Theory of Neutrino Masses and Mixings

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Lepton Photon 2001
Rome, July 27
What an exciting time!
Public Interest in Neutrinos
What we learned this year

- Atmospheric $\nu_\mu$ is lost ($>10\sigma$), converted mostly likely to $\nu_\tau$ ($>99\%$CL) (SK, MACRO)
- Solar $\nu_e$ is converted to either $\nu_\mu$ or $\nu_\tau$ ($>3\sigma$)
- Explanation is probably neutrino oscillation
  - Other possibilities: Neutrino decay, Violation of equivalence principle, spin resonant rotation, FCNC
  - Possible, but models tend to be ugly
- Tiny neutrino mass: the first evidence for incompleteness of Minimal Standard Model
Typical Theorists’ View 1990

- Solar neutrino solution *must* be small angle MSW solution because it’s cute  Most likely wrong!
- Natural scale for $\Delta m^2_{23} \sim 10^{-100} \text{eV}^2$ because it is cosmologically interesting  Wrong!
- Angle $\theta_{23}$ must be of the order of $V_{cb}$  Wrong!
- Atmospheric neutrino anomaly must go away because it needs a large angle  Wrong!
Outline

- Global Fits
- Models
- Leptogenesis
- Future
Global Fits
**Dark Side of Neutrino Oscillation**

- Traditional parameterization of neutrino oscillation in terms of $(\Delta m^2, \sin^2 2\theta)$ covers only a *half* of the parameter space (Fogli, Lisi, Montanino; de Gouvêa, Friedland, HM)

- Use $(\Delta m^2, \tan^2 \theta)$ instead.
  - Convention: $\nu_2$ heavier than $\nu_1$
  - Vary $\theta$ from 0 to 90°
    - $\sin^2 2\theta$ covers 0 to 45°
    - Light side (0 to 45°) and Dark Side (45° to 90°)
Impact of SNO

Global fit to solar neutrino data to
\[ \nu_e \rightarrow \nu_{\mu,\tau} \cos \eta + \nu_s \sin \eta \]

Oscillation with three parameters
\[ \Delta m^2, \tan^2 \theta, \eta \]

Large angle favored!

(Bahcall, Peña-Garay, Gonzalez-Garcia)

90%, 95%, 99%, 99.73% (3dof)
96%, 98%, 99.7%, 99.92% (2dof)
**MNS matrix**

- Standard parameterization of Maki-Nakagawa-Sakata matrix for 3 generations

\[
U_{\text{MNS}} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]

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

atmospheric    ???    solar
Three-generation

- Solar & atmospheric ν oscillations easily accommodated within three generations
- $\sin^2 2\theta_{23}$ near maximal, $\Delta m^2_{\text{atm}} \sim 3 \times 10^{-3} \text{eV}^2$
- $\sin^2 2\theta_{12}$ large, $\Delta m^2_{\text{solar}} \sim 3 \times 10^{-5} \text{eV}^2$?
- $\sin^2 2\theta_{13} < 0.05$ from CHOOZ, Palo Verde
- Because of small $\sin^2 2\theta_{13}$, solar & atmospheric ν oscillations almost decouple
- Need to know the solar situation,
- $\sin^2 2\theta_{13}$, and mass hierarchy
Sterile Neutrino

- **LSND**, atmospheric and solar neutrino oscillation signals
  \[ \Delta m^2_{\text{LSND}} \sim \text{eV}^2 \]
  \[ \Delta m^2_{\text{atm}} \sim 3 \times 10^{-3} \text{eV}^2 \]
  \[ \Delta m^2_{\text{solar}} < 10^{-3} \text{eV}^2 \]
  \( \Rightarrow \) Can’t be accommodated with 3 neutrinos
  \( \Rightarrow \) Need a sterile neutrino

- 3+1 or 2+2 spectrum?
Sterile Neutrino

- 3+1 spectrum: $\sin^2 2\theta_{\text{LSND}} = 4|U_{4e}|^2|U_{4\mu}|^2$
  - $|U_{4\mu}|^2$ can’t be big because of CDHS, SK U/D
  - $|U_{4e}|^2$ can’t be big because of Bugey
  - Marginally allowed (90% excl. vs 99% allw’d)

- 2+2 spectrum: past fits preferred
  - Atmospheric mostly $\nu_\mu \leftrightarrow \nu_\tau$
  - Solar mostly $\nu_e \leftrightarrow \nu_s$ (or vice versa)
  - Now solar sterile getting tight?
  
  (Barger et al, Giunti et al, Gonzalez-Garcia et al)
But Not Excluded Yet!

- Global fit to four-neutrino oscillation
  - Solar, Atmospheric, LSND
    (Gonzalez-Garcia, Maltoni, Pena-Garay@EPS01)
- One can still find a reasonable fit with 2+2
  ⇒ Wait for Mini-BooNE
Models
**Seesaw Mechanism**

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but $\nu_R$ SM neutral

\[
\begin{pmatrix}
\nu_L \\
\nu_R
\end{pmatrix}
\begin{pmatrix}
m_D & m_D \\
m_D & M
\end{pmatrix}
\begin{pmatrix}
\nu_L \\
\nu_R
\end{pmatrix}
\quad \Rightarrow \\
\frac{m_v^2}{M} << m_D
\]

To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim m_t$, $M \sim 10^{15}$GeV (GUT!)
SO(10)

- SO(10) GUT probably most natural because the family belongs to 16-plet of SO(10) with $\nu_R$ automatically there
  - Esthetic appeal
    - Smallest anomaly-free GUT with chiral fermions.
    - Largest GUT without additional fermions.
- But too predictive: $m_c = m_s = m_\mu$ etc, small mixings
State of Art Models

- Albright-Babu-Barr (LMA)
- Altarelli-Feruglio (LOW)
- Many others (*apology!*)
  - Lam, Alexandre, Sato, McKellar
- Essence: break naïve relations from SU(5) or SO(10) in a clever way
- Interesting possible connection to proton decay (Babu-Pati-Wilczek)
Question of Flavor

- What distinguishes different generations?
  - Same gauge quantum numbers, but different
- Probably a hidden flavor quantum number
  - If LMA, all mixing except $U_{e3}$ large
    - Two mass splittings not very different
    - Any new symmetry or structure behind it?

\[
\begin{pmatrix}
\text{big} & \text{big} & \text{small} \\
\text{big} & \text{big} & \text{big} \\
\text{big} & \text{big} & \text{big}
\end{pmatrix}
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
\]

\[
\frac{\Delta m_{solar}^2}{\Delta m_{atm}^2} \sim 0.01 - 0.2
\]
Is There A Structure In Neutrino Masses & Mixings?

- Monte Carlo random complex $3 \times 3$ matrix with seesaw mechanism

(Hall, HM, Weiner; Haba, HM)
**Anarchy**

- No particular structure in neutrino mass matrix
  - All three angles large
  - CP violation O(1)
  - Ratio of two mass splittings just right for LMA
- Three out of four distributions OK
  - Reasonable?

$\Rightarrow$ Underlying symmetries don’t distinguish 3 neutrinos.
Quarks, charged leptons?

- Clearly, hierarchy with small mixings: not anarchical ⇒ Need some ordered structure
- Flavor symmetry broken by a VEV $\langle \epsilon \rangle \sim 0.02$
- SU(5)-like:
  - $10(Q, u_R, e_R) (+2, +1, 0)$
  - $5*(L, d_R) (+1, +1, +1)$
  - $m_u : m_c : m_t ~ m_d : m_s : m_b \sim m_e : m_\mu : m_\tau \sim \epsilon^2 : \epsilon : 1$
  - Neutrinos anarchy
Anarchy is Peaceful

- Anarchy (Miriam-Webster): “A utopian society of individuals who enjoy complete freedom without government”
- Peaceful ideology that neutrinos work together based on their good will
- Predicts large mixings, LMA
- $\sin^22\theta_{13}$ just below the bound
- Wants globalization!
To Figure It Out...

- Models differ in flavor quantum number assignments
- Need data on $\sin^22\theta_{13}$, solar neutrinos, CP violation, B-physics, LFV, EWSB, proton decay
- Archaeology or Anthropology
- We will learn insight on origin of flavor by studying as many *fossils* as possible
  - *cf.* CMBR in cosmology
More Fossils:
Lepton Flavor Violation

- Neutrino oscillation
  \[ \Rightarrow \text{lepton family number is not conserved!} \]
  - Any tests using charged leptons?
  - Use \[ \Delta m^2_{\text{atm}} \approx 3 \times 10^{-3} \text{eV}^2 \] to estimate
    \[ \Rightarrow B(\tau \rightarrow \mu \gamma) \approx 10^{-41} \]
  - However, many supersymmetric models predict
    \[ B(\tau \rightarrow \mu \gamma), B(\mu \rightarrow e \gamma), \mu \rightarrow e \text{ at interesting levels} \]
  - Even overall lepton number violation
    \[ \text{(Bueno, Campanelli, Rico, Rubbia, Laveder)} \]
Leptogenesis
Original Baryogenesis

- Big Bang: $B=0$. Now: $B\neq 0$ (even in Tevatron ring). Why do we exist?
- GUT breaks $B$. Suppose a GUT-scale particle $X$ decays out-of-equilibrium with direct CP violation $B(X \rightarrow q) \neq B(\bar{X} \rightarrow \bar{q})$
- Now direct CP violation observed: $\varepsilon'$
  $B(K^0 \rightarrow \pi^+ \pi^-) \neq B(\bar{K}^0 \rightarrow \pi^+ \pi^-)$
- But no $B-L$ violation
Anomaly washout

• Actually, SM violates $B$ (but not $B-L$).
  – In Early Universe ($T > 100\text{GeV}$), $W/Z$ are massless and fluctuate in $W/Z$ plasma
  – Energy levels for left-handed quarks/leptons fluctuate correspondingly

\[ \Delta L = \Delta Q = \Delta Q = \Delta Q = \Delta B = 1 \Rightarrow B = L = 0 \]
Electroweak Baryogenesis

• 1st order phase transition produces bubbles of broken phase
  • Scattering of top, stop off the bubble wall picks up CP violation $\neq t_L \neq t_R$
  • $t_L$ converted to leptons via EW anomaly
  • Creates net $B \neq 0$

(Cohen, Kaplan, Nelson)
(Carera, Quiros, Wagner)
Leptogenesis

- You generate *Lepton Asymmetry* first.
- $L$ gets converted to $B$ via EW anomaly
  - *Fukugita-Yanagida*: generate $L$ from the direct CP violation in right-handed neutrino decay

\[
\Gamma(N_1 \rightarrow \nu_i H) - \Gamma(N_1 \rightarrow \bar{\nu}_i H) \propto \text{Im}(h_{1j}^* h_{1k}^* h_{lk} h_{lj})
\]
Does Leptogenesis Work?

- Much more details worked out
  (Buchmüller, Plümacher; Pilaftsis)
- \(\sim 10^{10} \text{ GeV} \nu_R \text{ OK}\)
- Some tension with supersymmetry because of unwanted gravitino overproduction
- Ways around: coherent oscillation of right-handed sneutrino (HM, Yanagida+Hamaguchi)
Can we prove it experimentally?

- We studied this question at Snowmass2001 (Ellis, Gavela, Kayser, HM, Chang)
  - Unfortunately, no: it is difficult to reconstruct relevant CP-violating phases from neutrino data
- But: we will probably **believe** it if
  - \(0\nu\beta\beta\) found
  - CP violation found in neutrino oscillation
  - EW baryogenesis ruled out

Archeological evidences
Future
Healthy Field

- Experimentalists and Theorists collaborate to plan for the future
  - Studies on neutrino factory, superbeams from all three regions of the world
  - Some experiments (e.g., KamLAND) even make theorists install phototubes
  - New model of collaboration: *If experiment fails, you blame theorists!*
Mini-BooNE

- Settles the issue of LSND evidence
- Major branch point: do we need a sterile neutrino?
MINOS (NuMI)  
OPERA/ICARUS (CNGS)

- MINOS: precision measurements of $(\Delta m_{23}^2, \sin^2 2\theta_{23})$
- OPERA/ICARUS @ CNGS: tau appearance in $\nu_\mu \rightarrow \nu_\tau$
- Extend reach in $\sin^2 2\theta_{13}$
- MONOLITH aims at verifying oscillation curves with atmospheric neutrinos

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KamLAND sensitivity on LMA

- Reactor neutrino experiment
- First terrestrial expt relevant to solar neutrino problem
- KamLAND will exclude or verify LMA definitively
Measurements at KamLAND

- Can see the dip when $\Delta m^2 > 2 \times 10^{-5} \text{eV}^2$
  
  (Bagger, Marfatia, Wood)

  (Pierce, HM)

  (de Gouvêa, Peña-Garay)

- Can measure oscillation parameters

Data/theory
If LMA confirmed...

- Dream case for neutrino oscillation physics!
- $\Delta m^2_{\text{solar}}$ within reach of long-baseline expts
- Even CP violation may be probable
  - neutrino superbeam
  - muon-storage ring neutrino factory
  $\Rightarrow$ Talk by Steve Geer
- If LMA excluded by KamLAND, study of lower energy solar neutrinos crucial
**CP Violation**

\[
P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = 16s_{12}c_{12}s_{13}c_{13}s_{23}c_{23}
\]

\[
\sin \delta \sin \left( \frac{\Delta m_{12}^2}{4E} L \right) \sin \left( \frac{\Delta m_{13}^2}{4E} L \right) \sin \left( \frac{\Delta m_{23}^2}{4E} L \right)
\]

- Possible only if:
  - \(\Delta m_{12}^2, s_{12}\) large enough (LMA)
  - \(\theta_{13}\) large enough
**superbeam**

- **Existing proposals of neutrino superbeam**
  
  *(Debbie Harris@Snowmass2001)*

<table>
<thead>
<tr>
<th>Name</th>
<th>Start Year</th>
<th>Proton Power</th>
<th>Proton Energy</th>
<th>Neutrino Energy</th>
<th>Baseline (km)</th>
<th>Years of Running</th>
<th>kton</th>
<th>(\sin^2 \theta_{13} ) (3(\sigma))</th>
<th>CP phase (\delta) (3(\sigma))</th>
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</thead>
<tbody>
<tr>
<td>JHF to SuperK</td>
<td>2008?</td>
<td>0.77 MW</td>
<td>50GeV</td>
<td>0.7GeV</td>
<td>350km</td>
<td>5 yrs v</td>
<td>50</td>
<td>0.016</td>
<td>none</td>
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<tr>
<td>JHF to HyperK</td>
<td>2013?</td>
<td>4MW</td>
<td>50GeV</td>
<td>0.7GeV</td>
<td>350km</td>
<td>2 yrs v 6 yrs (\nu)</td>
<td>1000</td>
<td>0.0025</td>
<td>(\approx 15^\circ)</td>
</tr>
<tr>
<td>CERN to UNO</td>
<td>(\geq 2011)</td>
<td>4MW</td>
<td>2.2GeV</td>
<td>250MeV</td>
<td>130km</td>
<td>2 yrs v 10 yrs (\nu)</td>
<td>400</td>
<td>0.0025</td>
<td>(\approx 40^\circ)</td>
</tr>
</tbody>
</table>
High-energy superbeam

- Higher $E$, longer $L \Rightarrow$ Can study matter effect to determine the mass hierarchy
  
  (Barger, Marfatia, Whisnant@Snowmass2001)

<table>
<thead>
<tr>
<th>Baseline (km)</th>
<th>Neutrino Energy (GeV)</th>
<th>$\sin^2 \theta_{13}$ Reach ($3\sigma$)</th>
<th>Sign ($\Delta m_{23}^2$)</th>
<th>CP phase $\delta$ ($3\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\nu$</td>
<td>$\nu$--bar</td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>1</td>
<td>.0013</td>
<td>.0016</td>
<td>–</td>
</tr>
<tr>
<td>730</td>
<td>2.1</td>
<td>.0017</td>
<td>.0026</td>
<td>–</td>
</tr>
<tr>
<td>1290</td>
<td>3.7</td>
<td>.0020</td>
<td>.0052</td>
<td>.04</td>
</tr>
<tr>
<td>1770</td>
<td>5</td>
<td>.0022</td>
<td>.0092</td>
<td>.02</td>
</tr>
<tr>
<td>2900</td>
<td>8.2</td>
<td>.0025</td>
<td>.037</td>
<td>.01</td>
</tr>
</tbody>
</table>
Solar Neutrino Spectrum

Bahcall-Pinsonneault

Neutrino Flux

Neutrino Energy (MeV)

Gallium | Chlorine | SuperK, SNO

$^7\text{Be}$ | $^7\text{Be}$ | pep

$^8\text{B}$ | hep

$^{13}$C $\rightarrow^{13}$N

$^{14}$N $\rightarrow^{14}$O

LT $\rightarrow$ MS

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VAC by seasonal variation

- $^7$Be neutrino monochromatic
- seasonal effect probes VAC region
  (de Gouvêa, Friedland, HM)
- Borexino crucial
**VAC by seasonal variation**

- Fit to seasonal variation to measure parameters

Can pep $\nu$ resolve degeneracy?
LOW by day/night effect

- $^7$Be neutrino monochromatic
- Day/night effect probes LOW region
- (de Gouvêa, Friedland, HM)
- Borexino crucial
LOW by zenith angle dependence

- More information in zenith angle depend.
  (de Gouvêa, Friedland, HM)
**SMA by pp neutrinos**

- SMA: Sharp falloff in probability in the pp neutrino region the survival
- Because of the condition for the level crossing
  \[
  \frac{\Delta m^2}{2E} < \sqrt{2G_F n_e(0)}
  \]
- Measure the falloff ⇒ $\Delta m^2$ measurement
Can pp neutrinos be studied?

- CC+NC (electron recoil)
  - gaseous He TPC
  - HERON: superfluid He (phonon & roton)
  - liquid Xe
  - GENIUS: Ge
- CC ($\nu_e$ capture)
  - LENS: Yb or In
  - MOON: Mo
- Would any of them work?
Conclusions

- Neutrino Physics going through a revolution
- Leptogenesis gaining momentum
- Neutrinos provide new insights into origin of flavor
- Lot more to learn from solar neutrinos
- Superbeams and neutrino factory
- \textit{Fossils}: $\sin^2 2\theta_{13}$, solar neutrinos, CP violation, B-physics, LFV, proton decay
**Extra Dimensions**

- Right-handed neutrinos SM gauge singlet
- Can propagate in the “bulk”
- Makes neutrino mass small  
  (Arkani-Hamed, Dimopoulos, Dvali, March-Russell; Dienes, Dudas, Gherghetta; Dvali, Smirnov)
- $m_\nu \sim 1/R$ if one extra D
- Equivalent to an infinite tower of sterile neutrinos
- Need also flavor mixing now