Recent highlights from neutrino theory

Pedro A. N. Machado
Fermilab soon to be at LANL as junior staff member
Neutrinos as a portal to new Physics

The existence of non-zero neutrino masses, inferred from neutrino oscillation measurements, is the only laboratory-based evidence of physics beyond the standard model.

Relatively poorly known sector of the standard model

Neutrino mass mechanism is unknown

Neutrino physics relates to many energy scales
Neutrinos as a portal to new Physics

- Ultra-light
- Warm
- WIMP
- Dark matter?
- Natural seesaw
- Flavor puzzle
- Leptogenesis
- Unification

- $0\nu\beta\beta$
- Solar $\nu$
- Supernova $\nu$
- Geo $\nu$
- Accelerator $\nu$
- Reactor $\nu$
- v matter effect
- v@LHC
- Icecube HE neutrinos
- Proton decay

- Coherent $\nu$-N scat.
- v masses
- tiny! eV keV MeV GeV TeV PeV YeV
Grand Unified Theories

Georgi Quinn Weinberg 1974

SM gauge couplings almost unify at a high scale

GUTs typically predict:
- Majorana neutrinos
- Normal mass ordering
- $\theta_{23}$ in first octant
- "large" $\theta_{13}$ if $\theta_{12}$ and $\theta_{23}$ are large
- No light sterile neutrino

Grand Unified Theories
Georgi Quinn Weinberg 1974

SM gauge couplings \textit{almost} unify at a high scale

GUTs typically predict:
- Majorana neutrinos
- Normal mass ordering
- $\theta_{23}$ in first octant
- "large" $\theta_{13}$ if $\theta_{12}$ and $\theta_{23}$ are large
- No light sterile neutrino

Revolution in Neutrino Astrophysics

Flavor composition of Icecube high energy neutrinos can probe new Physics unambiguously

Flavor composition of Icecube high energy neutrinos can probe new Physics unambiguously

For any flavor composition at the source, the flavor ratio at detection is constrained by the PMNS matrix uncertainty

New experimental technique to separate EM from hadronic showers can improve the flavor ratio determination considerably

\[
\bar{P}_{\nu_\alpha \rightarrow \nu_\beta}(E) = \sum_i |V_{\alpha i}(E)|^2 |V_{\beta i}(E)|^2
\]

Li Bustamante Beacom 2016
Neutrino masses could come from, e.g., type I seesaw
What is the scale of right-handed neutrinos?

- Minkowski 1977, Ramond 1979, Gell-Mann Ramond Slansky 1979,
  Yanagida 1979, Mohapatra Senjanovic 1980, Schechter Valle 1980

Look for seesaw where we can: LHC

(1) Collider phenomenology

- New developments in NLO corrections
  - Mattelaer Mitra Ruiz 2016
  - Ruiz Spannowsky Waite 2017

(2) Model building

- Dynamical lepton number breaking
  - Khalil 2010, Freitas Pires Silva 2014,
  - Aoki Haba Takahashi 2015, Escudero Rius Sanz 2016,
  - Bertuzzo Machado Tabrizi Zukanovich-Funchal 2017
  - De Romeri Fernandez-Martinez Gehrlein Machado Niro 2017
  - Berryman de Gouvêa Kelly Zhang 2017

- Thorough study of lepton flavor violation at LHC and meson decays
  - Abada De Romeri Teixeira 2015
  - De Romeri Herrero Marcano Scarcella 2016
  - Berryman de Gouvêa Kelly Kobach 2016

- Constraints on light-heavy neutrino mixing via precision physics
  - Abada Toma 2015 de Gouvêa Kobach 2015
  - Fernandez-Martinez Hernandez-Garcia Lopez-Pavon Lucente 2015

Impact on precision Higgs data

- Das Dev Kim 2017

Novel LHC searches: displaced vertices

- Gago Hernandez Jones-Perez Losada Briceño 2015
- Accomando Rose Moretti Oliya Shepherd-Themistocleous 2016

Naturalness: below $10^7$ GeV

- Vissani 1997
Neutrinos and low scale new Physics

TeV scale seesaw with local $U(1)_{B-L}$ can yield a GeV scalar!

![Graph showing meson decays and mixing](image)

Vast phenomenology:
- $B$ and $K$ decays
- $B$ mixing
- Cosmology
- LHC displaced vertices

$\sin \theta_1$

$m_{H_3}$ [GeV]
Neutrinos and low scale new Physics

TeV scale seesaw with local $U(1)_{B-L}$ can yield a GeV scalar!

Vast phenomenology:
B and K decays
B mixing
Cosmology
LHC displaced vertices

Dev Mohapatra Zhang 2017
Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???
Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???

$$\tan \beta = \frac{v_2}{v_1} = 10$$

**U(1) B – L of the third family**

**Complete model, including scalar sector and CKM generation**

**Vast phenomenology:**
- Z-X mixing ($s_X$)
- D oscillations
- Atomic Parity Violation
- Upsilon, B, D, and K decays
- Higgs, top, Z, and W decays
- Neutrino oscillations

...
Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???

\[ \tan \beta = \nu_2/\nu_1 = 10 \]

\[ X \]

\[ p,n,e^- \]

\[ p,n,e^- \]

\[ 2\sqrt{2}G_F \varepsilon^f_{\alpha \alpha} (\bar{\nu}_\alpha L \gamma_{\mu} \nu_{\alpha L}) (\bar{f} \gamma^\mu f) \]

\[ \varepsilon_{\tau \tau} \equiv \varepsilon_{\tau \tau}^p + \varepsilon_{\tau \tau}^n + \varepsilon_{\tau \tau}^e = \frac{3v_1^2v_2^2}{v_1^2v_2^2 + v_s^2v_2^2} \]

\[ |\varepsilon_{\tau \tau}| < 0.09 \]

MINOS: \( \nu_\mu \) and \( \bar{\nu}_\mu \) Disappearance

\[ P(\nu_\mu \rightarrow \nu_\mu) \]

\[ E_\nu \text{ (GeV)} \]

\[ \epsilon_{\mu \tau} = 0.0 \]

\[ \epsilon_{\tau \tau}^m = -2.16 \]
Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???

\[\tan \beta = \frac{v_2}{v_1} = 10\]

Neutrinos could probe low scale flavor physics

The third family is special: not so much for neutrinos!

Neutrino matter potential actually probes the symmetry breaking scale

\[V_{CC} = \sqrt{2}G_FN_e, \quad G_F = \frac{1}{\sqrt{2}v^2}\]

NSI: \[2\sqrt{2}G_F\varepsilon^{f}_{\alpha\alpha} (\bar{\nu}_{\alpha L} \gamma_\mu \nu_{\alpha L}) (\bar{f} \gamma^\mu f)\]

1% NSI translate into \(v' \sim 10v\)

Babu Friedland Machado Mocioiu 2017
Neutrinos and new Physics

Precise determination of neutrino oscillation parameters can probe new physics

Important to understand oscillation probabilities and what we are actually measuring

Neutrinos and new Physics

Precise determination of neutrino oscillation parameters can probe new physics

Important to understand oscillation probabilities and *what we are actually measuring*


With such understanding we can device new strategies for improving our knowledge of neutrino oscillations


What do we learn when we measure $\delta_{CP}$, $\theta_{23}$, and the mass ordering??
The mass ordering
May help answering the paramount question: Are neutrinos Dirac or Majorana?
Test of standard cosmology

<table>
<thead>
<tr>
<th>$m_{\beta\beta}$ [eV]</th>
<th>$m_{\text{lightest}}$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- **IH ($\Delta m^2 < 0$)**
- **NH ($\Delta m^2 > 0$)**

**Cosmology**
- Dell'Oro, Marcocci, Viel, Vissani 2016
- KamLAND-Zen ($^{136}$Xe) 2016
- IH ($\Delta m^2 < 0$)
- NH ($\Delta m^2 > 0$)
- Simpson Jimenez Pena-Garay Verde 2017
- DiValentino Melchiorri Silk 2016

**Constraint currently under discussion** (Schwetz et al 2017)
For a certain class of flavor groups:
1) $\delta_{CP}$ is related to the Clebsch-Gordan coefficients
2) Dependence on group and fermion representations

Some predictions

$\delta_\ell = 227^\circ$

Chen Mahanthappa 2009

$\theta_{13} \neq 0, \theta_{23} = \pi/4, \text{ and } \delta_{CP} = -\pi/2$

Ma 2016, Ma 2017

GUTs typically predict:
- Majorana neutrinos
- Normal mass ordering
- $\theta_{23}$ in first octant
- “large” $\theta_{13}$ if $\theta_{12}$ and $\theta_{23}$ are large
- No light sterile neutrino
Complete models prove that some NSIs are possible up to some extent


\[ \mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \epsilon^f_{\alpha\beta} (\bar{\nu}_\alpha L \gamma^\mu \nu^L_\beta) (\bar{f} \gamma^\mu f) \]
Neutrinos and new Physics

Complete models prove that some NSIs are possible up to some extent

\[ \mathcal{L}_{\text{NSI}} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^f (\bar{\nu}_{\alpha L} \gamma^\mu \nu_{\beta L})(\bar{f} \gamma^\mu f) \]

NSI induce degeneracies!
Generalized degeneracy with NSI leaves oscillation invariant for any matter potential:
Large NSI can flip the sign of matter potential
Coloma Schwetz 2016

Many other approximate degeneracies exist: extra work for current and future experiments

Possible effect of NSI on the determination of atmospheric parameter
Friedland Lunardini Maltoni 2004
Neutrinos and new Physics

Complete models prove that some NSIs are possible up to some extent

\[ \mathcal{L}_{\text{NSI}} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^f (\bar{\nu}_\alpha \gamma^\mu \nu_\beta \mathbf{L}) (f \gamma_\mu f) \]

Needs scattering data to solve generalized degeneracy

Neutrino-nucleus coherent scattering!
Neutrinos and new Physics

Dark matter detectors are excellent to probe new physics with solar neutrinos:
- Low background
- Low energy threshold
- Large detectors to compensate small cross sections


Dedicated experiments to study coherent ν-N scattering:
- CONNIE (Angra nuclear reactor)
- COHERENT (Oak Ridge)
- MINER (Texas A&M)
FIG. 1: The neutrino mode (top) and antineutrino mode (bottom) event excesses as a function of $L/E_\nu$ (meters/MeV). The data are compared to the expected background for various processes, including neutral current (NC) events, semi-leptonic reactions, and other backgrounds.

FIG. 2: The neutrino mode (top) and antineutrino mode (bottom) event excesses as a function of $E_{\nu}$ (GeV). The data are compared to theoretical predictions for NC and semi-leptonic reactions, as well as other backgrounds.

MiniBooNE 1207.4809

om neutrino theory

pmachado@fnal.gov
This corresponds to a neutrino (antineutrino) excess of (478) events pass the...
tineutrino data sets is given in Fig. 3, which shows the tineutrino events are stable over energy and time, and 

FIG. 1: The neutrino mode (top) and antineutrino mode (bot-

Errors). 

Events/MeV 

Neutrino 

Data (stat err.) 

ν̄ e from μ→ν̄ e 
ν̄ e from K±ν̄ e 
ν̄ e from K0 
π̄ μ misid 
π̄ e misid 
Δ → N̄ 

Other 

Constr. Syst. Error 

Antineutrino 

MiniBooNE 1207.4809 

see also Collin Arguelles Conrad Shaevitz 2016, Gariazzo Giunti Laveder Li 2017

Müller et al 2011
Null results combined

CDHS

LSND MB app reactors+Ga

MINOS/ MINOS+ 2016

MB disapp

IC (2016)

\[ \sin^2 \theta_{24} \]

see also Collin Arguelles Conrad Shaevitz 2016, Gariazzo Giunti Laveder Li 2017
YeV
PeV
TeV
GeV
MeV
keV
eV
zeV ($10^{-21}$ eV)
Neutrinos and new Physics

Going to even smaller scales:
Dark matter can be an ultra-light scalar field (e.g. $m_\phi = 10^{-21}$ eV)
It behaves like a classical field, not like a particle
If it couples to neutrinos, it induces temporal variations in parameters

10 min $< T < 10$ years: modulation signal @SNO, SK

few millisecond $< T < 10$ years: Distorted Neutrino Oscillations (DiNOs)
Many many many other fronts!

Neutrino cross sections (NuSTEC effort)

Neutrinos in cosmology
   Early universe - BBN
Abazajian, Barbieri, Cirelli, Chizov, Di Bari, Dodelson, Dolgov, Foot, Holanda, Iocco, Kirillova, Kusenko, Mangano, Lesgourgues, Pastor, Smirnov, Steigman, Volkas

Secret neutrino interactions

Supernova evolution: non-linear effects from collective oscillations
   Chen Ratz Trautner 2015

Cosmic neutrino background: ideas to measure it? Non-thermal component?

Type II, type III and radiative seesaw
Akhmedov, Bonnet, Babu, Barbieri, Barger, Berezhiani, Ellis, Gaillard, Glashow, Hirsch, Keung, Ma, Mohapatra, Ota, Pakvasa, Schechter, Senjanovic, Valle, Yanagida, Winter, Wolfenstein, Zee, and many others

Flat extra dimensions: light sterile neutrinos
Antoniadis, Arkani-Hamed, Barbieri, Berriyman, Davoudiasl, Dimopoulos, Dvali, de Gouveia, Langacker, Machado, Mohapatra, Nandi, Nunokawa, Perelstein, Peres, Perez-Lorenzana, Smirnov, Strumia, Tabrizi, Zukavich-Funchal, …

Leptogenesis
Barenboim, Davidson, Di Bari, Dolgov, Fukugita, Kuzmin, Rubakov, Servant, Shaposhnikov, Yanagida, Zeldovich, …

Sterile neutrino in long baseline oscillation experiments
   Agarwalla, Bhattacharya, Chaterjee, Dasgupta, Dighe, Donini, Fuki, Klop, Lopez-Pavon, Meloni, Migliozi, Palazzo, Ray, Tang, Terranova, Thalapillil, Wagner, Yasuda, Winter,…

Dark matter in neutrino detectors: light DM and light mediators
   Ballet, Batell, Chen, Coloma, deNiverville, Dobrescu, Frugiule, Harnik, McKeen, Pascoli, Pospelov, Ritz, Ross-Lonergan

Neutrinos and the standard solar model: CNO cycle and metallicity
Bailey, Busoni, Christensen-Dalsgaard, Krief, Simone, Serenelli, Scott, Vincent, Vilante, Vissani, Vynioli, …

Neutrino magnetic moment
   see e.g. Salam 1957, Barbieri Fiorentini 1988, Barbieri Mohapatra 1989, Babu Chang Keung Phillips 1992, Tarazona Diaz Morales Castillo 2015
   Cañas Miranda Parada Tortola Valle 2015, Barranco Delepine Napsuciale Yebra 2017
   Coloma Machado Martinez-Soler Shoemaker 2017

Discrete symmetries with non-zero $\theta_{13}$
Feruglio Hagedorn Toroop 2011, Lam 2012, Lam 2013, Holthausen Lim Lindner 2012, Neder King Stuart 2013, Hagedorn Meroni Vitale 2013
   King Neder 2014, Ishimori King Okada Tanimoto 2014, Yao Ding 2015, …

Effective operator approach to neutrino masses and collider/low scale pheno

New physics in neutrinoless double beta decay, lepton number violation at the LHC, left-right models, RS models and neutrino masses, neutrinos as dark matter, and much more!
Conclusions

Neutrinos: enormous range of energy scales - experimental and theoretical fronts

Most exciting aspect of neutrino physics and also a big challenge

DUNE range:
- $\text{zeV}$ ($\nu$-DM couplings)
- $\text{eV}$ (sterile $\nu$)
- $\text{GeV, TeV}$ (oscillations)
- $\text{YeV}$ (proton decay)

45 orders of magnitude!!!

Standard predictions: essential for probing BSM with neutrinos

Ongoing TH effort: identify all BSM testable with neutrinos

A coherent neutrino theory endeavor, addressing all aspects of neutrino physics, is essential for the success of the neutrino program