Direct neutrino mass measurements -

Christoph Wiesinger (TUM), Exploring the Dark Side of the Universe, 03.06.2024

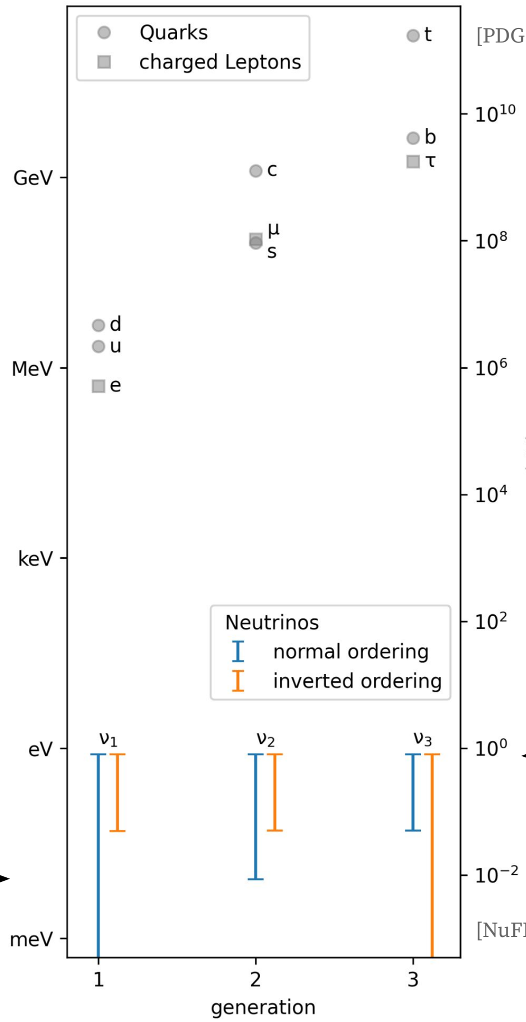
"for the discovery of neutrino oscillations, which shows that

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**

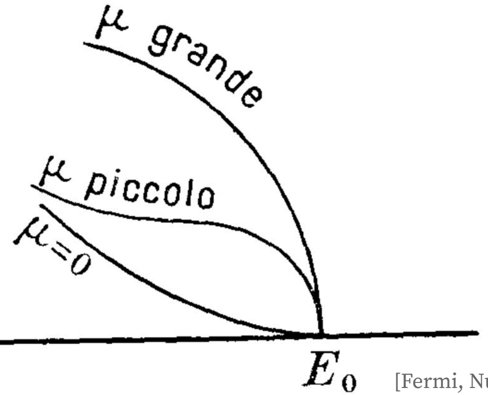
lower bounds from **oscillation experiments**

[NuFIT 5.3, nu-fit.org]

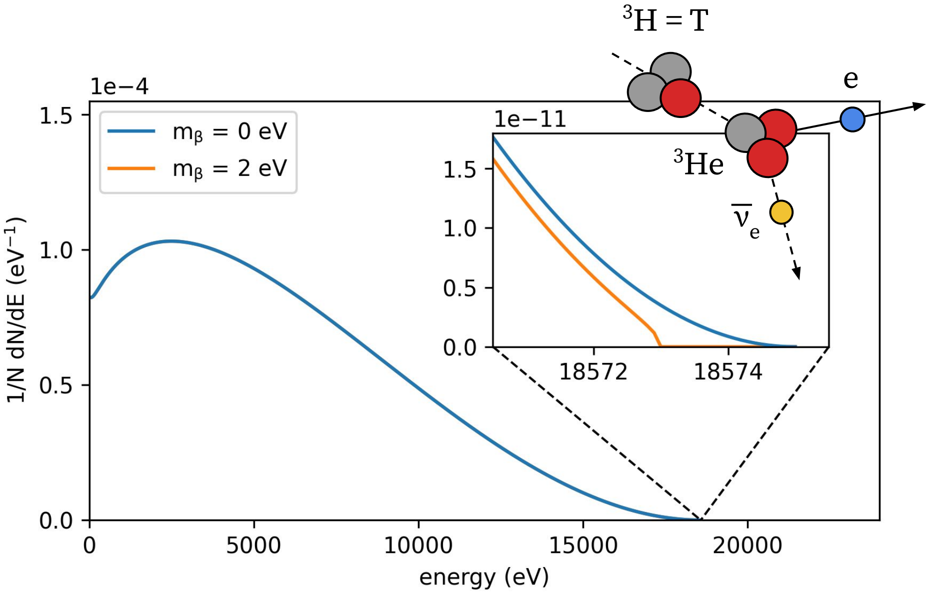
β-decay kinematics

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

➔ **spectral distortion**, maximal at kinematic endpoint



[Fermi, Nuovo Cim. 11 (1934)]

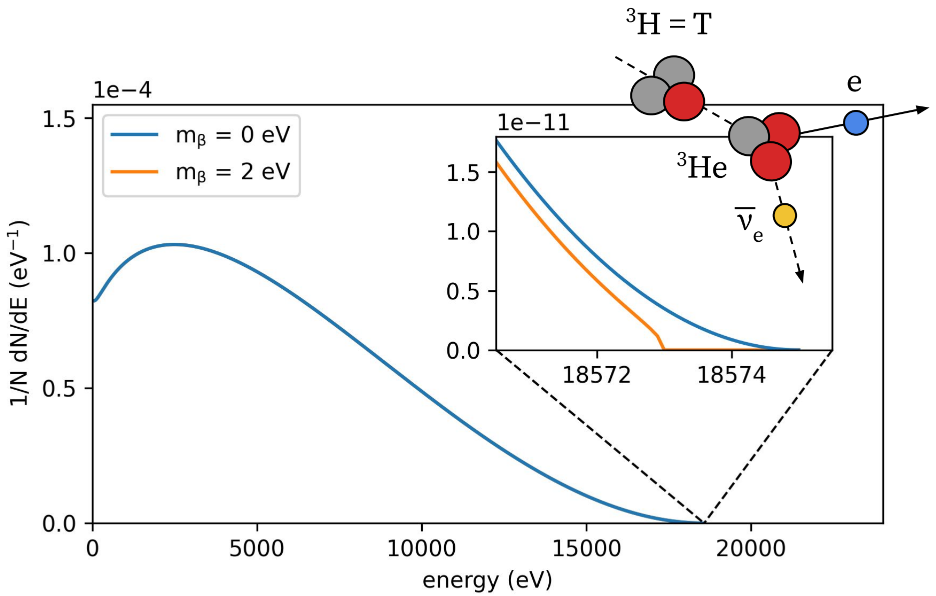


β-decay kinematics*

**or electron capture*

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

➔ **spectral distortion**, maximal at kinematic endpoint



Experimental challenges

- **high-activity** source, **low Q-value**

➔ **tritium** ^{3}H ($T_{1/2}$ = 12 yr, E_0 = 18.6 keV)

➔ **holmium** ^{163}Ho ($T_{1/2}$ = 5 kyr, E_0 = 2.8 keV)

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

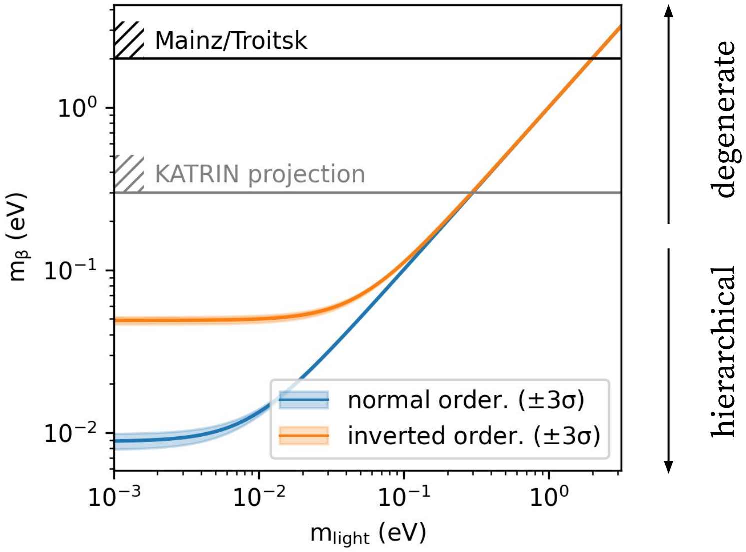
Effective electron neutrino mass

[NuFIT 5.3, nu-fit.org;
Kraus et al., EPJC 40 (2005); Aseev et al., PRD 84 (2011)]

- weighted **incoherent sum** of mass eigenstates

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

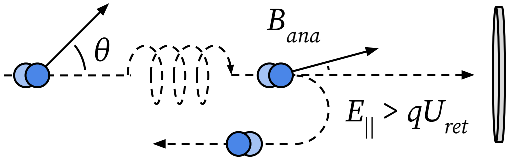
➔ **minimum value** at 0.01 (0.05) eV for normal (inverted) ordering



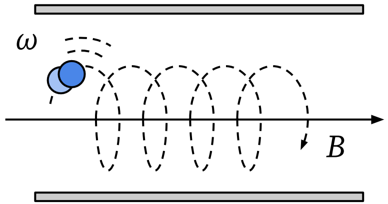
- current experiments probe **degenerate regime**, $m_1 \approx m_2 \approx m_3$

Experimental approaches

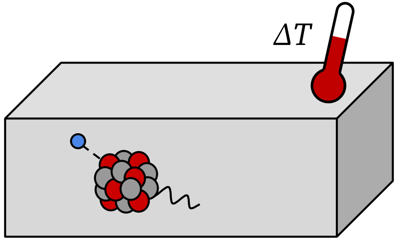
tritium-based



electrostatic
filtering (MAC-E)



cyclotron radiation emission
spectroscopy (CRES)



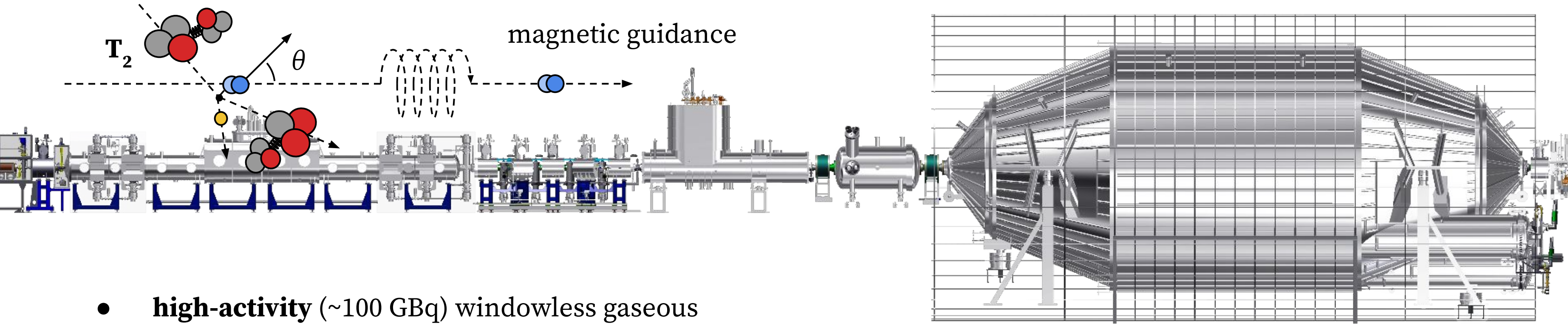
cryogenic
calorimetry

R & D

Karlsruhe Tritium Neutrino (KATRIN) experiment

Working principle

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



- **high-activity** (~100 GBq) windowless gaseous molecular tritium source, closed loop
- tritium removal in transport section

Working principle

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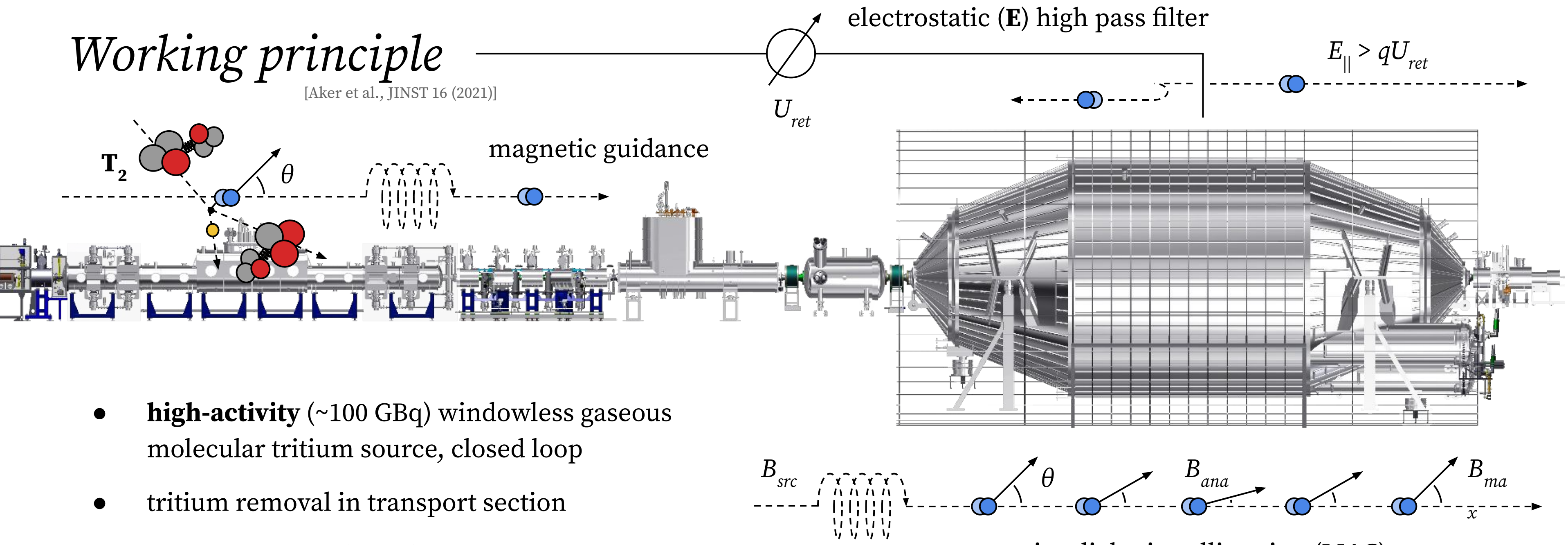
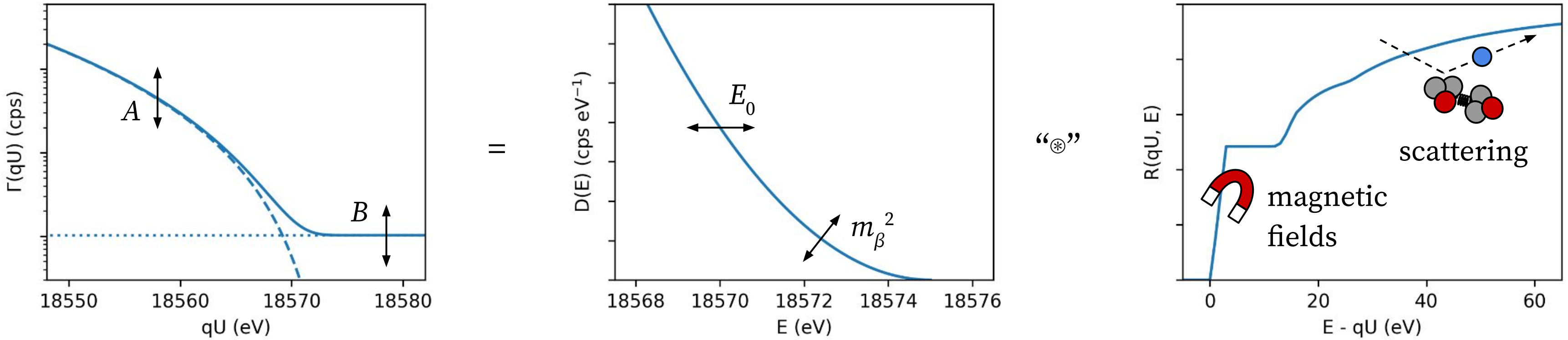


- **high-activity** (~100 GBq) windowless gaseous molecular tritium source, closed loop
- tritium removal in transport section
- **high-resolution** (~1 eV) **large-acceptance** (0-51°) spectrometer system
- **electron counting** at focal plane detector (148-pixel silicon PIN diode)

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

Analysis strategy

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



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

- **theoretical** and **experimental** inputs, calibration constraints

Neutrino mass results

1st campaign, 2 million events (22 days)

[Aker et al., PRL 123 (2019)]

- best fit, **p-value = 0.6**

$m_\beta^2 = (-1.0^{+0.9}_{-1.1})\ \mathrm{eV}^2$

➔ **upper limit**

m_β **< 1.1 eV** (90% CL)

2nd campaign, 4 million events (31 days)

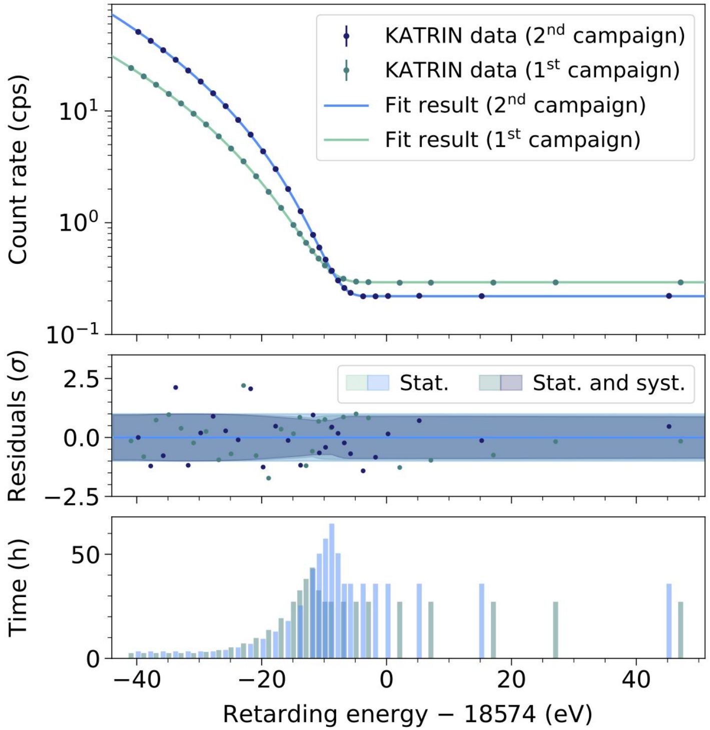
[Aker et al., Nature Phys. 18 (2022)]

- best fit, **p-value = 0.8**

$m_\beta^2 = (0.26 \pm 0.34)\ \mathrm{eV}^2$

➔ **upper limit**

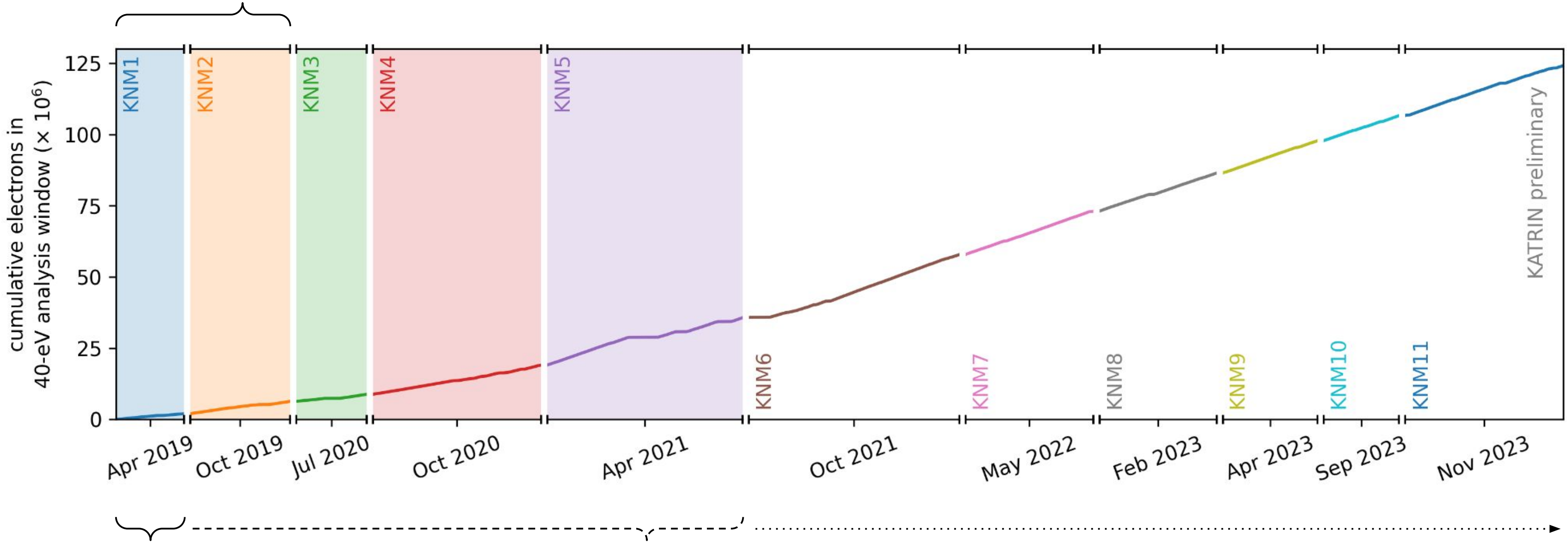
m_β **< 0.9 eV** (90% CL)



m_β **< 0.8 eV** (90% CL)

Data taking overview

world-best constraint, m_β **< 0.8 eV** (90% CL)
[Aker et al., Nature Phys. 18 (2022)]



first result, m_β **< 1.1 eV** (90% CL)
[Aker et al., PRL 123 (2019)]

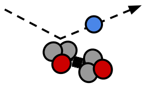
next release, main challenges

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

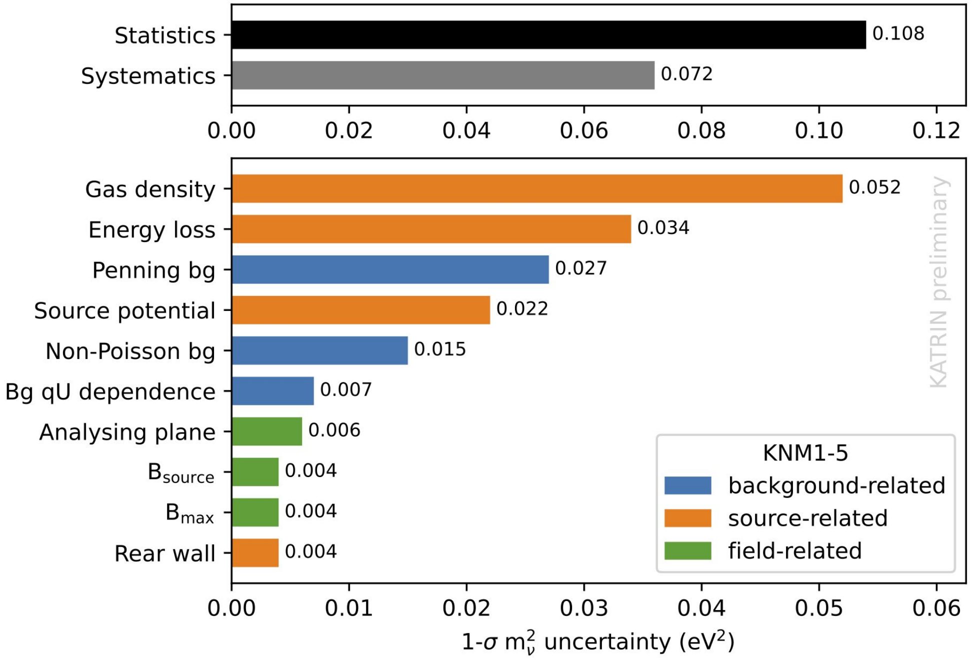
until end-2025

Upcoming neutrino mass result

- **successfully unblinded,** release in preparation
  - **6-fold increase in statistics,** 2-fold reduction of background by new spectrometer setting [Lokhov et al., EPJ C 82 (2022)]
  - **3-fold reduction of systematic uncertainties**, source effects leading



➔ statistics dominated, **projected sensitivity** m_β **< 0.5 eV** (90% CL)



KATRIN outlook

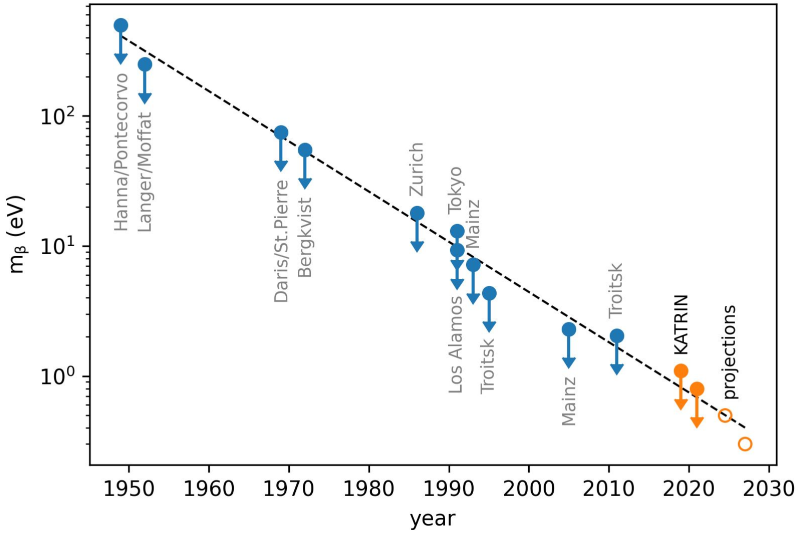
- data taking ongoing until end-2025, **projected final sensitivity**

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

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

- **TRISTAN** detector upgrade in 2026, high-granularity silicon drift detector array

➔ deep spectral exploration, search for **keV-scale sterile neutrinos**
  [Mertens et al., J.Phys.G 46 (2019)]



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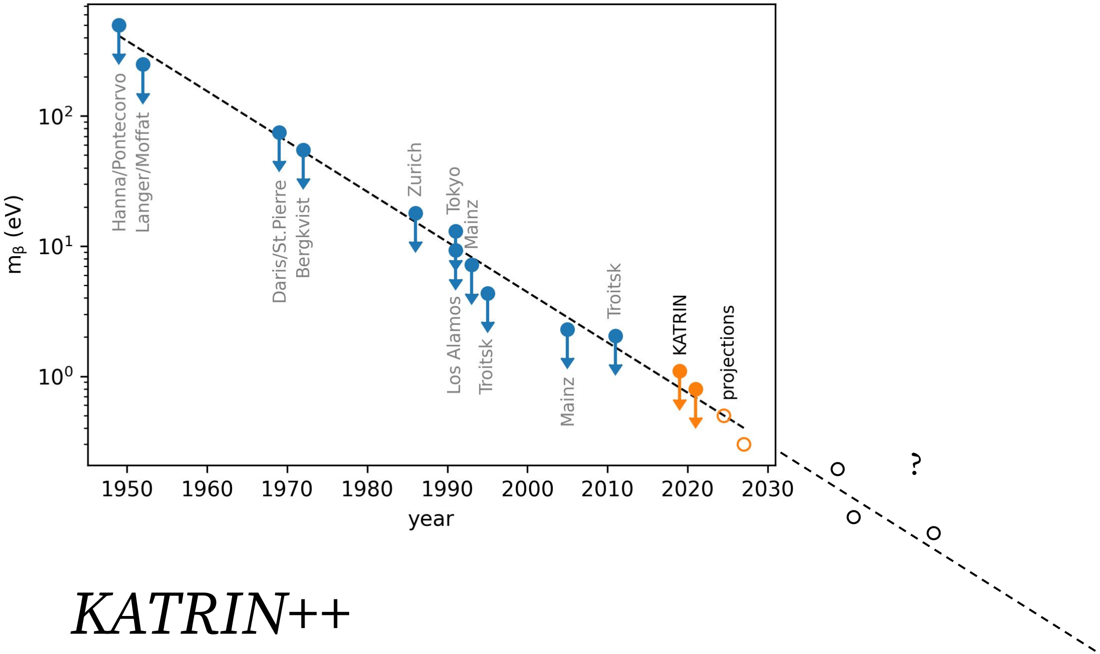
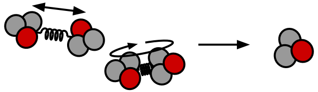


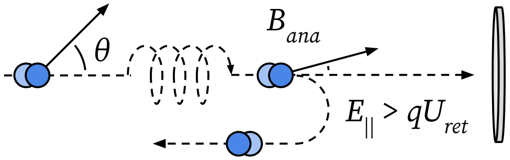
KATRIN++

- **differential** detection technologies, micro-calorimeters
- **atomic tritium** source



Experimental approaches

tritium-based



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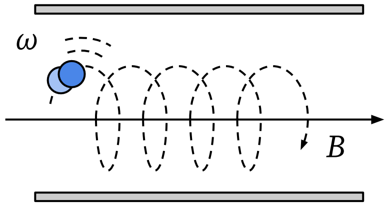

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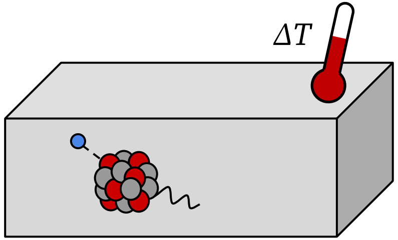


cryogenic
calorimetry

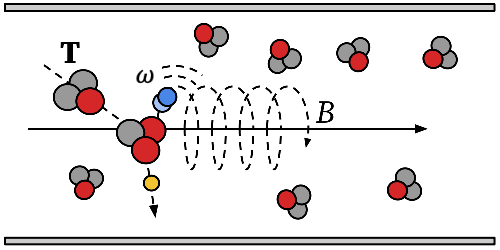
R & D

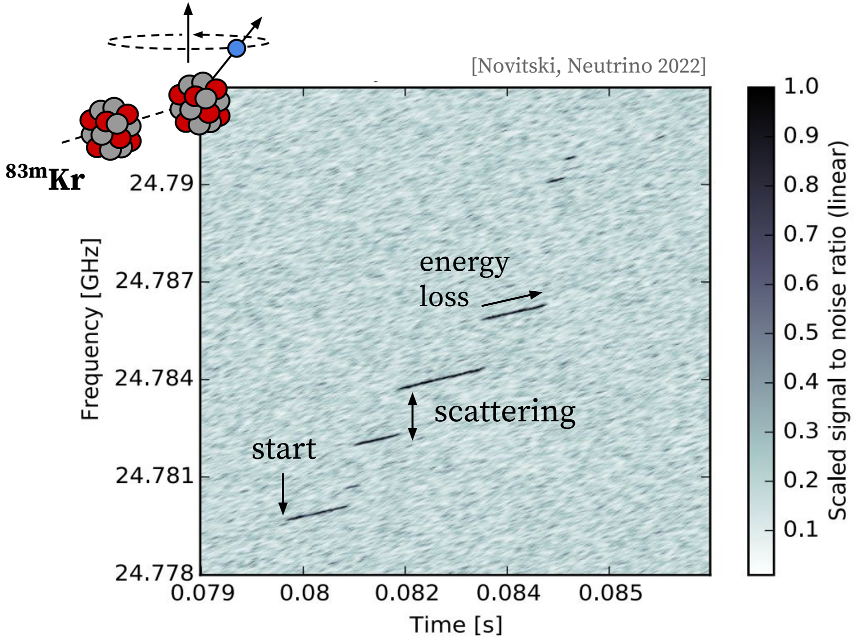
Cyclotron radiation emission spectroscopy (CRES)

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

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

antenna array





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

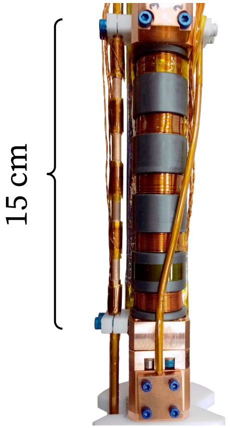
➔ **differential** frequency measurement, **eV-scale** resolution, **low background**

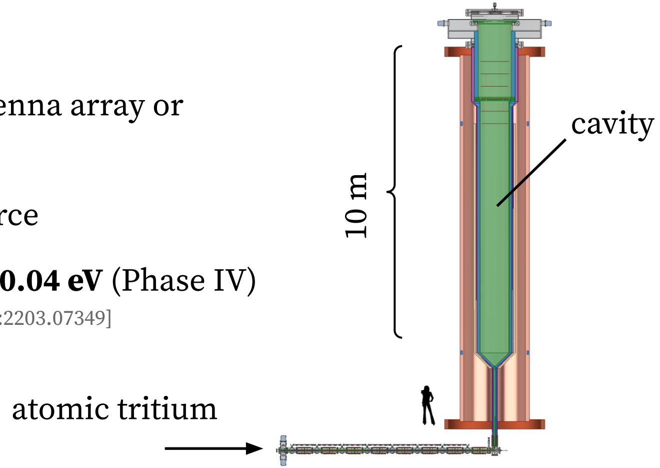
Project 8

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

$$m_\beta < 155 \text{ eV (90\% CI)}$$

- **m³-scale** traps (antenna array or cavity resonator)
- **atomic tritium** source
- sensitivity **down to 0.04 eV** (Phase IV)
  [Ashtari Esfahani et al., arXiv:2203.07349]





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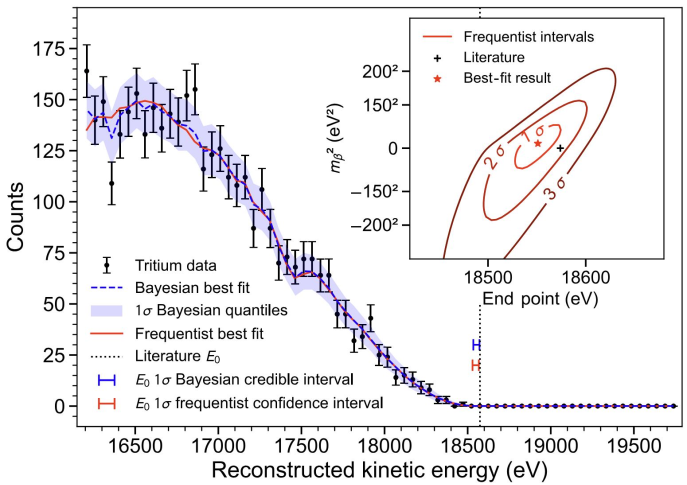

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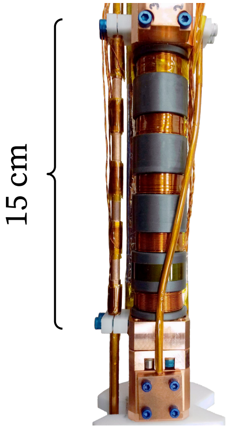

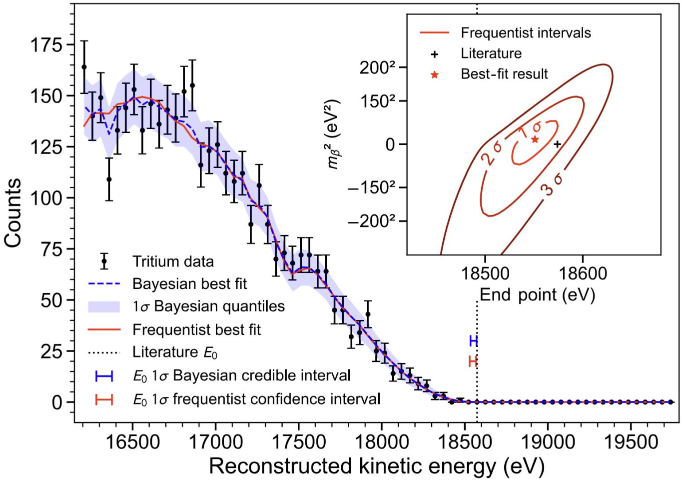

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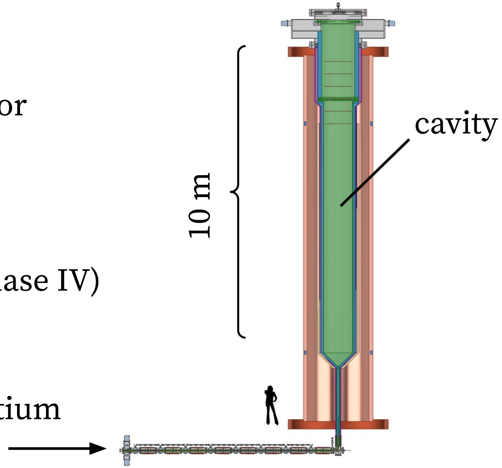
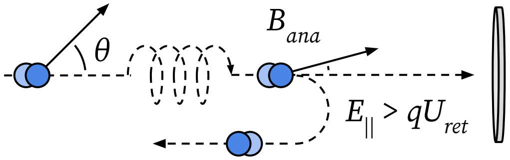


QTNM

- **storage ring** confinement, quantum-limited micro wave electronics

Experimental approaches

tritium-based



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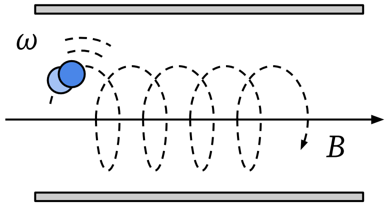

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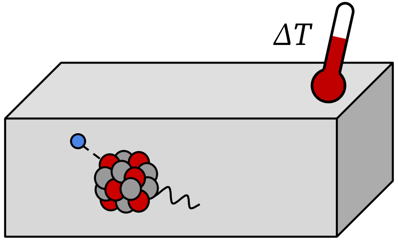

cryogenic
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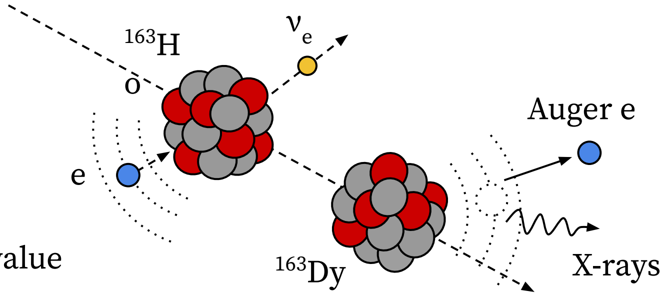
R & D

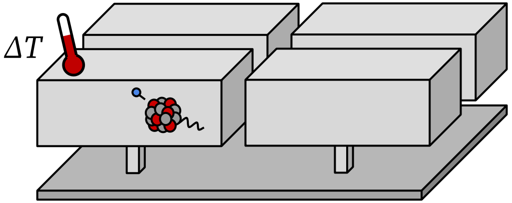


Cryogenic calorimetry

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

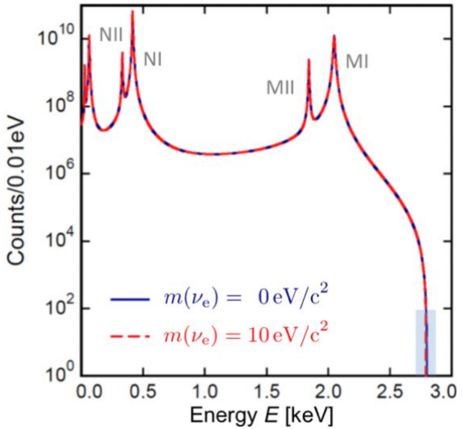
➔ **sub-eV** sensitivity with **MBq-scale activity**

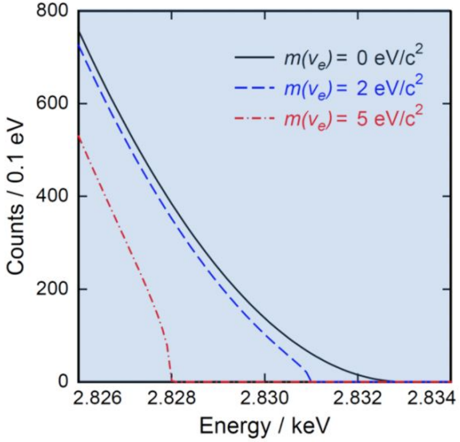
- ^{163}Ho-implanted cryogenic **micro-calorimeters**



thermal bath (mK)

[Gastaldo, Neutrino 2022]

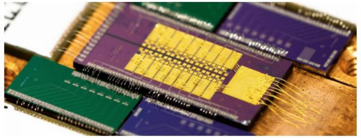




➔ eV-scale **differential** measurements

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

ECHO

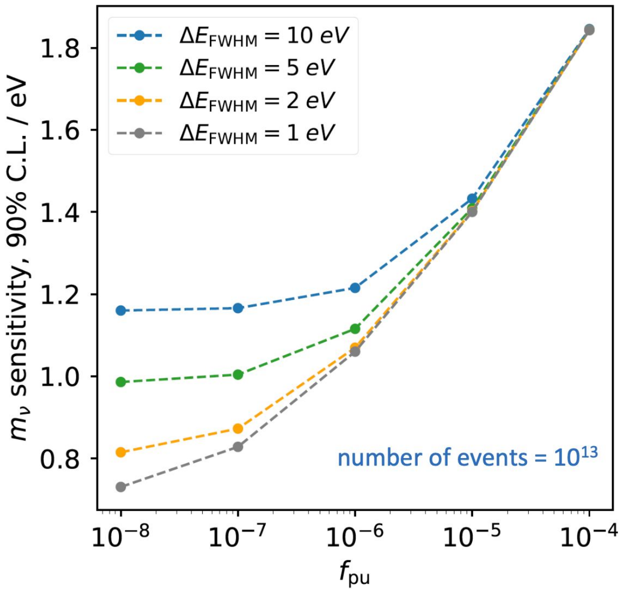


- array of **metallic magnetic calorimeters** (MMC) with ^{163}Ho-implanted absorber, 10 Bq per pixel
- first **neutrino mass limit**, 4 pixels with 0.2 Bq
  [Velte et al., EPJ C 79 (2019)]

$$m_\beta < 150 \text{ eV (95\% CL)}$$

- analysis of new data ongoing, sensitivity around 10 eV

[Gastaldo, TAUP 2023]



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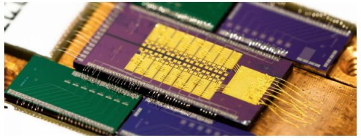

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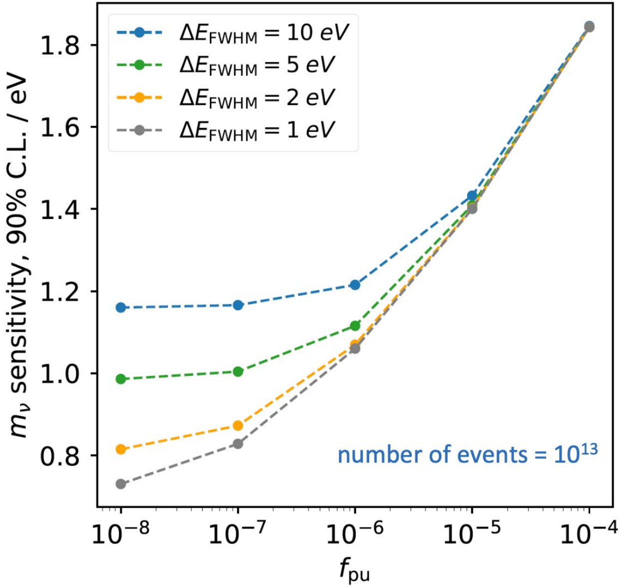
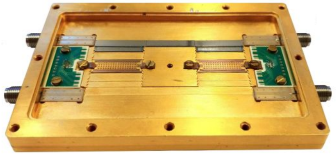


HOLMES



- array of **transition edge sensors** (TES) coupled to ^{163}Ho-implanted absorber, 300 Bq per pixel
- first neutrino mass data taken, sensitivity around 10 eV

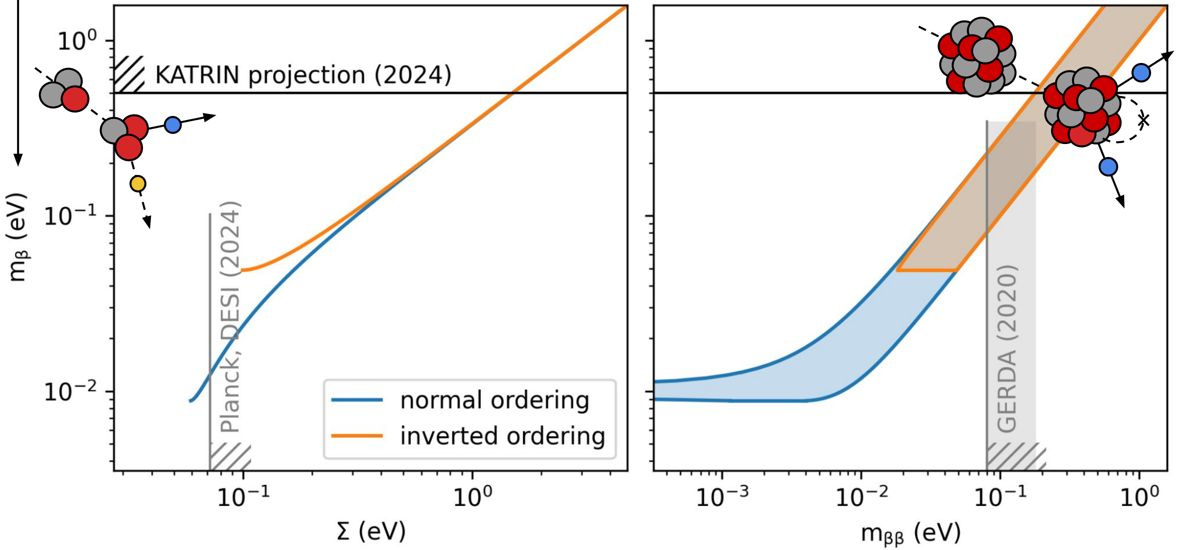
Neutrino mass observables

- β-decay kinematics offers **model-independent laboratory probe** for neutrino mass
- complementary to
  - **cosmology**
  - **0νββ decay**

➔ interplay will allow **model discrimination**

energy conservation

[NuFIT 5.3, nu-fit.org; Adame et al., arXiv:2404.03002; Agostini et al., PRL 125 (2020)]



cosmological model

Majorana nature, mass mechanism

Conclusions

- **KATRIN** measurement ongoing until end-2025
  - **substantial improvements** of systematic uncertainties and background
  - **data release** in preparation, projected sensitivity

$$m_\beta < \mathbf{0.5\ eV}\ (90\%\ \mathrm{CL})$$

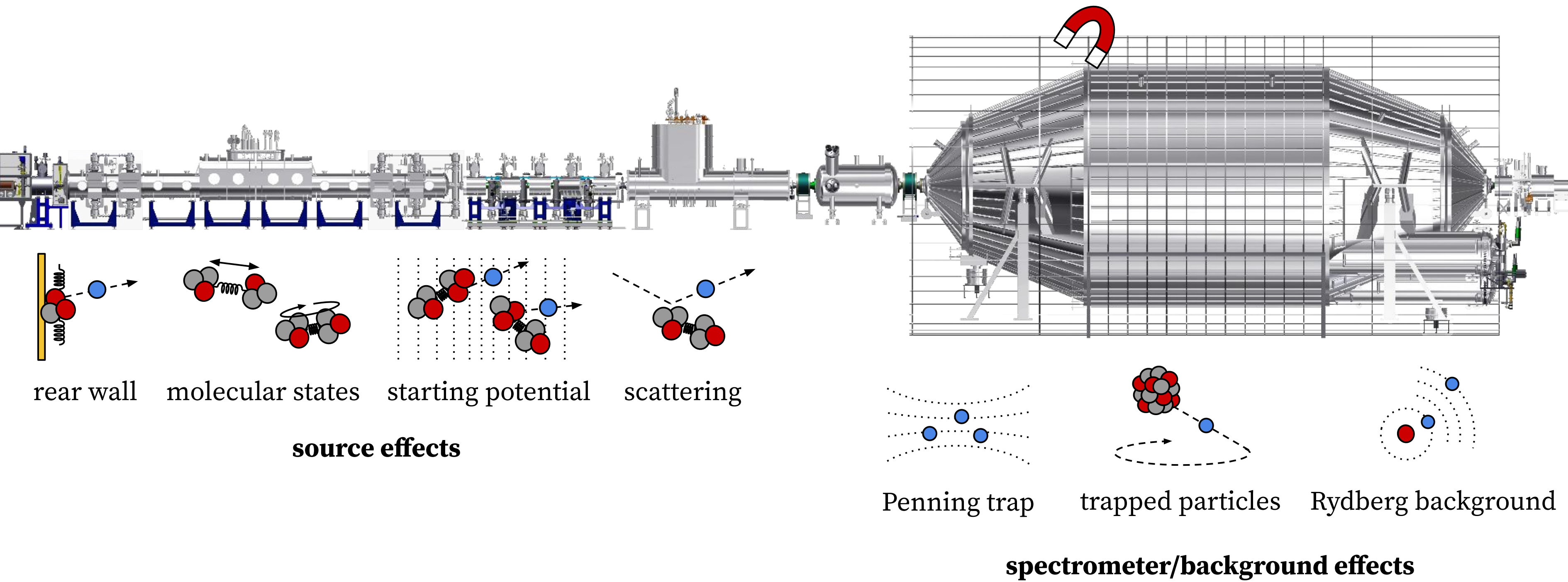
- **promising technology** development beyond KATRIN
  - **tritium CRES**, Project 8, QTNM
  - ^{163}Ho-implanted **cryogenic micro-calorimeters**, ECHO, HOLMES

- import **model-independent constraint**, complementary to cosmology and 0νββ decay

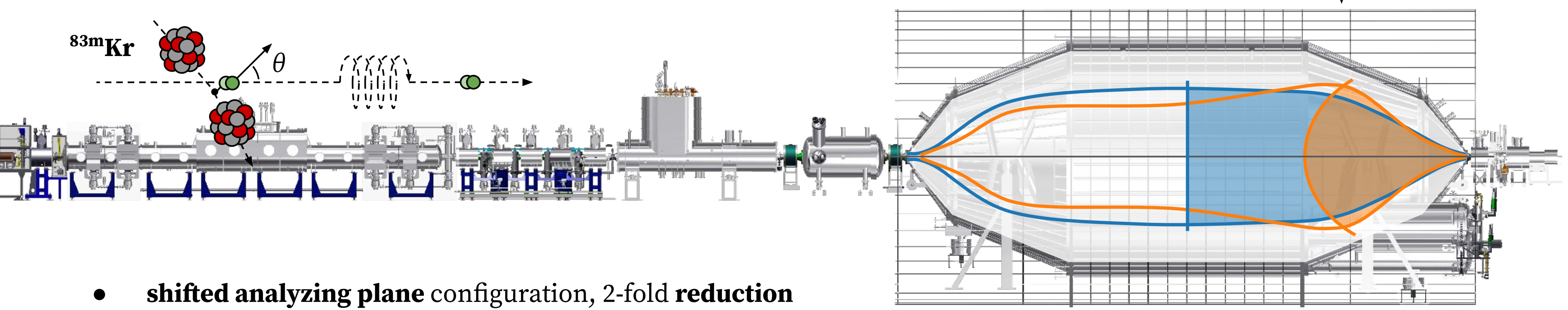
Backup

Backgrounds and systematic effects

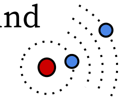
electromagnetic fields

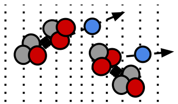


(Selected) experimental improvements



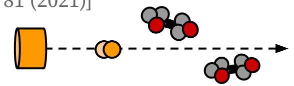
- **shifted analyzing plane** configuration, 2-fold **reduction of background**, Rydberg-induced background
  [Lokhov et al., EPJ C 82 (2022)]

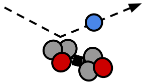




- **^{83m}Kr co-circulation** mode, conversion electrons, measure **source potential** and **spectrometer fields**
  [Altenmüller et al., J.Phys.G 47 (2020)]

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





Analysis challenge

- **high granularity**, different campaign settings, detector segmentation
- **high dimensionality**, parameter correlations across datasets
- **complex model**, differential spectrum integrated over response

.. status

5 campaigns, **>1500 data points**

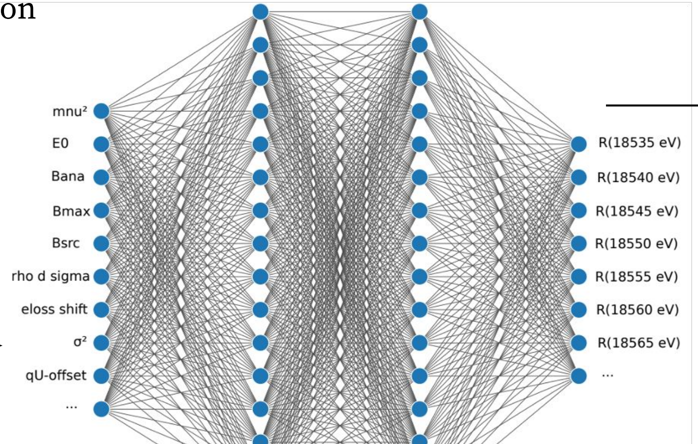
>150 free parameters

Analysis challenge *.. status*

- **high granularity**, different campaign settings, detector segmentation — 5 campaigns, **>1500 data points**
- **high dimensionality**, parameter correlations across datasets — **>150 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

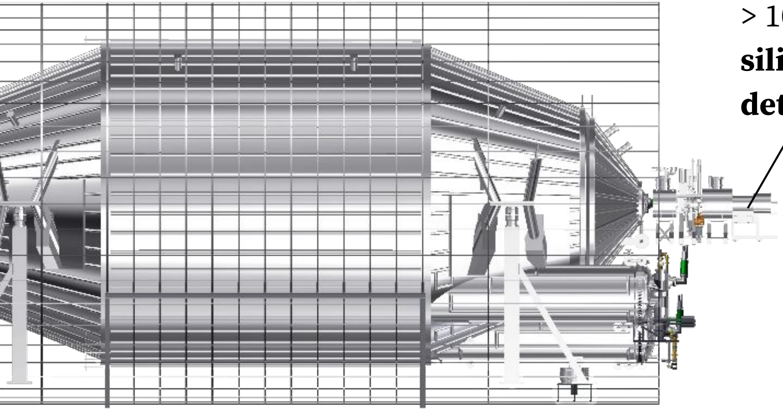
model parameters



rate prediction

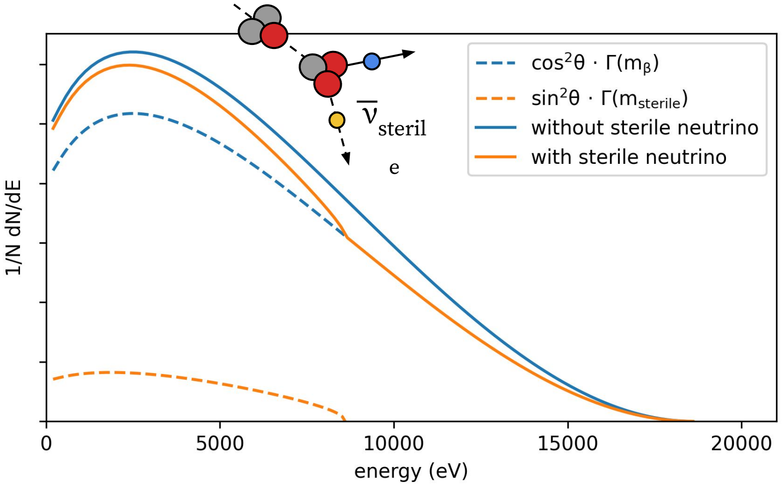
TRISTAN

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



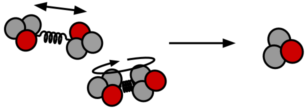
> 1000-pixel **silicon drift detector array**

- **high-rate electron spectroscopy**
- ultra-high vacuum compliance, calibration



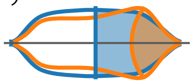
KATRIN++

- **differential** detection technologies, metallic magnetic calorimeters
- **atomic tritium** source

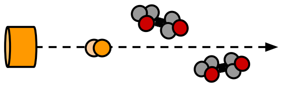


Upcoming neutrino mass result

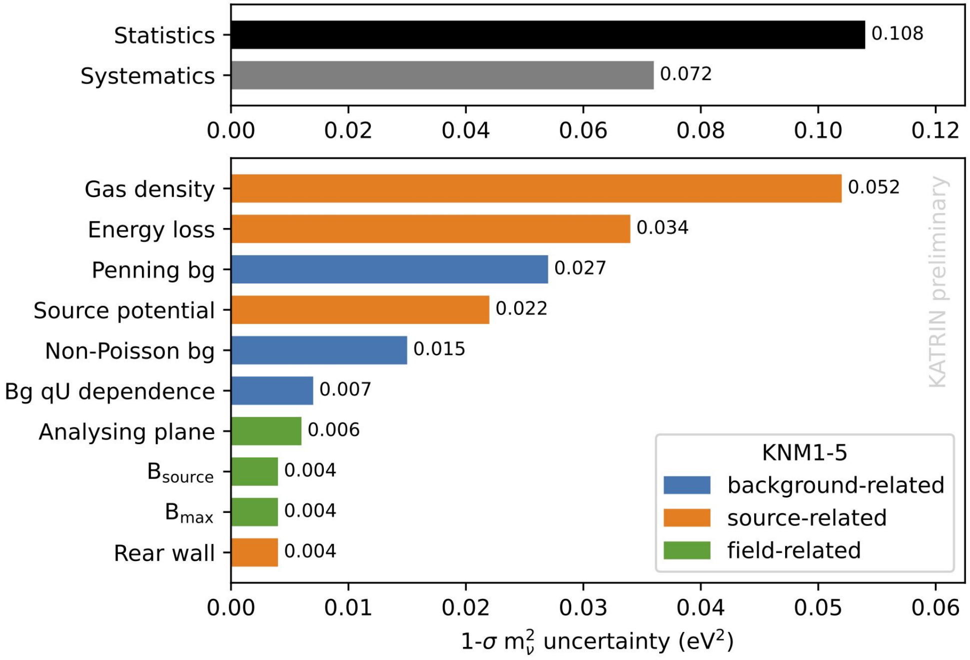
- **6-fold increase in statistics,** background reduction



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

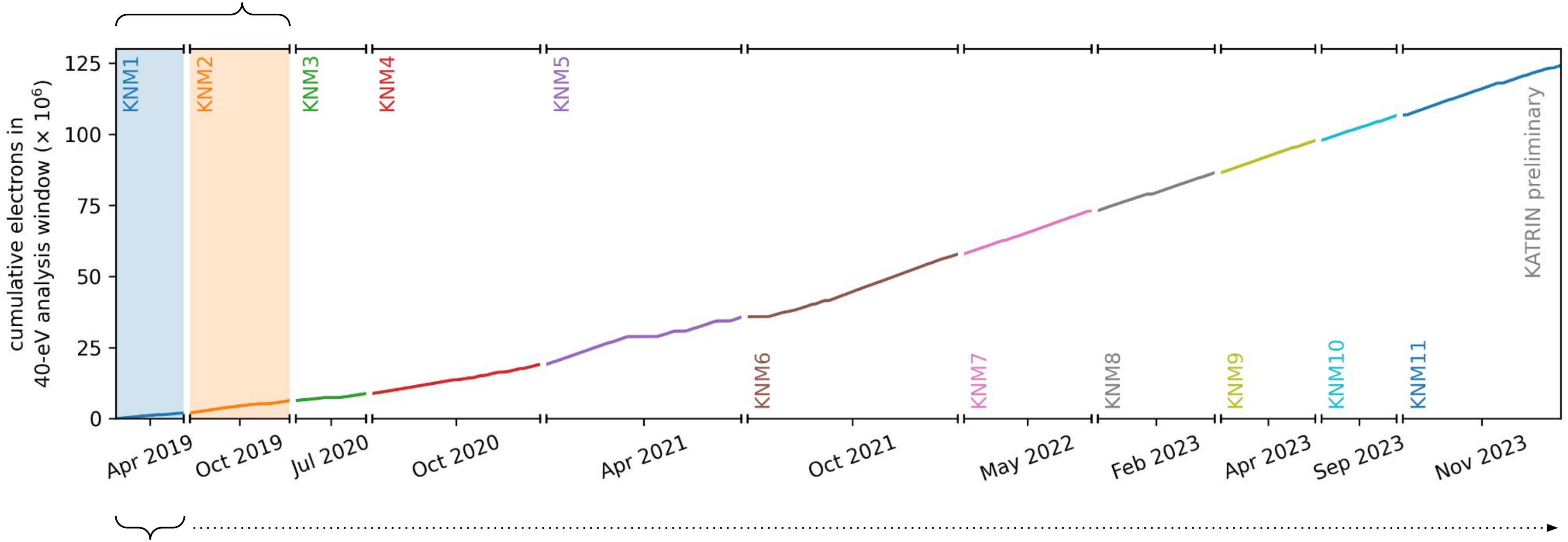


➔ statistics dominated, **projected sensitivity** m_β **< 0.5 eV** (90% CL)



Data taking overview

world-best constraint, m_β **< 0.8 eV** (90% CL)
[Aker et al., Nature Phys. 18 (2022)]



first result, m_β **< 1.1 eV** (90% CL)
[Aker et al., PRL 123 (2019)]

until end-2025