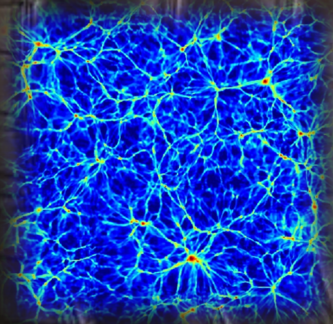
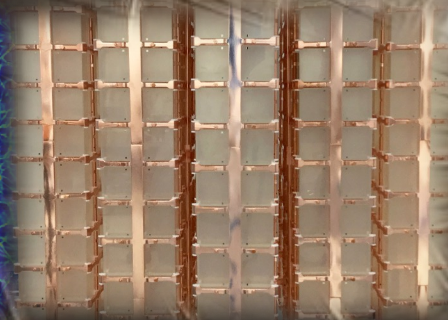
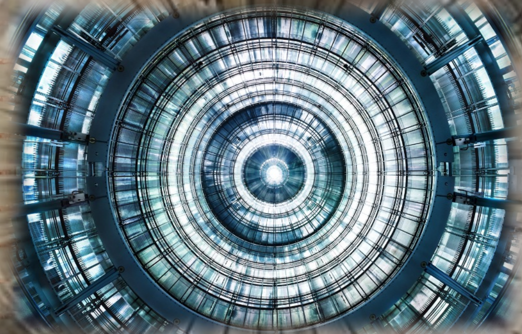
$0\nu\beta\beta$ and direct neutrino mass measurements

ICHEP - 2024

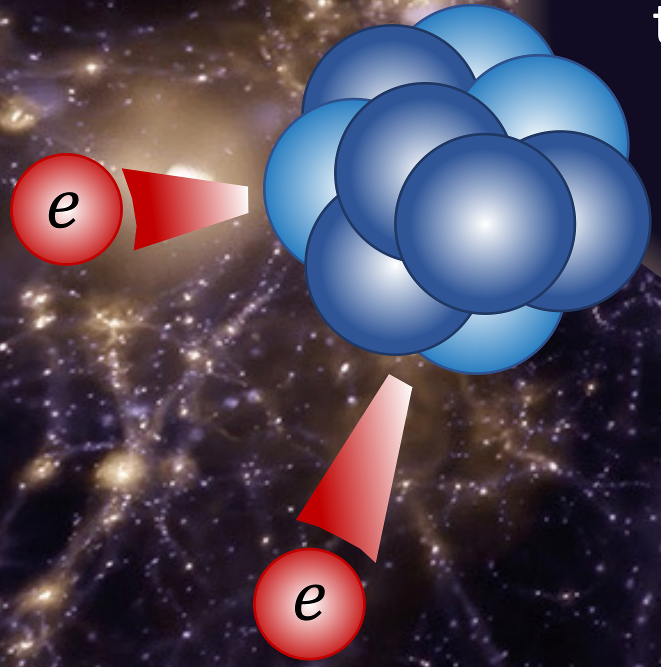




Prof. Dr. Susanne Mertens

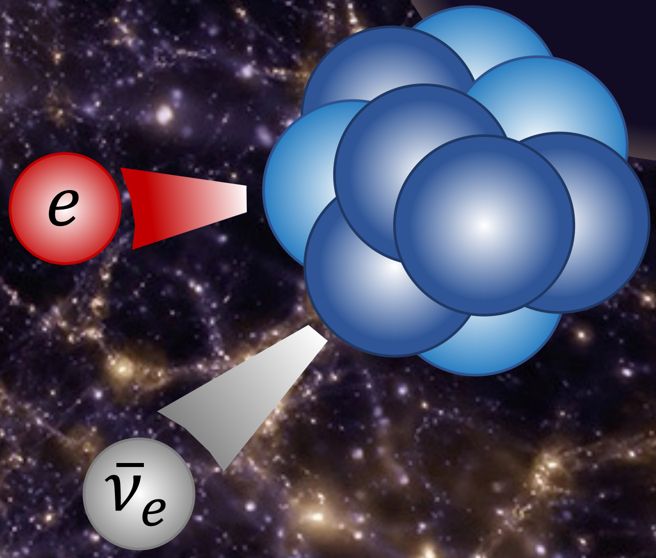
Technical University Munich & Max Planck Institute for Nuclear Physics

Neutrinos – open questions

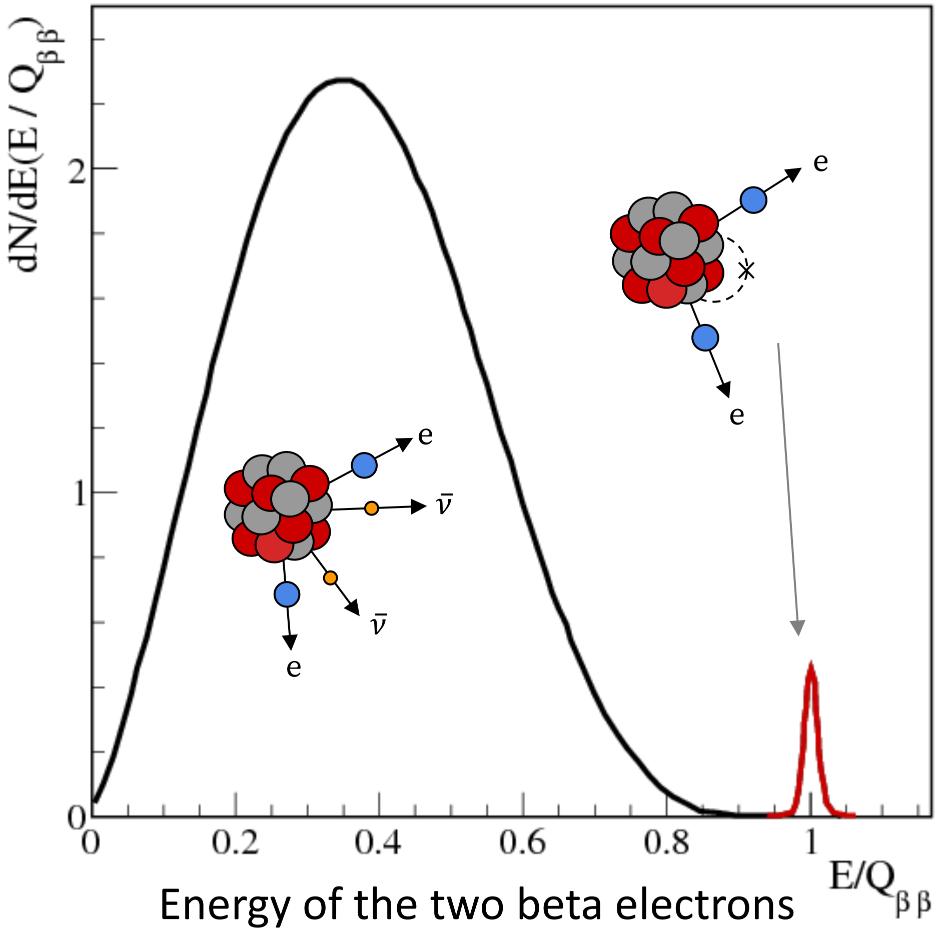
Are neutrinos their own anti-particle ?



What is the mass of neutrinos ?



The signature



Energy of the two beta electrons

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{110}Pd, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{136}Xe, ^{150}Nd

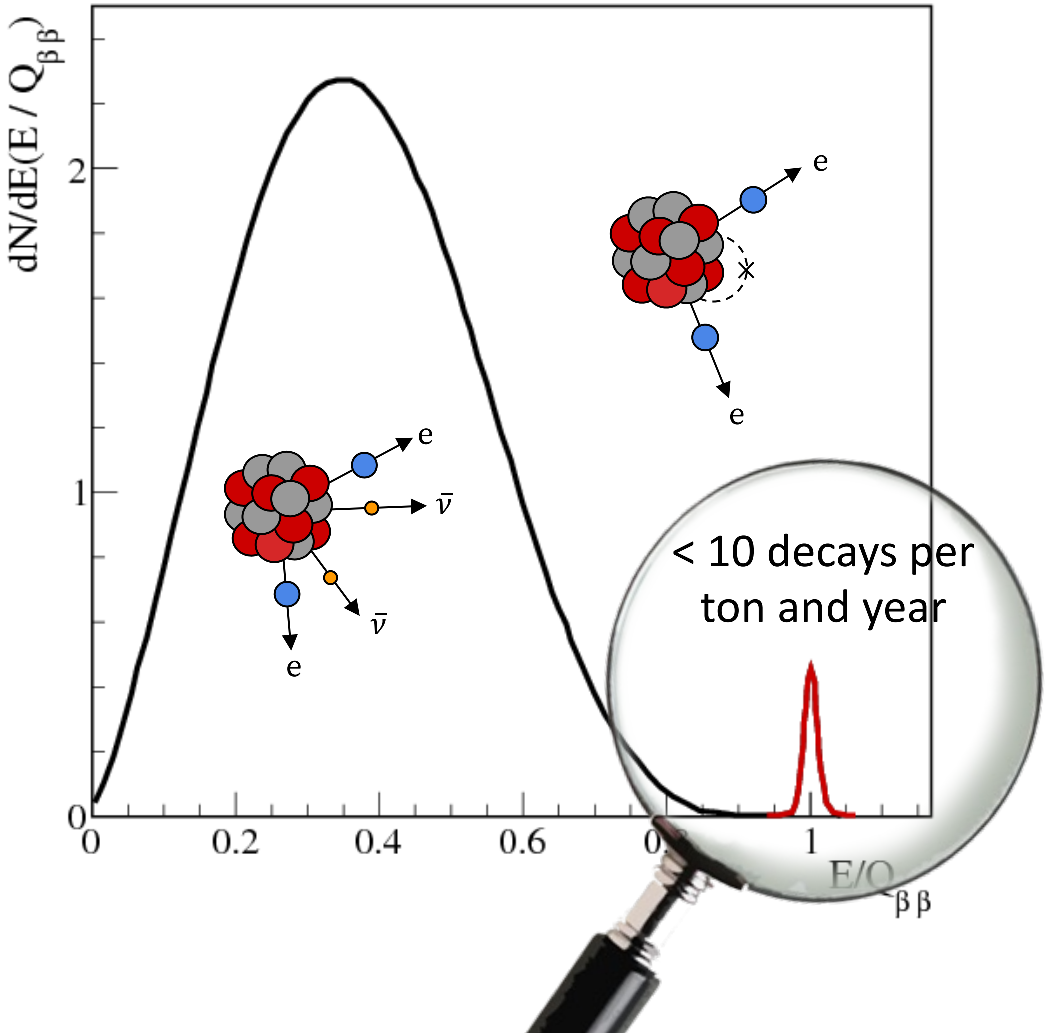
Discovery of 0νββ:

- Process which creates matter, without the balancing amount of anti-matter
- Neutrino is a Majorana particle
- Lepton-number violation
- Half life reveals neutrino mass:

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q,Z) \cdot |M^{0\nu}|^2 \cdot \boldsymbol{m_{\beta\beta}^2}$$

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

The challenge

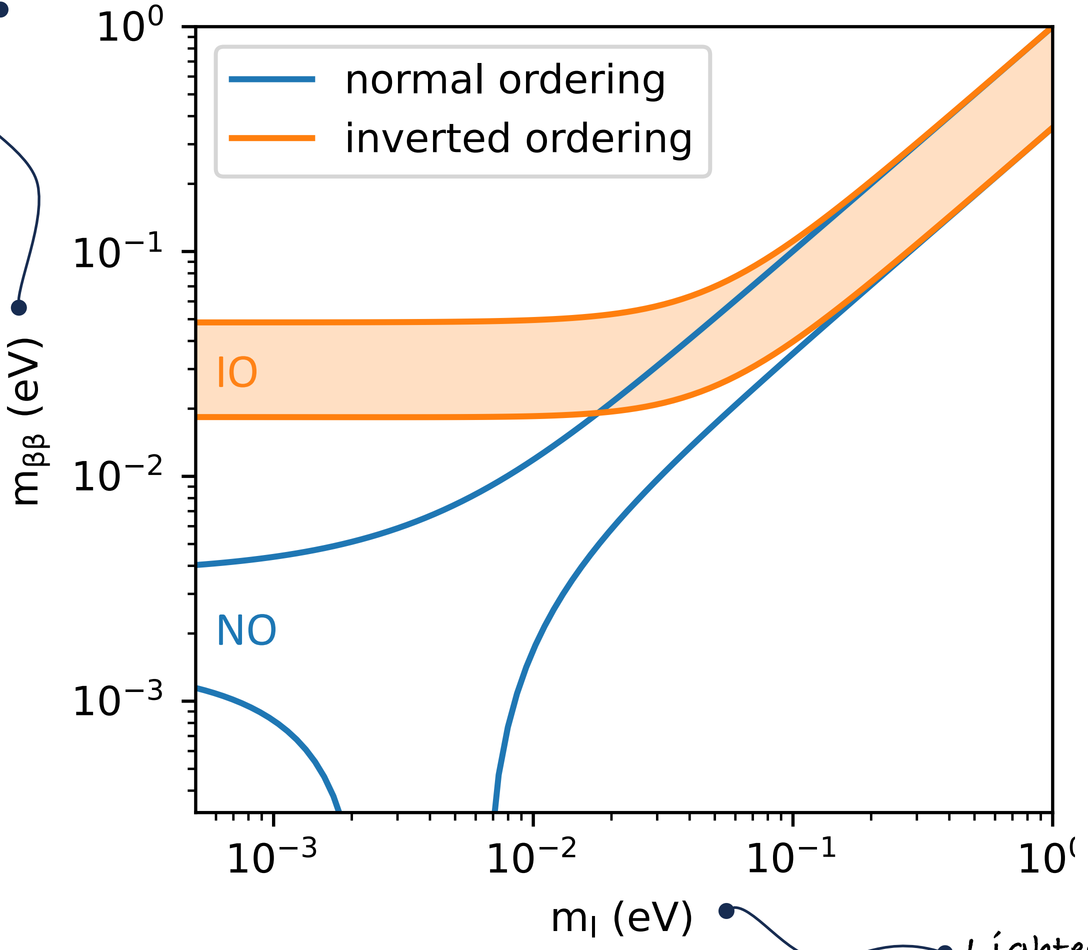


Key requirements:

- Large exposure (ton-scale)
- Low background (< 1 cts/year/t/ROI)
- Excellent energy resolution (< 1% @ $Q_{\beta\beta}$)

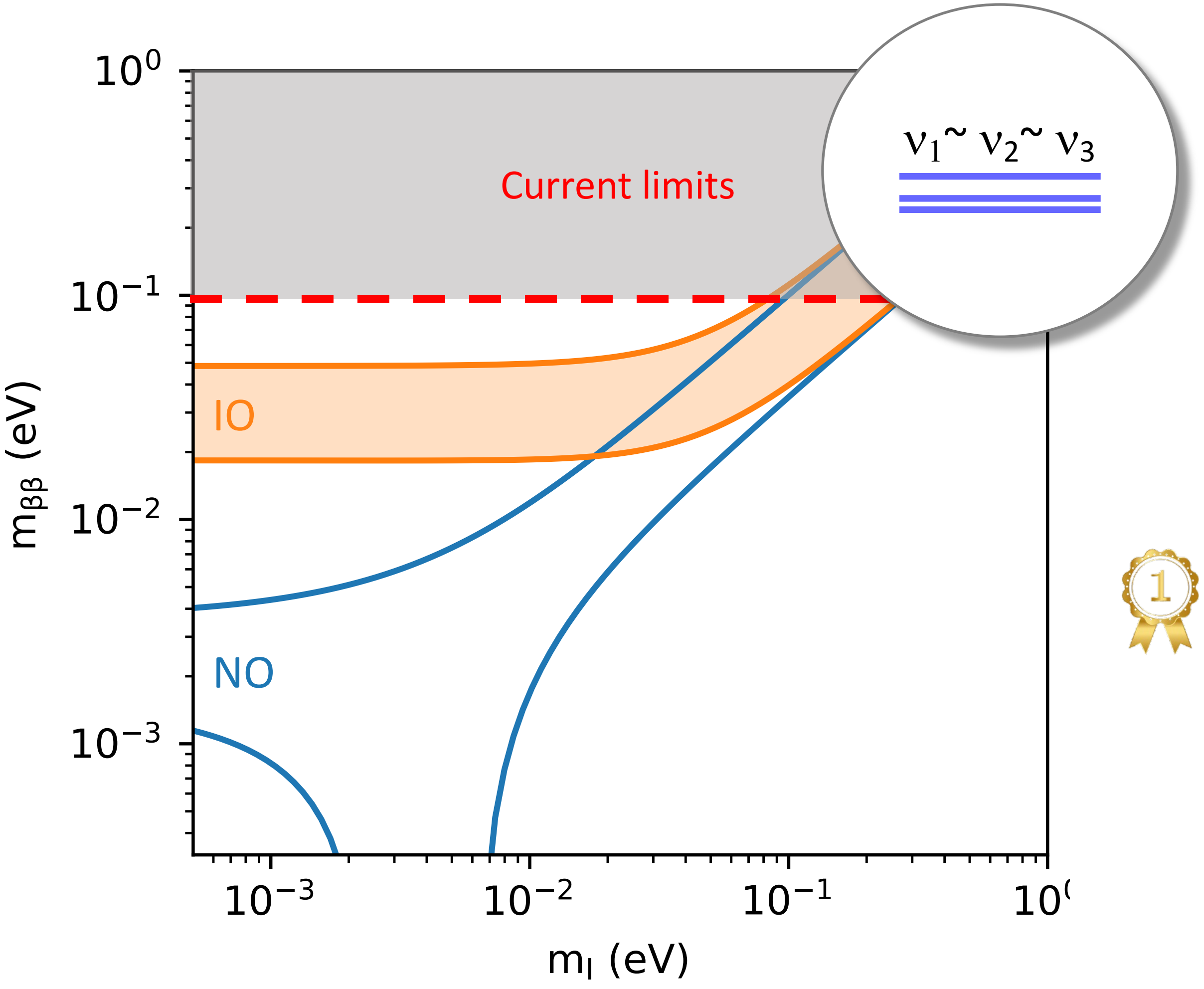
Where do we stand?

Coherent sum of mass eigenstates



Lightest mass eigenstate

Where do we stand?



- ongoing / completed projects probe degenerate regime
  e.g. LEGEND-200, CUORE, EXO, KamLAND-ZEN

NEW

KamLAND-Zen

Xe-loaded liq. scintillator

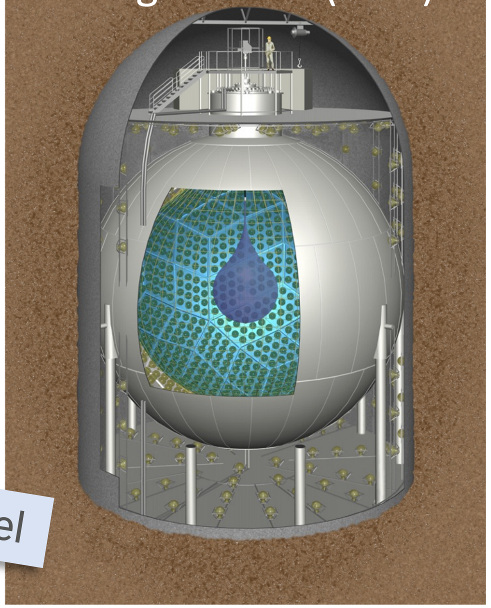
$T_{1/2} > 3.8 \cdot 10^{26}$

$m_{\beta\beta} < 28 - 122$ meV* (90% CL)

arXiv:2406.11438 (2024)

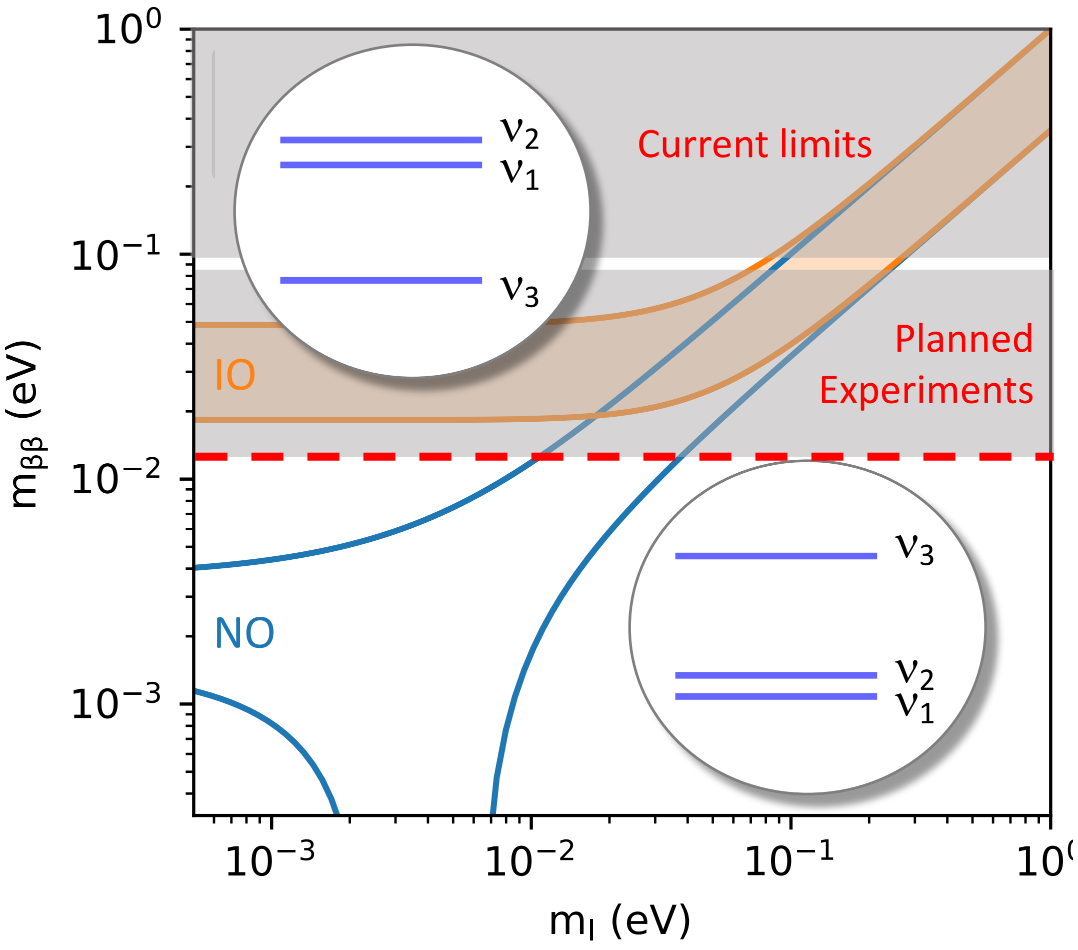
M. Eizuka, parallel

745 kg of ^{enr}Xe (91%)



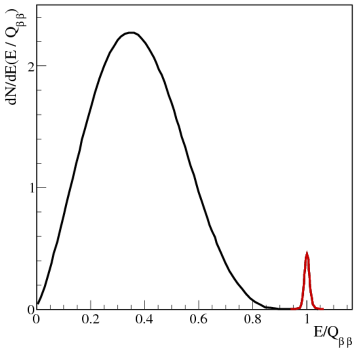
*Exposure: 970 kg · y ^{137}Xe, NME = 1.1 - 4.8

Where do we stand?



- ongoing / completed projects probe degenerate regime
  e.g. LEGEND-200, CUORE, EXO, KamLAND-ZEN
- planned projects will fully cover the inverted ordering scenario
  e.g. LEGEND-1000, CUPID, nEXO

Experimental efforts



Scintillation

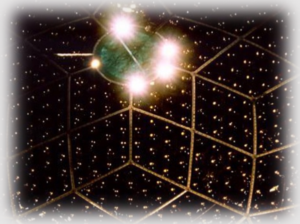
Heat

Ionization

Experimental efforts

KamLand2 Zen (^{136}Xe)

KamLand Zen (^{136}Xe)



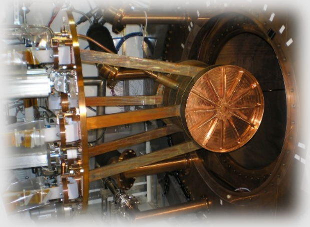
SNO+ (^{130}Te)

Scintillation

nEXO (^{136}Xe)

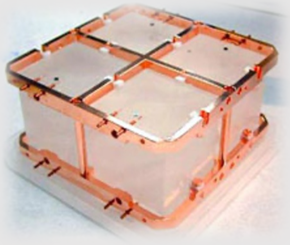
NEXT (^{136}Xe)

EXO-200 (^{136}Xe)



CUPID (^{100}Mo)

CUORE (^{130}Te)



LEGEND-1000 (^{76}Ge)

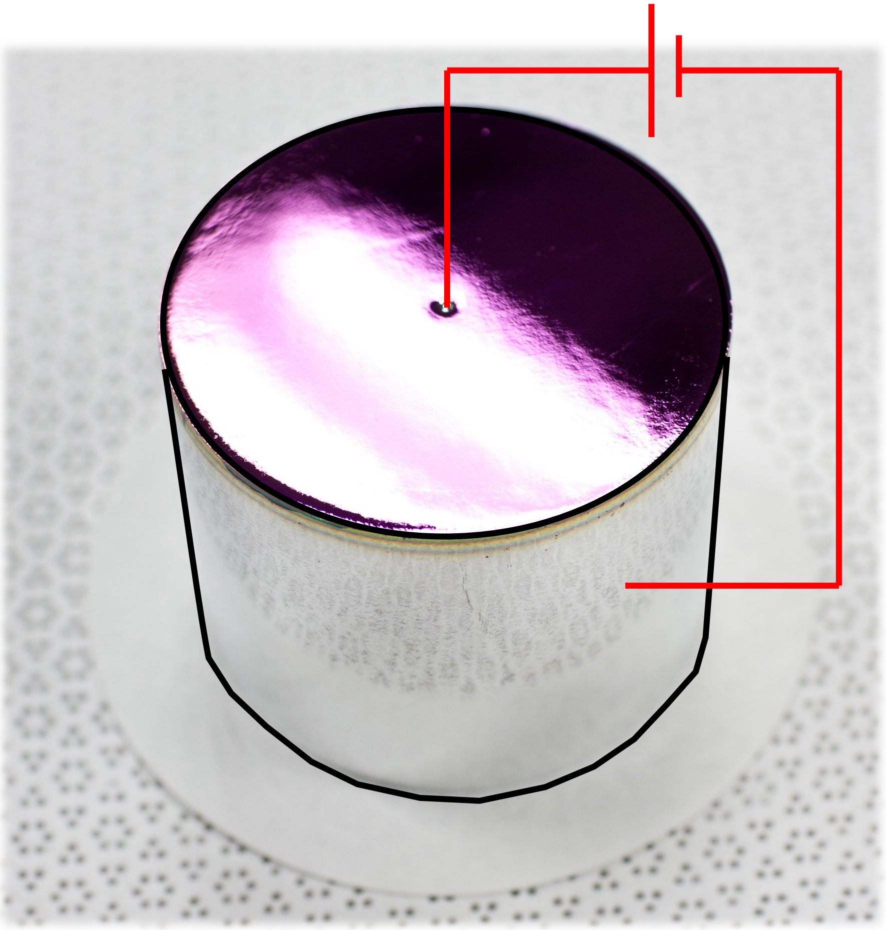
MAJORANA
GERDA
LEGEND-200
(^{76}Ge)

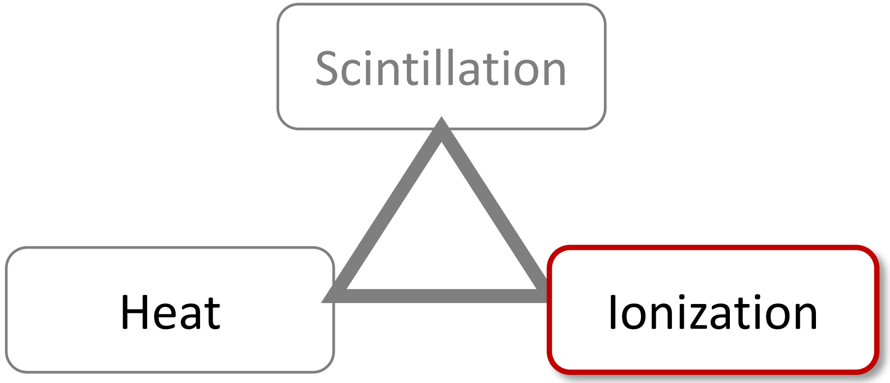
Heat

Ionization

Super-NEMO, Panda-X, CDEX, DARWIN, AMORE …

Experimental efforts





Germanium Semiconductors

✓ Enrichment to > 90% in ^{76}Ge ($Q_{\beta\beta}$=2039 keV)

✓ Excellent energy resolution (0.1 % FWHM @ $Q_{\beta\beta}$)

✓ Pulse-shape-discrimination against background

Ge-Semiconductor

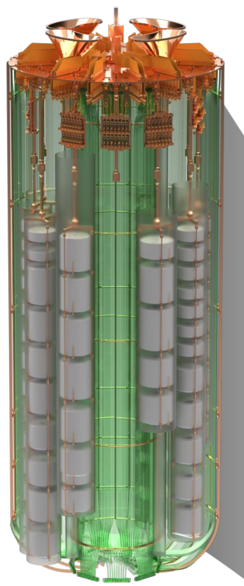
LEGEND 200 @ LNGS (Italy)

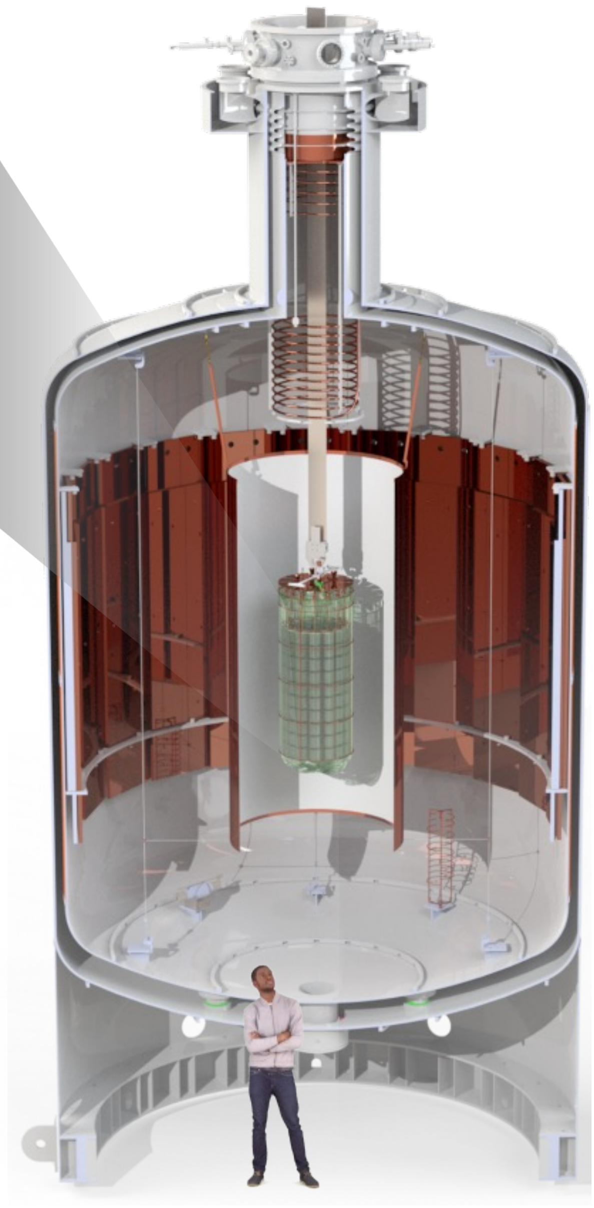
- **Method:** HPGe detector in liquid Ar
- **Mass:** 142 kg ^{enr}Ge (later 200 kg)
- **Background:** 0.5 cts/keV/t/year
- **E-resolution:** ~0.1% FWHM at $Q_{\beta\beta}$
- **Status:** running

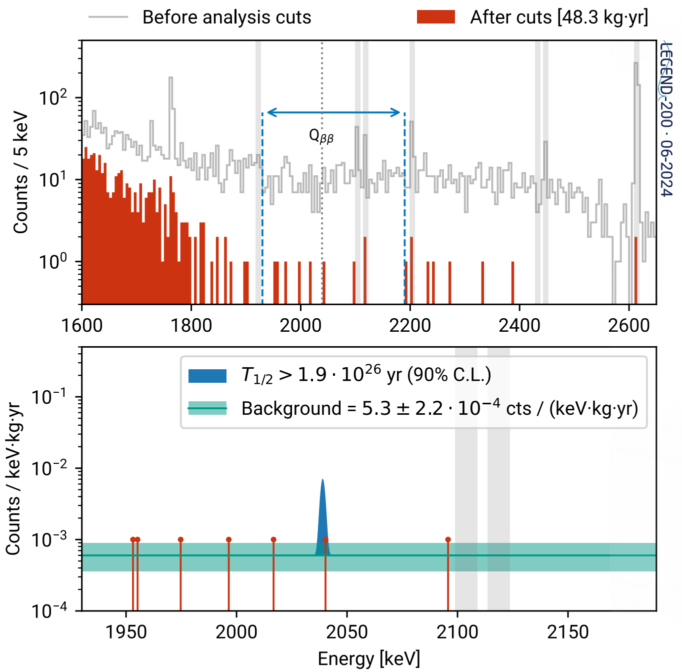
✓ $T_{1/2} > 1.9 \cdot 10^{26}$ (LEGEND + GERDA + MAJORANA)

✓ $m_{\beta\beta} < 75 - 178$ meV* NEW

PRL 125, 252502 (2020)
PRL 130, 062501 (2022)
Neutrino-24 (2024)

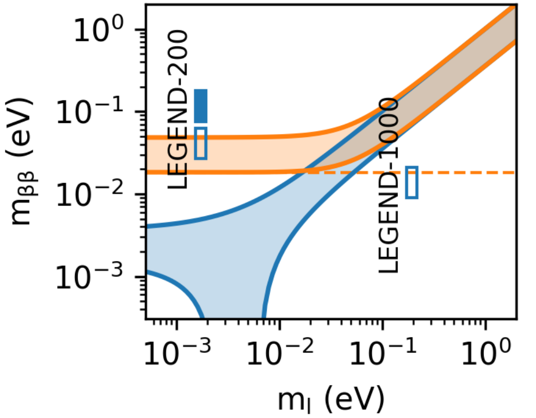






*Exposure: 240 kg · y ^{76}Ge, NME = 1.6 - 4.8

Ge-Semiconductor



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PRL 125, 252502 (2020)
PRL 130, 062501 (2022)
Neutrino-24 (2024)

LEGEND 1000 arXiv:2107.11462

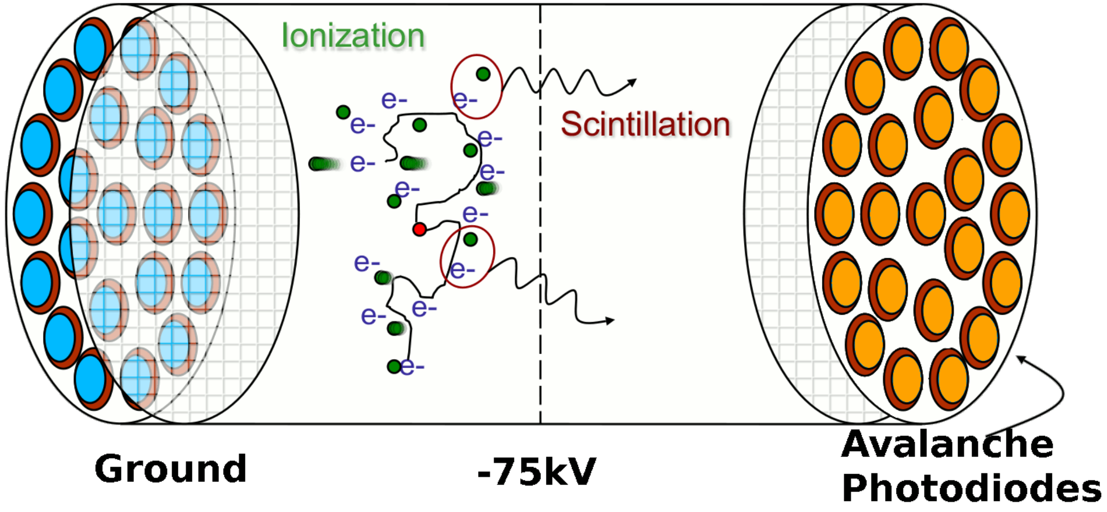
- **Upgrades:** 5 x more mass ÷ 20 lower background
- **Goal:** cover IO ($T_{1/2} > 10^{28}$ years)
- **Status:** construction starts 2025

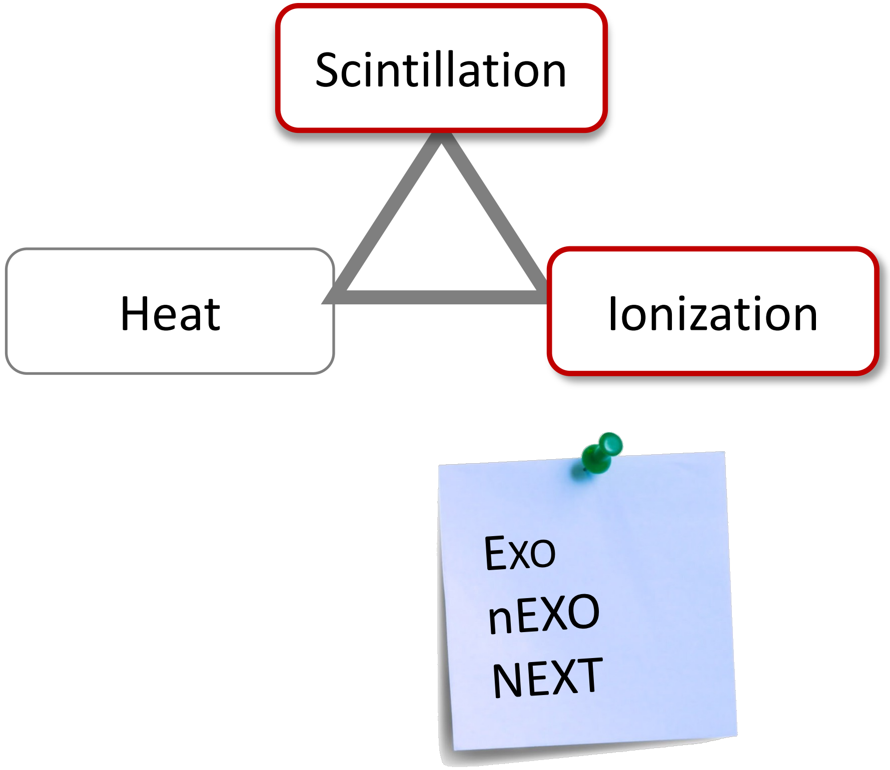
S. Calgaro, poster

M. Redchuk, parallel

*Exposure: 240 kg · y ^{76}Ge, NME = 1.6 - 4.8

Experimental efforts





Time projection chamber

- ✓ Liquid or gaseous xenon. Enrichment to > 90% in ^{136}Xe ($Q_{\beta\beta}$ = 2458 keV)
- ✓ Wrt. scintillation-only: improved **energy resolution** and **background discrimination**

Xenon-based TPC

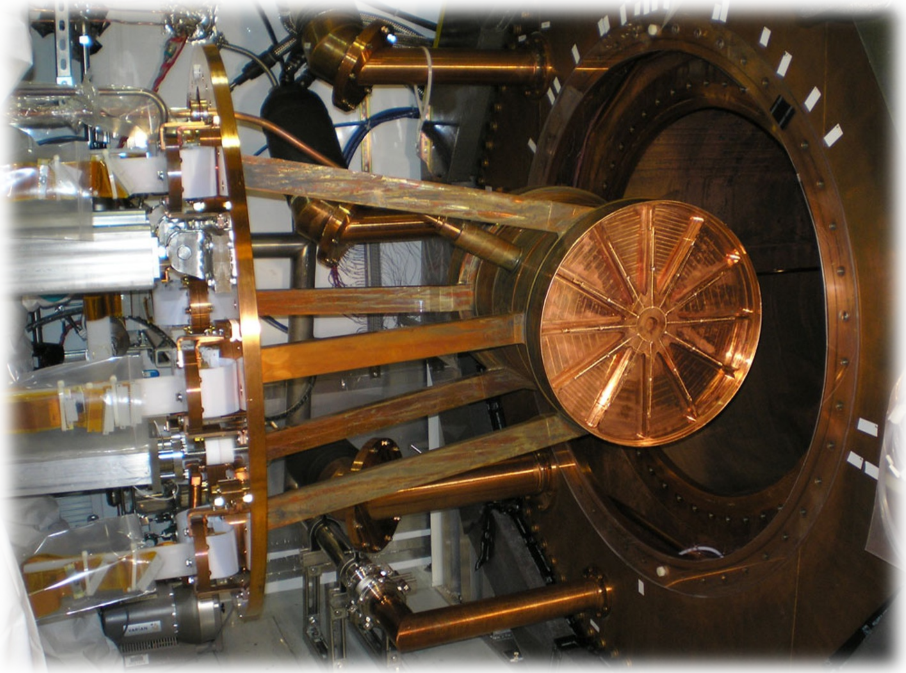
EXO-200 @ WIPP (USA)

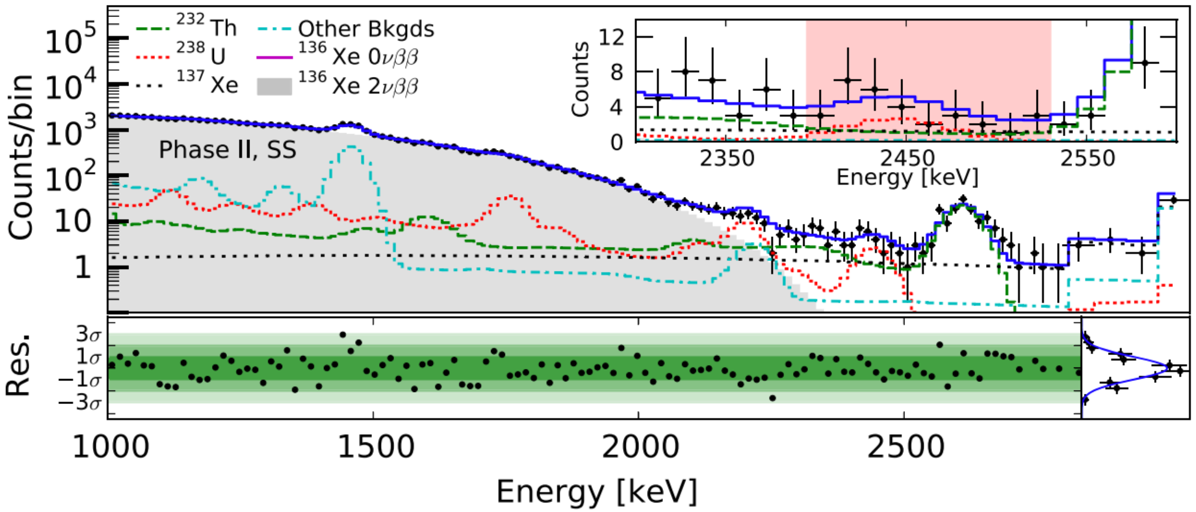
- **Method:** liquid Xe-TPC
- **Mass:** 75 kg of ^{136}Xe
- **Background:** 1.8 cts/keV/ton/year
- **E-resolution:** 2.7 % FWHM @ $Q_{\beta\beta}$
- **Status:** completed

✓ $T_{1/2} > 3.5 \times 10^{25}$ y (90% CL - data)

✓ $m_{\beta\beta} < 93 - 286$ meV*

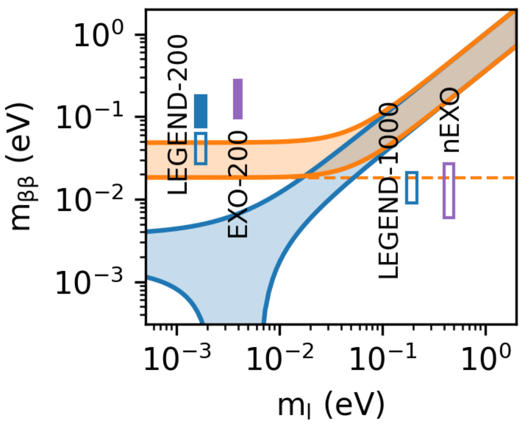
PRL 123, 161802 (2019)





*Exposure: 234.1 kg · y ^{137}Xe, NME = 1.4 - 6.4

Xenon-based TPC



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✓ $m_{\beta\beta} < 93 - 286$ meV*

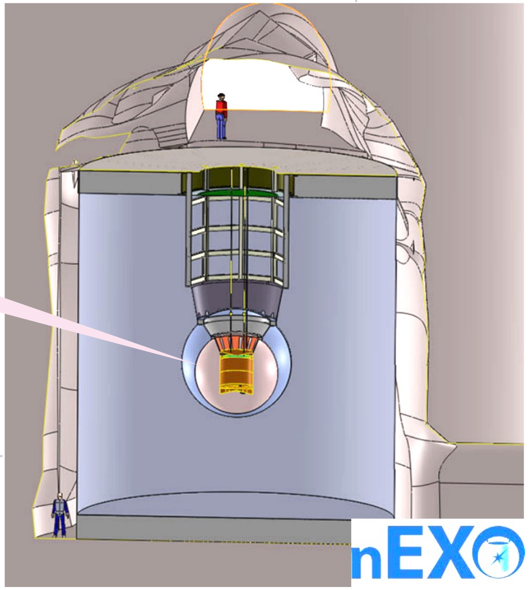
PRL 123, 161802 (2019)

nEXO

- **Upgrades:** 5 t liquid ^{enr}Xe
- **Goal:** cover IO ($T_{1/2} > 10^{28}$ years)
- **Status:** preparations started
- Advances in barium tagging

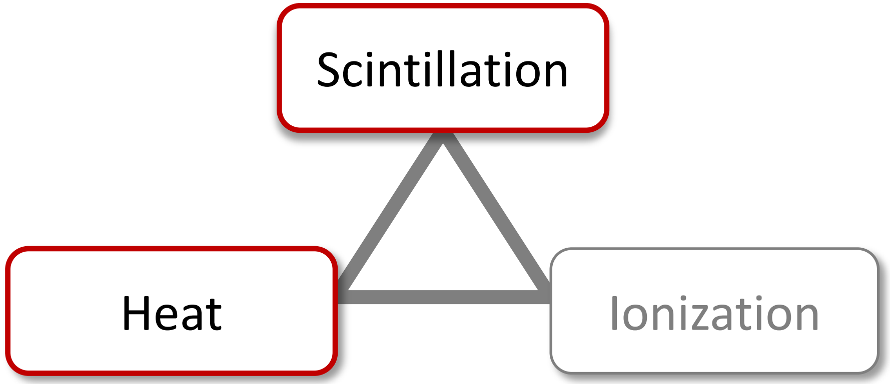
^{136}Xe
$\rightarrow$ $^{136}Ba^{++}$ + 2e + 0ν

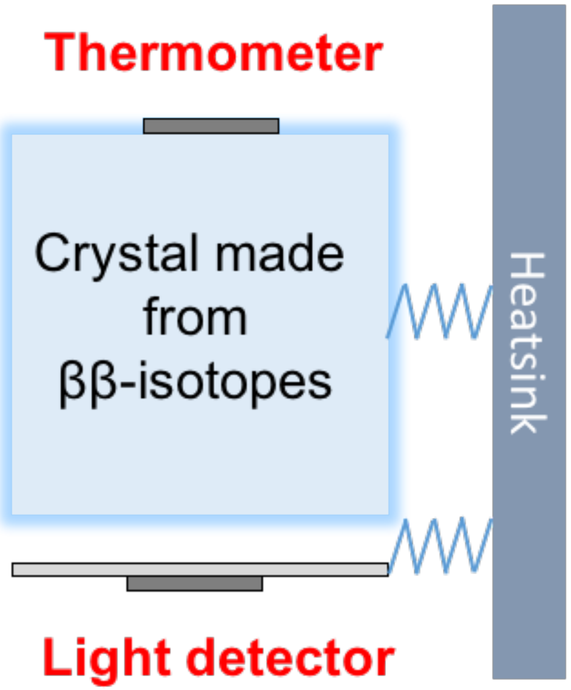
J.Phys.G 49 (2022) 1, 015104
Nature 569, 203–207 (2019)

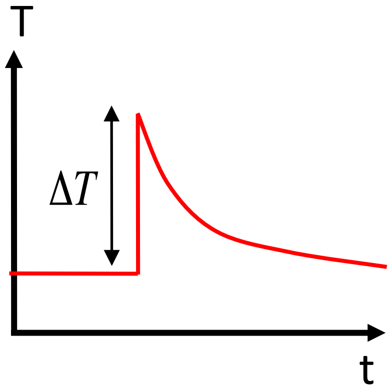


*Exposure: 234.1 kg · y ^{137}Xe, NME = 1.4 - 6.4

Experimental efforts







Cryogenic (scintillating) calorimeter

- ✓ Possible with different isotopes
- ✓ Excellent energy resolution (0.3% - level)
- ✓ Background discrimination based on heat and light signal

Cryogenic calorimeter

CUORE @ LNGS (Italy)

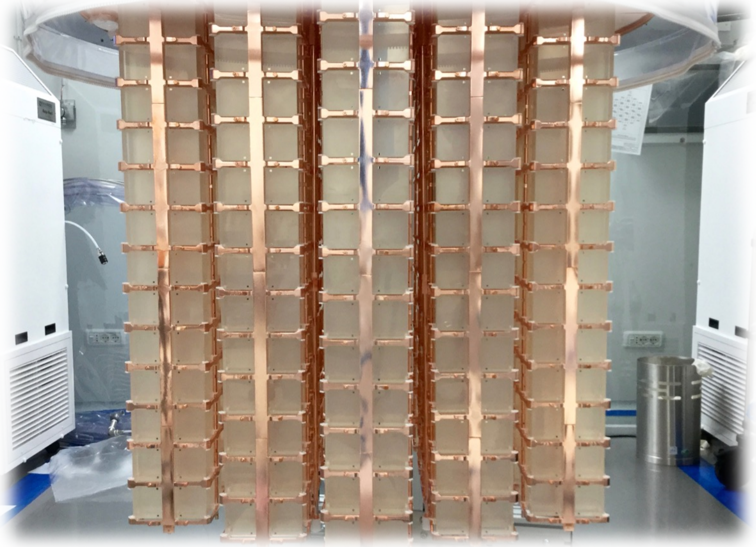
- **Method:** TeO_2 crystals (only heat)
- **Mass:** 206 kg ^{130}Te
- **Background:** 14 cts/keV/ton/y
- **E-resolution:** 0.3 % FWHM @ $Q_{\beta\beta}$
- **Status:** running

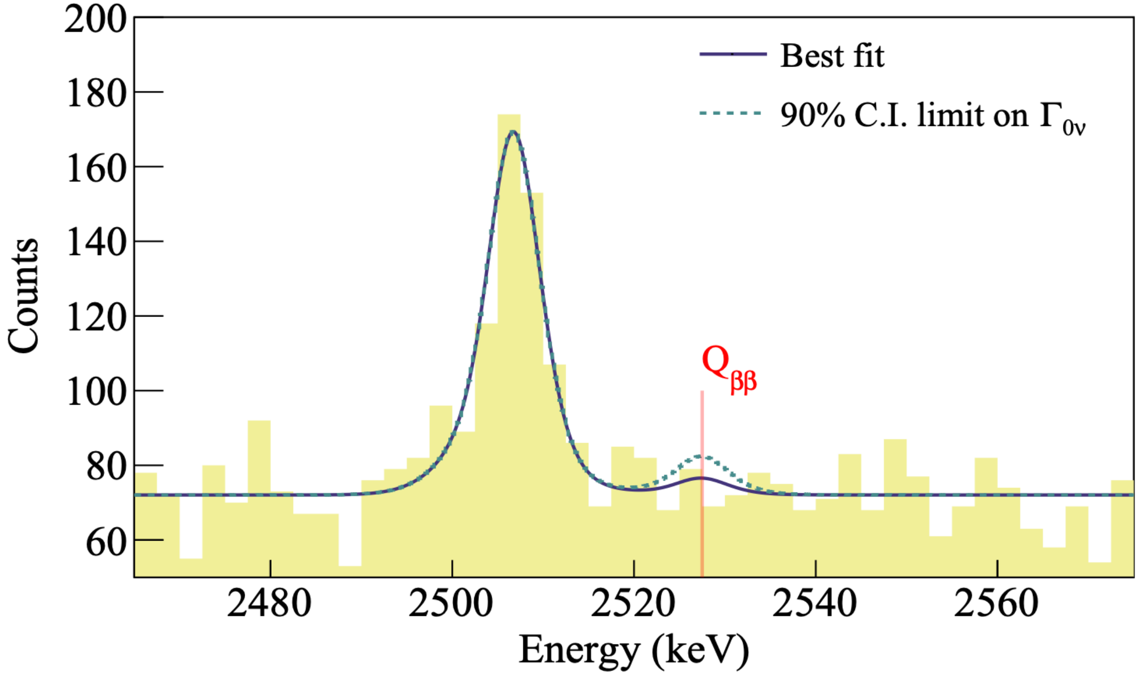
✓ $T_{1/2} > 3.8 \times 10^{25}$ y (90% CI - data) NEW

✓ $m_{\beta\beta} < 70 - 240$ meV*

Phys. Rev. Lett. 124, 122501 (2020)
Nature 604, 53 (2022)
Neutrino-24 (2024), arXiv:2404.04453 (2024)

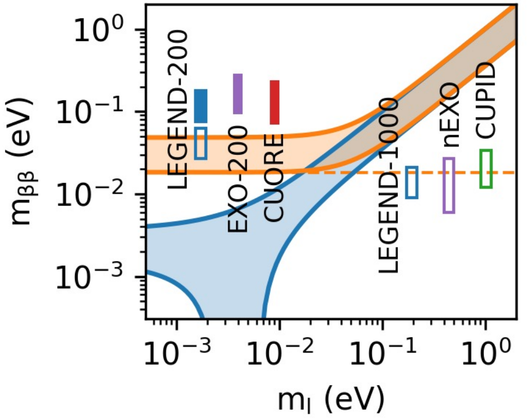
988 detectors at mK temperature





*Exposure: 567 kg · y ^{130}Te, NME = 1.4 - 6.4

Cryogenic calorimeter



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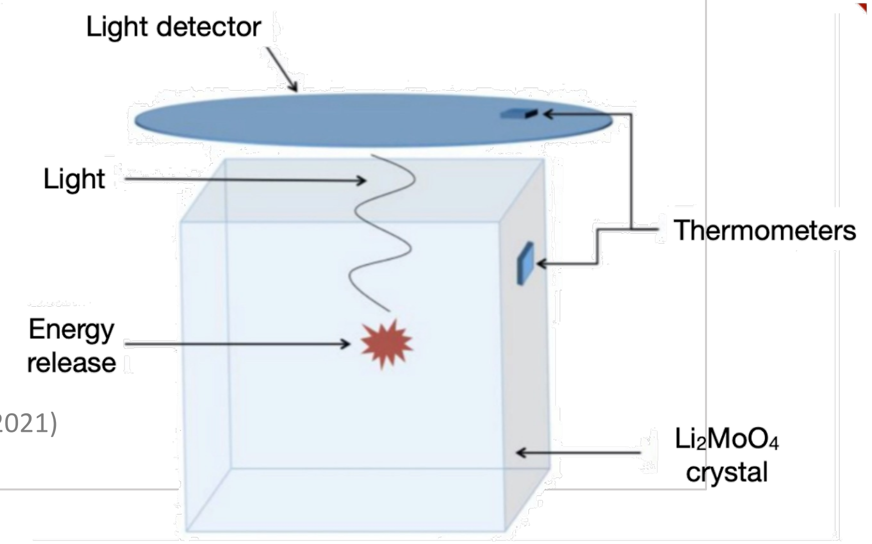
Phys. Rev. Lett. 124, 122501 (2020)
Nature 604, 53 (2022)
Neutrino-24 (2024), arXiv:2404.04453 (2024)

CUPID

- **Upgrades:** heat and light readout (bg÷100)
  ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV)
- **Goal:** cover IO
- **Status:** construction started

A. Campani, parallel

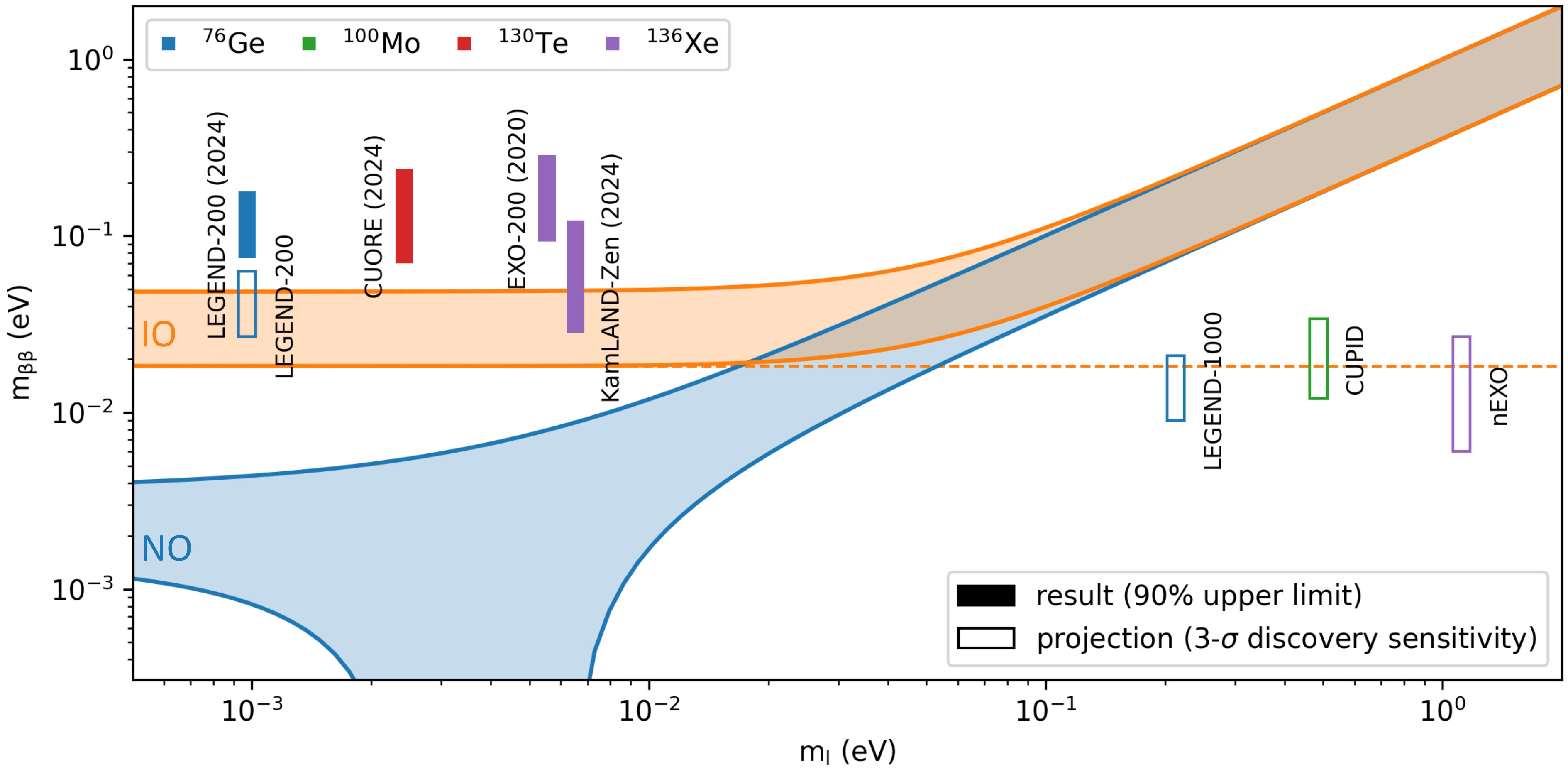
V. Berest, parallel



Phys. Rev. Lett. 126, 181802 (2021)
arXiv:1907.09376 (2019)

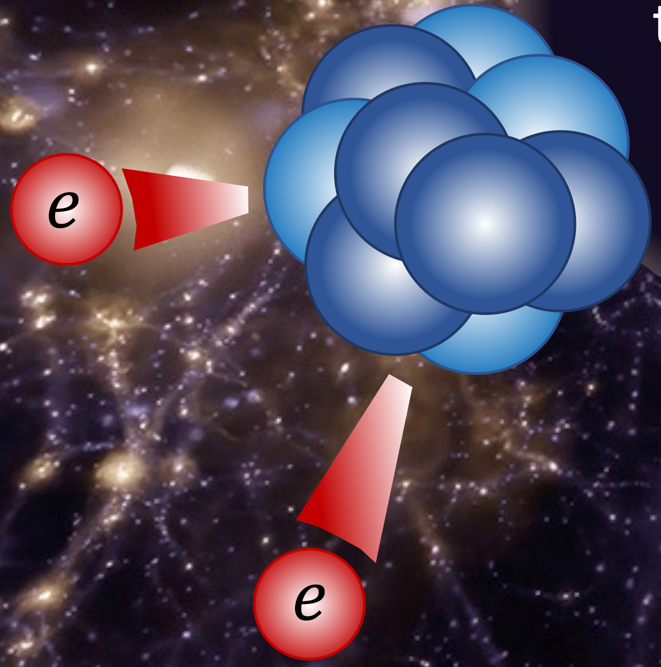
*Exposure: 567 kg · y ^{130}Te, NME = 1.4 - 6.4

Overview 0νββ

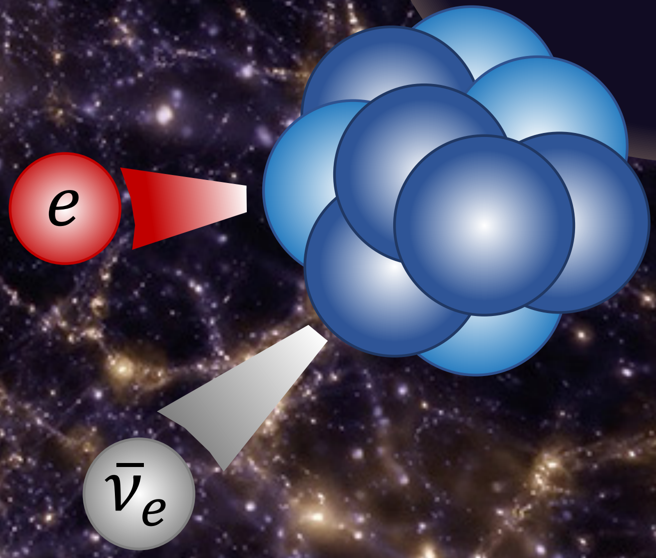


Neutrinos – open questions

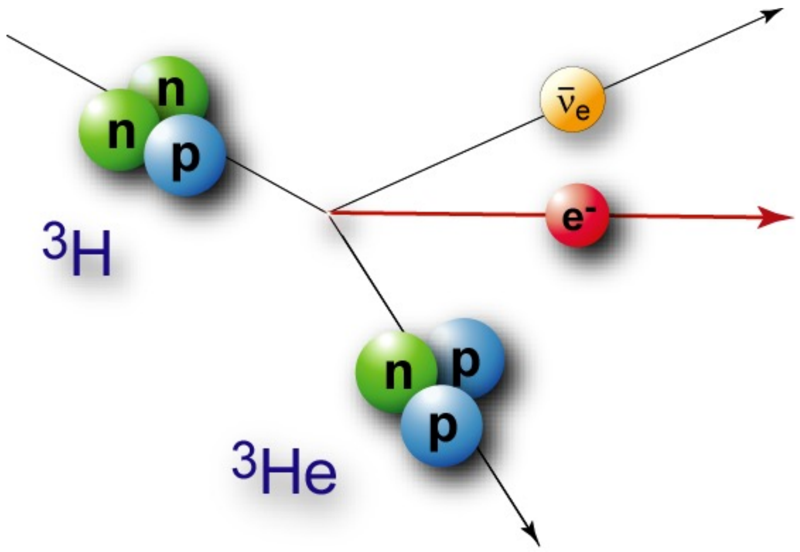
Are neutrinos their own anti-particle ?



What is the mass of neutrinos ?

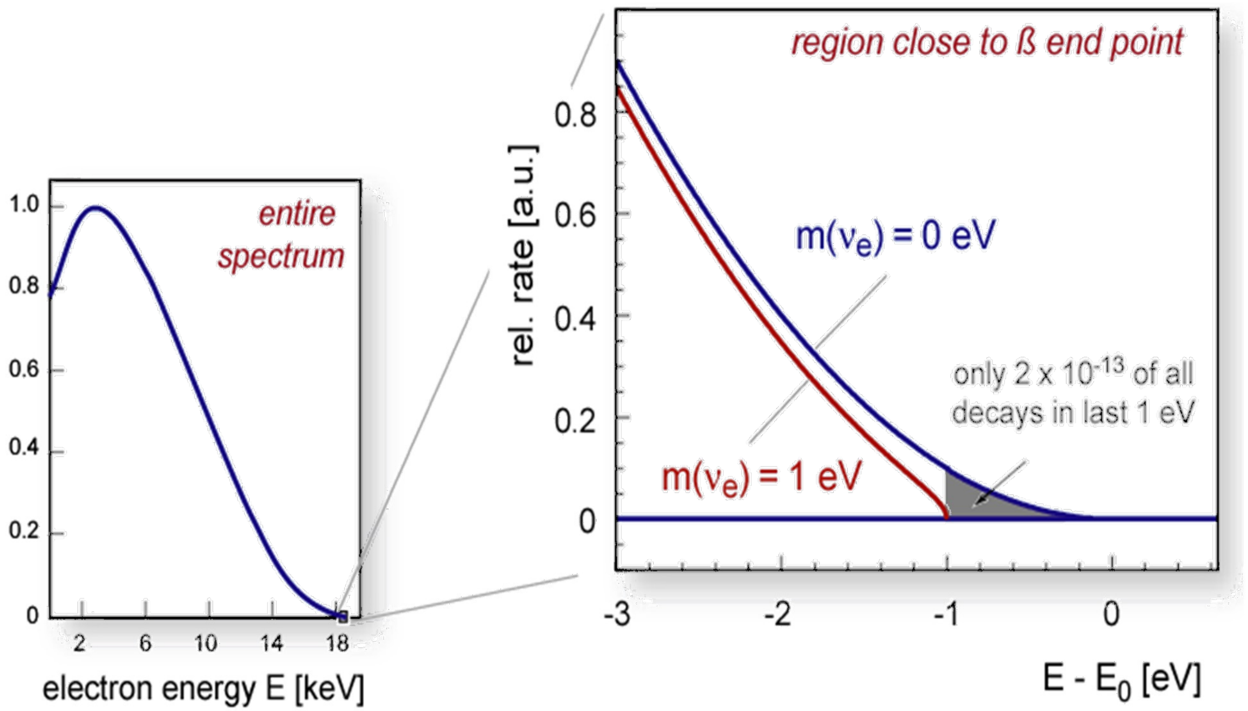


The signature



- ✓ Incoherent sum of neutrino masses
- ✓ Independent of neutrino nature (Dirac or Majorana)

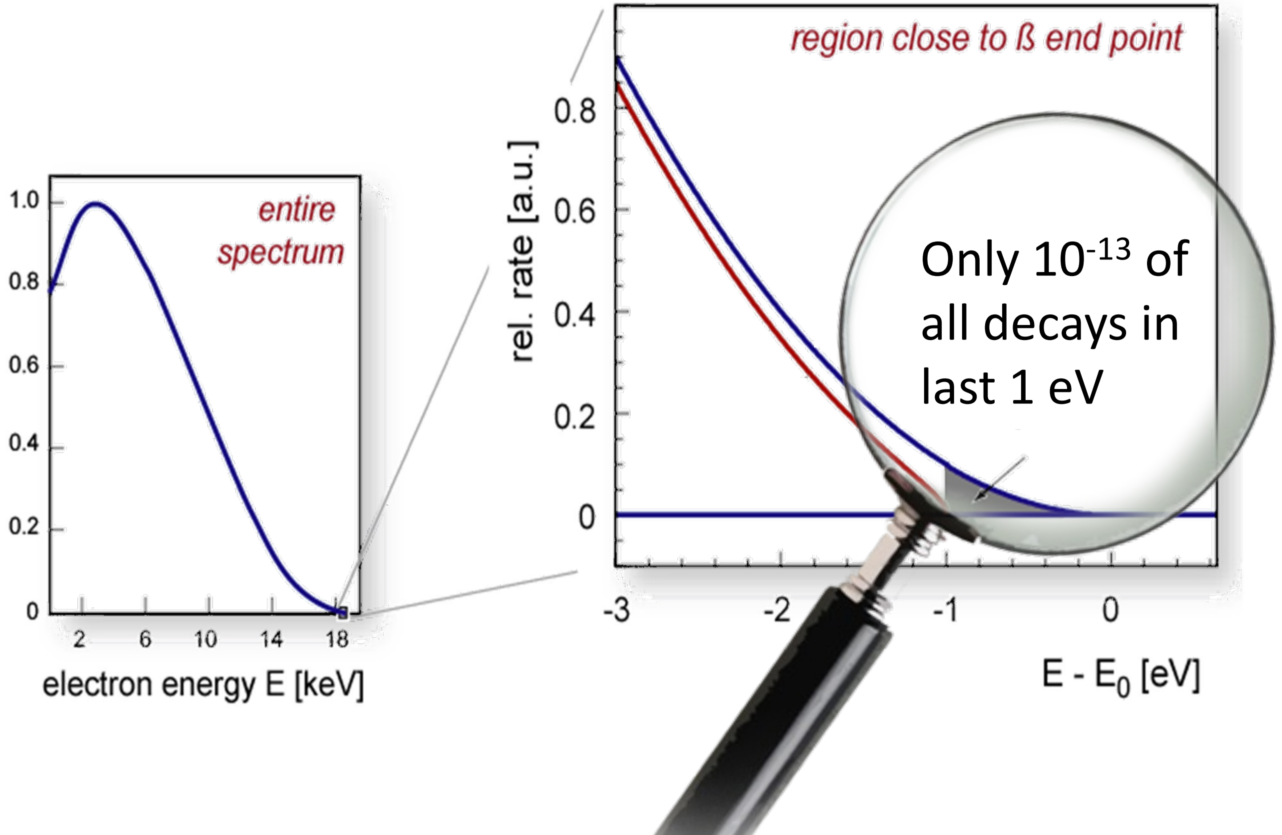
$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



The challenge

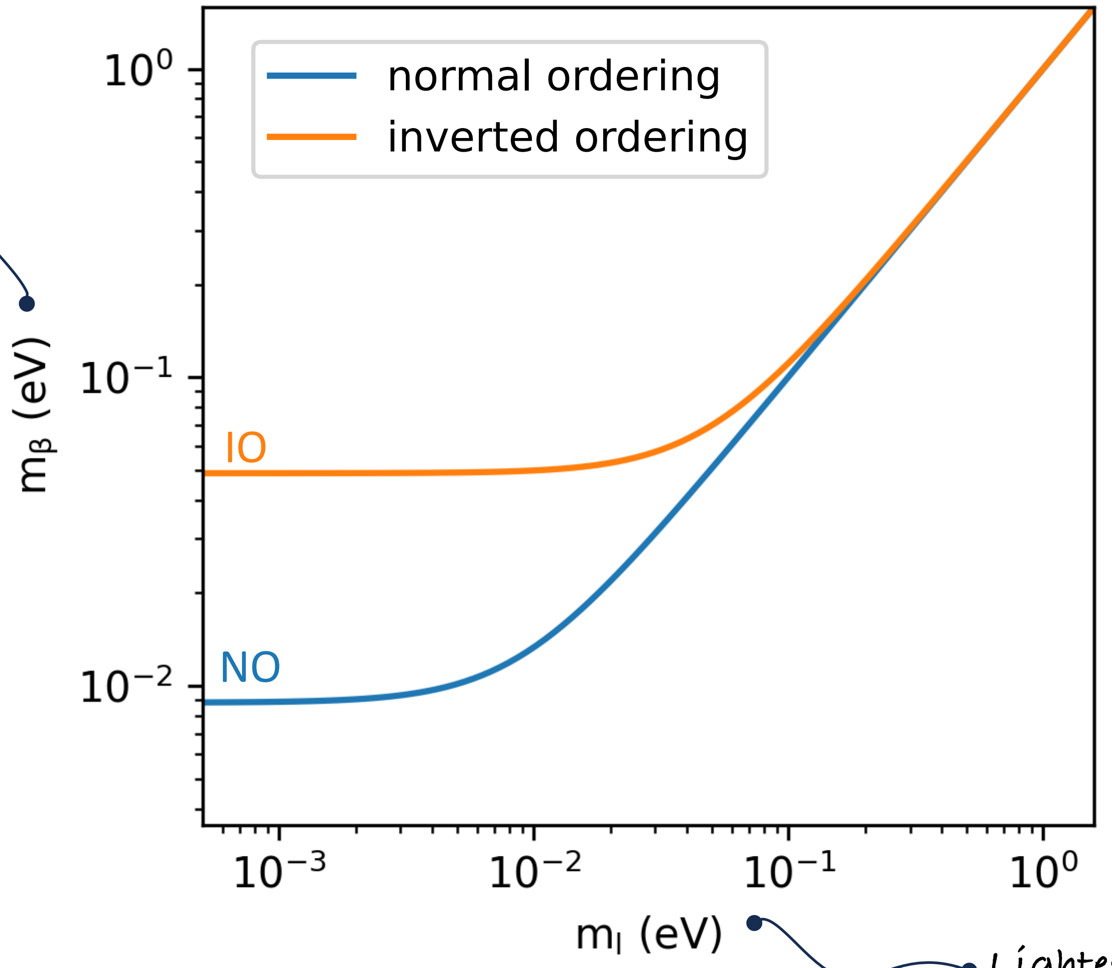
Key requirements:

- Strong radioactive source
    - Tritium (12.3 years, E_0 = 18.6 keV)
    - Holmium (4500 years, E_0 = 2.8 keV)
- Excellent energy resolution (~ 1 eV)
- Low background (< 100 mcps)
- Understanding of spectral shape



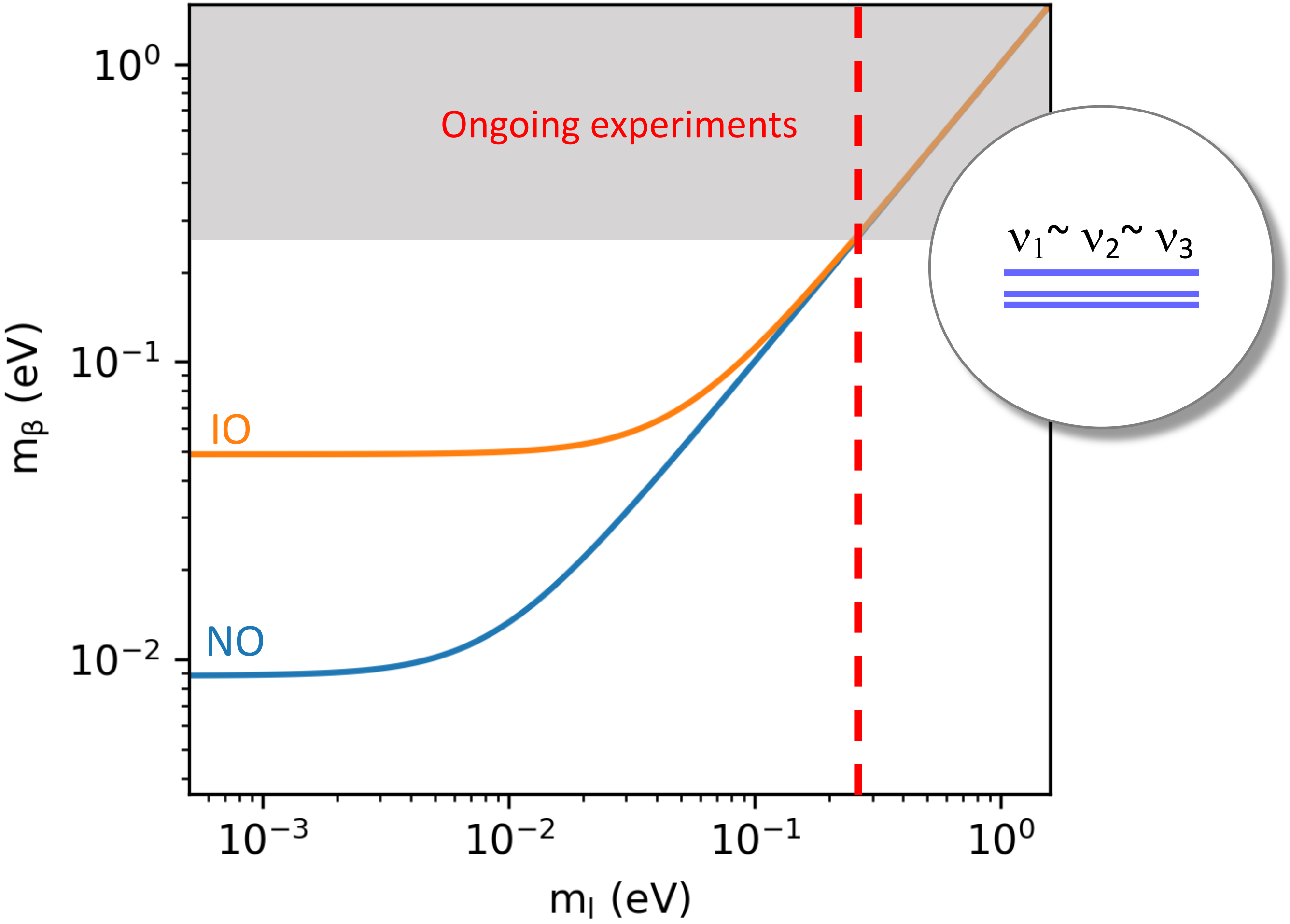
Where do we stand?

Incoherent sum of
mass eigenstates



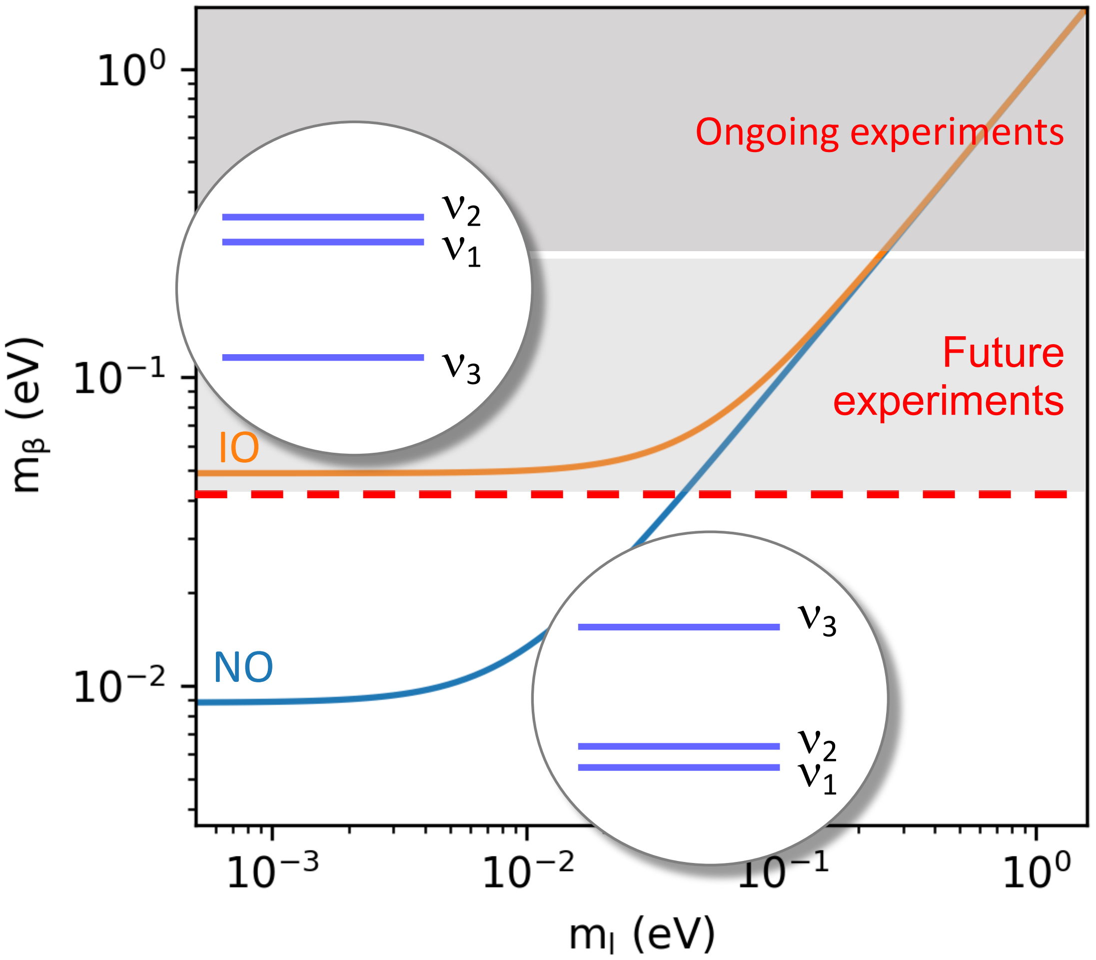
Lightest mass eigenstate

Where do we stand?



- KATRIN final: < **0.3 eV** (90% CL) Distinguish between **degenerate** and **hierarchical** scenario

Where do we stand?



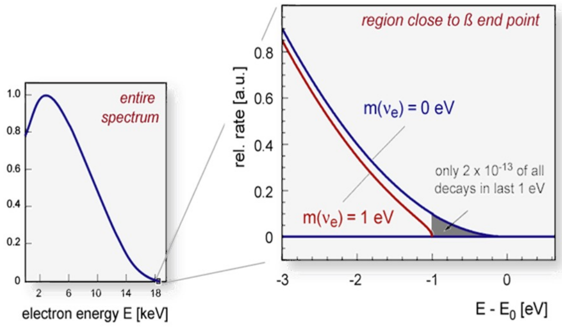
- KATRIN final: < **0.3 eV** (90% CL)
  Distinguish between **degenerate** and **hierarchical** scenario

- Future experiments: < **0.05 eV**
  Cover **inverted** ordering

Experimental efforts

Electrostatic filter (MAC-E)

counting above threshold



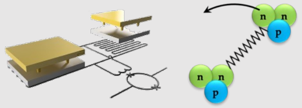
Cyclotron Radiation

Heat

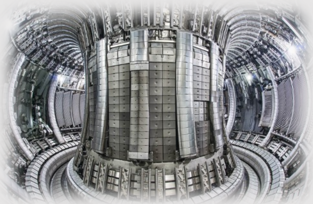
Experimental efforts

KATRIN
(Tritium)

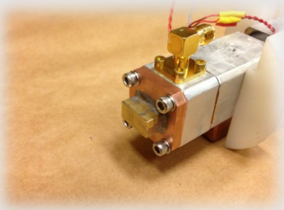
KATRIN++
(Tritium)



QTNM
(Tritium)



Project-8
(Tritium)



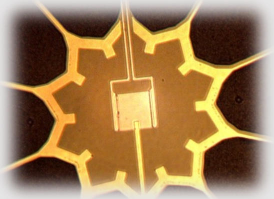
Electrostatic filter (MAC-E)

Cyclotron Radiation

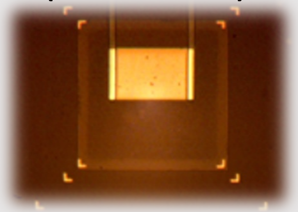
Phonons

Ptolemy
(Tritium)

Holmes
(Holmium)

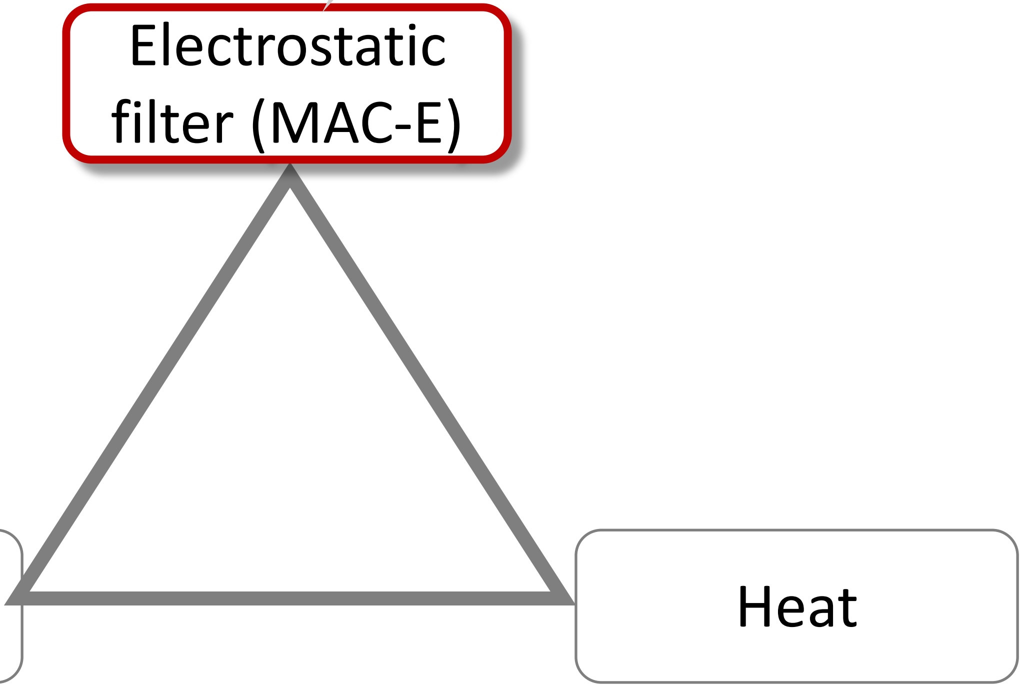


ECHo
(Holmium)



Experimental efforts

Karlsruhe Tritium Neutrino Experiment



J. Storek, poster

C. Köhler, poster

M. Böttcher, poster

J. Lauer, poster

C. Wiesinger, parallel

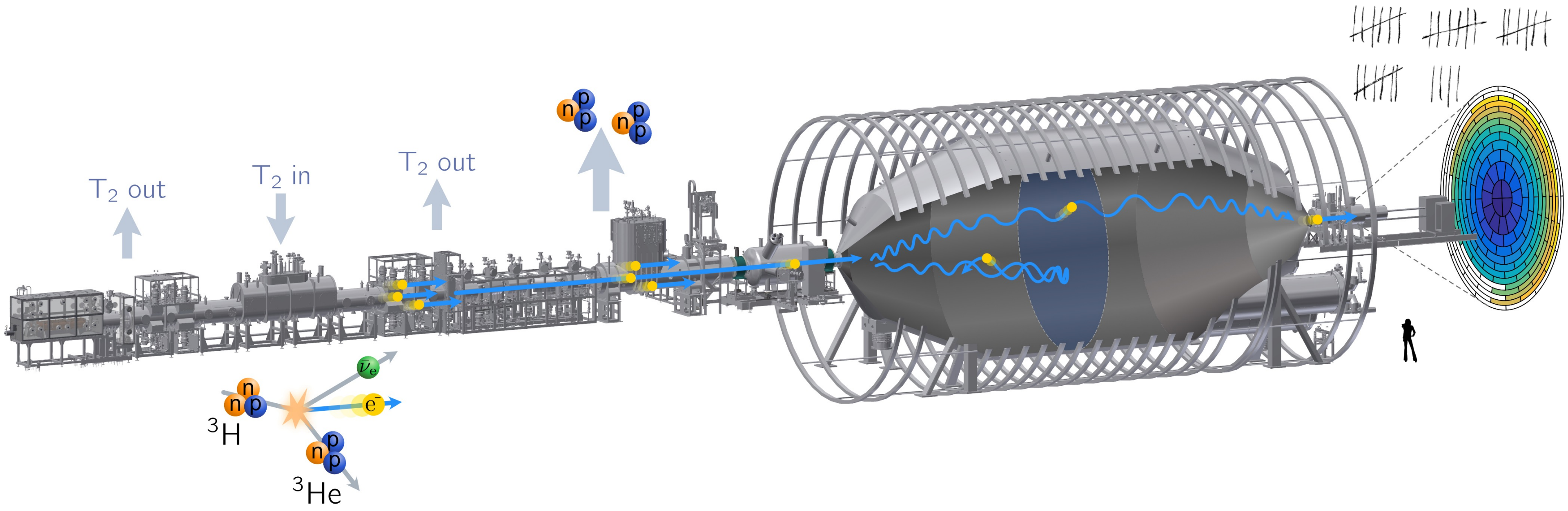
C. Fengler, parallel

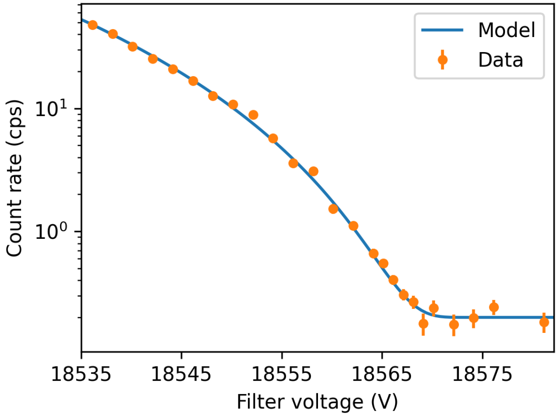
Working Principle

High-activity tritium source
- 30 μg of gaseous T_2
- 10^{11} T_2 decays/s

High-resolution spectrometer
- Electrostatic filter (MAC-E)
- Transmits e's above threshold

Integral spectrum
- Rate versus filter voltage
- Fit theoretical spectrum





New KATRIN result NEW

Data set:

- 250 days of data (5 campaigns)

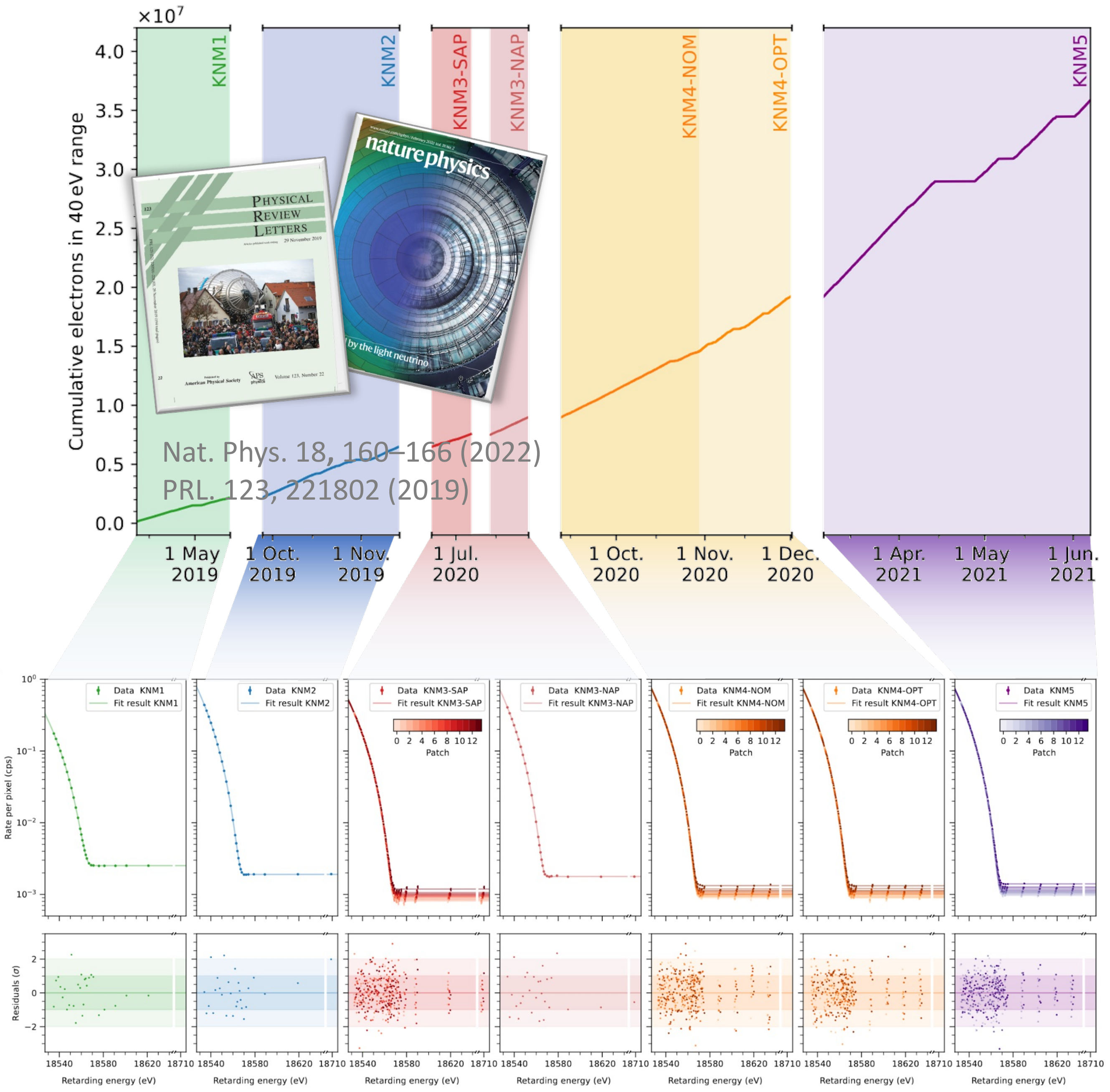
C. Wiesinger, parallel

Result:

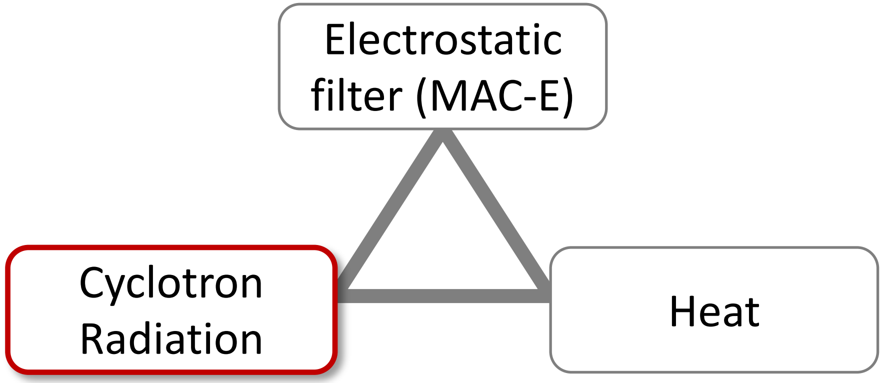
- Best fit:
  $m_\nu^2 = (-0.14^{+0.13}_{-0.15})\,\mathrm{eV}^2$ **(stat. dom.)**
- New limit:
  $m_\nu < 0.45$ **eV (90% CL)**
  Neutrino-24 (2024), arXiv:2406.13516 (2024)

Final goal (in 2026):

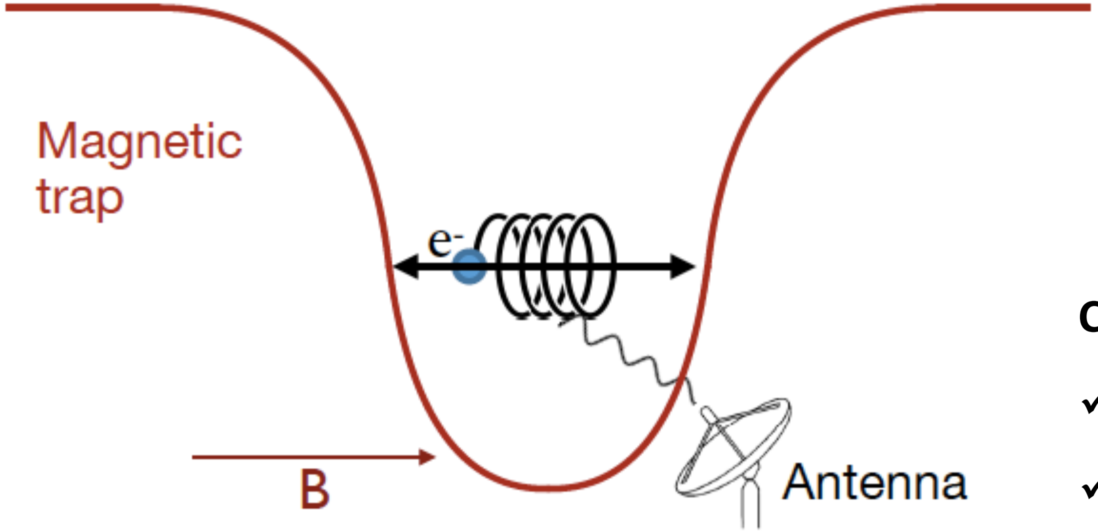
- < 0.3 eV sensitivity



Experimental efforts



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



Cyclotron Radiation Emission Spectroscopy (CRES)

✓(sub)-eV-scale differential measurement

✓no electron beamline

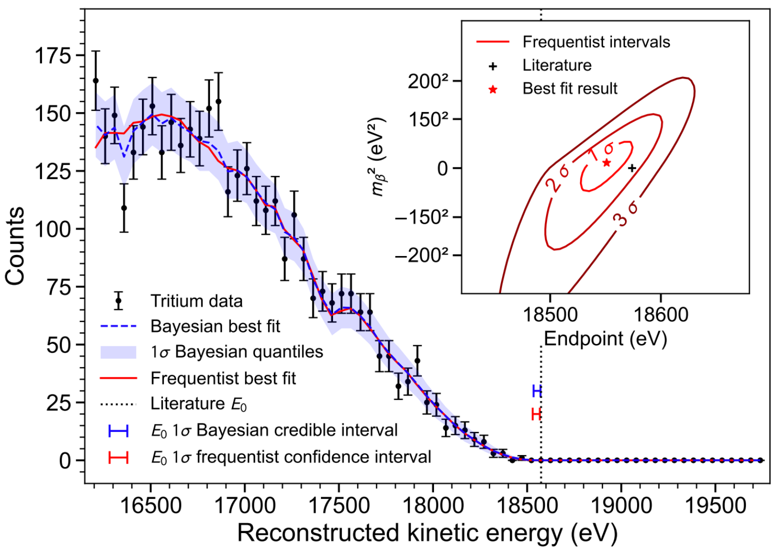
Project 8

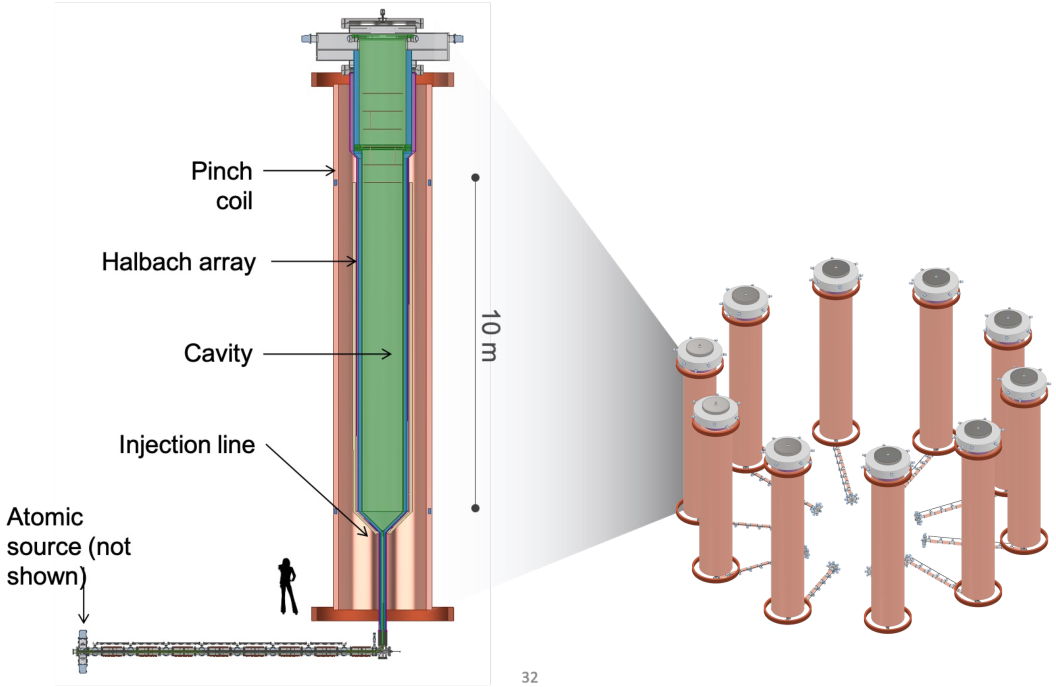
- **Achievements:**
  - ✓ Proof of CRES concept
    D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)
  - ✓ First neutrino mass limit: $m_\beta < 152$ eV (90% CL)
    PRL 131 (2023) 10, 102502

- **Next steps / challenges:**
  - large-volume (m^3) cavity resonator
  - develop atomic tritium source

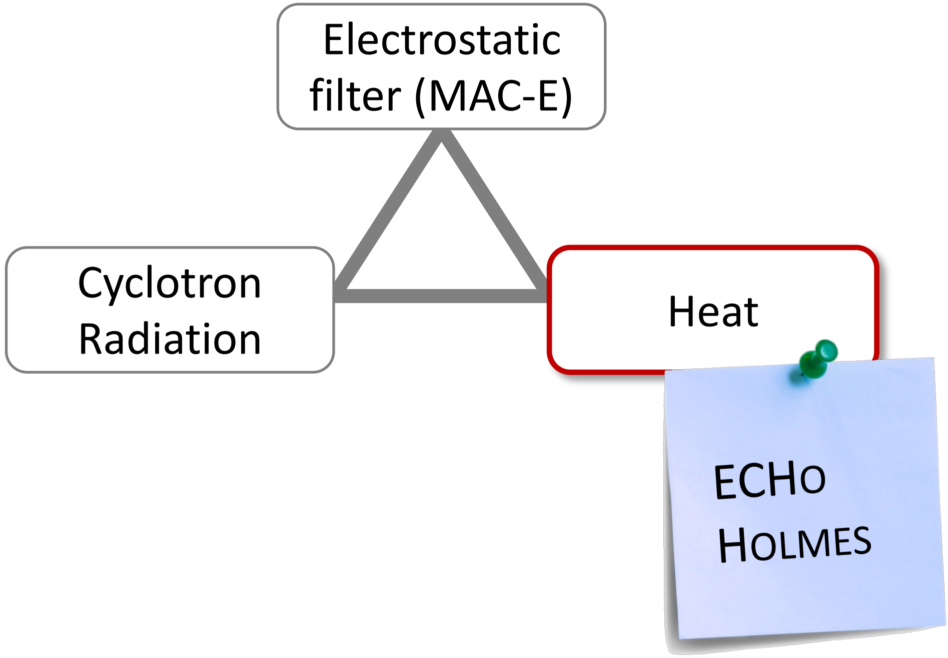
- **Ultimate goal:**
  - Cover inverted ordering: 40 meV sensitivity
    arXiv:2203.07349 (2022)

waveguide





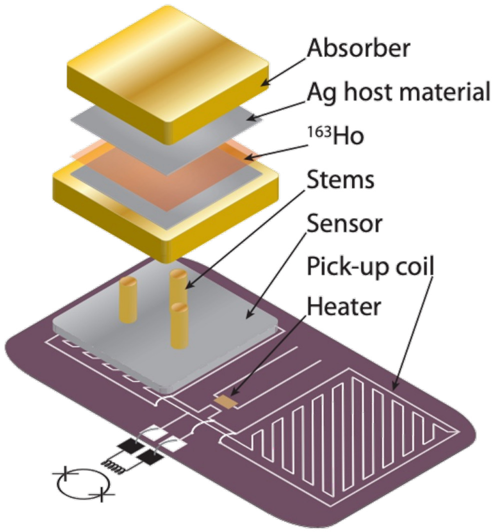
Experimental efforts



Low-temperature micro-calorimetry with holmium

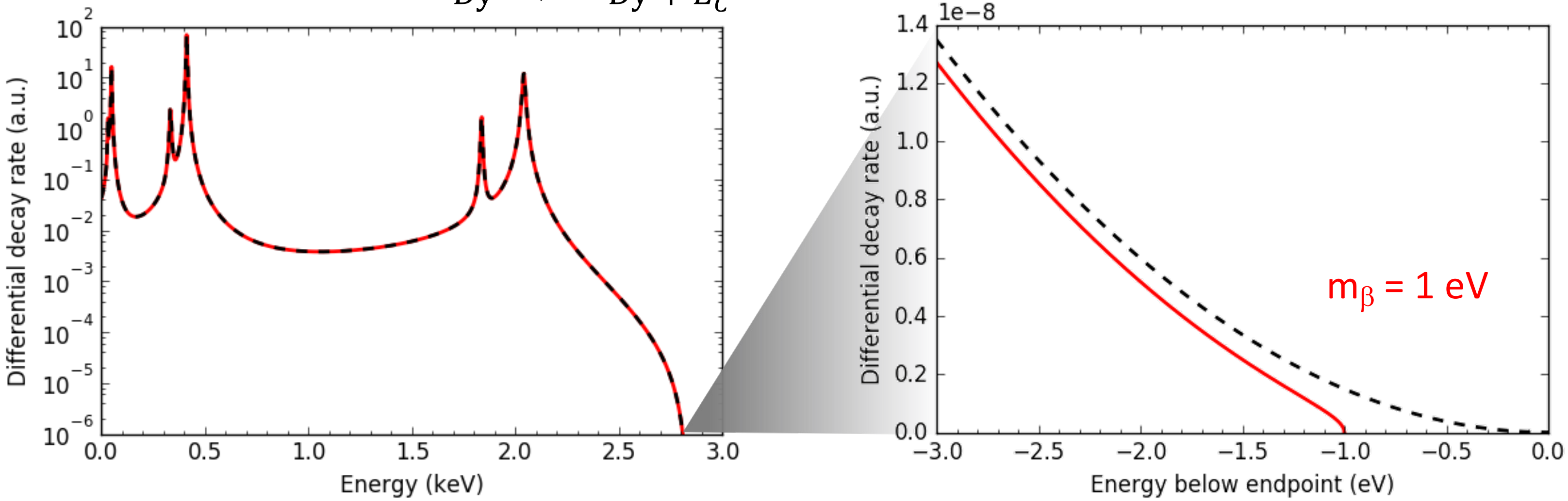
✓ eV-scale energy measurement

✓ holmium source embedded in detector



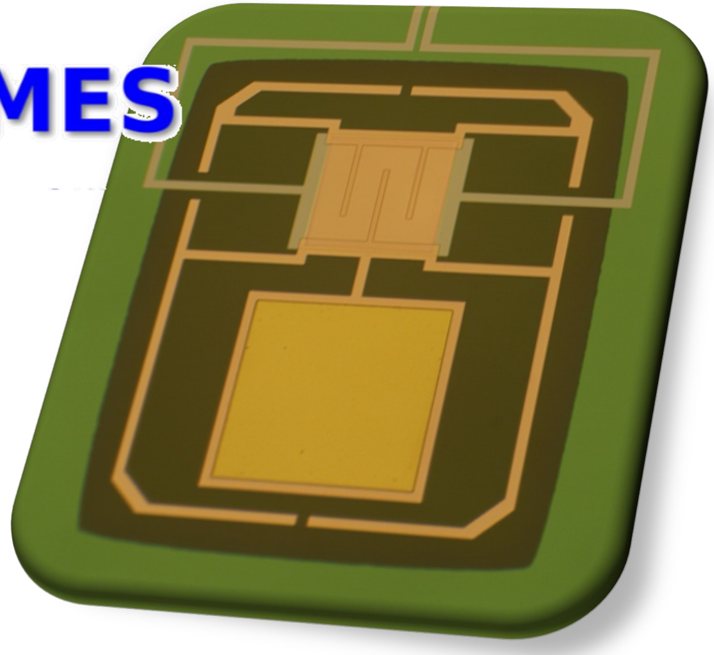
$$^{163}\mathrm{Ho} + \mathrm{e} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_e$$

$$^{163}\mathrm{Dy}^{*} \rightarrow {}^{163}\mathrm{Dy} + E_C$$

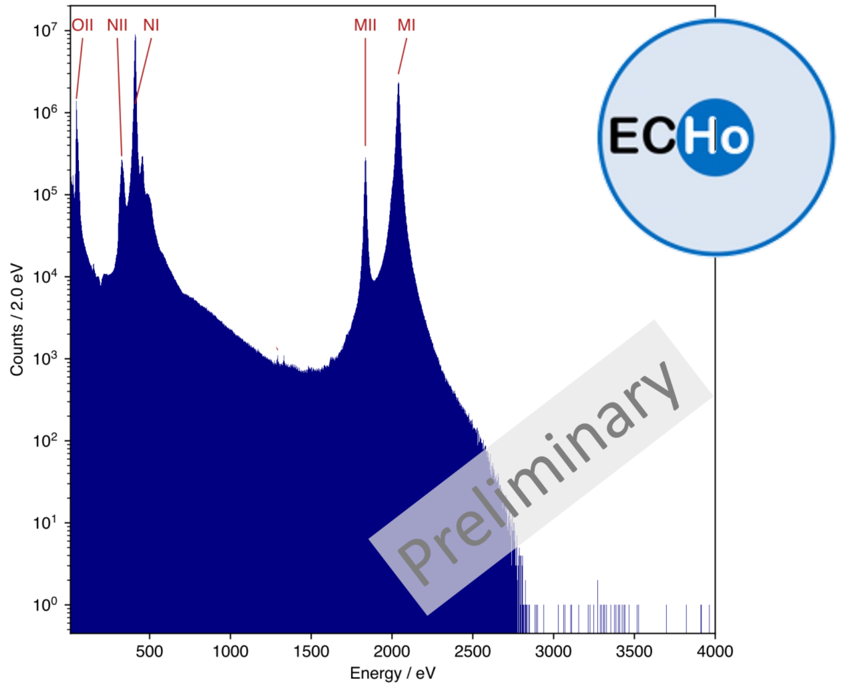


A. De Rujula and M. Lusignoli, *Phys. Lett.* 118B (1982)

ECHo & Holmes



- **Proof of concept:** NEW
  - **ECHo**: m_β < 19 eV @ 90% CI *(prelim)*
    34 pixels and 0.7 Bq/pixel, 10^9 events
  - **Holmes**: m_β < 28 eV @ 90% CI
    48 pixels with 0.3 Bq/pixel, 10^8 events
- **Next steps / challenges**
  - More activity, more pixels…
  - 10^5 - 10^6 pixels for sub-eV sensitivity
- **Ultimate goal:**
  - sub-eV sensitivity



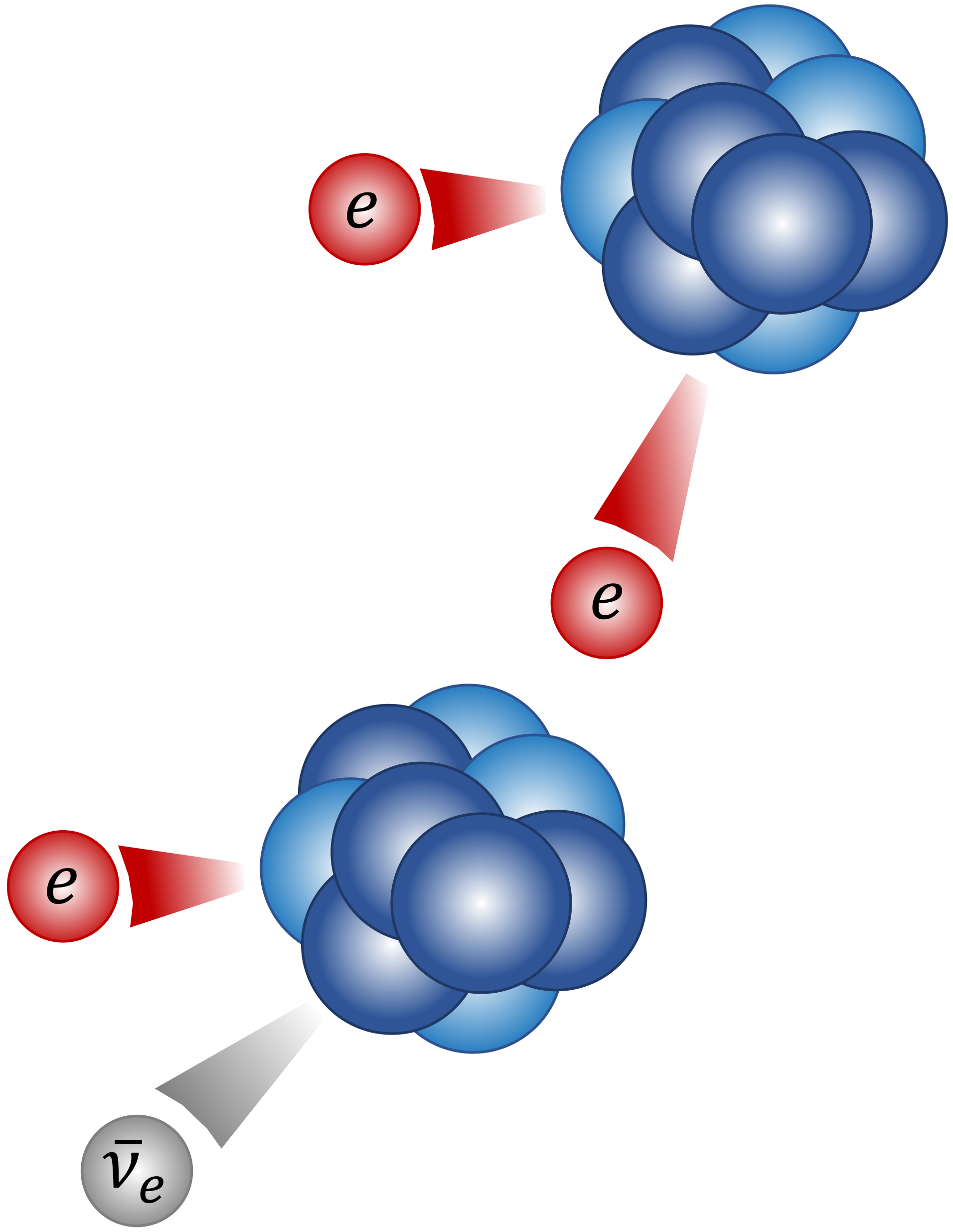
Neutrino-24 (2024)
L. Gastaldo et al. Eur. Phys. J. Spec. Top. 226 (2017)
J Low Temp Phys 184, 492–497 (2016)

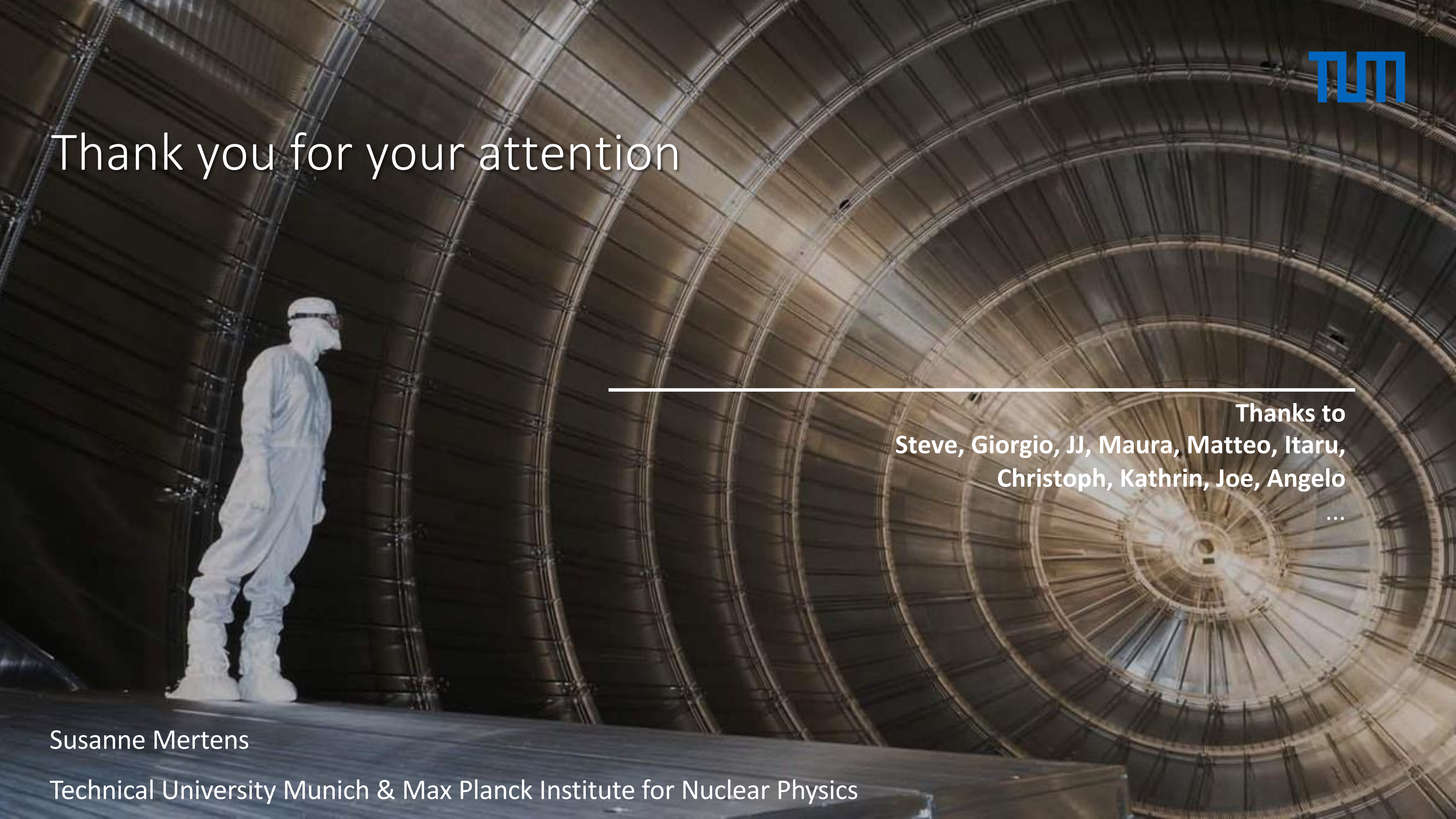
Summary

- $0\nu\beta\beta$ and single β decay are **unique** and **complementary** probes of neutrino mass and nature

- **Many new results**, a.o.:
  - First data release of LEGEND-200
  - KamLAND-Zen starts probing the IO band
  - New limit of $m_\beta < 0.45$ eV from KATRIN

- **High discovery potential** of future $0\nu\beta\beta$ experiments and **exciting technology advancements** for a direct neutrino mass measurement





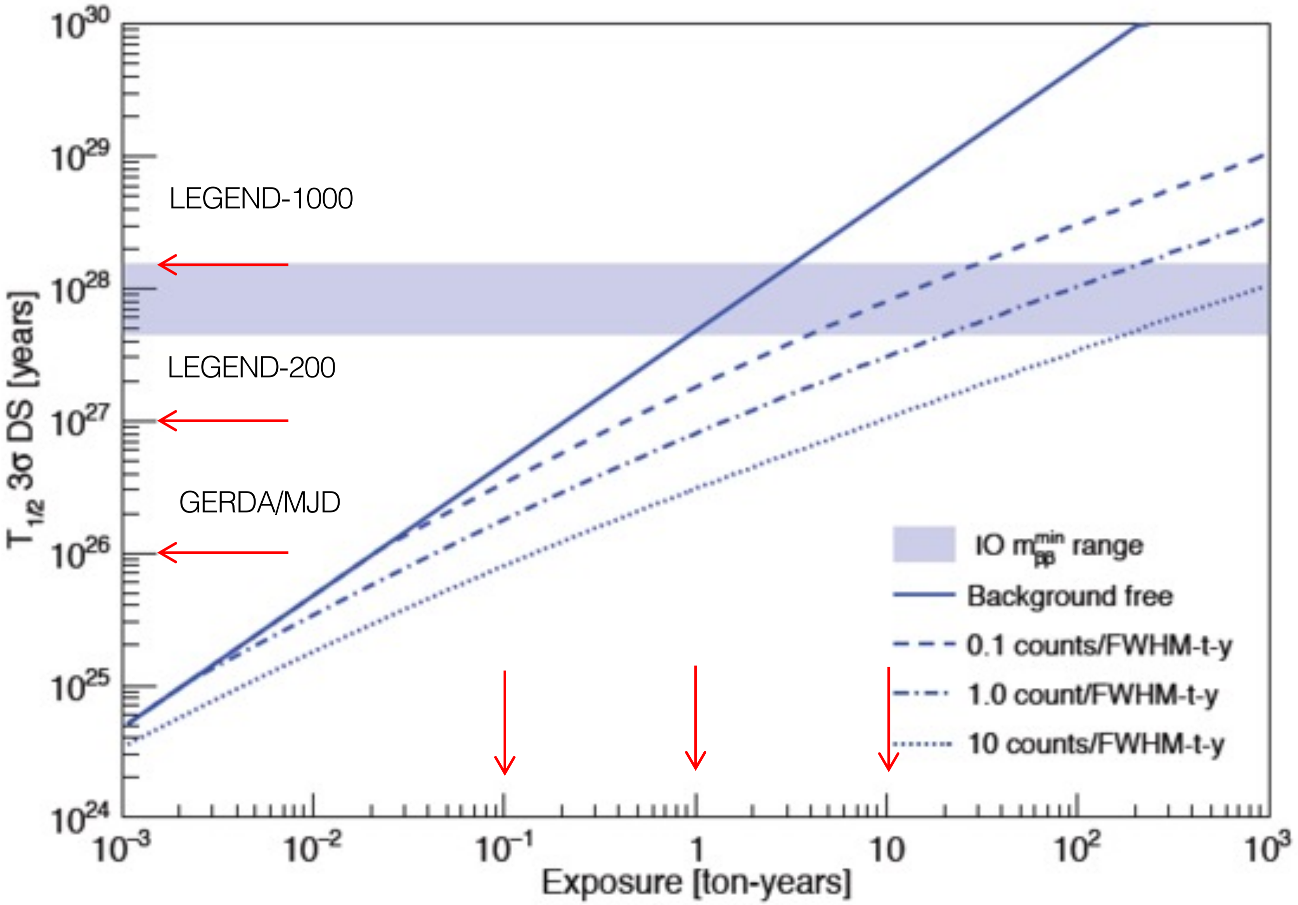
Thank you for your attention

Thanks to
Steve, Giorgio, JJ, Maura, Matteo, Itaru,
Christoph, Kathrin, Joe, Angelo
...

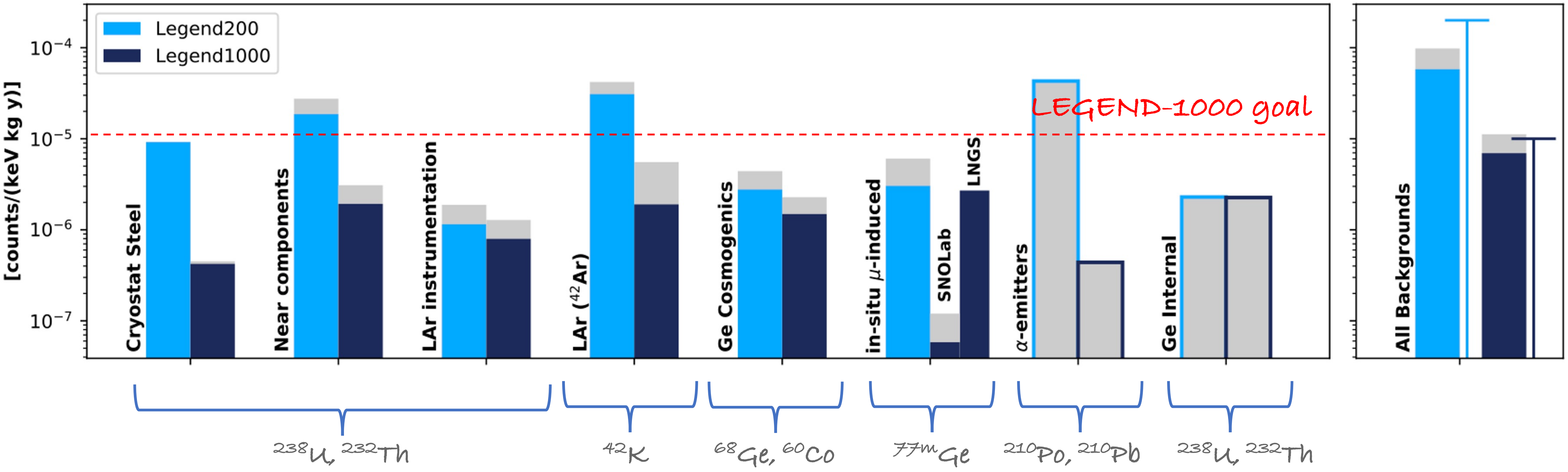
Susanne Mertens

Technical University Munich & Max Planck Institute for Nuclear Physics

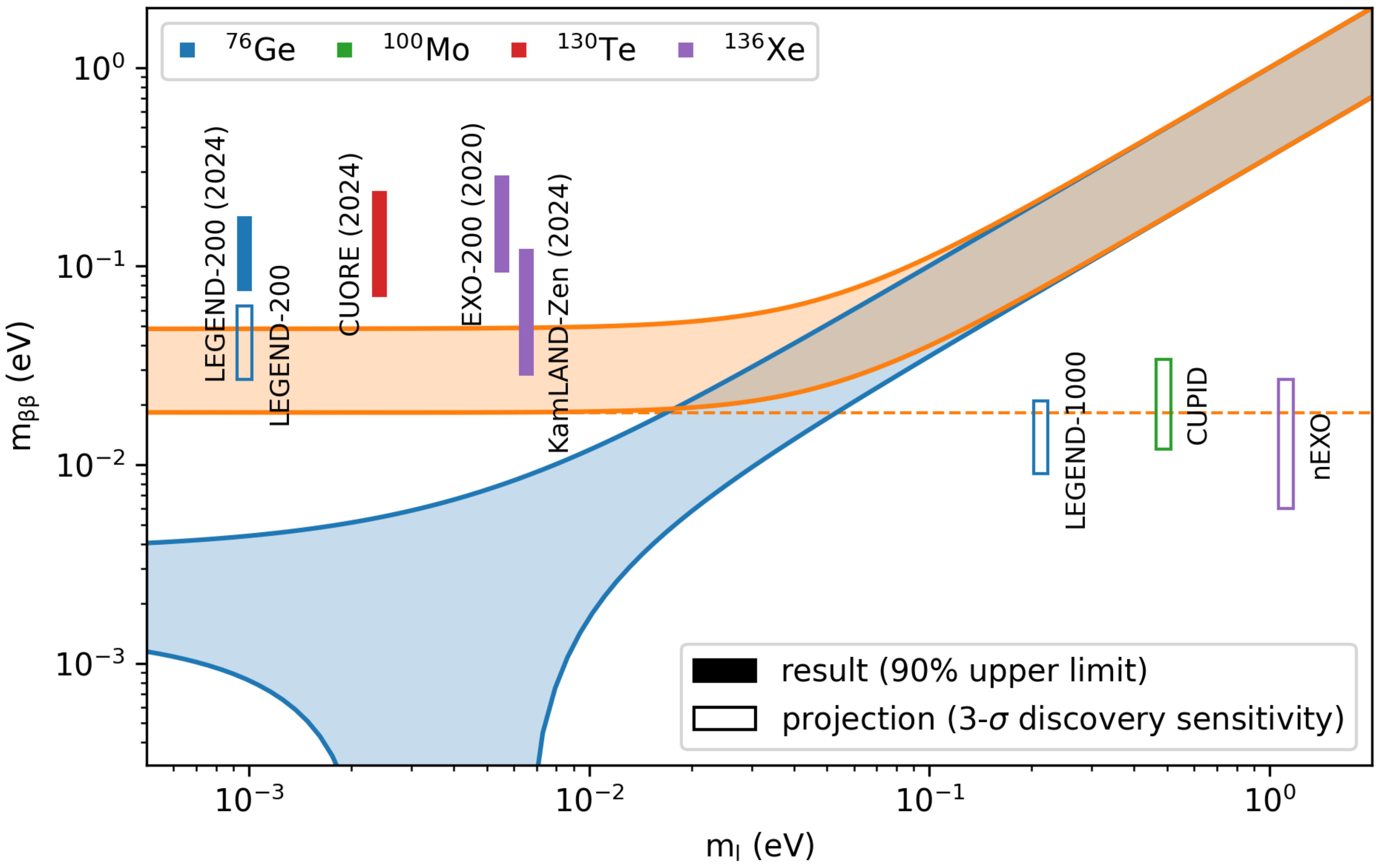
Importance of low background



LEGEND Background



➢ Legend-1000 is expected to meet the background goal ☺

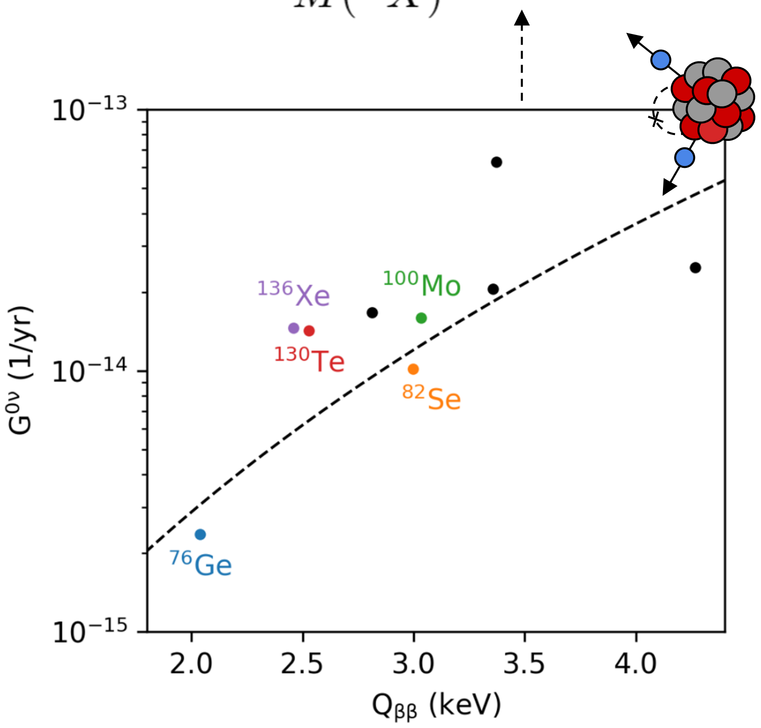


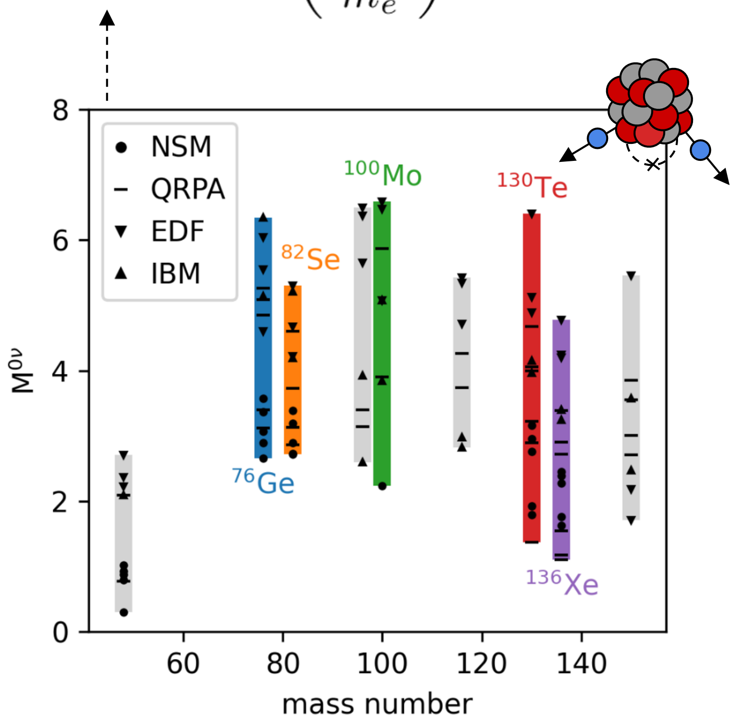
^{76}Ge
^{100}Mo
^{130}Te
^{136}Xe
LEGEND-200 (2024)
LEGEND-200
CUORE (2024)
EXO-200 (2020)
KamLAND-Zen (2024)
LEGEND-1000
CUPID
nEXO
result (90% upper limit)
projection (3-σ discovery sensitivity)
$m_{\beta\beta}$ (eV)
m_l (eV)
10^0
10^{-1}
10^{-2}
10^{-3}

Decay rate

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

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





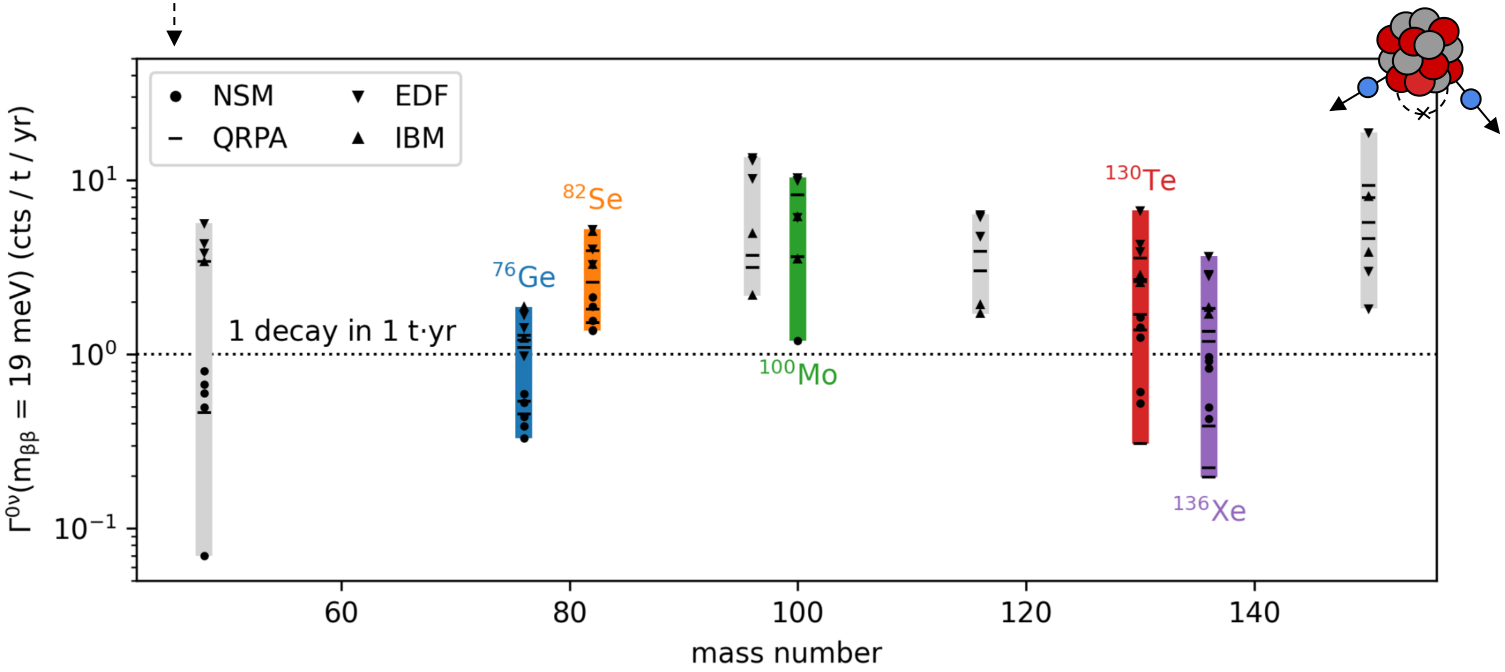
- accurate **phase space factor,** large Q-value favorable
  [Kotila, Iachello, PRC 85 (2012) 034316]

- 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**

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



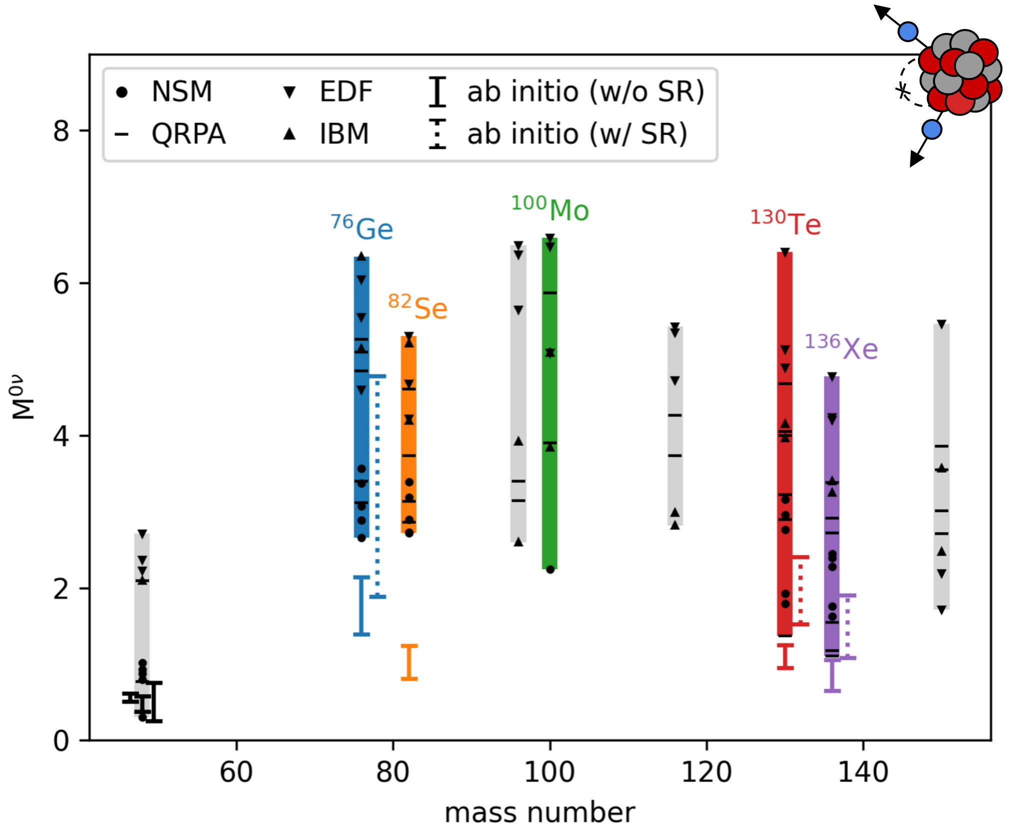
- probing **inverted ordering scenario** requires **tone-year exposure**

- 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]



Liquid Scintillators

M. Eizuka, parallel

KamLAND-Zen

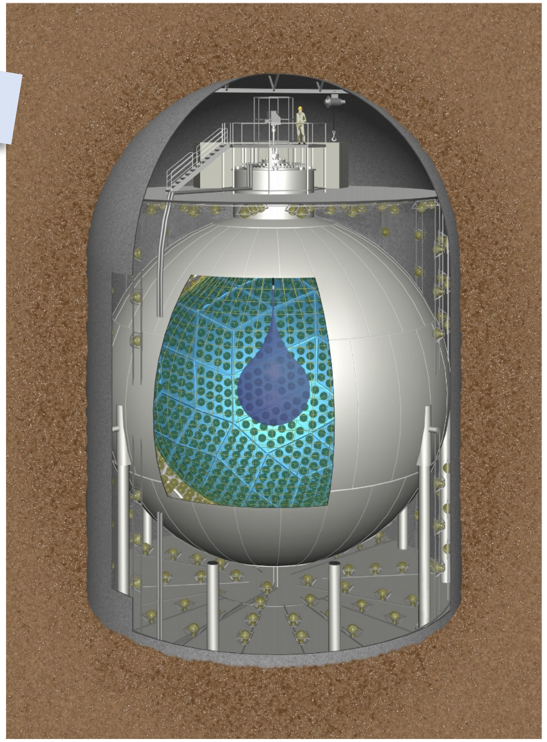
- **Location:** Kamioka (JP)
- **Method:** Xe-loaded liquid scintillator
- **Mass:** 745 kg of ^{136}Xe
- **Background:** 24 events in $2.35 < E < 2.70$ MeV
- **E-resolution:** 4.2 % @ $Q_{\beta\beta}$
- **Status:** completed

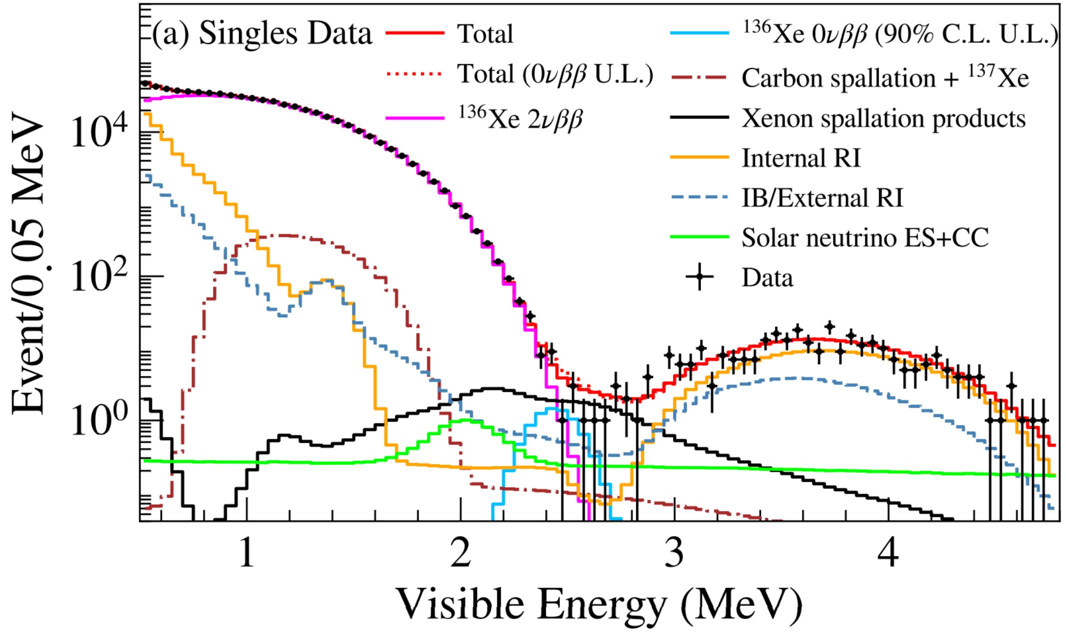
NEW

✓ $T_{1/2} > 3.8 \cdot 10^{26}$

✓ $m_{\beta\beta} < 28 - 122$ meV*

Abe et al., PRL 130 (2023) 5, 051801
Neutrino-24 (2024), arXiv:2406.11438 (2024)





*Exposure: 970 kg · y ^{137}Xe, NME = 1.1 - 4.8

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Abe et al., PRL 130 (2023) 5, 051801
Neutrino-24 (2024), arXiv:2406.11438 (2024)

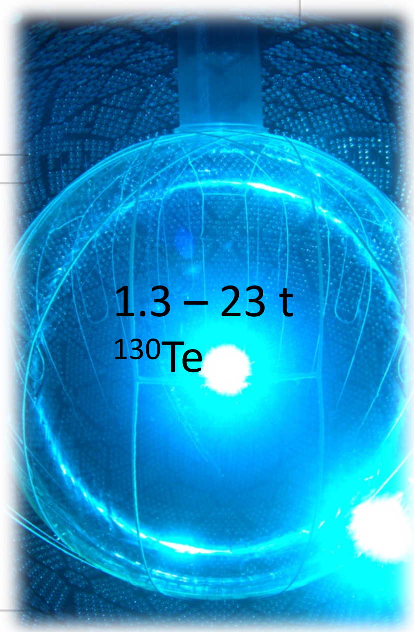
KamLAND2-Zen

- **Upgrades:** Lower background
- **Status:** Start in 2027
- **Goal:** reach/cover IO

SNO+

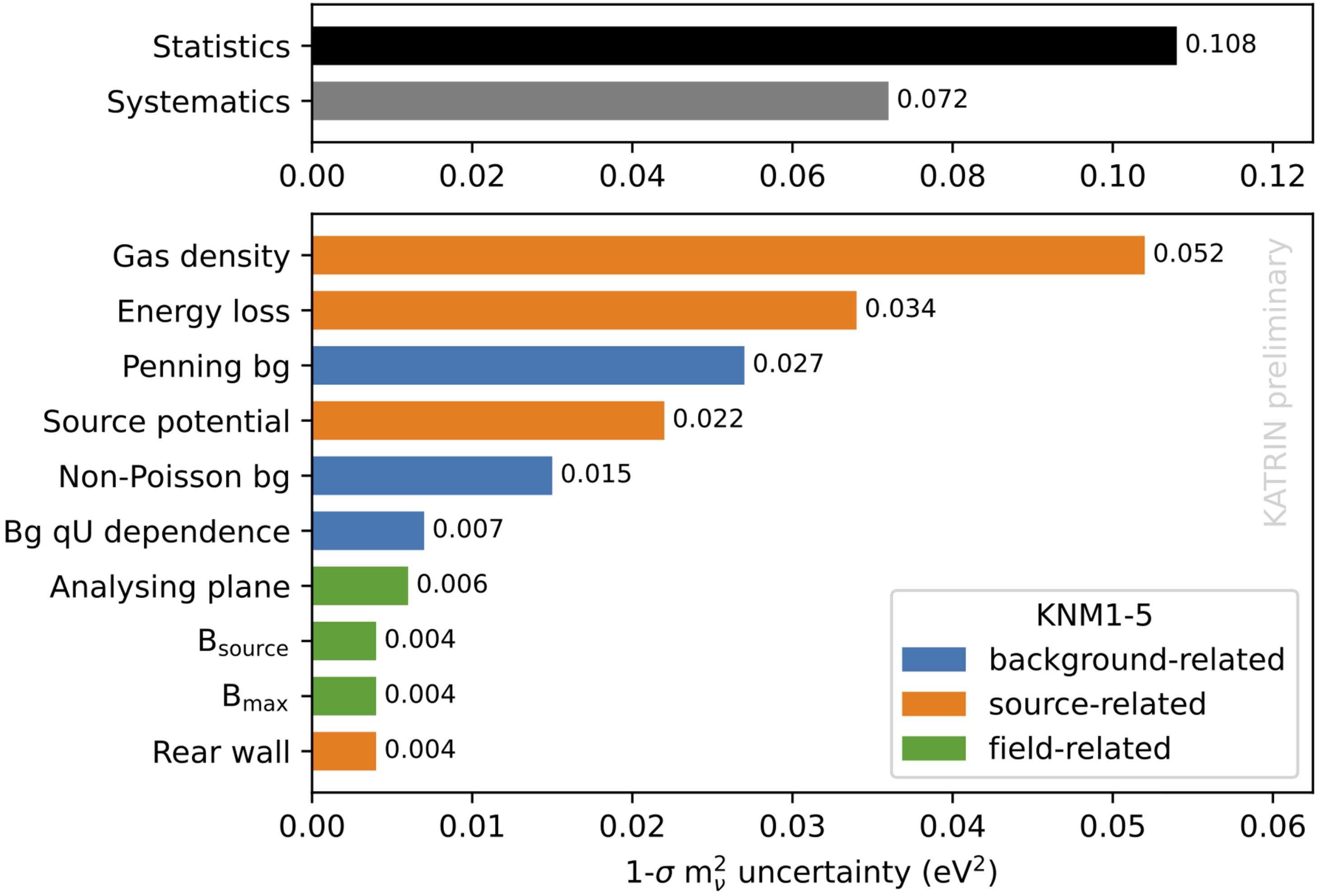
- Te-loaded (0.5 – 3 %) liq. Scin.
- **Status:** commissioning
- **Goal:** reach/cover IO

2021 JINST 16 P08059

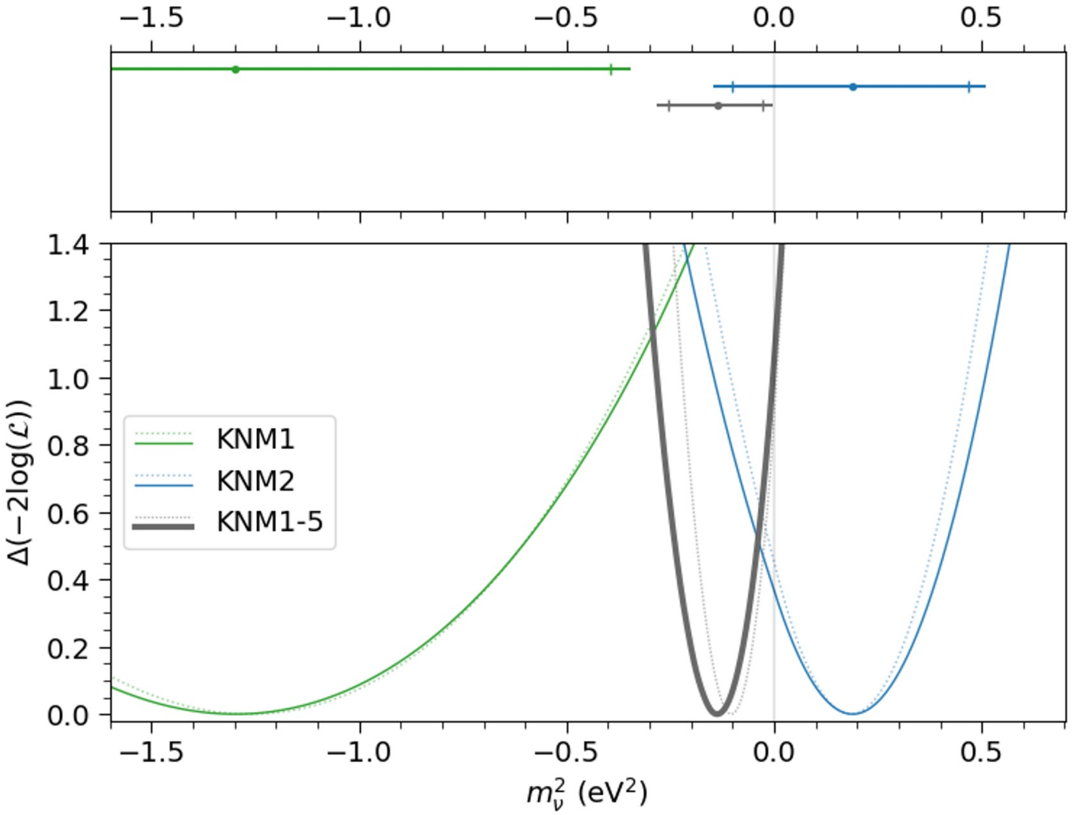


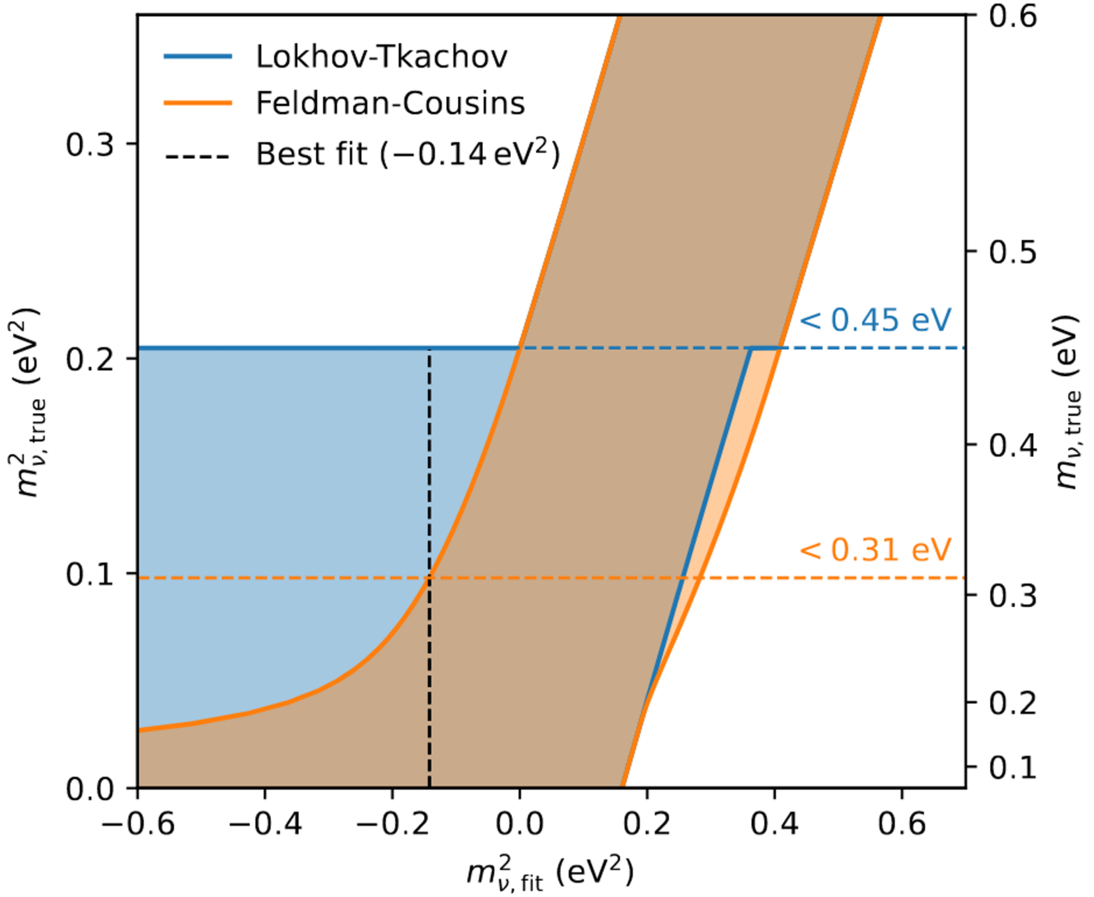
*Exposure: 970 kg · y ^{137}Xe, NME = 1.1 - 4.8

Systematic uncertainties



KATRIN result





KATRIN data taking continues

- 13 measurement campaigns completed on June 17
- **> 150 Mio** counts recorded – **x4** of this release!
- More data to come in **2024-2025** + calibration/systematics improvements