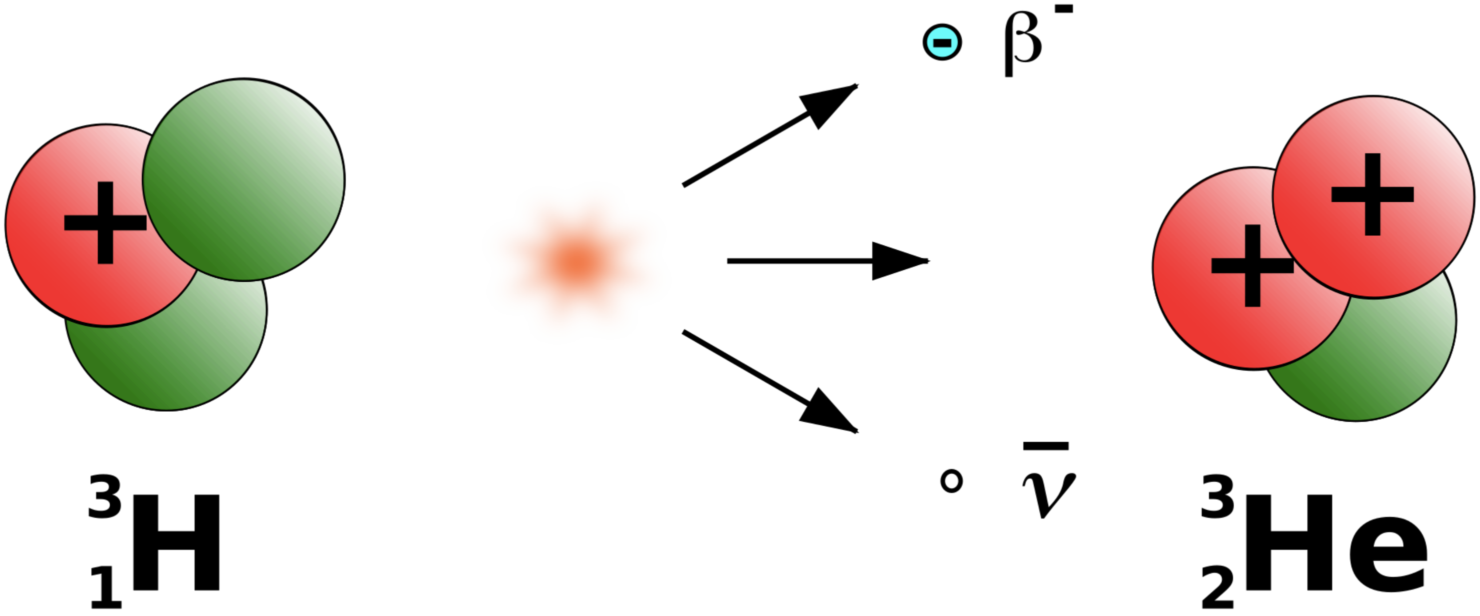
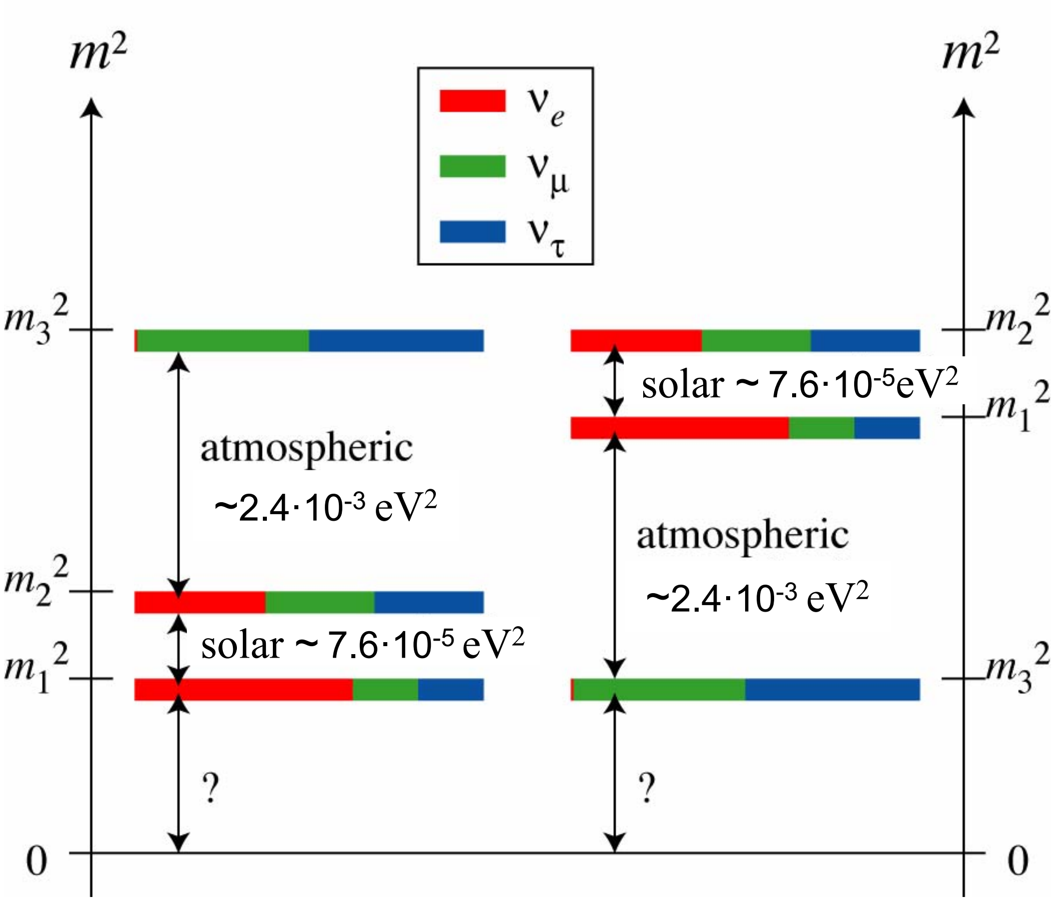
Neutrino Physics 2



*with thanks to Diana Parno,
John Wilkerson, and others,
from whom I borrowed liberally

Michelle Dolinski
Drexel University
NNPSS, 11 July 2019

What we know about neutrinos



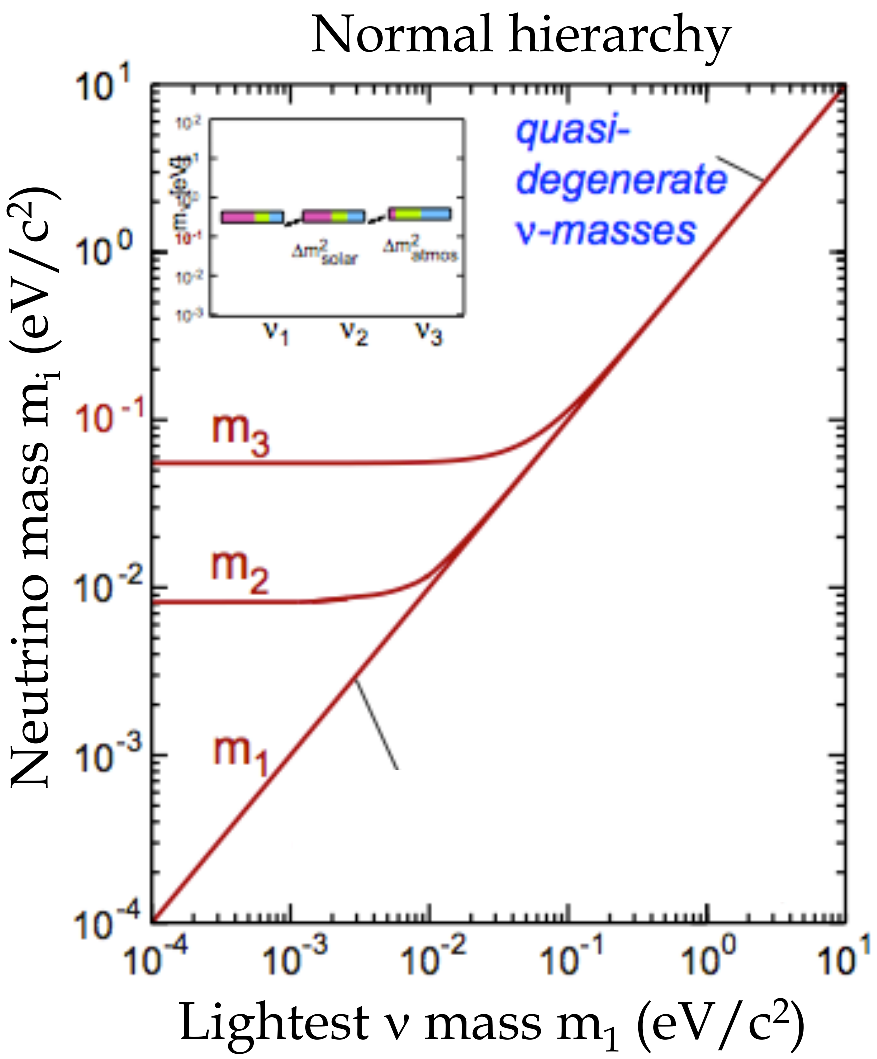
Absolute neutrino masses

~0.1 eV

From 0νββ if ν is Majorana

~2 eV

From tritium endpoint (Maintz and Troitsk)



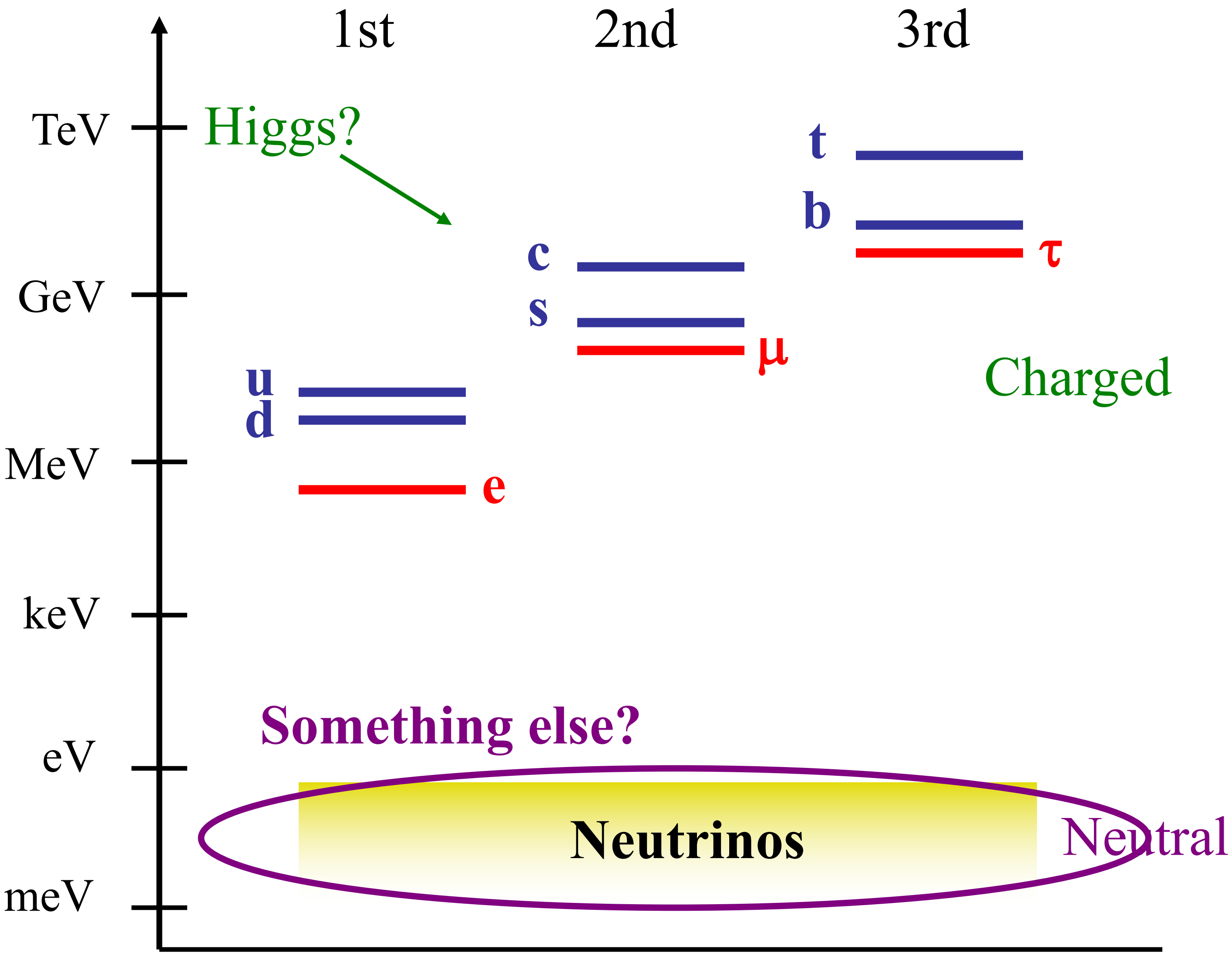
∑~0.2 eV

From Cosmology

~20 eV

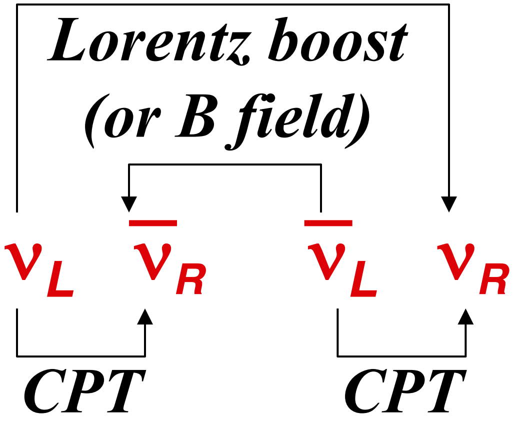
Time of flight from SN1987A (PDG 2002)

Neutrino mass puzzle



Massive neutrinos

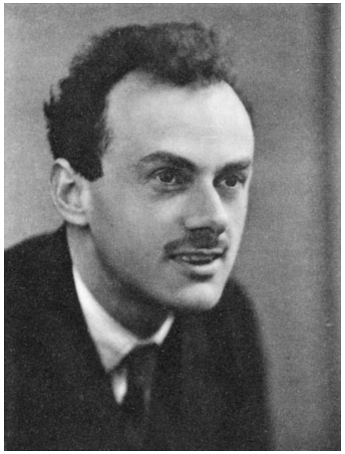
"Dirac" neutrinos



Lorentz boost
(or B field)

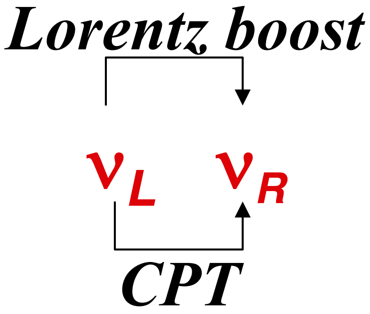
ν_L $\bar{\nu}_R$ $\bar{\nu}_L$ ν_R

CPT *CPT*



"Majorana" neutrinos

No lepton number conservation!



Lorentz boost

ν_L ν_R

CPT

The two descriptions are distinct and distinguishable only if $m_\nu \neq 0$.
Lecture 3 is how to tell the difference experimentally.

Seesaw mechanism

Experimentally, it is an open question whether neutrinos are Majorana or Dirac, but Majorana neutrinos are strongly preferred by theorists. Seesaw mechanism can be used to explain small neutrino masses (see 2019 PDG). Type I seesaw mechanism (Gell-Mann, Ramond, Slansky and Yanagida, 1979):

$$\mathcal{L}_{\mathrm{Y,M}}(x) = \left(\lambda_{il}\,\overline{N_{iR}}(x)\,\Phi^{\dagger}(x)\,\psi_{lL}(x) + \mathrm{h.c.}\right) - \frac{1}{2}M_i\,\overline{N_i}(x)\,N_i(x)$$

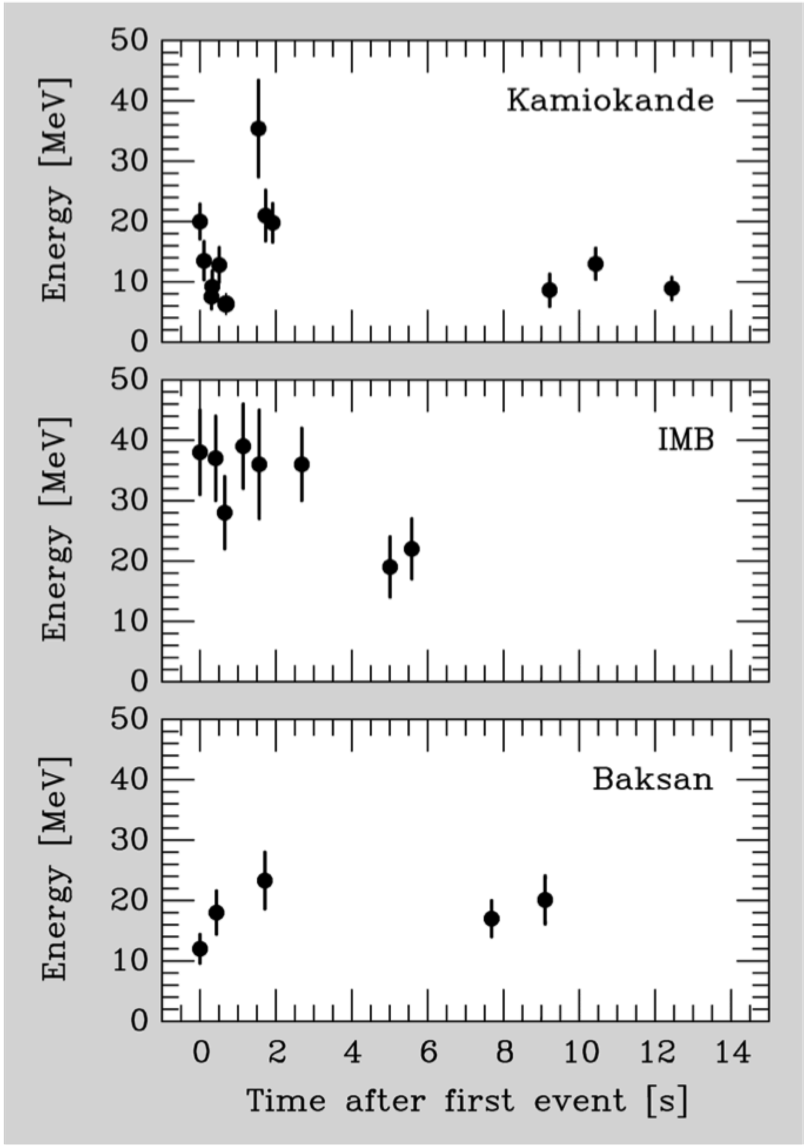
$$m^{LL}_{l'l} \cong -(m^{D})^{T}_{l'j}M_j^{-1}m^{D}_{jl} = -v^{2}(\lambda)^{T}_{l'j}M_j^{-1}\lambda_{jl}$$

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix}$$

$$Z^T M_\nu Z = D_\nu = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \approx \begin{bmatrix} m_D^2 / m_R & 0 \\ 0 & m_R \end{bmatrix}$$

How to weigh a neutrino?

Time of flight



Neutrino events from supernova 1987a (Large Magellanic Cloud) were detected in KamiokaNDE, IMB, and Baksan observatories.

With a model for neutrino production, it is possible to look for smearing due to neutrino mass. Early analyses gave limits ~20 eV.

Improved supernova modeling and Bayesian statistical approaches do better:

< 5.7 eV @ 95% C.L.
Loredo and Lamb, *PRD* 65 (2002)

Decay kinematics

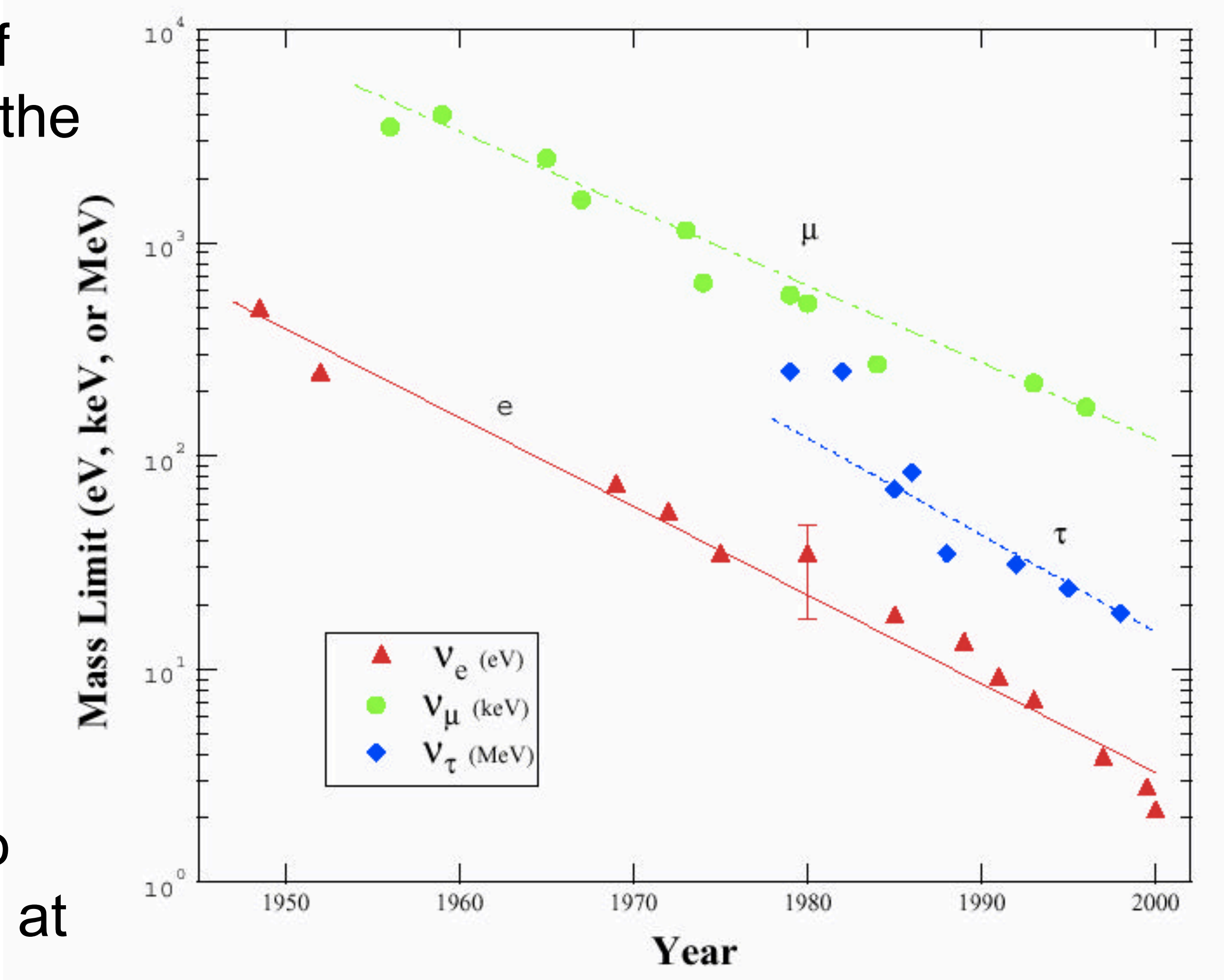
Look at the impact of non-zero ν mass on the following decays.

ν_e: beta decay

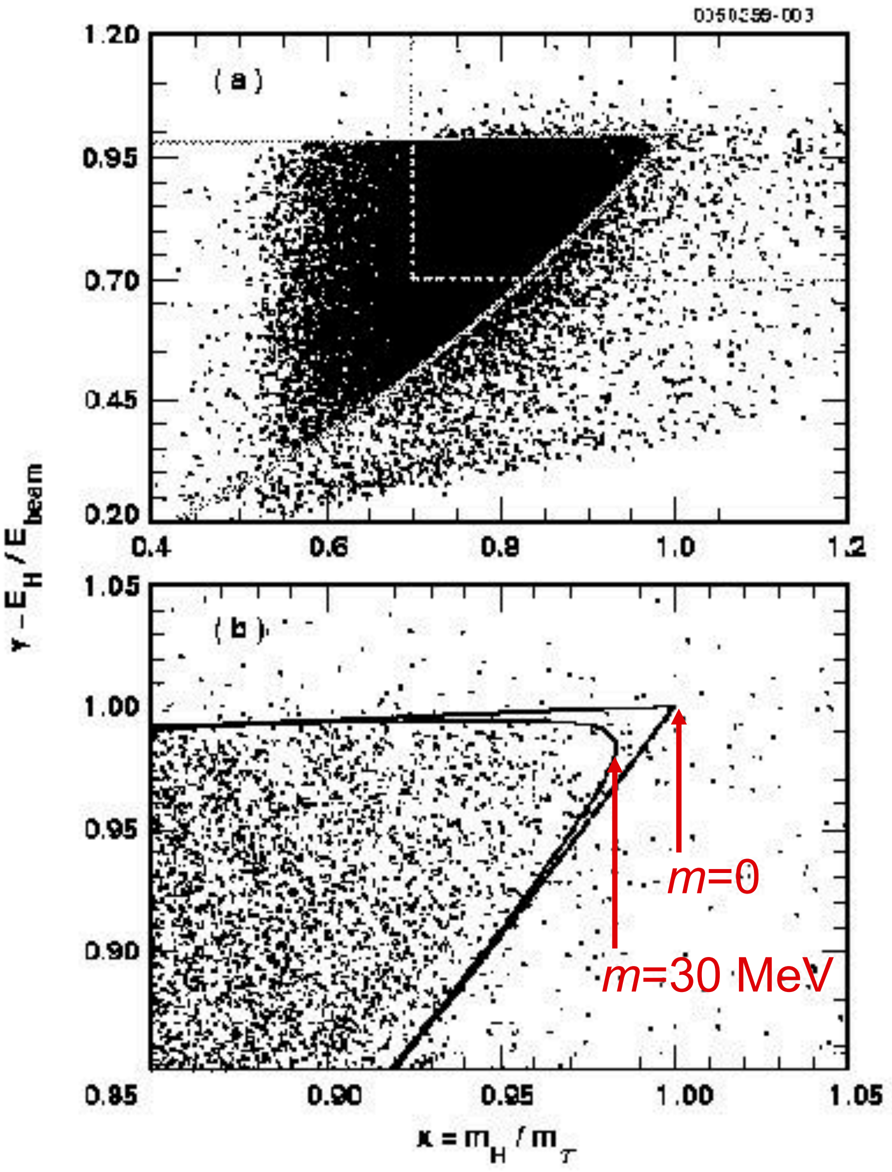
ν_μ: pion decay*

ν_τ: tau decay*

*thanks to Mike Shaevitz for next two slides, 2002 lectures at Lake Louise School



τ decay



Current best limit from studies of the kinematics of τ decays.

$$\tau^- \rightarrow 2\pi^- \pi^+ \nu_\tau$$

$$\tau^- \rightarrow 3\pi^- \; 2\pi^+ (\pi^0) \, \nu_\tau$$

- Fit to scaled visible energy vs. scaled invariant mass. Best limit

<18.2 MeV @ 95% C.L.
Aleph, EPJ C2 395 1998

Pion decay

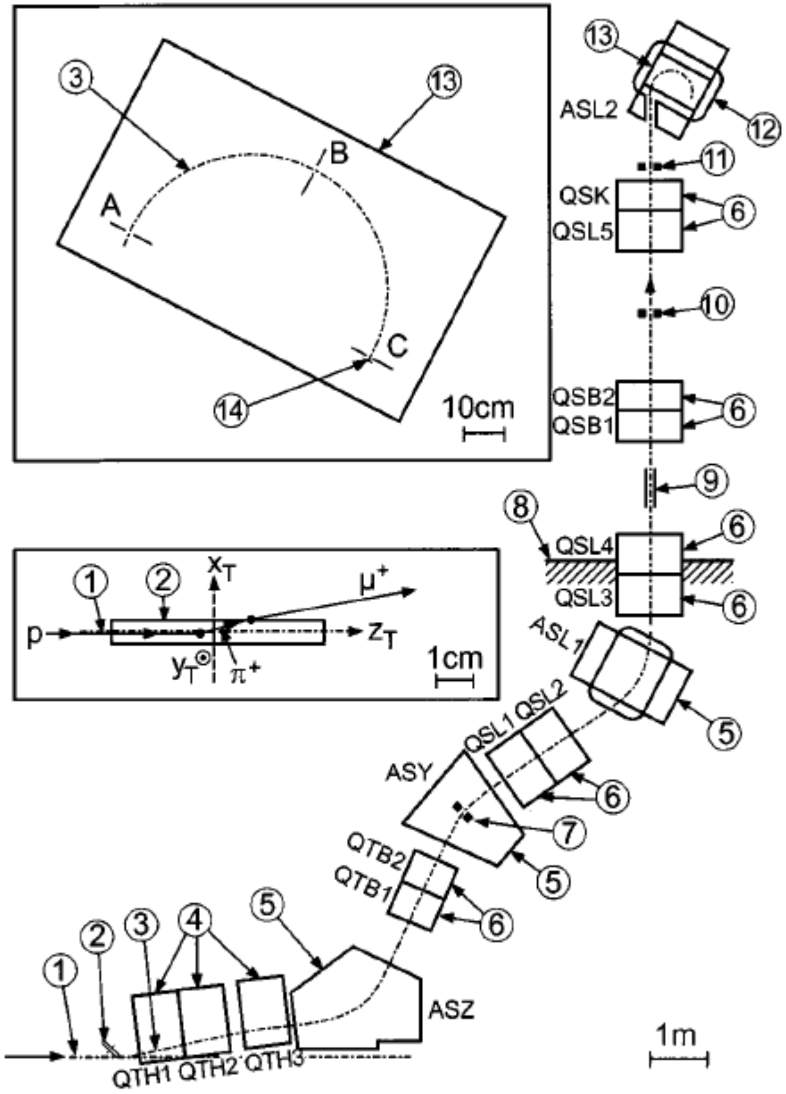
Current best limit from studies of the kinematics of $\pi \rightarrow \mu\nu_\mu$ decay.

$$p_\mu^2 + m_\mu^2 = (m_\pi^2 + m_\mu^2 - m_\nu^2)^2 / 4m_\pi^2$$

- Pion decay in flight is limited in practice by momentum resolution.
- Pion decay at rest is limited by pion mass uncertainty. This currently gives the best limits from PSI

<170 keV @ 95% C.L.
Assamagan et al., *PRD* (1996)

*Proposals exist to get this down to ~8 keV



Beta decay

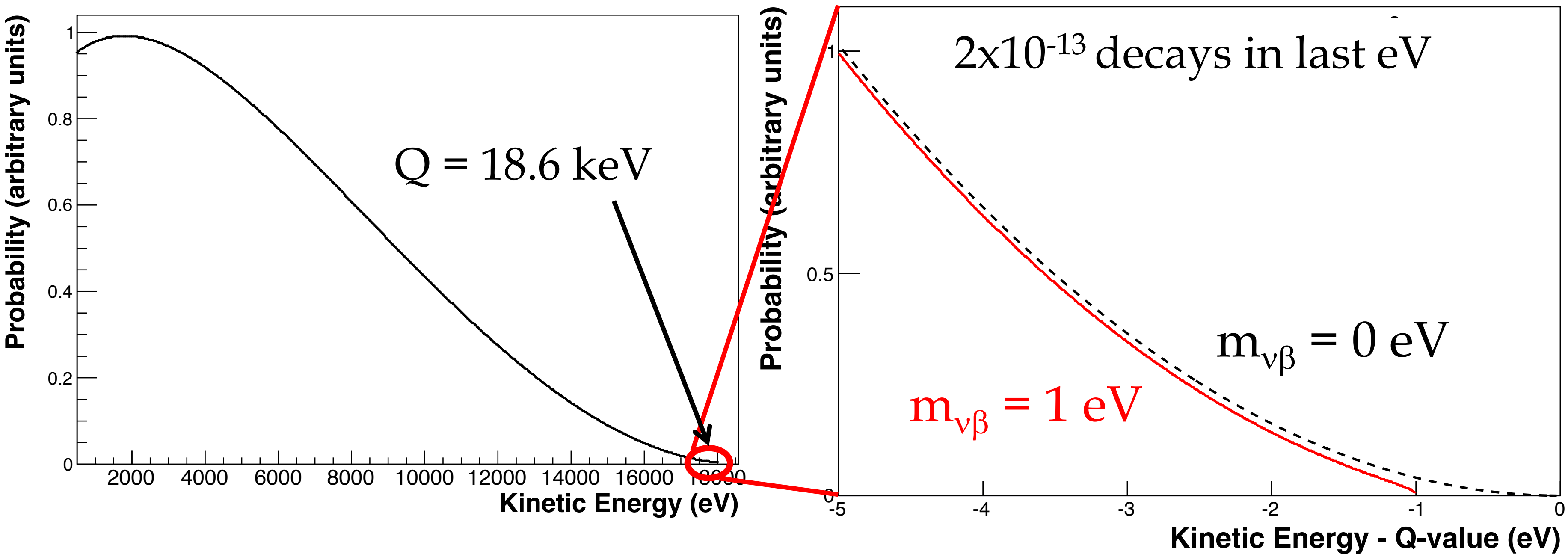
Taking into account ν mass eigenstates, the original spectrum

$$dN(E) = K|M|^2 F(Z,R,E)\, p_e E\, (E_0 - E)\ \{(E_0 - E)^2 - m^2_{\nu_e} c^4\}^{1/2}\, dE$$

becomes

$$dN(E) = K|M|^2 F(Z,R,E)\, p_e E\, (E_0 - E) \sum_i |U_{ei}|^2\ \{(E_0 - E)^2 - m^2_{\nu_i} c^4\}^{1/2}\, dE$$

For 3 ν mass spectrum, with degenerate states, the beta spectrum simplifies to an “effective mass” : $m_\beta = \sum |U_{ei}|^2 m^2_{\nu_i}$



Beta decay limits

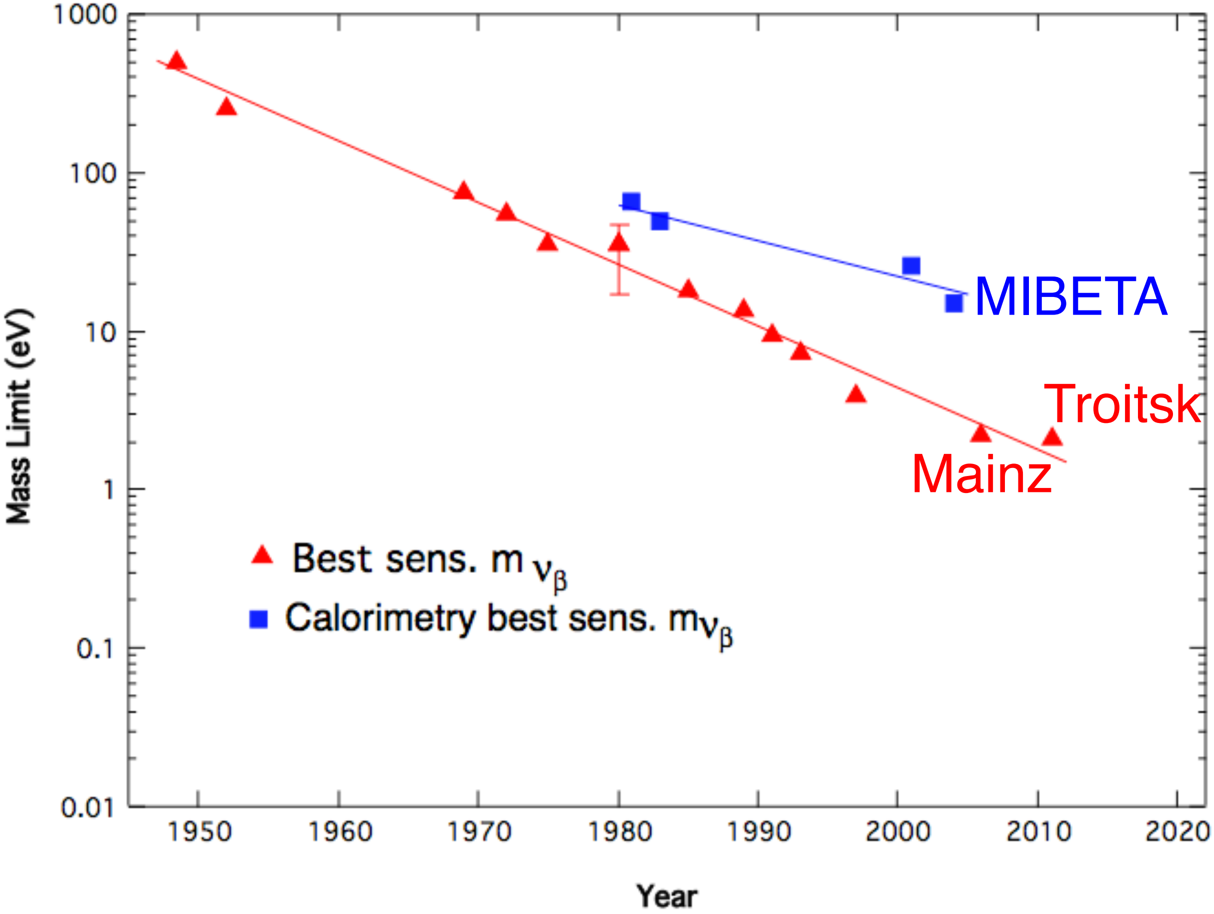


Figure from J. Wilkerson, Neutrino 2012

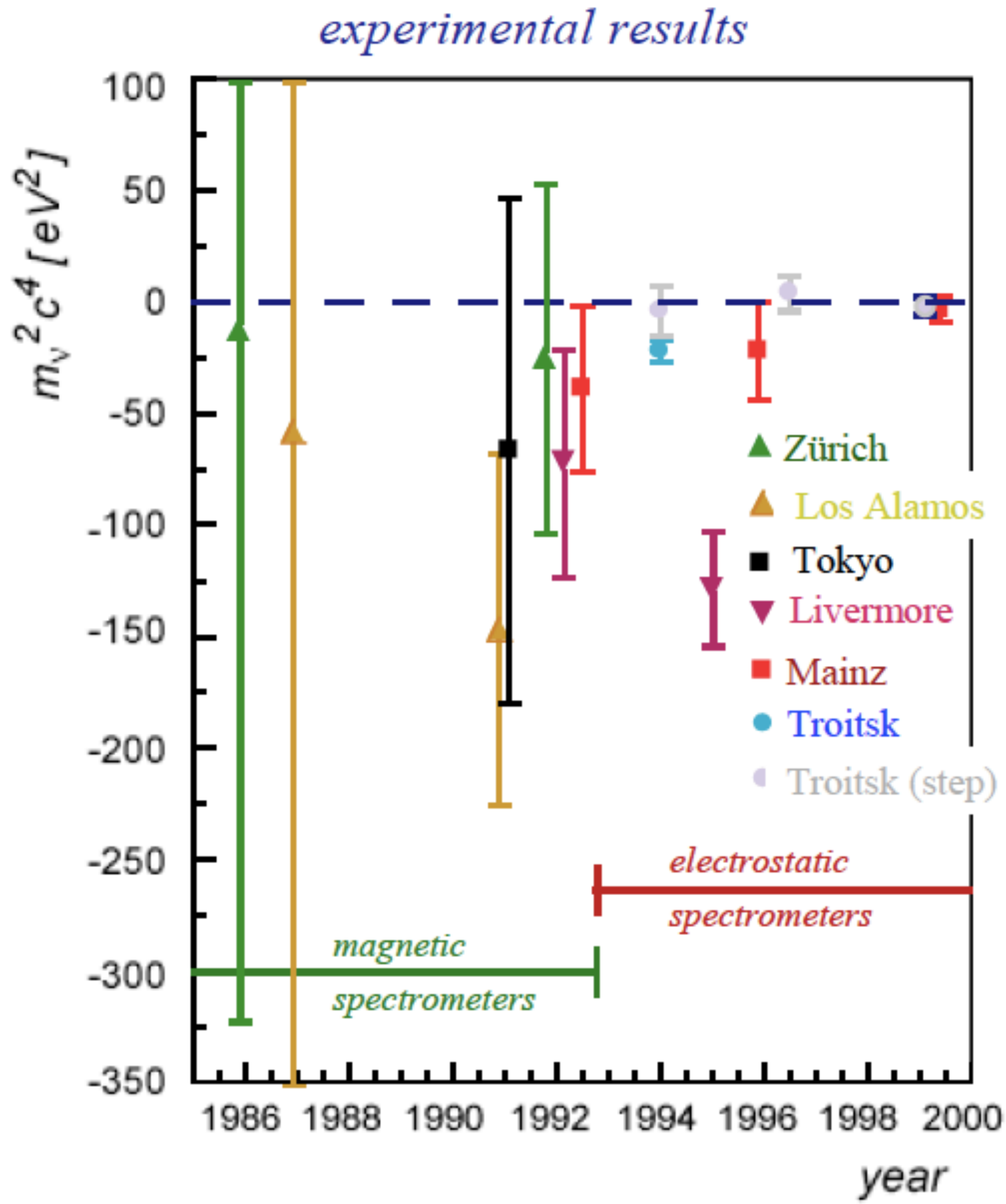
^{187}Re
$Q = 2.47$ keV
$t_{1/2} = 4.5 \times 10^9$ years
Forbidden

^{3}H (tritium)
$Q = 18.6$ keV
$t_{1/2} = 12.3$ years
Super-allowed

Existing tritium results

[redacted]

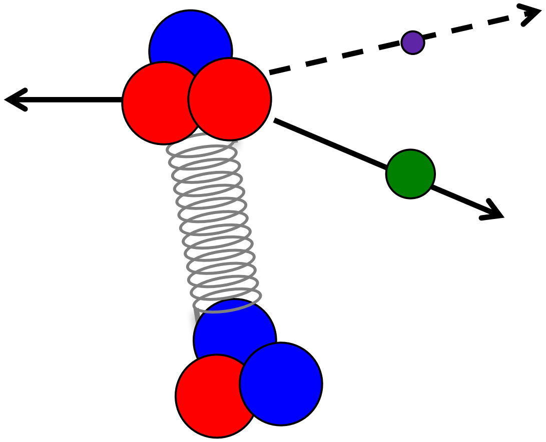
	m_ν
ITEP T_2 in complex molecule magn. spectrometer (Tret'yakov)	17-40 eV
Zürich T_2 - source impl. on carrier magn. spectrometer (Tret'yakov)	< 11.7 eV
Los Alamos gaseous T_2 - source magn. spectrometer (Tret'yakov)	< 9.3 eV
Tokyo T - source magn. spectrometer (Tret'yakov)	< 13.1 eV
Livermore gaseous T_2 - source magn. spectrometer (Tret'yakov)	
Mainz (1994-today) frozen T_2 - source electrostat. spectrometer	< 2.2 eV
Troitsk (1994-today) gaseous T_2 - source electrostat. spectrometer	(< 2.5 eV)



Tritium gas sources

Gas sources give the best results, but we're limited to using molecular tritium.

- Electronic excitations in T atoms
- Excitations in T_2 gas
  - Electronic: 20 eV
  - Vibrational: ~0.1 eV
  - Rotational: ~0.01 eV
- Beta spectrum depends on excitation energies V_k and probabilities P_k
- KATRIN needs 1% uncertainties on final state distribution.



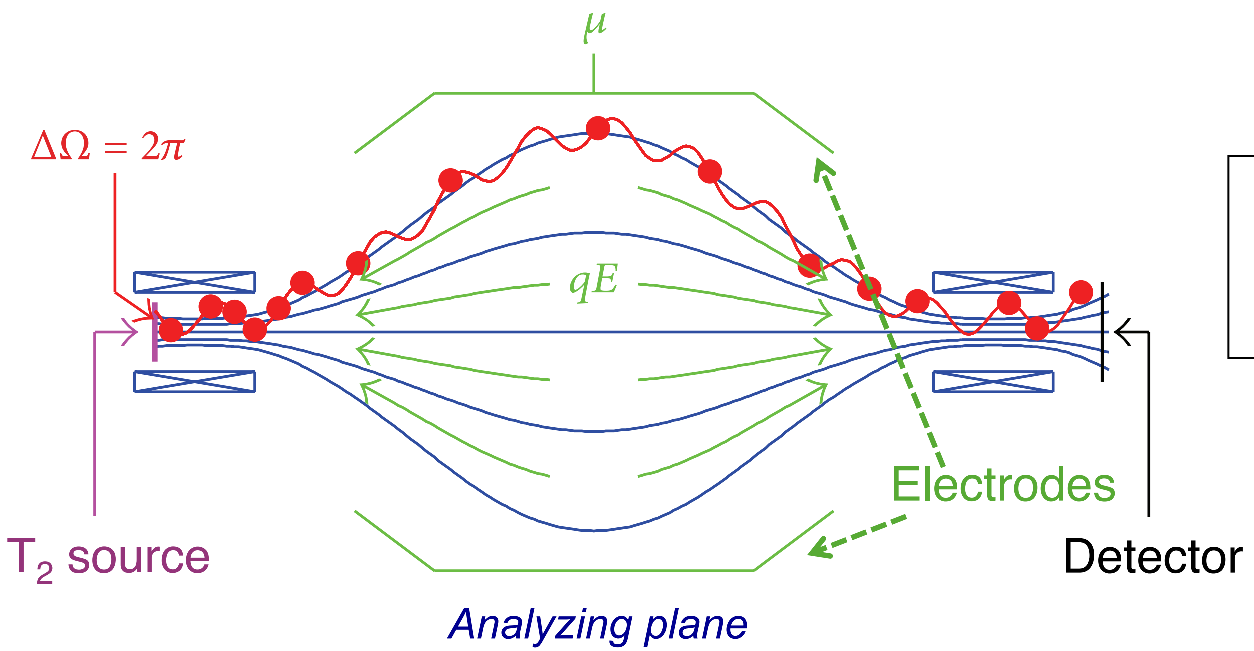
$$\frac{dN}{dE_e} = \frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7} |M_{\mathrm{nuc}}|^2 F(Z,E_e) p_e E_e \times \sum_{i,k} |U_{ei}|^2 P_k(E_{\mathrm{max}} - E_e - V_k)$$

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

MAC-E filter

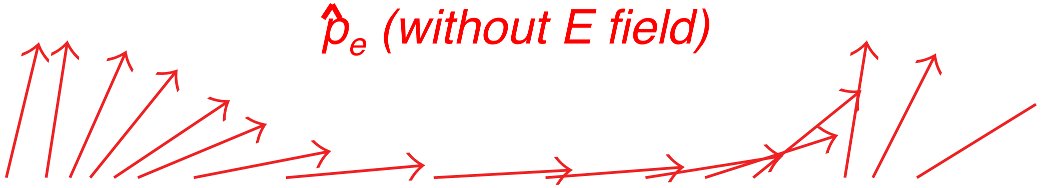
Magnetic Adiabatic Collimation and Electrostatic filter

The MAC-E filter allows measurement of integral spectrum with an adjustable threshold. Only see the endpoint of the decay!

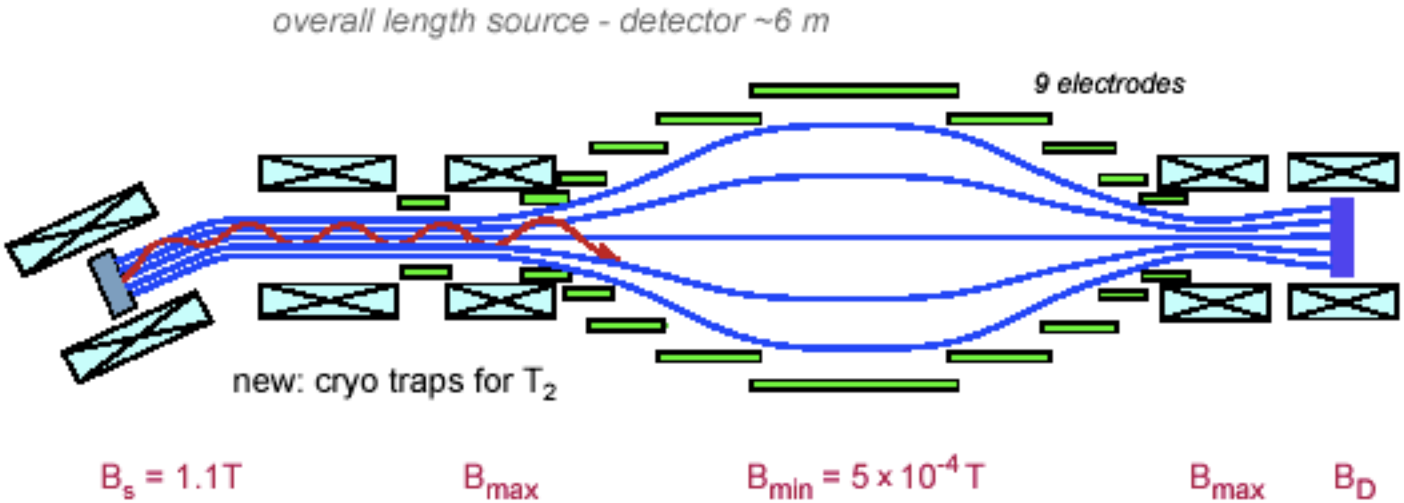


$$\boxed{\mu = \frac{E_\perp}{B} = \mathrm{const}}$$

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

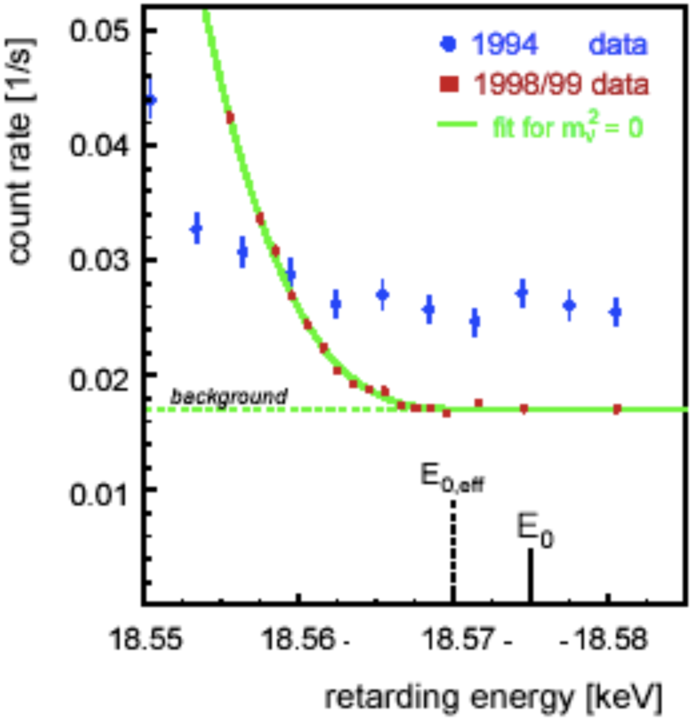


MAINZ



- Quench condensed solid T_2 source
- Early results (1994) showed systematic effects, traced to source film roughening transition (fixed by lowering temperature)
- 1995-1997 significant background reduction, signal improvement
- Best limit

< 2.2 eV @ 90% C.L.



Weinheimer et al., *Phys. Lett.* B 460219 (1999)

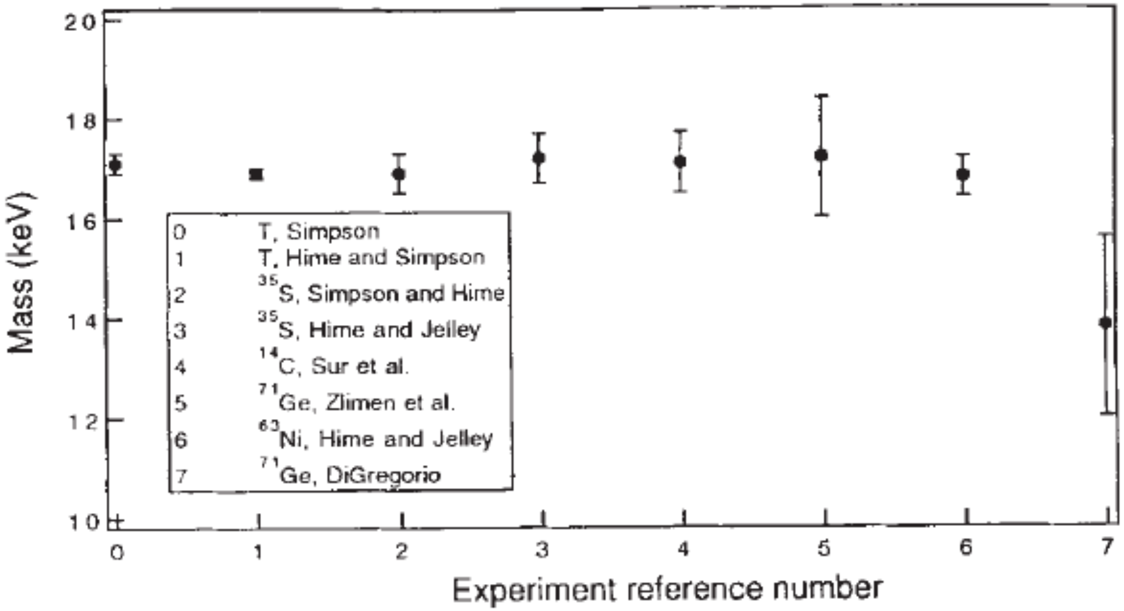
Speaking of anomalous results…

The rise and fall of the 17-keV neutrino

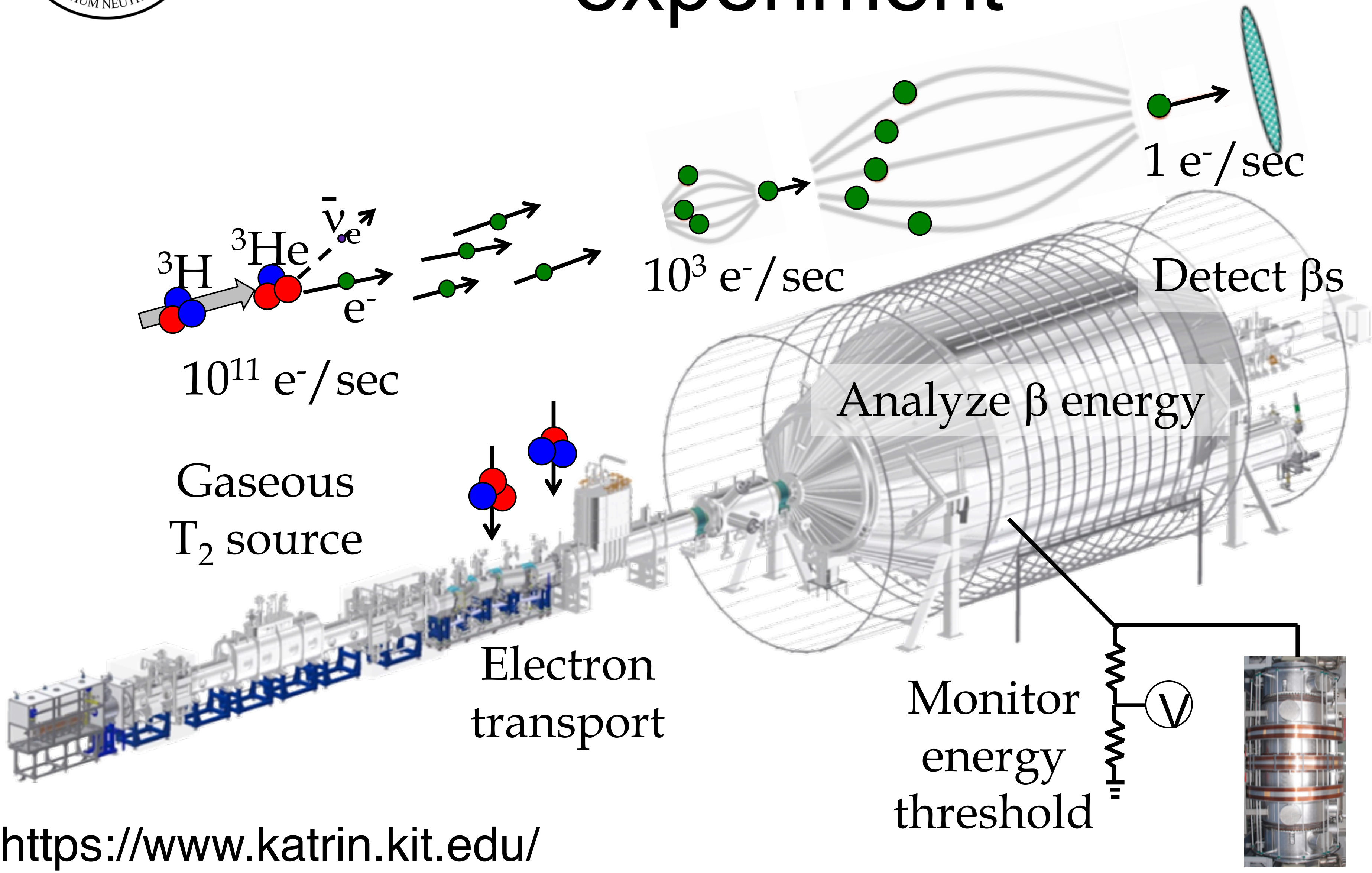
Douglas R. O. Morrison

Nature **366**, 29 - 32 (04 November 1993)

Experiments showing evidence for a heavy neutrino with a mass of 17 keV launched the new particle on an erratic eight-year career, during which it raised questions about the Standard Model of particle physics and about cosmological theories, stimulated many theoretical papers and pushed experimental techniques to their limit. Its demise provides grounds for faith in the efficacy of the scientific method.



KArlsruhe **TRI**tium **N**eutrino experiment



^{3}H

^{3}He

$\bar{\nu}_e$

e^-

10^{11} e^-/sec

10^3 e^-/sec

1 e^-/sec

Detect βs

Analyze β energy

Gaseous T_2 source

Electron transport

Monitor energy threshold

https://www.katrin.kit.edu/

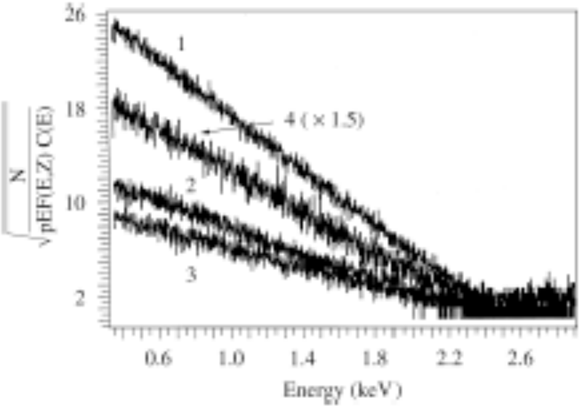
KATRIN outlook

- Intense T_2 source (10^{11} decays/second)
- Spectrum analysis with electromagnetic filter
- Design resolution 0.93 eV
- Design m_β sensitivity: **0.2 eV/c^2 at 90% C.L.**
- 2015 commissioning revealed high backgrounds from ^{210}Po
- Tritium commissioning began in May 2018! Stay tuned…

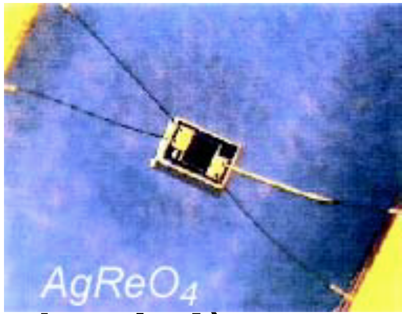

Leopoldshafen
November 2006

MIBETA and MARE

Bolometric measurements on ^{187}Re



- ~15 eV sensitivity for MiBETA (2004)
- R&D by MARE collaboration
  - Metallic Re (superconducting)
    - Complex thermalization
  - Dielectric $AgReO_4$
    - Long response time
- Low specific activity (10^5 pixels!)

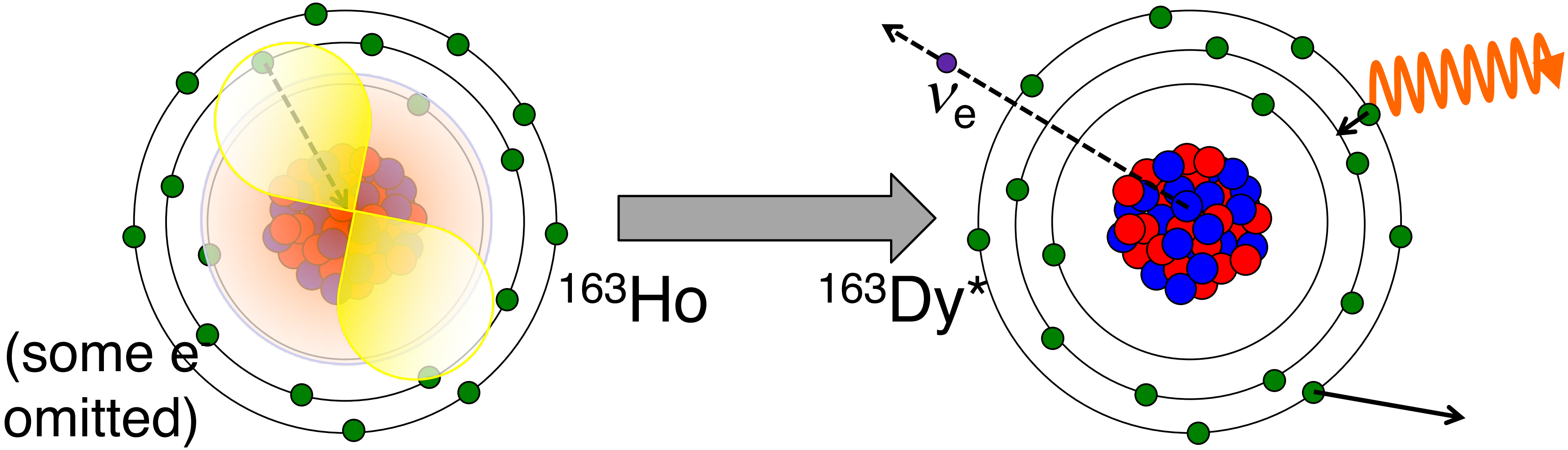


Community has moved on to ^{163}Ho

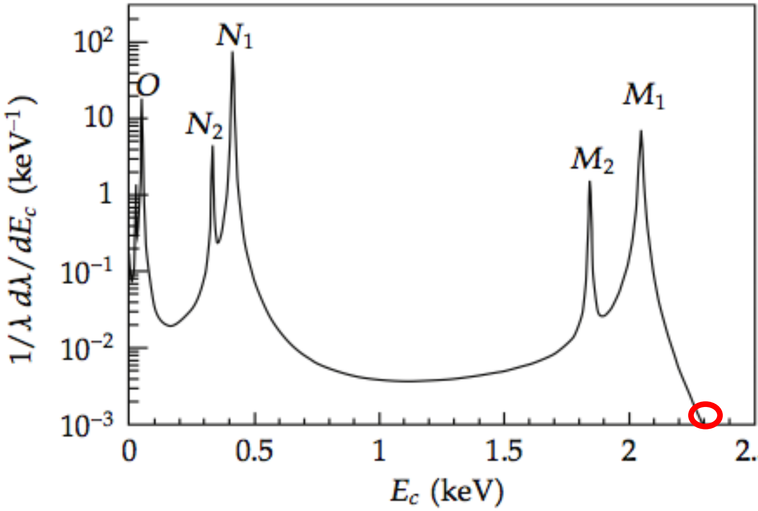
Nucciotti, arXiv:1511.00968

Holmium decay

$$^{163}\text{Ho} \rightarrow {}^{163}\text{Dy}^{*} + \nu_e$$



Lusignoli and Vignati, *Phys. Lett. B* ***697*** *(2011)*



^{163}Ho

$Q = 2.83$ keV

$t_{1/2} = 4750$ years

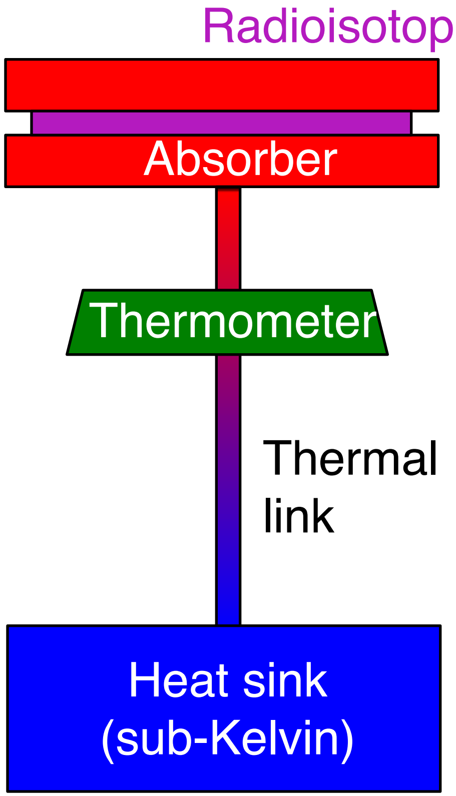
De Rújula and Lusignoli, Phys. Lett. B ***118*** *(1982) 429*

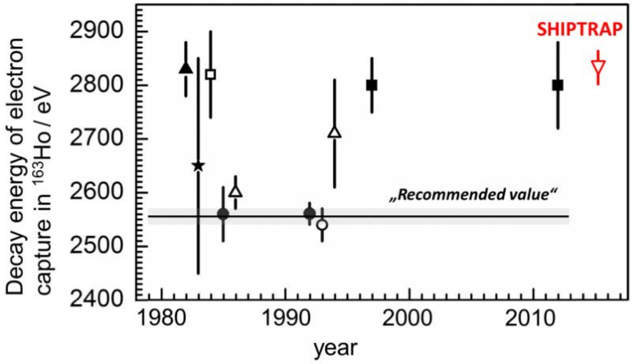
Holmium experiments

Holmium microcalorimetry, two competing experiments.

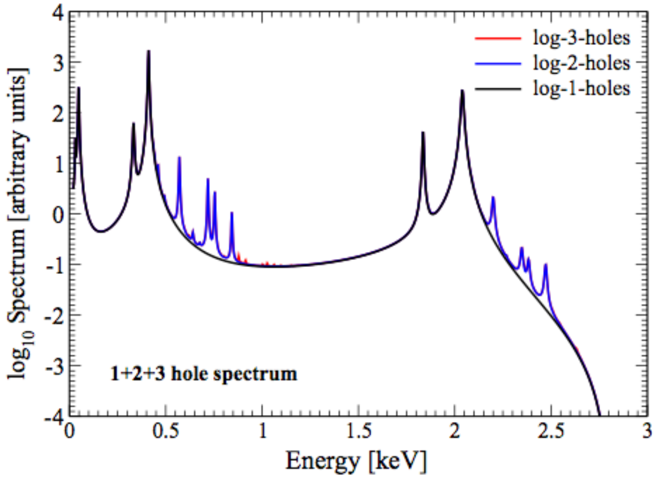
- HOLMES uses MKID sensor technology, ECHo uses MMCs

Big problems with the endpoint and theory





*Eliseev et al., PRL **115** (2015) 062501*



*Faessler et al., PRC **91** (2015) 064302*

A new approach: PROJECT 8

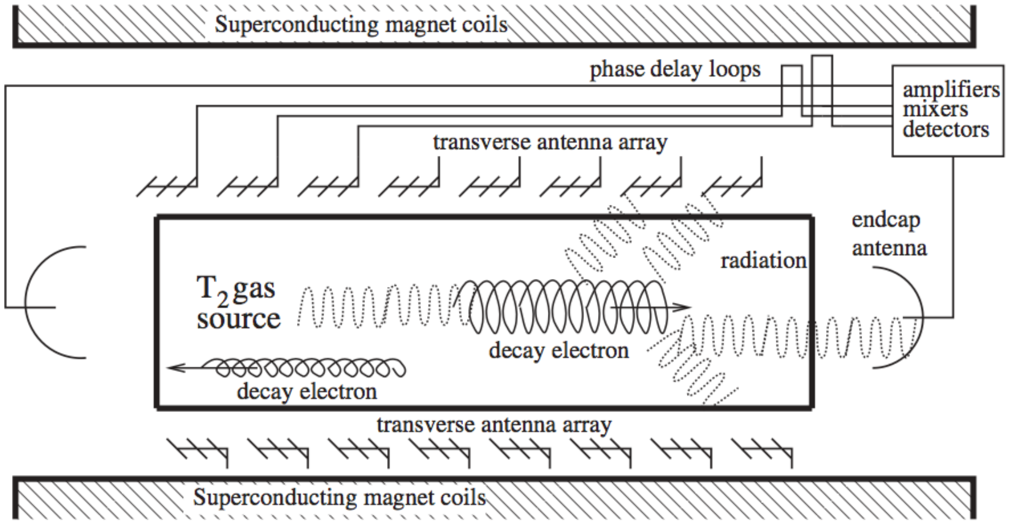
Never measure anything but frequency.

-Arthur Schawlow

An electron in a magnetic field will radiate at:

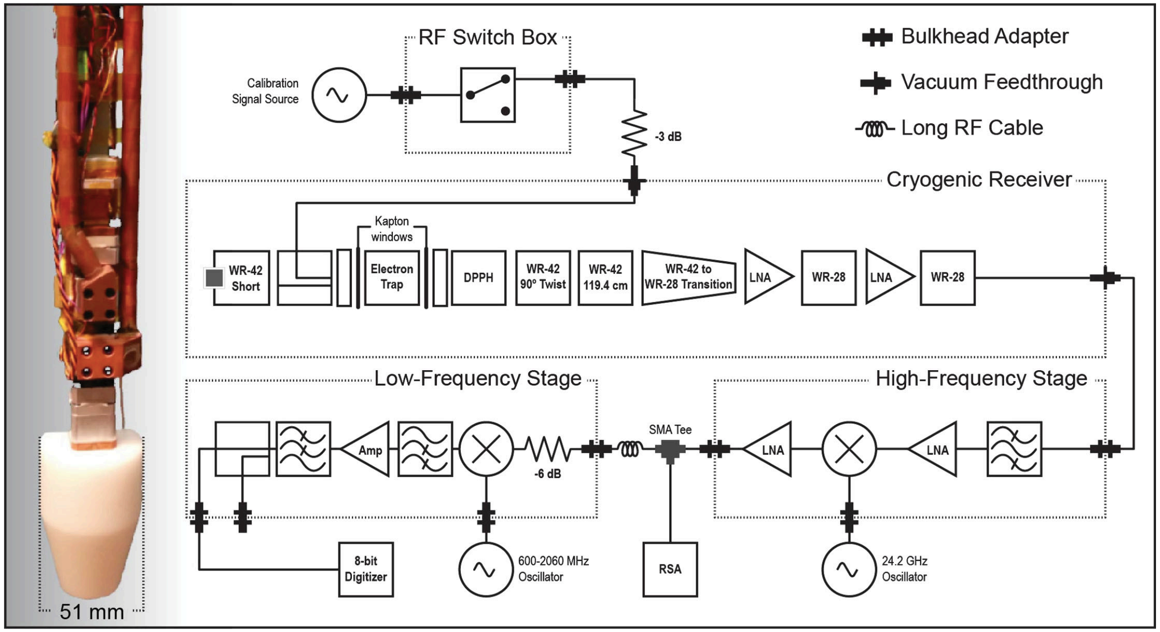
$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi}\frac{1}{m_e + {}^{1}\!/_{c^2}\, E_\beta}$$

Measure entire beta spectrum at once:
Cyclotron **R**adiation
Emission
Spectroscopy (**CRES**)



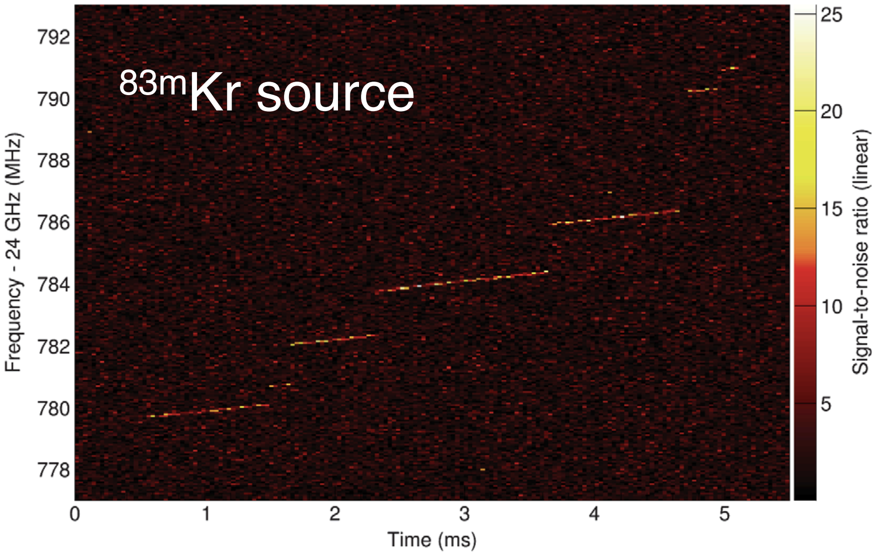
Monreal and Formaggio, PRD ***80*** *(2009)*

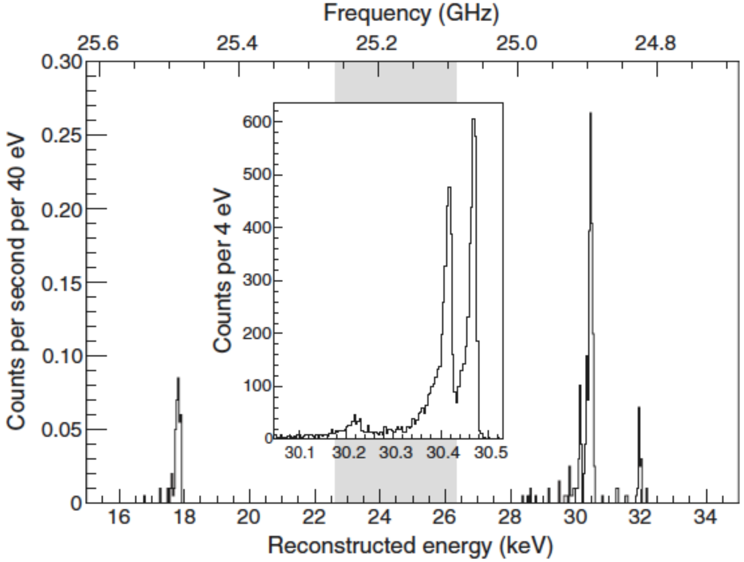
CRES single electron detection



PROJECT 8

PRL 114, 162501 (2015)

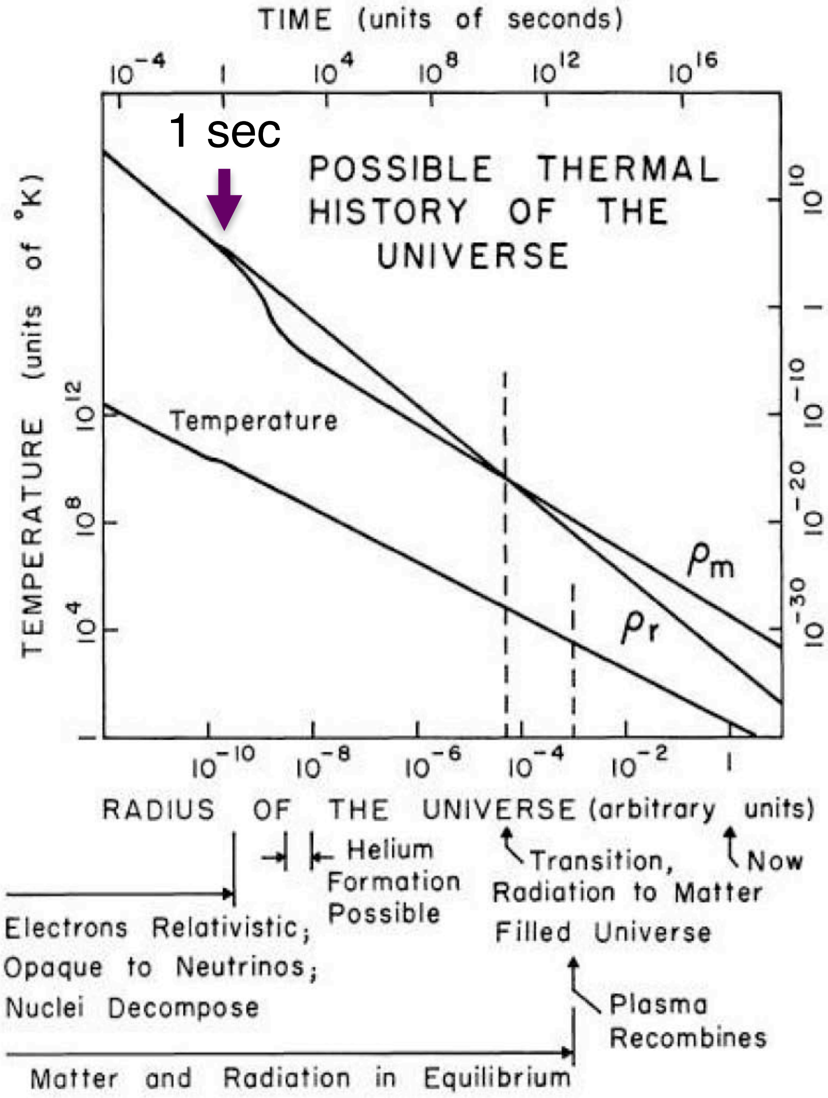




Cosmic neutrino background

Next few slides stolen from a talk by Chris Tully at LNGS in 2017
for more on PTOLEMY, see arXiv:1902.05508

Cosmic neutrino background



Dicke, Peebles, Roll, Wilkinson (1965)

$$n_\nu = \left(\frac{3}{4}\right)\left(\frac{4}{11}\right) n_\gamma = 112/\mathrm{cm}^3$$

per neutrino species
(neutrino+antineutrino)

$$T_\nu(t) = \left(\frac{4}{11}\right)^{1/3} T_{CMB}$$

T_ν~1.95K

start of nucleosynthesis
n/p~0.15*0.74~0.11

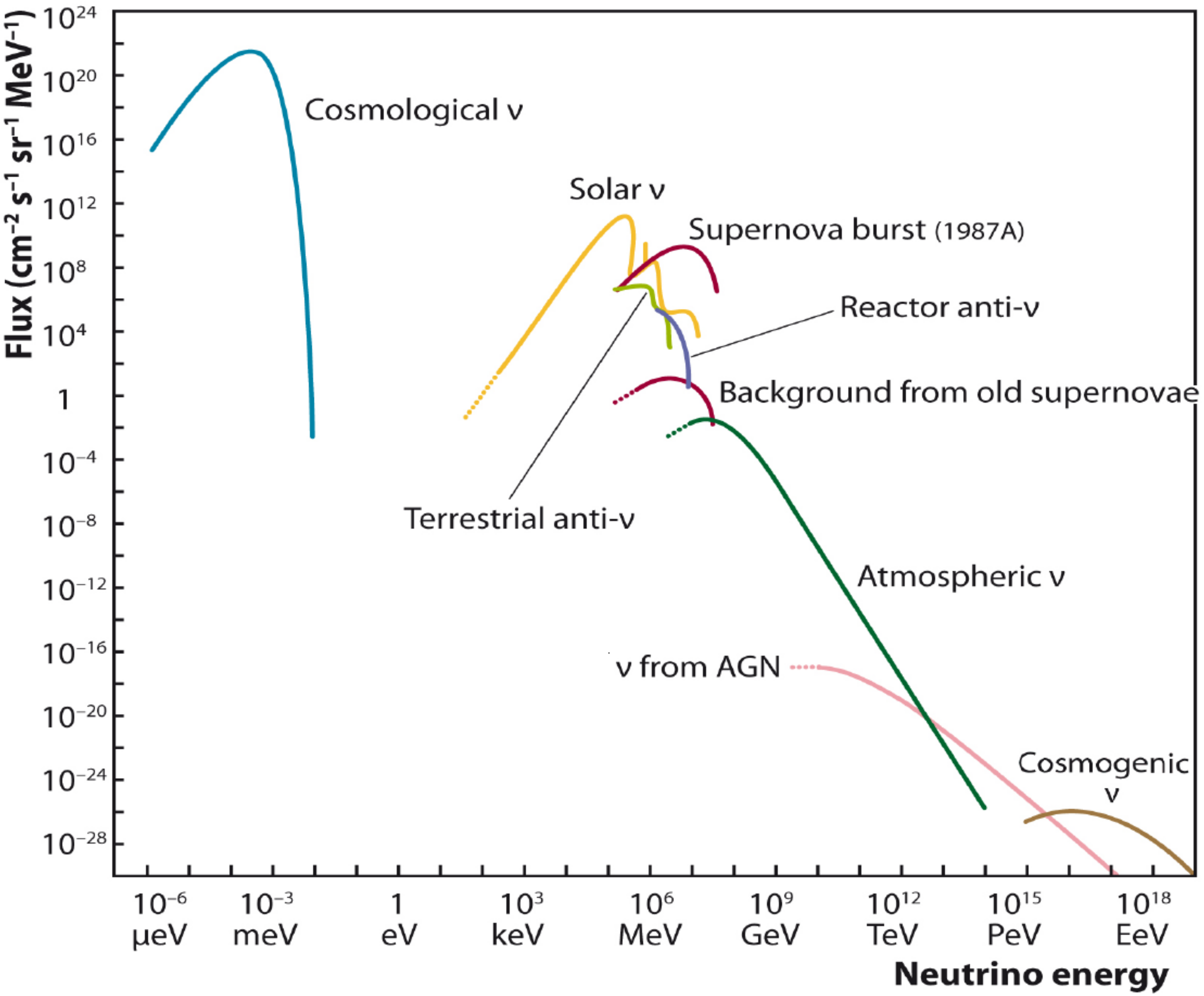
$$\frac{\lambda(p \to n)}{\lambda(n \to p)} = e^{-Q/kT}$$

Relic velocity depends on mass

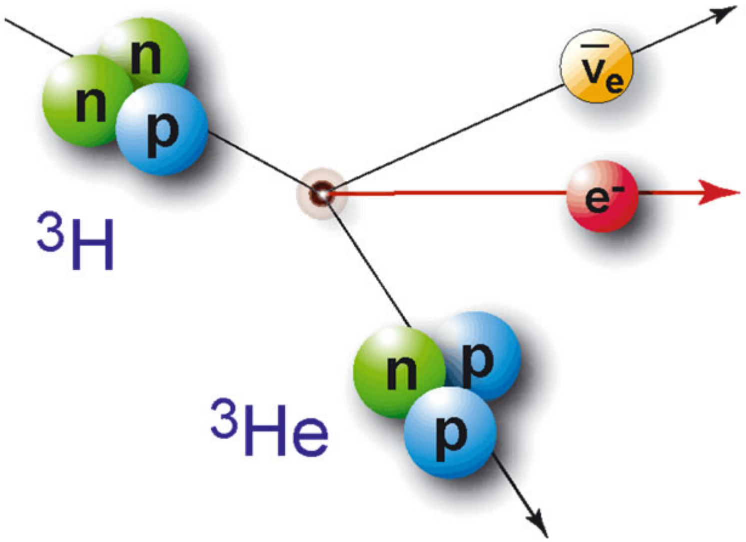
$$\langle \mathrm{v}_{rms} \rangle \propto T/m_\nu \text{ instead of } \propto \sqrt{T/m_\nu}$$

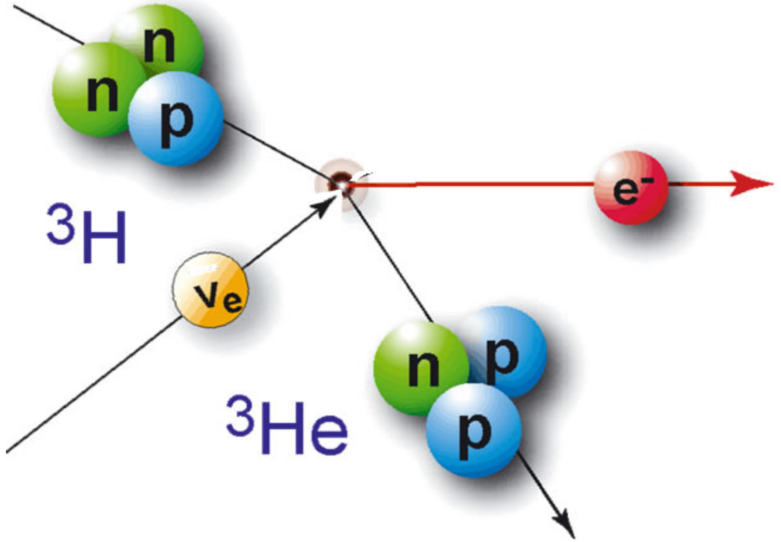
$$\langle \mathrm{v}_{rms} \rangle = 160\ \mathrm{km/s}\ \left(1\ \mathrm{eV}/m_\nu\right)$$

Cosmic neutrino background

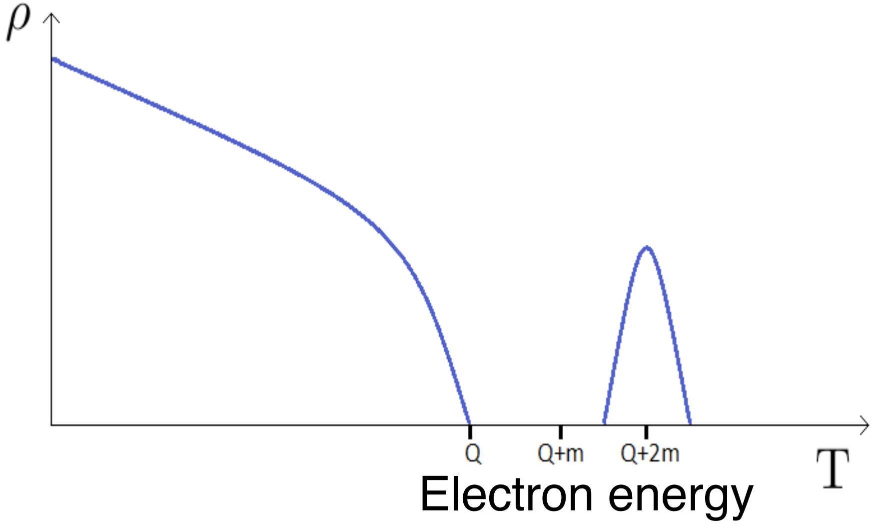


Neutrino capture





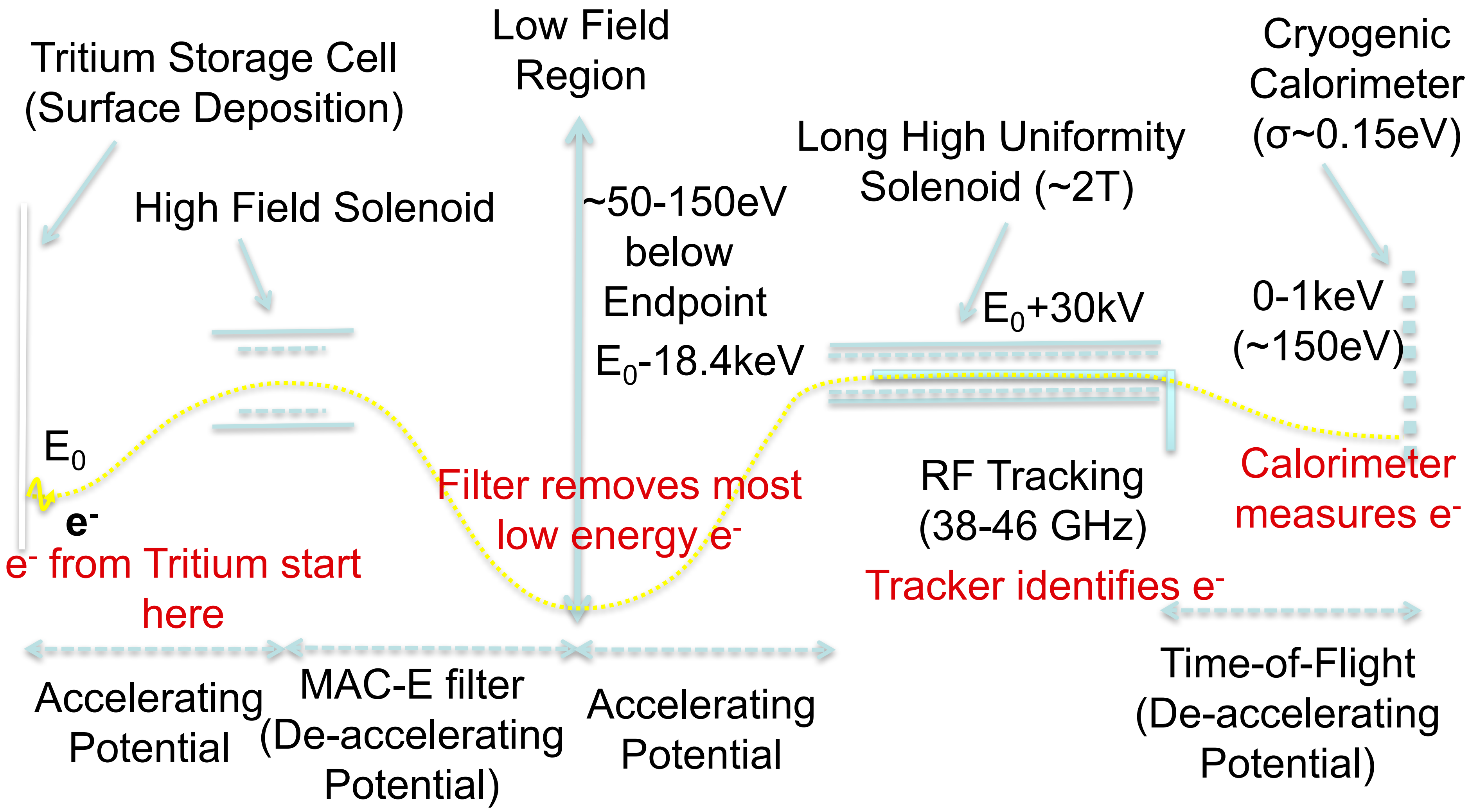
Capture cross section * (v/c) ~ 10^{-44} cm^2 (flat up to 10 keV)



Original idea: Steven Weinberg in 1962,
Phys. Rev. 128:3, 1457
JCAP 0706 (2007)015, hep-ph/0703075,
Cocco, Mangano, Messina

A little bit of everything: PTOLEMY

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield



Tritium Storage Cell (Surface Deposition)

High Field Solenoid

E_0

e^-

e^- from Tritium start here

Low Field Region

~50-150eV below Endpoint

E_0-18.4keV

Filter removes most low energy e^-

Long High Uniformity Solenoid (~2T)

E_0+30kV

RF Tracking (38-46 GHz)

Tracker identifies e^-

Cryogenic Calorimeter (σ~0.15eV)

0-1keV (~150eV)

Calorimeter measures e^-

Accelerating Potential

MAC-E filter (De-accelerating Potential)

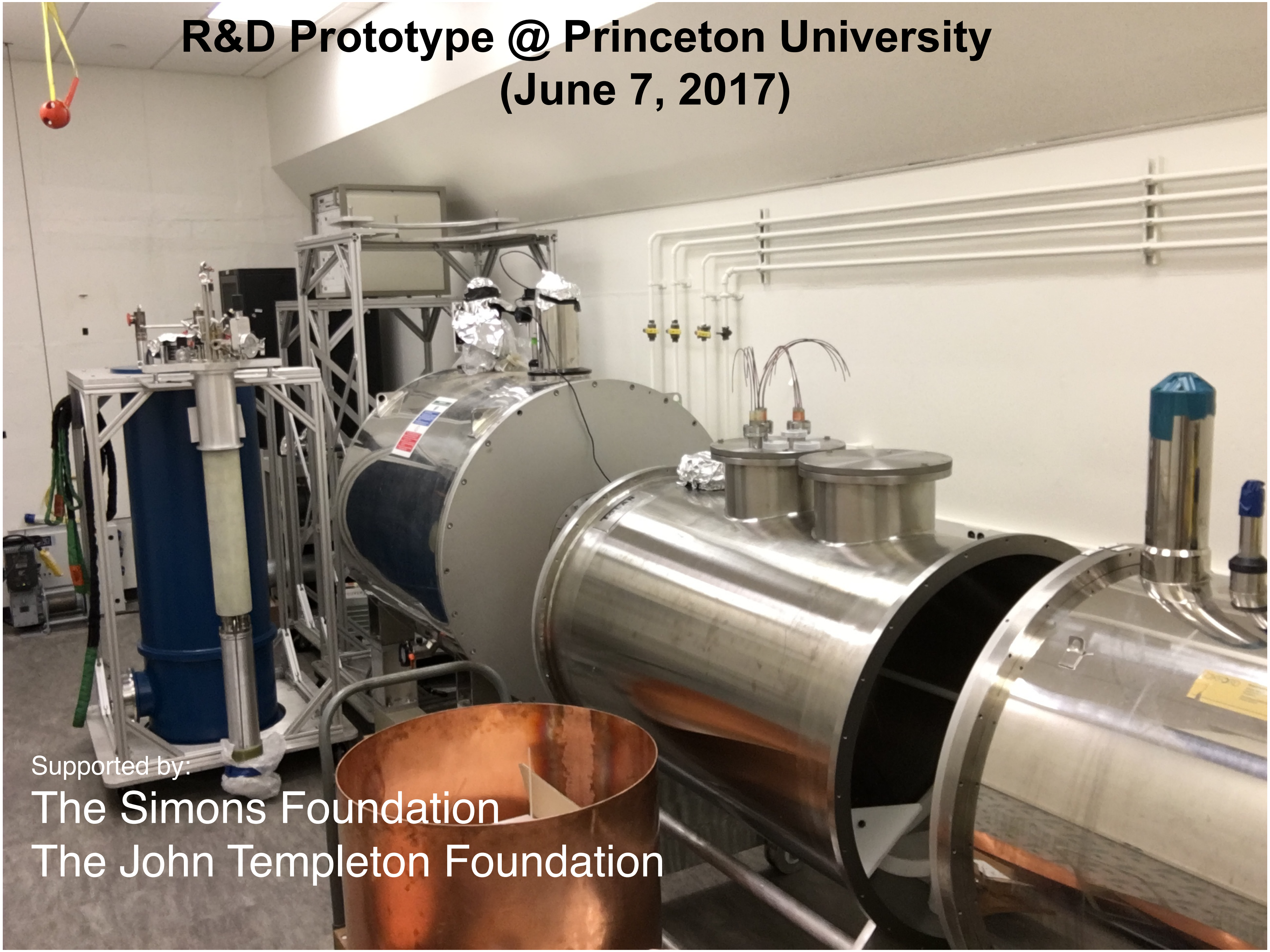
Accelerating Potential

Time-of-Flight (De-accelerating Potential)

R&D Prototype @ PPPL (August 2, 2016)

Supported by:
The Simons Foundation
The John Templeton Foundation

R&D Prototype @ Princeton University
(June 7, 2017)



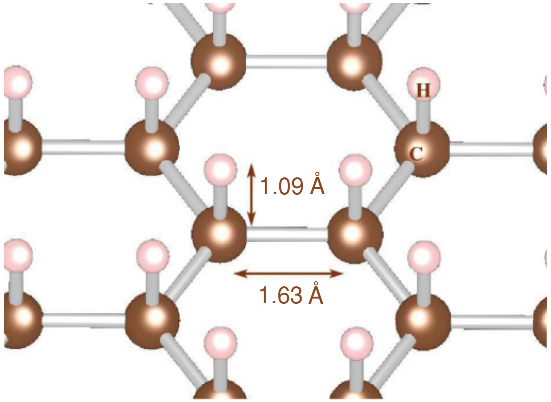
Supported by:

The Simons Foundation

The John Templeton Foundation

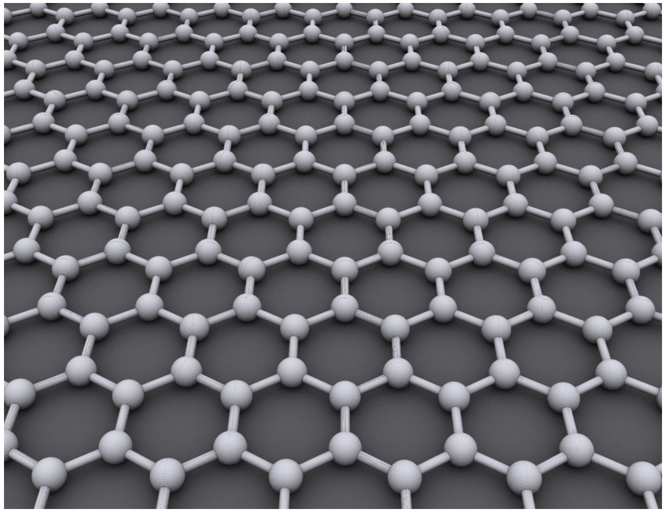
Major challenges

- Reduce molecular smearing
    - New source (Tritiated-Graphene or Cryogenic Au(111))
- Measure the energy spectrum directly with a resolution comparable to the neutrino mass
    - High-resolution electron microcalorimeters
- Compress a 70m spectrometer length – KATRIN's length – down to ~cm scale and replicate it at lower precision – final measurement from microcalorimeter
    - New filter concept (Newtonian vs. Galilean)
    - RF trigger system (Project 8 development)
    - G-FET as a potential trigger system



< 3eV binding energy

Graphene



Summary

- Beta decay measurements are the best tool we have for a precise measurement of small neutrino masses.
- KATRIN, following in the footsteps of MAINZ/TROITSK, will begin taking data soon, bringing limits on m_β to the 0.2 eV level.
- Bolometer experiments HOLMES and ECHo are also pursuing direct mass measurements in holmium.
- Radio frequency measurement developed by Project 8 is another promising technique with some recent technical success.
- These experiments can also potentially probe the CNB.
- The future of the field is dependent on nuclear theory!