# The Direct Road to Neutrino Mass

*Hamish Robertson, CENPA, University of Washington*

Hidden Neutrinos: Symposium
in honor of the 90th birthday of
**Frank Avignone**
May 19, 2023

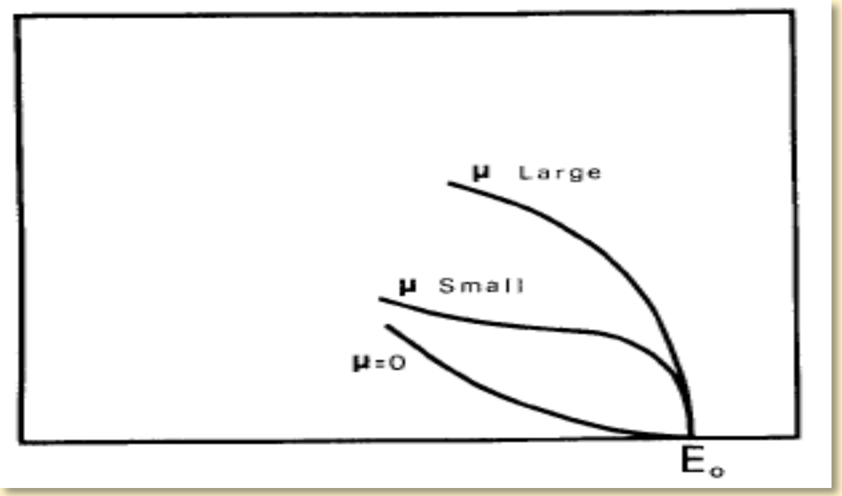
# My two favorite Italians

*Frank Avignone*

*Enrico Fermi*

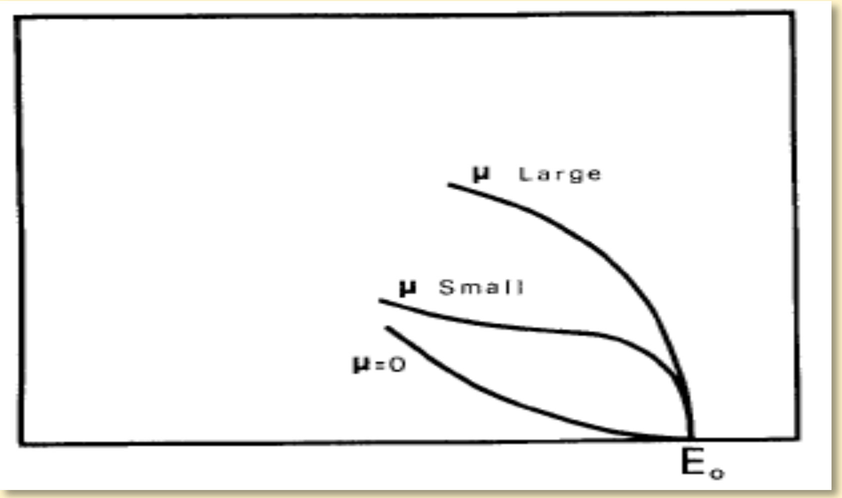
"Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron."

*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*



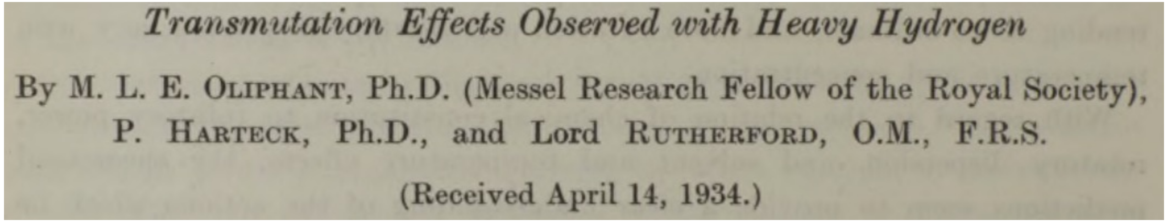
F. Wilson, Am. J. Phys. 36, 1150 (1968)

This is the "direct" method.

# TRITIUM

## Rutherford discovers tritium & $^3$He

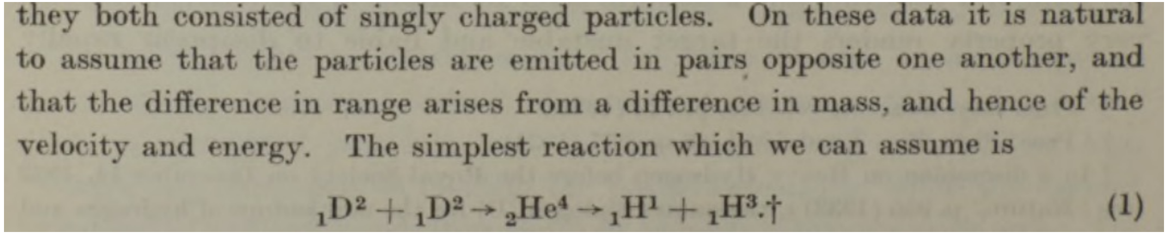
Proc. Roy. Soc. A 144, 692 (1934)



### *Transmutation Effects Observed with Heavy Hydrogen*

By M. L. E. Oliphant, Ph.D. (Messel Research Fellow of the Royal Society), P. Harteck, Ph.D., and Lord Rutherford, O.M., F.R.S.

(Received April 14, 1934.)



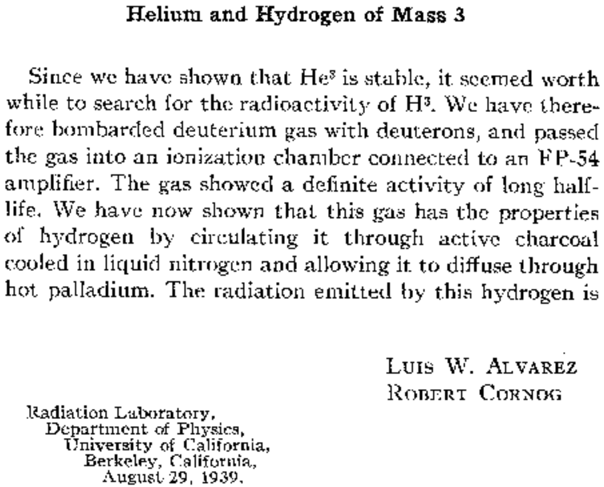
they both consisted of singly charged particles. On these data it is natural to assume that the particles are emitted in pairs opposite one another, and that the difference in range arises from a difference in mass, and hence of the velocity and energy. The simplest reaction which we can assume is

$$ {}_1D^2 + {}_1D^2 \rightarrow {}_2He^4 \rightarrow {}_1H^1 + {}_1H^3 .\dagger \quad (1)$$

But is tritium radioactive, or is $^3$He?

## Alvarez shows $^3$H is radioactive

Phys. Rev. 56, 613 (1939)



### Helium and Hydrogen of Mass 3

Since we have shown that $He^3$ is stable, it seemed worth while to search for the radioactivity of $H^3$. We have therefore bombarded deuterium gas with deuterons, and passed the gas into an ionization chamber connected to an FP-54 amplifier. The gas showed a definite activity of long half-life. We have now shown that this gas has the properties of hydrogen by circulating it through active charcoal cooled in liquid nitrogen and allowing it to diffuse through hot palladium. The radiation emitted by this hydrogen is

Luis W. Alvarez
Robert Cornog

Radiation Laboratory,
Department of Physics,
University of California,
Berkeley, California,
August 29, 1939.

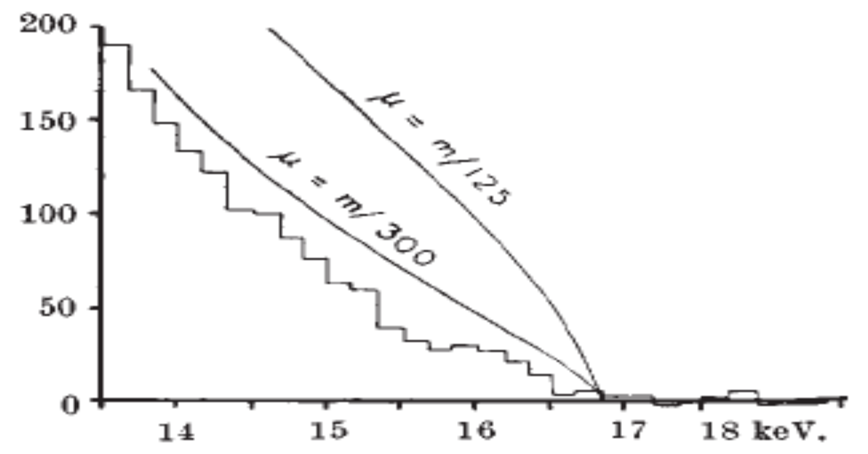
# First experiments used gaseous tritium

**Beta Spectrum of Tritium**

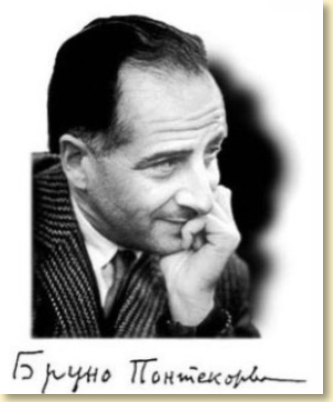
Nature 162, 302 (1948)

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

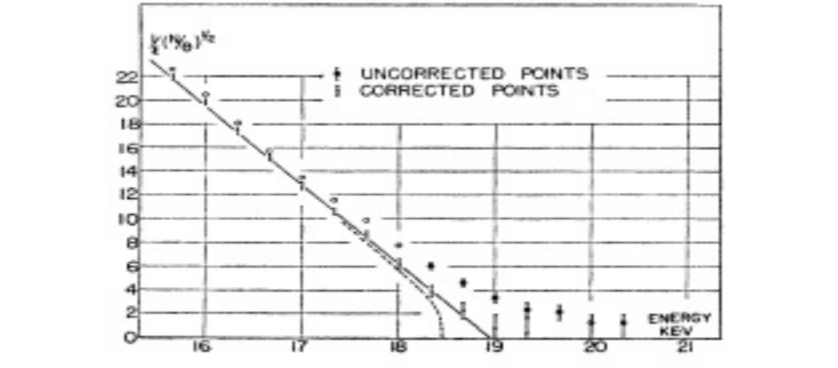
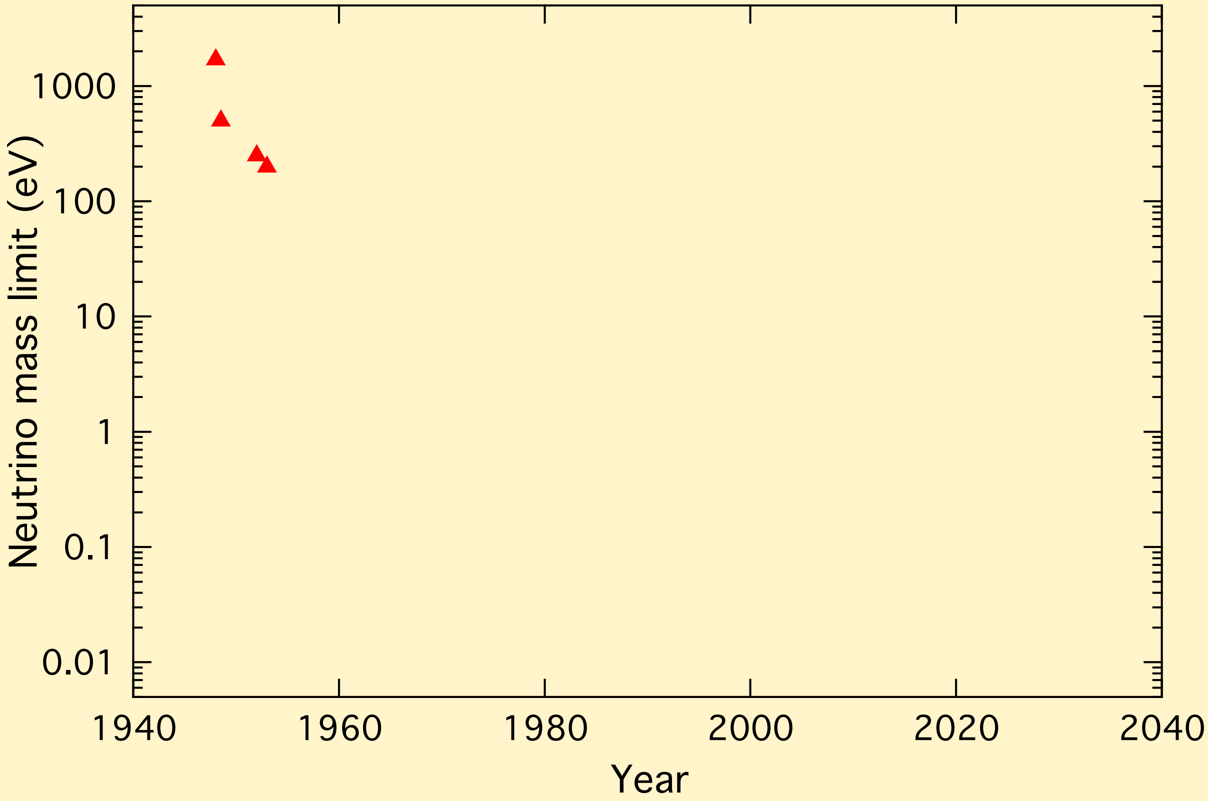
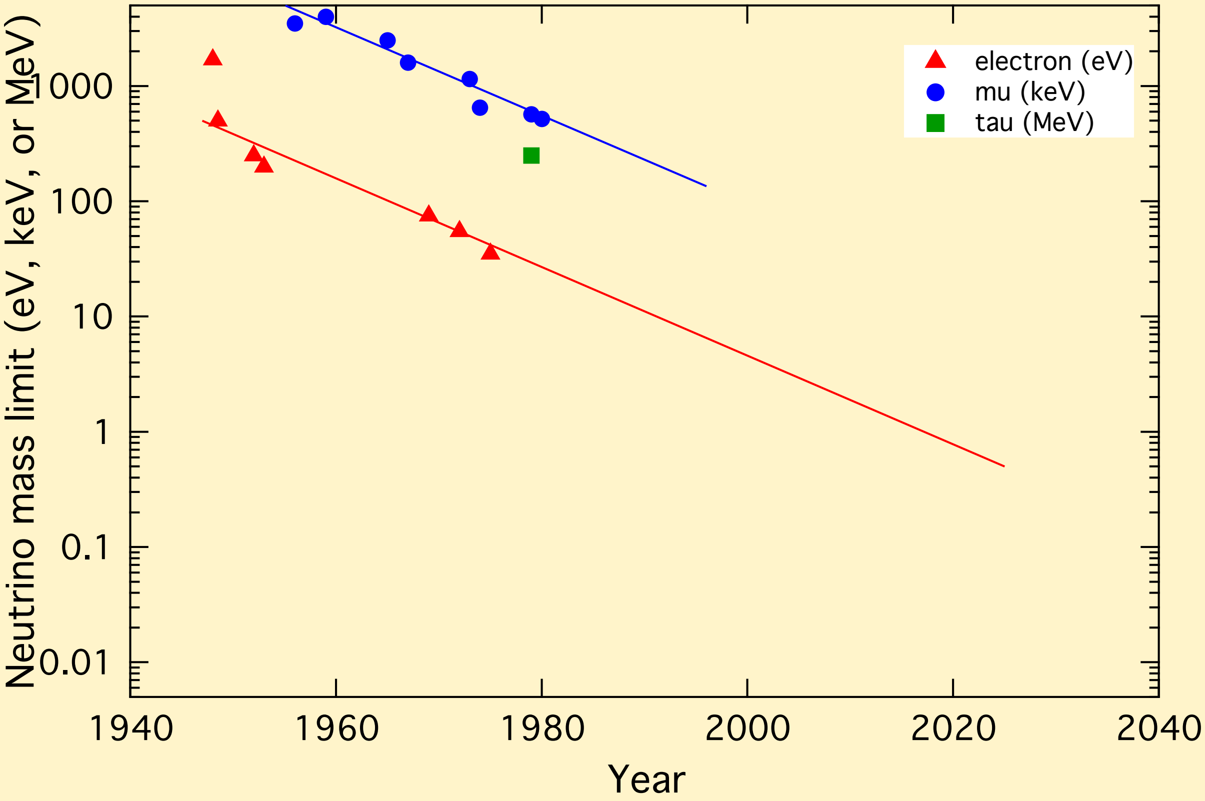


Fig. 2. "Kurie" plot of the end of the H³ spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.

# First steps on a long road



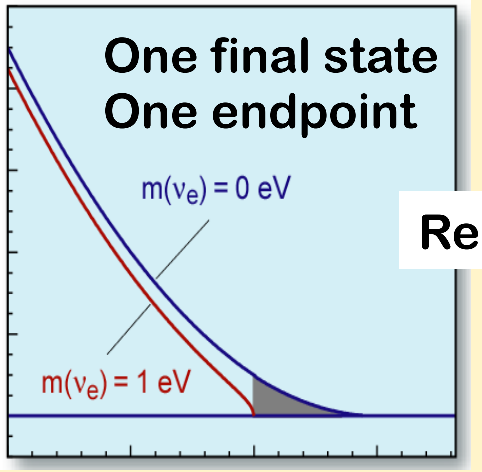
# Now 3 neutrinos



**1980:-**

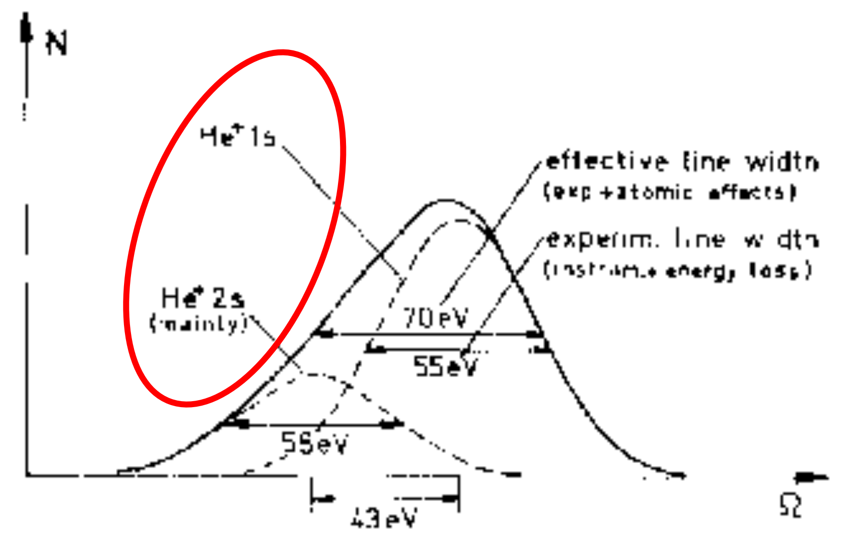
**Tom Bowles and HR plan on an atomic T experiment at Los Alamos. Soon joined by JFW.**

To determine
neutrino mass
from beta decay
the final-state
distribution must
be known.


One final state
One endpoint

Reality

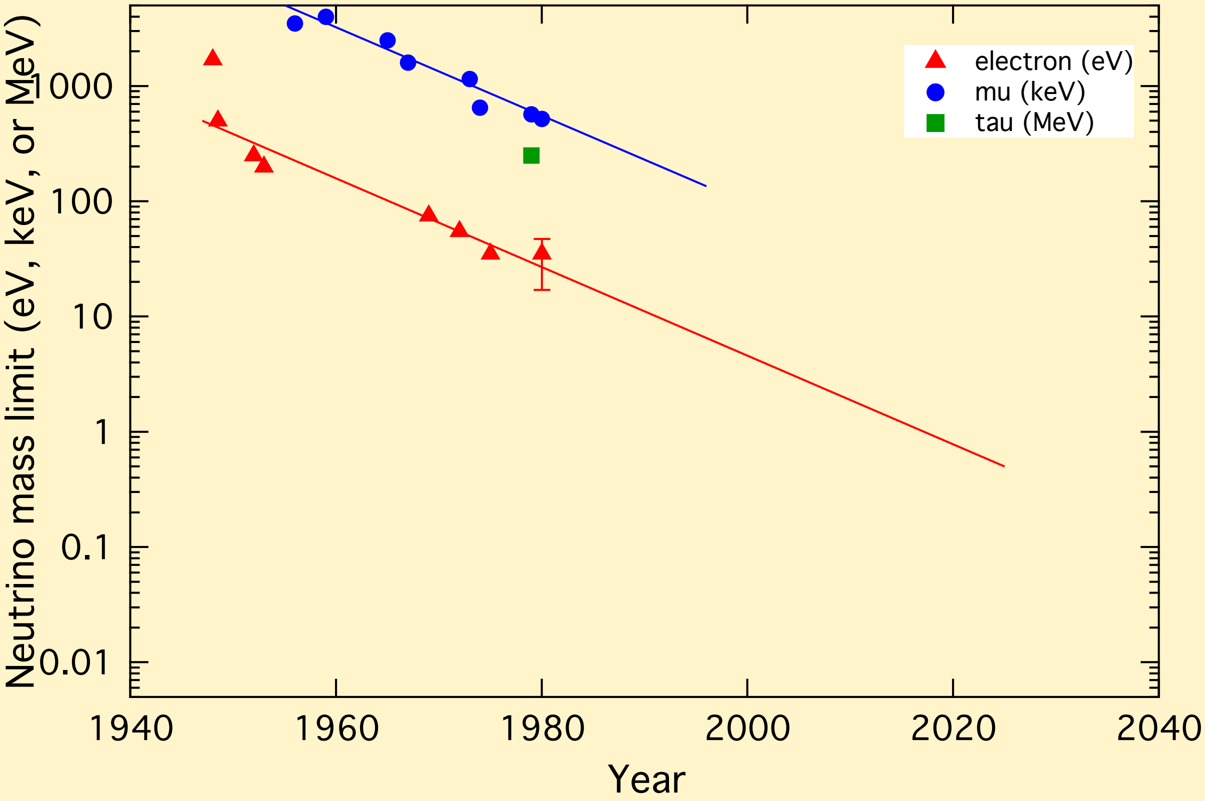
Many final states
Many endpoints



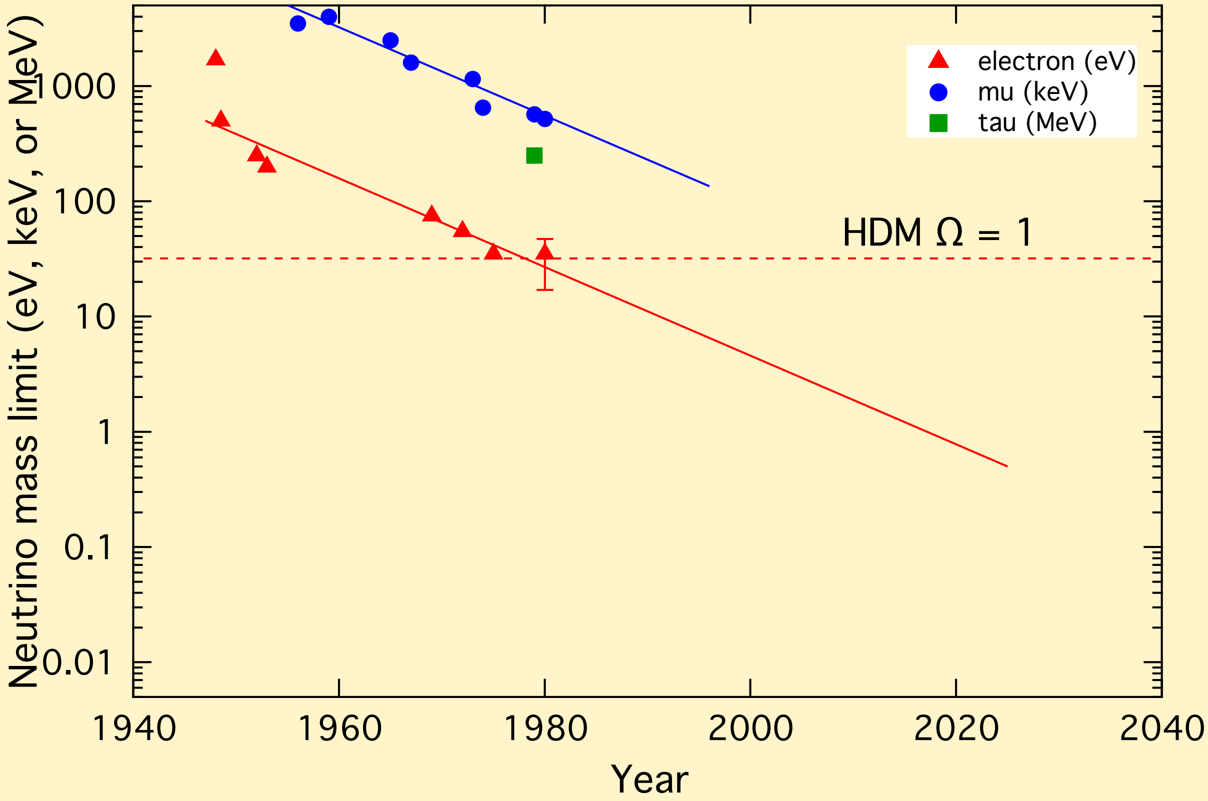
Source: T implanted in Al

K.-E. Bergkvist Nucl. Phys. B39 317 (1972)

# 1980: a signal!



# 1980: a signal! The universe is closed by $\nu_e$



# The Los Alamos Experiment:

3 kCi gaseous $T_2$, magnetic spectrometer

$m_\nu^2 = -147(79)\ \text{eV}^2$

PRL 67, 957 (1991)

0 eV

30 eV

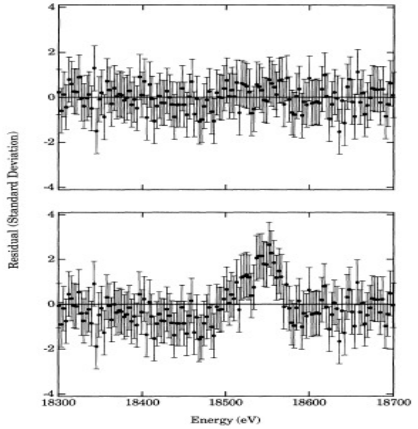
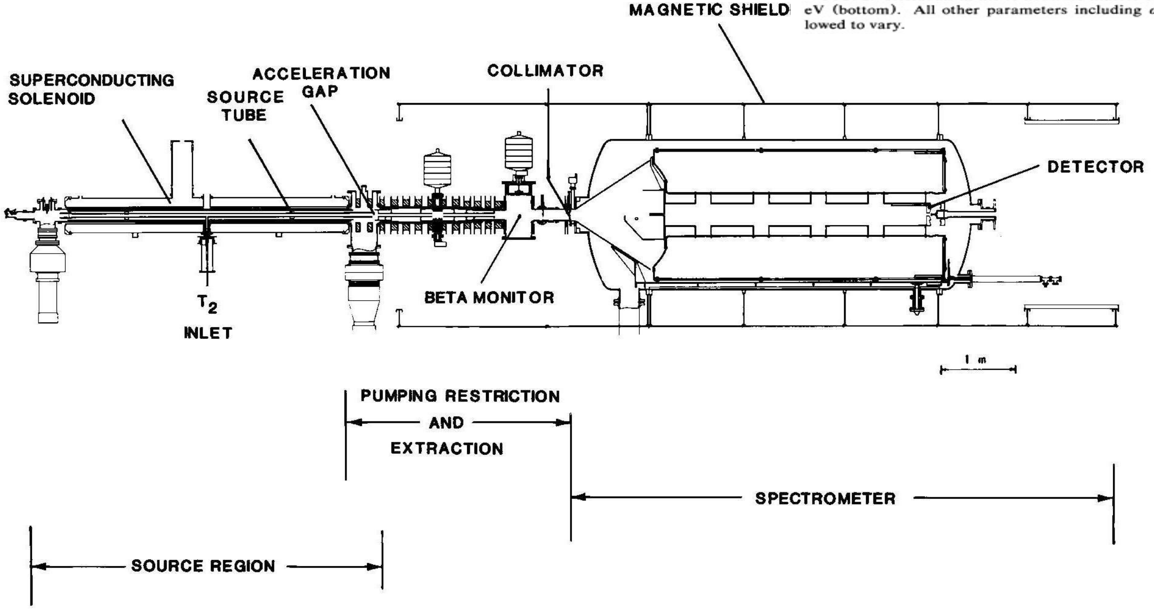
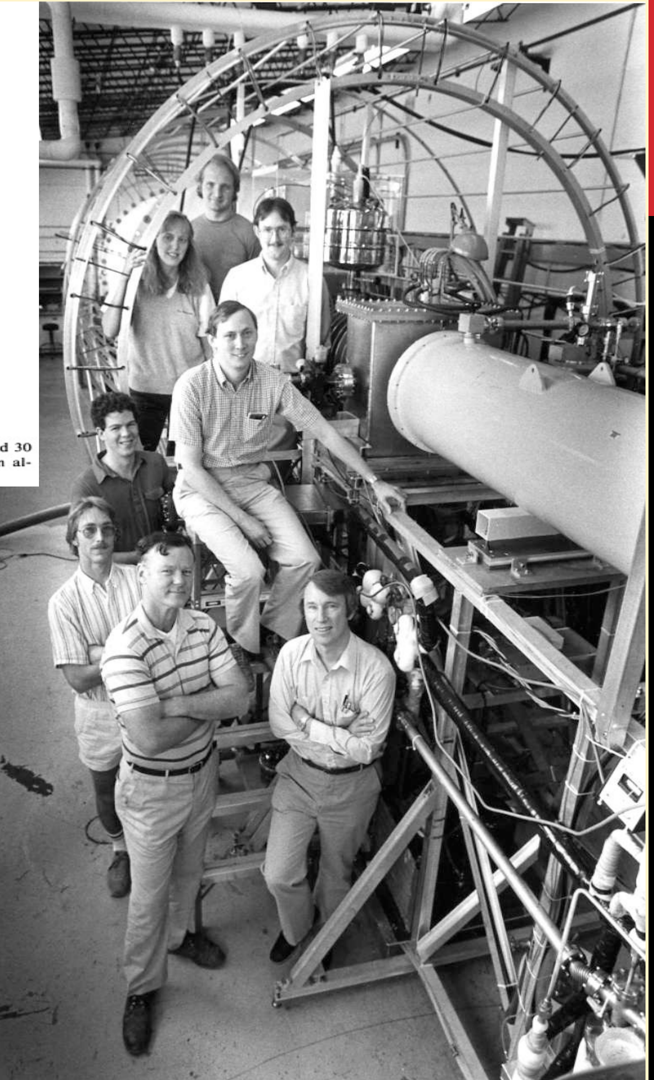


FIG. 2. Residuals in fits to neutrino masses of 0 (top) and 30 eV (bottom). All other parameters including $\alpha_1$ have been allowed to vary.





# ATOMIC TRITIUM

**In 1980 there was no good theory for the molecular final states, only the atom.**

**We set out to use atomic T. We failed for 5 reasons:**

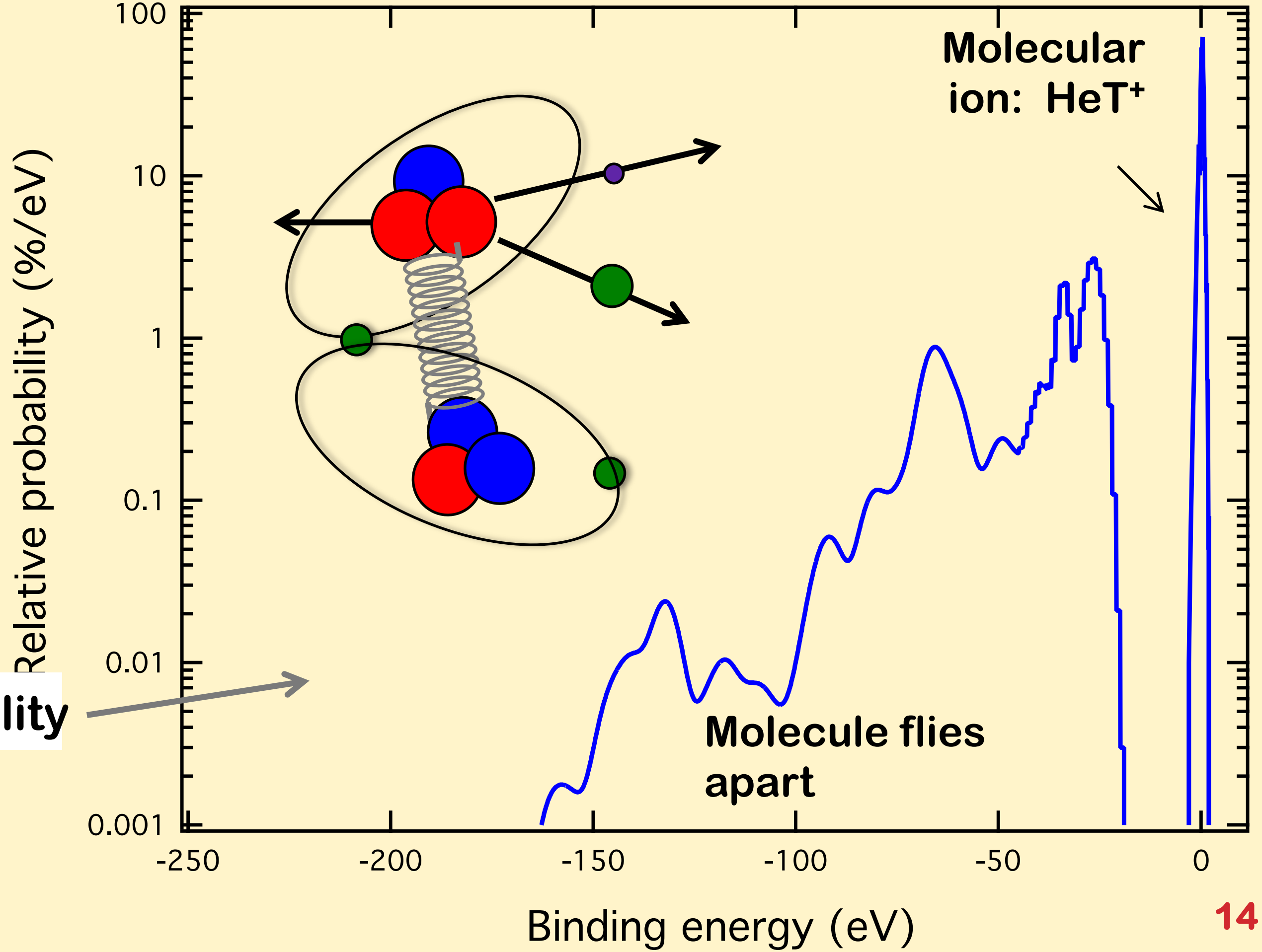
1. **RF dissociator had a lifetime ~ days.** ***(we know why now)***
2. **Severe loss of inventory ~ days.** ***(same thing)***
3. **RF got into all the electronics.**
4. **Different endpoints makes $T_2$ a tough background.**
5. **T density in source low.**

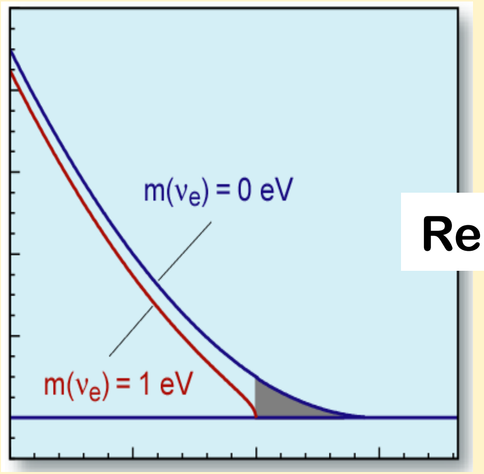
**We retreated to $T_2$. By 1985 theory became available.**

**And, in the end, it got us.**

**To determine neutrino mass from $T_2$ decay the final-state distribution must be known.**

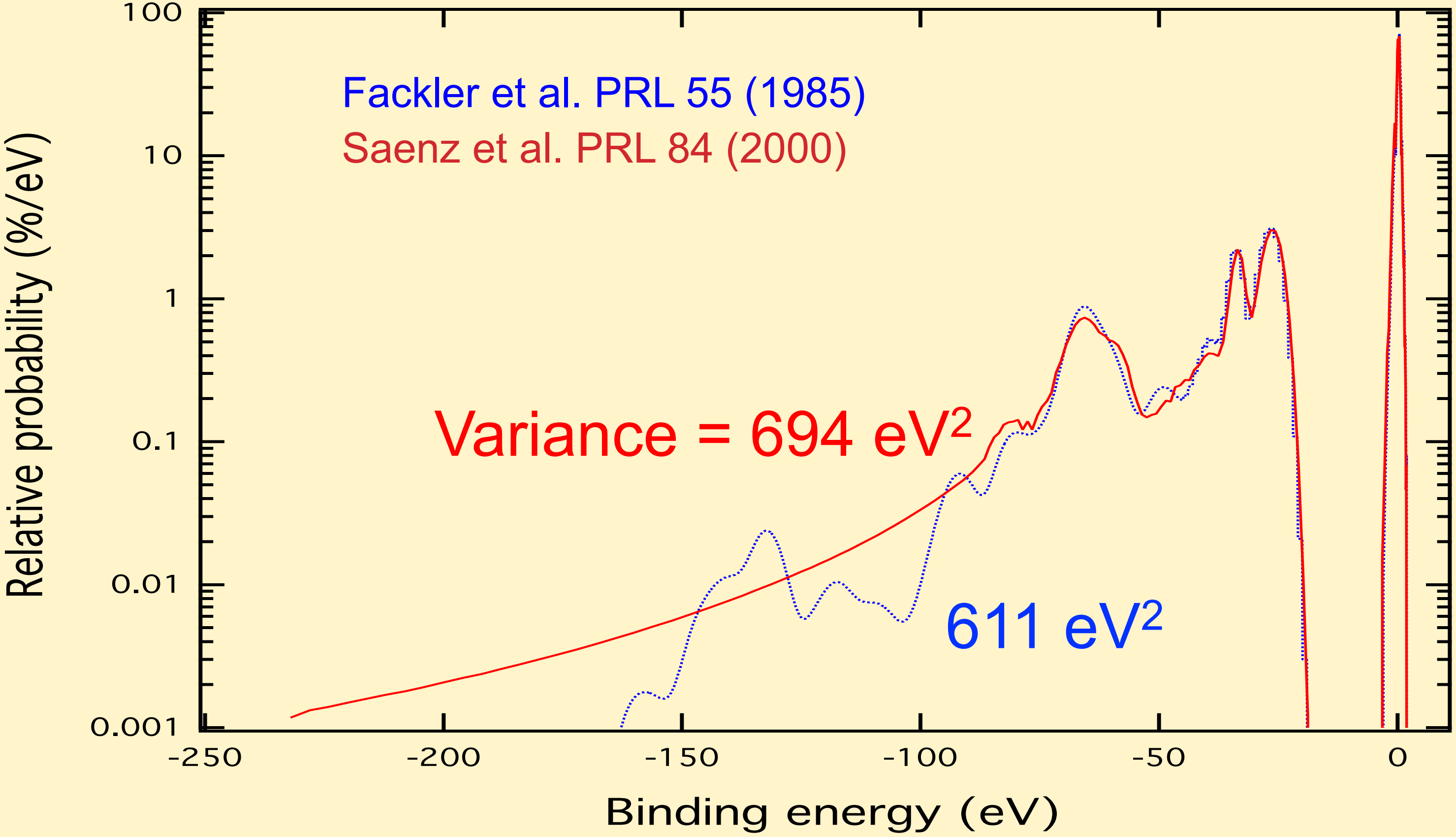
Fackler et al. PRL 55 (1985)

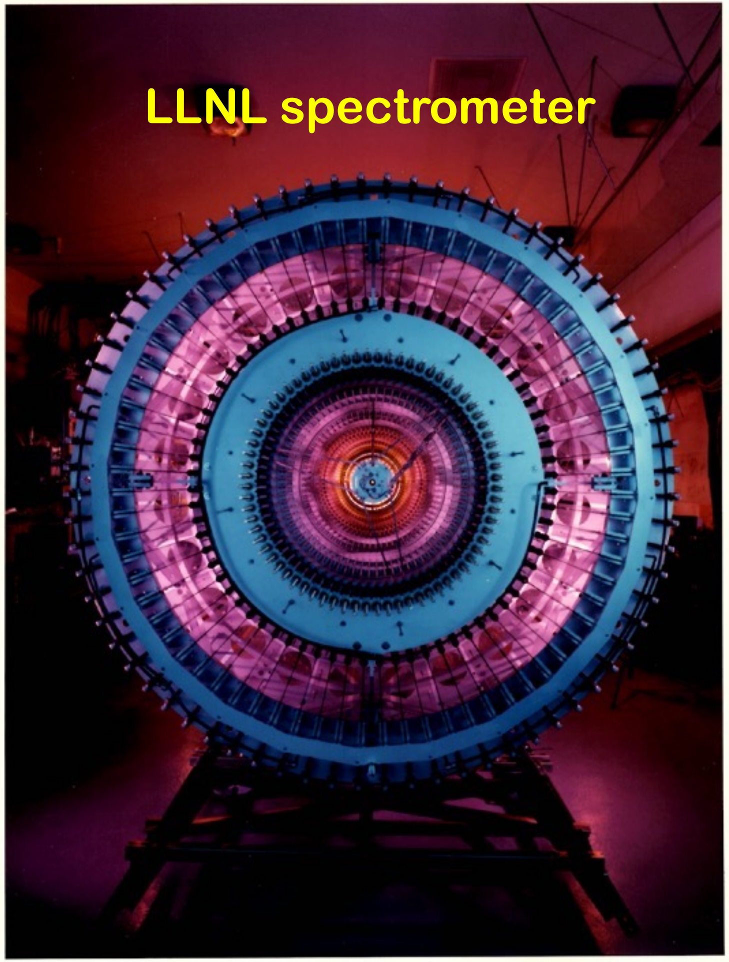




**Reality**

# 1996-2000: NEW THEORY



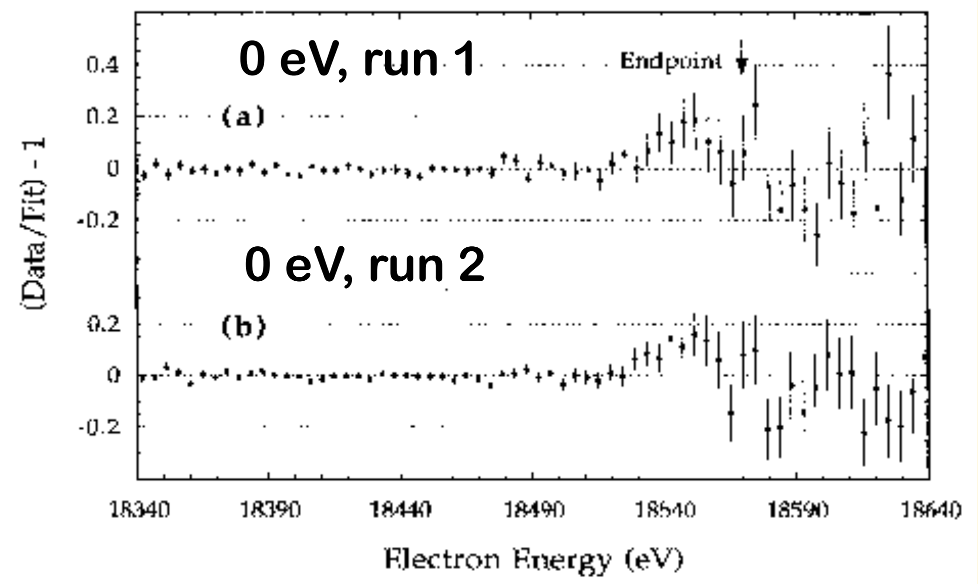


# The Livermore Experiment:

Gaseous $T_2$,
magnetic
spectrometer

$m_\nu^2 = -130(25)\ \mathrm{eV}^2$
PRL 75, 3237 (1995)

Wolfgang Stoeffl

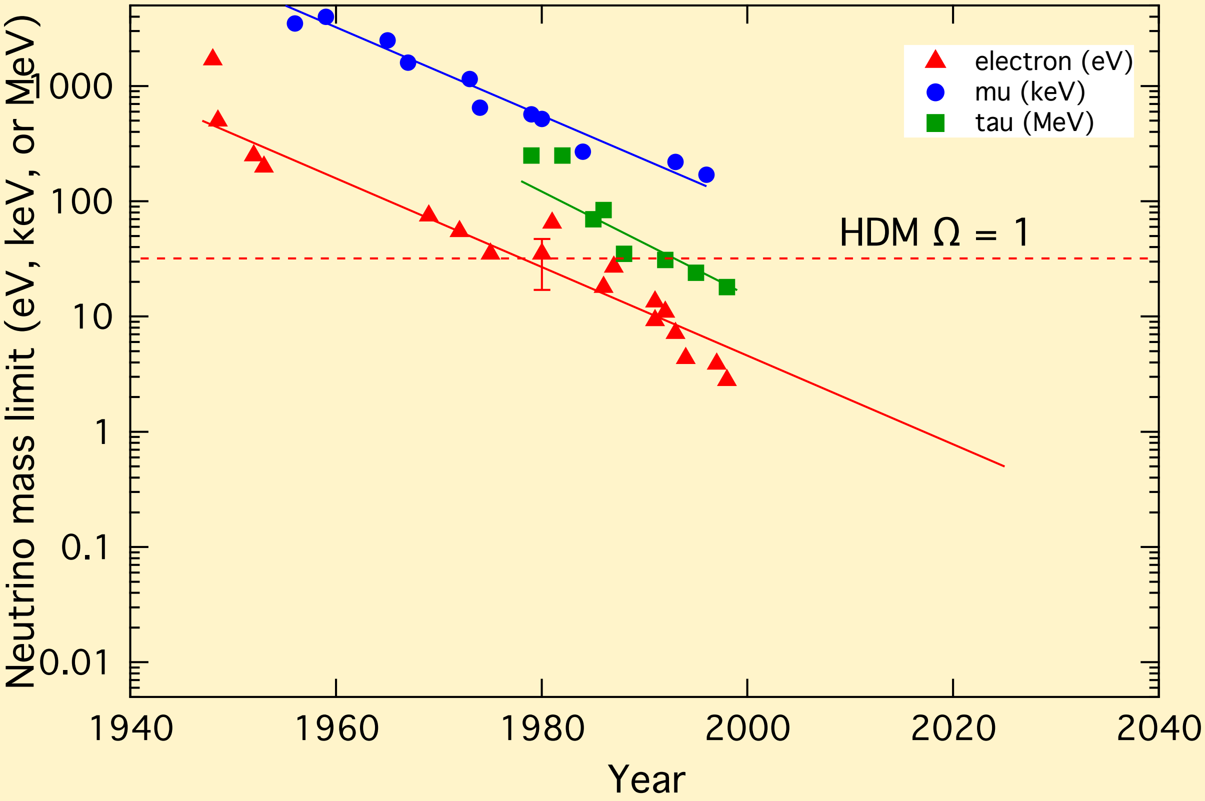


# 2015: AN OLD MYSTERY SOLVED

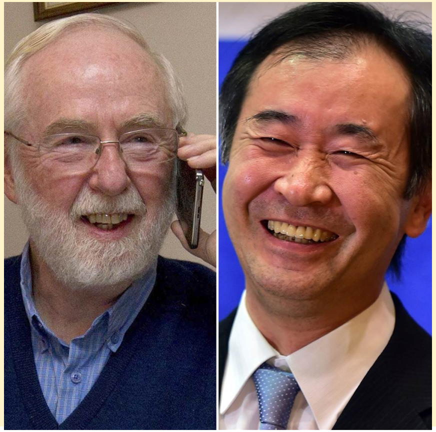
| **Theory** | Fackler et. al. 1985 | Variance = 611 $eV^2$ | |
|---|---|---|---|
| | Saenz et. al. 2000 | Variance = 694 $eV^2$ | |
| | Difference | - 83 $eV^2$ | |
| | $\Delta m_\nu^2$ = - 2 X difference | | + 167 $eV^2$ |
| | | **As published** | **Re-evaluated** |
| LANL | $m_\nu^2$ = | - 147(79) $eV^2$ | 20(79) $eV^2$ |
| LLNL | $m_\nu^2$ = | - 130(25) $eV^2$ | 37(25) $eV^2$ |

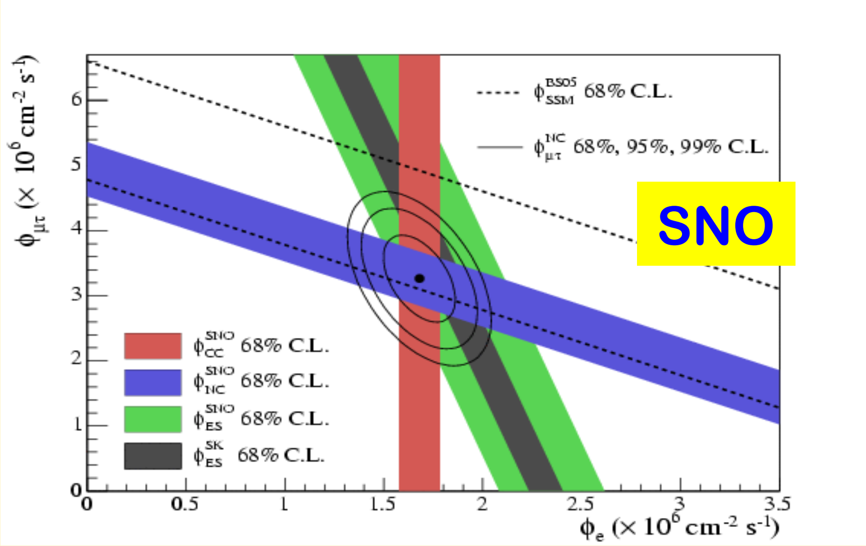
Bodine, Parno, HR; PRC **91** 035505 (2015)

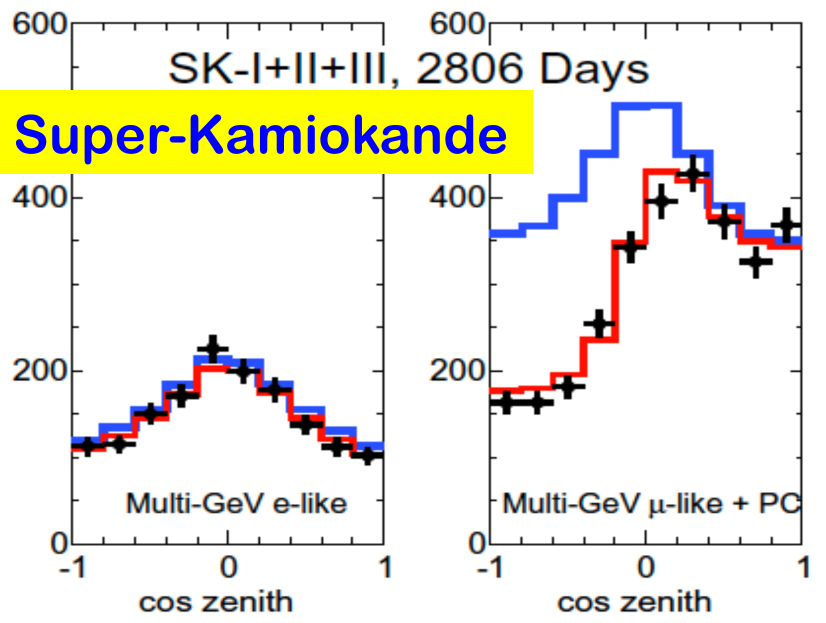
# 1980 – 2000: many experiments, no signal.

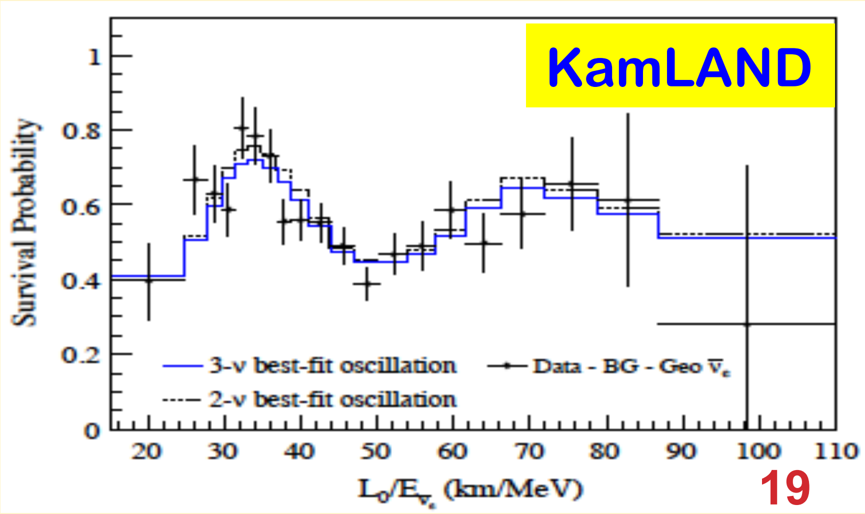


# Neutrinos oscillate, have mass

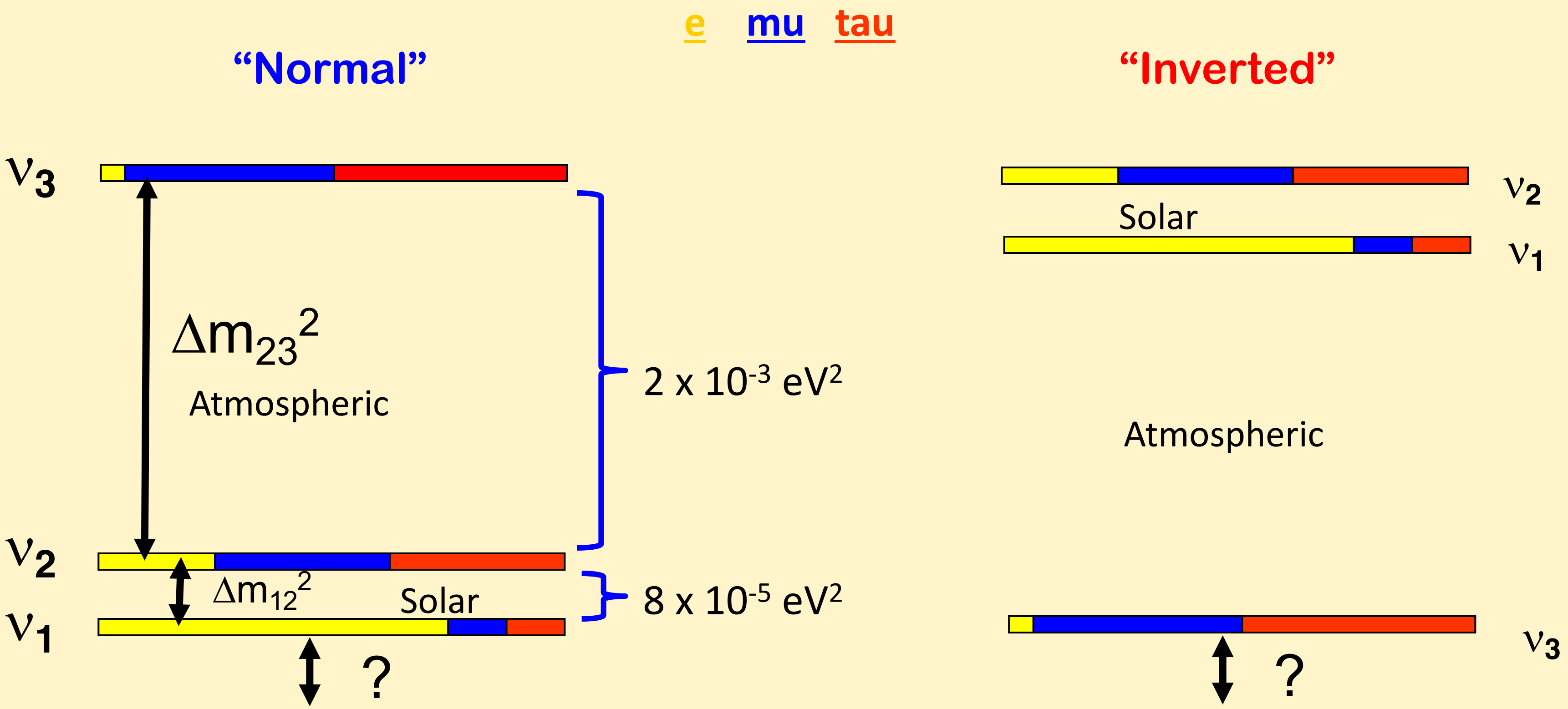



**SNO**

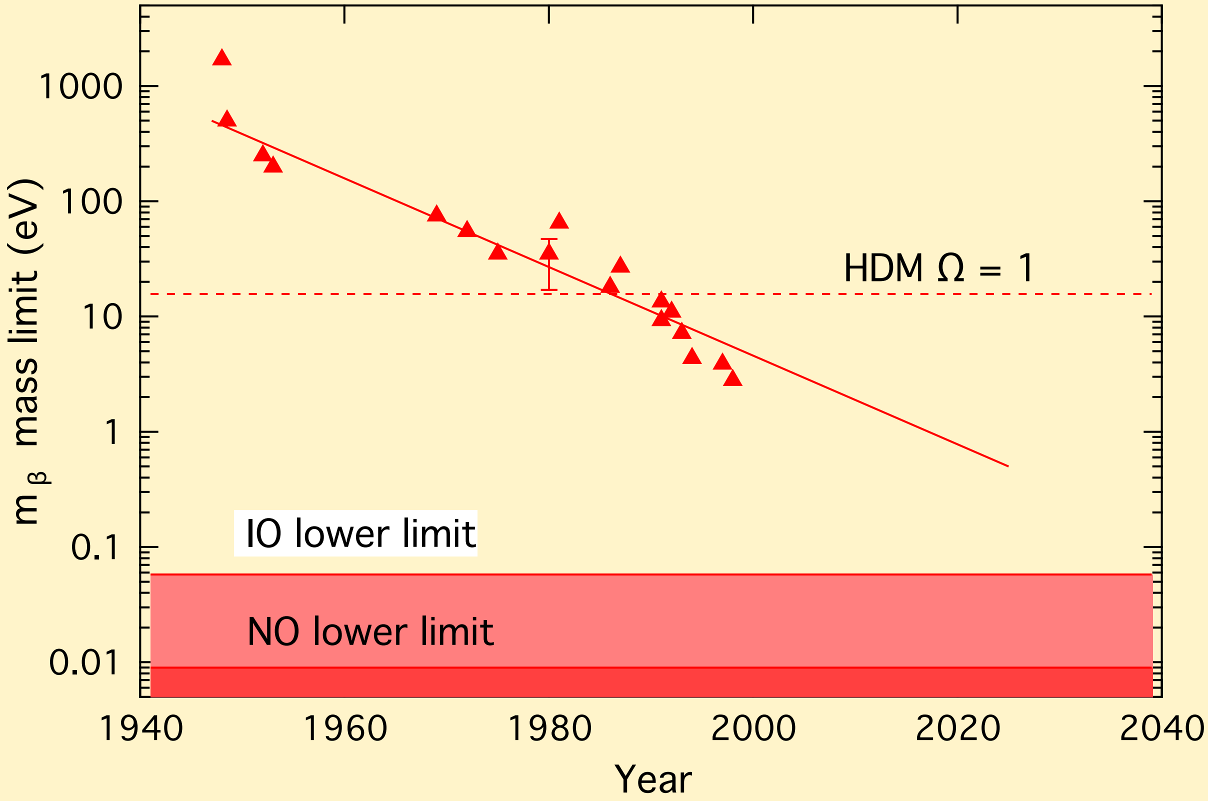

**Super-Kamiokande**


**KamLAND**

# NEUTRINO MASSES AND FLAVOR CONTENT

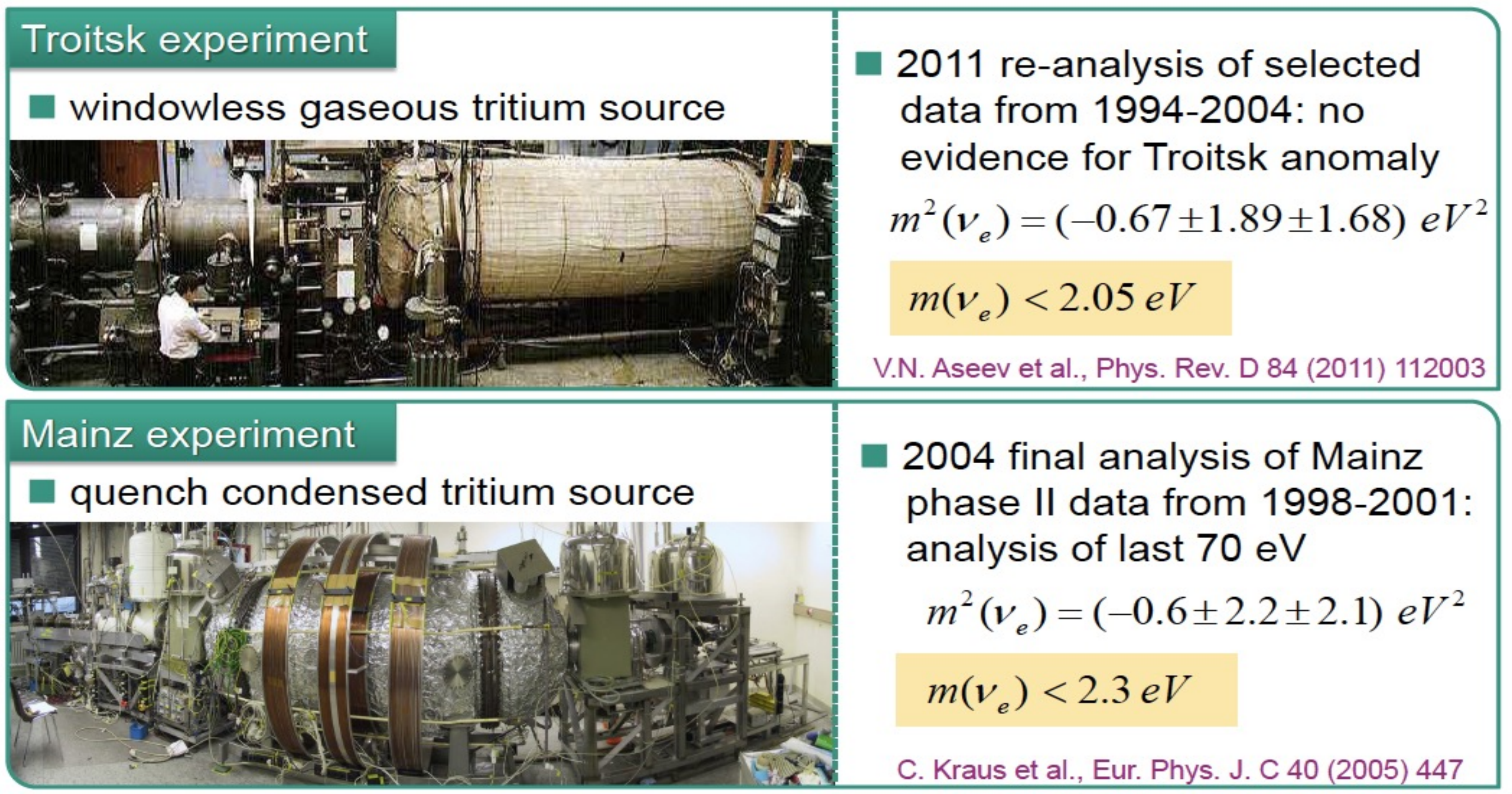


# 2000: Mass of $\nu_e \rightarrow m_\beta \sim m_1$. Tritium is key.



# 1995 – 2025: THE MAC-E FILTER ERA

$m_\nu < 2$ eV



**Troitsk experiment**

- windowless gaseous tritium source

- 2011 re-analysis of selected data from 1994-2004: no evidence for Troitsk anomaly

$$m^2(\nu_e) = (-0.67 \pm 1.89 \pm 1.68)\ eV^2$$

$$m(\nu_e) < 2.05\ eV$$

V.N. Aseev et al., Phys. Rev. D 84 (2011) 112003

**Mainz experiment**

- quench condensed tritium source

- 2004 final analysis of Mainz phase II data from 1998-2001: analysis of last 70 eV

$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1)\ eV^2$$

$$m(\nu_e) < 2.3\ eV$$

C. Kraus et al., Eur. Phys. J. C 40 (2005) 447

## STORY SO FAR:

- **Neutrinos DO have mass, and the average for the 3 must lie between 2 and 0.02 eV.**
- **Cosmological comments.**

## NOW:

- **The KATRIN experiment.**

## FUTURE:

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

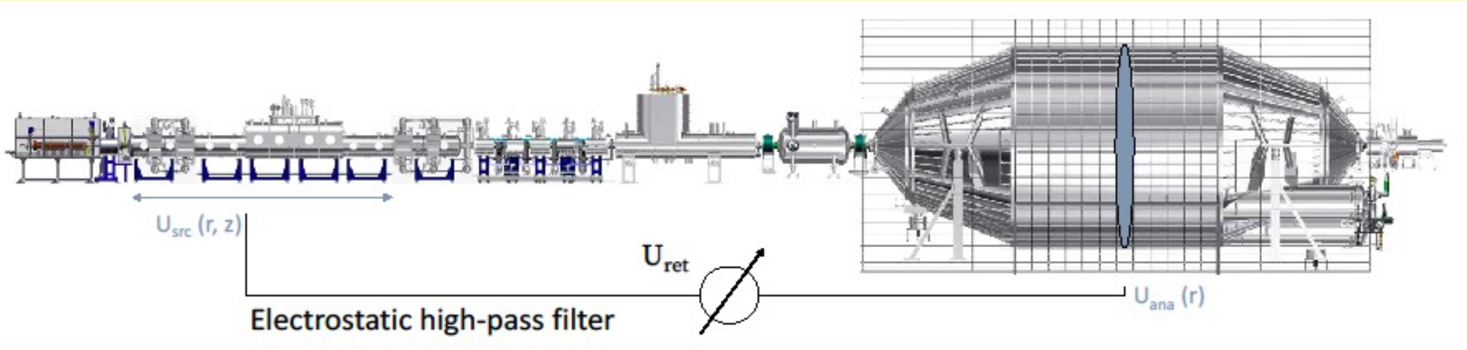
# The KATRIN Collaboration

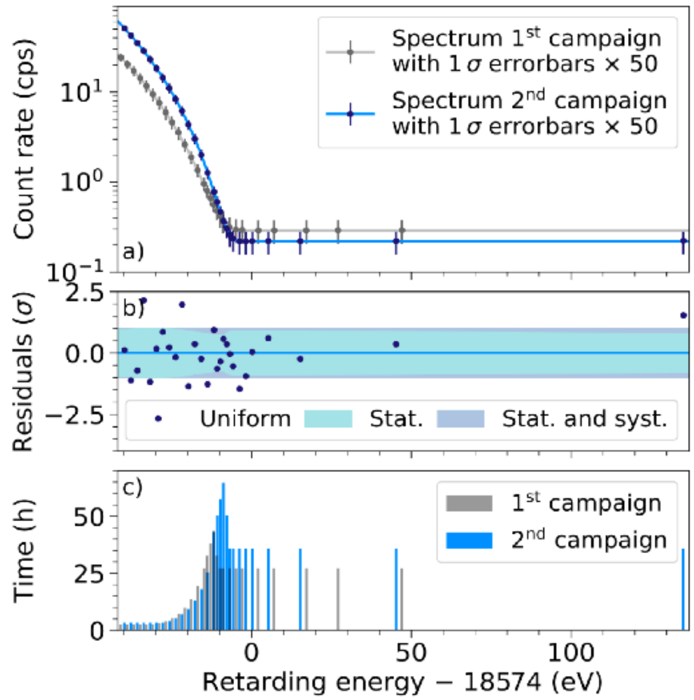
# KATRIN

**2001:** Collaboration of all previous $T_2$ groups (except LLNL)

**2023:** $m_\beta < 0.8$ eV

A. Onillon,
T. Laserre





**First campaign:**

[Aker et al., PRL 123 (2019) 22, 221802]

- **Total statistic: 2 million events**
- **Best fit:** $m_\nu^2 = \left(-1.0^{+0.9}_{-1,1}\right)$ eV²
- **Limit:** $m_\nu < 1.1$ eV (90% CL)

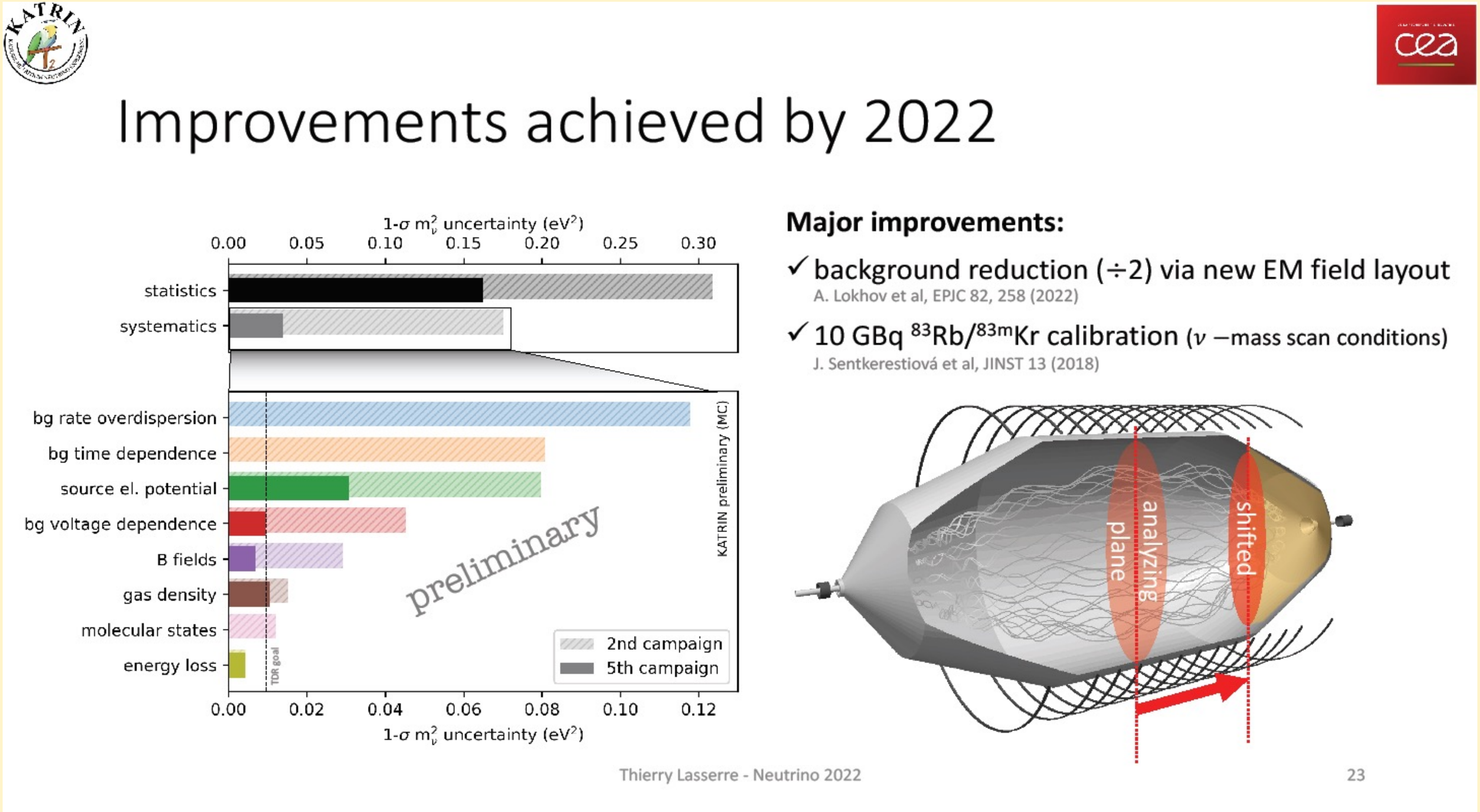
**Second campaign:**

[Aker et al., Nature Phys. 18 (2022) 2, 160-166]

- **Total statistic: 4.3 million events**
- **Best fit:** $m_\nu^2 = \left(0.26^{+0.34}_{-0,34}\right)$ eV²
- **Limit:** $m_\nu < 0.9$ eV (90% CL)

**Combined result:** $m_\nu < 0.8$ eV (90% CL)

# KATRIN’s viselike grip on systematics is key



## Improvements achieved by 2022

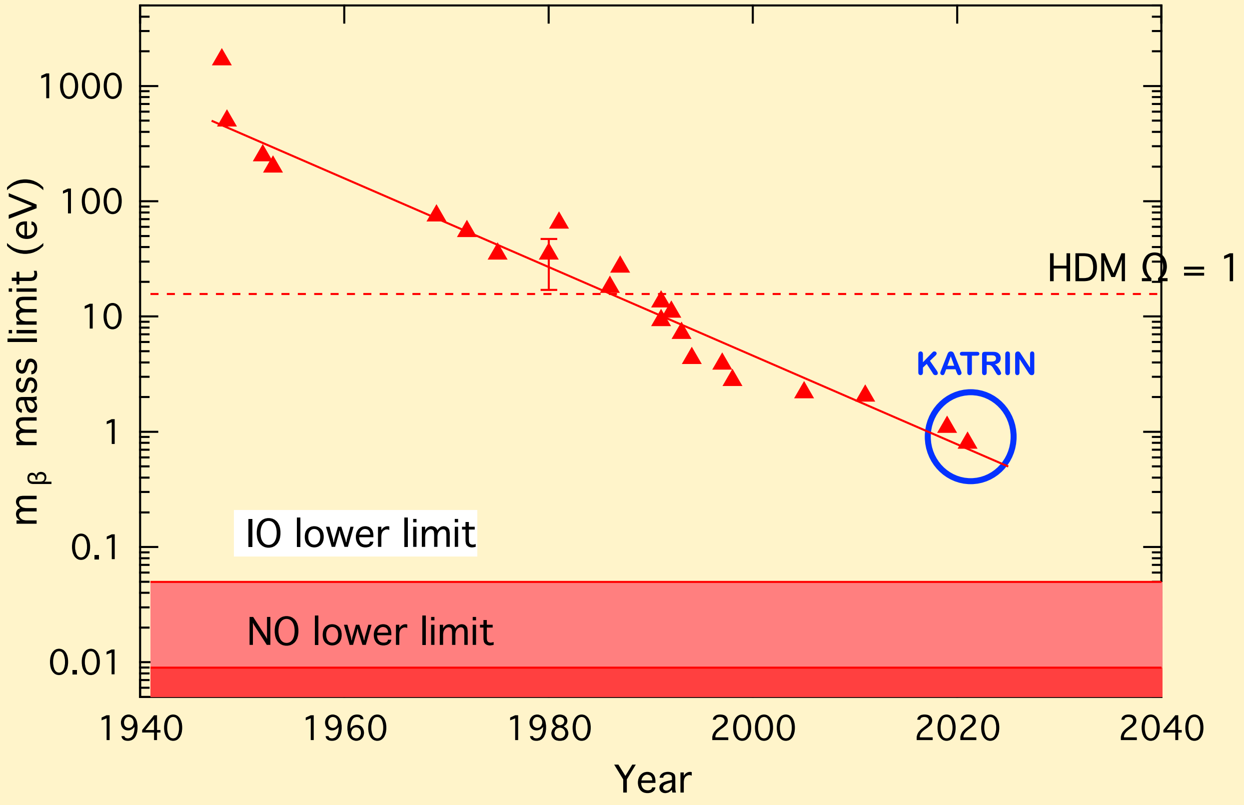
**Major improvements:**

- ✓ background reduction (÷2) via new EM field layout
  A. Lokhov et al, EPJC 82, 258 (2022)
- ✓ 10 GBq $^{83}$Rb/$^{83m}$Kr calibration ($\nu$ –mass scan conditions)
  J. Sentkerestiová et al, JINST 13 (2018)

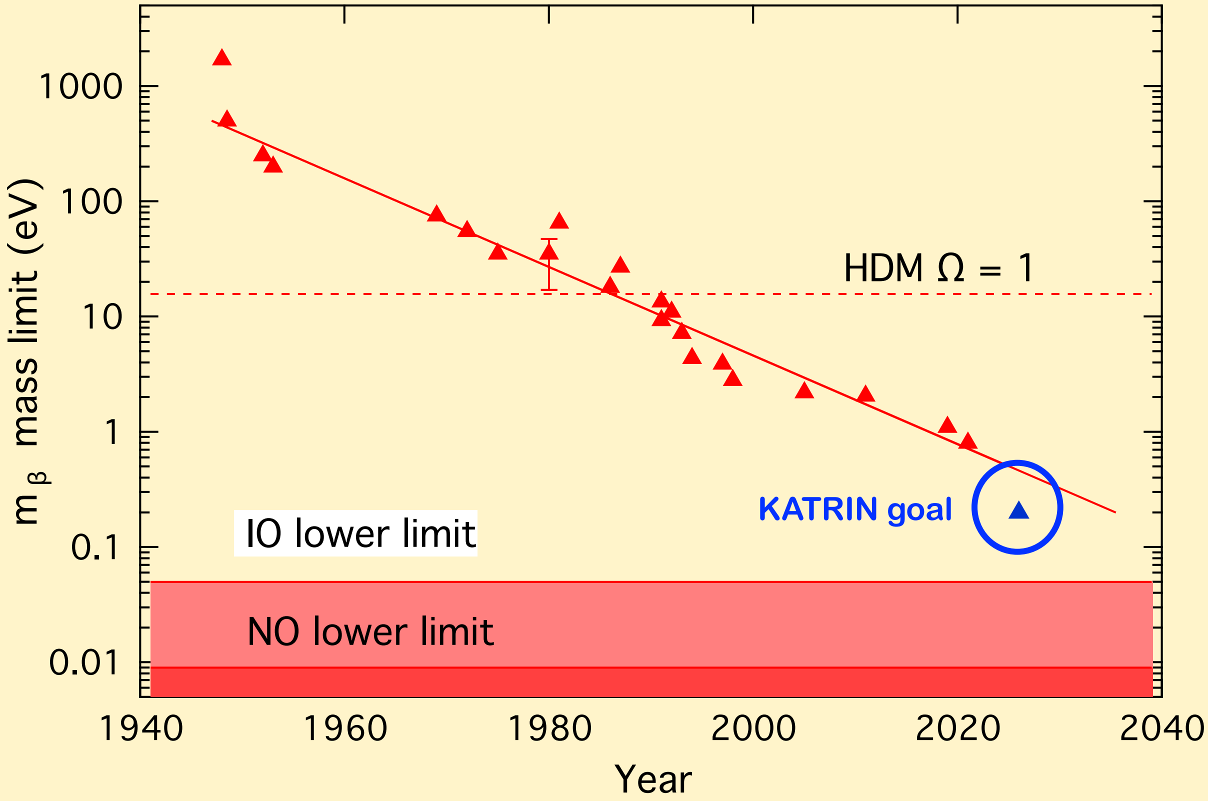
Thierry Lasserre - Neutrino 2022

23

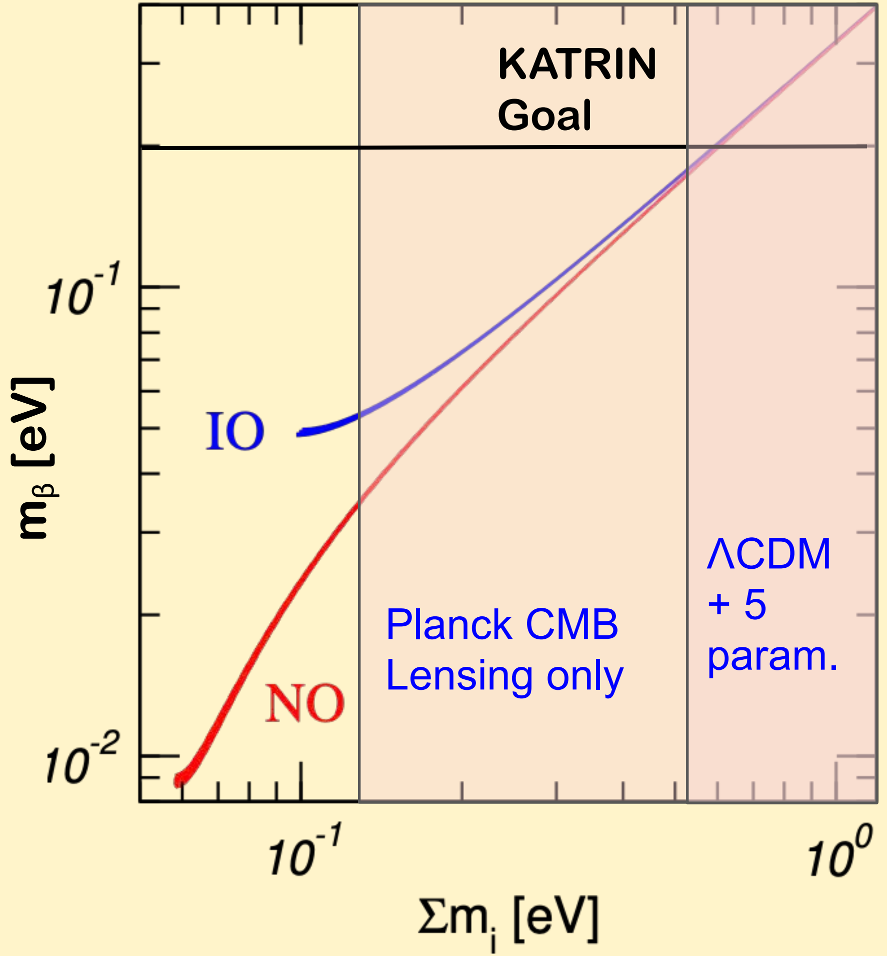
# 2000 – 2023: tritium rules.



# 2000 – 2023: tritium rules.



# Neutrinos in the cosmos



# 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.

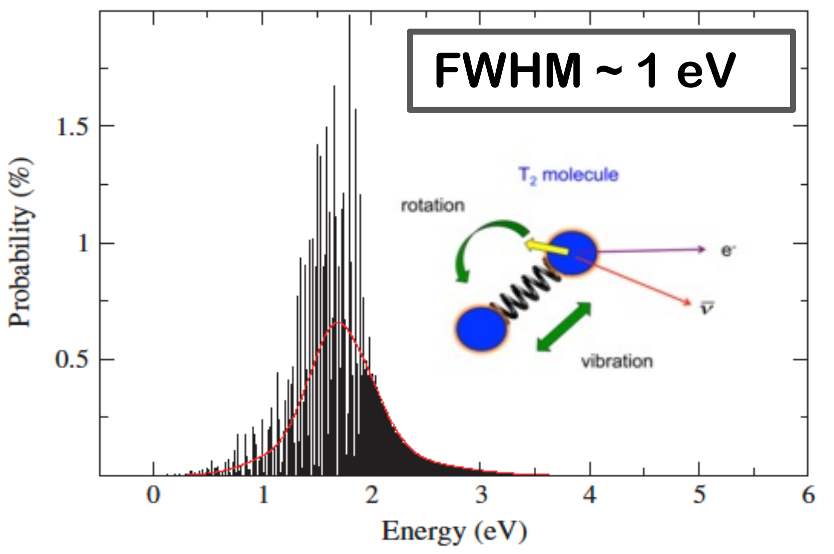
**Statistics**

Size of experiment now: 10 m diam.

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

Next diameter: 300 m!

**Systematics**



Molecular rotation and vibration

**Theory: Saenz et al. 2000,**
**Doss & Tennyson 2006**

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

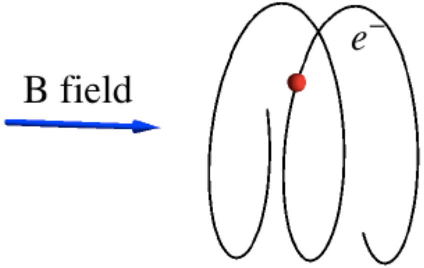
(B. Monreal and J. Formaggio, PRD 80:051301, 2009)

*Arthur Schawlow*
*(co-inventor of laser)*

***Only measure frequency!***

Cyclotron motion:

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



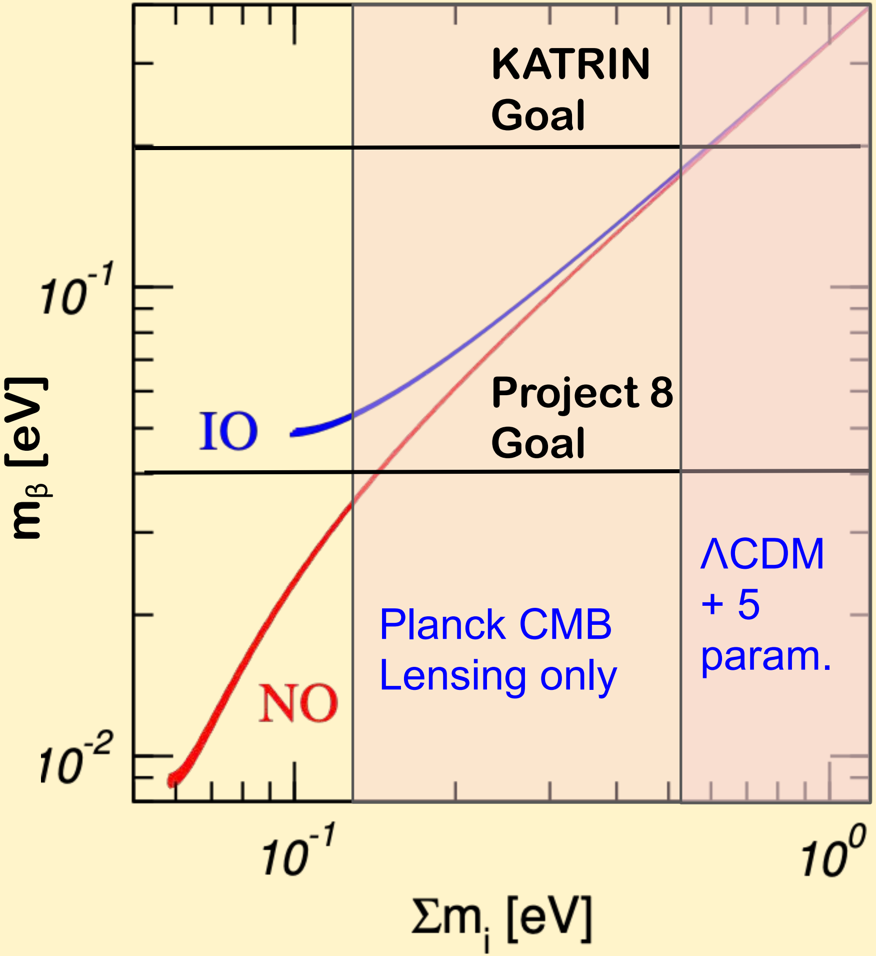
$$f_c = 27\,992.491\,10(6)\ \mathrm{MHz\,T^{-1}}$$

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

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

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

# Neutrinos in the cosmos



# THE PROJECT 8 COLLABORATION

**Case Western Reserve University**
- Razu Mohiuddin, Benjamin Monreal, Yu-Hao Sun

**University of Illinois**
- Chen-Yu Liu

**Indiana University**
- Walter Pettus

**Johannes Gutenberg-Universität Mainz**
- Sebastian Böser, Martin Fertl, Alec Lindman, Christian Matthé, Brunilda Mucogllava, René Reimann, Florian Thomas, Larisa Thorne

**Karlsruher Institut für Technologie**
- Thomas Thümmler

**Lawrence Livermore National Laboratory**
- Kareem Kazkaz

**Massachusetts Institute of Technology**
- Nicholas Buzinsky, Joseph Formaggio, Mingyu Li, Junior Peña, Juliana Stachurska, Wouter Van de Pontseele

**Pacific Northwest National Laboratory**
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**Pennsylvania State University**
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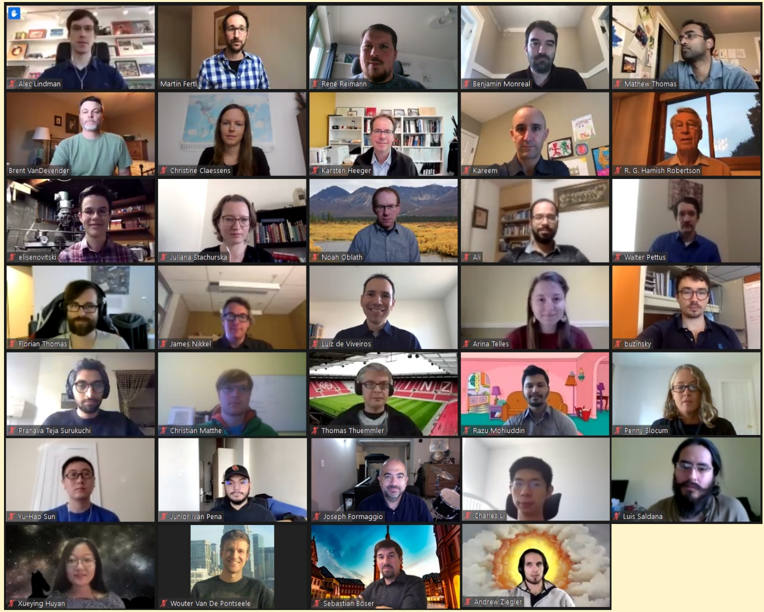
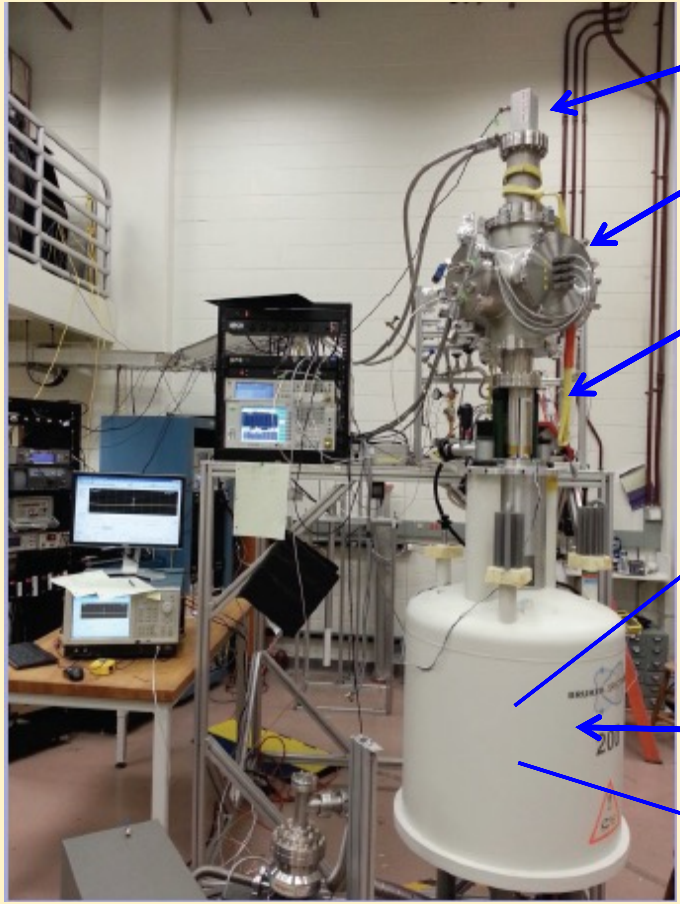
**University of Washington**
- Ali Ashtari Esfahani, Christine Claessens, Peter Doe, Sanshiro Enomoto, Alexander Marsteller, Elise Novitski, Hamish Robertson, Gray Rybka

**Yale University**
- Karsten Heeger, James Nikkel, Luis Saldaña, Penny Slocum, Pranava Teja Surukuchi, Arina Telles, Talia Weiss

+ UTexas Arlington, Heidelberg, …



Work supported by the US DOE Office of Nuclear Physics, the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all collaborating institutions.

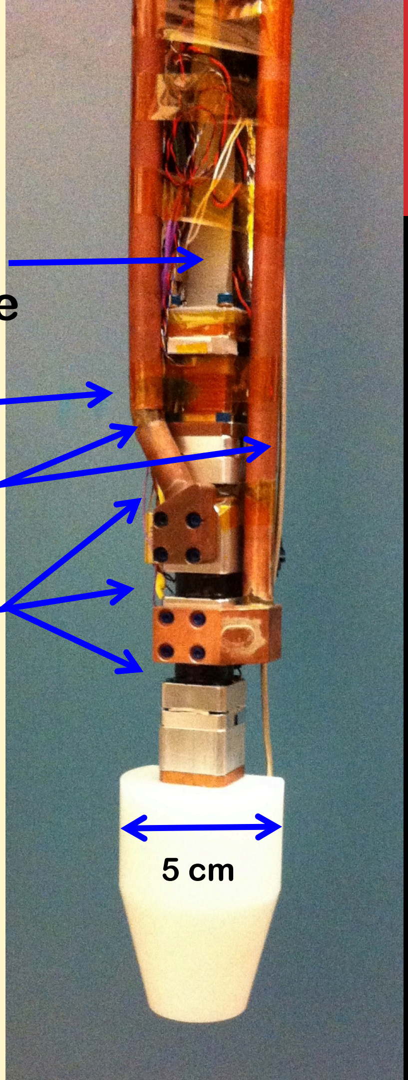


G-M cooler (35K)

26-GHz amplifiers

$^{83m}$Kr source (behind)

Superconducting Magnet (0.96 T)



WR-42 waveguide

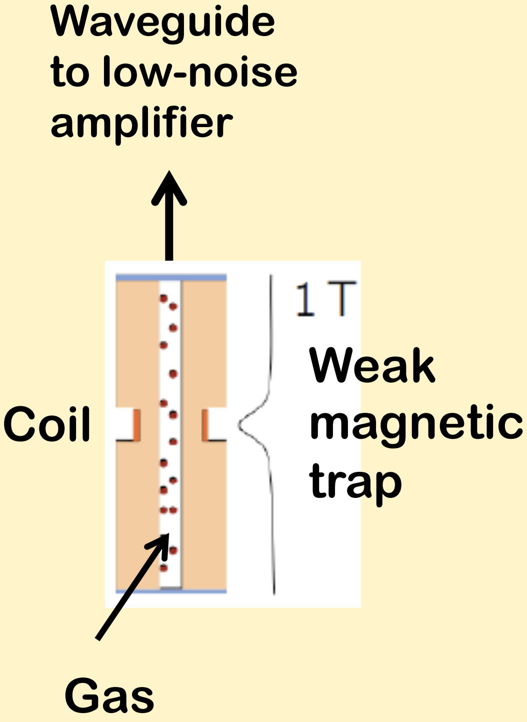
ESR cell

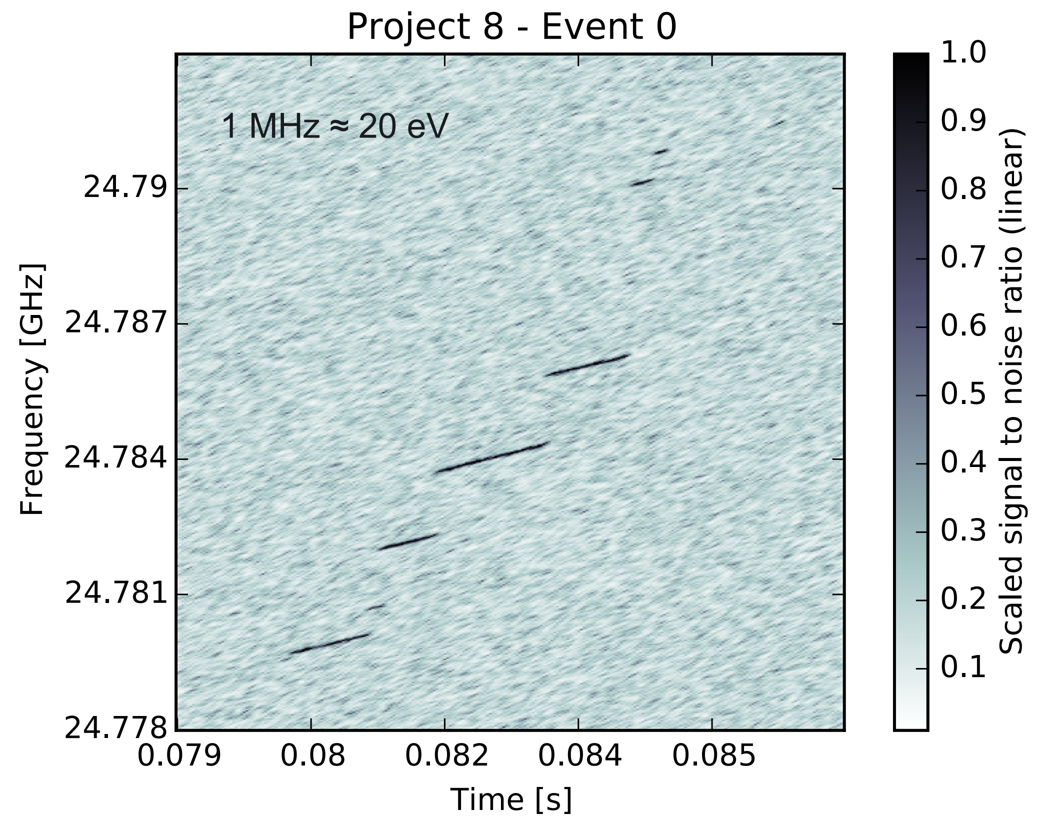
Gas lines

Trap coils

*Phase I* at University of Washington

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





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

●

start frequency of the first track gives kinetic energy.

→

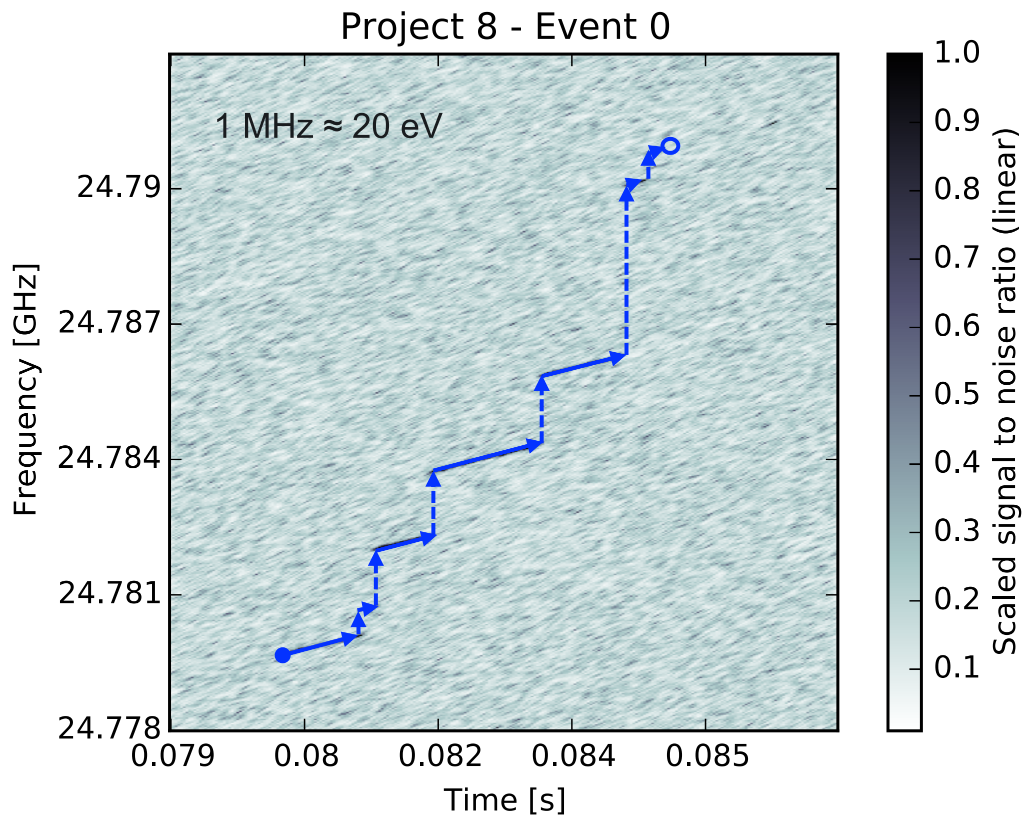
frequency chirps linearly, corresponding to ~1 fW radiative loss.

⇡

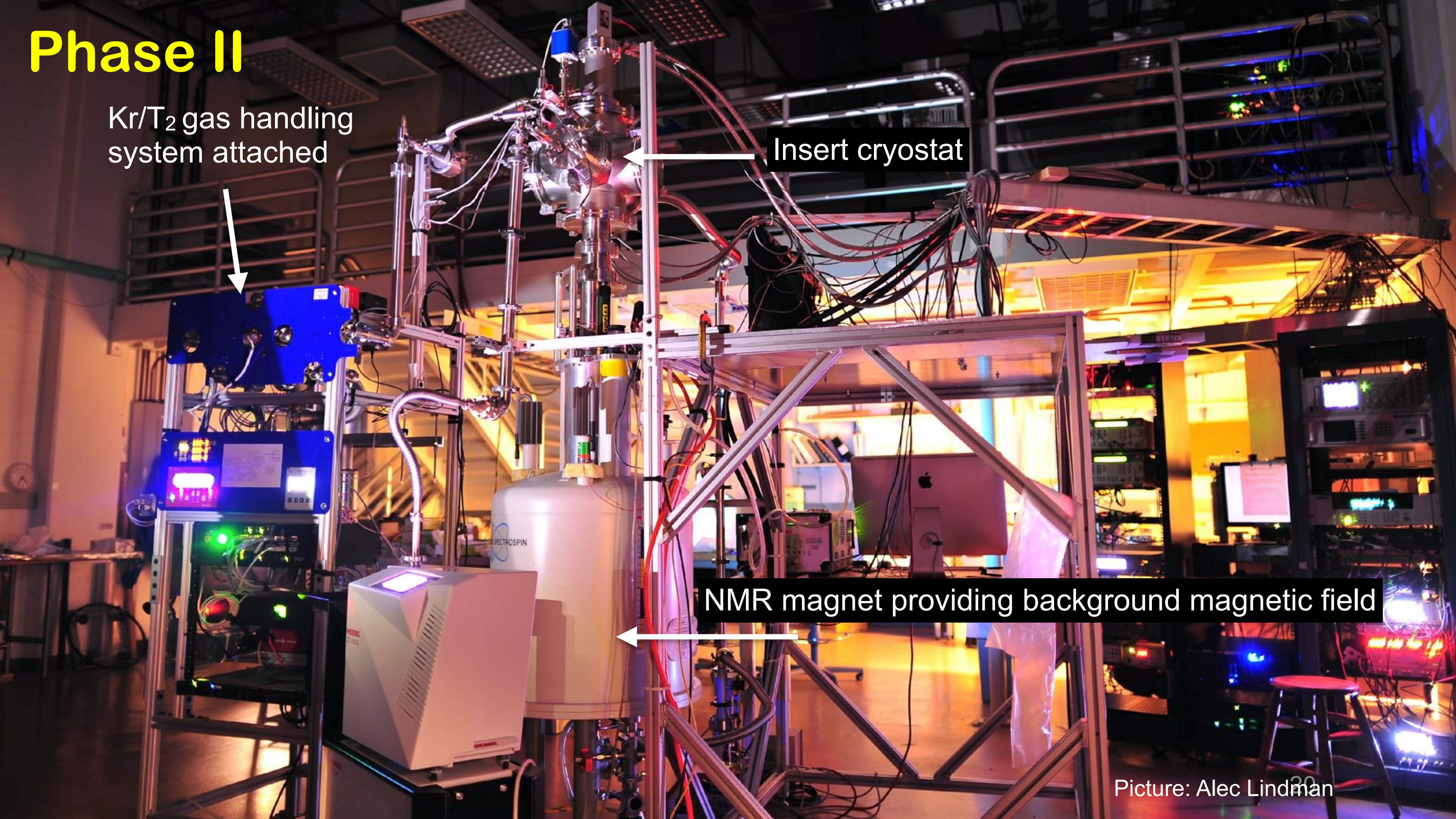
electron scatters inelastically, losing energy and changing pitch angle.

○

Eventually, scatters to an untrapped angle



# Phase II



Kr/T$_2$ gas handling system attached

Insert cryostat

NMR magnet providing background magnetic field

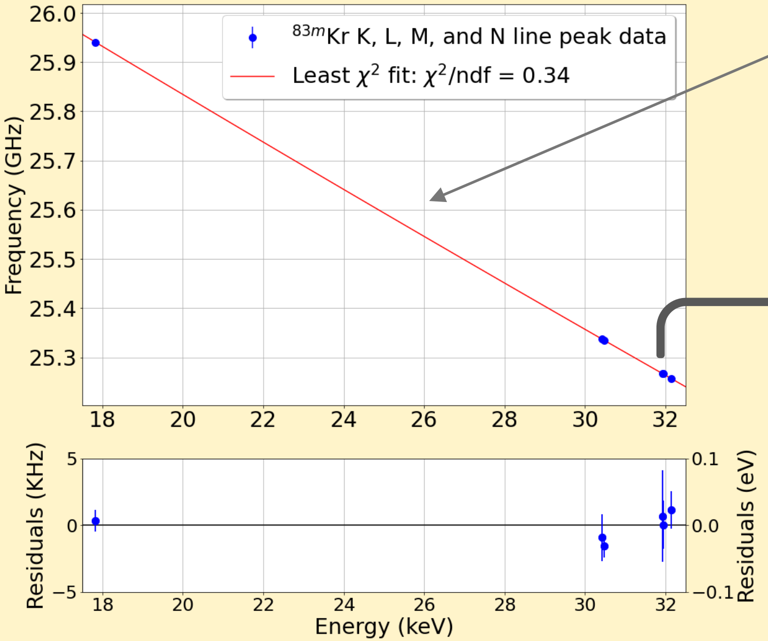
Picture: Alec Lindman

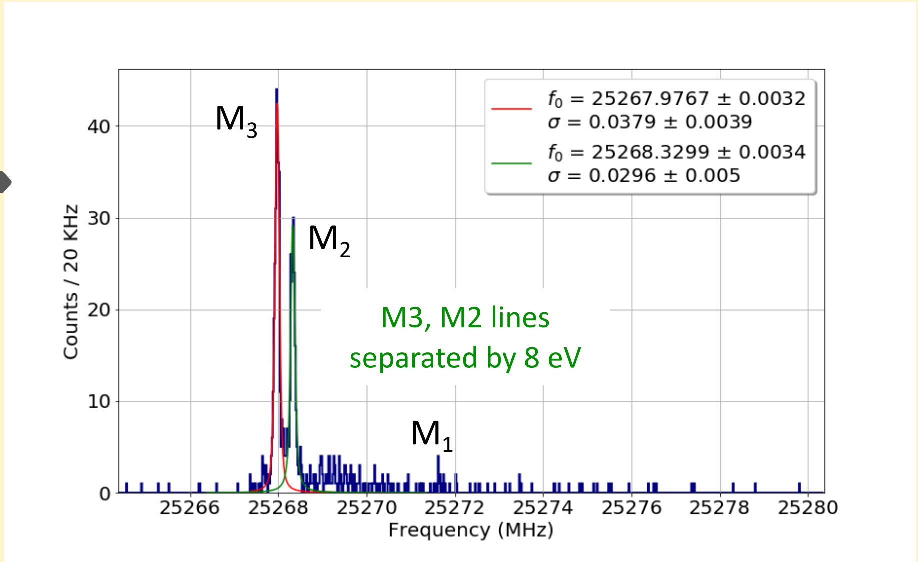
PROJECT 8

# $^{83m}$Kr data over 17 to 32 keV range

Monoenergetic conversion electrons at 18, 30, 32 keV, bookend the 18.6 keV tritium endpoint

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$



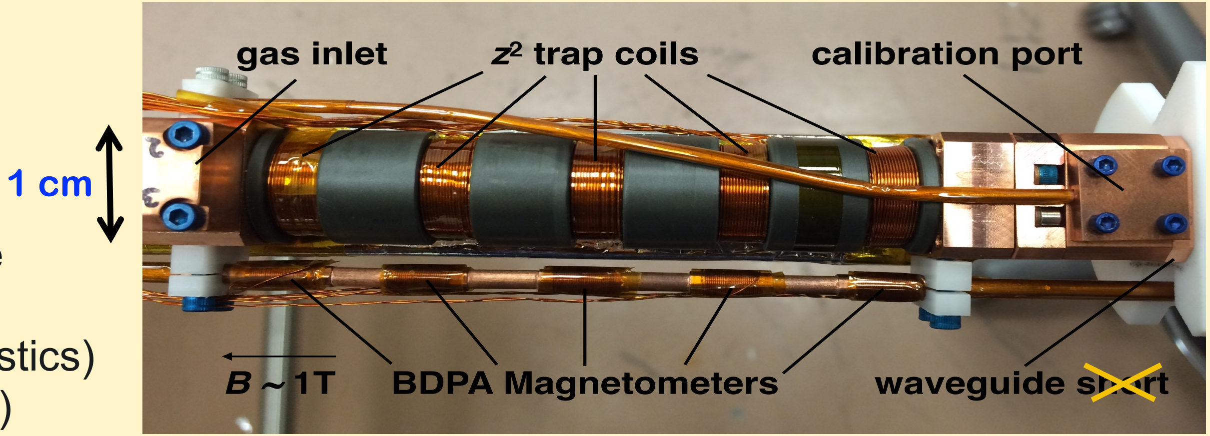


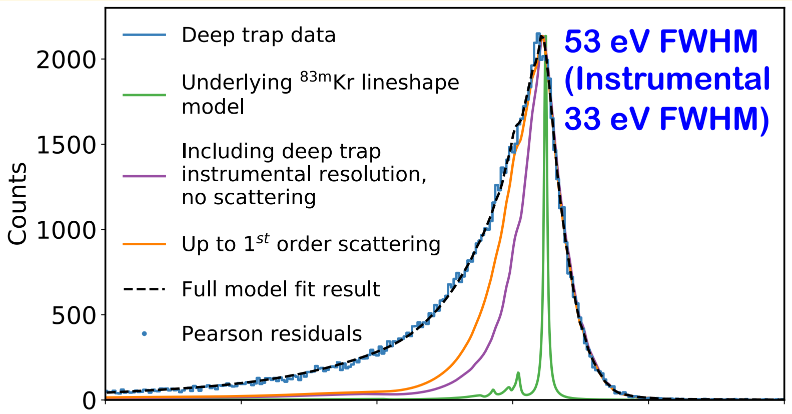
M3, M2 lines separated by 8 eV

# Tritium: Phase II Waveguide Cell

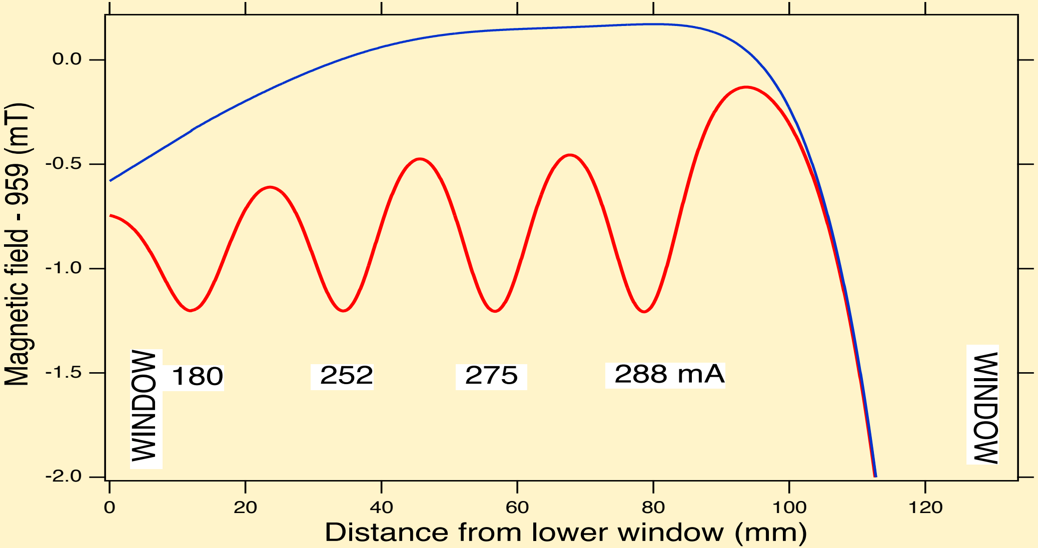
Improvements:

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





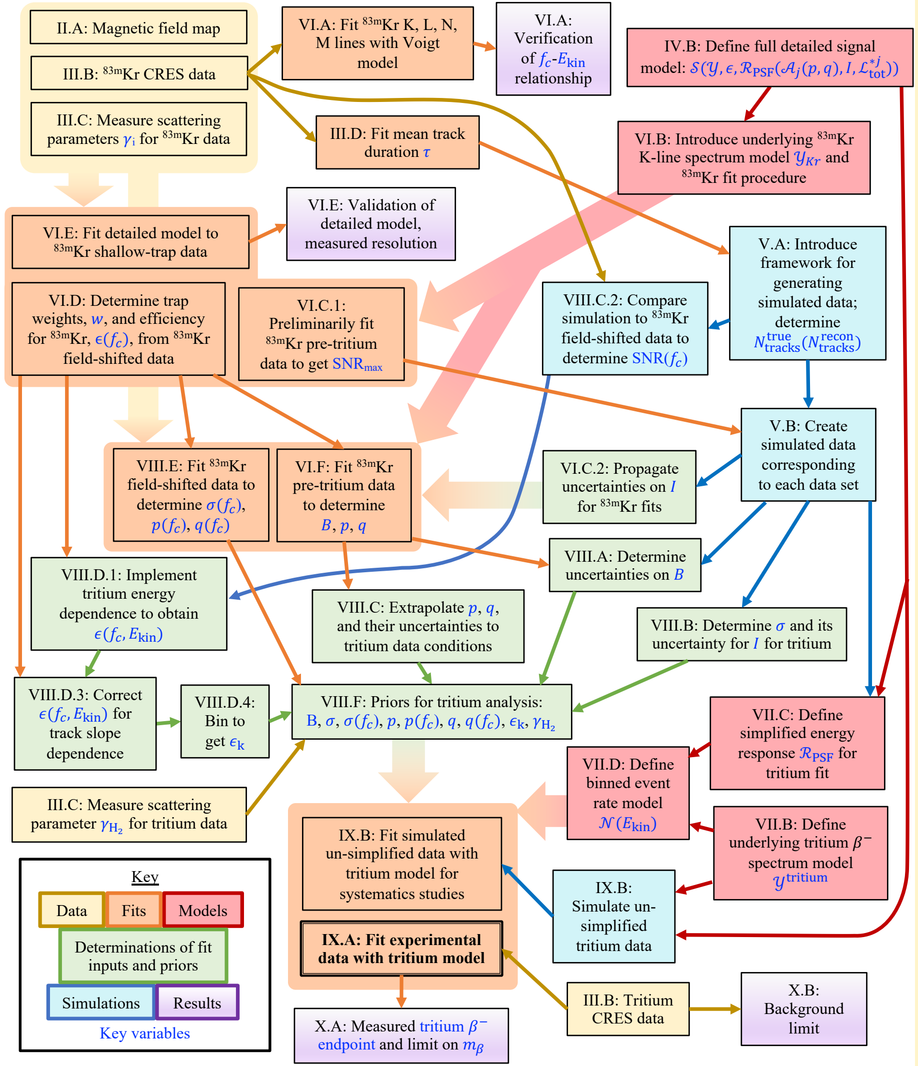
53 eV FWHM (Instrumental 33 eV FWHM)



# Analysis:

$^{83m}$Kr data
Tritium data
Models
Simulation
Bayesian & Frequentist fits

**Letter:** 2212.05048
**Long paper:** 2303.12055



II.A: Magnetic field map

III.B: $^{83m}$Kr CRES data

III.C: Measure scattering parameters $\gamma_i$ for $^{83m}$Kr data

VI.A: Fit $^{83m}$Kr K, L, N, M lines with Voigt model

VI.A: Verification of $f_c$-$E_{\text{kin}}$ relationship

IV.B: Define full detailed signal model: $\mathcal{S}(\mathcal{Y}, \epsilon, \mathcal{R}_{\text{PSF}}(\mathcal{A}_j(p,q), I, \mathcal{L}^{*j}_{\text{tot}}))$

III.D: Fit mean track duration $\tau$

VI.B: Introduce underlying $^{83m}$Kr K-line spectrum model $\mathcal{Y}_{Kr}$ and $^{83m}$Kr fit procedure

VI.E: Fit detailed model to $^{83m}$Kr shallow-trap data

VI.E: Validation of detailed model, measured resolution

VI.D: Determine trap weights, $w$, and efficiency for $^{83m}$Kr, $\epsilon(f_c)$, from $^{83m}$Kr field-shifted data

VI.C.1: Preliminarily fit $^{83m}$Kr pre-tritium data to get $\text{SNR}_{\text{max}}$

VIII.C.2: Compare simulation to $^{83m}$Kr field-shifted data to determine $\text{SNR}(f_c)$

V.A: Introduce framework for generating simulated data; determine $N^{\text{true}}_{\text{tracks}}(N^{\text{recon}}_{\text{tracks}})$

V.B: Create simulated data corresponding to each data set

VIII.E: Fit $^{83m}$Kr field-shifted data to determine $\sigma(f_c)$, $p(f_c)$, $q(f_c)$

VI.F: Fit $^{83m}$Kr pre-tritium data to determine $B$, $p$, $q$

VI.C.2: Propagate uncertainties on $I$ for $^{83m}$Kr fits

VIII.A: Determine uncertainties on $B$

VIII.D.1: Implement tritium energy dependence to obtain $\epsilon(f_c, E_{\text{kin}})$

VIII.C: Extrapolate $p$, $q$, and their uncertainties to tritium data conditions

VIII.B: Determine $\sigma$ and its uncertainty for $I$ for tritium

VIII.D.3: Correct $\epsilon(f_c, E_{\text{kin}})$ for track slope dependence

VIII.D.4: Bin to get $\epsilon_{\text{k}}$

VIII.F: Priors for tritium analysis: $\text{B}, \sigma, \sigma(f_c), p, p(f_c), q, q(f_c), \epsilon_{\text{k}}, \gamma_{\text{H}_2}$

VII.C: Define simplified energy response $\mathcal{R}_{\text{PSF}}$ for tritium fit

VII.D: Define binned event rate model $\mathcal{N}(E_{\text{kin}})$

III.C: Measure scattering parameter $\gamma_{\text{H}_2}$ for tritium data

IX.B: Fit simulated un-simplified data with tritium model for systematics studies

VII.B: Define underlying tritium $\beta^-$ spectrum model $\mathcal{Y}^{\text{tritium}}$

IX.B: Simulate un-simplified tritium data

**IX.A: Fit experimental data with tritium model**

III.B: Tritium CRES data

X.B: Background limit

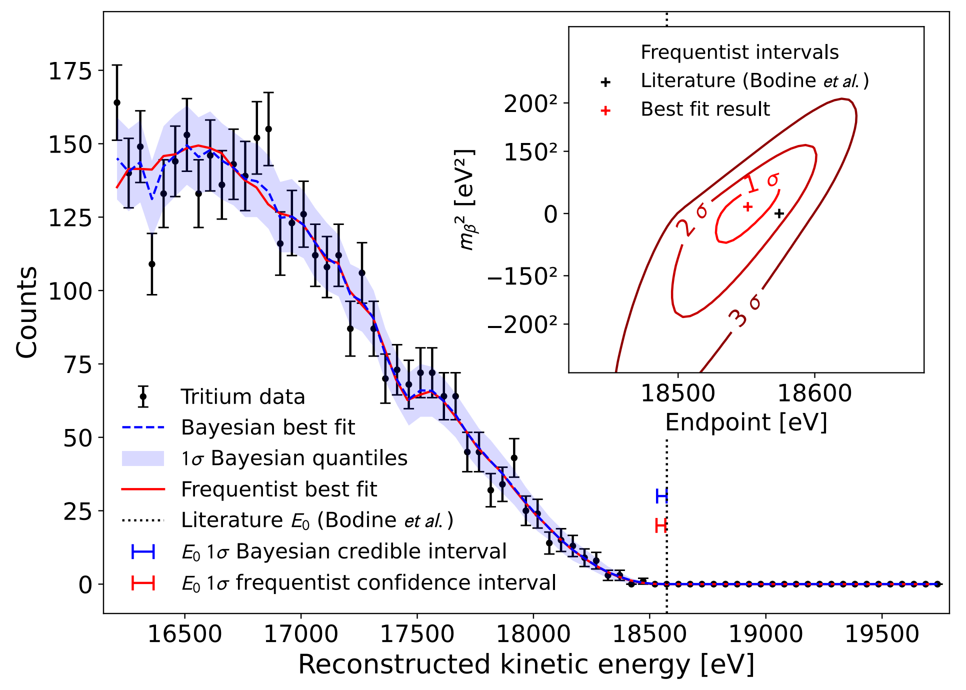
X.A: Measured tritium $\beta^-$ endpoint and limit on $m_\beta$

Key
Data | Fits | Models
Determinations of fit inputs and priors
Simulations | Results
Key variables

E. Novitski

!

# PHASE II TRITIUM RESULTS



Project 8 Collaboration, arXiv:2212.05048 (2022)

**$T_2$ endpoint**

Frequentist: $E_0 = (18548 \pm 19)$ eV $(1\sigma)$

Bayesian: $E_0 = (18553 \pm 19)$ eV $(1\sigma)$

**Neutrino mass**

Frequentist: $\leq 152$ eV/c² (90% C.L.)

Bayesian: $\leq 155$ eV/c² (90% C.L.)

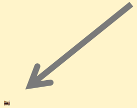
**Background rate**

$\leq 3\times10^{-10}$ eV$^{-1}$s$^{-1}$ (90% C.L.)

- First neutrino mass, $T_2$ endpoint measurements using CRES
- Demonstrated understanding of detector response, control of systematic effects from scattering & field inhomogeneity
- Stringent background limit— zero events above endpoint in 82 days!

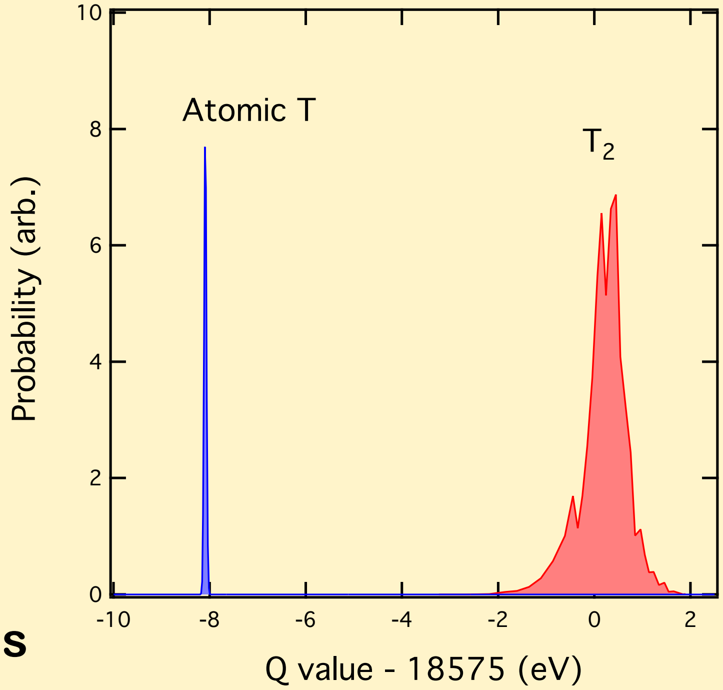
KATRIN spectrometer

Project 8 Phase II spectrometer
(to scale)



# CRES WORKS: WHY IS THIS IMPORTANT?

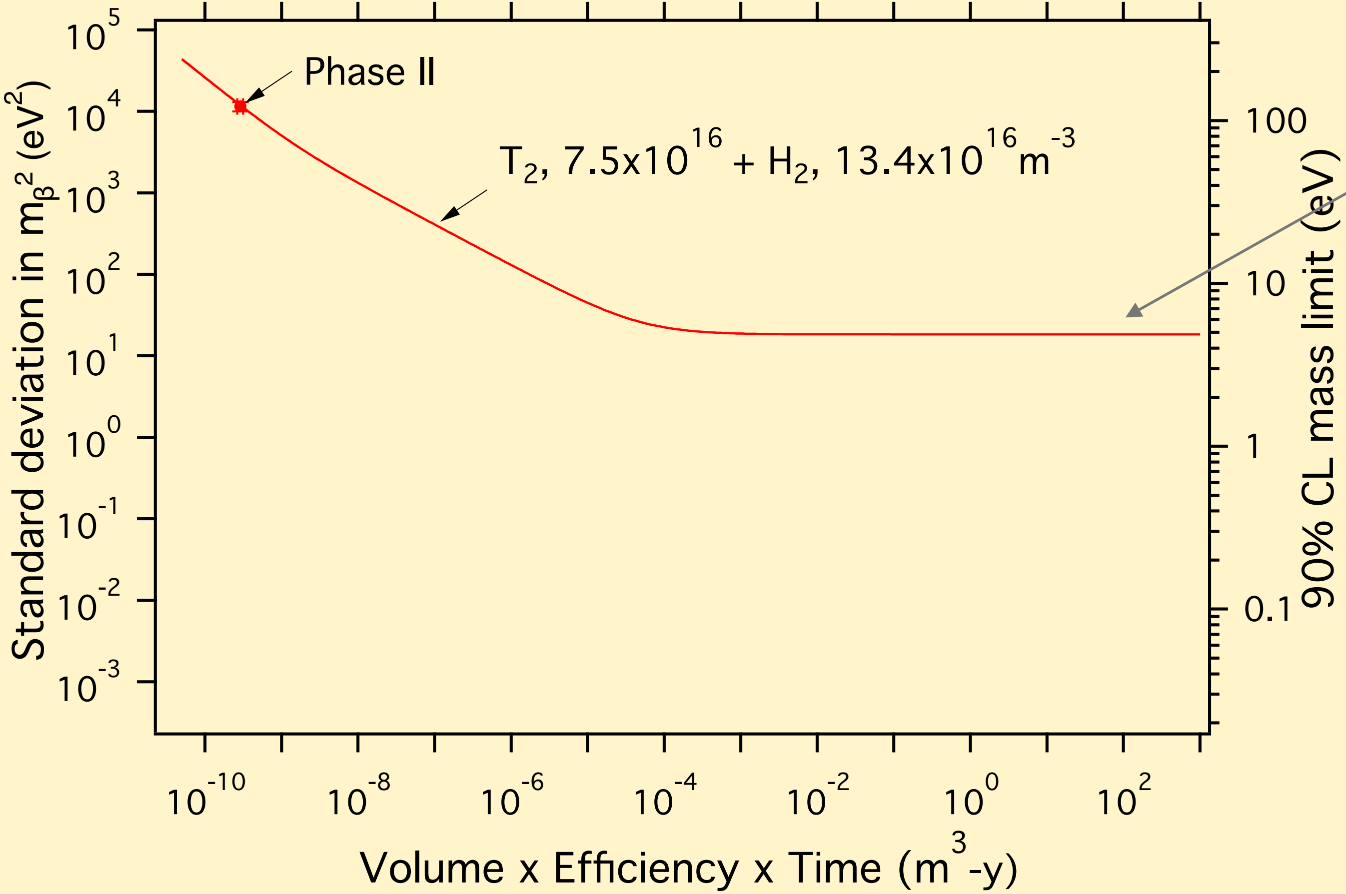
- **Source is transparent to microwaves: can make it big.**
- **Whole spectrum is recorded at once, not point-by-point.**
- **Excellent resolution obtainable.**
- **Low backgrounds are demonstrated.**
- **An atomic source of T (rather than molecular $T_2$) should be possible. Eliminates the molecular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



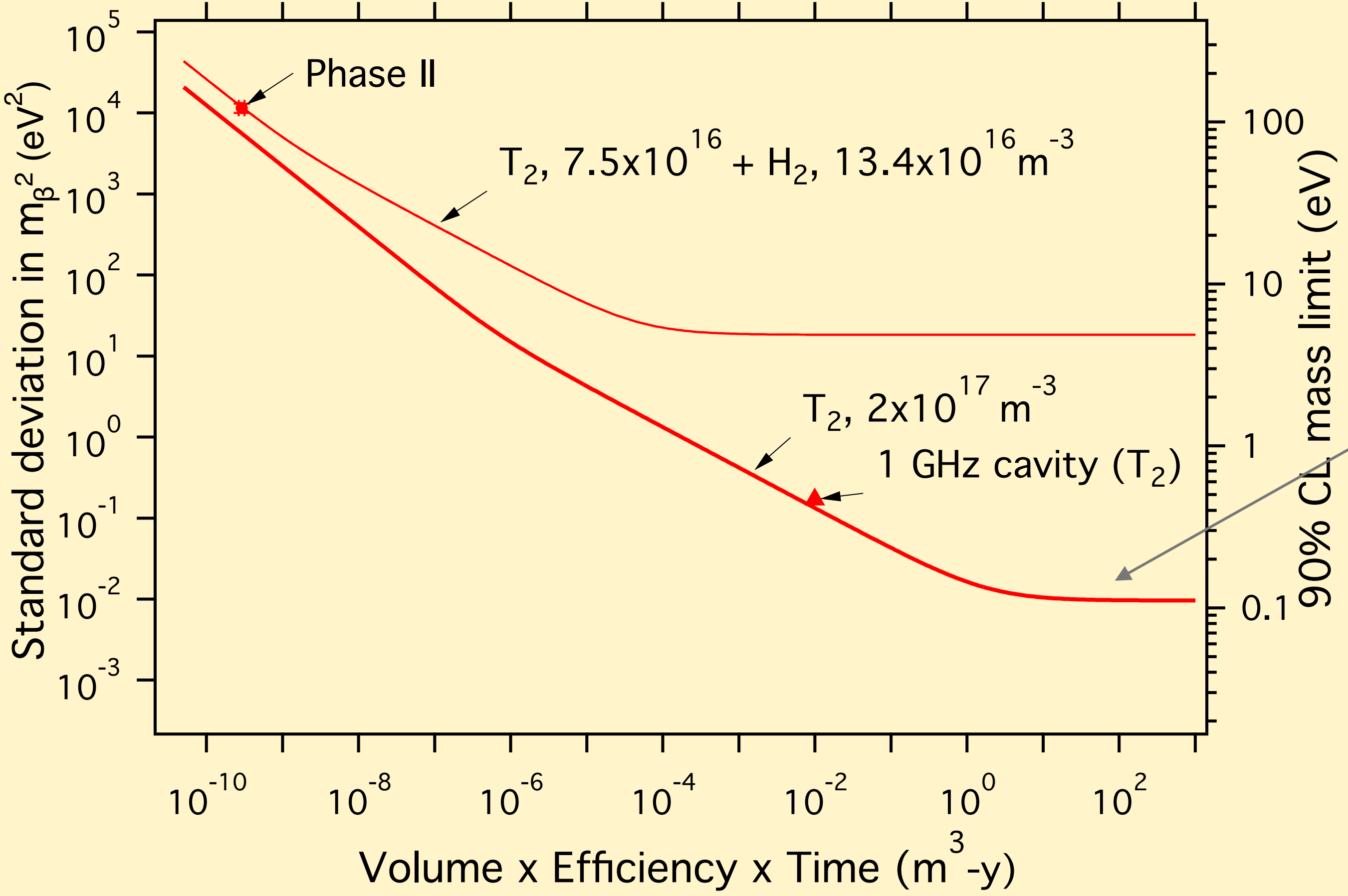
CRES…

BIG…

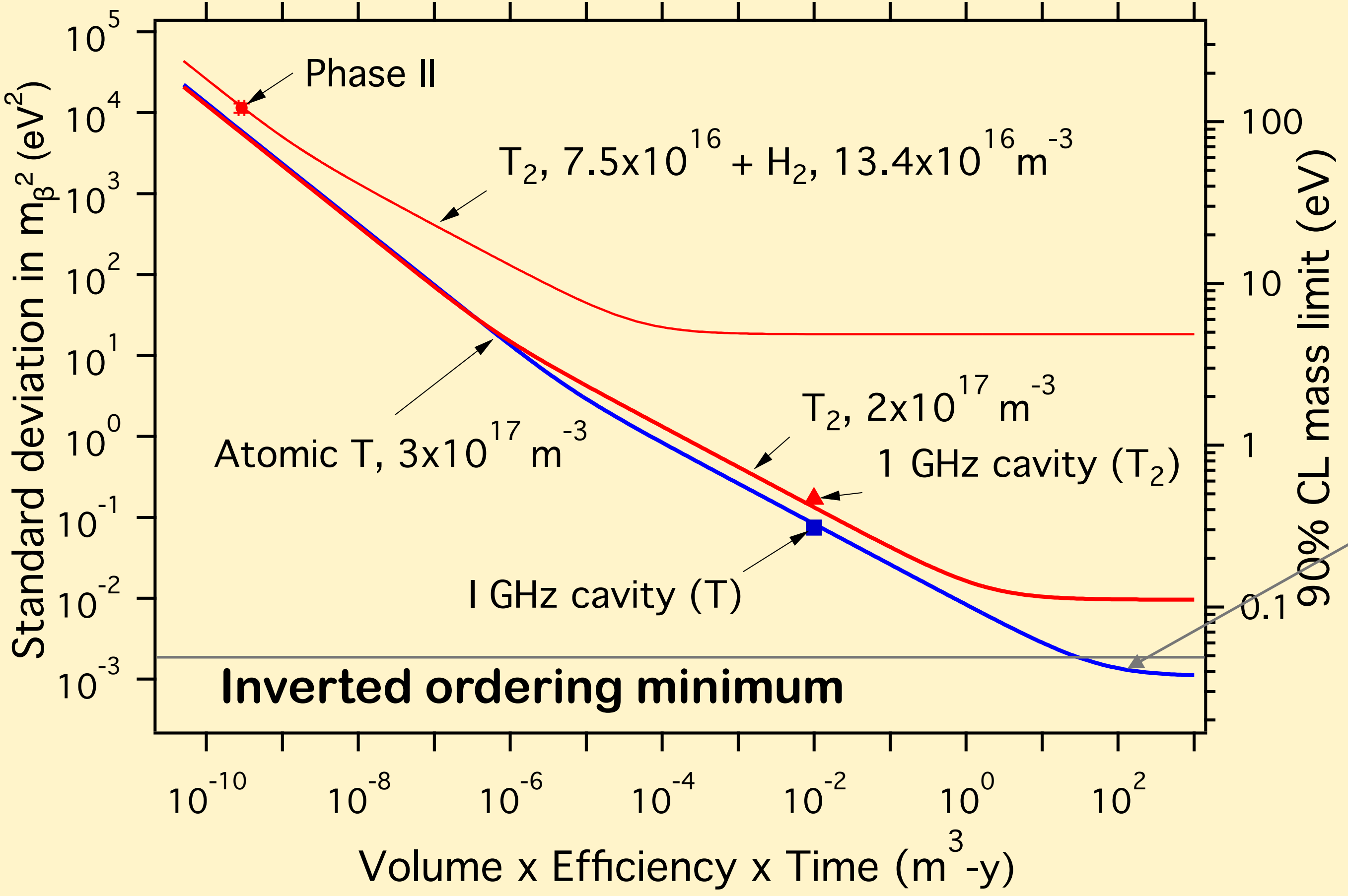
ATOMIC


Phase II
$T_2$, $7.5\times10^{16}$ + $H_2$, $13.4\times10^{16}\,m^{-3}$
Standard deviation in $m_\beta^2$ ($eV^2$)
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
90% CL mass limit (eV)
100
10
1
0.1
$10^{-10}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
$10^0$
$10^2$
Volume x Efficiency x Time ($m^3$-y)

**ΔE = 50 eV**


Phase II
$T_2$, $7.5\times10^{16}$ + $H_2$, $13.4\times10^{16}\,m^{-3}$
$T_2$, $2\times10^{17}\,m^{-3}$
1 GHz cavity ($T_2$)
Standard deviation in $m_\beta^2$ ($eV^2$)
90% CL mass limit (eV)
Volume x Efficiency x Time ($m^3$-y)
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
100
10
1
0.1
$10^{-10}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
$10^0$
$10^2$

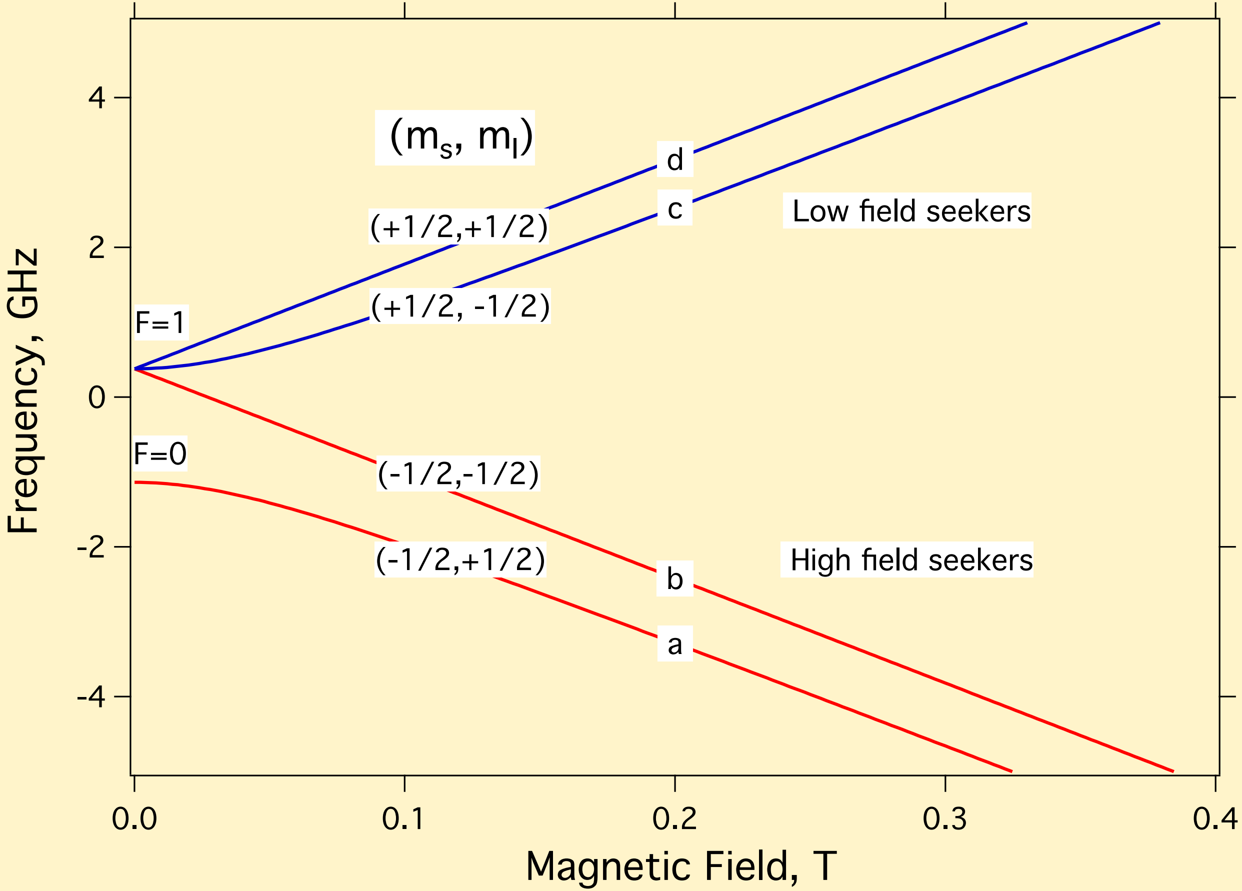
**ΔE = 1.5 eV**


Phase II
$T_2$, $7.5\text{x}10^{16}$ + $H_2$, $13.4\text{x}10^{16}\ m^{-3}$
Atomic T, $3\text{x}10^{17}\ m^{-3}$
$T_2$, $2\text{x}10^{17}\ m^{-3}$
1 GHz cavity ($T_2$)
I GHz cavity (T)
Inverted ordering minimum
Standard deviation in $m_\beta^2$ ($eV^2$)
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
90% CL mass limit (eV)
100
10
1
0.1
$10^{-10}$
$10^{-8}$
$10^{-6}$
$10^{-4}$
$10^{-2}$
$10^0$
$10^2$
Volume x Efficiency x Time ($m^3$-y)

**ΔE = 0.5 eV**

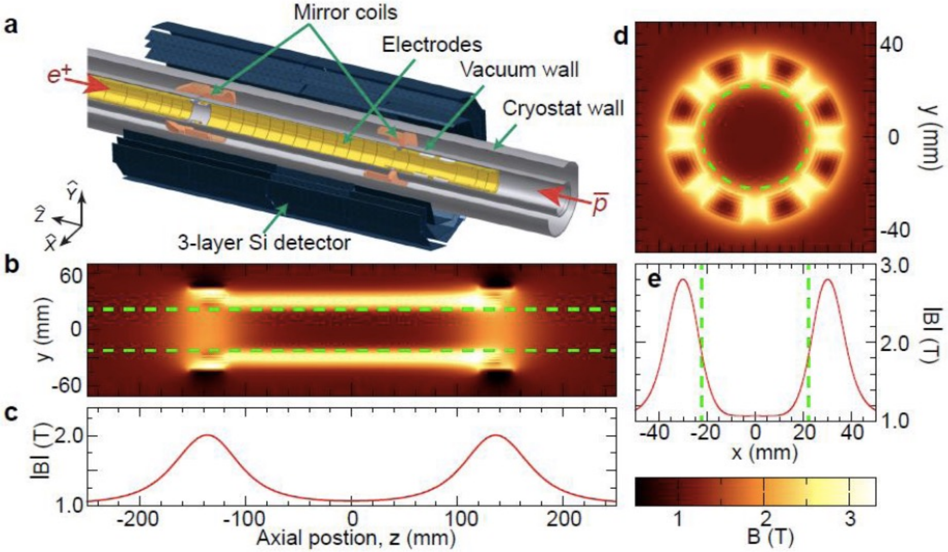
# Atomic tritium

**"Low-field seekers" can be magnetically trapped**



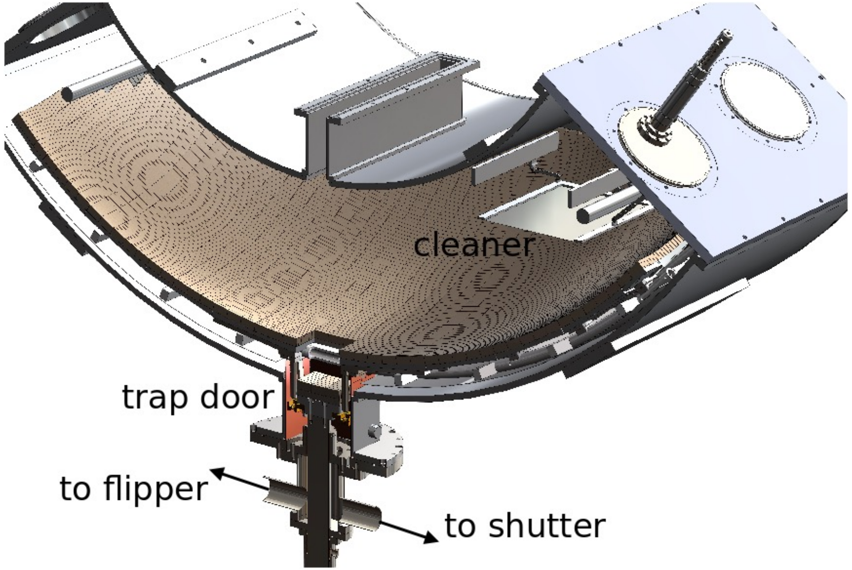
# MAGNETIC TRAP FOR ATOMIC T

## Ioffe-Pritchard trap



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

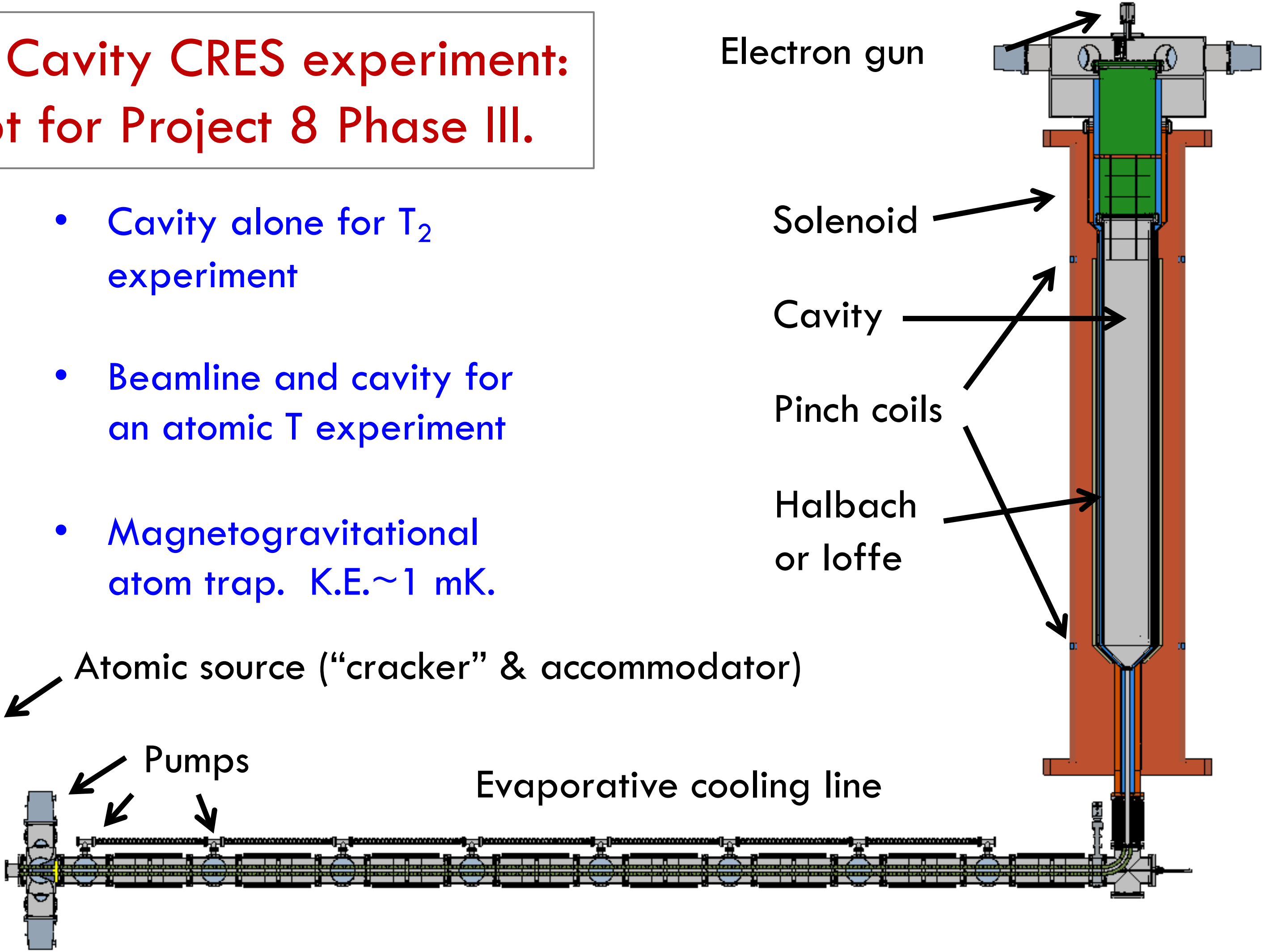
## Halbach magneto-gravitational trap



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

# 1-GHz Cavity CRES experiment: Concept for Project 8 Phase III.

- Cavity alone for $T_2$ experiment
- Beamline and cavity for an atomic T experiment
- Magnetogravitational atom trap.  K.E.~1 mK.



Electron gun

Solenoid

Cavity

Pinch coils

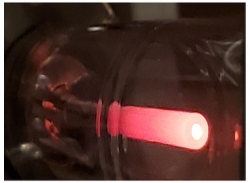
Halbach or Ioffe

3 m

Atomic source (“cracker” & accommodator)

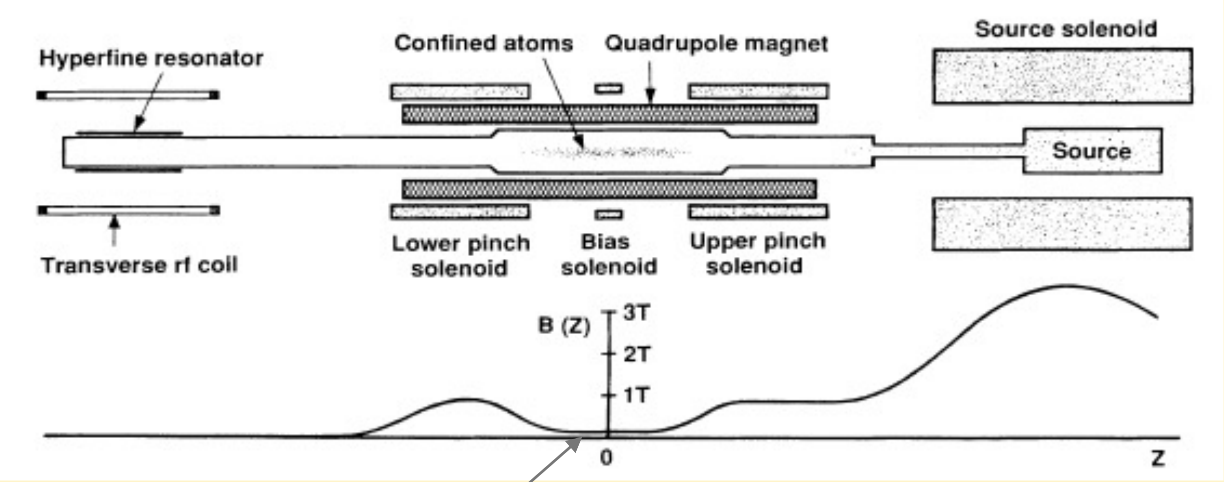
Pumps

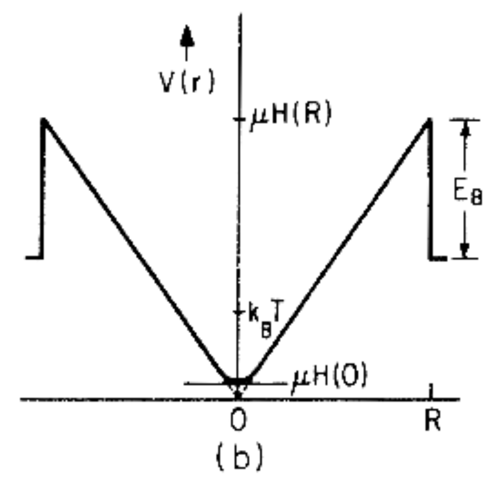
Evaporative cooling line

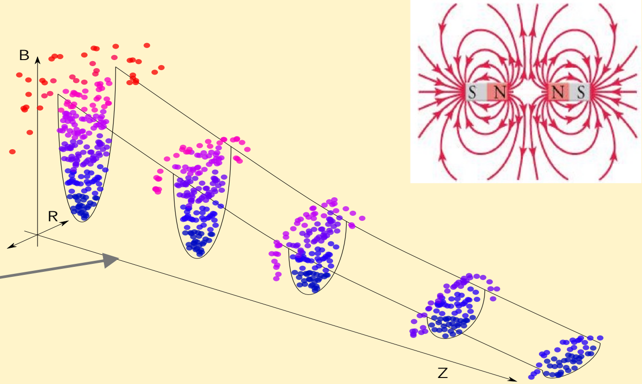


# Evaporative cooling concept

Hess et al. PRL 59, 672 [1987]



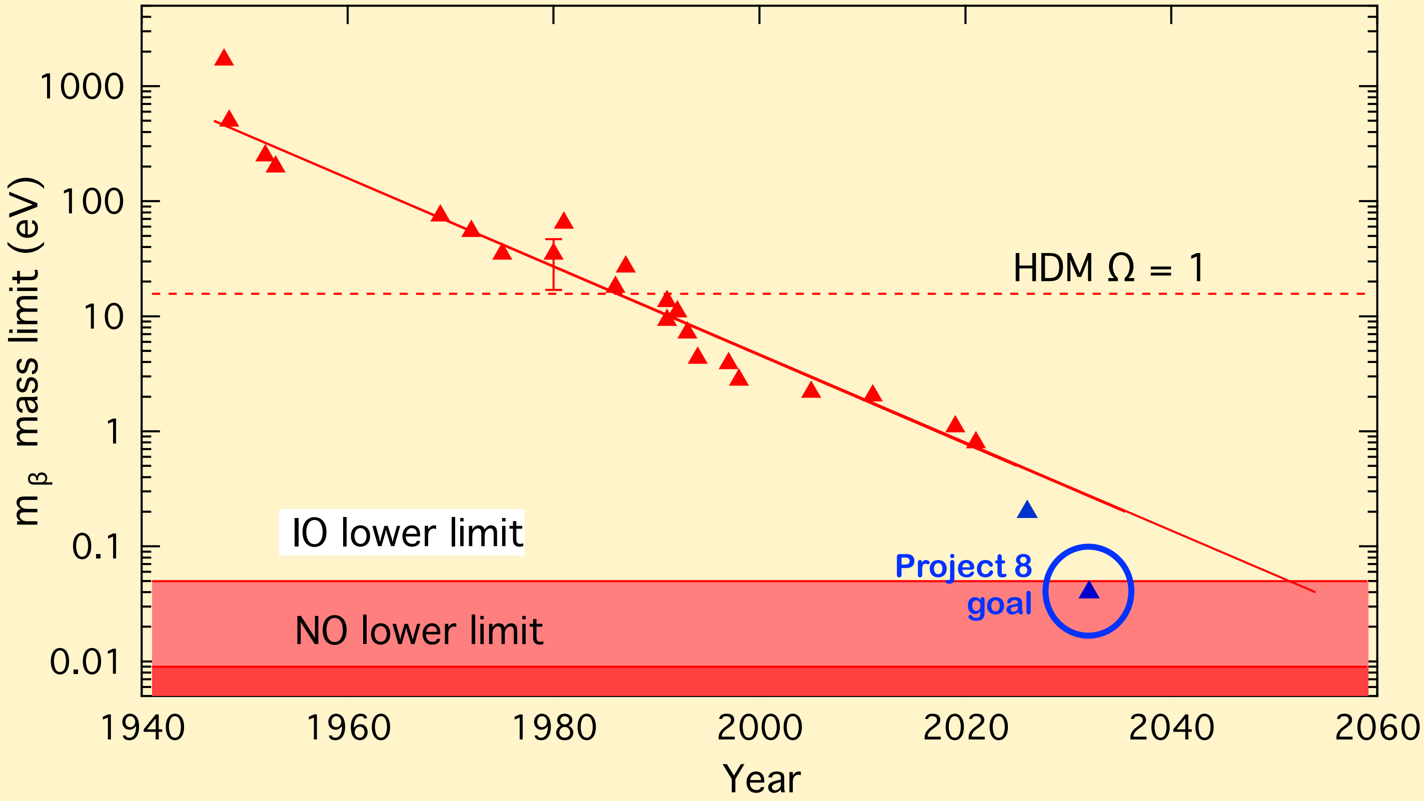




Confined atoms are cooled by lowering the field and evaporating the hottest atoms.

Can this be done in a <u>beam</u> instead of a fixed trap?

# 2000 – 2023: tritium rules.



# 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 0.8 eV (90% CL)**

**Success of Project 8 proof-of-concept. First tritium.**

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

Fin