Probing neutrino masses in the laboratory

Christoph Wiesinger (Technical University of Munich), LNF spring school, 16.05.2024

What we know about neutrinos

} **Gabriela Barenboim**'s lecture

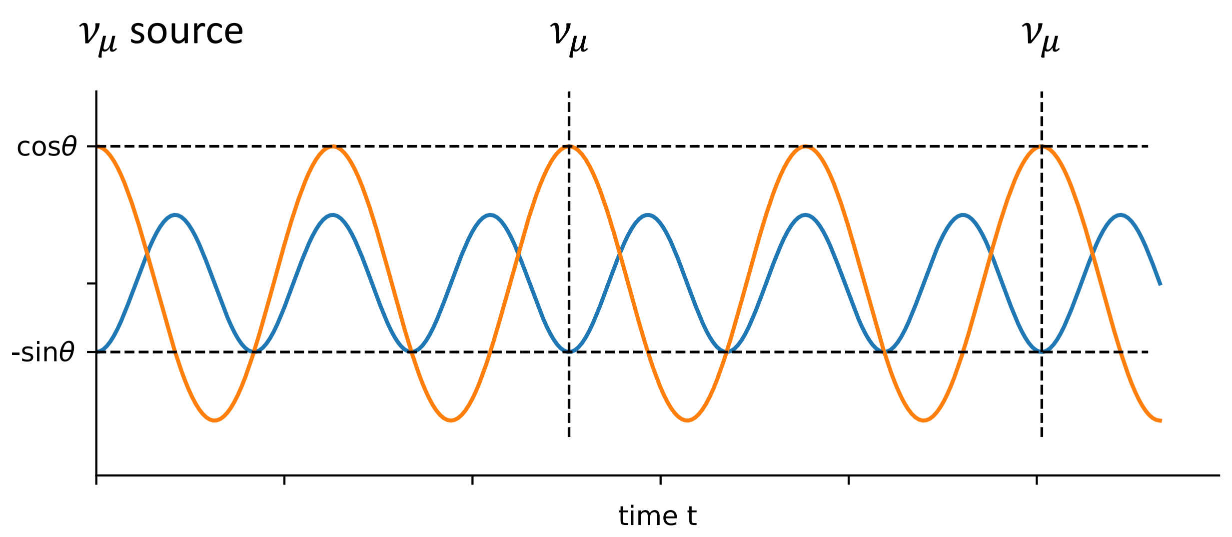
- three active **flavor eigenstates** ν_l with $l \in \{e, \mu, \tau\}$
- **linear combinations** of **mass eigenstates** ν_i

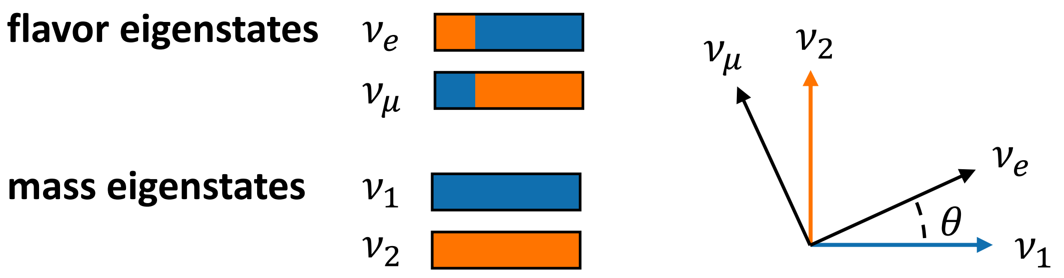
$$\nu_l = \sum_i U_{li}\, \nu_i$$

- **mass squared differences** $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- neutrino **oscillation** $P(\nu_l \rightarrow \nu_m) > 0$

  [Kajita, McDonald, Nobel Prize in Physics 2015]

› at least **two neutrinos have mass**





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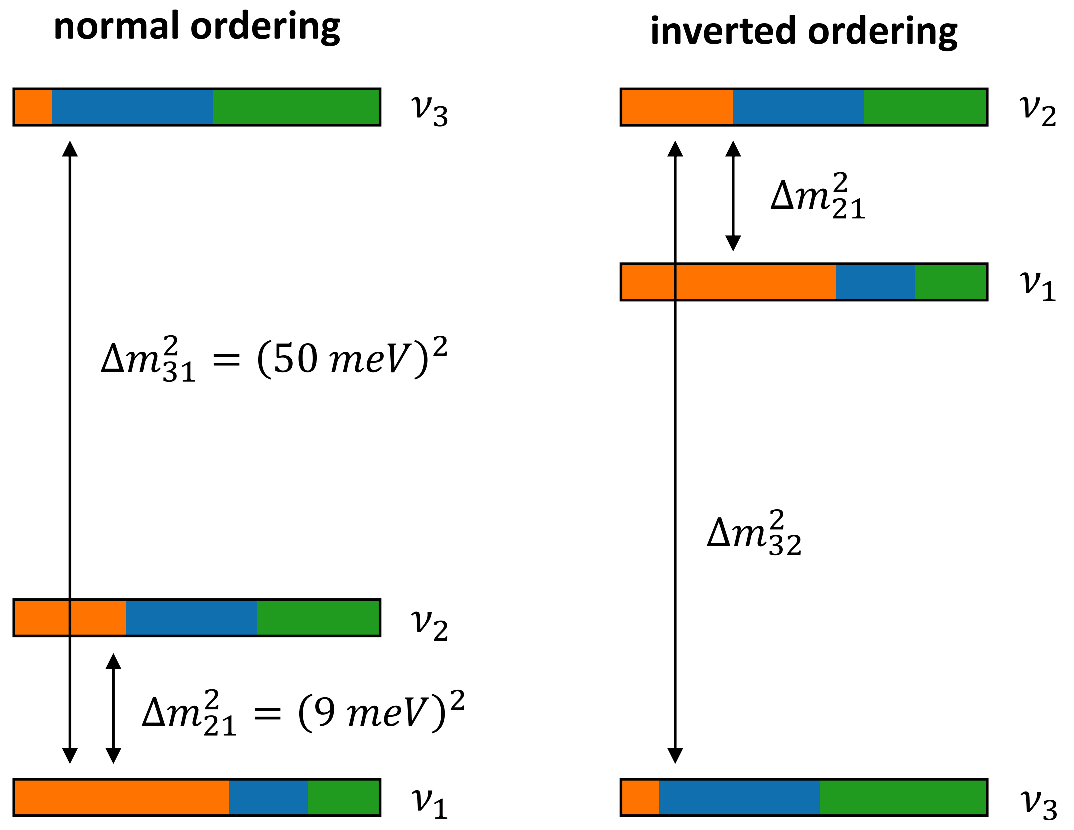
- **matter effects** in sun $m_1 < m_2$
  [Mikheyev, Smirnov, Sov.J.Nucl.Phys. 42 (1985); Wolfenstein, PRD 17 (1978)]

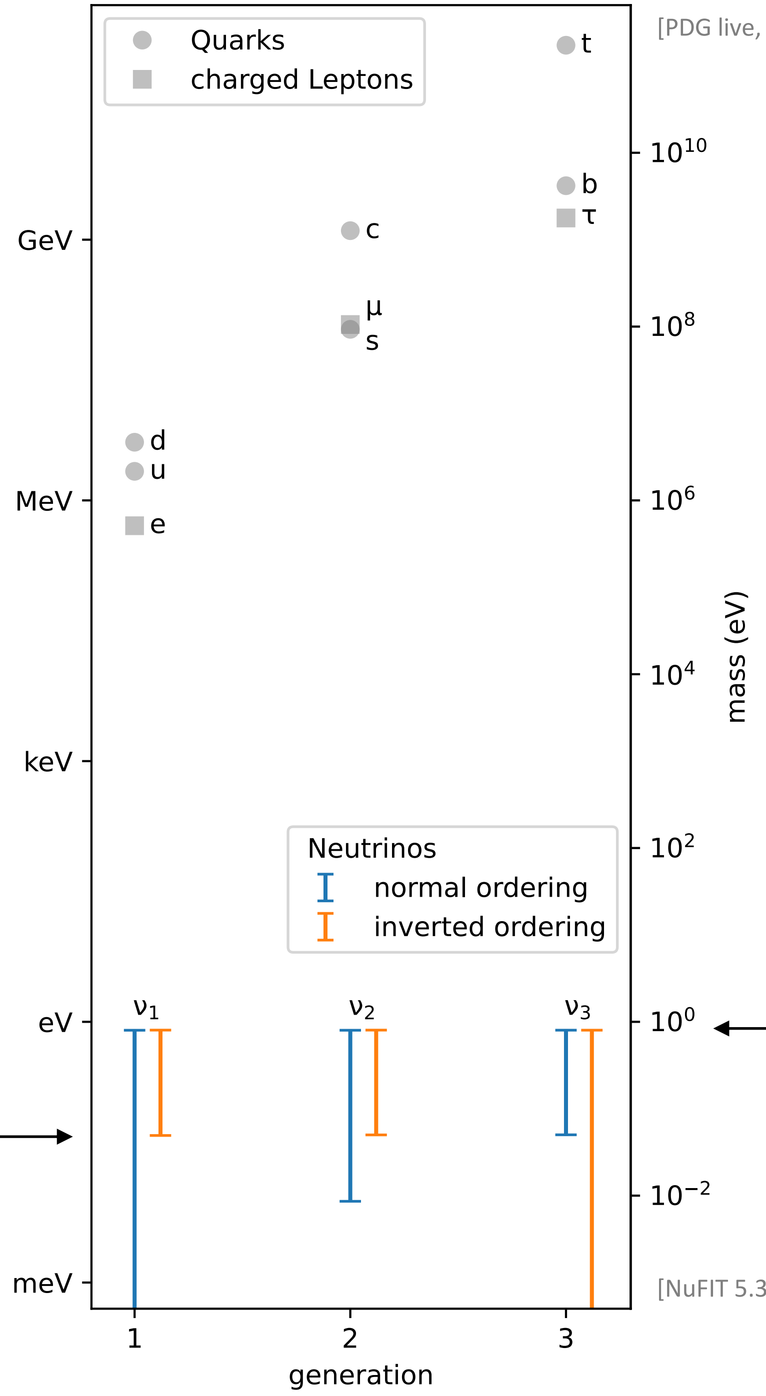
› there are **two ordering scenarios**



*What we **don't** know about neutrinos*

- Which is the **lightest neutrino**?
  What is the neutrino **mass ordering**?
- What is the **mass of the lightest neutrino**?
  What is the **absolute neutrino mass**?
- What is the **neutrino nature**?
  Is the neutrino its **own anti-particle**?
- Do neutrinos and anti-neutrinos behave differently?
  Is **CP violated** in the lepton sector?
- Are there **additional neutrinos**?

lower bounds from **oscillation experiments**



[PDG live, pdglive.lbl.gov]

[NuFIT 5.3, nu-fit.org]

upper bound from **direct mass measurements**

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  } **this lecture**

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  } **Riccardo Brugnera**'s lecture

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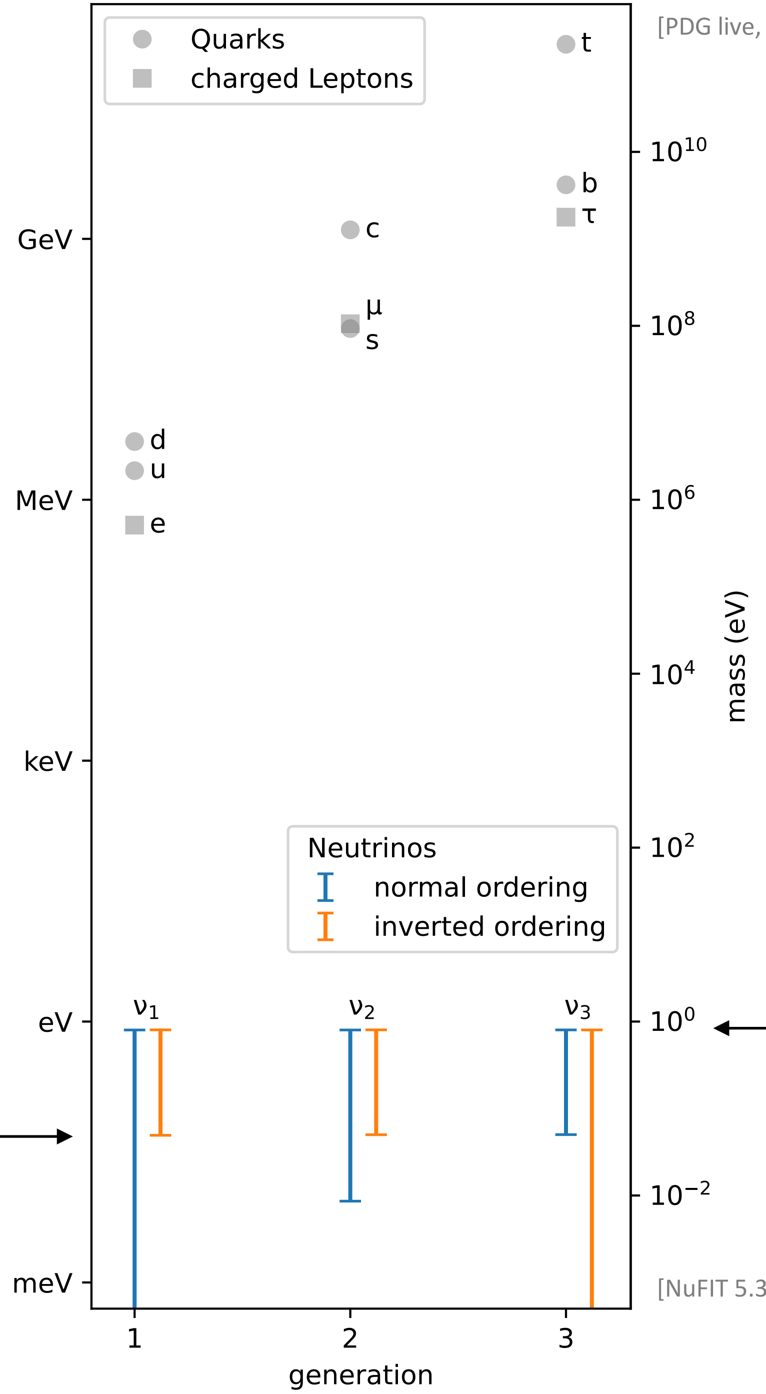

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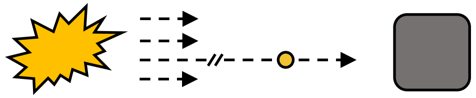
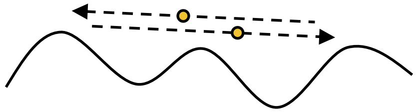
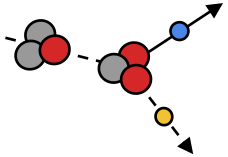
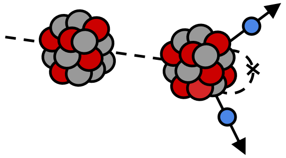
upper bound from **direct mass measurements**

Take away

- **How** can we measure the absolute neutrino mass?
- What are current **neutrino mass constraints**?
- **What assumptions** are behind different neutrino mass observables?
- How does the **KATRIN experiment** work?

Neutrino mass probes

- **Supernovae**, time-of-flight 
- **Cosmology** 
- Beta decay **kinematics**, direct neutrino mass measurements 
- Neutrinoless **double beta decay** 

} **laboratory**-based

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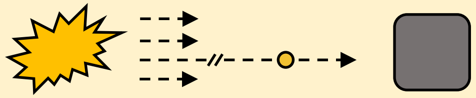
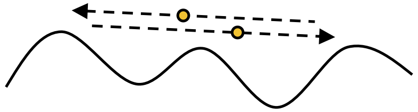
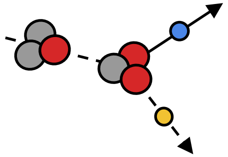
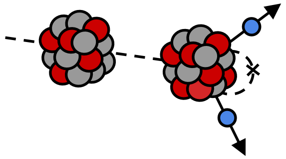
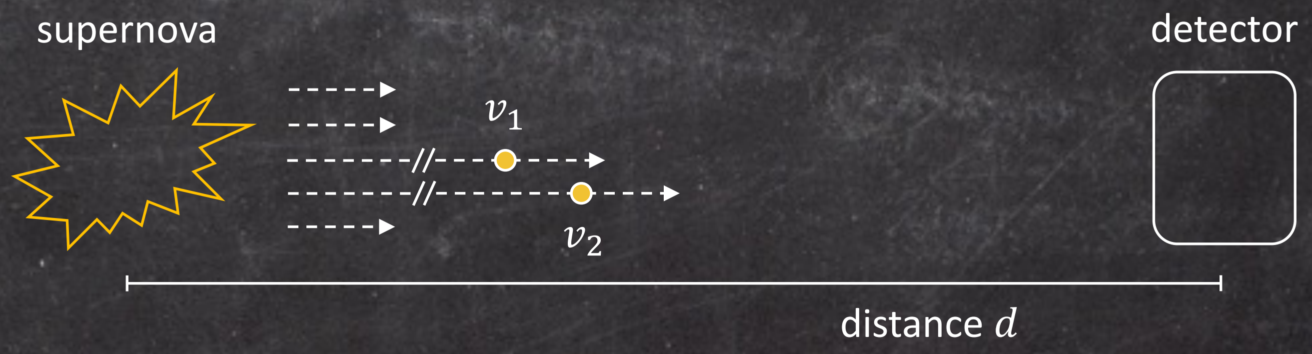
- **Supernovae**, time-of-flight 
- **Cosmology** 
- Beta decay **kinematics**, direct neutrino mass measurements 
- Neutrinoless **double beta decay** 

Time-of-flight



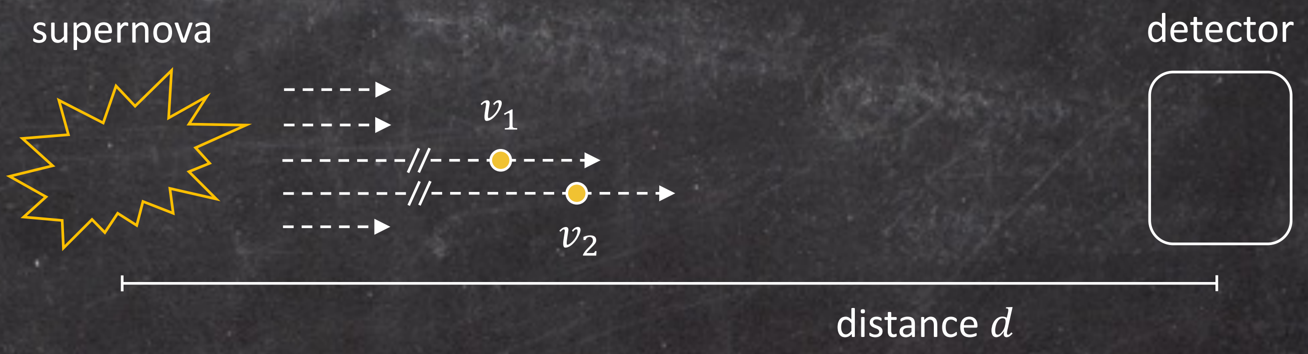
Velocity of relativistic neutrino $$v \approx c\sqrt{1-\frac{m^2c^4}{E^2}}$$

Travel time $$t=\frac{d}{v}=\frac{d}{c\sqrt{1-\frac{m^2c^4}{E^2}}}\approx\frac{d}{c}\left(1+\frac{1}{2}\frac{m^2c^4}{E^2}\right)$$

Time difference $$\Delta t=\frac{d}{v_1}-\frac{d}{v_2}=\frac{d}{2c}m^2c^4\left(\frac{1}{E_1^2}-\frac{1}{E_2^2}\right)$$

$$\rightarrow \quad mc^2=\sqrt{\frac{2c\Delta t}{d}\left(\frac{1}{E_1^2}-\frac{1}{E_2^2}\right)^{-1}}$$

Time-of-flight



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SN1987A: $d = 170\,000\ ly = 1.7\cdot 10^{21}\ m,\ E_1 = 6\ MeV,\ E_2 = 36\ MeV,\ \Delta t = 12\ s \quad \rightarrow \quad mc^2 = 12\ eV$

Supernova limits

- **SN1987A data** from Kamiokande, IMB and Baksan, **25 events** in total, recent supernova electron antineutrino **emission model**
  [Pagliaroli, Rossi-Torres, Vissani, Astropart.Phys. 33 (2010)]

m_ν **< 5.8 eV** (95% CL)

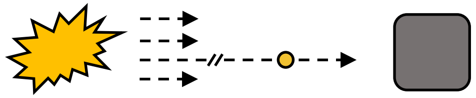
› independent, but not competitive bound

- **1-3 supernovae per century** in our galaxy, more powerful detectors online (e.g. SuperKamiokande) or under contruction (e.g. DUNE)

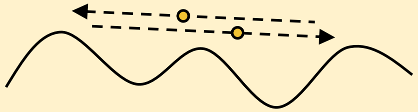
› **sub-eV sensitivity**, depends on circumstances (e.g. distance)
  [Pompa et al., PRL 129 (2022)]

Neutrino mass probes

- **Supernovae**, time-of-flight



- **Cosmology**



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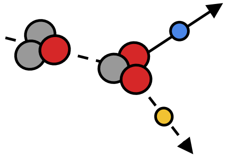

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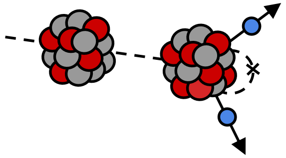


Neutrinos in the cosmos

- present in **primordial plasma**, **freeze-out** as temperature drops below weak interaction scale, **cosmic neutrino background** (CνB)

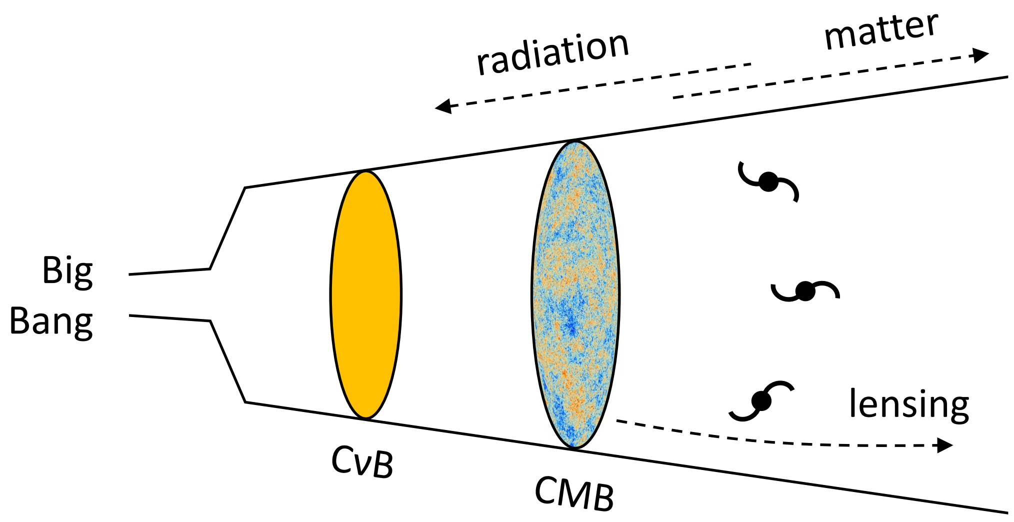
› **most abundant known massive particle** in the universe

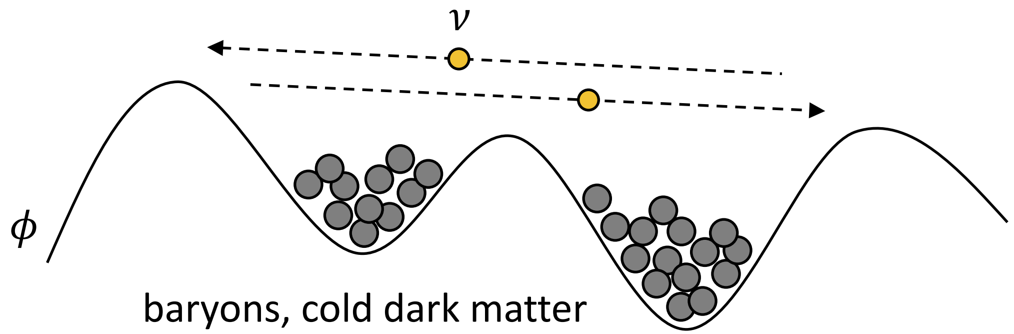
- neutrino mass defines transition from **radiation to matter behaviour**

› modifies **background evolution**, redshift to matter-to-radiation equality

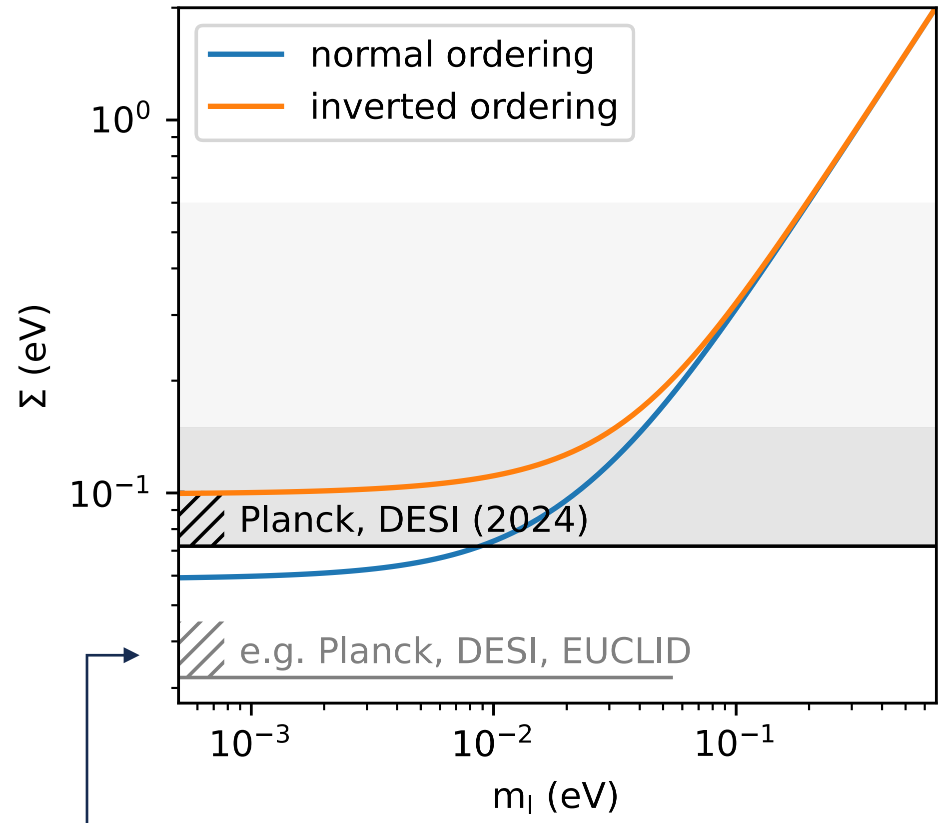
- heavy non-relativistic **matter clumps on small scales**, neutrinos disperse energy across overdensities, effectiveness depends on neutrino mass

› neutrino mass leaves **imprint on structure growth**, matter power spectrum





Sum of neutrino mass eigenstates, $\Sigma = \sum_i m_i$

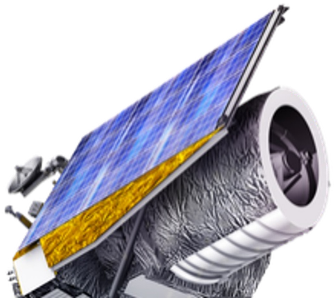


standard scenario **predicts detection**

- minimum at **0.06 eV** (normal ordering), **0.10 eV** (inverted ordering)
- most stringent bound driven by **Planck and DESI data**
  [Aghanim et al., A&A 641 (2020); Adame et al., arXiv:2404.03002]

Σ < 0.07 eV (95% CL)

- **model dependence** can weaken bounds
  - extended **cosmology** (dark energy dynamics, ..), **x2**
    [Choudhury, Hannestad, JCAP 07 (2020), ..]
  - non-standard **neutrino physics** (invisible neutrino decay, time-dependent neutrino mass, ..), **x10**
    [Escudero et al., JHEP 12 (2020); Dvali, Funke, PRD 93 (2016), ..]
- future observatories and missions (**EUCLID**, ..)
  [Brinckmann et al., JCAP 01 (2019), ..]



σ_Σ = **O(0.01) eV**

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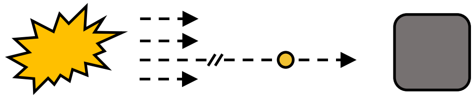

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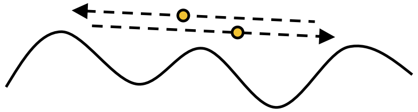

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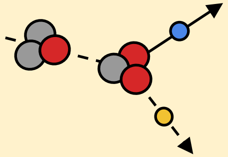

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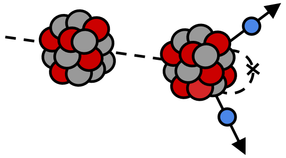
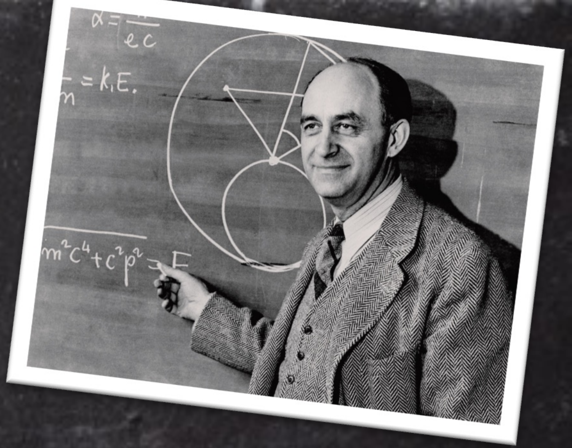


β *decay kinematics*

Enrico Fermi:
"Let's express this with the kinetic energy of the electron and the mass of the neutrino."

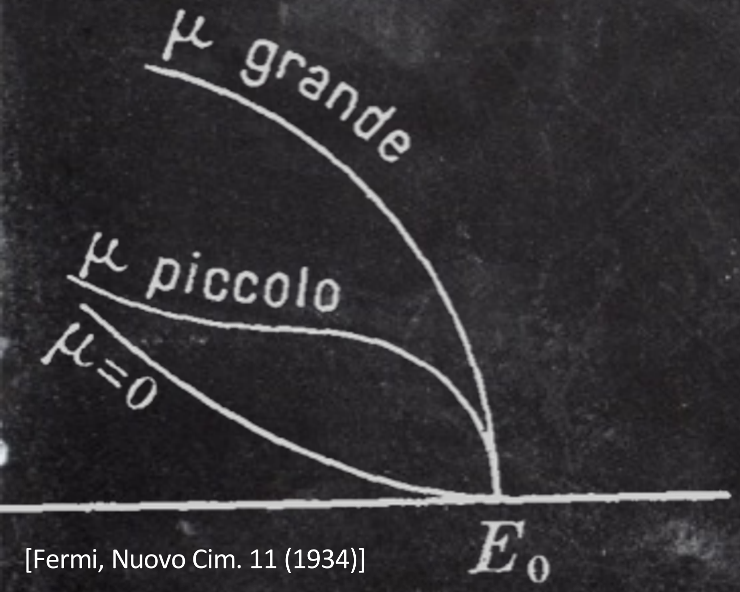


Fermi function ⏞ · phase space factor ⏞

differential decay rate $\frac{d\Gamma}{dE} \propto F(E,Z) \cdot E_e \cdot E_\nu \cdot p_e \cdot p_\nu$

$$= F(E,Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

electron energy · neutrino energy (endpoint E_0) · electron momentum ($E^2 = p^2 + m^2$) · neutrino momentum



[Fermi, Nuovo Cim. 11 (1934)]

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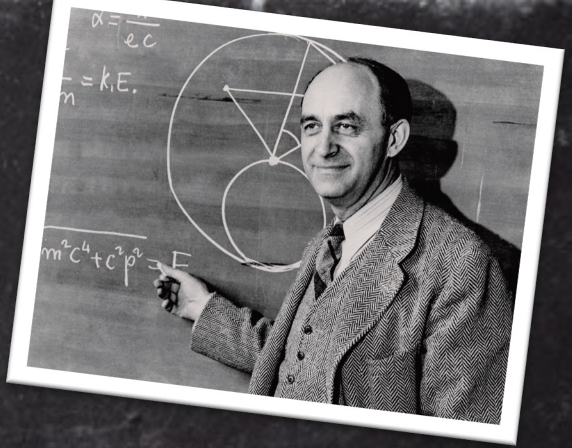

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Fermi function — phase space factor

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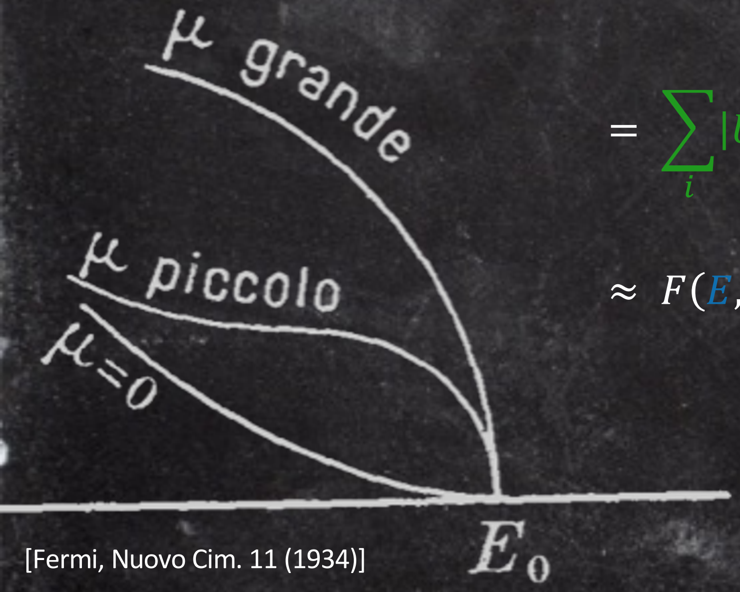
$$= \sum_i |U_{ei}|^2 \cdot F(E,Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - m_i^2}$$

$$\approx F(E,Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - m_\beta^2}$$



[Fermi, Nuovo Cim. 11 (1934)]

effective electron (anti-)neutrino mass (incoherent sum of mass eigenstates) $$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

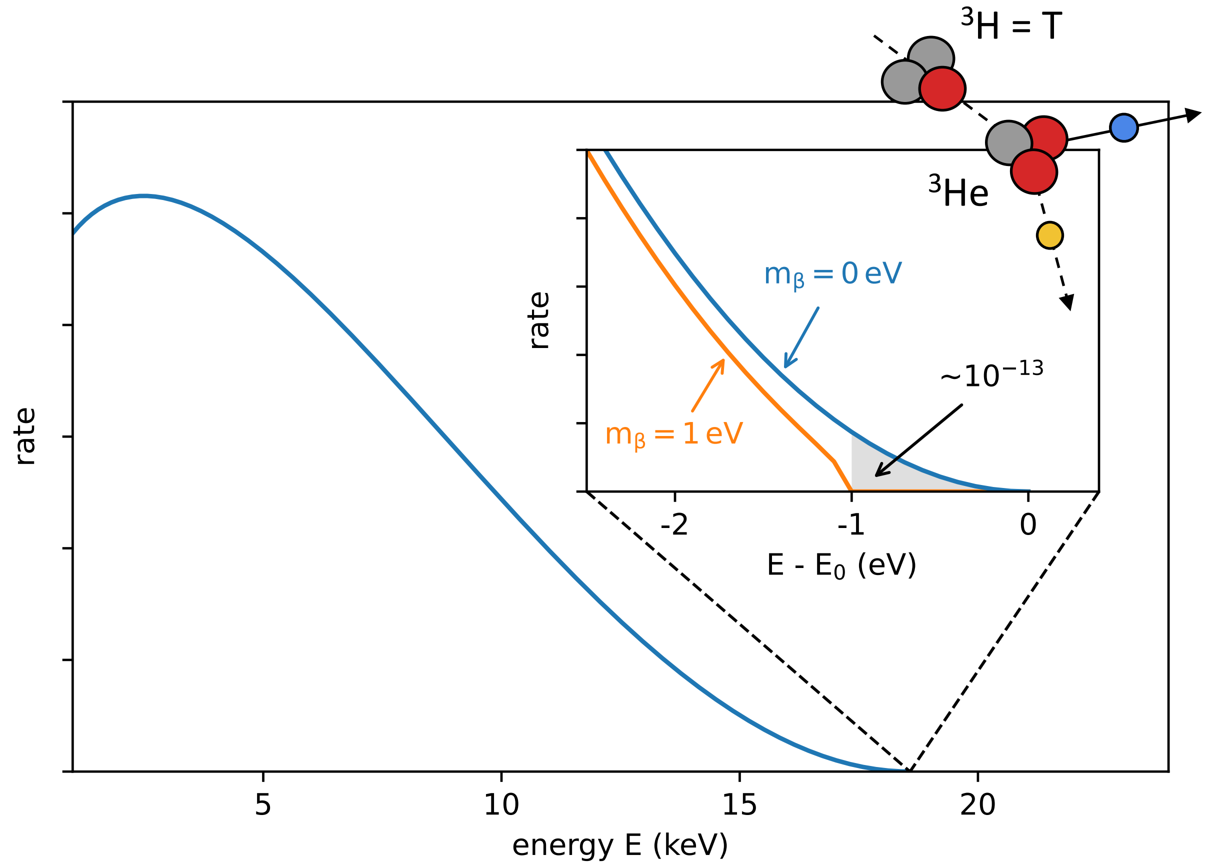
Shoichi Sakata:
"But there are three neutrino mass eigenstates."

Experimental challenge

measure eV-scale **spectral distortion**, maximal at keV-scale **kinematic endpoint**

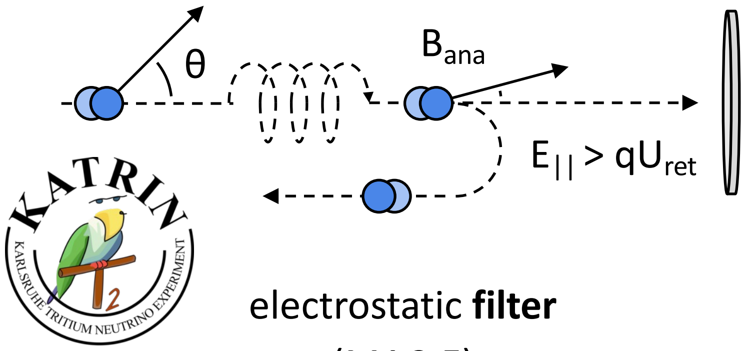
- **high-activity** source, **low Q-value**
    - **tritium** ^{3}H ($T_{1/2}$ = 12.3 yr, E_0 = 18.6 keV)
    - **holmium** ^{163}Ho ($T_{1/2}$ = 4570 yr, E_0 = 2.8 keV)

- excellent **energy resolution** (O(1) eV, < 0.01 %), low **background** (mcps)
- **high precision** understanding of theoretical spectrum and experimental response

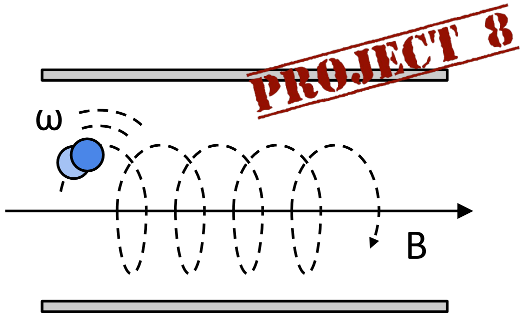


Experimental approaches

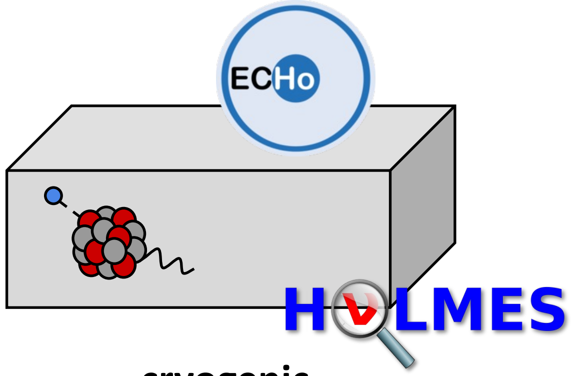
tritium



electrostatic **filter**
(MAC-E)



cyclotron radiation emission
spectroscopy (CRES)



cryogenic
calorimeters

R&D

Experimental approaches

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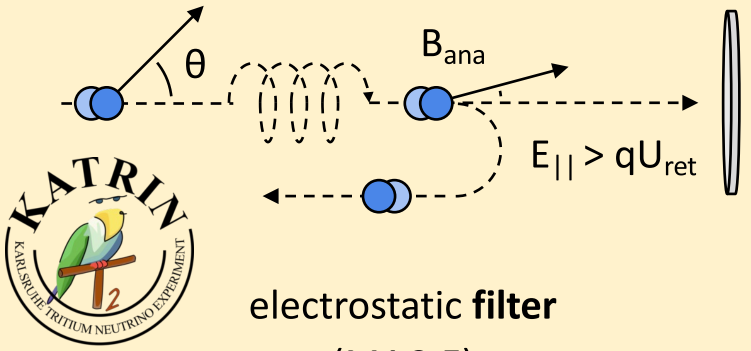

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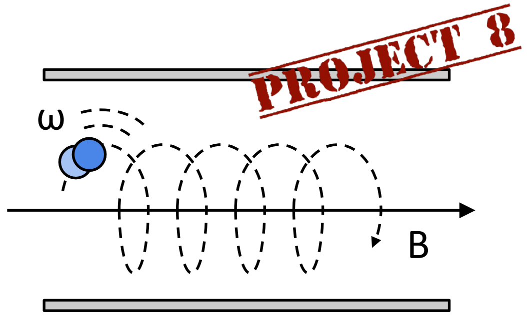

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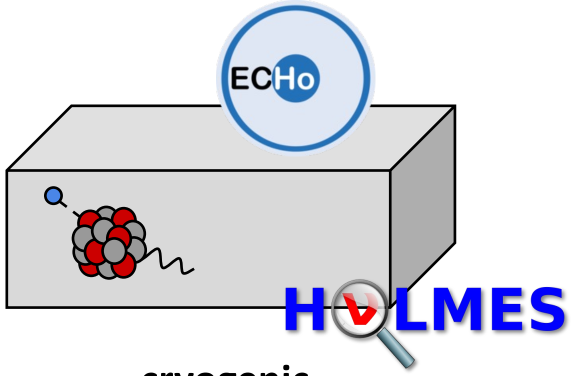

cryogenic
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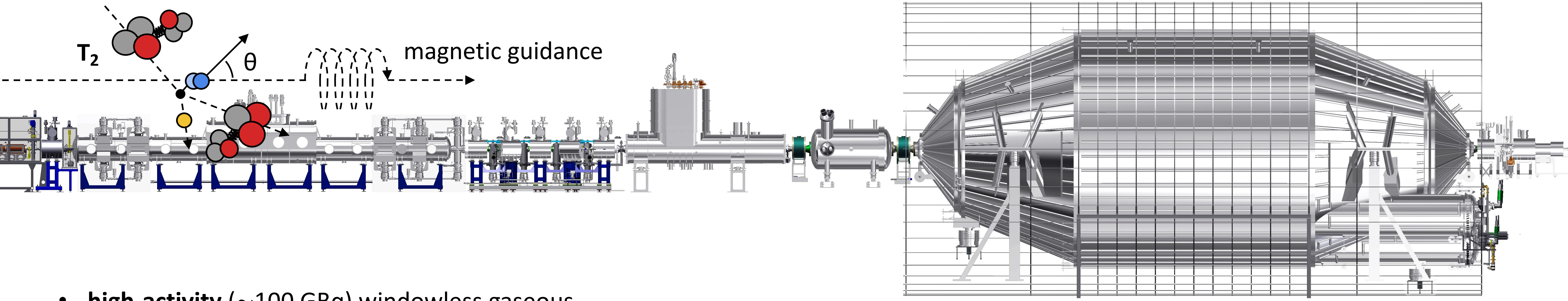
R&D

Karlsruhe Tritium Neutrino (KATRIN) experiment

KATRIN working principle

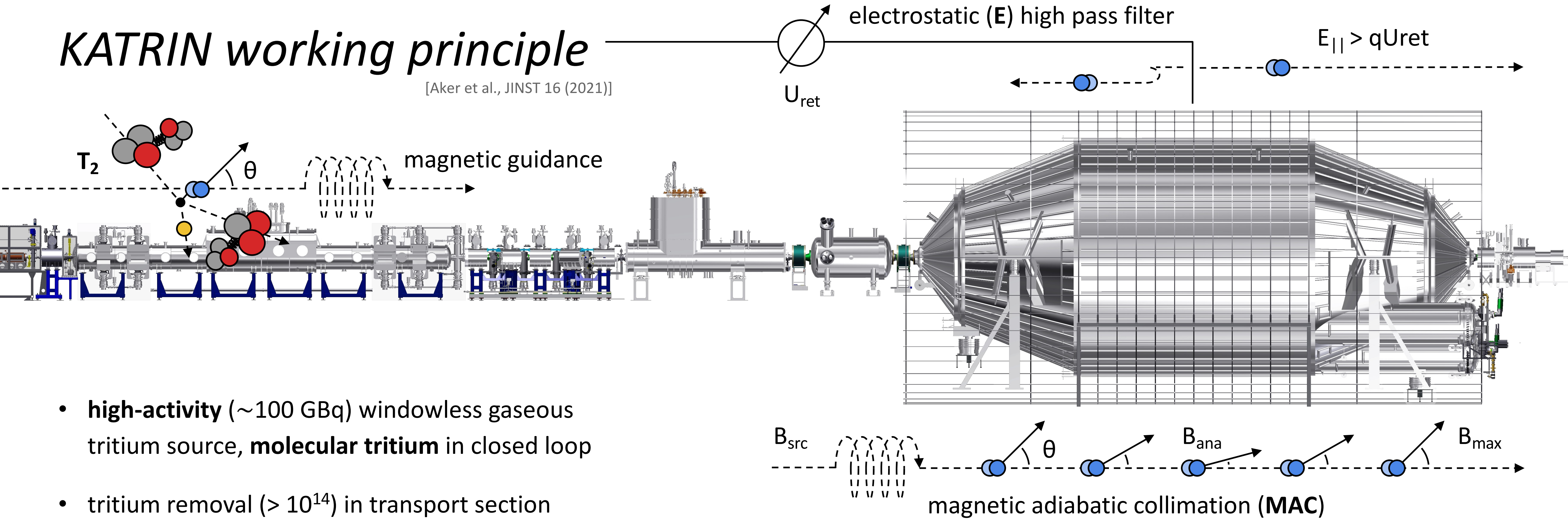
[Aker et al., JINST 16 (2021)]



- **high-activity** (~100 GBq) windowless gaseous tritium source, **molecular tritium** in closed loop
- tritium removal (> 10^{14}) in transport section

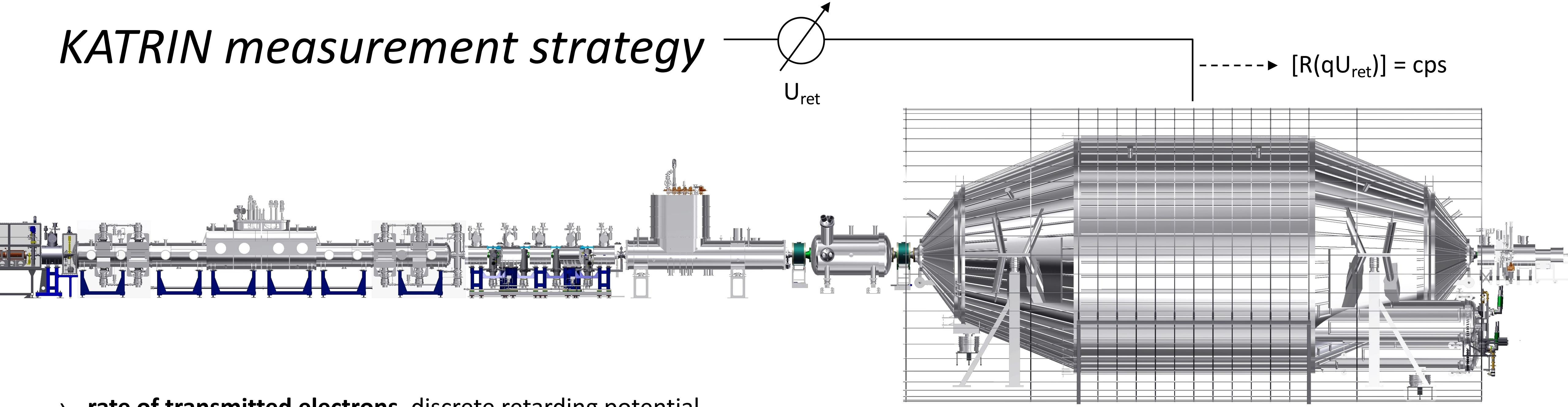
KATRIN working principle

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



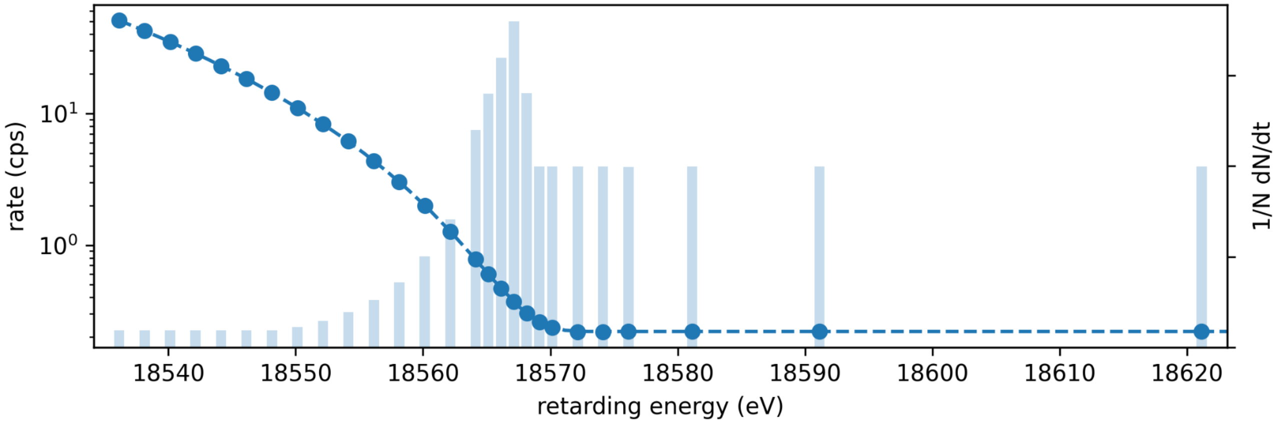
- **high-activity** (~100 GBq) windowless gaseous tritium source, **molecular tritium** in closed loop
- tritium removal (> 10^{14}) in transport section
- **high-resolution** (~ 1 eV) **large-acceptance** (0-51°) MAC-E spectrometer system
- **electron counting** with focal plane detector (148-pixel silicon PIN diode)

KATRIN measurement strategy



› **rate of transmitted electrons,** discrete retarding potential steps, optimized measurement time distribution

- **scans** in up, down and random sequence
- O(1h) per scan, O(100) scans per campaign, several **campaigns** per year



KATRIN neutrino mass results

1st campaign, 2 million events (22 days)
[Aker et al., PRL 123 (2019)]

- best fit (**p-value = 0.6**) $m_\beta^2 = -1.0^{+0.9}_{-1.1}\, eV^2$

› **upper limit** $m_\beta < 1.1\, eV\ (90\%\ CL)$

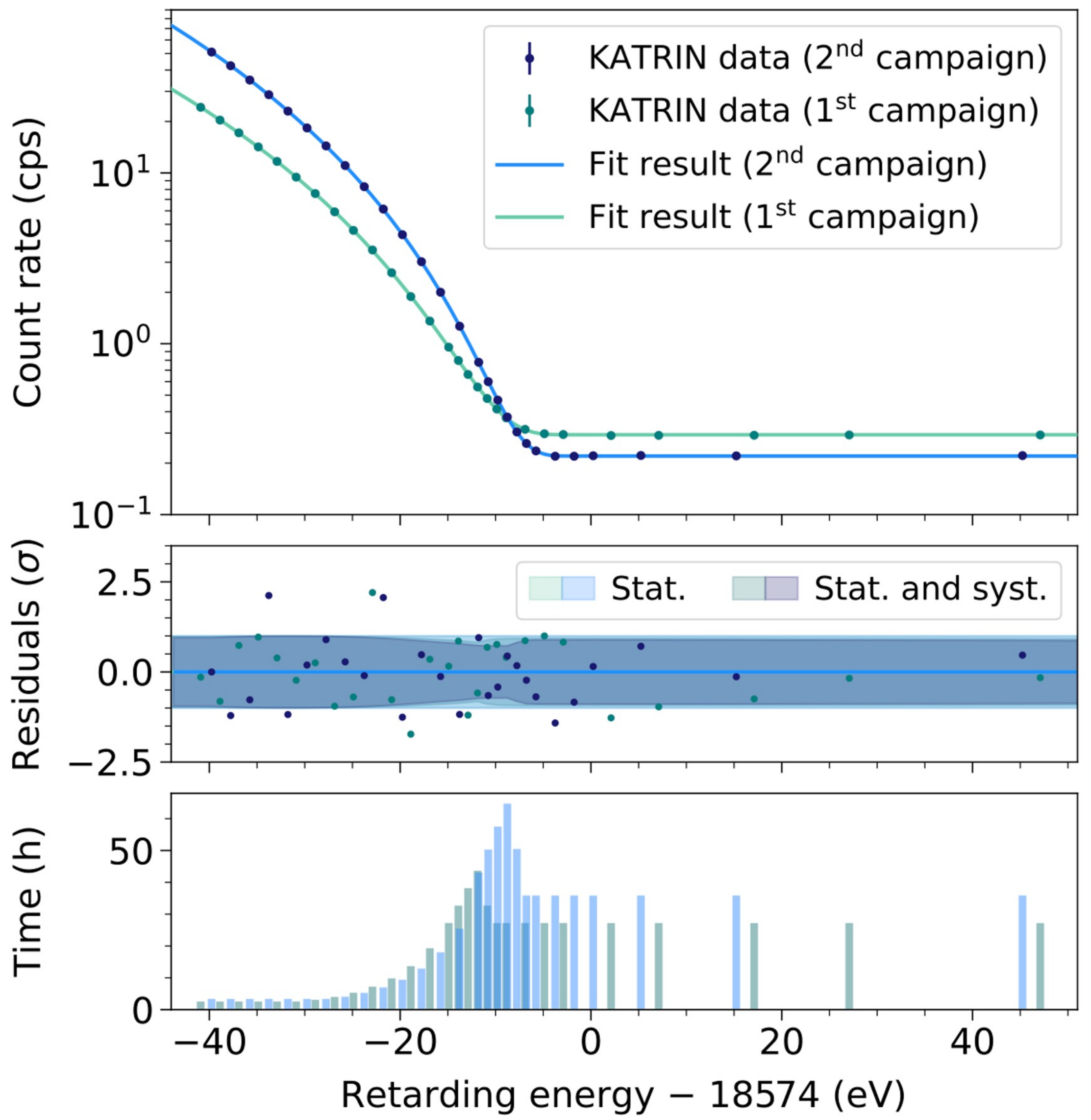
2nd campaign, 4 million events (31 days)
[Aker et al., Nature Phys. 18 (2022)]

- best fit (**p-value = 0.8**) $m_\beta^2 = (0.26\ \pm 0.34)\, eV^2$

› **upper limit** $m_\beta < 0.9\, eV\ (90\%\ CL)$

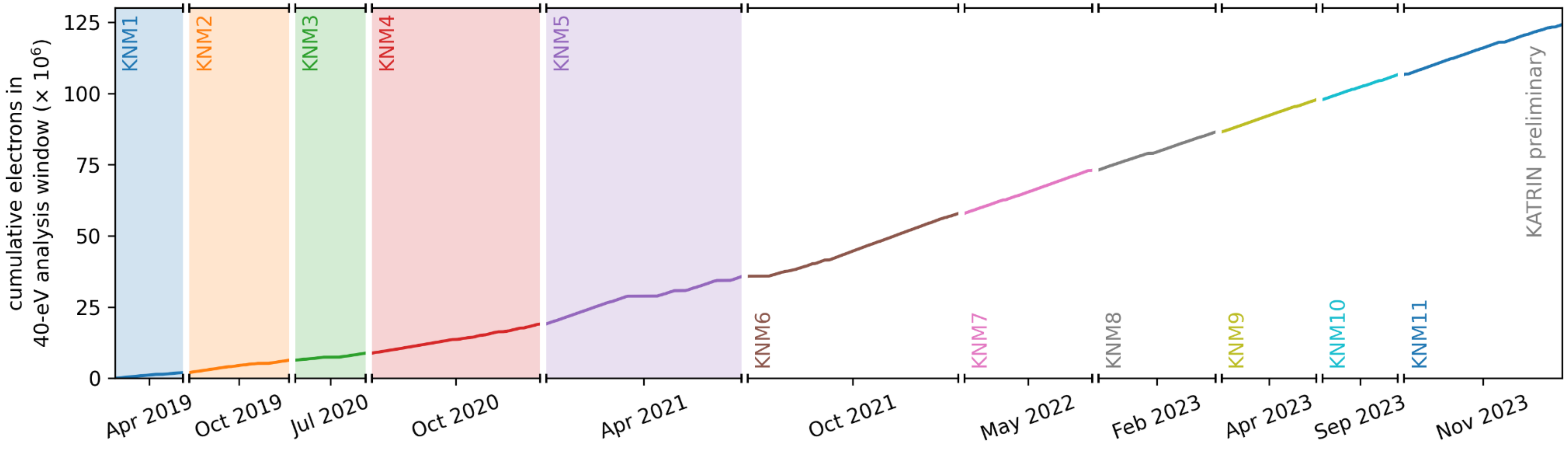
combined: $\boldsymbol{m_\beta < 0.8\, eV}\ (90\%\ CL)$

[Aker et al., Nature Phys. 18 (2022)]



KATRIN data taking overview

world-best constraint, $m_\beta < 0.8\ eV$ $(90\%\ CL)$

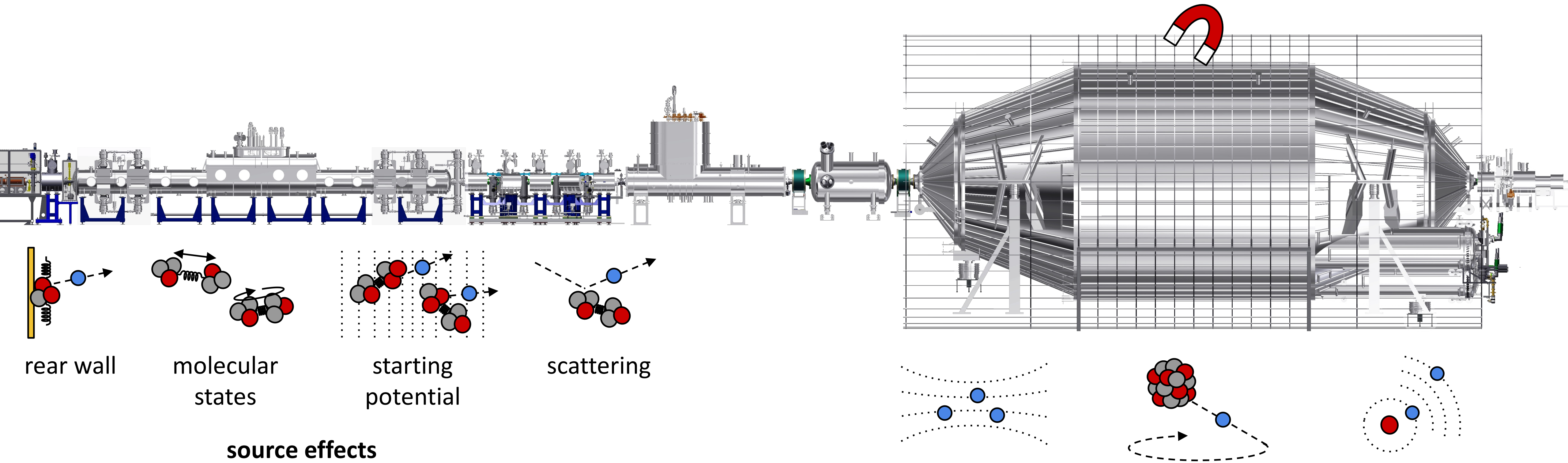


upcoming release, main challenges

until end-2025

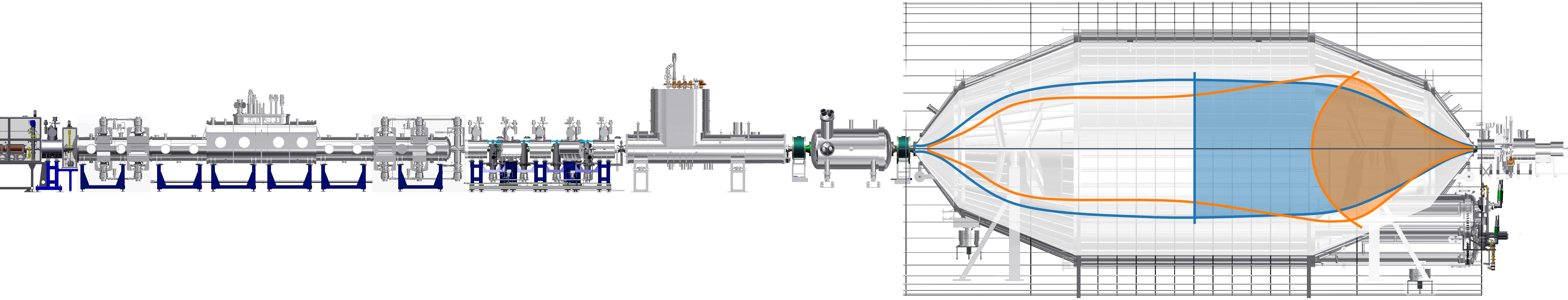
- **backgrounds** and **systematic effects**
- combination of **heterogeneous datasets**

KATRIN backgrounds and systematic effects



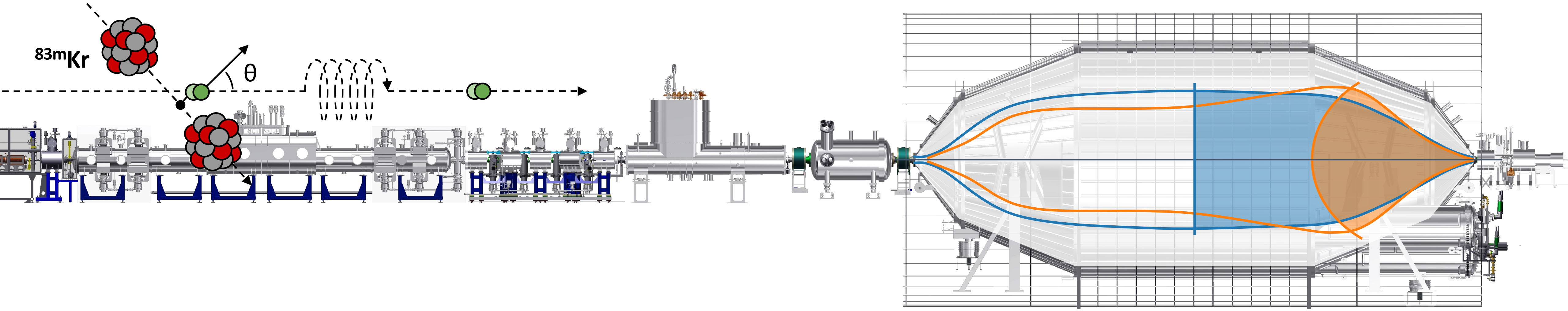
- **mitigation** of effects, e.g. real wall decontamination by O_3 treatment
  [Aker et al., Fusion Science and Technology 80 (2024)]
- high-precision **calibration**, e.g. spectrometer fields

KATRIN experimental improvements



- **shifted analyzing plane** configuration, **background reduction**
  [Lokhov et al., EPJ C 82 (2022)]

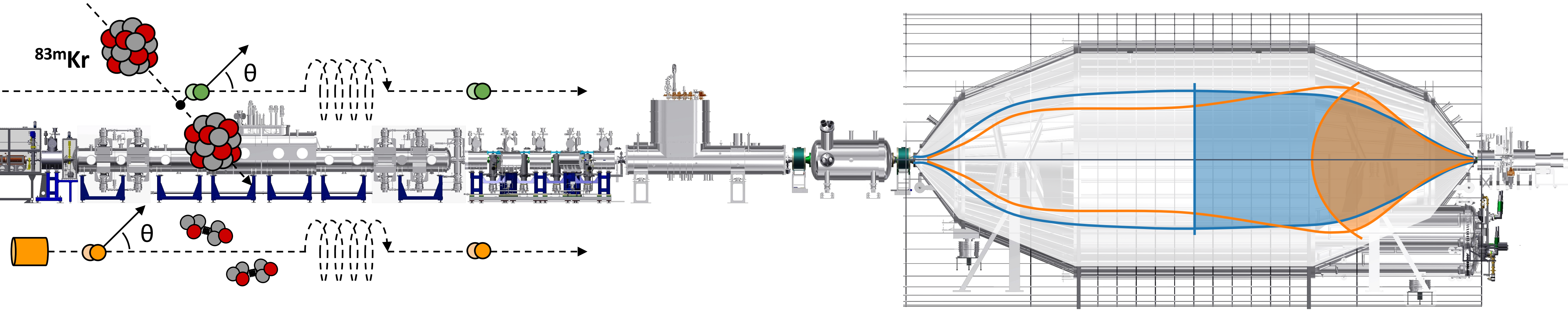
KATRIN experimental improvements



- **shifted analyzing plane** configuration, **background reduction**
  [Lokhov et al., EPJ C 82 (2022)]

- **^{83m}Kr co-circulation**, monoenergetic conversion electrons, probe **source potential** and **spectrometer fields**
  [Altenmüller et al., J.Phys.G 47 (2020)]

KATRIN experimental improvements



- **shifted analyzing plane** configuration, **background reduction**
  [Lokhov et al., EPJ C 82 (2022)]

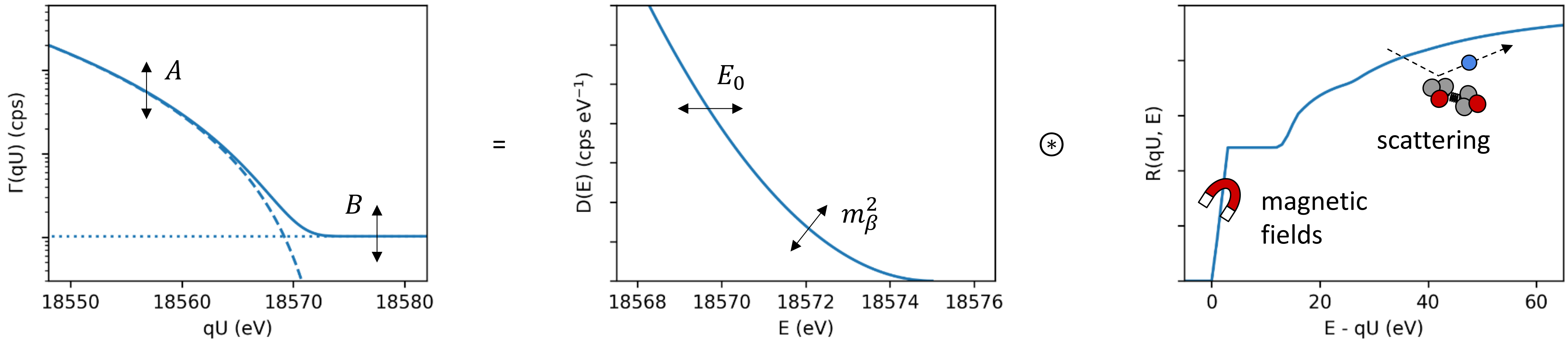
- **^{83m}Kr co-circulation**, monoenergetic conversion electrons, probe **source potential** and **spectrometer fields**
  [Altenmüller et al., J.Phys.G 47 (2020)]

- improved **electron gun**, mono-energetic angular-selective photoelectron source, probe **scattering effects**
  [Aker et al., EPJ C 81 (2021)]

KATRIN analysis procedure

- **maximum likelihood fit** of model $\Gamma(qU) \propto A \cdot \int_{qU}^{E_0} D\left(E, m_\beta^2, E_0\right) \cdot R(qU, E)\, dE \; + \; B$

integral spectrum = **differential spectrum** ⊛ **response function**



with free **squared neutrino mass $\boldsymbol{m_\beta^2}$**, effective endpoint E_0, amplitude A and background B

- **theoretical** (Fermi theory, molecular excitations) and **experimental** inputs (calibration measurements)

KATRIN analysis challenge

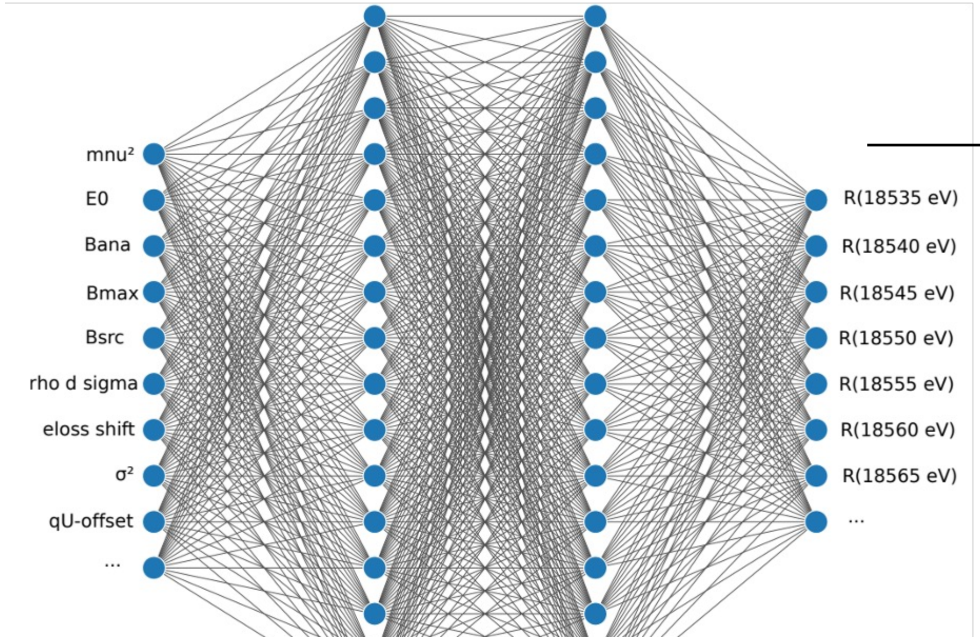
- **high granularity**, different campaign settings, detector segmentation — 7 datasets, 59 spectra, **1609 data points**
- **high dimensionality**, parameter correlations across datasets — **178 free parameters**
- **complex model**, differential spectrum integrated over response

KATRIN analysis challenge

- **high granularity**, different campaign settings, detector segmentation — 7 datasets, 59 spectra, **1609 data points**
- **high dimensionality**, parameter correlations across datasets — **178 free parameters**
- **complex model**, differential spectrum integrated over response

- two **independent analysis** frameworks — **successfully unblinded**, data release in preparation
  - optimized model evaluation, caching
  - neutral network surrogate, interpolation
    [Karl et al., EPJ C 82 (2022)]
- **two-stage blinding**, simulation analysis, model blinding

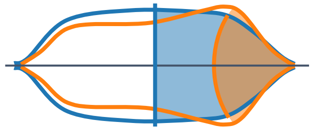
model **parameters**, e.g. gas density



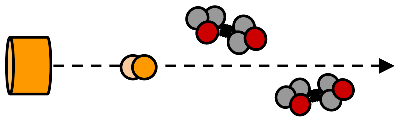
rate prediction

KATRIN upcoming result

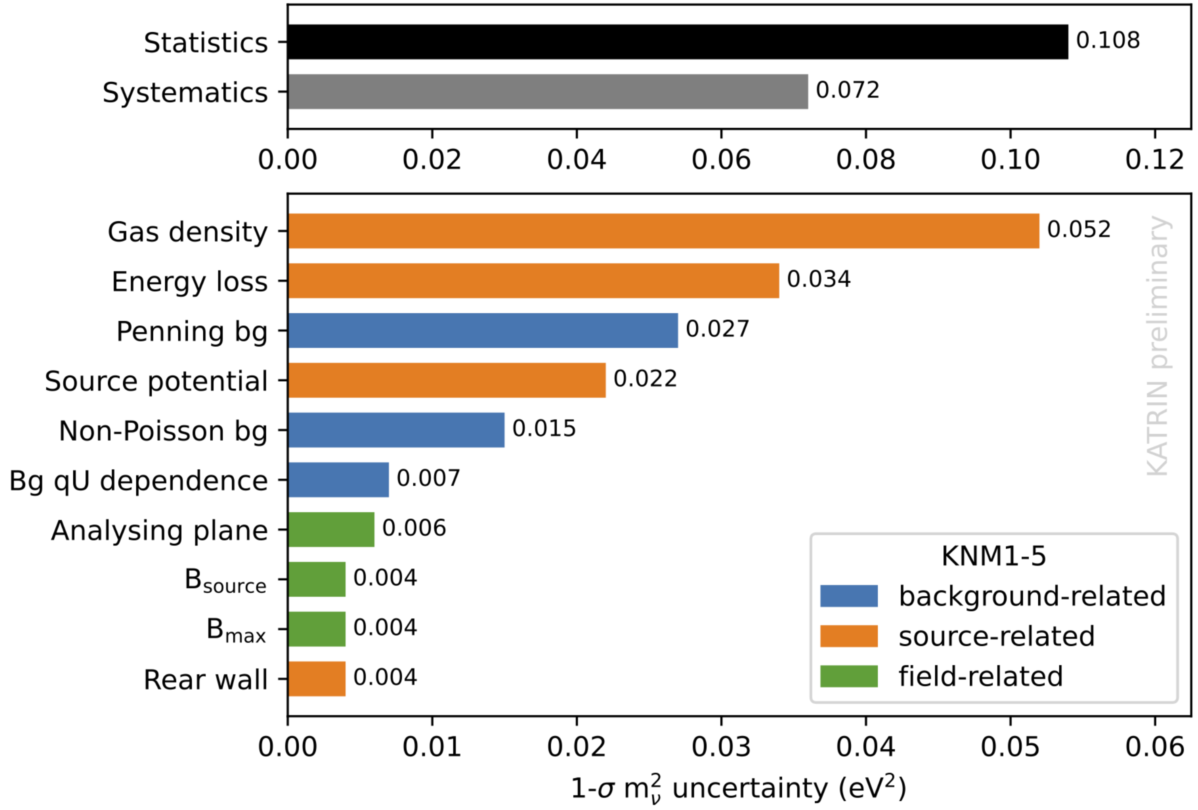
- **6-fold increase in statistics,** 2-fold reduction of background



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

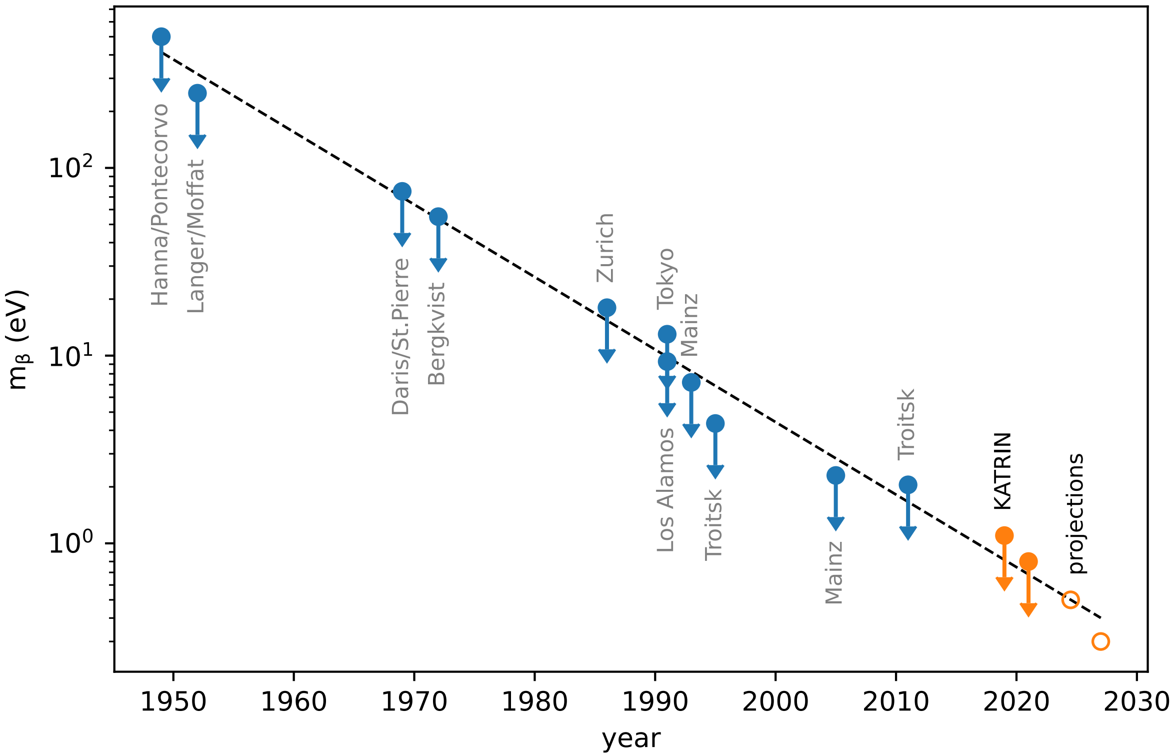


› statistics dominated, **projected sensitivity** $m_\beta < \mathbf{0.5\ eV}\ (90\%\ CL)$



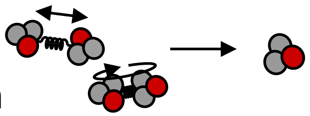
KATRIN outlook

- data taking **ongoing**, projected final sensitivity $m_\beta < \mathbf{0.3}\ \boldsymbol{eV}\ (90\%\ CL)$

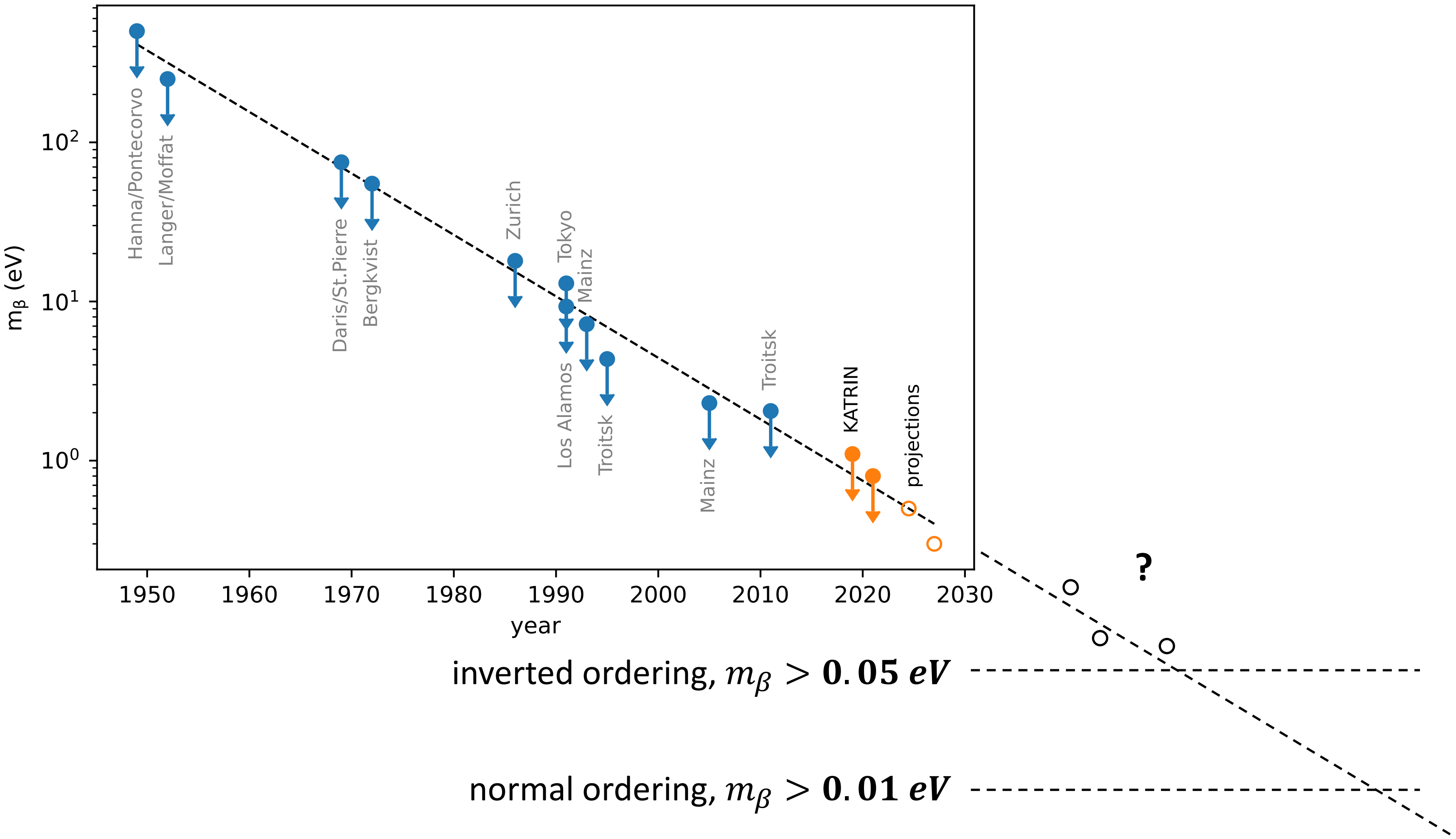


KATRIN outlook and beyond

- data taking **ongoing**, projected final sensitivity $m_\beta < \mathbf{0.3}\ \boldsymbol{eV}$ $(90\%\ CL)$
- m_β has **minimum value**, guaranteed measurement
- sensitivity beyond KATRIN requires **new technology**
  - **differential sub-eV** spectrocopy
  - **atomic tritium** (or **calorimetric** measurement)

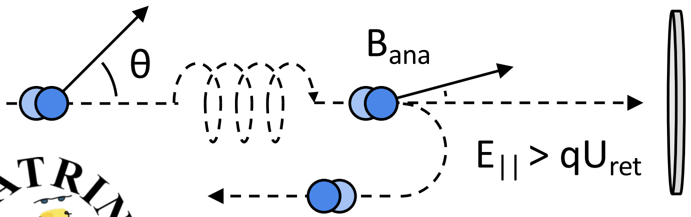


  › **KATRIN++** R&D efforts

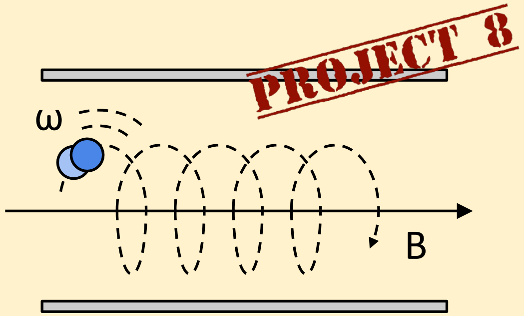


Experimental approaches

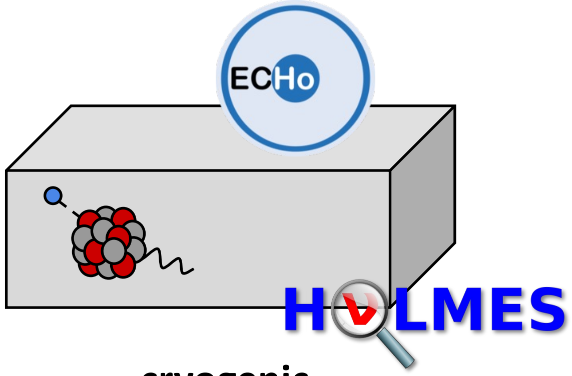
tritium



electrostatic **filter**
(MAC-E)



cyclotron radiation emission
spectroscopy (CRES)



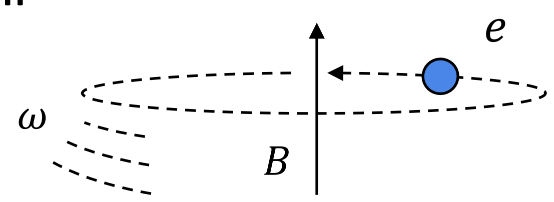
cryogenic
calorimeters

R&D

Cyclotron radiation emission spectroscopy (CRES)

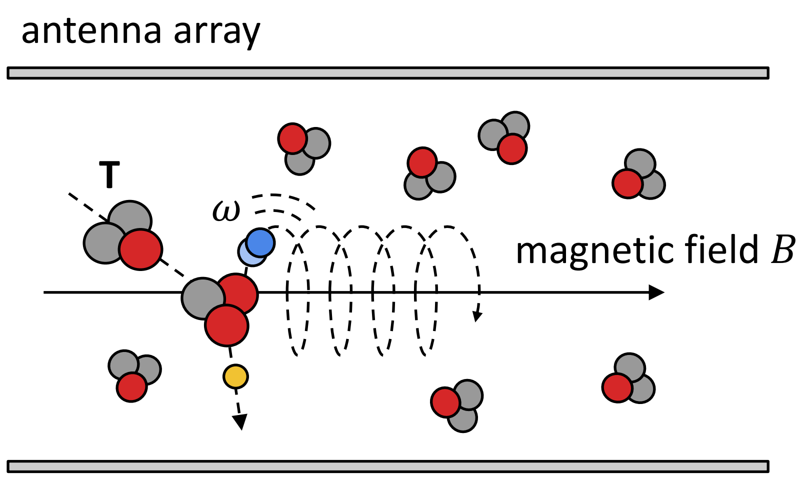
- **electromagnetic radiation** emitted by electron undergoing **cyclotron motion**

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{e\,B}{E + m_e}$$



› measure **cyclotron frequency**, determine energy of **trapped electron**

[Monreal, Formaggio, PRD 80 (2009) 051301]



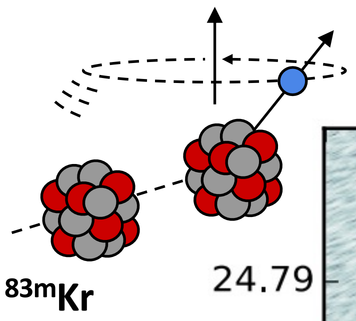
Cyclotron radiation emission spectroscopy (CRES)

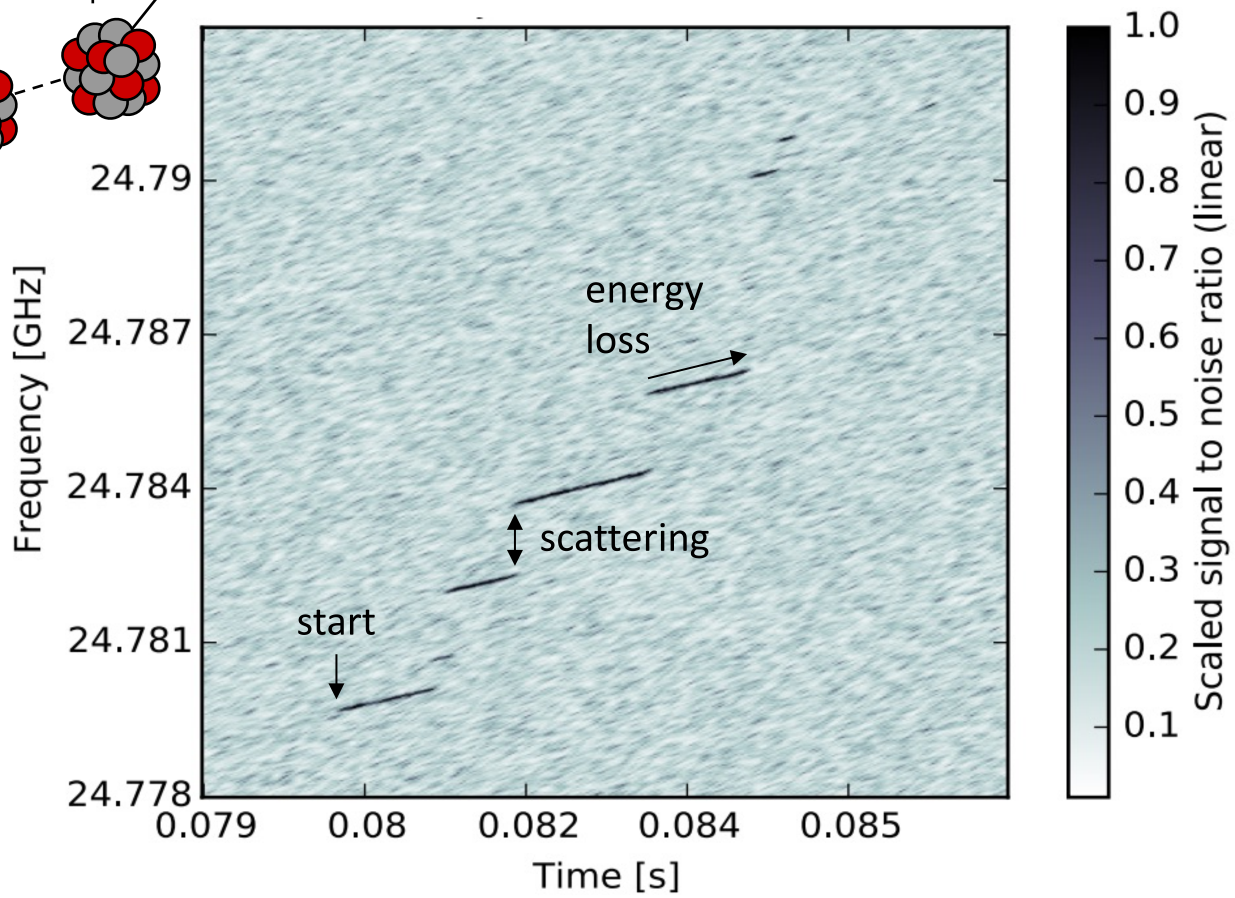
- **source transparent** to microwave radiation
  › **no electron extraction** needed

- **differential** frequency measurement
  › **eV-scale** resolution, **low background**

challenges

- sensitivity to **low power signal** ($< 10^{-15}$ W)
- **homogeneous** magnetic field (10^{-7})
- **large volume** trap (m^3)

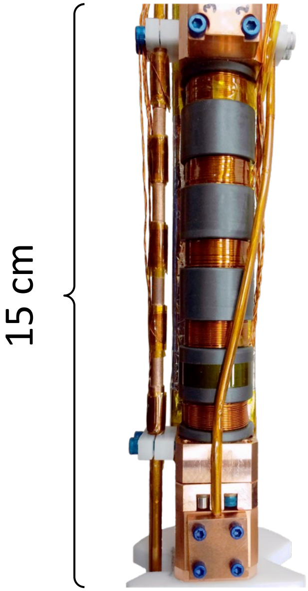




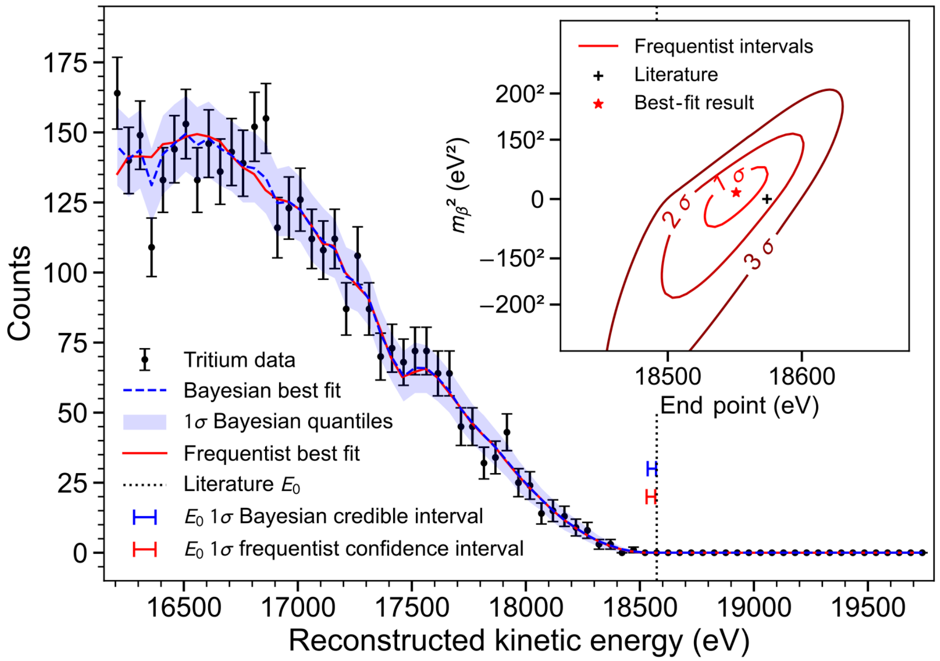
Project8

- **cold** atomic tritium **trap**, resonant **cavity**
- **proof-of-concept**, single electron spectroscopy
- molecular tritium **endpoint measurement**, first neutrino mass limit
  [Ashtari Esfahani et al., PRL 131 (2023)]

m_β < 155 eV (90% CL)

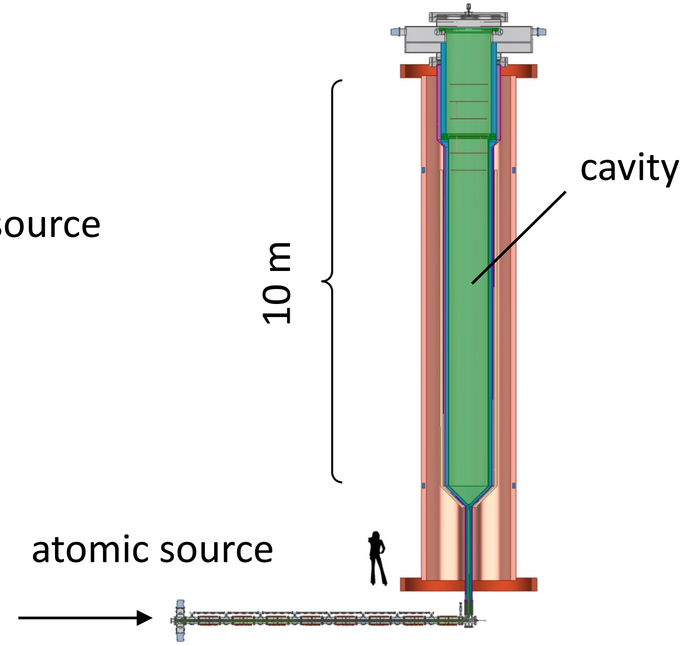


[Ashtari Esfahani et al., PRL 131 (2023)]



- **m³-scale** traps (antenna array or cavity resonator), **atomic tritium** source

› sensitivity **down to 0.04 eV**
  [Ashtari Esfahani et al., arXiv:2203.07349]

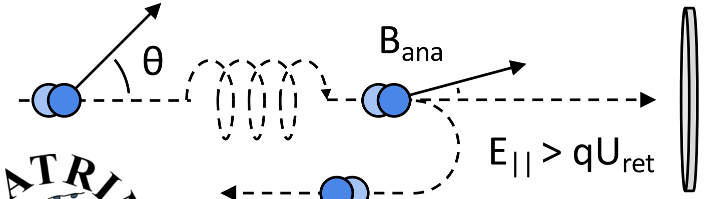


QTNM

- **storage ring** confinement, quantum limited micro-wave electronics
- in **conceptual stage**

Experimental approaches

tritium



electrostatic **filter**
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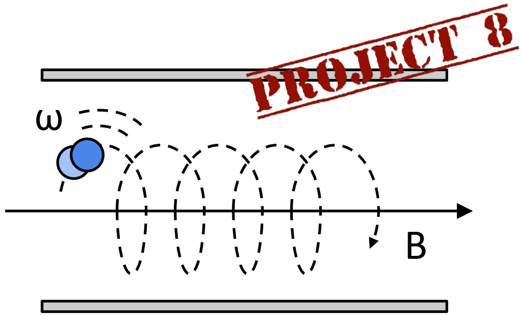
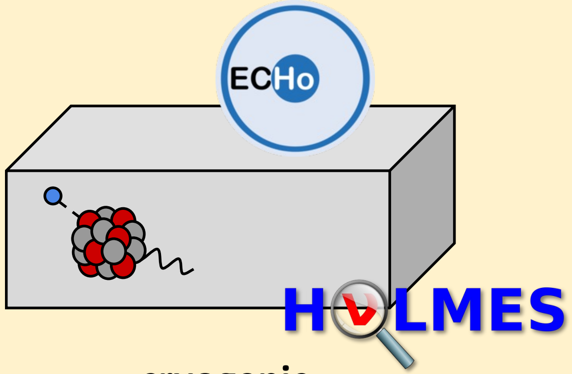


cyclotron radiation emission
spectroscopy (CRES)



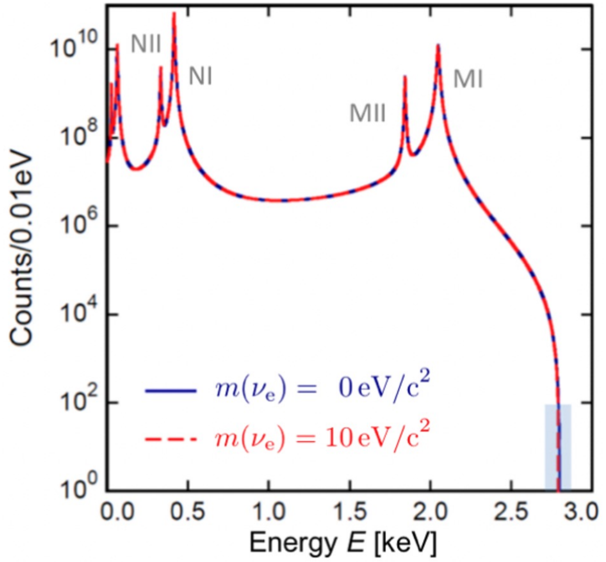
cryogenic
calorimeters

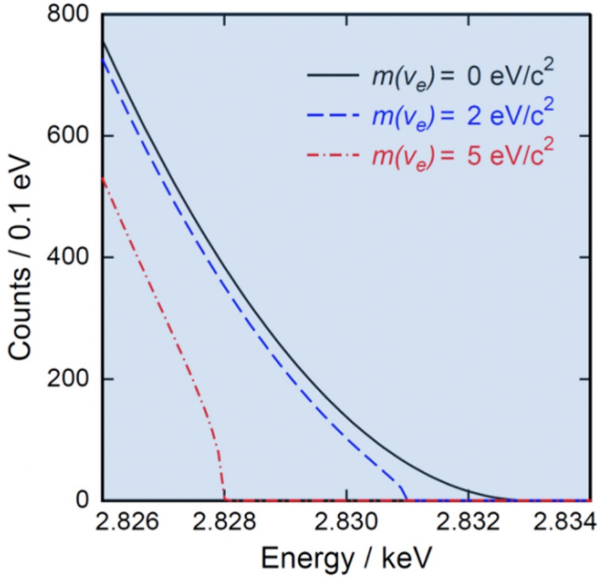
R&D

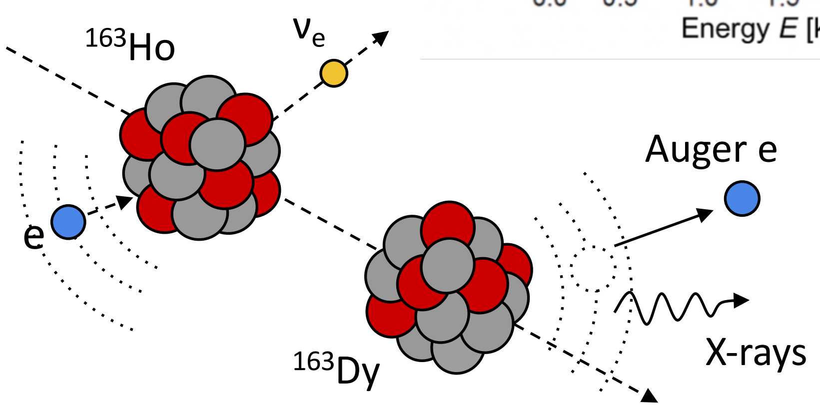
Holmium-163

- **electron capture** decay, energy shared between **excitation** and neutrino
- super-low **Q-value** (2.8 keV), **sub-eV** sensitivity with **MBq-scale activity**
  [Eliseev et al., PRL 115 (2015)]

› **calorimetric measurement** of decay energy
  [De Rujula, Lusignoli, PLB 118 (1982) 429]







Cryogenic calorimeters

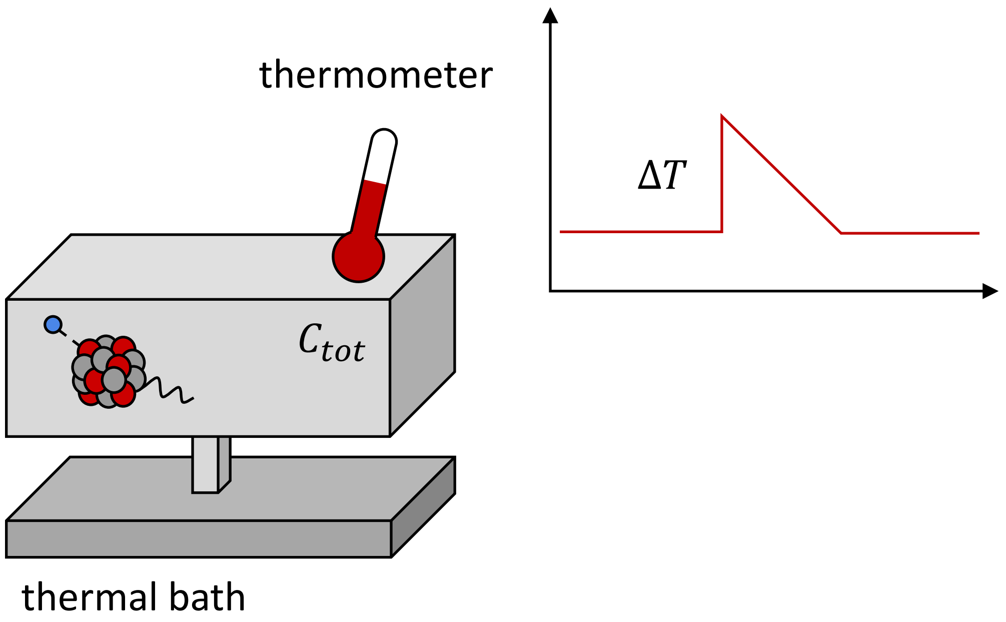
- **holmium implanted** in absorber with **small heat capacity** C_{tot}

› small volume, low tempertures (mK)

$$C_{tot} = \left(\frac{T}{T_D}\right)^3 \qquad \text{(Debye Law)}$$

› detection of **temperature increase** from decay energy

$$\frac{\Delta T}{E} \approx \frac{1}{C_{tot}} = O(1)\ mK/keV$$

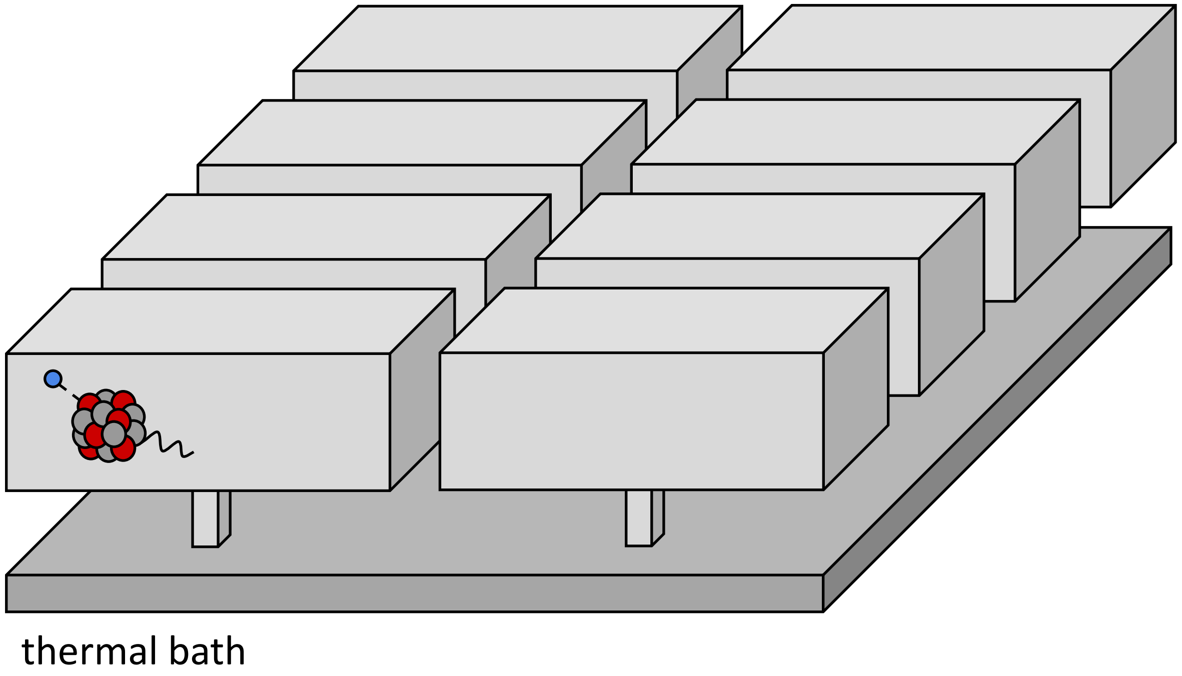


Cryogenic calorimeters

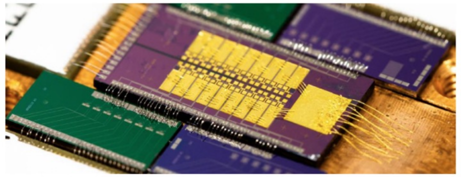
- **source = detector** concept, all decay energy is measured
- **eV-scale differential** measurement

challenges

- **pile-up** limits activity per pixel, multiplexed read-out
- difficult theoretical **spectrum calculation**



ECHO



- array of **metallic magnetic calorimeters** (MMC) with ^{163}Ho-implanted absorber, 10 Bq per pixel

- first **neutrino mass limit** (4 pixels with 0.2 Bq)
  [Velte et al., EPJ C 79 (2019)]

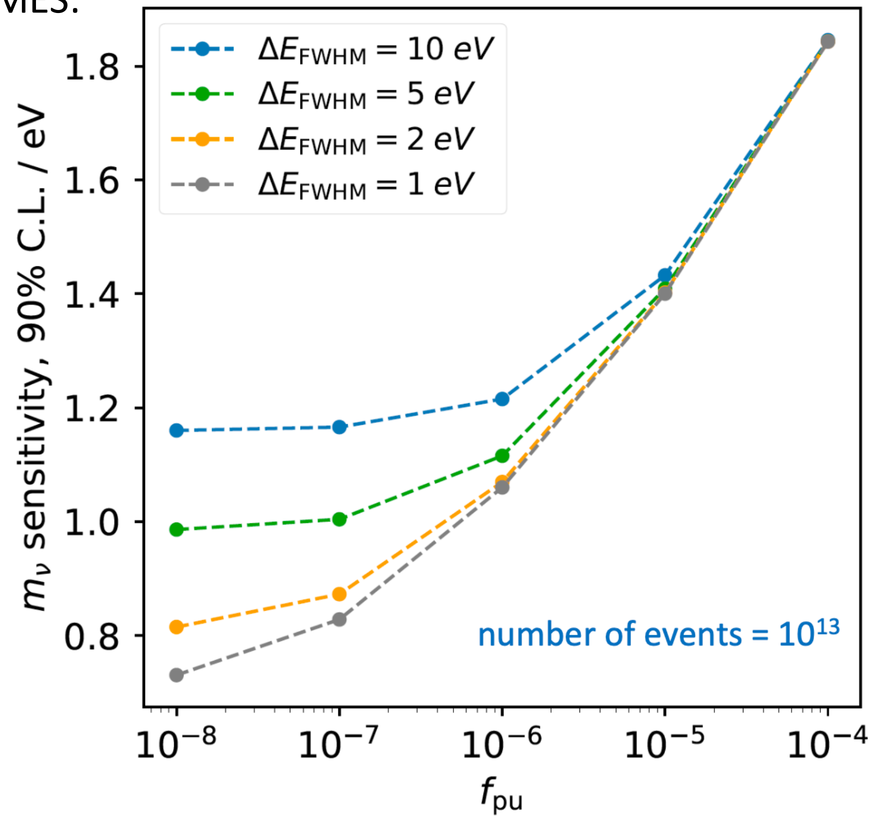
  m_β < 150 eV (95% CL)

- analysis of **new data** ongoing (60 pixels with 1 Bq)

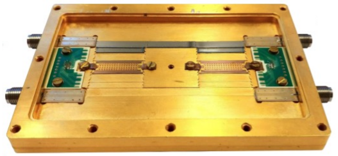
  sensitivity: m_β < 20 eV (95% CL)

sensitivity for **coming phases** of ECHO/HOLMES:

[Gastaldo, TAUP 2023]



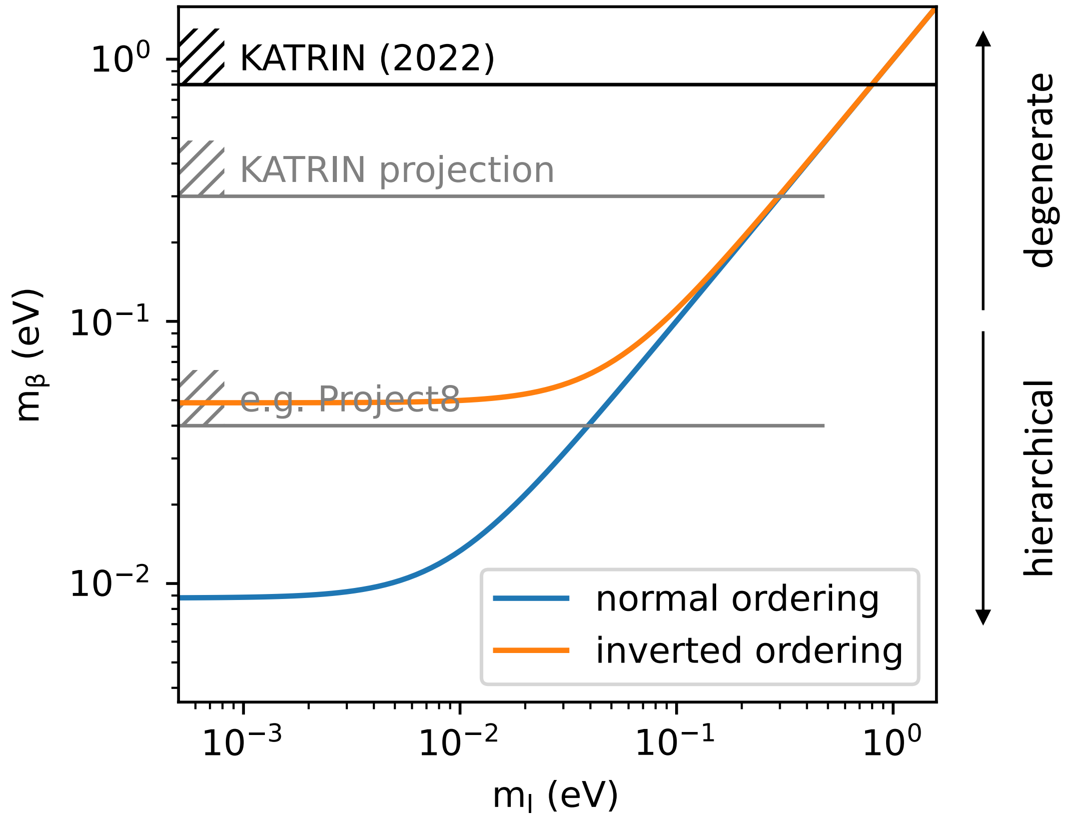
HOLMES



- array of **transition edge sensors** (TES) coupled to 163Ho-implanted absorber, 300 Bq per pixel

- first neutrino mass data taken, expect limit around 10 eV

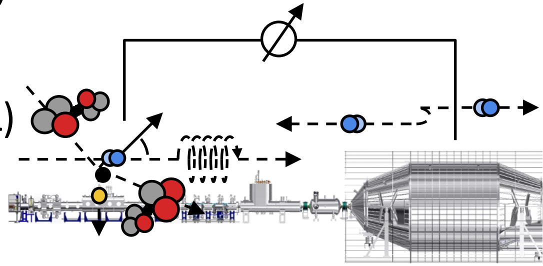
Effective electron neutrino mass, $m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$



- minimum at **0.01 eV** (normal ordering), **0.05 eV** (inverted ordering)

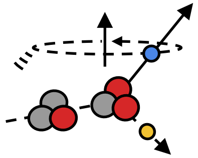
- current bound (KATRIN, 1st + 2nd campaign)
  [Aker et al., Nature Phys. 18 (2022) 2, 160-166]

  m_β **< 0.8 eV** (90% CL)



  and **data taking** is ongoing

- promising technologies to go beyond (**cyclotron radiation emission spectroscopy**, ..), differential detectors, atomic tritium
  [Ashtari Esfahani et al., arXiv:2203.07349]



  Project8 target: m_β < **0.04 eV** (90% CL)

Side note: relic neutrinos

- cosmic neutrino background (**CvB**)

$$\rho_{C\nu B} = 300\ cm^{-3} \text{ and } T_{C\nu B} = 1.95\ \mathrm{K}$$

- **capture on tritium**, no energy threshold, above endpoint

$$T \rightarrow {}^{3}He + e^{-} + \bar{\nu}_e$$

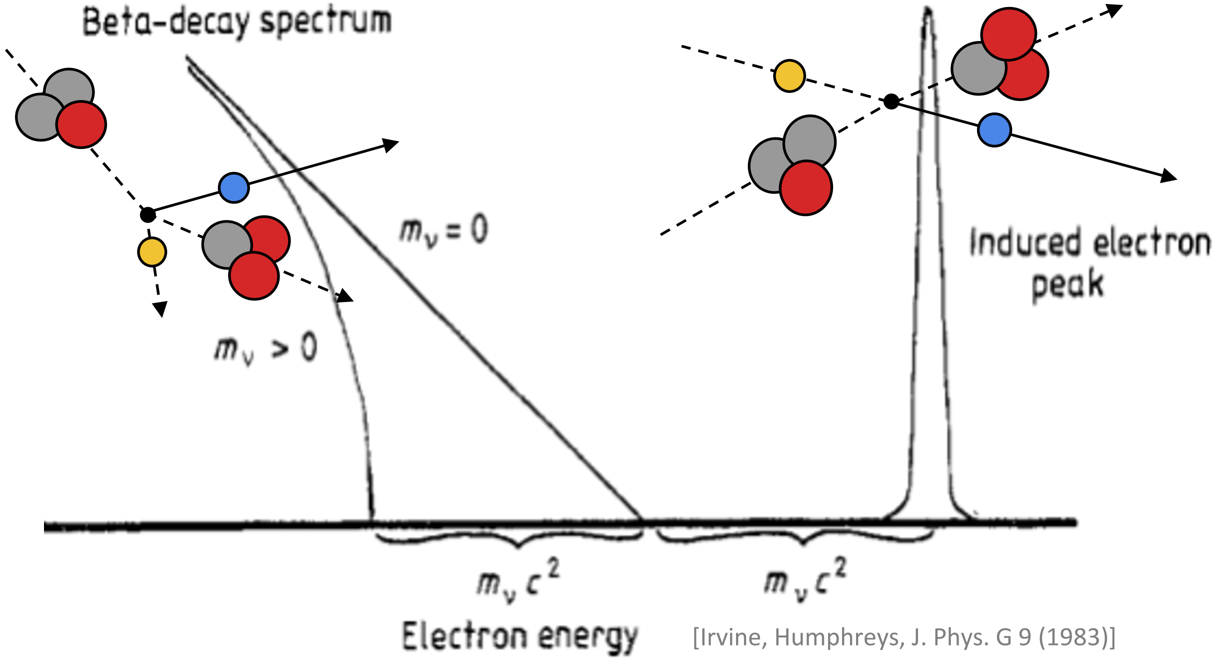
$$\nu_e + T \rightarrow {}^{3}He + e^{-}$$

- capture rate doubles for Majorana neutrinos (see later)

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

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

› **100x improvement** over previous laboratory bound



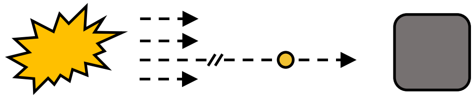
[Irvine, Humphreys, J. Phys. G 9 (1983)]

PTOLEMY

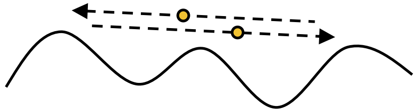
- monoatomic tritium in **graphene matrix**, **cyclotron emission** tagging, dynamic **electromagnetic filter**, micro **calorimeters**
  [Betti et al., PPNP 106 (2019)]

Neutrino mass probes

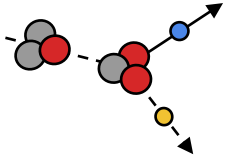
- **Supernovae**, time-of-flight



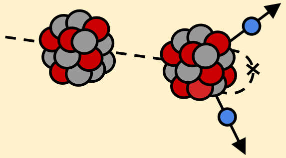
- **Cosmology**



- Beta decay **kinematics**, direct neutrino mass measurements

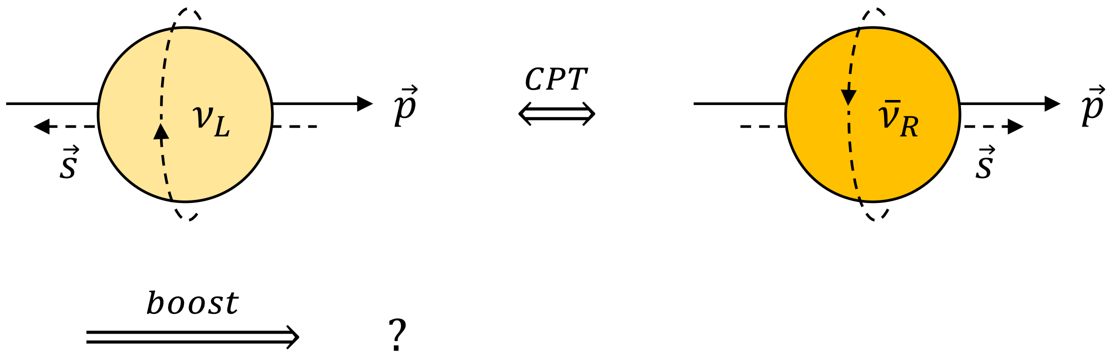


- Neutrinoless **double beta decay**



Neutrino nature

- **neutrinos** are left-handed, **anti-neutrinos** are right-handed



Paul Dirac:
"They are fundamentally different particles."

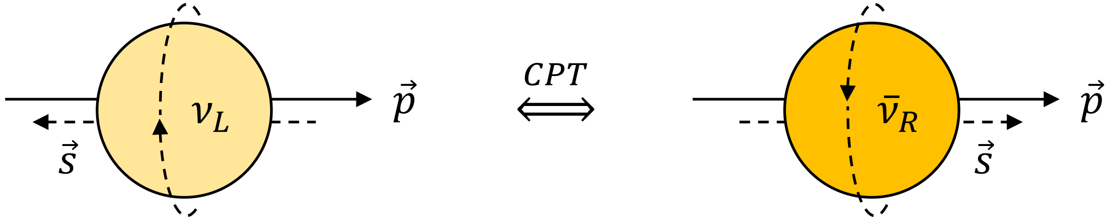
Ettore Majorana:
"That's the only difference."

Neutrino nature

Paul Dirac:
"They are fundamentally different particles."
*"This reaction **is not possible**."*

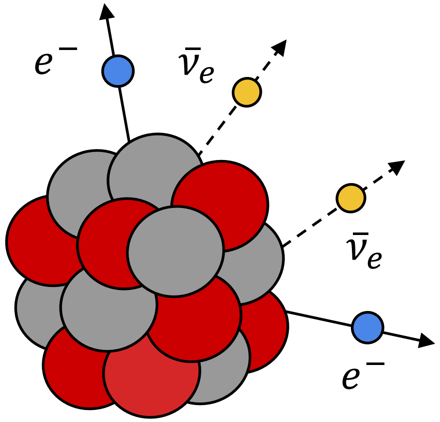
Ettore Majorana:
"That's the only difference."
*"This reaction **is possible**."*

- **neutrinos** are left-handed, **anti-neutrinos** are right-handed



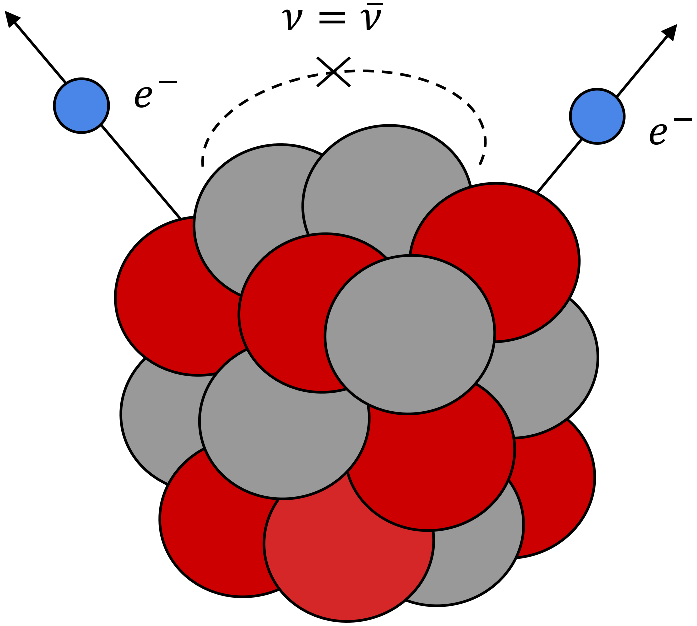
- double beta (**2νββ**) decay, second order weak process

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$n \rightarrow p + e^- + \bar{\nu}_e$$



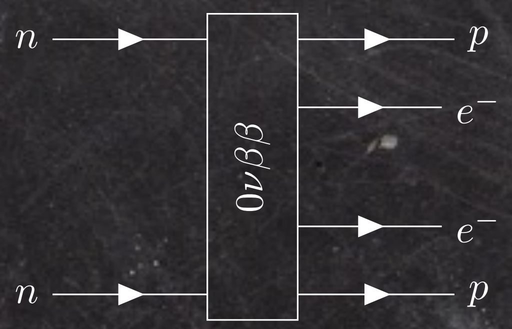
- neutrinoless double beta (**0νββ**) decay

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$n + \nu_e \rightarrow p + e^-$$

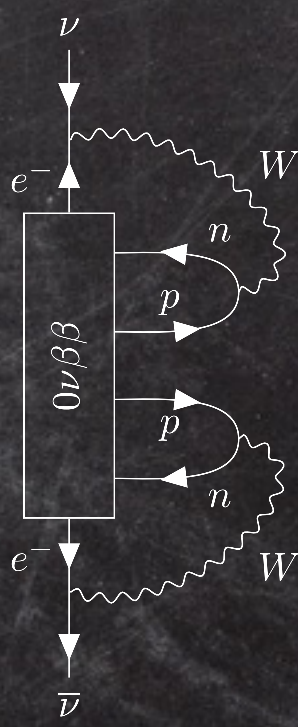


0νββ *decay*

$$\text{decay rate} \qquad \Gamma^{0\nu} \propto \sum_i \overbrace{G_i^{0\nu}}^{\text{phase space factor}} \cdot \overbrace{\left|\mathcal{M}_i^{0\nu}\right|^2}^{\text{nuclear matrix element}} \cdot \overbrace{\eta_i^2}^{\text{strength}}$$



lepton-number violating
($\Delta L = 2$) physics



black box /
Schechter-Valle theorem
[Schechter, Valle, PRD 22 (1980)]

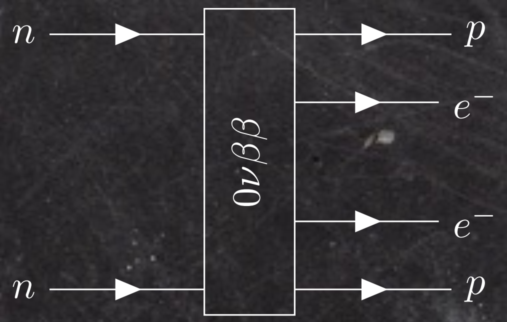
0νββ *decay*

phase space factor — nuclear matrix element — strength

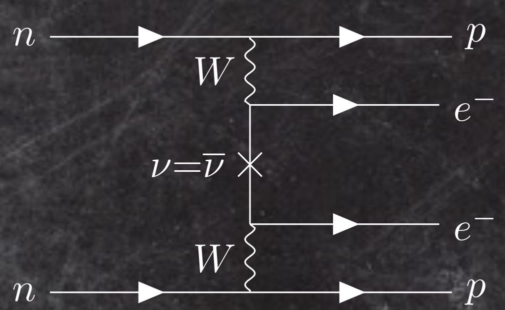
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2\, m_i\right|$$

decay rate $$\Gamma^{0\nu} \propto \sum_i \underbrace{G_i^{0\nu}}_{\text{phase space factor}} \cdot \underbrace{\left|\mathcal{M}_i^{0\nu}\right|^2}_{\text{nuclear matrix element}} \cdot \underbrace{\eta_i^2}_{\text{strength}} \approx G^{0\nu} \cdot \left|\mathcal{M}^{0\nu}\right|^2 \cdot \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

effective Majorana neutrino mass (coherent sum of mass eigenstates)



lepton-number violating ($\Delta L = 2$) physics

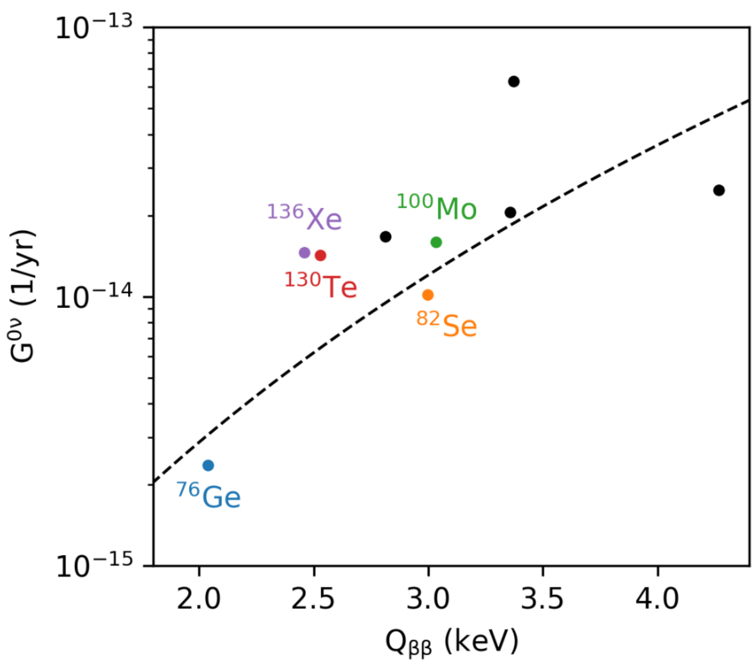


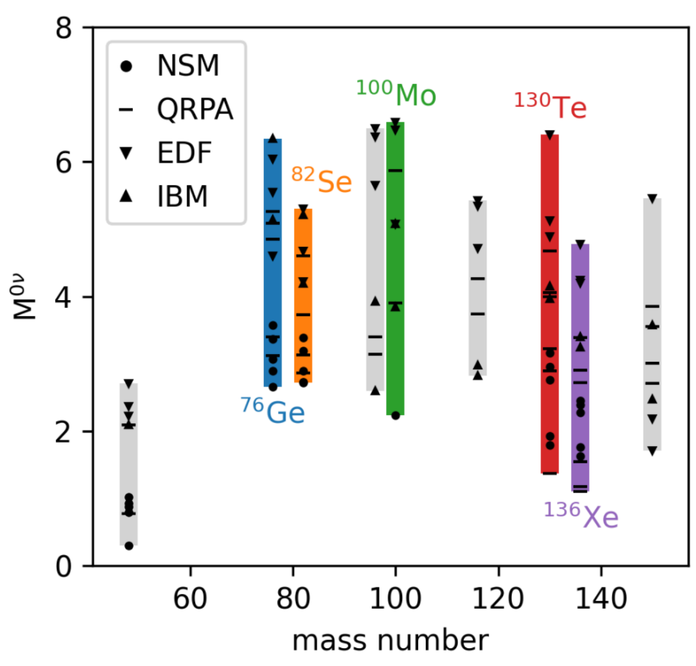
light Majorana neutrino exchange, mass mechanism

Decay rate

- interplay of **lepton-number violating physics** and **isotope properties**

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



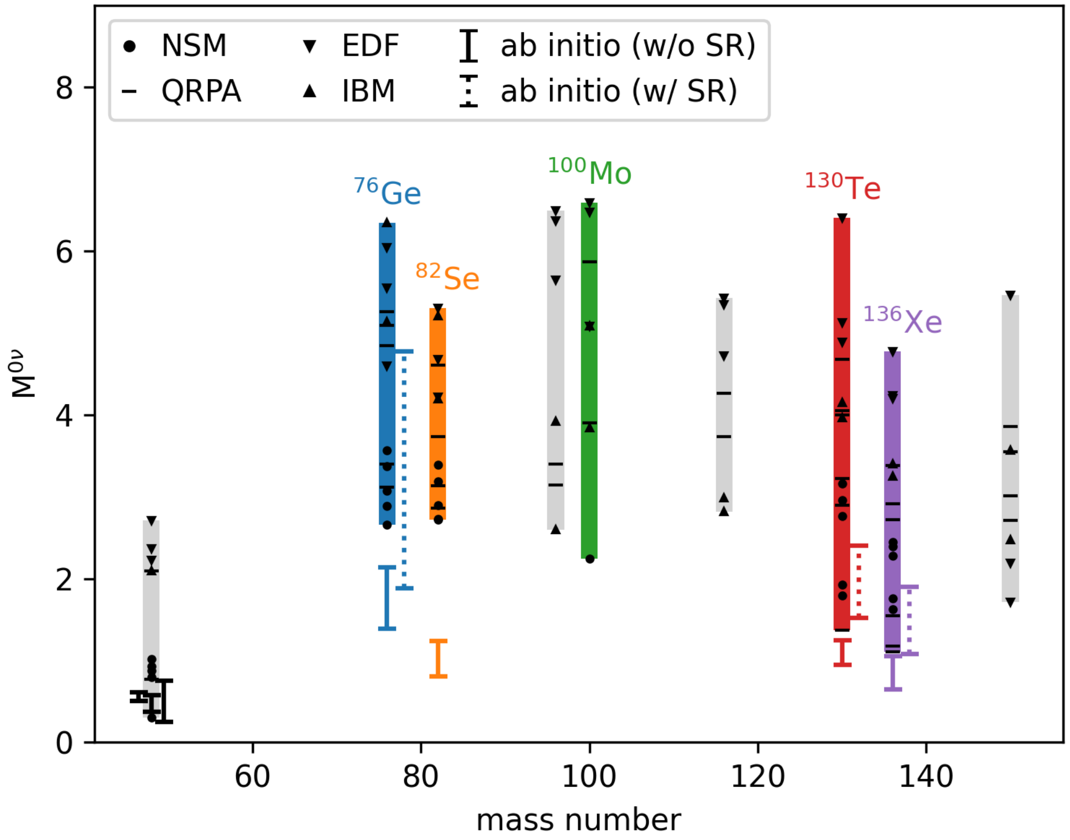


- accurate **phase space factor**, large Q-value favorable
  [Kotila, Iachello, PRC 85 (2012)]
- different **nuclear matrix elements** using various **many-body methods**, significant spread
  [Agostini et al., Rev.Mod.Phys. 95 (2023)]

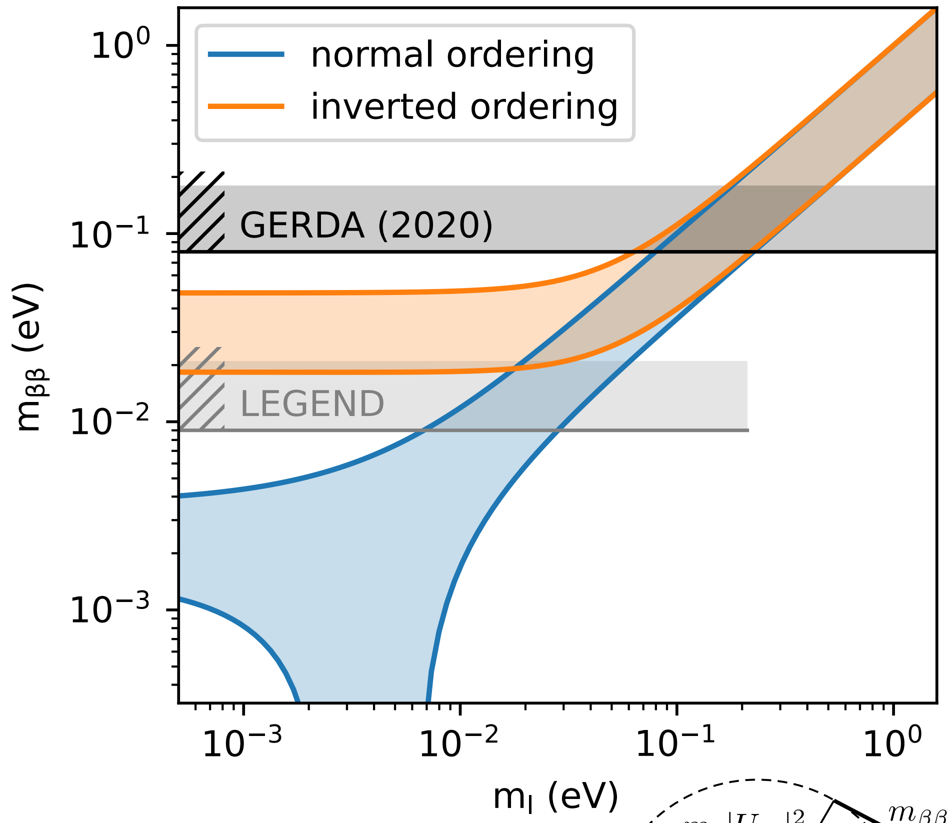
Nuclear matrix elements

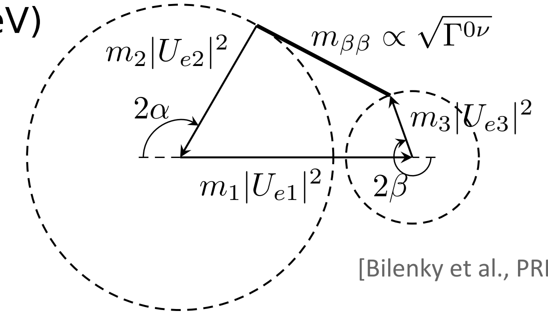
- first **ab initio calculations** available, could resolve **quenching issue, short-range operator** under investigation
  [Yao et al., PRL 124 (2020); Belley et al., PRL 126 (2021); Novario et al., PRL 126 (2021); Cirigliano et al., PRL 120 (2018); Belley et al., arXiv:2307.15156; Belley et al., PRL 132 (2024)]]

- experimental input by ..
  - .. precision **2νββ decay** measurements
    [Gando et al., PRL 122 (2019)]
  - .. heavy-ion double **charge exchange** reactions
    [Cappuzzello et al., EPJ A 54 (2018)]
  - .. ordinary **muon capture**
    [Zinatulina et al., PRC 99 (2019)]



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





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

- **complex Majorana phases**, cancelation possible (normal ordering), minimum at **0.02 eV** (inverted ordering)
- current bounds, e.g.

  [Agostini et al., PRL 125 (2020); Adams et al., arXiv:2404.04453; Abe et al., PRL 130 (2023)]

  GERDA (^{76}Ge): $m_{\beta\beta}$ **< [0.08, 0.18] meV** (90% CL)

  CUORE (^{130}Te): $m_{\beta\beta}$ **< [0.07, 0.24] meV** (90% CI)

  KamLAND-Zen (^{136}Xe): $m_{\beta\beta}$ **< [0.04, 0.17] meV** (90% CL)

- **next generation** experiments, e.g.

  [Abgrall et al., arXiv:2107.11462]

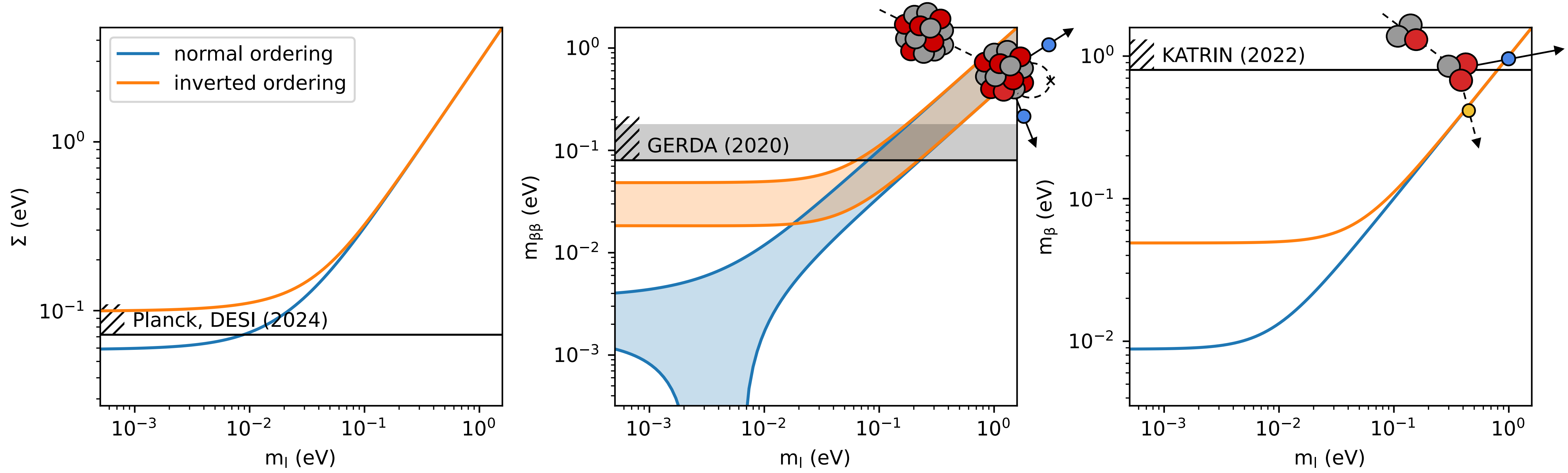
  LEGEND-1000: [0.01, 0.02] eV (3σ discovery)

  similar numbers for CUPID, nEXO, …

Neutrino mass observables

laboratory-based

cosmology | **0νββ decay** | **β decay kinematics**

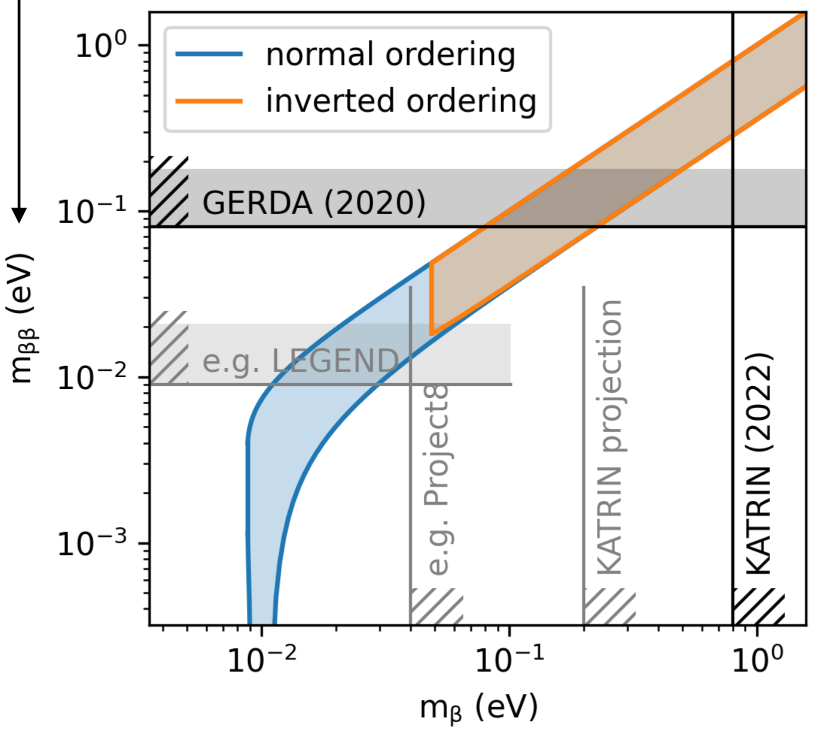


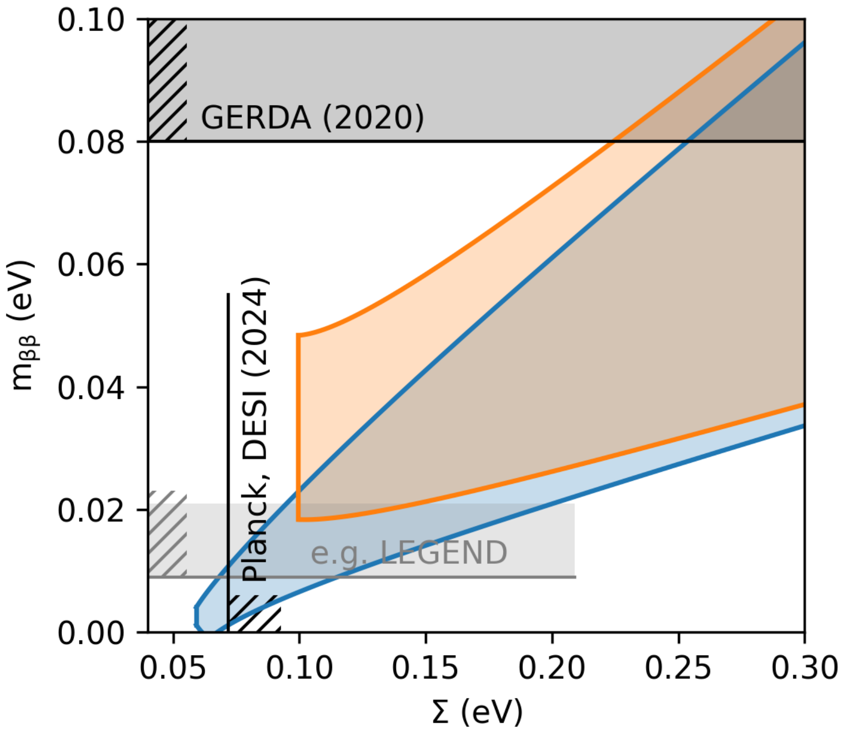
model-dependent

Interplay

Majorana nature,
light Majorana neutrino exchange

- **complementary** neutrino mass information
    - different **mass eigenstate combinations**
    - different **model assumptions**
- › **counter measurements**, model discrimination





energy conservation

cosmological model

Take away

- **How** can we measure the absolute neutrino mass?

  ? ___ ? ___ ? ___ ? ___

- What are current **neutrino mass constraints**?

  sum of mass eigenstates, $\Sigma <$?

  effective Majorana neutrino mass, $m_{\beta\beta} <$?

  effective electron neutrino mass, $m_{\beta} <$?

- **What assumptions** are behind different neutrino mass observables?

  sum of mass eigenstates, Σ: ?

  effective Majorana neutrino mass, $m_{\beta\beta}$: ?

  effective electron neutrino mass, m_{β}: ?

- How does the **KATRIN experiment** work?

  ?

Take away

- **How** can we measure the absolute neutrino mass?

  Supernovae **cosmology** β decay **kinematics** **0νββ decay**

- What are current **neutrino mass constraints**?

  sum of mass eigenstates, $\Sigma < \mathbf{0.07\ eV}\ (95\%\ CI)$

  effective Majorana neutrino mass, $m_{\beta\beta} < [\mathbf{0.04, 0.16}]\ \mathbf{eV}\ (90\%\ CL)$

  effective electron neutrino mass, $m_\beta < \mathbf{0.8\ eV}\ (90\%\ CL)$

- **What assumptions** are behind different neutrino mass observables?

  sum of mass eigenstates, Σ: **cosmological model**

  effective Majorana neutrino mass, $m_{\beta\beta}$: **Majorana nature, decay mechanism**

  effective electron neutrino mass, m_β: **energy conservation**

- How does the **KATRIN experiment** work?

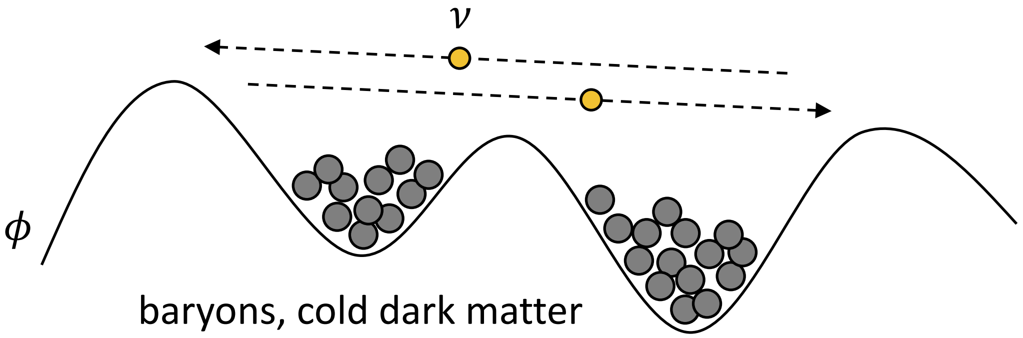
  high-activity **gaseous molecular tritium** source, magnetic adiabatic collimation with electrostatic filter (**MAC-E**) **spectrometer**

Backup

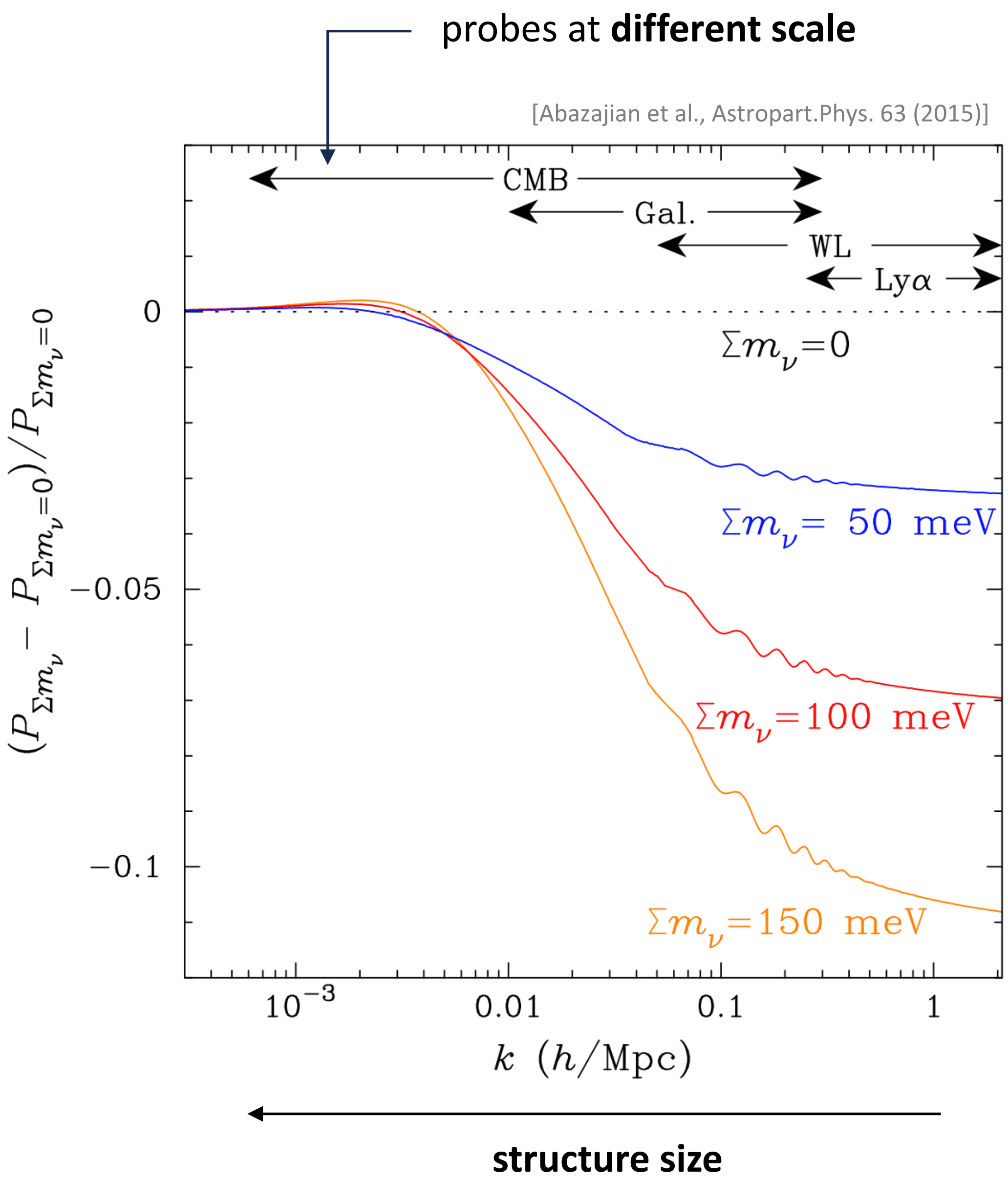
Neutrinos in the cosmos

- heavy, non-relativistic **matter clumps on small scales**
- **relativistic neutrinos** disperse energy across overdensities, effectiveness depends on neutrino mass

› neutrino mass leaves **imprint on structure growth**, matter power spectrum



[Abazajian et al., Astropart.Phys. 63 (2015)]



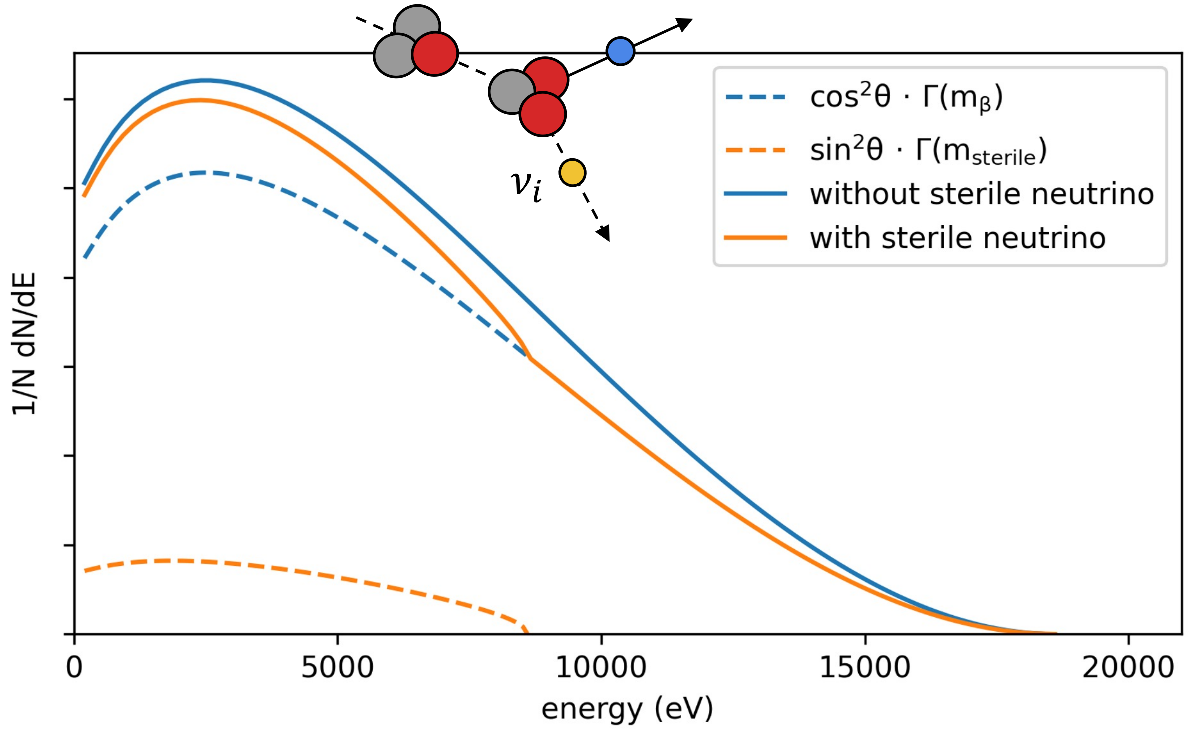
Side note: sterile neutrinos

- additional **sterile neutrino** state, mixing with electron neutrino

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \boldsymbol{U_{e4}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \boldsymbol{\nu_4} \end{pmatrix}$$

- motivated by **anomalies** (eV-scale), viable **dark matter candidate** (keV-scale)

› additional spectral component, kink-like signature



- unique test of **eV-scale parameter space**

- deep spectral exploration to search for **keV-sterile neutrinos**

› **TRISTAN upgrade** of KATRIN, silicon drift detector array