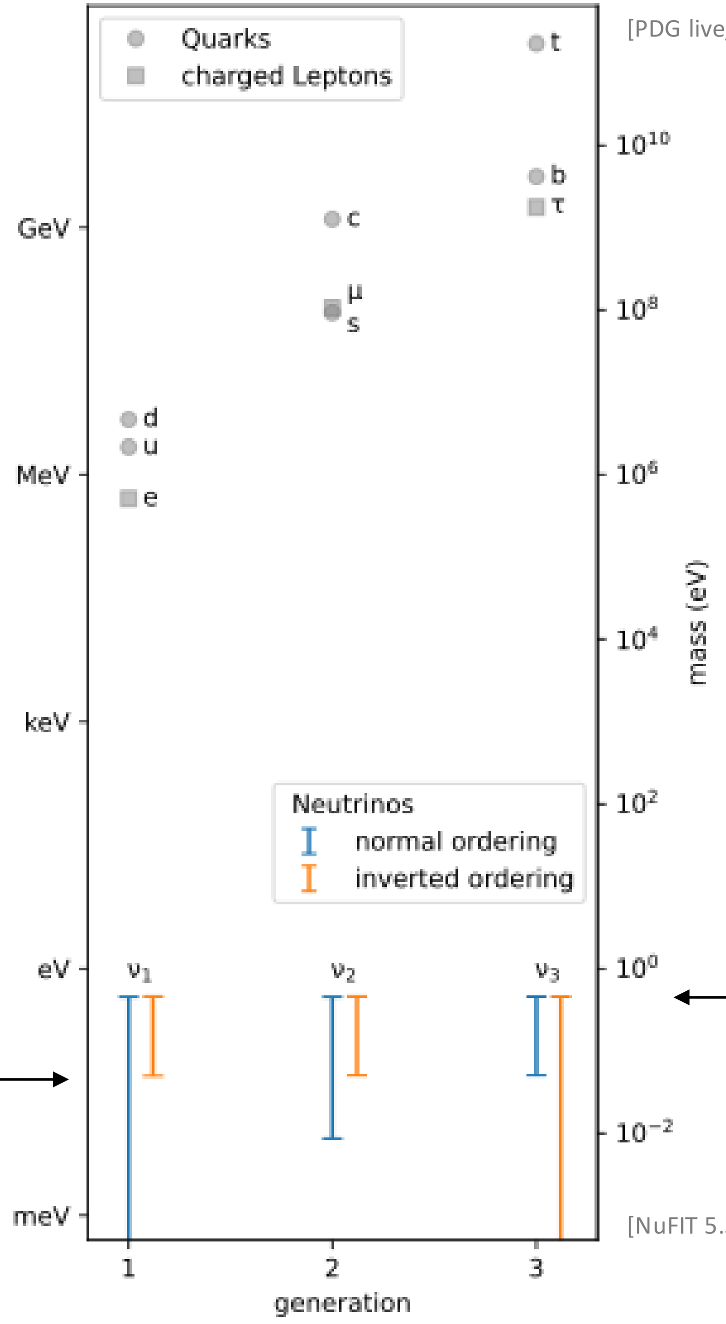
Neutrino masses and mixings –

Neutrinoless double beta decay searches

Christoph Wiesinger (Technical University of Munich), ISAPP school, 18.09.2024

*What we **don't** know about neutrinos*

- Which is the **lightest neutrino**?
  What is the neutrino **mass ordering**?
- Do **antineutrinos** behave differently?
  Is **CP violated** in the lepton sector?
- What is the **mass of the lightest neutrino**?
  What is the **absolute neutrino mass**?
- What is the **neutrino nature**?
  Is the neutrino its **own antiparticle**?
- Are there **additional neutrinos**?



[PDG live, pdglive.lbl.gov]

[NuFIT 5.3, nu-fit.org]

lower bounds from **oscillation experiments**

upper bound from **direct mass measurements**

*What we **don't** know about neutrinos*

- Which is the **lightest neutrino**?
  What is the neutrino **mass ordering**?
- Do **antineutrinos** behave differently?
  Is **CP violated** in the lepton sector?

} **Michael Wurm**'s lecture

- What is the **mass of the lightest neutrino**?
  What is the **absolute neutrino mass**?

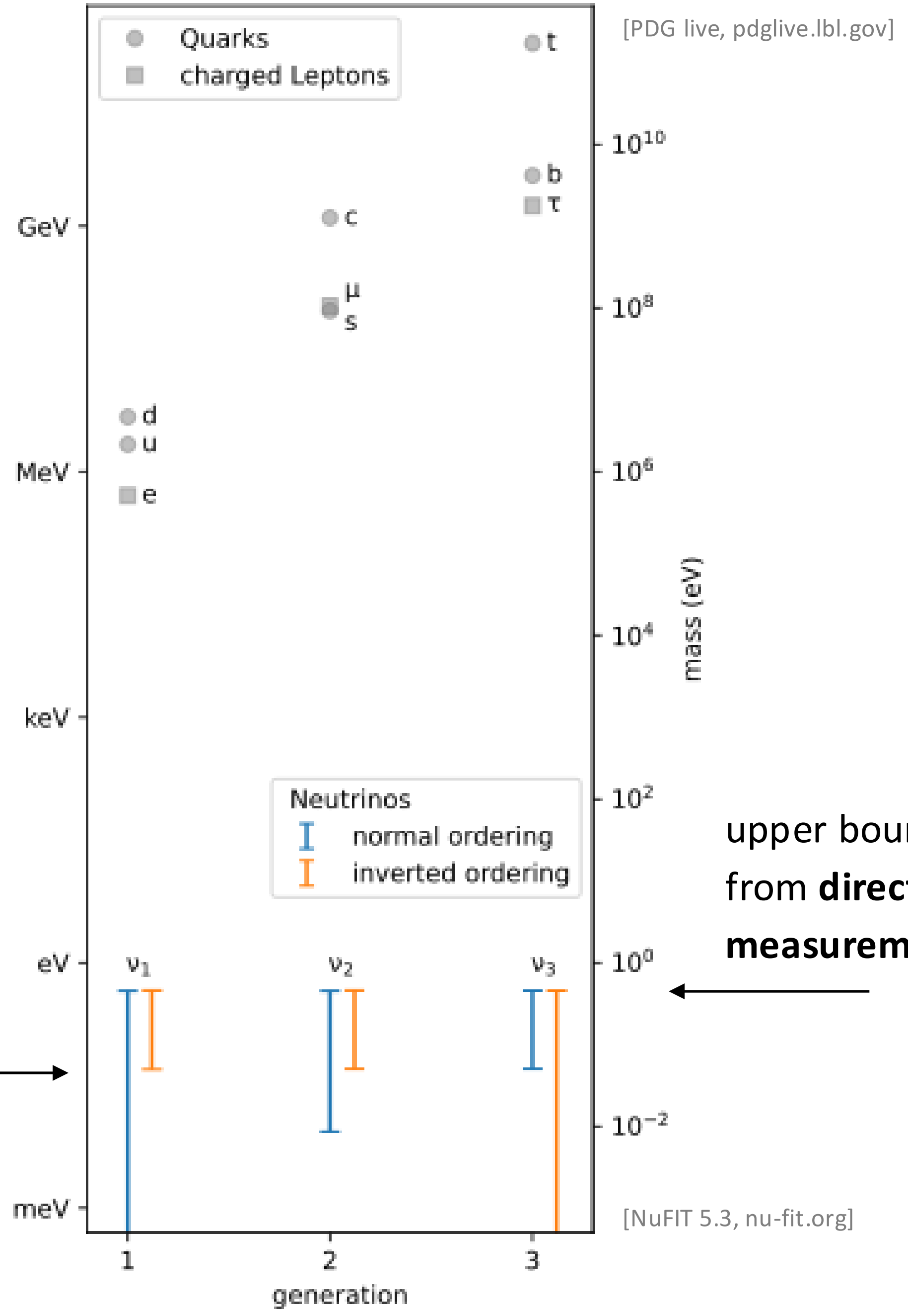
} **yesterday**'s lecture

- What is the **neutrino nature**?
  Is the neutrino its **own antiparticle**?

} **this lecture**

- Are there **additional neutrinos**?

Thierry Lasserre's lecture



Take away

- What would the observation of **neutrinoless double beta decay** tell us?
- What can we learn about the **absolute neutrino mass**? Which **assumptions** are needed?
- Is there a clearly **favoured isotope**?
- What are the **experimental challenges**?
- How does the **LEGEND experiment** work?
- Where are **current bounds**? Where is the minimum value?

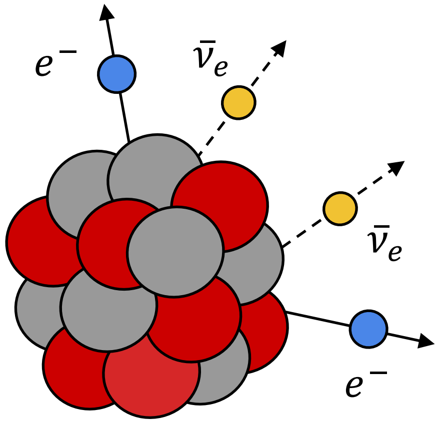
Double beta decay

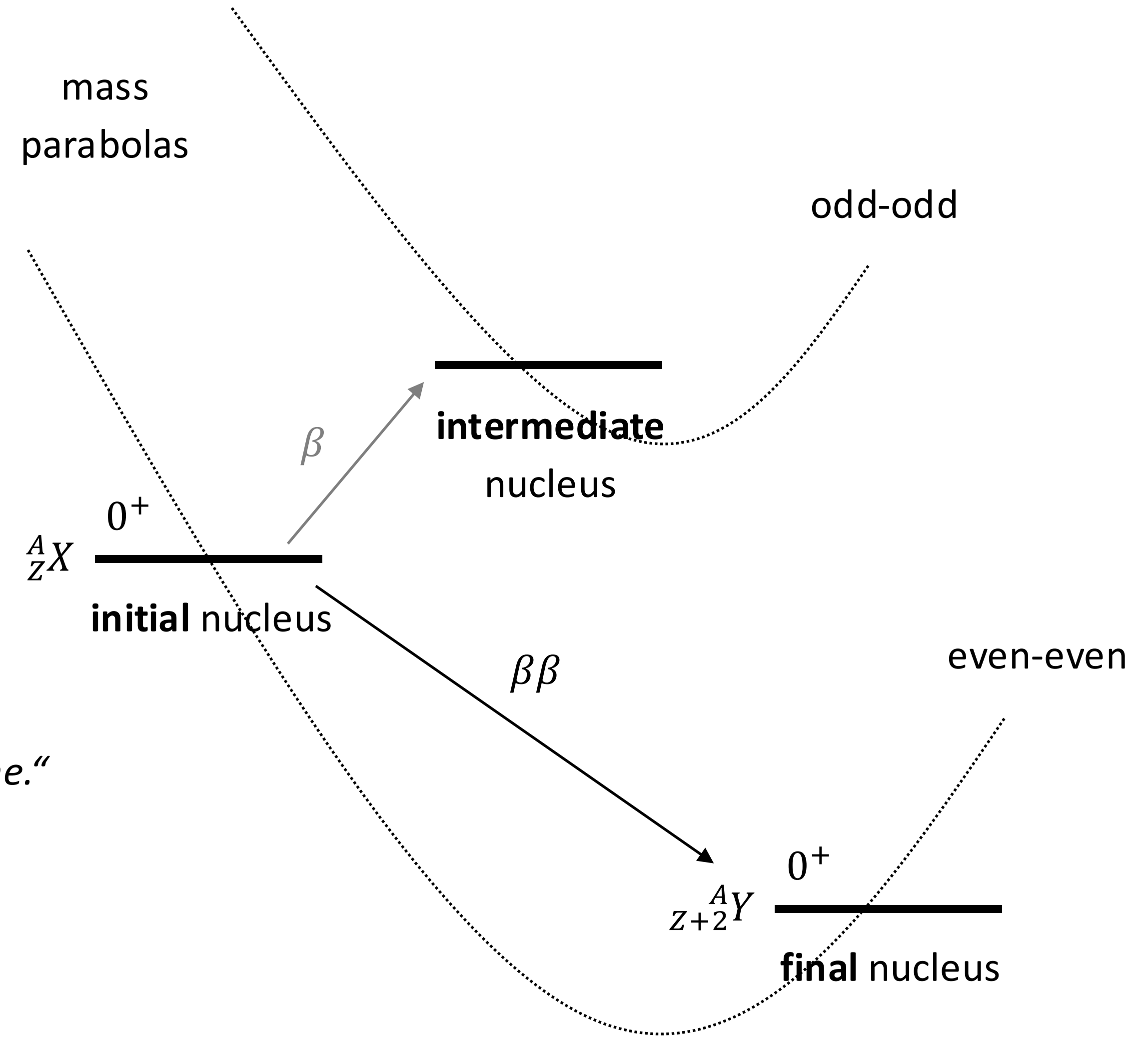
- **second-order weak process**, simultaneous beta decay of two neutrons [Goeppert-Mayer, Phys.Rev. 48 (1935) 512-516]

$$ {}^{A}_{Z}X \rightarrow {}^{\;\;A}_{Z+2}Y + 2\,e^{-} + 2\,\bar{\nu}_e $$

- observable when **first-order transitions suppressed** by energy (or spin) considerations

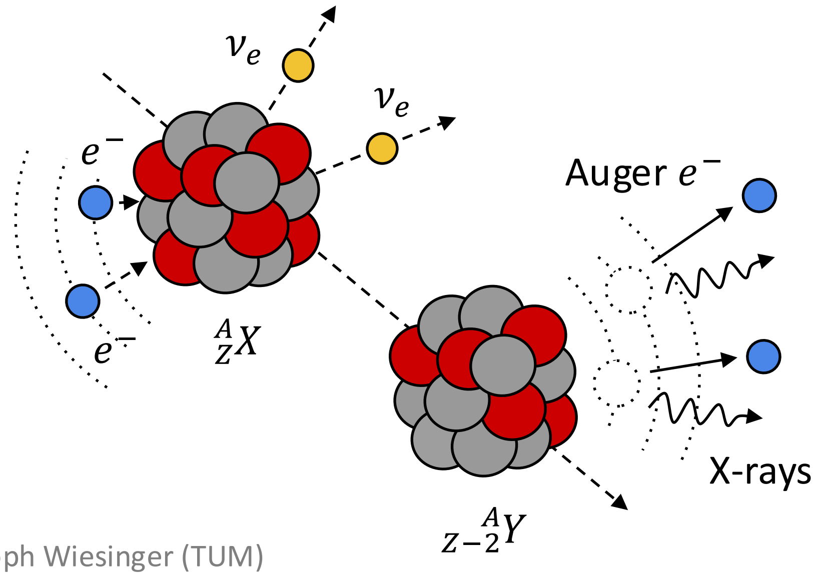
Maria Goeppert-Mayer:
“This reaction is possible but has a very long lifetime.“





Double beta isotopes

- **observed in 11 out of 35** naturally abundant candidate isotopes [Tretyak, Zdesenko, Atom.Data Nucl.Data Tabl. 80 (2002) 83-116]
- similar considerations for proton-rich nuclei, **double electron capture**
- **observed in 3 out of 36** naturally abundant candidate isotopes



$^A X \rightarrow {}^A Y$	Q-value (MeV)	$T_{1/2}$ (yr)
$^{48}Ca \rightarrow {}^{48}Ti$	**4.27**	$6.4 \cdot 10^{19}$
$^{76}Ge \rightarrow {}^{76}Se$	2.04	$2.0 \cdot 10^{21}$
$^{82}Se \rightarrow {}^{82}Kr$	3.00	$8.7 \cdot 10^{19}$
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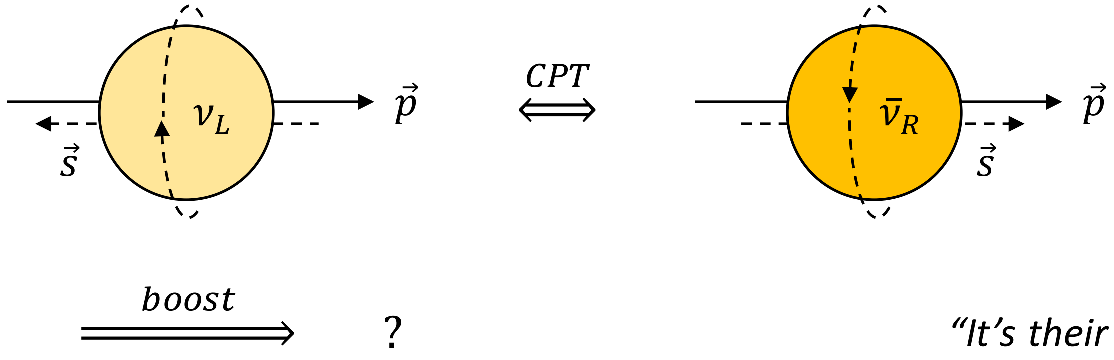
longest half-life measured, geochemical [Bernatowicz at al., PRL 69 (1992) 2341-2344; Adams, PRL 129 (2022) 22, 222501]

longest half-life measured **directly** [Aprile et al., PRL 129 (2022) 16, 161805]

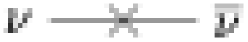
Neutrino nature

Paul Dirac:
"They are fundamentally different particles."

- **neutrinos** are left-handed, **anti-neutrinos** are right-handed



Ettore Majorana:
"It's their handedness that makes them different."

- **particle anti-particle transition**, Majorana propagator ()

› could explain small **neutrino masses**, seesaw mechanism

Neutrinoless double beta decay

Wendell Furry:
"If the neutrino is a Majorana particle, then this reaction is possible."

- double beta decay **without neutrino emission**
  [Furry, Phys.Rev. 56 (1939) 1184-1193]

$$^{A}_{Z}X \;\rightarrow\; ^{\;\;\;A}_{Z+2}Y \;+\; 2\,e^{-}$$

observation would ..

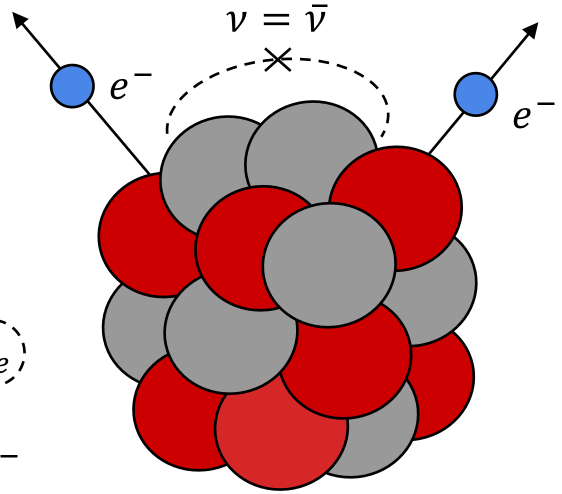
1. .. prove violation of lepton number conservation, **lepton pair creation**

   › could explain **matter-antimatter asymmetry**, leptogenesis

2. .. identify neutrino as **Majorana particle**
3. .. constrain the **absolute neutrino mass**,
   effective Majorana neutrino mass

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

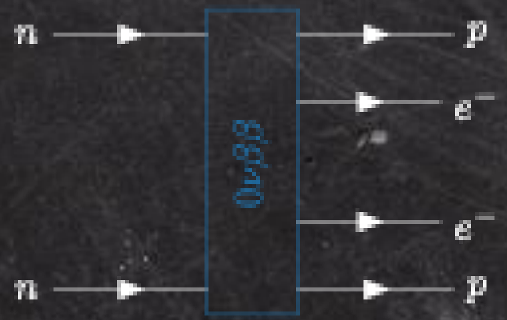
$$n + \nu_e \rightarrow p + e^{-}$$



Particle physics aspect

nuclear physics

decay rate $\Gamma^{0\nu} \propto \sum_i \underbrace{G_i^{0\nu} \cdot \left| g_{A,i}^2 \mathcal{M}_i^{0\nu} \right|^2}_{\text{nuclear physics}} \cdot \eta_i^2$



lepton-number violating
($\Delta L = 2$) physics

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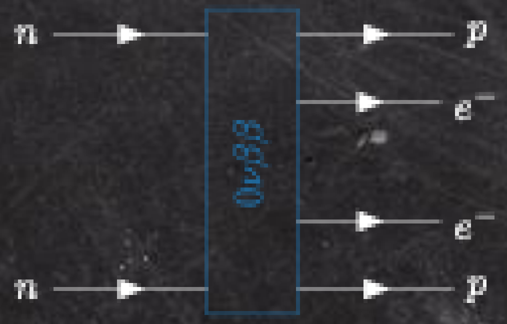

lepton-number violating
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neutrino anti-neutrino transition,
neutrino is Majorana particle

black box / **Schechter-Valle theorem**
[Schechter, Valle, PRD 22 (1980) 2227]

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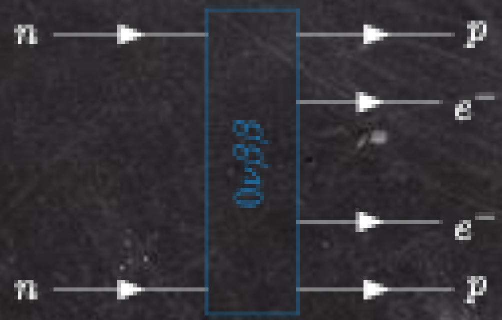
decay rate $$\Gamma^{0\nu} \propto \sum_i \overbrace{G_i^{0\nu} \cdot \left|g_{A,i}^2\, \mathcal{M}_i^{0\nu}\right|^2}^{\text{nuclear physics}} \cdot \eta_i^2 \approx G^{0\nu} \cdot \left|g_A^2\, \mathcal{M}^{0\nu}\right|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

effective Majorana neutrino mass, coherent sum of mass eigenstates

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2\, m_i\right|$$

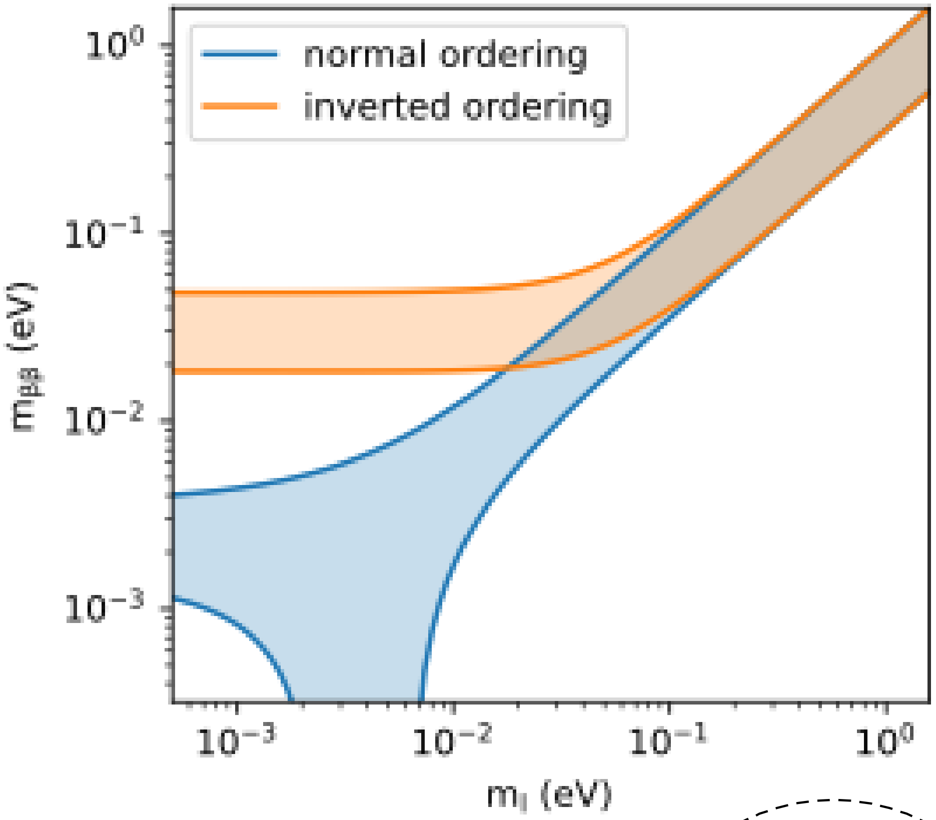


lepton-number violating ($\Delta L = 2$) physics

light Majorana neutrino exchange, mass mechanism

Effective Majorana neutrino mass

[NuFIT 5.3, nu-fit.org]



- **Majorana phases** in PMNS matrix

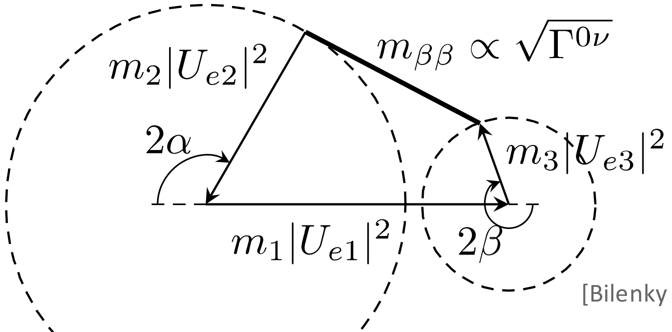
$$U = \ldots \times \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}_{Majorana}$$

- **coherent sum** of mass eigenstates, vector sum

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2\, m_i \right|$$

$$= \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{2i\alpha} + m_3 |U_{e3}|^2 e^{2i\beta} \right|$$

› **full cancelation** possible (normal ordering), minimum at **18 meV** (inverted ordering)



[Bilenky et al., PRD 64 (2001) 053010]

Take away

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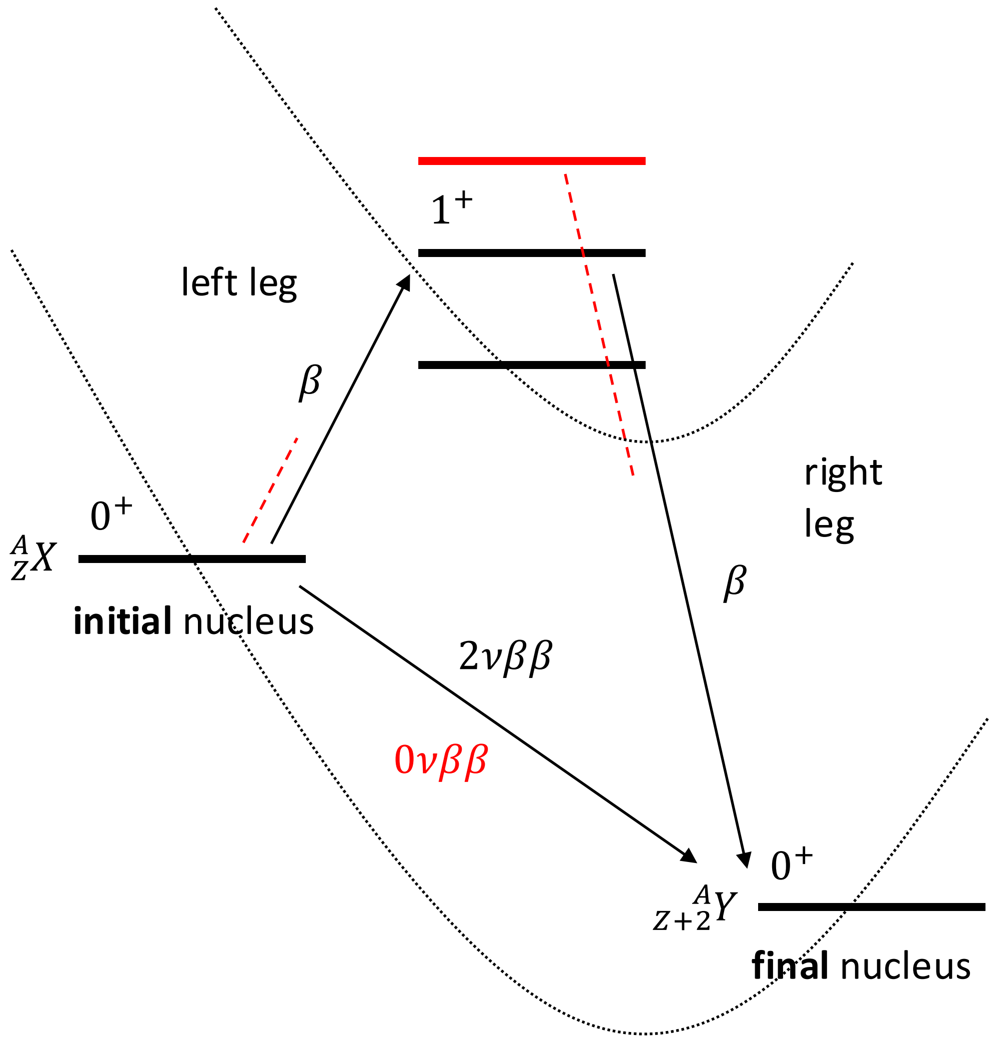
Nuclear physics aspect

decay rate $\Gamma^{0\nu} \propto \overbrace{G^{0\nu} \cdot \left|g_A^2\, \mathcal{M}^{0\nu}\right|^2} \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2$

- **phase space factor** $G^{0\nu}$, accurate calculations available, final state density depends primarily on **Q-value**
- **nuclear matrix element** $\mathcal{M}^{0\nu}$, encodes transition amplitude from initial nucleus over virtual intermediate states to final nucleus, **complicated many-body calculations**
- explicit **axial-vector coupling constant** g_A, unclear if subject to quenching



Momentum considerations

two-neutrino double beta decay

- two β decays, emission of **real particles**

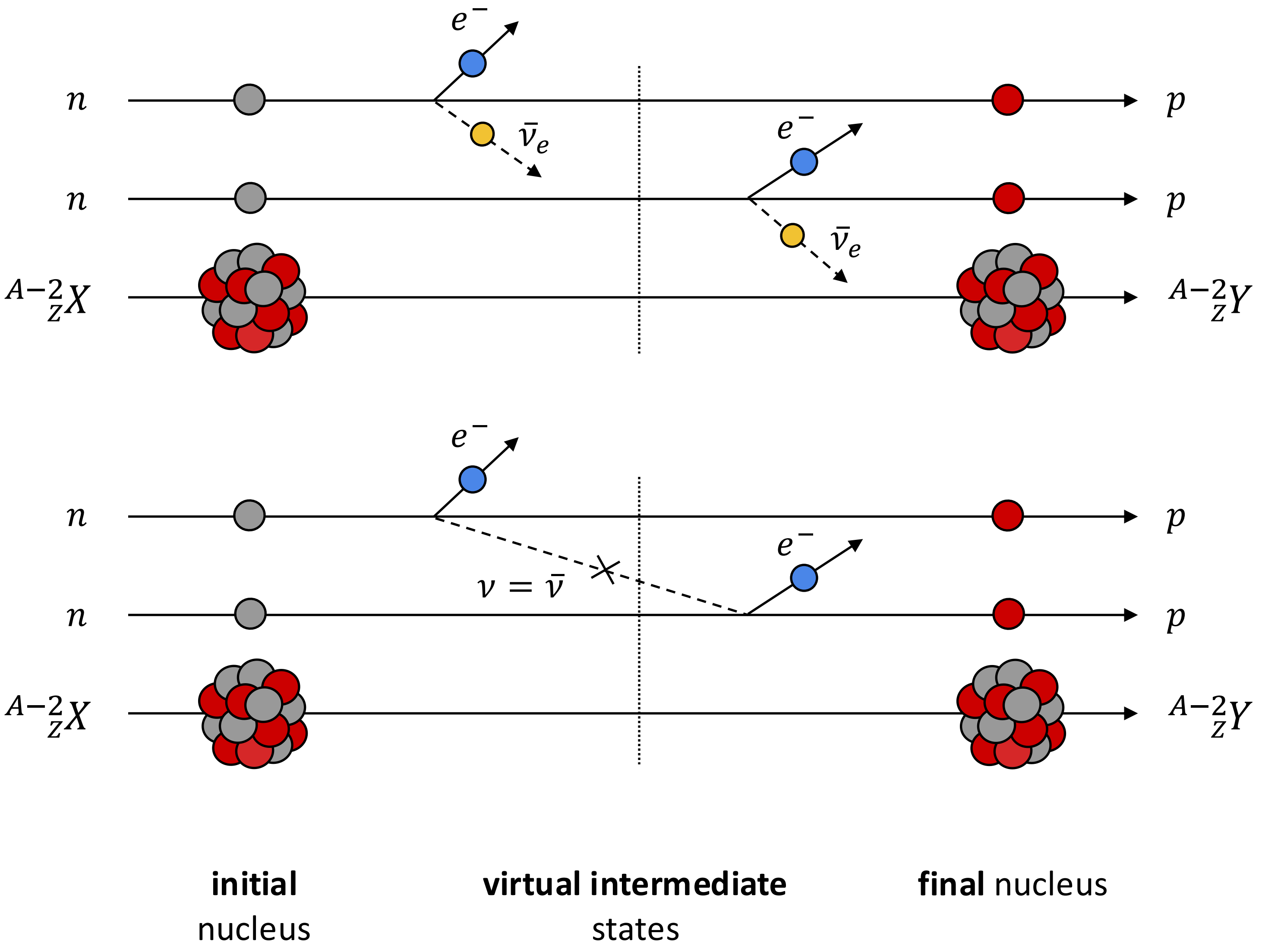
› momentum exertion on intermediate state **limited by Q-value**, strict selection rules

neutrinoless decay

- **virtual particle exchange** between decaying nucleons

› momentum exchange limited by internuclear distance, **up to several 100 MeV**

$$g_A^2\,\mathcal{M}^{0\nu} = g_A^2\left(\mathcal{M}_{GT}^{0\nu} + \left(\frac{g_V}{g_A}\right)^2 \mathcal{M}_F^{0\nu} + ..\right)$$



Nuclear matrix elements

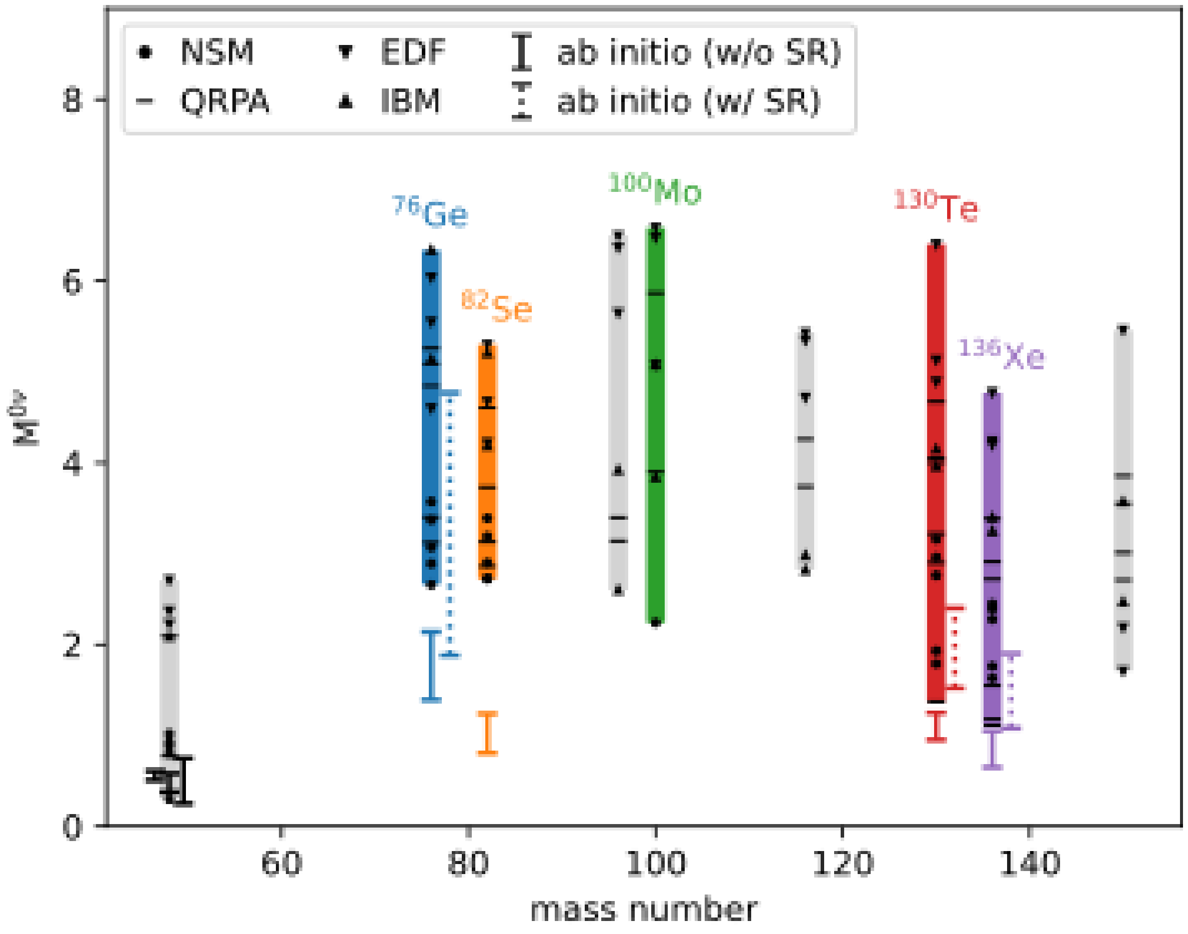
- different **phenomenological many-body methods** using different approximations (e.g. limited number of nuclear shells), **significant spread** [Agostini et al., Rev.Mod.Phys. 95 (2023) 2, 025002; ..]

› experiments typically provide **range of $m_{\beta\beta}$ constraints** (e.g. $T_{1/2}(^{76}Ge) > 1.8 \cdot 10^{26}$ yr translates to $m_{\beta\beta} < [79, 180]$ meV)

- first **ab initio calculations** available, may resolve **quenching issue**
  [Yao et al., PRL 124 (2020); Belley et al., PRL 126 (2021); Novario et al., PRL 126 (2021); Cirigliano et al., PRL 120 (2018); Belley et al., arXiv:2307.15156; Belley et al., PRL 132 (2024); ..]

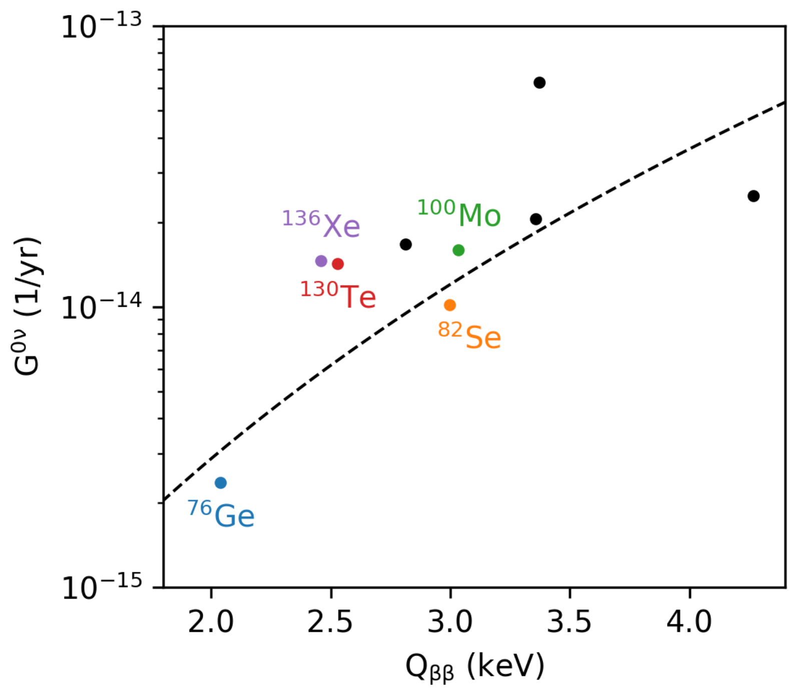
- effective field theory (EFT) analysis identified additional **short-range contribution**
  [Cirigliano et al., PRL 120 (2018) 20, 202001; ..]

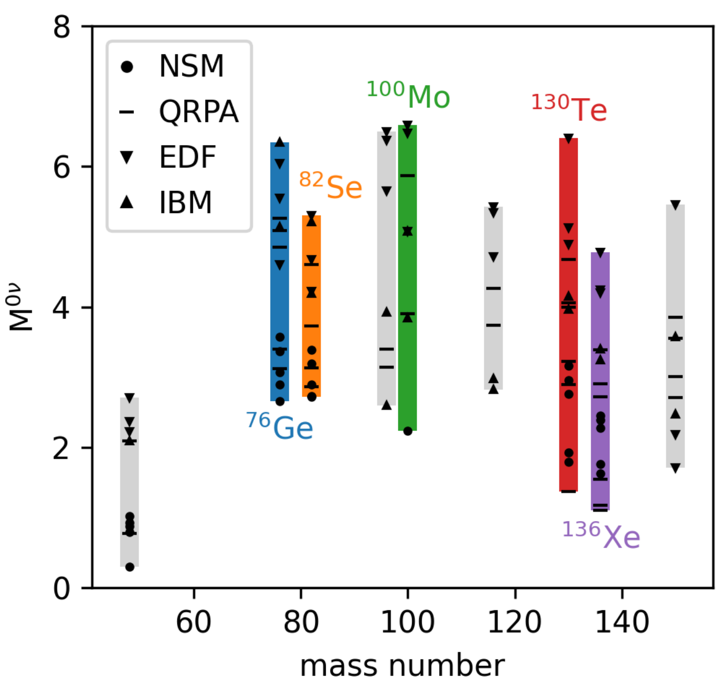
$$\mathcal{M}^{0\nu} = \mathcal{M}^{0\nu}_{long} + \mathcal{M}^{0\nu}_{short}$$



Isotope rates

decay rate $\Gamma^{0\nu} = \frac{N_A}{M(^AX)} \cdot G^{0\nu} \cdot \ln(2) \cdot |g_A^2 \mathcal{M}^{0\nu}|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2$





- **phase space factor** $G^{0\nu}$ accurately calculated, large Q-value favoured
- significant spread of **nuclear matrix element** $\mathcal{M}^{0\nu}$ values

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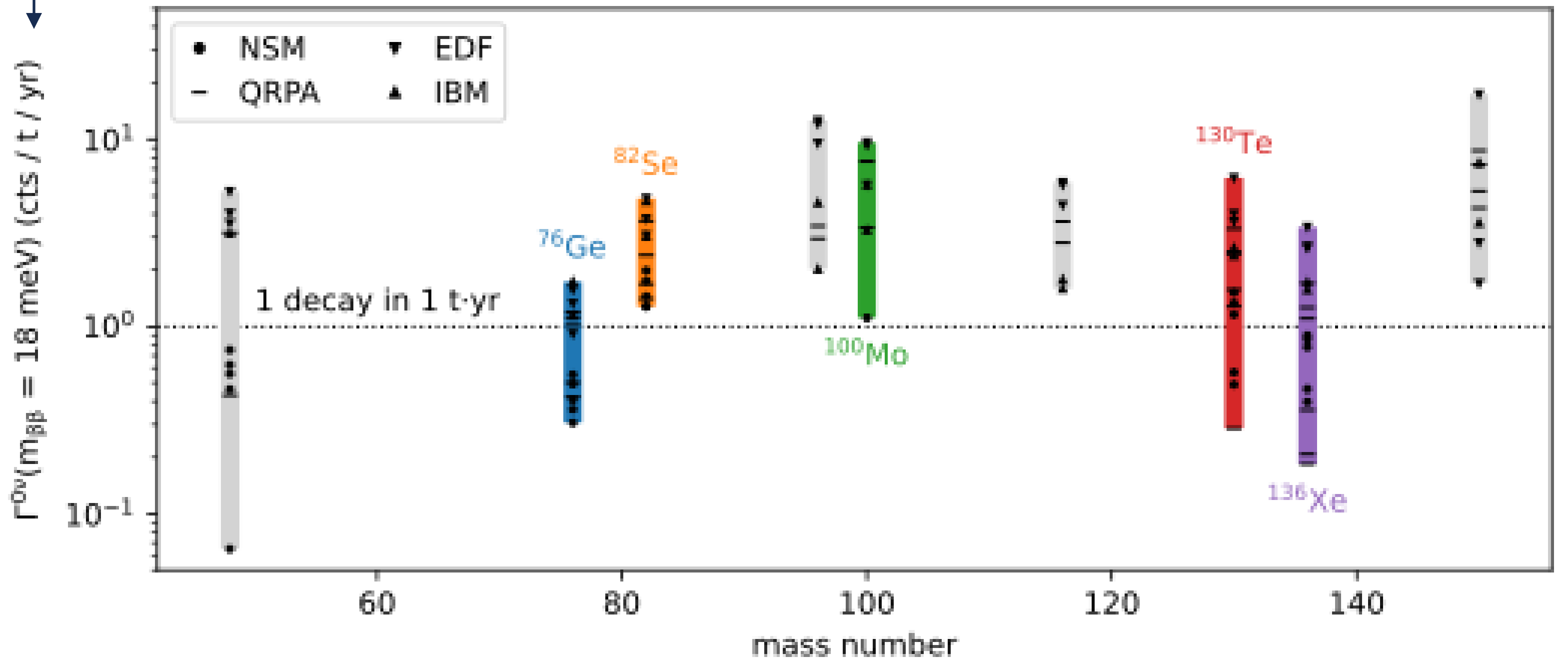


- **phase space factor** $G^{0\nu}$ accurately calculated, large Q-value favoured
- significant spread of **nuclear matrix element** $\mathcal{M}^{0\nu}$ values

› rate differences across different isotopes typically smaller than within one isotope

› **tonne-scale experiments** required to probe inverted ordering scenario

Nuclear matrix element probes

- single **β decay** and **2νββ decay** measurements
  [Gando et al., PRL 122 (2019) 19, 192501]

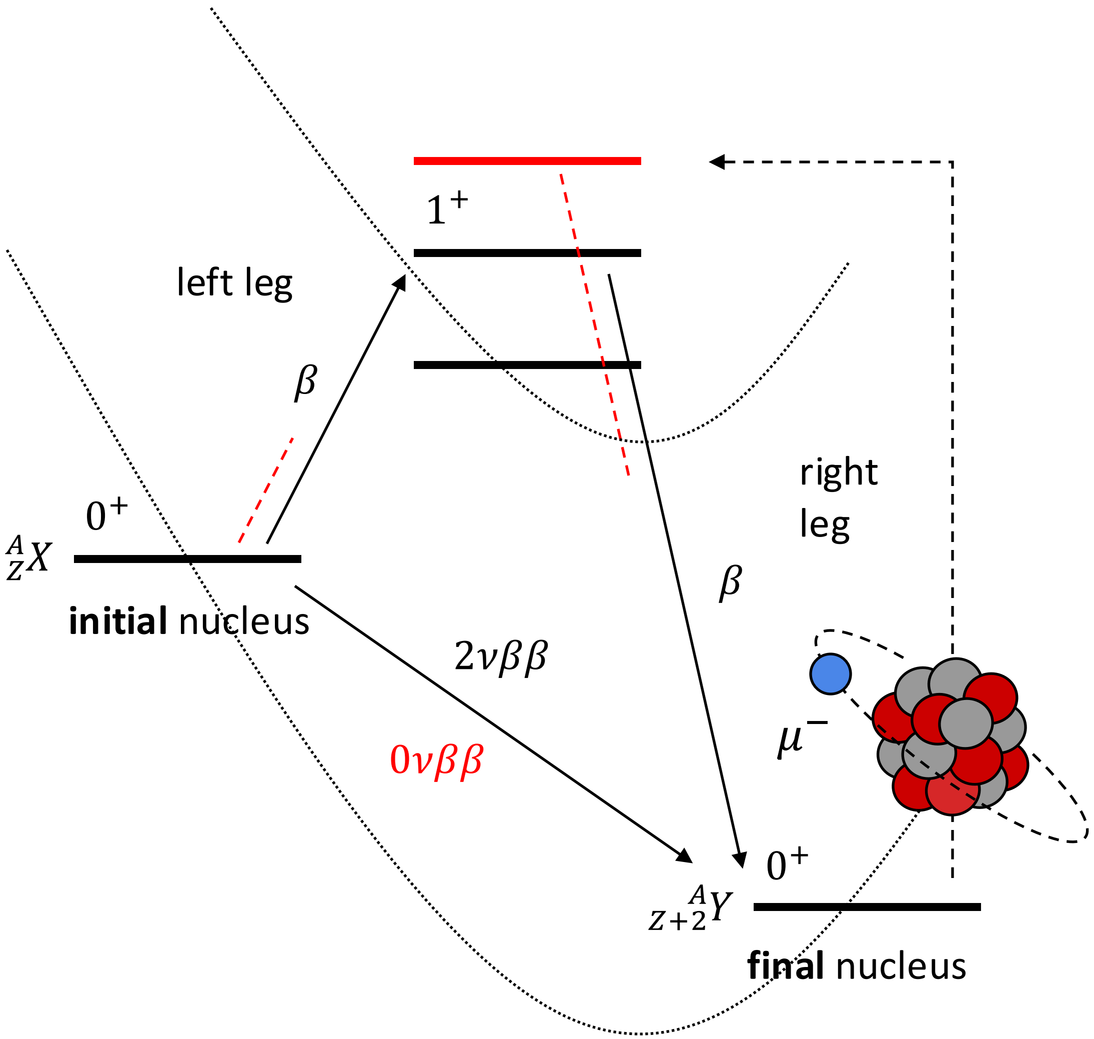
- heavy-ion **charge exchange** reactions, e.g.
  [Cappuzzello et al., EPJ A 54 (2018) 5, 72]

$$^{76}Ge(^{20}Ne,^{20}O)^{76}Se$$

- ordinary **muon capture**
  [Zinatulina et al., PRC 99 (2019), 2, 024327]

$$\mu^- + {}^{76}Se \rightarrow {}^{76}As^* + \nu_\mu$$

- **double gamma decay**, second-order electromagnetic transitions
  [Romeo et al., PLB 827 (2022) 136965]



Take away

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  coherent sum of mass eigenstates, effective Majorana neutrino mass, mediation by exchange of light Majorana neutrino
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- Is there a clearly **favoured isotope**?
  no, experimental considerations outweigh isotopic rate differences

- What are the **experimental challenges**?

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Double beta isotopes

- consider **practicalities**
  - detector technology constraints
  - **abundance**, possibility for **enrichment**
  - world-production

- current focus on **^{76}Ge,** ^{82}Se, **^{100}Mo,** ^{130}Te and **^{136}Xe**

[Meija et al., Pure and Applied Chemistry 88 (2016) 293–306; U. National Minerals Information Center (2020)]

$^{A}X \rightarrow {}^{A}Y$	Q-value (MeV)	$T_{1/2}$ (yr)	Abundance (%)	Production* (t / yr)
$^{48}Ca \rightarrow {}^{48}Ti$	4.27	$6.4 \cdot 10^{19}$	0.2	
$^{76}Ge \rightarrow {}^{76}Se$	2.04	$2.0 \cdot 10^{21}$	7.8	130
$^{82}Se \rightarrow {}^{82}Kr$	3.00	$8.7 \cdot 10^{19}$	8.8	2800
$^{96}Zr \rightarrow {}^{96}Mo$	3.36	$2.4 \cdot 10^{19}$	2.8	$1.4 \cdot 10^{6}$
$^{100}Mo \rightarrow {}^{100}Ru$	3.03	$7.1 \cdot 10^{18}$	9.7	$2.9 \cdot 10^{5}$
$^{116}Cd \rightarrow {}^{116}Sn$	2.81	$2.7 \cdot 10^{19}$	7.5	$2.5 \cdot 10^{4}$
$^{128}Te \rightarrow {}^{128}Xe$	0.87	$2.2 \cdot 10^{24}$		
$^{130}Te \rightarrow {}^{130}Xe$	2.53	$8.8 \cdot 10^{20}$	34.1	470
$^{136}Xe \rightarrow {}^{136}Ba$	2.46	$2.2 \cdot 10^{21}$	8.9	
$^{150}Nd \rightarrow {}^{150}Sm$	3.37	$9.3 \cdot 10^{18}$		
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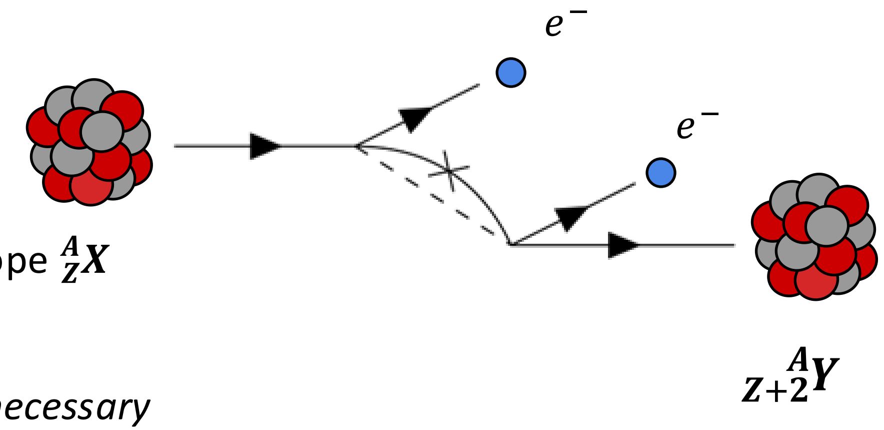
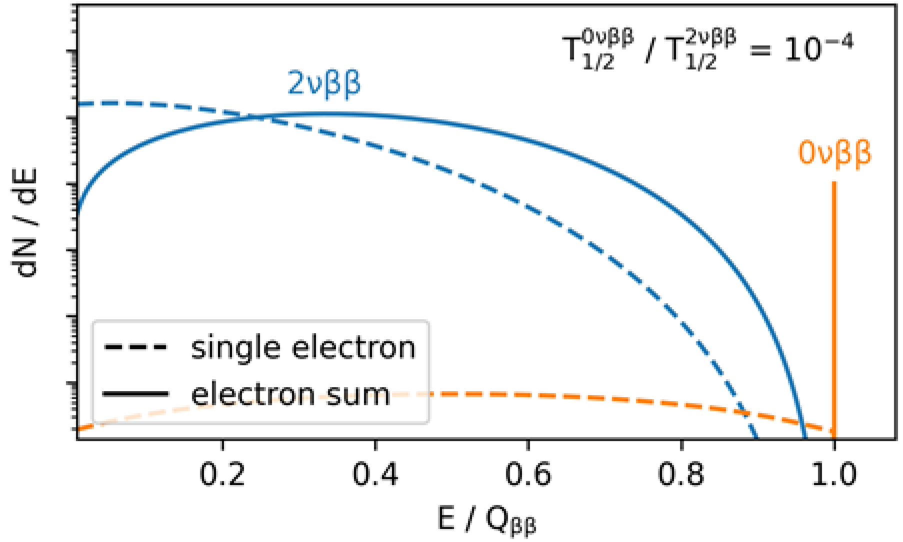
*Production of the element, e.g. Ge for ^{76}Ge

0νββ decay signature



- **unaccompanied emission of two electrons** from isotope $^{A}_{Z}X$
  - two electron/single-site **topology** *necessary*
  - **daughter isotope** production *necessary*
  - **electron energy sum** matches Q-value *sufficient*

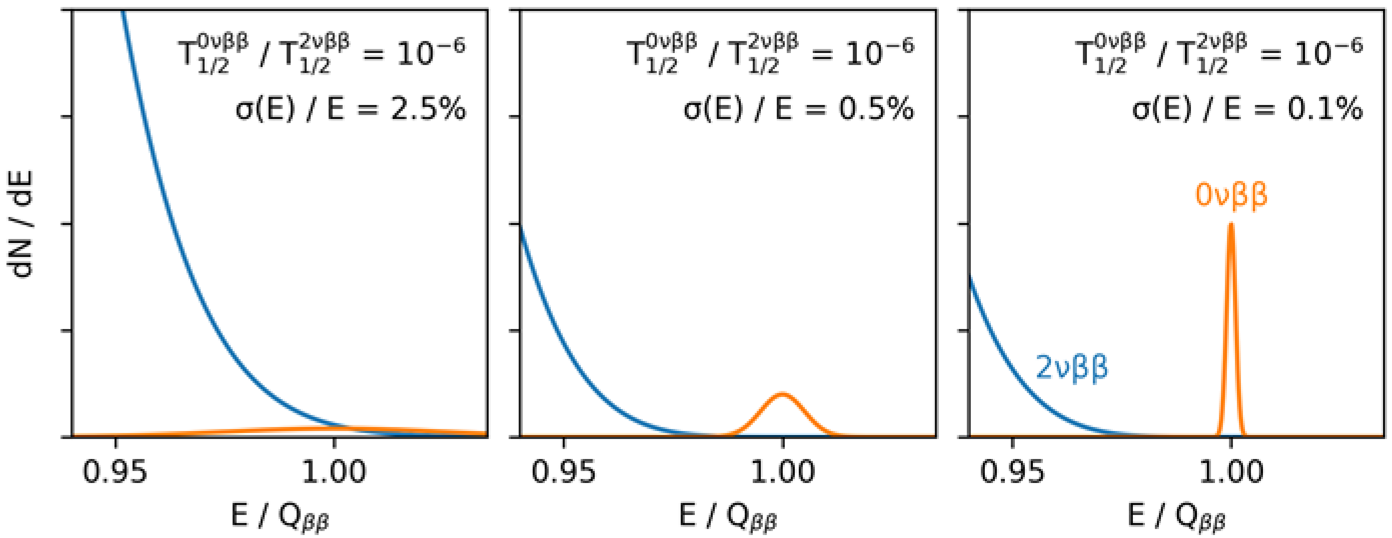


- **single electrons** can tell about **decay mechanism**

Experimental challenge

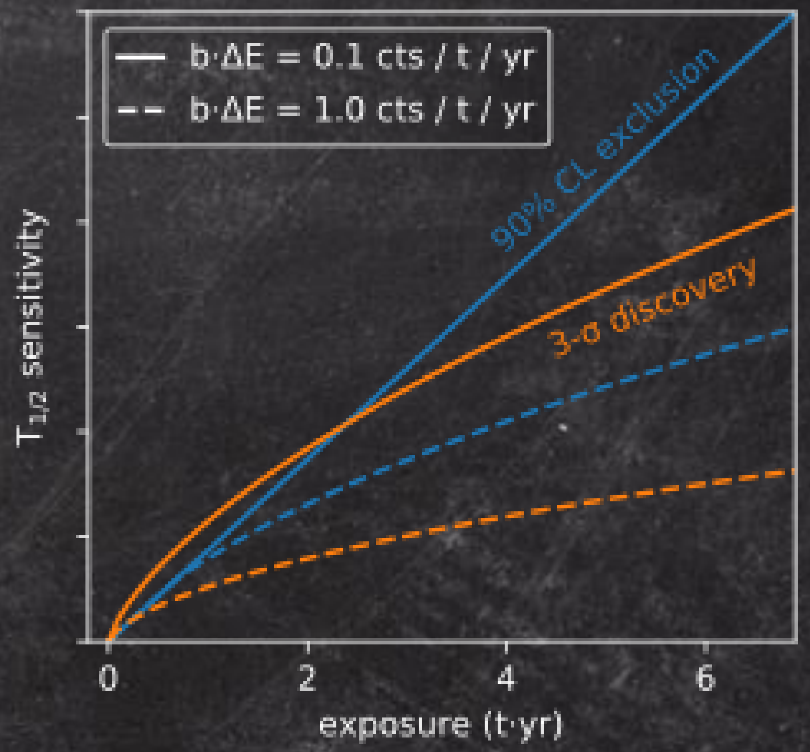
search for **single events** with mono-energetic emissions of two electrons from **macroscopic amount of double isotope**

- large **isotope mass**, tonne-scale
- maximal **detection efficiency** for electrons
- excellent **energy resolution**
- ultra-low **background**



Background considerations

[Agostini et al., Rev.Mod.Phys. 95 (2023) 2, 025002]



number of signals counts: $n_s \propto \underbrace{\frac{1}{T_{1/2}}}_{\text{inverse half-life}} \cdot \underbrace{m \cdot t}_{\text{exposure (mass x time)}}$

number of background counts: $n_b \propto \underbrace{b}_{\text{background index (e.g. cts / keV / kg /yr)}} \cdot \underbrace{\Delta E}_{\text{energy resolution}} \cdot m \cdot t$

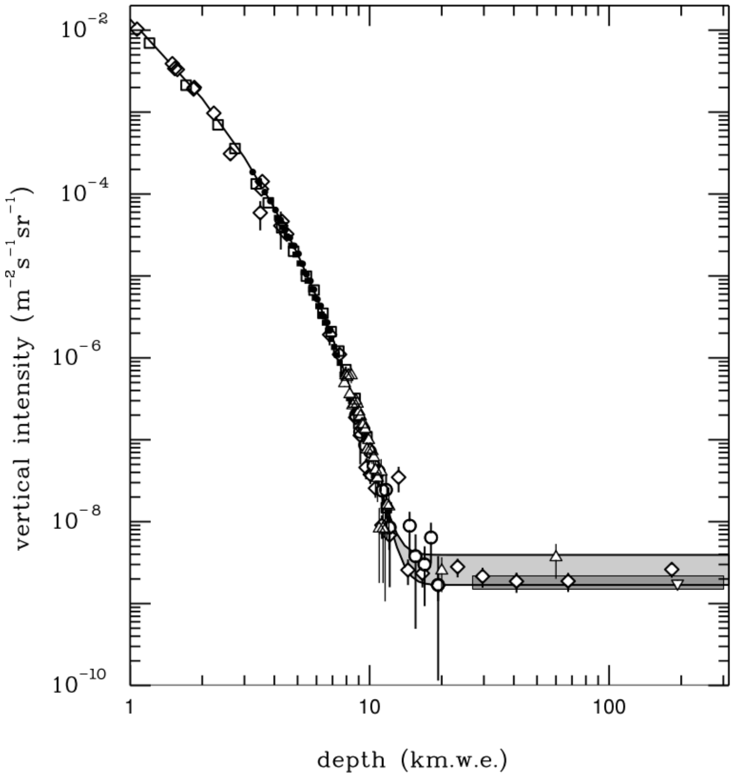
case A) **background-dominated** experiment ($n_s \propto \sqrt{n_b}$): $T_{1/2} \propto \sqrt{\frac{m \cdot t}{b \cdot \Delta E}}$ (square-root)

case B) **background-free** experiment ($n_b \ll 1$): $T_{1/2} \propto m \cdot t$ (linear)

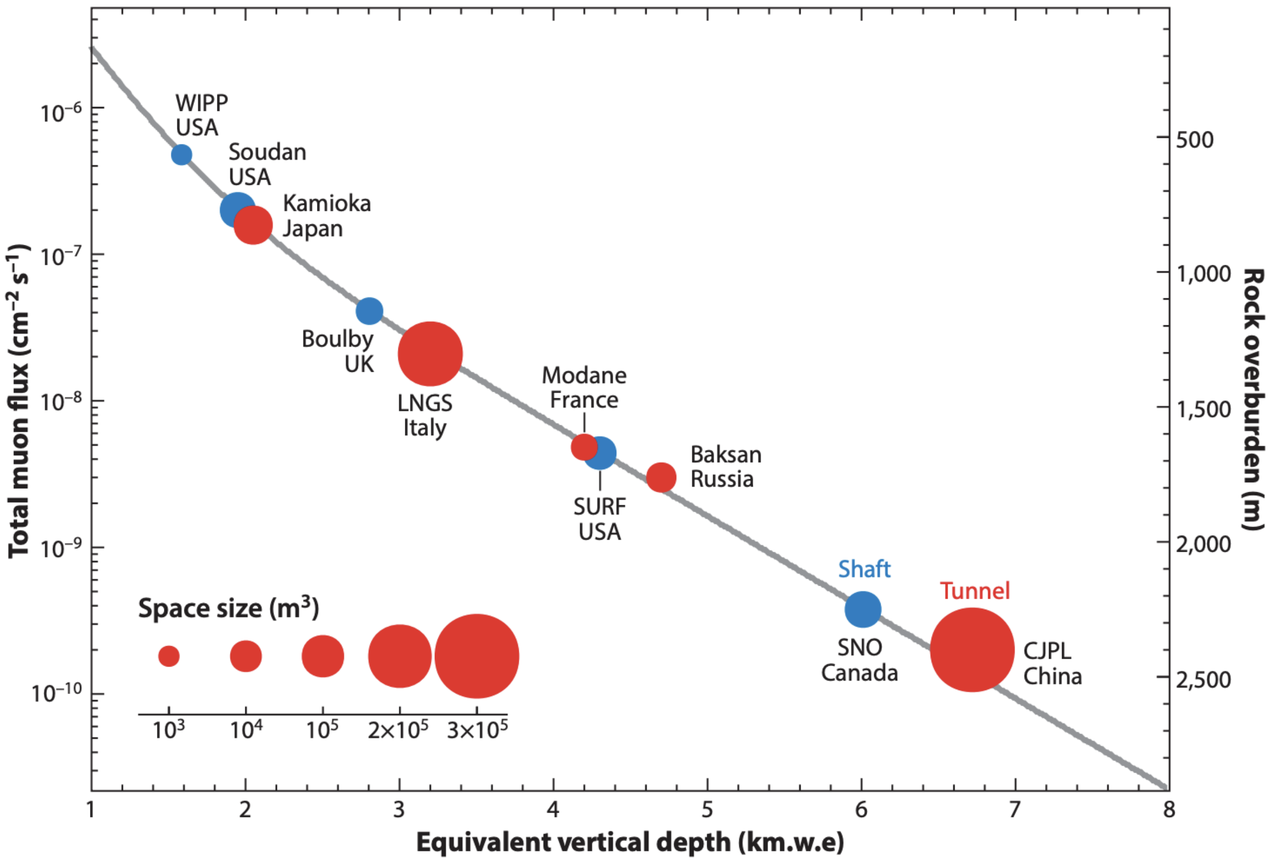
Backgrounds

- **cosmic background**, interactions of e.g. cosmic ray muons
  - › **deep underground** operation
  - › muon **veto systems**, water Cherenkov detectors, scintillator detectors, ..

[M. Tanabashi et al., PRD 98 (2018) no.3, 030001]



[Cheng et al., Ann.Rev.Nucl.Part.Sci. 67 (2017) 231-251]



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- **cosmogenic background**, cosmic-induced production of radioactive isotopes
  - **ex-situ** activation, before installation, e.g ^{60}Co in Cu
  - › limit above-ground handling
  - **in-situ** activation, during operation, e.g. ^{76}Ge(n,γ)^{77}Ge
  - › overburden, analysis cuts, ..

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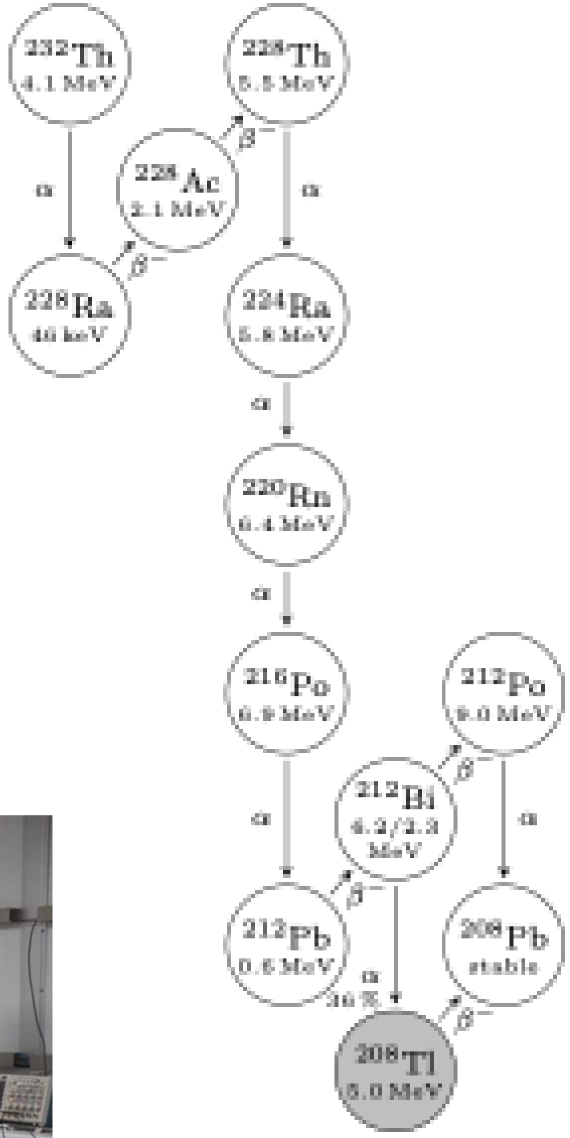
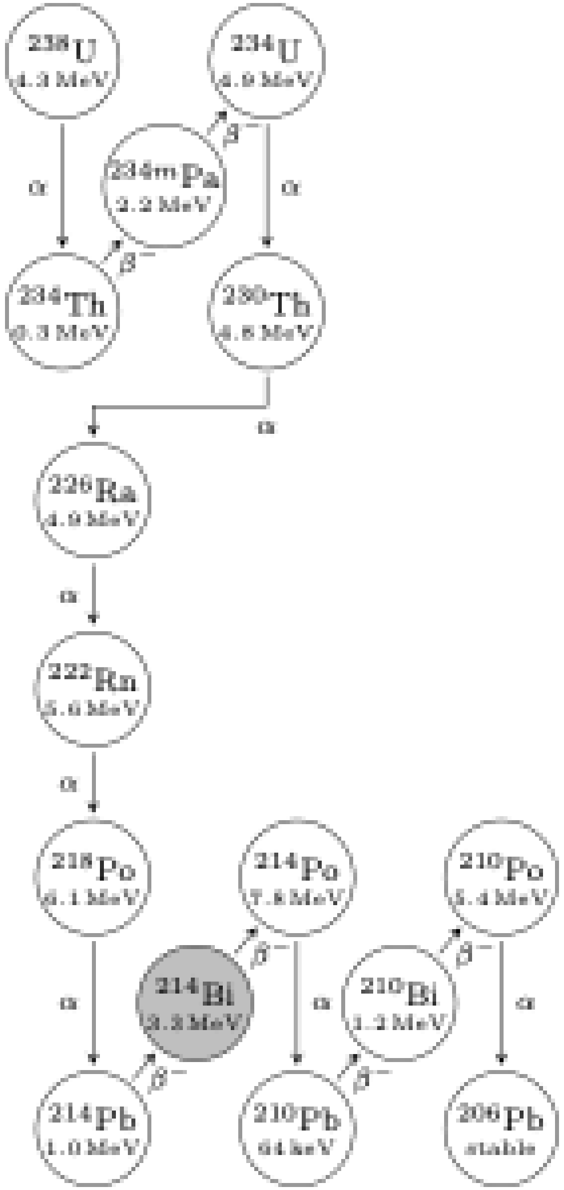
  - **in-situ** activation, during operation, e.g. ^{76}Ge(n,γ)^{77}Ge
  - › overburden, analysis cuts, ..

- **neutrinos**, elastic scattering and charged current interactions, i.e. ${}^{A}_{Z}X(\nu_e, e)\,{}^{A}_{Z+1}Y$ [Ejiri, Elliott, PRC 89 (2014) 5, 055501]

Backgrounds

- **radiogenic background**, radioactive impurities
  - **primordial** isotopes, **actinide chains**
  - **antropogenic** isotopes, e.g. ^{108m}Ag
    [Gando et al., PRC 85 (2012) 045504]
  - › sophisticated **material selection**, analysis cuts, ..





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  - › sophisticated **material selection**, analysis cuts, ..

- **2νββ decay**, unavoidable standard model background
  - spectral **overlap** [Elliott, Vogel, Ann.Rev.Nucl.Part.Sci. 52 (2002) 115-151]

$$\frac{S}{B} = \left(\frac{Q_{\beta\beta}}{\sigma_E}\right)^6 \frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$

  - **energy resolution**, in practice not relevant if σ_E / E < 1%
  - **pile-up**, in practice only relevant for ^{100}Mo
  - › **time resolution**, detector segmentation

Take away

- What would the observation of **neutrinoless double beta decay** tell us?
  lepton number is not conserved, neutrino is Majorana particle

- What can we learn about the **absolute neutrino mass**? Which **assumptions** are needed?
  coherent sum of mass eigenstates, effective Majorana neutrino mass, mediation by exchange of light Majorana neutrino

- Is there a clearly **favoured isotope**?
  no, experimental considerations outweigh isotopic rate differences

- What are the **experimental challenges**?

- How does the **LEGEND experiment** work?

- Where are **current bounds**? Where is the minimum value?

Take away

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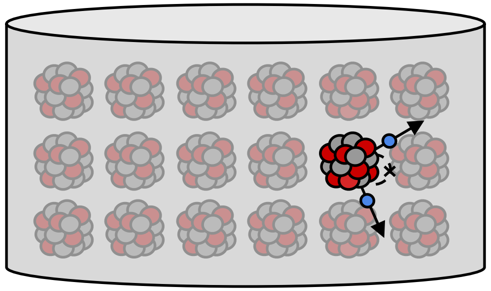
- Is there a clearly **favoured isotope**?
  no, experimental considerations outweigh isotopic rate differences
- What are the **experimental challenges**?
  ultra-low background, good energy resolution, large isotope mass, high efficiency
- How does the **LEGEND experiment** work?
- Where are **current bounds**? Where is the minimum value?

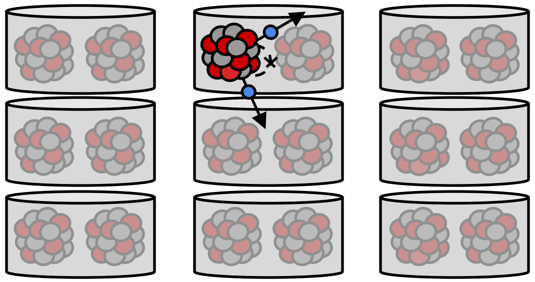
Experimental approaches

source = detector concepts



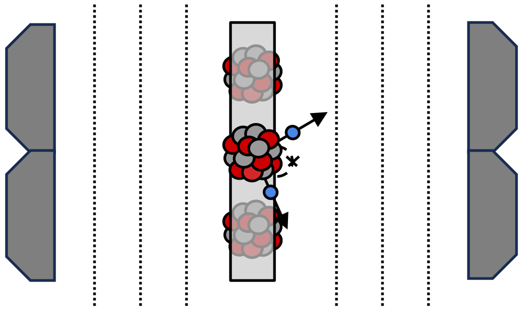
monolithic scintillation / ionization **detectors**

AXEL, DARWIN, **EXO**, JUNO, **KamLAND-Zen**, LiquidO, LZ, **nEXO**, **NEXT**, NvDEx, R2D2, THEIA, Panda-X, **SNO+**, XENON, ZICOS, ..



granular semiconductor / cryogenic **detectors**

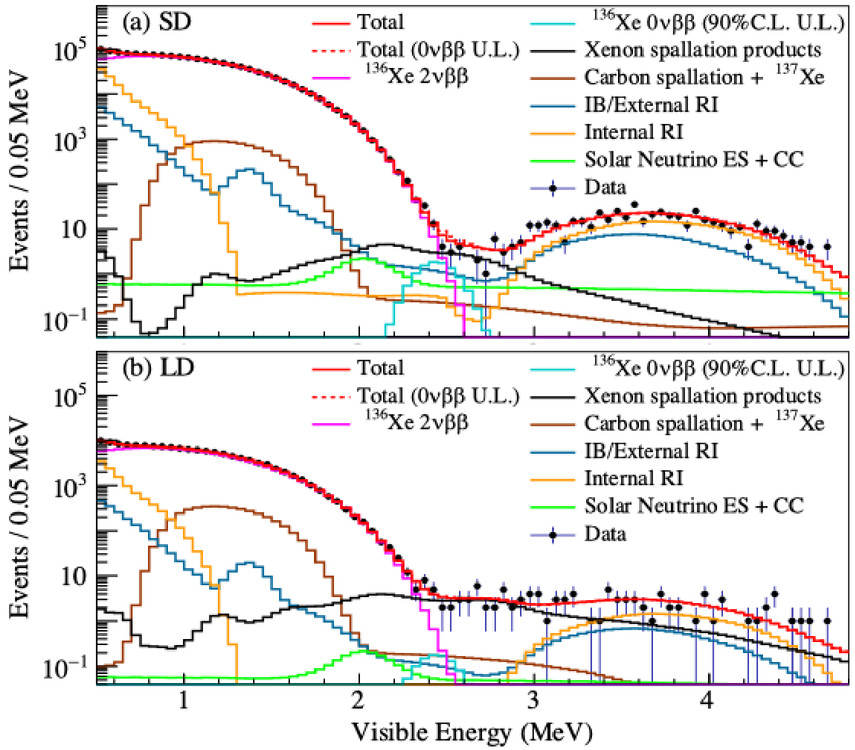
AMORE, BINGO, CANDLES, CEDEX, COBRA, **CUORE**, **CUPID**, CROSS, **GERDA**, **LEGEND**, **MAJORANA**, SELENA, ..



tracking Calorimeters

NEMO3, **SuperNEMO**, ..

Comparison



[Abe et al., arXiv:2406.11438]

KamLAND-Zen

- high-mass, **O(100) kg**
- low-resolution, **O(100) keV**
- **background-limited**

› **sensitivity**, result

[Abe et al., arXiv:2406.11438]

$T_{1/2}(^{136}Xe)$ **> 2.6·10²⁶ yr** (90% CL)

$T_{1/2}(^{136}Xe) > 3.8 \cdot 10^{26}$ yr (90% CL)

GERDA

- low-mass, **O(10) kg**
- high-resolution, **O(1) keV**
- **background-free**

› **sensitivity**, result

[Agostini et al., PRL 125 (2020) 25, 252502]

$T_{1/2}(^{76}Ge)$ **> 1.8·10²⁶ yr** (90% CL)

$T_{1/2}(^{76}Ge) > 1.8 \cdot 10^{26}$ yr (90% CL)

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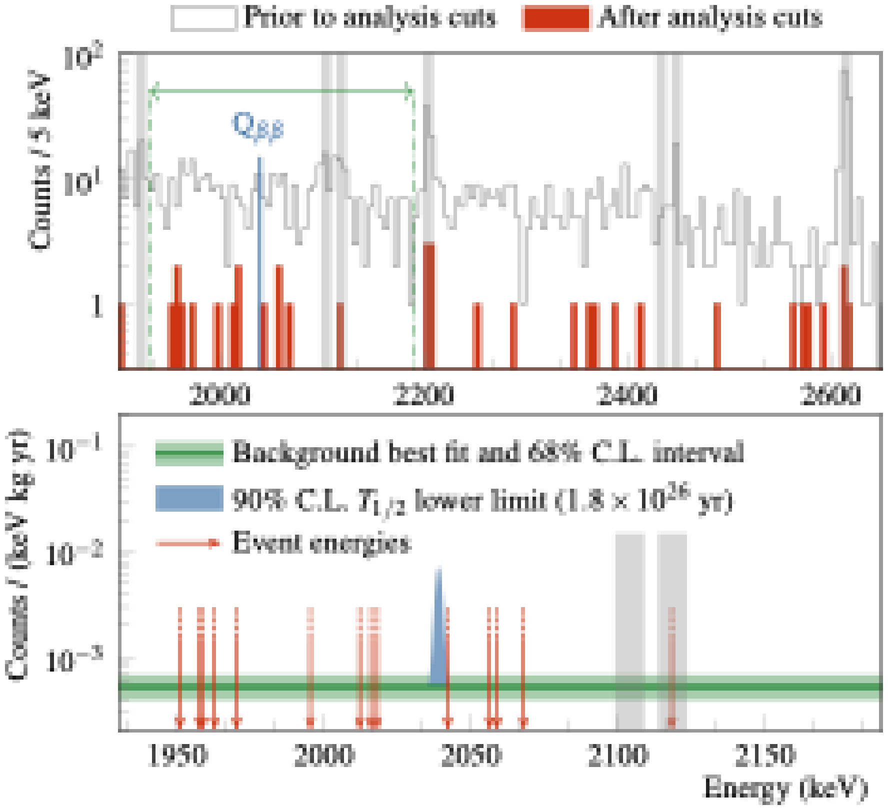

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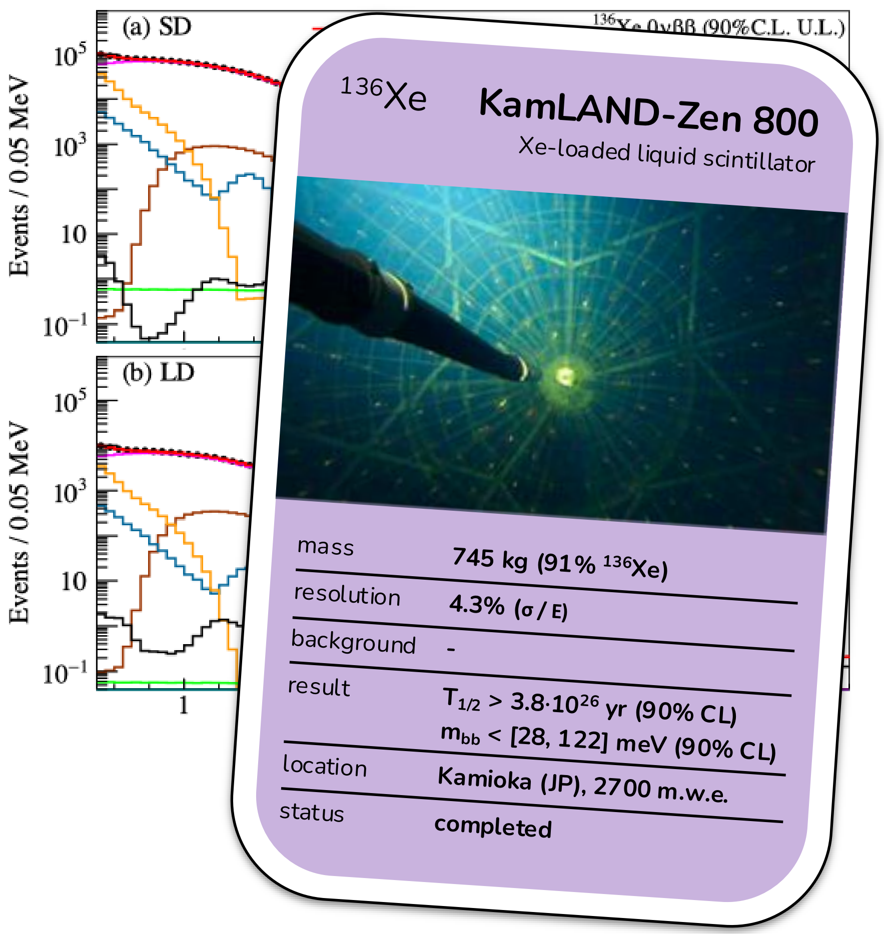

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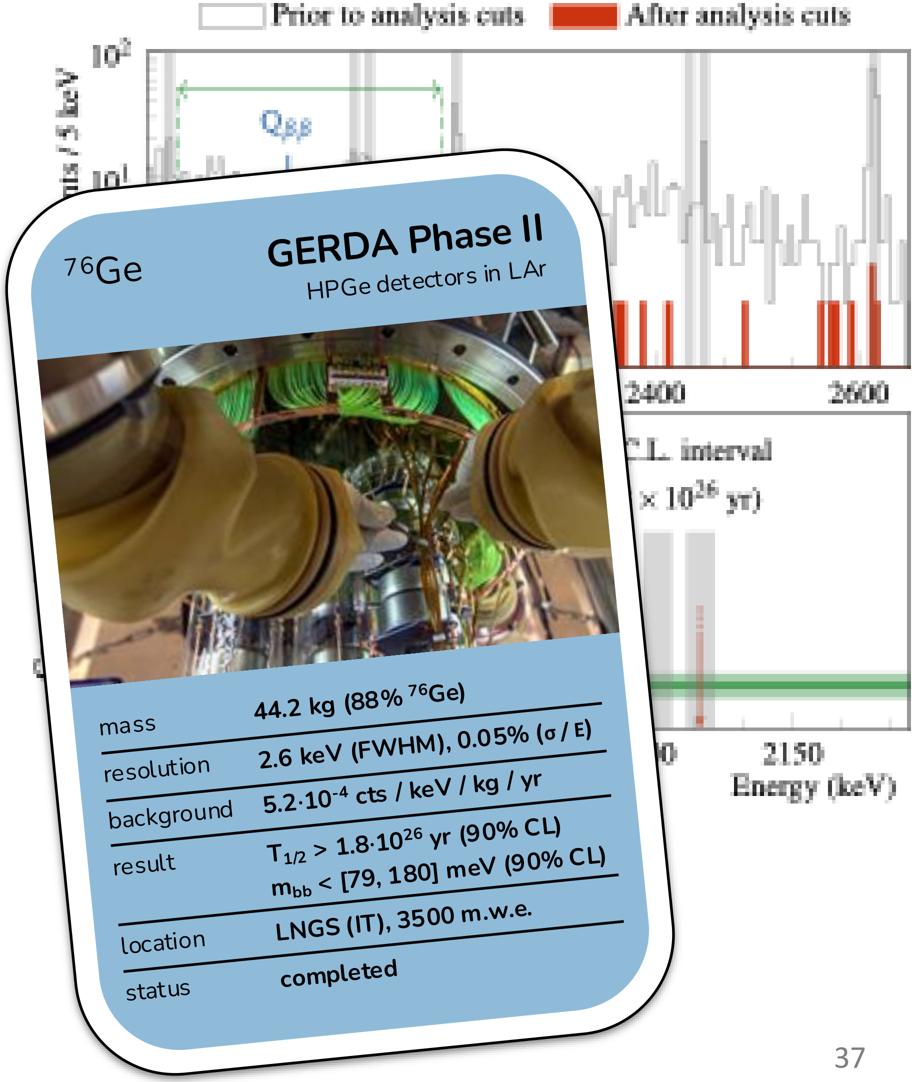
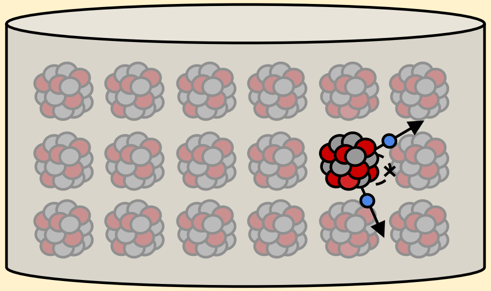


Experimental approaches

source = detector concepts



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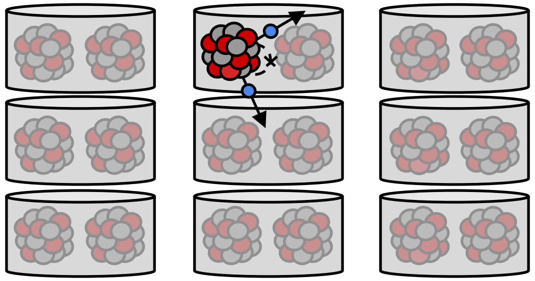
AXEL, DARWIN, **EXO**, JUNO, **KamLAND-Zen**, LiquidO, LZ, **nEXO**, **NEXT**, NvDEx, R2D2, THEIA, Panda-X, **SNO+**, XENON, ZICOS, ..



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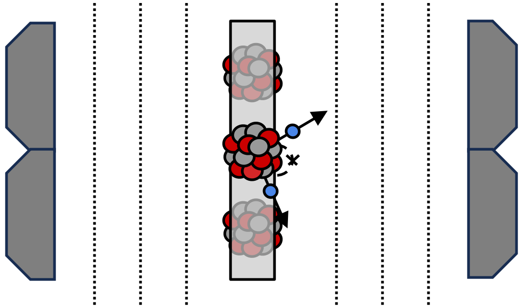

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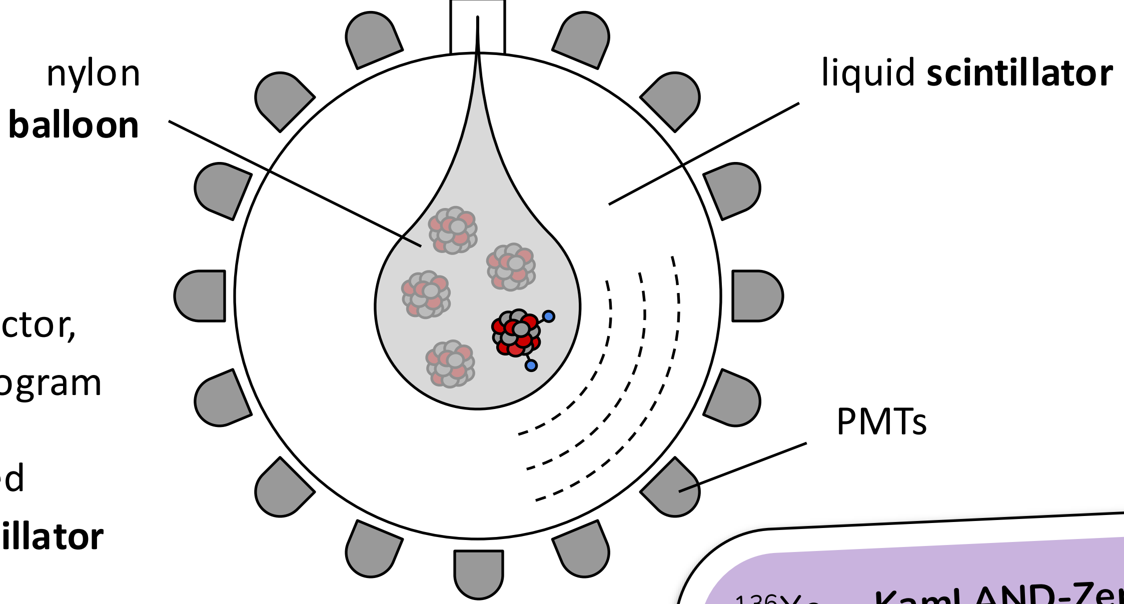
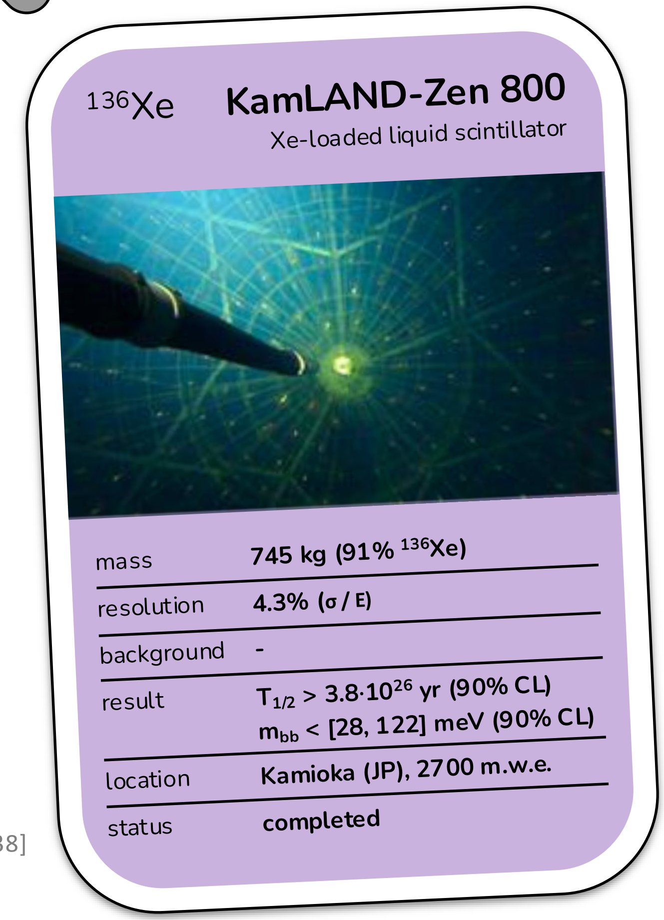


- 1000-t **liquid scintillator** detector, rich **non-ββ decay physics** program
- ultra-clean **nylon balloon** filled with **^{enr}Xe-loaded liquid scintillator**

KamLAND-Zen 800

- 800 kg phase **completed**, new **world-best** 0νββ decay constraint
  [Abe et al., arXiv:2406.11438]

$$T_{1/2}(^{136}\text{Xe}) > \mathbf{3.8 \cdot 10^{26}\ yr}\ (90\%\ \text{CL})$$
$$m_{\beta\beta} < \mathbf{[28, 122]\ meV}\ (90\%\ \text{CL})$$



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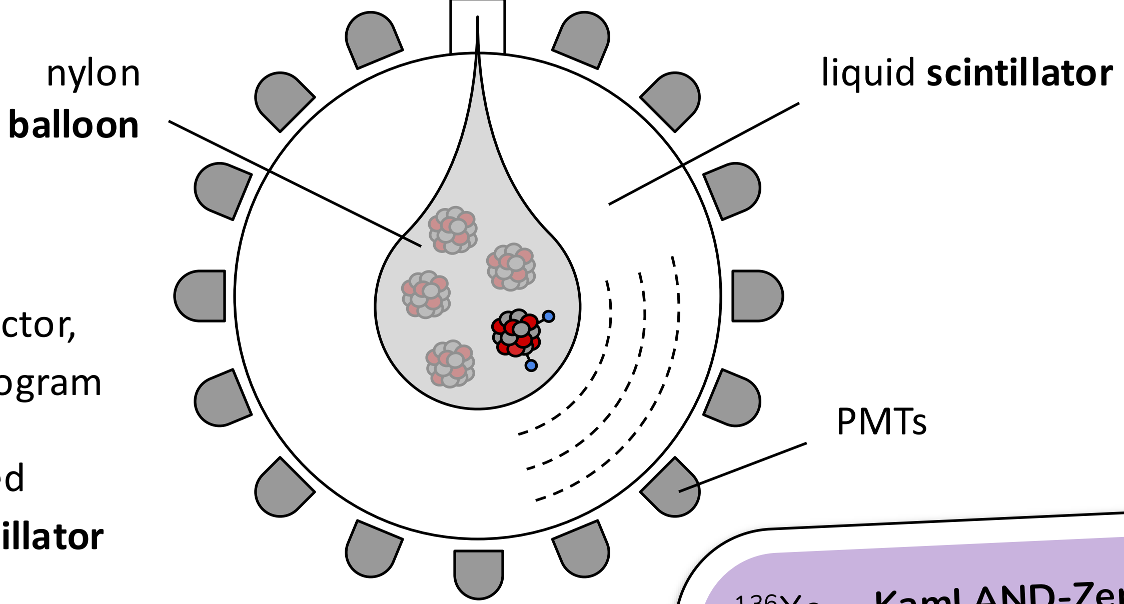
KamLAND-Zen



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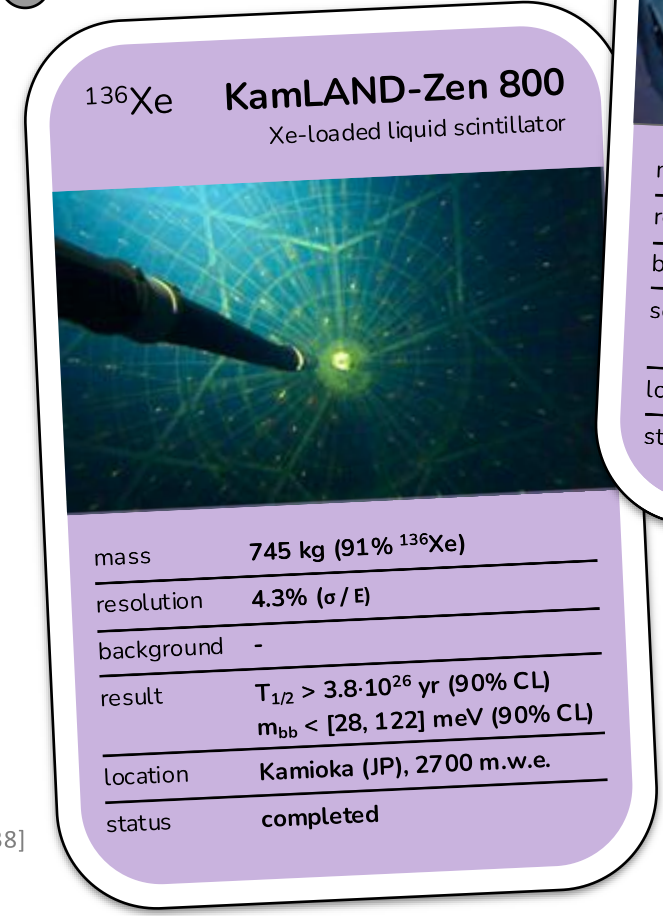
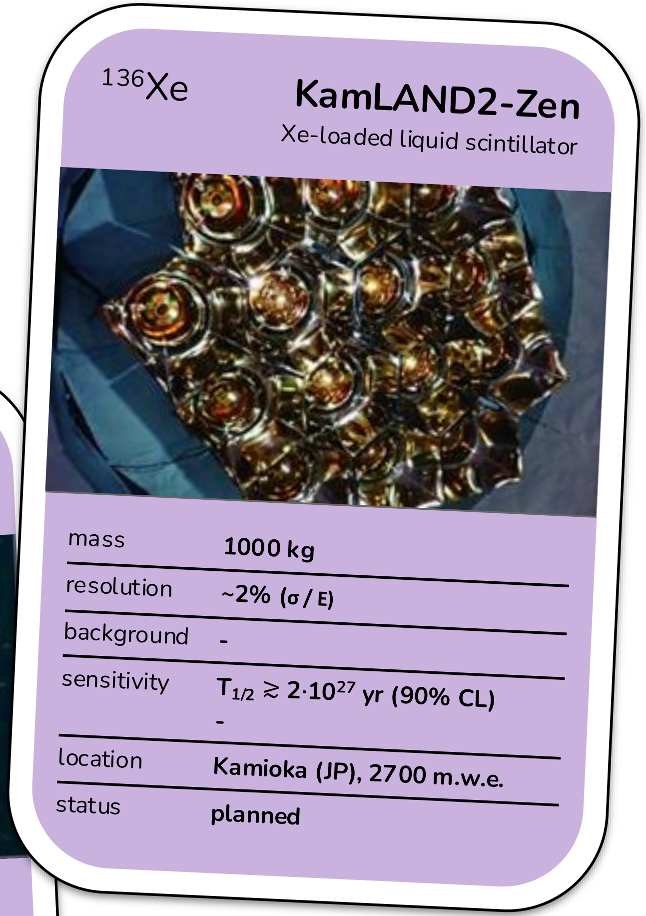
KamLAND2-Zen

- **detector upgrade**, better light collection, **improved resolution**





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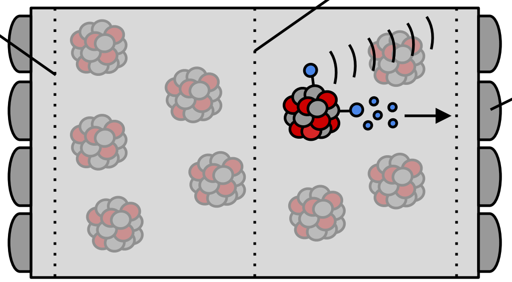
EXO



- **liquid ^{enr}Xe time projection chamber**, charge and light readout
- **enhanced resolution** by charge and light signal combination
- **topological discrimination**, single-/multi-site

^{136}Xe

EXO-200

LXe time projection chamber

mass	175 kg (81% ^{136}Xe)
resolution	1.15 % (σ / E)
background	$1.7 \cdot 10^{-3}$ cts / keV / kg / yr
sensitivity	$T_{1/2} > 3.5 \cdot 10^{25}$ yr (90% CL) m_{bb} < [93, 286] meV (90% CL)
location	WIPP (US), 1600 m.w.e.
status	completed

[Anton et al., PRL 123 (2019) 16, 161802]

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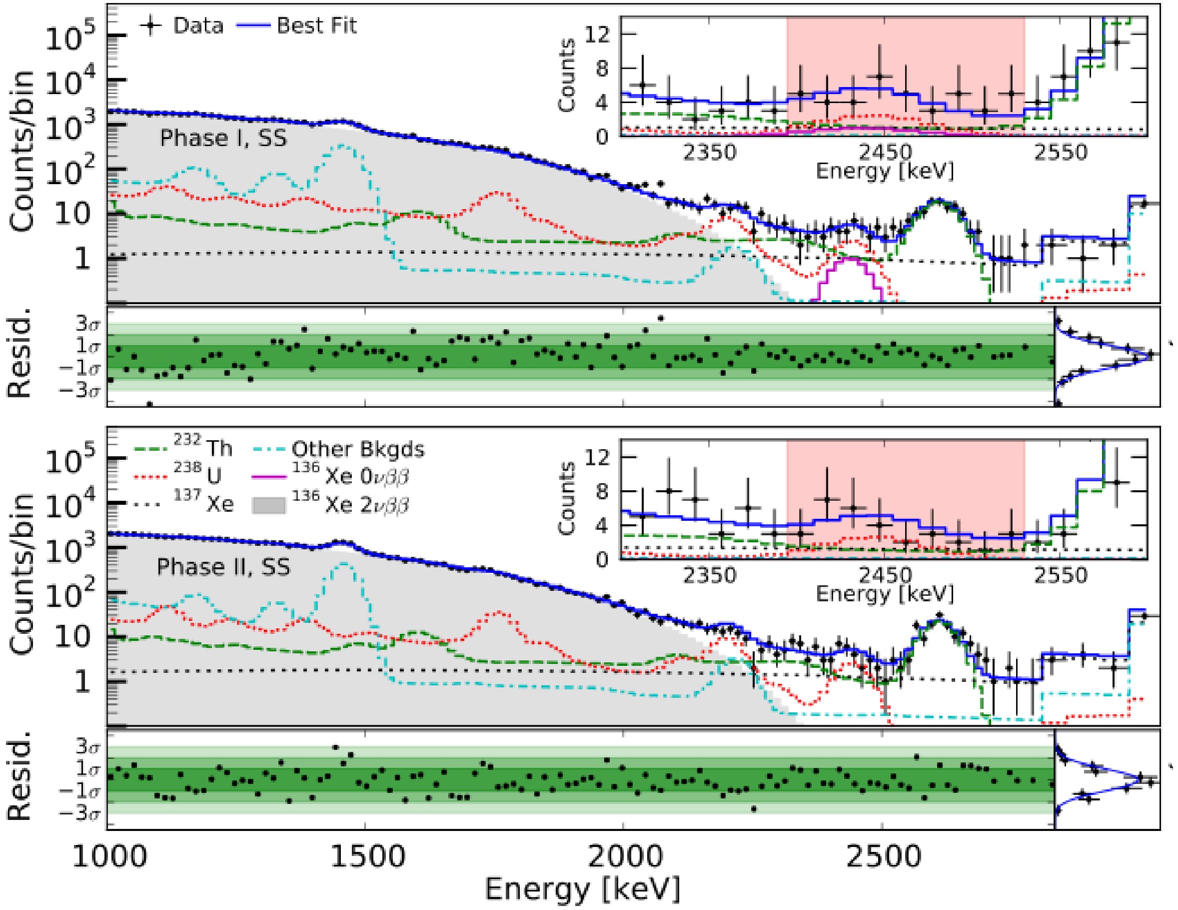

EXO

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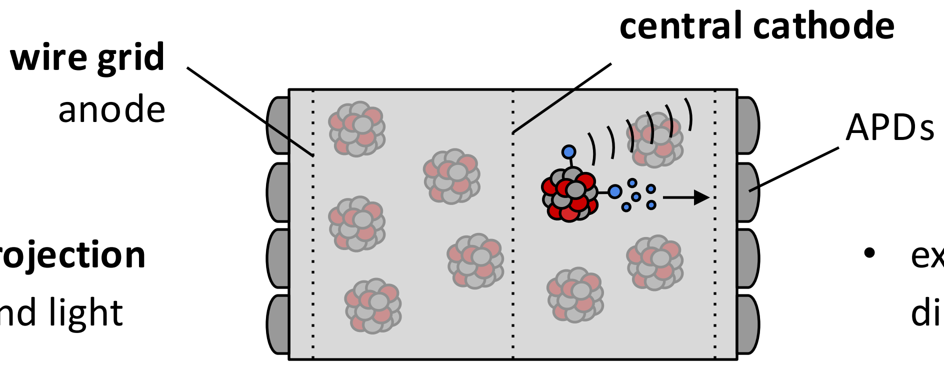
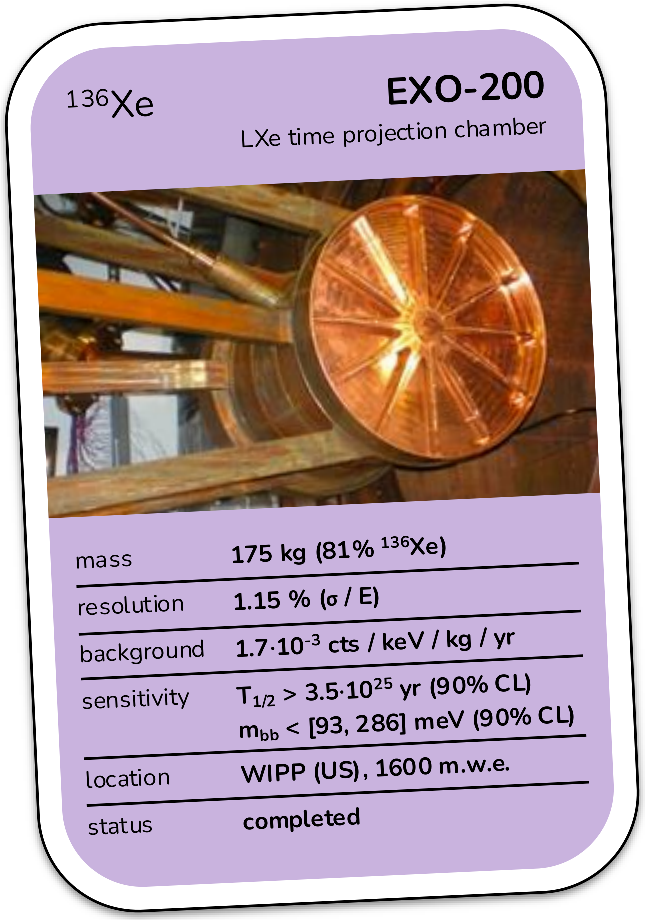
[Anton et al., PRL 123 (2019) 16, 161802]



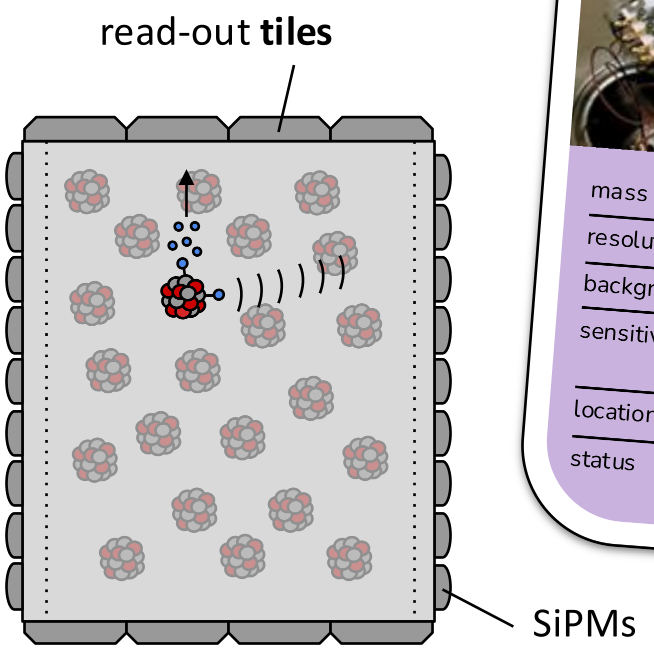


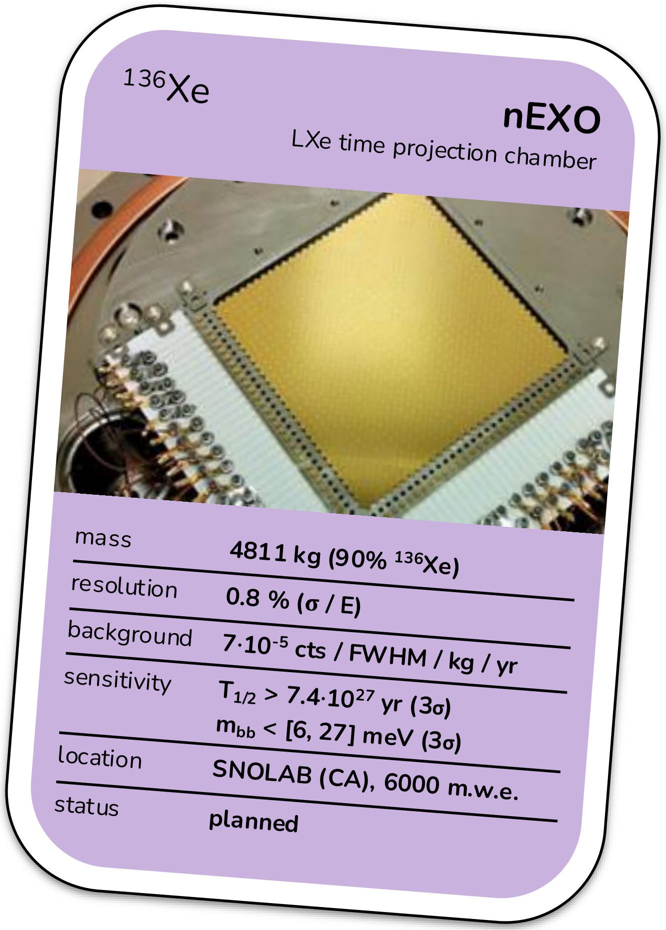
nEXO

- exploit **self-shielding**, multi-dimensional analysis
- development of **Ba tagging**, cryogenic probe

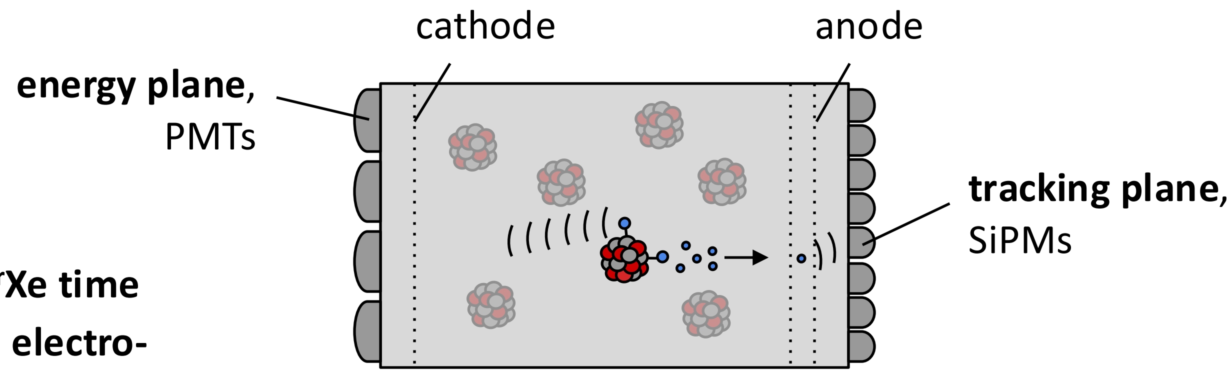
[Chambers et al., Nature 569 (2019) 7755, 203-207]

[Adhikari et al., J.Phys.G 49 (2022) 1, 015104]





NEXT



- high-pressure **gaseous ^{enr}Xe time projection chamber** with **electro-luminescence** region
- **best energy resolution** among monolithic detectors
- **topological separation** of ββ decay events
- development of **Ba tagging**, single molecule fluorescent imaging
  [McDonald et al., PRL 120 (2018) 13, 132504]

^{136}Xe

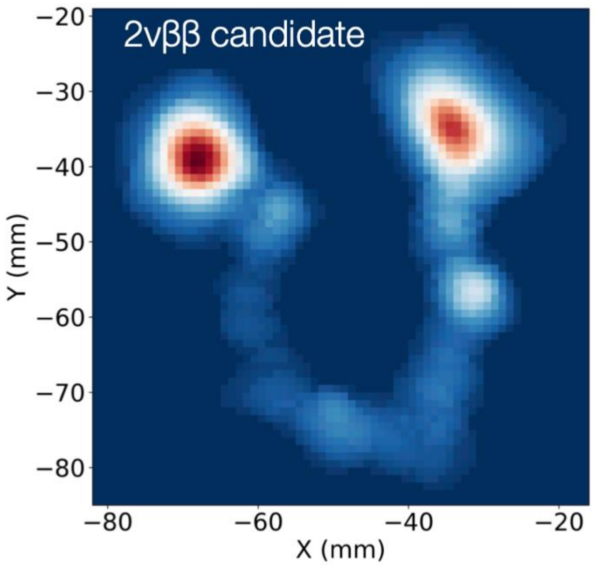
NEXT-100

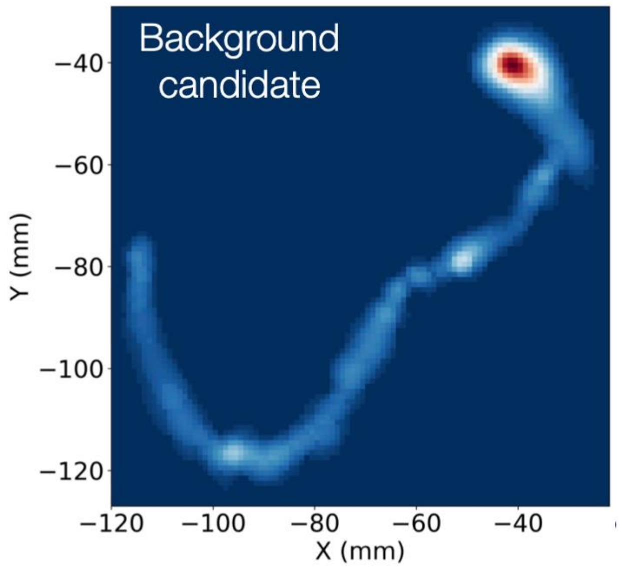
GXe time projection chamber

mass	**100 kg**
resolution	**< 1 % (σ / E)**
background	**$7.5 \cdot 10^{-4}$ cts / keV / kg / yr**
sensitivity	**$T_{1/2} > 4.1 \cdot 10^{25}$ yr (90% CL)** **-**
location	**LSC (ES), 2400 m.w.e.**
status	**commissioning**

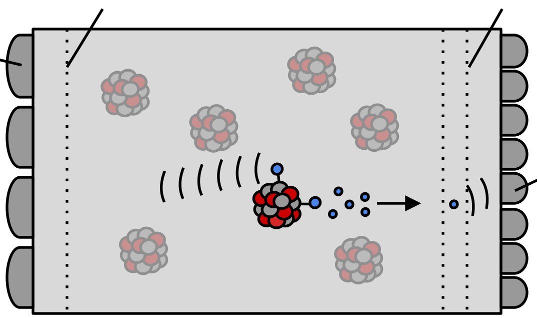
[Alvarez et al., JINST 7 (2012) T06001]

[Guenette, Neutrino 2024]





NEXT



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[Alvarez et al., JINST 7 (2012) T06001]

^{136}Xe **NEXT-100**
GXe time projection chamber

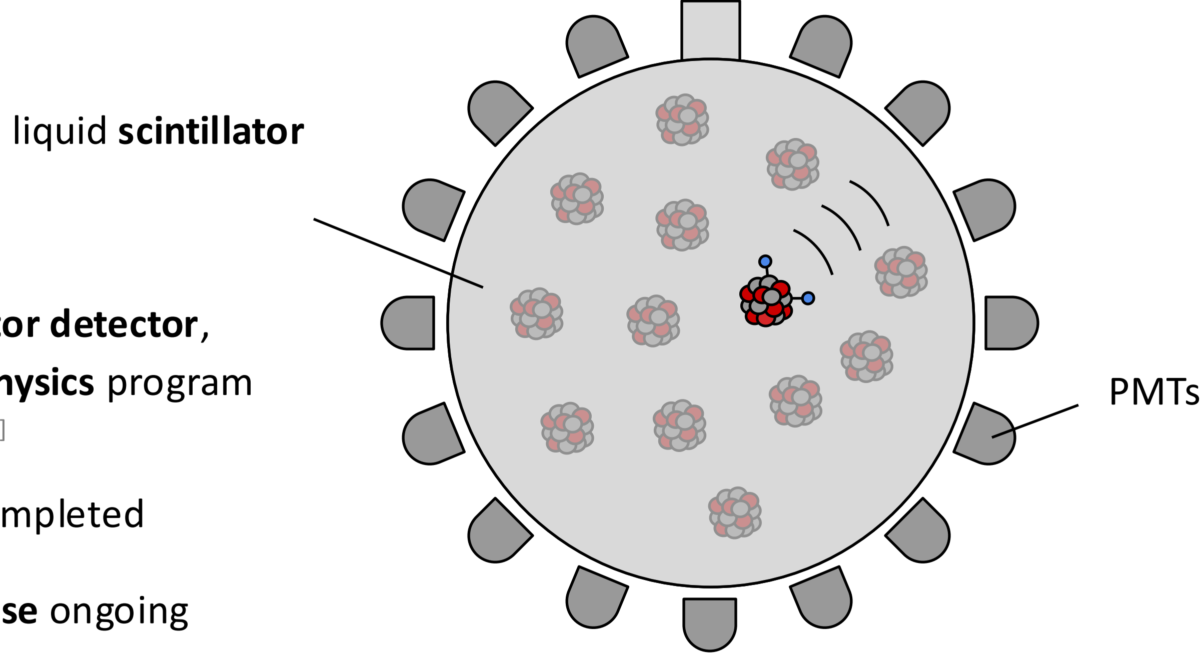
mass	**100 kg**
resolution	**< 1 % (σ / E)**
background	**$7.5 \cdot 10^{-4}$ cts / keV / kg / yr**
sensitivity	**$T_{1/2} > 4.1 \cdot 10^{25}$ yr (90% CL)** **-**
location	**LSC (ES), 2400 m.w.e.**
status	**commissioning**

^{136}Xe **NEXT-HD**
GXe time projection chamber

mass	**1109 kg**
resolution	**0.5 % (σ / E)**
background	**$4 \cdot 10^{-6}$ cts / keV / kg / yr**
sensitivity	**$T_{1/2} > 2.7 \cdot 10^{27}$ yr (90% CL)** **-**
location	**SNOLAB (CA), 6000 m.w.e.**
status	**planned**

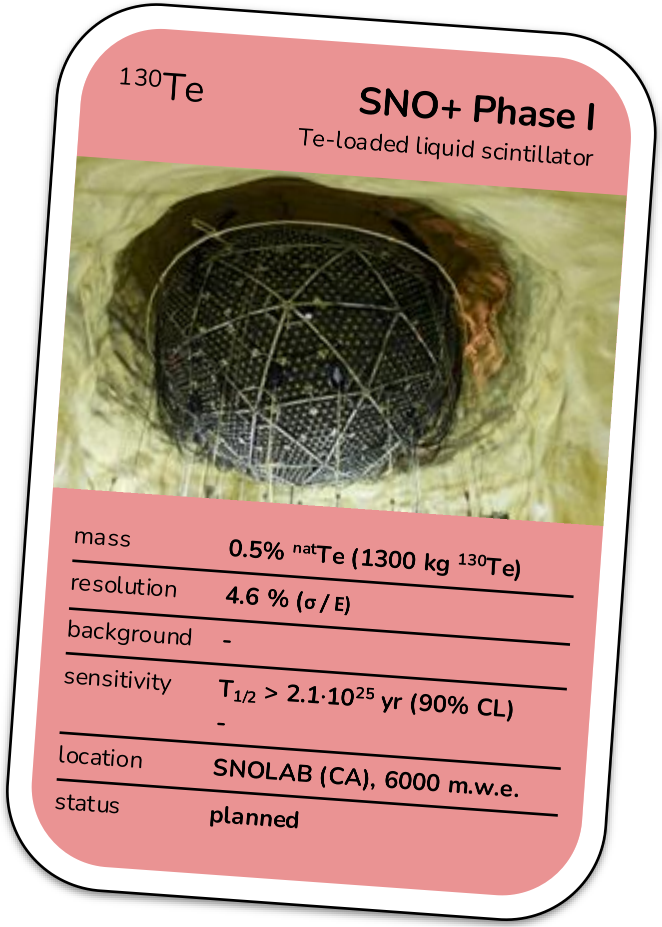
[Adams et al., JHEP 2021 (2021) 08, 164]

SNO+



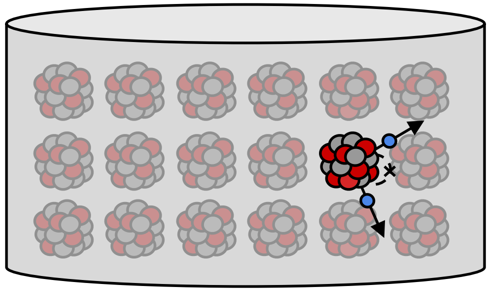
- 780-t **liquid scintillator detector**, **rich non-ββ decay physics** program
  [Allega et al., PRL 130 (2023) 9, 9]
  - water phase completed
  - **scintillator phase** ongoing
  - **staged natTe loading**, 0.5% loading planned
  - higher loading under development

[Andringa et al., Adv.High Energy Phys. 2016 (2016) 6194250;
Albanese et al., JINST 16 (2021) 08, P08059]



Experimental approaches

source = detector concepts



monolithic scintillation / ionization **detectors**

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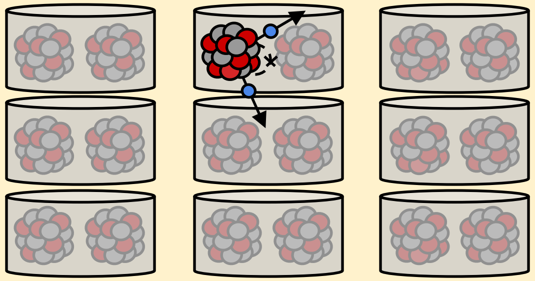

granular semiconductor / cryogenic **detectors**

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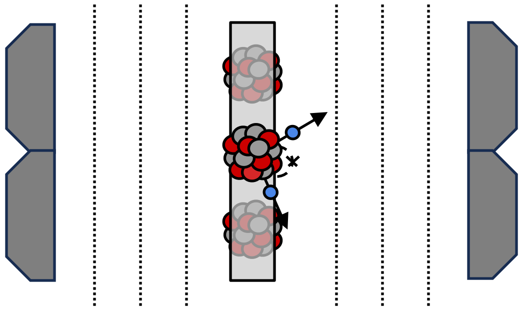
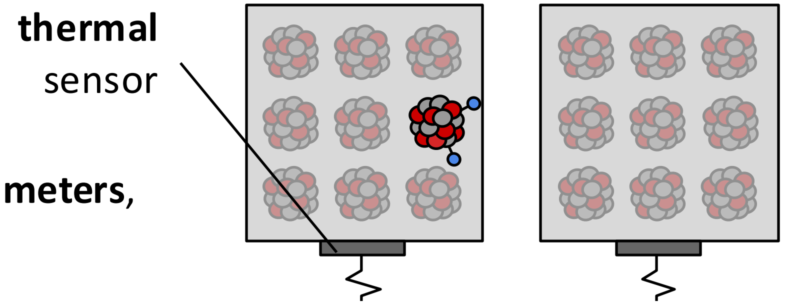


tracking
Calorimeters

NEMO3, **SuperNEMO**, ..

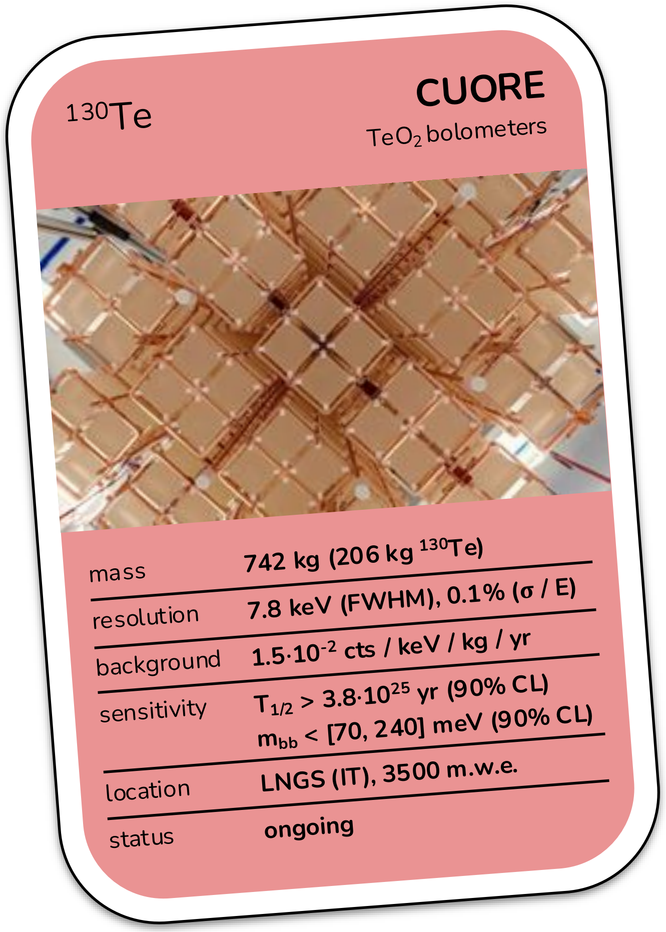
CUORE



- cryogenic $^{nat}TeO_2$ **bolometers**, dilution refrigerator
- **archeological lead** shielding
  [Alessandrello et al., NIM B142 (1998) 163-172]
- recent result
  [Adams et al., arXiv:2404.04453]

  $T_{1/2}(^{130}Te)$ **> 2.8·10^25 yr** (90% CI)
  $m_{\beta\beta}$ **< [70, 240] meV** (90% CI)

- measurement **ongoing**



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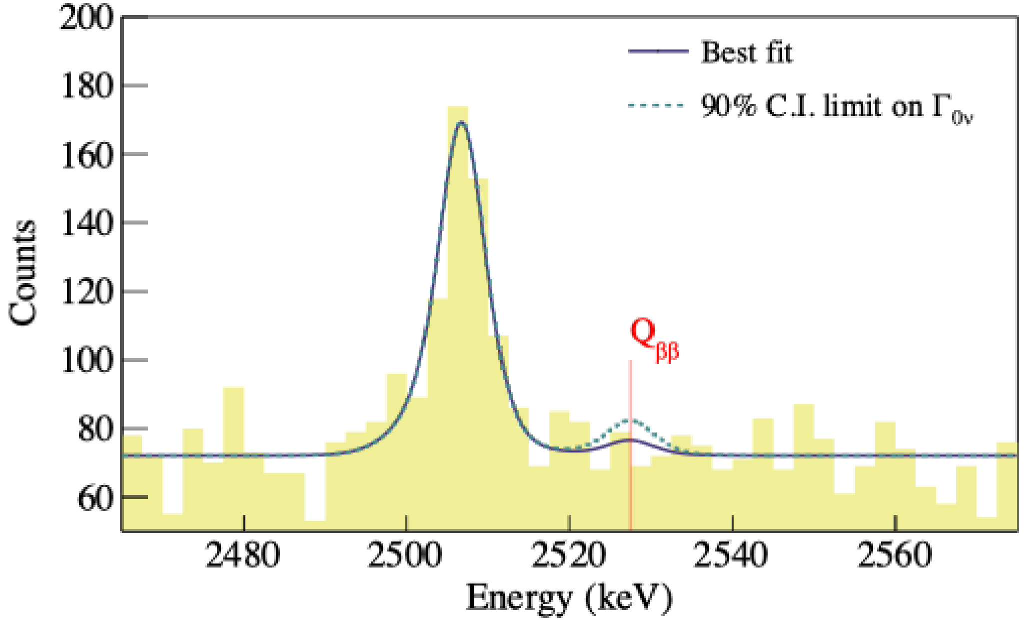
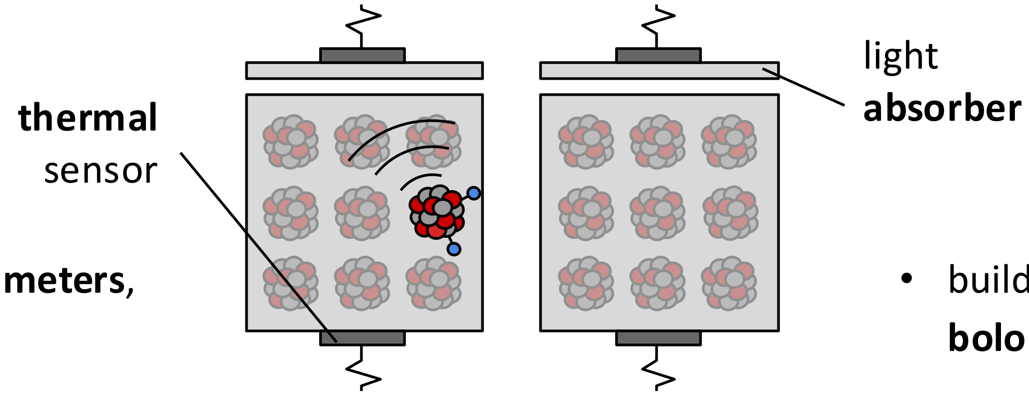


CUORE

CUPID



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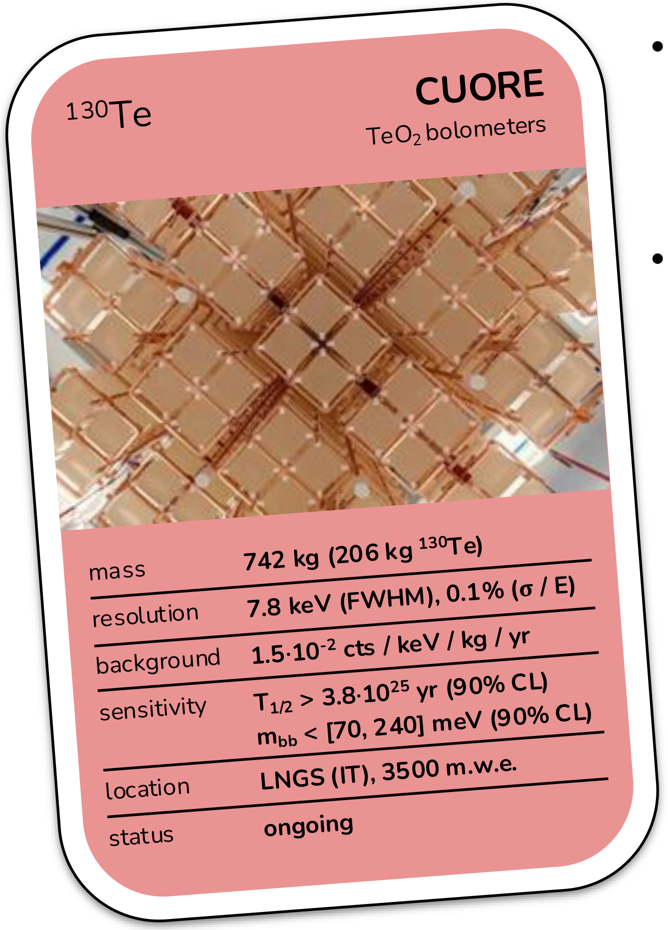
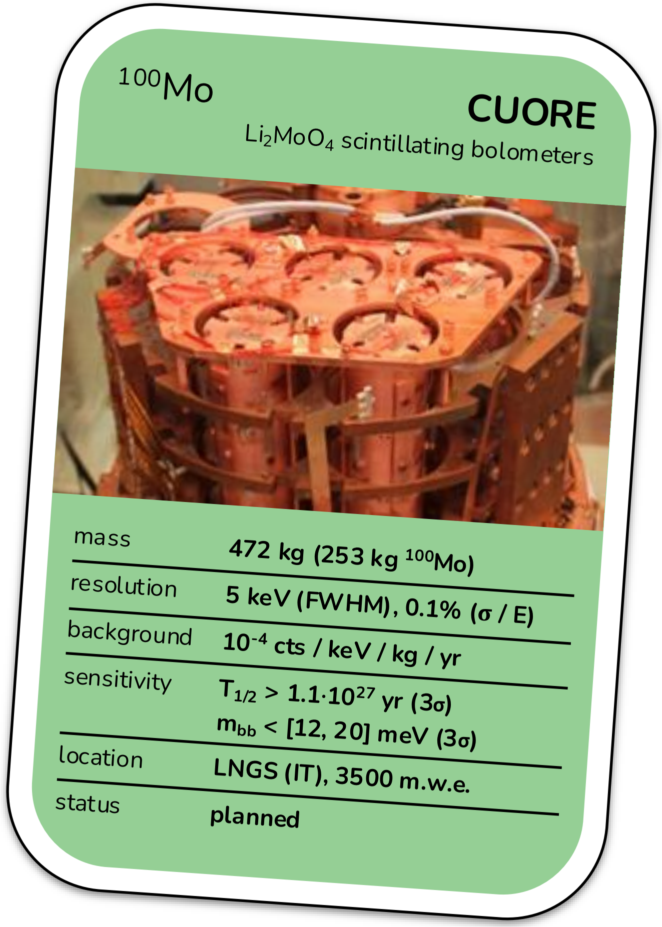


[Adams et al., arXiv:2404.04453]

- builds on CUPID-Mo and CUPID-0, **scintillating bolometers**

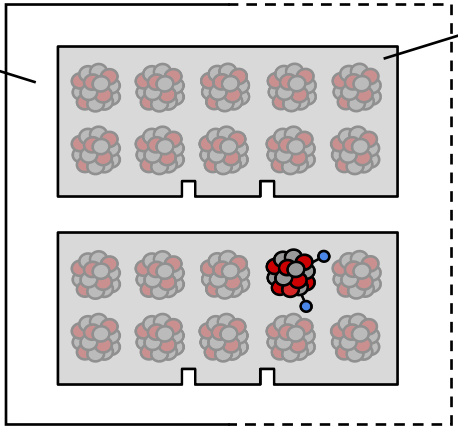
- **particle discrimination**, background rejection

- reuse existing **CUORE infrastructure**



[Armstrong et al., arXiv:1907.09376]

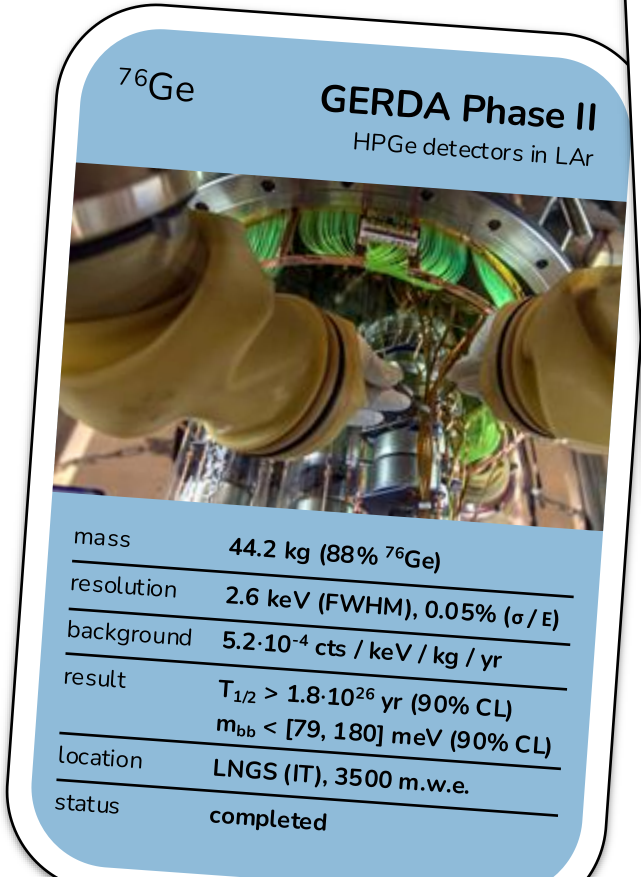
GERDA

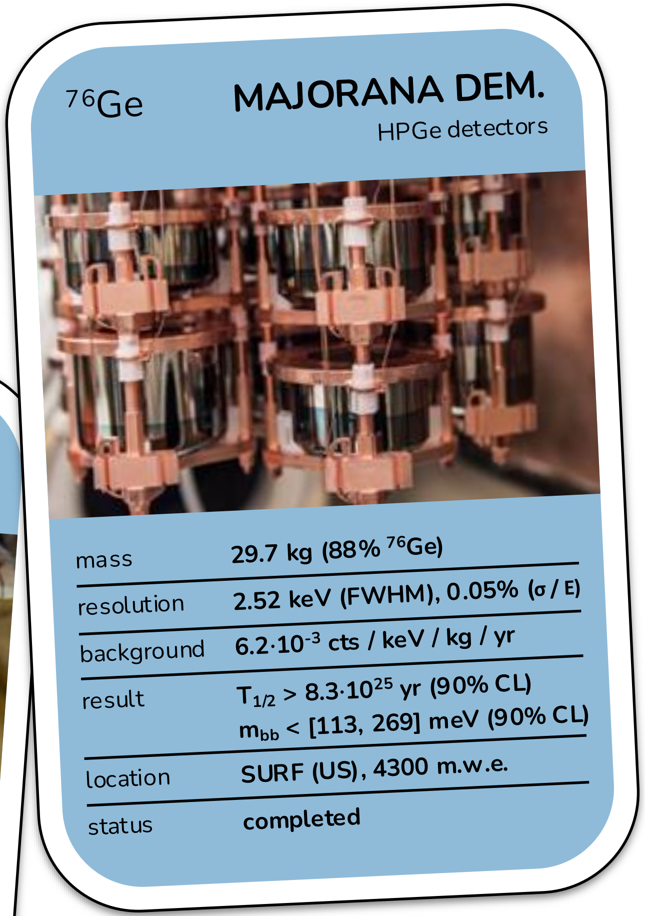


MAJORANA

- high-purity ^{enr}Ge **detectors** in **active liquid argon shield**
- **topology discrimination**, anti-coincidence, pulse shape
- **best background**, background-free scaling

[Agostini et al., PRL 125 (2020) 25, 252502]

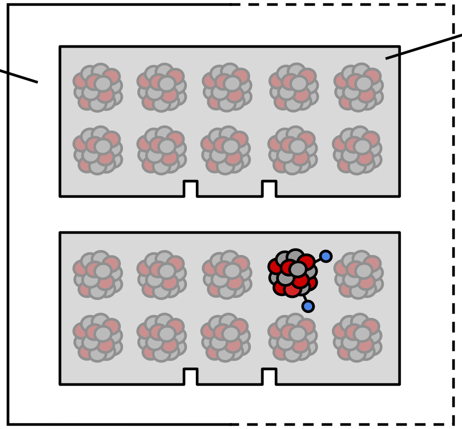




- high-purity ^{enr}Ge **detectors** in **compact shield** setup
- underground **electroformed copper**
- **best resolution**

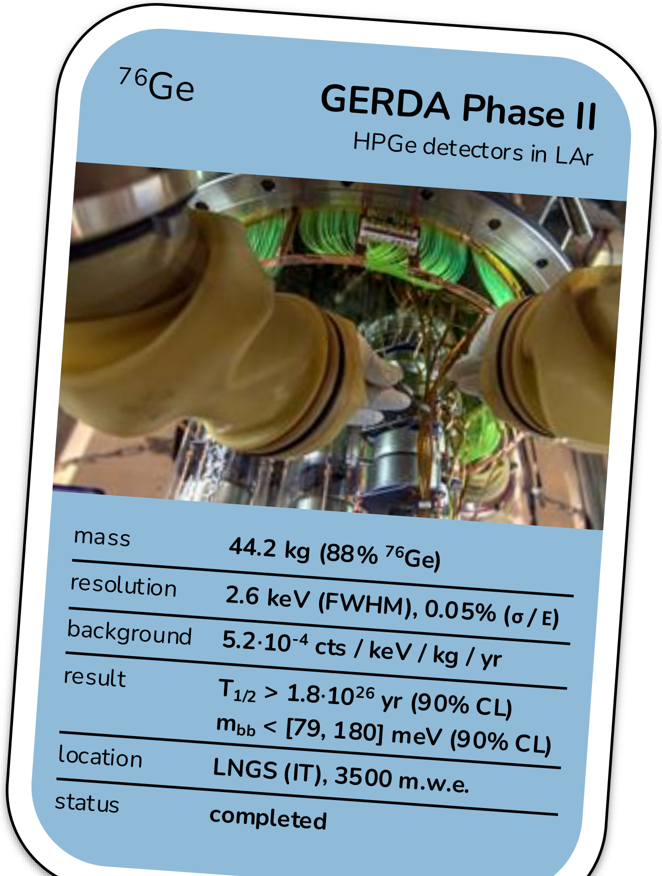
[Arnquist et al., PRL 130 (2023) 6, 062501]

GERDA

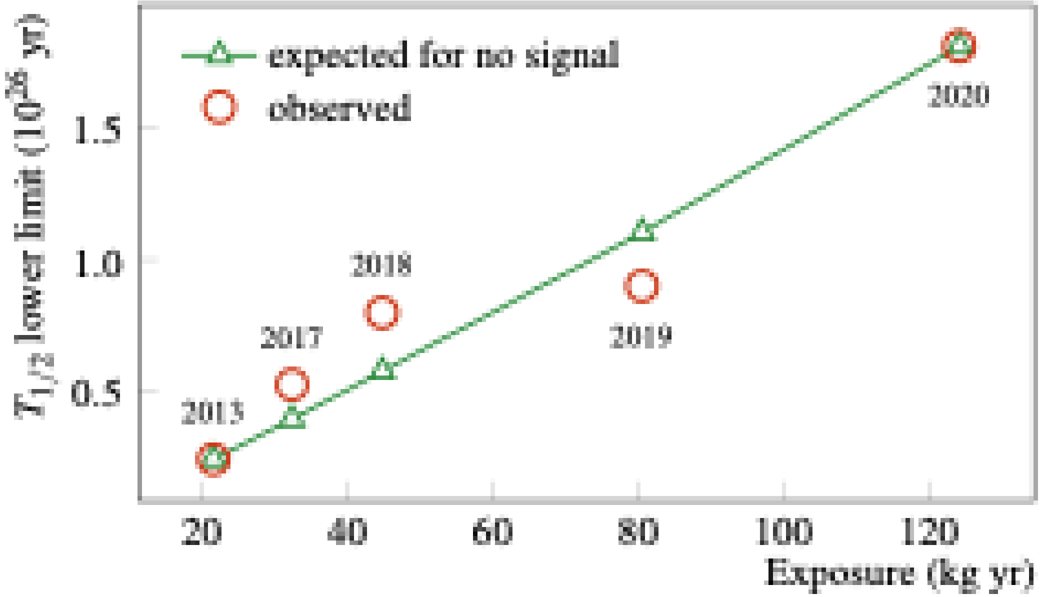


- high-purity ^{enr}**Ge detectors** in **active liquid argon shield**
- **topology discrimination**, anti-coincidence, pulse shape
- **best background**, background-free scaling

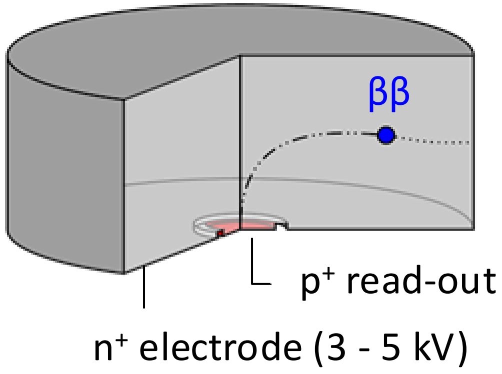
[Agostini et al., PRL 125 (2020) 25, 252502]



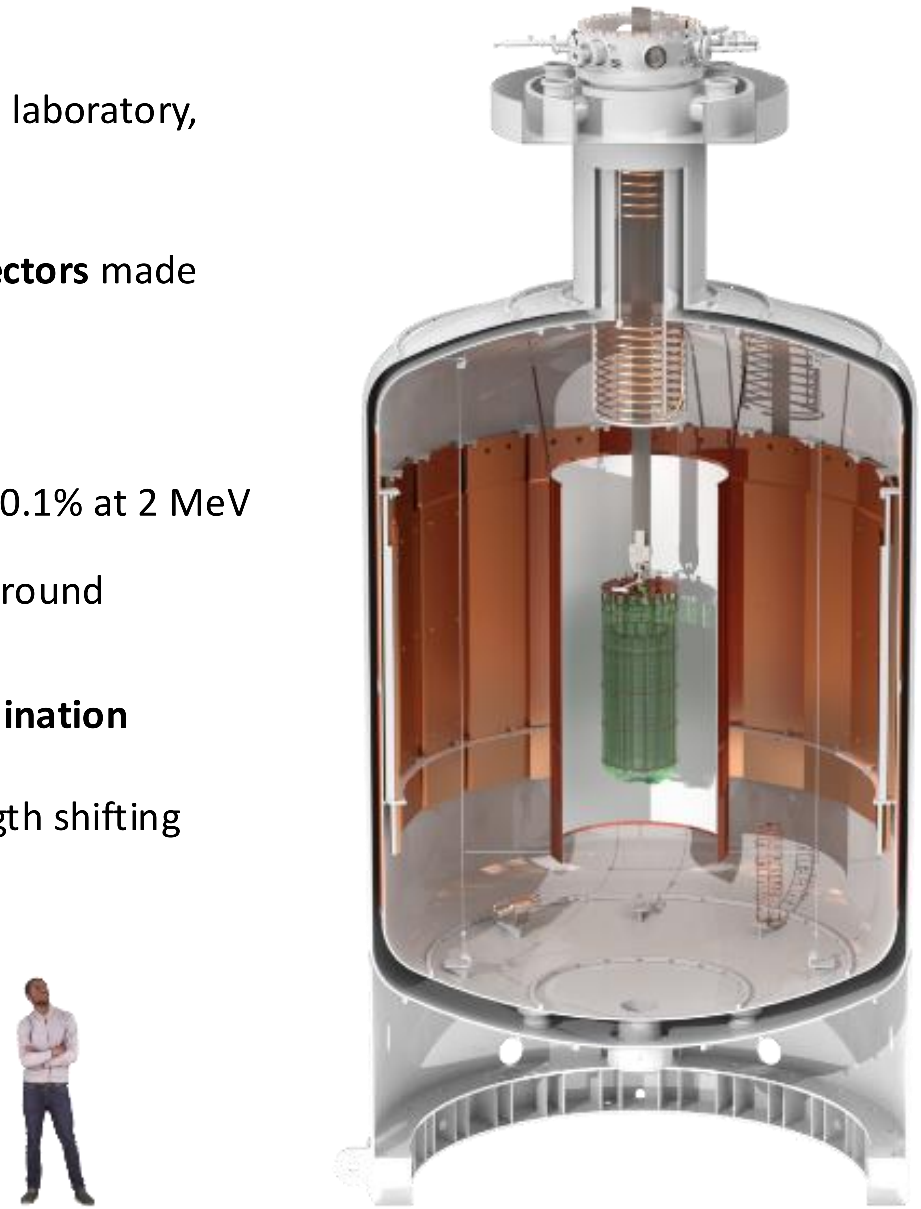
[Agostini et al., PRL 125 (2020) 25, 252502]



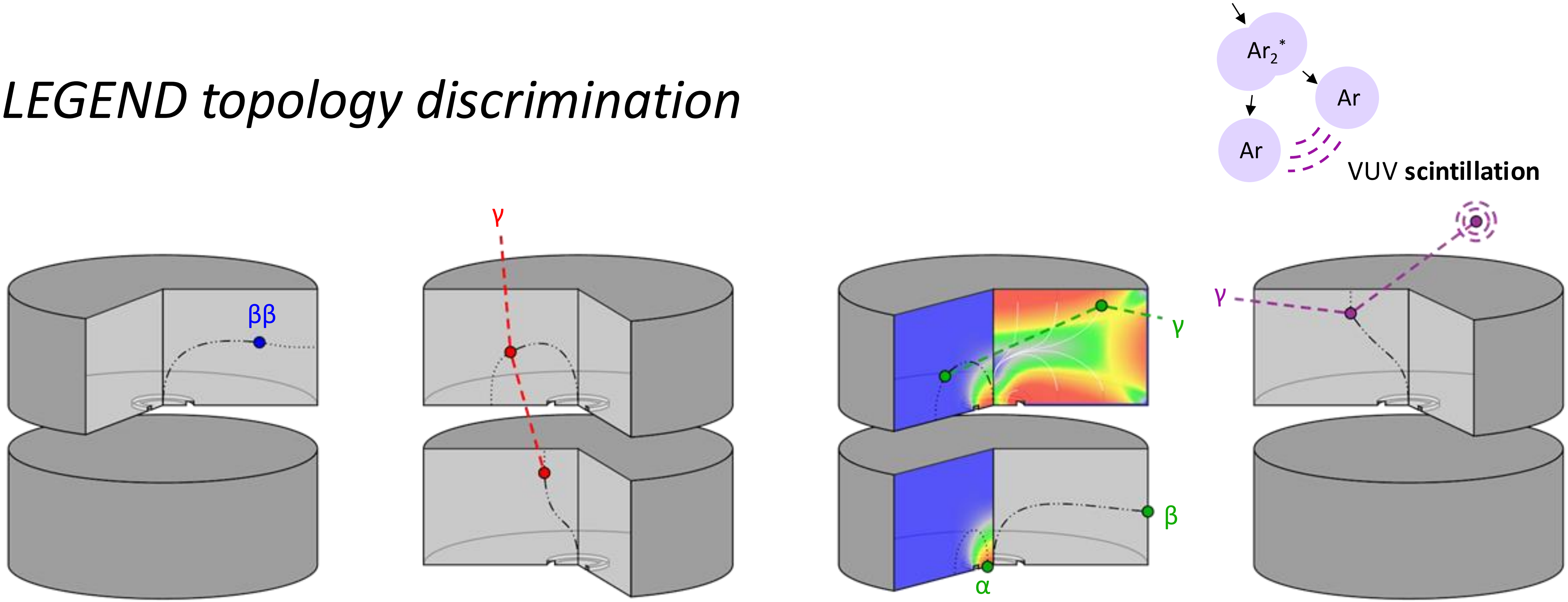
LEGEND-200 setup



- upgraded **GERDA infrastructure**, Gran Sasso laboratory, 3500 m.w.e
- up to **200 kg** of high-purity **germanium detectors** made from ^{enr}**Ge material**, 90% ^{76}Ge
  - **source = detector**, high efficiency
  - excellent **energy resolution,** σ(E) / E < 0.1% at 2 MeV
  - high-purity material, no intrinsic background
    [Agostini et al., Astropart.Phys. 91 (2017) 15-21]
  - high stopping power, **topology discrimination**
- instrumented **liquid argon shield**, wave-length shifting fibers with SiPM read-out
- water tank, Cherenkov muon veto



LEGEND topology discrimination



differentiate **point-like** ββ topology from:

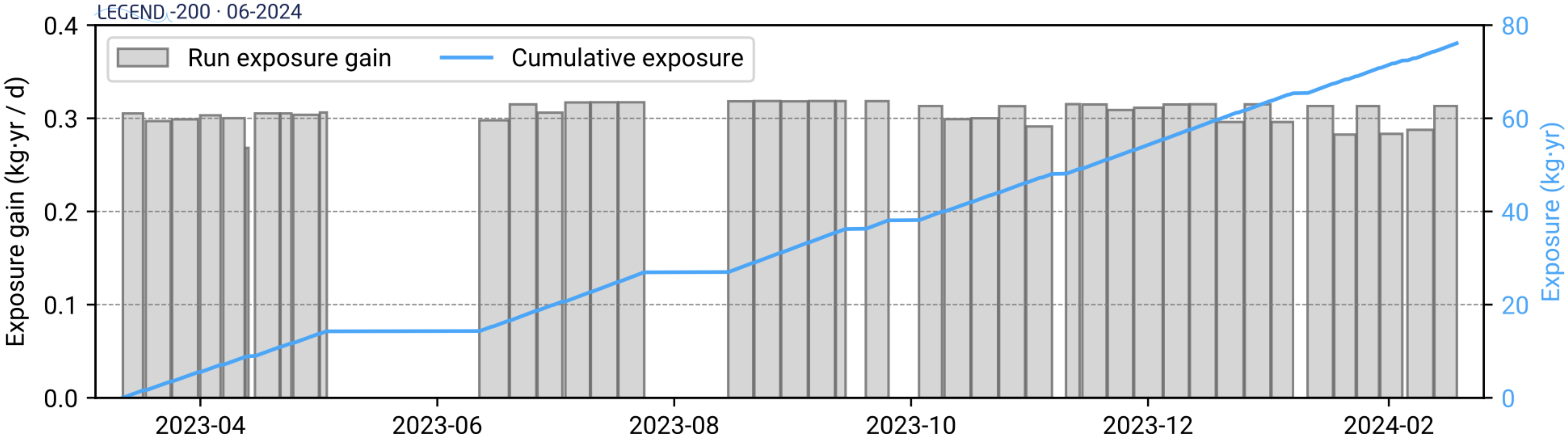
multi-detector interactions

multi-site/surface interactions

interactions with **partial energy depositions**

LEGEND-200 data taking

- collected **first year** of physics data with 140 kg of germanium detectors



› **76.2 kg yr** of exposure, +10.2 kg yr of background characterization data, **48.3 kg yr** selected for first 0νββ decay analysis

First LEGEND-200 result

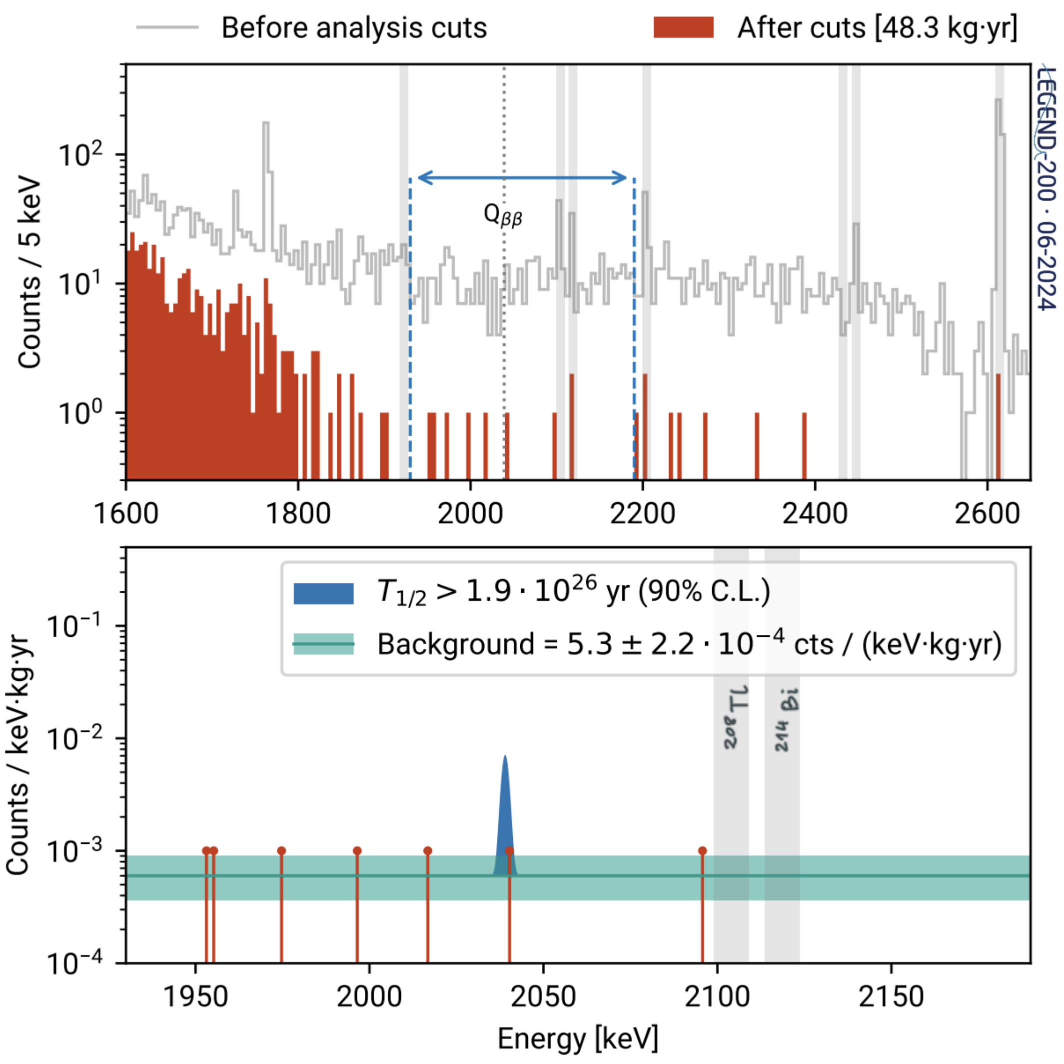
- **7 events** in analysis window, background index of **(5.3 ± 2.2) · 10^{-4} cts / keV / kg / yr**

- **combined analysis** with GERDA and MAJORANA

  $T_{1/2}(^{76}Ge)$ **> 1.9·10^{26} yr** (90% CL)
  $m_{\beta\beta}$ **< [75, 178] meV** (90% CL)

- median sensitivity $T_{1/2}(^{76}Ge)$ **> 2.8·10^{26} yr** (90% CL)

- data taking interrupted for **background characterization**, maintenance, and installation of additional detectors



LEGEND

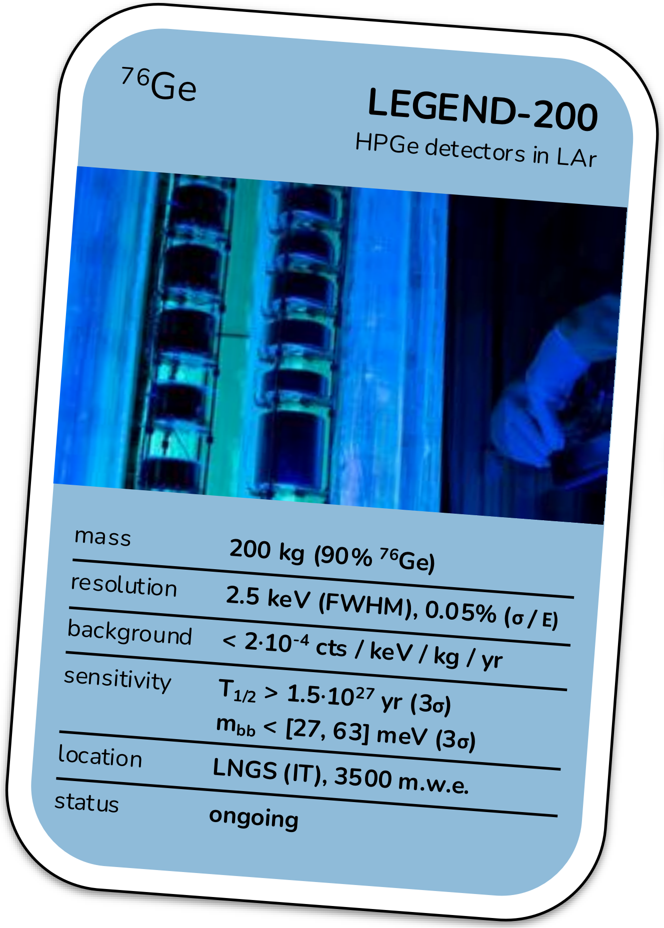
- builds on GERDA and MAJORANA, **staged approach**

LEGEND-200

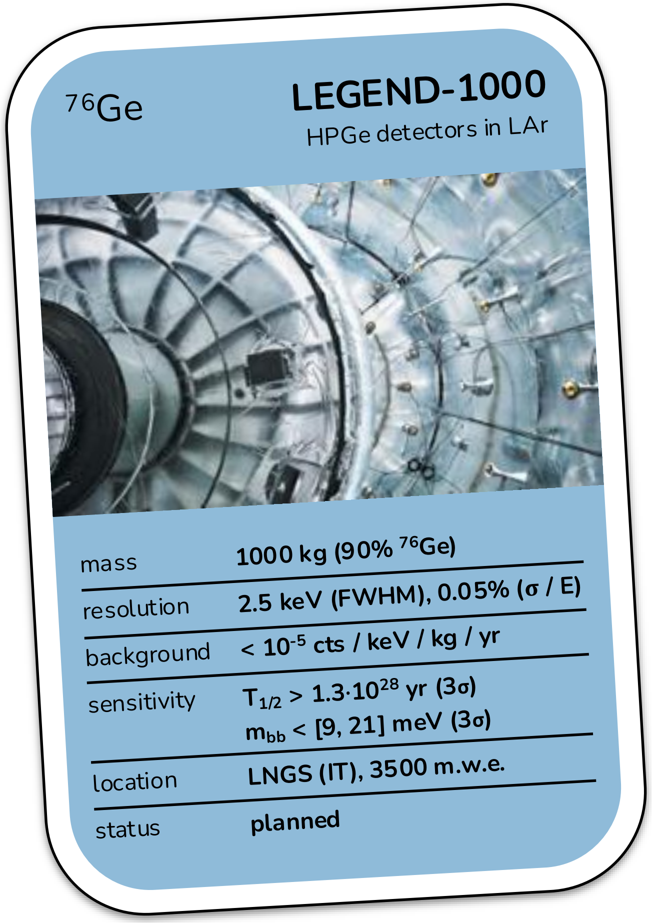
- upgraded **GERDA-infrastructure** with
  - new large volume detectors
  - reduced inactive materials
  - improved light read-out
- first 140 kg **in operation**

LEGEND-1000

- improved background mitigation, **underground-sourced argon**

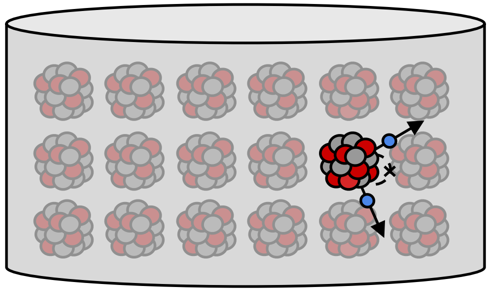


[Abgrall et al., arXiv:2107.11462]



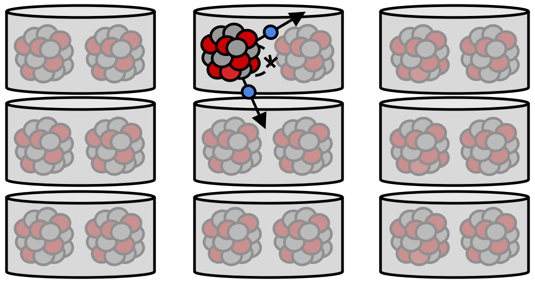
Experimental approaches

source = detector concepts



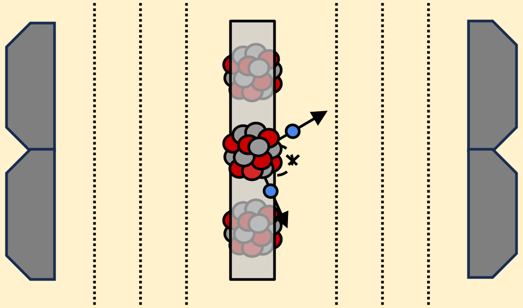
monolithic scintillation / ionization **detectors**

AXEL, DARWIN, **EXO**, JUNO, **KamLAND-Zen**, LiquidO, LZ, **nEXO**, **NEXT**, NvDEx, R2D2, THEIA, Panda-X, **SNO+**, XENON, ZICOS, ..



granular semiconductor / cryogenic **detectors**

AMORE, BINGO, CANDLES, CEDEX, COBRA, **CUORE**, **CUPID**, CROSS, **GERDA**, **LEGEND**, **MAJORANA**, SELENA, ..

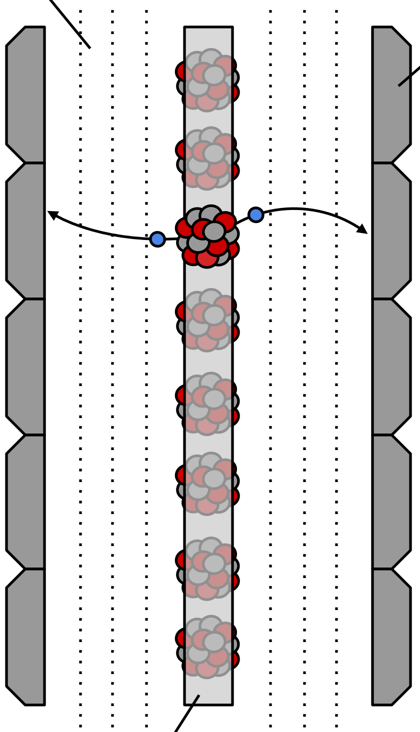


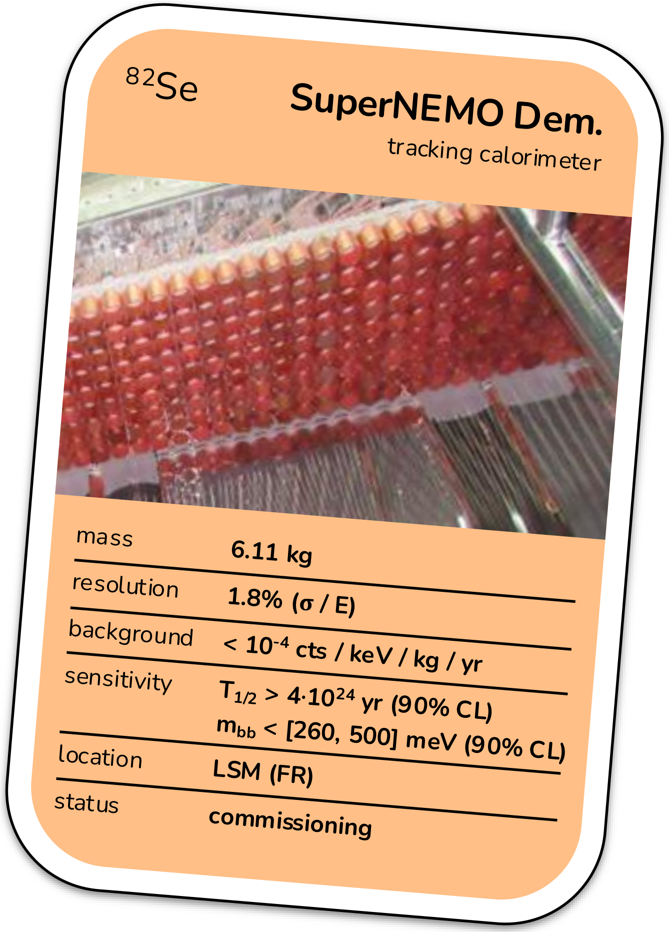
tracking Calorimeters

NEMO3, **SuperNEMO**, ..

SuperNEMO

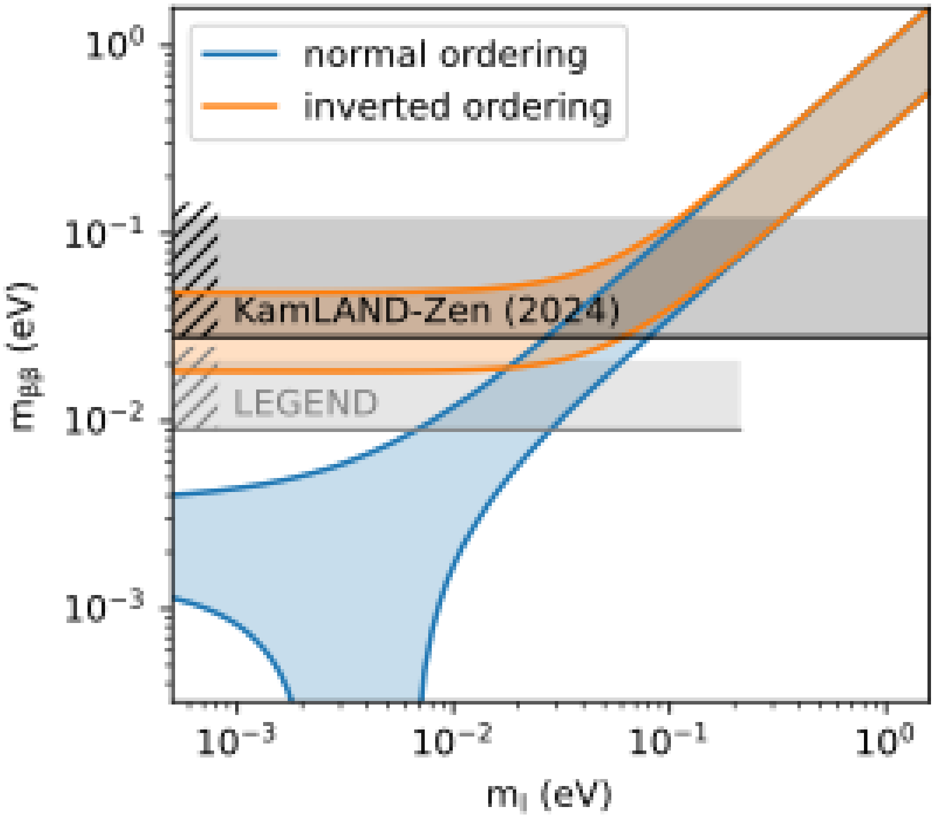
- builds on NEMO3 technology, **tracking calorimeter**
- almost **isotope-agnostic**, solid source material
- full **topological reconstruction**
  - unique **2νββ decay** measurements
  - probe **0νββ decay mechanism**
- **demonstrator** in operation





Effective Majorana neutrino mass , $m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$

[NuFIT 5.3, nu-fit.org]



- **complex Majorana phases**, cancelation possible (normal ordering), minimum at **18 meV** (inverted ordering)
- current bounds by e.g.
  [Pertoldi Neutrino 2024; Adams et al., arXiv:2404.04453; Abe et al., arXiv:2406.11438]

  LEGEND + GERDA .. (^{76}Ge): $m_{\beta\beta}$ **< [75, 178] meV** (90% CL)

  CUORE (^{130}Te): $m_{\beta\beta}$ **< [70, 240] meV** (90% CI)

  KamLAND-Zen (^{136}Xe): $m_{\beta\beta}$ **< [28, 122] meV** (90% CL)
- **next generation** experiments, e.g.
  [Abgrall et al., arXiv:2107.11462]

  LEGEND-1000: [9, 21] eV (3σ discovery)

  similar numbers for CUPID, nEXO, …

Take away

- What would the observation of **neutrinoless double beta decay** tell us?
  lepton number is not conserved, neutrino is Majorana particle

- What can we learn about the **absolute neutrino mass**? Which **assumptions** are needed?
  coherent sum of mass eigenstates, effective Majorana neutrino mass, mediation by exchange of light Majorana neutrino

- Is there a clearly **favoured isotope**?
  no, experimental considerations outweigh isotopic rate differences

- What are the **experimental challenges**?
  ultra-low background, good energy resolution, large isotope mass, high efficiency

- How does the **LEGEND experiment** work?

- Where are **current bounds**? Where is the minimum value?

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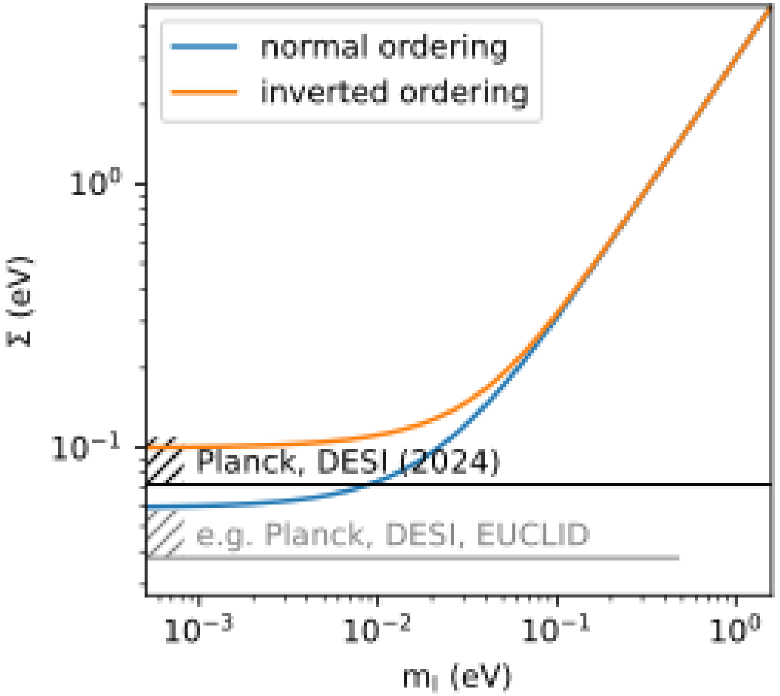
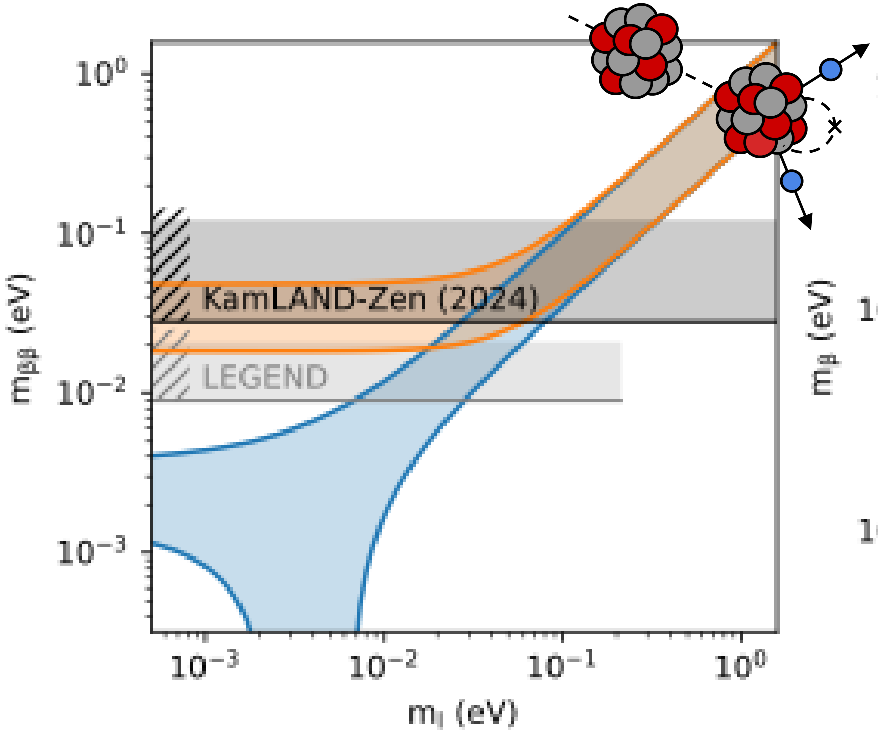
Neutrino mass observables

laboratory-based

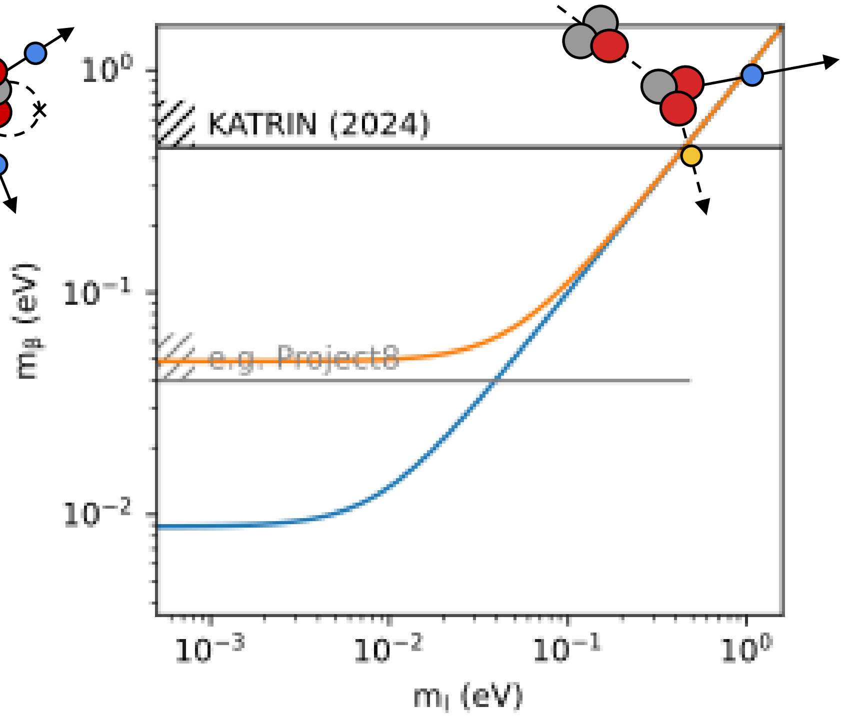
cosmology



0νββ decay



β decay kinematics

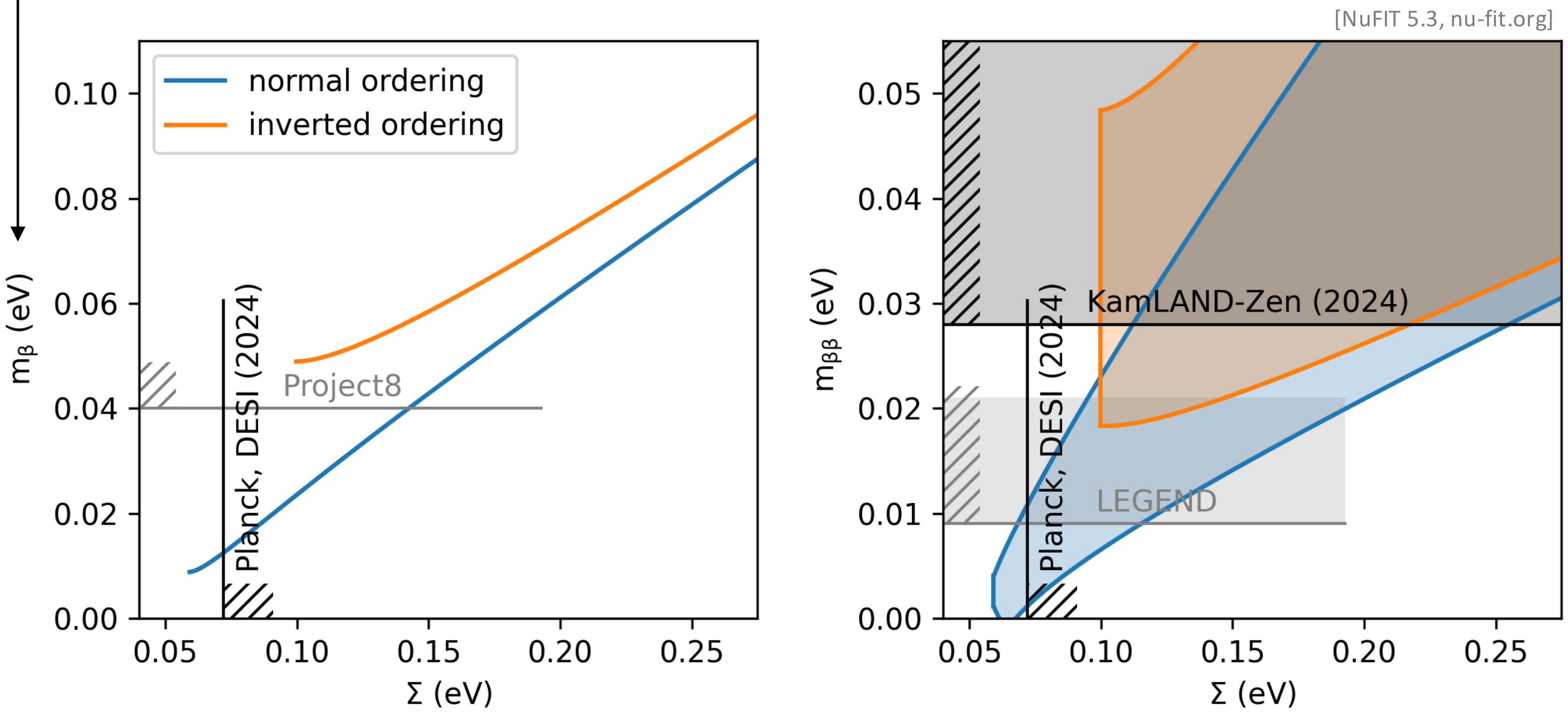


model-dependent

Interplay

- **complementary** neutrino mass information
  - different **mass eigenstate combinations**
  - different **model assumptions**
- › **counter measurements**, model discrimination

Majorana nature,
light Majorana neutrino exchange



energy conservation

cosmological model

Backup