Neutrino Mass Measurements with KATRIN

BERKELEY LAB

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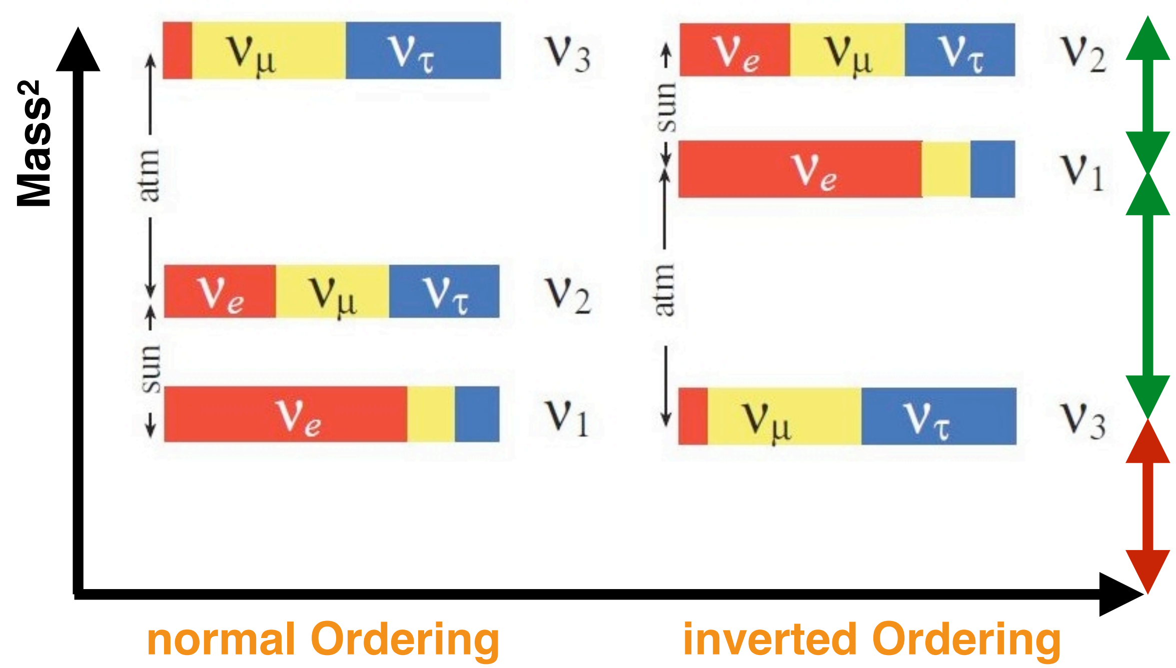
Neutrino Parameters

Neutrino mixing: PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

$$|\nu_{\text{flavor}}> = \sum_i U^*_{\alpha i} \cdot |\nu_{\text{mass}}>$$

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\Theta_{23} & s\Theta_{23} \\ 0 & -s\Theta_{23} & c\Theta_{23} \end{pmatrix} \begin{pmatrix} c\Theta_{13} & 0 & s\Theta_{13} \cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -s\Theta_{13} \cdot e^{-i\delta} & 0 & c\Theta_{13} \end{pmatrix} \begin{pmatrix} c\Theta_{12} & s\Theta_{12} & 0 \\ -s\Theta_{12} & c\Theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{pmatrix}$$

Neutrino masses:



$\sqrt{\Delta m^2_{12}} \approx 8\ \text{meV}$

$\sqrt{\Delta m^2_{23}} \approx 50\ \text{meV}$

??? absolute mass scale unknown

- Precision measurements with oscillation: $\Theta_{12}, \Theta_{13}, \Theta_{23}, \Delta m^2_{12}, \Delta m^2_{23}$
- Upcoming oscillation measurements (subdominant matter effects): CP phase $e^{i\delta}$, ordering $\text{sign}(\Delta \text{m}^2_{23})$
- Not accessible with oscillations: absolute mass scale, Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}, \alpha, \beta$)

Measured with KATRIN

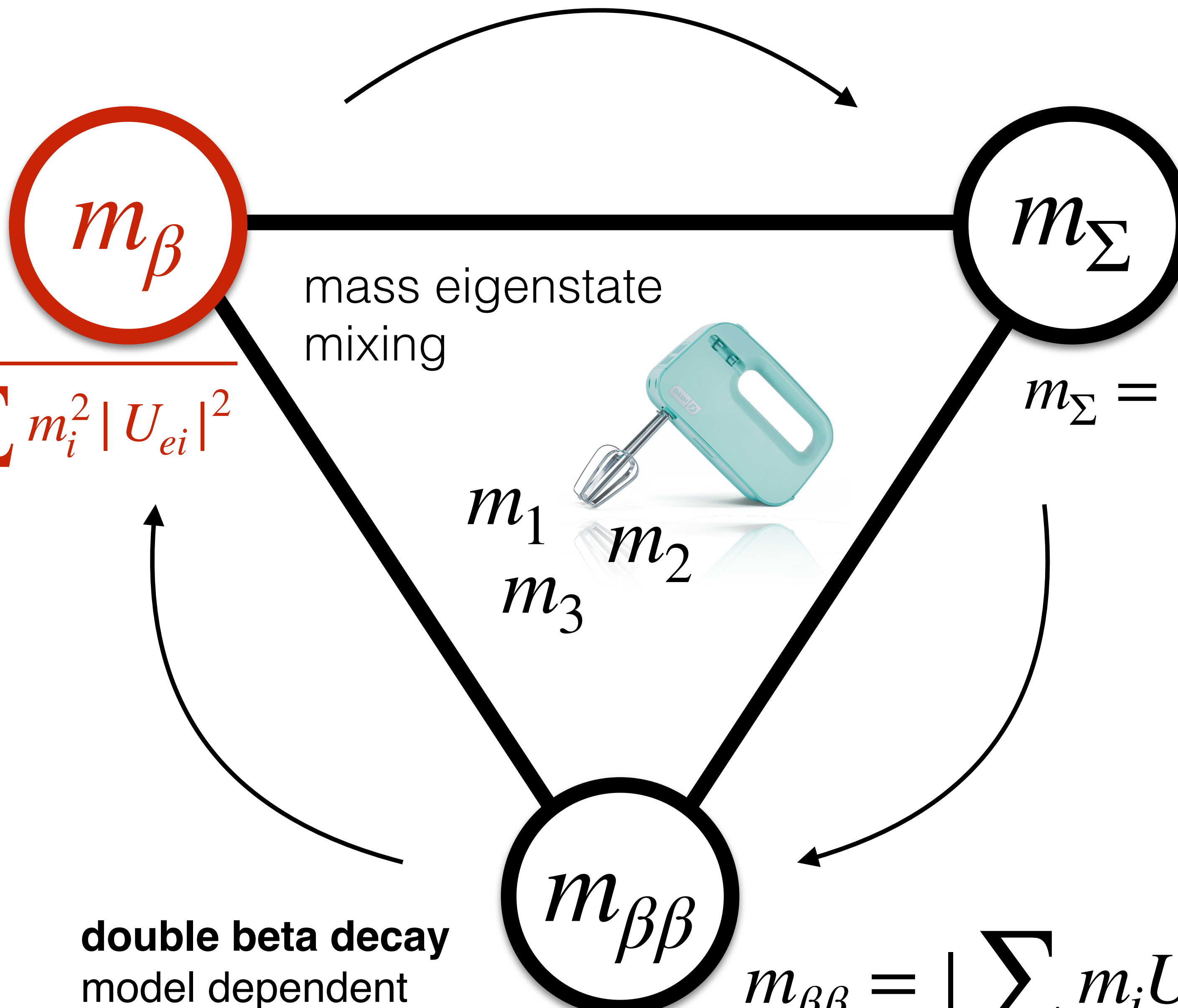
Different Neutrino Mass Observables

β**-decay (kinematic)**
model independent

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

cosmology
model dependent
- ΛCDM

$$m_\Sigma = \sum_i m_i$$

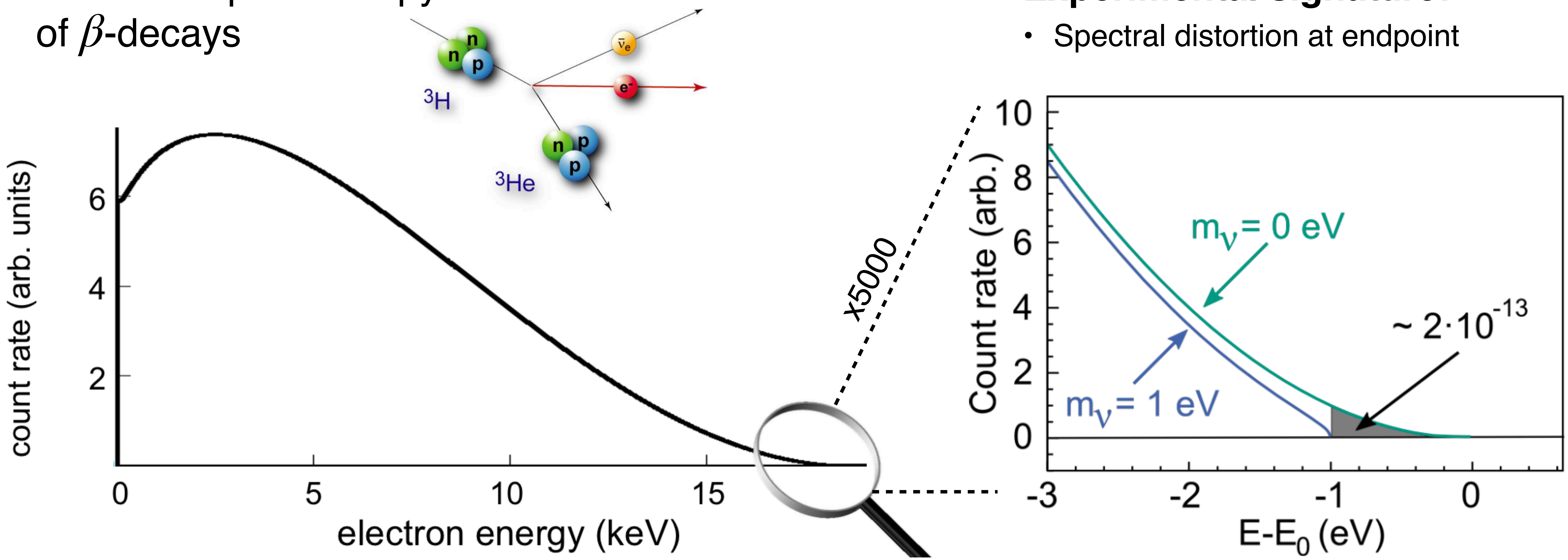


double beta decay
model dependent
- lepton number violation
- light Majorana neutrino exchange

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

Beta Decay Measurements

Precision spectroscopy of β-decays



Experimental signature:

- Spectral distortion at endpoint

Observable m_β^2:

- Appears in β-spectrum:

$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}^2} \cdot (E_e - E_0) \cdot F(E_e, Z)$$

normalization — Observable — Relativistic Fermi function

- No model dependence (only kinematics)

Experimental Challenges:

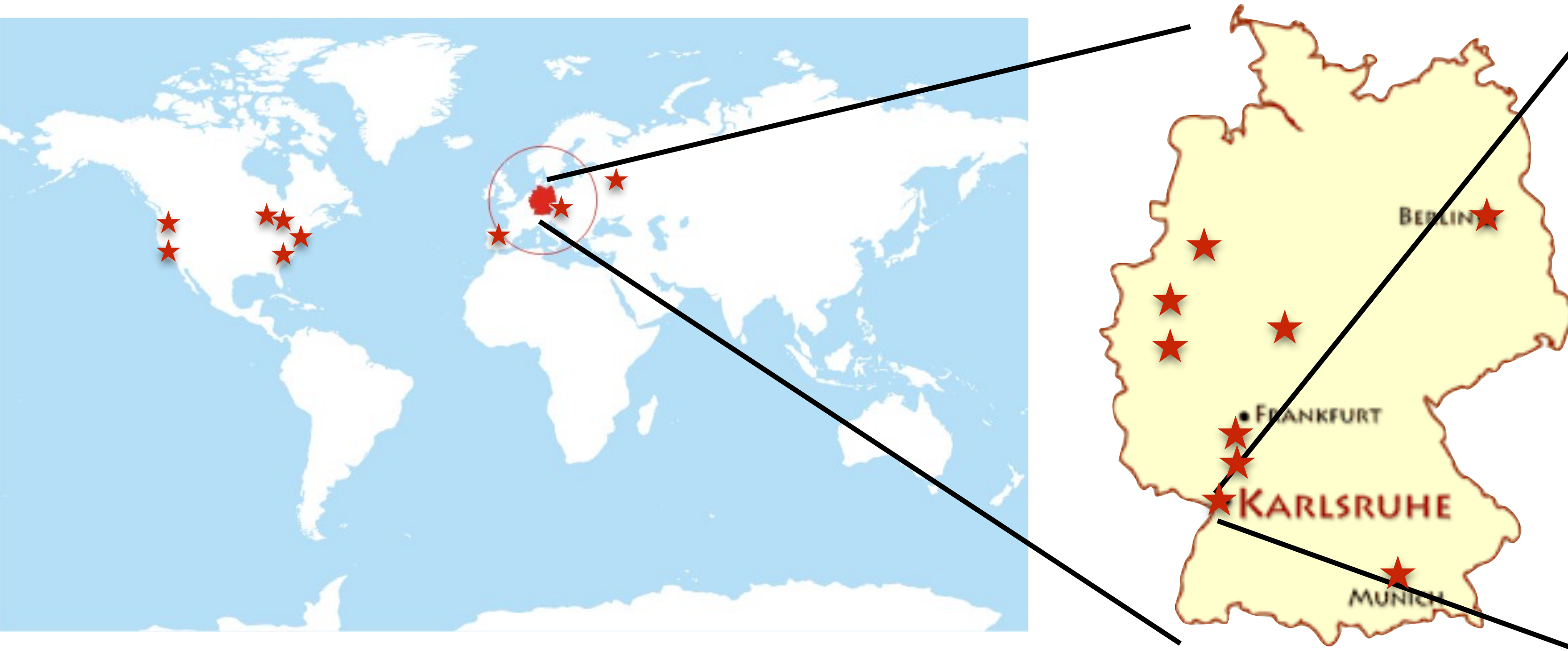
- High resolution
- Low background
- Convenient isotope: half-life, Q-value

^{3}H (12 yr, 18.6 keV), ^{163}Ho (4600 yr, 2.8 keV)

Other kinematic limits [pdg]**:**

•SN1987: $m_{\nu_e} < 5.8$ eV
•π-decay: $m_{\nu_\mu} < 190$ keV
•τ-decay: $m_{\nu_\tau} < 18.2$ MeV

KATRIN - KArlsruhe TRItium Neutrino Experiment



130 scientists in 20 institutions from 5 countries

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Max-Planck-Institut für Physik
MIT
Nuclear Physics Institute of the CAS public research institution
TUM TECHNISCHE UNIVERSITÄT MÜNCHEN
universität mainz
CASE WESTERN RESERVE UNIVERSITY 1826
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
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WWU MÜNSTER

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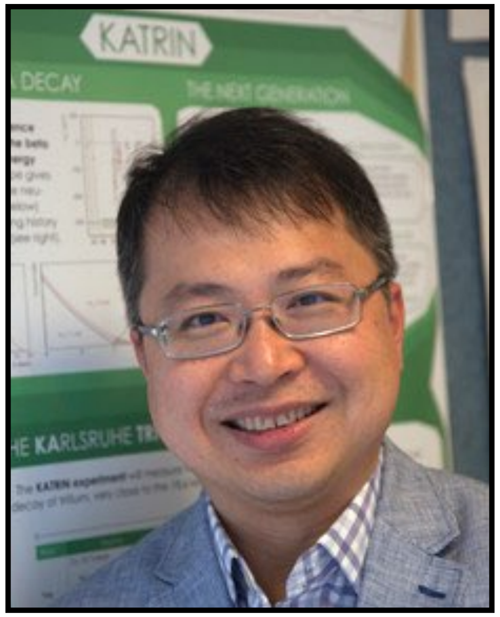
KATRIN @LBL



Alan
Poon

Rebecca
Carney

Pranav
Vaidhyanathan

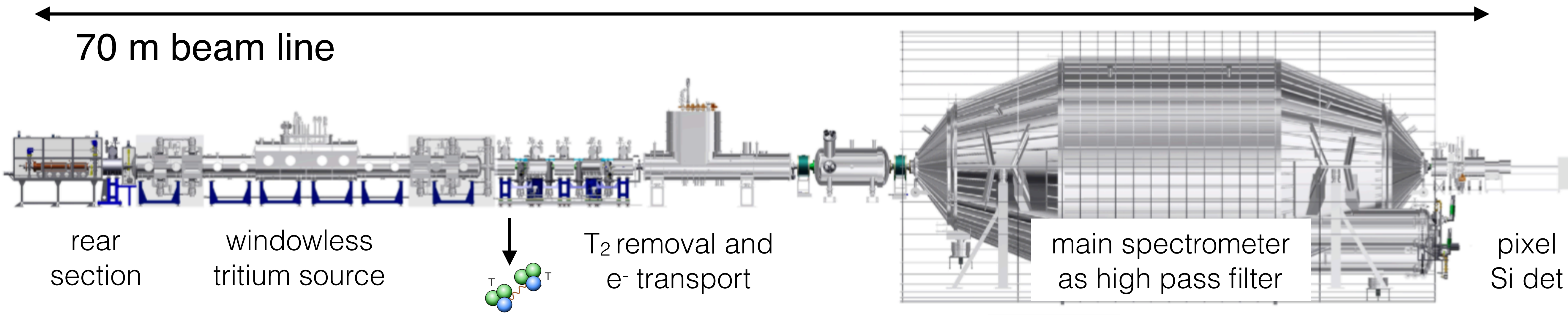
Bjoern
Lehnert

LBL / NSD contributions:

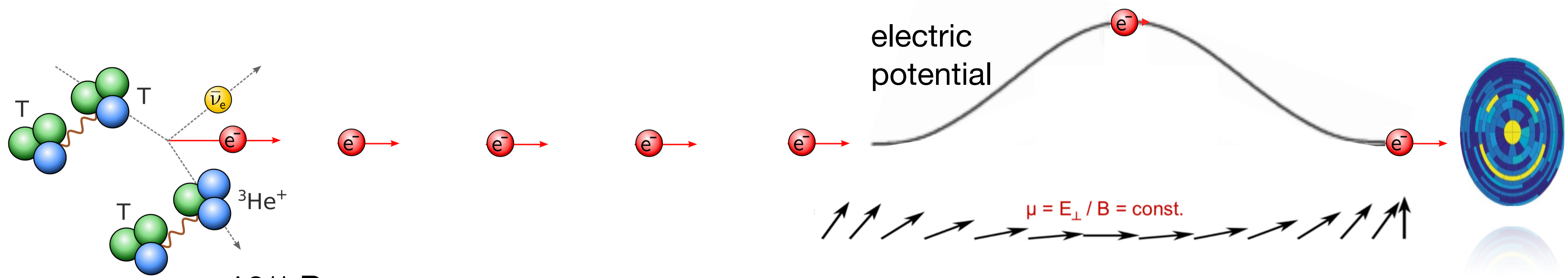
- Bayesian analysis of neutrino mass
- Electron energy loss function systematic
- Low level background counting
- Publication Committee

- Study detector upgrade options with Microsystems Lab (MSL), Physics Division

Experimental Setup

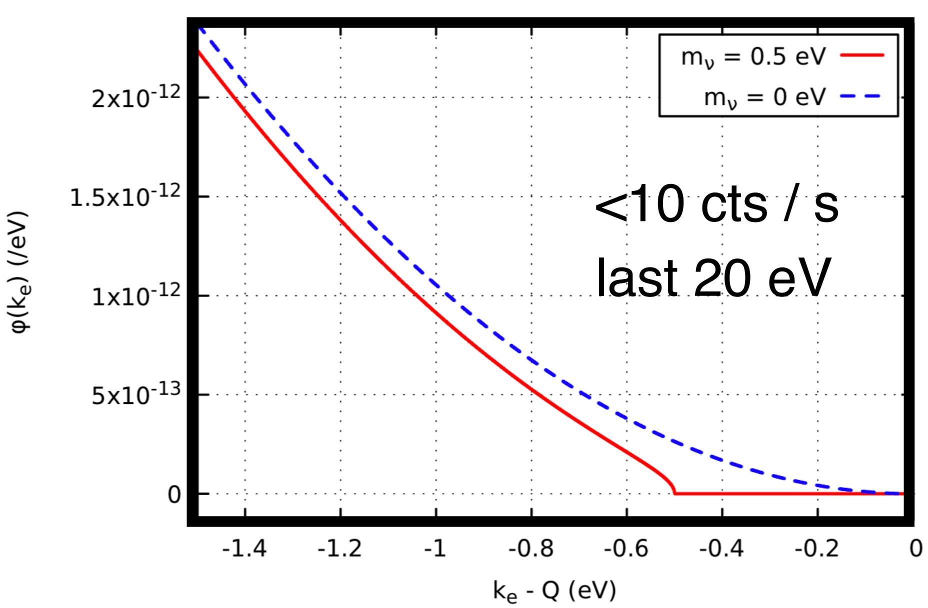


molecular tritium T_2



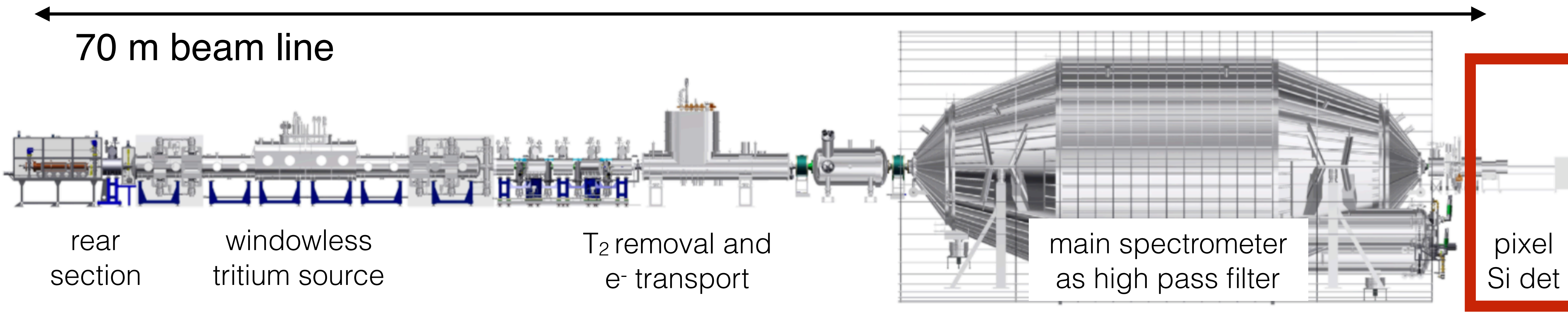
10^{11} Bq

resolution: ~1 eV
background: 0.29 cts/s

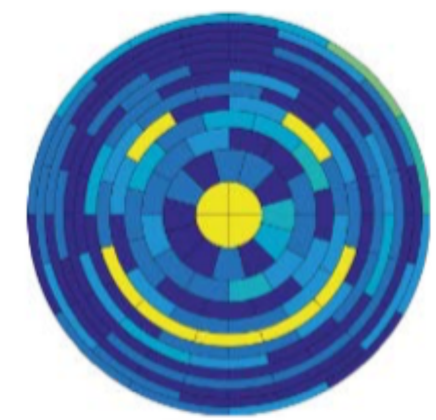


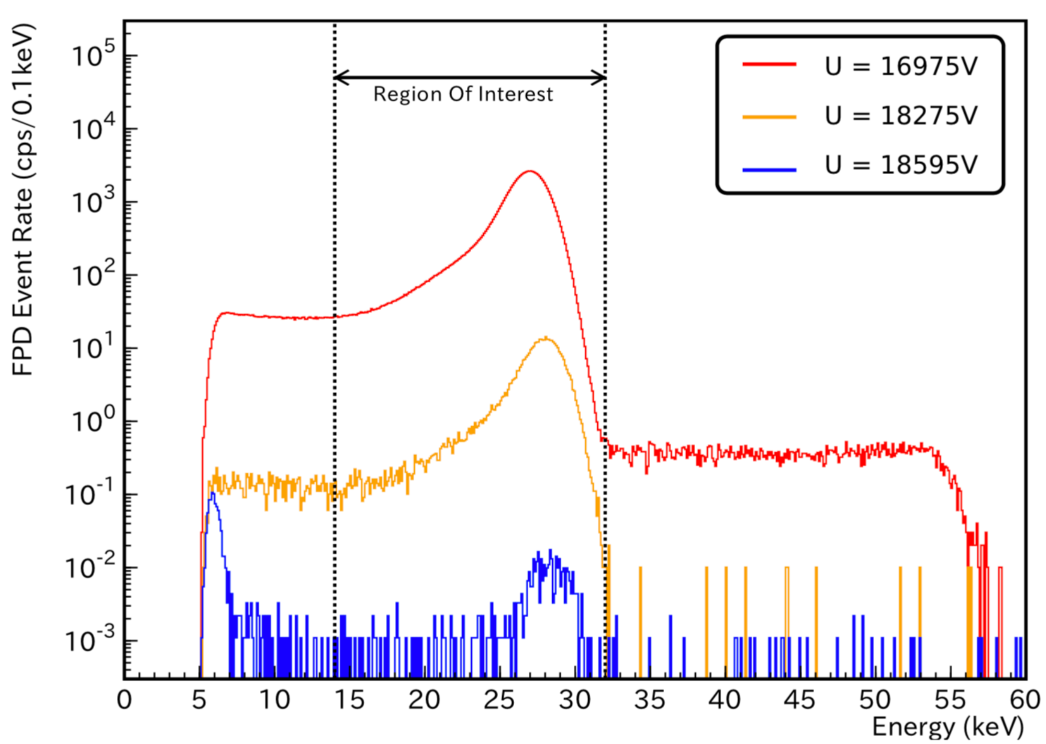
integral spectrum measured close to endpoint

Focal Plane Detector



e^- trajectories through different parts of the spectrometer have slightly different response functions

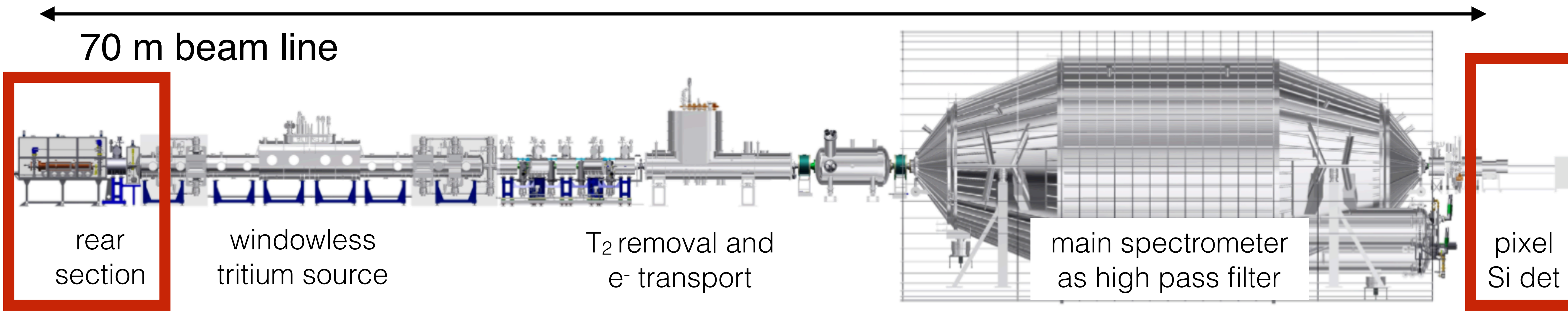


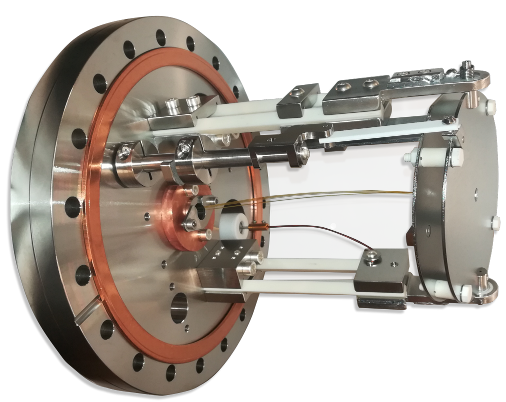


Focal plane detector:

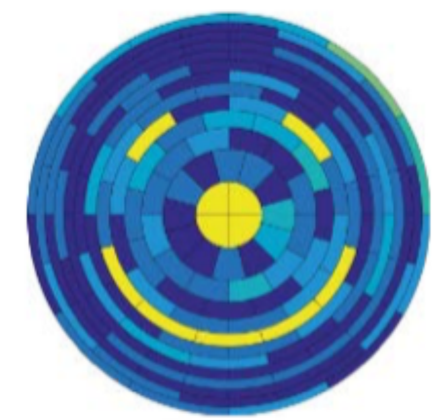
- 148 pixel Si-pin detector
- Counting electrons which pass main spectrometer

Electron Gun





e^- trajectories through different parts of the spectrometer have slightly different response functions



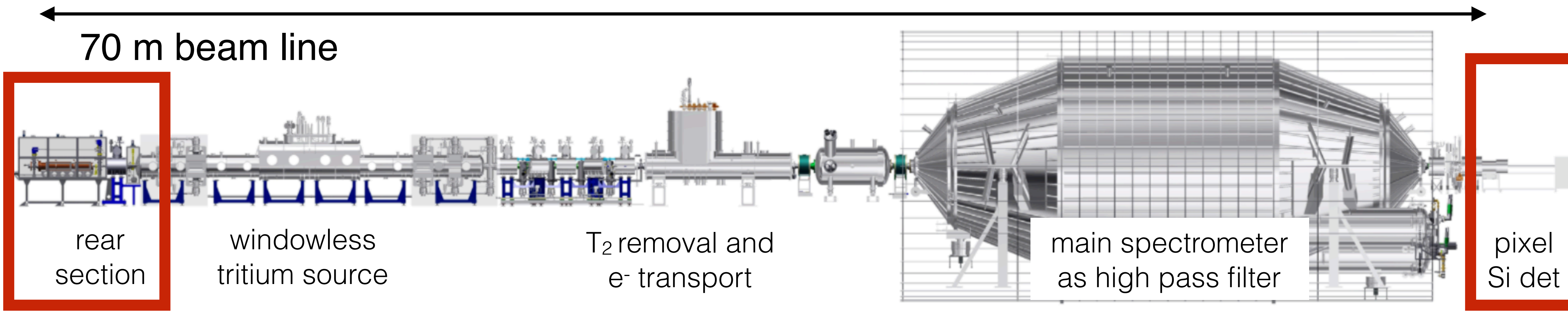
Electron gun:

- Mapping of analyzing plane with pulsed angular selected monoenergetic e^-
- Understanding source systematics
  - In-situ monitoring of column density
  - Electron scattering

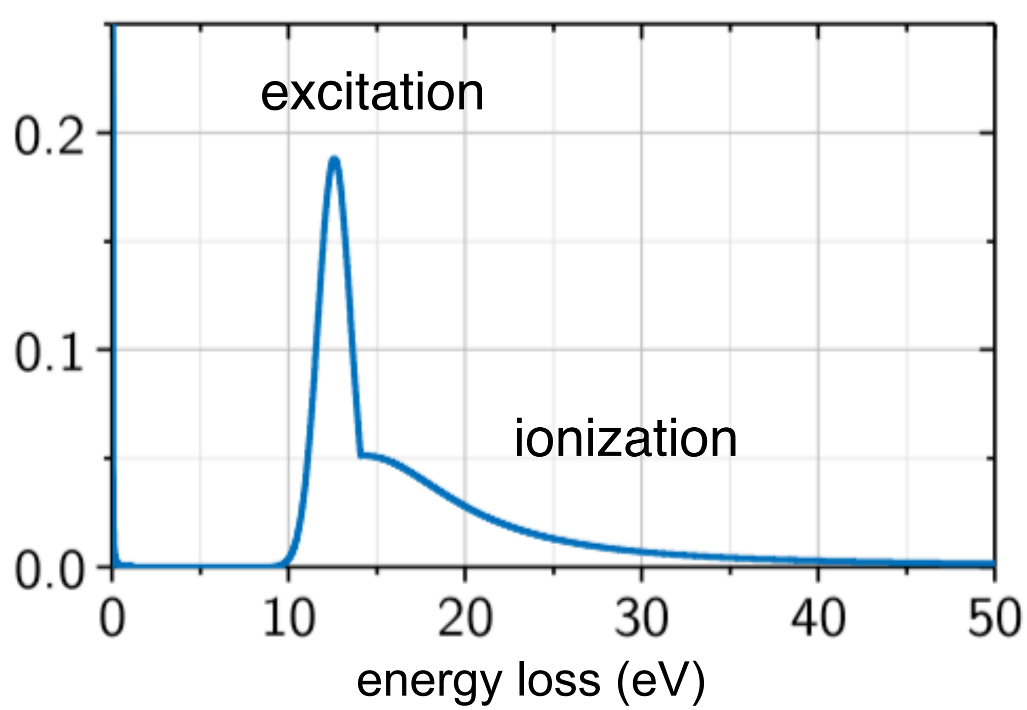
Focal plane detector:

- 148 pixel Si-pin detector
- Counting electrons which pass main spectrometer

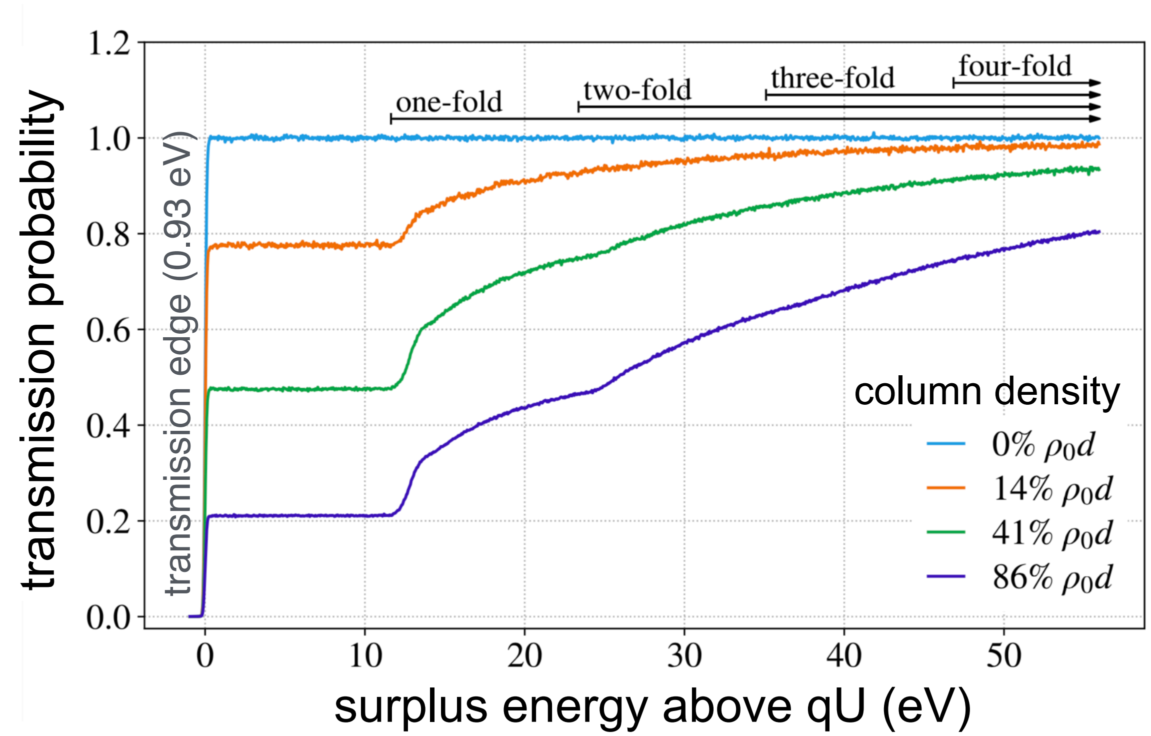
Systematic: Electron Scattering



inelastic scattering

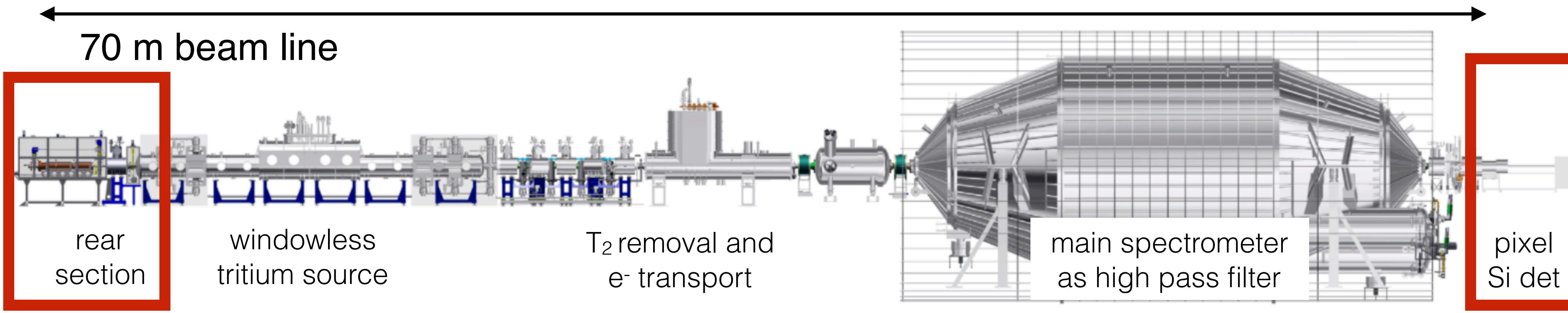


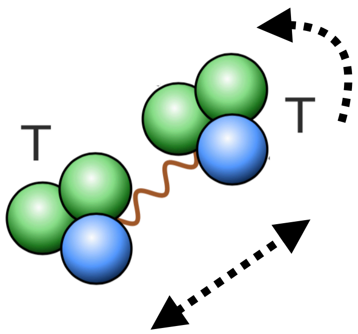
response function at different source densities



- Only ≈ 30% of electron leave source unscattered
- Literature knowledge of energy loss function not precise enough for final sensitivity
- Electron loss function measured in-situ with electron gun and novel ToF technique

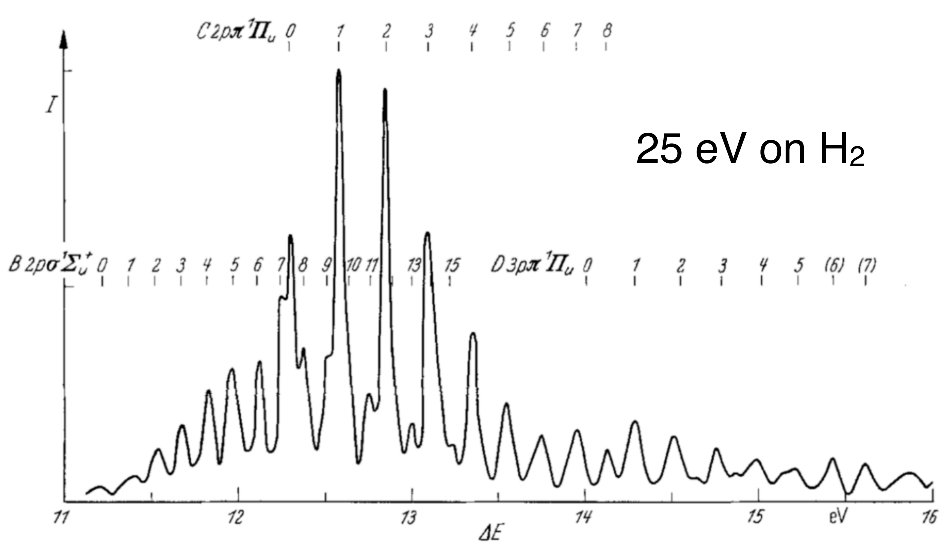
Systematic: Electron Scattering





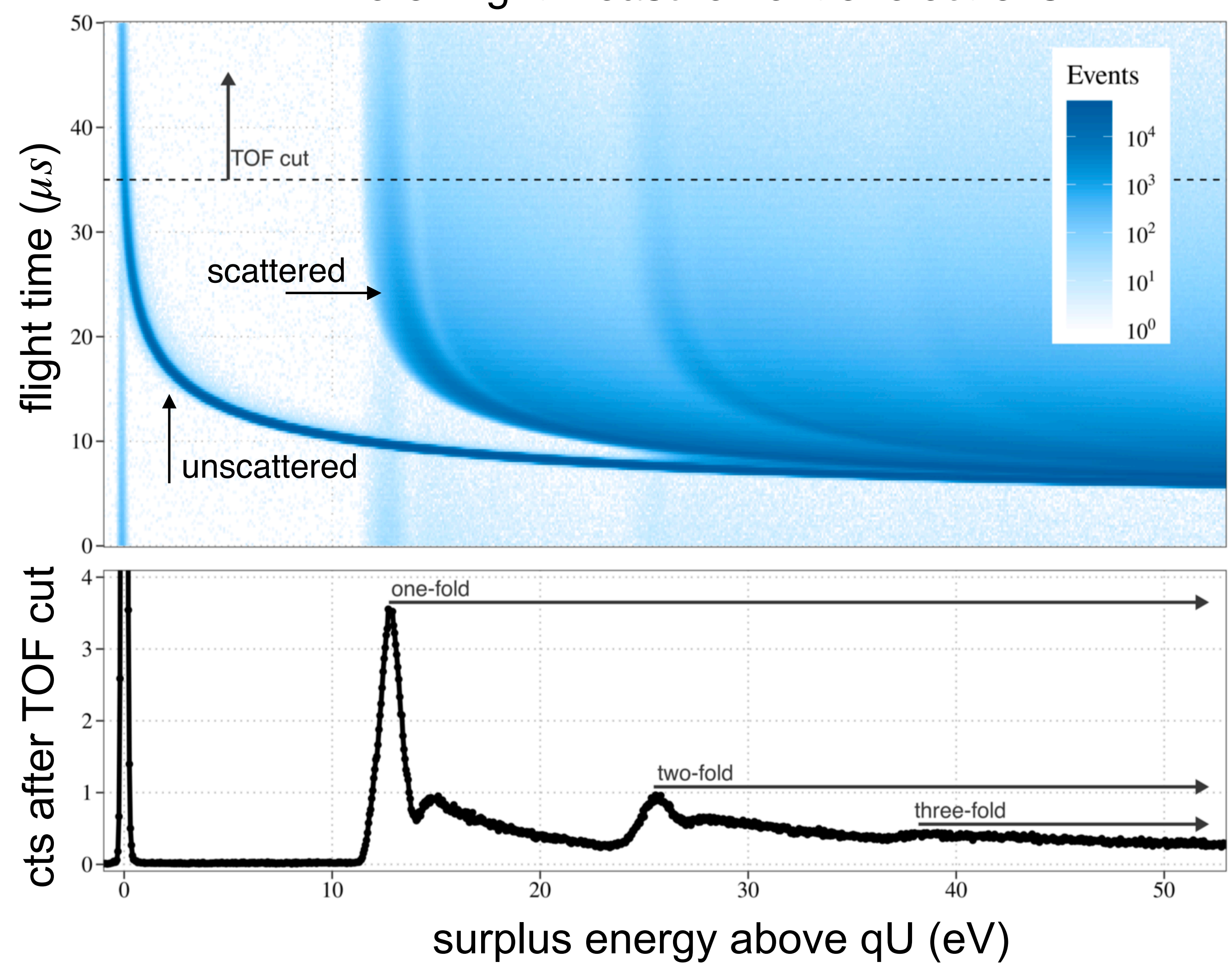
electronic,
rotational,
vibrational
excitations of T_2

25 eV on H_2

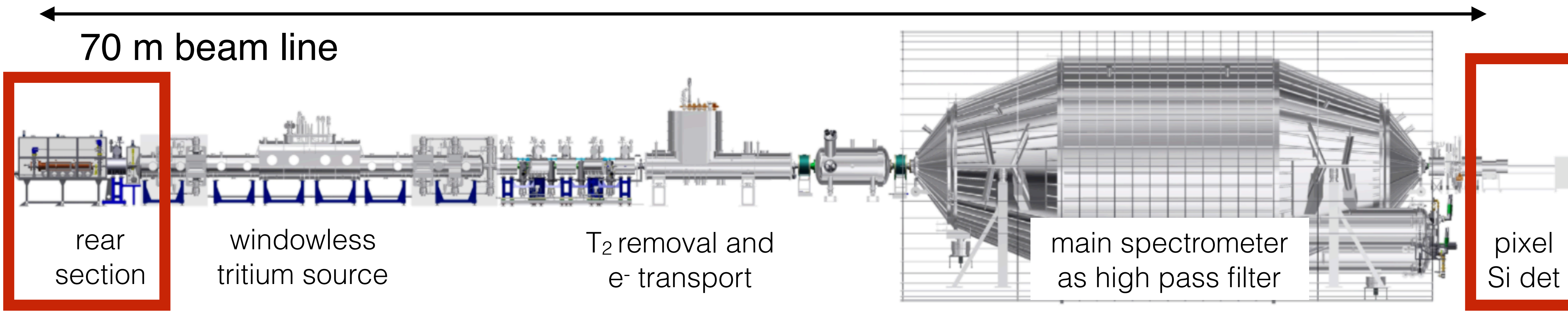


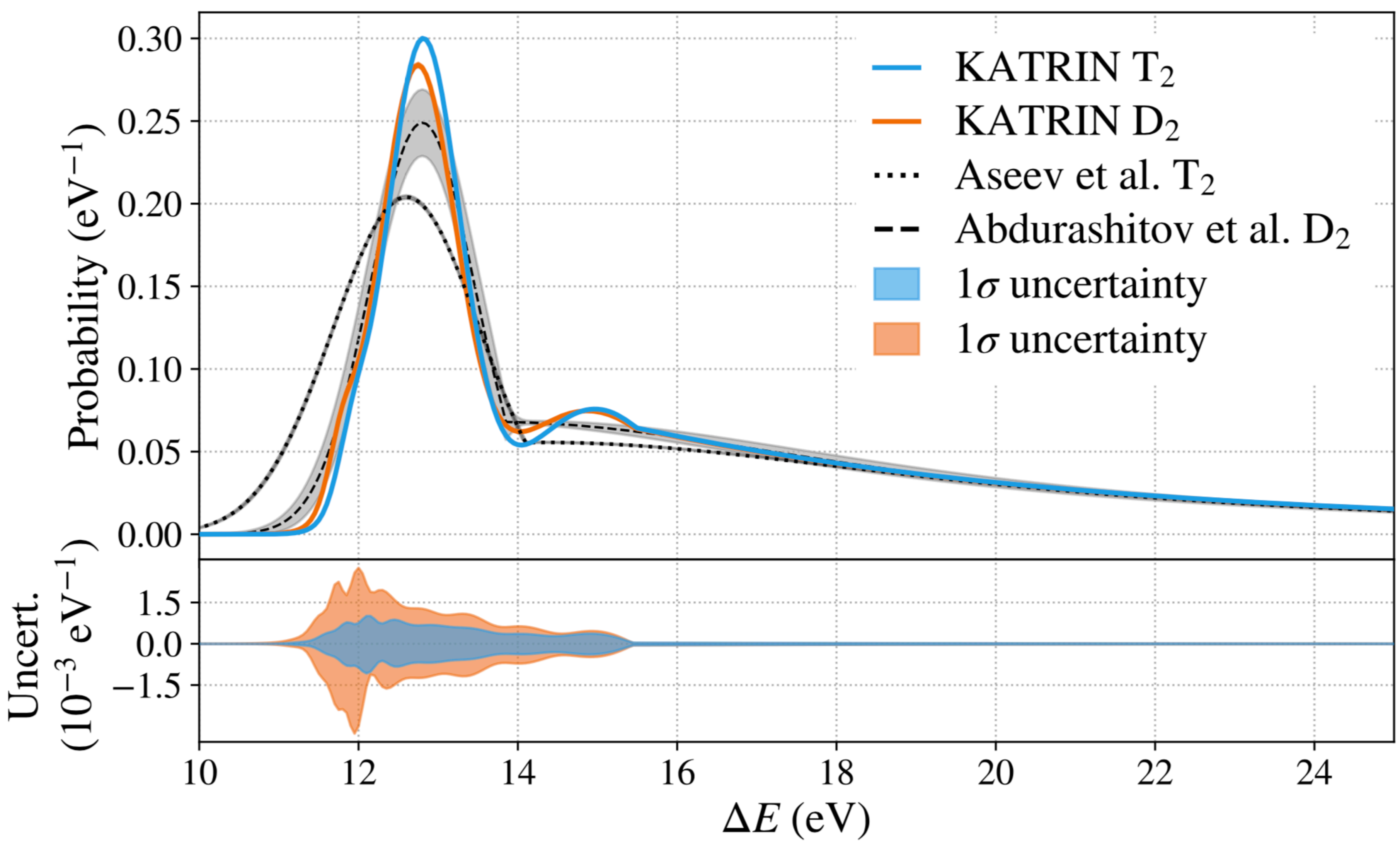
J. Geiger, Zeitschrift fuer Physik 181(4), 413 (1964)

Time-of-flight measurement of electrons



Systematic: Electron Scattering



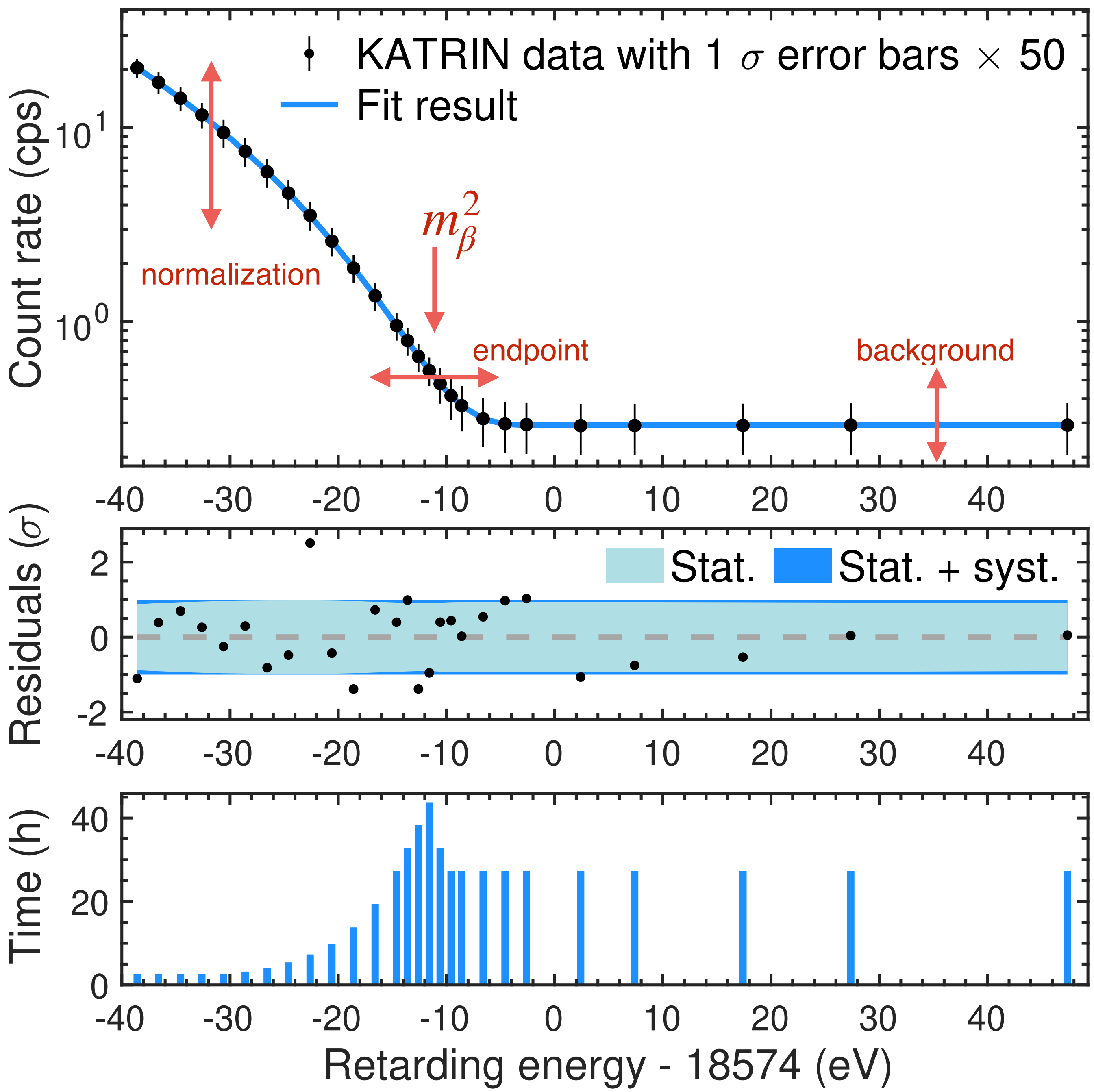


- Model parametrization with 3 Gaussians
- Most precise measurement to date
- One of the most important systematics became sub-dominant
- Ready for final KATRIN sensitivity
- Soon to be published

Analysis Strategy

First dataset:

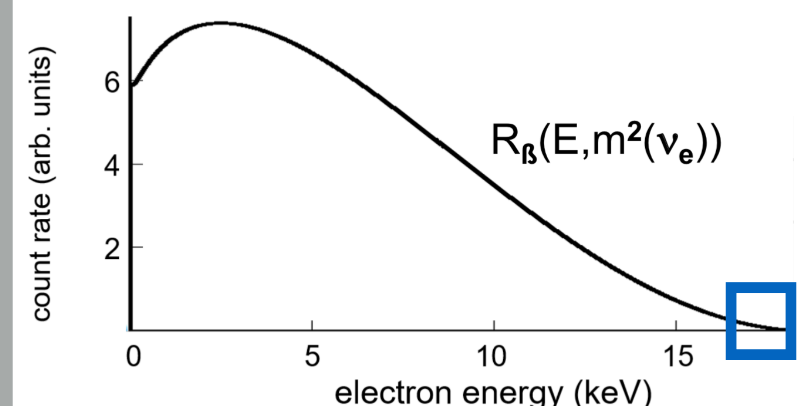
- April 10 2019 – May 13 2019 (33 d)
- Reduced source activity (22%)
- 274 runs in data set, 27 HV set-points
- 2.5 h per run, alternating up and down



Model ingredients and systematics

Beta spectrum:

- Multiple spectra from T_2, DT, HT
- Various final states

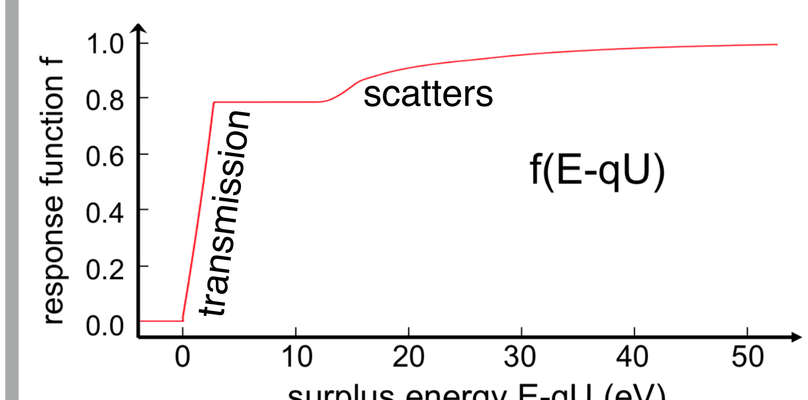


Constant background

- Time varying component
- Potential slope

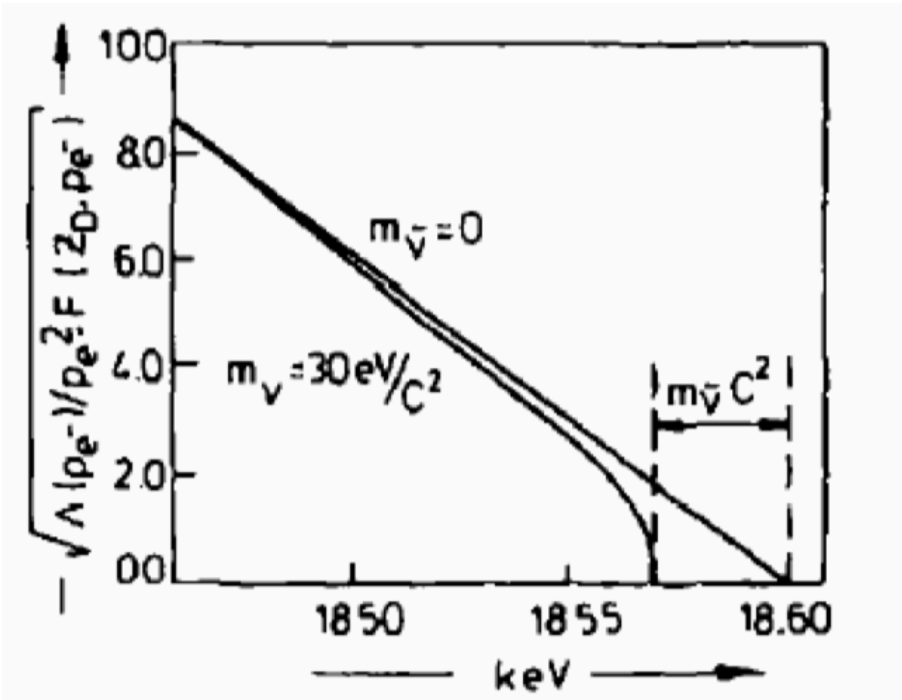
Response function:

- Transmission: B-fields
- Source density: Probability of scatter
- Electron energy loss: If scatter occurs

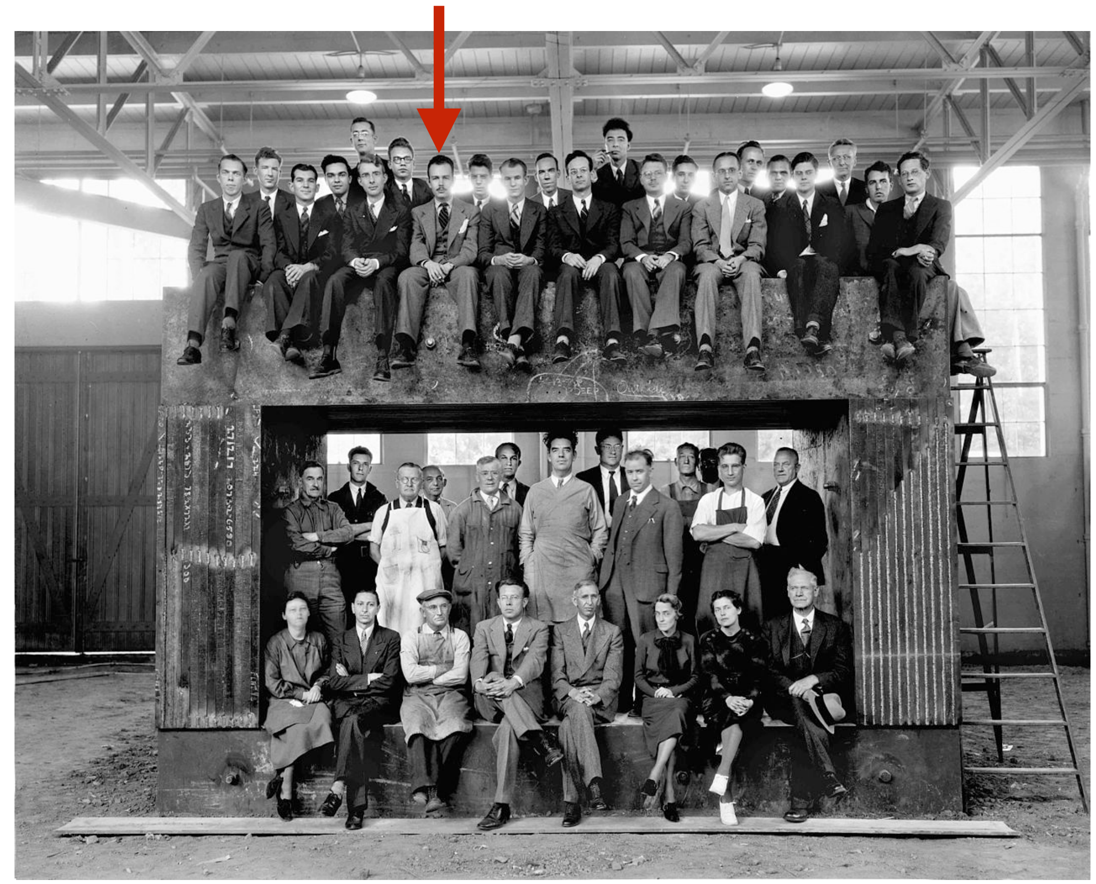


Past & Present

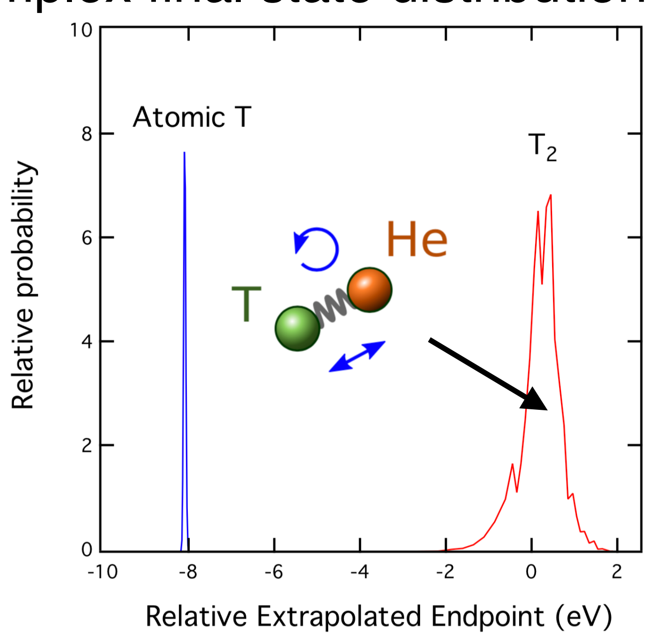
Past: Measuring neutrino mass with Kurie plot



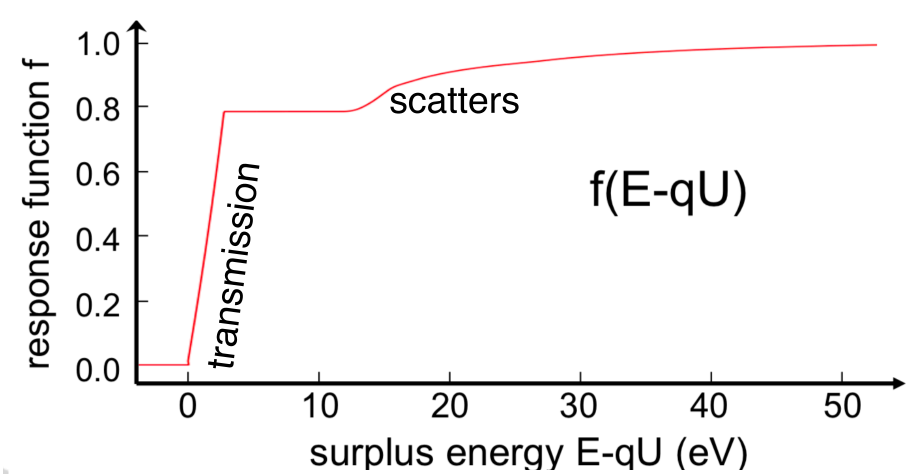
Franz N. D. Kurie @ LBL ~1939



Today: Complex final state distribution of T_2 decay



Detector response



First Results

PRL 123, 221802 (2019)

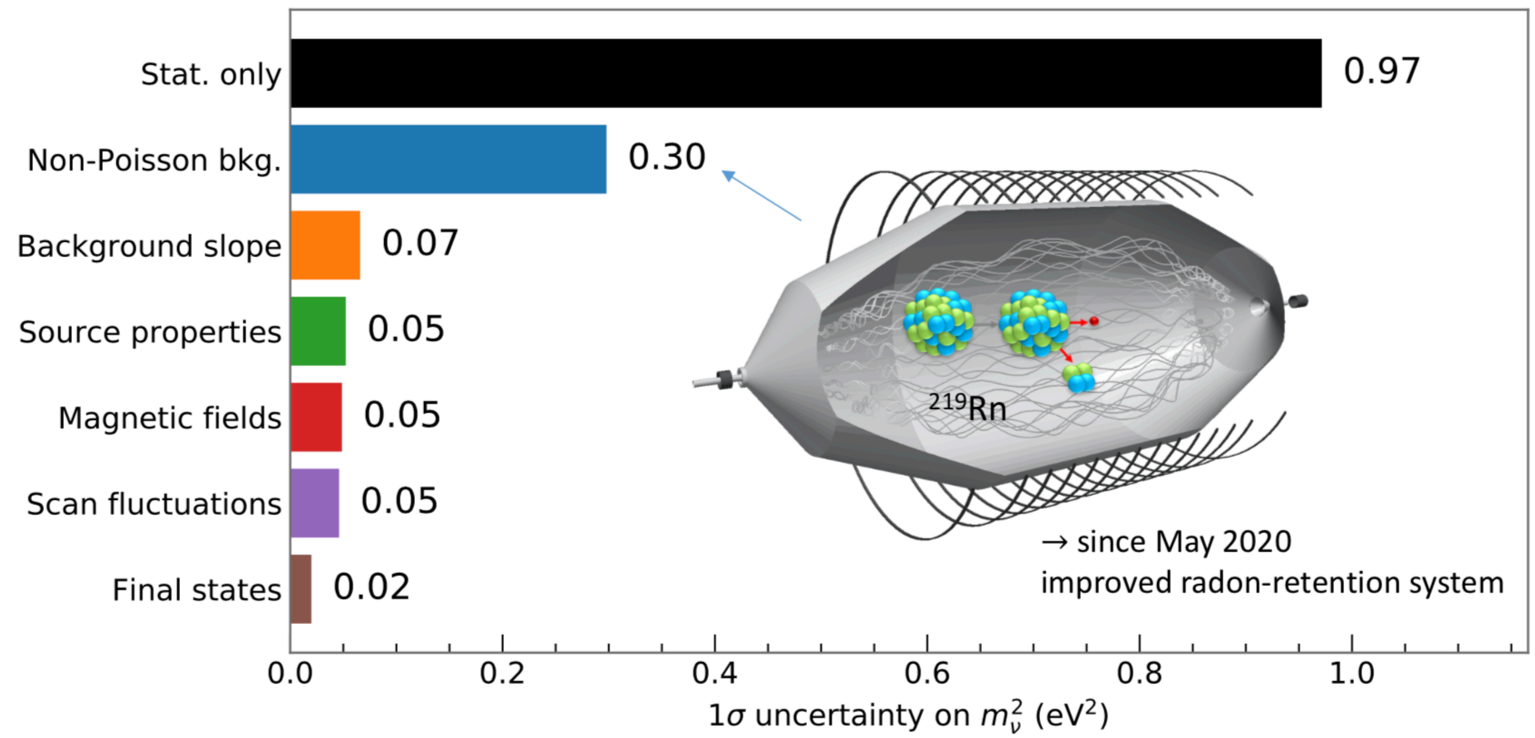
Best fit of m_β^2 :

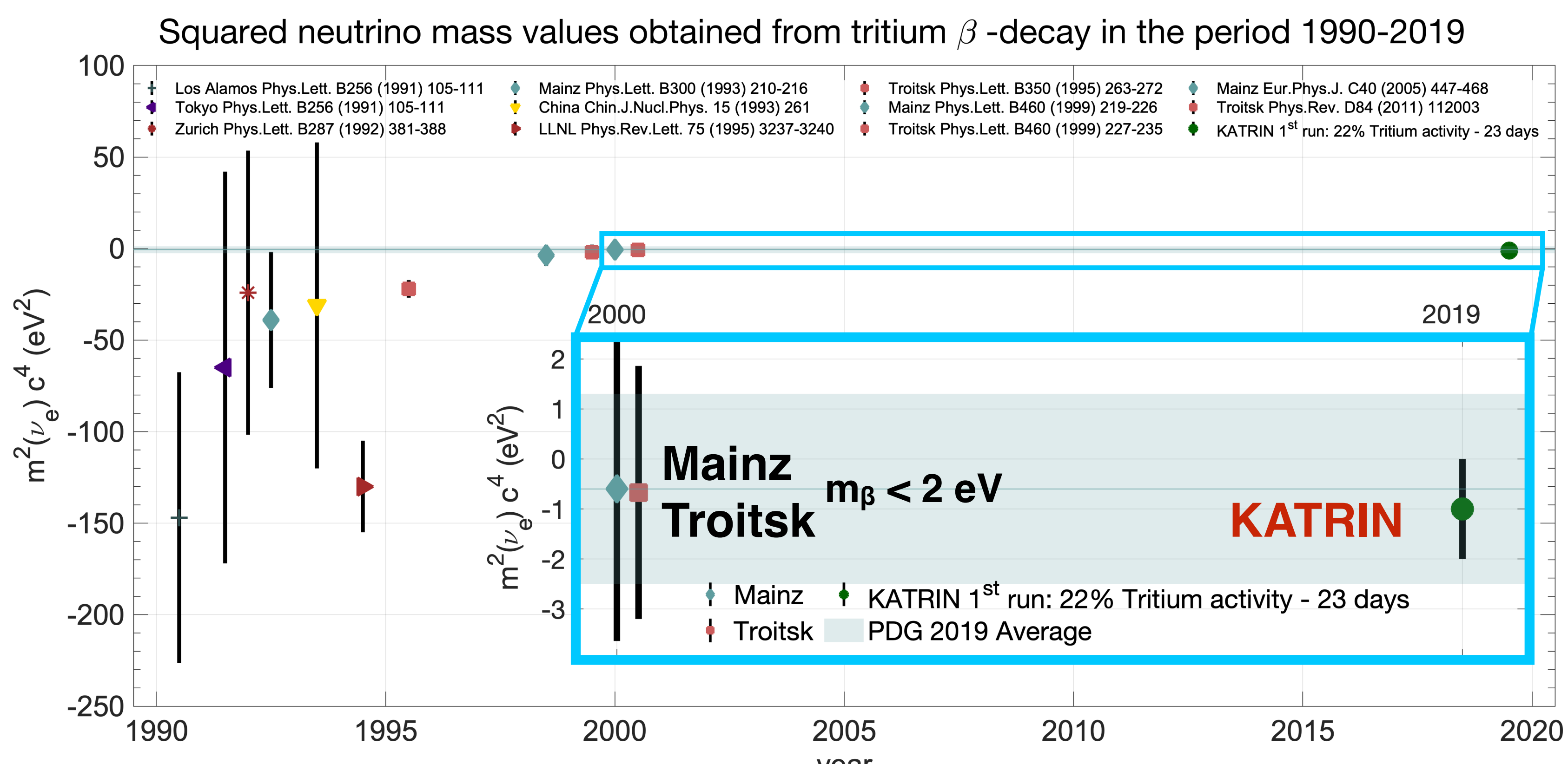
- $m_\beta^2 = -1.0^{+0.9}_{-1.1}$ eV^2
- Consistent with $m_\beta^2 = 0$ eV^2

19% probability to get same or smaller value

Uncertainty budget (m_β^2):

- Dominated by statistics
- Largest systematic from background



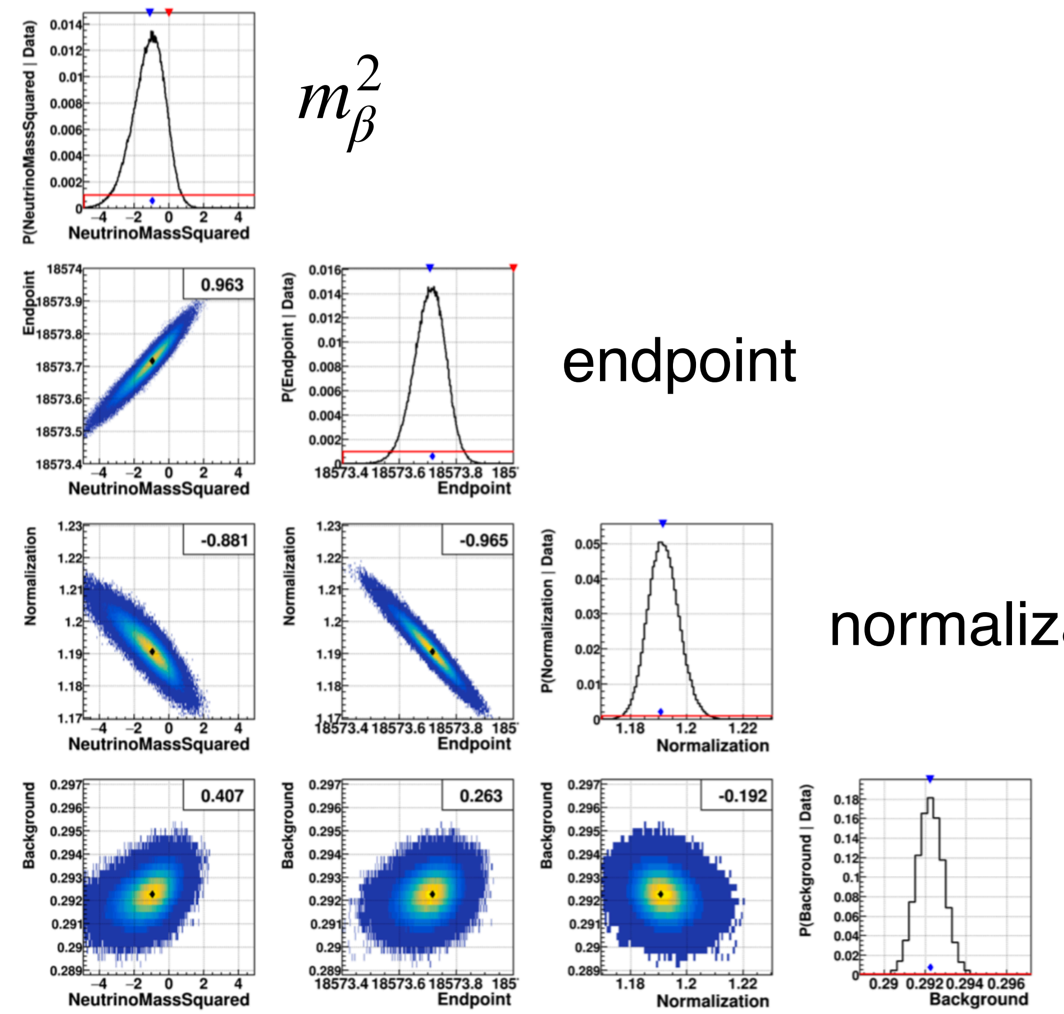


First KATRIN dataset:

- Statistics improved by x2
- Systematic improved by x6

Bayesian Analysis @LBL

- Bayesian analysis with flat prior on m_β^2 for comparison with other techniques
- Full posterior parameter correlations
- Yields similar results



m_β^2

endpoint

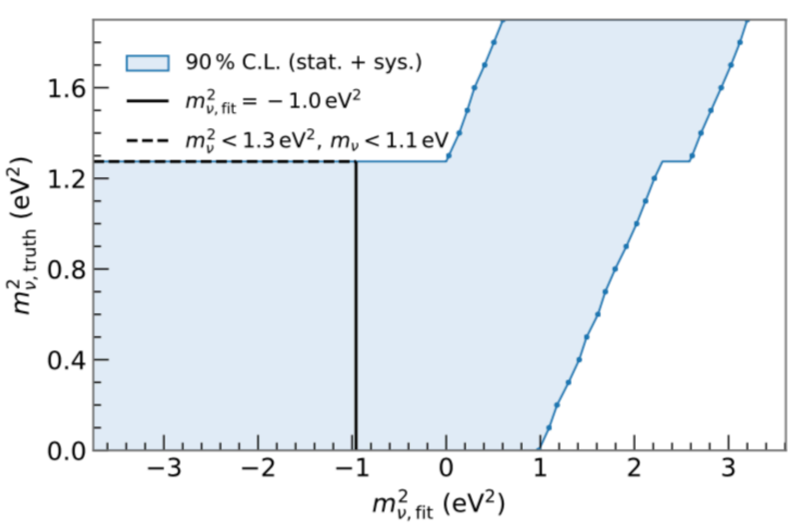
normalization

bg

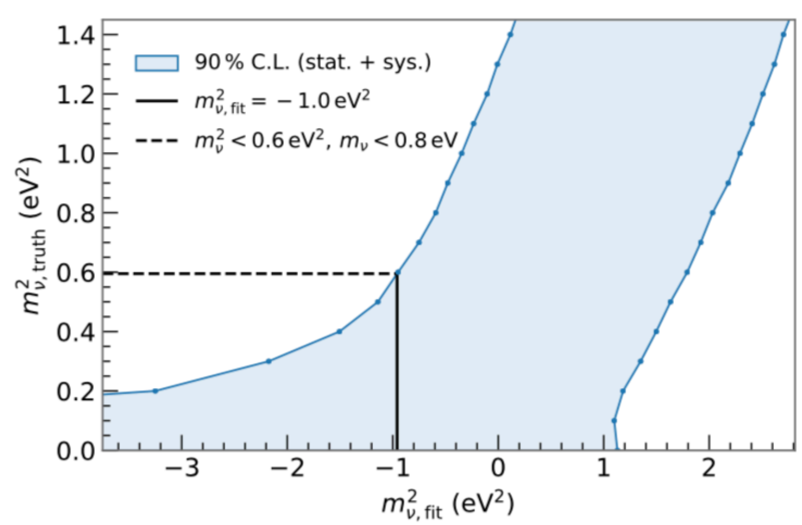
- Straight forward limit setting with positive flat prior on m_β^2

Limit setting on m_β :

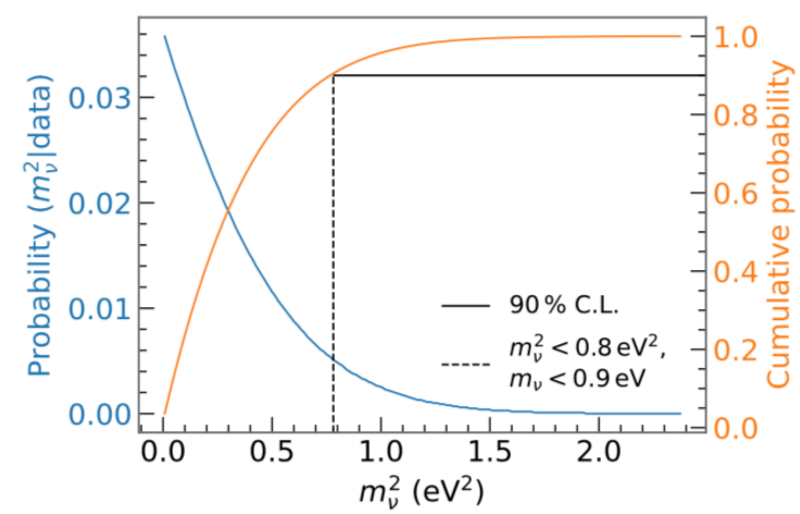
Lokhov-Tkachov (official):
$m_\beta < 1.1$ eV (90% CL)
identical to sensitivity



Feldman-Cousins:
$m_\beta < 0.8$ eV (90% CL)



Bayesian flat prior $m_\beta^2 > 0$:
$m_\beta < 0.9$ eV (90% CI)



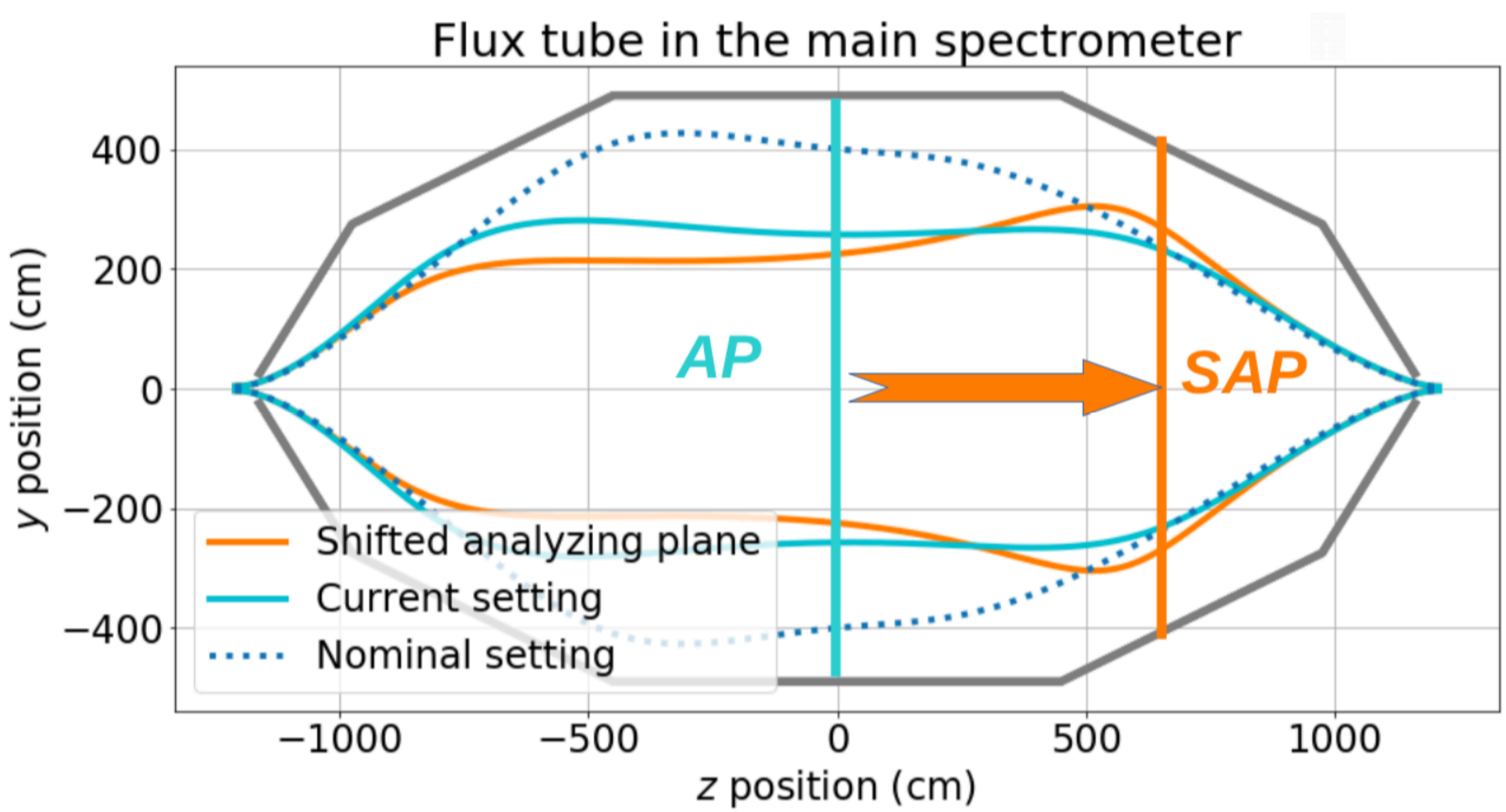
Recent Background Reduction

Spectrometer bake-out:

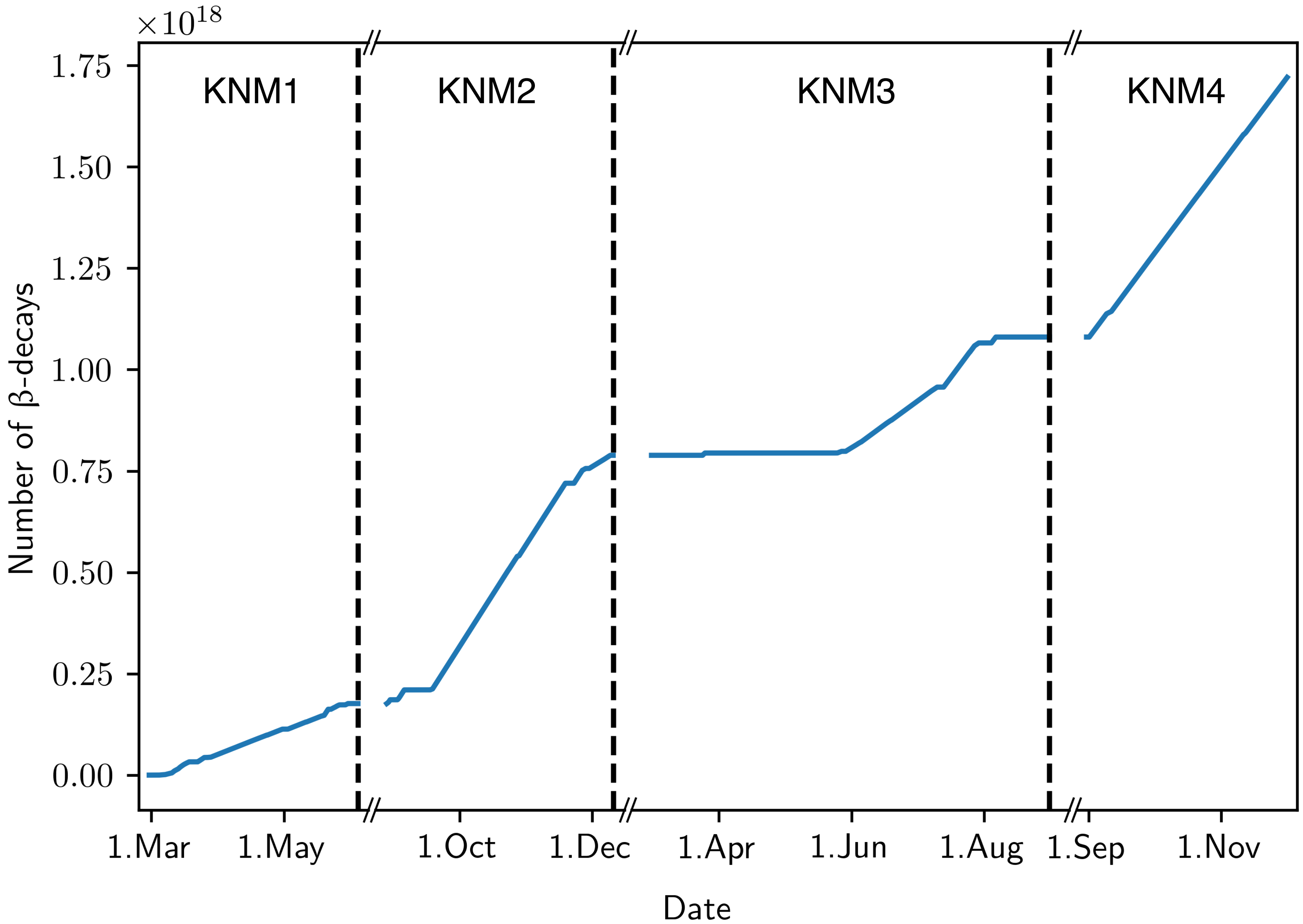
- Reduction in ^{219}Rn background
- Lower systematics form time varying background
- Performed end of 2019

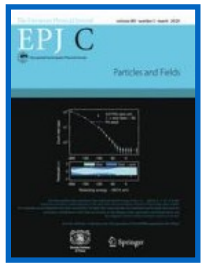
Shifted Analysis Plane (SAP):

- Modify field configuration shifting analysis plain towards detector
- Reduced volume and Rydberg background (x2)
- Currently running in this configuration



Measurement Periods





First tritium operations
EPJ C 80:264 (2020)

First results: $m_\beta < 1.1$ eV
PRL 123, 221802 (2019)

analyzed. publication in process

run in different configuration to optimize source and spectrometer

low background configuration

Conclusions & Outlook

KATRIN measures neutrino mass

- $m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$
- Complementary with Cosmology and Double Beta Decay
- Currently only leading experiment (Future: Project8, ECHo, HOLMES)

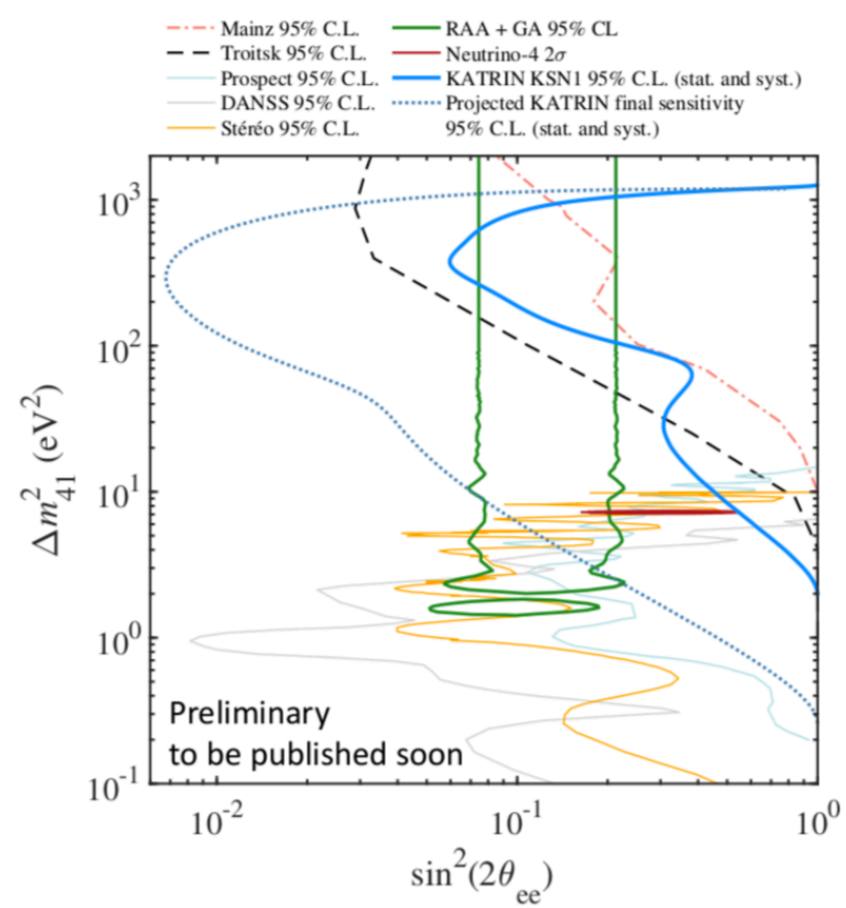
Current best limit from first dataset

- $m_\beta < 1.1$ eV (90% CL)
- x2 improvement over previous limits
- Statistics dominated, largest systematic from background

Optimizations performed last year:

- Background reduction with new spectrometer configuration
- Source plasma systematics reduced with new source configuration

Analysis of eV and keV sterile neutrinos

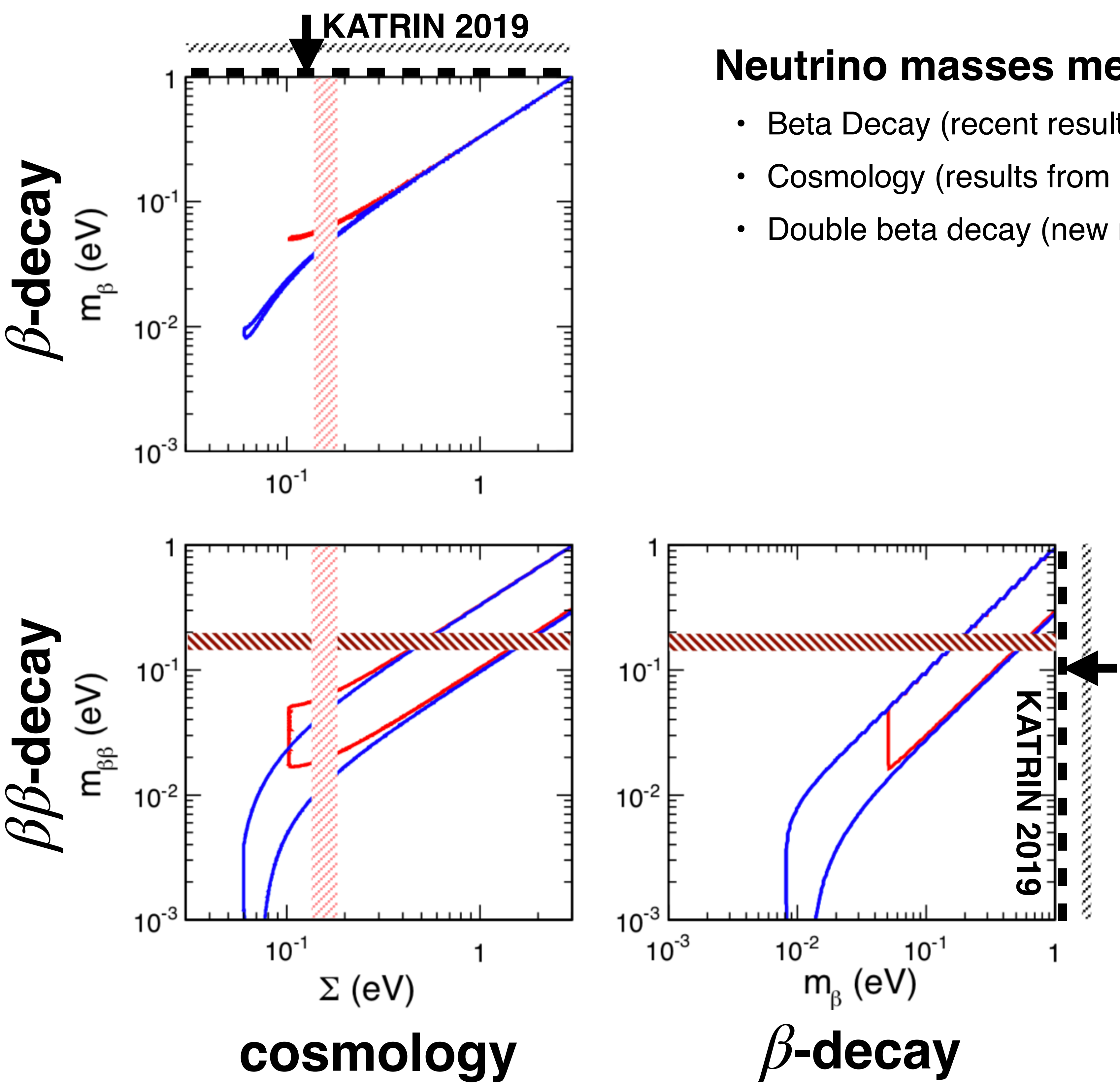


Bibliography:

- First operations: EPJC 80: 264 (2020)
- First results: PRL 123, 221802 (2019)
- Detailed analysis: arXiv:2101.05253
- Sterile neutrino search: arXiv:2011.05087
- Review of direct nu mass: arXiv:2102.00594
- Second results: soon

Backup

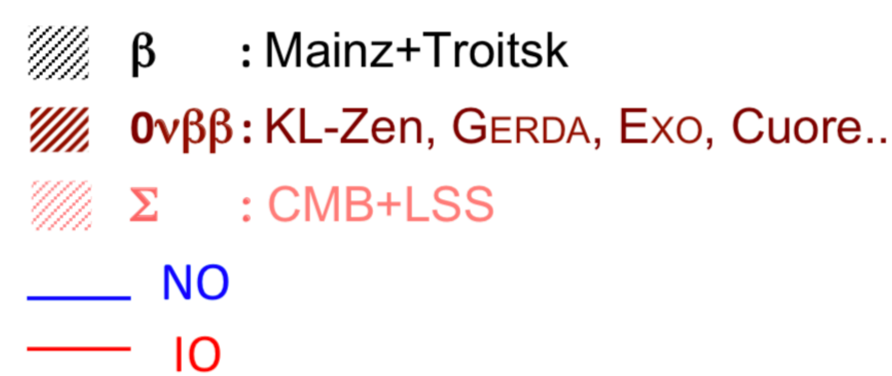
Global Picture



Neutrino masses measured in three observables:

- Beta Decay (recent results from KATRIN) $m_\beta < 1.1\mathrm{eV}$
- Cosmology (results from Planck + BAO) $m_\Sigma < 120\ \mathrm{meV}$
- Double beta decay (new results from GERDA) $m_{\beta\beta} < 60 - 170\ \mathrm{meV}$

Neutrino masses 1 year ago:
[from Eligio Lisi, TAUP19]



Background in KATRIN

- **Signal:** e^- have $E \approx 0$ keV in analyzing plane
- **Background:** low energy e^- in spectrometer volume can mimic signal (independent of qU)

Observed background 50x higher than designed

Two main components:

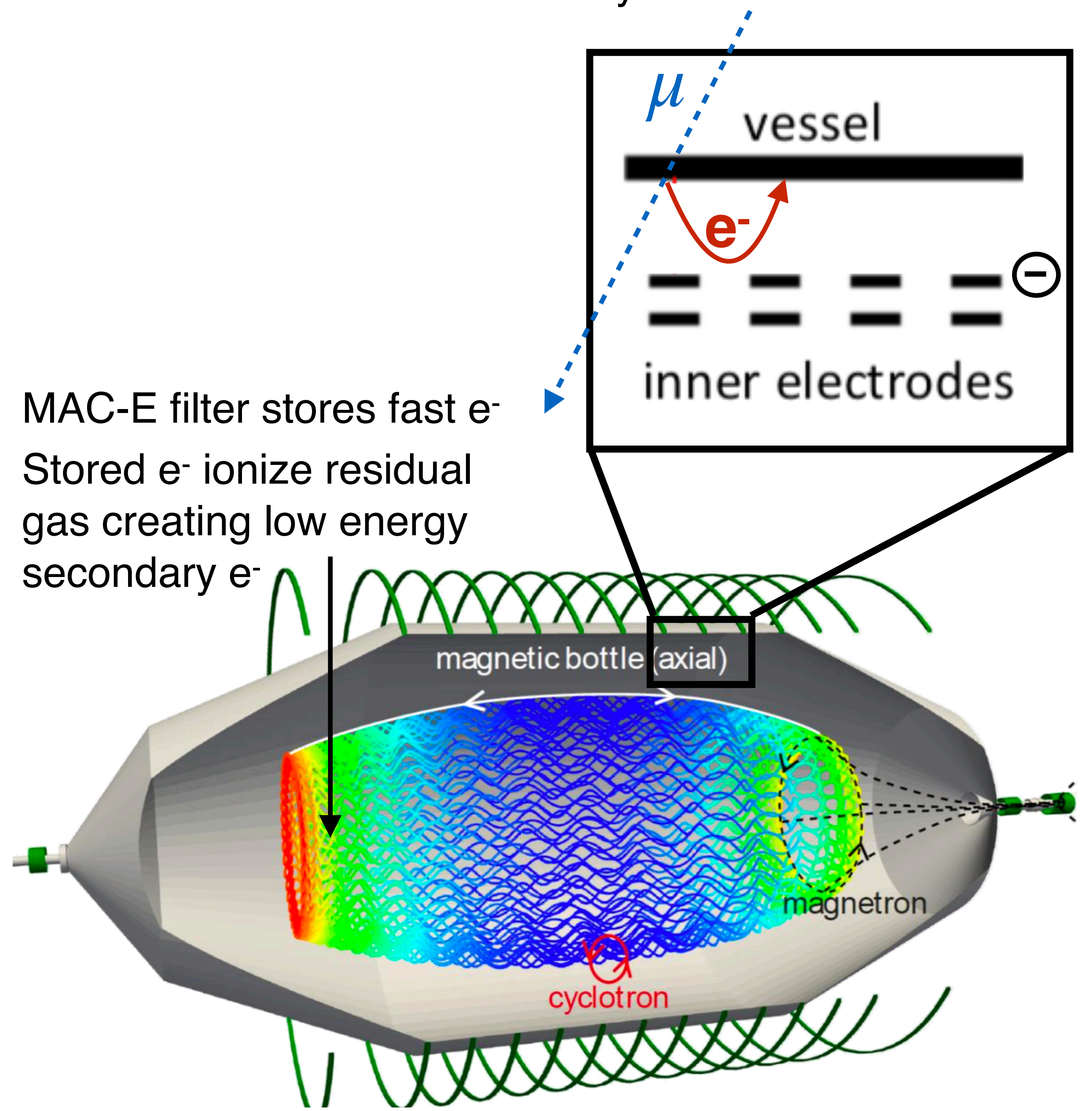
1. ^{219}Rn ($T_{1/2} = 4$s) from getter material in pumps
    - Decays in spectrometer creating fast e^-
    - Creates time varying background rate

2. Rydberg atoms from vessel walls
    - α decays spatter out neutral atoms in highly excited Rydberg states
    - Ionize in spectrometer creating low energy e^-
    - Creates radial dependent background rate

- Changes of measurement and analysis largely mitigates impact on sensitivity

Main electron background from cosmic μ mitigated by inner electrodes

- MAC-E filter stores fast e^-
- Stored e^- ionize residual gas creating low energy secondary e^-

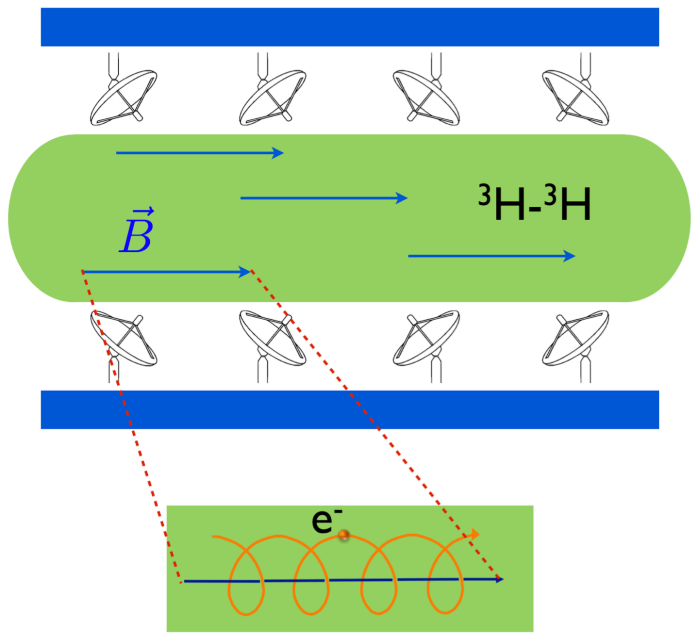


Project 8

Nu2020: Noah Oblath
Project 8 [link]

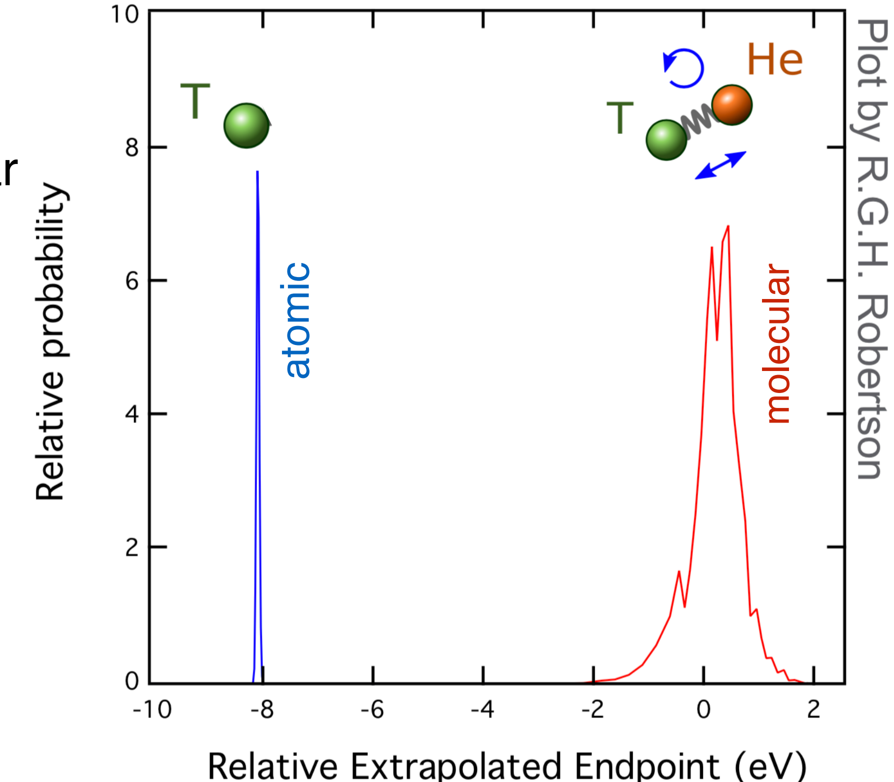
Idea: measure frequency very precisely

CRES (Cyclotron Radiation Emission Spectroscopy) of β-decay electrons



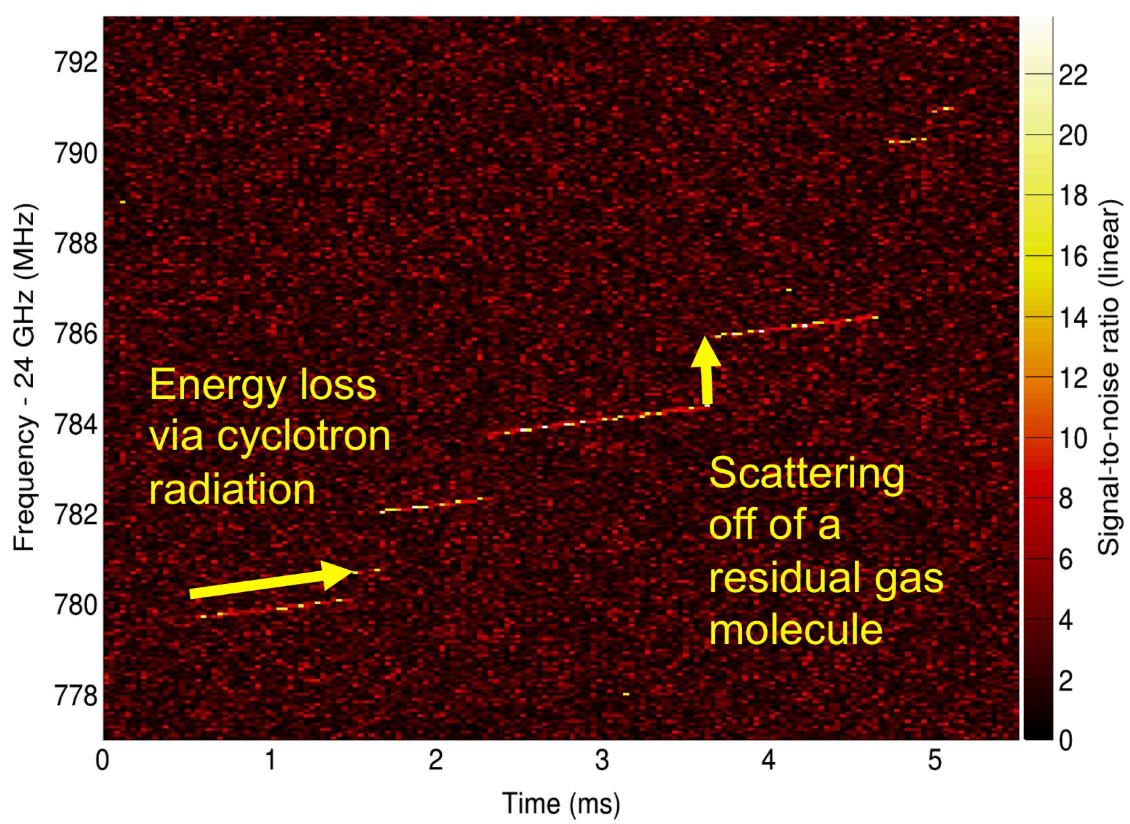
Ultimate plan:

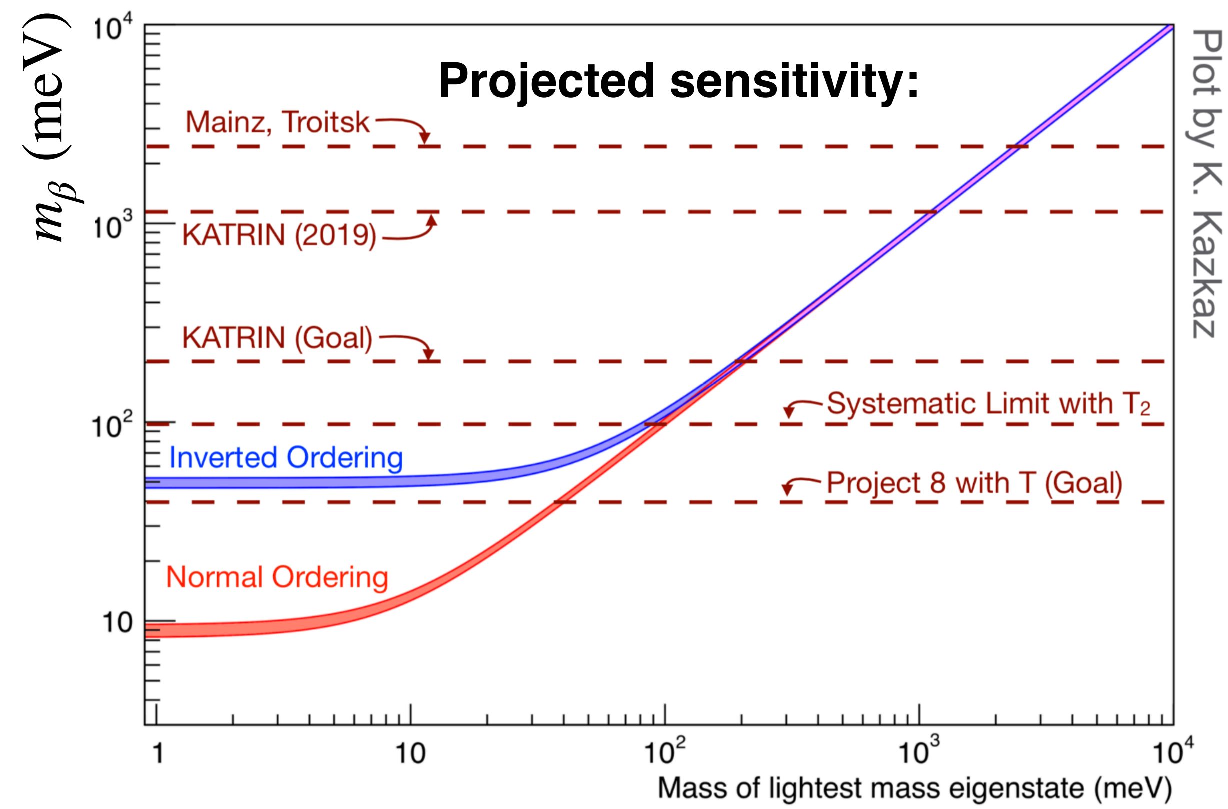
Use atomic tritium to reduce molecular final states



Status:

First measurement of T_2 spectrum with preliminary analysis





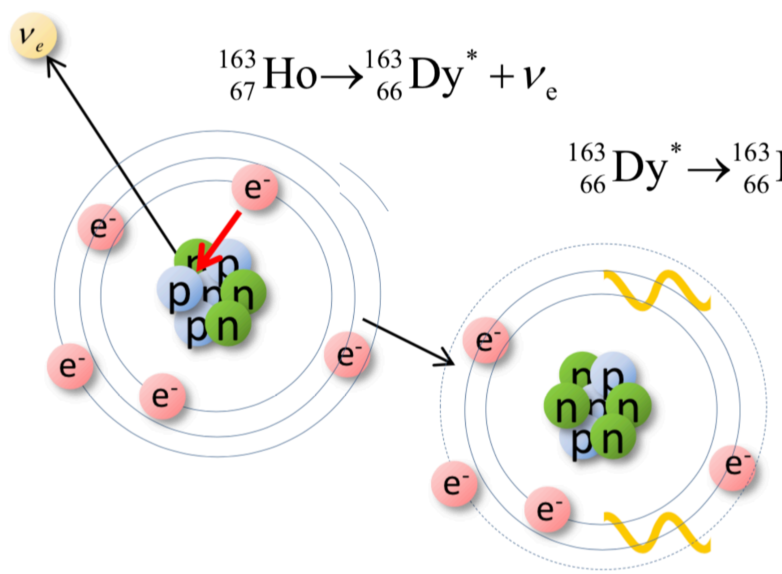
ECHo and HOLMES

Nu2020: Maurits Haverkort
Mass measurements with Ho-163 [link]

Electron capture in ^{163}Ho:
- $T_{1/2}$ = 4570 yr
- Q-value ~2.83 keV

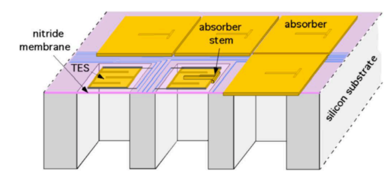
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$



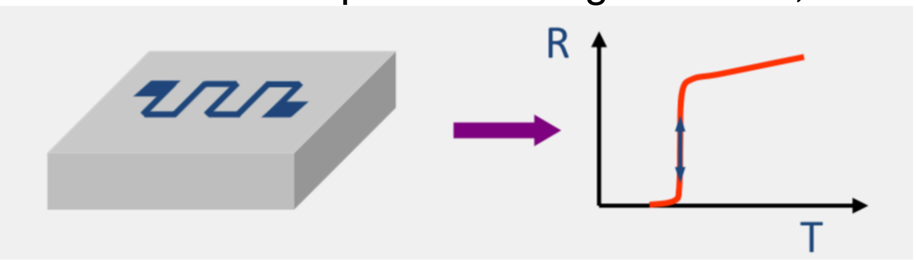
Technology:
- pixelated cryogenic bolometers (<100 mK)
- source = detector, calorimeter

HOLMES



J. of Low Temp. Phys. 184, 922 (2016)

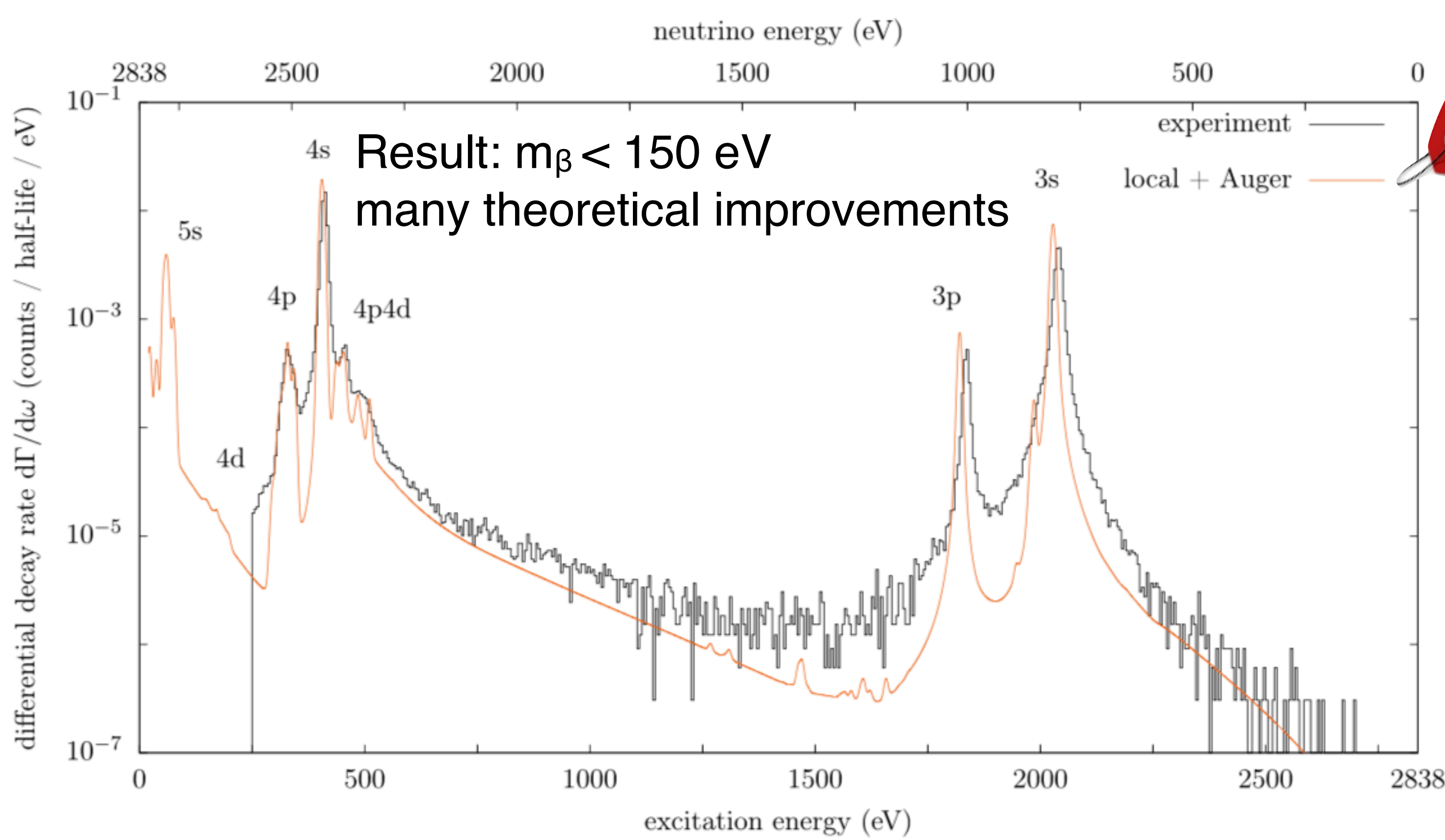
Resistance at superconducting transition, TES



ECHo

EPJ-ST 226 8 (2017) 1623

Magnetization of paramagnetic material, MMC



Result: $m_\beta < 150$ eV
many theoretical improvements

New

Future plans:
- soon 2020: $m_\beta < 20$ eV (ECHo)
- ~ 2022: $m_\beta \sim 2$ eV
- future: $m_\beta \sim 0.2$ eV