ABSOLUTE neutrino mass measurements

Markus Steidl
Why measuring ABSOLUTE neutrino mass(es)

Status & Perspectives

- Cosmology
- 0ν2β decay
- 1ν1β decay

Complimentarity of Methods
Why measuring ABSOLUTE neutrino mass(es)...
Why measuring ABSOLUTE neutrino mass(es)...

- Quasi-Degenerated Models vs. Hierarchical Models
- Discrimination for many modell extension of S.M.
- Next Generations of experiments have the sensitivity to exclude clearly the degenerated models
- Potential to answer DIRAC or MAJORANA (see section Complimenatrity)
Why measuring ABSOLUTE neutrino mass(es)...

- Past few years a new standard model of cosmology has been established

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubble parameter</td>
<td>$h$</td>
<td>$0.73 \pm 0.03$</td>
</tr>
<tr>
<td>Total matter density</td>
<td>$\Omega_m$</td>
<td>$\Omega_m h^2 = 0.128 \pm 0.008$</td>
</tr>
<tr>
<td>Baryon density</td>
<td>$\Omega_b$</td>
<td>$\Omega_b h^2 = 0.0223 \pm 0.0007$</td>
</tr>
<tr>
<td>Cosmological constant</td>
<td>$\Omega_\Lambda$</td>
<td>See Ref. 2</td>
</tr>
<tr>
<td>Radiation density</td>
<td>$\Omega_r$</td>
<td>$\Omega_r h^2 = 2.47 \times 10^{-5}$</td>
</tr>
<tr>
<td>Neutrino density</td>
<td>$\Omega_\nu$</td>
<td>See Sec. 21.1.2</td>
</tr>
<tr>
<td>Density perturbation amplitude</td>
<td>$\sigma_8$</td>
<td>$0.76 \pm 0.05$</td>
</tr>
<tr>
<td>Density perturbation spectral index</td>
<td>$n$</td>
<td>$n = 0.958 \pm 0.016$</td>
</tr>
<tr>
<td>Tensor to scalar ratio</td>
<td>$r$</td>
<td>$r &lt; 0.65$ (95% conf)</td>
</tr>
<tr>
<td>Ionization optical depth</td>
<td>$\tau$</td>
<td>$\tau = 0.089 \pm 0.030$</td>
</tr>
<tr>
<td>Bias parameter</td>
<td>$b$</td>
<td>See Sec. 21.3.4</td>
</tr>
</tbody>
</table>

- The precision of data (CMB, LSS, SNIa, …) allows probing particle physics, e.g. neutrino properties

- Conversely, cosmology is at a level where unknowns from particle physics can significantly bias estimates of cosmological data
Why measuring ABSOLUTE neutrino mass(es)...

Matter Content of Universe

TRANSITION FROM RADIATION TO MATTER COMPONENT WHEN GETTING NON RELATIVISTIC

\[ \Omega_\nu h^2 = \sum \frac{m_\nu}{93 \text{ eV}} \]
\[ \Omega_{\text{TOTAL}} = 1.02 \pm 0.02 \]

Growth of perturbations

FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH

Hannestad et al.

0.3 eV
Sensitivity benchmarks

2 $eV$
- Today’s reliable, model-independent mass limits
- Insignificant contributions to dynamical evolution of universe
- Negligible contribution to energy density
- Quasi-degenerated models ruled out

$\sim 200 \text{ meV}$
- Enter region of mass eigenstates in inverted hierarchy
- Inverted Hierarchy excluded

$\sim 50 \text{ meV}$
- Signal in Cosmology should be there

$< 50 \text{ meV}$
- Lab experiments: Positive signal depends on mixing angles and/or Majorana Phases
Content

- Why measuring ABSOLUTE neutrino mass(es)

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- Cosmology
- $0\nu 2\beta$ decay
- $1\nu 1\beta$ decay

Complementarity of Methods

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

$E_0 = 18.574$ keV

1 eV vs. 0 eV
Cosmological observations

**Large Scale Structures**

- Suppression of small scale fluctuations
- $k > 0.1 \, (h/\text{Mpc})$ non-linear regime
- Bias parameter must be incorporated
- $\Omega_\nu$ degenerated with others parameters
- $\rightarrow$ Combine fits with other data sets (at best from different epochs)
- Sensitivity on neutrino mass from CMB alone is modest compared to LSS
- Incorporation of CMB helps significantly to break degeneracies and improve precision of multi-parameter fits in cosmological models ($N_{\text{par}}>10$)
Cosmological observations

LSS

CMB

Baryonic Oscillations

\( \text{(c) all} \)

\[ k / h \text{ Mpc}^{-1} \]
Cosmological observations

- LSS
- CMB
- Baryonic Oscillations

**Lyman-α forest**

- Depleted flux → regions of hydrogen excess
- Reconstruction of 1D-mass distribution on scales of few Mpc
- Systematic studies ongoing
Cosmological observations

- Scatter of CMB photons on gravitational structures
- Smears out peaks at high l
- Allows reconstruction of mass distribution on small scales

Baryonic Oscillations

Weak Lensing
### Limits from Cosmology

<table>
<thead>
<tr>
<th>System</th>
<th>Limit</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>LSS</td>
<td>$\sum_{i} m_i \leq 1.8 \text{ eV}$</td>
<td>Elgaroy et al., PRL 89 (2002) 6</td>
</tr>
<tr>
<td>LSS + CMB</td>
<td>$\sum_{i} m_i \leq 1.2 \text{ eV}$</td>
<td>Sanchez et al., MNRAS, 366 (2006) 189</td>
</tr>
<tr>
<td>LSS + CMB + BAO</td>
<td>$\sum_{i} m_i \leq 0.62 \text{ eV}$</td>
<td>Hannestad, Raffelt, JCAP 11 (2006) 016</td>
</tr>
<tr>
<td>LSS + CMB + SN1a</td>
<td>$\sum_{i} m_i \leq 0.66 \text{ eV}$</td>
<td>Spergel et al., APJ 170 (2007) 377</td>
</tr>
</tbody>
</table>

### Pushing Limits:

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<thead>
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<tbody>
<tr>
<td>LSS + CMB + BAO + SN1A + Lyα</td>
<td>$\sum_{i} m_i \leq 0.17 \text{ eV}$</td>
<td>Seljak et al., JCAP 10 , (2006) 014</td>
</tr>
<tr>
<td>LSS + CMB + X-ray data</td>
<td>$\sum_{i} m_i = 0.56^{+0.30}_{-0.26} \text{ eV}$</td>
<td>S.W. Allen et al., MNRAS 346 , (2003) 593</td>
</tr>
</tbody>
</table>
The future

31 Oct 2008 (?): Launch of Planck satellite:

Improved precision on CMB data

Weak Lensing in reach
The future

31 Oct 2008 (?): Launch of Planck satellite:

Improved precision on CMB data

+ LSS (today)
\[ \sum m_\nu < 0.2 eV \quad (2\sigma) \]

+ LSST survey
\[ \sum m_\nu < 0.05 eV \quad (1\sigma) \]

+ High Redshift Galaxy Surveys
\[ \sum m_\nu < 0.08 eV \quad (95\% \text{ CL}) \]

**Distinction between Normal and Inverted Mass hierarchies**

Spread in derived limits will remain, boundaries will depend on number of free parameters (>10), data sets …
The ultimate future dreams

Not earlier than 10 years:

(Gravitational effects on Galaxy shapes)

Other ideas:
21 cm surveys
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Complimentarity of Methods
Neutrinoless Double Beta Decay

- Neutrino must be massive
- Neutrino must be **MAJORANA** particles

$2\beta2\nu$ well established

$^{100}$Mo, $^{82}$Se, $^{48}$Ca, $^{76}$Ge, $^{116}$Cd, $^{136}$Xe …
Neutrinoless Double Beta Decay

\[
[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} = G^{0\nu}(E_0, Z) \left| M_{GT}^{0\nu} - \frac{g_2^2}{g_A^2} M_{F}^{0\nu} \right|^2 \langle m_\nu \rangle^2.
\]

Measurement of half-life:
Additional systematic uncertainty in $\nu$-mass due to difficult accessible nuclear matrix elements.

Cancellations due to non-zero CP phases,

\[
\langle m_\nu \rangle^2 = \left| \sum_i^N U_{ei}^2 m_i \right|^2 = \left| \sum_i^N |U_{ei}|^2 e^{i\alpha_i} m_i \right|^2,
\]

Possible difference to single Beta masses (see section complimentarity of methods)
\begin{align*}
\langle m_\nu \rangle &= (2.50 \times 10^{-8} \text{ eV}) \left[ \frac{W}{f \chi e G^{0\nu} |M^{0\nu}|^2} \right]^{1/2} \left[ \frac{h \Lambda F}{MT} \right]^{1/4} \quad \text{background limited} \\
\langle m_\nu \rangle &= (2.67 \times 10^{-8} \text{ eV}) \left[ \frac{W}{f \chi e G^{0\nu} |M^{0\nu}|^2} \right]^{1/2} \times \frac{1}{\sqrt{MT}} \quad \text{zero background,}
\end{align*}

- Reject Backgrounds (Natural impurities, cosmogenics)  
  state of the art: Ge-experiments (goal $10^{-3}$ (cts/kg y))
- Excellent Energy Resolutions (Reject $2\beta 2n$)
- High Isotope abundances, large Q-values
- 50meV $\sim$ 1 ton scale

**Measure several isotopes with different techniques**
Current experiments

76Ge -experiments

- Well established technology
- Source = Detector
- Enriched HP Ge-crystals
- Bg’s in region < 0.1 cts/kg/y
- Good energy resolution

- $m < 0.33$-$1.35$ eV | 8.9 kg y | Physical Review D 65, 092007 (2002)
- $m < 0.32$-$1$ eV | 36 kg y | Nuclear Physics B Proceedings Supplements 100, 309 (2001), hep-ph/0102276
- $m = 0.24$-$0.58$ eV | 72 kg y | Physics Letters B 586, 198 (2004).
Selection of experiments (non-Ge)

NEMO

@ Modane Laboratory

Passive isotope on thin foils surrounded by Geiger mode drift cells for electron tracking and plastic scintillator for energy measurement.

$m_{ee} < 0.7\text{--}2.8 \text{ eV}$

100Mo

Future: SUPERNEMO

CUORICONO

@ Gran Sasso Lab

- 40,7 kg tower of TeO2
- Bolometric readout at 10 mK
- Energy Resolution
- Bg: 0.2 c/keV/kg/y

$m_{ee} < 0.2\text{--}0.7 \text{ eV}$

Future: CUORE

Today’s most sensitive Limits
Future experiments (some of them …)

**SUPERNEMO**
100-200 kg Se or Nd
~ 2016: 50-100 meV

**CANDLES III**
191 kg CaF2
Start 2009,
goal 50 meV

**MOON**
Several tons of $^{100}$Mo
~ 30 meV

**GERDA**

**MAJORANA**
Joined effort for 1 t Ge
Common attempt to achieve
Bg < 0.1 c/t/y
~20 meV in 5y live time

**EXO**
$^{136}$Xe (enriched)
(1t-10t) 33-5 meV

**CUORE**
741 kg TeO$_2$;
start in 2011
if Bg<1c/t/y in 5y
14-47 meV

+ : SNO+, COBRA, KIEV, XMass ...

Massive attack on 50 meV scale (exploring inverted hierarchy scale),
and/or excluding it
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Complimentarity of Methods
β-decay

phase space determines energy spectrum
transition energy $E_0 = E_e + E_\nu$ (+ recoil corrections)

$$\frac{dN}{dE} = K \times F(E, Z) \times p \times E_{tot} \times (E_0 - E) \times \sqrt{(E_0 - E)^2 - m_\nu^2 / m_e^2}$$

KINEMATIC MEASUREMENT
• DIRECT
• MODEL-INDEPENDANT

$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$
β Bolometers

Multiple purpose, scalable new detector technology

- basic idea: $\beta$ emitting crystal = cryodetector
- single final state: detection of total energy except $\nu$
- Choice of $\beta$ emitter: $^{187}$Re: $E_0 = 2.47$ keV ($t_{1/2} = 4.3 \times 10^{10}$y)

MANU2 (F. Gatti et al., Genua)
- Re metallic crystal (1.5 mg)
- BFFS observed (F. Gatti et al., Nature 397 (1999) 137)
- sensitivity:
  - future: eV resolution by s.c. transition sensors.
    (now typically: $\Delta E = 30$ cV)

MiBeta (E. Fiorini et al., Mailand, Como)
- AgReO$_4$ (10 $\times$ 250 -350 mg)
- Final result of MiBeta after 1 year data taking with 10 detectors
  (M. Sisti et al., NIMA520 (2004) 125)
  $m_{\nu}^2 = -112 \pm 207 \pm 90$ eV$^2$ $\Rightarrow m_{\nu} < 15$ eV (90% CL)

"Common future: MARE I: sensitivity 2-3 eV expected by 300 detectors
MARE II: better DE, Dt, 50000 detectors: sub-eV sensitivity"
Karlsruhe Tritium Neutrino Experiment

Physics Goal:
order of magnitude improvement in $m_\nu$
Limit $m_\nu \ 2.2 \text{ eV} \rightarrow 0.2 \text{ eV}$

**Improve Statistics**
- stronger source (factor $\sim 80$)
- longer measuring period (factor $\sim 10$)

**Improve energy resolution**
- $\Delta E = 0.93 \text{ eV}$ (factor of 4 improvement)
- Requires larger spectrometer

**Reduce systematic errors**
- better control of systematics
- energy losses (factor$\sim 10$)

Location:
Tritium laboratory, Karlsruhe
(Unique tritium handling facility)

Ground breaking September'05
Main components and function—Design report 2005, GKZK Report 7090
http://www.ik.fzk.de/~7Ekatrin/
KATRIN Sensitivity

Sensitivity: $m < 0.2\ eV$ (90\% C.L.)
Status

1,5 years ago
Experiments for systematic error of ν-mass measurement (e.g. spectrometer characteristics) start early 2009
Why measuring ABSOLUTE neutrino mass(es)

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- $0\nu2\beta\beta$ decay
- $1\nu1\beta$ decay

Complimentarity of Methods
Complimentarity of Methods

\[ m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2 \]
\[ m_{ee} = \left| \sum_i U_{ei}^2 \cdot e^{i\alpha_i} \cdot m_i \right| \]
\[ M = \sum_i m_i \]

In any case

- Lab-experiments as prior for multi-dimensional cosmological fits
  - improving limits and reliability
  - breaking degeneracies (e.g. \( w \) equation of state of dark energy with \( m_\nu \))

In case of evidence

- A Neutrinoless Universe
- Mass varying neutrinos
- Majorana or Dirac?
- Access to CP phases in PMNS matrix

Elagroy et al., arXiv:0709.4152v2 [astro-ph]
Hannestad et al. PRL 95, 221301 (2005)
e.g. Päs et al. arXiv:astro-ph/0311131v2
### Summary

<table>
<thead>
<tr>
<th>Methods</th>
<th>Present sensitivity</th>
<th>Future Sensitivity (5-15 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = \sum_{i} m_i$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cosmology (CMB + LSS)</td>
<td>0.7 eV ((\sum m_i))</td>
<td>0.05 eV</td>
</tr>
<tr>
<td>$m_{ee} = \left</td>
<td>\sum_{i} U_{ei}^2 e^{i\alpha_i} m_i \right</td>
<td>$</td>
</tr>
<tr>
<td>0(\nu)(\beta) Decay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{\beta}^2 = \sum_{i}</td>
<td>U_{ei}</td>
<td>^2 m_i^2$</td>
</tr>
<tr>
<td>Weak Decay Kinematics</td>
<td></td>
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</tr>
</tbody>
</table>

In all 3 fields expect high significant data within next ~5 years!