# *Neutrino mass measurements -*

Christoph Wiesinger (Technical University of Munich), NuFact, 21.09.2024

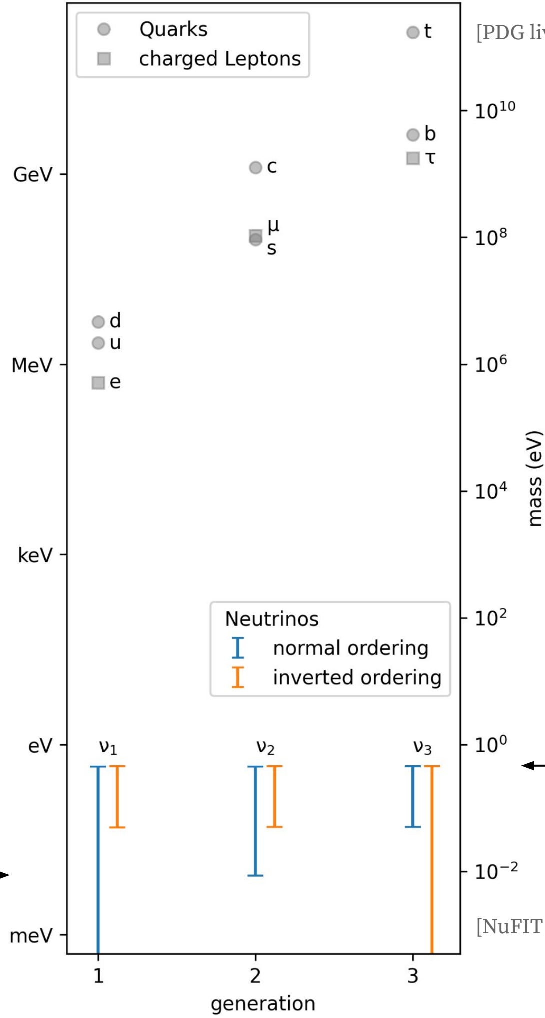
*"for the discovery of neutrino oscillations, which shows that*

# *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**

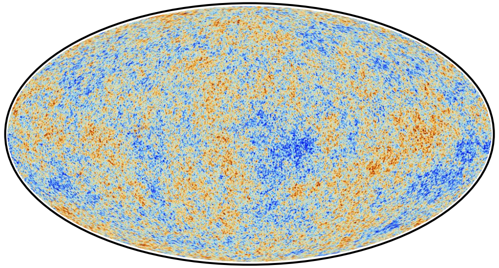
lower bounds from **oscillation experiments**

[NuFIT 5.3, nu-fit.org]

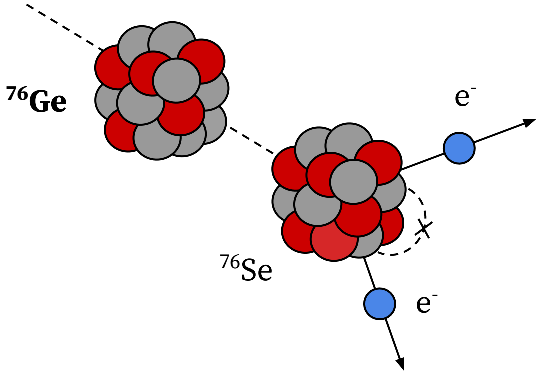
# *Neutrino mass probes*

**laboratory**-based

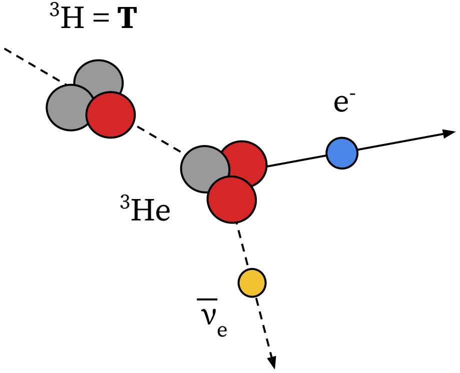
**cosmology**



**neutrinoless ββ decay**




**β decay kinematics**




model-dependent

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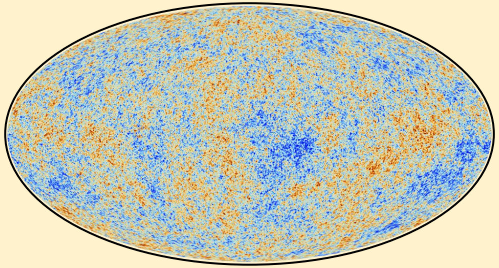

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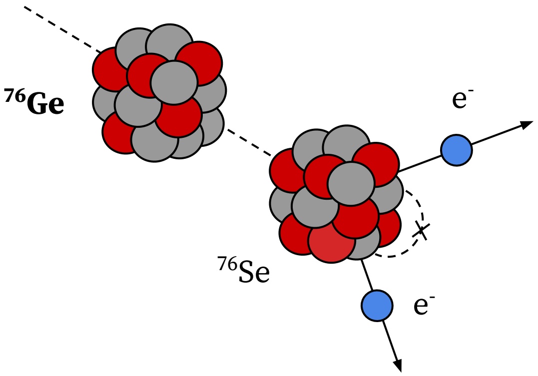


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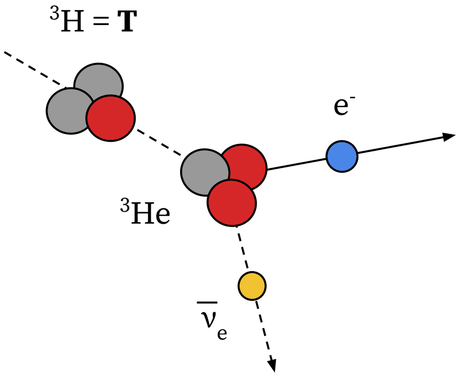



model-dependent

# *Neutrinos in cosmology*

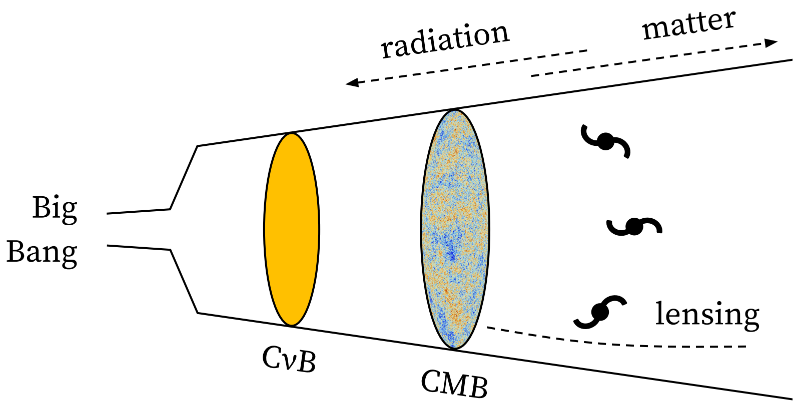
- primordial neutrinos, **most abundant known massive particles** in the universe

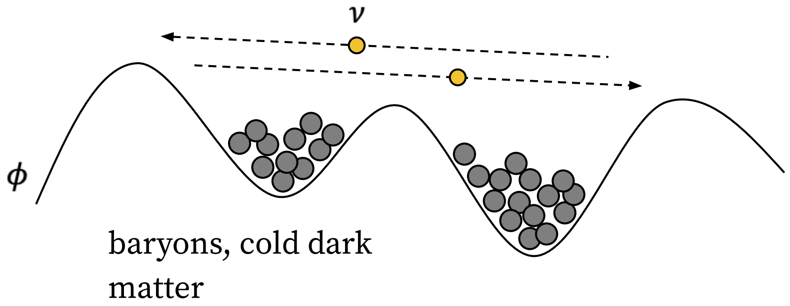
- neutrino mass defines **transition from radiation to matter behaviour**

➔ **background evolution**, redshift to matter-to-radiation equality

- **energy dispersion** across overdensities, effectiveness depends on neutrino mass

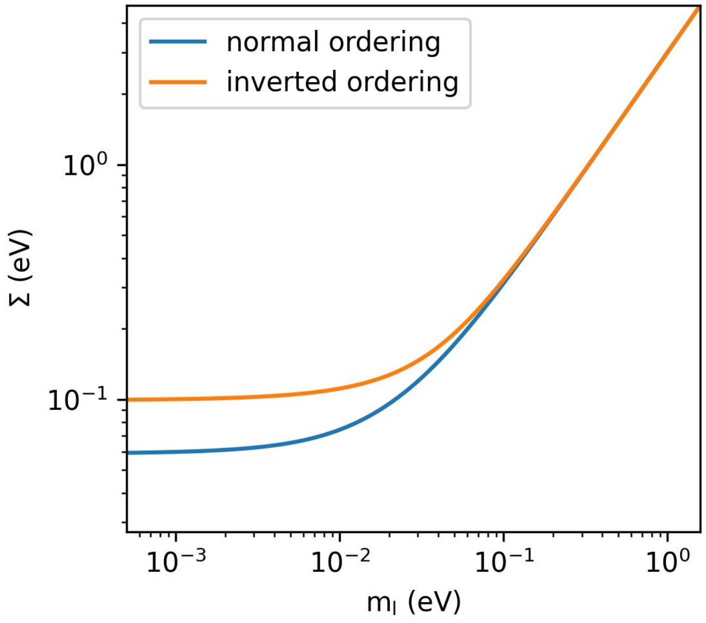
➔ **structure growth**, matter power spectrum



# *Sum of neutrino mass eigenstates, $\Sigma = \Sigma_i m_i$*

[NuFIT 5.3, nu-fit.org]




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

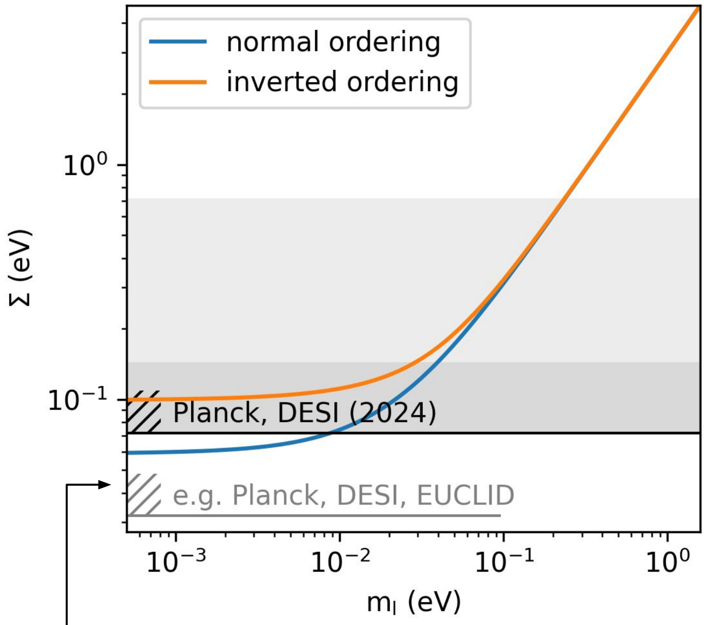
  $$min(\Sigma)_{NO} = \mathbf{0.06\ eV}$$

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

  $$min(\Sigma)_{IO} = \mathbf{0.10\ eV}$$

# *Sum of neutrino mass eigenstates,* $\Sigma = \Sigma_i m_i$

[NuFIT 5.3, nu-fit.org]




standard scenario **predicts detection**

- most stringent bound driven by **Planck and DESI data**
  [Adame et al., arXiv:2404.03002]

  $\Sigma$ **< 0.07 eV** (95% CI)

- **model dependence** can weaken bounds
  - **extended cosmology** (e.g. dark energy dynamics, ..), **x2**
    [Choudhury, Hannestad, JCAP 07 (2020) 037, ..]
  - **non-standard neutrino physics** (e.g. invisible neutrino decay, time-dependent neutrino mass, ..), **x10**
    [Escudero et al., JHEP 12 (2020) 119; Dvali, Funke, PRD 93 (2016) 11, 113002, ..]

- future observatories and missions (e.g. **EUCLID**)
  [Brinckmann et al., JCAP 01 (2019) 059, ..]

  $\sigma_\Sigma$ = **O(0.01) eV**

# *Neutrino mass probes*

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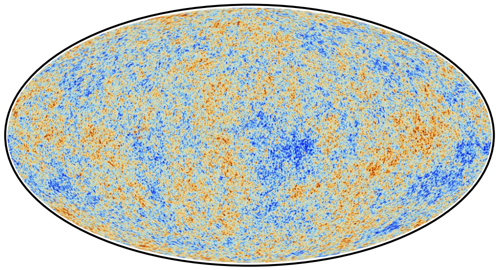
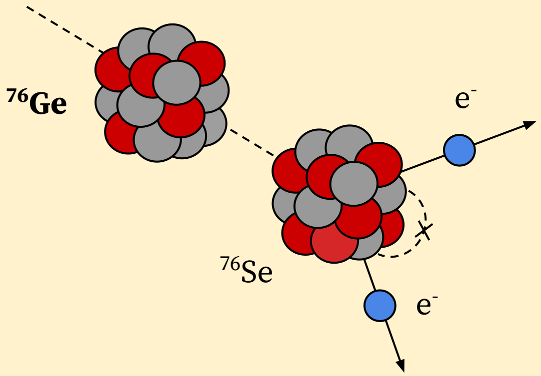


**neutrinoless ββ decay**

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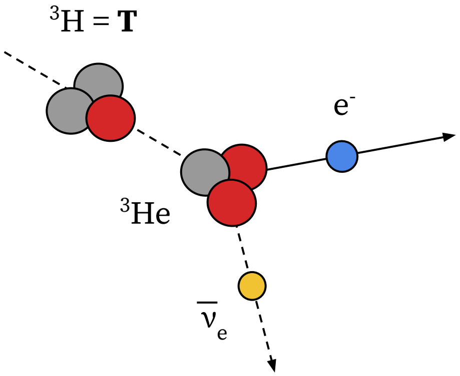
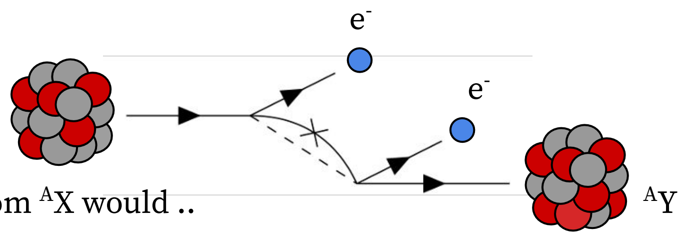



model-dependent

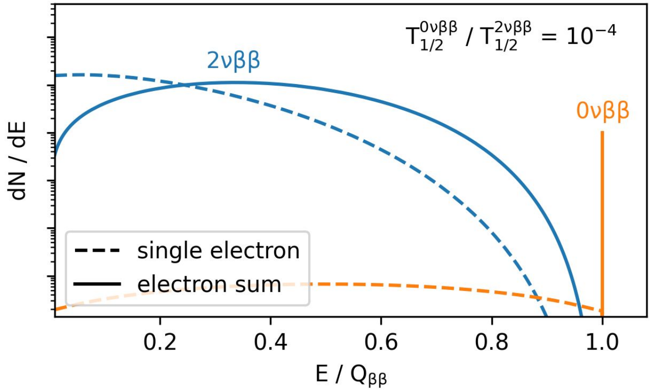
# *Neutrinoless ββ decay*




- unaccompanied **emission of two electrons** from $^{A}$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**

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

     assuming **light Majorana neutrino exchange** and corresponding nuclear physics inputs

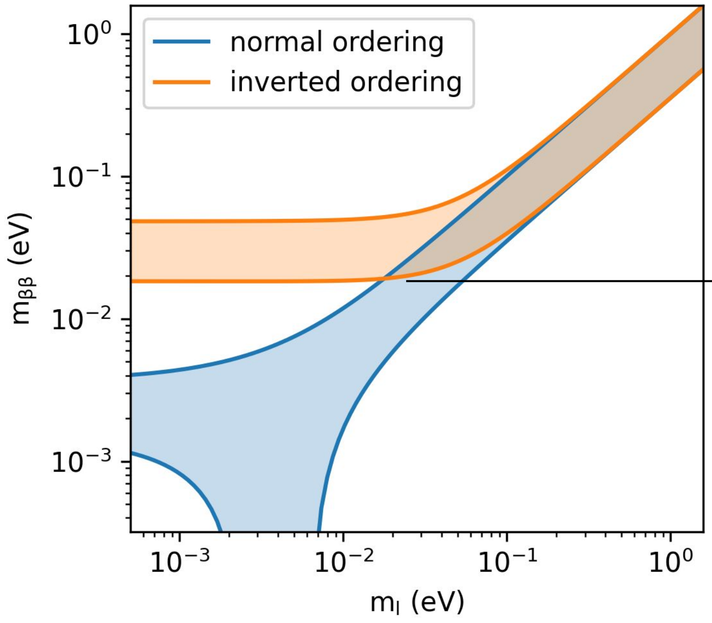



➔ search for **MeV-scale mono-energetic emission of two electrons**

- 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 5.3, nu-fit.org]

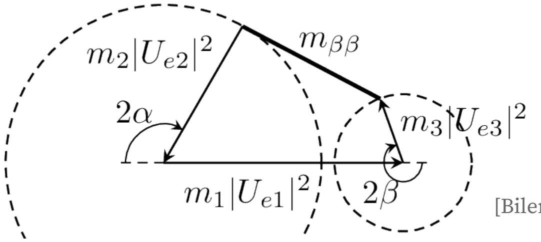



- **coherent sum** of mass eigenstates, sensitive to **complex Majorana phases**

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

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

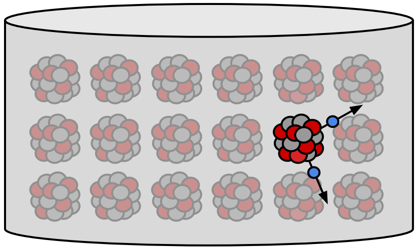
- **cancellation possible** for normal ordering, $m_1 < m_2 << m_3$




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

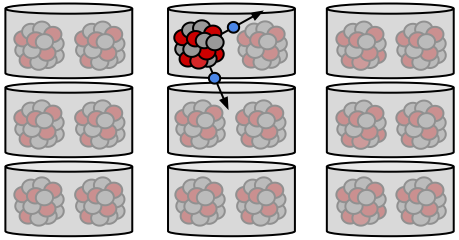
# *Experimental approaches*

**source = detector** concepts



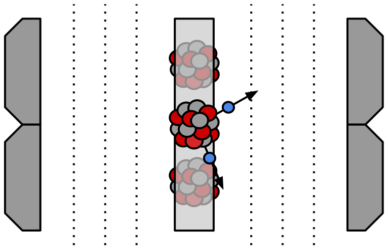
**monolithic** scintillation / ionization detectors

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



**granular** semiconductor / cryogenic detectors

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

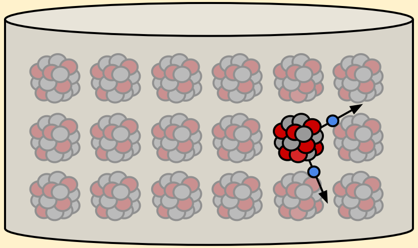


**tracking** calorimeters

NEMO3, SuperNEMO, ..

# *Experimental approaches*

**source = detector** concepts



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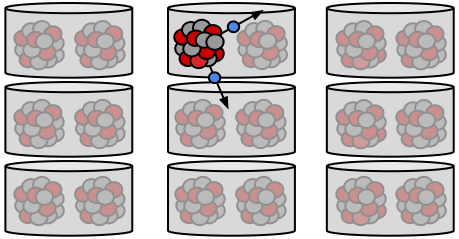

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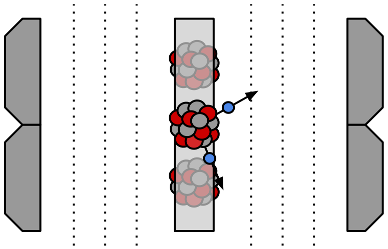
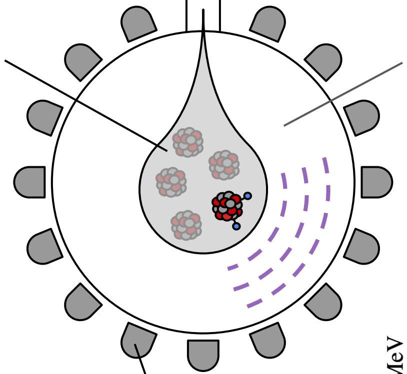


**tracking**
calorimeters

NEMO3, SuperNEMO, ..

# *KamLAND-Zen*




- 1000-t **liquid scintillator** detector, rich **non-ββ decay physics** program
  [Abe et al., PRL 100 (2008) 221803]

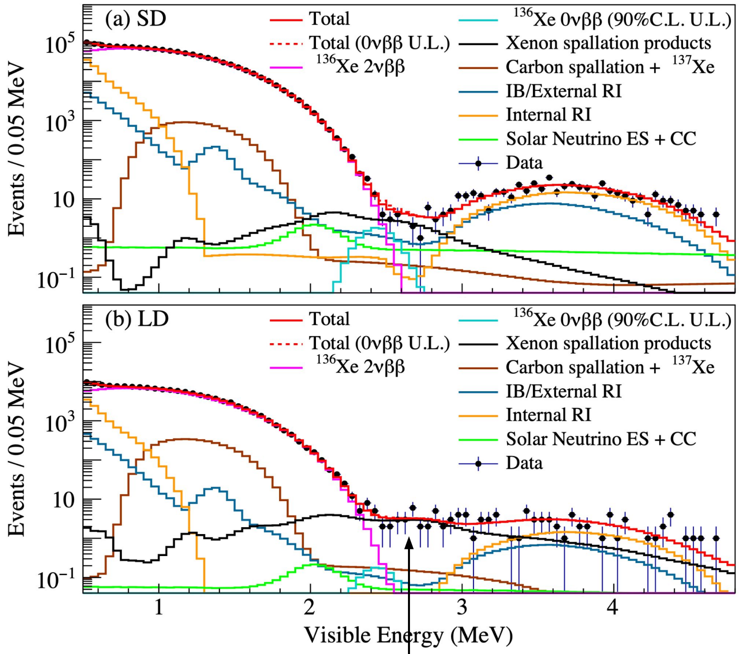
- clean **nylon balloon** filled with **$^{enr}$Xe-loaded liquid scintillator**
  - **large isotope mass,** 800 kg of 91% $^{136}$Xe
  - **poor energy resolution**, 4% at 2.5 MeV

➔ completed in 2024, new **world-best constraint**
[Abe et al., arXiv:2406.11438]

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

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

[Abe et al., arXiv:2406.11438]



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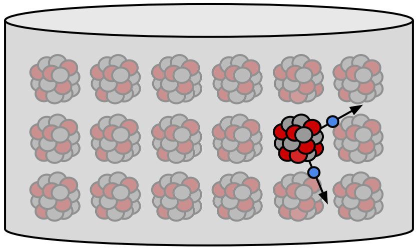
**source = detector** concepts



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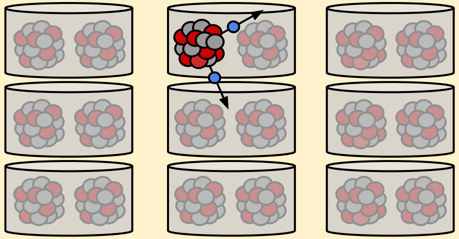

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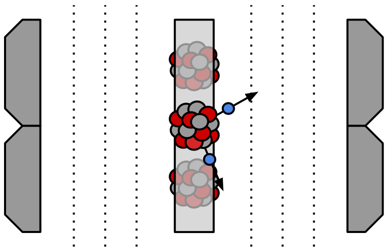

**tracking** calorimeters

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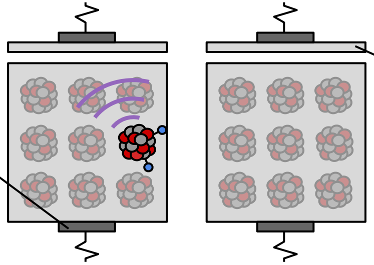
# *CUORE*

# *CUPID*




- cryogenic $^{nat}$**$TeO_2$ bolometers**, dilution refrigerator, 10 mK
  - **sizeable isotope mass**, 800 kg with 200 kg $^{130}$Te
  - **good resolution**, 7.3 keV (FWHM) at 2.5 MeV
  - **background dominated** by α decays

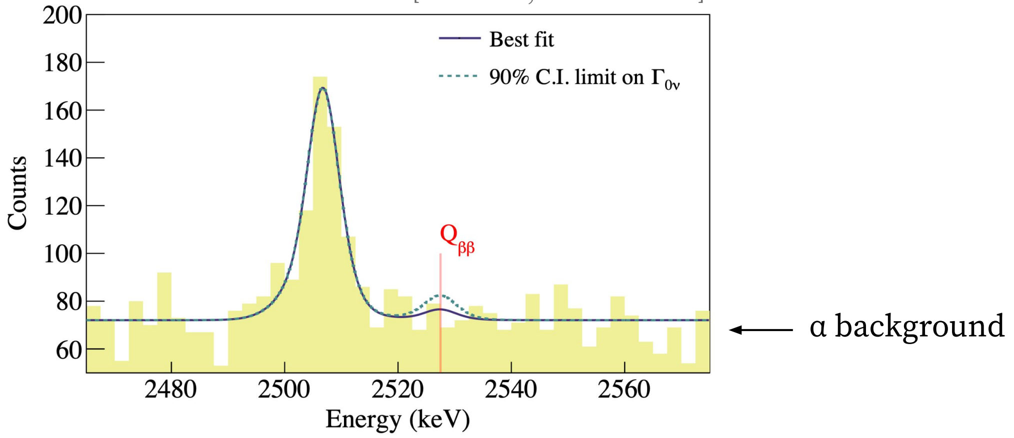
- cryogenic **scintillating $Li_2MoO_4$ bolometers** in CUORE infrastructure
  - **particle discrimination**
  - **similar isotope mass**, 250 kg $^{100}$Mo

➔ data taking ongoing, **new result**
[Adams et al, arXiv:2404.04453]

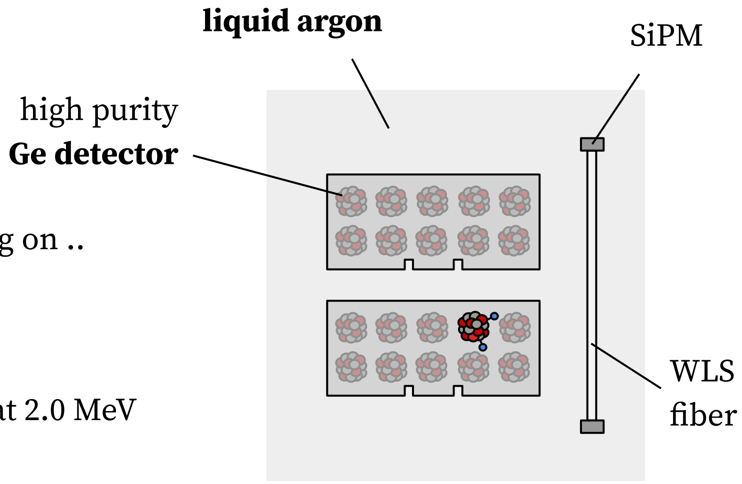
$T_{1/2}(^{130}Te)$ **> 2.8 · 10$^{25}$ yr** (90% CL)

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

[Adams et al, arXiv:2404.04453]

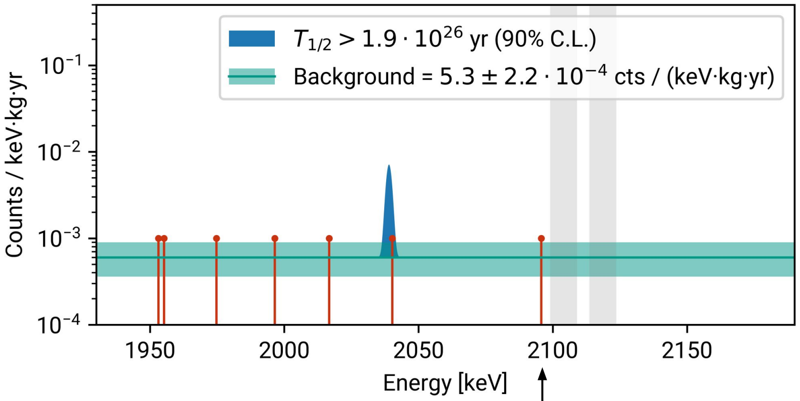


# *LEGEND*




- 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**, 2.52 keV (FWHM) at 2.0 MeV
    [Arnquist et al., PRL 130 (2023) 6, 062501]

[Pertoldi, Neutrino 2024]




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

➔ 140 kg deployed**, first result**
[Pertoldi, Neutrino 2024]

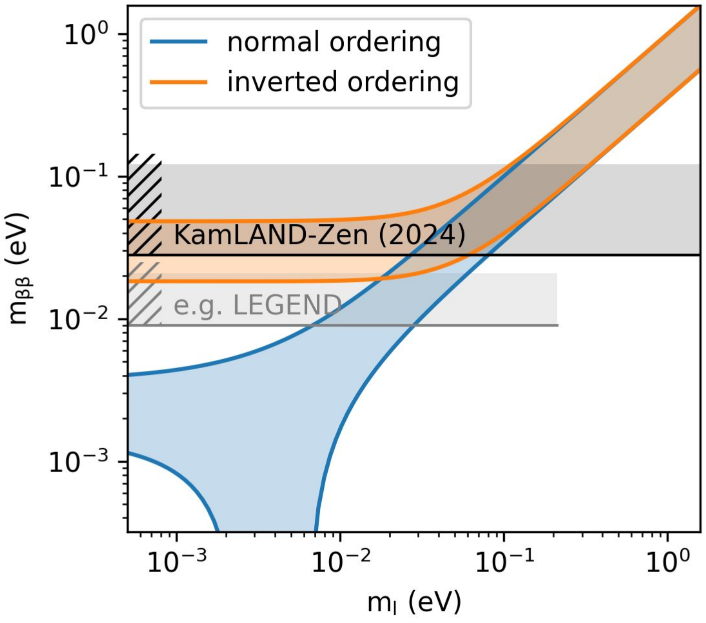
$$T_{1/2}(^{76}\text{Ge}) \mathbf{> 1.9 \cdot 10^{26}\ yr}\ (90\%\ \text{CL})$$

$$m_{\beta\beta} \mathbf{< [75, 178]\ meV}\ (90\%\ \text{CL})$$

- **LEGEND-1000**, 1 t of 90% $^{76}$Ge in new infrastructure

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

[NuFIT 5.3, nu-fit.org]




- most stringent bounds placed at
  [Pertoldi, Neutrino 2024; Adams et al, arXiv:2404.04453; Abe et al., arXiv:2406.11438]

  $m_{\beta\beta}$ < [75, 178] 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

- **tonne-scale projects** to probe inverted ordering scenario, e.g.
  [Abgrall et al., arXiv:2107.11462 (pCDR)]

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

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

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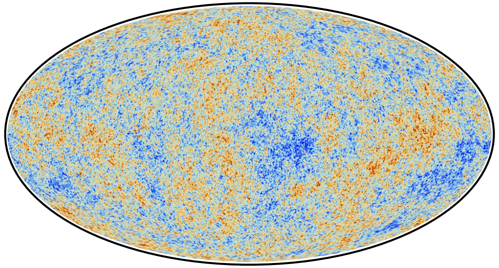

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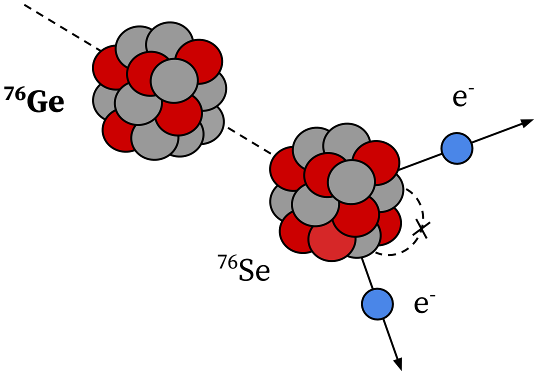
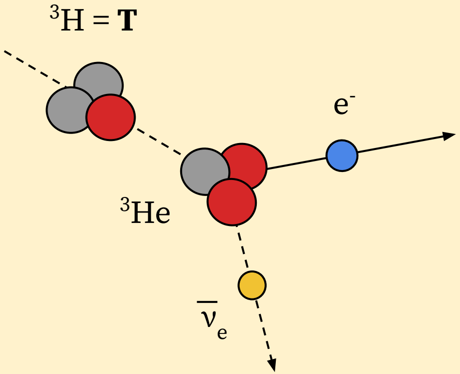



**β decay kinematics**

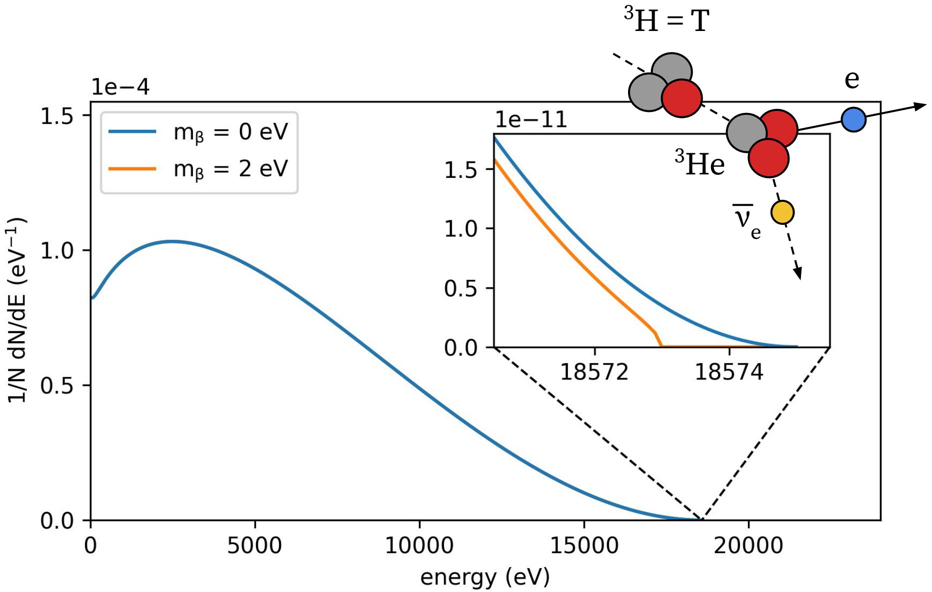



model-dependent

# $\beta$-decay* kinematics

**or electron capture*

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

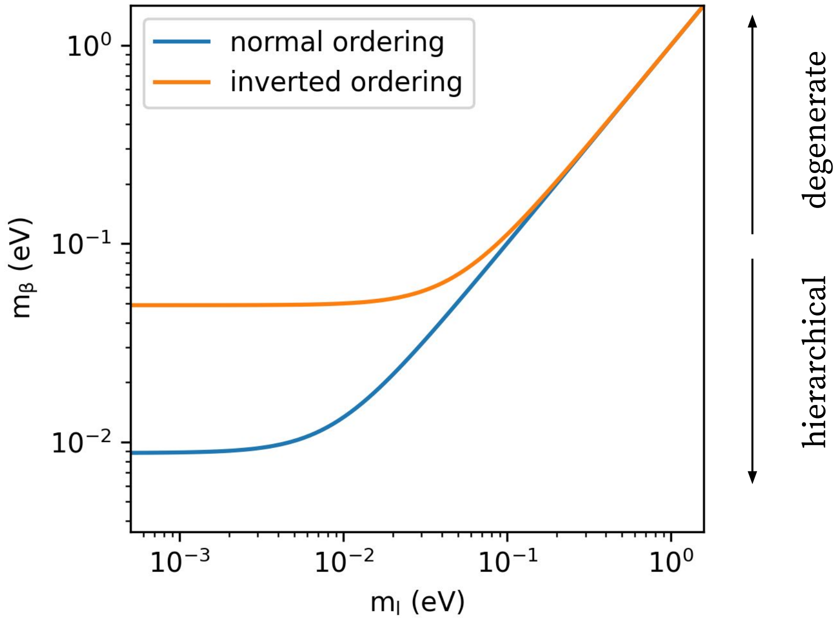



➔ measure **sub-eV scale spectral distortion** close to **keV-scale kinematic endpoint**

- **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 5.3, nu-fit.org]




- weighted **incoherent sum** of mass eigenstates

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

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

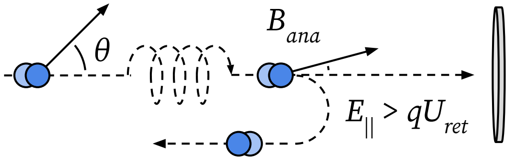
  and inverted ordering, $m_3 << m_1 \approx m_2$

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

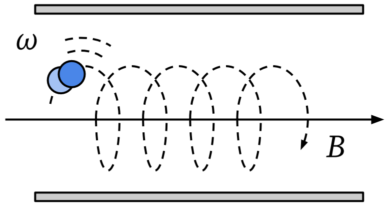
- current experiments probe **degenerate regime**, $m_1 \approx m_2 \approx m_3$

# *Experimental approaches*

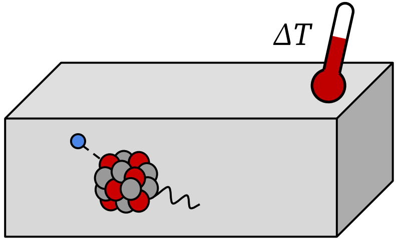
**tritium**-based




electrostatic
**filtering** (MAC-E)




**cyclotron radiation** emission
spectroscopy (CRES)




**cryogenic**
calorimetry

R&D stage

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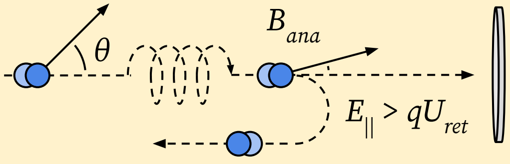


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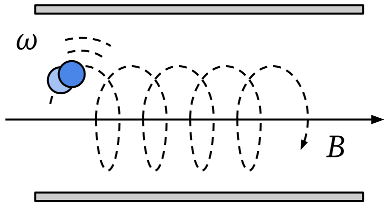


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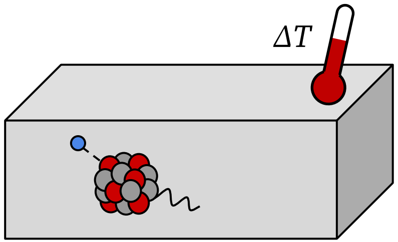


**cryogenic**
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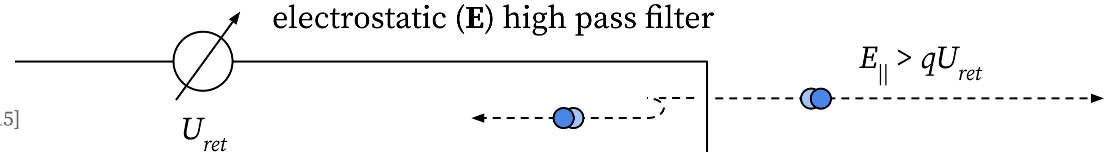
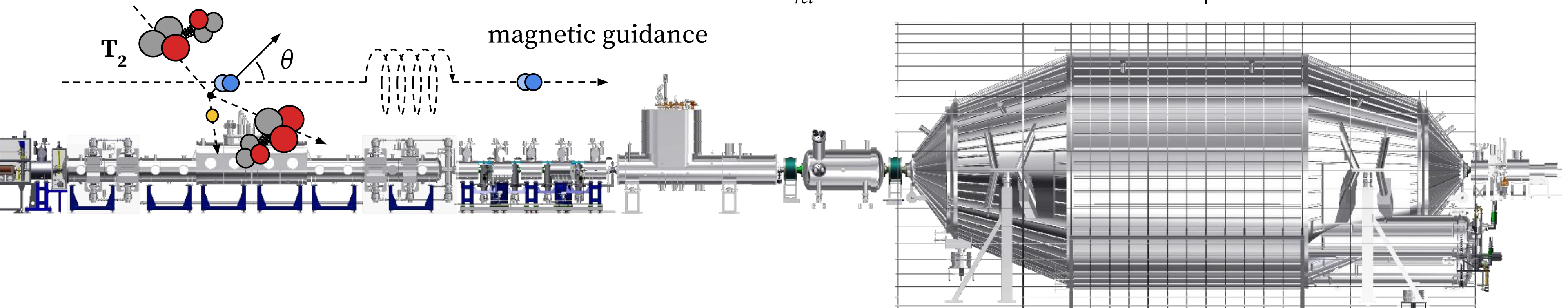
R&D stage

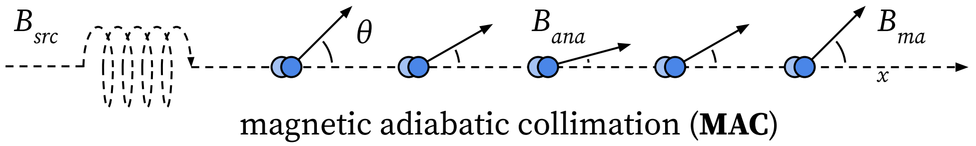
# *KATRIN working principle*

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



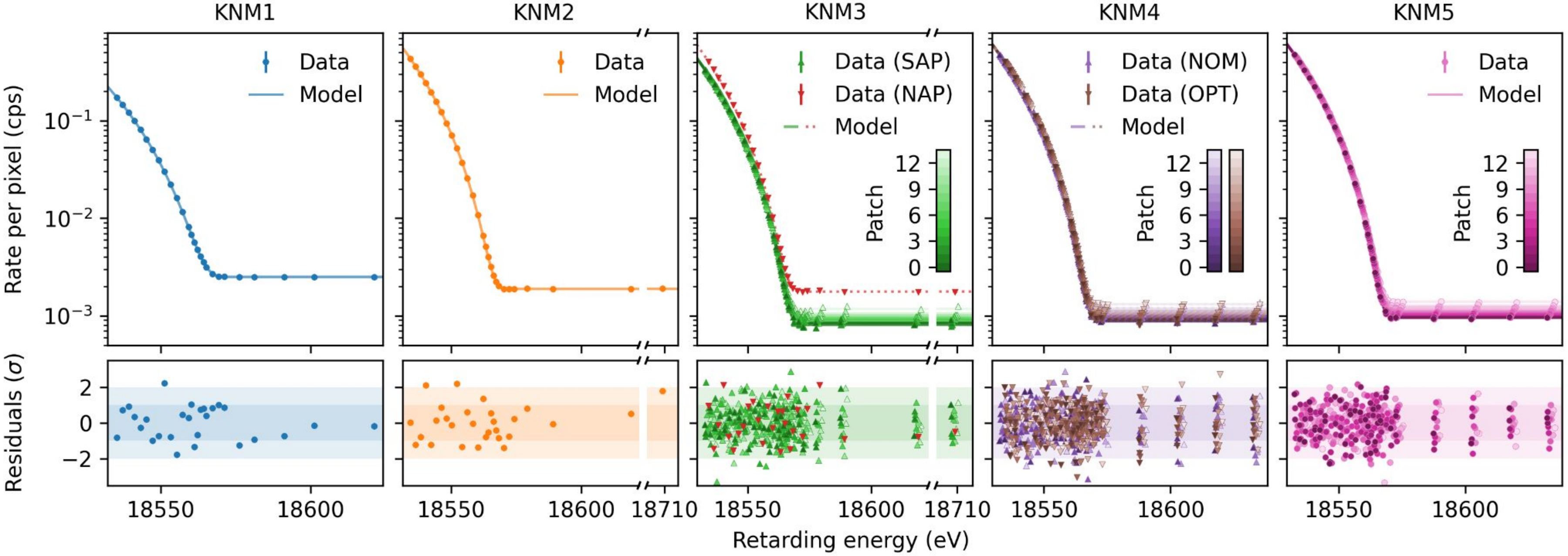

- **high-activity** (~100 GBq) windowless gaseous molecular tritium source, closed loop
- **high-resolution** (~1 eV) **large-acceptance** (0-51°) MAC-E spectrometer system
- **electron counting** with 148-pixel silicon PIN diode




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

# *KATRIN result*

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




- negative best-fit $m_\beta{}^2 = \mathbf{-0.14^{+0.13}_{-0.15}\ eV^2}$

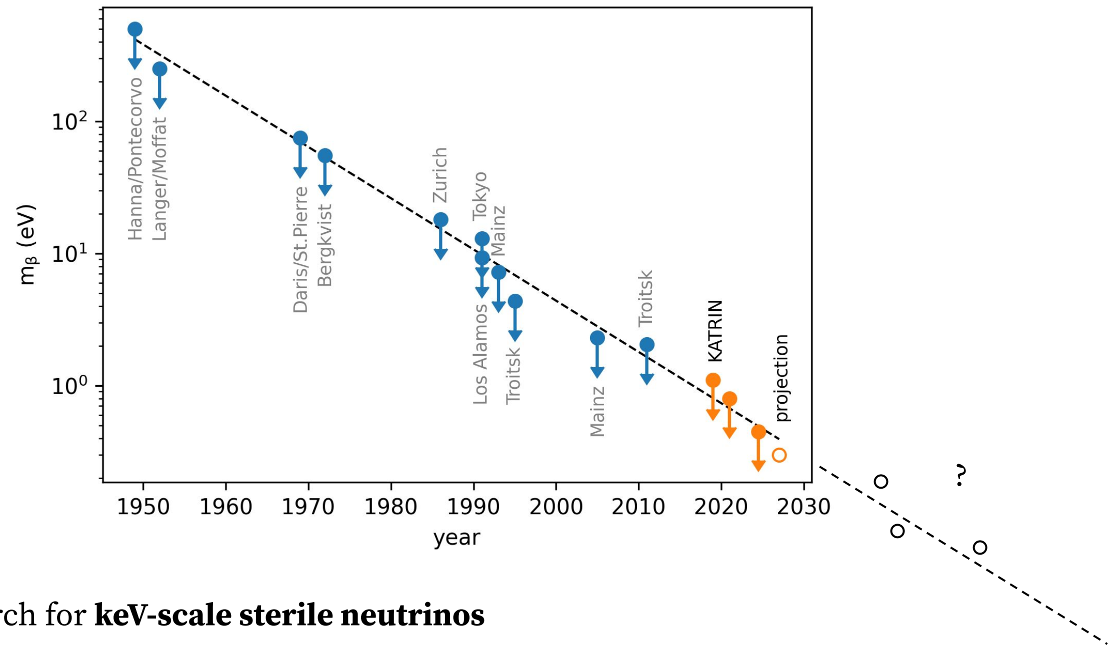
➔ new **world-best** constraint $m_\beta$ **< 0.45 eV** (90% CL)

[Aker et al., arXiv:2406.13516]

# *KATRIN outlook*

- data taking ongoing until end-2025, **projected final sensitivity**

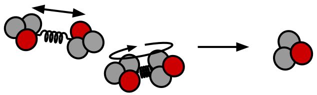
  $m_\beta$ **< 0.3 eV** (90% *CL*)




- rich **non-neutrino mass program**, sterile neutrinos, relic neutrinos, ..
  [Aker et al., PRD 105 (2022) 7, 072004; Aker et al., PRL 129 (2022), 1, 011806]

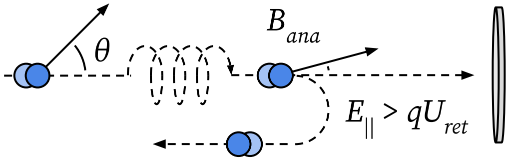
- **TRISTAN** detector upgrade in 2026, search for **keV-scale sterile neutrinos**
  [Mertens et al., J.Phys.G 46 (2019) 6, 065203]

- beyond 2027, **KATRIN++**, development of **differential** electron detection and **atomic** tritium technologies

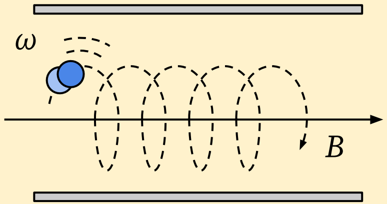


# *Experimental approaches*

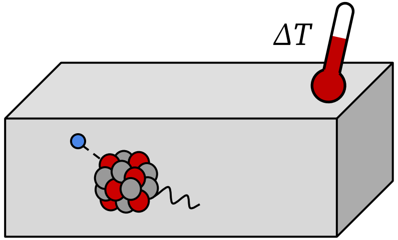
**tritium**-based




electrostatic
**filtering** (MAC-E)




**cyclotron radiation** emission
spectroscopy (CRES)




**cryogenic**
calorimetry

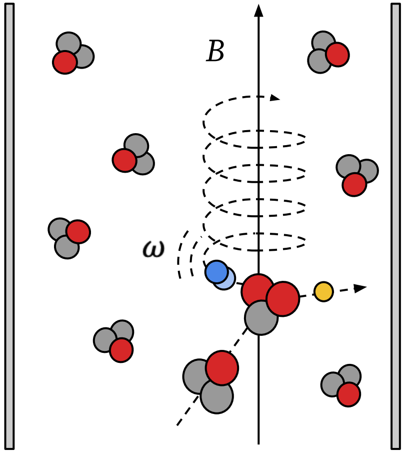
R&D stage

# *Cyclotron radiation emission spectroscopy (CRES)*

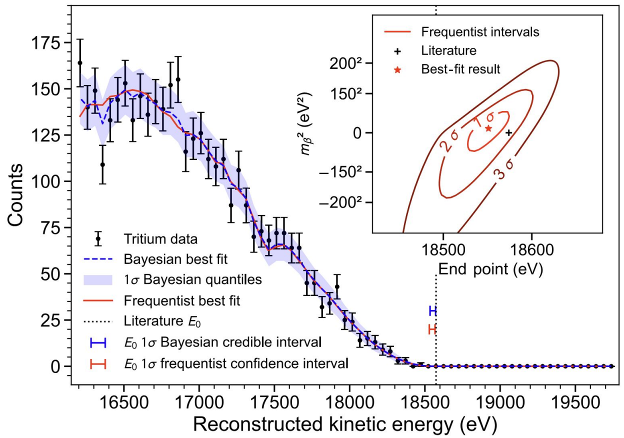
- measure **cyclotron radiation frequency** of trapped tritium decay electrons
  [Monreal, Formaggio, PRD 80 (2009) 051301]

➔ **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*

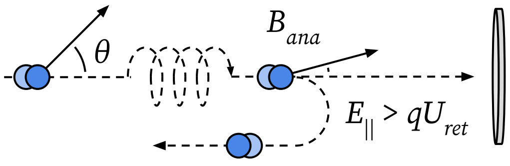
- **first result** with molecular tritium, Phase II
  [Ashtari Esfahani et al., PRL 131 (2023) 10, 102502]

$m_\beta$ **< 155 eV** (90% CL)

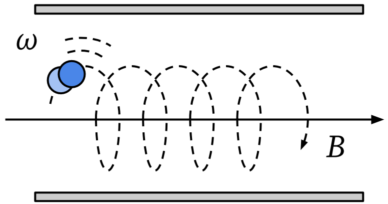
- development of **m$^3$-scale** traps and **atomic tritium** technology

# *Experimental approaches*

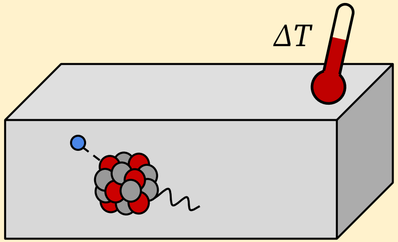
**tritium**-based




electrostatic
**filtering** (MAC-E)




**cyclotron radiation** emission
spectroscopy (CRES)




**cryogenic**
calorimetry

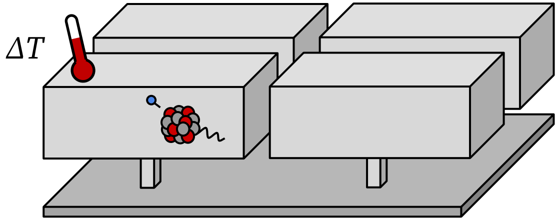
R&D stage

# *Cryogenic calorimetry*

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

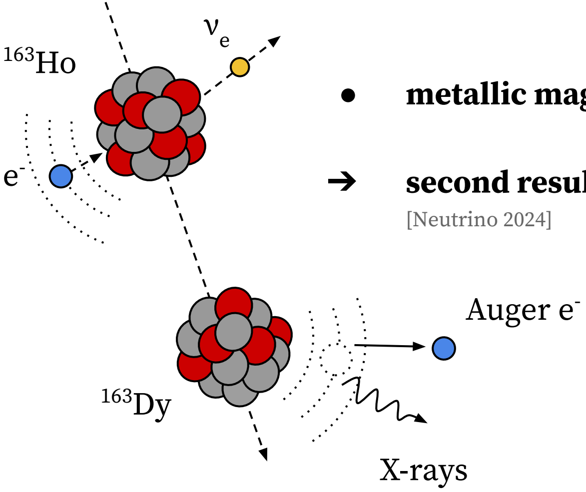
➔ **sub-eV** sensitivity with **MBq-scale activity**

- cryogenic **micro-calorimeters**




➔ eV-scale **differential** measurements

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




## *ECHO*

- **metallic magnetic calorimeters** (MMC)

➔ **second result** $m_\beta$ **< 19 eV** (90% CL)
[Neutrino 2024]

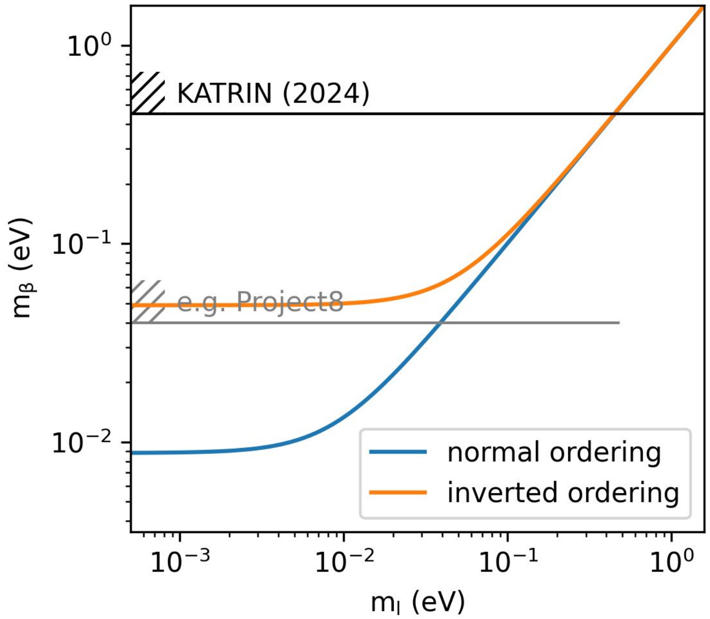
## *HOLMES*

- **transition edge sensors** (TES)

➔ **first result** $m_\beta$ **< 28 eV** (90% CI)
[Neutrino 2024]

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

[NuFIT 5.3, nu-fit.org]




- most stringent bound set by **KATRIN**
  [Aker et al., arXiv:2406.13516]

  $m_\beta$ **< 0.45 eV** (90% CL)

- KATRIN measurement is **ongoing**

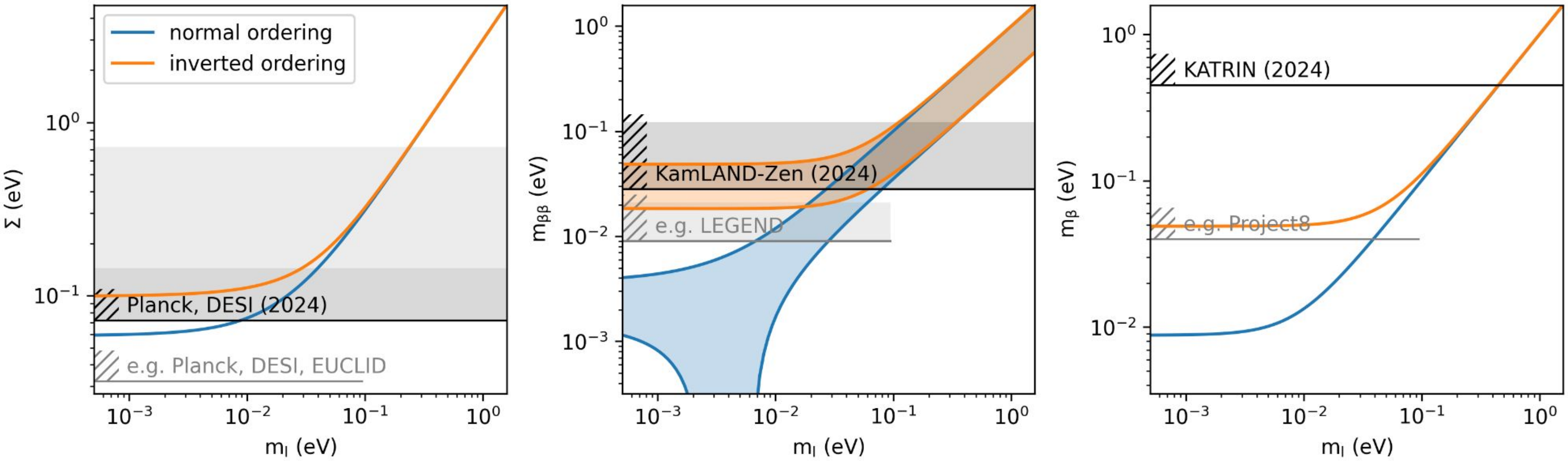
- promising **technology development** to go beyond, e.g.

  $m_\beta$ **< 0.04 eV** (90% CL), Project8 Phase IV goal

# *Neutrino mass observables*

**laboratory**-based

[NuFIT 5.3, nu-fit.org]




model-dependent

# *Conclusions*

- strong **complementarity**

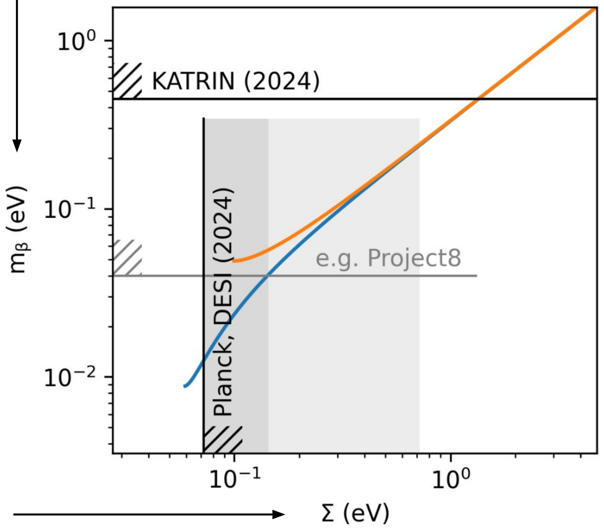
➔ interplay will allow to **test underlying models**

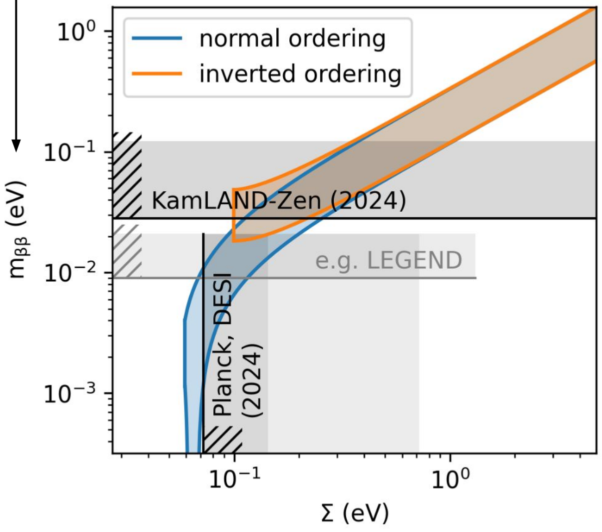
- many **new constraints** and new **powerful tools online**, e.g. LEGEND

energy conservation

light **Majorana neutrino** exchange

[NuFIT 5.3, nu-fit.org]




standard **cosmology**

cosmology (**Planck, DESI**)
[Adame et al., arXiv:2404.03002]

$\Sigma$ **< 0.07 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)

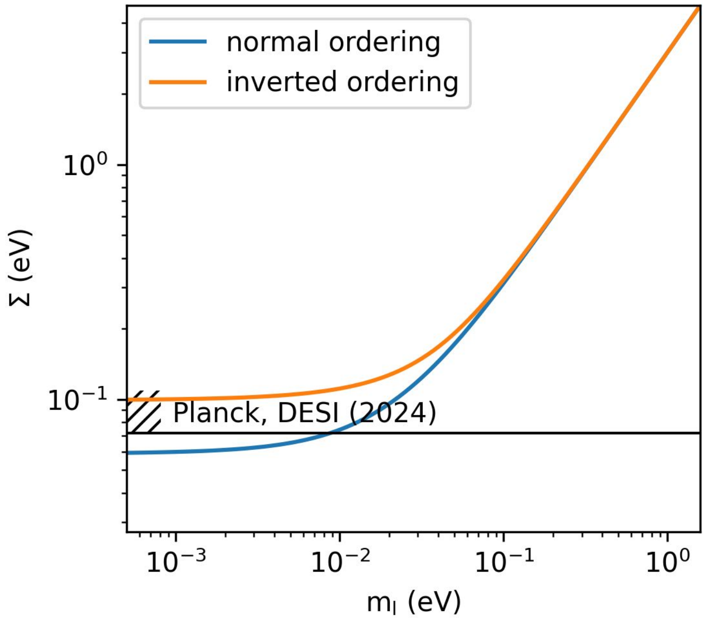
β decay kinematics (**KATRIN**)
[Aker et al., arXiv:2406.13516]

$m_\beta$ **< 0.45 eV** (90% CL)

*Backup*

# *Sum of neutrino mass eigenstates, $\Sigma = \Sigma_i m_i$*

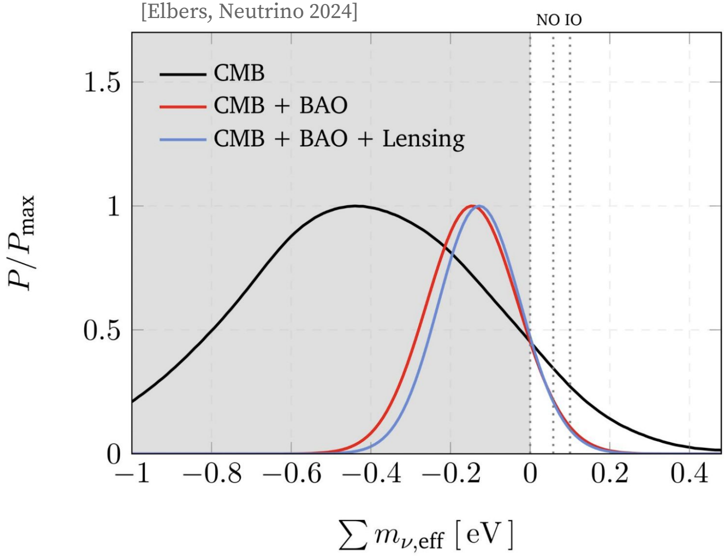
[NuFIT 5.3, nu-fit.org]




- most stringent bound driven by **Planck and DESI data**
  [Adame et al., arXiv:2404.03002]

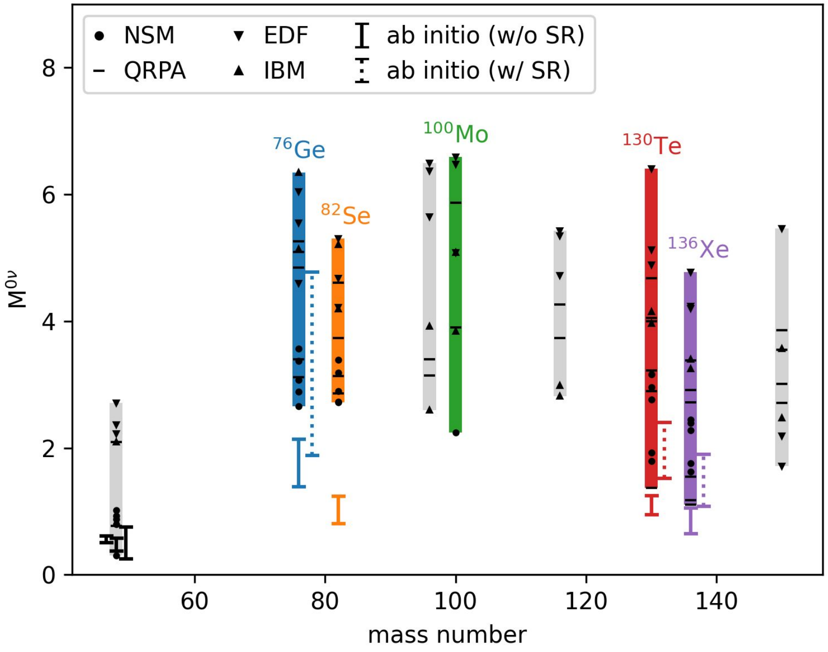
$\Sigma$ **< 0.07 eV** (95% CI)

[Elbers, Neutrino 2024]



# *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** (e.g. $T_{1/2}(^{76}Ge) > 1.8 \cdot 10^{26}$ yr translates to $m_{\beta\beta} < [79, 180]$ meV)
- first **ab initio calculations available**, may resolve quenching issue
  [Yao et al., PRL 124 (2020); Belley et al., PRL 126 (2021); Novario et al., PRL 126 (2021); Cirigliano et al., PRL 120 (2018); Belley et al., arXiv:2307.15156; Belley et al., PRL 132 (2024); ..]
- effective field theory (EFT) analysis identified additional **short-range contribution**
  [Cirigliano et al., PRL 120 (2018) 20, 202001; ..]



# *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]

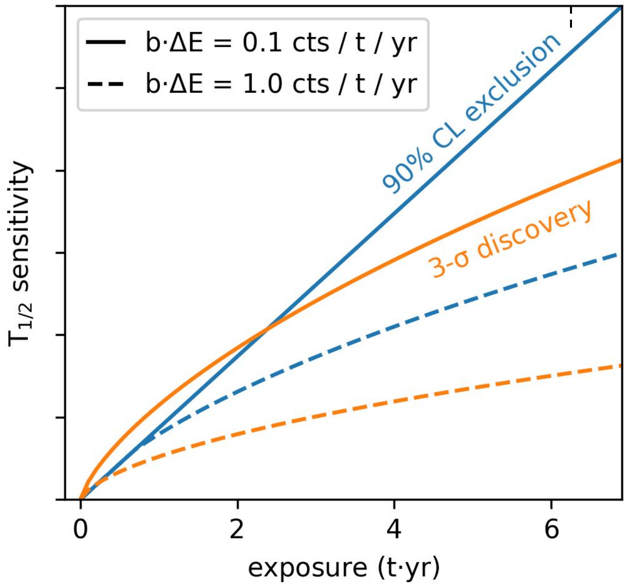
sensitivity **scaling**:

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

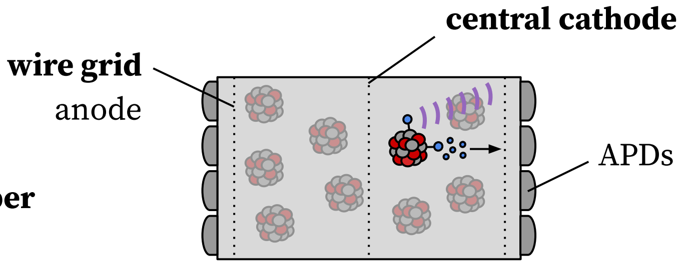
b. **background-free** ( $n_b \ll 1$ ): $T_{1/2} \propto m \cdot t$

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

*quasi-background free*



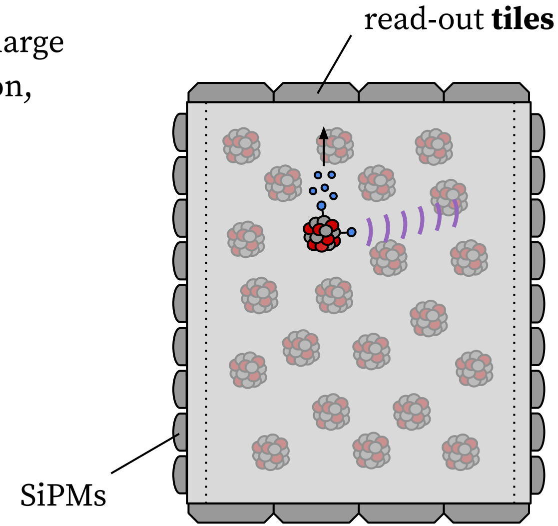
# *EXO-200*




- **liquid Xe time projection chamber**
  - **sizeable isotope mass,**
    200 kg $^{enr}$Xe with 80% $^{136}$Xe
  - **enhanced resolution** by charge and light signal combination, 1% at 2.5 MeV
  - **topology discrimination,**
    single-/multi-site

➔ completed in 2018
[Anton et al., PRL 123 (2019) 16, 161802]

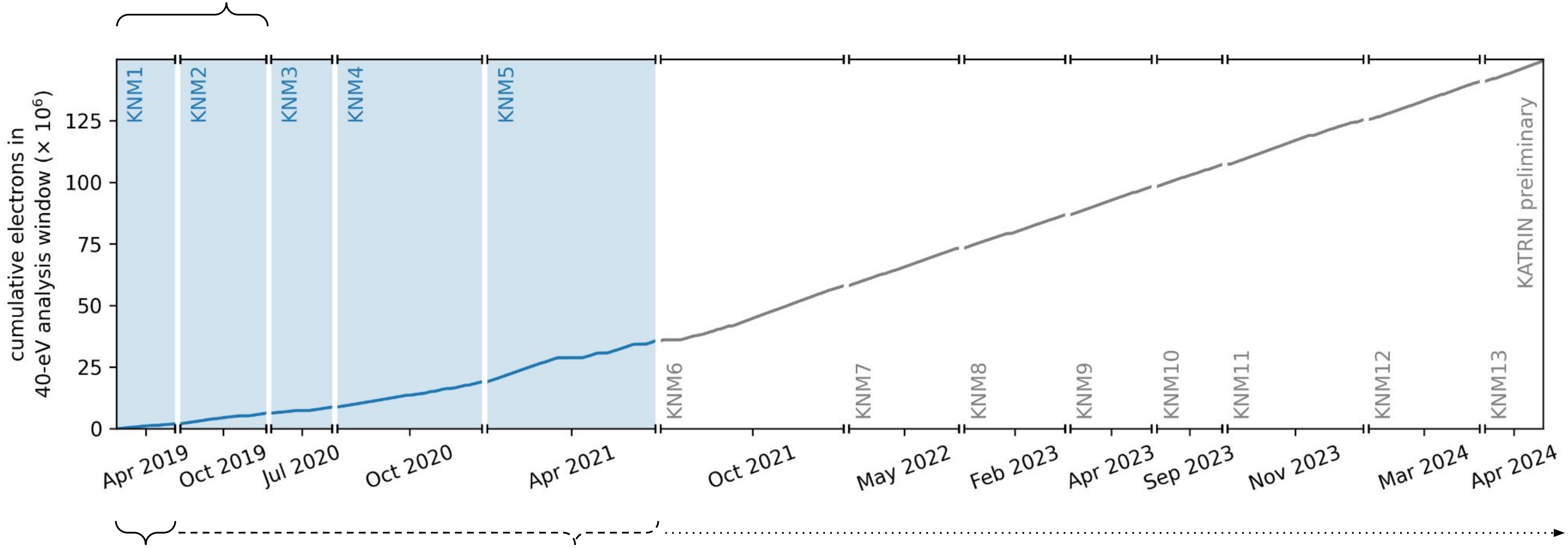
# *nEXO*




- building on EXO-200 technology
  - **increased isotope mass,**
    5 t of $^{enr}$Xe with 90% $^{136}$Xe
  - **improved background,**
    exploiting **self-shielding**
  - development of **Ba tagging,**
    cryogenic probe
    [Chambers et al., Nature 569 (2019) 7755, 203-207]

# *KATRIN data taking overiew*

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




first result, $\boldsymbol{m_\beta} < \mathbf{1.1\ eV}$ (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**