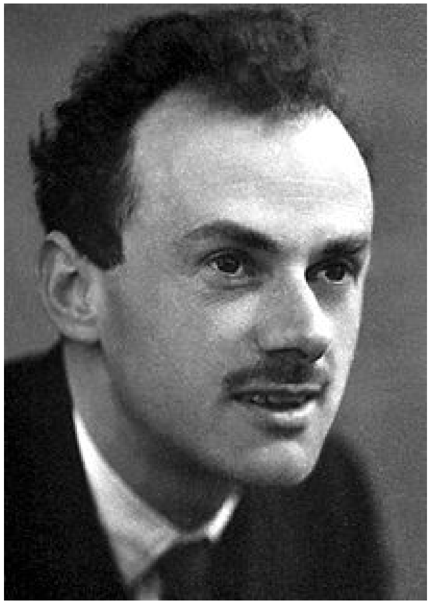
Sterile Neutrinos from the Top Down



- **Active-sterile mixing**
- **The landscape**
- **Small Dirac/Majorana masses**
- **The mini-seesaw**

- Light Sterile Neutrinos: A White Paper (K. Abazajian et al), 1204.5379
- Neutrino Masses from the Top Down, (PL), ARNPS 62, 1112.5992
- Light Sterile Neutrinos and Short Baseline Neutrino Oscillation Anomalies (JiJi Fan,PL), 1201.6662

Mixing Between Active and Sterile Neutrinos

- Most m_ν models involve sterile neutrinos (quark-lepton symmetry)
- Mass anywhere from sub-eV to $M_P \sim 10^{19}$ GeV
- LSND/MiniBooNE: possible oscillation between active and sterile
  - Mixing between active and sterile of *s*ame helicity
  - Need *two* types of small (eV-scale) masses (usually Dirac/Majorana)
- Warm dark matter (e.g., keV), pulsar kicks, supernovae, collider implications

Mixed Models

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

$$-\mathcal{L} = \frac{1}{2} \underbrace{\begin{pmatrix} \bar{\nu}_L^0 & \bar{\nu}_L^{0c} \end{pmatrix}}_{\text{weak eigenstates}} \begin{pmatrix} m_T & m_D \\ m_D & m_S \end{pmatrix} \begin{pmatrix} \nu_R^{0c} \\ \nu_R^0 \end{pmatrix} + h.c.$$

$m_T:$	$\lvert\Delta L\rvert = 2,$	$\lvert\Delta t_L^3\rvert = 1$	(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)

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 Δm^2 could affect Solar/supernova oscillations
  - Solar: need $m_{S,T} \lesssim 10^{-9}$ eV (de Gouvêa,Huang,Jenkins, 0906.1611)

The Landscape

- String vacuum enormously complicated
- Many points not consistent with what we know (but multiverse?)
- Goal 1: obtaining the MSSM
  - Possibilities for SUSY breaking/mediation, $\mu, B\mu,\ \not{R}_P, \cdots$
- Goal 2: beyond (instead of) MSSM paradigm (don't prejudge TeV)
  - (just) MSSM is not required by experimental data
  - Many string constructions involve TeV-scale *remnants* or *mechanisms* beyond the MSSM (may be hint)
- Bottom-up models of new physics usually motivated by minimality and/or solving problems

Minimality

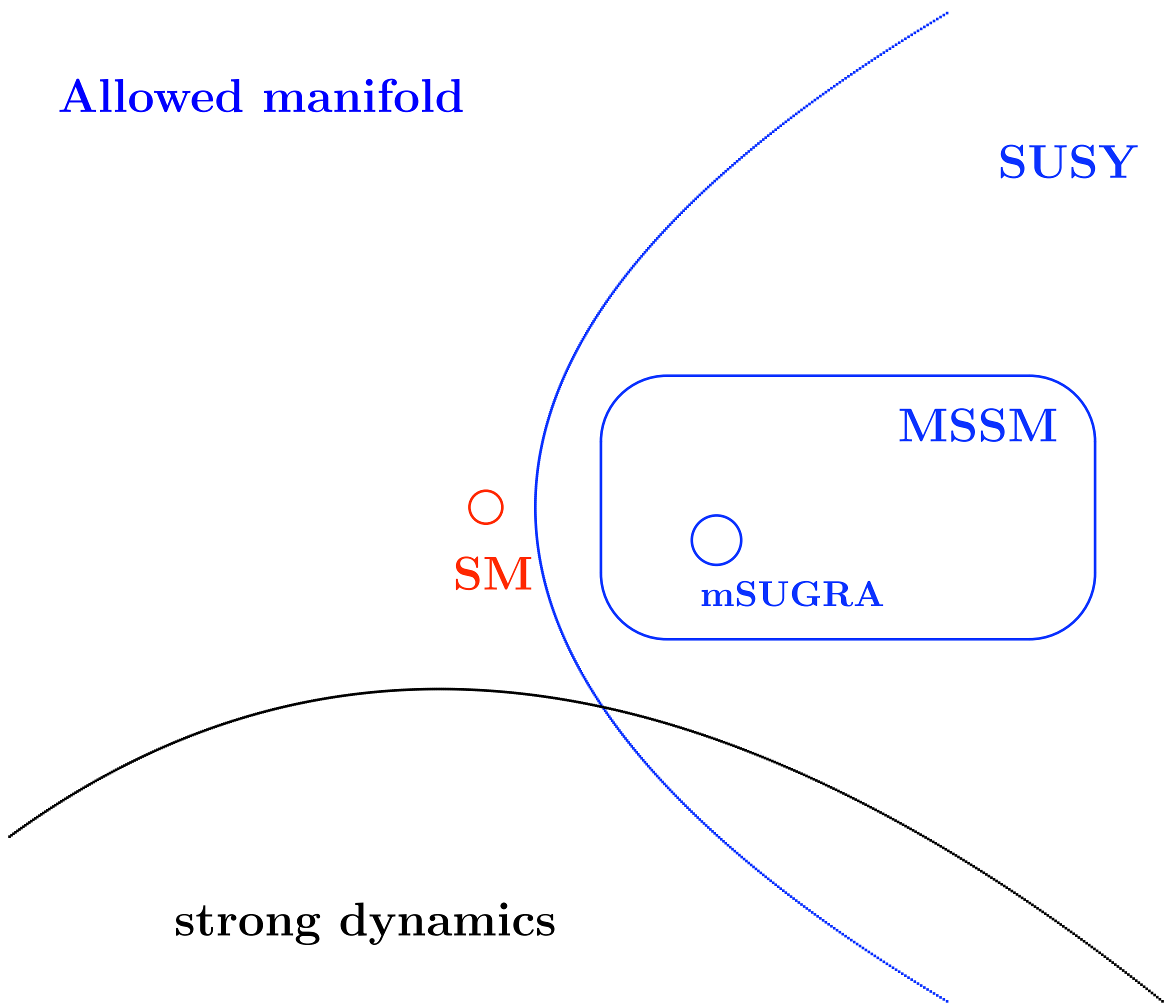

UNITED KINGDOM
IRELAND
Dublin
Belfast
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Celtic Sea
Irish Sea
Sea
DENMARK
Copenhagen
Malmö
Bornholm
Kaliningrad
Gdańsk
Hamburg
Bremen
Berlin
Poznań
POLAND
Warsaw
Łódź
Wrocław
Kraków
LITHUANIA
Vilnius
Minsk
Mahilyow
BELARUS
Hrodna
Homyel
Brest
Kiev
Rivne
L'viv
UKRAINE
Amsterdam
Rotterdam
NETH.
Essen
Cologne
Leipzig
GERMANY
Brussels
Lille
BEL.
Bonn
Frankfurt am Main
Prague
CZECH REPUBLIC
Brno
SLOVAKIA
Luxembourg
LUX.
Guernsey (U.K.)
Jersey (U.K.)
Paris
Stuttgart
Strasbourg
Munich
Vienna
AUSTRIA
Bratislava
Budapest
HUNGARY
Cluj-Napoca
Chernivtsi
Chişinău
MOLDOVA
Iaşi
Mykolayiv
Odesa
Nantes
FRANCE
Bay of Biscay
Zürich
Bern
Geneva
Vaduz
LIECH.
Lyon
Bordeaux
MASSIF CENTRAL
Turin
Milan
Venice
Ljubljana
SLOVENIA
Zagreb
CROATIA
BOSNIA AND HERZEGOVINA
Belgrade
Serbia
Sarajevo
ROMANIA
Bucharest
Constanta
Black Sea
Varna
BULGARIA
Sofia
Istanbul
Bilbao
Toulouse
Genoa
MONACO
SAN MARINO
Andorra la Vella
Marseille
PYRENEES
ANDORRA
Barcelona
Ligurian Sea
Florence
ITALY
Rome
VATICAN CITY
Adriatic Sea
Podgorica
Tirana
ALB.
Skopje
F.Y.R.O.M.
Thessaloniki
Bursa
TURKEY
Porto
Zaragoza
PORTUGAL
Madrid
Lisbon
SPAIN
Valencia
Balearic Sea
Corsica
Sardinia
Naples
Tyrrhenian Sea
GREECE
Athens
Aegean Sea
Izmir
BALEARIC ISLANDS
Cagliari
Sevilla
Málaga
Gibraltar (U.K.)
Strait of Gibraltar
Ceuta (SPAIN)
Alborán Sea
Mediterranean Sea
Algiers
Palermo
Sicily
Ionian Sea
Rhodes
Crete
Melilla (SPAIN)
Oran
Tunis
Valletta
MALTA
TUNISIA
Rabat
Casablanca
MOROCCO
ALGERIA
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
300 Kilometers
300 Miles

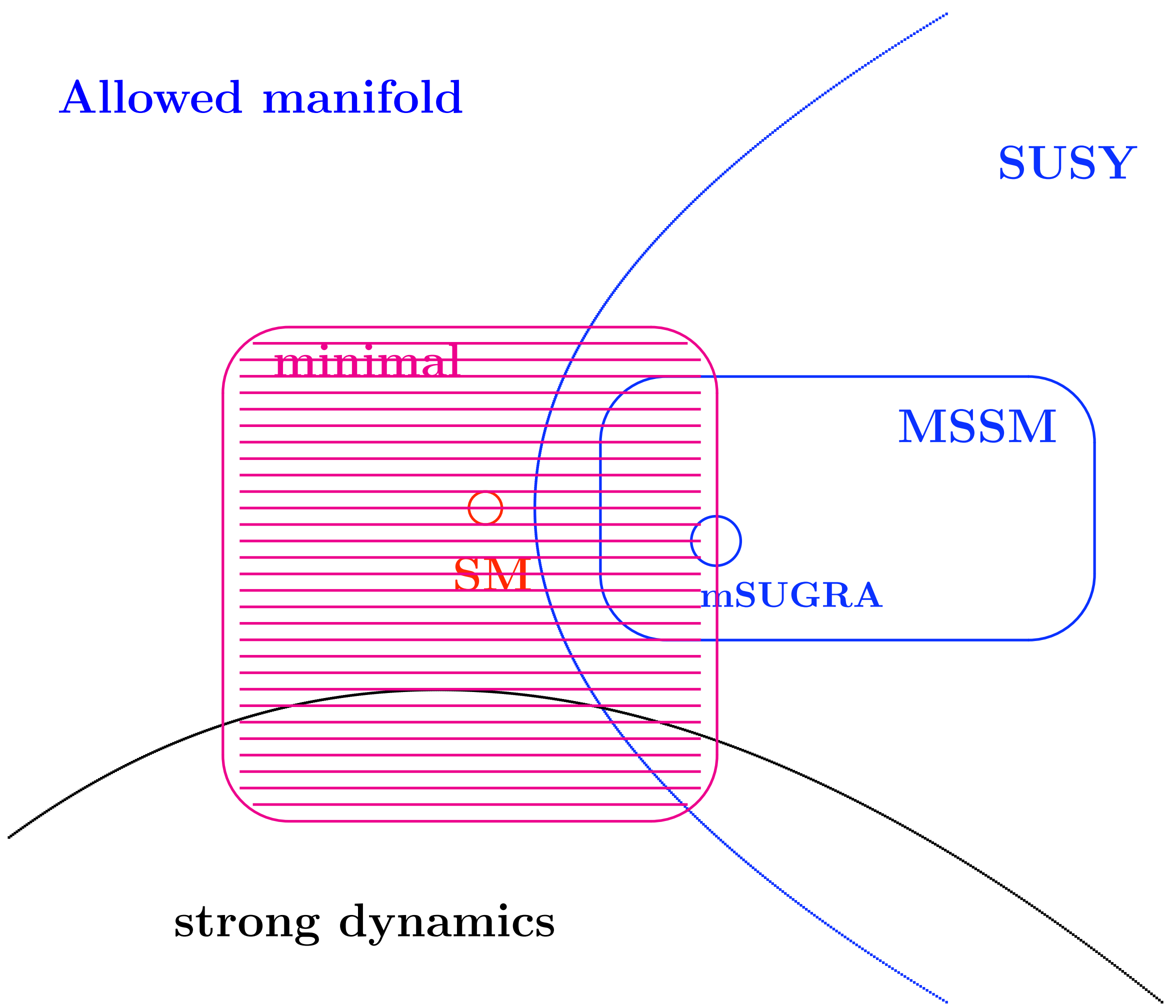
- **Top-down string remnants may not be minimal or motivated by SM problems**

- **Top-down may suggest new physical mechanisms** (e.g., string instantons: exponentially suppressed μ, Majorana or Dirac m_ν, etc)

- **Some bottom-up ideas unlikely to emerge from simple/perturbative string constructions** (e.g., high-dimensional representations)

- **Goal 3: mapping of string-likely or unlikely classes of new physics and mechanisms** (and contrast with field theory)


Allowed manifold
SUSY
MSSM
SM
mSUGRA
strong dynamics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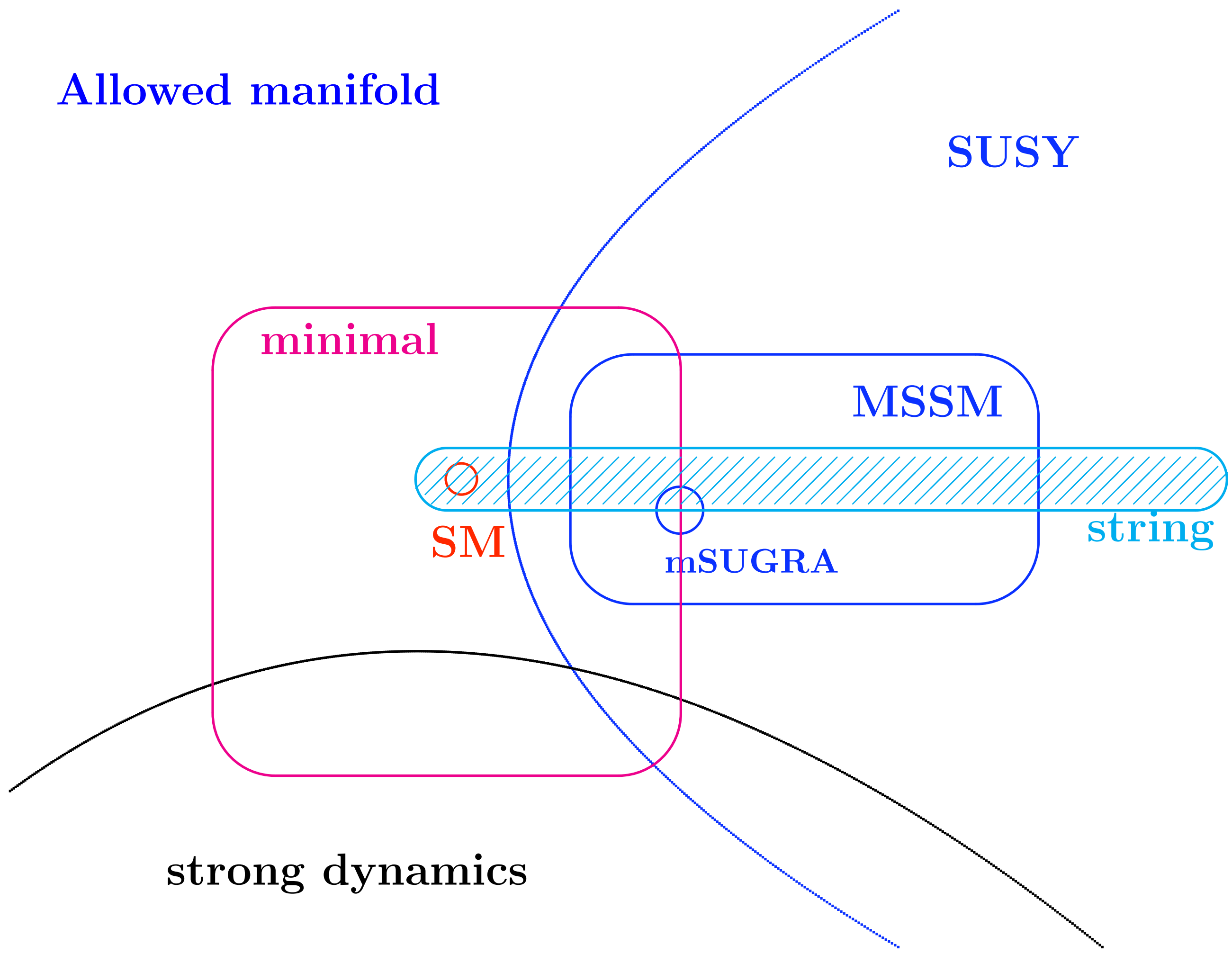

Allowed manifold
SUSY
minimal
MSSM
SM
string
mSUGRA
strong dynamics

- **Unlikely to find our exact vacuum**

- **Study semi-realistic/interesting vacua for suggestive features**

Very Small Masses

- **Mechanisms for very small masses** (Majorana, Dirac, or both)
  - Very small couplings
  - Loops
  - Geometric suppressions
  - Higher-dimensional operators (HDO)
- **Focus on correlated explanations for small Majorana and Dirac**

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

Apparent Fine-Tuning

- **Dirac:** $m_D \sim h_\nu \nu, \qquad \nu = 246$ GeV $\Rightarrow h_\nu \sim 10^{-12}$ for $m_D \sim 0.1$ eV

- **Sterile Majorana:**
  $m_S \sim \Gamma_S \overline{M}_P, \qquad \overline{M}_P \sim 2 \times 10^{18}$ GeV $\Rightarrow \Gamma_S \sim 10^{-27}$ for $m_S \sim 1$ eV

- May be due to geometric suppression or HDO in underlying theory

- No predictions without further input

Loops

- **Would need very high order** (or very small couplings)**, and suppression mechanism for lower-order**
- **Often combined with other mechanisms**

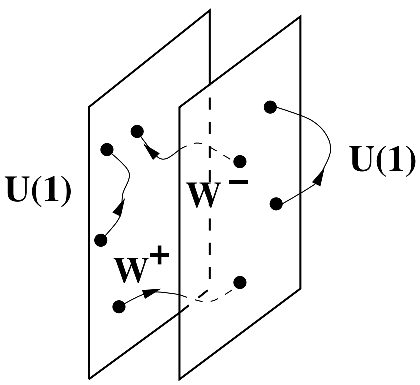
Geometric Suppressions

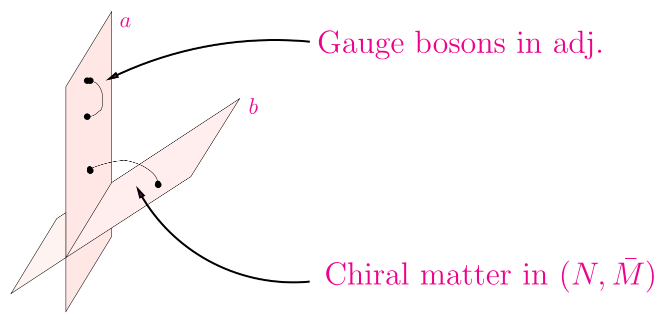
- Wave function overlaps in large (and/or warped) extra dimensions, with ν_R propagating in bulk (cf., gravity)

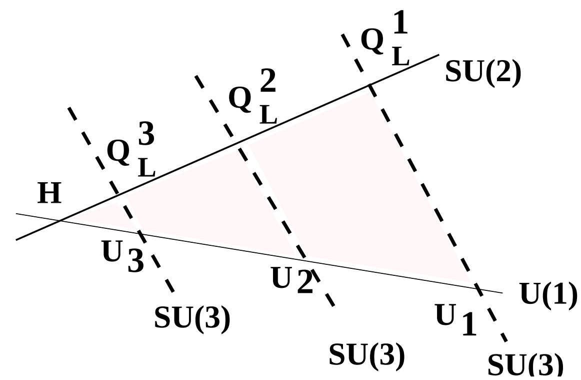
$$m_D \sim \frac{\nu M_F}{\overline{M}_P}, \qquad M_F = \left(\frac{\overline{M}_P^2}{V_\delta}\right)^{\frac{1}{\delta+2}} = \text{ fundamental scale}$$

  - $M_F \sim 100$ TeV $\Rightarrow m_D \sim 0.01$ eV
  - Kaluza-Klein excitations (Dirac sterile) for $V_\delta = R^\delta$:
    $m_{KK}/n \sim 1/R \sim M_F(M_F/\overline{M}_P)^{2/\delta} \xrightarrow[M_F \sim 100 \text{ TeV}, \ \delta=2]{} 10$ eV
  - Mixings too small in simplest versions
  - Can enhance by additional small mass terms, unequal dimensions
  - Can add Majorana masses

- **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

- **D-brane instantons**
  - Anomalous $U(1)'$: $M_{Z'} \sim M_{str}$; acts like perturbative global symmetry (may forbid μ, 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

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

  - Examples of small Dirac, small or intermediate M_S (ordinary seesaw), stringy Weinberg operator ($LH_uLH_u/\mathcal{M}$)
  - No known reason for correlated m_D, m_S

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)

- $L\nu_L^c$ 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 (HDO)

- Seesaw: $h_S \langle 0|S|0\rangle \sim 10^{14}$ GeV ($\ll \overline{M}_P$), $h_\nu \sim 1 \Rightarrow$ (Field theory) Weinberg operator, $\mathcal{M}/C \sim h_S \langle 0|S|0\rangle$, $\quad m_\nu \sim 0.1$ eV (or $h_S \langle 0|S|0\rangle \sim 10$ TeV for $h_\nu \sim 10^{-5} \sim m_e/\nu$)
  - $\mathcal{M}$ may also be induced by heavy triplet, neutralinos, string excitations, KK or winding modes, moduli, $\cdots$

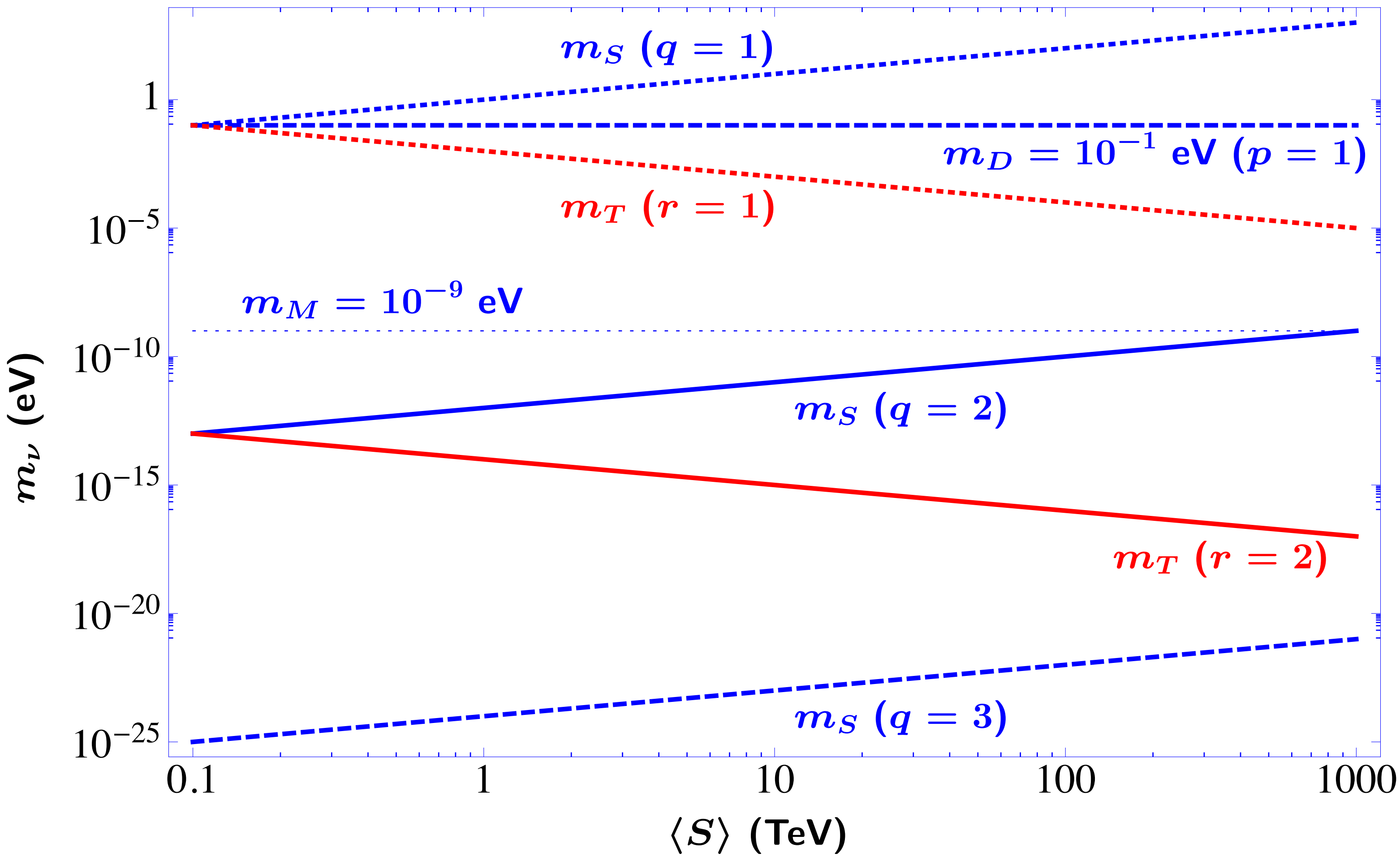
- **Additional symmetries** (gauge, global, discrete) **or string constraints** (heterotic or type II) **may further suppress coefficients**

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

  - $\frac{S^p}{\mathcal{M}^p} \rightarrow \frac{S_1 \cdots S_p}{\mathcal{M}_1 \cdots \mathcal{M}_p}$
  - Similar to Froggatt-Nielsen (but for overall scales)
  - Stringy or field-theoretic operators
  - Wide range of $S/\mathcal{M}, \mathcal{M}$ possible
  - E.g., $S/\mathcal{M} \sim 1/10$; large p, q; $\mathcal{M} \sim \overline{M}_P$ in heterotic seesaw (anomalous $U(1)'$)
  - Many modified/extended/inverted/radiative seesaws (various symmetries, $S, \mathcal{M} \gtrsim$ TeV scale)
  - May also be loop factors
  - Can extend to flavor structure

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

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



The Low-Scale Seesaw

- **Operators**

  PL, 9805281; Sayre,Wiesenfeldt,Willenbrock, 0504198; Chen,de Gouvêa,Dobrescu, 0612017

- **Motivations**

  Foot,Volkas, 9505359; Berezhiani,Mohapatra, 9505385; Ma, 9507348; Arkani-Hamed,Grossman, 9806223; Dvali,Nir, 9810257; Borzumati,Hamaguchi,Yanagida, 0011141; Appelquist,Shrock, 0204141; Babu,Seidl, 0405197; PL, 0801.1345; McDonald, 1010.2659; Barry,Rodejohann,Zhang, 1105.3911; Zhang, 1110.6838

- **Analysis**

  Casas,Ibarra, 0103065; de Gouvêa, 0501039; Smirnov,Zukanovich, 0603009; de Gouvêa,Jenkins,Vasudevan, 0608147; Donini,Hernandez,Lopez-Pavon,Maltoni, 1106.0064; Blennow,Fernandez-Martinez, 1107.3992; Xing, 1110.0083; de Gouvêa,Huang, 1110.6122; Fan,PL, 1201.6662

The Low-Scale Seesaw

- Both m_S and m_D suppressed by symmetries, e.g., $p = q = r = 1$

$$m_D \sim \Gamma_D \frac{S \nu_u}{\mathcal{M}}, \qquad m_S \sim \Gamma_S \frac{S^2}{\mathcal{M}} \sim 1 \text{ eV} , \qquad m_T \sim \Gamma_T \frac{\nu^2}{\mathcal{M}}$$

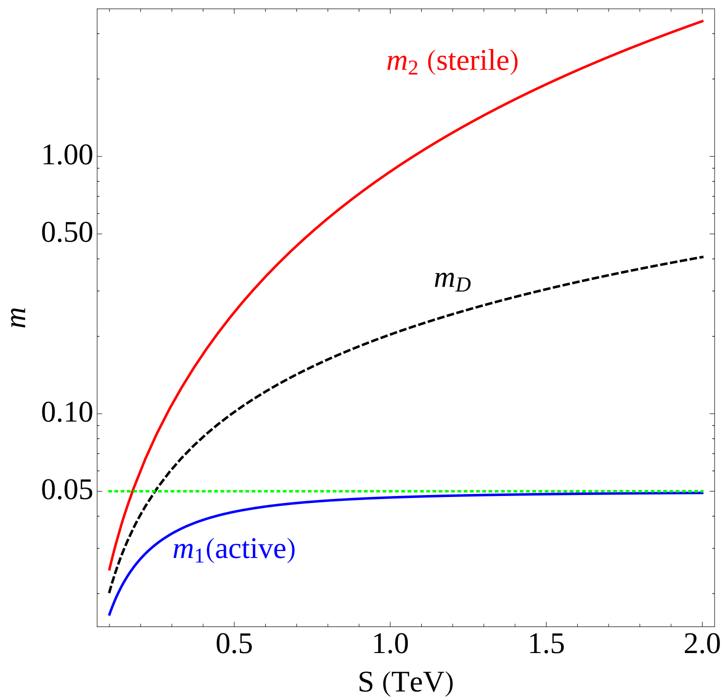
  – Example, minimal mini-seesaw (MMS): $(S \gg \nu)$ with $\Gamma_D = \Gamma_S = 1, \Gamma_T = 0 \Rightarrow$

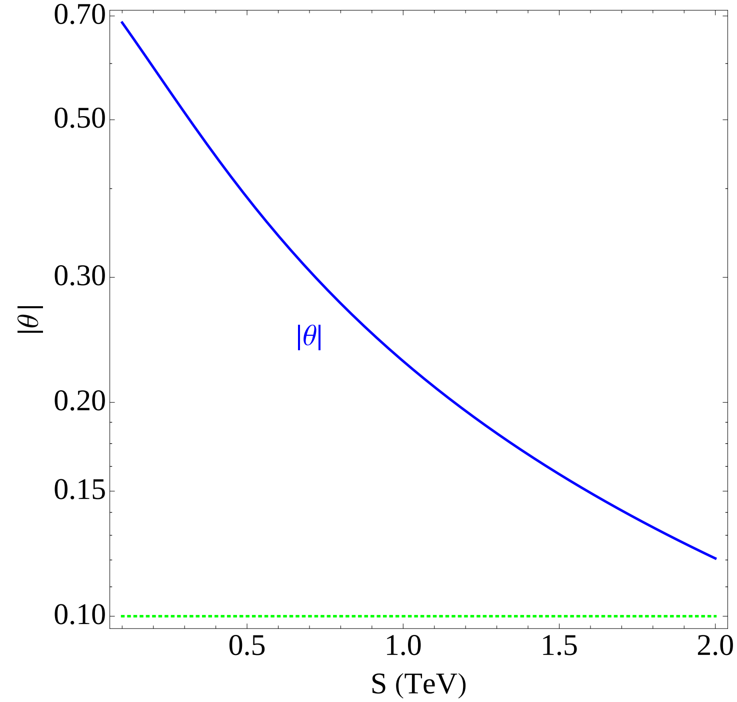
$$m_1 \sim -\frac{(\nu S/\mathcal{M})^2}{S^2/\mathcal{M}} = -\frac{\nu^2}{\mathcal{M}}, \qquad m_2 \sim \frac{S^2}{\mathcal{M}}$$

$$|\theta| \sim \frac{\nu}{S} \sim \sqrt{\frac{|m_1|}{m_2}}, \qquad \mathcal{M} \sim 10^{15} \text{ GeV}$$

  – m_T comparable for $\Gamma_T \sim 1$

Light Active





$$M = \begin{pmatrix} 0 & \Gamma_D \frac{\nu S}{\mathcal{M}} \\ \Gamma_D \frac{\nu S}{\mathcal{M}} & \Gamma_S \frac{S^2}{\mathcal{M}} \end{pmatrix}$$

$$\Gamma_D = \Gamma_S = 1$$

$$\mathcal{M} = 1.2 \times 10^{15} \text{ GeV}$$

$$\nu = 246 \text{ GeV}$$

- Can extend to $\mathbf{2+3}$ $[\mathbf{1+3}]$
  - Inverted [normal] hierarchy favored for $\Gamma_T \sim 0$
  - Can incorporate flavor structures, e.g., tri-bimaximal
- Examples from $U(1)'$, mirror worlds, TC/ETC (including loops)
- Hybrids with other schemes (e.g., ordinary high-scale seesaw) possible
- Alternative: heavy active (~ 1 eV) with $\Gamma_D = \Gamma_T = 1, \Gamma_S = 0$, $S < \nu$

Extension to $1+3$ and $2+3$

- $1+3$ **scheme:** $m_1 = m_2 = 0$

$$U_{\alpha 4} = i\frac{M_D^{\alpha 4}}{M_4} = \pm i \underbrace{A_L^{\nu\alpha 3}}_{\text{PMNS}} \sqrt{\frac{m_3}{M_4}}, \quad \alpha = e, \mu, \tau$$

  – $|U_{e4}|$ too small for LSND/MiniBooNE anomaly

$$|U_{e4}|\sqrt{M_4} = |A_L^{\nu e3}|\sqrt{m_3} \sim 0.033\sqrt{\text{eV}}$$
$$|U_{\mu 4}|\sqrt{M_4} = |A_L^{\nu\mu 3}|\sqrt{m_3} \sim 0.16\sqrt{\text{eV}}$$

  – No CP violation

- $2+3$ **scheme:** $m_3 = 0$ (IH) or $m_1 = 0$ (NH)

$$U_{\alpha i} = i A_L^{\nu \alpha j} \sqrt{m_j}\, R_{ji} \frac{1}{\sqrt{M_i}}$$

  - $R \equiv R(z) = \begin{pmatrix} \cos z & \sin z \\ -\sin z & \cos z \end{pmatrix}$ (2×2 *complex* rotation matrix) (Casas,Ibarra, 0103065)
  - $U_{\alpha i}$ determined up to $z \equiv r e^{i\theta}$ and one Majorana phase by masses and PMNS

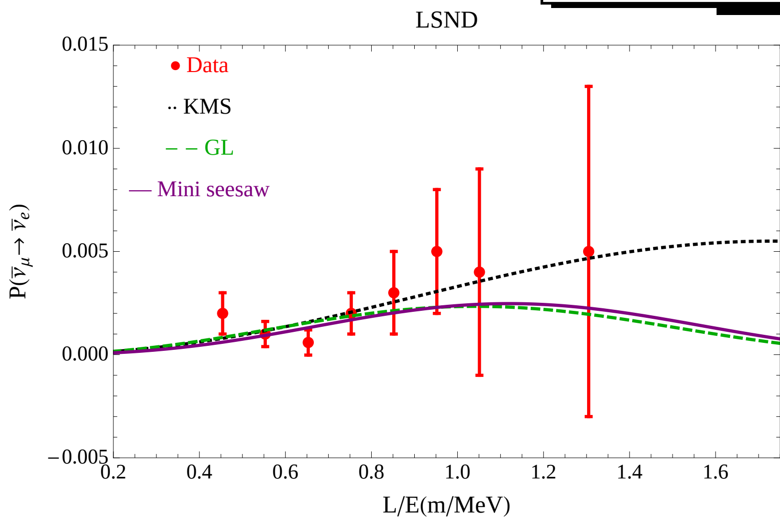
Comparison of mini-seesaw with LSND and MiniBooNE

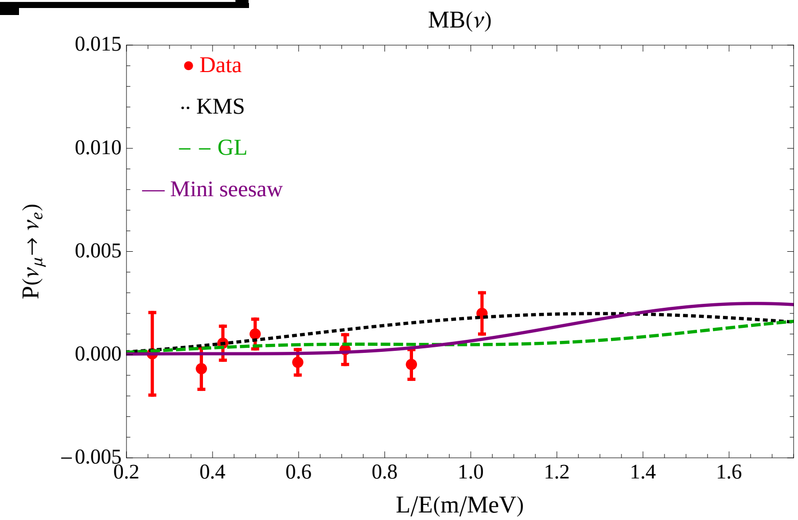
- Fit $z \equiv re^{i\theta}$, α_2 or α_3 (Majorana phase), M_4, M_5 to LSND/MiniBooNE
  (mock up other experiments by upper limit 0.15 on mixings)
  (Fan,PL, 1201.6662)

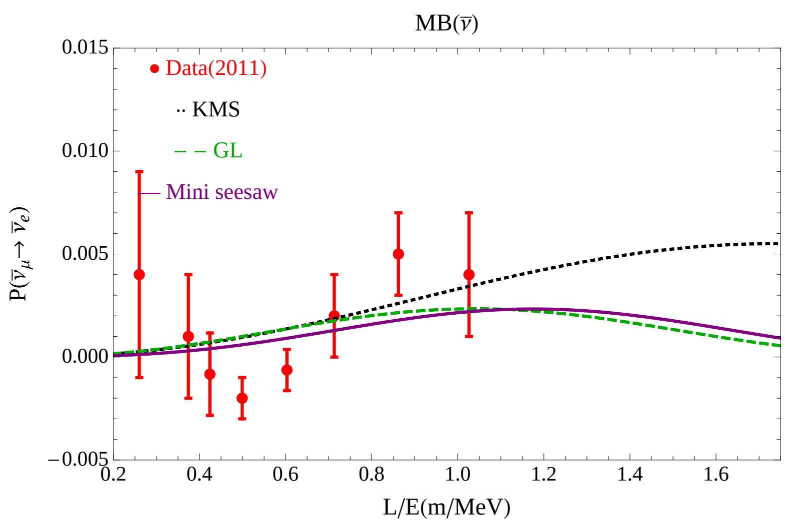
- Rough agreement with full analysis with general parameters by KMS (Kopp,Maltoni,Schwetz, 1103.4570), GL (Giunti,Laveder, 1107.1452)

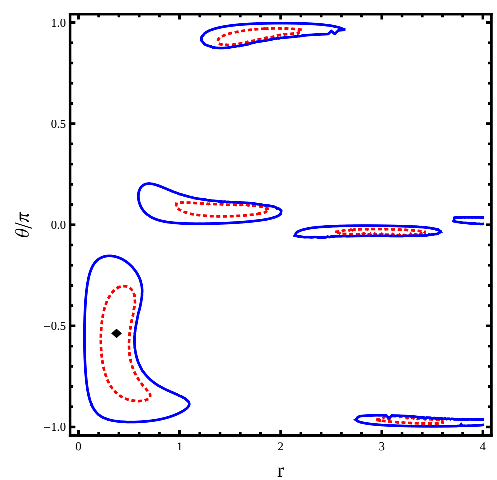
	z	$\alpha_2(\alpha_3)$	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
MMS-IH	$0.38\ e^{-i0.54\pi}$	1.92	0.89	1.76	0.15	0.15	0.07	0.15	1.21	24.3/19
MMS-NH	$1.22e^{-i0.69\pi}$	1.53	0.46	1.08	0.11	0.15	0.09	0.13	1.72	27.8/19
KMS			0.47	0.87	0.128	0.165	0.138	0.148	1.64	110.1/130
GL			0.90	1.60	0.13	0.13	0.13	0.08	1.52	22.2/5

Inverted Hierarchy

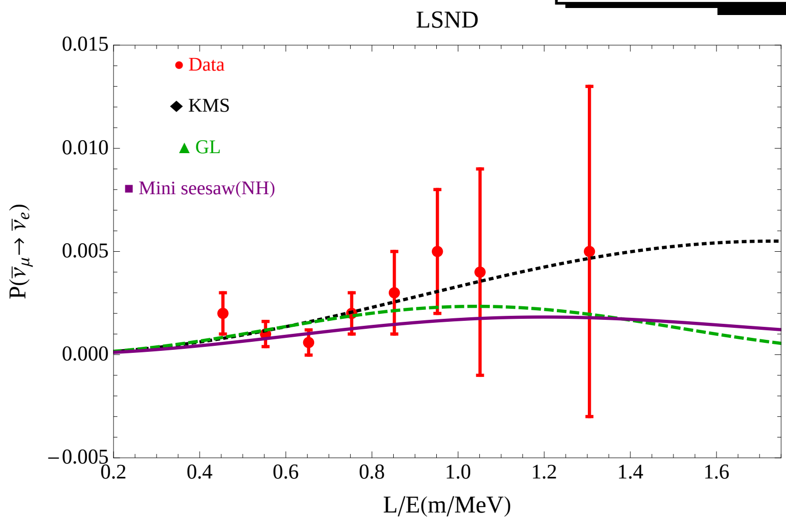


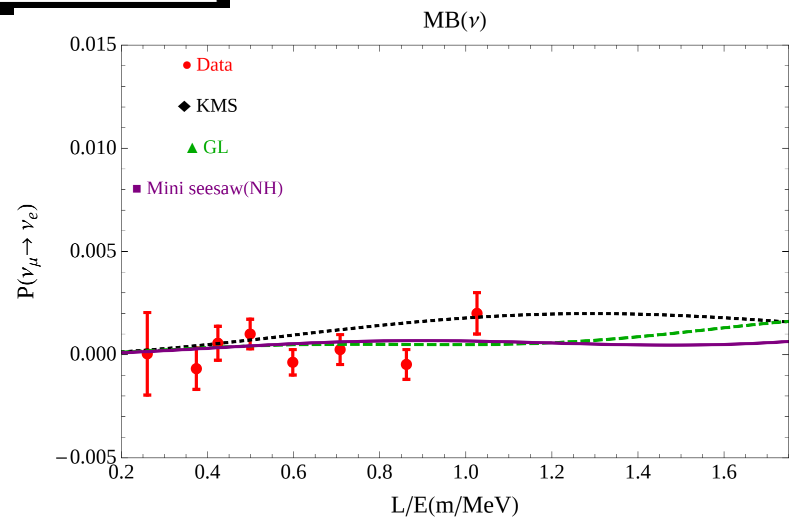


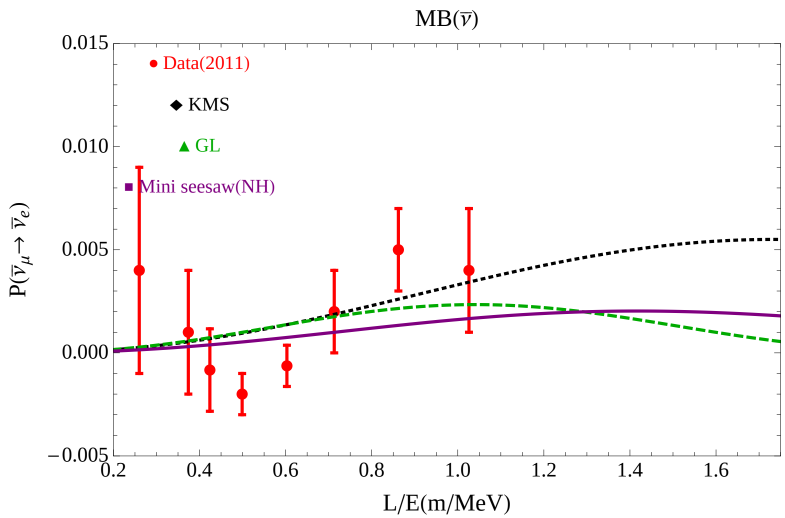


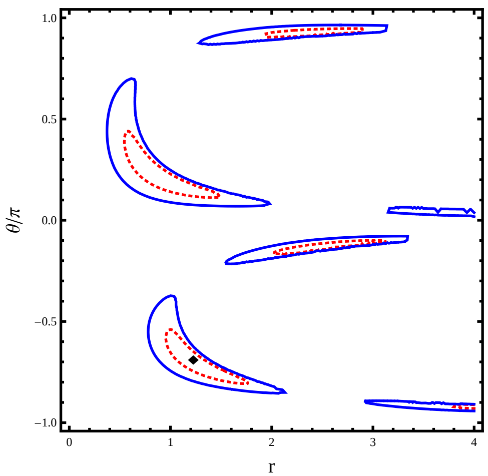


Normal Hierarchy









Implications

- **Parameters for tritium β decay, $\beta\beta_{0\nu}$, cosmology**

	3+2 (eV)	3+2 MSS-IH (eV)	3+2 MSS-NH (eV)	EXP (eV)
m_β	~ 0.2	0.18	0.12	$(1-2) \to 0.2$
$m_{\beta\beta}$	$0-0.08$	0	0	$(0.2-0.7) \to (0.01-0.03)$
Σ	~ 2	2.4	1.9	$(0.5-1) \to (0.05-0.1)$

- **Sum rules, $n \geq 2$,** (de Gouvêa,Huang, 1110.6122)

$$\sum_{i=4}^{n+3} |U_{\alpha i}|^2 M_i \geq \left| \sum_{j=1}^{3} A_L^{\nu\alpha j} \sqrt{m_j} \right|^2$$

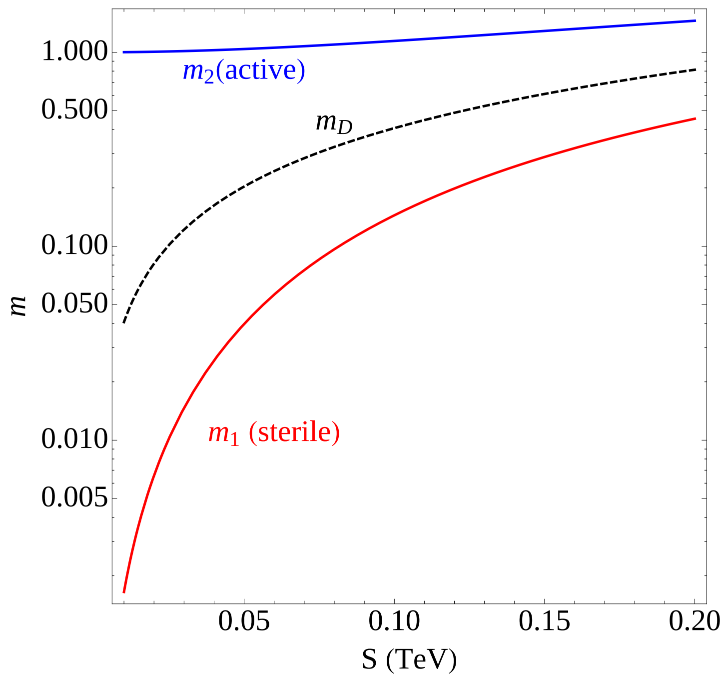
$$\xrightarrow[n=2,\text{IH}]{} \begin{pmatrix} 0.003 \\ 0.0014 \\ 0.0014 \end{pmatrix} \xrightarrow[n=2,\text{NH}]{} \begin{pmatrix} 0.001 \\ 0.02 \\ 0.02 \end{pmatrix}$$

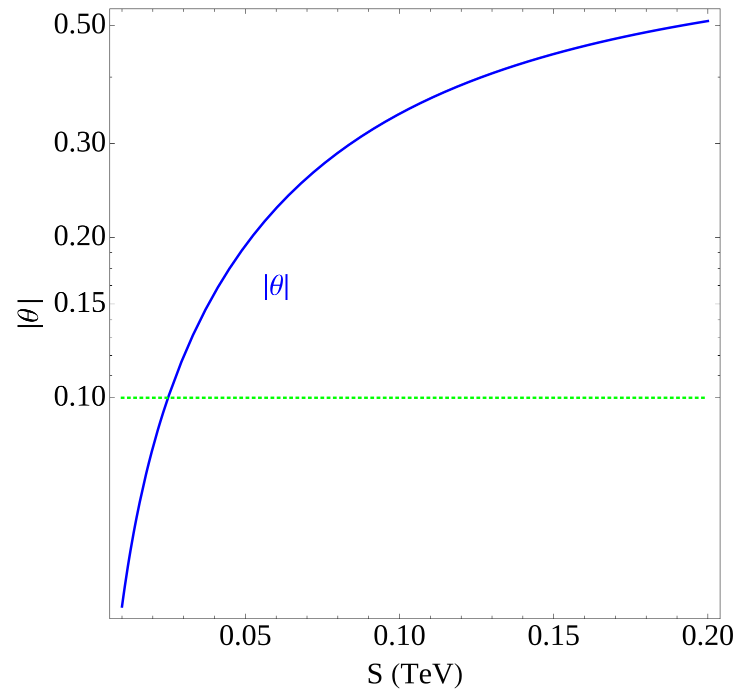
- **New MiniBooNE analysis?**

Conclusions

- Sterile neutrinos present in most theories
- LSND/MiniBooNE: need (small) active-sterile mixing (same helicity)
  - *Not* pure Majorana or Dirac, pseudo-Dirac, high-scale seesaw
  - The three miracles!
- Need mechanism for two types of small masses
  (usually Dirac and Majorana)
- Small masses from HDO, string instantons, large/warped extra dimensions
- Low-scale seesaw: Dirac and Majorana masses both suppressed by symmetries (mass-mixing relation) (cf. Froggatt-Nielsen)
  $\sim$consistent with data (new MiniBooNE?)

Heavy Active





$$M = \begin{pmatrix} \Gamma_T \frac{\nu^2}{\mathcal{M}} & \Gamma_D \frac{\nu S}{\mathcal{M}} \\ \Gamma_D \frac{\nu S}{\mathcal{M}} & 0 \end{pmatrix}$$

$\Gamma_D = \Gamma_T = 1$

$\mathcal{M} = 6 \times 10^{13}$ GeV

$\nu = 246$ GeV