Perspectives on Neutrino Physics

- Neutrinos as a probe
- The questions
- Underground physics/LBNE
- Heretical musings
- Small masses from the top down
- Active/sterile neutrino mixing
Neutrinos as a Unique Probe: $10^{-33} - 10^{+28}$ cm

- **Particle Physics**

  - $\nu N, \mu N, eN$ scattering: existence/properties of quarks, QCD

  - Weak decays ($n \to p e^- \bar{\nu}_e, \mu^- \to e^- \nu_\mu \bar{\nu}_e$): Fermi theory, parity violation, quark mixing

  - Neutral current, $Z$-pole, atomic parity: electroweak unification, field theory, $m_t$, $M_H$; severe constraint on physics to TeV scale

  - Neutrino mass: constraint on TeV physics, grand unification, superstrings, extra dimensions; seesaw: $m_\nu \sim m_q^2/M_{GUT}$
- **Astrophysics/Cosmology**
  - Core of Sun
  - Supernova dynamics
  - Atmospheric neutrinos (cosmic rays)
  - Violent events (AGNs, GRBs, cosmic rays)
  - Large scale structure/CMB (dark matter, dark radiation)
  - Nucleosynthesis (big bang - small $A$; stars $\rightarrow$ iron; supernova - large $N$)
  - Baryogenesis
    - Simultaneous probes of $\nu$ and astrophysics

- **Interior of Earth**
Questions in Particle Physics

- **New physics** (SUSY, remnants $[Z', \text{exotics, extended Higgs}]$, sterile $\nu$, · · ·)
- **Origin of flavor** ($\nu$, $B$, FCNC, EDM)
- **Scales** (TeV, intermediate, GUT, string)
- **Unification** (GUT, string, proton decay)
- **Hidden sectors** (dark, SUSY, random)
- **New dimensions** (small, large, warped, anticommuting)
- **Baryon asymmetry and CP** (leptogenesis, EWBG, Affleck-Dine)
- **Dark matter and energy**
- **Gravity and cosmological constant**

Asilomar (May, 2013) Paul Langacker (IAS, Princeton)
• **Uniqueness or environment** (landscape, multiverse)

• **Minimality or remnants**

• **Naturalness or tuning**
The Current Status of Neutrinos

- Three active neutrinos
  - $\Delta m_{21}^2 \sim 7.5 \times 10^{-5}$ eV$^2$, $|\Delta m_{32}^2| \sim 2.5 \times 10^{-3}$ eV$^2$
  - $\theta_{13}$ small but non-zero
  - $\theta_{23}$ may be non-maximal ($1^{st}$ octant?)
  - $\theta_{12}$ large but non-maximal
  - CP phase $\delta$ undetermined ($\pi - 2\pi$ favored?)
- Unknown: Majorana/Dirac; absolute scale; hierarchy; CP phases; mechanism/physics scale for masses and flavor; leptogenesis?

- Mixing with light sterile neutrinos?

- Non-standard properties? (new interactions, non-unitary, elm moments, decay, space/time variation, CPT/LIV)

Asilomar (May, 2013) Paul Langacker (IAS, Princeton)
Gonzalez-Garcia, Maltoni, Salvado, Schwetz, 1209.3023

Asilomar (May, 2013)  Paul Langacker (IAS, Princeton)
Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno, 1205.5254
Underground Physics/LBNE

- [LBNE Reconfiguration Report], [Physics Working Group Report (Appel et al)]

- Phase 1: 10 kton LAr-TPC on surface (outside funds?); 1300 km (Homestake); 700 kW beam; first two maxima; 10 yr run; existing near detectors

- Also, Nova(6) and T2K

- Soudan (735 km) and Ash River (810 km) also considered

- Later phases: 34 kton underground (4850 ft); 2.3 MW (Project X); new near detector
Mass Hierarchy Significance vs $\delta_{CP}$
Normal Hierarchy, $\sin^2(2\theta_{13})=0.07$ to 0.12

$\pi$ CP

CPV Significance vs $\delta_{CP}$
IH (considered), $\sin^2(2\theta_{13})=0.07$ to 0.12

$\pi$ CP
Non-Standard Interactions

NC NSI discovery reach (3σ C.L.)

- \( \sin^2 2\theta_{13}^{\text{true}} = 0 \)
- only one \( \epsilon \neq 0 \) at a time
- Left/right edges: Best/worst arg(\( \epsilon \))

LAr 33.4 kt @ 1300 km
120 GeV, 5 + 5 yrs

- 2\text{nd} max. only
- 1\text{st} max. only
- both maxima

Excl. by current bounds

- \( \epsilon^m_{\text{ee}} \)
- \( \epsilon^m_{\text{em}} \)
- \( \epsilon^m_{\text{e\mu}} \)
- \( \epsilon^m_{\text{e\tau}} \)
- \( \epsilon^m_{\text{\mu\mu}} \)
- \( \epsilon^m_{\text{\mu\tau}} \)
- \( \epsilon^m_{\text{\tau\tau}} \)

10^{-3} 10^{-2} 10^{-1} 10^{0} \text{ True } |\epsilon|
FIG. 29. Proton decay lifetime limit for $p \rightarrow K^+ \bar{\nu}$ as a function of time for Super-Kamiokande compared to different LAr masses at the 4850 level starting in 2020. The dashed lines show the effect of a 30% reduction of fiducial mass, conservatively assumed for a Soudan-depth detector. The limits are at 90% C.L., calculated for a Poisson process including background assuming that the detected events equal the expected background. (Figure from J. Raaf.)

Atmospheric neutrinos are very sensitive to alternative explanations or subdominant new physics effects that predict something other than the characteristic $L/E$ dependence predicted by oscillations in the presence of matter. Because atmospheric neutrinos are somewhat more tolerant of background than proton decay, a depth which is sufficient for a proton decay search should also be suitable for atmospheric neutrinos. For 4850 ft depth, a veto should not be necessary, and one can assume full fiducial mass; at Soudan depth, a 1 meter fiducial cut should be adequate.

Figure 30 shows expected sensitivity to mass hierarchy: for ten years of running, a Soudan-depth 20 kton detector could rival beam sensitivity, and even a 10 kton detector would add to world knowledge.

FIG. 30. Sensitivity to mass hierarchy using atmospheric neutrinos as a function of fiducial exposure in a LAr detector. (Figure from H. Gallagher, J. Coelho, A. Blake.)
Core Collapse Supernova

A nearby core-collapse supernova will provide a wealth of information via its neutrino signal (see [37, 38] for reviews). The neutrinos are emitted in a burst of a few tens of seconds duration. Energies are in the few tens of MeV range, and luminosity is divided roughly equally between flavors. Ability to measure and tag the different flavor components of the spectrum is essential for extraction of physics and astrophysics from the signal. Currently, world-wide sensitivity is primarily to electron anti-neutrinos, via inverse beta decay on free protons, which dominates the interaction rate in water and liquid scintillator detectors. Liquid argon has a unique sensitivity to the electron neutrino component of the flux, via the absorption interaction on $^{40}\text{Ar}$.

$$\text{\footnotesize}^{40}\text{Ar} + \nu_e \rightarrow e^- + ^{40}\text{K}$$

In principle, this interaction can be tagged via the de-excitation gamma cascade. About 3000 events would be expected in 34 kton of liquid argon for a supernova at 10 kpc; the number of signal events scales with mass and the inverse square of distance as shown in Fig. 31. For a collapse in the Andromeda galaxy, a 34-kton detector would expect about one event. This sensitivity would be lost for a smaller detector. However even a 5 kton detector would gather a unique $\nu_e$ signal from within the Milky Way.

**Distance to supernova (kpc)**

<table>
<thead>
<tr>
<th></th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>100</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

**Number of interactions**

- 34 kton
- 20 kton
- 15 kton
- 10 kton
- 5 kton

As noted above, due to their low energy, supernova events are subject to background, although the short-timescale burst nature of the signal means that the background can be well known and subtracted. Muons and their associated Michel electrons can in principle be removed. Radioactive decays, including cosmogenic spallation products, tend to make $<10$ MeV signals. They lie below the main supernova signal range, but inhabit a potential region of interest for physics signatures. Preliminary studies from reference [39], extended for cosmic ray rates on the surface, suggest that while Soudan depth is likely acceptable, the surface cosmic-ray associated signal rates are daunting. It will require at least a few orders of magnitude of background rejection to pull the signal from background. While more work needs to be done to determine the extent to which the background can be mitigated, a surface option is highly unfavorable for supernova neutrino physics.

**D. Summary**

Although more work needs to be done to understand backgrounds at shallow depth, the following findings are fairly robust:

- Proton decay capabilities as a function of depth are the best documented, and a search at the surface seems impossible. A modest fiducial mass reduction would be required at Soudan. A detector mass of at least 10 kton would be needed for competitiveness.

- For atmospheric neutrinos, less is known about signal selection on the surface; however it is probably extremely difficult. Soudan depth is acceptable. Underground, a 20 kton detector would be needed for competitiveness, although a smaller detector could still provide useful information.
Majorana or Dirac

- Many mechanisms for small neutrino mass, both Majorana and Dirac

- Bottom-up motivation for Majorana: no unbroken gauge symmetries forbid Majorana masses
  (i.e., if $L$ violation is not forbidden it is obligatory)

- Loopholes:
  - Non-gravity: large 126 of $SO(10)$, HDO, or other $L$ violation must be added by hand
  - Gravity: $m_\nu \lesssim \nu_{EW}^2 / \sqrt{M_P} \sim 10^{-5}$ eV (unless LED); often much smaller $\Rightarrow$ may be pseudo-Dirac (but Solar, future UHE)
  - New TeV or string scale physics/symmetries/constraints may invalidate assumptions
CP Violation and Leptogenesis

- **CP violation** (observable phases) *typical in quantum mech.* unless
  - System is simple *(absorb phases or no interference)*
  - Gauge interactions only

- **Needed to test flavor models**

- **CP violation** ($\delta$) *neither necessary nor sufficient for leptogenesis*

- **Majorana mass** *neither necessary nor sufficient for leptogenesis*

- **Plausible alternatives to leptogenesis**: **EWBG** *(especially extended Higgs)*; **Affleck-Dine** *(SUSY)*

- **Will we ever know? Perhaps not, unless**
  - TeV clues *(TeV seesaw; $Z'$ + Higgs; SUSY spectrum)*
  - Totally compelling model with other implications *(e.g., FCNC)*
Uniqueness or Environment

- **Gauge interactions**: determined by symmetry (but groups, representations, SSB)

- **Yukawa interactions** (flavor physics): apparently unconstrained, unless new symmetries/principles (local, global, discrete, stringy)

- **The uniqueness paradigm** (cf., Kepler’s Mysterium Cosmographicum)
  - Enormous effort (especially $\nu$) to understand spectrum/mixings by flavor symmetries/textures, usually in seesaw context (tri-bimaximal, bimaximal, complementarity, GUT + flavor, lopsided, Froggatt-Nielsen, haze, loops, $R_p$)
  - $\theta_{13} \neq 0, \theta_{23} \neq 45^\circ$ excludes many models or requires perturbations
Kepler’s Mysterium Cosmographicum
• **The environmental paradigm** (cf., planetary orbits)
  
  – No simple explanation of parameters
    (but scales/hierarchies by FN-like powers or exponentials?)
  
  – String landscape: $\gtrsim 10^{600}$ vacua with no known selection principle (A word?)
  
  – Subset habitable, with different groups, remnants, hierarchy mechanisms, parameters
  
  – Part of multiverse?
  
  – Underlying constraints often too complicated to unravel
  
  – Version of anarchy

• **Distinction of paradigms critical**
Active and Sterile Neutrinos

- **Active Neutrino** (a.k.a. ordinary, doublet)
  - in $SU(2)$ doublet with charged lepton $\rightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$ by CP
  - Only three light active allowed by $\Gamma_Z$

- **Sterile Neutrino** (a.k.a. singlet, right-handed)
  - $SU(2)$ singlet; no interactions except by mixing, Higgs, or BSM
  - $\nu_R \leftrightarrow \nu_L^c$ by CP
  - Almost always present: Are they light? Do they mix?
**Neutrino Mass Terms**

- **Dirac mass term** connects two distinct neutrinos:  \[ m_D (\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) \]
  (4 components)

- **Majorana mass term** connects neutrino with its \( CP \) conjugate:
  \[ \frac{m_T}{2} (\bar{\nu}_L \nu_R^c + \bar{\nu}_R^c \nu_L) \]
  (2 components)

- **Also possible for sterile:**
  \[ \frac{m_S}{2} (\bar{\nu}_L^c \nu_R + \bar{\nu}_R \nu_L^c) \]
Can have simultaneous Majorana and Dirac mass terms

\[-\mathcal{L} = \frac{1}{2} \left( \bar{\nu}_L \nu^c_L \right) \left( \begin{array}{cc} m_T & m_D \\ m_D & m_S \end{array} \right) \left( \begin{array}{c} \nu^c_R \\ \nu_R \end{array} \right) + h.c. \]

$m_T$ : $|\Delta L| = 2$, $|\Delta t^3_L| = 1$ (Majorana)

$m_D$ : $|\Delta L| = 0$, $|\Delta t^3_L| = \frac{1}{2}$ (Dirac)

$m_S$ : $|\Delta L| = 2$, $|\Delta t^3_L| = 0$ (Majorana)

(Type I) seesaw: $m_S \gg m_D, m_T = 0 \Rightarrow |m_1| \sim |m_D^2/m_S|$ (\sim active)
The String Landscape

- **String theory very promising** (finite quantum gravity & other interactions)

- **However, enormous landscape of vacua** ($> 10^{600}$)

- **Many contain SM or MSSM**

- **Many involve TeV-scale remnants** (e.g., $Z'$, exotics, extended Higgs) beyond the MSSM (hint?)

- **Top-down remnants may not be minimal or motivated by SM problems**

Asilomar (May, 2013)  Paul Langacker (IAS, Princeton)
Minimality or Remnants

Asilomar (May, 2013) Paul Langacker (IAS, Princeton)
Some bottom-up ideas unlikely to emerge from simple/perturbative string constructions (e.g., high-dimensional representations)

Top-down may suggest new physical mechanisms (e.g., string instantons: exponentially suppressed $\mu$, Majorana or Dirac $m_\nu$, etc)

Important to map string-likely or unlikely classes of new physics and mechanisms (and contrast with field theory)
Very Small Masses

- **Mechanisms for very small masses** (Majorana, Dirac, or both)
  - Very small couplings (fine-tuning? underlying mechanism?)
  - **Loops** (very high order or hybrid; must suppress low order)
  - Geometric suppressions (large, warped, stringy)
  - Higher-dimensional operators (HDO) (cf., Froggatt-Nielsen)

Review: *Neutrino Masses from the Top Down, ARNPS 62, 1112.5992*
Geometric Suppressions

- Wave function overlaps in large (and/or warped) extra dimensions, with $\nu_R$ propagating in bulk (cf., gravity)

$$m_D \sim \frac{\nu M_F}{M_P}, \quad M_F = \left( \frac{M_P^2}{V_\delta} \right)^{\frac{1}{\delta+2}} = \text{fundamental scale}$$

- $\overline{M}_P = M_P/\sqrt{8\pi} \sim 2.4 \times 10^{18}$ GeV; $V_\delta = \text{volume}$
- $M_F \sim 1000$ TeV $\Rightarrow m_D \sim 0.1$ eV
- Worldsheet instantons, e.g., intersecting D-brane (Type IIA)
  - Closed strings (gravitons) and open strings ending on D-branes
  - D6-branes: fill ordinary space and 3 of the 6 extra dimensions

- Yukawa interactions $\sim \exp(-A_{ijk}) \rightarrow$ hierarchies
- $m_D: A_{\nu\ell}^\ell H_u$ not large enough (at least in toroidal compactifications)
- $m_S$: no Majorana masses at perturbative level (anomalous $U(1)'$)
D-brane instantons

- Anomalous $U(1)'$: $M_{Z'} \sim M_s$; acts like perturbative global symmetry (may forbid $\mu$, $R_P$ violation, $\nu^c_L \nu^c_L$, $L\nu^c_L H_u$, $QU^c H_u$, ...)

- Field theory instantons: nonperturbative $e^{-1/g^2}$ effects from topologically non-trivial classical field configurations (e.g., $B + L$ violation in SM)

- D instantons: nonperturbative violation of global symmetries

\[ \exp(-S_{inst}) \sim \exp \left( -\frac{2\pi}{\alpha_{GUT}} \frac{V_{E2}}{V_{D6}} f(\text{winding}) \right) \]

- Examples of small Dirac, small or intermediate $m_S$
  (ordinary seesaw), stringy Weinberg operator ($LH_u L H_u / M$)
Higher-Dimensional Operators (HDO)

- Let $\mathcal{O}$ be an operator, such as $L \nu_L^c$ (Dirac mass), $\nu_L^c \nu_L^c$ (sterile Majorana), or $LL$ (active Majorana)
  
  $(L \equiv \begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$; Dirac and $SU(2)$ indices suppressed)

- Would typically be of order $\overline{M}_P \sim 10^{18}$ GeV if not suppressed

- However, $L \nu_L^c$ and $LL$ forbidden by $SU(2)$; $\nu_L^c \nu_L^c$ by new physics (usually) $\Rightarrow$
  
  \[ \mathcal{L} \sim h_{\nu} LH_u \nu_L^c, \quad h_S S \nu_L^c \nu_L^c, \quad \frac{C}{\mathcal{M}} \underbrace{LH_u LH_u}_\text{Weinberg op} \]

$H_u = \text{Higgs doublet, } S = \text{singlet, } \mathcal{M} = \text{new physics scale}$

$\langle 0|H_u|0 \rangle \lesssim \nu \sim 246$ GeV

Asilomar (May, 2013)  
Paul Langacker (IAS, Princeton)
The Weinberg Operator

• Most models for light Majorana neutrino: $\frac{C}{M} LH_u LH_u$

• Field theoretic HDOs: integrate out heavy particles from 4D field theory (e.g., conventional type I-III seesaws, neutralinos, extended seesaws)

• Stringy HDO: integrate out string excitations, KK or winding modes, moduli, · · ·
  
  - Typically, $\mathcal{M} \lesssim M_s \lesssim M_P$ (need low $M_s$ or multiple modes)
  
  - Hybrid: $\nu^c_L$ with masses from D instantons; multiple ($\mathcal{O}(100)$) $\nu^c_L$ with $m_d, m_S$ from high-dimension stringy HDO
  
  - Details typically environmental (anarchic?)

Asilomar (May, 2013) 
Paul Langacker (IAS, Princeton)
Small Dirac Masses

- Operators allowed by $SU(2)$

$$\mathcal{L} \sim h_\nu L H_u \nu_L^c, \quad m_S \nu_L^c \nu_L^c, \quad \frac{C}{\mathcal{M}} L H_u L H_u$$

- Need some form of seesaw for $h_\nu \gtrsim 10^{-12}$

- Additional symmetries (gauge, global, discrete) or string constraints (heterotic or type II) could forbid any or all of these

- Symmetry breaking by non-perturbative D instanton (exponential suppression) can yield tiny Dirac mass (and forbid Majorana)
• Or perturbative symmetry breaking by VEV of SM singlet $S$

\[ \mathcal{L} \sim \frac{S^p}{\mathcal{M}^p} LH_u \nu^c_L, \quad \frac{S^{q+1}}{\mathcal{M}^q} \nu^c_L \nu^c_L, \quad \frac{S^{r-1}}{\mathcal{M}^r} LH_u LH_u \]

• Small Dirac for $p > 0$
  
  – $p = 1, S/\mathcal{M} \sim 10^{-12} \Rightarrow m_D \sim 0.1$ eV ($\mathcal{M} = \overline{M}_P \Rightarrow S \sim 10^3$ TeV) (e.g., non-anomalous $U(1)'$, non-holomorphic SUSY)
  
  – Majorana masses may be forbidden ($\Rightarrow$ pure Dirac)
  
  – Alternative: pseudo-Dirac with $q \geq 2, r \geq 2$ ($m_{S,T} < 10^{-9}$ eV)
\[ m_D \approx \frac{S_p \nu}{\mathcal{M}_p} \approx 0.1 \text{ eV}, \quad m_S \approx \frac{S^{q+1}}{\mathcal{M}_q}, \quad m_T \approx \frac{S^{r-1} \nu^2}{\mathcal{M}_r} \]
Mixing Between Active and Sterile Neutrinos

- $\nu_e (\bar{\nu}_e)$ appearance (LSND, MiniBooNE)

- Reactor recalibration and SBL; Gallium source calibrations

- But spectrum, MINOS (disappearance), ICARUS/OPERA (appearance) limits

- Cosmology: $N_{\text{eff}}$ (Planck: $3.30 \pm 0.27$ vs 3.046), $\sum m_{\nu_i} (< 0.23 \text{ eV})$ (data sets?, priors? non-thermal?, other radiation?)

- No coherent picture
Do Active and Sterile Neutrinos Mix?

- Most $m_\nu$ models involve sterile neutrinos (quark-lepton symmetry)
- Mass anywhere from sub-eV to $\overline{M}_P = M_P / \sqrt{8\pi} \sim 2.4 \times 10^{18}$ GeV
- LSND/MiniBooNE: possible oscillation between active and sterile
  - Mixing between active and sterile of same helicity
  - No active-sterile mixing for pure Majorana, pure Dirac, or (ordinary type-I) seesaw
  - Need two types of tiny (eV-scale) masses (usually Dirac/Majorana)
  - Suggests TeV-scale symmetries ($\rightarrow$ HDO/mini-seesaw)
Simultaneous Majorana and Dirac mass terms

\[-\mathcal{L} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_L^c \end{pmatrix} \begin{pmatrix} m_T & m_D \\ m_D & m_S \end{pmatrix} \begin{pmatrix} \nu_R \\ \nu_R^c \end{pmatrix} + \text{h.c.} \]

weak eigenstates

\[m_T : |\Delta L| = 2, \quad |\Delta t^3_L| = 1 \quad \text{(Majorana)}\]

\[m_D : |\Delta L| = 0, \quad |\Delta t^3_L| = \frac{1}{2} \quad \text{(Dirac)}\]

\[m_S : |\Delta L| = 2, \quad |\Delta t^3_L| = 0 \quad \text{(Majorana)}\]
Active-sterile mixing suggests $p = q = r = 1$

$$\mathcal{L} \sim \frac{S}{\mathcal{M}} L H_u \nu_L^c, \quad \frac{S^2}{\mathcal{M}} \nu_L^c \nu_L^c, \quad \frac{1}{\mathcal{M}} L H_u L H_u$$

(with $\mathcal{M} \sim 10^{15}$ GeV, $S \sim 1$ TeV)

Ignore triplet term for simplicity (present in general)
Conclusions

• Neutrinos are very important and very interesting

• We need more information: LBNE; LAr-TPC (also proton decay, astrophysics); sterile mixing; $\beta\beta_{0\nu}$; · · ·

• Many possibilities for small masses: Majorana, Dirac, or both

• Flavor physics: uniqueness or environment
Backup
FIG. 1. The $\mu/\bar{\mu}$ vs neutrino energy and baseline with $\sin^2\theta_{13}=0$.1, $c_{\theta_{13}}=0$ for normal hierarchy (top) and inverted hierarchy (bottom). The solid blue lines correspond to the locations of the 1st and 2nd oscillation maxima in vacuum. The approximate formula given in Equation 1 is useful for understanding important features of the appearance probability shown in Figure 1:

1. The first three terms in the equation control the matter induced enhancement for normal mass ordering ($m_1 < m_2 < m_3$) or suppression for the inverted mass ordering ($m_3 < m_1 < m_2$) which dominates in the region of the...
FIG. 16. The fraction of $\delta_{CP}$ vs. detector mass. The dashed black line indicates the sensitivity from the experiment alone. The solid red line is the resolution obtained from the combination with T2K (neutrinos only) and NOvA (16).

FIG. 17. The fraction of $\delta_{CP}$ vs. detector mass. The dashed black line indicates the sensitivity from the experiment alone. The solid red line is the resolution obtained from the combination with T2K (neutrinos only) and NOvA (16).
Active-Sterile ($\nu^0_L - \nu^0_{Lc}$) Mixing (LSND/MiniBooNE)

- No active-sterile mixing for Majorana, Dirac, or seesaw

- $m_D$ and $m_S$ (and/or $m_T$) both small and comparable (mechanism?)
  (or small active-sterile and sterile-sterile Dirac)

- Pseudo-Dirac ($m_T, m_S \ll m_D$):
  - Small mass splitting, small $L$ violation, e.g.,
    \[
    m_T = \epsilon, \ m_S = 0 \implies |m_{1,2}| = m_D \pm \epsilon/2
    \]
  - But small extra $\Delta m^2$ could affect Solar/supernova oscillations
  - Solar: need $m_{S,T} \lesssim 10^{-9}$ eV (de Gouvêa, Huang, Jenkins, 0906.1611)
  - Future UHE $\nu$ telescopes: $10^{-17}$ eV?

Asilomar (May, 2013)

Paul Langacker (IAS, Princeton)