KATRIN
Toward a High-Precision Neutrino-Mass Determination with Tritium

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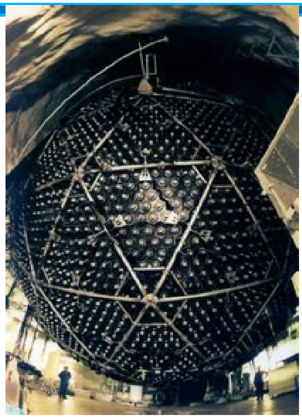
Carnegie Mellon University

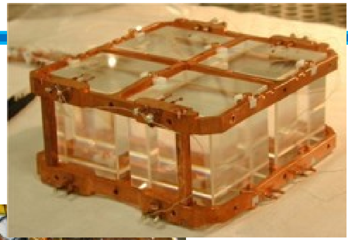
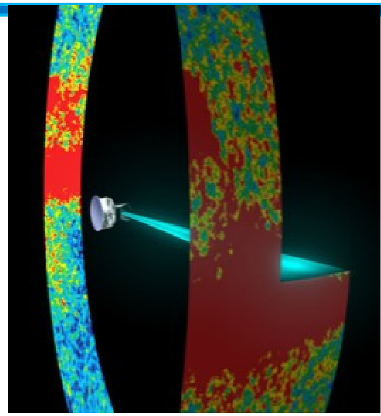
Neutrino 2018 – Heidelberg – 7 June

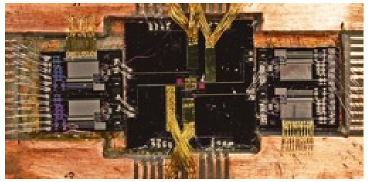
Outline

- Neutrino mass through β decay
- The KATRIN experiment
- The story through April
- First tritium runs
- Outlook

Probes of Neutrino Mass

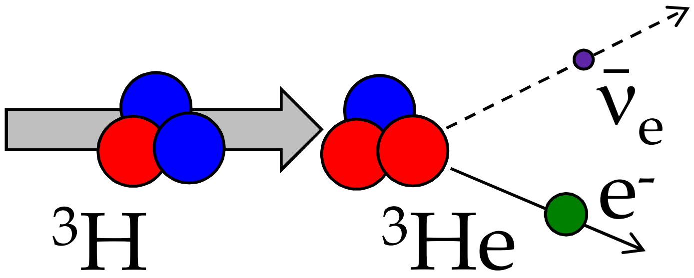


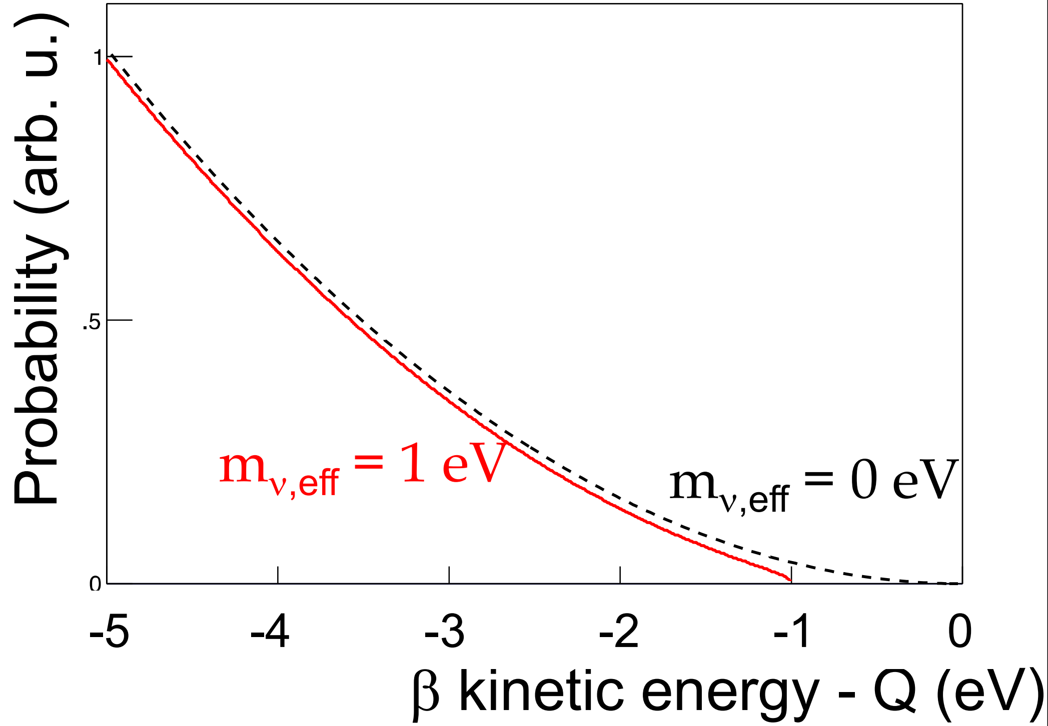


	ν oscillation
Observable	$\Delta m_{ij}^2 = m_i^2 - m_j^2$
Present knowledge	$\Delta m_{21}^2 = 7.53(18) \times 10^{-5}\,\mathrm{eV}^2$ $\Delta m_{32}^2 = 2.44(6) \times 10^{-3}\,\mathrm{eV}^2$
Next gen. / near future	
Model dependence of mass extraction	No mass-scale information

Kinematics of Tritium Decay



- Super-allowed decay
  - Q = 18.6 keV
  - $T_{1/2}$ = 12.3 yr



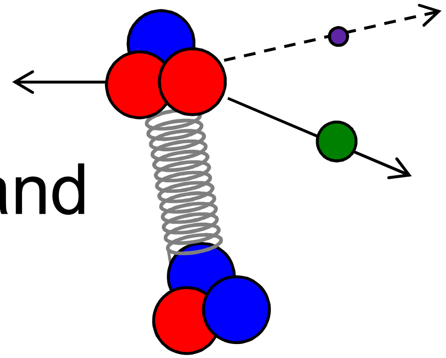
- Extract effective neutrino mass from spectral shape near endpoint

$$m^2_{\nu,eff} = \sum_i^3 |U_{ei}|^2 m_i^2$$

$$\approx m_\nu^2$$ *(quasi-degenerate regime)*

Molecular Tritium

*Bodine, DSP, Robertson, PRC **91** (2015) 035505*

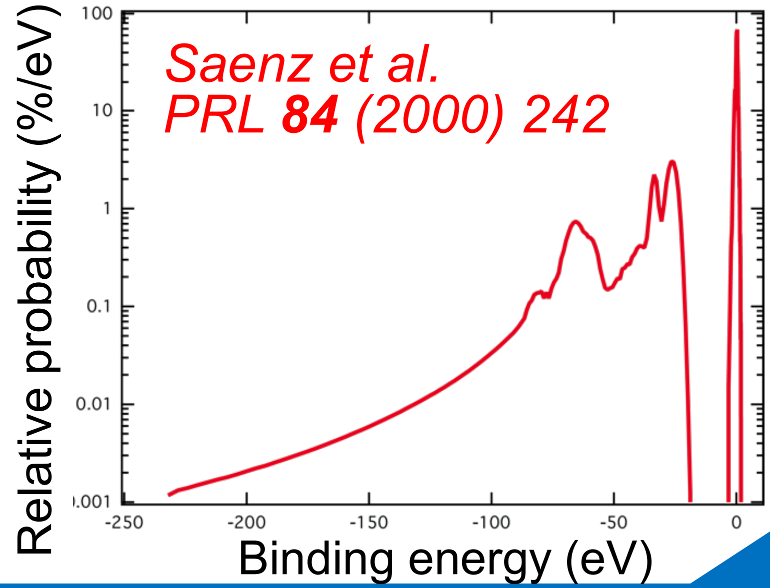


- KATRIN uses a T_2 source – not just T
- β spectrum depends on excitation energies V_k and probabilities P_k – need 1% accuracy

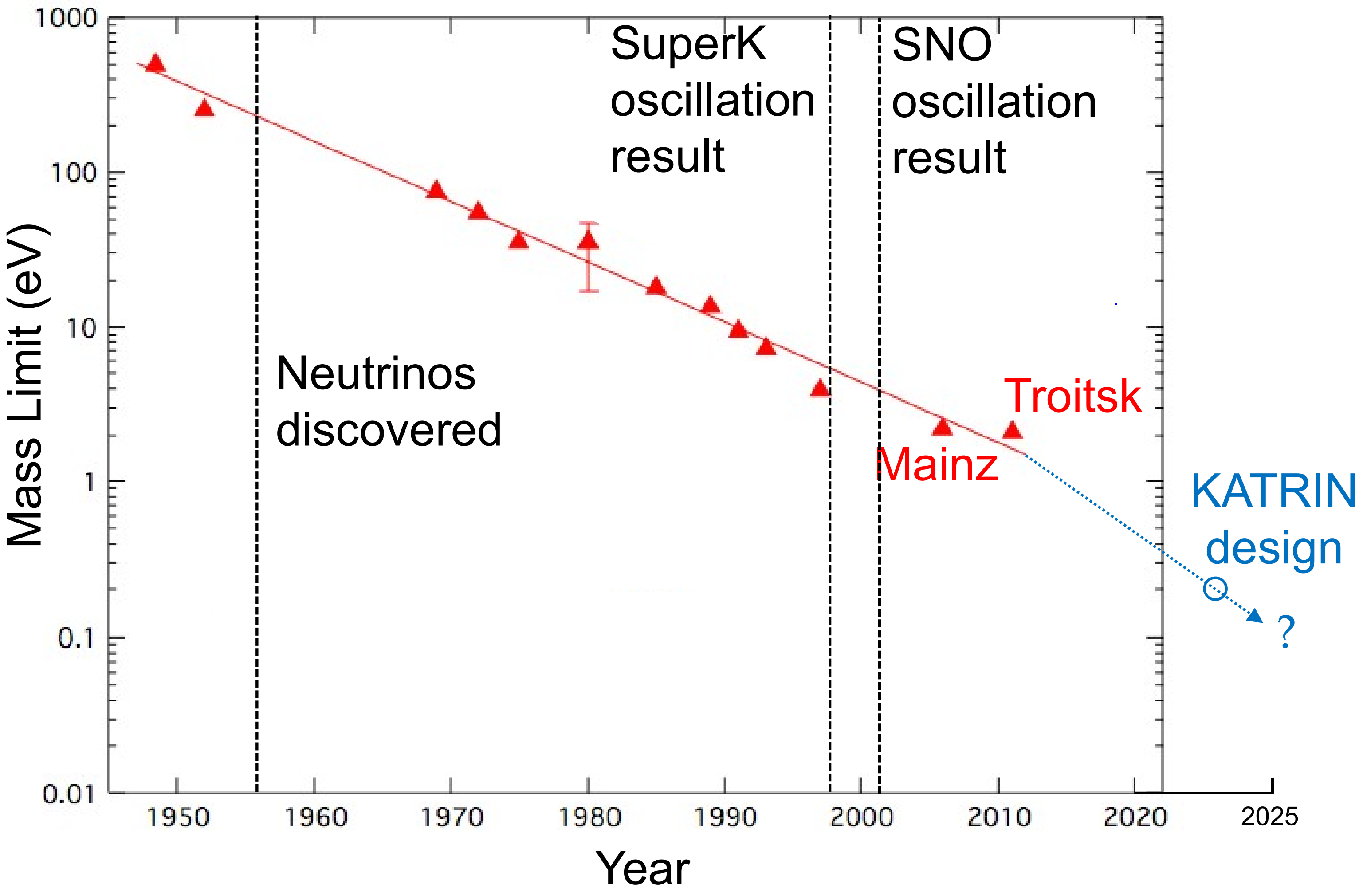
$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\mathrm{nuc}}|^2 F(Z, E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k (E_{\mathrm{max}} - E_e - V_k)$$

$$\times \sqrt{(E_{\mathrm{max}} - E_e - V_k)^2 - m_{\nu i}^2} \times \Theta(E_{\mathrm{max}} - E_e - V_k - m_{\nu i})$$

- Approaches to control uncertainty:
  - Ongoing improvement in calculations
  - Characterization of initial T_2 state
  - TRIMS experiment to re-check predicted observable



$m_{\nu,eff}^2$: A Brief History in Tritium



Adapted from J. Wilkerson, Neutrino 2012

Recipe for a New Measurement

- The observable is $m^2_{\nu,eff}$
  - 100x better uncertainty → 10x better $m_{\nu,eff}$ sensitivity
- Improve *statistics*
  - Luminous β source (10^{11} decays/s)
  - Excellent energy resolution (0.93 eV)
  - Low backgrounds (even at sea level)
- Improve *systematics*
  - Extensive commissioning
  - Molecular physics
  - Column density (activity, scattering)
  - Point-to-point energy scale
  - ...

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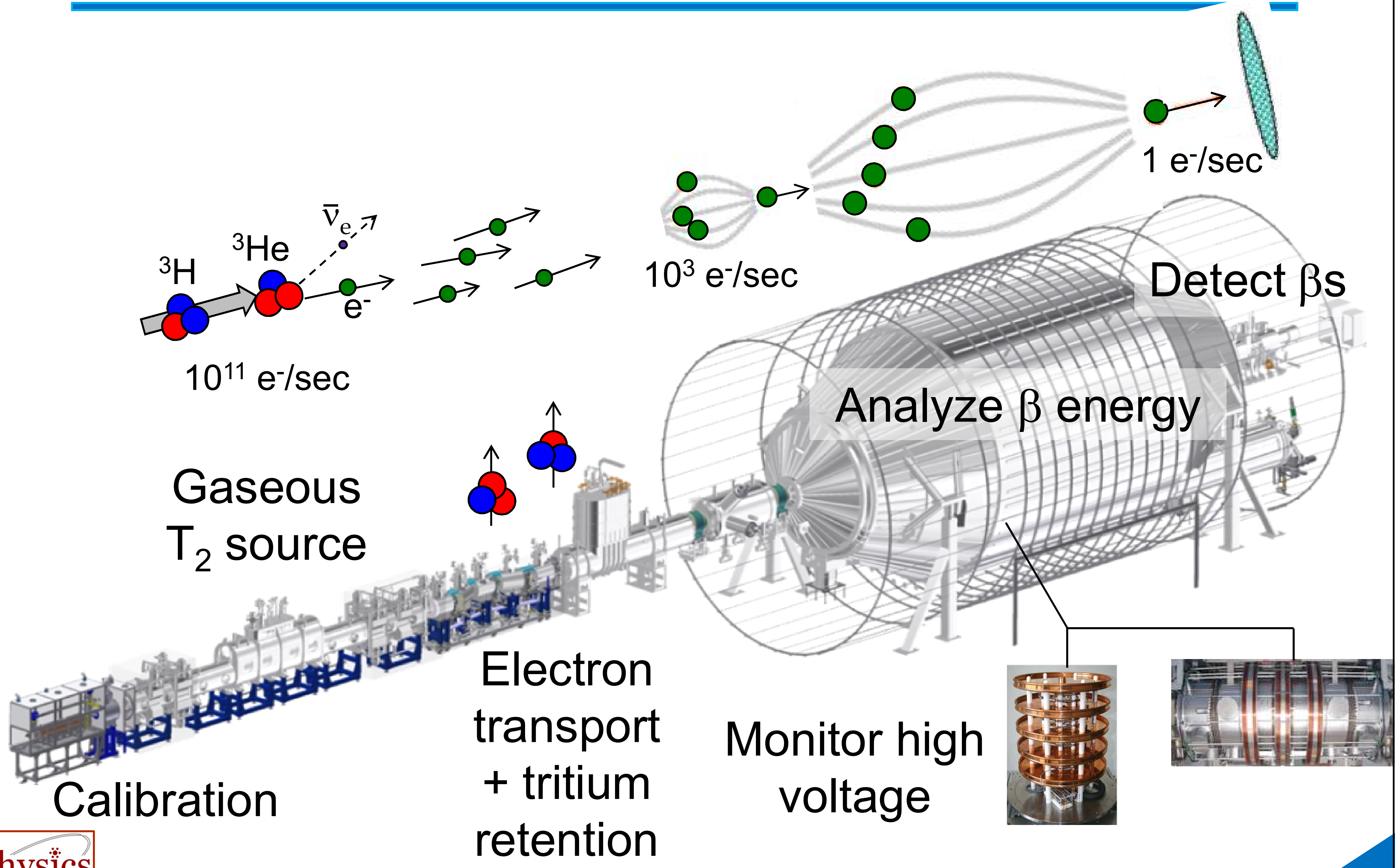
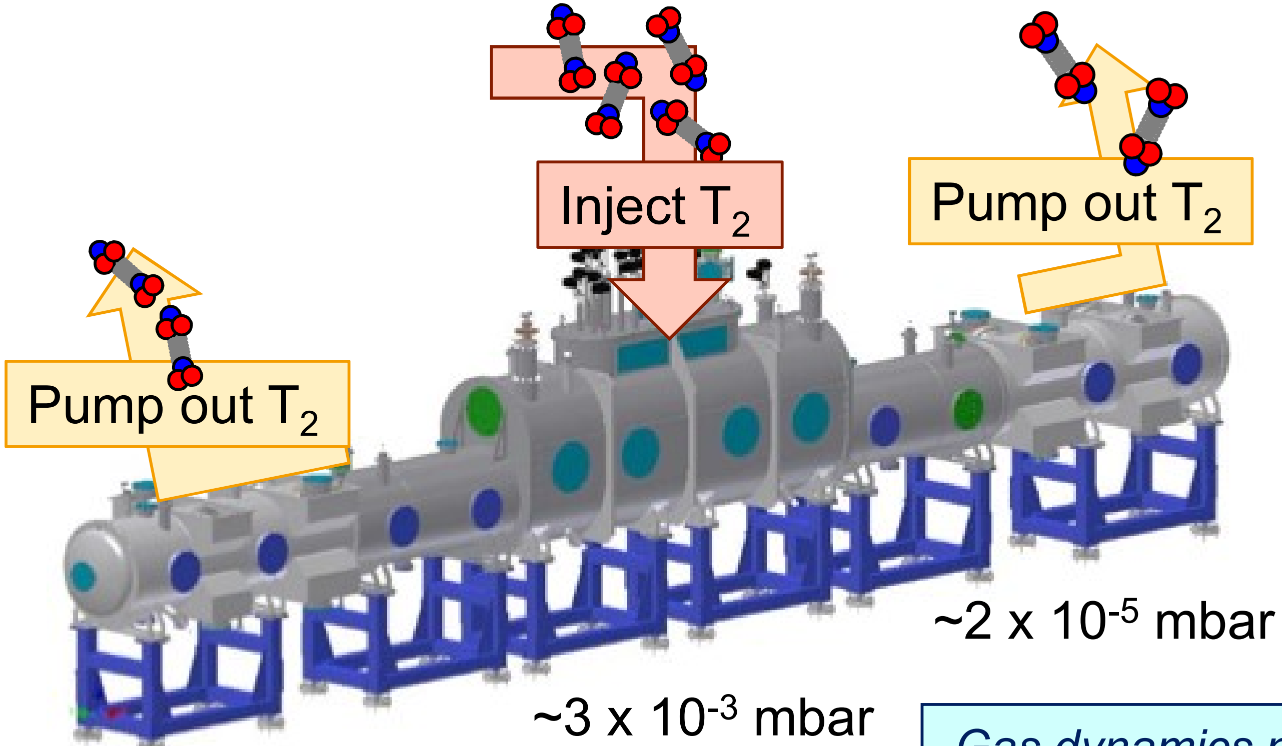
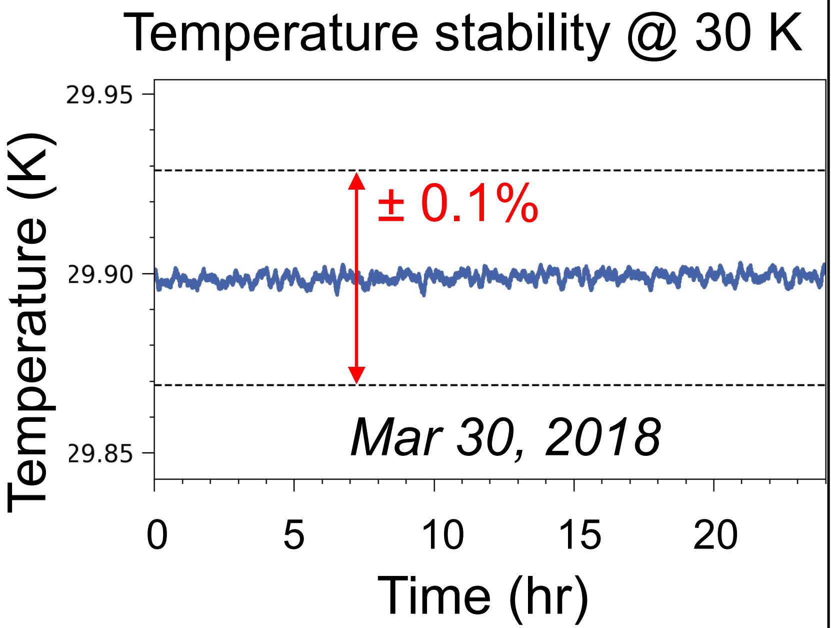
A Quick Tour of the Beamline



Windowless, Gaseous T_2 Source

- 16-m cryostat, 7 integrated superconducting solenoids
- T_2 gas kept at 30 K in beam tube
- Backed by closed tritium cycle with purification (40 g/day)



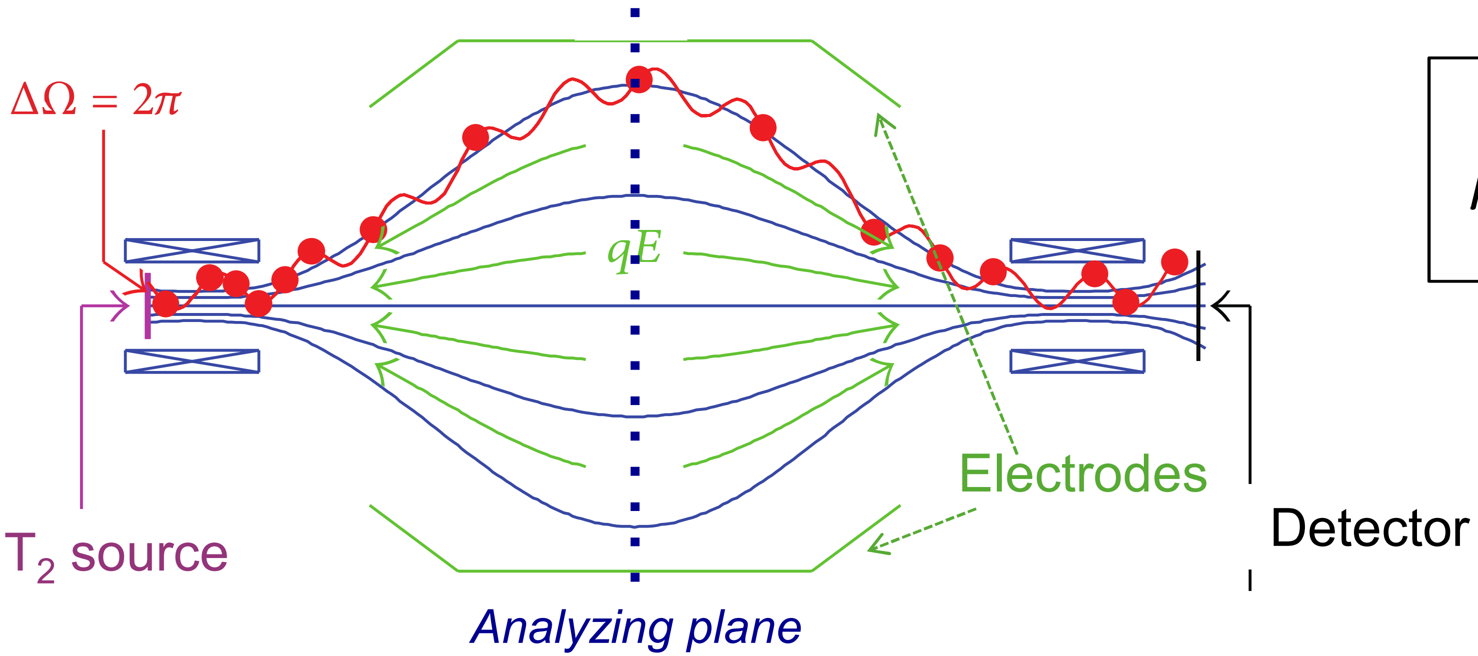


Gas dynamics model: Kuckert et al., arXiv:1805.05313

*Two-phase Ne cooling: Grohmann et al., Cryogenics **49** (2009) 413*

The MAC-E Filter

- Measure integral spectrum with moving threshold
- **M**agnetic **A**diabatic **C**ollimation + **E**lectrostatic filter



$$\mu = \frac{E_\perp}{B} = \text{const}$$

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

Detailed application to KATRIN: Kleesiek et al., arXiv:1806.00369

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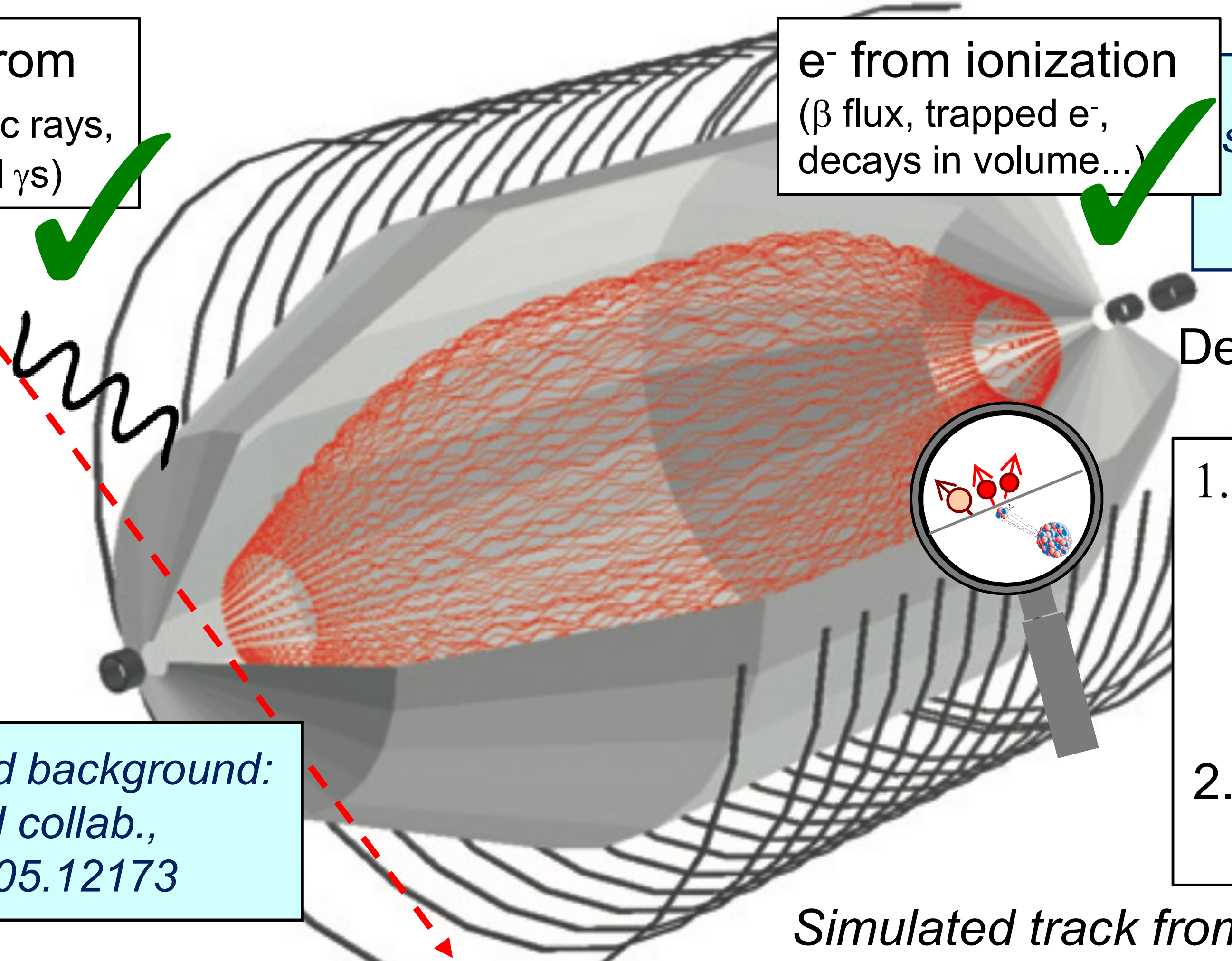
Spectrometer Backgrounds

- Signal βs have E~0 keV in analyzing plane
- Low-energy secondaries mimic the signal

Emission from walls (cosmic rays, environmental γs)

e^- from ionization (β flux, trapped e^-, decays in volume...)

Magnetic pulses vs stored-e^- background: KATRIN collab., arXiv:1805.01163



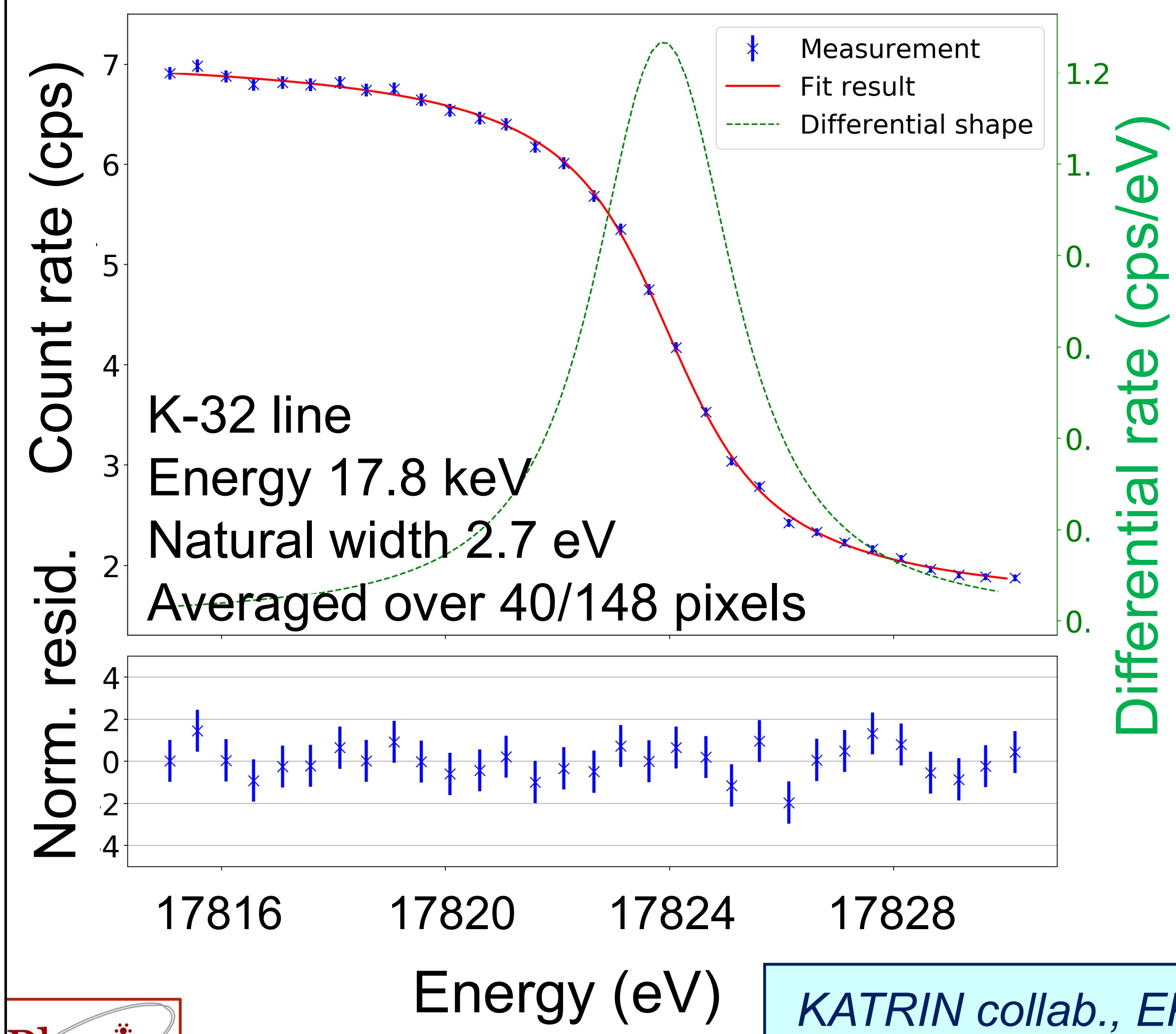
1. α decay in walls (^{210}Pb chain from Rn plateout) sputters highly excited atoms
2. Rydberg atoms ionize in volume

Muon-induced background: KATRIN collab., arXiv:1805.12173

Simulated track from Mertens et al., Astropart. Phys. ***41****, 52 (2013)*

2017: ^{83m}Kr Spectroscopy

- July 2017: Monoenergetic electrons from two beamline ^{83m}Kr sources



- Commissioning with isotropic source
  - Energy scans
  - Demonstrate sub-eV energy resolution
  - Calibration, monitoring equipment

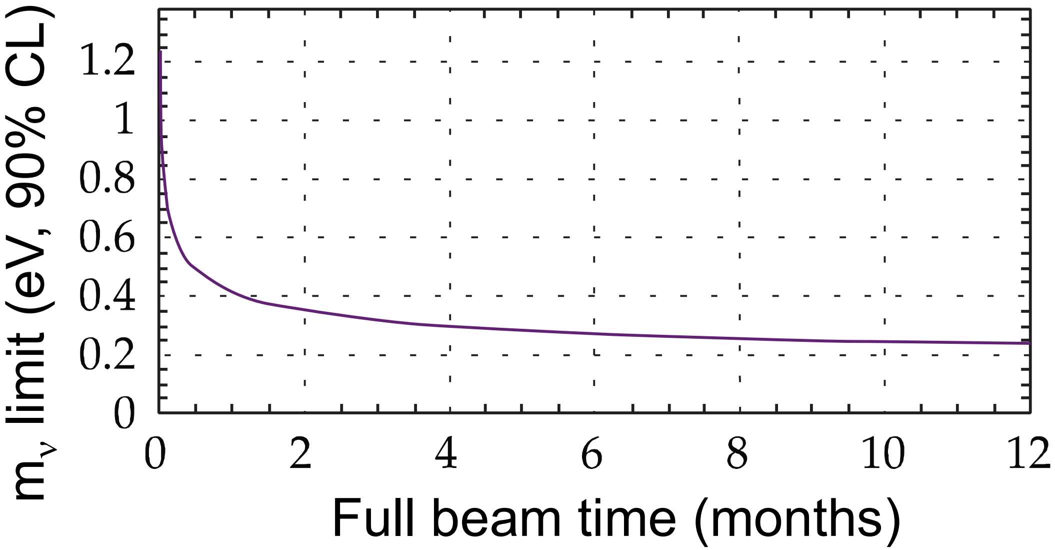
KATRIN collab., JINST ***13*** *P04020 (2018)*

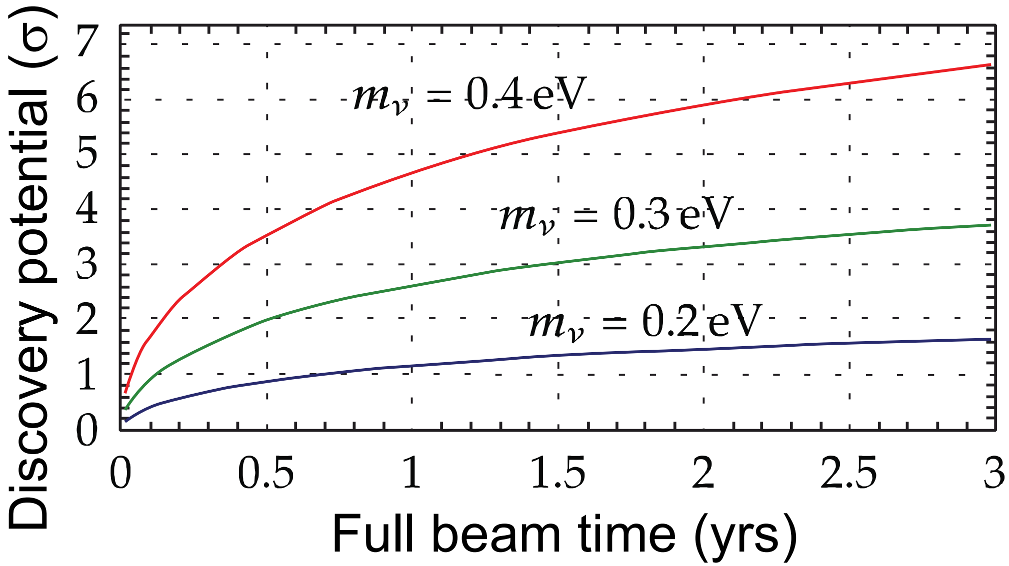
- New method for high-voltage calibration

KATRIN collab., EPJ C ***78*** *368 (2018)*

Neutrino-Mass Sensitivity

- Even with increased background, we can reach a sensitivity of 0.24 eV by adjusting scan strategy
- Full sensitivity ($\sigma_{syst} = \sigma_{stat}$) after 3 beam years (~5 calendar years)





G. Drexlin et al., Adv. High Energy Phys. ***2013*** *(2013) 293986*

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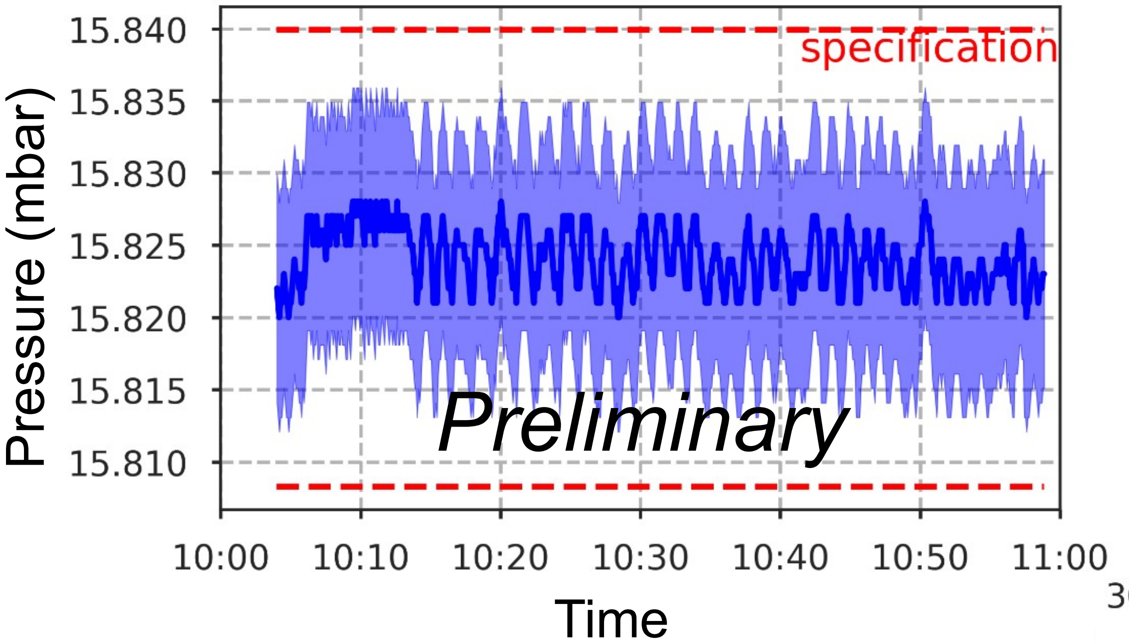
KATRIN'S Very First Tritium

- Normal operation: Continuous gas flow through closed tritium cycle with purification
- First commissioning: Inject known gas mix from prepared sample cylinders (4 doses)
  - 0.5% T atoms circulating in D_2 gas (90% nominal density)

First tritium injection:
Friday 18 May
7:48 am UTC

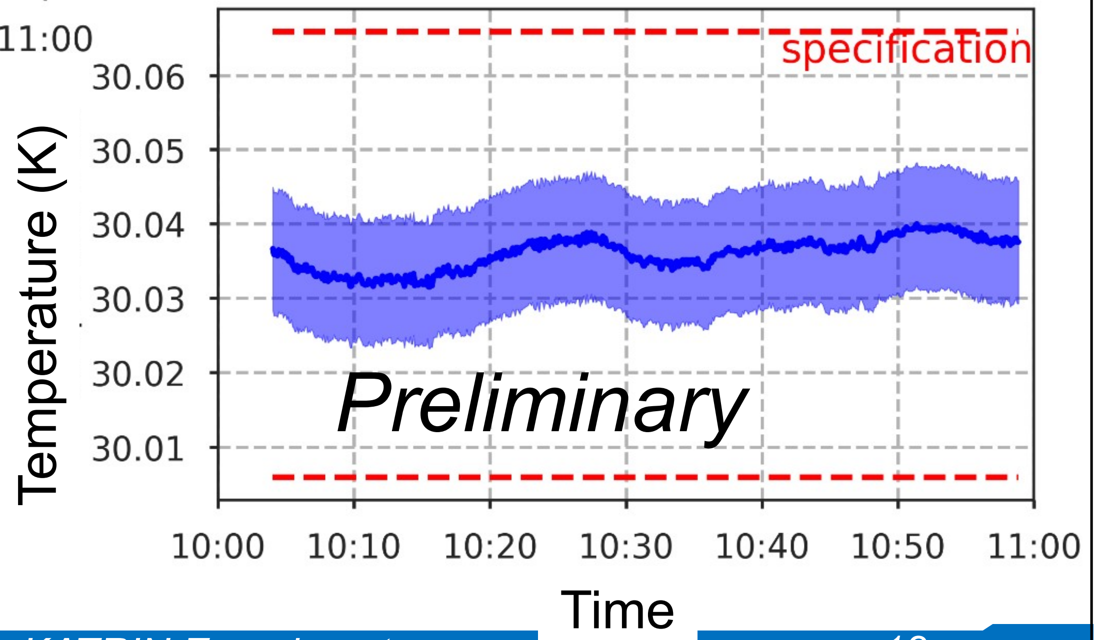
KATRIN in Operation

- Eight 30-minute voltage scans – is KATRIN stable?



- Pressure in buffer vessel
  - Standard deviation less than 0.2% over 60 min

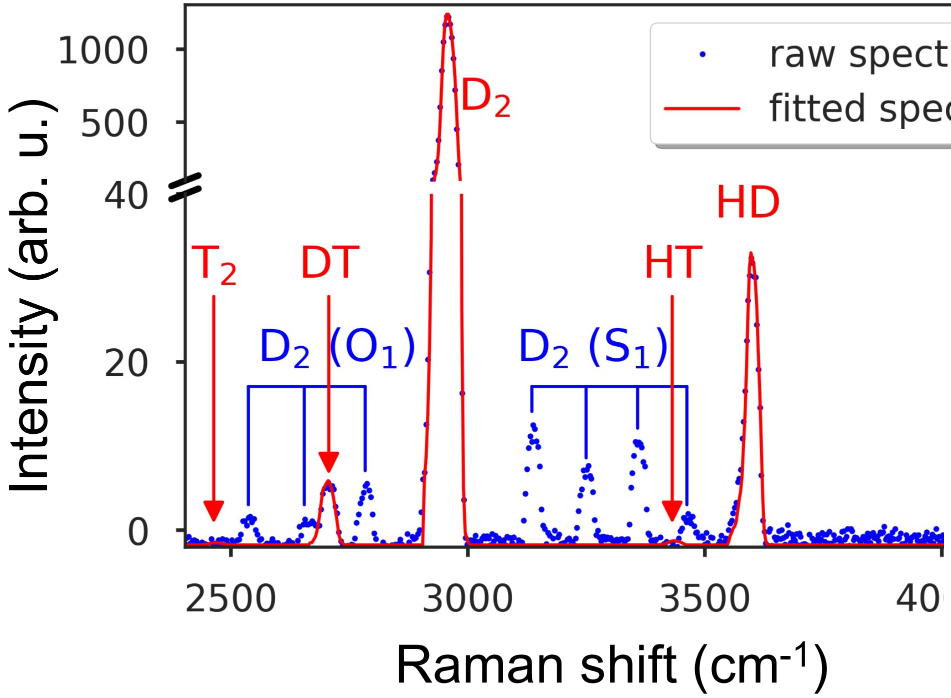
- WGTS beam-tube temperature
  - Standard deviation less than 0.1% over 60 min



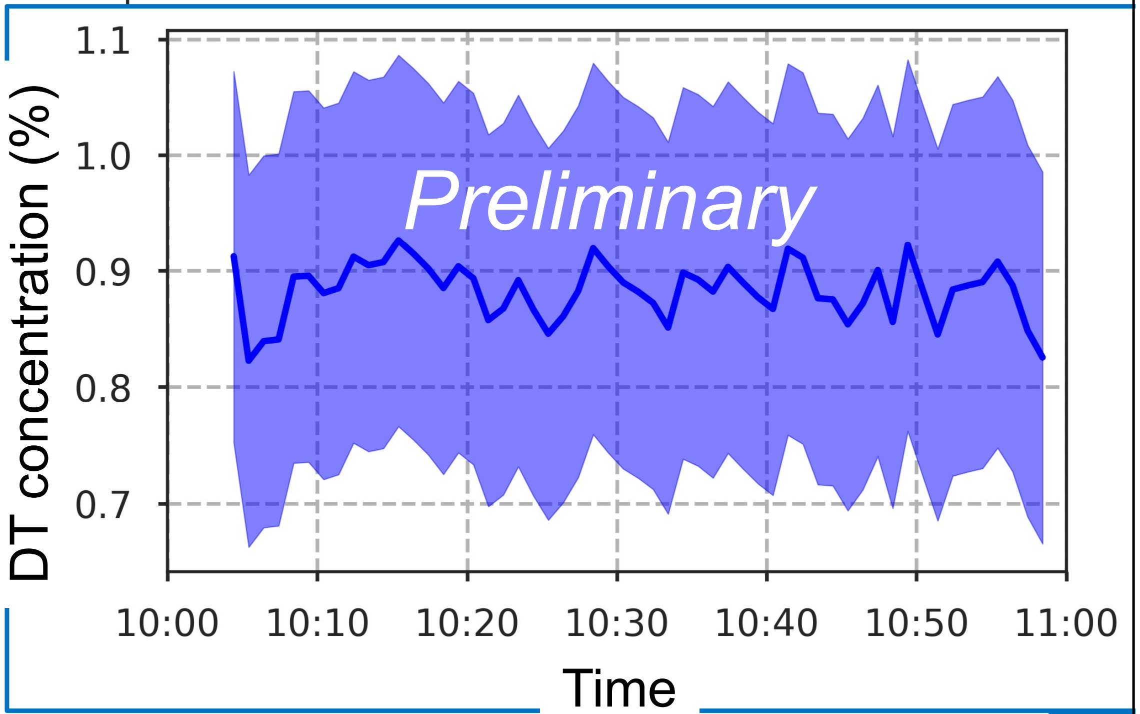
Concentrating on Tritium

- Measure tritium concentration (mostly bound in DT) with laser Raman spectroscopy

LARA system: Schlösser et al., J. Mol. Spect. ***1044*** *61 (2013)*

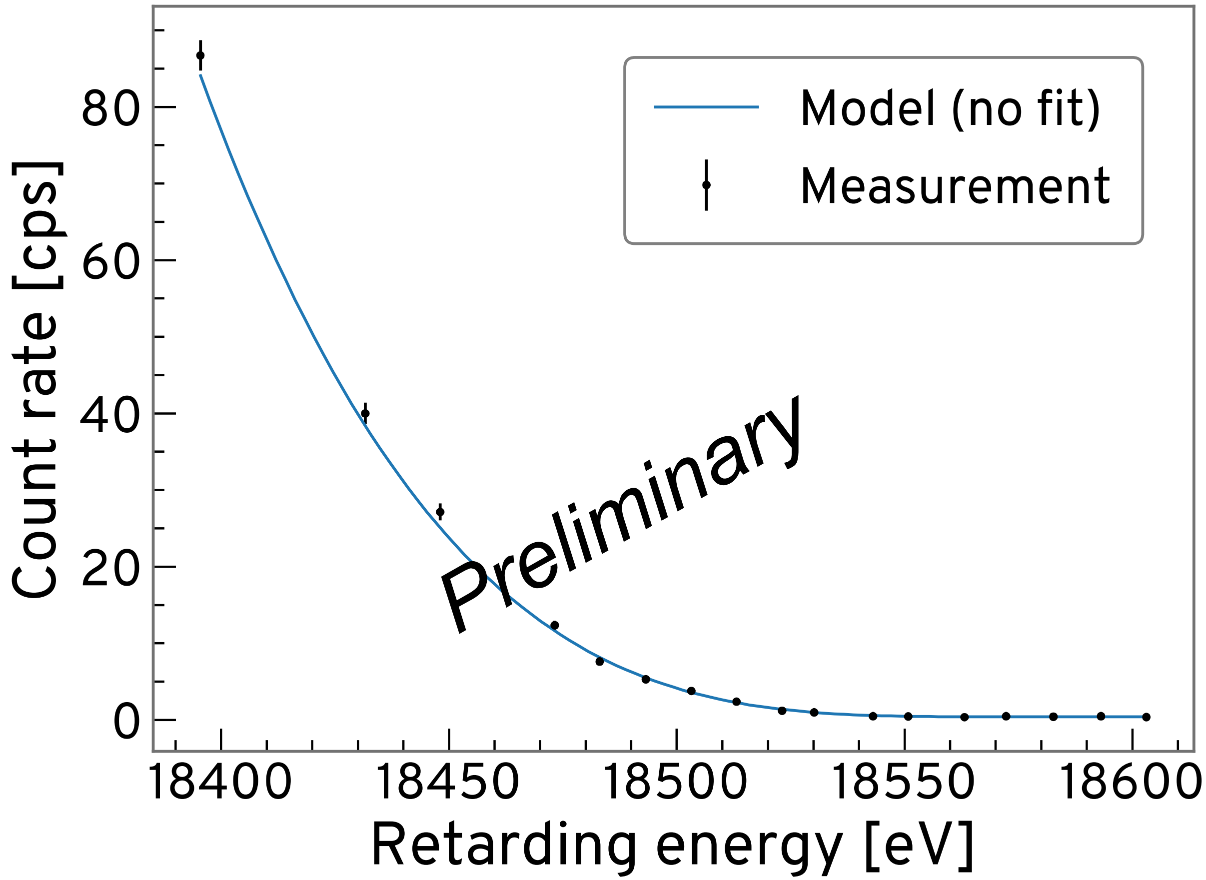


DT conc.: 0.9% (3% variation over scan)



Scanning the Tritium Spectrum

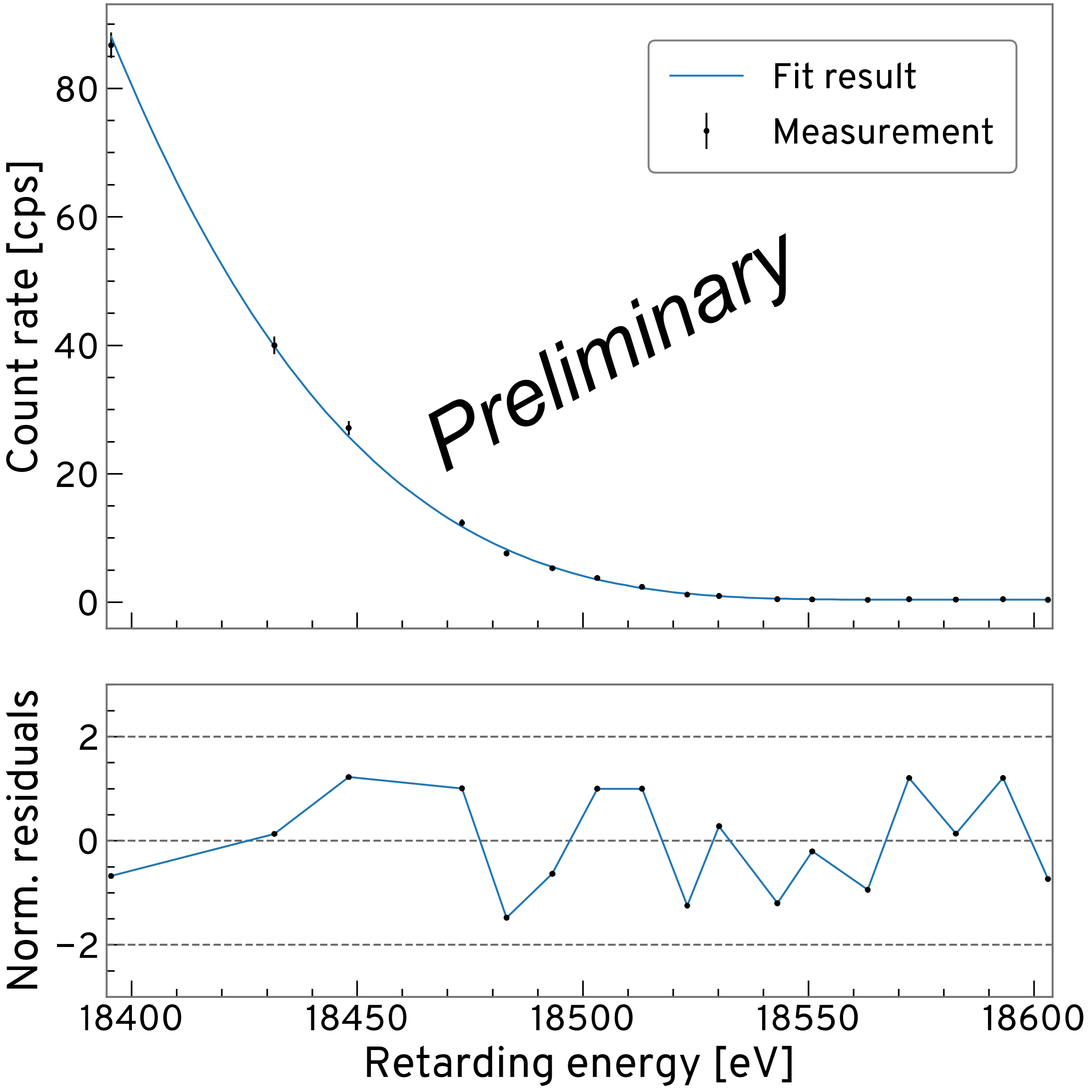
- KATRIN tritium scan #1 (Day 2 of tritium commissioning)
- Immediate comparison of data to model



- Model initialized with system parameters from slow controls
- Very good agreement “out of the box”

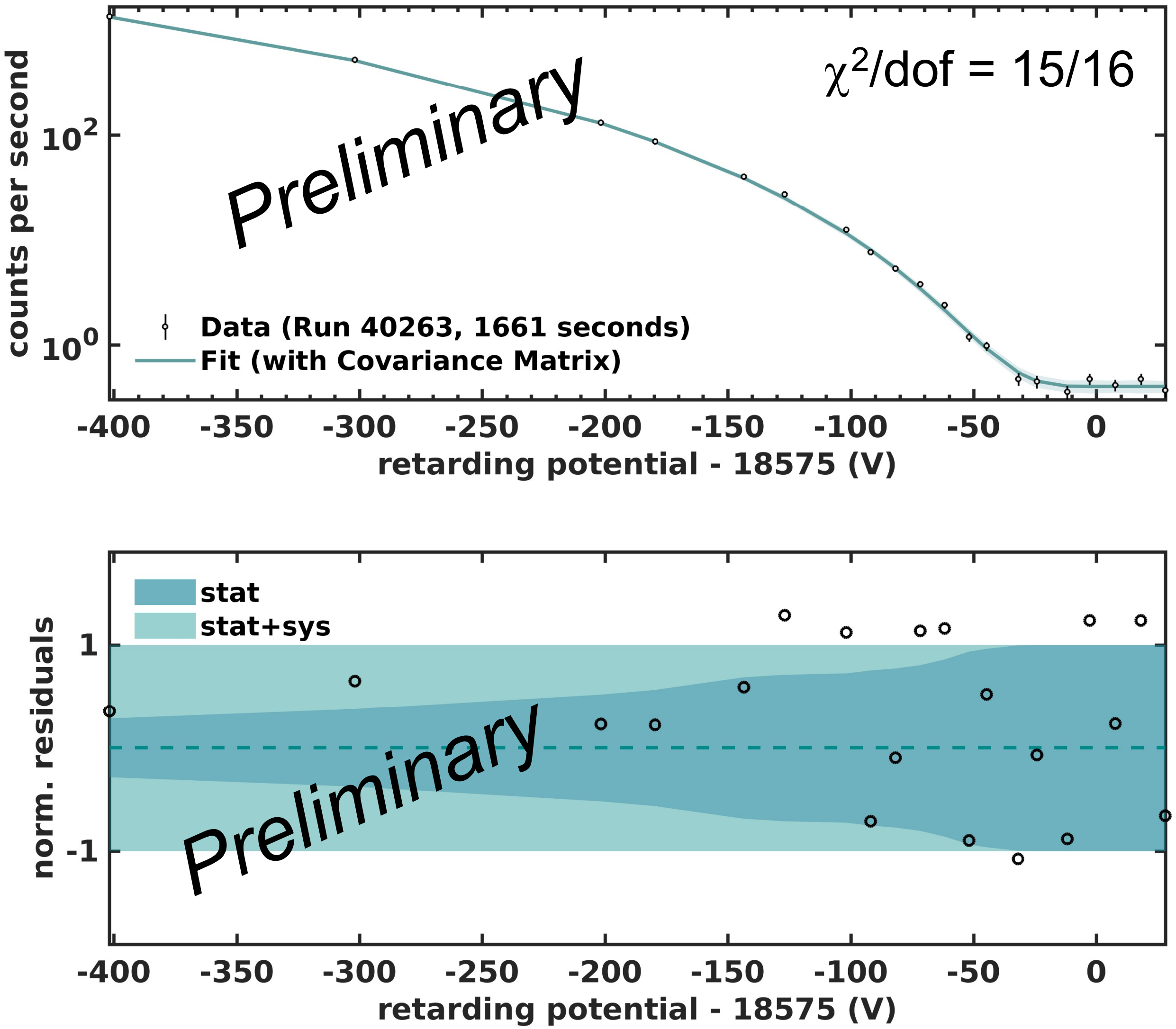
Fitting the Tritium Spectrum

- Later that day, we fit the last 200 eV of the spectrum



- Three fit parameters:
  - Overall activity
  - Constant background
  - Endpoint energy E_0
- Statistical errors only in this early fit
- χ^2/dof = 15.0/14

First Look at Fit Systematics



- Examined 400-eV analysis window for a single scan
- Covariance-matrix approach to systematics
- Propagated correlations with multisim method
- Many systematics will improve after this commissioning cycle (e.g., column density)

Outlook

- KATRIN is a working experiment
  - First full-beamline data, Oct. 2016
  - First spectral measurement of radioactive source, July 2017
  - ***First tritium, 3 weeks ago!***
  - Tritium commissioning still underway
- Still some more commissioning work to do
  - Measurements this fall with D_2 gas
- We expect $m_{\nu,\mathrm{eff}}$ data in early 2019
- Additional, bonus sensitivities as well
  - Sterile neutrinos at eV and keV scales
  - Right-handed weak currents
  - ...

KATRIN Collabora

KATRIN Inauguration
KIT, Campus North
Monday 11 June
https://indico.scc.kit.edu/event/397

You're invited!

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Backup Slides

- List of KATRIN posters at Neutrino 2018
  - (Check online proceedings for poster files!)
- Accounting for backgrounds in the KATRIN sensitivity
- List of recent technical papers
- Brief introduction to the TRIMS experiment

KATRIN Posters (all in Monday session)

KATRIN components

- **The Condensed Krypton Source (CKrS) as Calibration Tool for KATRIN** (Fulst, #2)
- **First stability measurements of the WGTS cryostat performance** (Seitz-Moskaliuk, #5)
- **Commissioning + Characterization of Tritium Gas Circulation** (Krasch, Marsteller, #11)
- **High Voltage Monitoring + Characterization** (Thorne, Rodenbeck, Thümmler, #12)
- **Sources of monoenergetic electrons from decay of ^{83m}Kr** (Suchopar et al., #19)
- **Retention measurements of the KATRIN Cryogenic Pumping Section** (Röttele, #25)
- **Electron Gun** (Ranitzsch, Sack, #26)
- **Calibration strategy + status of tritium purity monitoring** (Niemes, Zeller, Schlösser, #27)

Analysis and simulation methods

- **Analysis Strategies** (Karl, Edzards, #3)
- **Modeling of the response function** (Behrens, Schimpf, #15)
- **Methods for an unbiased neutrino mass analysis** (Sibille, Heizmann, Wolf, #29)
- **Samak: Matlab Simulation and Analysis** (Lasserre, Schlüter, Morales, #158)

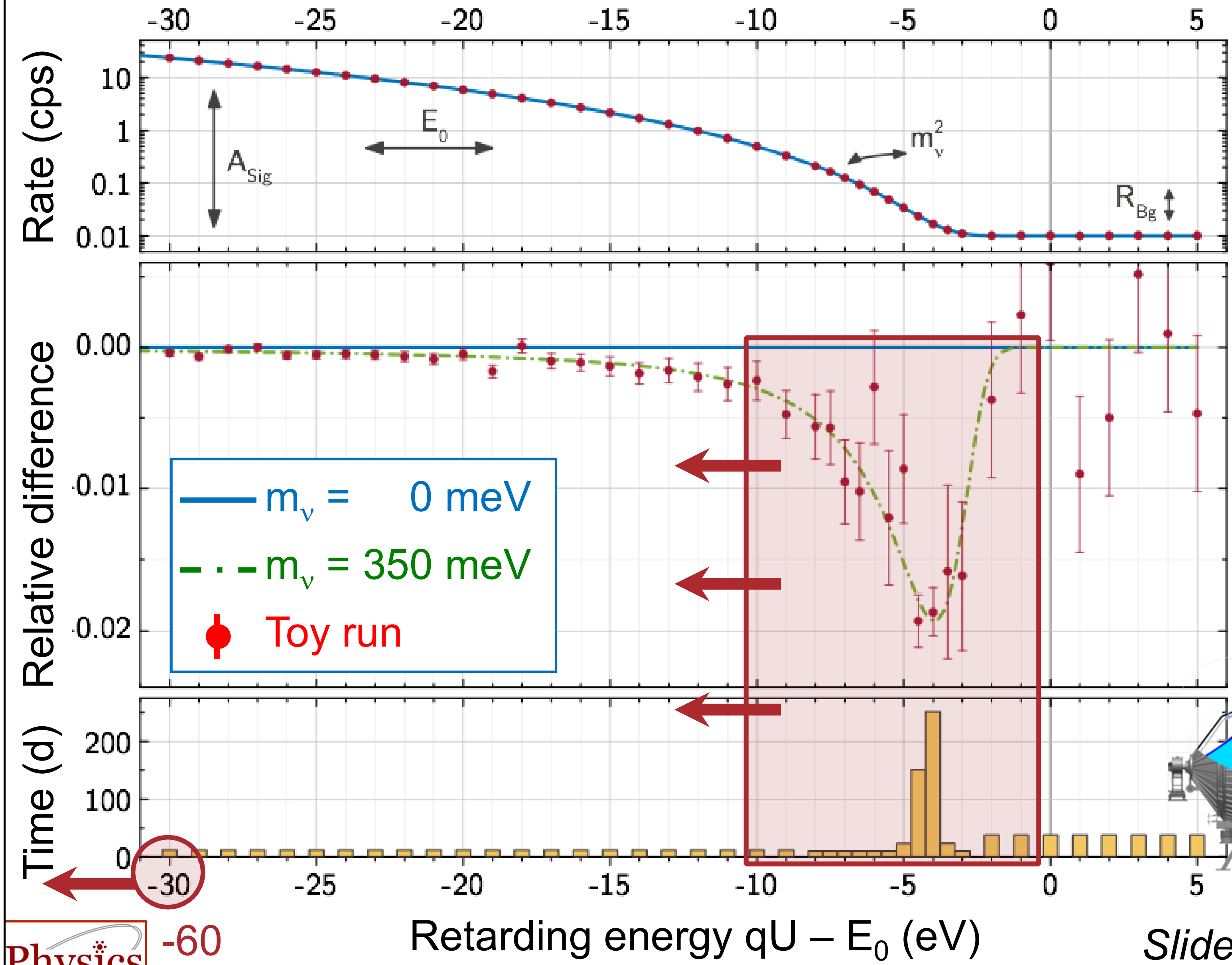
System commissioning analysis

- **Investigations of the interspectrometer Penning trap** (Fedkevych, #4)
- **Forward Beam Monitor data from KATRIN first tritium measurements** (Hickford et al, #7)
- **Alignment studies** (Deffert, Choi, #8)
- **First spectroscopic measurements of conversion electrons from the gaseous Kr-83m at the KATRIN experiment** (Slezák, #13)
- **Background Characterization** (Pollithy, #16)
- **Results from the First Tritium campaign** (Heizmann, Marsteller, #17)
- **Tritium ion monitoring during KATRIN First Tritium** (Klein et al., #28)

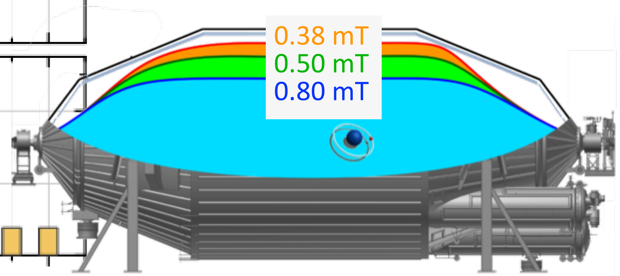
Sterile-neutrino searches

- **Silicon drift detector prototypes ... for keV-scale sterile neutrino search with TRISTAN and ... first tritium data** (Altenmüller et al., #116)
- **A model for a keV-scale sterile neutrino search with KATRIN: SSC-sterile** (Slezák, Lokhov, et al., #133)
- **Search for keV-scale sterile neutrinos with the first light of KATRIN** (Huber, #135)

Background and Sensitivity



- Shift scans to lower E_β
- Extend data range by 30 eV
- Shrink flux tube (slight cost in ΔE)



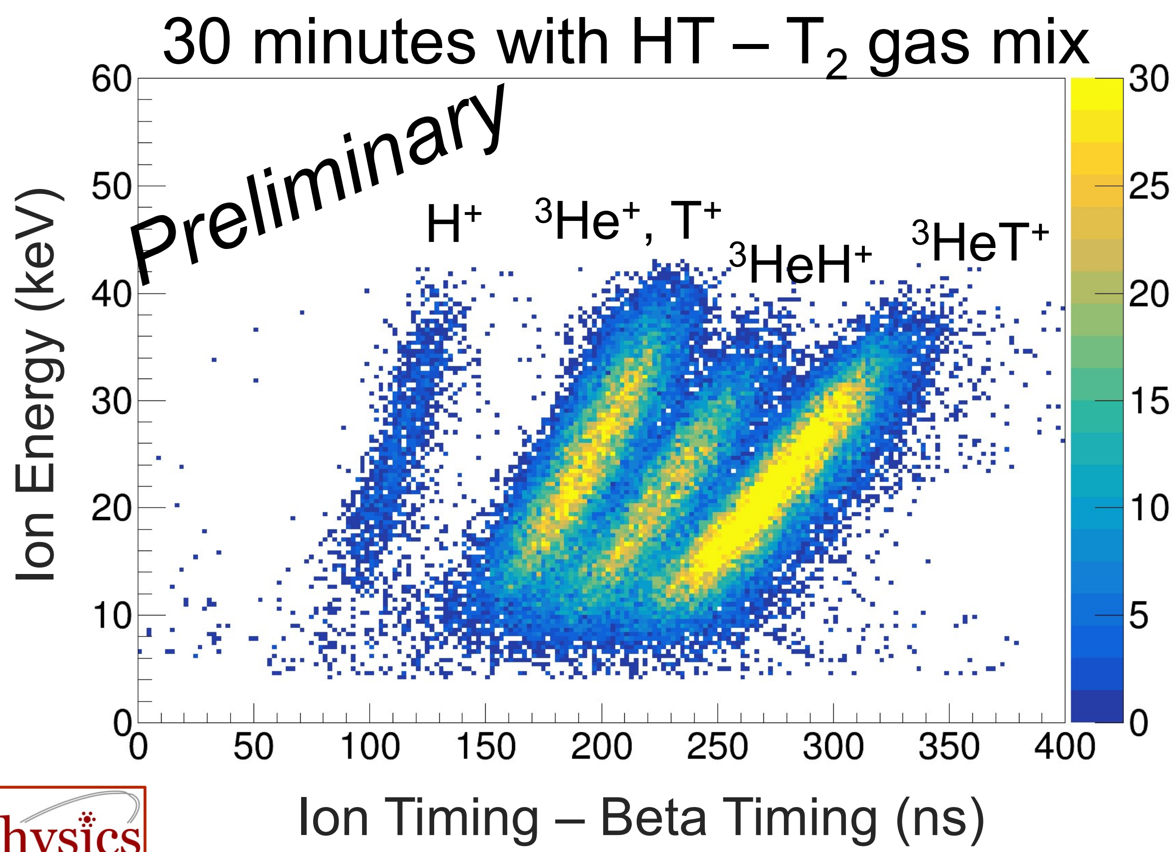
Slide from Kathrin Valerius

Recent Technical Papers

- **Mobile, external magnetic-field sensing**
  - Letnev et al., arXiv:1805.10819 [physics.ins-det]
- **Large-volume air-coil system**
  - Erhard et al., JINST **13** (2018) P02003
- **Electron gun for commissioning**
  - Behrens et al., Eur. Phys. J. C **77** (2017) 410
- **Kassiopeia particle-tracking software**
  - Furse et al., New J. Phys. **19** (2017) 053012

Tritium Recoil-Ion Mass Spectrometer

- Molecular theory[1] predicts $^3HeT^+$ should dissociate in 43-61% of β decays near endpoint
- Two 1950s experiments[2,3] found 5-10% dissociation over β spectrum
- TRIMS is a time-of-flight mass spectrometer, now taking data at University of Washington to resolve the discrepancy!



TRIMS collaboration: *Baek, Kallander, Lin, Machado, Parno, Robertson, Vizcaya Hernández*

TRIMS Posters (Mon. session)

- **TRIMS: Validating Tritium Molecular Effects for Neutrino Mass Experiments** (Lin, #6)
- **Detecting light ions and electrons with TRIMS silicon detectors** (Baek, Vizcaya Hernández, #88)

[1] Jonsell et al., PRC **60** 034601 (1999)
[2] Snell et al., J. Inorg. Nucl. Chem. **5** 112 (1957)
[3] Wexler, J. Inorg. Nucl. Chem. **10** 8 (1958)