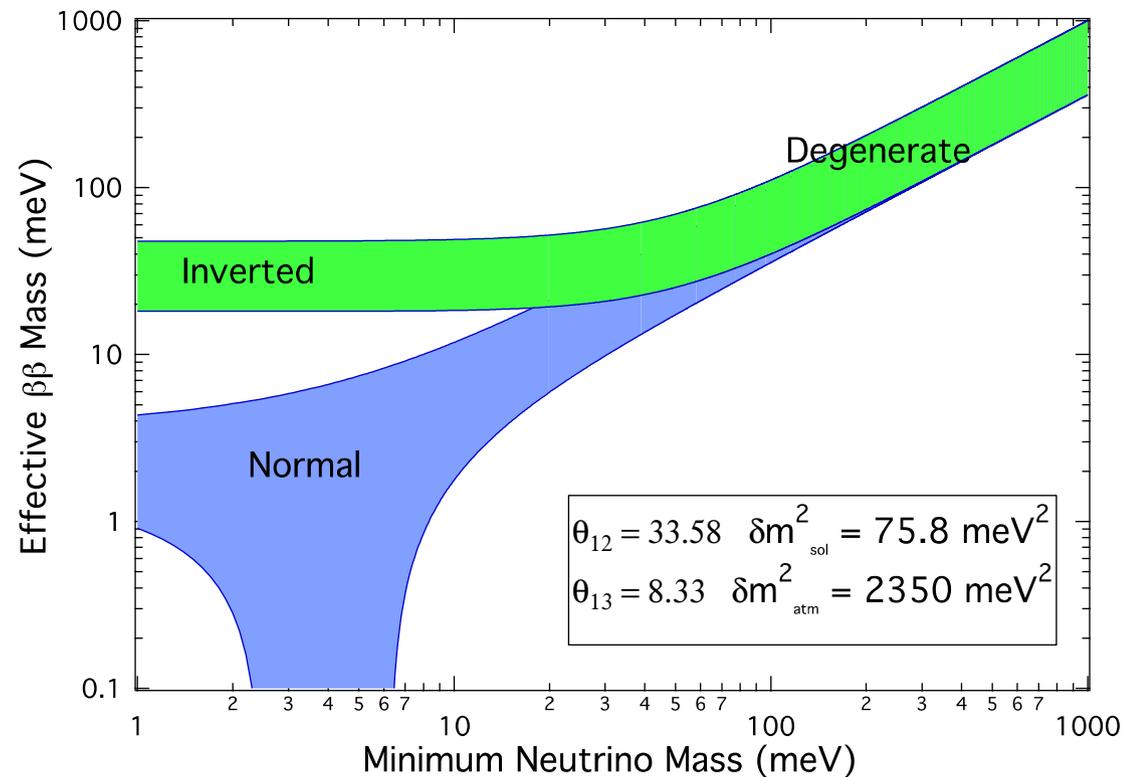


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- uncertainties in matrix element have direct on

- $T_{1/2}$
(theory predicts $\langle m_{\beta\beta} \rangle$)
- $\langle m_{\beta\beta} \rangle$
(experiment determines $T_{1/2}$)



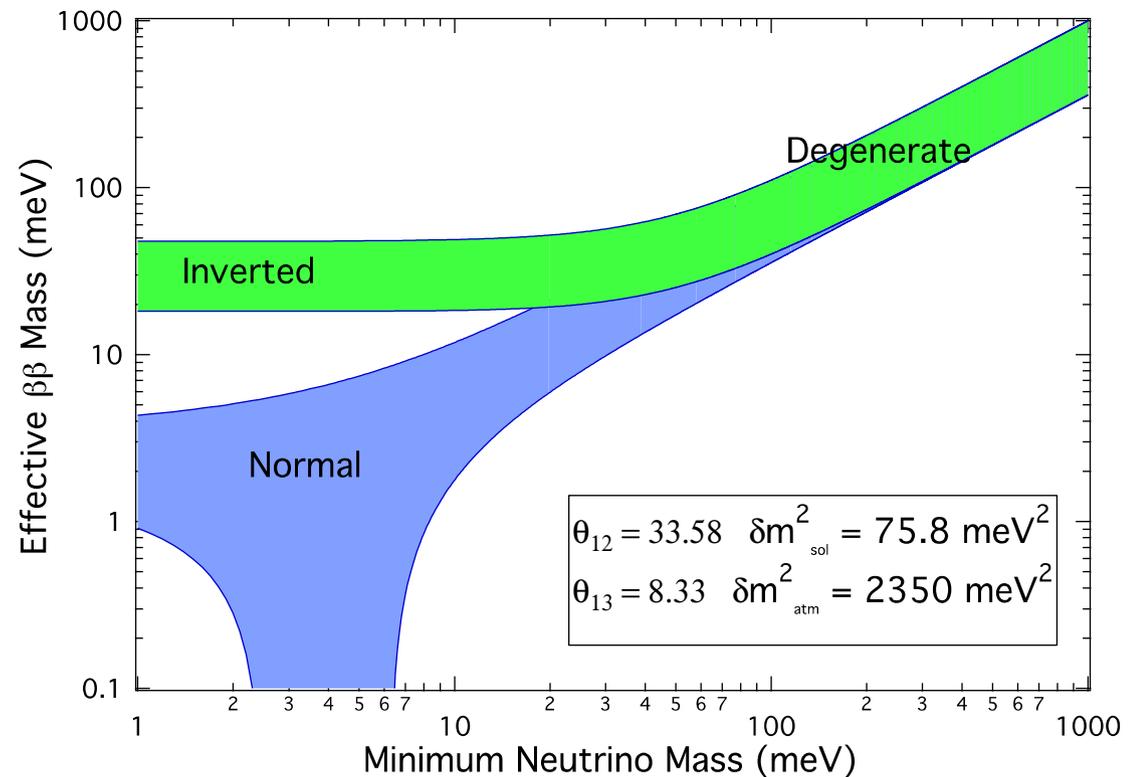
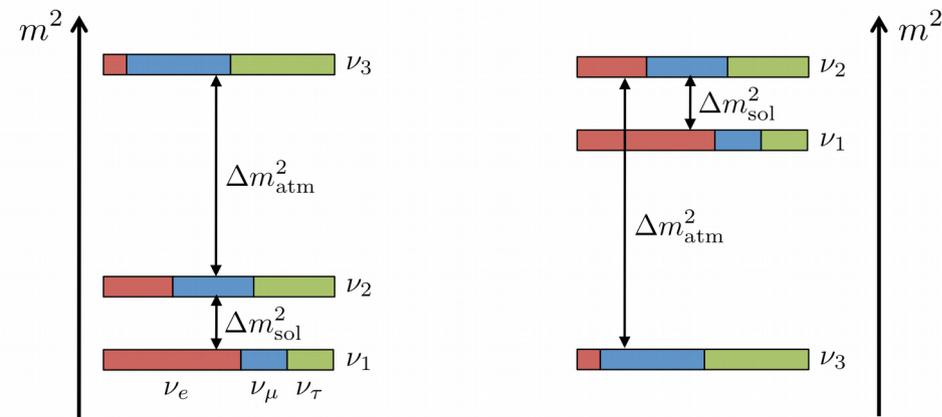
Introduction - neutrino masses / hierarchy



- from neutrino oscillation we know $m_\nu \neq 0$
- an experimental will give us a hint about neutrino mass hierarchy

normal hierarchy (NH)

inverted hierarchy (IH)

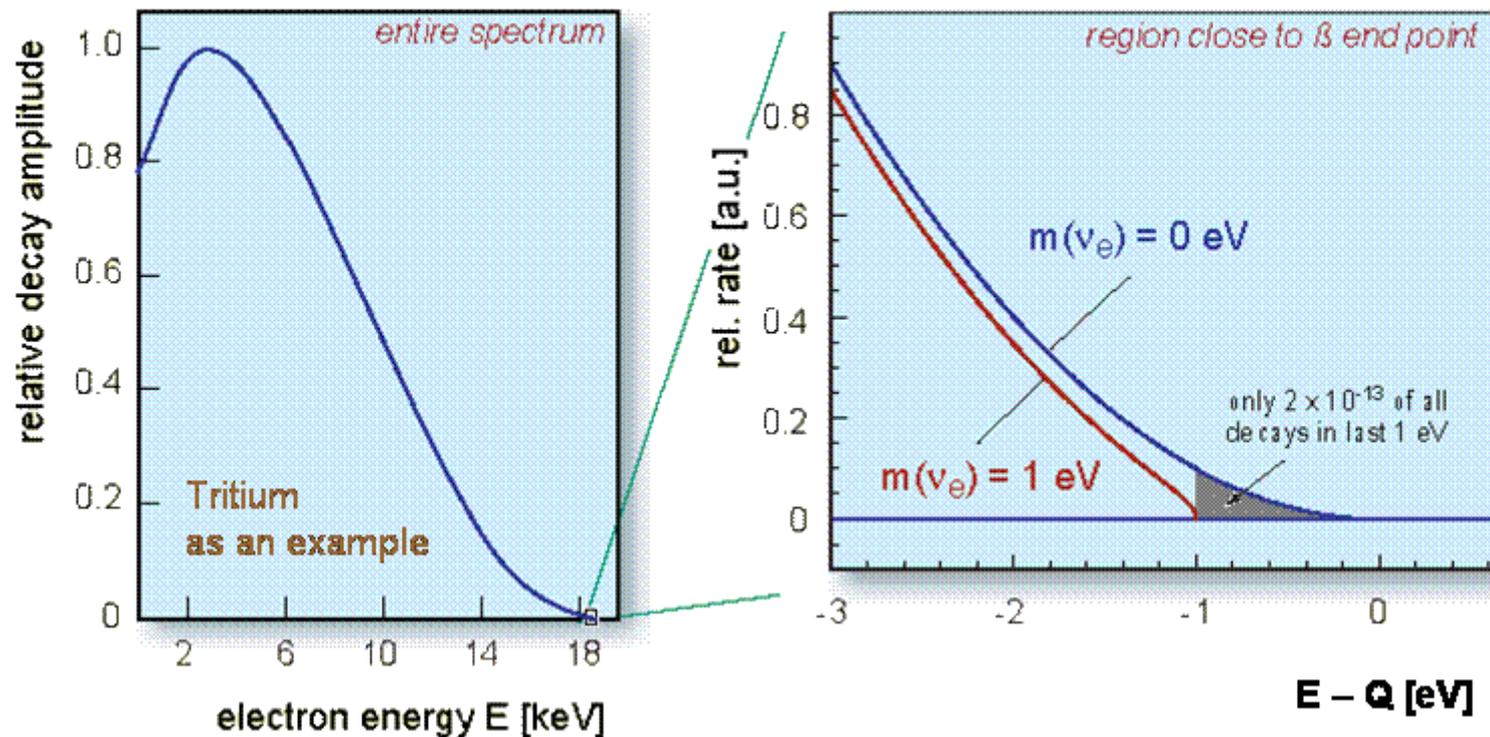


$$\langle m_{ee} \rangle = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_1} m_2 + |U_{e3}|^2 e^{i\alpha_2} m_3 \right|$$

Introduction – current limits



- direct (Kurie plot) $m_{\nu_e} < 2.3 \text{ eV}$ (goal for KATRIN 0.2eV)



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 $m_\nu (\Omega_h) < 0.24 \text{ eV}$ (three neutrino families)
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- neutrino-less double beta decay
 $T_{1/2} > 10^{25} \text{ yrs} \rightarrow m_{ee} < 0.3 \text{ eV}$

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

Introduction – current limits



- direct (Kurie plot)

pro: model independent
con: resolution

- accelerators:

pro: statistics
con: resolution, correlations

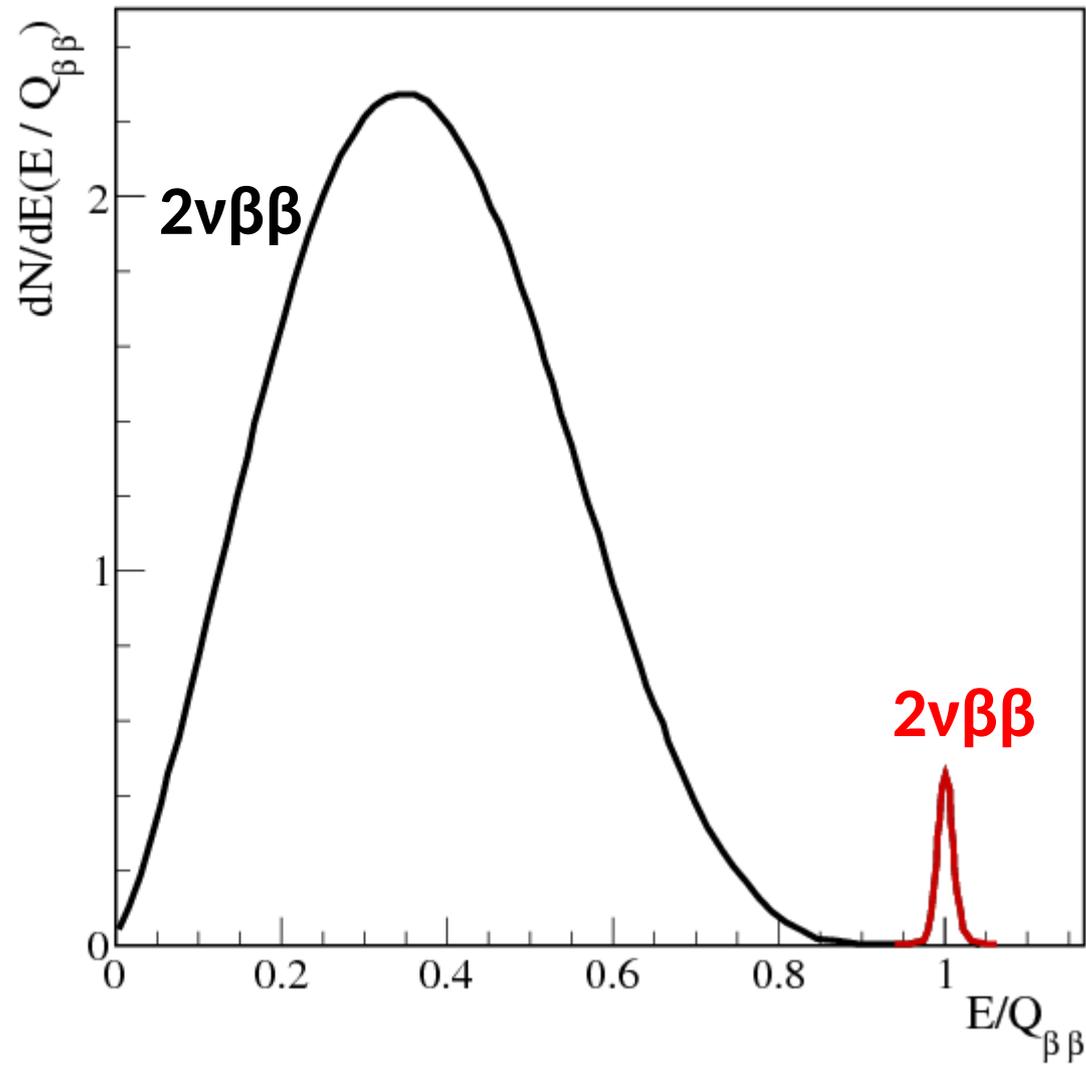
- indirect (cosmology using WMAP and galaxy surveys)

pro: best hierarchy prediction
con: model dependent

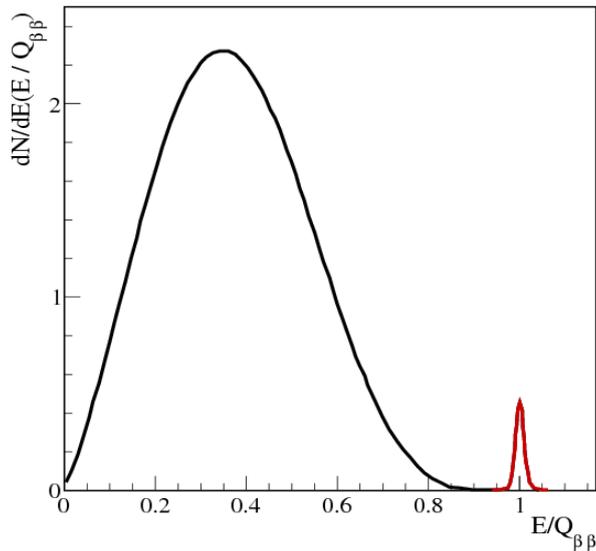
- neutrino-less double beta decay

pro: $T_{1/2}$ measurement straight forward
Majorana nature of the neutrino
con: big uncertainties in theory

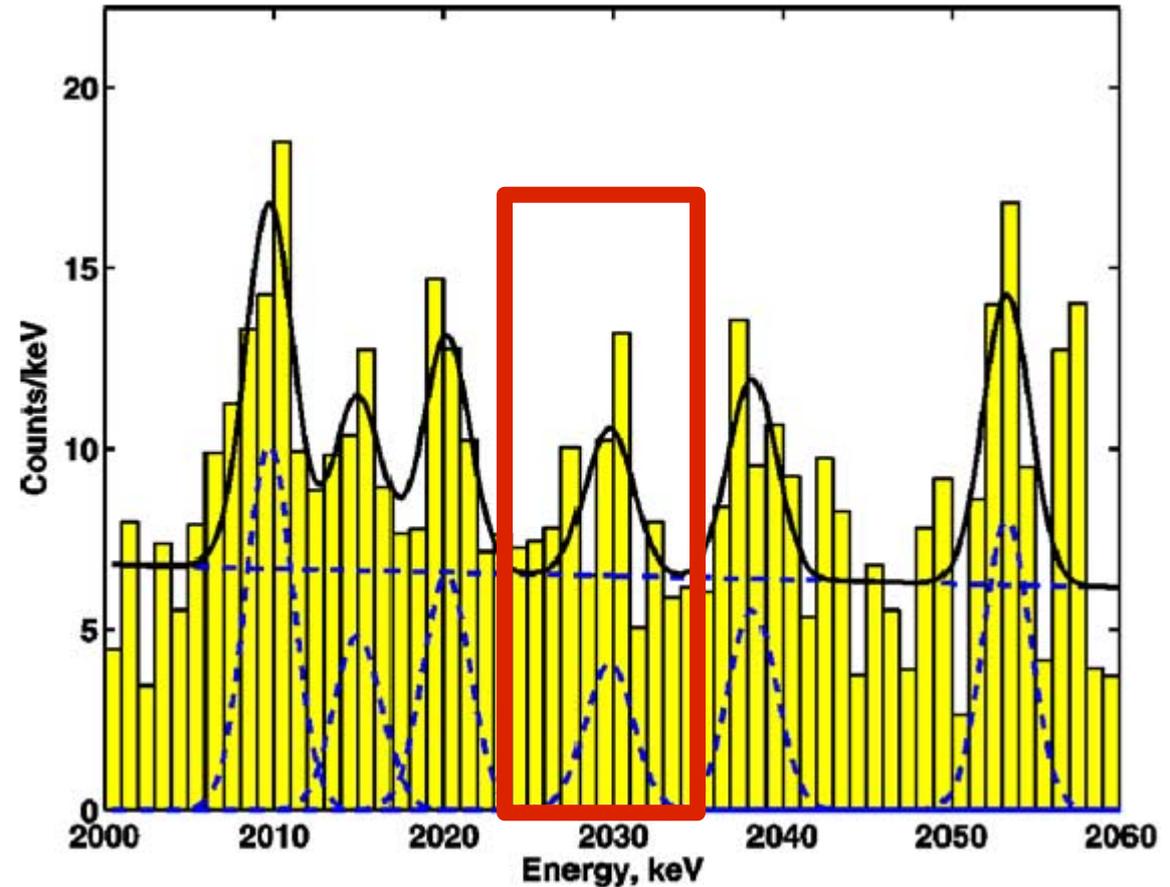
Neutrinoless double-beta decay measurements



Neutrinoless double-beta decay measurements



First claim in ^{76}Ge :

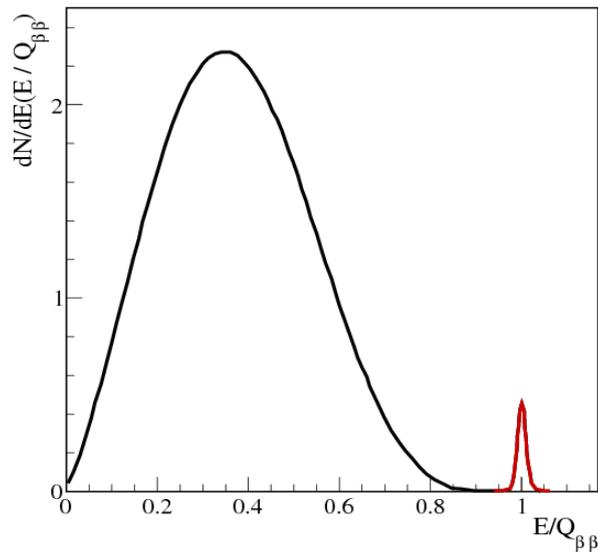


$$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24} \text{ yr}$$

$$\langle m_{\beta\beta} \rangle = 0.32 \pm 0.03 \text{ eV}$$

H.V. Klapdor-Kleingrothaus et al. / Physics Letters B 586 (2004) 198–212

Neutrinoless double-beta decay measurements



First claim in ^{76}Ge :

~~$T_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{24} \text{ yr}$~~

could not be reproduced by current experiments

~~$\langle m_{\beta\beta} \rangle = 0.32 \pm 0.03 \text{ eV}$~~

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Neutrinoless double-beta decay measurements



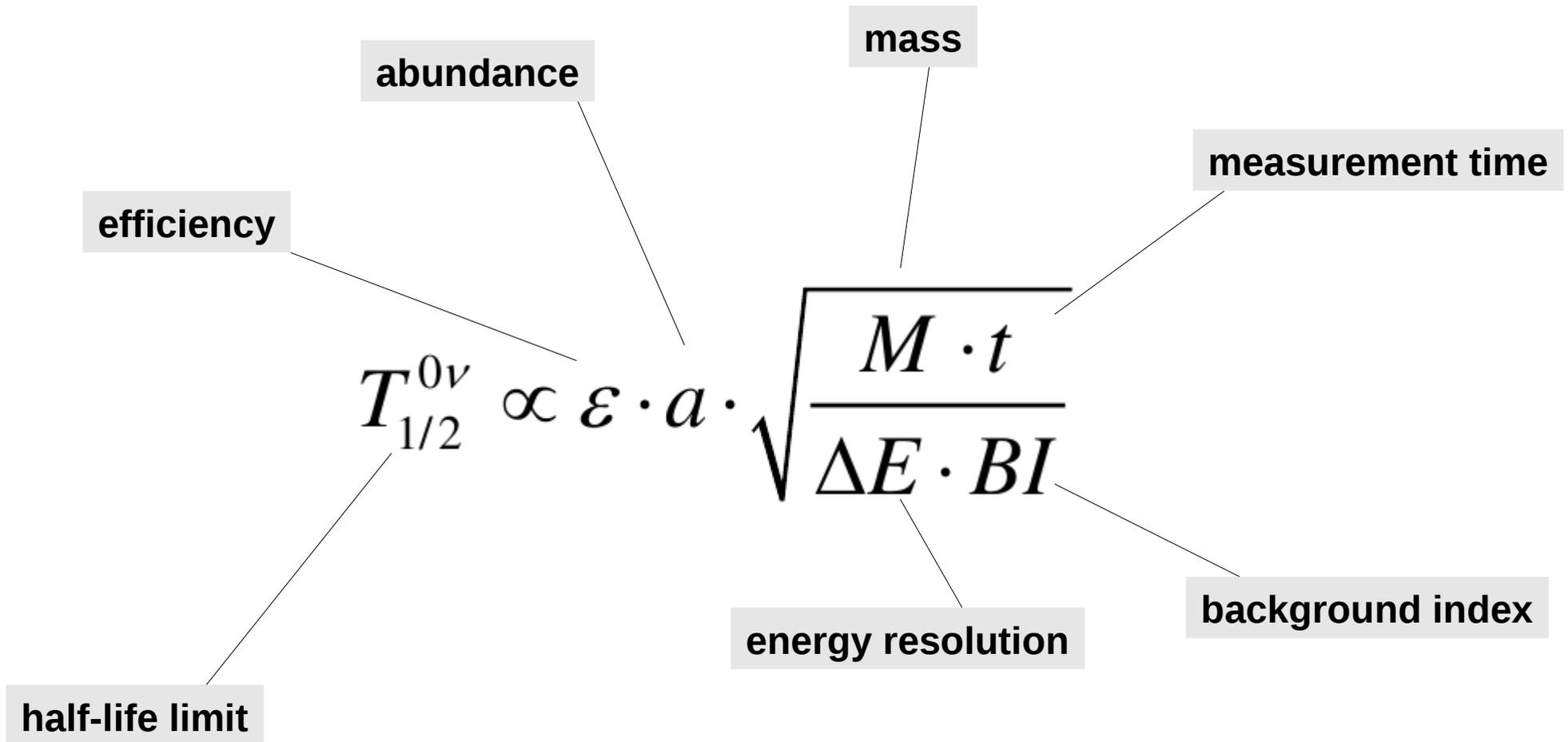
General thoughts about this type of experiment

$$T_{1/2}^{0\nu} \propto \varepsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

Neutrinoless double-beta decay measurements



General thoughts about this type of experiment



Neutrinoless double-beta decay measurements



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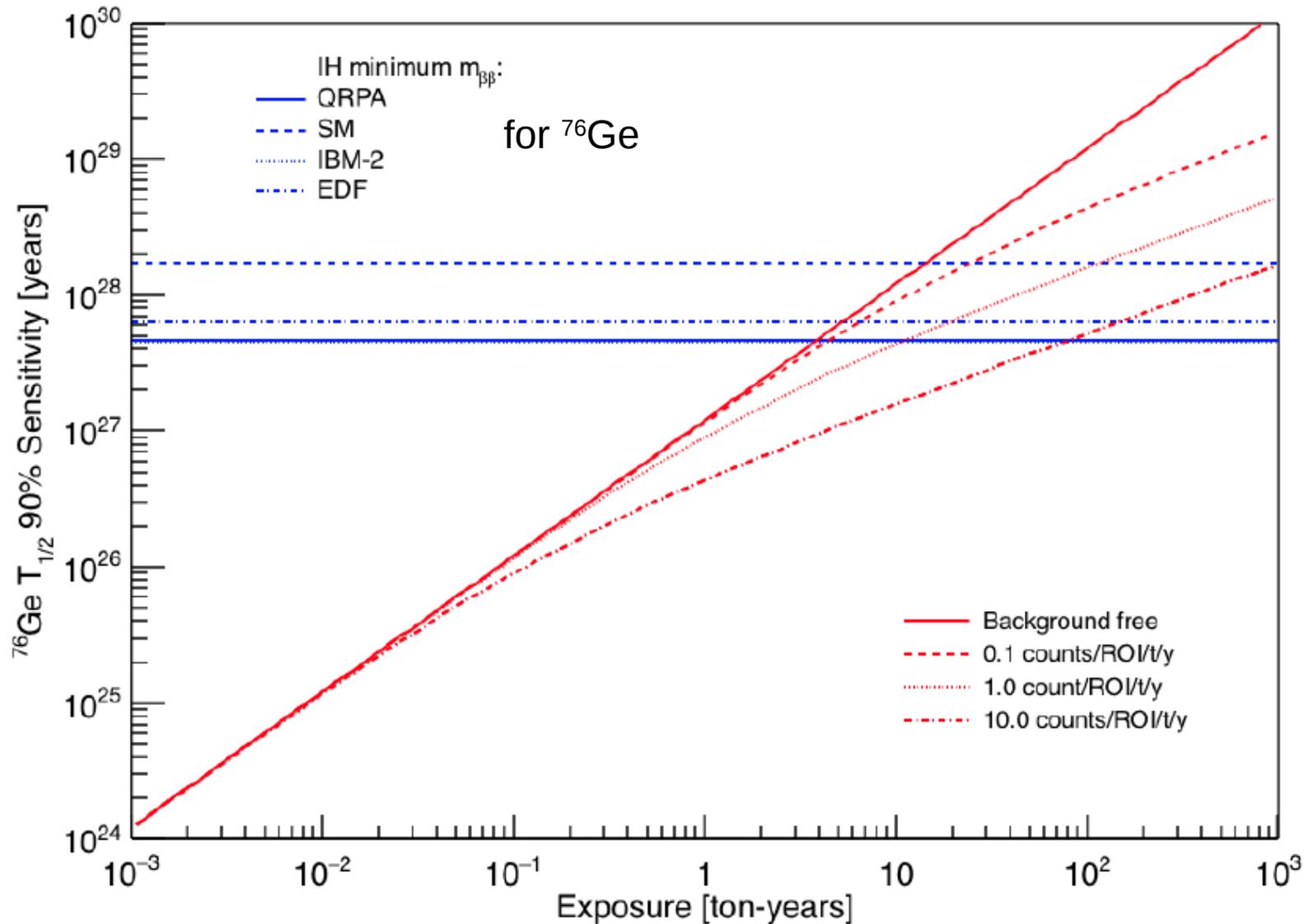
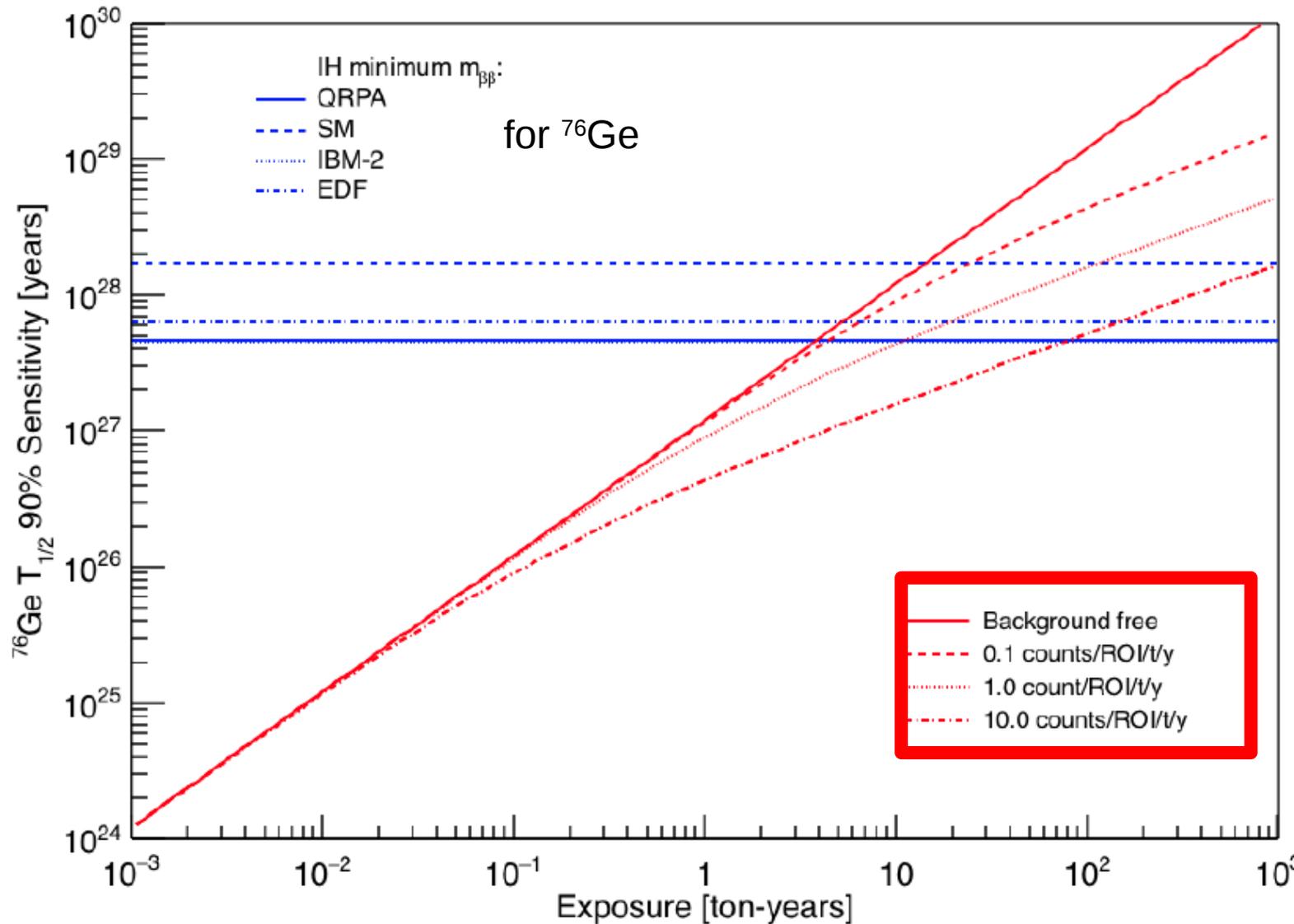


Fig: Courtesy J. Detwiler

Neutrinoless double-beta decay measurements



General thoughts about this type of experiment



counts /ROI /t /y:

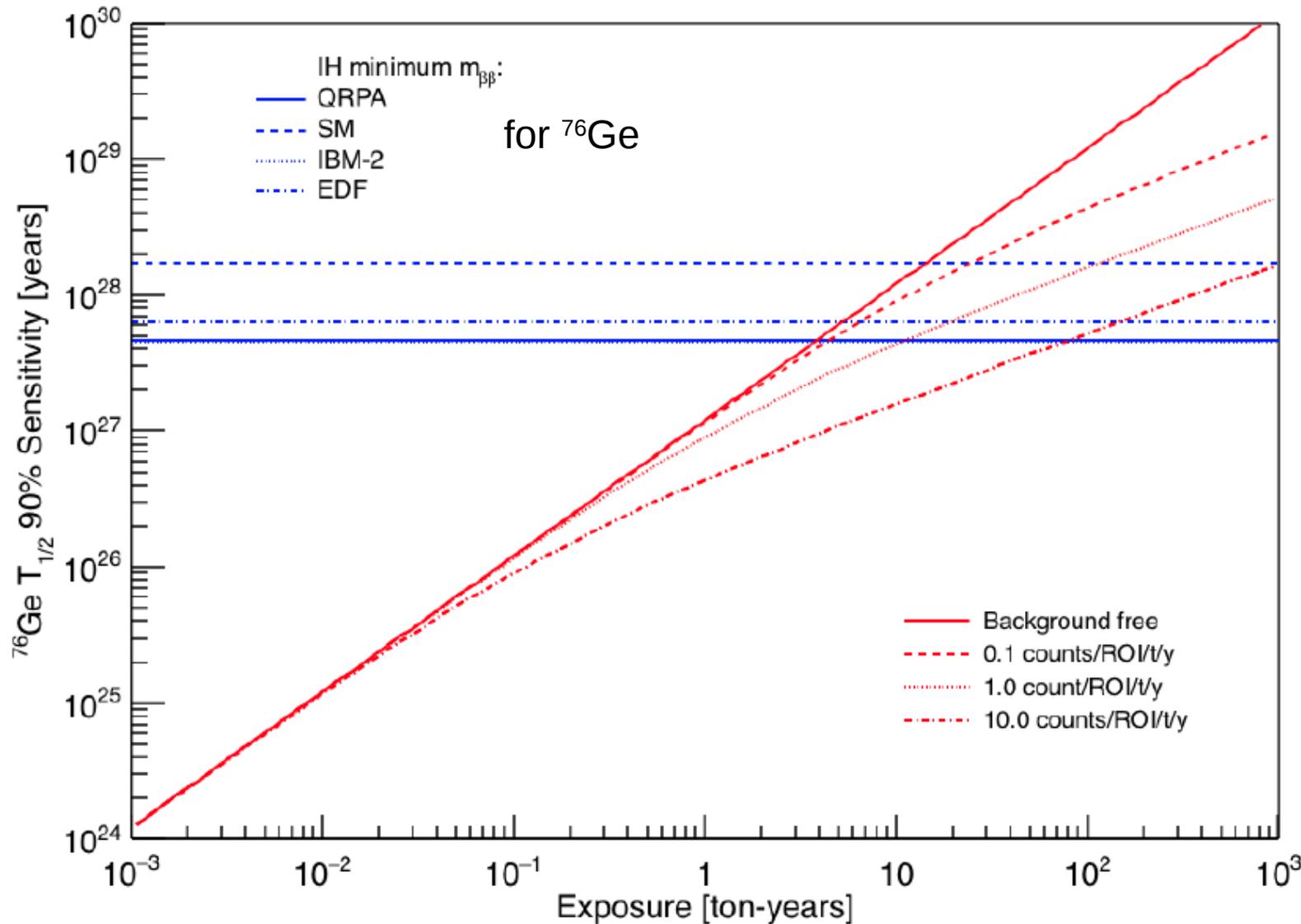
- ROI = $\sim 3\text{keV @ } 2\text{MeV}$
- t = ton of active detector material
- y = life time

Fig: Courtesy J. Detwiler

Neutrinoless double-beta decay measurements



General thoughts about this type of experiment



MJD goal:

< 3

normal detector
in a lab

~ $10^6 - 10^7$

Fig: Courtesy J. Detwiler

Experiments



different isotopes different ways to measure

past

Heidelberg-Moscow	^{76}Ge	ionization
Couricio	^{130}Te	bolometer
NEMO-3	$^{100}\text{Mo} / ^{82}\text{Se}$	tracking

current (running / in construction)

SuperNEMO	^{82}Se	tracking
EXO	^{136}Xe	liquid TPC
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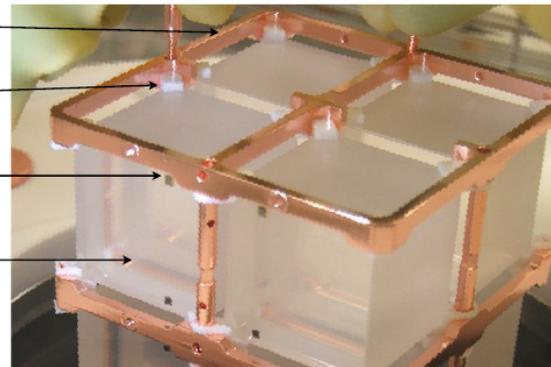
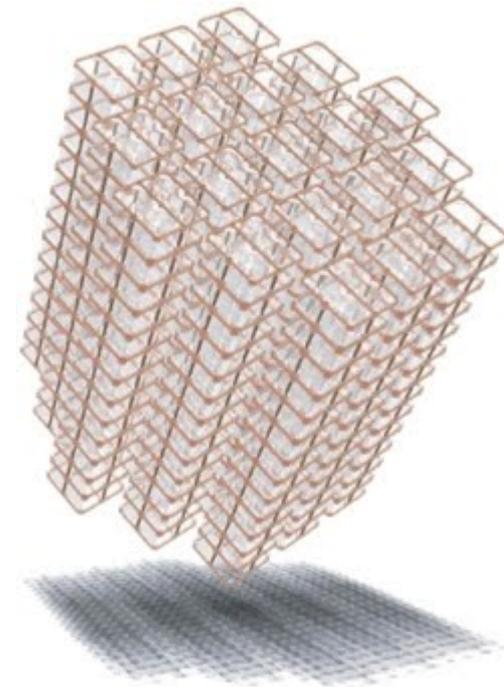
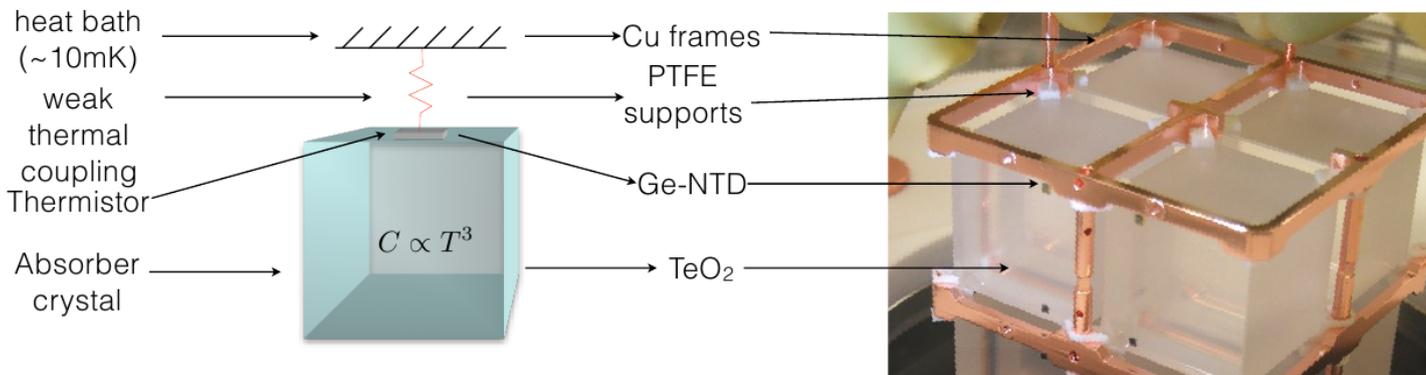
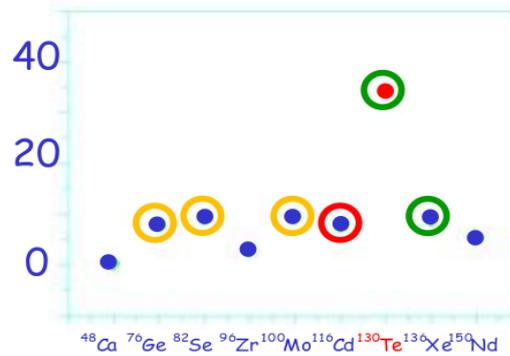
Bolometer, e.g. CUORE



Cryogenic Underground Observatory for Rare Events

- 741 kg natural tellurium (206kg ^{130}Te)
- source = detector
- 988 TeO_2 bolometers at 10-15mK @Gran Sasso
- 5 yr sensitivity $\sim 50\text{-}130$ meV

Isotopic abundance (%)

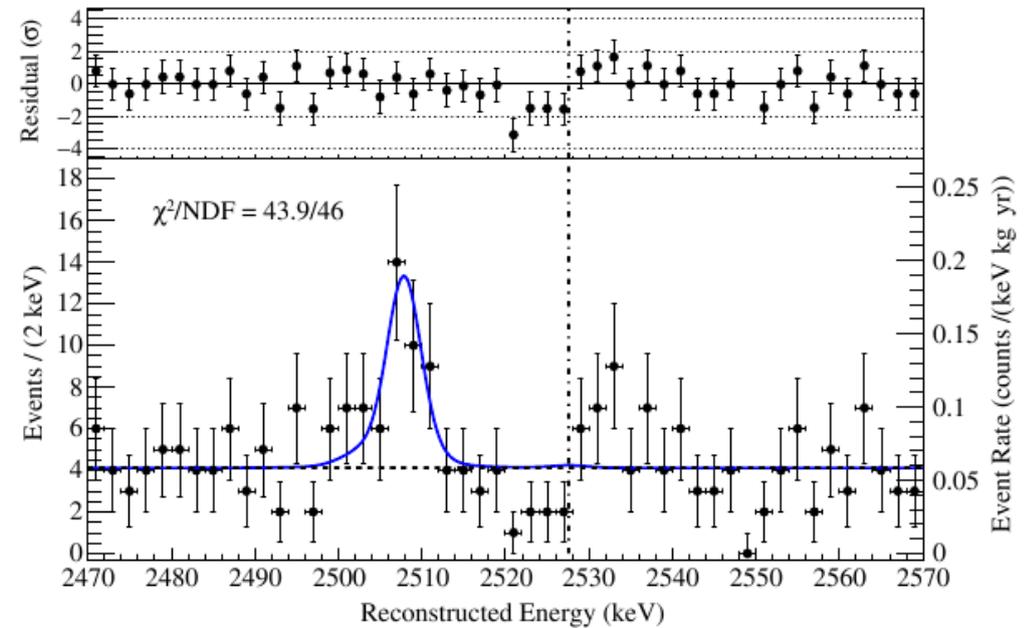


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- **in construction phase**
- first results from CUORE-0:
 - $T_{1/2} > 4 \cdot 10^{24}$ yr



PRL **115**, 102502 (2015)

Bolometer, e.g. CUORE

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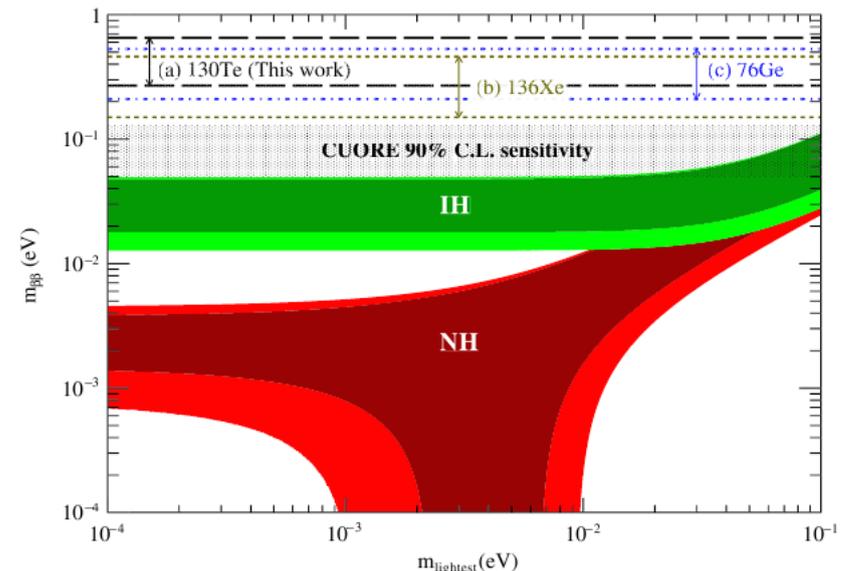
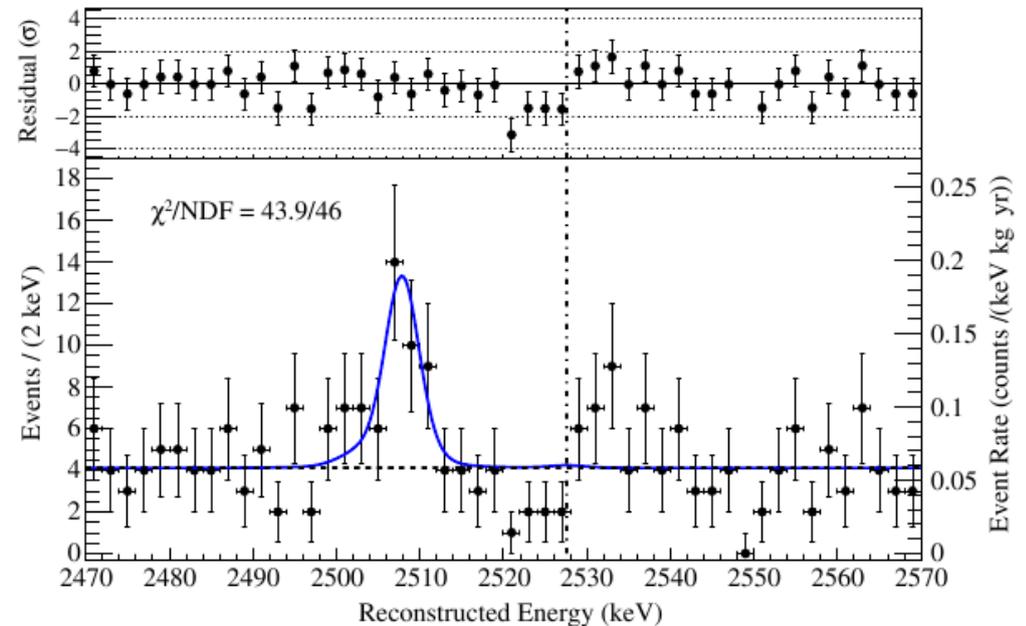


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- first results from CUORE-0:

- $T_{1/2} > 4 \cdot 10^{24}$ yr
- $m_{\beta\beta} < 270 - 760$ meV

<https://arxiv.org/abs/1604.05465>

PRL **115**, 102502 (2015)

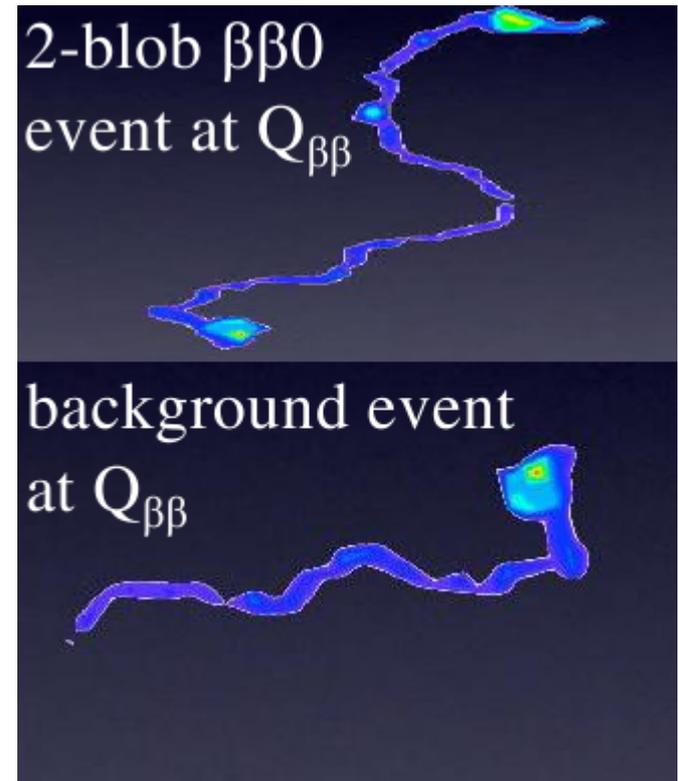
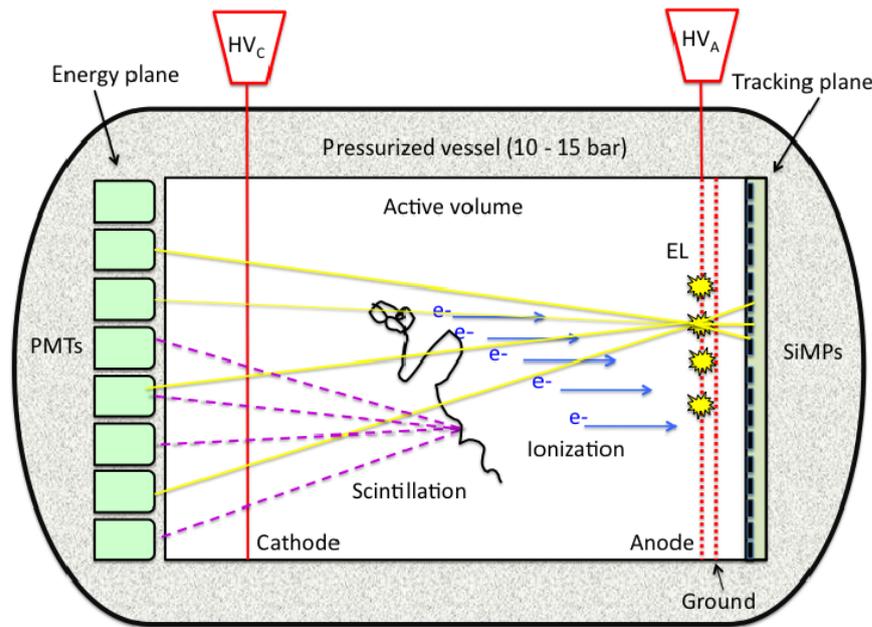


TPCs, e.g. NEXT-100



Neutrino Experiment with a Xenon TPC

- 90 kg enriched Xenon (90%)
@Canfranc
- source = detector
- tracking capability
- 5 yr sensitivity ~ 100 meV



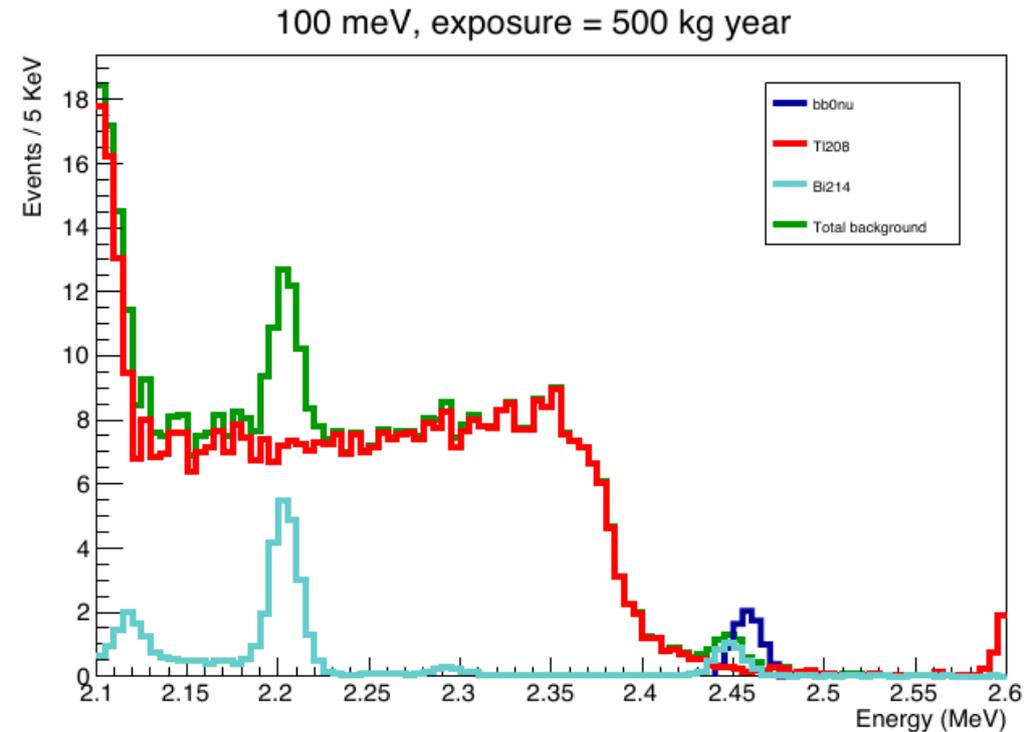
<http://arxiv.org/abs/1307.3914>

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- tracking capability
- 5 yr sensitivity ~ 100 meV
- NEXT-100 full data taking 2018 *currently NEW, a 10kg TPC*



simulation of *NEW* background

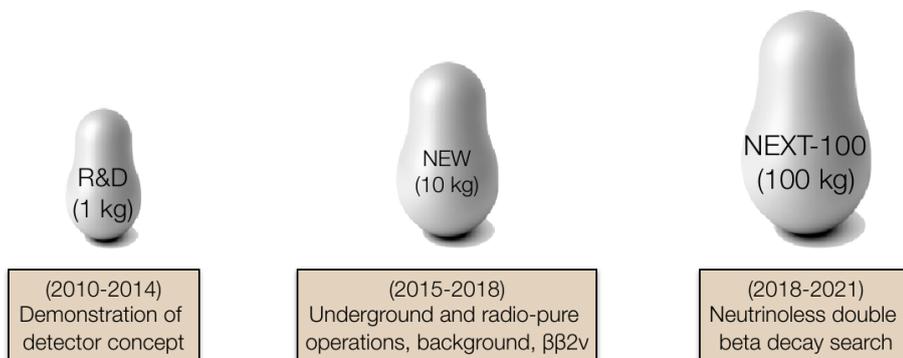


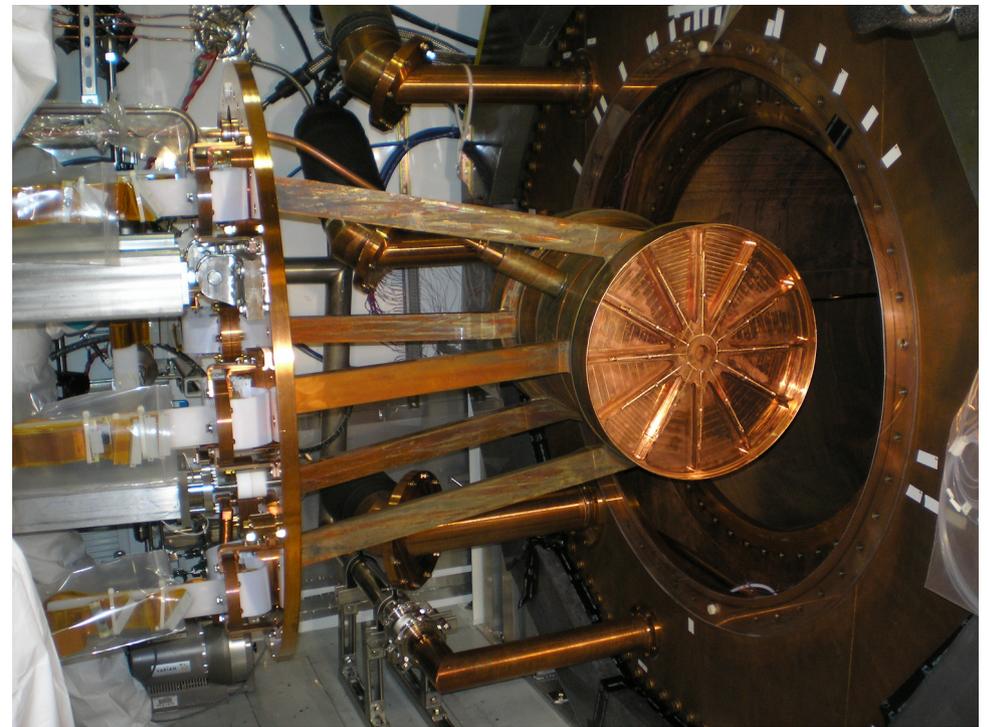
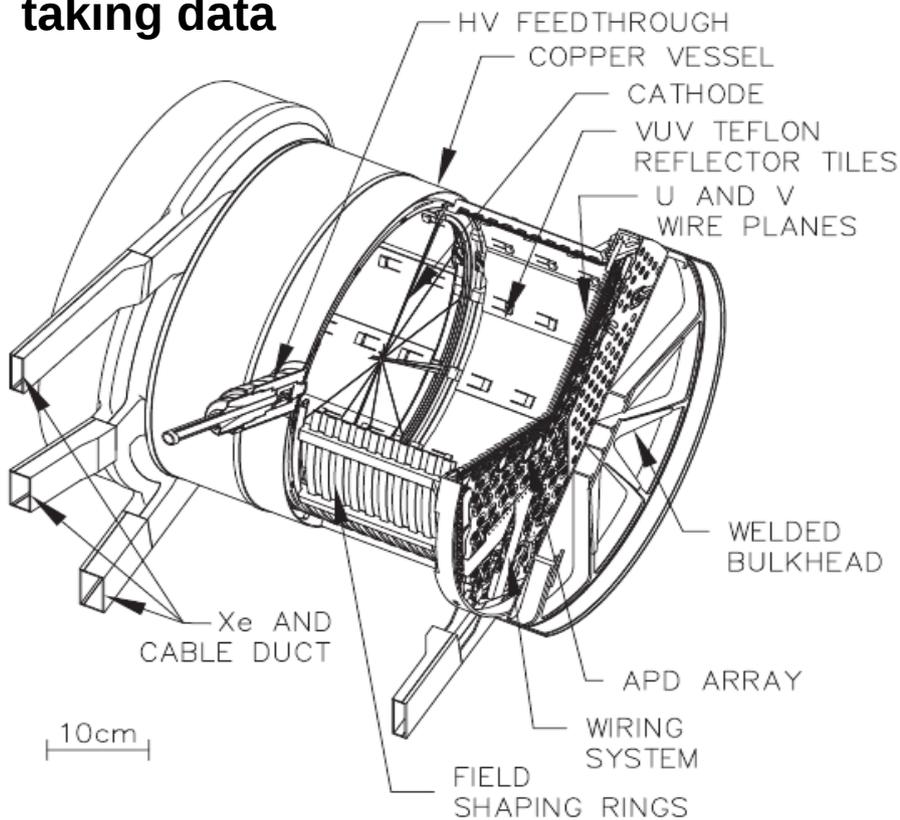
figure from Wrights talk at Neutrino2016

liquid TPCs, EXO-200



Neutrino Experiment with a Xenon TPC

- 200 kg enriched Xenon (80%) @WIPP
- source = detector
- current sensitivity $\sim 190\text{-}450$ meV
- **taking data**

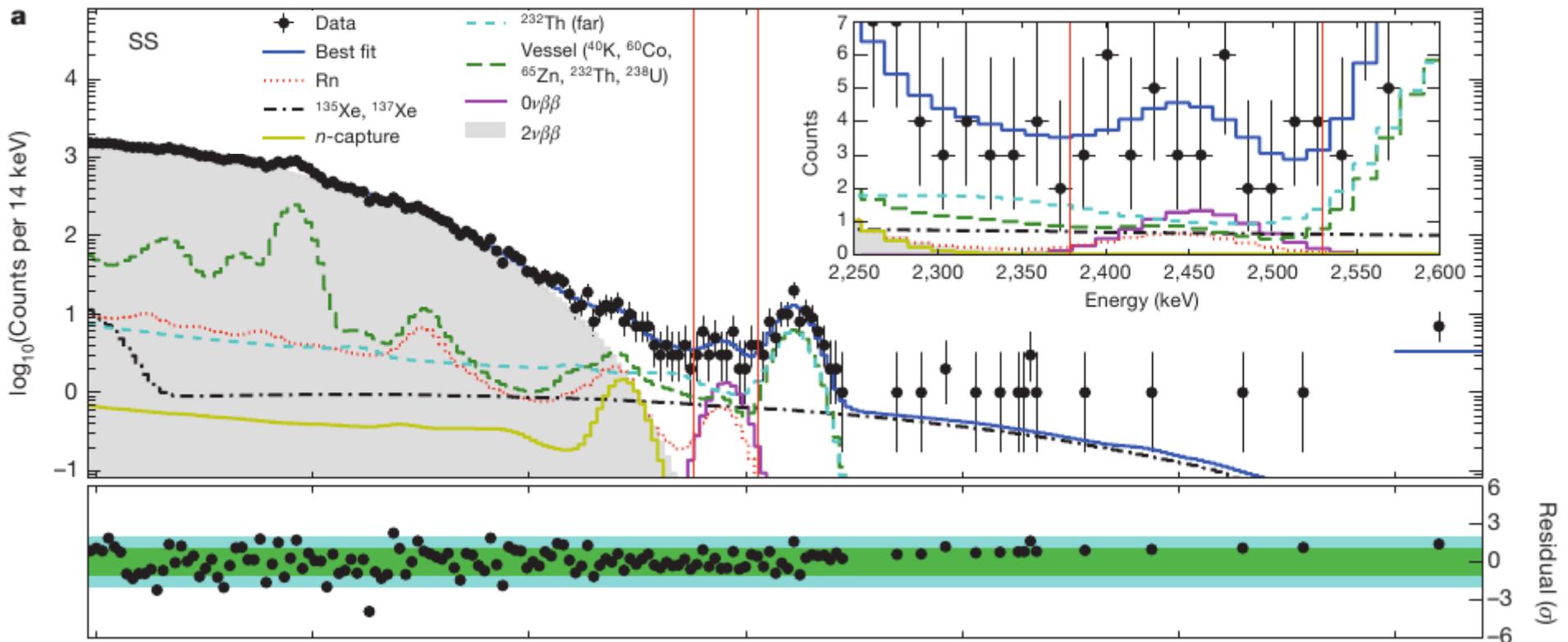


liquid TPCs, EXO-200

Enriched Xenon Observatory



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Nature **510** 229 (2014)

PRL **107**, 212501 (2011)

Ralph Massarczyk

5/15/2016

33

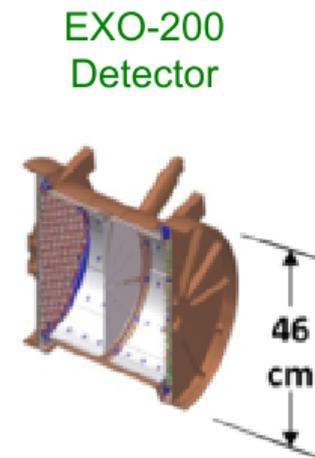
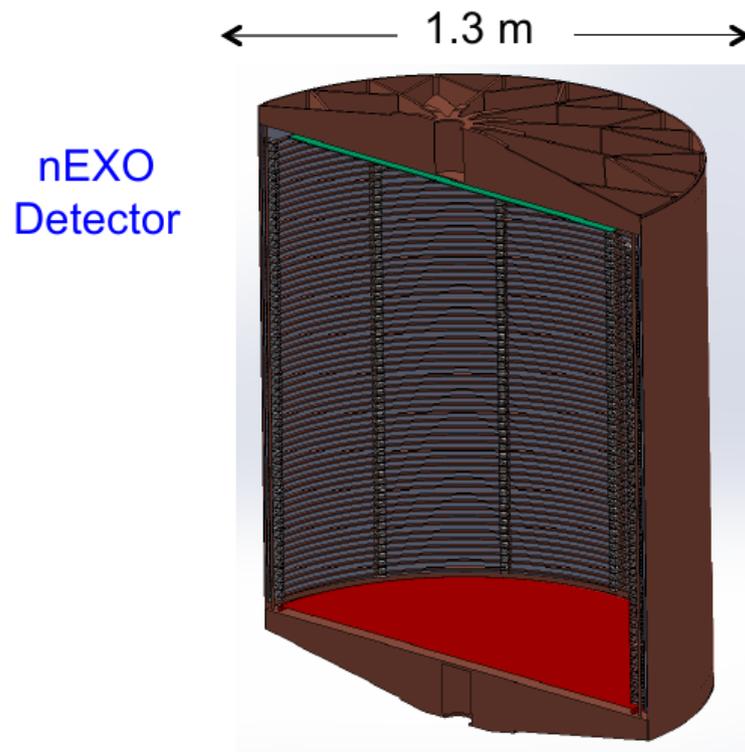
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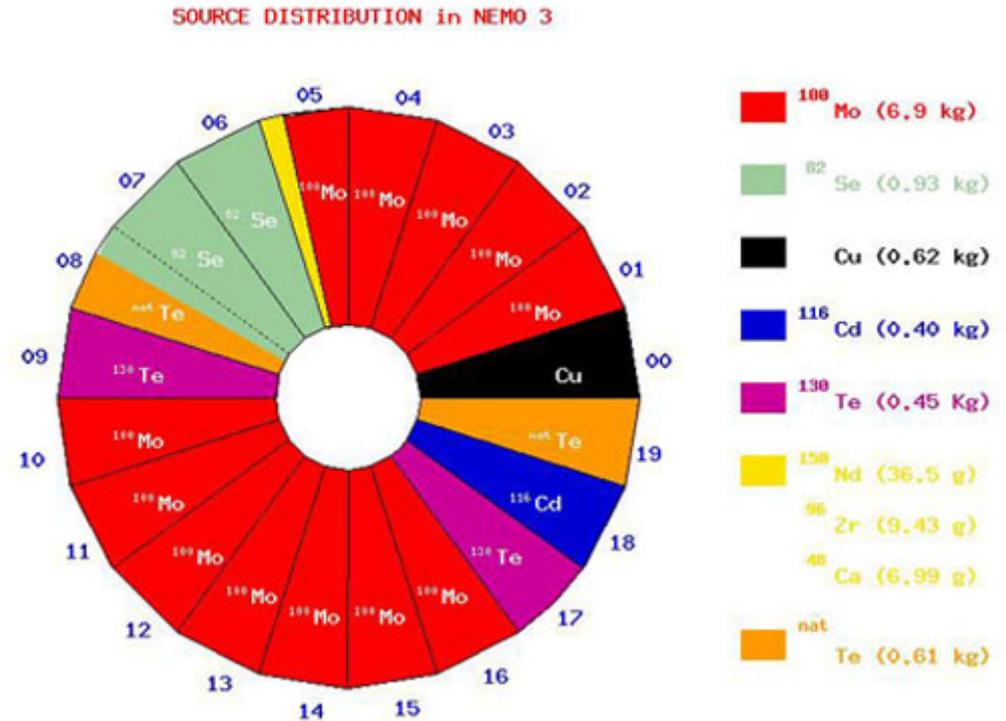
nEXO (4.7 tons)



Tracking Detectors, e.g. NEMO-3



- 10 kg (7kg ^{100}Mo , 1kg ^{82}Se ,...) enriched material @Modane
- source \neq detector



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- source \neq detector
- gaseous tracking detector around foils

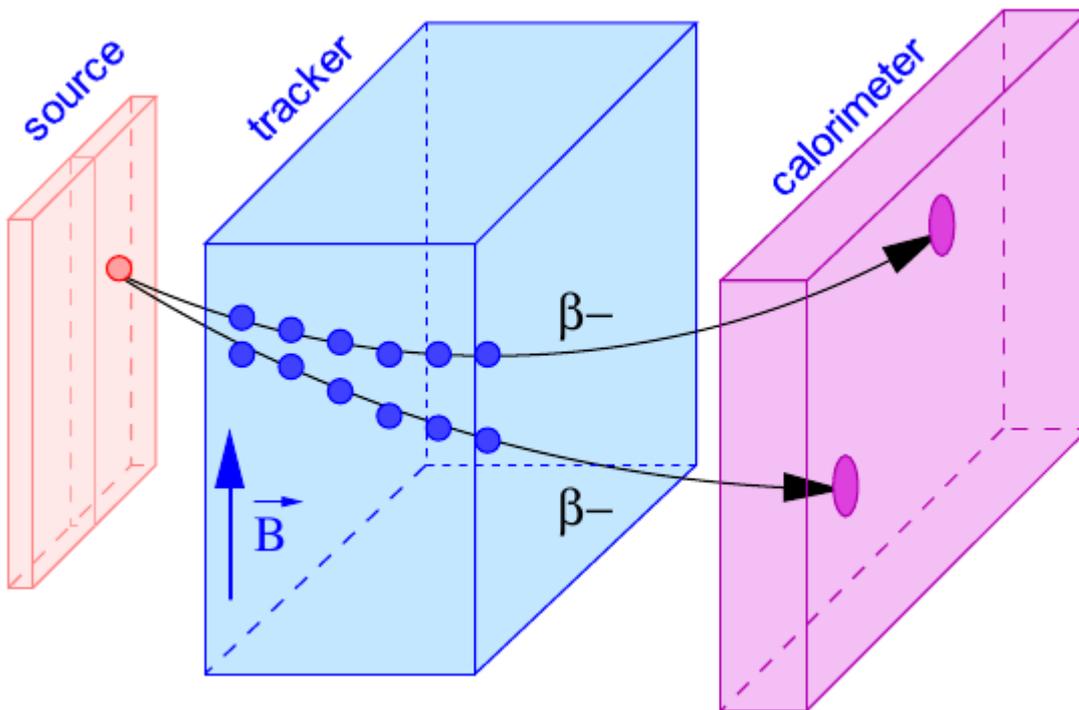
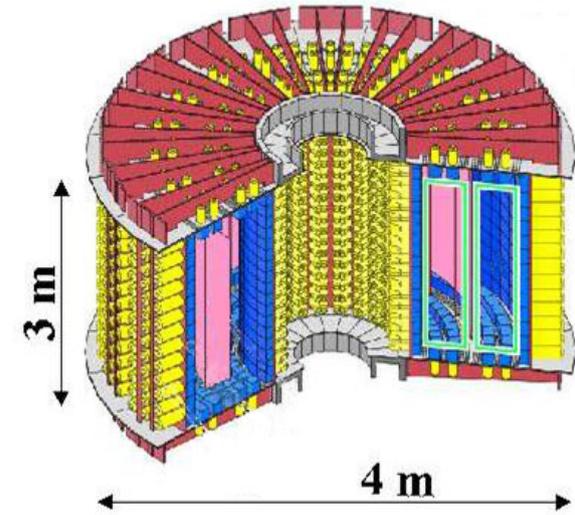
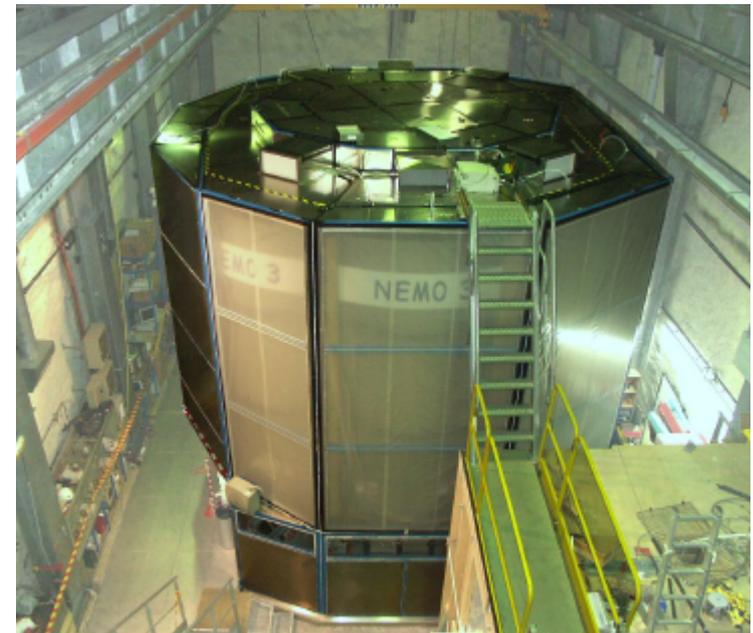


figure from Waters talk at Neutrino2016



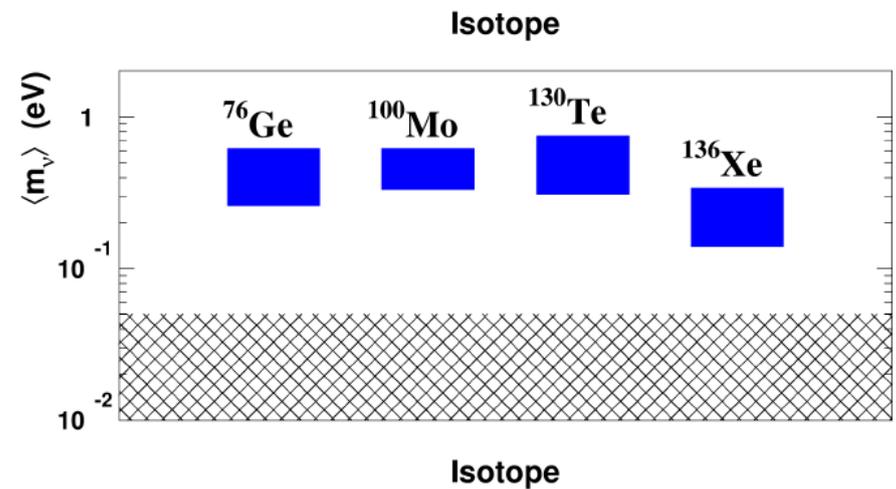
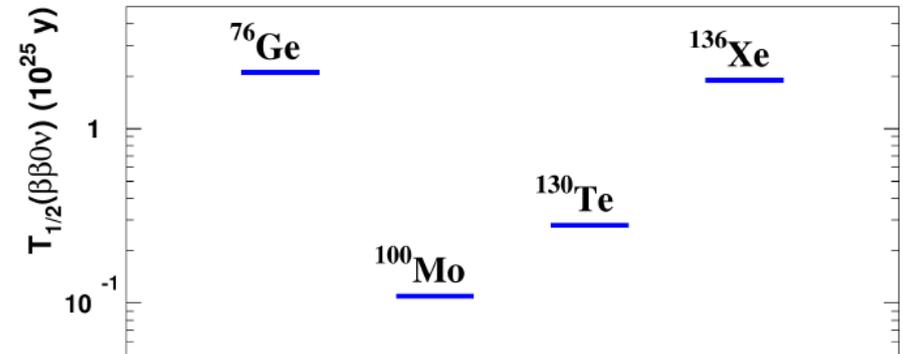
arXiv:1506.05825v4



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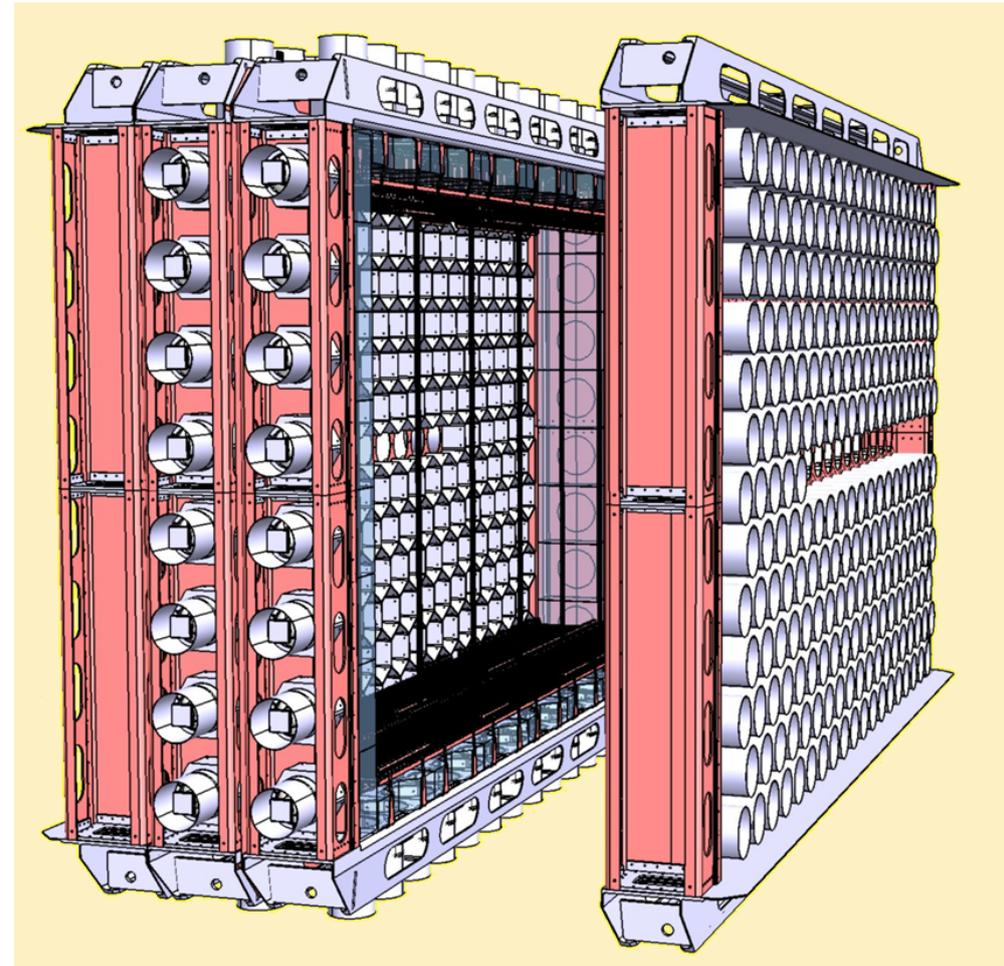


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- Nemo-3 until 2010, limits on various isotopes
- SuperNEMO m \sim 100kg, sensitivity \sim 50 meV
- Demonstrator running and taking data

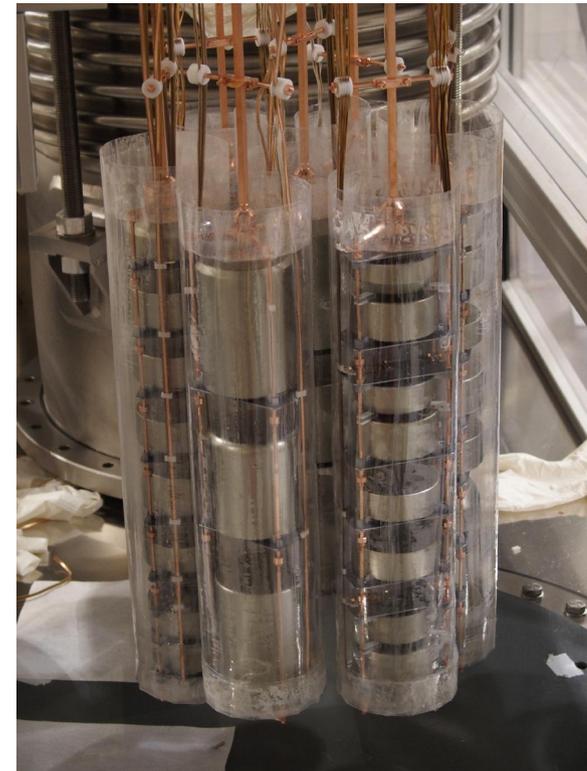
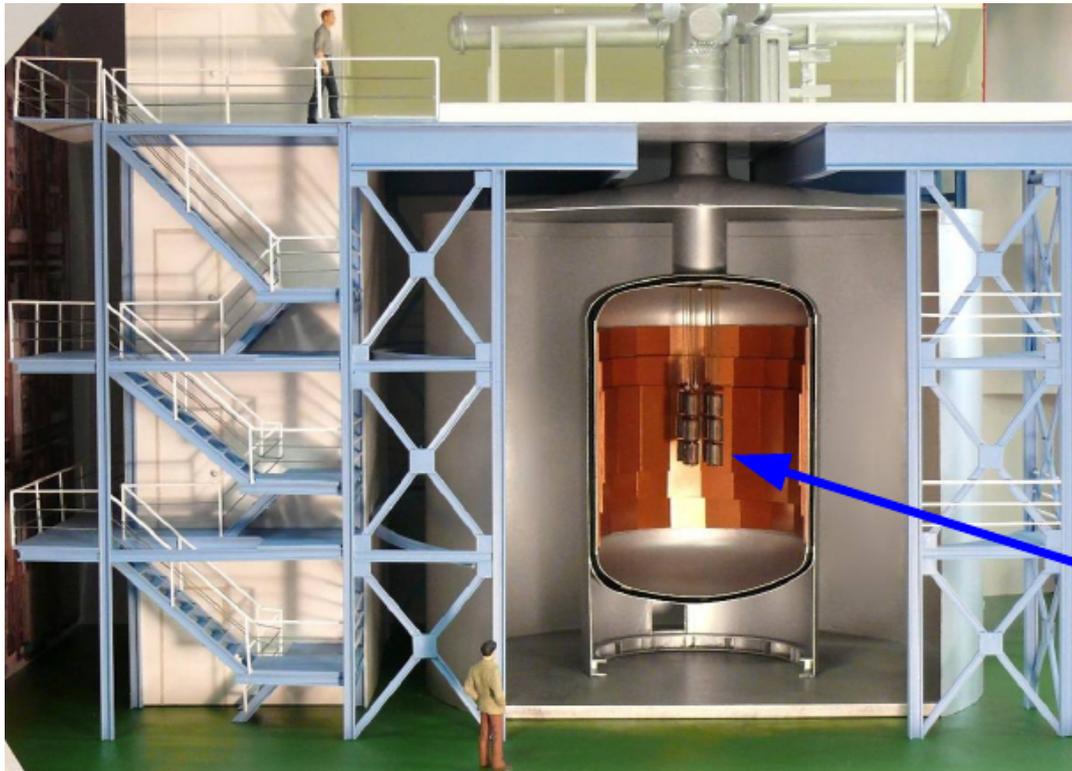
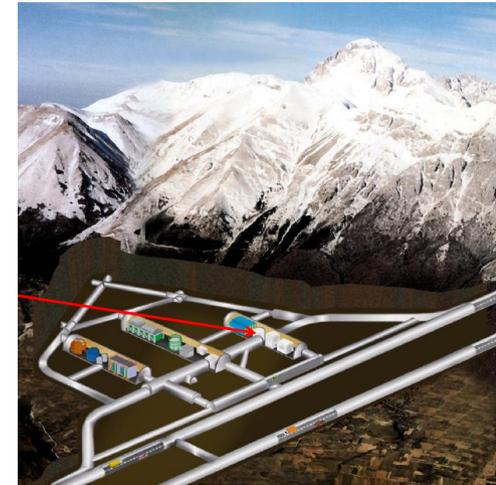


new NIM A Article in press, Povinec et al.

Germanium crystals, GERDA and MAJORANA



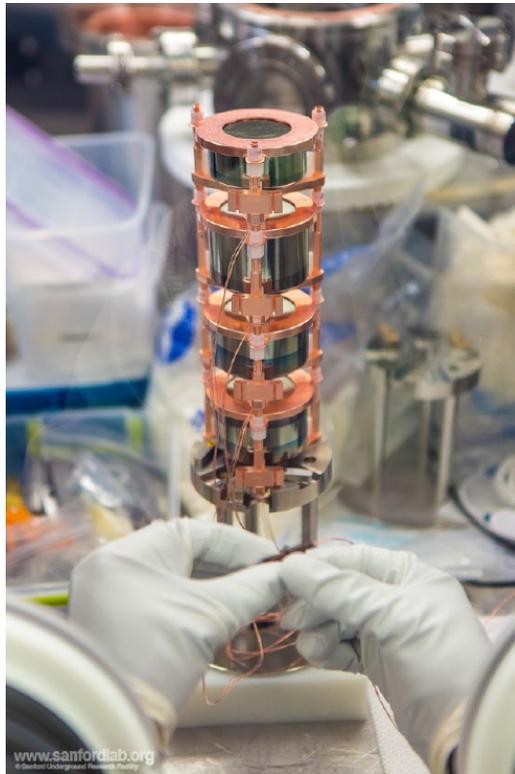
- highly enriched (up to 88%) and natural germanium detectors, total mass around 40kg each experiment
- detector in
 - lqAr (GERDA, @Gran Sasso)
 - vacuum cryostat (MAJORANA @SURF)



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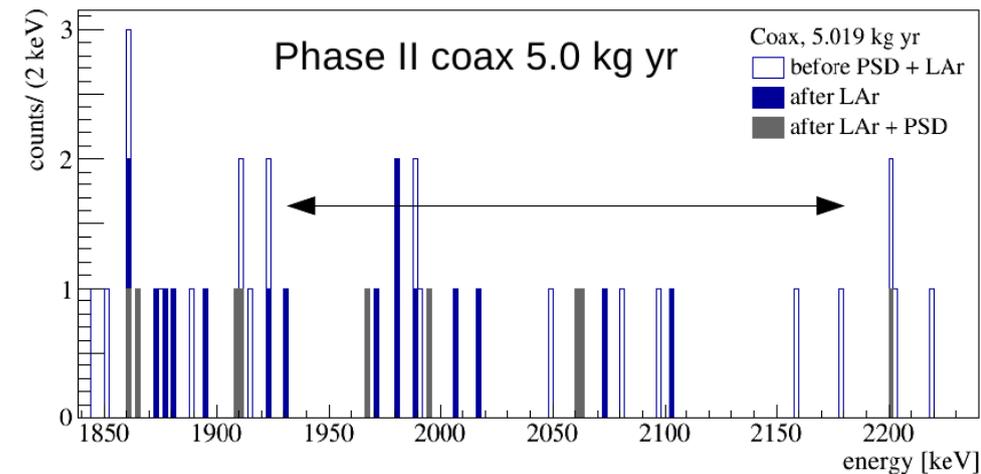
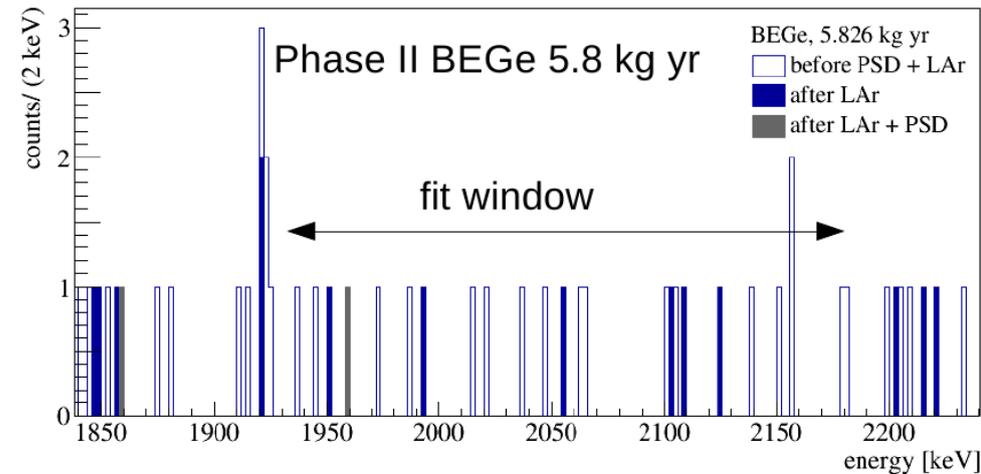


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- GERDA Phase I+II: $T_{1/2} > 3.5 \cdot 10^{25}$ yrs
- and on-going

PRL 111 (2013) 122503

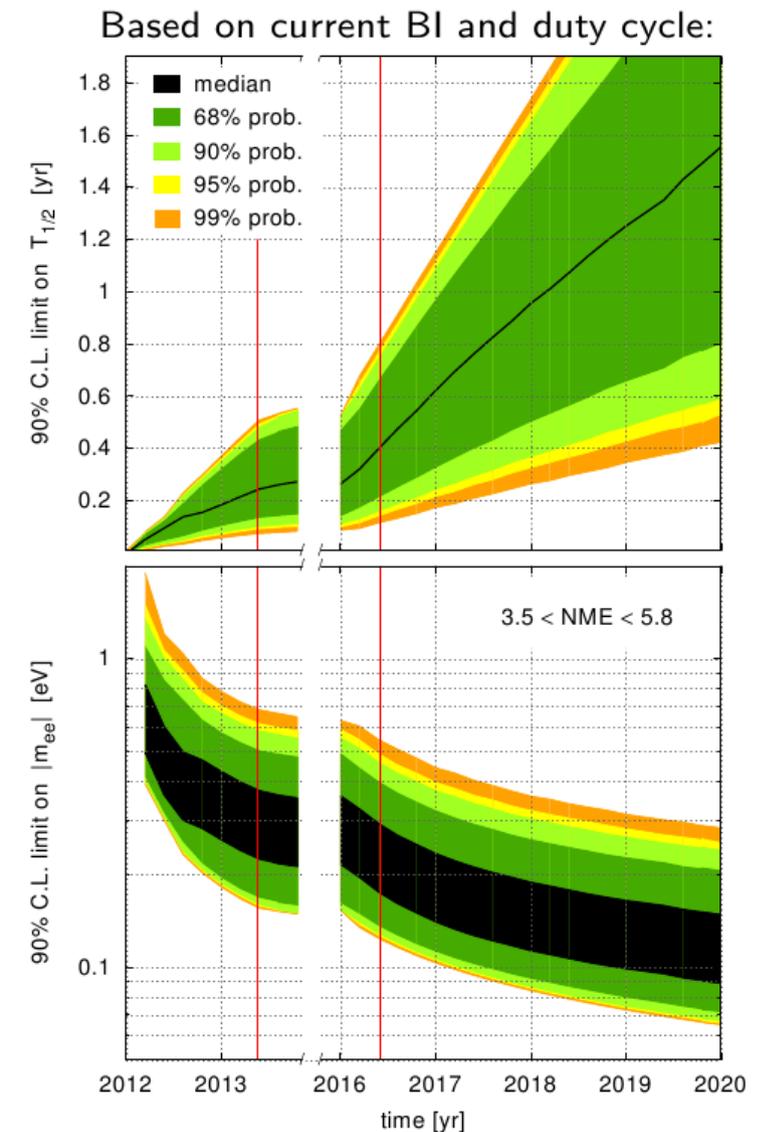


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both modules in shield in Aug 2016



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4.2 $\cdot 10^{25}$ yrs

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PRL 111 (2013) 122503

Neutrino2016

- MJD first module started data taking in '15
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comparable backgrounds (cts/t/yr/ROI):

MJD (module 1 only) 23^{+13}_{-10}

GERDA 3^{+4}_{-2} 14^{+9}_{-6}



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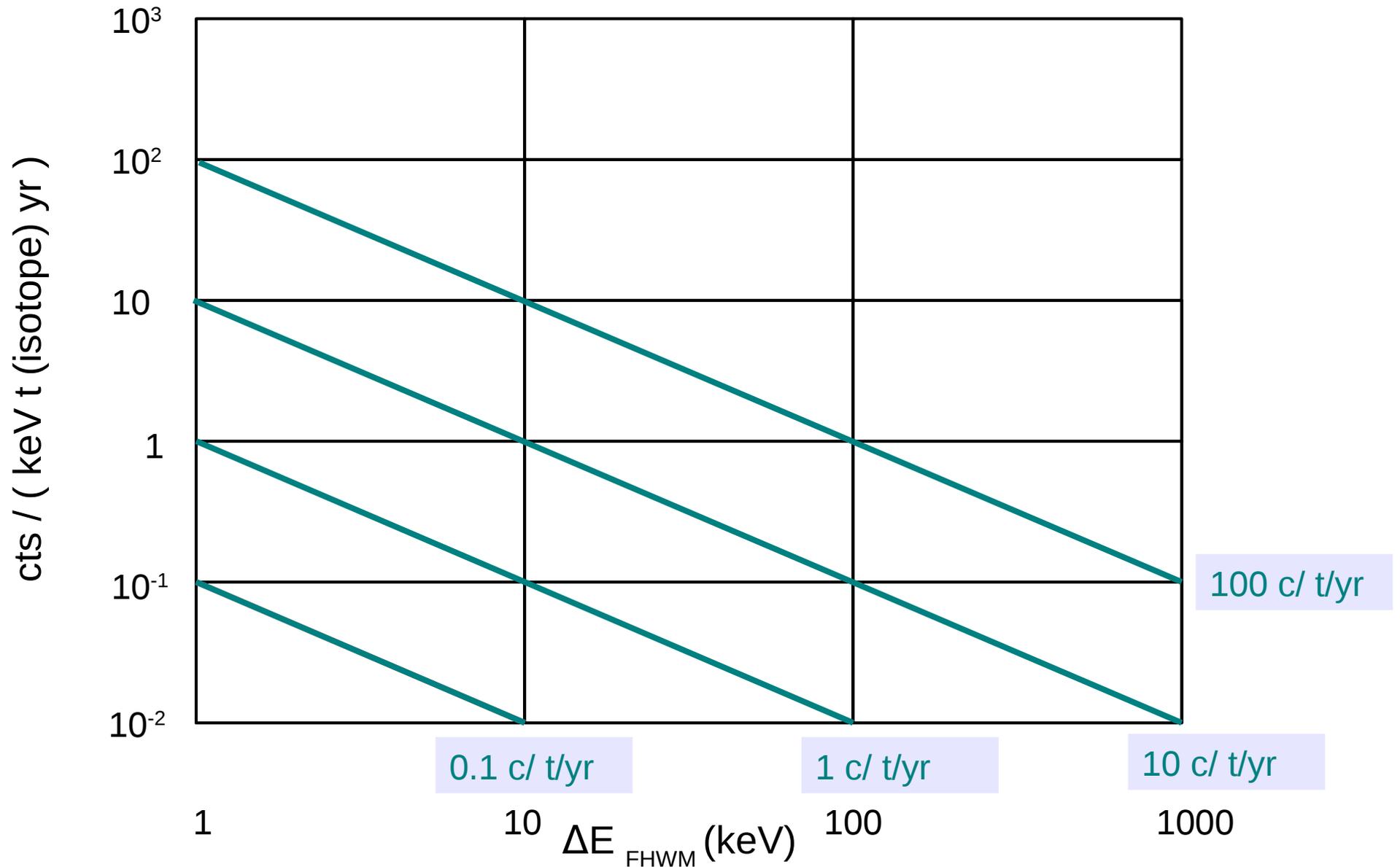
started efforts for a joined collaboration



Experiments



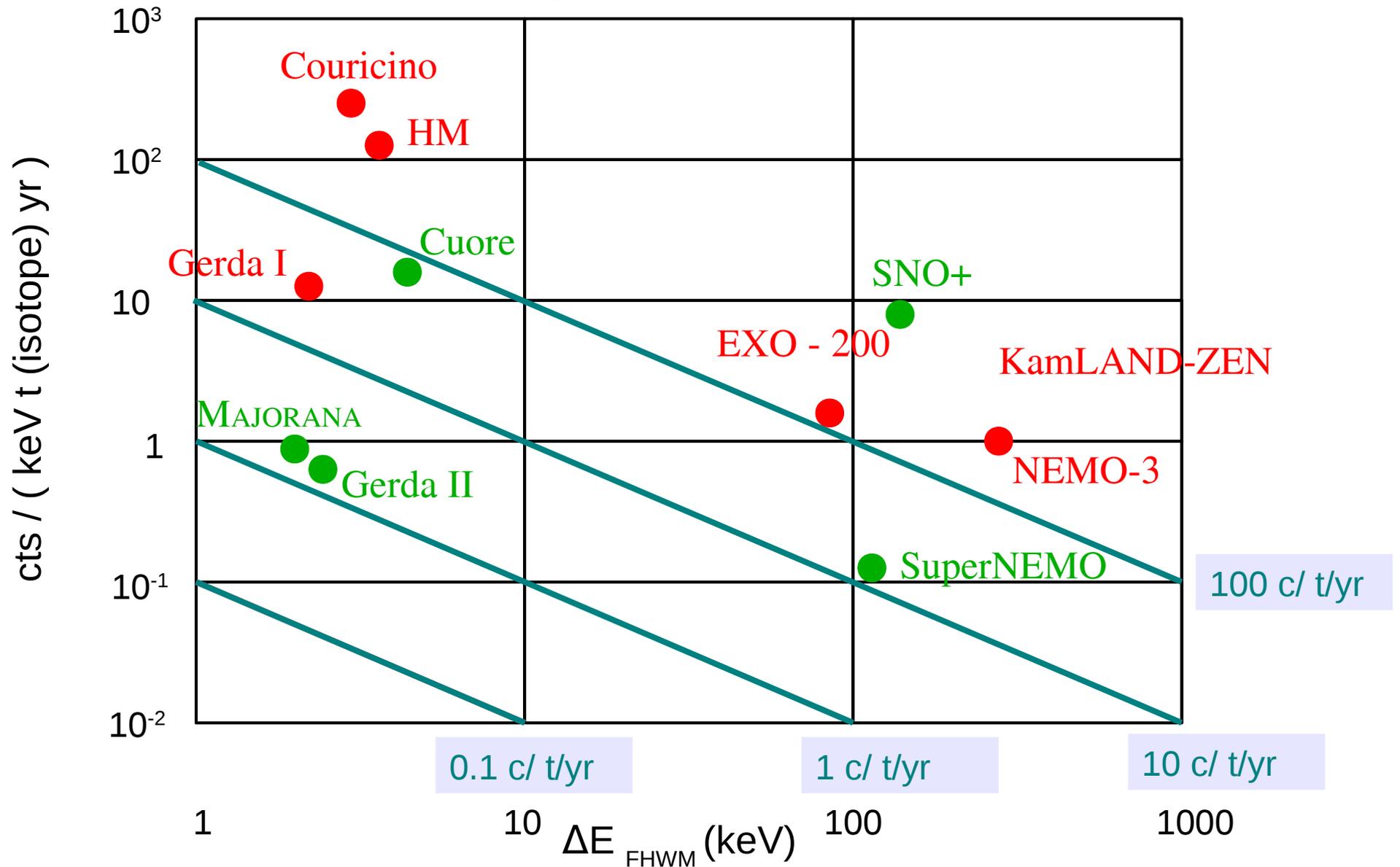
$$T_{1/2}^{0\nu} \propto \varepsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$



Experiments



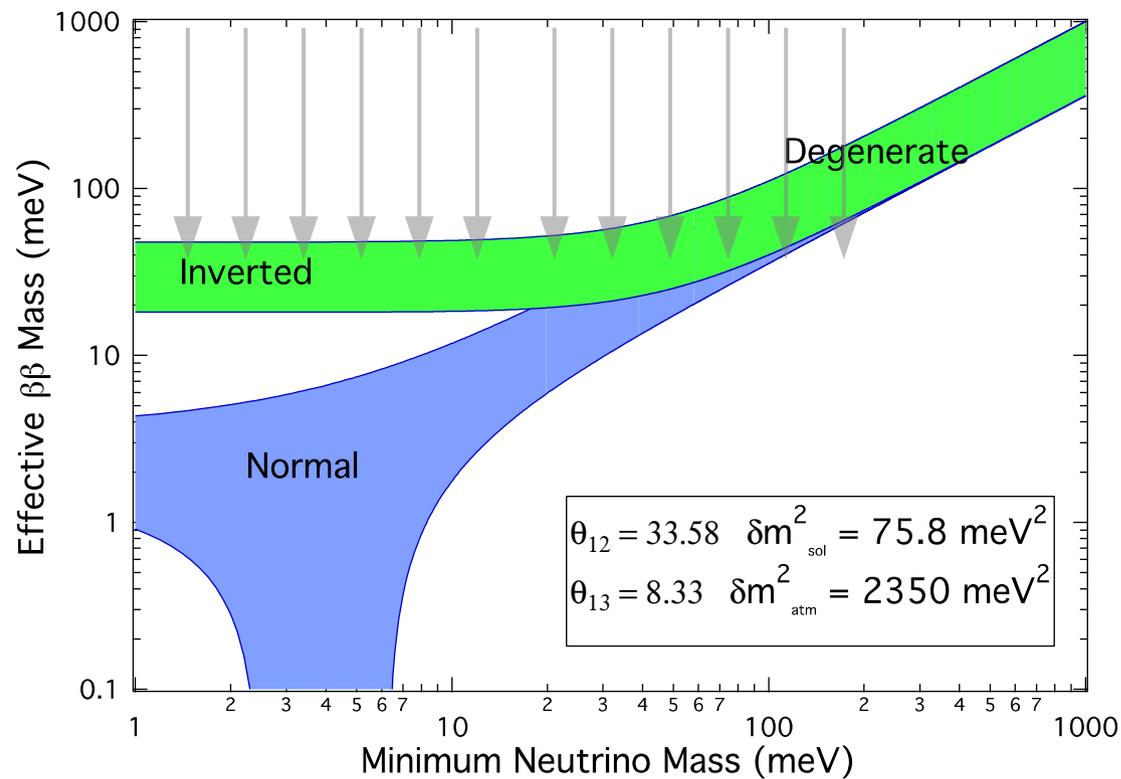
- In construction / started data taking / anticipated by MC
- done / running



Conclusions



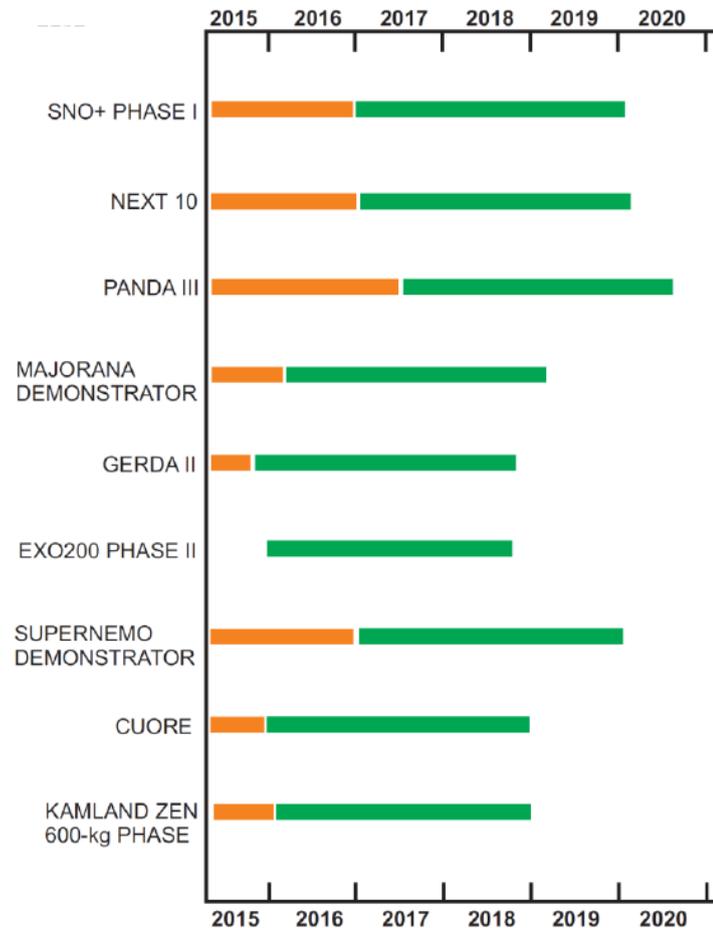
- Experiments on neutrinoless double-beta decay are an excellent tool to investigate neutrino mass-hierarchy, neutrino masses and therefore the nature of the neutrino itself.



Conclusions



- Experiments on neutrinoless double-beta decay are an excellent tool to investigate neutrino mass-hierarchy, neutrino masses and therefore the nature of the neutrino itself.
- Demonstrator experiments are running and first results show that it is reasonable to go to ton-scale experiments.



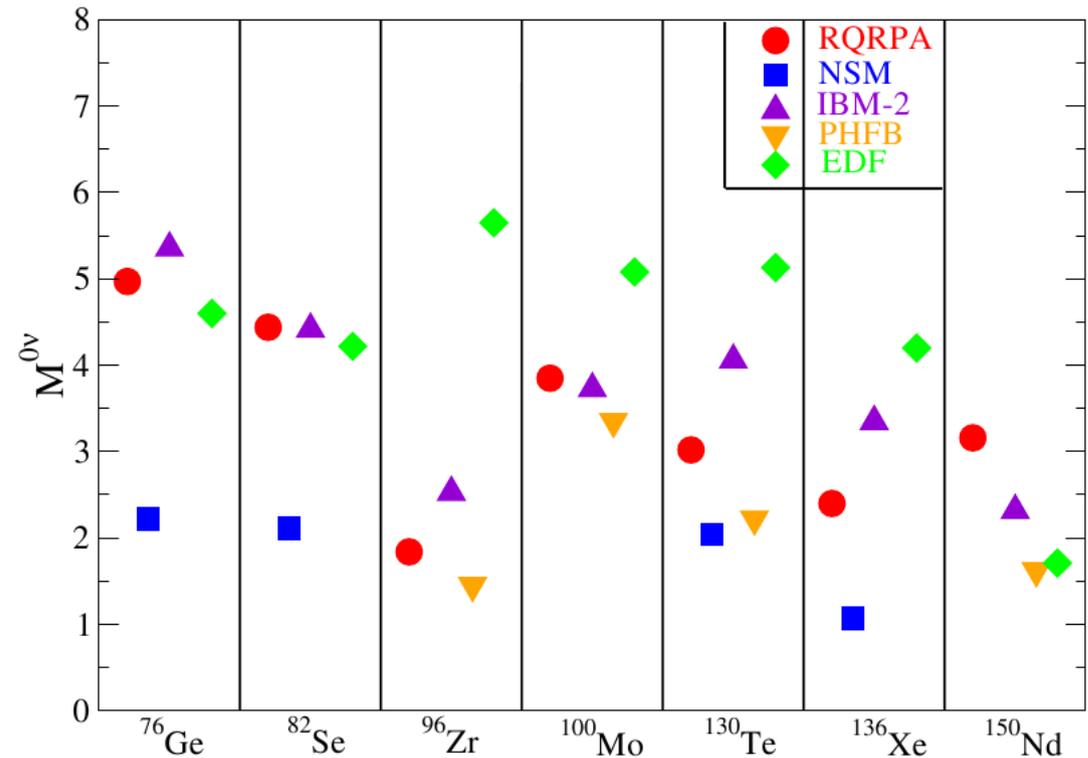
from
Neutrinoless Double Beta
Decay report
to the
NUCLEAR SCIENCE
ADVISORY COMMITTEE
(Nov 2015)

Conclusions



- Experiments on neutrinoless double-beta decay are an excellent tool to investigate neutrino mass-hierarchy, neutrino masses and therefore the nature of the neutrino itself.
- Demonstrator experiments show that it is reasonable to go to ton-scale experiments.
- We need a strong theoretical effort to support experimental findings.

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



Conclusions



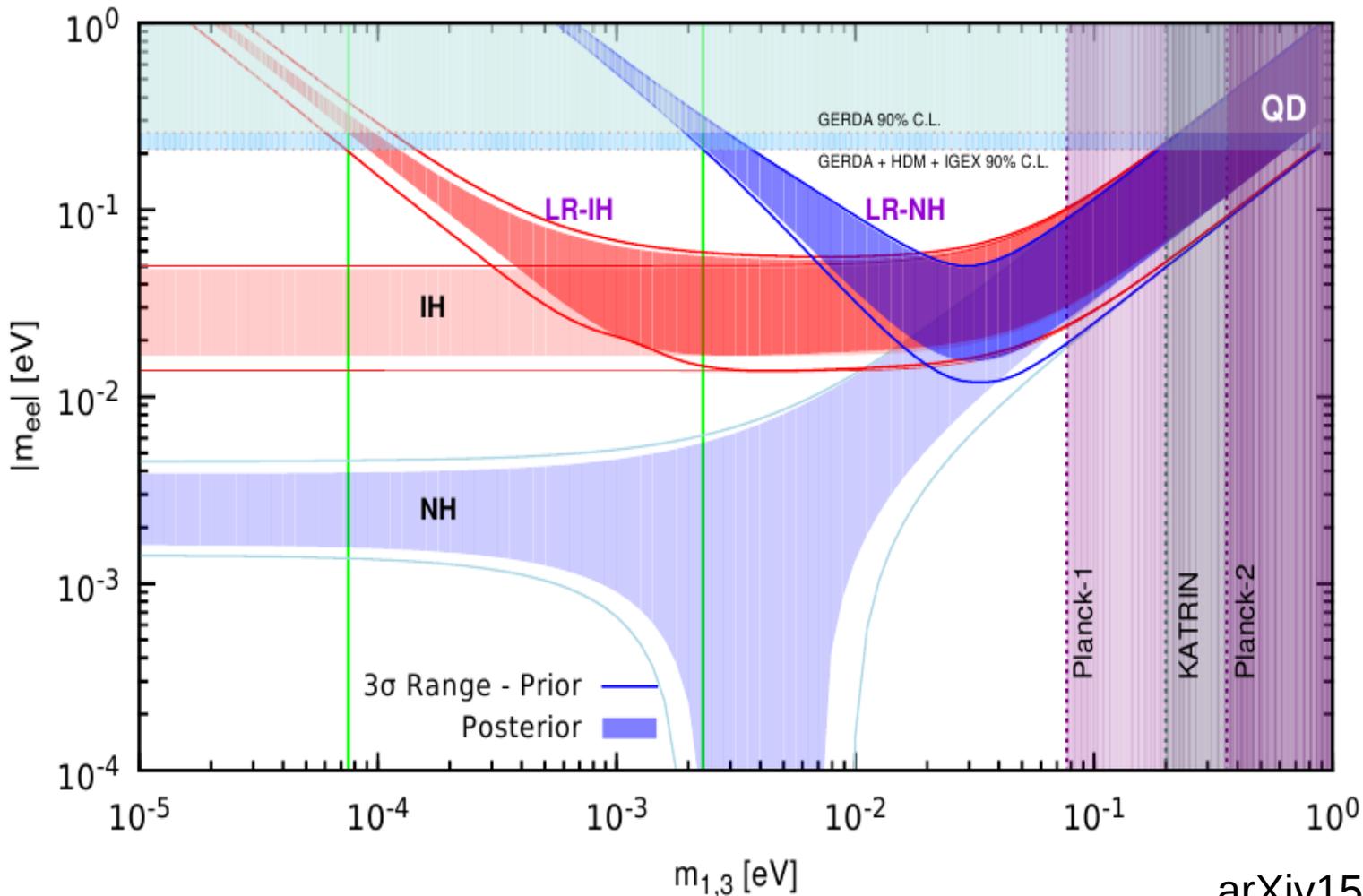
- Experiments on neutrinoless double-beta decay are an excellent tool to investigate neutrino mass-hierarchy, neutrino masses and therefore the nature of the neutrino itself.
- Demonstrator experiments show that it is reasonable to go to ton-scale experiments.
- We need a strong theoretical effort to support experimental findings.
- ... and/or theory might point to a new way to understand the nature of the neutrinos.

Outlook



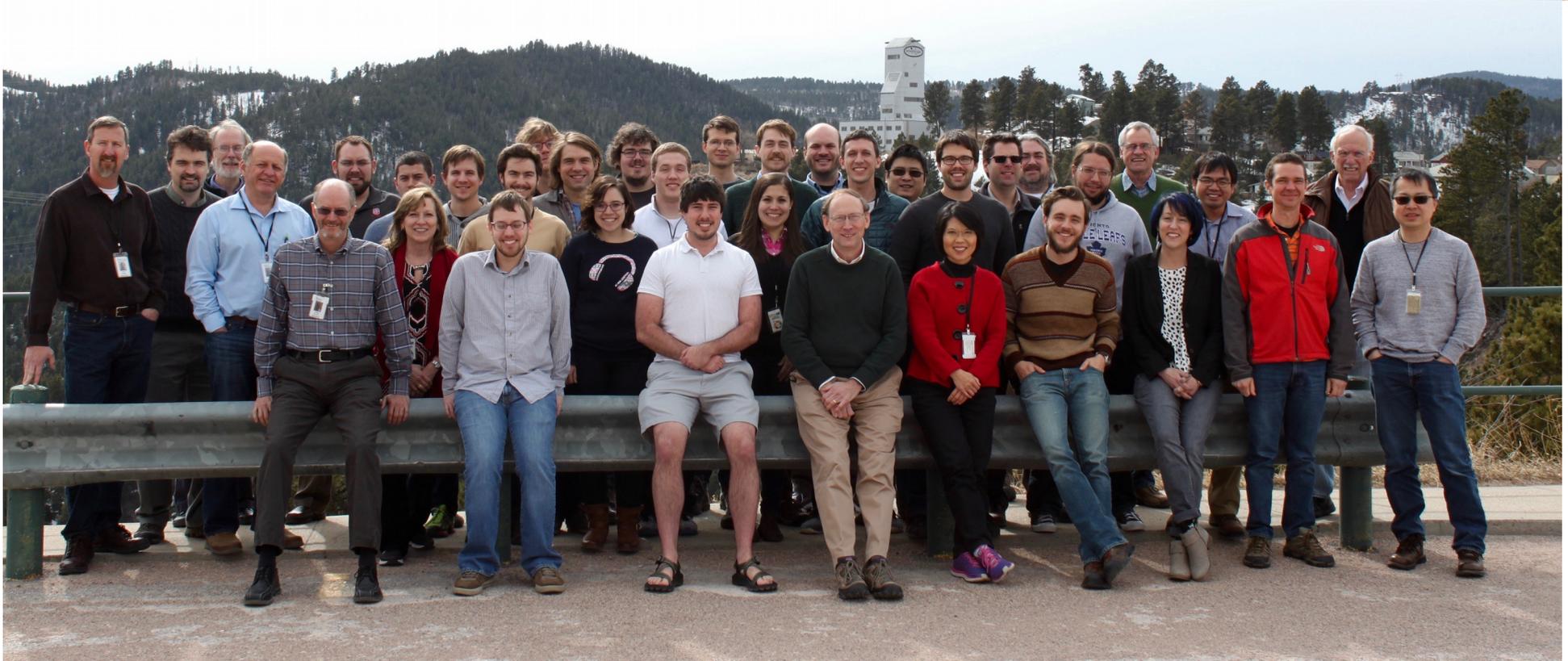
New experiments ... new theory

Left-Right symmetric type contributions to the effective Majorana mass parameter



arXiv1508.07286

MAJORANA collaboration



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