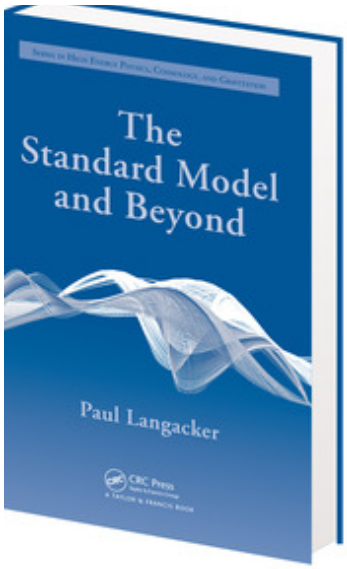
Beyond the Standard Paradigm

- Background
- The standard paradigm
- Uniqueness or environment
- The string landscape
- Extended MSSM quivers

Background

- **Career coincided with standard model**
  - **MIT (1964-1968)** (ugrad)
    Experiment? Theory? Mathematics?
  - **U. California, Berkeley (1968-1972)** (PhD)
  - **Rockefeller University (1972-1974)** (postdoc)
  - **U. Pennsylvania (1974-2006)** (postdoc, faculty, Chair)
    Formal theory or "phenomenology"?
  - **Institute for Advanced Study and Princeton (2006-)** ("postdoc")
- **Late 60's:** unlikely to understand strong or weak in our lifetimes
- **2014:** nature understood to 10^{-16} cm (but dark matter/energy; naturalness)
- **Hope for 2060:** nature understood to Planck scale, 10^{-33} cm
  (need top-down *and* bottom-up *and* cooperative Nature)

- **My research**
  - **Contact between theory and experiment**
  - **Chiral perturbation theory**
  - **Precision electroweak (global analyses)**
  - **Neutrino mass (early global analyses; MSW sign; sterile abundance)**
  - **BSM (GUTs, beyond MSSM, Z', string phenomenology)**
  - **Lecture series**
  - **Textbook:** *The Standard Model and Beyond*, **(CRC Press, 2010)**



The Standard Model

- Spectacularly successful/unsuccessful
- Mathematically consistent
- Describes nature to 10^{-16} cm
- Recent Higgs discovery
- However, complicated, fine-tuned
- Missing: dark matter and energy
- Most effort is BSM
- Most popular: supersymmetry
  (minimal version [MSSM])

The Standard Paradigm

- **MSSM at TeV scale** (but no LHC signal)
- **LSP WIMPs** (but no clear signal); **dark energy** (cosmological constant?)
- (Possibly) **GUT at unification scale** (gauge unification)
- **Seesaw model for m_ν**
  - **Leptogenesis**
  - (Possibly) **GUT relations for couplings** (large representations?)
  - **Flavor symmetries** (discrete, global, gauge)
- **SUSY breaking in hidden sector**
- **Assumptions of naturalness, uniqueness, minimality**

Beyond the MSSM

Even if TeV-supersymmetry found, MSSM may not be the full story

Most of the problems of standard model remain, new ones introduced
(FCNC, EDM, proton decay if no R_P)

μ problem introduced: $W_\mu = \mu \hat{H}_u \cdot \hat{H}_d, \quad \mu = \mathcal{O}(\text{electroweak})$

Remnants of GUT/Planck scale physics may survive to TeV scale

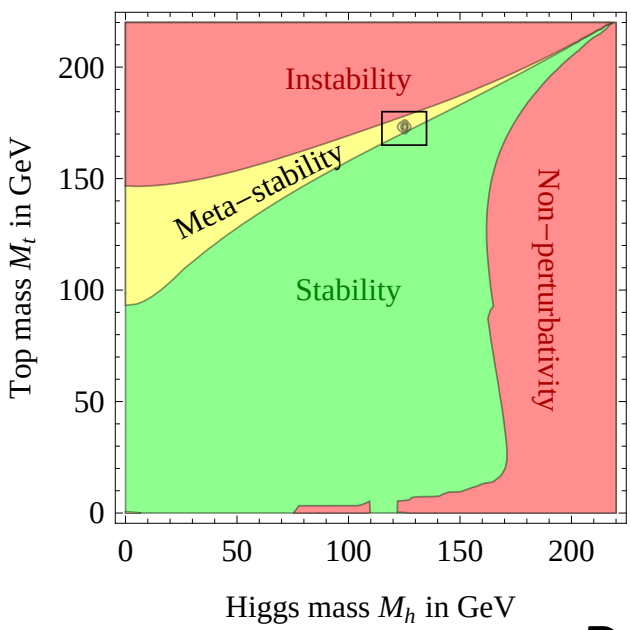
Specific string constructions often have extended gauge groups, exotics, extended Higgs/neutralino sectors (defect or hint?)

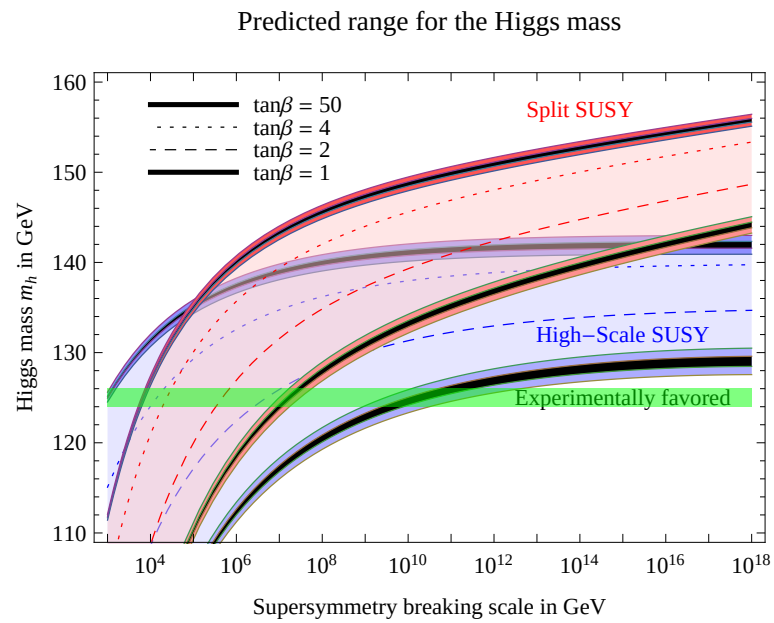
Ingredients of 4d GUTs hard to embed in string, especially large Higgs representations, Yukawa relations

Important to explore alternatives/extensions to MSSM

Naturalness or Tuning

- **ATLAS/CMS: no sign of supersymmetry or other new physics**
- **Higgs-like particle: consistent with elementary Higgs**
  - **SM: rather light (metastable vacuum or new physics below 10^{11} GeV)**
  - **MSSM: rather heavy (need heavy stop or large mixing)**





Degrassi et al, 1205.6497

- **Higgs mass^2 very unnatural (tuning by 10^{34}) unless TeV physics**
  (supersymmetry, alternative EWSB, large dimensions)

- **Is naturalness a good guide? cf dark energy (tuning by 10^{120})**
  (environmental solution?)

- **Even for higher-scale new physics: little (baby) hierarchy problem**
  (but reduces FCNC, EDM constraints)

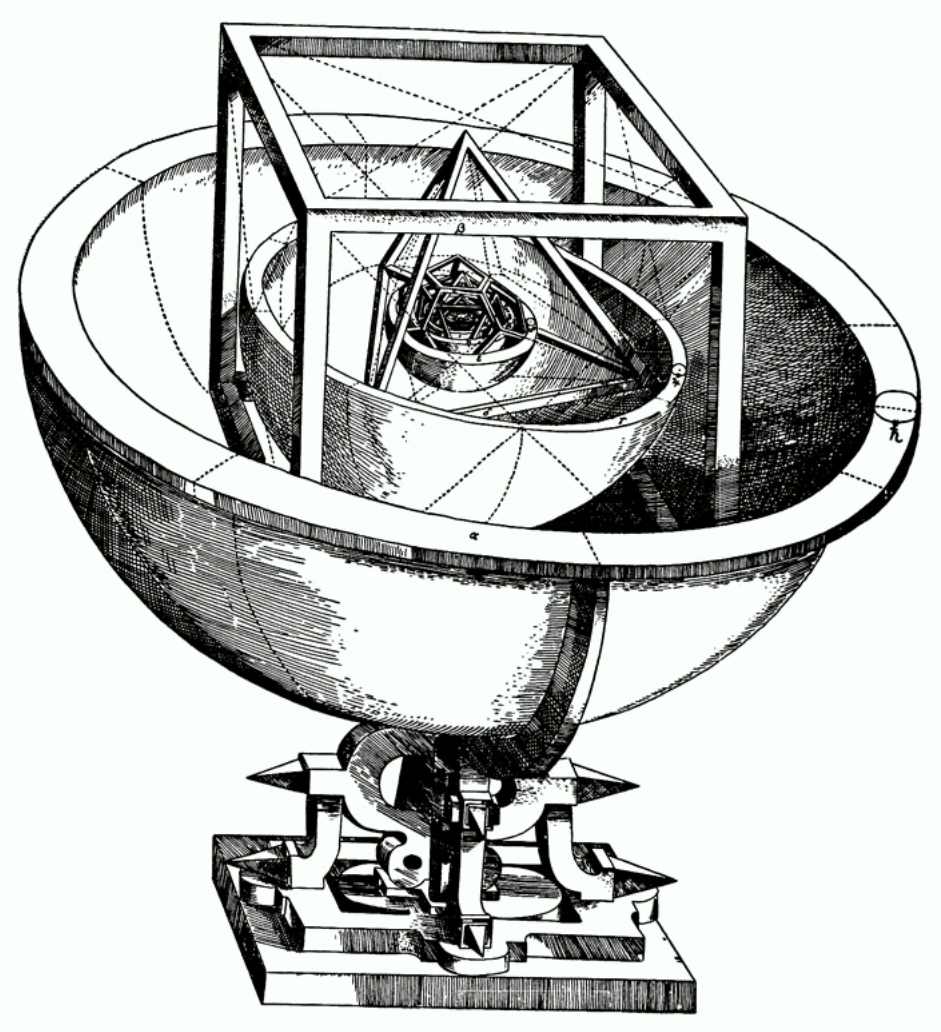
Uniqueness or Environment

- **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)**
  - *Assumption* **that there is a simple, unique, underlying theory**
  - **Enormous effort (especially ν) 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: may be $\gtrsim 10^{600}$ vacua with no known selection principle
  - Subset habitable, with different groups, remnants, hierarchy mechanisms, parameters
  - Multiverse sampled by eternal inflation?
  - Environmental selection? (A word?)

Early Speculations

Horatio:
O day and night, but this is wondrous strange!

Hamlet:
And therefore as a stranger give it welcome.
There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.

(William Shakespeare: Hamlet, 1603)

- **The environmental paradigm** (contd.)
  - Underlying constraints often too complicated to unravel
  - Version of anarchy
- **Distinction of paradigms critical**

The String Landscape

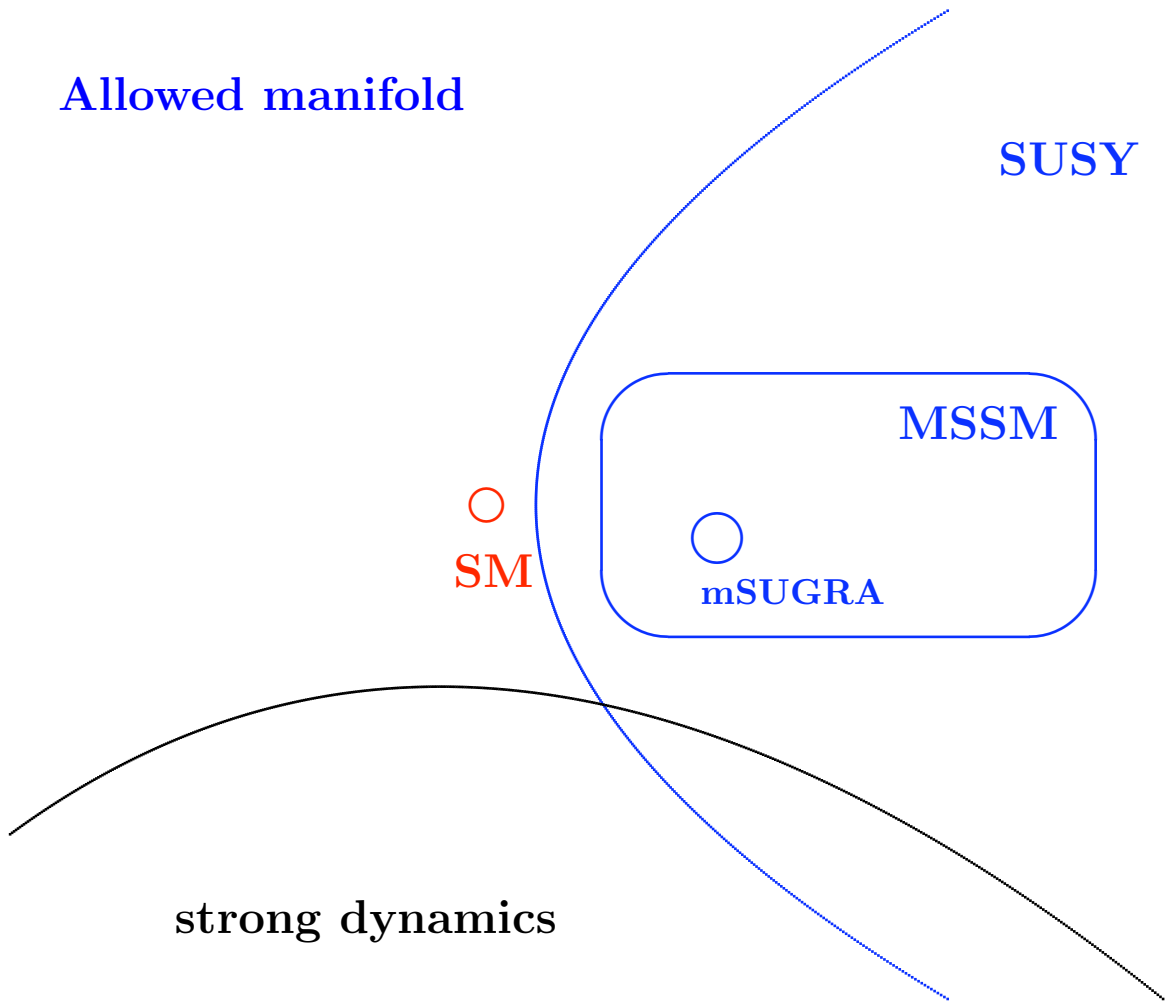
- **String theory very promising** (finite quantum gravity & other interactions)
- **However, may be enormous *landscape* of vacua** ($> 10^{600}$)
  (no known selection principle)
- **Many contain SM or MSSM**
- **Many involve TeV-scale *remnants*** (e.g., Z', exotics, extended Higgs, quasi-hidden sectors) **beyond the MSSM** (hint?)
- **Top-down remnants may not be minimal or motivated by SM problems**

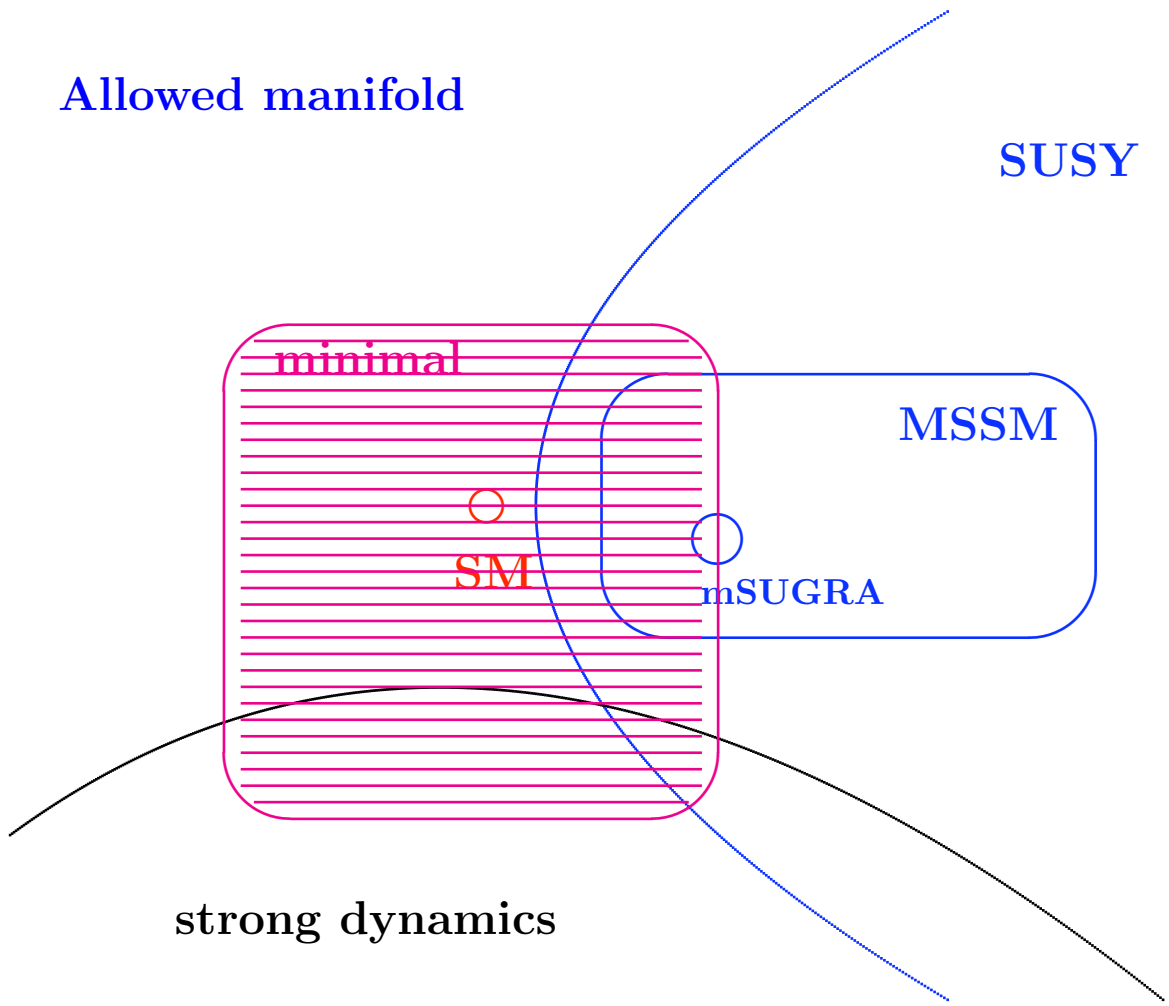
Minimality or Remnants

- **Some bottom-up ideas unlikely to emerge from simple/perturbative string constructions**
  (e.g., high-dimensional representations; tri-fundamental representations; very large groups; F theory?)

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

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


Allowed manifold
SUSY
MSSM
SM
mSUGRA
strong dynamics


Allowed manifold
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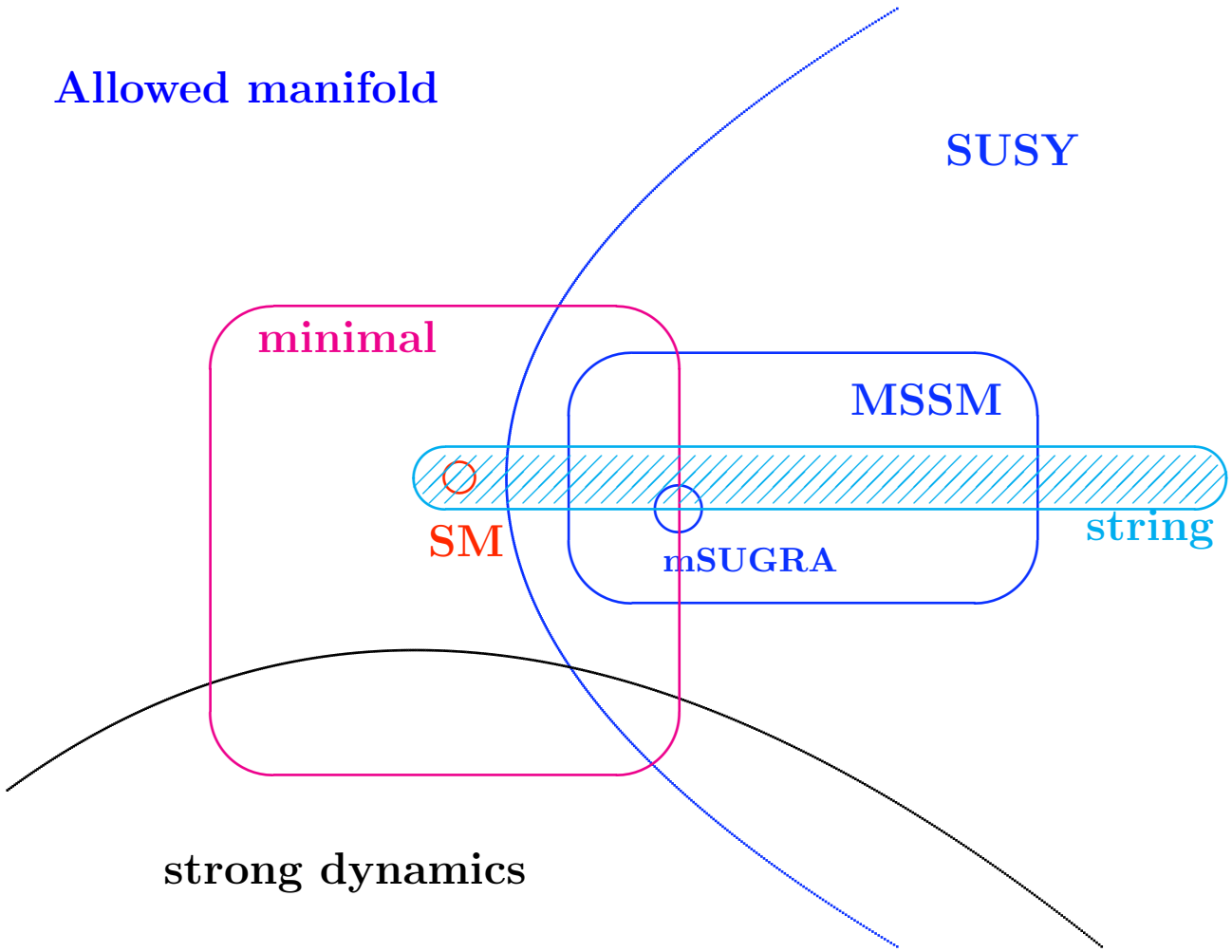

Allowed manifold
SUSY
minimal
MSSM
SM
mSUGRA
string
strong dynamics

Typical Stringy Effects

- Z' (or other gauge)
- Extended Higgs/neutralino (doublet, singlet)
- Quasi-chiral exotics
- Leptoquark, diquark, $\not{R}_P$ couplings
- Family non-universality (from different origins) (Yukawas, $U(1)'$)
- Various ν mass mechanisms (HDO: Majorana or Dirac; D (string) instantons: non-minimal seesaw, Weinberg op, Dirac, sterile)
- (Quasi-)hidden sectors (strong coupling? SUSY breaking? dark matter? random?); may be portals (exotics, Z', Higgs)

- *Perturbative* **global symmetries from anomalous $U(1)'$**
  (exponentially-suppressed breaking)

- **Nonstandard hypercharge embeddings/normalizations**

- **Fractionally charged color singlets (e.g., $\frac{1}{2}$)**
  (confined?, stable relic? millicharged?)

- **Large/warped dimensions, low string scale**
  (TeV black holes, stringy resonances)

- **Axions, moduli, cosmic strings**

- **Time/space/environment-varying couplings**

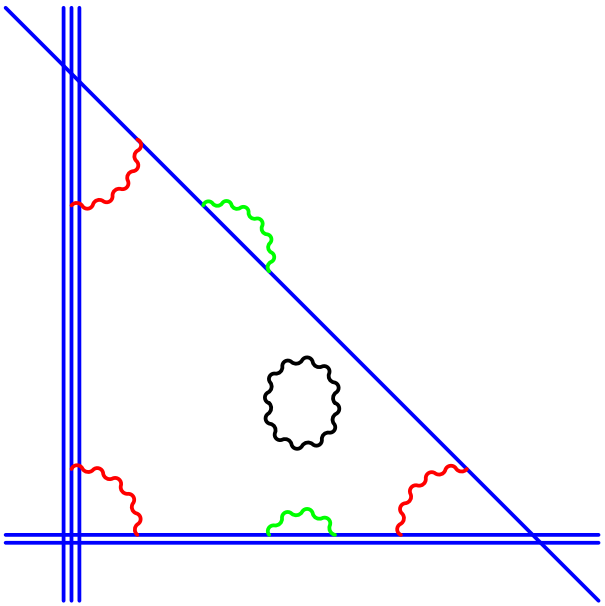
- **LIV, VEP (speeds, decays, [oscillations] of HE γ, e, gravity waves, [ν's])**

Surveying the Landscape

- **MSSM-like**
  - **Remnants common** **(but often explicity excluded)**
  - **Extensions of MSSM quivers may be needed** **(stringy constraints)**

- **Counting of group factors, families, etc; MSSM and beyond**
  - Denef, Douglas [0404116, 0411183]
  - Kumar, Wells [0409218]
  - DeWolfe, Giryavets, Kachru, Taylor [0411061]
  - Blumenhagen, Gmeiner, Honecker, Lust, Weigand [0411173, 0510170]
  - Dienes, Dudas, Gherghetta [0412185]
  - Arkani-Hamed, Dimopoulos, Kachru [0501082]
  - Kumar [0601053]
  - Dienes [0602286]; Dienes, Lennek, Senechal, Wasnik [0704.1320]
  - Anastasopoulos, Dijkstra, Kiritsis, Schellekens [0605226]
  - Shelton, Taylor, Wecht [0607015]
  - Gmeiner [0608227]; Gmeiner, Honecker [0708.2285]
  - Douglas, Kachru [0610102]
  - Blumenhagen, Kors, Lust, Stieberger [0610327]
  - Denef, Douglas, Kachru [0701050]
  - AbdusSalam, Conlon, Quevedo, Suruliz [0709.0221]
  - Balasubramanian, de Boer, Naqvi [0805.4196]
  - Gabella, He, Lukas [0808.2142]
  - Anderson, Gray, Lukas, Palti [1106.4804]
  - Schellekens [1306.5083]; Gato-Rivera, Schellekens [1401.1782]
  - Nibbelink, Loukas [1308.5145]
  - Faraggi, Rizos, Sonmez [1403.4107]

Intersecting Brane (Type IIA) Constructions



- $U(N)$ from N D6 branes
  (fill 3 of the 6 extra dimensions)
- Adjoints, bifundamentals (open); gravitons (closed)
- Also, symmetric, antisymmetric; $SO(2N), Sp(2N)$
- Families from multiple intersections
  (3-cycles wrapping 6d)

- Yukawa interactions $\sim \exp(-A_{ijk}) \rightarrow$ hierarchies
- Existing models: additional gauge factors, Higgs, chiral matter
- Global $U(1)$' s (may be broken by nonperturbative D instantons)

Tadpoles and Extended MSSM Quivers

Implications of String Constraints for Exotic Matter and Z's Beyond the Standard Model, M. Cvetič, J. Halverson, PL, JHEP 1111,058 (1108.5187);
Anomaly Nucleation Constrains $SU(2)$ Gauge Theories, J. Halverson, PRL 111, 261601 (1310.1091)

- **Intersecting brane type IIA constructions (and others): tadpole cancellation conditions stronger than anomaly cancellation in augmented field theory (for $N_a = 1, 2$)**
  (FT with anomalous $U(1)$'s and Chern-Simons terms)
  - **$U(N_a)$ from stack of N_a D6 branes:**

$$N_a \geq 2: \qquad \#a - \#\overline{a} + (N_a + 4)\ (\#\square\square_a - \#\overline{\square\square}_a) + (N_a - 4)\ (\#\square_a - \#\overline{\square}_a) = 0$$

$$N_a = 1: \qquad \#a - \#\overline{a} + (N_a + 4)\ (\#\square\square_a - \#\overline{\square\square}_a) = 0 \ \text{ mod } \ 3,$$

  - **$SU(N_a)^3$ triangle anomaly condition for $N_a \geq 3$**
  - **Landscape view: all vacua must be consistent**

- "Anomalous" $U(1)$ from trace generator of $U(N)$ usually acquires Stuckelberg mass near string scale M_s
  - Anomalies cancelled by Chern-Simons
  - $U(1) \Rightarrow$ global symmetry on (perturbative) superpotential
  - May be broken by non-perturbative D-instantons (exponentially suppressed)
- Linear combination $\sum q_x U(1)_x$ may be massless, non-anomalous if

$$-q_a N_a \left(\#\square\square_a - \#\overline{\square\square}_a + \#\square_a - \#\overline{\square}_a\right) + \sum_{x \neq a} q_x N_x \left(\#(a, \overline{x}) - \#(a, x)\right) = 0, \qquad N_a \geq 2$$

$$q_a \frac{\#(a) - \#(\overline{a}) + 8(\#\square\square_a) - \#\overline{\square\square}_a)}{3} + \sum_{x \neq a} q_x N_x \left(\#(a, \overline{x}) - \#(a, x)\right) = 0, \qquad N_a = 1$$

  - Require one linear combination $\Rightarrow$ weak hypercharge, Y
  - May be additional massless combinations, broken by Higgs singlet VEVs $\Rightarrow$TeV-scale Z' (even for $M_s = \mathcal{O}(M_{pl})$)

New Matter and Z's

- **Most quivers with just MSSM chiral matter don't satisfy tadpole** (plus $H \not\sim L$) **constraints** (none for 3 nodes with no vector pairs)
- **Systematically add matter to MSSM quivers to satisfy tadpole and hypercharge conditions** (eight 3 and 4-node hypercharge embeddings)
  - **Up to 5 additional fields**
  - **Don't allow purely vector pairs** (typically acquire M_s-scale masses)
  - **Allow quasi-chiral pairs** (vector under MSSM; chiral under "anomalous" or additional non-anomalous $U(1)$'s)
  - **May also exclude fractional charge, heavy chiral states, no $H_d - L$ distinction**

SM Rep	Total Multiplicity	Int. El.	4th Gen. Removed	Shifted 4th Gen. Also Removed
$(1,1)_0$	174276	173578	173578	173578
$(1,3)_0$	48291	48083	48083	48083
$(1,2)_{-\frac{1}{2}}$	39600	39560	38814	38814
$(1,2)_{\frac{1}{2}}$	38854	38814	38814	38814
$(\bar{3},1)_{\frac{1}{3}}$	25029	25007	24261	24241
$(3,1)_{-\frac{1}{3}}$	24299	24277	24277	24241
$(1,1)_1$	15232	15228	14482	14482
$(1,1)_{-1}$	14486	14482	14482	14482
$(\bar{3},1)_{-\frac{2}{3}}$	3501	3501	2755	2755
$(3,1)_{\frac{2}{3}}$	2755	2755	2755	2755
$(3,2)_{\frac{1}{6}}$	1784	1784	1038	1038
$(\bar{3},2)_{-\frac{1}{6}}$	1038	1038	1038	1038
$(1,2)_0$	852	0	0	0
$(1,2)_{\frac{3}{2}}$	220	220	220	184
$(1,2)_{-\frac{3}{2}}$	204	204	204	184
$(1,1)_{\frac{1}{2}}$	152	0	0	0
$(1,1)_{-\frac{1}{2}}$	152	0	0	0
$(3,1)_{\frac{1}{6}}$	124	0	0	0
$(\bar{3},1)_{-\frac{1}{6}}$	124	0	0	0
$(3,1)_{-\frac{4}{3}}$	36	36	36	0
$(1,3)_{-1}$	36	36	36	0
$(\bar{3},2)_{\frac{5}{6}}$	36	36	36	0
$(\bar{3},1)_{\frac{4}{3}}$	20	20	20	0
$(1,3)_1$	20	20	20	0
$(3,2)_{-\frac{5}{6}}$	20	20	20	0

- **MSSM singlets with anomalous $U(1)$ charge**
  - **Perturbative NMSSM-like singlet** $(S_\mu H_u H_d)$
    (alternative: D-instanton)
  - **Perturbative ν_L^c-like singlet** $(\nu_L^c H_u L)$
    (alternative: Dirac or Weinberg op by D-instanton)
  - **Random**

- **Isotriplets** $(Y = 0)$

- **Quasi-chiral pairs: lepton/Higgs doublets; down-type quark isosinglets; nonabelian singlets** $(Y = Q = \pm 1)$
  (+ some up-type quark isosinglets, quark isodoublets, shifted lepton/Higgs doublets $(Q = (\pm 1, \pm 2))$**)**
  - **Mass by** $SX\bar{X}$ **(**S **=MSSM singlet) or** $X\bar{X}$ **(D-instantons)**
  - **Produce quarks/scalar partners by QCD**
  - **Cascade decays to lightest**
  - **Decay: mixing, lepto/di-quark, HDO (rapid, delayed, quasi-stable)**
  - **Many have** $H_d - L$ **distinction (necessary for** L **and** R**-parity conservation)**

- **Small number fractional charges, chiral fourth family (Landau poles), shifted fourth families:**
  $(3, 2)_{-\frac{5}{6}}, (\bar{3}, 1)_{\frac{1}{3}}, (\bar{3}, 1)_{\frac{4}{3}}, (1, 2)_{-\frac{3}{2}}, (1, 3)_1$

- **Quivers with additional** (non-anomalous) $U(1)'$ **gauge symmetry**
  - $\lesssim$ **50% are family universal for** q_L, L, u_L^c, d_L^c, **and** e_L^c
  - **Family non-universal** (quiver distinct): **GIM violation, FCNC** (B_s **anomalies?**)

	Multiplicity of Quivers				
Hypercharge	$U(1)'$	H_d Candidate	Fam. Univ	$S_\mu H_u H_d$	$L H_u \nu_L^c$
$(-\frac{1}{3}, -\frac{1}{2}, 0)$	0	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2})$	1	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 0)$	198	146	56	70	94
$(-\frac{1}{3}, -\frac{1}{2}, 0, \frac{1}{2})$	0	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 1)$	78	16	10	0	5
$(\frac{1}{6}, 0, \frac{1}{2}, 0)$	0	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{1}{2})$	1803	1466	629	610	600
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{3}{2})$	82	0	0	0	0

Conclusions

- **String landscape/eternal inflation: physics may be (partially) environmental**

- **From bottom up: there may be more at TeV scale than MSSM**

- **From top down: there may be more at TeV scale than MSSM**
  (e.g., Z', extended Higgs/neutralino, quasi-chiral exotics, nonstandard ν)

- **Important to delineate difference between string possibilities and field theory possibilities**

A TeV-Scale Z'

Review: Rev.Mod.Phys.81,1199 (arXiv:0801.1345)

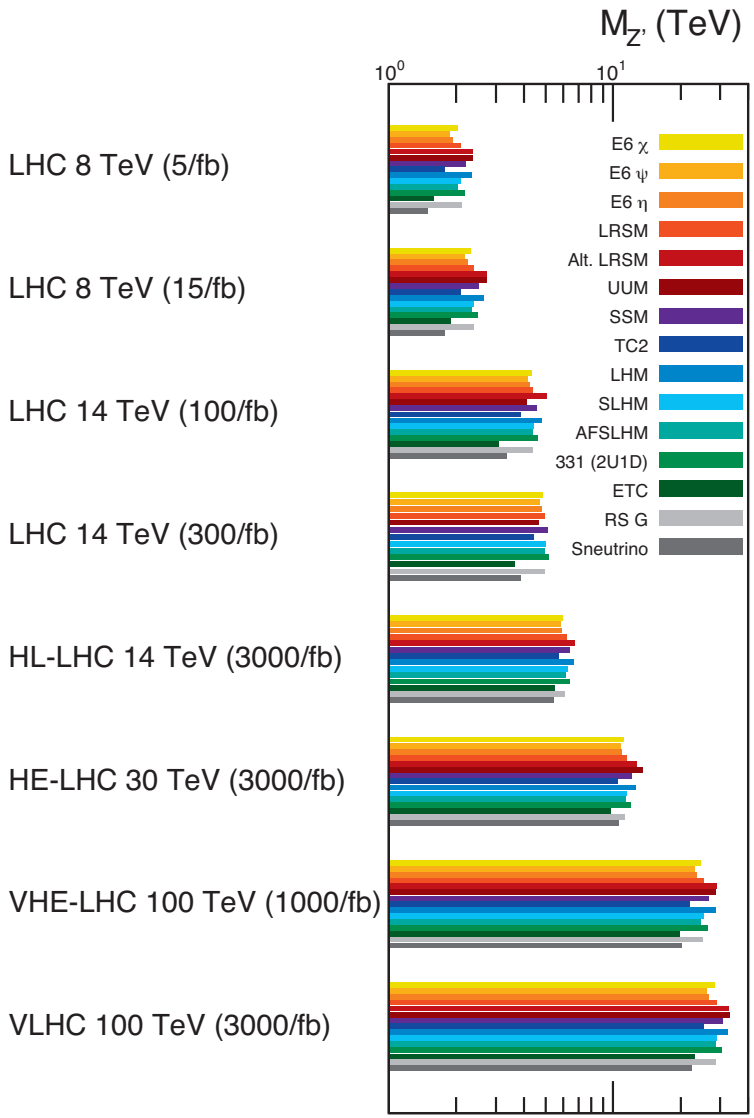
- **Strings, GUTs, DSB, little Higgs, LED often involve extra Z'**
  (harder to break $U(1)'$ factors than non-abelian: remnants)

- **Typically $M_{Z'} \gtrsim 2-3$ TeV for electroweak coupling**
  (LHC, Tevatron, LEP 2, WNC); $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)

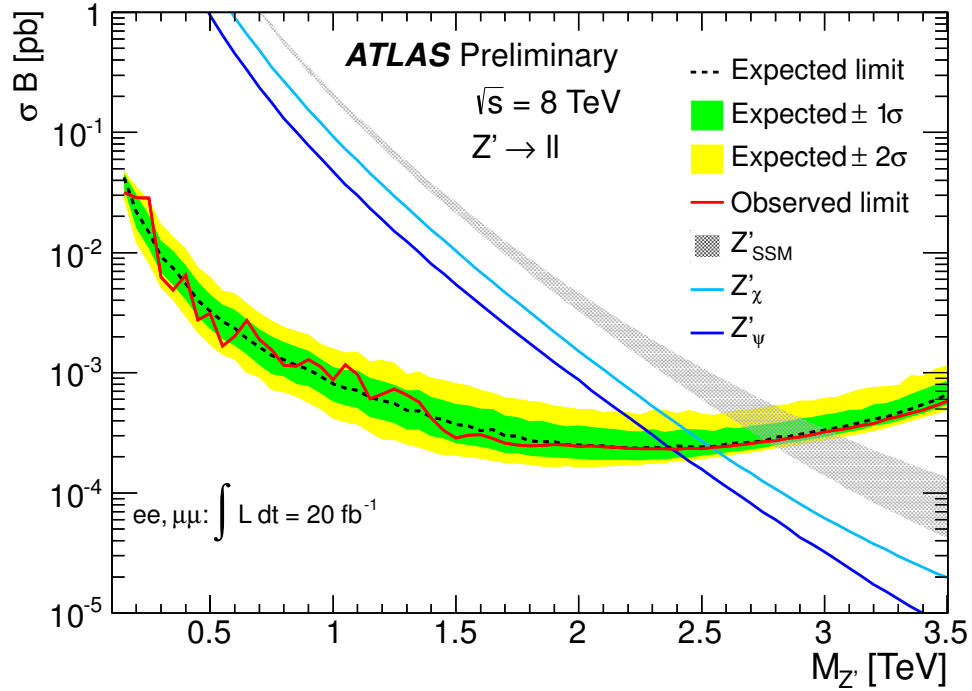
- **Discovery to $M_{Z'} \sim 5-6$ TeV at LHC-14, higher in e^-e^+**
  $(pp \to \mu^+\mu^-, e^+e^-, q\bar{q})$ (depends on couplings, exotics, sparticles)

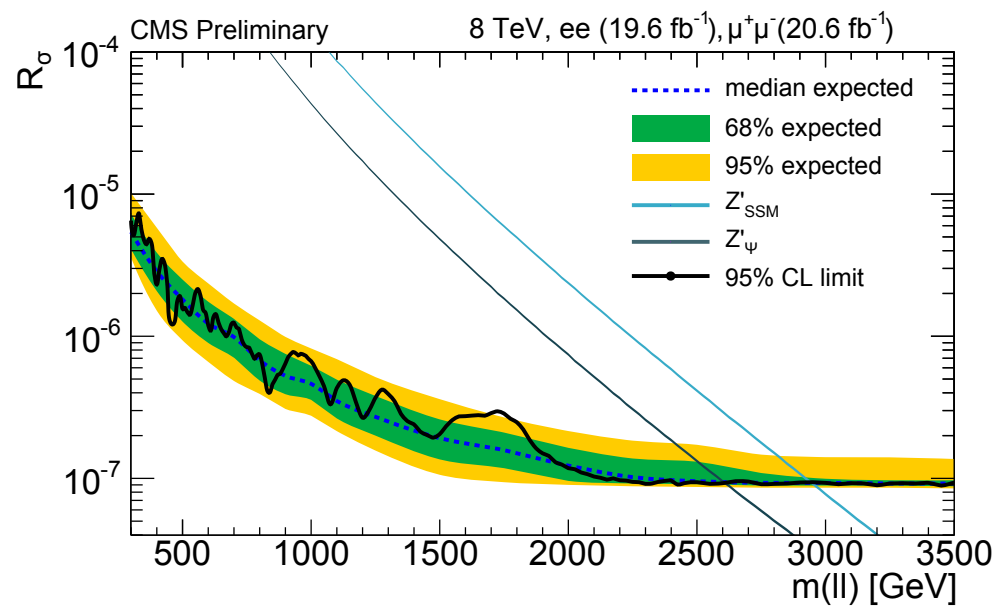
- **LHC diagnostics to 1-3 TeV** (BR's, asymmetries, polarizations,
  y distributions, associated production, rare decays);
  higher for ILC/CLIC/TLEP

- **Light** (150-300 GeV) **leptophobic, TeV-scale** (FCNC), **or very light**
  ($\lesssim$ 10 GeV) **Z' portal** (DM)



Godfrey, Martin, 1309.1688





String Z'

- **Non-anomalous, descending through non-abelian group ($E_6, SO(10)$, Pati-Salam** (may be T_{3R}, T_{BL}, E_6 or "random"))

- **Anomalous $U(1)'$, e.g., from $U(N)$ or $U(1)$ branes**
  - Stückelberg masses $\sim M_{str}$
  - Z' and Chern-Simons term may be observable for $M_{str} \sim$ TeV
  - Large M_{str}: may be anomaly-free combinations (in addition to Y); often family non-universal

Implications of a TeV-scale $U(1)'$

- Couplings $\rightarrow$ clues about embedding into underlying theory

- Natural solution to μ problem: $W \sim h_s S H_u H_d \rightarrow \ \mu_{eff} = h_s \langle S \rangle$

  ("stringy version" of NMSSM)

- Supersymmetry: $SU(2) \times U(1)$ and $U(1)'$ breaking scales *both* set by SUSY breaking scale (unless flat direction)

- Extended Higgs sector

  – Relaxed mass limits, couplings, parameters (e.g., $\tan\beta \sim 1$)
  – Higgs singlets needed to break $U(1)'$
  – Doublet-singlet mixing, extended neutralino sector
  ($\rightarrow$ non-standard collider signatures)

- **Extended neutralino sector**
  - Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  - Additional cold dark matter, $g_\mu - 2$ possibilities
- **Exotics (anomaly-cancellation)**
  - Non-chiral wrt SM but chiral wrt $U(1)'$
  - May decay by mixing; by diquark or leptoquark coupling; or be quasi-stable
- **Z' decays into sparticles/exotics (SUSY factory)**
- **Flavor changing neutral currents** (for non-universal $U(1)'$ charges)
  - Tree-level effects in B decay competing with SM loops (or with enhanced loops in MSSM with large $\tan\beta$)
  - $B_s - \bar{B}_s$ mixing, B_d penguins
  - $t\bar{t}$ forward-backward asymmetry (probably excluded)

- **Non-universal charges: MSW-type effects** (apparent CPT violation)
- **$Z' - \tilde{Z}'$ mediation of SUSY breaking**
- **Constraints on neutrino mass generation**
  - Various versions allow or exclude Type I or II seesaws, extended seesaw, small Dirac by HDO or non-holomorphic soft; stringy Weinberg operator, Majorana seesaw, small Dirac by string instantons; sterile mixing
    (e.g., Kang, PL, Li; Phys. Rev. D 71, 015012 (2005) [hep-ph/0411404])
- **Large A term and possible tree-level CP violation**
  (no new EDM constraints) $\rightarrow$ electroweak baryogenesis

Extended Higgs Sector

- **Standard model singlets S_i and additional doublet pairs $H_{u,d}$ very common**

- **Additional doublet pairs**
  - **Richer spectrum, decay possibilities (anomalies?)**
  - **May be needed (or expand possibilities for) quark/lepton masses/mixings (e.g., stringy symmetries may restrict single Higgs couplings to one or two families)**
  - **Extra neutral Higgs $\rightarrow$ FCNC (suppressed by Yukawas)**
  - **Significantly modify gauge unification (unless compensated)**

Higgs singlets S_i

- Standard model singlets common in string constructions
- Needed to break extra $U(1)'$ gauge symmetries
- Solution to μ problem ($U(1)'$, NMSSM, nMSSM, sMSSM)

$$W \sim h_s S H_u H_d \rightarrow \ \mu_{eff} = h_s \langle S \rangle$$

- $F(D)$ terms allow larger MSSM-like Higgs mass
- Modified couplings, parameter ranges, branching ratios
- Singlet-doublet mixing
- Large A term and possible tree-level CP violation $\rightarrow$ electroweak baryogenesis

Quasi-Chiral Exotics

- Often find exotic (wrt $SU(2) \times U(1)$) quarks/leptons at TeV scale
  - Assume non-chiral wrt SM gauge group (strong constraints on SM chiral from large Yukawas ($\Rightarrow$ Landau poles), precision EW)
  - Can be chiral wrt extra $U(1)'$s or other extended gauge
  - Usually needed for $U(1)'$ anomaly cancellation
  - Modify gauge unification unless in complete GUT multiplets
  - Strings typically yield (anti-) (bi-) fundamentals, adjoints, (anti-) symmetrics
  - May also be quasi-hidden, shifted charges, or fractional charges

- **Examples in 27-plet of E_6**
  - $D_L + D_R$ ($SU(2)$ singlets, chiral wrt $U(1)'$)
  - $\begin{pmatrix} E^0 \\ E^- \end{pmatrix}_L + \begin{pmatrix} E^0 \\ E^- \end{pmatrix}_R$ ($SU(2)$ doublets, chiral wrt $U(1)'$)

- **Pair produce $D + \bar{D}$ by QCD processes** (smaller rate for exotic leptons)

- **D or $\tilde{D}$ decay by**
  - $D \to u_i W^-$, $D \to d_i Z$, $D \to d_i H^0$ if driven by $D - d$ mixing (not in minimal E_6; FCNC)
  - $\tilde{D} \to$ quark jets if driven by diquark operator $\bar{u}\bar{u}\bar{D}$, or quark jet $+$ lepton for leptoquark operator $lq\bar{D}$ (still have stable LSP)
  - May be stable at renormalizable level due to accidental symmetry (e.g., extended gauge group) $\to$ hadronizes and escapes or stops in detector (quasi-stable from HDO $\to \tau < 1/10$ yr)
    (Kang, PL, Nelson, Phys.Rev. D77, 035003 (arXiv:0708.2701))

- **Applications: $H \to \gamma\gamma$, dark matter, baryogenesis, B-mixing/decays, FCNC, flavor structure, A^b_{FB}, gauge mediation**

  - PL, London [PR D38,886]
  - Choudhury, Tait, Wagner [0109097]
  - del Aguila, de Blas, Perez-Victoria [0803.4008]
  - Endo, Hamaguchi, Ishikawa, Iwamoto, Yokozaki [1108.3071,1112.5653,1212.3935]
  - Martin, James D. Wells [1206.2956]
  - Bonne, Moreau [1206.3360]
  - Joglekar, Schwaller, Wagner [1207.4235,1303.2969]
  - Botella, Branco, Nebot [1207.4440]
  - Arkani-Hamed, Blum, D'Agnolo, Fan [1207.4482]
  - Kearney, Pierce, Weiner [1207.7062]
  - Batell, Gori, Wang [1209.6382]
  - Cacciapaglia, Deandrea, Perries, Sordini, Panizzi [1211.4034]
  - Garberson, T. Golling [1301.4454]
  - Buras, Girrbach, Ziegler [1301.5498]
  - Aguilar-Saavedra, Benbrik, Heinemeyer, Perez-Victoria [1306.0572]
  - Alves, Barreto, Camargo, Dias [1306.1275]
  - Aguilar-Saavedra [1306.4432]
  - Ishiwata, Wise [1307.1112]
  - Alloul, Frank, Fuks, de Traubenberg [1307.1711]
  - Fairbairn, Philipp Grothaus [1307.8011]
  - Altmannshofer, Bauer, Carena [1308.1987]
  - Halverson [1310.1091]

Small neutrino masses

- Many mechanisms for small m_ν, 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
    [non-gravity: large 126 of $SO(10)$ or HDO added by hand]
    [gravity: $m_\nu \lesssim \nu_{EW}^2/\overline{M}_P \sim 10^{-5}$ eV (unless LED); often much smaller]
  - New TeV or string scale physics/symmetries/constraints may invalidate assumptions
    [No 126 in string-derived $SO(10)$]
- Bottom-up alternatives: Higgs (or fermion) triplets, extended (TeV) seesaws, loops, R_p violation

- **String-motivated alternatives**
  (review: ARNPS, 62, 215; arXiv:1112.5992)
  - **Higher-dimensional operators (HDO)**
    [non-minimal seesaw (not GUT-like), direct Majorana (Weinberg op), small Dirac (e.g., $U(1)'$ or non-holomorphic soft), mixed (LSND, MiniBooNE)]
  - **String instantons (exponential suppressions)**
    [non-minimal seesaw, direct Majorana, small Dirac]
  - **Geometric suppressions (large dimensions) [small Dirac]**
- **Alternatives often associated with new TeV physics, electroweak baryogenesis, etc.**

MSSM hypercharge embeddings

(Ibanez, Marchesano, Rabadan; Anastasopoulos, Dijkstra, Kiritsis, Schellekens)

- **Three-node embeddings** $(U(3)_a \times U(2)_b \times U(1)_c)$

Madrid: $$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c$$

non-Madrid: $$U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b$$

- **Four-node embeddings** $(U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d)$

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c + \frac{1}{2}U(1)_d \qquad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b + \frac{1}{2}U(1)_d$$

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c + \frac{3}{2}U(1)_d \qquad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b$$

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c \qquad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b + U(1)_d,$$

• 105 Madrid 3-node quivers (≤ 5 additions)

Multiplicity	Matter Additions				
4	$\square_b,\ (1,3)_0$	$\square_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$(a,\bar{b}),\ (3,2)_{\frac{1}{6}}$	$(\bar{a},\bar{b}),\ (\bar{3},2)_{-\frac{1}{6}}$
4	$\square_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$			
4	$\bar{\square}_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$			
4	$\square_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\bar{\square}_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\square_b,\ (1,3)_0$	$\bar{\square}_b,\ (1,1)_0$	$\bar{\square}_b,\ (1,1)_0$	$(a,\bar{b}),\ (3,2)_{\frac{1}{6}}$	$(\bar{a},\bar{b}),\ (\bar{3},2)_{-\frac{1}{6}}$
4	$\bar{\square}_b,\ (1,1)_0$	$\bar{\square}_b,\ (1,1)_0$			
4	$\bar{\square}_b,\ (1,1)_0$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$		
4	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$(a,\bar{b}),\ (3,2)_{\frac{1}{6}}$	$\square_a,\ (\bar{3},1)_{\frac{1}{3}}$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(\bar{a},\bar{c}),\ (\bar{3},1)_{-\frac{2}{3}}$	$\square_c,\ (1,1)_1$
4	$\square_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$
4	$\bar{\square}_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$
4	$\bar{\square}_b,\ (1,3)_0$	$\bar{\square}_b,\ (1,1)_0$	$\bar{\square}_b,\ (1,1)_0$		
4	$\bar{\square}_b,\ (1,3)_0$	$\bar{\square}_b,\ (1,1)_0$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$\bar{\square}_b,\ (1,3)_0$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\square_b,\ (1,1)_0$				
4	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	
4	$\bar{\square}_b,\ (1,3)_0$	$\bar{\square}_b,\ (1,3)_0$	$\bar{\square}_b,\ (1,1)_0$	$\bar{\square}_b,\ (1,1)_0$	
4	$\bar{\square}_b,\ (1,3)_0$	$\bar{\square}_b,\ (1,3)_0$	$\bar{\square}_b,\ (1,1)_0$	$(b,\bar{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$
4	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	$\square_b,\ (1,1)_0$	

Multiplicity	Matter Additions				
4	$\overline{\square\square}_b,\ (1,3)_0$	$\overline{\square\square}_b,\ (1,3)_0$	$\overline{\square\square}_b,\ (1,3)_0$	$\overline{\square}_b,\ (1,1)_0$	$\overline{\square}_b,\ (1,1)_0$
4	$\overline{\square\square}_b,\ (1,3)_0$	$\overline{\square\square}_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$		
1	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\square\square_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	
1	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\square\square_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	
1	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\square\square}_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	
1	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\square\square}_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	
1	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\square}_b,\ (1,1)_0$	$\overline{\square}_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	
1	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\square}_b,\ (1,1)_0$	$\overline{\square}_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	
1	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\square}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\square}_b,\ (1,1)_0$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(b,c),\ (1,2)_{\frac{1}{2}}$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$
1	$(a,\overline{b}),\ (3,2)_{\frac{1}{6}}$	$(b,\overline{c}),\ (1,2)_{-\frac{1}{2}}$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	$(\overline{a},\overline{c}),\ (\overline{3},1)_{-\frac{2}{3}}$	$\square\square_c,\ (1,1)_1$
1	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\square\square}_b,\ (1,3)_0$	$\overline{\square}_b,\ (1,1)_0$	$\overline{\square}_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\square\square}_b,\ (1,3)_0$	$\overline{\square}_b,\ (1,1)_0$	$\overline{\square}_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$
1	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\square_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\square_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$
1	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\square_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$		
1	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\square_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$		
1	$\square_a,\ (\overline{3},1)_{\frac{1}{3}}$	$\overline{\square\square}_b,\ (1,3)_0$	$\overline{\square\square}_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$(a,\overline{c}),\ (3,1)_{-\frac{1}{3}}$
1	$\overline{\square}_a,\ (3,1)_{-\frac{1}{3}}$	$\overline{\square\square}_b,\ (1,3)_0$	$\overline{\square\square}_b,\ (1,3)_0$	$\square_b,\ (1,1)_0$	$(\overline{a},c),\ (\overline{3},1)_{\frac{1}{3}}$

	Multiplicity of Quivers					
Hypercharge	Total	Int. El.	H_d Candidate	No 4th Gen	$S_\mu H_u H_d$	$\nu_L^c H_u L$
$(-\frac{1}{3}, -\frac{1}{2}, 0)$	41	41	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2})$	105	105	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 0)$	6974	6974	4954	4938	1824	2066
$(-\frac{1}{3}, -\frac{1}{2}, 0, \frac{1}{2})$	70	0	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 1)$	4176	4176	1842	1792	0	80
$(\frac{1}{6}, 0, \frac{1}{2}, 0)$	480	16	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{1}{2})$	77853	77853	54119	53654	16754	15524
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{3}{2})$	265	265	0	0	0	0

- **Remove quivers leading to fractionally charged color singlets**
- **Require H_d quiver-distinct from 3 L-doublets**
  (necessary for L, R-parity conservation)
- **Perturbative NMSSM-like singlet** $(S_\mu H_u H_d)$ **(alternative: D-instanton)**
- **Perturbative ν_L^c-like singlet** $(\nu_L^c H_u L)$
  (alternative: Dirac or Weinberg op by D-instanton)

	Multiplicity of Quivers				
Hypercharge	$U(1)'$	H_d Candidate	Fam. Univ	$S_\mu H_u H_d$	$L H_u \nu_L^c$
$(-\frac{1}{3}, -\frac{1}{2}, 0)$	0	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2})$	1	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 0)$	198	146	56	70	94
$(-\frac{1}{3}, -\frac{1}{2}, 0, \frac{1}{2})$	0	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 1)$	78	16	10	0	5
$(\frac{1}{6}, 0, \frac{1}{2}, 0)$	0	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{1}{2})$	1803	1466	629	610	600
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{3}{2})$	82	0	0	0	0

- Quivers with additional $U(1)'$ gauge symmetry
- $\lesssim$ 50% are family universal for q_L, L, u_L^c, d_L^c, and e_L^c
- Family non-universal (quiver distinct): GIM violation, FCNC (B_s anomalies?)

SM Rep	Total Multiplicity	4th Gen. Removed	Shifted 4th Gen. Also Removed
$(1,1)_0$	4556	4556	4556
$(1,3)_0$	1290	1290	1290
$(1,2)_{-\frac{1}{2}}$	631	619	619
$(1,2)_{\frac{1}{2}}$	619	619	619
$(\bar{3},1)_{\frac{1}{3}}$	478	466	458
$(3,1)_{-\frac{1}{3}}$	458	458	458
$(1,1)_1$	262	250	250
$(1,1)_{-1}$	250	250	250
$(1,2)_{-\frac{3}{2}}$	101	101	93
$(1,2)_{\frac{3}{2}}$	93	93	93
$(3,2)_{\frac{1}{6}}$	46	34	34
$(\bar{3},2)_{-\frac{1}{6}}$	34	34	34
$(\bar{3},1)_{-\frac{2}{3}}$	30	18	18
$(3,1)_{\frac{2}{3}}$	18	18	18
$(1,3)_1$	8	8	0
$(3,2)_{-\frac{5}{6}}$	8	8	0
$(\bar{3},1)_{\frac{4}{3}}$	8	8	0