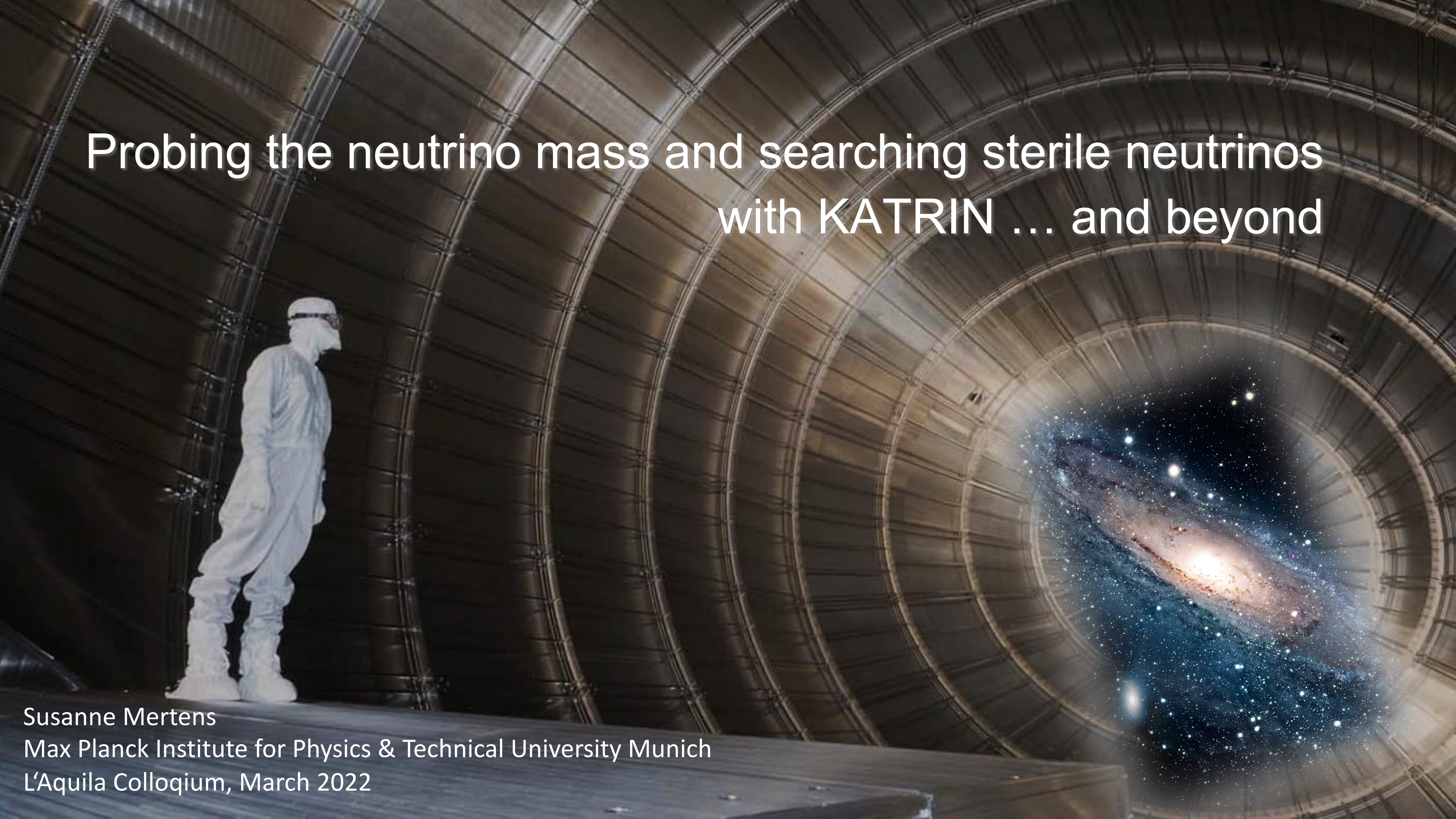
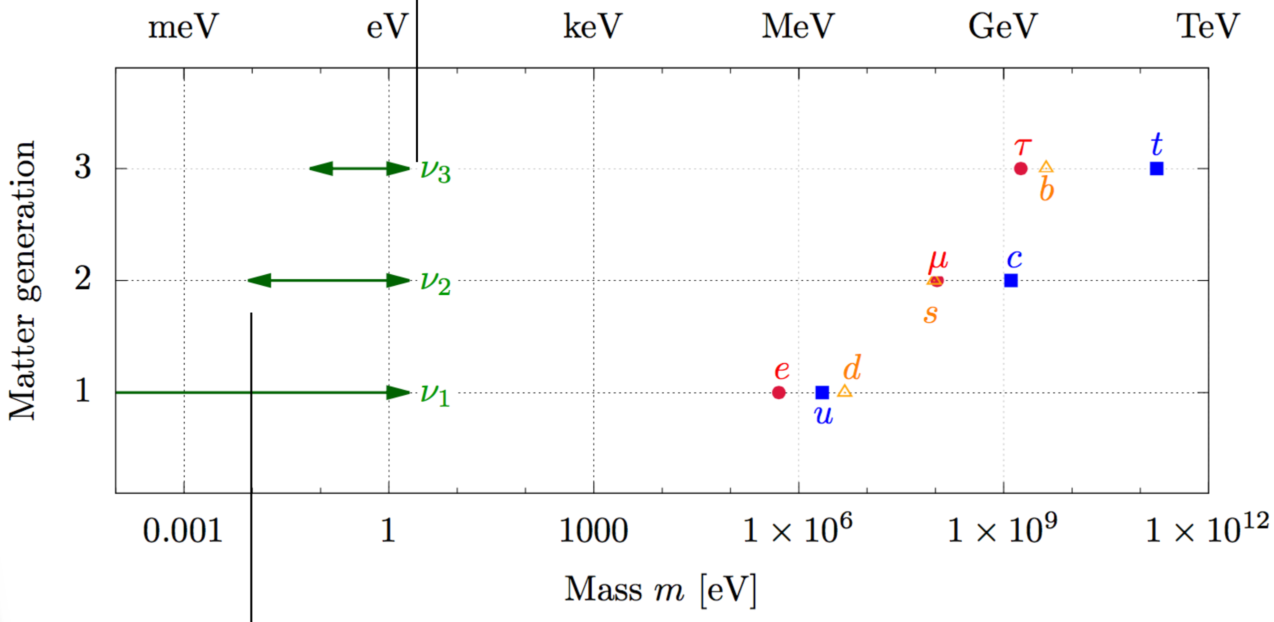


Probing the neutrino mass and searching sterile neutrinos with KATRIN … and beyond

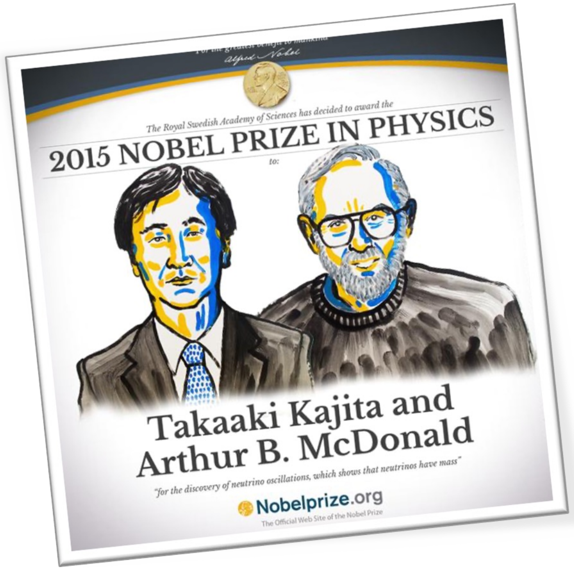
Susanne Mertens
Max Planck Institute for Physics & Technical University Munich
L'Aquila Colloqium, March 2022

Neutrino mass

Upper bound
from direct measurements



Lower bound
from oscillation experiments



Neutrino mass

Model dependence | Laboratory-based probes

Cosmology

potential: m_ν = 10 - 50 meV

$$m_\nu = \sum_i m_i$$

Search for 0νββ

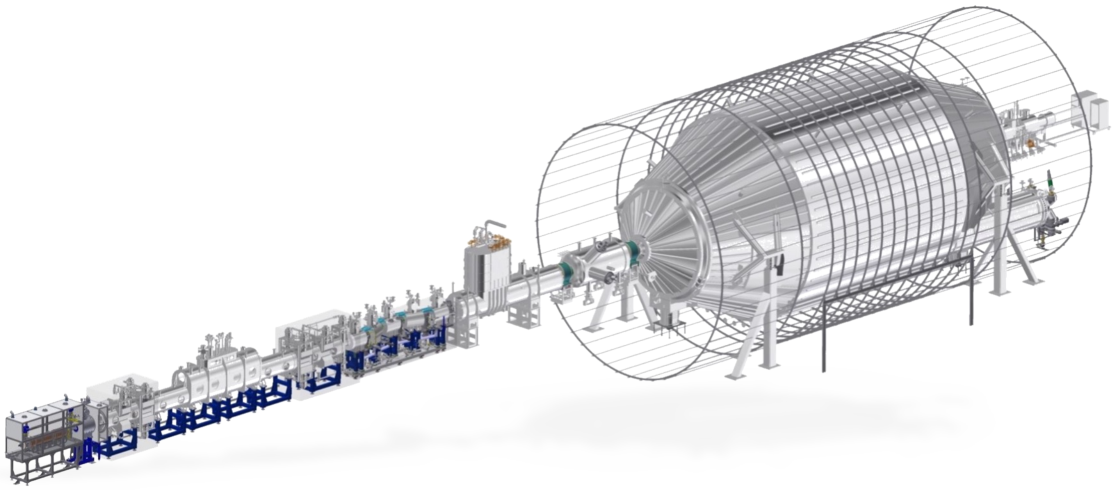
potential: $m_{ßß}$ = 7 - 17 meV

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

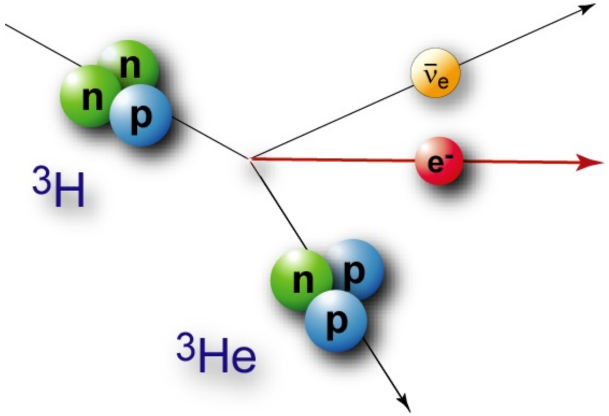
Kinematics of ß-decay

potential: m_β = 50 - 200 meV

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

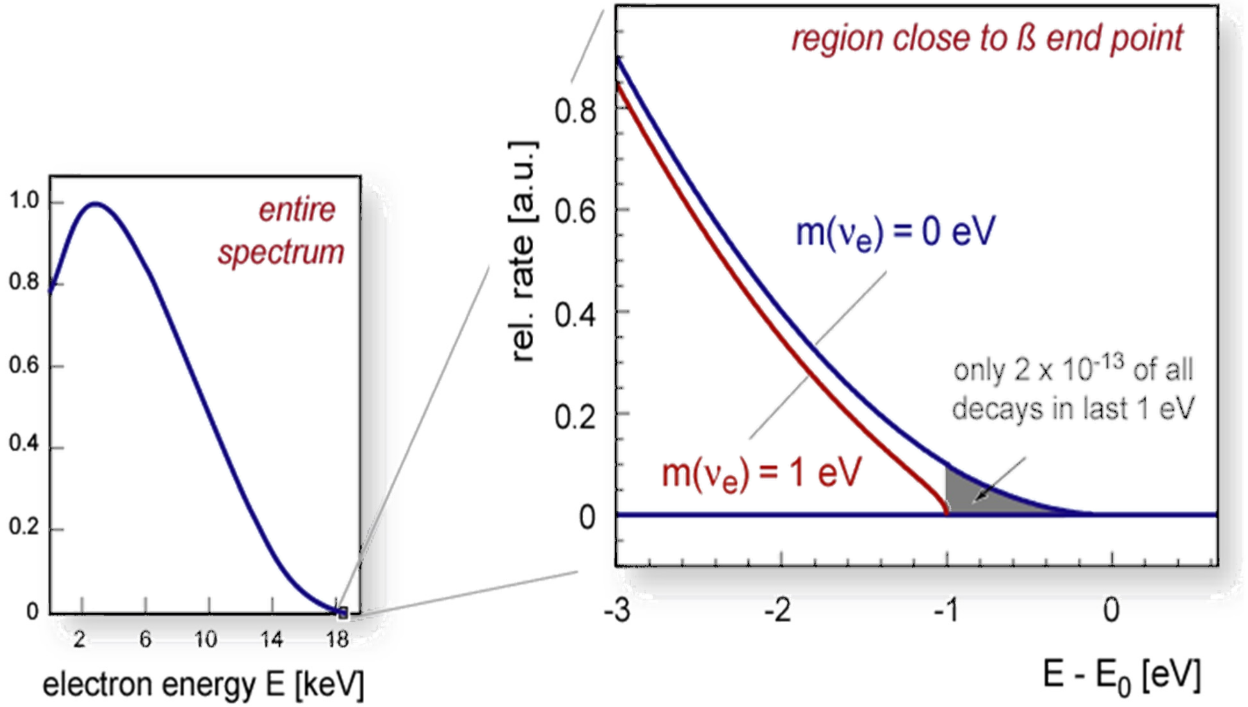


General idea



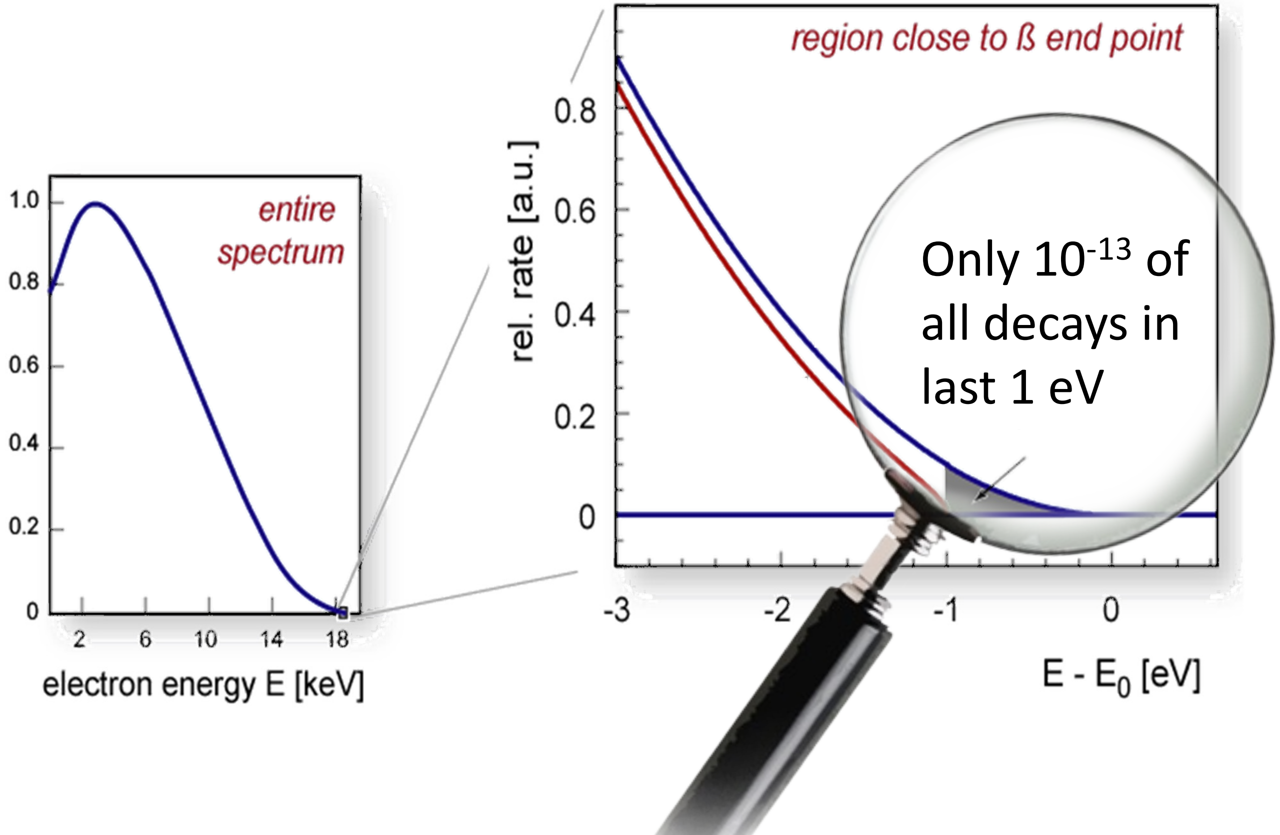
	^3H
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.56 keV

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$

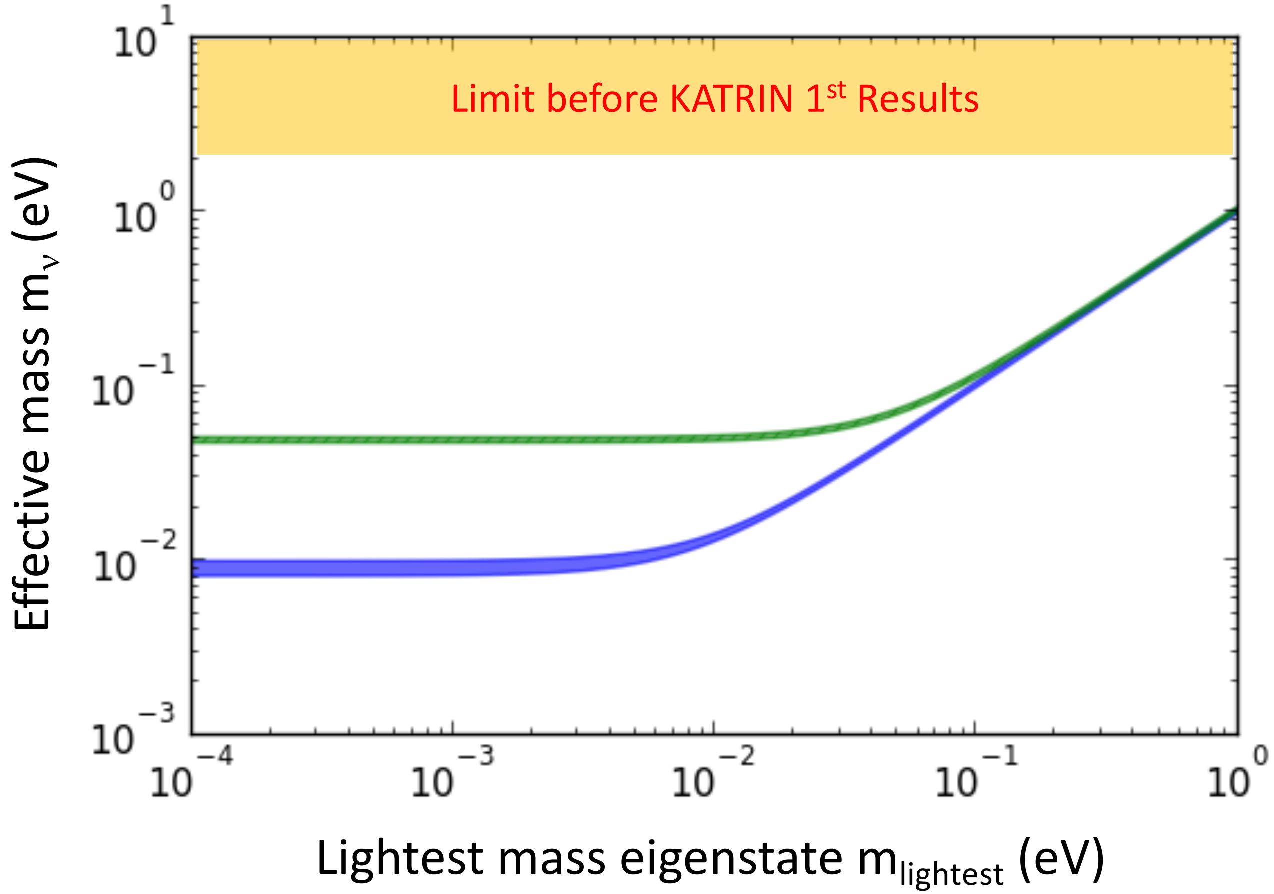


The challenge

- Strong tritium source: 10^{11} decays/s
- Low background level < 0.1 cps
- Excellent energy resolution ~ 1 eV



Where do we stand?



- Limit before KATRIN 1st Results: Mainz and Troitsk Experiment

V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

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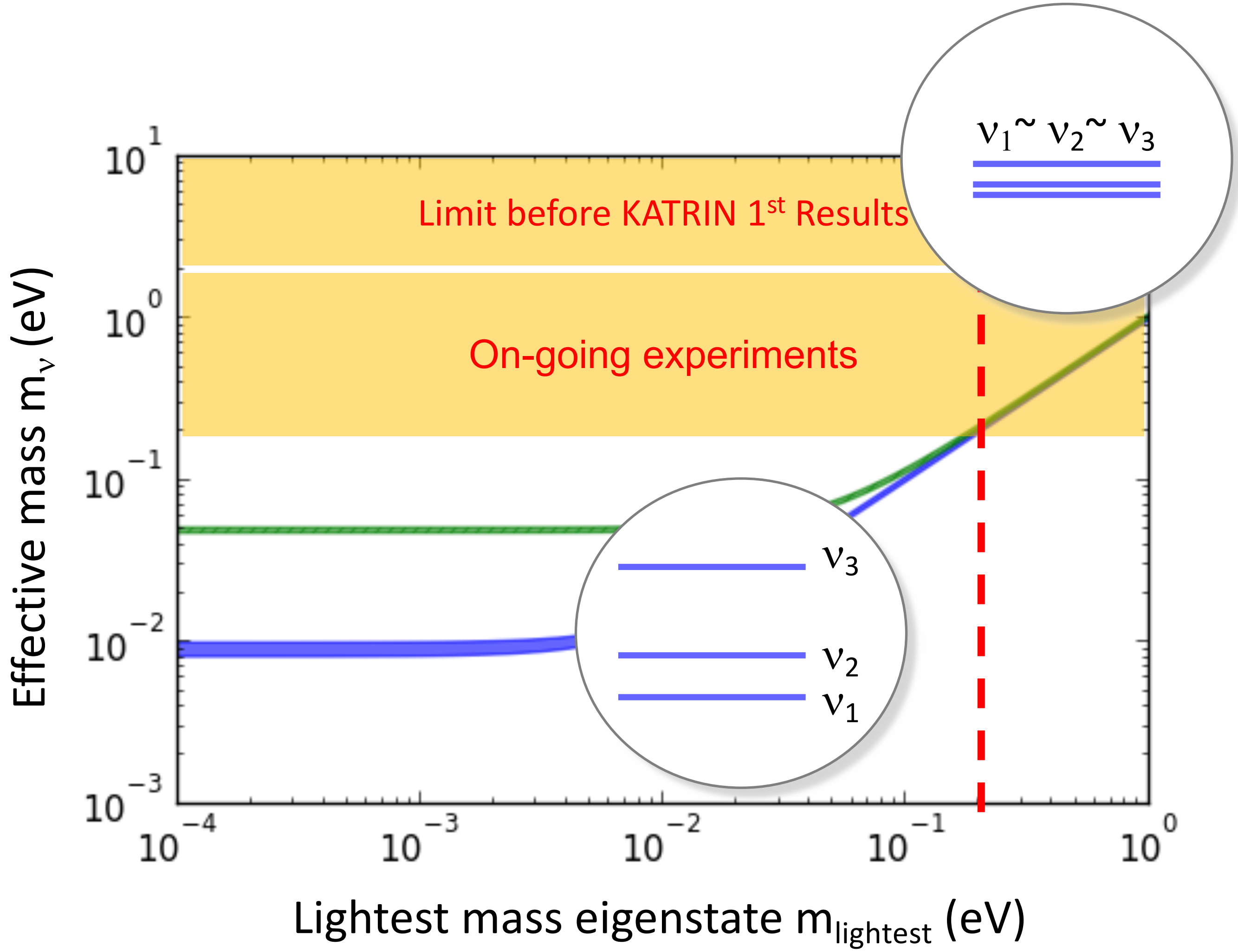

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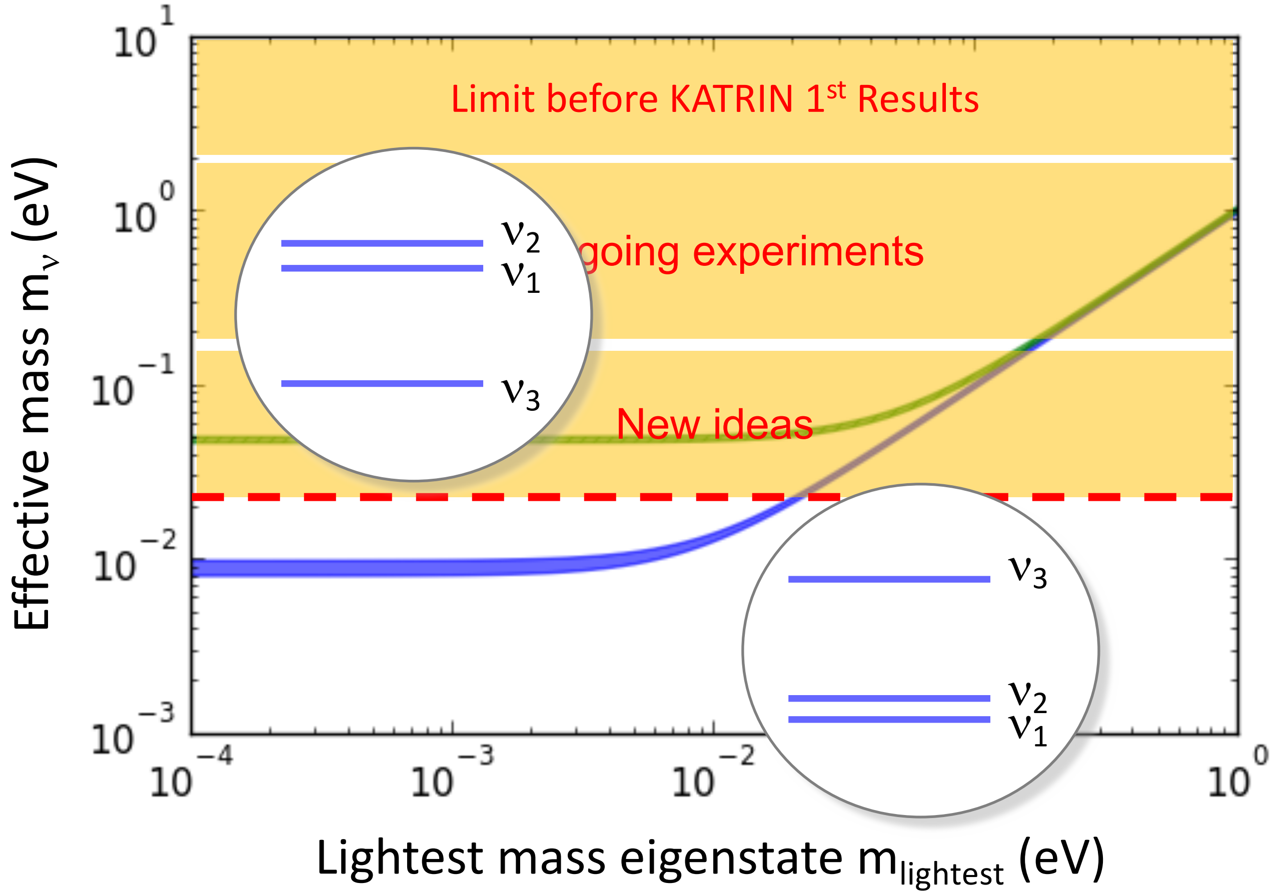
- Ongoing experiments: Distinguish between **degenerate** and **hierarchical** scenario

Where do we stand?



- Limit before KATRIN 1st Results: Mainz and Troitsk Experiment
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  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments: Distinguish between **degenerate** and **hierarchical** scenario
- New ideas: Resolve **normal** vs **inverted** neutrino mass hierarchy

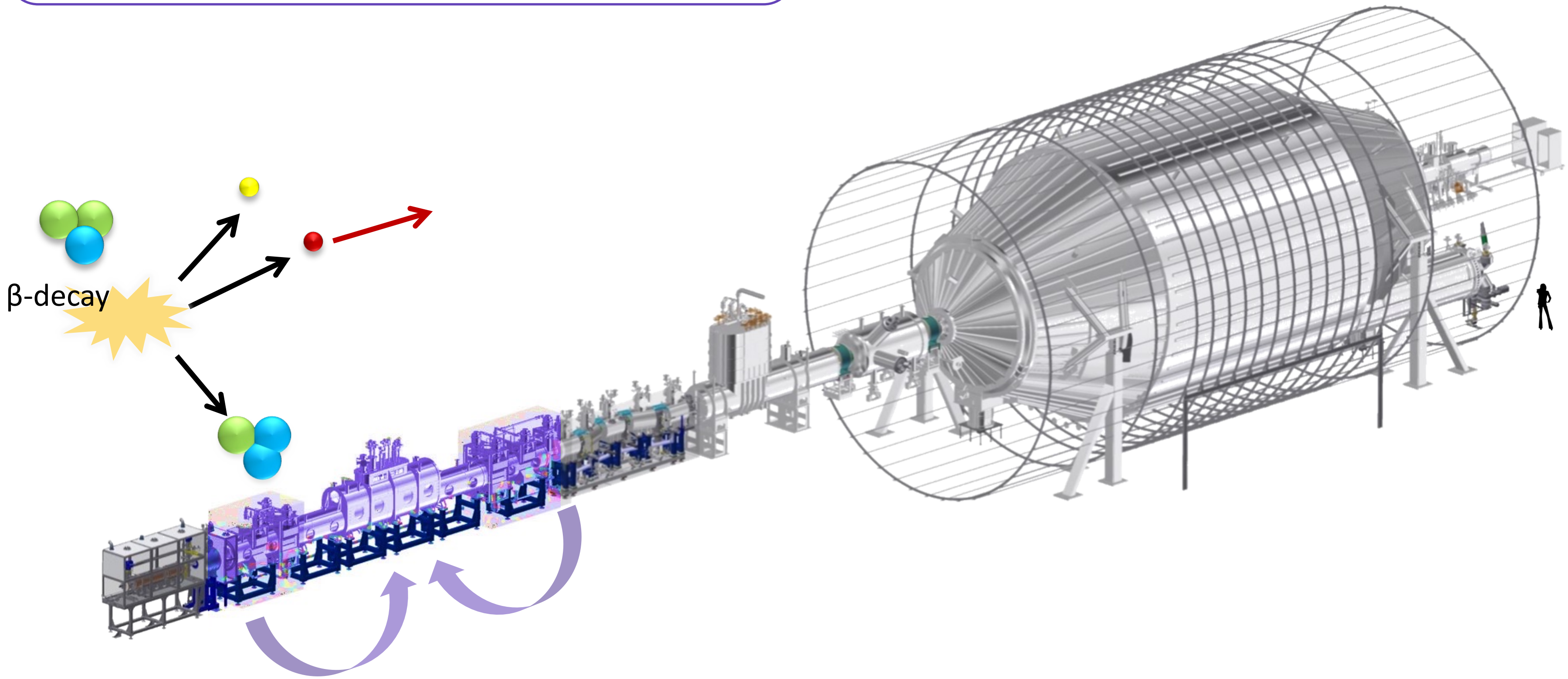

Karlsruhe
Tritium
Neutrino
Experiment

KATRIN

- **Experimental site: Karlsruhe Institute of Technology (KIT)**
- **International Collaboration (150 members)**
- **Design sensitivity: 0.2 eV (90% CL)**
  (5 years of measurement time)

KATRIN Working Principle

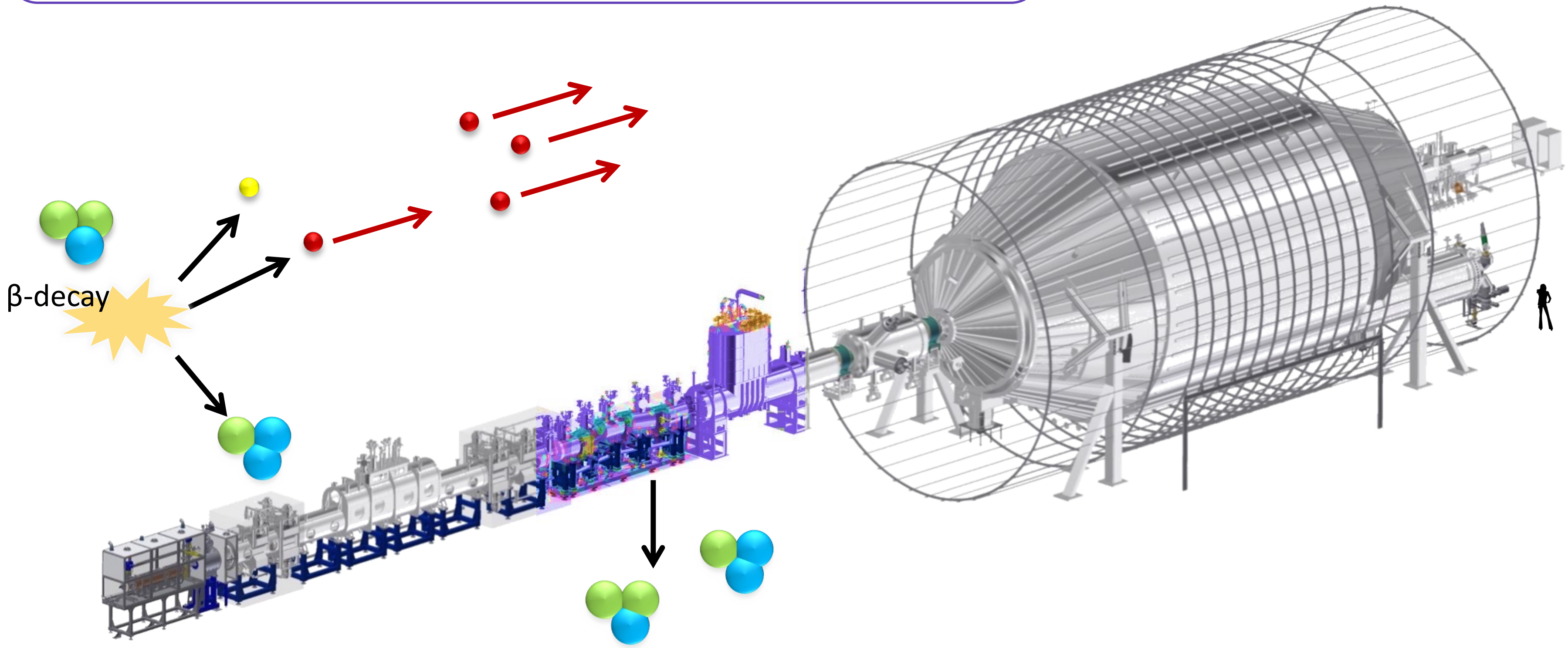
Windowless gaseous tritium source
- molecular tritium in closed loop system
- 10^{11} decays/s



KATRIN Working Principle

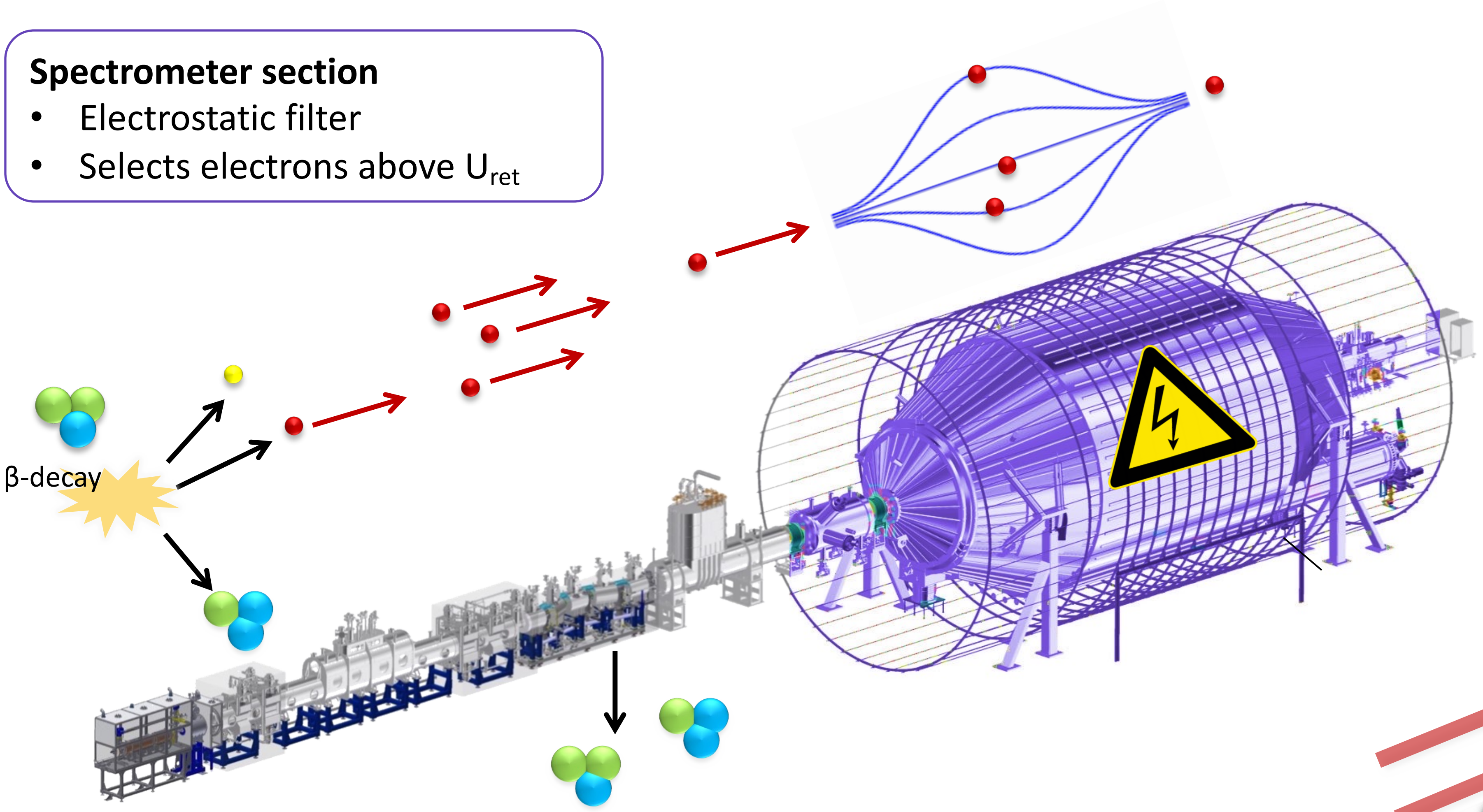
Transport section

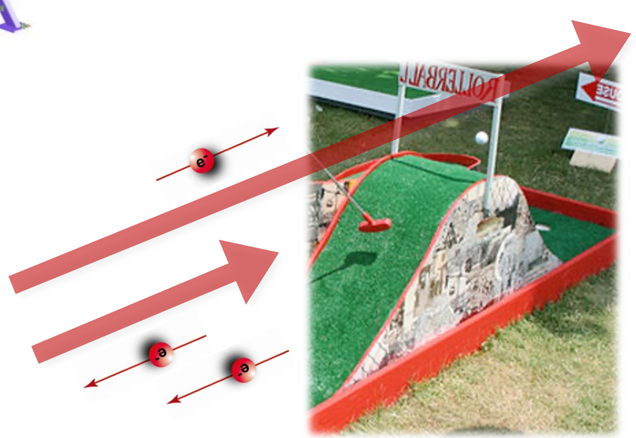
- magnetic guidance of electrons (@ 4 T)
- tritium flow reduction by > 10^{14} + tritium ion removal



KATRIN Working Principle

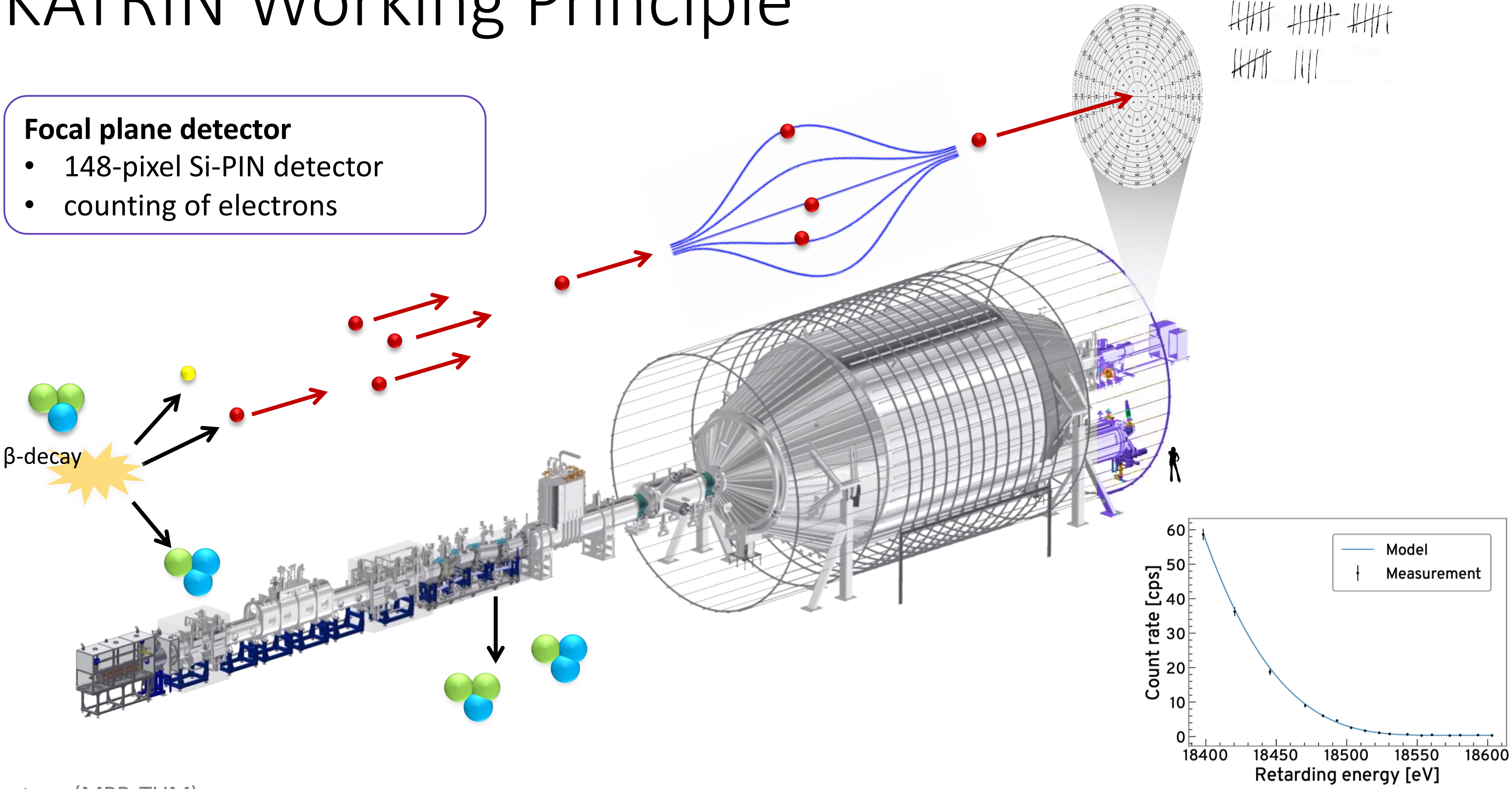
Spectrometer section
- Electrostatic filter
- Selects electrons above U_{ret}





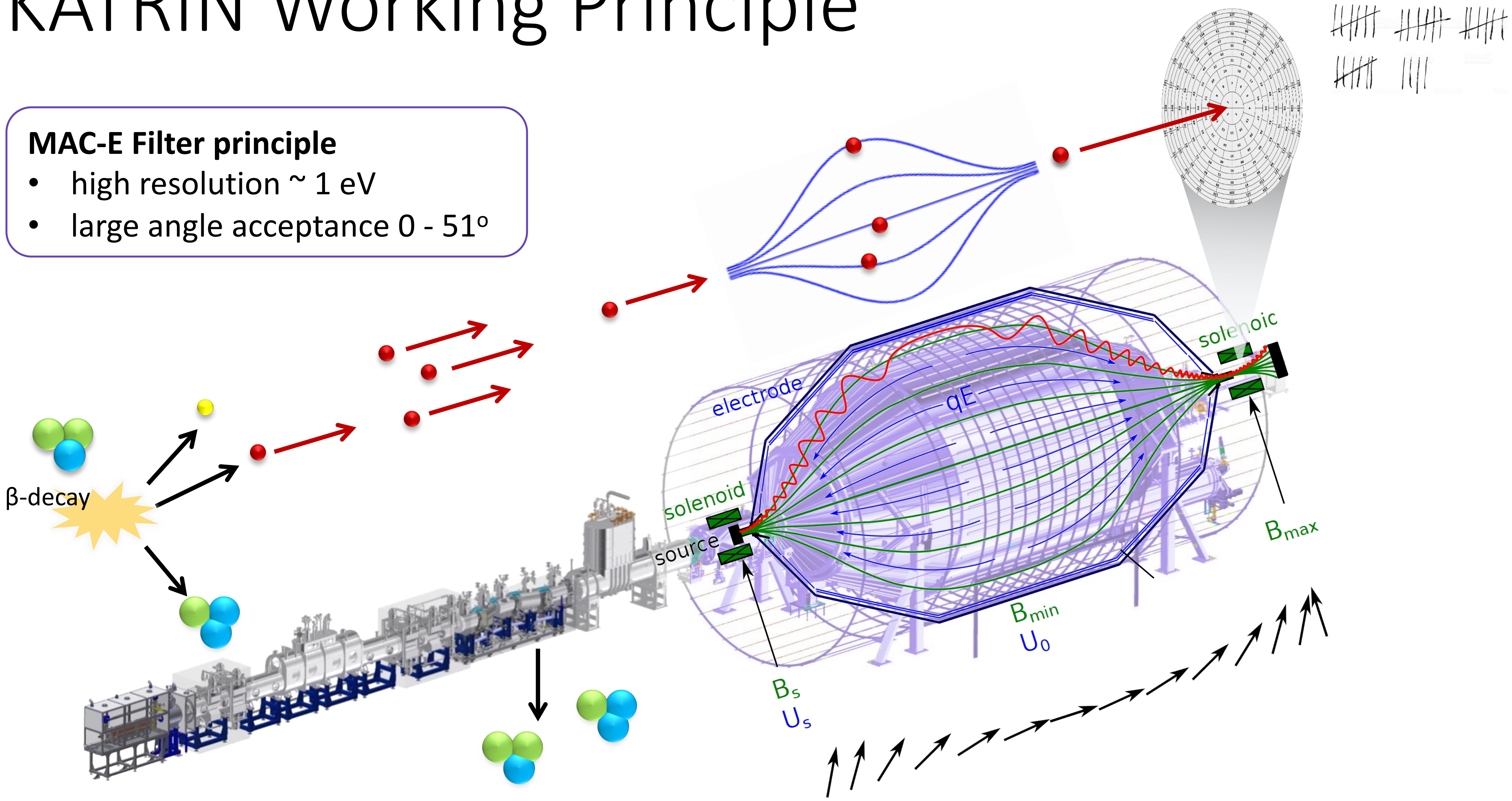
KATRIN Working Principle

Focal plane detector
- 148-pixel Si-PIN detector
- counting of electrons



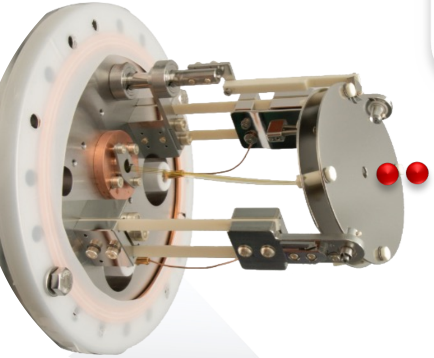
KATRIN Working Principle

MAC-E Filter principle
- high resolution ~ 1 eV
- large angle acceptance 0 - 51°

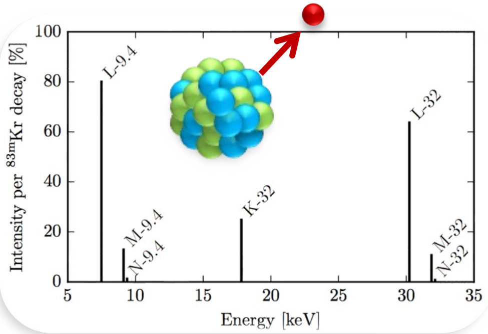


KATRIN Working Principle

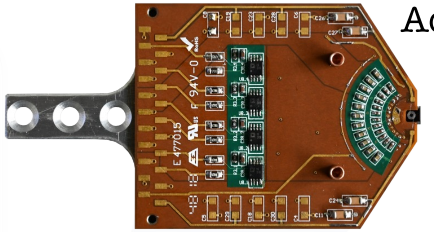
Electron gun:
Determination of scattering parameters



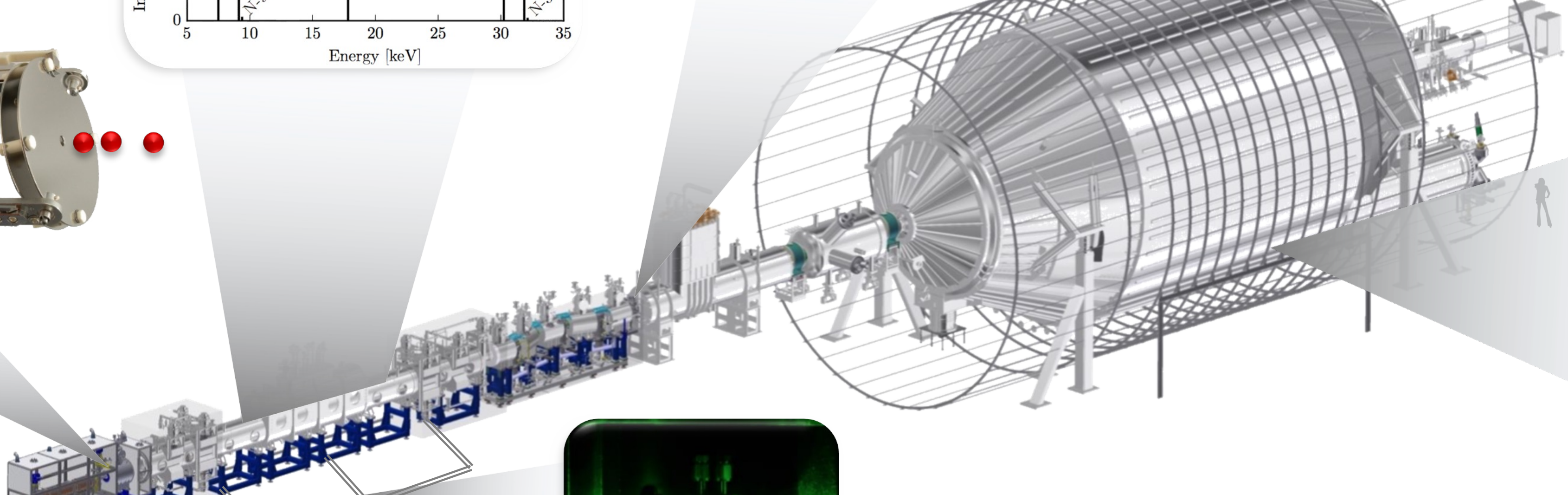
Gaseous krypton source:
EM field calibration



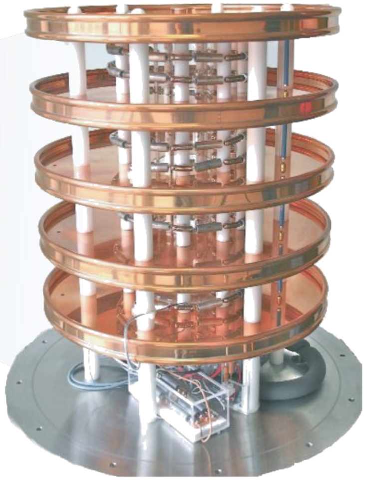
Forward Beam Monitor:
Activity monitoring @ 0.1%/min

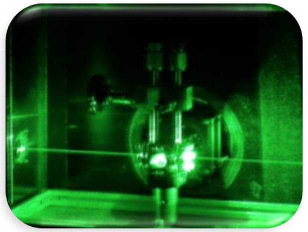


Magnetic field sensor system

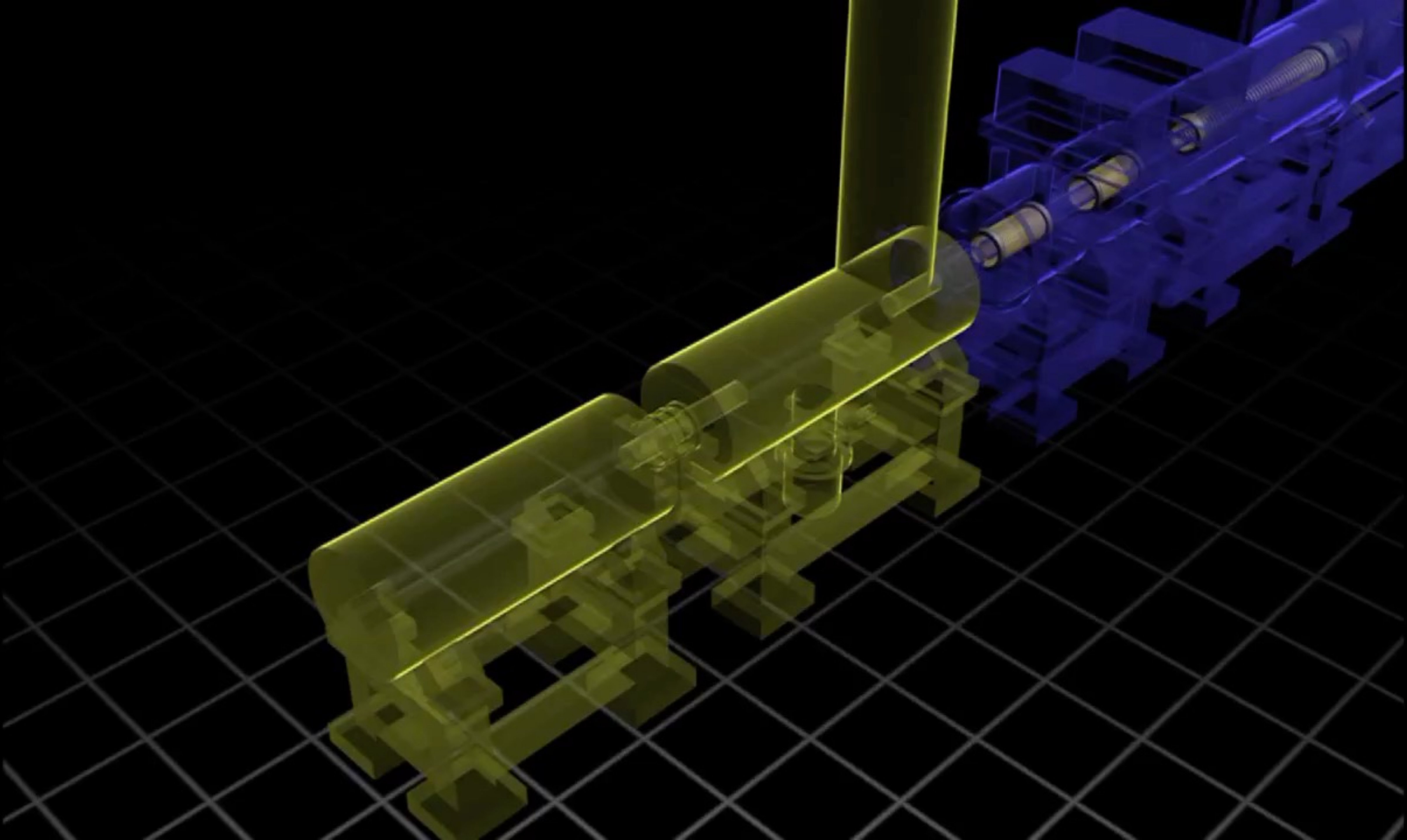


High Voltage System:
HV monitoring @ ppm-level





Laser Raman System:
Gas composition monitoring @ 0.1%/min

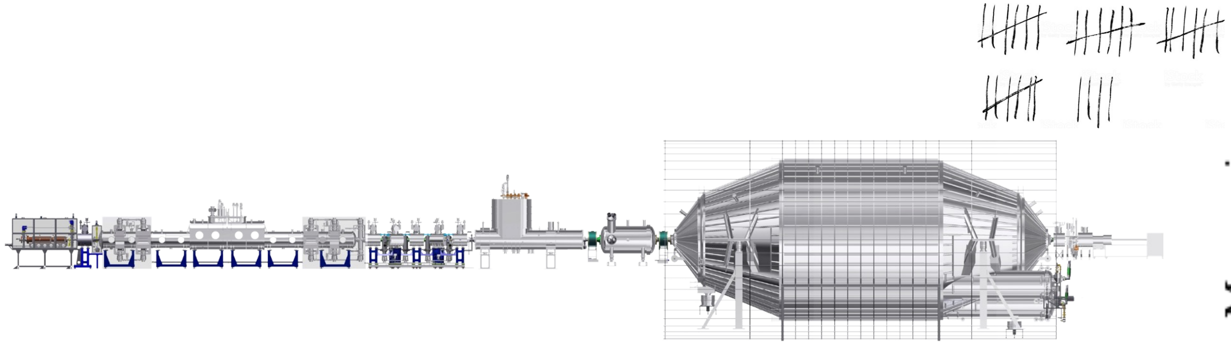


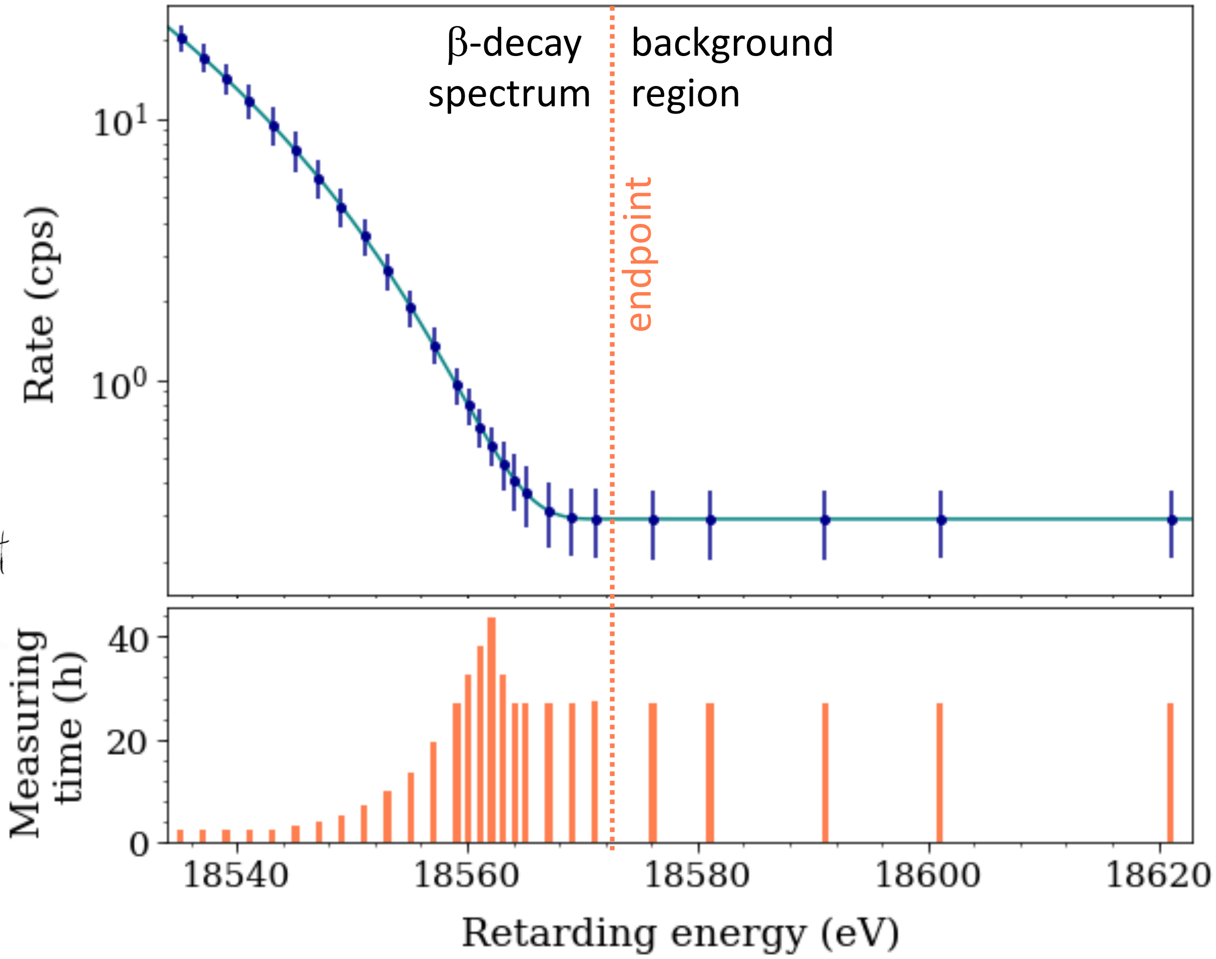
Measurement strategy

Several measurement campaigns per year

Each campaign consists of hundreds **β-scans**

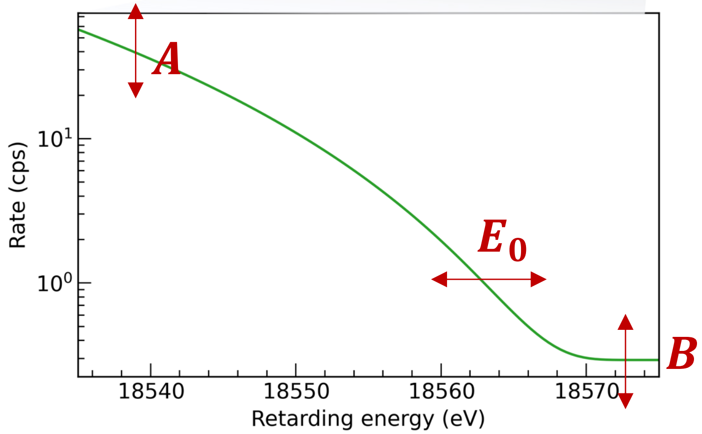
- Scan points: **30 HV set points**
- Scan interval: **E_0 – 40 eV , E_0 + 130 eV**
- Scan time: **2 hours**

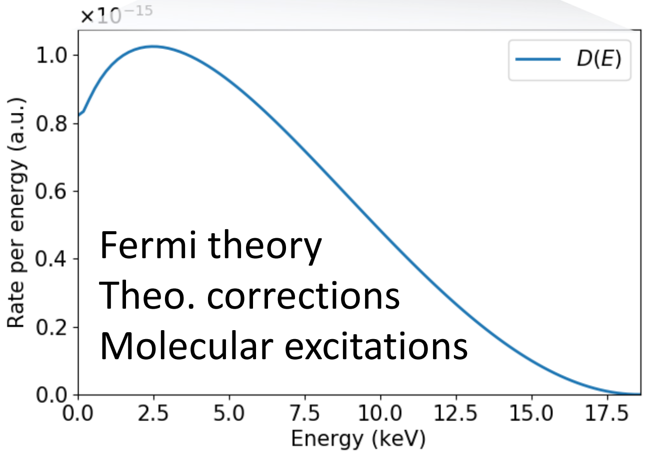


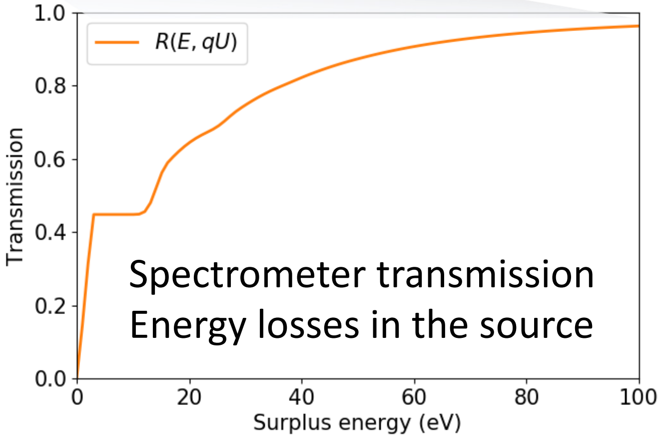


Analysis strategy

- Fit of theoretical prediction: $\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{\boldsymbol{E_0}} D(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}) \cdot R(qU, E)\, dE + \boldsymbol{B}$



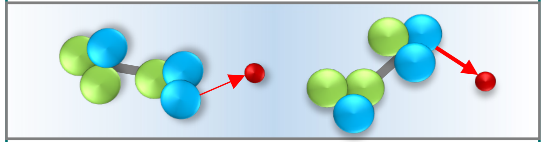




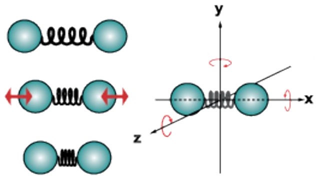
- Free parameters: $\boldsymbol{m_\nu^2}, \boldsymbol{E_0}, \boldsymbol{B}, \boldsymbol{A}$
- Fit model informed by **theoretical** and **experimental** inputs (e-gun, krypton, monitoring, …)

Systematic uncertainties

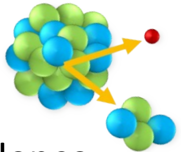
Source electric potential



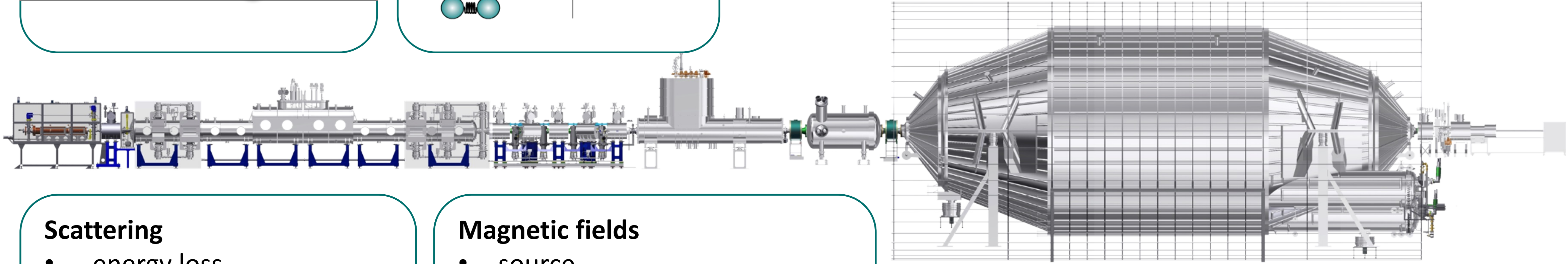
Molecular Final States



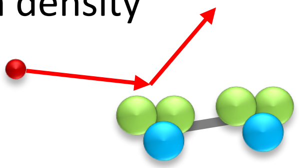
Background:



- time correlation
- retarding potential dependence



Scattering
- energy loss
- column density

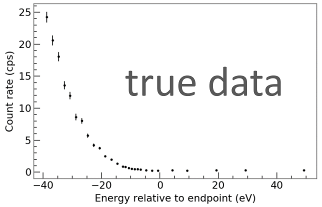


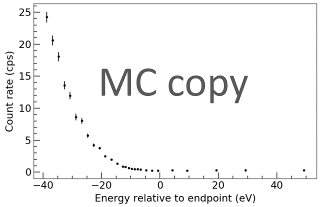
Magnetic fields
- source
- spectrometer
- detector

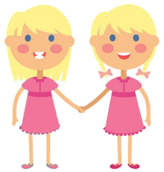
Blinded analysis

Freeze analysis on MC-twin data

- MC-copy of each scan (with m_ν = 0 eV)

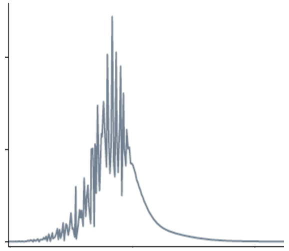


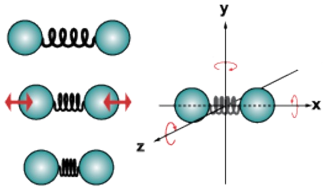




Blinded model

- Modified molecular final state dist.

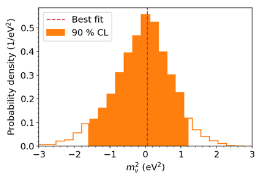


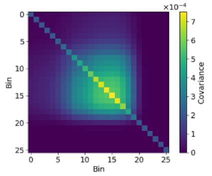


m_ν^2

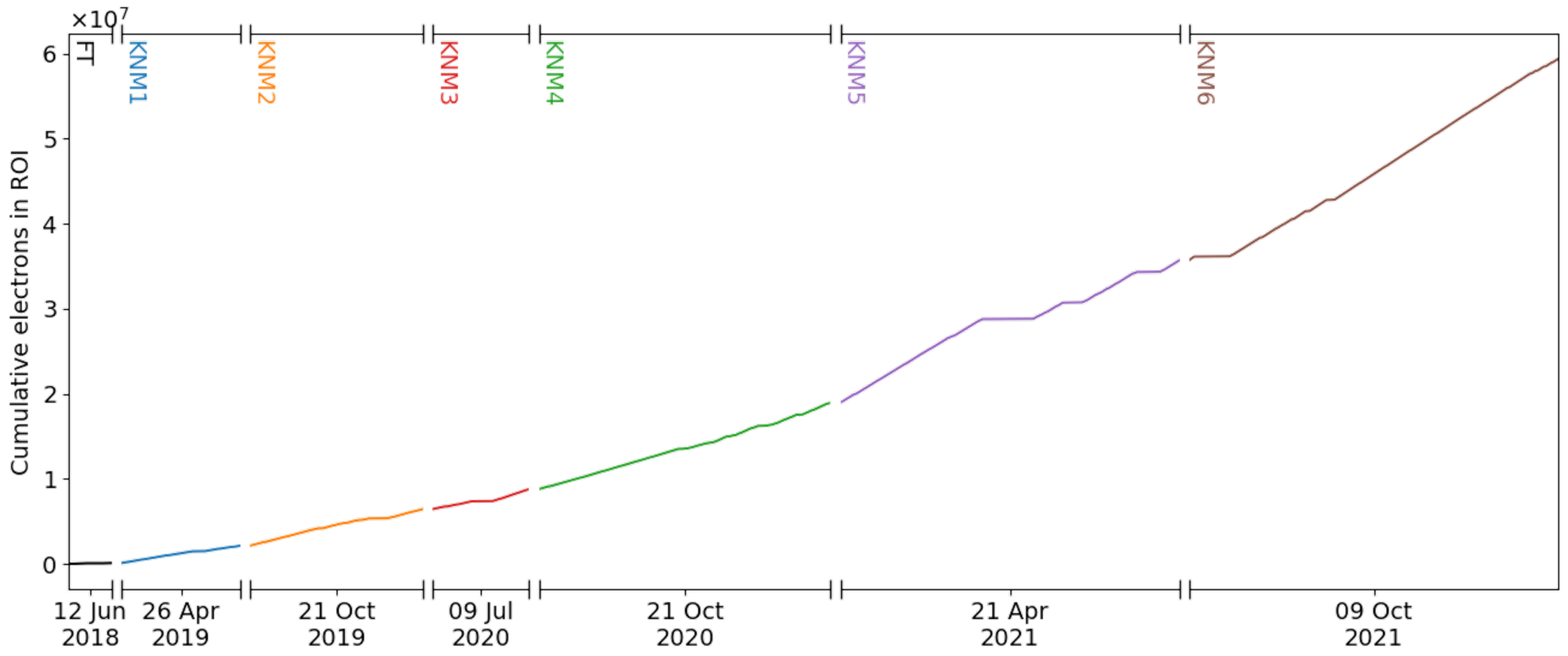
Independent analysis strategies

- Covariance matrix
- Monte Carlo propagation
- Pull term





KATRIN Data Taking Overview



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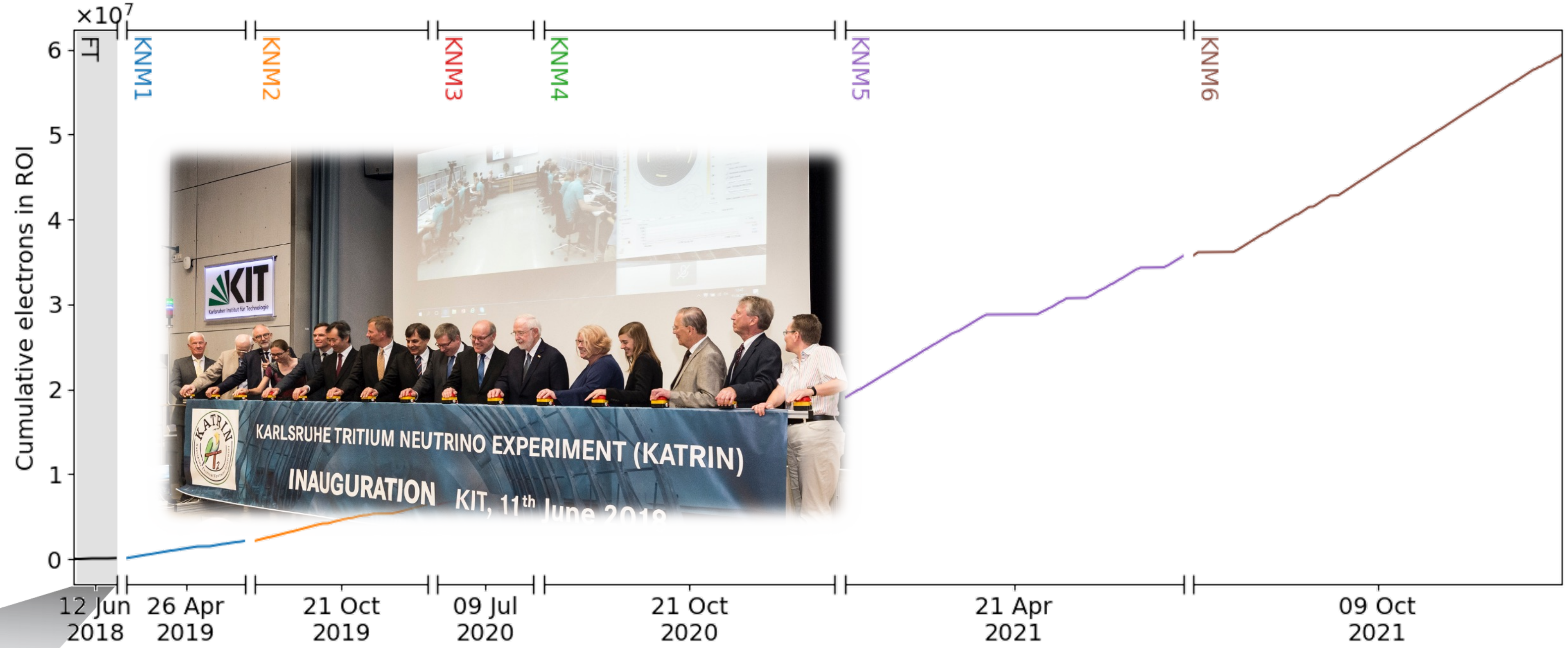
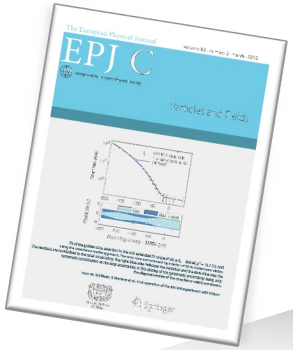
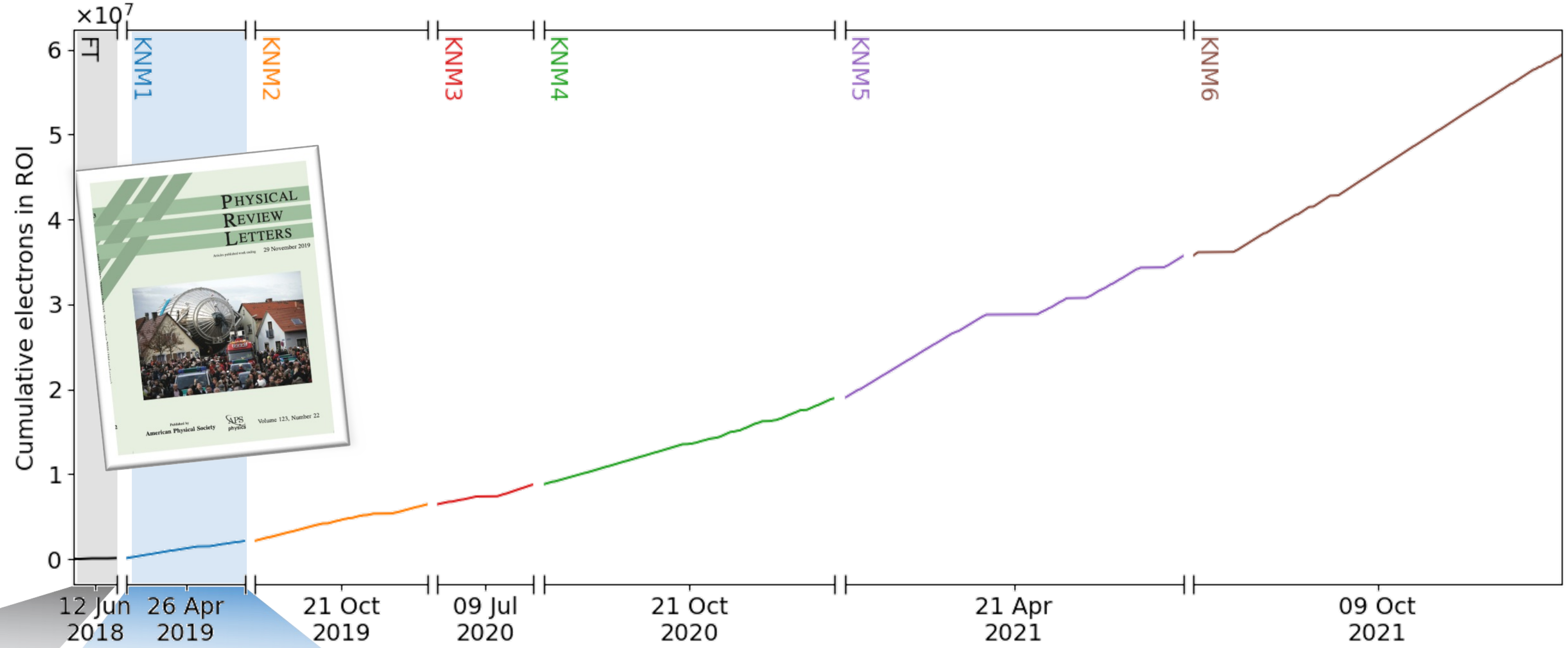


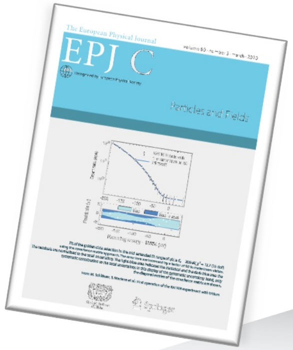


- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

KATRIN Data Taking Overview





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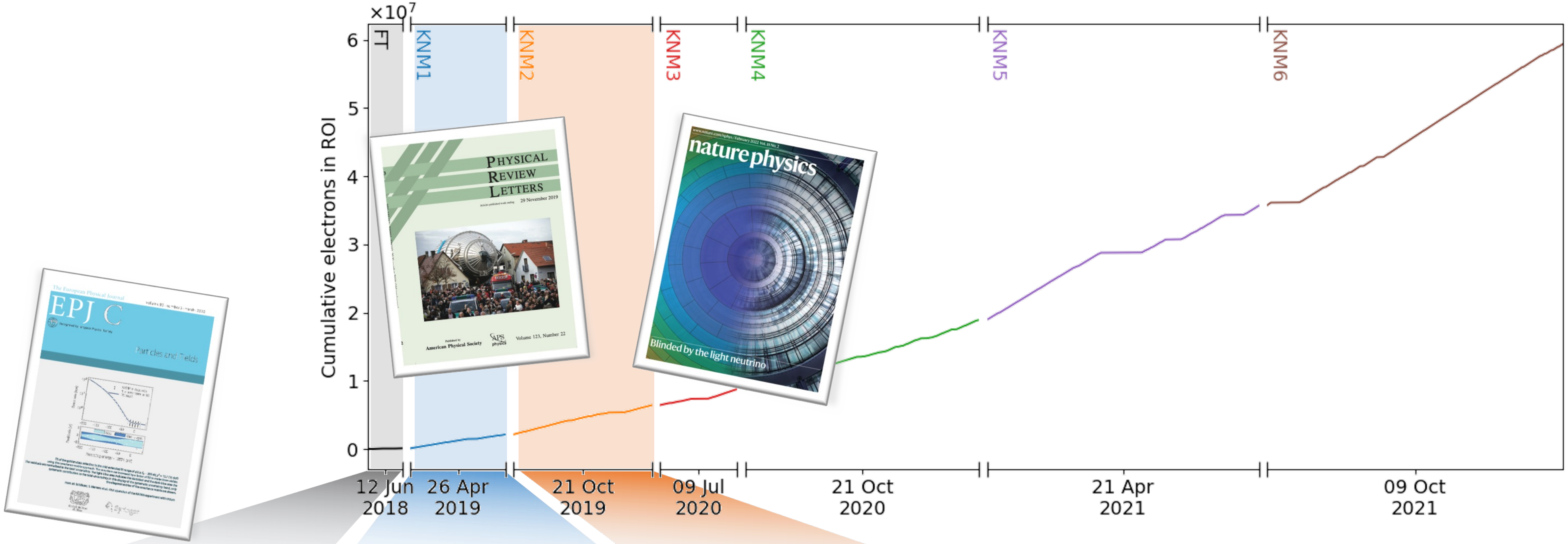
EPJ C 80, 264 (2020)

- 1^{st} m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)

KATRIN Data Taking Overview



- Commissioning
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EPJ C 80, 264 (2020)

- 1st m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)

- 2nd m_ν campaign
- Latest result

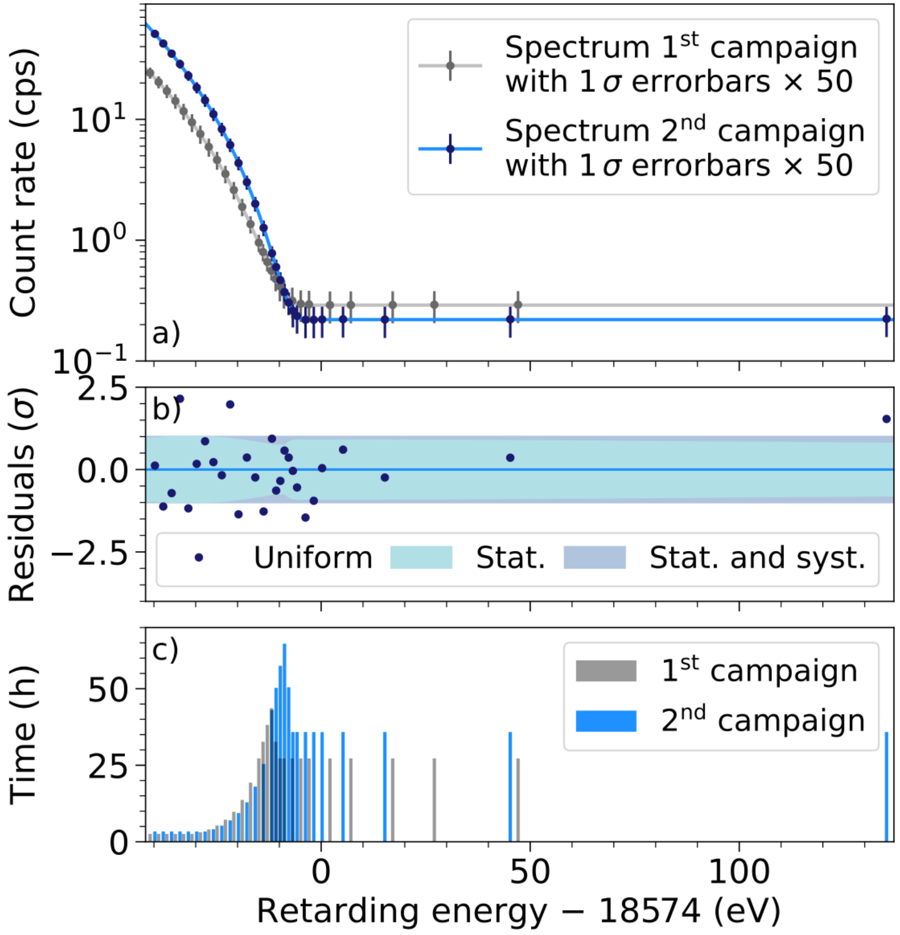
Nat. Phys. **18,** 160–166 (2022)

→ This talk

Improvements wrt 1st campaign

	1st campaign PRL 123 (2019)		2nd campaign Nat. Phys. (2022)
Campaign date	April-May 2019		Sept-Nov 2019
Total scan time	22 days		31 days
Source activity	25 GBq	nominal activity →	98 GBq
Background	290 mcps	reduction -25% →	220 mcps
Tritium purity	97.6%		98.7%
Electrons in RoI	2 Mio		4.3 Mio

New results



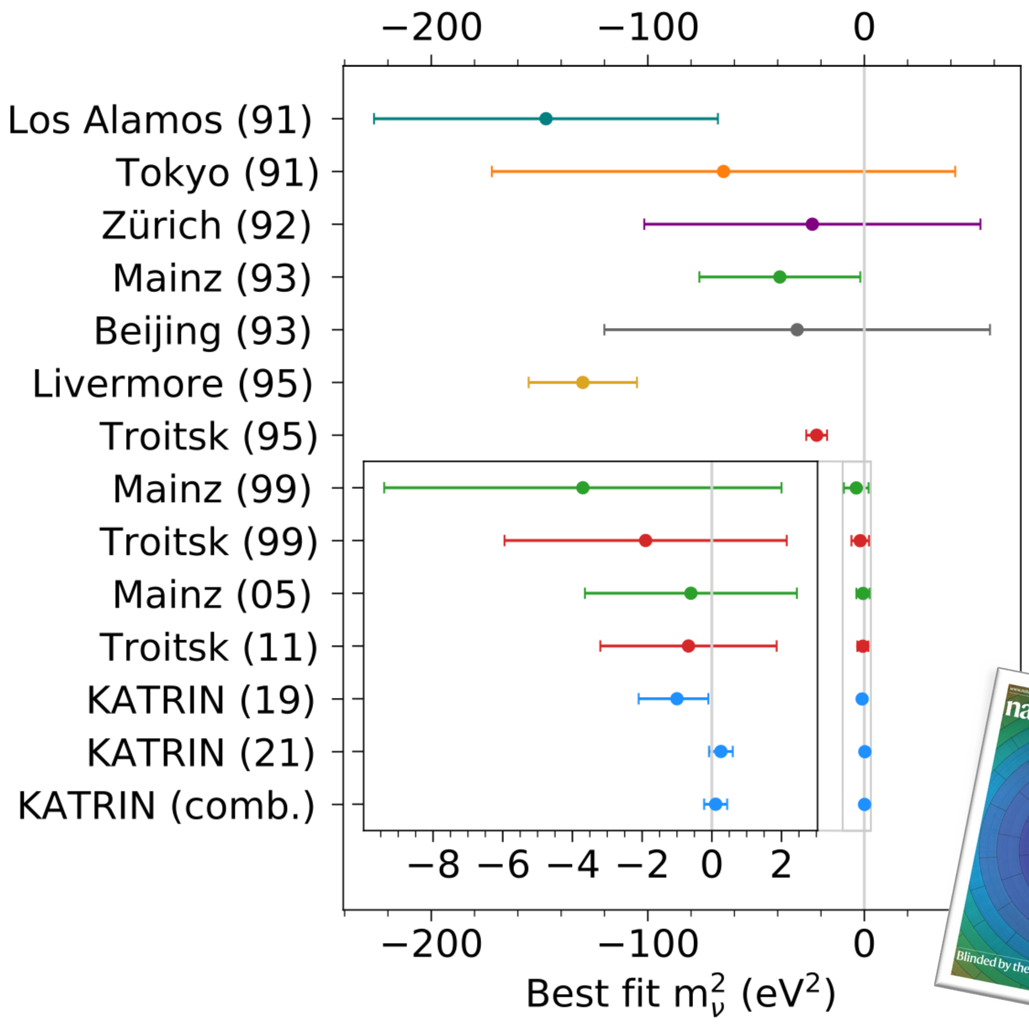
First campaign:

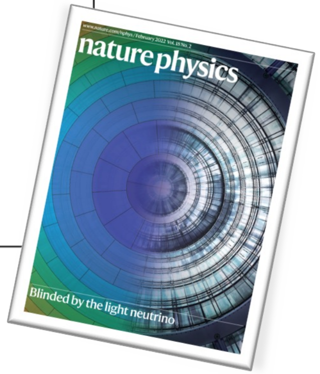
- total statistics: 2 million events
- excellent goodness-of-fit: p-value = 0.56
- best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ **eV² (stat. dom.)**
- limit: $m_\nu < 1.1$ **eV (90% CL)**

Second campaign:

- total statistics: 4 million events
- excellent goodness-of-fit: p-value = 0.8
- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$**eV² (stat. dom.)**
- limit: $m_\nu < 0.9$ **eV (90% CL)**

Historical context





- KATRIN (2nd campaign):

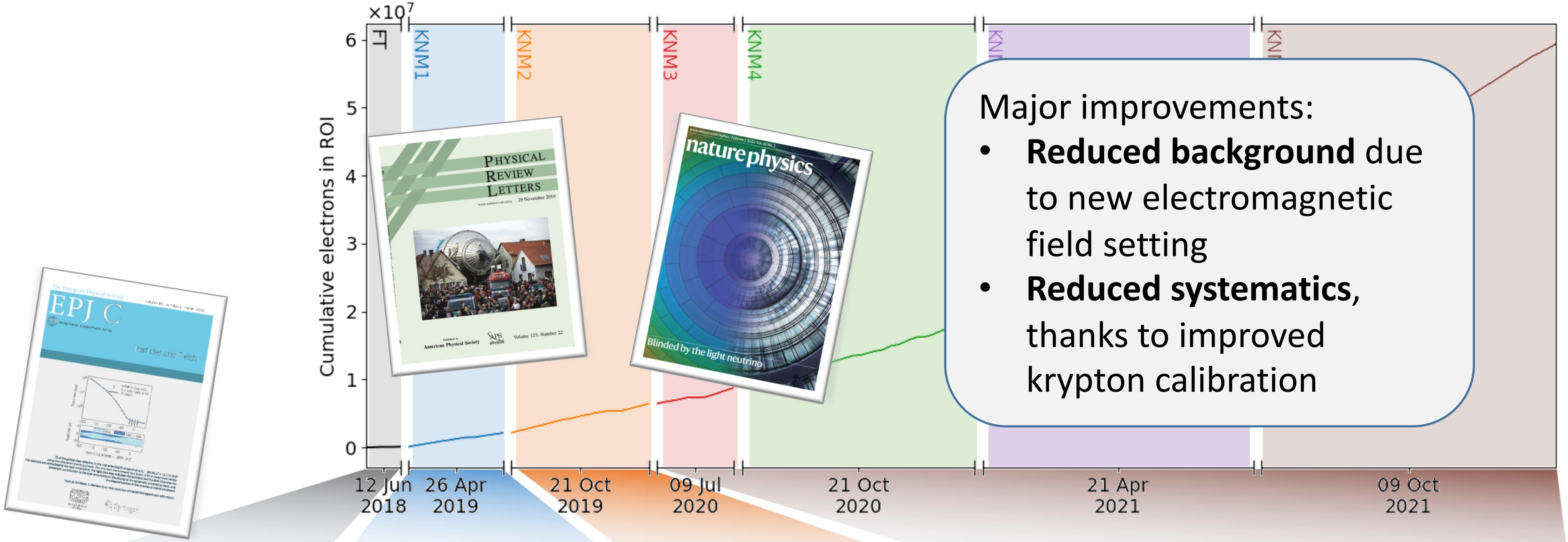
  first direct neutrino-mass experiment to reach sub-eV sensitivity and limit

- 1st and 2nd campaign combined limit:

  $m_\nu < 0.8$ **eV (90% CL)**

KATRIN Collab. Nat. Phys. **18,** 160–166 (2022)

KATRIN Data Taking Overview



Major improvements:

- **Reduced background** due to new electromagnetic field setting
- **Reduced systematics,** thanks to improved krypton calibration

- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

- 1^{st} m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)
Phys. Rev. D 104, 012005 (2021)

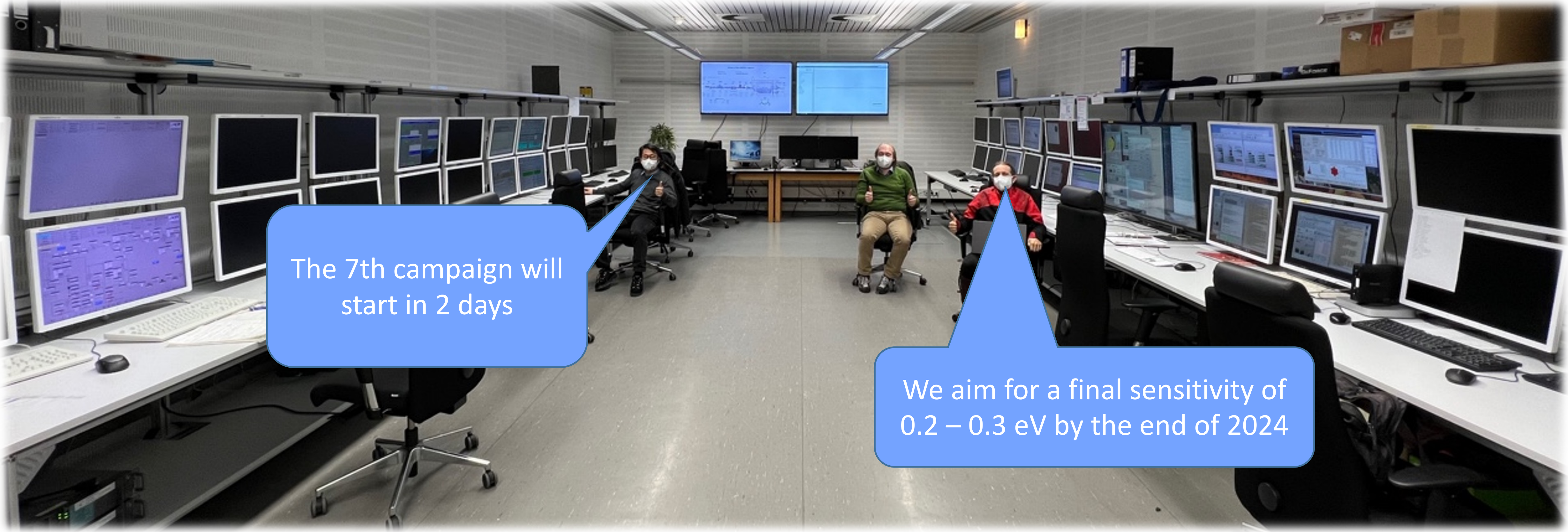
- 2^{nd} m_ν campaign
- Latest result

arXiv:2105.0853, in print

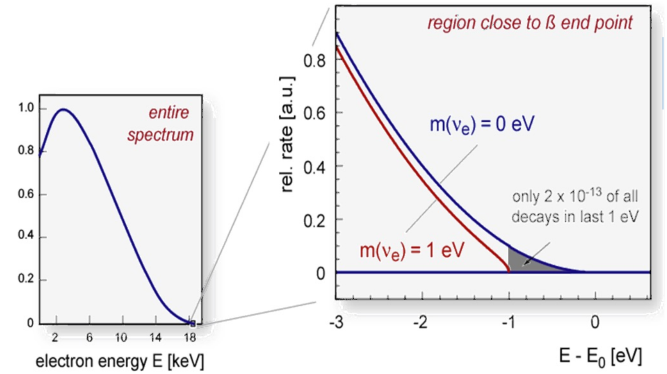
- $3^{rd} + 4^{th} + 5^{th} + 6^{th}$ m_ν campaign
- Analysis ongoing

Outlook

KATRIN control room:



Beyond KATRIN...



Electrostatic filter (MAC-E)

counting above threshold

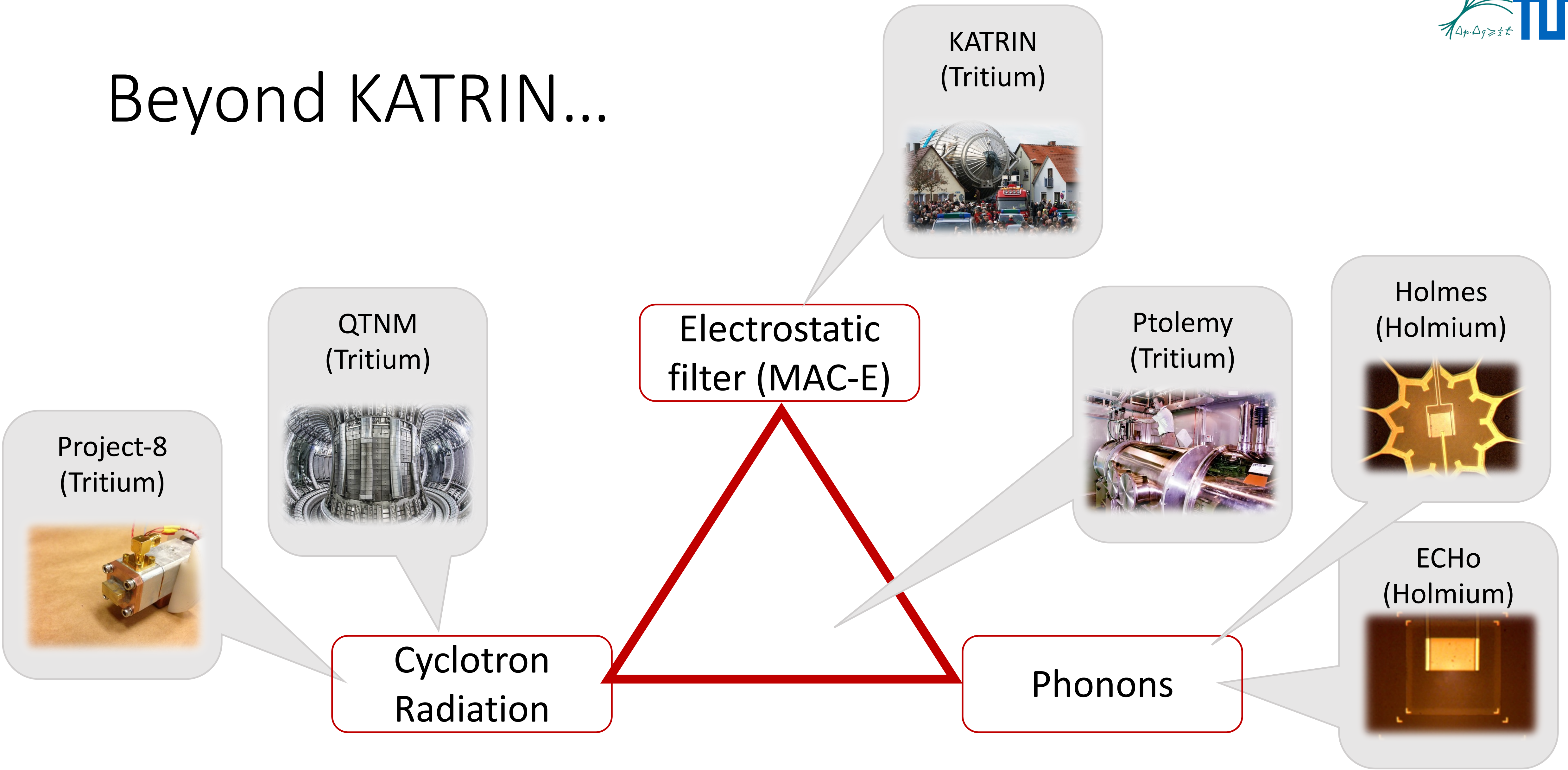
frequency

Cyclotron Radiation

Phonons

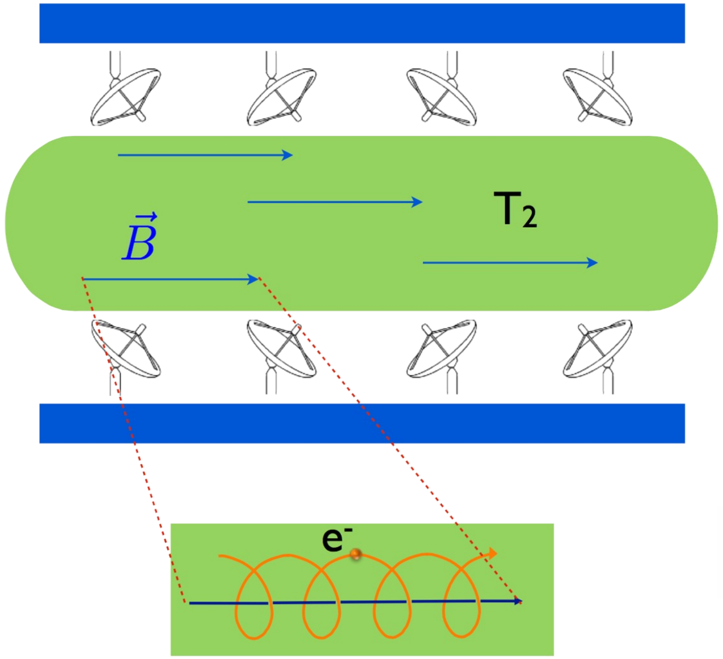
heat

Beyond KATRIN...

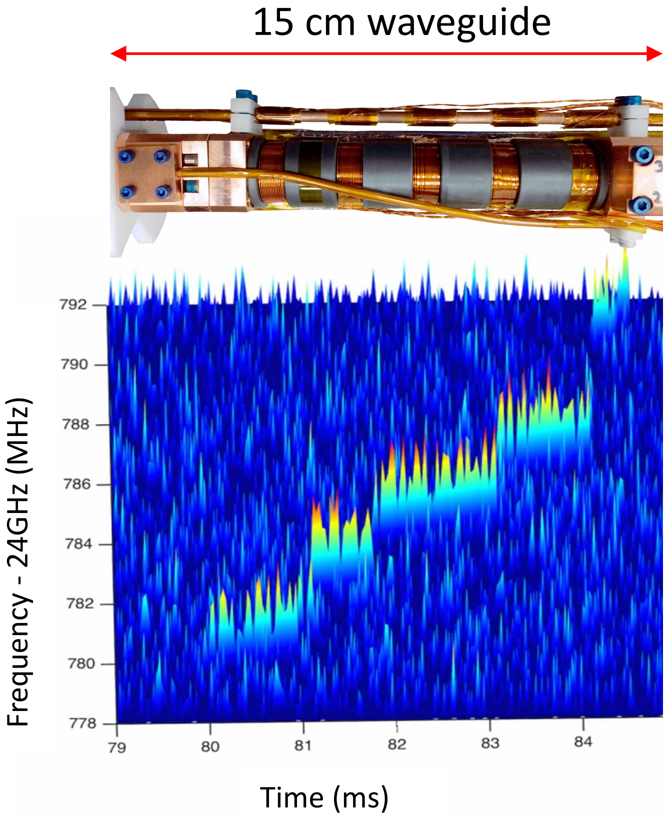


Project – 8

- Cyclotron Emission Radiation Spectroscopy (CRES)
  - ✓ eV-scale differential measurement
  - ✓ „source = detector“ concept
- CRES technology demonstrated
  Phys. Rev. Lett. 114, 1162501 (2015)
  J. Phys. G44 (2017) no.5, 054004
- Next steps:
  - large-volume (200 cm^3) cell
  - develop atomic tritium source
- Ultimate goal: 40 meV sensitivity
  Phys. Rev. C 103, No.6. (2021)

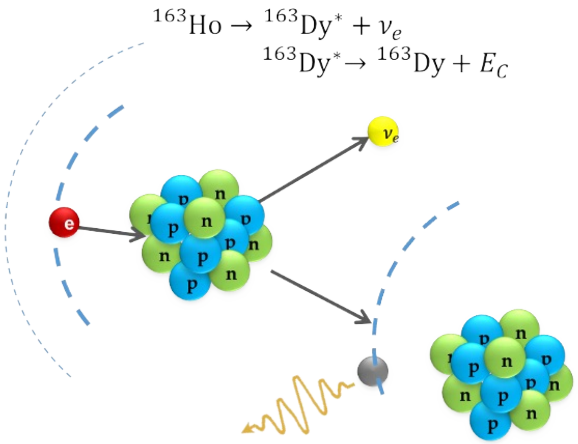


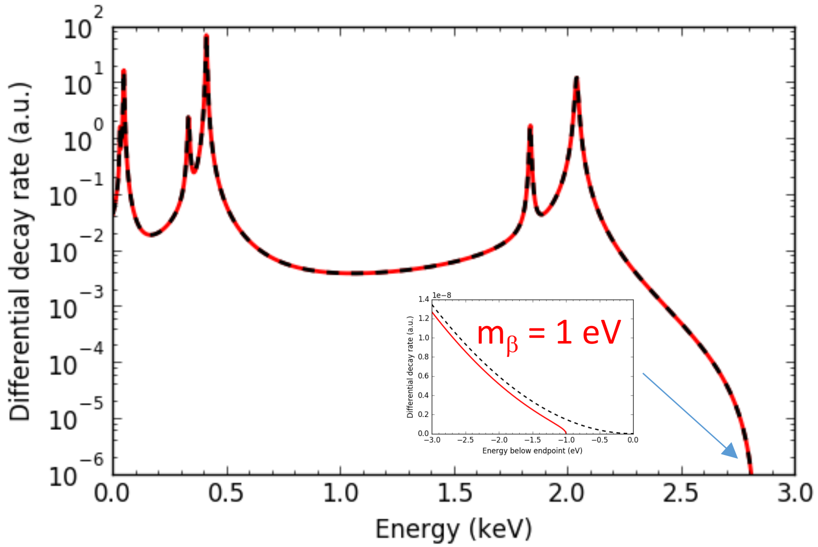
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$

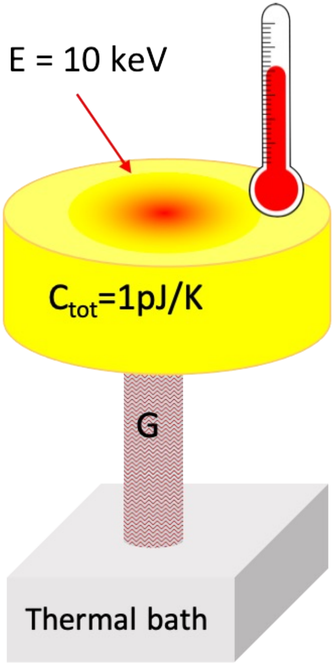


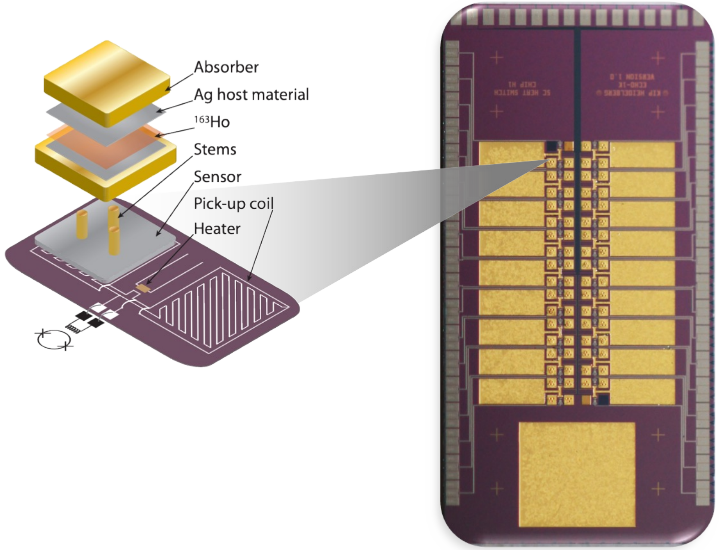
ECHo & HOLMES

- Electron capture on 163-holmium
- Low temperature calorimeters
  - ✓ eV-scale differential measurement
  - ✓ „source = detector“ concept
- Two approaches:
  - ECHo: metallic magnetic calorimeters (MMC)
    A. Fleischmann et al., *AIP Conf. Proc.* **1185**, 571, (2009)
    L. Gastaldo et al., Nucl. Inst. Meth. A, 711, 150-159 (2013)
  - HOLMES: transition edge sensors (TES)
    J Low Temp Phys **184,** 492–497 (2016)
- *Phase-1 of ECHo* completed (100 Bq)
  EPJ-C 81, 963 (2021), arXiv:2111.09945 (2021)
- Ultimate goal: 10 MBq
  (low sub-eV sensitivity)

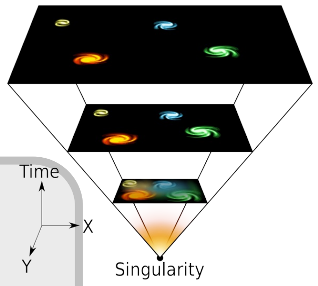




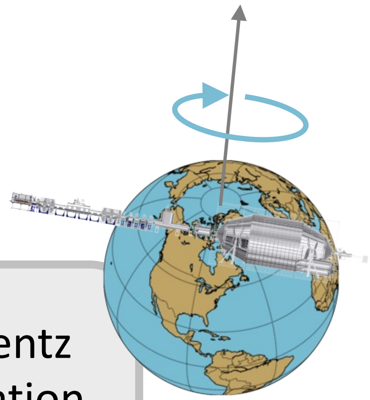




New physics in precision beta-spectroscopy



Search for Big Bang neutrinos
(peak search)



Search for Lorentz invariance violation
(sidereal modulation)

Search for eV-keV sterile neutrinos
(kink search)

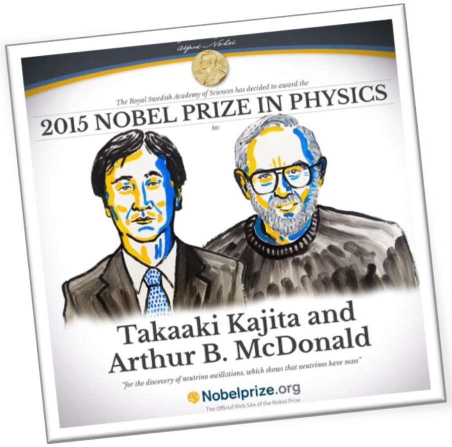
→ KATRIN: best limit based on terrestrial experiment
KATRIN Collab. arXiv:2202.04587 (2022)

→ KATRIN: First limit on specific LV parameter

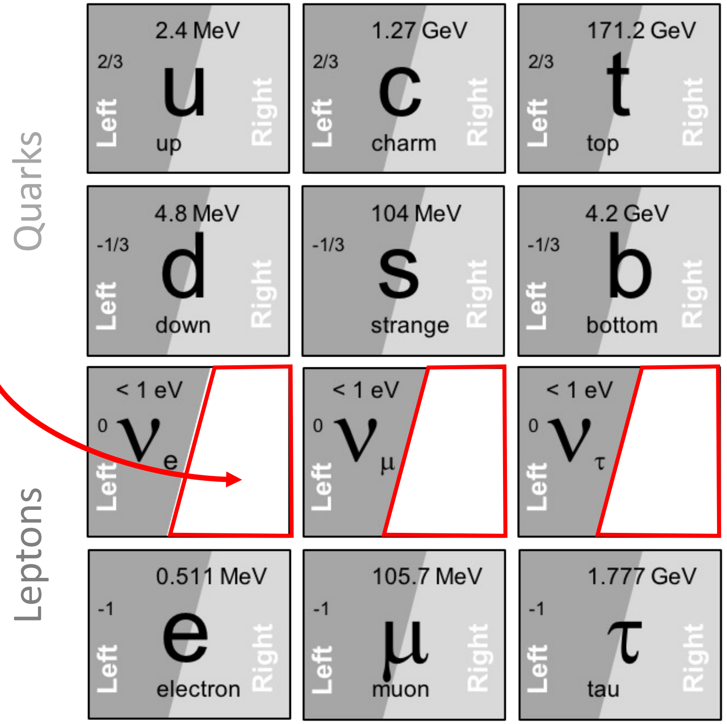
→ this talk

Sterile Neutrinos

Something is missing



Standard Model (SM)

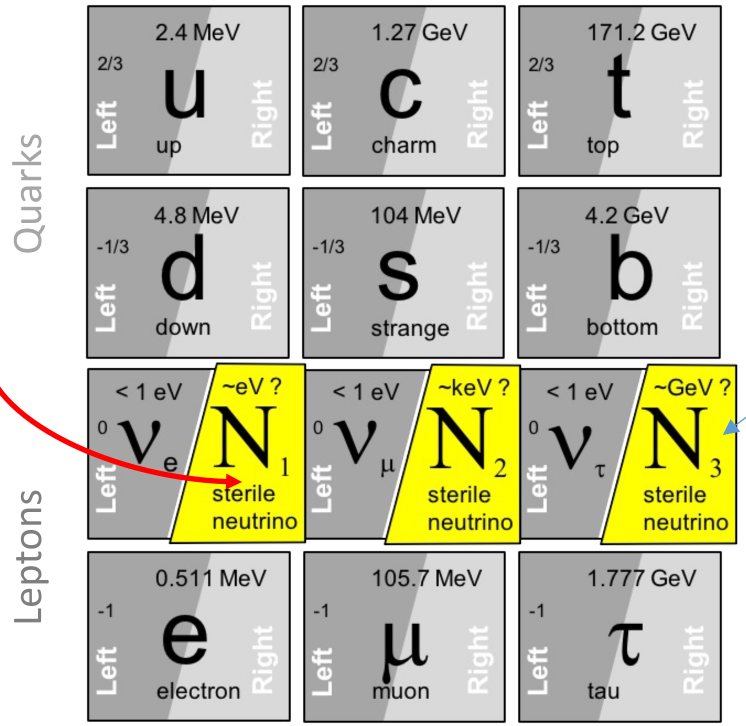


Sterile Neutrinos

Right-handed neutrinos are sterile

- ➢ additional mass eigenstates

ν–Minimal Standard Model

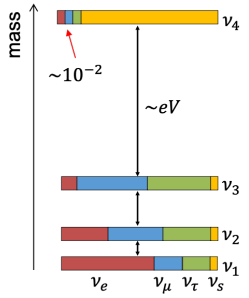


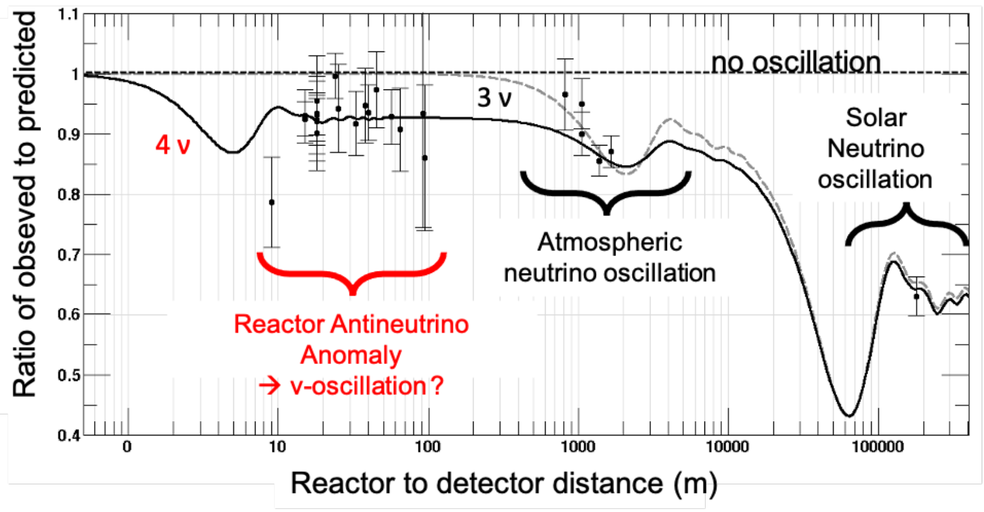
L. Canetti, M. Drewes, and M. Shaposhnikov, PRL **110** 061801 (2013)

Sterile Neutrinos

eV-scale sterile neutrino

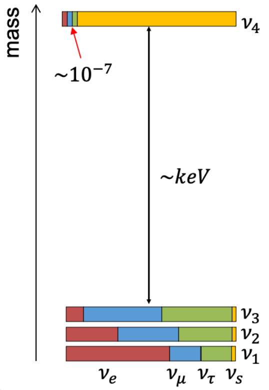
- Anomalies in ν–oscillation experiments
  Böser, Buck, Giunti, Lesgourgues, Ludhova, Mertens, Schukraft, Wurm, PPNP (2019)

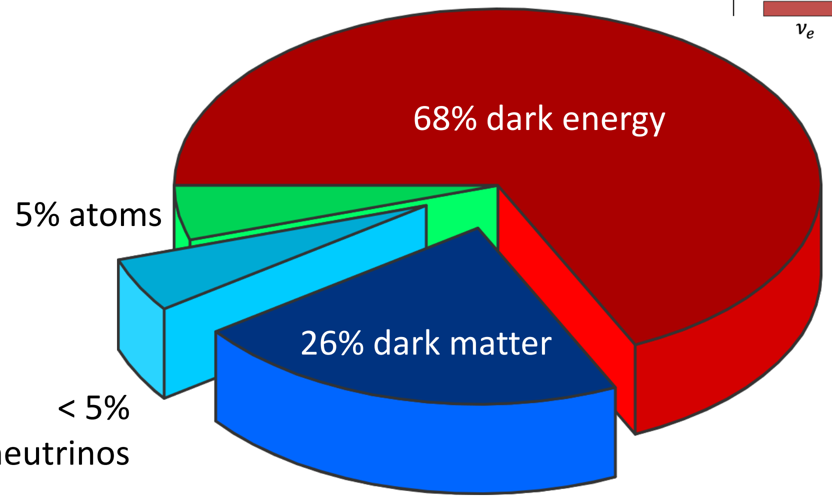




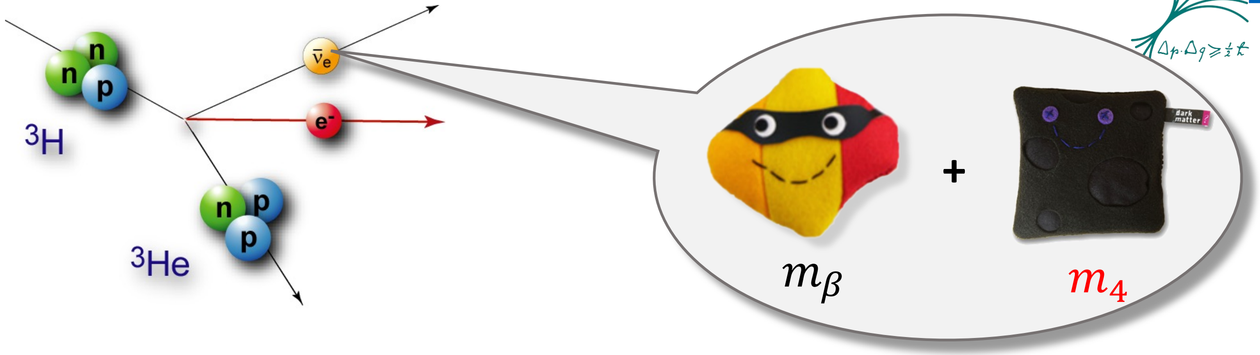
keV-scale sterile neutrino

- Dark matter candidate
  Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy, PPNP (2018)

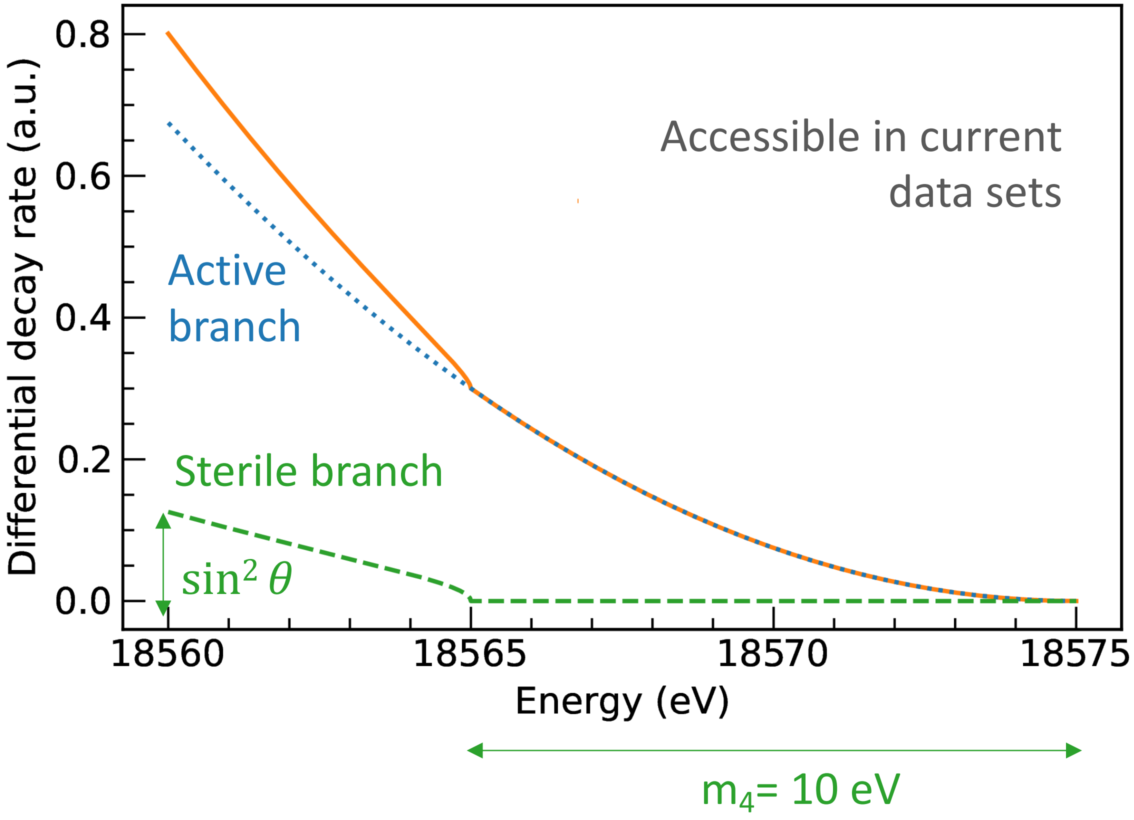




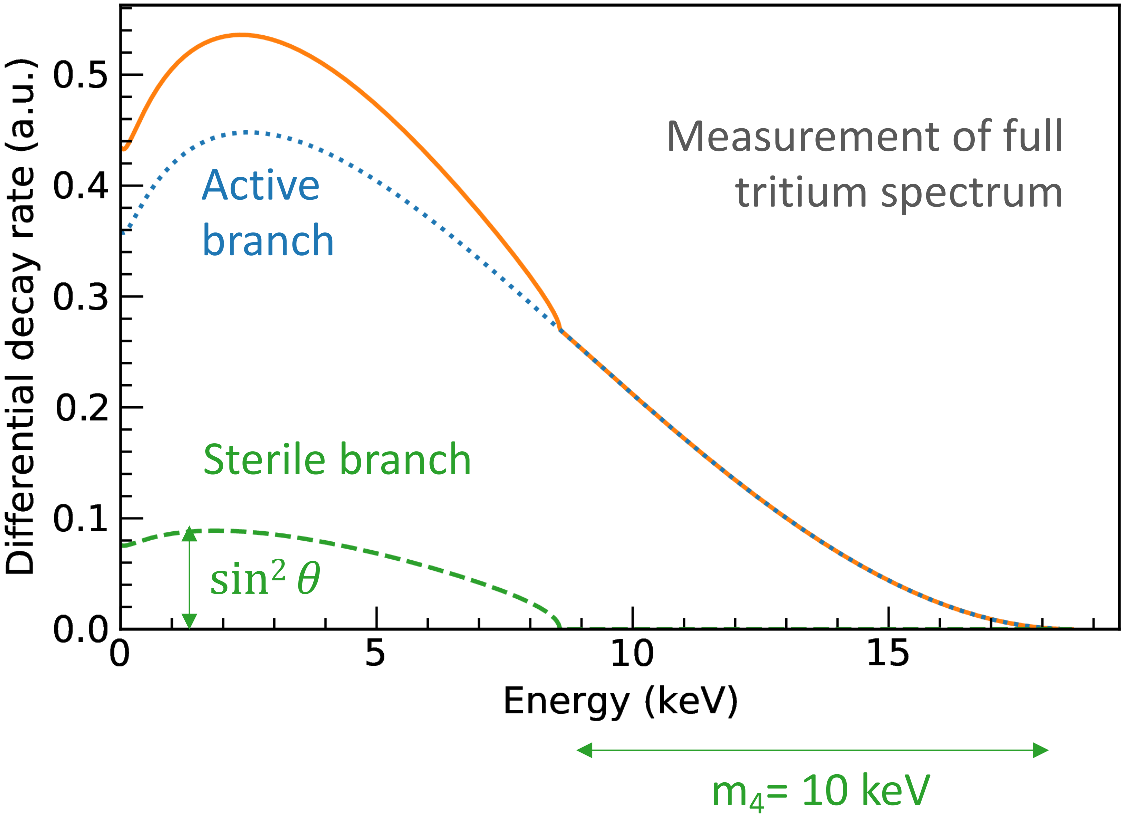
Sterile Neutrinos



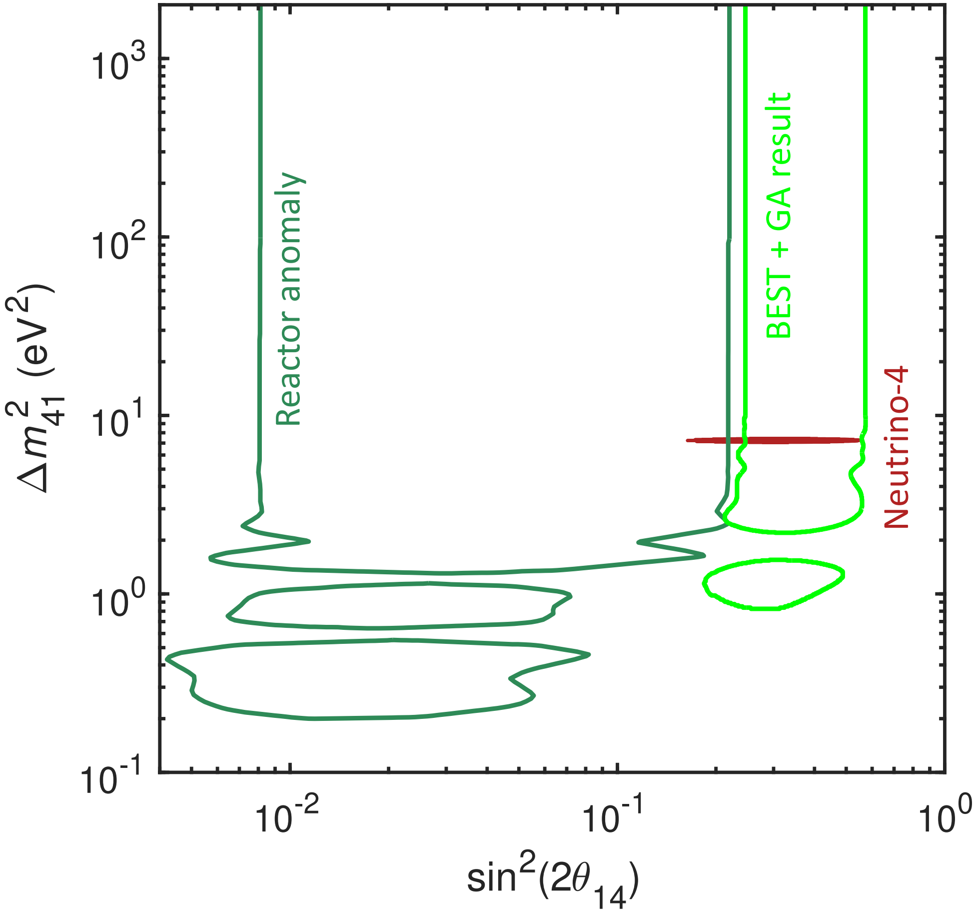
eV-scale sterile neutrino



keV-scale sterile neutrinos



Light sterile neutrino search in KATRIN

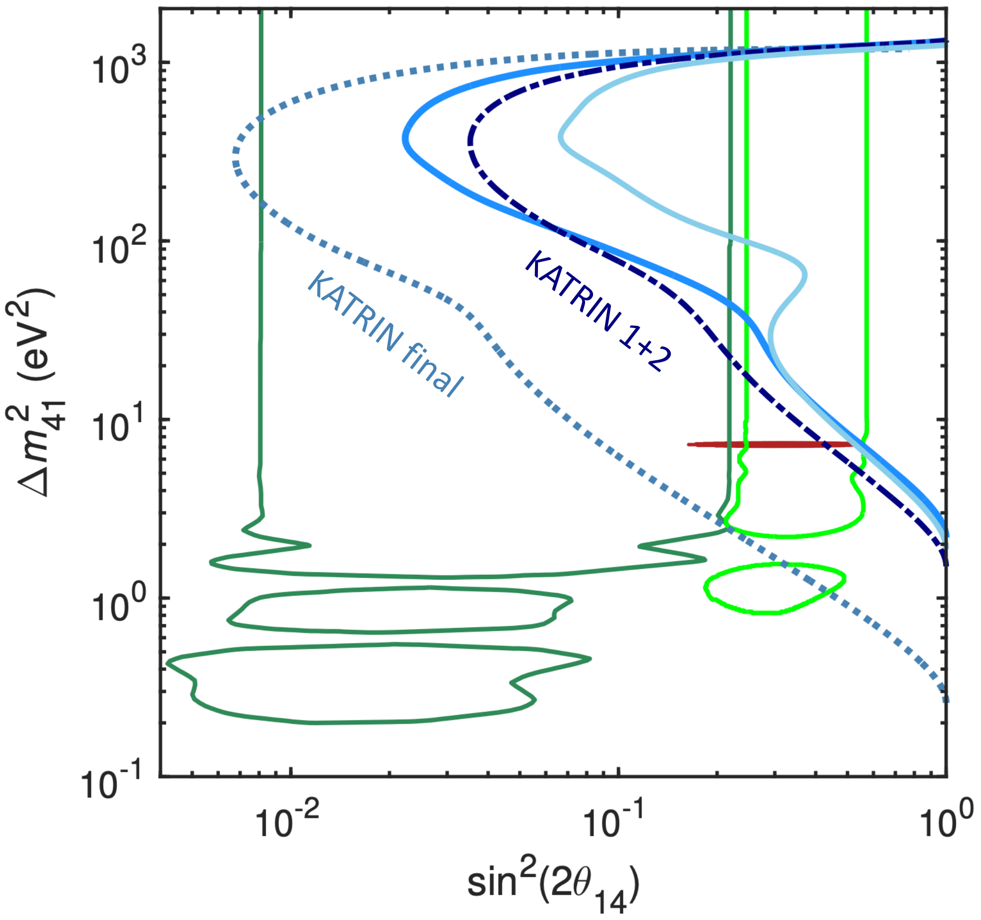


G. Mention et al Phys. Rev. D **83**, 073006 (2011)

A. P. Serebrov et al., Pisma Zh. Eksp. Teor. Fiz. 109, 209 (2019)

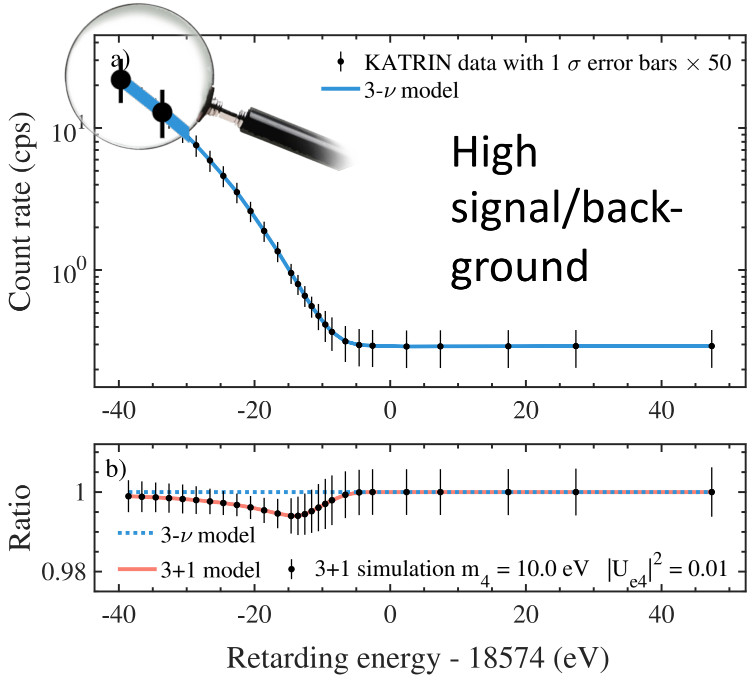
V. V. Barinov et al. (BEST), arXiv:2109.11482 (2021)

Light sterile neutrino search in KATRIN



✓ Start probing interesting parameters space

KATRIN Collab., PRL. 126, 091803 (2021)
KATRIN Collab. arXiv:2201.11593 (2022)



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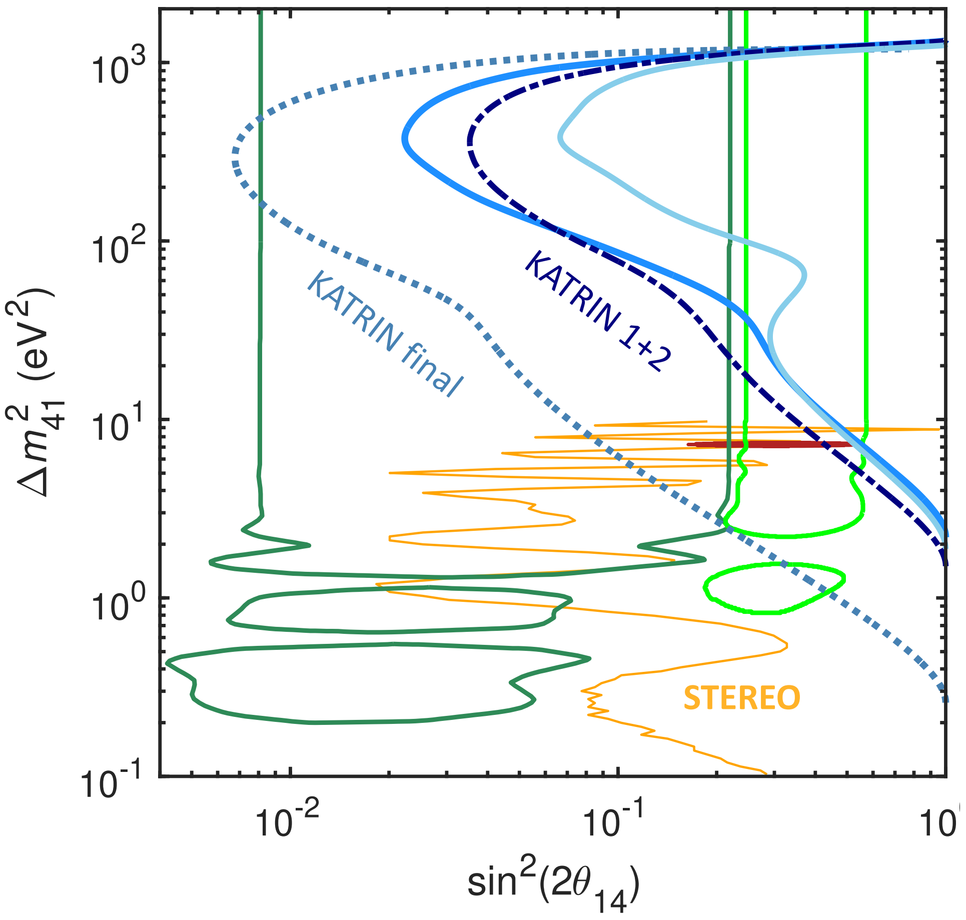


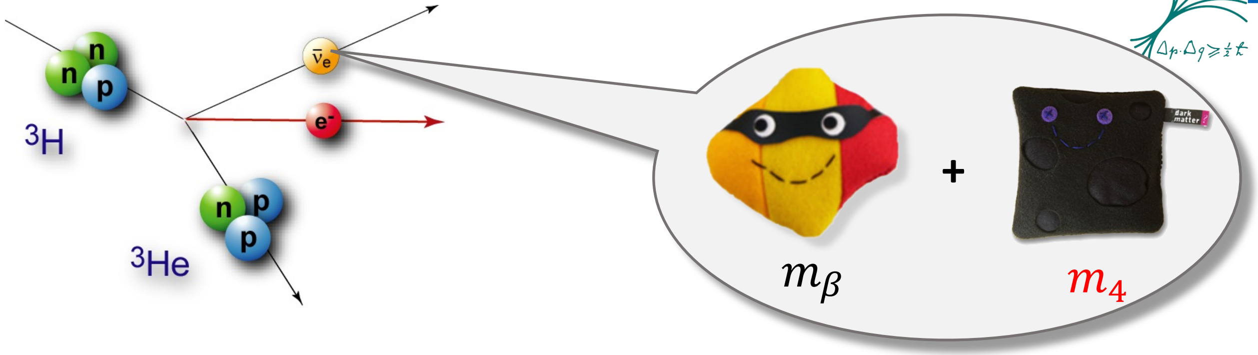
✓ Start probing interesting parameters space

KATRIN Collab., PRL. 126, 091803 (2021)
KATRIN Collab. arXiv:2201.11593 (2022)

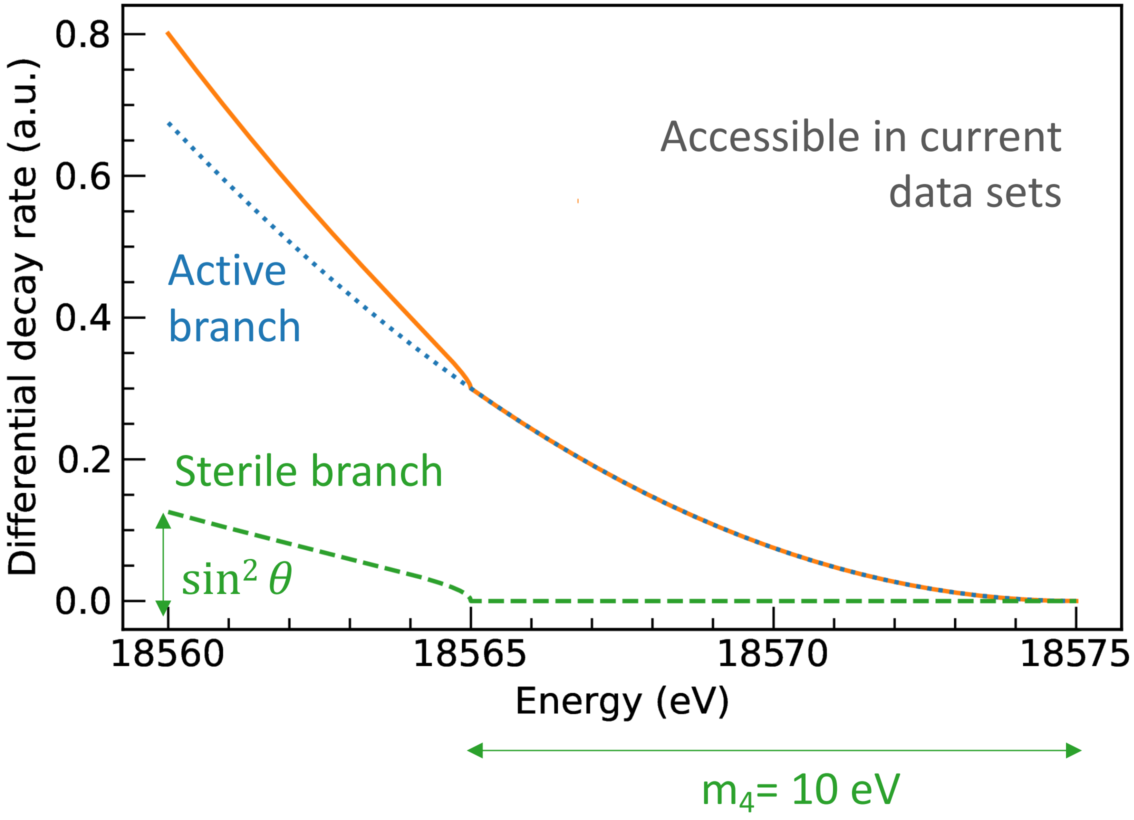
✓ Complementary probe to oscillation-based experiments

DANSS, arXiv:1911.10140 (2019)
STEREO, Phys. Rev. D 102, 052002 (2020)
PROSPECT, Phys. Rev. D 103, 032001 (2021)

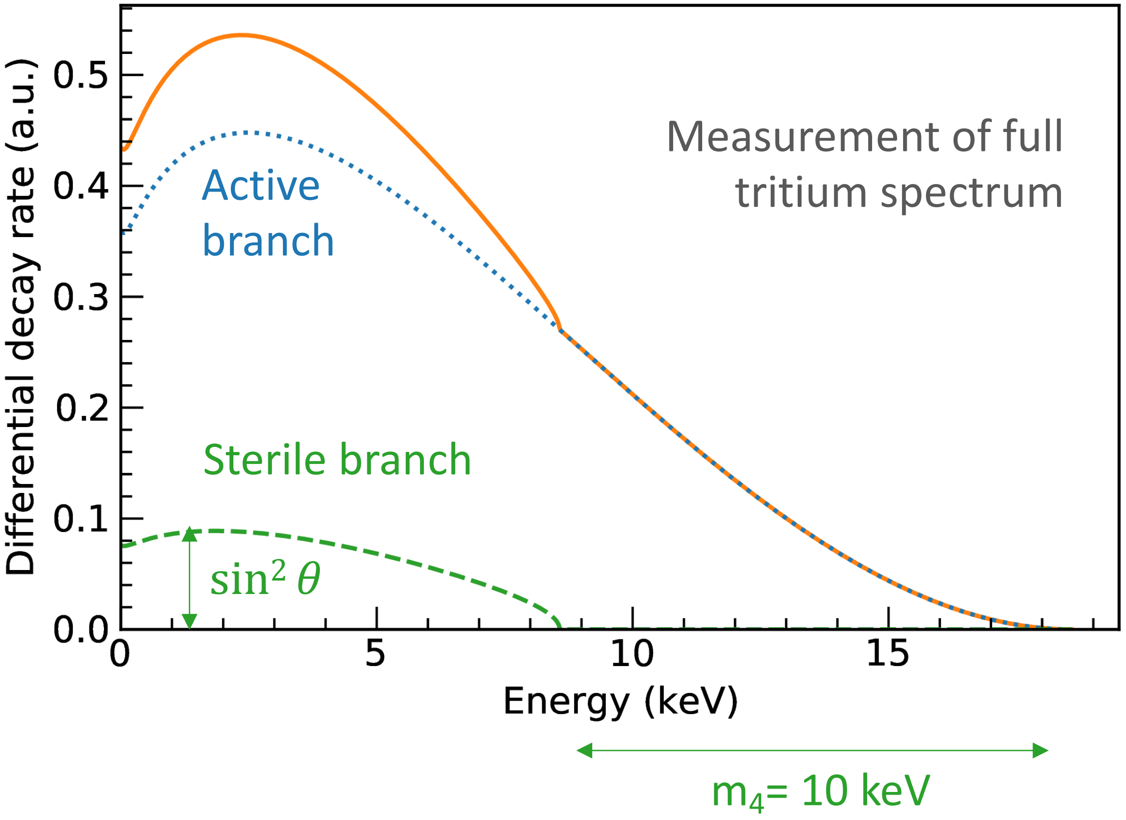
Sterile Neutrinos



eV-scale sterile neutrino

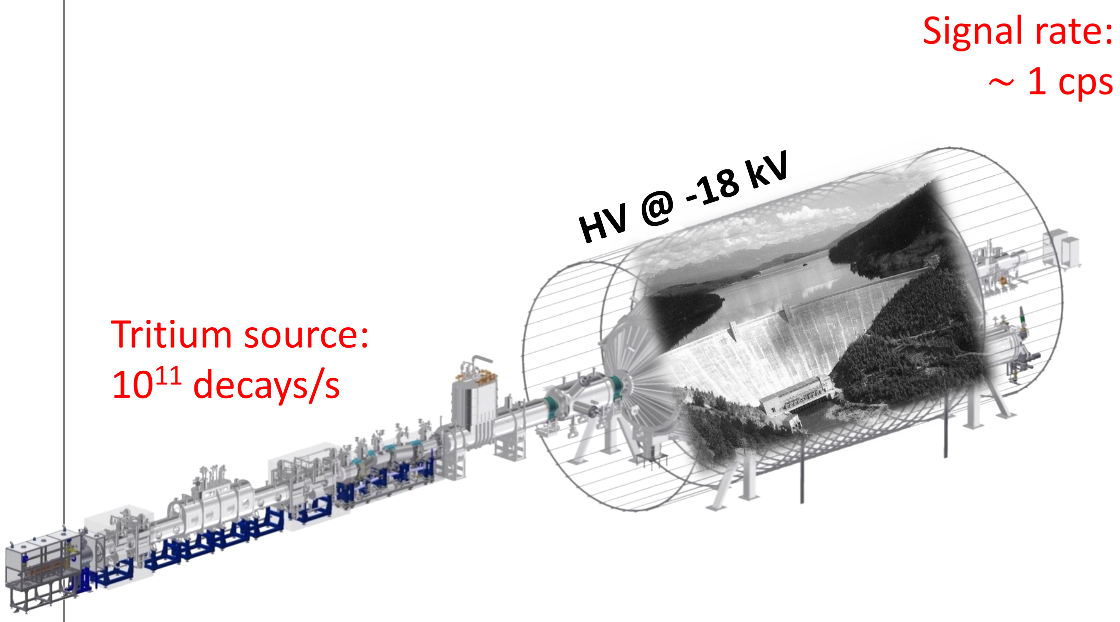


keV-scale sterile neutrinos

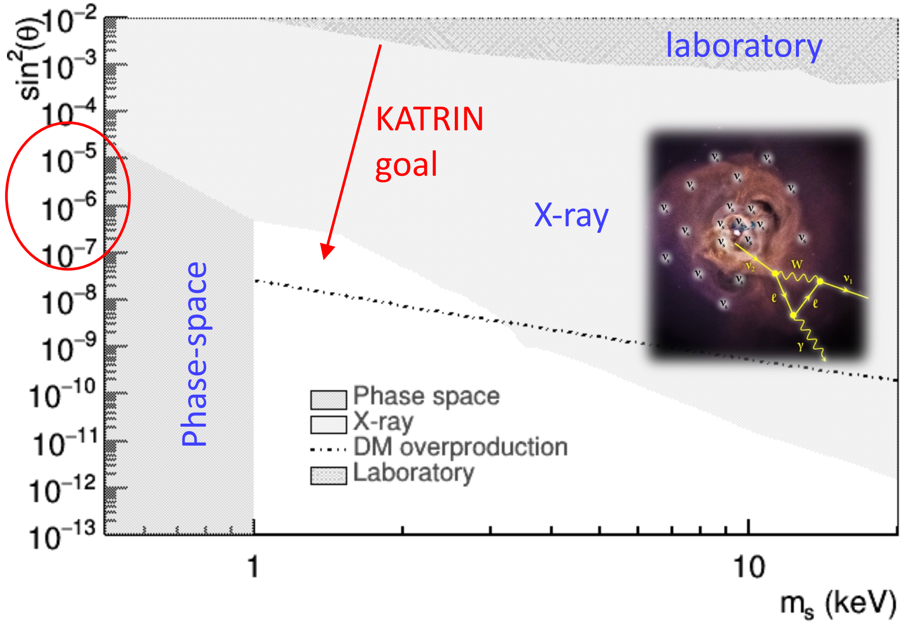


Challenges

Challenge 1:
High electron flux at the detector



Challenge 2:
Strong cosmological and astrophysical limits



Mertens et al, Phys.Rev. D91 (2015) 4, 042005
Mertens et. al. JCAP 1502 (2015)

Challenges

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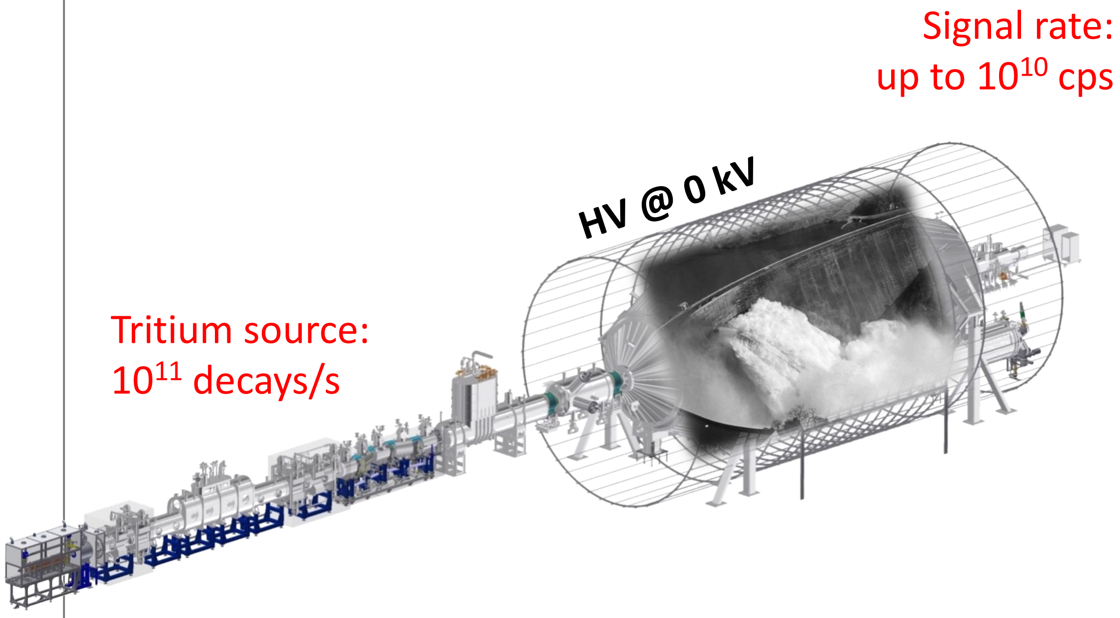

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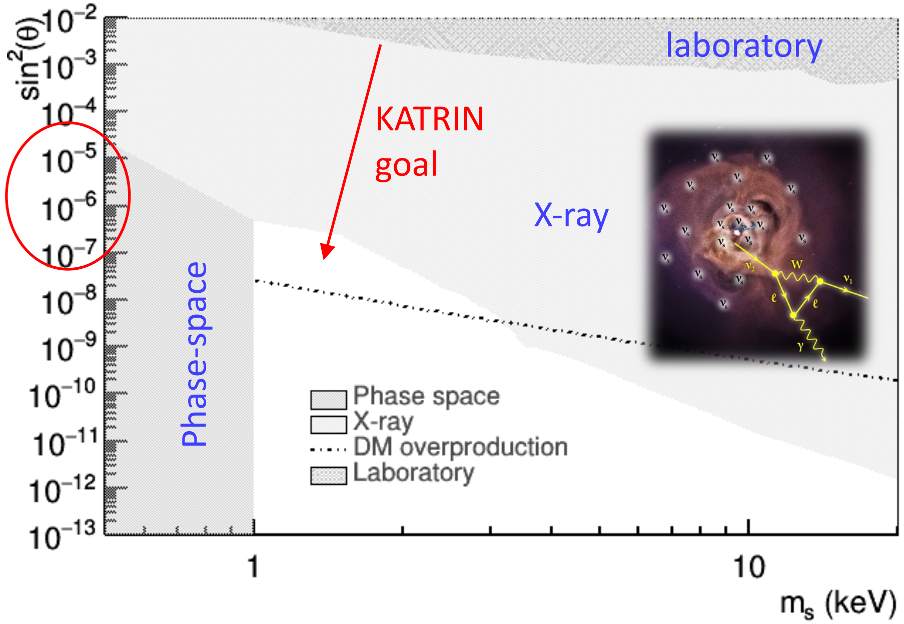
Strong cosmological and astrophysical limits

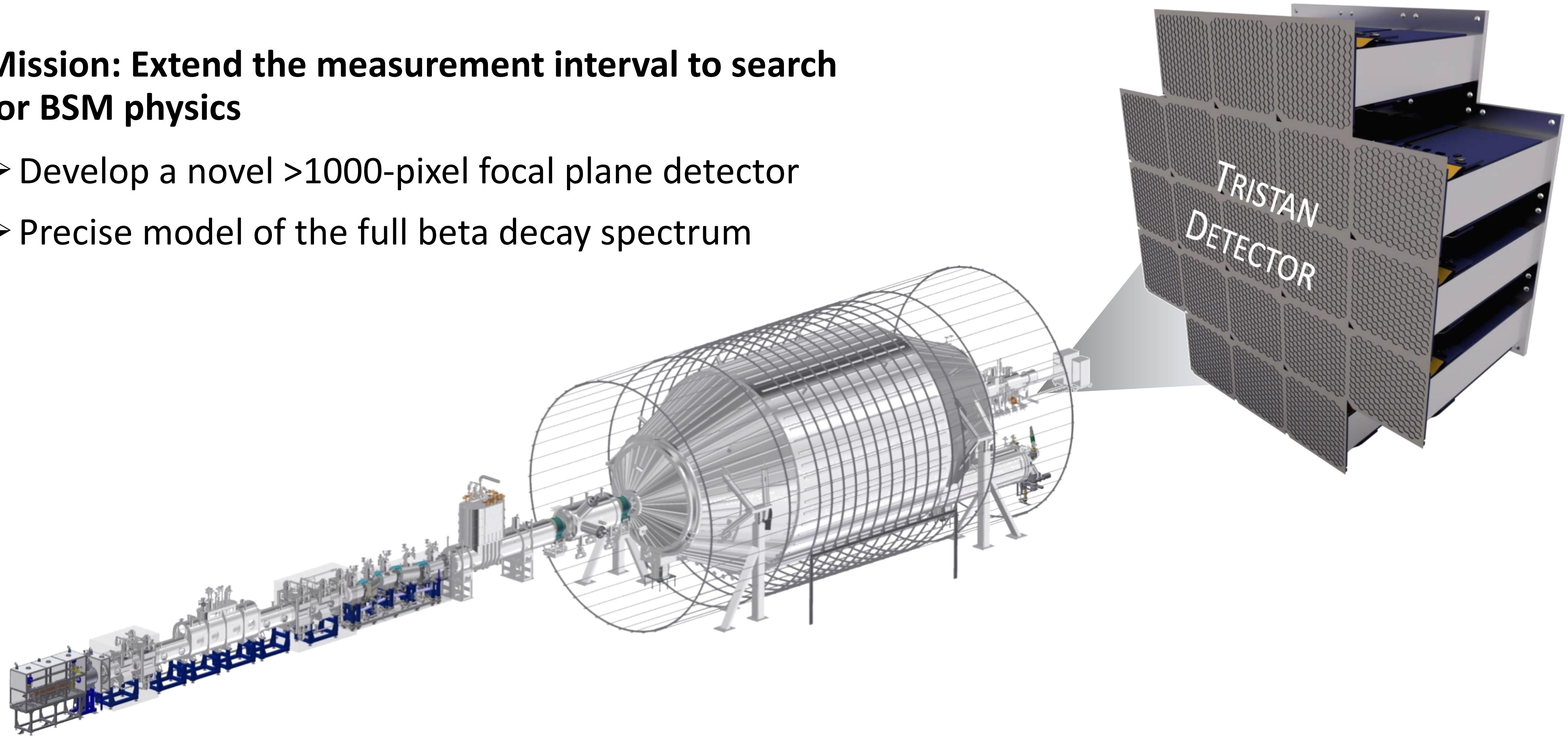


Mertens et al, Phys.Rev. D91 (2015) 4, 042005
Mertens et. al. JCAP 1502 (2015)

The TRISTAN project

Mission: Extend the measurement interval to search for BSM physics

- Develop a novel >1000-pixel focal plane detector
- Precise model of the full beta decay spectrum



Mertens et al, Phys.Rev. D91 (2015) 4, 042005
Mertens et. al. JCAP 1502 (2015)

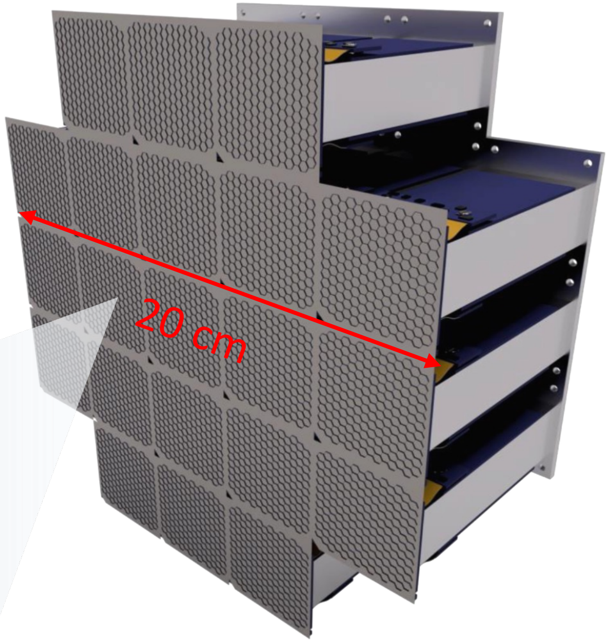
The TRISTAN project

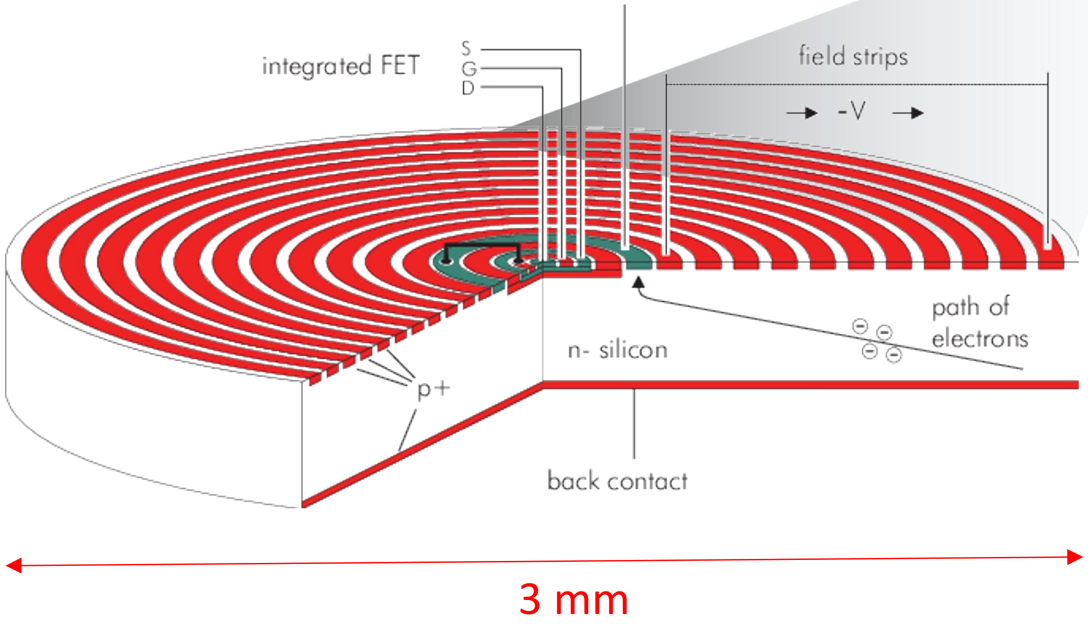
Silicon drift detector (SDD) technology

✓ Capability of handling high rates (> 10^8 cps)

✓ Excellent energy resolution (300 eV @ 20 keV)

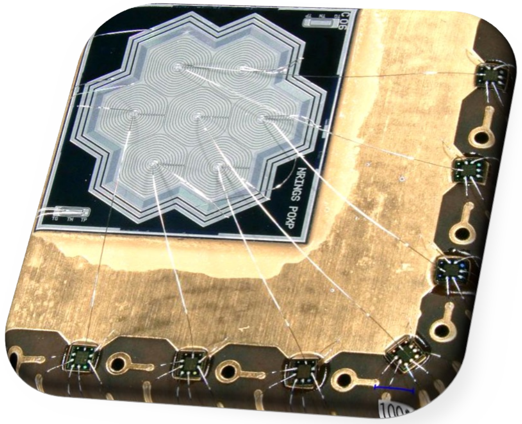
✓ Integrated read-out → focal plane design



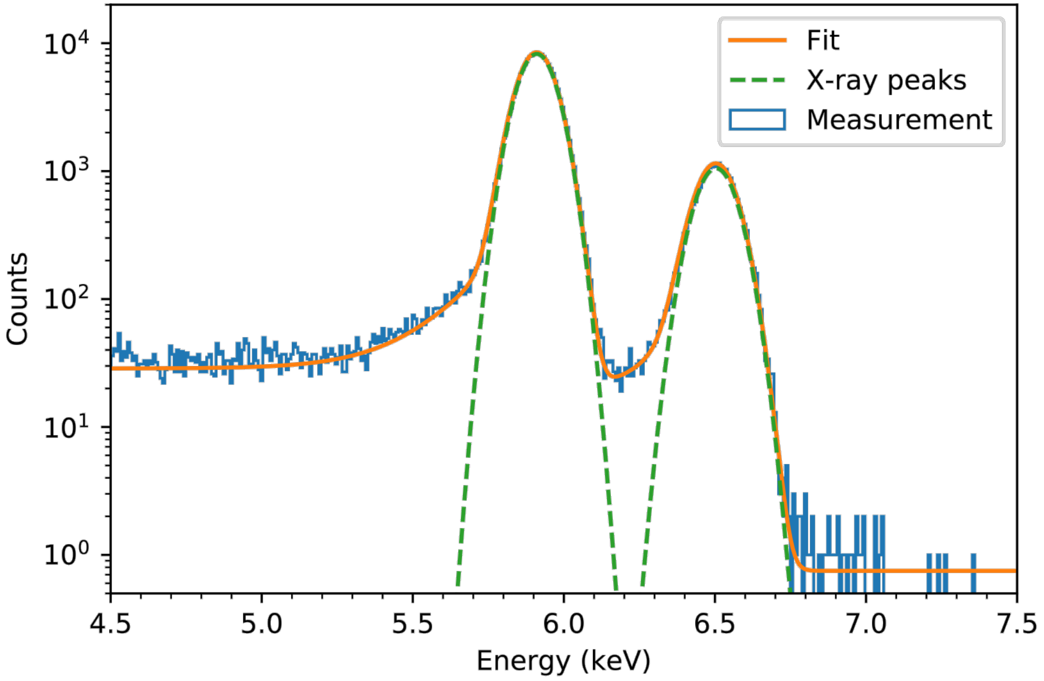


TRISTAN - Status

- ✓ Excellent performance of prototype
  S. Mertens et al, J. Phys. G46 (2019)
- ✓ Detailed characterization with electrons
  S. Mertens et al, J. Phys. G48 (2020)
  M. Biassoni et al, Eur. Phys. J. Plus 136, 125 (2021)
- ✓ First ever operation of 166-pixel module
  M. Gugiatti et al, NIM-A 979 (2020)
  P. King et al JINST 16 T07007 (2021)
- ✓ Prepare for integration of 9 modules in KATRIN beamline in 2025



130 eV (FWHM) @ 6 keV @ 1 μs shaping



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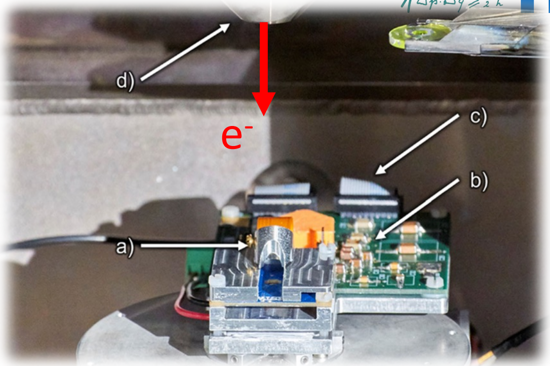
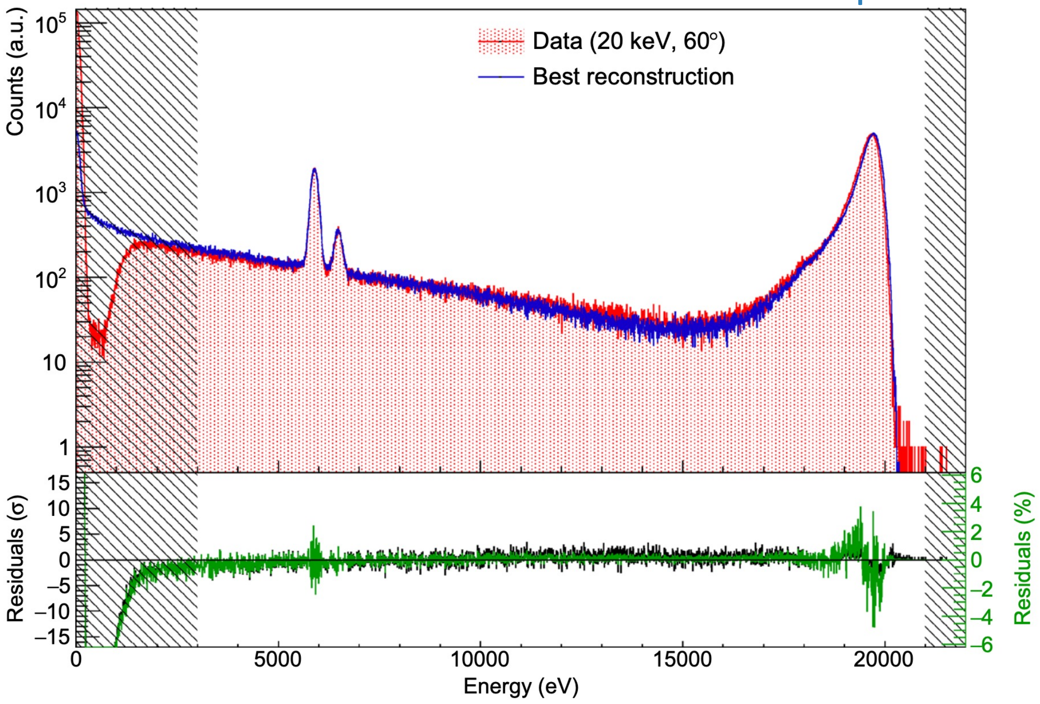
Dedicated test stands in Bicocca (Milano)



Characterization with electron microscope



M. Biassoni et al, Eur. Phys. J. Plus 136, 125 (2021)

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- ✓ First ever operation of 166-pixel module
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  P. King et al JINST 16 T07007 (2021)
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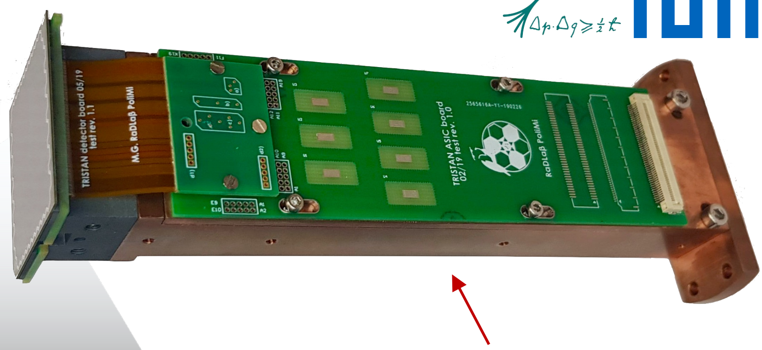
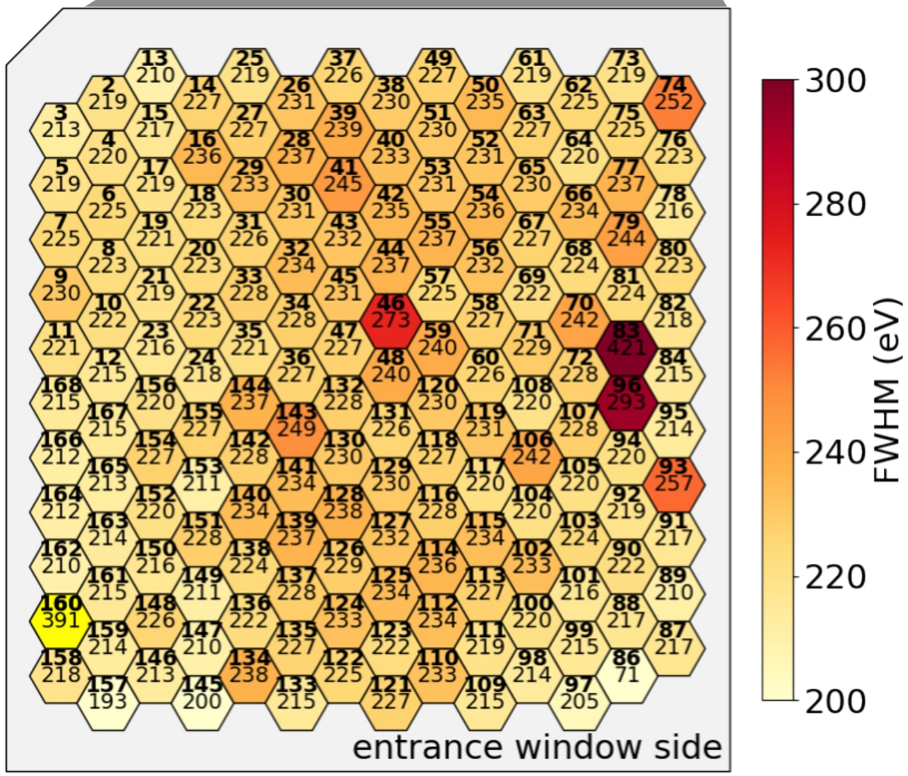


Front-end electronics developed at Polimi (Milano)



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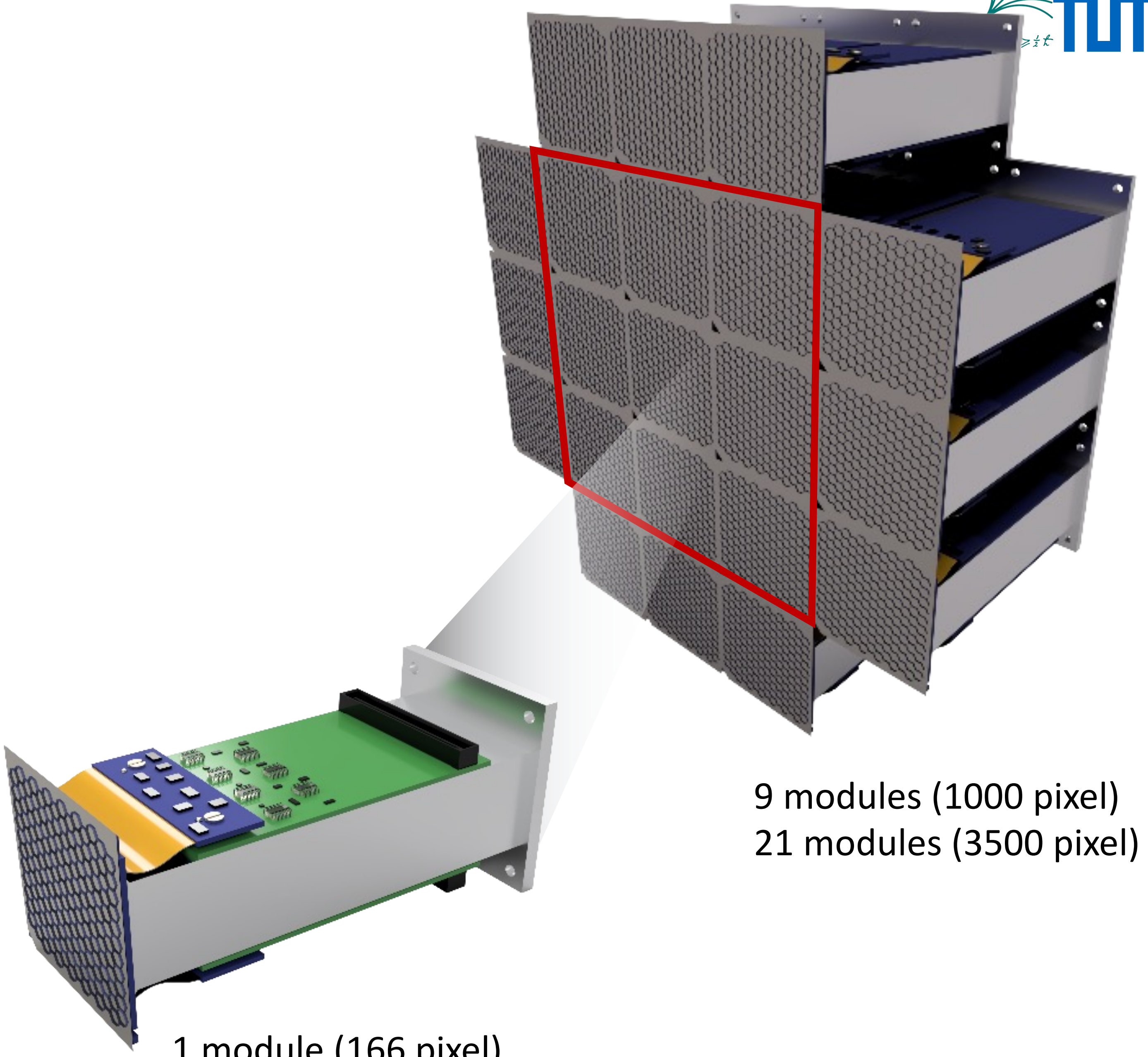
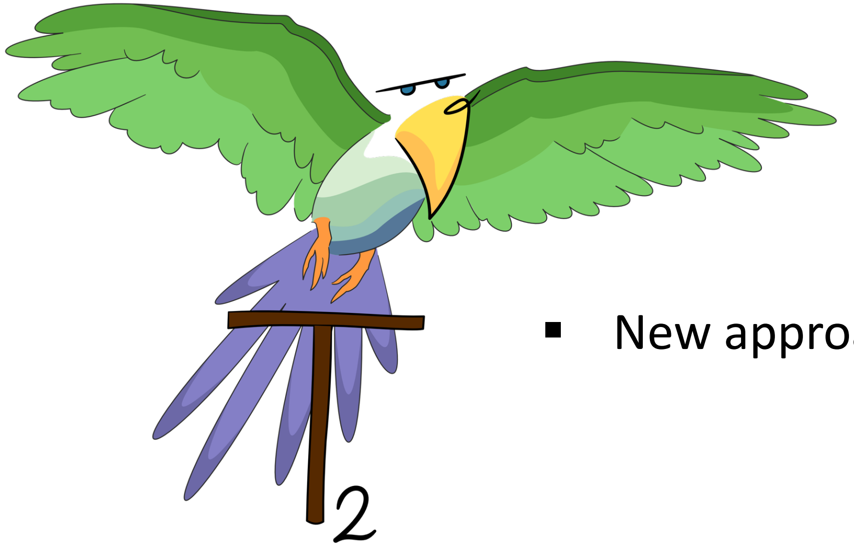


Conclusion



- First sub-eV neutrino mass limit from a direct experiment
- Sensitivity close to 0.2 eV (90% CL) targeted within next years
- New approaches are one way to tackle the hierarchical neutrino mass regime

- High precision KATRIN data available for interesting new physics searches
- First and complementary results on light sterile neutrinos
- Upgrade of KATRIN beamline with SDD array will allow to extend the measurement interval

Thank you for your attention

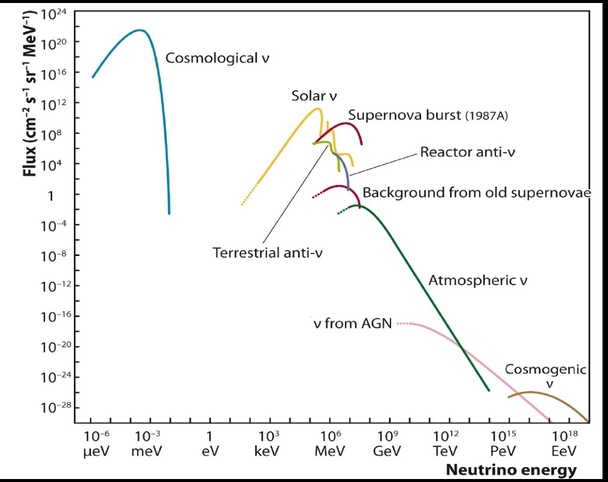
Thanks to
To my group
the KATRIN collaboration
and many others
...

Susanne Mertens

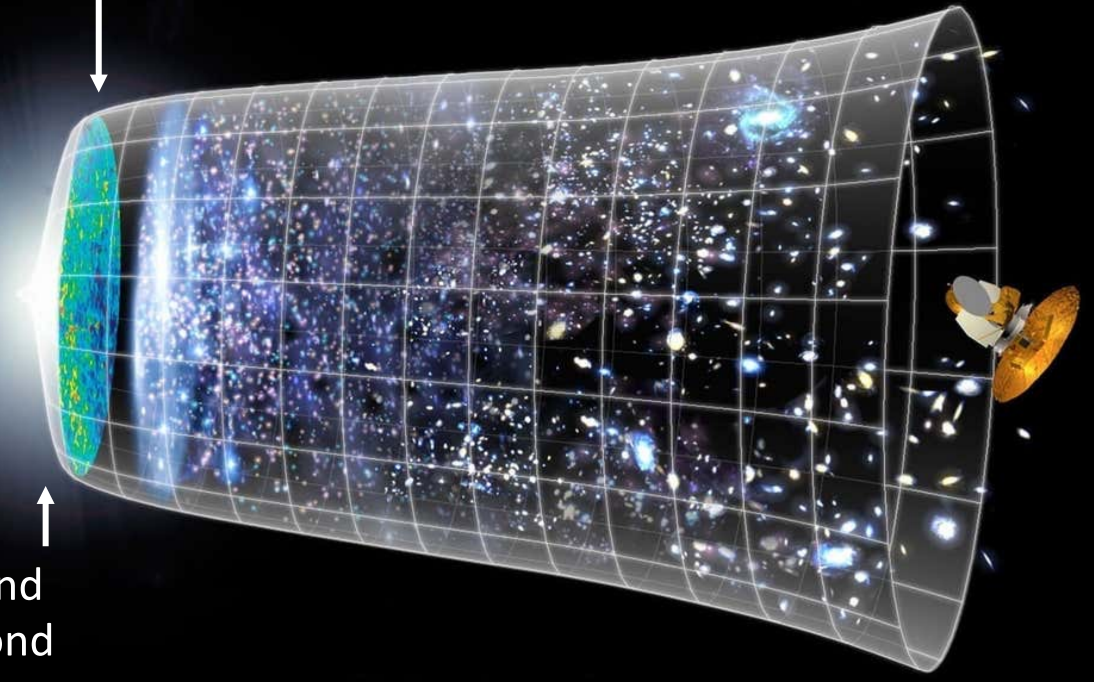
Technical University Munich & Max Planck Institute for Physics

Cosmic neutrino background

- Neutrinos decouple 1 s after the Big Bang
- Detection would confirm Big Bang theory
- About 400 ν's per cm^3 today
- Challenge: tiny cross-section



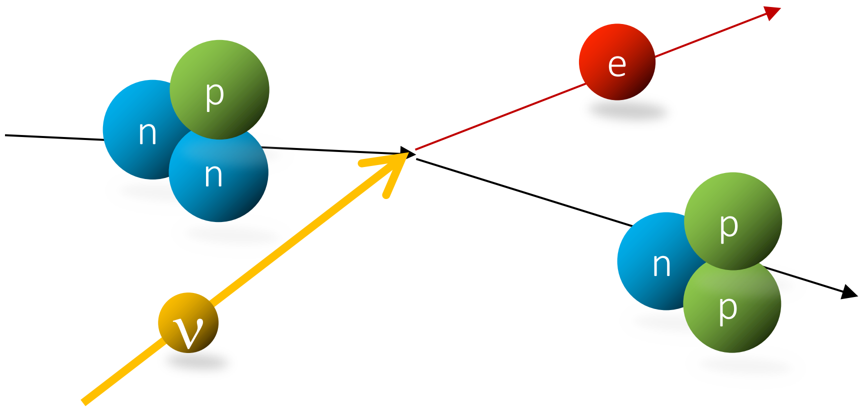
Comic microwave background
@ 380 000 years

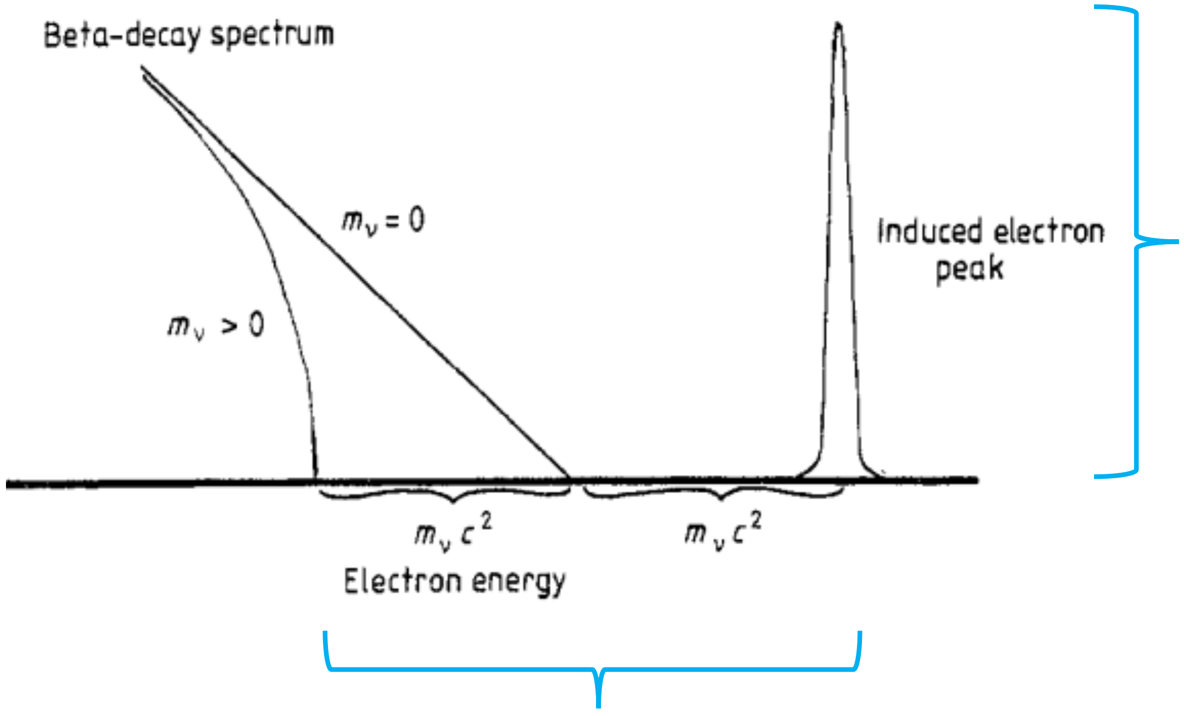


Comic neutrino background
@ < 1 second

Signature of Relic Neutrinos

- Neutrino capture on tritium: no energy threshold
- Electron peak above endpoint
- $^{3}\mathrm{H} + \nu_e \longrightarrow \ ^{3}\mathrm{He} + e$

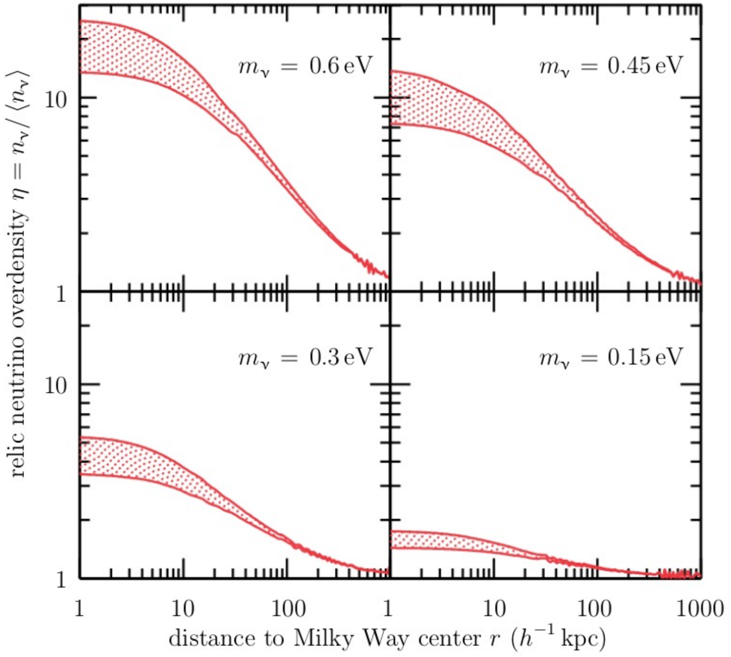




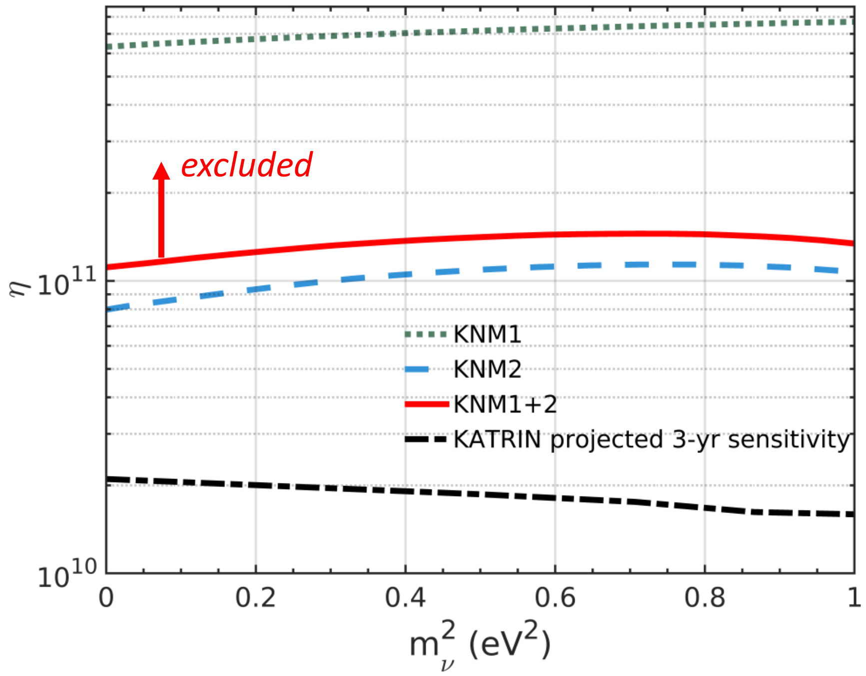
Relic Neutrino Search in KATRIN

- Test for large **overdensity** η of neutrinos in our galaxy (based on **1st** and **2nd** ν-mass campaigns)
- Improved limit by **2 orders of magnitude** wrt previous laboratory limits

Ringwald, Wong JCAP 0412 (2004) 005

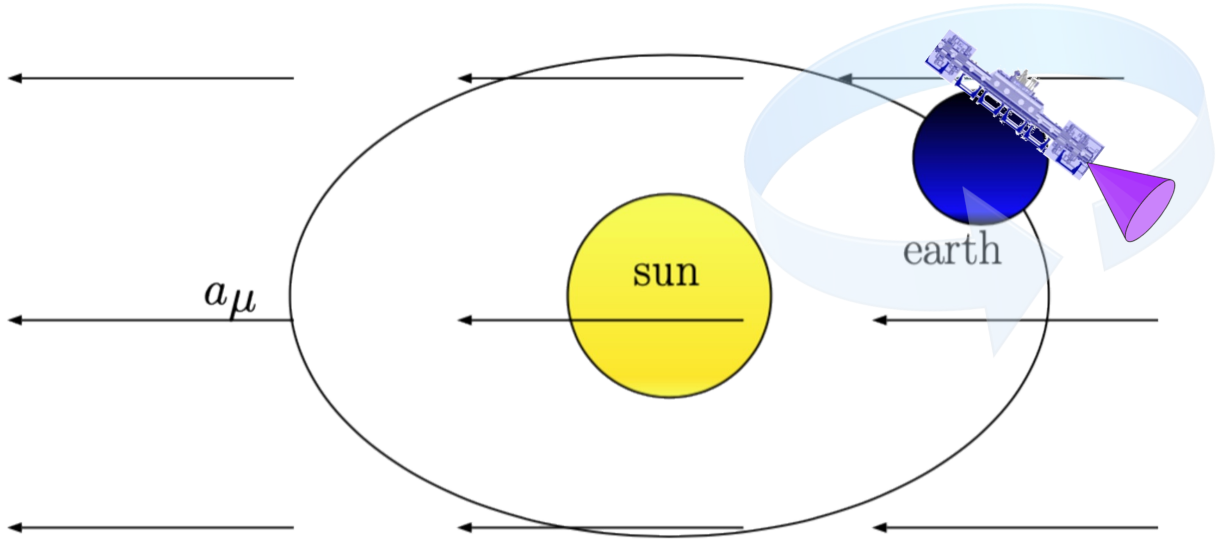


KATRIN Collab. arXiv:2202.04587 (2022)

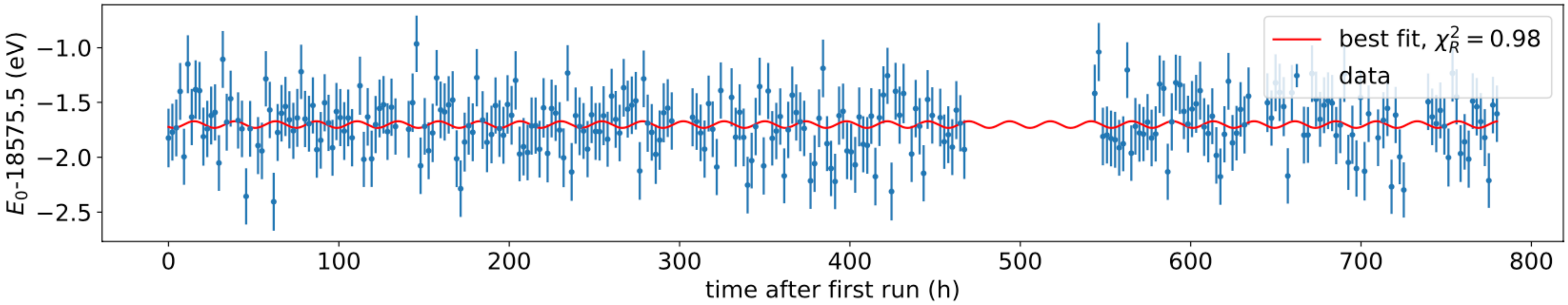


Lorentz Violation

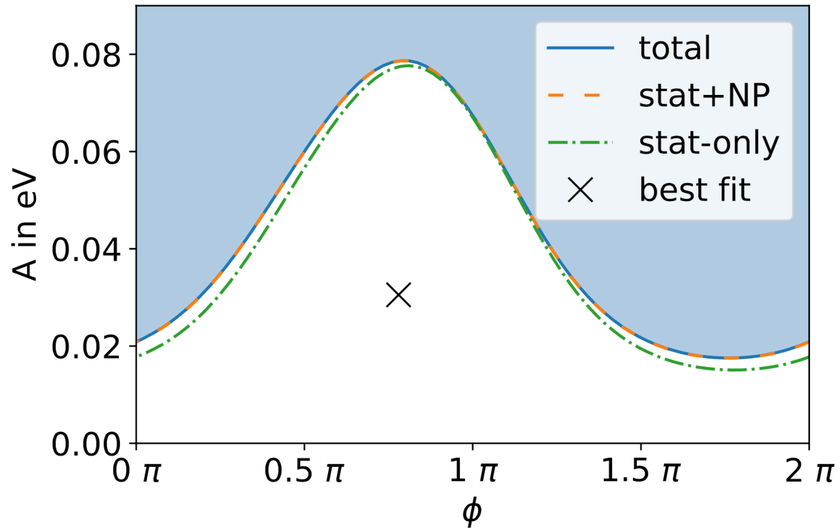
- LV parametrized with a_μ (vector field)
- KATRIN acceptance angle introduces a preferred "direction"
- As the earth is rotating, the relative direction of KATRIN to the LV-violating vector changes
- Signature: oscillation of tritium endpoint with sidereal frequency (23h 56 min)



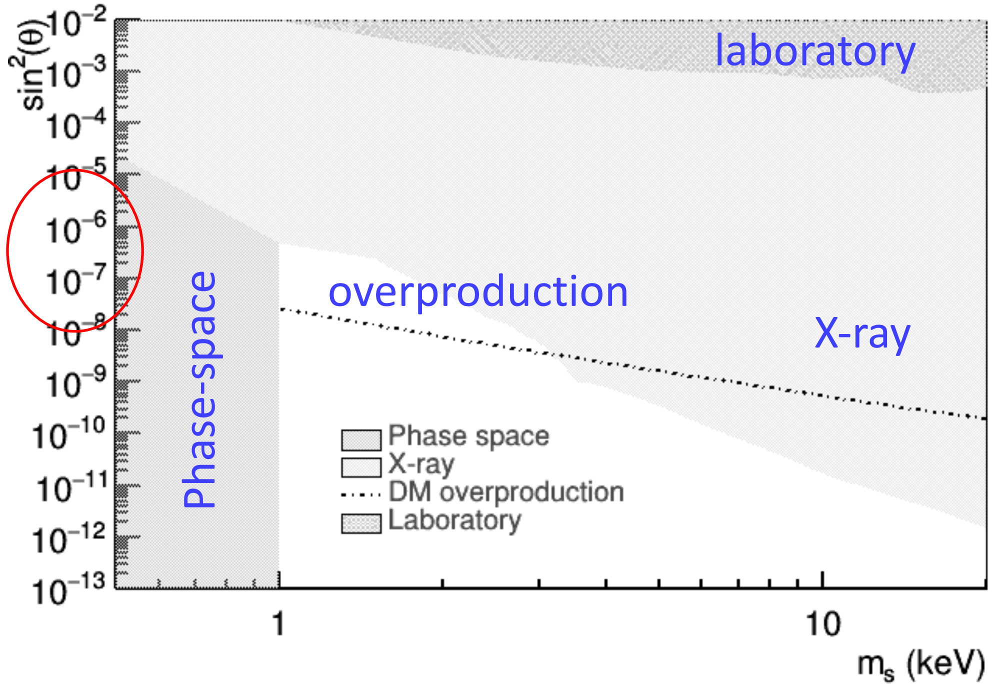
Lorentz Violation

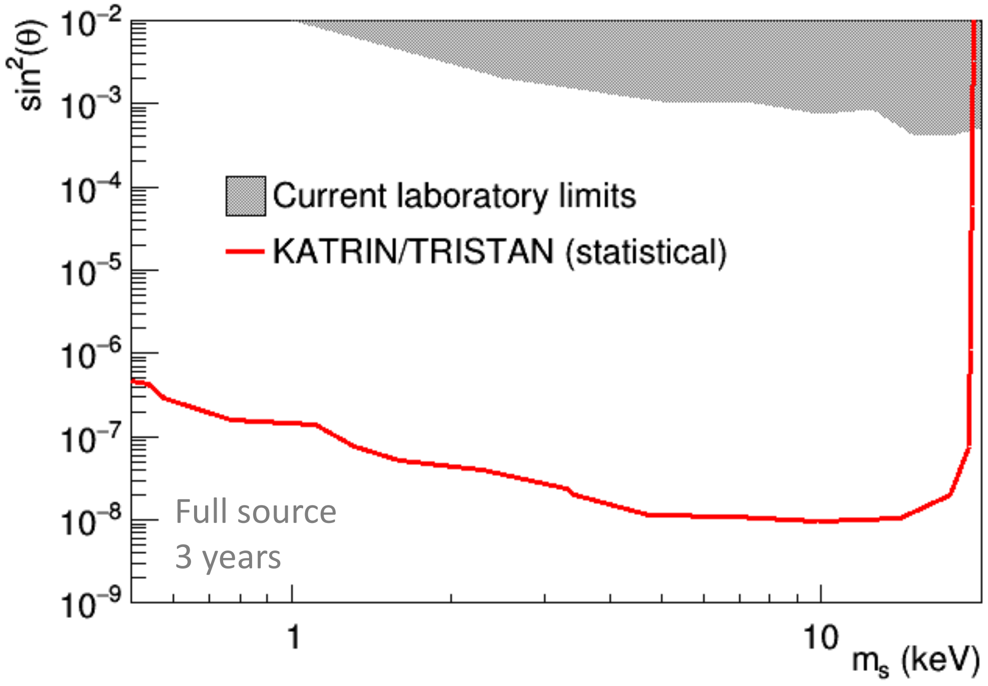


- Search for oscillation in **first** nu-mass data
- No significant oscillation found
- First limit on $\left|a_{11}^{(3)}\right|$ … to be published soon



Sensitivity to keV neutrinos





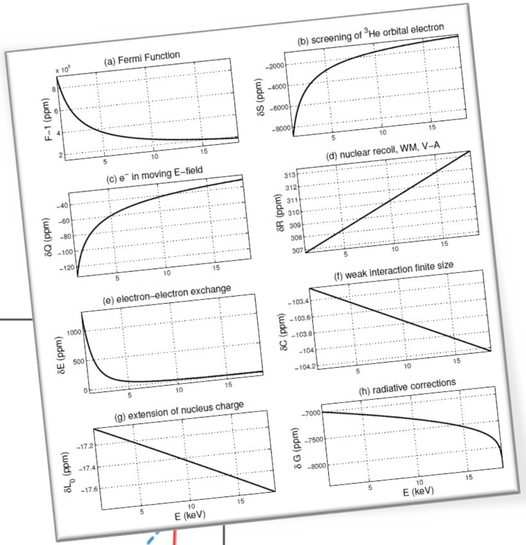
- Strong constrains from astrophysics (model-dependent)
  Benso et al, Phys. Rev. D 100, 115035 (2019)

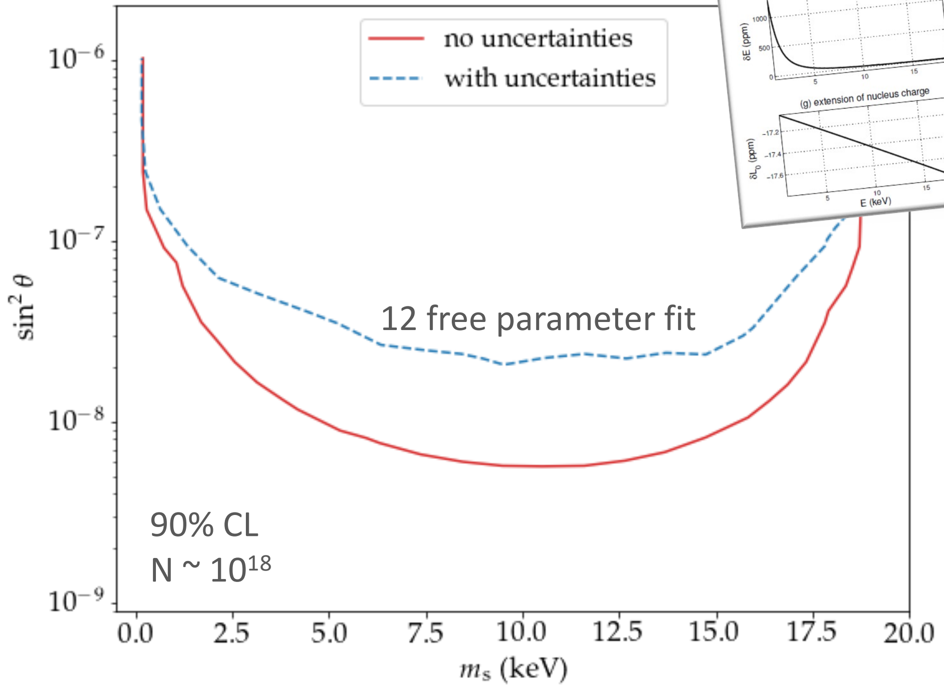
- KATRIN has the potential to significantly improve the current laboratory limits

Sensitivity to keV neutrinos

Impact of theoretical uncertainties

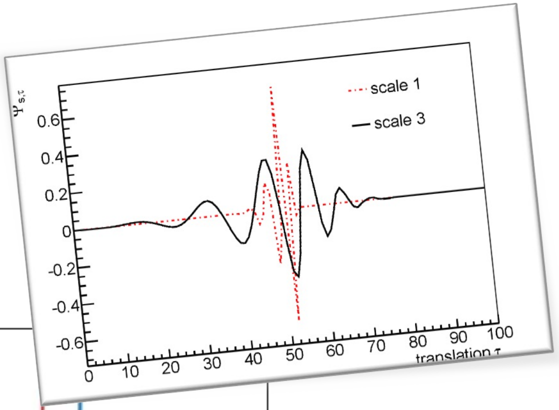
Mertens et. al. Phys. Rev. D91 (2015)

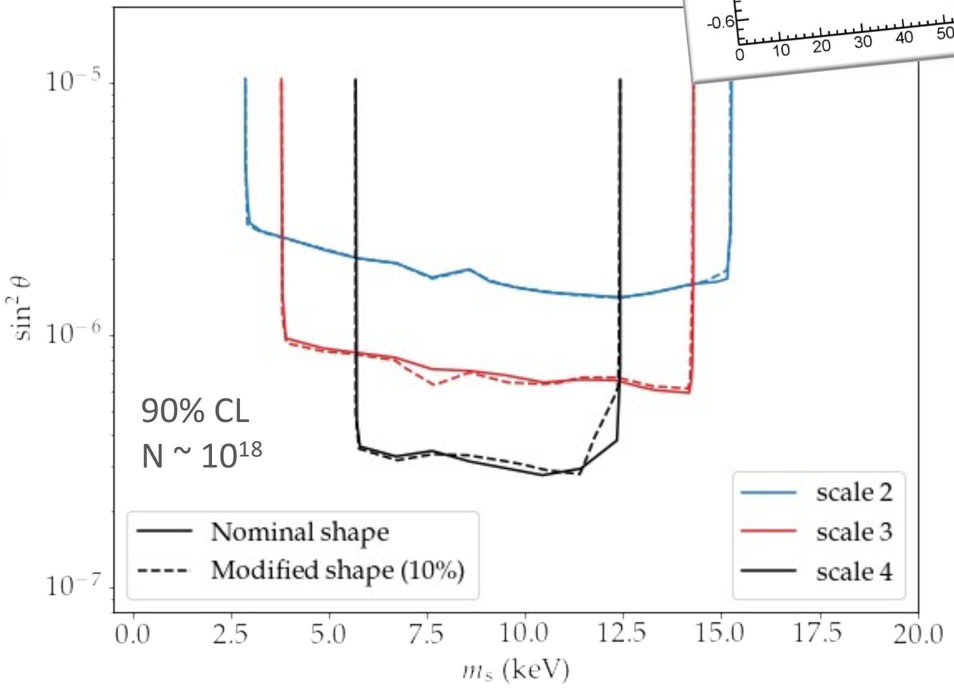




Wavelet approach

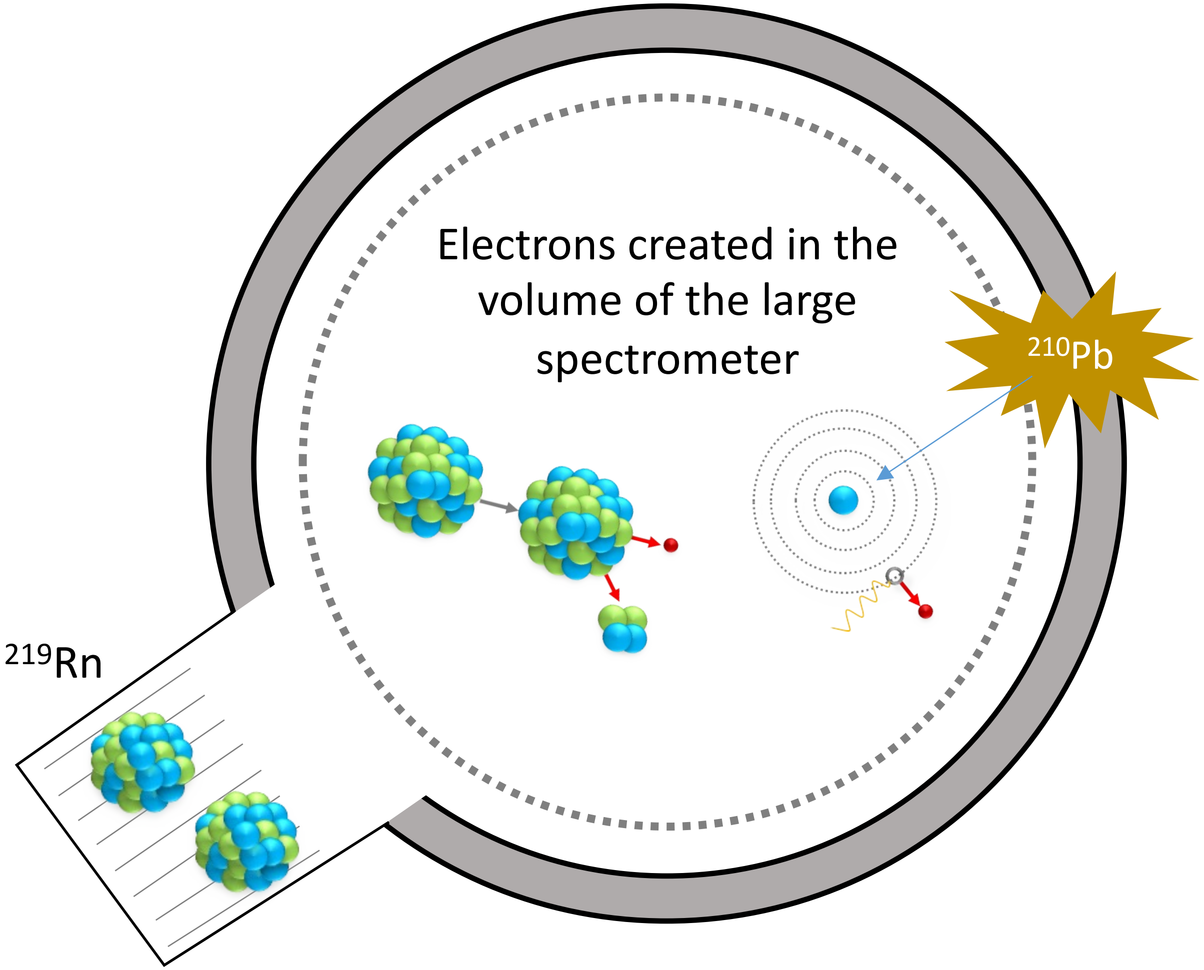
Mertens et. al. JCAP 1502 (2015)



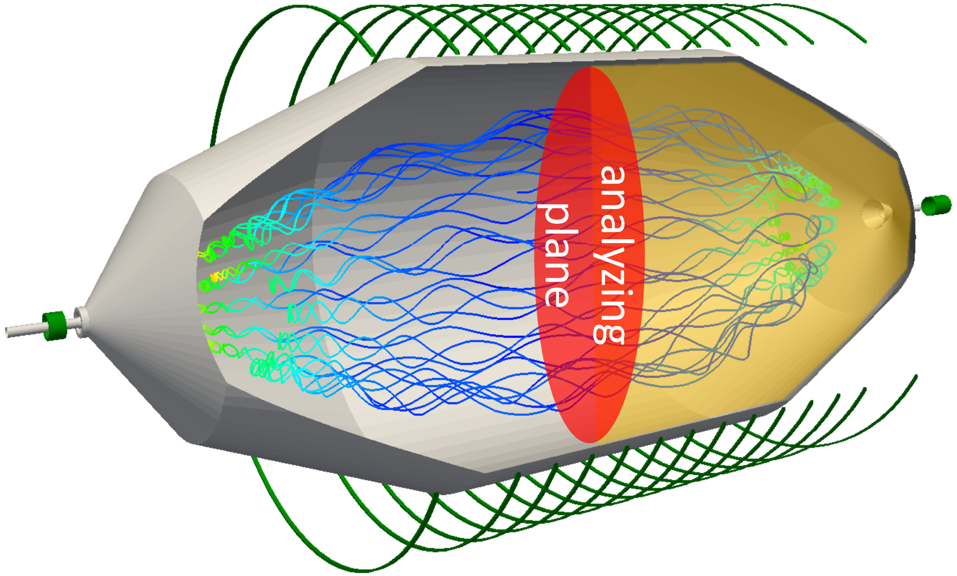


KATRIN backgrounds

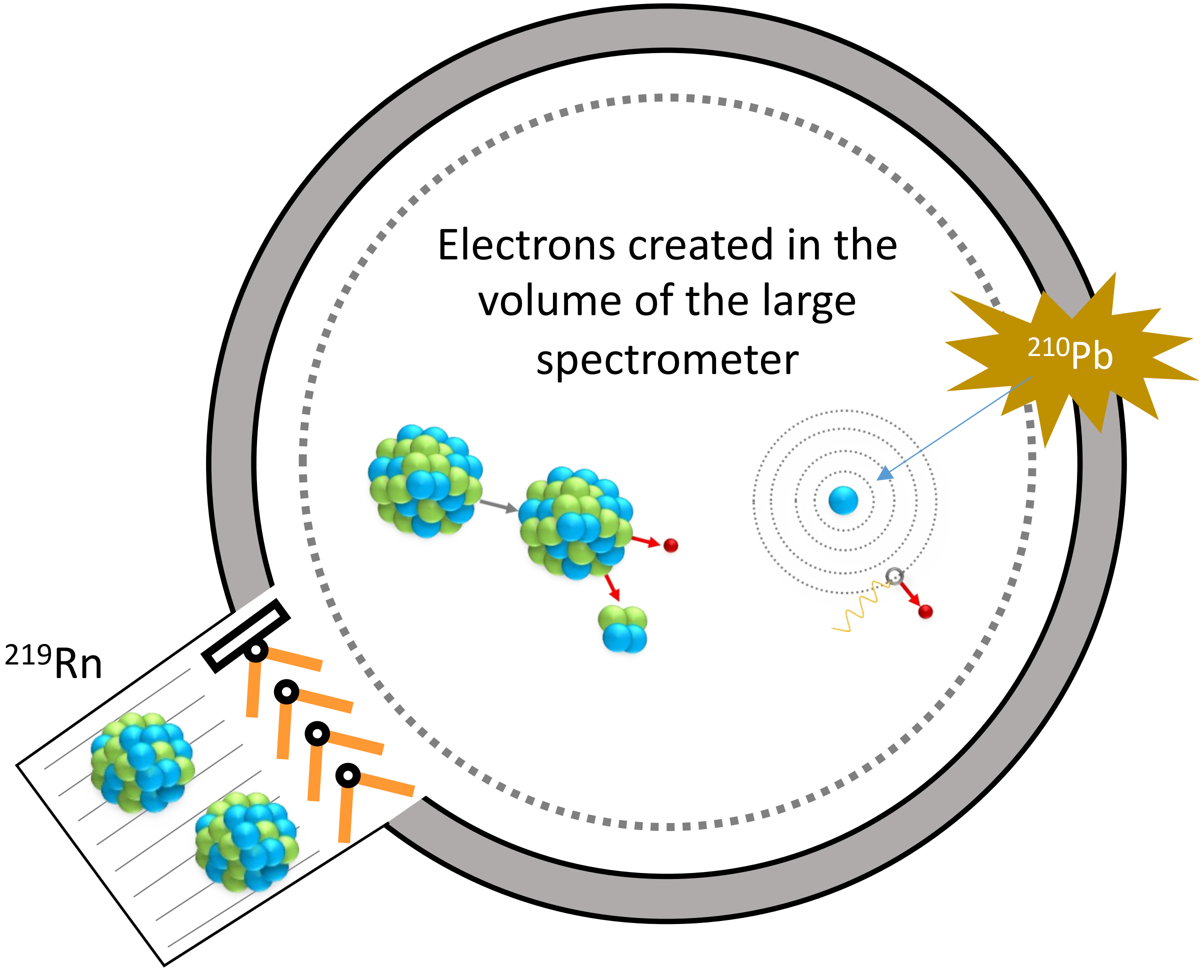
KATRIN backgrounds



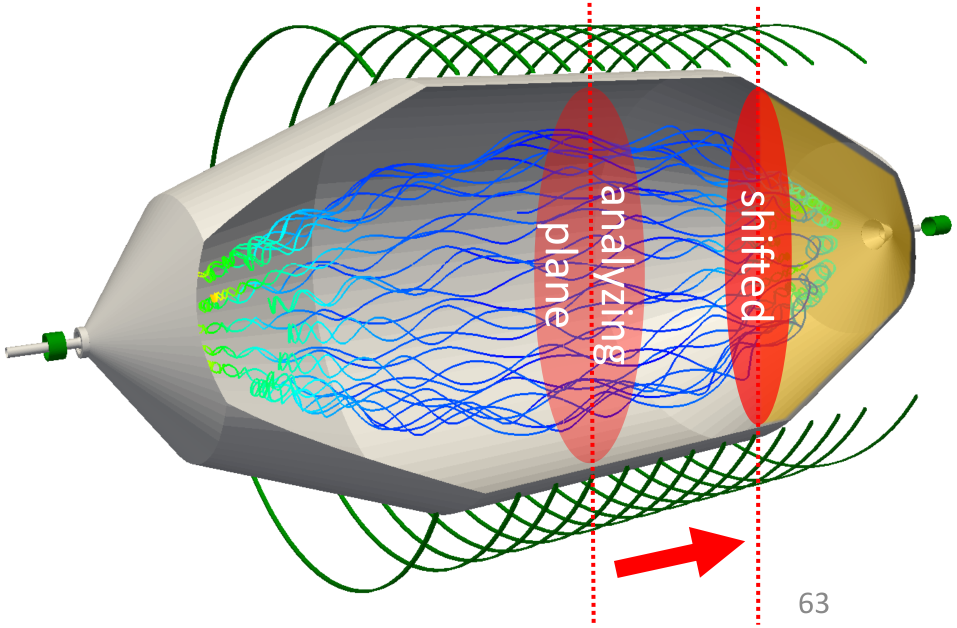
- ^{219}Rn-induced background
- ^{210}Pb-induced background



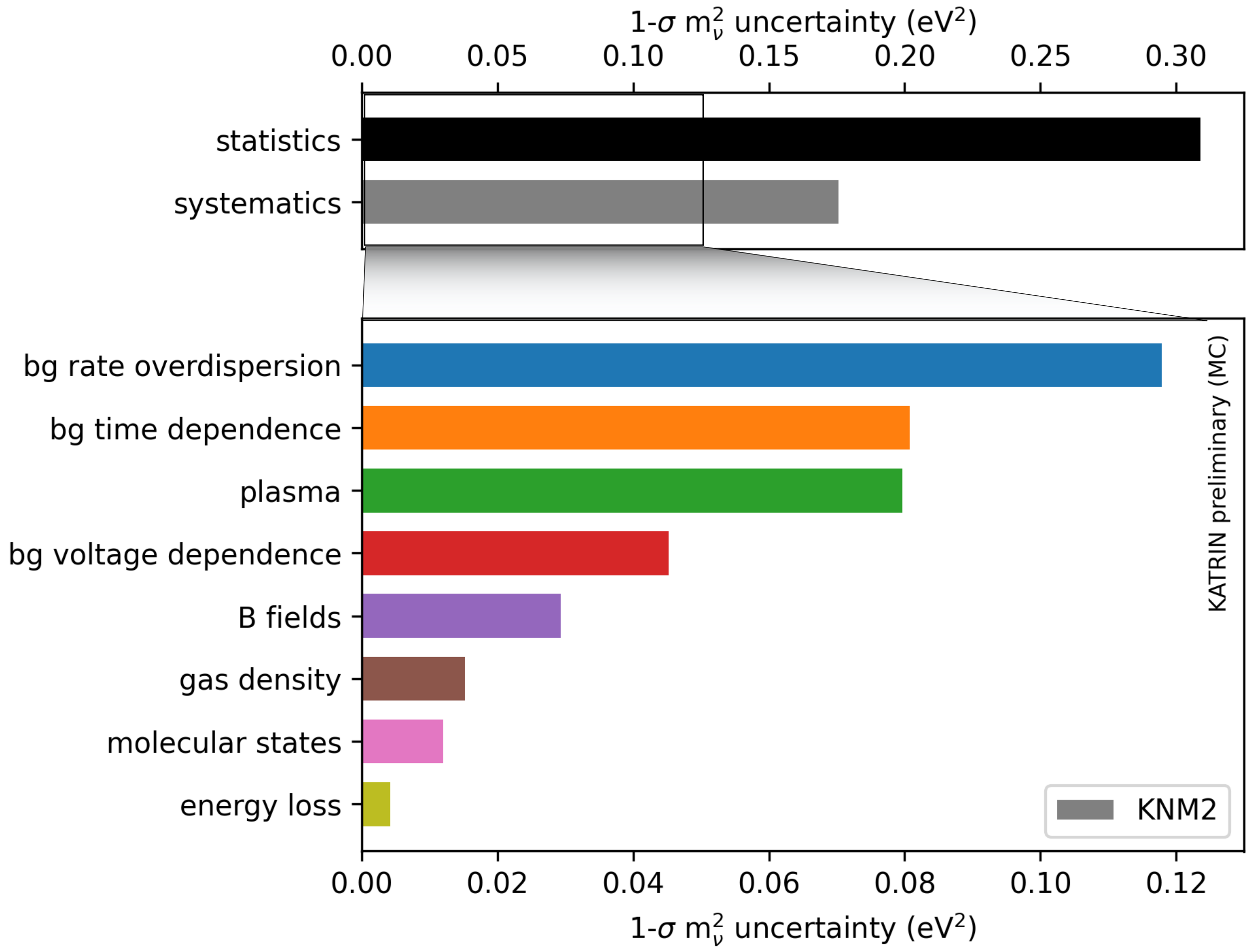
KATRIN background mitigation



- ✓ LN cooled baffle + shifted analyzing plane
  S. Goerhardt, et al., JINST 13 (2018) no.10, T10004
- ✓ Background reduction by factor of 2.3 to about 130 mcps (original design: 10 mcps)
- ✓ Further R&D ongoing



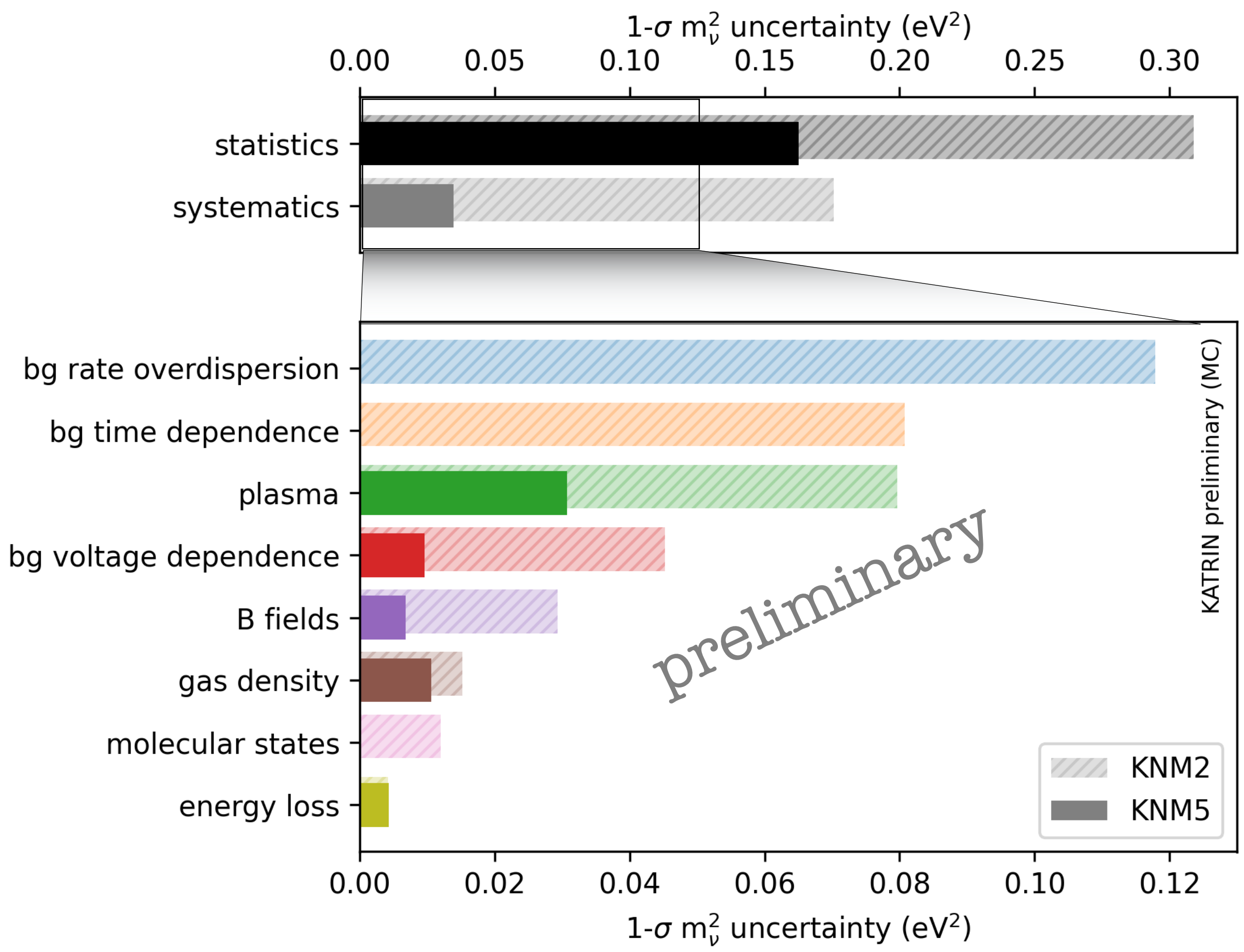
Uncertainty budget in 2nd campaign



Dominant uncertainties:

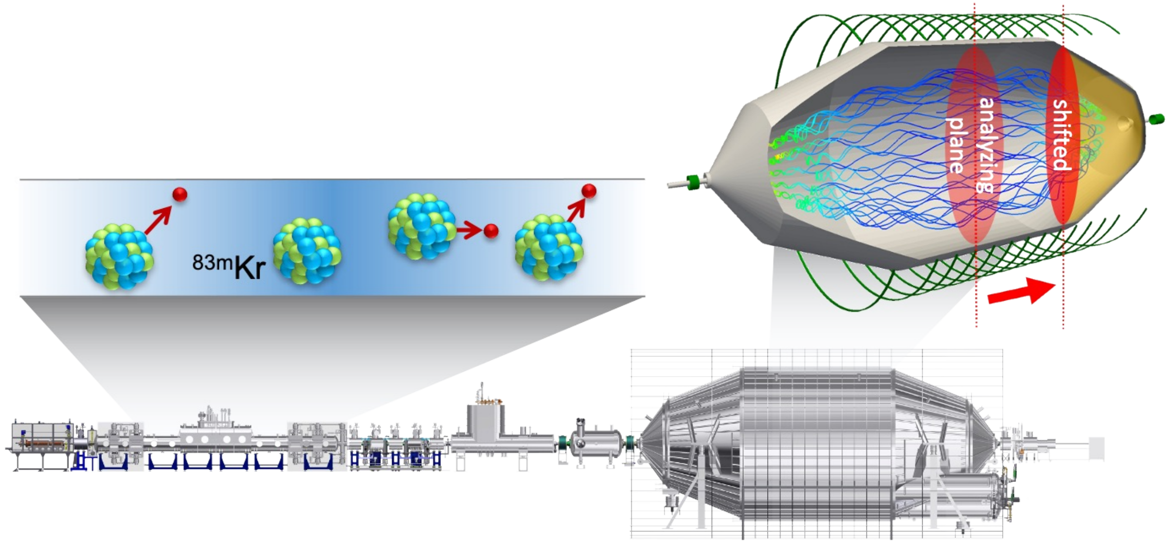
- Statistical error
- Background-related effects
- Source electric potential variations (plasma)

Sneak preview

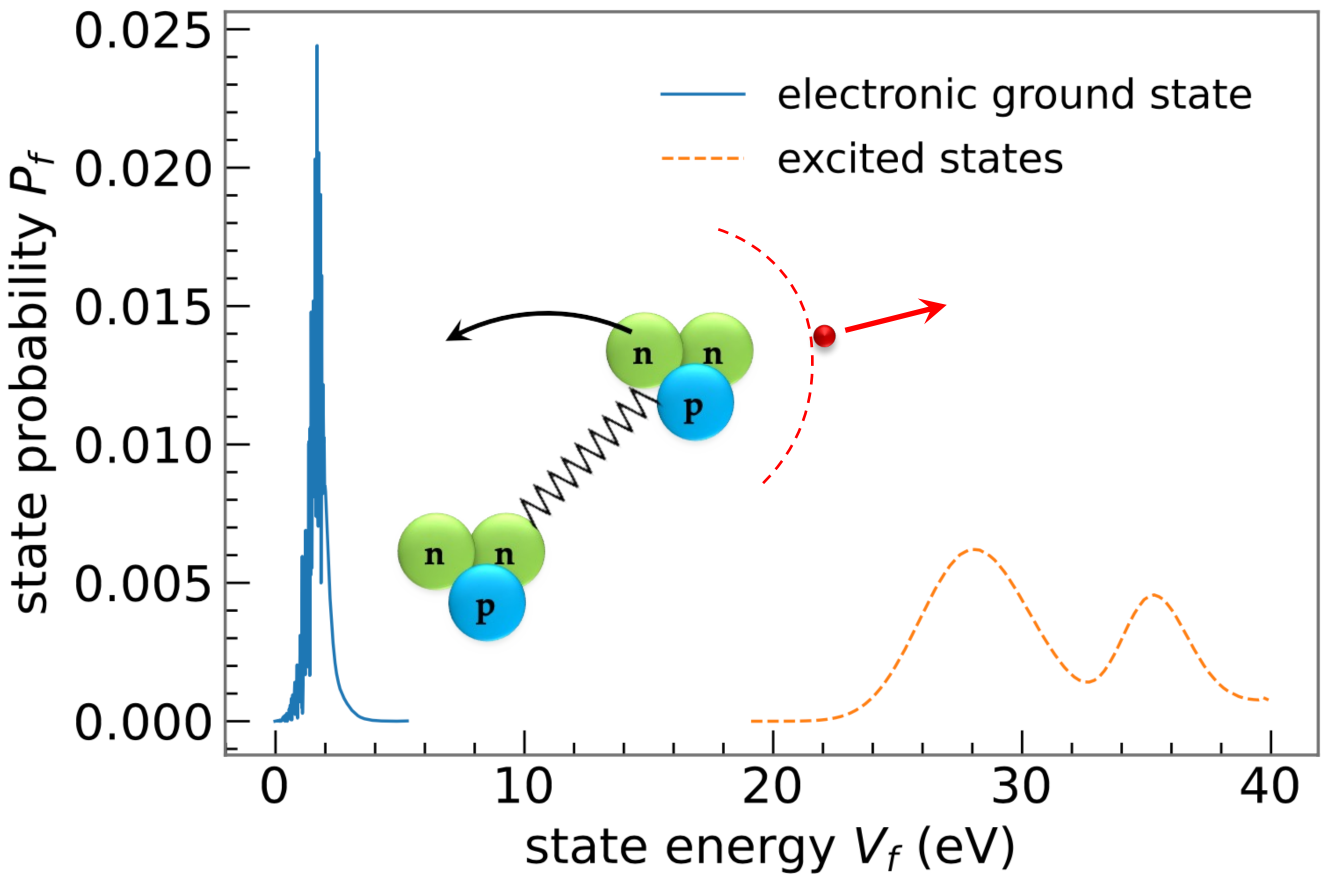


Major improvements:

- Background reduction via new electromagnetic field layout
  Lokhov et al arXiv:2201.11743 (2022)
- Calibration with high-intensity krypton source
  J. Sentkerestiová et al, JINST 13 (2018)



Molecular final states



- Unavoidable energy broadening
- Theoretical input molecular ground and excited final states needed
  A. Saenz et al, Phys. Rev. Lett. 84, 242 (2000)
  + updates
- Future: atomic tritium