• 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

<table>
<thead>
<tr>
<th>Mass (eV)</th>
<th>e</th>
<th>mu</th>
<th>tau</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric</td>
<td>ν₁ → ν₃</td>
<td>0.058</td>
<td>0.050</td>
</tr>
<tr>
<td>Solar</td>
<td>ν₂ → ν₁</td>
<td>0.009</td>
<td>0.050</td>
</tr>
</tbody>
</table>

Δm²₃ | Δm²₁₂

≡ 0

≡ 0
Mass and mixing parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.65^{+0.23}_{-0.20} \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{32}^2</td>
</tr>
<tr>
<td>$\Sigma m_i$</td>
<td>$&gt; 55.3$ meV (95% CL) $&lt; 6900$ meV (90% CL)*</td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>$33.5^{+1.3}_{-1.0}$ deg</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>$45^{+4.0}_{-3.5}$ deg</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>$7.2^{+2.0}_{-2.8}$ deg</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$&lt; 0.056$ (90% CL) $\sim$ Gaussian error</td>
</tr>
</tbody>
</table>

Marginalized 1-D 1-σ uncertainties.

Other refs, see HR, 0807.4258v1
Masses linked by oscillations

Average mass > 20 meV

Present Lab Limit 2.3 eV

Normal Hierarchy
\[ \Delta m_{12}^2 = 8 \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{23}^2 = 3 \times 10^{-3} \text{ eV}^2 \]

(Beacom & Bell PRD 65, 113009)
Mass Range Accessible

Normal Hierarchy
\[ \Delta m_{12}^2 = 8 \times 10^{-5} \text{ eV}^2 \]
\[ \Delta m_{23}^2 = 3 \times 10^{-3} \text{ eV}^2 \]

(Beacom & Bell PRD 65, 113009)

Average mass > 20 meV

Present Lab Limit 2.3 eV
Even small $m_\nu$ influences structure

SDSS + 2dFGRS

Barger et al. hep-ph/0312065

$\Sigma m_\nu$

280 meV

1500 meV

3000 meV
Planck will provide 3 separate $\Lambda$CDM constraints on $\Sigma m_\nu$:

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 $\bar{\nu}_e$ background?

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

Probably not. The $\nu$ density needs to be $\sim 10^{13}$ 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
\[ \beta\text{-decay electron spectrum...} \]

\[ \text{... shape determines the absolute neutrino mass squared:} \]

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

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

\[ K \sim \left[ g_\nu^2|M_F|^2 + g_A^2|M_{GT}|^2 \right] \]

\[ F(E,Z) = \text{Fermi function} \]

\[ m_\nu = \text{“mass” of electron (anti-)neutrino} = \sum |U_{ei}|^2 m_i = m_\nu \text{ in quasi-degenerate region.} \]

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

Size of experiment now:
Diameter 10 m.

Next diameter: 300 m!

Source $T_2$ column density near max

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

Rovibrational states of THe$^+$, HHe$^+$ molecule

$\sigma \approx 0.36$ eV
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 $\sim 100 \, \mu g$. 

<table>
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<th>Tritium</th>
<th>$^{187}$Re</th>
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<tbody>
<tr>
<td>Endpoint</td>
<td>18.58 keV</td>
<td>2.47 keV</td>
</tr>
<tr>
<td>Branch to last eV</td>
<td>$2 \times 10^{-13}$</td>
<td>$6 \times 10^{-11}$</td>
</tr>
<tr>
<td>Half-life</td>
<td>12.32 y</td>
<td>$4.32 \times 10^{10}$ y</td>
</tr>
<tr>
<td>Mass (1 dis/d in last 200 meV)</td>
<td>20 $\mu g$</td>
<td>13 kg</td>
</tr>
<tr>
<td>Mass (1 dis/d in last 20 meV)</td>
<td>20 mg</td>
<td>13000 kg</td>
</tr>
</tbody>
</table>
A very low-energy $\beta$ 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.

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</tr>
<tr>
<td>Mass (1 dis/d in last 200 meV)</td>
<td>20 μg</td>
<td>13 kg</td>
<td>880,000 kg</td>
</tr>
<tr>
<td>Mass (1 dis/d in last 20 meV)</td>
<td>20 mg</td>
<td>13000 kg</td>
<td>really a lot</td>
</tr>
</tbody>
</table>
Other ultra-low Q-values?
(J. Kopp and A. Merle, arXiv 0911.3329)

<table>
<thead>
<tr>
<th>Decay</th>
<th>$t_{1/2}$</th>
<th>$Q_0$ [keV]</th>
<th>$E^*$ [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuum $\beta^-$ decay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{188}\text{W} \rightarrow ^{188}\text{Re}^*$</td>
<td>69.4 d</td>
<td>349 $\pm$ 3</td>
<td>346.58</td>
</tr>
<tr>
<td>$^{193}\text{Os} \rightarrow ^{193}\text{Ir}^*$</td>
<td>30.5 h</td>
<td>1140.6 $\pm$ 2.4</td>
<td>1,131.2</td>
</tr>
<tr>
<td>$^{194}\text{Ir} \rightarrow ^{194}\text{Pt}^*$</td>
<td>19.15 h</td>
<td>2246.9 $\pm$ 1.6</td>
<td>2,239.8</td>
</tr>
</tbody>
</table>

The authors state that the decay rate into the last eV is $\sim$ 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 $\beta$ 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.
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 $\sim \frac{E_e}{m_\nu}$
  - Linear size $X$ of instrument scales with resolution:
    - Differential spectrometers $X \propto \frac{E_e}{m_\nu}$
    - Integral spectrometers $X \propto \sqrt{\frac{E_e}{m_\nu}}$
  - spectral fraction per decay in the last $m_n$ of the spectrum is $\sim (\frac{m_\nu}{E_0})^3$
  - 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 $\sim$1 event/day in last $m_\nu$ of the spectrum
    - for a 10-m long magnetic spectrometer $m_\nu \sim 1.7$ eV
    - for a 3-m dia. solenoid retarding field spectrometer $m_\nu \sim 0.3$ 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.