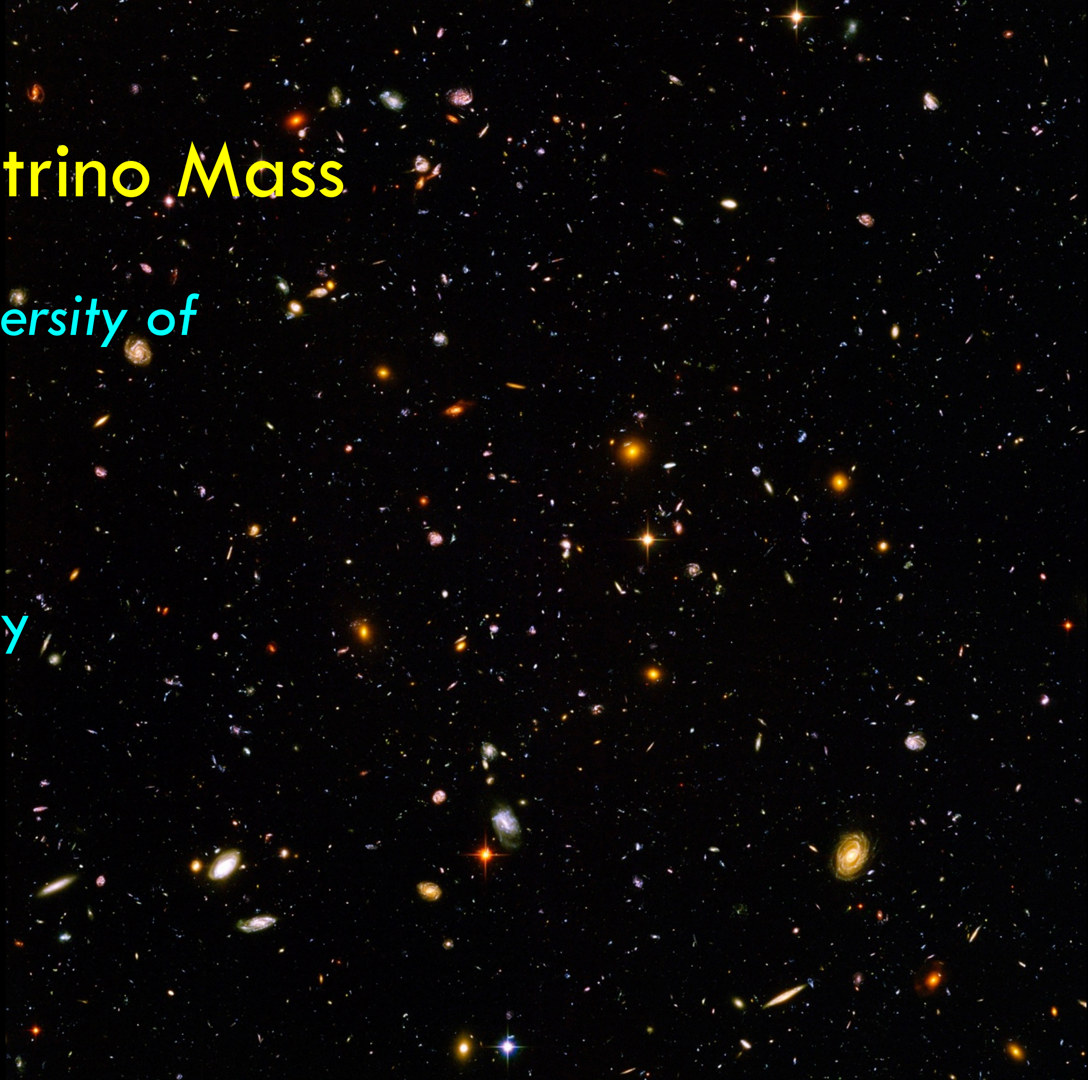
The Direct Road to Neutrino Mass

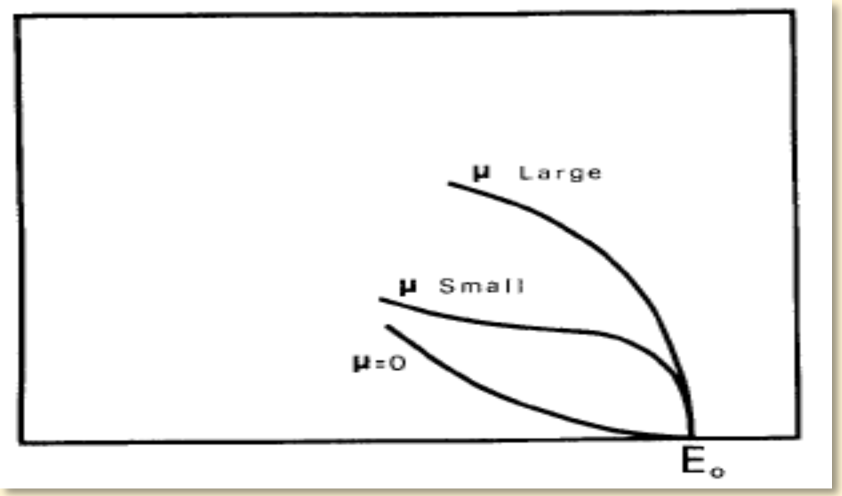


Hamish Robertson, CENPA, University of Washington

Physics Division seminar
Oak Ridge National Laboratory

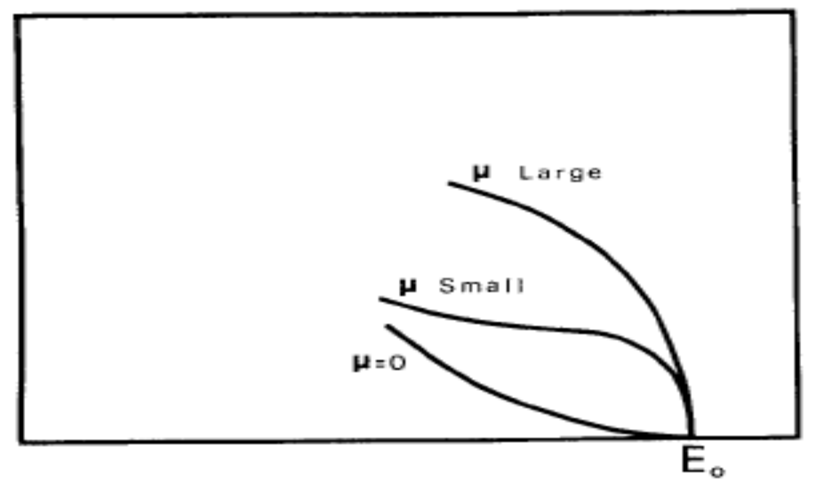
“Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron.”

E. Fermi, 1934



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

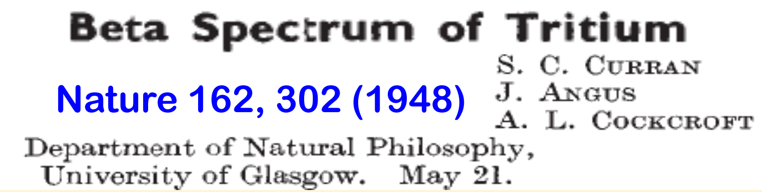
"Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron." *E. Fermi, 1934*



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

This is the "direct" method.

First experiments with gaseous tritium !

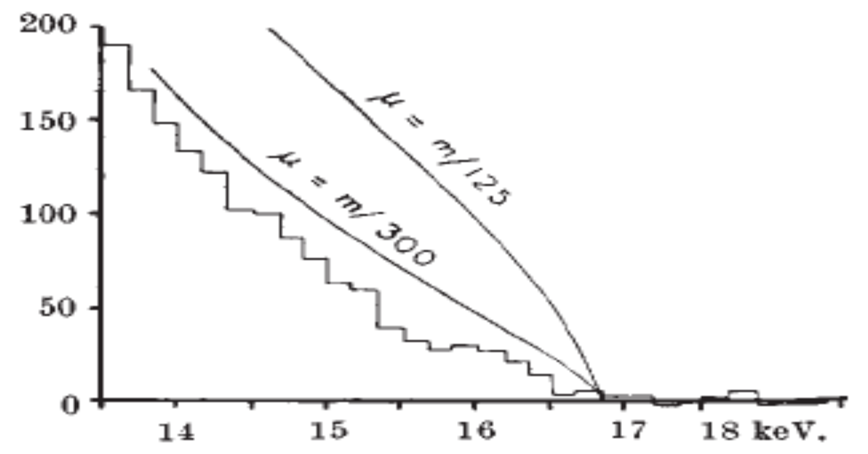


Beta Spectrum of Tritium

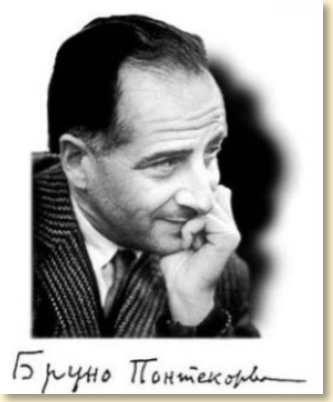
Nature 162, 302 (1948)

S. C. Curran
J. Angus
A. L. Cockcroft

Department of Natural Philosophy,
University of Glasgow. May 21.

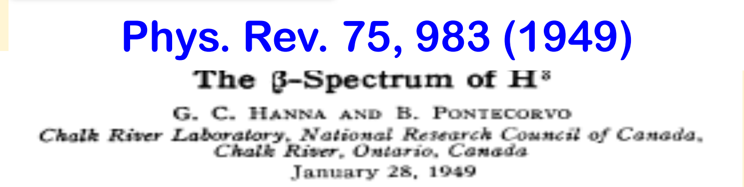


$m_\nu < 1700$ eV



Бруно Понтекорво

$m_\nu < 500$ 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

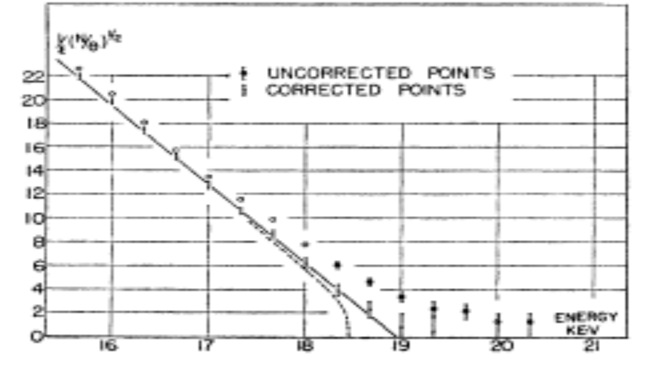
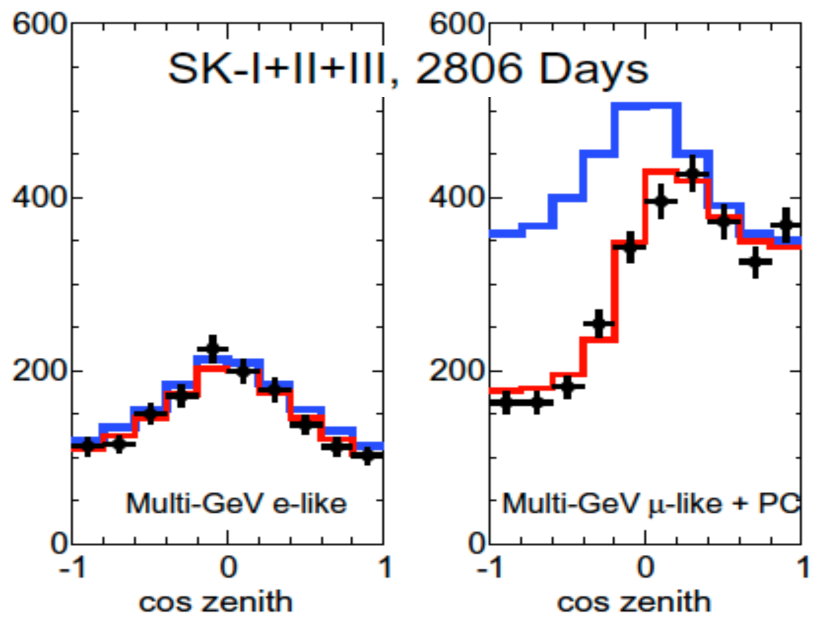
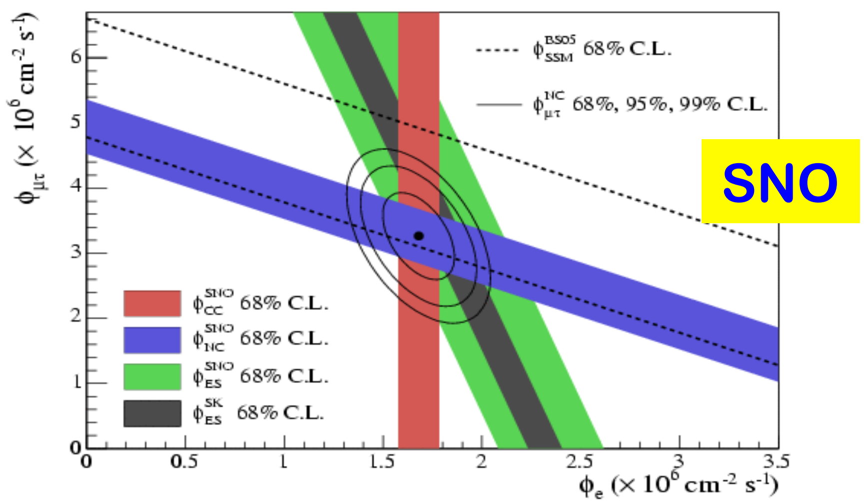


Fig. 2. "Kurie" plot of the end of the H³ spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev—see text) has been included for comparison.

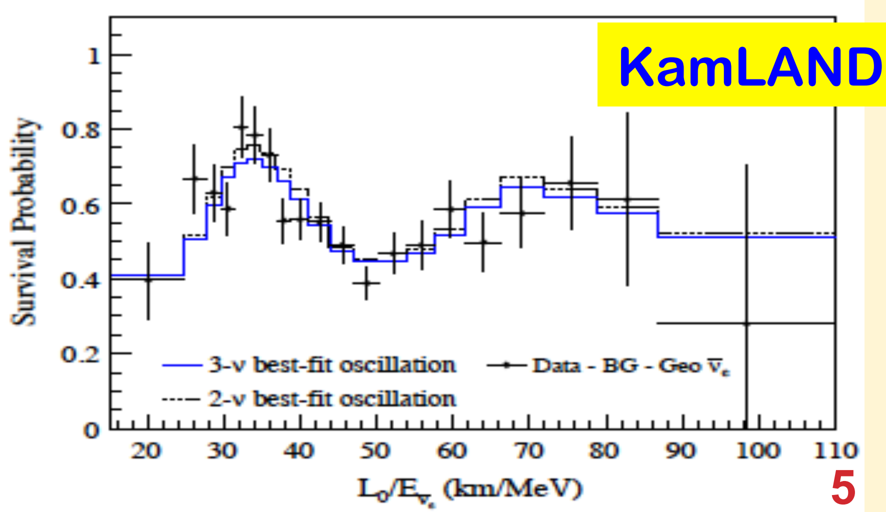
Neutrinos oscillate, have mass



Super-Kamiokande



SNO



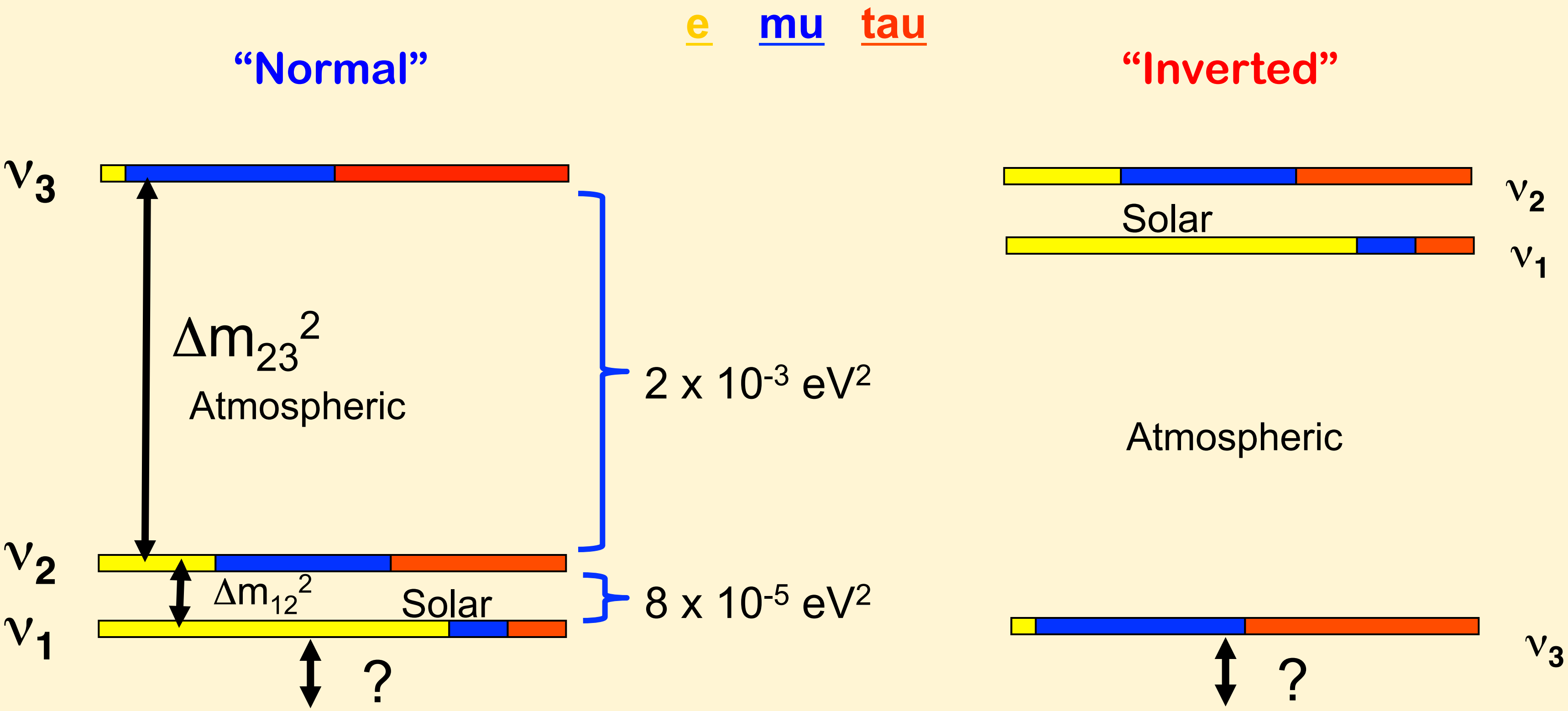
KamLAND

OUTLINE

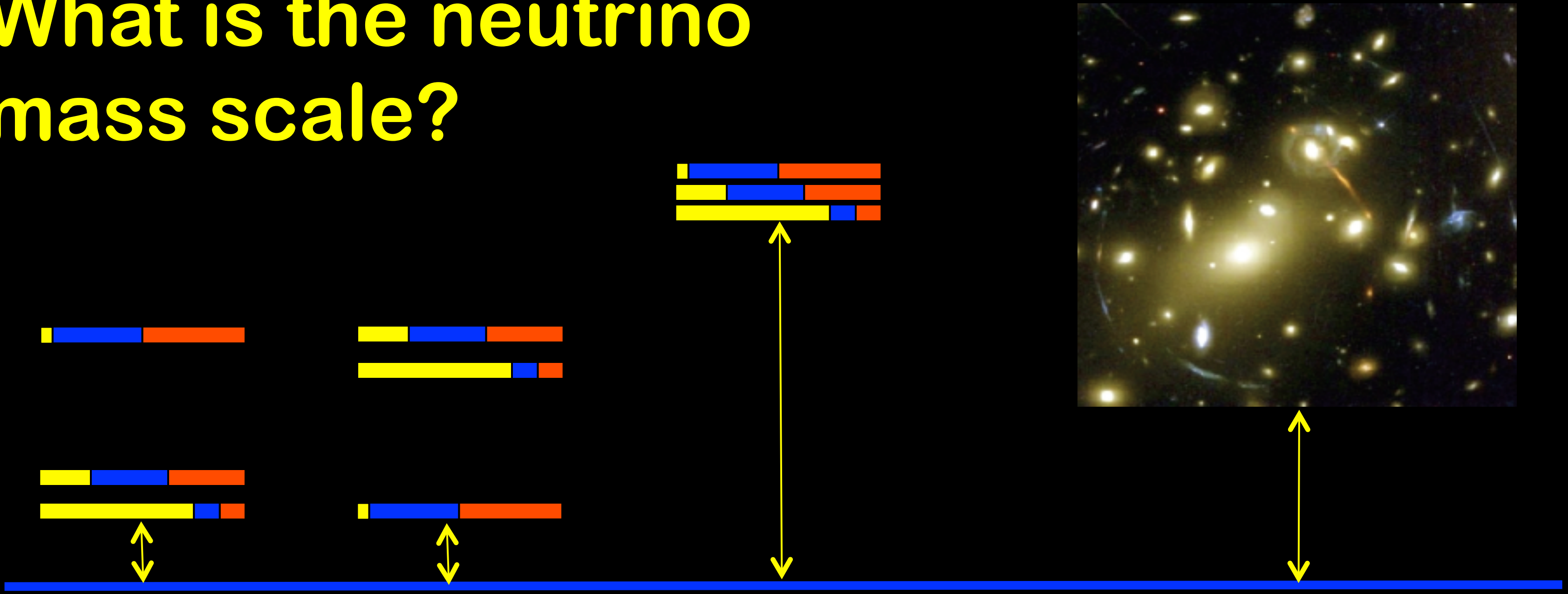
- **The story so far: Neutrinos DO have mass, and the average for the 3 must lie between 2 and 0.02 eV.**
- **The KATRIN experiment.**
- **A new idea: CRES (Cyclotron Radiation Emission Spectroscopy).**
- **Cosmological comments.**

but… nothing on sterile neutrinos, double beta decay, ^{163}Ho.

NEUTRINO MASSES AND FLAVOR CONTENT



What is the neutrino mass scale?

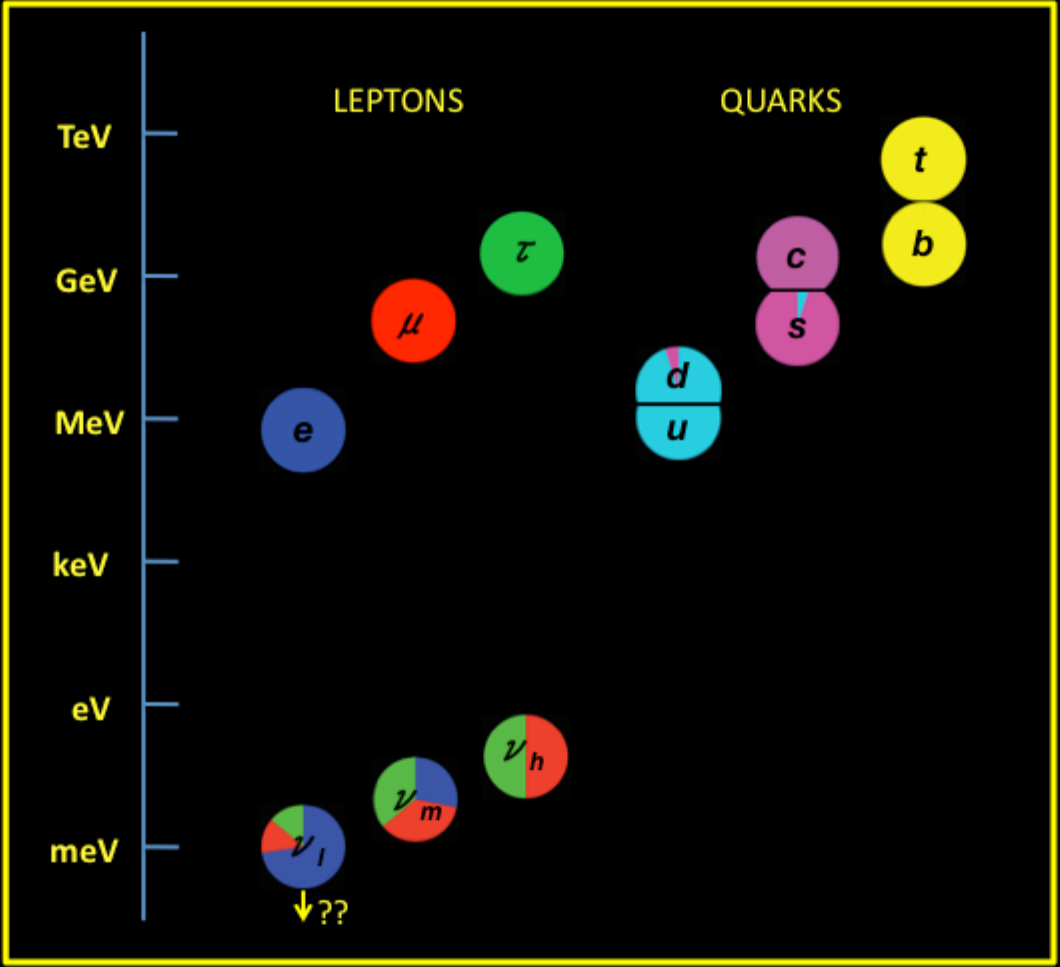


Particle Physics

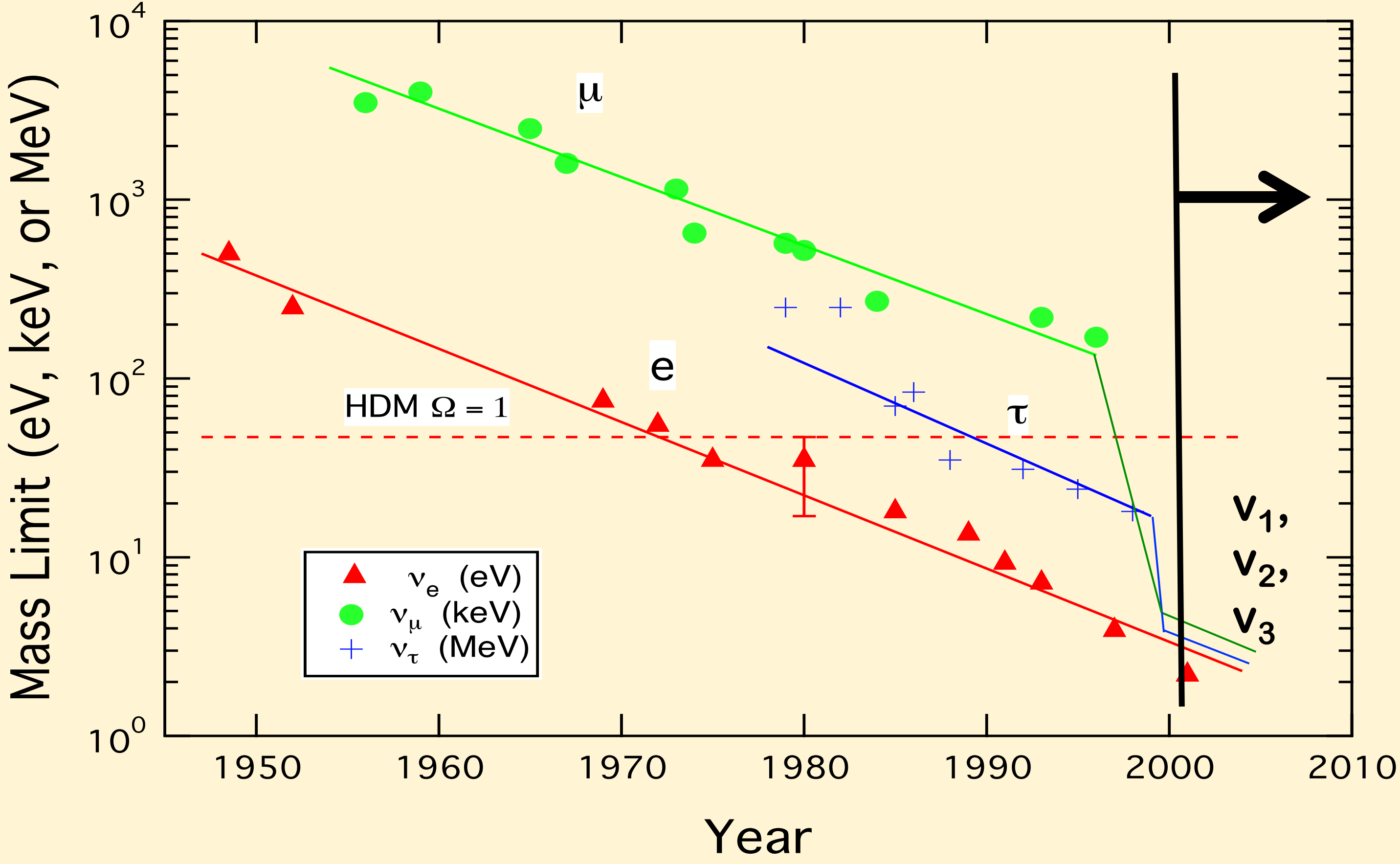
Cosmology

Some things are simply missing from the standard model (dark matter, gravity…) but neutrino mass is the only *contradiction* to the SM.

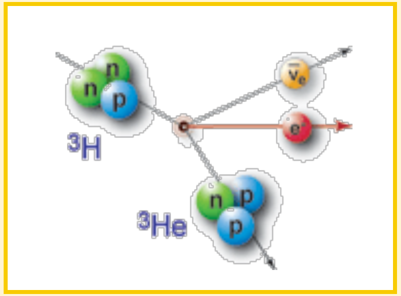
Perhaps neutrinos can help us understand the patterns of mass



Neutrino oscillations discovered – neutrinos have mass!



NEUTRINO MASS FROM BETA SPECTRA



With flavor mixing:

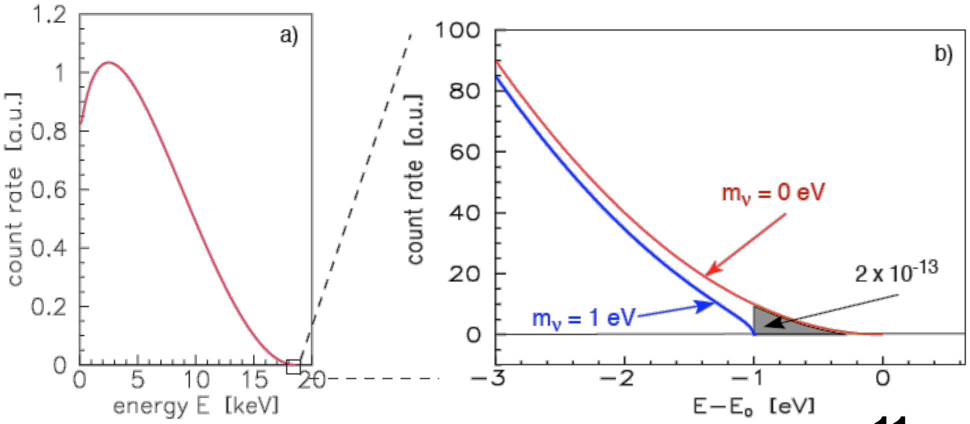
$$\frac{dN}{dE} \approx 3rt(E_0 - E) \sum_{i=1,3} |U_{ei}|^2 [(E_0 - E)^2 - m_i^2]^{1/2} \Theta(E_0 - E - m_i)$$

$$= 3rt(E_0 - E)[(E_0 - E)^2 - m_\beta^2]^{1/2} \Theta(E_0 - E - m_\beta)$$

$$\boxed{m_\beta^2 = m_1^2 + |U_{e2}|^2 \Delta m_{21}^2 + |U_{e3}|^2 \Delta m_{31}^2}$$

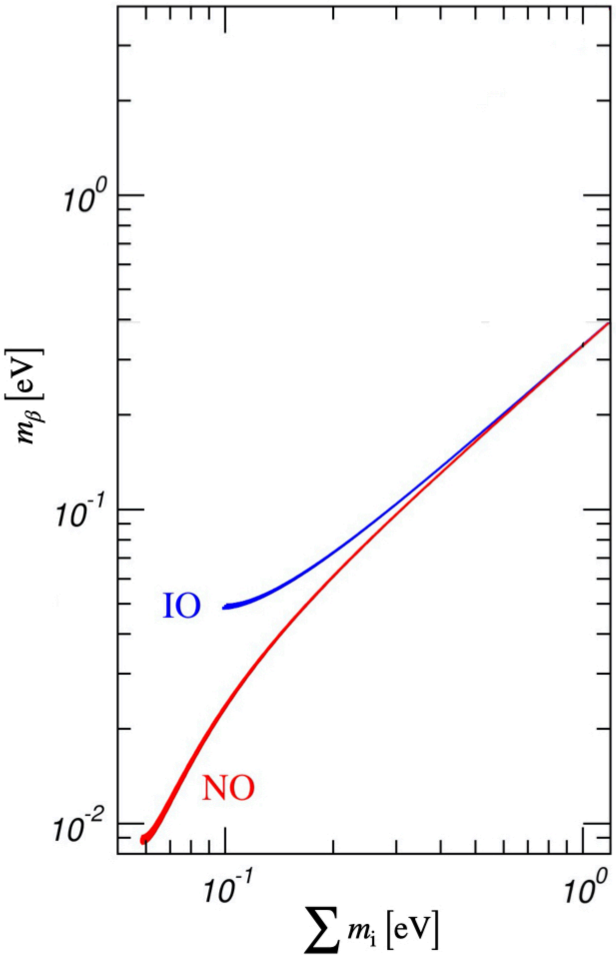
3×10^{-5} eV^2 $\pm 6 \times 10^{-5}$ eV^2

$$\boxed{m_\beta = m_1}$$



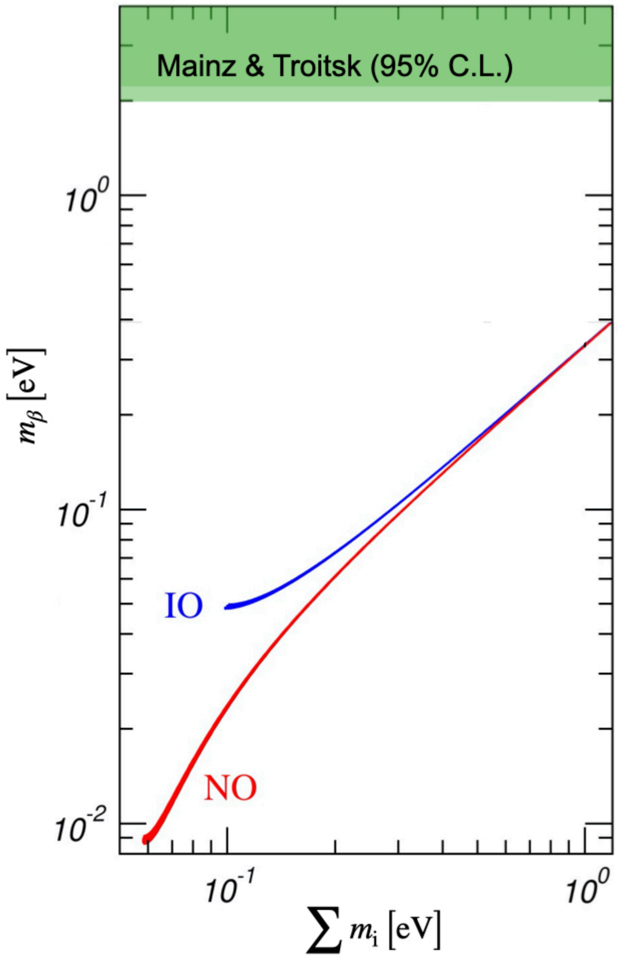
MASS RANGE ACCESSIBLE

3 masses and neutrino oscillation data give two possibilities, Inverted Order and Normal Order:



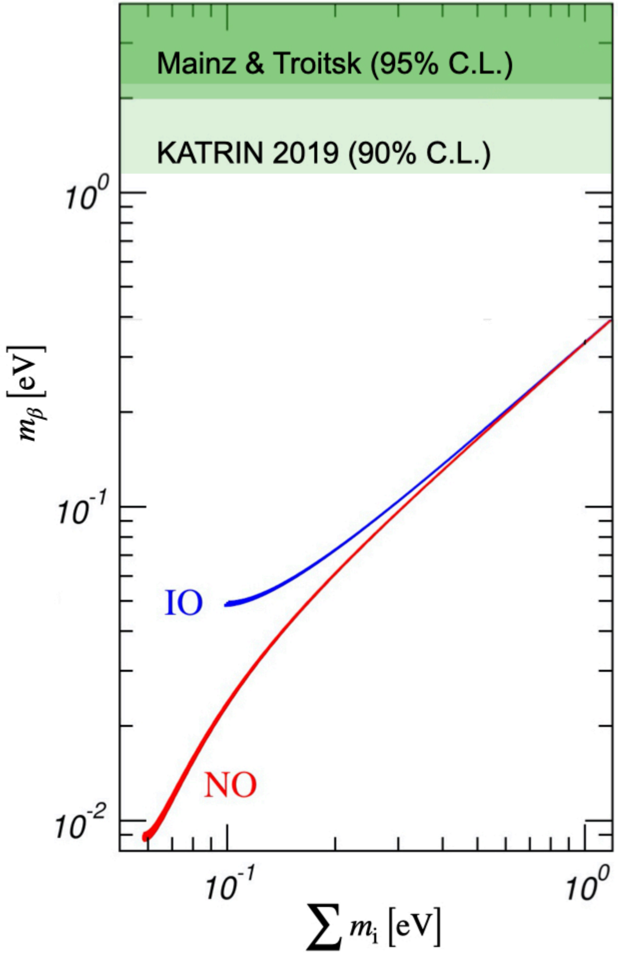
Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

MASS RANGE ACCESSIBLE



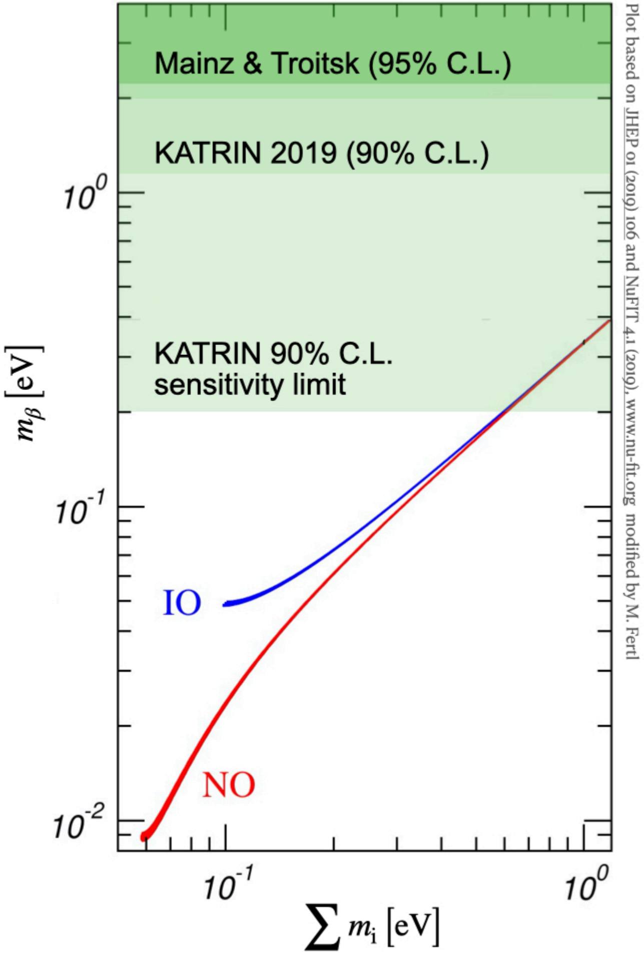
Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

MASS RANGE ACCESSIBLE



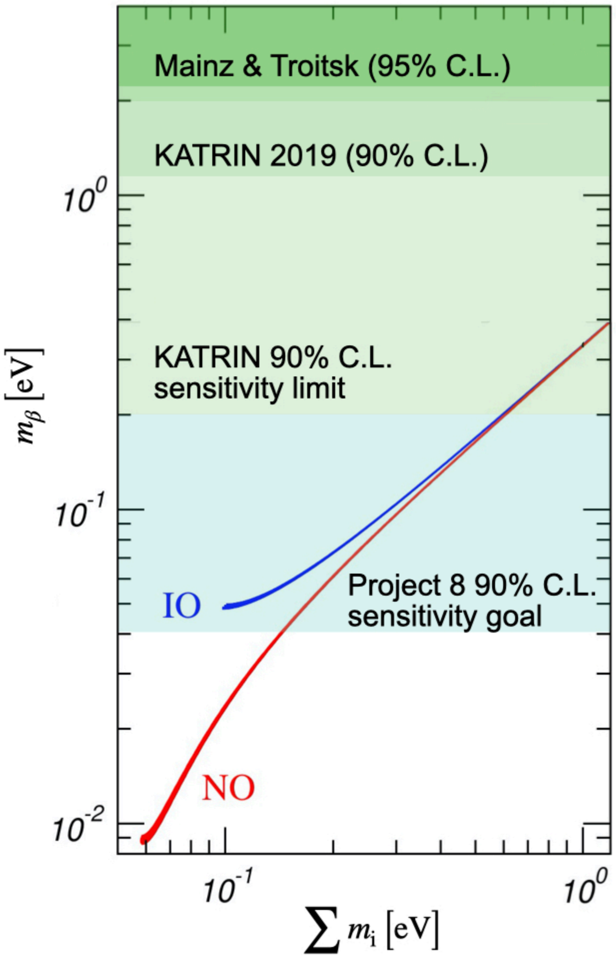
Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

MASS RANGE ACCESSIBLE



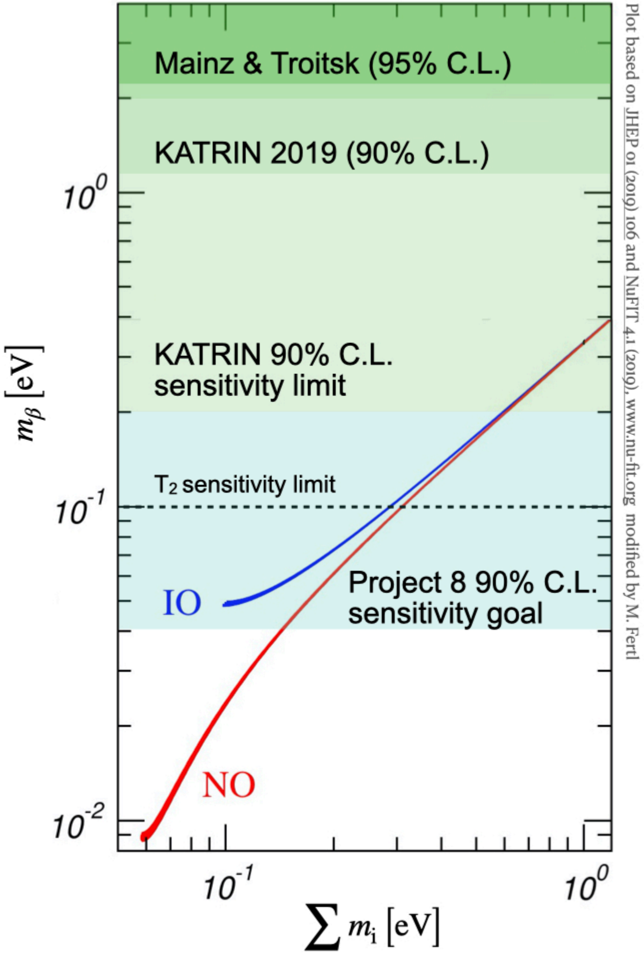
Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

MASS RANGE ACCESSIBLE



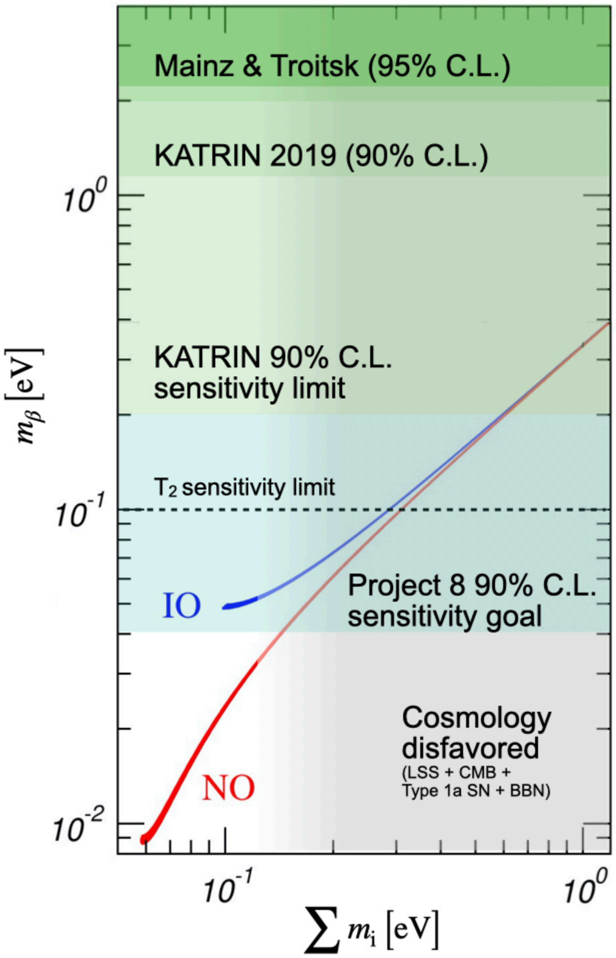
Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

MASS
RANGE
ACCESSIBLE



Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

MASS RANGE ACCESSIBLE

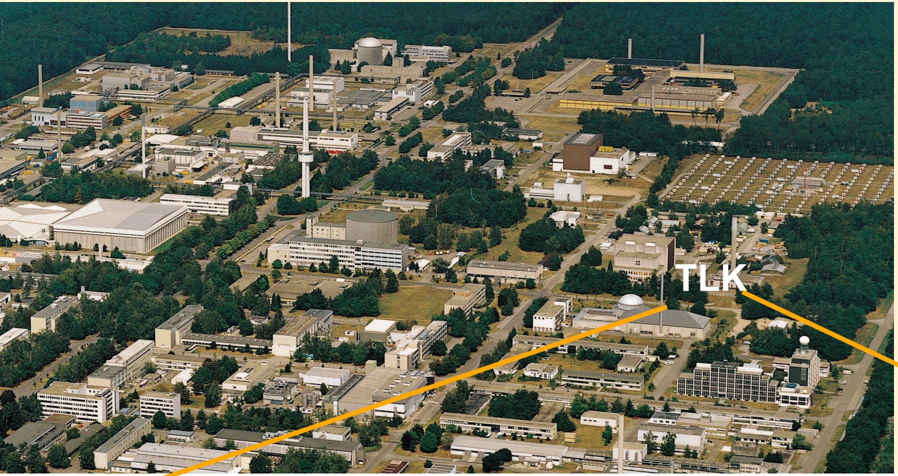


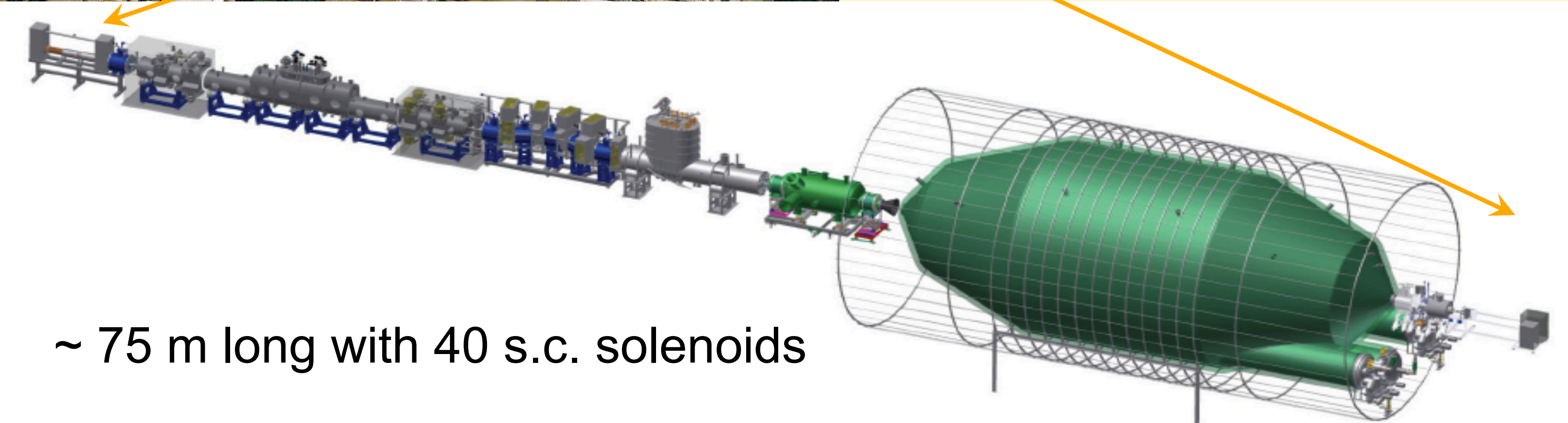
Plot based on JHEP 01 (2019) 106 and NuFIT 4.1 (2019), www.nu-fit.org modified by M. Fertl

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.





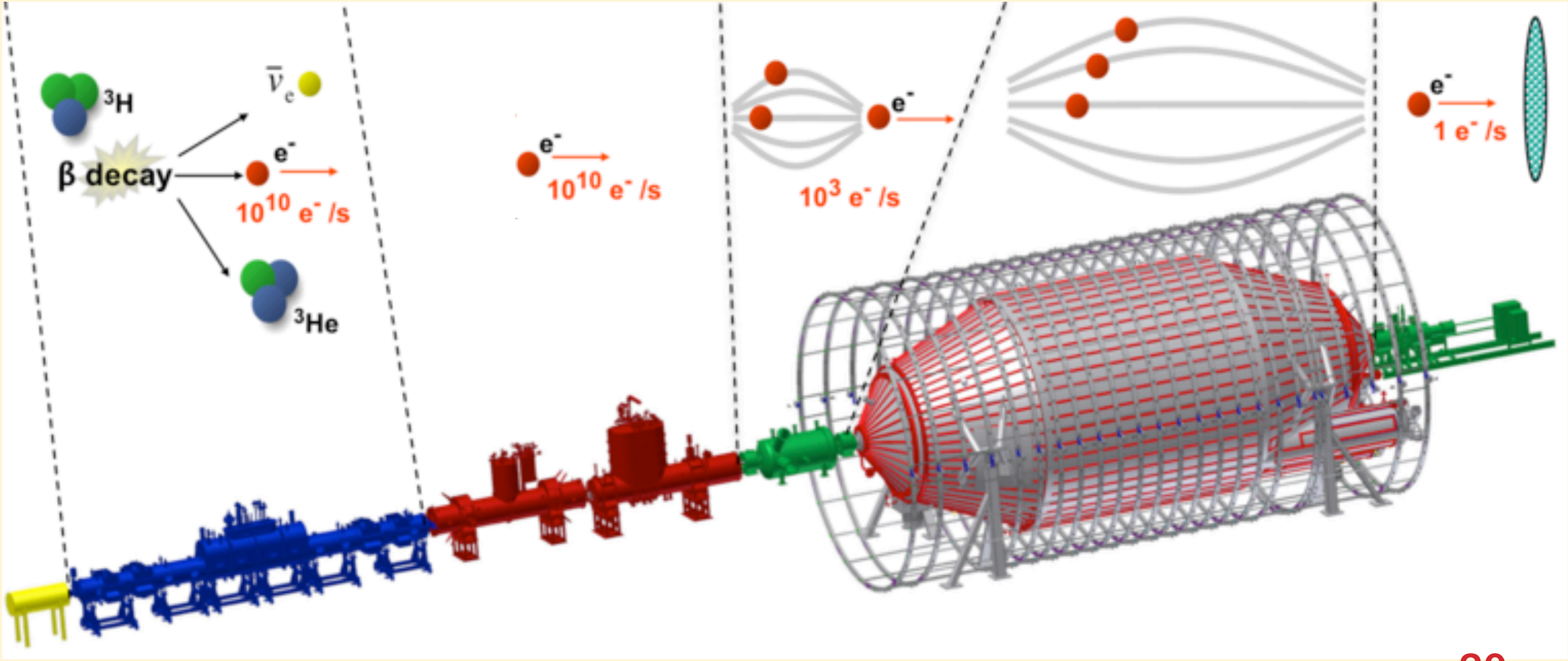
~ 75 m long with 40 s.c. solenoids

Overview of KArlsruhe TRItium Neutrino Experiment

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

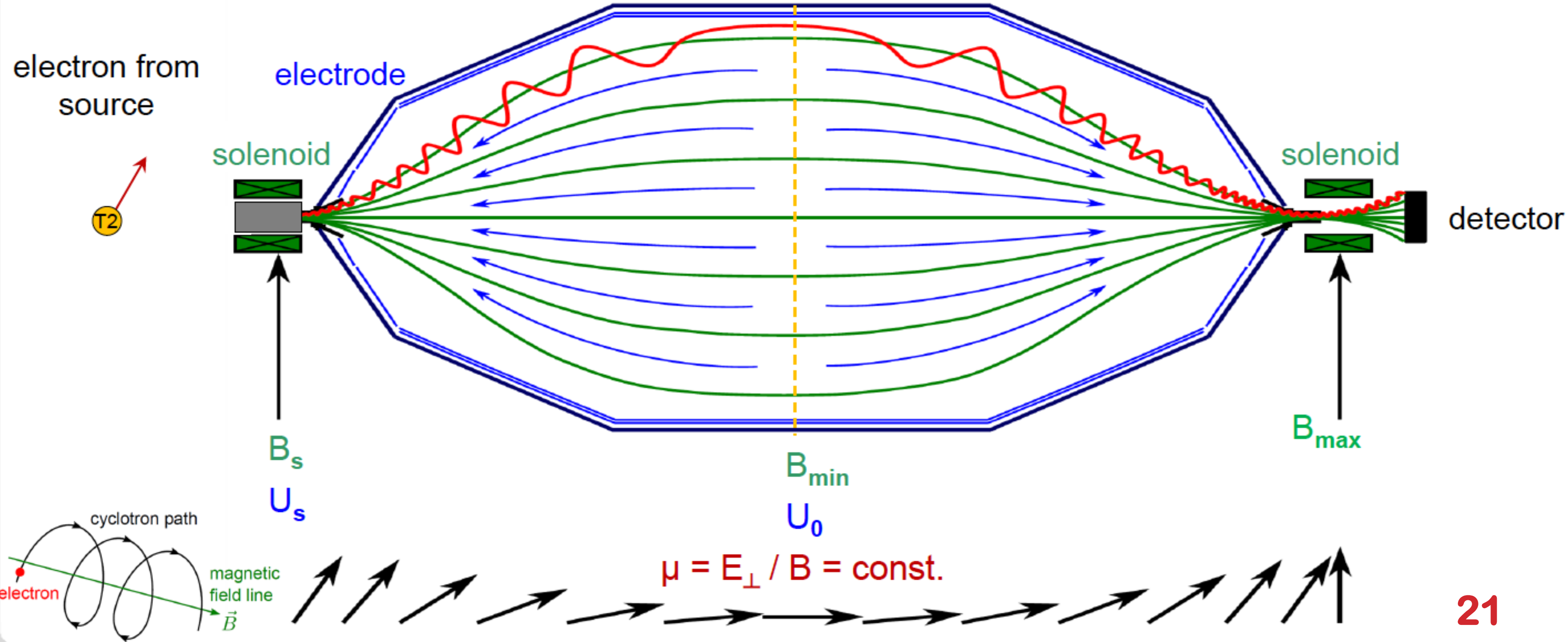
10^{-3} mbar

10^{-11} mbar



KATRIN forms *integral* spectrum with MAC-E filter

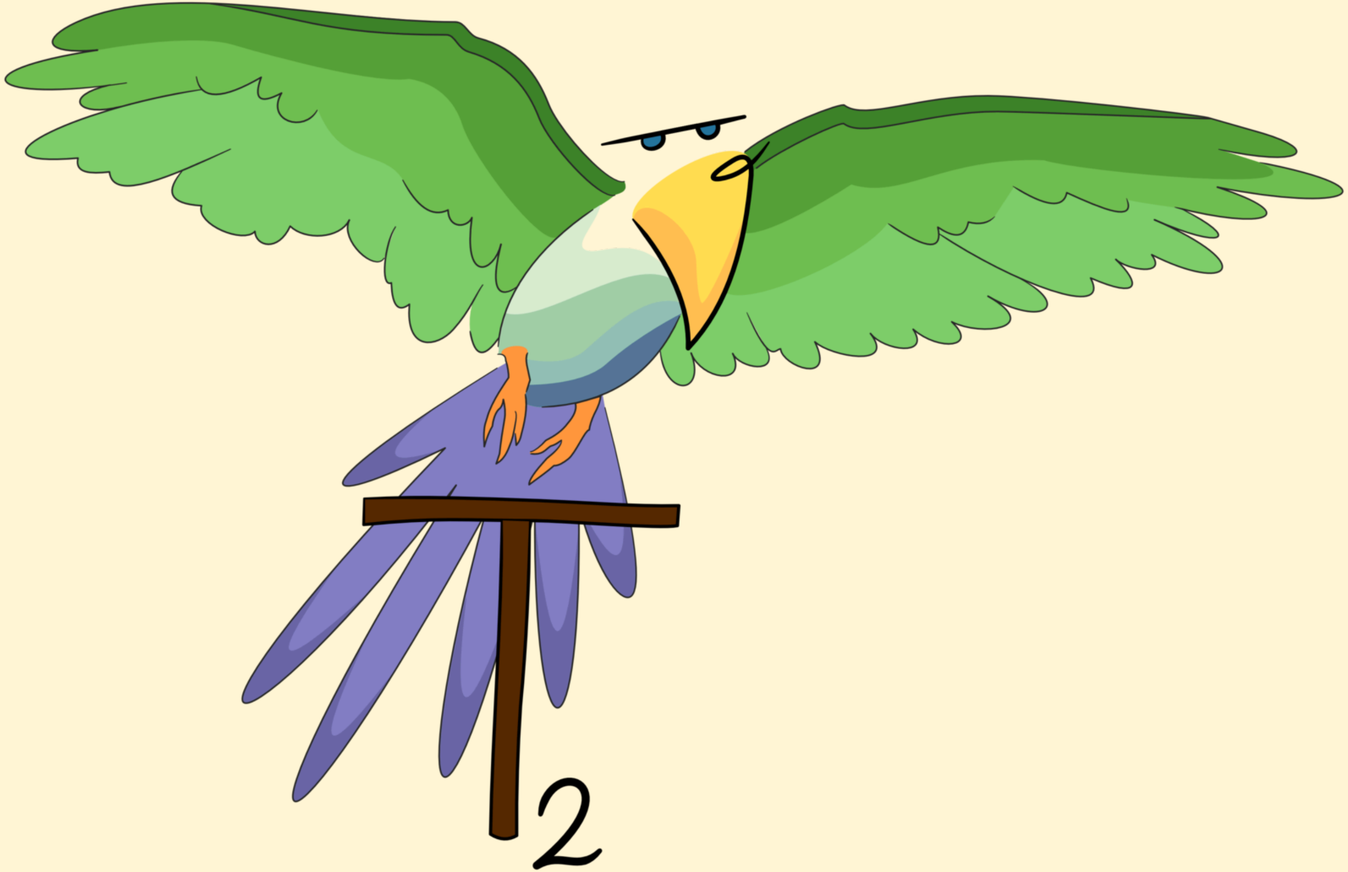
- **Magnetic Adiabatic Collimation & Electrostatic Filter:** adiabatic conversion $E_\perp \rightarrow E_\parallel$



$\mu = E_\perp / B = \text{const.}$

KATRIN

Karlsruhe Tritium Neutrino Experiment



KATRIN

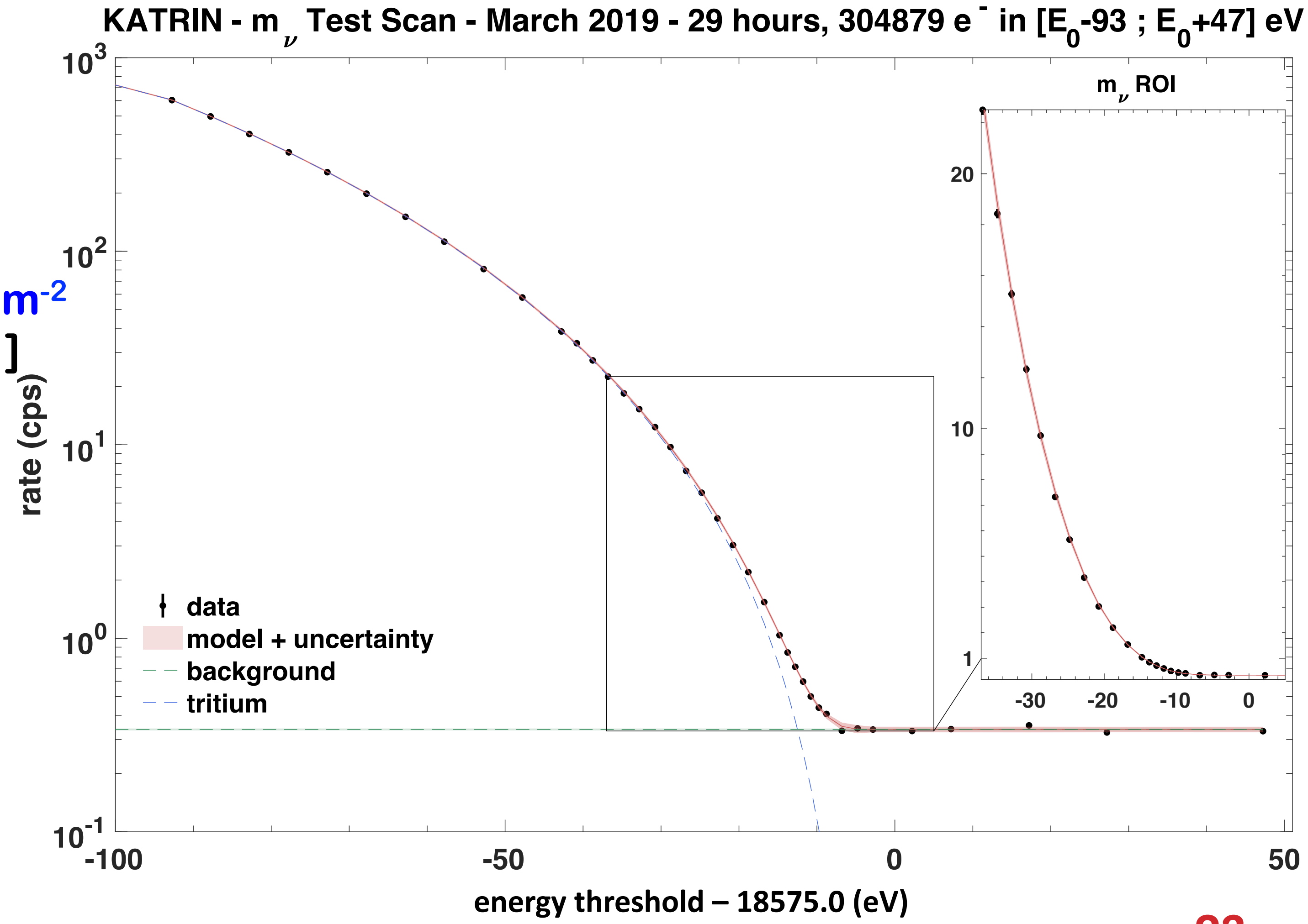
March 18-19, 2019

305,000 events

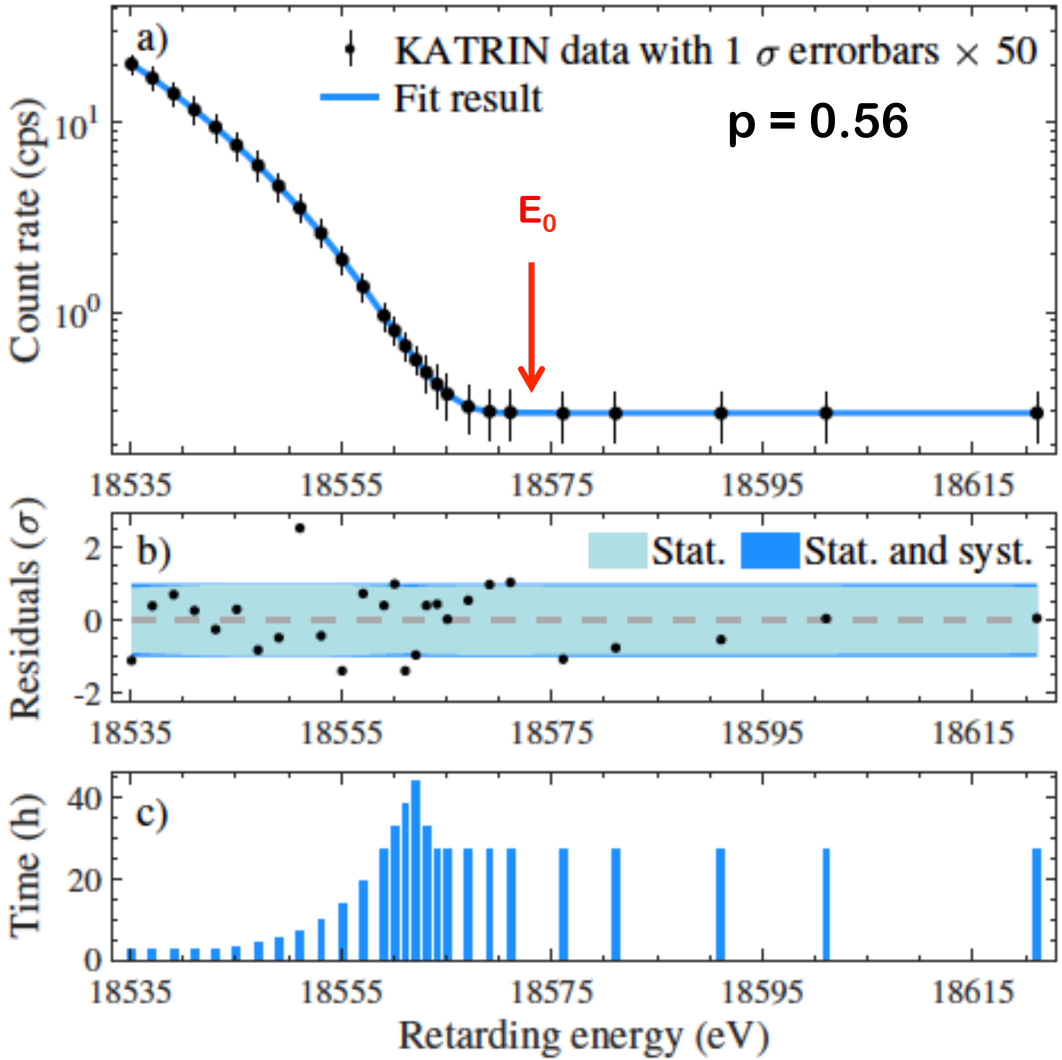
Col dens: 2×10^{17} cm^{-2}
[CDR: 5×10^{17} cm^{-2}]

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

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



KATRIN - m_ν Test Scan - March 2019 - 29 hours, 304879 e^- in $[E_0-93 ; E_0+47]$ eV

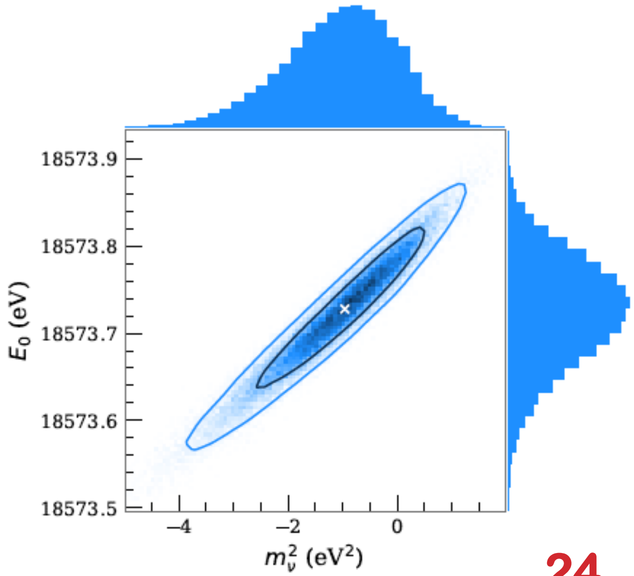


KATRIN

April 10 - May 13

PRL 123, 221802 (2019)

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

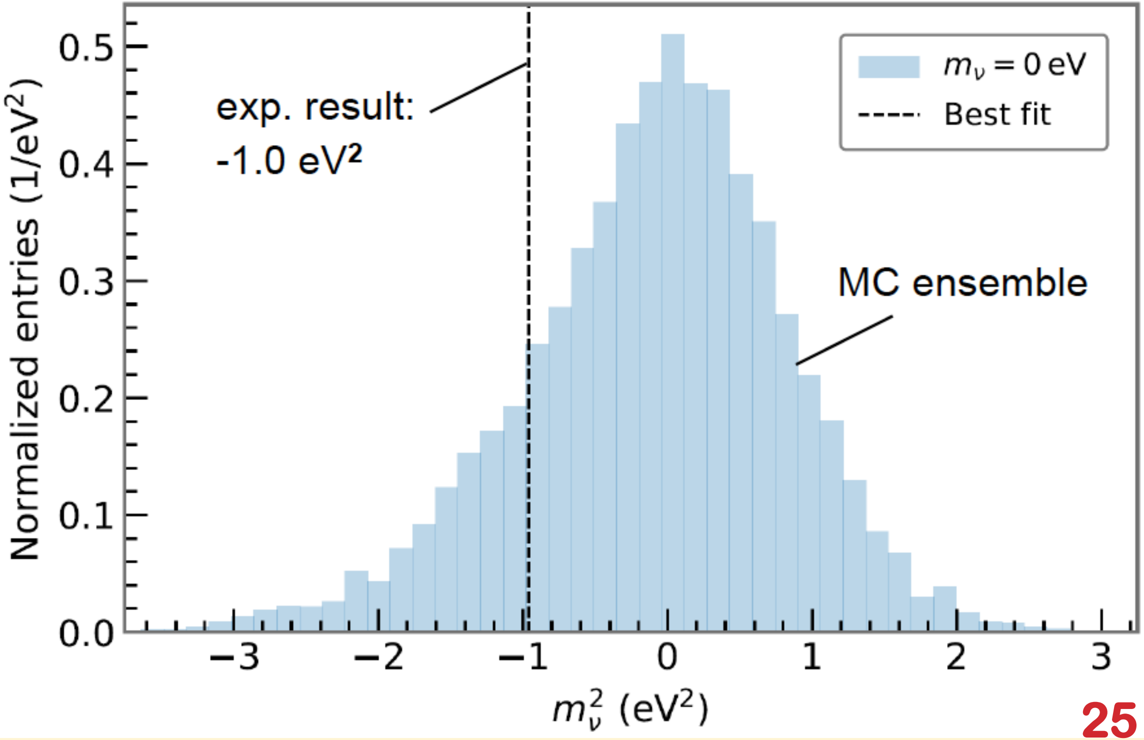


Result is statistically probable

- **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}

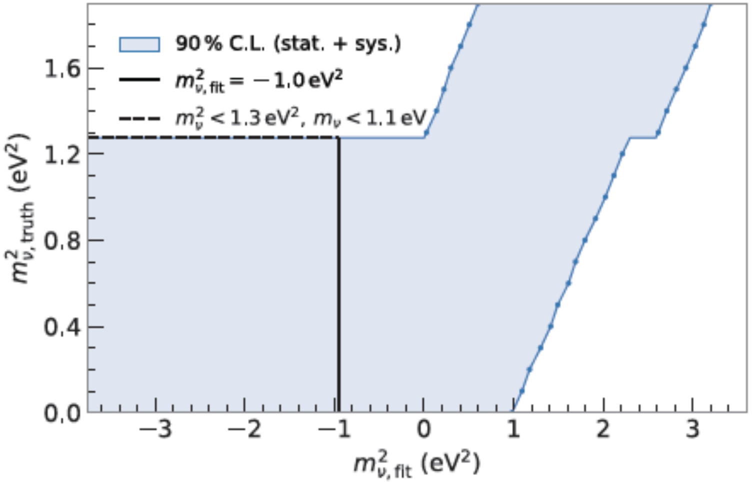
p-value = 0.16



Derivation of mass limit

Lokhov-Tkachov

- $m_\nu < 1.1$ eV (90% CL) = sensitivity

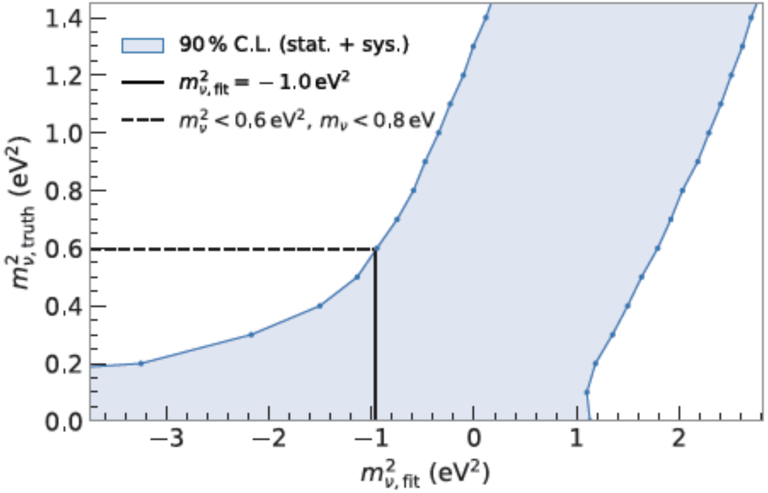


Feldman-Cousins

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

Bayesian Confidence Interval ($m_\nu^2 > 0$, flat)

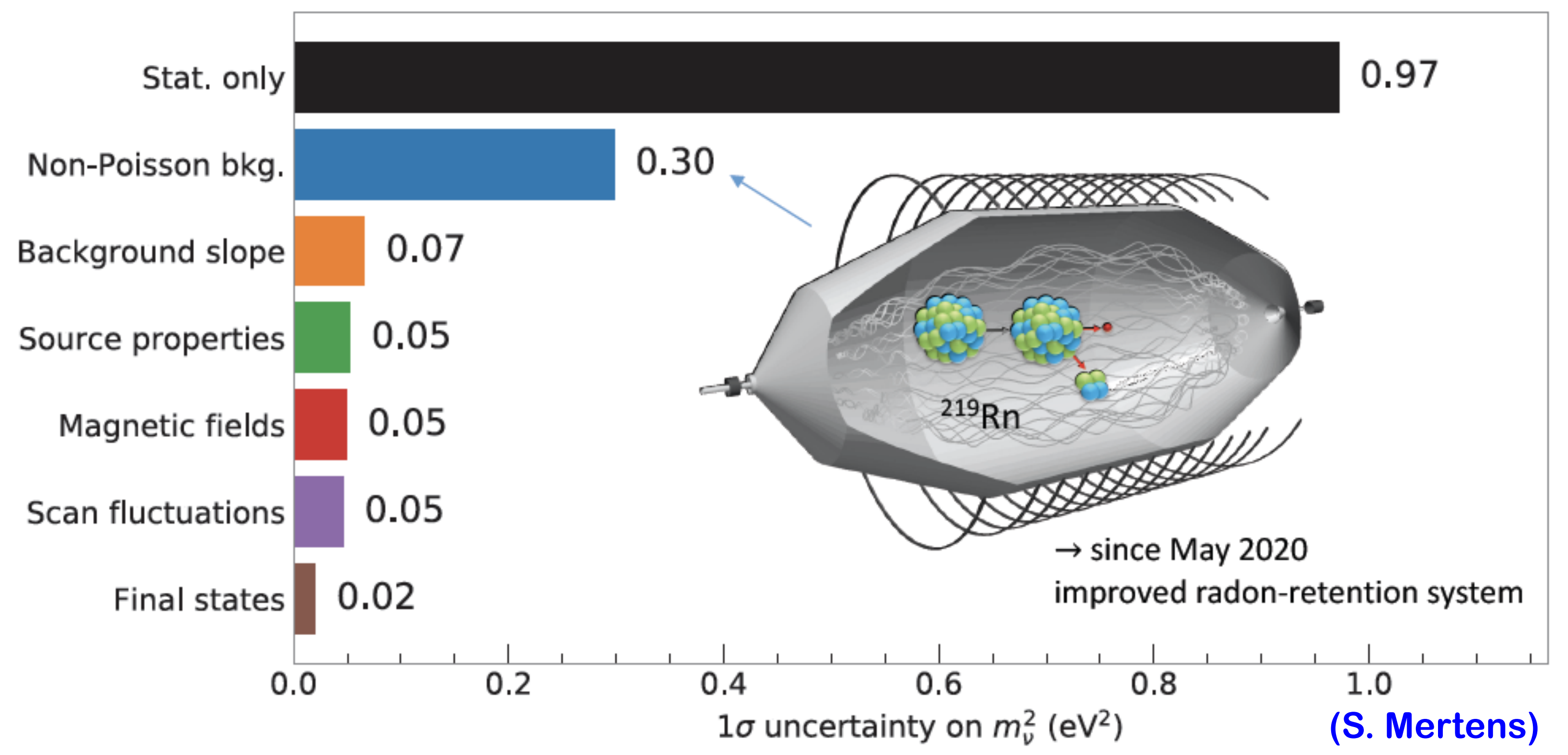
- $m_\nu < 0.9$ eV (90% CI)



Lokhov & Tkachov, Phys. Part. Nucl. 46, 347 (2015)

Still mainly statistical

- total statistical uncertainty budget σ_{stat} = 0.97 eV^2
- total systematic uncertainty budget σ_{syst} = 0.32 eV^2

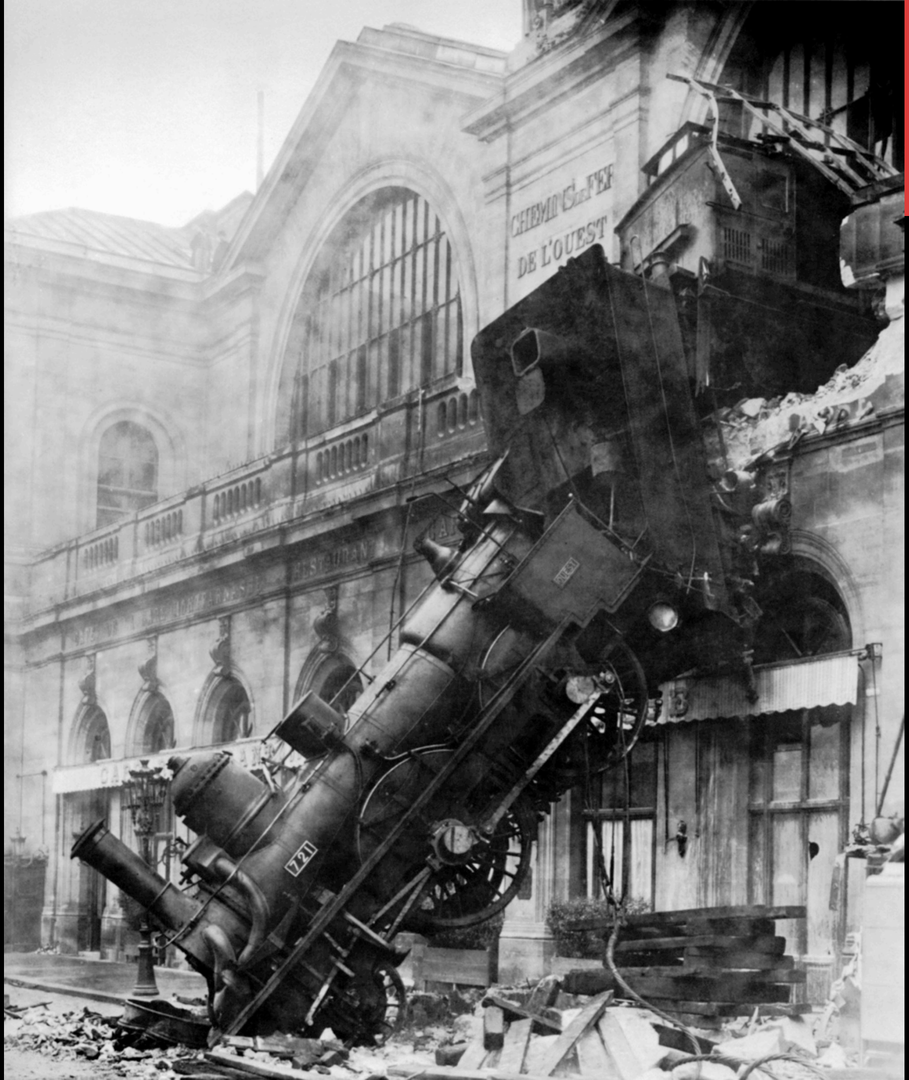


→ since May 2020
improved radon-retention system

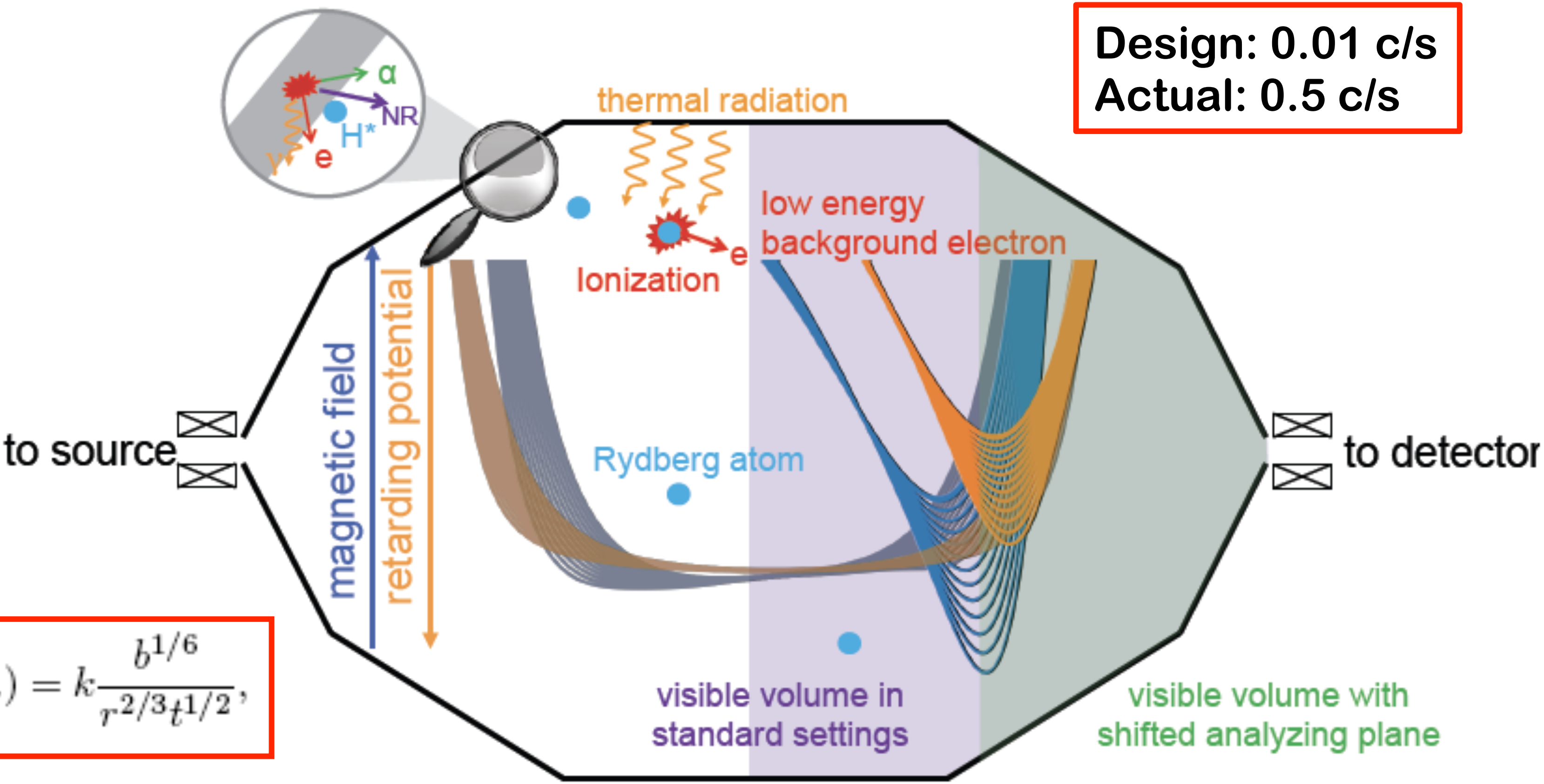
(S. Mertens)

Problems, always problems

- Background
- Plasma
- Pandemic



Backgrounds predominantly originate from main spectrometer: stored particles from radon decays, ionisation of Rydberg states.



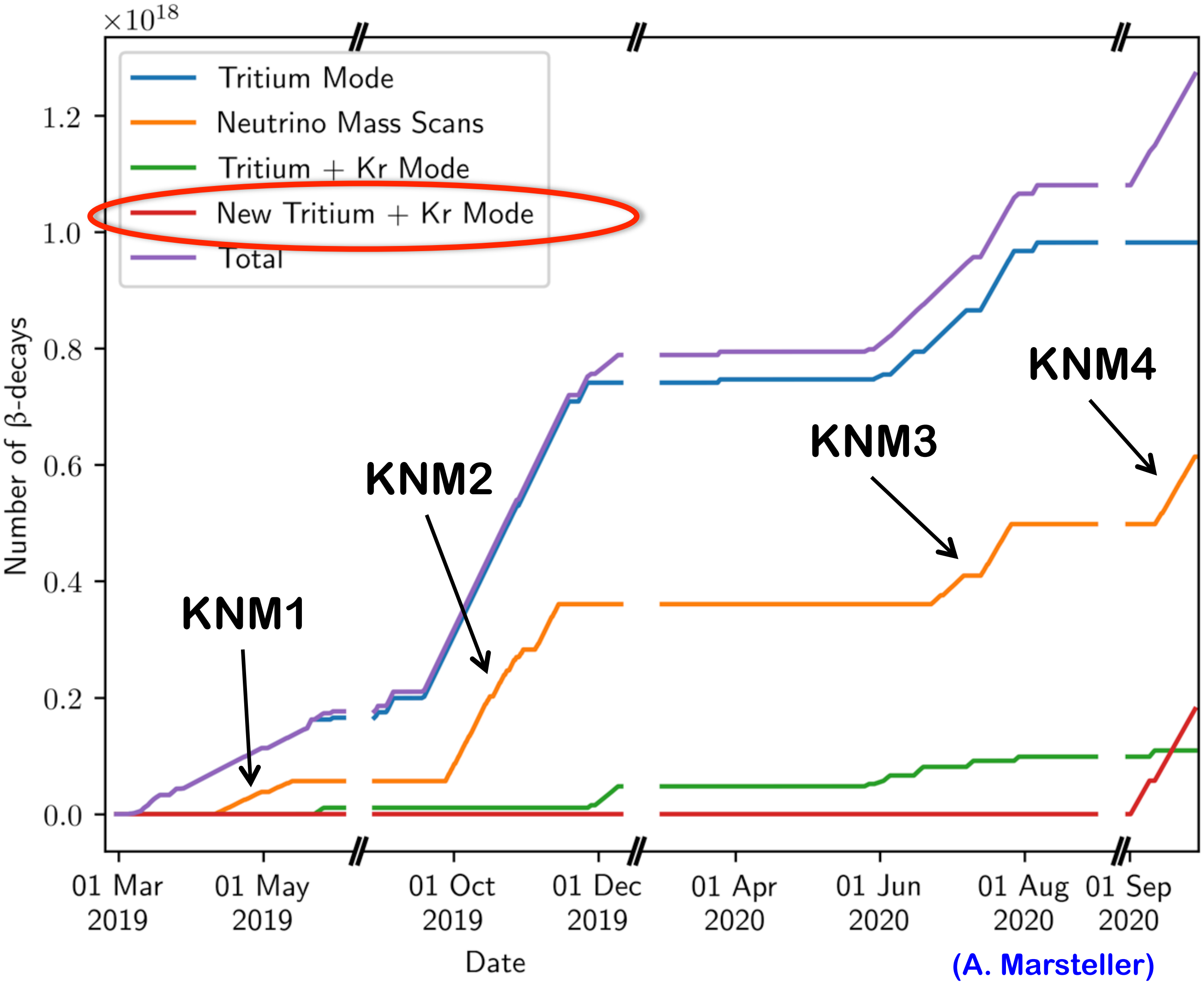
Design: 0.01 c/s
Actual: 0.5 c/s

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

K. Valerius, Heraeus 2019

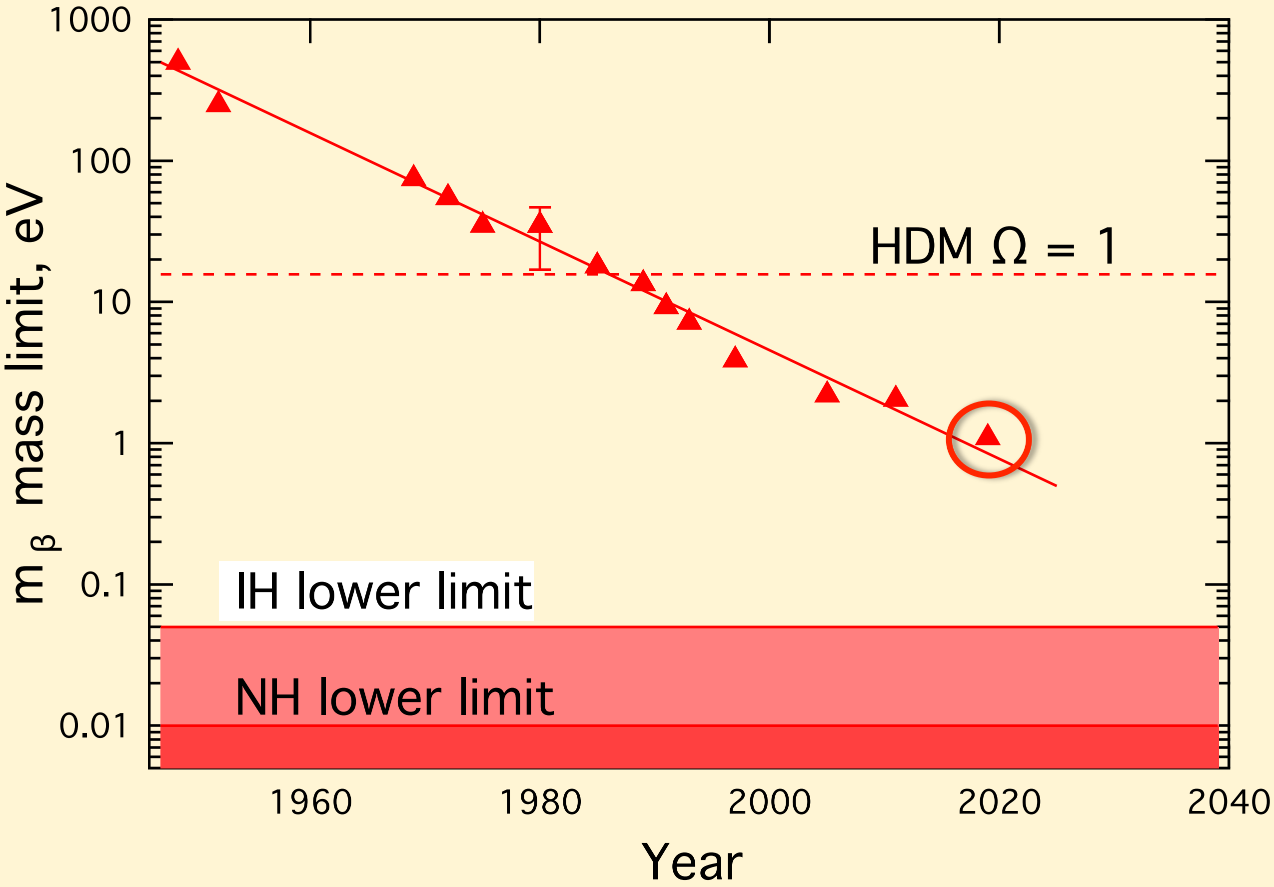
Run KNM1 is published, KNM2 under analysis, KNM3 mainly systematic studies, KNM4 now running

Destination: 0.2 eV



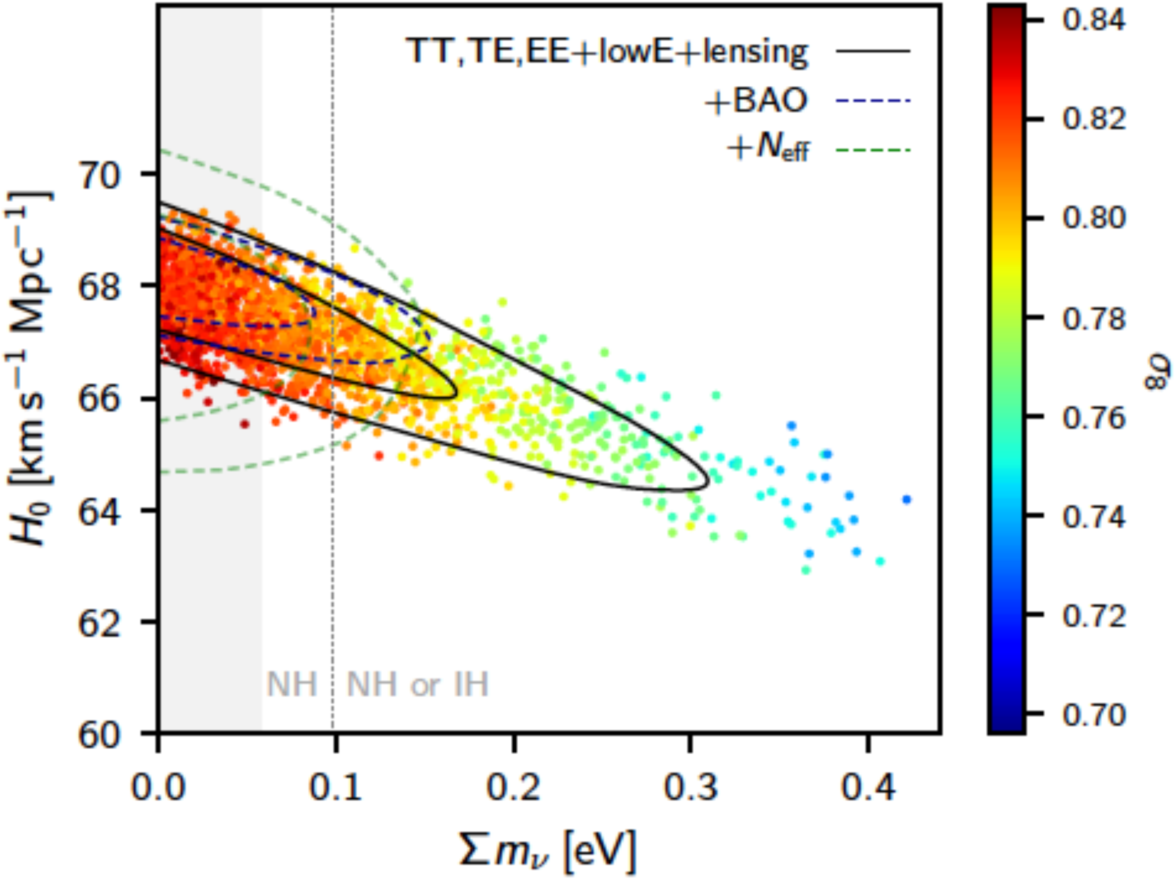
(A. Marsteller)

The road is direct, but long!



Neutrinos in the cosmos

Planck CMB (1807.06209)



Throwing in everything, Planck finds

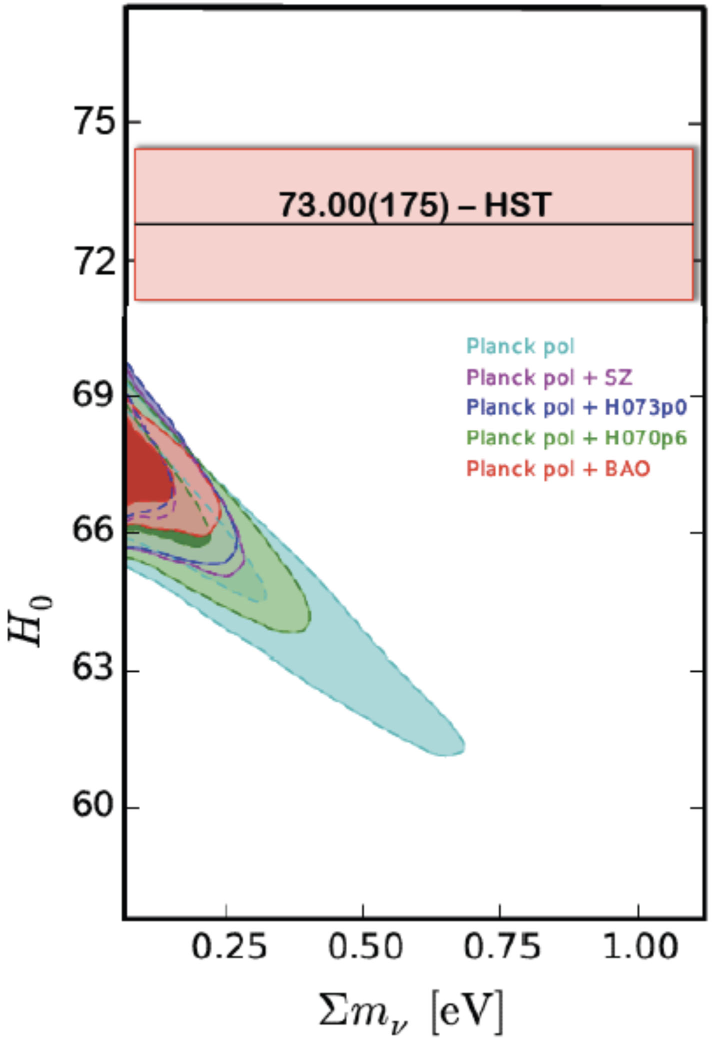
$$\Sigma m_\nu < 0.12 \text{ eV}$$

But they used degenerate approximation. Actually:

$$\Sigma m_\nu < 0.26 \text{ eV}$$

Loureiro et al. PRL 123, 081301 (2019)

Neutrinos in the cosmos

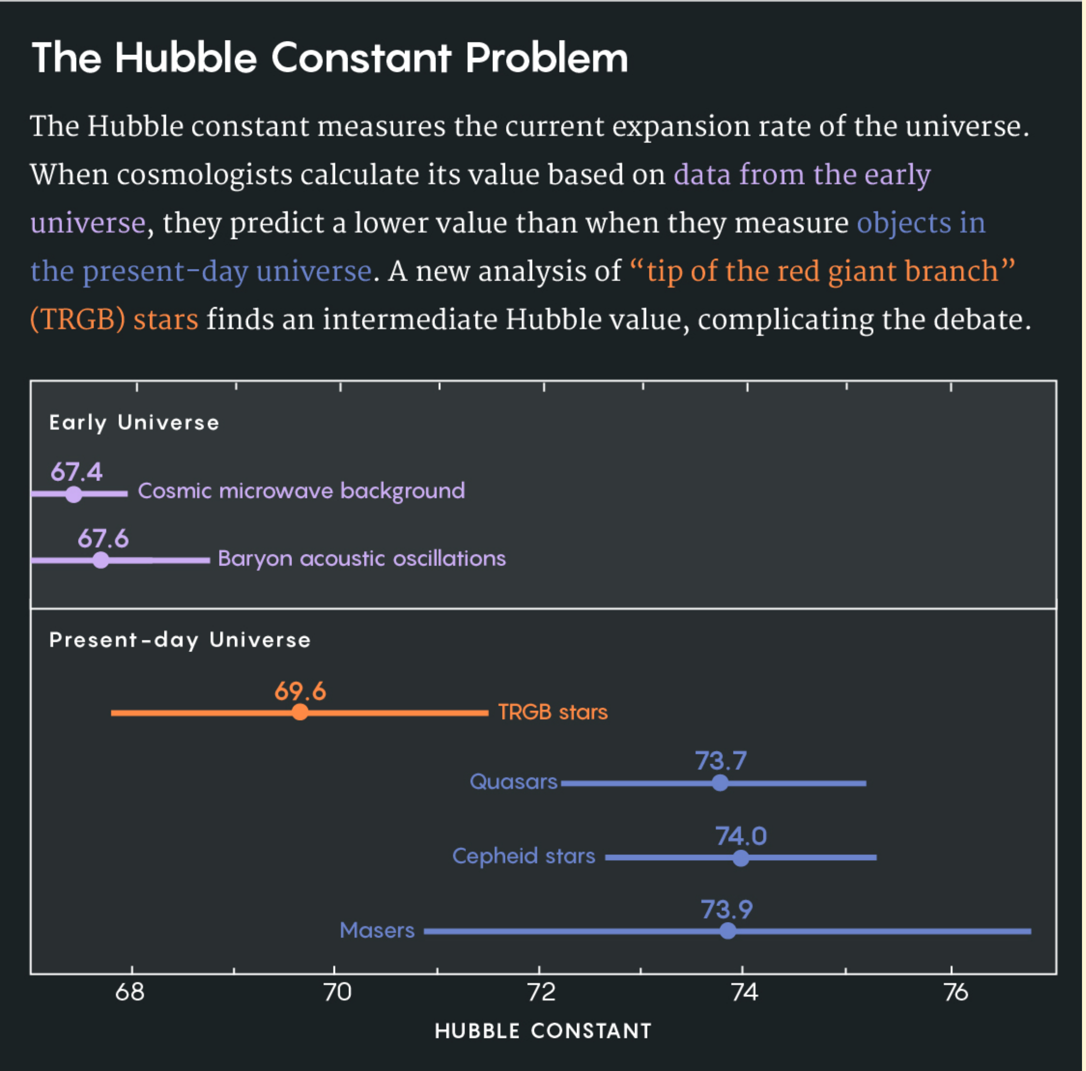


Tension with the HST galaxy low-z data can be resolved by relaxing w:

w ~ $-1.14^{+0.12}_{-0.10}$

Σm_ν ~ $0.35^{+0.16}_{-0.25}$ **eV**

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

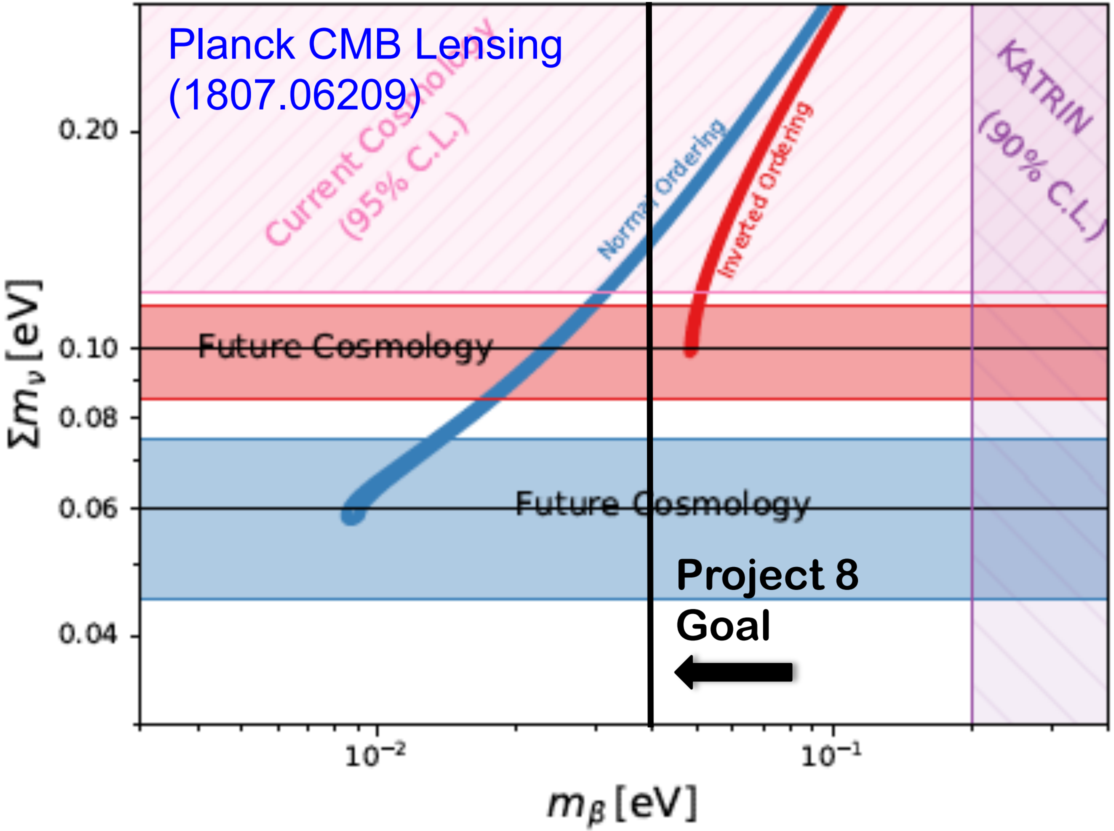


The Hubble Constant Problem

The Hubble constant measures the current expansion rate of the universe. When cosmologists calculate its value based on data from the early universe, they predict a lower value than when they measure objects in the present-day universe. A new analysis of “tip of the red giant branch” (TRGB) stars finds an intermediate Hubble value, complicating the debate.

From Quanta 2/20/20

Neutrinos in the cosmos



Abazajian et al., "CMB-S4 Science" 1907.04473

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.

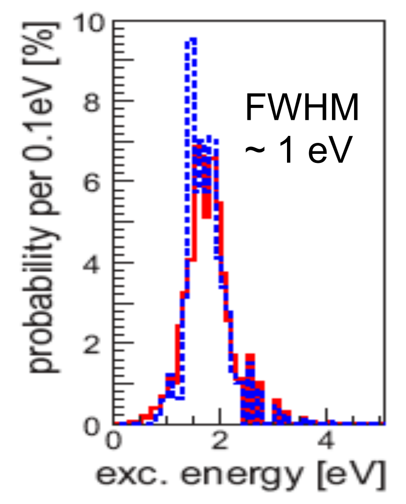
Statistics

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

Theory: Saenz et al. 2000

A new idea : Cyclotron Radiation Emission Spectroscopy (CRES). (B. Monreal and J. Formaggio, PRD 80:051301, 2009)

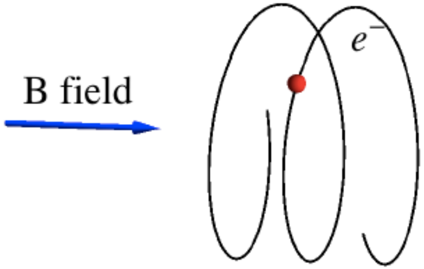
Arthur Schawlow

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

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

Cyclotron motion:

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

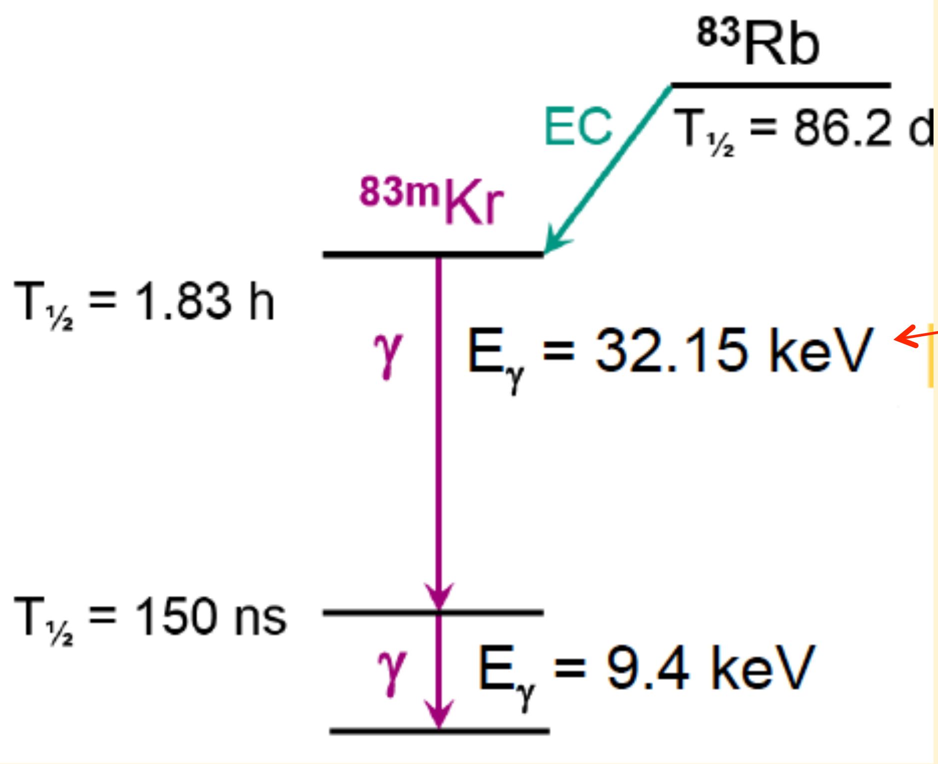


$$f_c = 27\,992.491\,10(6)\,\mathrm{MHz\,T^{-1}}$$

$$P\left(E_{\mathrm{kin}}, m, \theta\right) = \frac{1}{4\pi\epsilon_0} \frac{2}{3} \frac{e^4}{m^4 c^5} B^2 \left(E_{\mathrm{kin}}^2 + 2\,E_{\mathrm{kin}}\,m\,c^2\right) \sin^2\theta$$

$$P\left(17.8\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}\right) = 1\,\mathrm{fW}$$

^{83m}Kr: NICE TEST SOURCE



E_γ = 32152 eV

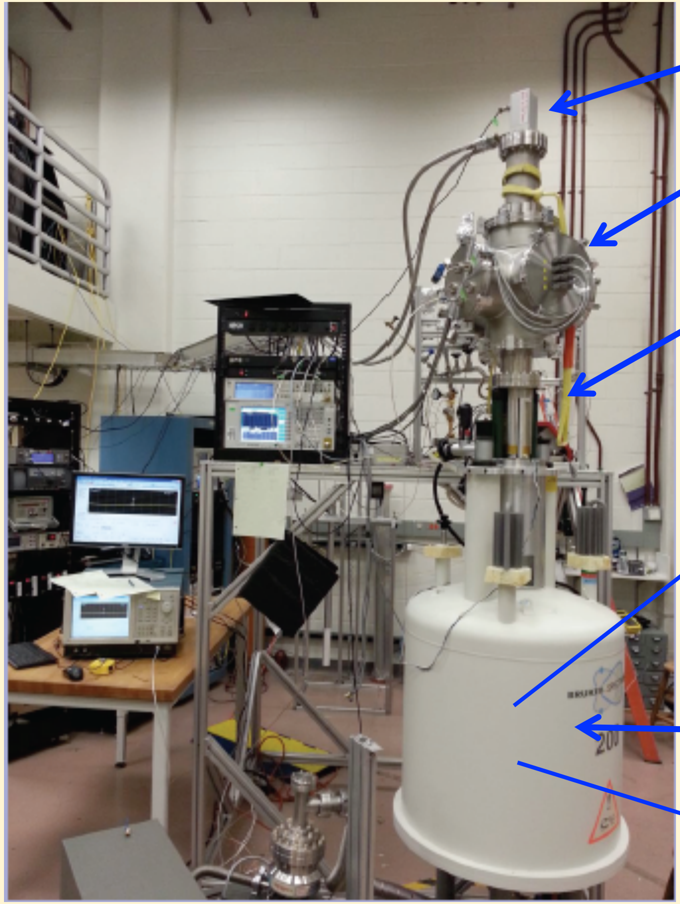
Conversion e^-
K: 17824.3 eV
L_2: 30424.4 eV
L_3: 30477.2 eV
…

ENERGY RESOLUTION & TRAPS

$$\frac{\Delta E_{kin}}{E_{kin}} = \left(1 + \frac{m_e c^2}{E_{kin}}\right)\frac{\Delta f}{f}$$

~30

- For 1 eV energy resolution, you need about 2 ppm frequency.
- For 2 ppm frequency, you need 500,000 cycles, or 15 μs.
- Electron travels 2 km.
- You need a trap!

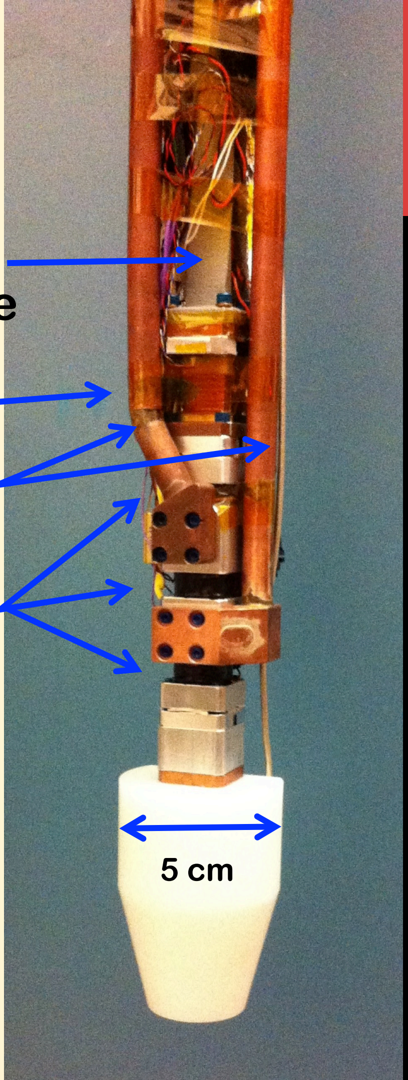


G-M cooler (35K)

26-GHz amplifiers

^{83m}Kr source (behind)

Superconducting Magnet (0.96 T)



WR-42 waveguide

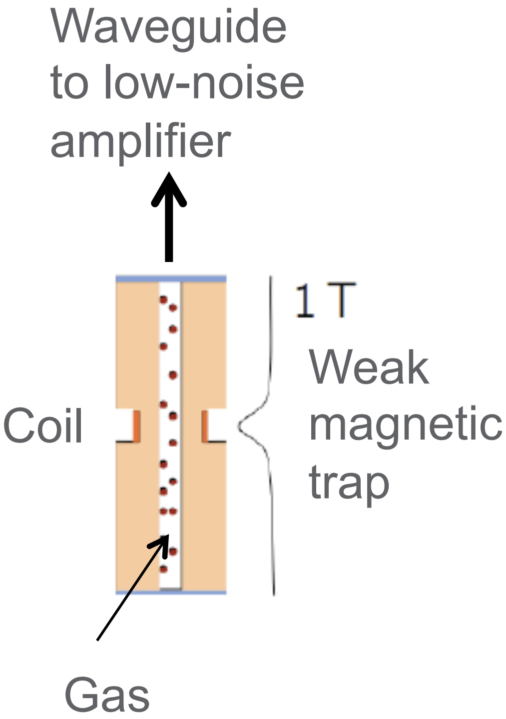
ESR cell

Gas lines

Trap coils

University of Washington: *Phase I*

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



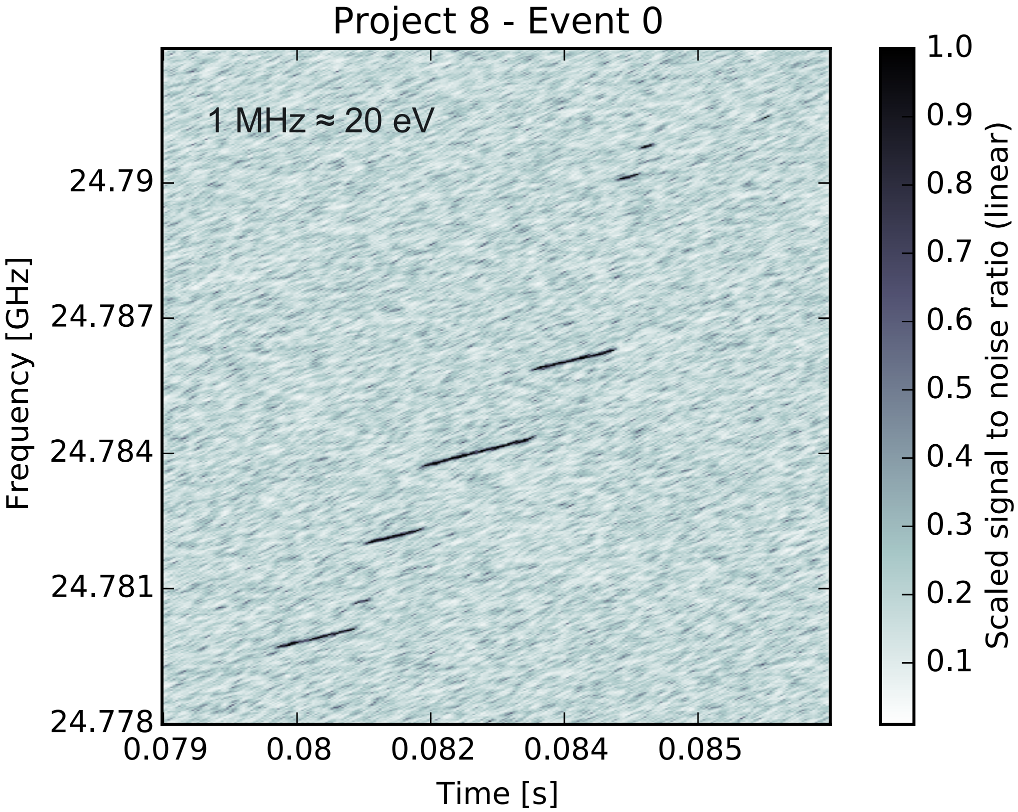
Waveguide to low-noise amplifier

1 T

Weak magnetic trap

Coil

Gas



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

●

start frequency of the first track gives kinetic energy.

→

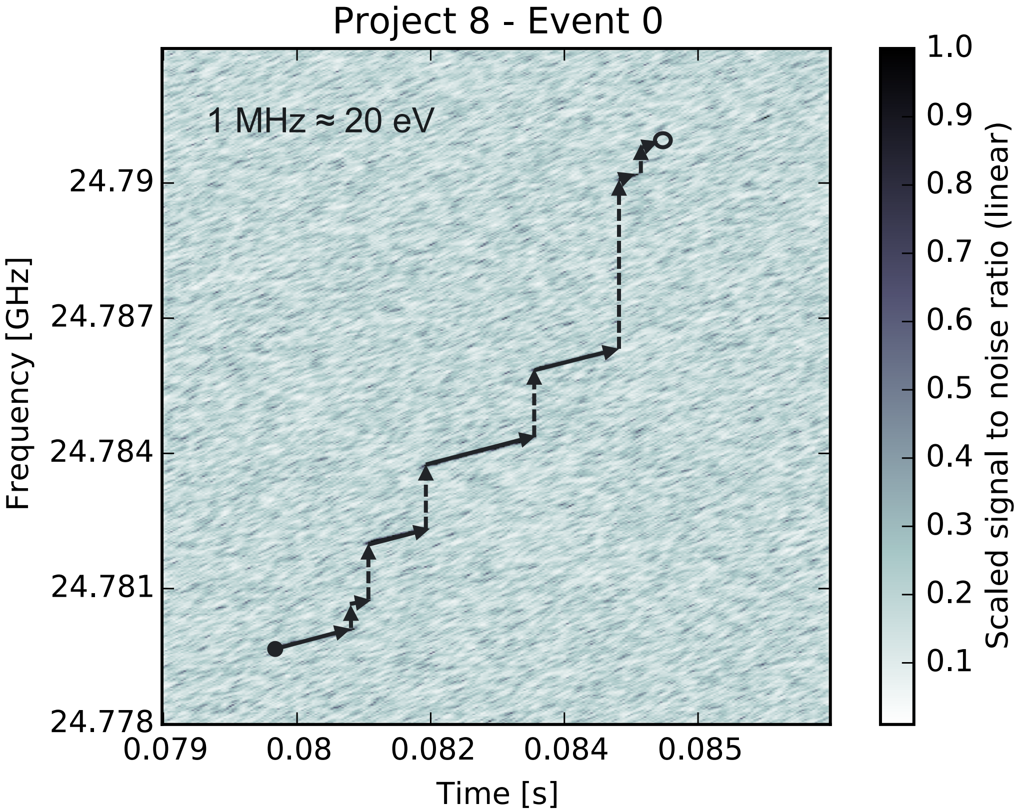
frequency chirps linearly, corresponding to ~1 fW radiative loss.

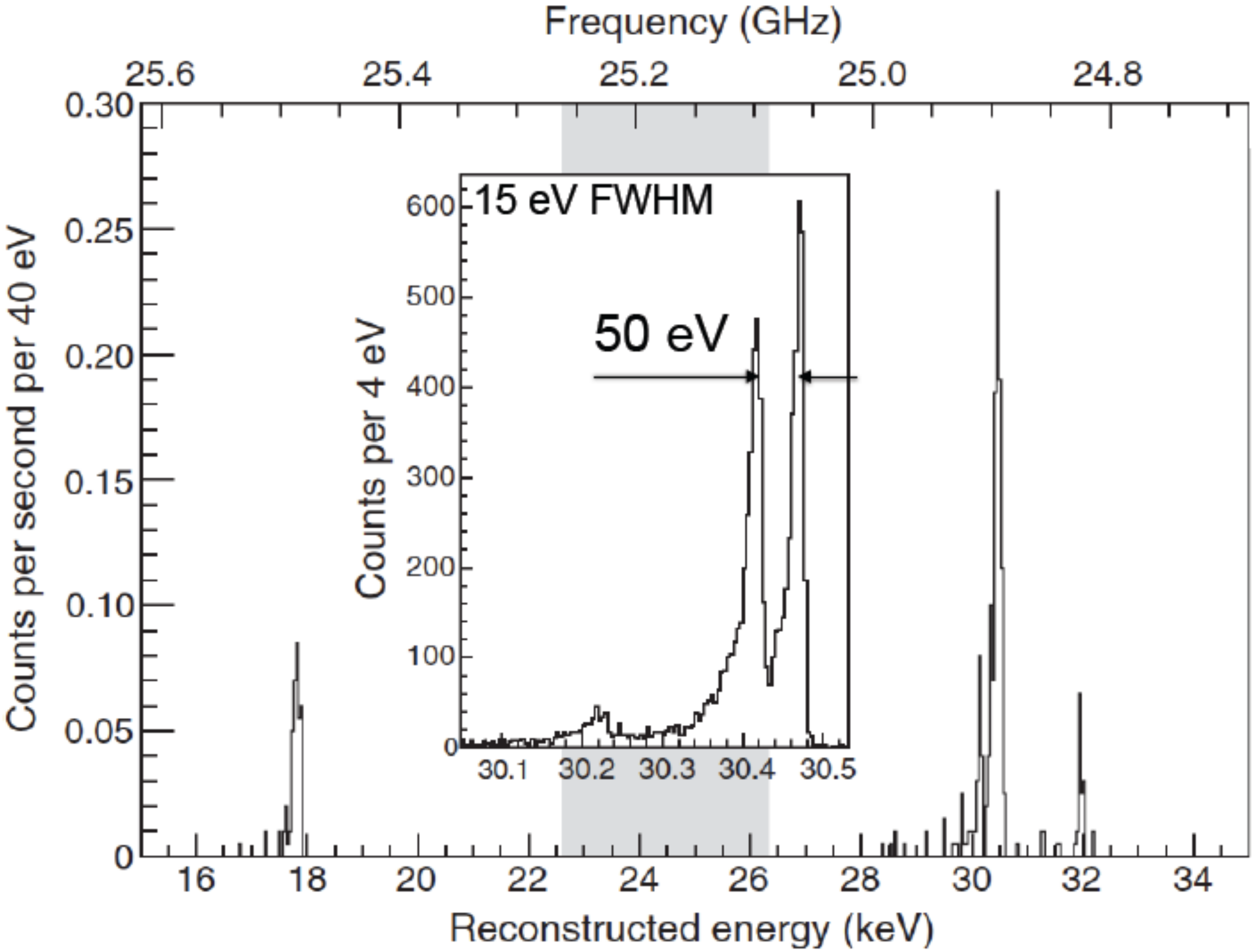
⇡

electron scatters inelastically, losing energy and changing pitch angle.

○

Eventually, scatters to an untrapped angle





physicsworld

TOP 10

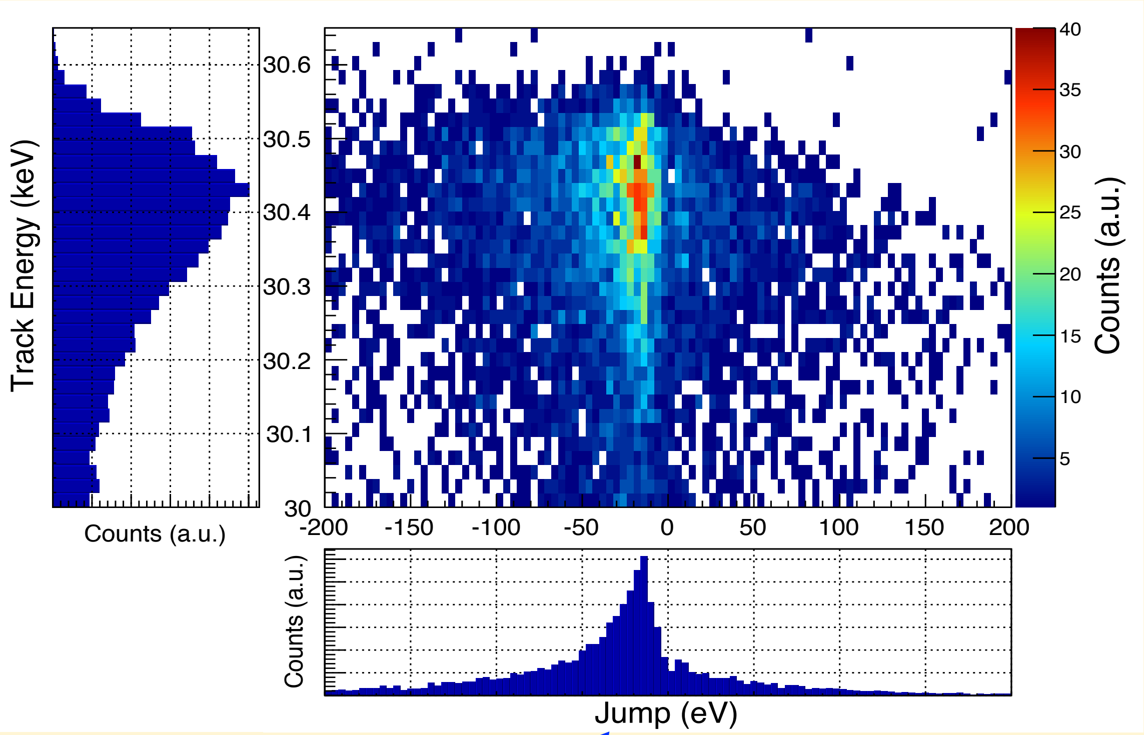
BREAKTHROUGH

2015

Asner et al. PRL 114, 162501 (2015)

“JUMP” SPECTRUM

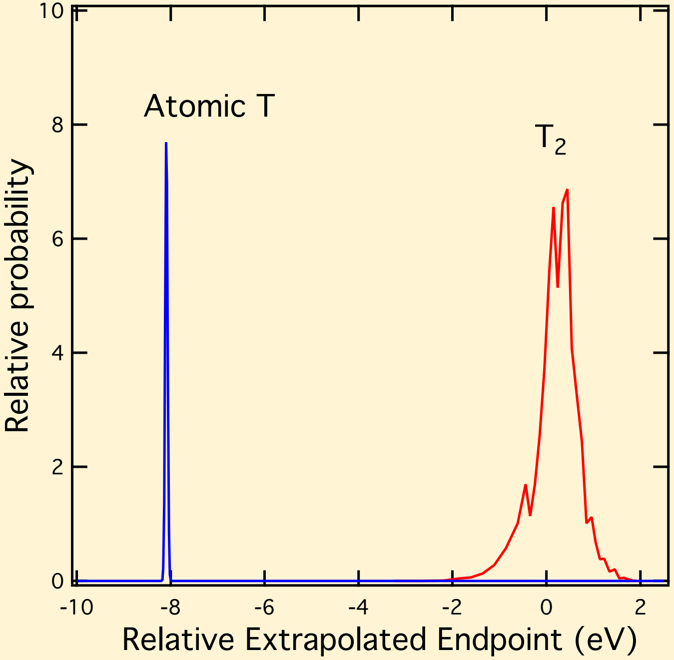
^{83m}Kr 30.4 keV line



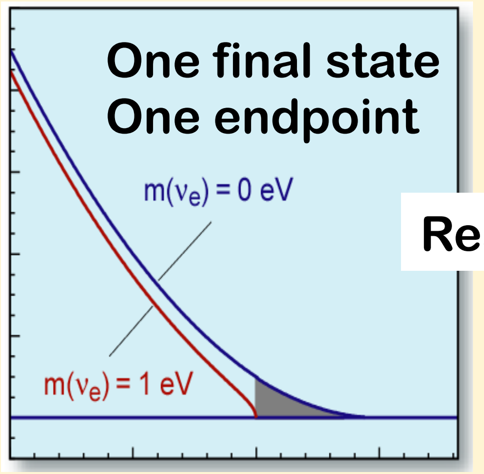
Most probable jump is 14 eV.

CRES WORKS: WHY IS THIS IMPORTANT?

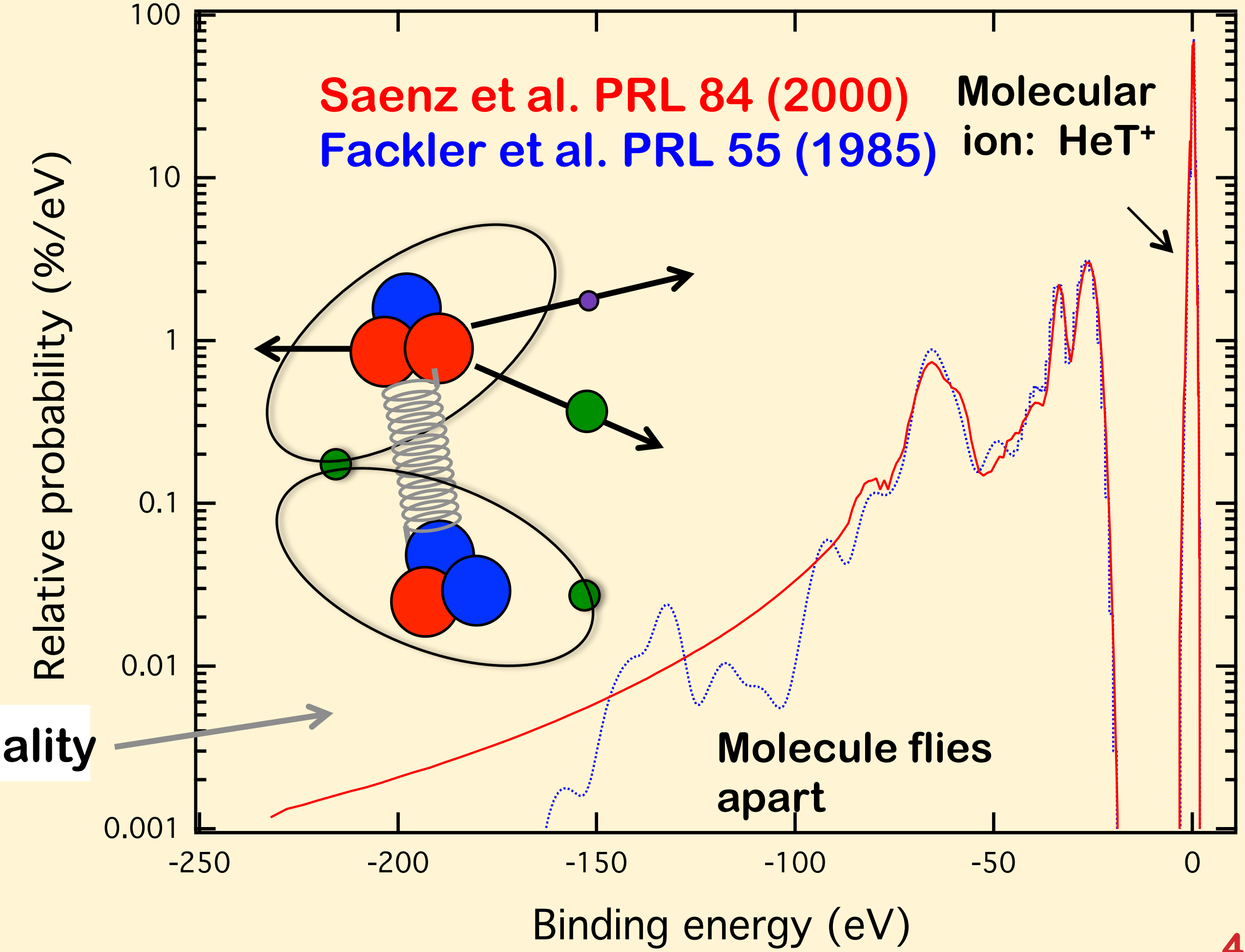
- Source is transparent to microwaves: can make it as big as necessary.
- Whole spectrum is recorded at once, not point-by-point.
- Excellent resolution should be obtainable.
- Low backgrounds are expected.
- An atomic source of T (rather than molecular T_2) may be possible. Eliminates the molecular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

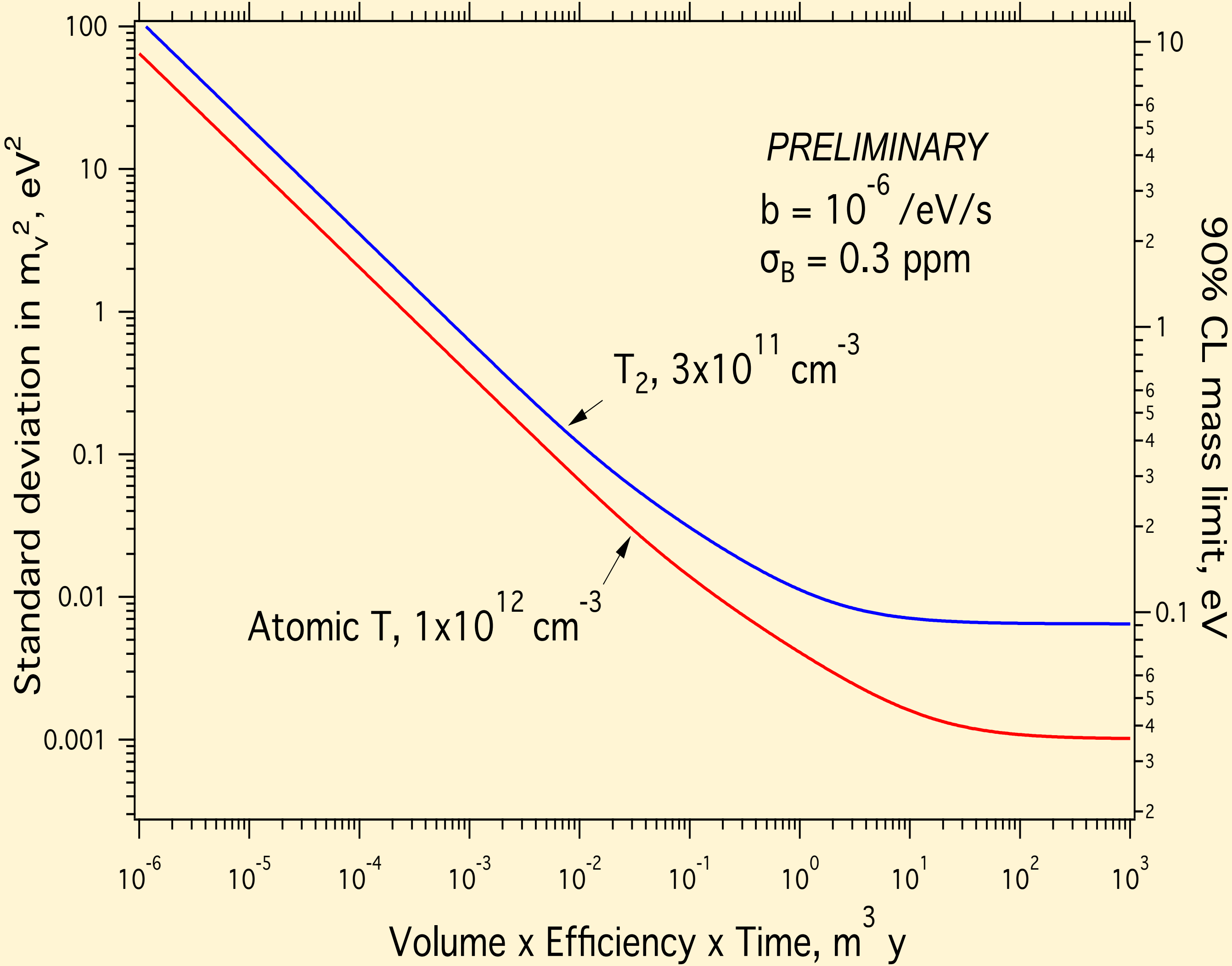


To determine **neutrino mass** from T_2 decay (**KATRIN**), the final-state distribution must be known.

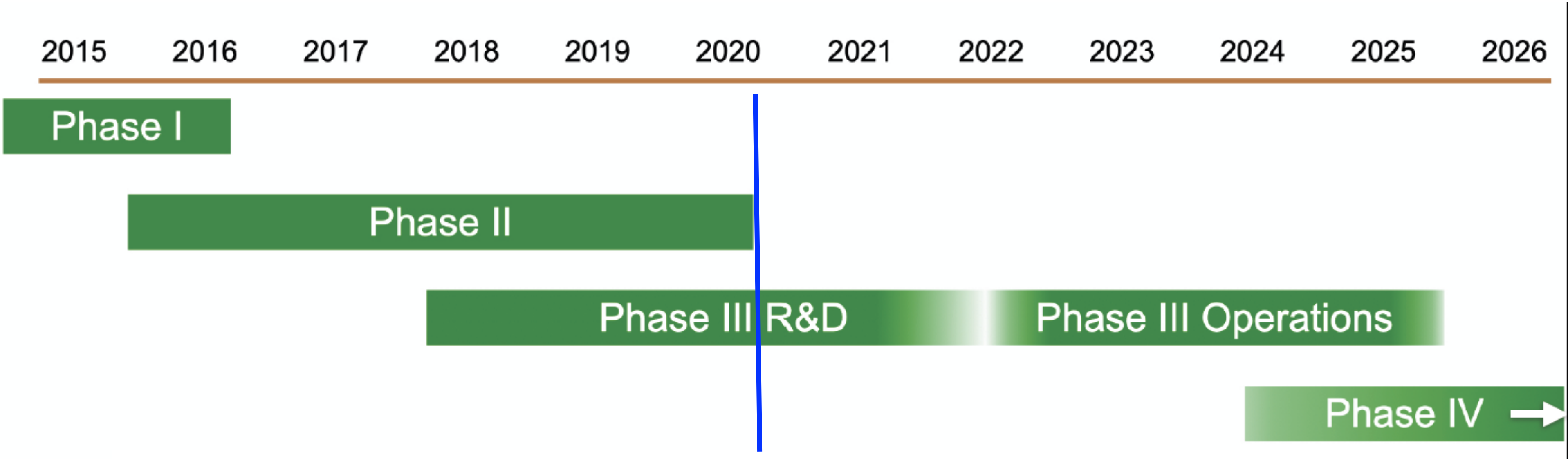


Reality



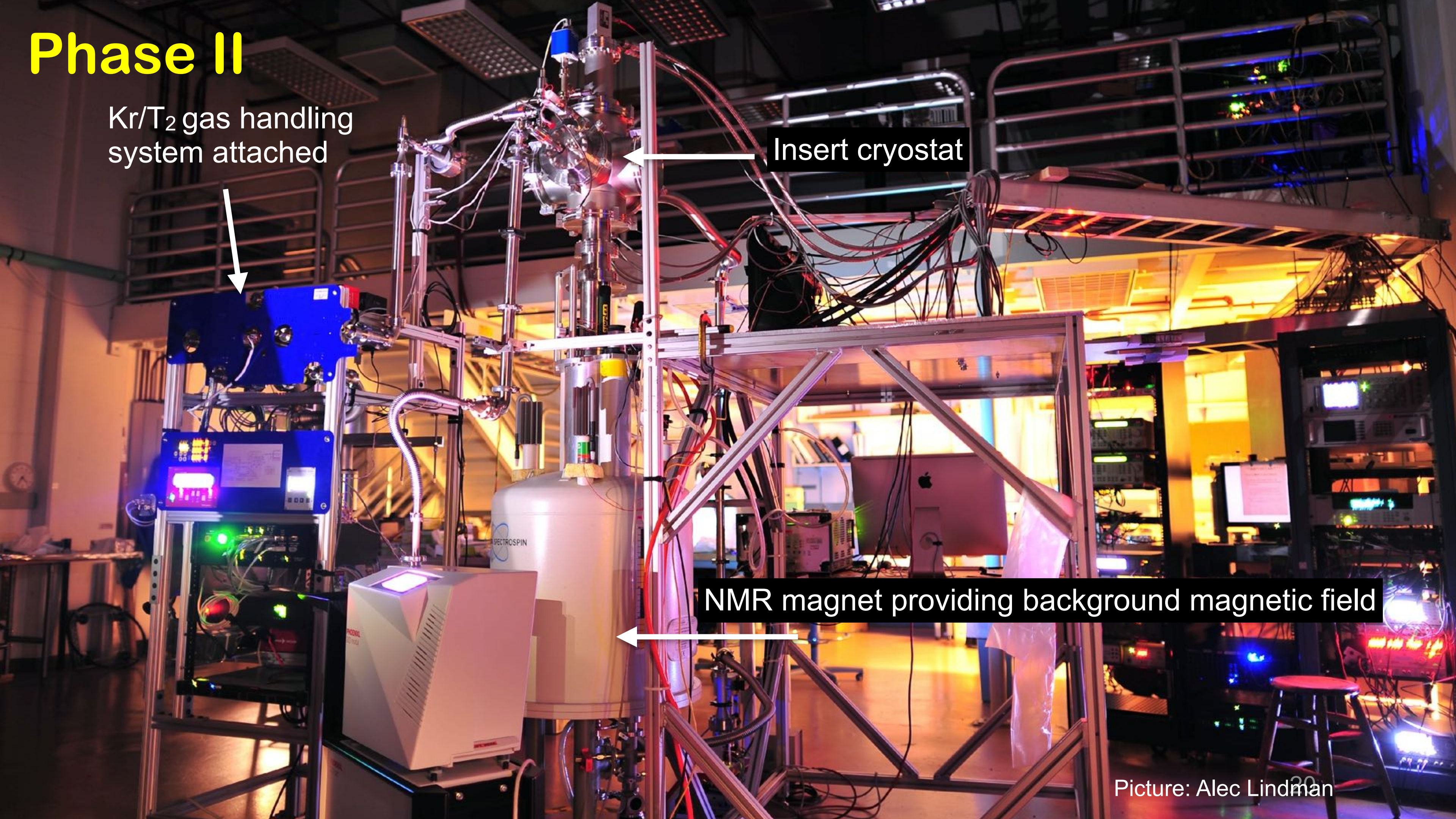

PRELIMINARY
b = 10^-6 /eV/s
σ_B = 0.3 ppm
T_2, 3x10^11 cm^-3
Atomic T, 1x10^12 cm^-3
Standard deviation in m_ν^2, eV^2
100
10
1
0.1
0.01
0.001
90% CL mass limit, eV
10
6
5
4
3
2
1
6
5
4
3
2
0.1
6
5
4
3
2
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
Volume x Efficiency x Time, m^3 y

Phased approach to a neutrino mass measurement



Goal: a mass measurement sensitive to 40 meV

Phase II



Kr/T$_2$ gas handling system attached

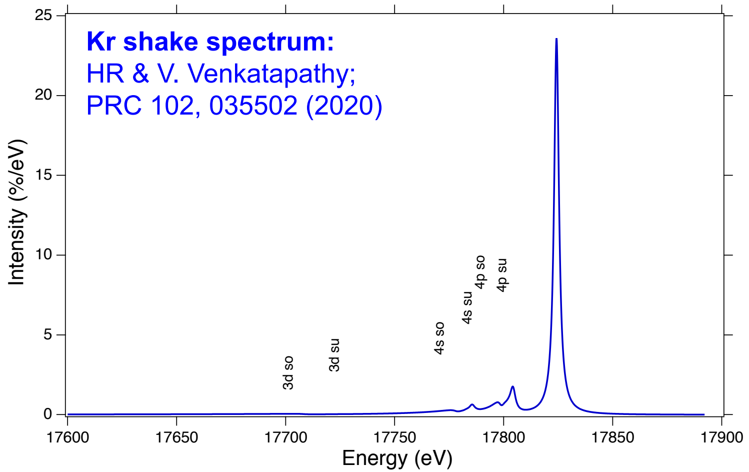
Insert cryostat

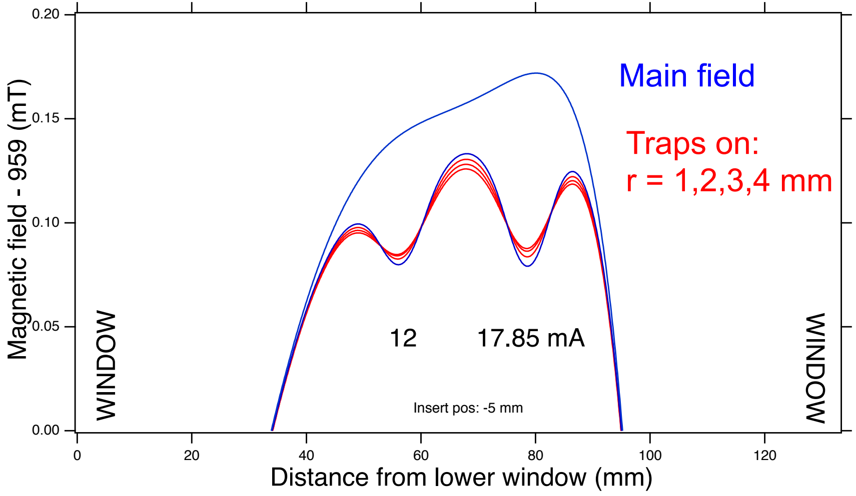
NMR magnet providing background magnetic field

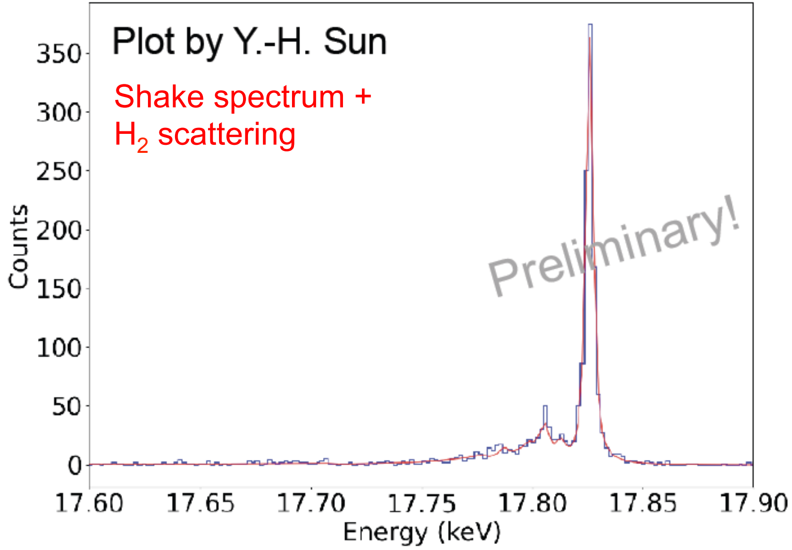
Picture: Alec Lindman

Phase II high resolution ^{83m}Kr data (shallow trap)

Two trap coils
Small acceptance: 90.0(1)°
0.2 + 0.2 mm^3
Natural width of line: 2.8(1) eV
Instrumental Resolution: 2.0(1) eV



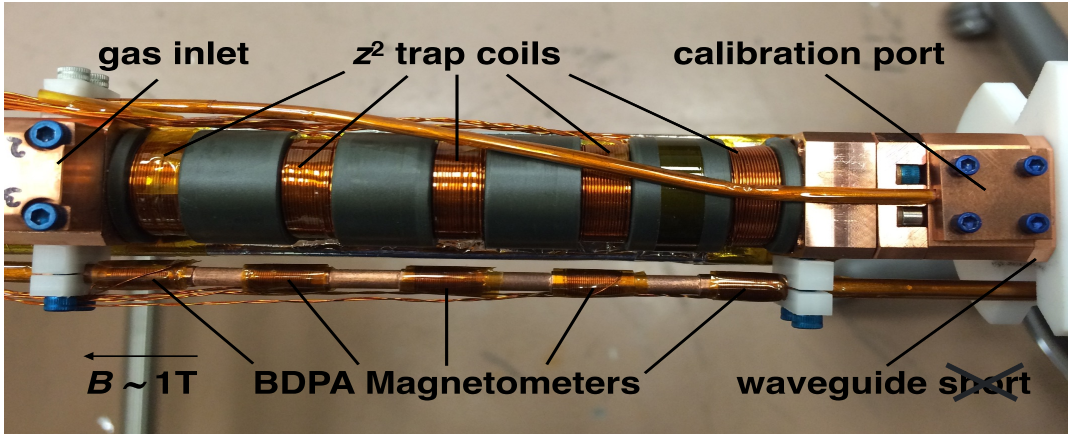




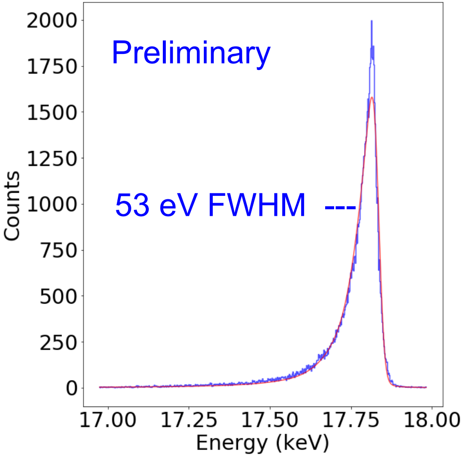
Phase II Waveguide Cell

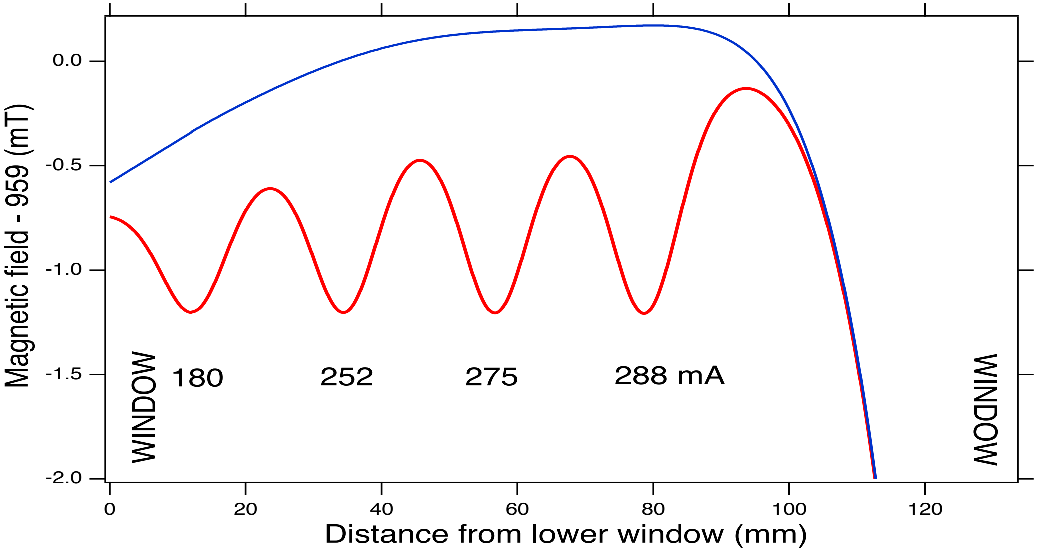
Improvements:

- Cylindrical waveguide (more volume)
- 4 deep trap coils (more statistics)
- Amplifiers colder (less noise)
- Terminator replaces short
- CaF_2 windows for tritium



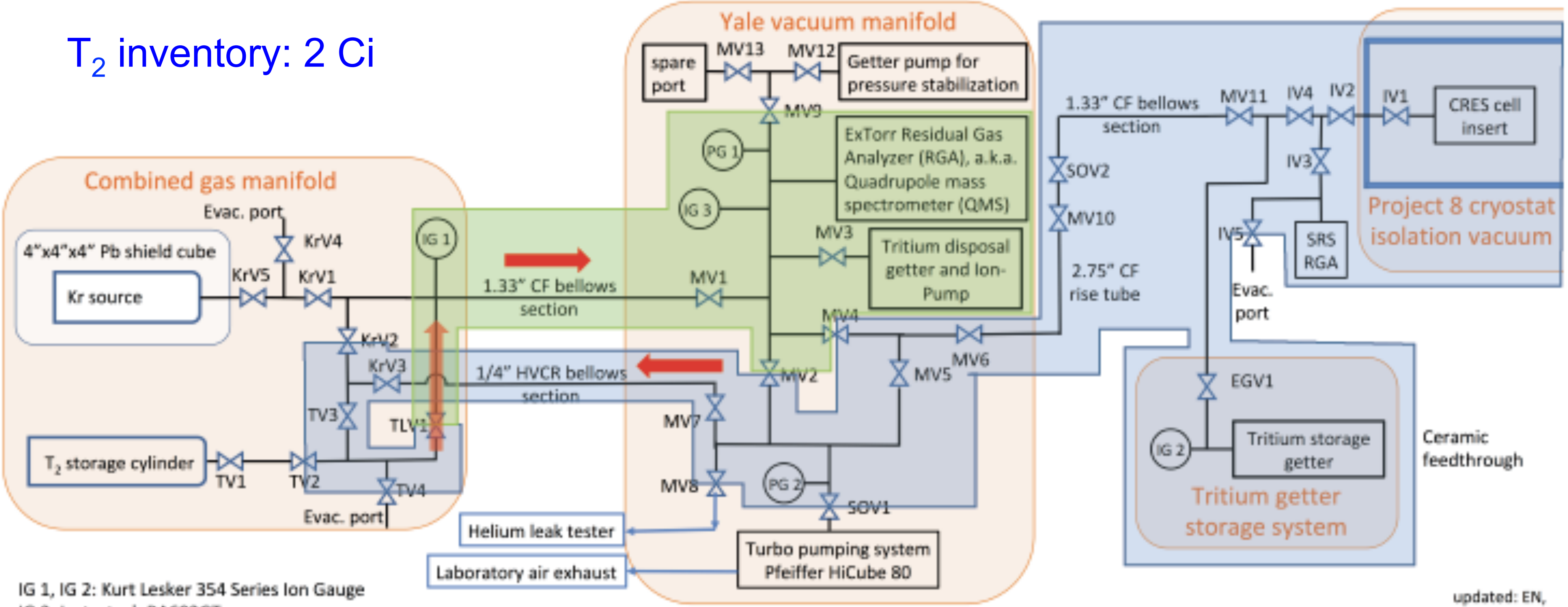
Instrumental
33 eV FWHM





Phase II Kr & T_2 gas system

T_2 inventory: 2 Ci



IG 1, IG 2: Kurt Lesker 354 Series Ion Gauge
IG 3: Instrutech BA602GT
PG 1, PG 2: Instrutech CVG101GF
SOV1: VAT 57036-GE41 (pneumatic)
SOV2: VAT 57124-GE41 (pneumatic)

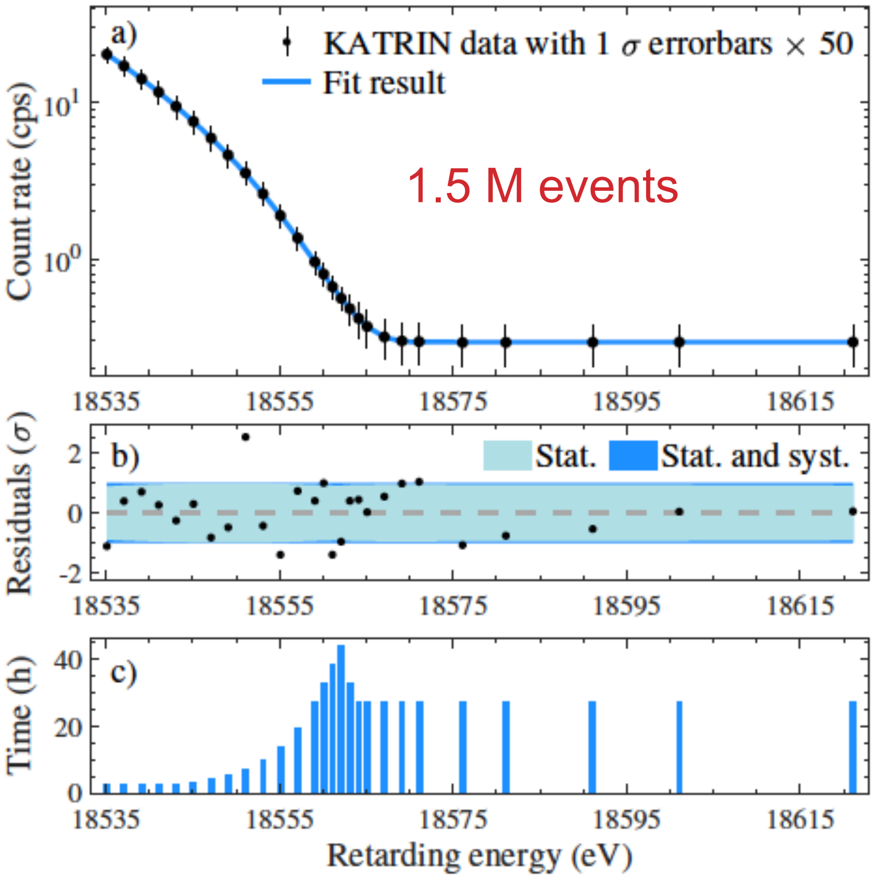
MV1-MV6, MV9: VAT 54132-GE02
IV1, IV4, MV7, MV8, MV10-11, and EGV1: VAT 54124-GE02

TV1-TV2: Swagelok SS-4BG-TW
TV3-TV4, KrV1-KrV2: Swagelok SS-4BW-V51
KrV3: Swagelok SS-4BG-V51

TLV1: VAT 59024-GEGY
QMS/RGA: Extorr XT100, SRS RGA100
IV2, IV3, 1V5: NorCal AMV_0752_CF

updated: EN, 10/28/2019

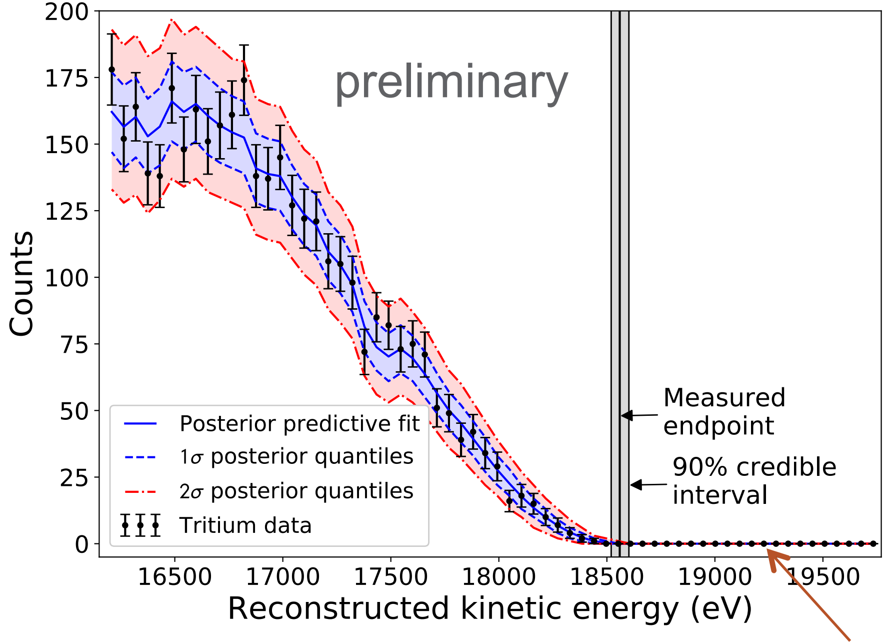
KATRIN



1.5 M events

Project 8

3770 events



Zero background events in 82 days!

KATRIN spectrometer

Project 8 Phase II
spectrometer
(to scale)

Phase III

1. Demonstrate free-space CRES detection
2. Demonstrate atomic trapping

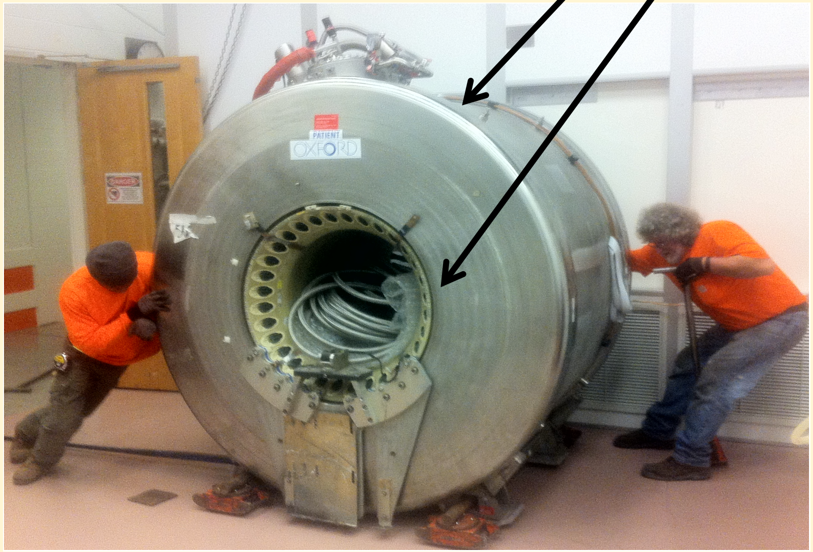
Tritium experiment at Mainz/Troitsk scale.

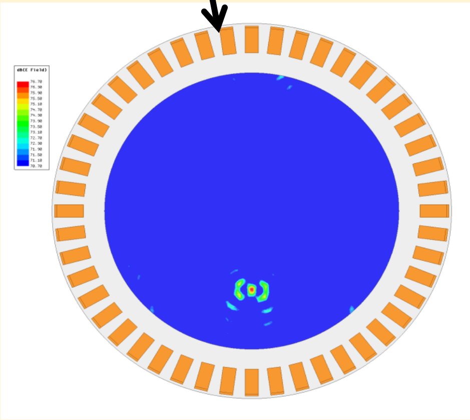
Changes from Phase II:

Large MRI magnet

200 cm^3 effective volume

Ring array of antennas

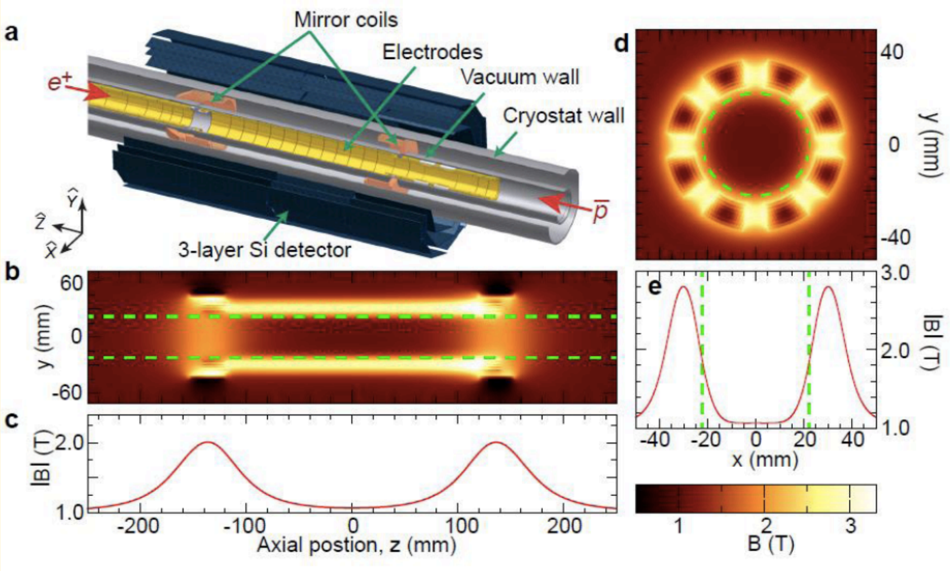




Concept: M. Jones

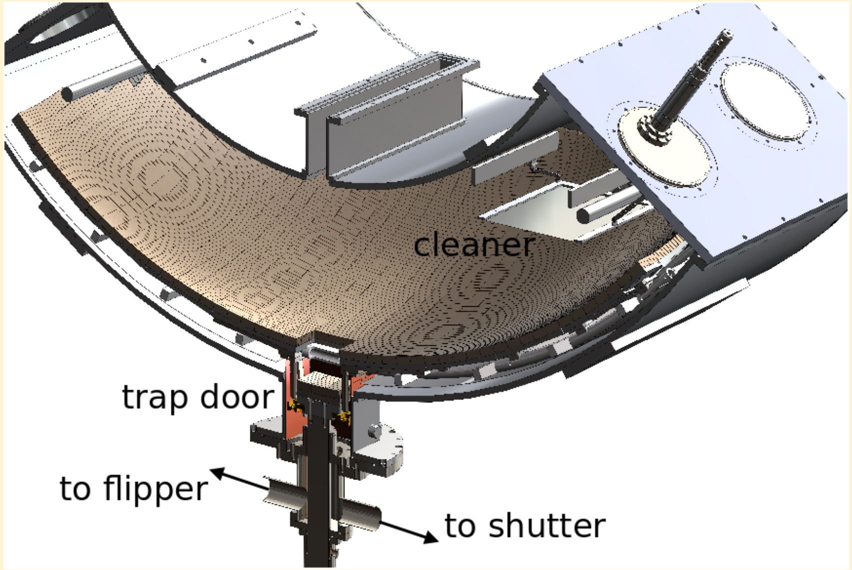
MAGNETIC TRAP FOR T

Ioffe-Pritchard trap



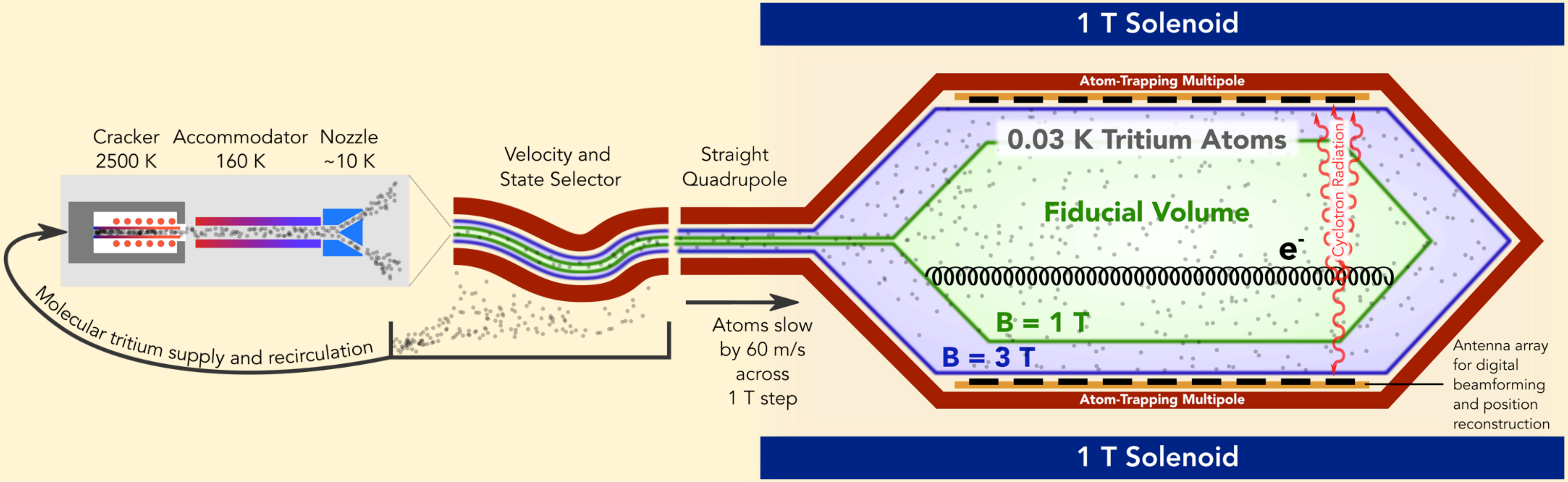
ALPHA Collaboration: Nature Phys 7:558, 2011; arXiv 1104.4982

Halbach magneto-gravitational trap



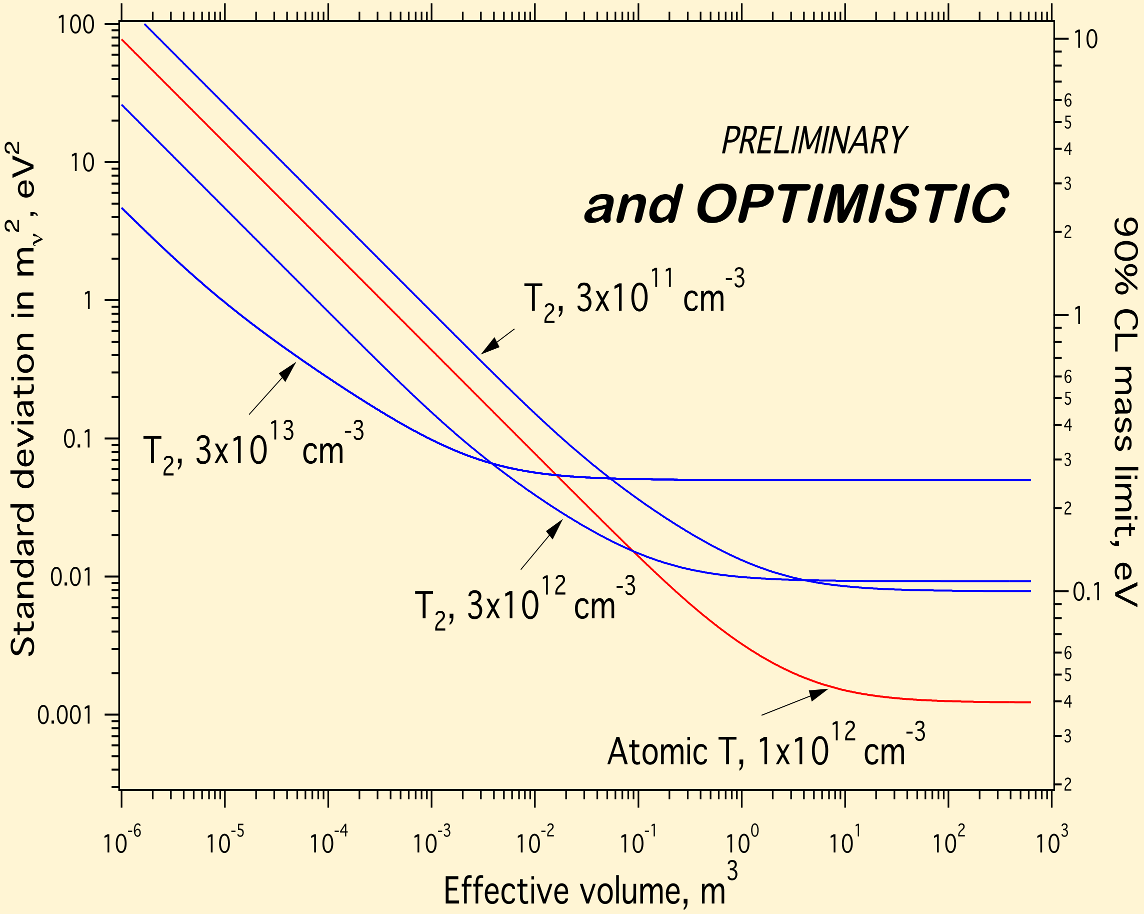
UCNtau Collaboration: Phys Rev C89, 052501, 2014; arXiv 1310.5759v3

PHASE IV CONCEPT

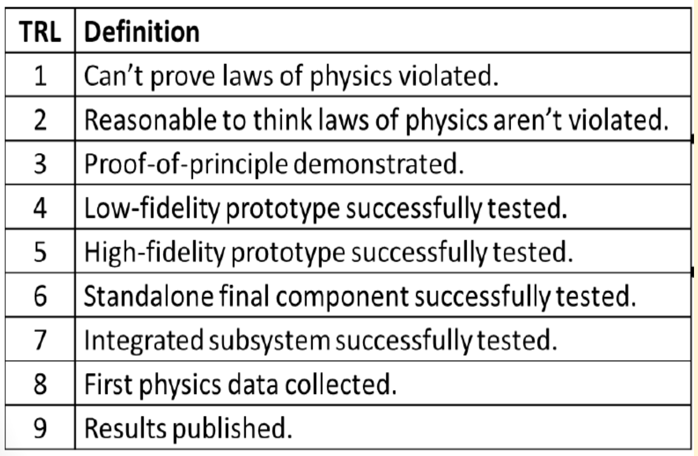


(A. Lindman)

PROJECT 8 SENSITIVITY



Technical Readiness Levels



TRL	Definition
1	Can't prove laws of physics violated.
2	Reasonable to think laws of physics aren't violated.
3	Proof-of-principle demonstrated.
4	Low-fidelity prototype successfully tested.
5	High-fidelity prototype successfully tested.
6	Standalone final component successfully tested.
7	Integrated subsystem successfully tested.
8	First physics data collected.
9	Results published.

Phase I: 9
Phase II: 8
Phase III: 2
Phase IV: 1

DIRECT MASS MEASUREMENTS…


E. Fermi

… **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.

Fin