Neutrinos

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PreSusy School 2016
Mass differences:

\[ \Delta m_{12}^2 = 72 - 80 \text{ (meV)}^2 \]
\[ \Delta m_{31}^2 = 2180 - 2640 \text{ (meV)}^2 \]

\[ m_{ve} = \left( \sum |U_{ei}|^2 m_i^2 \right)^{1/2} \]
Detecting neutrinos

No neutrino tracks...

Basic principle is to look for evidence that neutrinos have interacted, by detecting products of the interaction
Detecting neutrinos

- Large volumes needed to combat weak interaction
- Shielding required to reduce backgrounds $\implies$ underground
- Three main detection techniques

Radio-chemical: Radioactive atoms formed by capture of neutrinos in target Eg Ray Davis’s solar neutrino experiment, used the isotope $^{37}$Cl, neutrino capture produces radioactive $^{37}$Ar, a gas, which was removed from the target, purified, and counted.

Scintillation Use liquid scintillator, organic liquid that gives off light, when charged particles pass through it. The scintillator is monitored by optical detectors.

Cherenkov light detectors Cherenkov light is produced by particles moving faster than the speed of light in the medium. Optical detectors detect the Cherenkov light.
Neutrino detectors

ANITA ANNIE ANTARES ARIANNA BDUNT (NT-200+) BOREXINO CLEAN COBRA Daya Bay Double Chooz EXO-200 GALLEX GERDA GNO HALO HERON HOMESTAKE ICARUS IceCube INO JUNO Kamiokande KamLAND KM3NeT LAGUNA LBNE/DUNE LENS MAJORANA DEMONSTRATOR MicroBooNE MINERvA MiniBooNE MINOS MINOS+ NEMO Experiment MOON NEMO Telescope NEVOD NOvA OPERA RENO SAGE SciBooNE SNO SNO+ Super-K T2K UNO
Direct neutrino mass measurement

Using the end point of the beta decay spectrum
Eg Katrin experiment using tritium

\[ m_{\nu_e} = \left( \sum |U_{ei}|^2 m_i^2 \right)^{1/2} \]
Direct neutrino mass measurement - Katrin

Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated $\beta$-spectrum.
Cosmic Neutrino Background
Neutrino Cosmology

• There is a cosmic background neutrino population which is a relic from the early universe

• The neutrino background affects cosmological processes
  • Primordial nucleosynthesis
  • Cosmic microwave background
  • Large structure formation

• Observations probing these processes give us information about neutrinos

• It is important to include the neutrino background effects to be able to interpret observations and learn about other constituents of the universe
## Generic Solutions of Friedman Equation

<table>
<thead>
<tr>
<th>Equation of state</th>
<th>Behavior of energy-density under cosmic expansion</th>
<th>Evolution of cosmic scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>$p = \frac{\rho}{3}$</td>
<td>$\rho \propto a^{-4}$</td>
</tr>
<tr>
<td>Matter</td>
<td>$p = 0$</td>
<td>$\rho \propto a^{-3}$</td>
</tr>
<tr>
<td>Vacuum energy</td>
<td>$p = -\rho$</td>
<td>$\rho = \text{const}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Energy-momentum tensor of a perfect fluid with density $\rho$ and pressure $p$**

$$T_{\mu\nu} = \begin{pmatrix} \rho & p \\ p & \rho \end{pmatrix}$$

$$T_{\text{vac}}^{\mu\nu} = \rho \, g_{\mu\nu} \begin{pmatrix} \rho & -\rho \\ -\rho & -\rho \end{pmatrix}$$
Assumed neutrino masses:
- $m_3 = 50 \text{ meV}$
- $m_2 = 9 \text{ meV}$
- $m_1 = 0$

Lesgourgues & Pastor
astro-ph/0603494
Dark Energy $\sim 70\%$ (Cosmological Constant)

Ordinary Matter $\sim 5\%$ (of this only about 10% luminous)

Dark Matter $\sim 25\%$

Neutrinos $0.1-1\%$
Matter-Radiation Equality (Redshift 3400)

- Dark Matter: 42%
- Photons: 30%
- Massless Neutrinos: 20%
- Baryons: 8%
After Electron-Positron Annihilation (T = 100 keV)

- Neutrinos: 41%
- Photons: 59%

Relevant for Big Bang Nucleosynthesis (BBN)
Before Electron-Positron Annihilation (T = 1 MeV)

- Neutrinos: 48.8%
- Photons: 18.6%
- Electrons/Positrons: 32.6%
Neutrino Background

\[ n_{\nu\bar{\nu}}(1 \text{ flavour}) \approx 112 \text{ cm}^{-3} \]

\[ T_{\nu} = \left( \frac{4}{11} \right)^{1/3} \]

\[ T_{\gamma} \approx 1.95 \text{ K} \quad \text{for massless neutrinos} \]
Equilibrium Particle Interactions

• Boltzmann equation governs distributions

\[
\frac{df_X}{dt} + 3 \frac{\dot{a}}{a} f_X + \langle \sigma_A v \rangle (f_X^2 - f_{Xeq}^2) = 0
\]

• Two regimes:

\[\Gamma = \langle \sigma_A v \rangle n_X > H\]
Thermal equilibrium
Interaction rate > Expansion rate

\[f_{eq}(p) = \frac{1}{e^{Ep/T} \pm 1}\]

+ Fermions, - Bosons

\[\Gamma \ll H\]
Freezeout
Distribution constant at freezeout level, only redshifted

\[n_X(n_X^{eq})\]
## Thermal Radiation

### Thermodynamics of Radiation

<table>
<thead>
<tr>
<th>Property</th>
<th>General</th>
<th>Bosons</th>
<th>Fermions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number density n</td>
<td>$g \int \frac{d^3 p}{(2\pi)^3} \frac{1}{e^{E_p/T} \pm 1}$</td>
<td>$g_B \frac{\zeta_3}{\pi^2} T^3$</td>
<td>$\frac{3}{4} g_F \frac{\zeta_3}{\pi^2} T^3$</td>
</tr>
<tr>
<td>Energy density ρ</td>
<td>$g \int \frac{d^3 p}{(2\pi)^3} \frac{E_p}{e^{E_p/T} \pm 1}$</td>
<td>$g_B \frac{\pi^2}{30} T^4$</td>
<td>$\frac{7}{8} g_F \frac{\pi^2}{30} T^4$</td>
</tr>
<tr>
<td>Pressure P</td>
<td>$g \int \frac{d^3 p}{(2\pi)^3} \frac{</td>
<td>p</td>
<td>^2}{E_p} \frac{1}{e^{E_p/T} \pm 1}$</td>
</tr>
<tr>
<td>Entropy density s</td>
<td>$\frac{\rho + P}{T} = \frac{4}{3} \frac{\rho}{T}$</td>
<td>$g_B \frac{2\pi^2}{45} T^3$</td>
<td>$\frac{7}{8} g_F \frac{2\pi^2}{45} T^3$</td>
</tr>
</tbody>
</table>

\[ dE = TdS - PdV \]
\[ TdS = (\rho + P)dV \]

\[ Riemann \ Zeta \ Function \]
\[ \zeta = 1.2020569 \ldots \]

\[
\int_0^\infty \frac{x^2 dx}{\exp(x) - 1} = 2\zeta(3),
\int_0^\infty \frac{x^2 dx}{\exp(x) + 1} = \frac{6}{8} \zeta(3),
\int_0^\infty \frac{x^3 dx}{\exp(x) - 1} = 6\zeta(4) = \frac{\pi^4}{15},
\int_0^\infty \frac{x^3 dx}{\exp(x) + 1} = \frac{7}{48} \zeta(4) = \frac{7}{8} \frac{\pi^4}{15}
\]
# Thermal Degrees of Freedom

\[ g^* = g_B + \frac{7}{8} g_F \]

<table>
<thead>
<tr>
<th>Mass threshold</th>
<th>Particles</th>
<th>( g_B )</th>
<th>( g_F )</th>
<th>( g^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>( \gamma, 3\nu )</td>
<td>2</td>
<td>6</td>
<td>(7.25)</td>
</tr>
<tr>
<td>( m_e )</td>
<td>0.5 MeV</td>
<td>e(^\pm )</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>( m_\mu )</td>
<td>105 MeV</td>
<td>( \mu^\pm )</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>( m_\pi )</td>
<td>135 MeV</td>
<td>( \pi^0, \pi^\pm )</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>( \Lambda_{QCD} )</td>
<td>( \sim 170 ) MeV</td>
<td>u, d, s, gluons</td>
<td>18</td>
<td>50</td>
</tr>
<tr>
<td>( m_{c,\tau} )</td>
<td>2 GeV</td>
<td>c, ( \tau )</td>
<td>18</td>
<td>66</td>
</tr>
<tr>
<td>( m_b )</td>
<td>6 GeV</td>
<td>b(^\pm )</td>
<td>18</td>
<td>78</td>
</tr>
<tr>
<td>( m_{W,Z} )</td>
<td>90 GeV</td>
<td>Z(^0, W^\pm )</td>
<td>27</td>
<td>78</td>
</tr>
<tr>
<td>( m_H )</td>
<td>126 GeV</td>
<td>Higgs</td>
<td>28</td>
<td>78</td>
</tr>
<tr>
<td>( m_t )</td>
<td>170 GeV</td>
<td>t</td>
<td>28</td>
<td>90</td>
</tr>
<tr>
<td>( \Lambda_{SUSY} )</td>
<td>( \sim 1 ) TeV ?</td>
<td>SUSY particles</td>
<td>118</td>
<td>118</td>
</tr>
</tbody>
</table>
## Neutrino Thermal Equilibrium

### Neutrino reaction rate

Examples of neutrino processes

\[
e^+ + e^- \leftrightarrow \bar{\nu} + \nu
\]
\[
\bar{\nu} + \nu \leftrightarrow \bar{\nu} + \nu
\]
\[
\nu + e^\pm \leftrightarrow \nu + e^\pm
\]

Reaction rate in a thermal medium

for \( T \ll m_{W,Z} \)

\[
\Gamma \sim G_F^2 T^5
\]

### Cosmic expansion rate

Friedmann equation (flat universe)

\[
H^2 = \frac{8\pi}{3} \frac{\rho}{m^2_{Pl}} \quad \left( G_N = \frac{1}{m^2_{Pl}} \right)
\]

Radiation dominates

\[
\rho \sim T^4
\]

Expansion rate

\[
H \sim \frac{T^2}{m_{Pl}}
\]

**Condition for thermal equilibrium:** \( \Gamma > H \)

\[
T > \left( m_{Pl} G_F^2 \right)^{-1/3} \sim \left[ 10^{19} \text{GeV} \left( 10^{-5} \text{GeV}^{-2} \right)^2 \right]^{-1/3} = 1 \text{ MeV}
\]

**Neutrinos are in thermal equilibrium for** \( T \gtrsim 1 \text{ MeV} \) **corresponding to** \( t \lesssim 1 \text{ sec} \)
### Present-Day Neutrino Density

<table>
<thead>
<tr>
<th>Neutrino decoupling (freeze out)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \sim \Gamma$</td>
</tr>
<tr>
<td>$T \approx 2.4$ MeV (electron flavour)</td>
</tr>
<tr>
<td>$T \approx 3.7$ MeV (other flavours)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Redshift of Fermi-Dirac distribution (&quot;nothing changes at freeze-out&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{d n_{\nu\bar{\nu}}}{dE} = \frac{1}{\pi^2} \frac{E^2}{e^{E/T} + 1}$</td>
</tr>
<tr>
<td>Temperature scales with redshift $T_\nu = T_\gamma \propto (z + 1)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electron-positron annihilation beginning at $T \approx m_e = 0.511$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\sqrt{2}}{2} \left( \frac{7}{8} + \frac{4}{11} \right) = \frac{11}{2} \sqrt{2}$</td>
</tr>
<tr>
<td>$g_\ast T_\gamma^3 \bigg</td>
</tr>
<tr>
<td>$T_\gamma^3 \bigg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Redshift of neutrino and photon thermal distributions so that today we have</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\nu\bar{\nu}}(1$ flavour$) = \frac{4}{11} \times \frac{3}{4} \times n_\gamma = \frac{3}{11} n_\gamma \approx 112$ cm$^{-3}$</td>
</tr>
<tr>
<td>$T_\nu = \left( \frac{4}{11} \right)^{1/3} T_\gamma \approx 1.95$ K for massless neutrinos</td>
</tr>
</tbody>
</table>
Weighing Neutrinos with the Universe
Basic Idea

Comparison of theoretical predictions with observations of the anisotropy (temperature (and polarisation) differences from isotropy) of the cosmic microwave background and correlations in the large scale structure

Wmap9 CMB
http://wmap.gsfc.nasa.gov/resources/cmbimages.html

Sky Map of Galaxies (2MASS XSC)
http://spider.ipac.caltech.edu/staff/jarrett/2mass/XSC/jarrett_allsky.html
Neutrino effect on large scale structure growth

$Z = 32.33$

Standard $\Lambda$CDM Model

Neutrinos with $\Sigma m_\nu = 6.9$ eV

Troels Haugbølle, http://users-phys.au.dk/haugboel
Neutrino Mass Limits Post Planck (2013)

Depends on the data sets used
Many different analyses in the literature

Planck alone: $\sum m_\nu < 1.08$ eV (95% CL)
CMB + BAO limit: $\sum m_\nu < 0.23$ eV (95% CL)

Ade et al. (Planck Collaboration), arXiv:1303.5076
IceCube high energy astrophysical neutrino discovery
Multimessenger Astronomy
Neutrino source fluxes

- Cosmological $\nu$
- Solar $\nu$
- Supernova burst (1987A)
- Reactor anti-$\nu$
- Background from old supernova
- Terrestrial anti-$\nu$
- Atmospheric $\nu$
- $\nu$ from AGN
- GZK $\nu$

Christian Spiering
IceCube is a LARGE neutrino detector...
IceCube detector

IceCube Lab

IceTop
- 81 Stations, each with 2 IceTop Cherenkov detector tanks
- 2 optical sensors per tank
- 324 optical sensors

IceCube Array
- 86 strings including 8 DeepCore strings
- 60 optical sensors on each string
- 5160 optical sensors

December, 2010: Project completed, 86 strings

DeepCore
- 8 strings-spacing optimized for lower energies
- 480 optical sensors

Eiffel Tower
- 324 m

Bedrock
Detection principle
Cosmic rays – interacting in the Earth’s atmosphere
– source of atmospheric neutrinos and muon background

Earth's atmosphere

Muon rate:
In ice: \(~3000\) Hz

Atmospheric neutrinos:
\(~1\) neutrino/10 minutes

Neutrino Detection:
Requires \(10^6\) background rejection

“Conventional”
- From \(\pi / K\) decay
- \(\Phi \sim E^{-3.7}\)

“Prompt”
- From charmed meson decay
- \(\Phi \sim E^{-2.7}\)
- Undetected so far
Sky map of high-energy, starting events

Largely isotropic $\Rightarrow$ extragalactic origin!
Point source search in six years of data
Point source search in six years of data

IceCube Preliminary

Northern hemisphere ($\alpha = 249.6^\circ$, $\delta = 63.6^\circ$)

- $\log_{10}(p)$
  - North: 5.51
  - Post-Trial: 35%

Southern hemisphere ($\alpha = 300.4^\circ$, $\delta = -33.2^\circ$)

- $\log_{10}(p)$: 4.74
- Post-Trial: 87%

Atmospheric $\mu$
Neutrinos
Neutrinos

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
U
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[
U = 
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i \delta}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0
\end{pmatrix}
\begin{pmatrix}
c_{13} & s_{13} e^{i \delta} & 0 \\
-s_{13} e^{-i \delta} & c_{13} & 0
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

PreSusy School 2016
Earth attenuation $E > \text{TeV}$

The diagram shows the transmission of neutrinos through the Earth for different energies: $1 \text{ EeV}$, $10 \text{ PeV}$, $100 \text{ TeV}$, and $10 \text{ TeV}$. The graph plots the transmission as a function of the zenith angle. The labels for horizontal and straight-up transmission through the Earth are indicated.