Neutrino properties: experimental overview

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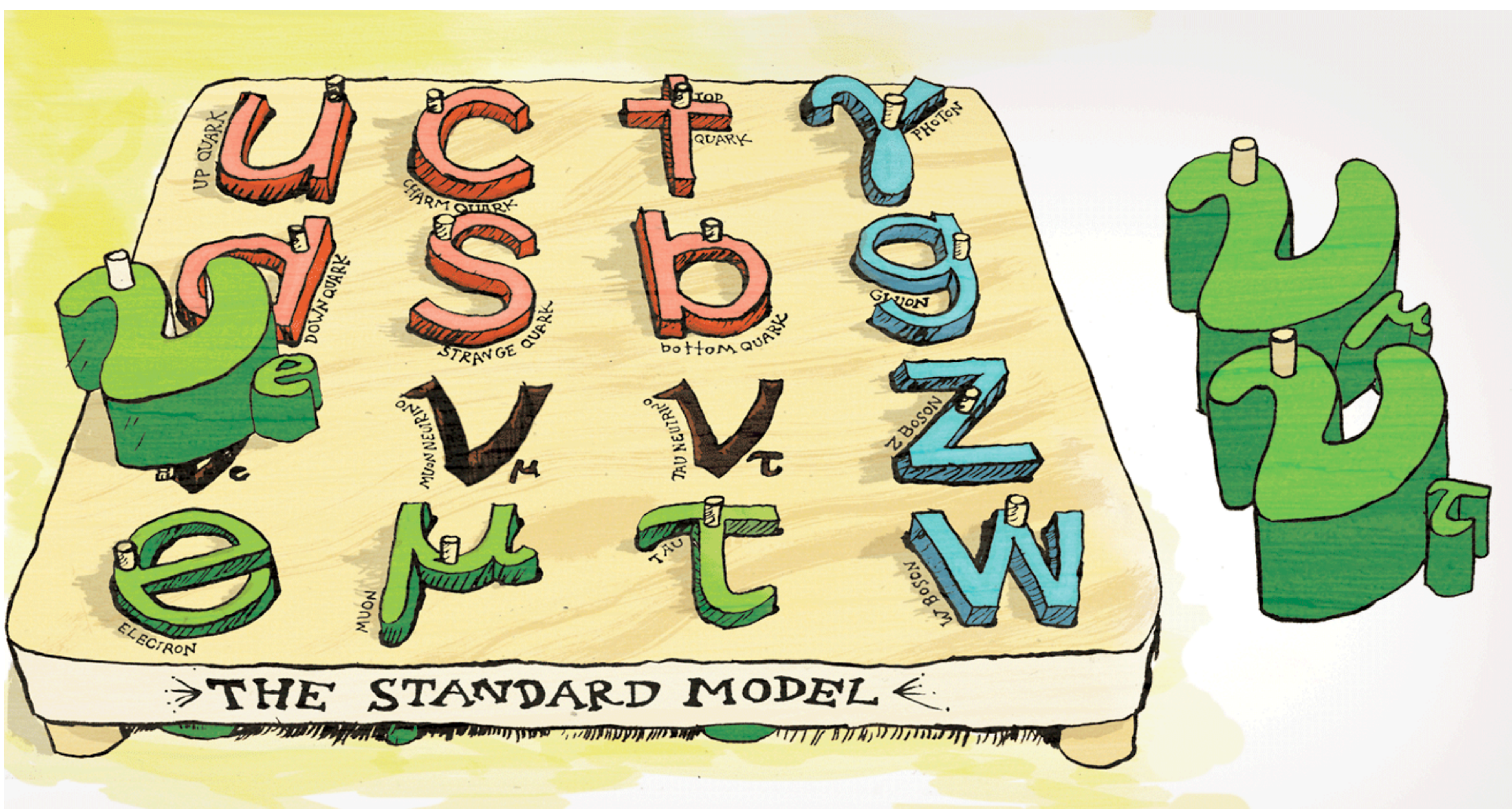
CSN, April 2025

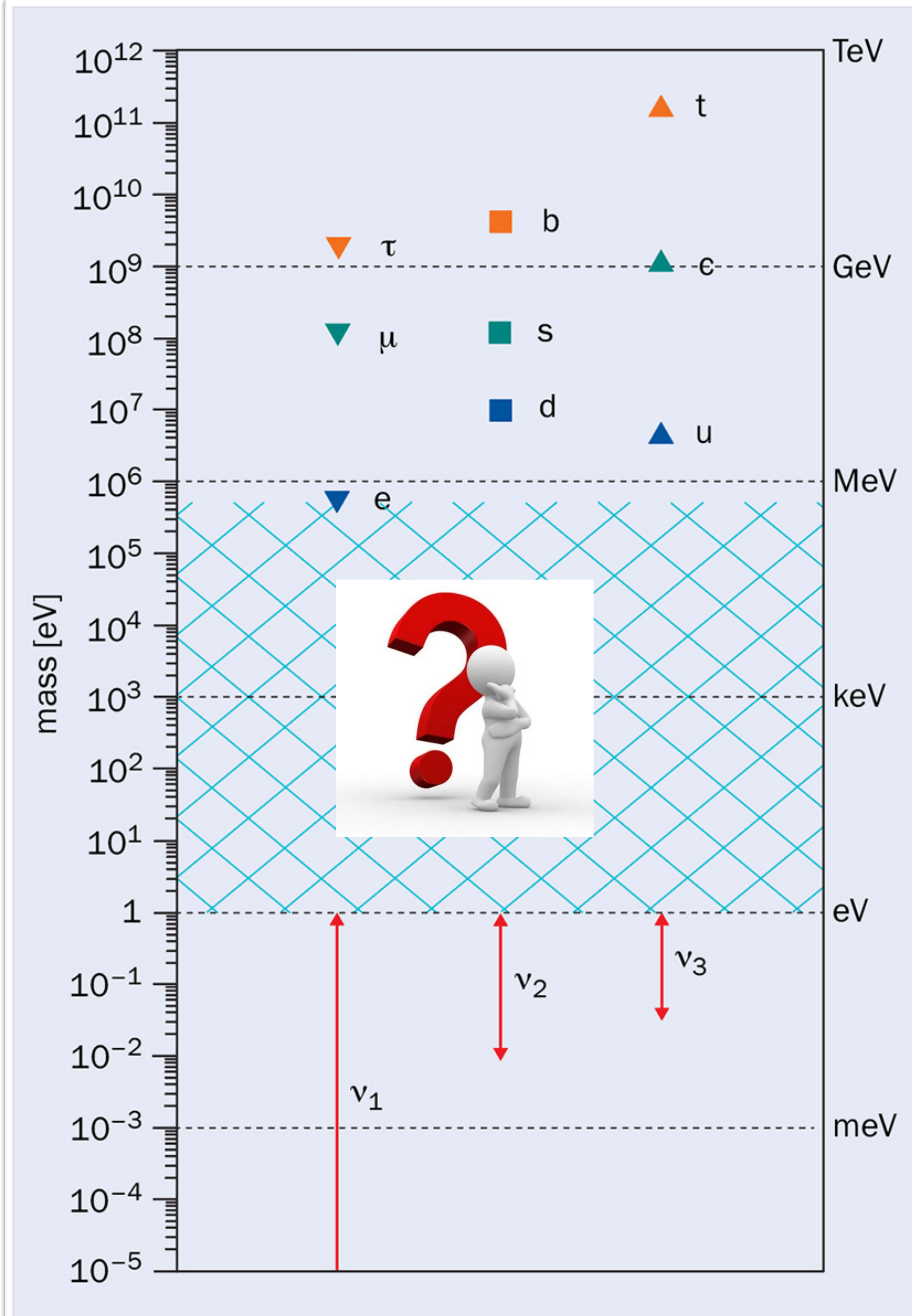
Neutrino properties: my selection

- Masses
- Nature (Majorana question)
- E.m. properties (magnetic moment, milli-charge)

NOT:

- Oscillations (mass differences, sterile neutrinos, hierarchy) → Davide, Gioacchino
- "Astro-physical" neutrinos → Rosa

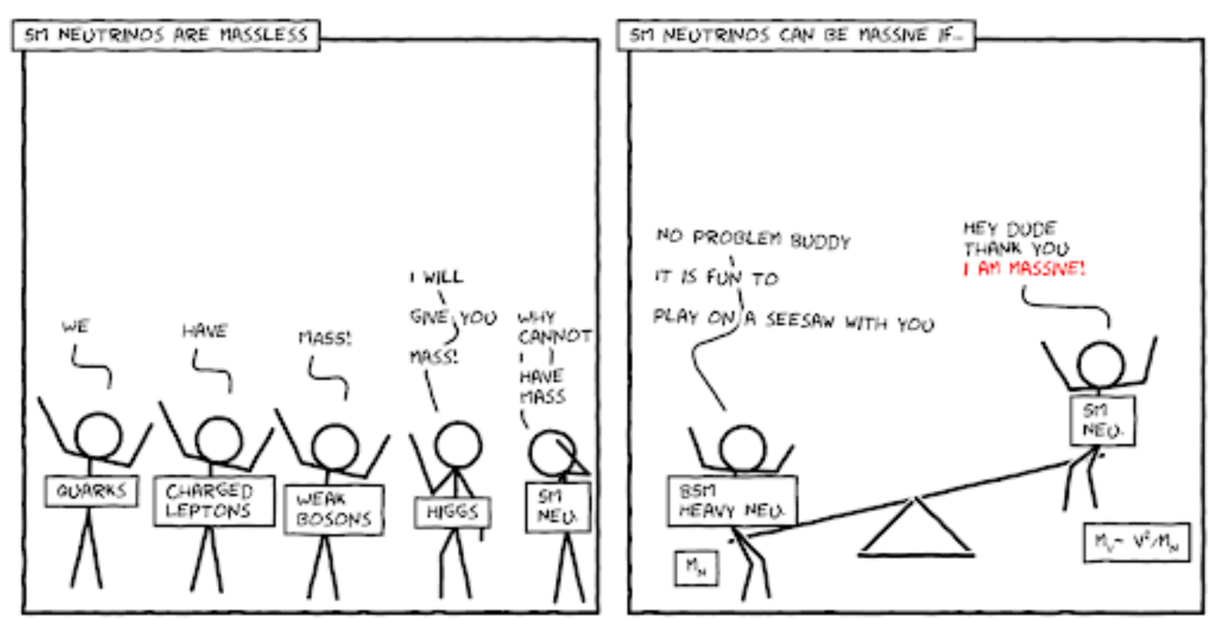




mass [eV]
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
TeV
GeV
MeV
keV
eV
meV
t
b
τ
c
μ
s
d
u
e
ν_1
ν_2
ν_3

One has to do two things:

- Conjecture and come up with a theory for such small masses (e.g. Majorana mass term opens option for See-Saw mechanism, etc)
- Measure masses and correlations with other neutrino observables, predicted by the theory, to verify or rule out (next slides)
- While the former has some good candidates, the latter is HARD!



Mechanisms for Majorana Neutrino Masses

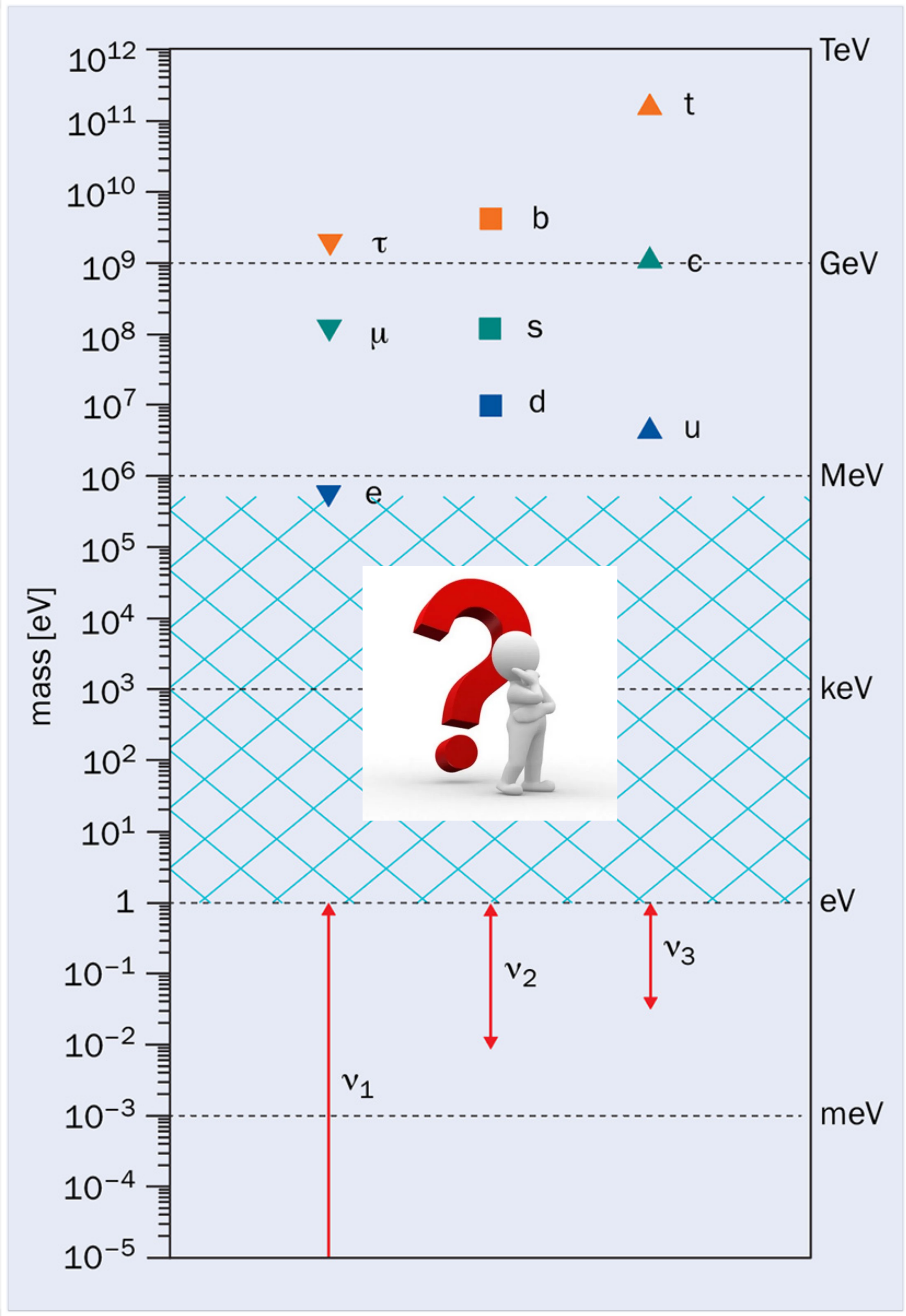
$$\mathcal{L} \supset \frac{1}{2} \nu_L^T C M_M \nu_L$$

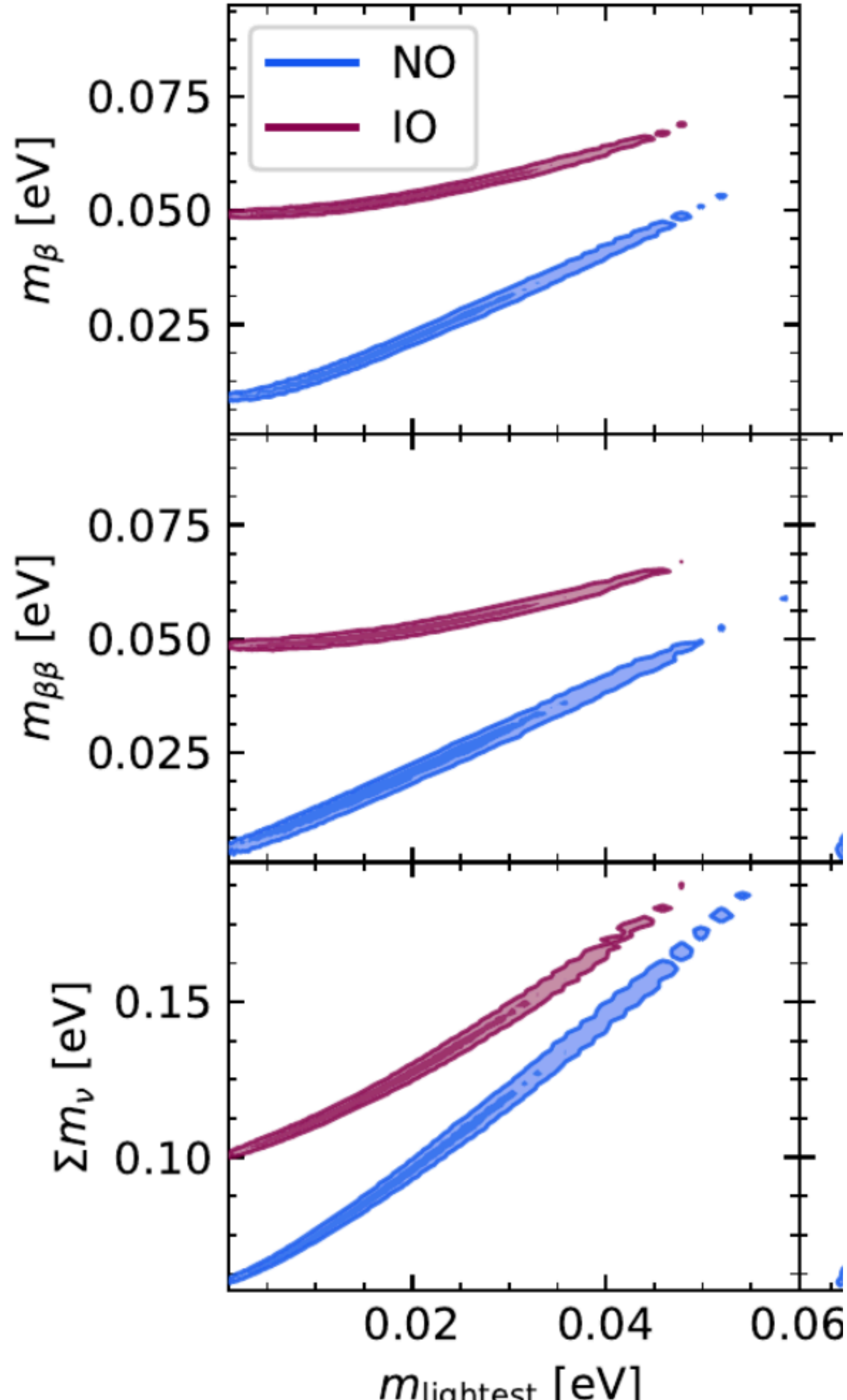
- Type I Seesaw
- Type II Seesaw
- Type III Seesaw
- Zee's Model
- Colored Seesaw
- Witten's Model

…

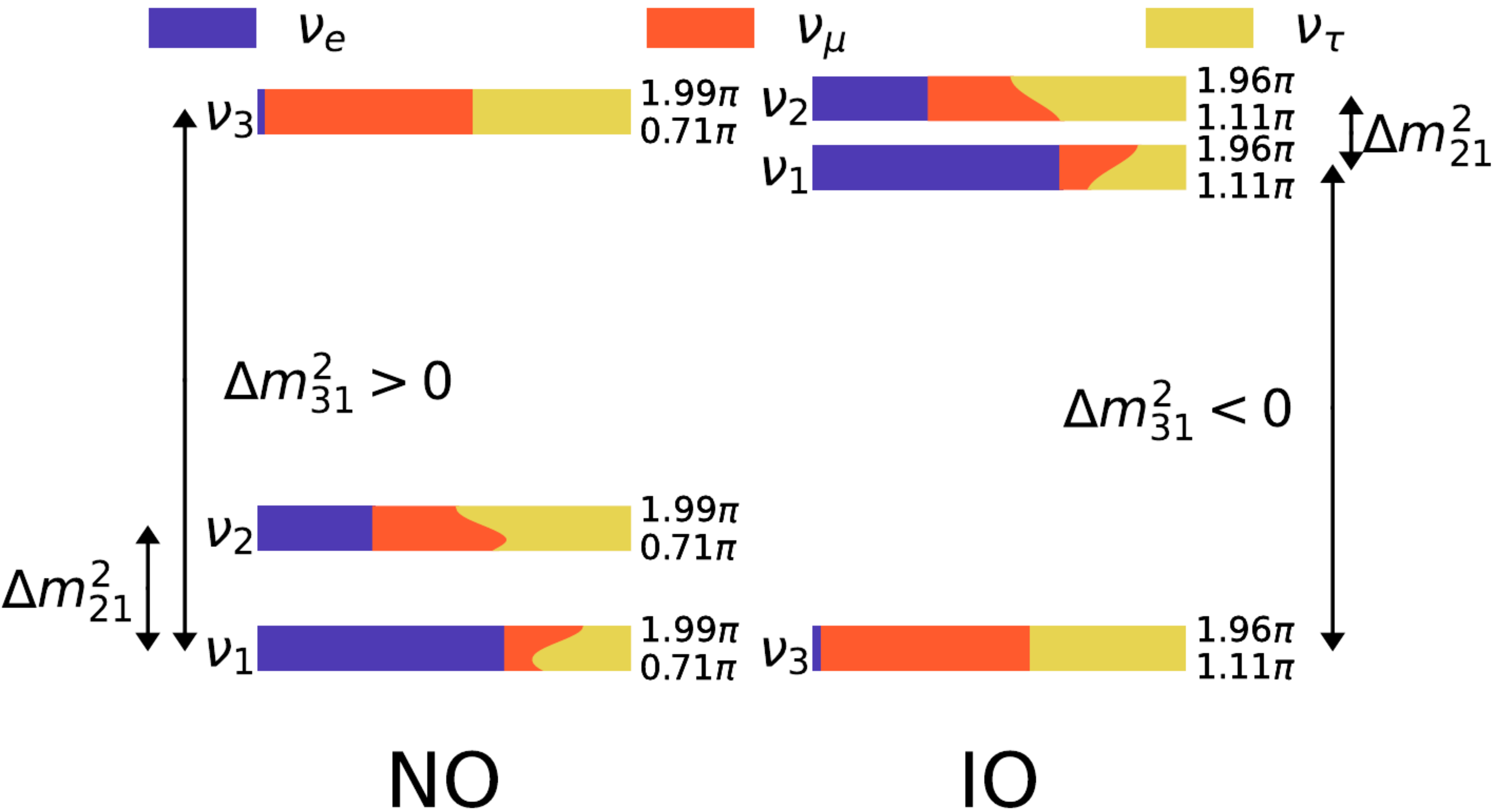
…

Theories: B-L, Left-Right Symmetry, Pati-Salam, GUTs, ….



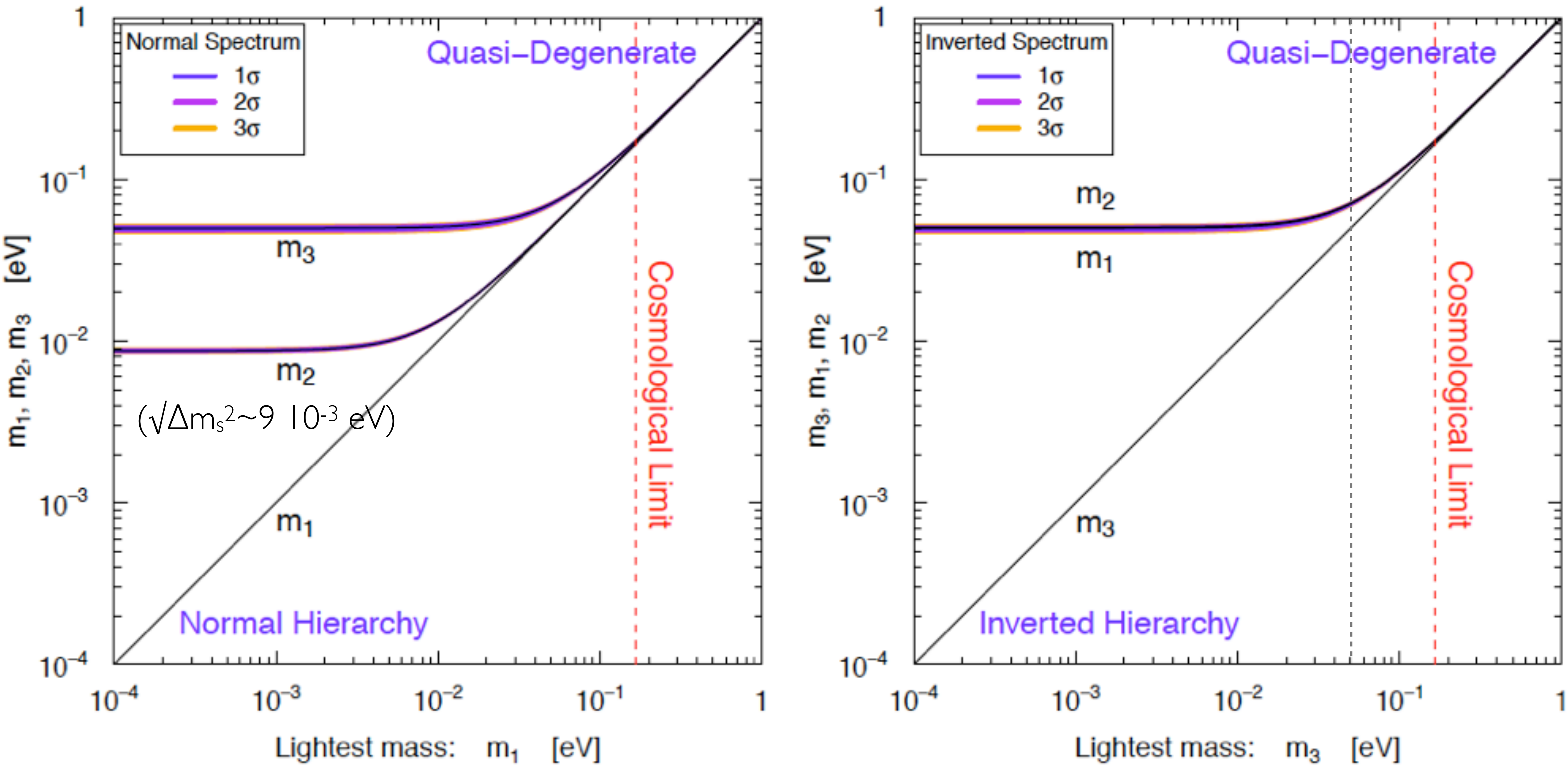


https://globalfit.astroparticles.es/2020/06/24/neutrino-masses/



https://globalfit.astroparticles.es/2018/07/03/neutrino-mass-ordering/

Absolute Values of Neutrino Masses



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\,\text{eV}$

Observables sensitive to m_ν

The absolute mass scale can be measured through:
(numbers on the right are current upper limits)

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

< 0.45 eV @ 90% CL (KATRIN, arXiv 2406.13516)

- neutrinoless double beta decay

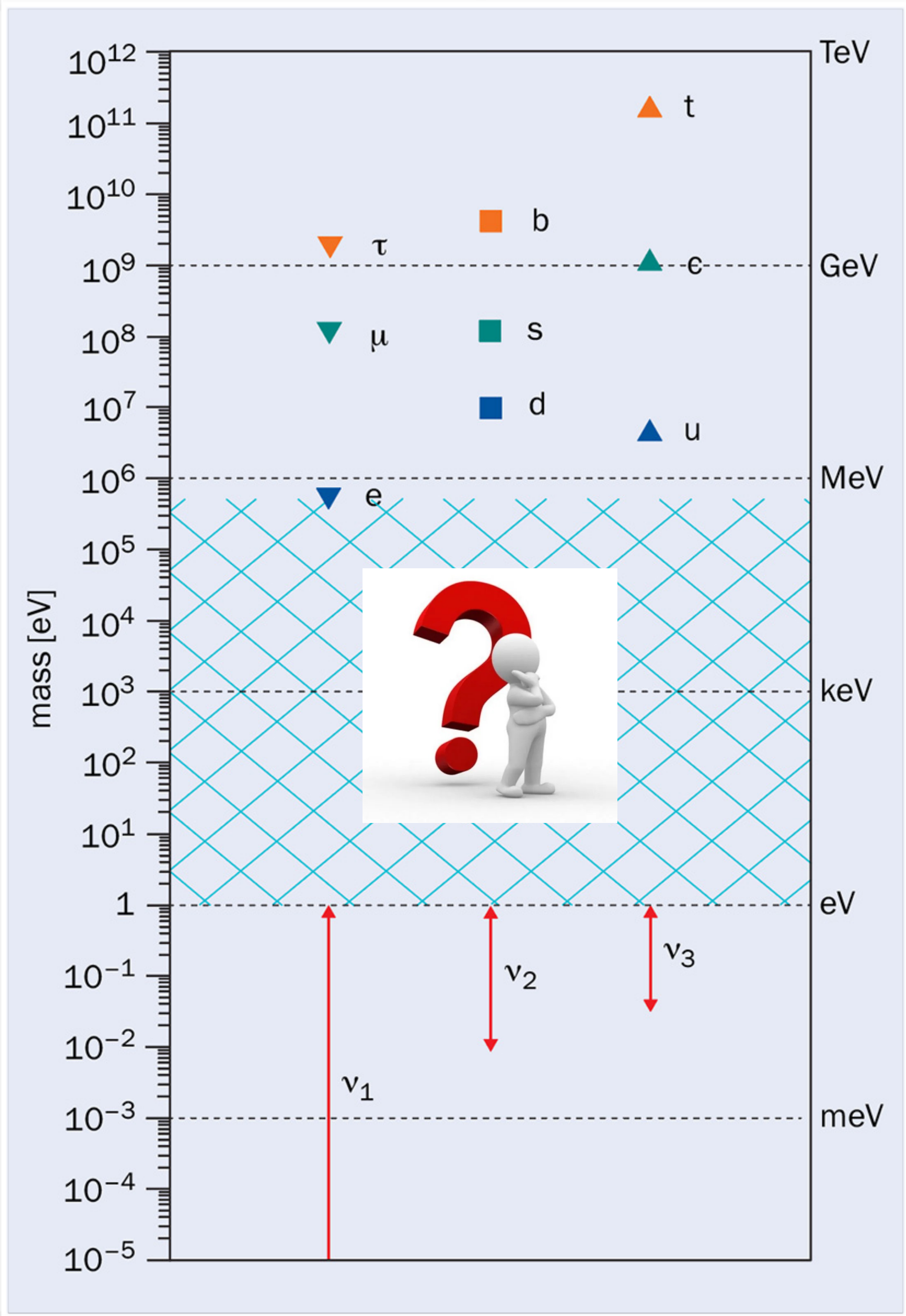
$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$

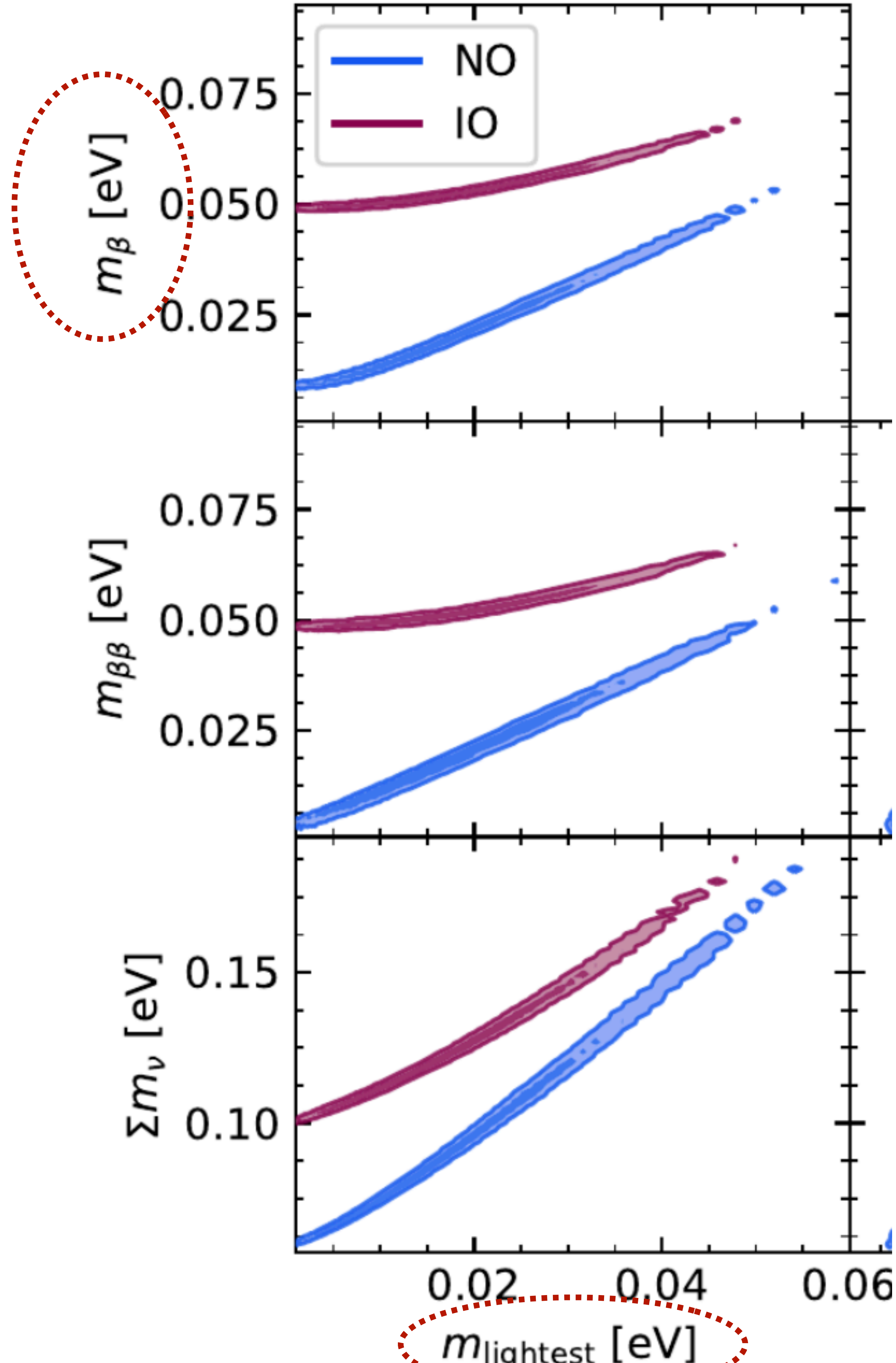
< 0.028-0.122 eV @ 90% CL (KLDZ, arXiv 2406.11438)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i$$

< 0.2 eV @ 90% CL (Lisi et al, arXiv 2503.07752)





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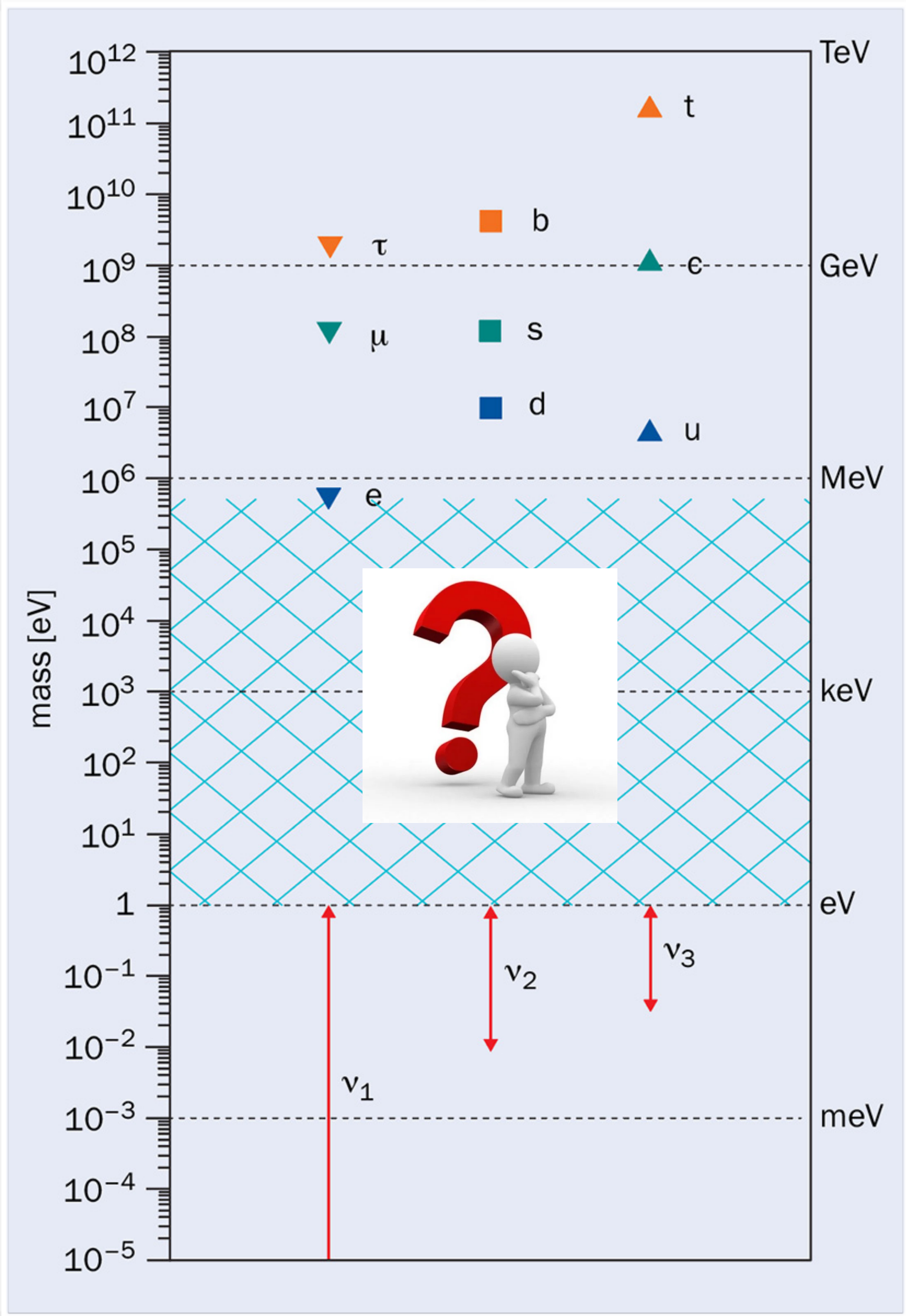
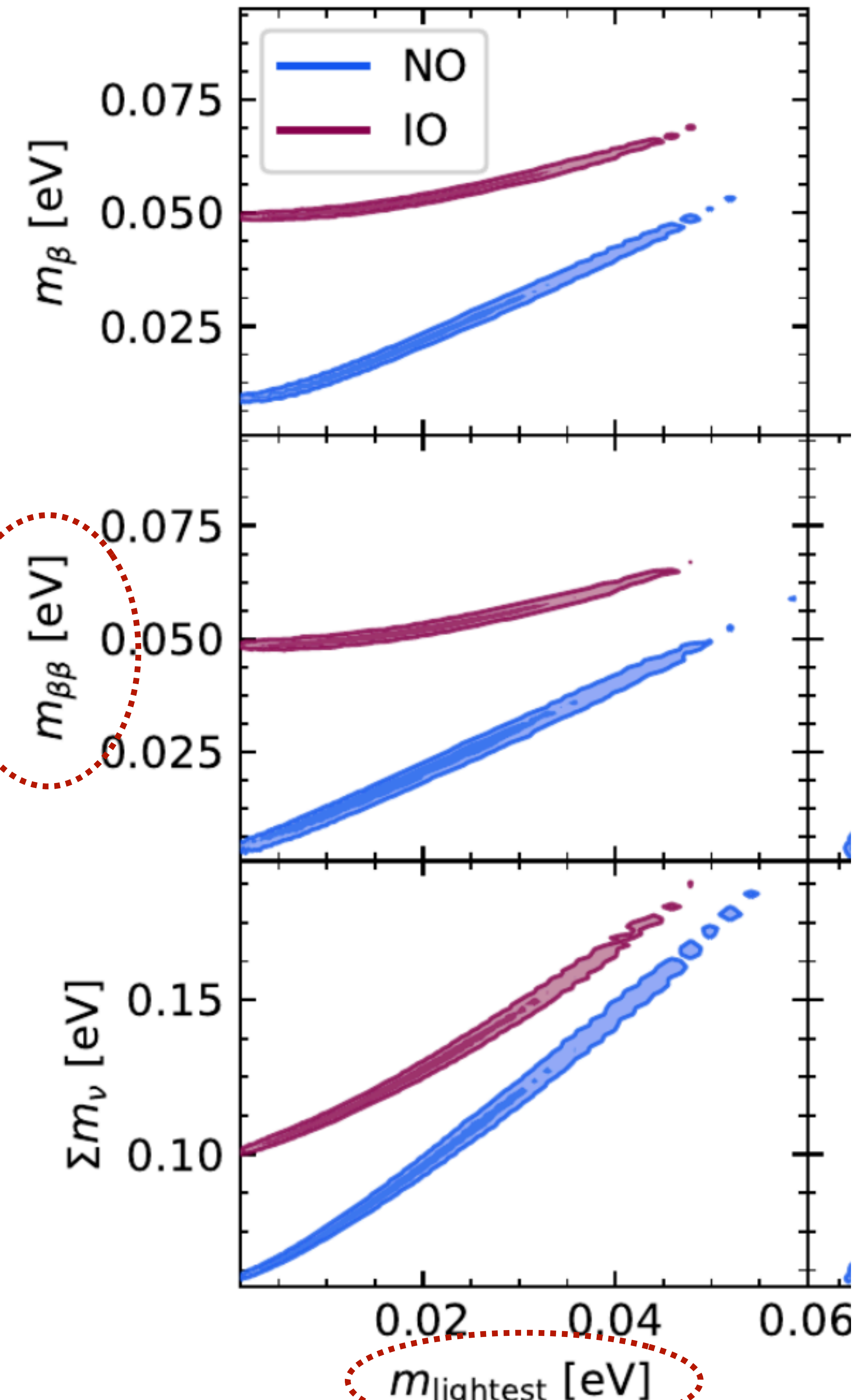




https://globalfit.astroparticles.es/2020/06/24/neutrino-masses/

Direct mass measurements from kinematics

+ : This method relies **purely** on 3-body kinematics, without any assumption on the nature of the ν or on the cosmological "environment"

- : statistics, especially at the end point massless. On the other hand, if the electron neutrino has a mass m_{ν_e}, the maximal kinetic energy of the electron is

$$T_{\max} = Q_\beta - m_{\nu_e} \tag{14.5}$$

Since the neutrino momentum is given by

$$p_\nu = \sqrt{E_\nu^2 - m_{\nu_e}^2} = \sqrt{(Q_\beta - T)^2 - m_{\nu_e}^2}\,, \tag{14.6}$$

the differential decay rate in eqn (14.2) can be written, for $T \le T_{\max}$, as[75]

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}T} = \frac{G_\mathrm{F}^2\, m_e^5}{2\,\pi^3} \cos^2\theta_\mathrm{C}\, |\mathcal{M}|^2\, F(Z, E_e)\, E_e\, p_e\, (Q_\beta - T) \sqrt{(Q_\beta - T)^2 - m_{\nu_e}^2}\,, \tag{14.8}$$

➡ What we measure:

Kurie plot

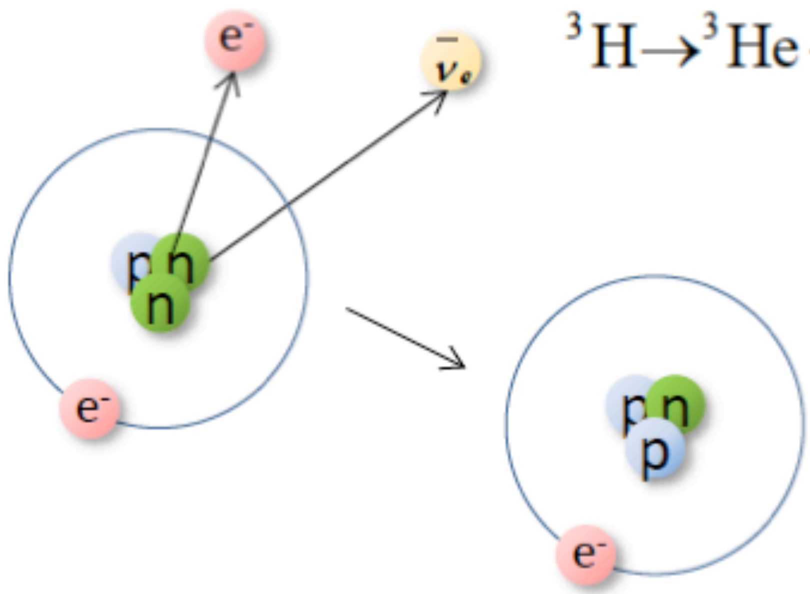
$$K(T) = \sqrt{\frac{\mathrm{d}\Gamma/\mathrm{d}T}{\frac{(\cos\vartheta_C\, G_F)^2}{2\pi^3} |\mathcal{M}|^2\, F(E)\, pE}} = \left[(Q - T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}\right]^{1/2}$$

Beta decay of ^{3}H

$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

- $\tau_{1/2} \cong 12.3$ years (4*10^8 atoms for 1 Bq)

reasonably short lifetime

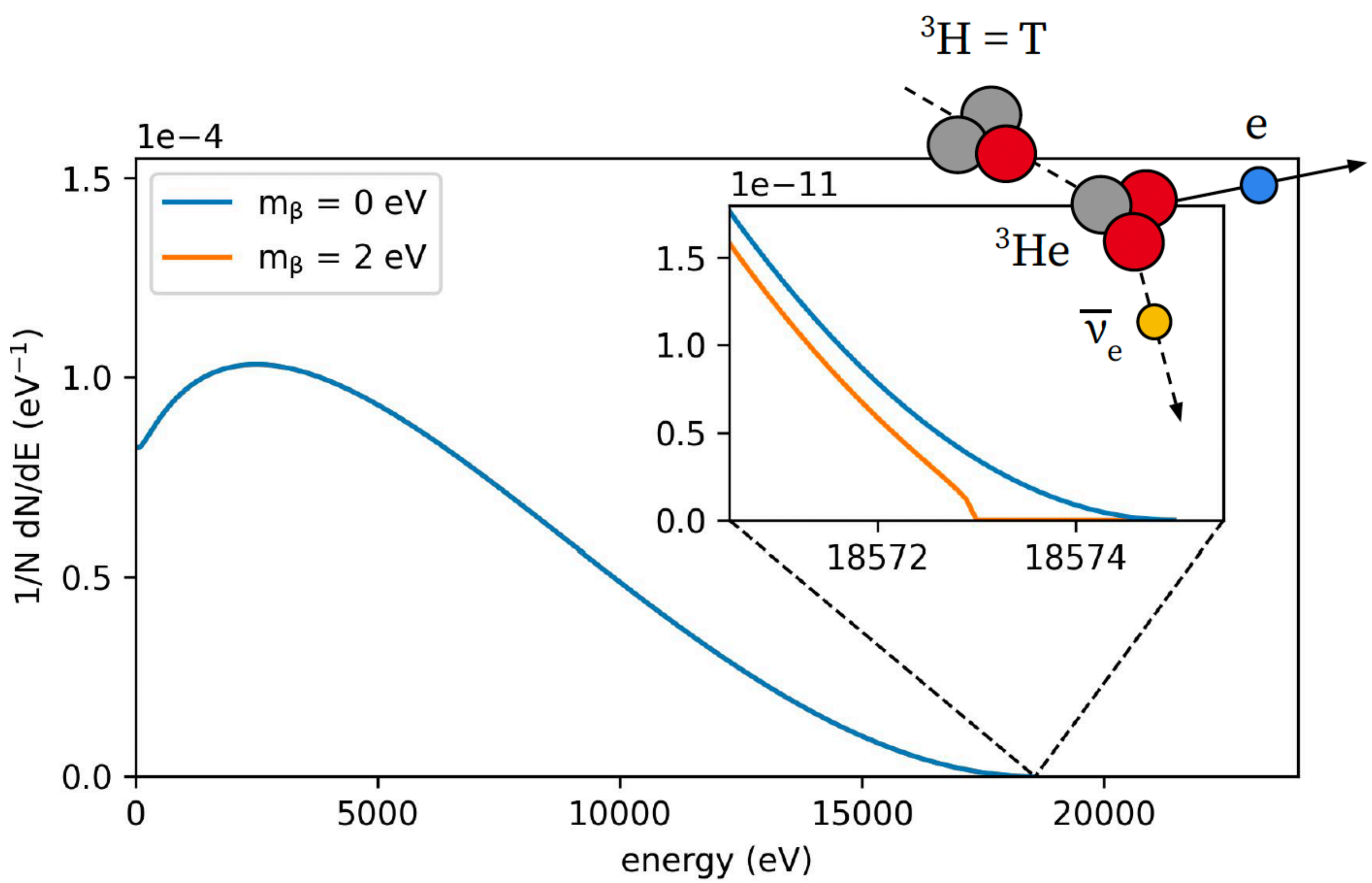


$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_e$$

^{3}H: chosen because:

✓ low Q ⇒ enhanced $\frac{n(\Delta T)}{n} \propto \left(\frac{\Delta T}{Q_\beta}\right)^3$

✓ simple atomic structure (small uncertainties on $|\mathcal{M}|^2 F(Z, E_e)$



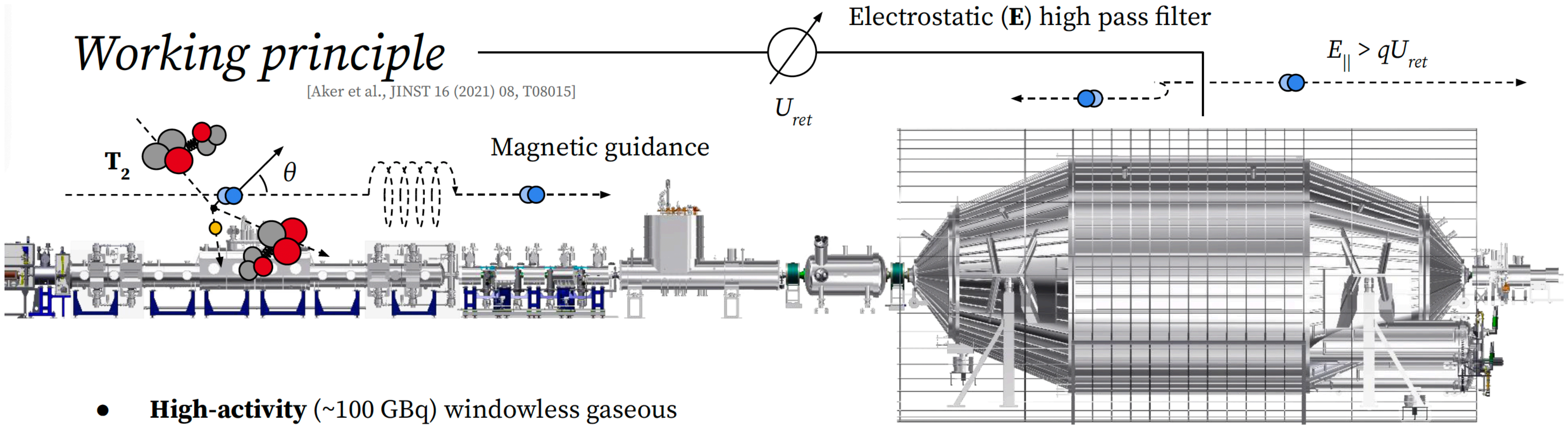
Only a small fraction of events in the last eV below the endpoint: **2 *10^{-13}**

Triutium is present as **bi-atomic molecules**

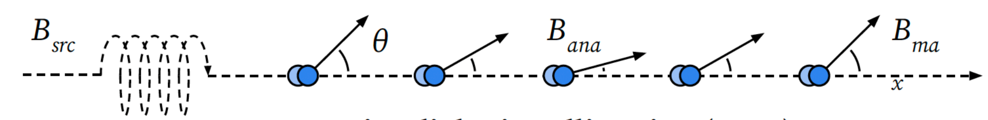
KATRIN

Working principle

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



- **High-activity** (~100 GBq) windowless gaseous molecular tritium source, closed loop
- Tritium removal in transport section
- **High-resolution** (~1 eV) **large-acceptance**

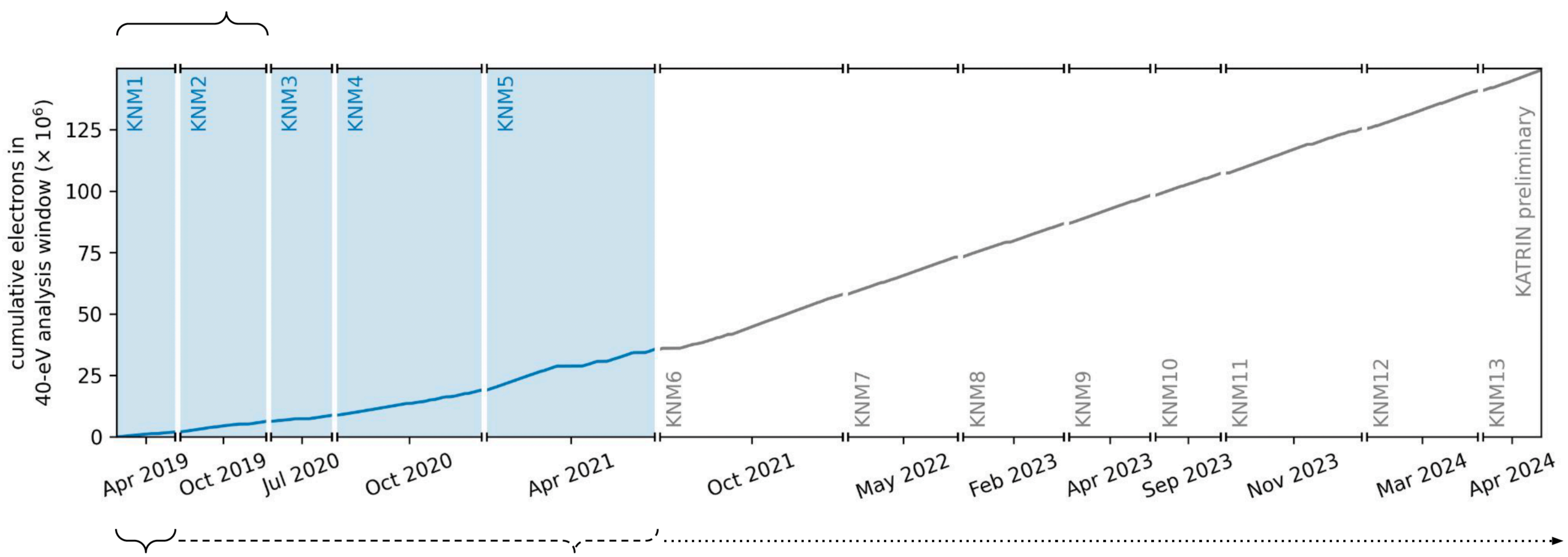


Magnetic adiabatic collimation (**MAC**)

➔ Discrete **retarding potential steps**, measurement time distribution, **integral spectra**

Data taking overview

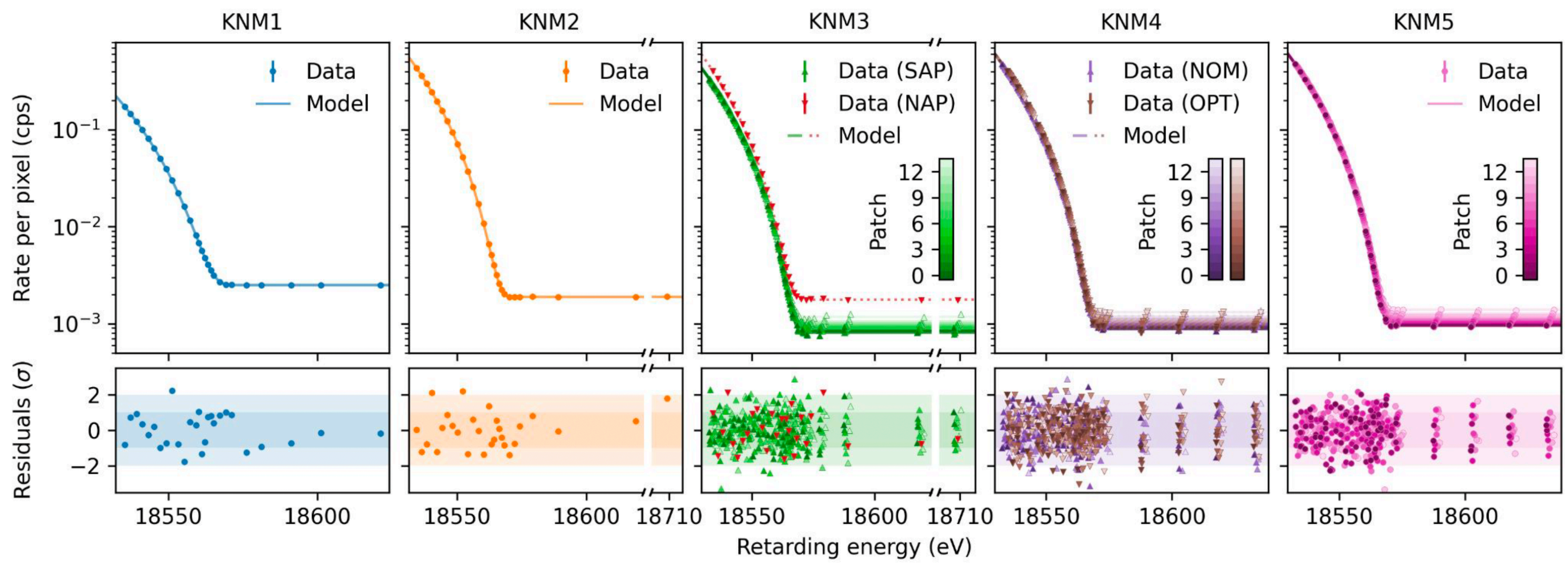
Second result, $\boldsymbol{m_\beta}$ **< 0.8 eV** (90% CL)
[Aker et al., Nature Phys. 18 (2022), 2, 160-166]



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

Third result, 5 campaigns, 1757 scans,
259 measurement days

Continue until end-2025,
1000 measurement days

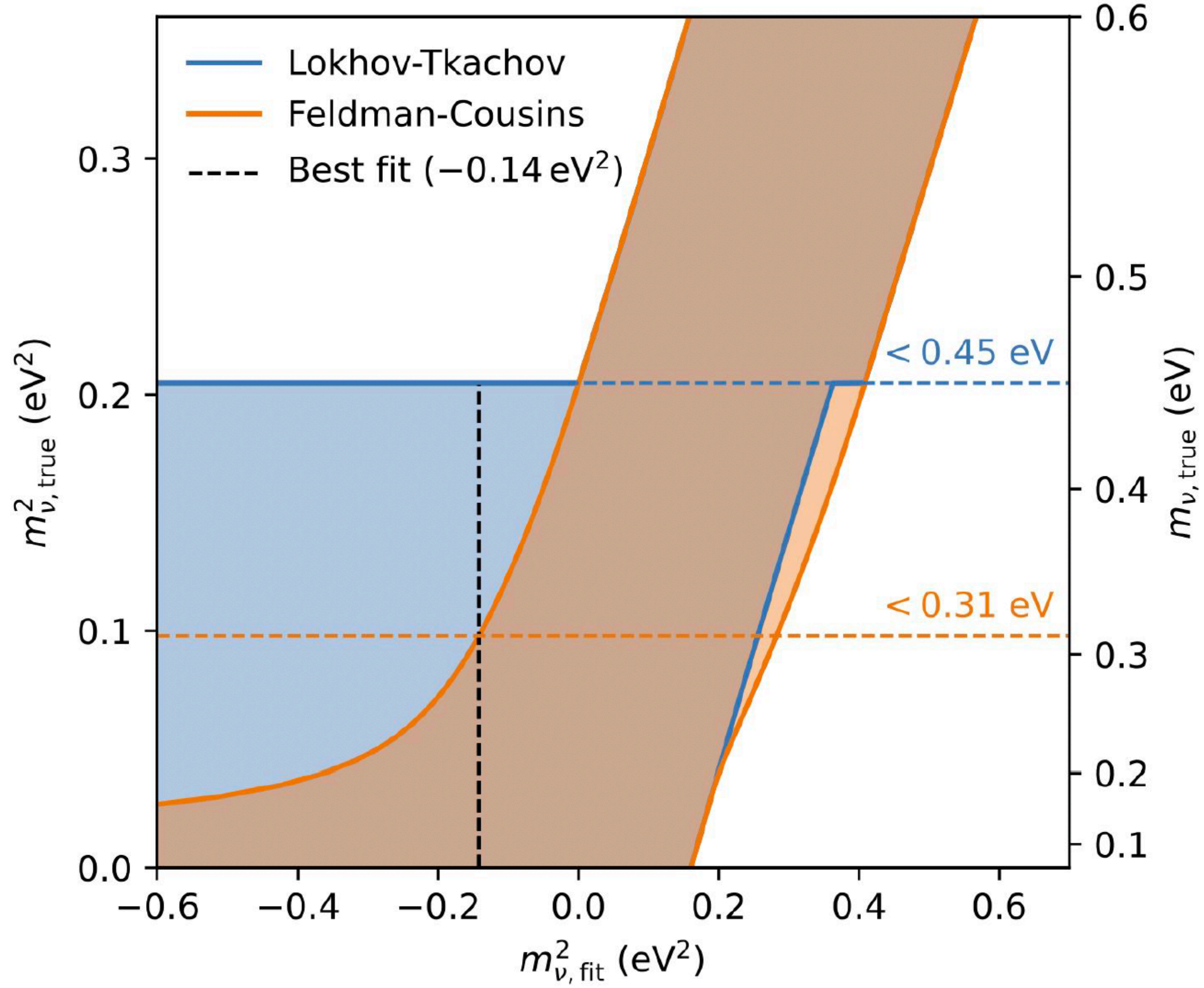


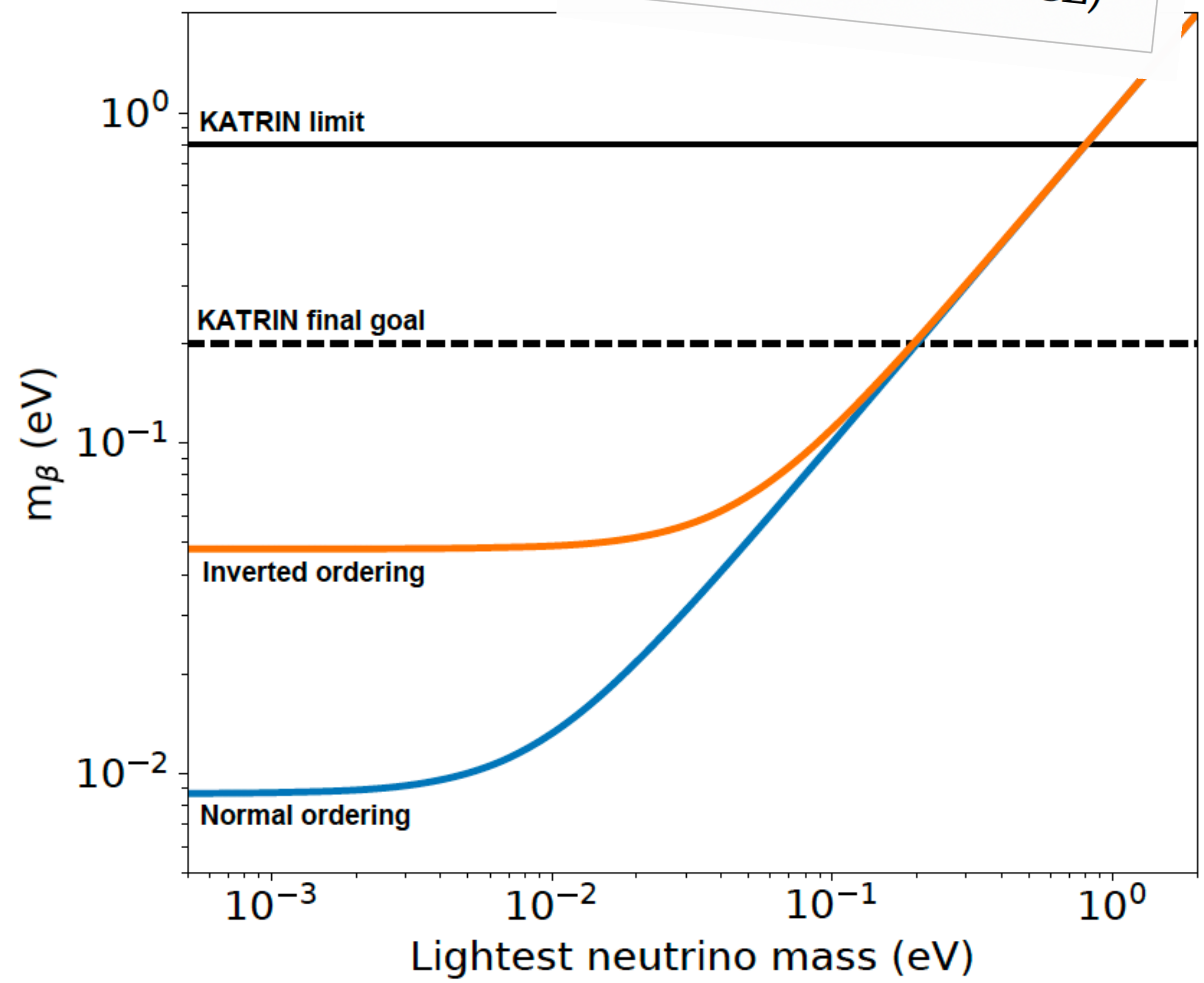
- **2 analysis frameworks**, neural network surrogate [Karl et al., EPJ C 82 (2022) 5, 439]

➔ p-value = 0.84, squared neutrino mass best-fit $\boldsymbol{m_\beta^2 = -0.14^{+0.13}_{-0.15}}$ **eV²**

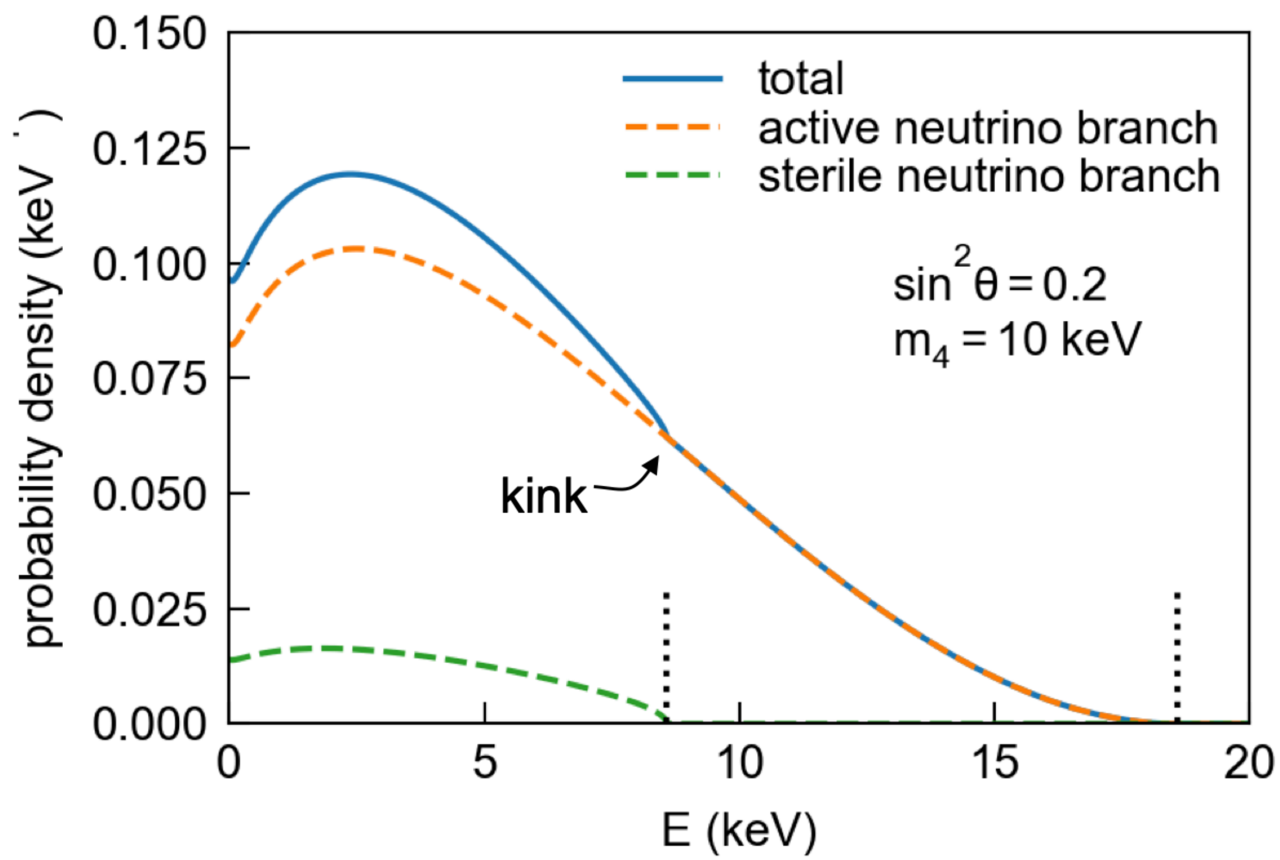
➔ Discrete **retarding potential steps**, measurement time distribution, **integral spectra**

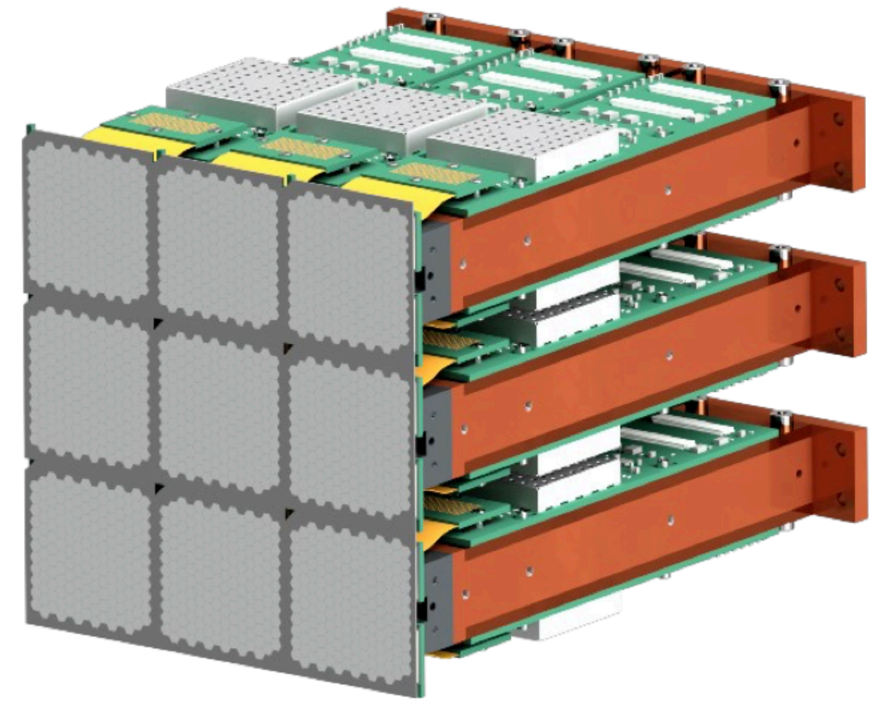
m_β **< 0.45 eV** (90% CL)





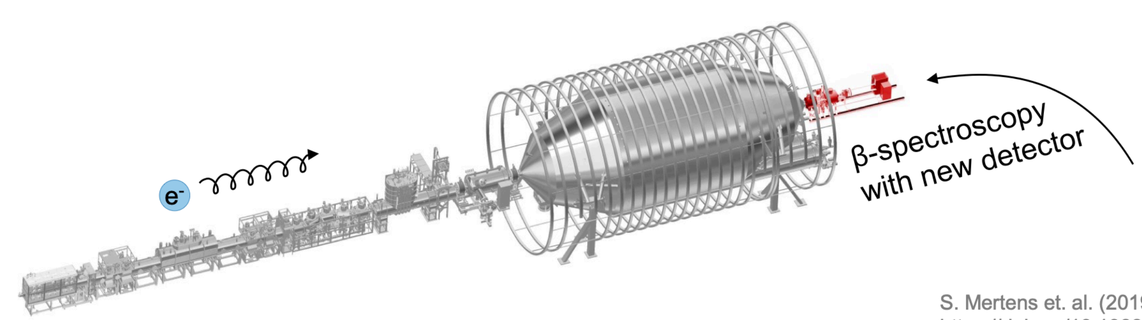
(Promising) evolution(s)/1:TRISTAN

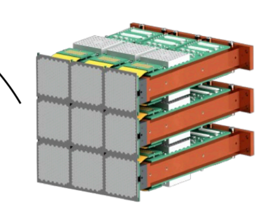




- precise spectral shape measurement (**FWHM <300 eV**) across entire energy range
- Ability to handle high rates at the detector (~108 cps)

~~integral~~ spectra
differential





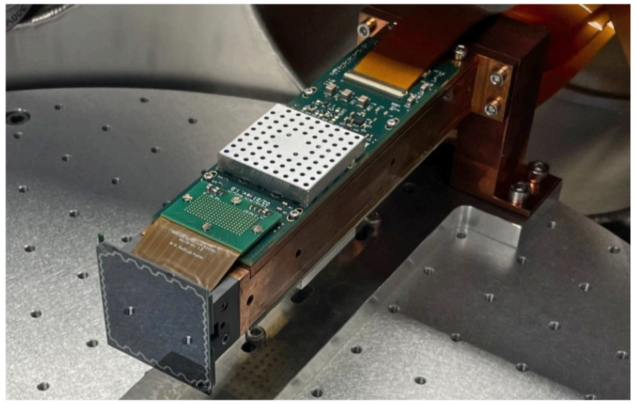
S. Mertens et. al. (2019)
https://doi.org/10.1088/1361-6471/ab12fe

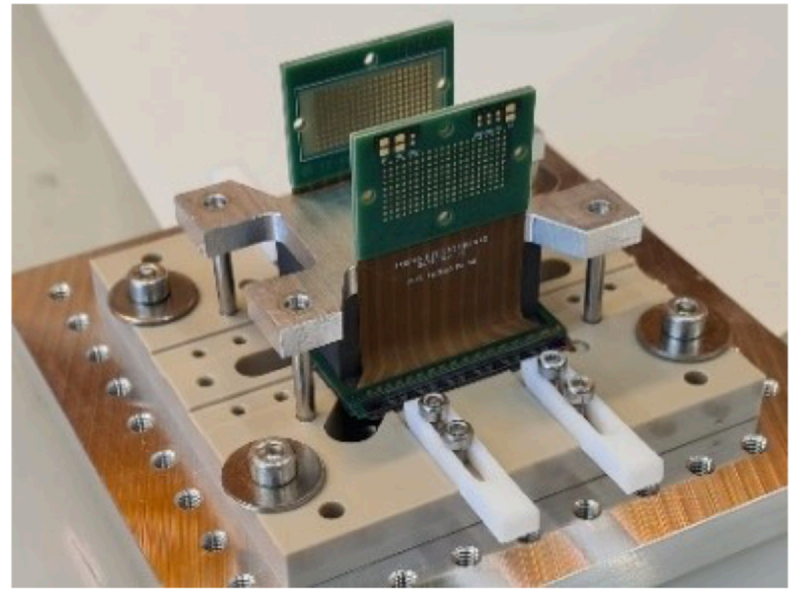
Challenges:

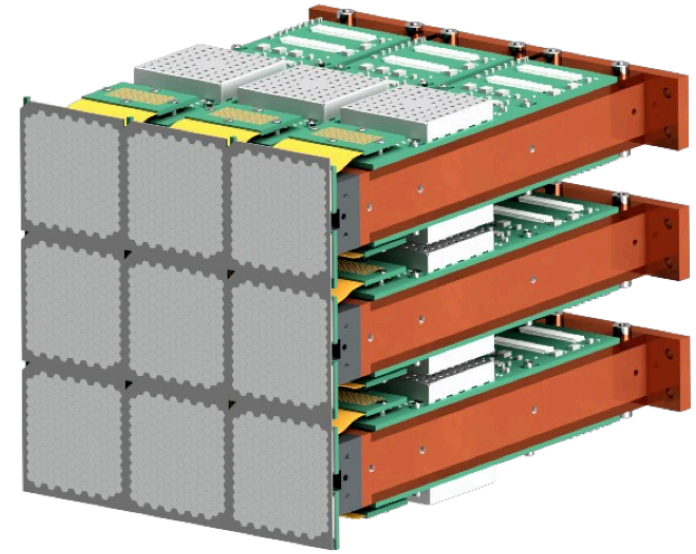
- scaling to focal plane array (>1000 pixels)
- electron spectroscopy
- difficult environment: UHV, magnetic fields, high voltage etc.

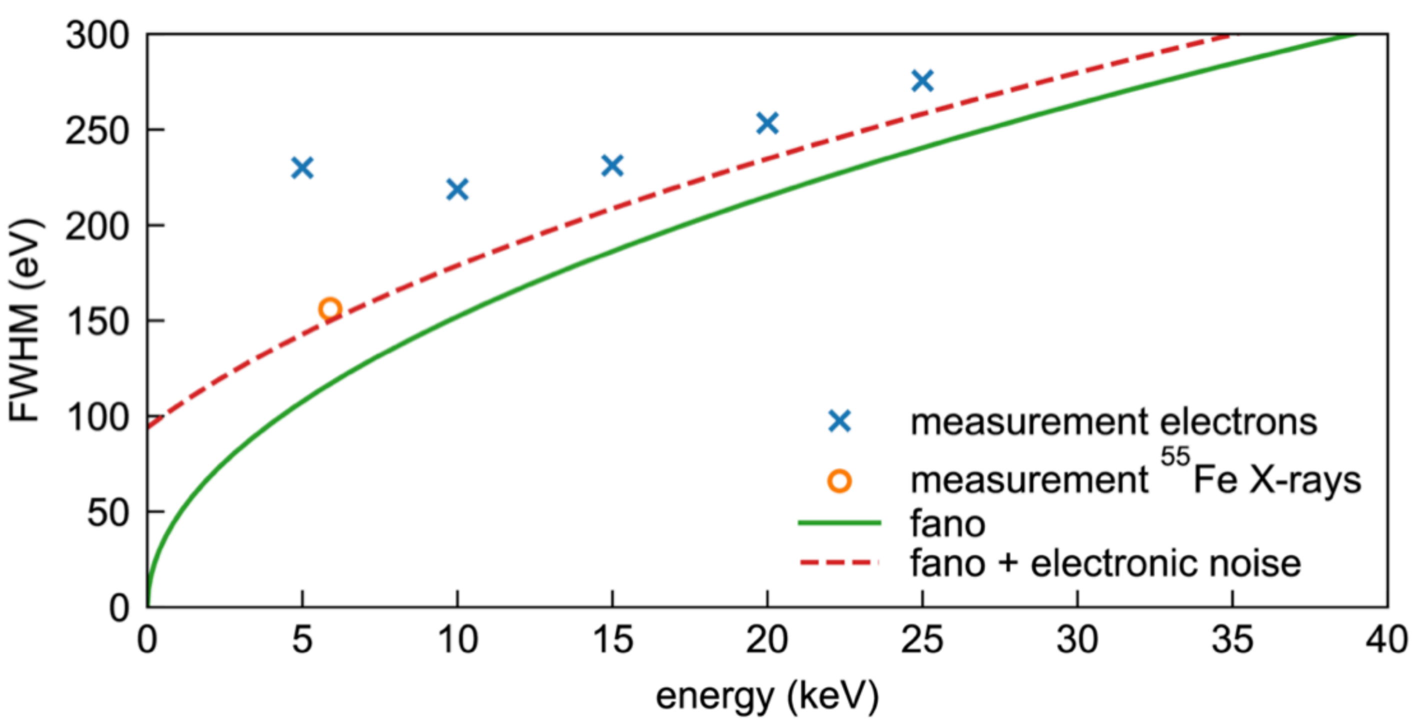
(Promising) evolution(s)/1:TRISTAN

https://indico.global/event/8935/contributions/85462/attachments/39892/74205/2024_07_04_urban_iworid.pdf









247 eV FWHM at 20 keV

Under extensive characterization now for various response effects, including x'talk

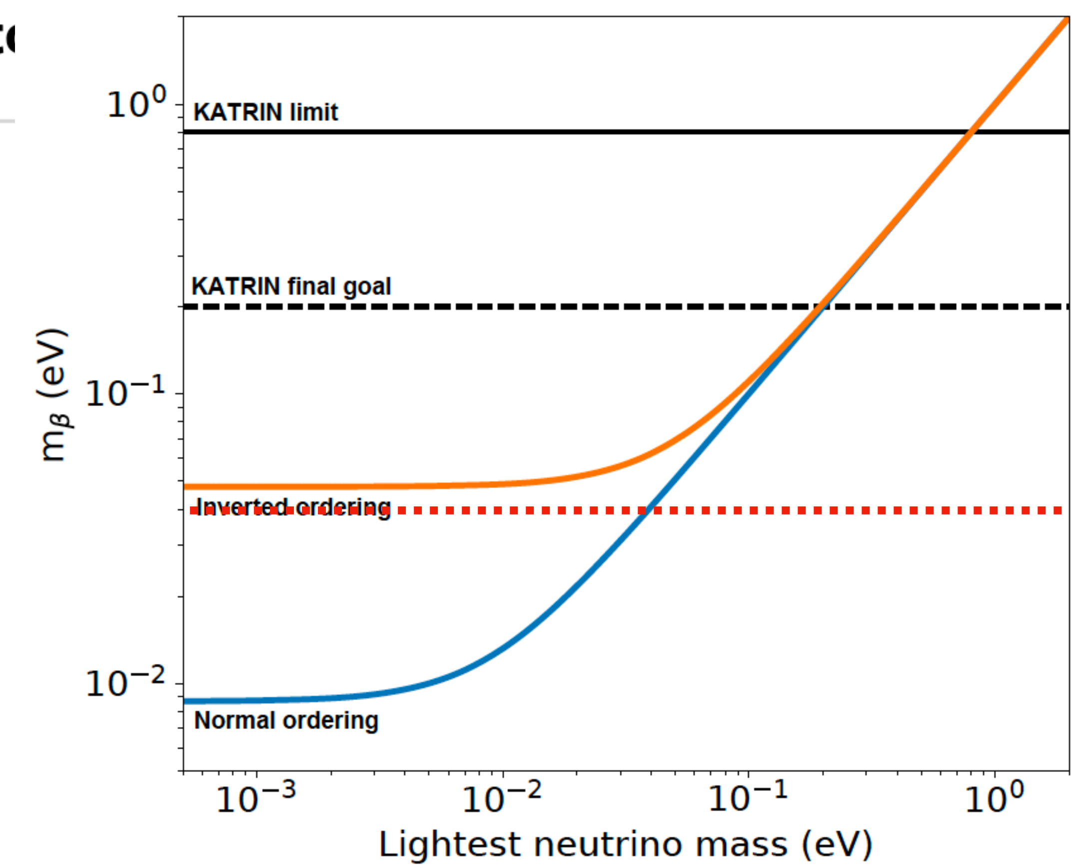
2025:
- 9 modules in replica of KATRIN detector section

2026:
- installation in KATRIN beam line
- start of sterile neutrino physics program (~1 year)

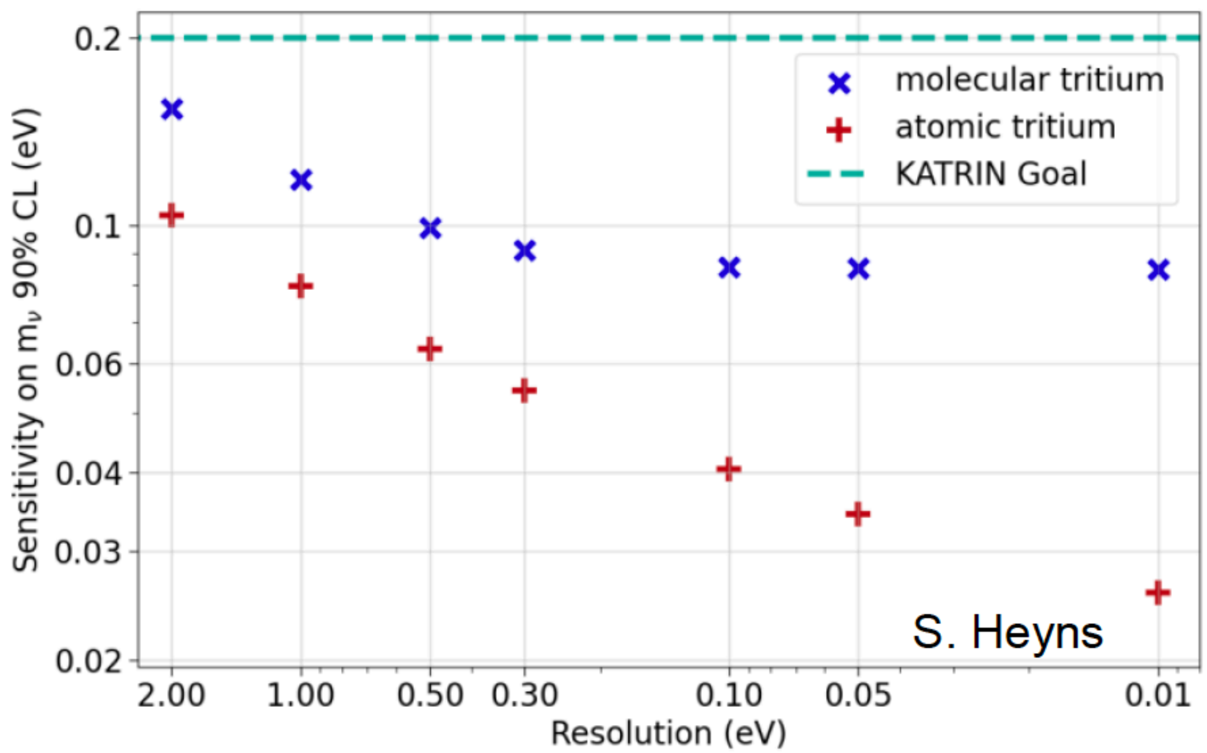
(Promising) evolution(s)/2: KATRIN++

2019-2025 (PoF-IV)	2026-2027 (PoF-IV)	2028-2034 (PoF-V)	Scientific goal
Phase 1 (Integral) Neutrino mass	Phase 2 (Differential) keV sterile ν	**R&D Phase KATRIN ++** Atomic Tritium Demonstrator Quantum Sensor Demonstrator	Neutrino mass

- **KATRIN** on way to achieve 1000 d measurement time **(final sensitivity m_β < 0.3 eV).** Next m_β result : ~ **0.5 eV sensitivity**
- We will be ready for **TRISTAN**-Operation at the end of 2025 (**Search for keV sterile neutrinos)**
- Ultimate neutrino mass experiment (Normal Ordering; **sensitivity on m_β < 40 meV**) requires **differential detector principle** und **an atomic tritium source → R&D Plan for PoF-V**
- KATRIN++ invites research groups for **tackling challenges t**



- **Differential measurement (FWHM < 1 eV)**
  - ✓ Better use of statistics
  - ✓ Lower background
- **Atomic tritium**
  - ✓ Avoid broadening (~ 1 eV)
  - ✓ Avoid limiting systematics of T_2

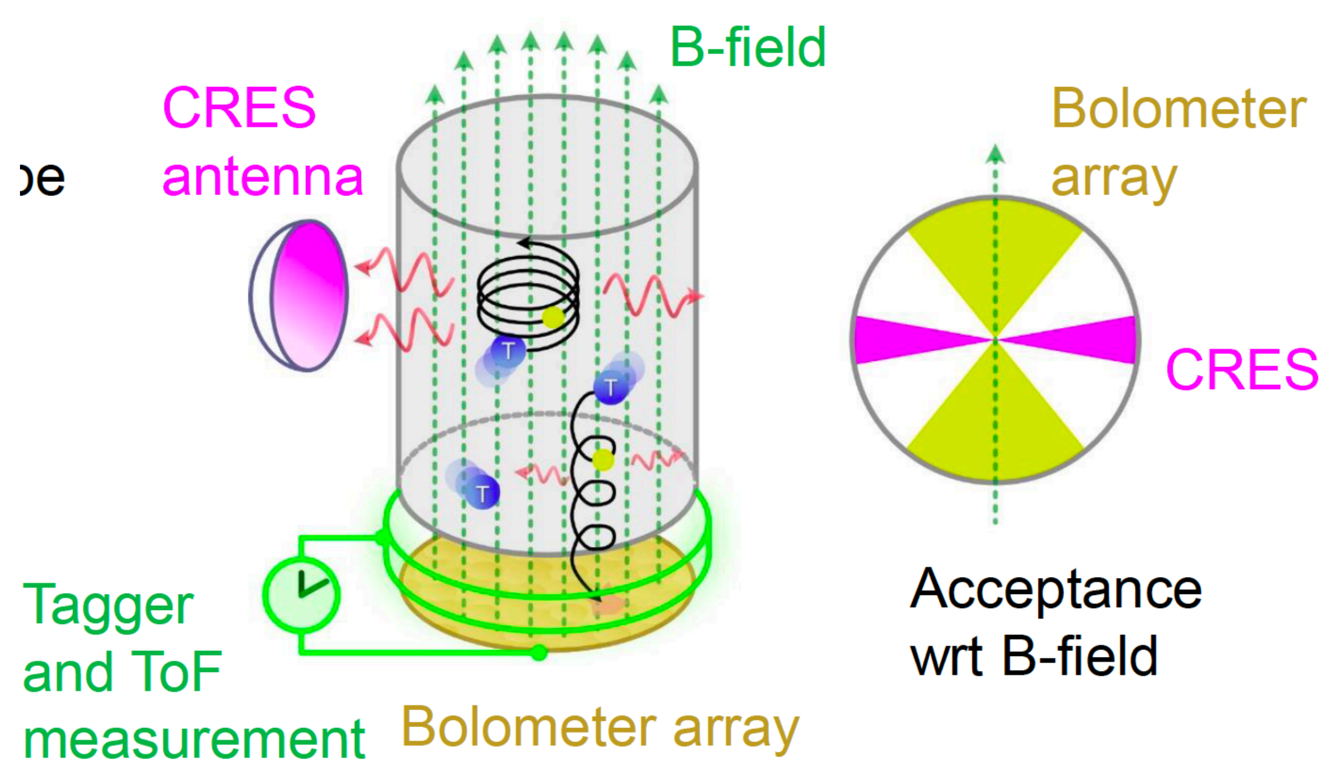


Current KATRIN : ΔE = 2.7 eV, bkg rate = 0.1 cps

Differential measurement
Energy resolution determined by
A)detector or
B) time of flight

Significant R&D effort based almost entirely at Karlsruhe and UNC:

- Metallic Magnetic Calorimeters (MMC) with Kr83m decay electrons currently reaches 25 eV FWHM for now, but should go down?
- TOF with single electron tagging is tough, but trying approach a la Project-8
- Towards a unified approach….?



	Molecular tritium T_2	Atomic tritium T	Quasi-atomic tritium (tritiated graphene)
Type of source	Dynamic injection	Long-lifetime trap	Surface-bound
Scalability to higher luminosity		Challenging	Promising
Effective limitation of resolution			?
Final-state-distribution			
Baseline for	KATRIN	PROJECT 8 KATRIN QTNM	tritiated? PTOLEMY

A lot of work on a T atom trap at KIT, but too long here to delve into it

⇛PTOLEMY: last CSN2@Bologna, Marcello (*but no slides posted… :(*)

Meanwhile in Italy…

The HOLMES experiment

low temperature **microcalorimeter arrays** with ion-implanted ^{163}Ho

scalable proof-of-principle for an experiment with **$\lesssim$0.1 eV m_ν sensitivity**

- 6.5×10^{13} atom/det → A_{EC}=300 c/s/det
- $\Delta E \approx 1$ eV and $\tau_R \approx 1$ μs
- 1000 TES microcalorimeters
  → 16 × 64-pixel arrays with microwave multiplexed read-out
- 6.5×10^{16} ^{163}Ho nuclei → ≈18 μg
  → 3×10^{13} events in 3 years
  → m_ν statistical sensitivity ≈1 eV

realistic rescaled intermediate target

- $A_{EC}\approx1$ c/s/det
- $\Delta E \approx 1$ eV and $\tau_R \approx 1$ μs
- 64-pixel array Of which **48** usable after successful implantation
  → 2×10^{9} events in 1 year
  → m_ν statistical sensitivity O(10 eV)

HOLMES

B. Alpert et al., Eur. Phys. J. C, (2015) 75:112

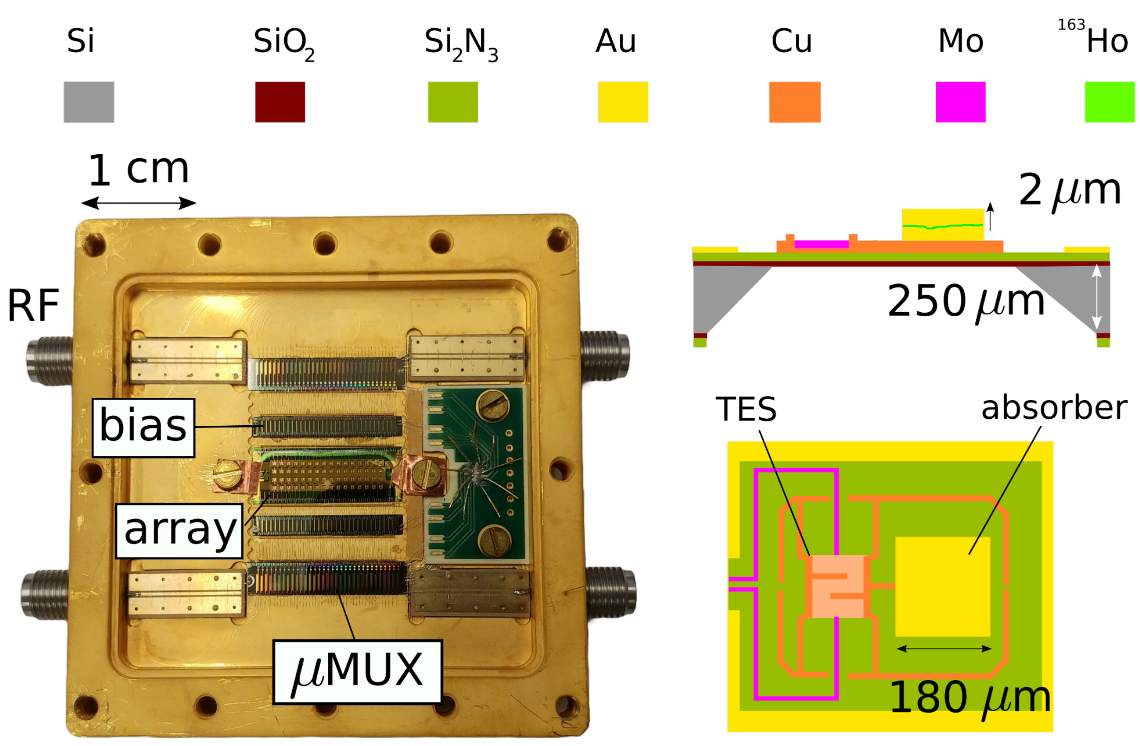
PRL w/ 48 TES

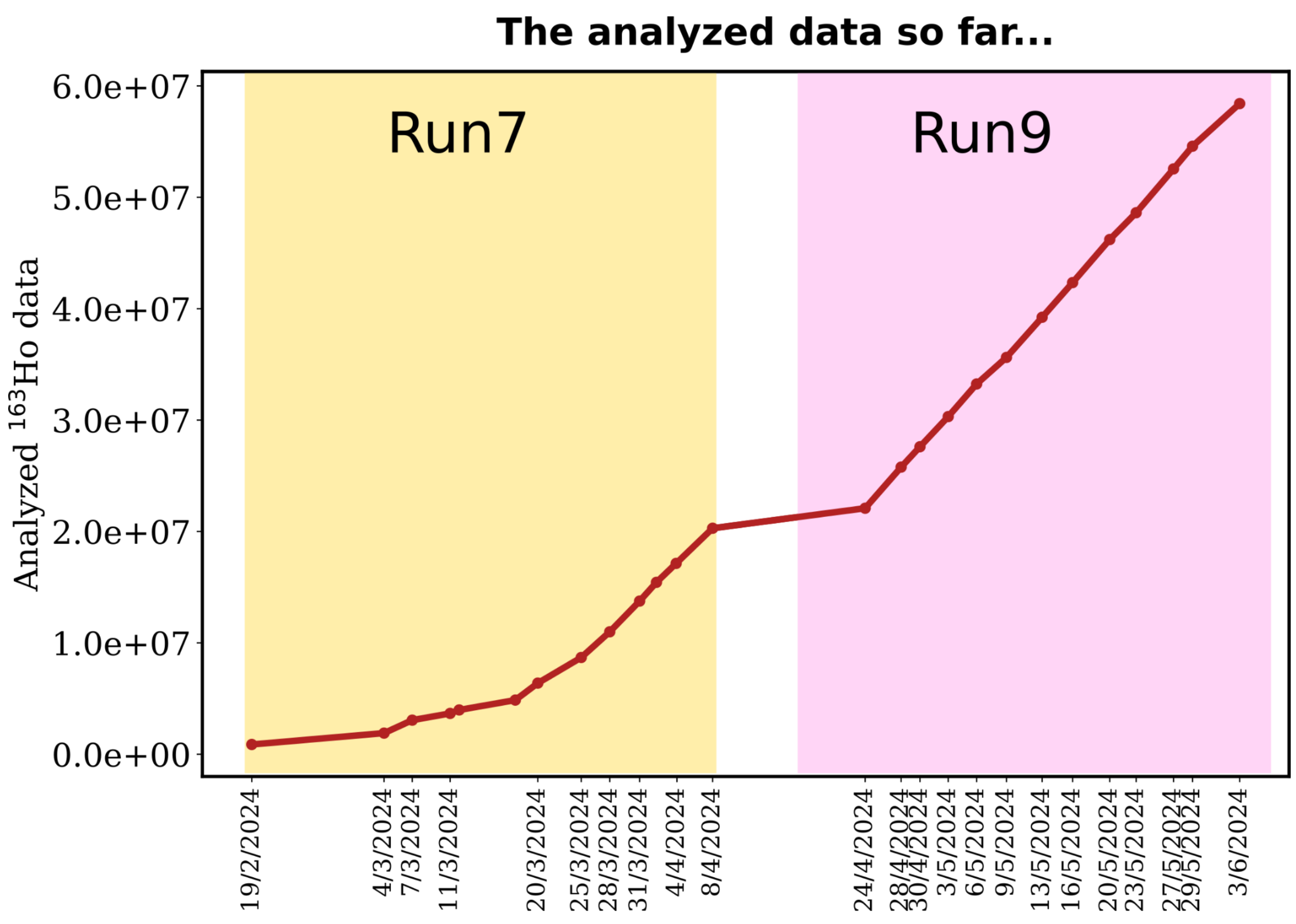
- 1st neutrino mass measurement of HOLMES (submitted to PRL): https://arxiv.org/pdf/2503.19920

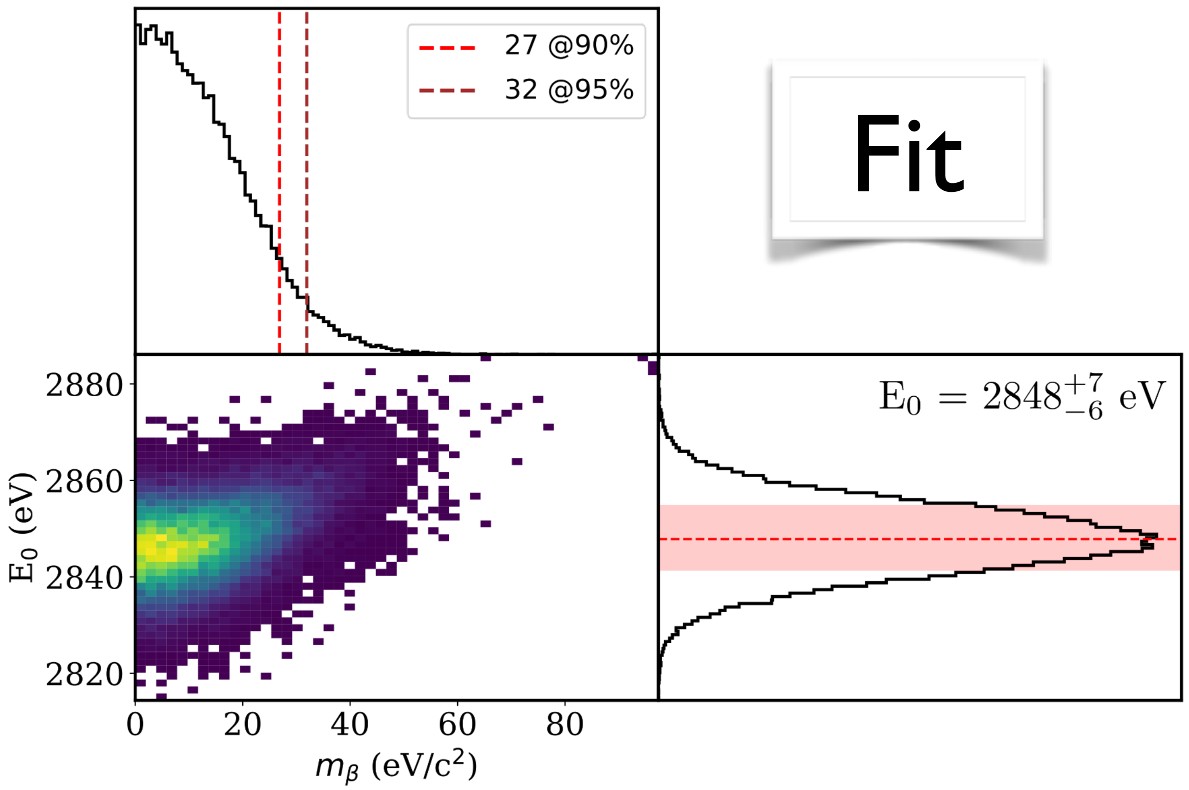
Not competitive with KATRIN but
- validates the approach implemented in recent years by HOLMES and ECHo
- Can extract info on the neutrino mass using 163Ho even without knowing well the ^{163}Ho spectral shape

→ m(nu) < 27 eV at 90% C.L. with

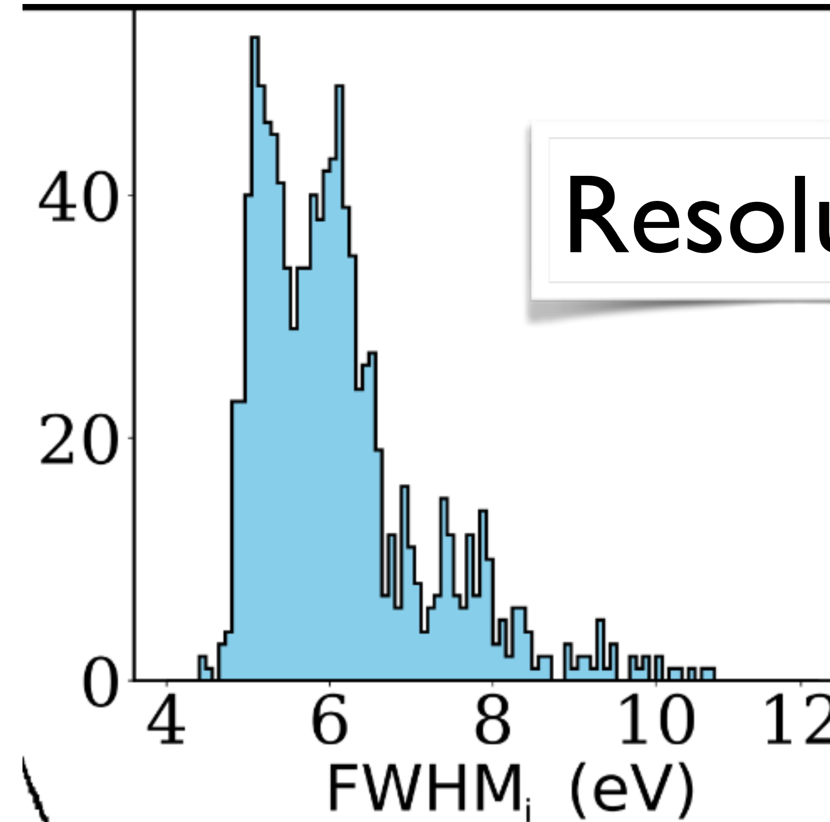
- **48 detectors (microwave multiplexed readout)**
- **2 months**
- **15 Bq total activity = 10^7 decadimenti**



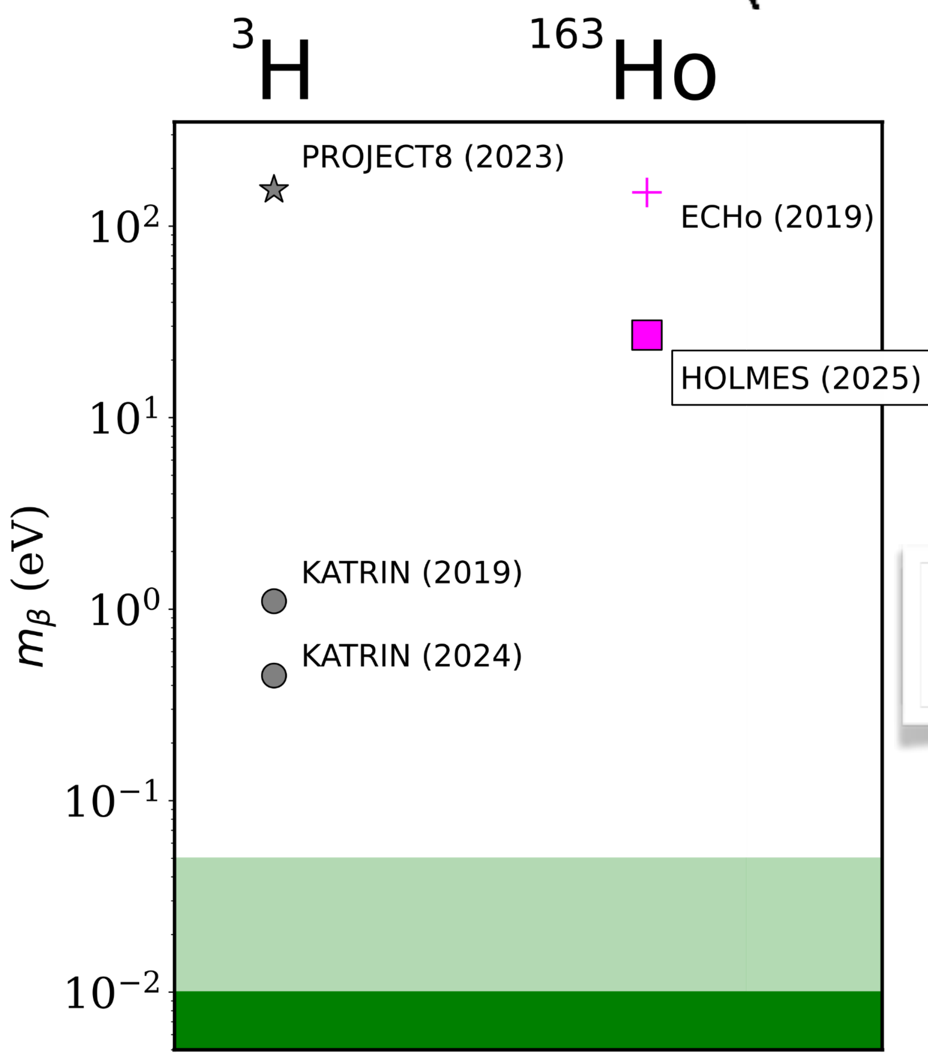




Fit



Resolution



State of the art

EChO

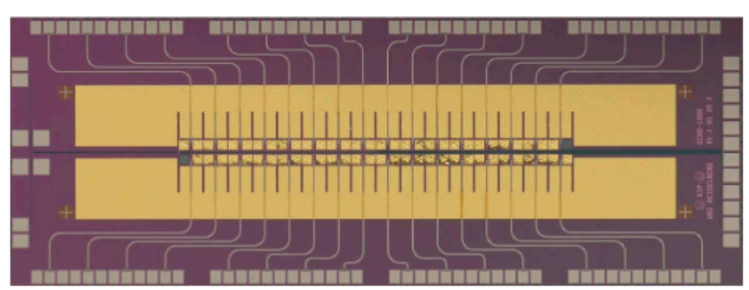
- At least to me their situation is not so clear
- They gave a proof of principle limit in 2019: ***m<150 eV***
- They have some spectra away (E<2.5 keV for EC spectrum, E>3 keV for pileup) of the Q_{EC} analysed with a similar number of channels as HOLMES, but no update of mass result

ECHo-1k chip-Ag
34 pixel with implanted ^{163}Ho
6 background pixels
average activity = 0.71 Bq
total activity of 25.9 Bq

Towards ECHo-100K

ECHo-100k baseline: large arrays of MMCs

Number of detectors:	12000
Activity per pixel:	10 Bq



Present status:

MMCs arrays:	reliable fabrication of large MMC array succesfull characterization of arrays with ^{163}Ho
High Purity ^{163}Ho source:	available about 30 MBq
Ion implantation system:	demostrated co-deposition of Ag for larger activities

- They are working on improving to "EChO-100k"
  - Latest news at Neutrino 2024
- But no plan to go beyond eV mass sensitivity

Next steps with Ho^{163} (discarding EChO)

HOLMES_2: almost there (48/64 TES)

HOLMES_PLUS: 64 → 256 TES

- still a demonstrator, but with:
  - Better implantation technique to increase activity and uniformity across TES's (LNL expertise joining)
  - Decrease per channel cost of read out and DAQ
  - Request: until 2027.
  - Experiment with 1M chns: 2035, m~100 meV (see back up)

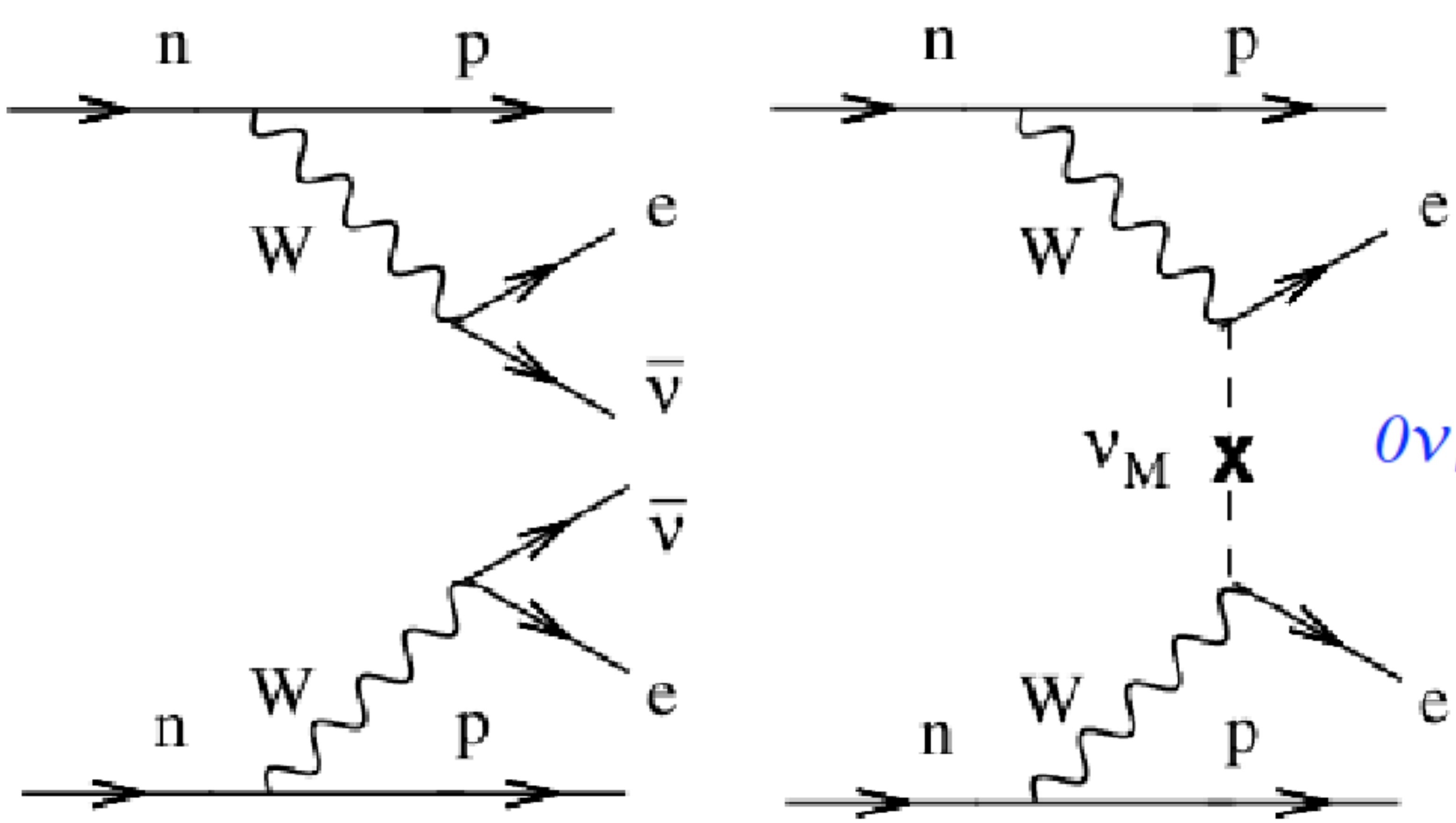
Indirect mass measurements from "exotic" Maiorana mass term

+ : Several isotopes and techniques more or less at same (advanced) stage, ton-scale could bury IO.

- : a bet on neutrino being Maiorana-like and on m(light) <~ 10 meV. Ton scale is costly and money is a problem more than technology

$0\nu 2\beta$ decays

$\Delta L = 2$



$$0\nu\beta\beta : (A, Z) \to (A, Z+2) + 2e^-$$

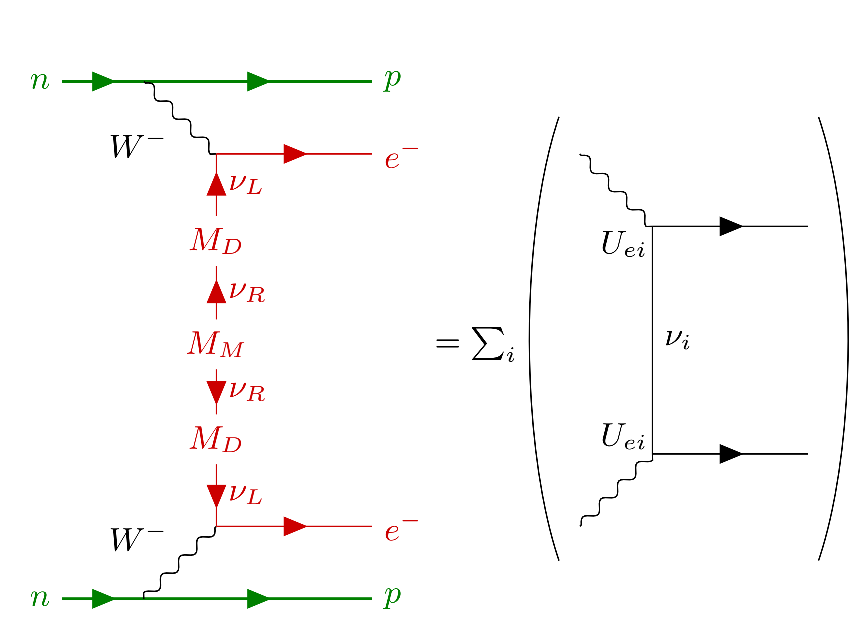
- Could happens if neutrinos are Majorana fermions (Majorana mass term)
- Prosaically: $\nu \equiv \bar{\nu}$
- It's not the only process available, but the one with the highest sensitivity
- Other BSM mechanisms could allow this, but some form of "suppressed Majoranism" should still be underlying

(Majorana!) Neutrino mass

- If process is consequence of Majorana nature, then rate:

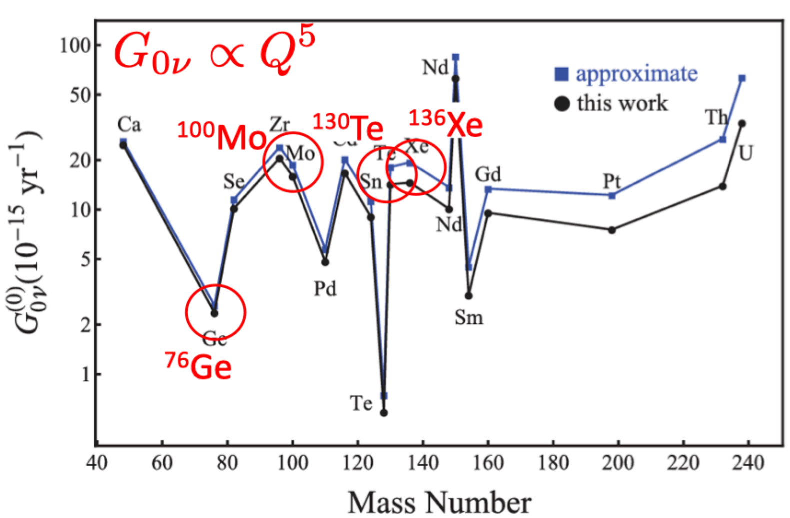
$$\frac{\Gamma^{0\nu}}{\ln 2} = (T^{0\nu}_{1/2})^{-1}$$

$$= G^{0\nu}(Q,Z) g_A^4 |M^{0\nu}|^2 \frac{\langle m^2_{\beta\beta}\rangle}{m_e^2}$$



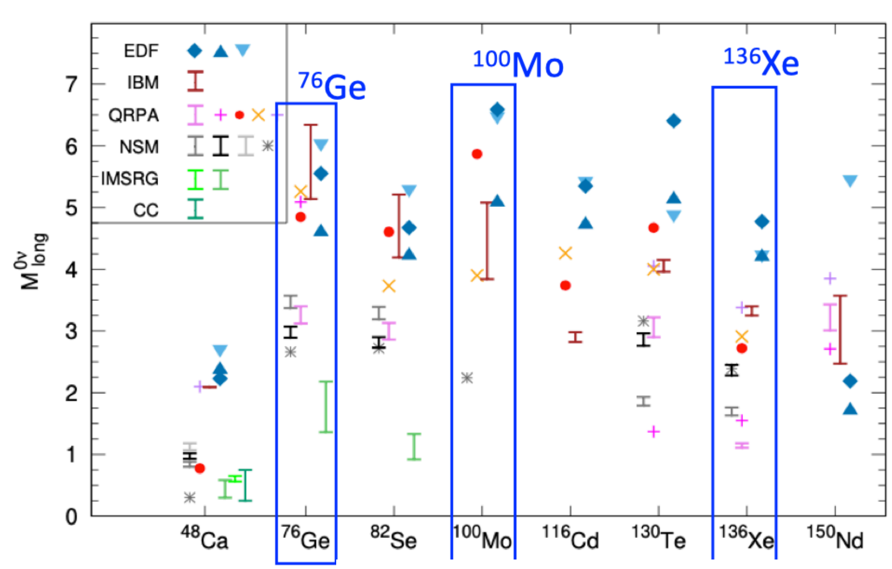
Rev. Mod. Phys. 95, 025002, 2023

Phase space (accurately calculated):



Phys. Rev. C 85, 034316 (2012)

Nuclear Matrix Element (significant theory uncertainty):



Effective Majorana Mass (assumes "standard" mechanism):

$$\langle m_{\beta\beta}\rangle = \left|\sum |U_{ei}|^2 e^{i\phi_i} m_i\right|$$

$$= \left|c^2_{12}c^2_{13}m_1 + s^2_{12}c^2_{13}m_2 e^{i\alpha} + s^2_{13}m_3 e^{i\beta}\right|$$

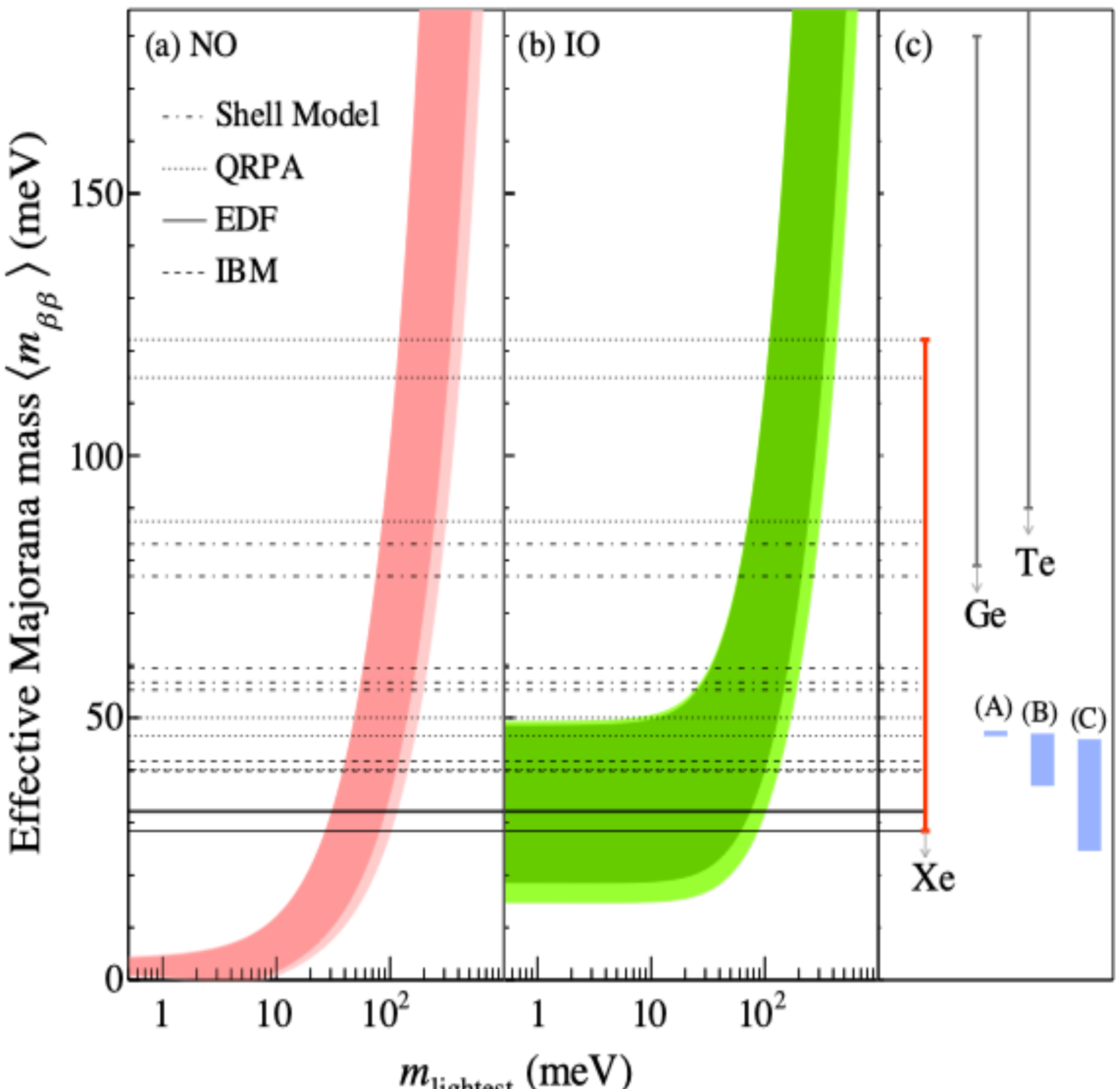
α, β are unknown Majorana phases

→ *Not measurable in oscillation experiments*

This is only one model -- other LNV physics also possible!

Mass ordering sensitivity

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$
$$= \left|m_0 c_{12}^2 c_{13}^2 + \sqrt{m_0^2+\delta m_{\rm sol}^2}\, s_{12}^2 c_{13}^2 e^{2i(\alpha_2-\alpha_1)} + \sqrt{m_0^2+\delta m_{\rm sol}^2+\delta m_{\rm atm}^2}\, s_{13}^2 e^{-2i(\delta_{\rm CP}+\alpha_1)}\right| \quad \text{NO}$$
$$= \left|m_0 s_{13}^2 + \sqrt{m_0^2-\delta m_{\rm atm}^2}\, s_{12}^2 c_{13}^2 e^{2i(\delta_{\rm CP}+\alpha_2)} + \sqrt{m_0^2-\delta m_{\rm sol}^2-\delta m_{\rm atm}^2}\, c_{12}^2 c_{13}^2 e^{2i(\delta_{CP}+\alpha_1)}\right| \quad \text{IO.}$$



KamLAND-Zen Collaboration, 2024
https://arxiv.org/abs/2406.11438

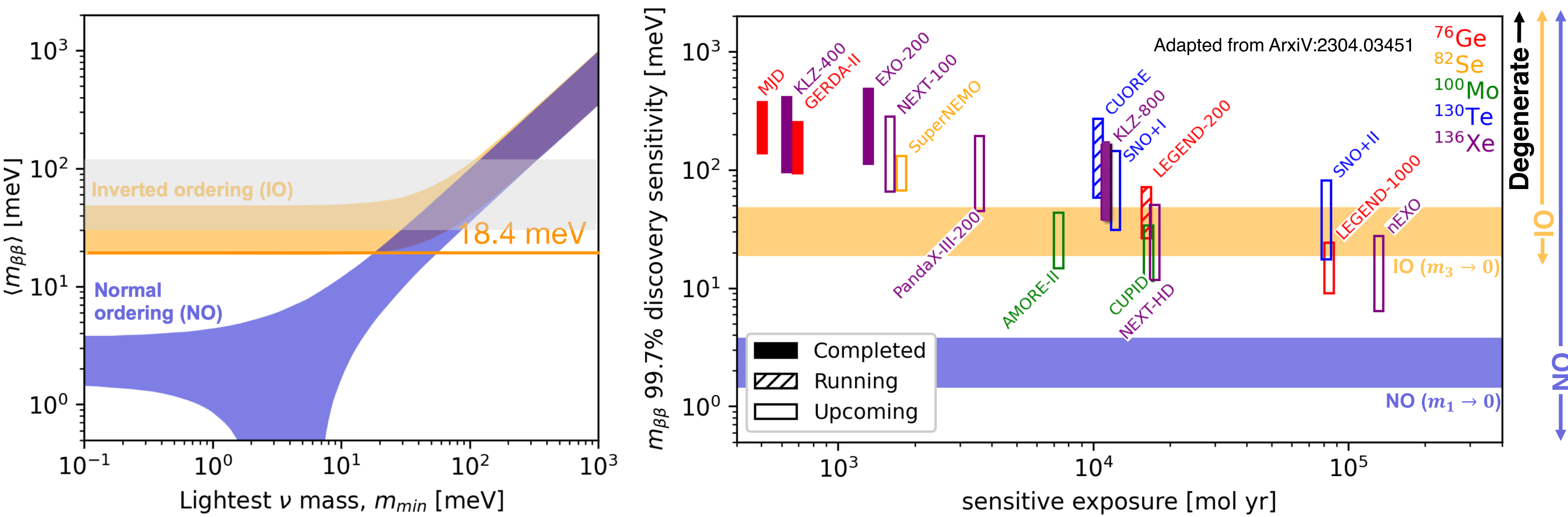
Best limits $m_{\beta\beta}$ < 28-122 meV

Discovery Sensitivity

Nicked from F. Bellini, NOW 2024

$\langle m_{\beta\beta}^2 \rangle \propto (T_{1/2}^{0\nu})^{-1}$

- Bkgd free operation mode $\rightarrow T^{0\nu} \propto \varepsilon m_{iso}^{FV} t$ (isotope-weighted exposure)



Experiments taking data **currently** (both at LNGS)

- CUORE: Ton·yr scale sensitivity now, but background dominated
- LEGEND-200: background-free mode, Ton scale sensitivity expected in few yrs

Future generation experiments designed to cover I.O. region fully (10 Ton · yr)

Lively experimental programme!

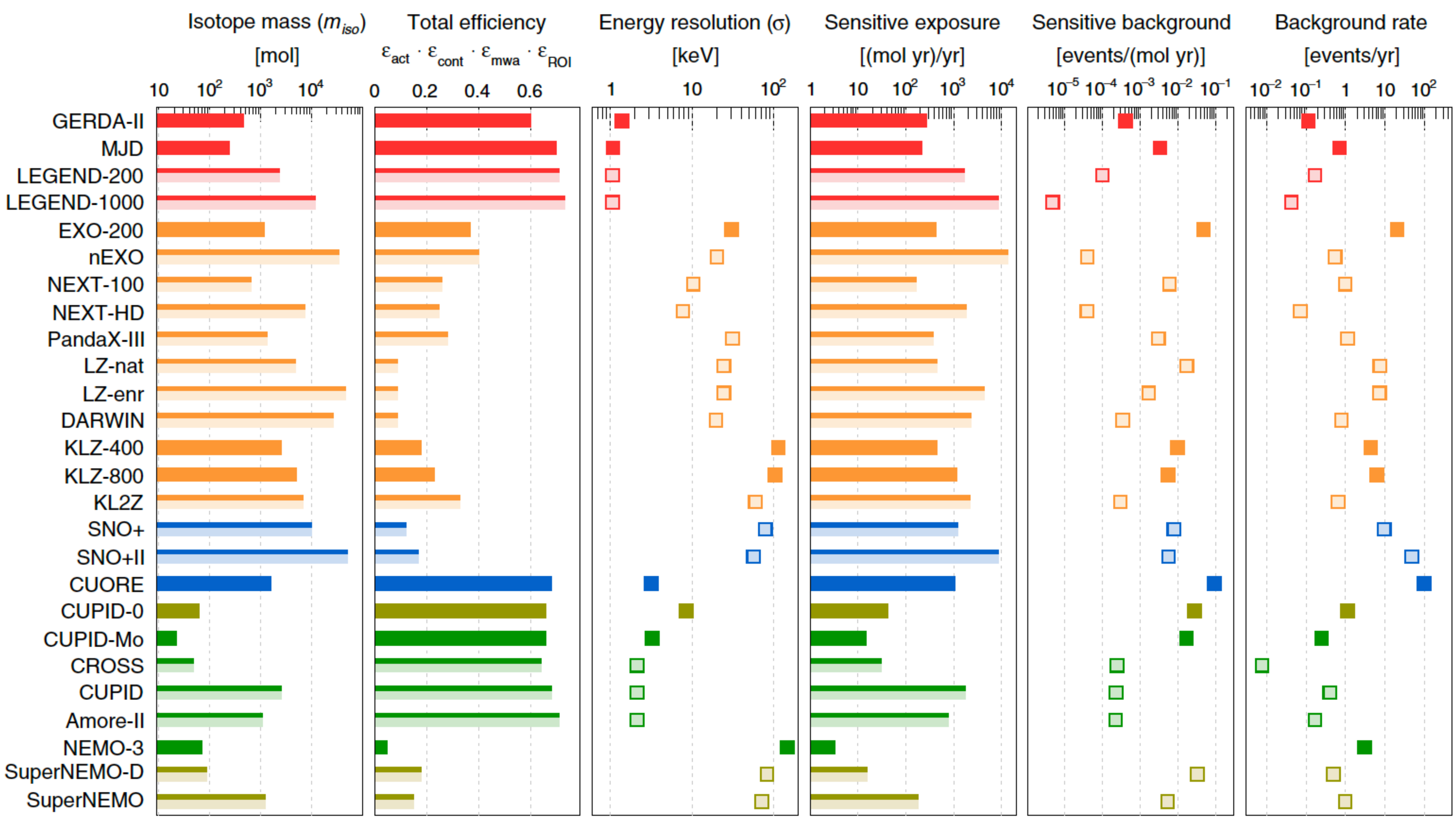
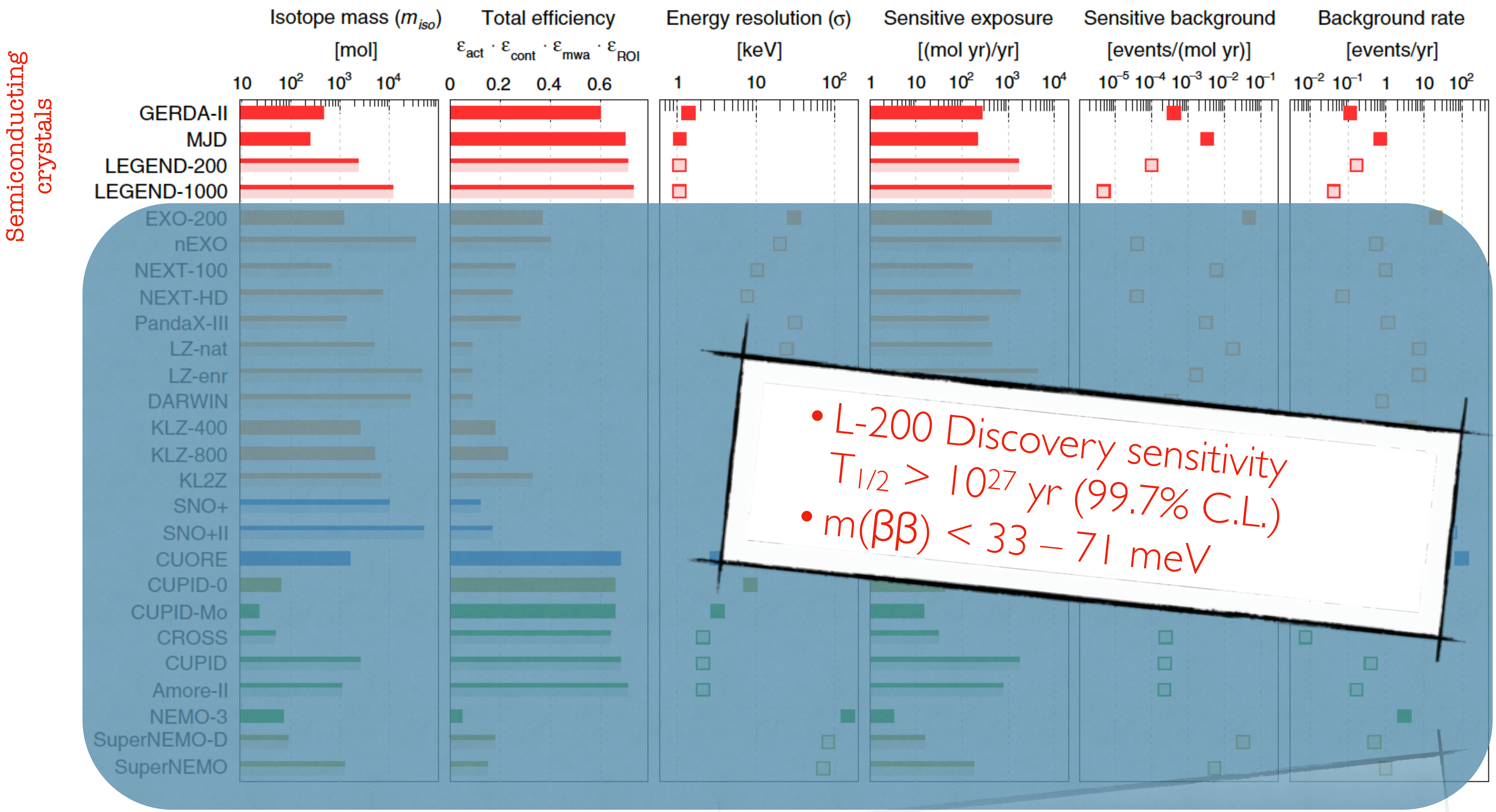


FIG. 20. Fundamental parameters driving the sensitive background and exposure, and hence the sensitivity, of recent and future phases of existing experiments; see Eq. (38). Red bars are used for ^{76}Ge experiments, orange bars are used for ^{136}Xe, blue bars are used for ^{130}Te, green bars are used for ^{100}Mo, and sepia bars are used for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency using gas and liquid detectors, or with small mass but high resolution and efficiency by solid-state detectors. The sensitive exposure is computed for 1 yr of live time. Lighter shades indicate experiments that are either under construction or proposed.

Rev. Mod. Phys. **95**, 025002

Lively experimental programme!



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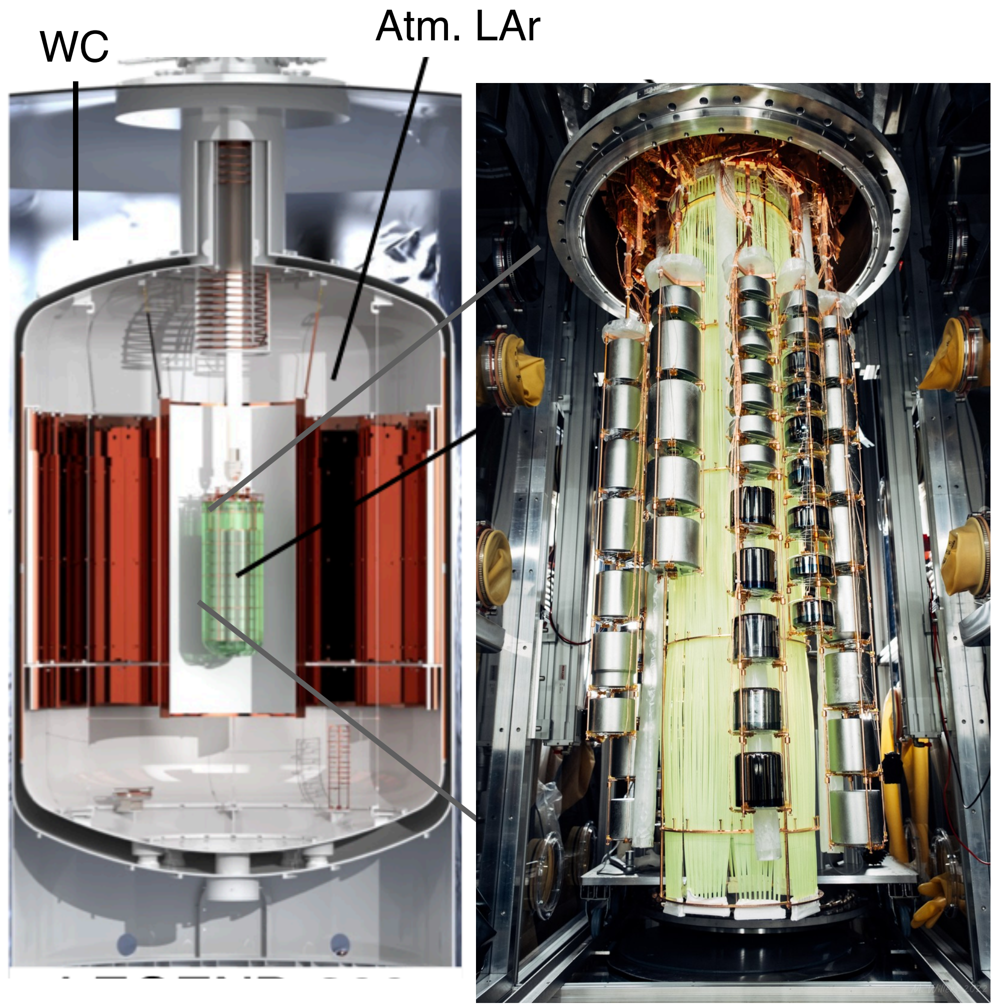
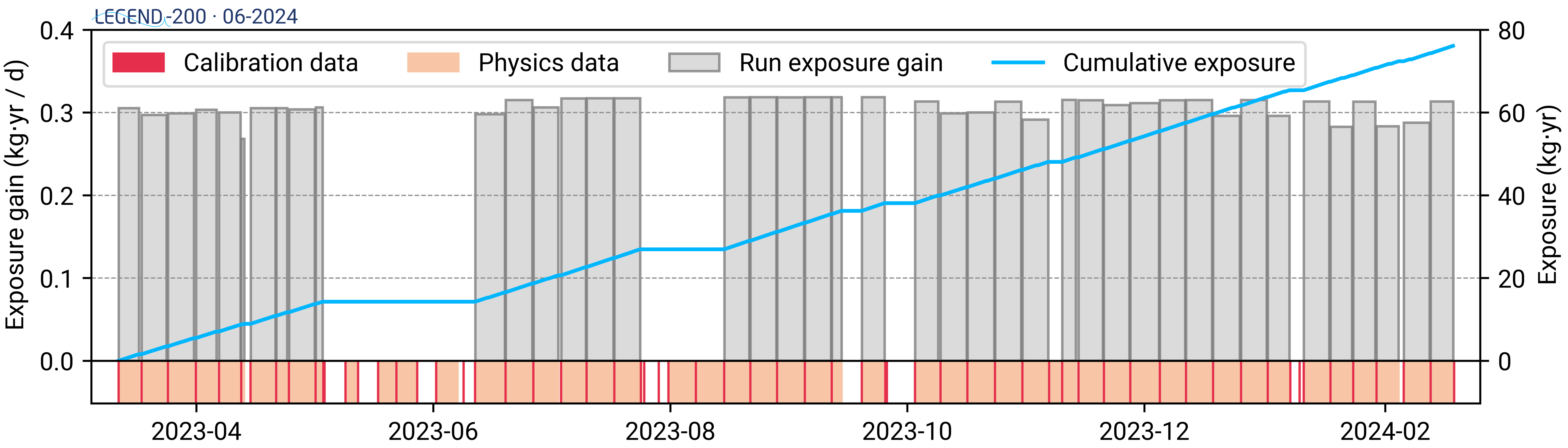
Rev. Mod. Phys. **95**, 025002



LEGEND-200

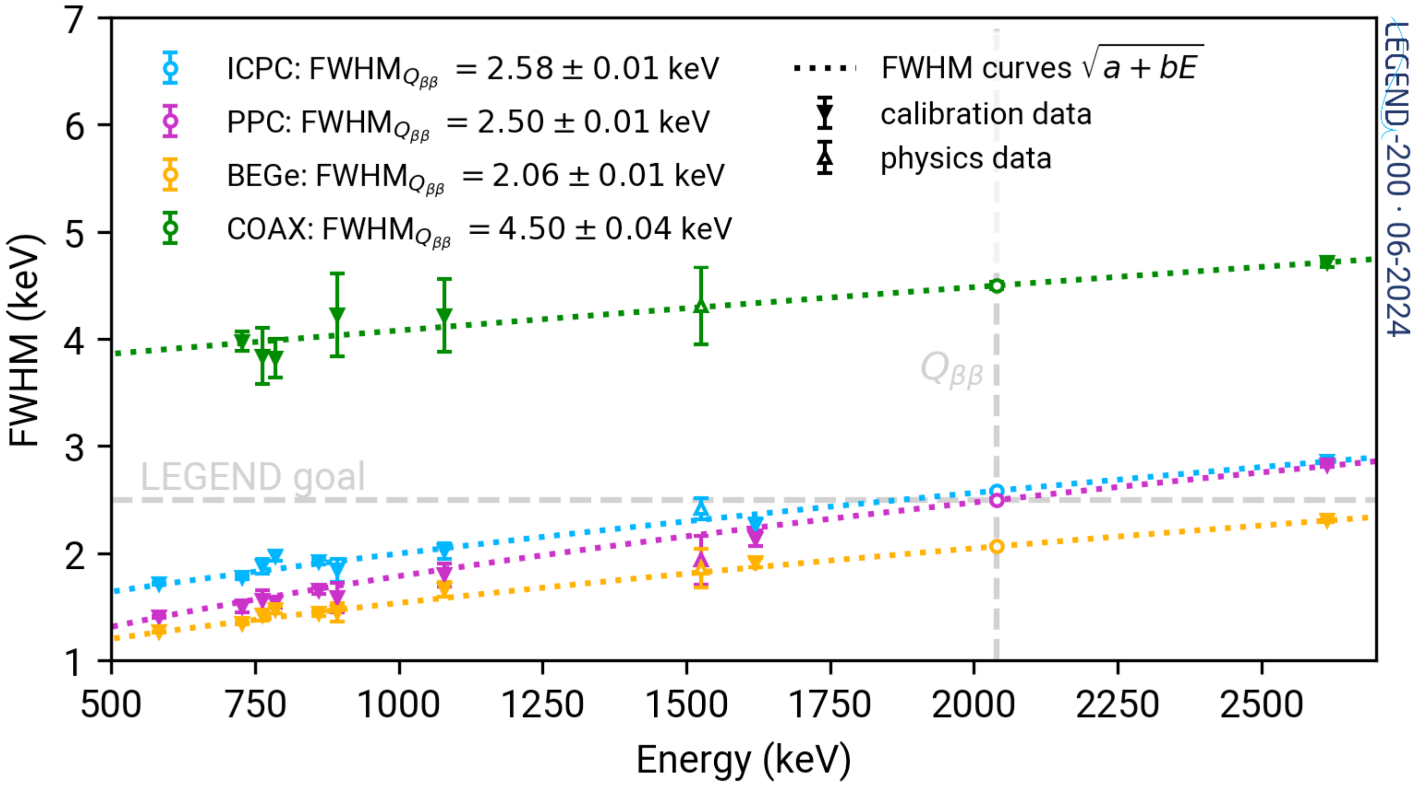
- ☑ Overall exposure so far ~ 80 kg×yr over about 0.7 years of live time (~130 kg active HPGe)
- ☑ "Golden" exposure for 0ν2β search = 48.3 kg×yr

- Plus another about 30 kg yr of "silver" data for bkg characterisation
- About 1 year of maintenance and material screening to reduce background further towards target *(^{228}Th contribution higher than expected, but effectively reduced)*
- Almost ready to resume data taking
  - *Additional about 35 kg of HPGe to be included*



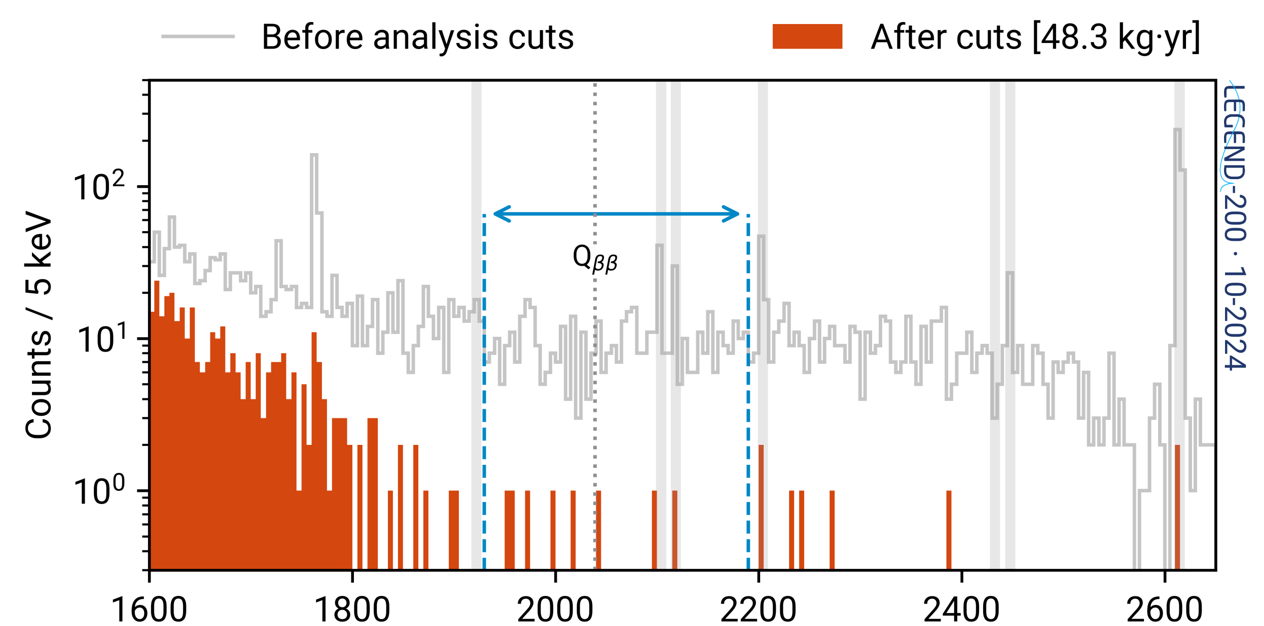
LEGEND-200

Paper in preparation



Overall resolution of 0.1% FWHM at $Q_{\beta\beta}$

- *Energy scale stable over data taking with 0.3±0.2 keV bias at $Q_{\beta\beta}$*
- *ICPC show very good resolution even at higher masses → promising for LEGEND-1000*

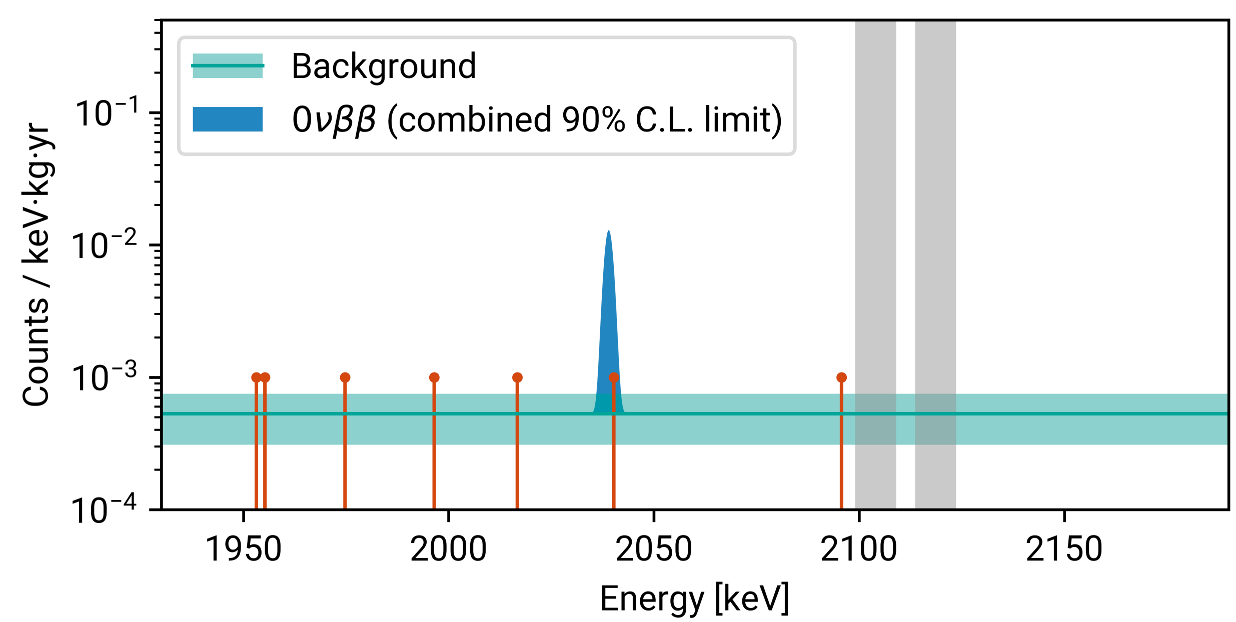


World best exclusion limit from Ge

(L200+Gerda+Majorana Demonstrator, L200 improves by 30%):

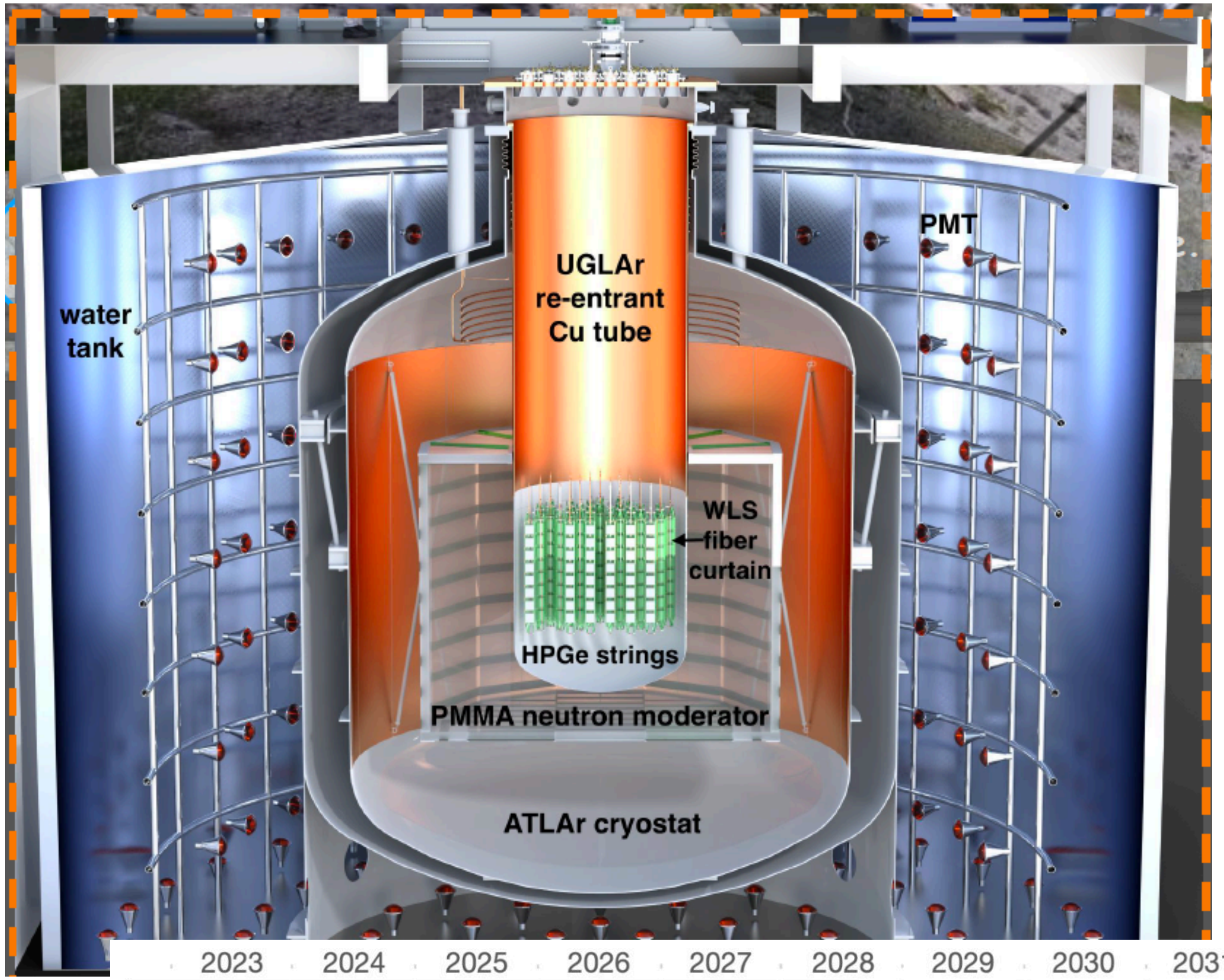
- Sensitivity $T_{1/2} = 2.8 \times 10^{26}$ yr (90% CL)
- Observed $T_{1/2} > 1.9 \times 10^{26}$ yr (90% CL)

- BI = $(5.3 \pm 2.2) \times 10^{-4}$ cts/(keV·kg·yr)
  - Very low thanks to PSD in HPGe and high efficiency of LAr vetoing

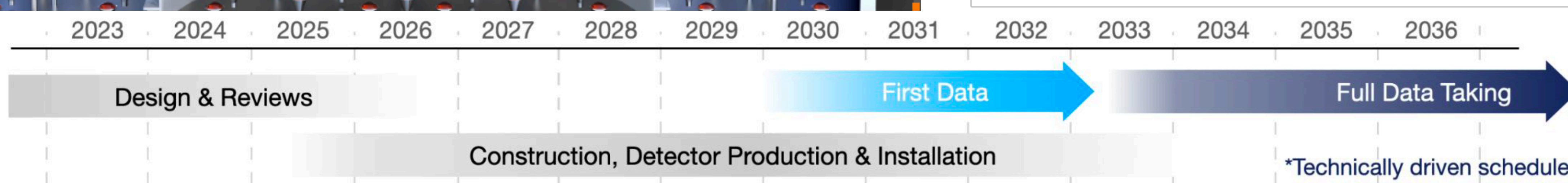


https://agenda.infn.it/event/37867/contributions/233912/

LEGEND-1000



- Independent strings to allow production and independent installation of ~400 HPGe detectors
- Dedicated Underground Ar cryostat, contains HPGe and scintillation detectors, while (cosmogenic) neutron veto system in outer Atmospheric Ar volume
- Expect further improvements: larger ICPC, new electronics, radio-cleaner LAr detector fibers, cleaner Cu



- Projected background in the ROI around $Q_{\beta\beta}(^{76}Ge) = 10^{-5}$ counts/(keV·kg·yr)
- Expected sensitivity $T_{1/2} > 10^{28}$ yr (10 yrs data taking) $\Rrightarrow$ $m_{\beta\beta}$: [10-20] meV
- Brand new infrastructure at LNGS
- Expected start ~ 2030, but subject to HPGe procurement and international funding scenario

Lively experimental programme!

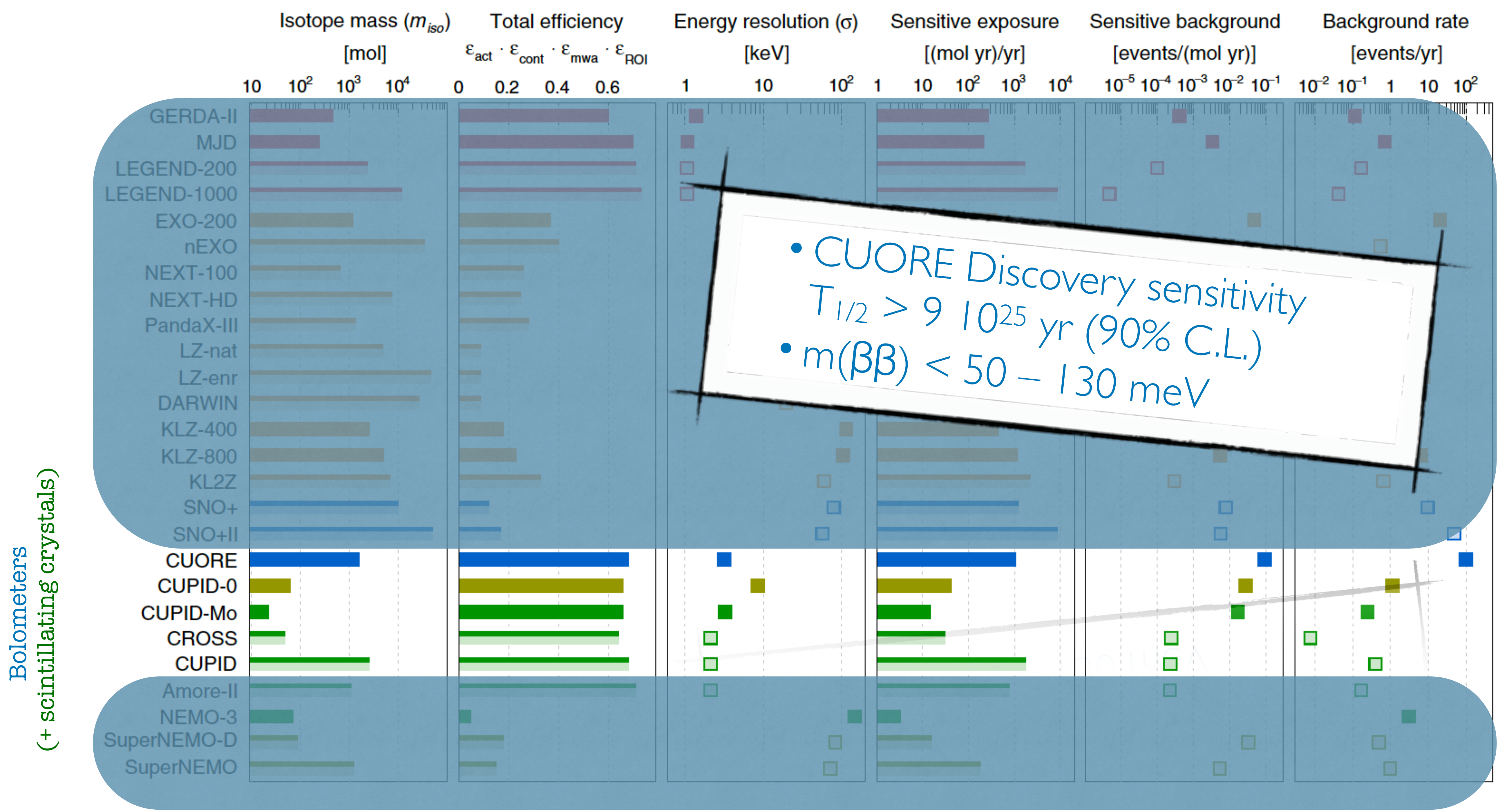
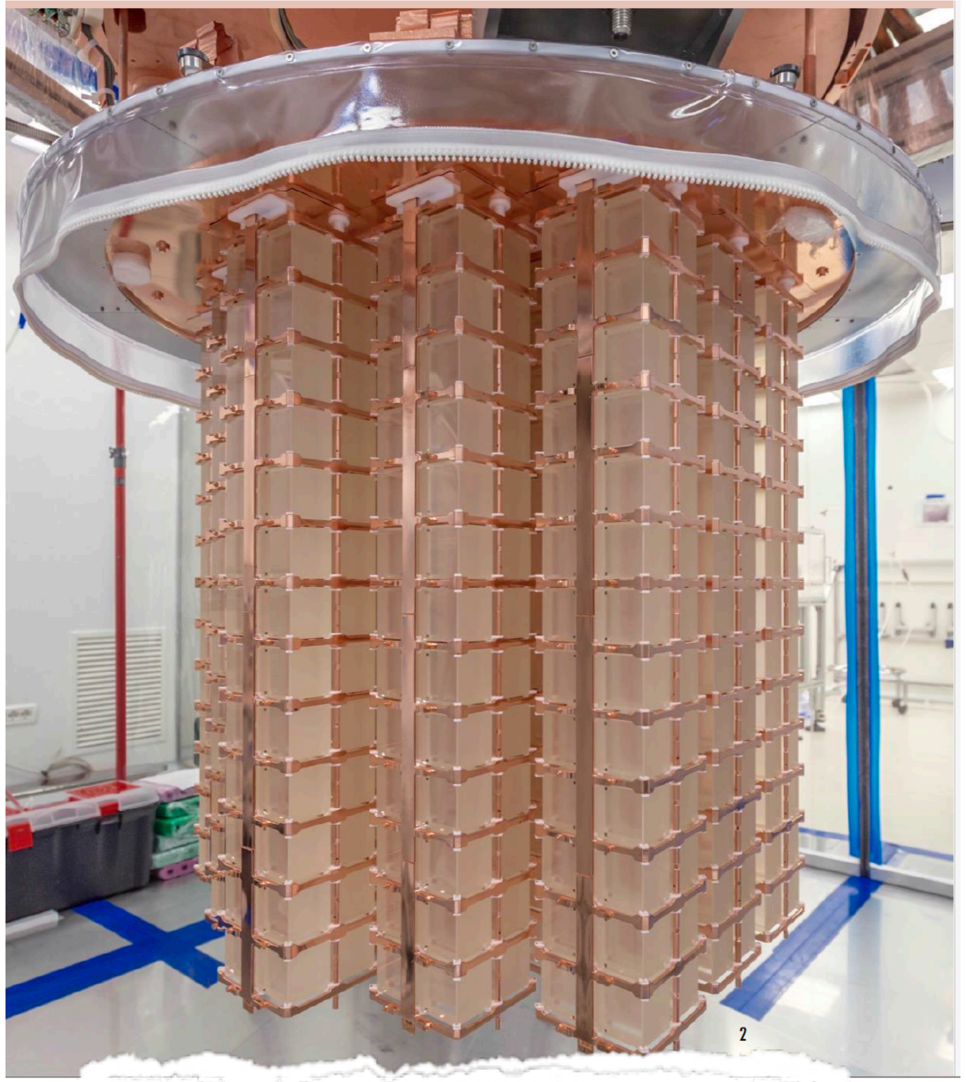
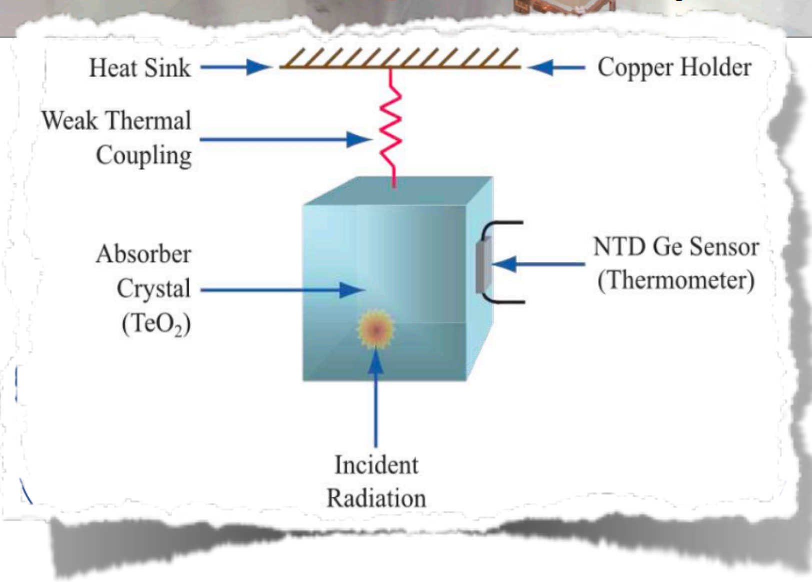


FIG. 20. Fundamental parameters driving the sensitive background and exposure, and hence the sensitivity, of recent and future phases of existing experiments; see Eq. (38). Red bars are used for ^{76}Ge experiments, orange bars are used for ^{136}Xe, blue bars are used for ^{130}Te, green bars are used for ^{100}Mo, and sepia bars are used for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency using gas and liquid detectors, or with small mass but high resolution and efficiency by solid-state detectors. The sensitive exposure is computed for 1 yr of live time. Lighter shades indicate experiments that are either under construction or proposed.

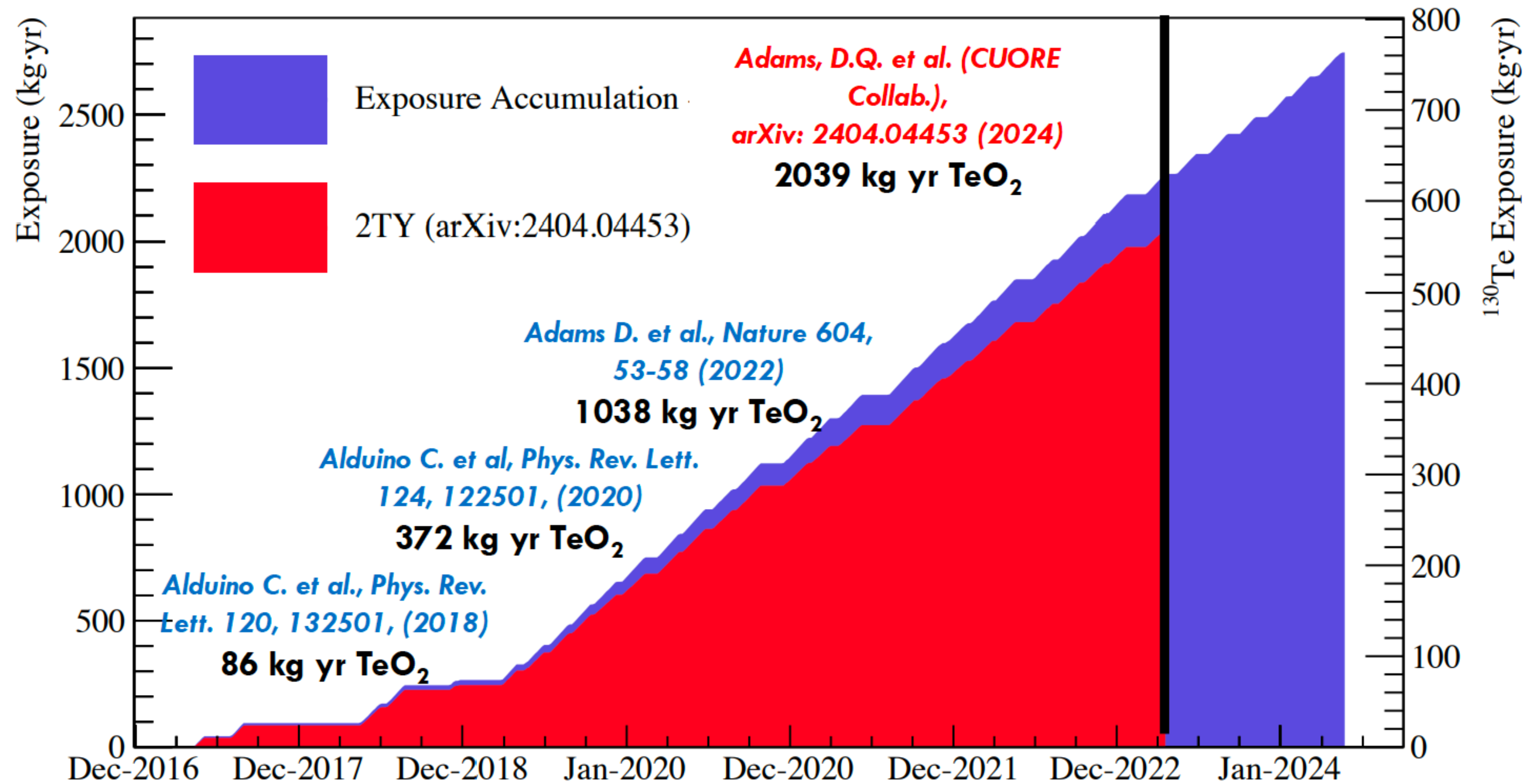
Rev. Mod. Phys. **95**, 025002





CUORE

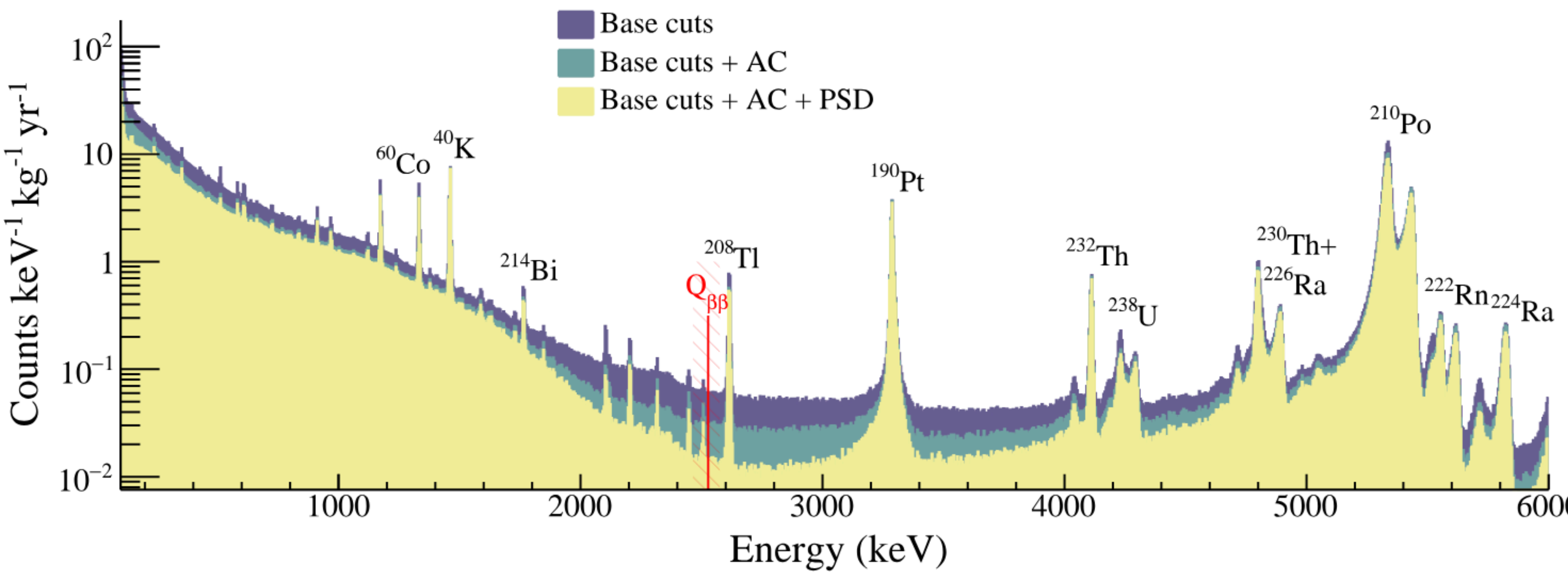
- ☑ Largest and coldest bolometer ever built
- ☑ 19 towers of 52 independent TeO_2 crystals, T=10 mK
  - ☑ Overall 742 kg total mass - 206 kg of ^{130}Te
- ☑ Steadily increasing data set since 2019 has lead to exposure for 0ν2β search = 2039 kg×yr worth of TeO_2 (567 kg×yr of ^{130}Te)



- ☑ ΔE_{FWHM} @ $Q_{\beta\beta}$ = 2527 keV: 7.3 keV
  - Continuously monitoring detector stability (NTD resistance and Pulse Tubes)

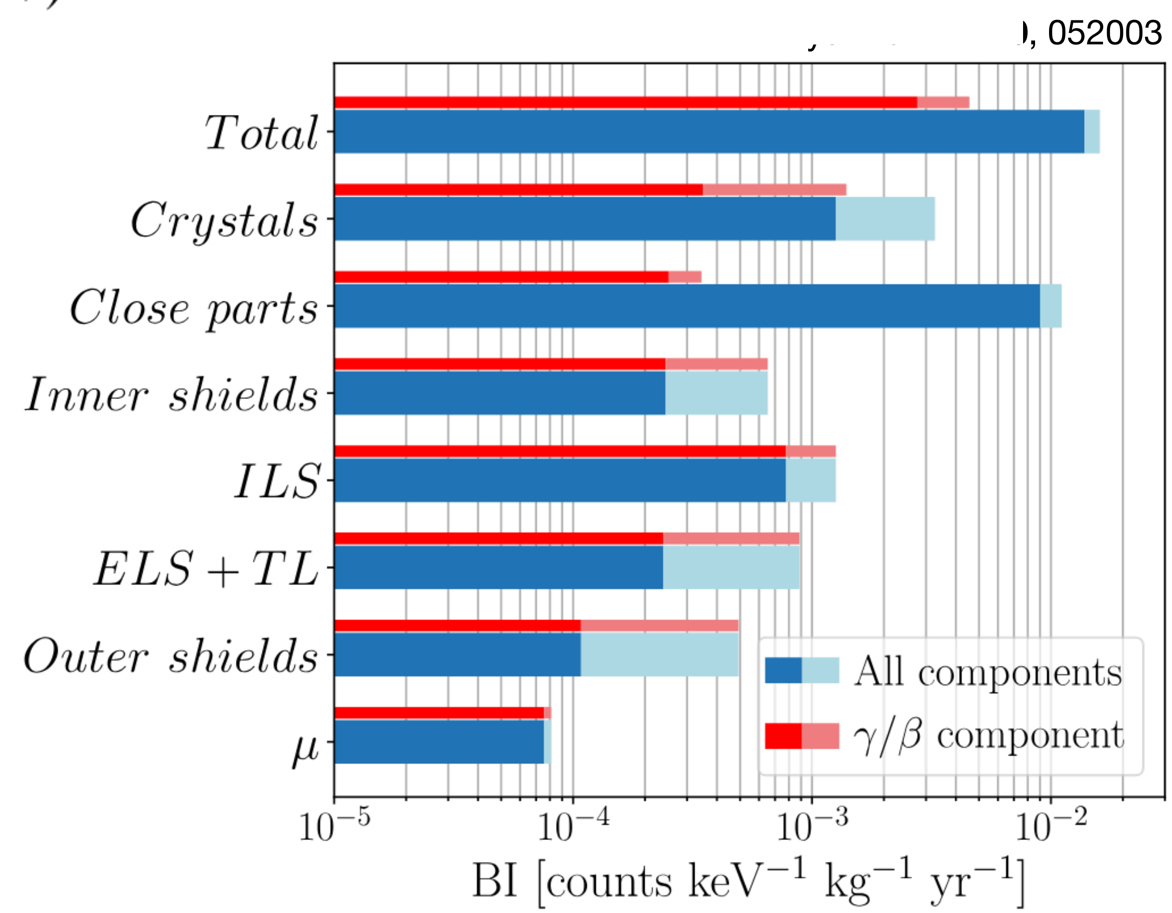
CUORE

arXiv:2404.04453



- Results from Te (arXiv:2404.04453)
  - Sensitivity $T_{1/2} = 4.4 \times 10^{25}$ yr (90% CL)
  - Observed $T_{1/2} > 3.8 \times 10^{25}$ yr (90% CL)

  - BI = $(1.42 \pm 0.02) \times 10^{-2}$ cts/(keV·kg·yr)
    - Mostly dominated by α particles from "close parts" (PTFE spacing, Cu supports, etc)

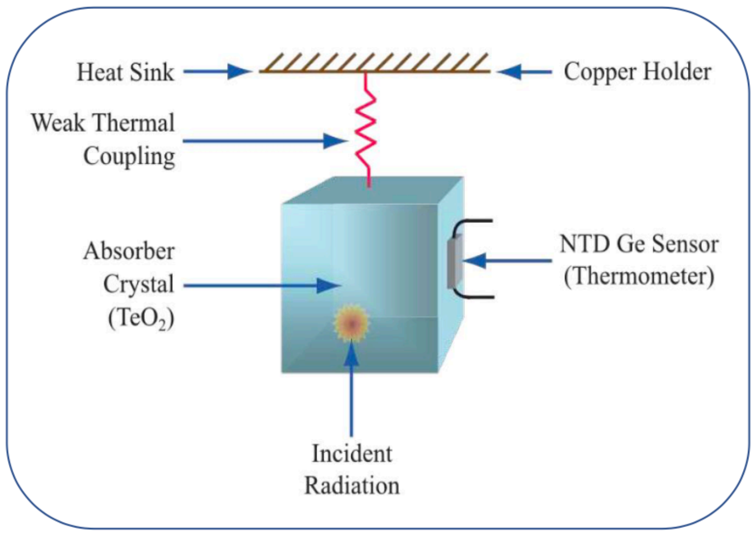


arXiv:1907.09376

CUPID

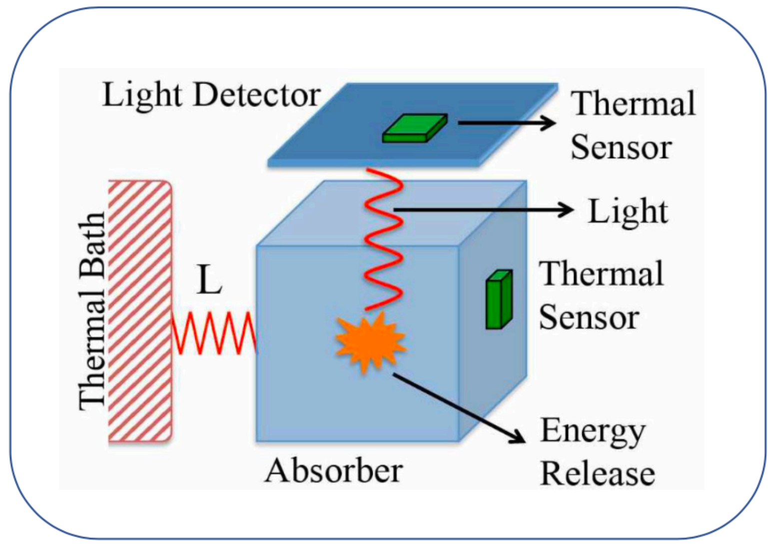
- Identify and suppress α radiation by conjugating scintillation capabilities and bolometer energy resolution → leverages on experience and achievements of CUORE and CUPID0/CUPID-Mo
- Re-use CUORE infrastructure + 1600 $Li_2{}^{100}MoO_4$ (⇒240 kg ^{100}Mo)

CUORE ^{130}**Te**
pure thermal detector
(bolometer)



No PID
Q = 2527 keV < 2615 keV

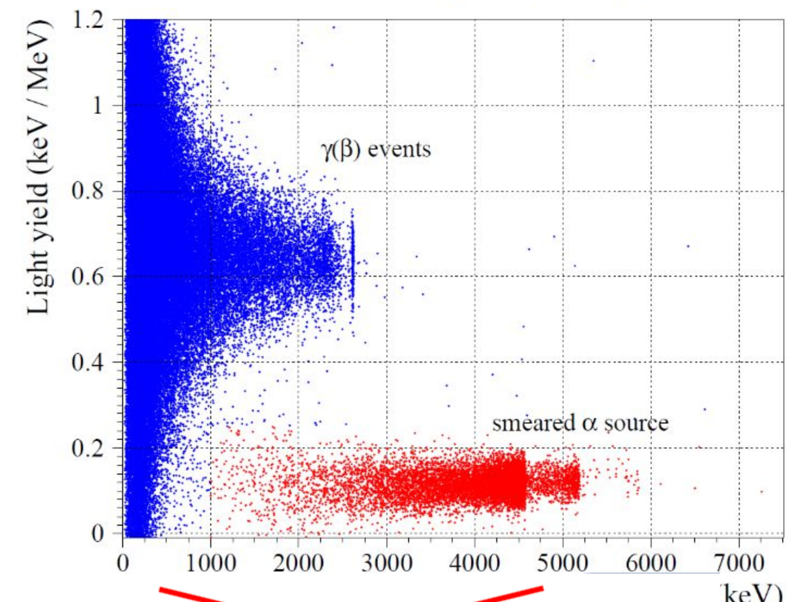
CUPID ^{100}**Mo**
heat + light
(scintillating bolometer)



PID
Q = 3034 keV > 2615 keV

Nicked from F. Bellini, NOW 2024

LMOenr, Th (125 h)



~~α background~~
~~γ background~~

- Projected background in the ROI around $Q_{\beta\beta}(^{100}Mo) = 10^{-4}$ counts/(keV·kg·yr)
- Expected sensitivity $T_{1/2} > 10^{27}$ yr (10 yrs data taking) ⇒ $m_{\beta\beta}$: [12-20] meV
- Re-use CUORE infrastructure at LNGS
- Expected start ~ 2030, but subject to crystal procurement and international funding scenario

Lively experimental programme!

FIG. 20. Fundamental parameters driving the sensitive background and exposure, and hence the sensitivity, of recent and future phases of existing experiments; see Eq. (38). Red bars are used for ^{76}Ge experiments, orange bars are used for ^{136}Xe, blue bars are used for ^{130}Te, green bars are used for ^{100}Mo, and sepia bars are used for ^{82}Se. Similar exposures are achieved with high mass but poorer energy resolution and efficiency using gas and liquid detectors, or with small mass but high resolution and efficiency by solid-state detectors. The sensitive exposure is computed for 1 yr of live time. Lighter shades indicate experiments that are either under construction or proposed.

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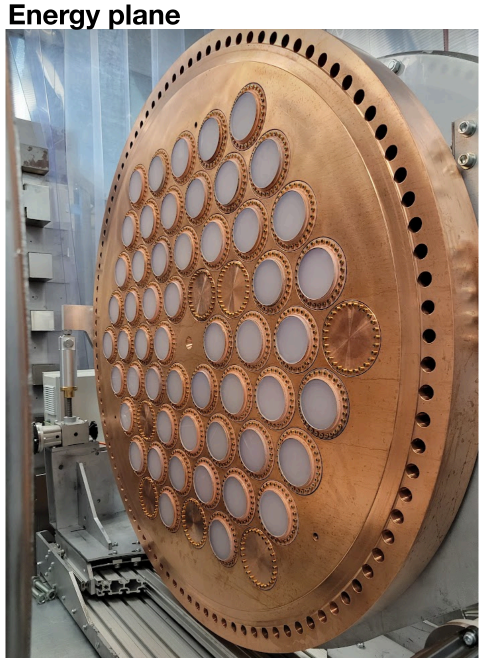
JHEP 2016, 159

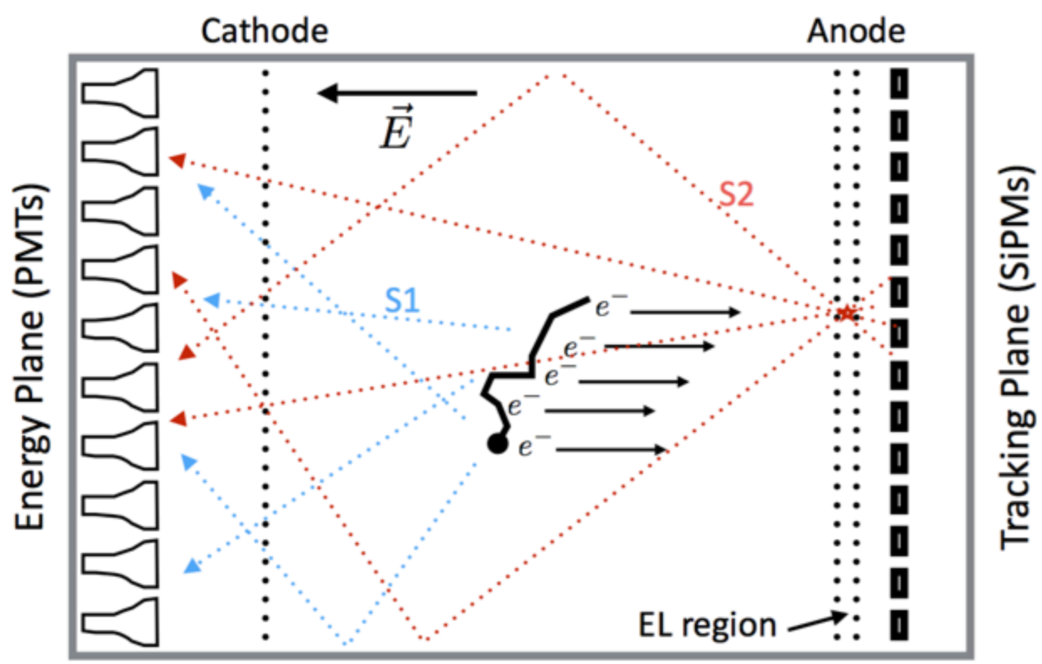
NEXT-100

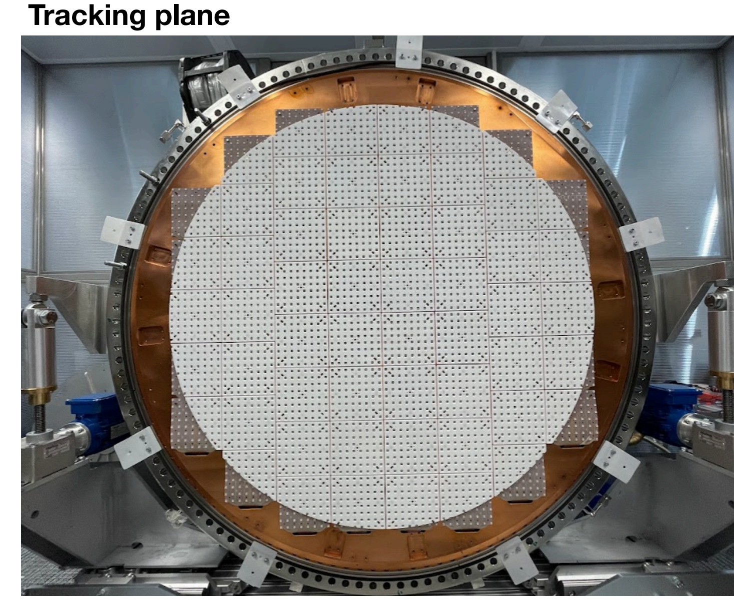
- 100 kg 90% enr. ^{136}Xe High Pressure (15 bar) gas TPC with Electroluminescence amplification:
  - Primary scintillation z coordinate + EL for tracking (SiPM) and energy resolution (PMT) ⇨ topological information
- Started operations in 2024, with initial run at 5 bar due to PMT support Cu plate deformation
  - Solution now found, high pressure run will start this summer. 2027: upgrade to Fiber barrel and novel ASIC SiPM read out ⇨ demonstrator for NEXT-HD

☑ **Expected ΔE_{FWHM} @ $Q_{\beta\beta}$ = 2459 keV: ~ 12 keV**, as extrapolated from current analysis of ^{83}Kr decays

Projected bkg: 4 × 10^{-4} cts/(keV·kg·yr) ⇨ $T_{1/2}$ ~6 × 10^{25} yr, $m_{\beta\beta}$: [66-281] meV (3 effective yrs)



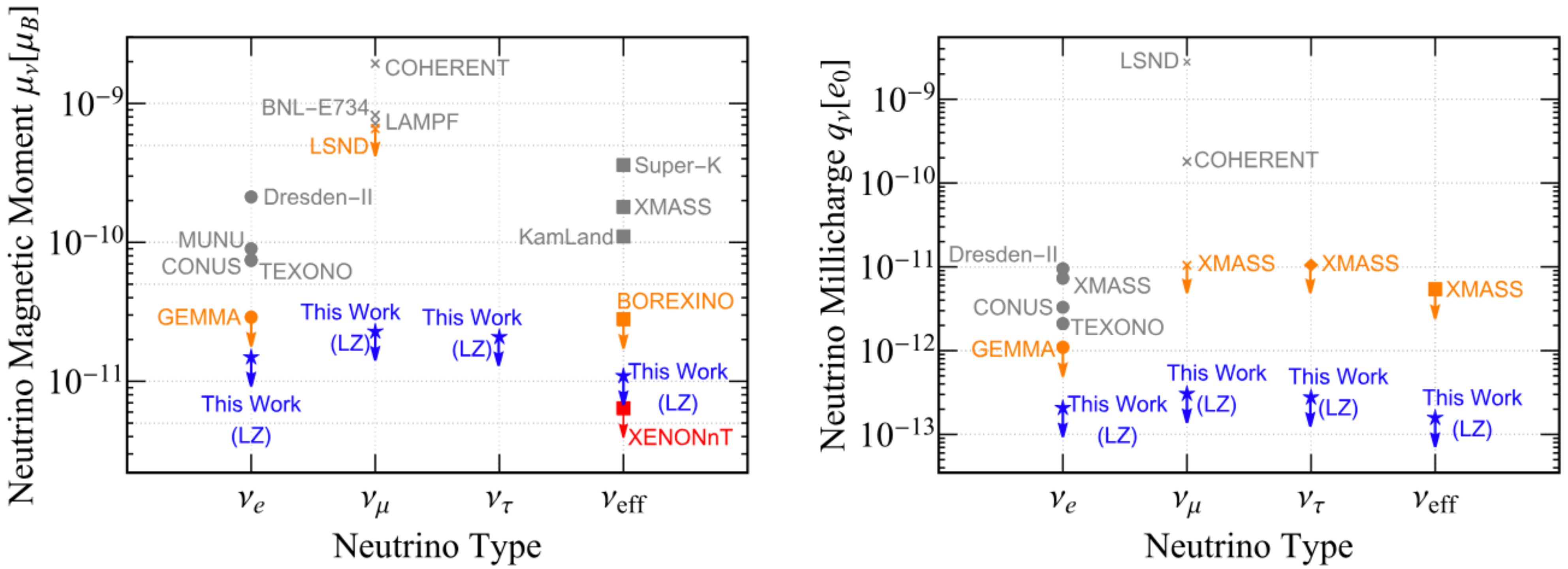




- NEXT-HD (2030): 1 Ton central cathod symmetric + SiPM readout+barrel fiber detector
  bkgd: 5 10^{-5} ckky ⇨.$T_{1/2}$ ~2 × 10^{27} yr $m_{\beta\beta}$: [12-50] meV (10 yrs)
- R&D NEXT-BOLD(Barium iOn Light Detector): NEXT-HD + Ba^{++} tag. Fluorescence Imaging of Individual Ions and Molecules in Pressurized Noble Gases (arXiv: 2406.15422) $T_{1/2}$ ~8 × 10^{27} yr, $m_{\beta\beta}$: [6-27] meV

New constraint on neutrino magnetic moment and neutrino millicharge from LUX-ZEPLIN dark matter search results

$\mu_{eff} < 1.1 \times 10^{-11} \mu_B$ at 90% C.L., $|q_{eff}| < 1.5 \times 10^{-13}\ e_0$ at 90% C.L.



(a) (b)

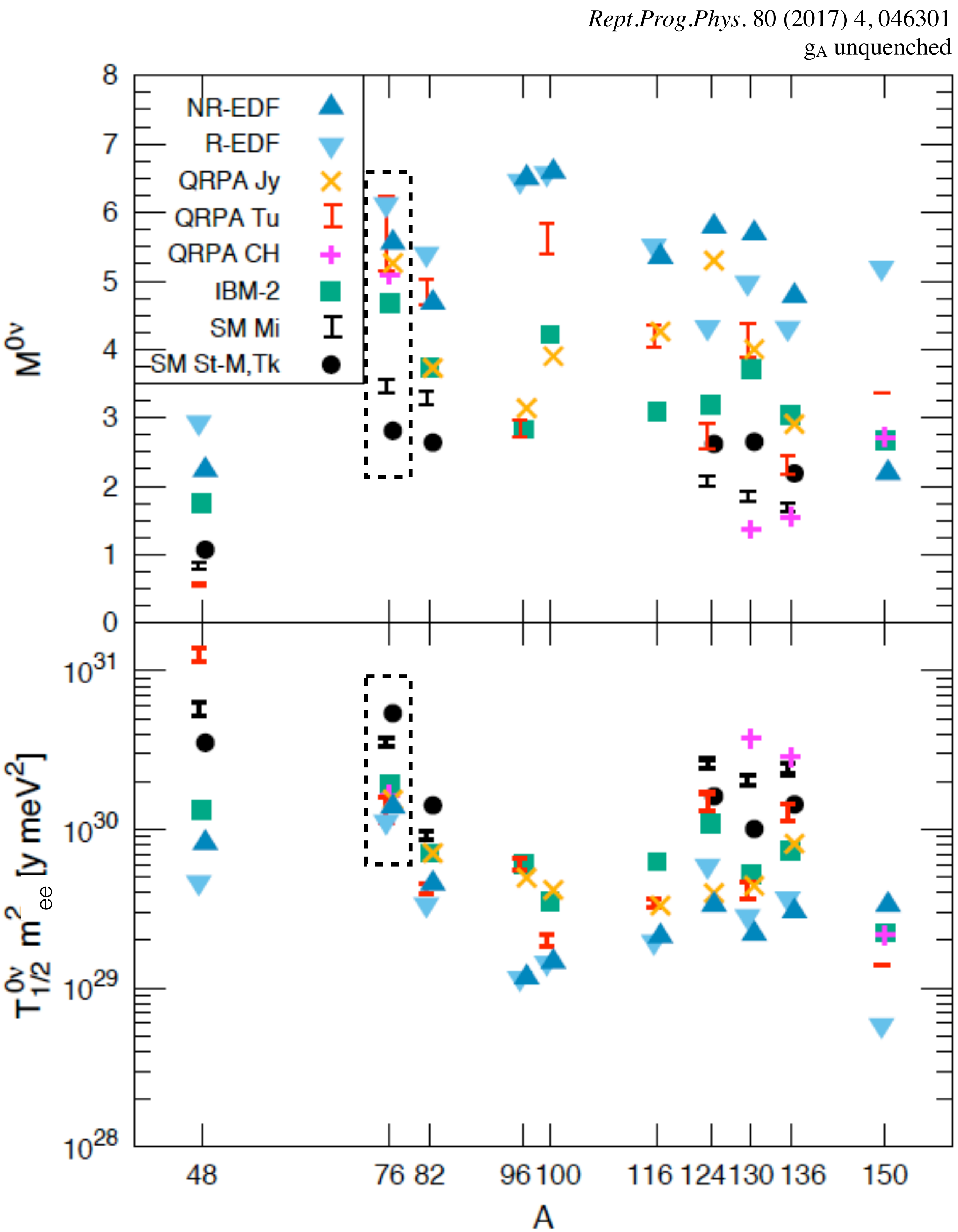
FIG. 5. Summary of existing limits at 90% C.L. on the neutrino magnetic moment (a) and the neutrino millicharge (b) coming from a variety of experiments [6,8,15,24,48,56–63]. The limits are divided in flavor components μ_{ν_e} (q_{ν_e}) (dots), μ_{ν_μ} (q_{ν_μ}) (crosses), and μ_{ν_τ} (q_{ν_τ}) (diamonds) and also the ones on the effective magnetic moment μ_ν^{eff} (q_ν^{eff}) (squares) are shown. In orange, we highlighted the best limits before the LZ data release and in red the XENONnT limit on the MM [12]. The results derived in this work for the effective parameter as well as divided in flavors are shown by the blue stars.

Cadeddu et al PHYS. REV. D 107, 053001 (2023)

No conclusions.

Back up

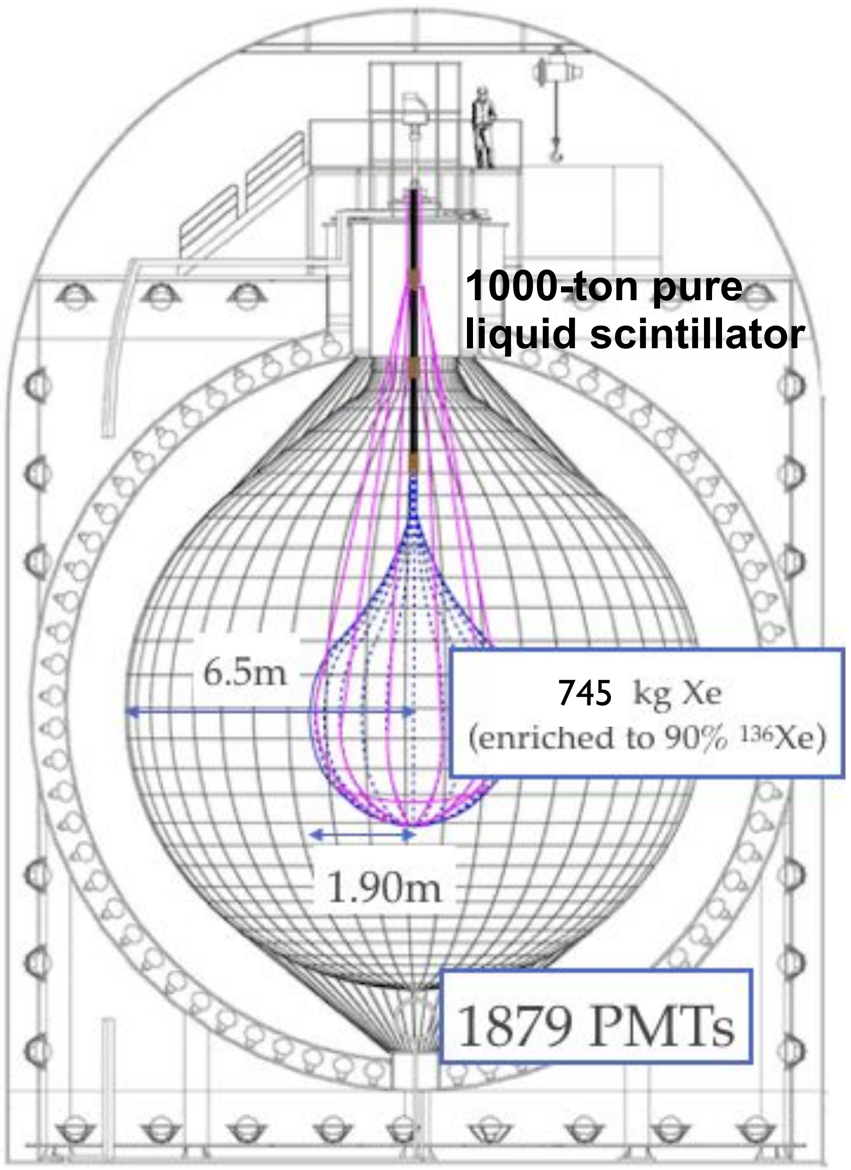
Nuclear Matrix Element values from various nuclear models

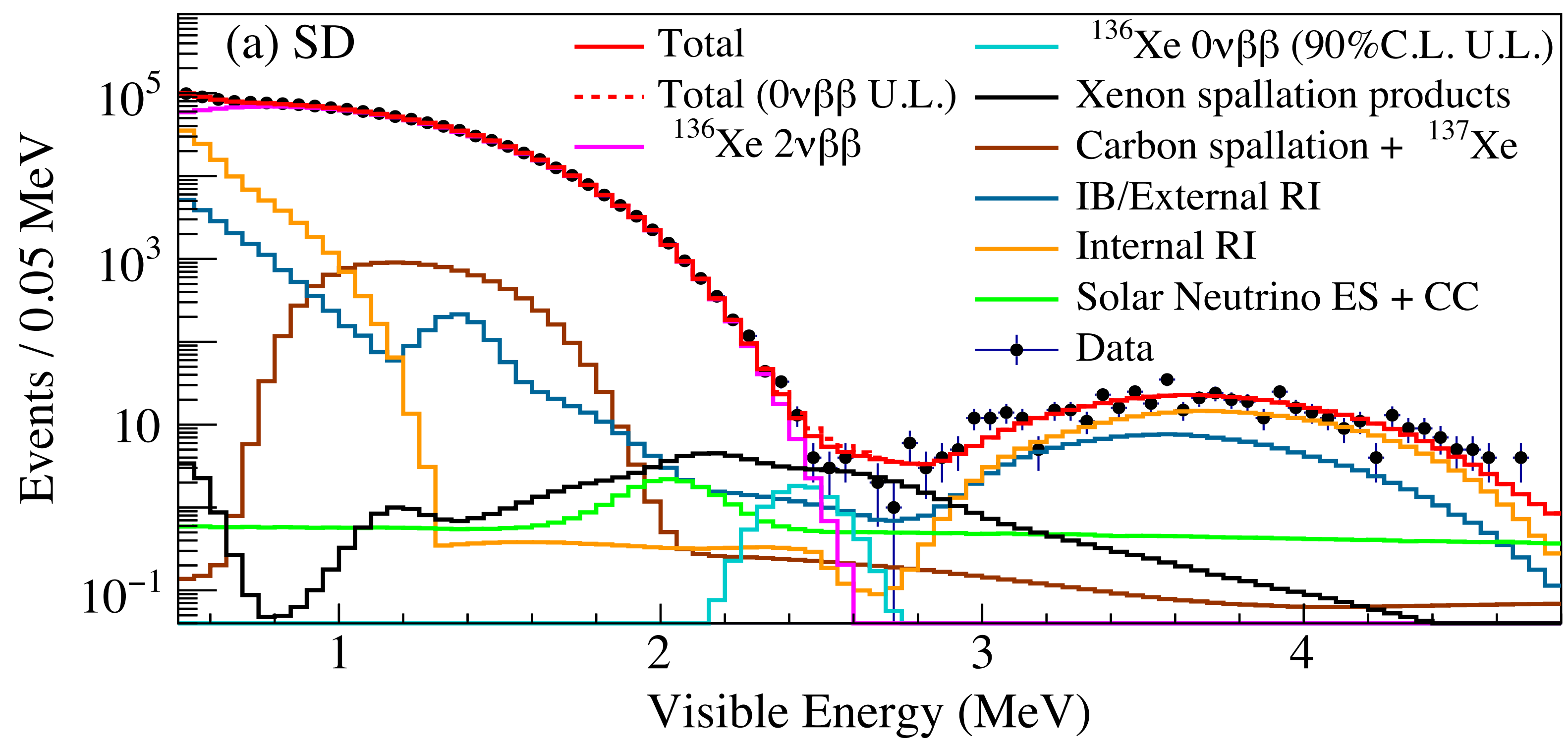


- Various models predict quite different values, throughout the isotope A range
- Affects the conversion from $T_{1/2}$ to m_{ee}

KAMLAND-ZEN

- 745 kg 90% enr. ^{136}Xe diluted in liquid scintillator in acrylic inner balloon inside KamLAND





- Very easily scalable and very good radio purity
- ΔE_{FWHM} @ $Q_{\beta\beta}$ (^{136}Xe) : 250 keV

☑ Combined with KLZ-400, total exposure ~ 2500 kg yr
- Observed $T_{1/2} > 3.8 \times 10^{26}$ yr (90% CL)
- 59 events in the energy region 2.35 < E < 2.70 MeV within the 1.57-m-radius spherical volume were observed ⇢ ~4 10^{-2} cts/(FWHM*kg*yr)

☑ Upgrade **KL2-Zen** will improve x2 energy resolution with increased isotope mass
- Projected sensitivity $T_{1/2} > 10^{27}$ yr in 10 years

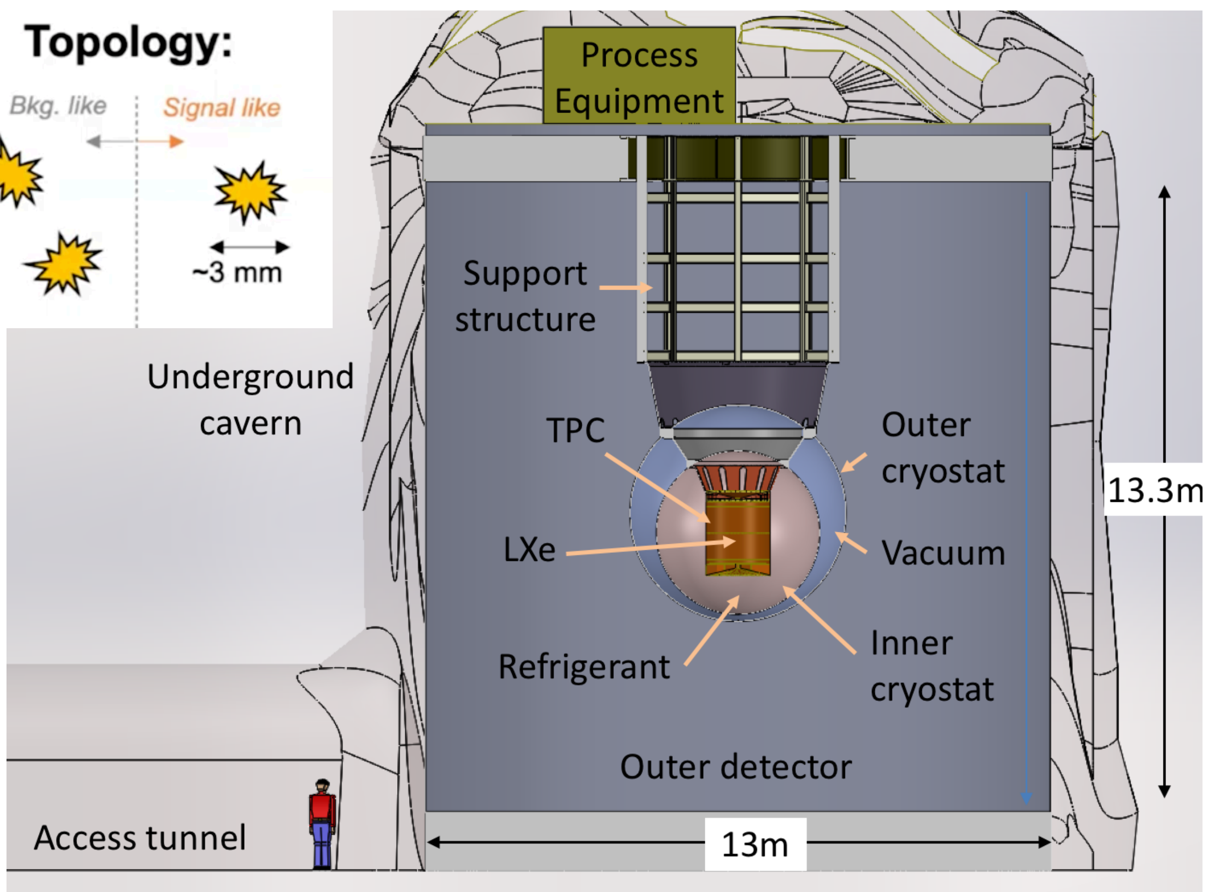
EXO-200/NEXO

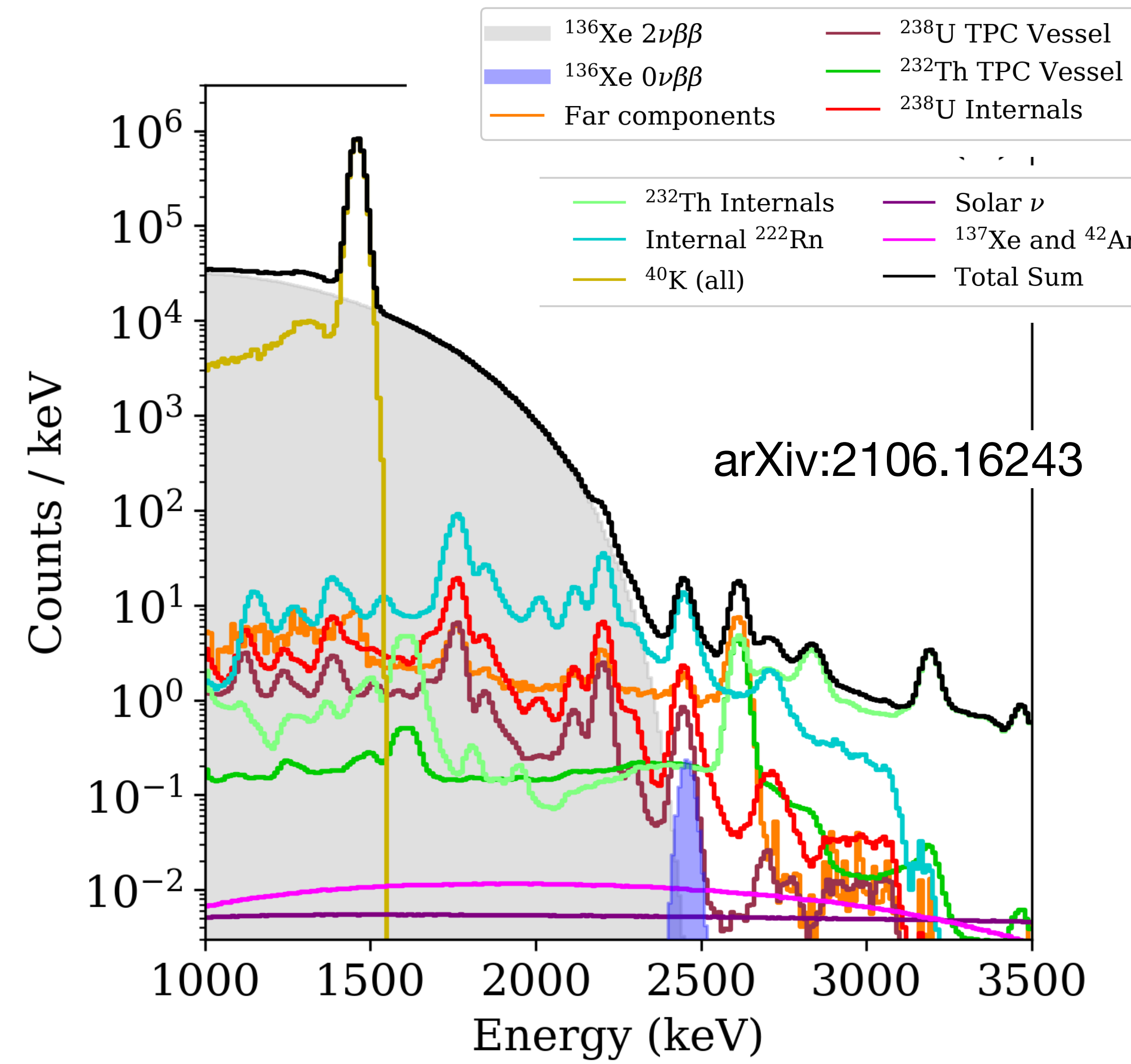
PRL. 123 (2019) 16, 161802

- **EXO200**: 200 kg LXe TPC(80% ^{136}Xe)
  - Reading and correlating ionisation and scintillation signals
  - ΔE_{FWHM} @ $Q_{\beta\beta}$: 66 keV

☑ Total exposure ~ 234.1 kg yr (completed)

- Observed $T_{1/2} > 3.5 \times 10^{25}$ yr (90% CL)
- BI = 1.7×10^{-3} cts/(keV·kg·yr)





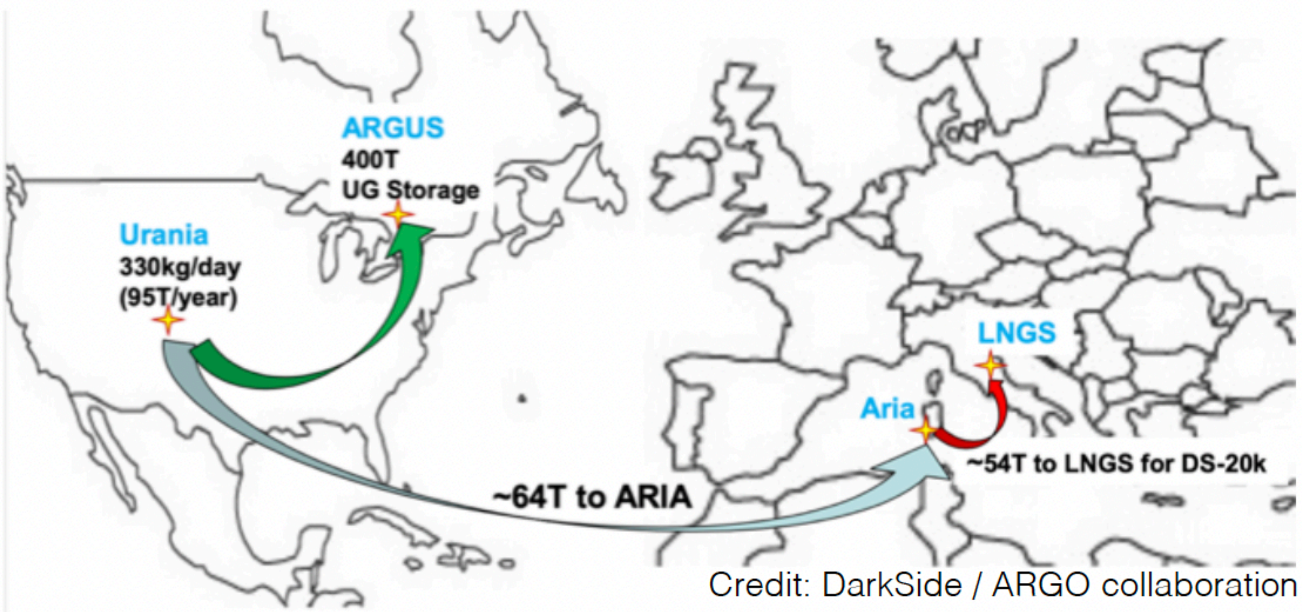
- **nEXO**: 5 Ton
- Self shielding but no staged (FV 80%)
- APD→SiPM, Electro-formed Cu

Projected bkg: 5 10^{-6} cts/(keV·kg·yr) + $\sigma_E/E<1\%$

$T_{1/2}$ ~7 10^{27} yr, $m_{\beta\beta}$: [6-27] meV

The Baseline Design: Underground Liquid Argon

- L1000 needs 20-25 t of UGLAr
- Builds on pioneering work of DarkSide collaboration
- UGAr will be mined at Urania facility (U.S.) 95 t/y
- Logistics and storage technology under development by DarkSide/ARGO collaboration for LNGS and SNOLAB
- Expression of interest from INFN president[1] and DarkSide leadership
- UGAr production for LEGEND-1000 in 2023 (after DS-20k)



Credit: DarkSide / ARGO collaboration

UGAr is depleted in ^{42}Ar (^{39}Ar)

Isotope	Abundance	Half-life ($t_{1/2}$)	Decay mode	Product
^{36}Ar	0.334%	stable		
^{37}Ar	syn	35 d	ε	^{37}Cl
^{38}Ar	0.063%	stable		
~~^{39}Ar~~	~~trace~~	~~269 y~~	~~β^-~~	~~^{39}K~~
^{40}Ar	99.604%	stable		
^{41}Ar	syn	109.34 min	β^-	^{41}K
~~^{42}Ar~~	~~syn~~	~~32.9 y~~	~~β^-~~	~~^{42}K~~

[1] " ...we are confident that the production of the required UAr can be completed in a time scale useful for the accomplishment of the LEGEND-1000 experiment.. The present statement is an expression of interest and availability from INFN..."

NIM A, Volume 396, Issue 3, 1997, Pages 360-370,

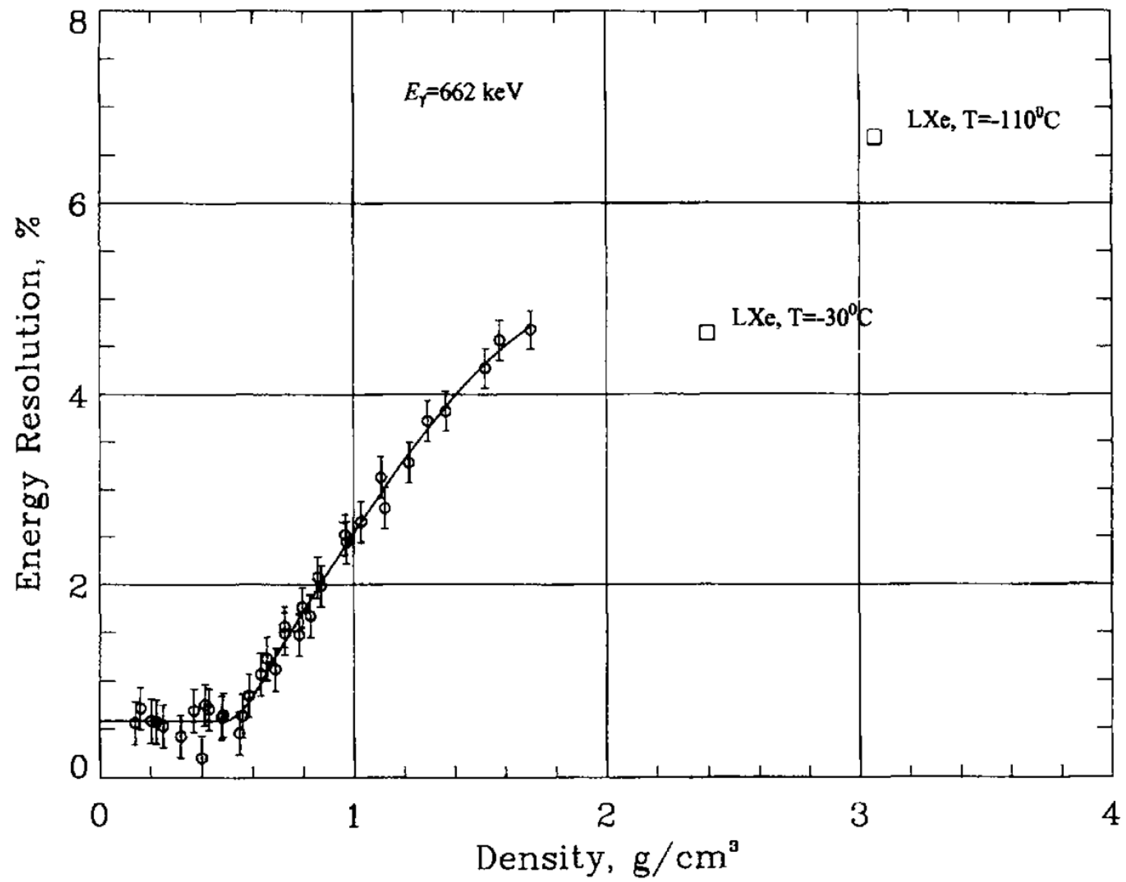
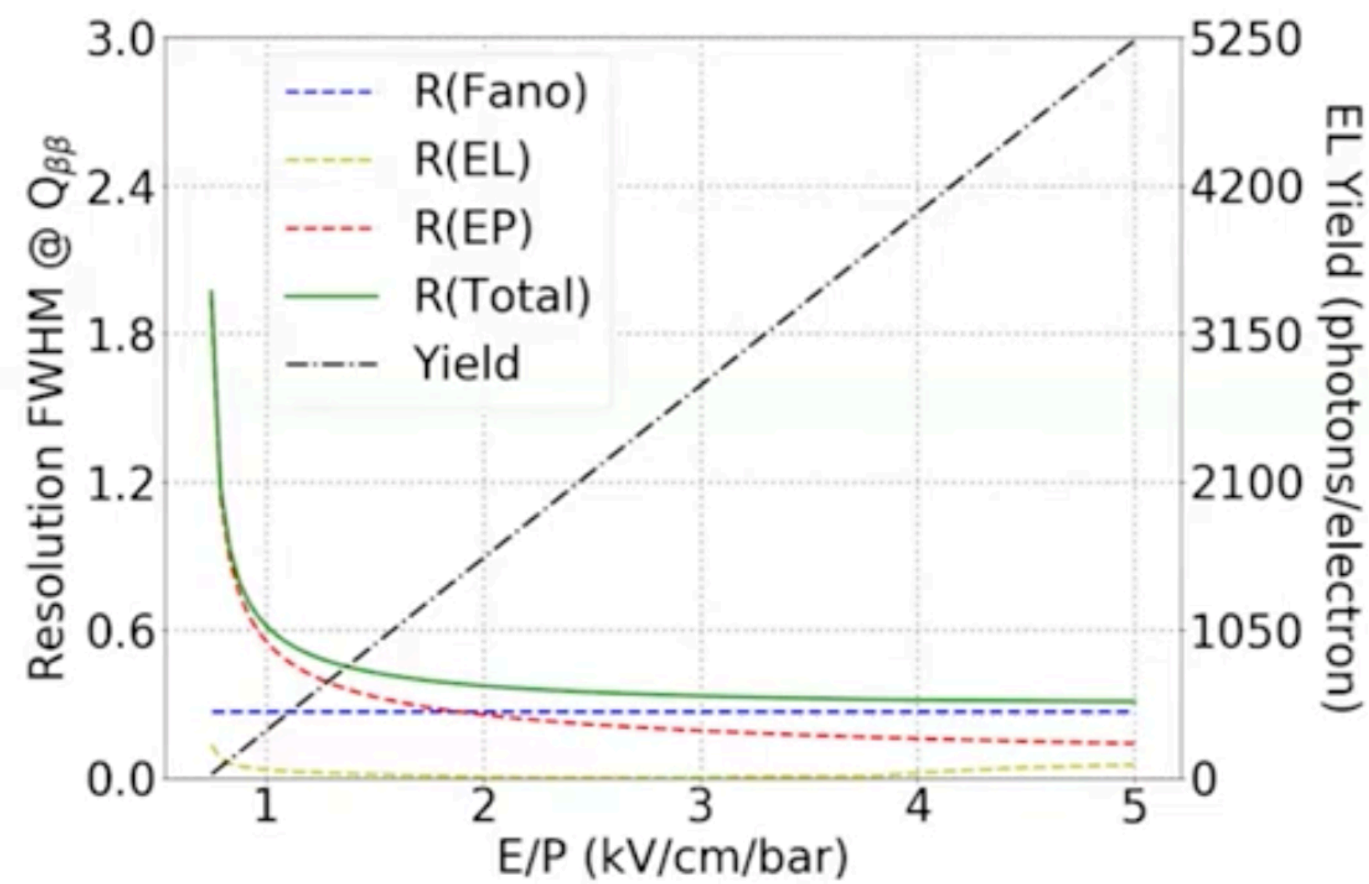


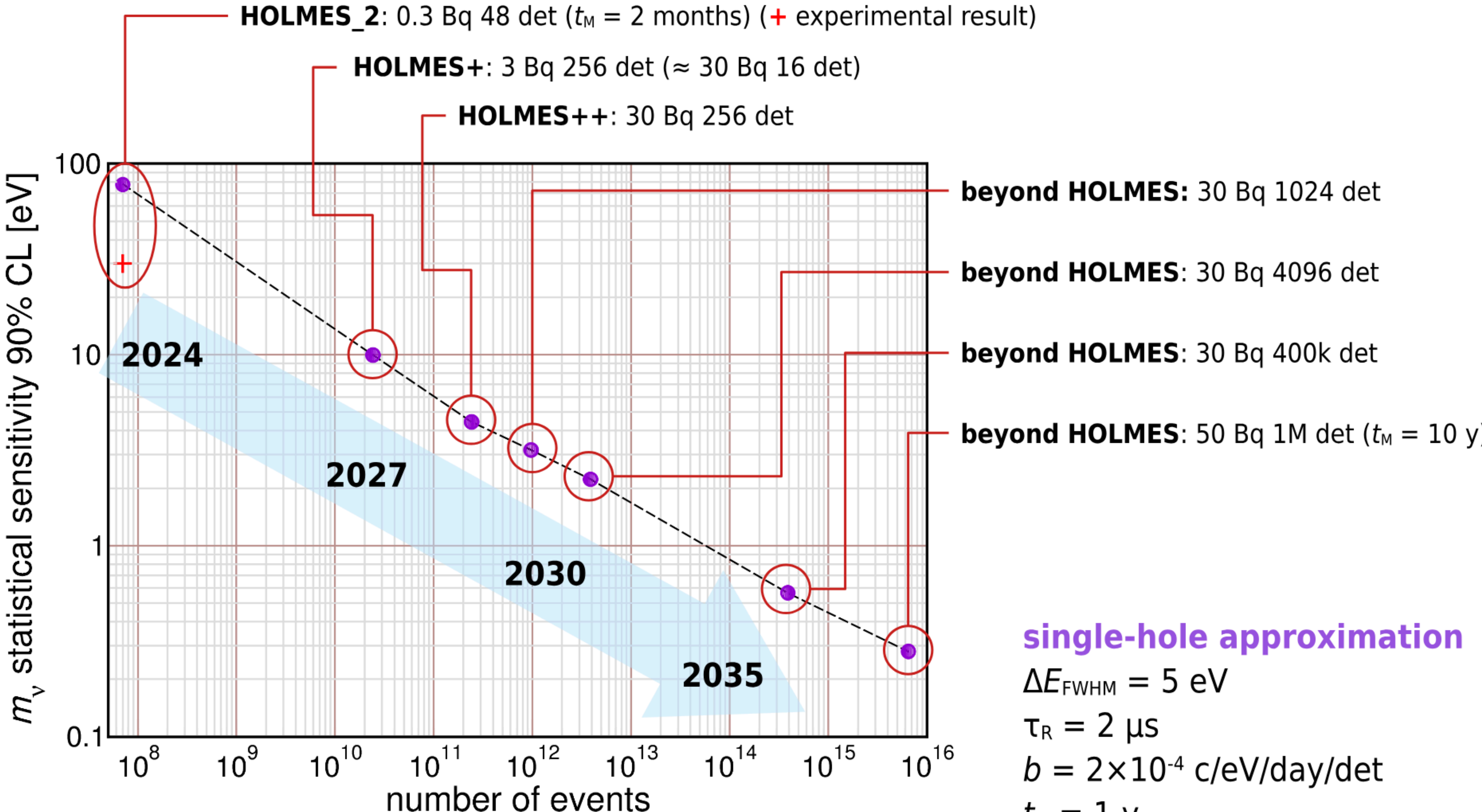
Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

Bolotnikov, Ramsey
Ionization only, no EL!



Nicked from JJ's 2024 school lecture at INFN GGI

A possible roadmap towards 0.1 eV sensitivity



single-hole approximation

ΔE_{FWHM} = 5 eV

τ_R = 2 μs

$b = 2\times10^{-4}$ c/eV/day/det

t_M = 1 y