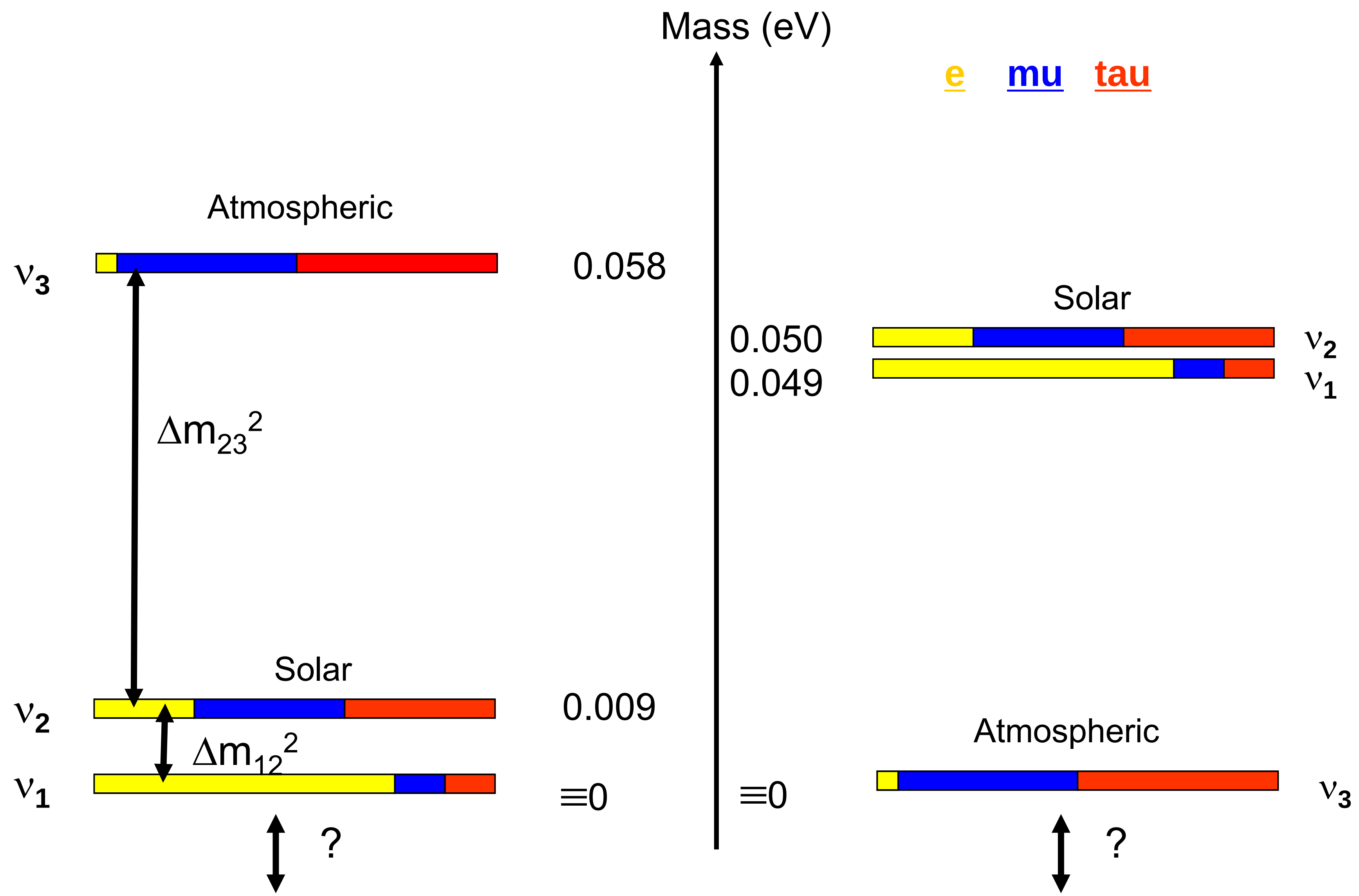
Kinematic Determination of Neutrino Mass

- Neutrino oscillations tell us two important things:
  - Neutrinos HAVE mass: $\Sigma m > 55$ meV
  - We can use electron neutrinos to get the mass.

- Beta Decay
  - Tritium
  - ^{187}Re
  - Other ideas?
- Cosmology
- Cosmic rays

Neutrino mass spectrum and flavor content



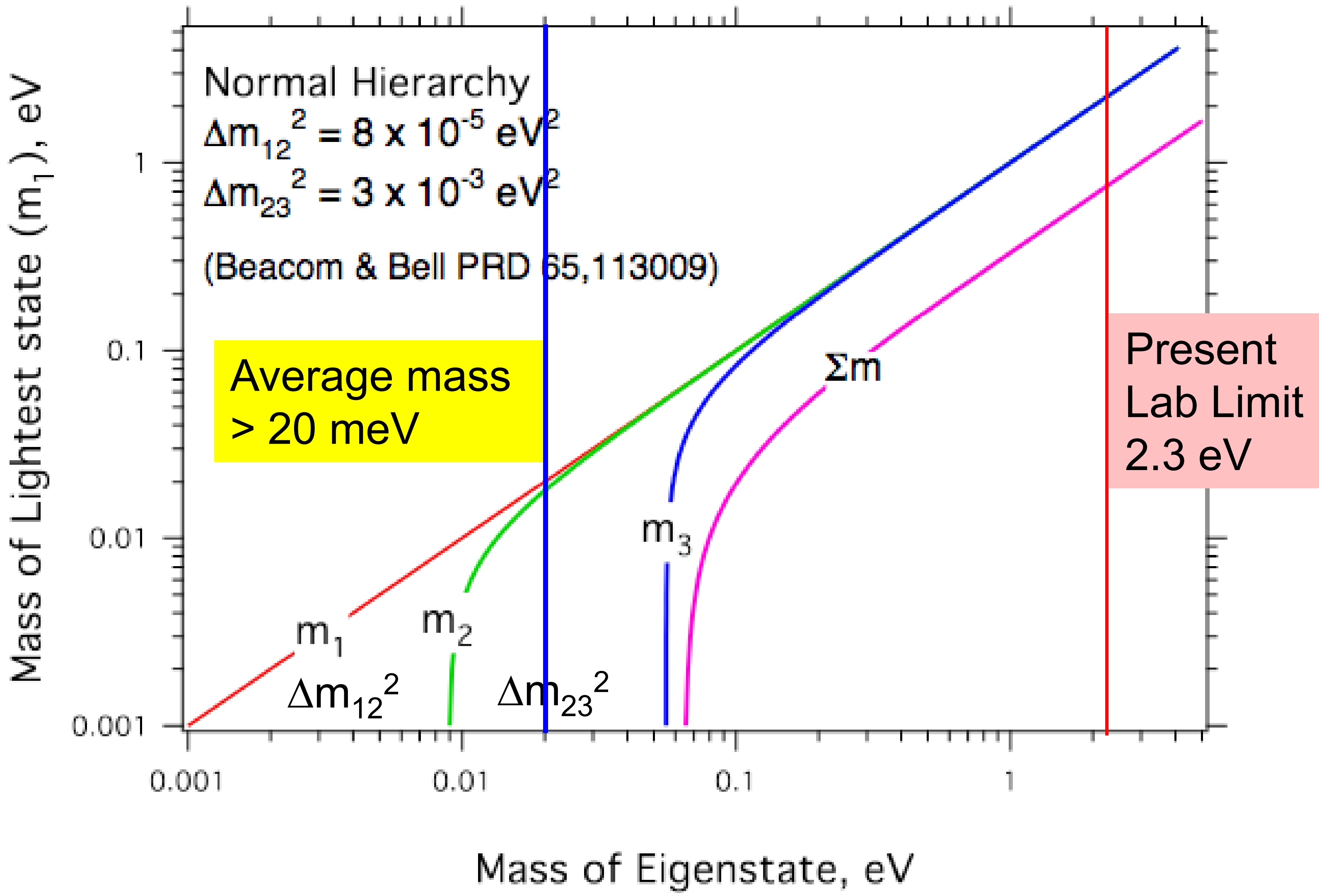
Mass and mixing parameters

Δm_{21}^2	$7.65^{+0.23}_{-0.20} \times 10^{-5}$ eV^2	
$\|\Delta m_{32}^2\|$	$2.40^{+0.12}_{-0.11} \times 10^{-3}$ eV^2	
Σm_i	> 55.3 meV (95% CL)	< 6900 meV (90% CL)*
θ_{12}	$33.5^{+1.3}_{-1.0}$ deg	
θ_{23}	$45^{+4.0}_{-3.5}$ deg	
θ_{13}	$7.2^{+2.0}_{-2.8}$ deg	Non-Gaussian error!
$\sin^2\theta_{13}$	< 0.056 (90% CL)	~ Gaussian error

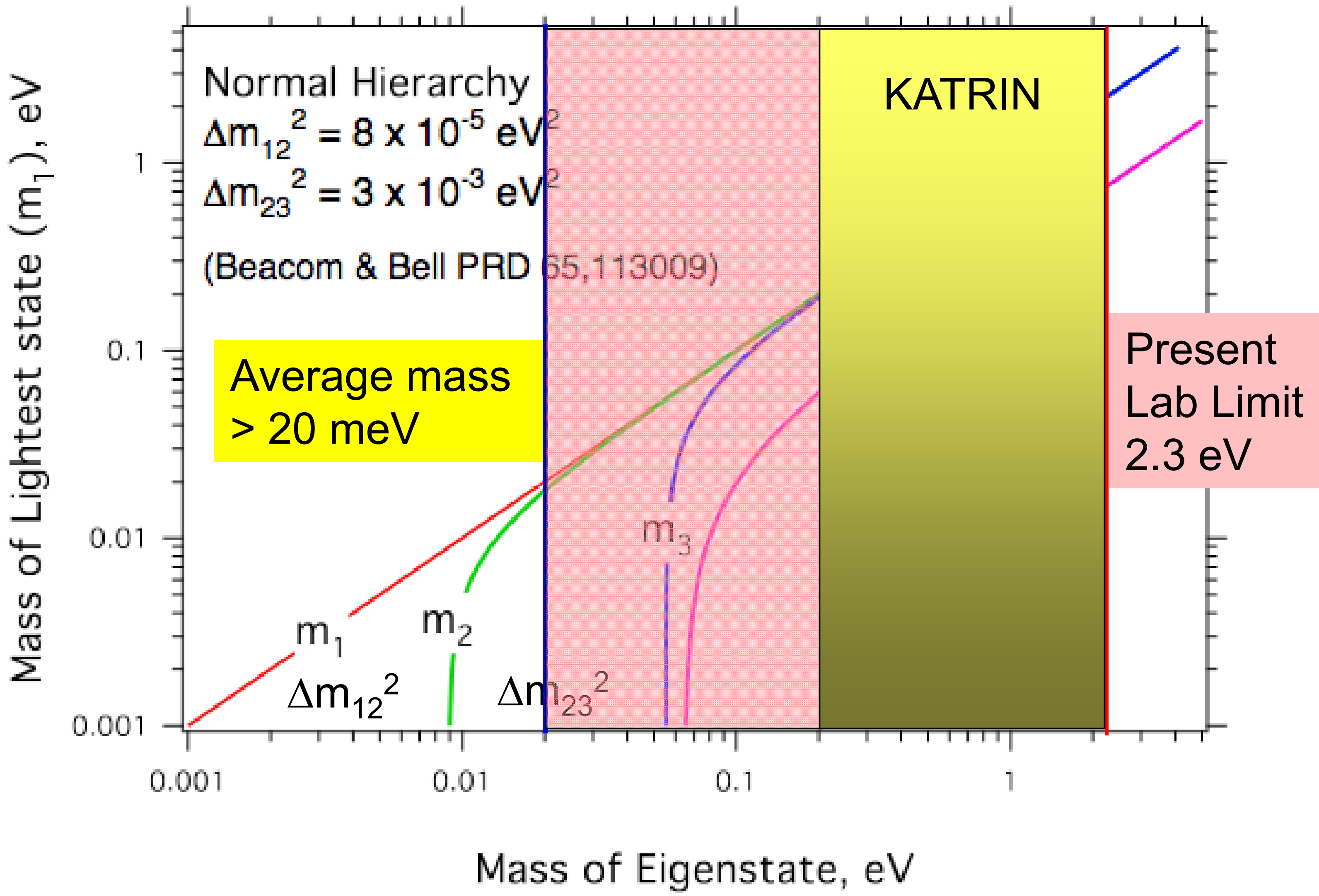
Marginalized 1-D 1-σ uncertainties.

*C. Kraus et al., Eur. Phys. J. C40, 447 (2005)
Other refs, see HR, 0807.4258v1

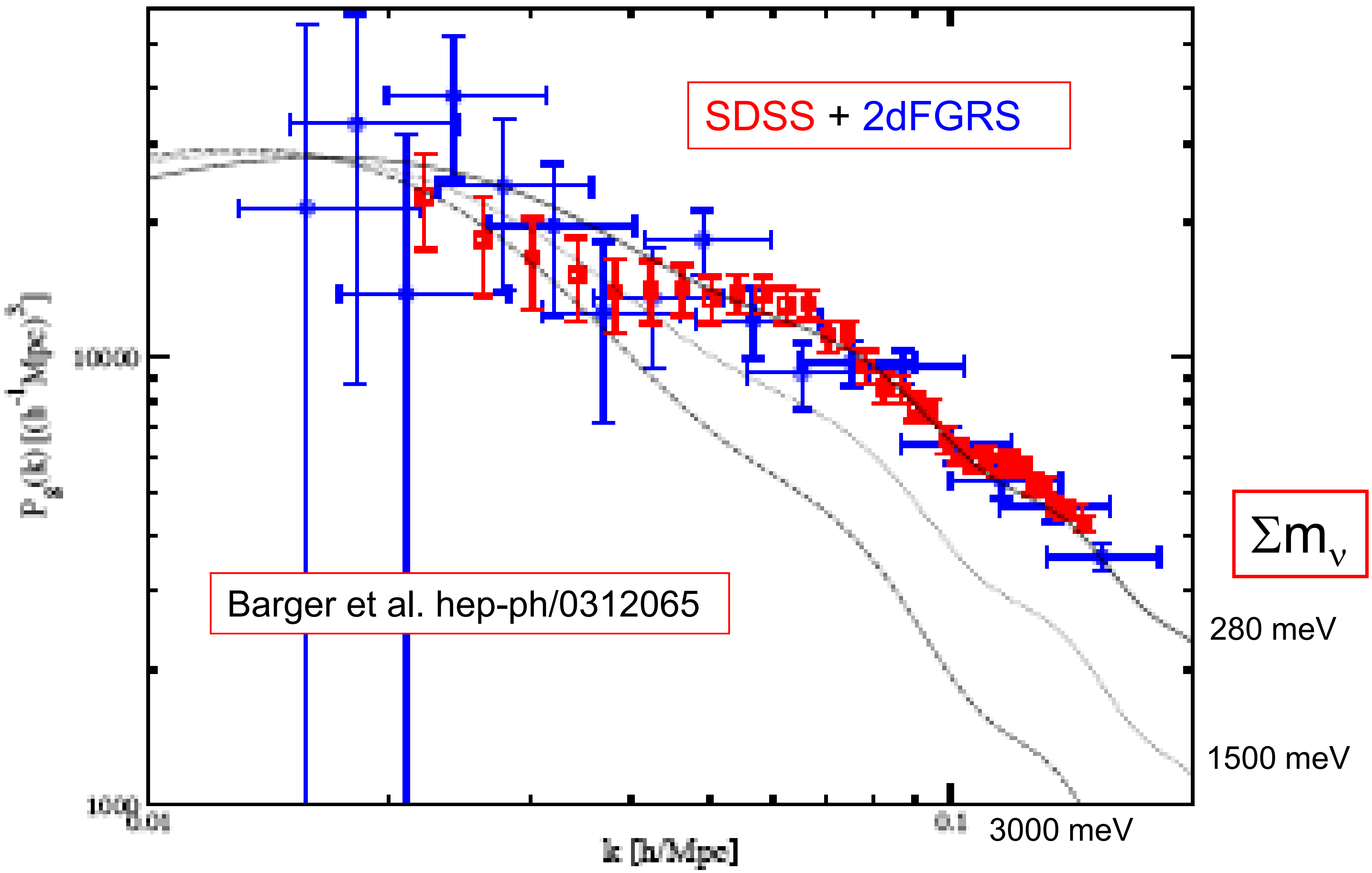
Masses linked by oscillations

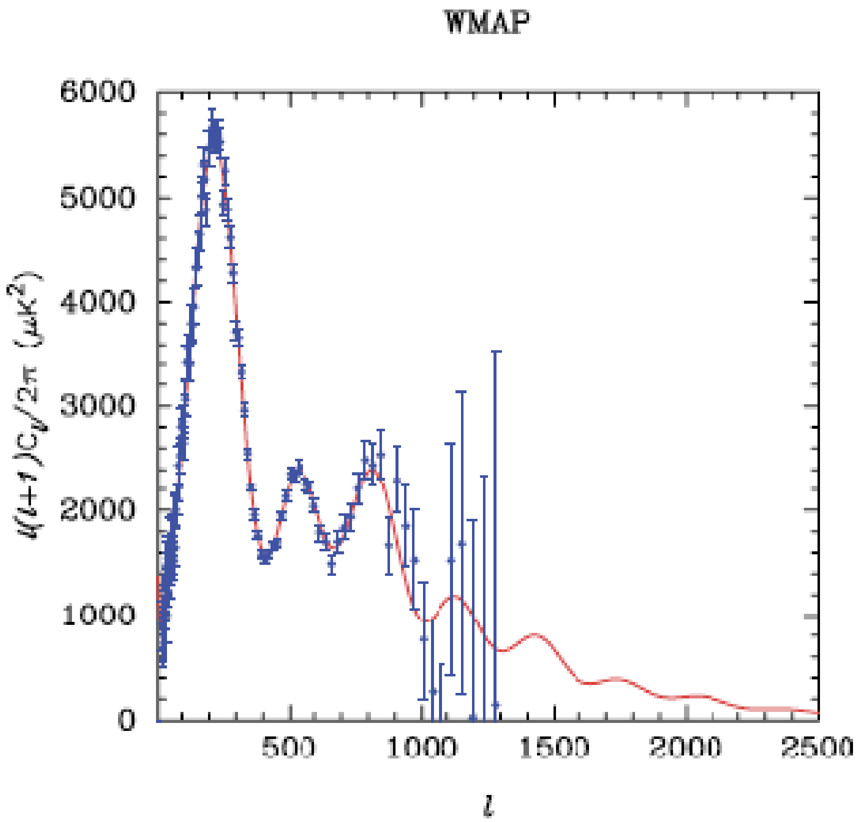


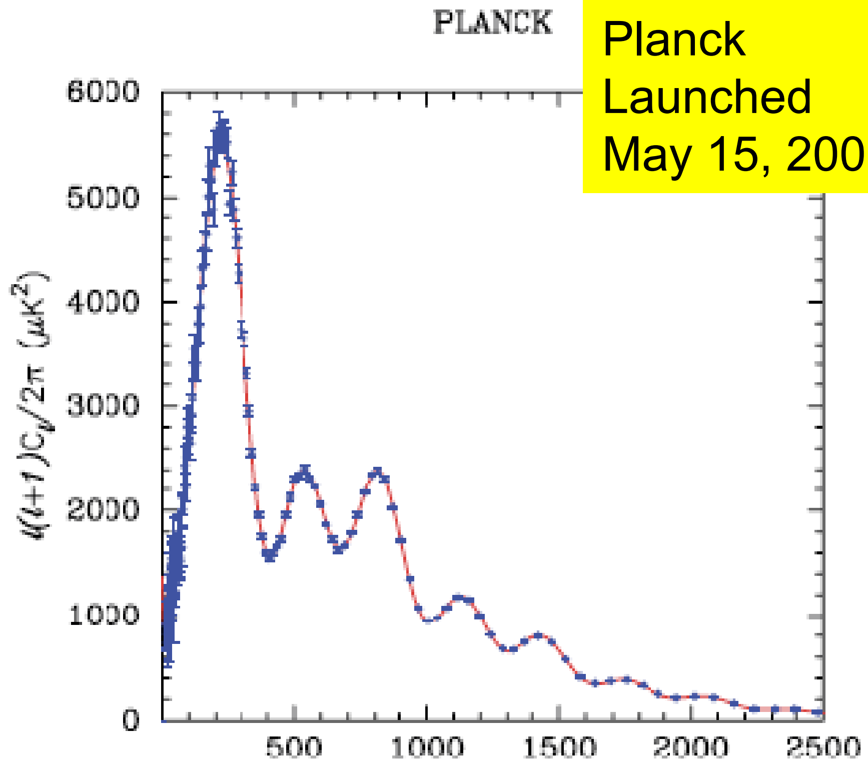
Mass Range Accessible



Even small m_ν influences structure



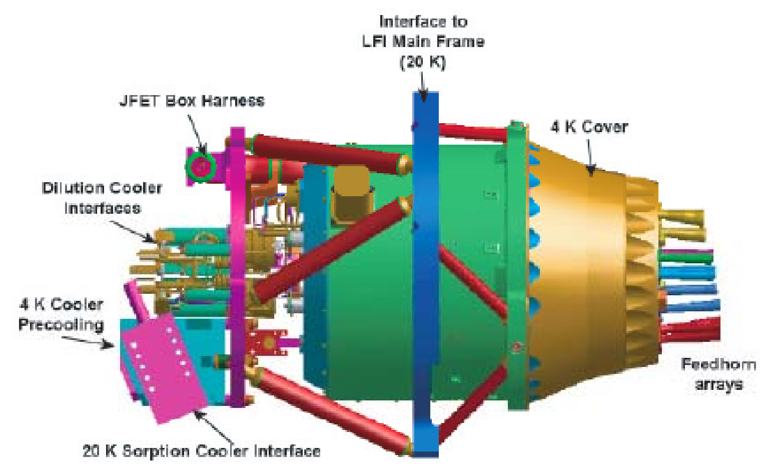




Planck
Launched
May 15, 2009

Planck will provide 3 separate ΛCDM constraints on Σm_ν:

1. Planck + SDSS 0.2 eV
2. Planck only 0.26 eV
3. CMBR + grav. lensing 0.15 eV

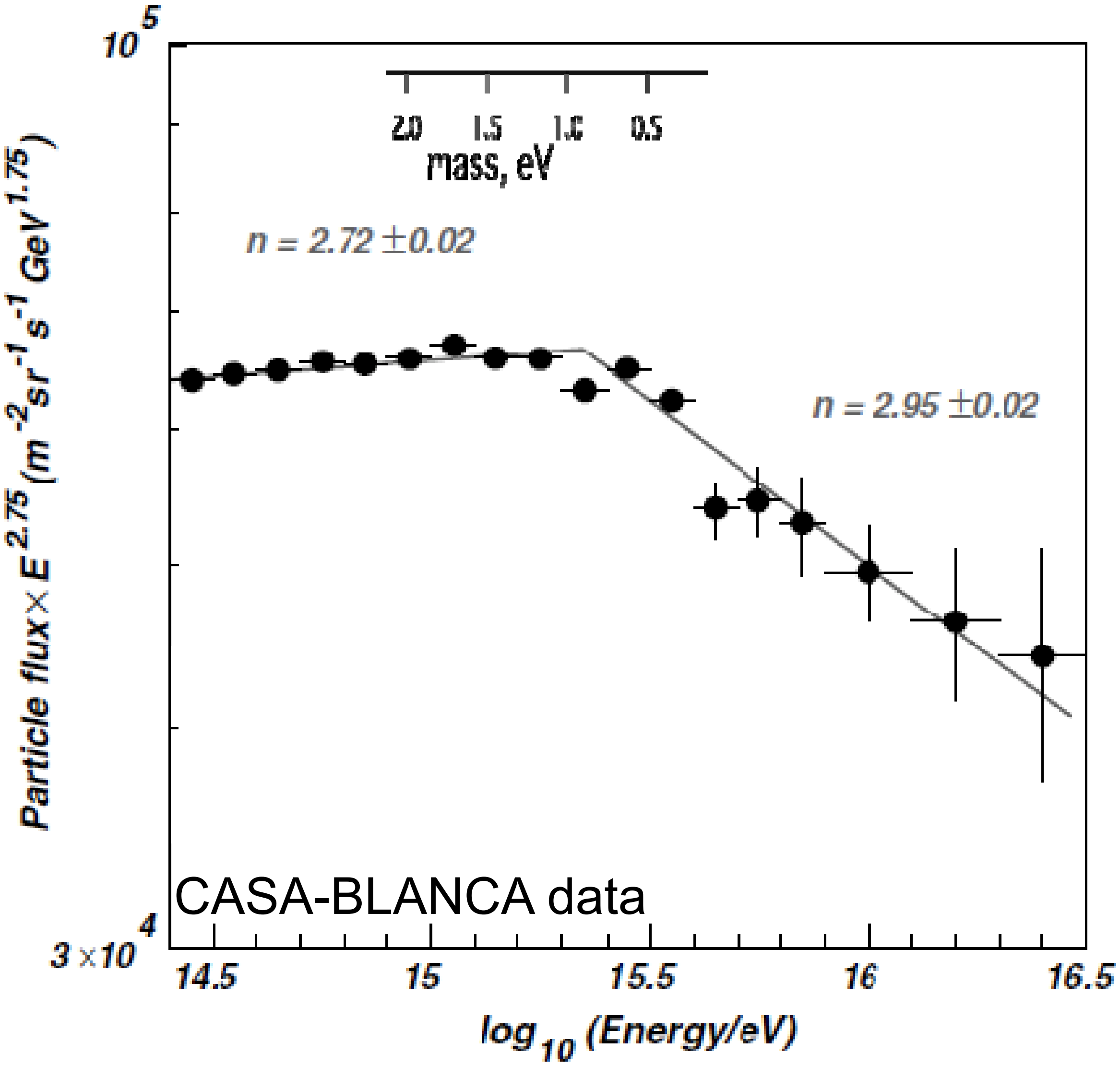


From Planck “Bluebook”

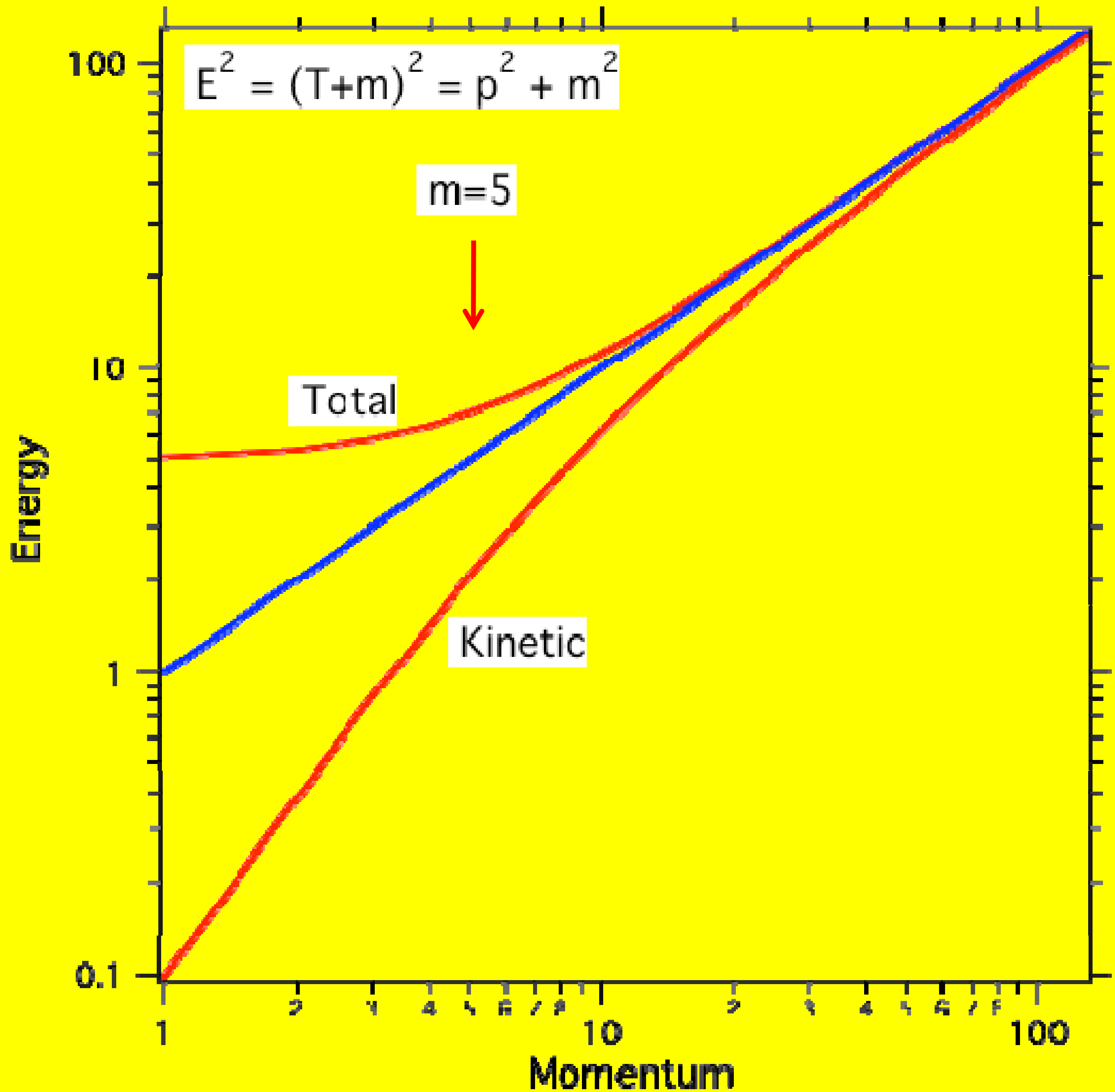
Are protons interacting with the relic $\overline{\nu}_e$ background?

$$p + \overline{\nu}_e \rightarrow n + e^+$$

Probably not. The ν density needs to be ~10^{13} times higher than expected. But could be clustered around BH, also CR source.

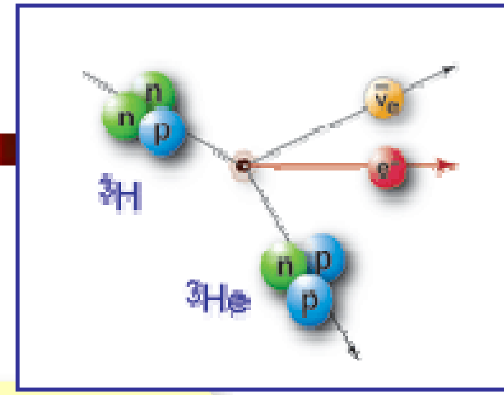


R. Wigmans, Astropart. Phys. 2003;
W-Y P Hwang & B-Q Ma, NJP 2005



$E^2 = (T+m)^2 = p^2 + m^2$
m=5
Total
Kinetic
Energy
Momentum
100
10
1
0.1
1
10
100

β-decay electron spectrum…



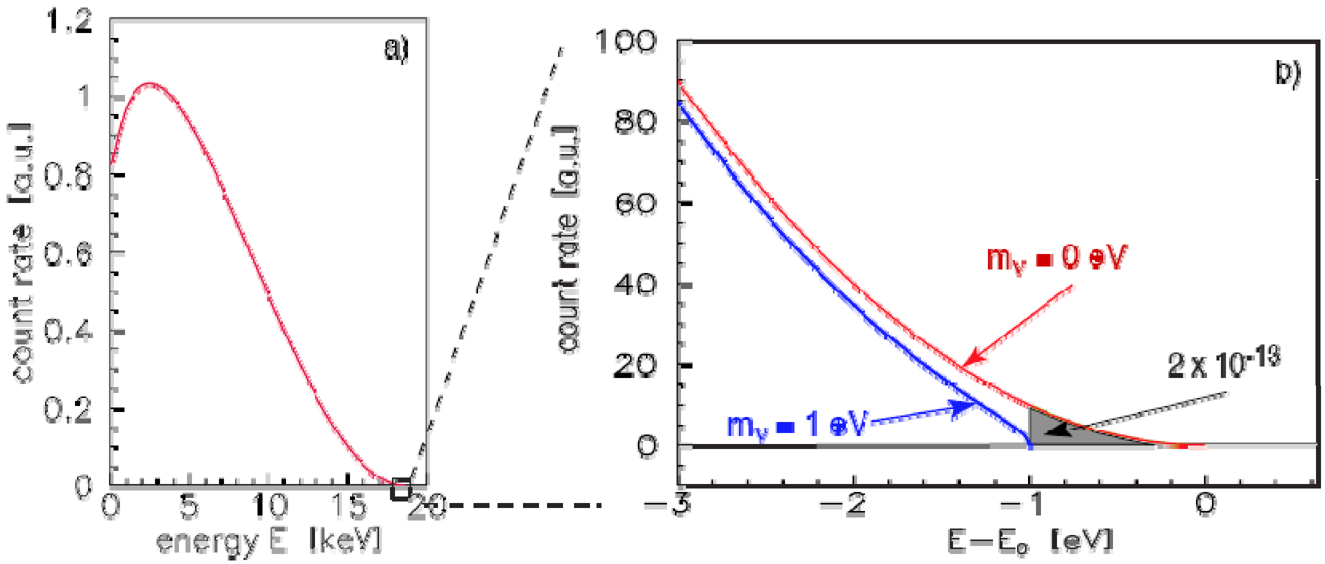
… shape determines the absolute neutrino mass squared:

$$N(E) = \frac{dN}{dE} = K \times F(E,Z) \times p_e \times E_e \times p_\nu \times E_\nu$$

$$= K \times F(E,Z) \times p \times E \times \sqrt{(E_0 - E)^2 - m_\nu^2} \times (E_0 - E)$$

$K \sim [\, g_V^2 |M_F|^2 + g_A^2 |M_{GT}|^2 \,]$ $F(E,Z)$ = Fermi function

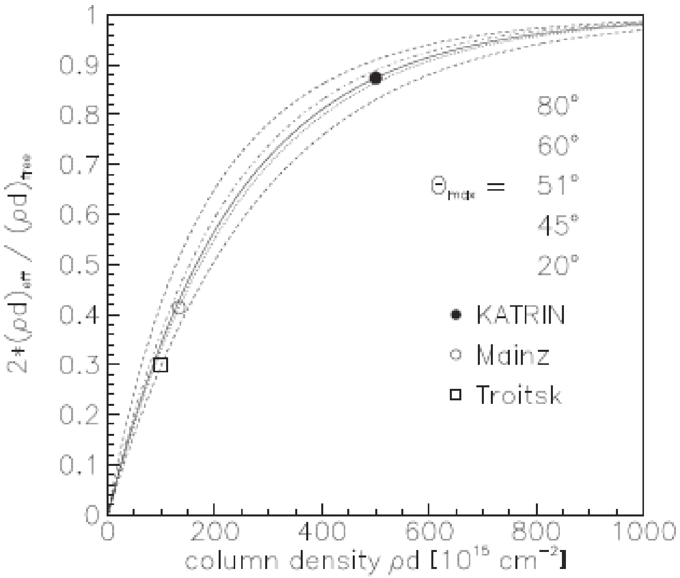
m_ν = "mass" of electron (anti-)neutrino = $\Sigma_i |U_{ei}|^2 m_i = m_\nu$ in quasi-degenerate region.



Present Limit:
2.3 eV (95% CL)
Kraus et al.
hep-ex/0412056

The Last Order of Magnitude

If the mass is NOT in the 200-2300 meV window, but the 20-200 meV window instead, how can we measure it?
KATRIN may be the largest such experiment possible.

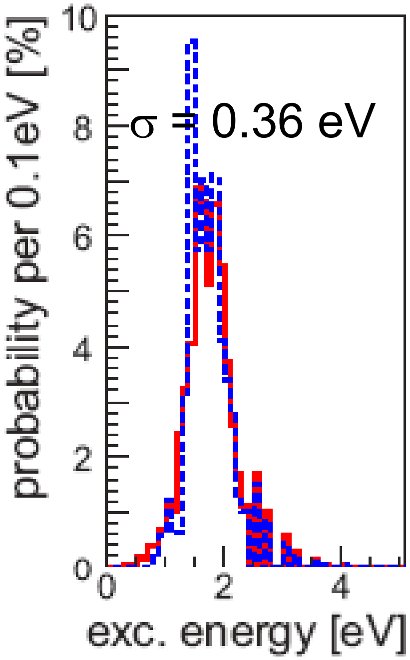


Source T_2 column density near max

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!



Rovibrational states of THe^+, HHe^+ molecule

The Last Order of Magnitude

KATRIN-type experiment limit: Source and detector are separate. Can evade by making them the same.

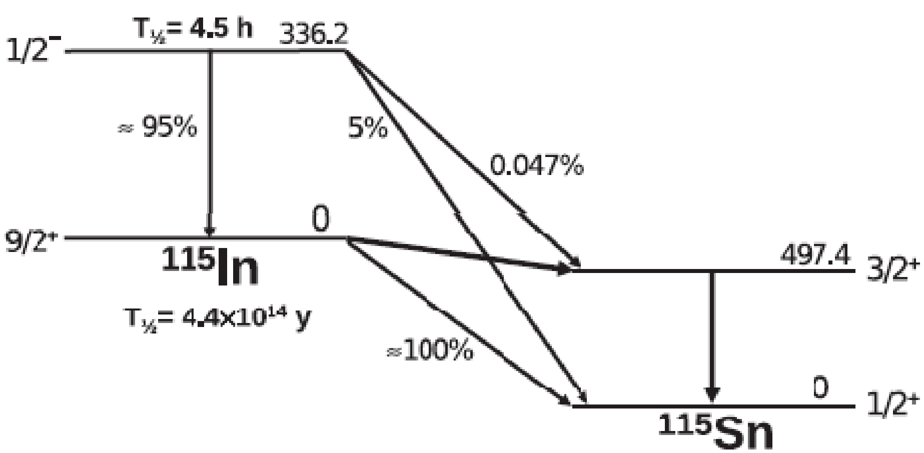
MARE ^{187}Re uses microcalorimeters: source=detector. BUT **pileup** limits size of each to **~ 100 μg**.

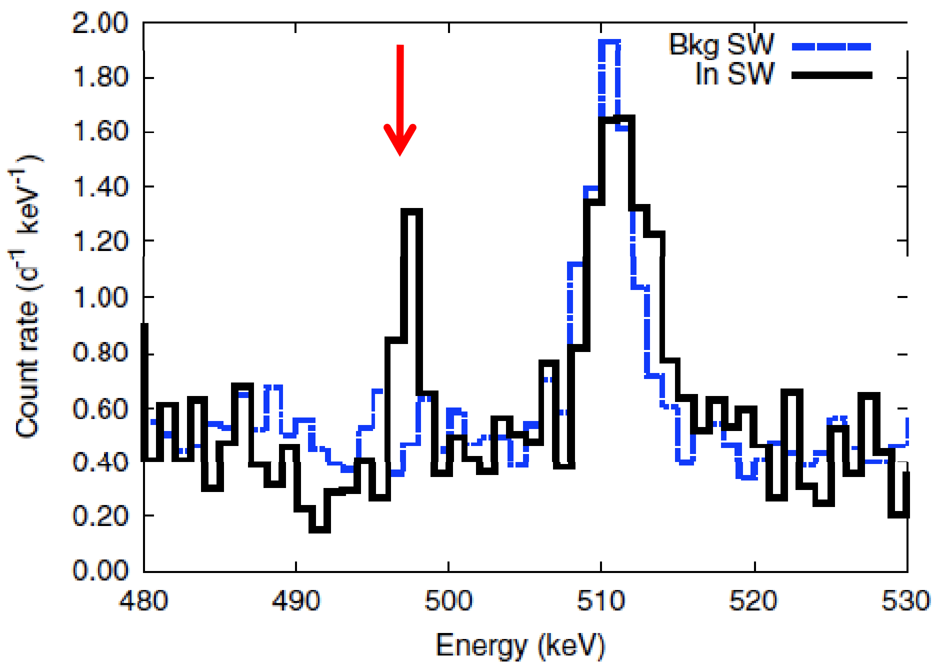
	Tritium	^{187}Re
Endpoint	18.58 keV	2.47 keV
Branch to last eV	2×10^{-13}	6×10^{-11}
Half-life	12.32 y	4.32×10^{10} y
Mass (1 dis/d in last 200 meV)	20 μg	13 kg
Mass (1 dis/d in last 20 meV)	20 mg	13000 kg

A very low-energy β transition discovered

The gamma decay of the first excited state of ^{115}Sn has been observed in the beta decay of ^{115}In [C. Cattadori et al., Nucl. Phys. A748, 333 (2005); J. S. E. Wieslander et al., PRL 103, 122501 (2009)].

From mass spectroscopy, Q = 0.35(17) keV.
From half-life and theory, Q = 0.057(19) keV.





Is ^{115}In a possible source?

Although the very low Q-value and the 497-keV gamma tag make this intriguing, the highly forbidden transition ($9/2^+ \rightarrow 3/2^+$) puts it out of contention.

	Tritium	^{187}Re	^{115}In
Endpoint	18.58 keV	2.47 keV	0.057 keV
Branch to last eV	2×10^{-13}	6×10^{-11}	6×10^{-12}
Half-life	12.32 y	4.32×10^{10} y	4.4×10^{14} y
Mass (1 dis/d in last 200 meV)	20 μg	13 kg	880,000 kg
Mass (1 dis/d in last 20 meV)	20 mg	13000 kg	really a lot

Other ultra-low Q-values?
(J. Kopp and A. Merle, arXiv 0911.3329)

Decay	$t_{1/2}$	Q_0 [keV]	E^* [keV]
Continuum β^- decay			
$^{188}\mathrm{W} \to {}^{188}\mathrm{Re}^*$	69.4 d	349 ± 3	346.58
$^{193}\mathrm{Os} \to {}^{193}\mathrm{Ir}^*$	30.5 h	1140.6 ± 2.4	1,131.2
$^{194}\mathrm{Ir} \to {}^{194}\mathrm{Pt}^*$	19.15 h	2246.9 ± 1.6	2,239.8

The authors state that the decay rate into the last eV is ~ independent of Q, so you always need KATRIN-sized sources (10^{19} or so). That is not promising.

New schemes

◆Decay of ^{187}Re (Q = 2.47 keV) observed in bolometers.

- For 20 meV, need 13 T of Re or 20 mg of ^{3}H.

◆Atomic T in a trap, full kinematic reconstruction: arXiv 0901:3111

- For 200 meV, technically challenging.

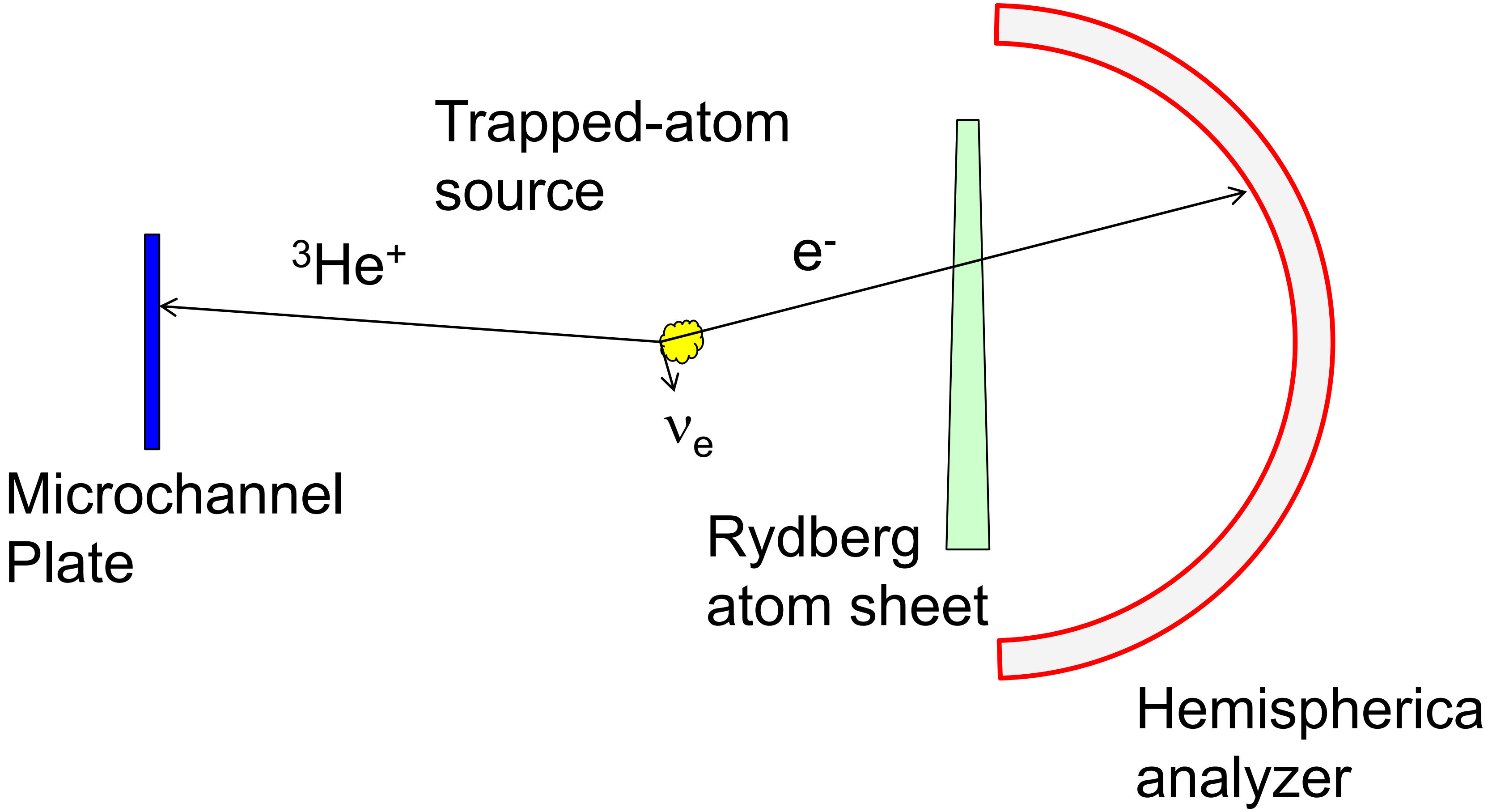
◆Decay of radioactive ions in a storage ring at a specific momentum: arXiv 0904:1089

- For 200 meV, need 10^{18} – 10^{20} decays in beam.

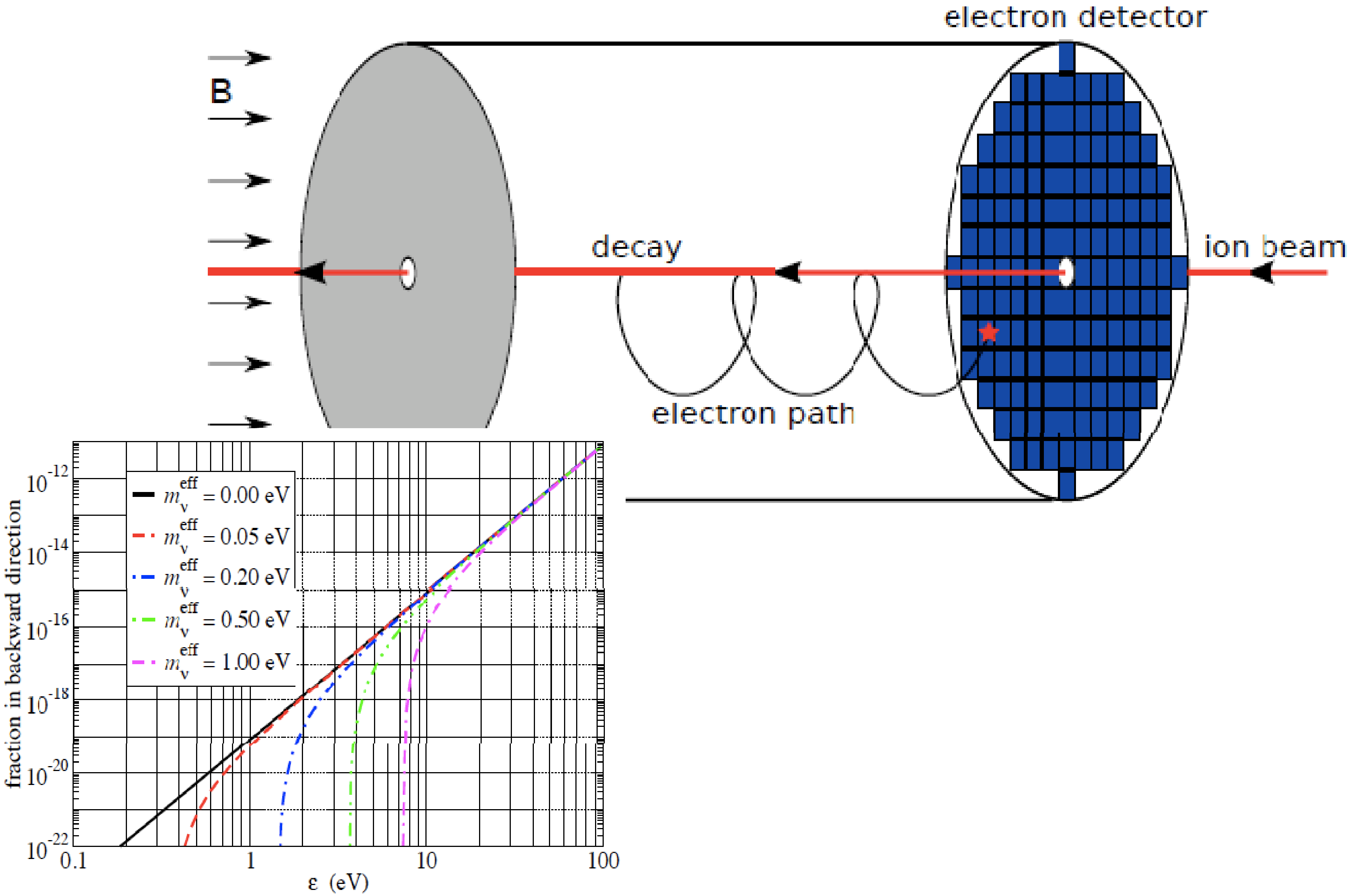
◆Detection of RF cyclotron radiation from β orbiting in B-field: arXiv 0904:2860

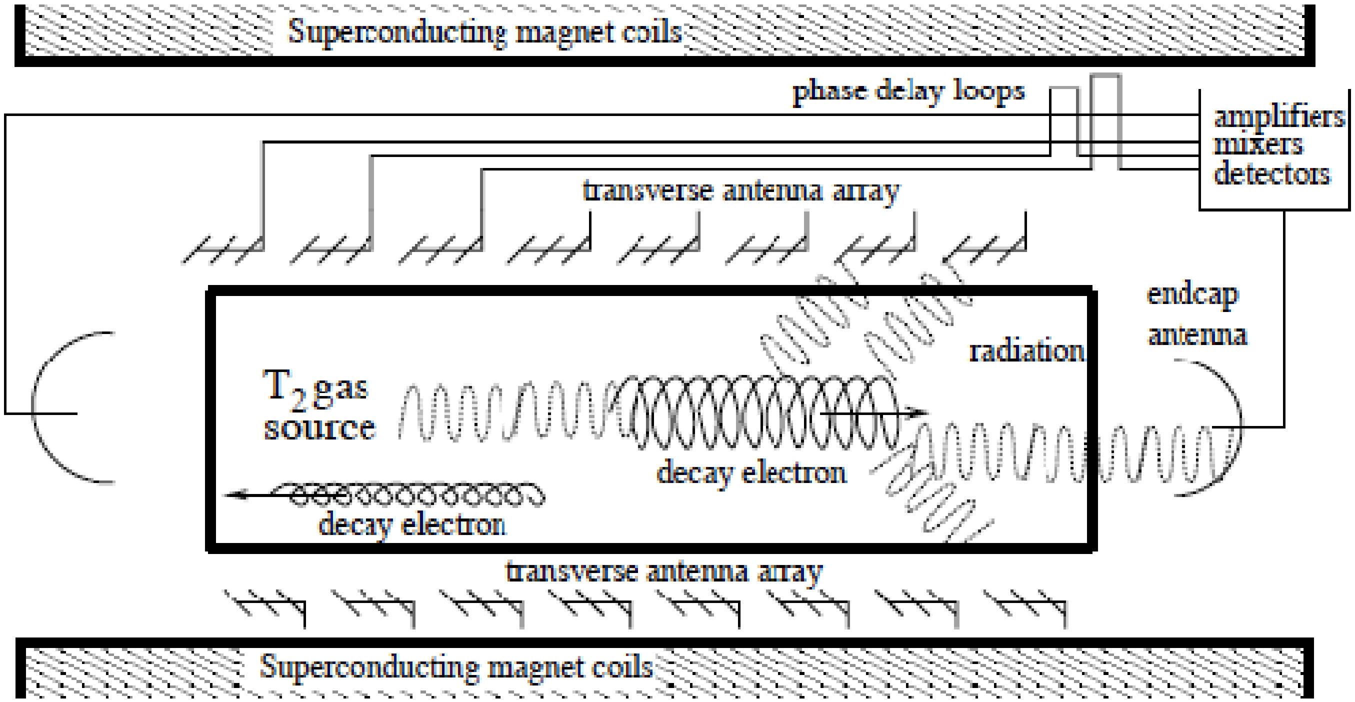
- For 20 meV. Needs further thought, might be feasible.

Tritium Beta Decay: Reconstruct the velocities.
(M. Jerkins et al., arXiv 0901.3111v3)

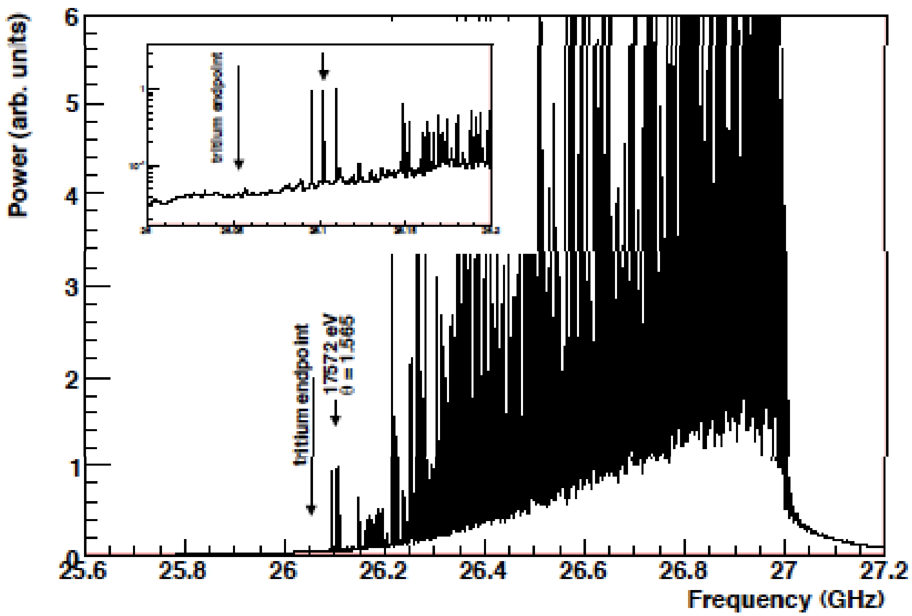


Tritium Beta Decay: Phase space, but selected.
(M. Lindroos et al., Eur. Phys. J. **C64**:549, 2009)





Cyclotron radiation from T_2
(B. Monreal and J. Formaggio, PRD 80:051301, 2009)



$$\omega = \frac{eB}{\gamma m_e} = \frac{\omega_c}{\gamma} = \frac{\omega_c}{1 + \frac{K_e}{m_e c^2}}$$

Future tritium measurements?

- Ultimate sensitivity of spectrometers
  - require instrumental resolution of ~ E_e / m_ν
  - Linear size X of instrument scales with resolution:
    - Differential spectrometers $X \propto E_e / m_\nu$
    - Integral spectrometers $X \propto \sqrt{E_e / m_\nu}$

2008

  - spectral fraction per decay in the last m_n of the spectrum is ~ $(m_\nu/E_o)^3$
  - source thickness is set by the inelastic scattering cross-section (3.4 x 10^{-18} cm^2), $\sigma n \leq 1$. Can't make it thicker, only wider.
  - If one wants ~1 event/day in last m_ν of the spectrum
    - for a 10-m long magnetic spectrometer m_ν ~ 1.7 eV
    - for a 3-m dia. solenoid retarding field spectrometer m_ν ~ 0.3 eV

KATRIN is probably the end of the road for tritium beta decay

To measure the mass

Cosmology is sensitive to masses down to about 150 meV (e.g. Planck).

KATRIN will explore the range $600 < \Sigma m < 6900$ meV. Perhaps it will be in that range, as H. Klapdor-Kleingrothaus proposes.

If it is below 600 meV, what new laboratory experiment can be devised? There are exciting new ideas around…

The mass of the lightest neutrino might be close to 0, but a measurement with $\Sigma m \sim 60$ meV sensitivity would be essentially definitive even if it saw no mass. The hierarchy would be established, and cosmology constrained.