NEUTRINO PHYSICS FROM PRECISION COSMOLOGY

$\nu_e \leftrightarrow \nu_\mu \\
\nu_\tau$
NEUTRINO MIXING

**FLAVOUR STATES**

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
\]

**PROPAGATION STATES**

\[
\begin{pmatrix}
\nu_1(m_1) \\
\nu_2(m_2) \\
\nu_3(m_3)
\end{pmatrix}
\]

**MIXING MATRIX (UNITARY)**

\[
U = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}
\end{pmatrix}
\]

- \( c_{12} = \cos \theta_{12} \)
- \( s_{12} = \sin \theta_{12} \)
LATE-TIME COSMOLOGY IS (ALMOST) INSENSITIVE TO THE MIXING STRUCTURE.
If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses.

However, if neutrino masses are degenerate

$$m_0 \gg \delta m_{\text{atmospheric}}$$

no information can be gained from such experiments.

Experiments which rely on either the kinematics of neutrino mass or the spin-flip in neutrinoless double beta decay are the most efficient for measuring $m_0$. 
The diagram illustrates the relationship between the lightest neutrino mass and the total neutrino mass. The axes are labeled as follows:

- Vertical axis: $\Sigma m_\nu$ (eV)
- Horizontal axis: LIGHTEST $m_\nu$ (eV)

There are three curves on the graph:
- **INVERTED**: A blue curve
- **NORMAL**: A red curve

The graph is divided into two regions:
- HIERARCHICAL
- DEGENERATE

The vertical line at $0.100$ eV marks the transition between these two regions.
**β-decay and neutrino mass**

Model independent neutrino mass from β-decay kinematics

- Only assumption: relativistic energy-momentum relation

\[
\frac{d\Gamma_i}{dE} = C \rho (E + m_e) (E_0 - E) \sqrt{(E_0 - E)^2 - m_i^2} F(E) \theta(E_0 - E - m_i)
\]

Experimental observable is \( m_\nu^2 \)

- \( E_0 = 18.6 \text{ keV} \)
- \( T_{1/2} = 12.3 \text{ y} \)
Tritium decay endpoint measurements have provided limits on the electron neutrino mass.

\[ m_{\nu_e} = \left( \sum |U_{ei}|^2 m_i^2 \right)^{1/2} \leq 2.3 \text{ eV} \quad (95\%) \]

Mainz experiment, final analysis (Kraus et al.)

This translates into a limit on the sum of the three mass eigenstates

\[ \sum m_i \leq 7 \text{ eV} \]
KATRIN experiment

Karlsruhe Tritium Neutrino Experiment

\( \sigma(m_{\nu_e}) \sim 0.2 \text{ eV} \)
A DANISH VERSION OF KATRIN???

THE CARLSBERG NEUTRINO MASS EXPERIMENT
NEUTRINO MASS AND ENERGY DENSITY FROM COSMOLOGY

NEUTRINOS AFFECT STRUCTURE FORMATION BECAUSE THEY ARE A SOURCE OF DARK MATTER \((n \sim 100 \text{ cm}^{-3})\)

\[
\Omega_v h^2 = \frac{\sum m_\nu}{93 \text{ eV}}
\]

FROM \(T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \approx 2 \text{ K}\)

HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

\[
d_{\text{FS}} \sim 1 \text{ Gpc } m_{\text{eV}}^{-1}
\]

SCALES SMALLER THAN \(d_{\text{FS}}\) DAMPED AWAY, LEADS TO SUPPRESSION OF POWER ON SMALL SCALES
N-BODY SIMULATIONS OF $\Lambda$CDM WITH AND WITHOUT NEUTRINO MASS (768 Mpc$^3$) – GADGET 2

$\sum m_\nu = 0$

$\sum m_\nu = 6.9$ eV

T Haugboelle, Aarhus University
AVAILABLE COSMOLOGICAL DATA
THE COSMIC MICROWAVE BACKGROUND

CMB TEMPERATURE MAP
PLANCK TEMPERATURE POWER SPECTRUM

ADE ET AL, ARXIV 1303.5076

ADDITIONAL DATA ON SMALLER SCALES FROM
ATACAMA COSMOLOGY TELESCOPE (Sievers et al. 2013)
SOUTH POLE TELESCOPE (Hou et al. 2012)
...AND OF COURSE THE B-MODE DETECTION FROM BICEP2
LARGE SCALE STRUCTURE SURVEYS

2dF Galaxy Redshift Survey
SDSS DR-7
LRG SPECTRUM
(Reid et al ’09)
FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH

\[ \Delta P \left( k \gg k_{FS} \right) \sim -8 \frac{\rho_v}{\rho_{TOT}} \]

\[ \frac{P(k)}{P_{m=0}} \left( k \gg k_{FS} \right) \sim \Sigma m \]

\[ \Sigma m = 0 \text{ eV} \]

\[ \Sigma m = 0.3 \text{ eV} \]

\[ \Sigma m = 1 \text{ eV} \]
NOW, WHAT ABOUT NEUTRINO PHYSICS?
WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

THERE ARE MANY ANALYSES IN THE LITERATURE

\[ \sum m_\nu \leq 1.08 \text{ eV @ 95 C.L.} \quad \text{Planck only} \]

\[ \sum m_\nu \leq 0.32 \text{ eV @ 95 C.L.} \quad \text{Planck + BAO} \]

arXiv:1303.5076 (Planck)
THE NEUTRINO MASS FROM COSMOLOGY PLOT

More data

+ Ly-alpha
+ SNI-a
+ WL

+ SDSS

CMB only

Minimal \( \Lambda \)CDM

+ \( N_v \)

+ \( \omega \)……

Larger model space

0.4 eV

~ 1 eV

1.1 eV

~ 2 eV

0.2-0.3 eV

0.5-0.6 eV

~ 0.2 eV

~ 0.5 eV

~ 2 eV

2.\( \omega \) eV

??? eV
<table>
<thead>
<tr>
<th>Model</th>
<th>Observables</th>
<th>$\Sigma m_\nu$ (eV) 95% Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega$CDM + $\Delta N_{rel}$ + $m_\nu$</td>
<td>CMB+H0+SN+BAO</td>
<td>$\leq 1.5$</td>
</tr>
<tr>
<td>$\omega$CDM + $\Delta N_{rel}$ + $m_\nu$</td>
<td>CMB+H0+SN+LSSPS</td>
<td>$\leq 0.76$</td>
</tr>
<tr>
<td>$\Lambda$CDM + $m_\nu$</td>
<td>CMB+H0+SN+BAO</td>
<td>$\leq 0.61$</td>
</tr>
<tr>
<td>$\Lambda$CDM + $m_\nu$</td>
<td>CMB+H0+SN+LSSPS</td>
<td>$\leq 0.36$</td>
</tr>
<tr>
<td>$\Lambda$CDM + $m_\nu$</td>
<td>CMB (+SN)</td>
<td>$\leq 1.2$</td>
</tr>
<tr>
<td>$\Lambda$CDM + $m_\nu$</td>
<td>CMB+BAO</td>
<td>$\leq 0.75$</td>
</tr>
<tr>
<td>$\Lambda$CDM + $m_\nu$</td>
<td>CMB+LSSPS</td>
<td>$\leq 0.55$</td>
</tr>
<tr>
<td>$\Lambda$CDM + $m_\nu$</td>
<td>CMB+H0</td>
<td>$\leq 0.45$</td>
</tr>
</tbody>
</table>

Gonzalez-Garcia et al., arxiv:1006.3795
WHAT IS $N_\nu$?

A MEASURE OF THE ENERGY DENSITY IN NON-INTERACTING RADIATION IN THE EARLY UNIVERSE

THE STANDARD MODEL PREDICTION IS

$$N_\nu \equiv \frac{\rho}{\rho_{\nu,0}} = 3.046 \quad , \quad \rho_{\nu,0} \equiv \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \rho_\gamma$$

Mangano et al., hep-ph/0506164

BUT ADDITIONAL LIGHT PARTICLES (STERILE NEUTRINOS, AXIONS, MAJORONS,.....) COULD MAKE IT HIGHER
PRE-PLANCK
EVOLUTION OF THE
95% BOUND ON $N_\nu$. 

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Pre-WMAP</td>
</tr>
<tr>
<td>2001</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>WMAP-1</td>
</tr>
<tr>
<td>2005</td>
<td>WMAP-3</td>
</tr>
<tr>
<td>2006</td>
<td>WMAP-5</td>
</tr>
<tr>
<td>2008</td>
<td>WMAP-7</td>
</tr>
<tr>
<td>2010</td>
<td></td>
</tr>
</tbody>
</table>
\[ N_{\text{eff}} = 3.36^{+0.68}_{-0.64} \ @ \ 95\% \quad \text{Planck only} \]

\[ N_{\text{eff}} = 3.52^{+0.48}_{-0.45} \ @ \ 95\% \quad \text{Planck+BAO+}H_0 \]

THE SITUATION IS (UNFORTUNATELY) NOT YET RESOLVED....
THERE ARE A NUMBER OF HINTS FROM EXPERIMENTS THAT A FOURTH, eV-MASS STERILE STATE MIGHT BE NEEDED:
LSND, MiniBoone, reactor anomaly, Gallium

Giunti & Laveder 2011
ASSUMING A NUMBER OF ADDITIONAL STERILE STATES OF APPROXIMATELY EQUAL MASS, TWO QUALITATIVELY DIFFERENT HIERARCHIES EMERGE. IN ANALOGY WITH THE STANDARD MODEL NEUTRINO HIERARCHY WE CAN CALL THEM NORMAL AND INVERTED HIERARCHY.

\[ \nu_S \quad \nu_A \]

\[ \nu_A \quad \nu_S \]

3+N (NORMAL) \hspace{5cm} N+3 (INVERTED)
\[ N_s = \frac{\rho_s}{\rho_{\nu,0}} = N_{eff} - 3 \]

See also
Dodelson et al. 2006
Melchiorri et al. 2009
Acero & Lesgourgues 2009
Hamann et al 2011
Joudaki et al 2012
Motohashi et al. 2012
Archidiacono et al 2012, 2013
and many others
Bottom line: Sterile neutrinos in the mass range preferred by SBL data can be accommodated by cosmology, but ONLY if they are not fully thermalised
STERILE NEUTRINO THERMALISATION WITH ZERO LEPTON ASYMMETRY

STH, Tamborra, Tram 2012 (arXiv:1204.5861)
STERILE NEUTRINO THERMALISATION WITH LARGE LEPTON ASYMMETRY

STH, Tamborra, Tram 2012 (arXiv:1204.5861)
(see also Saviano et al. arXiv:1302.1200)
The presence of a significant asymmetry can block the production of steriles and make them compatible with cosmology.

However, from a model building perspective the generation of the asymmetry is difficult because it must be done at low energy.

Could there be another way of modifying the matter potential?

YES! Non-standard interactions for either active or sterile neutrinos.

Interactions must be relatively strong and for active neutrinos they might be excluded.

Sterile neutrino self-interactions are possible, and perhaps even natural.
It is possible that the sterile states couple to a new, hidden Fermi-like Interaction characterised by a coupling strength $G_X = g_X^2/m_X^2$.
If dark matter couples to the new vector boson it causes self-interactions which have implications for structure formation.

Dasgupta & Kopp 1310.6337
However, sterile neutrinos and dark matter might also couple to a light or massless pseudoscalar. In that case a background potential appears even in a CP-symmetric medium and suppressing oscillations Requires only a very weak coupling.

Archidiacono, STH, Hansen, Tram (tomorrow)
Neutrinos coupled to a massless mediator become strongly interacting at late times. This is excluded for the active neutrinos, but not for partially thermalised steriles!

Archidiacono, STH, Hansen, Tram (tomorrow)
A coupling with the same strength to dark matter can make dark matter sufficiently self-interacting to impact galactic dynamics.

Archidiacono, STH, Hansen, Tram (tomorrow)
WHAT IS IN STORE FOR THE FUTURE?

- BETTER CMB TEMPERATURE AND POLARIZATION MEASUREMENTS (PLANCK)
- LARGE SCALE STRUCTURE SURVEYS AT HIGHER REDSHIFT AND IN LARGER VOLUMES
- MEASUREMENTS OF WEAK GRAVITATIONAL LENSING ON LARGE SCALES
WEAK LENSING – A POWERFUL PROBE FOR THE FUTURE

Distortion of background images by foreground matter

Unlensed

Lensed
FROM A WEAK LENSING SURVEY THE ANGULAR POWER SPECTRUM CAN BE CONSTRUCTED, JUST LIKE IN THE CASE OF CMB

\[ C_\ell = \frac{9}{16} H_0^4 \Omega_m^2 \int_0^{\chi_H} \left[ \frac{g(\chi)}{a\chi} \right]^2 P(\ell / r, \chi) d\chi \]

\[ P(\ell / r, \chi) \quad \text{MATTER POWER SPECTRUM (NON-LINEAR)} \]

\[ g(\chi) = 2 \int_0^{\chi_H} n(\chi') \frac{\chi(\chi' - \chi)}{\chi'} d\chi' \quad \text{WEIGHT FUNCTION DESCRIBING LENSING PROBABILITY} \]

(SEE FOR INSTANCE JAIN & SELJAK ’96, ABAZAJIAN & DODELSON ’03, SIMPSON & BRIDLE ’04)
Shear power spectra for 2 tomography bins

Bin 2: $1.5 < z < 3$

Bin 1: $0 < z < 1.5$

STH, TU, WONG 2006
THE EUCLID MISSION
EUCLID WILL FEATURE:

- A WEAK LENSING MEASUREMENT OUT TO $z \sim 2$, COVERING APPROXIMATELY $20,000 \text{ deg}^2$ (THIS WILL BE MAINLY PHOTOMETRIC)

- A GALAXY SURVEY OF ABOUT $\text{few} \times 10^7$ GALAXIES (75 x SDSS)

- A WEAK LENSING BASED CLUSTER SURVEY
HAMANN, STH, WONG 2012: COMBINING THE EUCLID WL AND GALAXY SURVEYS WILL ALLOW FOR AT A 2.5-5σ DETECTION OF THE NORMAL HIERARCHY (DEPENDING ON ASSUMPTIONS ABOUT BIAS)

arXiv:1209.1043 (JCAP)
Basse, Bjælde, Hamann, STH, Wong 2013: Adding information on the cluster mass function will allow for a $5\sigma$ detection of non-zero neutrino mass, even in very complex cosmological models with time-varying dark energy.

arXiv:1304.2321 (JCAP)
THIS SOUNDS GREAT, BUT UNFORTUNATELY THE THEORETICIANS CANNOT JUST LEAN BACK AND WAIT FOR FANTASTIC NEW DATA TO ARRIVE.....
FUTURE SURVEYS LIKE EUCLID WILL PROBE THE POWER SPECTRUM TO ~ 1-2 PERCENT PRECISION!

WE SHOULD BE ABLE TO CALCULATE THE POWER SPECTRUM TO AT LEAST THE SAME PRECISION!
In order to calculate the power spectrum to 1% on these scales, a large number of effects must be taken into account.

- Baryonic physics - star formation, SN feedback,.....
- Neutrinos, even with normal hierarchy
- Non-linear gravity
- ..................
NON-LINEAR EVOLUTION PROVIDES AN ADDITIONAL SUPPRESSION OF FLUCTUATION POWER IN MODELS WITH MASSIVE NEUTRINOS

\[ \frac{\Delta P}{P} \sim -8 \frac{\Omega_v}{\Omega_m} \]

\[ \frac{\Delta P}{P} \sim -9.6 \frac{\Omega_v}{\Omega_m} \]

Brandbyge, STH, Haugbølle, Thomsen ’08
Brandbyge & STH ’09, ’10, Viel, Haehnelt, Springel ’10
STH, Haugbølle & Schultz ’12, Wagner, Verde & Jimenez ’12
Villaescusa-Navarro et al. ’13 (I-IV)
INDIVIDUAL HALO PROPERTIES

$512 \, h^{-1} \, \text{Mpc}$

$5 \times 10^{14} \, M_{\text{sun}}$

$0 < p/T < 1$

$1 < p/T < 2$

$2 < p/T < 3$

$3 < p/T < 4$

$4 < p/T < 5$

$5 < p/T < 6$

$\sum m_\nu = 0.6 \, \text{eV}$
CONCLUSIONS

- Neutrino physics is perhaps the prime example of how to use cosmology to do particle physics.

- The bound on neutrino masses is significantly stronger than what can be obtained from direct experiments, albeit much more model dependent.

- Cosmological data might actually be pointing to physics beyond the standard model in the form of sterile neutrinos.

- New data from Planck and Euclid may provide a positive detection of a non-zero neutrino mass.