Concha Gonzalez-Garcia

(YITP Stony Brook & ICREA U. Barcelona)

UB, June 1th, 2016

Neutrino Flavour Transition: Data and Interpretation
Some Implications for/from Cosmology

http://www.nu-fit.org
Phenomenology with Massive Neutrinos

Concha Gonzalez-Garcia

The Big Bang
\[ \rho_\nu = 330/\text{cm}^3 \]
\[ \rho_\nu = 0.0004 \text{ eV} \]

SN1987
\[ E_\nu \sim \text{MeV} \]

ExtraGalactic
\[ E_\nu \gtrsim 30 \text{TeV} \]

Sources of \( \nu 's \)

The Sun
\[ \nu_e \]
\[ \Phi_\nu^{\text{Earth}} = 6 \times 10^{10} \nu/\text{cm}^2\text{s} \]
\[ E_\nu \sim 0.1-20 \text{ MeV} \]

Atmospheric \( \nu 's \)
\[ \nu_e, \nu_\mu, \overline{\nu}_e, \overline{\nu}_\mu \]
\[ \Phi_\nu \sim 1 \nu/\text{cm}^2\text{s} \]

Earth’s radioactivity
\[ \overline{\nu}_e \]
\[ \Phi_\nu \sim 6 \times 10^6 \nu/\text{cm}^2\text{s} \]

Human Body
\[ \Phi_\nu = 340 \times 10^6 \nu/\text{day} \]

Nuclear Reactors
\[ E_\nu \sim \text{few MeV} \]

Accelerators
\[ E_\nu \sim 0.3-30 \text{ GeV} \]

Concha Gonzalez-Garcia

- Fermilab
- CERN
- KEK
# Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM} \]

With three generation of fermions

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There is no \( \nu_R \)
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Three and only three

\[ \text{Accidental global symmetry: } B \times L_e \times L_\mu \times L_\tau \quad \text{(hence } L = L_e + L_\mu + L_\tau) \]

\[ \nu \text{ strictly massless} \]
• By 2016 we have observed with high (or good) precision:

* Atmospheric $\nu_\mu$ & $\bar{\nu}_\mu$ disappear most likely to $\nu_\tau$ (SK, MINOS, ICECUBE)
* Accel. $\nu_\mu$ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, T2K/ MINOS, NO$\nu$A)
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All this implies that $L_\alpha$ are violated and There is Physics Beyond SM
The New Minimal Standard Model

• Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino

  * Introduce $\nu_R$ AND impose $L$ conservation $\Rightarrow$ Dirac $\nu \neq \nu^c$:
    \[ \mathcal{L} = \mathcal{L}_{SM} - M_{\nu} \nu_L \nu_R + h.c. \]

  * NOT impose $L$ conservation $\Rightarrow$ Majorana $\nu = \nu^c$
    \[ \mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_{\nu} \nu_L^{\dagger} \nu_L^C + h.c. \]
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• The charged current interactions of leptons are not diagonal (same as quarks)

\[
\frac{g}{\sqrt{2}} W^+_{\mu} \sum_{i,j} \left( U^{i,j}_{\text{LEP}} \bar{l}_i \gamma^\mu L \nu^j + U^{i,j}_{\text{CKM}} \bar{U}^i \gamma^\mu L D^j \right) + h.c.
\]
**ν Mass Oscillations in Vacuum**

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \rightarrow \nu_\alpha + N'$ is a linear combination of the mass eigenstates ($|\nu_i\rangle$): $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i} |\nu_i\rangle$

- After a distance $L$ it can be detected with flavour $\beta$ with probability

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{j \neq i}^{n} \text{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2 \left( \frac{\Delta_{ij}}{2} \right) + 2 \sum_{j \neq i}^{n} \text{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin (\Delta_{ij})$$

$$\Delta_{ij} = \frac{(E_i - E_j)L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{\text{eV}^2} \frac{L/E}{\text{Km/GeV}}$$
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No information on $\nu$ mass scale nor Majorana versus Dirac
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  No information on $\nu$ mass scale nor Majorana versus Dirac

- For 2-$\nu$:

  $$P_{\alpha\alpha} = 1 - P_{osc}$$

  $$P_{osc} = \sin^2 (2\theta) \sin^2 \left( 1.27 \frac{\Delta m^2 L}{E} \right)$$

  Disappear

  Appear
Matter Effects

• If $\nu$ cross matter regions (Sun, Earth...) it interacts *coherently*

  – But Different flavours have different interactions :

  ⇒ Effective potential in $\nu$ evolution : $V_e \neq V_{\mu,\tau} \Rightarrow \Delta V^\nu = -\Delta V^{\bar{\nu}} = \sqrt{2}GFN_e$

  ⇒ *Modification of mixing angle and oscillation wavelength* ≡ MSW effect

• The mixing angle in matter

\[
\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\sqrt{(\Delta m^2 \cos(2\theta) - 2E\Delta V)^2 + (\Delta m^2 \sin(2\theta))^2}}
\]

• For solar neutrinos in adiabatic regime

\[
P(\nu_e \rightarrow \nu_e) = \frac{1}{2} [1 + \cos(2\theta_m) \cos(2\theta)]
\]
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Confirmed: Vacuum oscillation $L/E$ pattern with 2 frequencies MSW conversion in Sun
3ν Flavour Parameters

- For 3 ν’s: 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

\[ U_{\text{LEP}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

- Two Possible Orderings
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- Two Possible Orderings

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<td>( \theta_{12} )</td>
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Phenomenology with Massive Neutrinos

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Flavour Parameters: Status in 6/2016

Maltoni, Schwetz, Martinez-Soler, Esteban, MCG-G

\[
\begin{align*}
\Delta \chi^2 & = 6.5, 7, 7.5, 8, 8.5 \\
\Delta m_{21}^2 & = \left[10^{-5} \text{ eV}^2\right] \\
\sin^2 \theta_{12} & = 0.2, 0.25, 0.3, 0.35, 0.4 \\
\sin^2 \theta_{23} & = 0.0, 0.05, 0.1, 0.15, 0.2 \\
\sin^2 \theta_{13} & = 0.015, 0.02, 0.025, 0.03, 0.035 \\
\delta_{\text{CP}} & = 0, 90, 180, 270, 360
\end{align*}
\]

\[\theta_{23} \neq 45 \quad \theta_{23} < 45?\]

\[\text{N/I?} \quad \delta_{\text{CP}}\]
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3\nu Analysis: Leptonic CP violation

• “Hint” CP phase around $\delta_{CP} = \frac{3\pi}{2}$ (maximal)

![Graph showing $\Delta \chi^2$ vs $\delta_{CP}$ for IO and NO](image)

$\nu$ Analysis: Leptonic CP violation

• Leptonic Jarslog Determinant

![Graph showing $\Delta \chi^2$ vs $J_{CP}$](image)

Potentially much larger than the quark sector $J_{CMK} = (3.06^{+0.21}_{-0.20}) \times 10^{-5}$
Issues with the Solar Fluxes

- Newer determination of abundance of heavy elements in solar surface give lower values
- Solar Models with these lower metallicities fail in reproducing helioseismology data

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Most difference in CNO fluxes

- Two sets of SSM:
  Starting from Bahcall et al. 05, Serenelli et al. 0909.2668
  **GS98** uses older metallicities
  **AGSXX** uses newer metallicities
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  Impact in Osc Parameter Determination

  Negligable ⇒ Possible to Invert and Extract Fluxes from Data.
Learning how the Sun Shines with $\nu'$s

Results of Oscillation analysis with solar flux normalizations free: $f_i = \frac{\Phi_i}{\Phi_{GS98}}$

Present limit on CNO:

$$\frac{L_{\text{CNO}}}{L_\odot} < 2\% \ (3\sigma)$$

Test of Luminosity Constraint:

$$\frac{L_\odot (\nu - \text{inferred})}{L_\odot} = 1.04 \pm 0.07$$

Comparing with the Models:

Both statistically equally probable

New experiments needed
more sensitive to CNO fluxes

New models with new Nuclear Rates
New problems with Helioseismology

Beyond 3ν’s: Light Sterile Neutrinos

- Several Observations which can be Interpreted as Oscillations with $\Delta m^2 \sim eV^2$

**Reactor Anomaly**

New reactor flux calculation

$\Rightarrow$ Deficit in data at $L \lesssim 100$ m

Explained as $\nu_e$ disappearance

**Gallium Anomaly**

Acero, Giunti, Laveder, 0711.4222
Giunti, Laveder, 1006.3244

Radioactive Sources ($^{51}$Cr, $^{37}$Ar)
in calibration of Ga Solar Exp;

$\nu_e + ^{71}$Ga $\rightarrow ^{71}$Ge + $e^-$

Give a rate lower than expected

$$R = \frac{N_{\text{obs}}}{N_{\text{Bahc}}^{\text{th}}} = 0.86 \pm 0.05 \ (2.8\sigma)$$

Explained as $\nu_e$ disappearance

**LSND, MiniBoone**

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Kopp et al, ArXiv 1303.3011

Kopp et al, ArXiv 1303.3011
• These explanations require $3+N_s$ mass eigenstates $\rightarrow N_s$ sterile neutrinos

$$\nu_e \rightarrow \nu_e \text{ disapp} \ (\text{REACT,Gallium,Solar, LSND/KARMEN})$$

• Problem: fit together
  $$\nu_\mu \rightarrow \nu_e \text{ app} \ (\text{LSND,KARMEN,NOMAD,MiniBooNE,E776,ICARUS})$$
  $$\nu_\mu \rightarrow \nu_\mu \text{ disapp} \ (\text{CDHS,ATM,MINOS,MiniBooNE})$$

• Generically: $P(\nu_e \rightarrow \nu_\mu) \sim |U_{ei}^* U_{\mu i}| \ [i = \text{heavier state(s)}]$ 
  
  But $|U_{ei}|$ constrained by $P(\nu_e \rightarrow \nu_e)$ disappearance data
  And $|U_{\mu i}|$ constrained by $P(\nu_\mu \rightarrow \nu_\mu)$ disappearance data \} \Rightarrow \text{Severe tension}
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Light Sterile Neutrinos: 3+1

• Comparing the parameters required to explain signals with bounds from disappearance

Kopp et al, ArXiv 1303.3011

Further Disfavoured by ICECUBE

Giunti et al, ArXiv 1308.5288

Somewhat different conclusions
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Somewhat different conclusions


More latter...
**Neutrino Mass Scale: Laboratory Probes**

**Single $\beta$ decay**: Dirac or Majorana $\nu$ mass modify spectrum endpoint

\[ m_{\nu_e}^2 = \sum m_j^2 |U_{ej}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \]

Present bound: \( m_{\nu_e} \leq 2.2 \) eV (at 95% CL)
Katrin (2016?) Sensitivity to \( m_{\nu_e} \sim 0.2 \) eV
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$$m_{\nu_e}^2 = \sum m_j^2 |U_{ej}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$

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Katrin (2016?) Sensitivity to $m_{\nu_e} \sim 0.2$ eV

**$\nu$-less Double-$\beta$ decay**: $\iff$ Majorana $\nu'$s

If $m_\nu$ only source of $\Delta L$ 

$$T_{1/2}^{0\nu} = \frac{m_e}{G_{0\nu} M_{\text{nucl}}^2 m_{ee}^2}$$

$$m_{ee} = |\sum U_{ej}^2 m_j|$$

$$= |c_{13}^2 c_{12} m_1 e^{i\eta_1} + c_{13}^2 s_{12} m_2 e^{i\eta_2} + s_{13}^2 m_3 e^{-i\delta_{CP}}|$$
Bounds from $^{136}\text{Xe}$ (EXO and KamLAND-ZEN), $^{76}\text{Ge}$ (Gerda) and $^{130}\text{Te}$ (Cuore-0)
The Emerging Picture

- At least two neutrinos are massive ⇒ There is NP

- Oscillations DO NOT determine the lightest mass but β decay:
  \[ \sum m_{\nu_i} \leq 2 \text{ eV/c}^2 \]

⇒ Heaviest \( \nu \) is at least 1 million de times lighter than the electron

- Dirac or Majorana?: We do not know

- Three mixing angles are non-zero (and relatively large) ⇒ very different from CKM

  – The two arising questions

    * Why are neutrinos so light?

      The Origin of Neutrino Mass

    * Why are lepton mixing so different from quark’s?

      The Flavour Puzzle
**Bottom-up: Light \( \nu \) from Generic New Physics**

If SM is an effective low energy theory, for \( E \ll \Lambda_{NP} \)
- The same particle content as the SM and same pattern of symmetry breaking
- But there can be non-renormalizable 
  \( (\text{dim} > 4) \) operators

\[
\mathcal{L} = \mathcal{L}_{SM} + \sum_n \frac{1}{\Lambda_{NP}^{n-4}} \mathcal{O}_n
\]

First NP effect \( \Rightarrow \text{dim=}5 \) operator
There is only one!

\[
\mathcal{L}_5 = \frac{Z_{ij}^{\nu}}{\Lambda_{NP}} \left( \overline{L_{L,i}} \tilde{\phi} \right) \left( \tilde{\phi}^T L_{L,j}^C \right)
\]
If SM is an effective low energy theory, for $E \ll \Lambda_{NP}$

– The same particle content as the SM and same pattern of symmetry breaking

– But there can be non-renormalizable

$$L = L_{SM} + \sum_n \frac{1}{\Lambda_{NP}^{n-4}} O_n$$

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

which after symmetry breaking

induces a $\nu$ Majorana mass

$$\begin{align*}
L_5 &= \frac{Z_{ij}^\nu}{\Lambda_{NP}} \left( \overline{L}_L i \phi \right) \left( \phi^T L_L^C \right) \\
(M_\nu)_{ij} &= Z_{ij}^\nu \frac{v^2}{\Lambda_{NP}}
\end{align*}$$

Implications:

– It is natural that $\nu$ mass is the first evidence of NP

– Naturally $m_\nu \ll$ other fermions masses $\sim \lambda^f v$ if $\Lambda_{NP} \gg v$
Phenomenology with Massive Neutrinos

Concha Gonzalez-Garcia

Bottom-up: Light $\nu$ from Generic New Physics

If SM is an effective low energy theory, for $E \ll \Lambda_{NP}$

- The same particle content as the SM and same pattern of symmetry breaking
- But there can be non-renormalizable
  (dim > 4) operators

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum_n \frac{1}{\Lambda_{NP}^{n-4}} \mathcal{O}_n \]

First NP effect $\Rightarrow$ dim=5 operator

There is only one!

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\[ (M_\nu)_{ij} = Z_{ij}^\nu \frac{v^2}{\Lambda_{NP}} \]

Implications:

- It is natural that $\nu$ mass is the first evidence of NP

- Naturally $m_\nu \ll$ other fermions masses $\sim \lambda^f v$ if $\Lambda_{NP} \gg v$

- $m_\nu > \sqrt{\Delta m^2_{atm}} \sim 0.05$ eV for $Z' \sim 1 \Rightarrow \Lambda_{NP} \sim 10^{15}$ GeV $\Rightarrow \Lambda_{NP} \sim$ GUT scale

  $\Rightarrow$ Leptogenesis possible

  [ But if $Z' \sim (Y_e)^2 \Rightarrow \Lambda_{NP} \sim$ TeV scale ]
Phenomenology with Massive Neutrinos

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Implications: Leptogenesis

- Majorana $m_\nu \Rightarrow$ Lepton $\neq$ violating $\Rightarrow$ Matter-Antimatter asymmetry possible
**Implications: Leptogenesis**

- **Majorana** $m_\nu \Rightarrow$ Lepton $\neq$ violated $\Rightarrow$ Matter-Antimatter asymmetry possible

- **How?** In the Early Universe via decay of heavy state $N$ related to $\nu$-mass generation

  - If $\mathcal{CP}$: $\Gamma(N \rightarrow X l) \neq \Gamma(N \rightarrow \overline{X} \overline{l})$
  - And decay is out of equilibrium: ($\Gamma_N \ll$ Universe expansion rate)

  \[
  \Delta L \text{ is generated}
  \]

  \[
  \Delta L \text{ is transformed in } \Delta B
  \]

- Today

  \[
  \mu_B = -\frac{g_{*_{\text{today}}}}{g_{*_{\text{end}}}} a_{\text{sph}} N_{L_{\text{end}}} \simeq -\frac{3.92}{106.75} \frac{28}{79} N_{L_{\text{end}}} \simeq 10^{-2} N_{L_{\text{end}}}
  \]
Implications: Leptogenesis

- Majorana $m_\nu \Rightarrow$ Lepton $\#$ violated $\Rightarrow$ Matter-Antimatter asymmetry possible

- How? In the Early Universe via decay of heavy state $N$ related to $\nu$-mass generation

\[
\begin{align*}
N & \rightarrow l \\
N & \rightarrow \bar{l}
\end{align*}
\]

- If $\not CP : \Gamma(N \rightarrow X l) \neq \Gamma(N \rightarrow X \bar{l})$

- And decay is out of equilibrium:
  \((\Gamma_N \ll \text{Universe expansion rate})\)

SM sphaleron processes $\Rightarrow \Delta L$ is transformed in $\Delta B$

- Today
  \[
  \mu_B = -\frac{g_*^{\text{today}}}{g_*^{\text{end}}} a_{\text{sph}} N_L^{\text{end}} \simeq -\frac{3.92}{106.75} \frac{28}{79} N_L^{\text{end}} \simeq 10^{-2} N_L^{\text{end}}
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- To obtain $N_L^{\text{end}}$: solve Boltzman Eqs. with all relevant processes
  $\Rightarrow$ Details and connection to $\nu$ parameters are model dependent
Leptogenesis connection to $\nu$’s: Challenge

$\mathcal{O}_5$ is generated for example by tree-level exchange of singlet ($N_i \equiv (1, 1)_0$) (Type-I) or triplet fermions ($N_i \equiv \Sigma_i \equiv (1, 3)_0$) (Type-III) or a scalar triplet $\Delta \equiv (1, 3)_1$ (Type-II)
\( \mathcal{O}_5 \) is generated for example by tree-level exchange of singlet \((N_i \equiv (1, 1)_0)\) (Type-I) or triplet fermions \((N_i \equiv \Sigma_i \equiv (1, 3)_0)\) (Type-III) or a scalar triplet \(\Delta \equiv (1, 3)_1\) (Type-II).

- For fermionic see-saw
  \[-\mathcal{L}_{NP} = -iN_i\phi N_i + \frac{1}{2} M_{Nij} \bar{N}_i^{C} N_j + \lambda^\nu_T \lambda^{\nu}_\alpha N_j \nu L_\alpha \bar{\phi} N_j \mu \tau \]
  \[\Rightarrow \mathcal{O}_5 = \frac{(\lambda^{\nu T} \lambda^{\nu})_{\alpha \beta}}{\Lambda_{NP}} \left( \bar{L}_\alpha \phi \right) \left( \tilde{\phi}^T L^C_\beta \right) \text{ with } \Lambda_{NP} = M_N \]

- For scalar see-saw
  \[-\mathcal{L}_{NP} = f_{\Delta \alpha \beta} \bar{L}_\alpha \Delta L^C_\beta + M^2_{\Delta} |\Delta|^2 + \kappa \phi^T \Delta^\dagger \phi \ldots \]
  \[\Rightarrow \mathcal{O}_5 = \frac{f_{\Delta \alpha \beta}}{\Lambda_{NP}} \left( \bar{L}_\alpha \phi \right) \left( \tilde{\phi}^T L^C_\beta \right) \text{ with } \Lambda_{NP} = \frac{M^2_{\Delta}}{\kappa} \]

Very different HE physics, but same LE \(\nu\) parameters.
Leptogenesis connection to $\nu$’s: Example

- Generically in these see-saw models successful leptogenesis
  - Lower bound on heavy decaying particle (for enough asymmetry)
  - Upper bound on light neutrino mass (for not too much washout)
- For example in Type-I see-saw

\[
\begin{align*}
M_1 &\gtrsim 3 \times 10^9 \text{ GeV} \quad (\text{for zero initial abundance}) \\
M_1 &\gtrsim 6 \times 10^8 \text{ GeV} \quad (\text{for thermal initial abundance})
\end{align*}
\]

$\Rightarrow$ Upper bound on neutrino mass $\bar{m} = \sqrt{m_1^2 + m_2^2 + m_3^2} \lesssim \mathcal{O}(\text{eV})$
Light massive $\nu$ in Cosmology

Relic $\nu'$s: Effects in several cosmological observations at several epochs

<table>
<thead>
<tr>
<th>Primordial Nucleosynthesis</th>
<th>Cosmic Microwave Background</th>
<th>Large Scale Structure Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BBN</td>
<td>CMB</td>
<td>LSS</td>
</tr>
<tr>
<td>$T \sim \text{MeV}$</td>
<td>$T \lesssim \text{eV}$</td>
<td>$N_{\text{eff}}$ and $\sum m_\nu$</td>
</tr>
<tr>
<td>Number of $\nu'$s ($N_{\text{eff}}$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Observables also depend on all other cosmological parameters

See also talk by V. Niro on Friday and posters by Cuesta and Giusarma
In general at $T < m_e$ we can always write

$$\rho_r = \left[ 1 + \frac{7}{8} \times \left( \frac{4}{11} \right)^{\frac{4}{3}} N_{\text{eff}} \right] \rho_\gamma$$

$\Delta N_{\text{eff}} = N_{\text{eff}} - 3$ (exactly -3.04) parametrizes:

- Any new relativistic states (accounting for their decoupling temperature)
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• At BBN $N_{\text{eff}} > 3$:
  ⇒ Faster expansion of Universe
  ⇒ Weak Interac freeze-out earlier
  ⇒ Larger $\frac{n_n}{n_p}$ ⇒ Larger $^4\text{He}$ abundance
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Cyburt et al arXiv:1505.0176

BBN $^4$He and Deut: $N_{\text{eff}} = 2.85 \pm 0.28$
• CMB almost unaffected by 3 $\nu$’s if they are relativistic at recombination $z_{rec} = 1089$

At recombination $T_{\gamma}^{rec} \approx 3000 \text{ K} \approx 0.26 \text{ eV}$

$\Rightarrow T_{\nu}^{rec} = \left( \frac{4}{11} \right) \frac{1}{3} T_{\gamma}^{rec} \approx 0.18 \text{ eV}$

The mean momenta of the neutrino

$\langle p_{\nu} \rangle_{rec} = \frac{7\pi^4}{180\xi(3)} T_{\nu}^{rec} = 0.58 \text{ eV}$

So $\nu$’s direct effect of CMB if $\sum m_{\nu_i} > \mathcal{O}(\text{eV})$
**CMB: Effects of Neutrinos**

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- But parameter degeneracies:
  Same effect by change of other cosmological parameters

---

CMB: Effect of Neutrinos

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- For more than 3 $\nu$’s: a change in $N_{\text{eff}}$ changes the time of matter-radiation equality

$$1 + z_{eq} = \frac{\Omega_m}{\Omega_r} = \frac{\Omega_m h^2}{\Omega_\gamma h^2} \frac{1}{1 + 0.2271 N_{\text{eff}}}$$

- The ratio 1st/3rd peak in CMB $\Rightarrow z_{eq} = 3386 \pm 69$ but $N_{\text{eff}}$ degenerated with $\Omega_m$
Phenomenology with Massive Neutrinos

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CMB: Effect of Neutrinos

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The conclusions is:

*Combined analysis of Several Observables to break Degeneracies*
Matter Power Spectrum: Effects of $\nu$'s

- Contrary to CDM, $\nu$'s move at speed $v_\nu \sim \min\left[c, 3 \frac{T_\nu}{m_\nu}\right]$

  $\Rightarrow$ They can travel freely over distances $\lambda_{FS} \sim \frac{v_\nu}{H(t)}$

  $\Rightarrow$ They affect structures formed over scales $k$ with $\frac{2\pi a(t)}{k} \leq \lambda_{FS}$

  $k \geq k_{nr} \simeq 0.018 \Omega_m^{1/2} \frac{m_\nu}{1\text{ eV}}$
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  $k \geq k_{nr} \simeq 0.018 \Omega_{m}^{1/2} \frac{m_{\nu}}{1 \text{eV}}$

- If all DM formed of $\nu$’s (Hot Dark Matter) no structure formed with $k \geq k_{nr}$

  $\Rightarrow$ Pure HDM Ruled out by Observations

  $\Rightarrow$ Subdominant contribution of $\nu$’s to DM Constrained by Observations
Matter Power Spectrum: Effects of $\nu$'s

- In a Universe with CDM+$\nu'$s with $f_\nu = \frac{\Omega_\nu}{\Omega_m} \ll 1$

\[
\frac{\Delta P(k)}{P(k)} \simeq -8f_\nu \simeq -0.09 \sum m_{\nu_i} \frac{1}{1 \text{eV} \Omega_m h^2} \quad \text{for } k \gg k_{nr}
\]

Phenomenology with Massive Neutrinos

Concha Gonzalez-Garcia

**Cosmological Analysis by Planck**

**arXiv:1502.01589**

<table>
<thead>
<tr>
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**Neutrino Mass Scale**

**Single $\beta$ decay**: Dirac or Majorana $\nu$ mass modify spectrum endpoint

$$m_{\nu_e}^2 = \sum m_j^2 |U_{ej}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$

Present bound: $m_{\nu_e} \leq 2.2$ eV (at 95% CL)

Katrin (2016?) Sensitivity to $m_{\nu_e} \sim 0.2$ eV

**$\nu$-less Double-$\beta$ decay**:⇔ Majorana $\nu'$s sensitive to Majorana phases

If $m_{\nu}$ only source of $\Delta L$ $(T_{1/2}^{0\nu})^{-1} \propto (m_{ee})^2$

$$m_{ee} = |\sum U_{ej}^2 m_j|$$

$$m_{ee} = |c_{13}^2 c_{12}^2 m_1 e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2 e^{i\eta_2} + s_{13}^2 m_3 e^{-i\delta_{CP}}|$$

Present Bounds: $m_{ee} < 0.06–0.76$ eV

**COSMO** Neutrino mass (Dirac or Majorana) modify the growth of structures

$$\sum m_i$$
Global oscillation analysis

⇒ Correlations $m_{\nu_e}$, $m_{ee}$ and $\sum m_\nu$

(Fogli et al (04))

Nufit (95%)

- Width due to range in oscillation parameters very narrow
- High precision determination of $m_{\nu_e}$ and $\sum m_i$ can give information on ordering

- Wide band due to unknown Majorana phases ⇒ Possible Det of Maj phases
  
  If Matrix Element Uncertainty Reduced
Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis
⇒ Correlations $m_{\nu_e}$, $m_{ee}$ and $\sum m_\nu$
(Fogli et al hep-ph/0408045)

Nufit (95%)

Presently only Bounds
• From Tritium $\beta$ decay (Mainz & Troisk expe)
  $m_{\nu_e} < 2.2$ eV (95%)
Katrin (2016?) Sensitivity to $m_{\nu_e} \sim 0.2$ eV
• From $0\nu\beta\beta$ decay for Majorana Neutrinos
  $m_{ee} < 0.06 - 0.15$ eV (90%)
Goal of Next Decade ⇒ $m_{ee}$ at IO
• From Analysis of Cosmological data
Bound on $\sum m_\nu$ changes with:
  cosmo parameters fix in analysis
  cosmo observables considered

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See also talk by V. Niro on Friday and posters by Cuesta and Giusarma
One light $\nu_s$ mixed with 3 $\nu'_a$s contributes to $\rho$ as $N_{\text{eff}}$.

From evol eq for 3 + 1 ensemble one finds
\[ \Rightarrow \text{So if “explaination” to SBL anomalies} \]
1 $\nu_s$ contributes as much as 1 $\nu_a$

But analysis of cosmo data in $\Lambda$CDM+$r$ + $\nu_s$ tells us

Plank+WP+high-l+BAO

J. Bergstrom, etal, ArXiv:1407.3806
In string inspired $E_6$ models, 3 light $\nu_R$’s with new interactions

$$ (Z' \text{ with coupling } Y^{\nu_R}_{Z'} = \cos \beta \frac{5}{\sqrt{40}} - \frac{1}{\sqrt{24}} \sin \beta) $$

In these scenarios $\Delta N_{\text{eff}} = 3 \times \left( \frac{T_{\nu R}}{T_{\nu L}} \right)^4 = 3 \times \left( \frac{g(T_{\nu R}^{\text{dec}})}{g(T_{\nu R}^{\text{dec}})} \right)^4$ Determined by $\sigma(\bar{\nu}_R \nu_R \rightarrow \bar{f} f)$ mediated by $Z'$ (ie $M_{Z'}$ and coupling parameter $\beta$)

⇒ Interplay between cosmological determination of $\Delta N_{\text{eff}}$ and $Z'$ LHC searches
Phenomenology with Massive Neutrinos

Concha Gonzalez-Garcia

Summary

• Neutrino oscillation searches have shown us

\[ \Delta m_{21}^2 = 7.49 \times 10^{-5} \text{ eV}^2 \ (2.3\%) \]
\[ \Delta m_{31}^2 = 2.48 \times 10^{-3} \text{ eV}^2 \ \text{NO} \ (1.8\%) \]
\[ \Delta m_{32}^2 = -2.47 \times 10^{-3} \text{ eV}^2 \ \text{IO} \]

\[ \sin^2 \theta_{12} = 0.308 \ (4\%) \]
\[ \sin^2 \theta_{23} = \begin{cases} 0.579 & \text{IO} \ (7.2\%) \\ 0.479 & \text{NO} \end{cases} \]
\[ \sin^2 \theta_{13} = 0.022 \ (4.8\%) \]

\[ \Rightarrow U_{\text{LEP}} \ \text{Very different from } U_{\text{CKM}} \]

• \( m_\nu \neq 0 \Rightarrow \) Need to extend SM

\[ \text{NP breaking total } L \rightarrow \text{Majorana } \nu : \nu = \nu^C \]
\[ \text{NP conserving total } L \rightarrow \text{Dirac } \nu : \nu \neq \nu^C \]

• Still ignore or not significantly determined

Majorana/Dirac?  \( m_\nu \) scale  \( \text{leptonic } C P \)  Ordering? \{ \Rightarrow \) New experiments

Standing Puzzles: SBL anomalies  light sterile \( \nu \)’s?

• More physics than \( \nu \) masses: VLI, NSI, Solar Physics, Cosmological effects . . .

• Majorana \( \nu' \)s: generic if SM is LE effective theory and explain \( \nu \) lightness

\[ \Lambda_{NP} \sim 10^{15} \text{ GeV} \ \text{Fits OK in GUT} \]

Leptogenesis may explain the baryon asymmetry

• \( \nu' \)s example of interplay Particle Physics-Cosmology to learn about BSM physics
Atmospheric $\nu_{e,\mu}$ are produced by the interaction of cosmic rays (p, He . . . ) with the atmosphere.

$$R_{\mu/e} = \frac{N_{\nu_\mu^+} N_{\nu_\mu^-}}{N_{\nu_e^+} N_{\nu_e^-}} \approx 2$$
**Atmospheric Neutrinos: Results**

- **SKI+II+III+IV data:**

  - **Sub-GeV (e):**
    - $E_{\nu}$ range: $10^{-1}$ to $10$ GeV
    - $dN/d\ln E$ distribution
    - Events vs. $\cos(\text{zenith})$
  
  - **Sub-GeV (µ):**
    - $E_{\nu}$ range: $10^{-1}$ to $10$ GeV
    - $dN/d\ln E$ distribution
    - Events vs. $\cos(\text{zenith})$
  
  - **Mid-GeV (e):**
    - $E_{\nu}$ range: $10^{-1}$ to $10^2$ GeV
    - $dN/d\ln E$ distribution
    - Events vs. $\cos(\text{zenith})$
  
  - **Mid-GeV (µ):**
    - $E_{\nu}$ range: $10^{-1}$ to $10^2$ GeV
    - $dN/d\ln E$ distribution
    - Events vs. $\cos(\text{zenith})$
  
  - **Multi-GeV PC (µ):**
    - $E_{\nu}$ range: $10^2$ to $10^3$ GeV
    - $dN/d\ln E$ distribution
    - Events vs. $\cos(\text{zenith})$
  
  - **Multi-GeV FC (µ):**
    - $E_{\nu}$ range: $10^2$ to $10^3$ GeV
    - $dN/d\ln E$ distribution
    - Events vs. $\cos(\text{zenith})$
  
  - **Stopping (µ):**
    - $E_{\nu}$ range: $10^2$ to $10^3$ GeV
    - $dN/d\ln E$ distribution
    - Events vs. $\cos(\text{zenith})$
  
  - **Through (µ):**
    - $E_{\nu}$ range: $10^2$ to $10^3$ GeV
    - $dN/d\ln E$ distribution
    - Events vs. $\cos(\text{zenith})$

**Legend:**
- $\nu_e$, $\nu_\mu$, $\nu_\tau$, $\pi$, $K$, $\mu$, $e$
- $L \approx 1.2 \times 10^4$ km
- $L \approx 10^2$ km
- $L = 10^3$ km
- $L = 10^4$ km
- [not to scale]
- $dN/d\ln E$ (Kt.yr)
- $E_{\nu}$, GeV
- $E_{\nu}$, GeV
- $dN/d\ln E$, (Kt.yr)$^{-1}$
- $E_{\nu}$, GeV
- $dN/d\ln E$, (Kt.yr)$^{-1}$
- $E_{\nu}$, GeV
- $dN/d\ln E$, (Kt.yr)$^{-1}$
- $E_{\nu}$, GeV
- $dN/d\ln E$, (Kt.yr)$^{-1}$
- $E_{\nu}$, GeV
Atmospheric Neutrinos: Results

- SKI+II+III+IV data:

→ $\nu_\mu$ Deficit grows with $L$

→ $\nu_\mu$ Deficit decreases with $E$
Atmospheric Neutrinos: Results

- SKI+II+III+IV data:

![Graphs showing data distributions for different energy ranges.](image)

Best explained by $\nu_\mu \rightarrow \nu_\tau$

$\Delta m^2 \sim 2.4 \times 10^{-3} \text{ eV}^2$

$\tan^2 \theta \sim 1 \Rightarrow \theta \sim \frac{\pi}{4}$

$\cos(\text{zenith})$
νµ Disappearance in Accelerator ν Fluxes

T2K:
νµ produced in Tokai (Japan)
detected in SK at ~ 250 Km

MINOS, NOνA
νµ produced en Fermilab (Illinois)
detected in Minnesota at ~ 800 Km

Lectures by G. Feldman
Phenomenology with Massive Neutrinos

Concha Gonzalez-Garcia

Long Baseline Experiments: $\nu_\mu$ Disappearance

K2K/T2K 2004–: spectral distortion

MINOS 2006–: spectral distortion

$\nu_\mu$ oscillations with $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV$^2$ and mixing compatible with $\frac{\pi}{4}$
Solar Neutrinos

- Sun shines by nuclear fusion of protons into He

- Two main chains of nuclear reactions
  
  **pp Chain:**

  1. \( p + p \rightarrow D + e^+ + \nu_e \) (99.75%)
  2. \( p + e^- + p \rightarrow D + \nu_e \) (0.25%)
  3. \( ^3\text{He} + ^3\text{He} \rightarrow \alpha + 2p \) (p-p I : 86%)
  4. \( ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \)
  5. \( ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \) (0.00002%)

- **CNO cycle:**

  \( ^7\text{Li} + p \rightarrow 2\alpha \) (p-p II : 14%)

  \( ^8\text{Be} \rightarrow 2\alpha \) (p-p III : 0.015%)

And only \( \nu_e \) are produced
Solar Neutrinos: Fluxes

Phenomenology with Massive Neutrinos
Concha Gonzalez-Garcia

PP CHAIN

\( p + p \rightarrow ^2 H + e^+ + \nu_e \leq 0.42 \)

\( p + e^- + p \rightarrow ^2 H + \nu_e \quad 1.552 \)

\((^7\text{Be}) \)

\( ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \quad 0.862 (90\%) \quad 0.384 (10\%) \)

\((\text{hep}) \)

\( ^2\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \leq 18.77 \)

\((^8\text{B}) \)

\( ^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e \leq 15 \)

CNO CHAIN

\((^{13}\text{N}) \)

\( ^{13}N \rightarrow ^{13}C + e^+ + \nu_e \leq 1.199 \)

\((^{15}\text{O}) \)

\( ^{15}O \rightarrow ^{15}N + e^+ + \nu_e \leq 1.732 \)

\((^{17}\text{F}) \)

\( ^{17}F \rightarrow ^{17}O + e^+ + \nu_e \leq 1.74 \)
**Solar Neutrinos: Results**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Detection</th>
<th>Flavour</th>
<th>$E_{\text{th}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>$^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$</td>
<td>$\nu_e$</td>
<td>$E_\nu &gt; 0.81$</td>
</tr>
<tr>
<td>Sage + Gallex+GNO</td>
<td>$^{71}\text{Ga}(\nu, e^-)^{71}\text{Ge}$</td>
<td>$\nu_e$</td>
<td>$E_\nu &gt; 0.23$</td>
</tr>
<tr>
<td>Kam ⇒ SK</td>
<td>ES $\nu_x e^- \rightarrow \nu_x e^-$</td>
<td>$\nu_e, \nu_{\mu/\tau}$</td>
<td>$E_e &gt; 5$</td>
</tr>
<tr>
<td>SNO</td>
<td>CC $\nu_e d \rightarrow ppe^-$</td>
<td>$\nu_e$</td>
<td>$T_e &gt; 5$</td>
</tr>
<tr>
<td></td>
<td>NC $\nu_x d \rightarrow \nu_x p n$</td>
<td>$\nu_e, \nu_{\mu/\tau}$</td>
<td>$T_\gamma &gt; 5$</td>
</tr>
<tr>
<td>Borexino</td>
<td>ES $\nu_x e^- \rightarrow \nu_x e^-$</td>
<td>$\nu_e, \nu_{\mu/\tau}$</td>
<td>$E_\nu = 0.862$</td>
</tr>
</tbody>
</table>

Experiments measuring $\nu_e$ observe a deficit.

Deficit is energy dependent.

Deficit disappears in NC.
• Real Time experiments can also give information on Energy and Direction of $\nu'$s and can search for Energy and Time variations of the effect

• From SK (also from SNO)

**Energy Dependence**

Deficit indep $E_\nu \gtrsim 5$ MeV

**Day-Night Variation**

Not significant

**Seasonal Variation**

Nothing beyond $1/R^2$
\[ \Delta m^2 \sim 5 \times 10^{-5} \text{ eV}^2 \]
\[ \tan^2 \theta \sim 0.4 \Rightarrow \theta \sim \frac{\pi}{6} \]
Different frequency and flavour than ATM and LBL
**Terrestrial test of LMA: KamLAND**

Lectures by K. Heeger

**KamLAND**: Detector of $\bar{\nu}_e$ produced in nuclear reactors in Japan at an average distance of 180 Km
**Terrestrial test of LMA: KamLAND**

**KamLAND:** Detector of $\bar{\nu}_e$ produced in nuclear reactors in Japan at an average distance of 180 Km

Results of KamLAND compared with $P_{ee}$ for $\theta = 35^\circ$ and $\Delta m^2 = 7.5 \times 10^{-5} \text{ (eV/c}^2)^2$

![Graph showing survival probability vs. $L_0/E_{\bar{\nu}_e}$ (km/MeV)]

- Data - BG - Geo $\bar{\nu}_e$
- Expectation based on osci. parameters determined by KamLAND
• Searches for $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance at $L \sim K m$ ($E/L \sim 10^{-3} \, eV^2$)
• Relative measurement: near and far detectors

Daya-Bay

Reno
Daya-Bay and Reno Reactor Experiments

- Searches for $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance at $L \sim$ Km ($E/L \sim 10^{-3}$ eV²)
- Relative measurement: near and far detectors

Daya-Bay: 4 Near+ 4 Far

Described with $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV²
(as $\nu_\mu$ ATM and LBL acc but for $\nu_e$)
and $\theta \sim 9^\circ$
Long Baseline Experiments: $\nu_e$ Appearance

- Observation of $\nu_\mu \rightarrow \nu_e$ transitions with $E/L \sim 10^{-3}$ eV$^2$

**T2K**

**MINOS**

**NO\nuA** also

Well described with $\nu_\mu \rightarrow \nu_e$ oscillations with $\Delta m^2 \sim 2 \times 10^{-3}$ eV$^2$ and $\theta \sim 11^\circ$
\( \nu \) Oscillations: Lab Searches at Short Distance

**Appearance Experiment**

\[ \nu_\alpha \text{ source} \rightarrow \nu_\beta \text{ detector} \]

Searches for \( \beta \text{ diff} \alpha \)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \langle \frac{E}{\text{MeV}} \rangle )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCFR</td>
<td>100</td>
<td>( \nu_\mu, \nu_e, \nu_\tau )</td>
<td></td>
</tr>
<tr>
<td>E531</td>
<td>25</td>
<td>( \nu_\mu, \nu_e, \nu_\tau )</td>
<td></td>
</tr>
<tr>
<td>Nomad</td>
<td>13</td>
<td>( \nu_\mu, \nu_e, \nu_\tau )</td>
<td></td>
</tr>
<tr>
<td>Chorus</td>
<td>13</td>
<td>( \nu_\mu, \nu_e, \nu_\tau )</td>
<td></td>
</tr>
<tr>
<td>E776</td>
<td>2.5</td>
<td>( \nu_\mu, \nu_e )</td>
<td></td>
</tr>
<tr>
<td>Karmen2</td>
<td>2.5</td>
<td>( \bar{\nu}_\mu, \bar{\nu}_e )</td>
<td></td>
</tr>
<tr>
<td>LSND</td>
<td>3</td>
<td>( \bar{\nu}_\mu, \bar{\nu}_e )</td>
<td></td>
</tr>
<tr>
<td>Miniboone</td>
<td>3</td>
<td>( \nu_\mu, \nu_e )</td>
<td></td>
</tr>
<tr>
<td>ICARUS</td>
<td>1</td>
<td>( \nu_\mu, \nu_e )</td>
<td></td>
</tr>
</tbody>
</table>

**Disappearance Experiment**

\[ \nu_\alpha \text{ source} \rightarrow \nu_\alpha \text{ detector} \rightarrow \nu_\alpha \text{ detector} \]

**Comparing** \( \Phi_{\alpha I} \) and \( \Phi_{\alpha II} \) to look for loss

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \langle \frac{E}{\text{MeV}} \rangle )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDHSW</td>
<td>1.4</td>
<td>( \nu_\mu )</td>
</tr>
<tr>
<td>BugeyIII</td>
<td>0.05</td>
<td>( \bar{\nu}_e )</td>
</tr>
<tr>
<td>Chooz</td>
<td>0.005</td>
<td>( \bar{\nu}_e )</td>
</tr>
</tbody>
</table>
**LSND and MiniBooNE**

- **LSND**: Main signal for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with $E_\nu \sim 0.03$ GeV and $L = 30$ m
- **MiniBooNE**: Search for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with $E_\nu = 0.3 - 2$ GeV and $L = 540$ m

*Compatibility (?)* for $\Delta m^2 \sim \text{eV}^2$

a third osc frequency?