The Direct Road to Neutrino Mass

Hamish Robertson, CENPA, University of Washington

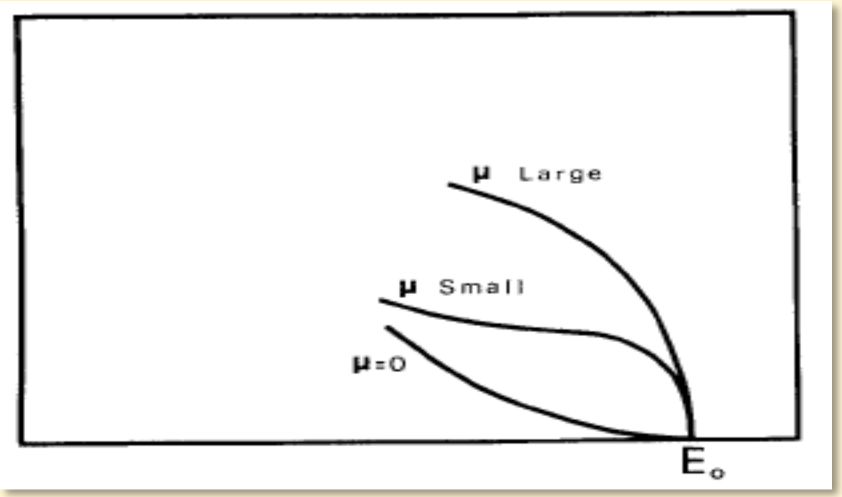
Wick Haxton Festschrift

"Looking for ν Physics on Earth and in the Cosmos"

LBNL January 7, 2020

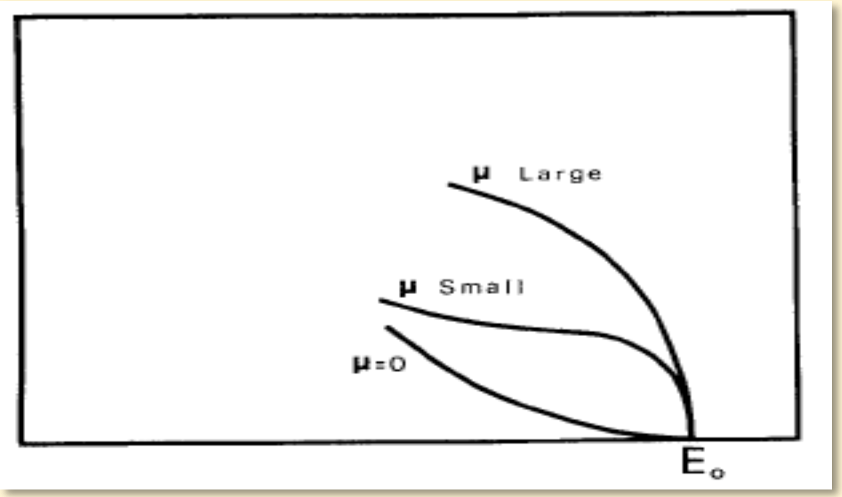
"Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron."

E. Fermi, 1934



F. Wilson, Am. J. Phys. 36, 1150 (1968)

"Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron." *E. Fermi, 1934*



F. Wilson, Am. J. Phys. 36, 1150 (1968)

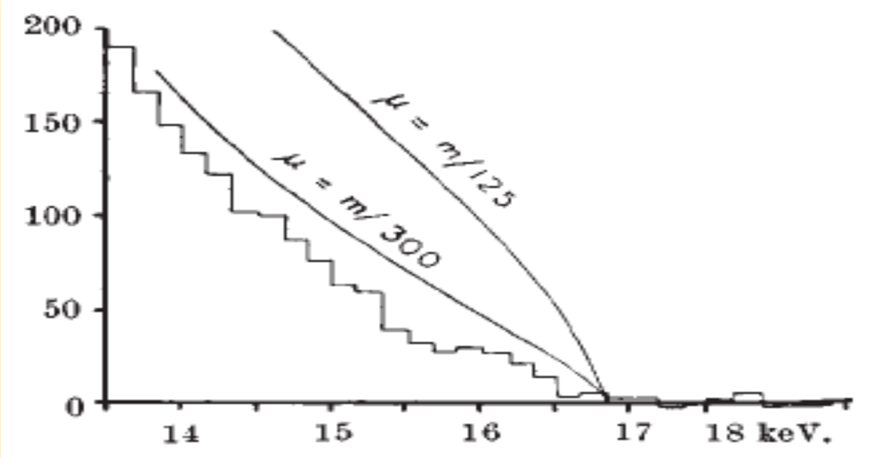
This is the "direct" method.

First experiments with gaseous tritium !

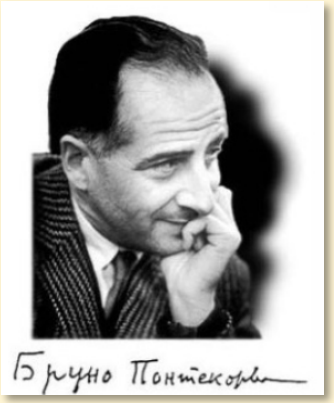
Beta Spectrum of Tritium

Nature 162, 302 (1948)

S. C. Curran
J. Angus
A. L. Cockcroft
Department of Natural Philosophy,
University of Glasgow. May 21.



$m_\nu < 1700$ eV



$m_\nu < 500$ eV

Phys. Rev. 75, 983 (1949)

The β-Spectrum of H³

G. C. Hanna and B. Pontecorvo
Chalk River Laboratory, National Research Council of Canada, Chalk River, Ontario, Canada
January 28, 1949

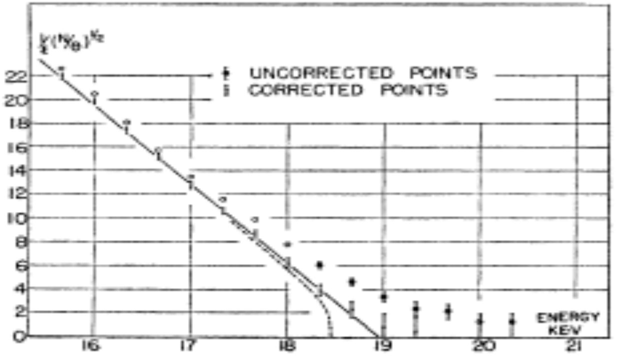
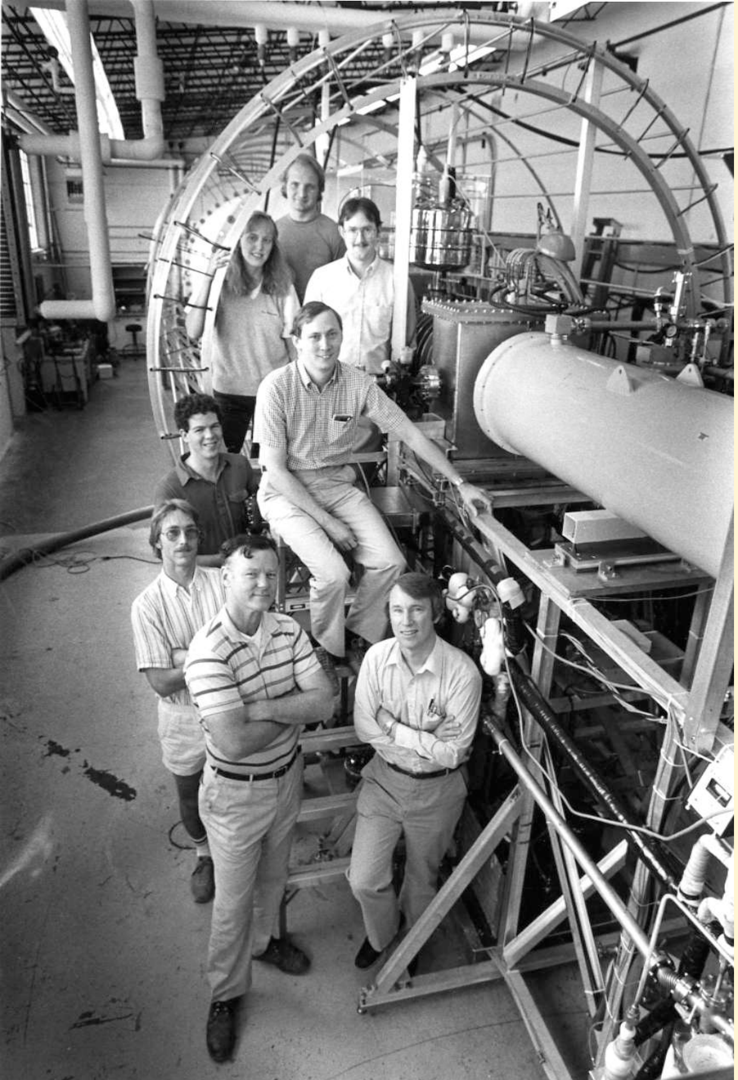


FIG. 2. "Kurie" plot of the end of the H³ spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev—see text) has been included for comparison.

Los Alamos



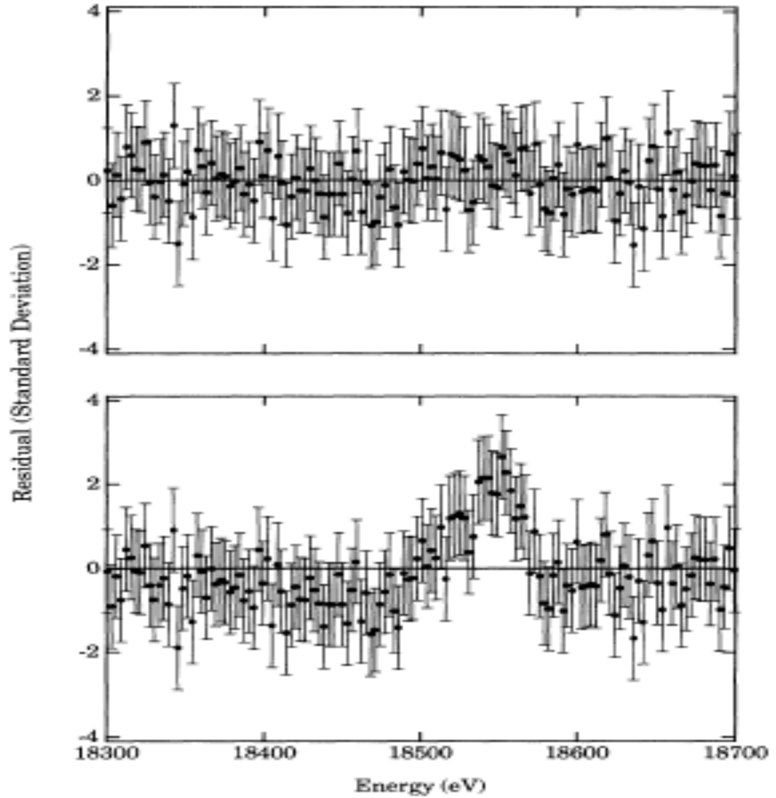
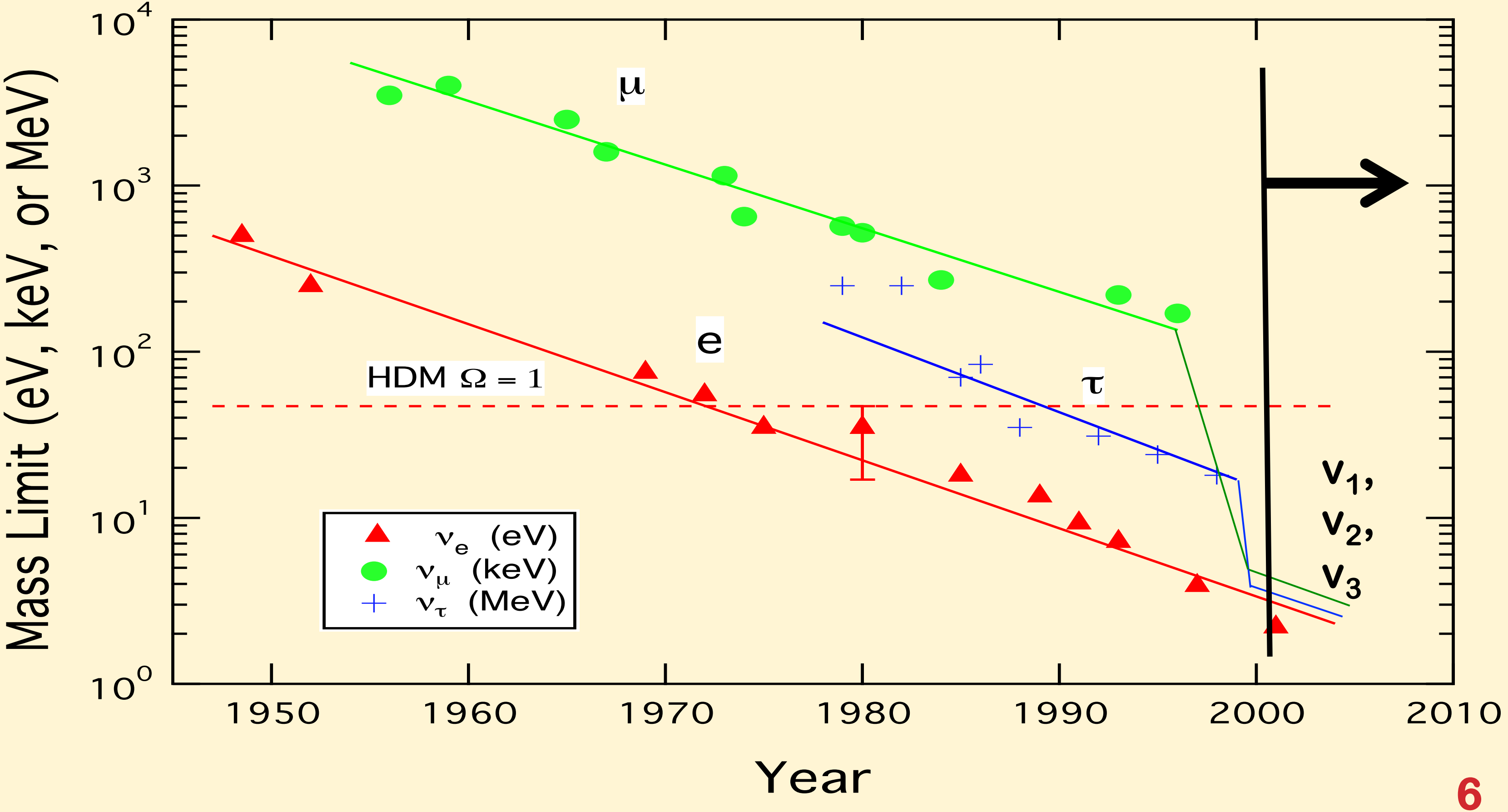


FIG. 2. Residuals in fits to neutrino masses of 0 (top) and 30 eV (bottom). All other parameters including α_1 have been allowed to vary.

PRL 67, 957 (1991)

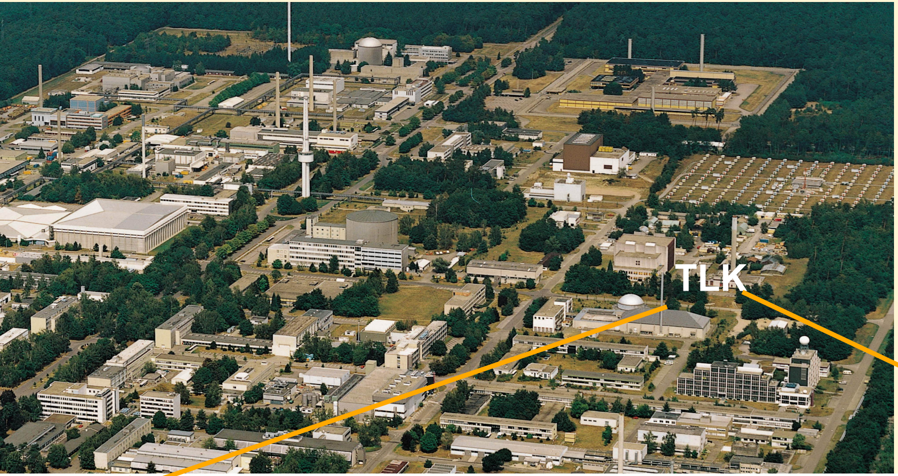
Neutrino oscillations discovered – neutrinos have mass!

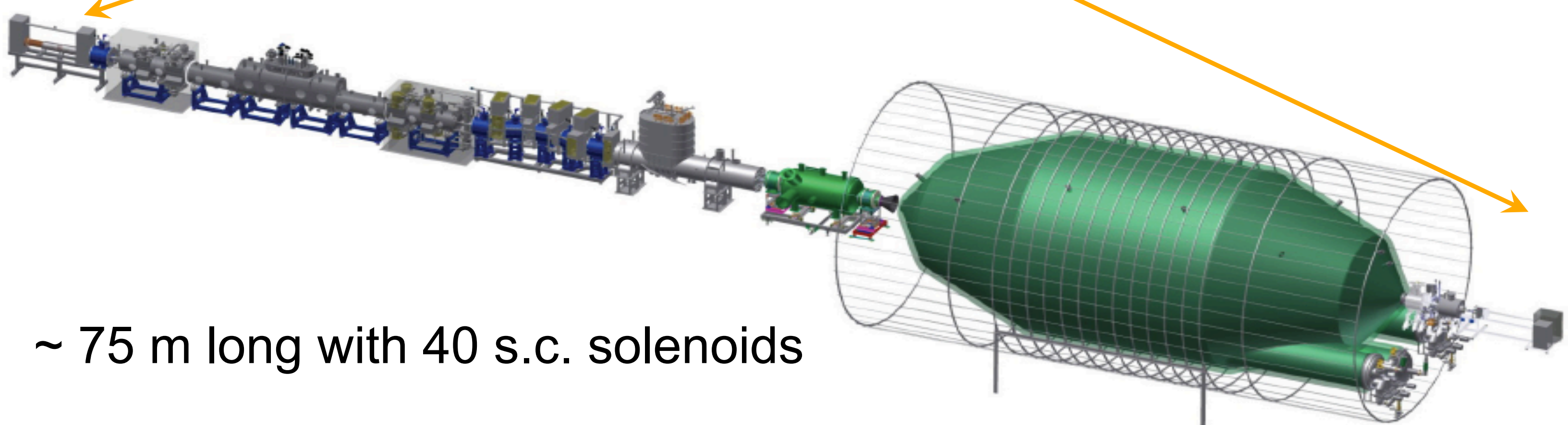


KATRIN

At Karlsruhe Institute of Technology
unique facility for closed T_2 cycle:
Tritium Laboratory Karlsruhe

A direct, model-independent, kinematic method, based on β decay of tritium.





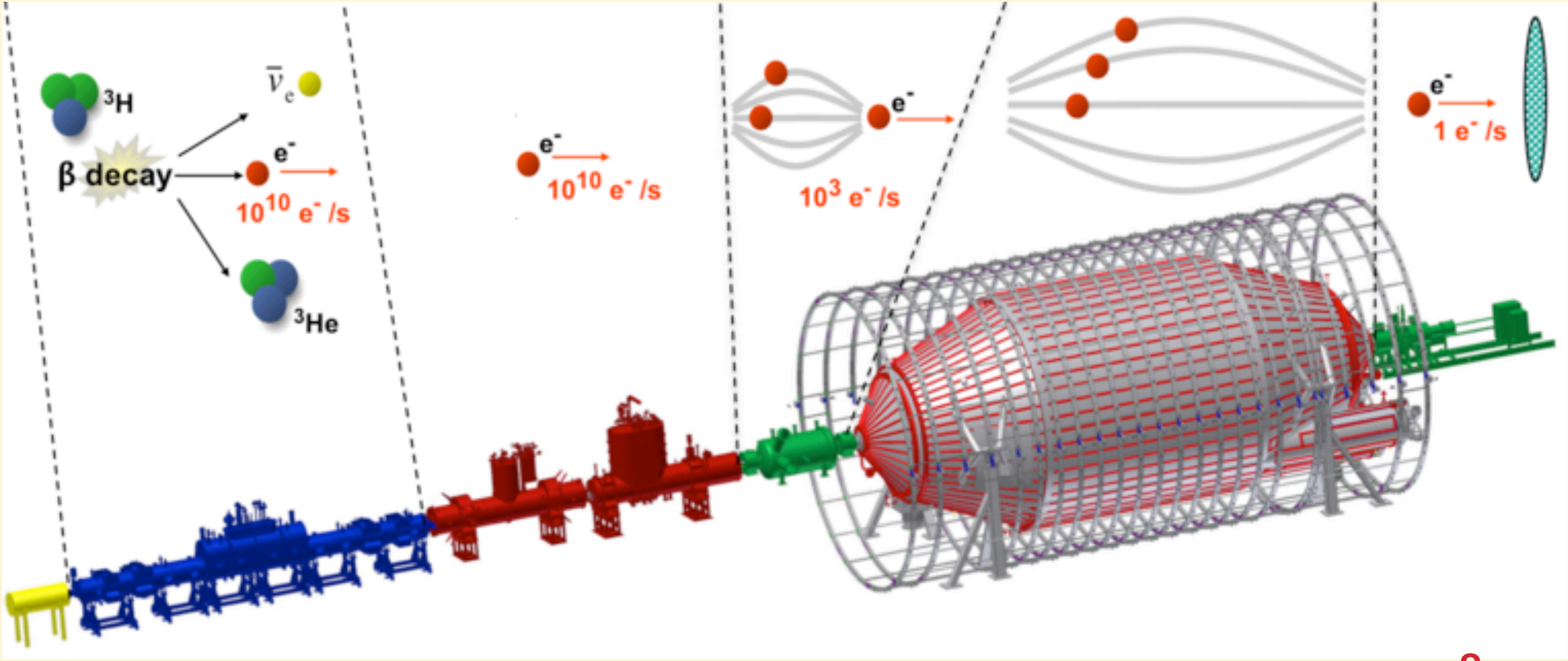
~ 75 m long with 40 s.c. solenoids

Overview of KArlsruhe TRItium Neutrino Experiment

Windowless gaseous source | Transport section | Pre-spectrometer | Main-spectrometer | Detector

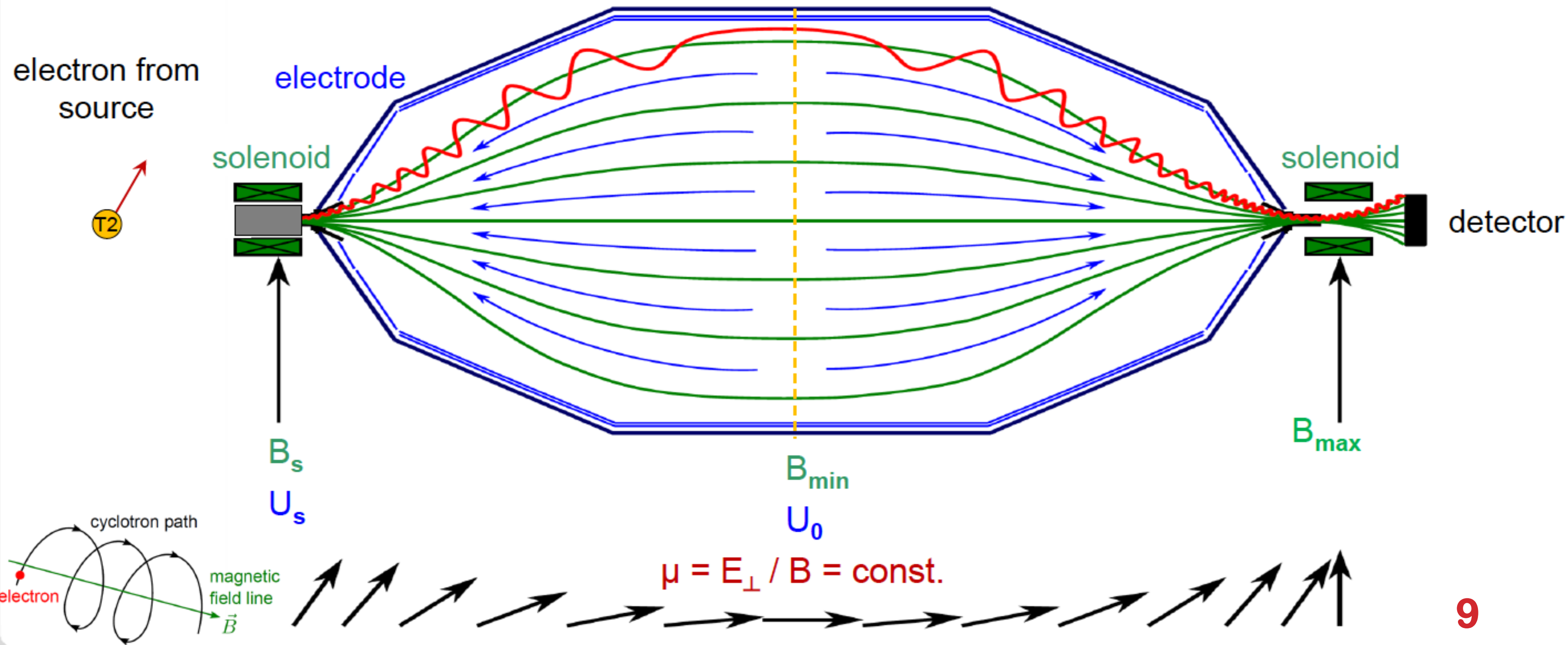
10^{-3} mbar

10^{-11} mbar

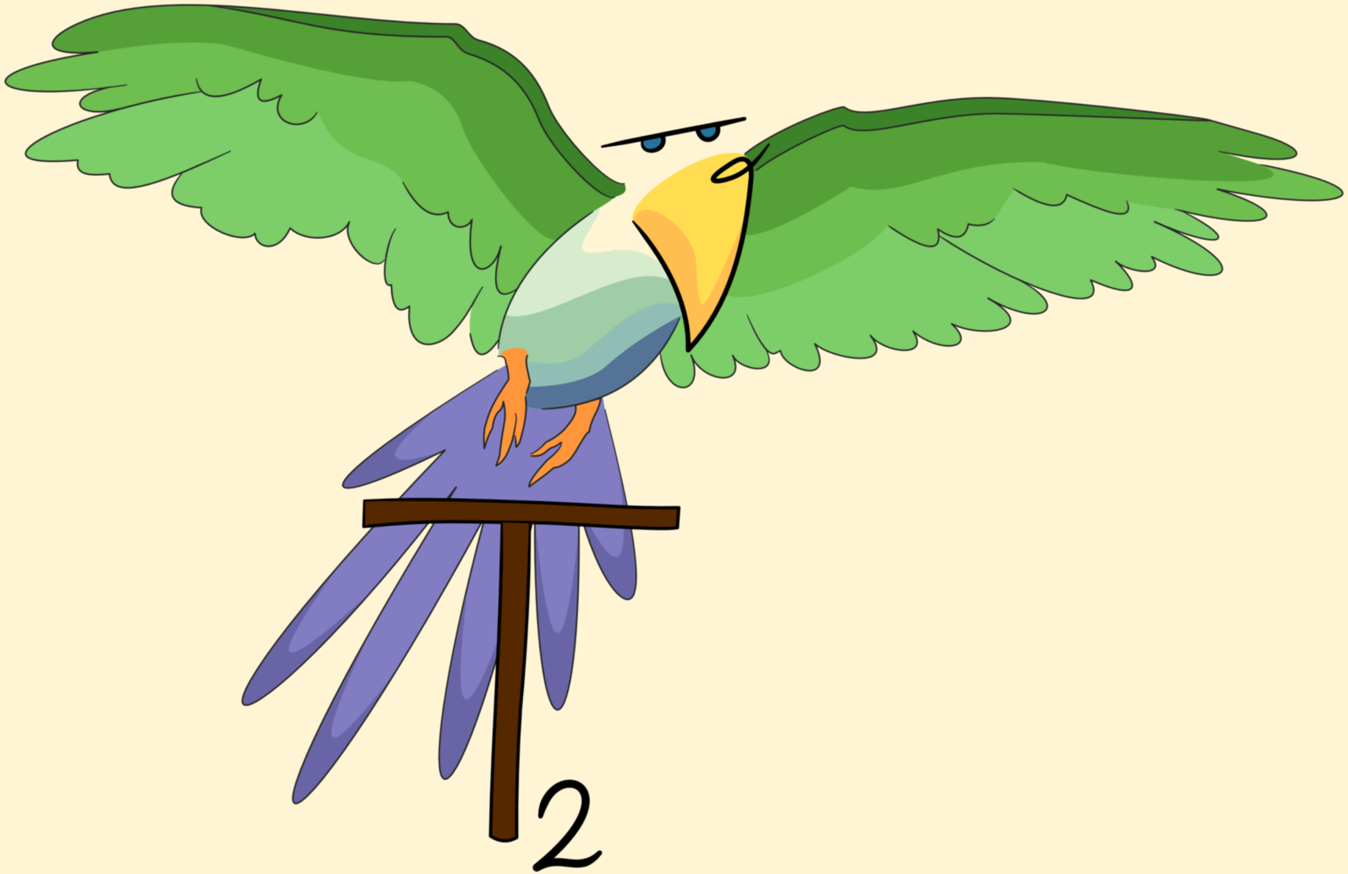


KATRIN forms *integral* spectrum with MAC-E filter

- Magnetic Adiabatic Collimation & Electrostatic Filter: adiabatic conversion $E_\perp \rightarrow E_\parallel$



KATRIN
Karlsruhe Tritium Neutrino Experiment



KATRIN

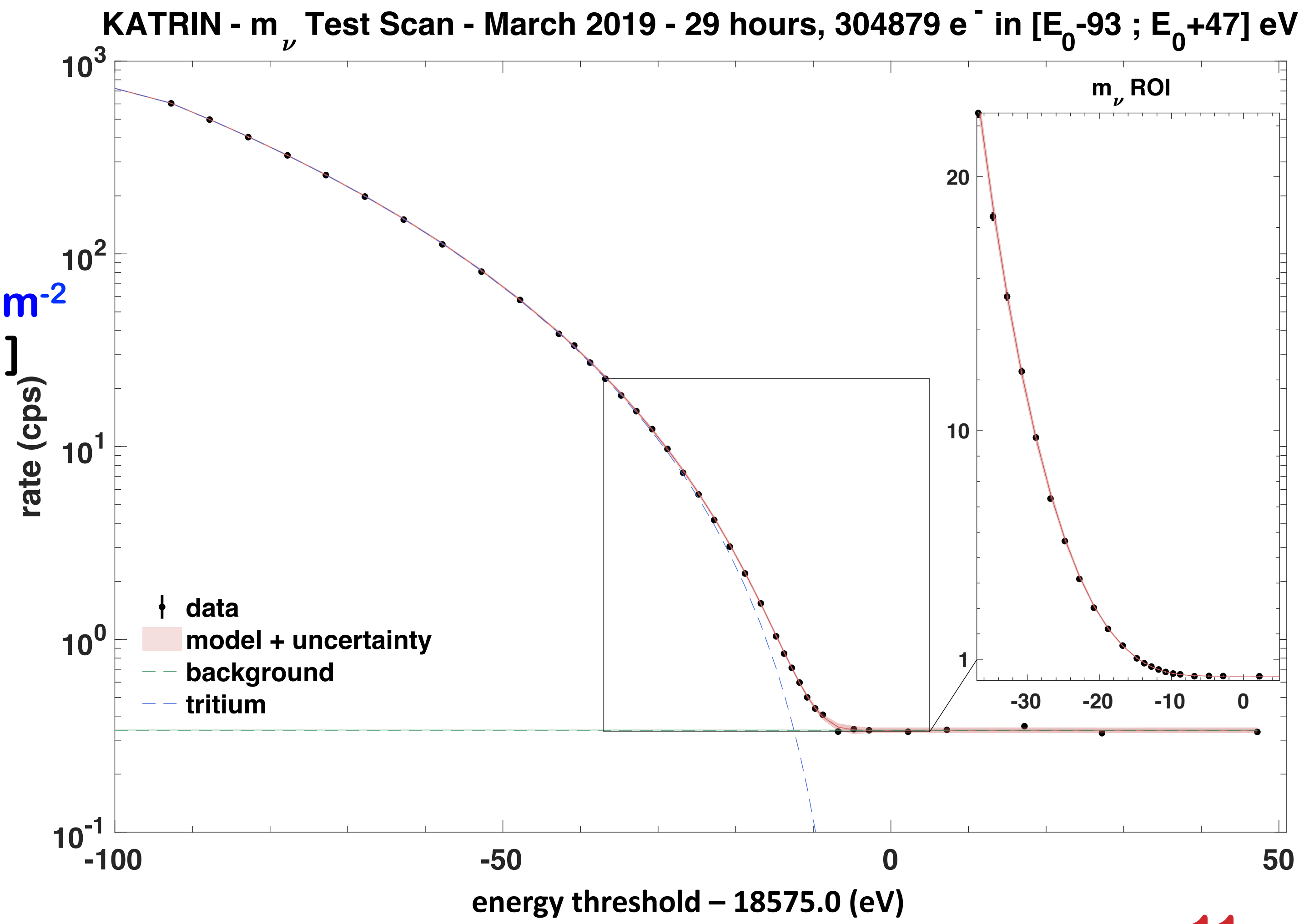
March 18-19, 2019

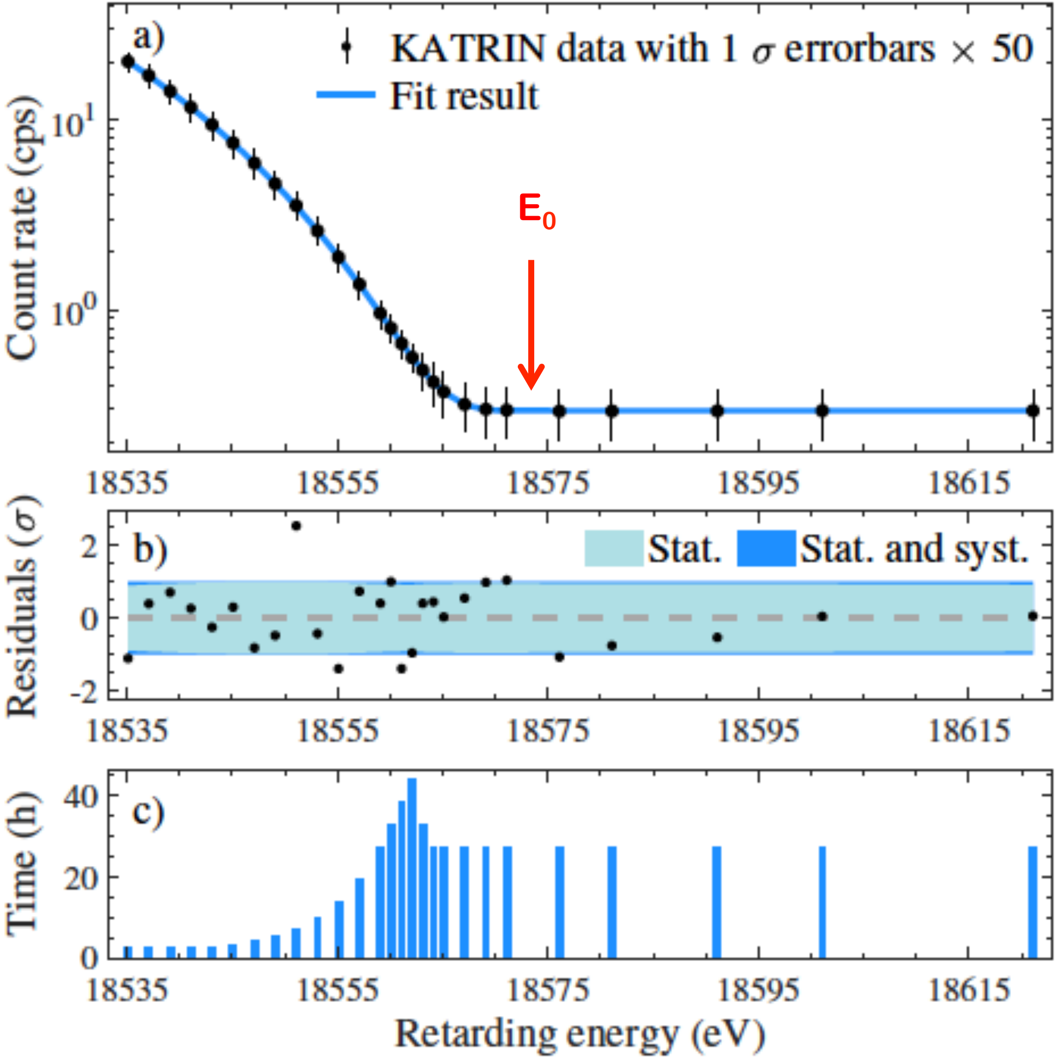
305,000 events

Col dens: 2 x 10^{17} cm^{-2}
[CDR: 5 x 10^{17} cm^{-2}]

E/dE = 42000/6.3
= 6670
~2.8 eV base width
[CDR: 20000]

Bkg: 0.33 c/s
[CDR: 0.01 c/s]

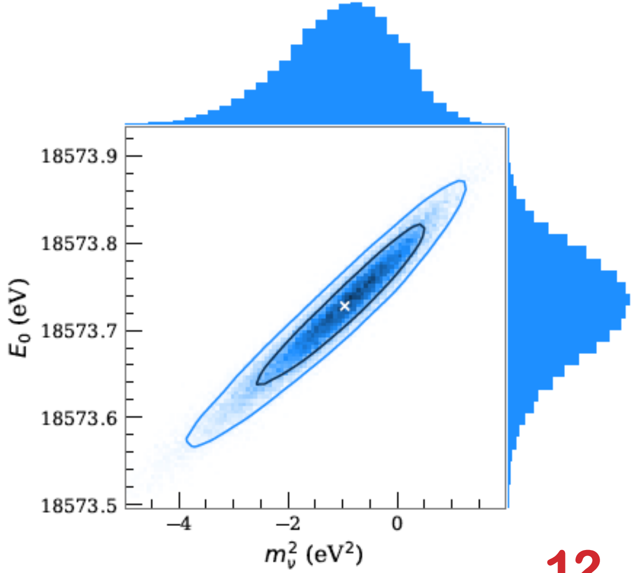




KATRIN

PRL 123, 221802 (2019)

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

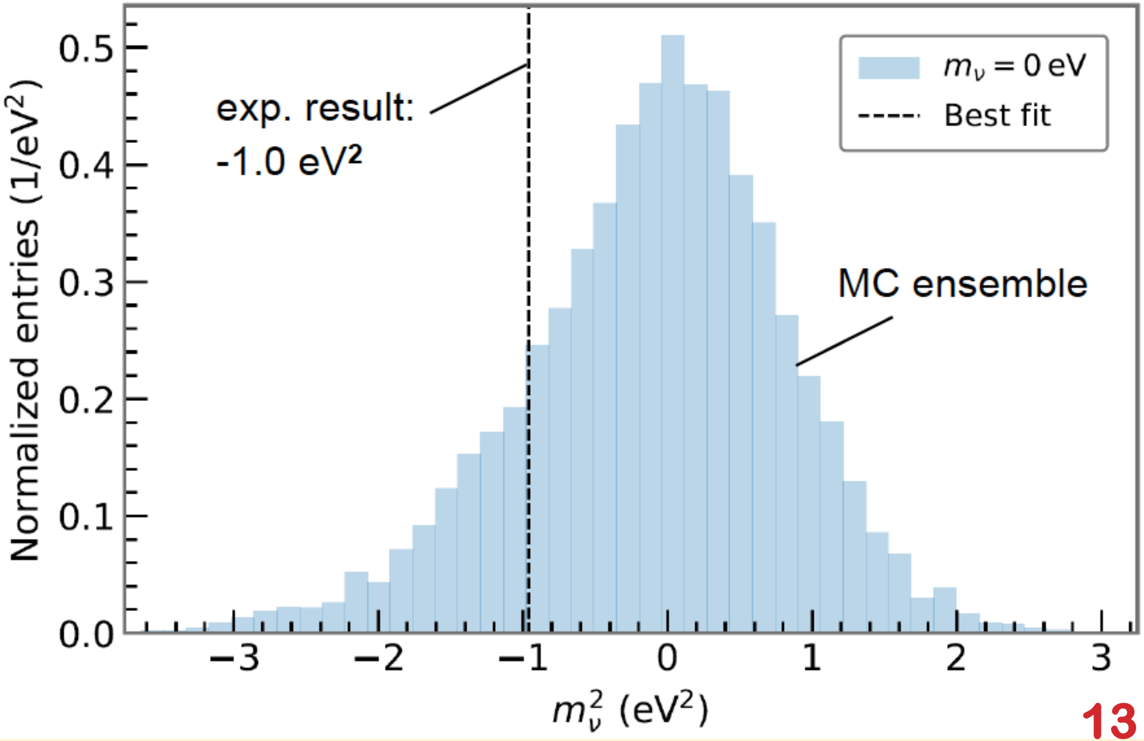


Result is statistically probable

- **best-fit result corresponds to a 1-σ statistical fluctuation to negative $m^2(\nu_e)$**

  - p-value is derived from 13 000 MC samples with $m^2(\nu_e)$ = 0 and properly fluctuated σ_{stat} and σ_{syst}

p-value = 0.16



Derivation of mass limit

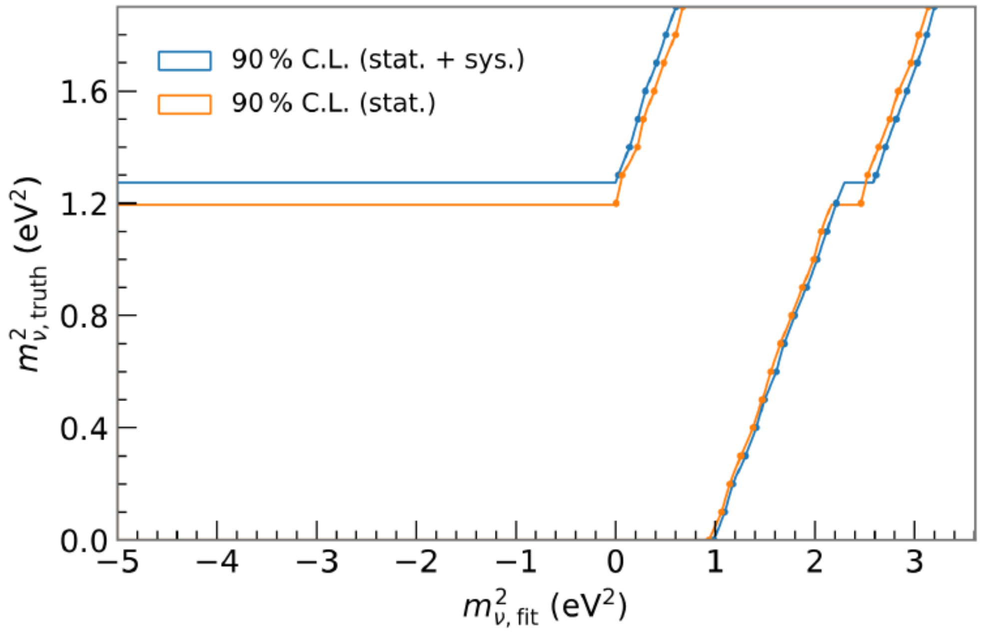
- **confidence belts:** procedures of Lokhov and Tkachov (LT) + Feldman and Cousins (FC)

- for this first result we follow the robust LT method
- LT yields experimental sensitivity by construction for $m^2(\nu_e) < 0$

- **KATRIN upper limit on neutrino mass:**

LT $m(\nu) < 1.1$ eV (90% CL)

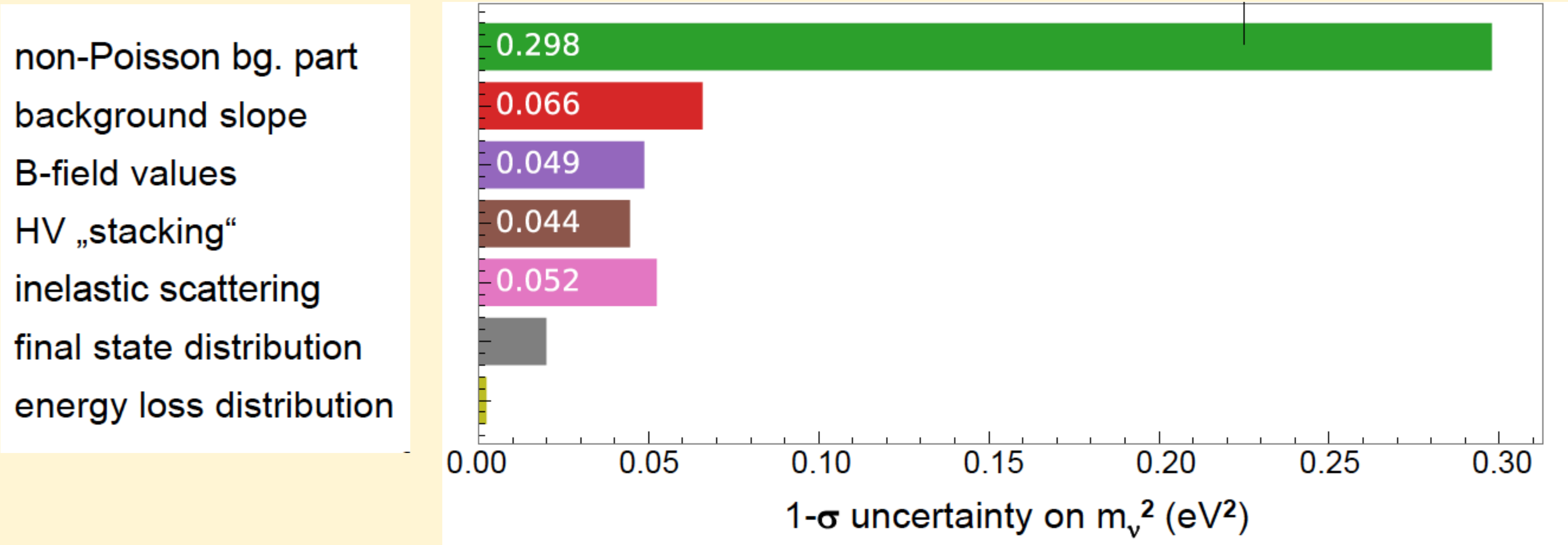
FC $m(\nu) < 0.8$ eV (90% CL)
< 0.9 eV (95% CL)



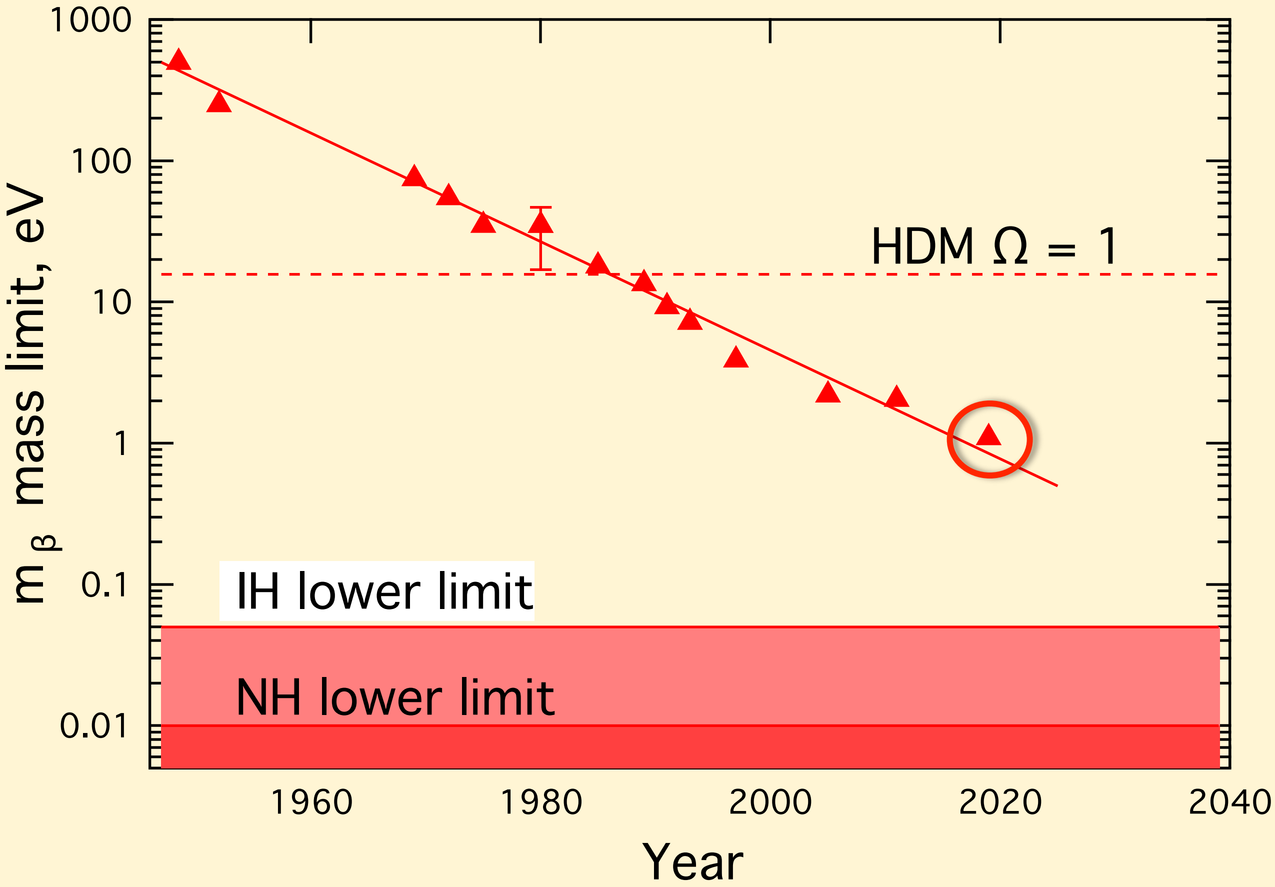
A.V. Lokhov, F.V. Tkachov, Phys. Part. Nucl. 46 (2015) 347

Still mainly statistically limited

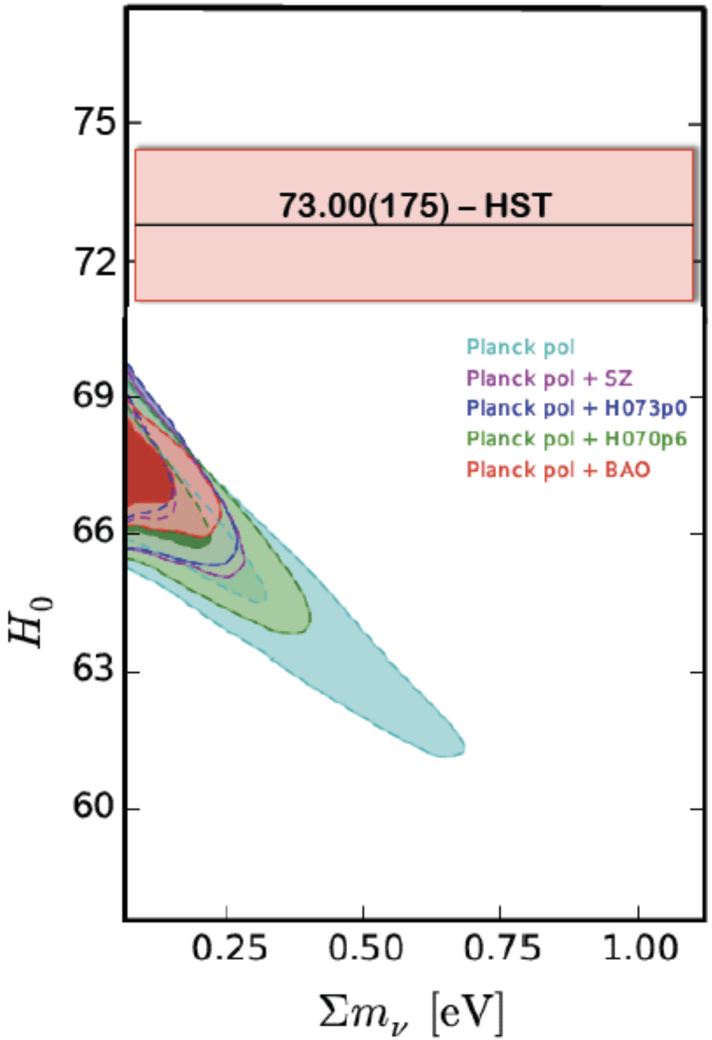
- total statistical uncertainty budget σ_{stat} = 0.97 eV²
- total systematic uncertainty budget σ_{syst} = 0.32 eV²



The road is direct, but long!



Neutrinos in the cosmos



Tension with the HST galaxy low-z data can be resolved by relaxing w:

$$w \sim -1.14^{+0.12}_{-0.10}$$

$$\Sigma m_\nu \sim 0.35^{+0.16}_{-0.25} \text{ eV}$$

Di Valentino et al. PLB 761, 242 (2016)

THE LAST ORDER OF MAGNITUDE

If the mass is below 0.2 eV, how can we measure it?
KATRIN may be the largest such experiment possible.

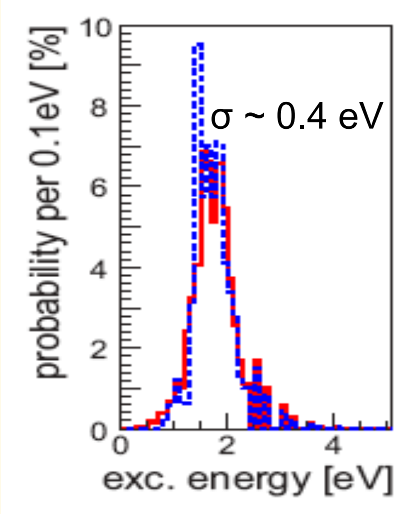
Statistics

Size of experiment now:
Diameter 10 m.

$$\sigma(m_\nu^2) = k\frac{b^{1/6}}{r^{2/3}t^{1/2}},$$

Next diameter: 300 m!

Systematics



Molecular rotation and vibration

A new idea : Cyclotron Radiation Emission Spectroscopy (CRES).

(B. Monreal and J. Formaggio, PRD 80:051301, 2009)

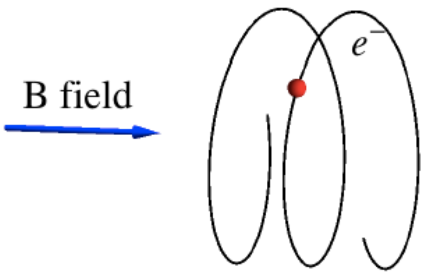
Arthur Schawlow

If you are going to measure anything with precision, measure frequency.

Cyclotron motion:

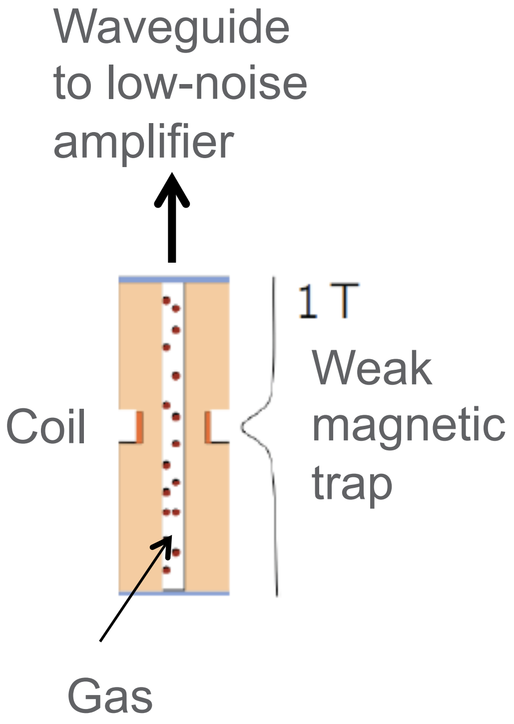
$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

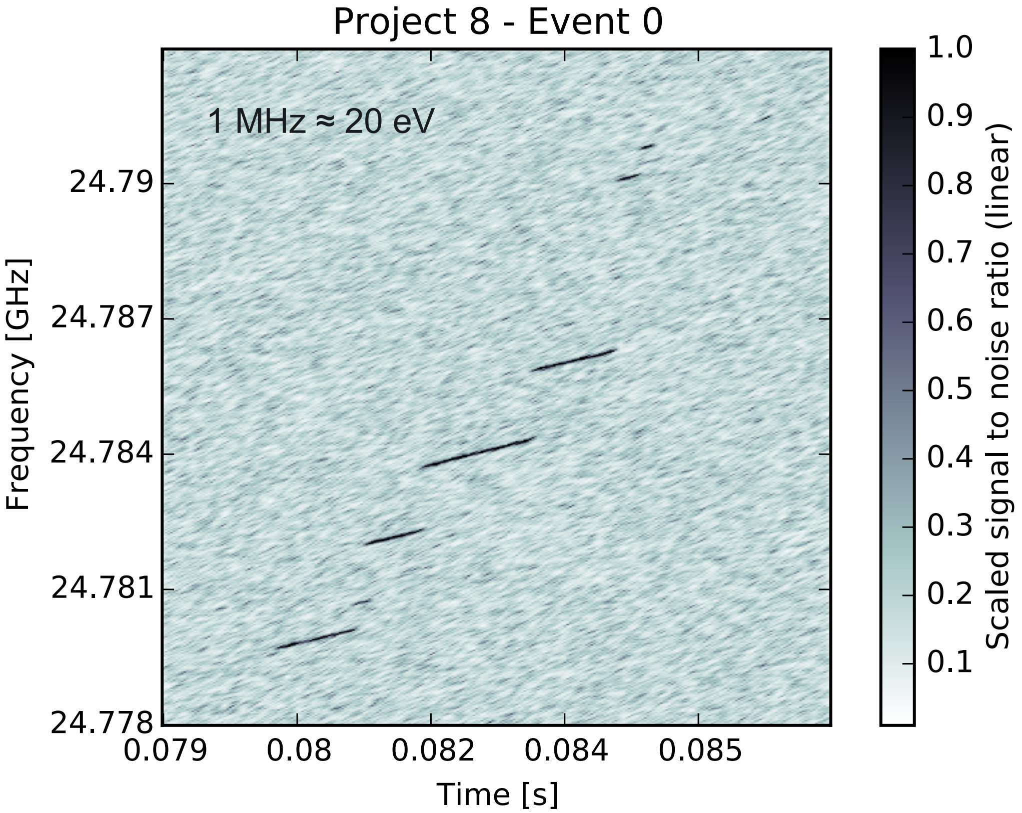
$$f_c = 27\,992.491\,10(6)\ \mathrm{MHz\,T^{-1}}$$



Surprisingly, this had never been observed for a single electron.

First CRES event (from ^{83m}Kr)





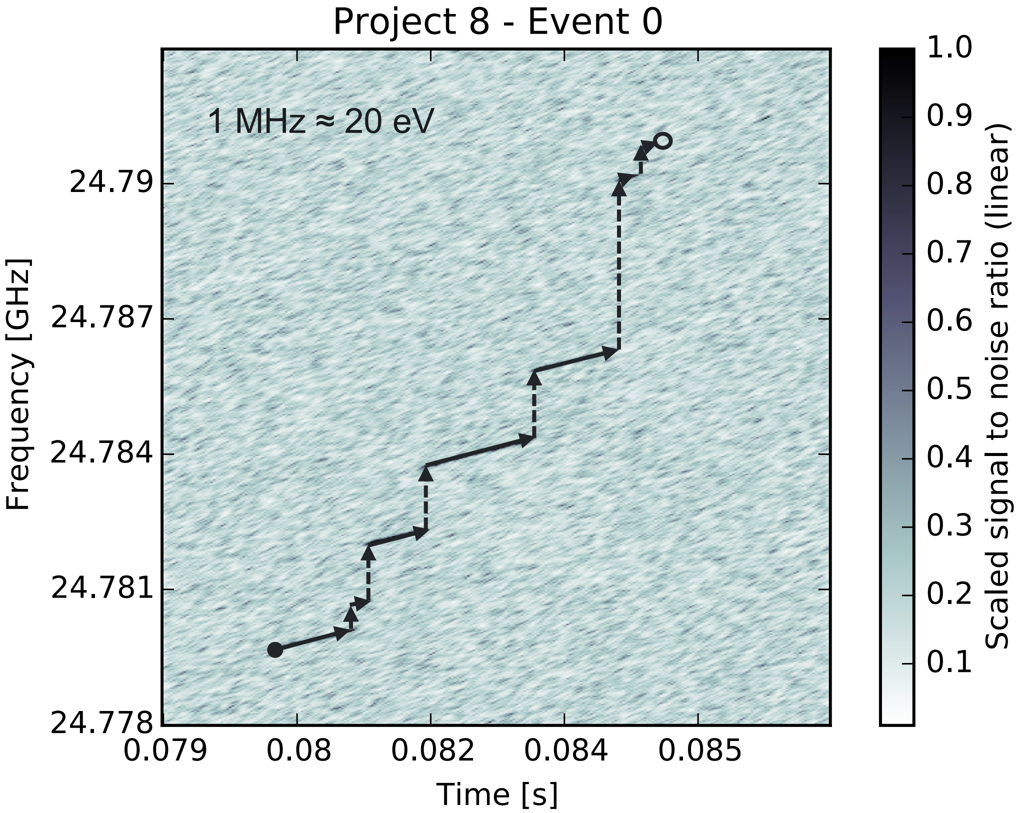
First CRES event (from ^{83m}Kr)

start frequency of the first track gives kinetic energy.

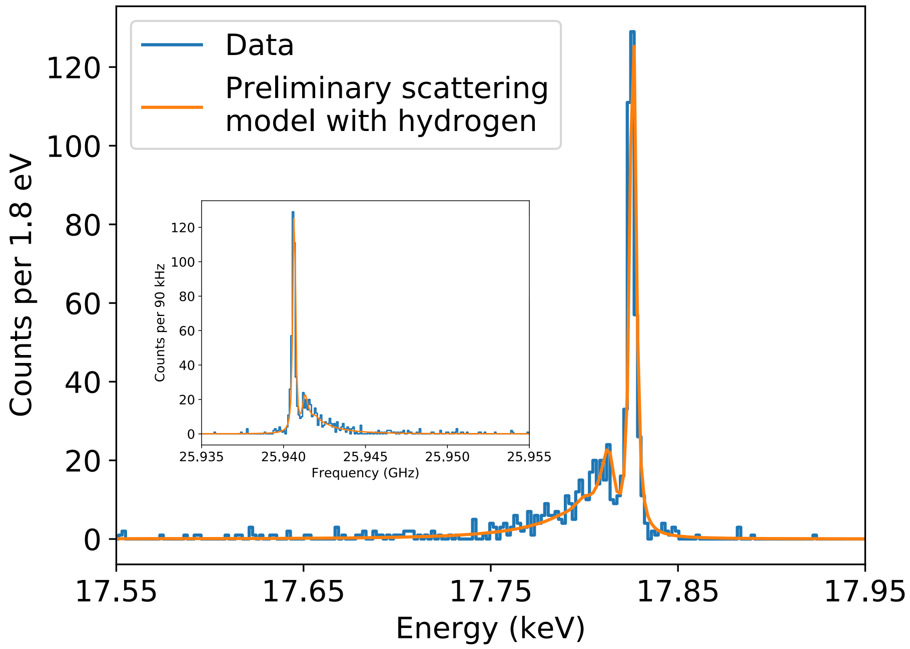
frequency chirps linearly, corresponding to ~1 fW radiative loss.

electron scatters inelastically, losing energy and changing pitch angle.

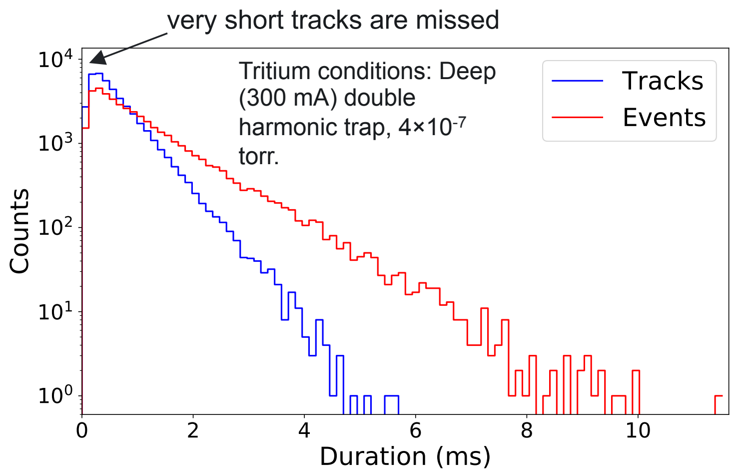
Eventually, scatters to an untrapped angle



High resolution ^{83m}Kr data (shallow trap)

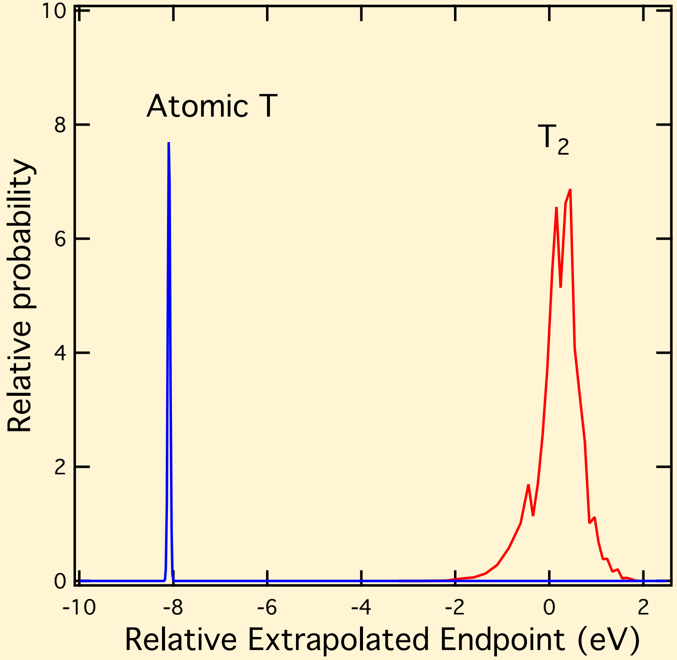


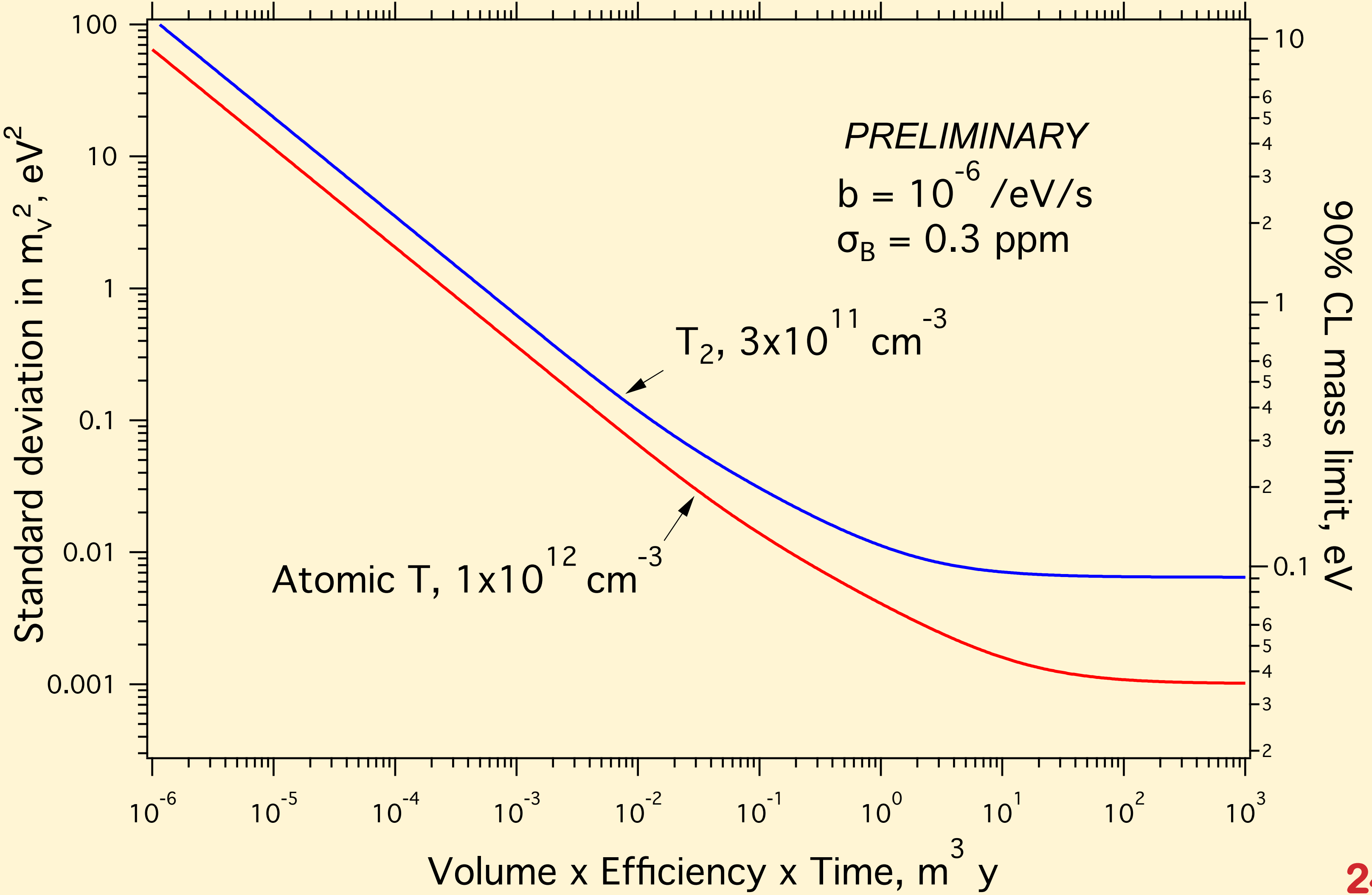
- Data in a shallow trap demonstrates 4 eV FWHM, including 2.83 eV natural width of ^{83m}Kr 17.8 keV K conversion electron.
- Main line shape consistent with a Voigt profile
- Shakeup and shakeoff in Kr, and scattering before detection, leads to high-*f* (low-*E*) tail.



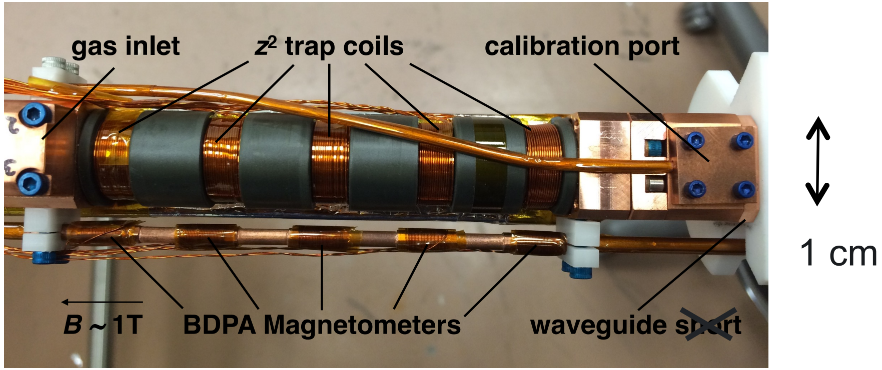
WHY IS THIS IMPORTANT?

- Source is transparent to microwaves: can make it as big as necessary.
- Whole spectrum is recorded at once, not point-by-point.
- Excellent resolution should be obtainable.
- Low backgrounds are expected.
- An atomic source of T (rather than molecular T_2) may be possible. Eliminates the molecular broadening.

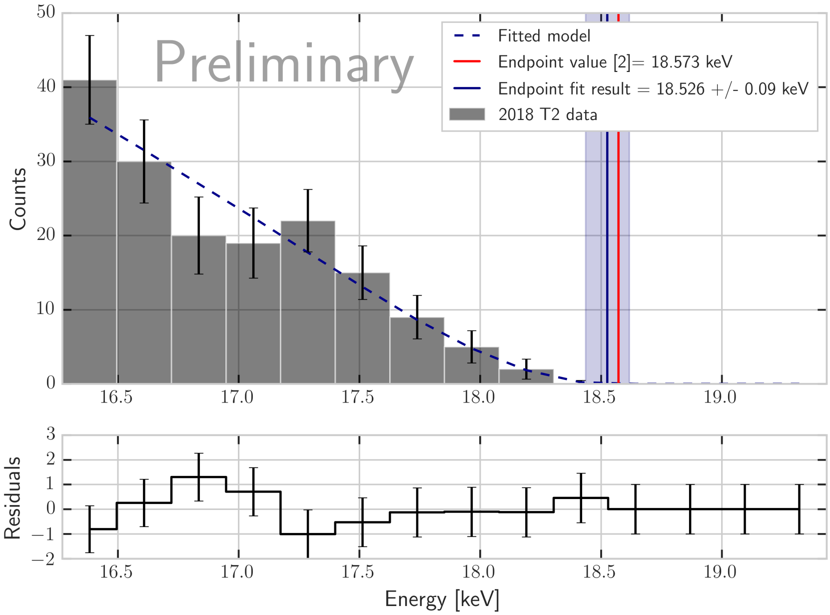



PRELIMINARY
b = 10^-6 /eV/s
σB = 0.3 ppm
T2, 3x10^11 cm^-3
Atomic T, 1x10^12 cm^-3
Standard deviation in mν², eV²
90% CL mass limit, eV
Volume x Efficiency x Time, m³ y
100
10
1
0.1
0.01
0.001
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3

CRES Molecular T_2 spectrum (deep trap)



- Tritium endpoint spectrum based on 7 days data from Oct 2018
  - Fits well, yielding correct endpoint, and no background above
  - More tritium running now in progress

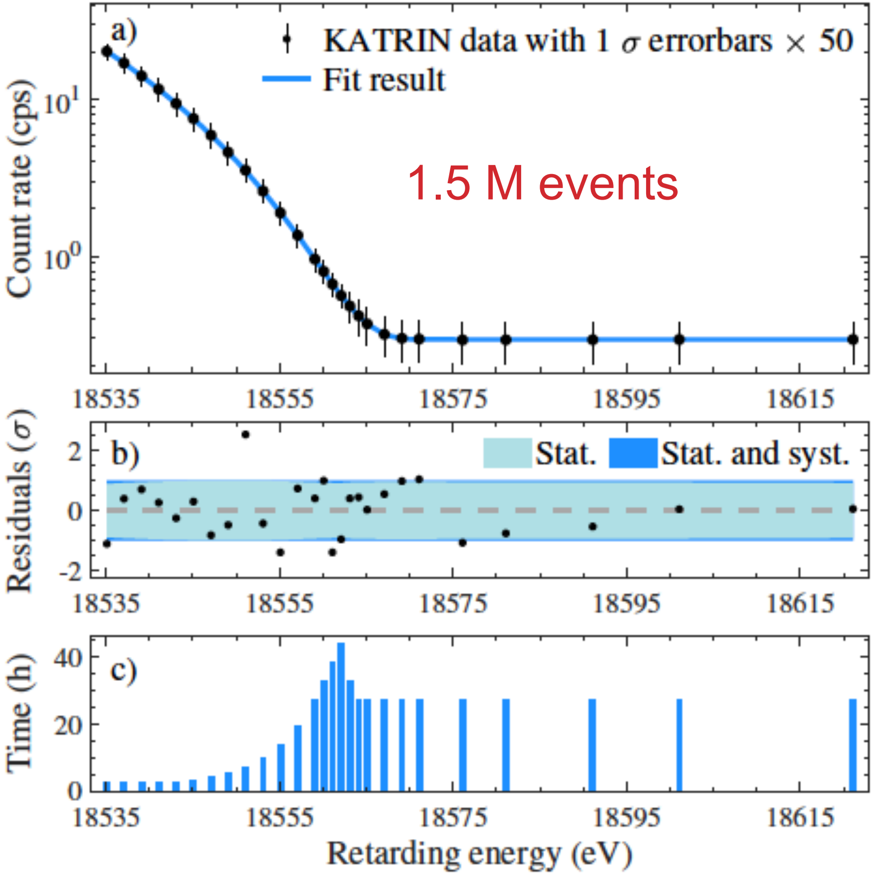


Phase II Instrument improvements:

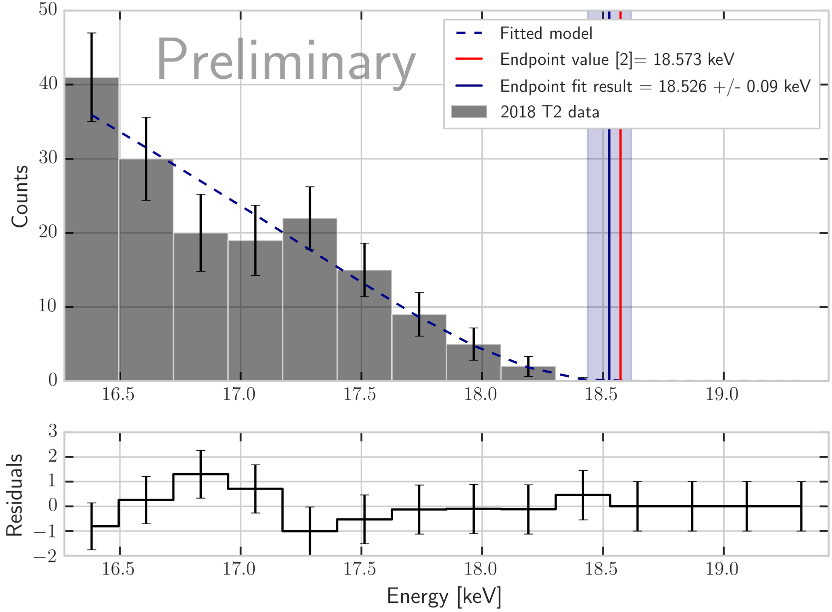
- Cylindrical waveguide (more volume)
- 4 deep trap coils (more statistics)
- Amplifiers colder (less noise)
- BUT 35 eV resolution (deep trap)

KATRIN

Project 8



:m



KATRIN spectrometer

Project 8 spectrometer (to scale)

DIRECT MASS MEASUREMENTS…

… **are largely model independent:**

- Majorana or Dirac
- No nuclear matrix element complications
- No complex phases
- No cosmological degrees of freedom

KATRIN is running! New mass limit 1.1 eV (90% CL)

Success of Project 8 proof-of-concept.

- New spectroscopy based on frequency
- Potential atomic T source: eliminate molecular broadening. Design and testing underway.

Wick and I have collaborated!

PHYSICAL REVIEW C VOLUME 59, NUMBER 1 JANUARY 1999

Solar neutrino interactions with ^{18}O in the SuperKamiokande water Cerenkov detector

W. C. Haxton[1,3] and R. G. H. Robertson[2,3]
[1]*Institute for Nuclear Theory, Box 351550, University of Washington, Seattle, Washington 98195*
[2]*Nuclear Physics Laboratory, Box 354290, University of Washington, Seattle, Washington 98195*
[3]*Department of Physics, Box 351560, University of Washington, Seattle, Washington 98195*

(Received 26 June 1998)

Wick and I have collaborated!

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(Received 26 June 1998)

143. W.C. Haxton. Solar neutrino interactions with ^{18}O in the SuperKamiodande water Cerenkov detector. *Phys. Rev. C* **59**, 515 (1999).

Happy Birthday, Wick!

KATRIN neutrino mass campaign #1

- **4-week long measuring campaign in spring 2019 with high-purity tritium**

  - April 10 – May, 13 2019 780 h
  - high-purity tritium (ε_T = 97.5 %) laser-Raman
  - high source activity: $2.45 \cdot 10^{10}$ Bq
  - high-quality data collected
  - full analysis chain using two independent methods
  - target: **first neutrino mass result at TAUP 2019**

T. Lasserre
First
KATRIN
Tritium Data

Neutrino # 19

M. Slezak
Analysis strategies
& treatment of
systematic effects
in KATRIN

Neutrino # 19

KATRIN

First tritium data!

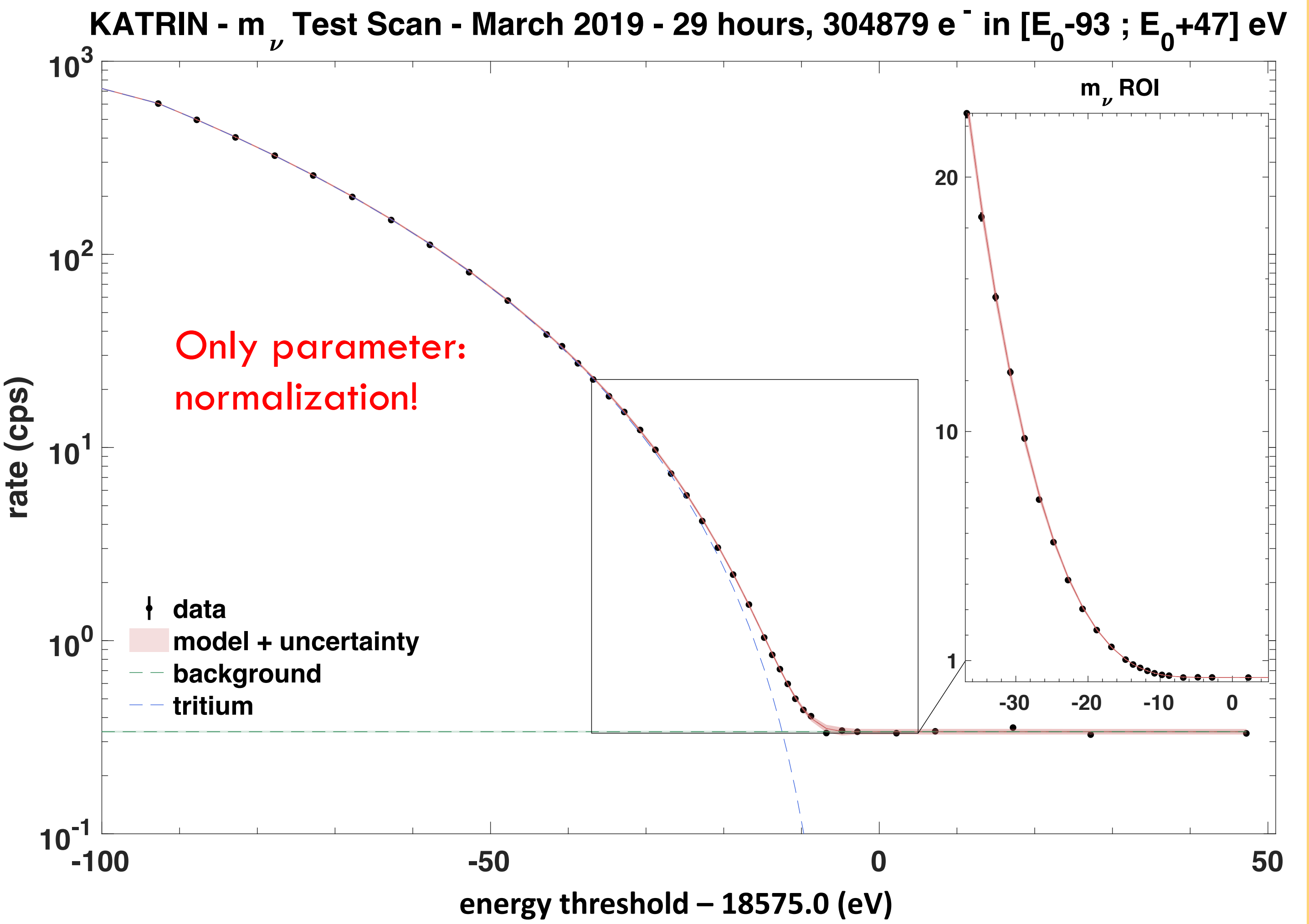
Column density:

$2 \times 10^{17}\ T_2\ cm^{-2}$

Resolution:

~2.8 eV base width

Expecting to report on neutrino mass in September 2019.



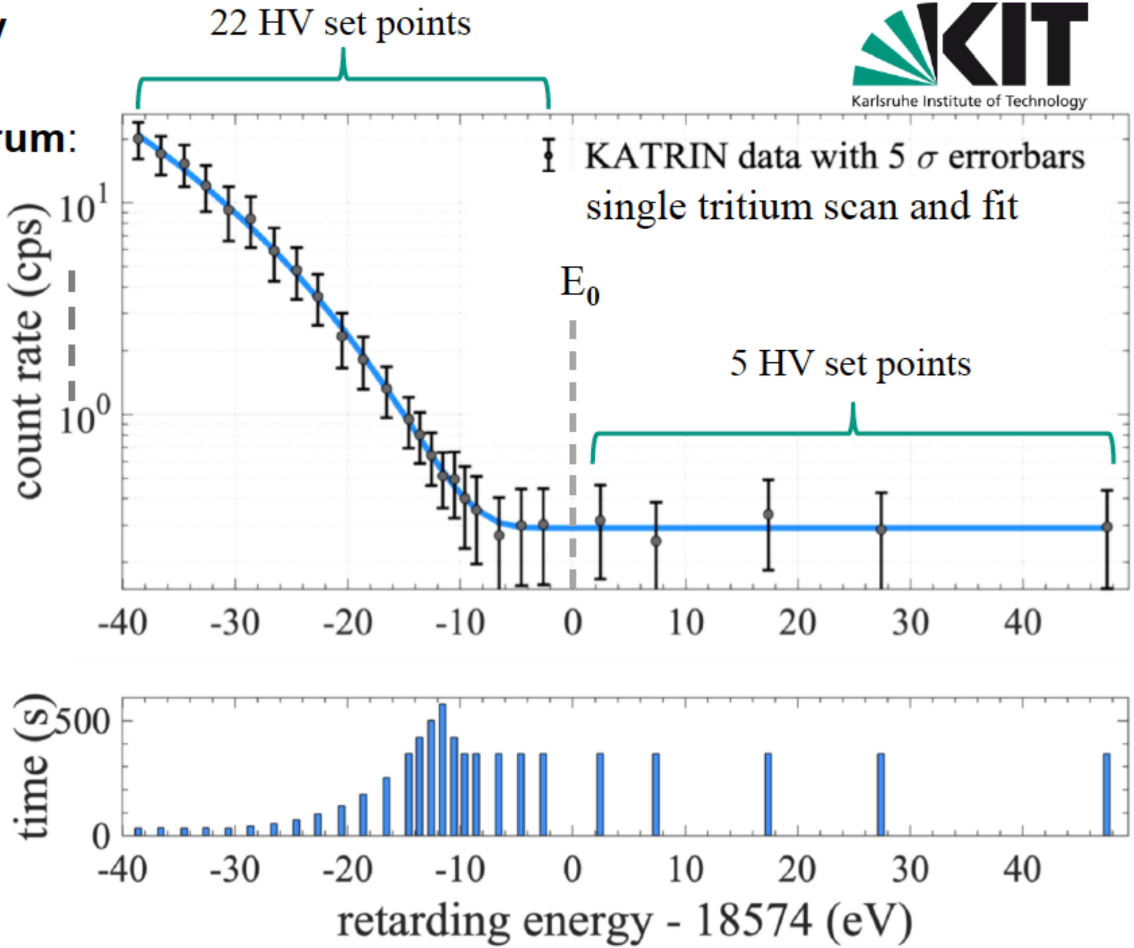
H. Robertson 7/19

tritium scanning – strategy

- **274 scans of tritium ß-decay sepctrum**:
  - alternating up- / down- scans
  - 2 h net scanning time
  - analysis: 27 HV set points
  - [E_0 – 40 eV , E_0 + 50 eV]

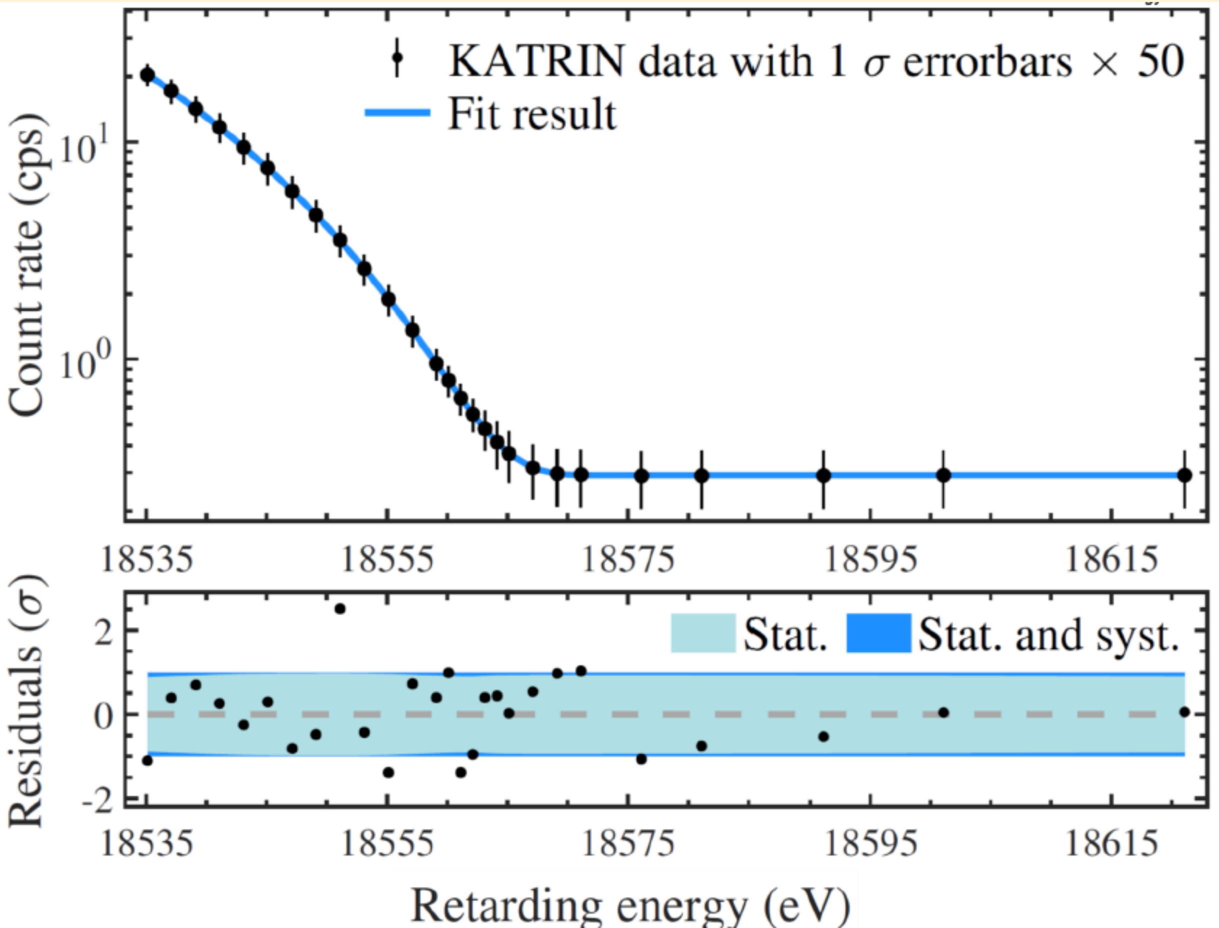
FSD   bg-slope

- **MTD maximises ν-mass sensitivity**
  - focus on region close to E_0



Integral tritium spectrum from KATRIN

- **High-statistics ß-spectrum**
  - 2 million events in in 90-eV-wide interval (522 h of scanning)
  - excellent goodness-of-fit $\chi^2 = 21.4$ for 23 d.o.f. (p-value = 0.56)
- **bias-free analysis**
  - blinding of FSD
  - full analysis chain first on MC data sets
  - final step: unblinded FSD for experimental data

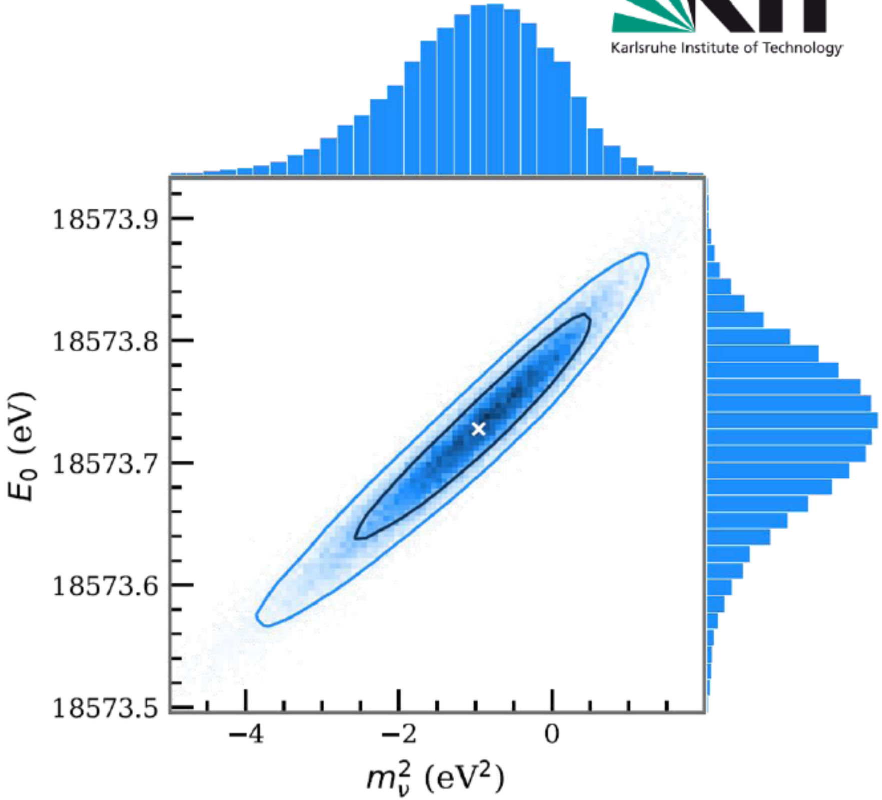


analysis chain & ν-mass result

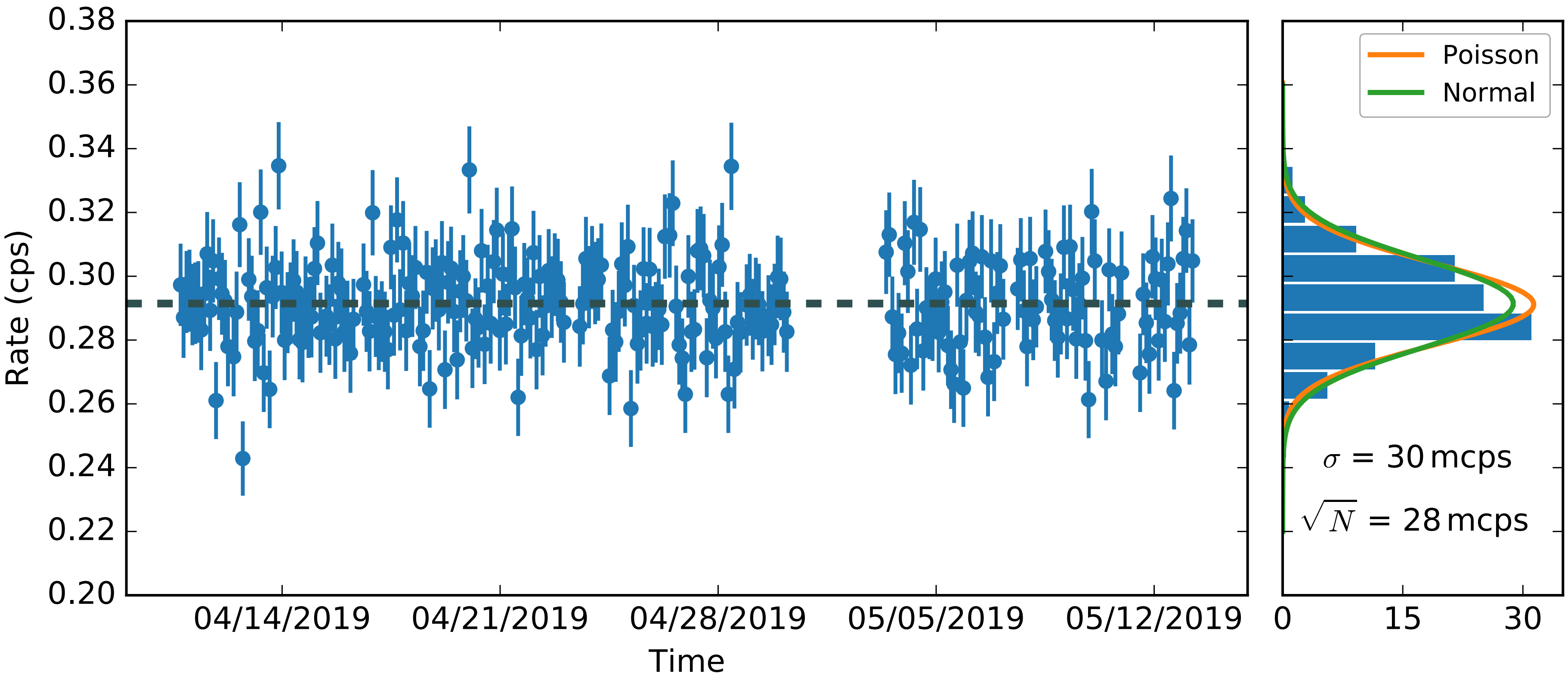
- **two independent analysis methods**
  to propagate uncertainties & infer parameters
  - Covariance matrix:
    covariance matrix + χ^2-estimator
  - MC propagation:
    10^5 MC samples + likelihood ($-2 \ln \mathcal{L}$)
  - both methods agree to a few percent

- **ν-mass and E_0: best fit results**

$$m^2(\nu_e) = \left(-1.0 \begin{array}{l} +0.9 \\ -1.1 \end{array}\right) \mathrm{eV}^2 \ (90\% \ \mathrm{CL})$$



$E_0 = (18573.7 \pm 0.1)$ eV ⇨ Q-value : (18575.2 ± 0.5) eV   Q-value [$\Delta M(^3H, ^3He)$]: (18575.72 ± 0.07) eV



0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
Rate (cps)
04/14/2019
04/21/2019
04/28/2019
05/05/2019
05/12/2019
Time
Poisson
Normal
σ = 30 mcps
$\sqrt{N}$ = 28 mcps
0
15
30

■ **KATRIN near- and long-term future** :

- further reduction of background

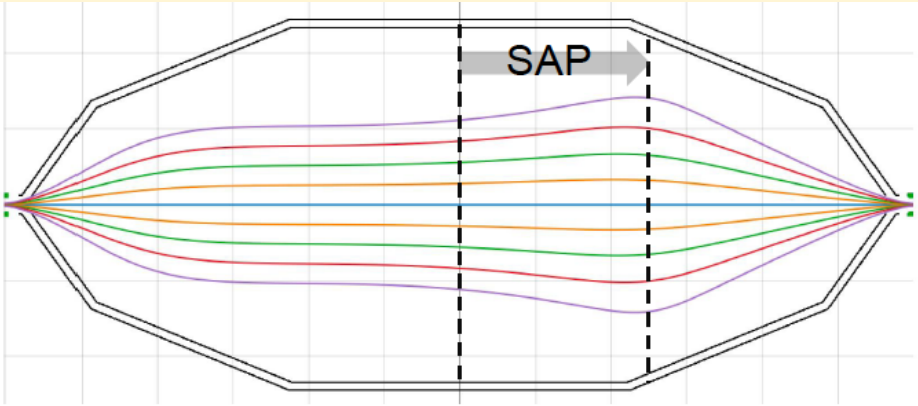
from decays of Radon & Rydberg atoms

⇨ spectrometer bake-out successful ☑

⇨ upgraded aircoil system ☑

„shifted analysis plane“ (SAP)

bg-studies & tritium scans soon



- further reduction of systematics

energy loss via egun in ToF modus, …

R&D works on ToF-technique for differential tritium scanning

- 1000 days of measurements at

nominal ρd ($5 \cdot 10^{17}$ molecules cm^{-2})

3 tritium campaigns (65 days each)

per calendar year

sensitivity $m(\nu_e)$ = 0.2 eV (90% CL)

0.35 eV (5σ)

CYCLOTRON RADIATION EMISSION SPECTROSCOPY (CRES)

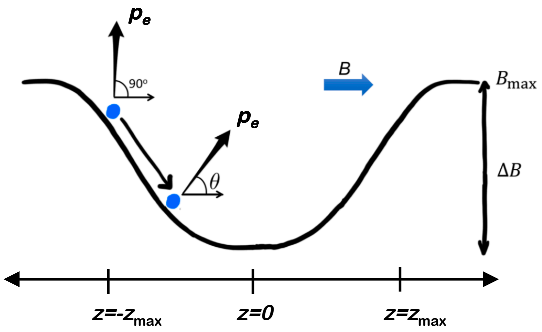
Real experiments must confine electrons in a magnetic trap for sufficient observation time:

- *B* is the average field sampled by the electron in an observation time window.
- Introduces pitch angle (θ) dependence.
- E.g., harmonic traps ($B \sim z^2$) have an analytical solution for instantaneous frequency:

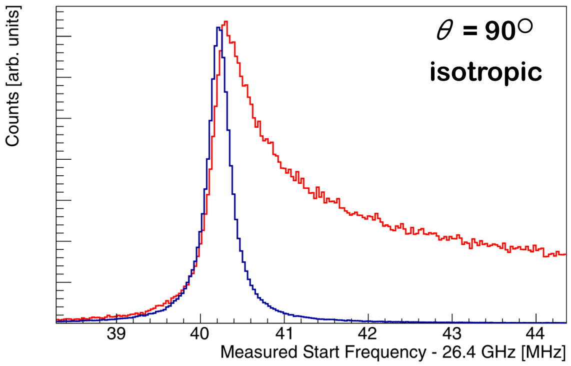
$$\omega(t) \approx \Omega_c \left(\left(1 + \frac{\cos^2\theta}{2\sin^2\theta} \right) + \frac{Pt}{\gamma_0 m_e c^2} + \frac{z_{max}\Omega_a}{v_p} \cos(\Omega_a t) \right)$$

- 1st term is “naïve” cyclotron frequency plus a correction due to slightly different field variations sampled by electrons w/ different starting angles θ.
- 2nd term is a *chirp* due to energy lost to cyclotron radiation power *P*
- 3rd term is a *warble* due to reflections at the end of the trap – leads to doppler sidebands in frequency spectra.

•CRES phenomenology in a waveguide environment is detailed in Ashtari Esfahani et al., Phys. Rev. C 99 (2019)



4 mT harmonic trap response



Project 8

Oct 8-13, 2018

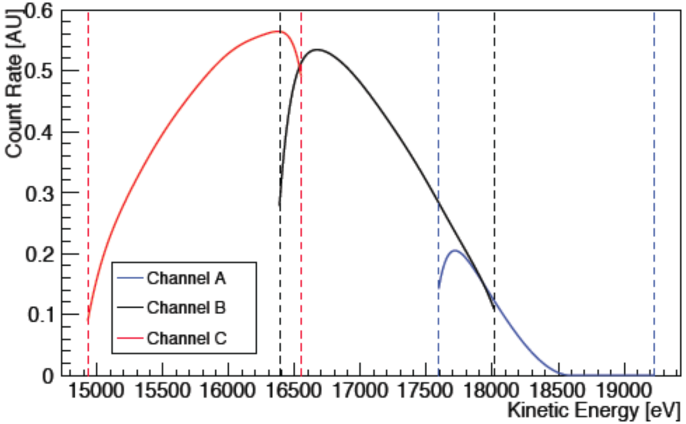
417 events

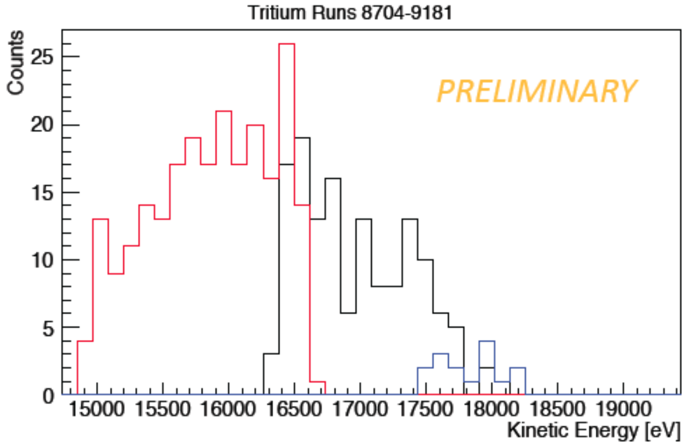
~50 eV FWHM

Bkg: 0.0 c/s

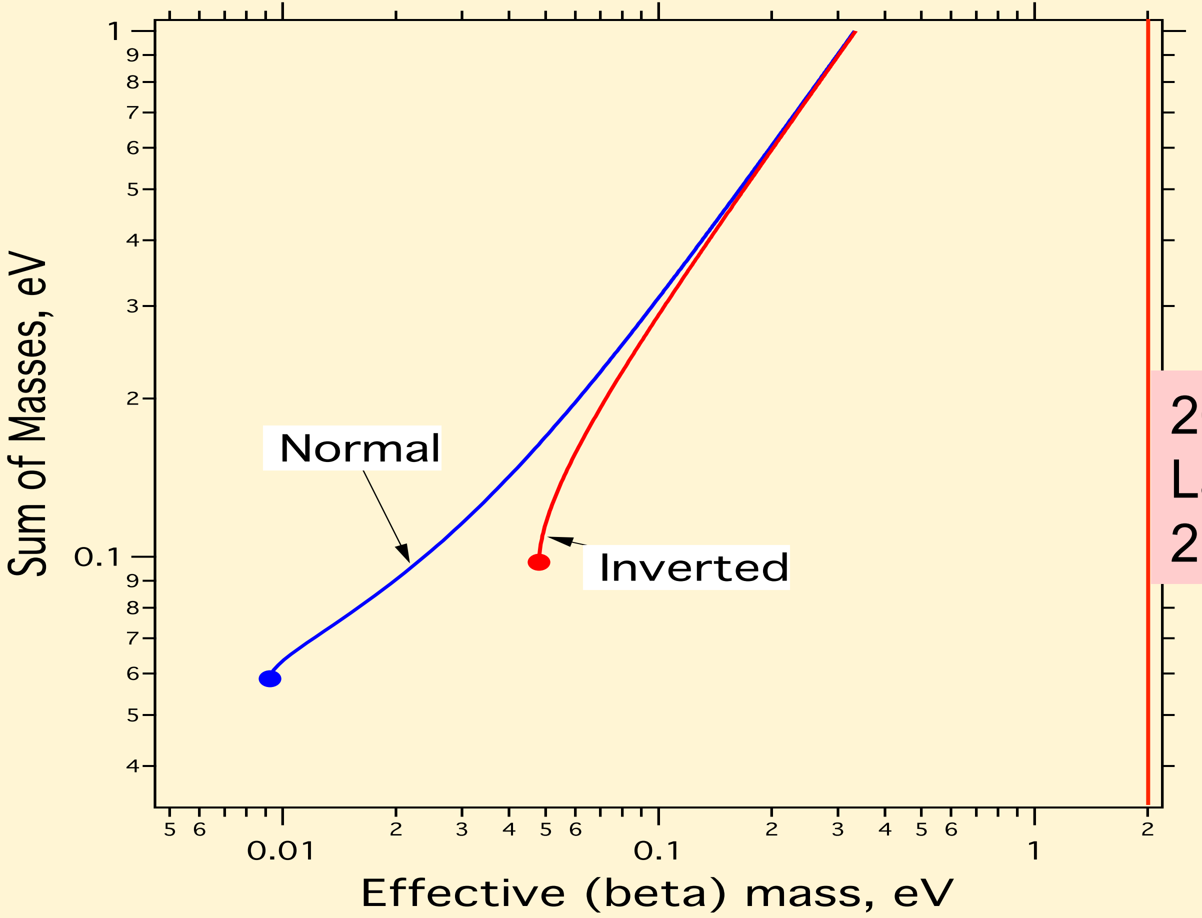
Tritium – Spectrum (Walter's talk at DNP)

> 417 tritium events reconstructed from data
> Agreement with predicted spectral shape
> No background events beyond endpoint

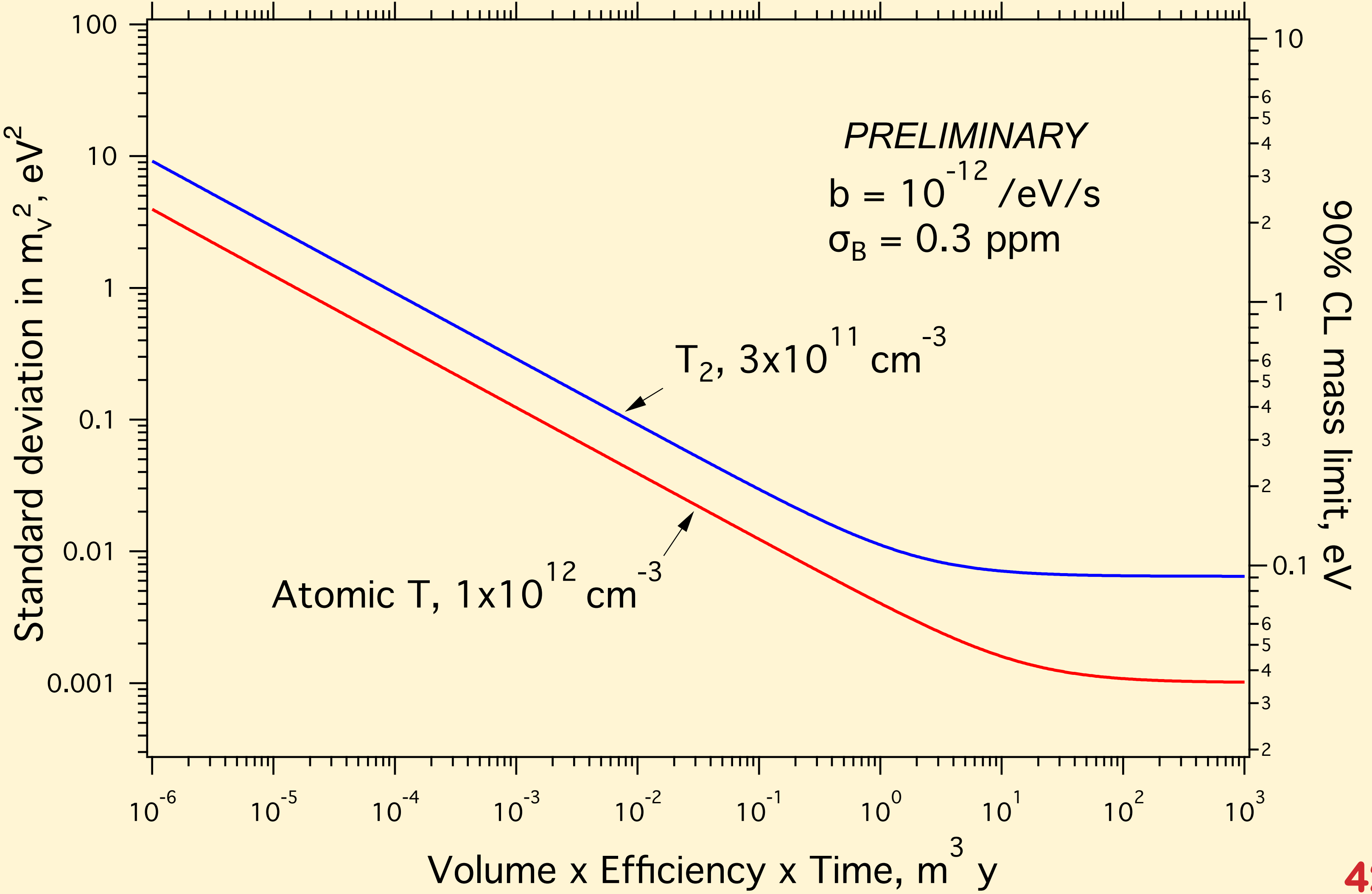




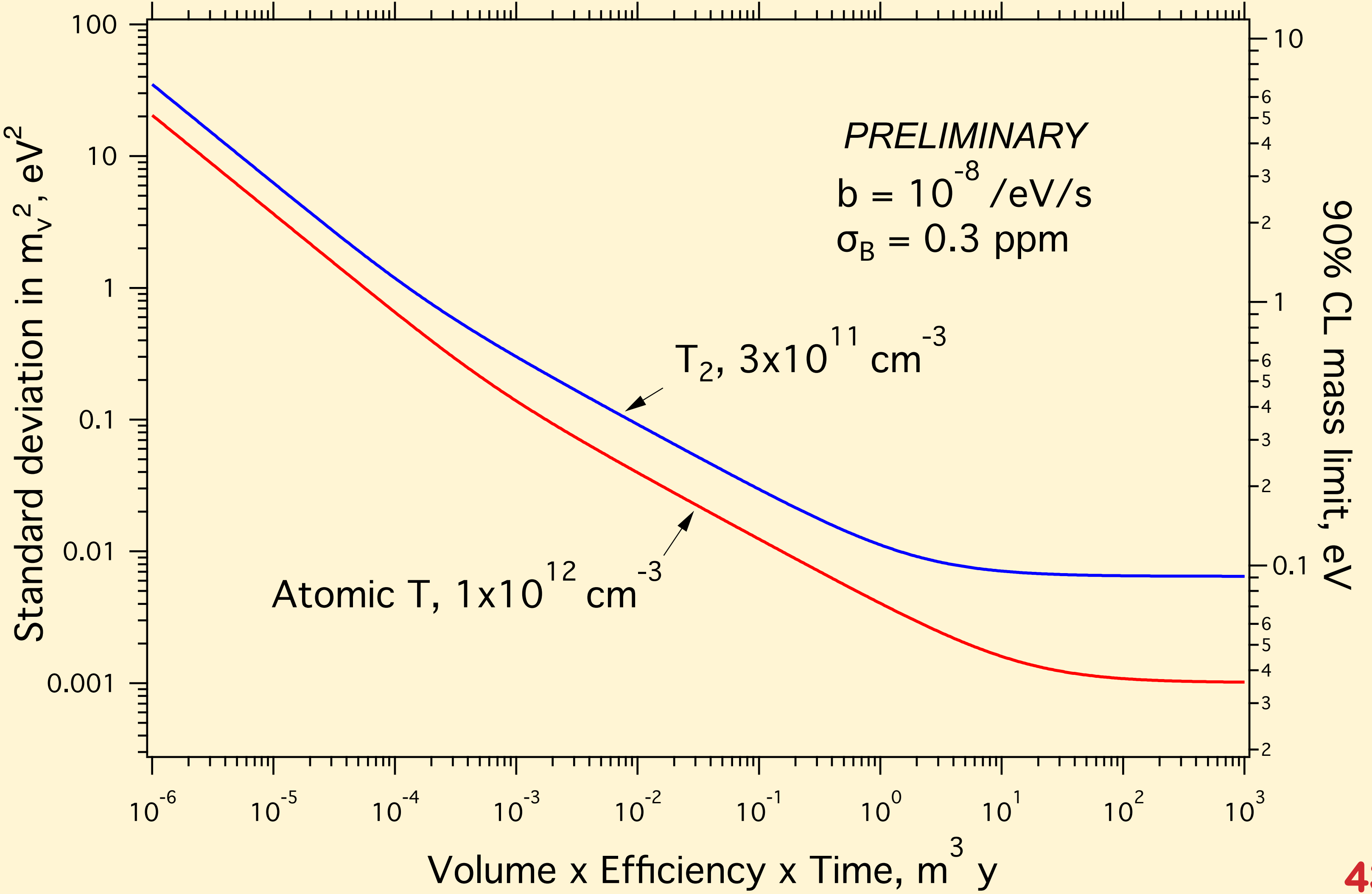
MASS RANGE ACCESSIBLE



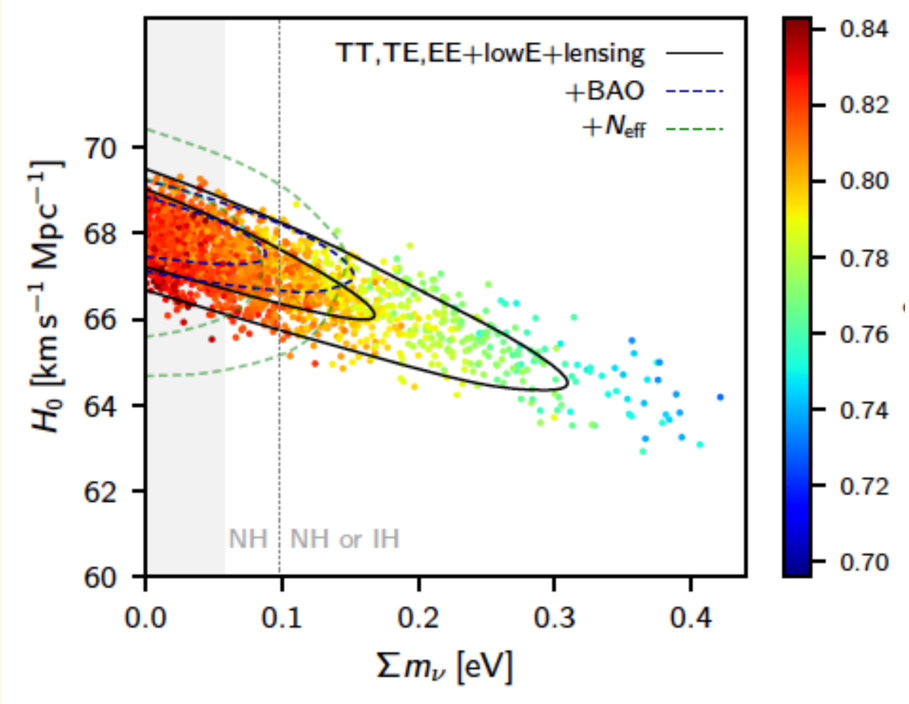
2018
Lab Limit
2 eV

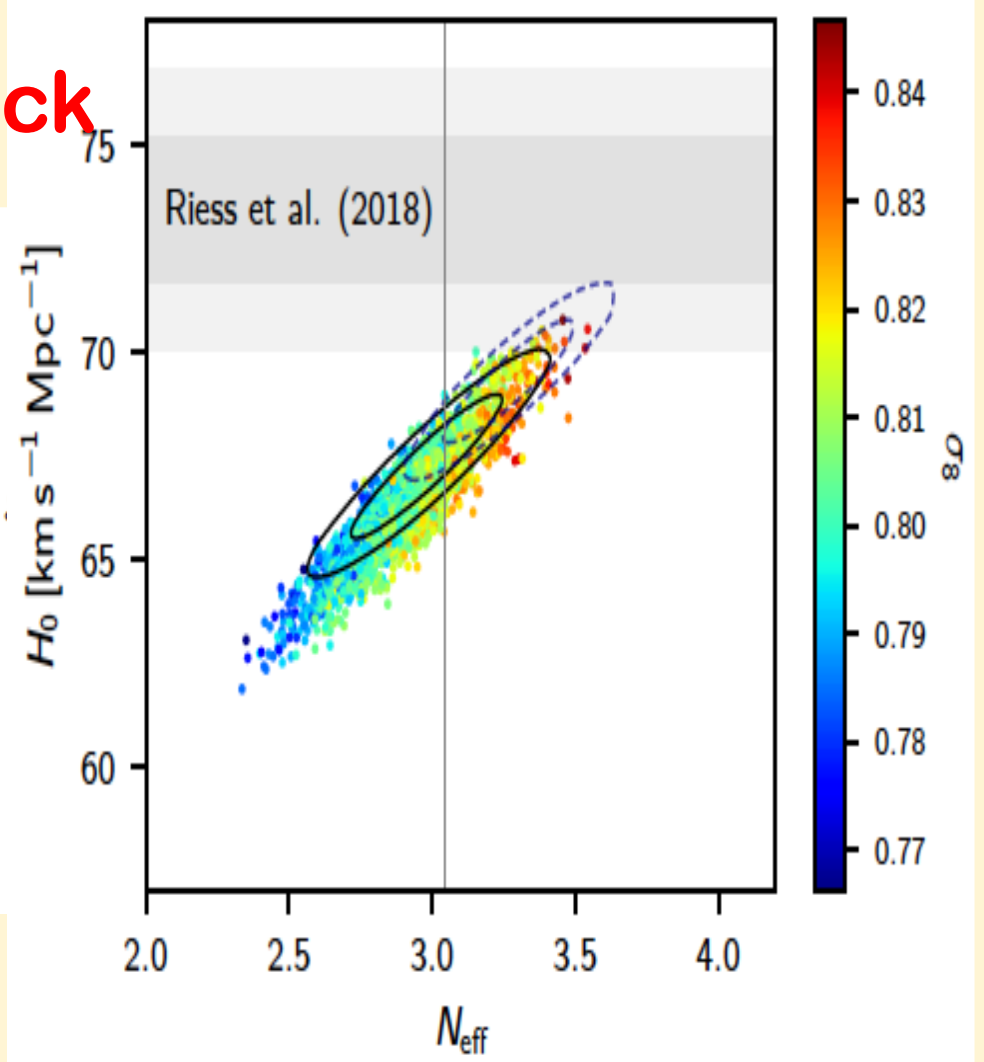


PRELIMINARY
b = 10^-12 /eV/s
σB = 0.3 ppm
T2, 3x10^11 cm^-3
Atomic T, 1x10^12 cm^-3
Standard deviation in mν^2, eV^2
90% CL mass limit, eV
Volume x Efficiency x Time, m^3 y
100
10
1
0.1
0.01
0.001
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3


PRELIMINARY
b = 10^-8 /eV/s
σB = 0.3 ppm
T2, 3x10^11 cm^-3
Atomic T, 1x10^12 cm^-3
Standard deviation in mν^2, eV^2
90% CL mass limit, eV
Volume x Efficiency x Time, m^3 y
100
10
1
0.1
0.01
0.001
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3

Neutrinos and Planck





Planck 2018: 1806.06209