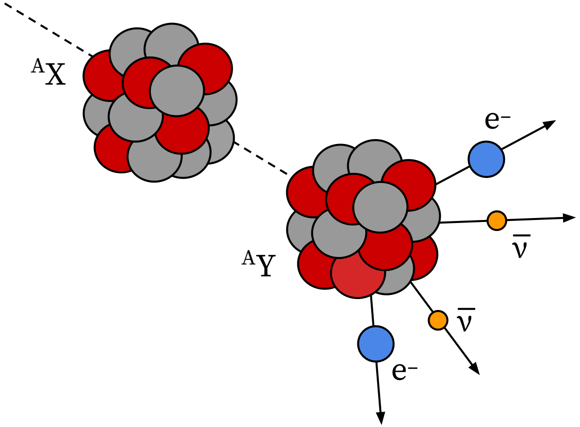
Neutrinoless double beta decay

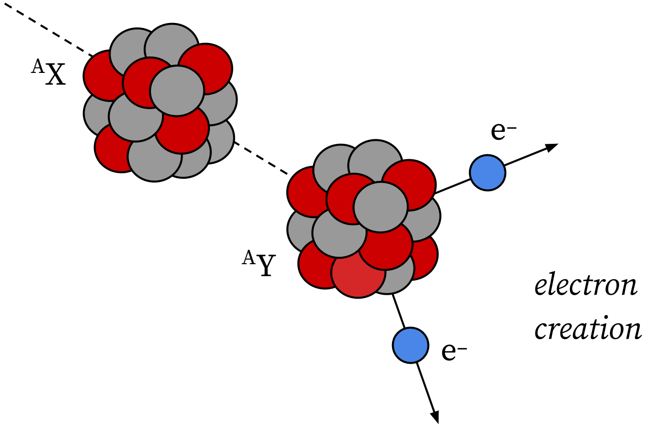
Christoph Wiesinger (TUM), NNN23, 12.10.2023

Double beta decay



- SM-allowed two-neutrino double beta (**2νββ**) **decay**
- observed in **11** out of 35 naturally abundant **even-even nuclei** [Tretyak, Zdesenko, Nucl.Data Tabl. 80 (2002) 83-116]

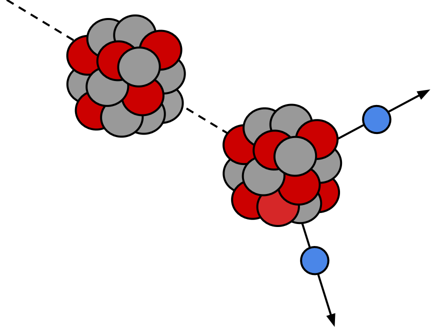
$$\mathbf{T_{1/2} \approx 10^{18} - 10^{21}\ yr}$$



- neutrinoless double beta (**0νββ**) **decay**
- beyond-SM physics, **lepton number violation**

$$\mathbf{T_{1/2} \gtrsim 10^{26}\ yr}$$

0νββ decay



- neutrino could be its **own antiparticle** (ν —×— $\overline{\nu}$)

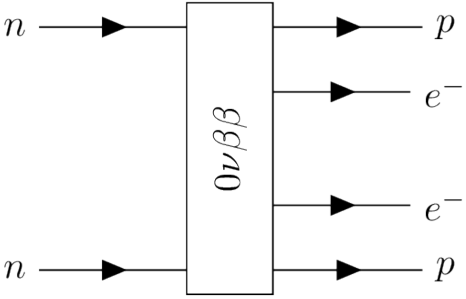
- observation of **0νββ decay** would ..

  a. .. prove **lepton number violation** (LNV)

  b. .. identify neutrino as **Majorana particle**
     [Schechter, Valle, PRD 25 (1982) 2951]

  c. .. determine **effective Majorana mass**

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



0νββ decay

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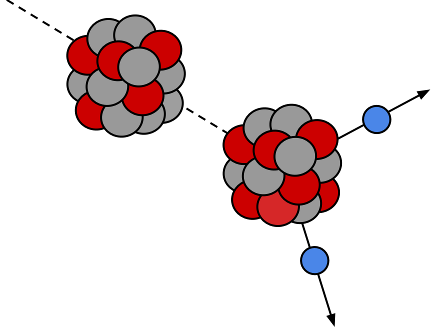
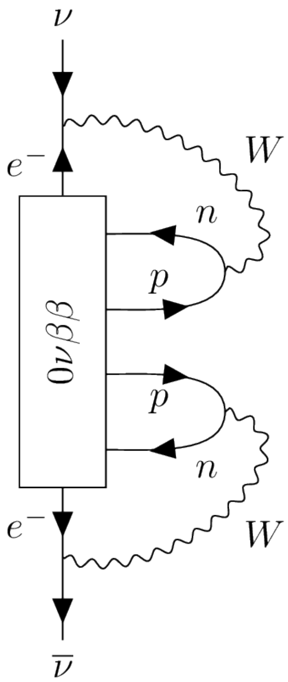
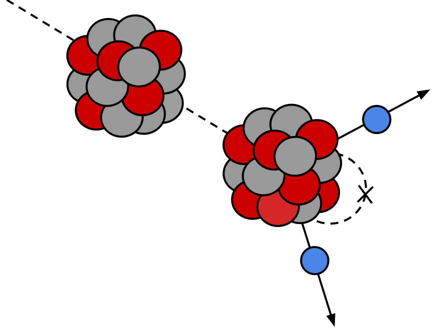


black box theorem



$0\nu\beta\beta$ decay



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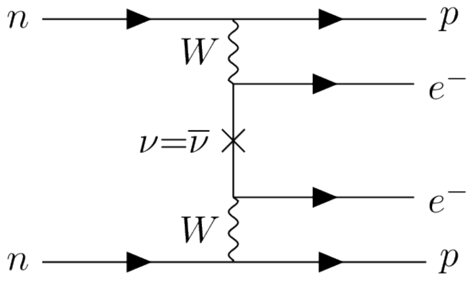
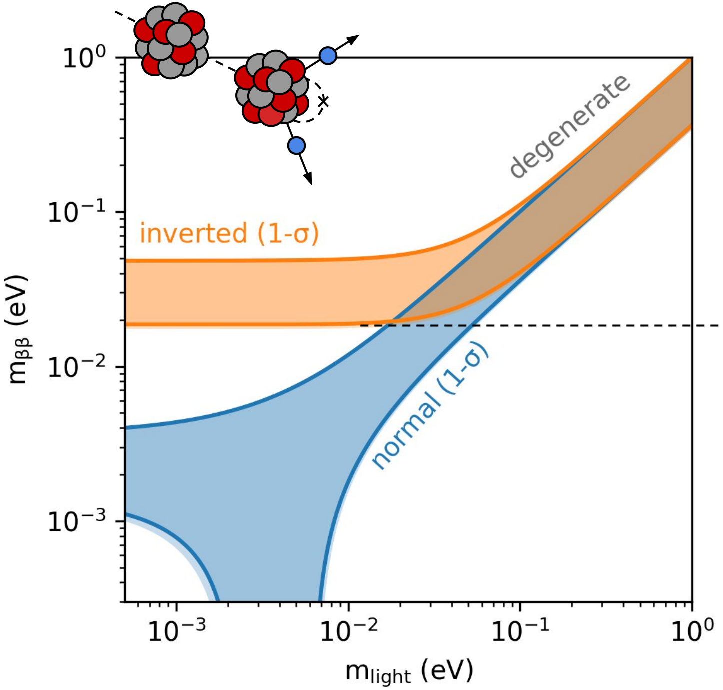


mass mechanism

Effective Majorana mass



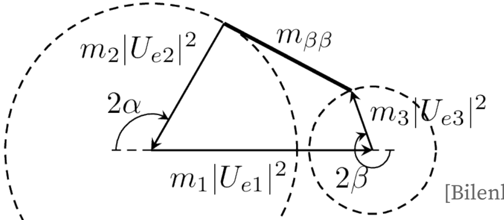
- **coherent sum** of mass eigenstates

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

  - sensitive to **complex Majorana phases**
  - **minimum value** in inverted ordering scenario
    [NuFIT 5.2, nu-fit.org]

$$\min(m_{\beta\beta}^{io}) = (19 \pm 1)\,\text{meV}$$

  - **potential cancellation** in normal ordering scenario

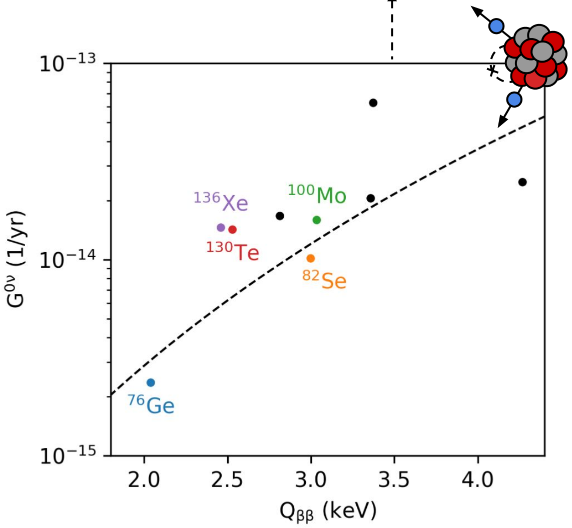


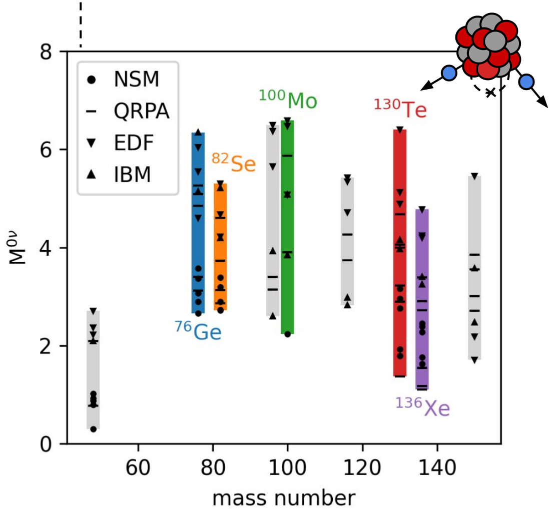
[Bilenky et al., PRD 64 (2001) 053010]

Decay rate

- interplay of **LNV physics** and **isotope properties**

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





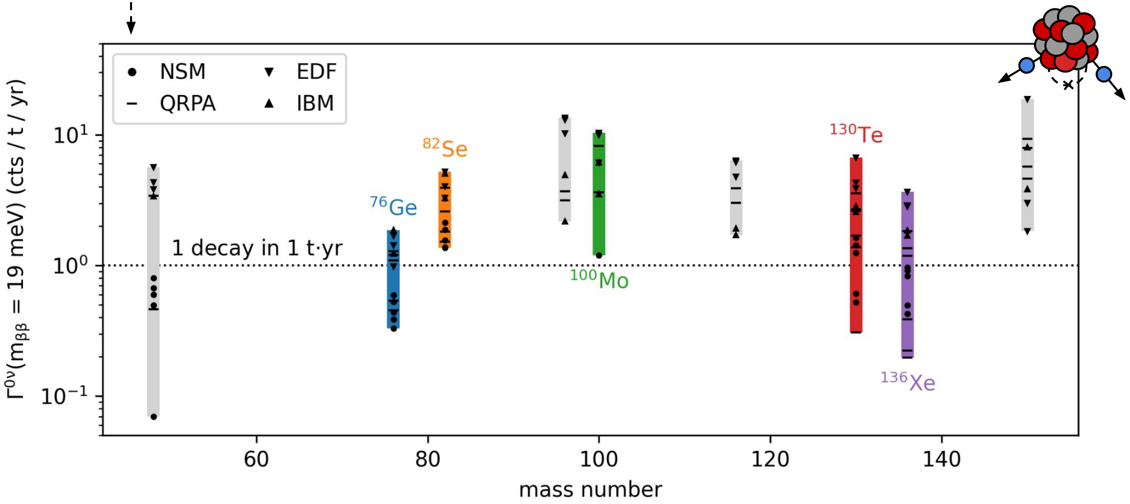
- accurate **phase space factor,** large Q-value favorable
  [Kotila, Iachello, PRC 85 (2012) 034316]

- different **nuclear matrix elements** using various **many-body methods,** significant spread
  [Agostini et al., Rev.Mod.Phys. 95 (2023) 2, 025002]

Decay rate

- interplay of **LNV physics** and **isotope properties**

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



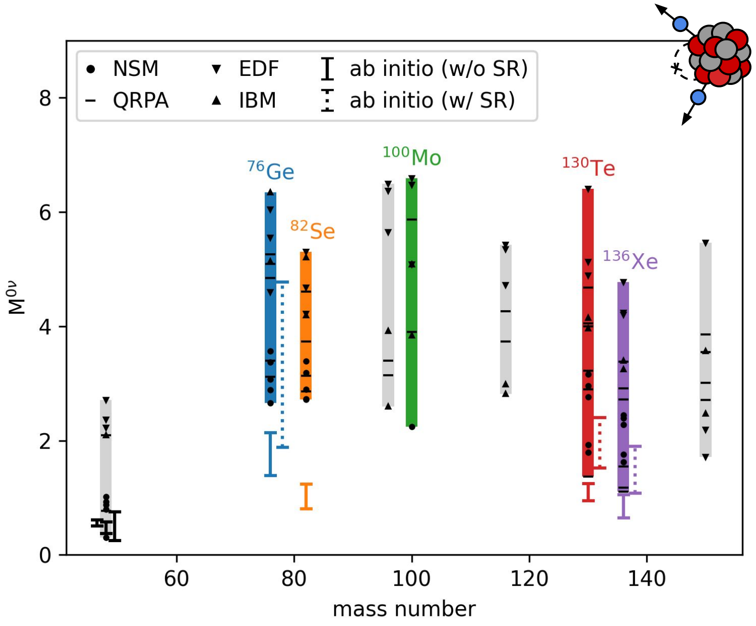
- probing **inverted ordering scenario** requires **tone-year exposure**

- isotope differences do not outweigh **experimental considerations**

there is no super-isotope

Nuclear matrix elements

- first **ab initio calculations** available, could resolve **quenching issue**
  [Yao et al., PRL 124 (2020) 23, 232501; Belley et al., PRL 126 (2021) 4, 042502; Novario et al., PRL 126 (2021) 18, 182502]
- **short-range operator** under investigation
  [Cirigliano et al., PRL 120 (2018) 20, 202001;
  Belley et al., arXiv:2307.15156; Belley et al., arXiv:2308.15634]
- experimental input by ..
  - .. precision **2νββ decay** measurements
    [Gando et al., PRL 122 (2019) 19, 192501]
  - .. heavy-ion **double charge exchange** reactions
    [Cappuzzello et al., EPJ A 54 (2018) 5, 72]
  - .. ordinary **muon capture**
    [Zinatulina et al., PRC 99 (2019) 2, 024327]

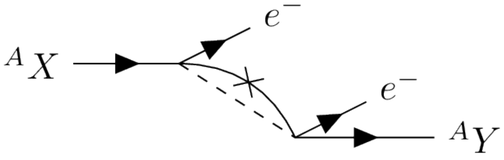


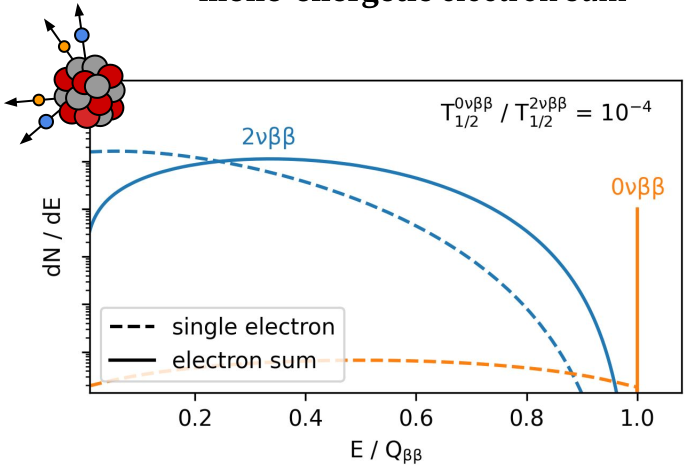
Decay signature

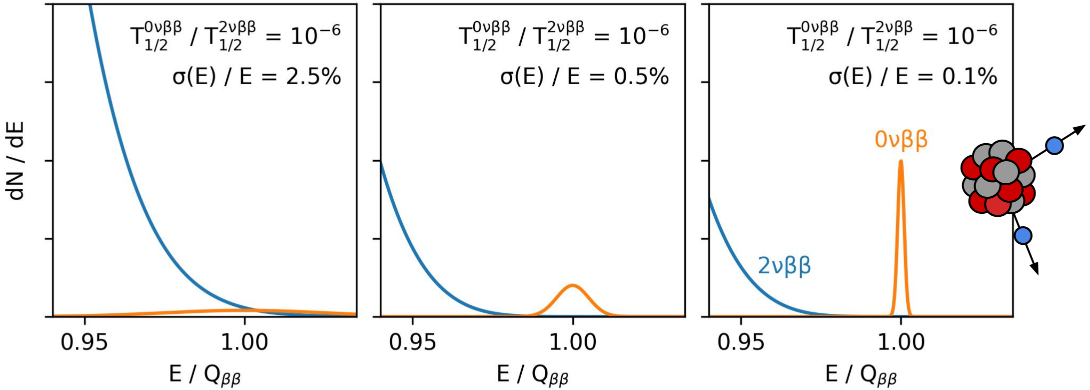
- unaccompanied emission of **two electrons** from isotope
  - two-electron / single-site **topology**
  - **daughter isotope** production
  - **mono-energetic** electron sum

necessary

sufficient







Background importance

- signal counts $n_s \propto m \cdot t \, / \, T_{1/2}$
- background counts $n_b \propto b \cdot \Delta E \cdot m \cdot t$

b → **background index** in e.g. [cts / keV / kg / yr]

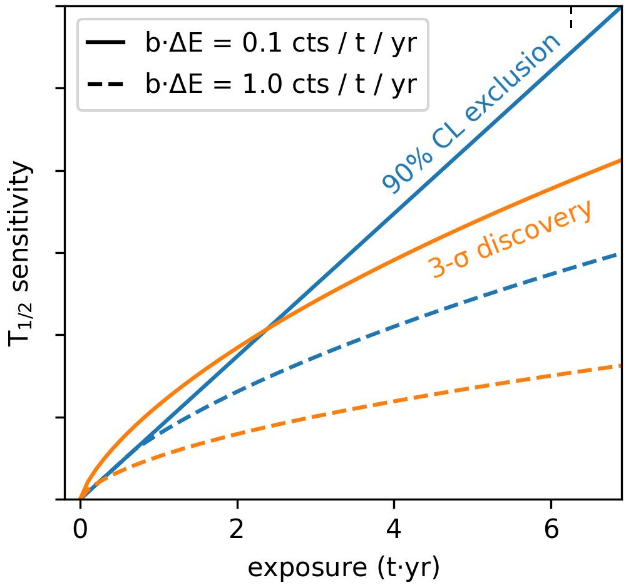
sensitivity **scaling**:

a. **background-limited** ($n_s \propto \sqrt{n_b}$): $T_{1/2} \propto \sqrt{\frac{m \cdot t}{b \cdot \Delta E}}$

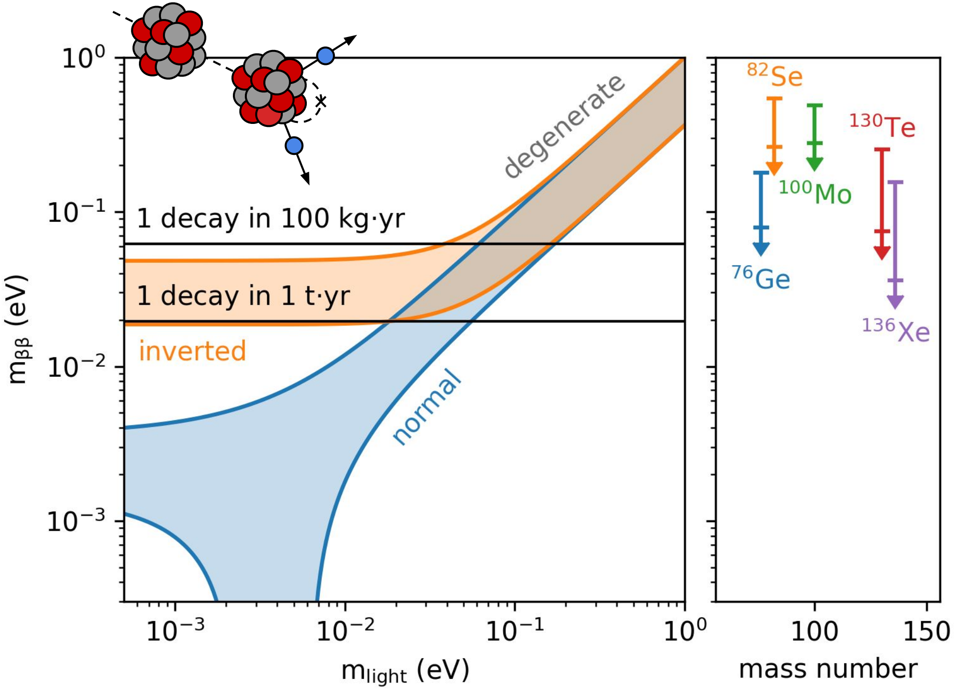
b. **background-free** ($n_b \ll 1$): $T_{1/2} \propto m \cdot t$

only a background-free experiment makes efficient use of the precious isotope material

quasi-background free



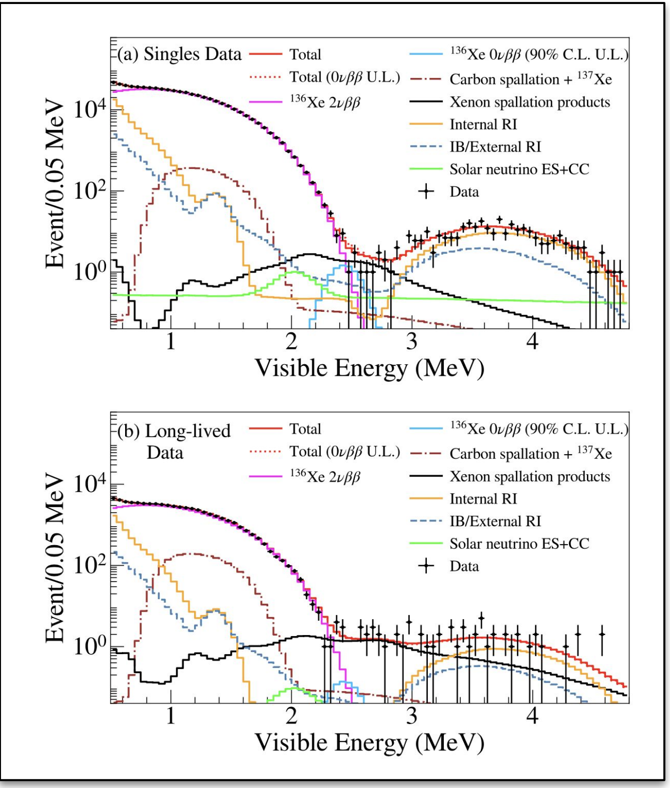
Current status



- ongoing / completed **sub-tone scale projects** probe **degenerate regime**
  - ^{76}Ge, **GERDA**, HPGe detectors
    $m_{\beta\beta}$ < [79, 180]meV (90% CL)
    [Agostini et al., PRL 125 (2020) 25, 252502]
  - ^{130}Te, **CUORE**, cryogenic bolometers
    $m_{\beta\beta}$ < [75, 255]meV (90% CI)
    [Alfonso, TAUP 2023]
  - ^{136}Xe, **KamLAND-Zen**, liquid scintillator
    $m_{\beta\beta}$ < [36, 156]meV (90% CL)
    [Abe et al., PRL 130 (2023) 5, 051801]
- planned **tone-scale projects** will probe **inverted ordering scenario**

Comparison

[Abe et al., PRL 130 (2023) 5, 051801]



KamLAND-Zen

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

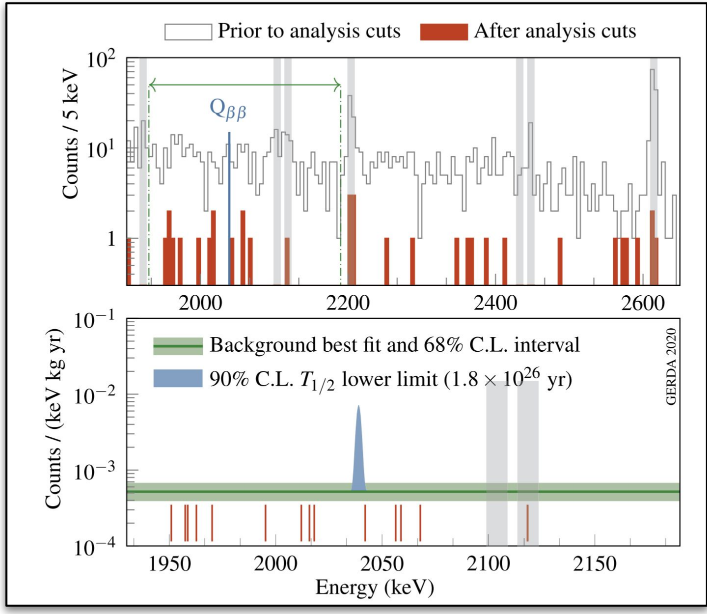
$\mathbf{T_{1/2}(^{136}Xe) > 2.3 \cdot 10^{26}}$ **yr** (90% CL)

GERDA

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

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

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



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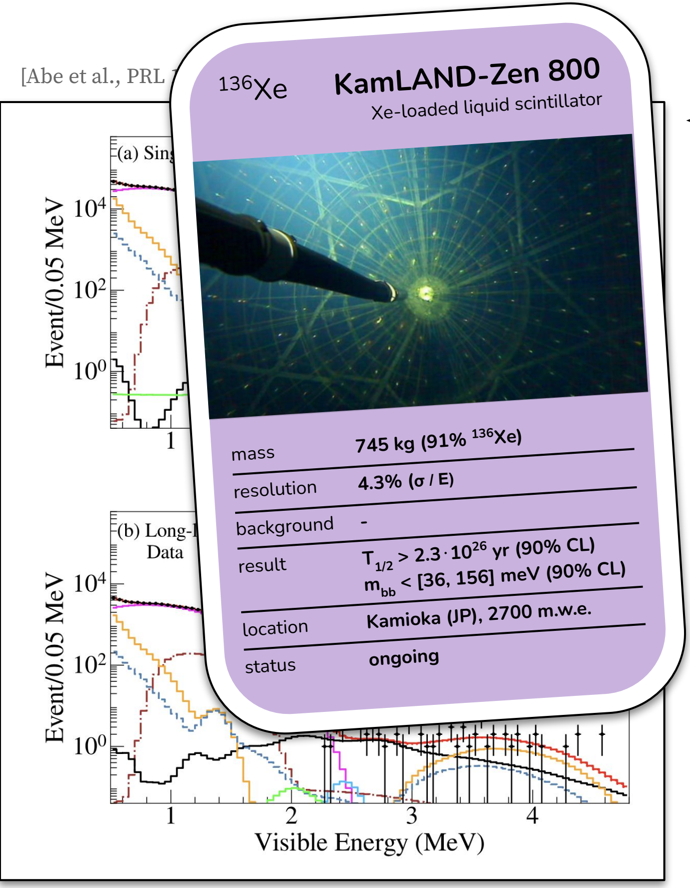

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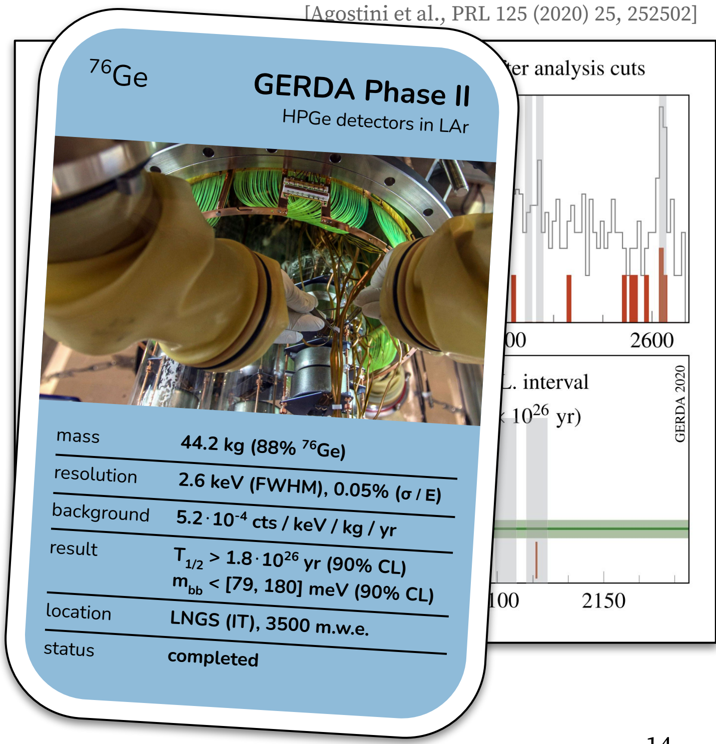
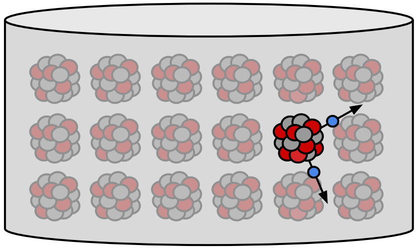


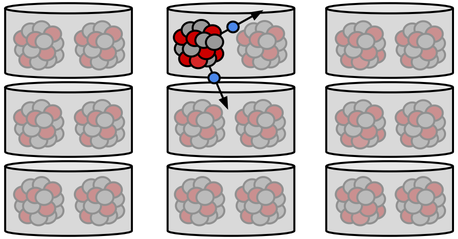
Experimental approaches

source = detector concepts



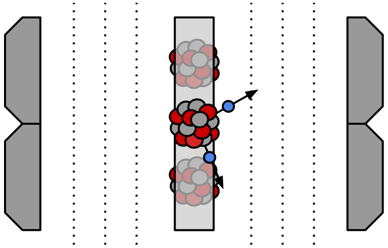
monolithic **scintillation** / **ionization** detectors

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



granular **semiconductor** / **cryogenic** detectors

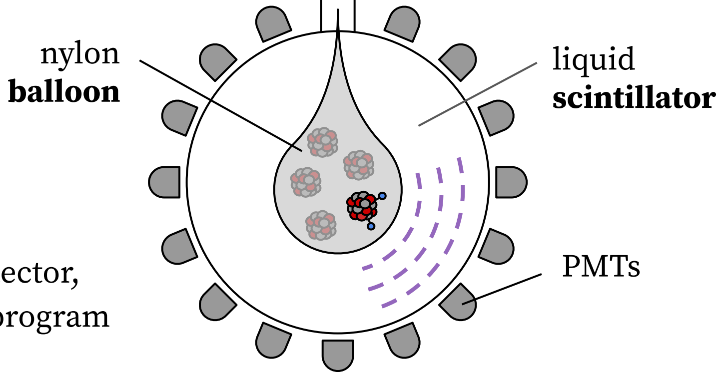
AMORE, BINGO, CANDLES, CEDEX, COBRA, **CUORE**, **CUPID**, CROSS, **GERDA**, **LEGEND**, **MAJORANA**, SELENA, ..



tracking calorimeters

NEMO3, **SuperNEMO**, ..

KamLAND-Zen



- 1000-t **liquid scintillator** detector, rich **non-ββ decay physics** program
  [Abe et al., PRL 100 (2008) 221803]
- ultra-clean **nylon balloon** filled with **^{enr}Xe-loaded liquid scintillator**

KamLAND-Zen 800

- **best half-life limit**, measurement **ongoing**
  [Abe et al., PRL 130 (2023) 5, 051801]

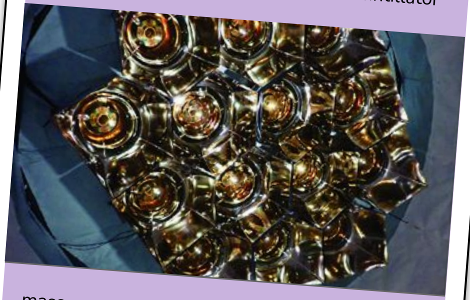
KamLAND2-Zen

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

^{136}Xe **KamLAND-Zen 800**
Xe-loaded liquid scintillator

mass	745 kg (91% ^{136}Xe)
resolution	4.3% (σ / E)
background	-
result	$T_{1/2}$ > 2.3·10^{26} yr (90% CL) m_{bb} < [36, 156] meV (90% CL)
location	Kamioka (JP), 2700 m.w.e.
status	ongoing

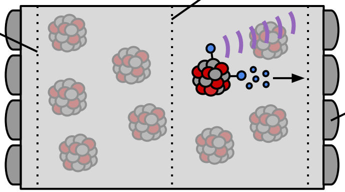
^{136}Xe **KamLAND2-Zen**
Xe-loaded liquid scintillator



mass	1000 kg
resolution	~2% (σ / E)
background	-
sensitivity	$T_{1/2} \gtrsim 2\cdot 10^{27}$ yr (90% CL) -
location	Kamioka (JP), 2700 m.w.e.
status	planned

[Abe et al., PRL 130 (2023) 5, 051801]

EXO



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

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

^{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

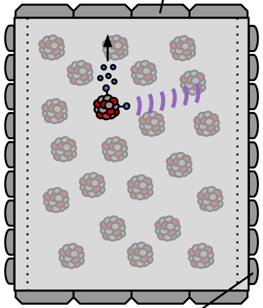
nEXO (see talk by **R. Tsang**)

- exploit **self-shielding**, **multi-dimensional analysis**

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

- development of **Ba tagging**, cryogenic probe

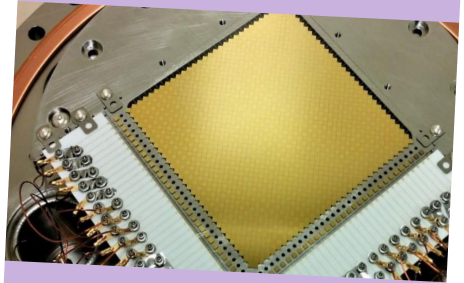
[Chambers et al., Nature 569 (2019) 7755, 203-207]



^{136}Xe

nEXO

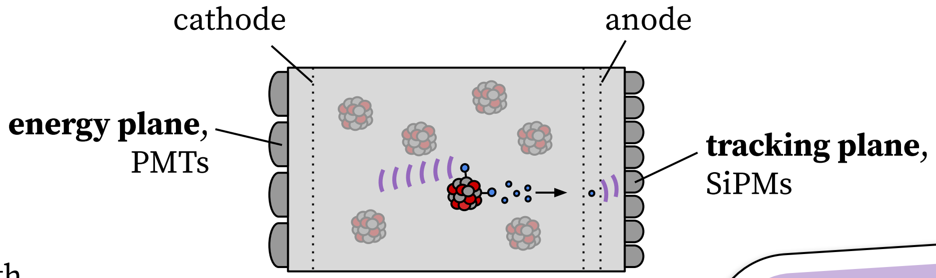
LXe time projection chamber



mass	4811 kg (90% ^{136}Xe)
resolution	0.8 % (σ / E)
background	$7 \cdot 10^{-5}$ cts / FWHM / kg / yr
sensitivity	$T_{1/2} > 7.4 \cdot 10^{27}$ yr (3σ) m_{bb} < [6, 27] meV (3σ)
location	SNOLAB (CA), 6000 m.w.e.
status	planned

Christoph Wiesinger (TUM)

NEXT

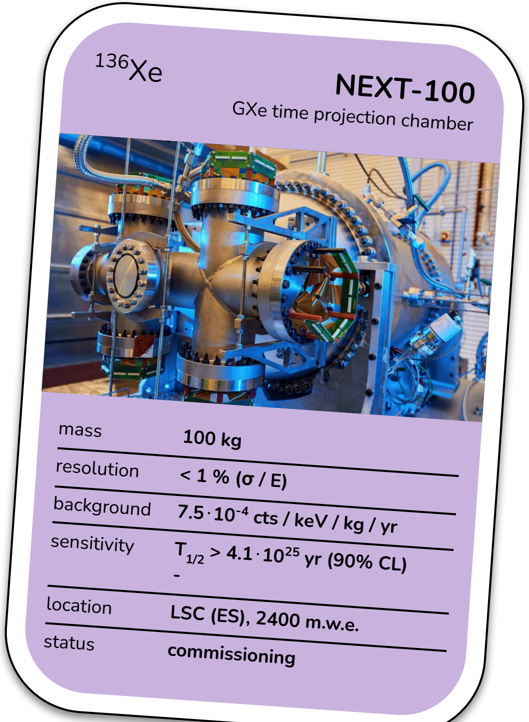


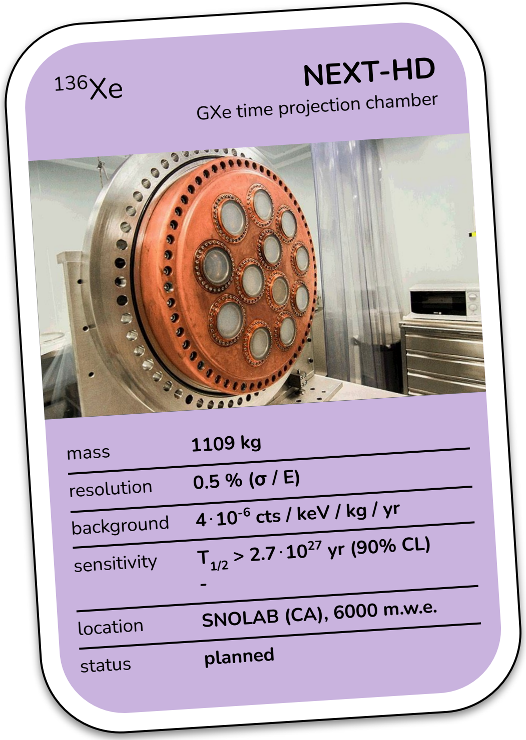
[Adams et al., JHEP 2021 (2021) 08, 164]

- high-pressure **gaseous ^{enr}Xe time projection chamber** with **electro-luminescence** region

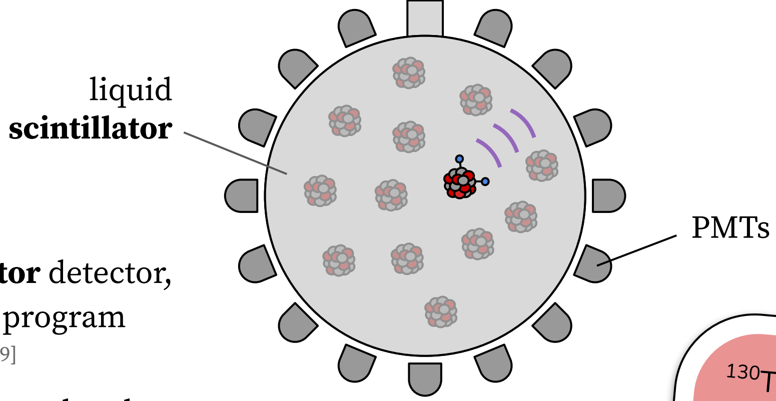
- best **energy resolution** among monolithic detectors
- **topological separation** of ββ decay events
- development of **Ba tagging**, single molecule fluorescent imaging
  [McDonald et al., PRL 120 (2018) 13, 132504]

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



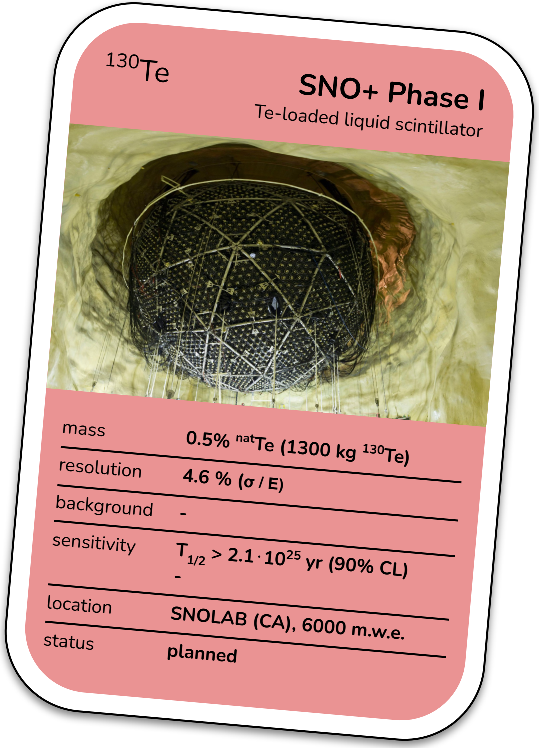


SNO+



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

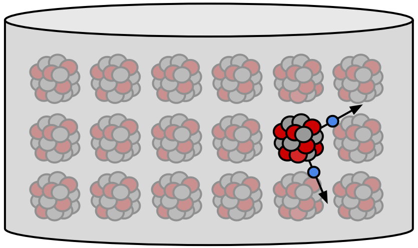
- potential for **solar neutrino suppression** by directionality [Allega et al., arXiv:309.06341]



[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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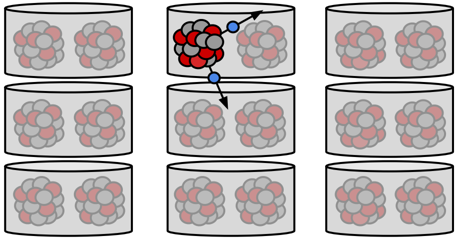
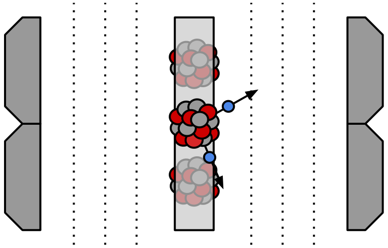


granular **semiconductor** / **cryogenic** detectors

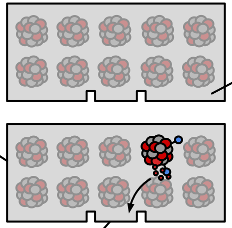
AMORE, BINGO, CANDLES, CEDEX, COBRA, **CUORE**, **CUPID**, CROSS, **GERDA**, **LEGEND**, **MAJORANA**, SELENA, ..



tracking calorimeters

NEMO3, **SuperNEMO**, ..

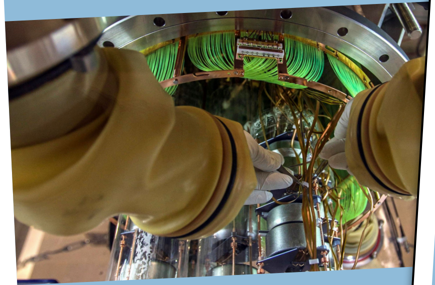
GERDA



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

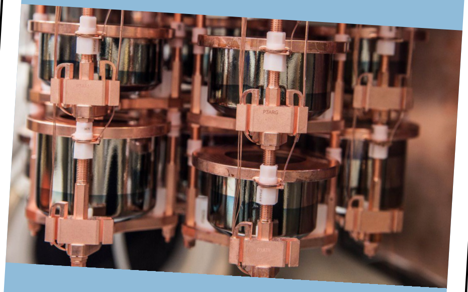
[Agostini et al., PRL 125 (2020) 25, 252502]

^{76}Ge **GERDA Phase II**
HPGe detectors in LAr



mass	44.2 kg (88% ^{76}Ge)
resolution	2.6 keV (FWHM), 0.05% (σ /
background	$5.2 \cdot 10^{-4}$ cts / keV / kg / yr
result	$T_{1/2} > 1.8 \cdot 10^{26}$ yr (90% CL) $m_{bb} <$ [79, 180] meV (90% CL)
location	LNGS (IT), 3500 m.w.e.
status	completed

^{76}Ge **MAJORANA DEM.**
HPGe detectors



mass	29.7 kg (88% ^{76}Ge)
resolution	2.52 keV (FWHM), 0.05% (σ / E)
background	$6.2 \cdot 10^{-3}$ cts / keV / kg / yr
result	$T_{1/2} > 8.3 \cdot 10^{26}$ yr (90% CL) $m_{bb} <$ [113, 269] meV (90% CL)
location	SURF (US), 4300 m.w.e.
status	completed

MAJORANA

- high-purity ^{enr}**Ge detectors** in **compact shield setup**
- underground **electroformed copper**
  [Abgrall et al., NIM. A828 (2016) 22-36]
- **best resolution**

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

LEGEND (see talk by **R. Brugnera**)

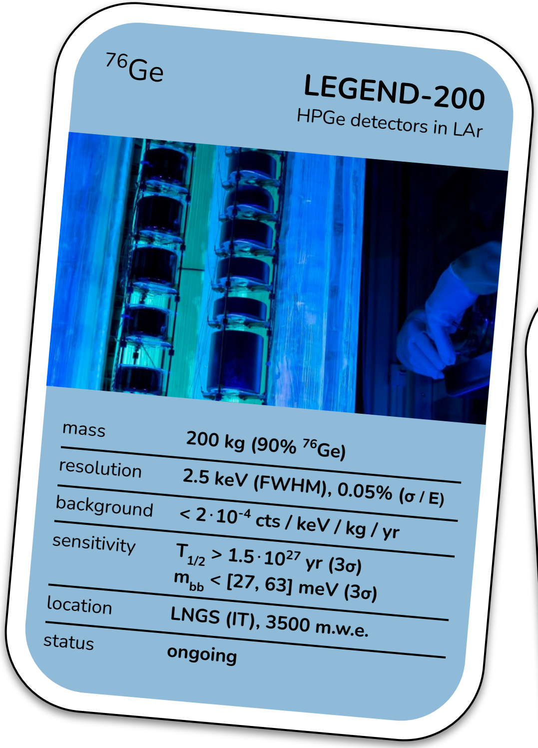
- builds on GERDA and MAJORANA, **staged approach**

LEGEND-200

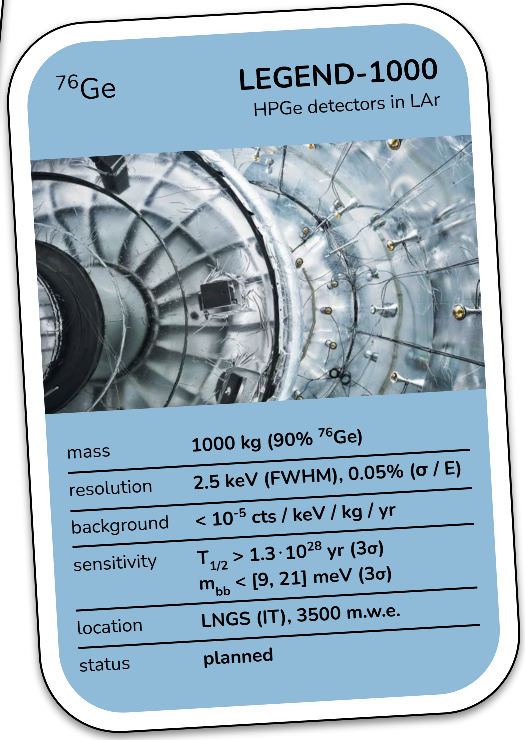
- upgraded **GERDA-infrastructure** with
  - new large volume detectors
  - reduced inactive materials
  - improved light read-out
- first 140 kg **in operation**

LEGEND-1000

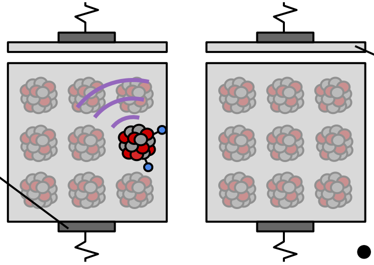
- improved background mitigation, **underground-sourced argon**



[Abgrall et al., arXiv:2107.11462]

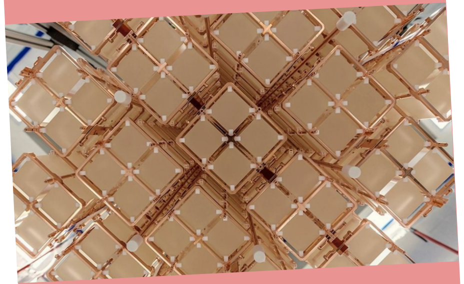


CUORE



- cryogenic ^{nat}**TeO2 bolometers**, dilution refrigerator
- **archeological lead** shielding
  [Alessandrello et al., NIM B142 (1998) 163-172]
- **most recent result**
- measurement **ongoing**

^{130}Te — **CUORE**
TeO_2 bolometers



mass	742 kg (206 kg ^{130}Te)
resolution	7.8 keV (FWHM), 0.1% (σ / E)
background	$1.5 \cdot 10^{-2}$ cts / keV / kg / yr
sensitivity	$T_{1/2} > 3.3 \cdot 10^{25}$ yr (90% CL) $m_{bb} <$ [75, 255] meV (90% CL)
location	LNGS (IT), 3500 m.w.e.
status	ongoing

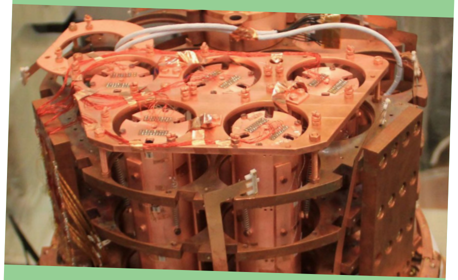
[Adams et al., Nature 604 (2022) 7904, 53-58; Alfonso, TAUP2023]

CUPID (see talk by **M. Girola**)

- builds on CUPID-Mo and CUPID-0, **scintillating bolometers**
- **particle discrimination**, background rejection
- reuse existing **CUORE infrastructure**

[Armstrong et al., arXiv:1907.09376]

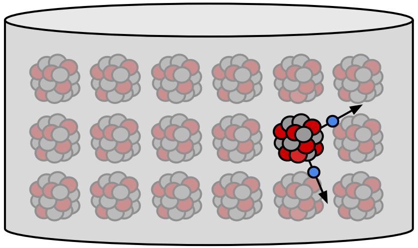
^{100}Mo — **CUORE**
Li_2MoO_4 scintillating bolometers



mass	472 kg (253 kg ^{100}Mo)
resolution	5 keV (FWHM), 0.1% (σ / E)
background	10^{-4} cts / keV / kg / yr
sensitivity	$T_{1/2} > 1.1 \cdot 10^{27}$ yr (3σ) $m_{bb} <$ [12, 20] meV (3σ)
location	LNGS (IT), 3500 m.w.e.
status	planned

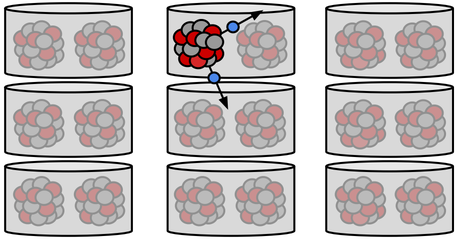
Experimental approaches

source = detector concepts



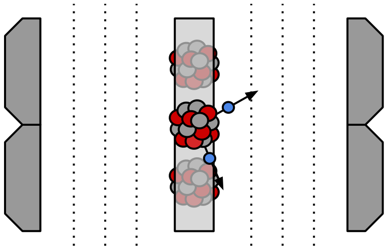
monolithic **scintillation** /
ionization detectors

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



granular **semiconductor** /
cryogenic detectors

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

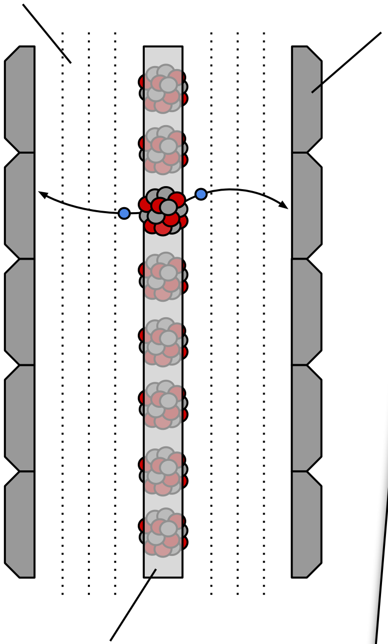


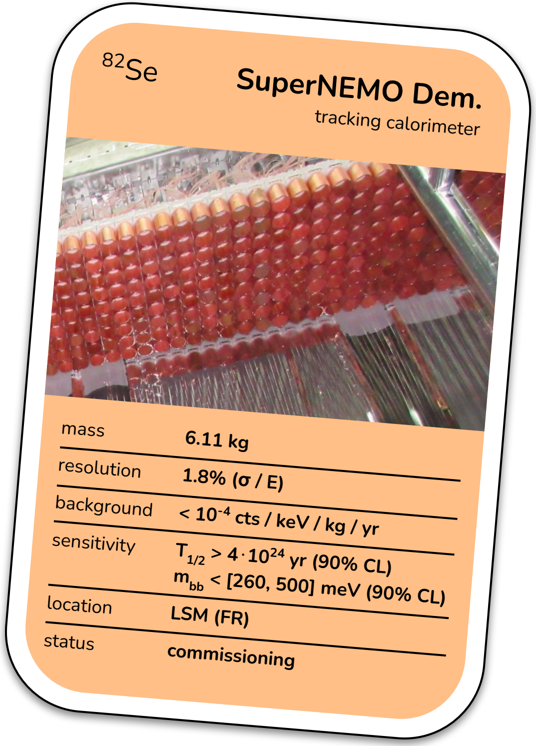
tracking
calorimeters

NEMO3, **SuperNEMO**, ..

SuperNEMO

- builds on NEMO3
  [Arnold et al., EPJ C 79 (2019) 5, 440]
- **tracking calorimeter**
- almost **isotope-agnostic**, solid source material
- full **topological reconstruction**
  - unique **2νββ decay** measurements
  - probe **0νββ decay mechanism**
- **demonstrator** in operation



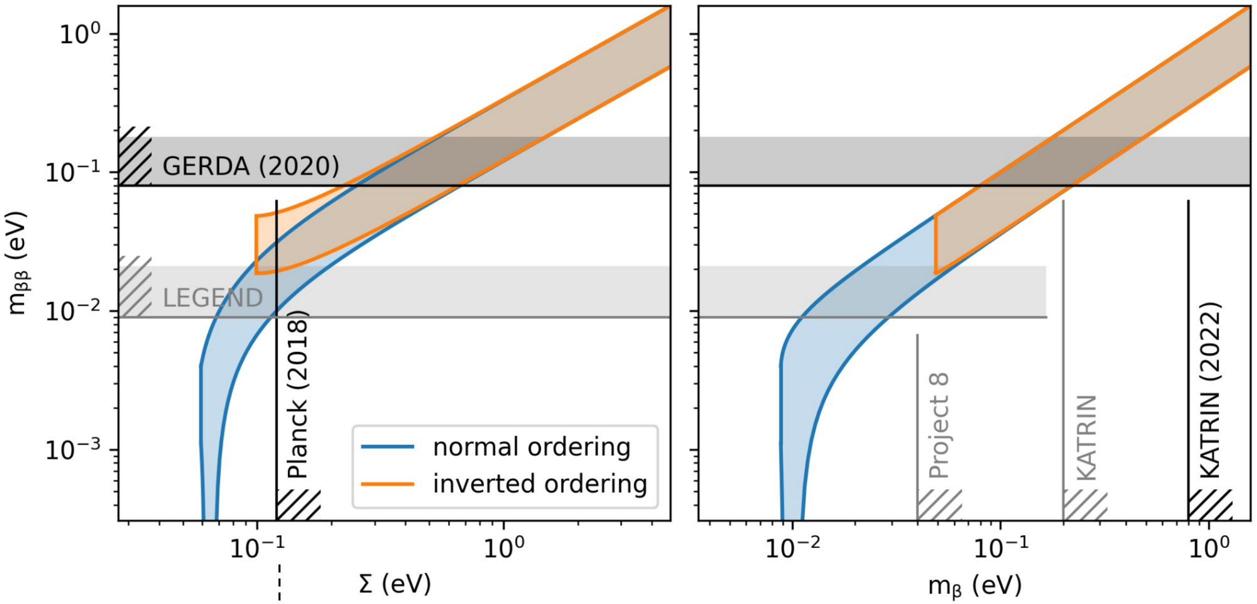


[Patrick, TAUP2023]

Complementarity

- **0νββ decay** constraints complement **cosmology** and **β decay** bounds
- **test underlying models** (ΛCDM, light Majorana neutrino exchange, ..), counter measurements
- future observatories / missions (**DESI**, **EUCLID**, ..)
  [Brinckmann et al., JCAP 01 (2019) 059, ..]

σ_Σ = **O(10) meV**



standard scenario predicts discovery

(see talk by **T. Lasserre**)

Conclusions

- **vibrant field**, different technologies and isotopes 
- several **sub-tone scale** searches ongoing
  - ^{76}Ge, **LEGEND-200** (140 kg)
  - ^{130}Te, **CUORE** (206 kg)
  - ^{136}Xe, **KamLAND-Zen** (745 kg)
- **tone-scale era** about to start (see talks by **R. Brugnera**, **R. Tsang**, **M. Girola**)
  - probe **full inverted ordering scenario**
  - test **significant normal ordering space**

Backup