Recent developments in Neutrino Physics

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Samara
**Plan**

**Oscillation sector**
- Standard 3-neutrino oscillation
- Anomalies in neutrino data

**Flavor sector**
- Problem of neutrino masses and mixings: the role of family symmetries

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New data from neutrino oscillation experiments have given precise results on mixing parameters.

Possible leptonic CP violation ($\leq 5\text{ y}$) (T2K, NoVA...)

However:

not a unique extension of the Standard Model that allows to explain:

- origin of masses and mixing angles
- differences with respect to the quark sector

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Neutrinos can be described in terms of mass or weak eigenstates.

\[ |\nu_\alpha \rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i \rangle \]

Simple time evolutions of the vector \( \nu(t) = (\nu_e(t), \nu_\mu(t), \nu_\tau(t)) \):

\[ i \frac{d}{dt} |\nu(t) \rangle = H |\nu(t) \rangle \]

\[ H = \frac{1}{2E_\nu} U \text{Diag} [0, m_2^2 - m_1^2, m_3^2 - m_1^2] U^+ \]

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Flavour changing transitions

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | \nu_\alpha(t) \rangle \right|^2 = \left| \sum_j U_{\beta j} e^{-i m_j^2 L / 2E_\nu} U_{\alpha j}^* \right|^2 \]

\( \alpha = \beta \rightarrow \text{disappearance} \)
\( \alpha \neq \beta \rightarrow \text{appearance} \)

In the case of two neutrinos only:

\[ P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right) \]

\( U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \]

U = unitary matrix

Distance source-detector

Mixing angle
The neutrino mixing matrix depends on 4 real parameters

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

A more complicated mismatch between the $\nu$ bases

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Experiments measure...

**Mixing angles**

\[ \begin{align*}
\theta_{13} \\
\theta_{12} \\
\theta_{23}
\end{align*} \]

**Mass differences**

\[ \begin{align*}
\Delta m^2_{23} \\
\Delta m^2_{12}
\end{align*} \]

- unknowns: leptonic CP violation and the ordering of the mass eigenstates
Global fit

| Parameter                  | Result     |
|----------------------------|------------|
| \( \theta_{12} \)         | 33.36\( ^{+0.81}_{-0.78} \) |
| \( \theta_{13} \)         | 8.66\( ^{+0.44}_{-0.46} \) |
| \( \theta_{23} \)         | 40.0\( ^{+2.1}_{-1.5} \) |
| \( \delta \)              | 300\( ^{+66}_{-138} \) |
| \( \Delta m^2_{23} \) (10\( ^{-3} \) eV\(^2\)) | 2.47\( ^{+0.07}_{-0.07} \) |
| \( \Delta m^2_{12} \) (10\( ^{-5} \) eV\(^2\)) | 7.50\( ^{+0.18}_{-0.19} \) |

- Masses @3%
- Angles between 5% and 10%
### Global fit

| Parameter | Result       |
|-----------|--------------|
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| $\theta_{23}$ | 40.0$^{+2.1}_{-1.5}$ |
| $\delta$ | 300$^{+66}_{-138}$ |
| $\Delta m^2_{23} (10^{-3} \text{eV}^2)$ | 2.47$^{+0.07}_{-0.07}$ |
| $\Delta m^2_{12} (10^{-5} \text{eV}^2)$ | 7.50$^{+0.18}_{-0.19}$ |

\[
|U| = \begin{pmatrix}
0.795 & 0.846 & 0.513 & 0.585 & 0.126 & 0.178 \\
0.205 & 0.543 & 0.416 & 0.730 & 0.579 & 0.808 \\
0.215 & 0.548 & 0.409 & 0.725 & 0.567 & 0.800
\end{pmatrix}
\]
Neutrino oscillation anomalies

- **LSND**
  
evidence for oscillations $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with $L/E \sim 1 \text{ km}/\text{GeV} (\nu_e \text{ appearance})$

- **Anomalies in Gallium experiments** *(SAGE & GALLEX)*
  
  they measured an electron neutrino flux from the Sun smaller than expected ($\nu_e \text{ disappearance}$)

- **Anomalies due to new computations of reactor neutrino fluxes**
  
  fluxes from reactor neutrinos are $\sim 3.5\%$ larger than in the past $\rightarrow$

  experiments with $L \leq 100 \text{ m}$ show deficit of neutrinos ($\nu_e \text{ disappearance}$ - Bugey, Rovno...)

In addition there are **null results**: $\nu_\mu \text{ disappearance} (\text{CDHS,SK, MINOS}) \; \nu_e \text{ appearance} (\text{KARMEN, NOMAD, ICARUS, OPERA})$ which gave **no signal**
Neutrino oscillation anomalies

Joachim Kopp
August 21, Aspen

- **LSND**
  - evidence for oscillations
    \[ \overline{\nu}_e \rightarrow \overline{\nu}_\mu \ \text{con} \ L/E \sim 1 \ km/GeV \]
- **MiniBooNE**
  - no significative excess of $\nu_e$ or $\overline{\nu}_e$ in the LSND preferred region but antinu results consistent with LSND

\[ \Delta m^2_{12} \]
\[ \Delta m^2_{23} \]
\[ \Delta m^2_{34} \]
\[ \Delta m^2_{45} \]

explanation in terms of sterile neutrinos

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3+1 scheme

These states are considered as "degenerate"

\[ P_{\nu_\alpha \rightarrow \nu_\beta}^{(-)} = \delta_{\alpha\beta} - 4|U_{\alpha 4}|^2 \left( \delta_{\alpha\beta} - |U_{\beta 4}|^2 \right) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

\[ \sin^2 2\theta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2 \text{ of } \nu_\mu \rightarrow \nu_e \text{ transitions.} \]

\[ \sin^2 2\theta_{ee} = 4|U_{e4}|^2 \left( 1 - |U_{e4}|^2 \right) \text{ of } \nu_e \text{ disappearance} \]

\[ \sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2 \left( 1 - |U_{\mu 4}|^2 \right) \text{ of } \nu_\mu \text{ disappearance} \]

\[ \Delta m_{34}^2 \]

\[ \Delta m_{23}^2 \]

\[ \Delta m_{12}^2 \]

\[ m_4 \text{ is at a much higher scale, around } 1 \text{ eV}^2: \]

effective description in terms of two-flavor

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Global fit of **nue appearance** data are consistent

\[
\sin^2 2\theta_{\mu e} = 0.013 \\
\Delta m^2_{41} = 0.42 \text{ eV}^2 \\
\chi^2_{\text{min}}/\text{dof} = 87.9/66
\]
\( \nu_e \) disappearance

- Global fit on \( \nu_e \) disappearance data are consistent among themselves

\[
\sin^2 2\theta_{ee} = 0.09 \\
\Delta m^2_{41} = 1.78 \text{ eV}^2 \\
\chi^2_{\text{min}} / \text{dof} = 403 / 427
\]
Global fit on **numu disappearance** data:

Kopp, Machado, Maltoni, Schwetz 2013

---

no signal $\rightarrow$ strong constraints on masses and mixing

---
Global picture

Tension between appearance and disappearance

Tension between exp's with and without signal

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The (hard) job of a theorist

Take hints from experiments seriously
And explain:

- Some ideas...
- Smallness of masses
- Values of the mixing angles
Easy part: neutrino Yukawa couplings smaller than those of the other fermions

Neutrinos are Dirac fermions: we have to introduce a right-handed neutrino field

\[ \nu \bar{\psi}_L \tilde{H} \nu_R \]

\[ \text{electrons: } Y_e \bar{\psi}_L H e^c \]

\[ \frac{Y}{Y_e} \sim 10^{-5} \]

But we want to go beyond this “unnatural” scheme...

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Neutrino mass terms

we assume the existence of $\nu_L$ and
the SM singlet $\nu_R$

must be conserved: $|\Delta I| = 0$

| Weak isospin | $\nu_L$ | $\nu_R$ | $H = (h^+, h^0)$ |
|--------------|---------|---------|-----------------|
| $I$          | $1/2$   | $0$     | $1/2$           |
| $I_3$        | $1/2$   | $0$     | (+1/2, -1/2)    |

$\nu$ | $\bar{\nu}$

Lepton number

$1$ | $-1$

• **Dirac mass term**
(same for quarks and leptons)

lepton number $L$ is conserved

$$L_D = m_D \bar{\psi}_L \tilde{H} \nu_R$$

• **Majorana mass term**

lepton number $L$ is not conserved

$$L_M = m_M \nu_R^T \nu_R$$

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The see-saw mechanism

- Total lagrangian

\[ L_m = m_D \bar{\psi}_L \tilde{H} \nu_R + m_M \nu_R^T \nu_R \]

Electroweak symmetry breaking → see-saw

\[ \langle H \rangle = \begin{pmatrix} 0 \\ \nu \end{pmatrix} \quad \rightarrow \quad m_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix} \]

\[ m_\nu = -m_D^T \frac{1}{m_M} m_D \]

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An indicative numerical example

\[ m_v \sim \frac{m_D^2}{m_M} \]

for \( m_D \sim 100 \text{ GeV} \), \( m_v \sim 0.05 \text{ eV} \)

\[ m_M \sim 10^{14} - 10^{15} \text{ GeV} \]

Probe into GUT!

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Two different approaches and equally (not?) promising

- **Models with non-trivial dynamics**: means that the structure of the mixing matrix is determined by discrete symmetries. Such symmetries are motivated by the fact that the data themselves suggest rotations with fixed special angles ($\frac{1}{2}, 1/3...$), permutational groups like $A_4, S_4 ...$

- **Models where the main idea is that there is no need of introducing additional symmetries to explain the mixing angles**

In such models, the *chance* plays the fundamental role (anarchical models and variants)

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Special mixing matrices

- Mixing angles are obtained from the diagonalization of the mass matrix

\[ m^{\text{Diag}}_\nu = U^T m_\nu U \]

- Good starting point suggested by the data:

\[ \sin^2 \theta_{23} = \frac{1}{2}, \quad \sin^2 \theta_{13} = 0 \]

\[
\begin{align*}
\text{TBM} & : \quad \sin^2 \theta_{12} = \frac{1}{3} \\
\text{BM} & : \quad \sin^2 \theta_{12} = \frac{1}{2} \\
\text{GR} & : \quad \sin^2 \theta_{12} = \frac{2}{5 + \sqrt{5}}
\end{align*}
\]

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• How good are such starting points?

\[ \sin^2 \theta_{12} \]

\[ \lambda_c = \text{Cabibbo angle} \]

\[ \sin \theta_{13} \]

Corrections are needed to stay on the experimental data

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Special mixing matrices

- in models with no baroque dynamics, all mixing angles receive corrections of the same order of magnitude

\[
\begin{align*}
\text{TBM} & \quad \sin^2 \theta_{12} = \frac{1}{3} + O(\lambda_C^2) \quad \sin^2 \theta_{23} = \frac{1}{2} + O(\lambda_C^2) \quad \sin \theta_{13} = O(\lambda_C^2) \\
\text{BM} & \quad \sin^2 \theta_{12} = \frac{1}{2} + O(\lambda_C) \quad \sin^2 \theta_{23} = \frac{1}{2} + O(\lambda_C) \quad \sin \theta_{13} = O(\lambda_C)
\end{align*}
\]

This pattern seems to be favored

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Possible origin of corrections

- $U_{\text{PMNS}}$ receives contributions from the charged lepton diagonalization

\[
\nu_\alpha = U_{\alpha i}^\nu \nu_i \quad l_\alpha = U_{\alpha i}^l l_i
\]

diagonalizes the neutrino mass matrix
diagonalizes the charged lepton mass matrix

\[
\bar{l}_\alpha \gamma_\mu \nu_\alpha W^\mu \rightarrow \left( U_{\alpha i}^l \right)^* U_{\alpha j}^\nu \bar{l}_i \gamma_\mu \nu_j W^\mu
\]
The previous patterns are easily obtained using *flavor symmetries*

- **gauge** symmetries act on members of particle multiplets
- **flavor** symmetries act on different families

Vantages: strong correlation among the entries of the mass matrices, so less free parameters → predictability

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The models work as follows:

- Theory invariant under $G_F$

- Residual symmetry given by a subset of the generators of $G_F$

  - in the neutrino sector $G_v \rightarrow U_v$
  - in the charged lepton sector $G_l \rightarrow U_l$

- Symmetry breaking of the flavor group: new scalar fields $\Phi$ in the theory with non vanishing vevs

\[
U_{\text{PMNS}} = U_l^+ U_v
\]

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Altarelli-Feruglio 2012
A possible flavor group: $A_4$

$A_4$ is the group of even permutation of 4 objects (also the symmetry of a tetrahedron)

The 12 elements are obtained considering all possible even permutations of 1234. They belong to 4 conjugacy classes...

$A_4$, given $a$ of $G$ $g^{-1} a g$, $\forall g \in G$

$A_4$ has 4 irreducible representations

- three singlets $1, 1'$ and $1''$
- 1 triplet 3

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A possible flavor group: $A_4$

After breaking of $A_4$

- charged lepton mass matrix (residual symmetry generated by $T$)

$$m_e^{(0)} = v_d \begin{pmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{pmatrix} \eta$$

$$U_l = I$$

- neutrino mass matrix (generated by a non-diagonal generator $S$ of $A_4$)

$$m_\nu^{(0)} = \begin{pmatrix} x & y & y \\ y & x+z & y-z \\ y & y-z & x+z \end{pmatrix}$$

$$U_\nu = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

$$\sin^2 \theta_{23} = \frac{1}{2} \quad \sin^2 \theta_{12} = \frac{1}{3} \quad \sin^2 \theta_{13} = 0$$

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A possible flavor group: $A_4$

After breaking of $T$ and $S$

- Charged lepton rotation

- Neutrino rotation

\[
\sin^2 \theta_{23} = \frac{1}{2} + \mathcal{R}(c_{23}^e) \xi + \frac{1}{\sqrt{3}} \left( \mathcal{R}(c_{13}^\nu) - \sqrt{2} \mathcal{R}(c_{23}^\nu) \right) \xi
\]

\[
\sin^2 \theta_{12} = \frac{1}{3} - \frac{2}{3} \mathcal{R}(c_{12}^e + c_{13}^e) \xi + \frac{2\sqrt{2}}{3} \mathcal{R}(c_{12}^\nu) \xi
\]

\[
\sin \theta_{13} = \frac{1}{6} \left| 3\sqrt{2} (c_{12}^e - c_{13}^e) + 2\sqrt{3} \left( \sqrt{2} c_{13}^\nu + c_{23}^\nu \right) \right| \xi.
\]

\[
\left\langle \Phi \right\rangle \sim O(0.1)
\]

Altarelli, Feruglio, Merlo, Stamou '12

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Typical predictions of A4 models

\[ c_{ij} = \text{random complex with abs. value gaussian around 1 with variance 0.5} \]
The chance is the basis of the success

Only abelian U(1) to generate the hierarchies among fermions

- fields transform as: \( \psi \rightarrow e^{iq} \psi \)
- so a mass term transforms as:

\[
y \bar{\psi}_L H \psi_R \rightarrow e^{i(-q_{\psi_R} + q_{\psi_L} + q_H)} y \bar{\psi}_L H \psi_R
\]

If \( (-q_{\psi_R} + q_{\psi_L} + q_H) = 0 \) the mass term is allowed, otherwise we need a new scalar field \( \theta \) with charge \( q \) and vev \( v_{\theta} \):

\[
y \bar{\psi}_L H \psi_R \left( \frac{\theta}{\Lambda} \right)^k \rightarrow e^{i(-q_{\psi_R} + q_{\psi_L} + q_H + k q_{\theta})} y \left( \frac{v_{\theta}}{\Lambda} \right)^k \bar{\psi}_L H \psi_R
\]

Models with no special dynamics

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Suppression factor
**A GUT example**

- Standard Model particles in the $10$ and $\bar{5}$ representations (3 copies)

\[
\begin{align*}
\bar{5} &= \begin{pmatrix}
    d^c_1 \\
    d^c_2 \\
    d^c_3 \\
    e \\
    -\nu
\end{pmatrix}_L, \\
10 &= \frac{1}{\sqrt{2}} \begin{pmatrix}
    0 & u^c_5 & -u^c_5 & u_1 & d_1 \\
    -u^c_5 & 0 & u^c_1 & u_2 & d_2 \\
    u^c_2 & -u^c_1 & 0 & u_3 & d_3 \\
    -u_1 & -u_2 & -u_3 & 0 & e^c \\
    -d_1 & -d_2 & -d_3 & -e^c & 0
\end{pmatrix}_L
\end{align*}
\]

- $1 = \text{right-handed neutrino}$

- **SU(5) mass terms:**

\[
\begin{align*}
m_{\text{up}} &\sim 10 \times 10 \\
m_d &= m_e^T \sim 10 \times \bar{5} \\
m_{\nu_D} &\sim \bar{5} \times 1 \\
m_M &\sim 1 \times 1
\end{align*}
\]

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Choosing appropriate U(1) charges we can get several mass matrices structures:

- **Anarchycal models (A)**
  
  \[ q_5 = (0,0,0) \]
  \[ q_{10} = (3,2,0) \]
  \[ q_1 = (0,0,0) \]
  
  \[
  m_l = \begin{pmatrix}
  \lambda^3 & \lambda^3 & \lambda^3 \\
  \lambda^2 & \lambda^2 & \lambda^2 \\
  1 & 1 & 1
  \end{pmatrix},
  m_\nu = \begin{pmatrix}
  1 & 1 & 1 \\
  1 & 1 & 1 \\
  1 & 1 & 1
  \end{pmatrix}
  \]

- **Hierachycal model (H)**
  
  \[ q_5 = (2,1,0) \]
  \[ q_{10} = (5,3,0) \]
  \[ q_1 = (2,1,0) \]
  
  \[
  m_l = \begin{pmatrix}
  \lambda^7 & \lambda^6 & \lambda^5 \\
  \lambda^5 & \lambda^4 & \lambda^3 \\
  \lambda^2 & \lambda & 1
  \end{pmatrix},
  m_\nu = \begin{pmatrix}
  \lambda^4 & \lambda^3 & \lambda^2 \\
  \lambda^3 & \lambda^2 & \lambda \\
  \lambda^2 & \lambda & 1
  \end{pmatrix}
  \]

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Models with no special dynamics

no see-saw

see-saw

message: \( H \) performs better than \( A \)

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The future (personal view)

Oscillation sector

- Better determination of the oscillation parameters and the mass pattern
- Check for new physics effects

Flavor sector

- Interplay of flavor symmetries and realistic GUT theories
- Differences among quarks and leptons

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backup

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**Global fit**

$e \rightarrow e \ (\delta m^2, \theta_{12})$

$\mu \rightarrow \mu \ (\Delta m^2, \theta_{23})$

$e \rightarrow e \ (\Delta m^2, \theta_{13})$

$e \rightarrow e \ (\delta m^2, \theta_{12})$

$\mu \rightarrow \mu \ (\Delta m^2, \theta_{23})$

$\mu \rightarrow e \ (\Delta m^2, \theta_{13}, \theta_{23})$

$\mu \rightarrow \tau \ (\Delta m^2, \theta_{23})$

Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], MACRO, MINOS etc.; (d) T2K [plot], MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS; (g) OPERA [plot], Super-K atmospheric.

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New results from Planck

For $T < m_e$, radiation content of the Universe is

$$\varepsilon_R = \varepsilon_\gamma + \varepsilon_\nu + \varepsilon_x$$

non-electromagnetic contribution is parametrized in terms of effective neutrino species $N_{\text{eff}}$

$$\varepsilon_\nu + \varepsilon_x = \frac{7}{8} \frac{\pi^2}{15} T_\nu^4 N_{\text{eff}} = \frac{7}{8} \frac{\pi^2}{15} T_\nu^4 (N_{\text{eff}}^{\text{SM}} + \Delta N)$$

3.046
(relativistic degrees of freedom)

Planck 2015:

$$N_{\text{eff}} = 3.15 \pm 0.46$$

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Ninetta Saviano,
talk a Moriond2015

Extra radiation, for example from sterile neutrinos

Not a large room for sterile states!
A peculiarity of the neutrino

- For electrons: 4 different helicity states and all of them are needed

- For neutrinos: from experiments we have identified $\nu_L$ and $\bar{\nu}_R$ only

if $\nu_L \sim \bar{\nu}_R$ no additive quantum numbers are conserved

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A$_4$ is the discrete group of even permutations of 4 objects 
($4!/2 = 12$ elements) generated by $S$ and $T$

\[ S^2 = T^3 = (ST)^3 = 1 \]

The action of the generators $S$ and $T$ can be assigned as follows:
$S$: $(1234) \rightarrow (4321) \quad T$: $(1234) \rightarrow (2314)$

irreducible representations:
a triplet and 3 different singlets $3, 1, 1', 1''$ (promising for 3 generations)

invariance under $S$ and $T$ is automatic while $A_{23}$ is not contained in $A_4$

(2-3 symmetry happens in $A_4$ if $1'$ and $1''$ symm. breaking flavons are absent or have equal VEV's)

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A comment on the CP violating phase

- Long Baseline experiments (T2K) indicates $\delta \sim 3/2 \pi$

- Reactor experiments model the CL form for $\sin^2\theta_{13} \sim 0.02$
Appearance–disappearance tension

\[
\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}
\]