Neutrino masses and mixings –

Direct mass measurements

Christoph Wiesinger (Technical University of Munich), ISAPP school, 17.09.2024

What we know about neutrinos

Joachim Kopp's lecture

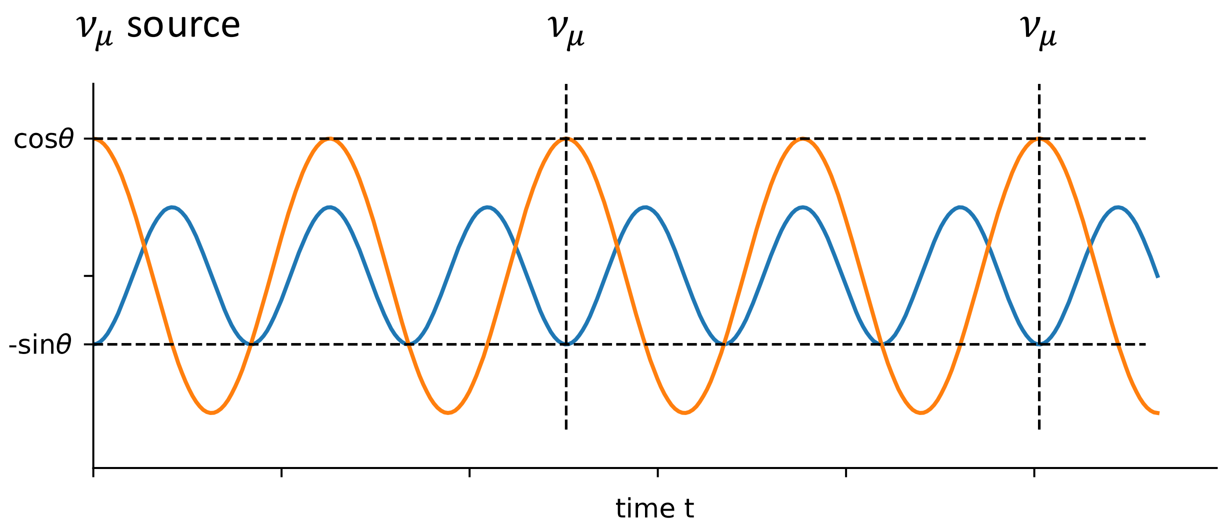
- three active **flavor eigenstates** ν_l with $l \in \{e, \mu, \tau\}$
- flavor eigenstates are linear combinations of **mass eigenstates** ν_i

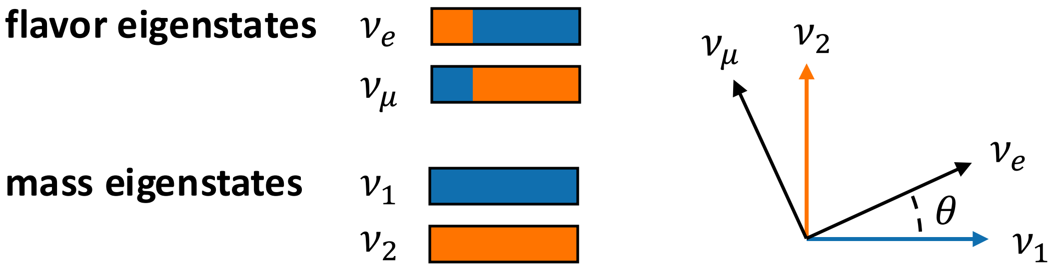
$$\nu_l = \sum_i U_{li}\, \nu_i$$

- **mass squared differences** $\Delta m_{ij}^2 = m_i^2 - m_j^2$

› neutrino **oscillations** $P(\nu_l \to \nu_m) > 0$

[Kajita, McDonald, Nobel Prize in Physics 2015]





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› neutrino **oscillations** $P(\nu_l \rightarrow \nu_m) > 0$

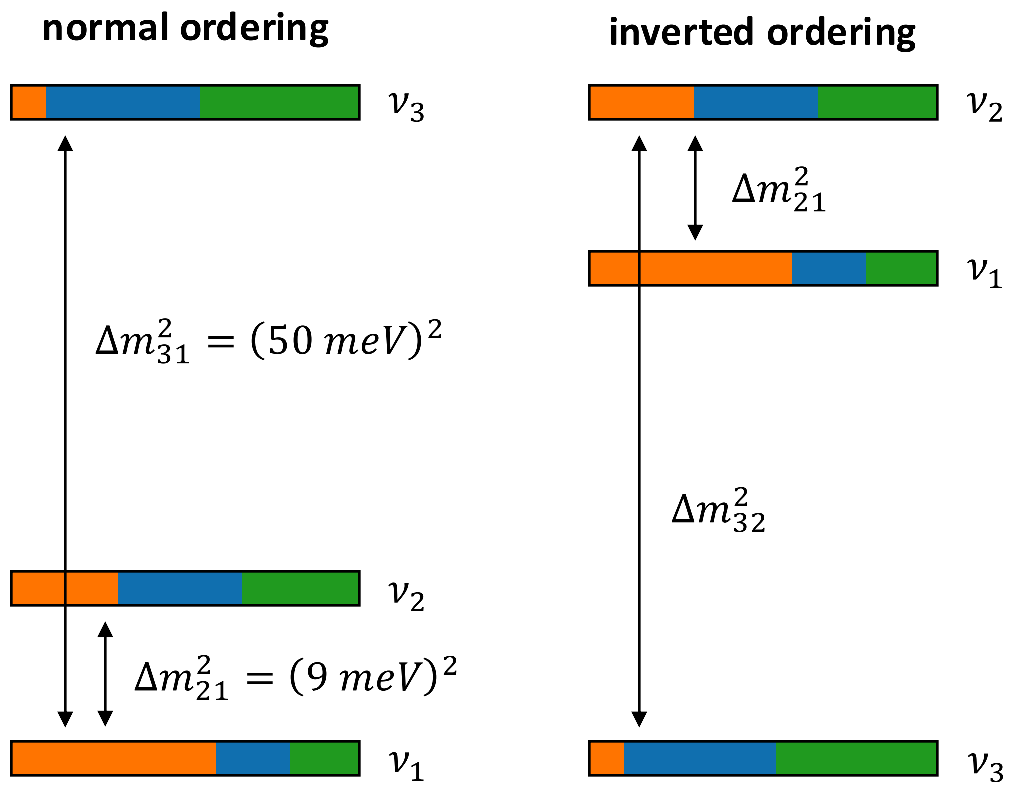
[Kajita, McDonald, Nobel Prize in Physics 2015]

› at least **two neutrinos have mass**

- **matter effects** in sun $m_1 < m_2$

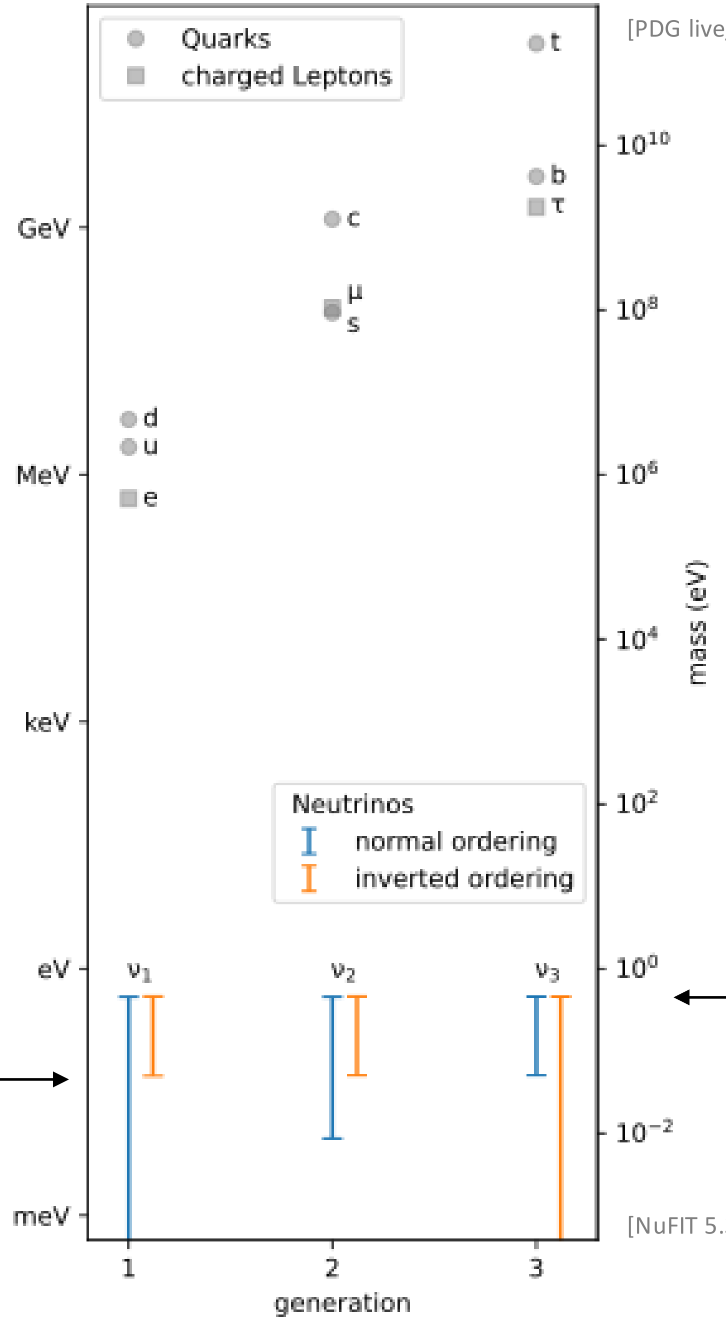
[Mikheyev, Smirnov, Sov.J.Nucl.Phys. 42 (1985) 913-917; Wolfenstein, PRD 17 (1978) 2369-2374]

› there are **two ordering scenarios**



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

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



[PDG live, pdglive.lbl.gov]

upper bound from **direct mass measurements**

lower bounds from **oscillation experiments**

[NuFIT 5.3, nu-fit.org]

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} **Michael Wurm**'s lecture

- What is the **mass of the lightest neutrino**?
  What is the **absolute neutrino mass**?

} **this lecture**

- What is the **neutrino nature**?
  Is the neutrino its **own antiparticle**?

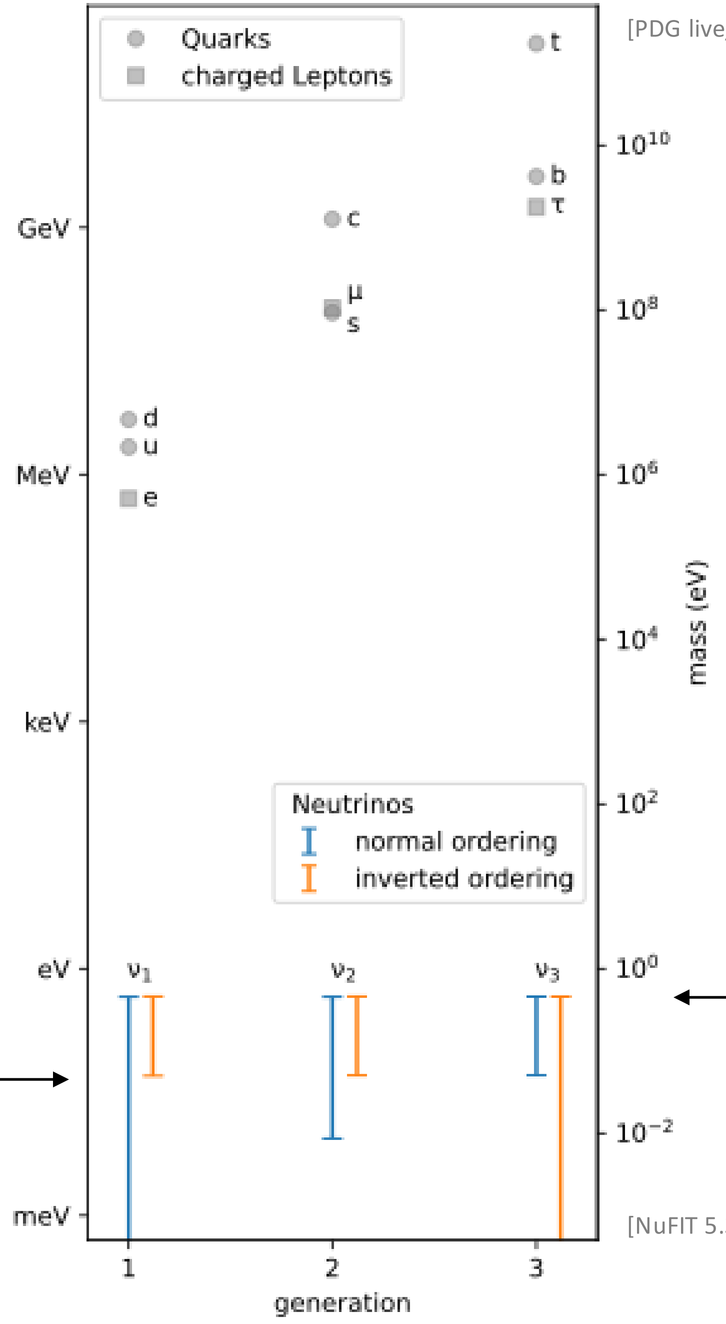
} **tomorrow**'s lecture

- Are there **additional neutrinos**?

Thierry Lasserre's lecture

lower bounds from **oscillation experiments**

[PDG live, pdglive.lbl.gov]



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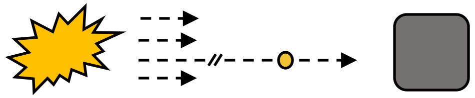
upper bound from **direct mass measurements**

Take away

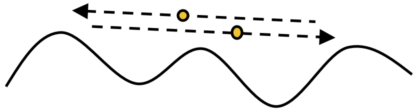
- How can we measure the **absolute neutrino mass**?
- What is a **direct neutrino mass measurement**?
- Which **neutrino mass observable** are we probing?
- What are the **experimental challenges**?
- How does the **KATRIN experiment** work?
- Where are **current bounds**? Where is the minimum value?

Neutrino mass probes

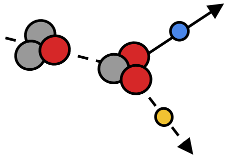
- **Supernovae**, time-of-flight



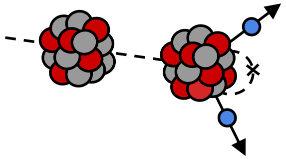
- **Cosmology**



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



- Neutrinoless **double beta decay**



laboratory-based

Neutrino mass probes

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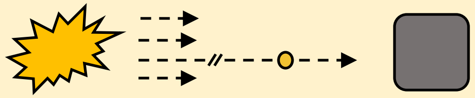

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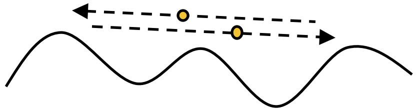

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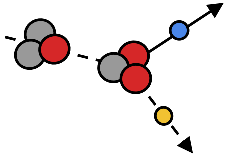

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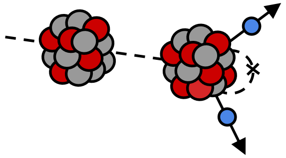
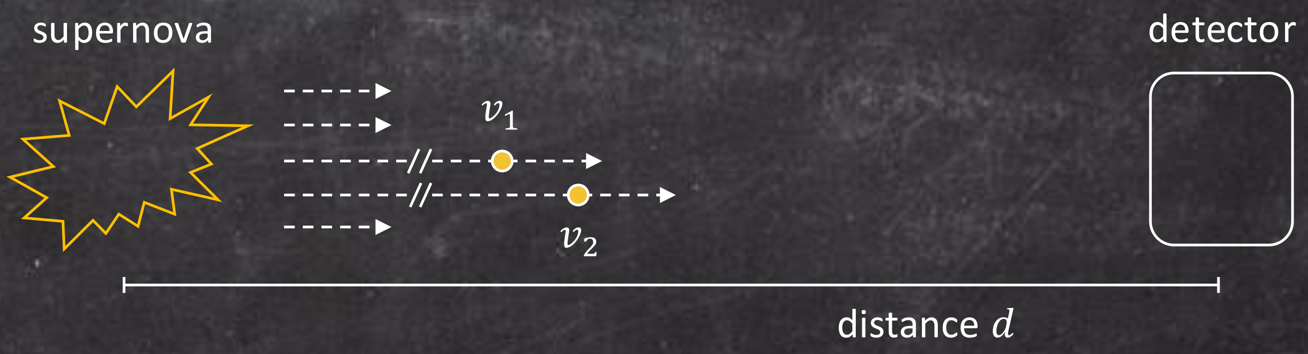


Time-of-flight

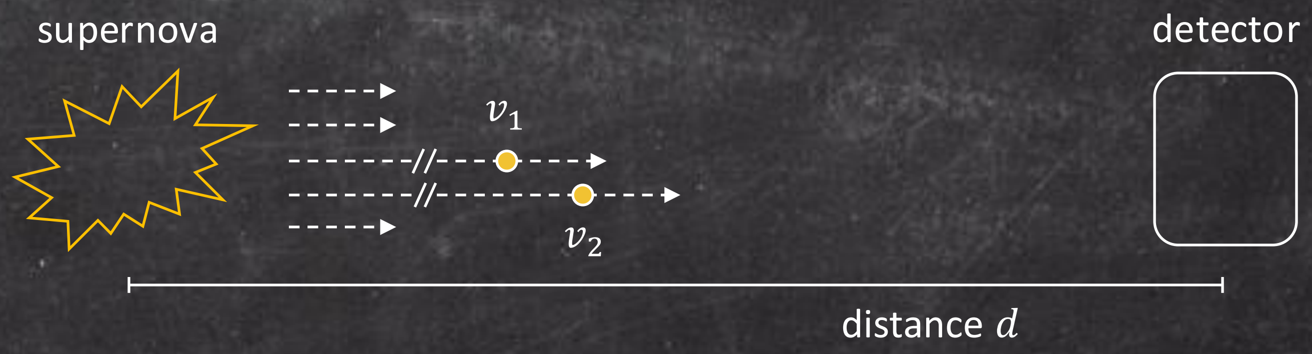


Velocity of relativistic neutrino $$v \approx c\sqrt{1-\frac{m^2c^4}{E^2}}$$

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

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

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) 287-291]

m_ν **< 5.8 eV** (95% CL)

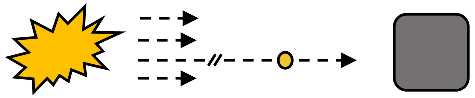
› independent, but not competitive bound

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

› **sub-eV sensitivity** expected, but depends on circumstances (e.g. supernova distance, available detectors)
[Pompa et al., PRL 129 (2022) 12, 121802]

Neutrino mass probes

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



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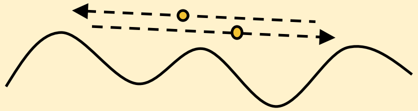

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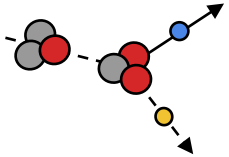

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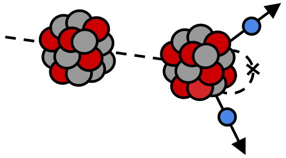
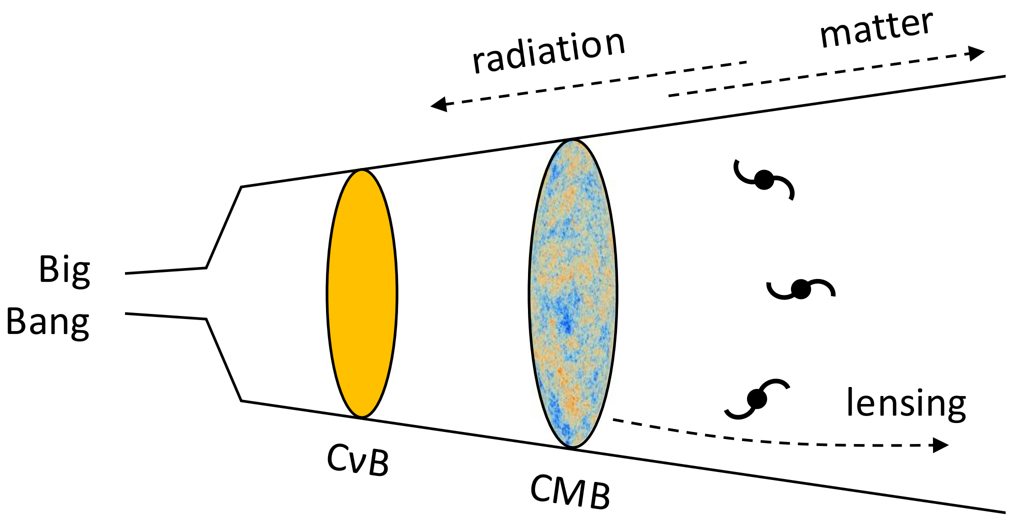
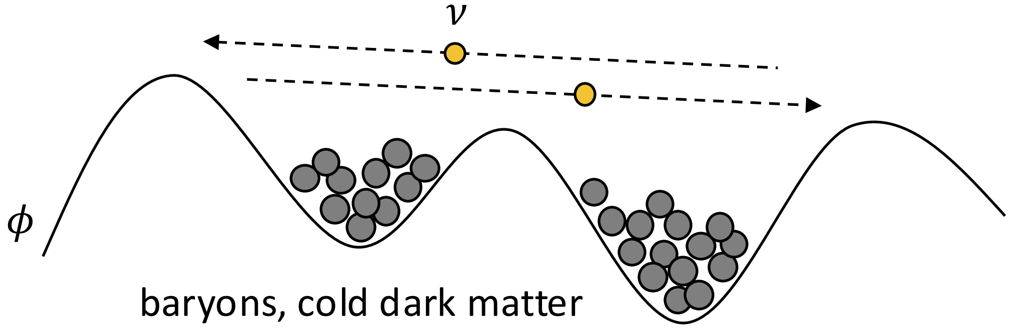


Neutrinos in the cosmos

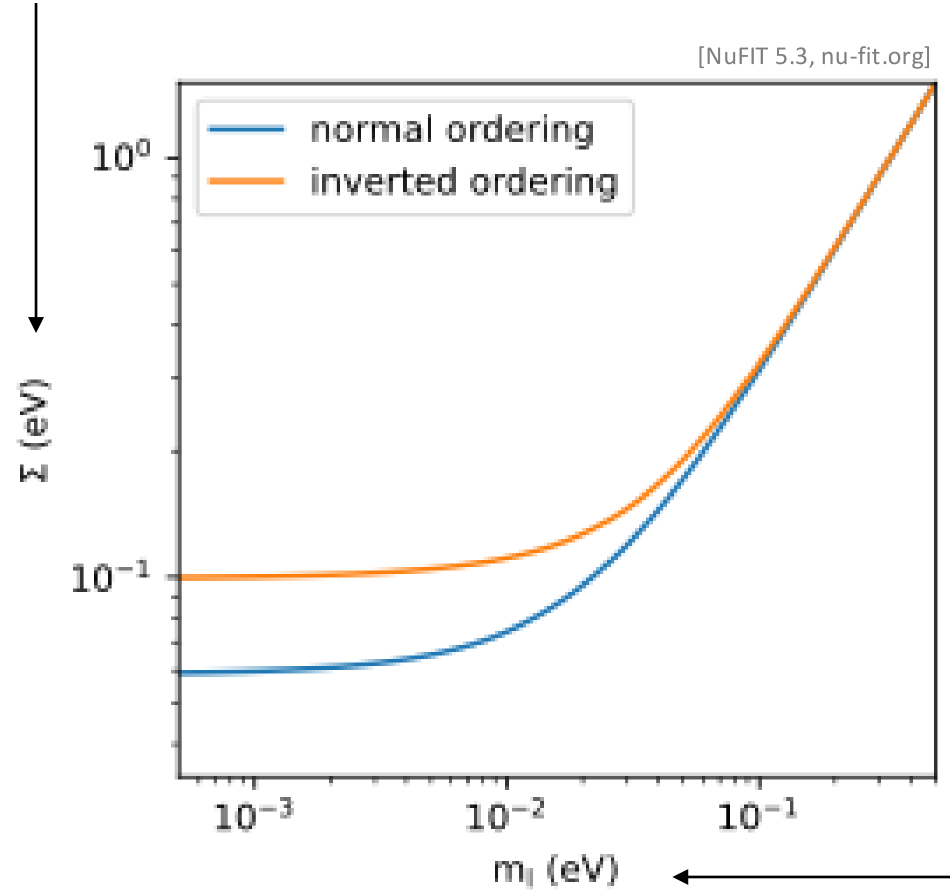
} **Miguel Escudero**'s lecture

- 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 **impacts structure growth**, matter power spectrum

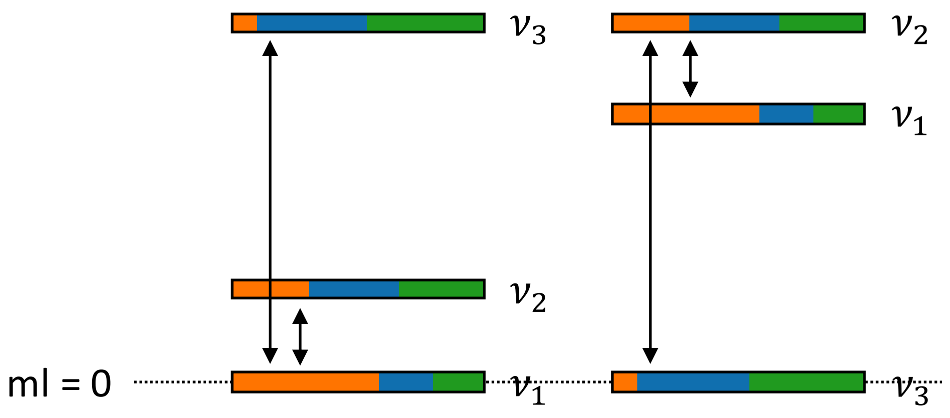




Sum of neutrino mass eigenstates, $\Sigma = \sum_i m_i$

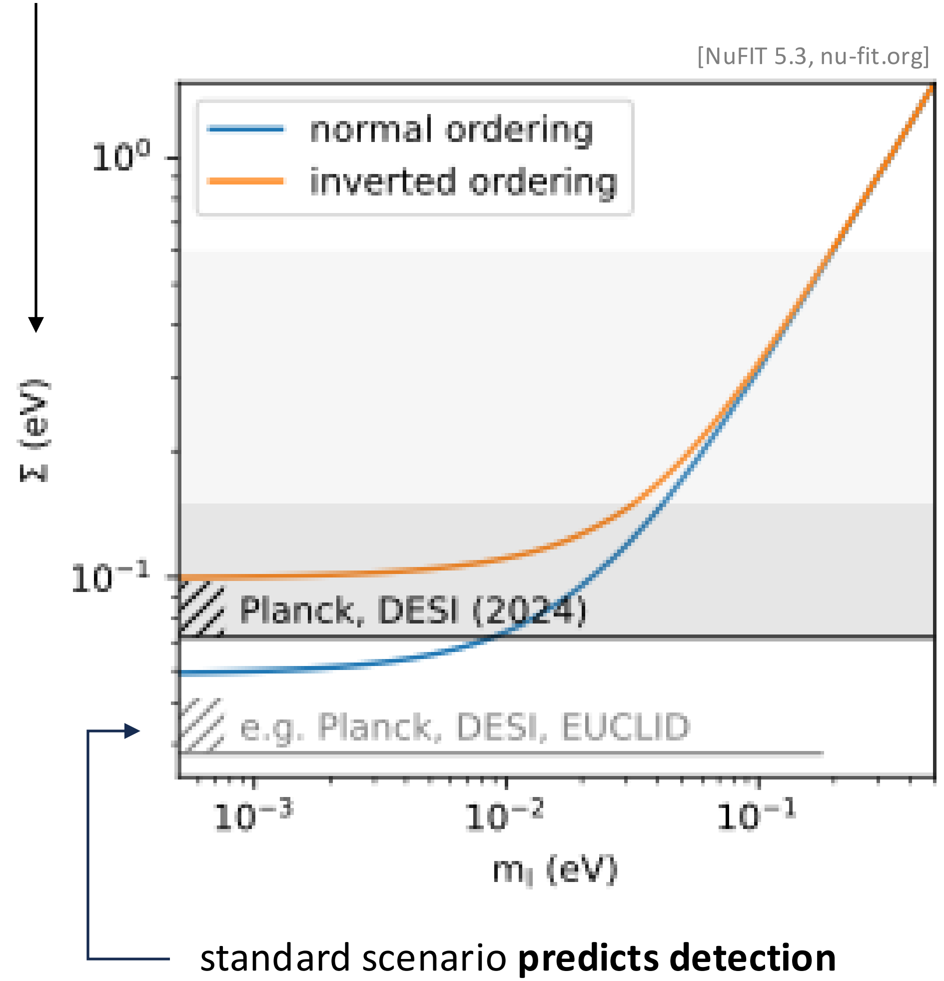


- minimum at **0.06 eV** (normal ordering), **0.10 eV** (inverted ordering)



lightest mass eigenstate, $\min(m_i)$

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

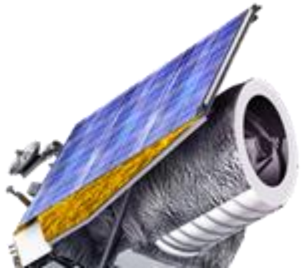


standard scenario **predicts detection**

- minimum at **0.06 eV** (normal ordering), **0.10 eV** (inverted ordering)
- most stringent bounds driven by **Planck and DESI data**
  [Aghanim et al., A&A 641 (2020) A6; Adame et al., arXiv:2404.03002]

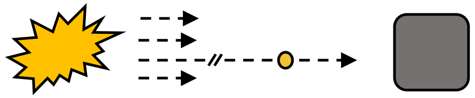
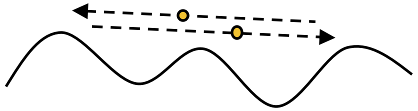
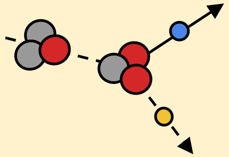
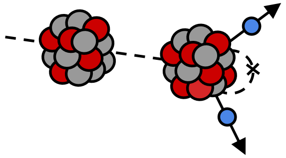
  Σ **< 0.07 eV** (95% CI)

- **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, ..]



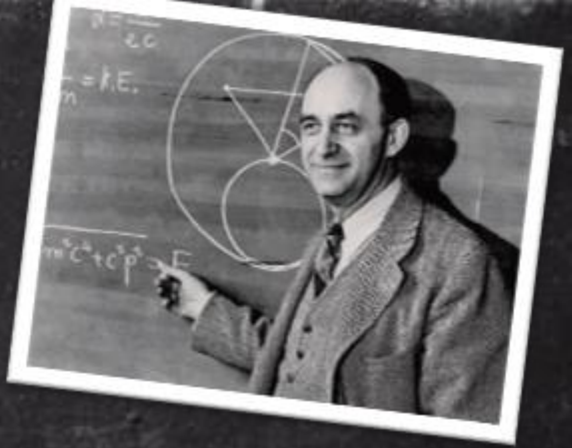
σ_Σ = **O(0.01) eV**

Neutrino mass probes

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

β *decay kinematics*

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

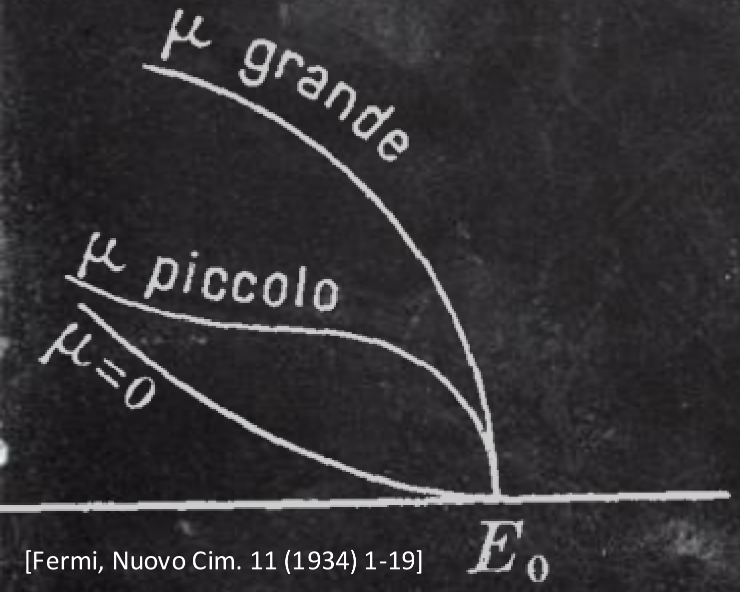


differential decay rate

$$\frac{d\Gamma}{dE} \propto \underbrace{F(E,Z)}_{\text{Fermi function}} \cdot \underbrace{E_e \cdot E_\nu \cdot p_e \cdot p_\nu}_{\text{phase space factor}}$$

$$= F(E,Z) \cdot \underbrace{(E + m_e)}_{\text{electron energy}} \cdot \underbrace{(E_0 - E)}_{\text{neutrino energy (endpoint } E_0)} \cdot \underbrace{\sqrt{(E + m_e)^2 - m_e^2}}_{\text{electron momentum}} \cdot \underbrace{\sqrt{(E_0 - E)^2 - m_\nu^2}}_{\text{neutrino momentum}}$$

electron momentum ($E^2 = p^2 + m^2$)



[Fermi, Nuovo Cim. 11 (1934) 1-19]

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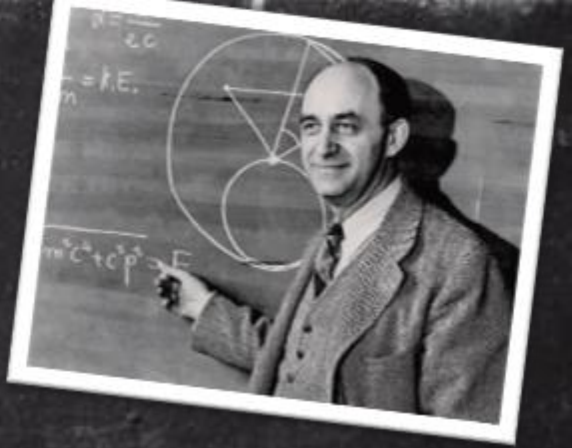


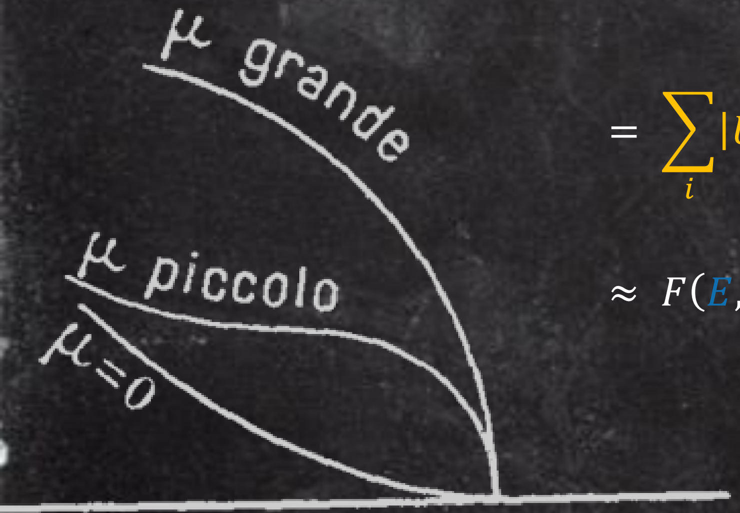
Fermi function — phase space factor

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

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

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

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



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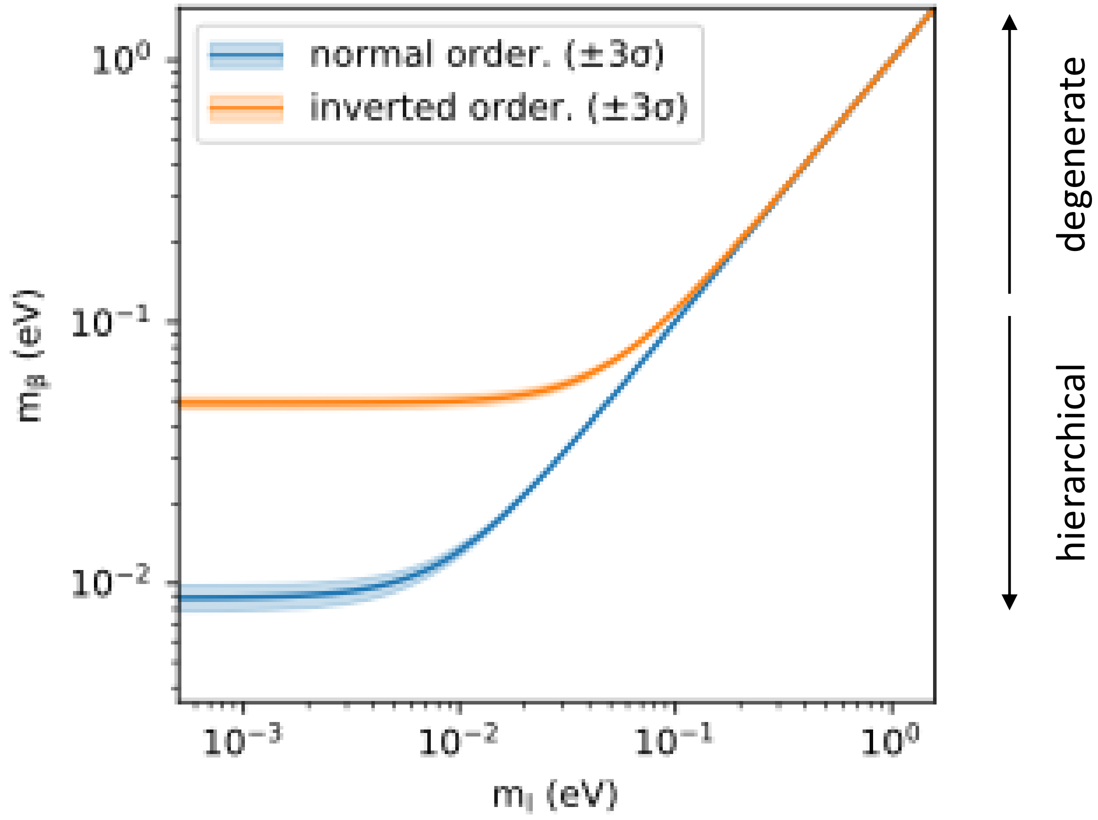
effective electron (anti-)neutrino mass, $m_\beta = \sqrt{\sum_i |U_{ei}|^2 \, m_i^2}$

incoherent sum of mass eigenstates

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

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

[NuFIT 5.3, nu-fit.org]



- minimum at **0.01 eV** (normal ordering), **0.05 eV** (inverted ordering)
- current experiments (**KATRIN**) probe **degenerate regime**, $m_1 \approx m_2 \approx m_3$
- **technology development** for future experiments that aim to enter **hierarchical regime**, $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 \approx m_2$

Take away

- How can we measure the **absolute neutrino mass**?
- What is a **direct neutrino mass measurement**?
- Which **neutrino mass observable** are we probing?
- What are the **experimental challenges**?
- How does the **KATRIN experiment** work?
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  supernovae, cosmology, beta decay, neutrinoless double beta decay
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  neutrino mass experiment relying on beta decay kinematics
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  incoherent sum of mass eigenstates, effective electron neutrino mass
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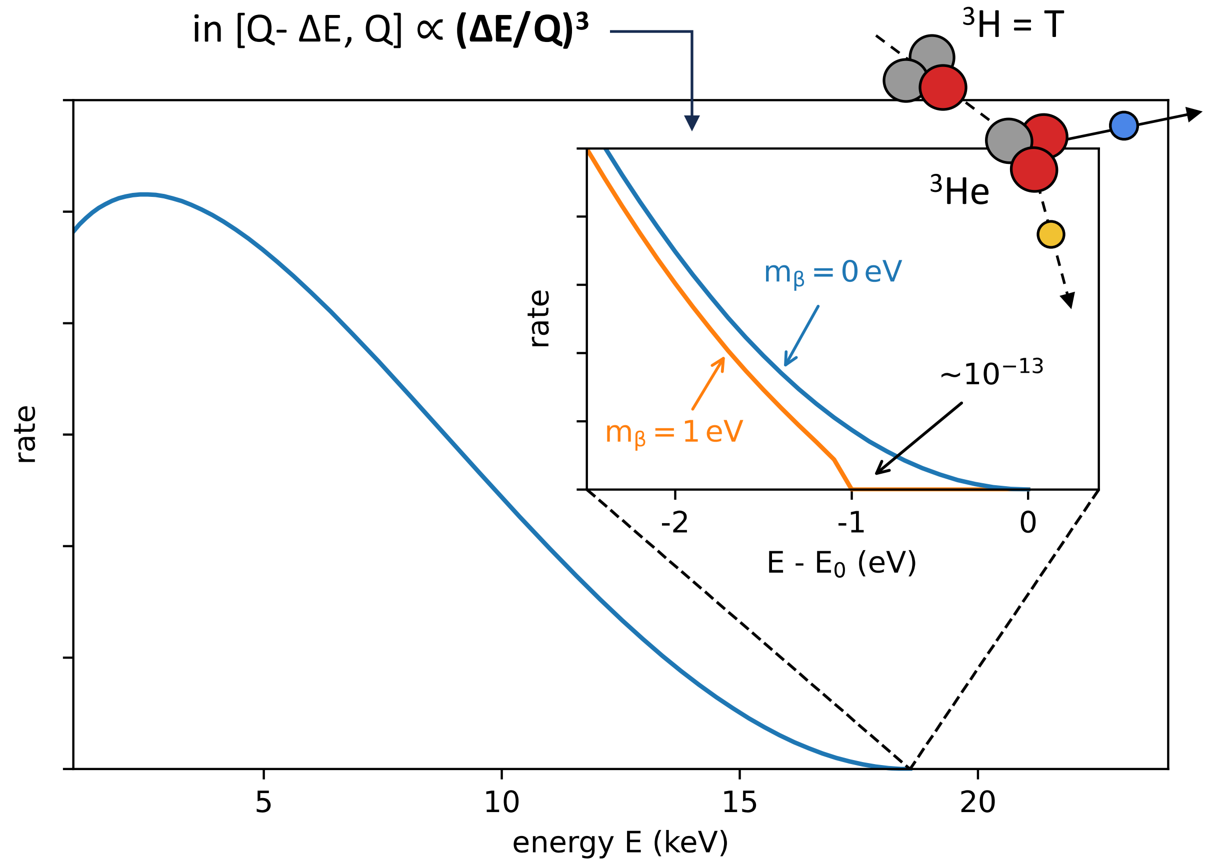
Experimental challenge

measure sub-eV scale **spectral distortion** close to 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)

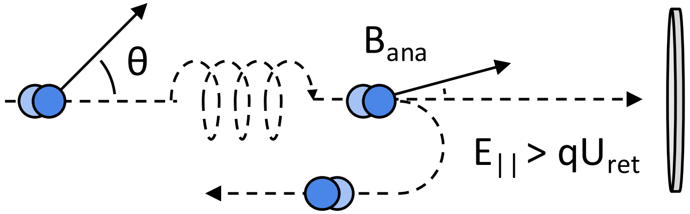
- high **acceptance**, excellent **energy resolution** (O(1) eV, < 0.01 %), low **background** (mcps)
- **high precision** understanding of theoretical spectrum and experimental response

fraction of events in [Q- ΔE, Q] ∝ **(ΔE/Q)³**

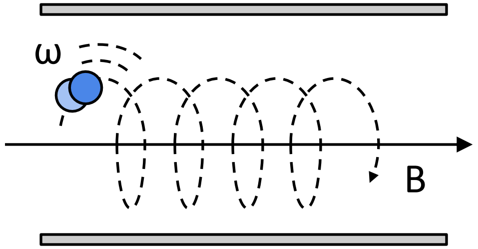


Experimental approaches

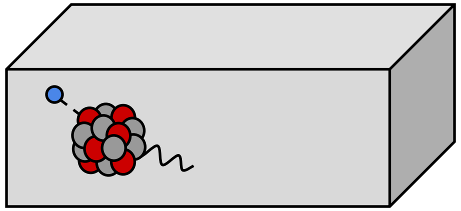
tritium



electrostatic
filtering (MAC-E)



cyclotron radiation emission
spectroscopy (CRES)



cryogenic
calorimetry

R&D

Experimental approaches

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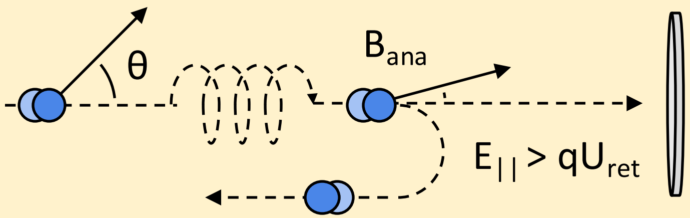

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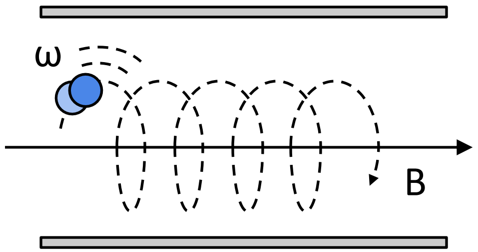

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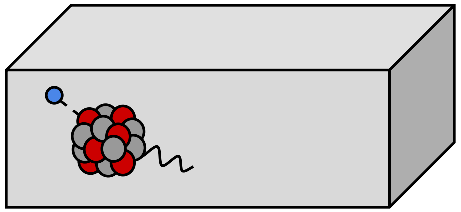

cryogenic
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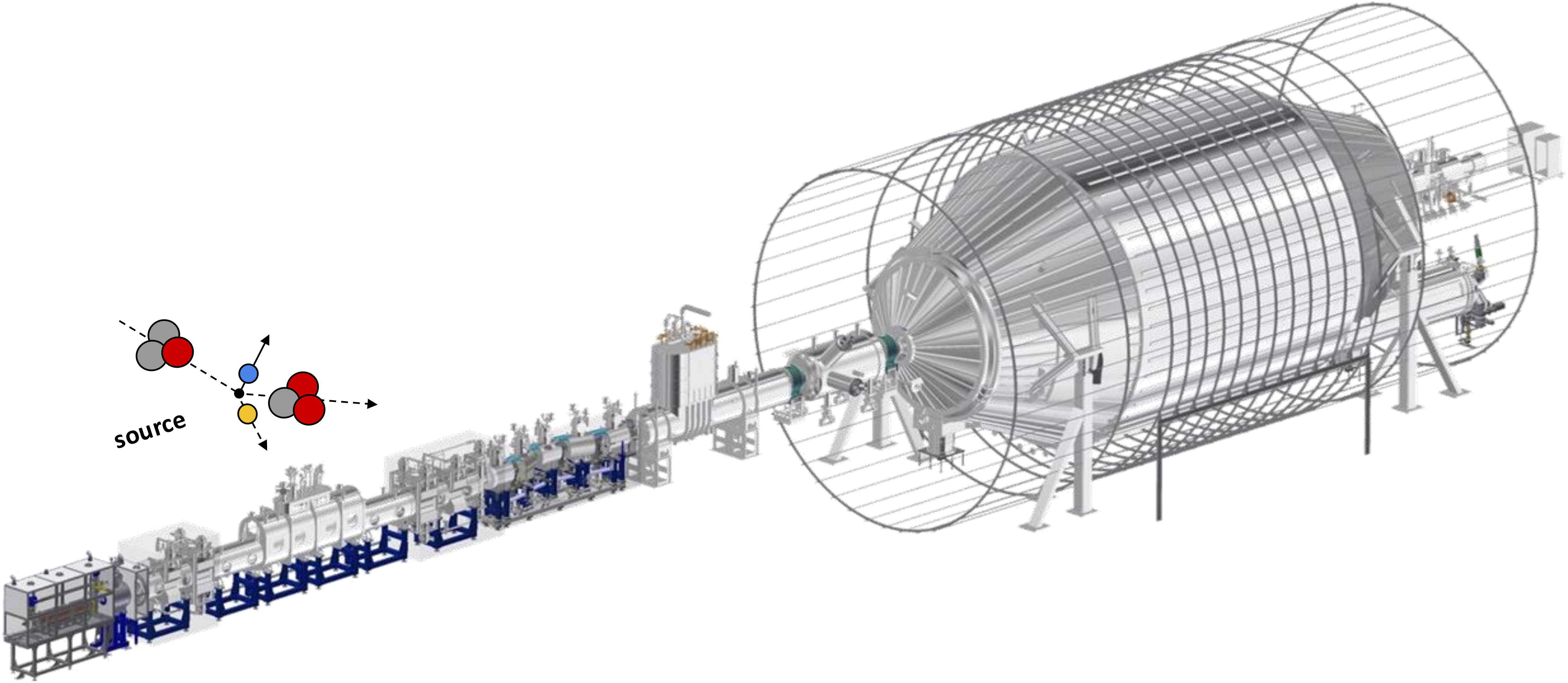
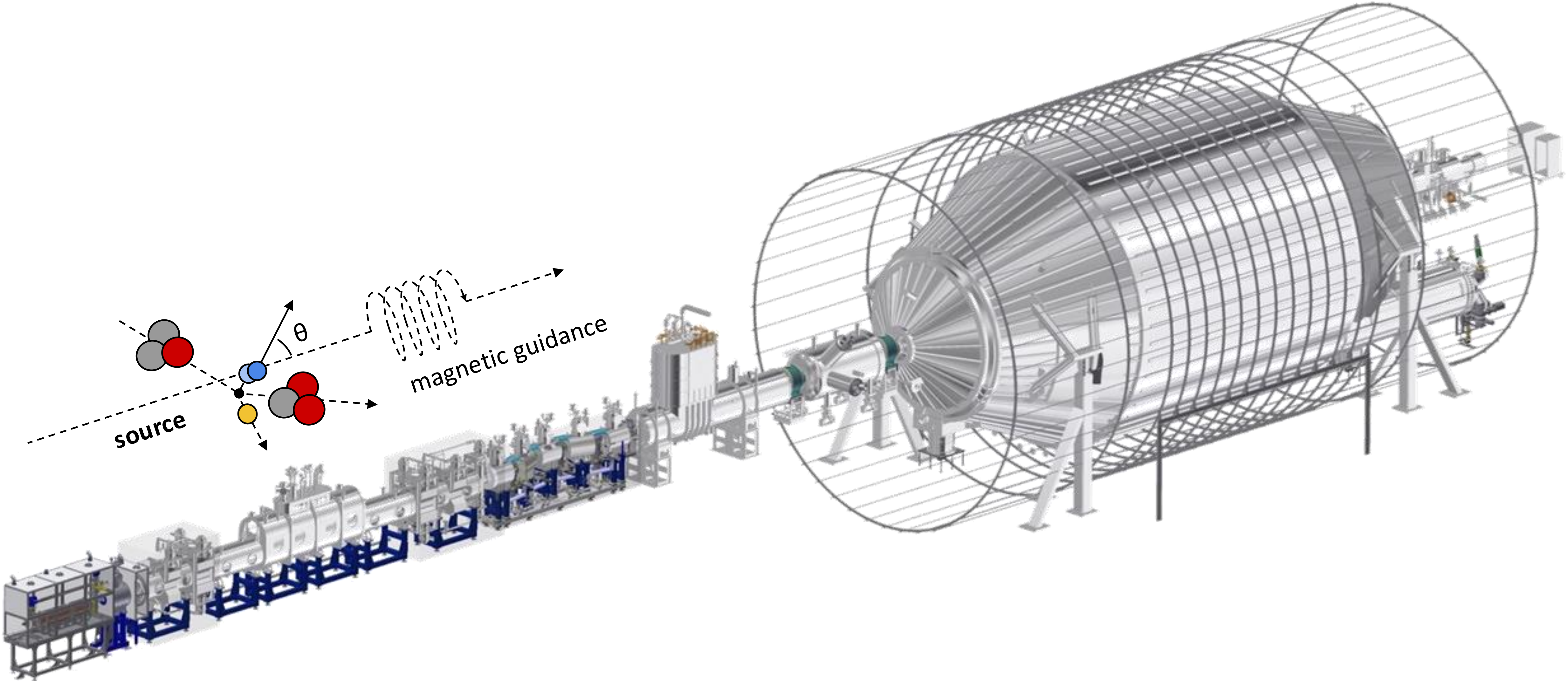
Karlsruhe Tritium Neutrino (KATRIN) experiment

Working principle



Working principle



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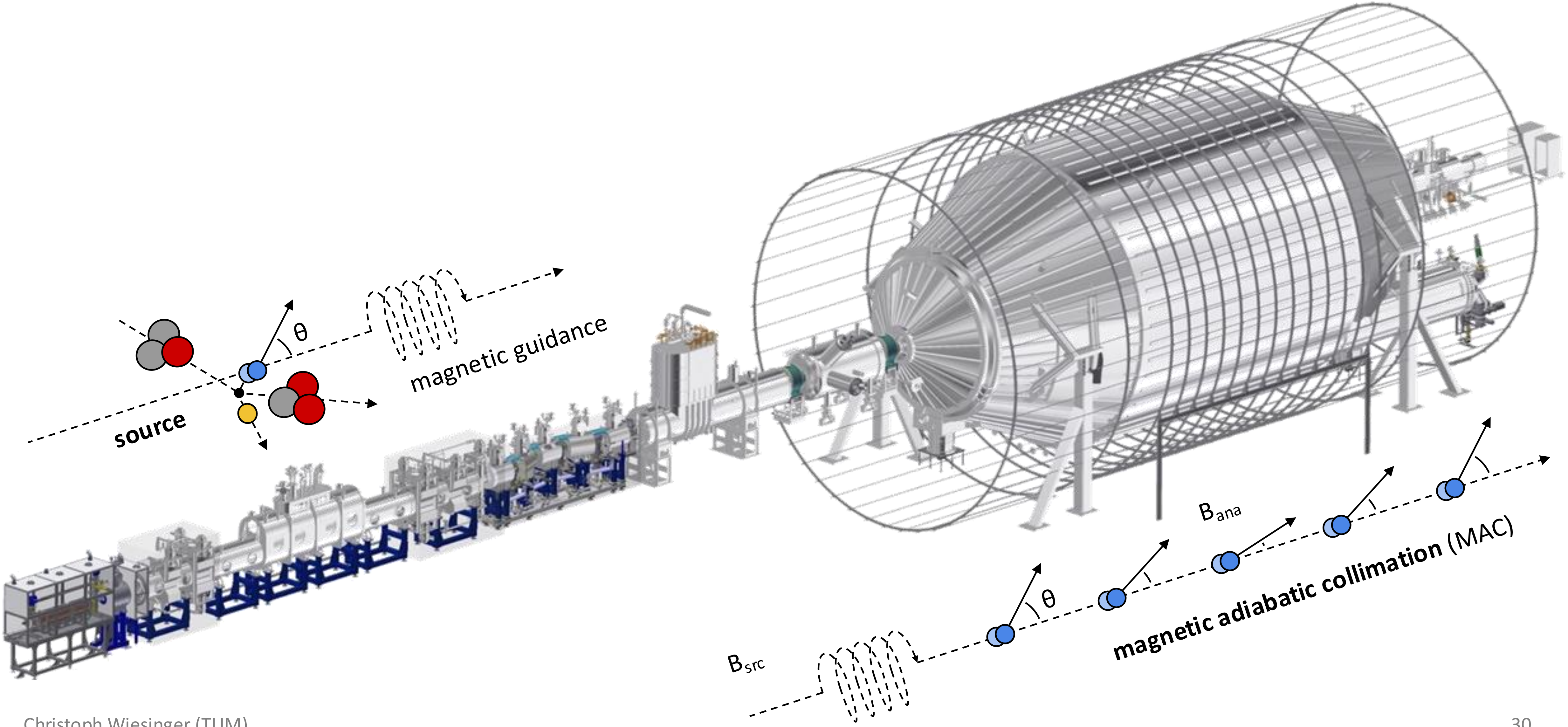

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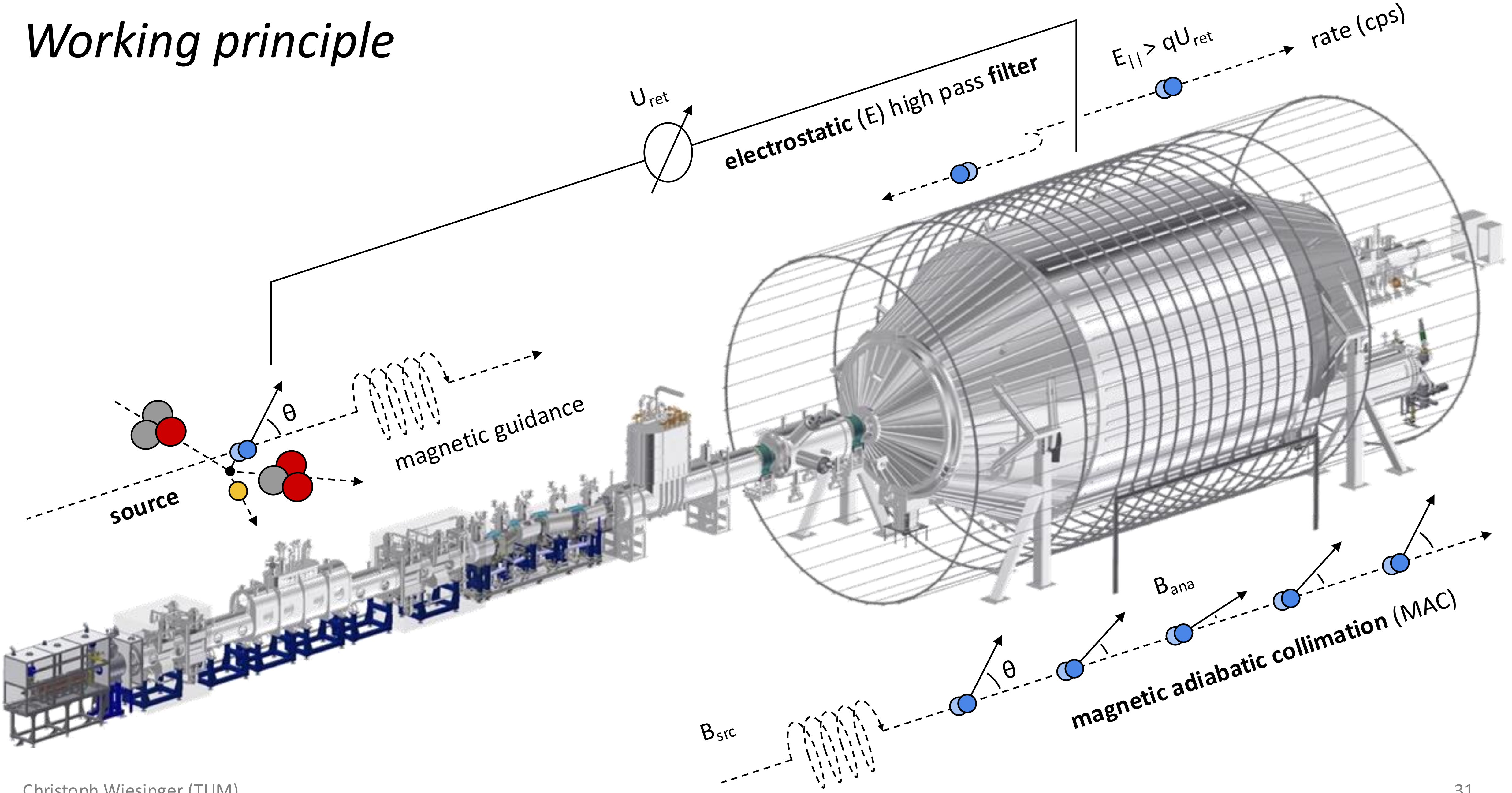
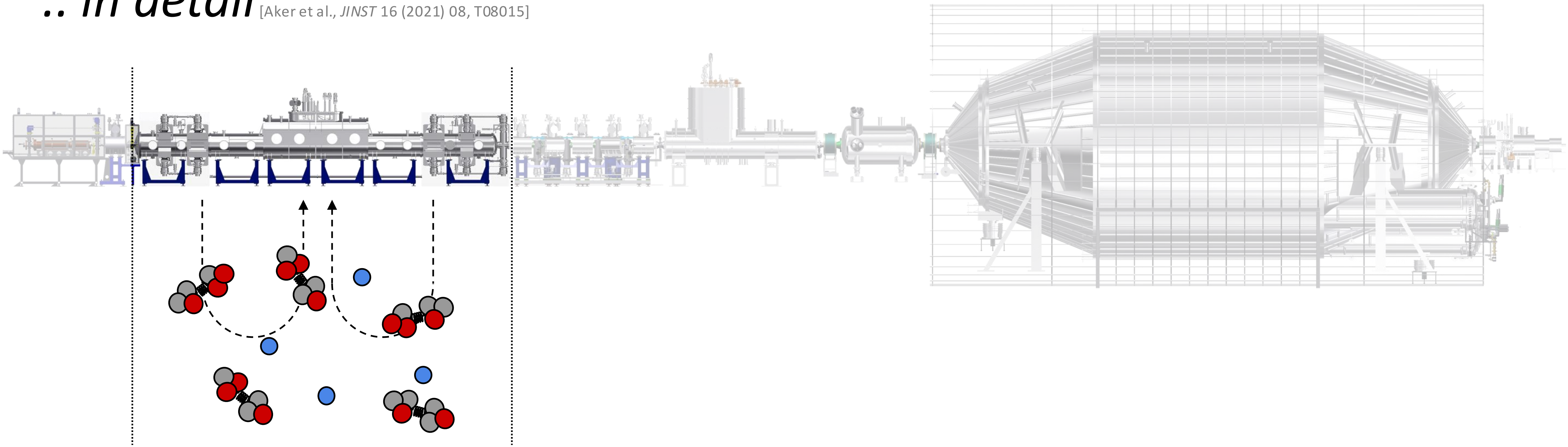


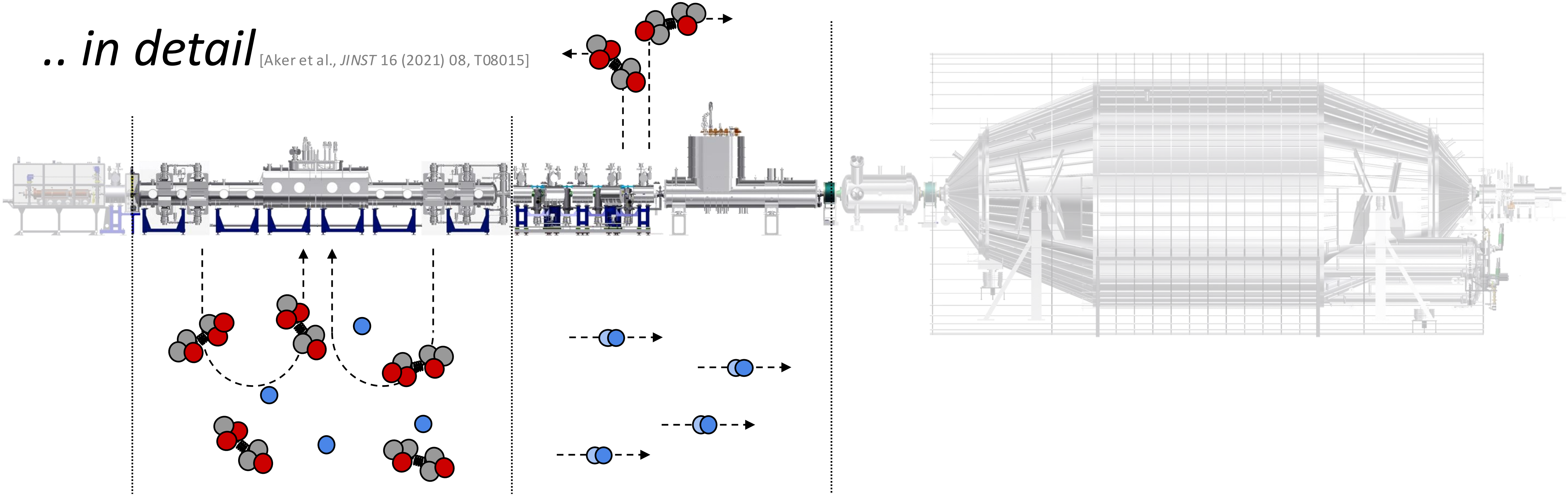
.. *in detail* [Aker et al., *JINST* 16 (2021) 08, T08015]



windowless gaseous tritium source

- molecular tritium, **closed loop** operation
  › high activity, up to **100 GBq**

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



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transport section

- tritium **gas/ion removal**
  › reduction by **> 10^{14}**

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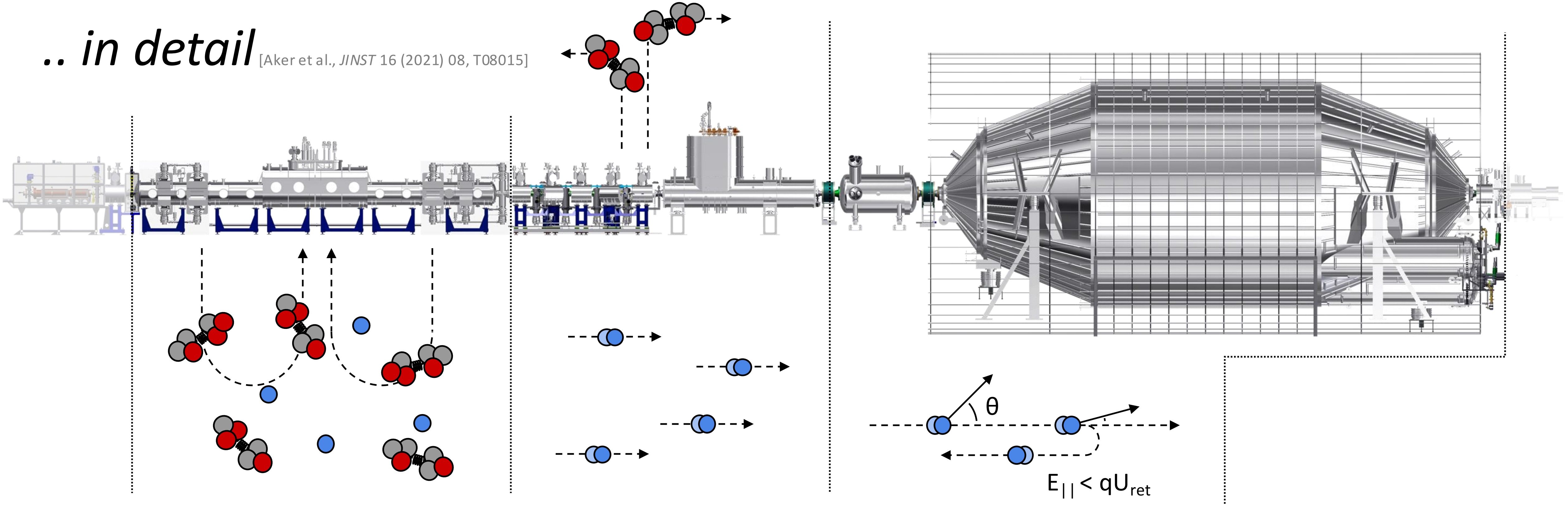

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spectrometer system

- pre/main spectrometer
  - › high resolution, **O(1) eV**, high acceptance, **0-51°**

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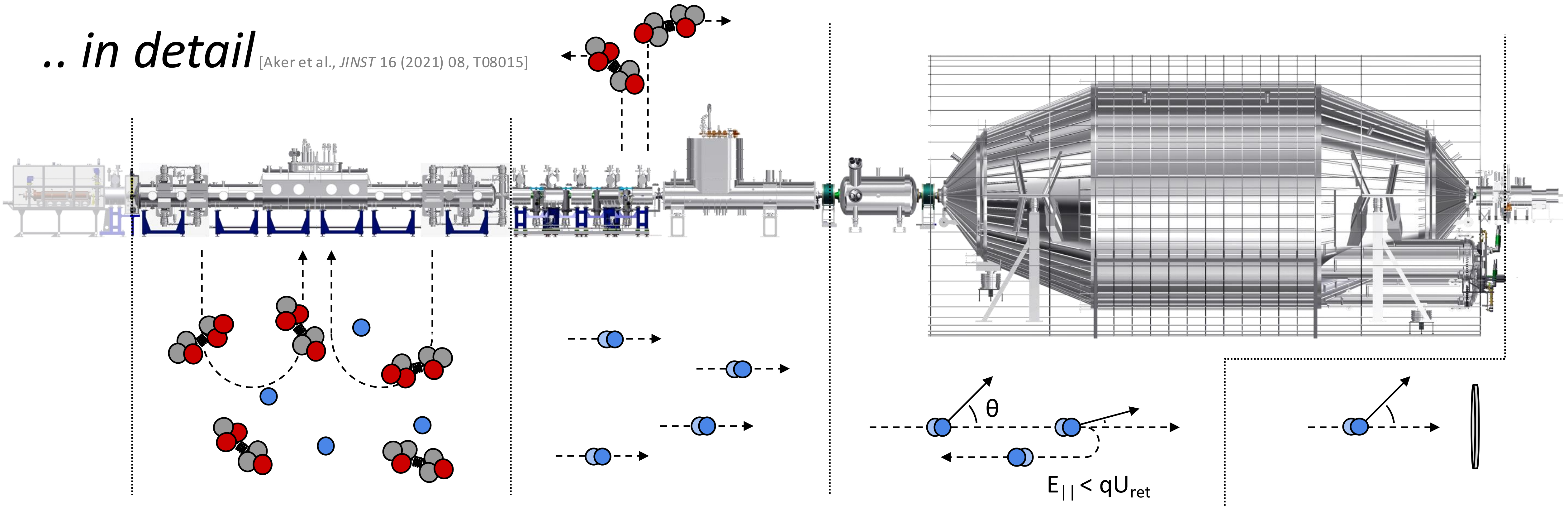

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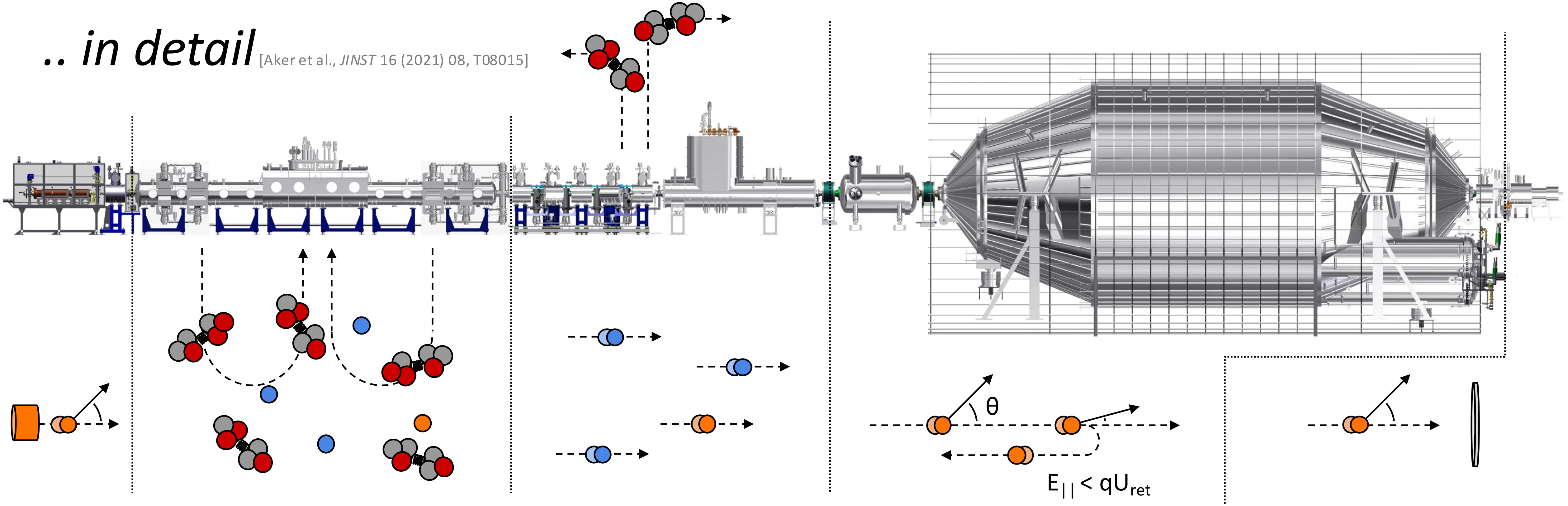
detector section

- focal plane detector, **148-pixel** silicon PIN-diode

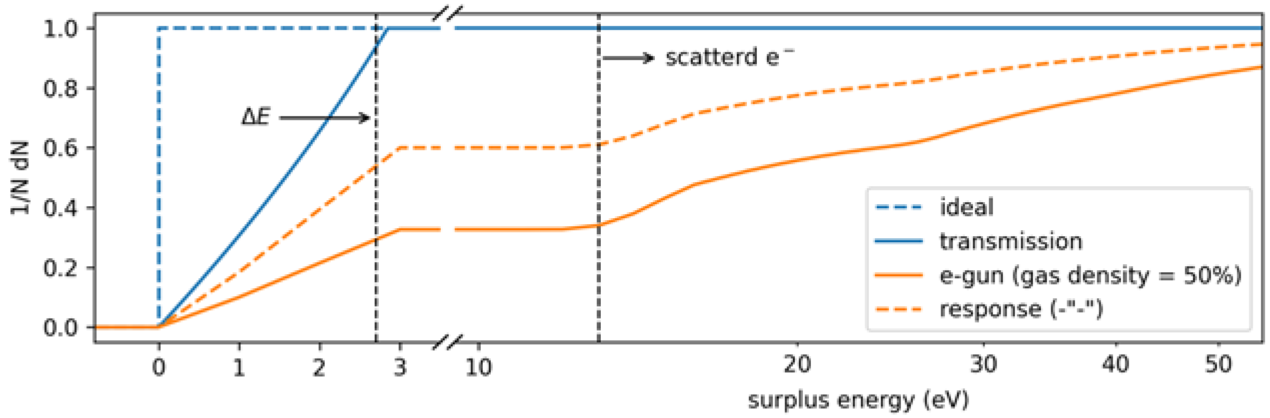
.. in detail [Aker et al., *JINST* 16 (2021) 08, T08015]



rear section

- mono-energetic angular-selective photoelectron source
  [Behrens et al., EPJC 77 (2017) 6, 410]

› precise determination **scattering effects**, i.e gas density and energy loss function



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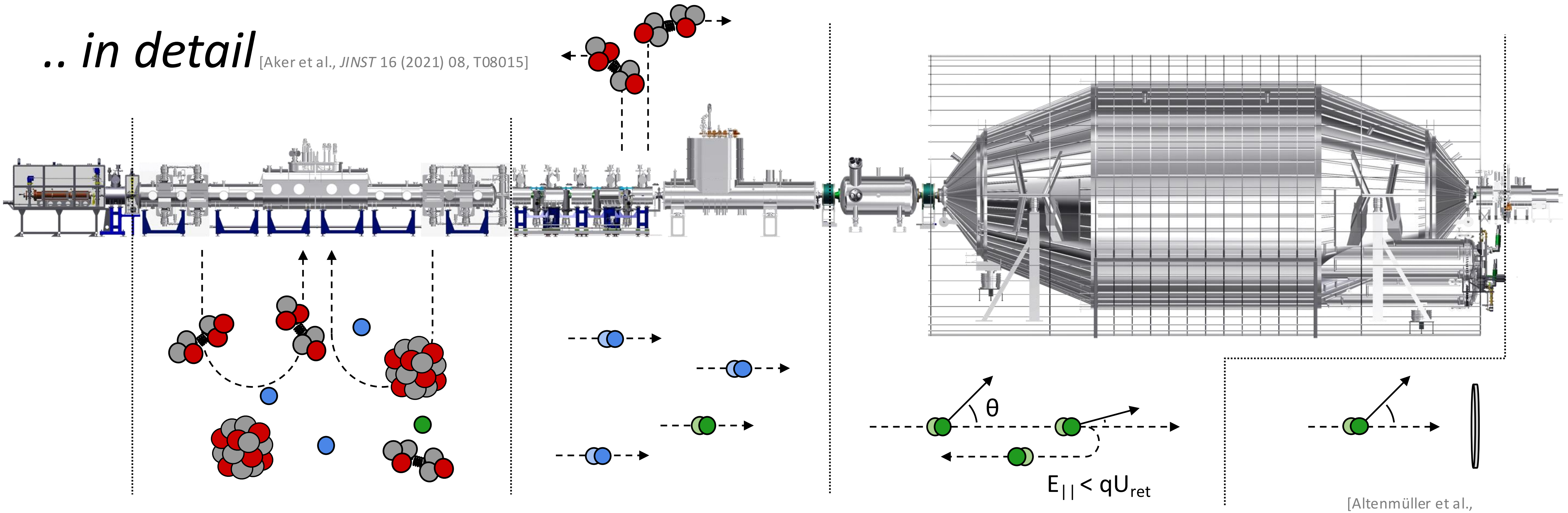
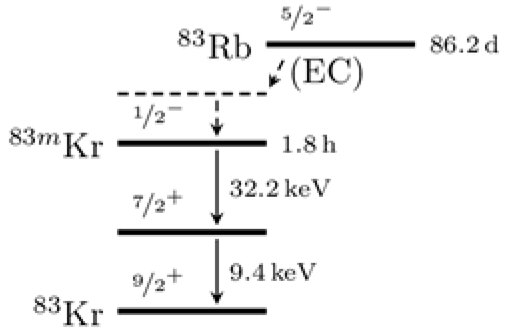
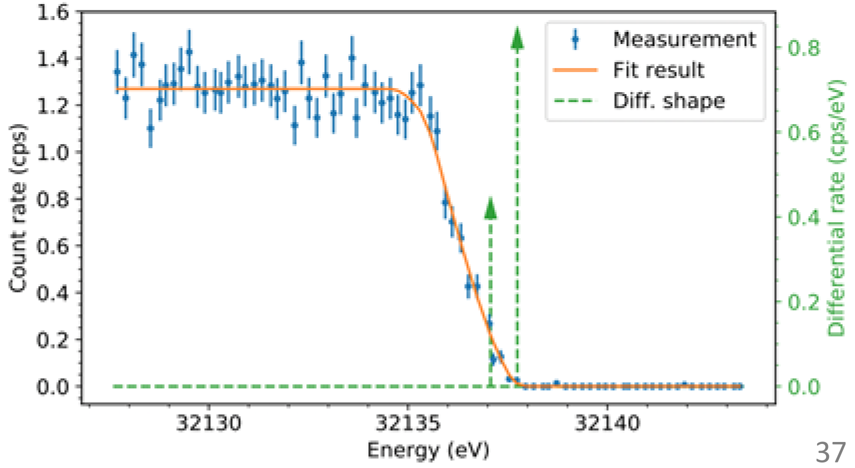


windowless gaseous ~~tritium~~ source

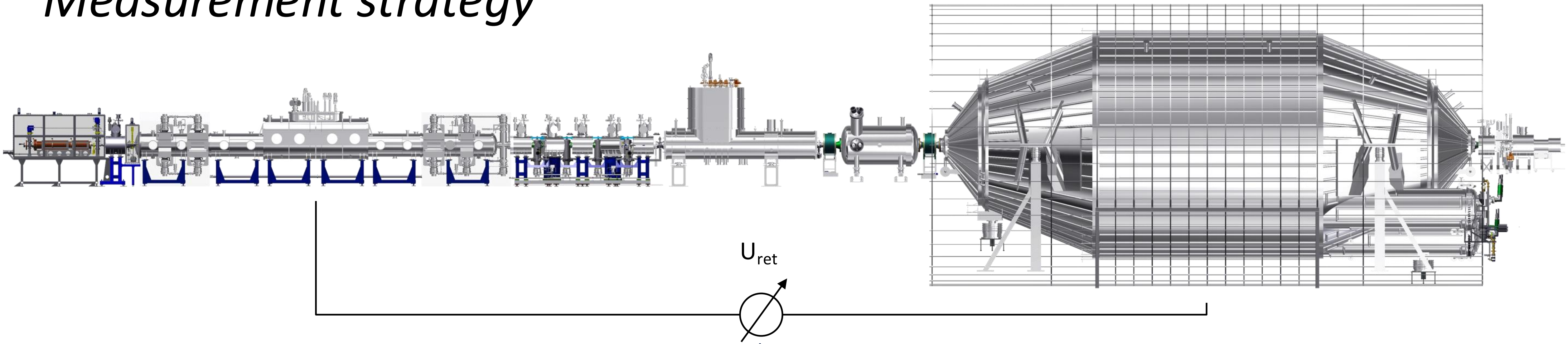
- mono-energetic ^{83m}Kr **conversion electrons** [Arenz et al., JINST 13 (2018) 04, P04020]
  - determination of **source potential** variations and **spectrometer fields**



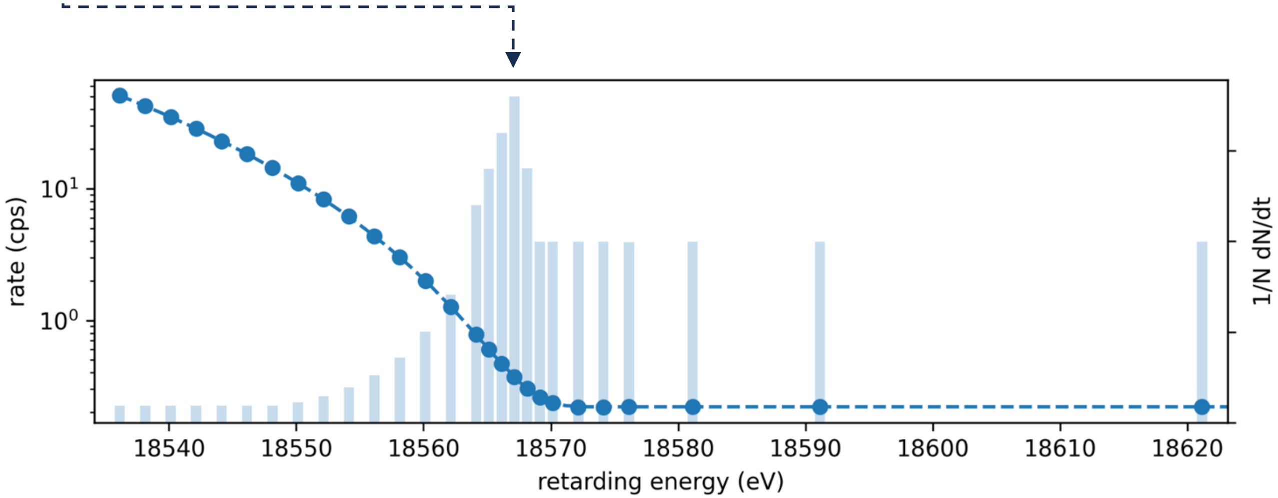
[Altenmüller et al., J.Phys.G 47 (2020) 6, 065002]



Measurement strategy



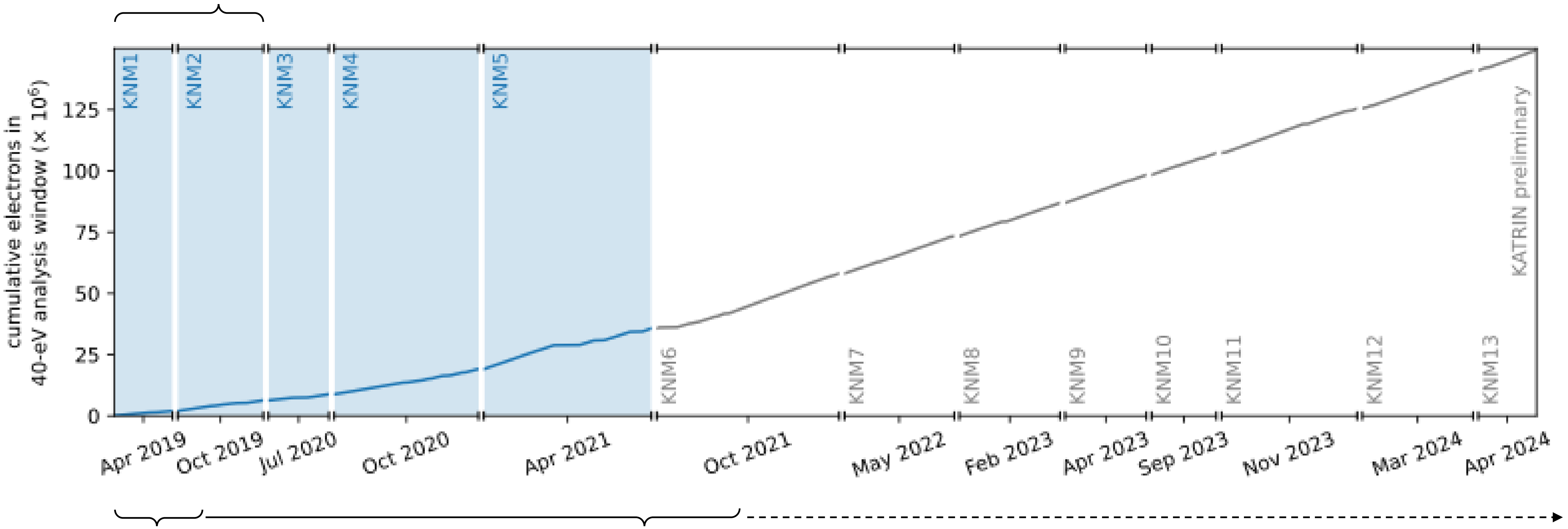
› **rate of transmitted electrons,** discrete retarding potential steps, optimized measurement time distribution



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

Data taking overview

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



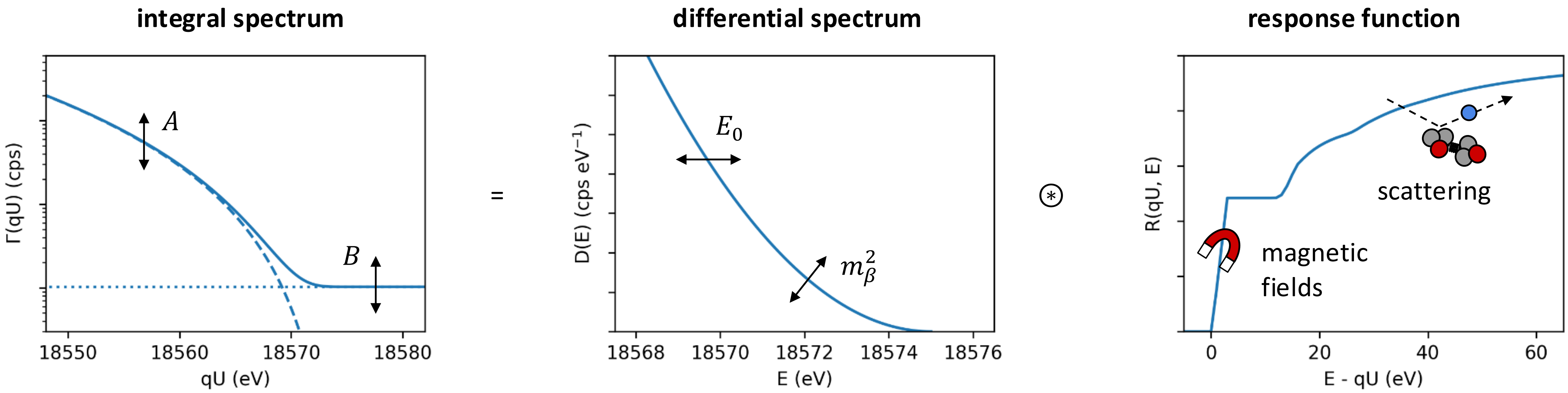
first result, $\mathbf{m_\beta < 1.1}$ **eV** (90% CL)
[Aker et al., PRL 123 (2019) 22, 221802]

third results, 5 campaigns, 1757 scans,
259 measurement days

continue until end-2025,
1000 measurement days

Analysis procedure

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

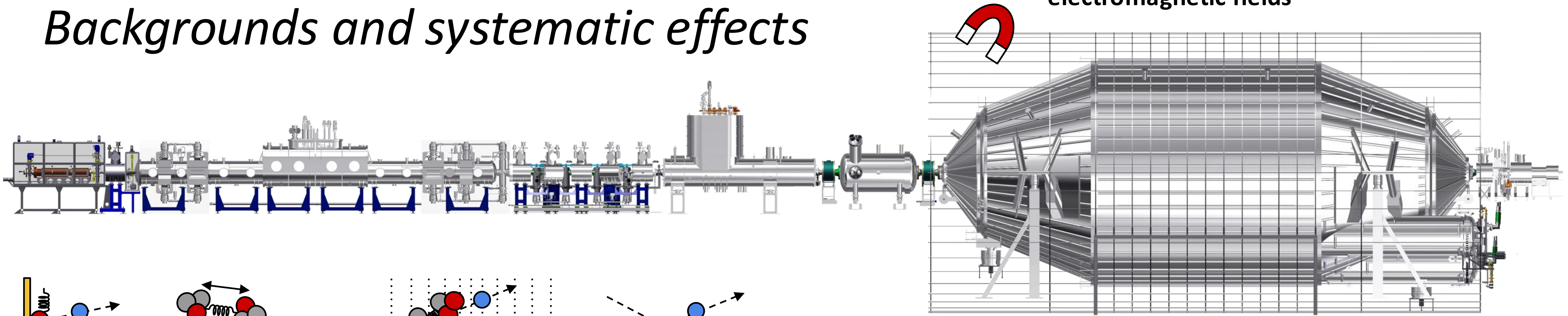


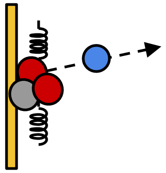
with free **squared neutrino mass $\boldsymbol{m_\beta^2}$**, effective endpoint E_0, amplitude A and background B

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

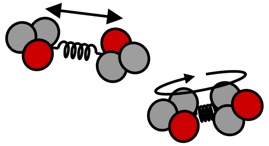
Backgrounds and systematic effects

electromagnetic fields

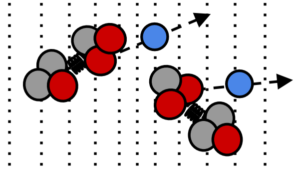




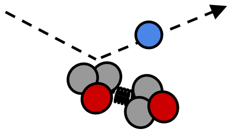
rear wall



molecular states

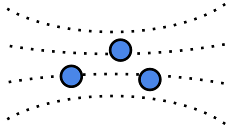


starting potential

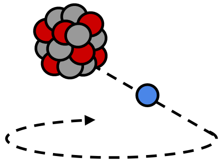


scattering

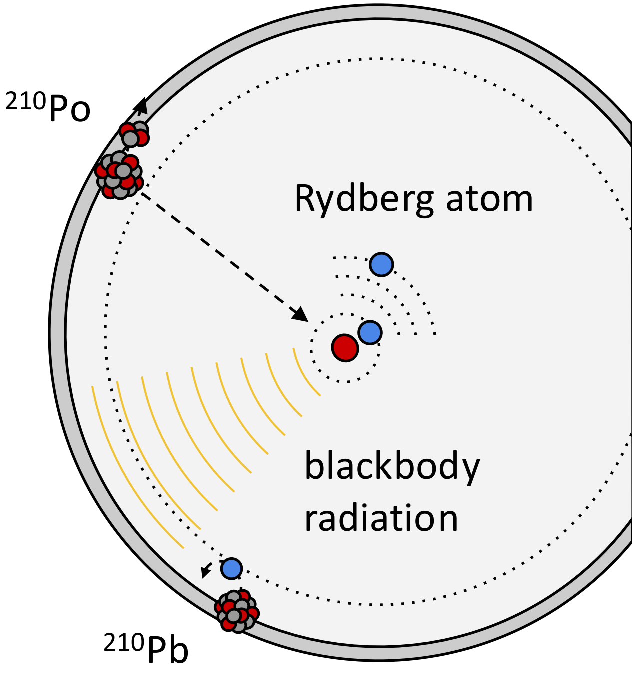
source effects



Penning trap



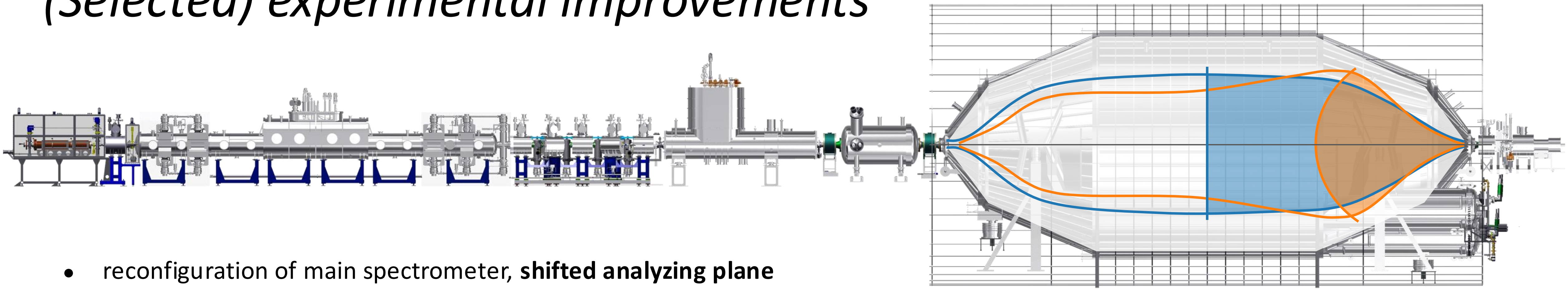
trapped particles



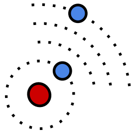
spectrometer/background effects

Rydberg background

(Selected) experimental improvements



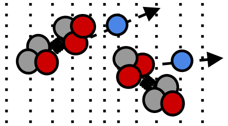
- reconfiguration of main spectrometer, **shifted analyzing plane**
  [Lokhov et al., EPJ C 82 (2022) 3, 258]

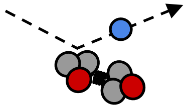
  \+ 2-fold **reduction of background**, Rydberg-induced background

  \- increased spectrometer **field variance**, use detector segmentation

- ^{83m}**Kr co-circulation** mode, conversion electrons, calibrate **source potential** and **spectrometer fields**, neutrino mass scans under same conditions
  [A. Marsteller et al., INST 17 (2022) 12, P12010]

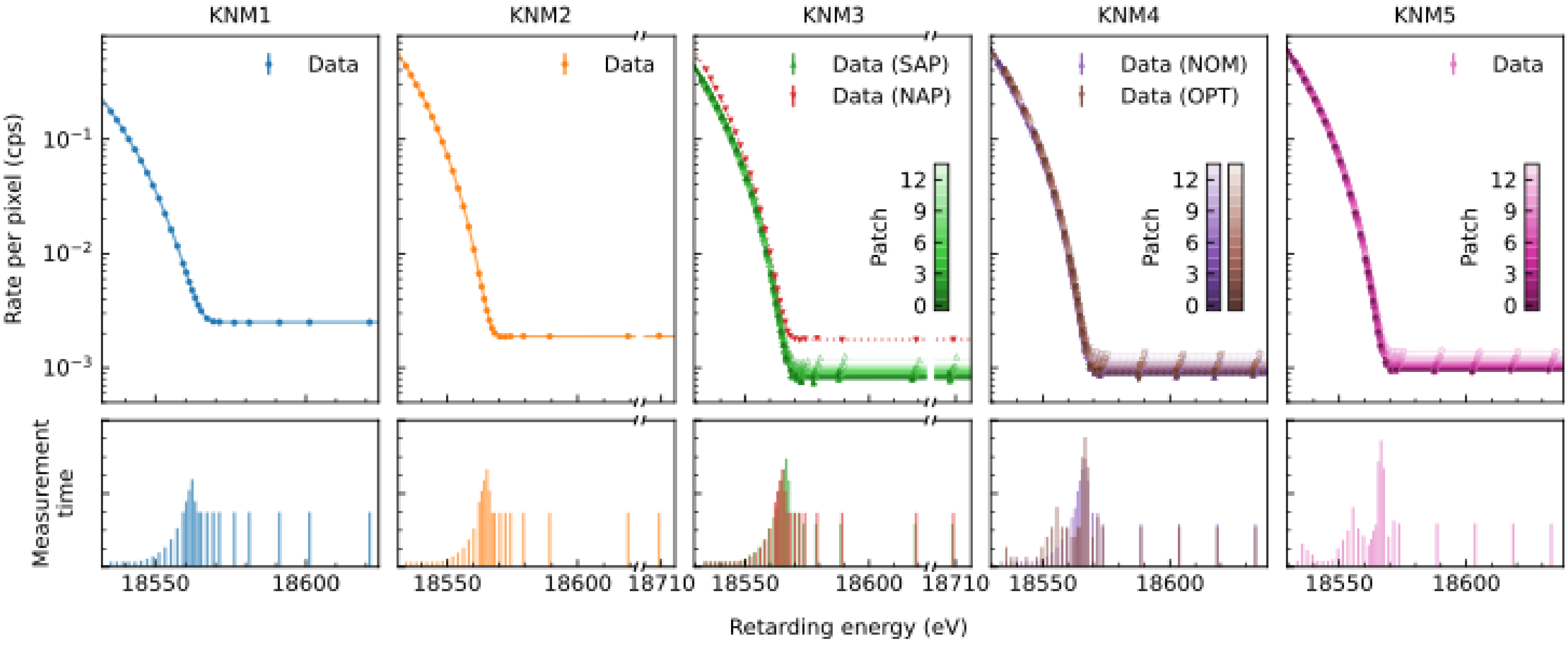


- improved **electron gun**, mono-energetic angular-selective photoelectron source, probe **scattering effects**
  [Aker et al., EPJ C 81 (2021) 7, 579]



Analysis challenge

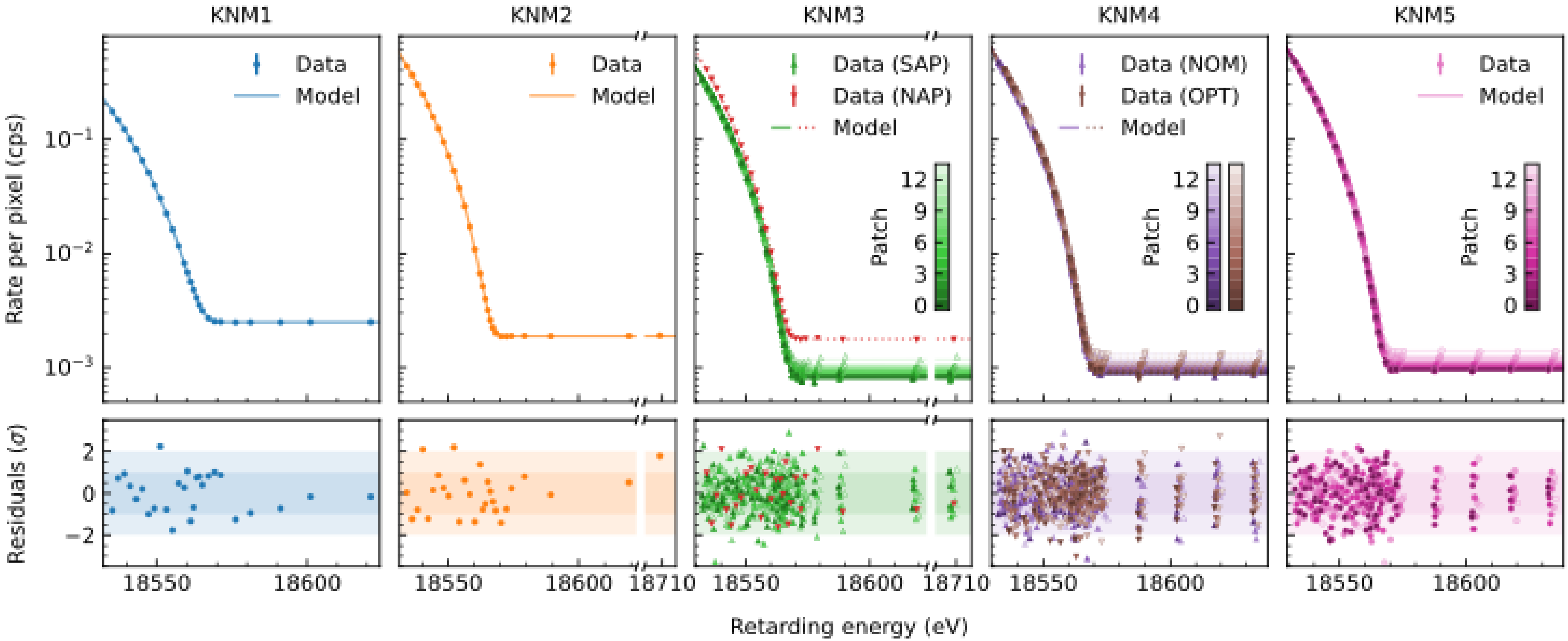
- 7 different configurations, 59 spectra, **1609 data points**, **parameter correlations** across datasets



- **2-stage blinding**, simulated data, blinded molecular final states, **2 analysis frameworks**, neural network surrogate [Karl et al., EPJ C 82 (2022) 5, 439]

Fit result

- 7 different configurations, 59 spectra, **1609 data points**, **parameter correlations** across datasets

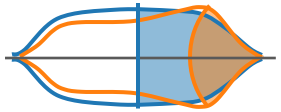


- **2-stage blinding**, simulated data, blinded molecular final states, **2 analysis frameworks**, neural network surrogate [Karl et al., EPJ C 82 (2022) 5, 439]

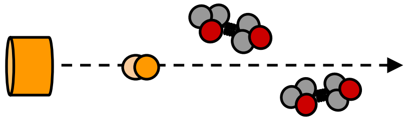
› p-value = 0.84, best-fit $\mathbf{m_\beta^2 = -0.14^{+0.13}_{-0.15}\ eV^2}$ [Aker et al., arXiv:2406.13516]

Uncertainty breakdown

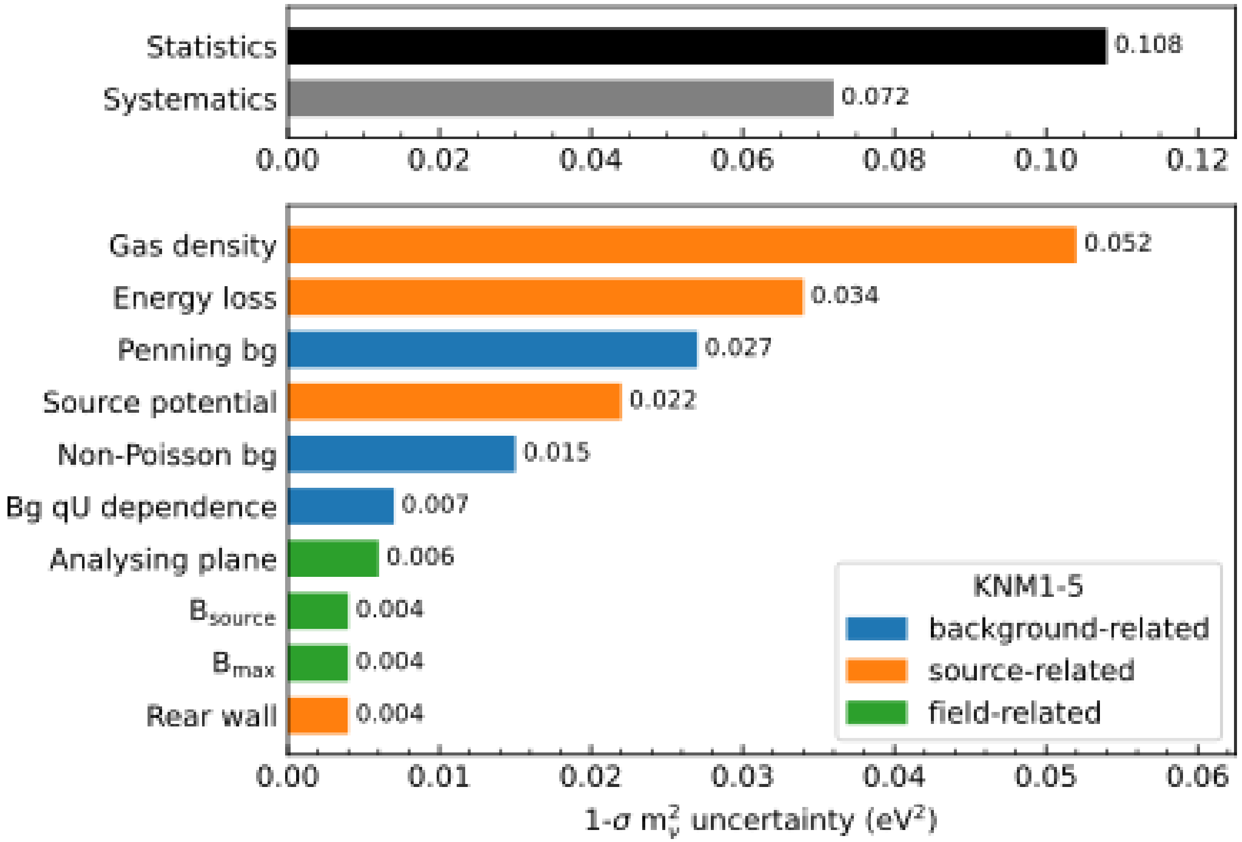
- **6-fold increase in statistics**, 2-fold reduction of background



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



› **statistical uncertainty dominates**, improved calibration precision in recent campaigns



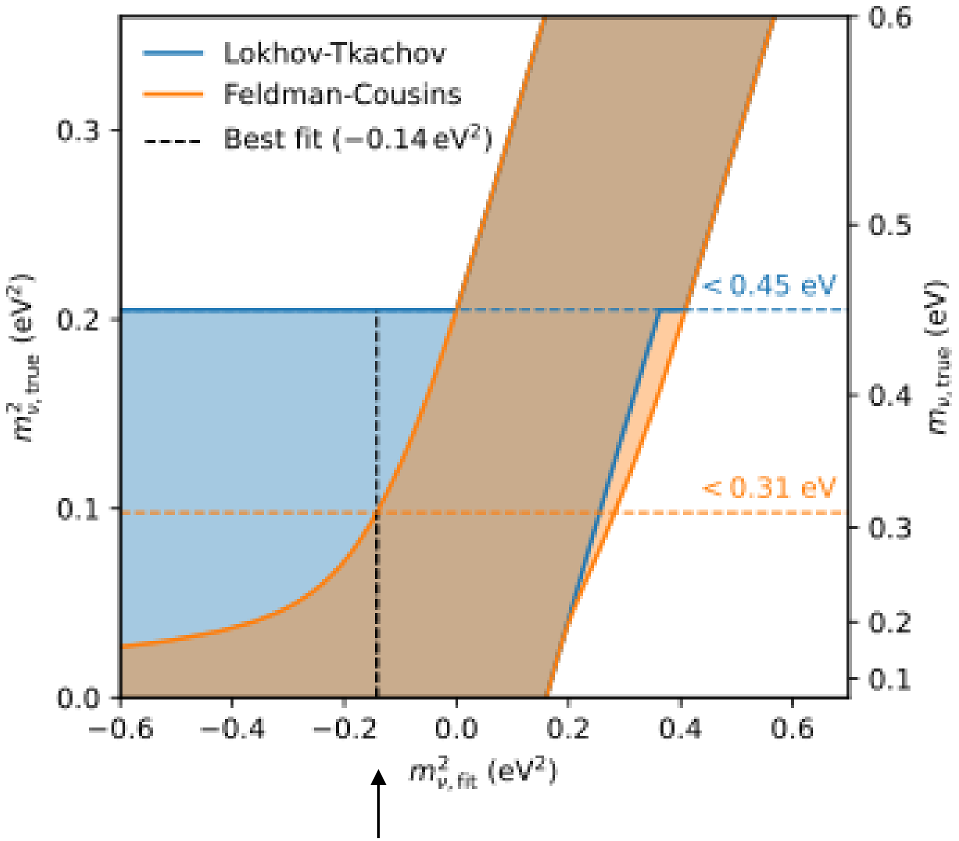
Neutrino mass limit

- new **world-best** direct neutrino mass constraint
  [Aker et al., arXiv:2406.13516]

  m_β **< 0.45 eV** (90% CL)

  using **Lokhov-Tkachov** confidence interval construction, recovers **sensitivity** for negative best-fit value
  [Lokhov, Tkachov, Phys.Part.Nucl. 46 (2015) 3, 347-365]

- Feldman-Cousins construction, benefits from negative best-fit value, m_β < 0.31 eV (90% CL)



best-fit value, i.e. $\mathbf{m_\beta^2 = -0.14\ eV^2}$

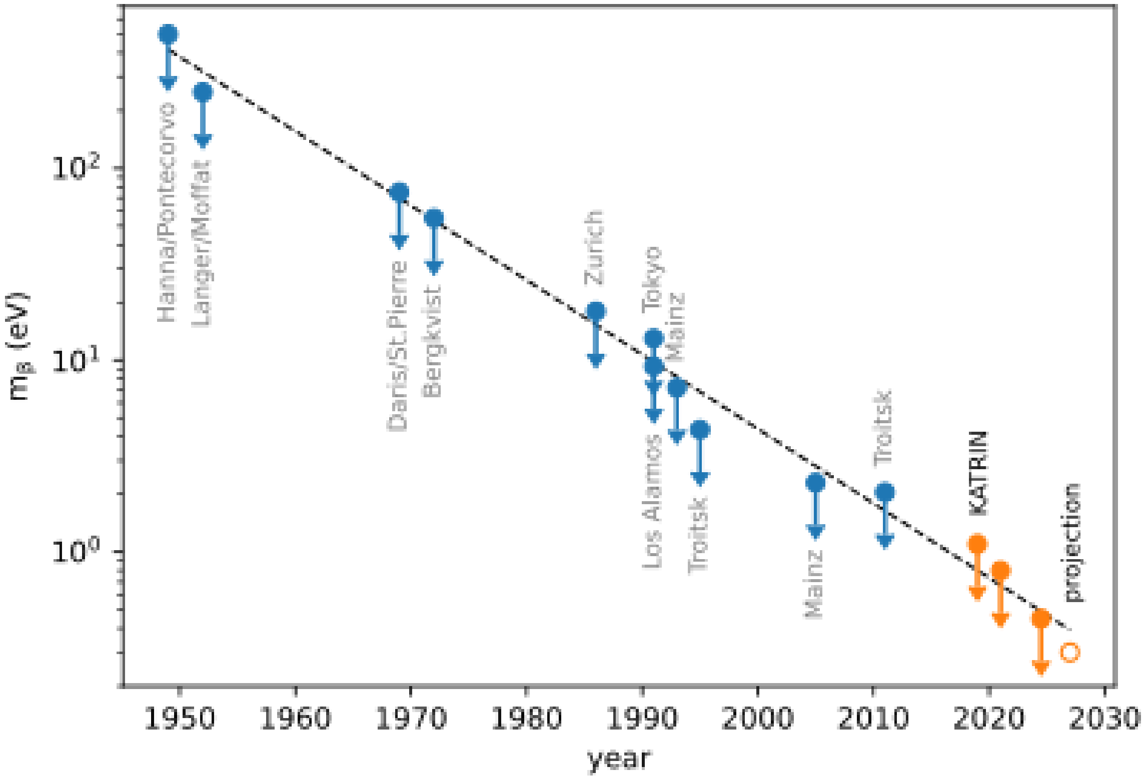
Outlook

- new **world-best** direct neutrino mass constraint
  [Aker et al., arXiv:2406.13516]

  m_β **< 0.45 eV** (90% CL)

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

  m_β **< 0.3 eV** (90% CL)



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  m_β **< 0.45 eV** (90% CL)

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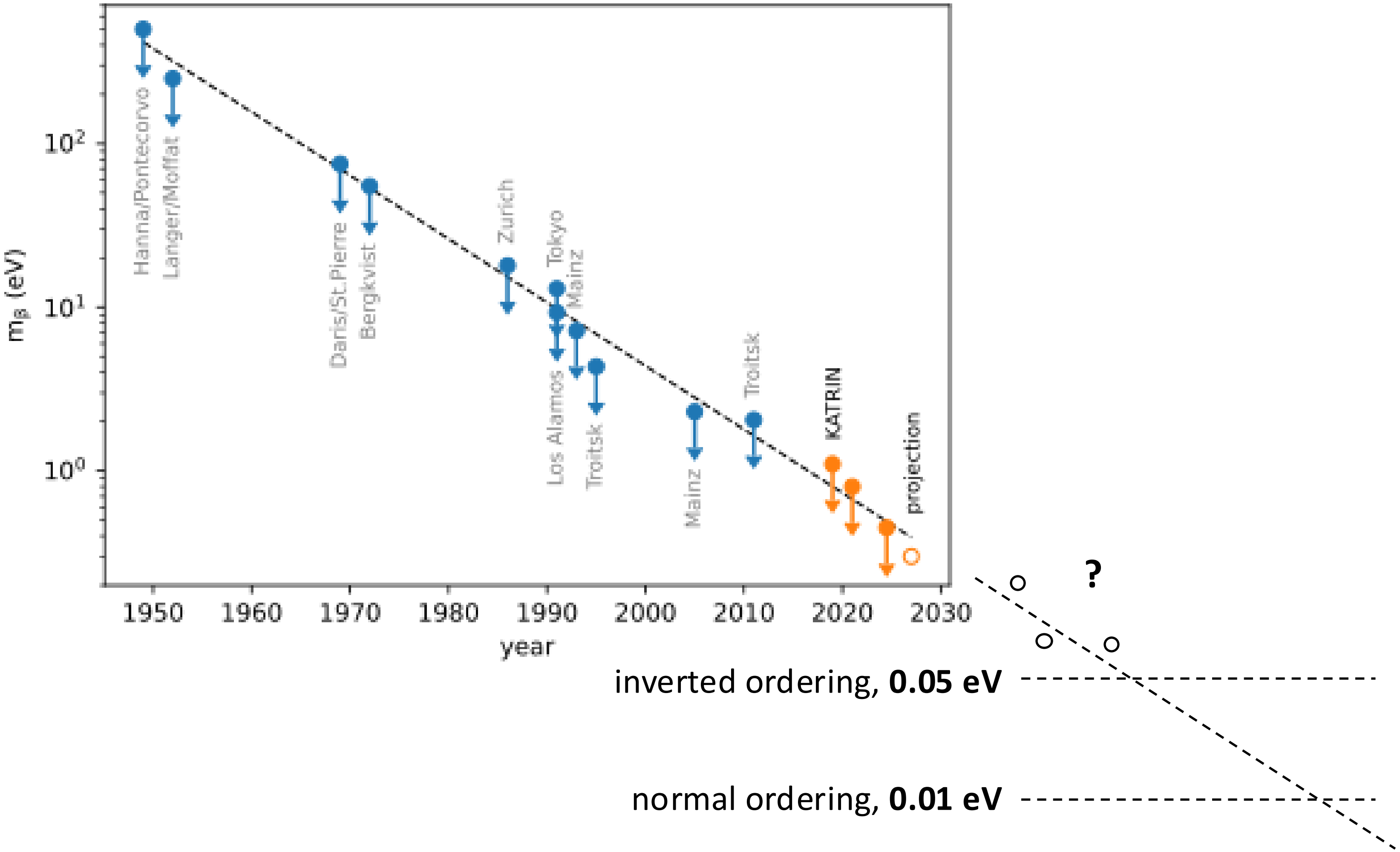
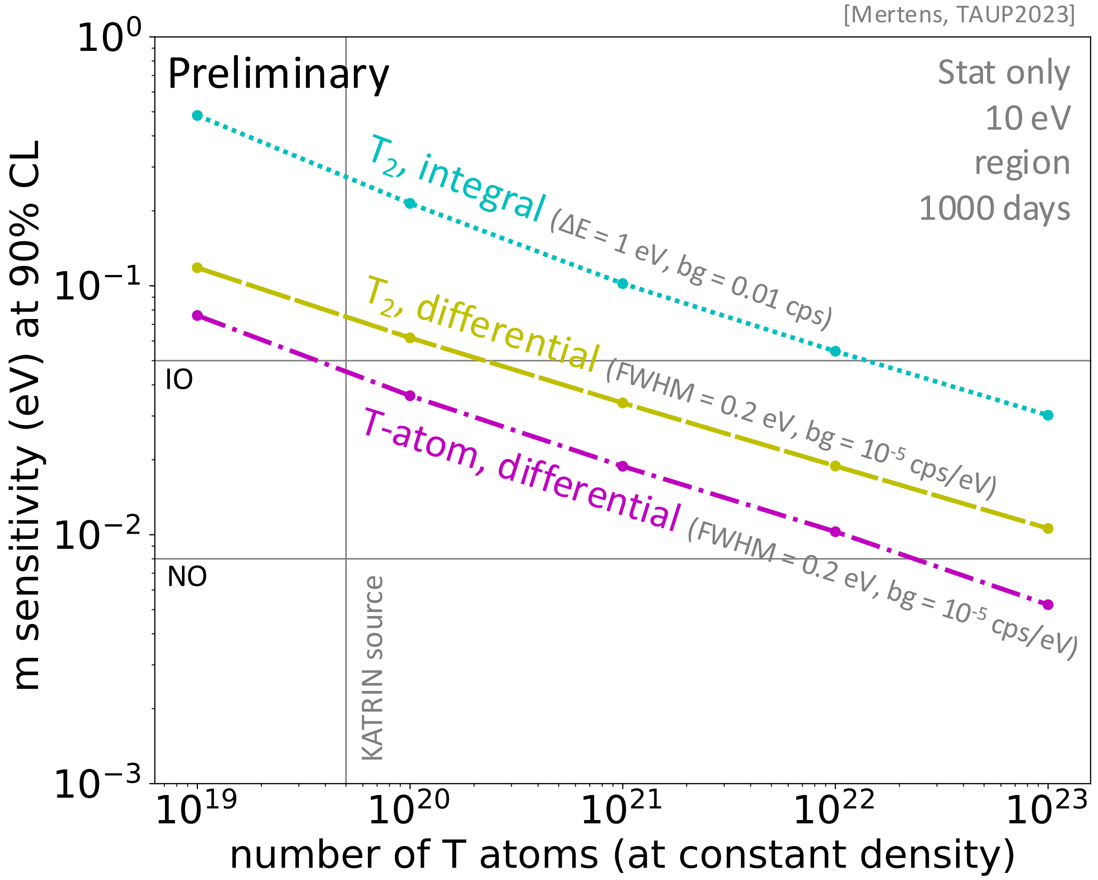
  m_β **< 0.3 eV** (90% CL)

- sensitivity beyond KATRIN requires **new technology**

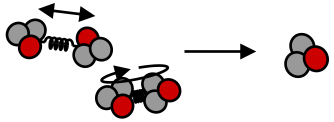
- m_β has **minimum value**, guaranteed measurement



Beyond KATRIN



- sub-eV scale **differential measurement**
  - \+ **better use of statistics**
  - \+ lower background
- **atomic tritium**

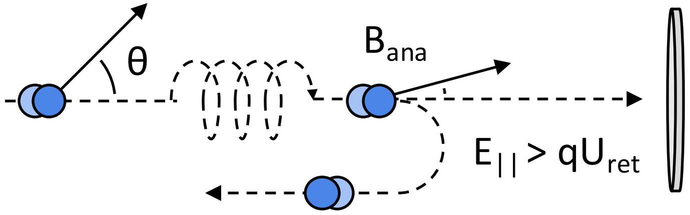


  - \+ avoid **broadening effect**
  - \+ avoid limiting T_2 systematics

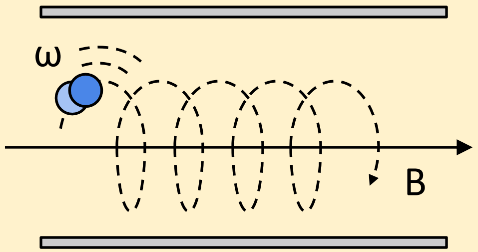
› **KATRIN++** efforts, development of micro calorimeters, time-of-flight concepts, atomic tritium technology, ..

Experimental approaches

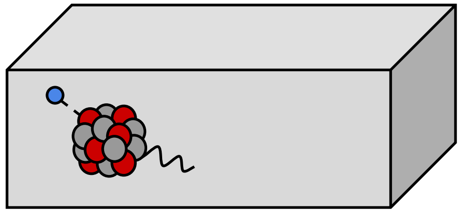
tritium



electrostatic
filtering (MAC-E)



cyclotron radiation emission
spectroscopy (CRES)



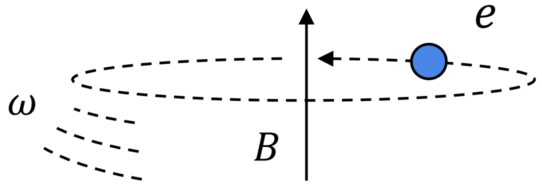
cryogenic
calorimetry

R&D

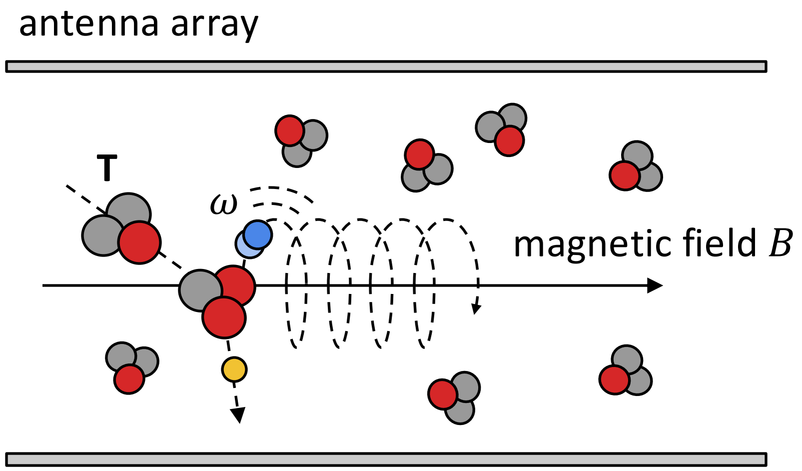
Cyclotron radiation emission spectroscopy (CRES)

- **electromagnetic radiation** emitted by charged particles undergoing **cyclotron motion**

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

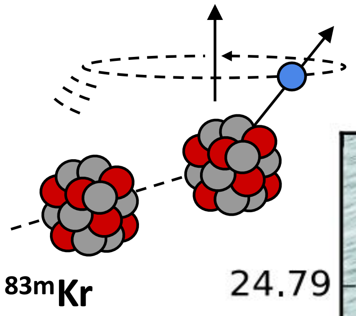


› measure **cyclotron frequency** of **trapped electron** to determine energy
[Monreal, Formaggio, PRD 80 (2009) 051301]

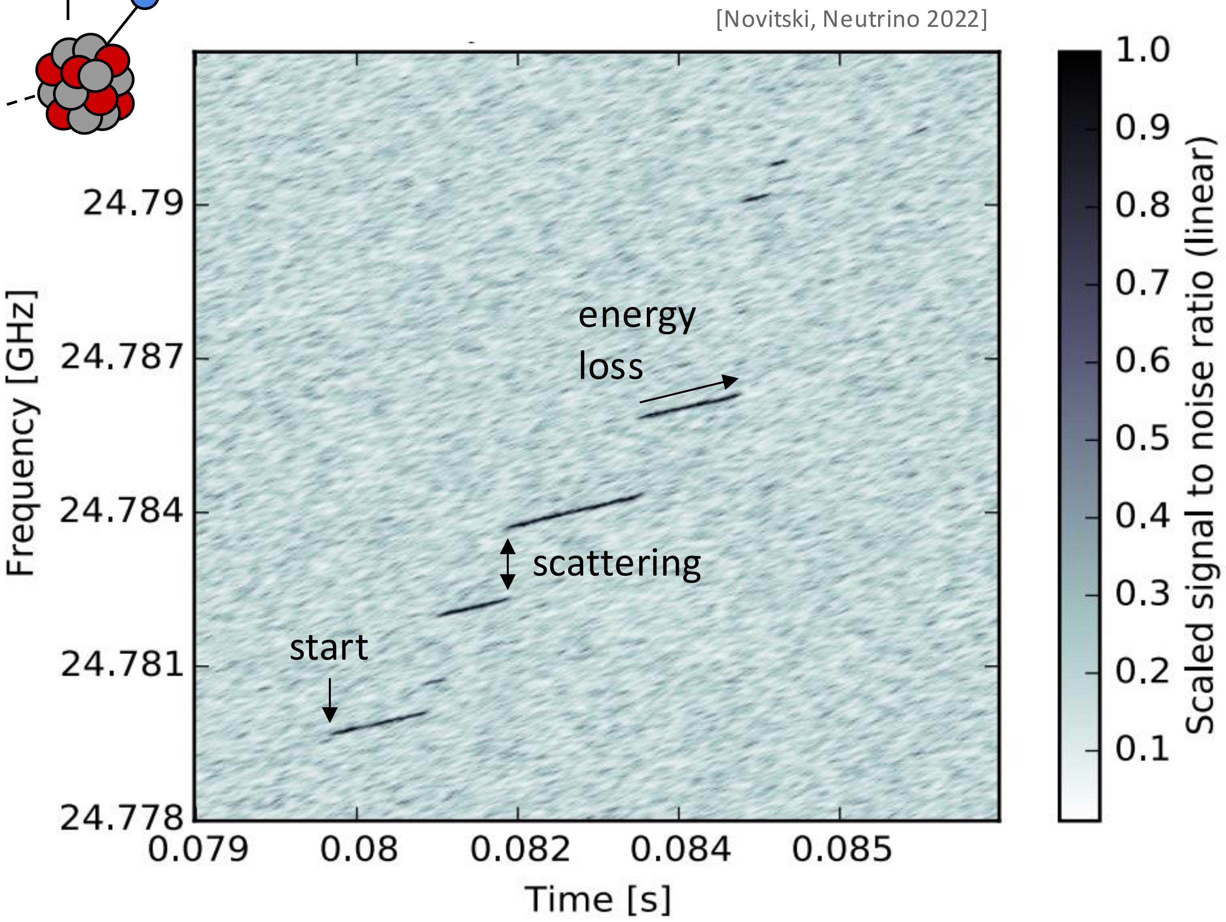


Cyclotron radiation emission spectroscopy (CRES)

- **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)

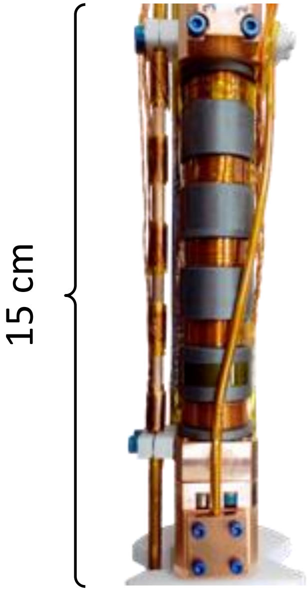
Project8

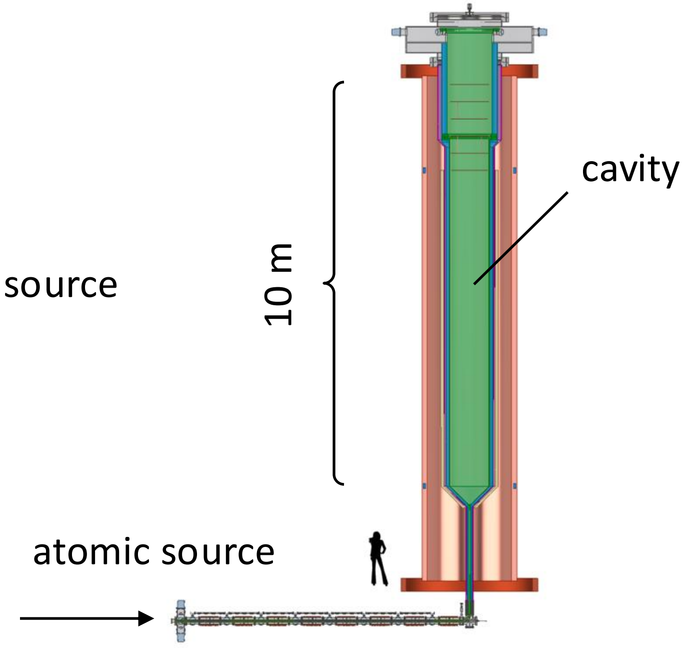
- **cold** atomic tritium **trap**, resonant **cavity**
- **proof-of-concept**, single electron spectroscopy
- molecular tritium **endpoint measurement**, first neutrino mass result
  [Ashtari Esfahani et al., PRL 131 (2023) 10, 102502]

m_β **< 155 eV** (90% CL)

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

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





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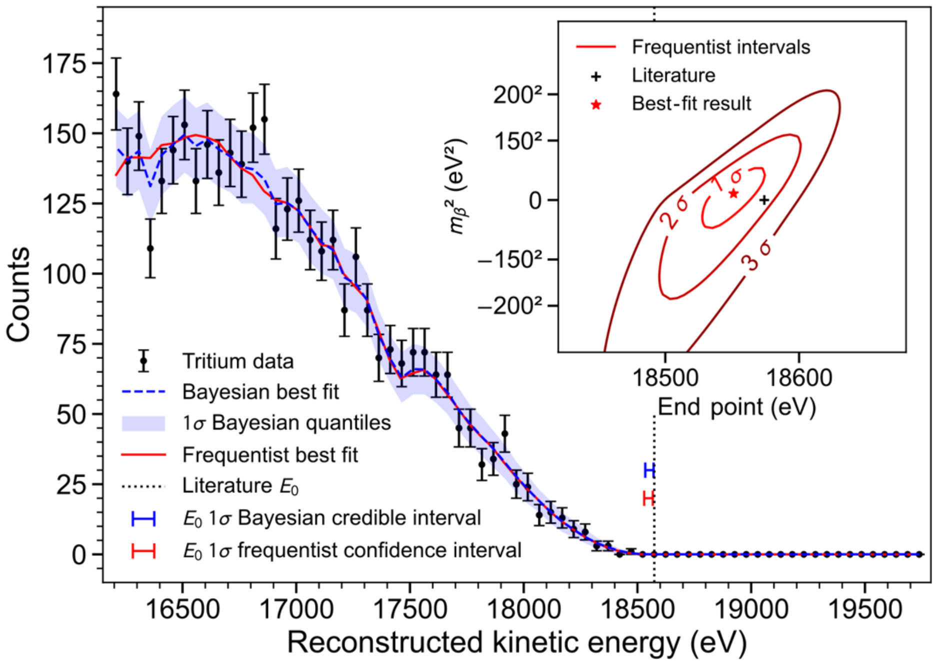

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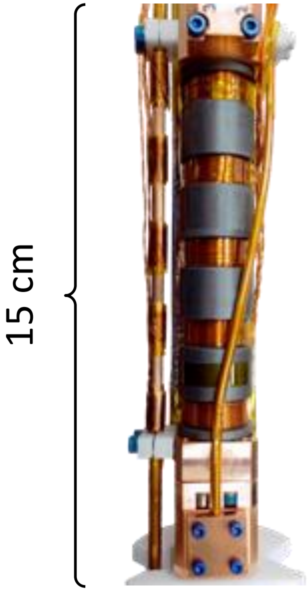

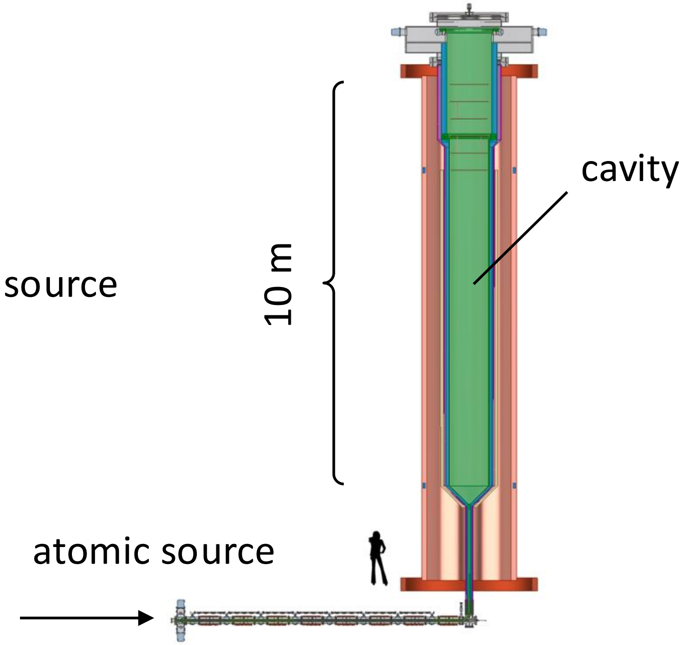

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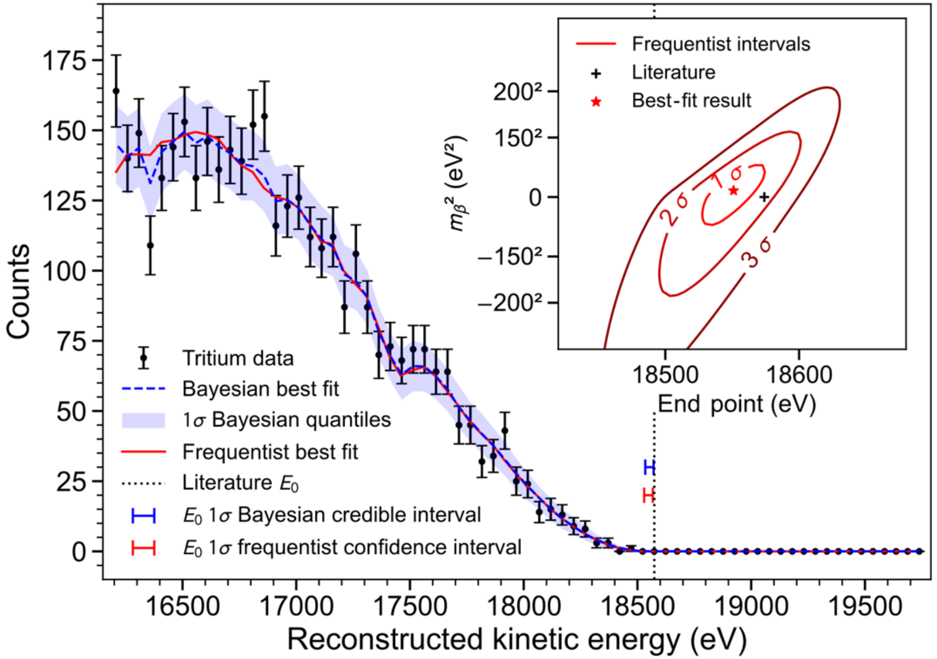
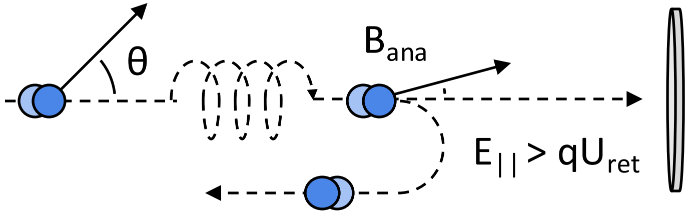


QTNM

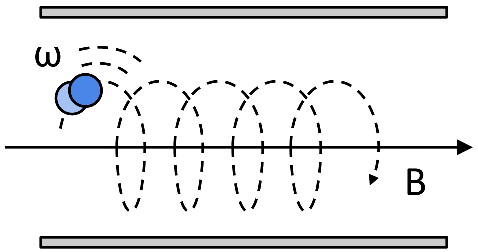
- **storage ring** confinement, quantum limited micro-wave electronics
- in **conceptual stage**

Experimental approaches

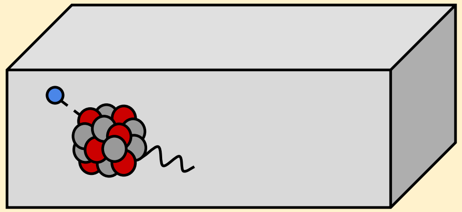
tritium



electrostatic
filtering (MAC-E)



cyclotron radiation emission
spectroscopy (CRES)



cryogenic
calorimetry

R&D

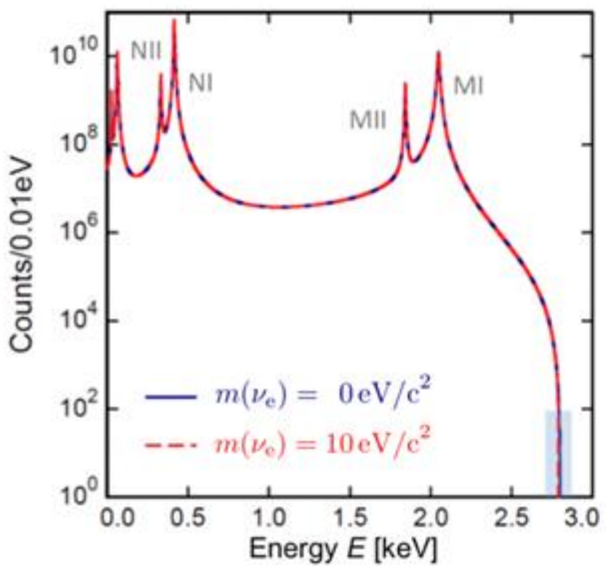
Holmium-163

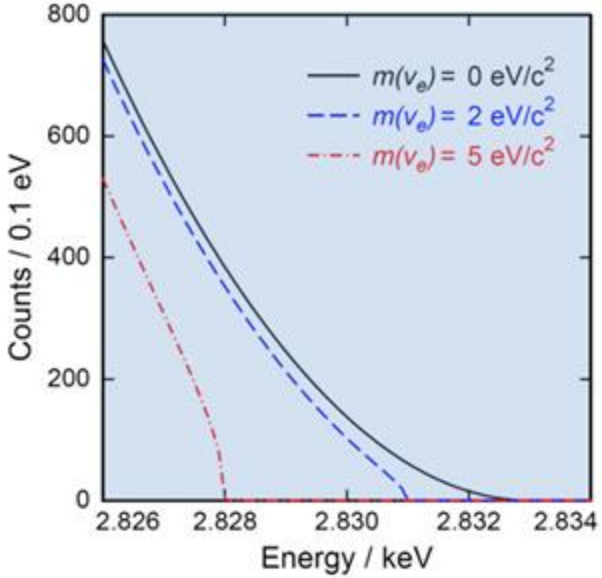
- **electron capture** decay, energy shared between **excitation** and neutrino

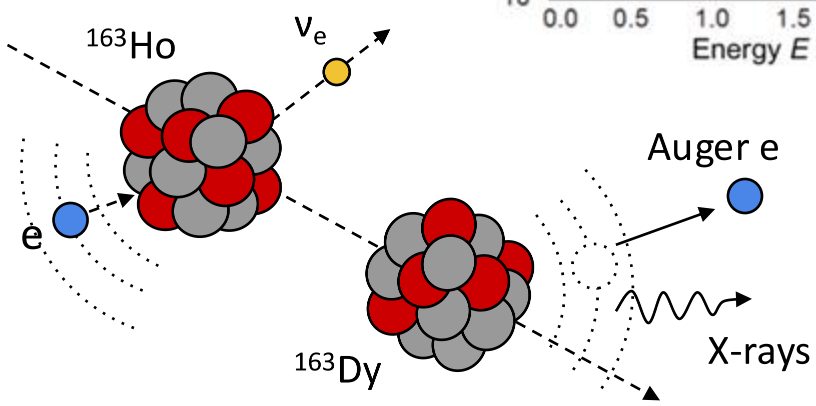
- super-low **Q-value** (2.8 keV), **sub-eV** sensitivity with **MBq-scale activity**
  [Eliseev et al., PRL 115 (2015) 6, 062501]

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

[Gastaldo, Neutrino 2022]







Cryogenic calorimetry

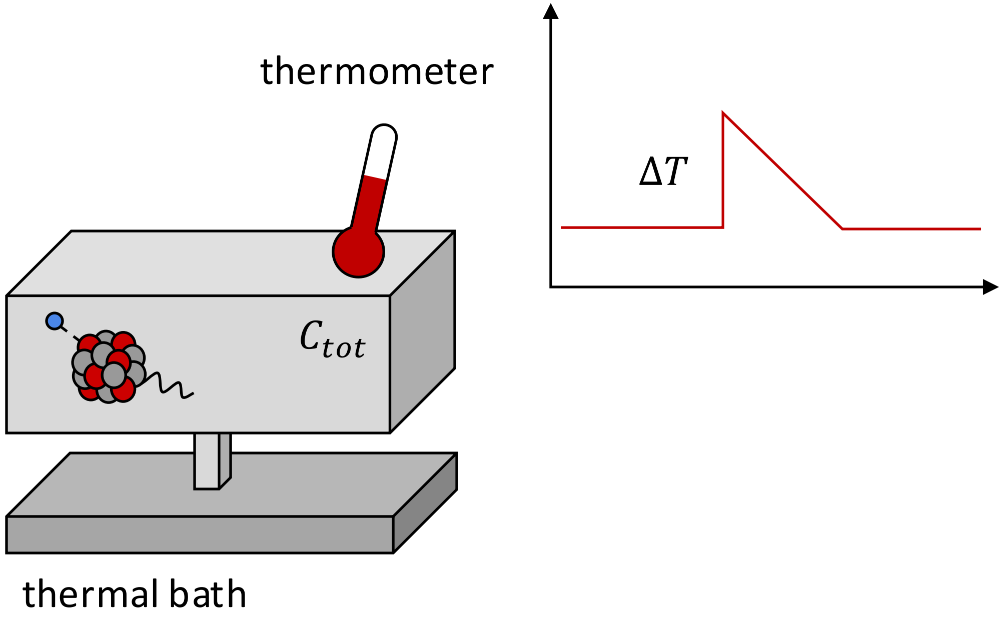
- **holmium implanted** in absorber with **small heat capacity** C_{tot}

› 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

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

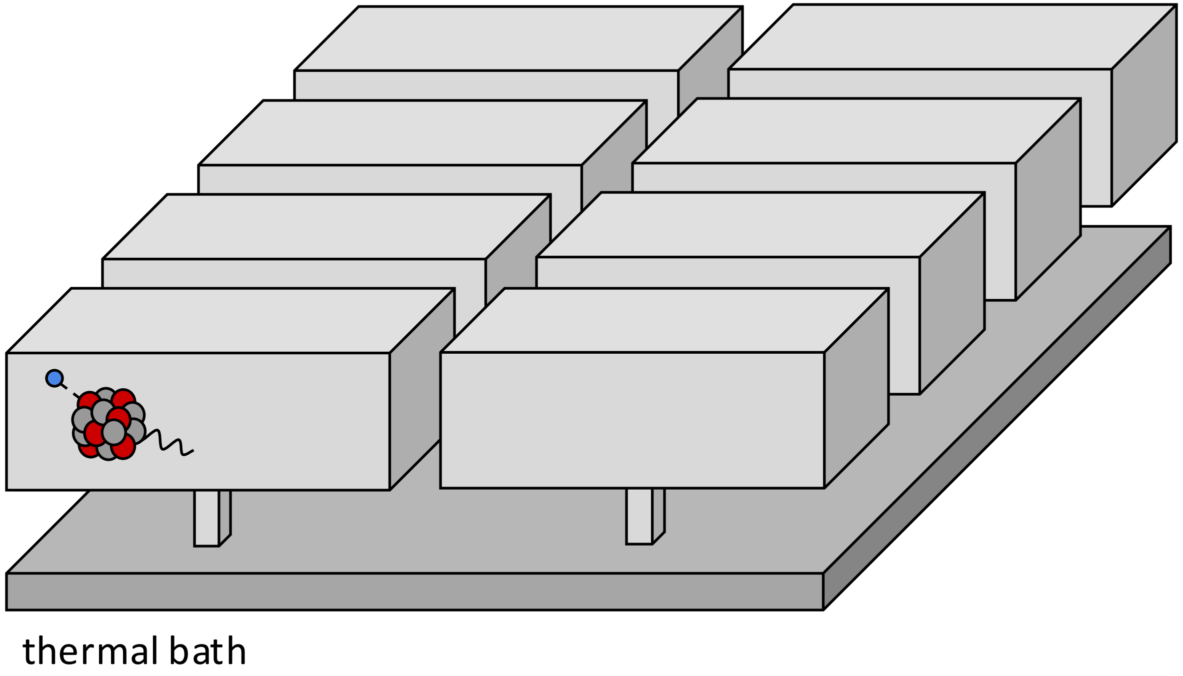


Cryogenic calorimetry

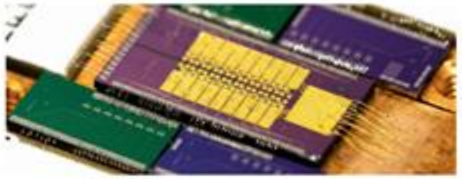
- **source = detector** concept, all decay energy is measured
- **eV-scale differential** measurement

challenges

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



ECHO



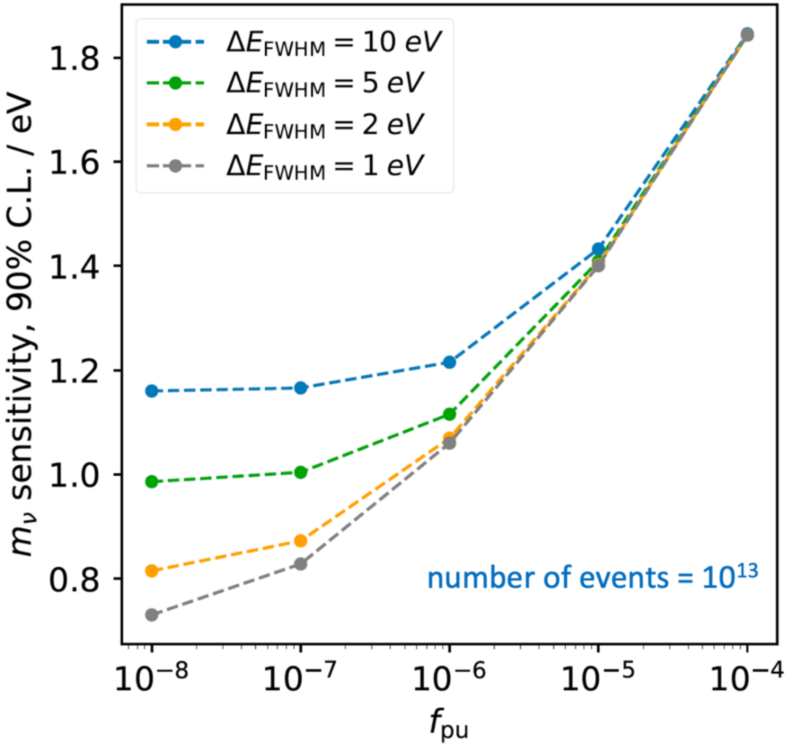
- array of **metallic magnetic calorimeters** (MMC) with ^{163}Ho-implanted absorber
- first **neutrino mass result**, 4 pixels with 0.2 Bq each m_β < 150 eV (95% CL)
  [Velte et al., EPJ C 79 (2019) 12, 1026]
- **second result**, 34 pixels with 0.7 Bq each m_β **< 19 eV** (90% CL)
  [Neutrino 2024]

HOLMES

- array of **transition edge sensors** (TES) coupled to ^{163}Ho-implanted absorber
- **first result**, 48 pixels with 0.3 Bq each m_β **< 28 eV** (90% CI)
  [Neutrino 2024]

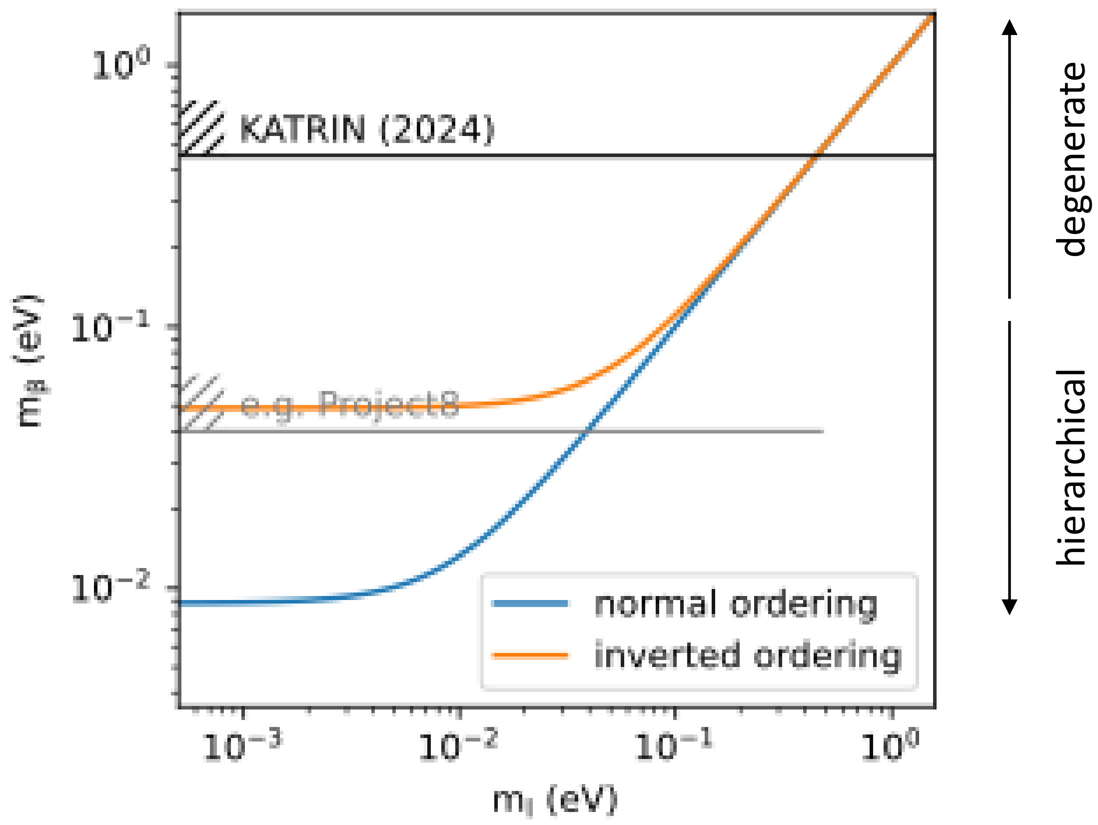
sensitivity for **coming phases** of ECHO/HOLMES:

[Gastaldo, TAUP 2023]



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

[NuFIT 5.3, nu-fit.org]

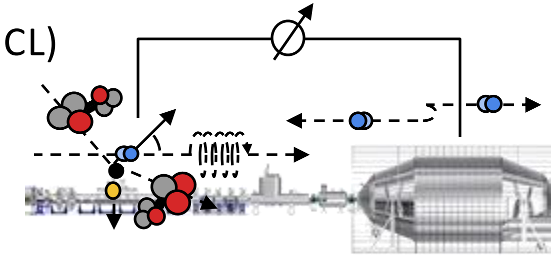


- minimum at **0.01 eV** (normal ordering), **0.05 eV** (inverted ordering)

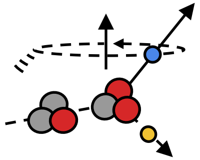
- most stringent bound by KATRIN, first five campaigns
  [Aker et al., arXiv:2406.13516]

  m_β **< 0.45 eV** (90% CL)

  and **data taking** is ongoing



- promising technologies for **future experiments**, differential detectors (e.g. CRES, cryogenic calorimeters), atomic tritium, holmium, ..
  [Ashtari Esfahani et al., arXiv:2203.07349]



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

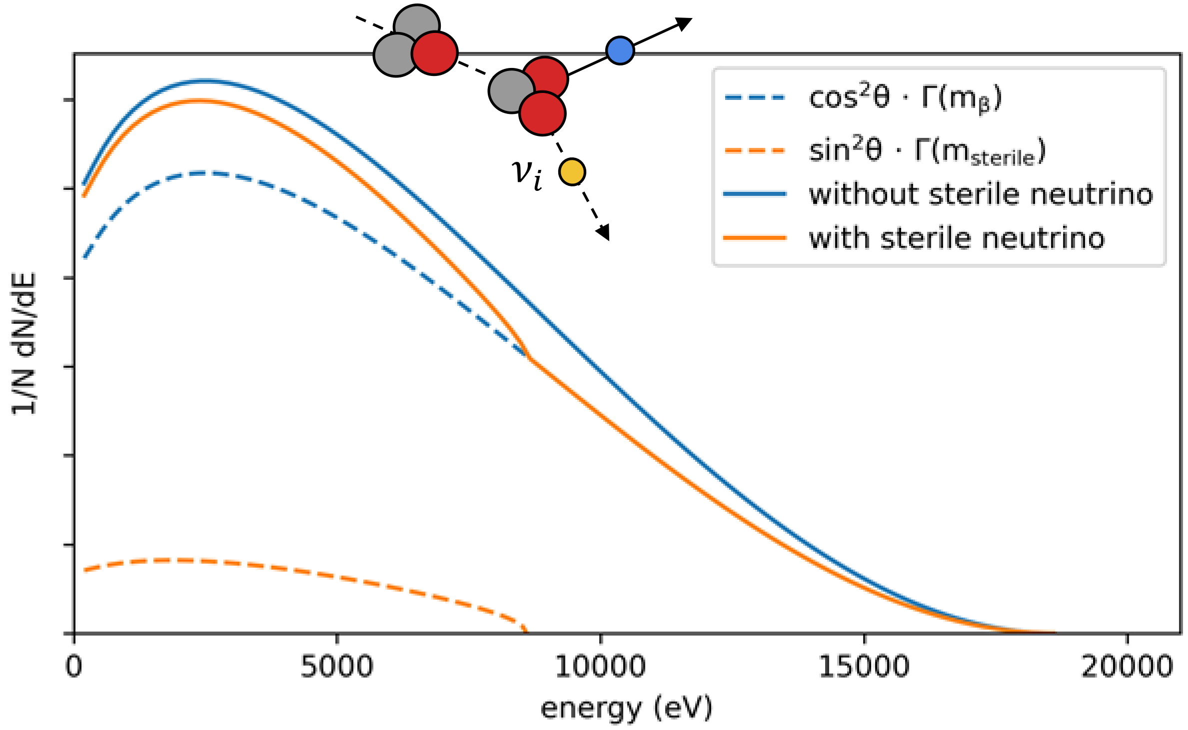
Side note: sterile neutrinos

Thierry Lasserre's lecture

- 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** with KATRIN
  [Aker et al., PRD 105 (2022) 7, 072004]

- deep spectral exploration to search for **keV-sterile neutrinos** with **TRISTAN upgrade** of KATRIN, silicon drift detector array
  [Mertens et al., J.Phys.G 46 (2019)]

Side note: relic neutrinos

- cosmic neutrino background (**CvB**)

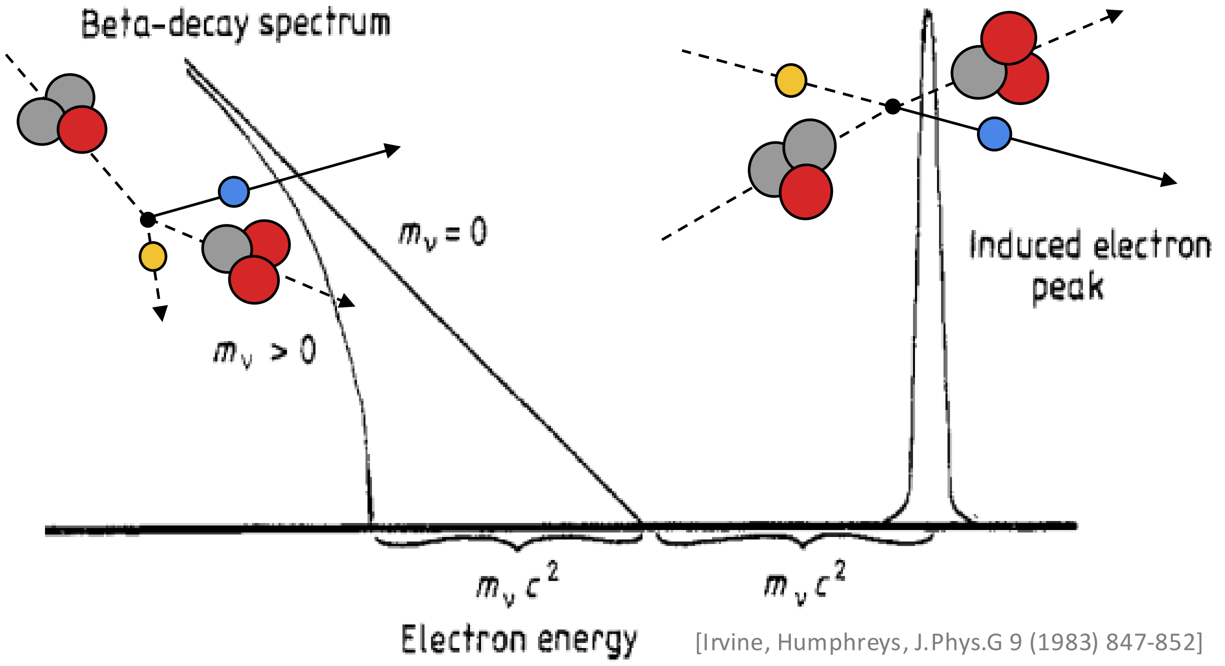
$$\rho_{C\nu B} = 300\ cm^{-3} \text{ and } T_{C\nu B} = 1.95\ \text{K}$$

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

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

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

- capture rate doubles for Majorana neutrinos (see tomorrow)



[Irvine, Humphreys, J.Phys.G 9 (1983) 847-852]

- ~10 µg KATRIN target, constraint on **local overdensity**
  [Aker et.al, PRL 129 (2022) 1, 011806]

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

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

PTOLEMY

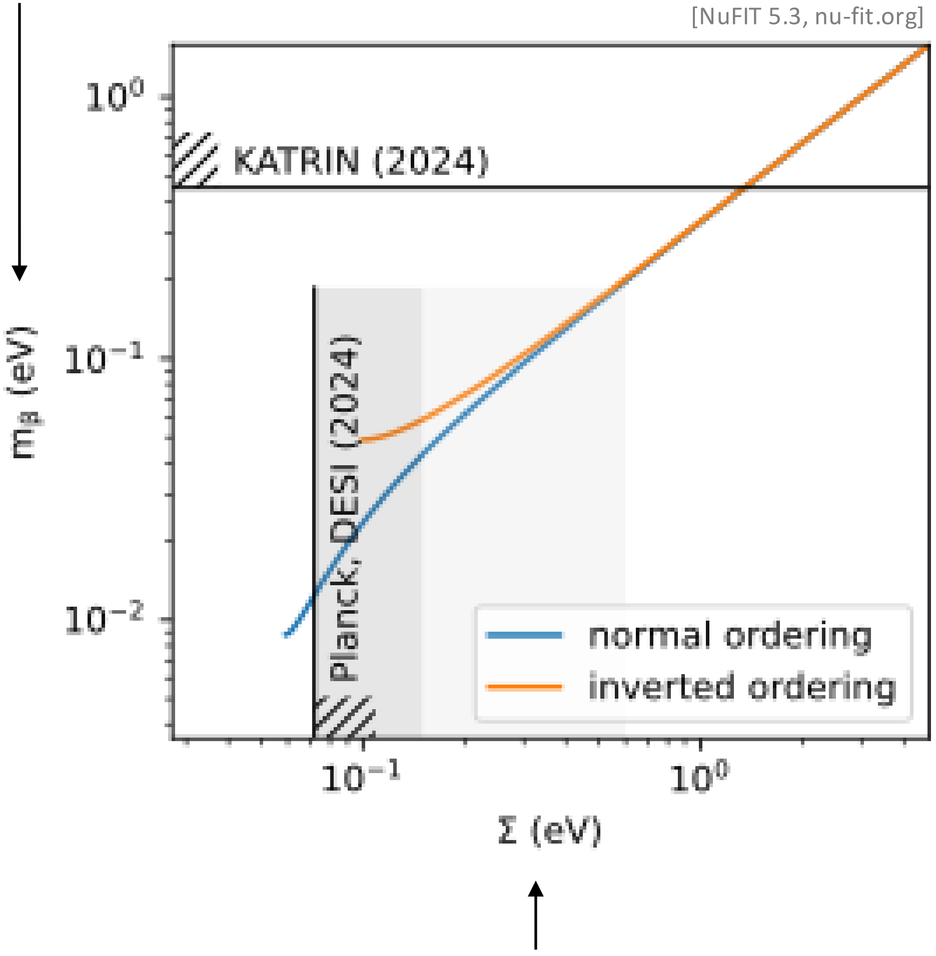
- monoatomic tritium in **graphene matrix**, **cyclotron emission** tagging, dynamic **electromagnetic filter**, micro **calorimeters**
  [Betti et al., Prog.Part.Nucl.Phys. 106 (2019) 120-131]

Interplay with cosmology

- β-decay kinematics offers **model-independent laboratory test** of absolute neutrino mass
- **complementary** to cosmological probes

› interplay will allow **model discrimination**

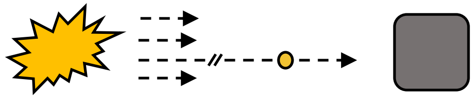
energy conservation



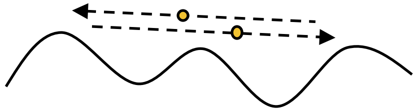
cosmological model

Neutrino mass probes

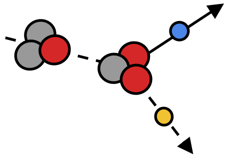
- **Supernovae**, time-of-flight



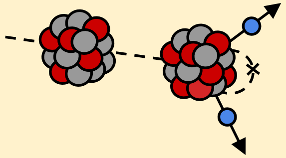
- **Cosmology**



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



- Neutrinoless **double beta decay**



Take away

- How can we measure the **absolute neutrino mass**?
  supernovae, cosmology, beta decay, neutrinoless double beta decay
- What is a **direct neutrino mass measurement**?
  neutrino mass experiment relying on beta decay kinematics
- Which **neutrino mass observable** are we probing?
  incoherent sum of mass eigenstates, effective electron neutrino mass
- What are the **experimental challenges**?
- How does the **KATRIN experiment** work?
- Where are **current bounds**? Where is the minimum value?

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Backup