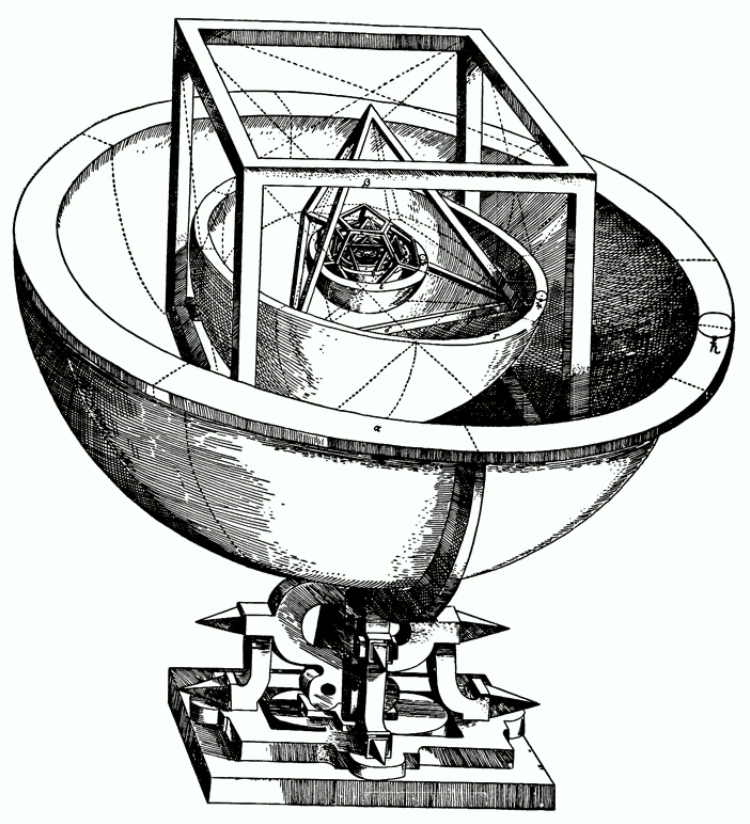
# Perspectives on Neutrino Physics



- 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 ($n \to pe^-\bar{\nu}_e, \mu^- \to e^-\nu_\mu\bar{\nu}_e$): 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: $m_\nu \sim m_q^2/M_{\rm GUT}$

- **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**

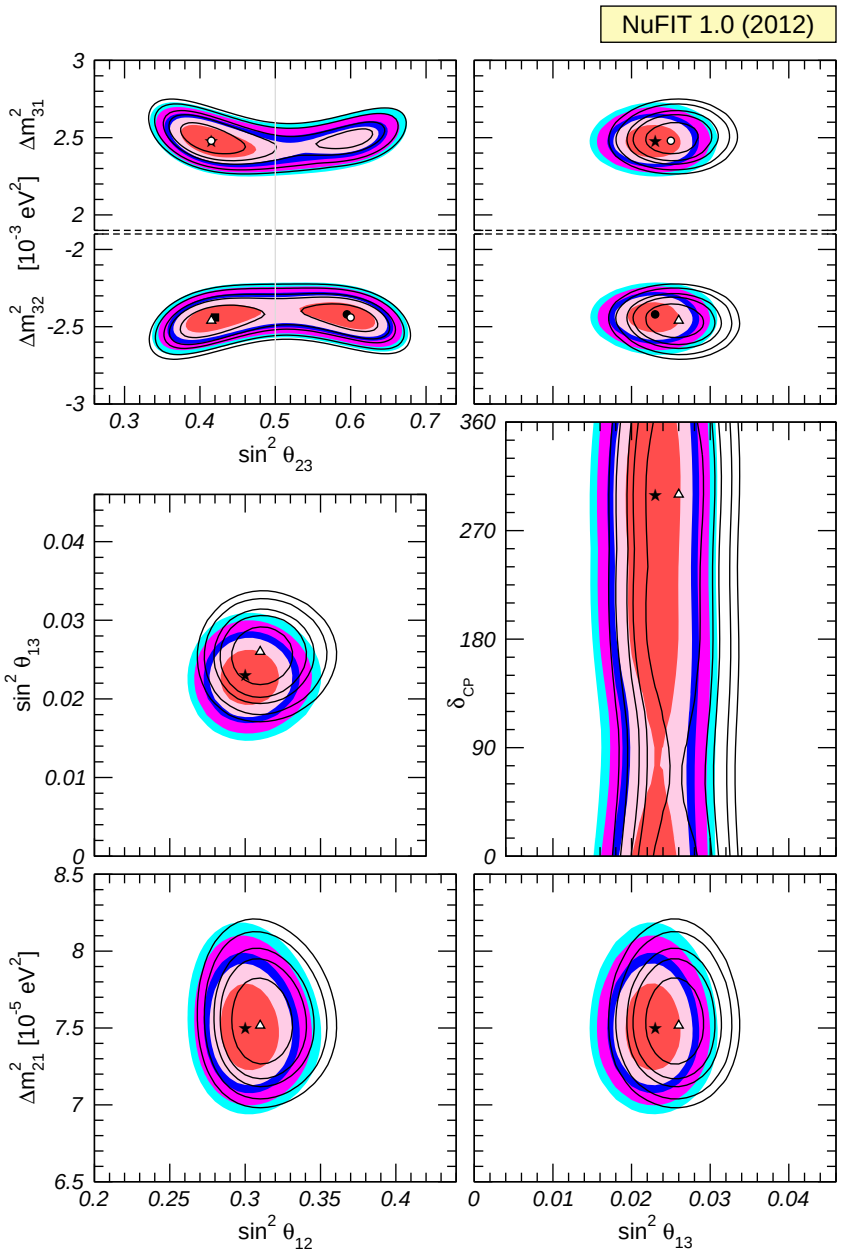
# Questions in Particle Physics

- **New physics** (SUSY, remnants [$Z'$, exotics, extended Higgs], sterile $\nu$, $\cdots$)
- **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**

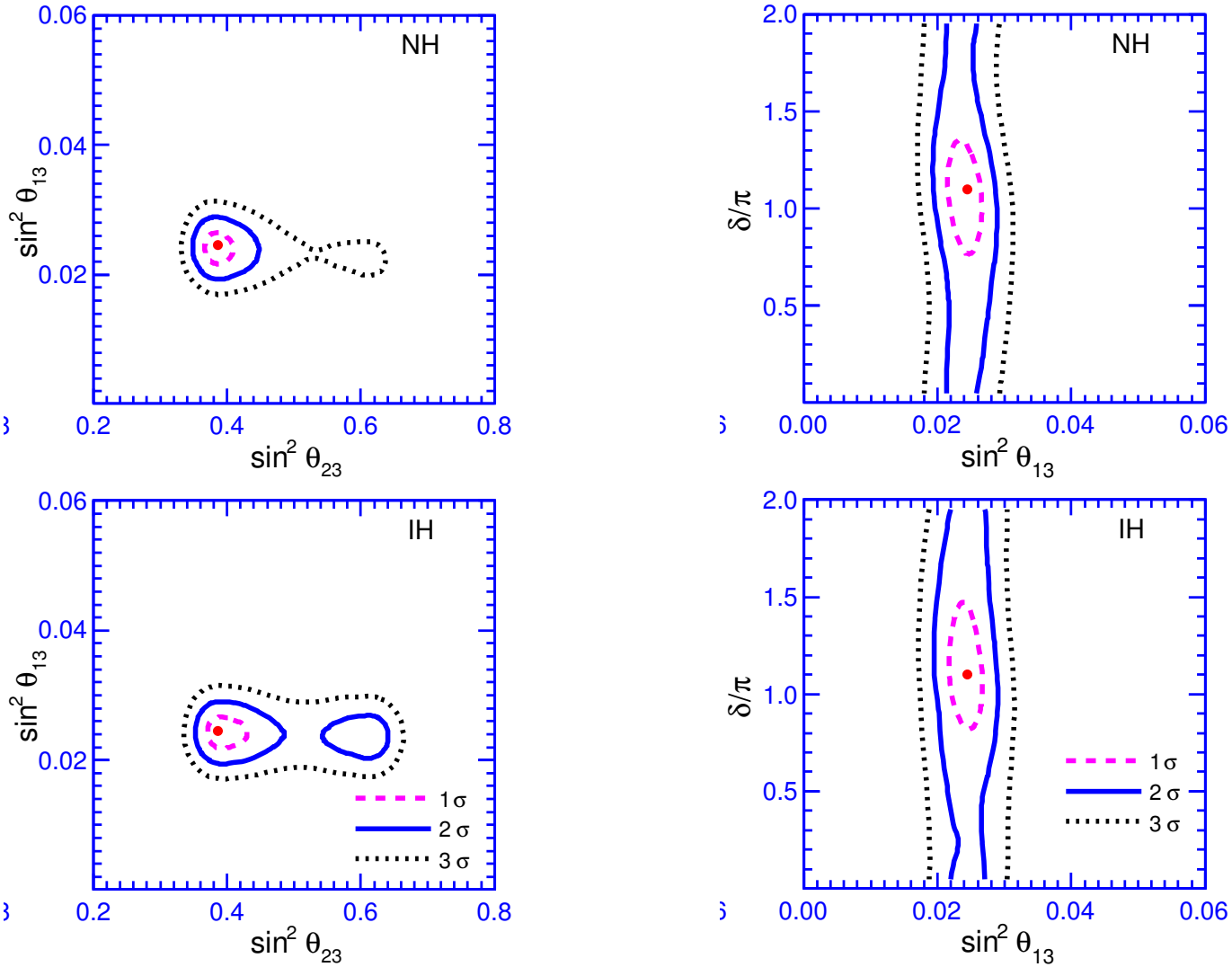
- **Uniqueness or environment** (landscape, multiverse)
- **Minimality or remnants**
- **Naturalness or tuning**

# The Current Status of Neutrinos

- **Three active neutrinos**
  - $\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV$^2$, $|\Delta m^2_{32}| \sim 2.5 \times 10^{-3}$ eV$^2$
  - $\theta_{13}$ small but non-zero
  - $\theta_{23}$ may be non-maximal (1$^{\rm st}$ 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)




**Gonzalez-Garcia, Maltoni, Salvado, Schwetz, 1209.3023**




**Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno, 1205.5254**

# Underground Physics/LBNE

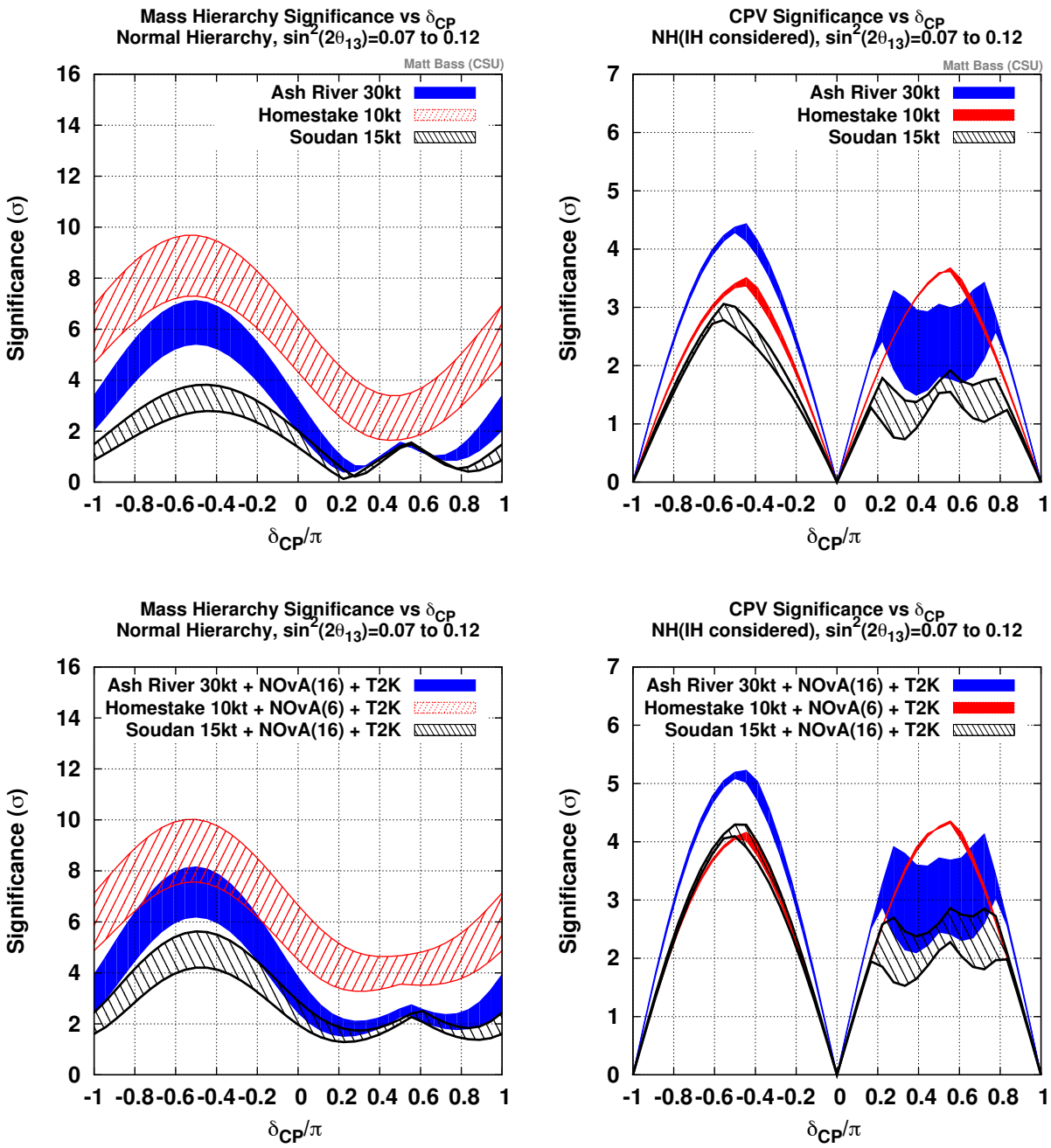
- [*LBNE Reconfiguration Report*],
  [*Physics Working Group Report* (Appel et al)]

- 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, No$\nu$a(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
Matt Bass (CSU)
Ash River 30kt
Homestake 10kt
Soudan 15kt
Significance ($\sigma$)
$\delta_{CP}/\pi$
CPV Significance vs $\delta_{CP}$
NH(IH considered), $\sin^2(2\theta_{13})$=0.07 to 0.12
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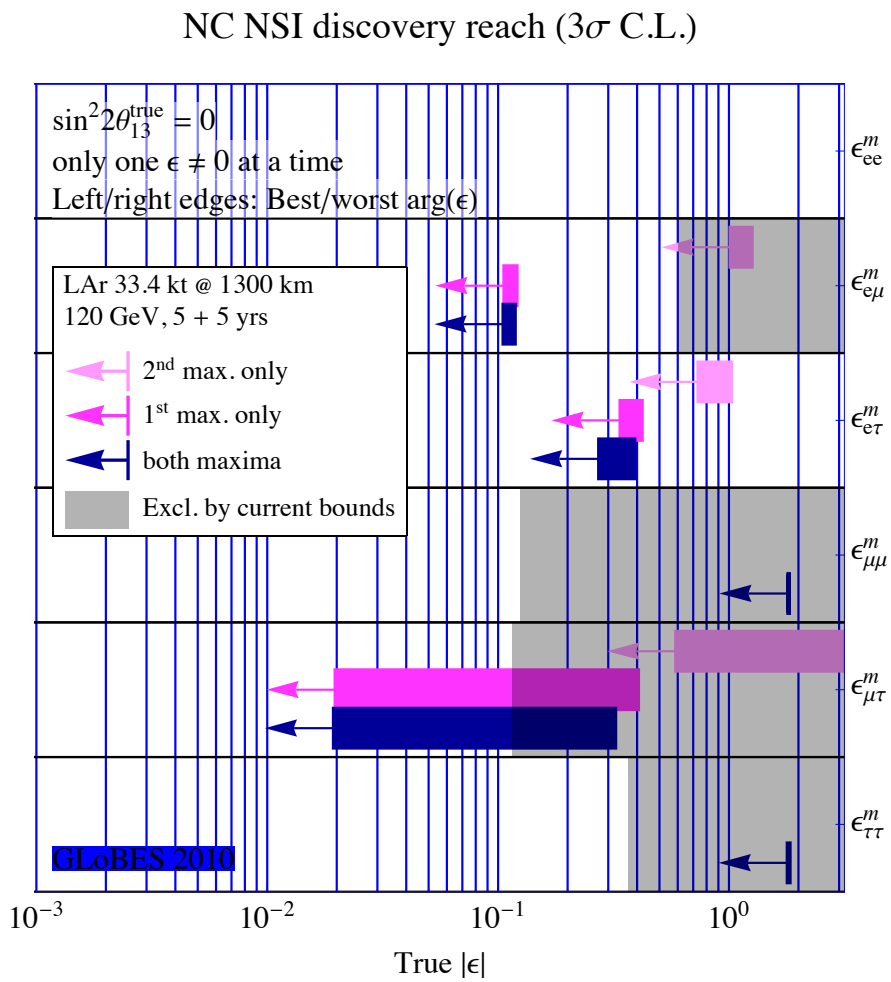
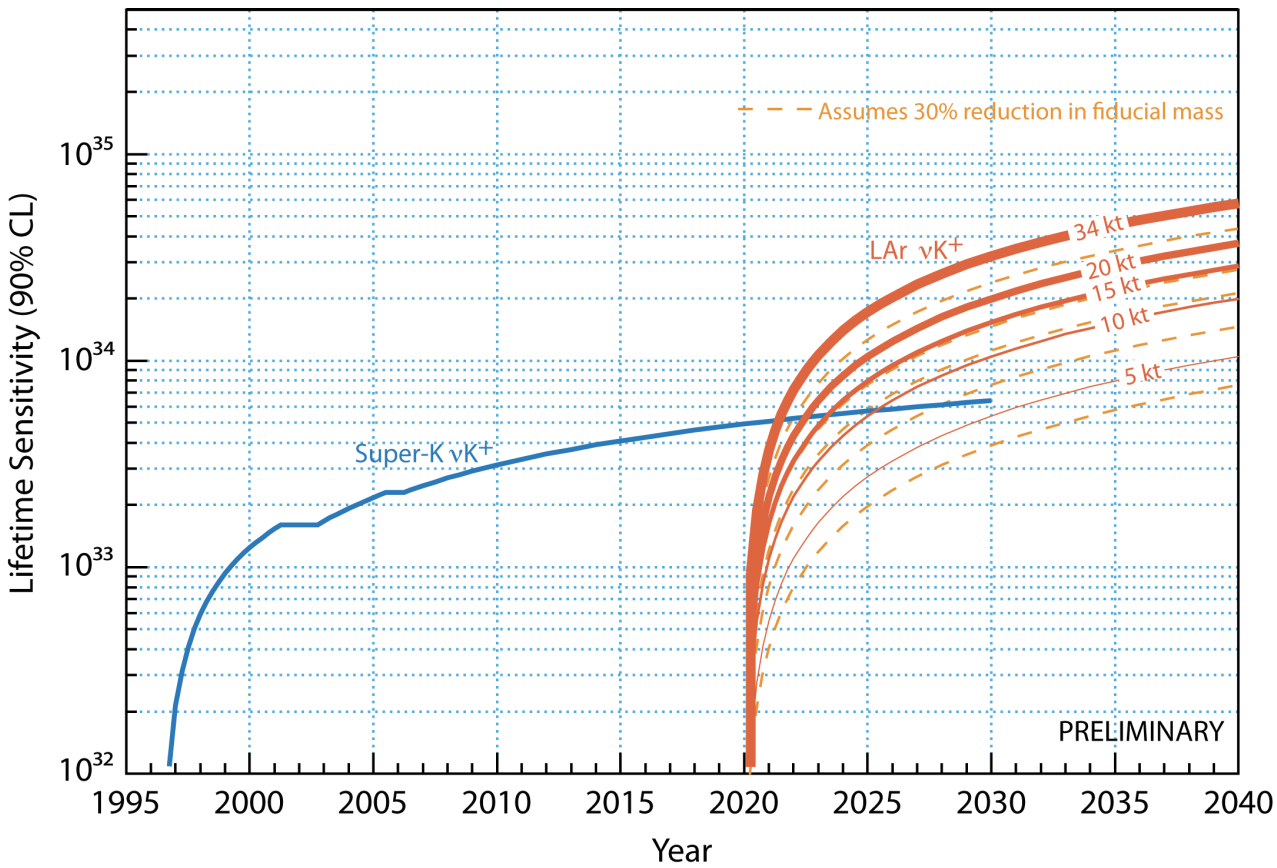
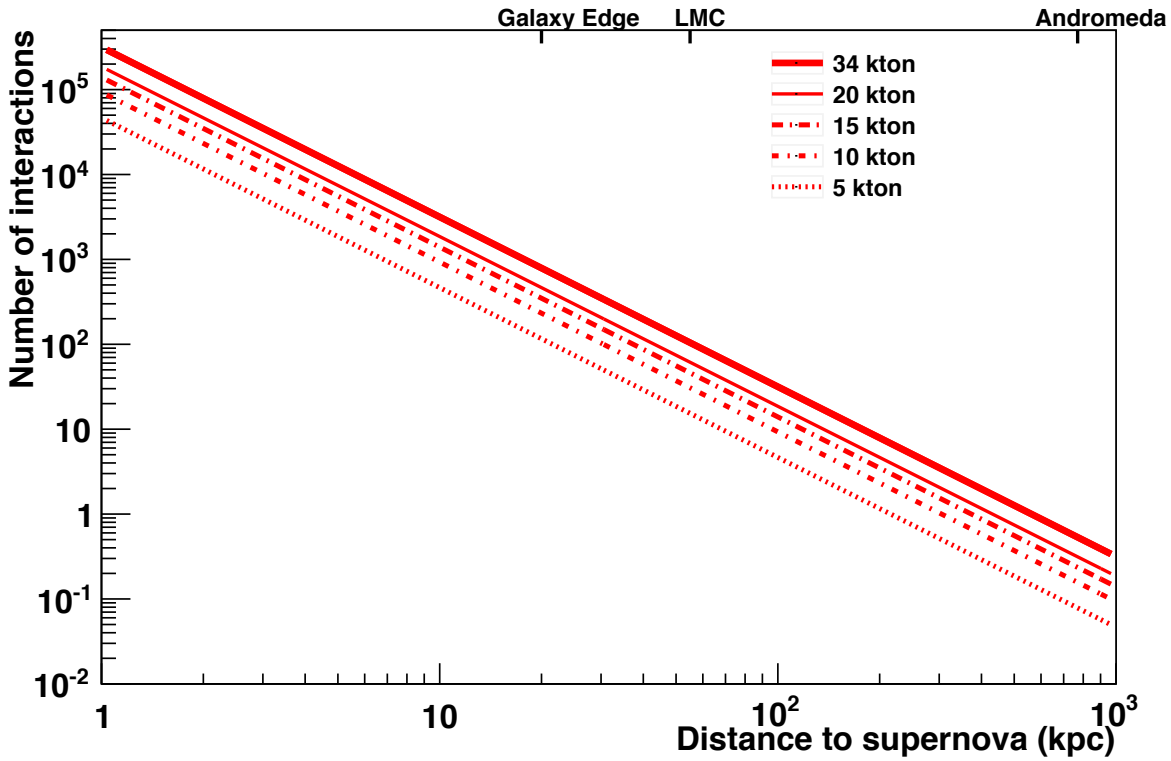
# Non-Standard Interactions



# Proton Decay



# Core Collapse Supernova



# 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: $m_\nu \lesssim \nu_{EW}^2/\overline{M}_P \sim 10^{-5}$ 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)

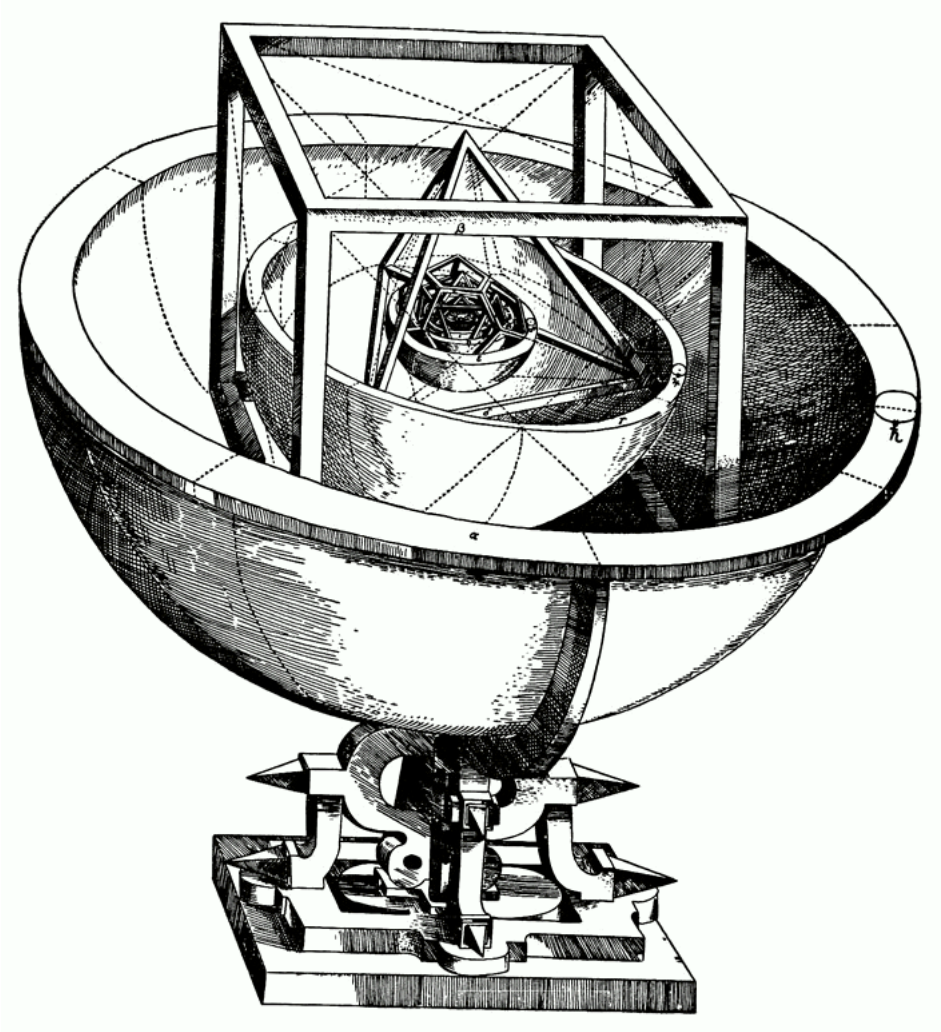
# Uniqueness or Environment

- **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, $\not{R}_p$)
  - $\theta_{13} \neq 0, \theta_{23} \neq 45^\circ$ excludes many models or requires perturbations

# Kepler's Mysterium Cosmographicum



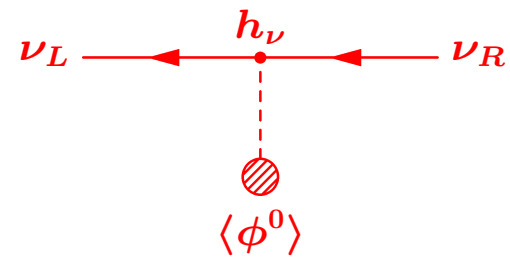
- **The environmental paradigm** (cf., planetary orbits)
  - No simple explanation of parameters
    (but scales/hierarchies by FN-like powers or exponentials?)
  - String landscape: $\gtrsim 10^{600}$ vacua with no known selection principle (A word?)
  - Subset habitable, with different groups, remnants, hierarchy mechanisms, parameters
  - Part of multiverse?
  - Underlying constraints often too complicated to unravel
  - Version of anarchy
- **Distinction of paradigms critical**

# Active and Sterile Neutrinos

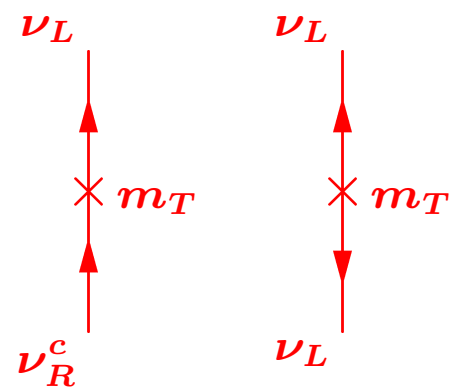
- **Active Neutrino (a.k.a. ordinary, doublet)**
  - in $SU(2)$ doublet with charged lepton $\rightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$ by $CP$
  - Only three light active allowed by $\Gamma_Z$
- **Sterile Neutrino (a.k.a. singlet, right-handed)**
  - $SU(2)$ singlet; no 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

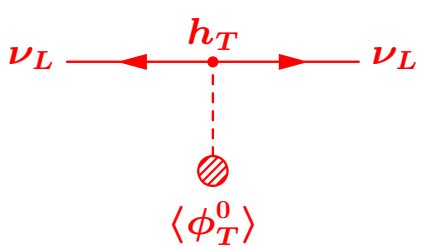
- **Dirac mass term connects two distinct neutrinos:** $m_D\left(\bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L\right)$
  **(4 components)**

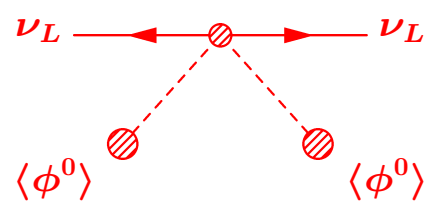



- **Majorana mass term connects neutrino with its $CP$ conjugate:**
  $\frac{m_T}{2}\left(\bar{\nu}_L\nu_R^c + \bar{\nu}_R^c\nu_L\right)$ **(2 components)**




- **Also possible for sterile:**
  $\frac{m_S}{2}\left(\bar{\nu}_L^c\nu_R + \bar{\nu}_R\nu_L^c\right)$



- **Can have simultaneous Majorana and Dirac mass terms**

$$-\mathcal{L} = \frac{1}{2} \underbrace{\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_L^c \end{pmatrix}}_{\text{weak eigenstates}} \begin{pmatrix} m_T & m_D \\ m_D & m_S \end{pmatrix} \begin{pmatrix} \nu_R^c \\ \nu_R \end{pmatrix} + h.c.$$

| | | | |
|---|---|---|---|
| $m_T$ : | $\lvert\Delta L\rvert = 2,$ | $\lvert\Delta t_L^3\rvert = 1$ | (Majorana) |
| $m_D$ : | $\lvert\Delta L\rvert = 0,$ | $\lvert\Delta t_L^3\rvert = \frac{1}{2}$ | (Dirac) |
| $m_S$ : | $\lvert\Delta L\rvert = 2,$ | $\lvert\Delta t_L^3\rvert = 0$ | (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**

# Minimality or Remnants

- **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

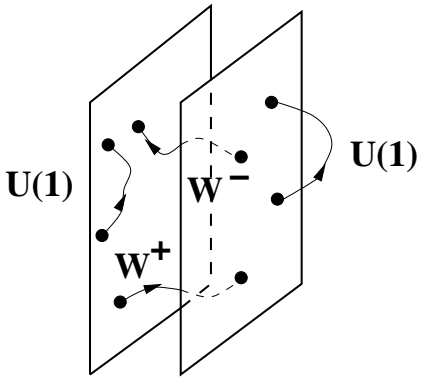
# Geometric Suppressions

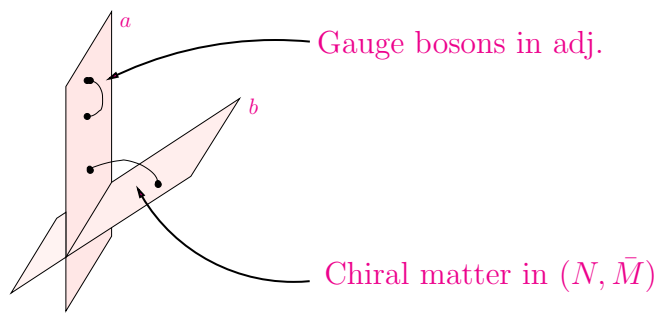
- **Wave function overlaps in large** (and/or warped) **extra dimensions, with $\nu_R$ propagating in bulk** (cf., gravity)

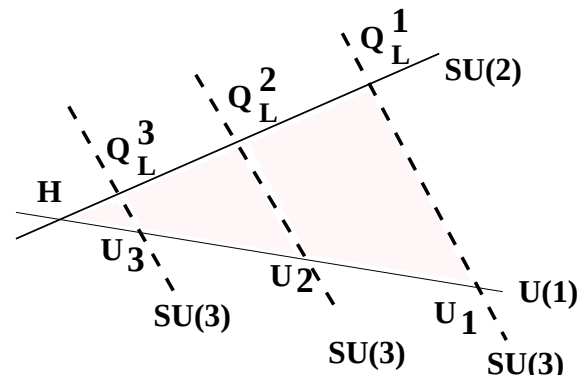
$$m_D \sim \frac{\nu M_F}{\overline{M}_P}, \qquad M_F = \left(\frac{\overline{M}_P^2}{V_\delta}\right)^{\frac{1}{\delta+2}} = \text{fundamental scale}$$

  - $\overline{M}_P = M_P/\sqrt{8\pi} \sim 2.4 \times 10^{18}$ GeV; $V_\delta =$ 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**
  - $m_D$: $A_{L\nu_L^c H_u}$ **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, $\nu_L^c \nu_L^c$, $L\nu_L^c H_u$, $QU^c H_u$, ...)
  - 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

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

  - Examples of small Dirac, small or intermediate $m_S$ (ordinary seesaw), stringy Weinberg operator ($LH_u LH_u/\mathcal{M}$)

# 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) $\Rightarrow$

$$\mathcal{L} \sim h_\nu L H_u \nu_L^c, \qquad h_S S \nu_L^c \nu_L^c, \qquad \frac{C}{\mathcal{M}} \underbrace{L H_u \, L H_u}_{\text{Weinberg op}}$$

$H_u$ = Higgs doublet, $S$ = singlet, $\mathcal{M}$ = new physics scale;
$\langle 0|H_u|0\rangle \lesssim \nu \sim 246$ GeV

# The Weinberg Operator

- **Most models for light Majorana neutrino:** $\frac{C}{\mathcal{M}} L H_u \, L H_u$

- **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,** $\cdots$
  - Typically, $\mathcal{M} \lesssim M_s \leq \overline{M}_P$ (need low $M_s$ or multiple modes)
  - Hybrid: $\nu_L^c$ with masses from D instantons; multiple ($\mathcal{O}(100)$) $\nu_L^c$ with $m_d, m_S$ from high-dimension stringy HDO
  - Details typically environmental (anarchic?)

# Small Dirac Masses

- Operators allowed by $SU(2)$

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

- 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

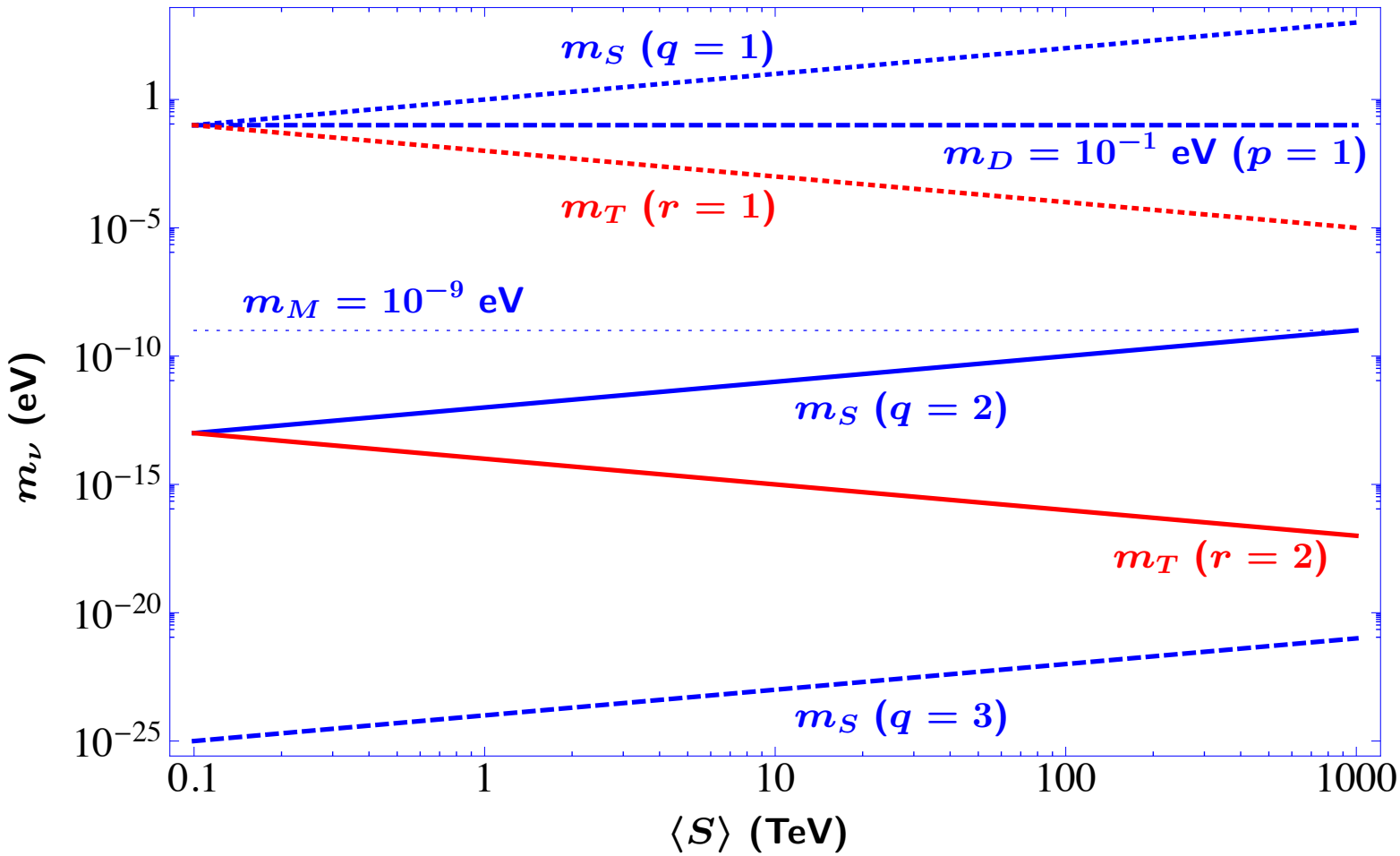
- Symmetry breaking by non-perturbative D instanton (exponential suppression) can yield tiny Dirac mass (and forbid Majorana)

- **Or perturbative symmetry breaking by VEV of SM singlet $S$**

$$\mathcal{L} \sim \frac{S^p}{\mathcal{M}^p} L H_u \nu_L^c, \qquad \frac{S^{q+1}}{\mathcal{M}^q} \nu_L^c \nu_L^c, \qquad \frac{S^{r-1}}{\mathcal{M}^r} L H_u \, L H_u$$

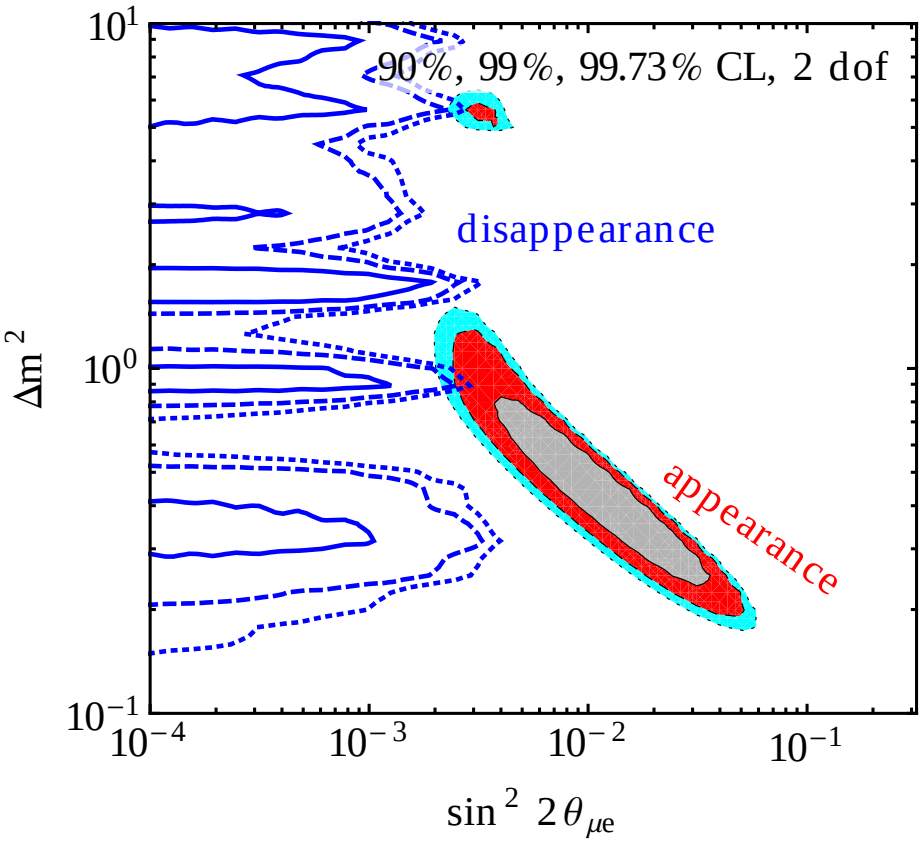
- **Small Dirac for $p > 0$**
  - $p = 1$, $S/\mathcal{M} \sim 10^{-12} \Rightarrow m_D \sim 0.1$ eV ($\mathcal{M} = \overline{M}_P \Rightarrow S \sim 10^3$ TeV)
    (e.g., non-anomalous $U(1)'$, non-holomorphic SUSY)
  - Majorana masses may be forbidden ($\Rightarrow$ pure Dirac)
  - Alternative: pseudo-Dirac with $q \geq 2, r \geq 2$ ($m_{S,T} < 10^{-9}$ eV)

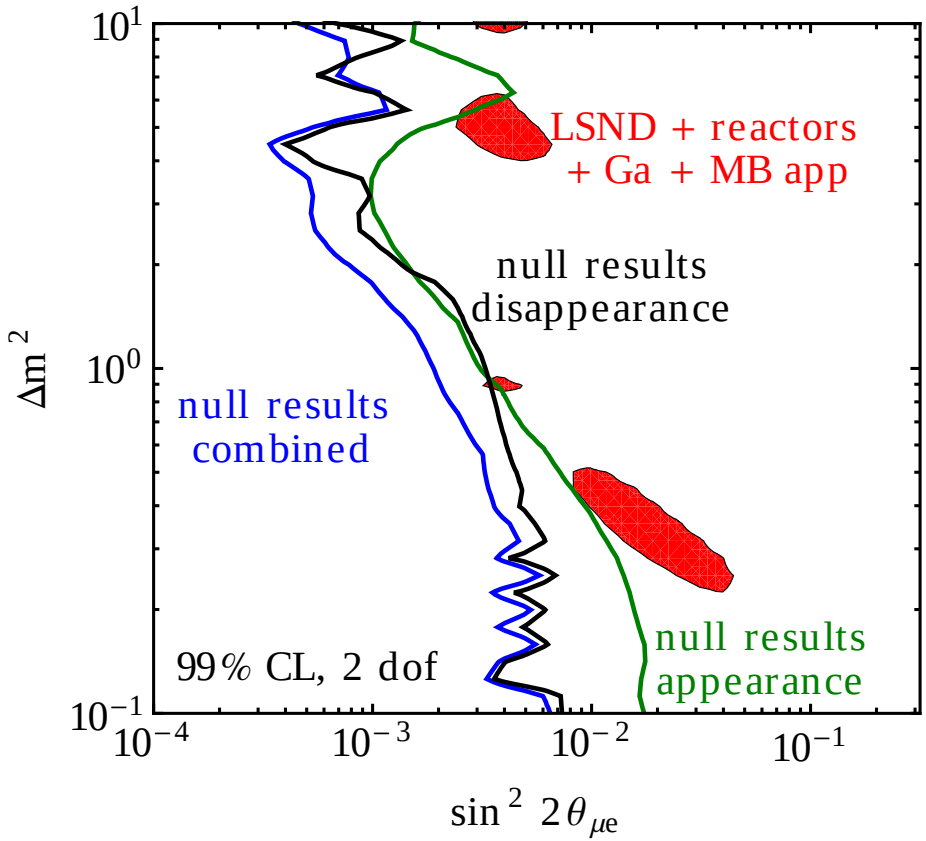
$$m_D \sim \frac{S^p \nu}{\mathcal{M}^p} \sim 0.1 \text{ eV} , \qquad m_S \sim \frac{S^{q+1}}{\mathcal{M}^q}, \qquad m_T \sim \frac{S^{r-1}\nu^2}{\mathcal{M}^r}$$



# 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: $N_{\rm eff}$ (Planck: $3.30 \pm 0.27$ vs 3.046), $\sum m_{\nu_i}$ ($< 0.23$ eV)
  (data sets?, priors? non-thermal?, other radiation?)
- No coherent picture




**Kopp, Machado, Maltoni, Schwetz, 1303.3011**

# 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**

$$-\mathcal{L} = \frac{1}{2} \underbrace{\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_L^c \end{pmatrix}}_{\text{weak eigenstates}} \begin{pmatrix} m_T & m_D \\ m_D & m_S \end{pmatrix} \begin{pmatrix} \nu_R^c \\ \nu_R \end{pmatrix} + h.c.$$

| | | | |
|---|---|---|---|
| $m_T$ : | $\lvert\Delta L\rvert = 2,$ | $\lvert\Delta t_L^3\rvert = 1$ | (Majorana) |
| $m_D$ : | $\lvert\Delta L\rvert = 0,$ | $\lvert\Delta t_L^3\rvert = \frac{1}{2}$ | (Dirac) |
| $m_S$ : | $\lvert\Delta L\rvert = 2,$ | $\lvert\Delta t_L^3\rvert = 0$ | (Majorana) |

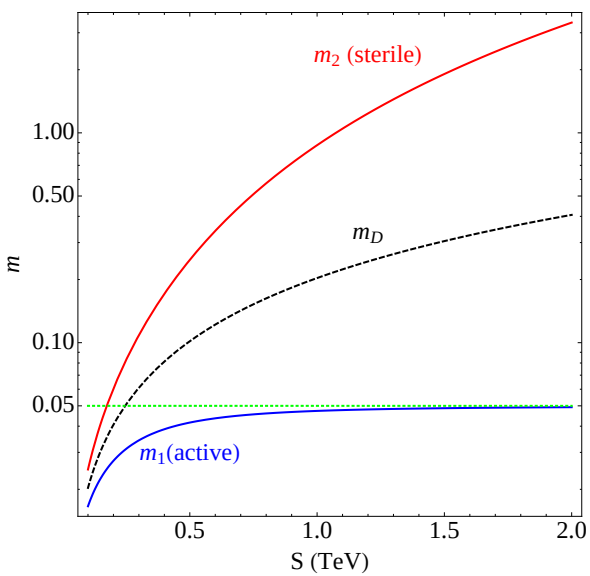
# The Mini-Seesaw

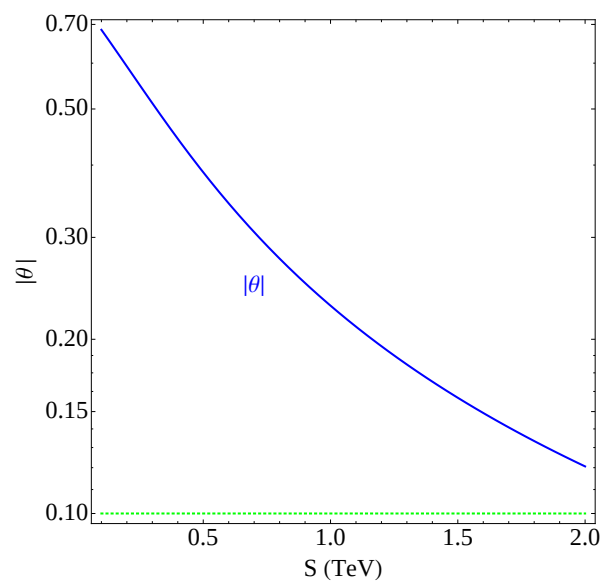
- **Active-sterile mixing suggests** $p = q = r = 1$

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

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

- **Ignore triplet term for simplicity** **(present in general)**

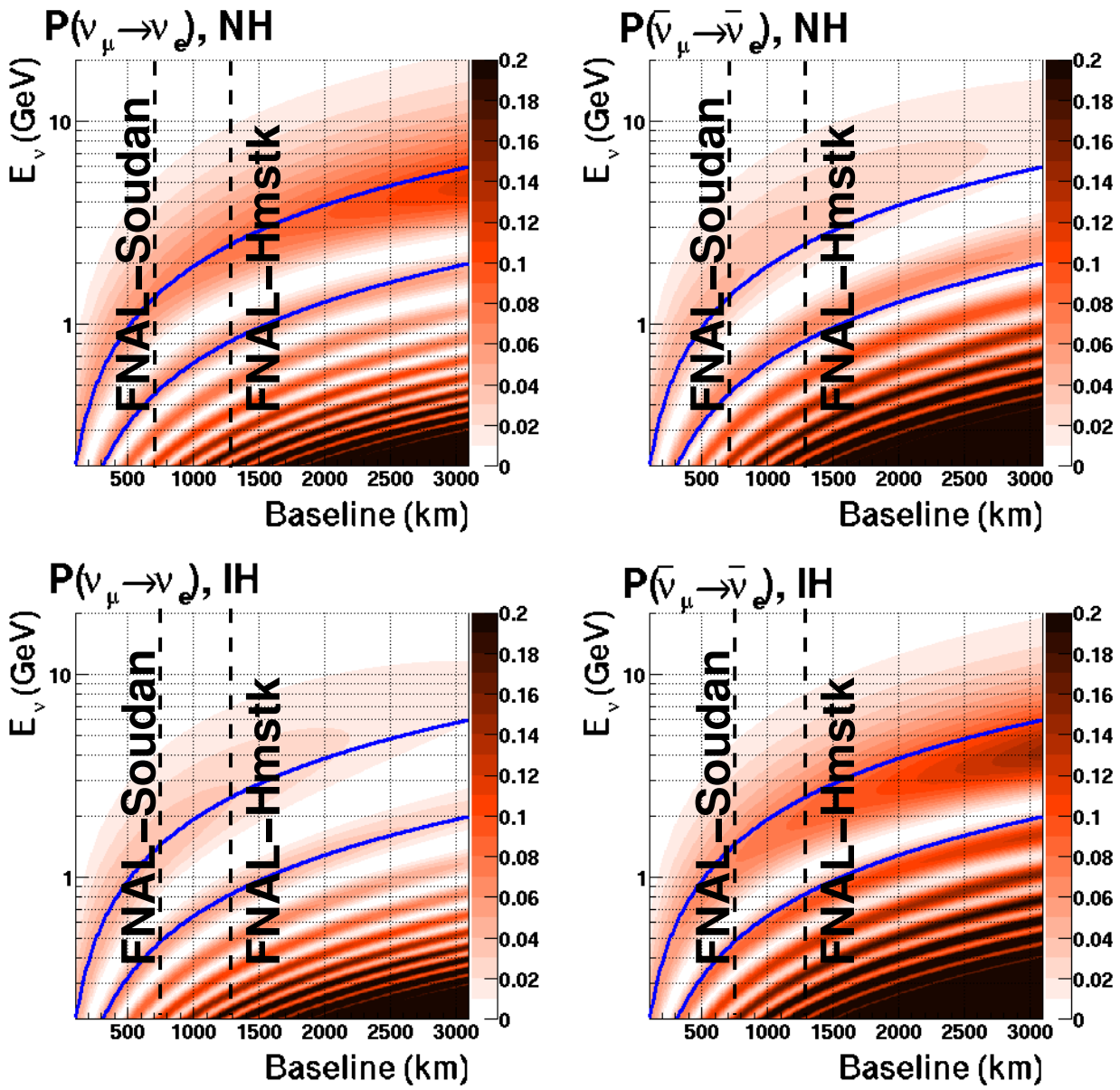


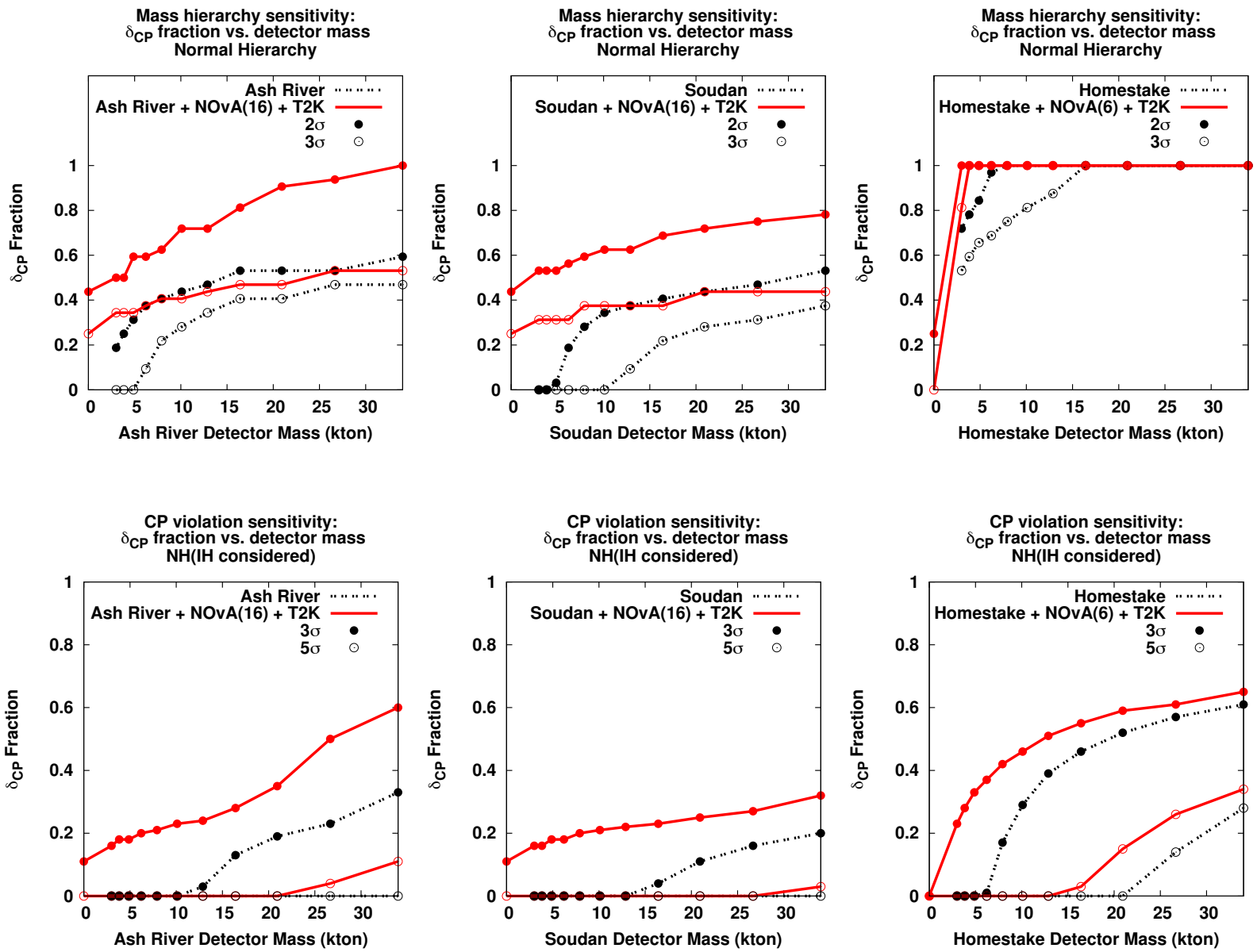



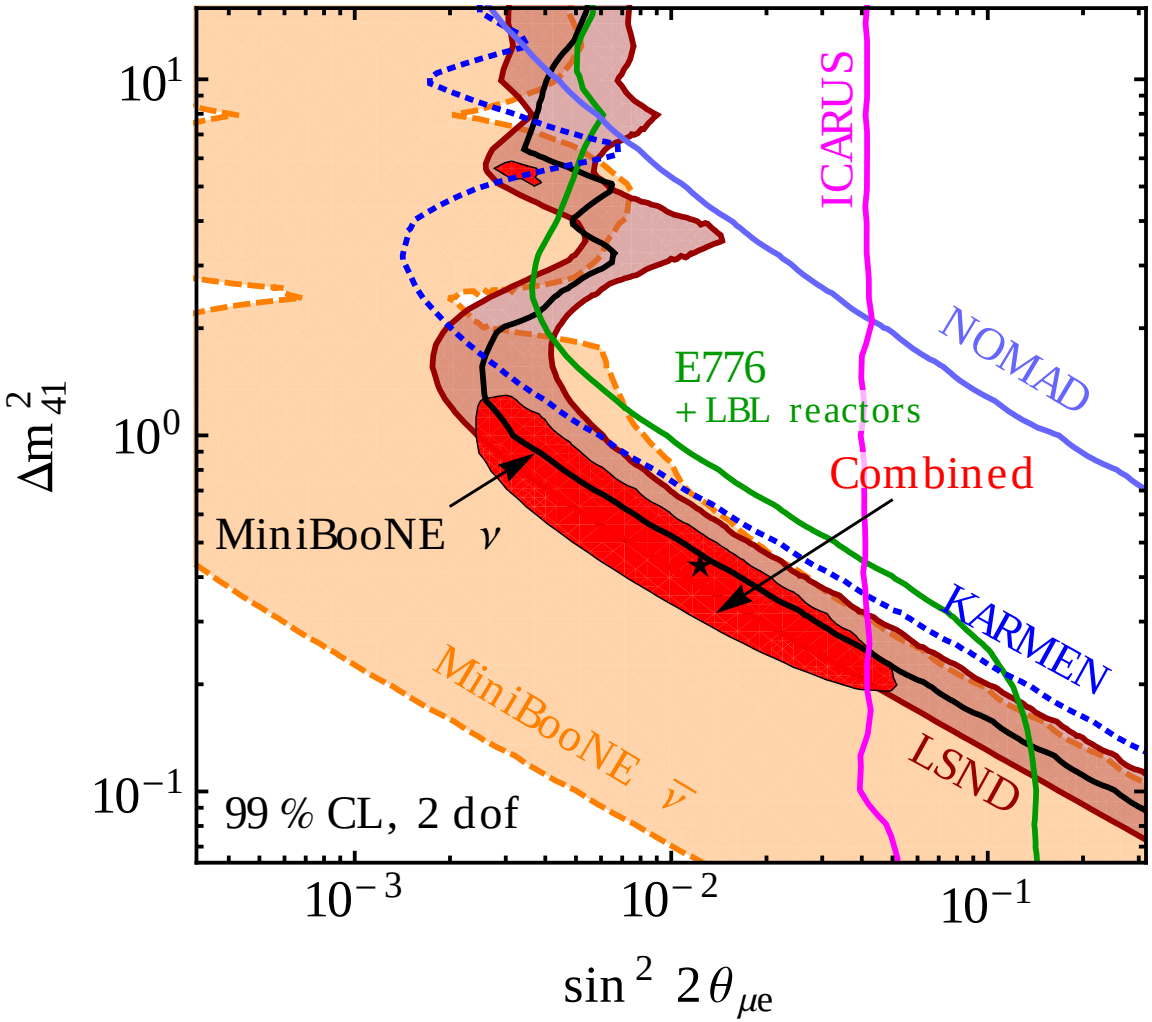
# Conclusions

- **Neutrinos are very important and very interesting**
- **We need more information: LBNE; LAr-TPC** (also proton decay, astrophysics); **sterile mixing;** $\beta\beta_{0\nu}$; $\cdots$
- **Many possibilities for small masses: Majorana, Dirac, or both**
- **Flavor physics: uniqueness or environment**

# Backup

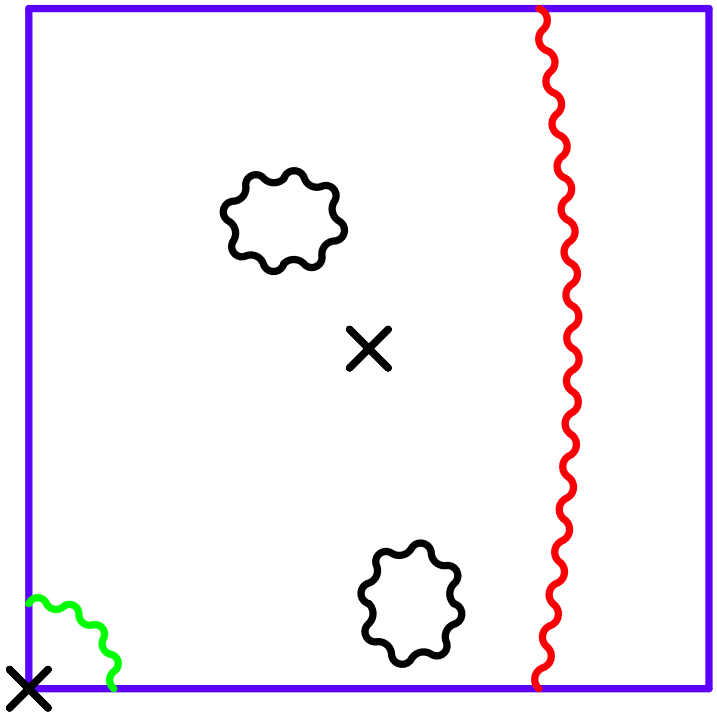

P(ν_μ→ν_e), NH
P(ν̄_μ→ν̄_e), NH
P(ν_μ→ν_e), IH
P(ν̄_μ→ν̄_e), IH
E_ν (GeV)
Baseline (km)
FNAL–Soudan
FNAL–Hmstk
500
1000
1500
2000
2500
3000
1
10
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

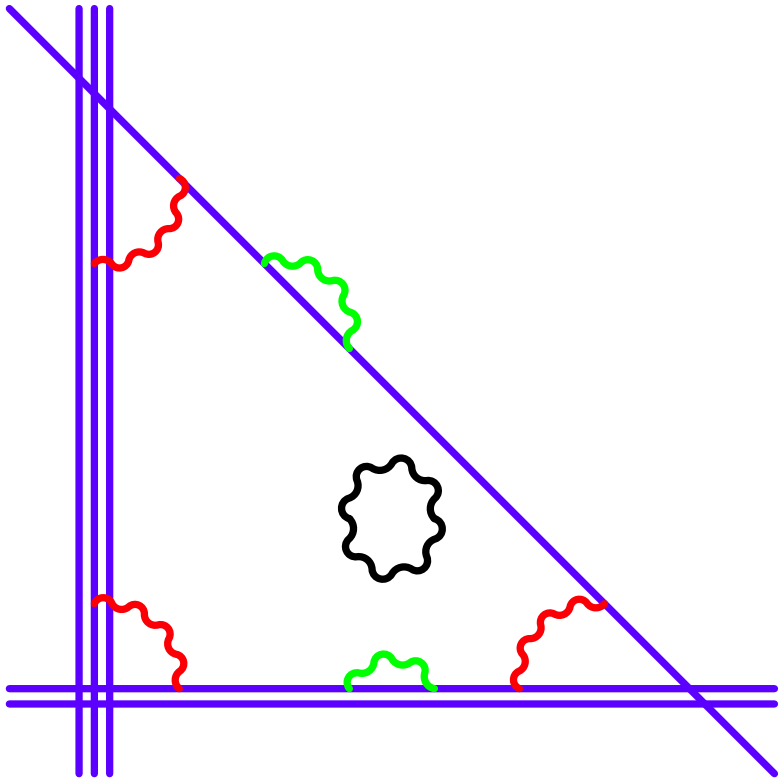

Mass hierarchy sensitivity:
δCP fraction vs. detector mass
Normal Hierarchy
Ash River
Ash River + NOvA(16) + T2K
2σ
3σ
δCP Fraction
Ash River Detector Mass (kton)
Mass hierarchy sensitivity:
δCP fraction vs. detector mass
Normal Hierarchy
Soudan
Soudan + NOvA(16) + T2K
2σ
3σ
δCP Fraction
Soudan Detector Mass (kton)
Mass hierarchy sensitivity:
δCP fraction vs. detector mass
Normal Hierarchy
Homestake
Homestake + NOvA(6) + T2K
2σ
3σ
δCP Fraction
Homestake Detector Mass (kton)
CP violation sensitivity:
δCP fraction vs. detector mass
NH(IH considered)
Ash River
Ash River + NOvA(16) + T2K
3σ
5σ
δCP Fraction
Ash River Detector Mass (kton)
CP violation sensitivity:
δCP fraction vs. detector mass
NH(IH considered)
Soudan
Soudan + NOvA(16) + T2K
3σ
5σ
δCP Fraction
Soudan Detector Mass (kton)
CP violation sensitivity:
δCP fraction vs. detector mass
NH(IH considered)
Homestake
Homestake + NOvA(6) + T2K
3σ
5σ
δCP Fraction
Homestake Detector Mass (kton)




**Kopp, Machado, Maltoni, Schwetz, 1303.3011**

# Heterotic and Intersecting Brane States





# Active-Sterile ($\nu_L^0 - \nu_L^{0c}$) 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.,

$$m_T = \epsilon,\ m_S = 0 \quad \Rightarrow \quad |m_{1,2}| = m_D \pm \epsilon/2$$

  - 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?