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Neutrinoless double beta decay

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Outline

- $2\nu\beta\beta$ and $0\nu\beta\beta$ beta decay
- Background issue
- Physics beyond the SM
- Present and future of $0\nu\beta\beta$ searches
- Summary

Double Beta Decay

Standard Model and Beyond

- ββ decay
- Bcg issue
- Physics BSM
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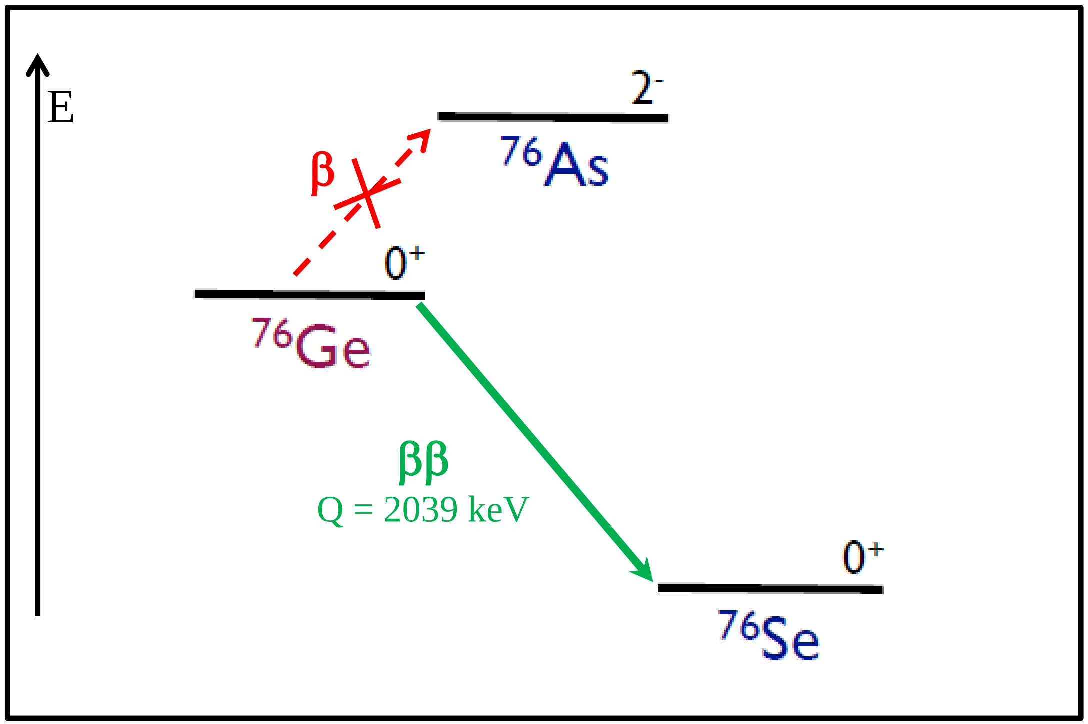
In a number of even-even nuclei, β decay due to energy/angular momentum balance is forbidden, while double beta decay from a nucleus (A,Z) to (A, Z+2) is energetically allowed.



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

Standard Model and Beyond
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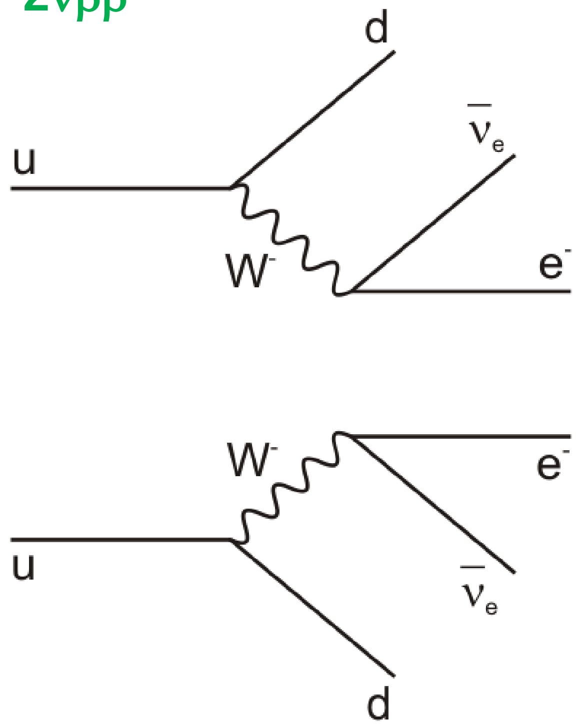
Double Beta Decay Modes

$2\nu\beta\beta$

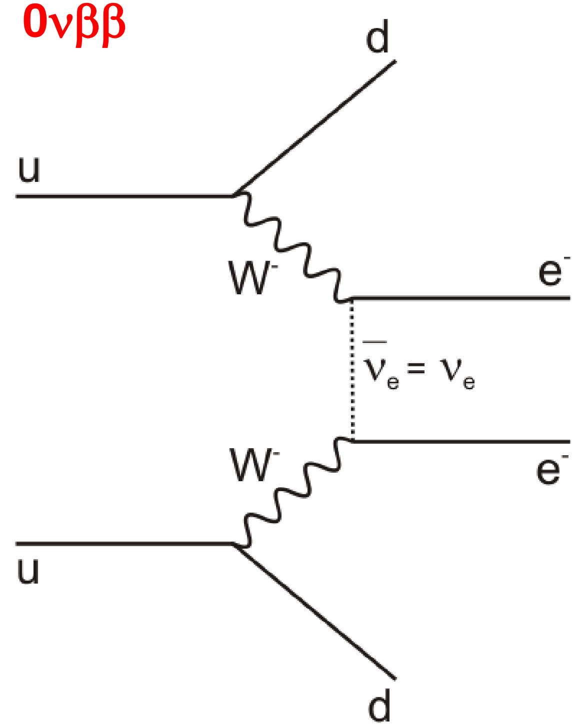


$(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

$\Delta L = 0$

$T_{1/2} \sim 10^{18} - 10^{24}$ yr

$0\nu\beta\beta$



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

$\Delta L = 2$

$T_{1/2}^{exp} > 2.3\times10^{26}$ yr

Double Beta Decay Modes

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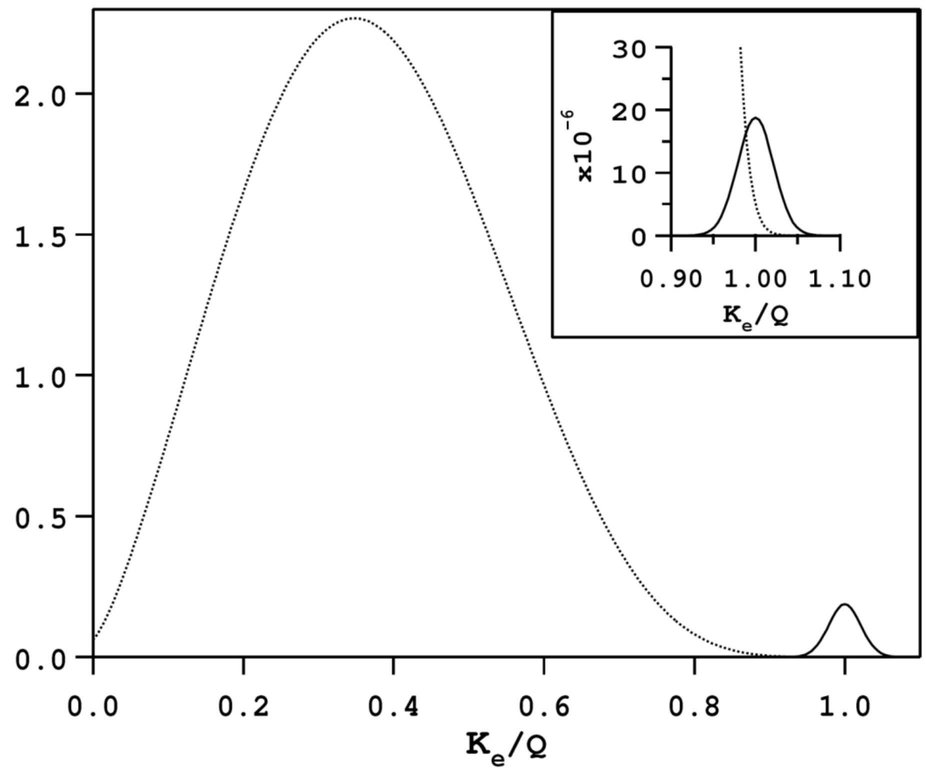

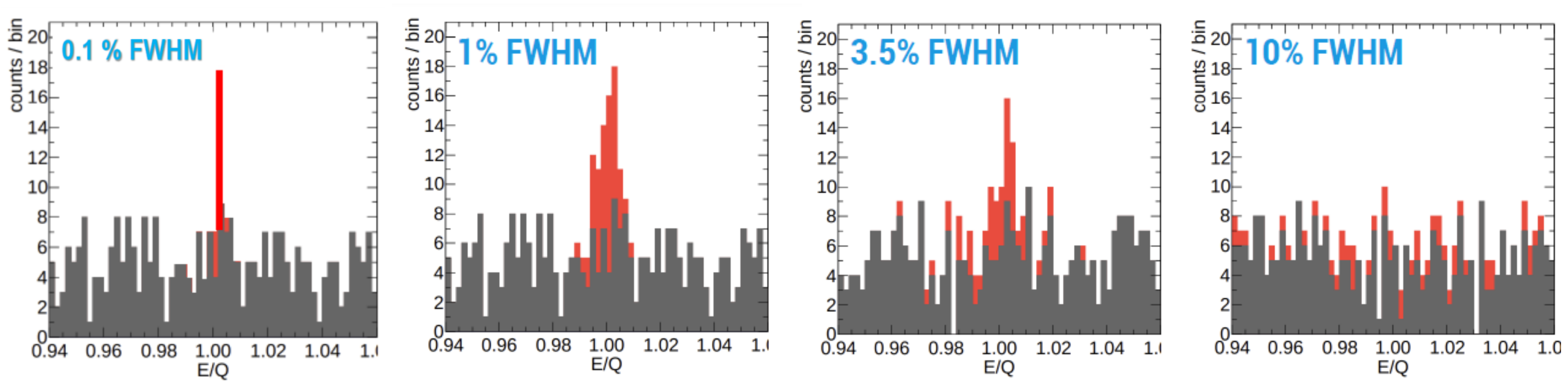

A. Simon

Background Issue

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a \cdot M \cdot T$$

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

ε – detection efficiency
A – isotope molar mass
a – isotope mass fraction
M – active mass
T – measurement time
B – background rate
ΔE – energy resolution
M·T – exposure

Background Issue

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

$$\frac{1}{T_{1/2}} = G(Q,Z) \cdot |M_{nuc}|^2 \cdot < m_{ee} >^2$$

Space phase factor (~Q_{bb}^5)

Nuclear matrix element

Effective neutrino mass

$$< m_{ee} > = |\sum_j m_j U_{ej}^2|$$

Background Issue

No background

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a \cdot M \cdot T$$

Background

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a \sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

$$\frac{1}{T_{1/2}} = G(Q,Z) \cdot |M_{nuc}|^2 \cdot < m_{ee} >^2$$

$$< m_{ee} > \sim \frac{1}{\sqrt{T_{1/2}}} \sim \sqrt[4]{\frac{B \cdot \Delta E}{M \cdot T}}$$

$$(M \cdot T)\uparrow \times 100 \rightarrow T_{1/2} \uparrow 10 \rightarrow < m_{ee} > \downarrow \times \sim 3$$

0νββ Decay Expected Rate

Zero-background case back on an envelope

$$T_{1/2} = \frac{ln2}{N_{\beta\beta}} \frac{N_A}{A} M \cdot T$$

If one wants to measure **$T_{1/2} \sim 10^{27}$ yr ($m_{ee} \sim 50$ meV)**
Then **1 event/y** requires about **10^{27} source atoms**
It means about **1000 moles** of isotope is needed
implying mass of **~100 kg**

And now one can only loose because of:

abundance, detection efficiency, background, energy resolution

Neutrino Mass / Hierarchy Problem

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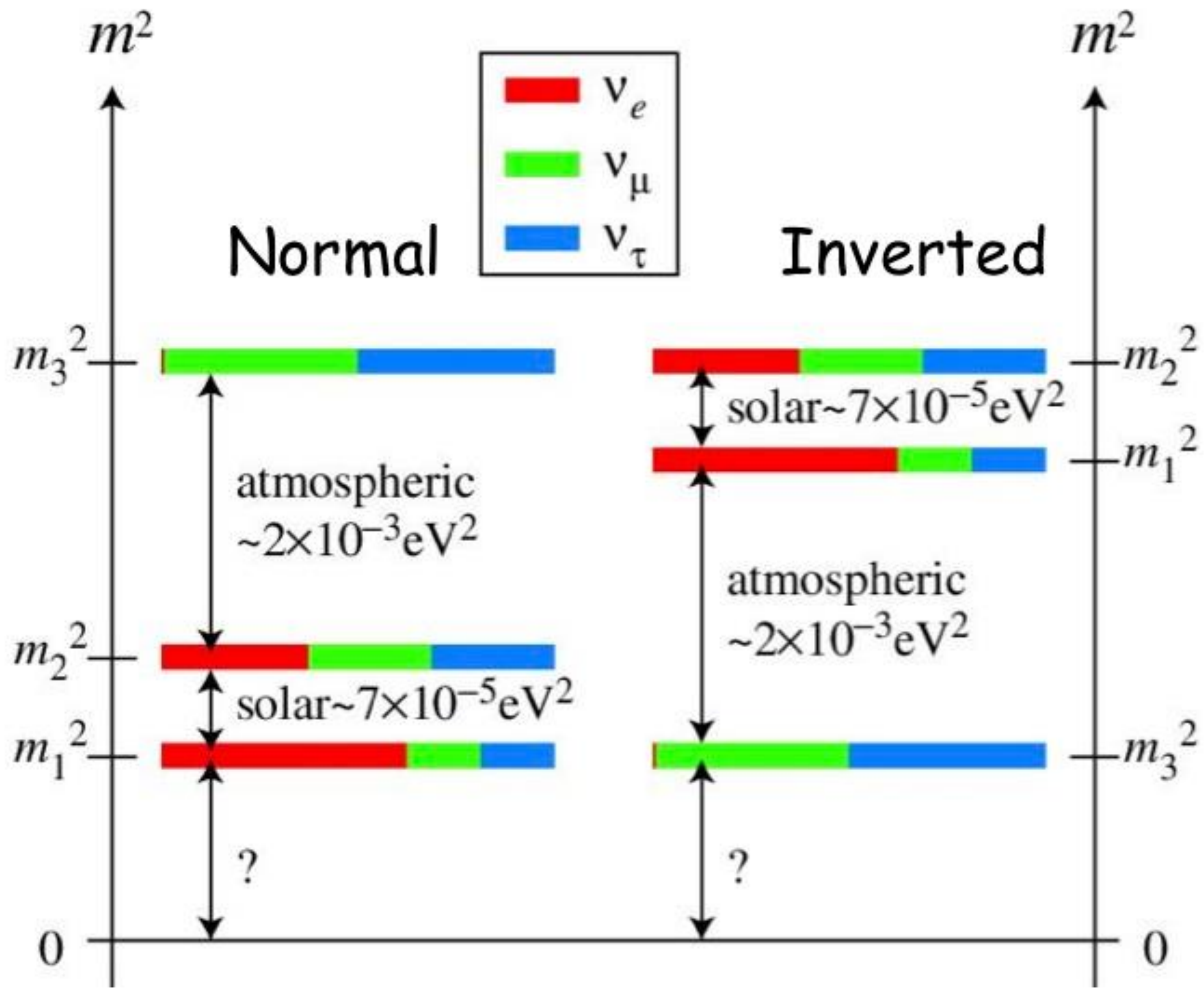
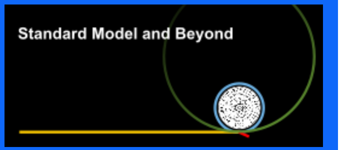


Neutrino Mass / Hierarchy Problem



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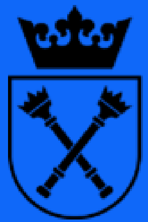

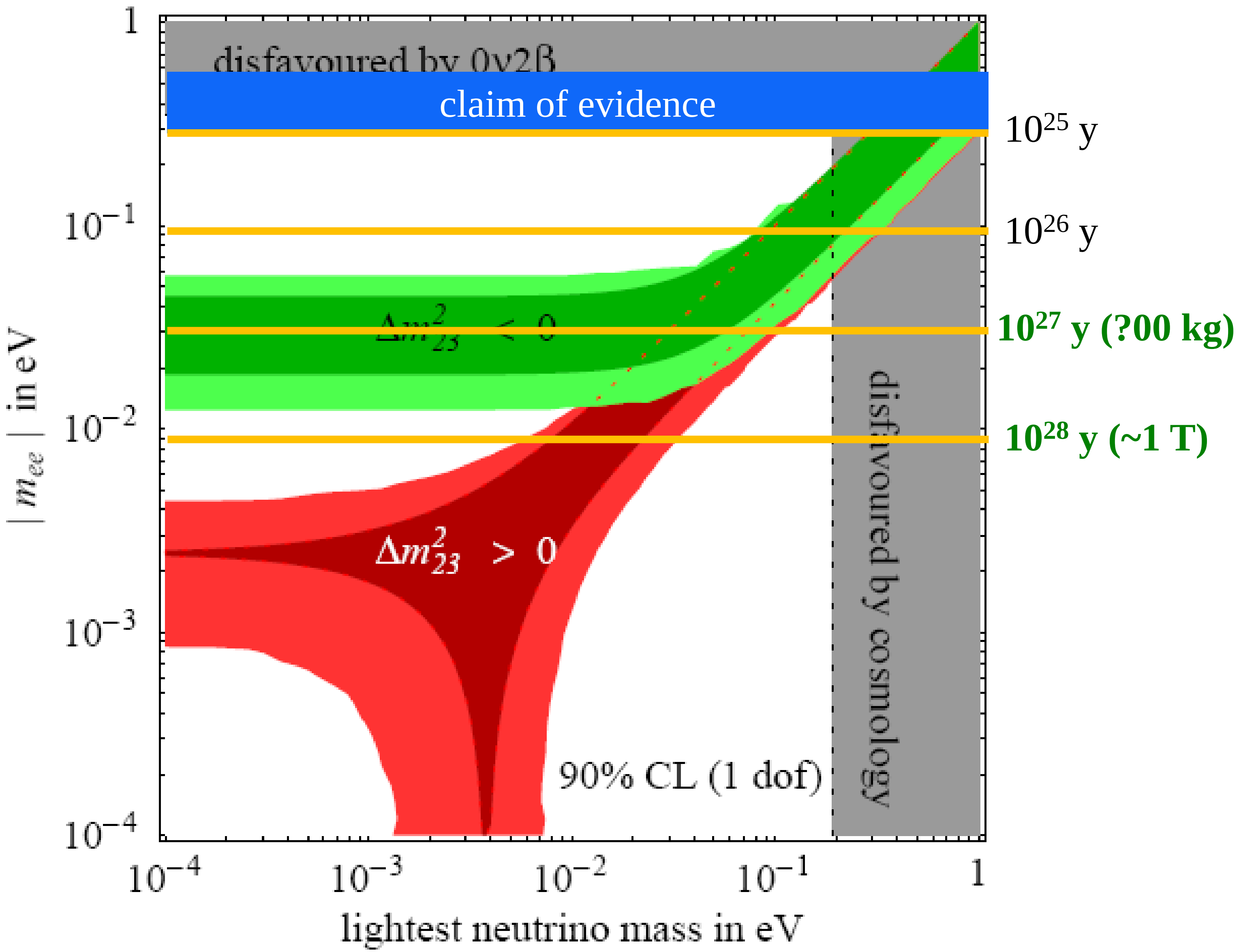

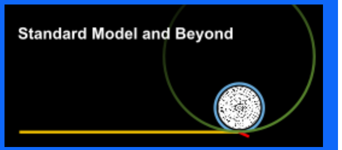

Physics Beyond the Standard Model

If 0νββ decay observed:

- Neutrino is a Majorana particle (its own antiparticle)
- Lepton number is not conserved
- Dealing with physics beyond the Standard Model

0νββ decay gives opportunity to determine:

- Absolute neutrino mass scale (meV scale !)
- Neutrino mass hierarchy
- CP violation in the lepton sector

Significant contribution to Particle Physics, Astrophysics and Cosmology

Experimental Requirements

- Large detector masses → tones to reach 10^{28} yr
  - scalability / modularity
  - moderate costs
- High isotopic abundance → enrichment
- High detection efficiency → target = detector
- **True background-free operation**
  - Underground location (cosmic rays)
  - Intrinsic (target) / external (shielding) background
  - Event identification
  - Event topology
  - PSD
- **Very good energy resolution → discovery**
- Stable operation over many years → proven technology

0νββ Decay Experiments

Ionization

Tracking
(Super)NEMO

Crystals
GERDA
LEGEND
MAJORANA
COBRA

Ionization + Scintillation: TPC
(n)EXO, PANDA, DARWIN (LXe)
NEXT (GXe)

Scintillation

LS
KAMLAND-Zen
SNO+

Crystals
CANDLES

Scintillating Bolometers
CUPID, AMoRE

Heat

Bolometers
CUORE

0νββ Decay Isotopes

35 isotopes can undergo 0νββ decay

only ~1/3 is experimentally relevant

Isotope	$Q_{\beta\beta}$ [keV]	A [%]	$G_{0\nu}$ [10^{-15} y]	$M_{0\nu}$	Experiments
$^{48}Ca \rightarrow {}^{48}Ti$	4271	0.19	24.8	0.7 – 3.0	CANDLESS
$^{76}Ge \rightarrow {}^{76}Se$	2039	7.8	2.36	2.2 – 6.2	GERDA, MAJORANA, LEGEND
$^{82}Se \rightarrow {}^{82}Kr$	2995	9.2	10.2	2.2 – 5.6	CUPID-0
$^{96}Zr \rightarrow {}^{96}Mo$	3350	2.8	20.6	2.8 – 6.6	ZICOS
$^{100}Mo \rightarrow {}^{100}Ru$	3034	9.6	15.9	3.8 – 6.8	CUPID, AMORE, NEMO-III
$^{110}Pd \rightarrow {}^{110}Cd$	2013	11.8	4.8	4.0 – 6.6	ISOLDE
$^{116}Cd \rightarrow {}^{116}Sn$	2802	7.5	16.7	3.0 – 5.6	Aurora
$^{124}Sn \rightarrow {}^{124}Te$	2228	5.6	9.0	2.0 – 5.8	TIN.TIN
$^{130}Te \rightarrow {}^{130}Xe$	2530	34.5	14.2	1.2 – 6.6	CUORE, SNO+
$^{136}Xe \rightarrow {}^{136}Ba$	2458	8.9	14.6	1.4 – 4.8	EXO, NEXT, PANDA, KamLAND-Zen
$^{150}Nd \rightarrow {}^{150}Sm$	3367	5.6	63.0	2.0 – 5.2	NEMO-III

^{136}Xe vs. ^{76}Ge

Parameter	EXO-200	KamLAND - Zen 800	NEXT-White	GERDA
M [kg]	175	745	4.3	44.2
M×T [kg×yr]	234.1	970	2.8	127.2
FWHM at $Q_{\beta\beta}$ [keV]	25	100	22	3
BI [cts/(kg×keV×yr)]	1.8×10^{-3}	$\sim10^{-4}$		5.2×10^{-4}
Bcg-free operation [Y/N]	N (~20)	N (~30)	N	Y (<1)
$T_{1/2}^{0\nu}$ [10^{26} yr]	0.35	2.3		1.8

- Presently the best limit on $T_{1/2}^{0\nu}$ comes form Xe
- Good energy resolution and low background are key factors for discovery
- Costs: experiment specific

^{136}Xe vs. ^{76}Ge

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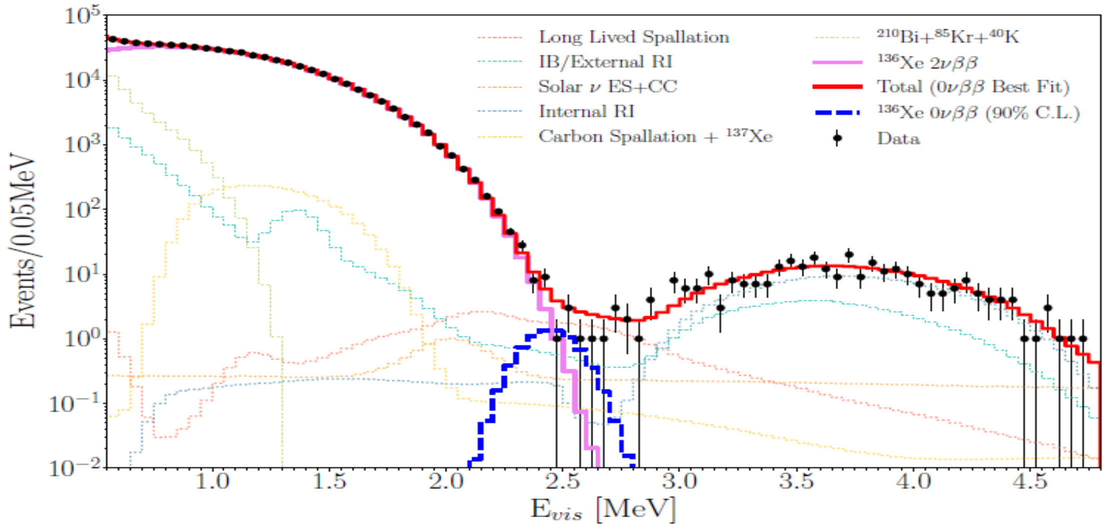
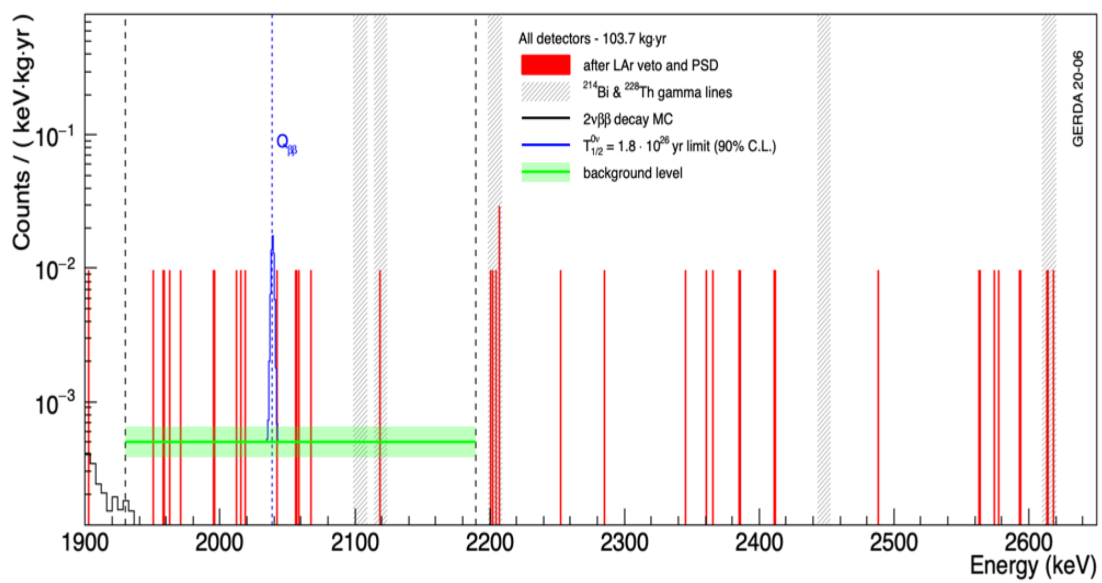


– $N_{0vbb} \leq 8$
– $T_{1/2}$ (0νββ) > 2.3×10^{26} yr
– $m_{\beta\beta} \leq$ (36 – 156) meV

PRL 110 (2013) 062502
PRL 117 (2016) 082503
PRL 122 (2019) 192501
e-Print: 2203.02139 [hep-ex] (03.2022)



– N_{0vbb} = 0
– $T_{1/2}$ (0νββ) > 1.8×10^{26} yr
– $m_{\beta\beta} \leq$ (80 – 182) meV

PRL 111 (2013) 122503
Nature 544 (2017) 47
PRL 120 (2018) 132503
Science 365, 1445 (2019)
PRL 125 (2020) 252502

ββ decay
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Future of 0νββ Decay Searches

- Several projects with ?00 kg of various isotopes ($T_{1/2}^{0\nu} \sim 10^{27}$ yr) running or under preparation (LEGEND-200, CUPID, EXO, NEXT, AMORE, SNO+,…)
- 13 – 16 July 2021: DOE-NP Portfolio Review of three ton-scale experiments:
  LEGEND-1000 (^{76}Ge), nEXO (^{136}Xe), NEXT (^{136}Xe), CUPID (^{100}Mo),
  - LEGEND performed exceedingly well and emerged as the leader,
  - LEGEND-1000 is now being supported by DOE to proceed to CD-1,
  - Location still to be defined (SNOLAB lab or LNGS),
- First phase, LEGEND-200 aims for $T_{1/2}^{0\nu} \sim 10^{27}$ yr with 200 kg of ^{enr}Ge
- LEGEND-200 at LNGS (GERDA technology) is presently under commissioning:
  - cryostat filled with purified LAr
  - 60 kg of HP^{enr}Ge deployed
  - LAr veto operational
- LEGEND-200 data taking to start still in 2022
- nEXO may still be financed by DOE (SNOLAB)
- CUPID-250 is proceeding at LNGS

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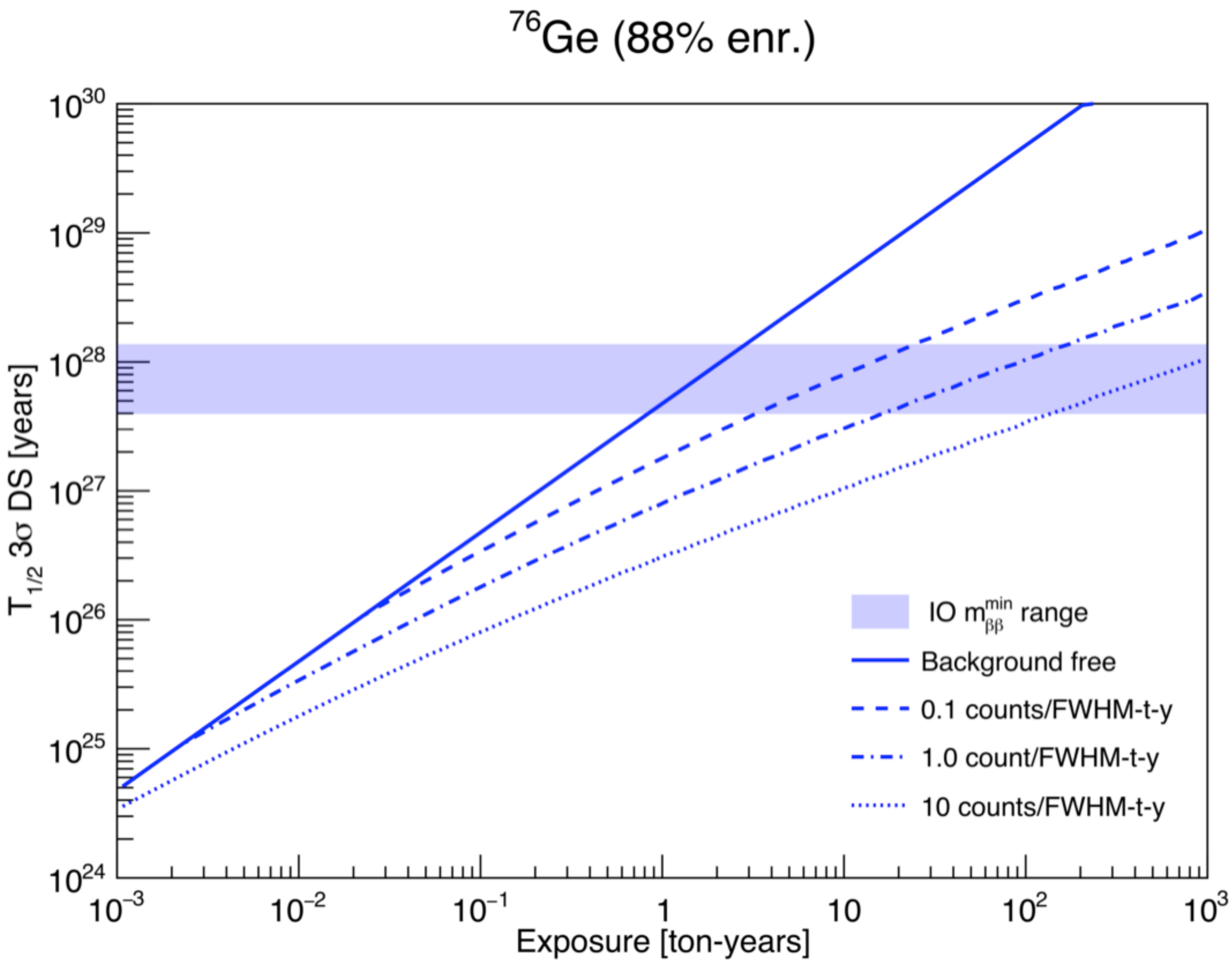
Summary

- Neutrinoless double beta decay plays an important role in particle and astro-particle physics
- If discovered, the 0νββ decay involves physics beyond the SM, some neutrino problems may be solved
- Several experimental efforts exploring different techniques are implemented
- Nex generation experiments needs to probe $T_{1/2}^{0\nu}$ at the level of ~ 10^{28} yr to explore IH
- Efforts to improve the detector parameters
- Presently the best limit for $T_{1/2}^{0\nu}$ comes form Xe-based experiment
- Energy resolution and background are key parameters for discovery potential

  → Ge-based experiments favored

Participation of scientists from the Jagiellonian University in the GERDA and LEGEND projects is supported by the Polish National Science Centre and the Polish Ministry for Education and Science

Backup



^{76}Ge (88% enr.)
10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
$T_{1/2}$ 3σ DS [years]
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
Exposure [ton-years]
IO $m_{\beta\beta}^{min}$ range
Background free
0.1 counts/FWHM-t-y
1.0 count/FWHM-t-y
10 counts/FWHM-t-y

Backup

Next generation $0\nu\beta\beta$ decay experiments

Experiment	Iso.	Iso. mass [kg]	Run Time [yr]	FWHM [keV]	BI [FWHM]]	BI [keV]	Eff.	3σ Discovery $T^{0\nu}_{1/2}$ [10^{27} yr]	3σ Discovery $\langle m_{\beta\beta}\rangle$ [meV]	Sensitivity $T^{0\nu}_{1/2}$ [10^{27} yr]	Sensitivity $\langle m_{\beta\beta}\rangle$ [meV]
LEGEND-200	^{76}Ge	180	5	2.5	0.6	0.2	0.69	0.9	35 – 73	1.4	29 – 60
LEGEND-1000	^{76}Ge	910	10	2.5		0.01	0.70	12.	10 – 20	14	9 – 19
CUPID	^{100}Mo	253	10	5		0.1	0.71	1.1	12 – 20	1.5	10 – 17
AMoRE-II	^{100}Mo	200	5	5		0.1	0.91			1.1	12 – 20
SNO+ Ph. I	^{130}Te	442	5	190		0.1				0.2	41 – 99
SNO+ Ph. II	^{130}Te									1	
KamLAND-Zen 800	^{136}Xe	745	5	235						0.5	
KamLAND2-Zen	^{136}Xe	1000									
nEXO	^{136}Xe	4038	10	58	0.14		0.74	5.7	7.3 – 22.3	9.2	5.7 – 17.7
PandaX-III 200	^{136}Xe	180	3	74		0.1	0.35			0.1	65 – 165
PandaX-III 1000	^{136}Xe	900	3	74		0.01	0.35			1	20 – 50
LUX-ZEPLIN natural	^{136}Xe	500	2.7	58						0.11	53 – 164
LUX-ZEPLIN enriched	^{136}Xe	5040	2.7	58						1.06	17 – 52
DARWIN	^{136}Xe	311	2.8	58		0				8.5	