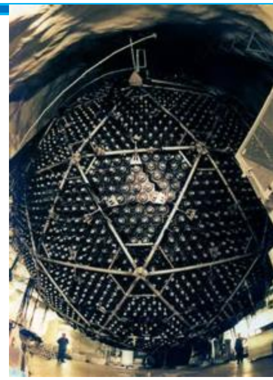
Status of KATRIN and TRISTAN

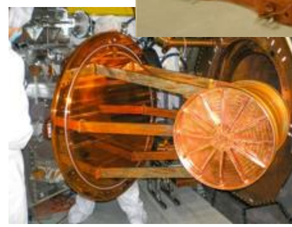
Diana Parno for the KATRIN Collaboration
Carnegie Mellon University
NuTheories, Pittsburgh, November 2018

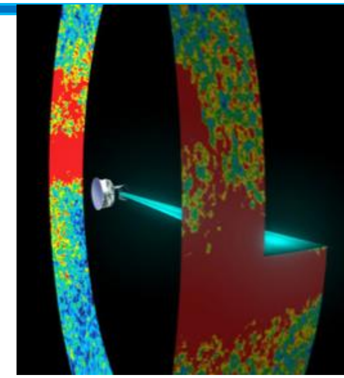
Outline

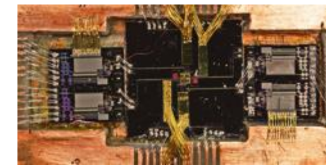
- Neutrino mass through β decay
- Basics of the KATRIN experiment
- First tritium runs
- KATRIN and TRISTAN: eV and keV sterile searches
- Outlook

Probes of Neutrino Mass



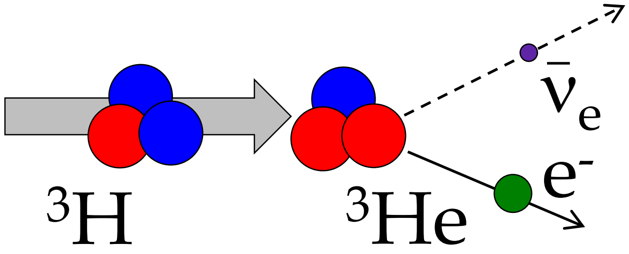


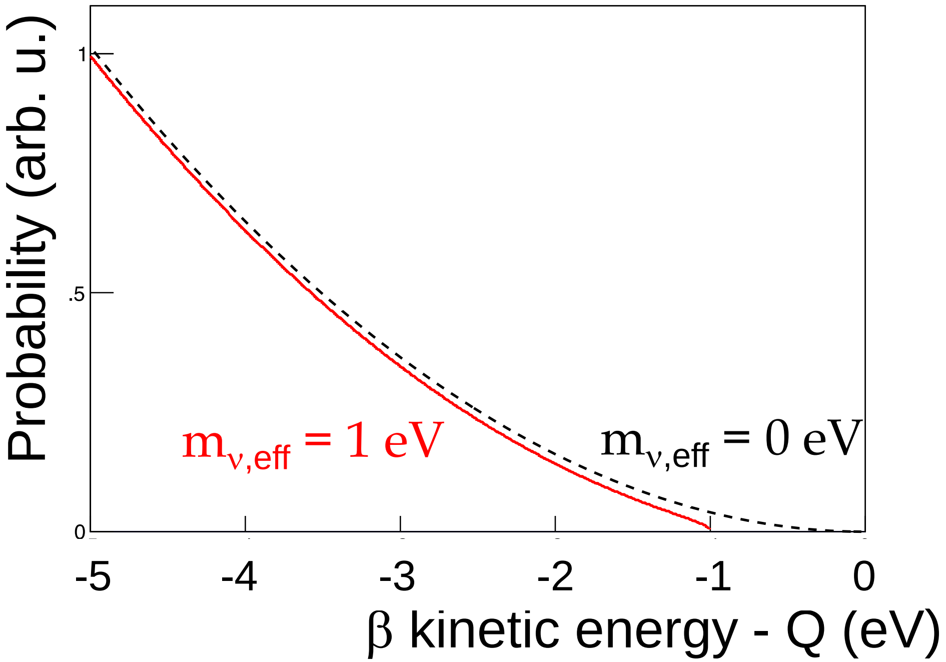




	ν oscillation
Observable	$\Delta m_{ij}^2 = m_i^2 - m_j^2$
Present knowledge	$\Delta m_{21}^2 = 7.53(18) \times 10^{-5}\,\mathrm{eV}^2$ $\Delta m_{32}^2 = 2.44(6) \times 10^{-3}\,\mathrm{eV}^2$
Next gen. / near future	
Model dependence of mass extraction	No mass-scale information

Kinematics of Tritium Decay





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

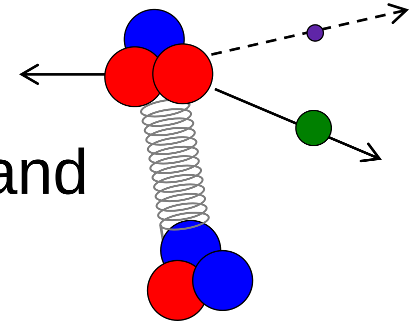
- Extract effective neutrino mass from spectral shape near endpoint

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

$$\approx m_\nu^2 \quad \textit{(quasi-degenerate regime)}$$

Molecular Tritium

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

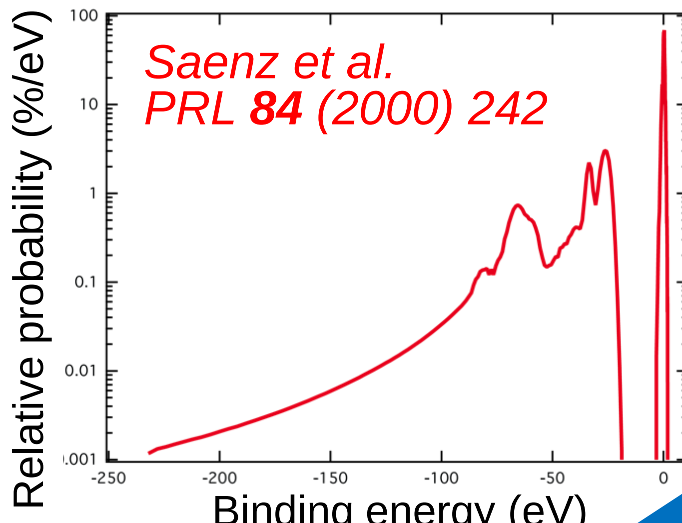


- KATRIN uses a T_2 source – not just T
- β spectrum depends on excitation energies $\boldsymbol{V_k}$ and probabilities $\boldsymbol{P_k}$ – need 1% accuracy

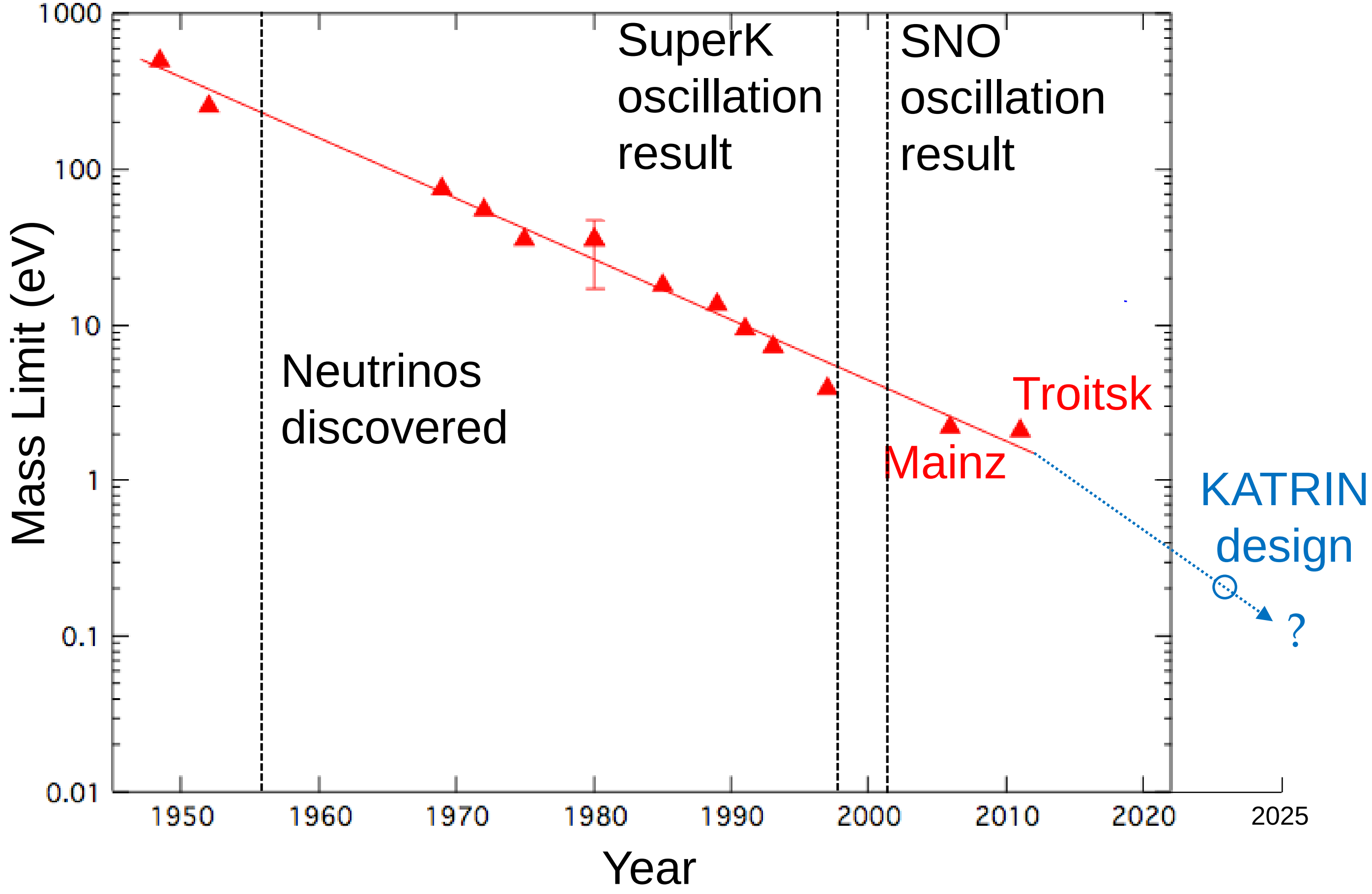
$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\text{nuc}}|^2 F(Z,E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k (E_{\max} - E_e - V_k)$$

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

- 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 $m^2_{\nu,\mathrm{eff}}$
  - 100x better uncertainty → 10x better $m_{\nu,\mathrm{eff}}$ 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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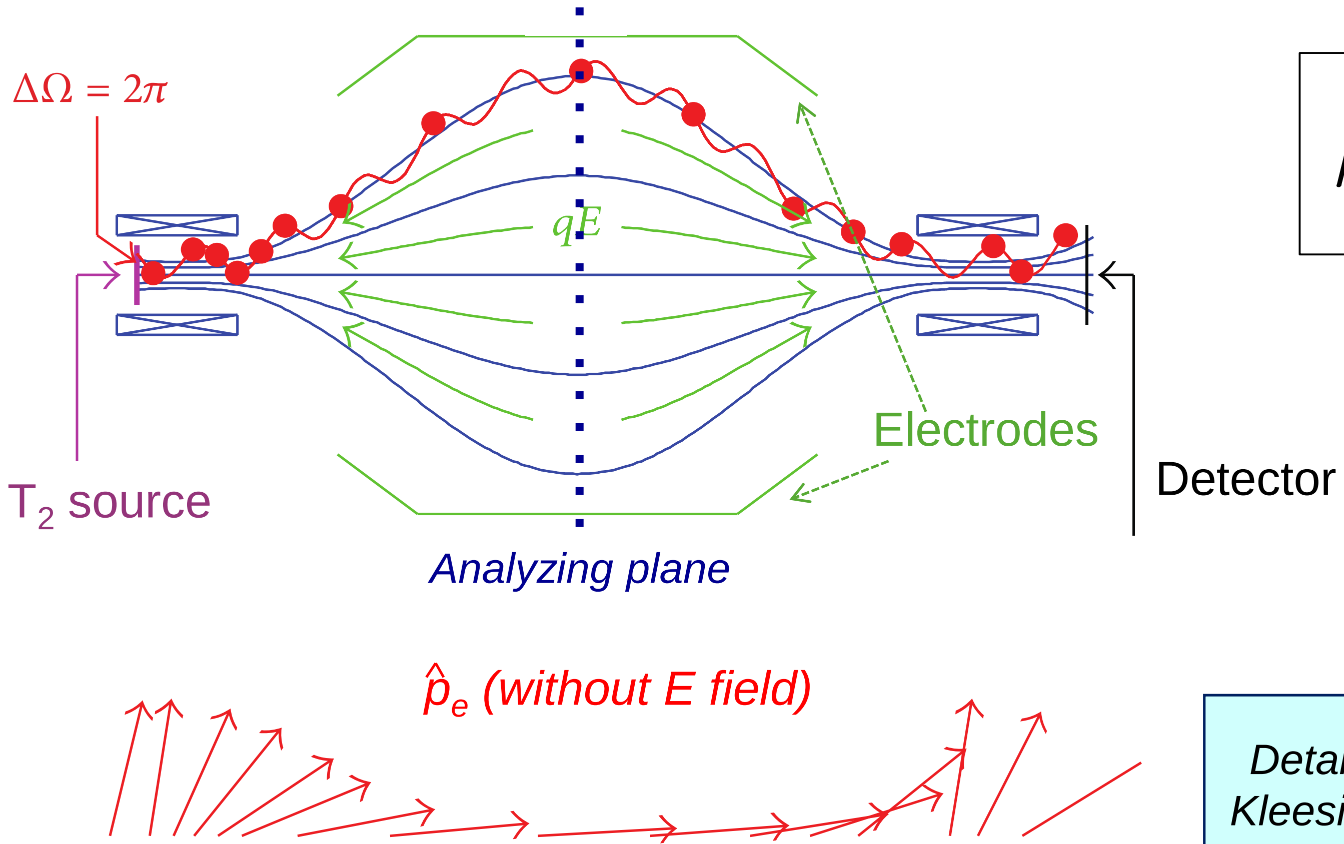
The MAC-E Filter

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

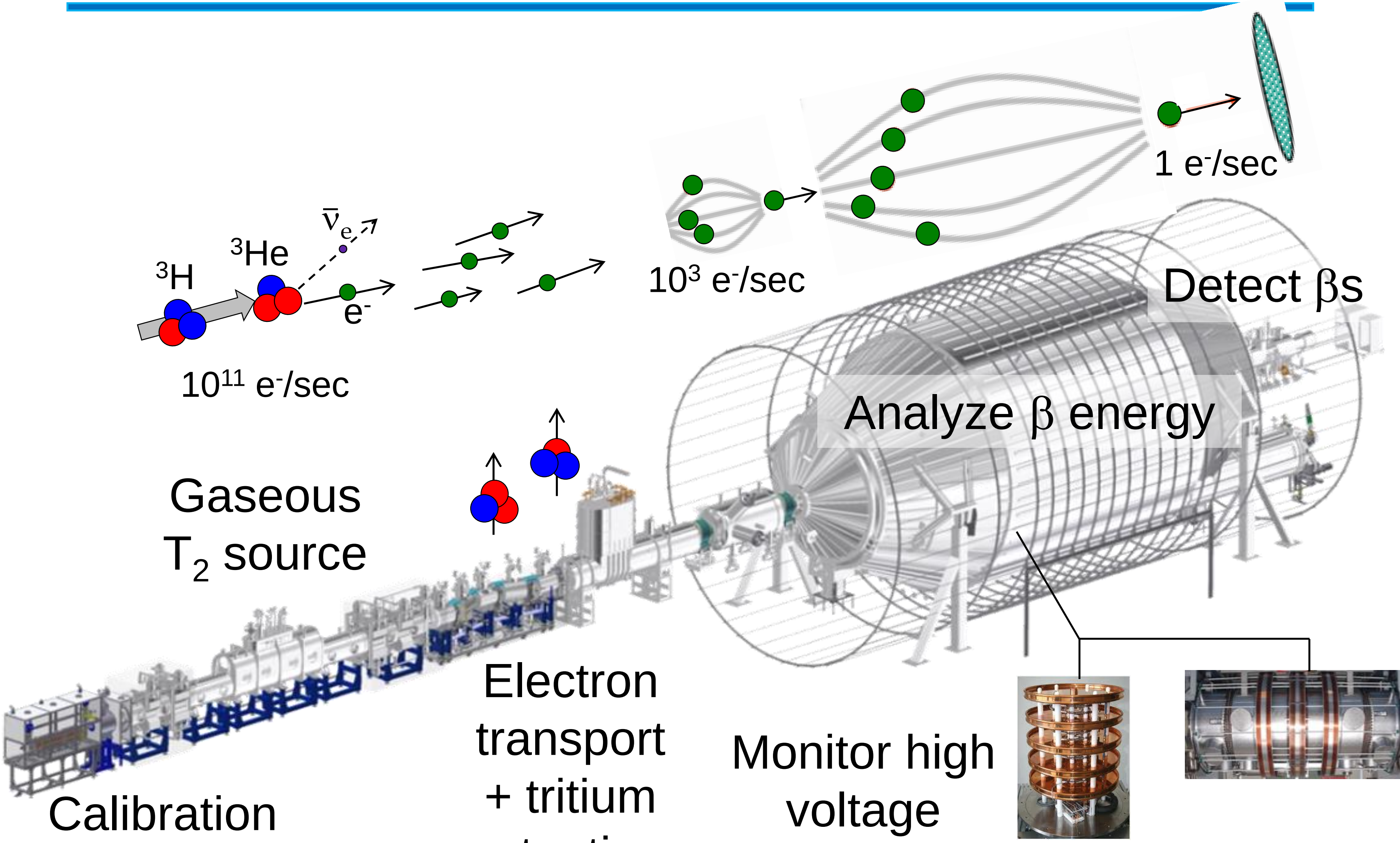


$$\mu = \frac{E_\perp}{B} = \text{const}$$

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

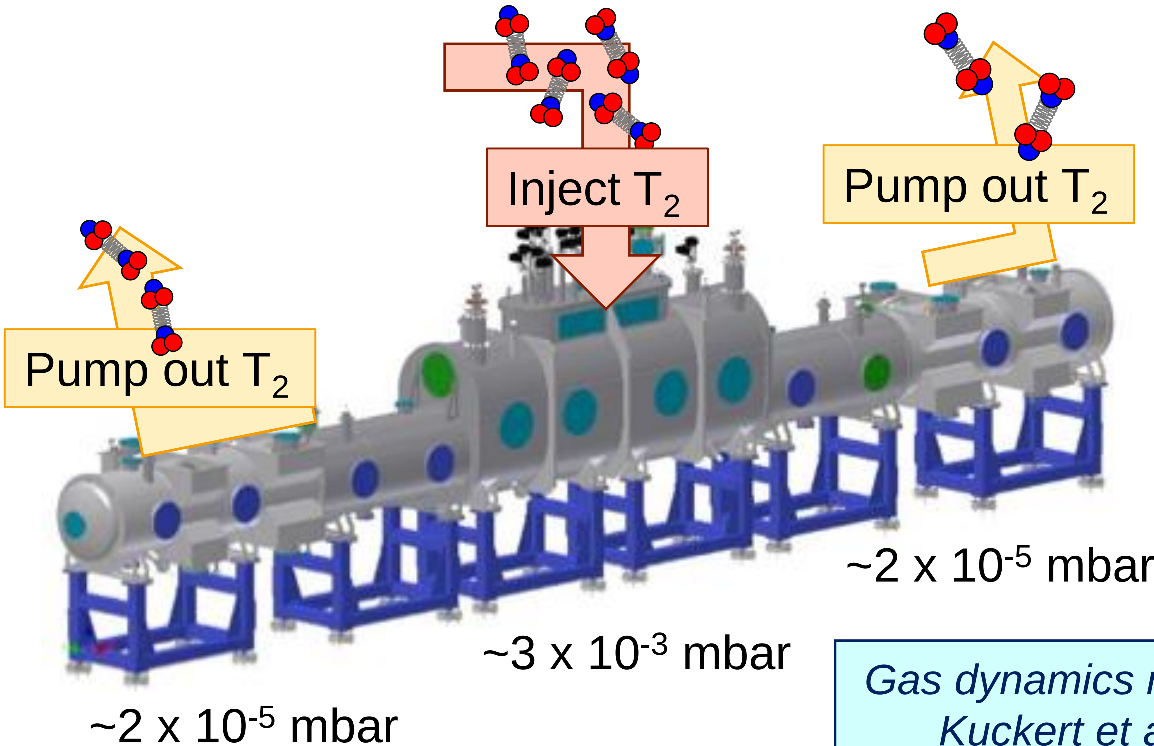
Detailed application to KATRIN: Kleesiek et al., arXiv:1806.00369

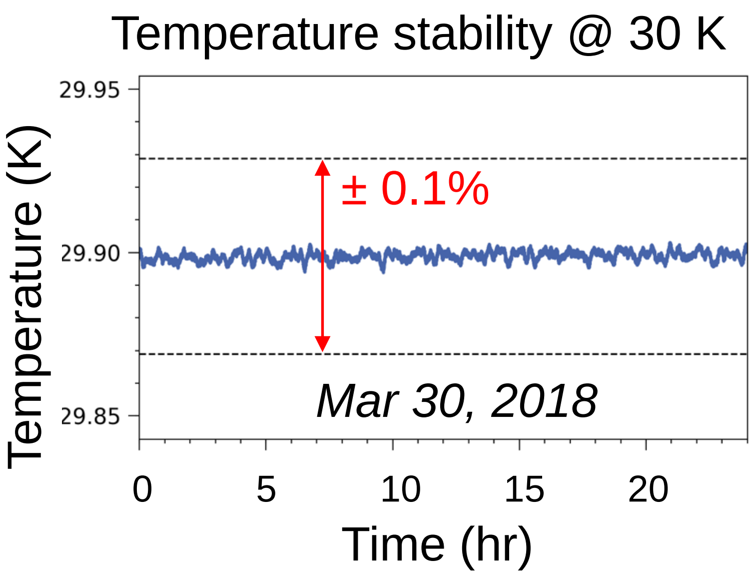
A Quick Tour of the Beamline



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)



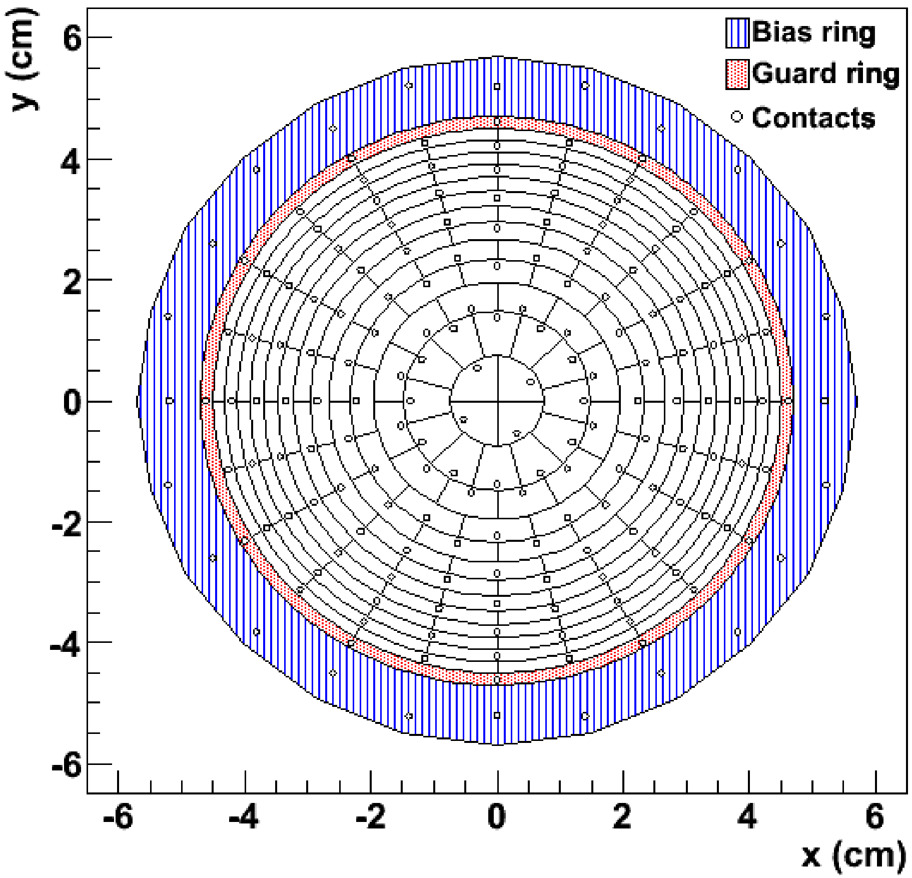


Gas dynamics model: Kuckert et al., arXiv:1805.05313

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

Focal-Plane Detector

- Image analyzing plane with Si p-i-n diode from Canberra



Amsbaugh *et al*., NIM A, **778** 40 (2015)

- 90-mm active diameter
- Entrance window 150 nm with 46% charge collection
- 148 pixels in dartboard pattern
- Energy resolution around 2 keV FWHM

KATRIN by the Numbers

- 10^{11} tritium decays per second
- Magnetic field range 3 – 60000 G
- Design filter width $\Delta E = 0.93$ eV
- Design sensitivity: 0.2 eV at 90% CL

Leopoldshafen, Germany
(near Karlsruhe)
November 2006

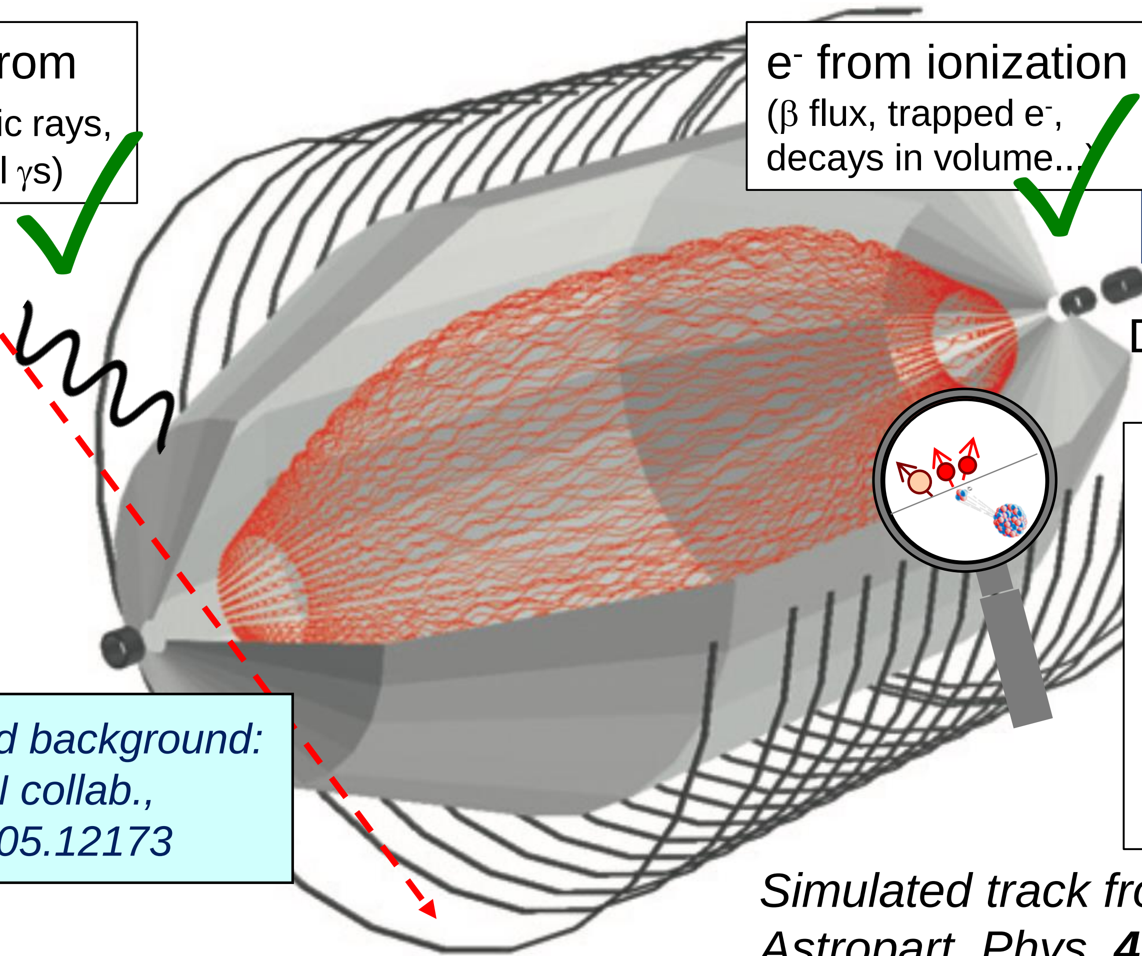
Spectrometer Backgrounds

- 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., EPJC **78**, 778 (2018)*



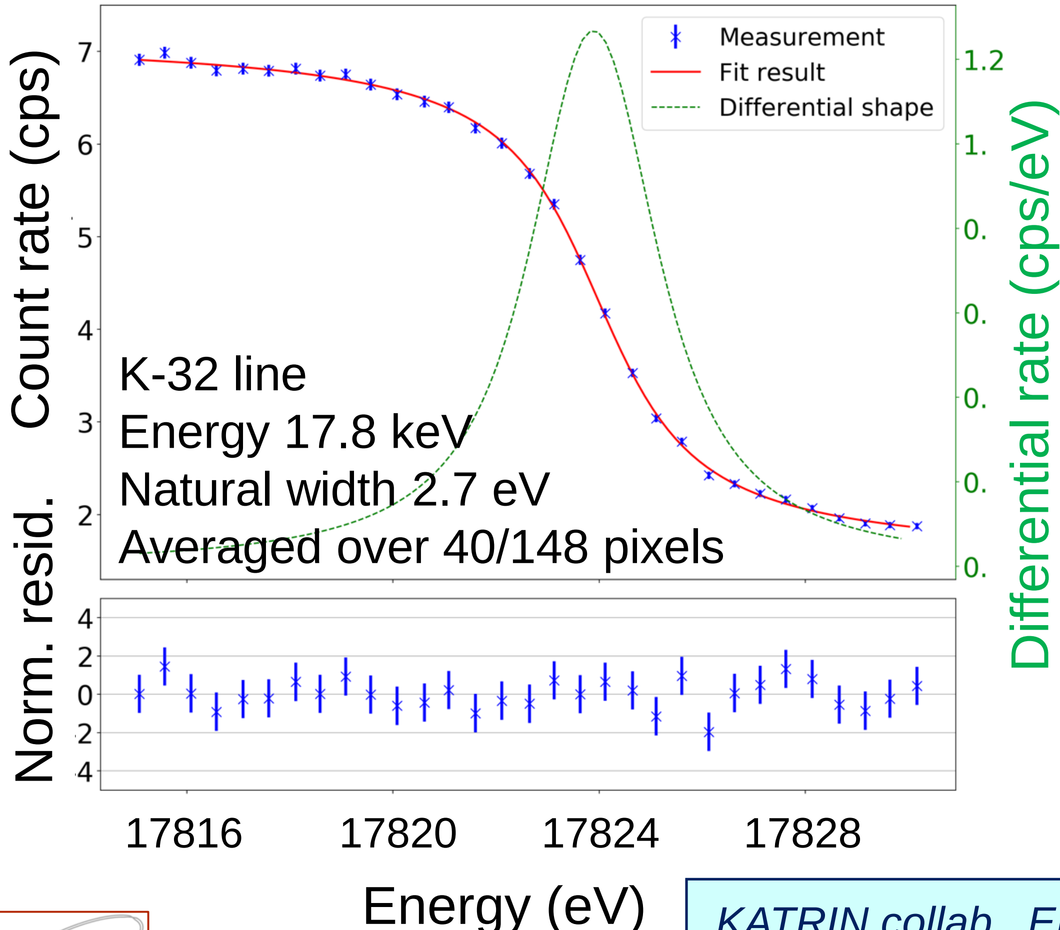
1. α decay in walls (^{210}Pb chain from Rn plateout) sputters highly excited atoms
2. Rydberg atoms ionize in volume

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)*

- Long-term stability of high-voltage divider: *2 ppm over 4 years*

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

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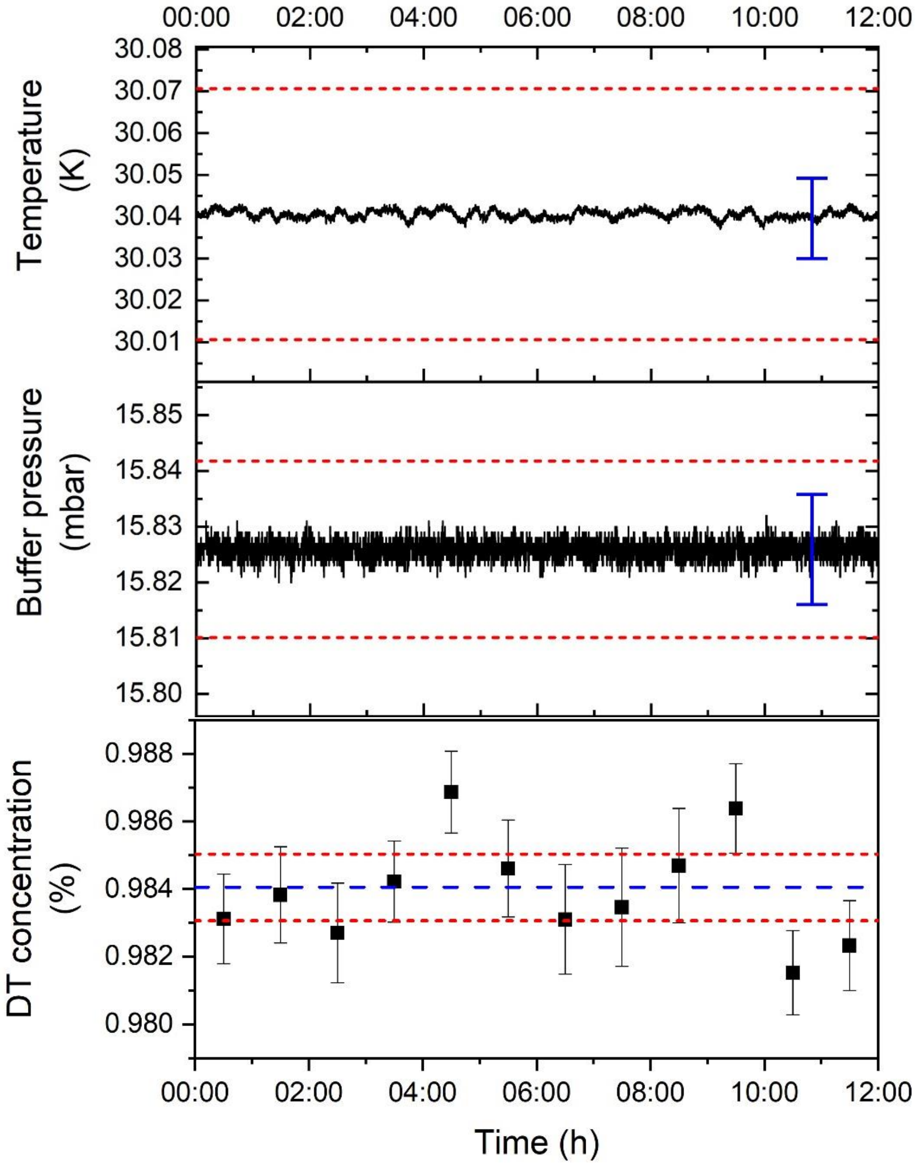
KATRIN'S Very First Tritium

- 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

Source Stability over 12 Hours

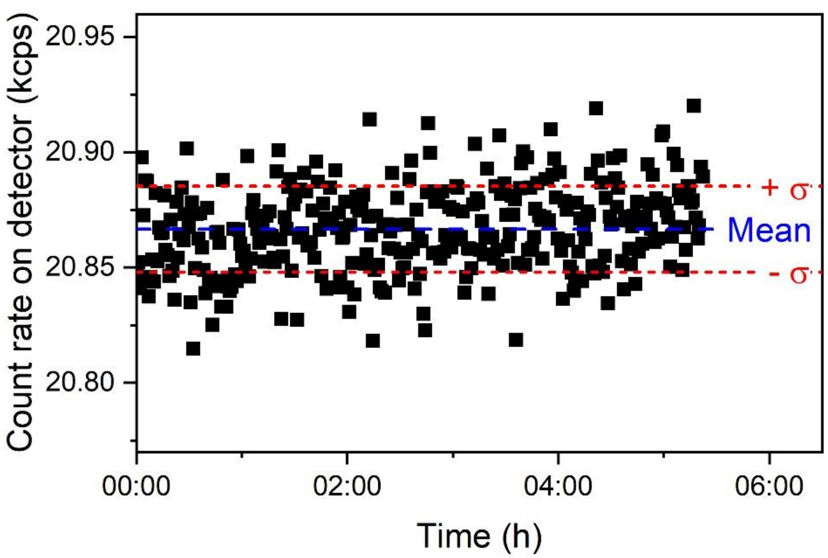


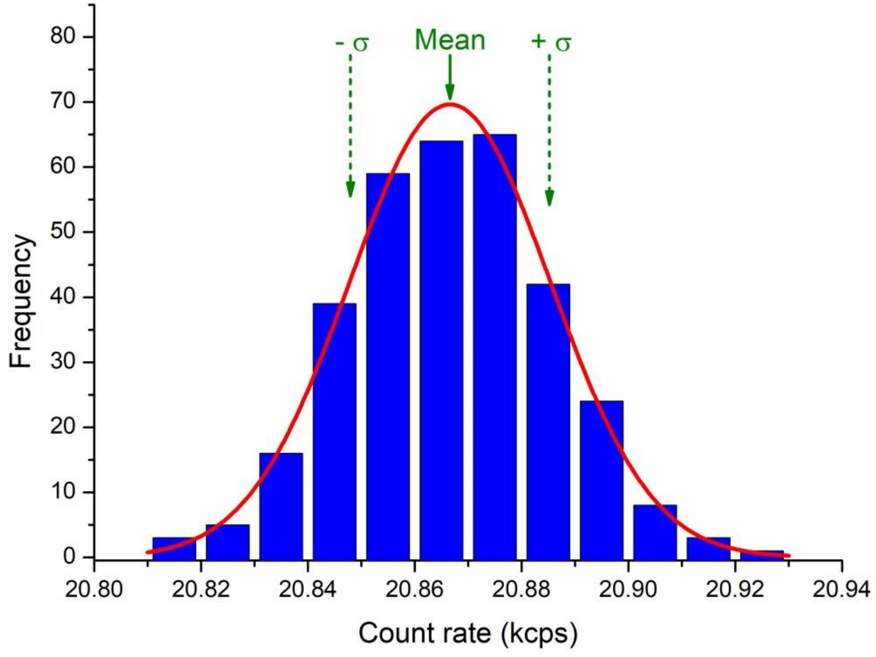
- Blue error bars indicate systematic uncertainty
- Red dashed lines indicate 0.1% stability tolerance for neutrino-mass running

Slide credit: Magnus Schlösser

Integral Rate Stability (5 hours)

- Retarding potential set to 1000 V below endpoint for 5 hours
- Rate stability reflects overall performance of system





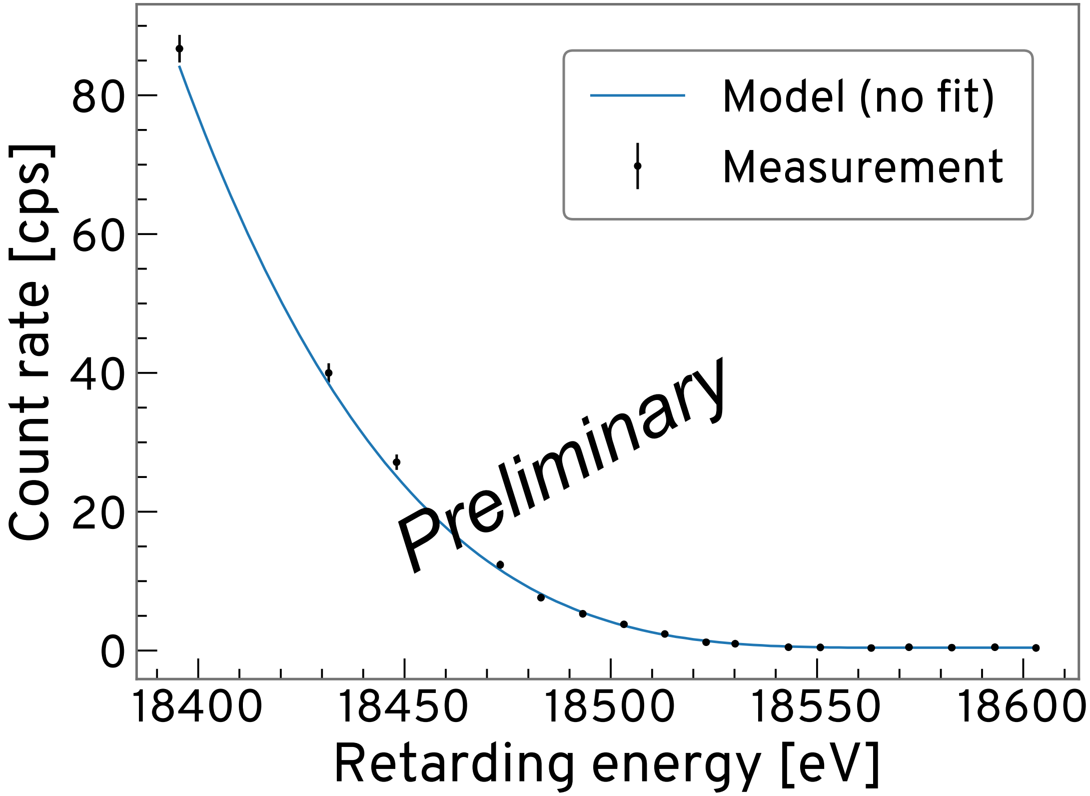
Expected 0.1% statistical precision at this rate: **18.7 cps**

Measured precision (1-minute base): **σ = 18.9 cps**

Slide credit: Magnus Schlösser

Scanning the Tritium Spectrum

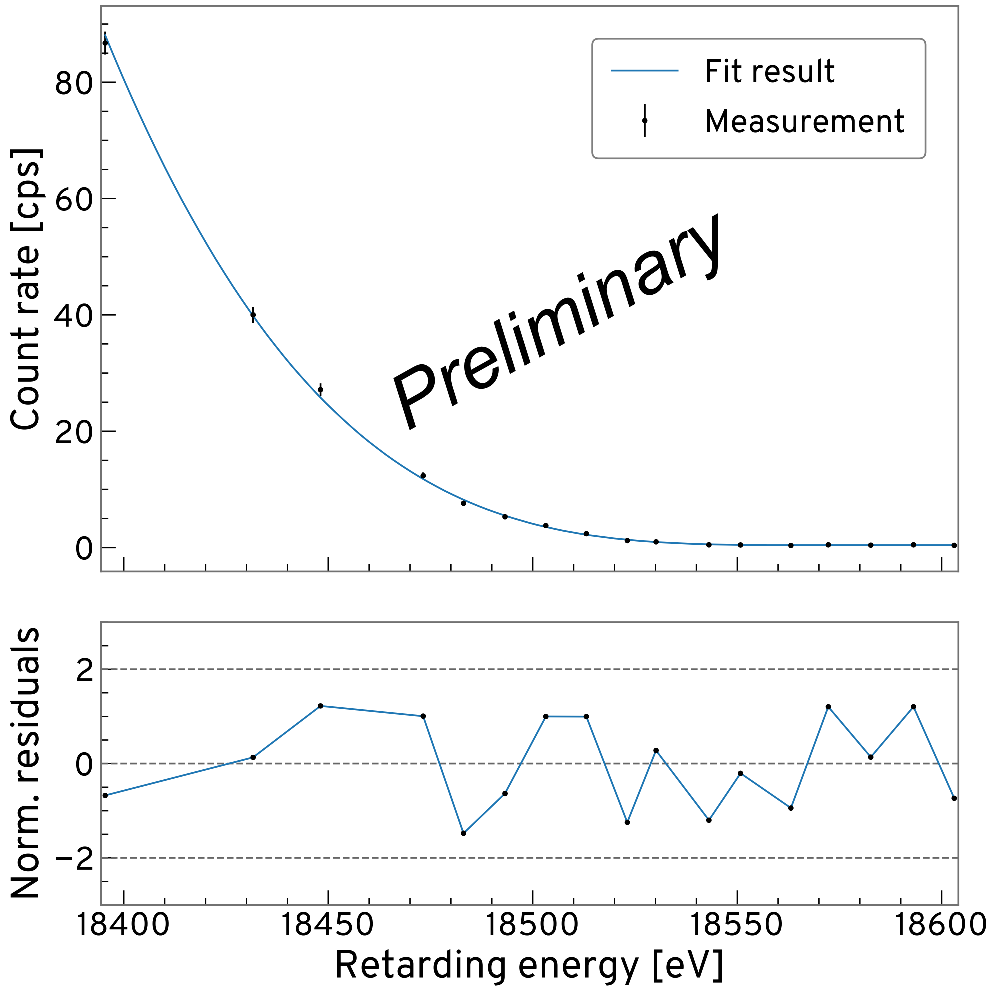
- KATRIN tritium scan #1 (Day 2 of tritium commissioning)
- Immediate comparison of data to model



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

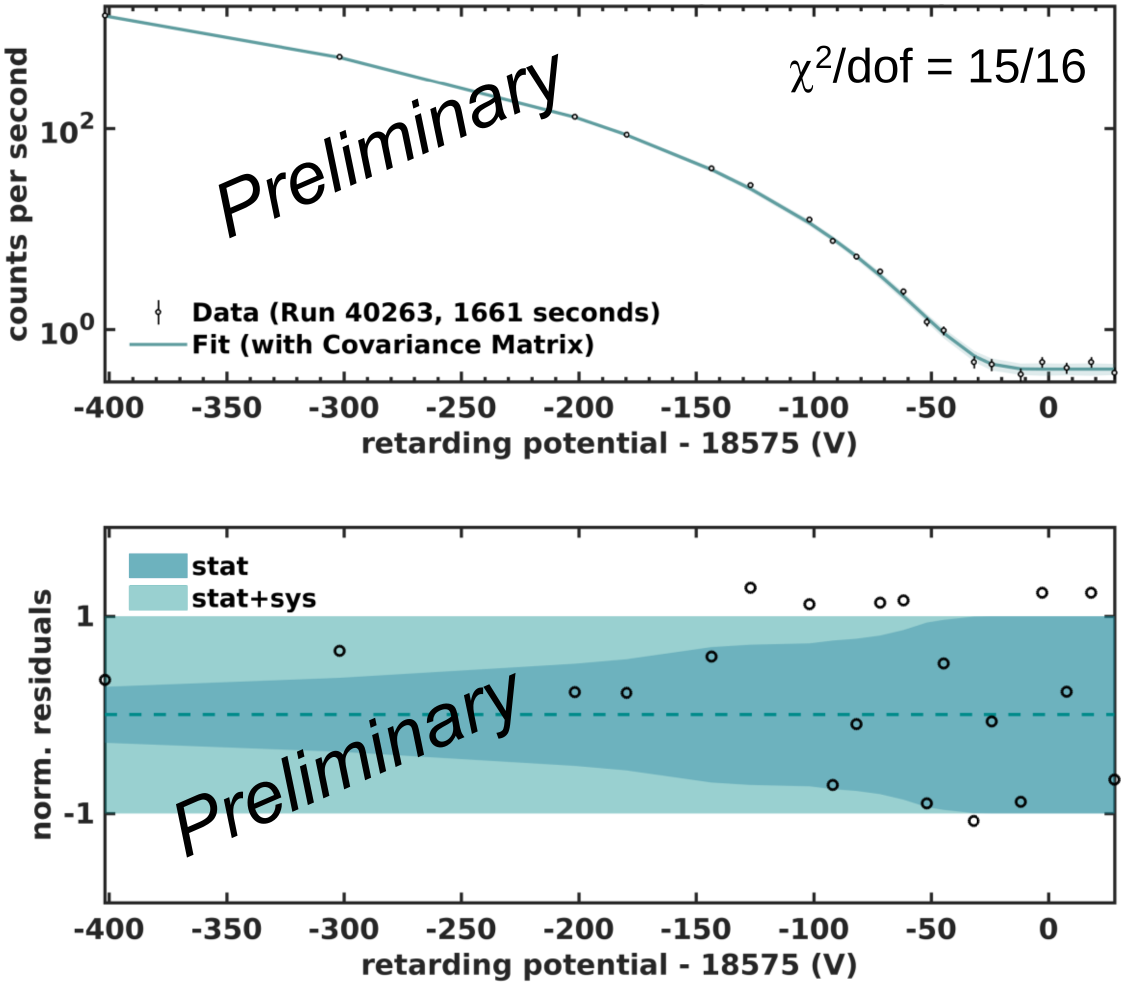
Fitting the Tritium Spectrum

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



- Three fit parameters (neutrino mass fixed to 0):
  - Overall activity
  - Constant background
  - Endpoint energy E_0
- Statistical errors only in this early fit
- χ^2/dof = 15.0/14

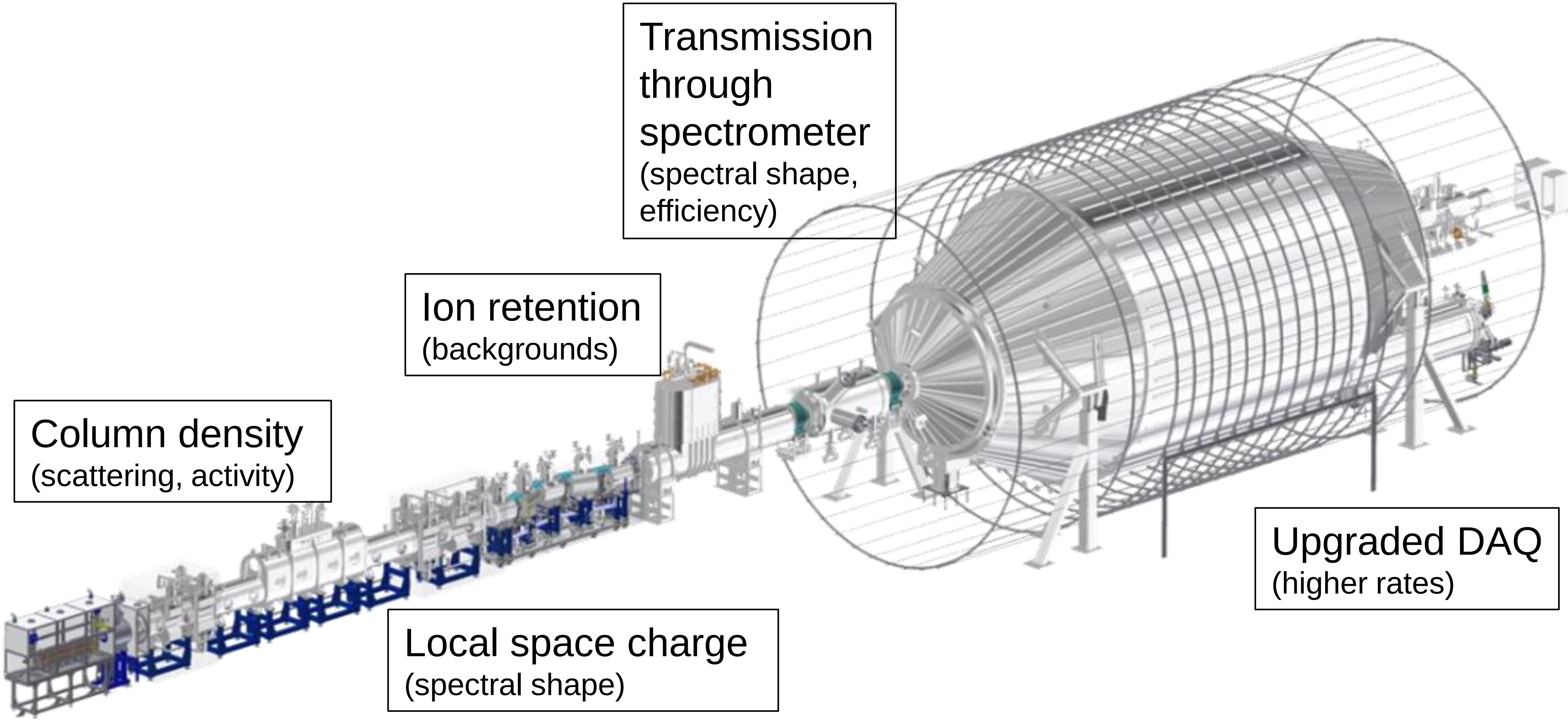
First Look at Fit Systematics



- 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)

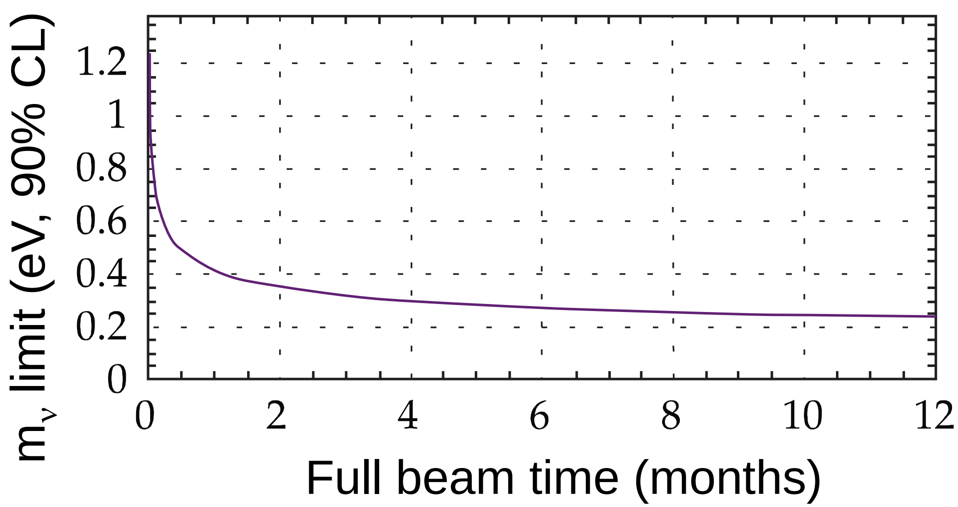
Inactive-Gas Commissioning

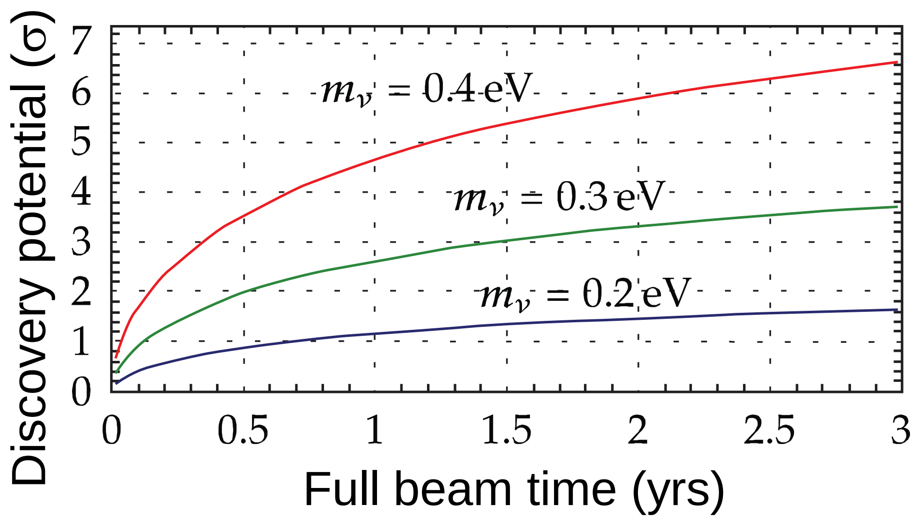
- September– October of this year
- Tackle multiple systematics before next tritium runs



The Next Few Years

- Spring 2019: Further commissioning + tritium purity ramp-up
- Summer/Fall: Neutrino mass running
- Stay tuned! 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 yrs (~5 calendar yrs)





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

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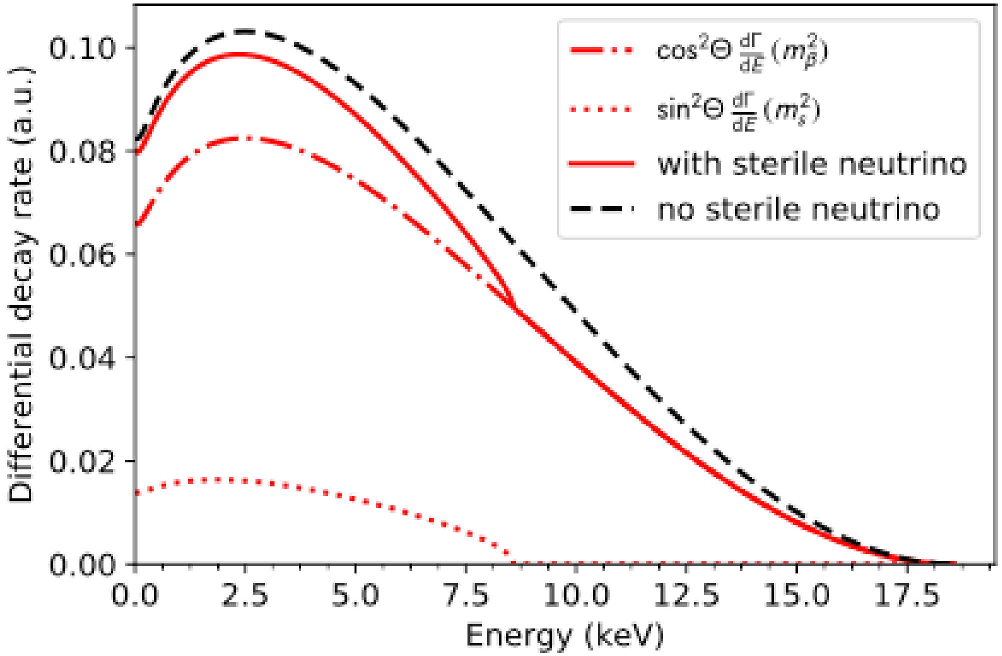
Sterile Neutrinos in β Decay

- The large hypothesized mass splitting between the active and sterile sectors could be resolved by KATRIN!

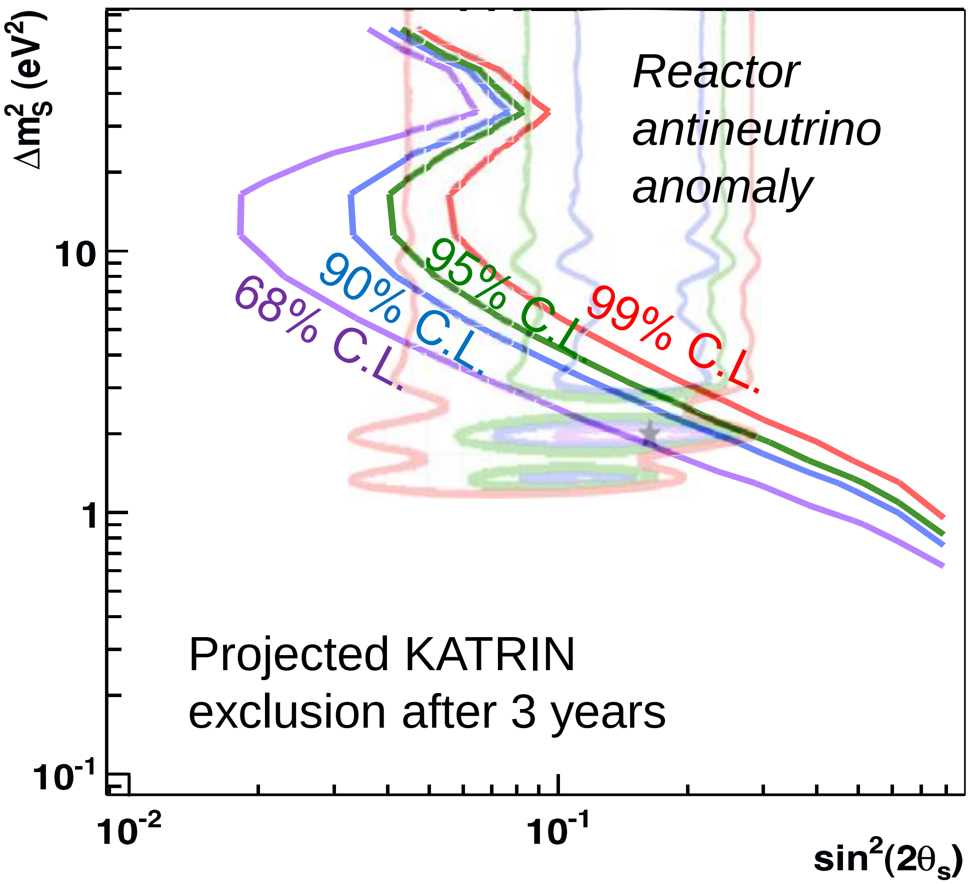


S. Mertens et al., arXiv:1810.06711

- Search for characteristic kink structure in spectrum (exaggerated in figure)
- Sensitive to eV and keV scales

$$\frac{d\Gamma}{dE} = \cos^2\theta \frac{d\Gamma}{dE}(m_\beta) + \sin^2\theta \frac{d\Gamma}{dE}(m_s)$$

Sterile Neutrinos at eV Scales



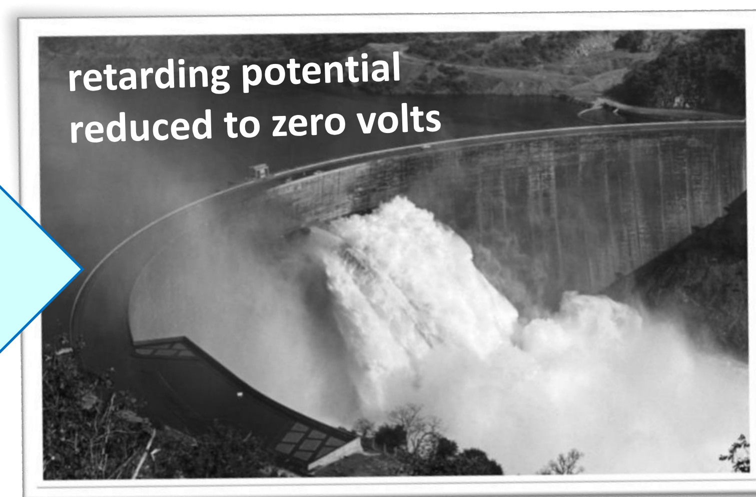
*Formaggio and Barrett, PLB **706** (2011) 68*

- Kink structure is within standard KATRIN analysis window (order 10 eV below endpoint)
- Sensitivity improves further if combined with short-baseline oscillation data

Sterile Neutrinos at keV Scales

- Endpoint of tritium β decay is 18.6 keV
  - Sensitivity to m_s < 18.6 keV ?
- First challenge: **statistics**

Regular neutrino-mass measurement

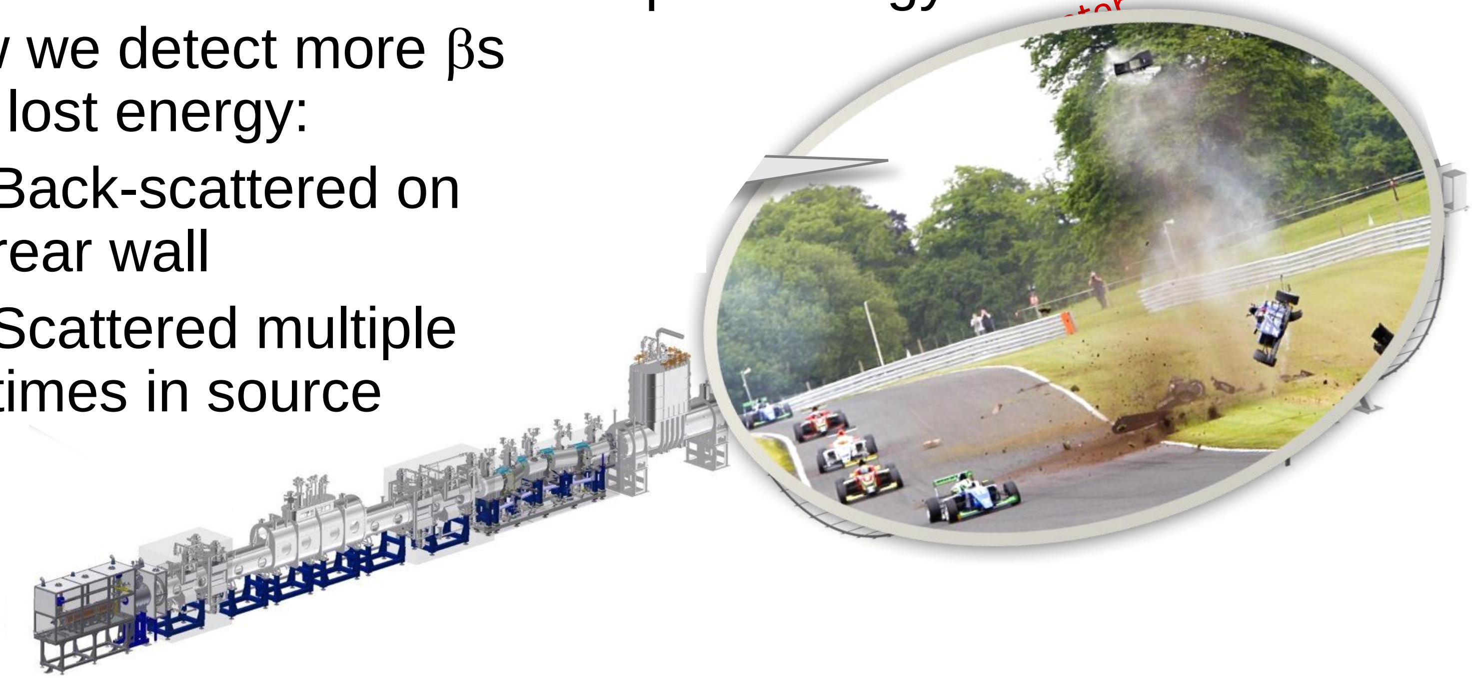


keV-scale sterile search

Imagery credit: Susanne Mertens

keV-Scale Search: Systematics

- Adiabatic guiding of βs even with high surplus energy
- Loss of βs back-scattered at detector
- Now we detect more βs that lost energy:
  - Back-scattered on rear wall
  - Scattered multiple times in source



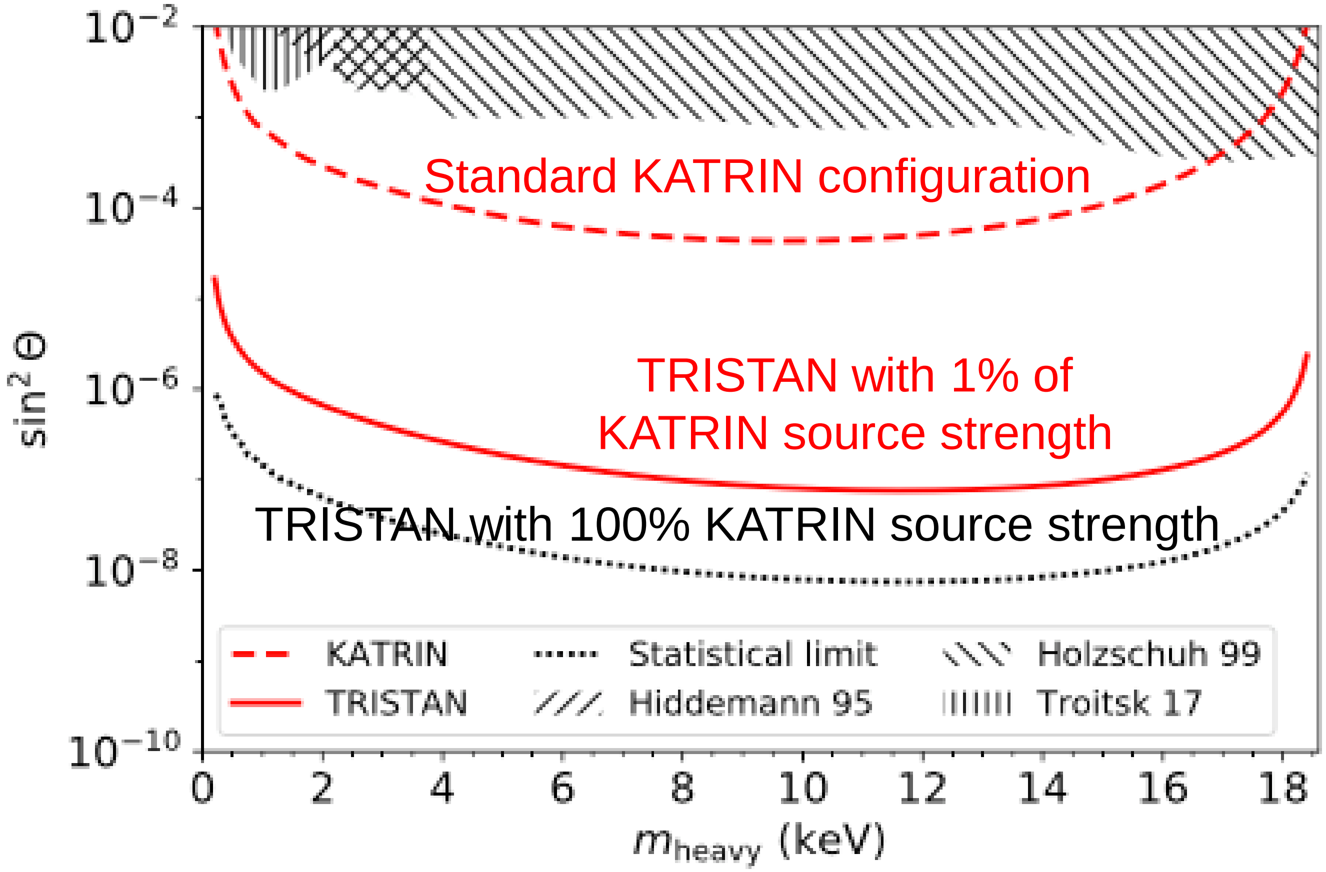
Slide credit: Susanne Mertens

The TRISTAN Project

- R&D for KATRIN extension (after neutrino-mass running)
  - Characterize KATRIN performance far below T endpoint (backgrounds, stability, transmission)
  - Possible upgrades on source side
    - Reduce back-scattering on rear wall via changes in composition and magnetic field?
  - Detector upgrades
    - Anticipated rates of 10^8 cps or more
    - Energy resolution ~ 300 eV (FWHM) at 30 keV
    - Minimal backscattering
    - High efficiency with minimal energy dependence

The TRISTAN Project

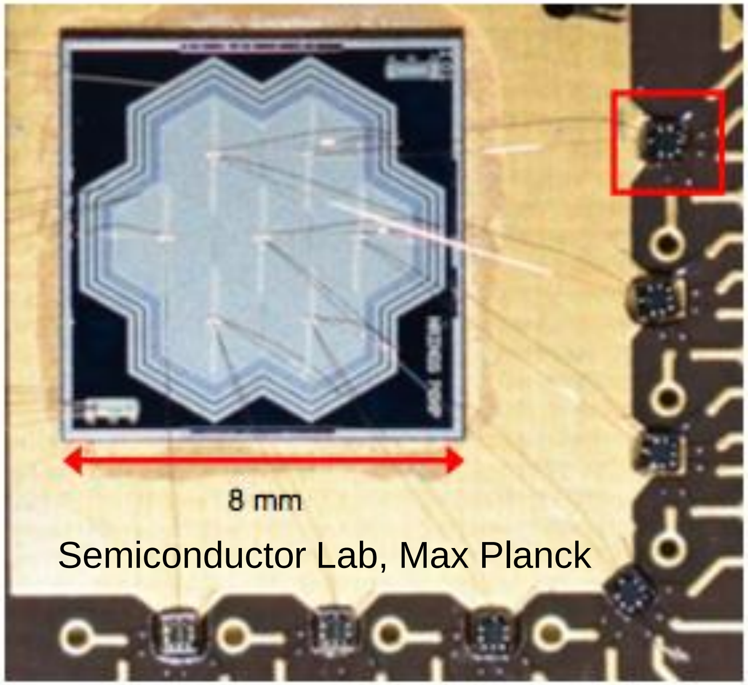
- Anticipated 95% C.L. exclusion limits for 3 beam years of:

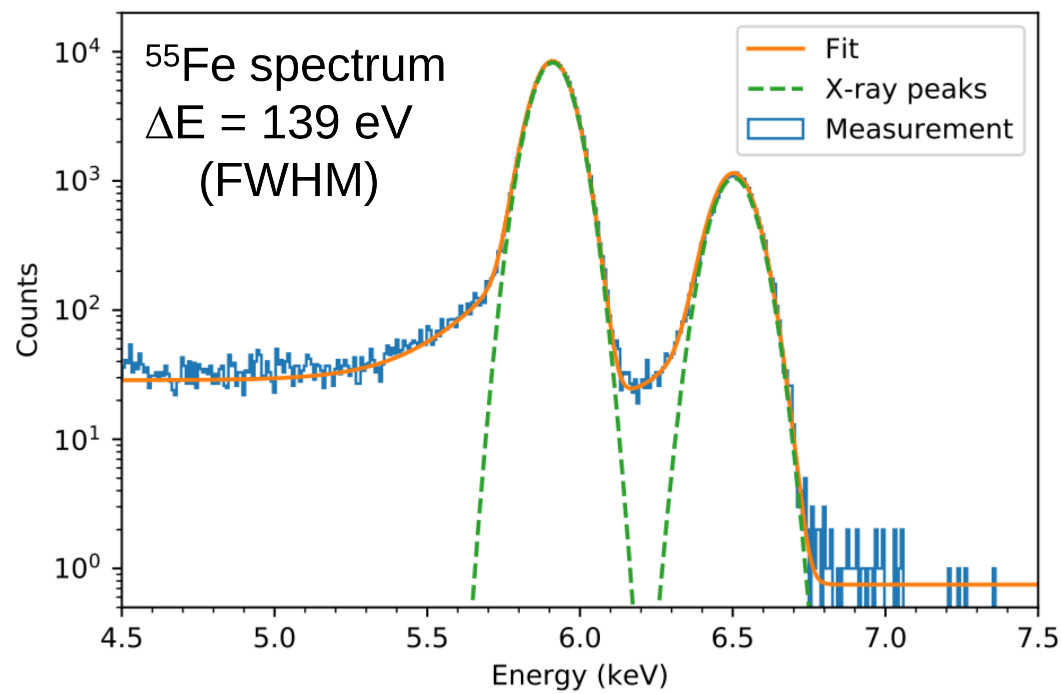


S. Mertens et al., arXiv:1810.06711

TRISTAN Detector Studies

- Plan: Silicon drift detectors (SDDs) with integrated nJFET
- Prototype: SDDs with external FET-equipped ASICs
- Waveform digitization to mitigate ADC nonlinearities

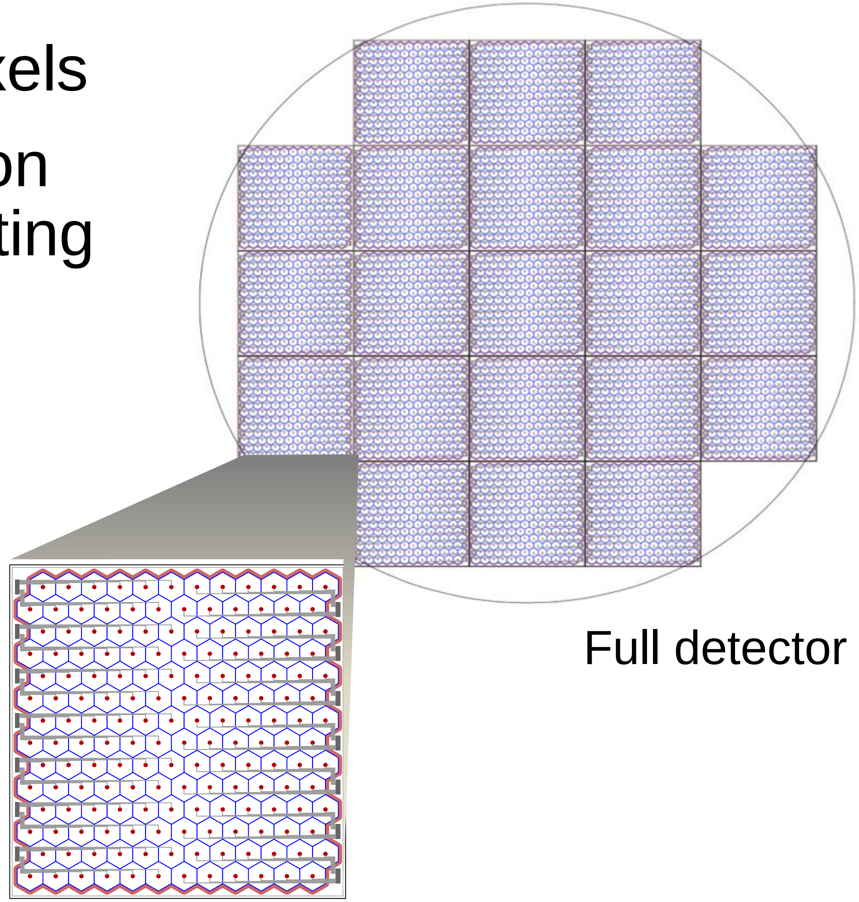




S. Mertens et al., arXiv:1810.06711

TRISTAN Next Steps

- Next-generation prototype under construction: 166 pixels
- 4-cm module to be tested on bench and at Troitsk's existing MAC-E filter
- TRISTAN concept has 21 modules for ~3500 pixels within a 20-cm diameter



Full detector

Detector module

Outlook

- KATRIN is a working experiment
  - First full-beamline data, Oct. 2016
  - First spectral measurement of radioactive source, July 2017
  - ***First tritium, 6 months ago!***
  - Fresh systematics data on disk
- We expect $m_{\nu,eff}$ data in first half of 2019
- TRISTAN R&D is proceeding well
  - Staged detector prototypes
  - Analysis of KATRIN commissioning data
  - Active engineering work
  - Deployment at KATRIN is possible after neutrino-mass run – 2025?

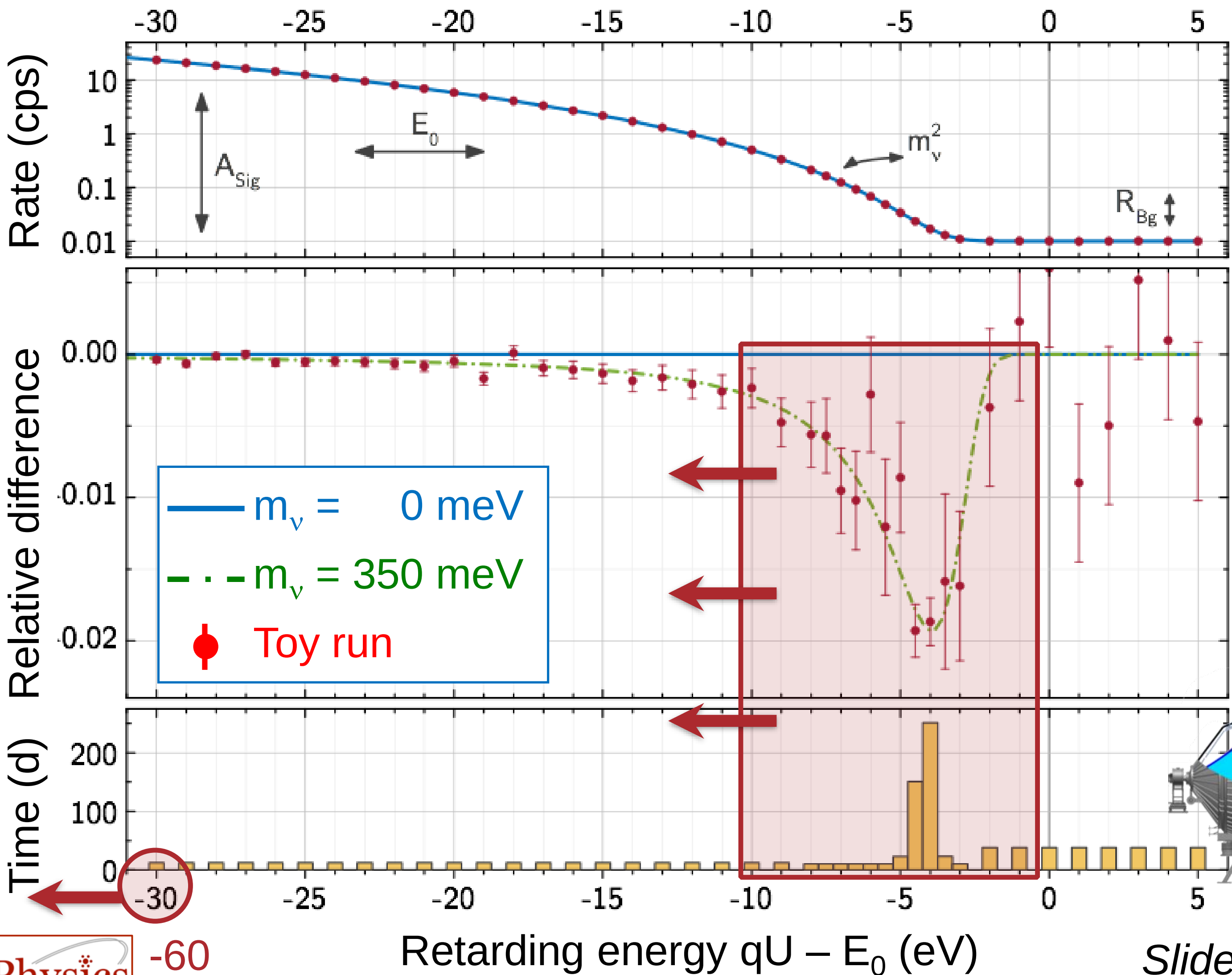
KATRIN Collaboration

Funding and support from: **Helmholtz Association** (HGF), **Ministry for Education and Research BMBF** (05A17PM3, 05A17PX3, 05A17VK2, and 05A17WO3), **Helmholtz Alliance for Astroparticle Physics** (HAP), and **Helmholtz Young Investigator Group** (VH-NG-1055) in Germany; **Ministry of Education, Youth and Sport** (CANAM-LM2011019), cooperation with the **JINR Dubna** (3+3 grants) 2017–2019 in the Czech Republic; and the **Department of Energy** through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, DE-SC0011091, and **DE-SC0019304** in the United States.

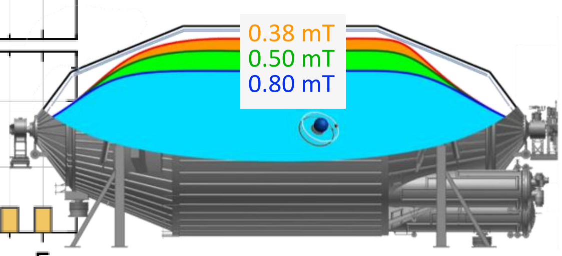
Backup Slides

- Accounting for backgrounds in the KATRIN sensitivity
- List of recent technical papers
- Brief introduction to the TRIMS experiment

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

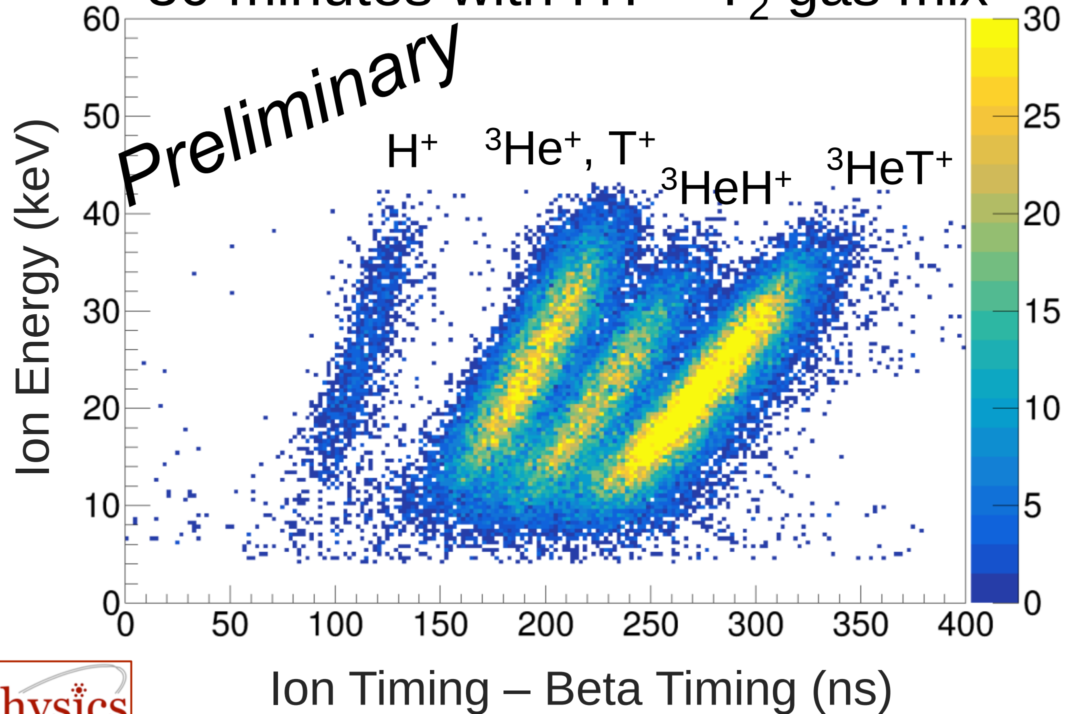
Recent Technical Papers

- **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!

30 minutes with HT – T_2 gas mix



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)