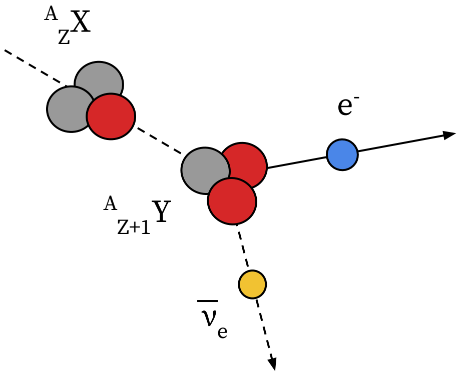
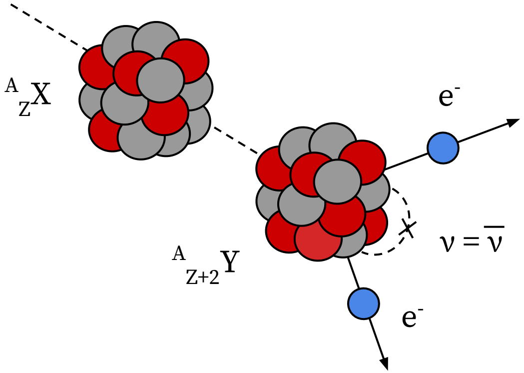
Single and double beta decay:
Probing neutrino mass and nature in the laboratory - 

Christoph Wiesinger (Max-Planck-Institut für Kernphysik), TAUP, 25.08.2025

Single and double beta decay

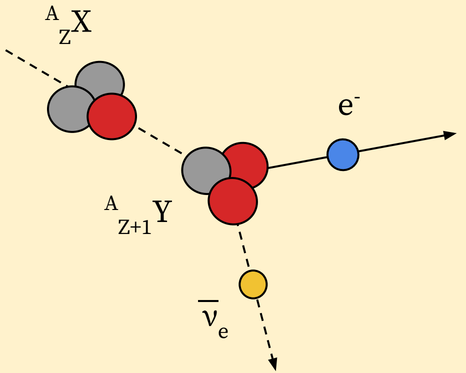


Beta decay **kinematics**,
direct **neutrino mass** measurement



Search for **neutrinoless double beta decay**,
test **neutrino nature**

Single and double beta decay



Beta decay **kinematics**,
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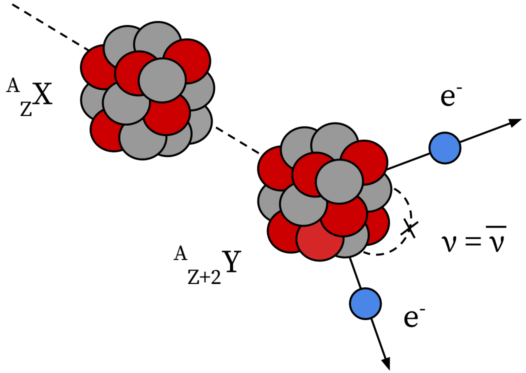
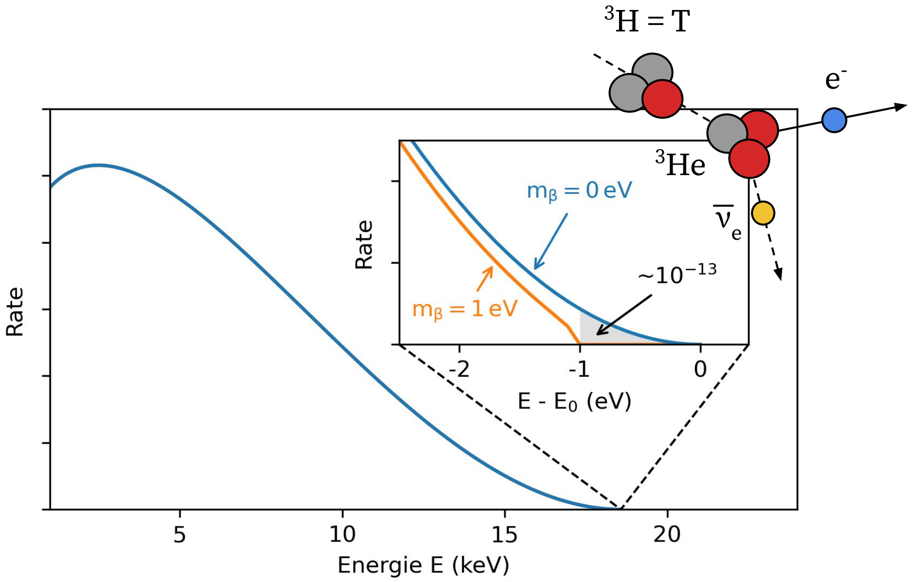


Search for **neutrinoless double beta decay**,
test **neutrino nature**

Beta decay kinematics*

**or electron capture*

- **Direct measurement** of phase space modification, squared **neutrino mass**

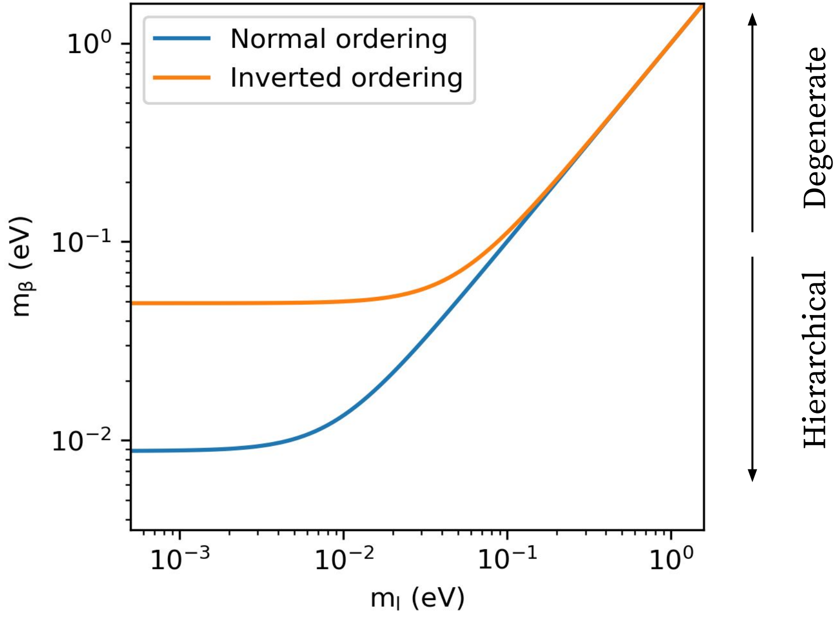


➔ Measure **sub-eV scale spectral distortion** close to **keV-scale kinematic endpoint**

- **High-activity** source (>> MBq), **low-Q value** (T with 18.6 keV, ^{163}Ho with 2.8 keV)
- High acceptance, excellent **energy resolution** (~eV), low **background** (~mcps)
- **High precision** understanding of theoretical spectrum and experimental response

Effective electron neutrino mass, $m_\beta^2 = \Sigma_i |U_{ei}|^2 m_i^2$

[NuFIT 6.0, nu-fit.org]



- Weighted **incoherent sum** of mass eigenstates

- **Minimum values** for normal ordering, $m_1 < m_2 << m_3$

  $$min(m_\beta)_{NO} = \mathbf{0.01\ eV}$$

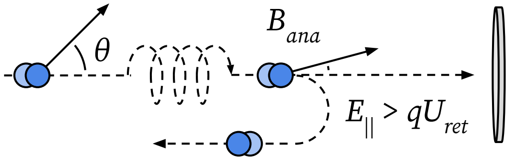
  and inverted ordering, $m_3 << m_1 \approx m_2$

  $$min(m_\beta)_{IO} = \mathbf{0.05\ eV}$$

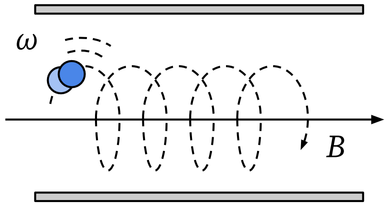
- Current experiments probe **degenerate regime**, $m_1 \approx m_2 \approx m_3$

Experimental approaches

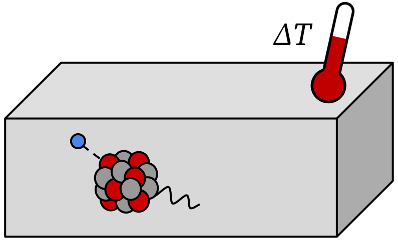
Tritium-based



Electrostatic
filtering (MAC-E)



Cyclotron radiation emission
spectroscopy (CRES)

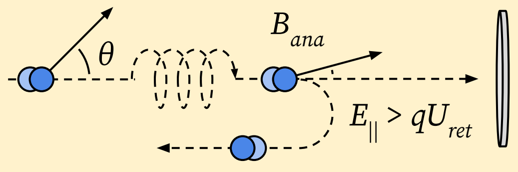


Cryogenic
calorimetry

R&D stage

Experimental approaches

Tritium-based



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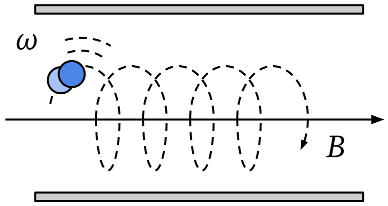

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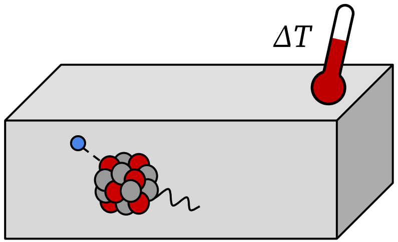
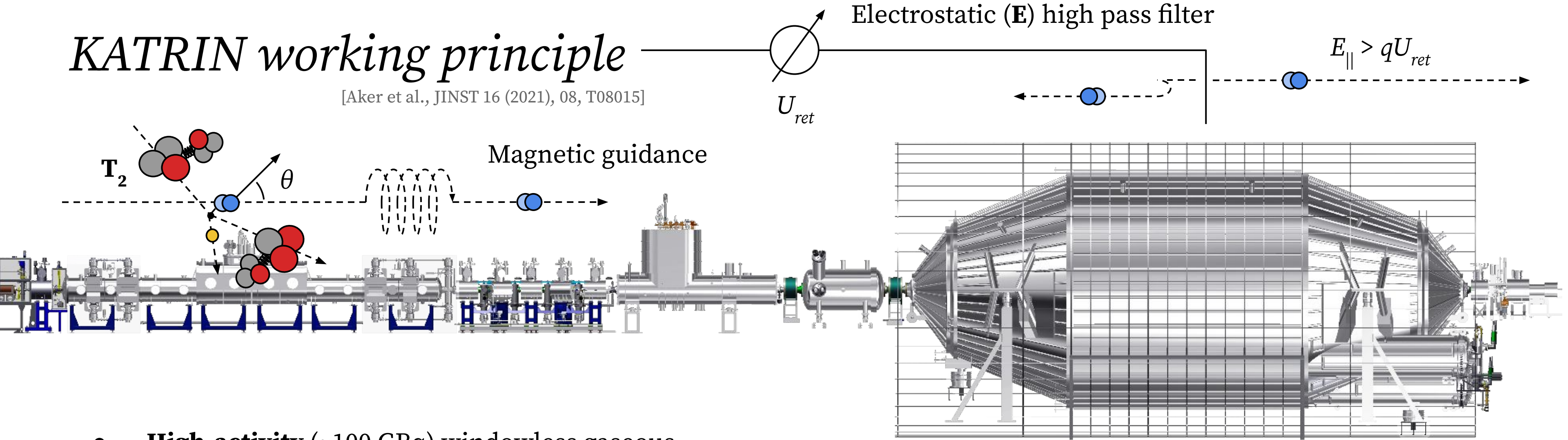


Cryogenic
calorimetry

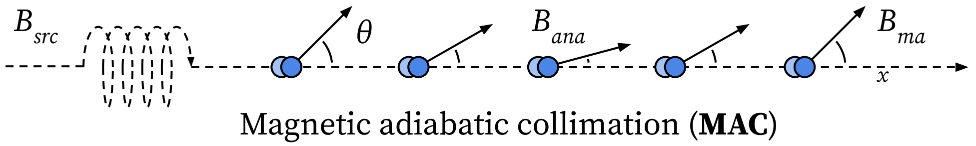
R&D stage

KATRIN working principle

[Aker et al., JINST 16 (2021), 08, T08015]



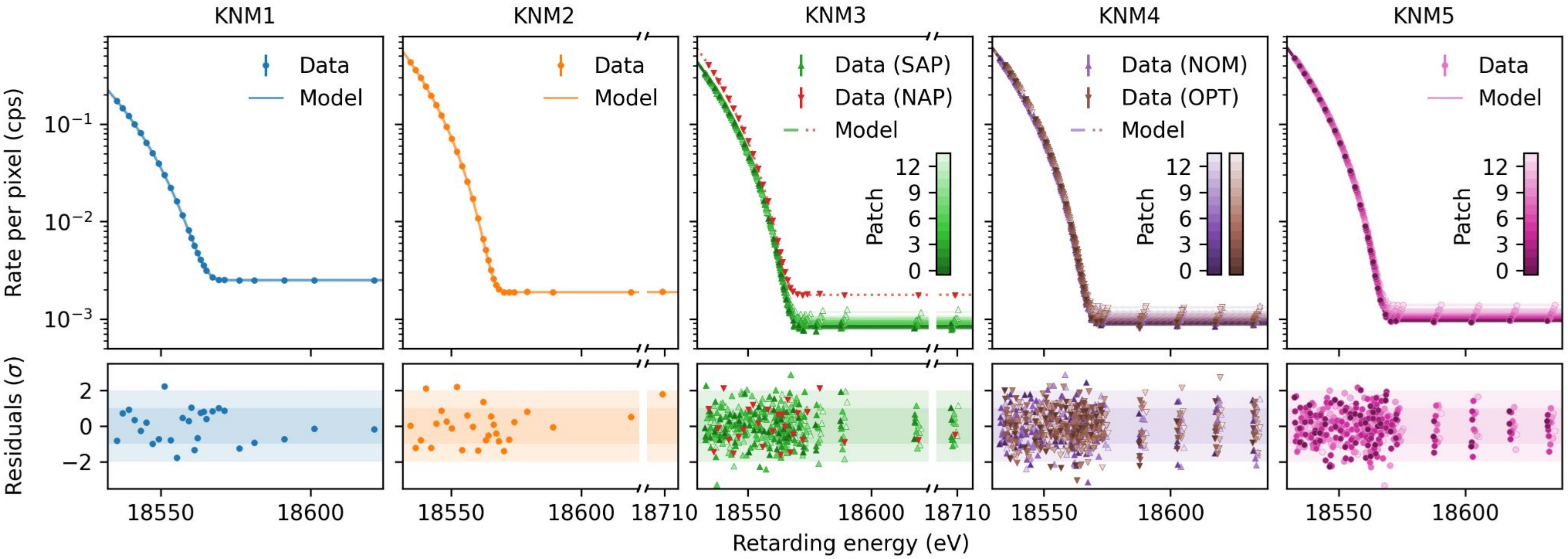
- **High-activity** (~100 GBq) windowless gaseous molecular tritium source, closed loop
- **High-resolution** (~1 eV) **large-acceptance** (0-51°) MAC-E spectrometer system
- **Electron counting** with silicon PIN diode



➔ **Integral spectrum** scans, discrete **retarding potential steps**

KATRIN result

- **3rd result**, 5 campaigns, 1757 scans, **259 measurement days,** 7 different configurations, **1609 data points**

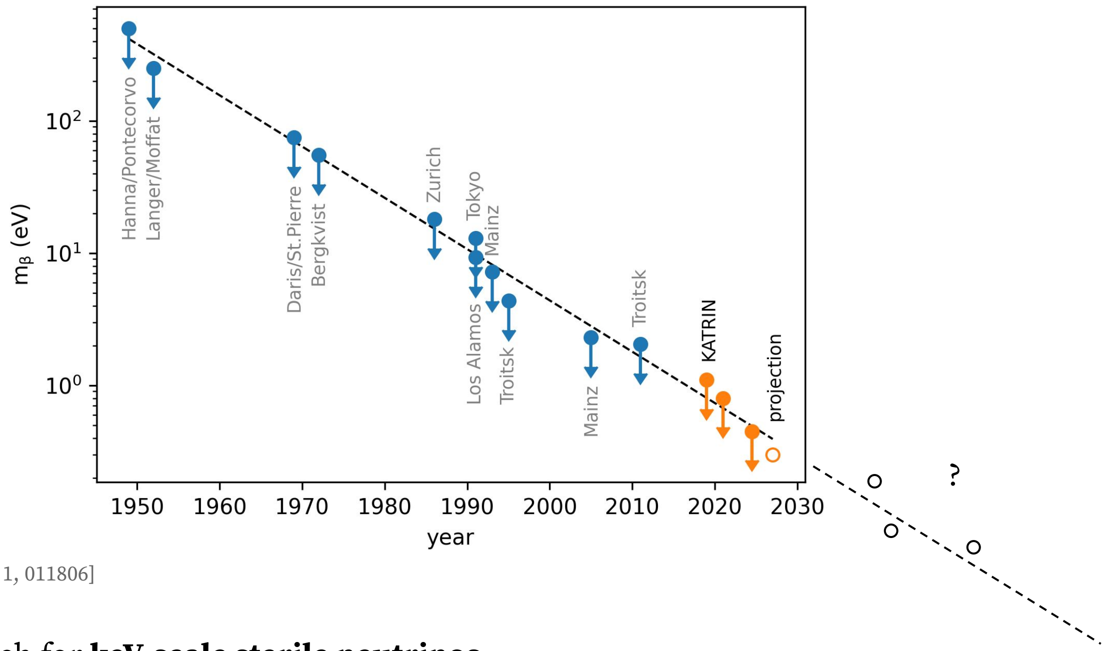


- Best-fit compatible with zero $m_\beta^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$

➔ **World-best** constraint m_β **< 0.45 eV** (90% CL)

[Aker et al., Science 388 (2025) 6743]

KATRIN outlook



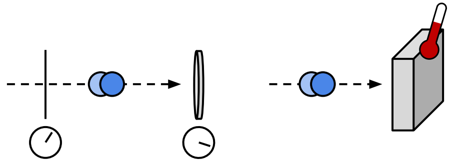
- Data taking ongoing until end-2025, **1000 measurement days**, projected final sensitivity

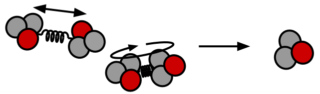
  $$m_\beta < \mathbf{0.3\ eV}\ (90\%\ CL)$$

- **Rich physics program** beyond neutrino mass, **eV-scale sterile neutrinos**, relic neutrinos, ..
  [Acharya et al., arXiv:2503.18667; Aker et al., PRL 129 (2022), 1, 011806]

- **TRISTAN** detector upgrade in 2026, search for **keV-scale sterile neutrinos**
  [Mertens et al., J.Phys.G 46 (2019) 6, 065203]

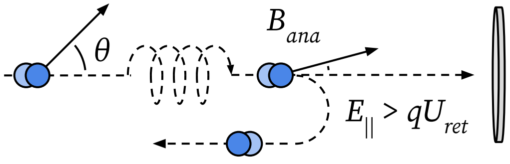
- **KATRIN++**, development of **differential** electron detection and **atomic** tritium technologies





Experimental approaches

Tritium-based



Electrostatic
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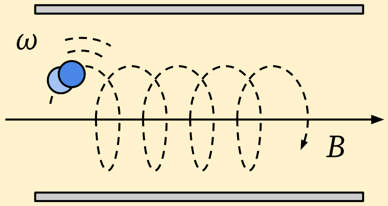

Cyclotron radiation emission
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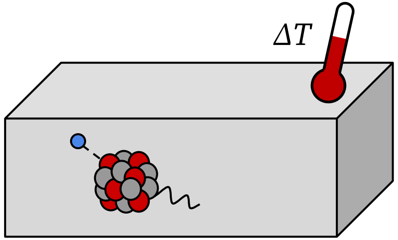
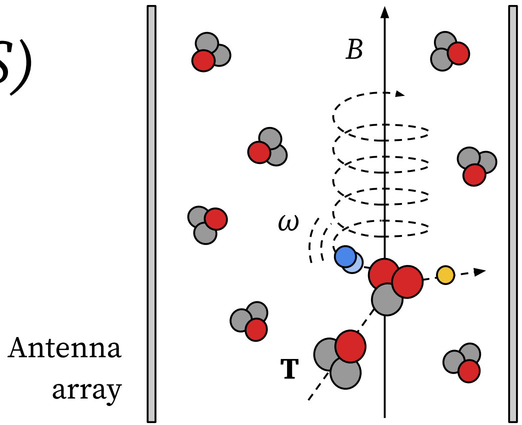


Cryogenic
calorimetry

R&D stage

Cyclotron radiation emission spectroscopy (CRES)

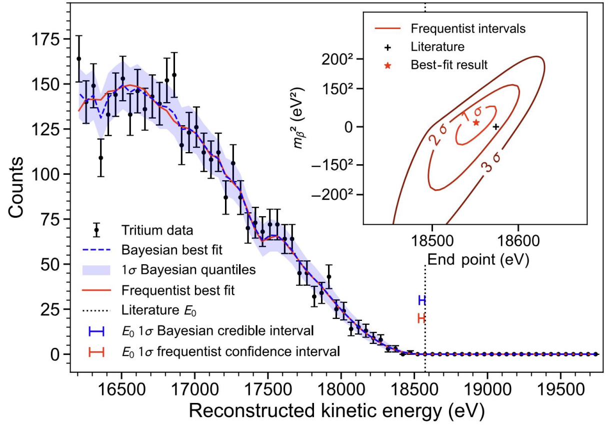


- Measure **cyclotron radiation frequency** of trapped tritium decay electrons
  [Monreal, Formaggio, PRD 80 (2009) 051301]

➔ **Source transparent** to microwave radiation, **no electron extraction**,

➔ **Differential** measurement, **eV-scale** resolution, **low background**

[Ashtari Esfahani et al., PRL 131 (2023) 10, 102502]



Project8

- **1st result** with molecular tritium
  [Ashtari Esfahani et al., PRL 131 (2023) 10, 102502]

  m_β **< 155 eV** (90% CL)

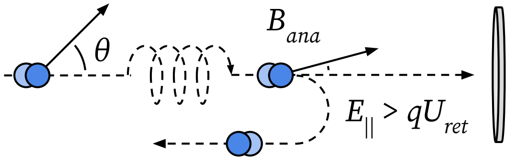
- Development of **m³-scale** traps and **atomic tritium** technology

QTNM

- **Storage ring** confinement, quantum-limited microwave electronics
  [Amad et al., arXiv:2412.06338]

Experimental approaches

Tritium-based



Electrostatic
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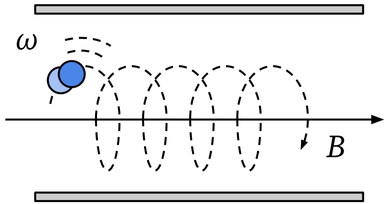
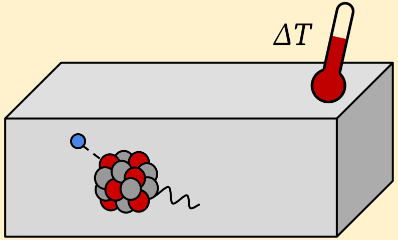


Cyclotron radiation emission
spectroscopy (CRES)



Cryogenic
calorimetry

R&D stage

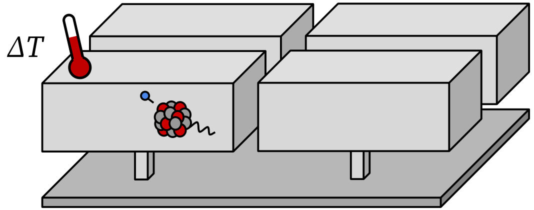
Cryogenic calorimetry

ECHO

- **^{163}Ho electron capture,** super-low Q-value
  [De Rujula, Lusignoli, PLB 118 (1982) 429]

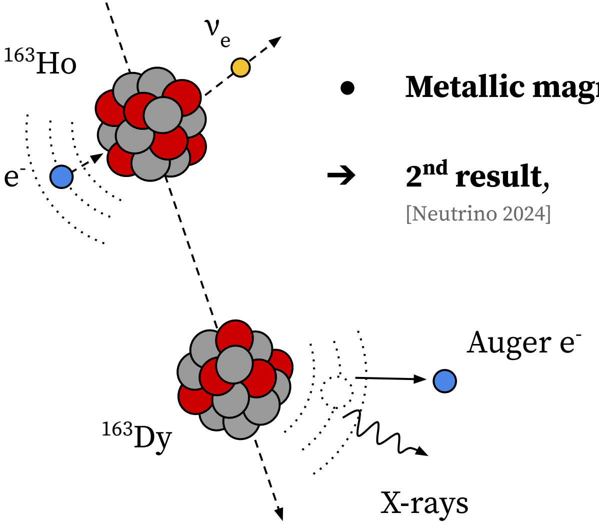
➔ **Sub-eV** sensitivity with **MBq-scale activity**

- Cryogenic **micro-calorimeters**



➔ eV-scale **differential** measurements

➔ **Source = detector** concept, pile-up limits pixel activity



- **Metallic magnetic calorimeters** (MMC)

➔ **2nd result,** m_β **< 19 eV** (90% CL)
  [Neutrino 2024]

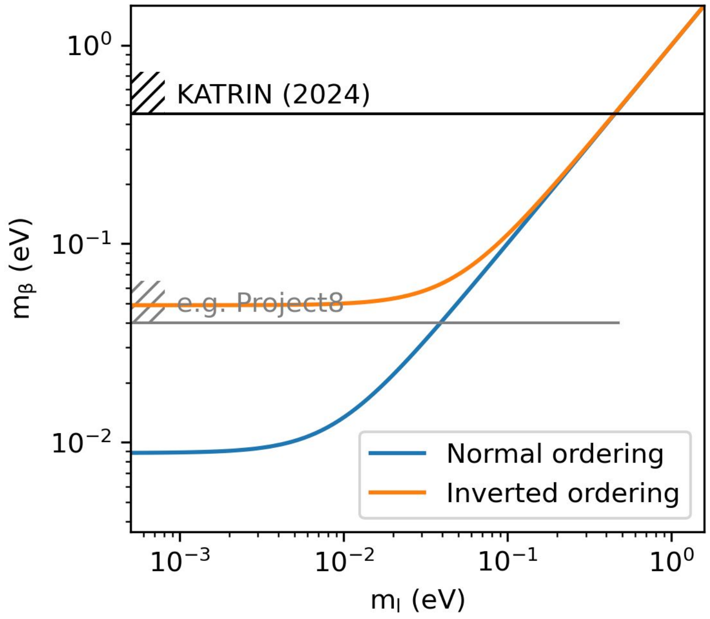
HOLMES

- **Transition edge sensors** (TES)

➔ **1st result,** m_β **< 27 eV** (90% CI)
  [Alpert et al., arXiv:2503.19920]

Effective electron neutrino mass, $m_\beta^2 = \Sigma_i |U_{ei}|^2 m_i^2$

[NuFIT 6.0, nu-fit.org]



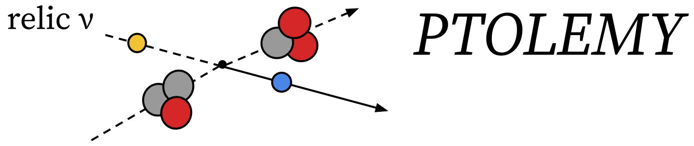
- Most stringent bound set by **KATRIN**
  [Aker et al., Science 388 (2025) 6743]

  m_β **< 0.45 eV** (90% CL)

- KATRIN measurement **ongoing**

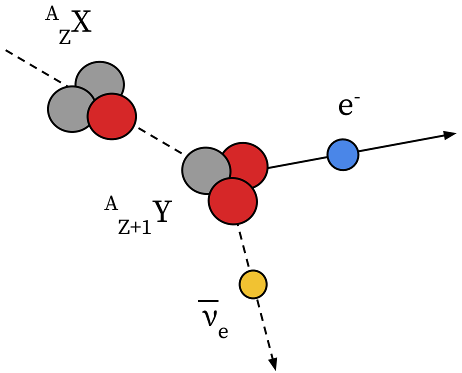
- Promising **technology developments** to go beyond, e.g.

  m_β **< 0.04 eV** (90% CL), Project8 Phase IV goal



- Monoatomic tritium in **graphene matrix**, **cyclotron emission** tagging, dynamic **electromagnetic filter**, **micro calorimeters**
  [Betti et al., Prog.Part.Nucl.Phys. 106 (2019) 120-131]

Single and double beta decay



Beta decay **kinematics**,
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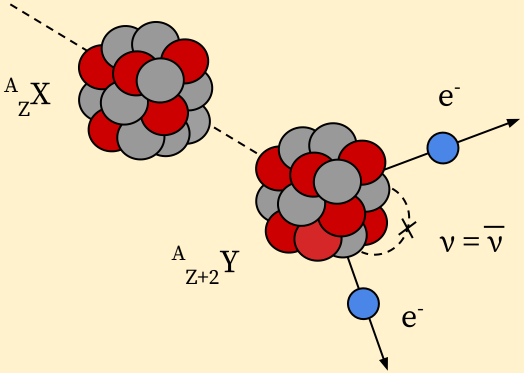
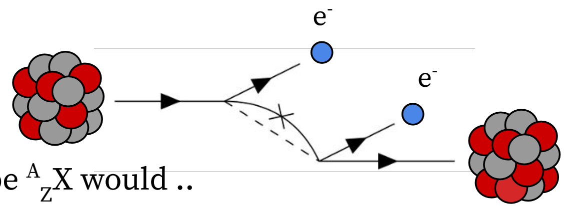


Search for **neutrinoless double beta decay**,
test **neutrino nature**

Neutrinoless double beta decay



- Unaccompanied **emission of two electrons** from isotope $^{A}_{Z}X$ would ..

  a. .. prove **lepton number violation**

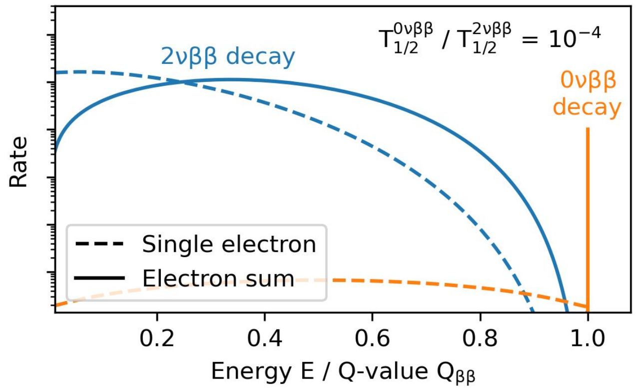
  b. .. identify the neutrino as a **Majorana particle**
  [Schechter, Valle, PRD 25 (1982) 2951]

  c. .. constrain the **absolute neutrino mass**

$$T_{1/2}(^{A}X) = .. \rightarrow m_{\beta\beta} = [.., ..]$$

  assuming **light Majorana neutrino exchange** and corresponding **nuclear matrix element**

$^{A}_{Z+2}Y$



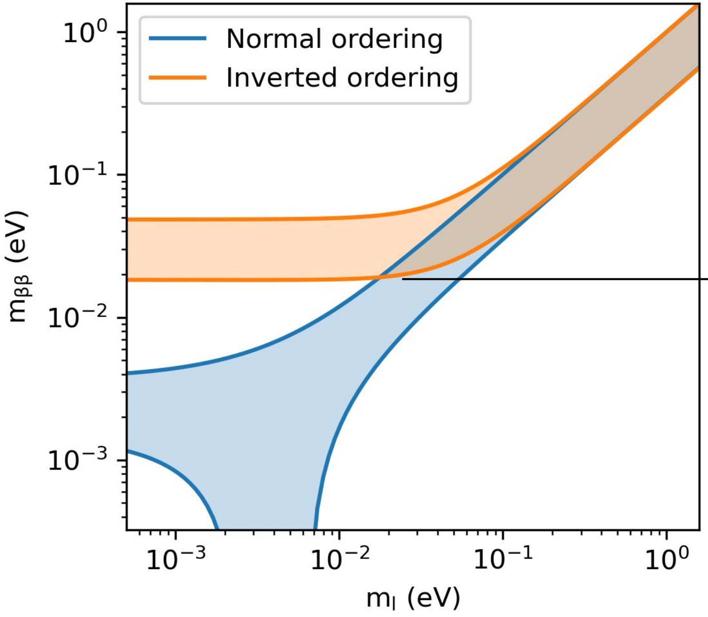
➔ Search for **MeV-scale mono-energetic emission of two electrons**

  ○ Macroscopic amount of **ββ isotope** (~t), maximal **detection efficiency**

  ○ Excellent **energy resolution** (~keV), ultra-low **background** (~cts / t / yr)

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

[NuFIT 6.0, nu-fit.org]

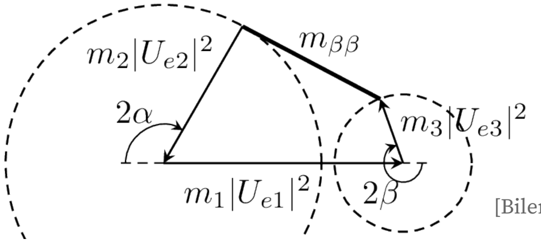


- **Coherent sum** of mass eigenstates, sensitive to **complex Majorana phases**

- **Minimum value** for inverted ordering, $m_3 << m_1 \approx m_2$

  $min(m_{\beta\beta})_{IO}$ = **18 meV**

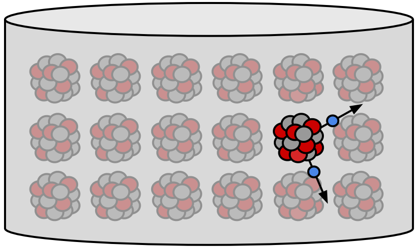
- **Cancellation possible** for normal ordering, $m_1 < m_2 << m_3$



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

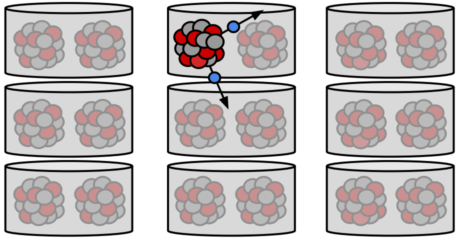
Experimental approaches

Source = detector concepts



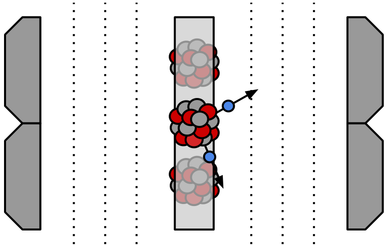
Monolithic scintillation / ionization detectors

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



Granular semiconductor / cryogenic detectors

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

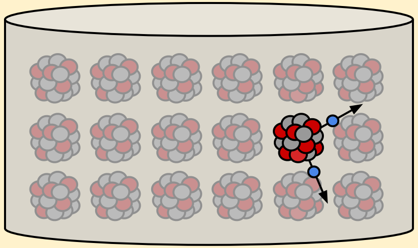


Tracking calorimeters

NEMO3, SuperNEMO, ..

Experimental approaches

Source = detector concepts



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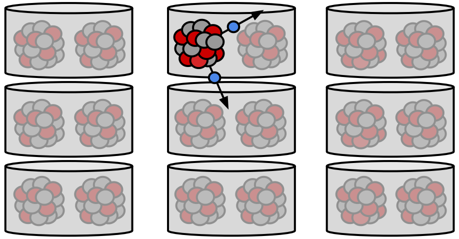

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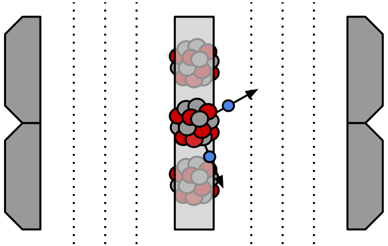
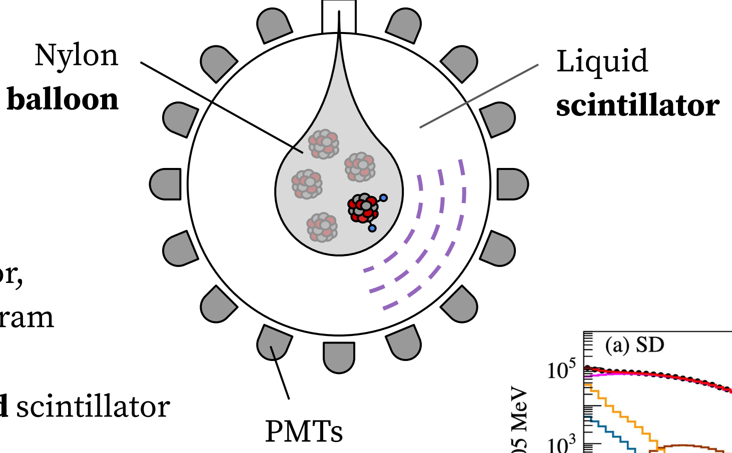


Tracking
calorimeters

NEMO3, SuperNEMO, ..

KamLAND-Zen



- 1000-t **liquid scintillator** detector,
  rich **non-ββ decay physics** program
  [Abe et al., PRL 100 (2008) 221803]
- **Nylon balloon** with **^{enr}Xe-loaded** scintillator
- **KamLAND-Zen-800**, 2nd phase
  - **Large isotope mass**, 750 kg of 91% ^{136}Xe
  - **Poor energy resolution**, 4% at 2.5 MeV

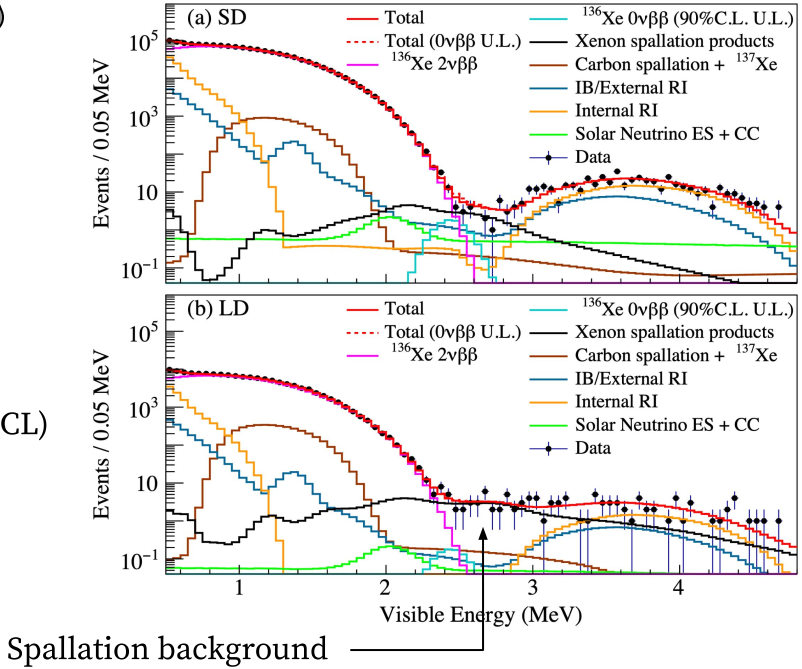
➔ Final result, **world-best constraint** [Abe et al., arXiv:2406.11438]

$T_{1/2}(^{136}\text{Xe})$ **> 3.8 · 10²⁶ yr** (90% CL) → $m_{\beta\beta}$ **< [28, 122] meV** (90% CL)

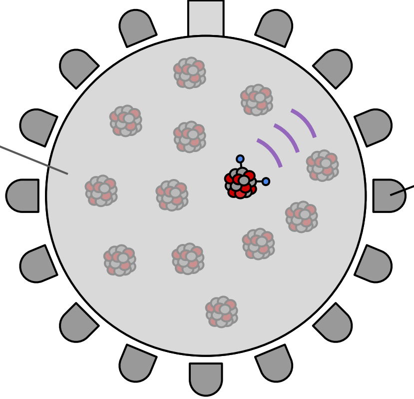
> 2.6 · 10²⁶ yr (90% CL, sensitivity)

- **KamLAND2-Zen**, planned detector upgrade

[Abe et al., arXiv:2406.11438]



SNO+



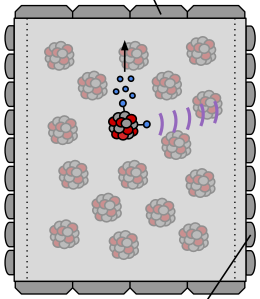
- 780-t **liquid scintillator** detector, rich **non-ββ physics** program
  [Allega et al., PRL 130 (2023) 9, 9]
- Staged ^{nat}**Te loading**
  - **Large isotope mass,** e.g. 1.3 t of ^{130}Te for 0.5% loading
  - **Poor energy resolution**, 4% at 2.5 MeV
- Water phase completed, scintillator phase ongoing**, 0.5% loading in preparation**

➔ Projected sensitivity

$T_{1/2}(^{130}\text{Te})$ **> 2.0 · 10^{26} yr** (90% CL), 3 yr with 0.5%

$T_{1/2}(^{130}\text{Te})$ **> 7.4 · 10^{26} yr** (90% CL), 5 yr with 1.5 %

nEXO



- **Liquid ^{enr}Xe time projection chamber,** building on EXO-200
  - **Large isotope mass**, 5 t of 90% ^{136}Xe
  - **Reasonable energy resolution**, 1% at 2.5 MeV

➔ Projected sensitivity, 10 yr
[Adhikari et al., J.Phys.G 49 (2022) 1, 015104]

$T_{1/2}(^{136}\text{Xe})$ **> 1.4 · 10^{28} yr** (90% CL)

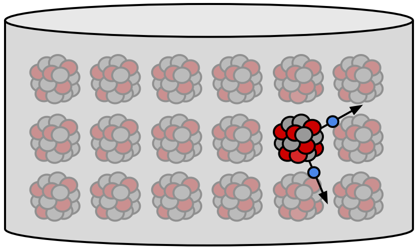
$T_{1/2}(^{136}\text{Xe})$ = **7.4 · 10^{27} yr** (3σ)

discovery

- Development of **Ba tagging**
  [Chambers et al., Nature 569 (2019) 7755, 203-207; Ray et al., Atoms 12 (2024) 12, 71]

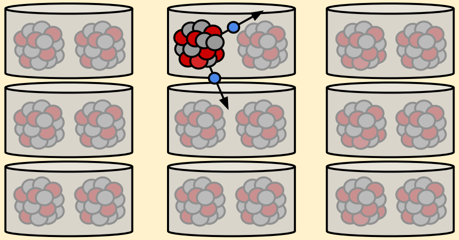
Experimental approaches

Source = detector concepts



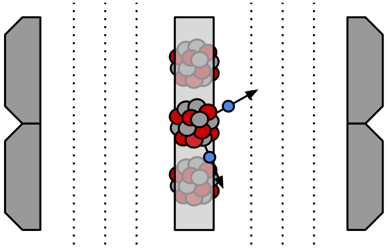
Monolithic scintillation / ionization detectors

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



Granular semiconductor / cryogenic detectors

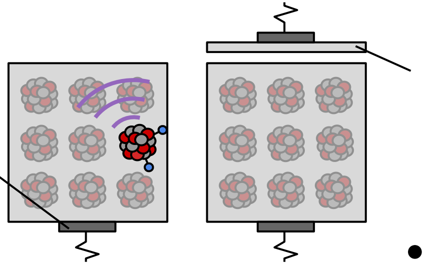
AMORE, BINGO, CANDLES, **CDEX**, COBRA, **CUORE**, **CUPID**, CROSS, GERDA, **LEGEND**, MAJORANA, SELENA, ..



Tracking calorimeters

NEMO3, SuperNEMO, ..

CUORE



CUPID

- Cryogenic $^{nat}TeO_2$ **bolometers**, dilution refrigerator, 10 mK
  - **Sizeable isotope mass**, 740 kg with 200 kg ^{130}Te
  - **Good energy resolution**, 7.3 keV (FWHM) at 2.5 MeV
  - **Background dominated** by α decays

➔ **2nd result**, 2 t yr of TeO_2 exposure

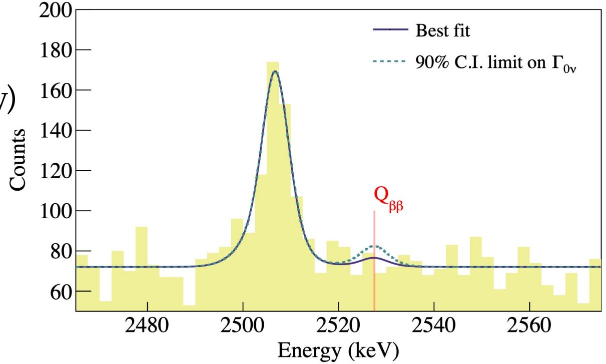
$T_{1/2}(^{130}\text{Te})$ **> 3.8 · 10^{25} yr** (90% CI)

> 4.4 · 10^{25} yr (90% CI, sensitivity)

→ $m_{\beta\beta}$ **< [70, 240] meV** (90% CI)

- Data taking **ongoing**, then low energy upgrade

[Adams et al, arXiv:2404.04453]



← α background

- Cryogenic **scintillating Li_2MoO_4 bolometers** in CUORE infrastructure
  - **Particle identification**, background reduction
  - **Similar isotope mass,** 250 kg ^{100}Mo

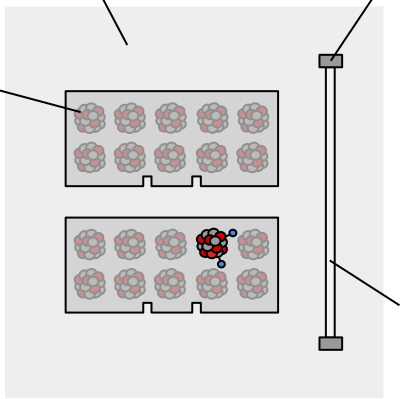
➔ Projected sensitivity, 10 yr

[Armstrong et al., arXiv:1907.09376]

$T_{1/2}(^{100}\text{Mo})$ = **1.5 · 10^{27} yr** (90% CL)

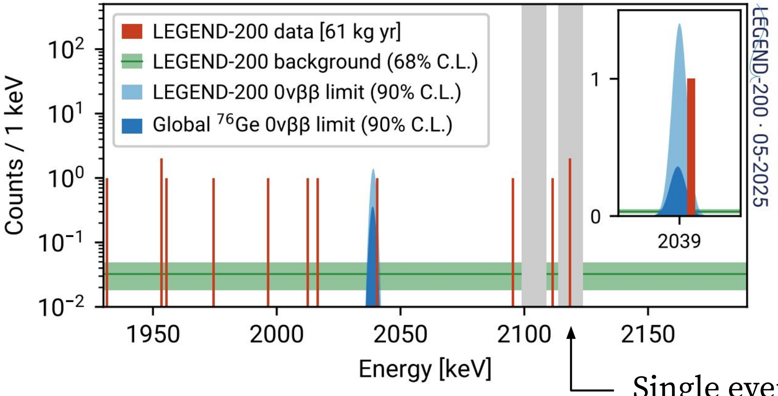
$T_{1/2}(^{100}\text{Mo})$ = **1.1 · 10^{27} yr** (3σ)

LEGEND



- High-purity ^{enr}**Ge detectors** in **active liquid argon shield**, building on ..
  - .. GERDA, **lowest background**, background-free scaling
    [Agostini et al., PRL 125 (2020) 25, 252502]
  - .. MAJORANA, **best energy resolution**, 2.5 keV (FWHM) at 2.0 MeV
    [Arnquist et al., PRL 130 (2023) 6, 062501]

[Acharya et al., arXiv:2505.10440]



- **LEGEND-200**, up to 200 kg of 90% ^{76}Ge in upgraded GERDA infrastructure, improved light read-out

➔ First 140 kg deployed, **1st result**
[Acharya et al., arXiv:2505.10440]

$T_{1/2}(^{76}\mathrm{Ge})$ **> 1.9 · 10²⁶ yr** (90% CL) → $m_{\beta\beta}$ **< [75, 200] meV** (90% CL)

> 2.8 · 10²⁶ yr (90% CL, sensitivity)

LEGEND outlook

- LEGEND-200, **data taking resumed** after maintenance

➔ Projected sensitivity, 5 yr
[Agostini et al., Rev.Mod.Phys. 95 (2023) 2, 025002]

$$T_{1/2}(^{76}\text{Ge}) = \mathbf{1.5 \cdot 10^{27}\ yr}\ (3\sigma)$$

- **LEGEND-1000**, new infrastructure in preparation at LNGS
    - **Sizeable isotope mass**, 1 t of 90% ^{76}Ge
    - **Nested active shield**, 20 t underground LAr, 250 t atmospheric LAr with neutron moderator, 700 t water

➔ Projected sensitivity, 10 yr
[Abgrall et al., arXiv:2107.11462]

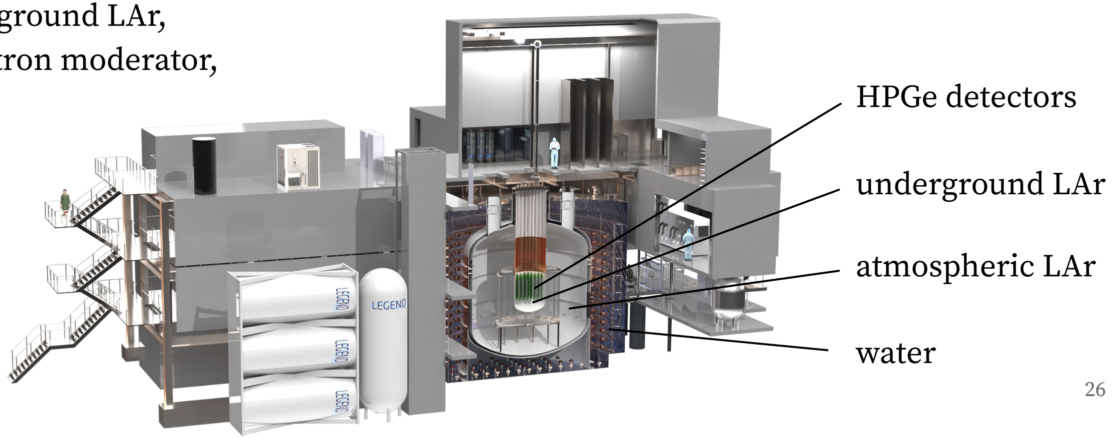
$$T_{1/2}(^{76}\text{Ge}) > \mathbf{1.6 \cdot 10^{28}\ yr}\ (90\%\ \text{CL})$$

$$T_{1/2}(^{76}\text{Ge}) = \mathbf{1.3 \cdot 10^{28}\ yr}\ (3\sigma)$$

CDEX

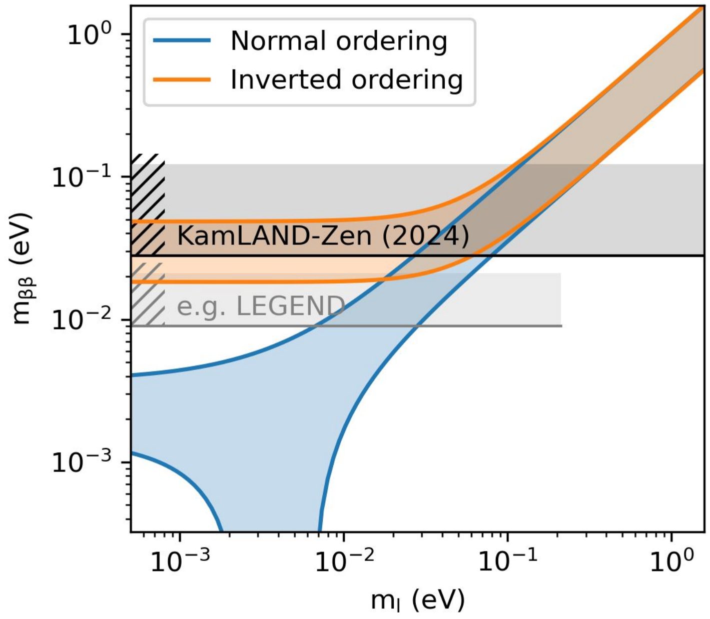
- **CDEX-300ν**, in preparation at **CJPL**
    - 225 kg HPGe detectors, >86% ^{76}Ge
    - 20 t **active LAr shield**, 1725 m^3 **passive LN2 shield**
- Plans for **CDEX-1T** and **CDEX-10T**

LEGEND-1000



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

[NuFIT 6.0, nu-fit.org]



- Most stringent bounds placed at
  [Acharya et al., arXiv:2505.10440; Adams et al, arXiv:2404.04453; Abe et al., arXiv:2406.11438]

  $m_{\beta\beta}$ < [75, 200] eV (90% CL), LEGEND-200 + .. (^{76}Ge)

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

  $m_{\beta\beta}$ **< [28, 122] eV** (90% CL), **KamLAND-Zen** (^{136}Xe)

- **LEGEND-200** and **CUORE** ongoing, **SNO+** about to start

- **Tonne-scale projects** will probe inverted ordering scenario (and significant part of normal ordering space), e.g.
  [Abgrall et al., arXiv:2107.11462]

  $m_{\beta\beta}$ **= [9, 21] meV** (3σ), **LEGEND-1000**

  similar numbers for **CUPID**, **nEXO**, ..

Conclusions

Energy conservation

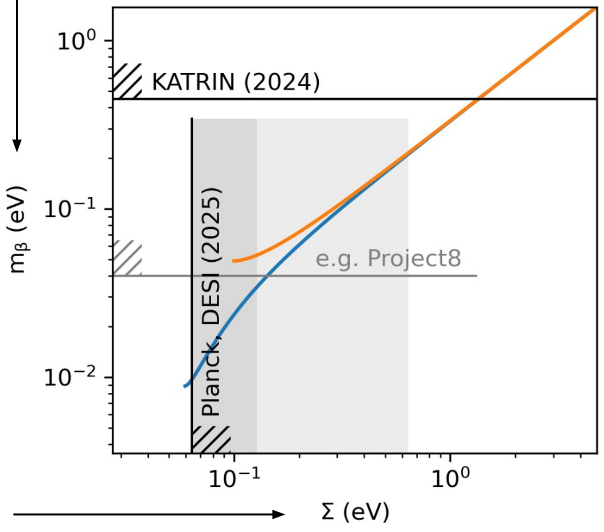
Light **Majorana neutrino** exchange

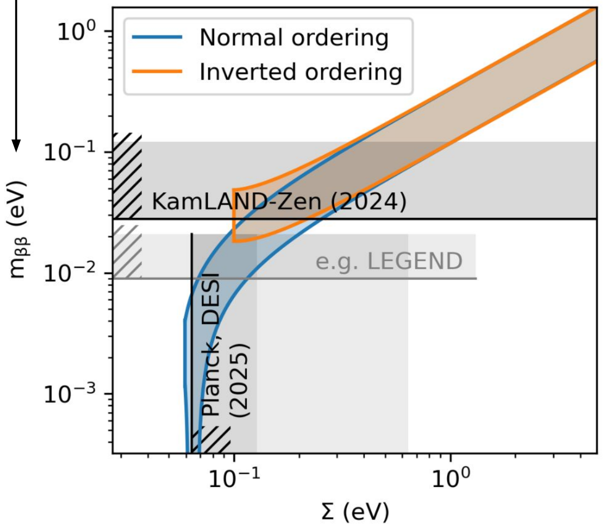
[NuFIT 6.0, nu-fit.org]

- Strong **complementarity**, also with cosmology

➔ Interplay allows to **test underlying models**

- Many **new constraints** and **powerful tools online**, e.g. LEGEND-200





Standard **cosmology**

Cosmology (**Planck, DESI**)
[Abdul Karim et al., arXiv:2503.14738]

Σ **< 0.06 eV** (95% CI)

Neutrinoless ββ decay (**KamLAND-Zen**, ^{136}Xe)
[Abe et al., arXiv:2406.11438]

$m_{\beta\beta}$ **< [0.03, 0.12] eV** (90% CL)

β decay kinematics (**KATRIN**)
[Aker et al., Science 388 (2025) 6743]

m_β **< 0.45 eV** (90% CL)

Many thanks to
Carlo, Joe, Kathrin, Loredana, Mark, Matteo,
Stefan, Steve, Susanne, Thomas, Qian

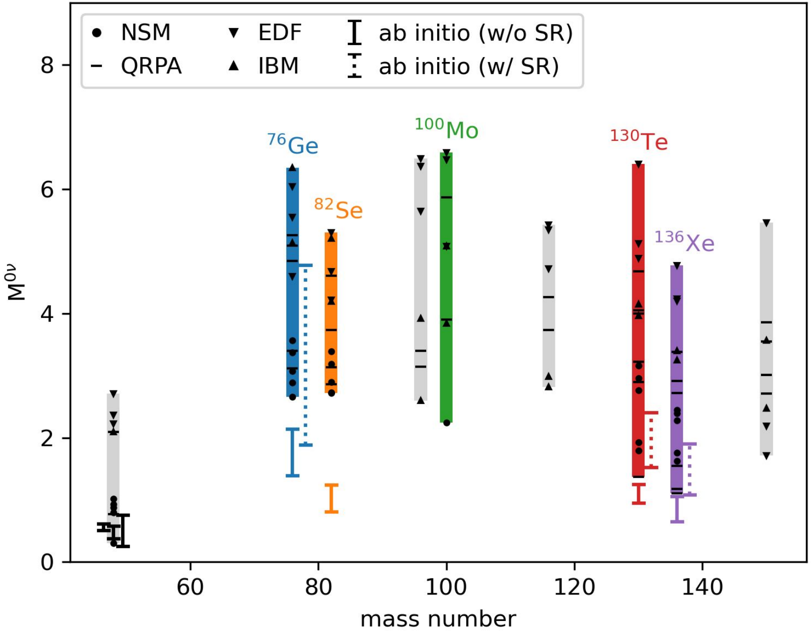
Backup

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 provide **range of $m_{\beta\beta}$ constraints**

$$T_{1/2} = .. \rightarrow m_{\beta\beta} = [.., ..]$$

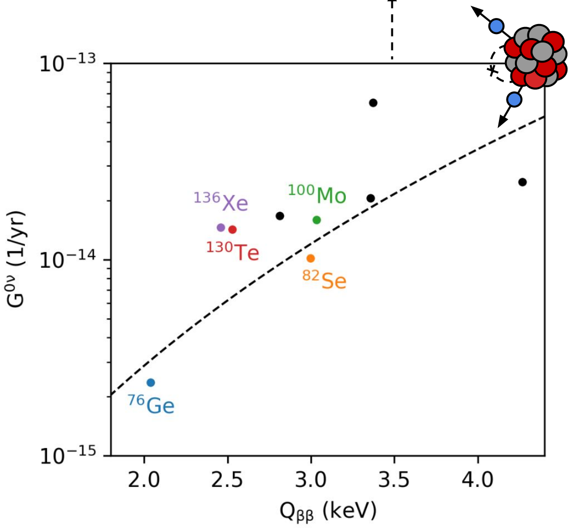
- First **ab initio calculations available**, may resolve quenching issue
  [Yao et al., PRL 124 (2020); Belley et al., PRL 126 (2021); Novario et al., PRL 126 (2021); Cirigliano et al., PRL 120 (2018); Belley et al., arXiv:2307.15156; Belley et al., PRL 132 (2024); ..]
- Effective field theory (EFT) analysis identified additional **short-range contribution**
  [Cirigliano et al., PRL 120 (2018) 20, 202001; ..]

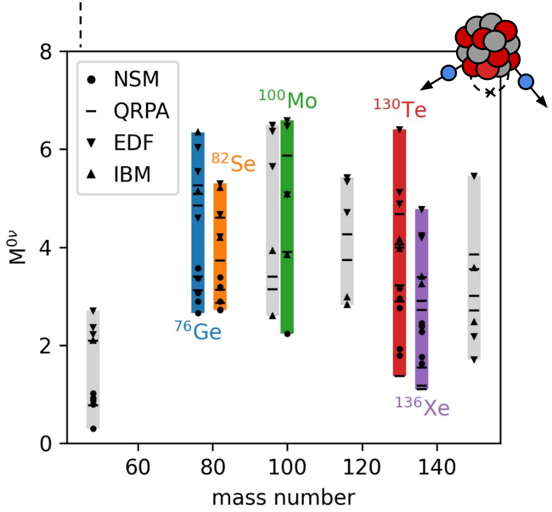


Decay rate

- Interplay of **BSM physics** and **isotope properties**

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





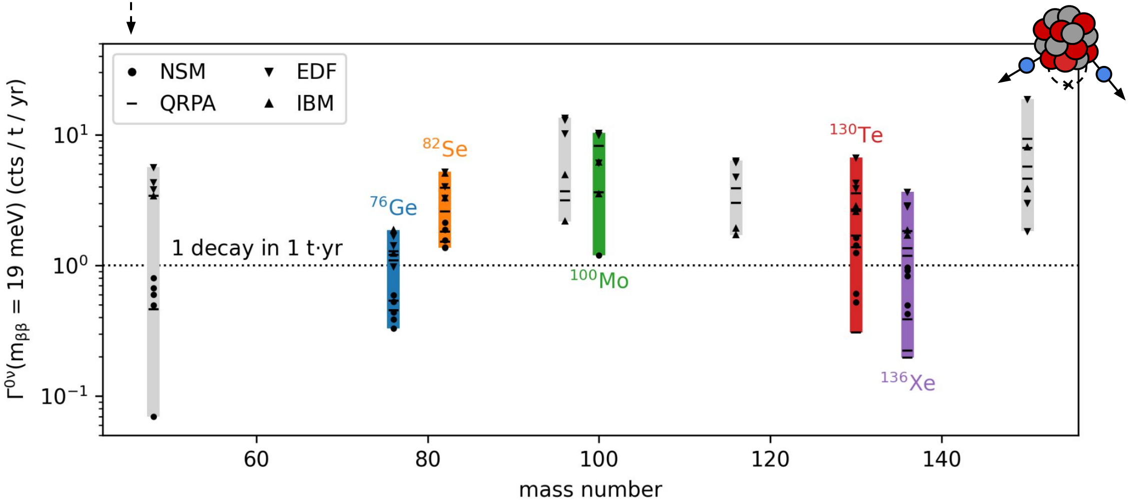
- Accurate **phase space factor,** large Q-value favorable
  [Kotila, Iachello, PRC 85 (2012) 034316]

- 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 **BSM physics** and **isotope properties**

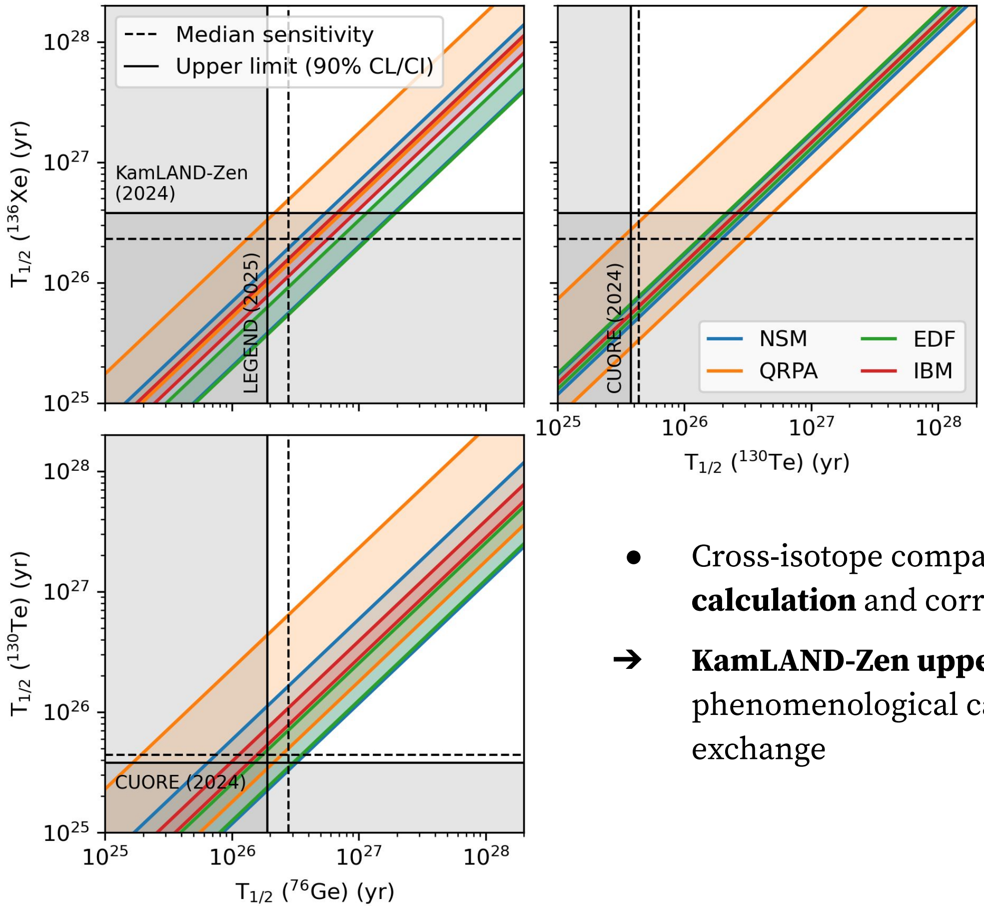
$$\Gamma^{0\nu} = \frac{N_A}{M(^A X)} \cdot G^{0\nu} \cdot ln(2) \cdot \left|g_A^2\, \mathcal{M}^{0\nu}\right|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$



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

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

There is no super-isotope



Intercomparison of neutrinoless double beta decay constraints

- Cross-isotope comparison depends on choice of **nuclear matrix element calculation** and corresponding mediator

➔ **KamLAND-Zen upper limit provides strongest constraint** for all phenomenological calculations, assuming light Majorana neutrino exchange

Background importance

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

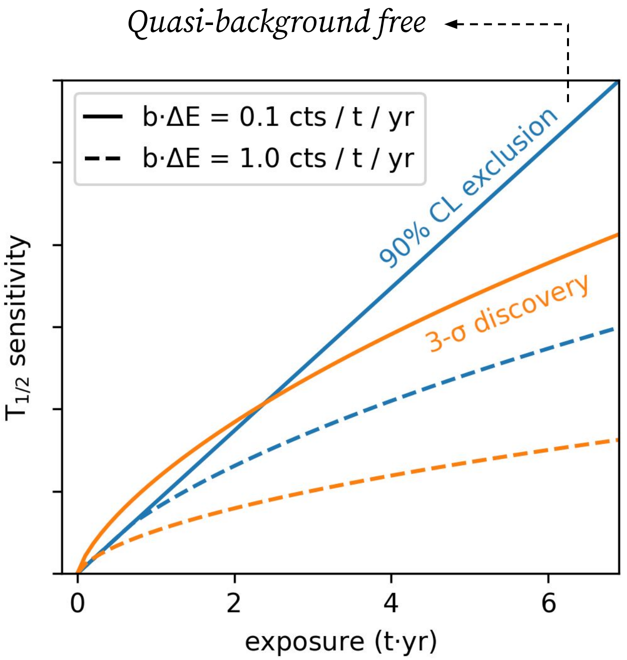
→ **Background index** in e.g. [cts / keV / kg / yr]

Sensitivity **scaling**:

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

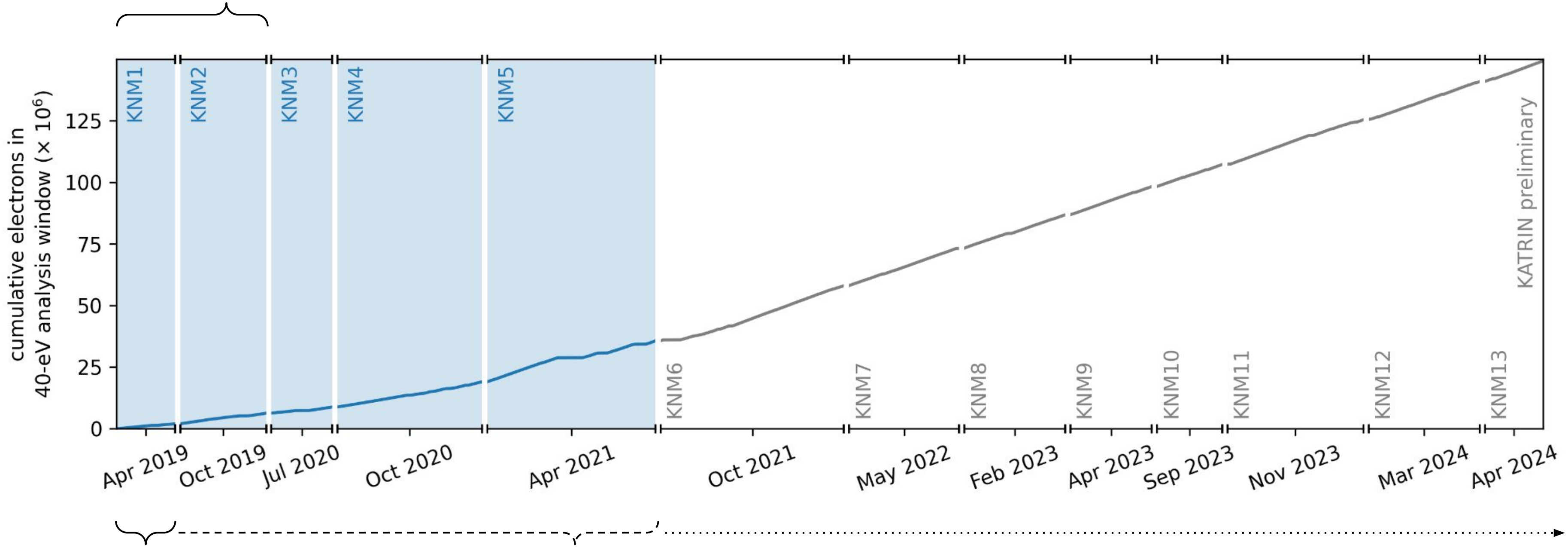
b. **Background-free** ($n_b \ll 1$): $T_{1/2} \propto m \cdot t$

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



KATRIN data taking overiew

2nd result, $\boldsymbol{m_\beta} < \mathbf{0.8}$ **eV** (90% CL)
[Aker et al., Nature Phys. 18 (2022), 2, 160-166]



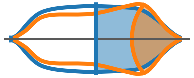
1st result, $\boldsymbol{m_\beta} < \mathbf{1.1}$ **eV** (90% CL)
[Aker et al., PRL 123 (2019) 22, 221802]

3rd result, 5 campaigns, 1757 scans,
259 measurement days

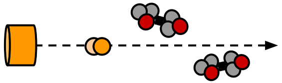
Continue until end-2025,
1000 measurement days

Uncertainty breakdown

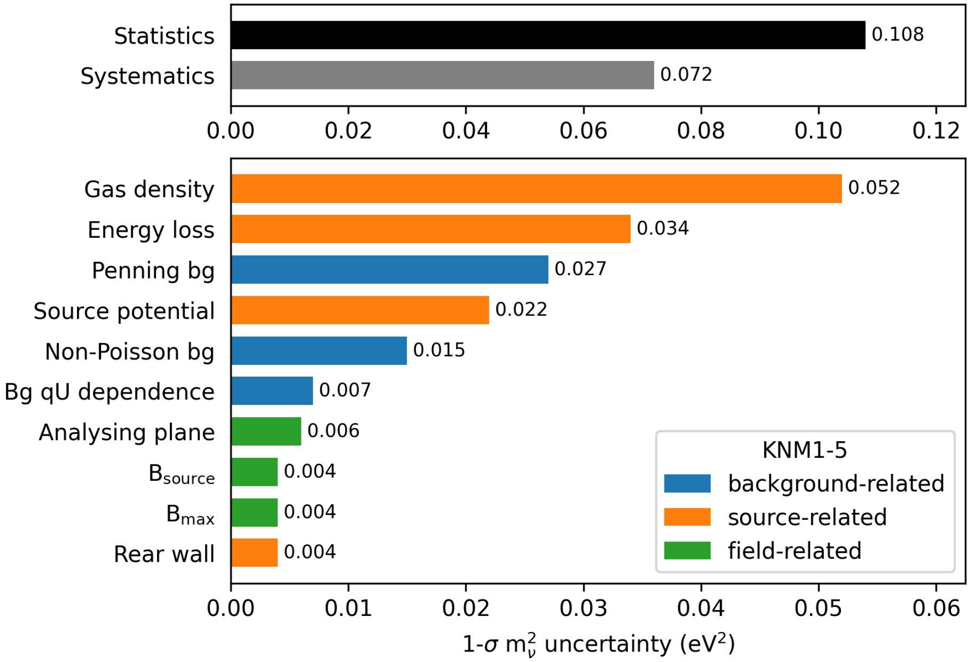
- **6-fold increase in statistics**, 2-fold reduction of background



- **3-fold reduction of systematic uncertainties**, source effects leading

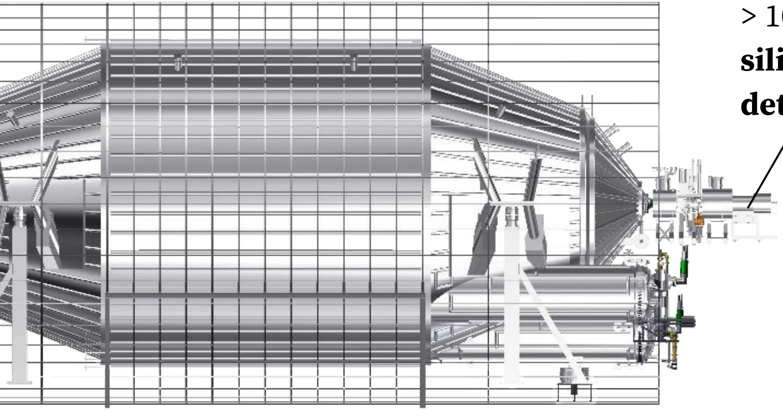


➔ **Statistical uncertainty dominates**, improved calibration precision in recent campaigns



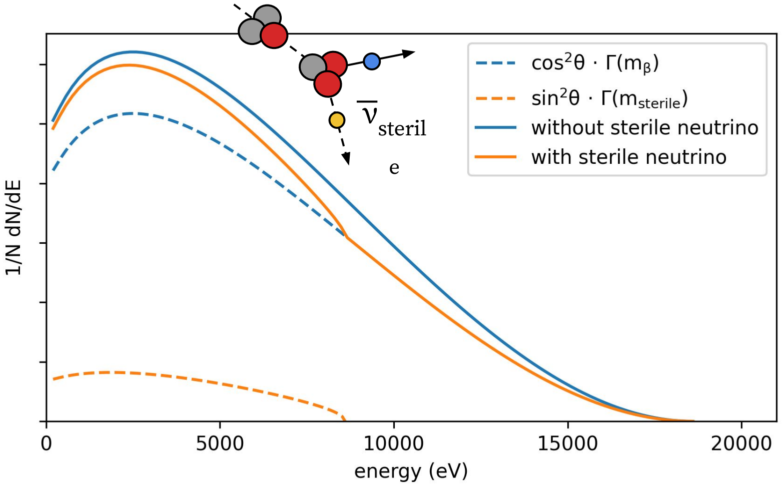
TRISTAN

- **keV-sterile neutrino** search with KATRIN
  [Mertens et al., J.Phys.G 46 (2019) 6, 065203]



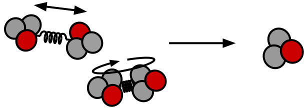
> 1000-pixel **silicon drift detector array**

- **High-rate electron spectroscopy**
- Ultra-high vacuum compliance, calibration



KATRIN++

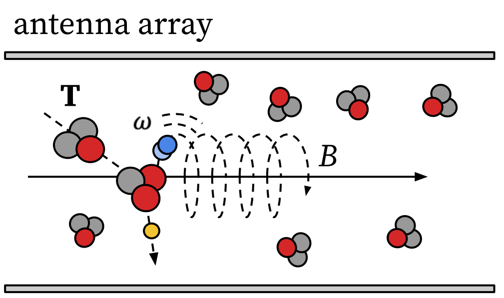
- **Differential** detection technologies, metallic magnetic calorimeters
- **Atomic tritium** source



Cyclotron radiation emission spectroscopy (CRES)

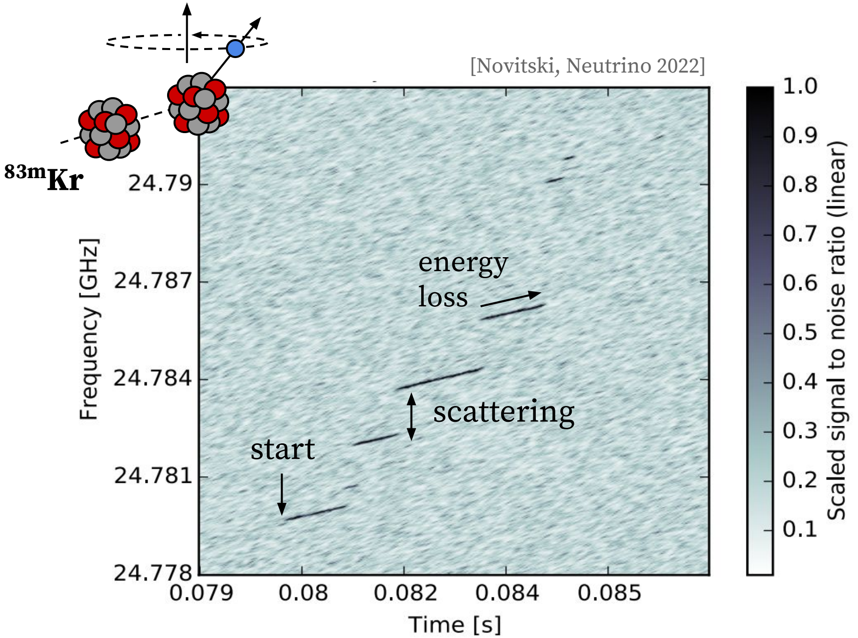
- Measure **cyclotron radiation** of trapped tritium decay electrons
  [Monreal, Formaggio, PRD 80 (2009) 051301]

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$



➔ **Source transparent** to microwave radiation, **no electron extraction**

➔ **Differential** frequency measurement, **eV-scale** resolution, **low background**



Relic neutrino overdensity

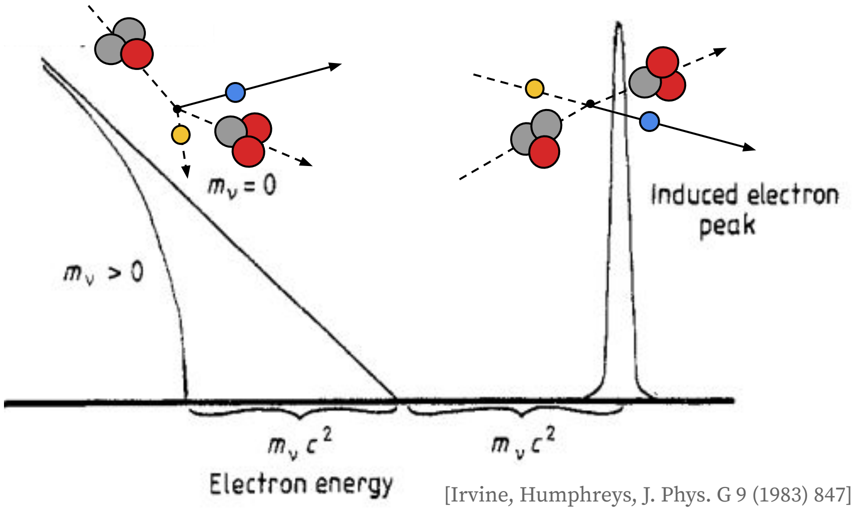
- **Capture on tritium**, no energy threshold

➔ Population **above endpoint**

- **~10 µg "target"**, constraint on local overdensity
[Aker et al., PRL 129 (2022) 1, 011806]

$$\eta < \mathbf{1.1 \cdot 10^{11}} \text{ (95\% CL)}$$

➔ **x100 improvement** over previous laboratory bounds



[Irvine, Humphreys, J. Phys. G 9 (1983) 847]

PTOLEMY

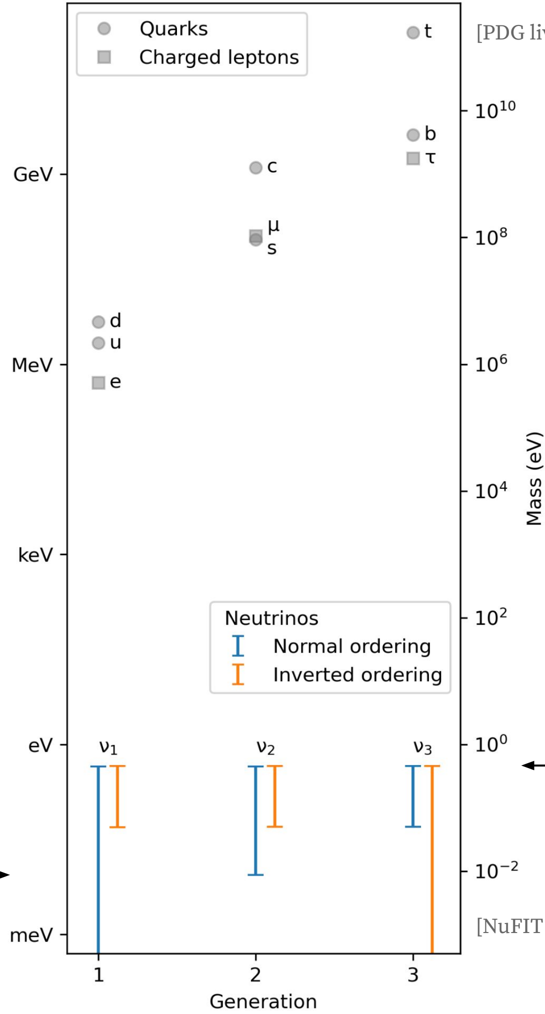
- monoatomic tritium in **graphene matrix**, **cyclotron emission** tagging, dynamic **electromagnetic filter**, **micro calorimeters** [Betti et al., Prog.Part.Nucl.Phys. 106 (2019) 120-131] *“for the discovery of neutrino oscillations, which shows that*

Neutrinos have mass

[Kajita, McDonald, Nobel Prize in Physics 2015]

- Neutrino oscillations assess mass squared differences, $\Delta m_{ij}^2 = m_i^2 - m_j^2$

➔ Mass mechanism, mass ordering, and **absolute mass** remain **unknown**



[PDG live, pdglive.lbl.gov]

Upper bound from **direct measurements**

Lower bounds from **oscillation experiments**

[NuFIT 6.0, nu-fit.org]