Alternatives to the GUT Seesaw

- **Motivations**
- **Higher-dimensional operators**
- **String instantons**
- **Other (higher dimensions, Higgs triplets)**

Motivations

- Many mechanisms for small neutrino mass, both Majorana and Dirac
- Minimal Type I seesaw
  - Bottom-up motivation: no gauge symmetries prevent large Majorana mass for ν_R
  - Connection with leptogenesis
  - Argument that L *must be violated* is misleading
    (large 126 of $SO(10)$ or HDO added by hand)
  - New TeV or string scale physics/symmetries/constraints may invalidate assumptions

- **Standard alternatives: Higgs triplets, extended (TeV) seesaws, loops, R_p violation**

- **Explore plausible possibilities of string landscape**

  - **String-motivated alternatives: HDO (non-minimal seesaw, direct Majorana, Dirac); string instantons; geometric suppressions**

- **Alternatives often associated with new TeV physics, electroweak baryogenesis, etc.**

Higher-dimensional operators

- **The Weinberg operator** (most Majorana models)

$$-\mathcal{L}_{\phi\phi} = \frac{C}{2M}\left(\bar{\ell}_L \vec{\tau}\, \tilde{\ell}_R\right)\cdot\left(\phi^\dagger \vec{\tau}\tilde{\phi}\right) + h.c.$$
$$= \frac{C}{M}\left(\bar{\ell}_L\, \tilde{\phi}\right)\left(\phi^\dagger\, \tilde{\ell}_R\right) + h.c.$$
$$= \frac{C}{M}\bar{\ell}_L \begin{pmatrix} \phi^{0\dagger}\phi^- & \phi^{0\dagger}\phi^{0\dagger} \\ -\phi^-\phi^- & -\phi^-\phi^{0\dagger} \end{pmatrix} \tilde{\ell}_R + h.c.,$$

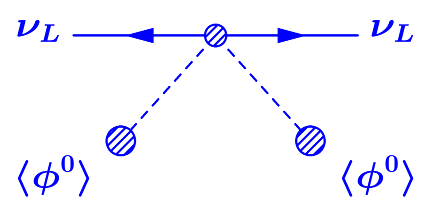
$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \tilde{\ell}_R = \begin{pmatrix} e_R^c \\ -\nu_R^c \end{pmatrix}, \quad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \tilde{\phi} = \begin{pmatrix} \phi^{0\dagger} \\ -\phi^- \end{pmatrix}$$

- **Superpotential:** $W = \frac{C}{M} L L H_u H_u$

- **Generate directly in string construction, or in effective 4d theory**

Direct generation of Weinberg operator

- Simplest possibility: generate operator by underlying string dynamics



$$W = \frac{C}{M} L L H_u H_u, \quad \text{with } C \lesssim 1, M = M_s \sim \overline{M}_P = \frac{M_P}{\sqrt{8\pi}} \sim 2.4 \times 10^{18} \text{ GeV}$$

$$\Rightarrow m_\nu \lesssim 10^{-5} \text{ eV } (\Rightarrow \text{need } M/C \sim 10^{14} \text{ GeV} \ll \overline{M}_P)$$

- Can compactify on internal volume

$$V_6 \gg M_s^{-6} \Rightarrow \overline{M}_P^2 \sim M_s^8 V_6$$

- Can obtain $m_\nu \sim 0.1$ eV for $V_6 \sim 10^{15} M_s^{-6}$ (Conlon,Cremades)
- $M_s \sim 10^{11}$ GeV still large compared to LED scenarios
- Will discuss string instanton induced case

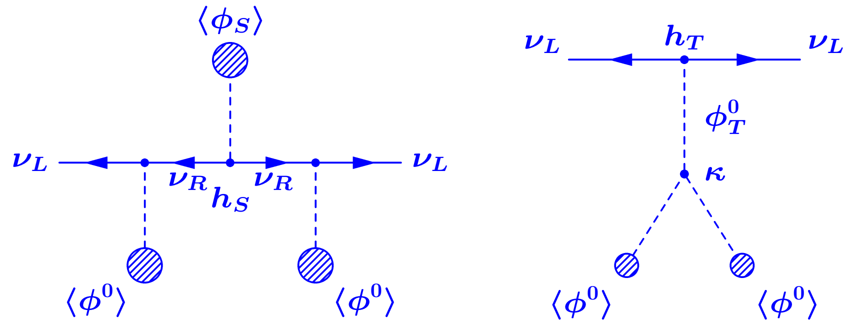
The GUT seesaw

- Realize Weinberg operator via heavy particle exchange in effective 4d theory

- Seesaw implementation

  Type I: heavy Majorana ν_R

  Type II: heavy Higgs triplet



- Type I in $SO(10)$: $\phi_S \in 126^*_H$ (Type II also possible)

$$W \sim h_u \underbrace{16 \times 16 \times 10_H}_{\bar{\nu}_L \nu_R \phi^0} + h_S \underbrace{16 \times 16 \times 126^*_H}_{\bar{\nu}_L \nu_R^c \phi_S}$$

- Alternative (Babu,Pati,Wilczek): replace 126^*_H by higher-dimensional operator: $W \sim \frac{\lambda}{M} 16 \times 16 \times 16^*_H \times 16^*_H$

  – Need $h_S |\langle\phi_{126^*_H}\rangle|$ or $\frac{\lambda}{M}|\langle\phi_{16^*_H}\rangle|^2 \sim 10^{14}$ GeV $\left|\frac{h_u \langle\phi_{10_H}\rangle}{100 \text{ GeV}}\right|^2$

The string seesaw

- Heterotic: Majorana mass for N^c from

$$W_N \sim c_{ij}\frac{S^{q+1}}{M_s^q}N_i^c N_j^c \quad \Rightarrow (m_N)_{ij} \sim c_{ij}\frac{\langle S\rangle^{q+1}}{M_s^q}, \quad q \geq 0$$

  - Simultaneous Dirac mass terms from

$$W_D \sim \left(\frac{S}{M_s}\right)^p LN^c H_u \quad \Rightarrow m_D \sim \left(\frac{\langle S\rangle}{M_s}\right)^p \langle H_u\rangle, \quad p \geq 0$$

  - SM singlet fields S may be different
  - Typically, $\frac{\langle S\rangle}{M_s} = \mathcal{O}(10^{-1})$ at minimum (e.g., if from FI term)
  - Must be consistent with string constraints/symmetries; with $F = D = 0$ (supersymmetry); $W = 0$ (cosmological constant)

- Difficult to satisfy all conditions
  - Caveat: $N_1^c N_2^c \Rightarrow$ Dirac; $N_1^c N_2^c + N_1^c N_3^c \Rightarrow$ Dirac + Weyl; need $N_1^c N_1^c$ or $N_1^c N_2^c + N_1^c N_3^c + N_2^c N_3^c$ for Majorana
  - No examples in Z_3 heterotic orbifold (Giedt,Kane,PL,Nelson)
- At least two examples in heterotic $E_8 \times E_8$ orbifold on $Z_3 \times Z_2$ (Buchmuller,Hamaguchi,Lebedev,Ramos-Sanchez,Ratz; Lebedev,Nilles,Raby,Ramos-Sanchez,Ratz,Vaudrevange,Wingerter)
  - May be many ($\mathcal{O}(10-100)$) N^c; $p \sim 0, \ldots, 6$, $q \sim 3, \ldots, 8$.
- Nonminimal. Simple $SO(10)$ relations lost
- Will comment on intersecting brane, F-theory

Other higher-dimensional operators

- HDO for ν_R mass possible for string seesaw, but *other* HDO also possible from string or effective theory
- Example: $W = \mu H_u H_d$
  - μ problem: why is $\mu = \mathcal{O}(M_{SUSY})$?
  - Can promote μ to dynamical variable ($e.g.$, $d > 2$ in W or in K, or string instanton)
  - NMSSM, nMSSM, UMSSM: $W = \lambda_S S H_u H_d$
    $\Rightarrow \mu_{eff} = \lambda_S \langle S \rangle$ (S= SM singlet; usually $\langle S \rangle = \mathcal{O}(\nu) \sim 246$ GeV)
  - Giudice-Masiero: $K = \frac{X^\dagger}{M} H_u H_d + h.c.$, where $X = \theta\theta F$ (SM singlet); for $M_{SUSY} = F/M \Rightarrow \mu_{eff} = \mathcal{O}(M_{SUSY})$
    (e.g., $M = \overline{M}_P$ in supergravity)
  - Both cases: assume new symmetry of effective theory *or* string constraints forbids elementary μ

- Many other possibilities for small neutrino masses utilizing W or K (both Majorana and Dirac)
  (Cleaver,Cvetič,Espinosa,Everett,PL; PL; Arkani-Hamed,Hall,Murayama,Smith,Weiner; Borzumati,Nomura; March-Russel,West; Dvali,Nir; Frere,Libanov,Troitsky; Casas,Espinosa,Navarro; Demir,Everett,PL)

- Invoke extra symmetries (e.g., $U(1)'$) or string constraints to forbid, e.g., elementary Dirac Yukawa $W = LN^c H_u$

- Example: small Dirac from HDO in W (CCEEL): $W \sim \frac{S}{M} LN^c H_u$

$$m_\nu \sim \frac{\langle S \rangle \nu_u}{M} \Rightarrow \langle S \rangle = 1000 \text{ TeV for } M = \overline{M}_P$$

  - e.g. (approximately) flat breaking of $U(1)'$(CCEEL); Z' mediation (PL,Paz,Wang,Yavin), . . .

- **Example: small Majorana from non-holomorphic K (CEN)**

$$K \sim \frac{1}{M^2} L H_u L \tilde{H}_d + h.c., \qquad \tilde{H}_d \equiv \begin{pmatrix} H_d^+ \\ -H_d^{0\dagger} \end{pmatrix}$$

  - But $F_{H_d^*} = -\mu H_u$ (or $-\mu_{eff} H_u$) $\Rightarrow m_\nu \sim \frac{\mu \nu_u^2}{M^2}$
  - $\mu \sim 100$ GeV $\Rightarrow M \sim 10^8$ GeV, e.g., SUSY mediation scale

- **Example: small Dirac from non-holomorphic K (DEL)**

$$K \sim \frac{1}{M^2} X^\dagger L N^c \tilde{H}_d + h.c., \text{ with } X = \theta\theta F$$

  - $M =$ SUSY mediation scale (e.g., 10^{14} GeV), $M_{SUSY} = F/M$
  - "W" $= \frac{M_{SUSY}}{M} L N^c \tilde{H}_d \Rightarrow m_\nu \sim \frac{M_{SUSY} \nu_d}{M}$

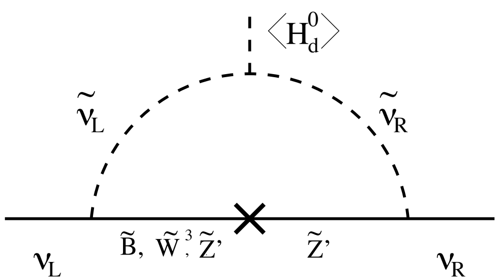
- **Alternative**

$$K \sim \frac{1}{M} L N^c \tilde{H}_d + h.c., \text{ with } F_{H_d^*} = -\mu H_u$$

- **Non-holomorphic A terms** (suppressed by M_{SUSY}/M)(DEL)

$$K \sim \frac{1}{M^3} X X^\dagger L N^c \tilde{H}_d + h.c. \Rightarrow A \sim \frac{M_{SUSY}^2}{M}$$

  – **Small Dirac mass from loop** (need $U(1)'$; also forbids normal Yukawa)



String Instantons

- Intersecting brane: hard to achieve Majorana or small Dirac masses perturbatively

- Anomalous $U(1)'$: $M_{Z'} \sim M_s$, but acts like perturbative global symmetry
  (may forbid μ, R_P violation, $N^c N^c$, $L N^c H_u$, $Q U^c H_u$, $\ldots$)

- String instantons: nonperturbative violation of global symmetries

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

$$\frac{V_{E2}}{V_{D6}} = f(\text{winding numbers})$$

- **Majorana masses from string instantons (seesaw)** (also, μ, Yukawas) (Blumenhagen,Cvetič,Weigand;Ibanez,Uranga)

$$m_{\nu_R} \sim M_s e^{-S_{inst}}$$

- **Small Dirac,** $e^{-S_{inst}} L N^c H_u$ (natural scale, $10^{-3} - 10^{-1}$ eV) (Cvetič,PL)

- **Stringy Weinberg operator with low** M_s (Cvetič,Halverson,PL,Richter)

$$W_5 = \frac{e^{-S_{inst}}}{M_s} L L H_u H_u, \qquad M_s \sim (10^3 - 10^{14}) \text{ GeV}$$

  - Systematic analysis of semi-realistic 4 and 5 stack D-brane quivers yielding W_5
  - Examples include $M_s \sim (10^3 - 10^7)$ GeV (μ_{eff}) and $M_s \sim (10^9 - 10^{14})$ GeV (Yukawa)

Other possibilities

- Large extra dimensions, with ν_R propagating in bulk $\Rightarrow$ small Dirac masses from wave function overlap, cf., gravity (Dienes,Dudas,Gherghetta; Arkani-Hamed,Dimopoulos,Dvali,March-Russell)

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

- Small Dirac from wave function overlap in warped dimensions, L and ν_R in bulk (Chang,Ng,Wu)

- Majorana ν_R as Kaluza-Klein modes, moduli, etc (F-theory) (Tatar,Tsuchiya,Watari; Bouchard,Heckman,Seo,Vafa)

- Heavy Higgs triplets with $Y = \pm 1$ (Type II seesaw). Difficult to embed in strings (singlets, bifundamentals, adjoints) (PL,Nelson; Cvetič,PL)

Conclusions

- Can implement version of seesaw in strings, using complicated higher-dimensional operators, string instantons, Kaluza-Klein states, $\cdots$

- Other HDO in W or K, string instantons, or volume effects also possible, yielding small Majorana (stringy Weinberg operator) *or* Dirac


Scale 1: 19,500,000
Lambert Conformal Conic Projection,
standard parallels 40°N and 56°N
300 Kilometers
300 Miles
Mediterranean Sea
Black Sea
Bay of Biscay
Adriatic Sea
Tyrrhenian Sea
Ionian Sea
Aegean Sea
Celtic Sea
FRANCE
GERMANY
SPAIN
PORTUGAL
ITALY
AUSTRIA
HUNGARY
ROMANIA
BULGARIA
GREECE
TURKEY
POLAND
UKRAINE
BELARUS
ALGERIA
MOROCCO
TUNISIA
IRELAND
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Bonn
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Vienna
Budapest
Belgrade
Constanța
Istanbul