The neutrinoless double beta-decay: a brief overview

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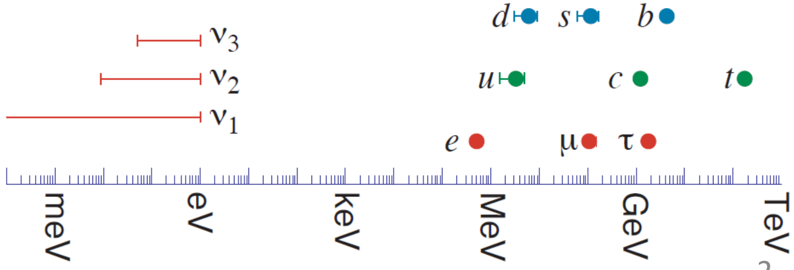
"The Most Tiny Quantity of Reality …"

F. Reines, ca. 1956

- … is the most abundant matter particle in the universe
- …plays important roles in :
  - Cosmology : BBN, CMB anisotropies & structure formation
  - Astrophysics : 99% of energy released in supernovae carried by neutrinos
- …has a small but non-zero mass,
  very different in scale from the other fermions : $\frac{m_\nu}{m_e} \sim 10^{-7}$
- Could the very small neutrino mass be related to physics at extremely high energy scales ? → "See-saw" mechanism ???
- Is there CP violation in the lepton sector and could this be related to the observed matter-antimatter asymmetry in the universe?

Masses of particles



What we can learn from 0νββ ?

- neutrinos have mass and they mix
- precision measurements of mixing angles and Δm^2
- nature of neutrinos :

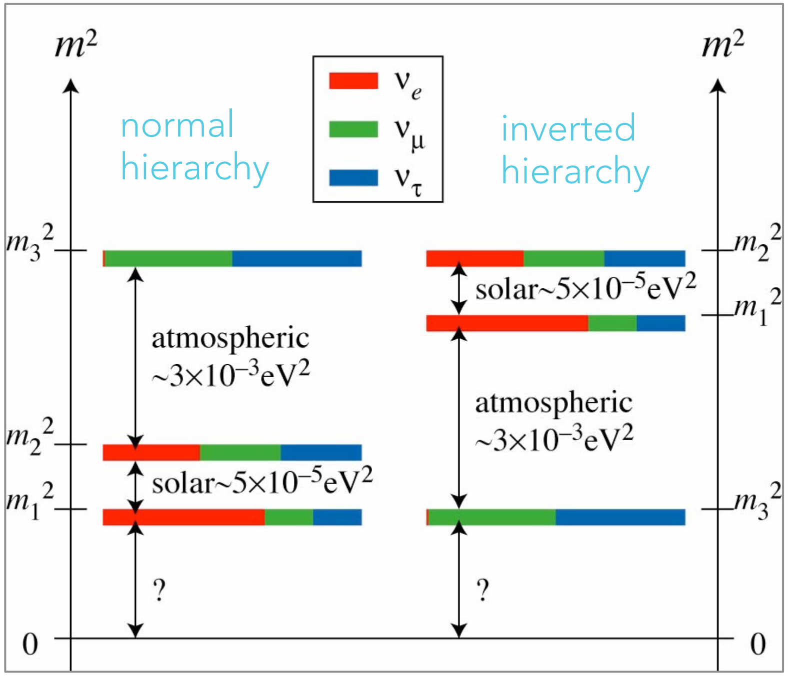
  Dirac ($\nu \neq \overline{\nu}$) or Majorana ($\nu = \overline{\nu}$)
- absolute neutrino mass scale :

  Only limits so far :
  - $m_{\nu e}$ < 2.2 eV (Tritium end-point)
  - $\Sigma m_{\nu i}$ < 0.3 eV (Cosmology)
- neutrino mass-hierarchy :
  - normal : $m_1 < m_2 < m_3$
  - inverted : $m_3 < m_1 < m_2$
- CP-violation in neutrino sector :
  - Dirac phase : $\delta \neq 0,\pi$
  - Majorana phases : $\alpha_{21}, \alpha_{31} \neq 0,\pi$

PMNS mixing matrix :

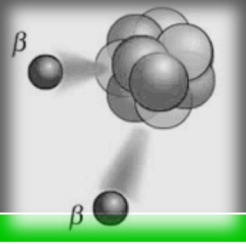
Majorana Phases

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$



Graphics taken from DOE Nuclear Science Advisory Committee report on 0νββ (24 April 2014)

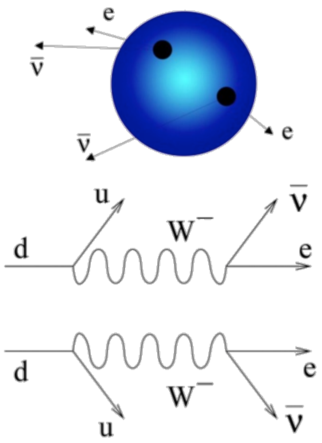
Double Beta Decay



2-neutrino double beta decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}$$

[Maria Goeppert-Meyer in 1935]

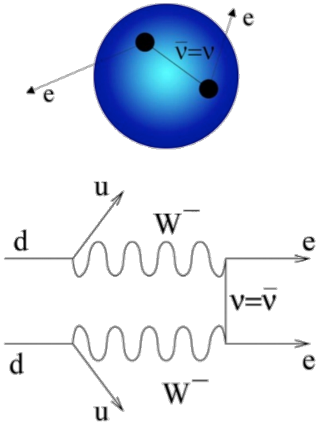


- 2nd order process allowed within SM
- first observed in 1987 (Elliott et al.)
- today measured in several isotopes

0-neutrino double beta decay

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$

[Furry in 1939]

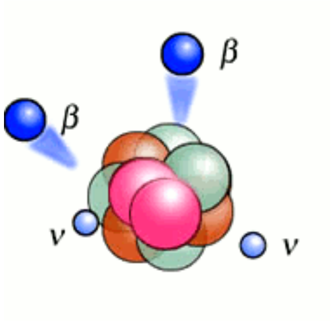


- Lepton number violating process ΔL=2
- forbidden in SM →new physics !!!
- rate (0νββ) << rate (2νββ)
- no positive detection so far, with the exception of Klapdor- Kleingrothaus *et al.*, however result been disproved.

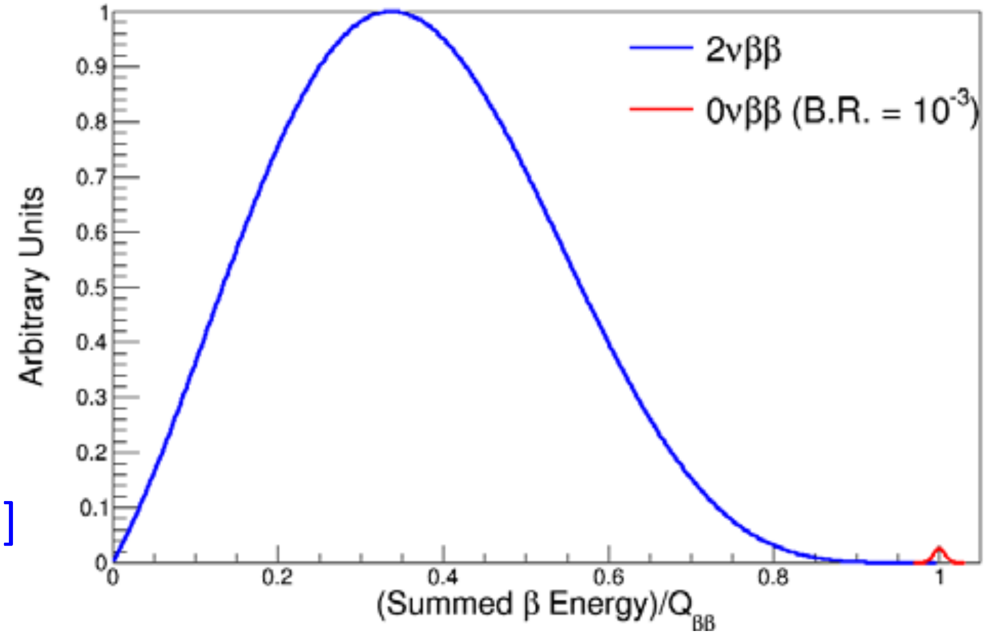
Experimental signature

Experiments measure the sum of the kinetic energies of the two emitted β s

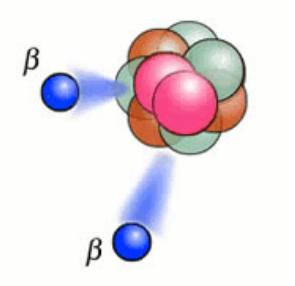
Signature: monochromatic line at the Q-value of the decay



(E1 + E2) ∈ [0,$Q_{\beta\beta}$]



Graphics taken from DOE Nuclear Science Advisory Committee report on 0νββ (24 April 2014)



(E1 + E2) / $Q_{\beta\beta}$ ≈ 1

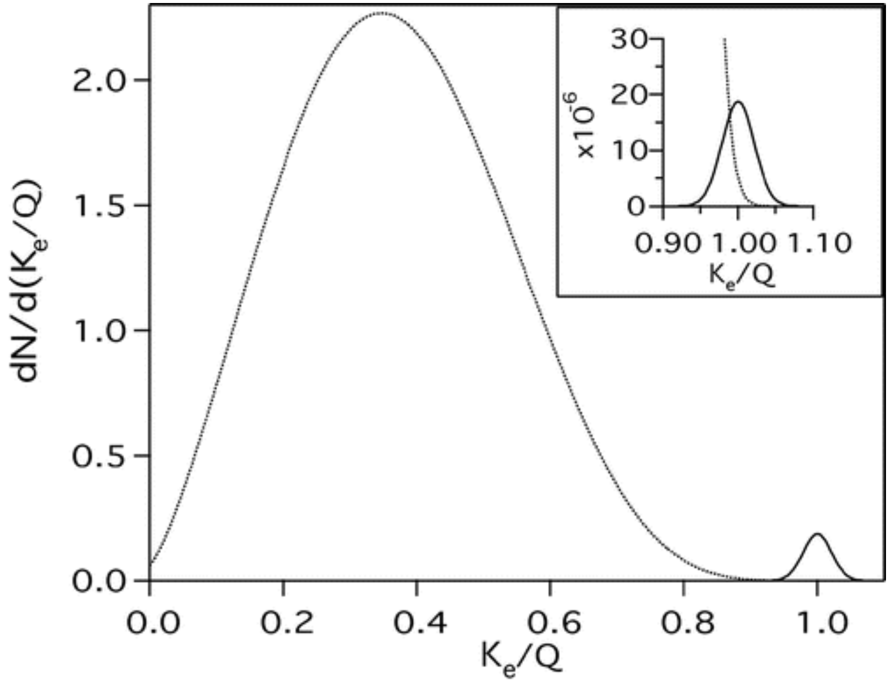
Energy resolution!!

Irreducible background

Experiments measure the sum of the kinetic energies of the two emitted β s

Signature: monochromatic line at the Q-value of the decay

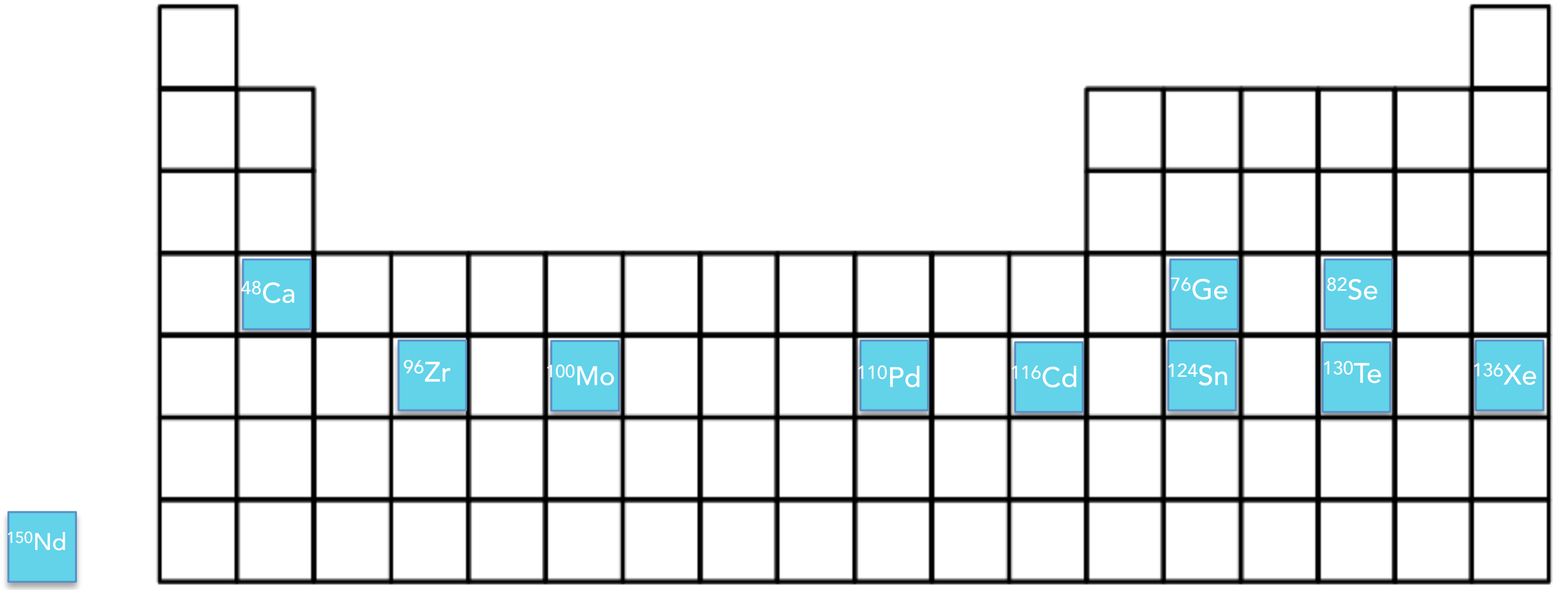
2νββ irreducible background:



good energy resolution ΔE necessary!

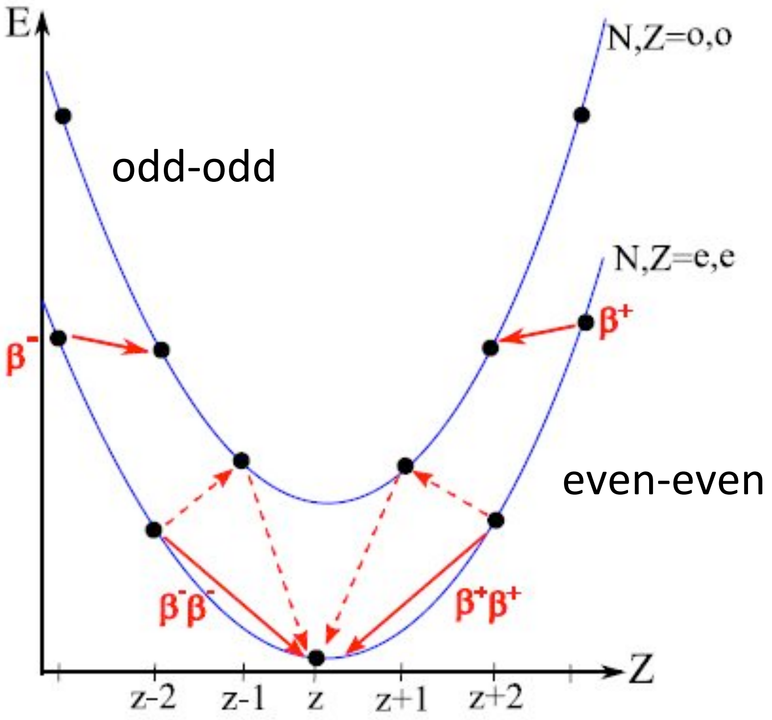
Who can do 0νββ?

35 isotopes available, interesting for 0νββ searches only 11:



Isotopes of choice

only even-even nuclei can undergo a double beta decay



Candidate Isotope	Q-value [MeV]	Natural abundance [%]
^{48}Ca	4.272	0.187
^{76}Ge	2.039	7.8
^{82}Se	2.996	9.2
^{96}Zr	3.350	2.8
^{100}Mo	3.034	9.6
^{110}Pd	2.004	11.8
^{116}Cd	2.814	7.6
^{124}Sn	2.530	5.6
^{130}Te	2.530	34.5
^{136}Xe	2.459	8.9
^{150}Nd	3.371	5.6

higher Q-value
→ less background !!

Enrichment possible
but always expensive !!

Effective Neutrino Mass (light ν exchange)

REMEMBER: If neutrino has a non-zero mass, mass eigenstates (ν_1, ν_2, ν_3) and weak interactions eigenstates (ν_e, ν_μ, ν_τ) do not necessarily have to coincide!

$$\nu_l = \sum_i U_{li} \nu_i$$

- β -decay: incoherent sum
  real neutrino

$$\langle m_\beta \rangle \equiv \left(\sum_{i=1}^{3} m_i^2 |U_{li}|^2 \right)^{1/2}$$

- cosmology: simple sum
  pure kinematic effect

$$\Sigma \equiv \sum_{i=1}^{3} m_i$$

- 0νββ-decay: coherent sum
  virtual neutrino
  Majorana phases

$$\langle m_{\beta\beta} \rangle \equiv \left(\sum_{i=1}^{3} m_i \, |U_{li}|^2 \, e^{i\alpha_i} \right)^{1/2}$$

α_i = Majorana phases

0νDBD experiments are sensitive to an effective neutrino mass!

Half-life of the decay

The decay half-life $T_{1/2}^{0\nu}$ is the measurable quantity. It depends on the effective Majorana mass $\langle m_{\beta\beta} \rangle^2$ of the neutrino exchanged between the two electron vertexes

Depending on g_A half- lives can vary by a factor of 4-16

axial vector coupling constant

effective Majorana mass
particle physics

$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 G_{0\nu} \left| M_{0\nu} \right|^2 \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2$$

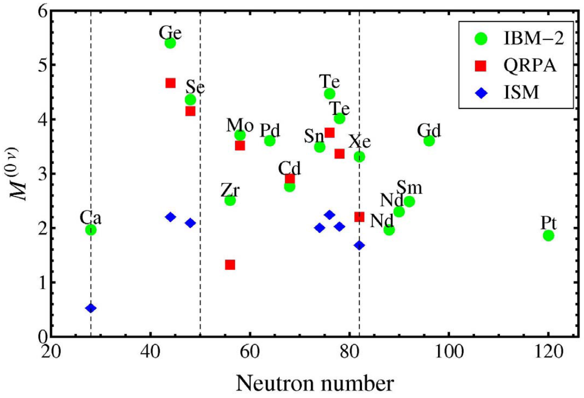
half-life

phase space integral ~ Q^5
atomic physics

nuclear matrix element (NME)
nuclear physics

$$m_{\beta\beta} = f(\theta_{12}, \theta_{23}, \theta_{13}, \Delta m_{12}, \pm\Delta m_{13}, \Sigma_{cosm}, e^{i\alpha}, e^{i\beta})$$

Several methods have been used to evaluate $M0\nu$:
QRPA (Quasiparticle Random Phase Approximation)
ISM (Shell Model)
IBM-2 (Interacting Boson Model)
EDF (Density Functional Theory)



IBM-2 from J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009);
J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 87, 014315 (2013). MS-SRC.
QRPA from F. Šimkovic *et al.*, Phys. Rev. C 77, 045503 (2008).
ISM from E. Caurier *et al.*, Phys. Rev. Lett. 100, 052503 (2008).

Experimental sensitivity

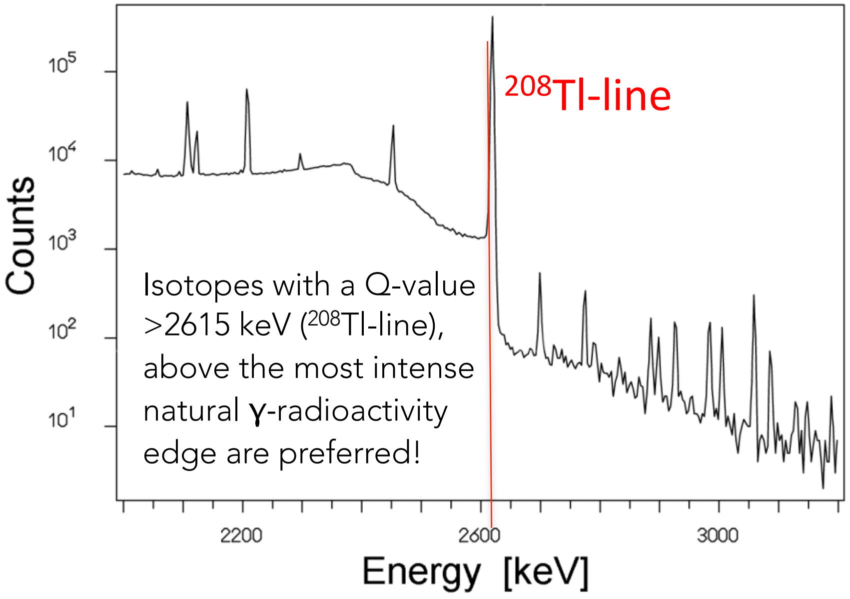
$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

- M = detector mass [kg]
- T = live time [y]
- B = background in ROI [counts $keV^{-1}\,kg^{-1}\,y^{-1}$]
- W = molecular weight
- η = isotopic abundance
- N_A = Avogadro number
- ε = detector efficiency
- ΔE = energy resolution at Q-value

STRATEGY

- low background
  - underground experiment
  - material selection, purification
- high Q-value
  - reject most of natural radioactivity
- high number of DBD nuclei
  - enrichment: ^{136}Xe easy, ^{48}Ca difficult
  - ^{130}Te natural high abundance
- **excellent energy resolution** to limit effect from **2νββ**

Environmental "underground" HPGE bck: ^{238}U and ^{232}Th trace contaminations



Isotopes with a Q-value >2615 keV (^{208}Tl-line), above the most intense natural γ-radioactivity edge are preferred!

How to build a 0νββ detector?

detector
≠
source

Tracker

^{82}Se, ^{150}Nd

PRO
full final state kinematics
“Smoking-gun” signature for **0νββ**
Isotope flexible

TPC
= Time Projection Chambers

^{136}Xe

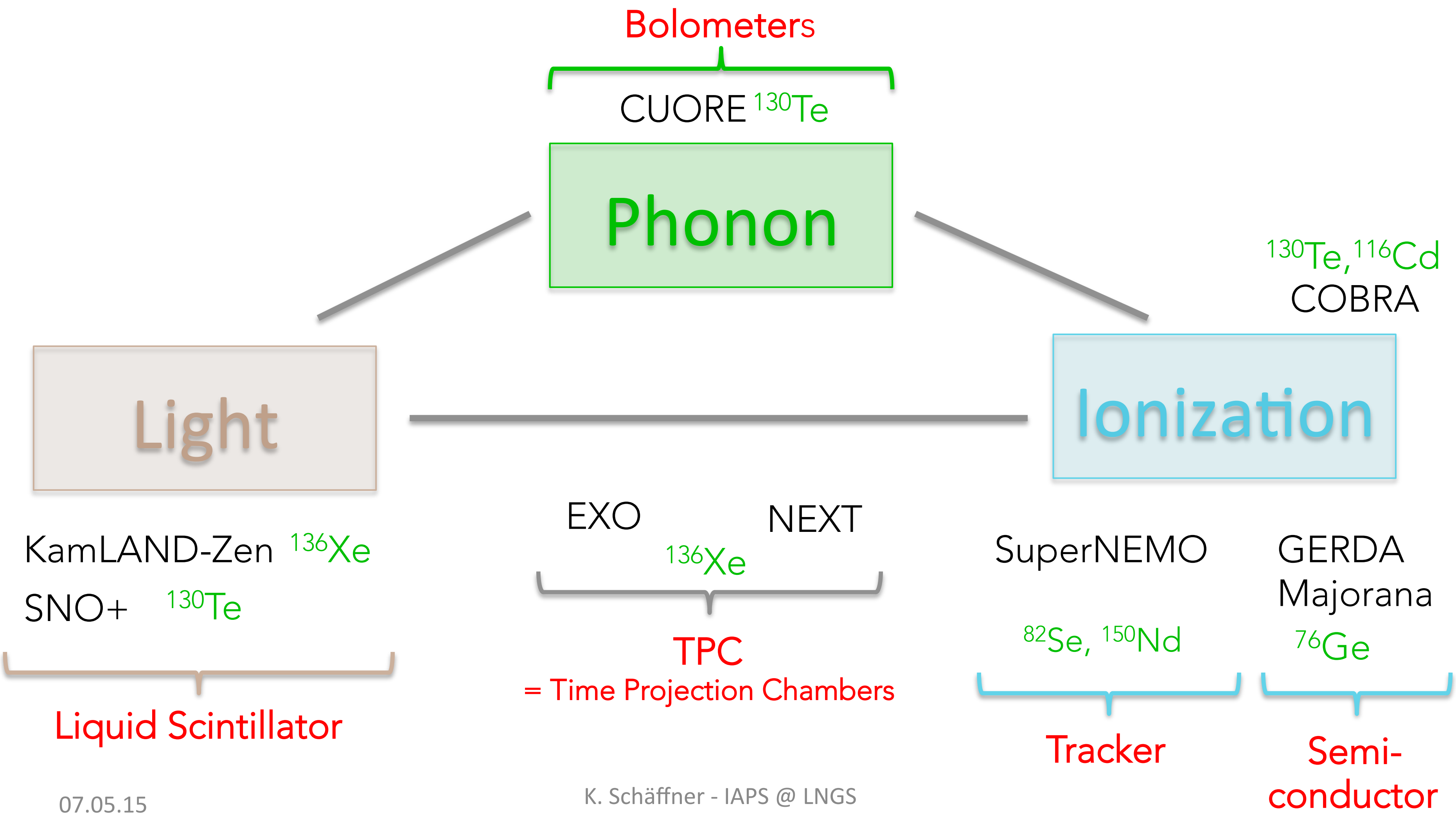
detector
=
source

Bolometers
Semiconductors
Liquid Scintillators
Scintillator

^{76}Ge ^{130}Te ^{116}Cd

PRO
excellent energy resolution
compact
high detection efficiency

Present detection technologies



Bolometers

CUORE ^{130}Te

Phonon

^{130}Te, ^{116}Cd
COBRA

Light

Ionization

KamLAND-Zen ^{136}Xe
SNO+ ^{130}Te

Liquid Scintillator

EXO NEXT
^{136}Xe

TPC
= Time Projection Chambers

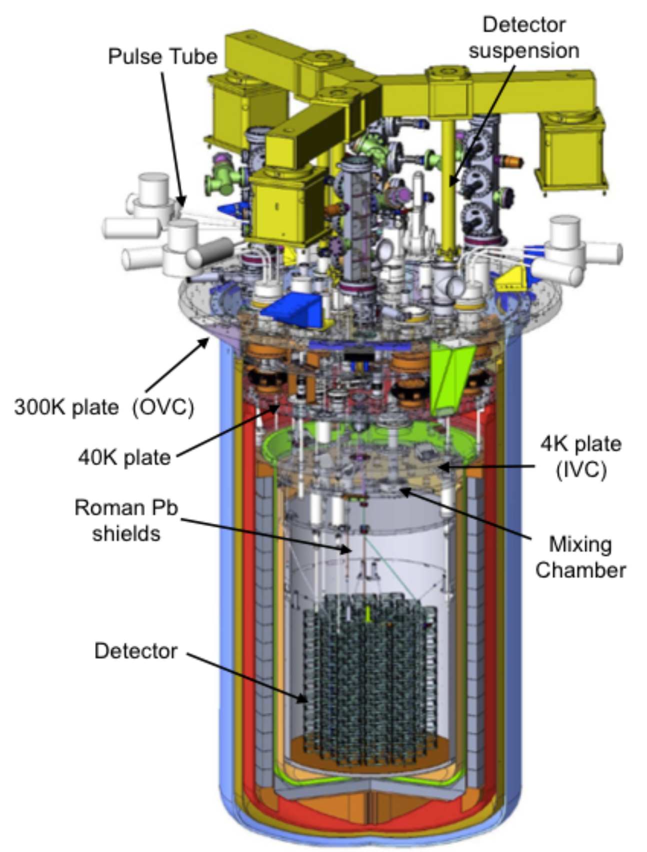
SuperNEMO
^{82}Se, ^{150}Nd

Tracker

GERDA
Majorana
^{76}Ge

Semi-conductor

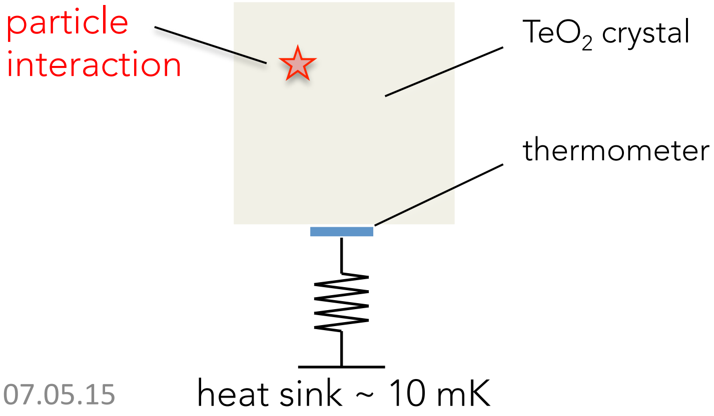
CUORE

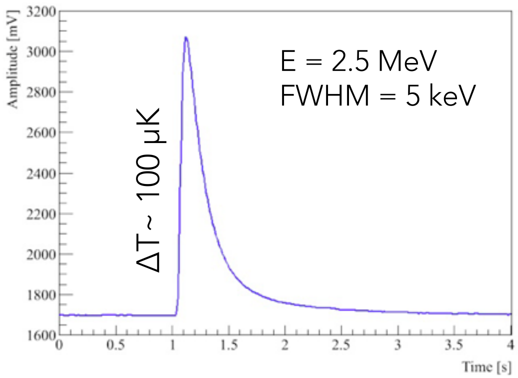


- located at LNGS in Italy, start within 2015
- cryogenic bolometer experiment @ 10mK
- target: 988 crystals of TeO_2
- 206 kg fiducial mass of ^{130}Te
- Q-value: 2527 keV
- ΔE ~ 5keV in ROI

GOAL

- background < 10 counts / (keV ton y)
- 5 years sensitivity: $T_{1/2}^{0\nu} > 9.5 \times 10^{25}$ y
  $\langle m_{\beta\beta} \rangle <$ 50 - 130 meV

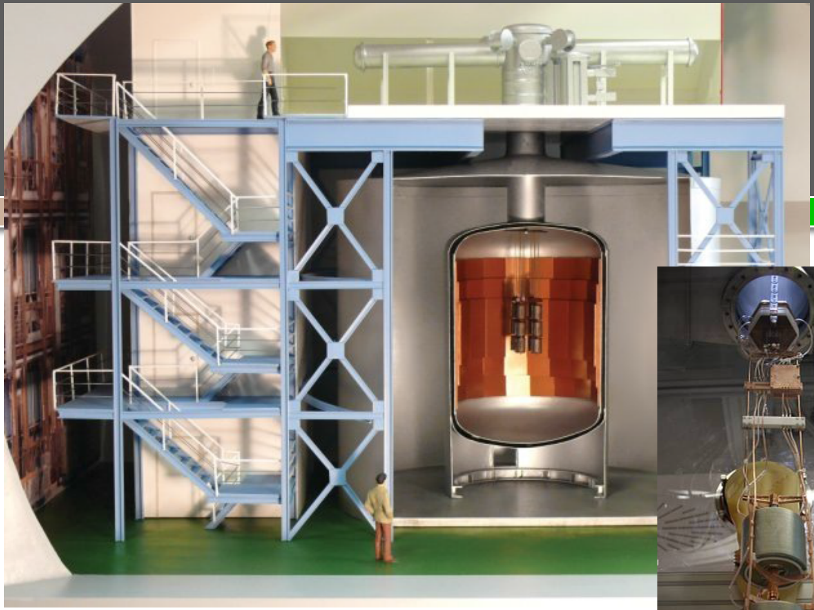




Advantages of bolometers:

- excellent energy resolution
- large mass array
- low background in ROI
- wide choice of target material

GERDA phase II



- located at LNGS in Italy
- Ge diodes enriched to 86% with ^{76}Ge
- Q-value: 2039 keV
- ΔE ~ 3 keV in ROI
- GERDA phase I completed (2011-2013):
  $T^{0\nu}_{1/2}$ > 2.1 x 10^{25} y (90% C.L.)
  excluded claim from Heidelberg-Moscow experiment
- GERDA phase II:
  - increase target mass 18kg + 20 kg
  - PSD to distinguish multi-site events from single-site events
  - Compton veto using scintillation light detection from LAr

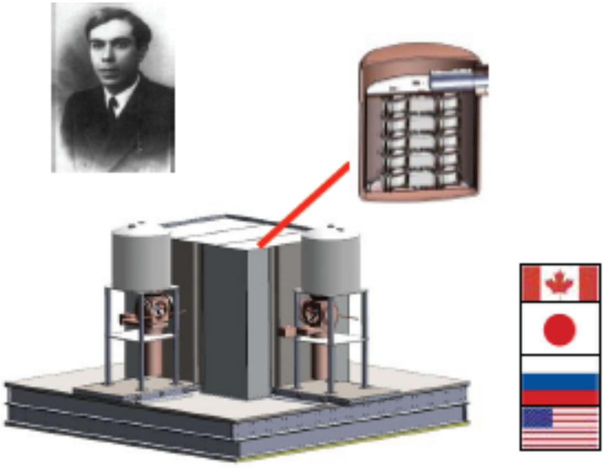
GOAL

- background < 0.001 counts / (keV kg y)
- sensitivity after 4 years: $T^{0\nu}_{1/2}$ > 1.5 x 10^{26} y
  $\langle m_{\beta\beta} \rangle$ < 80 -190 meV

Advantages of Ge-detectors:
- known technology
  (enrichment + diode production)
- best energy resolution
- low bck in ROI
- flat background at Q-value

Majorana Demonstator

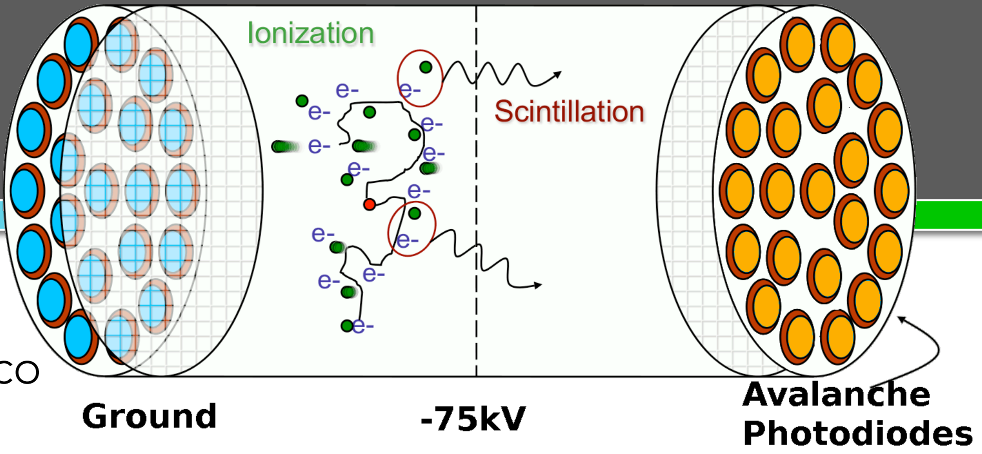
- located at Sanford Underground Research Facility (SURF), South Dakota
- modular instrument composed of two cryostats
- cryostat built from ultra-pure electroformed copper
- p-type point contact Ge diodes:
  - 10 kg natural Ge
  - 30 kg enriched to 87% with ^{76}Ge
- Q-value: 2039 keV
- ΔE ~ 3 keV in ROI (4keV wide window)



GOAL

- background ~ 3 counts / (ROI t y)
- collaborations aims to establish scalability to 1-tonne detector

EXO-200



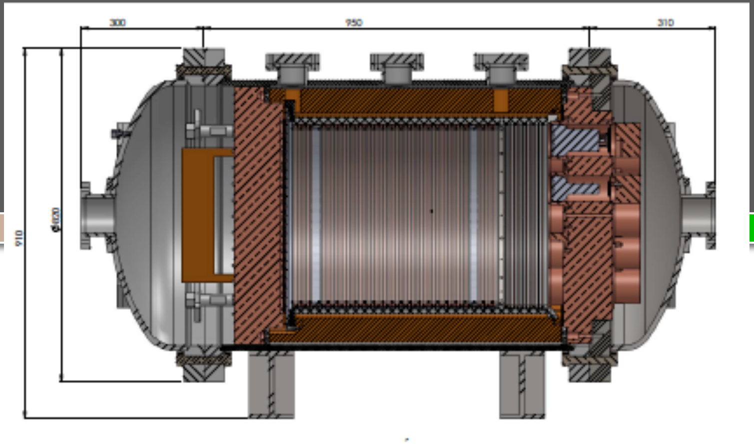
- located at Waste Isolation Pilot Plant (WIPP) near Carlsbad New Mexico
- <u>liquid filled TPC:</u>
  200 kg of enriched Xe (80.7% of ^{136}Xe)
  of which 110 kg (79 kg fiducial isotope mass) are active in the detector
- discrimination of multi-scattering events from single-scatters
- Q-value: 2457.8 keV
- ΔE ~ 88.5 keV in ROI
- <u>EXO-200 (since 2011 in operation):</u>
  $T_{1/2}^{0\nu} > 1.1 \times 10^{25}$ y (90% C.L.)

GOAL

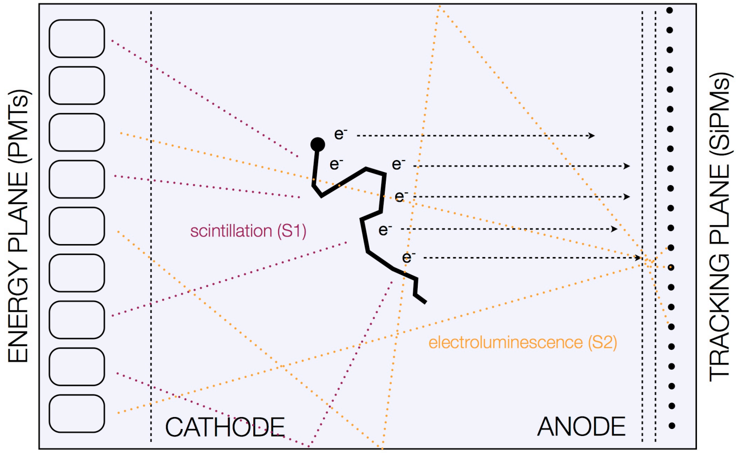
- reduce background from ^{214}Bi (Q=2447.8 keV) and ^{208}Tl (Q=2614.5 keV)
- reduce fiducial volume uncertainty
- improve energy resolution to about 56 keV
- aimed sensitivity after 3 years: $T_{1/2}^{0\nu} \sim 10^{26}$ y

Advantages of TPCs:
- easy to scale
- good self shielding if large

NEXT



- will be installed at Canfranc Underground Laboratory in Spain
- NEXT phase I presently in construction
- gaseous TPC (15 bar):
  10 kg of ^{136}Xe for phase I
  100 kg for NEXT-100 (scheduled for 2016)
- Q-value: 2457.8 keV
- tracking: silicon photomultipliers
- calorimetry: PMTs
- ΔE ~ 18 keV in NEXT R&D



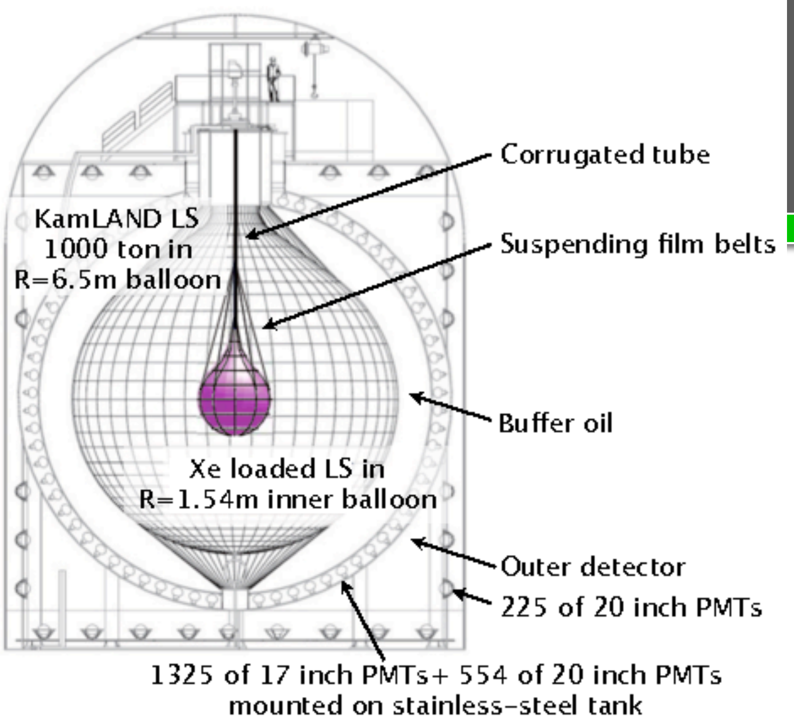
GOAL

- demonstrate that ΔE ~ 18 keV are reachable
- increase fully tagged reconstruction efficiency (presently ~ 30 %)

Advantages of high pressure TPCs:

- easy to scale
- measure and image the final state kinematics of 0νββ event

KamLAND-Zen



- housed in the Kamioka mine in Japan
- mini-balloon filled with liquid scintillator loaded with enriched ^{136}Xe (90%)
- Q-value: 2457.8 keV
- ΔE ~ 250 keV in ROI
- Phase I
  - 320 kg of ^{136}Xe (90%), background from ^{110m}Ag
  - $T_{1/2}^{0\nu}$ > 1.9 x 10^{25} y (90% C.L.)
- Phase II (from Dec 2013)
  - 383 kg of ^{136}Xe (90%); LS purification; ^{110m}Ag reduced by a factor of 10
  - $T_{1/2}^{0\nu}$ > 1.3 x 10^{25} y (90% C.L.) → combined results: $T_{1/2}^{0\nu}$ > 2.6 x 10^{25} y (90% C.L.)

$\langle m_{\beta\beta} \rangle$ < (140-280)meV

GOAL

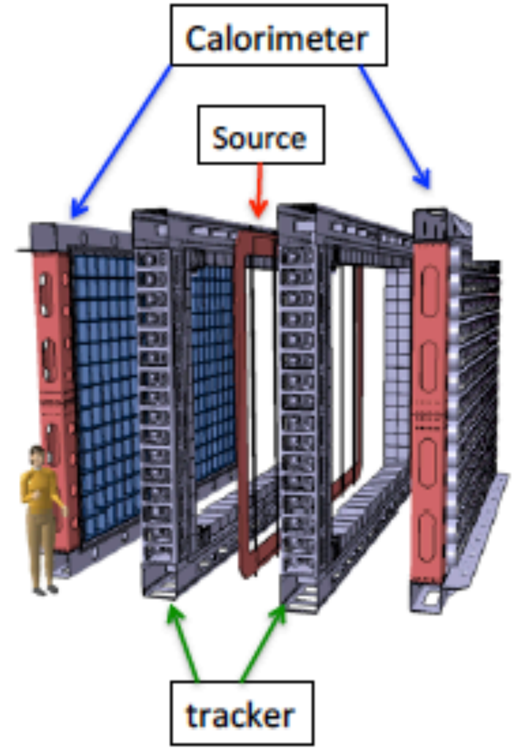
- Purification of liquid scintillator
- Increase mini-balloon volume to 600 kg
- sensitivity after 2 years: $T_{1/2}^{0\nu}$ > 2.0 x 10^{26} y

$\langle m_{\beta\beta} \rangle$ ~ 50 meV

Advantages of Liquid Scintillators
- easy to scale
- possibility of loading LS with other isotopes

SuperNEMO

- located at the Modane Underground Laboratory at Fréjus
- the frist "Demonstrator" module (7kg of ^{82}Se and/or ^{150}Nd) in commissioning and will run from 2015-2017
- 100-kg full SuperNEMO planned to start from 2017
- Tracking-and-calorimetry approach:
  - Central source frame: isotope on thin foils
  - Tracking: 2000 drift chambers
  - Segmented calorimetric elements (plastic scintillator) for measurement of the β^- energy and time-of-flight
- ΔE ~ 250 keV @ 1MeV



GOAL

- No background expected in ROI for 2 years of data
- sensitivity after 2 years: $T_{1/2}^{0\nu}$ > 6.6 x 10^{24} y for ^{82}Se

  $\langle m_{\beta\beta} \rangle$ ~ 160- 440 meV

Advantages:

- allows to measure full kinematics of β^- products (angular distribution)
- scaling possible
- choose not mainstream isotopes: ^{48}Ca, ^{150}Nd, ^{82}Se (large PSF and low bck)

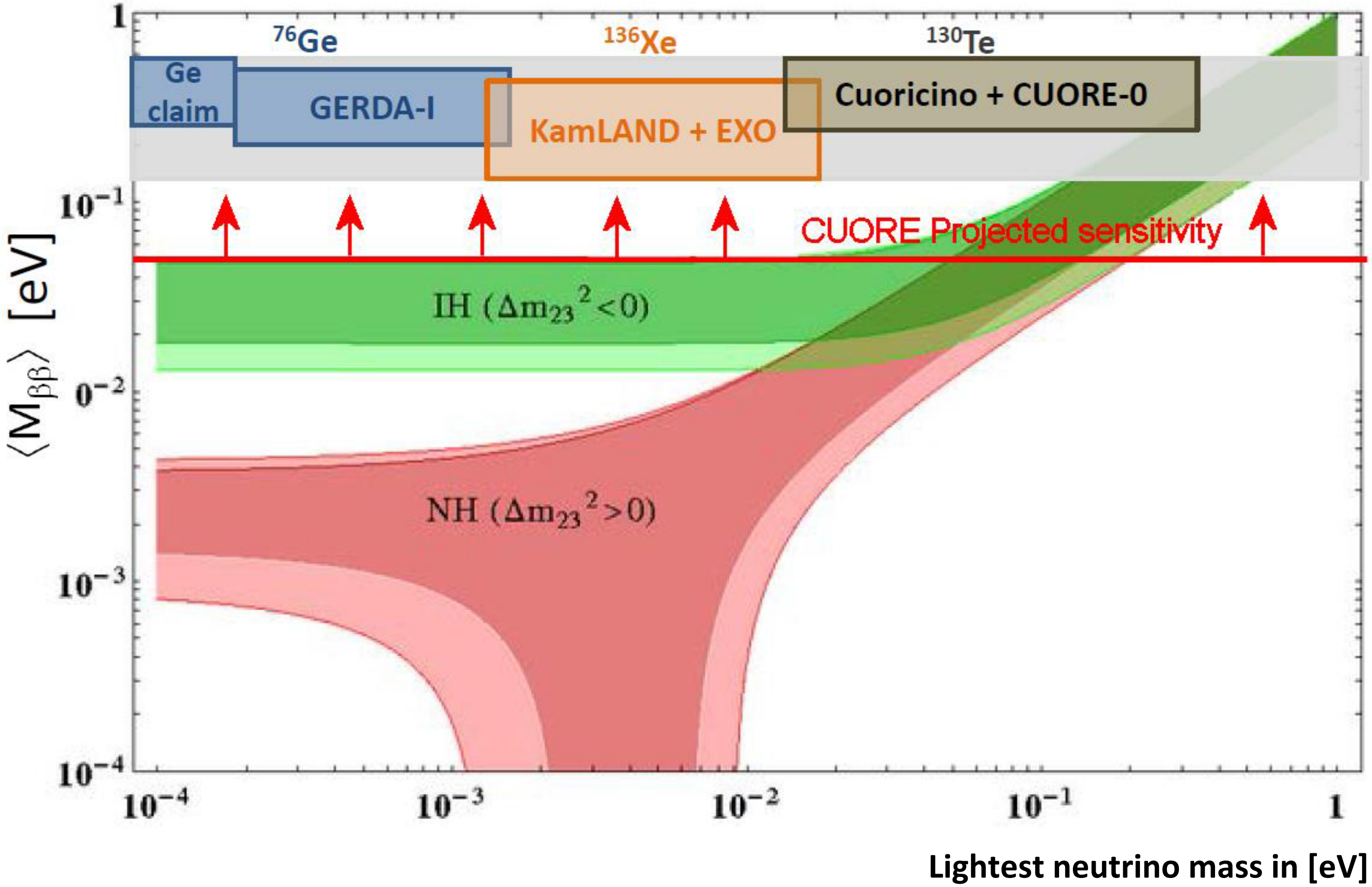
Timeline of present projects

construction time

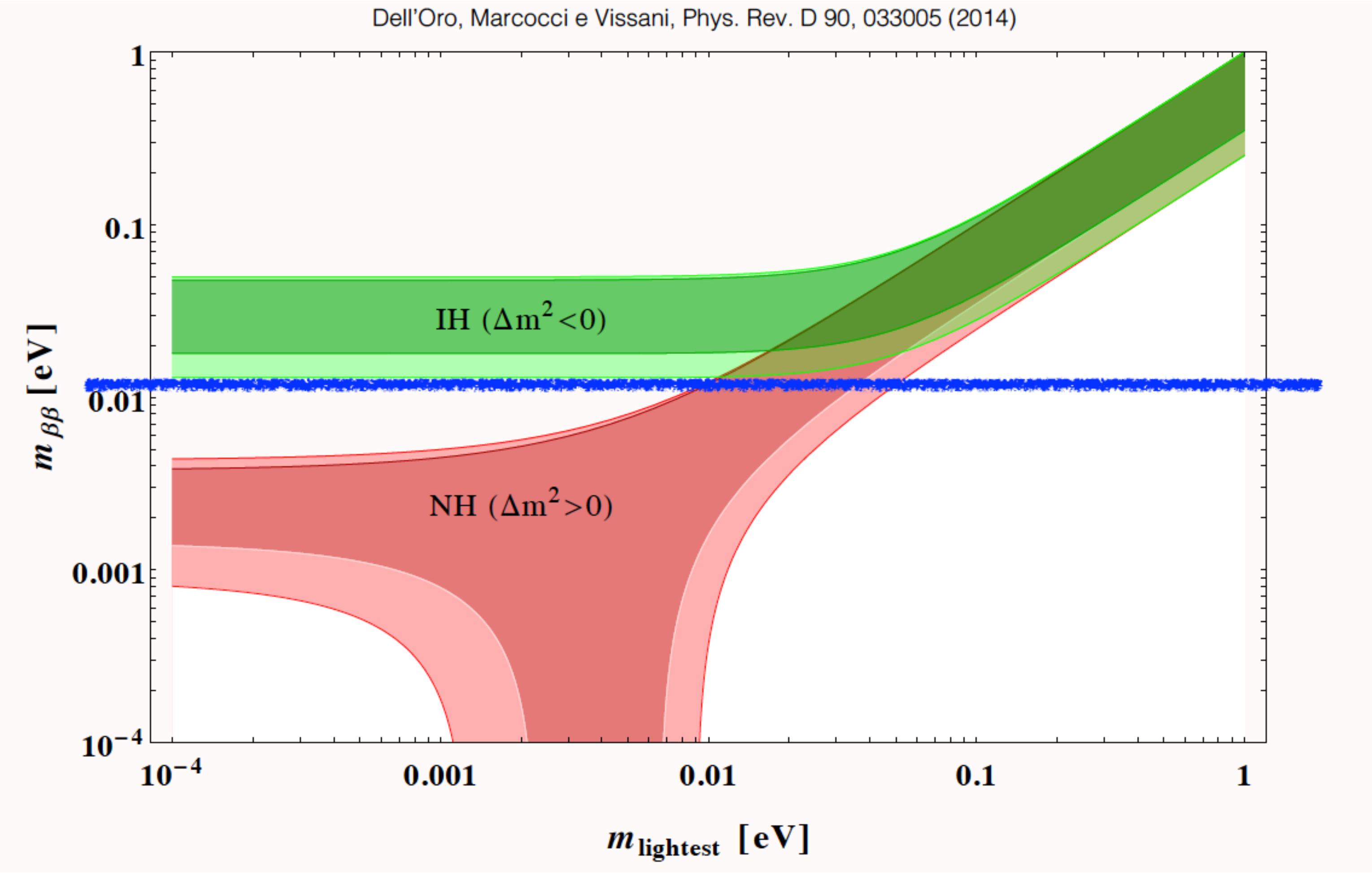
actual and
intended running time

Graphics taken from DOE Nuclear Science Advisory Committee report on 0νββ (24 April 2014)

State of the art



What next ??



Dell'Oro, Marcocci e Vissani, Phys. Rev. D 90, 033005 (2014)

What is the ultimate strategy?

$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} \sqrt{\frac{M \cdot T}{\Delta E \cdot B}}$$

Time T : not much to do other than wait

Increase in energy resolution ΔE:

- translates in an increase of the sensitivity of the experiments
- allows to better identify and account for background contributions from natural decay chains (^{214}Bi for ^{136}Xe experiments)
- allows to minimize the contribution from the irreducible contribution of the 2νββ decay

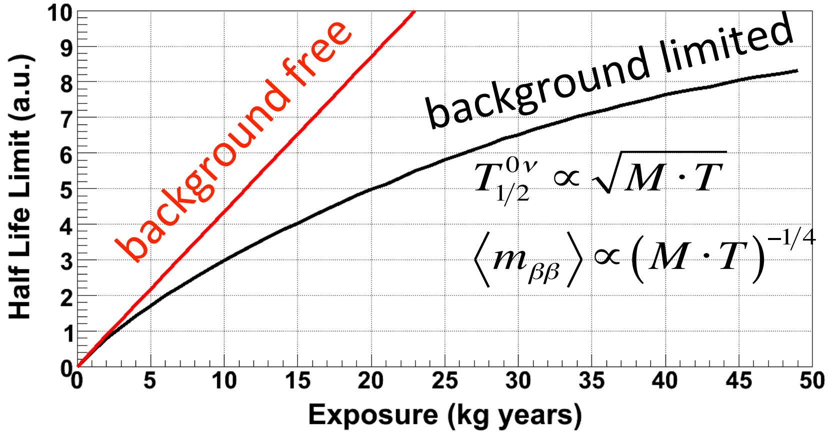
BUT: Ge-diodes and bolometers already show very good energy resolutions and liquid scintillator experiments are limited by light production and consequent light detection (R&D needed)

The ultimate experiment …

…. is all about background!!

(1) ZERO BACKGROUND FRAMEWORK

$$S_{0\nu} = ln(2) N_A \frac{\eta \cdot \epsilon}{W} \boxed{M \cdot T}$$

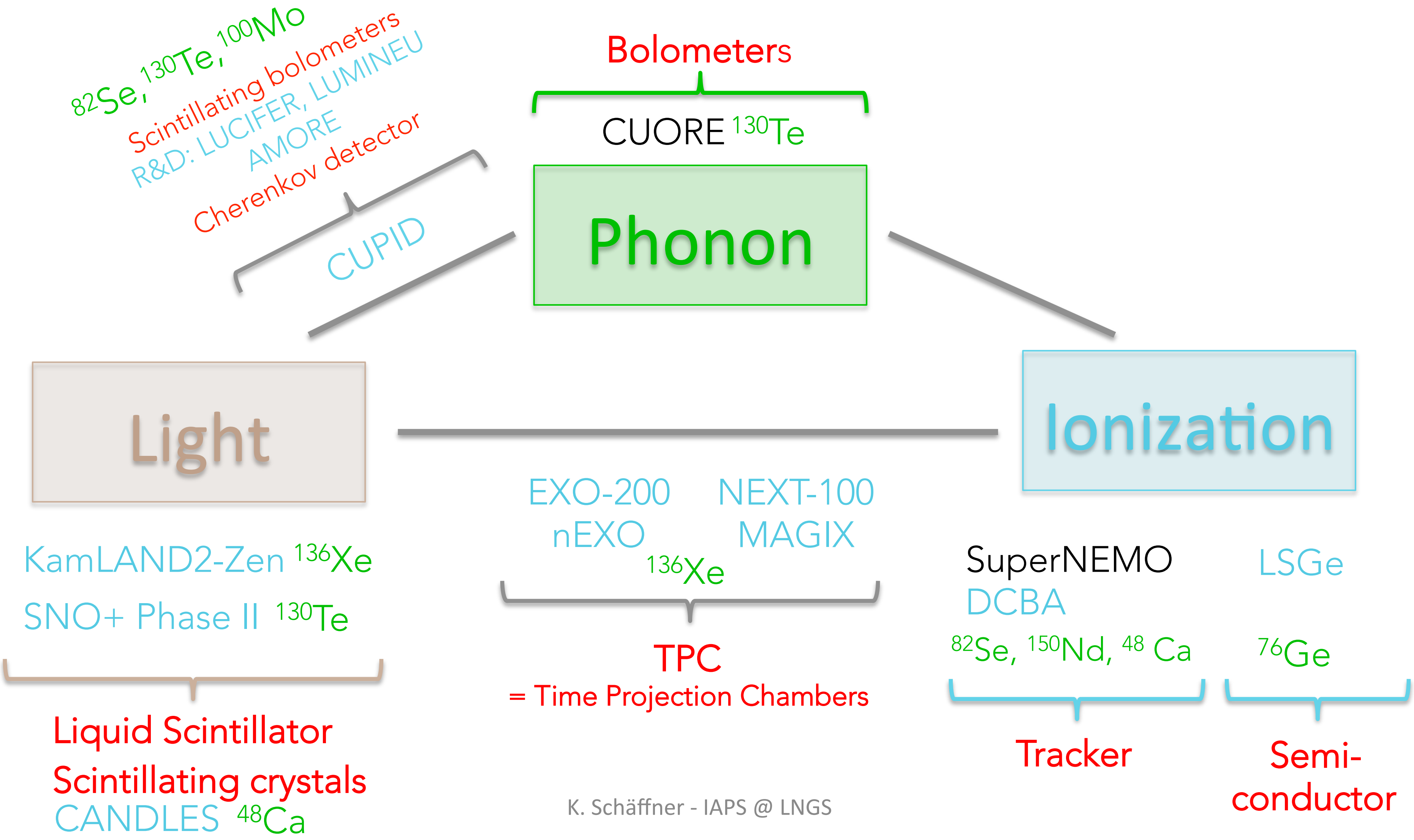


and

(2) increase the number of active DBD nuclei

BUT: translates to a huge necessary budget for enrichment !

Future generation experiments



Bolometers

CUORE ^{130}Te

Phonon

^{82}Se, ^{130}Te, ^{100}Mo

Scintillating bolometers

R&D: LUCIFER, LUMINEU

AMORE

Cherenkov detector

CUPID

Light

KamLAND2-Zen ^{136}Xe

SNO+ Phase II ^{130}Te

Liquid Scintillator

Scintillating crystals

CANDLES ^{48}Ca

EXO-200 NEXT-100

nEXO MAGIX

^{136}Xe

TPC

= Time Projection Chambers

Ionization

SuperNEMO

DCBA

^{82}Se, ^{150}Nd, ^{48} Ca

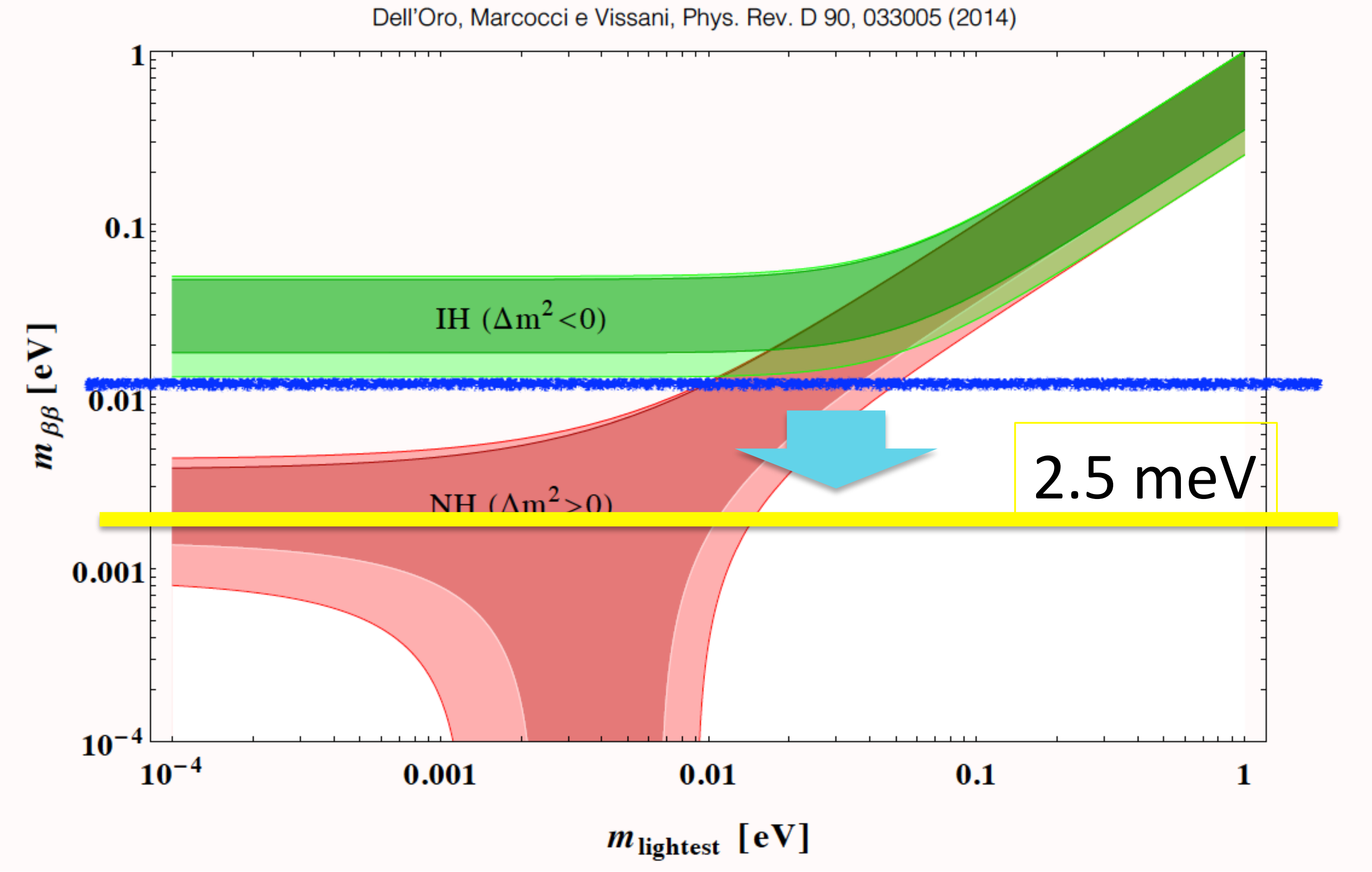
Tracker

LSGe

^{76}Ge

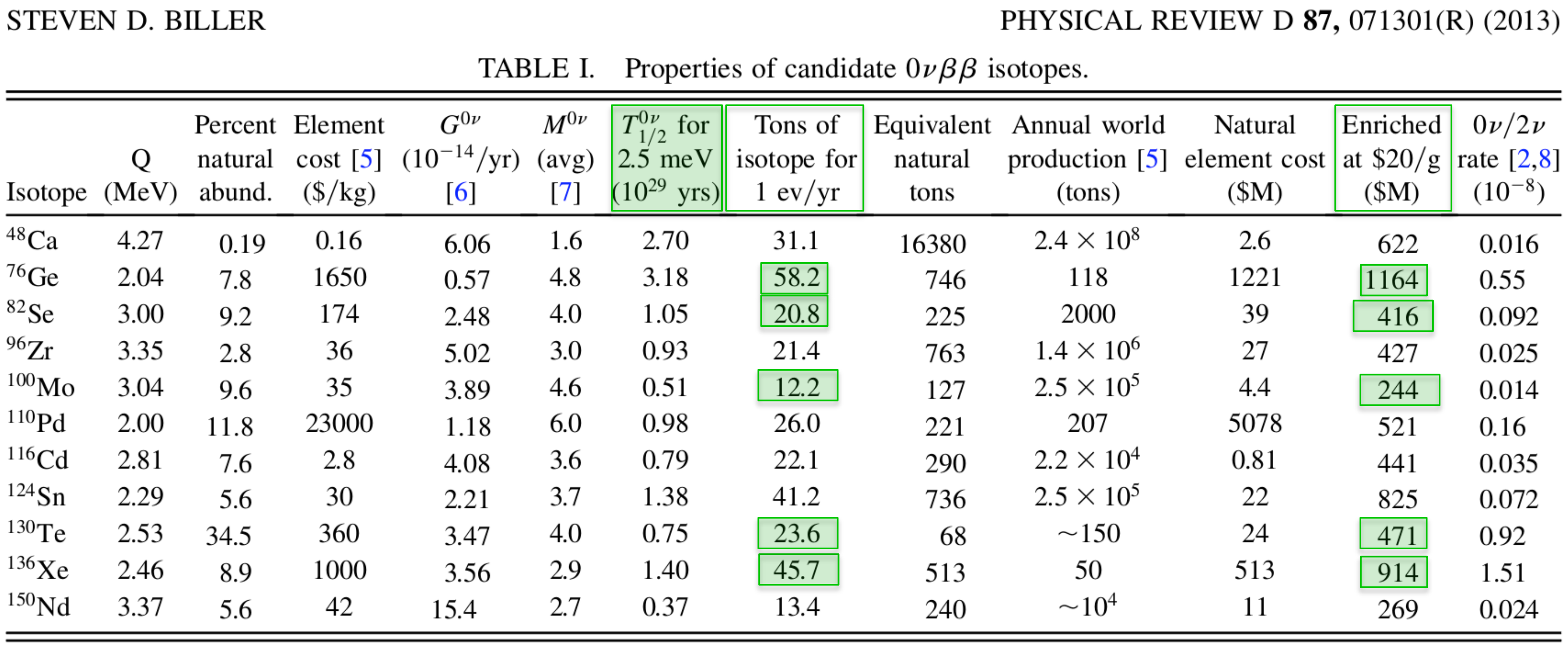
Semi-conductor

far future… assume



2.5 meV

Isotope costs -normal hierarchy region



STEVEN D. BILLER PHYSICAL REVIEW D **87,** 071301(R) (2013)

TABLE I. Properties of candidate $0\nu\beta\beta$ isotopes.

Isotope	Q (MeV)	Percent natural abund.	Element cost [5] ($/kg)	$G^{0\nu}$ (10^{-14}/yr) [6]	$M^{0\nu}$ (avg) [7]	$T^{0\nu}_{1/2}$ for 2.5 meV (10^{29} yrs)	Tons of isotope for 1 ev/yr	Equivalent natural tons	Annual world production [5] (tons)	Natural element cost ($M)	Enriched at $20/g ($M)	$0\nu/2\nu$ rate [2,8] (10^{-8})
^{48}Ca	4.27	0.19	0.16	6.06	1.6	2.70	31.1	16380	2.4×10^8	2.6	622	0.016
^{76}Ge	2.04	7.8	1650	0.57	4.8	3.18	58.2	746	118	1221	1164	0.55
^{82}Se	3.00	9.2	174	2.48	4.0	1.05	20.8	225	2000	39	416	0.092
^{96}Zr	3.35	2.8	36	5.02	3.0	0.93	21.4	763	1.4×10^6	27	427	0.025
^{100}Mo	3.04	9.6	35	3.89	4.6	0.51	12.2	127	2.5×10^5	4.4	244	0.014
^{110}Pd	2.00	11.8	23000	1.18	6.0	0.98	26.0	221	207	5078	521	0.16
^{116}Cd	2.81	7.6	2.8	4.08	3.6	0.79	22.1	290	2.2×10^4	0.81	441	0.035
^{124}Sn	2.29	5.6	30	2.21	3.7	1.38	41.2	736	2.5×10^5	22	825	0.072
^{130}Te	2.53	34.5	360	3.47	4.0	0.75	23.6	68	~150	24	471	0.92
^{136}Xe	2.46	8.9	1000	3.56	2.9	1.40	45.7	513	50	513	914	1.51
^{150}Nd	3.37	5.6	42	15.4	2.7	0.37	13.4	240	$\sim 10^4$	11	269	0.024

approximate quantities and costs of material that would be required to achieve a rate of one 0νββ decay per year for an effective Majorana neutrino mass of 2.5 meV.

(center of the normal hierarchy phase space as the eigenvalue of the smallest neutrino mass eigenstate approaches zero).

My Conclusions

- the search for the neutrinoless DBD addresses urgent questions of present day physics
- half-lives are unknown and a discovery might be around the corner
- many different detection technologies were developed within the last decade
- The results from the second generation of present experiments will allow us to:
  - start to scratch the inverted hierarchy region
  - check the discovery potential of the techniques for future generation experiments able to probe the complete inverted hierarchy region

- future generation experiments
  - target mass of DBD nuclei ~ 1 tonne
  - increase energy resolution
  - high costs for enrichment and isotope O(100 M Euro) -> few exp. in the world
  - in direction of zero background experiments (the hardest task)

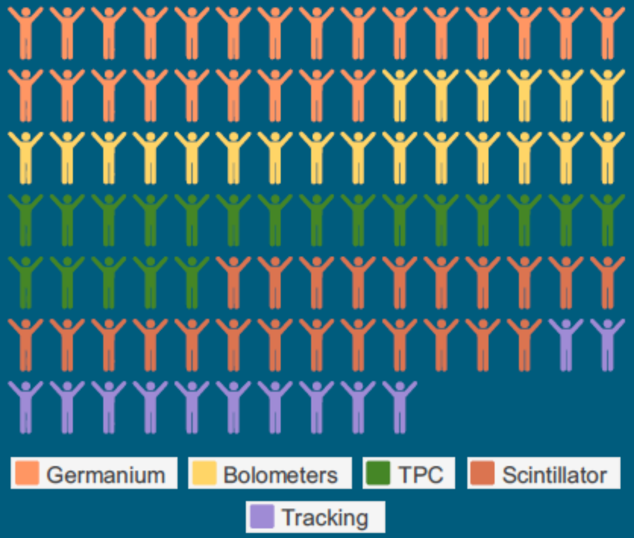
- a single experiment however will not be enough for a discovery!!!
- investment in economic enrichment techniques for isotopes of interest ???
- hope for a small $g_{A,}$ otherwise half-lives can change by a factor of 4-16 and a detection becomes very challenging
- a lot hands and brains needed ☺

Double Beta Community

A Worldwide Effort

about **840**
physicists worldwide

Underground labs
around the world



Graphics adopted from L. Winslow: talk @ Neutrino 2014

Thank you for your attention

Additional material

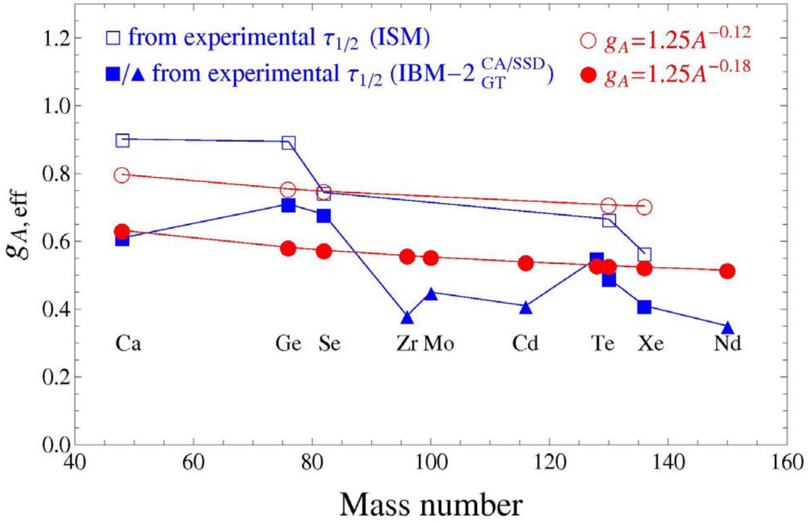
adopted from F. Iachello lectures

Axial vector coupling constant g_A

The question of whether or not g_A in **0νββ** is renormalized as much as in **2νββ** is of much debate. In **2νββ** only the 1^+ (GT) multipole contributes. In **0νββ** all multipoles 1^+, 0^+, 2^-, 1^- … contribute.
Some of these could be unquenched. However, even in **0νββ**, 1^+ intermediate states dominate. Hence, our current understanding is that g_A is renormalized in **0νββ** as much as in **2νββ**.

This problem is currently being addressed from various sides. Experimentally by measuring the matrix elements to and from the intermediate odd-odd nucleus in **2νββ** decay [1]. Theoretically, by using effective field theory (EFT) to estimate the effect of non- nucleonic degrees of freedom (two-body currents) [2].

[1] P. Puppe et al., Phys. Rev. C 86, 044603 (2012).
[2] J. Menendez, D. Gazit, and A. Schwenk, Phys. Rev. Lett. 107, 062501 (2011).



J. Barea, J. Kotila and F. Iachello, Phys. Rev. C 87, 014315 (2013).

adopted from F. Iachello lectures

Effective Neutrino Mass

The average light neutrino mass can be written as

$$\langle m_\nu \rangle = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\varphi_2} + s_{13}^2 m_3 e^{i\varphi_3} \right|$$

$$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}, \varphi_{2,3} = [0, 2\pi]$$

$$\left(m_1^2, m_2^2, m_3^2\right) = \frac{m_1^2 + m_2^2}{2} + \left(-\frac{\delta m^2}{2}, +\frac{\delta m^2}{2}, \pm\Delta m^2\right)$$

A fit to oscillation experiments gives §

$$\sin^2\theta_{12} = 0.312, \sin^2\theta_{13} = 0.016, \sin^2\theta_{23} = 0.466$$

$$\delta m^2 = 7.67 \times 10^{-5} eV^2, \Delta m^2 = 2.39 \times 10^{-3} eV^2$$

§ G.L. Fogli *et al.*, Phys. Rev. D75, 053001(2007); D78, 033010 (2008).

[A recent result from Daya Bay, Phys. Rev. Lett. 108, 171803 (2012) gives $\sin^2\theta_{13}$=0.024±0.005, which slightly modifies the fit.]

PMNS mixing matrix :

Majorana Phases

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

$$\langle m_\nu \rangle = \left| \sum U_{ei}^2 m_i \right| = \left| U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}} \right|$$

Why Ge?

Current experiments

		mass [kg]* (total/FV)	FWHM [keV]	background$^{\&}$ [cnt/mol yr FWHM]	$T_{1/2}$ limit [10^{25} yr] after 4 yr	$\langle m_{ee} \rangle$ limit [meV]	date
Gerda II	Ge	35/27	3	0.0004	15	80-190	-2019
MajoranaD	Ge	30/24	3	0.0004	15	80-190	-2019
EXO-200	Xe	170/80	88	0.03	6	80-220	-2019
Kamland-Zen	Xe	383/88 (600/?)	250	0.03	20	44-120	-2018
NEXT	Xe	100/80	17	0.0036	6	100-200	-2020
Cuore	Te	600/206	5	0.02	9	50-200	-2019
SNO+	Te	2340/160	270	0.02	9	50-200	-2020

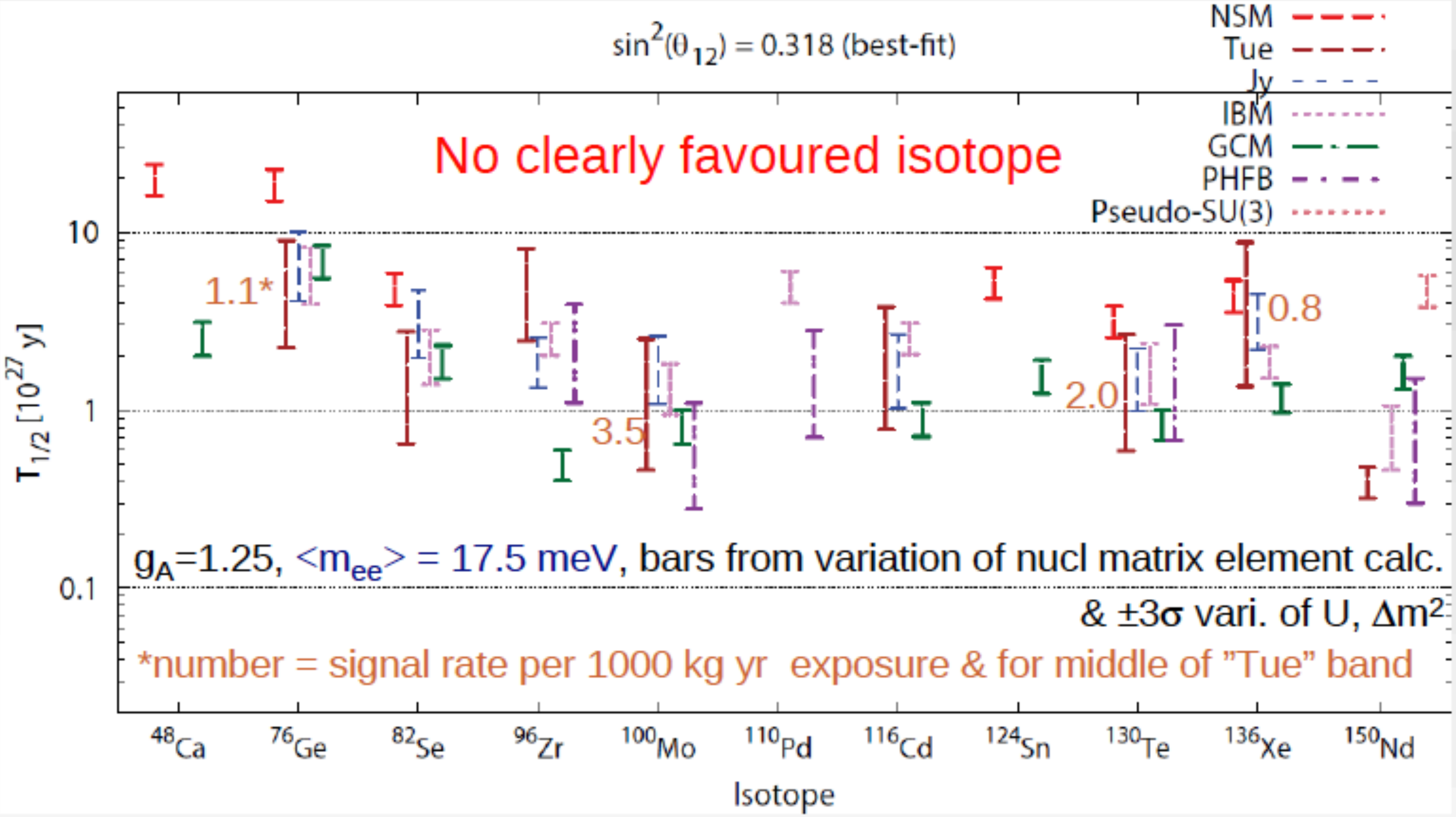
* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

$^{\&}$ mol of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

Note: values are design numbers except for EXO-200 and Kamland-Zen

Ge experiments have lowest background → similar sensitivity despite small mass

Expected $T_{1/2}$ for different matrix elements



No clearly favoured isotope

$g_A=1.25$, $\langle m_{ee}\rangle = 17.5$ meV, bars from variation of nucl matrix element calc.

& ±3σ vari. of U, Δm^2

*number = signal rate per 1000 kg yr exposure & for middle of "Tue" band

taken from DOE Nuclear Science Advisory Committee report on $0\nu\beta\beta$ (24 April 2014)
adopted from A. Dueck, W. Rodejohann and K. Zuber, Phys. Rev. D83 (2011) 113010

warning from theory colleague: unclear whether light Majorana neutrino exchange is dominating & other ν properties unknown → motivation to cover inverted mass hierarchy is artificial

Spectrum of KamLAND-Zen

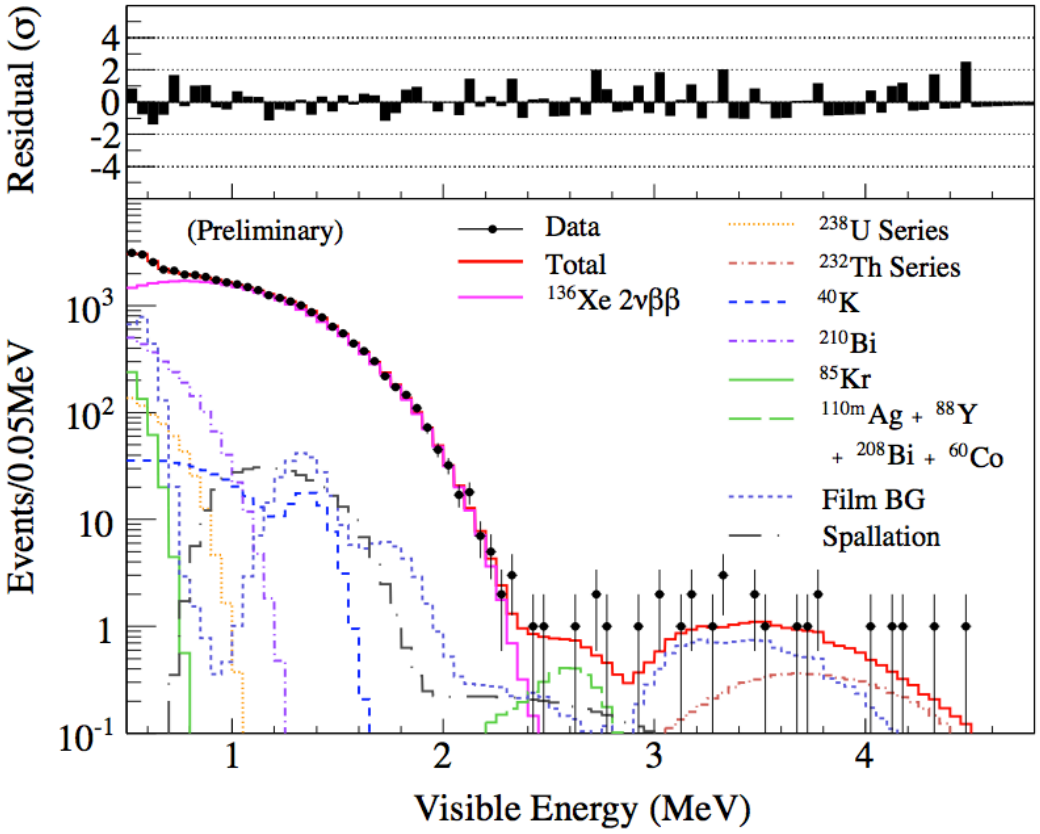


FIGURE 3. Preliminary energy spectrum of selected $\beta\beta$ candidates within 1.0 m fiducial radius is shown together with the best-fit backgrounds, with the $2\nu\beta\beta$ decay fit. The residuals from the best-fit are shown in the upper panel.

$<m_{\beta\beta}>=12$ meV and zero bck

- Objective: $<m_{\beta\beta}>=12$ meV
- sensitivity of 1 sigma
- Nuclear matrix elements from IBM-2
- zero background condition (i.e. $M \cdot T \cdot B \cdot \Delta E \lesssim 1$)
- measuring time T = 5 y

- enrichment level 90%
- actual costs for enrichment
- detector efficiency (fiducial volume) as present
- energy resolution as present
- $g_A = 1.269$

	T1/2 0v [anni]	Massa isotopo [ton]	Efficienza (volume fiduciale)	Massa totale rivelatore [ton]	a.i. [%]	Costo isotopo/kg [k€]	Costo isotopo [M€]	B*ΔE [c/kg/y]	ΔE FWHM [keV]	Fondo [c/keV/kg/y]	Q value [keV]	T1/2 2v [anni]	Rapporto eventi 0v/2v
^{76}Ge GERDA	1,0E+28	0,365	0,82	0,49	7,8	70,00	34,64	5,5E-04	3	**1,8E-04**	2039	1,8E+21	**6,3E+08**
^{82}Se Lucifer	3,7E+27	0,145	0,80	0,36	9,2	70,00	14,11	1,4E-03	10	**1,4E-04**	2996	9,2E+19	**4,4E+05**
^{100}Mo (ZnMO$_4$)	3,2E+27	0,151	0,80	0,48	7,6	100,00	20,97	1,3E-03	9	**1,5E-04**	3034	7,1E+18	**8,0E+04**
^{116}Cd (CdWO$_4$)	5,4E+27	0,301	0,80	1,31	9,6	150,00	62,64	6,7E-04	6	**1,1E-04**	2814	2,8E+19	**1,4E+06**
^{130}Te CUORE	3,0E+27	0,189	0,87	0,30	34,2	13,00	3,14	1,1E-03	5	**2,1E-04**	2527	6,8E+20	**1,1E+08**
^{130}Te SNO+	3,0E+27	0,189	0,20	350,61	34,2	13,00	13,67	1,1E-03	270	**3,9E-06**	2527	6,8E+20	**4,3E-03**
^{136}Xe EXO	4,3E+27	0,281	0,50	0,63	8,9	8,00	5,00	7,1E-04	58	**1,2E-05**	2458	2,1E+21	**8,4E+01**
^{136}Xe Kam-Zen	4,3E+27	0,281	0,30	42,72	8,9	8,00	8,34	7,1E-04	250	**2,8E-06**	2458	2,1E+21	**1,3E-02**
^{136}Xe NEXT	4,3E+27	0,281	0,30	1,04	8,9	8,00	8,34	7,1E-04	15	**4,7E-05**	2458	2,1E+21	**2,8E+05**

Table adopted from the presentation of C. Bucci hold at "What Next" workshop @ LNGS