Neutrino mass-scale in the era of precision cosmology

Martina Gerbino
University of Rome 'Sapienza'
Gerbino M., Lattanzi M. and Melchiorri A., in prep
Roadmap

- Introduction
  Neutrino physics: which parameters?
  What experiments?

- Data analysis: the likelihood

- Results

- Conclusions
Neutrinos are weakly interacting and electrically neutral particles.

Postulated by Pauli in 1930 to explain non-monochromatic beta decay
Accepted by Fermi's theory of beta decay in 1933
First detected by Cowan and Reines in 1956

More than one neutrino flavor exists:
Cowan and Reines detected electronic neutrinos
Muonic neutrino interactions observed by Lederman, Schwartz and Steinberger in 1962
Tauonic neutrino first detected in 2000

Neutrino nature still debated

Dirac particles $\nu_j \neq \bar{\nu}_j$

Majorana particles $\chi_j \equiv \bar{\chi}_j$
Oscillations

First suggested by Pontecorvo in 1957
Observed in solar, atmospheric and reactor neutrino experiments

Oscillations are transitions in flight between neutrino flavors
Due to non-zero neutrino mass and neutrino mixing

\[ P(\nu_\mu \rightarrow \nu_\tau; E, L) \neq 0 \]

\[ \nu_{lL}(x) = \sum_j U_{lj} \nu_{jL}(x), \quad l = e, \mu, \tau \]

\[ j=1,\ldots,n \]
\[ n=3 \text{ light neutrinos with different masses (<1eV) compatible with Z-decay} \]
\[ \text{Additional one or two sterile neutrinos (~1eV)} \]

Parameterized with mixing angles \( \theta_{ij} \) and phases (one \( \delta \) if Dirac, two \( \phi_2 \) and \( \phi_3 \) if Majorana)
Oscillation experiments are sensible to squared mass differences and mixing angles

\[ \delta m^2 = m_2^2 - m_1^2 \]
\[ \Delta m^2 = m_3^2 - \frac{1}{2}(m_2^2 - m_1^2) \]
\[ \sin^2 \theta_{ij}, i, j = 1, 2, 3 \]

**NORMAL HIERARCHY**

\[ \Delta m^2 > 0 \]

\[ \begin{cases} 
  m_1 \equiv m_l \\
  m_2 = \sqrt{m_1^2 + \delta m^2} \\
  m_3 = \sqrt{m_1^2 + \frac{\delta m^2}{2} + \Delta m^2} 
\end{cases} \]

**INVERTED HIERARCHY**

\[ \Delta m^2 < 0 \]

\[ \begin{cases} 
  m_1 = \sqrt{m_3 + \Delta m^2 - \frac{\delta m^2}{2}} \\
  m_2 = \sqrt{m_3 + \Delta m^2 + \frac{\delta m^2}{2}} \\
  m_3 \equiv m_l 
\end{cases} \]
Tritium $\beta$ decay spectrum

$^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \bar{\nu}_e$

$Q = 18.6\text{ keV}$

$t_{1/2} = 12.3\text{ y}$

Pros: direct and model independent

Cons: less sensible than other methods

The Mainz Neutrino Mass Experiment:
http://www.physik.uni-mainz.de/exakt/neutrino/en_index.html

Current upper limits:

$m_\beta < 2.12\text{ eV (95\% CL)}$ Troitsk

$m_\beta < 2.20\text{ eV (95\% CL)}$ Mainz


Expected sensitivity from future experiments:

$m_\beta < 0.2\text{ eV (90\% CL)}$ KATRIN experiment:
http://www.katrin.kit.edu

$m_\beta = 0.35\text{ eV at } 5\sigma$

$m_\beta = 0.30\text{ eV at } 3\sigma
Neutrinoless double beta decay

Pros: if observed, it will solve the dilemma about neutrino nature

Cons: uncertainties from nuclear models

$T_{1/2} = \frac{1}{G_{\nu}^{(0)} M^{(0\nu)}} \frac{m_e^2}{m_{\beta\beta}^2}$

Nuclear Matrix Element
Hard to model

Phase space factor

Majorana effective mass

$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$T_{1/2}(10^{25} \text{ yr})$</th>
<th>Current limits at 90% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND-Zen</td>
<td>$&gt; 1.9$</td>
<td>$m_{\beta\beta} &lt; (0.2 - 0.4) \text{ eV}$</td>
</tr>
<tr>
<td>EXO-200</td>
<td>$&gt; 1.1$</td>
<td></td>
</tr>
<tr>
<td>H-M</td>
<td>$&gt; 1.9$</td>
<td></td>
</tr>
<tr>
<td>GERDA</td>
<td>$&gt; 2.1$</td>
<td></td>
</tr>
<tr>
<td>CUORE</td>
<td>$&gt; 10$</td>
<td></td>
</tr>
<tr>
<td>Majorana</td>
<td>$&gt; 70$</td>
<td></td>
</tr>
<tr>
<td>NEXT</td>
<td>$&gt; 10$</td>
<td></td>
</tr>
</tbody>
</table>

Expected limits
$m_{\beta\beta} < 0.1 \text{ eV}$
Cosmology

\[ \Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum_i m_i}{93.14 h^2 \text{ eV}} \]

Effects on the expansion rate of the Universe
Effects on growth of cosmological structures

CMB is only sensitive to the sum of neutrino masses

Pros: Tightest constraints on the total mass come from cosmology
Cons: model dependent

\[ \sum_i m_i < 0.66 \text{ eV} \quad \text{(Planck + WP + highl)} \]
\[ \sum_i m_i < 0.23 \text{ eV} \quad \text{(Planck + WP + highl + BAO)} \]


Baryon Acoustic Oscillations

Counteraction of gravitational attraction and radiation pressure produces acoustic oscillations

Acoustic peaks in the CMB spectrum (see previous slide)

Overdensity of galaxies separated by a characteristic scale (sound horizon)

Several galaxy surveys observed BAO (SDSS, WiggleZ, 6dFGS,...)

Courtesy of Chris Blake and Sam Moorfield

Building the likelihood

Baseline: oscillation parameters

\[ \Delta \chi^2 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>68% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta m^2 ) [10^{-5} \text{ eV}^2]</td>
<td>7.600 \pm 0.185</td>
</tr>
<tr>
<td>(</td>
<td>\Delta m^2</td>
</tr>
<tr>
<td>( s_{12}^2 )</td>
<td>0.323 \pm 0.016</td>
</tr>
<tr>
<td>( s_{13}^2 )</td>
<td>0.0234 \pm 0.0020 (0.0240 \pm 0.0019)</td>
</tr>
</tbody>
</table>

\[ \mathcal{L}_{osc} = \prod_i \mathcal{L}(x_i) \]

Gaussian likelihood and MCMC analysis

Parameters:

\( s_{12}^2, s_{13}^2, \delta m^2, \Delta m^2, \phi_2, \phi_3, \Sigma m_\nu \)


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### Additional datasets

<table>
<thead>
<tr>
<th>Name</th>
<th>Data ((68% CL))</th>
<th>Dataset combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>GERDA</td>
<td>(T_{1/2} &gt; 2.1 \cdot 10^{25}) yr</td>
<td>Gerda experiment, phase 1 [16]. Mean value from different NME calculations and marginalization over NME uncertainty [17, 22].</td>
</tr>
<tr>
<td>P + WP + high(\ell)</td>
<td>(\Sigma m_\nu &lt; 0.33)</td>
<td>Planck[2], ACT[4] and SPT[5] TT power spectra in combination with WMAP9 lowl polarization. We refer to the Planck+WMAP9 combination as P+WP hereafter.</td>
</tr>
<tr>
<td>CMB + LSS1a</td>
<td>(\Sigma m_\nu = 0.36 \pm 0.10)</td>
<td>P+WP[2] marginalized over the weak lensing amplitude parameter (A_L[3]), CMASS measurements from (Beutler,2013), CFHTlens (Kilbinger,2013), GGLensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).</td>
</tr>
<tr>
<td>CMB + LSS2</td>
<td>(\Sigma m_\nu = 0.38 \pm 0.11)</td>
<td>P+WP[2] marginalized over the weak lensing amplitude parameter (A_L[3]), CMASS measurements from (Chuang,2013), CFHTlens (Kilbinger,2013), GGLensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).</td>
</tr>
<tr>
<td>CMB + LSS3</td>
<td>(\Sigma m_\nu = 0.324 \pm 0.099)</td>
<td>P+WP[2] marginalized over the weak lensing amplitude parameter (A_L[3]), CMASS measurements from (Samushia,2013), CFHTlens (Kilbinger,2013), GGLensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).</td>
</tr>
<tr>
<td>CMB + LSS4</td>
<td>(\Sigma m_\nu = 0.27 \pm 0.11)</td>
<td>P+WP[2] marginalized over the weak lensing amplitude parameter (A_L[3]), CMASS measurements from (Anderson,2013b), CFHTlens (Kilbinger,2013), GGLensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).</td>
</tr>
<tr>
<td>CMB + LSS1b</td>
<td>(\Sigma m_\nu = 0.35 \pm 0.10)</td>
<td>WMAP9[6], CMASS measurements from (Beutler,2013), CFHTlens (Kilbinger,2013), GGLensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).</td>
</tr>
<tr>
<td>CMB + LSS1c</td>
<td>(\Sigma m_\nu = 0.27 \pm 0.12)</td>
<td>P+WP, CMASS measurements from (Beutler,2013), CFHTlens (Kilbinger,2013), GGLensing (Mandelbaum,2013) and BAO (6dFGS from Beutler,2011 and LOWZ from Anderson,2013b, Tojeiro,2014).</td>
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Great uncertainty from nuclei models

Trick: introduce $\xi$ as a nuisance parameter and marginalize over it


$$\xi = \frac{M_0^{(0\nu)}}{M^{(0\nu)}}$$

Reference value

Unknown exact value

$$T_{1/2} = \frac{1}{G^{(0)}_\nu M^{(0\nu)}} \frac{m_e^2}{m_{\beta\beta}^2} = \frac{\xi^2}{G^{(0)}_\nu M_0^{(0\nu)}} \frac{m_e^2}{m_{\beta\beta}^2}$$

From GERDA lower limit on the Ge half life

$$T_{1/2} > 2.1 \cdot 10^{25} \text{ yr (90\% CL)}$$


Flat prior on $\xi$ within $[0.5; 2]$ range


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Parameter constraints from oscillation data

NORMAL HIERARCHY
INVERTED HIERARCHY
Improving constraints on $\Sigma m$ would increase the evidence for $m_{bb}$.

Need for reaching the region far below $m_{bb} = 0.1$ eV in order to discriminate between hierarchies.
A plot illustrates the relationship between $m_\beta$ [eV] and $\sum m_\nu$ [eV]. The plot is divided into two sections: KATRIN and an area labeled as 'Planck TT + lensing + BAO + JLA + H0' with a note 'Preliminary.' The horizontal axis represents $\sum m_\nu$ [eV] ranging from $10^{-2}$ to $10^{0}$, and the vertical axis represents $m_\beta$ [eV] ranging from $10^{-3}$ to $10^{1}$. The KATRIN region is shaded grey, with separate areas labeled 'NORMAL' and 'INVERTED.'
Planck TTTEEE + lowP + BAO
(Preliminary)
Conclusions

- Combinations of CMB and LSS give the tightest constraints on the scale-mass parameters
  - CMB+LSS hints for $m_{bb}$ and $m_{b}$ to be within the region [0-0.2] eV
  - Better constraints on $\Sigma m_{\nu}$ will result in stronger evidence for $m_{bb}\neq 0$

- Discrimination between hierarchies possible if future achieved sensibility is $\ll 0.1$ eV

For further questions:
martina.gerbino@uniroma1.it
NORMAL HIERARCHY
68% and 95% CL from ν oscillation data and
CMB + LSS1a
CMB + LSS4

INVERTED HIERARCHY
68% and 95% CL from ν oscillation data and
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