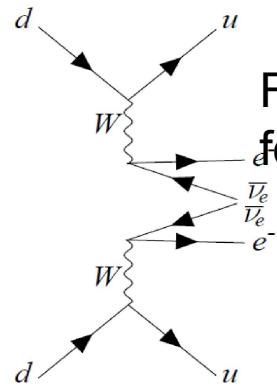
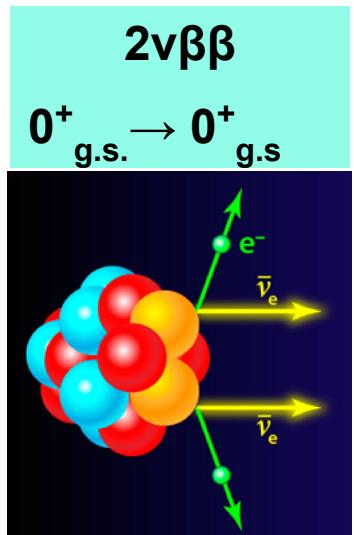


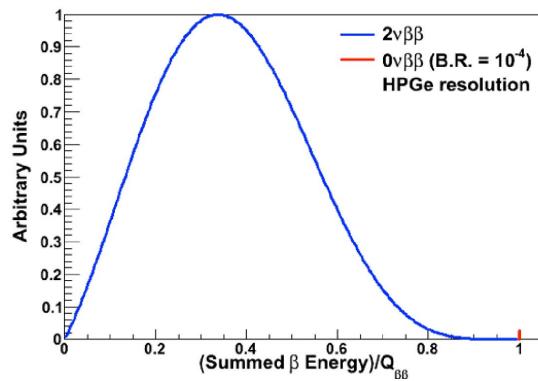
# **Neutrino Properties on the Basis of Neutrinoless Double Beta Decay**

**Alexander A. Klimenko**

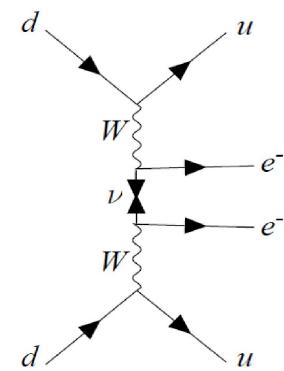
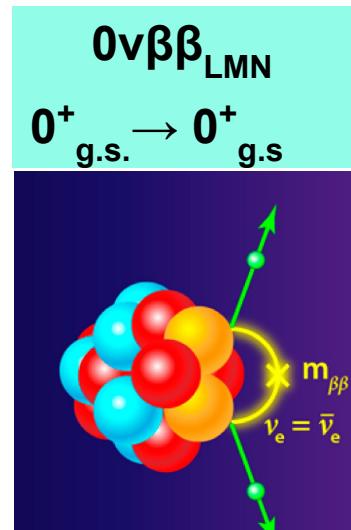
$$(A,Z) \rightarrow (A,Z+2) + 2 e^- + \{2\nu\}$$



**two-neutrino double beta decay**  
(allowed in SM)



Feynman diagrams at the quark level  
for:



**neutrinoless double beta decay**  
LNM- light Majorana neutrino mechanism  
(beyond SM)

# NDBDecayers

The following known nuclides with  $A \leq 260$  are theoretically capable of double beta decay, where the red color is the isotopes in which the double beta rate has been measured experimentally, and the black color has yet to be measured experimentally:

$^{46}\text{Ca}$ ,  $^{48}\text{Ca}$ ,  $^{70}\text{Zn}$ ,  $^{76}\text{Ge}$ ,  $^{80}\text{Se}$ ,  $^{82}\text{Se}$ ,  $^{86}\text{Kr}$ ,  $^{94}\text{Zr}$ ,  $^{96}\text{Zr}$ ,  $^{98}\text{Mo}$ ,  $\underline{\text{100 Mo}}$ ,  $^{104}\text{Ru}$ ,  $^{110}\text{Pd}$ ,  
 $^{114}\text{Cd}$ ,  $\underline{\text{116 Cd}}$ ,  $^{122}\text{Sn}$ ,  $^{124}\text{Sn}$ ,  $^{128}\text{Te}$ ,  $\underline{\text{130 Te}}$ ,  $^{134}\text{Xe}$ ,  $^{136}\text{Xe}$ ,  $^{142}\text{Ce}$ ,  $^{146}\text{Nd}$ ,  $^{148}\text{Nd}$ ,  
 $\underline{\text{150 Nd}}$ ,  $^{154}\text{Sm}$ ,  $^{160}\text{Gd}$ ,  $^{170}\text{Er}$ ,  $^{176}\text{Yb}$ ,  $^{186}\text{W}$ ,  $^{192}\text{Os}$ ,  $^{198}\text{Pt}$ ,  $^{204}\text{Hg}$ ,  $^{216}\text{Po}$ ,  $^{220}\text{Rn}$ ,  
 $^{222}\text{Rn}$ ,  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$ ,  $\underline{\text{238 U}}$ ,  $^{244}\text{Pu}$ ,  $^{248}\text{Cm}$ ,  $^{254}\text{Cf}$ ,  $^{256}\text{Cf}$ ,  $^{260}\text{Fm}$

## ECEC

The following known nuclides with  $A \leq 260$  are theoretically capable of double electron capture, where the red color is the isotopes for which the double electron capture rate has been measured, and the black color has not yet been measured experimentally:

$\underline{\text{36 Ar}}$ ,  $^{40}\text{Ca}$ ,  $^{50}\text{Cr}$ ,  $^{54}\text{Fe}$ ,  $^{58}\text{Ni}$ ,  $^{64}\text{Zn}$ ,  $^{74}\text{Se}$ ,  $\underline{\text{78 Kr}}$ ,  $^{84}\text{Sr}$ ,  $^{92}\text{Mo}$ ,  $^{96}\text{Ru}$ ,  $^{102}\text{Pd}$ ,  $\underline{\text{106 Cd}}$ ,  $^{108}\text{Cd}$ ,  
 $^{112}\text{Sn}$ ,  $^{120}\text{Te}$ ,  $\underline{\text{124 Xe}}$ ,  $^{126}\text{Xe}$ ,  $\underline{\text{130 Ba}}$ ,  $^{132}\text{Ba}$ ,  $^{136}\text{Ce}$ ,  $^{138}\text{Ce}$ ,  $^{144}\text{Sm}$ ,  $^{148}\text{Gd}$ ,  $^{150}\text{Gd}$ ,  $^{152}\text{Gd}$ ,  
 $^{154}\text{Dy}$ ,  $^{156}\text{Dy}$ ,  $^{158}\text{Dy}$ ,  $^{162}\text{Er}$ ,  $^{164}\text{Er}$ ,  $^{168}\text{Yb}$ ,  $^{174}\text{Hf}$ ,  $^{180}\text{W}$ ,  $^{184}\text{Os}$ ,  $^{190}\text{Pt}$ ,  $^{196}\text{Hg}$ ,  $^{212}\text{Rn}$ ,  
 $^{214}\text{Rn}$ ,  $^{218}\text{Ra}$ ,  $^{224}\text{Th}$ ,  $^{230}\text{U}$ ,  $^{236}\text{Pu}$ ,  $^{242}\text{Cm}$ ,  $^{252}\text{Fm}$ ,  $^{258}\text{No}$

# A Portal to Physics Beyond the Standard Model

Particle  
Physics

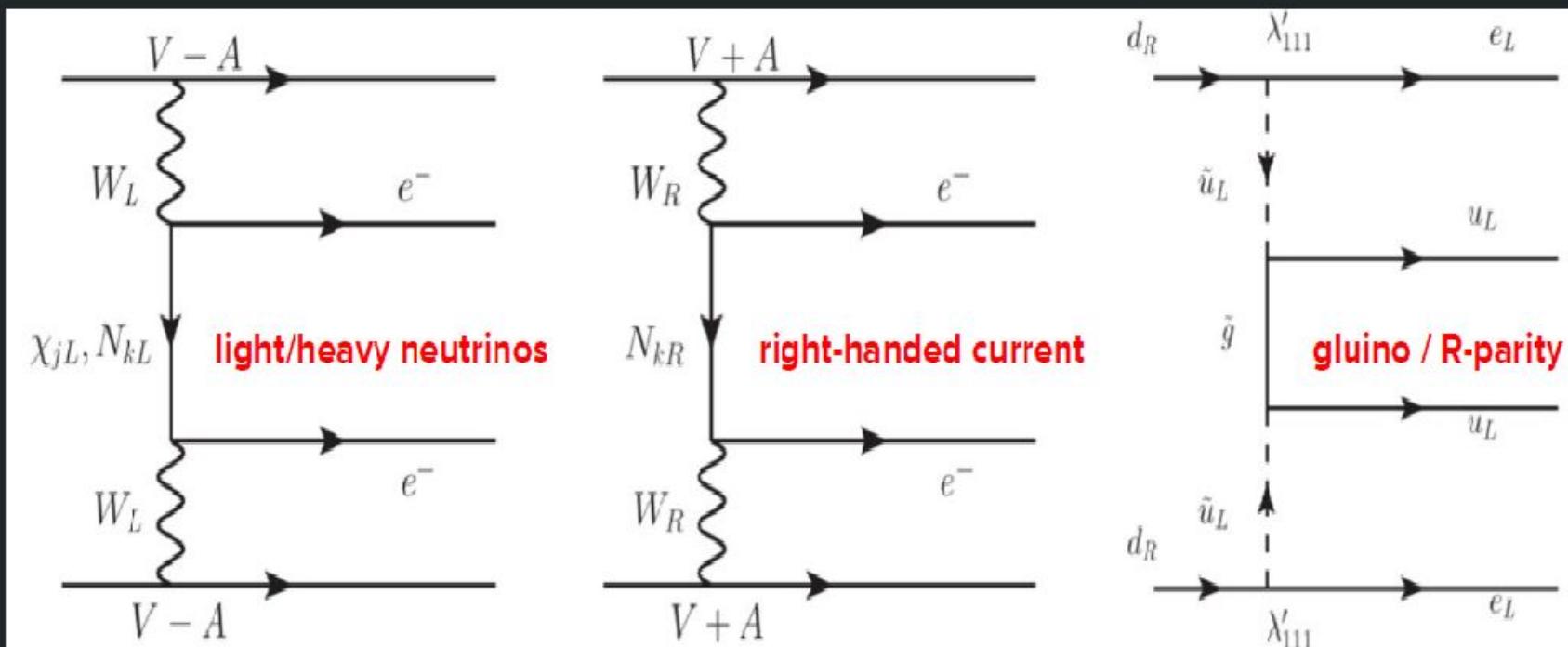
Decay probability proportional to coherent sum of involved mechanisms:

$$\Gamma = \frac{1}{T_{1/2}} = \left| \sum_i \sqrt{G_i} \times g_i^2 \times \mathcal{M}_i \times \eta_i \right|^2$$

Phase Space Factor

Hadronic coupling

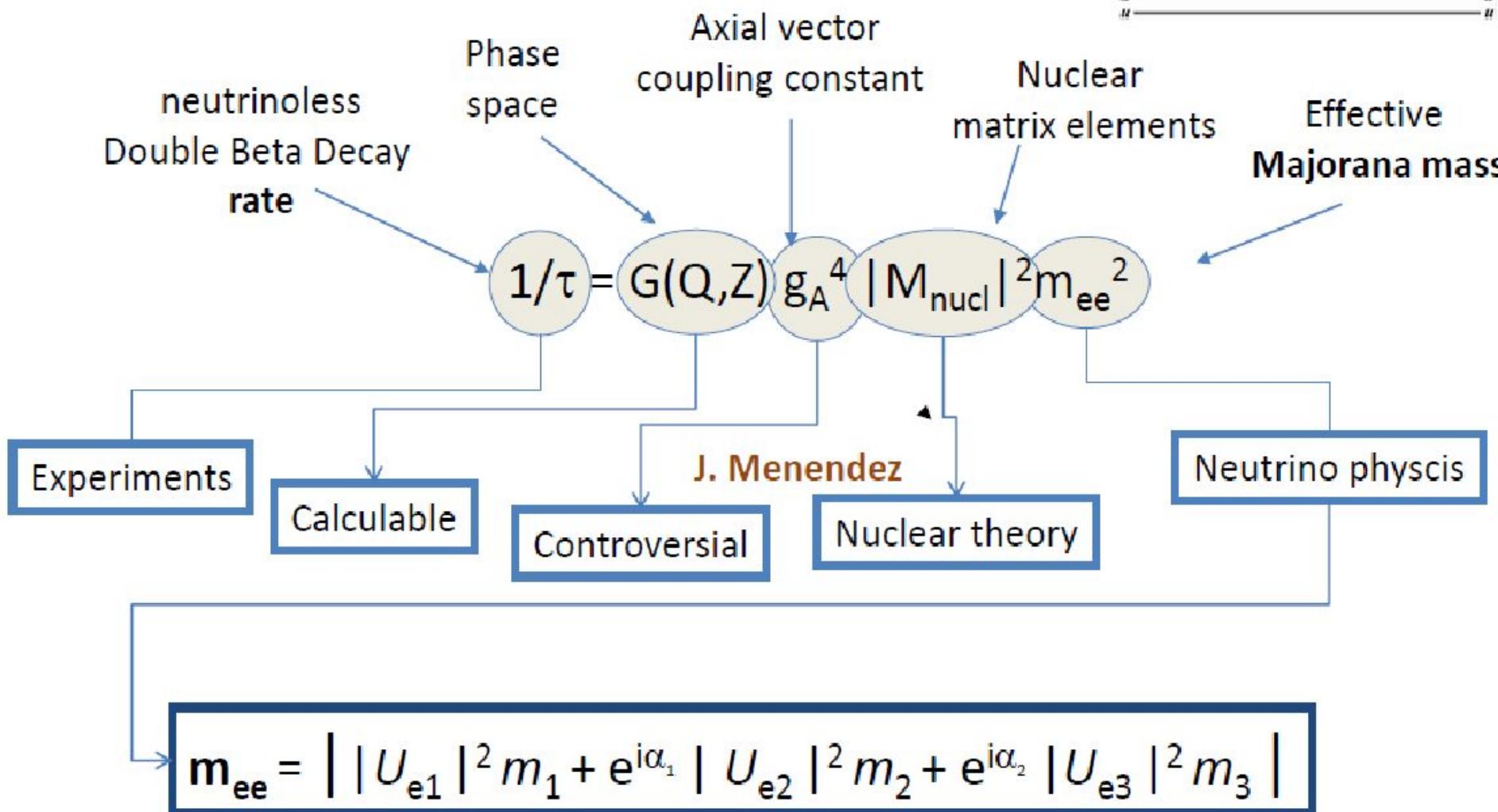
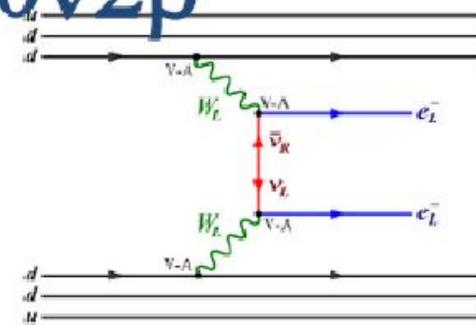
Nuclear Physics



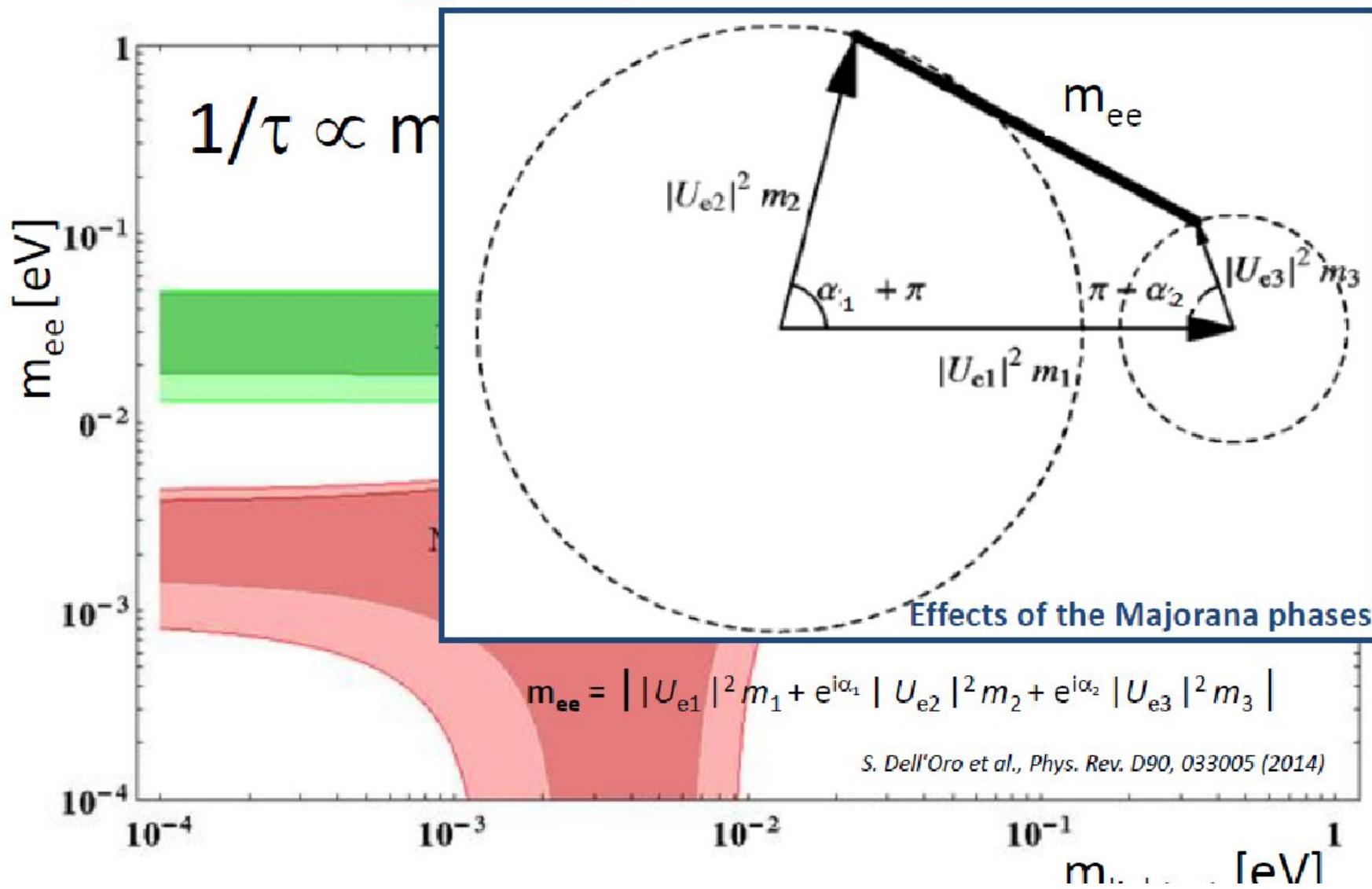
[Faessler et al, PRD, 83, 11 (2011), 113003]

# Standard mechanism for $0\nu2\beta$

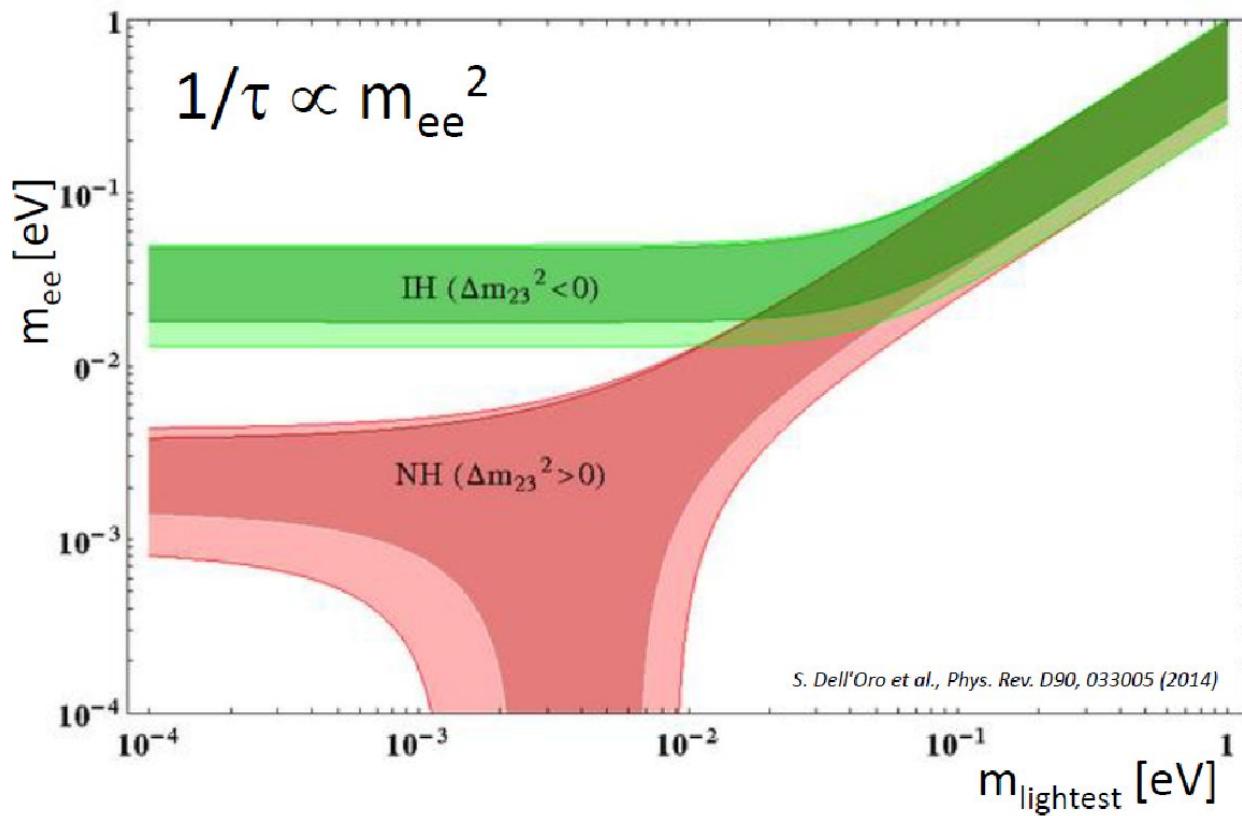
How  **$0\nu$ -DBD** is connected to **neutrino mixing matrix** and **masses** in case of process induced by light  $\nu$  exchange (**mass mechanism**).



## $m_{ee}$ vs. lightest $\nu$ mass



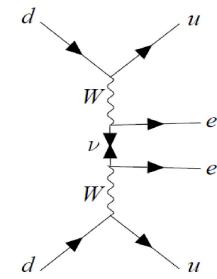
## $m_{ee}$ vs. lightest $\nu$ mass



## Effects of a quenched $g_A$ on NMEs of $0\nu$ decays:

$$\left[ T_{1/2}^{(0\nu)} \right]^{-1} = (g_{A,0\nu})^4 G^{(0\nu)} |M^{(0\nu)}|^2 \left( \frac{\langle m_\nu \rangle}{m_e} \right)^2$$

$$M^{(0\nu)} = M_{\text{GT}}^{(0\nu)} - \left( \frac{g_V}{g_{A,0\nu}} \right)^2 M_{\text{F}}^{(0\nu)} + M_{\text{T}}^{(0\nu)}$$



### Example: $0\nu\beta\beta$ NMEs of $^{76}\text{Ge}$ , effect on the half-life

Quenching:

$$\eta = g_A / g_A^{\text{free}}$$

Free value of  $g_A$  (Particle Data Group 2016) from the decay of free neutron:

$$g_A^{\text{free}} = 1.2723(23)$$

Effective value of  $g_A$ :

$$g_A^{\text{eff}} = \eta g_A^{\text{free}}$$

Mass range	$A = 76 - 82$	$A = 100 - 116$	$A = 122 - 136$
$g_{A,0\nu}^{\text{eff}}$	0.7 – 0.9	0.5	0.5 – 0.7

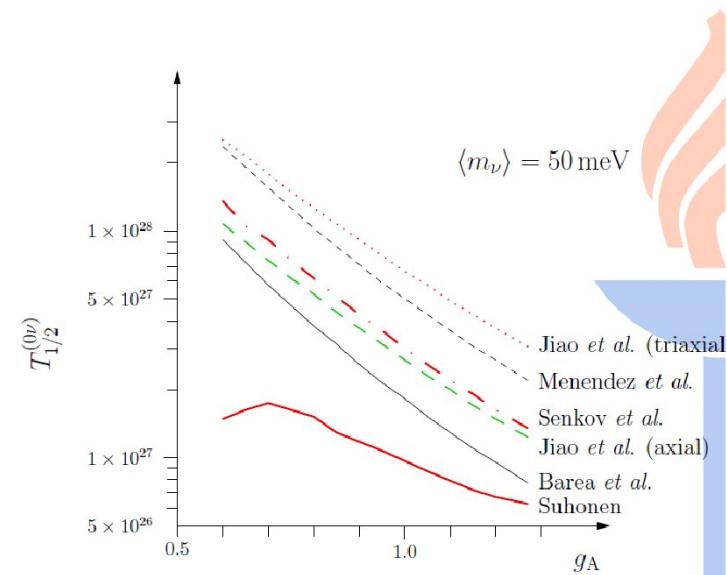
- Jiao *et al.*: Phys. Rev. C 96 (2017) 054310  
(GCM+ISM)

- Menendez *et al.*: Nucl. Phys. A 818 (2009) 139  
(ISM)

- Senkov *et al.*: Phys. Rev. C 93 (2016) 044334  
(ISM)

- Barea *et al.*: Phys. Rev. C 91 (2015) 034304 (IBM-2)

- Suhonen: Phys. Rev. C 96 (2017) 055501 (pnQRPA + isospin restoration + data on  $2\nu\beta\beta$ )



# Neutrino Mass Ordering From Oscillations and Beyond: 2018 Status and Future Prospects

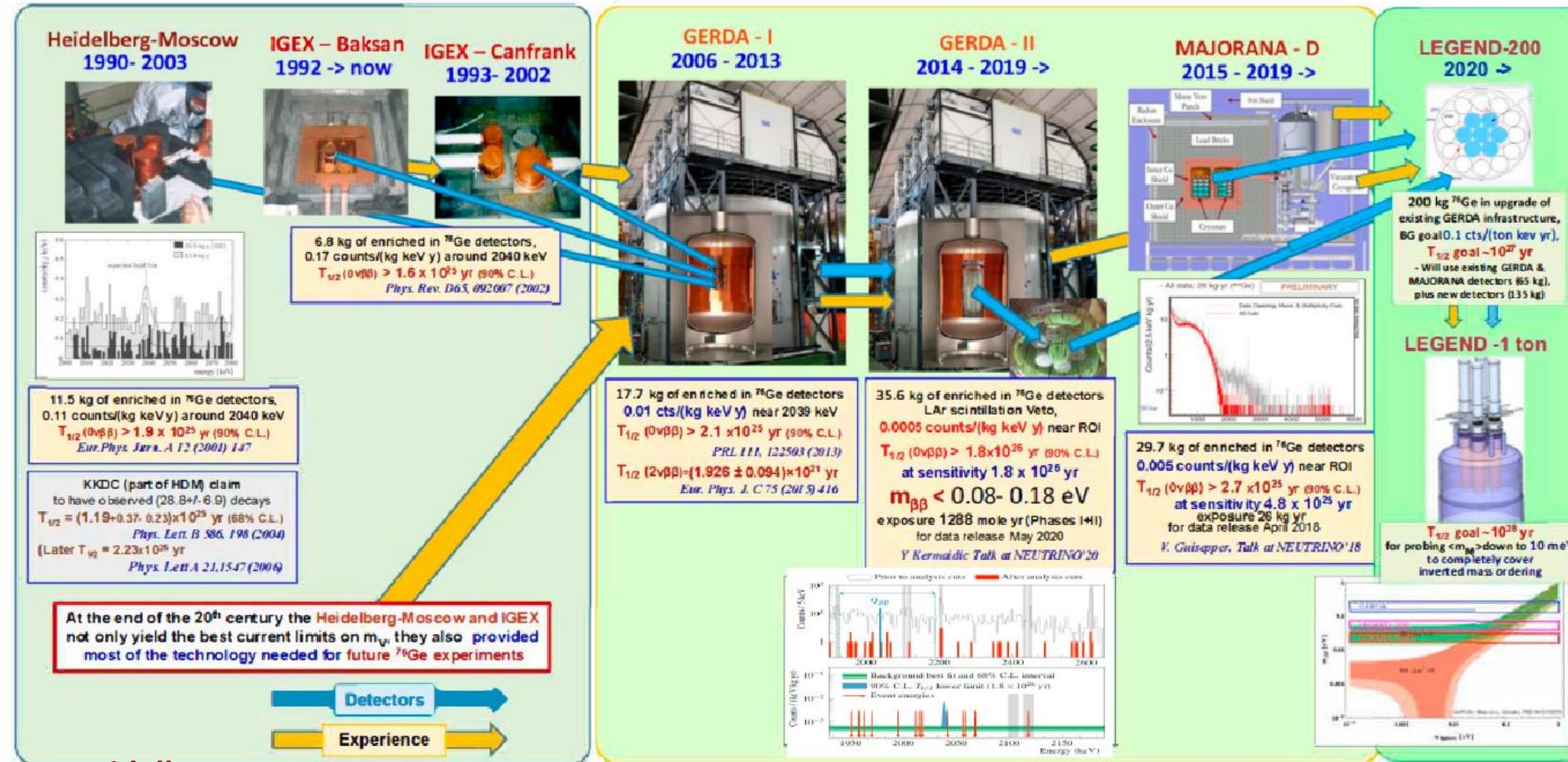
Pablo F. de Salas, Stefano Gariazzo, Olga Mena\*, Christoph A. Ternes and Mariam Tórtola

*Frontiers in Astronomy and Space Sciences* | October 2018 | Volume 5 | Article 36 /  
published: 09 October 2018 doi: 10.3389/fspas.2018.00036

Global fit: the Bayesian analysis to the 2018 publicly available oscillation and cosmological data sets

provides strong evidence for the normal neutrino mass ordering vs. the inverted scenario, with a significance of 3.5 standard deviations.

In order to exclude the inverted ordering allowed range for  $m_{33}$  (in case there is no sterile neutrino), one would need to constrain  $m_{33} \sim 10$  meV, which corresponds to  $T_{0v}^{1/2} \approx 1 \times 10^{28}$  year, with some dependence on the material (phase space and NME). This means that none of the current generation experiments will be able to reach the required sensitivity, and we will have to wait for next generation upgrades and new projects.



## Heidelberg-Moscow 1990- 2003

11.5 kg of enriched in  ${}^{76}\text{Ge}$  detectors,  
0.11 counts/(kg keV y) around 2040 keV  
 $T_{1/2} (0\nu\beta\beta) > 1.9 \times 10^{25} \text{ yr (90% C.L.)}$   
*Eur.Phys. Jurn. A 12 (2001) 147*

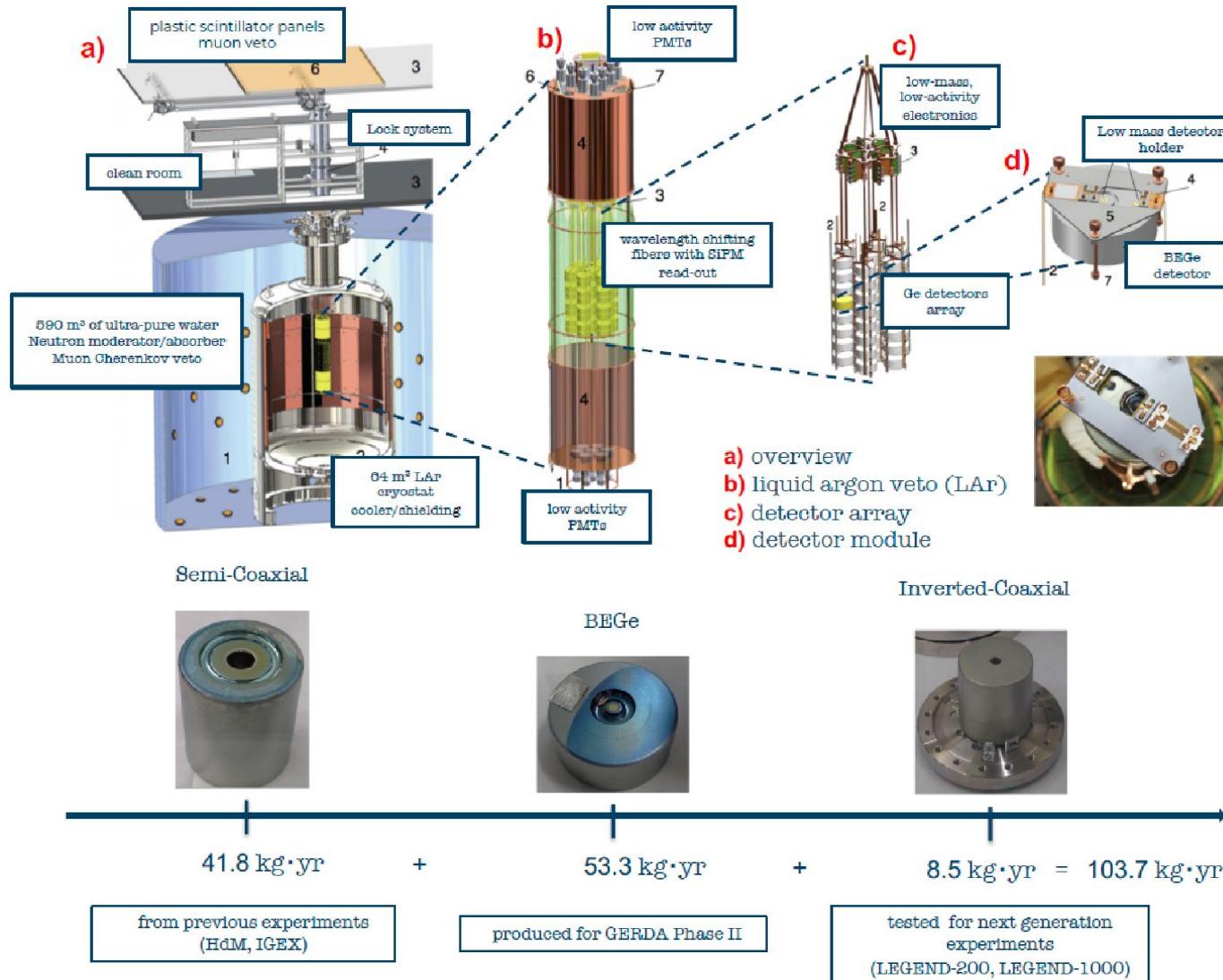
~ 20 years

35.6 kg of enriched in  ${}^{76}\text{Ge}$  detectors  
LAr scintillation Veto,  
0.0005 counts/(kg keV y) near ROI  
 $T_{1/2} (0\nu\beta\beta) > 1.8 \times 10^{26} \text{ yr (90% C.L.)}$   
 $m_{\beta\beta} < 0.08- 0.18 \text{ eV}$   
exposure 1288 mole yr (Phases I+II)  
*V. Kermanic Talk at NEUTRINO'20*

$$\left[ T_{1/2}^{(0\nu)} \right]^{-1} = (g_{A,0\nu})^4 G^{(0\nu)} |M^{(0\nu)}|^2 \left( \frac{\langle m_\nu \rangle}{m_e} \right)^2$$

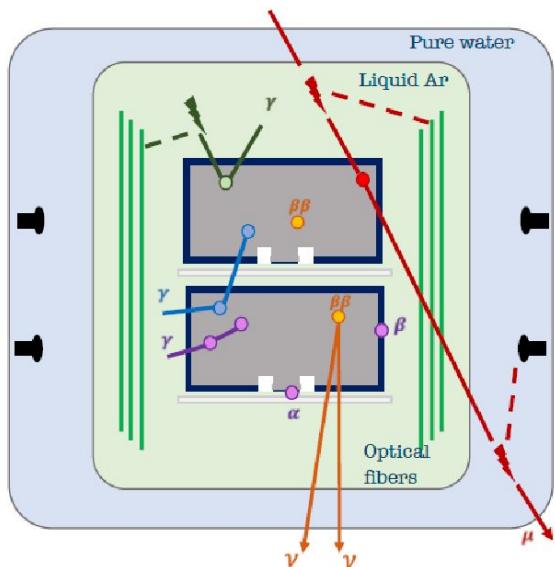
# GERDA Phase II

## GERDA Setup



# GERDA Phase II

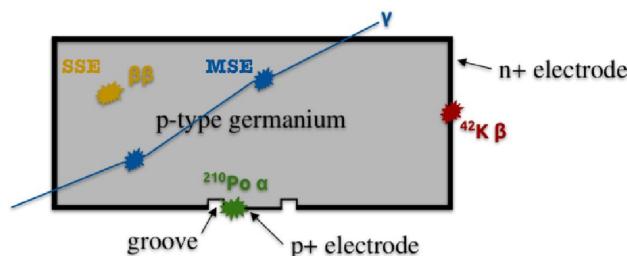
## Active Background Reduction



- Muon veto based on Cherenkov light and plastic scintillator
- LAr veto based on Ar scintillation light read by fibers and PMT
- Ge detector anti-coincidence
- Pulse shape discrimination (PSD) for multi-site and surface  $\alpha$  events

$\beta\beta$  decay signal: single energy deposition  
( $Q_{\beta\beta} = 2039$  keV) in a  $1 \text{ mm}^3$  volume

PSD: Reject multi-site and surface events based on detector signal shape

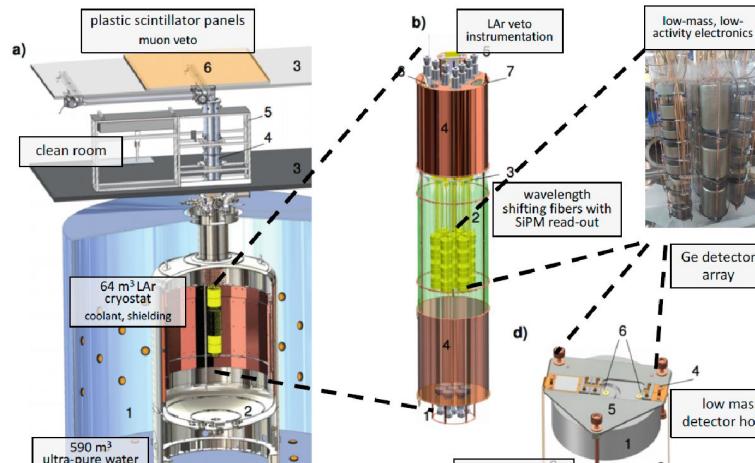


Present

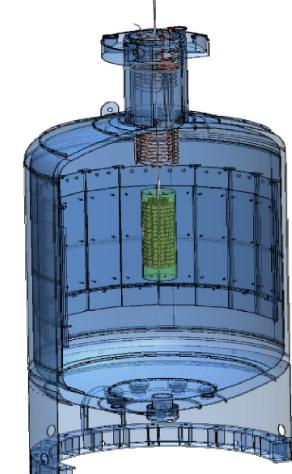
&

Future

## GERDA-II at LNGS

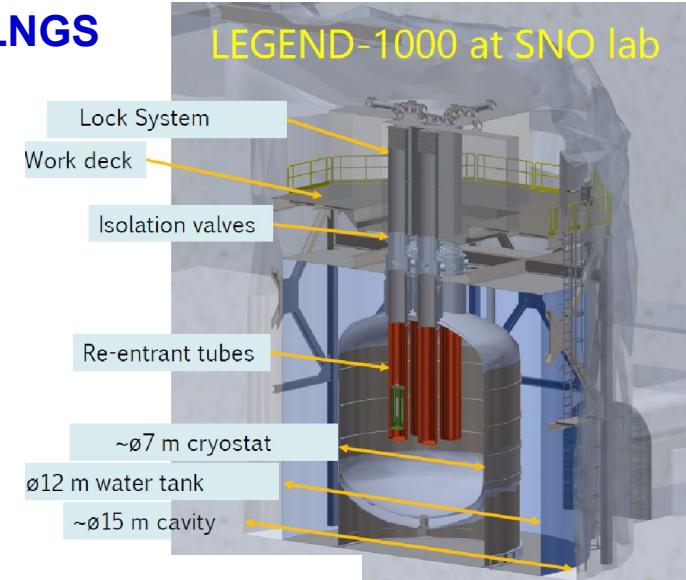


## LEGEND-200 at LNGS



$^{76}\text{Ge}$  (88% enr.)

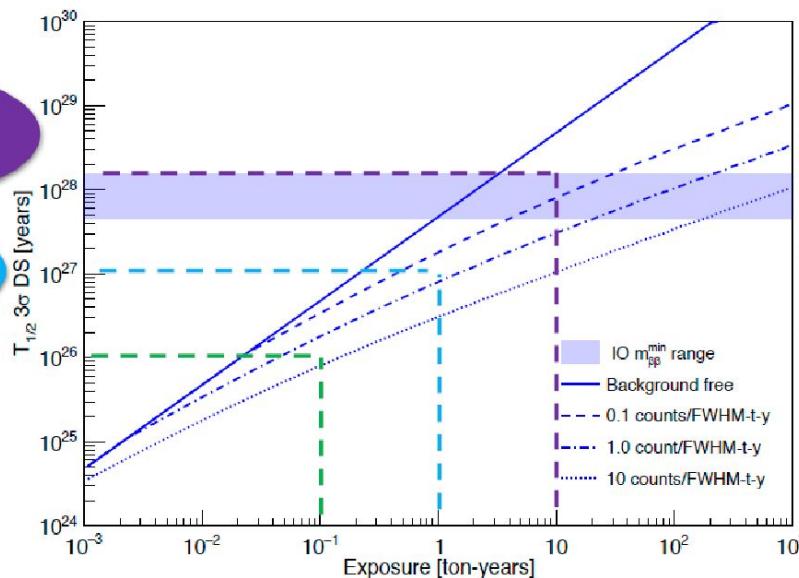
## LEGEND-1000 at SNO lab



LEGEND  
1000

LEGEND  
200

GERDA  
MAJORANA



long-term  
1 ton  
 $T_{1/2}^{0\nu} > 10^{28}$  yr

mid-term  
200 kg  
 $T_{1/2}^{0\nu} > 10^{27}$  yr

running/ended  
30 kg  
 $T_{1/2}^{0\nu} > 10^{26}$  yr

Основная цель эксперимента **GERDA (GERmanium Detector Array)** - поиск  $0\nu\beta\beta$ -распада  $^{76}\text{Ge}$ . GERDA достигла беспрецедентно низкого **фонового индекса  $5 \cdot 10^{-4}$  отсчетов / (кэВ· кг·год)** в области искомого сигнала за счет использования открытых германиевых детекторов из обогащенного  $^{76}\text{Ge}$  в активной защите из жидкого аргона. За общую экспозицию **127,2 кг·лет** искомый сигнал не наблюдается и установлен новый предел на период полураспада  **$0\nu\beta\beta$  для  $^{76}\text{Ge}: T_{1/2} > 1,8 \cdot 10^{26}$  лет.** Отличные характеристики, достигнутые в GERDA, проложили путь к эксперименту следующего поколения, подготовленному коллаборацией **LEGEND**. Эксперимент LEGEND нацелен **на увеличение чувствительности по  $T_{1/2}$  ( $0\nu\beta\beta$ ) до  $10^{28}$  лет, или по массе легкого электронного майорановского нейтрино до  $m_{\nu} < 17$  мэВ.** На первом этапе LEGEND-200 используется имеющаяся инфраструктура GERDA в лаборатории LNGS (Италия). **Начало набора данных с 200 кг  $^{76}\text{Ge}$  намечено на 2021 г.**

Несмотря на то, что поиск  $0\nu\beta\beta$  распада  $^{76}\text{Ge}$  на основной уровень дочернего ядра  $^{76}\text{Se}$  является на данный момент главной и наиболее амбициозной целью GERDA и LEGEND, широкий спектр других  $\beta\beta$ -мод и механизмов, а также ряд редких процессов, был, есть и будет исследоваться в рамках GERDA и LEGEND, обещая много новых важных результатов.

# моды $\beta\beta$ -распада и поиск других редких процессов в GERDA ( ... и LEGEND)

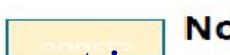
N	Process	Isotope	Exposure in Phase I $T_{1/2}$ (limit)	Exposure in Phase I+II $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	Final Exposure in GERDA (I+II) $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	$\sim$ Exposure in LEGEND-200 $\sim T_{1/2}$ (sensitivity)
1	$0\nu\beta\beta_{LMN, \dots}$ $0^+_{g.s.} \rightarrow 0^+_{g.s.}$	Ge-76	$21.6 \text{ kg}\cdot\text{yr}$ $> 2.1 \cdot 10^{25} \text{ yr}$	$82.4 \text{ kg}\cdot\text{yr}$ $> 0.9 \cdot 10^{26} \text{ yr}$ $> 1.1 \cdot 10^{26} \text{ yr}$	$127.2 \text{ kg}\cdot\text{yr}$ $> 1.8 \cdot 10^{26} \text{ yr}$ $S \sim 1.8 \cdot 10^{26} \text{ yr}$	$200 \text{ kg} \times 5 \text{ yr}$ $S \sim 1 \cdot 10^{27} \text{ yr}$
2	$2\nu\beta\beta$ $0^+_{g.s.} \rightarrow 0^+_{g.s.}$	Ge-76	$17.9 \text{ kg}\cdot\text{yr}$ $= (1.926 \pm 0.094) \cdot 10^{21} \text{ yr}$	—	$= (1.9.. \pm 0.03) \cdot 10^{21} \text{ yr}$	$= (1.9.. \pm 0.01) \cdot 10^{21} \text{ yr}$
3 3a 3b 3c	$2\nu\beta\beta$ $0^+_{g.s.} \rightarrow 2^+_1$ $0^+_{g.s.} \rightarrow 0^+_1$ $0^+_{g.s.} \rightarrow 2^+_2$	Ge-76	$22.3 \text{ kg}\cdot\text{yr}$ $> 1.6 \cdot 10^{23} \text{ yr}$ $> 3.7 \cdot 10^{23} \text{ yr}$ $> 2.3 \cdot 10^{23} \text{ yr}$	$> 5.3 \cdot 10^{23} \text{ yr}$ $> 3.3 \cdot 10^{23} \text{ yr}$ $> 2.7 \cdot 10^{23} \text{ yr}$	$S \sim 1.2 \cdot 10^{24} \text{ yr}$ $S \sim 1.1 \cdot 10^{24} \text{ yr}$	— +
4 4a 4b 4c	$0\nu\beta\beta$ $0^+_{g.s.} \rightarrow 2^+_1$ $0^+_{g.s.} \rightarrow 0^+_1$ $0^+_{g.s.} \rightarrow 2^+_2$	Ge-76		$> 5.5 \times 10^{24} \text{ yr}$ $> 1.9 \times 10^{25} \text{ yr}$	$S \sim 8 \times 10^{24} \text{ yr}$ $S \sim 3 \times 10^{25} \text{ yr}$	— +
5 5a 5b 5c 5d	$0\nu\beta\beta_X$ $n = 1$ $n = 2$ $n = 3$ $n = 7$	Ge-76	$20.3 \text{ kg}\cdot\text{yr}$ $> 4.2 \cdot 10^{23} \text{ yr}$ $> 1.8 \cdot 10^{23} \text{ yr}$ $> 0.8 \cdot 10^{23} \text{ yr}$ $> 0.3 \cdot 10^{23} \text{ yr}$	$30.8 \text{ kg}\cdot\text{yr (BEGe)}$ $> 1 \cdot 10^{24} \text{ yr}$ $> 4 \cdot 10^{23} \text{ yr}$ $> 2 \cdot 10^{23} \text{ yr}$ $> 0.7 \cdot 10^{23} \text{ yr}$	$S \sim 2 \cdot 10^{24} \text{ yr}$ $S \sim 8 \cdot 10^{23} \text{ yr}$ $S \sim 5 \cdot 10^{23} \text{ yr}$ $S \sim 2 \cdot 10^{23} \text{ yr}$	+ +
6	$0\nu\beta\beta LV$	Ge-76		$30.8 \text{ kg}\cdot\text{yr (BEGe)}$ $> 1.0 \cdot 10^{24} \text{ yr}$	$S \sim 2 \cdot 10^{24} \text{ yr}$	+ +

All at 90% C.L.

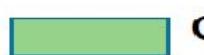


Standard  $\beta\beta$

$0\nu\beta\beta_{LMN}$  - light Majorana neutrino mechanism



Non-standard  $\beta\beta$



Other processes

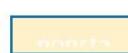
Продолжение Таблицы

N	Process	Isotope	Exposure in Phase I $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	Exposure in Phase I+II $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	Final Exposure in GERDA (I+ II) $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	~Exposure in LEGEND-200 ~ $T_{1/2}$ (sensitivity)
7	0νECEC	$^{36}\text{Ar}$	$> 3.6 \cdot 10^{21} \text{ yr}$	-	$S \sim 1 \cdot 10^{22} \text{ yr}$	++
8	Tri-nucleon decay $\text{ppp} \rightarrow$ $\text{ppn} \rightarrow$ $\text{pnn} \rightarrow$ $\text{nnn} \rightarrow$	Ge-76	-	$> 7.1 \cdot 10^{25} \text{ yr}$ $> 7.4 \cdot 10^{25} \text{ yr}$ $> 7.7 \cdot 10^{25} \text{ yr}$ $> 3.4 \cdot 10^{25} \text{ yr}$	$> 2.29 \cdot 10^{26} \text{ yr}$ $> 2.33 \cdot 10^{26} \text{ yr}$ $> 2.44 \cdot 10^{26} \text{ yr}$ $> 1.42 \cdot 10^{26} \text{ yr}$	++
9	Super-WIMPs axion-like dark photons	Ge-76	-	at $M = 150 \text{ keV}/c^2$ $g_{ae} < 3 \times 10^{-12}$ $\alpha'/\alpha < 6.5 \times 10^{-24}$	-	++
10	Others...					++

All at 90% C.L.



Standard  $\beta\beta$



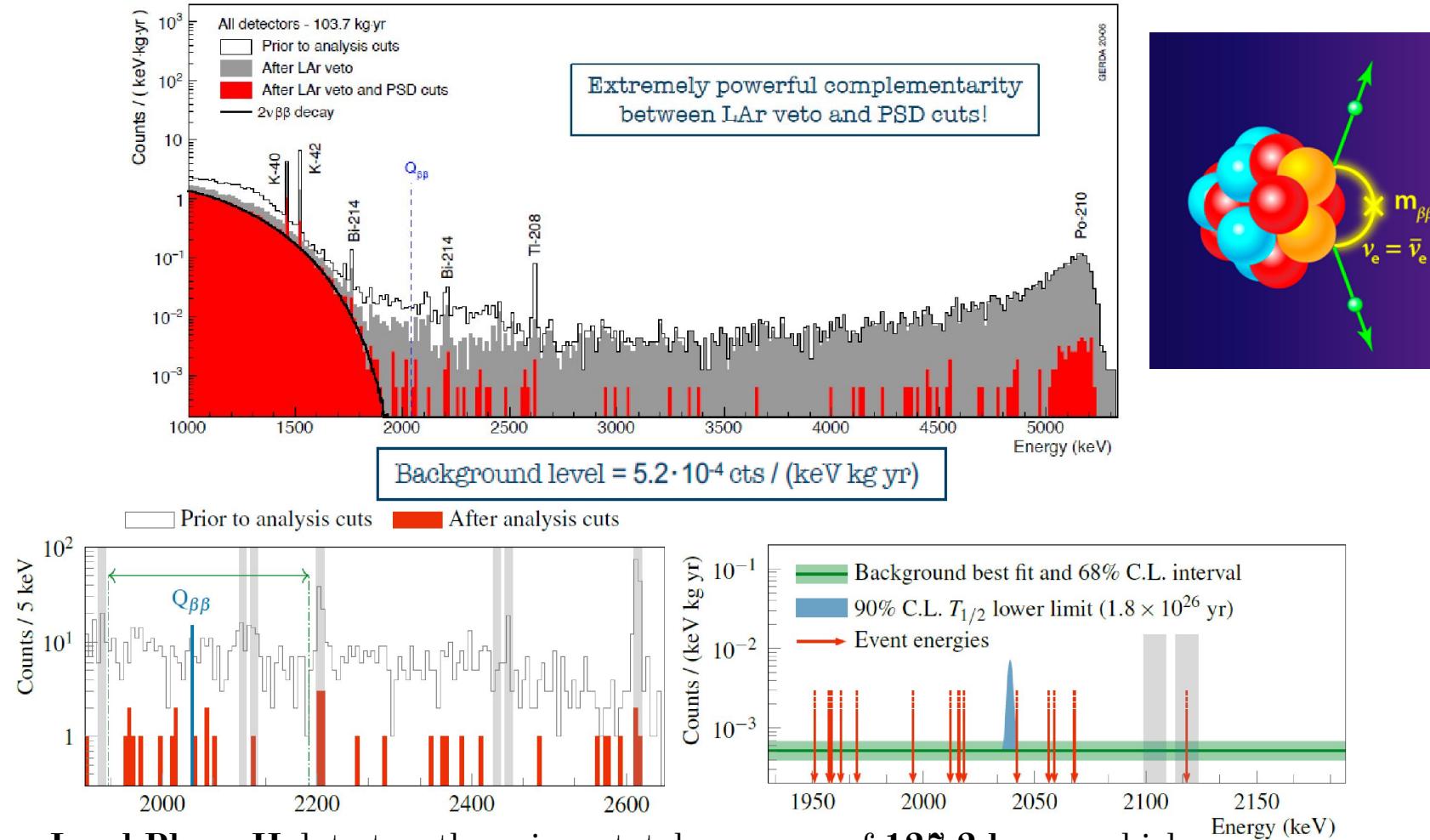
Non-standard  $\beta\beta$



Other processes

For more details see: A.A.Smolnikov, GERDA Searches for 0νββ and other ββ Decay Modes of 76Ge,  
AIP Conference Proceedings, 2165, 020024, 1-4, 2019

# Final Results of GERDA on the Search for $0\nu\beta\beta$ decay of $^{76}\text{Ge}$



**Phase I and Phase II** data together give a total exposure of **127.2 kg yr**, which corresponds to **1288 mol yr** of  **$^{76}\text{Ge}$** . The combined analysis has a best fit for null signal strength, and provides a half-life limit of

$$T_{1/2} > 1.8 \times 10^{26} \text{ yr at 90% C.L.}$$

arXiv:2009.06079v1 [nucl-ex] 13 Sep 2020  
submitted to PRL



## Half-life of $2\nu\beta\beta$ decay of $^{76}\text{Ge}$

From Phase I

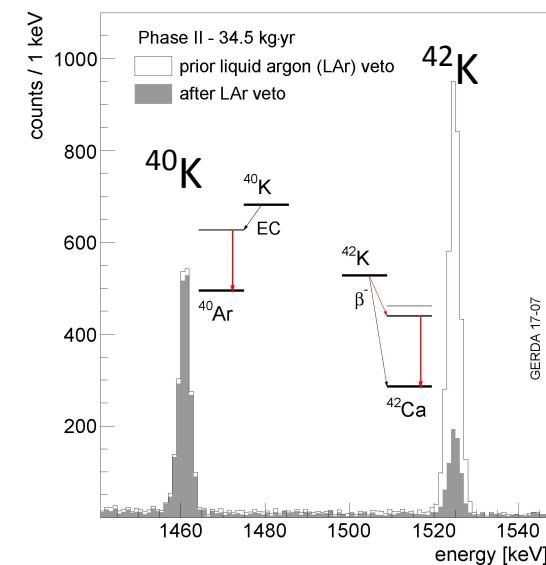
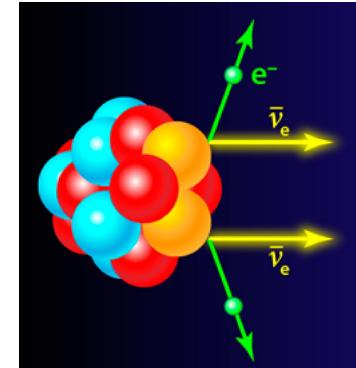
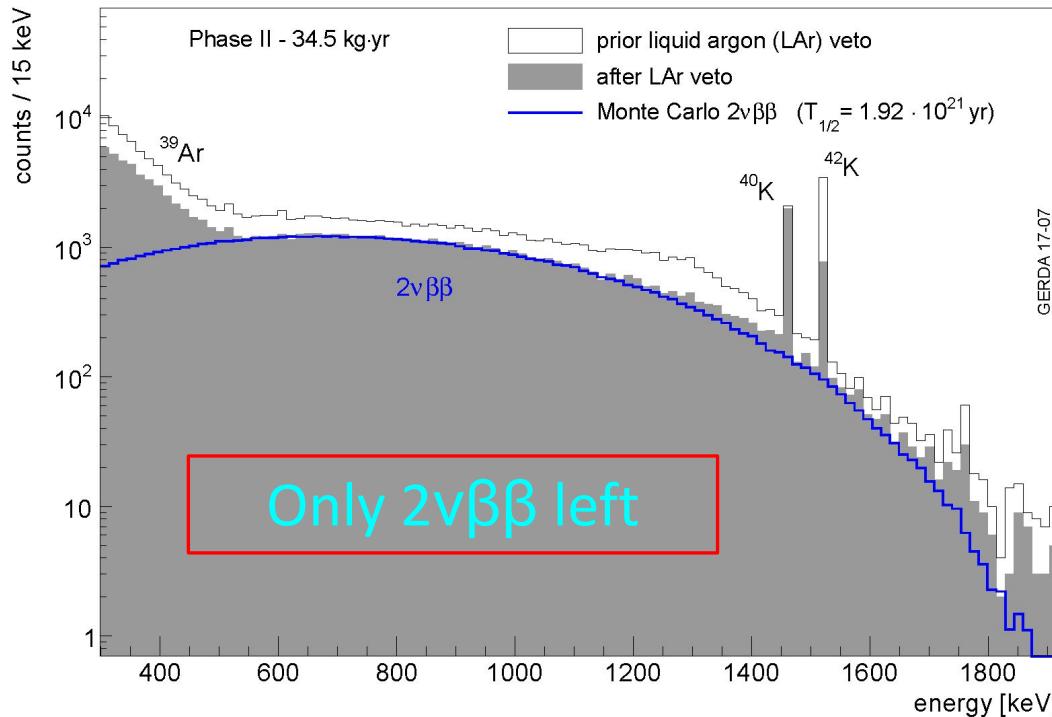
$$(1.926 \pm 0.094) \cdot 10^{21}$$

yr

Phase II

$$(2.03 \pm 0.02) \cdot 10^{21} \text{ yr}$$

After LAr Veto performance



Survival fraction between 0.6 and 1.3 MeV:

$$(68.6 \pm 0.3)\%$$

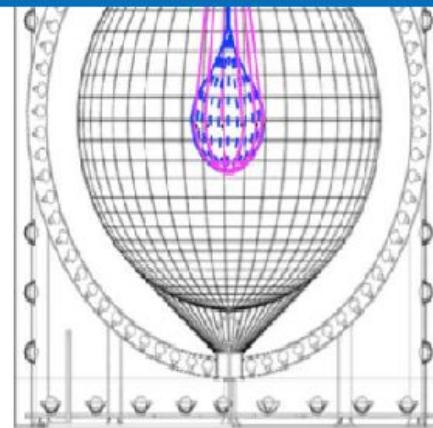
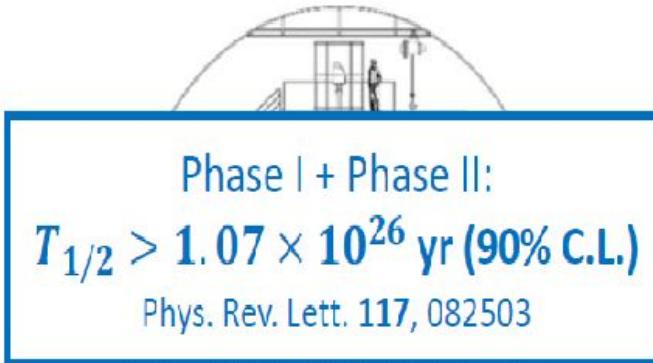
$T_{1/2}(2\nu 2\beta)$  fixed as  $2.03 \cdot 10^{21} \text{ yr}$

$^{40}\text{K}$  and  $^{42}\text{K}$  continua  
strongly suppressed

## $0\nu\beta\beta$ with liquid scintillators

## KamLAND-Zen

### Past



KamLAND-Zen 400

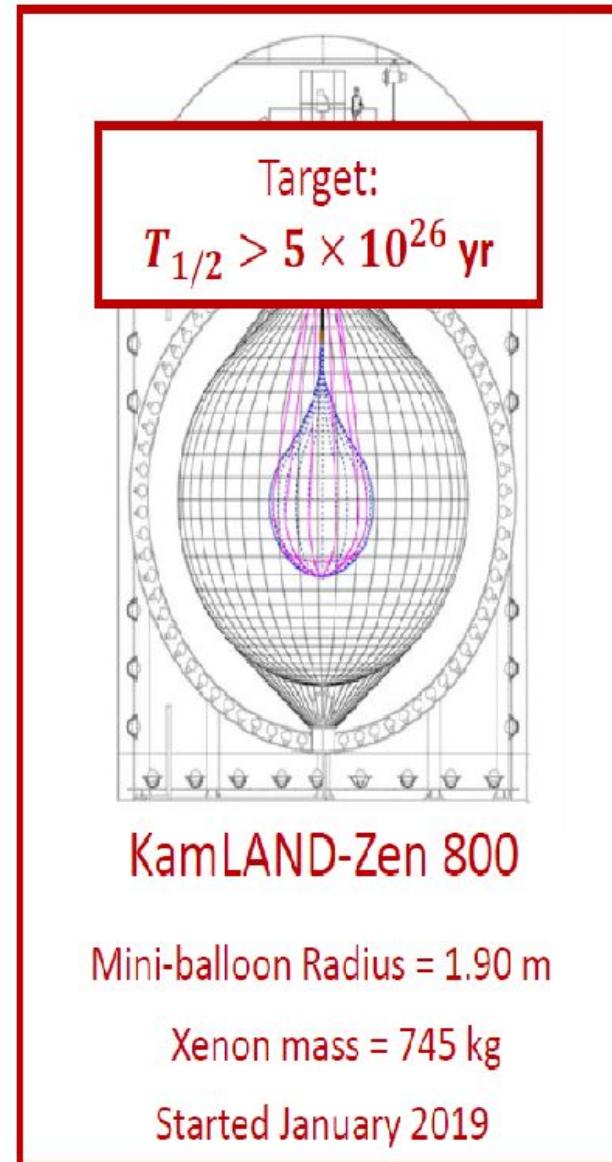
Mini-balloon Radius = 1.54 m

Xenon mass = 320 ~ 380 kg

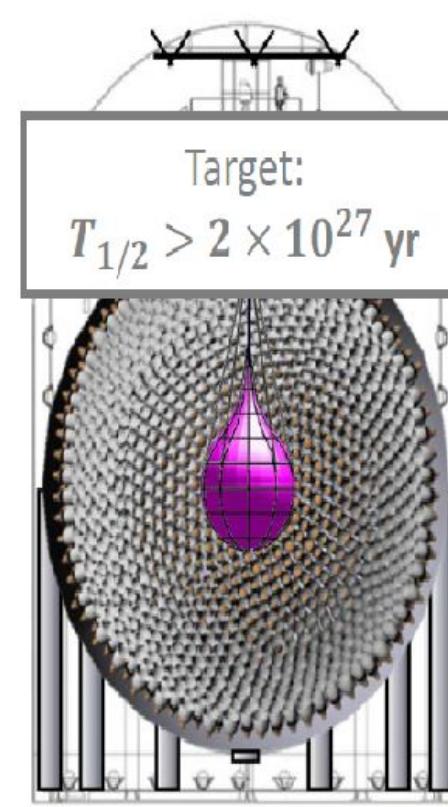
К. Гусев

2011 ~ 2015

### Current



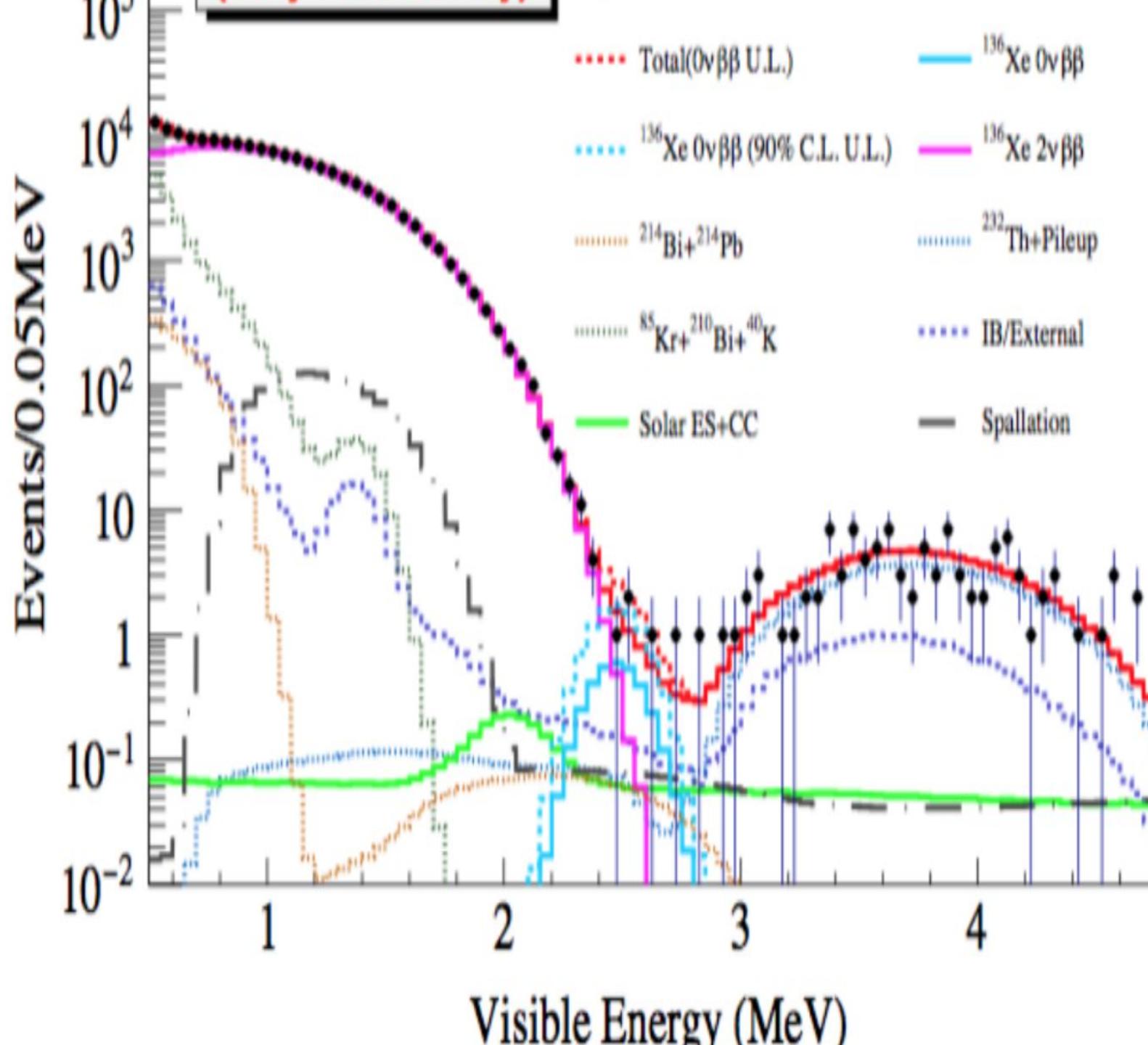
### Future



Xenon mass ~ 1 ton

× 5 increase in light collection

Scintillation balloon film



# SNO+ D=12 m Te-130 = 0.5% in LSTe

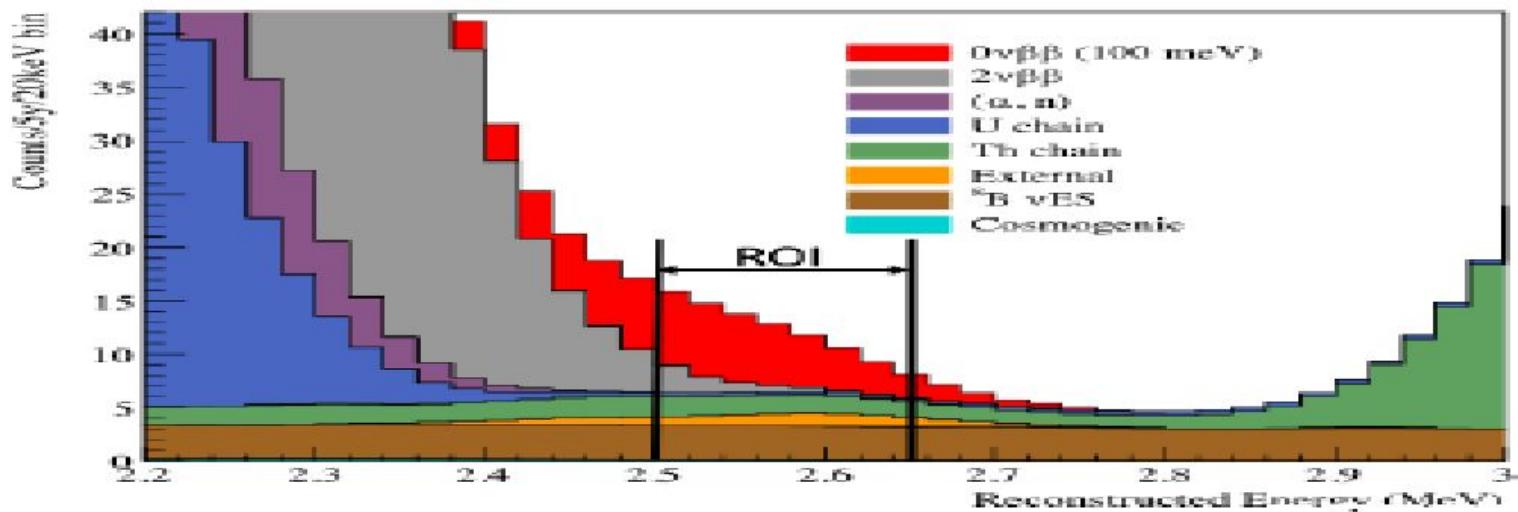


Figure 3: Energy spectrum of  $0\nu\beta\beta$  signal (red) and background[6]  
Region of interest: 2.49 - 2.65 MeV

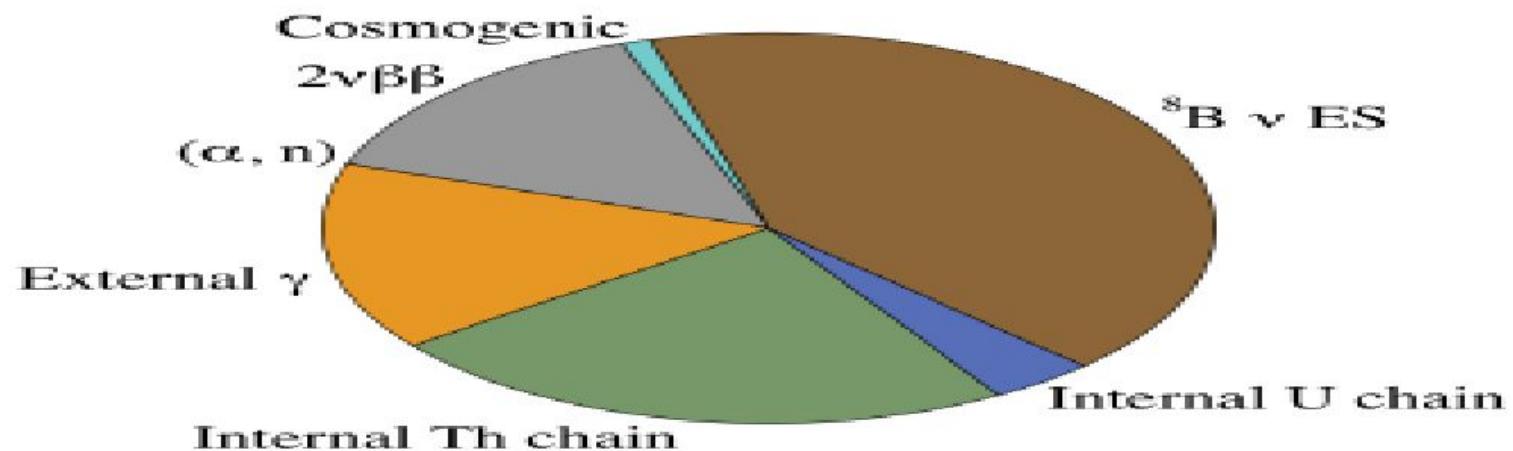
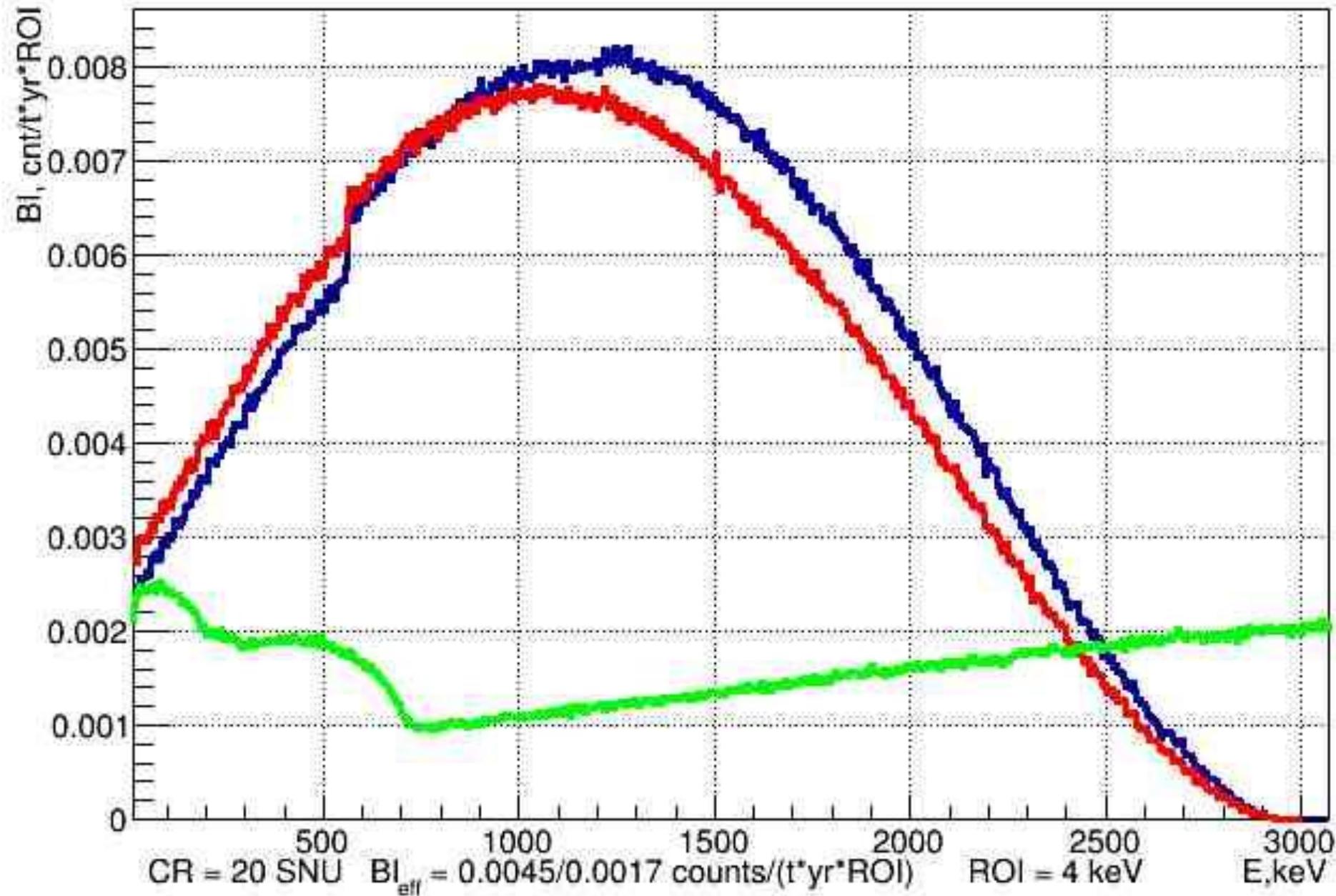
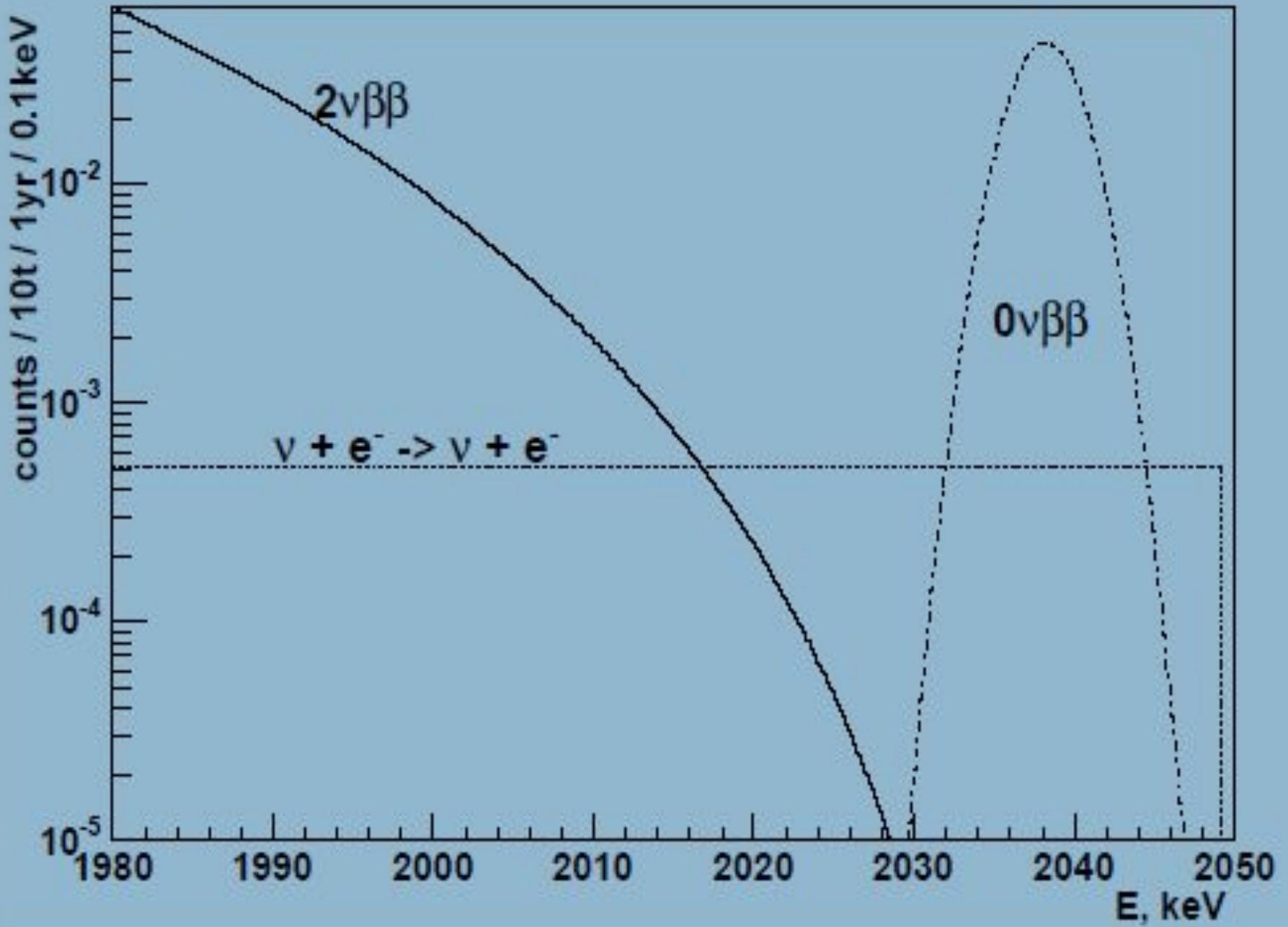


Figure 4: Background counts within ROI in first year of data taking[6]  
Total counts: 12.4

single Coax / BEGe / electrons [blue/red/green]

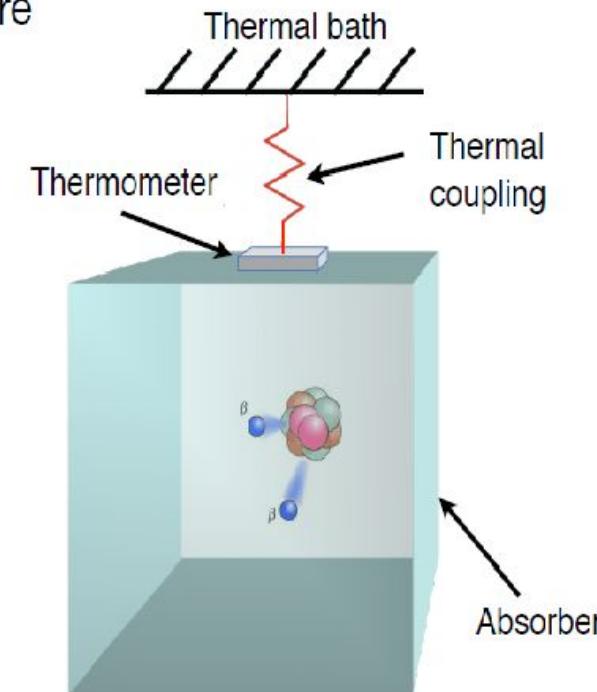
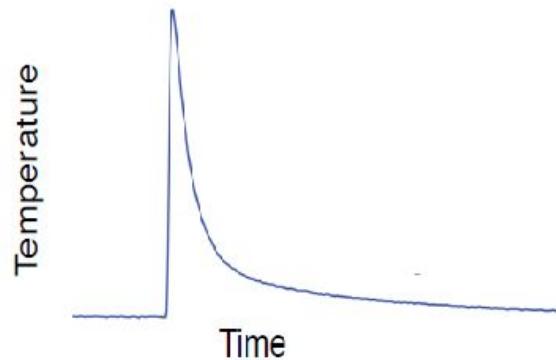
$^{76}\text{Ge}(\nu, e)^{76}\text{As}$





# Macro Bolometer Technique

- The absorbed energy causes an increase in absorber temperature
- Use temperature change to measure energy absorbed

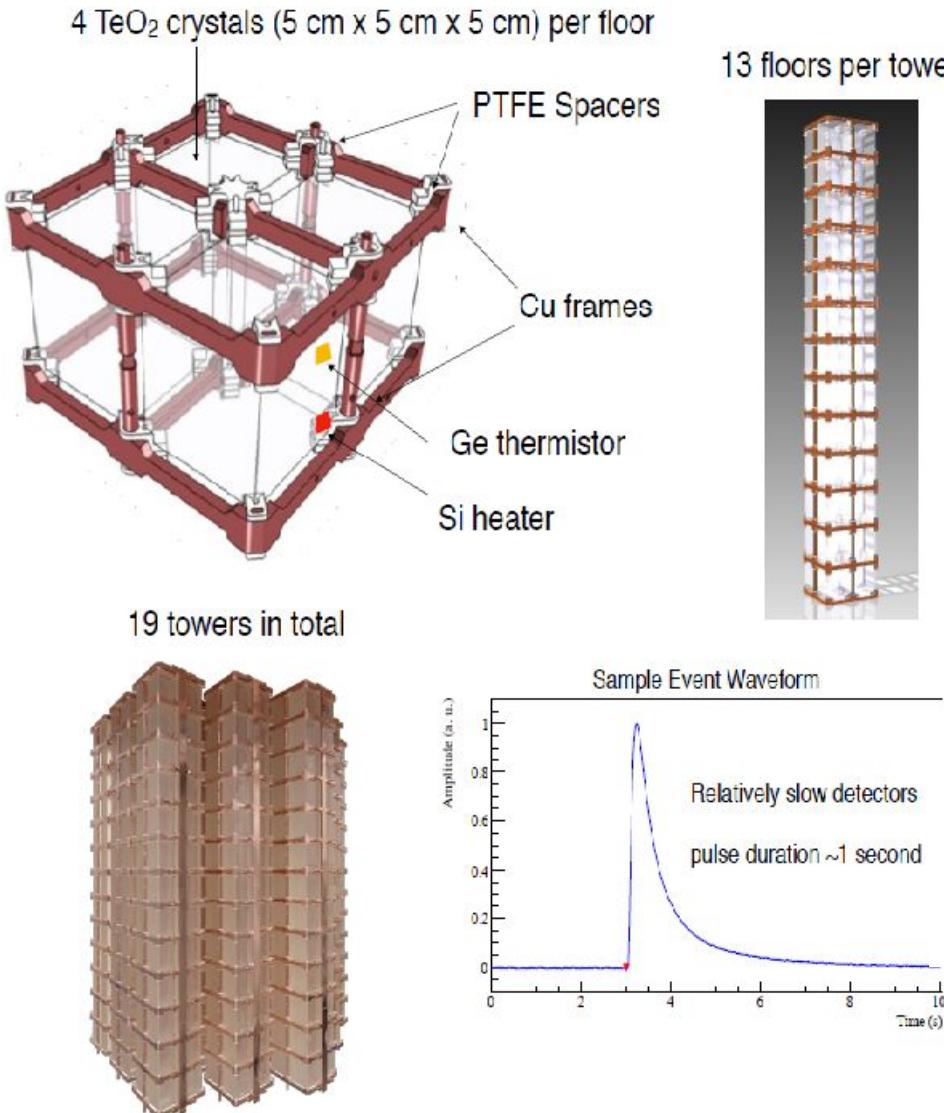


- For dielectric crystal absorbers, heat capacity  $\sim T^3$
- Typically operated at  $\sim 10\text{mK}$
- Relative energy resolution of 0.2~0.3% FWHM routinely achieved

**CUORE uses  
this technique**

# CUORE

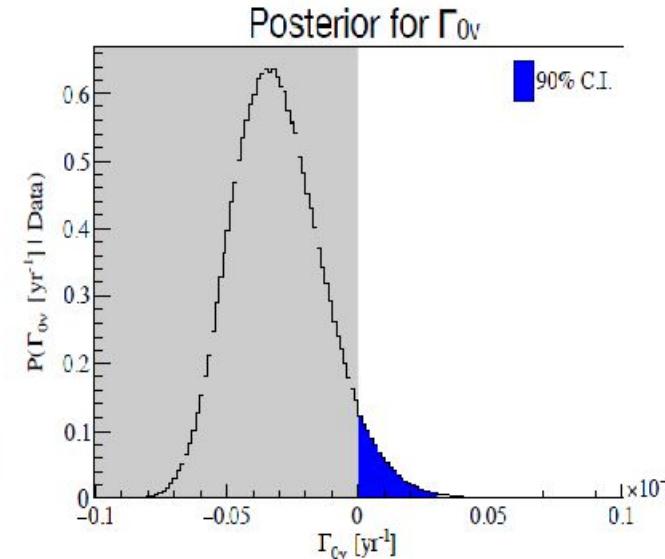
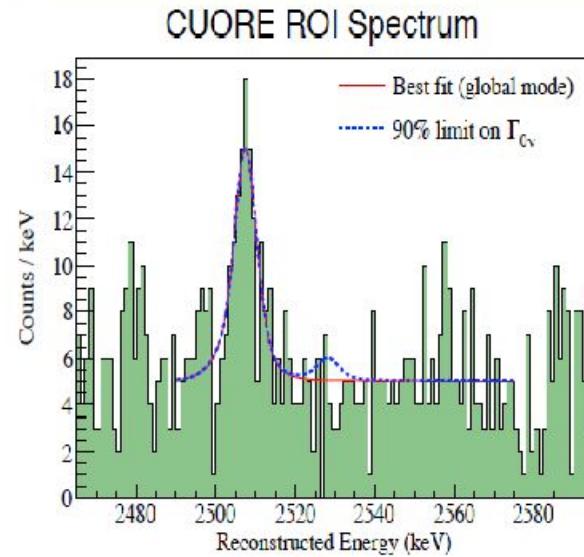
Cryogenic Underground Observatory for Rare Events



- Hosted at Gran Sasso Underground Lab
- Close-packed array of 988 <sup>nat</sup>TeO<sub>2</sub> bolometers (Total active mass: 742 kg)
- Operated at T~11 mK
- Primary physics goal: 0νββ decay of <sup>130</sup>Te
  - ▶ Isotopic abundance 34% => 206 kg
  - ▶ Q-value: 2527.5 keV
- CUORE design goals:
  - ▶ Energy resolution: 5 keV FWHM near Q<sub>ββ</sub>
  - ▶ Background: 0.01 c/keV/kg/y near Q<sub>ββ</sub>
  - ▶ 0νββ sensitivity for 5 years of livetime:

$$T_{1/2}^{0\nu} = 9 \times 10^{25} \text{ yr}$$

# CUORE: 0νββ Search



- No evidence for 0νββ decay

$$T_{1/2}^{0\nu} > 3.2 \times 10^{25} \text{ yr (90\% C.I.)}$$

- Interpretation in context of light Majorana neutrino exchange

$$m_{\beta\beta} < 75 - 350 \text{ meV}$$

[Phys. Rev. Lett. 124, 122501 \(2020\)](#)

- Total exposure TeO<sub>2</sub>: 372.5 kg · yr
- Bayesian Analysis (BAT)
- Likelihood model: flat continuum (Bl), posited peak for 0νββ (rate), peak for <sup>60</sup>Co (rate + position)
- Unbinned fit on physical range (rates non-negative), uniform prior on  $\Gamma_{0\nu}$
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit)

See A. Campani, Poster  
#101 Session 1

## Detector Performance Parameters

### Background Index

$$(1.38 \pm 0.07) \times 10^{-2} \text{ cnts/(keV} \cdot \text{kg} \cdot \text{yr})$$

### Characteristic FWHM ΔE at Q<sub>ββ</sub>

$$7.0 \pm 0.3 \text{ keV}$$

# How to reach the few meV scale

80 000 bolometers of  $\text{TeO}_2$  (natural isotopic composition)

20 dilution refrigerators with experimental space 4 x wrt CUORE  
↳ can be hosted by an LNGS hall

Mass of each crystal: 1.3 kg (6×6×6 cm)

Efficiency: 90%

Energy resolution: 5 keV FWHM

Background index:  $b = 10^{-5}$  counts/(keV kg y) (testable in CUPID)

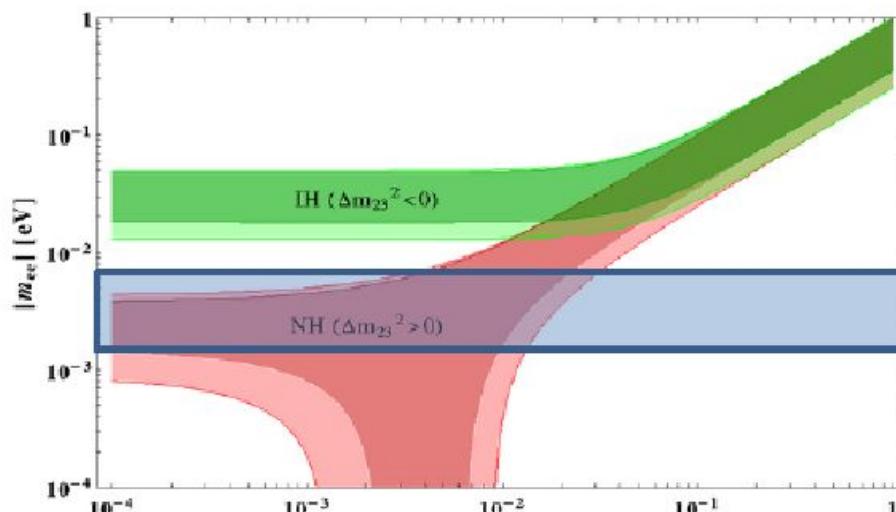
Live time: 10 y

90% sensitivity:

$T_{1/2} > 7 \times 10^{28}$  y

$m_{ee} < 1.6 - 7.5$  meV

} Already achieved



# Sensitivity

The reach of an experiment is typically characterized through

**limit setting sensitivity:**

“limit on signal strength expected assuming no signal”

**signal discovery sensitivity:**

“minimal signal strength for which a discovery is expected”

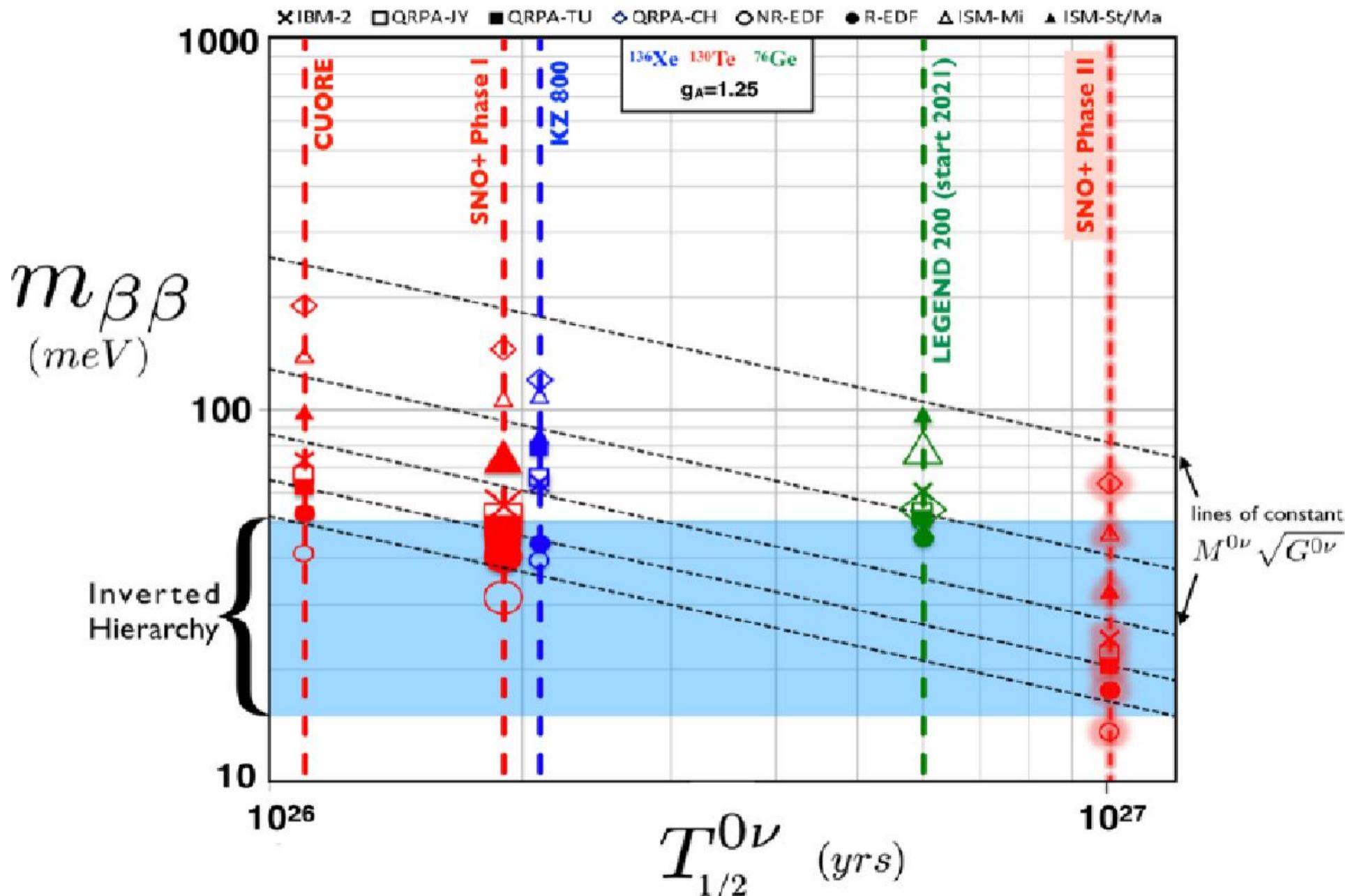
At the background level of next-gen experiments:

- Different sensitivity definitions  $\Rightarrow$  different numbers
- limit setting sensitivity has pathological behaviours

We search for a signal...

let's focus on the discovery sensitivity

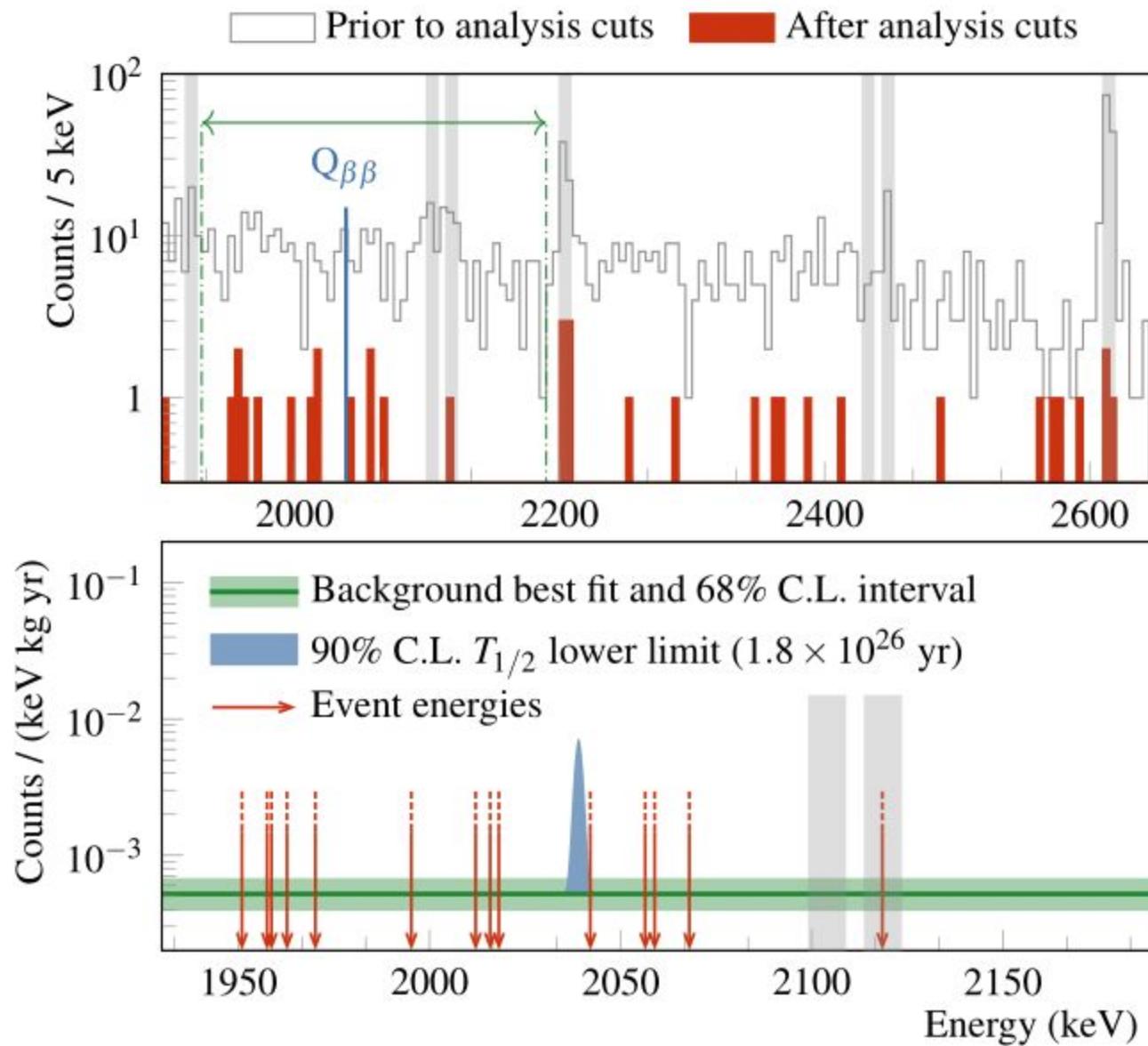
# Projected 2024 0νββ Sensitivities



**Table 1. Comparison of present and prior experiments.** Lower half-life limits  $L(T_{1/2})$  and sensitivities  $S(T_{1/2})$ , both at 90% C.L., reported by recent  $\text{Ov}\beta\beta$  decay searches with indicated deployed isotope masses  $M_i$  and FWHM energy resolutions. Sensitivities  $S(T_{1/2})$  have been converted into upper limits of effective Majorana masses  $m_{\beta\beta}$  using the nuclear matrix elements quoted in (20).

AgAgostini et al., Science 365 , 1445-1448 (2019) 27 Septembre 2019

Experiment	Isotope	$M_i$ (kmol)	FWHM (keV)	$L(T_{1/2})$ ( $10^{25}$ years)	$S(T_{1/2})$ ( $10^{25}$ years)	$m_{\beta\beta}$ (meV)
GERDA (this work)	$^{76}\text{Ge}$	0.41	3.3	9	11	104 to 228
MAJORANA (27)	$^{76}\text{Ge}$	0.34	2.5	2.7	4.8	157 to 346
CUPID-0 (28)	$^{82}\text{Se}$	0.063	23	0.24	0.23	394 to 810
CUORE (29)	$^{130}\text{Te}$	1.59	74	1.5	0.7	162 to 757
EXO-200 (30)	$^{136}\text{Xe}$	1.04	71	1.8	3.7	93 to 287
KamLAND-Zen (21)	$^{136}\text{Xe}$	2.52	270	10.7	5.6	76 to 234
Combined						66 to 155
EXPERIMENTS	ISOTOPE	M, kmol	FWHM, keV	$S(T_{1/2})$ , Yyr	$m_{\beta\beta}$ , meV	
LEGEND	Ge-76	2.29	2.9	1100	32.9 – 72.1	
GERDA	Ge-76	0.41	3.3	180	81.3 – 178.2	
CUORE	Te-130	1.59	7.0	90	44.8 – 210.9	
KamLAND Zen-800	Xe-136	4.98	270	500	25.4 – 78.2	
KLNDZen-400	Xe-136	2.52	270	56	76 - 234	
COMBINED						23.4 - 51.3



# GERDA SENSITIVITY CALCULATIONS

It was used BAT-0.9.4. mtf model: apriori ,Gauss,flat,1/sqrt(S).

- Two channels: Phasel + PhaselI
  - Phasel – 61 EVENTS; FWHM = 4.13 keV
  - PHASEII – 13 EVENTS; FWHM = 3.29 keV
- 5 channels: Golden+Silver+BEGe+Phasel+  
+ PhaselI
  - (47+9) EVENTS / 4.26 keV 3 EVENTS / 2.73
  - 2 EVENTS / 4.16 keV

# BAT SENSITIVITY

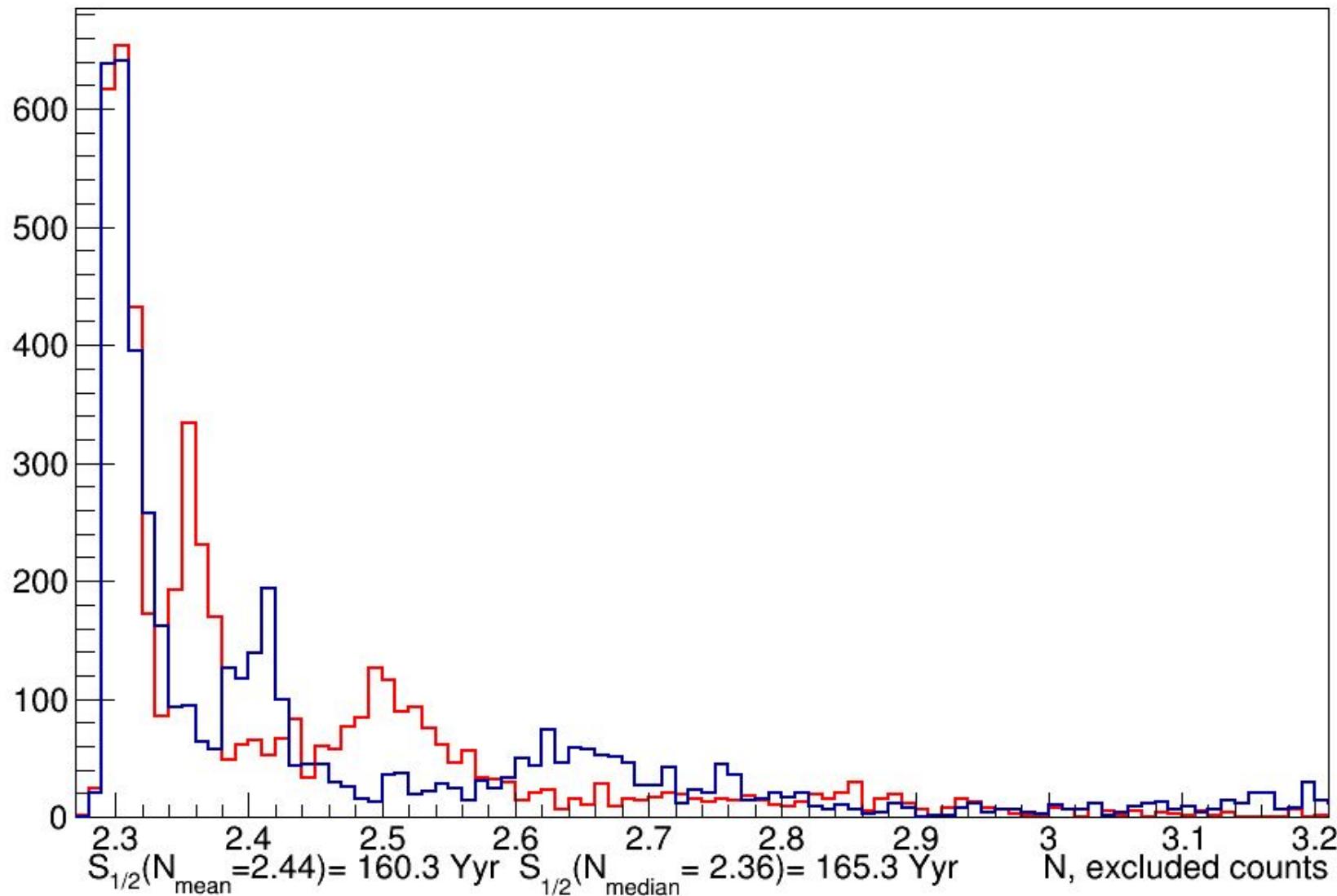
- Poissons in the energy interval 260 keV with line  
 $y = 1.417 - 5.742e-4 \cdot E$
- 0) Systematics – E, FWHM, Eff
- A) full region [ 1930,2190] keV
- B) with exclusion of effect region – [2037,2041] keV
- C) statistics – 5000 FITS

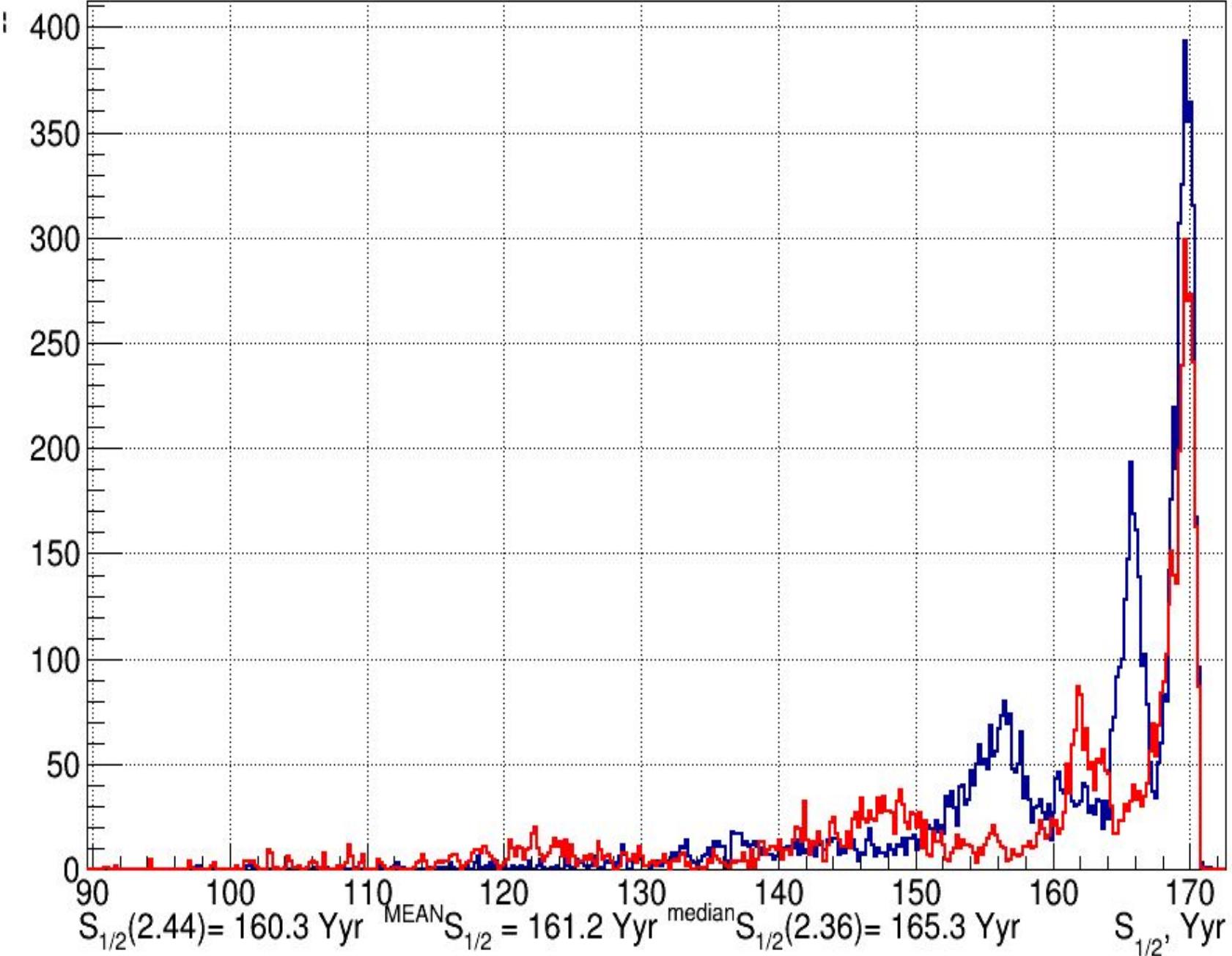
GERDA final – per ALL detectors were made 408 partitions, i.e. time intervals with stable resolution and efficiency.

SENSITIVITY = 180 Yyr.

# Blue - 2 channels Red-5 channels

$N = 5000$  BAT  $N_{\text{exl}}$  distribution





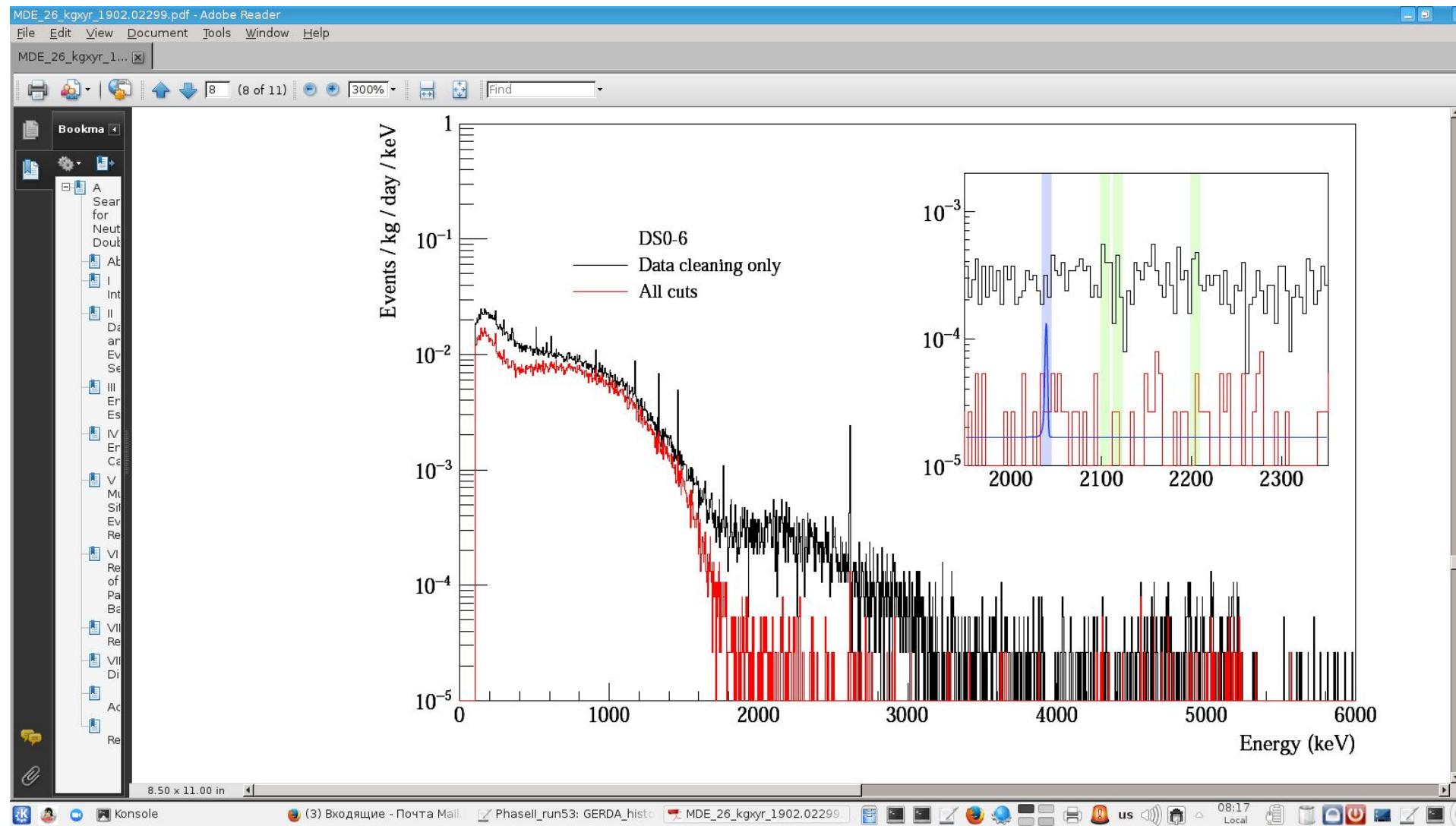
## Summary

The combined analysis of sensitivities of current searching for the  $0\nu\beta\beta$  decay experiments in active phase and some finished ones gives us for  $\langle m_{\beta\beta} \rangle$  restriction in range **23.4 – 51.3 meV**.

**GERDA BI is 2 counts / FWHM / t\*yr**

**Sensitivity -  $1.8 \times 10^{26}$  yr.**

# BACKUP SLIDES



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 en Sep 18 10:12 131.58% Zoom In Zoom Out Full Screen Close

## Effective Majorana neutrino mass and hierarchy

$|\langle m_\nu \rangle| = |\sum U_{ei}^2 m_i| = |\cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13}|$

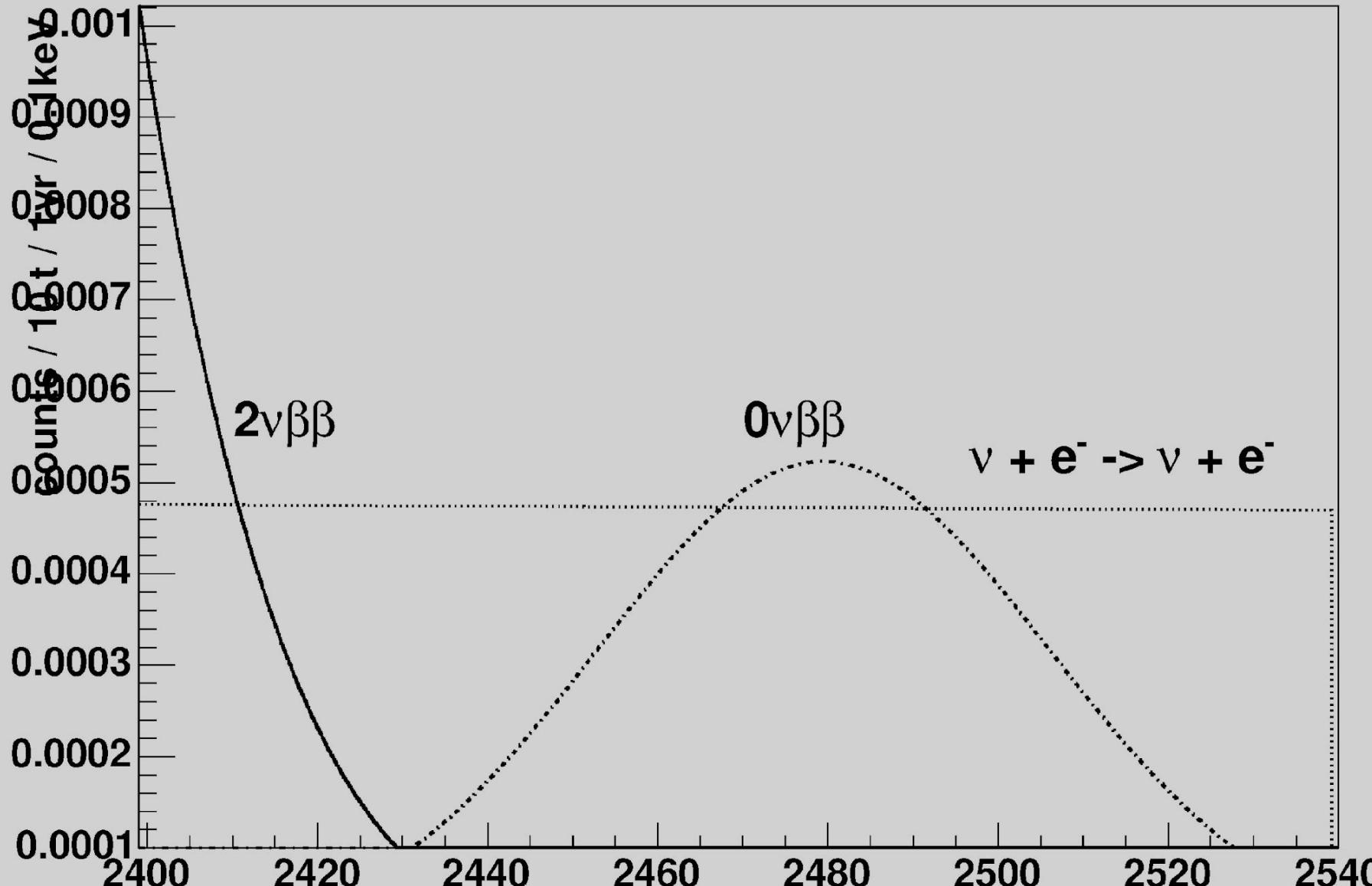
$$\langle m_{ee} \rangle^{\text{nor}} = \left| m_1 c_{12}^2 c_{13}^2 + \sqrt{m_1^2 + \Delta m_\odot^2} s_{12}^2 c_{13}^2 e^{2i\alpha} + \sqrt{m_1^2 + \Delta m_A^2} s_{13}^2 e^{2i\beta} \right|$$

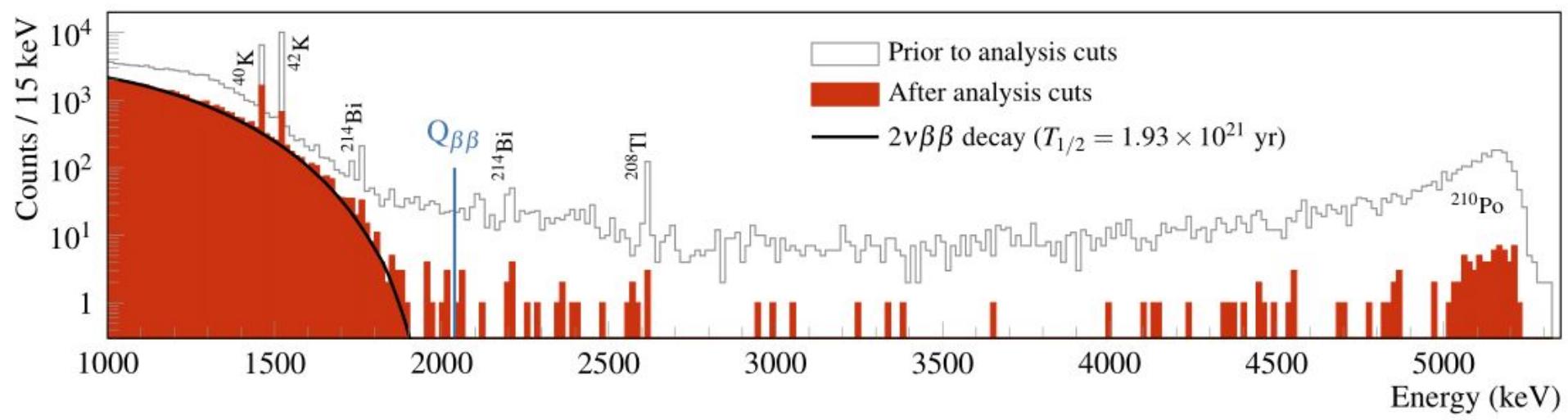
$$\langle m_{ee} \rangle^{\text{inv}} = \left| \sqrt{m_3^2 + \Delta m_A^2} c_{12}^2 c_{13}^2 + \sqrt{m_3^2 + \Delta m_\odot^2 + \Delta m_A^2} s_{12}^2 c_{13}^2 e^{2i\alpha} + m_3 s_{13}^2 e^{2i\beta} \right|$$

Masayuki Koga ICNFP2017 S. M. Bilenky, arXiv:1203.5250 7

Out... x  
 KamLAND-... 1  
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 KamLAND ... 3  
 スライド... 4  
 Why neutr... 5  
 Double bet... 6  
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 スライド... 9  
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# The sensitivity

**sensitivity F:** lifetime corresponding to the minimum detectable number of events over background at a given confidence level

