Present knowledge about neutrinos

Neutrinos are massive fermions

There are 3 active neutrino flavors (ν_α)

Neutrino flavor states are mixtures of mass states (ν_k)

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

Pontecorvo–Maki–Nakagawa–Sakata matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric / Accelerator

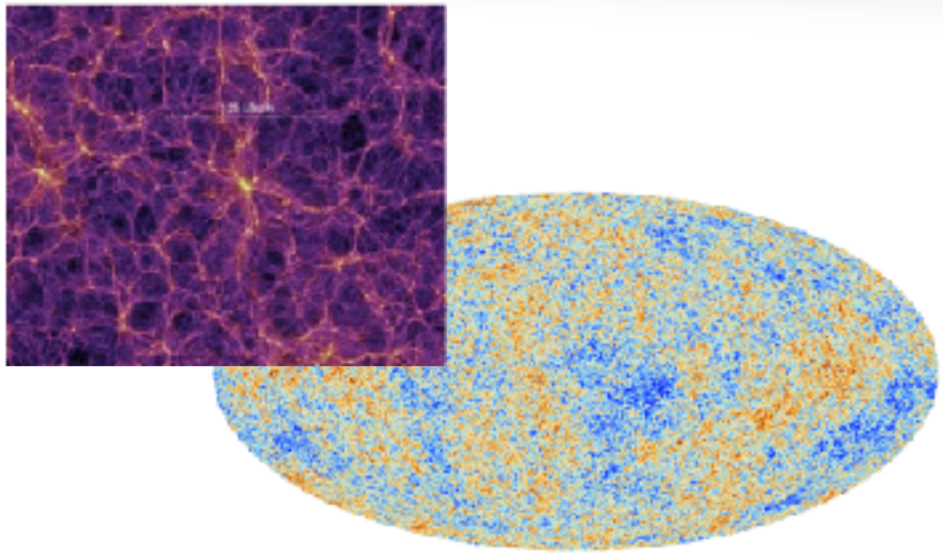
Reactor / Accelerator

Solar / Reactor

Measurements of neutrino parameters from:

- neutrino oscillations
- single beta decay
- neutrinoless double beta decay
- cosmology

To the absolute ν mass scale



Cosmology

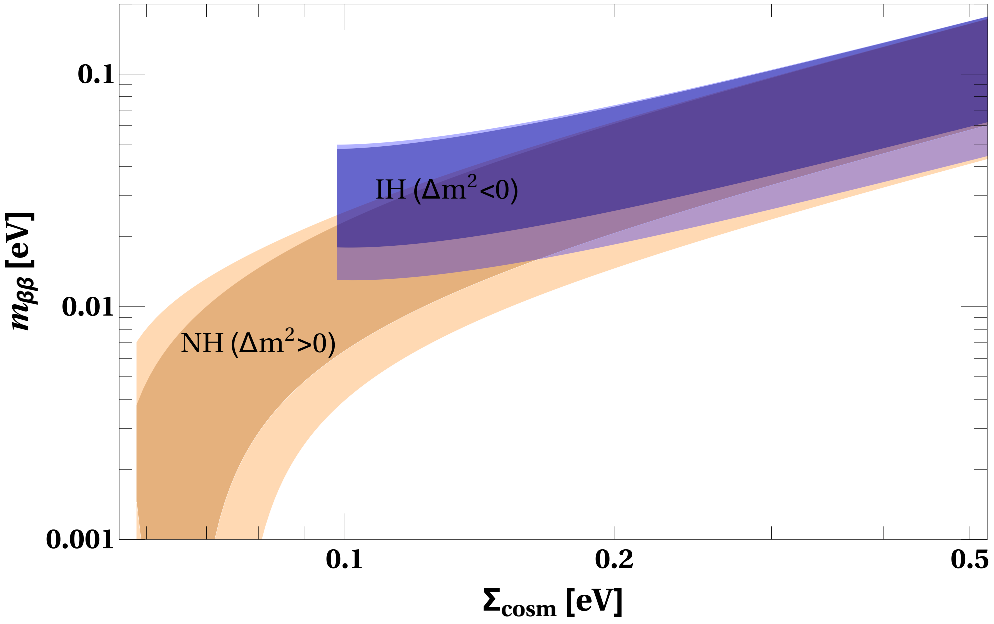
- neutrinos influence large scale structures.
- very sensitive, but model dependent
- $\sum m_\nu$

Direct neutrino mass measurement

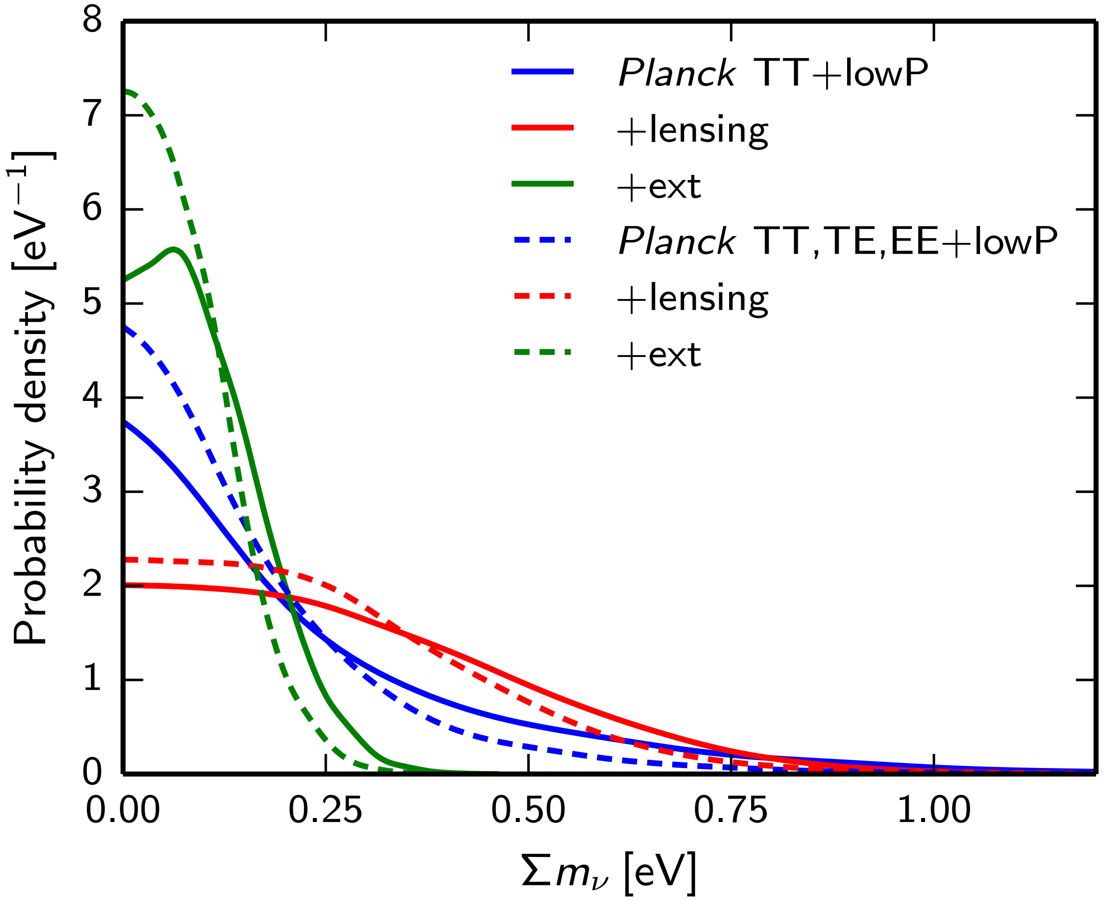
- β-decay: the end-point of the β-spectrum is affected by the ''effective electron neutrino mass'' (no further assumptions needed)
- β-decay searches for $m(\nu_e)$: Tritium β^-, ^{187}Re β^-,^{163}Ho EC
- Time-of-flight measurements (ν from supernova): SN1987a -> $m(\nu_e) < 5.7$ eV

Neutrinoless Double Beta Decay

- 0νββ-decay: the decay rate depends on the ''effective Majorana mass''



Limits from cosmology



$$\sum m_\nu < 0.72eV \qquad Planck\,TT + lowP$$

$$\sum m_\nu < 0.21eV \qquad Planck\,TT + lowP + BAO$$

$$\sum m_\nu < 0.49eV \qquad Planck\,TT, TE, EE + lowP$$

$$\sum m_\nu < 0.17eV \qquad Planck\,TT, TE, EE + lowP + BAO$$

$$\left\{ \begin{array}{c} \sum m_\nu < 0.23eV \\ \Omega_\nu h^2 < 0.0025 \end{array} \right\} 95\% \qquad Plank\,TT + lowP + lensing + ext.$$

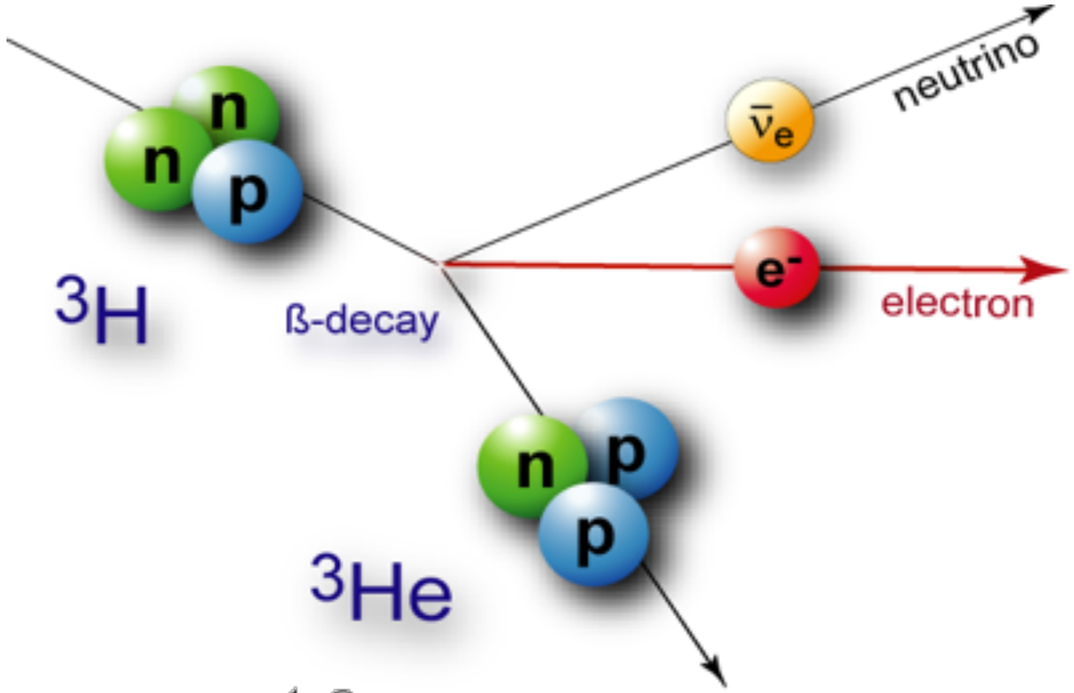
Plank Collaboration: Astronomy and Astrophysics 594 (2016) A13

$$\sum m_\nu < 0.14 \quad 95\%, \qquad Plank + WMAP9 + ACT + SPT + BOSS.$$

N. Palanque-Delabrouille et al.: J. Cosm. Astropart. Phys. 1502, 045 (2015).

All limits are ΛCDM based

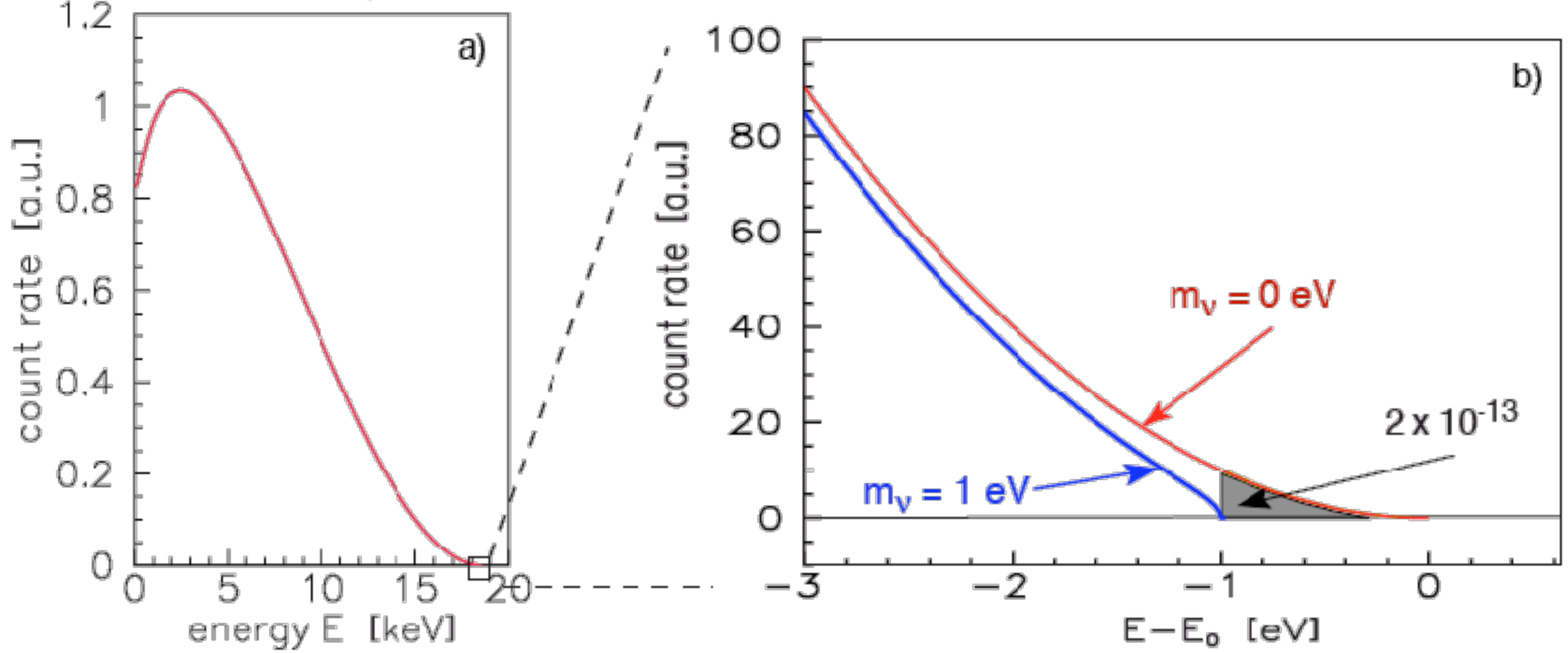
Single Beta Decay



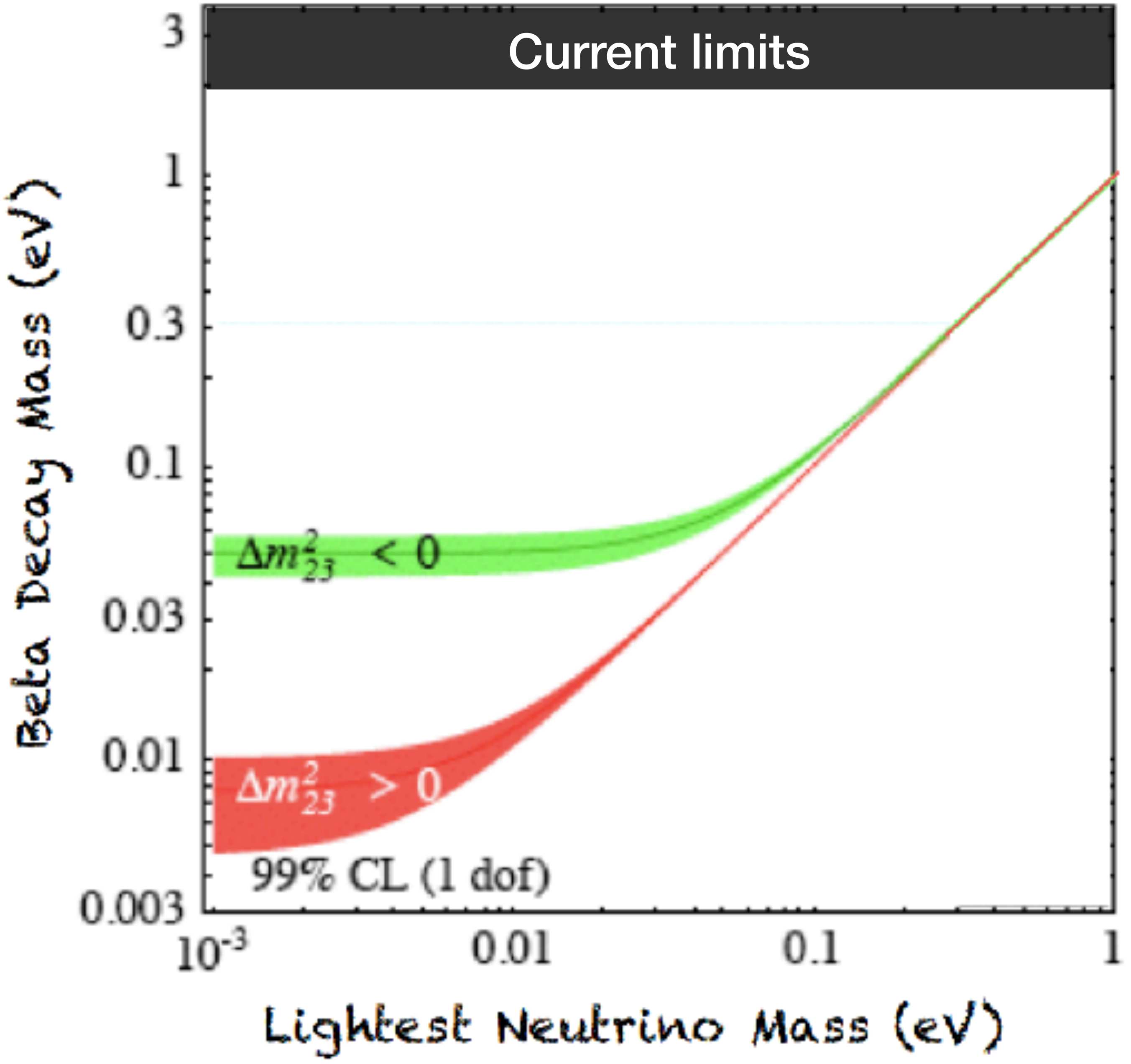
A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Present limits $m_\nu < 2$ eV (Mainz, Troitsk)



Single Beta Decay



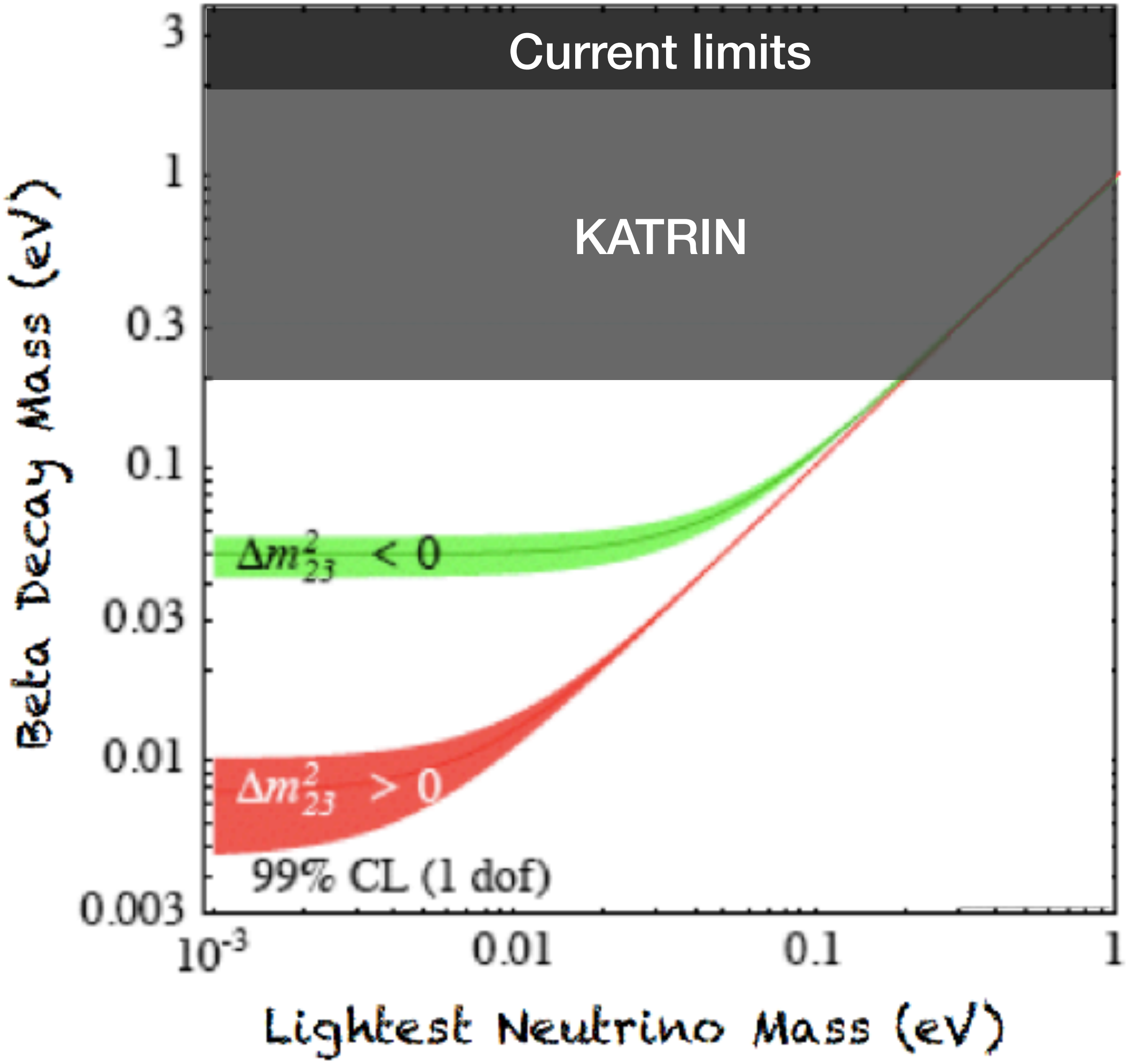
$m_\nu > 2$ eV (eV scale, current)

Neutrinos ruled out as dark matter

$m_\nu > 0.2$ eV (degeneracy scale)

Impact on cosmology and 0νββ reach

Single Beta Decay



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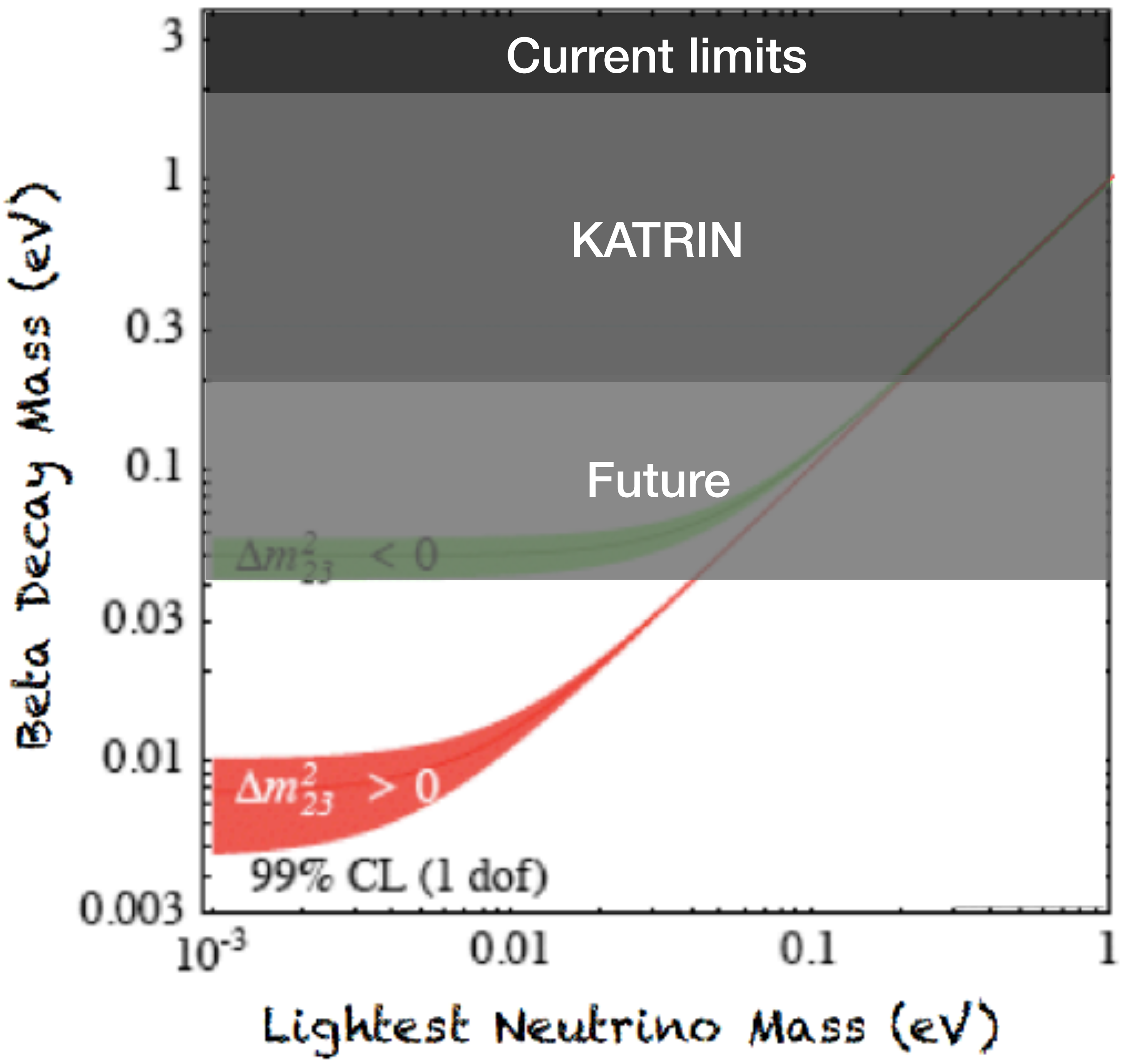
Single Beta Decay



m_ν > 2 eV (eV scale, current)

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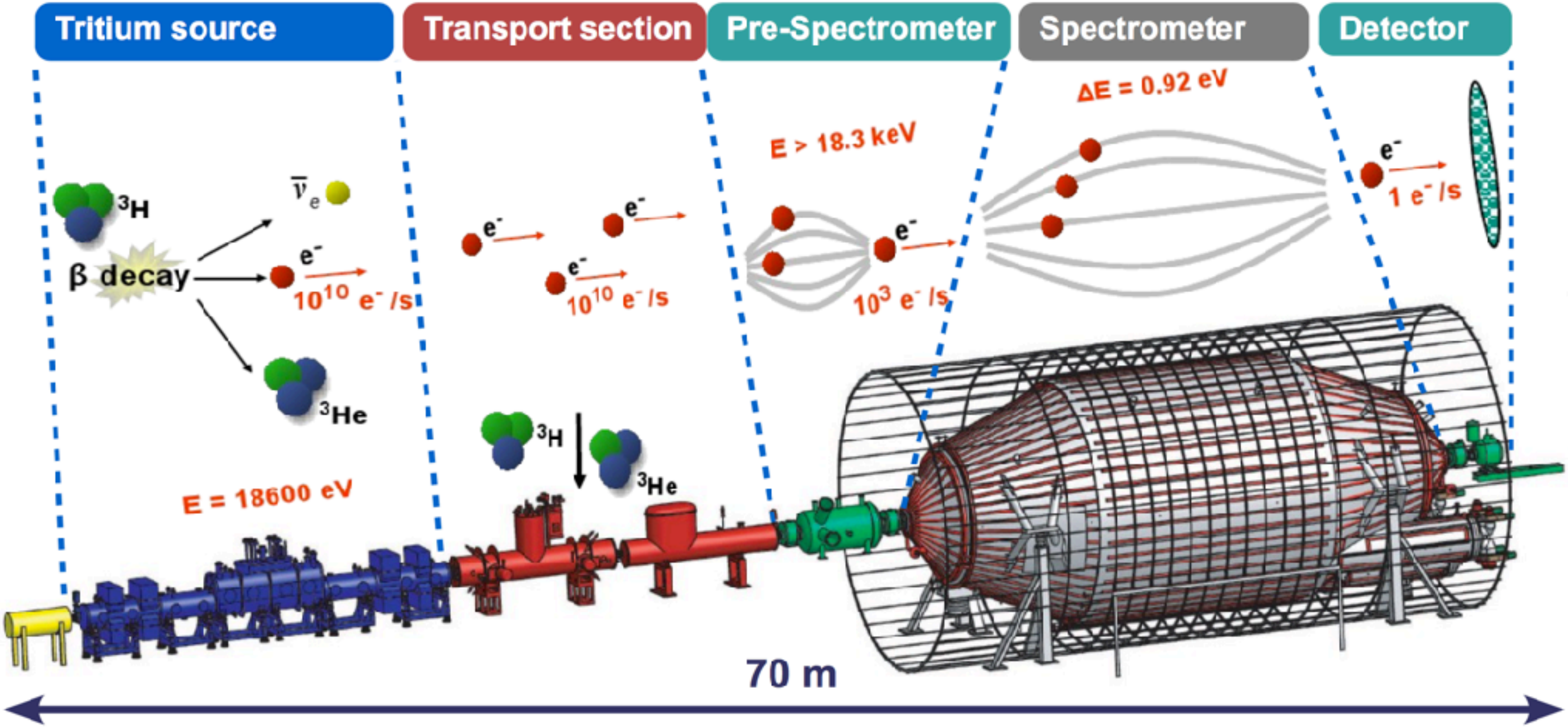
Impact on cosmology and 0νββ reach

KATRIN



KATRIN sensitivity:

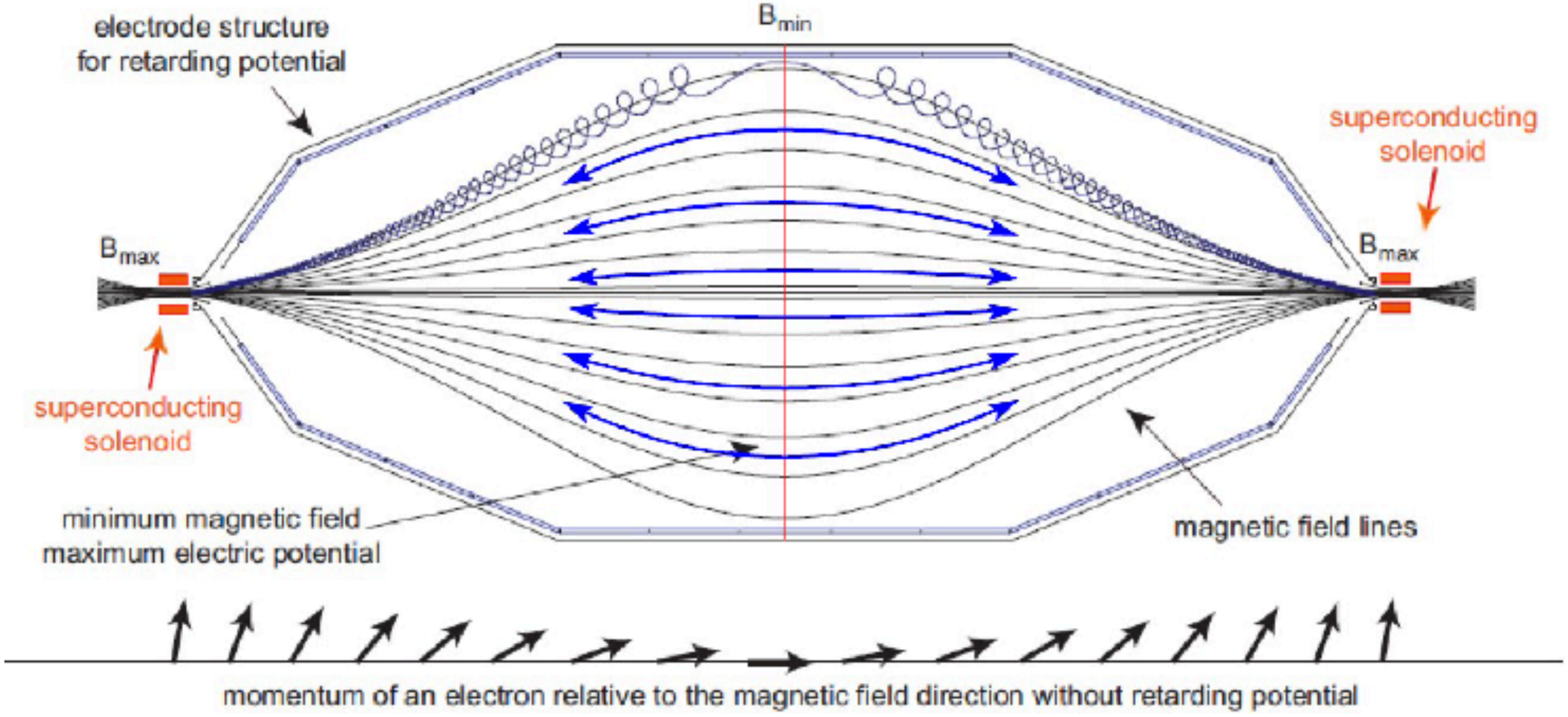
- 5 year measurement (60% duty cycle)
- systematic uncertainty $\sigma_{sys,tot} \approx 0.017$ eV^2
- statystical uncertainty $\sigma_{stat} \approx 0.018$ eV^2

→ sensitivity for upper limit: 200 meV/c^2 (90% C.L.)

$m(\nu_e) = 0.35$ eV observable with 5σ

KATRIN

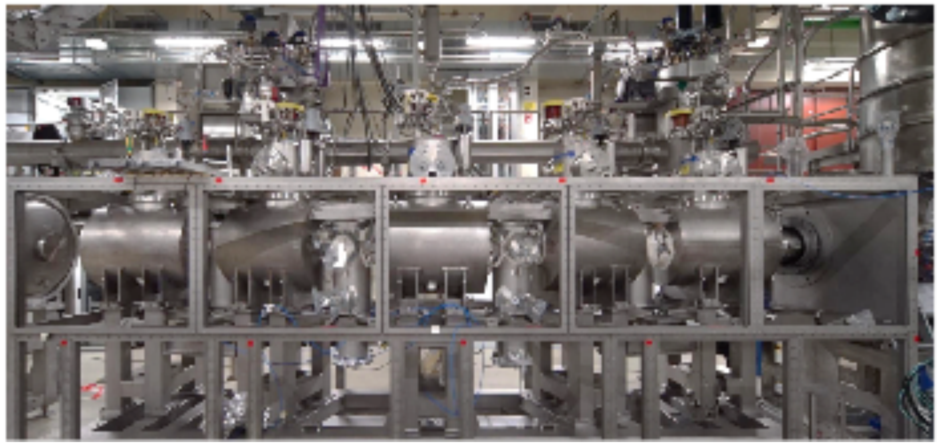
Magnetic Adiabatic Collimation with Electrostatic Filter (MAC-E)



- Inhomogeneous magnetic guiding field.
- Retarding potential acts as high-pass filter
- High energy resolution ($\Delta E/E$ = Bmin/Bmax = 0.93 eV)

KATRIN






- System is complete (except tritium loops and rear wall and calibration system):
  - 1st light in October 2016, ^{83m}Kr calibration measurements in July 2017 very successful
- Tritium data taking: start in 2018

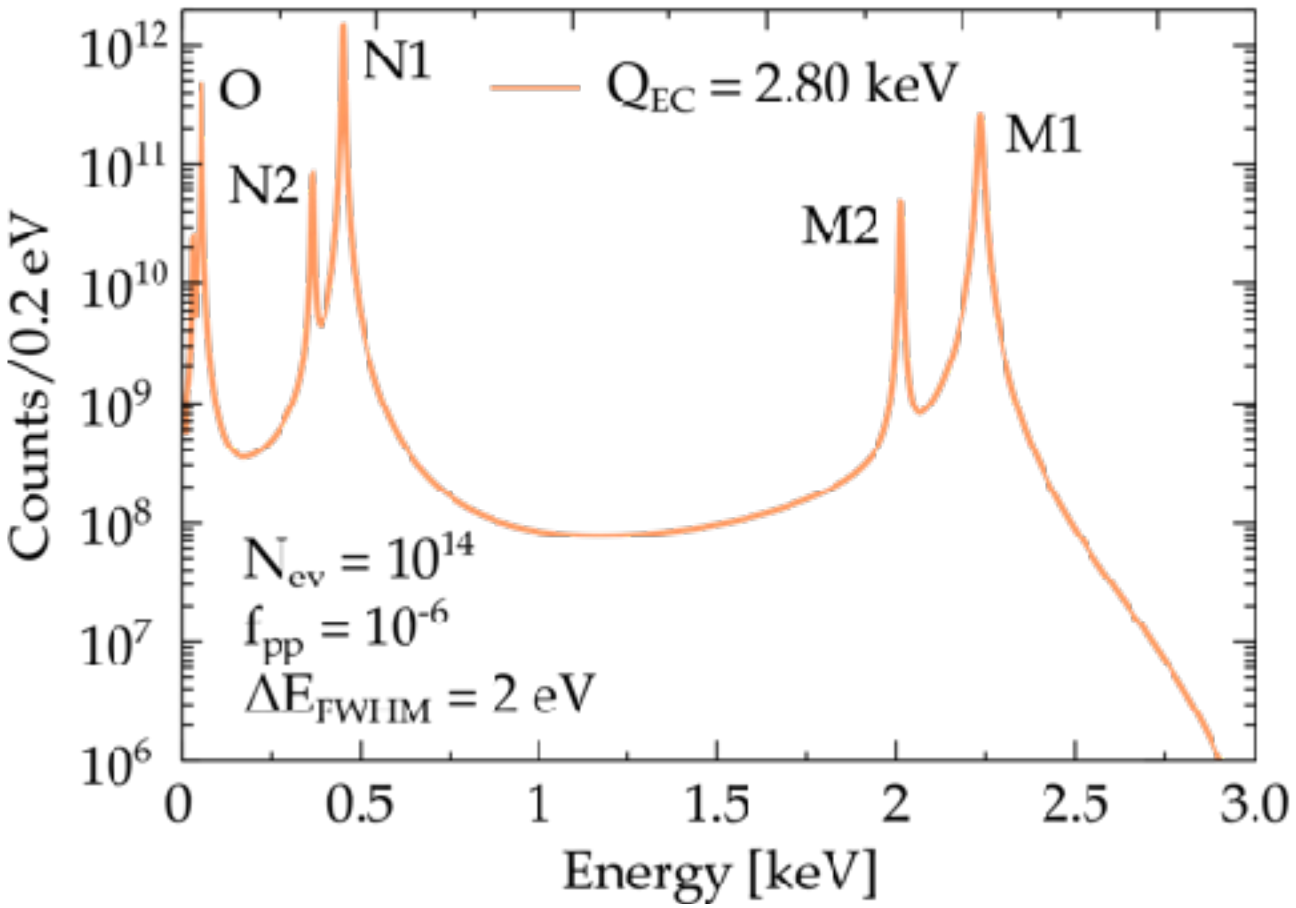
- KATRIN inauguration ceremony: June 11, 2018 (after Neutrino 2018 at Heidelberg)

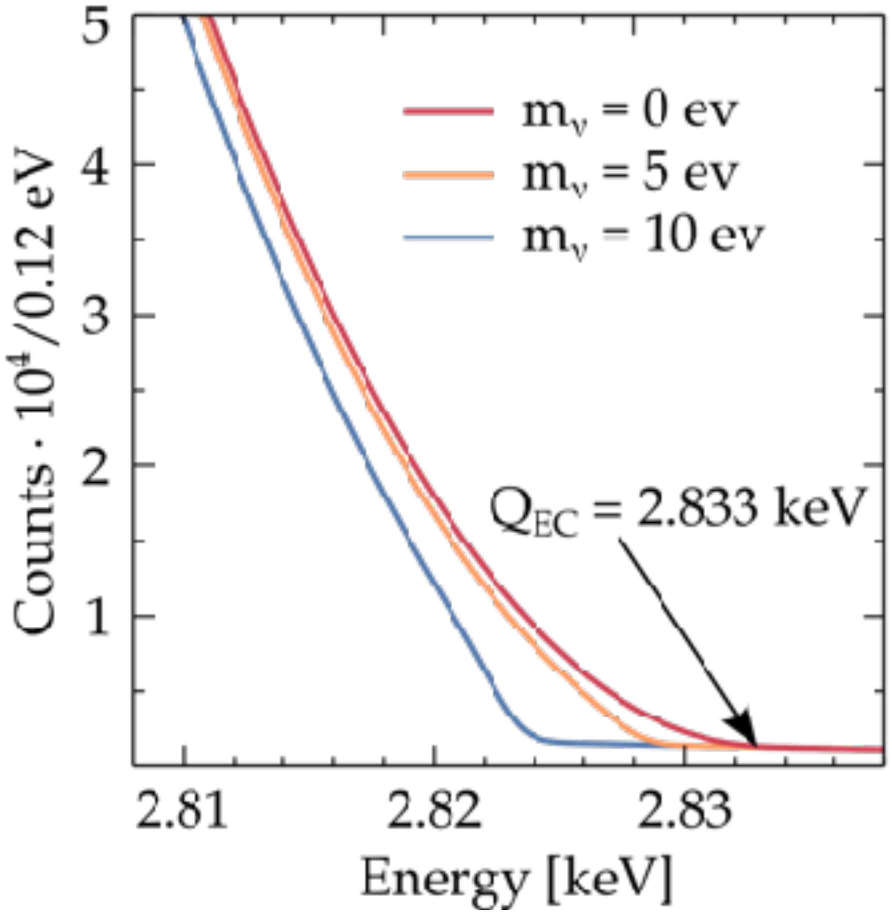
Holmium experiments

$$^{163}Ho + e^{-} \rightarrow \; ^{163}Dy^{*} + \nu_e$$

Proposed by A. De Rujula and M. Lusignoli, Phys. Lett. B 118 (1982) 429

- calorimetric measurement of the Dy atomic de-excitation (mostly non-radiative)
- rate at the end point depends on (Q–EM1): the proximity to M1 resonance peak enhances the statistics at the end point (i.e. sensitivity on m_ν)
- $t_{1/2}$~4570 years: few nuclei are needed ($2\text{x}10^{11}$ ^{163}Ho nuclei = 1 Bq)

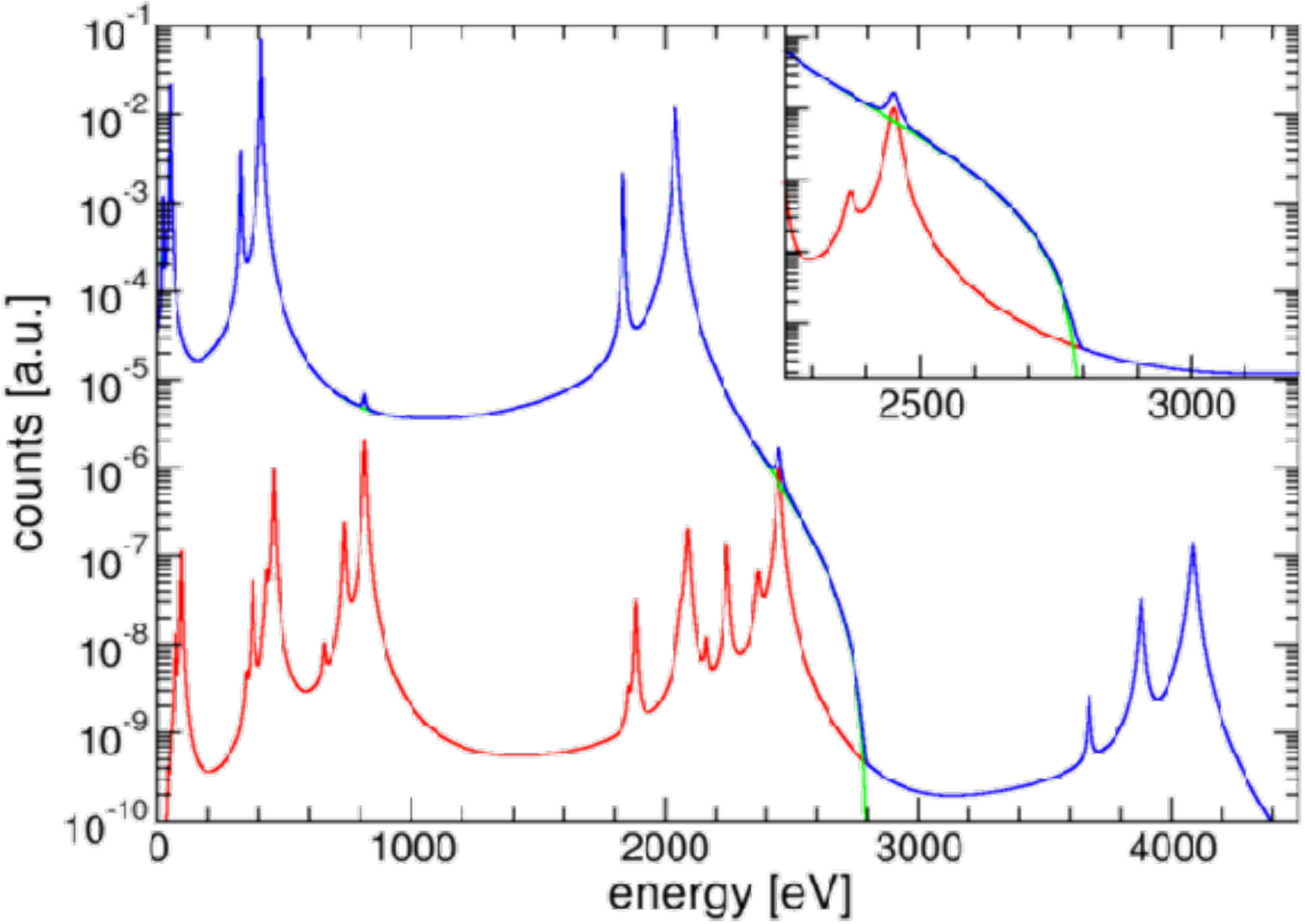




Pile-up

Pile-up is the major difficulty in calorimetric measurements

$$N_{pp}(E) = f_{pp} \times N_{EC} \otimes N_{EC}, \quad with\ f_{pp} \approx A_{EC}\,\tau_R$$



A_{EC} :activity/detector

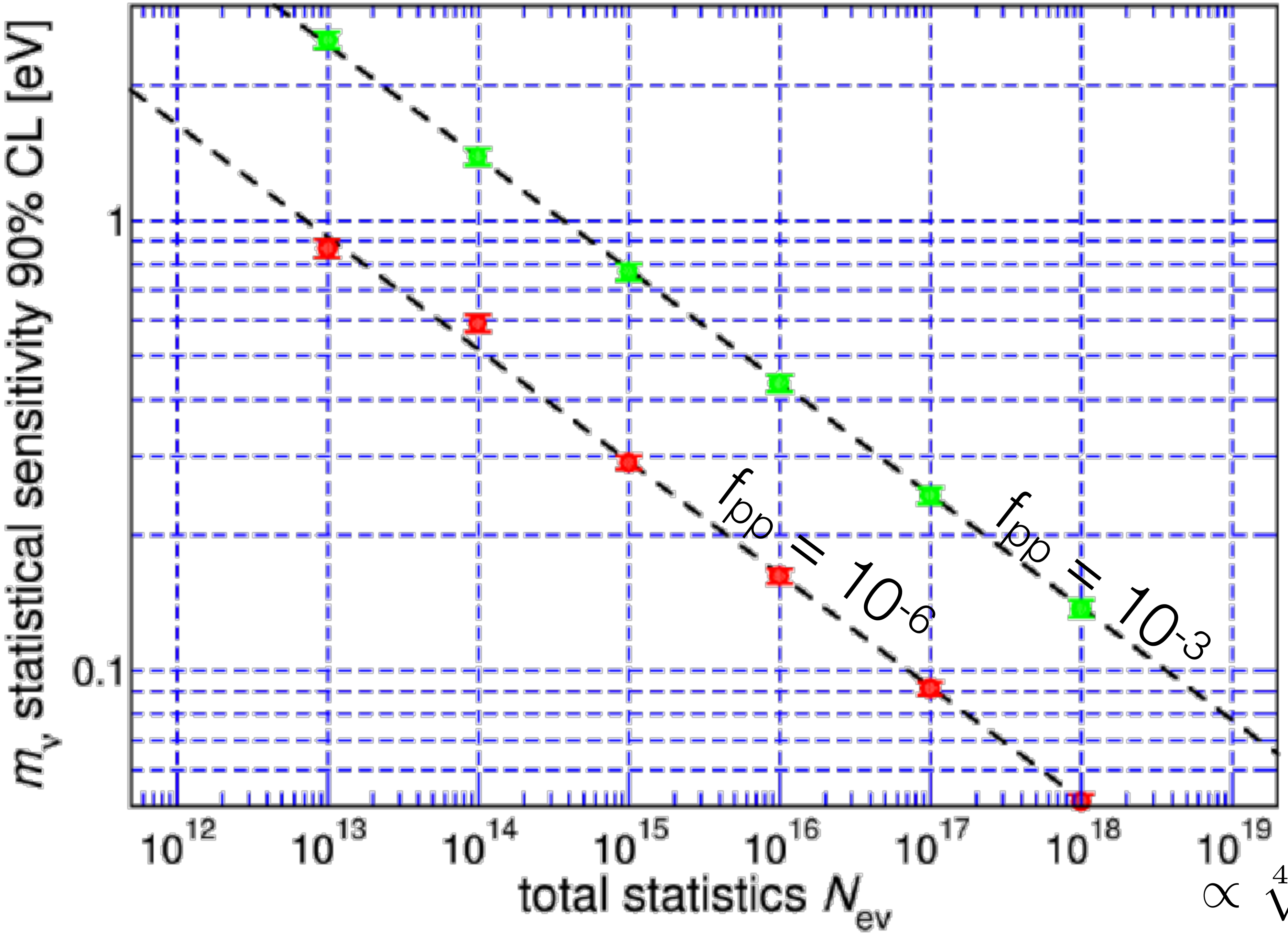
τ_R :time resolution (~rise time)

- fast detectors
- limited activity/detector
- large number of detectors needed

Statistical sensitivity

In order to reach Σmν ≤ 0.1 eV

- Two examples



$\propto \sqrt[4]{1/N_{ev}}$

MC simulation
Q= 2.8 keV
ΔE = 1 eV
$\tau_R \approx 1$ μs

A_{EC}= 1 Bq, $f$pp= 10^{-6}
$N_{\text{det}}\ t_M \approx 2\times10^9$ det· y

A_{EC}= 1000 Bq, $f$pp= 10^{-3}
$N_{\text{det}}\ t_M \approx 10^8$ det· y

M. Galeazzi et al., arXiv:1202.4763v2
A. Nucciotti, Eur. Phys. J. C (2014) 74:3161

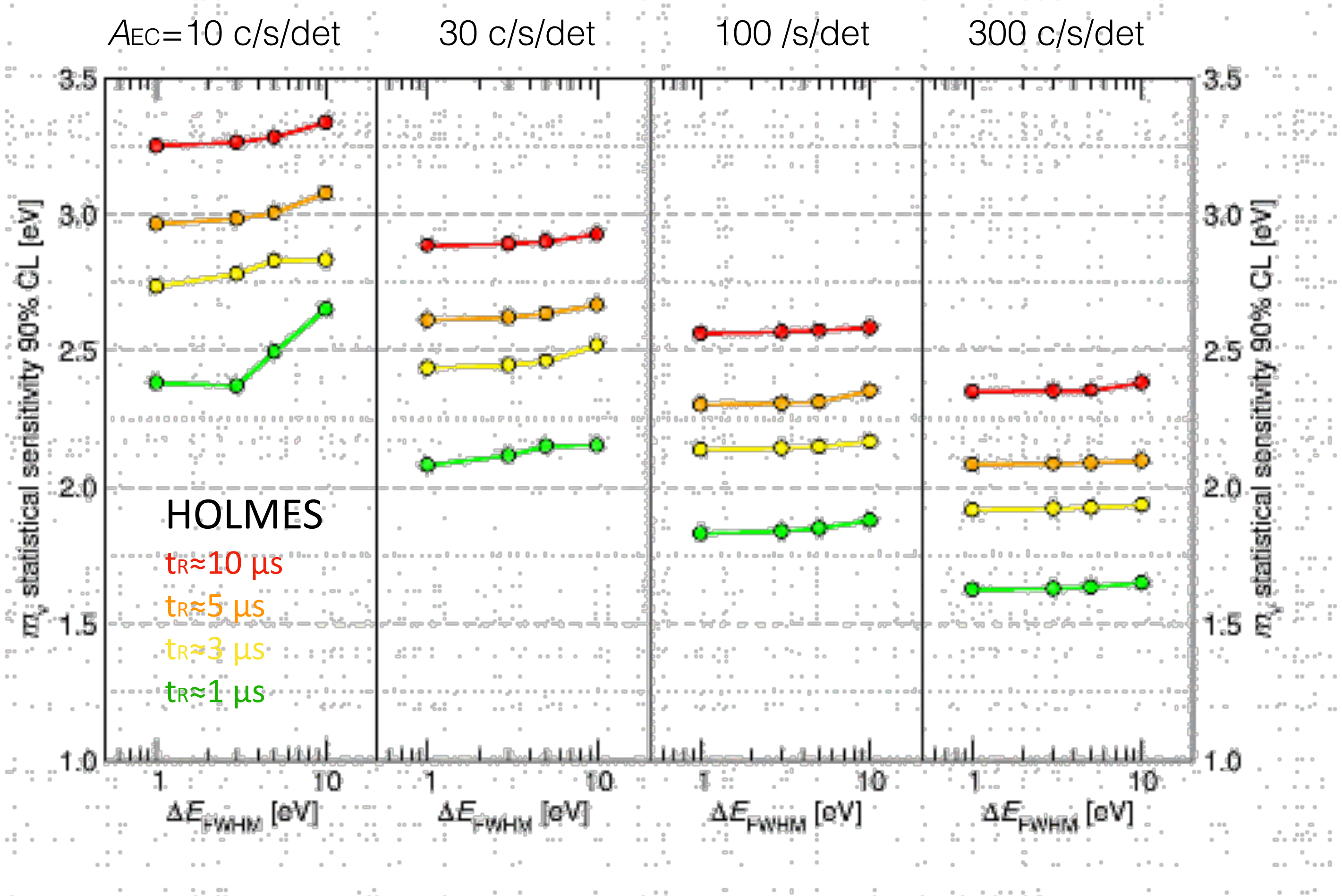
HOLMES

Detectors: Transition Edge Sensor with ^{163}Ho implanted in Au absorbers

Activity: 6.5×10^{13} nuclei per detector → 300 dec/s

Performances: $\Delta E_{FWHM} \approx 1$ eV, $\tau_R \approx 1$ μs

MonteCarlo with 1000 detectors x 3 years



B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

GOAL

Neutrino mass determination with a sensitivity as low as ~1 eV

- proof potential and scalability of the approach
- precise calorimetric determination of Q
- systematic errors assessment

Two steps approach:

- 64 channels mid-term prototype, (t_M= 1 month, m_ν< 10 eV)
- full scale: 1000 channels, 3×10^{13} events collected in 3 years
- 6.5×10^{16} ^{163}Ho nuclei (≈18 mg)

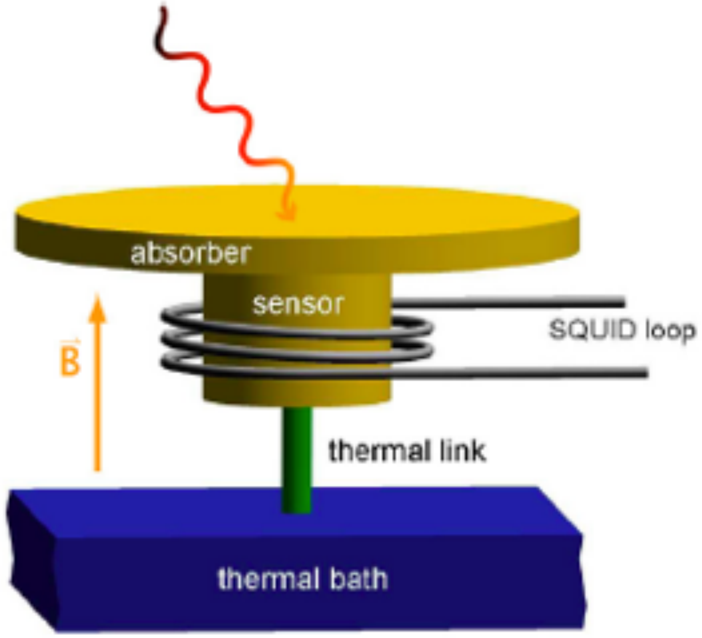
HOLMES (ERC-Adv. Grant 340321)
5 years project started on Feb. 1st 2014

ECHo

Detectors: Au:Er Metallic Magnetic Calorimeter (MMC) with implanted ^{163}Ho

Activity: 6.5×10^{13} nuclei per detector → 300 dec/s

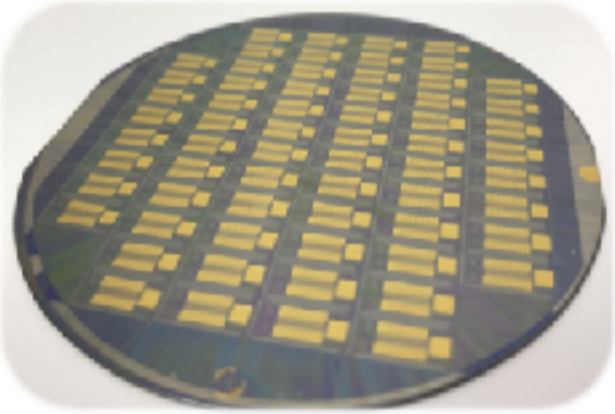
Performances: $\Delta E \approx 1$ eV, $\tau_R \approx 1$ μs

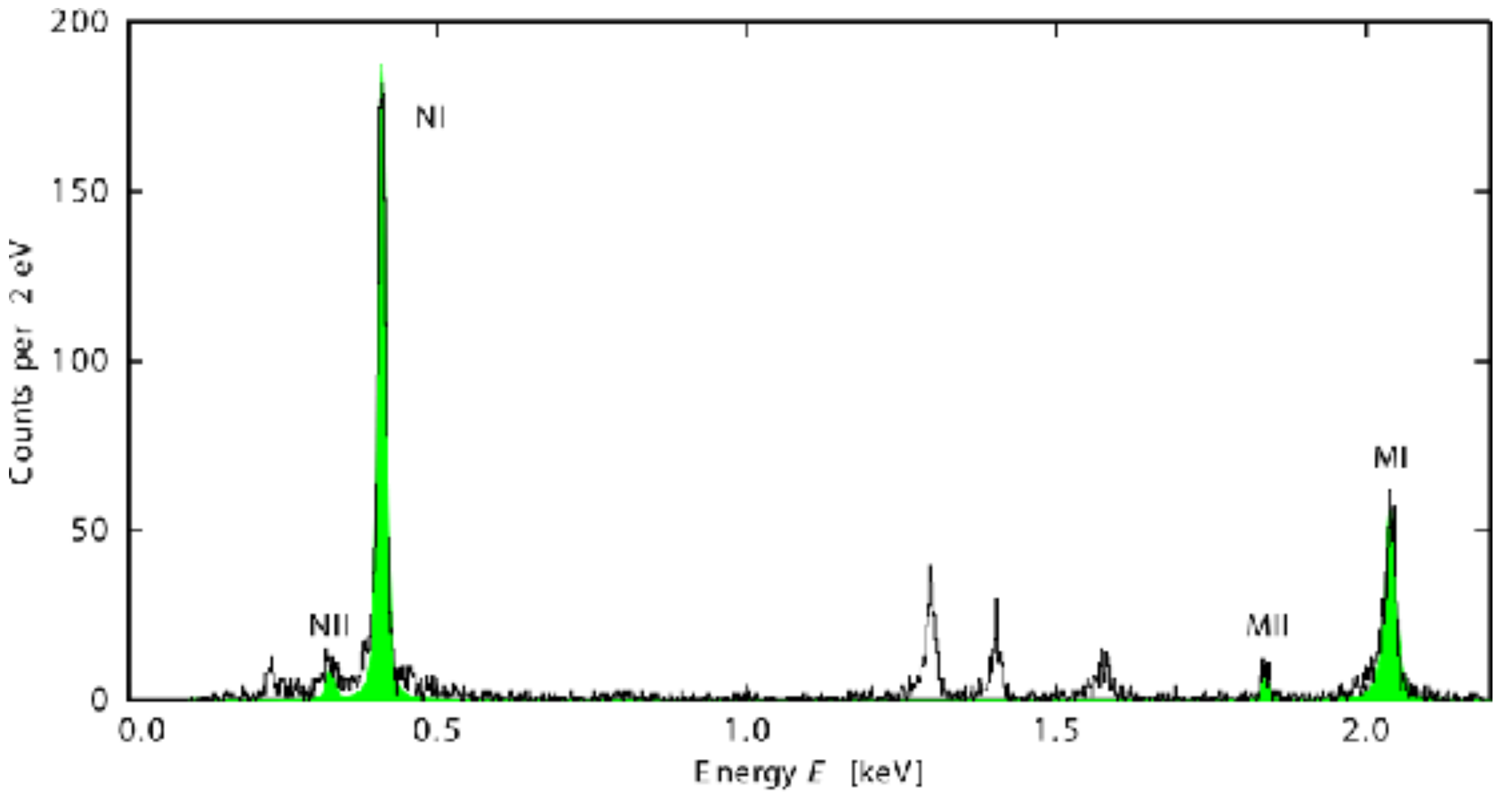


Prove scalability with medium large experiment ECHo-1k (2015-2018)

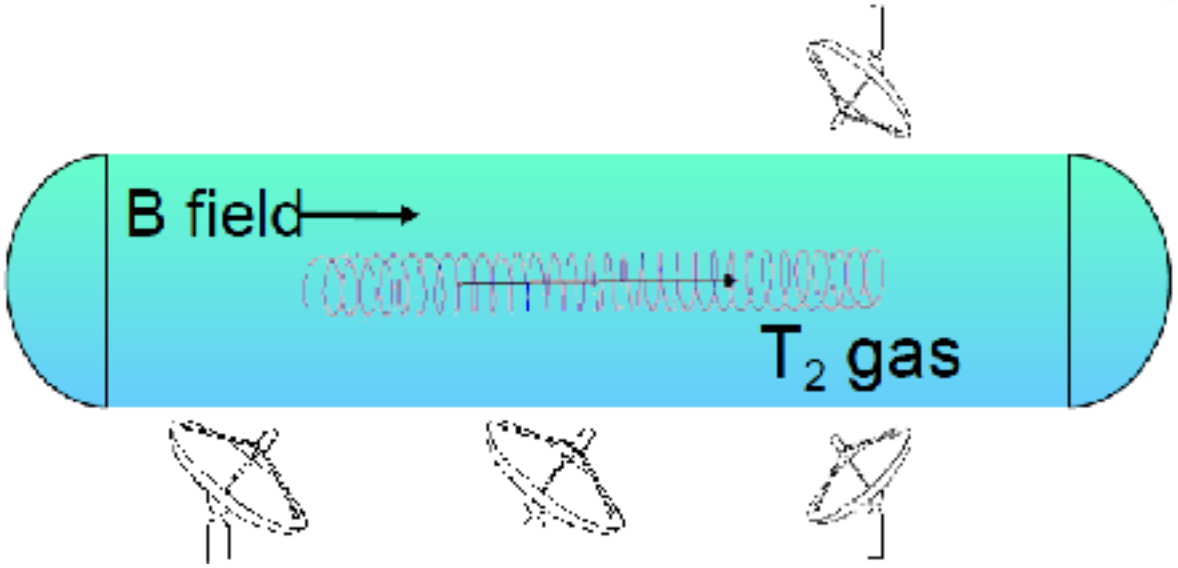
- total activity 1 kBq, high purity ^{163}Ho source (produced at reactor)
- $\Delta E_{FWHM} < 5$ eV, $\tau_R < 1$ μs
- multiplexed arrays → microwave SQUID multiplexing
- 1 year measuring time 10^{10} counts → neutrino mass sensitivity $m < 10$ eV
- Data taking will starting early 2018

Future: ECHo-10M sub-eV sensitivity



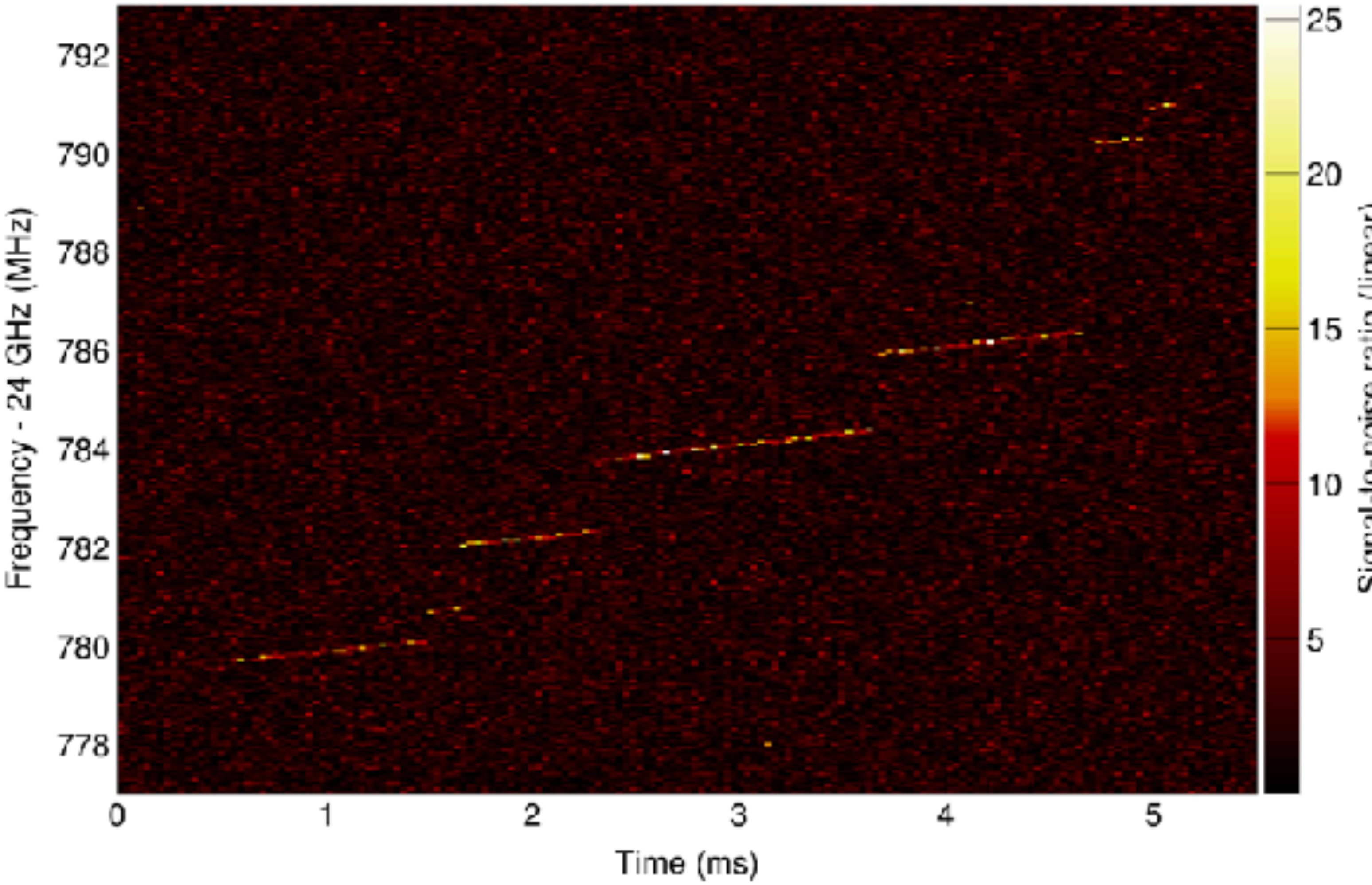


Project-8



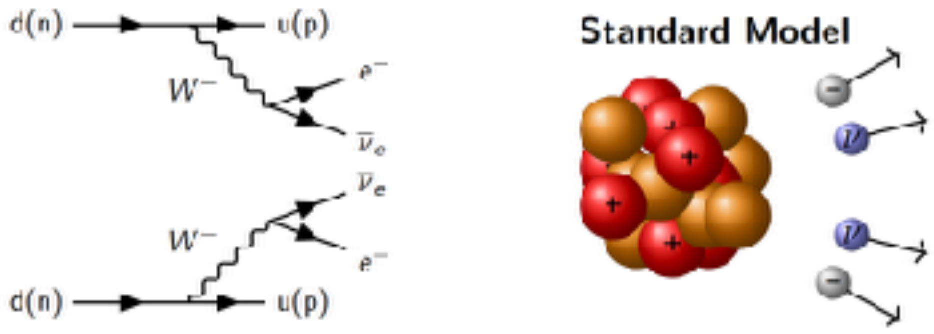
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

- Use cyclotron frequency to extract electron energy
- Non destructive measurement of electron energy
- Source=Detector (no need extract the electrons from the Tritium)



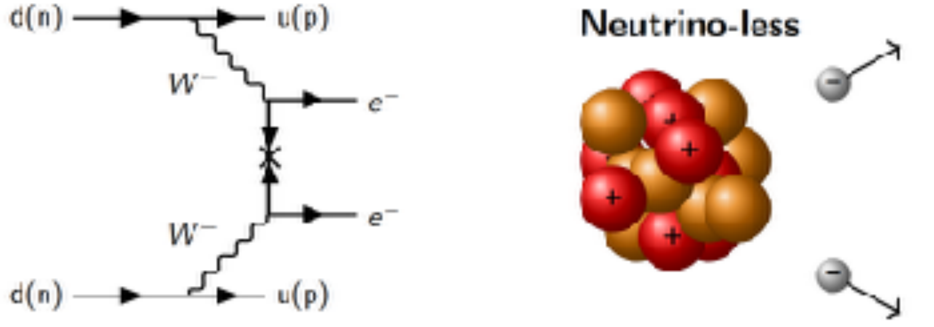
First detection of single-electron cyclotron radiation

Double Beta Decay



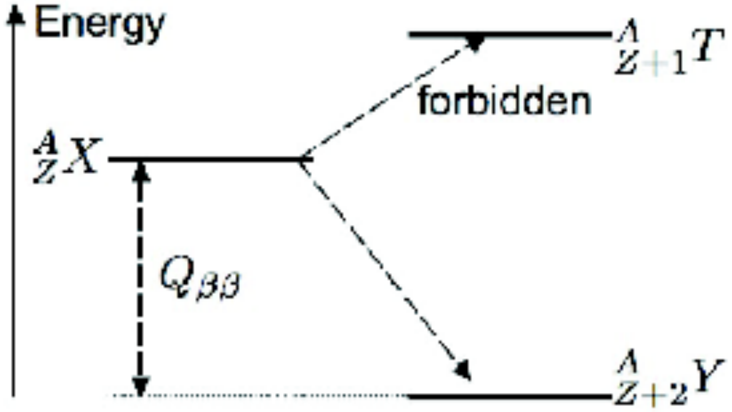
$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu}$$

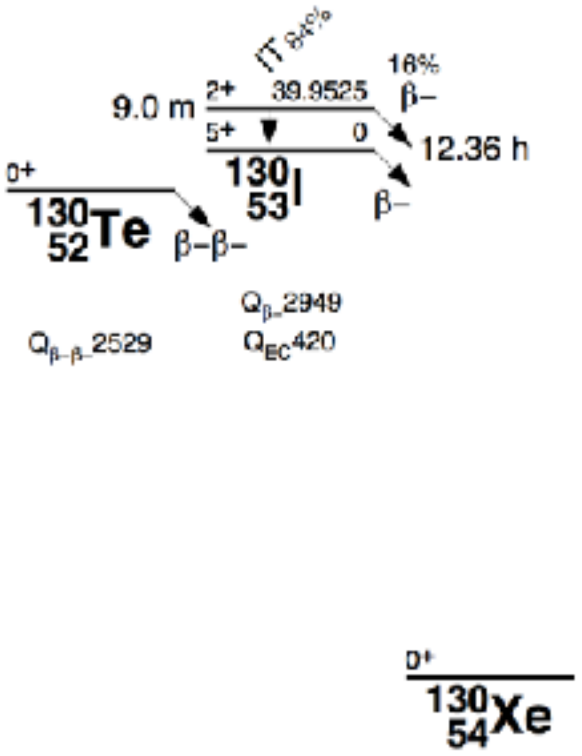
- 2nd order process allowed in the SM
- observed in several nuclei with $\tau_{2\nu} \sim 10^{19} - 10^{21}$ y



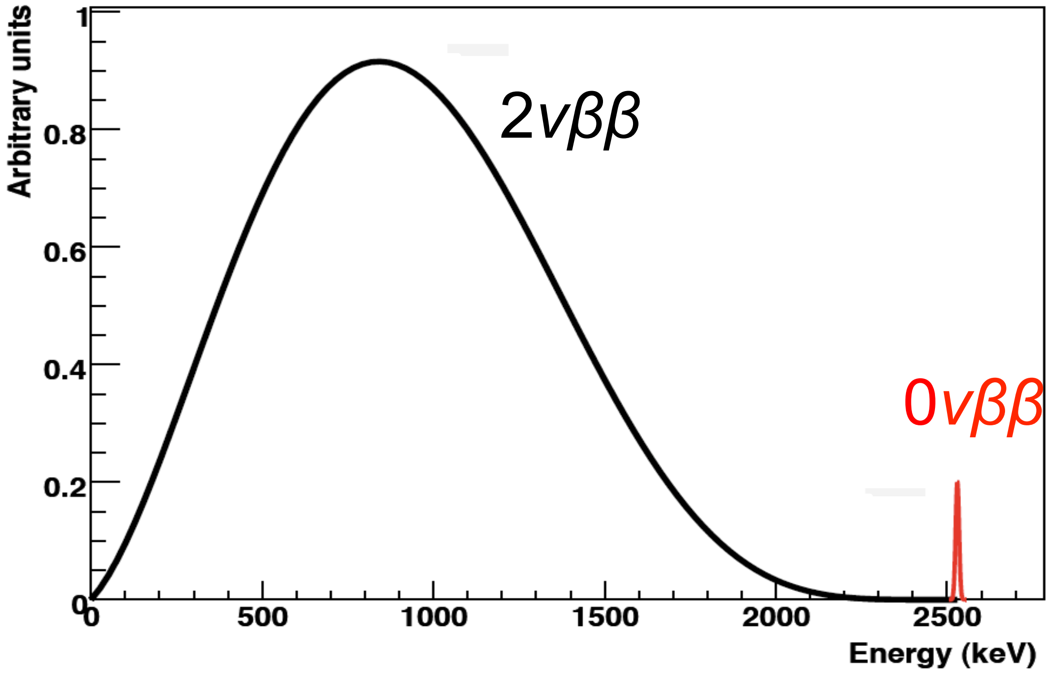
$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

- lepton number violating process
- $\tau_{0\nu} > 10^{25} - 10^{26}$ y
- exists if neutrino is a Majorana particle and $m_\nu \neq 0$





ββ summed e^- energy spectrum



0ν-ββ and Majorana mass

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu} g_A^4 |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

0νββ decay rate

Phase space factor

Axial vector coupling

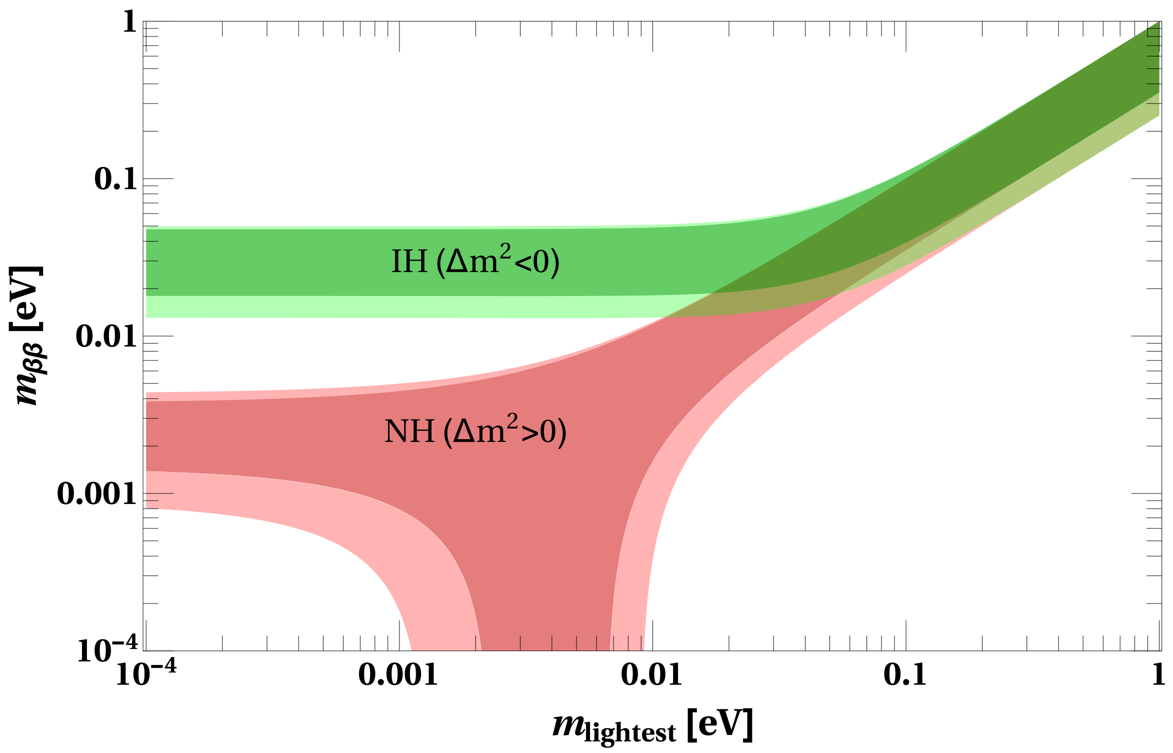
Nuclear matrix element

Effective Majorana mass

MASS EIGENVALUES

$$\langle m_{\beta\beta} \rangle = \sum_k U_{ek}^2 m_k = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

MIXING MATRIX



Sensitivity

Half-life corresponding to the minimum detectable number of events over background at a given confidence level

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

finite background: M·T·B·ΔE >1

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

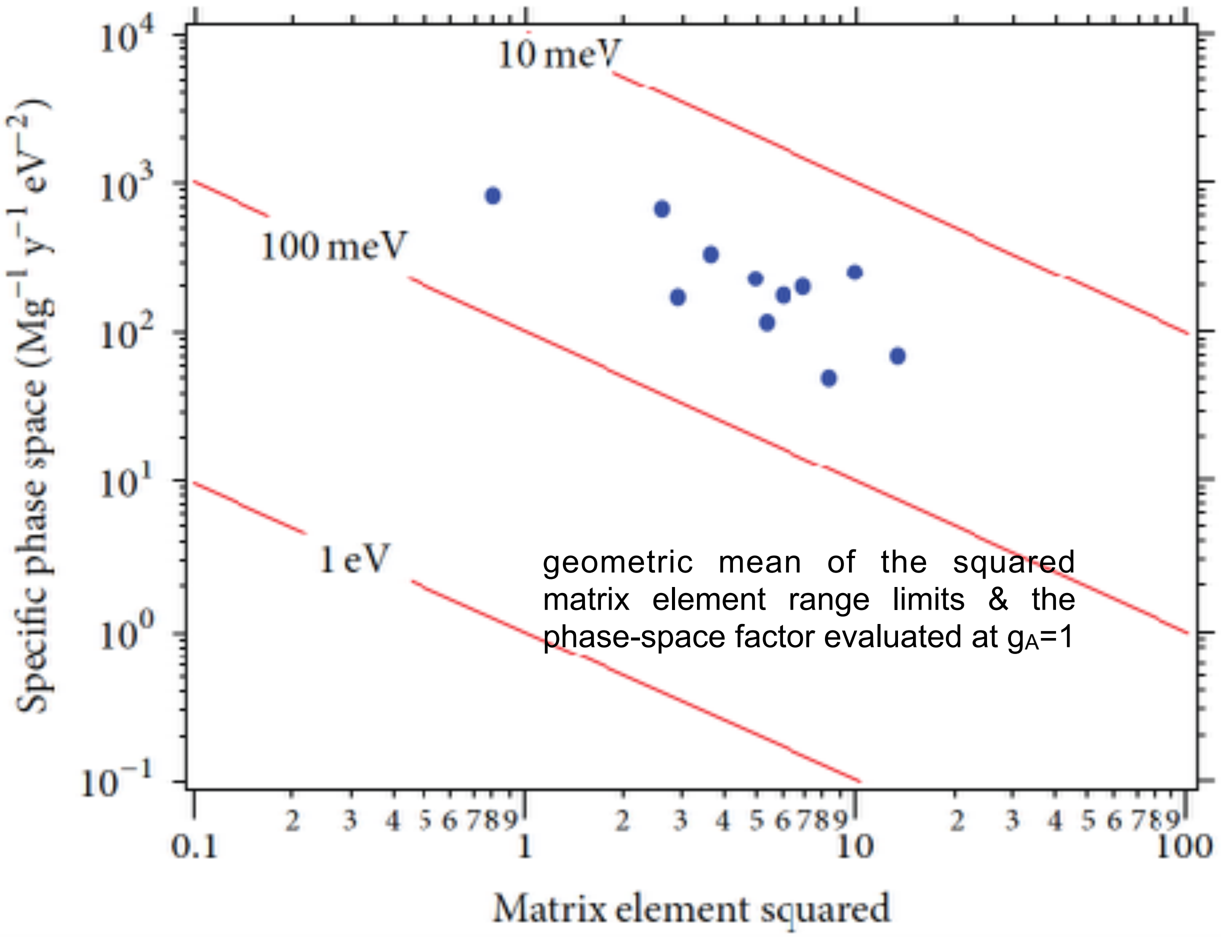
zero background: M·T·B·ΔE ≲1

M: active detector mass [kg]
T: measurement life time [anni]
B: background in the ROI [counts keV^{-1} kg^{-1} y^{-1}]
W: molecular weight

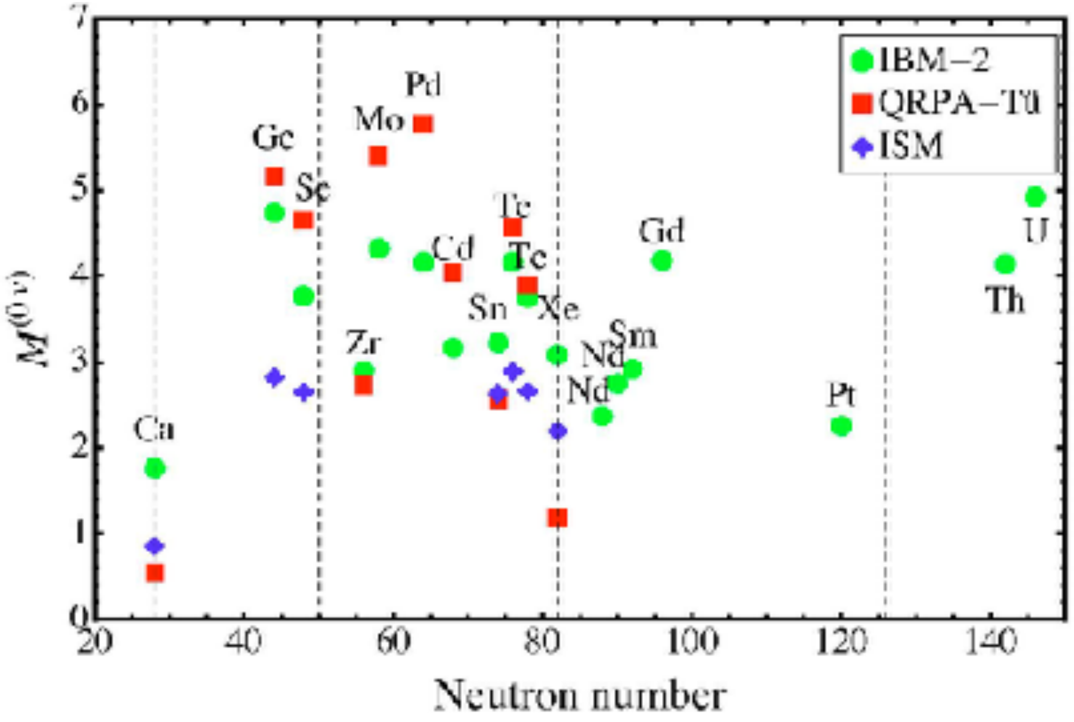
N_A: Avogadro number
η: isotopic abundance
ε: detector efficiency
ΔE: FWHM energy resolution @ Q-value

Is there a preferred isotope?

- Nuclear matrix elements calculations are rapidly improving and today the differences between different methods (IBM, QRPA, ISM) are much smaller than in the past (30% btw QRPA and IBM-2)
- Uncertainty on g_A could play a relevant role: factor 2 in g_A is a factor 16 in decay rate
- inverse correlation observed between phase space and square of the nuclear matrix element (but still large deviations)



geometric mean of the squared matrix element range limits & the phase-space factor evaluated at g_A=1



Axial vector coupling

Even if QRPA/IBM-2 agree within 30%, other methods of calculation (as ISM) suggest caution

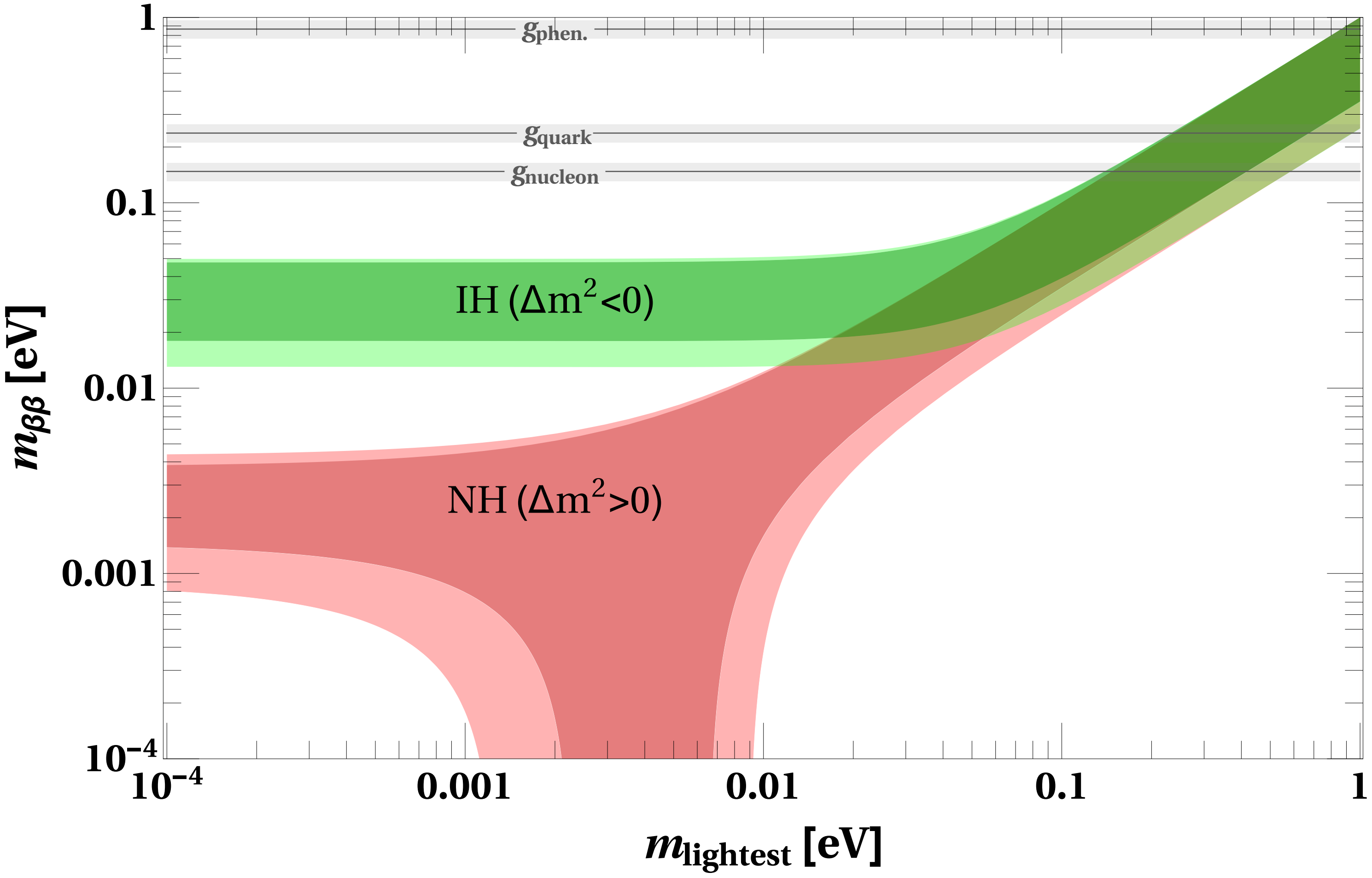
For 2ν2β, IBM-2 (and QRPA) overestimate matrix elements much more than 30%

- matrix elements are overestimated because g_A is quenched?
- approximate scaling in IBM-2, $g_A = 1.269 \times A^{-0.18}$

- Possible dramatic impact of gA quenching on the experiments results

- The "quenching" of g_A is a phenomenological observation; however it is likely to depend upon the momentum of the virtual states

- In 0ν2β, q^2 is much larger than in 2ν2β and g_A could also be larger



Isotope choice

In many cases driven by the detector characteristics.

- ^{76}Ge with Germanium diodes
- ^{136}Xe with Xenon TPCs
- bolometers and scintillators have multiple choices

Isotopic abundance as high as possible

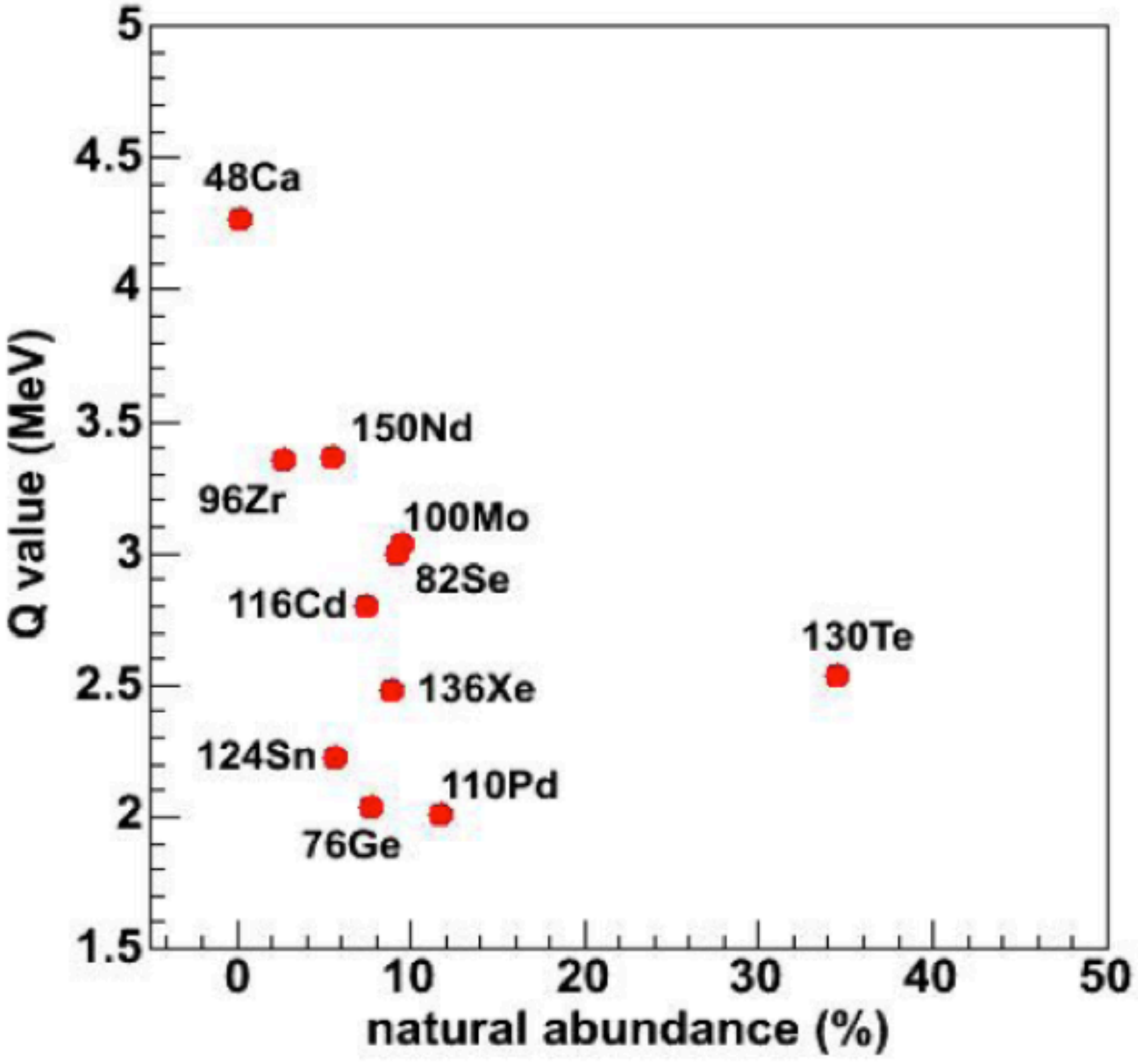
- money issue

Q-value as high as possible

- phase space
- background

2v-DBD half-life as high as possible

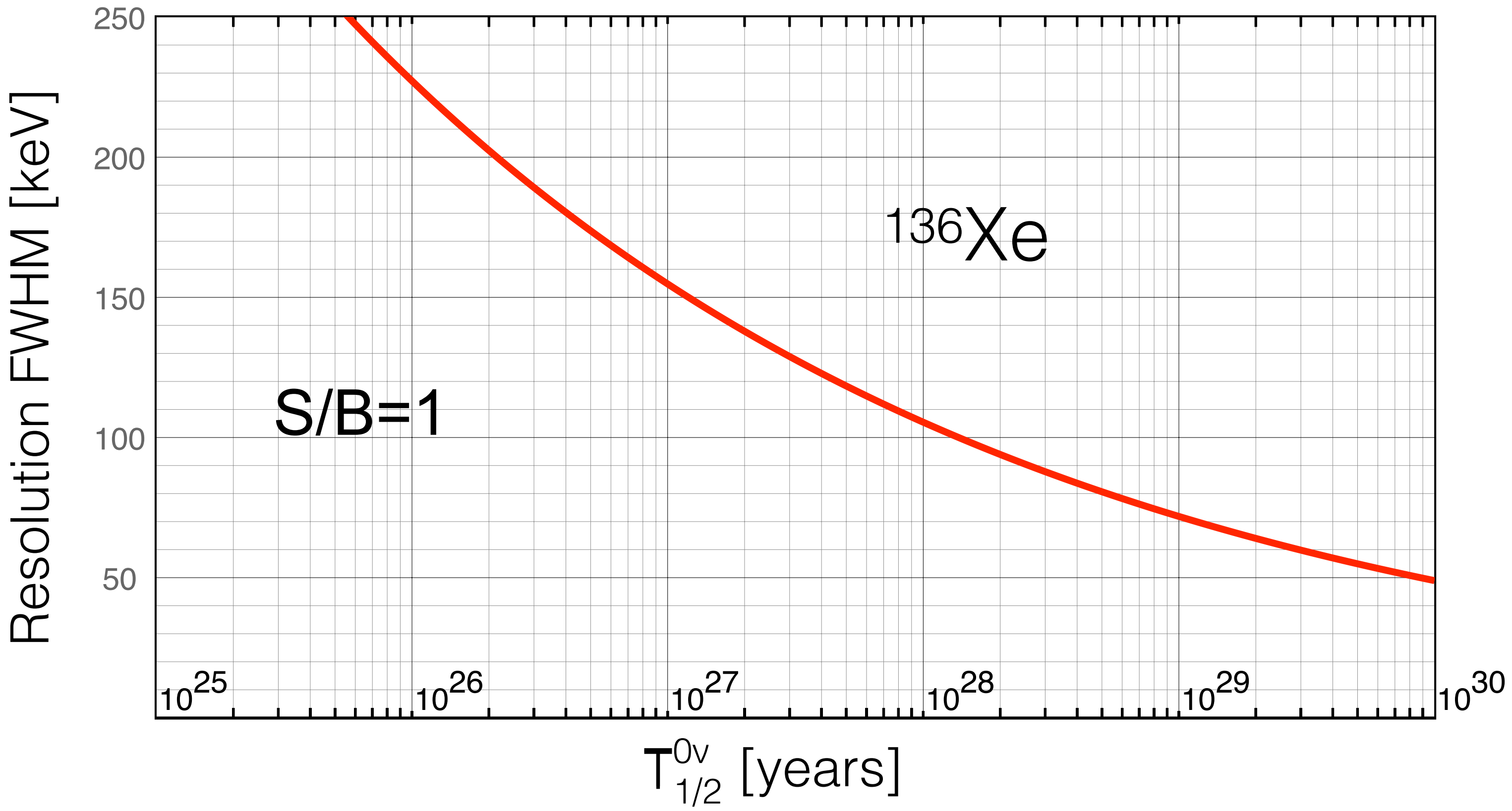
- energy resolution

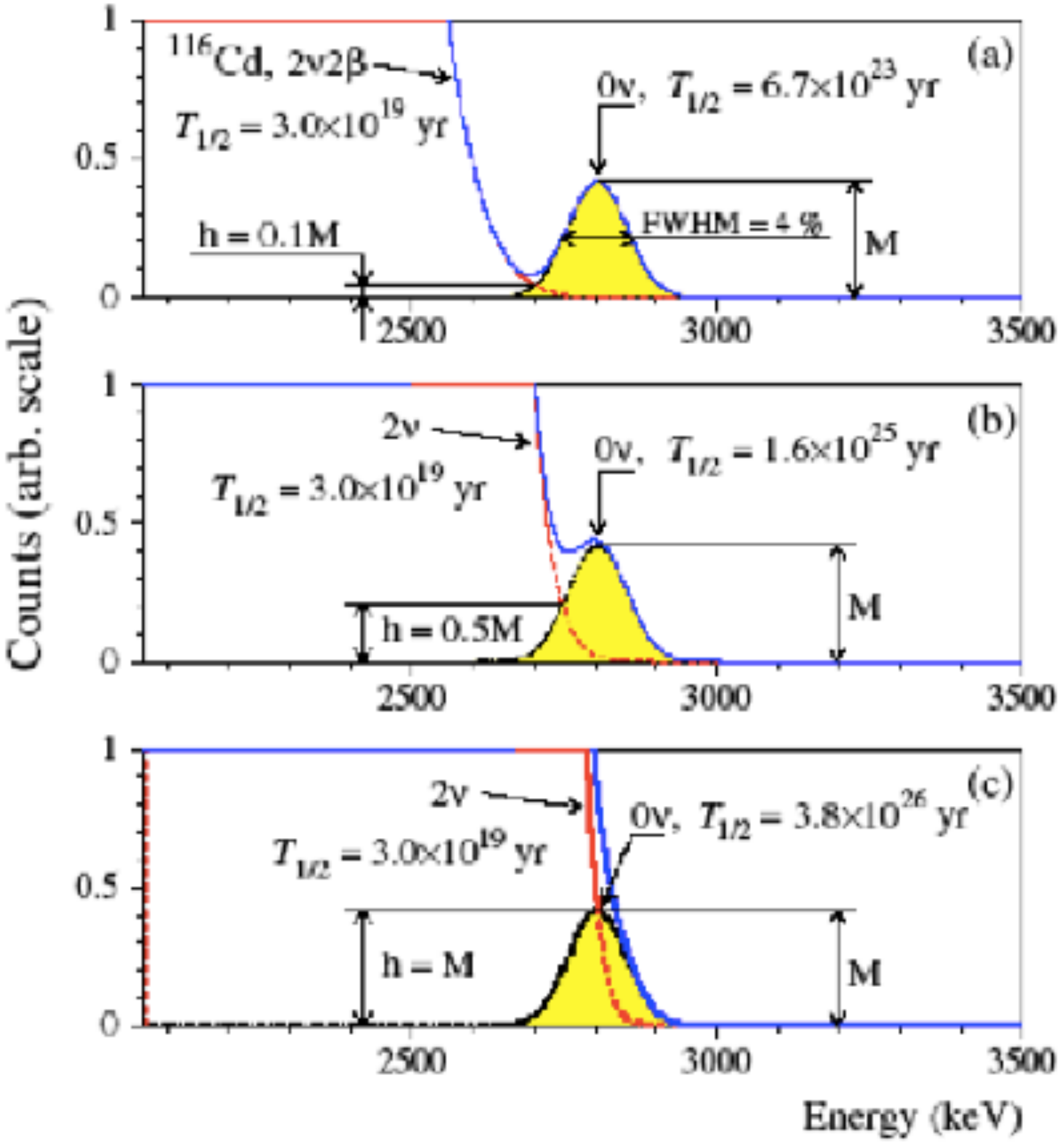


Limits vs Discovery

- The irreducible background induced by the $2\nu\beta\beta$ could be mitigated by the energy resolution
- The effect can be partially attenuated with an asymmetric ROI (but losing efficiency)

Energy resolution is a key issue: a positive result from experiments with a poor energy resolution is anyway weak





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

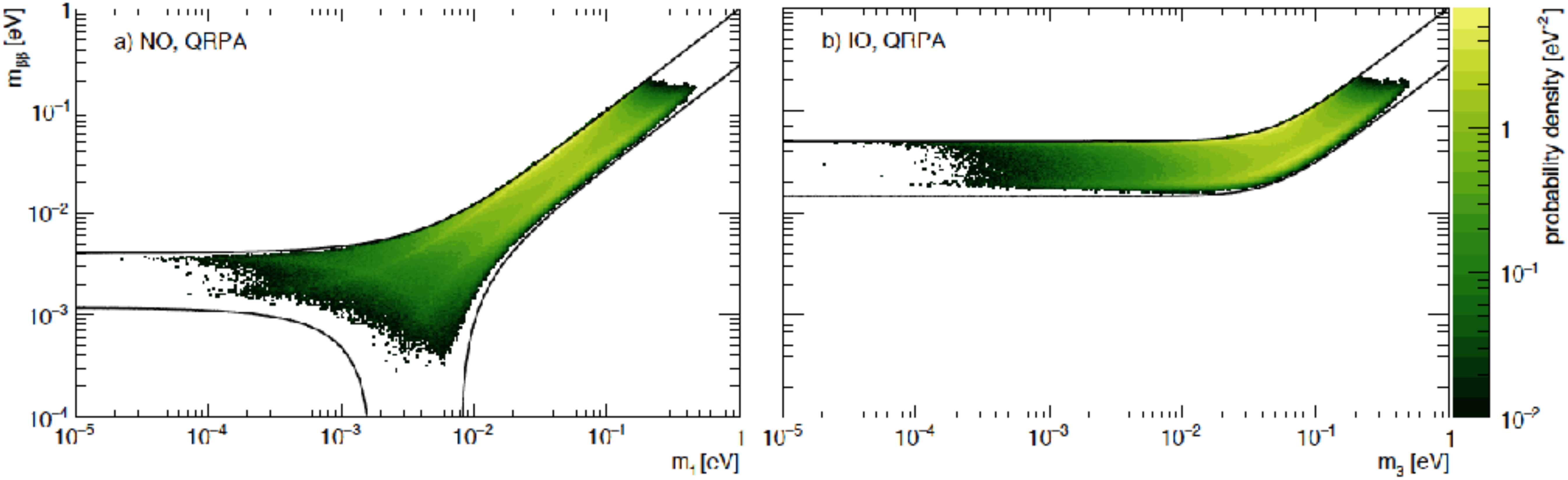
$$\frac{S}{B} = \frac{m_e}{7Q\delta^6}\frac{\Gamma_{0\nu}}{\Gamma_{2\nu}} = \frac{m_e}{7Q\delta^6}\frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}}$$

Discovery probability

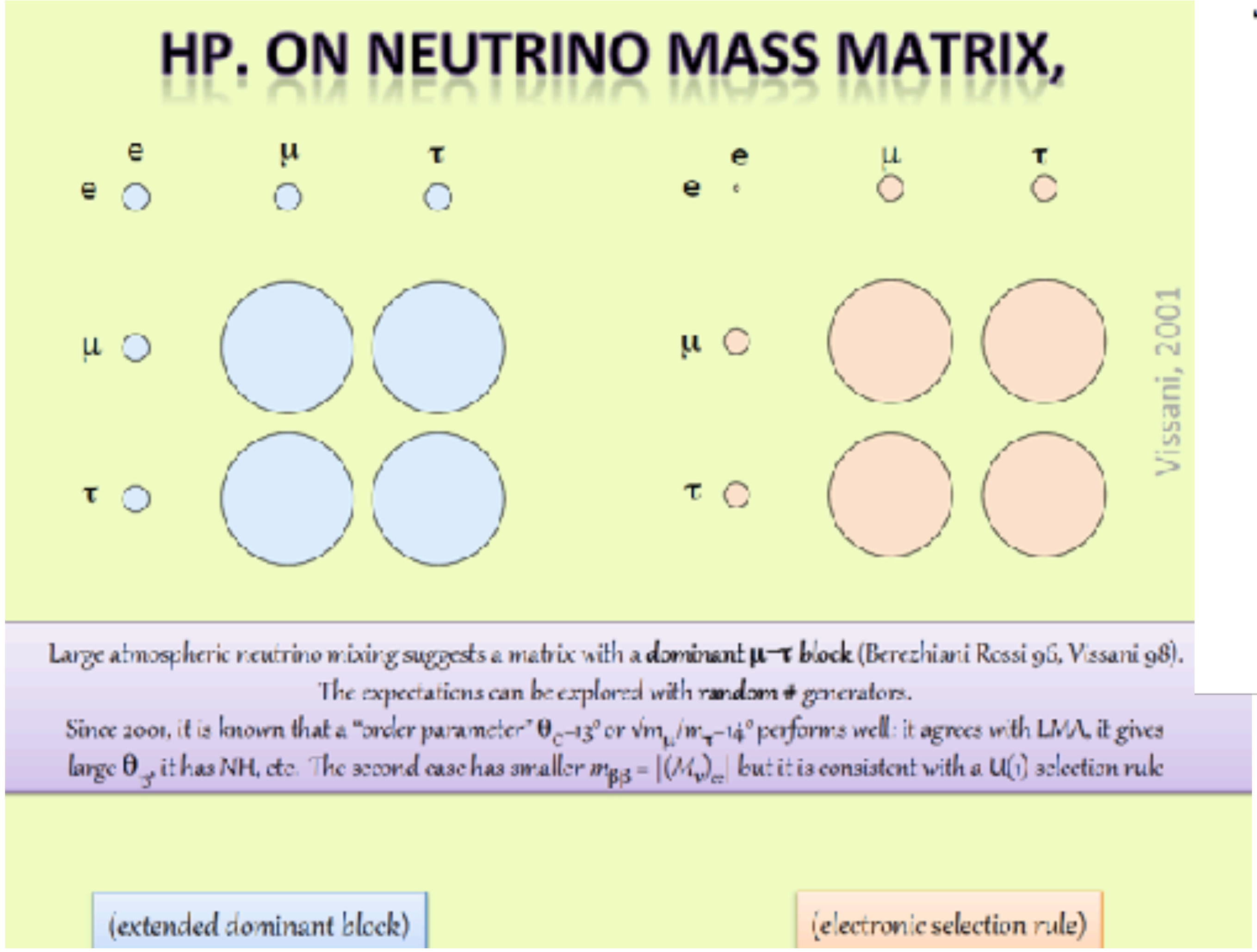
Global Bayesian analysis including ν-oscillation, mβ mββ, Σm$_ν$

Priors:

- flat Majorana phases
- m_1 (scale invariant)



Discovery probability

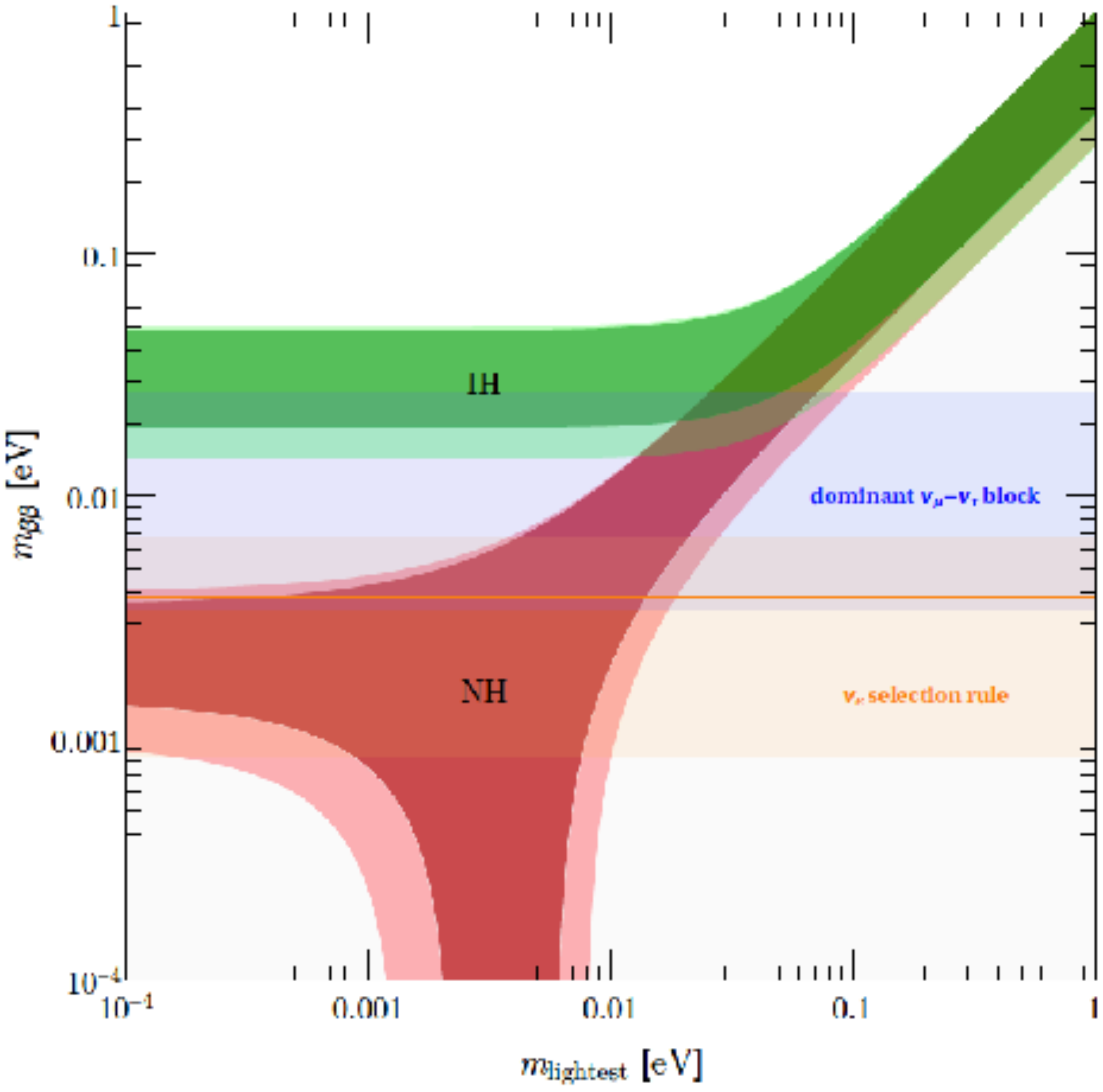


HP. ON NEUTRINO MASS MATRIX,

Large atmospheric neutrino mixing suggests a matrix with a **dominant μ–τ block** (Berezhiani Rossi 95, Vissani 98).
The expectations can be explored with **random #** generators.
Since 2001, it is known that a "order parameter" $\theta_C \sim 13°$ or $\sqrt{m_\mu/m_\tau} \sim 14°$ performs well: it agrees with LMA, it gives large θ_{23}, it has NH, etc. The second case has smaller $m_{\beta\beta} = |(M_\nu)_{ee}|$ but it is consistent with a U(1) selection rule

(extended dominant block)

(electronic selection rule)



0νββ decay sensitivity

***$F_{0\nu}$* figure of merit = total decay half life corresponding to the minimum detectable signal at a given confidence level**.

Two scenarios:

N_{bkg} = MT BΔ

> 1

- “finite background” FB: the average number of background events in the ROI collected during the experiment live time is larger than one; the minimum detectable signal at a given C.L. depends on the fluctuation of the number of background events

≤1

- “zero background” ZB: the probability of collecting more than one event event in the ROI during the live time is negligible; the minimum detectable signal only depends on signal fluctuations and is fixed for a given C.L. (*nCL* = 1.14 for 68% C.L.)

The sensitivity formula for the two cases becomes:

≤ 1 $M{\cdot}T{\cdot}B{\cdot}\varDelta$ > 1

ZB

$$\begin{aligned} F_{0\nu}^{\mathrm{ZB}} &= \ln 2\ N_{\beta\beta}\epsilon\frac{T}{n_{\mathrm{CL}}} = \\ &= \ln 2 \times \frac{x\ \eta\ \epsilon\ N_A}{A}\frac{M\ T}{n_{\mathrm{CL}}} \end{aligned}$$

Golden Region

FB

$$\begin{aligned} F_{0\nu} &= \tau_{1/2}^{Back.Fluct.} = \ln 2\ N_{\beta\beta}\epsilon\frac{T}{n_B} = \\ &= \ln 2 \times \frac{x\ \eta\ \epsilon\ N_A}{A}\sqrt{\frac{M\ T}{B\ \varDelta}}\ (68\% CL) \end{aligned}$$

Parameters redefinition

By redefining the experimental parameters the sensitivity formula can be greatly simplified into

$$F_{0\nu} = \begin{cases} \ln 2 \; N_A \times \sqrt{\frac{S}{P}}, & \text{if } P \cdot S > 1 \quad \text{FB} \\ \ln 2 \; \frac{N_A}{n_L} \times S, & \text{if } P \cdot S \lesssim 1 \quad \text{ZB} \end{cases}$$

$$S = \zeta M \, T$$

SCALE: represents the “dimension” of the experiment, both in terms of size and live time. It has the same dimensions of an exposure, expressed as number of moles of detectable emitting isotope times years of live time. **It’s a measure of how much signal can be expected in the experiment**

$$P = \frac{B}{\zeta} \Delta$$

PERFORMANCE: **measures how good is the experiment in measuring the signal** compared to the background level. It’s expressed in background counts per mole of detectable emitting isotope per year

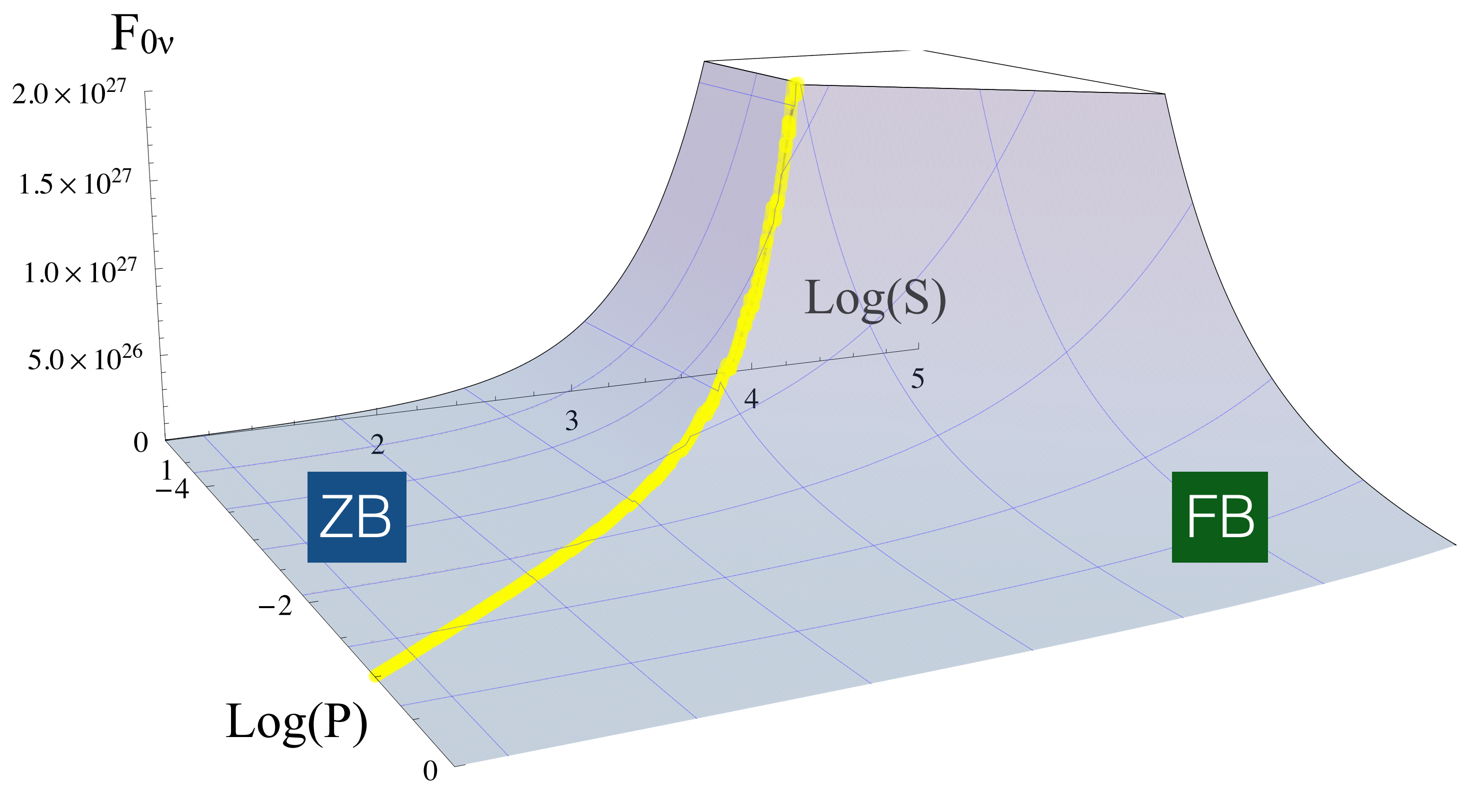
$$\zeta = \frac{x \eta \epsilon}{A}$$

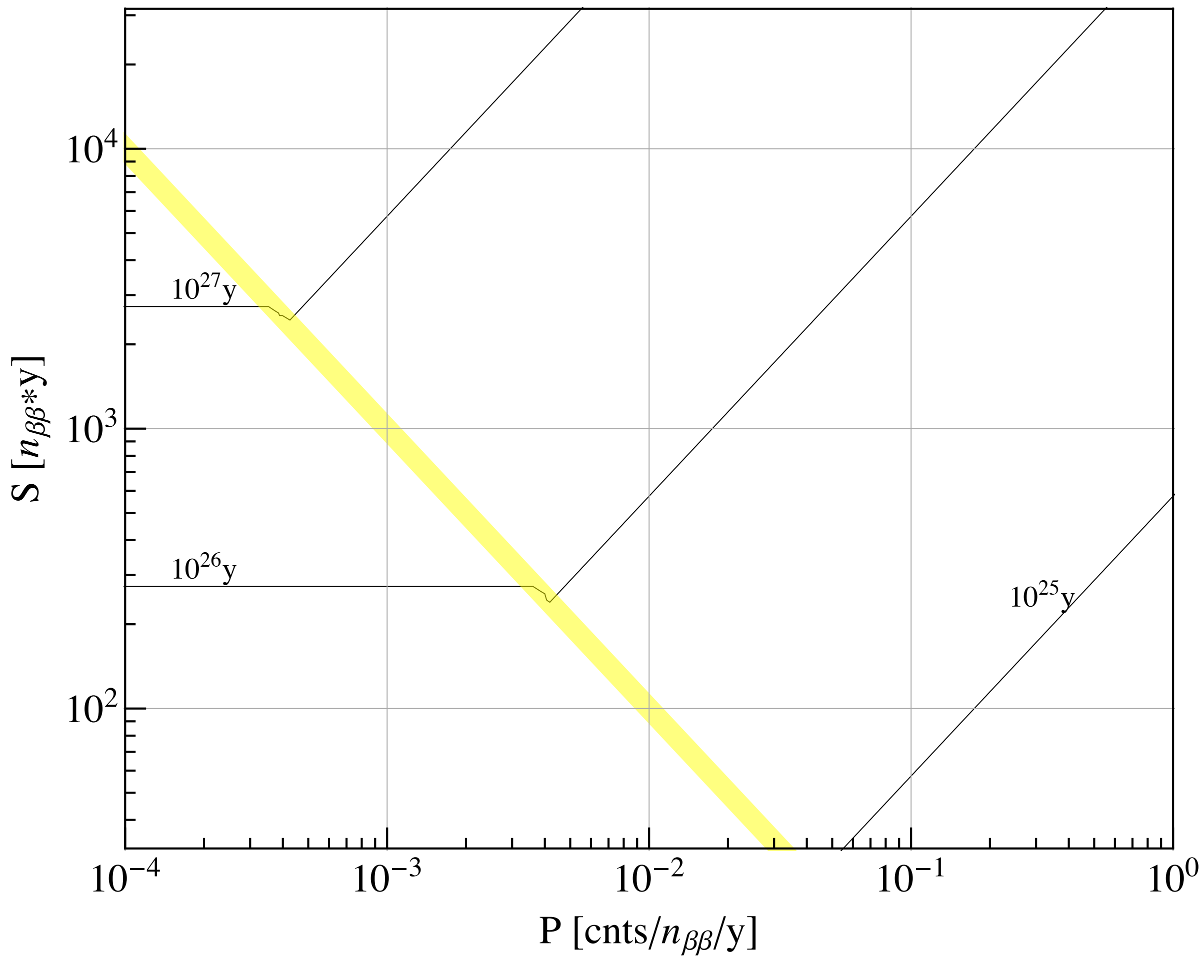
DIMENSIONAL FACTOR: moles of “efficient” (=detectable) isotope per unit mass. Gathers properties of the experimental technique (stoichiometric factor **x**, isotopic abundance **η**, signal efficiency **ε**), usually unchanged from one generation to next. **Linear effect on sensitivity.**

M. Biassoni, O. Cremonesi, P. Gorla,
http://arxiv.org/abs/1310.3870

The (P,S,$F_{0\nu}$) space

Each experiment can be represented in the same (P,S,$F_{0\nu}$) space as a point on the $F_{0\nu}(P,S)$ surface representing the sensitivity

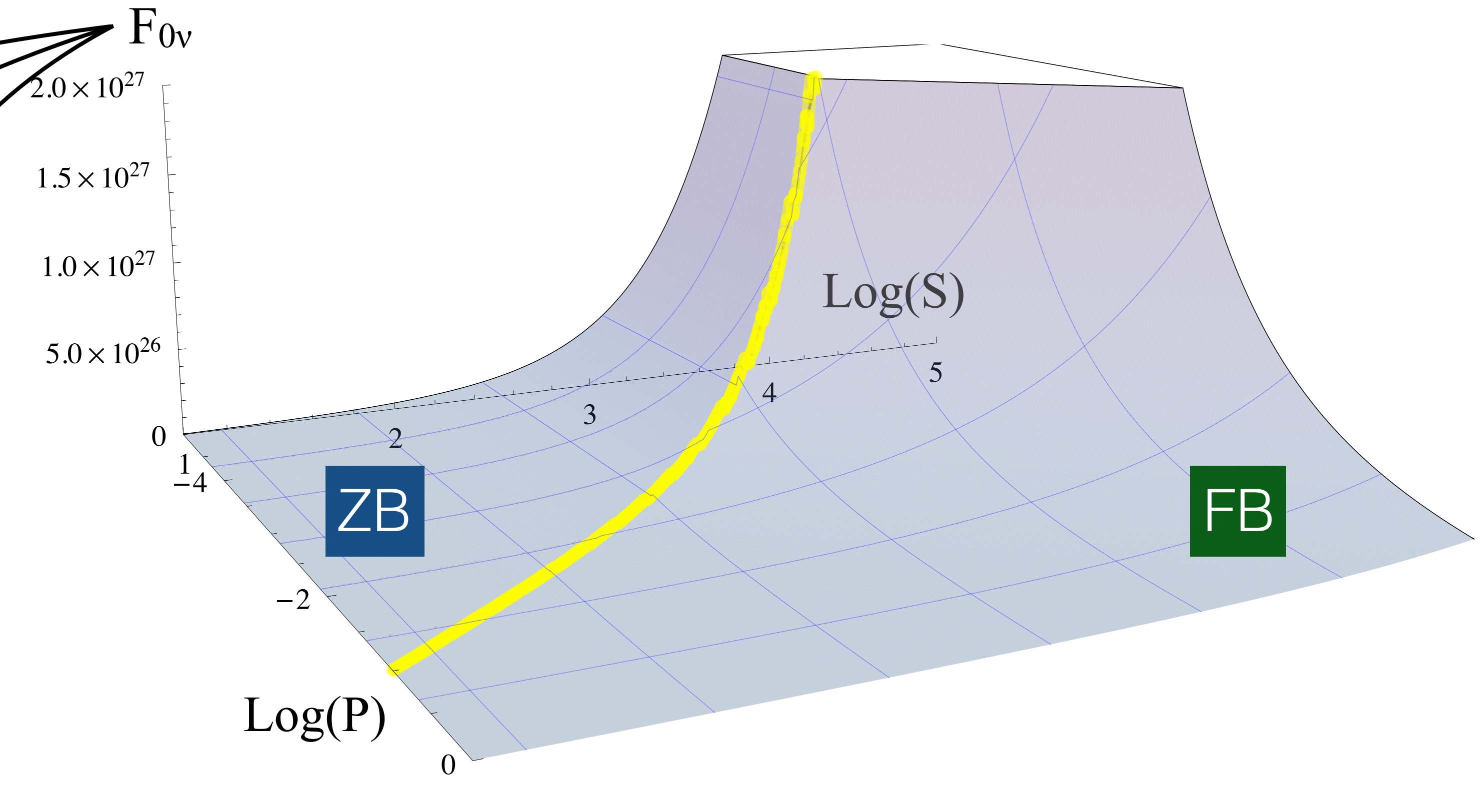


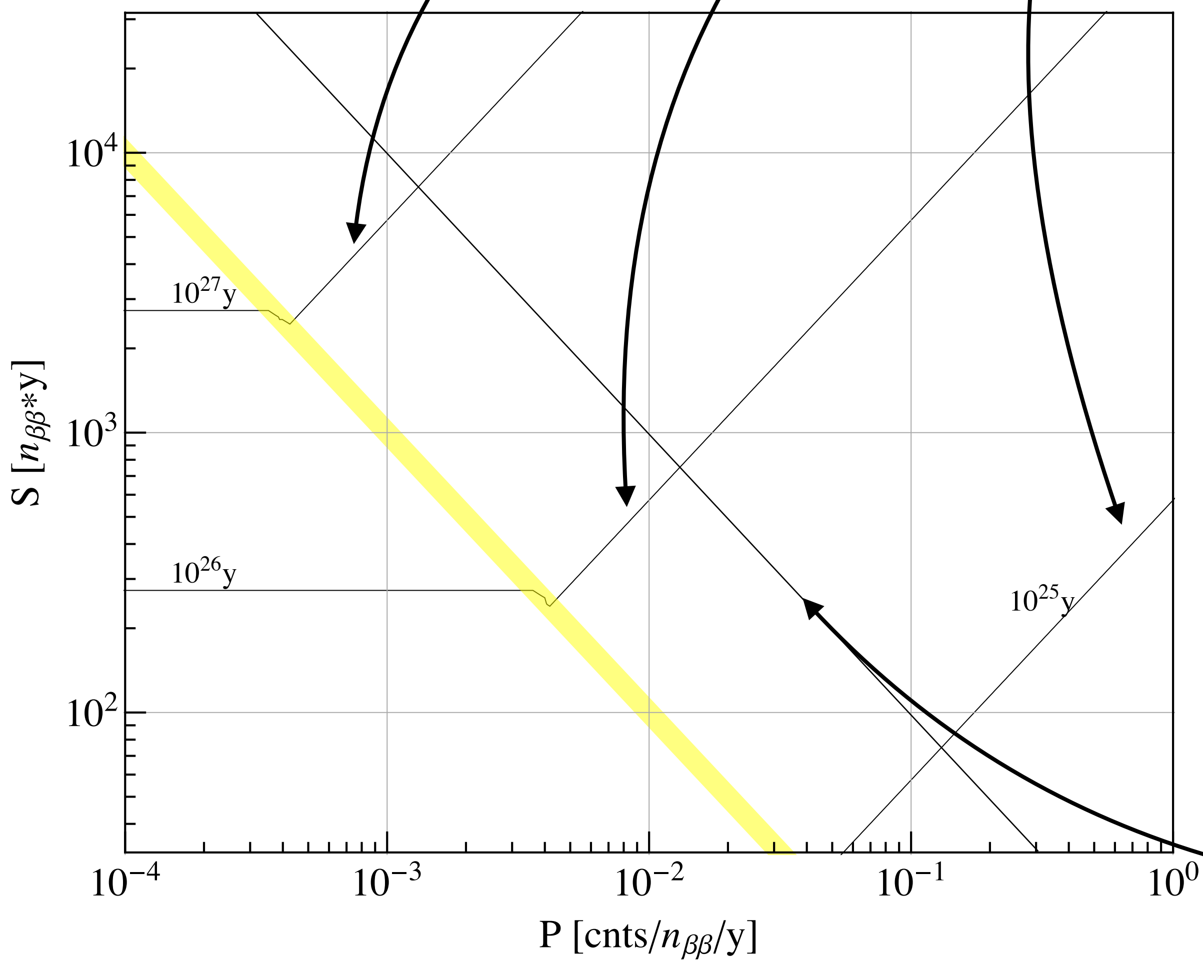


The (P,S,$F_{0\nu}$) space

Each experiment can be represented in the same (P,S,$F_{0\nu}$) space as a point on the $F_{0\nu}(P,S)$ surface representing the sensitivity

Iso-sensitivity curves





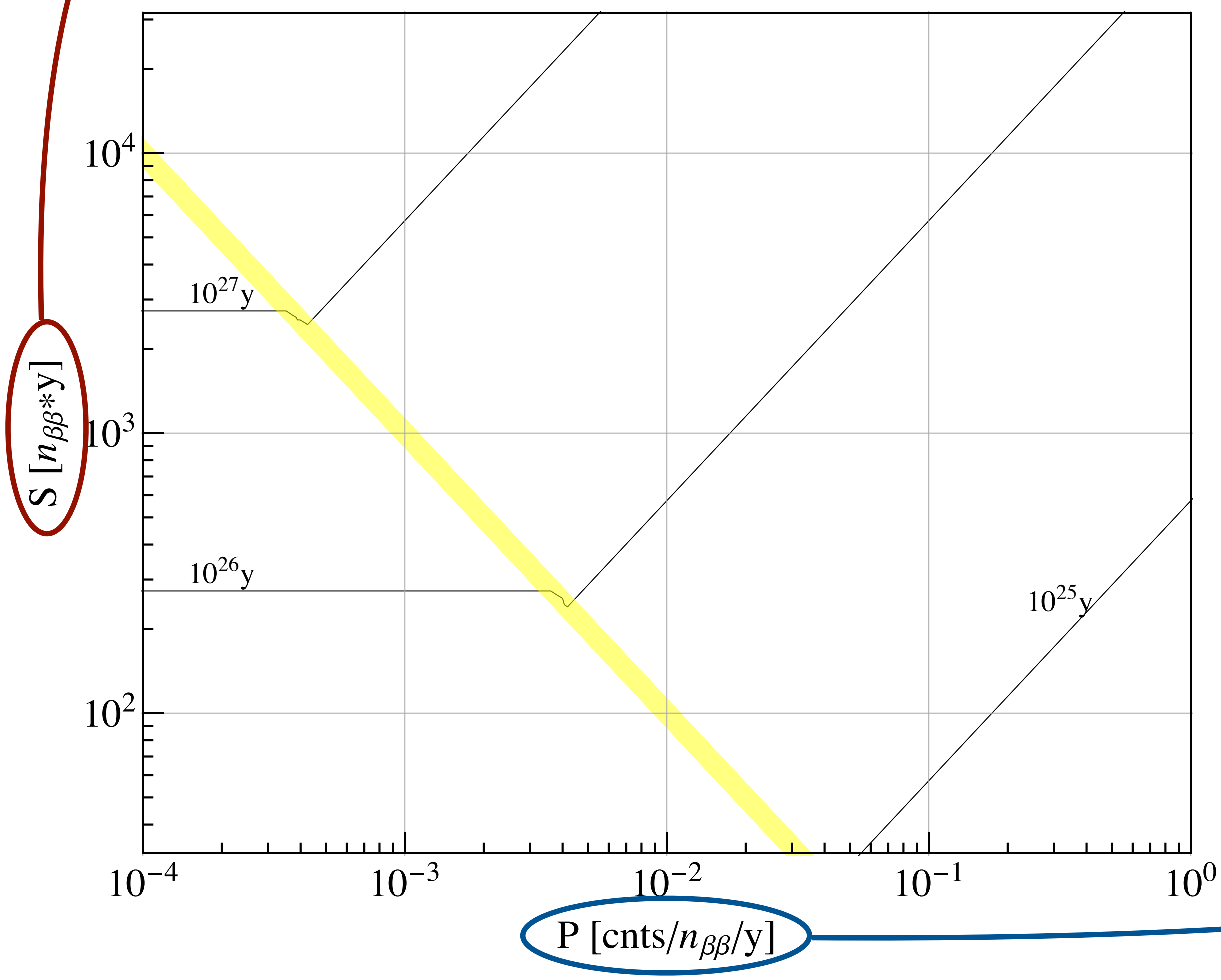
Golden region: condition where the maximal improvement of sensitivity per unit improvement in performance and scale can be achieved (more on this later…)

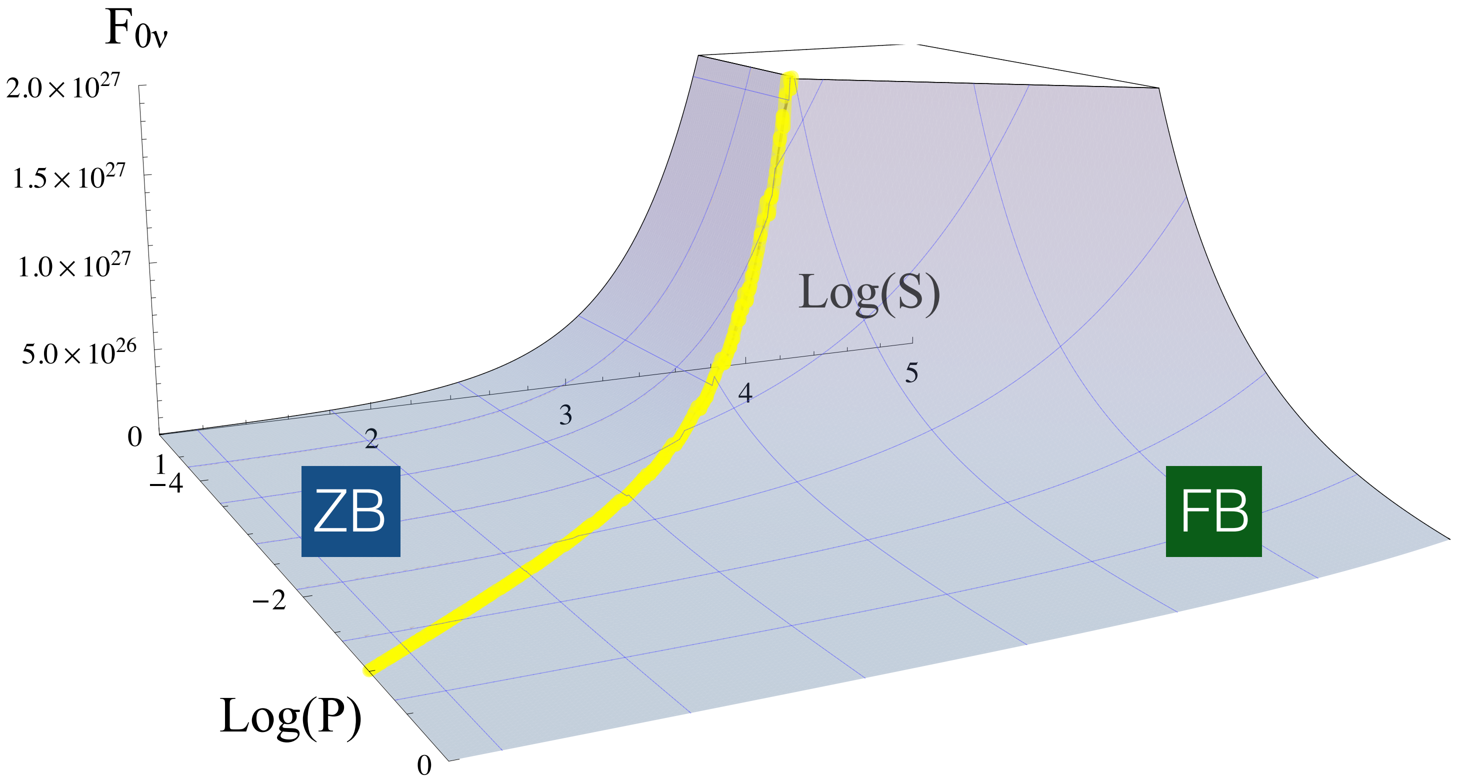
Iso-bkg-counts curve

The (P,S,$F_{0\nu}$) space

Each experiment can be represented in the same (*P*,*S*,$F_{0\nu}$) space as a point on the $F_{0\nu}(P,S)$ surface representing the sensitivity

10-1000kg of isotope (100kg-10ton of active material depending on i.a. and fiducial volume)

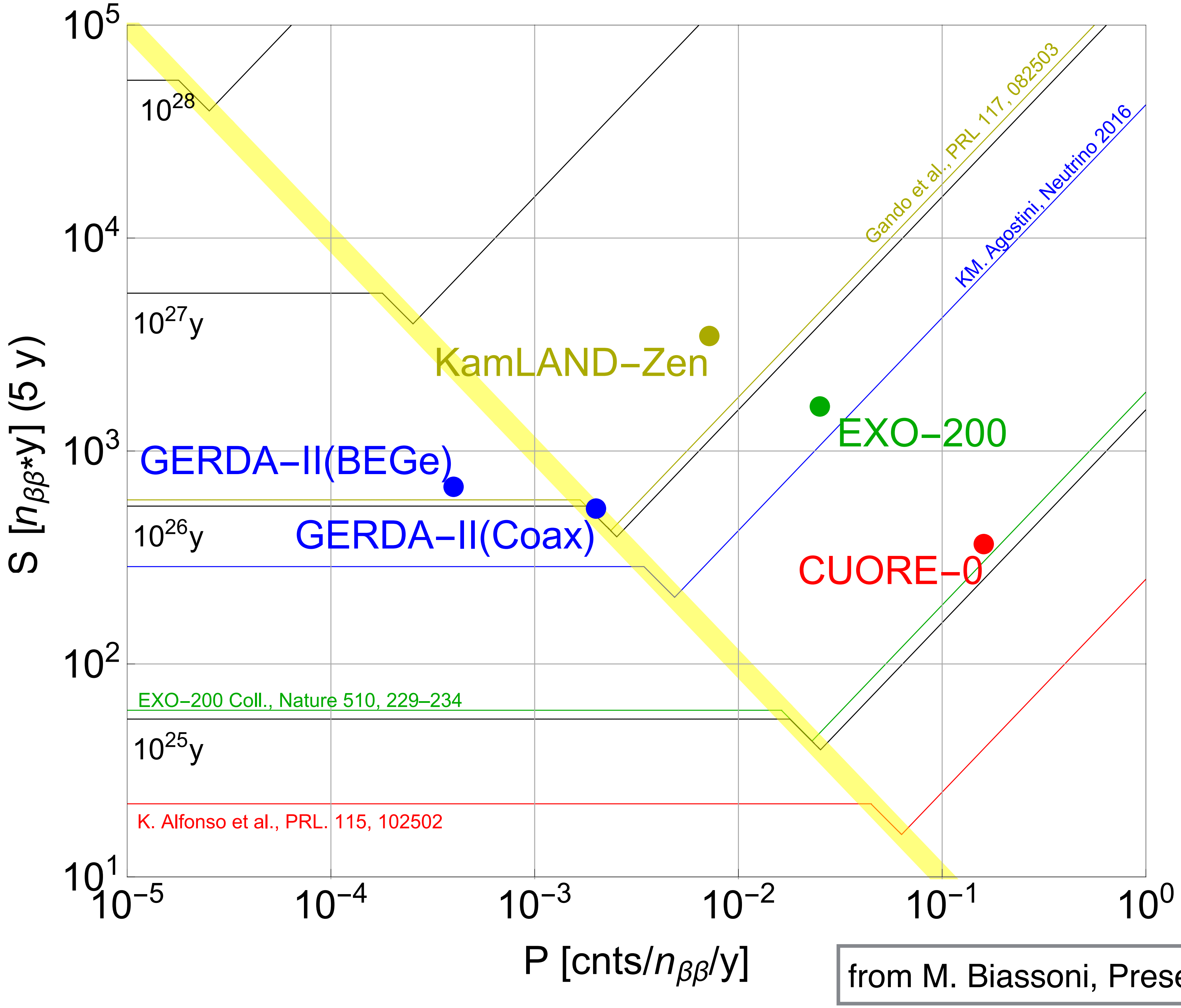




From few tens to 0 background counts (including 2νββ) in the ROI per year

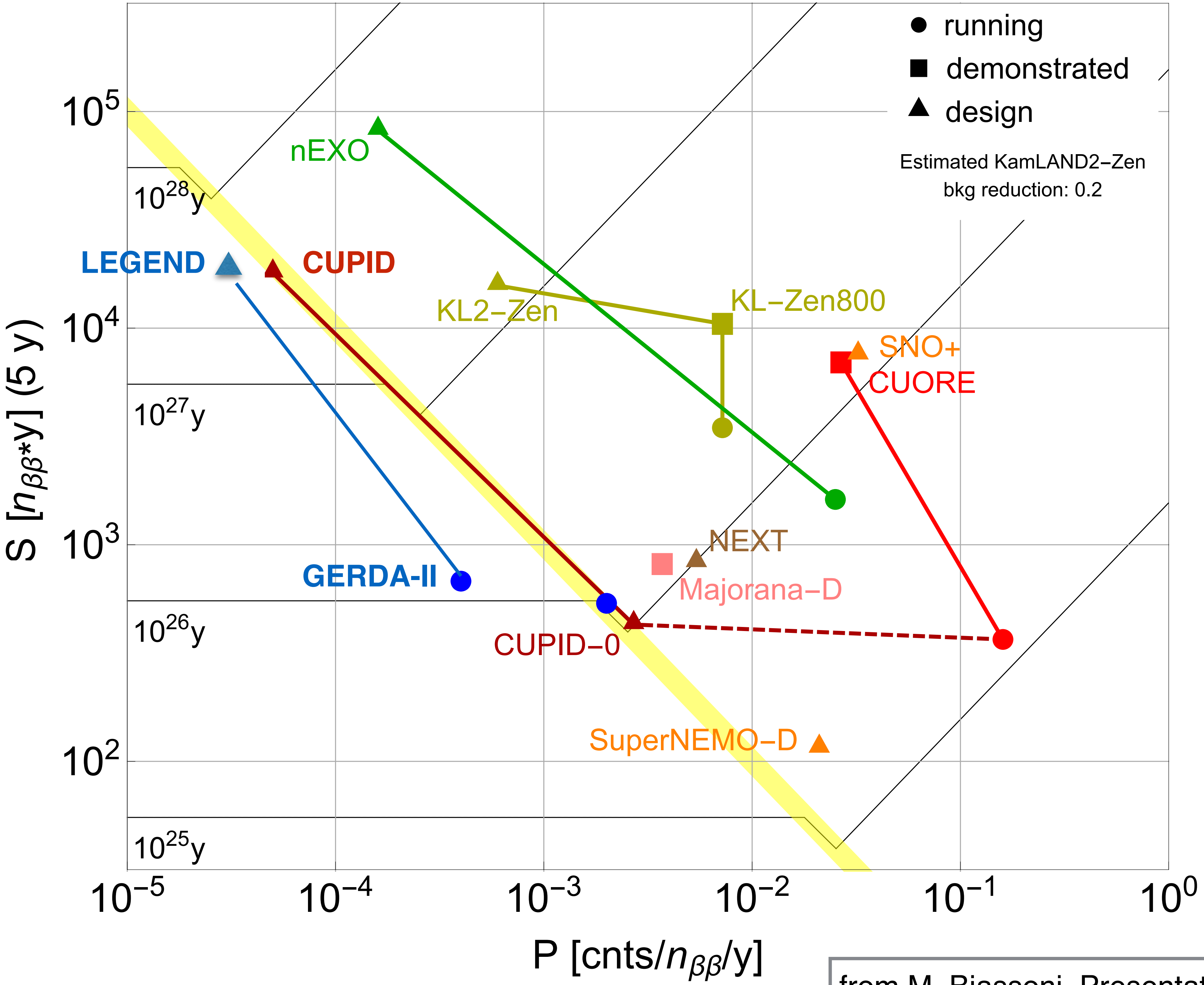
Present experiments ($F_{0\nu}$)

Each experiment can be represented in the (P,S,$F_{0\nu}$) space as a point on the $F_{0\nu}$(P,S) surface representing the sensitivity



from M. Biassoni, Presentation at NOW2016

Towards next generation



from M. Biassoni, Presentation at NOW2016

g_A problem

NME (including Fermi, Gamow-Teller and tensor terms) can be written as:

$$M^{0\nu} = g_A^2 \left(M_{GT}^{0\nu} - \left(\frac{g_V}{g_A} \right)^2 M_F^{0\nu} + M_T^{0\nu} \right)$$

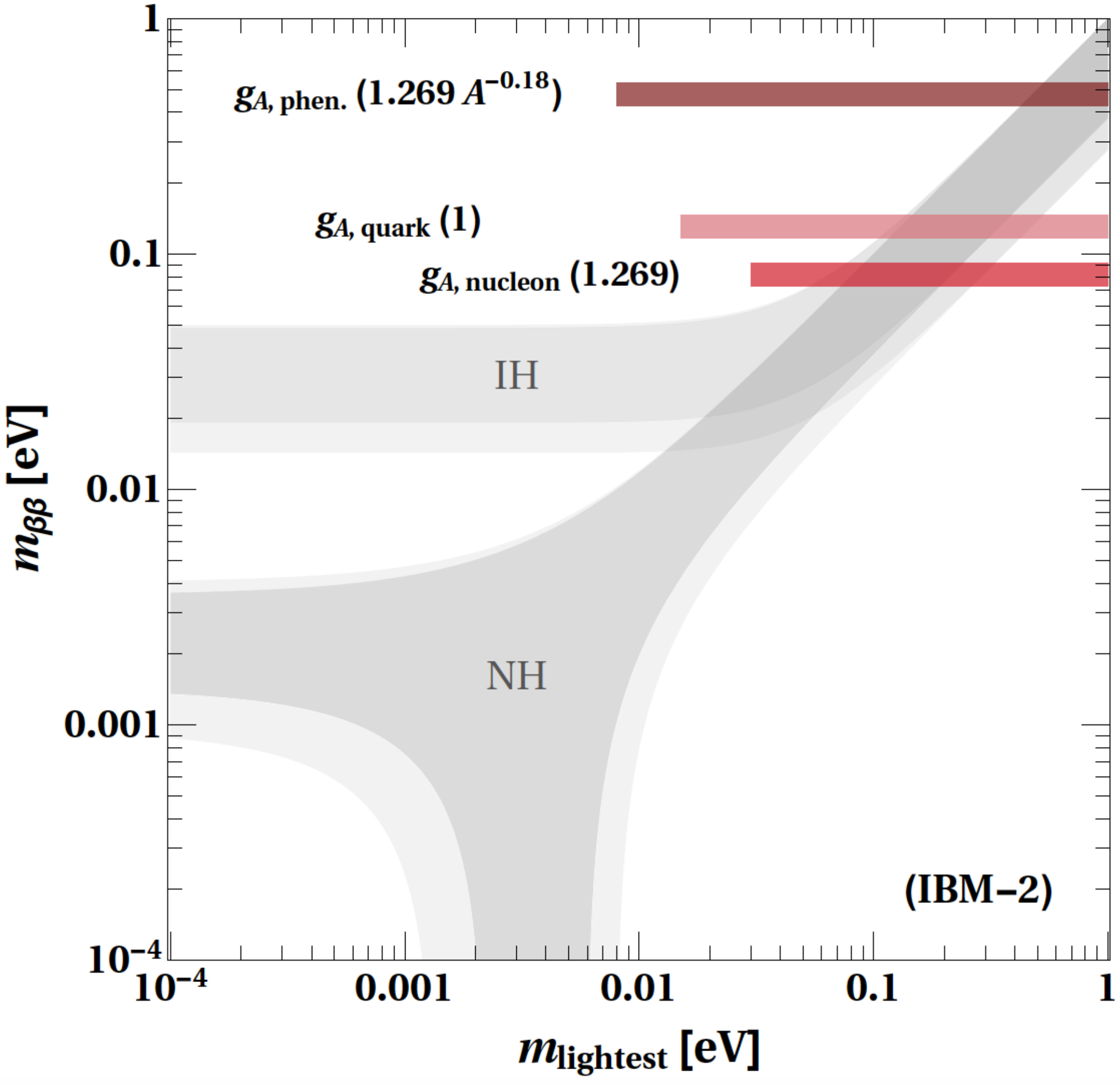
thus factorising out most of the dependence from g_A, which is known to depend on the reaction "environment":

$$g_A^{\text{quark}} = 1$$
$$g_A^{\text{nucleon}} = 1.27$$
$$g_A^{2\nu\beta\beta} = 1.27 \cdot A^{-0.18}$$
$$g_A^{0\nu\beta\beta} = \;??$$

$$F^{0\nu} \propto \frac{1}{|M^{0\nu}|^2} \propto \frac{1}{g_A^4}$$

Sensibility strongly depends on g_A: a factor 2 quenching translates into (catastrophic?) factor 16 in $T_{1/2}$ sensitivity

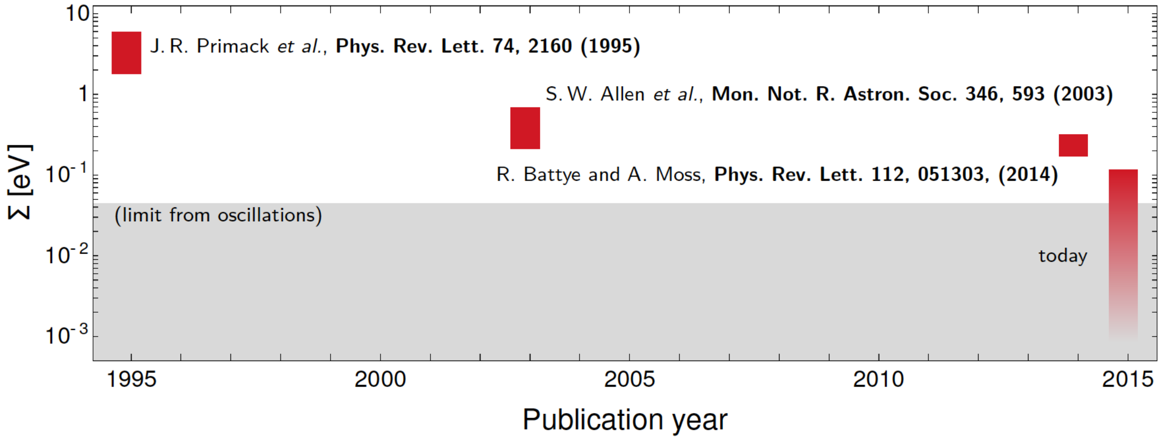
Example: Xe



Measuring and understanding g_A dependence on nuclear effects is mandatory for long term planning of neutrino-less double beta decay searches

What can we learn from cosmology

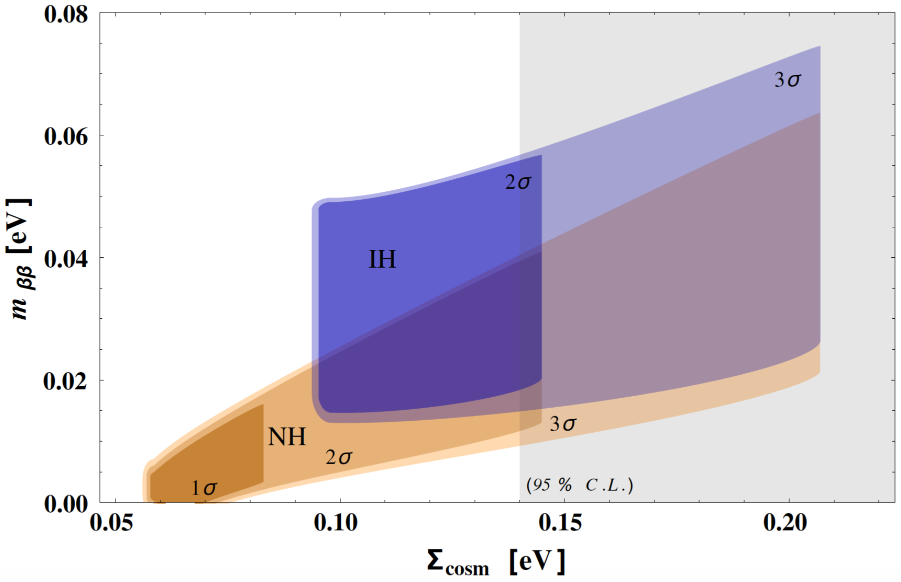
Cosmology is providing more and more stringent limits on the sum of neutrino masses, approaching oscillation limit. Data probing different scales (CMB, BAOs, Lyman-α, lensing…) agree (but all results are model dependent).



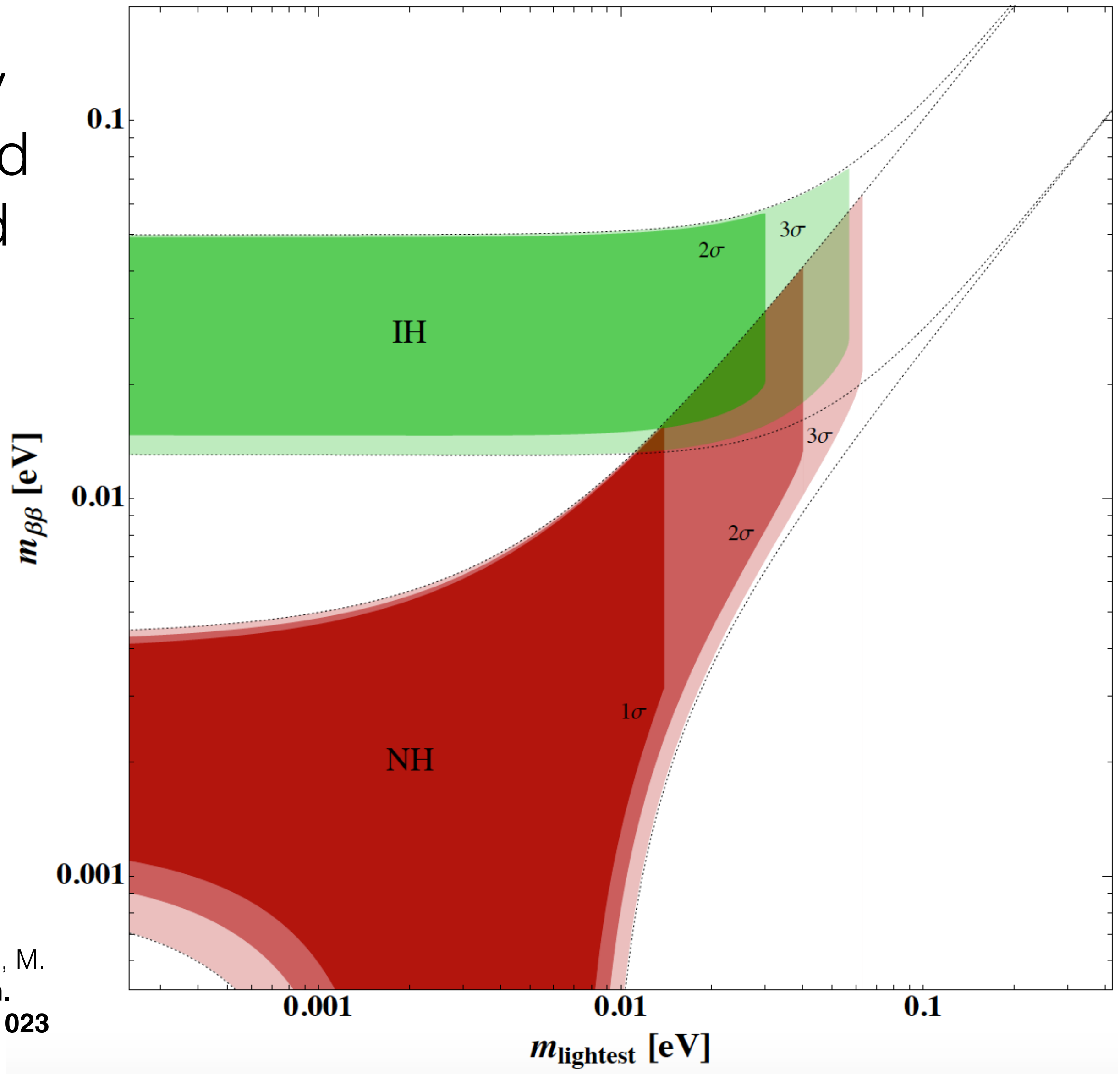
$\Sigma^{\max}$ (95% C. L.)	Reference
153 meV	P. A. R. Ade *et al.* (Planck Collaboration), `arXiv:1502.01589 [astro-ph.CO]` (2015)
130 meV	A. J. Cuesta *et al.*, **Phys. Dark Universe 13, 77 (2016)**
126 meV	E. Di Valentino *et al.*, **Phys. Rev. D 93, 083527 (2016)**
176 meV	E. Giusarma *et al.*, `arXiv:1605.04320 [astro-ph.CO]` (2016)
120 meV	N. Palanque-Delabrouille *et al.*, **J. Cosm. Astropart. Phys. 1511, 011 (2015)**
177 meV	X. Zhang, **Phys. Rev. D 93, 083011 (2016)**

$\Sigma < 140$ meV

(N. Palanque-Delabrouille *et al.* **J. Cosm. Astropart. Phys. 1502, 45 (2015)**)



IH slightly disfavoured (excluded @1σ)

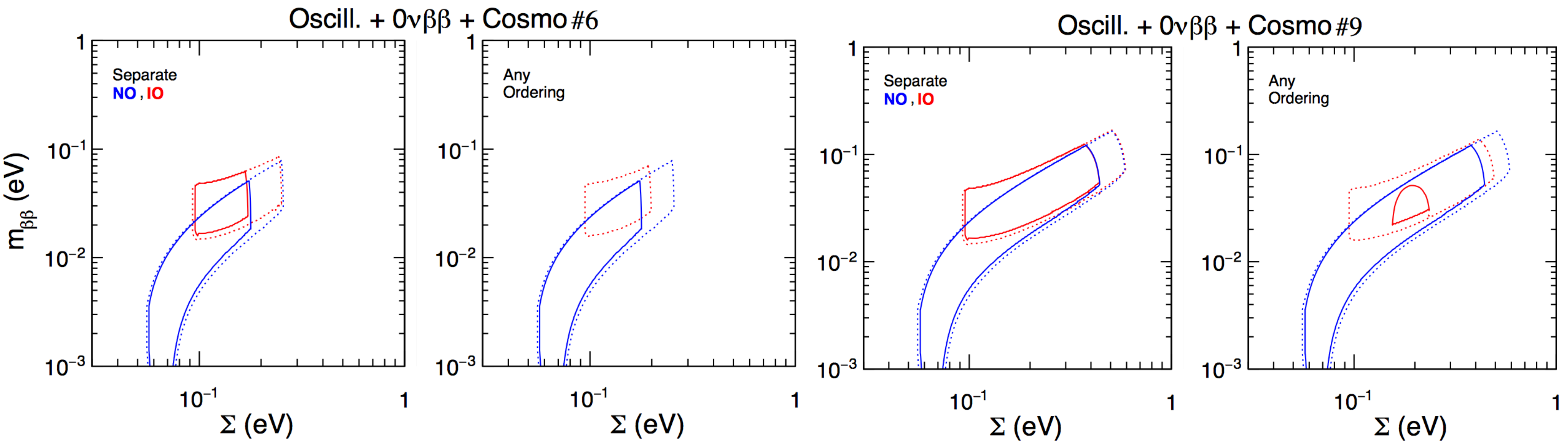


S. Dell'Oro., S.Marcocci, M. Viel, F. Vissani, **J. Cosm. Astropart. Phys. 1512, 023 (2015)**

What can we learn from global fits

F. Capozzi et al.,
arXiv:1703.04471

"In the global analysis, NO appears to be somewhat favored with respect to IO at the level of 1.9–2.1σ, mainly by neutrino oscillation data (especially atmospheric), corroborated by cosmological data in some cases. This intriguing indication, although not statistically mature yet, deserves to be monitored with future data. "



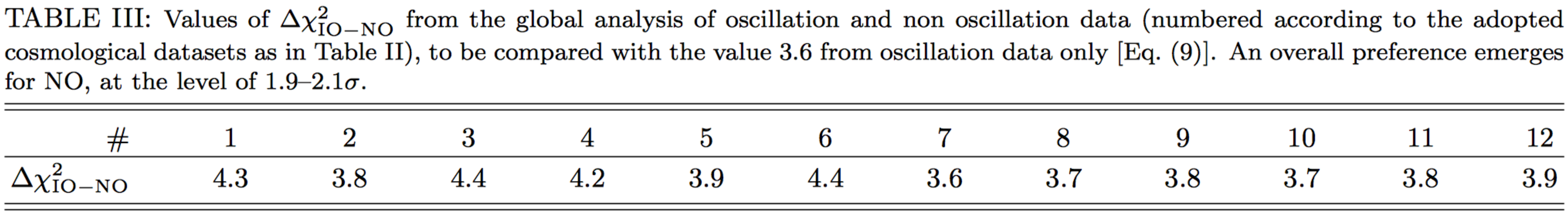
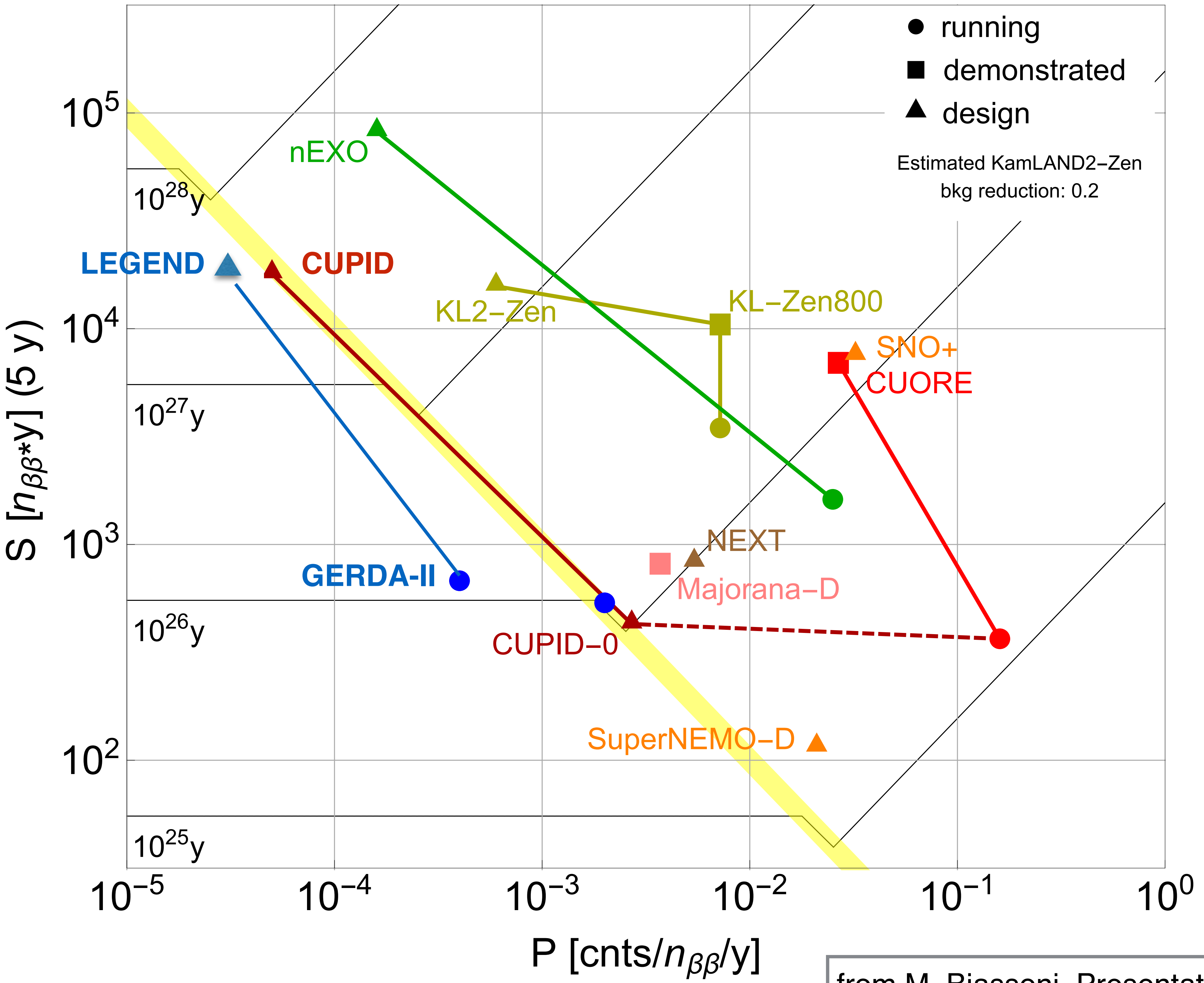


TABLE III: Values of $\Delta\chi^2_{\mathrm{IO-NO}}$ from the global analysis of oscillation and non oscillation data (numbered according to the adopted cosmological datasets as in Table II), to be compared with the value 3.6 from oscillation data only [Eq. (9)]. An overall preference emerges for NO, at the level of 1.9–2.1σ.

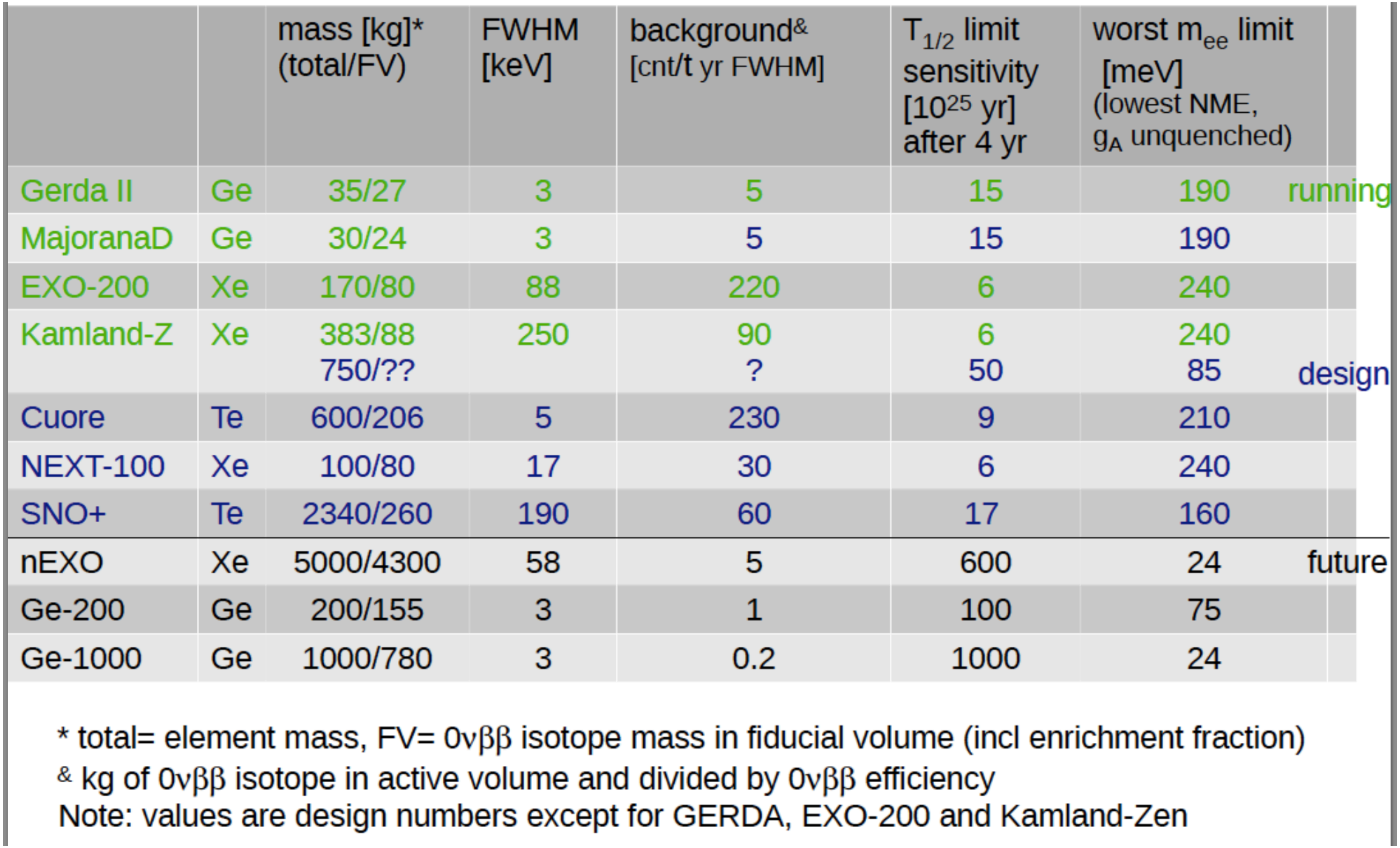
#	1	2	3	4	5	6	7	8	9	10	11	12
$\Delta\chi^2_{\mathrm{IO-NO}}$	4.3	3.8	4.4	4.2	3.9	4.4	3.6	3.7	3.8	3.7	3.8	3.9

Towards next generation



from M. Biassoni, Presentation at NOW2016

Comparing present and future experiments



		mass [kg]* (total/FV)	FWHM [keV]	background$^{\&}$ [cnt/t yr FWHM]	$T_{1/2}$ limit sensitivity [10^{25} yr] after 4 yr	worst m_{ee} limit [meV] (lowest NME, g_A unquenched)	
Gerda II	Ge	35/27	3	5	15	190	running
MajoranaD	Ge	30/24	3	5	15	190	
EXO-200	Xe	170/80	88	220	6	240	
Kamland-Z	Xe	383/88 750/??	250	90 ?	6 50	240 85	 design
Cuore	Te	600/206	5	230	9	210	
NEXT-100	Xe	100/80	17	30	6	240	
SNO+	Te	2340/260	190	60	17	160	
nEXO	Xe	5000/4300	58	5	600	24	future
Ge-200	Ge	200/155	3	1	100	75	
Ge-1000	Ge	1000/780	3	0.2	1000	24	

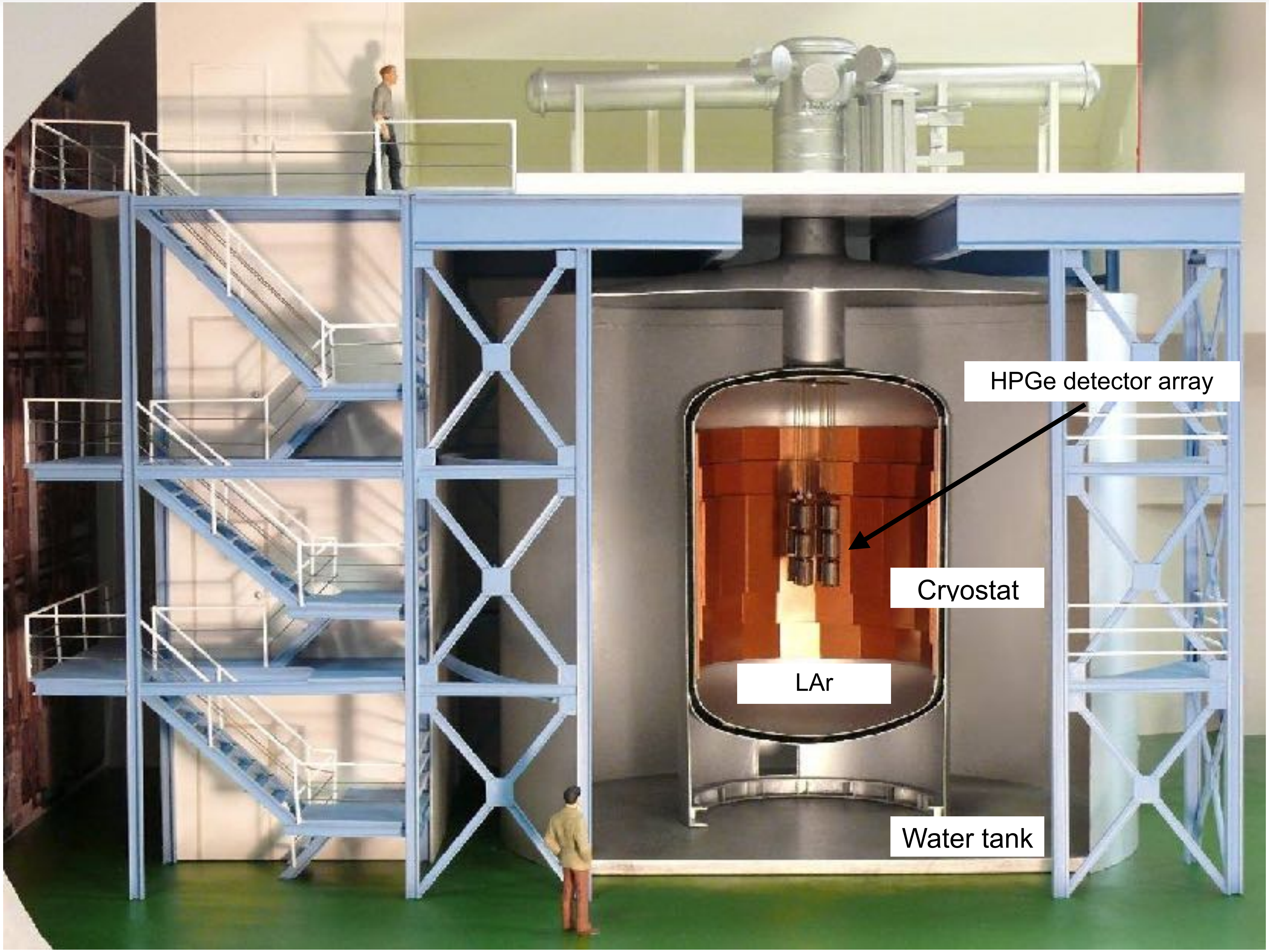
* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

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

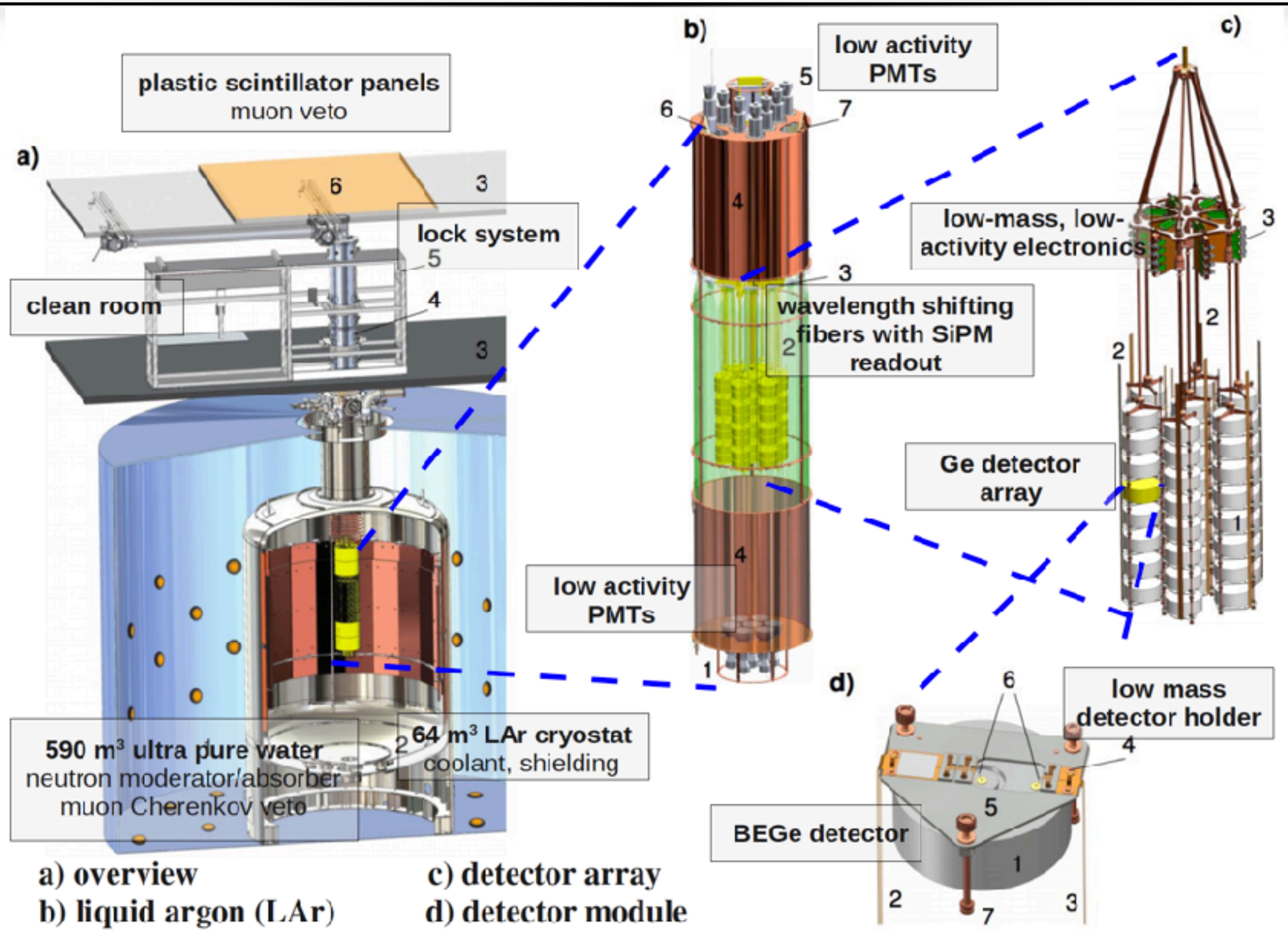
Note: values are design numbers except for GERDA, EXO-200 and Kamland-Zen

from GERDA presentation at LNGS-SC, April '17

GERDA



GERDA



plastic scintillator panels
muon veto

lock system

clean room

590 m³ ultra pure water
neutron moderator/absorber
muon Cherenkov veto

64 m³ LAr cryostat
coolant, shielding

low activity PMTs

wavelength shifting fibers with SiPM readout

low activity PMTs

low-mass, low-activity electronics

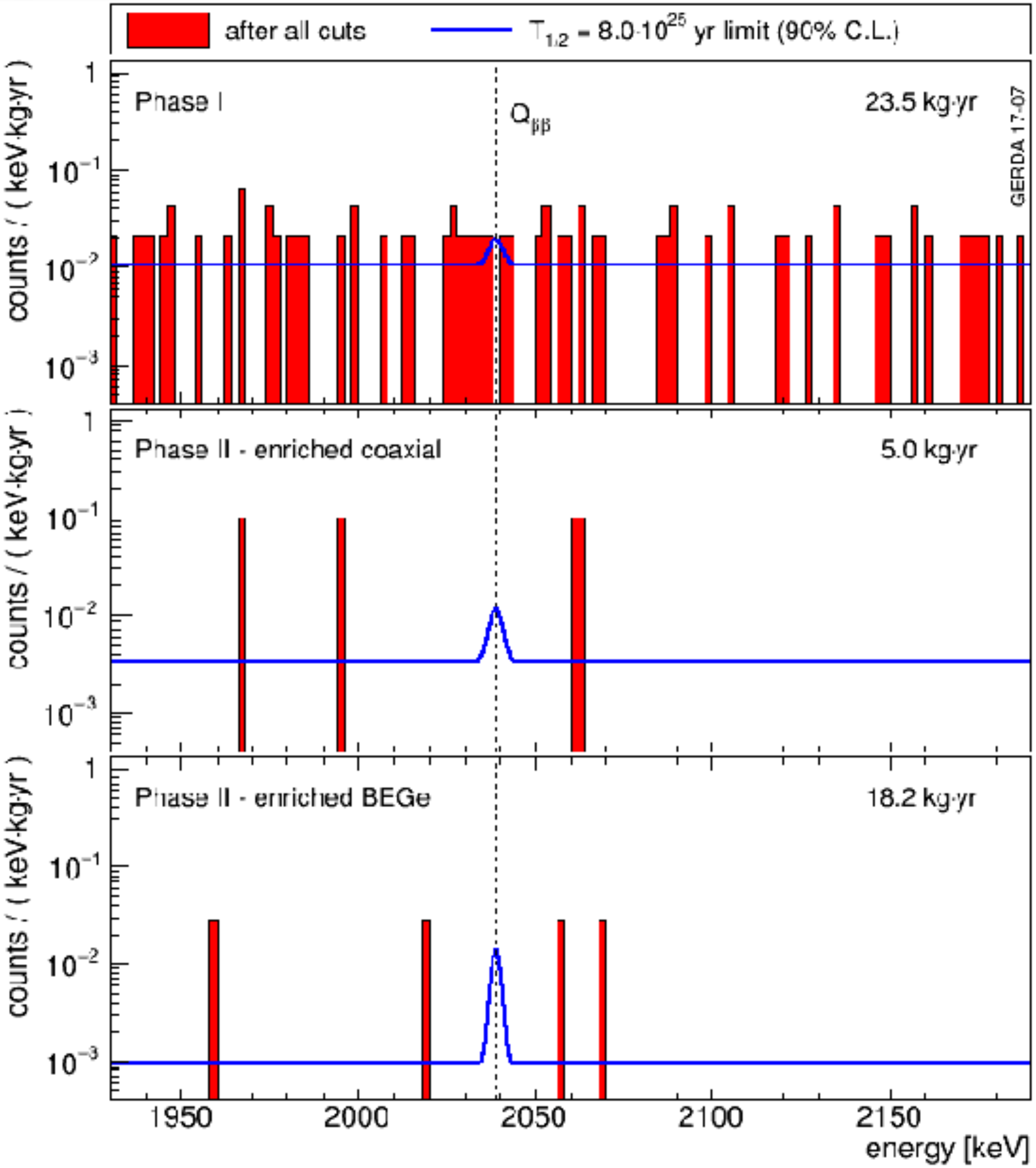
Ge detector array

low mass detector holder

BEGe detector

a) overview
b) liquid argon (LAr) veto instrumentation
c) detector array
d) detector module

Results

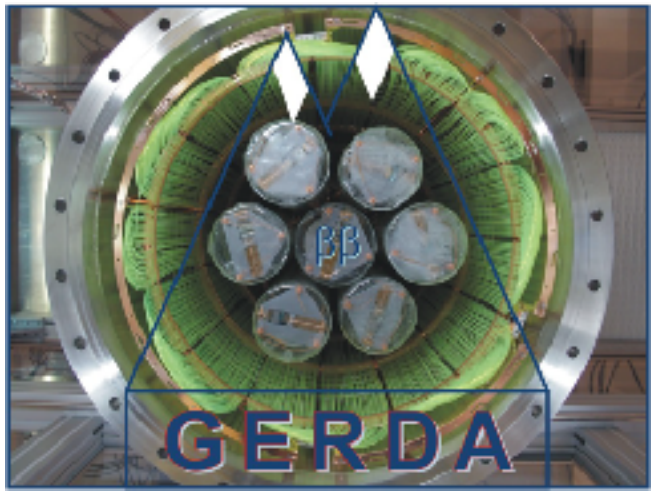


Frequentist limit

- $T_{0\nu}^{1/2} > 8.0\times10^{25}$ yr @ 90% C.L.
- $m_{\beta\beta} < 0.12 – 0.27$ eV

Background Index

- Coax: $2.7^{+1.0}_{-0.8} \cdot 10^{-3}$ cts/(keV· kg · yr)
- BeGe: $1.0^{+0.6}_{-0.4} \cdot 10^{-3}$ cts/(keV· kg · yr)



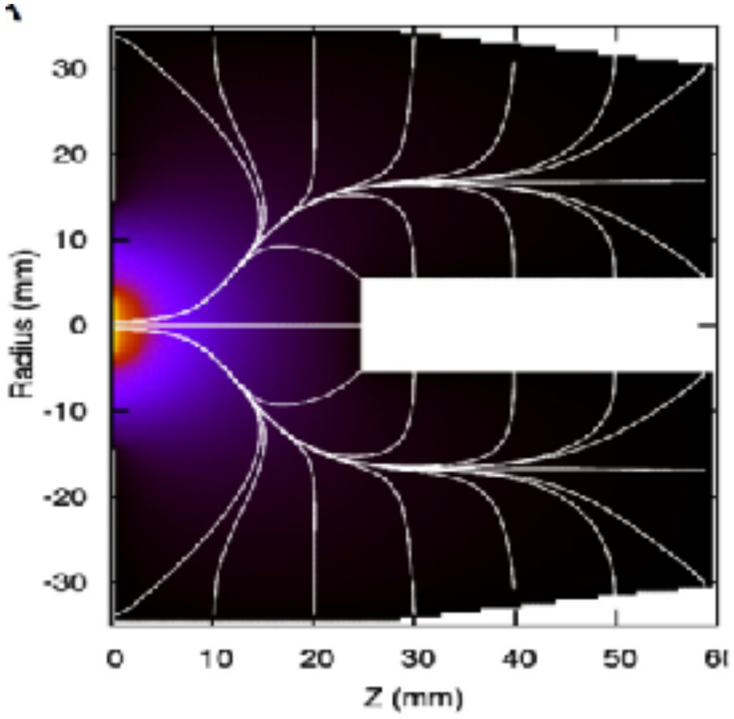
Upgrade of GERDA Phase II

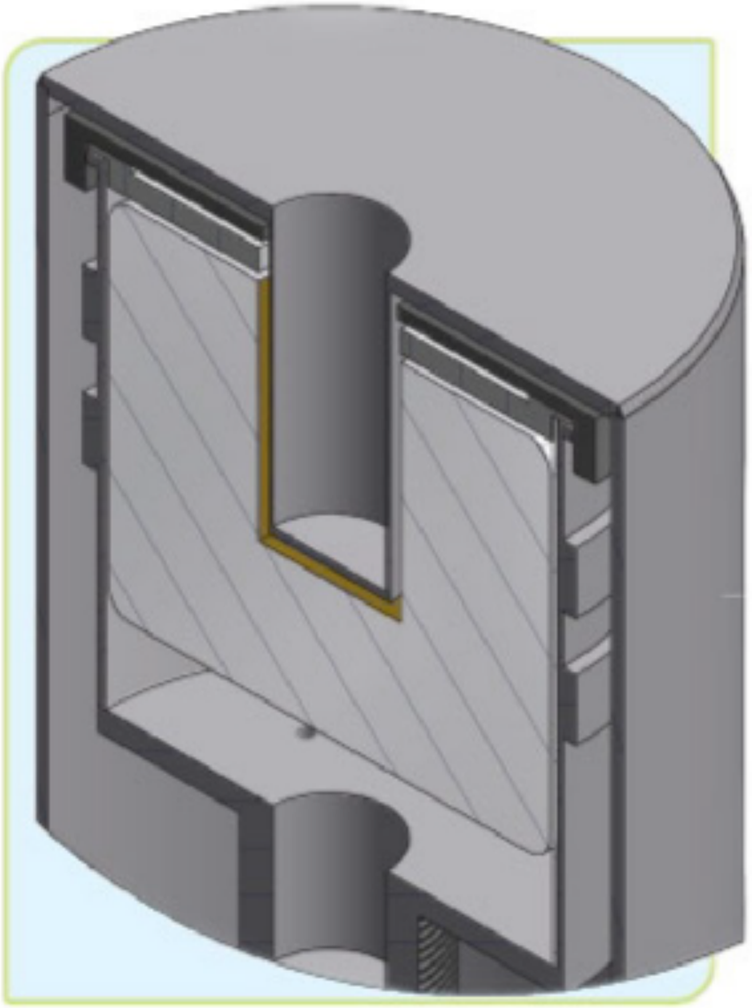
Upgrade of GERDA Phase II in April 2018

- cables substitution (radiopurity)
- FE modification: protection diodes & substitution of 3 JFET
- new scintillating fibres: larger light yield
- ^{nat}Ge string substituted with new enriched diodes (inverted-coaxial PPC detectors)

upgrade duration ~ 3 months

Main motivation is LEGEND





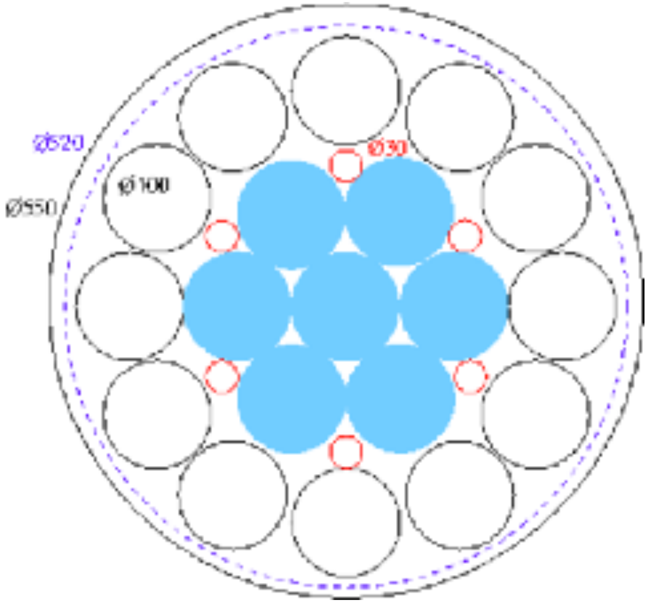
LEGEND-200

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

- Bigger diodes, but same performances of BEGe
- Internal diameter of the cryostat neck will be enlarged to 610 mm
- Better optical purity of LAr (light yield, attenuation lenght)
- Improved scintillation light readout
- Better material selection to limit U/Th contaminations next to detectors

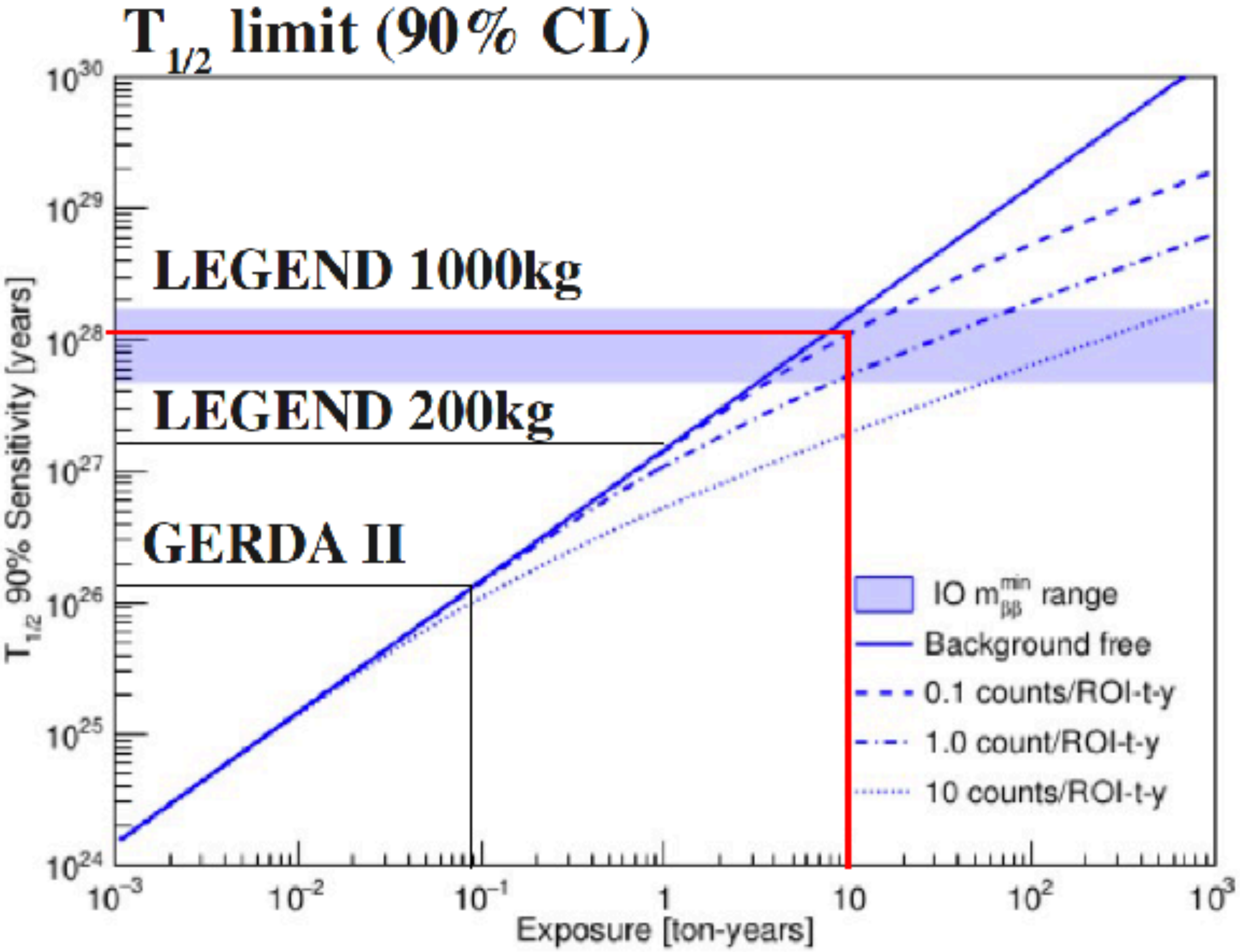
- Background reduction goal: 3-5 times better respect to GERDA Phase II

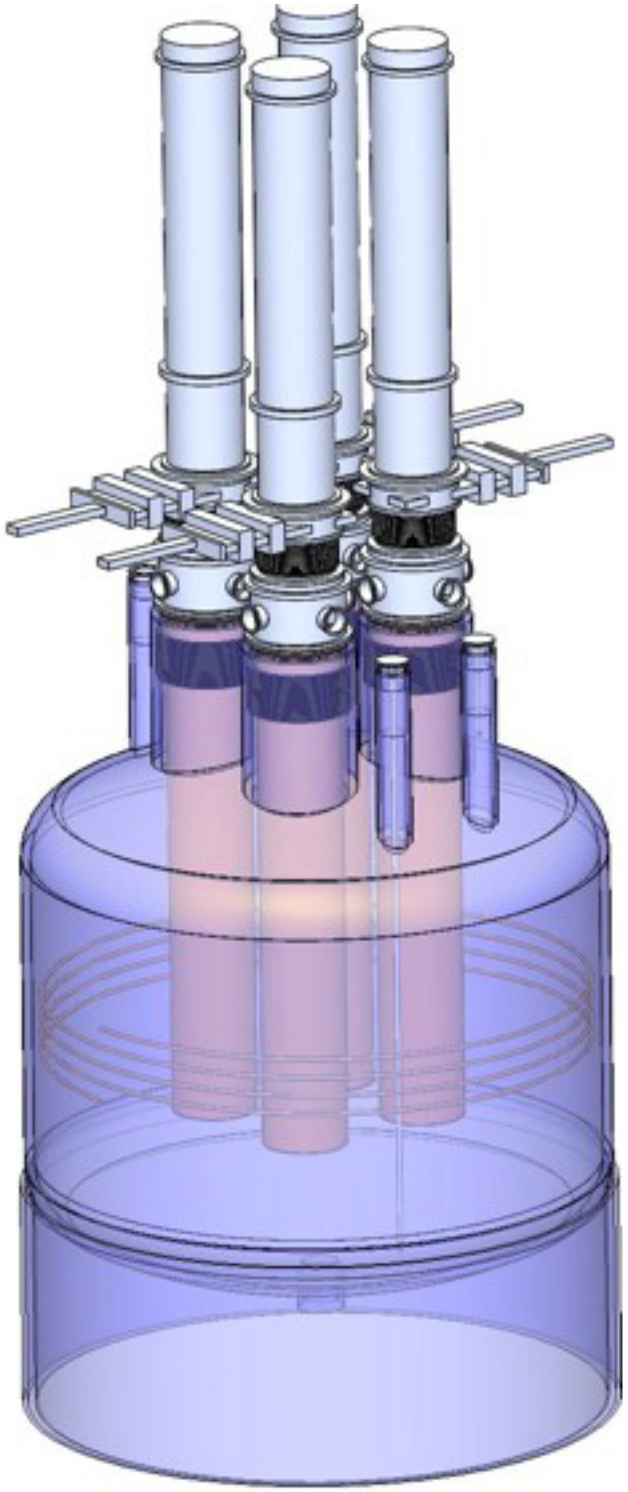
October 2017 LoI, March 2018 Proposal to the LNGS SC



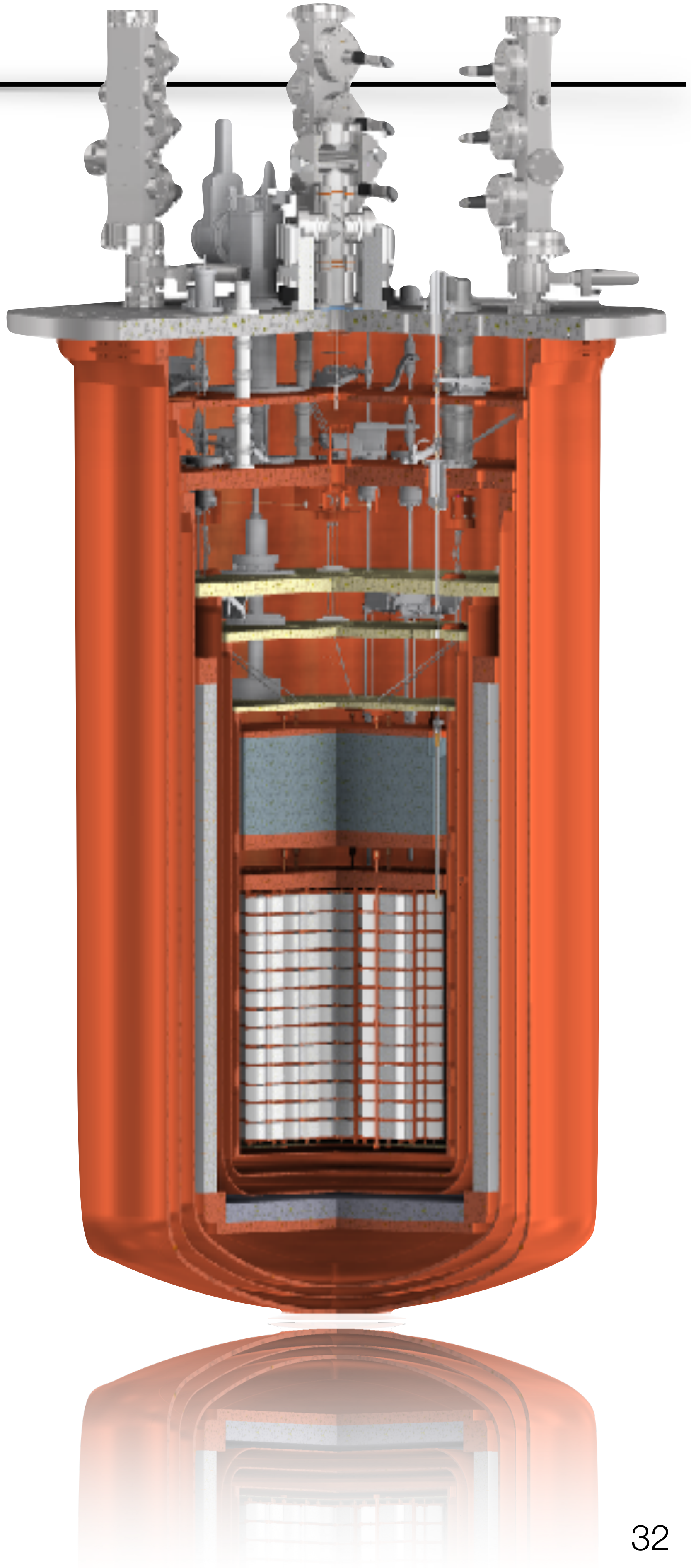
LEGEND- 1k

- up to 1000 kg (in steps)
- timeline connected to DOE DBD program
- background reduction: 30 respect to GERDA Phase II
- Underground lab to be defined (depth influence ^{77m}Ge background)





CUORE



Cryogenic Underground Observatory for Rare Events

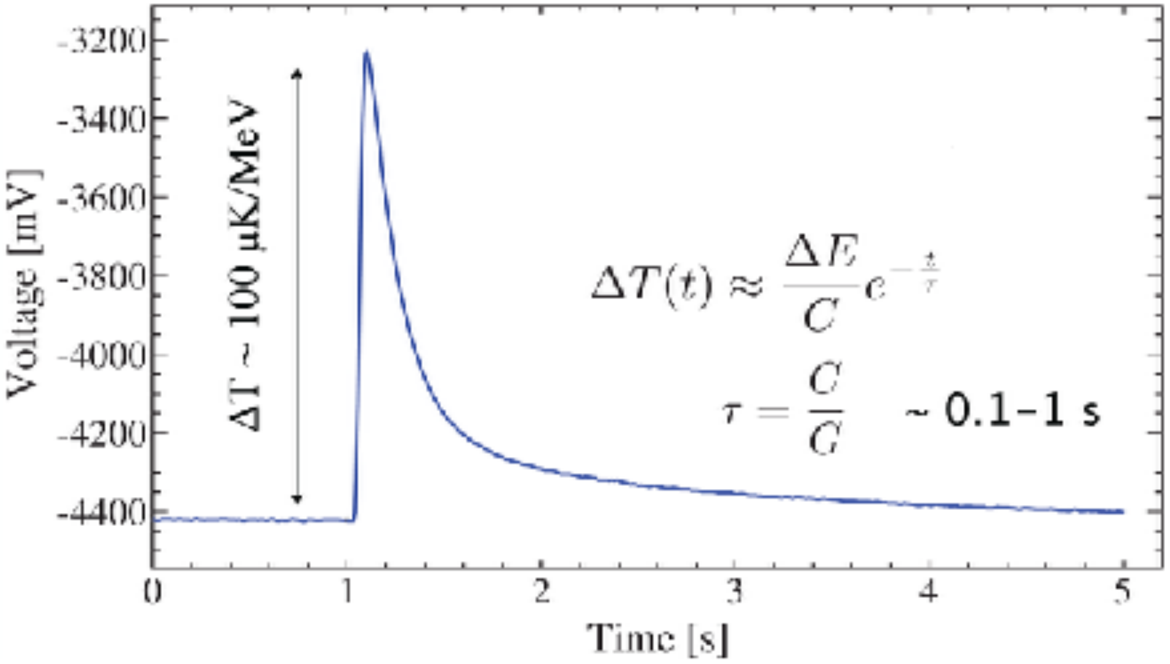
- Closely packed array of 988 TeO_2 crystals (19 towers of 52 crystals 5×5×5 cm^3, 0.75 kg each)
- Mass of TeO_2: 742 kg (~206 kg of ^{130}Te)
- Operating temperature: ~ 10 mK
- Mass to be cooled down: ~ 15 tonnes (Pb, Cu and TeO_2)
- Background aim: 10^{-2} c/keV/kg/year
- Target energy resolution: 5 keV FWHM @ 2615 keV
- Projected sensitivity in 5 years (90% C.L.): $T_{1/2} > 9 \times 10^{25}$ yr

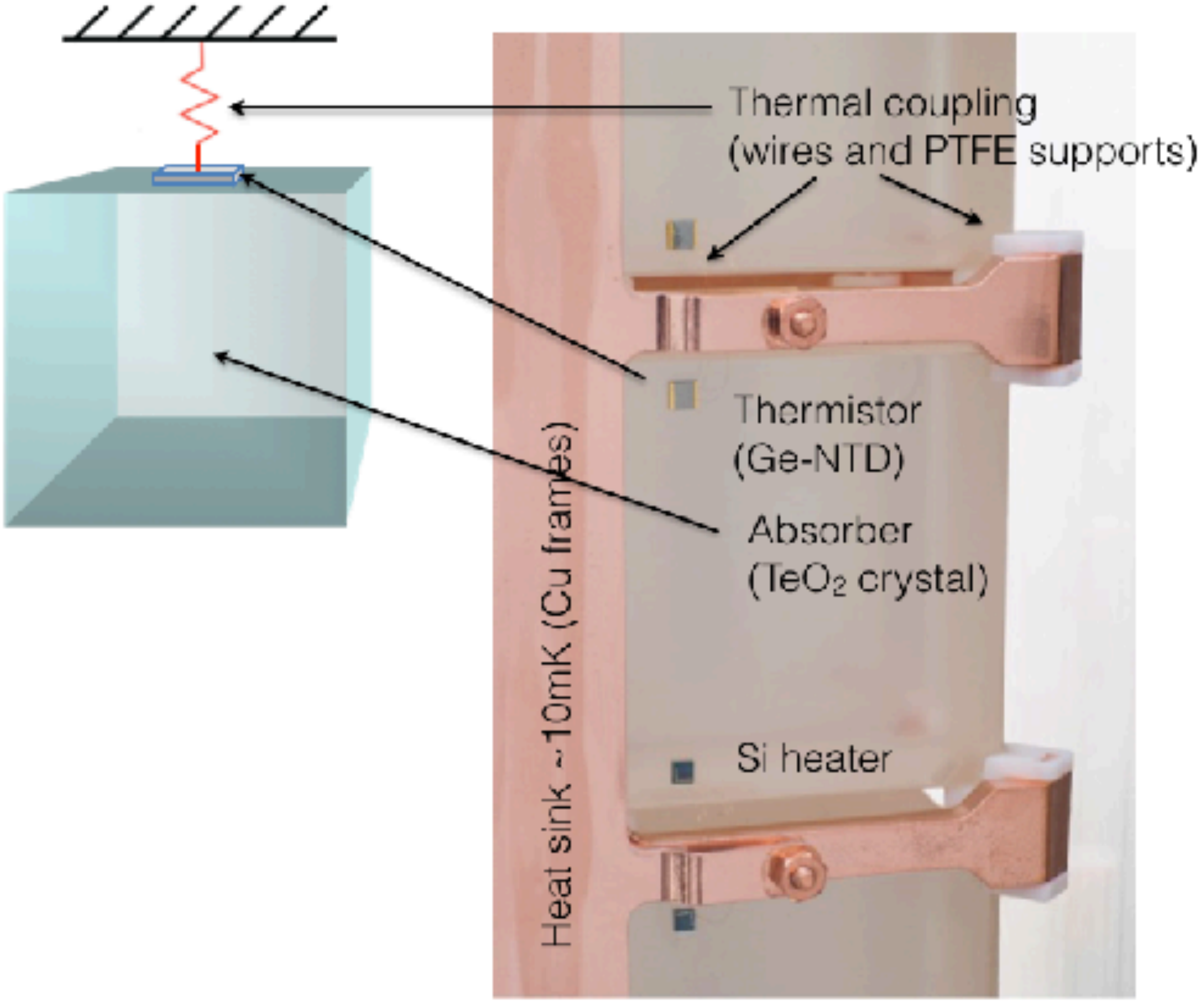
TeO_2 bolometers

Thermal detectors

- low heat capacity @ T_{work} ($C \sim T^3$)
- excellent energy resolution (~0.2% FWHM)
- slowness (suitable for rare event searches)

The absorbed energy is converted into a variation of the crystal temperature, measured by the thermistor





Results

ROI background index: **$(1.49_{-0.17}^{+0.18}) \times 10^{-2}$ c/(keV·kg·yr)**

$(1.35_{-0.18}^{+0.20}) \times 10^{-2}$ c/(keV·kg·yr)

Best fit for ^{60}Co mean: **(2506.4 ± 1.2) keV**

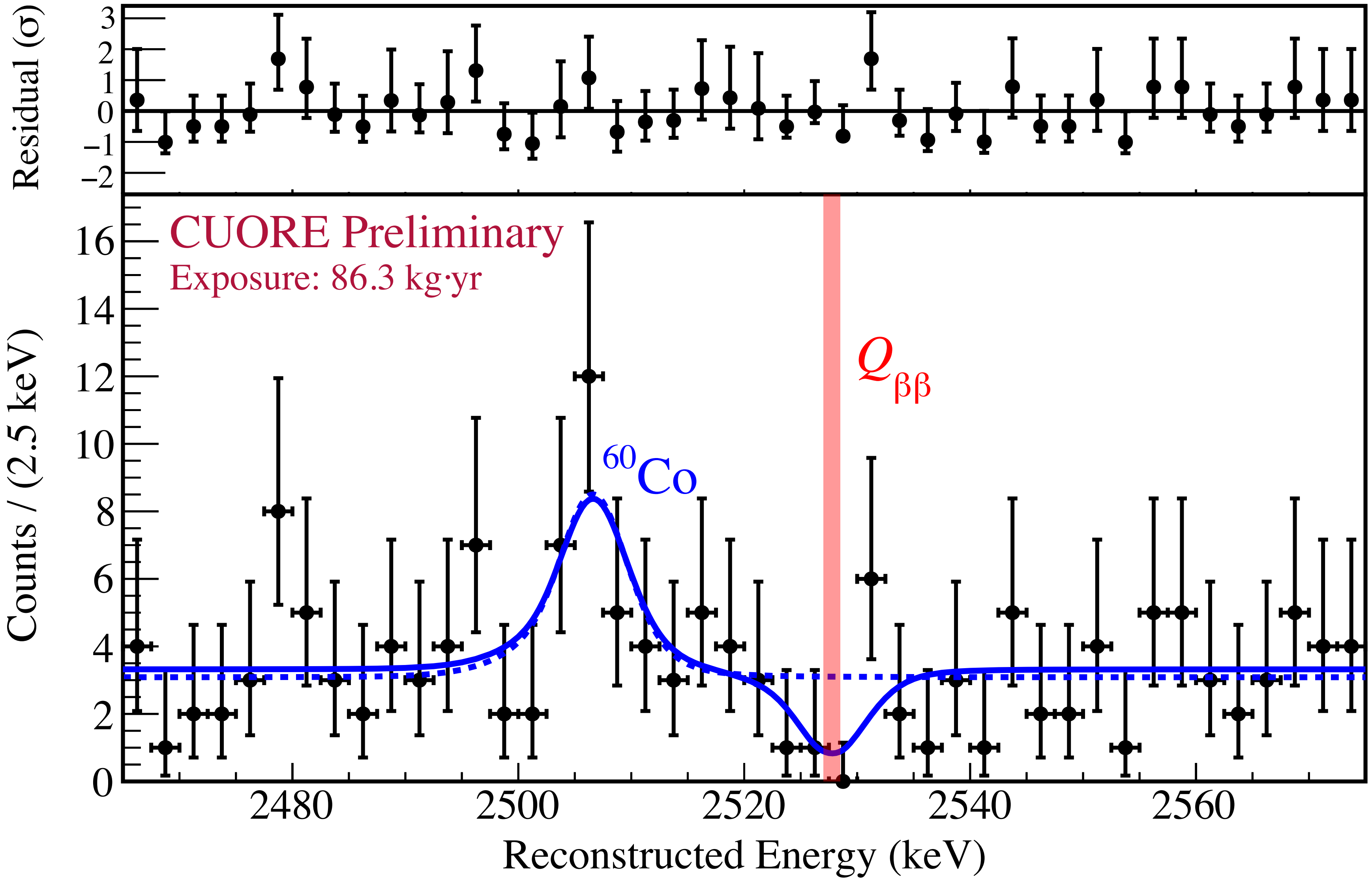
Best fit decay rate: **$(-1.0_{-0.3}^{+0.4}$ (stat.) ± 0.1 (syst.)$)\times 10^{-25}$ / yr**

- Combining the CUORE result with the existing ^{130}Te
  - 19.75 kg·yr of Cuoricino
  - 9.8 kg·yr of CUORE-0

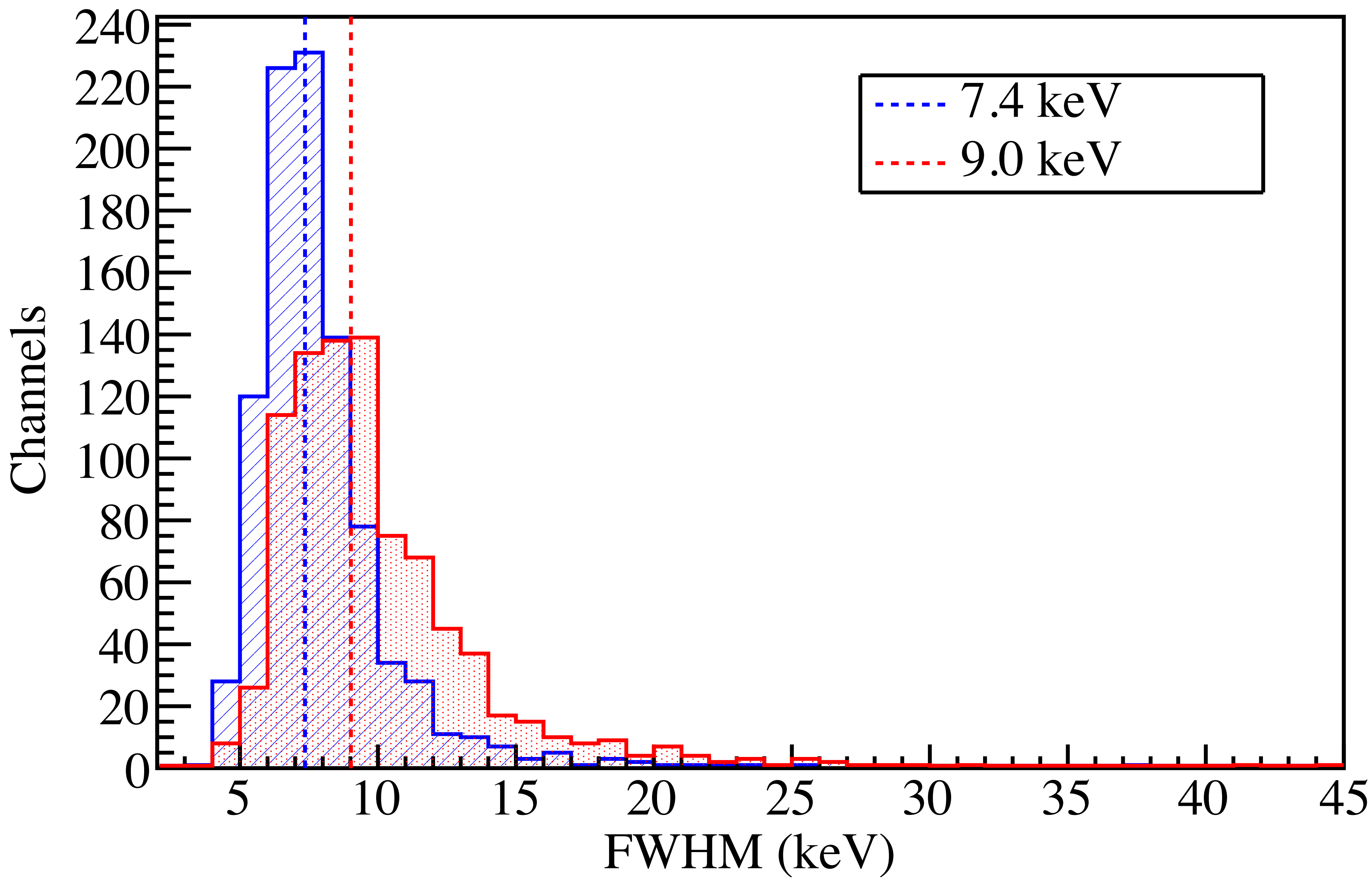
- The combined 90% C.L. limit is

$T_{0\nu} > 1.5 \times 10^{25}$ yr

$m_{\beta\beta} <$ 140–400 meV



Resolution improvements



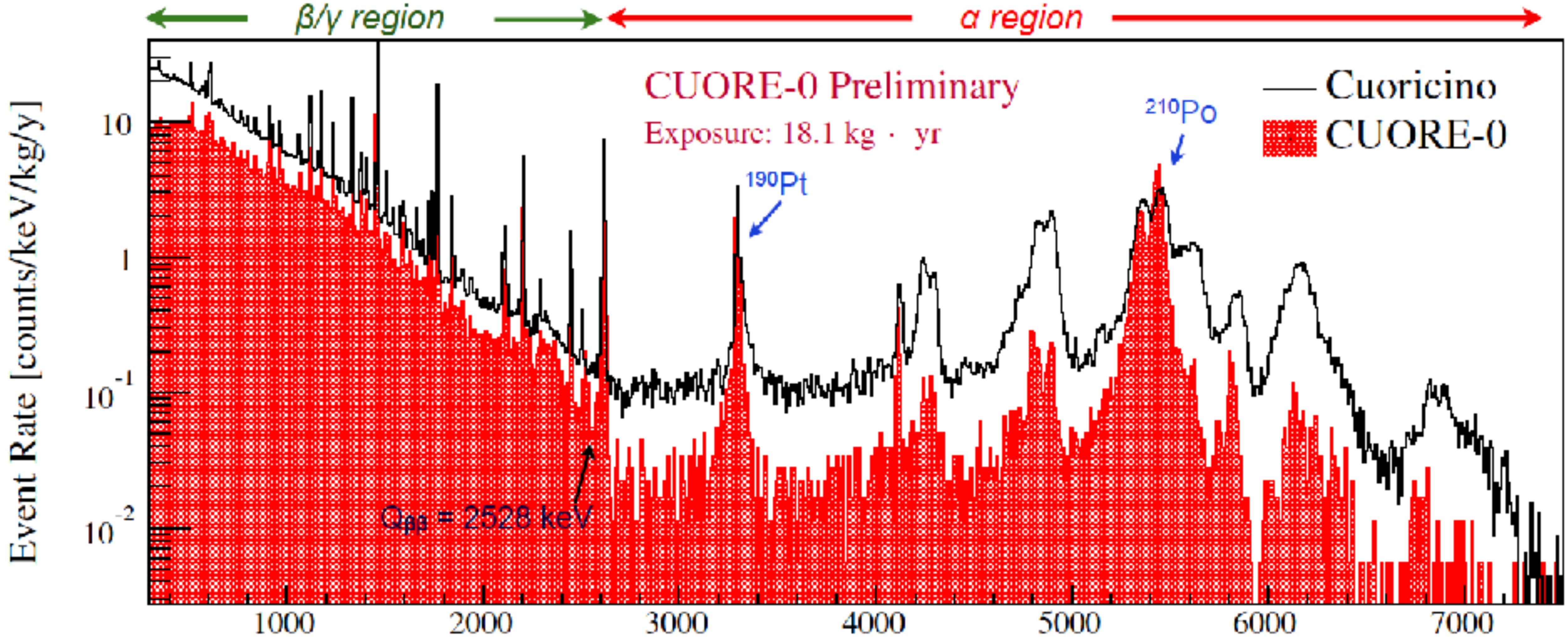
Dataset 1

Dataset 2

CUPID

Cuore Upgrade with Particle Identification

Main motivation is the discrimination of the degraded alpha background that limits CUORE



Is necessary to adopt a discrimination

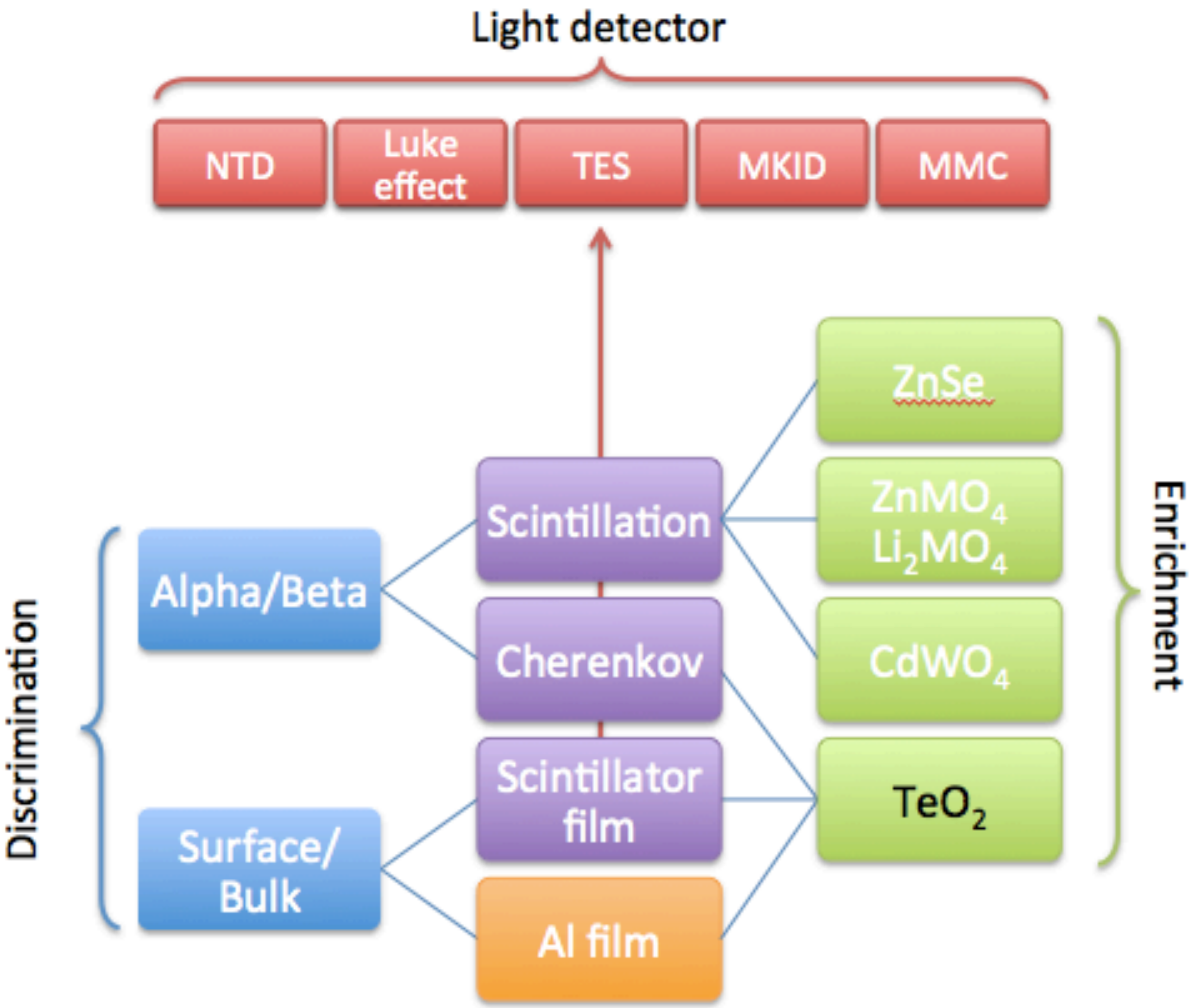
- alpha/beta or bulk/surface

CUPID

Two main approches for the background discrimination:

Scintillating bolometers

- Scintillating crystals @ low T
- High light yield
- Possible PSD
- Simple requirements for the bolometric light detectors



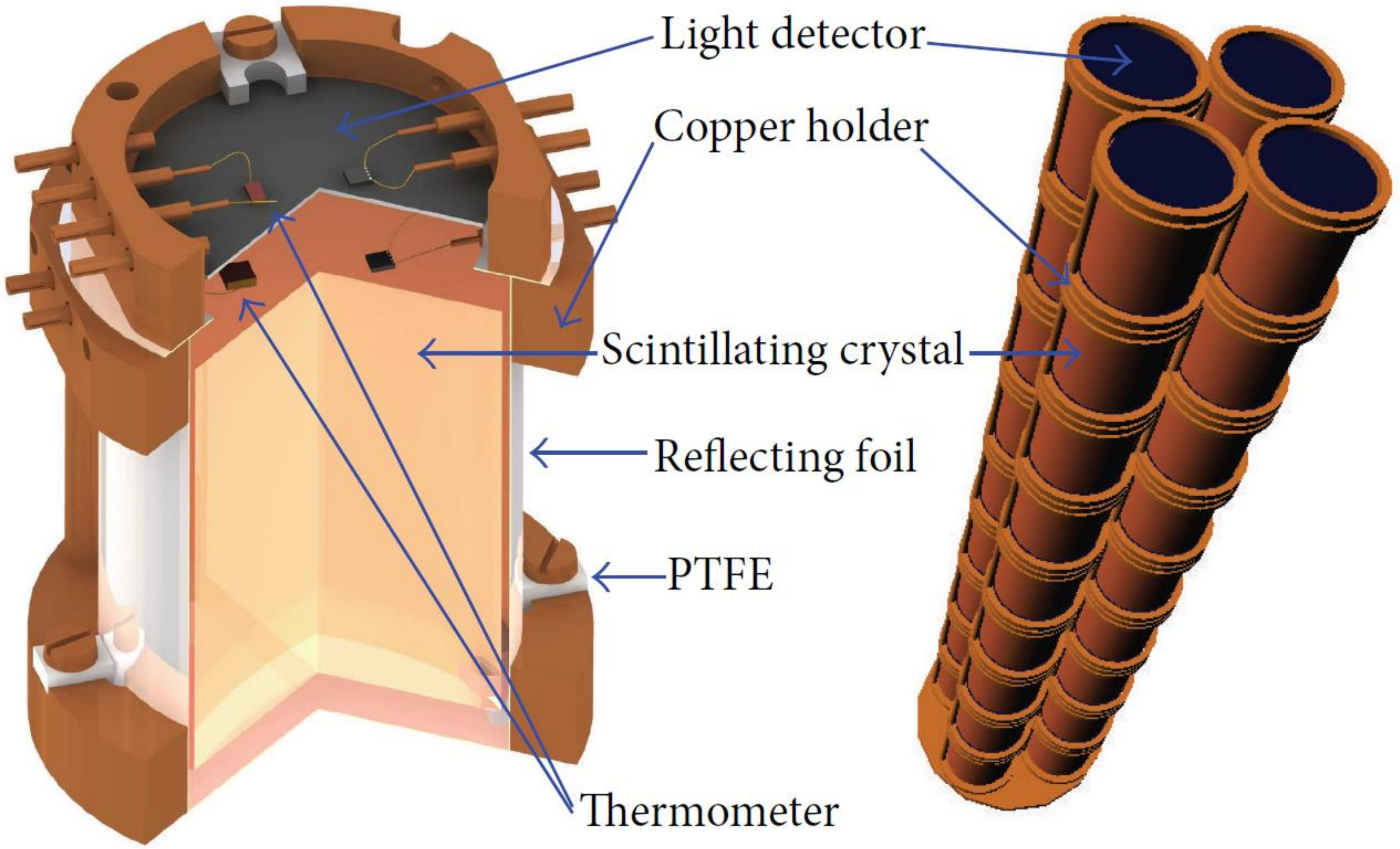
Cherenkov bolometers (TeO_2)

- Non scintillating crystals
- few Cherenkov photons
- Challenging requirements for the bolometric light detectors
- enrichment not strictly needed

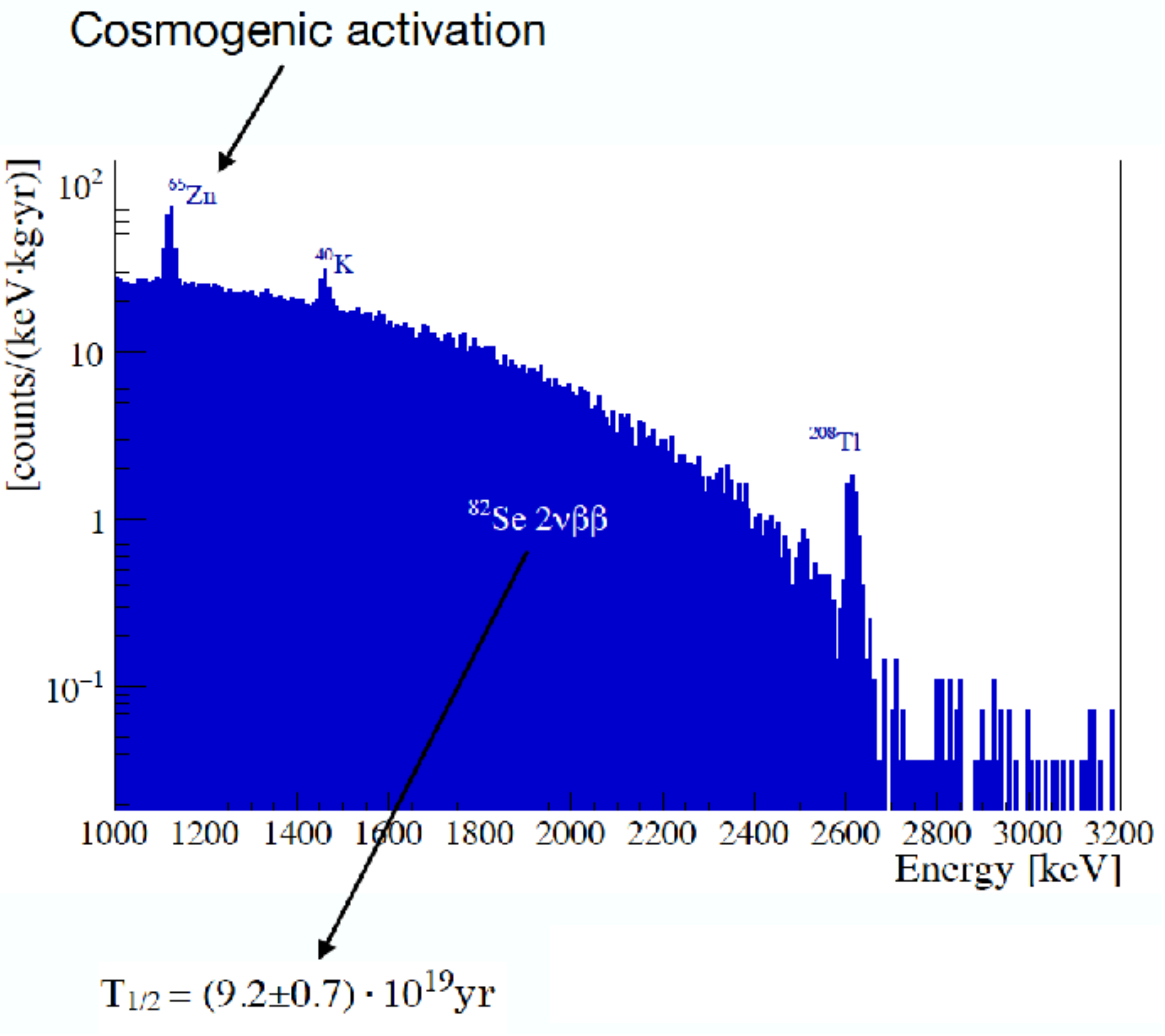
-

ZnSe (Lucifer/CUPID-0)

- 24 $Zn^{82}Se$ bolometers, for a total mass ~ 5.1 kg of ^{82}Se
- 2 ZnSe bolometers ~400 g each, not enriched in ^{82}Se
- $Q_{\beta\beta}(^{82}Se)$ = 2996 keV
- Light detectors high purity Ge wafers with antireflecting coating
- Thermal sensors: Ge-NTD thermistors
- Detector assembled in 5 towers cooled down in Cuoricino/CUORE-0 cryostat
- Total active mass of the detector ~10.5 kg

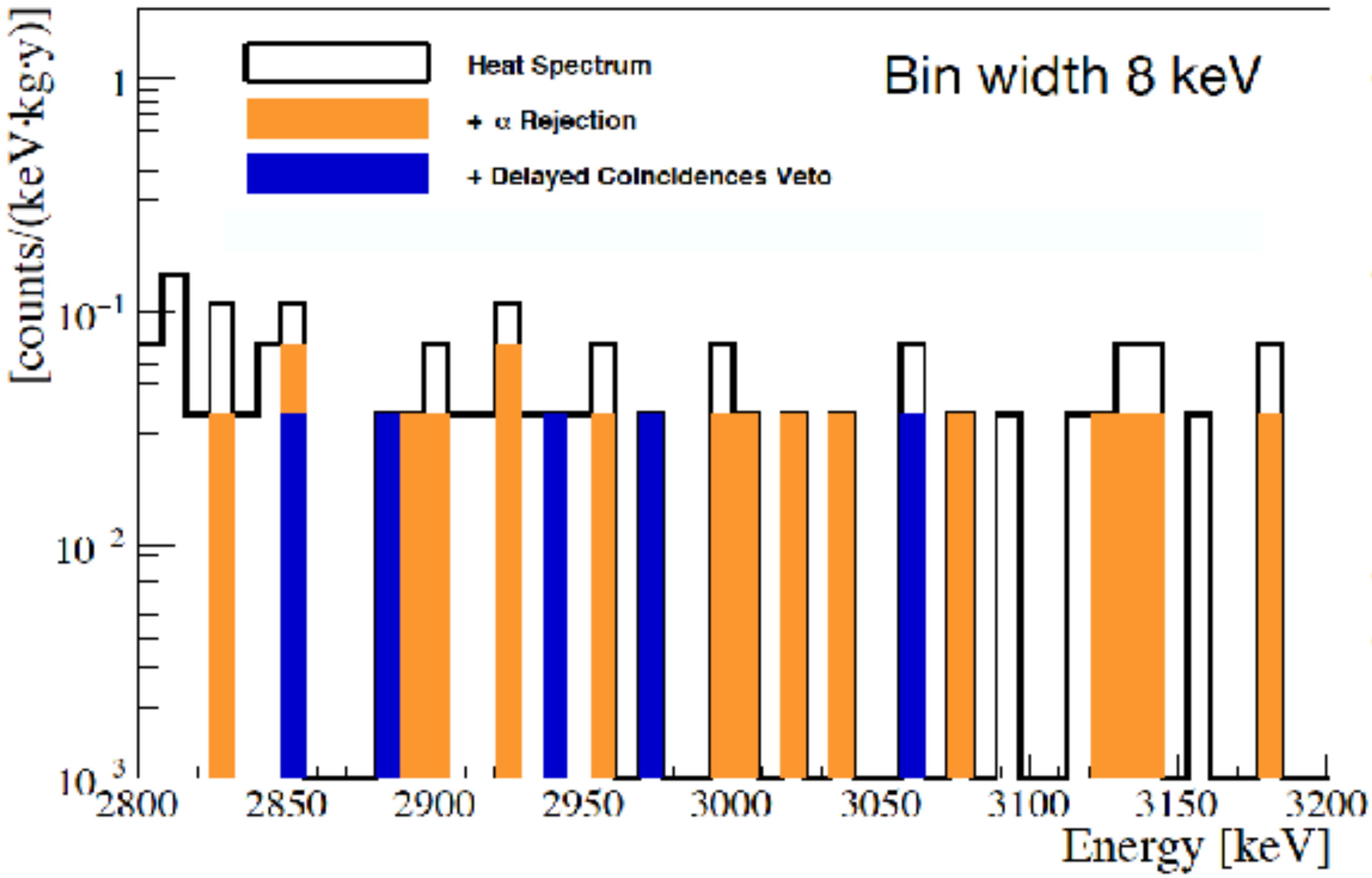


ZnSe (Lucifer/CUPID-0)



$T_{1/2} = (9.2 \pm 0.7) \cdot 10^{19}$yr

ZnSe (Lucifer/CUPID-0)



- Rejection of "non-particle-like" events through pulse shape on thermal pulses.
- Anti-coincidence between ZnSe crystals

+

- α particles rejection
- Delayed coincidence veto

All cuts efficiency 93±2%

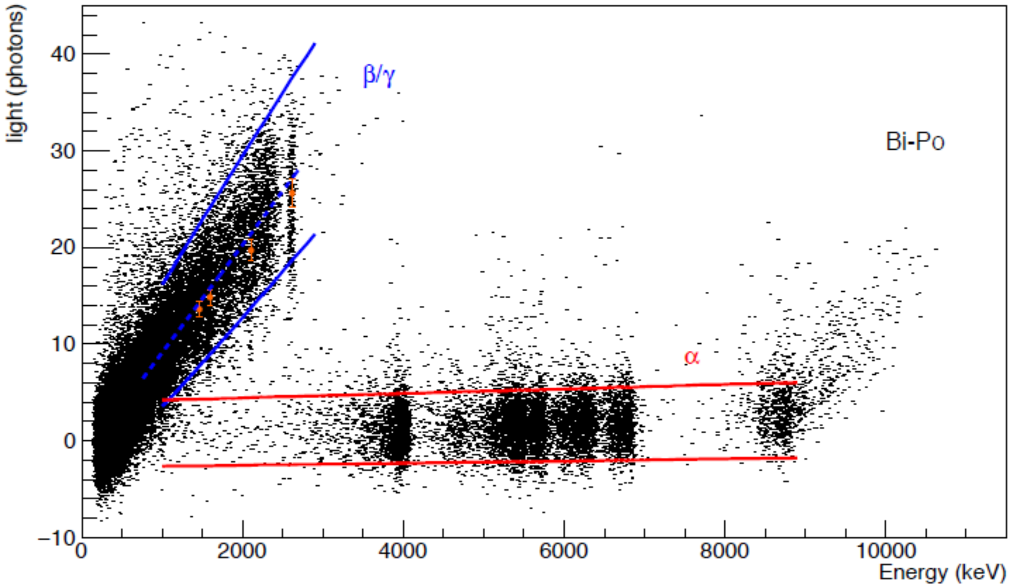
5 events survive all cuts

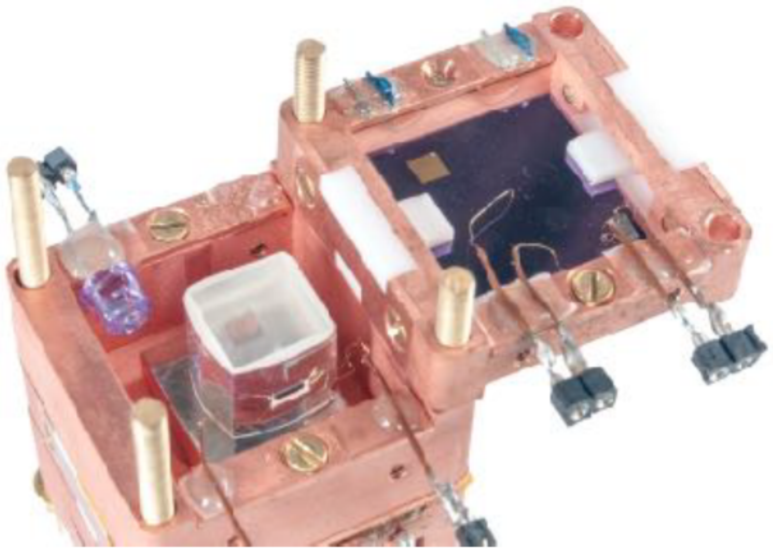
UEML SIMULTANEOUS FIT OVER THE DATASETS

$$3.6^{+1.9}_{-1.4} \times 10^{-3}\ \text{counts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$$

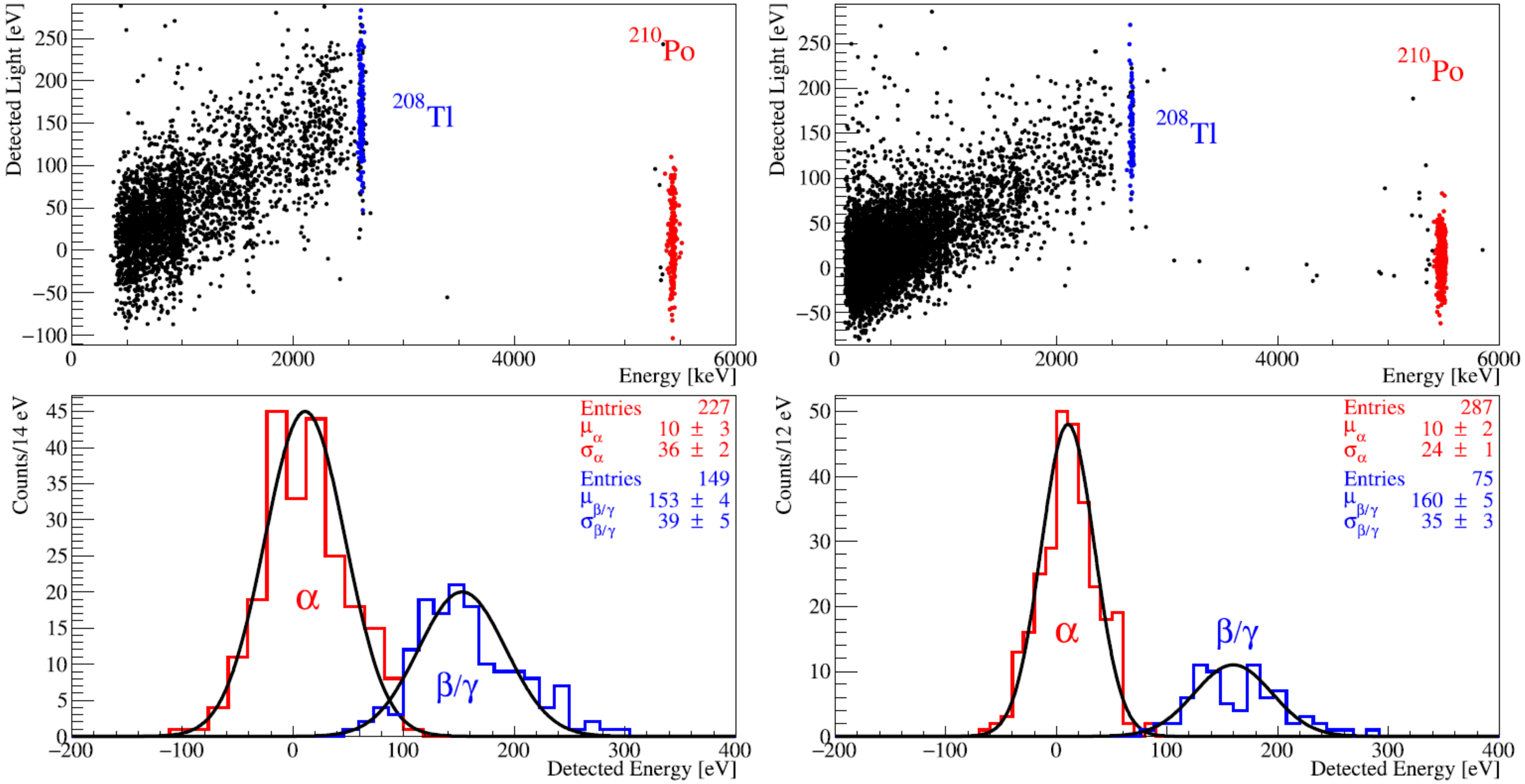
(1.5±0.3) x 10^{-3} counts/(keV kg yr) from muons (PRELIMINARY MC simulation)

TeO$_2$



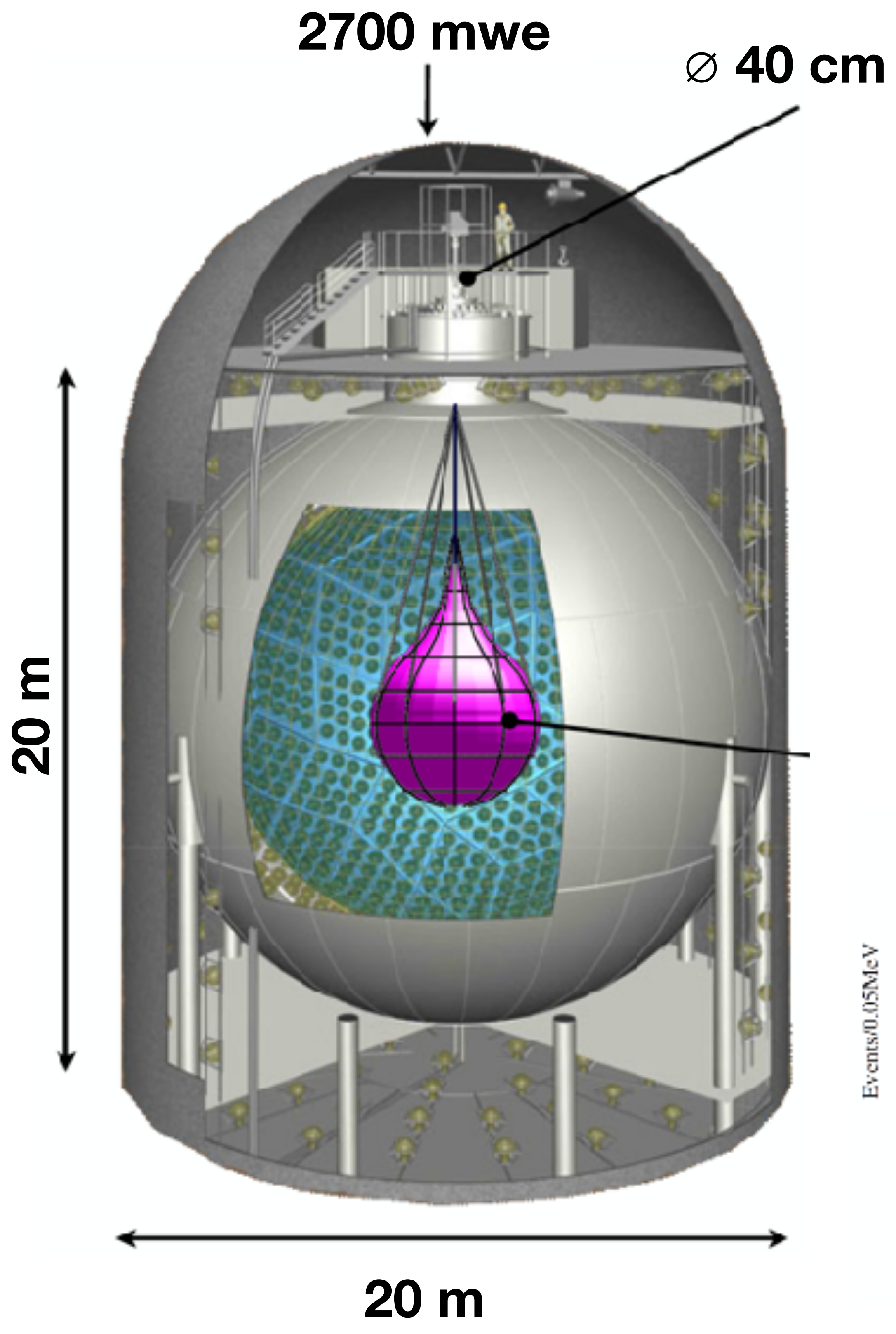


Cerenkov light measured with Si-Luke light detector on small (1x1x1 cm^3) TeO$_2$ crystal



Cerenkov light measured with Ge-Luke light detector on CUORE size (5x5x5 cm^3) TeO$_2$ crystal

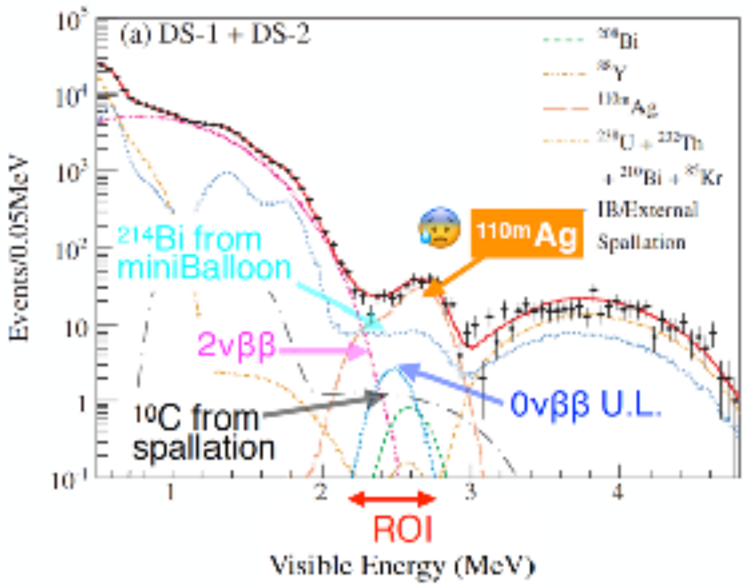
Kamland-Zen



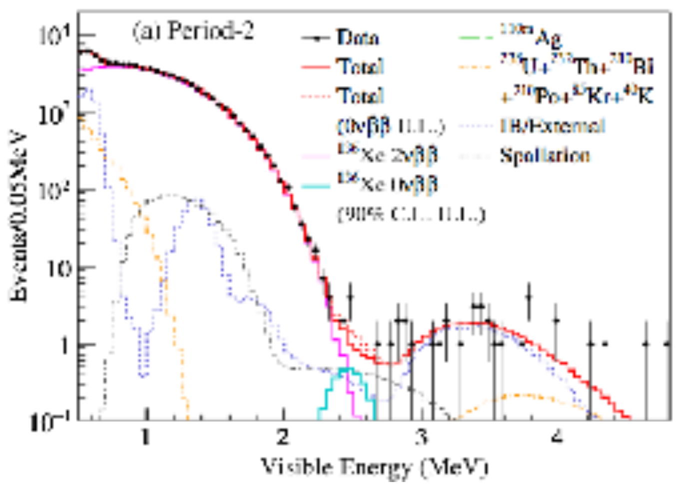
KamLAND-Zen400

- ^{136}Xe loaded LS in mini-balloon
- ~3 % of ^{136}Xe in LS by weight
- 90% enrichment
- 360 kg of Xe dissolved in ~17 m^3 LS
- σE/E: ~11% @ Q value
- Position reconstruction for bkg rejection and sources identification

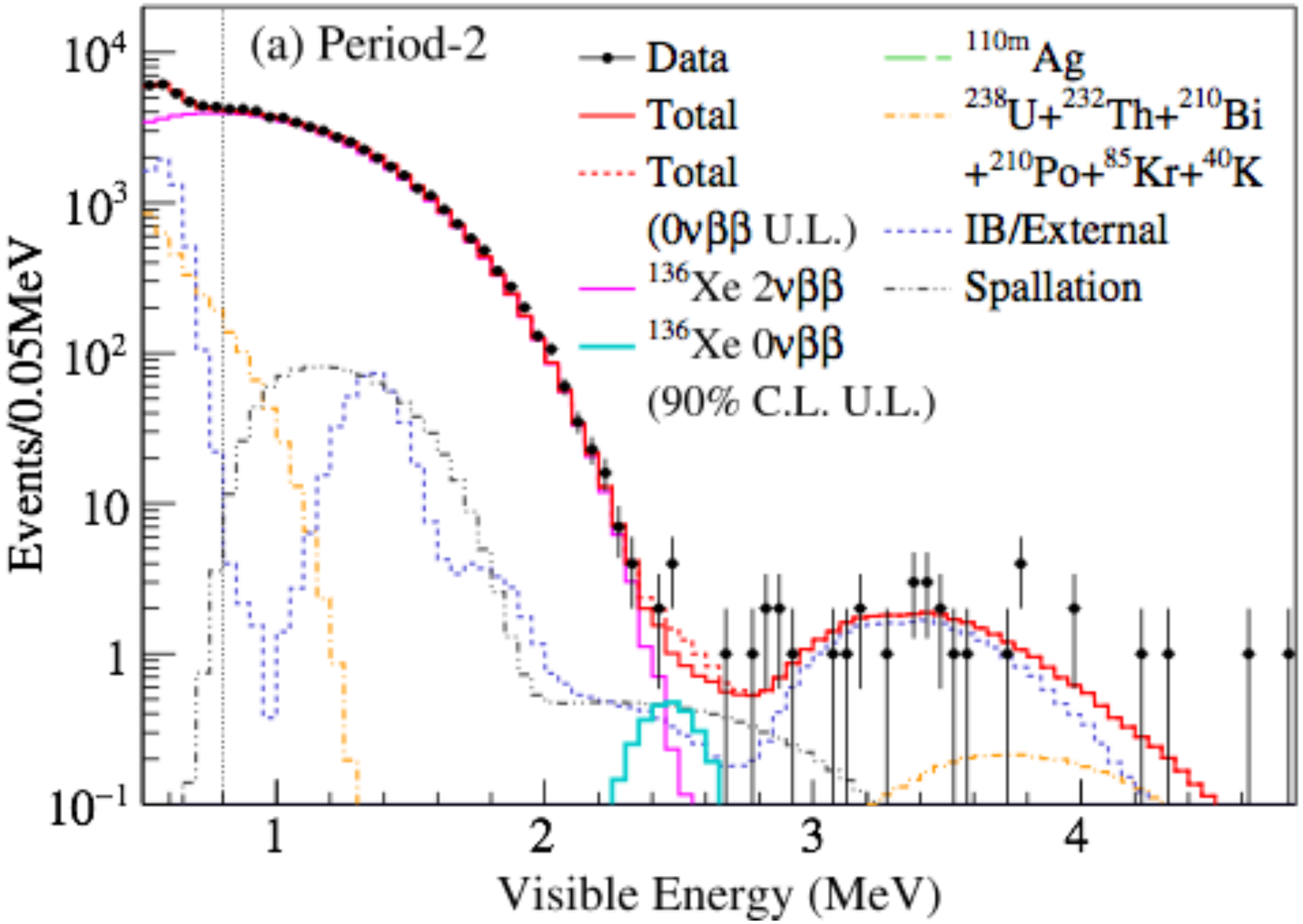
Phase I



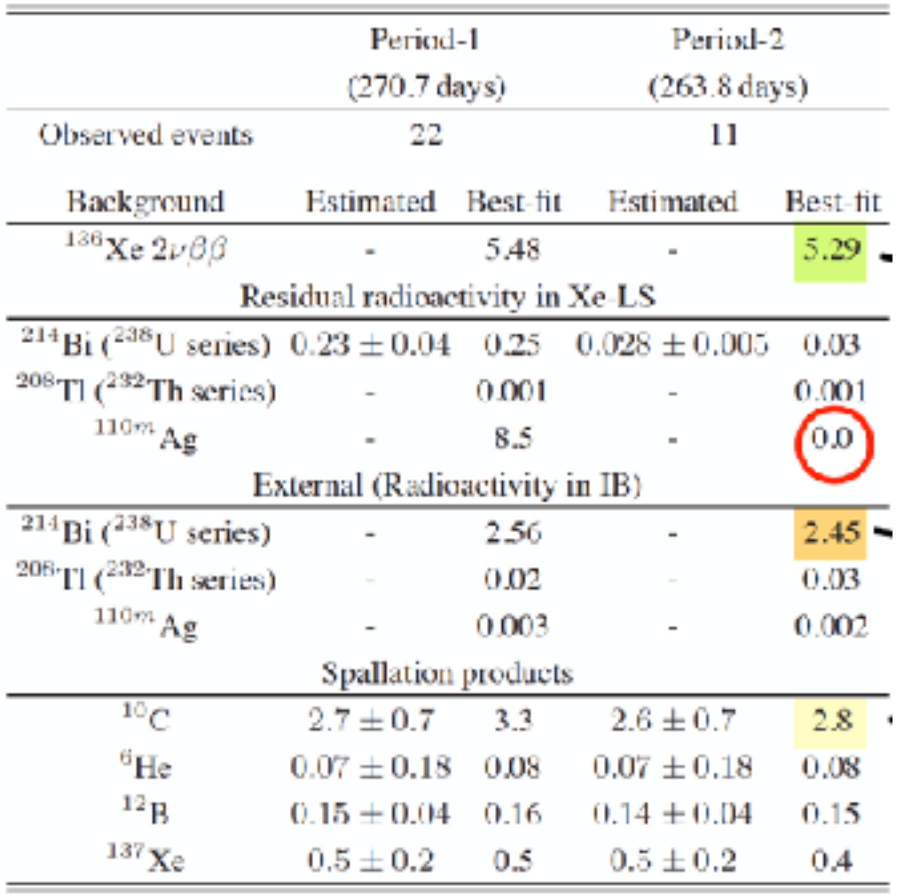
Phase II



Kamland-Zen



$2.3 < E < 2.7$ MeV, $R < 1$m



	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4

KamLAND-Zen400 (completed)

Phase-2: 2013/12/11 - 2015/10/27: 534.5 days (504 kg-yr)

Sensitivity: > 5.6 10^{25} yr (90% C.L.)

- Unconstraint fit: > 9.2 10^{25} yr (90% C.L.)
- Phase I + II: > 1.07 10^{26} yr (90% C.L.)
- $m_{\beta\beta} < (61\text{-}165)$ meV @90 % C.L

- KamLAND-Zen800 (coming soon)
- The first 800 balloon failed but the second one has been constructed with a lot of improvements.

Kamland-Zen

25 μm Nylon6

transparency 99.4% @400nm

Xe barrier < 220 g/year

CURRENT STATUS:

✓ Improved welding technique

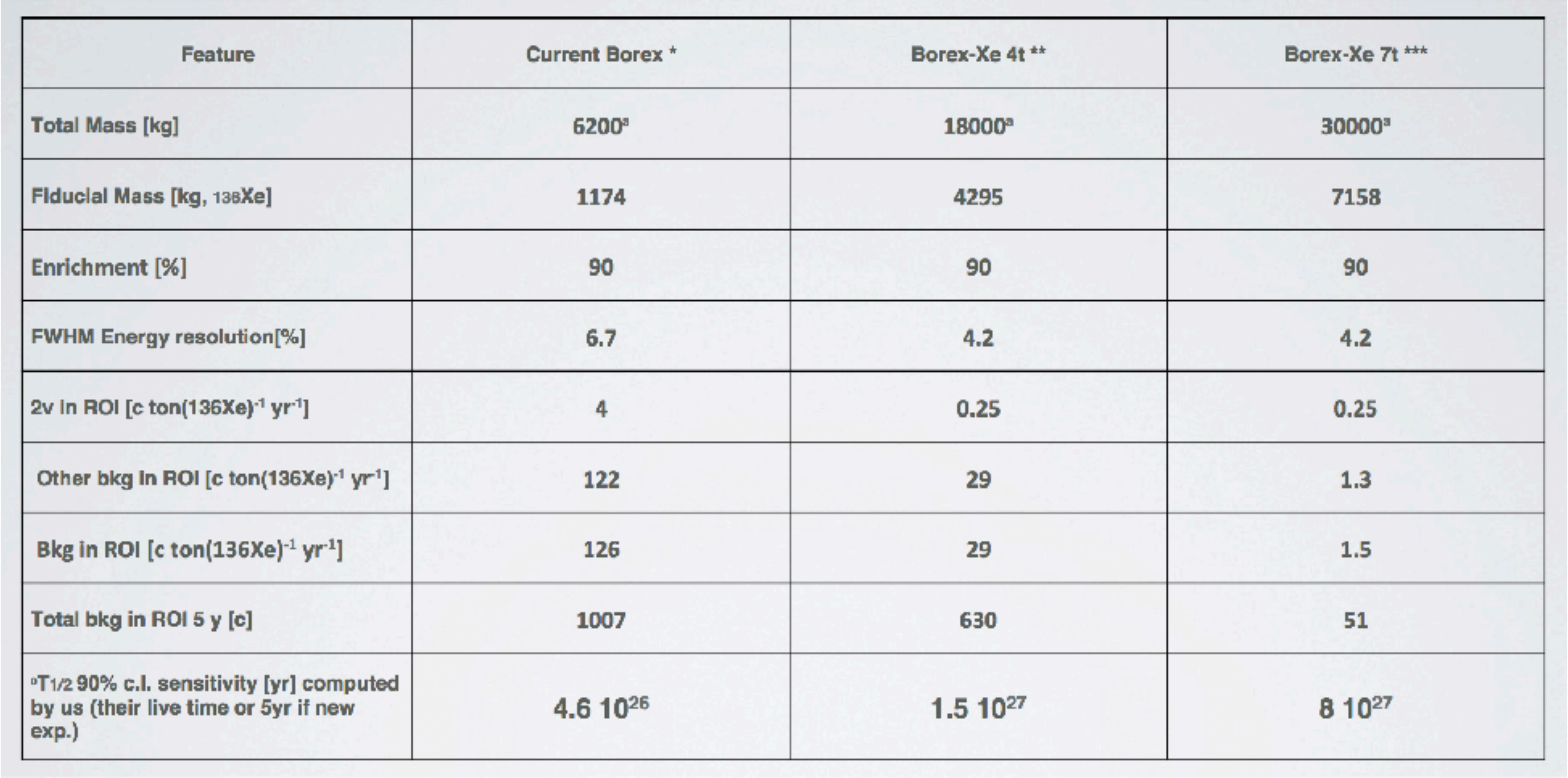
✓ Improved cutting technique to avoid shape distortion

✓ Finish manufacturing and cleaning sub-components

✓ Leak check & repair

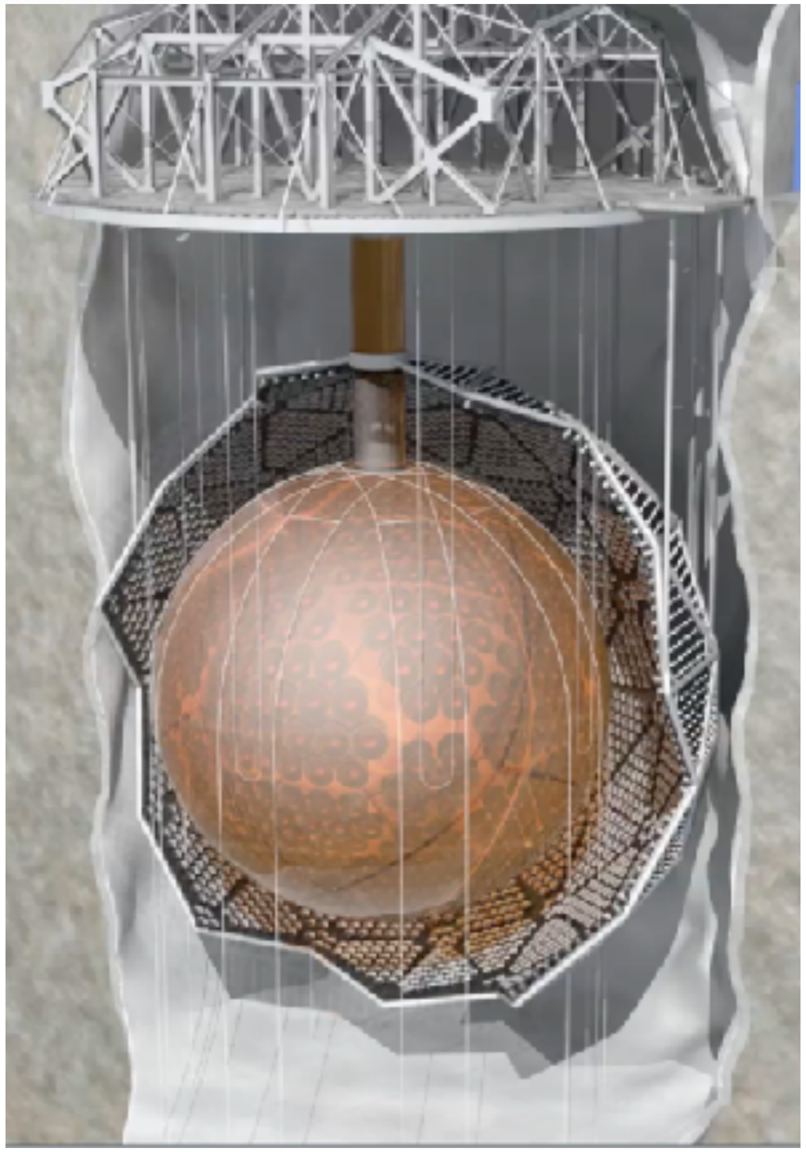
- Folding and packing
- Delivery to KamLAND site
- New LS purification (half done)
- Installing the miniBalloon filled with Xe-less LS
- Replacing the Xe-less LS with Xe-loaded LS

Borexino - Xe

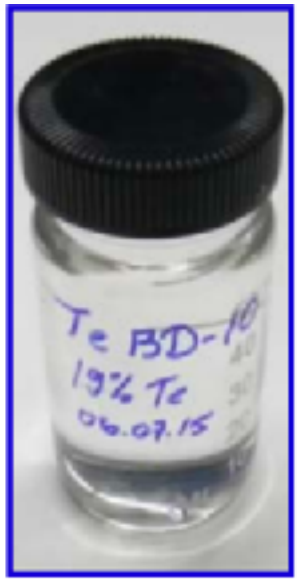


Feature	Current Borex *	Borex-Xe 4t **	Borex-Xe 7t ***
Total Mass [kg]	6200^{a}	18000^{a}	30000^{a}
Fiducial Mass [kg, ^{136}Xe]	1174	4295	7158
Enrichment [%]	90	90	90
FWHM Energy resolution[%]	6.7	4.2	4.2
2ν in ROI [c ton(136Xe)$^{-1}$ yr^{-1}]	4	0.25	0.25
Other bkg in ROI [c ton(136Xe)$^{-1}$ yr^{-1}]	122	29	1.3
Bkg in ROI [c ton(136Xe)$^{-1}$ yr^{-1}]	126	29	1.5
Total bkg in ROI 5 y [c]	1007	630	51
^{a}T$_{1/2}$ 90% c.l. sensitivity [yr] computed by us (their live time or 5yr if new exp.)	$4.6\ 10^{26}$	$1.5\ 10^{27}$	$8\ 10^{27}$

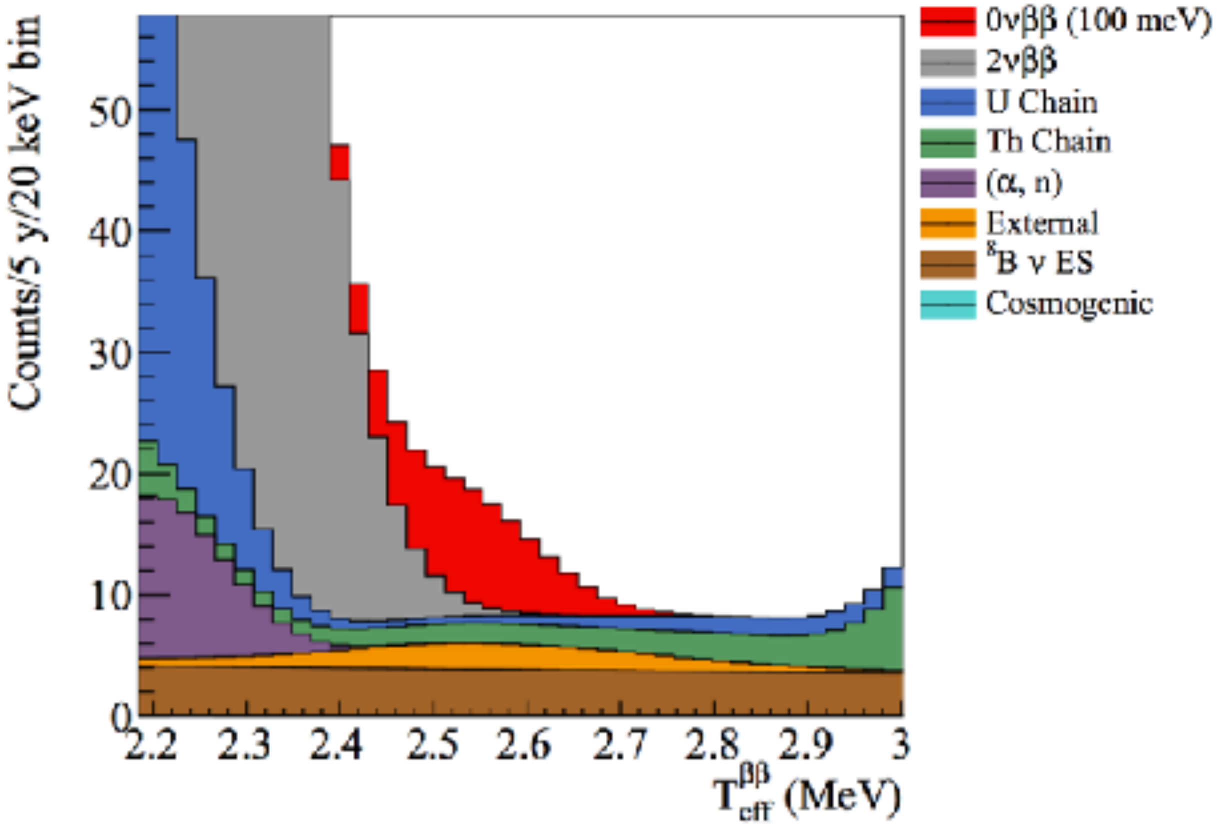
SNO+



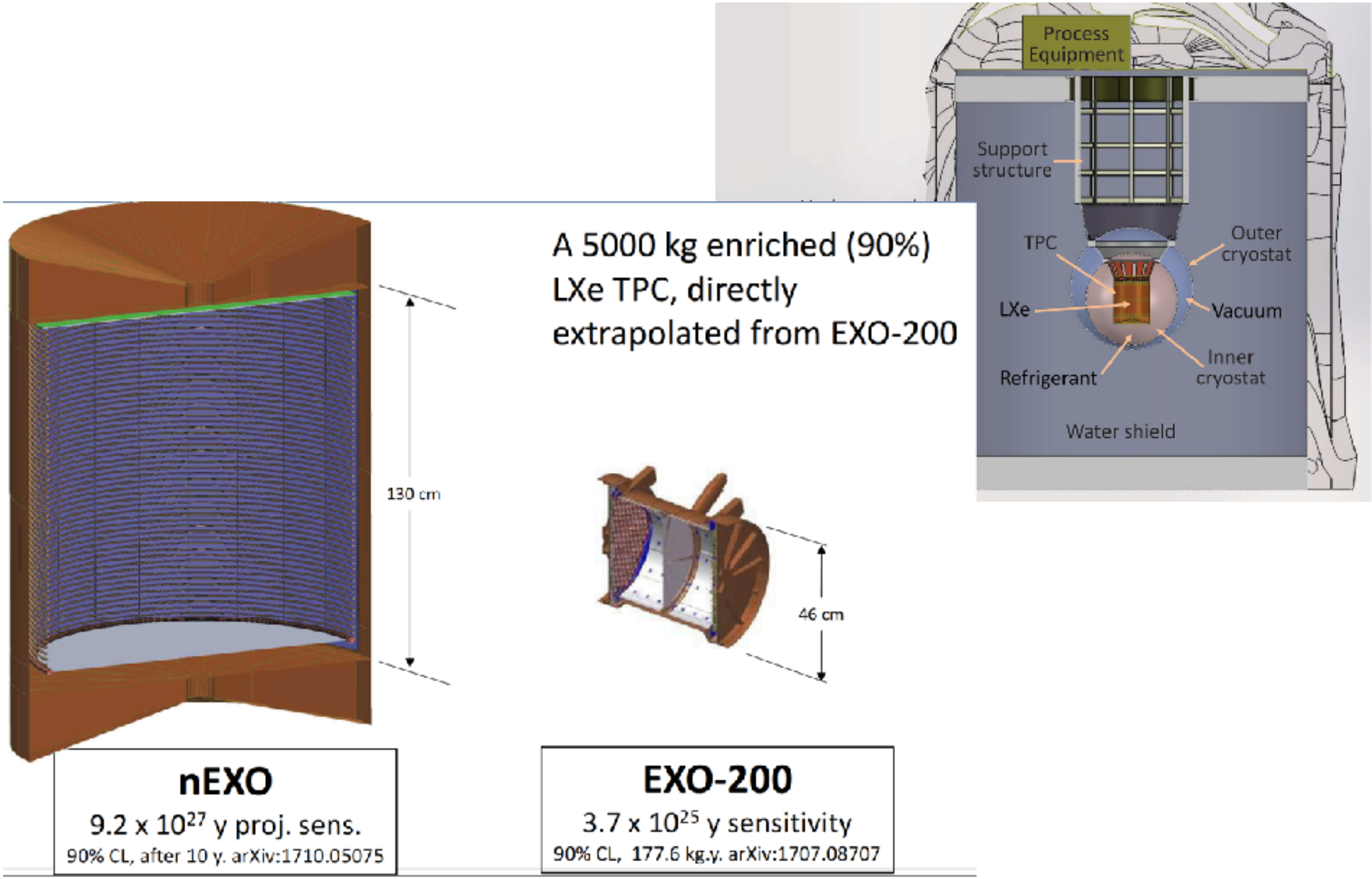
25 μm Nylon6
transparency 99.4% @400nm
Xe barrier < 220 g/year



780 t Liquid scintillator + 3.9 t Tellurium
0.5% Te (~1300 kg ^{130}Te)



nEXO



A 5000 kg enriched (90%) LXe TPC, directly extrapolated from EXO-200

nEXO

9.2×10^{27} y proj. sens.

90% CL, after 10 y. arXiv:1710.05075

EXO-200

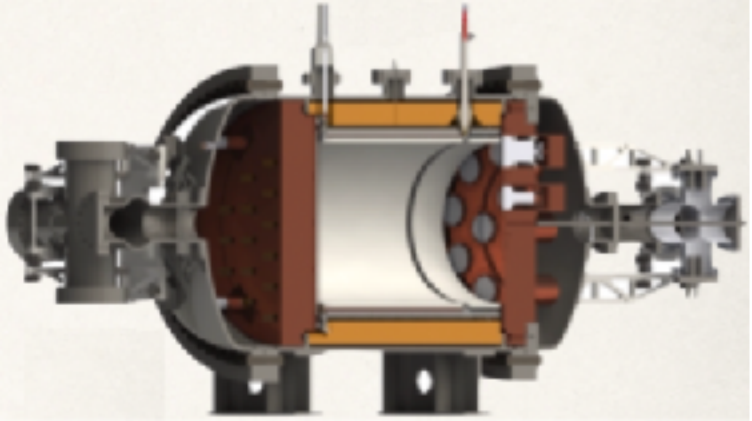
3.7×10^{25} y sensitivity

90% CL, 177.6 kg.y. arXiv:1707.08707

NEXT

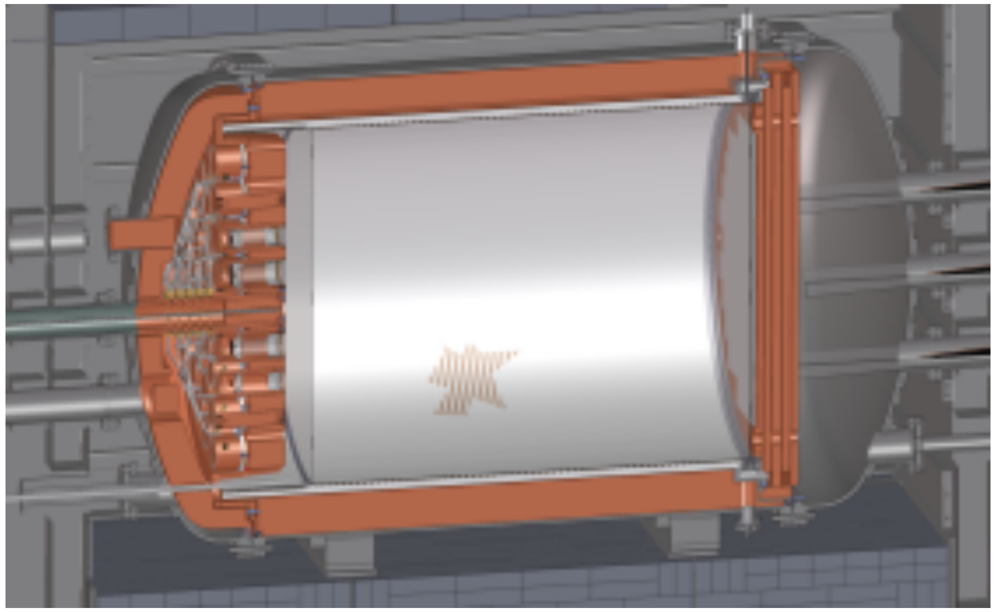
^{136}Xe high-pressure (10-15 bar) TPC

NEXT-NEW (5 kg) 2015-2018

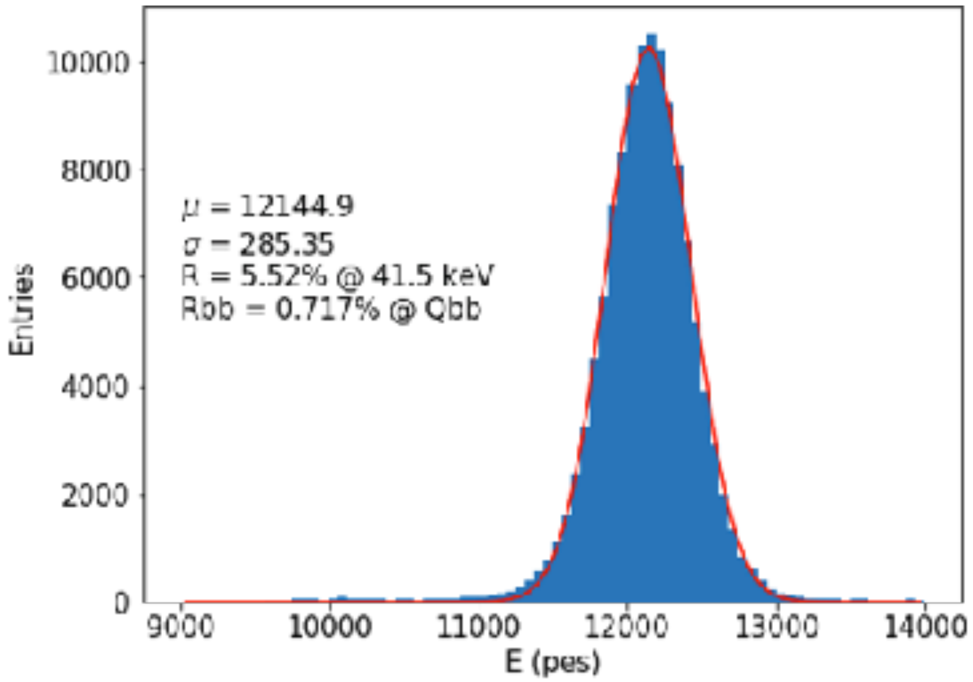


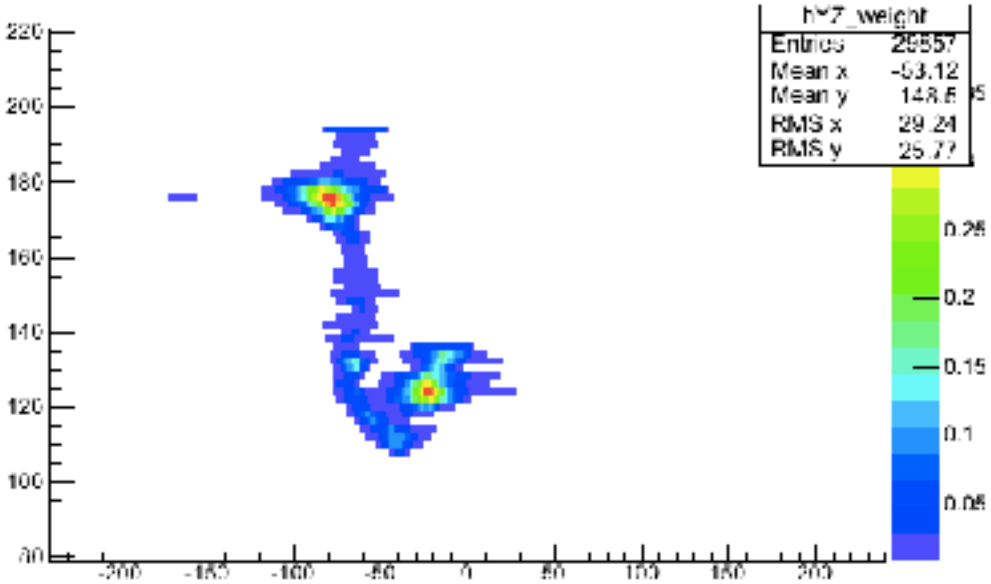
Underground & radio-pure operations, background, 2νββ

NEXT-100 (100 kg) 2018-2020’s



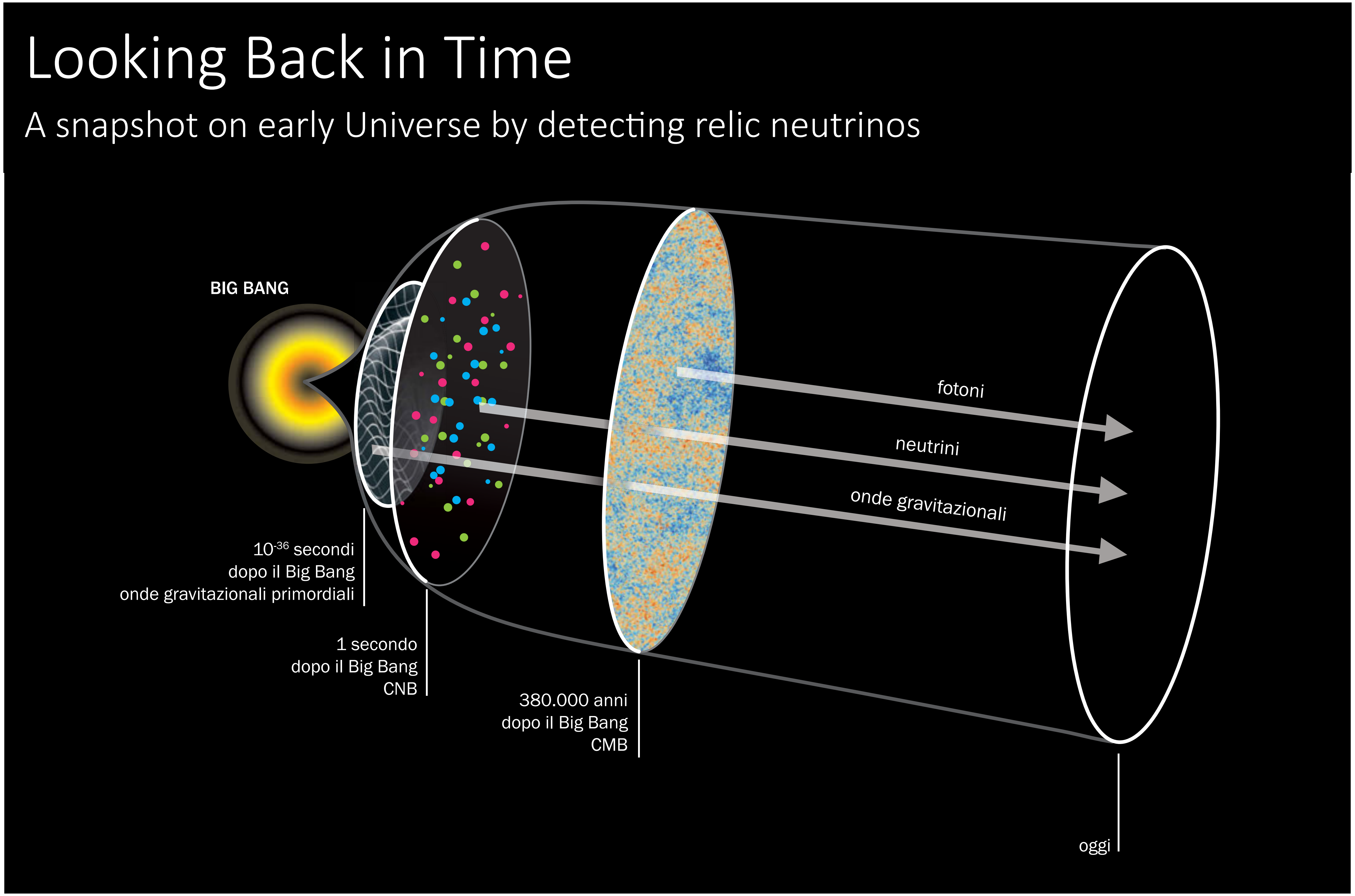
0νββ search





PTOLEMY

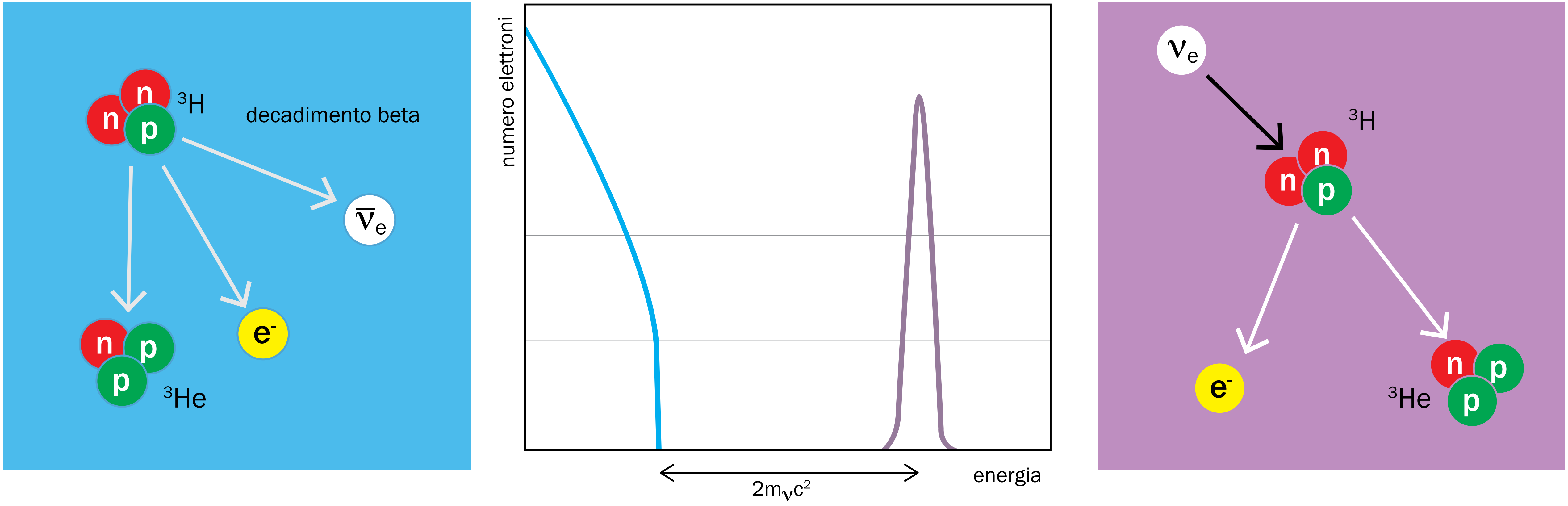
Project aiming at demonstrating the capability to detect Cosmological Relic Neutrinos



Looking Back in Time

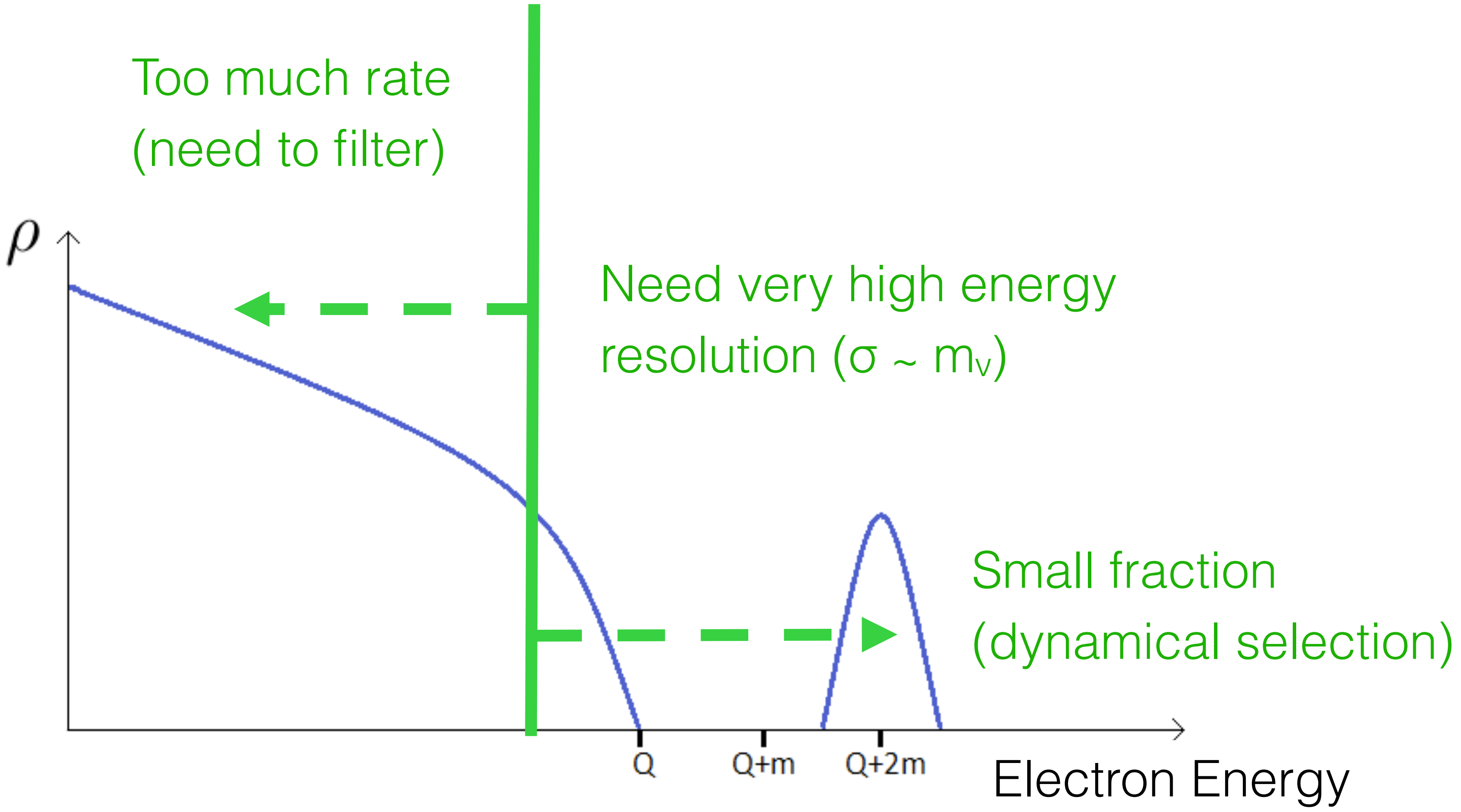
A snapshot on early Universe by detecting relic neutrinos

Detection Concept: neutrino capture



Experimental Perspective

Project aiming at demonstrating the capability to detect Cosmological Relic Neutrinos



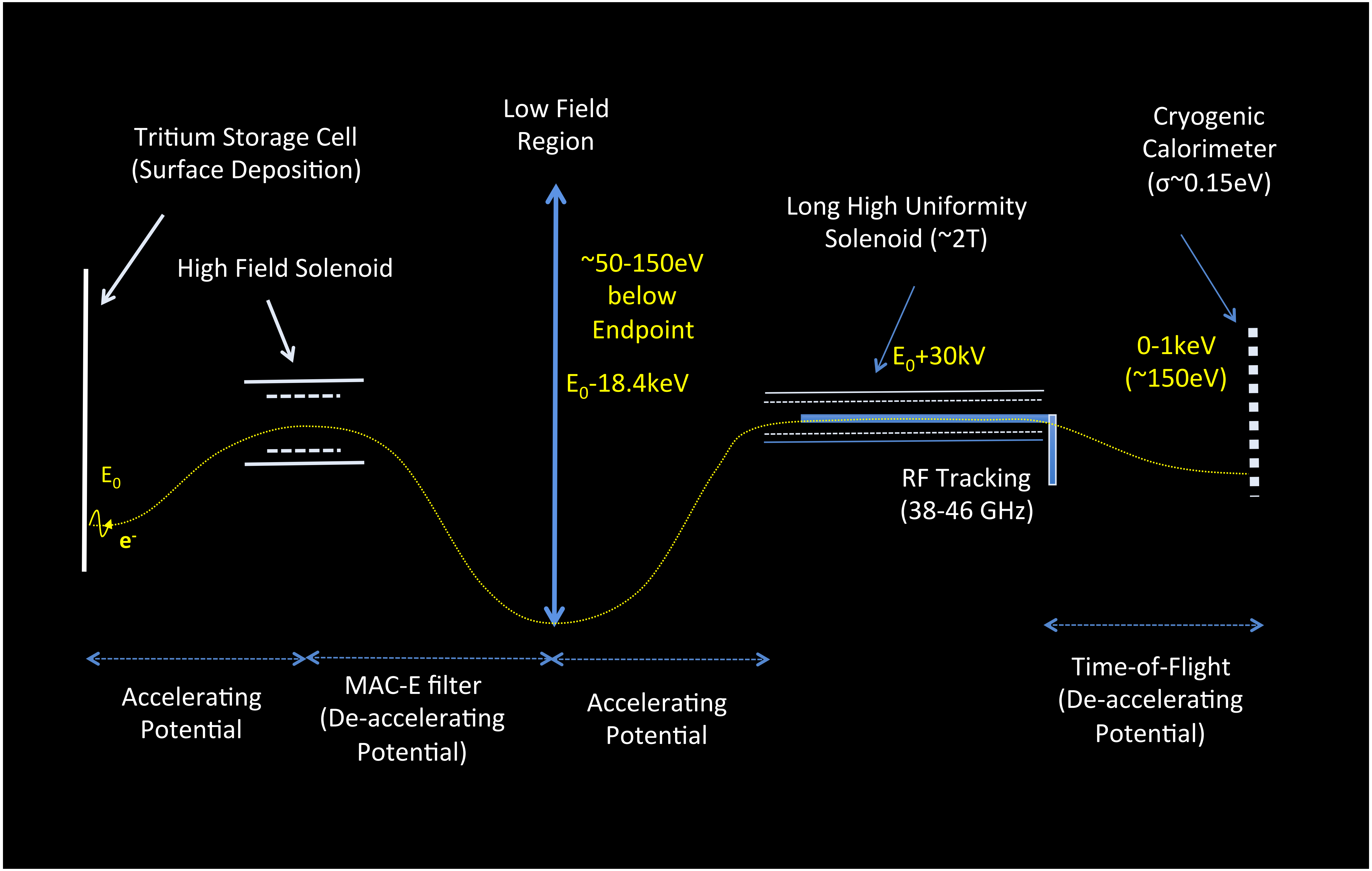
Too much rate
(need to filter)

Need very high energy
resolution ($\sigma \sim m_\nu$)

Small fraction
(dynamical selection)

Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

PTOLEMY Experimental Concept



Tritium Storage Cell
(Surface Deposition)

High Field Solenoid

Low Field
Region

~50-150eV
below
Endpoint

E_0-18.4keV

Long High Uniformity
Solenoid (~2T)

E_0+30kV

Cryogenic
Calorimeter
(σ~0.15eV)

0-1keV
(~150eV)

E_0

e^-

RF Tracking
(38-46 GHz)

Accelerating
Potential

MAC-E filter
(De-accelerating
Potential)

Accelerating
Potential

Time-of-Flight
(De-accelerating
Potential)

PTOLEMY proof-of-principle at LNGS

The proposed work plan for the activities to be carried out in three to five years in order to complete the PTOLEMY phase-I can be summarized as follows

- Validate graphene as target substrate, measure hydrogen/tritium bond characteristics (width of the bound state), measure electron-graphene interaction properties.
- Achieve an electron energy measurement resolution of 0.05 eV to separate the CNB signal from the β-decay spectrum, couple detector with spectrometer magnetic field,
- Commission the prototype with high stability HV and (single) electron gun
- Operate the prototype and measure the background rate in the CNB signal region (using a pure graphene tritium-free target)
- further reduce background by implementing high radio-pure graphene -- eventually exploiting a concurrent program in MeV dark matter searches
- Implement RF antenna for triggering on single electrons in coincidence with an energy measurement, and
- Design and simulate a scalable target mass setup with high acceptance kinematic filtering.