Direct neutrino mass measurements - 

Christoph Wiesinger (TUM, MPP), FPCapri, 12.06.2022

Neutrino Mass | KATRIN | Project 8 | ECHo / HOLMES | Outlook *"for the discovery of neutrino oscillations, which shows that*

Neutrinos have mass"

[Kajita, McDonald, Nobel Prize in Physics 2015]

- flavor eigenstates are **linear combinations** of mass eigenstates

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

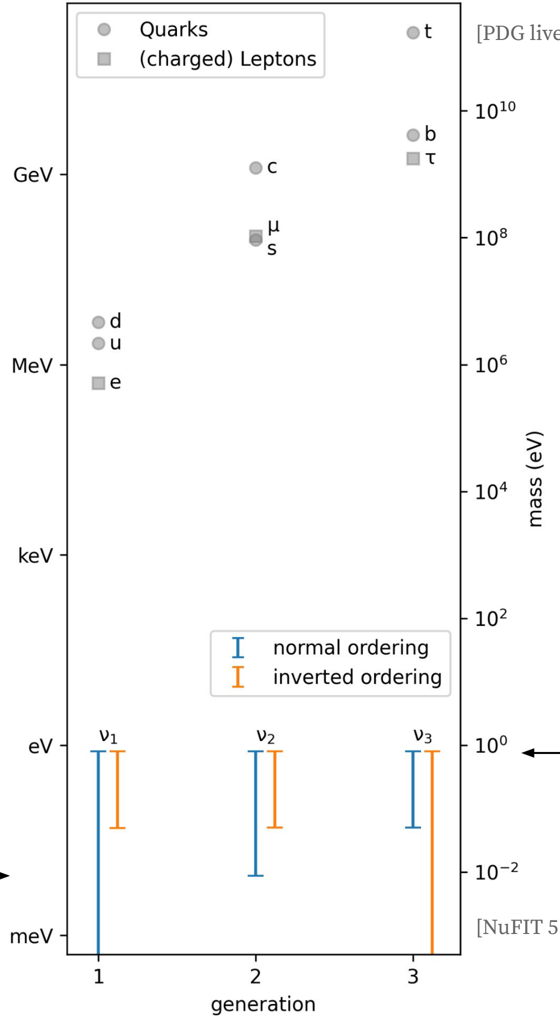
- mass squared differences

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

➔ **neutrino oscillations**

- mass mechanism, **absolute mass** and mass ordering **unknown**

lower bounds from oscillation experiments



[PDG live, pdglive.lbl.gov]

upper bound from direct measurements

[NuFIT 5.1, nu-fit.org]

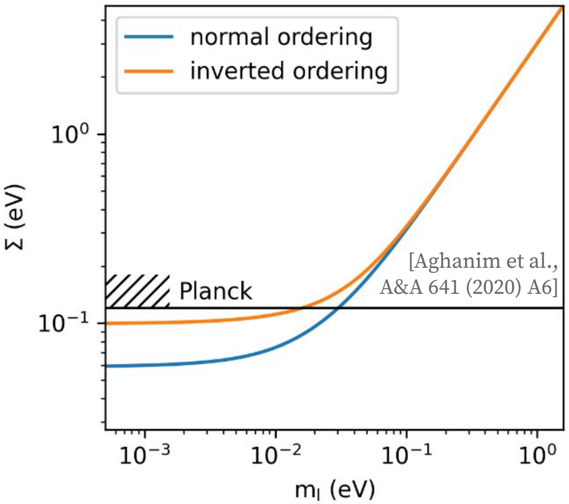
Mass observables

laboratory-based

cosmology

$$\Sigma = \sum_i m_i$$

[NuFIT 5.1, nu-fit.org]



model-dependent

Mass observables

laboratory-based

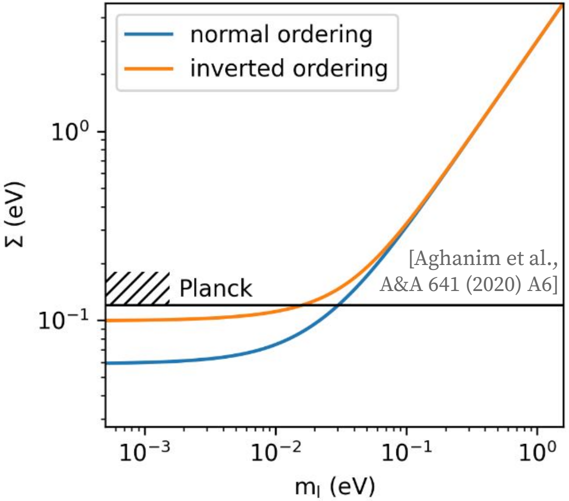
cosmology

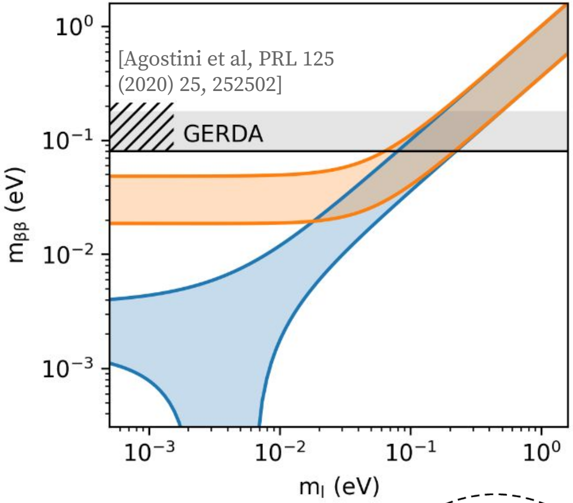
neutrinoless ββ-decay

$$\Sigma = \sum_i m_i$$

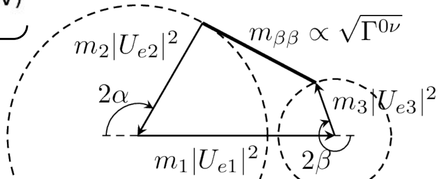
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

[NuFIT 5.1, nu-fit.org]





model-dependent



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

Mass observables

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cosmology

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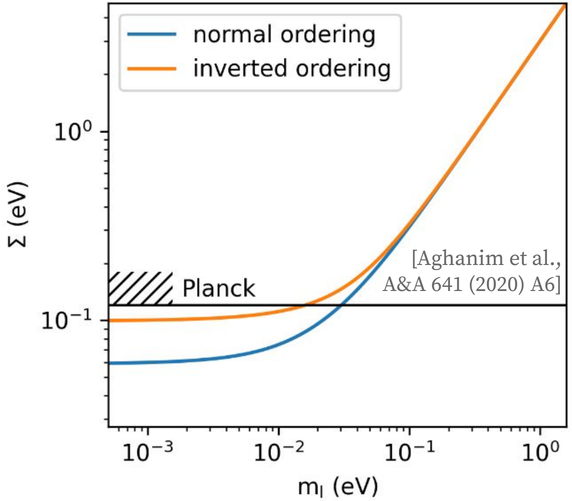

neutrinoless ββ-decay

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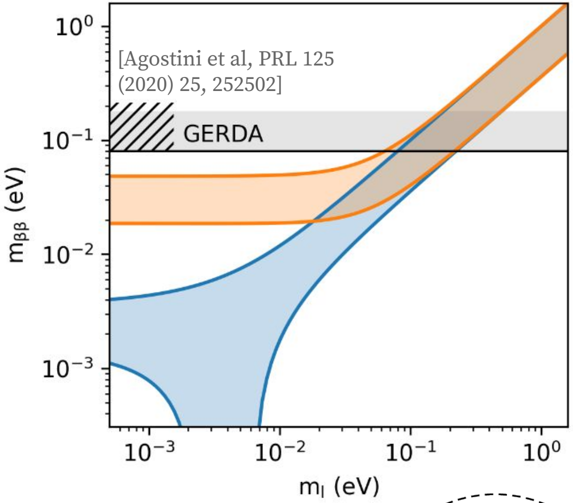
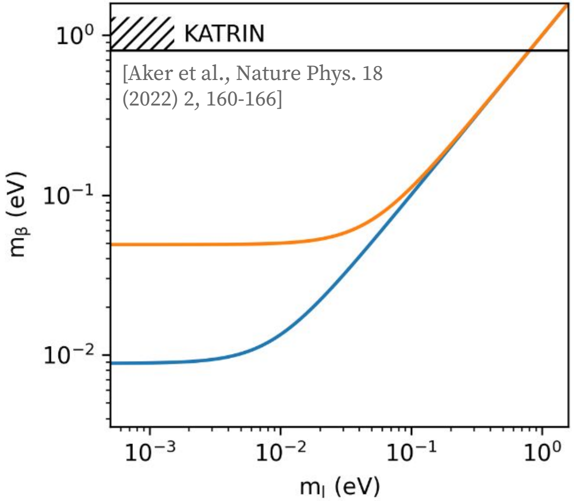
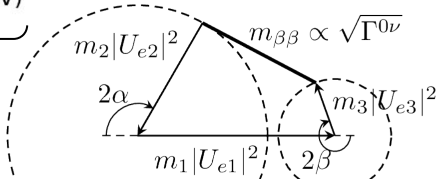


β-decay kinematics

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



model-dependent



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

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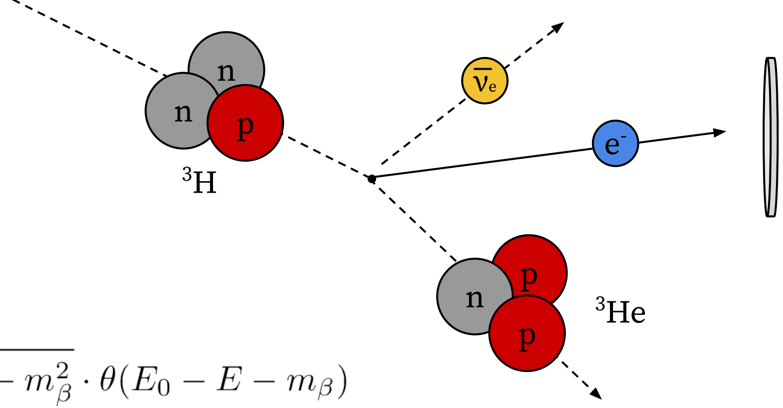
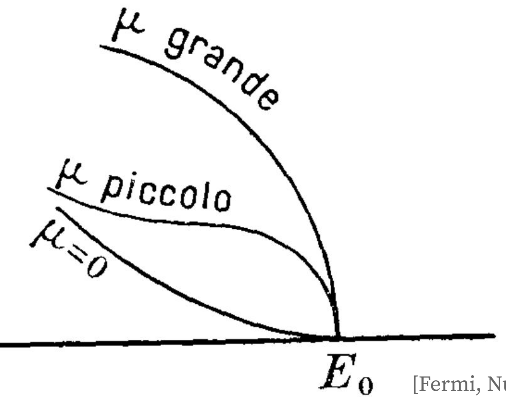


- **spectral distortion**, maximal at **endpoint** energy E_0

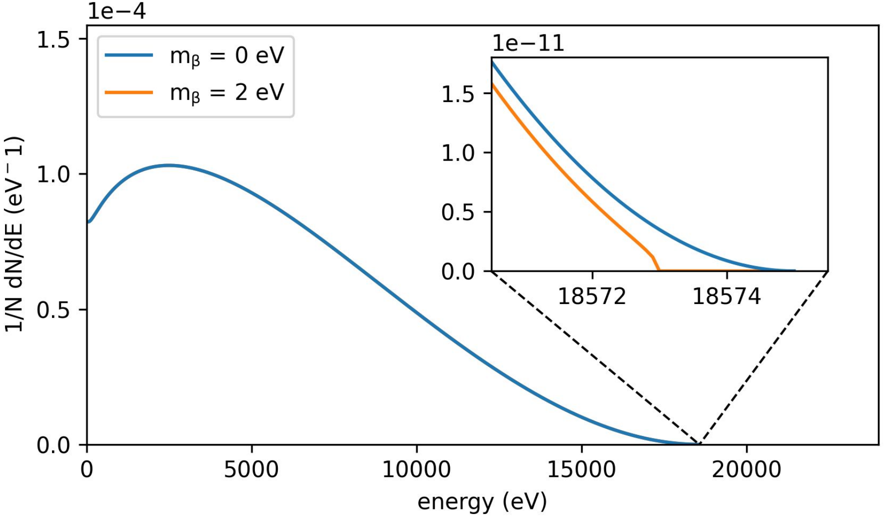
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \propto F(E,Z)\cdot p\cdot(E+m_e)\cdot(E_0-E)\cdot\sqrt{(E_0-E)^2-m_\beta^2}\cdot\theta(E_0-E-m_\beta)$$

- purely based on **kinematics** and **energy conservation**

➔ independent on neutrino nature



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



Experimental challenges

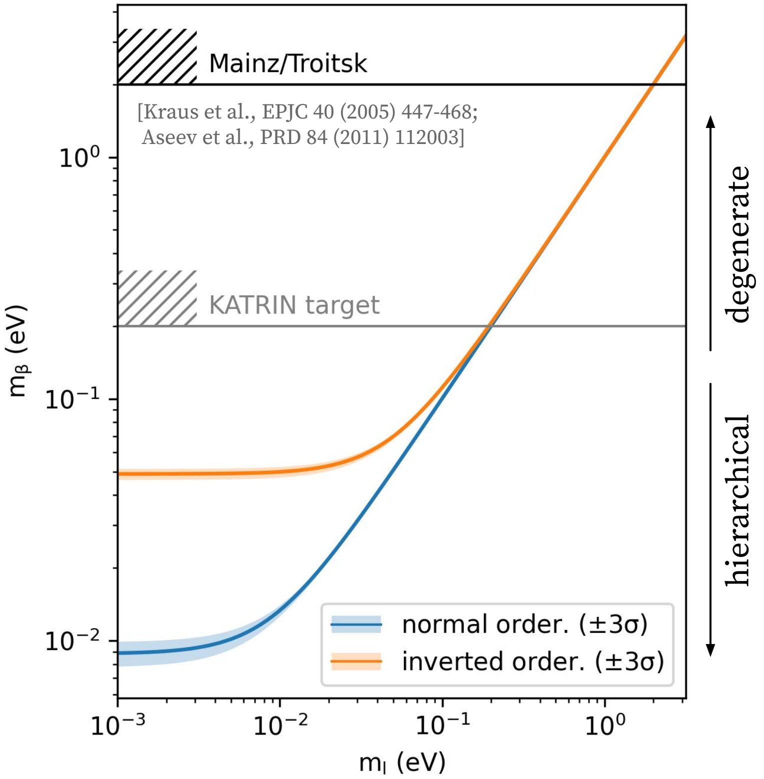
- **high activity** radioactive source, **low Q-value**

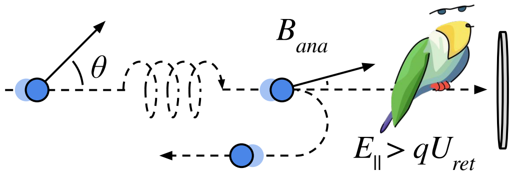
➔ **tritium** ^{3}H ($T_{1/2}$ = 12.3 yr, E_0 = 18.6 keV),
holmium ^{163}Ho ($T_{1/2}$ = 4570 yr, E_0 = 2.8 keV)

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

- **current:** Karlsruhe Tritium Neutrino (**KATRIN**) experiment, probe **degenerate** scale
- **future**: resolve **normal** vs. **inverted** ordering

[NuFIT 5.1, nu-fit.org]

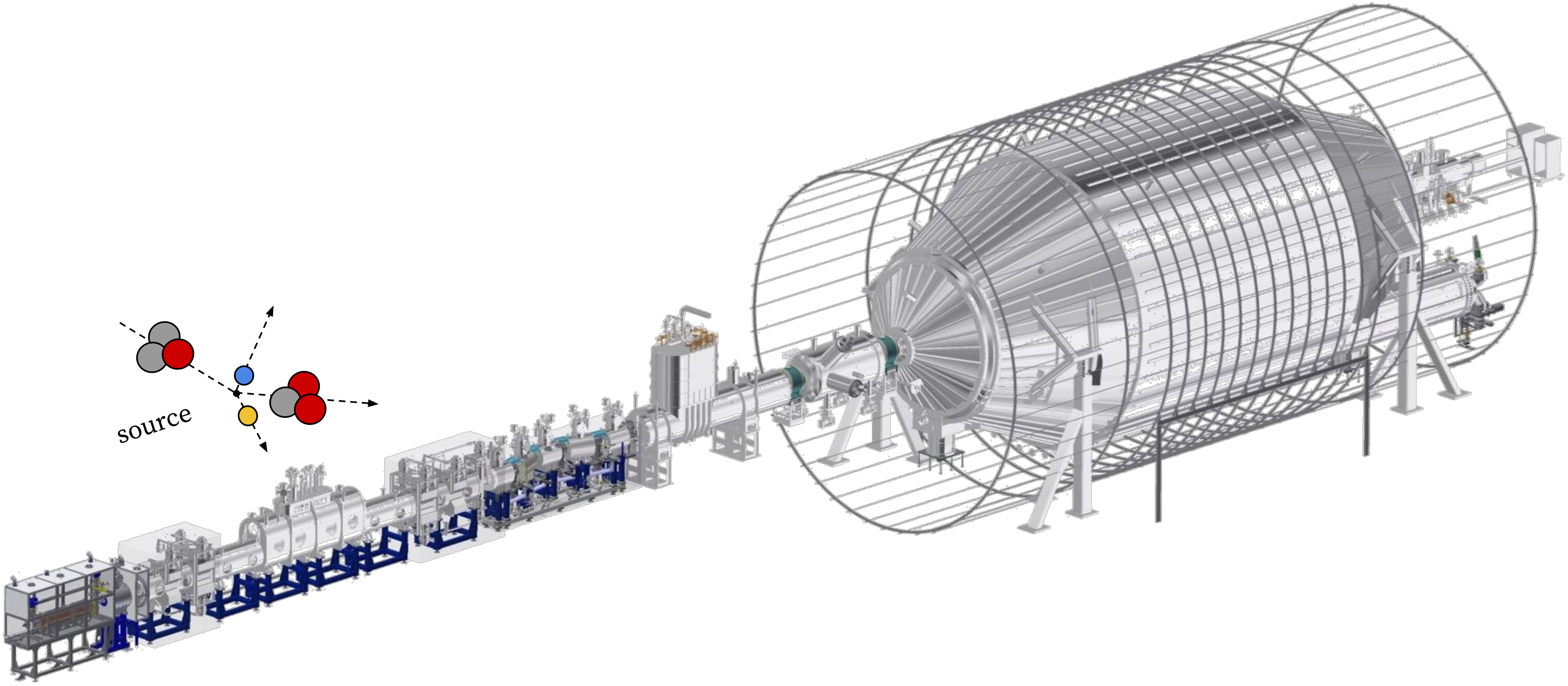




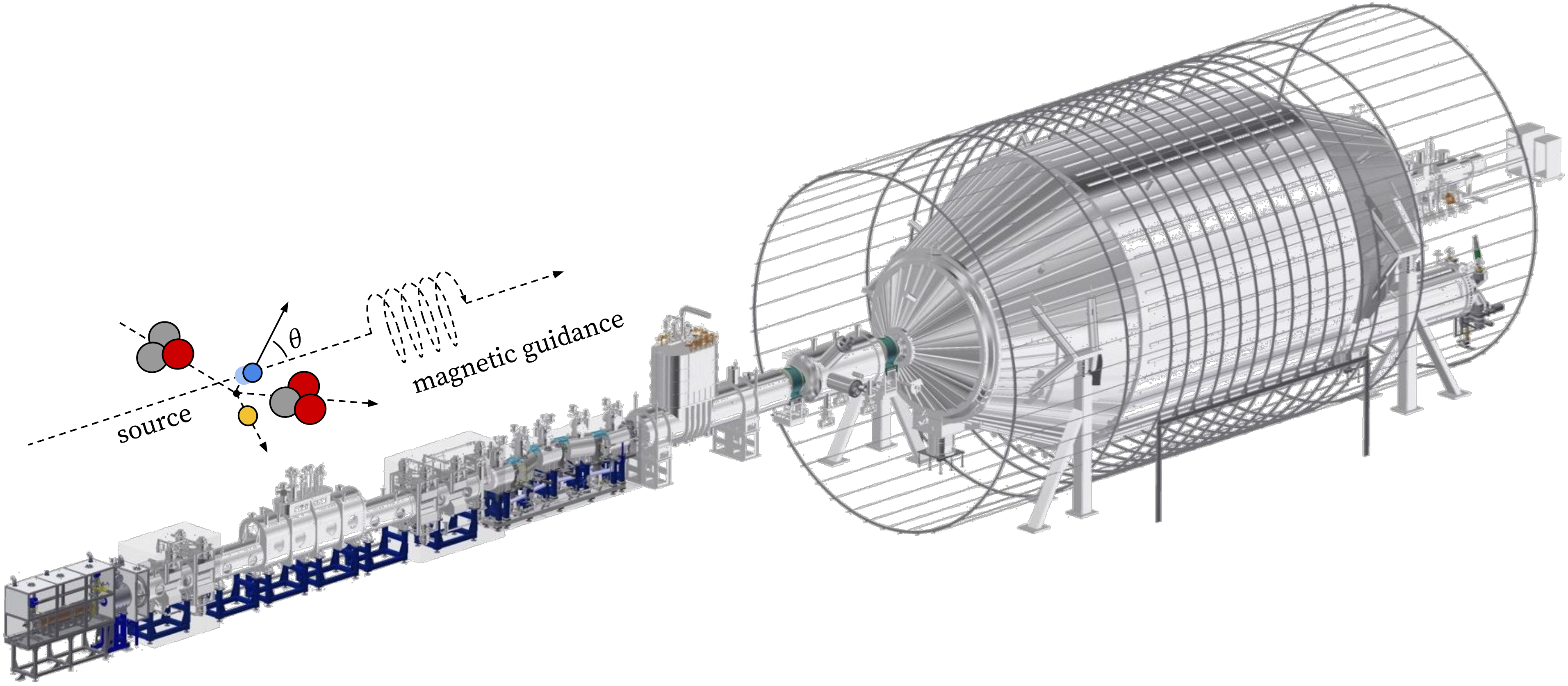
Neutrino Mass | **KATRIN** | Project 8 | ECHo / HOLMES | Outlook

Enter KATRIN

Working principle



Working principle



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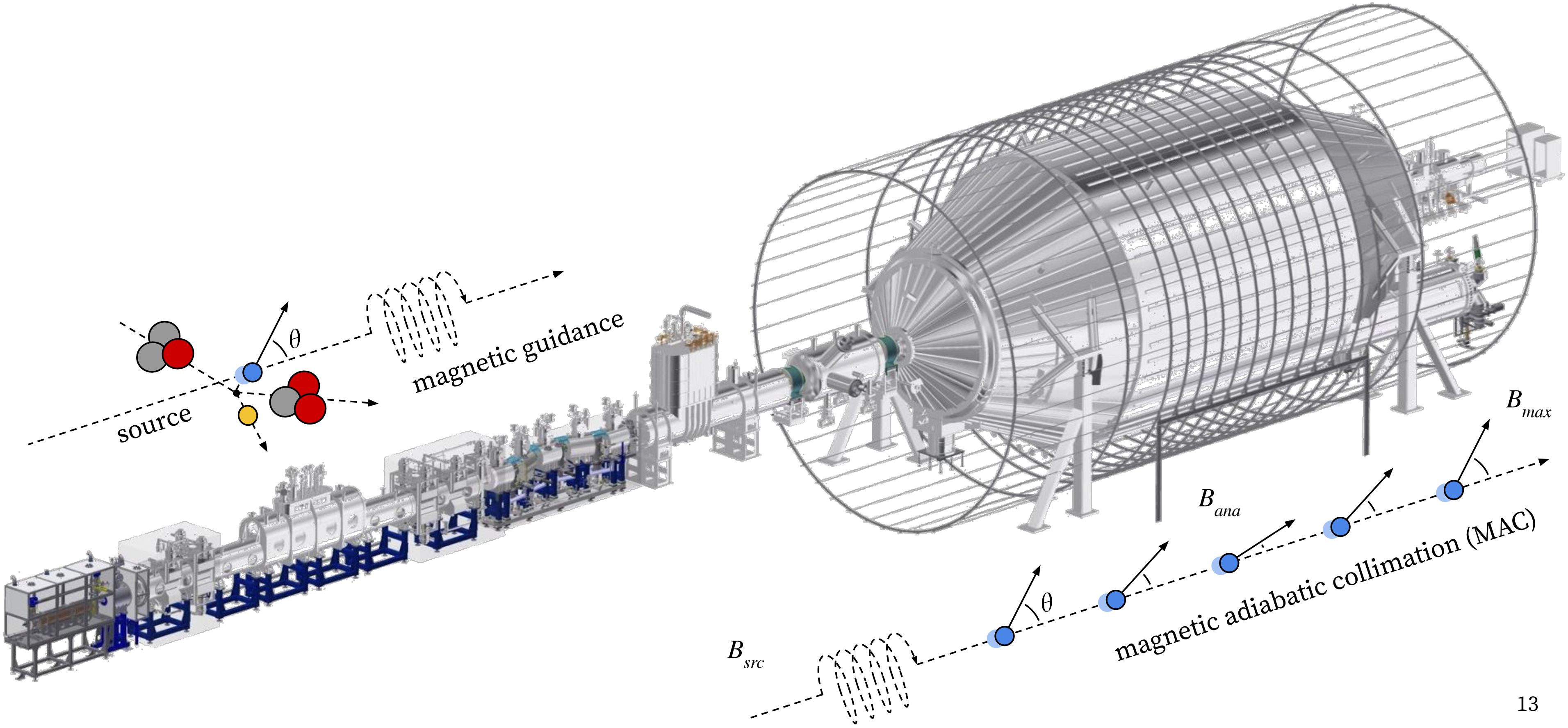

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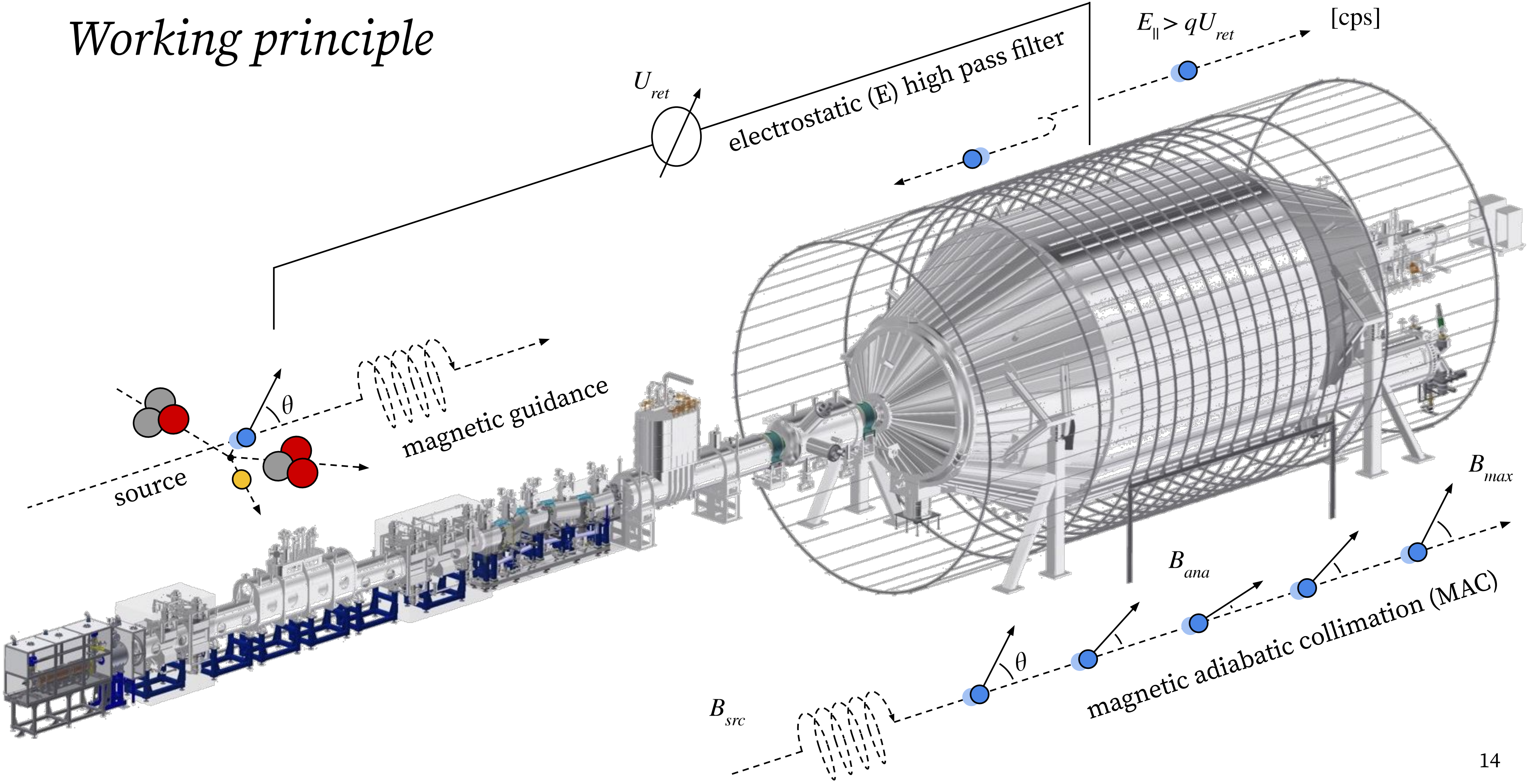
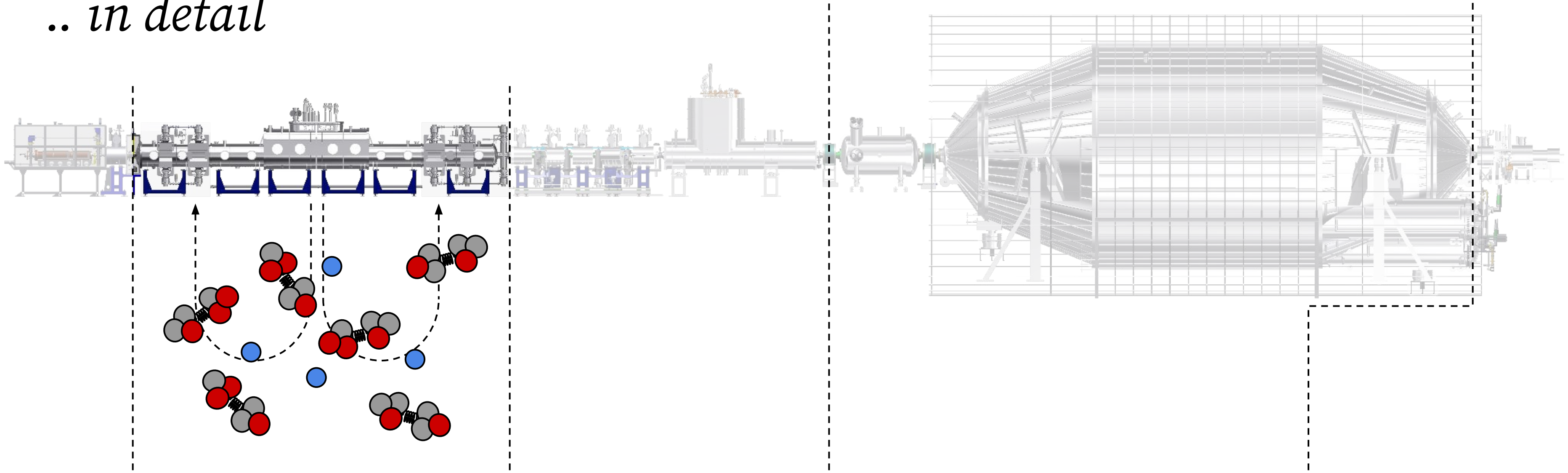


.. in detail

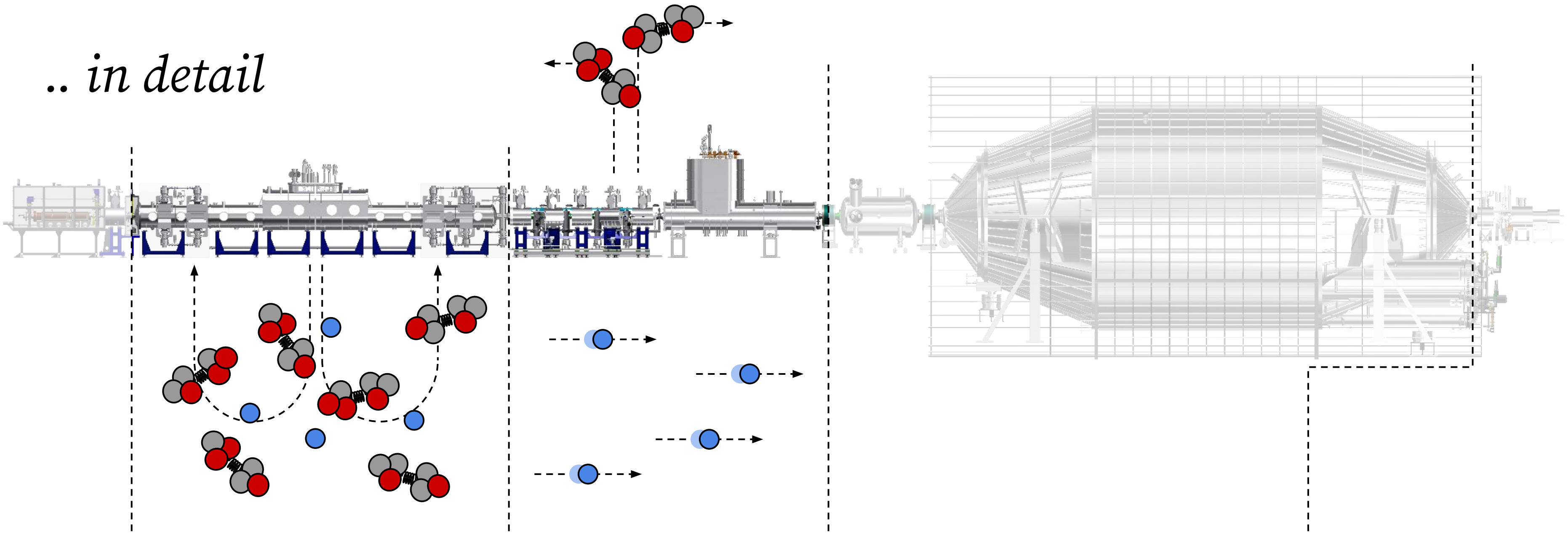


windowless gaseous tritium source

- molecular tritium in **closed loop**

➔ **100 GBq**

.. in detail



windowless gaseous tritium source

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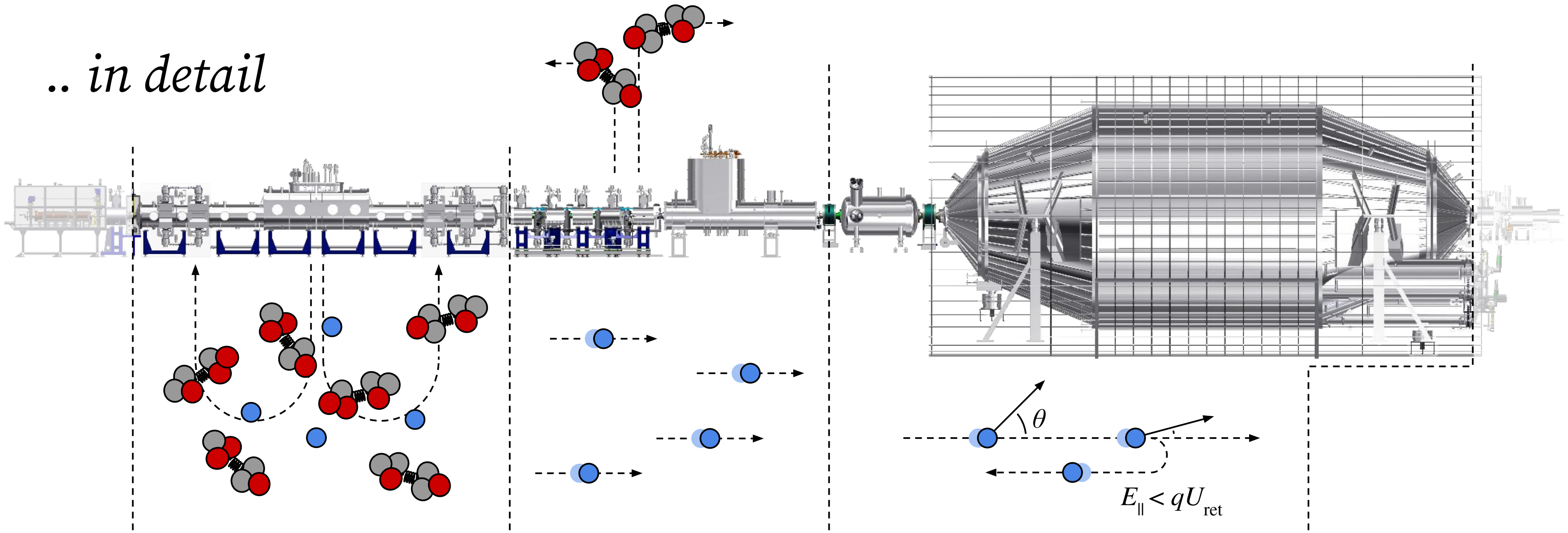
➔ **100 GBq**

transport section

- tritium gas/ion removal

➔ reduction by **> 10^{14}**

.. in detail



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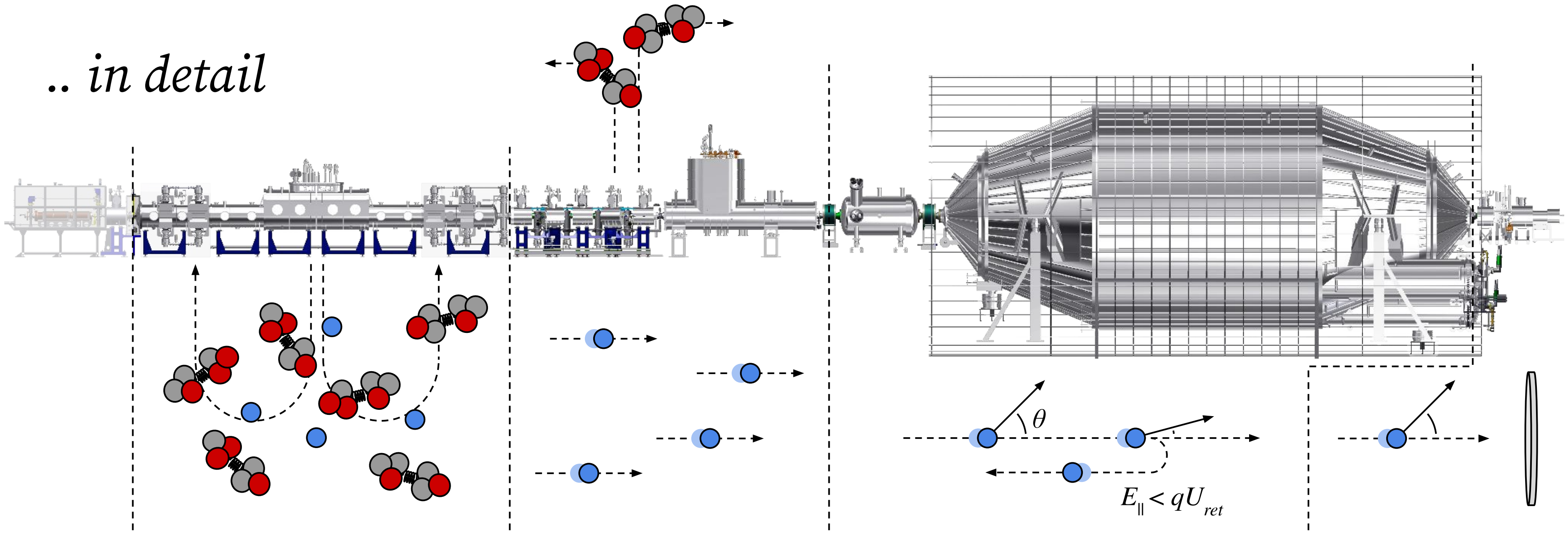
spectrometer system

- (pre-)/main-spectrometer

➔ high resolution, **O(1) eV**

➔ large acceptance angle, **0-51°**

.. in detail



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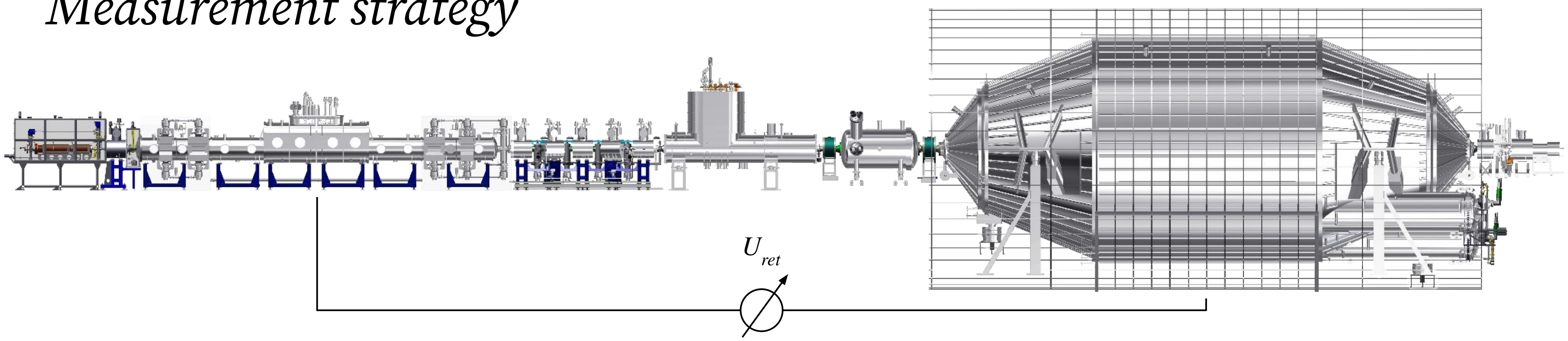
➔ high resolution, **O(1) eV**

➔ large acceptance angle, **0-51°**

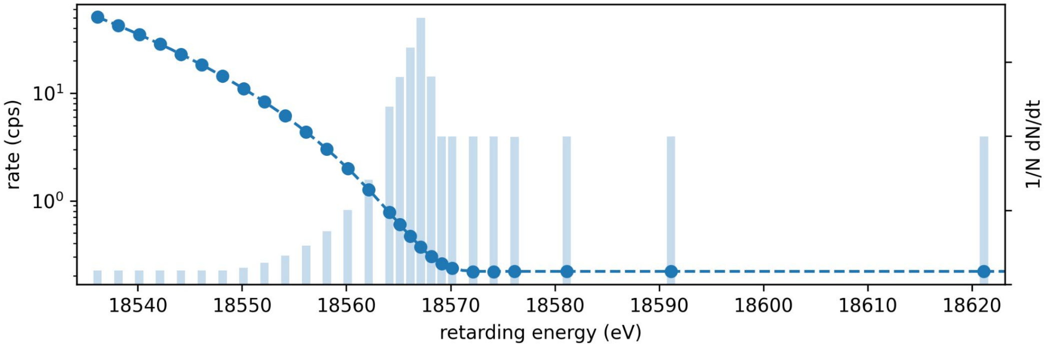
detector section

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

Measurement strategy



- **~30 scan steps** with varying duration, measurement time distribution (MTD)
- **~2 h scan** duration, up/down/random scans, O(100) scans per campaign
- several **campaigns** per year

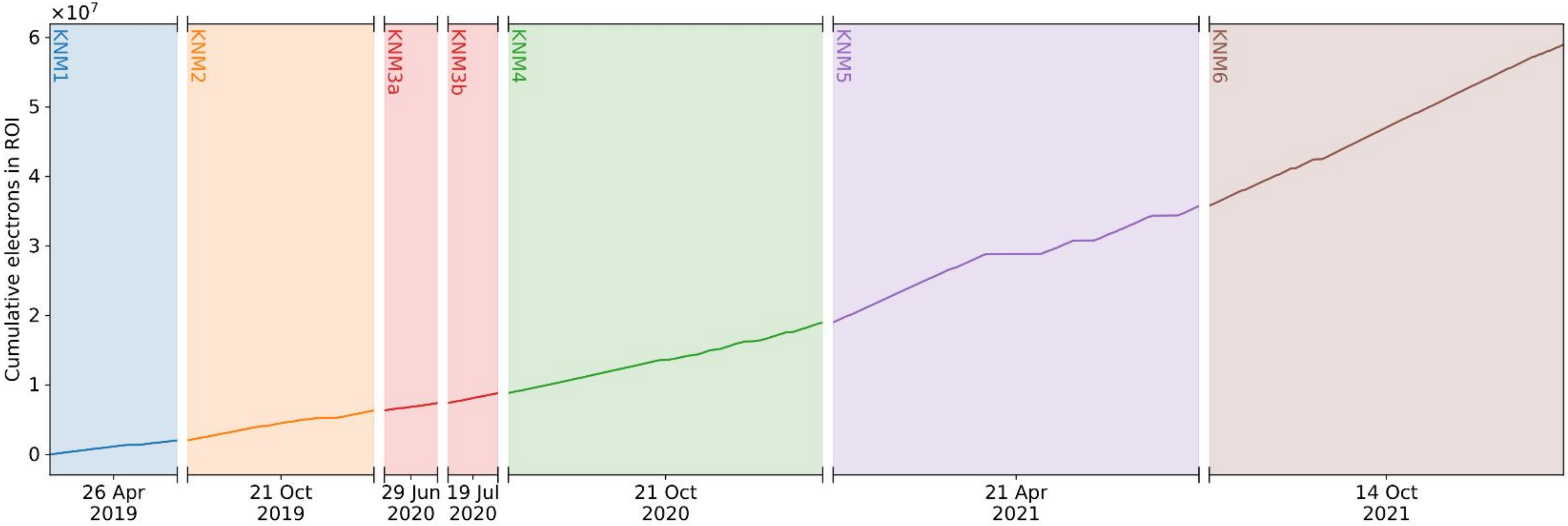


Data taking overview

< 0.8 eV (90% CL)

[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

?

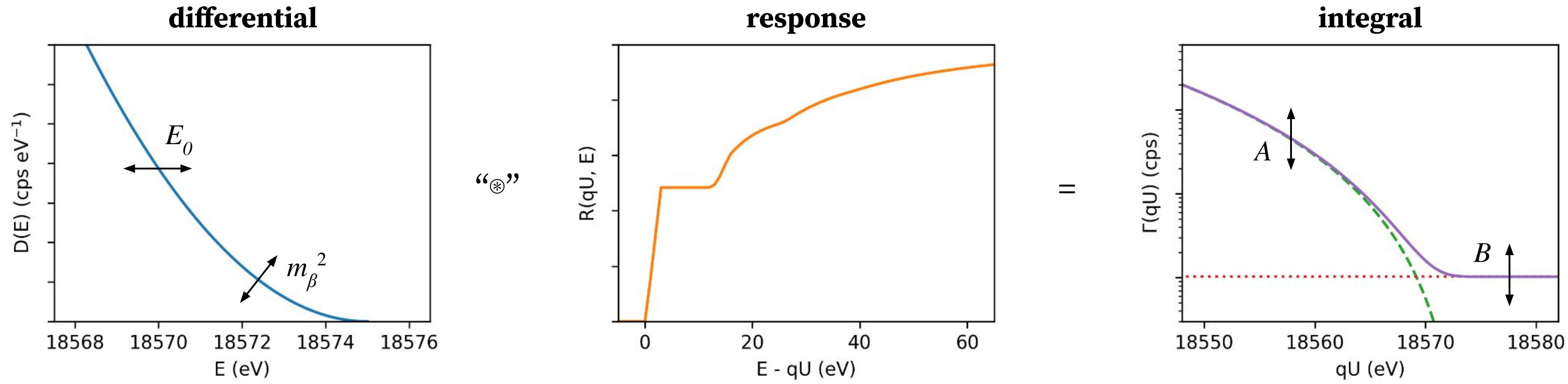


< 1.1 eV (90% CL)

[Aker et al., PRL 123 (2019) 22, 221802]

Analysis strategy

- maximum likelihood fit of **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 **amplitude** A, **squared neutrino mass** m_β^2, **endpoint** E_0 and **background** B

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

Neutrino mass results

1st campaign, 2 million events (22 days)

[Aker et al., PRL 123 (2019) 22, 221802]

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

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

➔ **upper limit**

$$m_\beta < \mathbf{1.1\ eV}\ (90\%\ \mathrm{CL})$$

2nd campaign, 4 million events (31 days)

[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

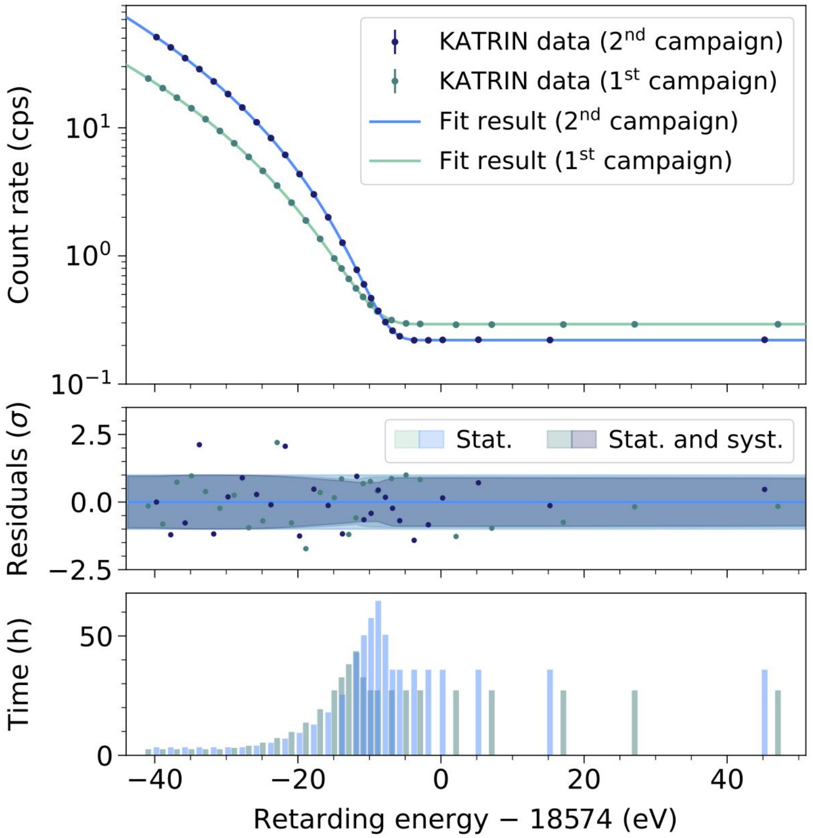
- best fit, **p-value = 0.8**

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

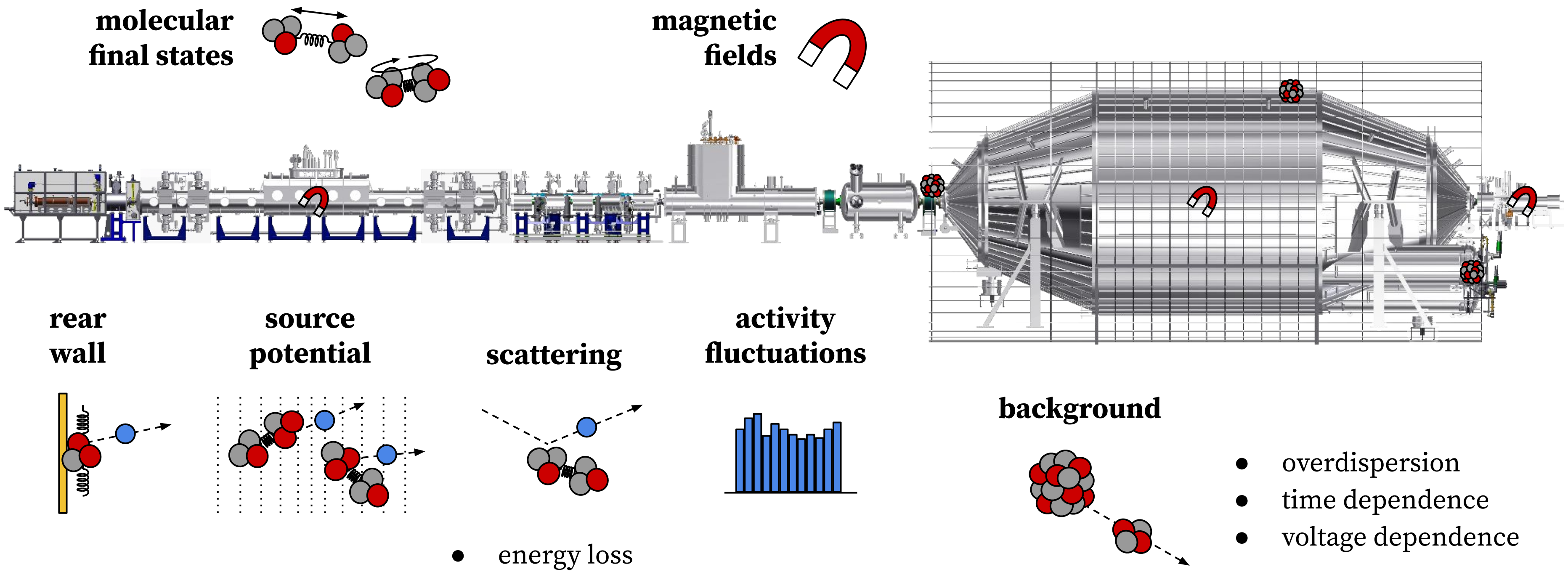
➔ **upper limit**

$$m_\beta < \mathbf{0.9\ eV}\ (90\%\ \mathrm{CL})$$

$$m_\beta < \mathbf{0.8\ eV}\ (90\%\ \mathrm{CL})$$



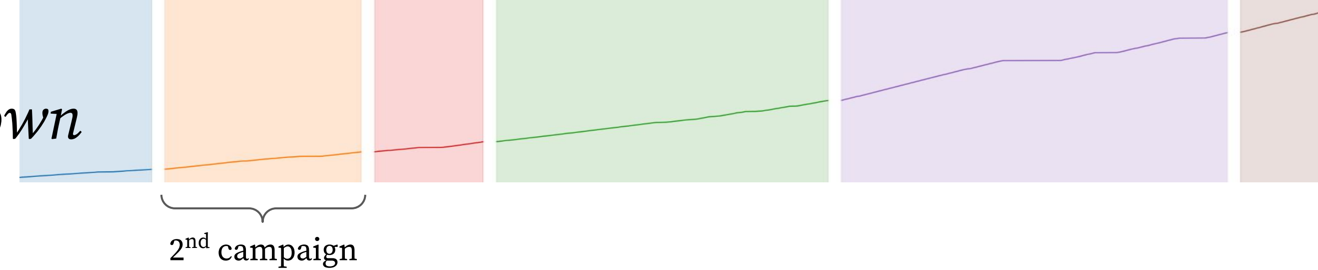
Systematic uncertainties



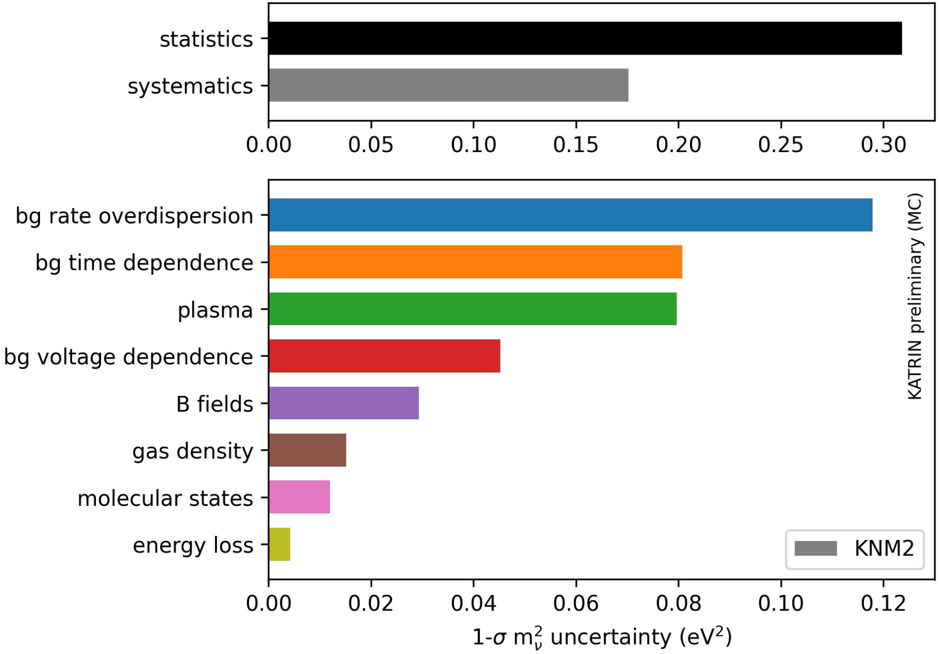
- energy loss
- column density

- overdispersion
- time dependence
- voltage dependence

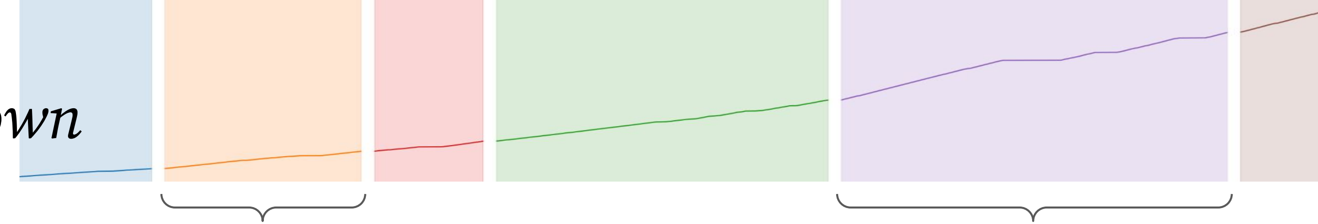
Uncertainty breakdown



- **statistical uncertainty dominates**, systematics non-negligible
- **background**-related uncertainties dominate systematics budget
- significant **plasma** uncertainty

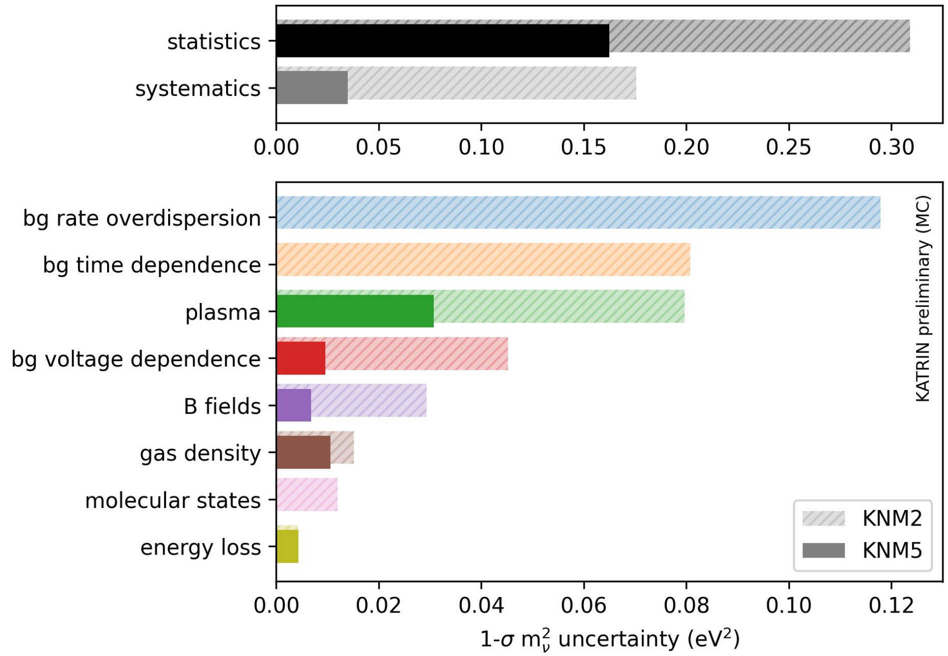


Uncertainty breakdown



- **statistical uncertainty dominates**, systematics non-negligible

➔ still statistics dominated, **systematics largely improved**



- **background**-related uncertainties dominate systematics budget

➔ **mitigation** techniques, avoid Penning trap, shifted analyzing plane (SAP)

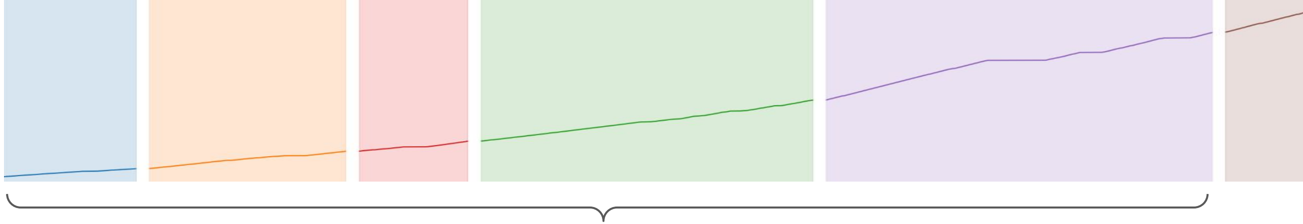
[Lokhov et al., EPJ C 82 (2022) 3, 258]

- significant **plasma** uncertainty

➔ high-statistics **^{83m}Kr** campaign, tritium scans at same temperature/gas density

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

Outlook



- **combined analysis** of first 5 periods, significant increase of statistics
- model evaluation **computationally challenging**

➔ fast **neural network** interpolation

[Karl et al., EPJ C 82 (2022) 5, 439]

- **substantial improvement** of systematics and background

➔ sensitivity projection (in case of no signal)

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

- **data taking ongoing**

➔ final sensitivity goal

$$m_\beta < \mathbf{0.2\ eV}\ (90\%\ \mathrm{CL})$$

beyond neutrino mass:

- search for eV-scale **sterile neutrinos**

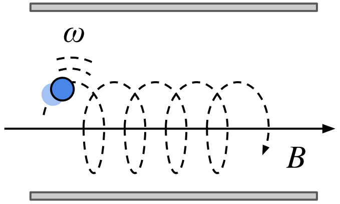
[Aker et al., PRD 105 (2022) 7, 072004]

- **relic neutrino** search

[Aker et al., arXiv:2202.04587]

- test of **Lorentz invariance**

[Lehnert, PLB 828 (2022) 137017]



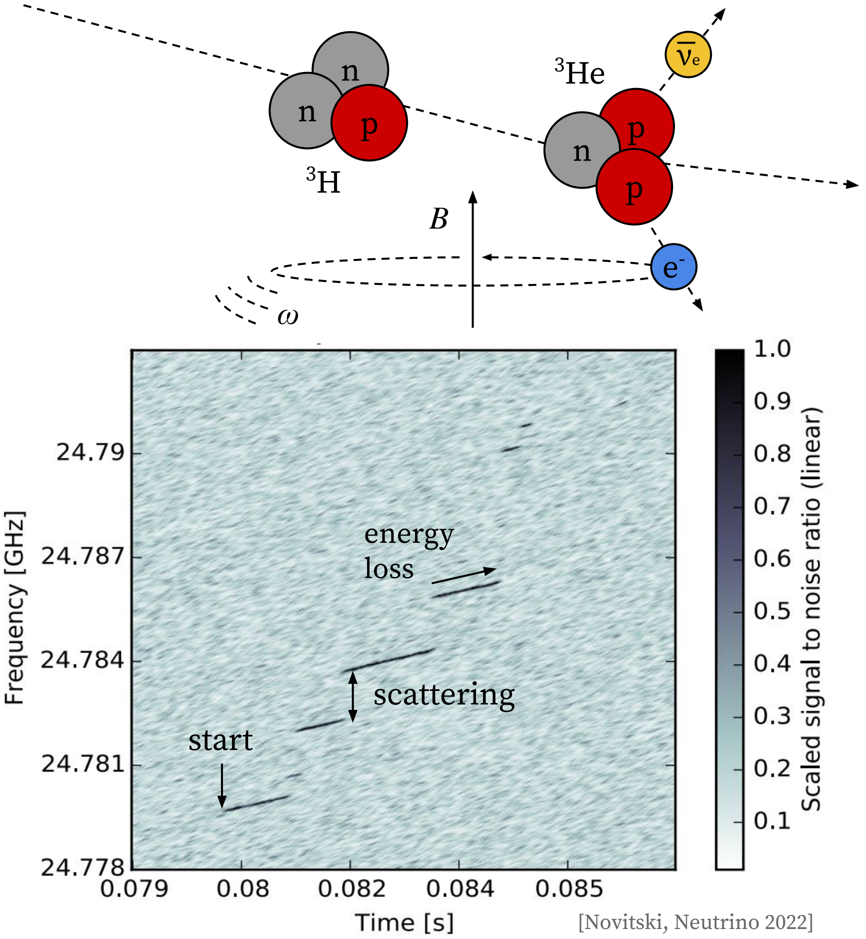
Neutrino Mass | KATRIN | ***Project 8*** *| ECHo / HOLMES | Outlook*

Working principle

- **cyclotron radiation** emission spectroscopy (CRES) for tritium decay electrons
  [Monreal, Formaggio, PRD 80 (2009) 051301]

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

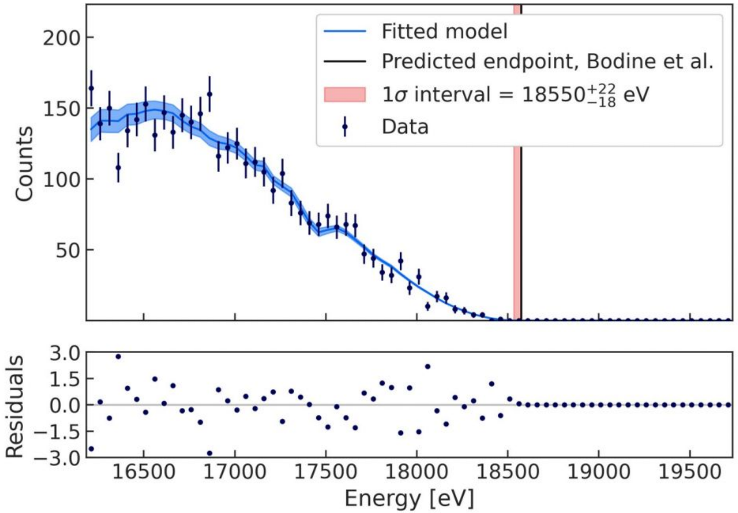
  - **source transparent** to microwave radiation, *source* = *detector* concept
  - high precision **differential** frequency measurement, eV-scale resolution
  - **low background**

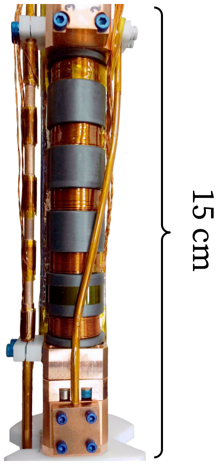


[Novitski, Neutrino 2022]

Project 8

[Novitski, Neutrino 2022]





- **proof-of-concept**, single electron spectroscopy
- (molecular) tritium endpoint measurement, first **neutrino mass limit**

$$m_\beta < 178 \text{ eV (90\% CL)}$$

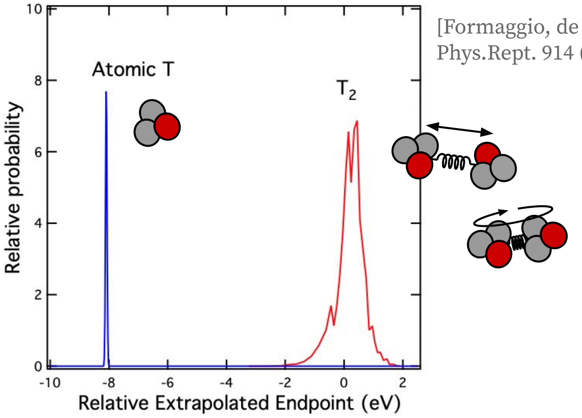
[Novitski, Neutrino 2022]

path beyond:

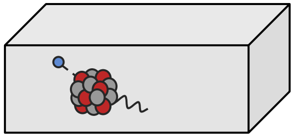
- **m³-scale trap** (antenna array or cavity resonator)
- **atomic tritium** source

➔ sensitivity down to 40 meV

[Ashtari Esfahani et al., arXiv:2203.07349]



[Formaggio, de Gouvea, Robertson, Phys.Rept. 914 (2021) 1-54]

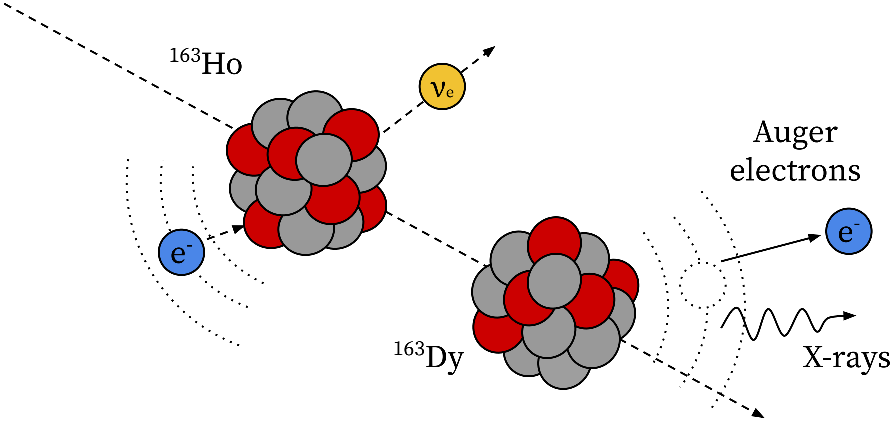


Neutrino Mass | KATRIN | Project 8 | **ECHo / HOLMES** | Outlook

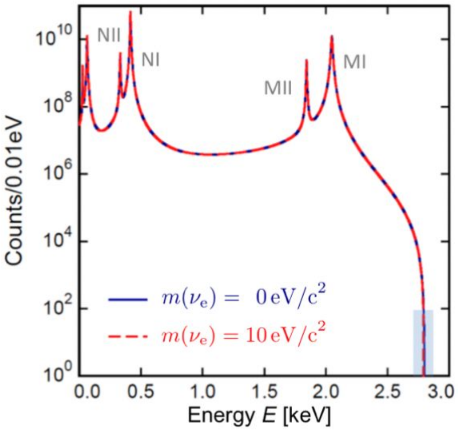
Working principle

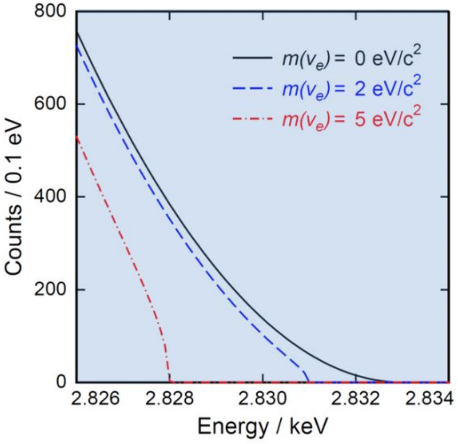
- calorimetric measurement of **^{163}Ho electron capture** decay
  [De Rujula, Lusignoli, PLB 118 (1982) 429]
    - super-low **Q-value**
      Q_{EC} = (2.833 ± 0.034) keV
      [Eliseev et al., PRL 115 (2015) 062501]
    - **sub-eV** sensitivity requires **MBq-scale activity**

- ^{163}Ho **implanted** into **cryogenic micro-calorimeters**
    - eV-scale **differential** measurement
    - *source* = *detector* concept, pile-up limits pixel activity

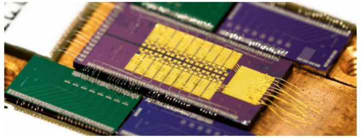


[Gastaldo, Neutrino 2022]





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)

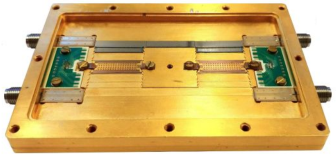
$$m_\nu < 150 \text{ eV (95\% CL)}$$

[Velte et al., EPJ C 79 (2019) 12, 1026]

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

$$\text{sensitivity: } m_\nu < 20 \text{ eV (95\% CL)}$$

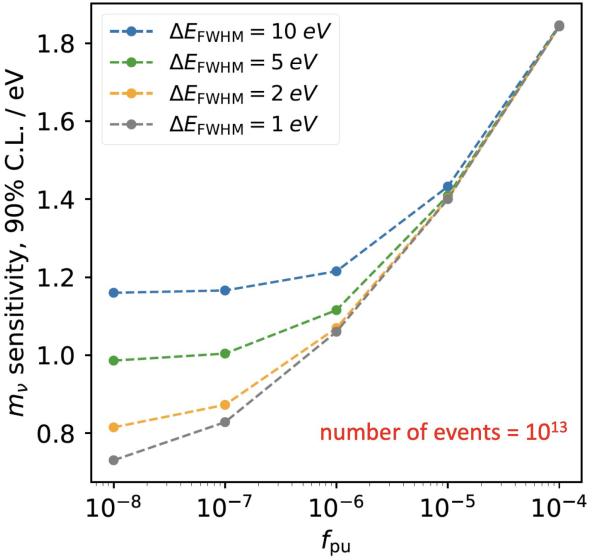
HOLMES



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

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

[Gastaldo, Neutrino 2022]



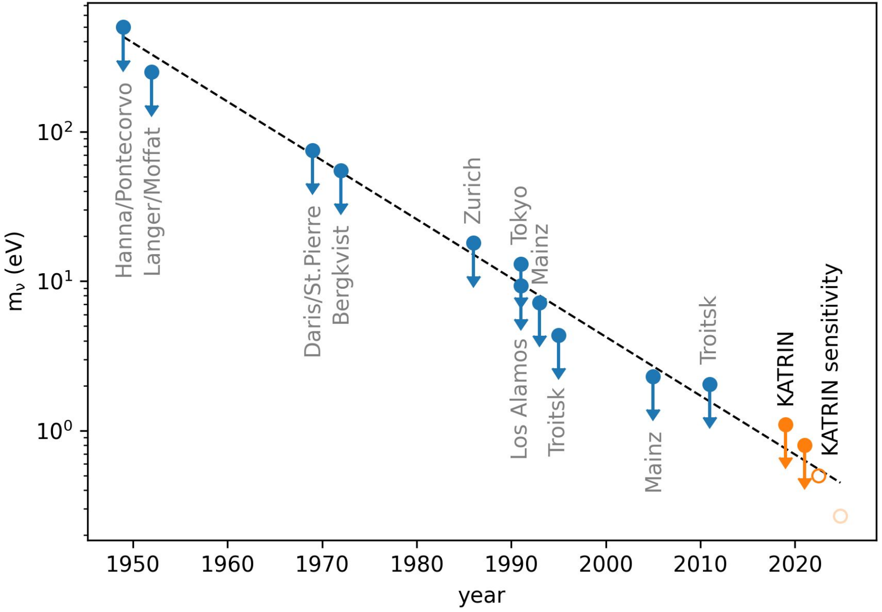
Neutrino Mass | KATRIN | Project 8 | ECHo / HOLMES | *Outlook*

Conclusions

- **KATRIN** measurement ongoing
  - first direct **sub-eV** neutrino mass limit
    [Aker et al., Nature Phys. 18 (2022) 2, 160-166]

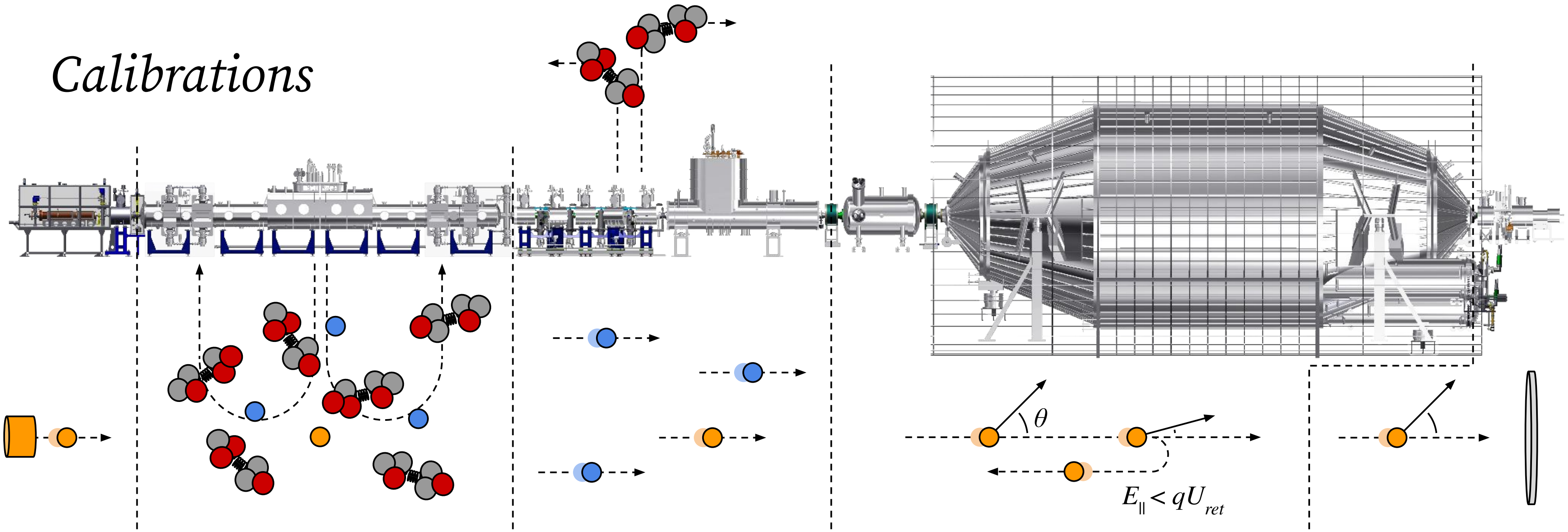
    m_β **< 0.8 eV** (90% CL)
  - substantial improvement of **systematics** and **background**, increased **statistics**

- **promising perspectives** to go beyond
  - tritium cyclotron radiation emission spectroscopy, **Project 8**
  - holmium-implanted cryogenic micro-calorimeters, **ECHo/HOLMES**
  - ...



Backup

Calibrations



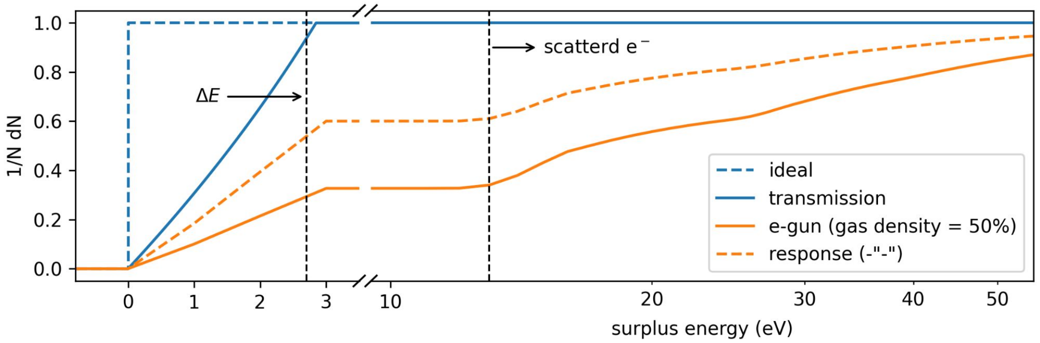
rear section

- high intensity **e-gun**

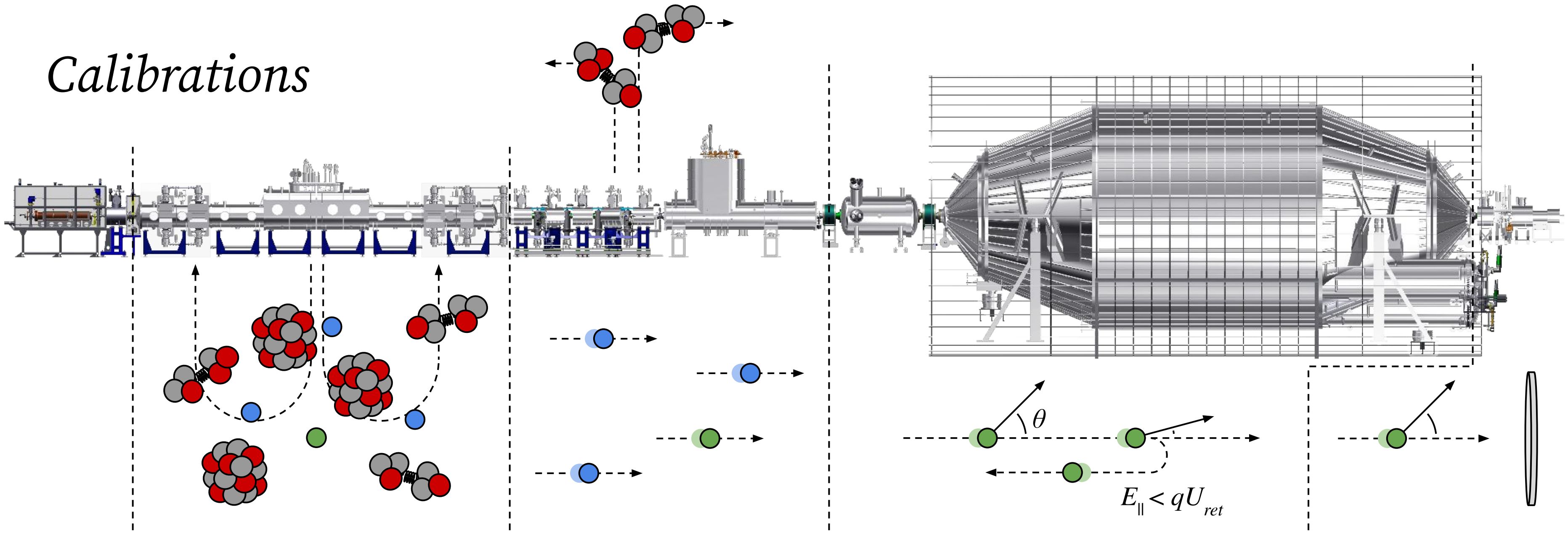
[Behrens et al., EPJ C 77 (2017) 6, 410]

➔ precise determination of **column density** and **energy-loss** function

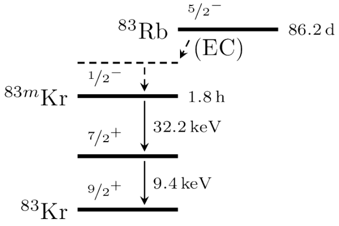
[Hannen et al., Astropart.Phys. 89 (2017) 30-38; Aker et al., EPJ C 81 (2021) 7, 579]



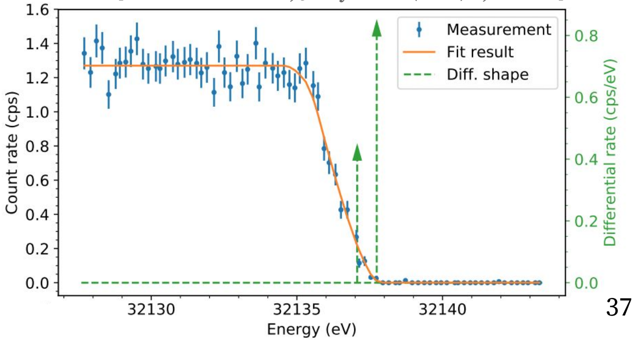
Calibrations



windowless gaseous
~~tritium~~ source



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



- **^{83m}Kr** from ^{83}Rb, **conversion electrons**

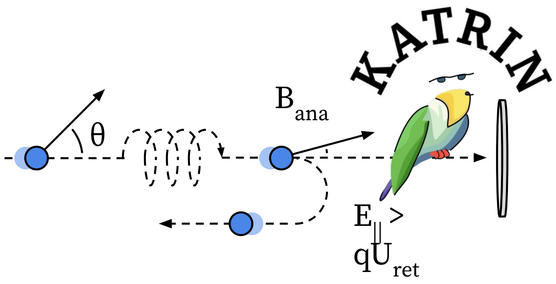
  [Sentkerestiová et al., J.Phys.Conf.Ser. 888 (2017) 1, 012072; Arenz et al., JINST 13 (2018) 04, P04020]

➔ variations of **source potential** and **spectrometer fields**

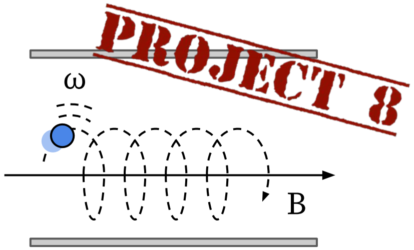
[Arenz et al., EPJ C 78 (2018) 5, 368]

Experimental efforts

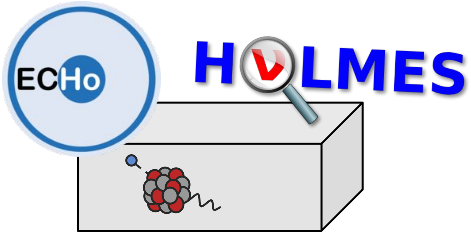
tritium



electrostatic **filter**
(MAC-E)



cyclotron radiation
emission spectroscopy
(CRES)



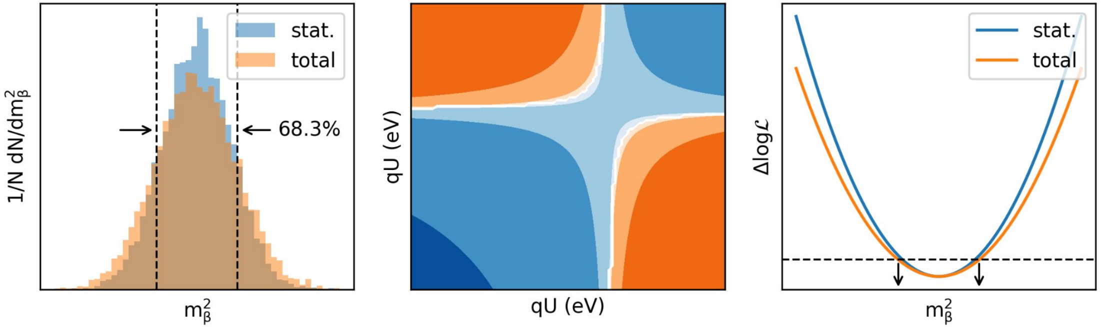
cryogenic
calorimeters

R&D phase

Analysis strategy

- **blind analysis**, procedures and inputs frozen on Monte Carlo data (MC twins) with $m_\beta = 0$
- cross-checks between **3 independent analysis frameworks**/groups
- **2-step unblinding**
  - fit on data w/ **blinded** molecular **final state distribution** (FSD)
  - fit on data w/ correct FSD

- **uncertainty propagation**
  - Monte Carlo propagation (sampling)
  - covariance matrices
  - nuisance parameter, pull terms



KATRIN neutrino mass (KNM) 2

[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

- analysed **ring-wise** (consistent with uniform fit), excellent goodness-of-fit, **p-value = 0.8**,

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

compatible with zero

➔ **upper limit** using Lokhov-Tkachov

[Lokhov, Tkachov, Phys.Part.Nucl. 46 (2015) 3, 347-365]

(consistent with Feldman-Cousins)

[Feldman, Cousins, PRD 57 (1998) 3873-3889]

$$\boldsymbol{m_\beta < 0.9\ \mathrm{eV}}\ (90\%\ \mathrm{CL})$$

sensitivity: $m_\beta < 0.7$ eV (90% CL)

- combination with KNM1

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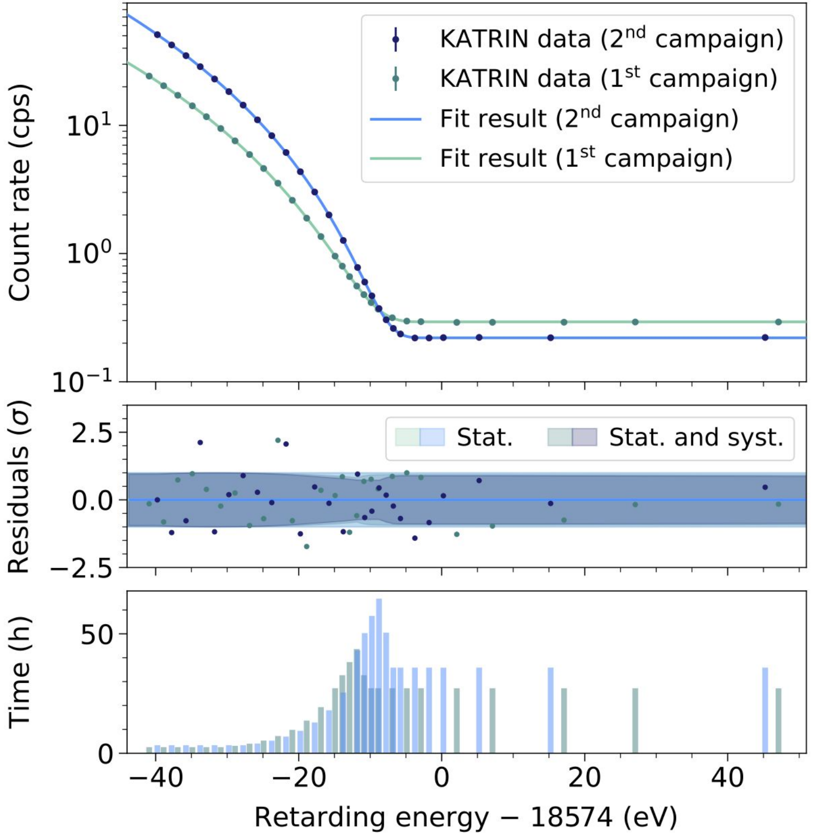

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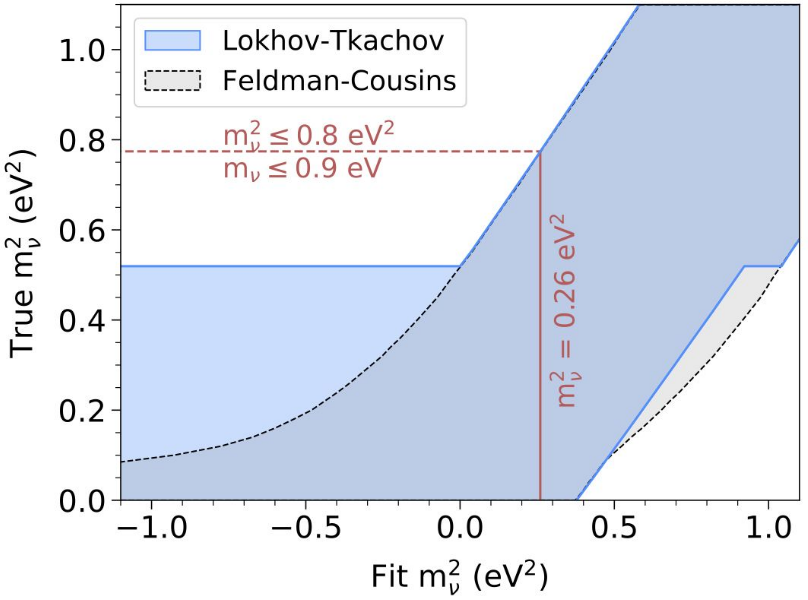
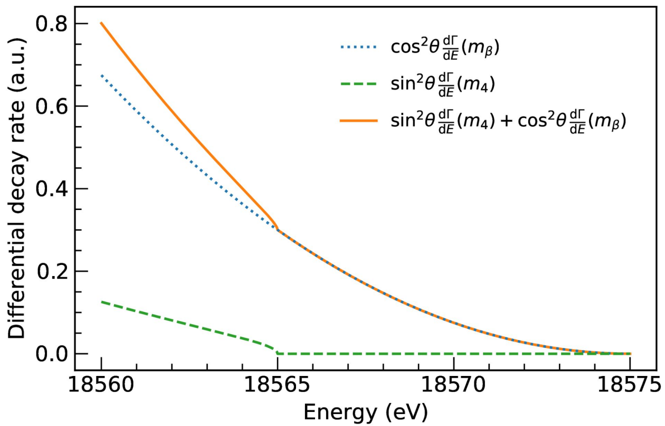


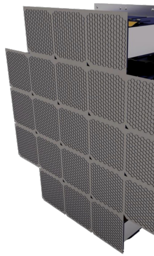
Beyond neutrino mass

- search for eV-scale **sterile neutrinos**

➔ kink in spectrum

[Aker et al., PRD 105 (2022) 7, 072004]



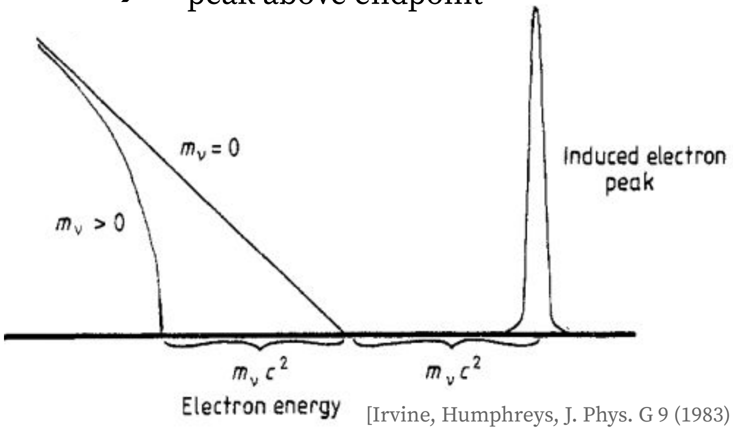


- keV-scale steriles with **TRISTAN**

[Mertens et al., J.Phys.G 46 (2019) 6, 065203]

- **relic neutrino** overdensity

➔ peak above endpoint

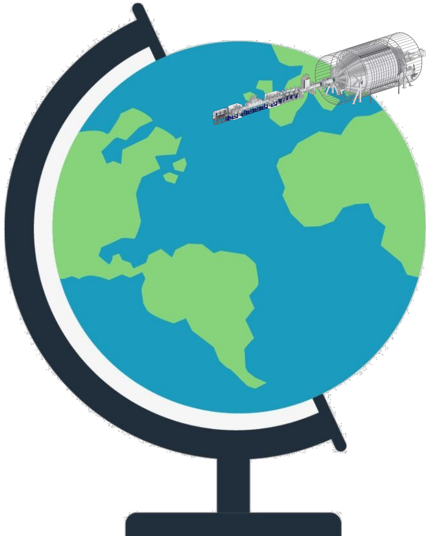


[Irvine, Humphreys, J. Phys. G 9 (1983) 847]

- **Lorentz invariance** violation

➔ sidereal modulation

[Lehnert, PLB 828 (2022) 137017]



Spectrometer backgrounds

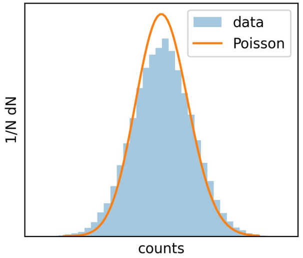
- ^{219}**Rn decays** ($T_{1/2}$ = 4s) in spectrometer

➔ trapped electrons, **non-Poisson rate**

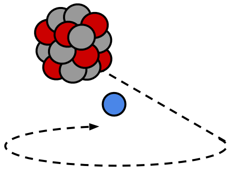
[Mertens et al., Astropart.Phys. 41 (2013) 52-62]

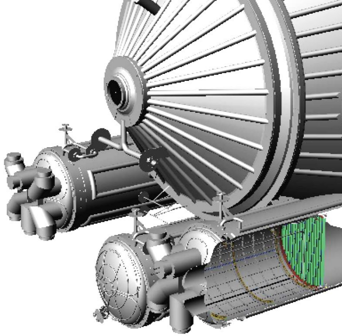
- improved nitrogen cooled baffles

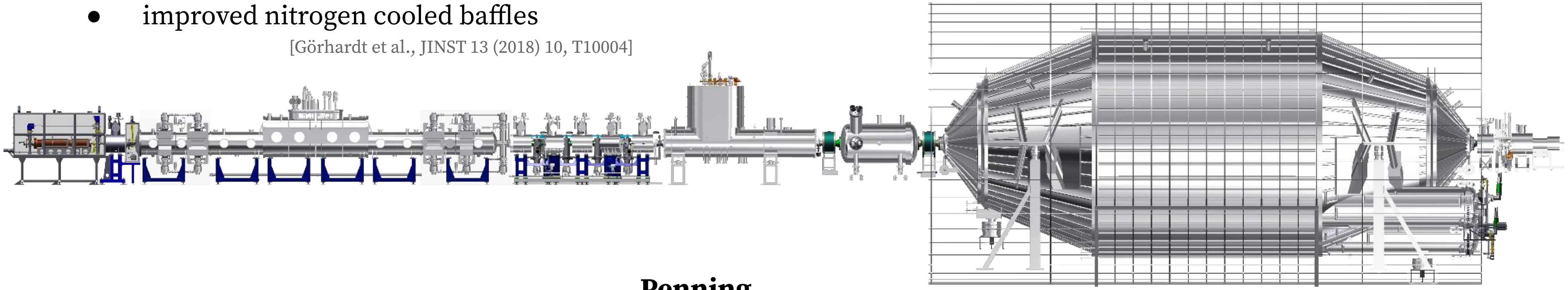
[Görhardt et al., JINST 13 (2018) 10, T10004]



Radon-219







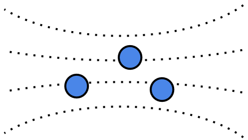
- emptied in between scan steps

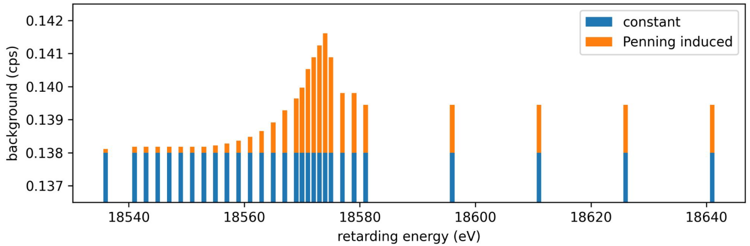
➔ **background increase** during measurement **O(1) µcps/s**

➔ scan-step-**duration dependent**

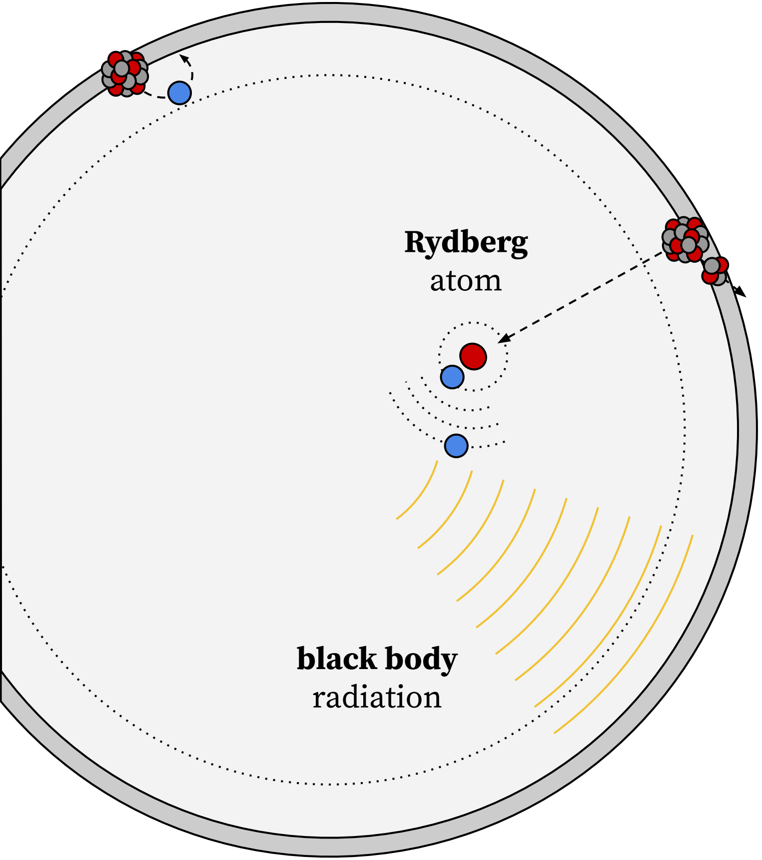
- switch off pre-spectrometer

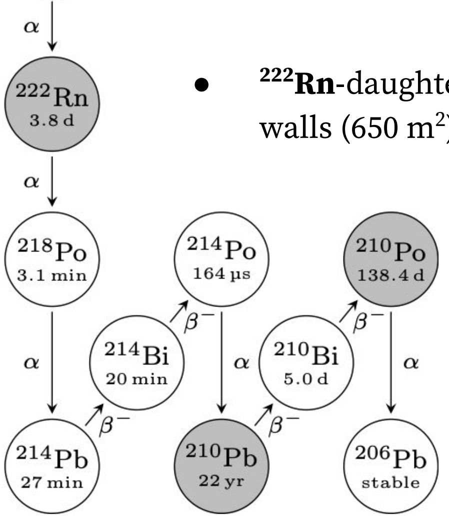
Penning trap





Spectrometer backgrounds





- ^{222}**Rn**-daughter **plate out** on spectrometer walls (650 m^2)
  - ➔ sputtering of **Rydberg atoms** in ^{210}Po decay
  - ➔ **ionized** by black body radiation
- **shifted-analyzing plane** (SAP)