Neutrino Properties on the Basis of Neutrinoless Double Beta Decay

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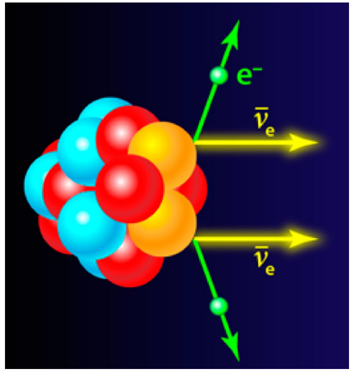
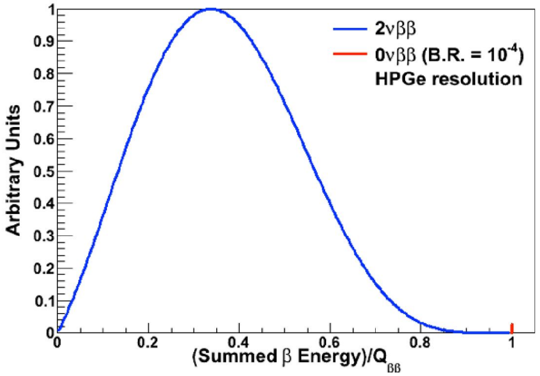
DLNP of JINR, February 24, 2021

(A,Z) -> (A,Z+2) + 2 e$^-$ + {2ν}

2νββ

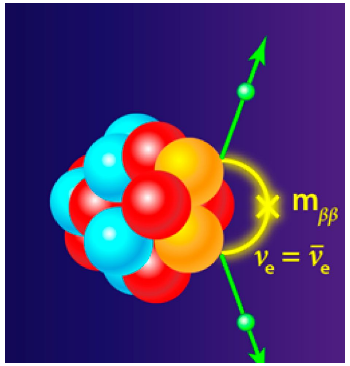
$0^+_{g.s.} \rightarrow 0^+_{g.s}$



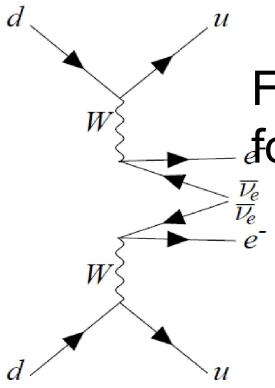


$0νββ_{LMN}$

$0^+_{g.s.} \rightarrow 0^+_{g.s}$

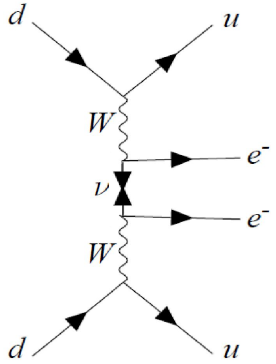


Feynman diagrams at the quark level for:



two-neutrino double beta decay

(allowed in SM)



neutrinoless double beta decay

LNM- light Majorana neutrino mechanism

(beyond SM)

NDBDecayers

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

ECEC

The following known nuclides with A ≤ 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:

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

A Portal to Physics Beyond the Standard Model

Decay probability proportional to coherent sum of involved mechanisms:

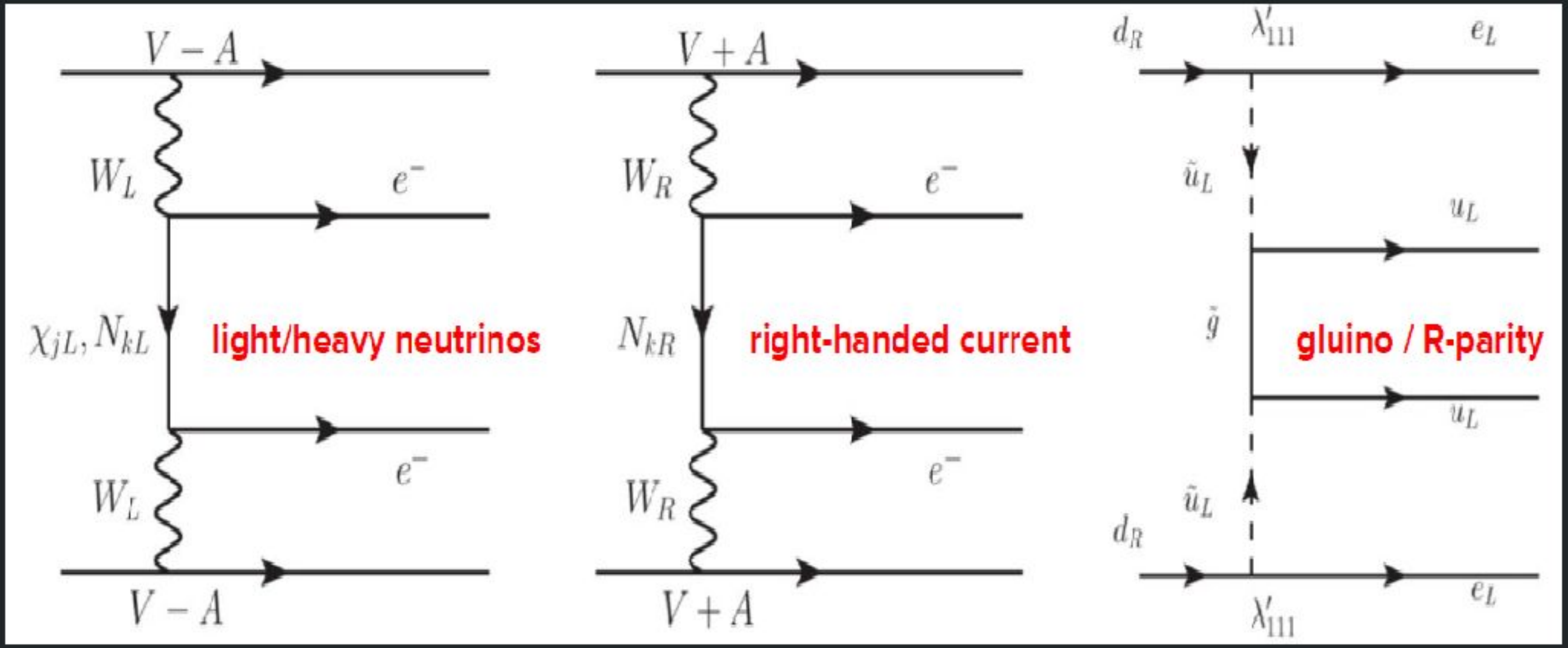
$$\Gamma = \frac{1}{T_{1/2}} = \left|\sum_i \sqrt{G_i} \times g_i^2 \times \mathcal{M}_i \times \eta_i\right|^2$$

Particle Physics

Phase Space Factor

Hadronic coupling

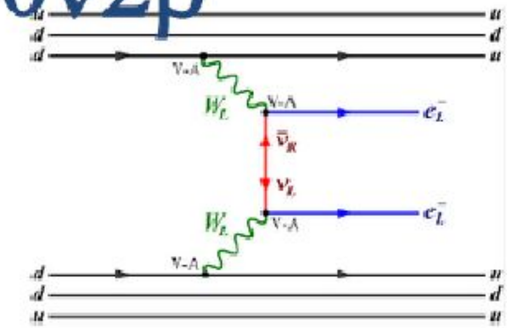
Nuclear Physics

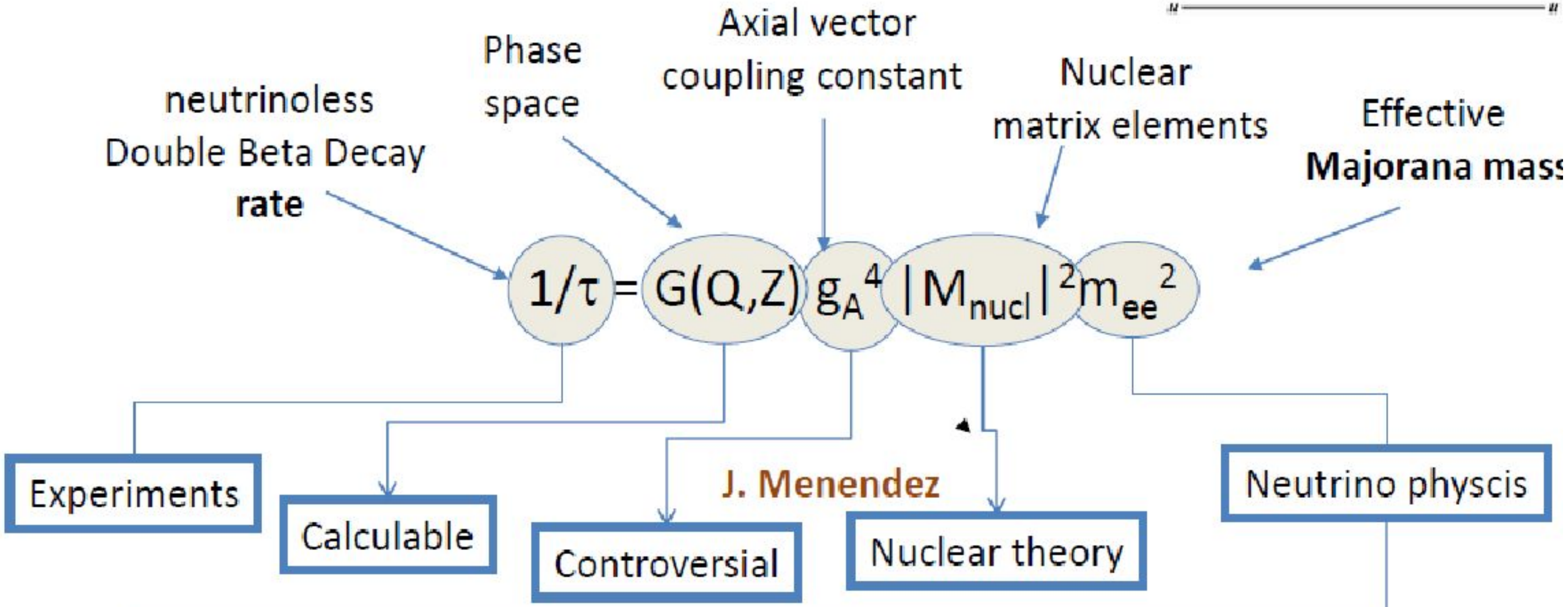


[Faessler et al, PRD, 83, 11 (2011), 113003]

Standard mechanism for 0ν2β

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





neutrinoless Double Beta Decay **rate**

Phase space

Axial vector coupling constant

Nuclear matrix elements

Effective **Majorana mass**

$$1/\tau = G(Q,Z)\, g_A^4\, |M_{nucl}|^2 m_{ee}^2$$

Experiments

Calculable

Controversial

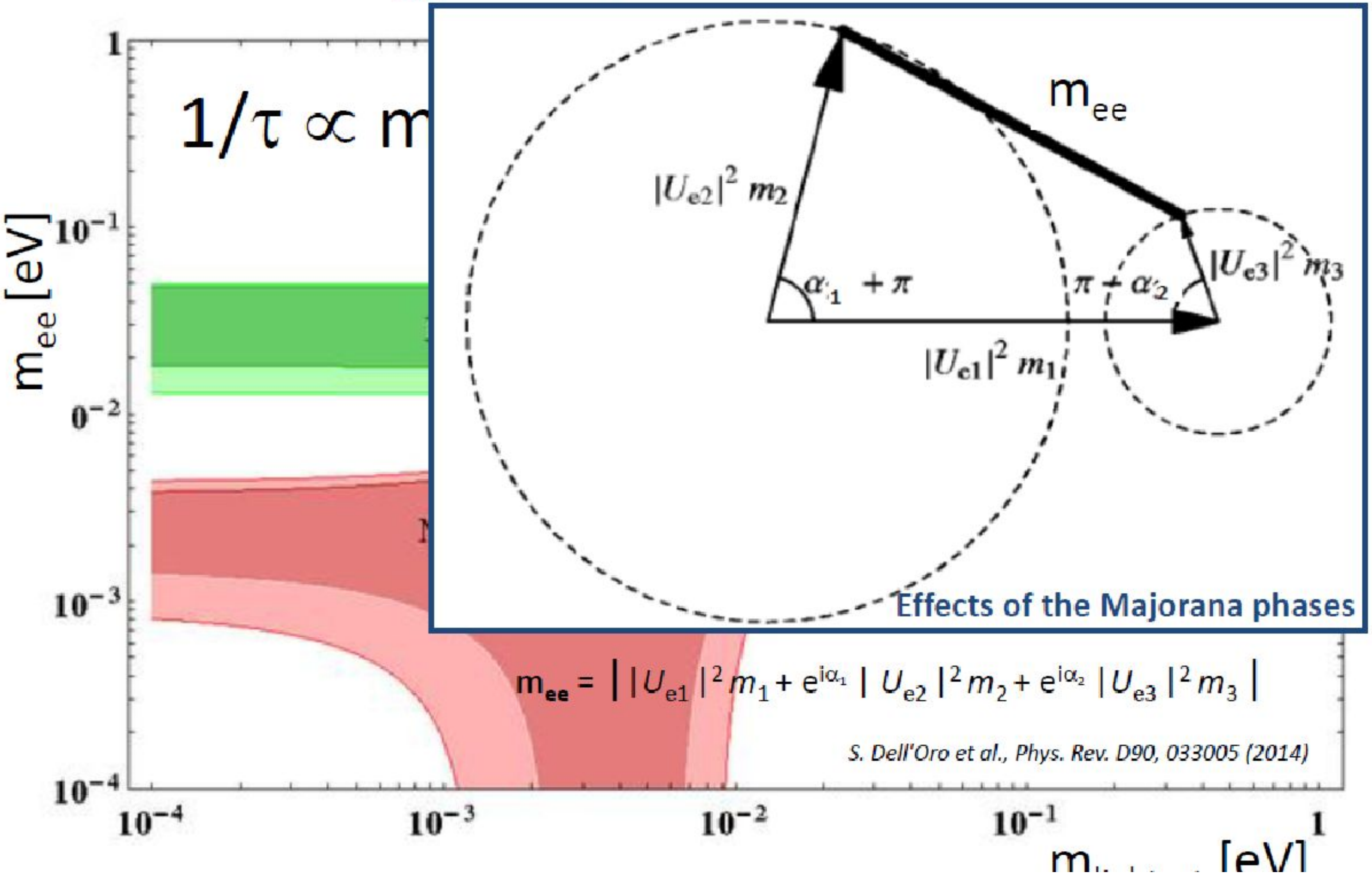
J. Menendez

Nuclear theory

Neutrino physcis

$$\mathbf{m_{ee}} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

m_{ee} vs. lightest ν mass

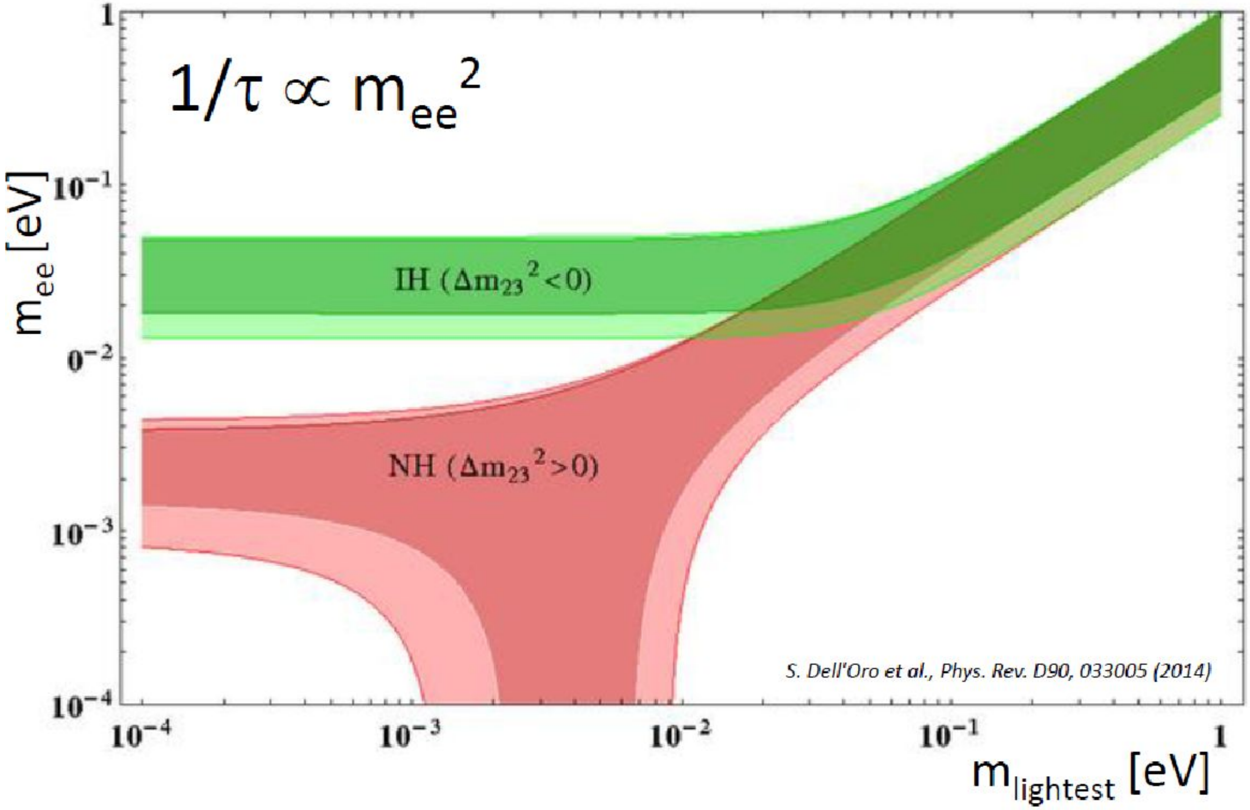


Effects of the Majorana phases

$$m_{ee} = \left| |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \right|$$

S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)

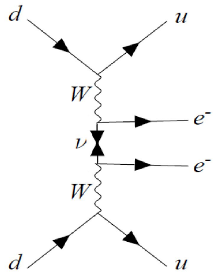
m_{ee} vs. lightest ν mass



$1/\tau \propto m_{ee}^2$

S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)

Effects of a quenched gA on NMEs of 0 decays:



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

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

Quenching:

$$q = g_{\mathrm{A}}/g_{\mathrm{A}}^{\mathrm{free}}$$

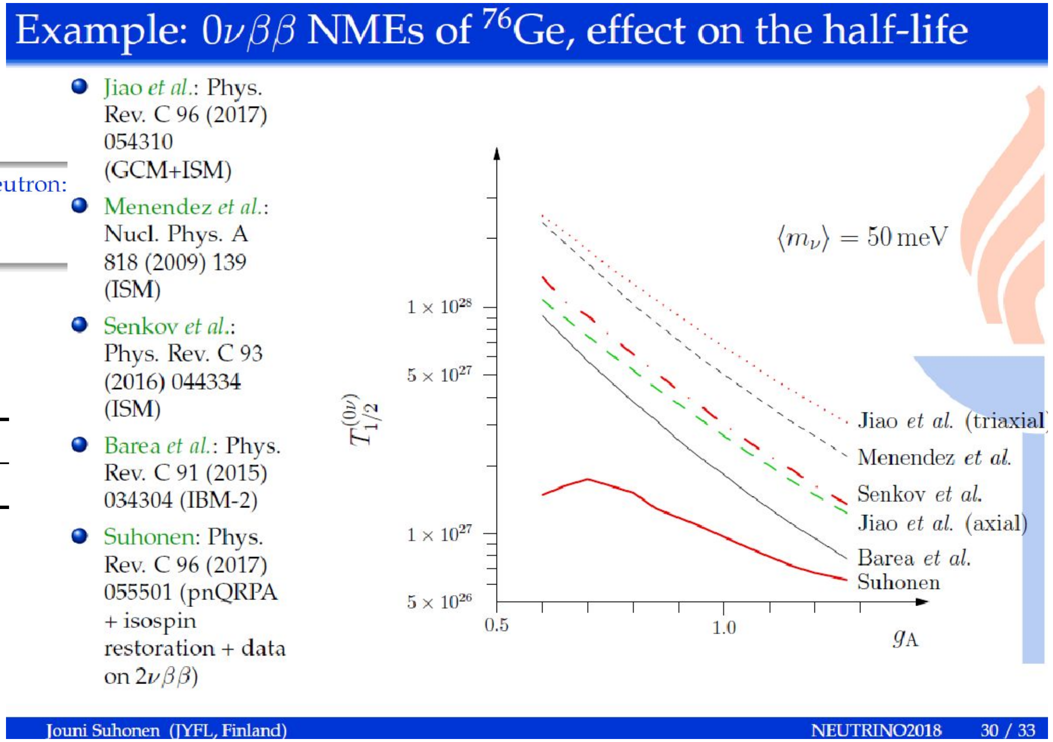
Free value of g_{A} (Particle Data Group 2016) from the decay of free neutron:

$$g_{\mathrm{A}}^{\mathrm{free}} = 1.2723(23)$$

Effective value of g_{A}:

$$g_{\mathrm{A}}^{\mathrm{eff}} = q g_{\mathrm{A}}^{\mathrm{free}}$$

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



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

- 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 $2\nu\beta\beta$)

Jouni Suhonen (JYFL, Finland) NEUTRINO2018 30 / 33

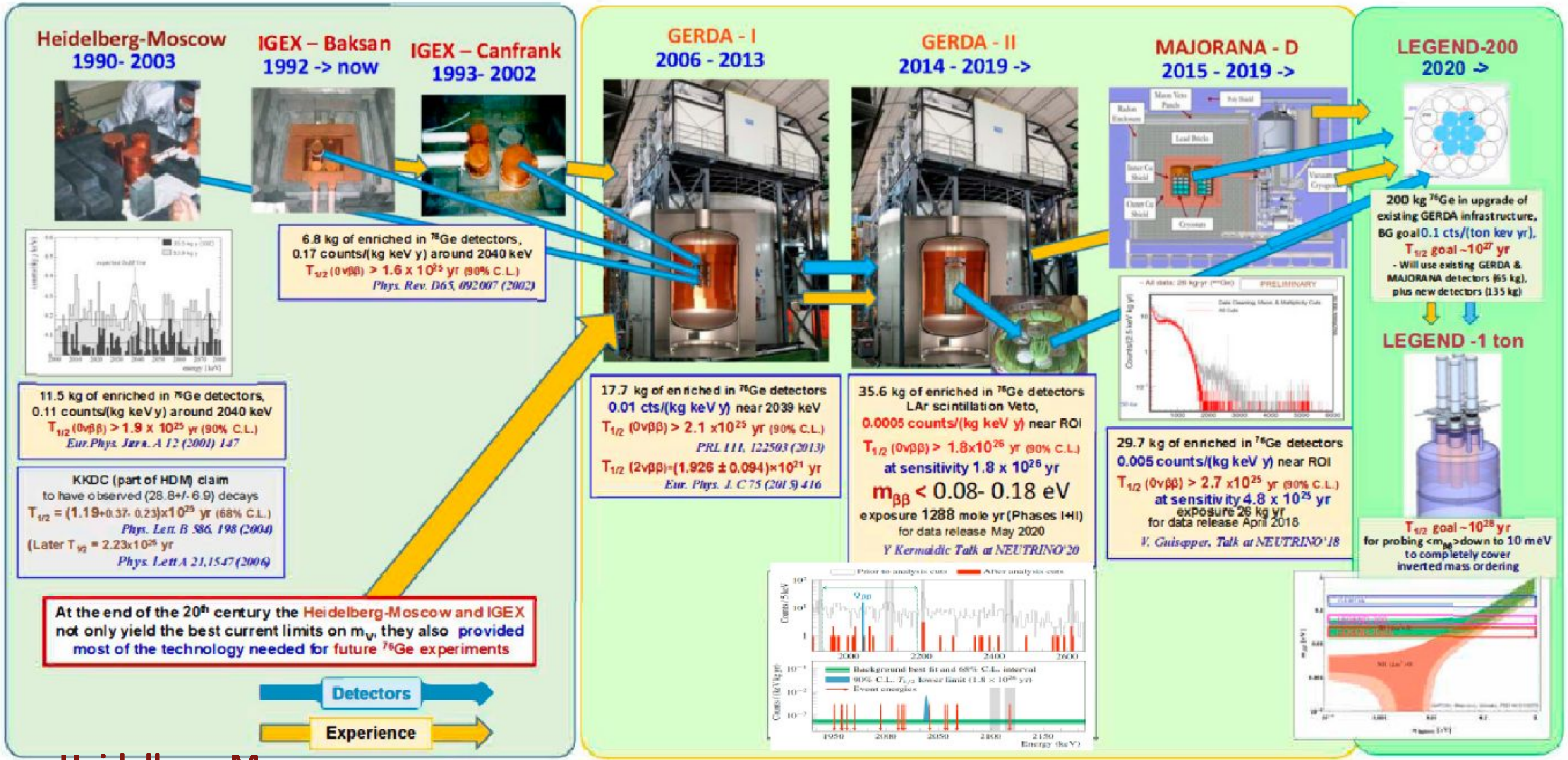
Neutrino Mass Ordering From Oscillations and Beyond: 2018 Status and Future Prospects

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 [redacted]$_{\beta\beta}$ (in case there is no sterile neutrino), one would need **to constrain [redacted]$_{\beta\beta}$ ~10 meV**, which corresponds to **[redacted]$_{0\nu\ 1/2}$ ≃ 1×10^{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

IGEX – Baksan 1992 -> now

IGEX – Canfrank 1993- 2002

GERDA - I 2006 - 2013

GERDA - II 2014 - 2019 ->

MAJORANA - D 2015 - 2019 ->

LEGEND-200 2020 ->

6.8 kg of enriched in ^{76}Ge detectors,
0.17 counts/(kg keV y) around 2040 keV
$T_{1/2}(0\nu\beta\beta) > 1.6 \times 10^{25}$ yr (90% C.L.)
Phys. Rev. D65, 092007 (2002)

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

KKDC (part of HDM) claim
to have observed (28.8+/-6.9) decays
$T_{1/2} = (1.19{+0.37 \atop -0.23}) \times 10^{25}$ yr (68% C.L.)
Phys. Lett. B 586, 198 (2004)
(Later $T_{1/2} = 2.23 \times 10^{25}$ yr
Phys. Lett A 21,1547 (2006)

At the end of the 20th century the Heidelberg-Moscow and IGEX not only yield the best current limits on m_ν, they also provided most of the technology needed for future ^{76}Ge experiments

Detectors

Experience

17.7 kg of enriched in ^{76}Ge detectors
0.01 cts/(kg keV y) near 2039 keV
$T_{1/2}(0\nu\beta\beta) > 2.1 \times 10^{25}$ yr (90% C.L.)
PRL 111, 122503 (2013)
$T_{1/2}(2\nu\beta\beta) = (1.926 \pm 0.094) \times 10^{21}$ yr
Eur. Phys. J. C 75 (2015) 416

35.6 kg of enriched in ^{76}Ge detectors
LAr scintillation Veto,
0.0005 counts/(kg keV y) near ROI
$T_{1/2}(0\nu\beta\beta) > 1.8 \times 10^{26}$ yr (90% C.L.)
at sensitivity 1.8×10^{26} yr
$m_{\beta\beta} < 0.08$- 0.18 eV
exposure 1288 mole yr (Phases I+II)
for data release May 2020
Y Kermaidic Talk at NEUTRINO'20

29.7 kg of enriched in ^{76}Ge detectors
0.005 counts/(kg keV y) near ROI
$T_{1/2}(0\nu\beta\beta) > 2.7 \times 10^{25}$ yr (90% C.L.)
at sensitivity 4.8×10^{25} yr
exposure 26 kg yr
for data release April 2018
V. Guiseppe, Talk at NEUTRINO'18

200 kg ^{76}Ge in upgrade of existing GERDA infrastructure,
BG goal 0.1 cts/(ton kev yr),
$T_{1/2}$ goal ~10^{27} yr
- Will use existing GERDA & MAJORANA detectors (65 kg), plus new detectors (135 kg)

LEGEND -1 ton

$T_{1/2}$ goal ~10^{28} yr
for probing $\langle m_{\beta\beta} \rangle$ down to 10 meV
to completely cover
inverted mass ordering

Heidelberg-Moscow **1990- 2003**

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

~ 20 yeas

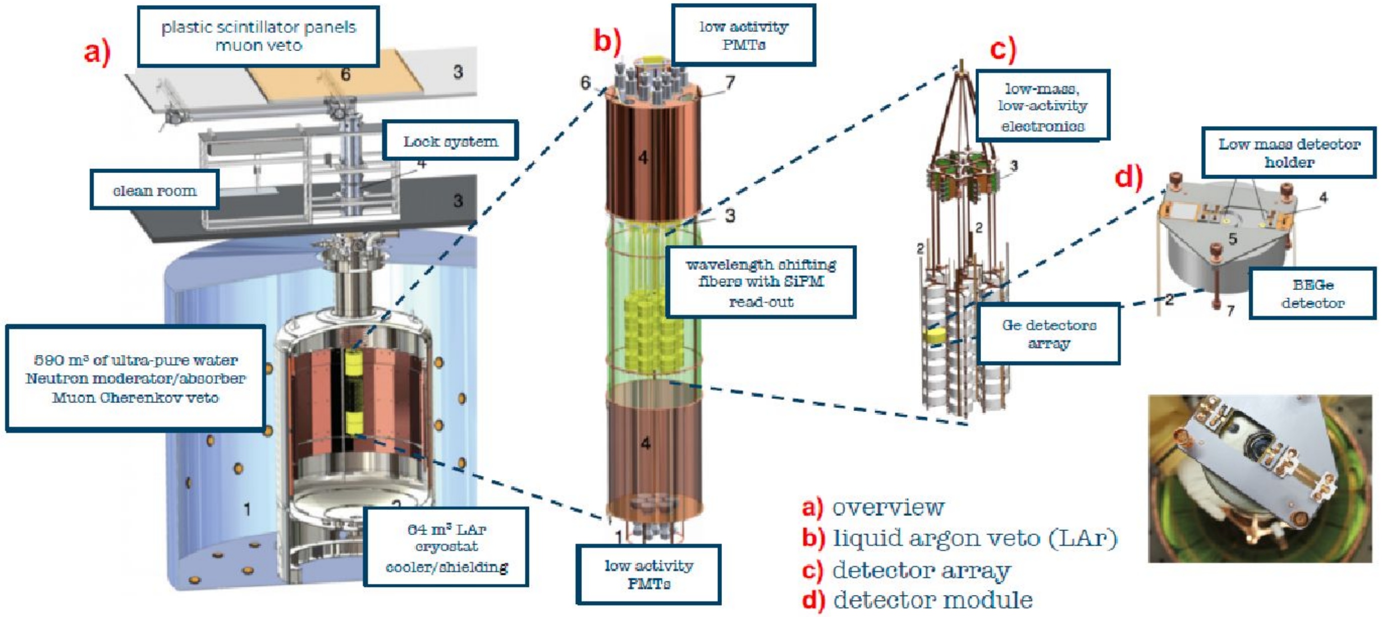
GERDA - II 2014- 2020

35.6 kg of enriched in ^{76}Ge detectors
LAr scintillation Veto,
0.0005 counts/(kg keV y) near ROI
$T_{1/2}$ (0νββ) > 1.8 x10^{26} yr (90% C.L.)
$m_{\beta\beta}$ < 0.08- 0.18 eV
exposure 1288 mole yr (Phases I+II)

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

GERDA Phase II

GERDA Setup



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

Semi-Coaxial

BEGe

Inverted-Coaxial

41.8 kg·yr + 53.3 kg·yr + 8.5 kg·yr = 103.7 kg·yr

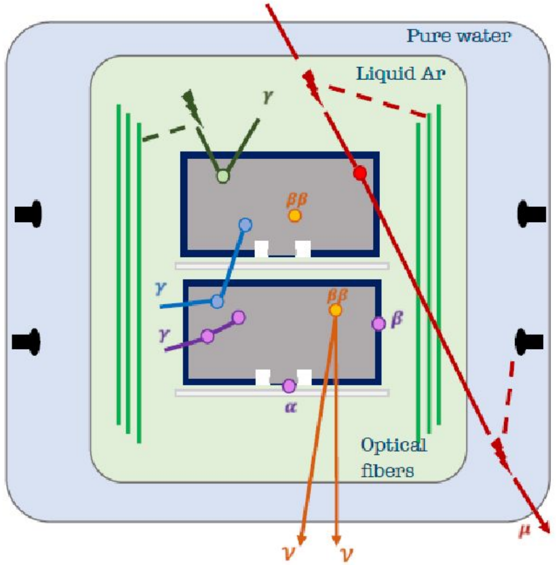
from previous experiments (HdM, IGEX)

produced for GERDA Phase II

tested for next generation experiments (LEGEND-200, LEGEND-1000)

GERDA Phase II

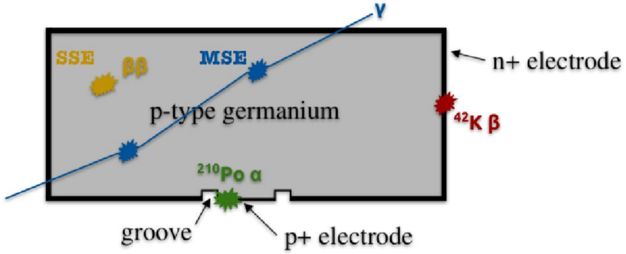
Active Background Reduction



- 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 α events

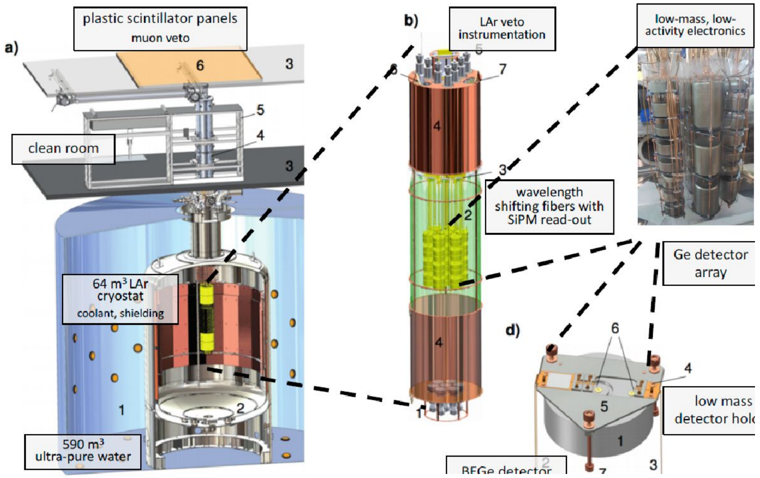
$\beta\beta$ decay signal: single energy deposition ($Q_{\beta\beta}$ = 2039 keV) in a 1 mm³ volume

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

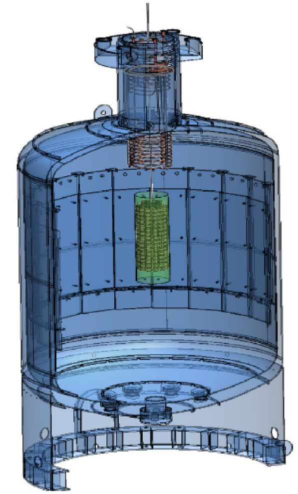


Present & Future

GERDA-II at LNGS

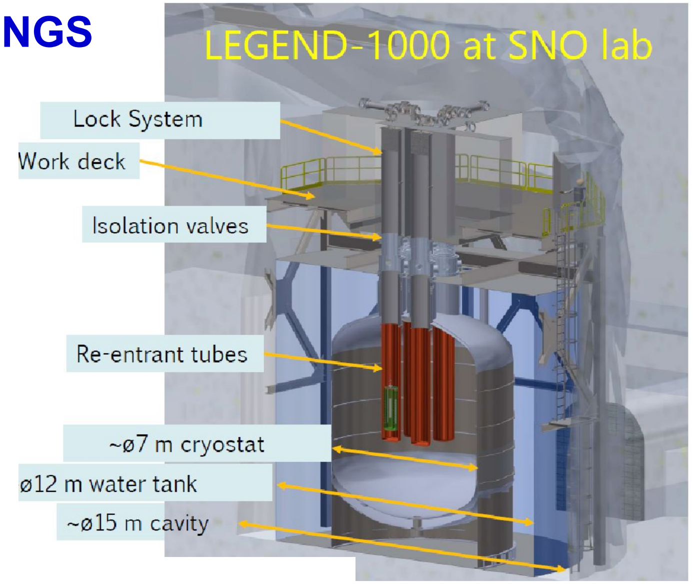


LEGEND-200 at LNGS



^{76}Ge (88% enr.)

LEGEND-1000 at SNO lab



Lock System

Work deck

Isolation valves

Re-entrant tubes

~ø7 m cryostat

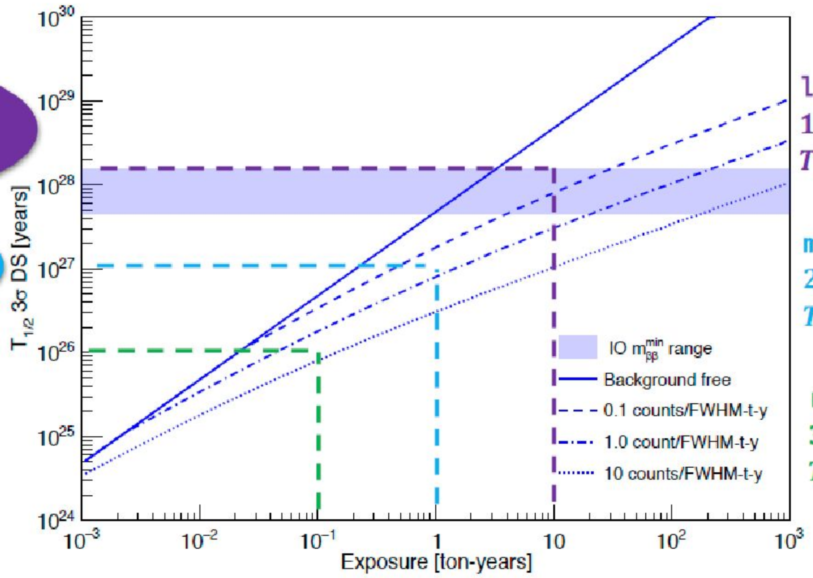
ø12 m water tank

~ø15 m cavity

LEGEND 1000

LEGEND 200

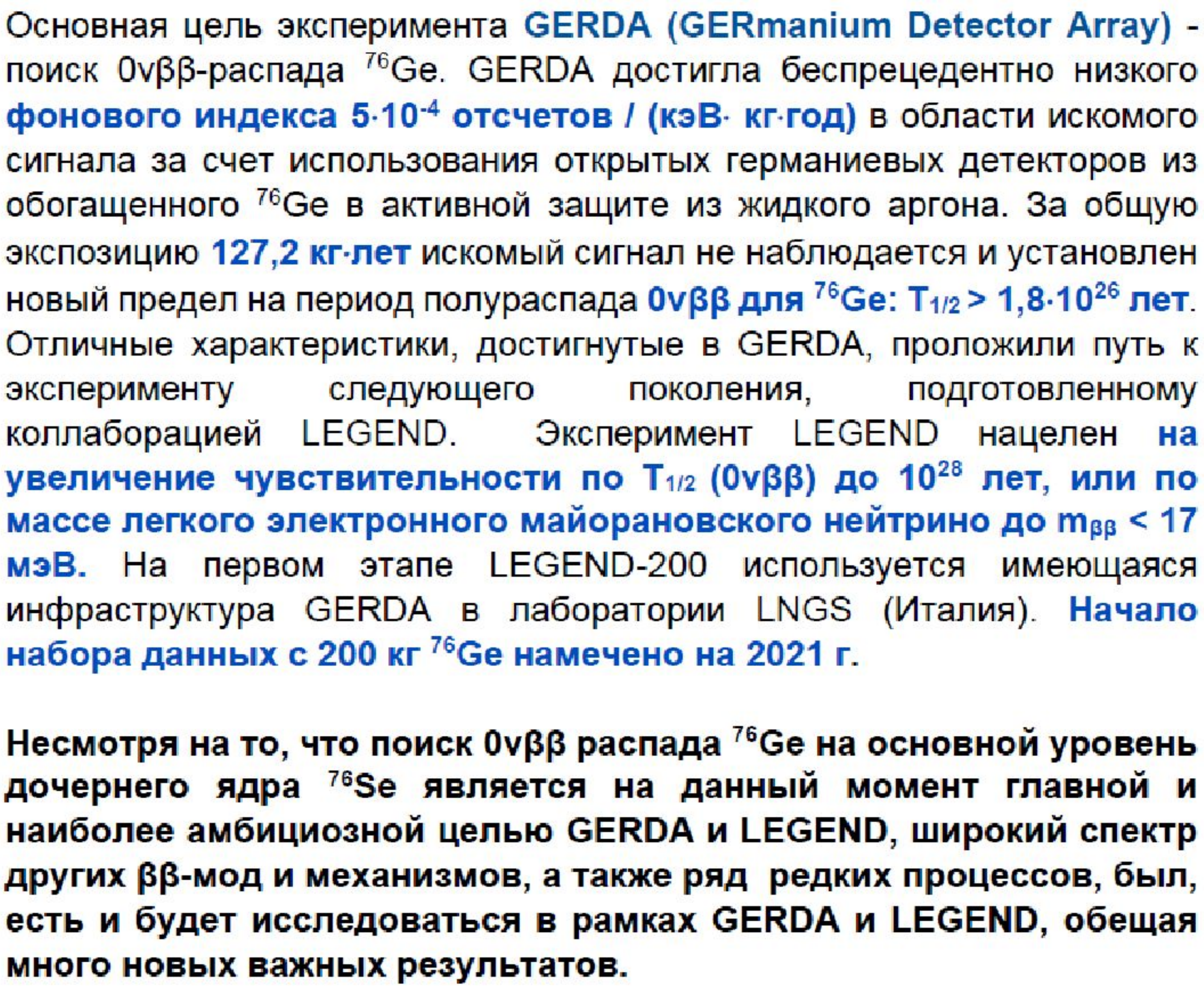
GERDA MAJORANA



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

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

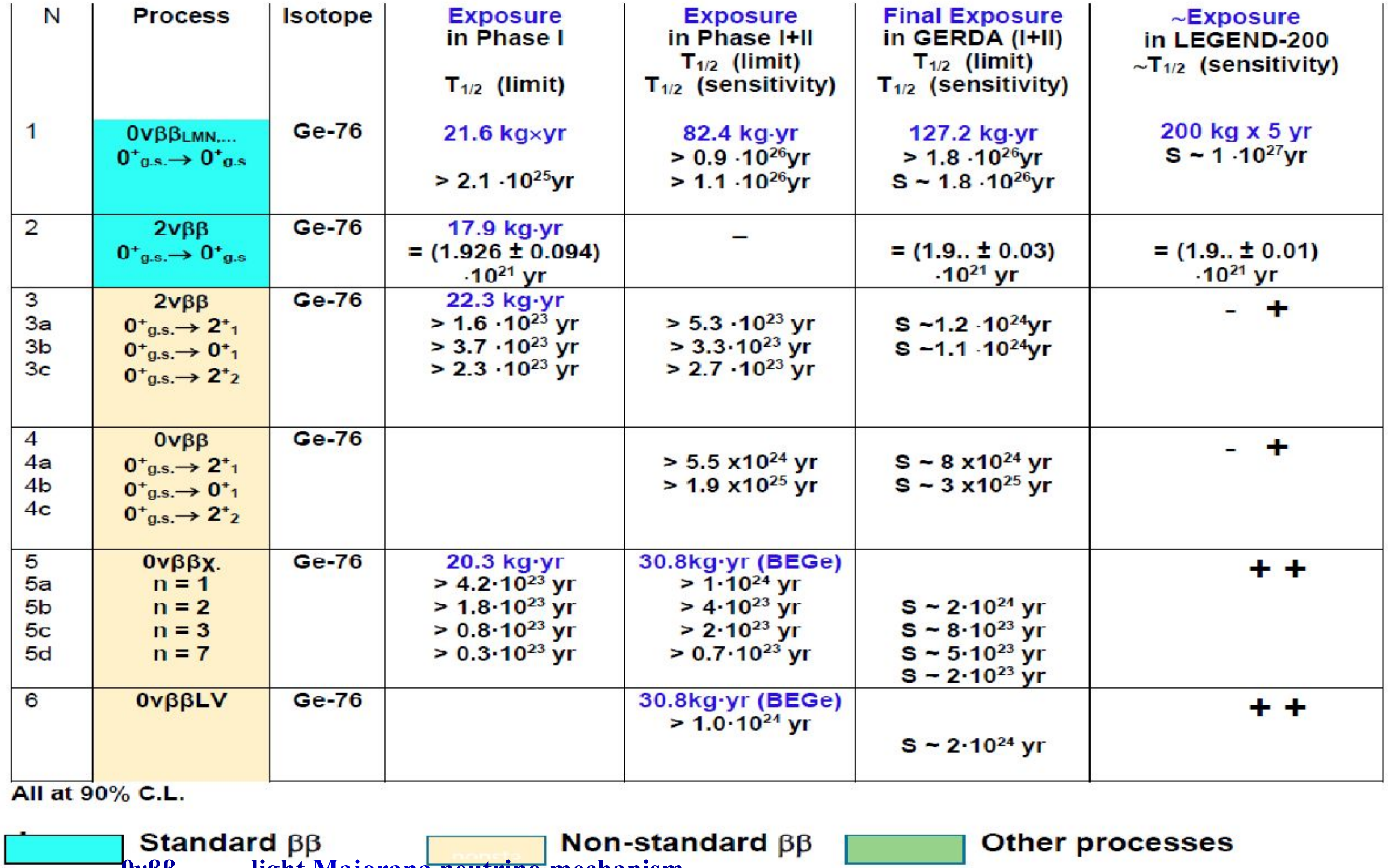
running/ended
30 kg
$T_{1/2}^{0\nu} > 10^{26}$ yr



Основная цель эксперимента **GERDA (GERmanium Detector Array)** - поиск 0νββ-распада ^{76}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}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 **0νββ для ^{76}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 $T_{1/2}$ (0νββ) до 10^{28} лет, или по массе легкого электронного майорановского нейтрино до $m_{\beta\beta} < 17$ мэВ.** На первом этапе LEGEND-200 используется имеющаяся инфраструктура GERDA в лаборатории LNGS (Италия). **Начало набора данных с 200 кг ^{76}Ge намечено на 2021 г.**

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

моды ββ-распада и поиск других редких процессов в GERDA (… и LEGEND)

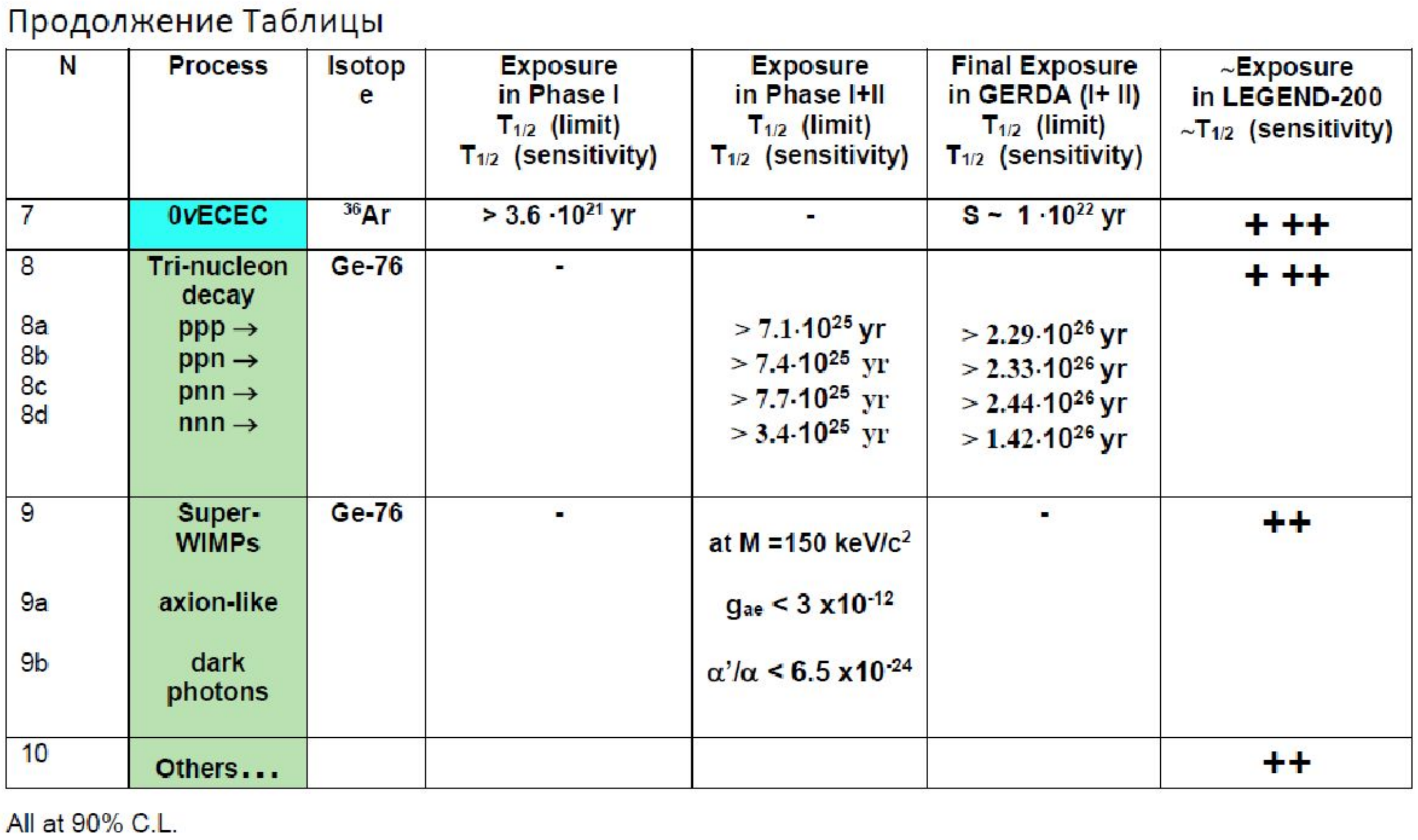


N	Process	Isotope	Exposure in Phase I $T_{1/2}$ (limit)	Exposure in Phase I+II $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	Final Exposure in GERDA (I+II) $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	~Exposure in LEGEND-200 $\sim T_{1/2}$ (sensitivity)
1	$0\nu\beta\beta_{LMN,...}$ $0^+_{g.s.} \to 0^+_{g.s}$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

All at 90% C.L.

🟦 Standard ββ 🟨 Non-standard ββ 🟩 Other processes

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



Продолжение Таблицы

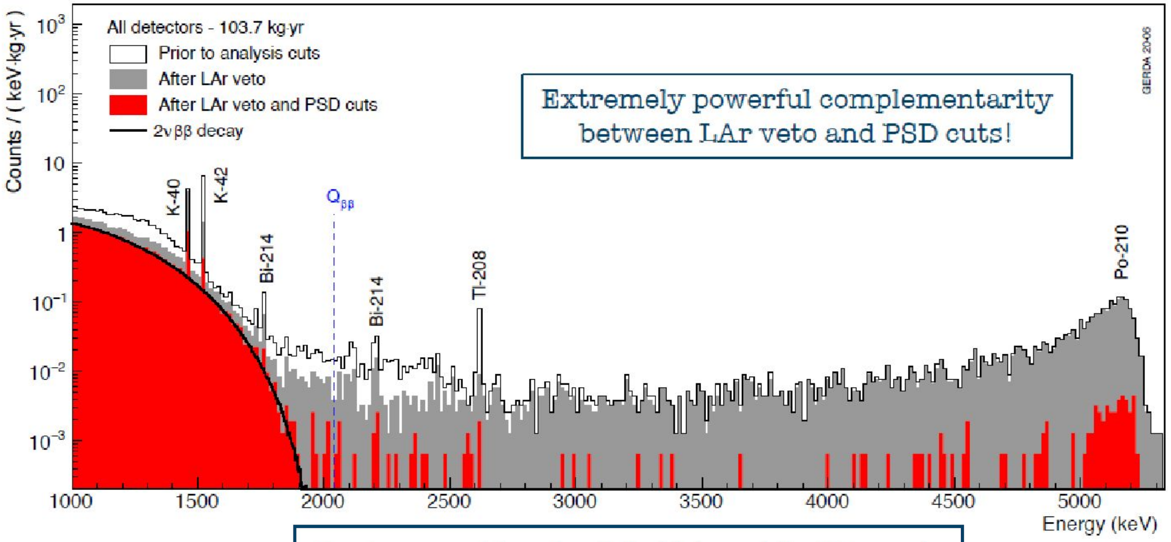
N	Process	Isotope	Exposure in Phase I $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	Exposure in Phase I+II $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	Final Exposure in GERDA (I+ II) $T_{1/2}$ (limit) $T_{1/2}$ (sensitivity)	~Exposure in LEGEND-200 ~$T_{1/2}$ (sensitivity)
7	0νECEC	^{36}Ar	> $3.6 \cdot 10^{21}$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

All at 90% C.L.

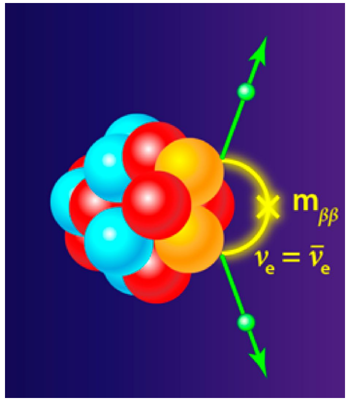
🟦 **Standard ββ** 🟨 **Non-standard ββ** 🟩 **Other processes**

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

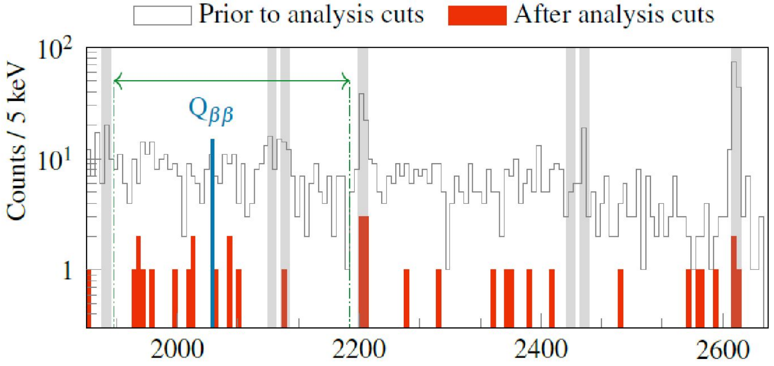
Final Results of GERDA on the Search for 0νββ decay of 76Ge

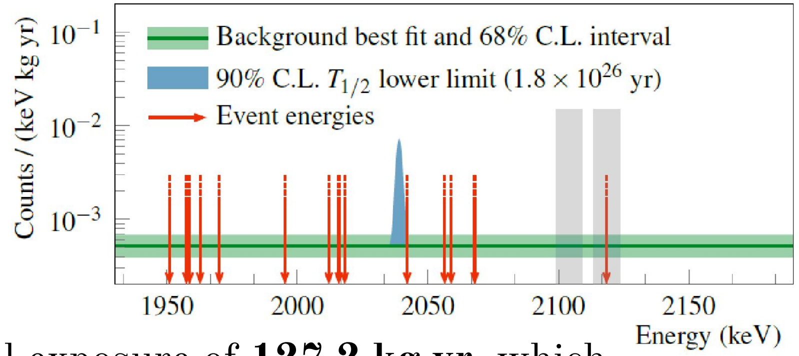


Extremely powerful complementarity
between LAr veto and PSD cuts!



Background level = $5.2 \cdot 10^{-4}$ cts / (keV kg yr)



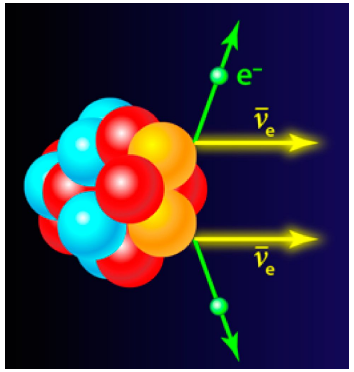


Phase I and Phase II data together give a total exposure of **127.2 kg yr**, which corresponds to **1288 mol yr of 76Ge**. The combined analysis has a best fit for null signal strength, and provides a half-life limit of

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

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

Half-life of 2vββ decay of 76Ge



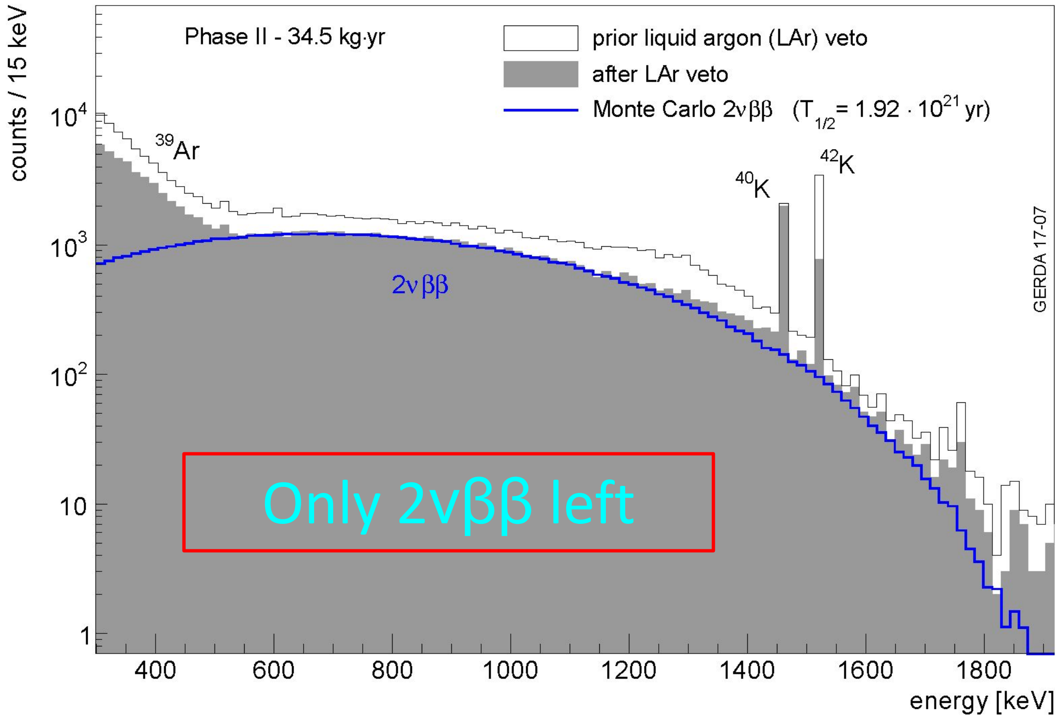
From Phase I

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

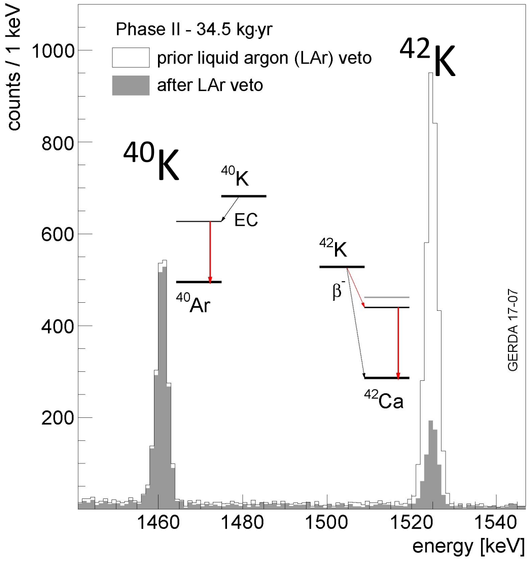
Phase II

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

After LAr Veto performance



Only 2vββ left



Survival fraction between 0.6 and 1.3 MeV:

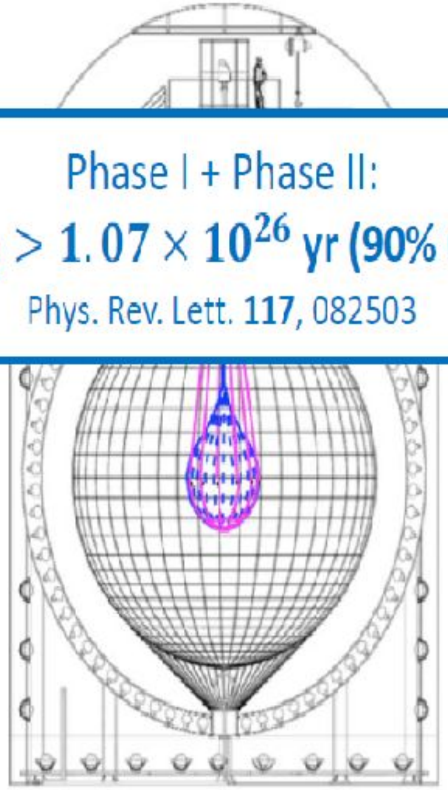
$(68.6 \pm 0.3)\%$

$T_{1/2}(2v2\beta)$ fixed as $2.03\ 10^{21}$ yr

^{40}K and ^{42}K continua strongly suppressed

KamLAND-Zen

Past



Phase I + Phase II:

$T_{1/2} > 1.07 \times 10^{26}$ yr (90% C.L.)

Phys. Rev. Lett. **117**, 082503

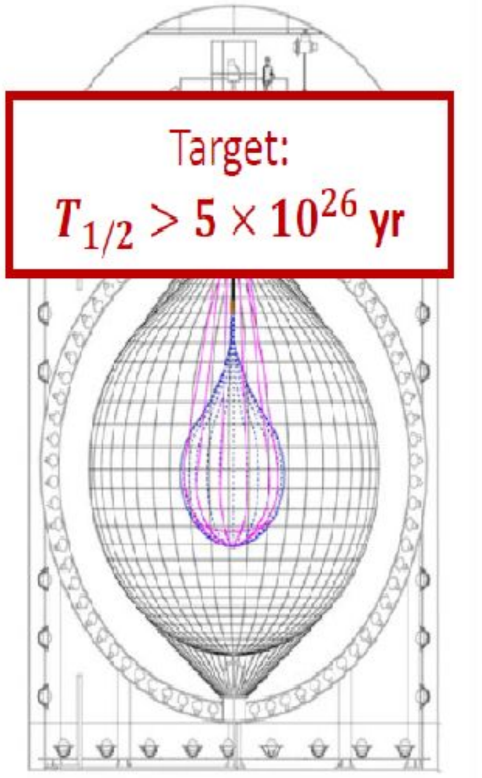
KamLAND-Zen 400

Mini-balloon Radius = 1.54 m

Xenon mass = 320 ~ 380 kg

2011 ~ 2015

Current



Target:

$T_{1/2} > 5 \times 10^{26}$ yr

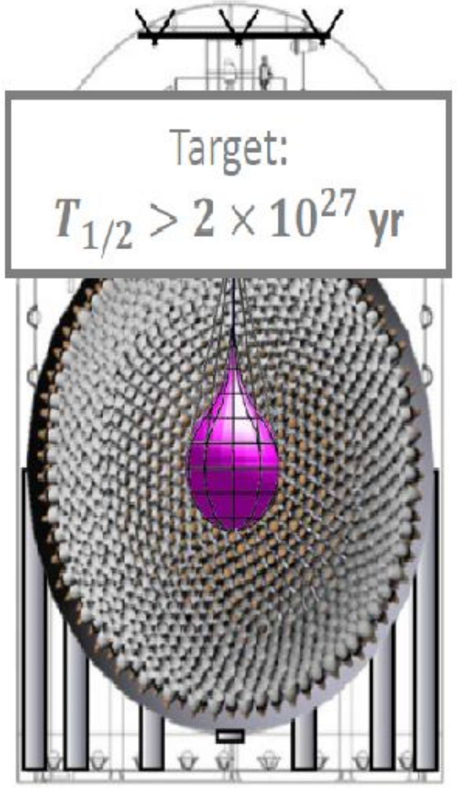
KamLAND-Zen 800

Mini-balloon Radius = 1.90 m

Xenon mass = 745 kg

Started January 2019

Future



Target:

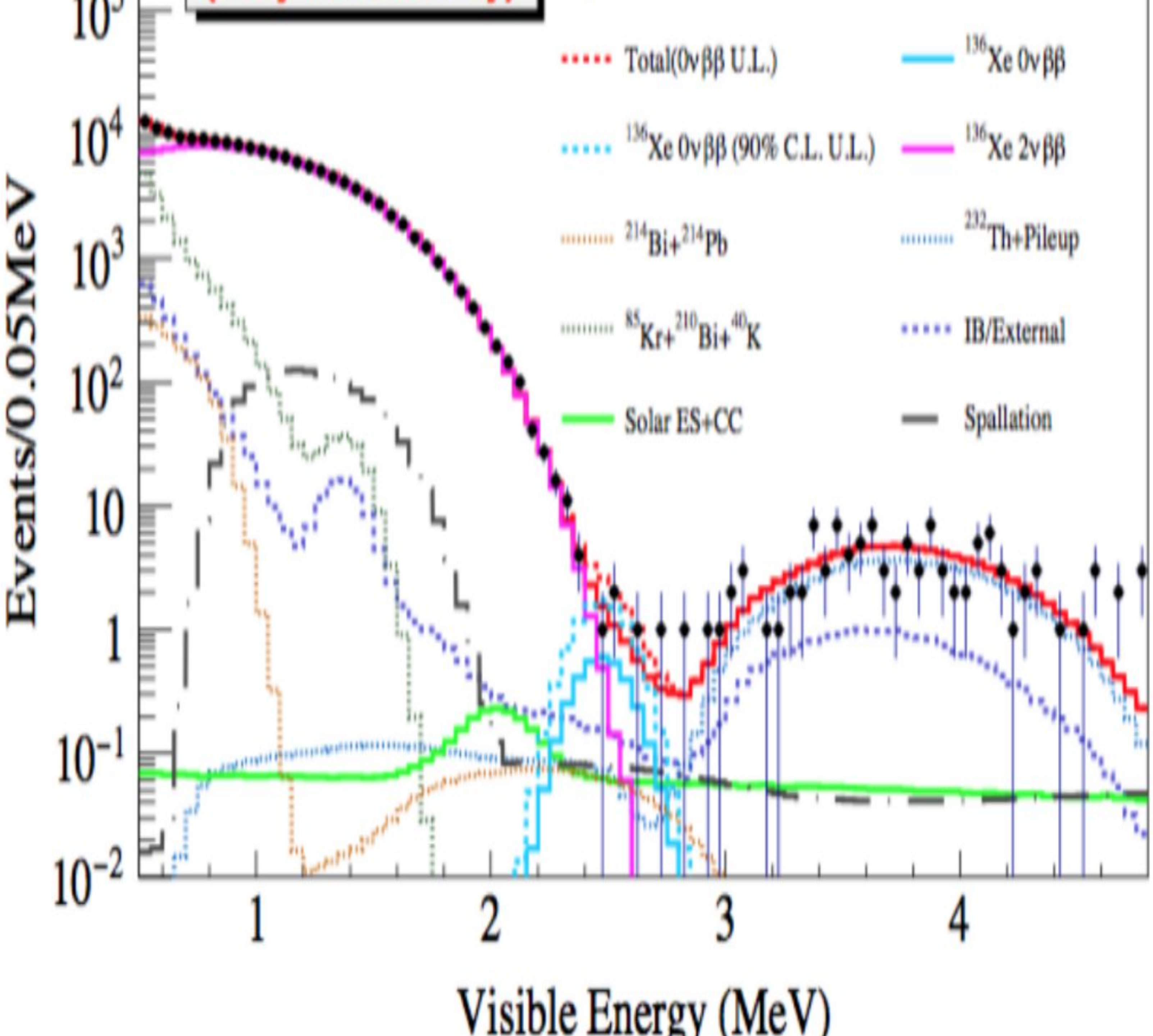
$T_{1/2} > 2 \times 10^{27}$ yr

KamLAND2-Zen

Xenon mass ~ 1 ton

× 5 increase in light collection

Scintillation balloon film


Total(0νββ U.L.)
^{136}Xe 0νββ
^{136}Xe 0νββ (90% C.L. U.L.)
^{136}Xe 2νββ
^{214}Bi+^{214}Pb
^{232}Th+Pileup
^{85}Kr+^{210}Bi+^{40}K
IB/External
Solar ES+CC
Spallation
Events/0.05MeV
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
1
2
3
4
Visible Energy (MeV)

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

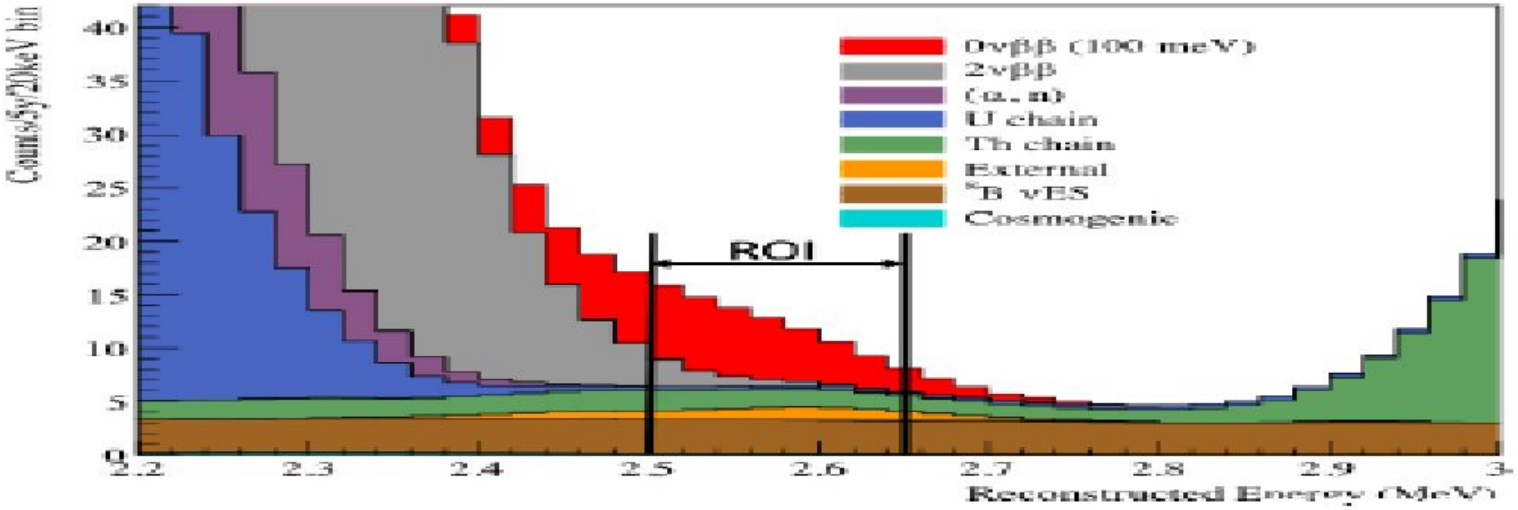


Figure 3: Energy spectrum of 0νββ signal (red) and background[6]
Region of interest: 2.49 - 2.65 MeV

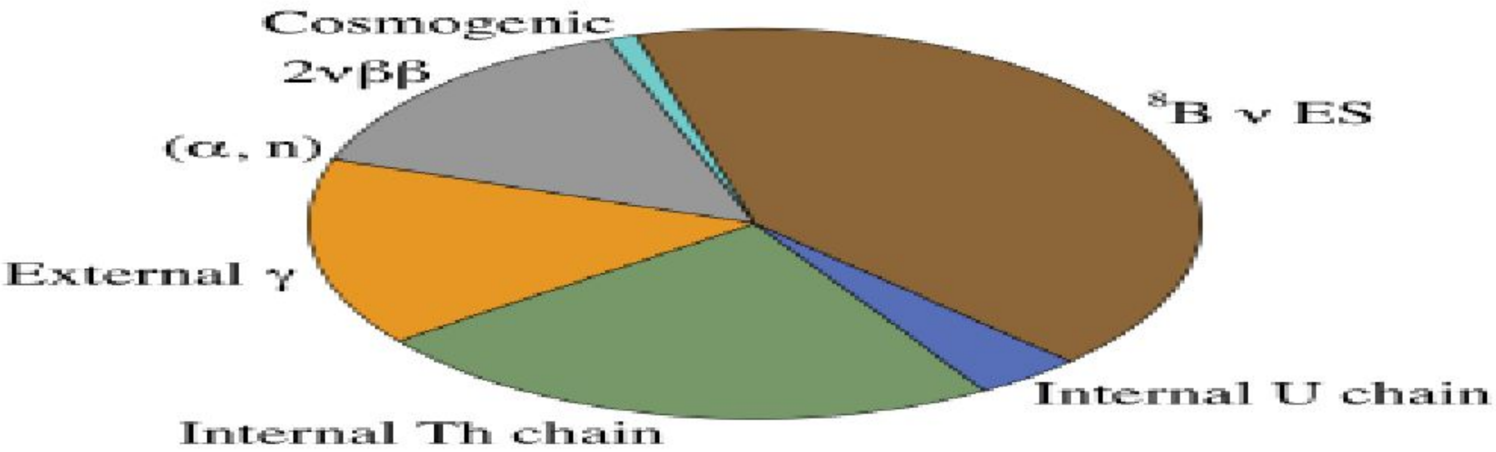
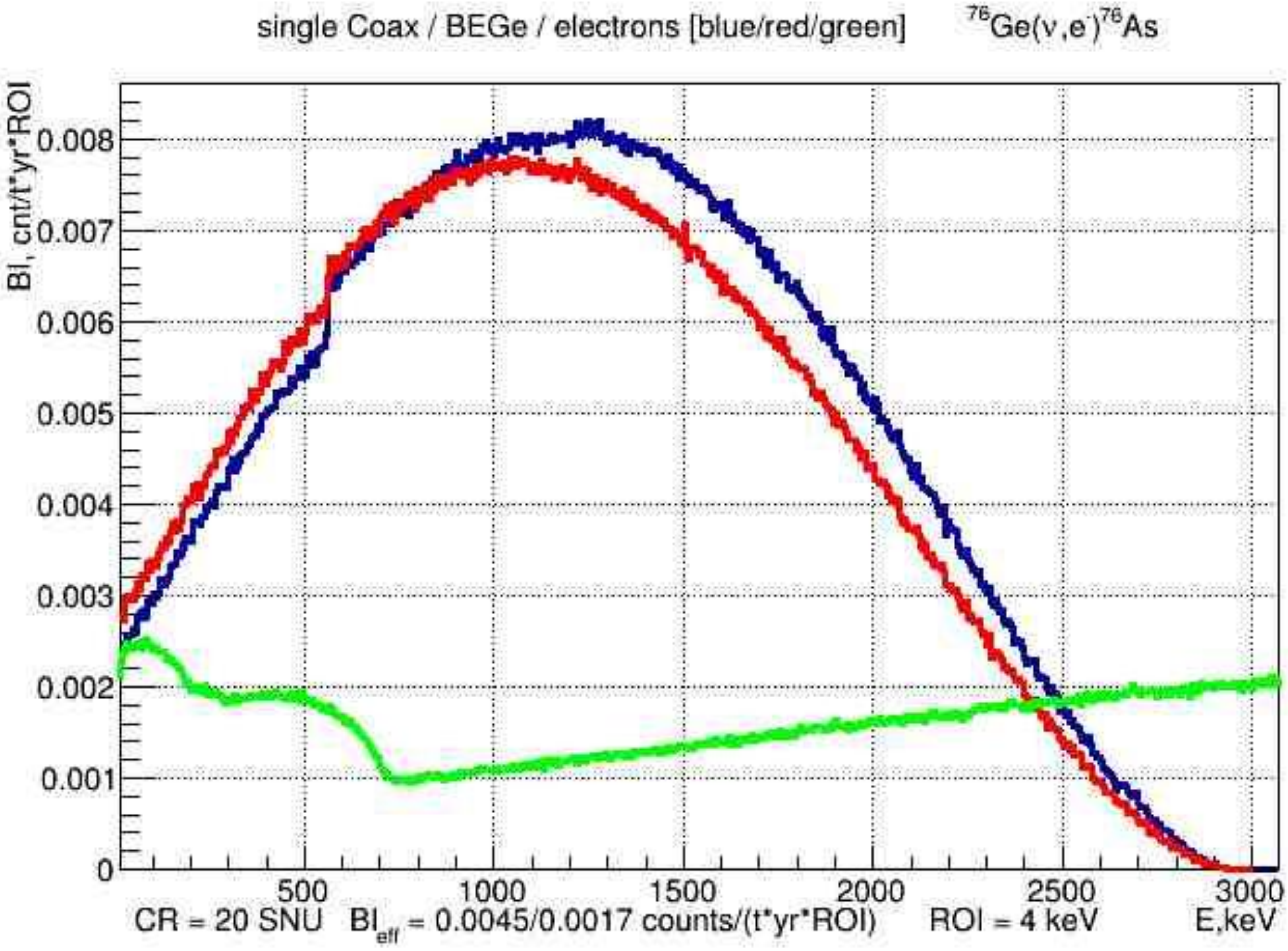
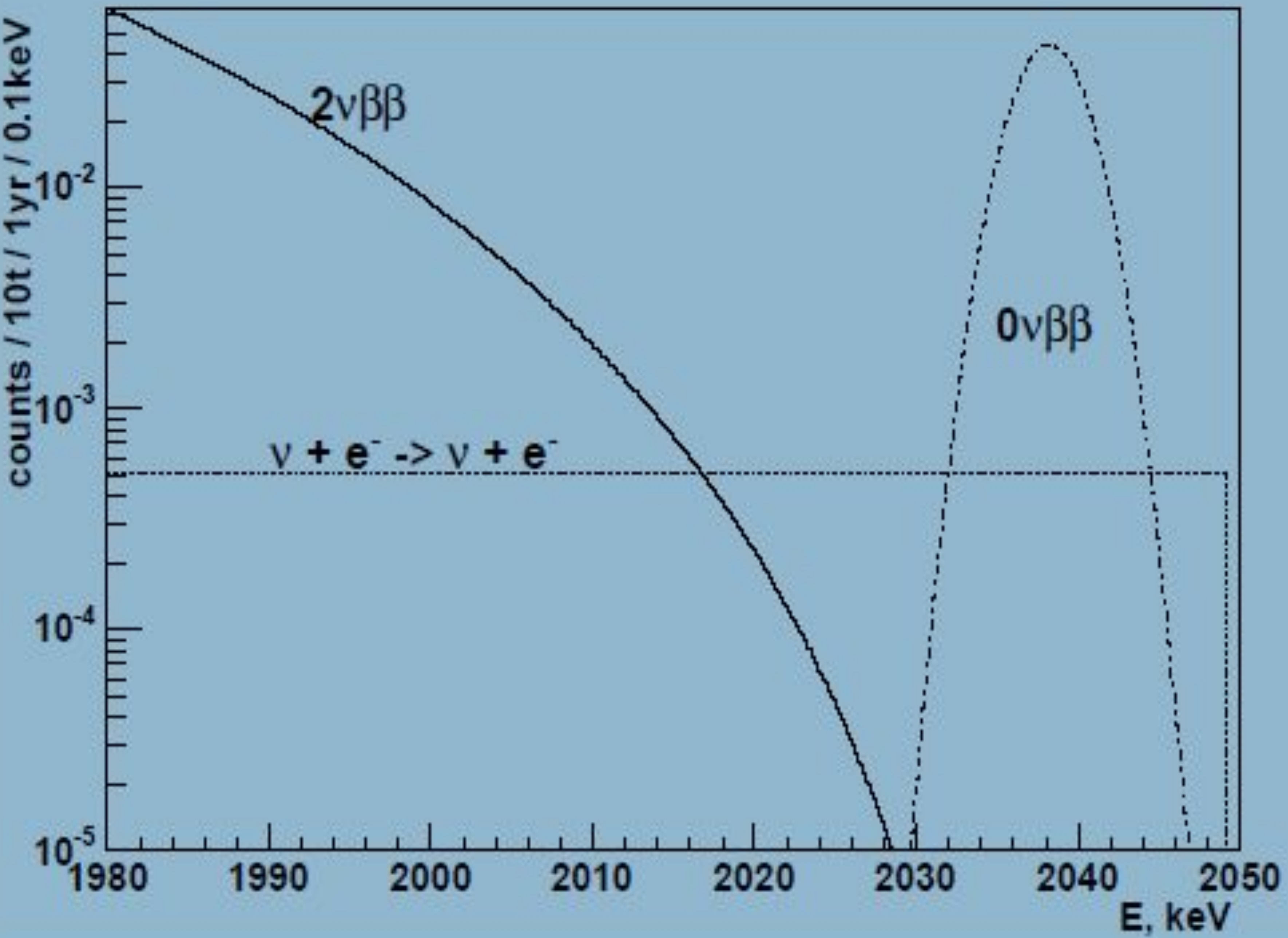


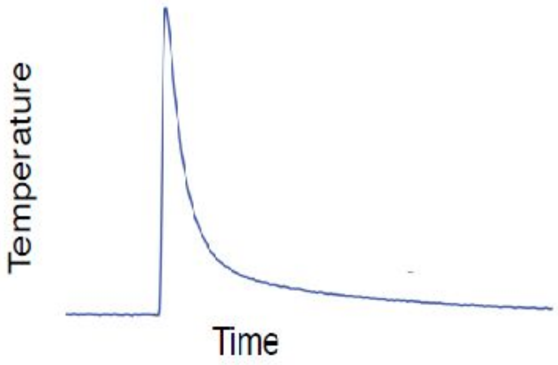
Figure 4: Background counts within ROI in first year of data taking[6]
Total counts: 12.4

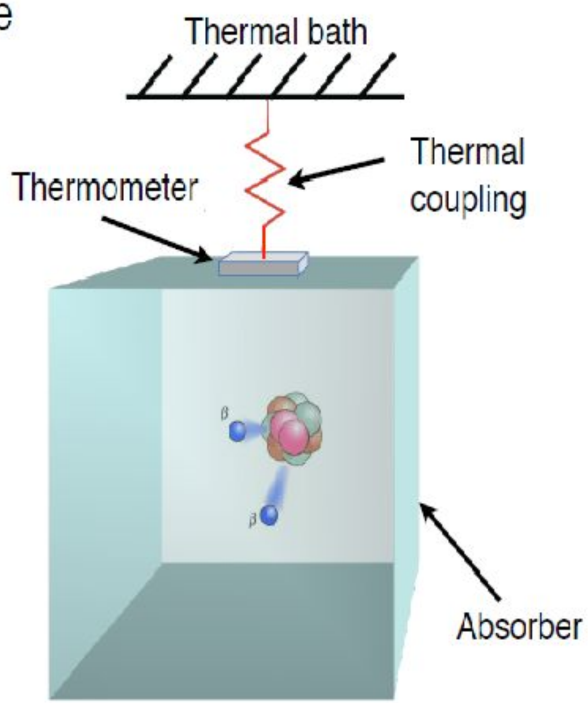

single Coax / BEGe / electrons [blue/red/green]
^{76}Ge(ν,e^{-})^{76}As
BI, cnt/t*yr*ROI
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
500
1000
1500
2000
2500
3000
CR = 20 SNU
BI$_{eff}$ = 0.0045/0.0017 counts/(t*yr*ROI)
ROI = 4 keV
E,keV


counts / 10t / 1yr / 0.1keV
10^{-2}
10^{-3}
10^{-4}
10^{-5}
2νββ
0νββ
ν + e^- -> ν + e^-
1980
1990
2000
2010
2020
2030
2040
2050
E, keV

Macro Bolometer Technique

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



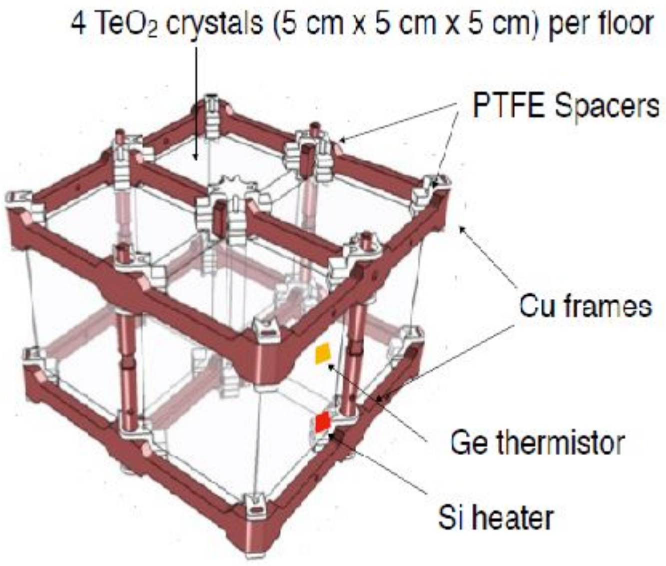


- For dielectric crystal absorbers, heat capacity $\sim T^3$
- Typically operated at ~10mK
- Relative energy resolution of 0.2~0.3% FWHM routinely achieved

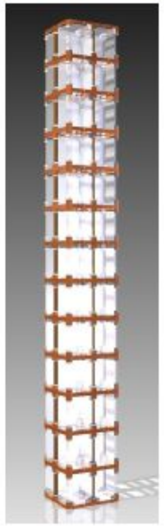
CUORE uses this technique

CUORE

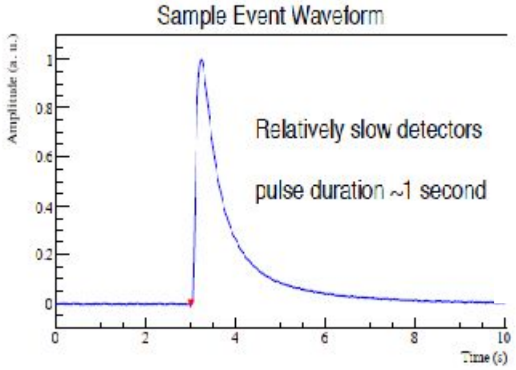
CUORE Cryogenic Underground Observatory for Rare Events



13 floors per tower



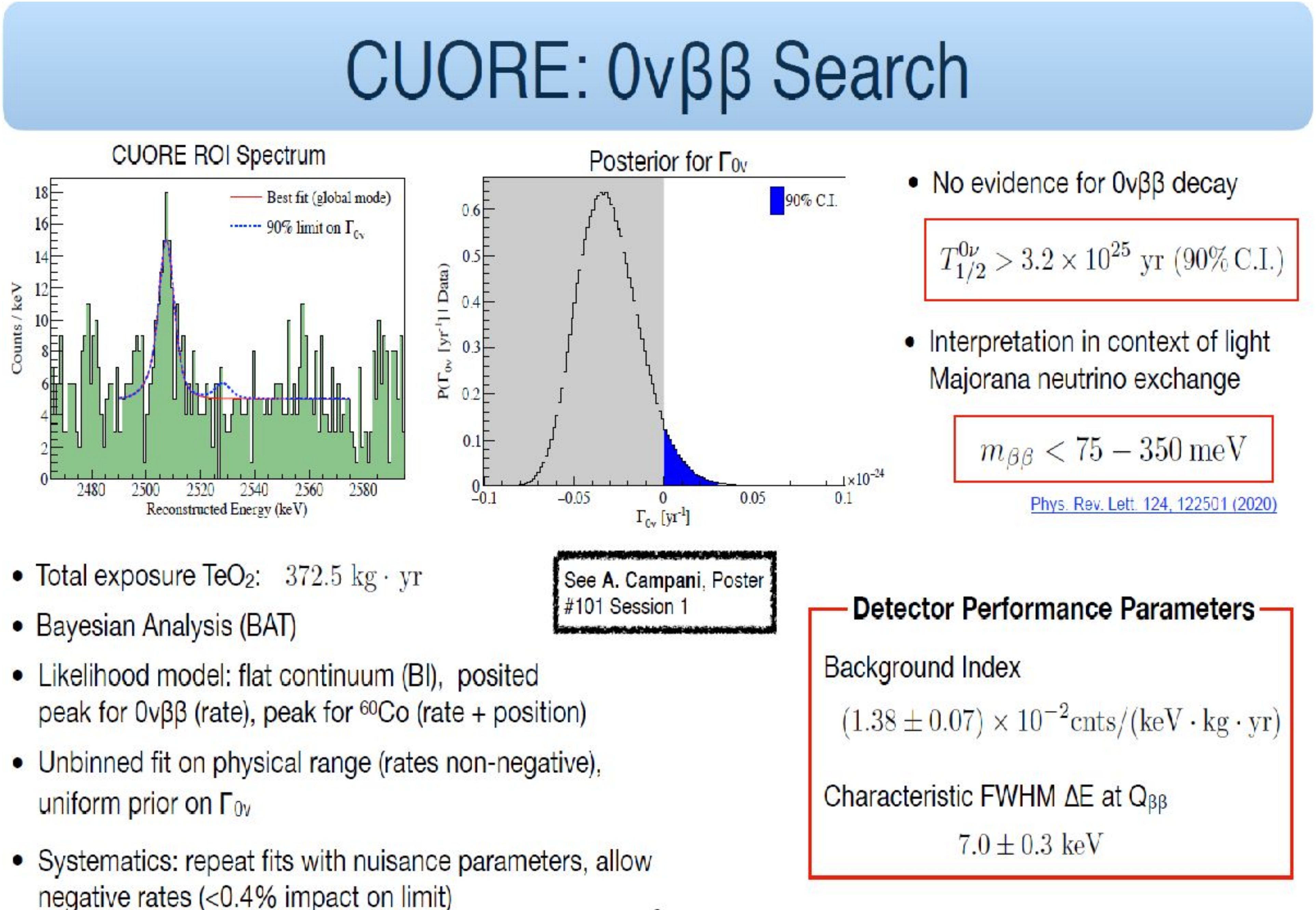
19 towers in total



- Hosted at Gran Sasso Underground Lab
- Close-packed array of 988 $^{nat}TeO_2$ bolometers (Total active mass: 742 kg)
- Operated at T~11 mK
- Primary physics goal: 0νββ decay of ^{130}Te
  - Isotopic abundance 34% => 206 kg
  - Q-value: 2527.5 keV
- CUORE design goals:
  - Energy resolution: 5 keV FWHM near $Q_{\beta\beta}$
  - Background: 0.01 c/keV/kg/y near $Q_{\beta\beta}$
  - 0νββ sensitivity for 5 years of livetime:

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

CUORE



CUORE: 0νββ Search

- No evidence for 0νββ decay

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

- Interpretation in context of light Majorana neutrino exchange

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

Phys. Rev. Lett. 124, 122501 (2020)

- Total exposure TeO_2: $372.5\ \mathrm{kg \cdot yr}$
- Bayesian Analysis (BAT)
- Likelihood model: flat continuum (BI), posited peak for 0νββ (rate), peak for ^{60}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

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

Characteristic FWHM ΔE at $Q_{\beta\beta}$

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

How to reach the few meV scale

80 000 bolometers of 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 FHWM

} Already achieved

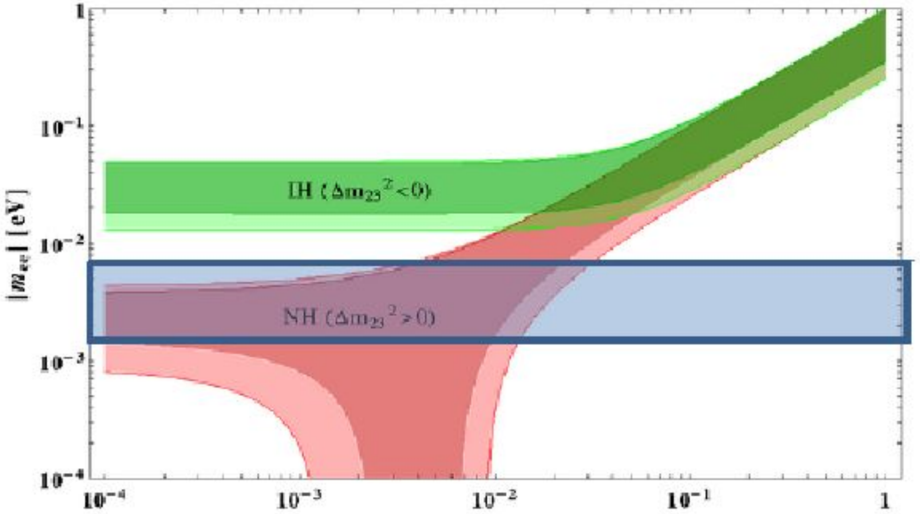
Background index: b = 10^{-5} counts/(keV kg y) (testable in CUPID)

Live time: 10 y

90% sensitivity:

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

$m_{ee} < 1.6 - 7.5$ meV



Sensitivity

The reach of an experiment is typically characterized through

limit setting sensitivity:
“limit on signal strength expected assuming no signal”

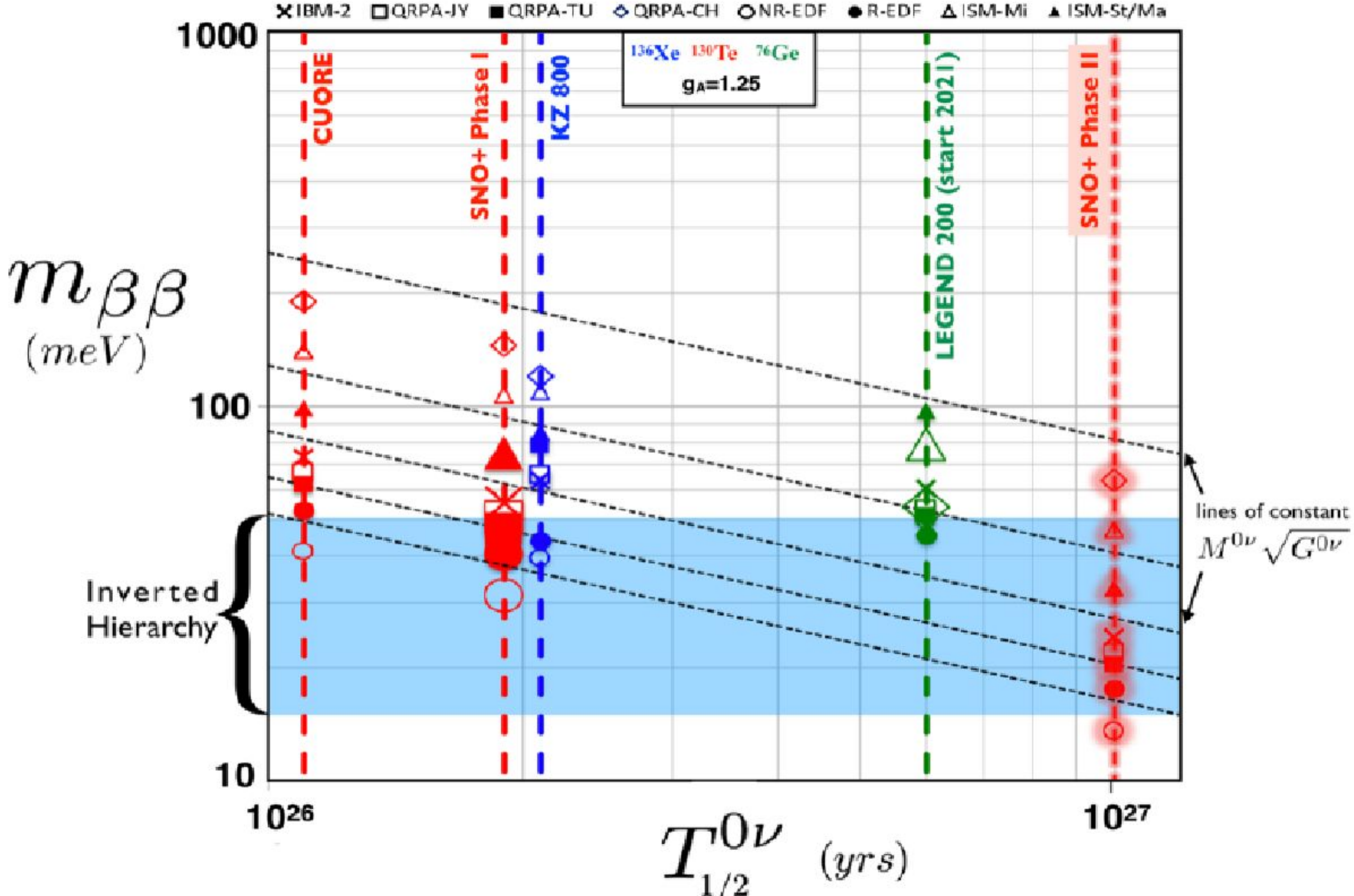
signal discovery sensitivity:
“minimal signal strength for which a discovery is expected”

At the background level of next-gen experiments:

- ➢ Different sensitivity definitions ➪ different numbers
- ➢ limit setting sensitivity has pathological behaviours

We search for a signal…
let’s focus on the discovery sensitivity

Projected 2024 0νββ Sensitivities



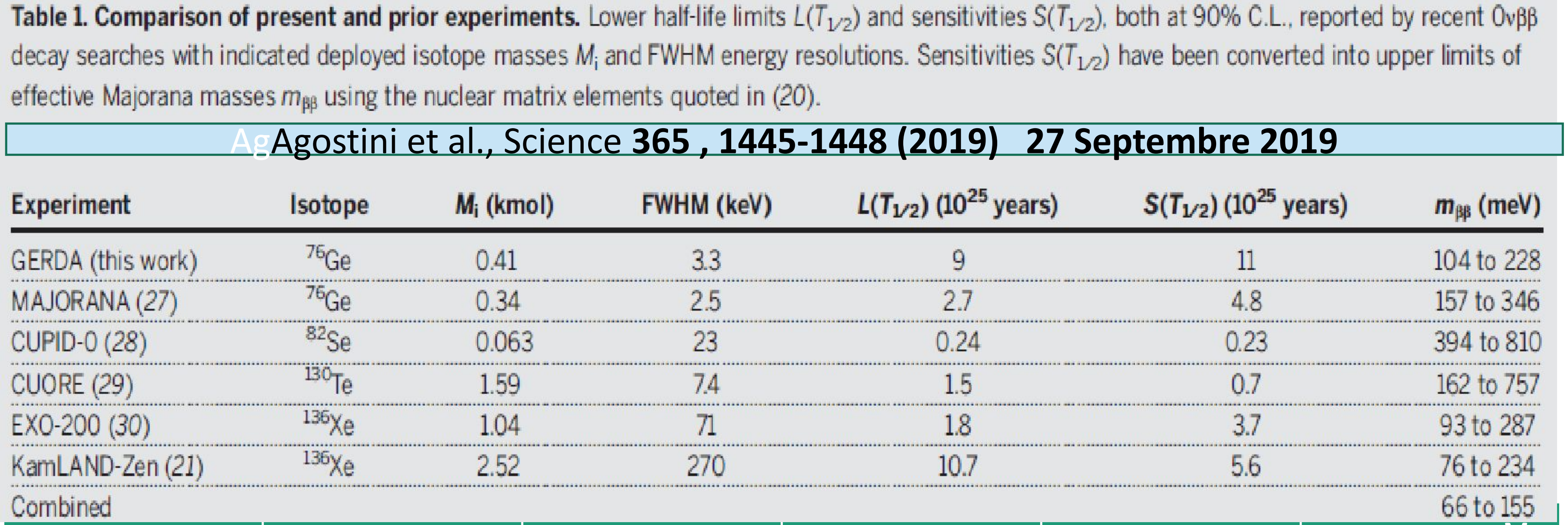
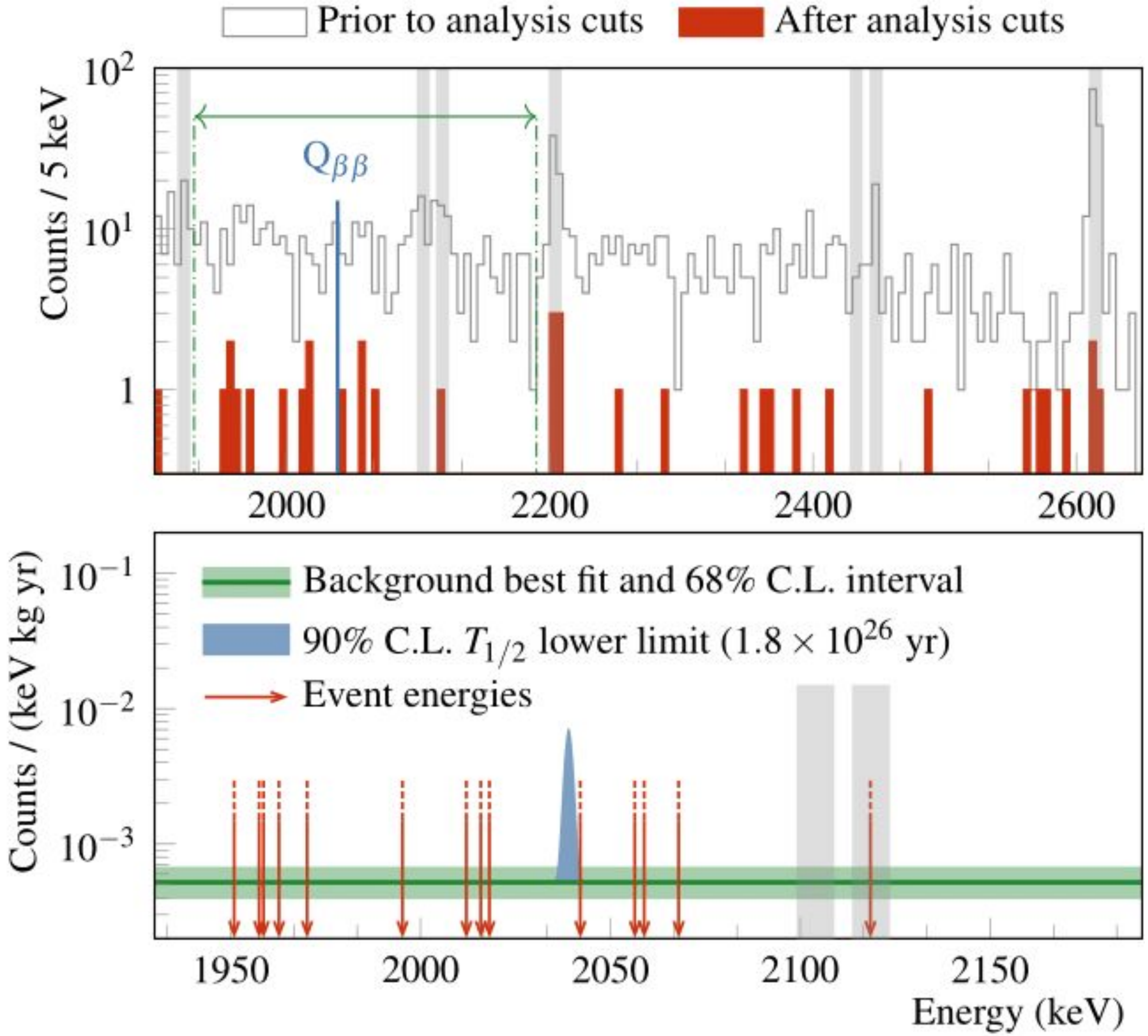


Table 1. Comparison of present and prior experiments. Lower half-life limits $L(T_{1/2})$ and sensitivities $S(T_{1/2})$, both at 90% C.L., reported by recent 0νββ decay searches with indicated deployed isotope masses M_i and FWHM energy resolutions. Sensitivities $S(T_{1/2})$ have been converted into 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}Ge	0.41	3.3	9	11	104 to 228
MAJORANA (*27*)	^{76}Ge	0.34	2.5	2.7	4.8	157 to 346
CUPID-0 (*28*)	^{82}Se	0.063	23	0.24	0.23	394 to 810
CUORE (*29*)	^{130}Te	1.59	7.4	1.5	0.7	162 to 757
EXO-200 (*30*)	^{136}Xe	1.04	71	1.8	3.7	93 to 287
KamLAND-Zen (*21*)	^{136}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


Prior to analysis cuts
After analysis cuts
Counts / 5 keV
10^2
10^1
1
$Q_{\beta\beta}$
2000
2200
2400
2600
Counts / (keV kg yr)
10^{-1}
10^{-2}
10^{-3}
Background best fit and 68% C.L. interval
90% C.L. $T_{1/2}$ lower limit (1.8×10^{26} yr)
Event energies
1950
2000
2050
2100
2150
Energy (keV)

GERDA SENSITIVITY CALCULATIONS

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

- Two channels: PhaseI + PhaseII

- PhaseI – 61 EVENTS; FWHM = 4.13 keV
- PHASEII – 13 EVENTS; FWHM = 3.29 keV

- 5 channels: Golden+Silver+BEGe+PhaseI+ + PhaseII

(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*E

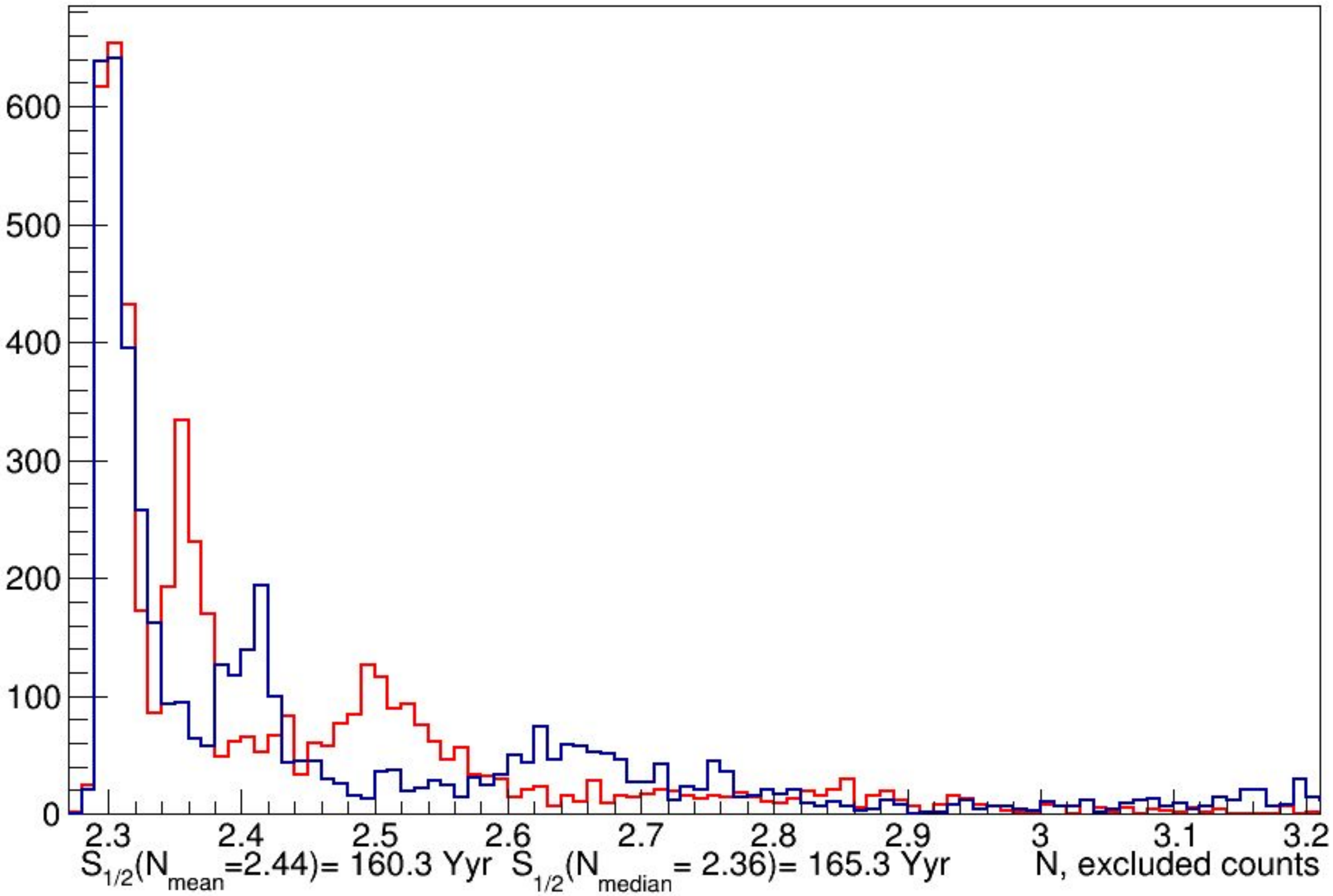
- 0) Systematics – E, FWHM, Eff
- A) full region [1930,2190] keV
- B) with exclusion of effect region – [2037,2041] keV
- C) statistics – 5000 FITS

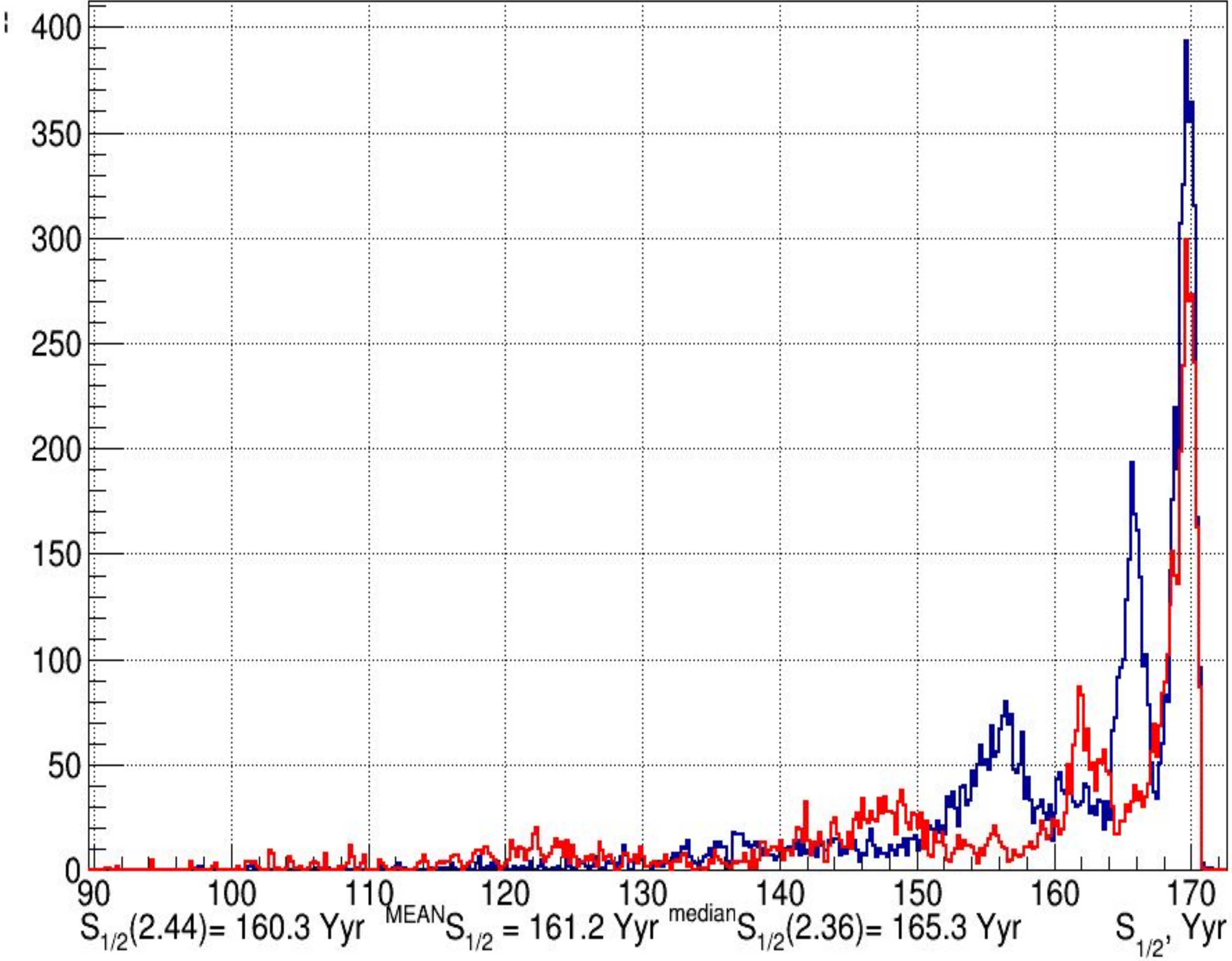
GERDA final – per ALL detectors were made 408 partitions, i.e. time intervals with stable resolution and efficiency.

SENSITIVITY = 180 Yyr.

Blue - 2 channels Red-5 channels

N = 5000 BAT N_{exl} distribution




0
50
100
150
200
250
300
350
400
90
100
110
120
130
140
150
160
170
$S_{1/2}(2.44) = 160.3$ Yyr ${}^{MEAN}S_{1/2} = 161.2$ Yyr ${}^{median}S_{1/2}(2.36) = 165.3$ Yyr
$S_{1/2}$, Yyr

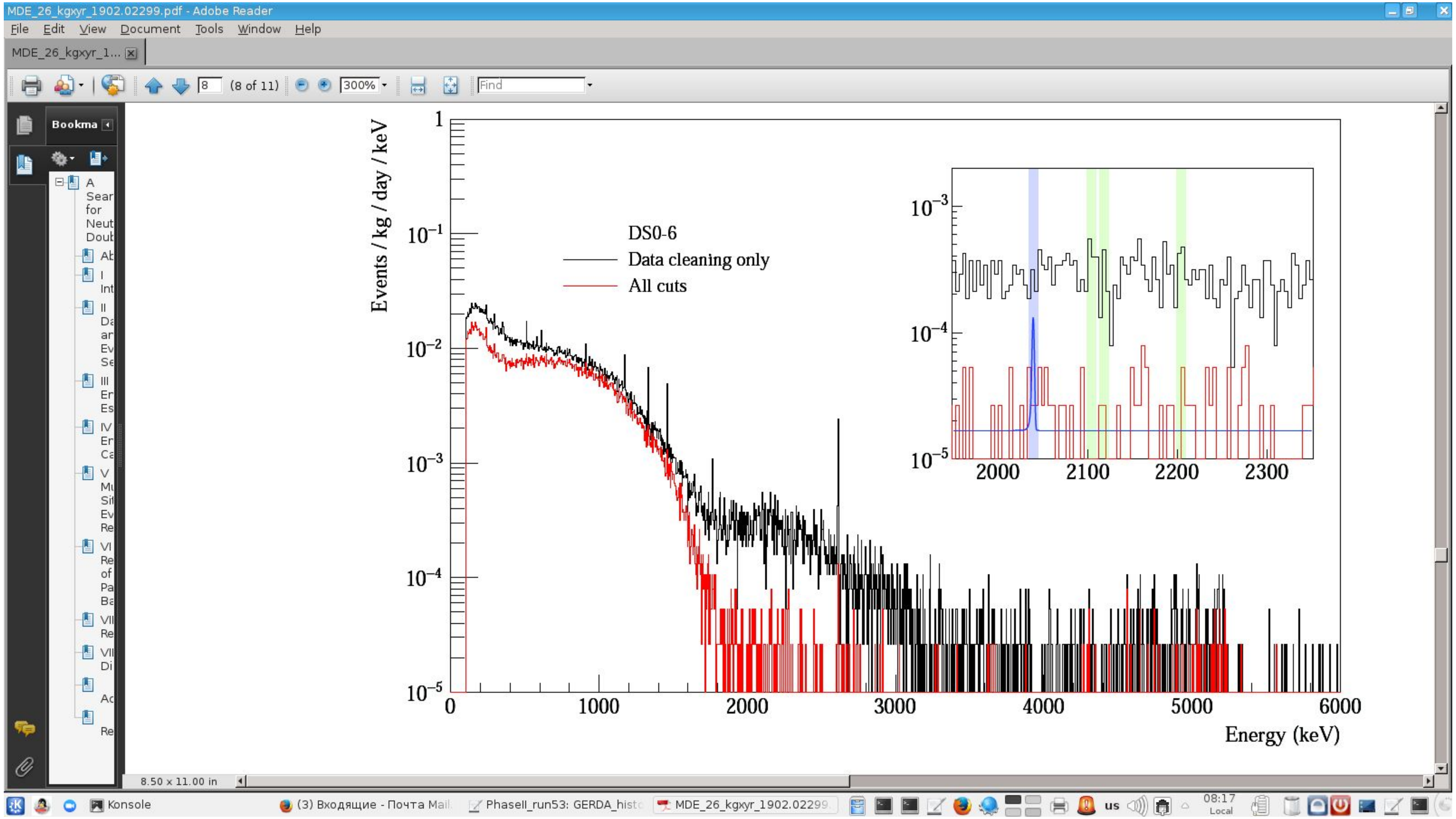
Summary

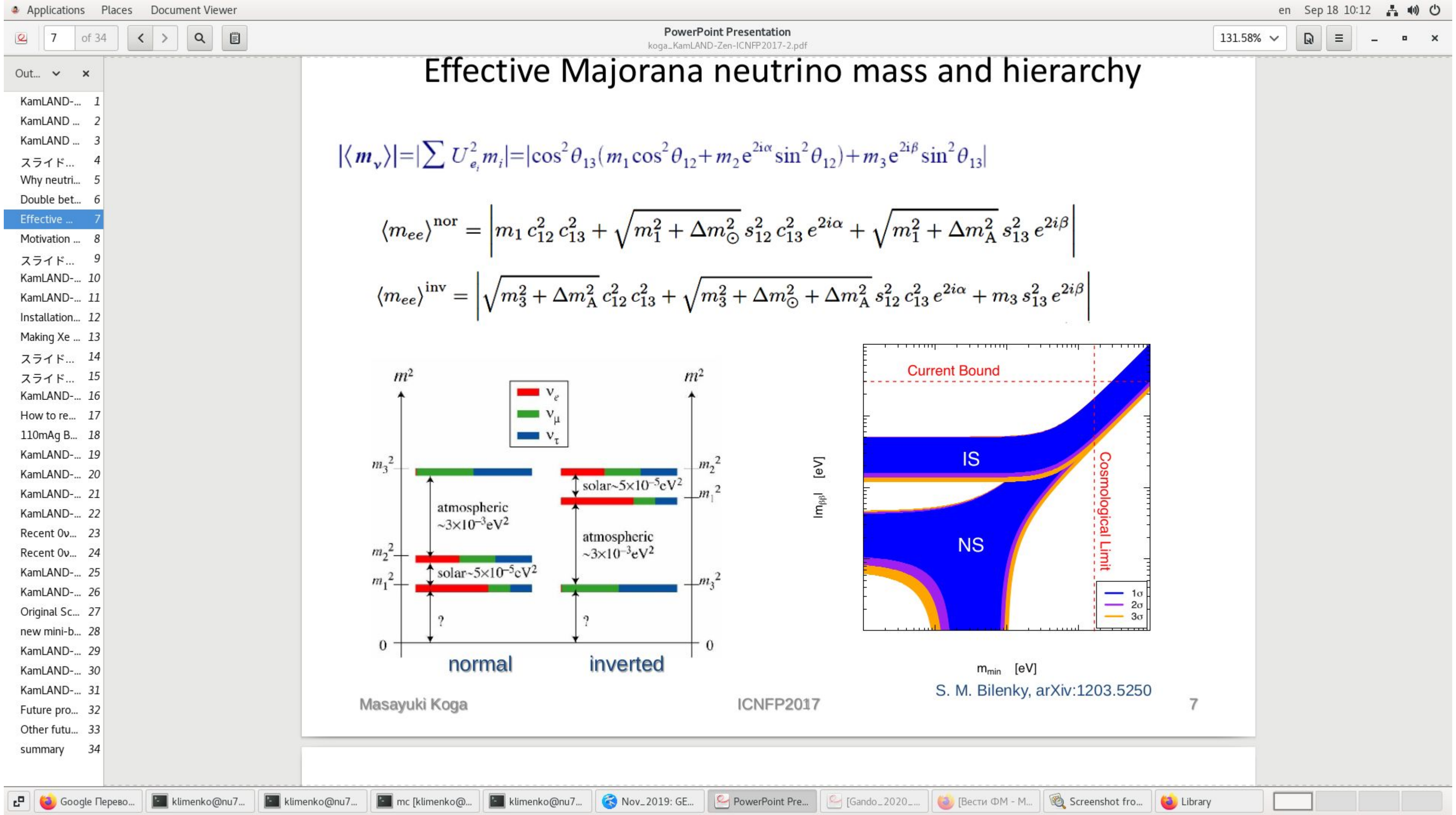
The combined analysis of sensitivities of current searching for the $0\nu\beta\beta$ decay experiments in active phase and some finished ones gives us for $\langle m_{\beta\beta} \rangle$ restriction in range 23.4 – 51.3 meV .

GERDA BI is 2 counts / FWHM / t*yr

Sensitivity - 1.8×10^{26} yr.

BACKUP SLIDES


MDE_26_kgxyr_1902.02299.pdf - Adobe Reader
File Edit View Document Tools Window Help
MDE_26_kgxyr_1...
8 (8 of 11)
300%
Find
Bookma
8.50 x 11.00 in
Events / kg / day / keV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
1000
2000
3000
4000
5000
6000
Energy (keV)
DS0-6
Data cleaning only
All cuts
10^{-3}
10^{-4}
10^{-5}
2000
2100
2200
2300
Konsole
(3) Входящие - Почта Mail
PhaseII_run53: GERDA_hist
MDE_26_kgxyr_1902.02299
us
08:17
Local



Effective Majorana neutrino mass and hierarchy

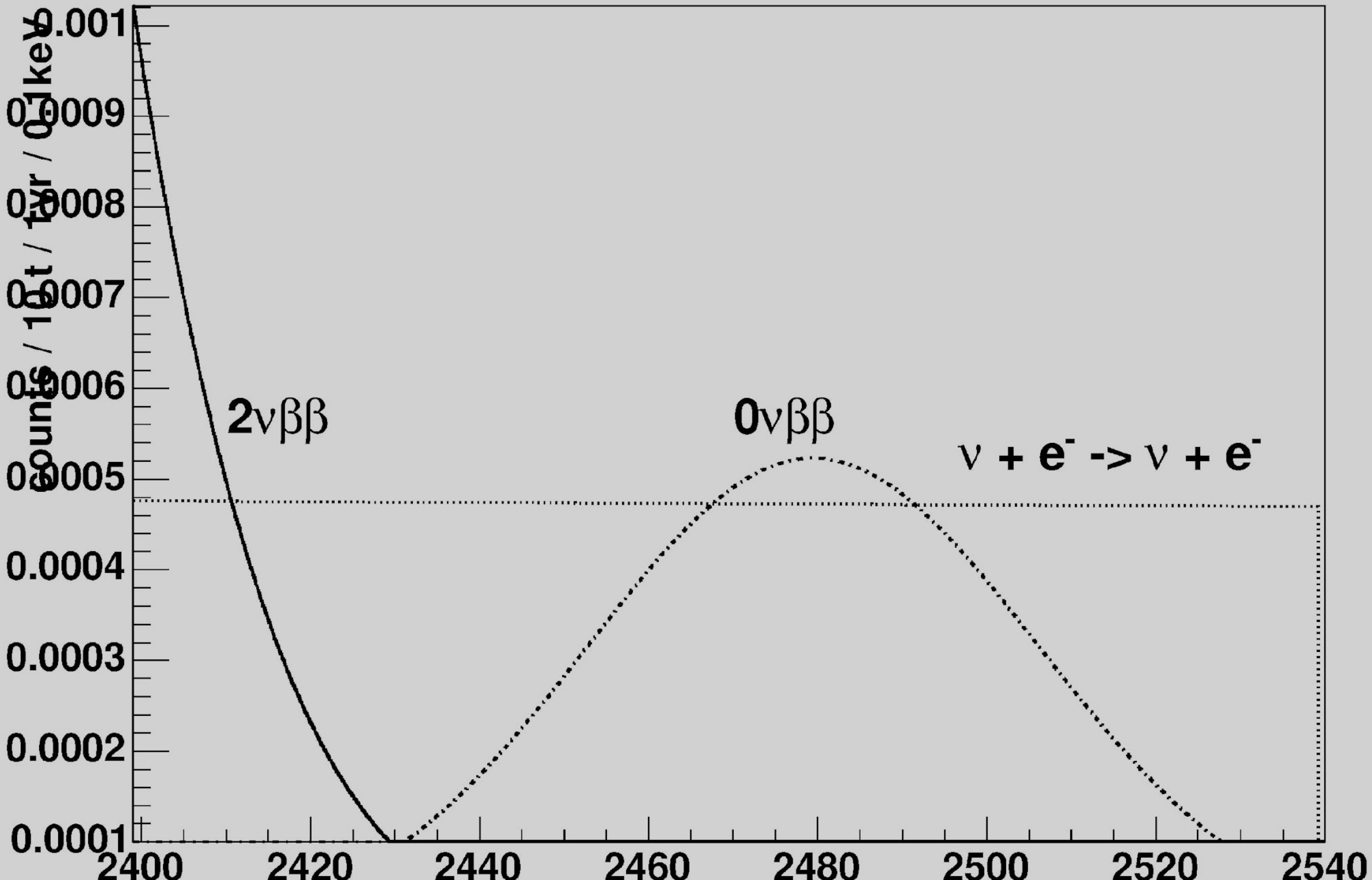
$$|\langle m_\nu\rangle| = |\sum U_{e_i}^2 m_i| = |\cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}|$$

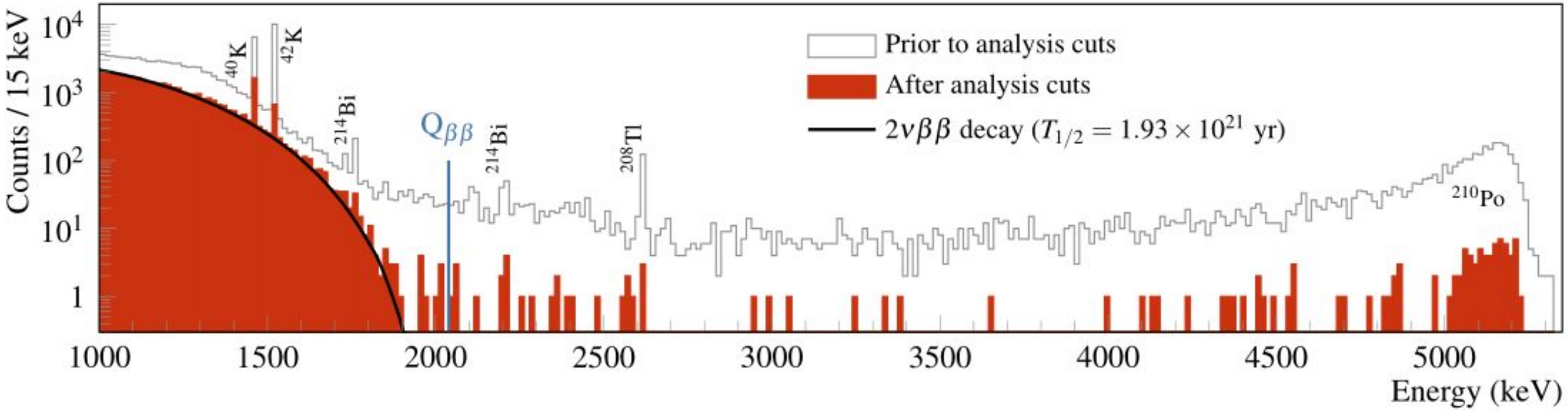
$$\langle m_{ee}\rangle^{\rm nor} = \left| m_1\, c_{12}^2\, c_{13}^2 + \sqrt{m_1^2 + \Delta m_\odot^2}\, s_{12}^2\, c_{13}^2\, e^{2i\alpha} + \sqrt{m_1^2 + \Delta m_{\rm A}^2}\, s_{13}^2\, e^{2i\beta} \right|$$

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

S. M. Bilenky, arXiv:1203.5250

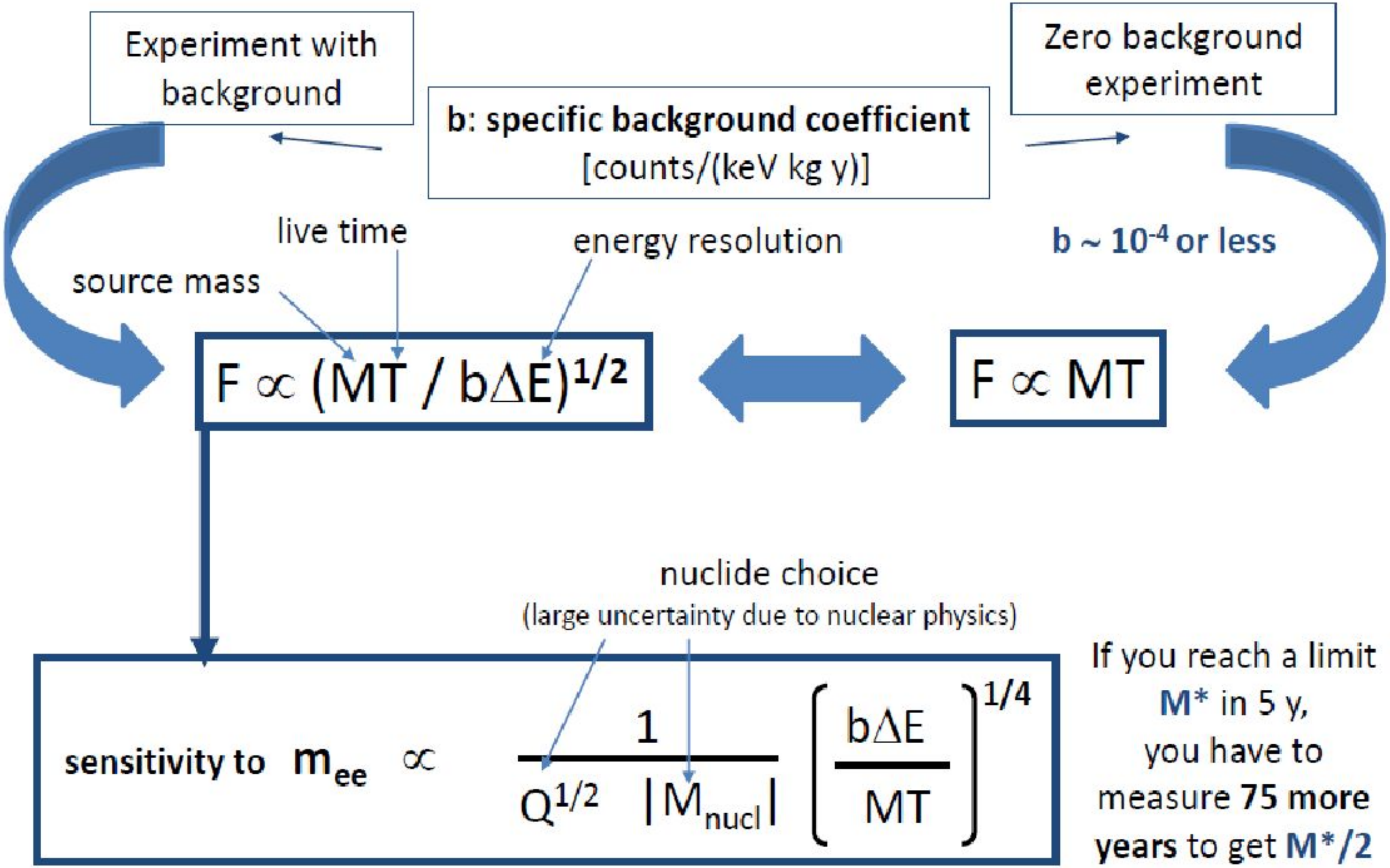
Masayuki Koga ICNFP2017 7


counts / 10 t / 1yr / 0.1keV
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
2400
2420
2440
2460
2480
2500
2520
2540
2νββ
0νββ
ν + e⁻ -> ν + e⁻


Counts / 15 keV
10^4
10^3
10^2
10^1
1
^{40}K
^{42}K
^{214}Bi
Q$_{\beta\beta}$
^{214}Bi
^{208}Tl
^{210}Po
Prior to analysis cuts
After analysis cuts
$2\nu\beta\beta$ decay ($T_{1/2} = 1.93 \times 10^{21}$ yr)
1000
1500
2000
2500
3000
3500
4000
4500
5000
Energy (keV)

The sensitivity

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



Experiment with background

b: specific background coefficient
[counts/(keV kg y)]

Zero background experiment

source mass

live time

energy resolution

b ~ 10^{-4} or less

$F \propto (MT / b\Delta E)^{1/2}$

$F \propto MT$

nuclide choice
(large uncertainty due to nuclear physics)

sensitivity to $m_{ee} \propto \dfrac{1}{Q^{1/2}\ |M_{nucl}|}\left(\dfrac{b\Delta E}{MT}\right)^{1/4}$

If you reach a limit **M*** in 5 y, you have to measure **75 more years** to get **M*/2**