# Phenomenological Issues in Beyond the Standard Model

- The Structure of the Standard Model
- Testing the Standard Model
- Neutrino Physics
- Beyond the MSSM

(Second lecture available at dept.physics.upenn.edu/∼pgl/tasi2.pdf)

# The Structure of the Standard Model

**Remarkably successful gauge theory of the microscopic interactions.**

1. **The Standard Model Lagrangian**
2. **Spontaneous Symmetry Breaking**
3. **The Gauge Interactions**
   - (a) **The Charged Current**
   - (b) **QED**
   - (c) **The Neutral Current**
   - (d) **Gauge Self-interactions**
4. **Problems With the Standard Model**

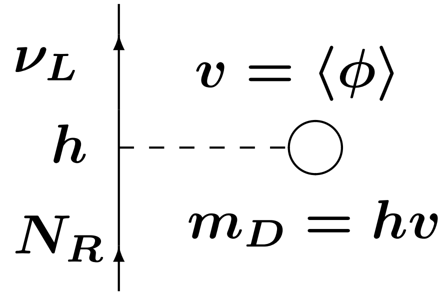
**(See "Structure Of The Standard Model," hep-ph/0304186)**

# Neutrino Preliminaries

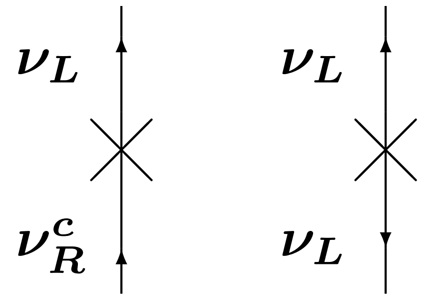
- Weyl fermion
  - Minimal (two-component) fermionic degree of freedom
  - $\psi_L \leftrightarrow \psi_R^c$ by CPT
- Active Neutrino (a.k.a. ordinary, doublet)
  - in $SU(2)$ doublet with charged lepton $\longrightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$ by CPT
- Sterile Neutrino (a.k.a. singlet, right-handed)
  - $SU(2)$ singlet; no interactions except by mixing, Higgs, or BSM
  - $N_R \leftrightarrow N_L^c$ by CPT
  - Almost always present: Are they light? Do they mix?

- **Dirac Mass**

  - Connects distinct Weyl spinors (usually active to sterile): $(m_D \bar{\nu}_L N_R + h.c.)$
  - 4 components, $\Delta L = 0$
  - $\Delta I = \frac{1}{2} \rightarrow$ Higgs doublet
  - Why small? LED? HDO?

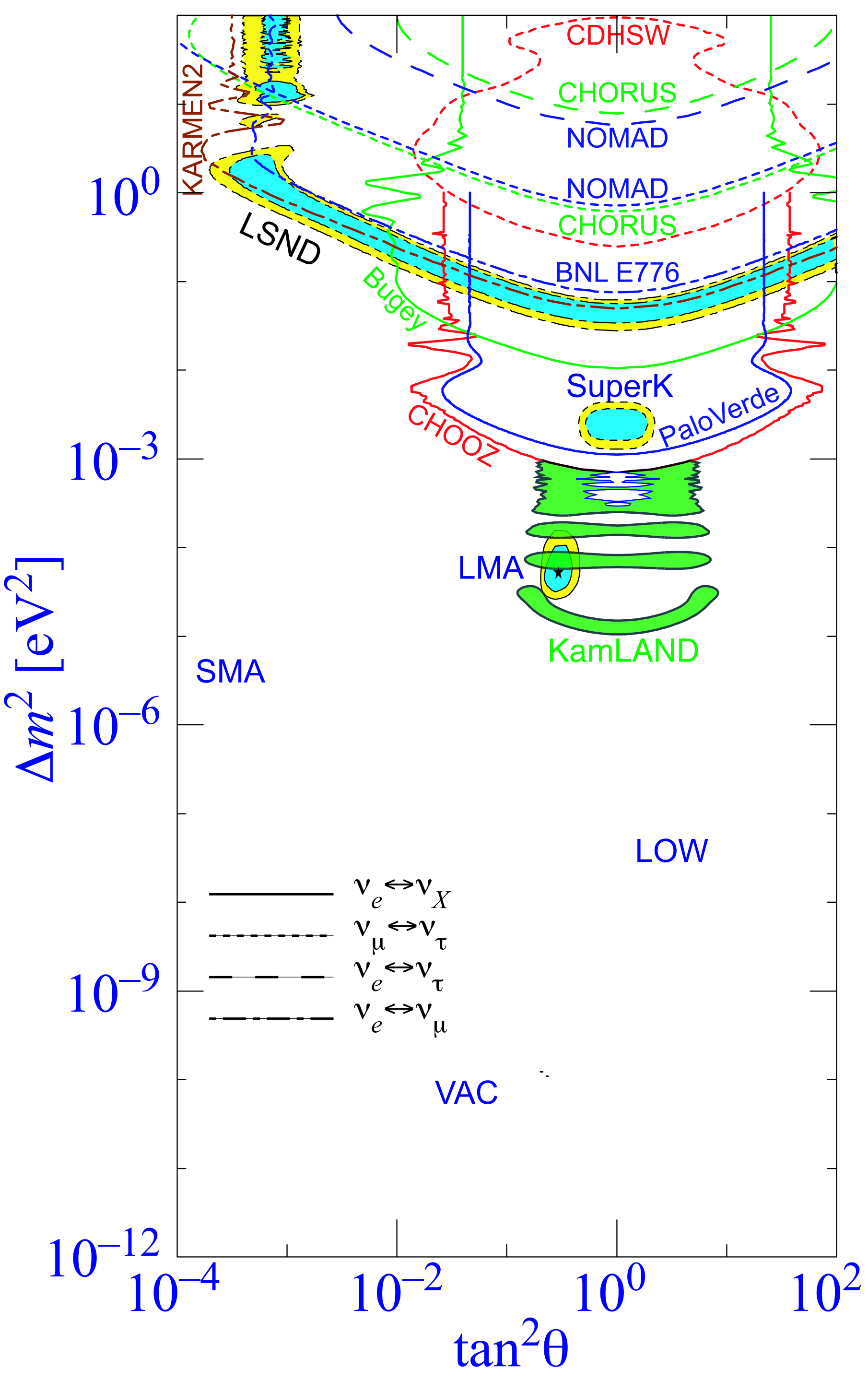


- **Majorana Mass**
  - Connects Weyl spinor with itself:
    $\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.)$ (active);
    $\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.)$ (sterile)
  - 2 components, $\Delta L = \pm 2$
  - Active: $\Delta I = 1 \rightarrow$ triplet or seesaw
  - Sterile: $\Delta I = 0 \rightarrow$ singlet or bare mass



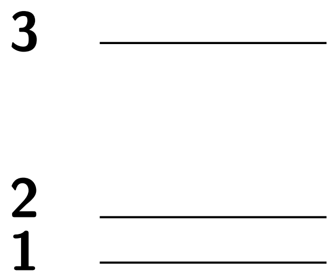

- **Mixed Masses**
  - Majorana and Dirac mass terms
  - Seesaw for $m_S \gg m_D$
  - Ordinary-sterile mixing for $m_S$ and $m_D$ both small and comparable (or $m_S \ll m_d$ (pseudo-Dirac))

- **3 $\nu$ Patterns**
  - **Solar: LMA (SNO, Kamland)**
  - $\Delta m^2_\odot \sim (10^{-5} - 10^{-4})$ **eV$^2$ for LMA**
  - **Atmospheric:** $\Delta m^2_{\rm Atm} \sim 3\times10^{-3}$ **eV$^2$, near-maximal mixing**
  - **Reactor:** $U_{e3}$ **small**



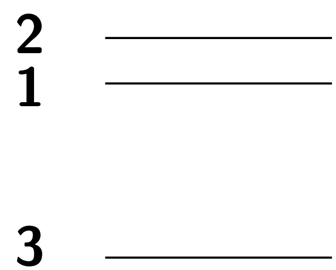
– Mixings: let $\nu_\pm \equiv \frac{1}{\sqrt{2}}(\nu_\mu \pm \nu_\tau)$:

$$\begin{aligned} \nu_3 &\sim \nu_+ \\ \nu_2 &\sim \cos\theta_\odot\ \nu_- - \sin\theta_\odot\ \nu_e \\ \nu_1 &\sim \sin\theta_\odot\ \nu_- + \cos\theta_\odot\ \nu_e \end{aligned}$$




– Hierarchical pattern

* Analogous to quarks, charged leptons
* $\beta\beta_{0\nu}$ rate very small



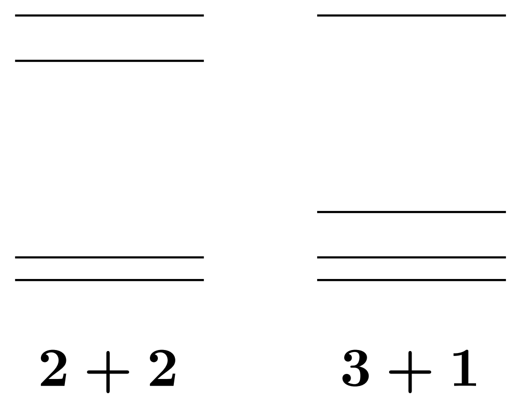

– Inverted quasi-degenerate pattern

* $\beta\beta_{0\nu}$ if Majorana
* SN1987A energetics (if $U_{e3} \neq 0$)?
* May be radiative unstable

– **Degenerate patterns**

  * **Motivated by CHDM (no longer needed)**
  * **Strong cancellations needed for $\beta\beta_{0\nu}$ if Majorana**
  * **May be radiative unstable**

- 4 $\nu$ Patterns
  - LSND: $\Delta m^2_{\rm LSND} \sim 1\ eV^2$
  - $Z$ lineshape: $2.986(7)$ active $\nu$'s lighter than $M_Z/2 \rightarrow$ fourth sterile $\nu_S$
  - $2 + 2$ patterns
  - $3 + 1$ patterns




- Pure $(\nu_\mu - \nu_s)$ excluded for atmospheric by SuperK, MACRO

- Pure $(\nu_e - \nu_s)$ excluded for solar by SNO, SuperK

- More general admixtures possible, but very poor global fits

# Problems with the Standard Model

**Lagrangian after symmetry breaking:**

$$\mathcal{L} = L_{\rm gauge} + L_{\rm Higgs} + \sum_i \bar{\psi}_i \left( i \not{\partial} - m_i - \frac{m_i H}{\nu} \right) \psi_i$$
$$- \frac{g}{2\sqrt{2}} \left( J_W^\mu W_\mu^- + J_W^{\mu\dagger} W_\mu^+ \right) - e J_Q^\mu A_\mu - \frac{g}{2\cos\theta_W} J_Z^\mu Z_\mu$$

**Standard model: $SU(2)\times U(1)$ (extended to include $\nu$ masses) + general relativity**

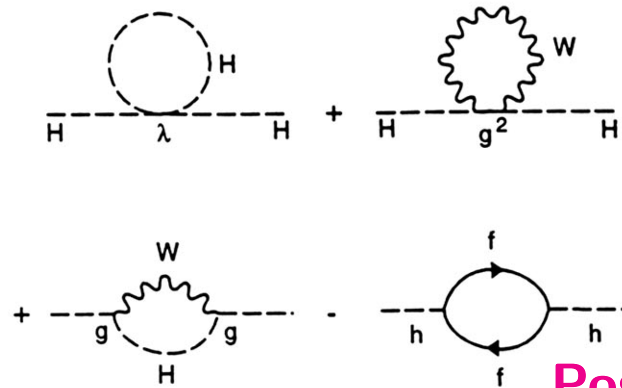
**Mathematically consistent, renormalizable theory**

**Correct to $10^{-16}$ cm**

However, too much arbitrariness and fine-tuning ($O(20)$ parameters, not including $\nu$ masses/mixings, which add at least 7 more, and electric charges)

- Gauge Problem
  - complicated gauge group with 3 couplings
  - charge quantization ($|q_e| = |q_p|$) unexplained
  - Possible solutions: strings; grand unification; magnetic monopoles (partial); anomaly constraints (partial)
- Fermion problem
  - Fermion masses, mixings, families unexplained
  - Neutrino masses, nature?
  - CP violation inadequate to explain baryon asymmetry
  - Possible solutions: strings; brane worlds; family symmetries; compositeness; radiative hierarchies. New sources of CP violation.

- **Higgs/hierarchy problem**
  - **Expect** $M_H^2 = O(M_W^2)$
  - **higher order corrections:** $\delta M_H^2 / M_W^2 \sim 10^{34}$




**Possible solutions: supersymmetry; dynamical symmetry breaking; large extra dimensions; Little Higgs**

- **Strong CP problem**
  - **Can add** $\frac{\theta}{32\pi^2} g_s^2 F\tilde{F}$ **to QCD (breaks, P, T, CP)**
  - $d_N \Rightarrow \theta < 10^{-9}$
  - **but** $\delta\theta|_{\rm weak} \sim 10^{-3}$
  - **Possible solutions: spontaneously broken global** $U(1)$ **(Peccei-Quinn)** $\Rightarrow$ **axion; unbroken global** $U(1)$ **(massless** $u$ **quark); spontaneously broken CP + other symmetries**

- **Graviton problem**
  - gravity not unified
  - quantum gravity not renormalizable
  - cosmological constant: $\Lambda_{\rm SSB} = 8\pi G_N \langle V \rangle > 10^{50} \Lambda_{\rm obs}$ ($10^{124}$ for GUTs, strings)
  - Possible solutions:
    * supergravity and Kaluza Klein unify
    * strings yield finite gravity.
    * $\Lambda$?

# The Two Paths: Unification or Compositeness

- **The Bang**
  - unification of interactions
  - grand desert to unification (GUT) or Planck scale
  - elementary Higgs, supersymmetry (SUSY), GUTs, strings
  - possibility of probing to $M_P$ and very early universe
  - hint from coupling constant unification
  - tests
    - light ($< 130 - 150$ GeV) Higgs (LEP 2, TeV, LHC)
    - *absence* of deviations in precision tests (usually)
    - supersymmetry (LHC)
    - possible: $m_b$, proton decay, $\nu$ mass, rare decays
    - SUSY-safe: $Z'$; seq/mirror/exotic fermions; singlets
  - variant versions: large dimensions, low fundamental scale, brane worlds

- **The Whimper**
  - onion-like layers
  - composite fermions, scalars (dynamical sym. breaking)
  - *not* like to atom $\rightarrow$ nucleus $+e^-$ $\rightarrow p + n \rightarrow$ quark
  - at most one more layer accessible (LHC)
  - rare decays (e.g., $K \rightarrow \mu e$)
    - severe problem
    - no realistic models
  - effects (typically, few %) expected at LEP & other precision observables (4-f ops; $Zb\bar{b}$; $\rho_0$; $S, T, U$)
  - anomalous $VVV$, new particles, future $WW \rightarrow WW$
  - recent variant: Little Higgs

# Beyond the MSSM

(aka, what to look for in string constructions)

Even if supersymmetry holds, MSSM is unlikely to be the full story

Most of the problems of standard model remain (hierarchy of electroweak and Planck scales is stabilized but not explained)

$\mu$ problem introduced

Could be that all new physics is at GUT/Planck scale, but there could be remnants surviving to TeV scale

Extreme example: Fundamental scale $M_F \sim 1 - 100$ TeV $\ll \bar{M}_{Pl} = 1/\sqrt{8\pi G_N} \sim 2.4 \times 10^{18}$ GeV

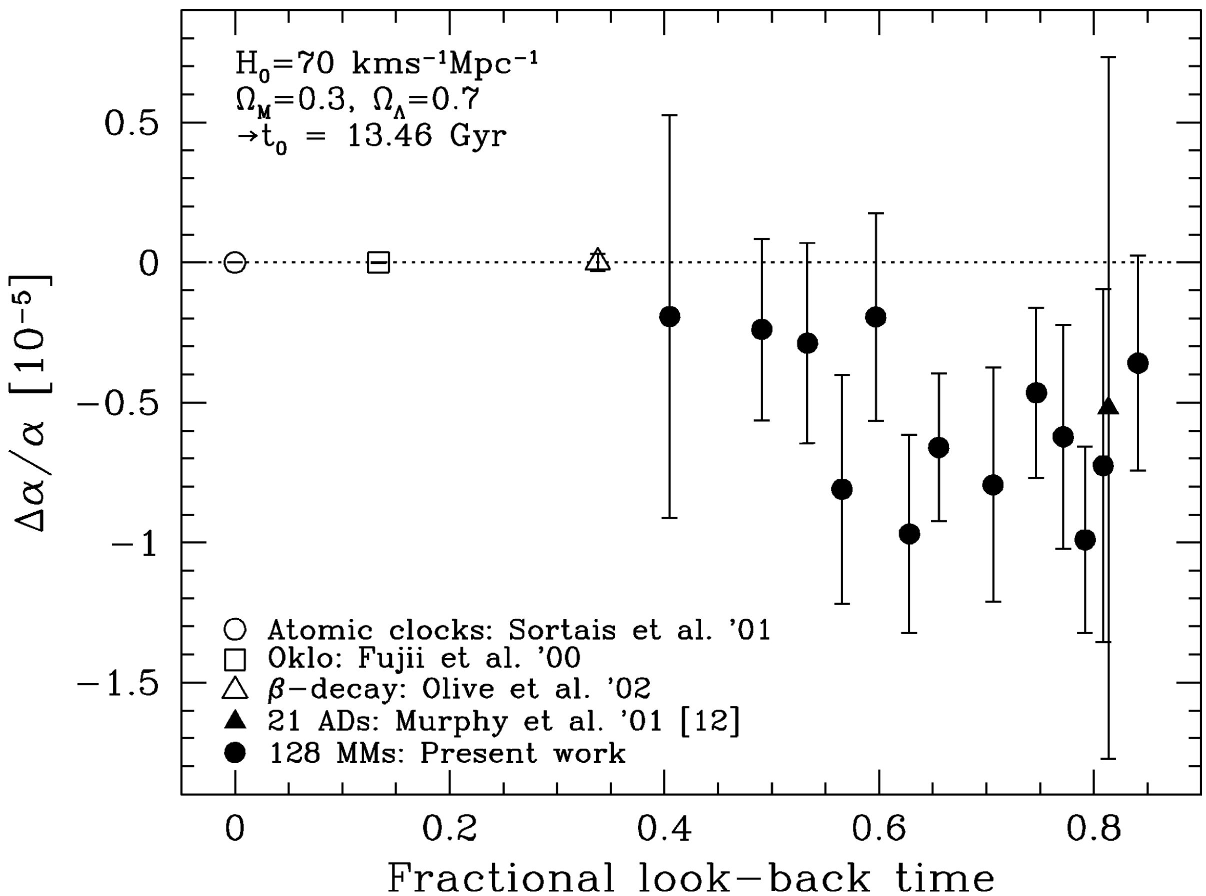
Assume $\delta$ extra dimensions with volume $V_\delta \gg M_F^{-\delta}$

$$\bar{M}_{Pl}^2 = M_F^{2+\delta} V_\delta \gg M_F^2$$

(Introduces new hierarchy problem)

Black holes, graviton emission at colliders!

# Second extreme example: time varying couplings and parameters




**(Murphy et al, astro-ph/0209488)**

Suggested by absorption by molecular clouds (Webb et al)

Expected at some level in string/brane models in which couplings are related to moduli, which could be time varying

$$\mathcal{L}_{\rm elm} \sim \frac{1}{4}\left[1+\frac{\lambda\phi}{M_{\rm PL}}\right] F_{\mu\nu}F^{\mu\nu}+\cdots$$

*However*, natural scale

$$\dot{\alpha}/\alpha \sim M_{\rm PL} \sim 10^{+43} s^{-1},$$

while Webb et al. results suggest

$$\dot{\alpha}/\alpha \sim 10^{-15} yr^{-1} \sim 10^{-66} M_{\rm PL}$$

May be analogous to dark energy: Type IA supernova and CMB suggest

$$\rho_{\rm vac} \sim 10^{-124} M_{\rm PL}^4 \neq 0$$

$\alpha$ **variation likely correlated with variations in other dimensionless couplings, mass ratios** **(PL, Segre, Strassler; Calmet, Fritzsch)**

**Will mainly consider less extreme examples of new interactions, particles at TeV scale**

# Unification: from the Top Down

**Bottom up: usually motivated by SM problems**

**Top down:**

- **Ambitious/promising string/M theory paradigm. However:**
  - **many realms of perturbative and non-perturbative M theory**
  - **compactification**
  - **dilaton/moduli**
  - **SUSY breaking, $\Lambda_{\rm cosm}$**

- **Detailed study of specific constructions:**
  - **develop techniques**
  - **suggest new TeV-scale physics**
  - **suggest promising new directions**

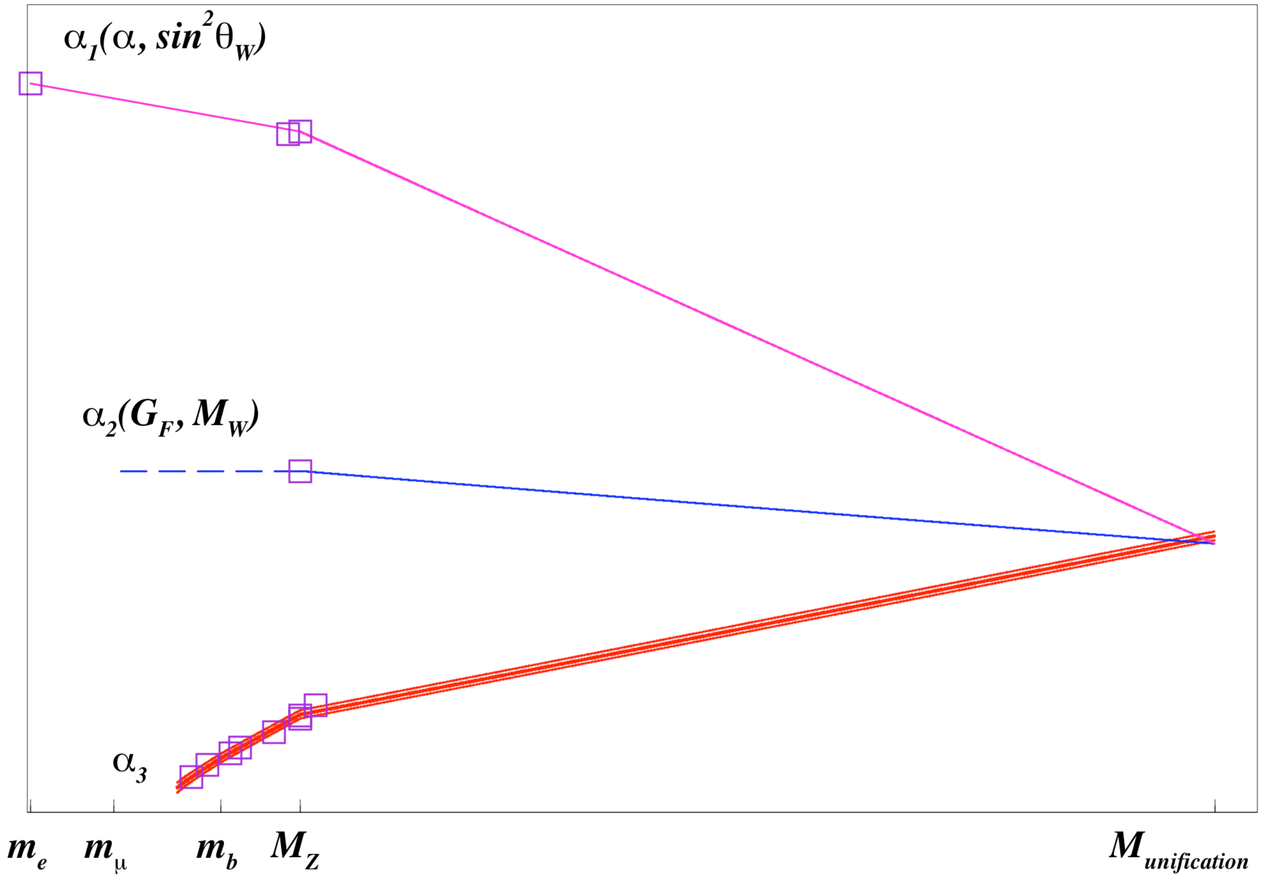
(M. Cvetič, PL; G. Cleaver, L. Everett, J.R. Espinosa, J. Wang, G. Shiu)

- **Unlikely to find fully realistic theory soon. Studies emphasize specific features:**
  - **fundamental scale $M_{\rm fund} \ll M_{\rm pl}$ (LED)**
  - **SUSY breaking, $\Lambda_{\rm cosm}$**
  - **dilaton/moduli stabilization**
  - **semi-realistic 4D gauge theories containing MSSM ($M_{\rm fund} \sim M_{\rm pl}$)**

# To GUT or not to GUT

- String $\rightarrow$ GUT $\rightarrow$ MSSM ($+$ extended?) *or* String $\rightarrow$ MSSM ($+$ extended?)
  - gauge unification
  - quantum numbers for family (15-plet)
  - seesaw $\nu$ mass scale/leptogenesis
  - $m_b/m_\tau$
  - large lepton mixings
  - other fermion mass relations
  - additional GUT scale; no adjoints in simple heterotic
  - hierarchies, e.g. doublet-triplet
  - proton decay

- **Gauge unification: GUTs, string theories**
  - $\alpha + \hat{s}^2_Z \rightarrow \alpha_s = 0.130 \pm 0.010$
  - $M_G \sim 3 \times 10^{16}$ **GeV**
  - **Perturbative string:** $\sim 5 \times 10^{17}$ **GeV (10% in** $\ln M_G$**). Exotics:** $O(1)$ **corrections.**



$\alpha_1(\alpha, sin^2\theta_W)$
$\alpha_2(G_F, M_W)$
$\alpha_3$
$m_e$
$m_\mu$
$m_b$
$M_Z$
$M_{unification}$

# Discovery of Pluto

**1781:** Uranus observed by Sir William Herschel

**1846:** Uranus orbit anomalies → Neptune predicted (John Adams, Jean Leverrier)

**1846:** Neptune observed in predicted location (in Berlin)

**1900's:** Further Uranus anomalies → Pluto predicted by "computers" (several possible locations)

**1930:** Pluto discovered in one of predicted locations (Clyde Tombaugh)

**1978:** Charon discovered → $m_{\text{Pluto}}$ too small to affect Uranus orbit

# Direct compactification

- String $\rightarrow$ MSSM ($+$ extended?) in 4D
- Constructions with $SU(3) \times SU(2) \times U(1)$ and 3 families
- Usually additional surviving gauge groups
  - quasi-hidden non-abelian
  - $U(1)'$ (non-anomalous), often family non-universal
- Usually exotic chiral supermultiplets
  - standard model singlets
  - quarks/leptons w. non-standard $SU(2) \times U(1)$
  - extra Higgs doublets
  - possibly Higgs/lepton mixing ($\not{R}_P$)

# Things to watch for

**Examples of new physics which could emerge in specific constructions**

# Gauge unification?

- Gauge unification usually present in modified form (higher Kač-Moody, exotics, moduli boundary conditions)
  - no new exotics?
  - complete GUT multiplets?
  - cancellations (accidental or otherwise)?

# A TeV scale $Z'$?

- Motivations
  - Strings, GUTs, DSB often involve extra $U(1)'$(GUTs require extra fine tuning for $M_{Z'} \ll M_{\rm GUT}$)
  - String models: radiative breaking of electroweak (SUGRA or gauge mediated) often yield EW/TeV scale $Z'$ (unless breaking along flat direction $\longrightarrow$ intermediate scale)
  - Solution to $\mu$ problem

$$W \sim hSH_uH_d,$$

$S$ = standard model singlet, charged under $U(1)'$. $\langle S \rangle$ breaks $U(1)'$, $\mu_{eff} = h\langle S \rangle$ (like NMSSM, but no domain walls)

- Experimental limits (precision and collider) model dependent, but typically $M_{Z'} > (500 - 800)\ GeV$ and $Z - Z'$ mixing $|\delta| < \text{few} \times 10^{-3}$

- Models: $M_{Z'} \gtrsim 10 M_Z$ by either modest tuning (Demir et al), or by secluded sector (Erler, PL, Li)

- Implications
  - Exotics
  - FCNC (especially in string models)
  - Non-standard Higgs masses, couplings (doublet-singlet mixing)
  - Non-standard sparticle spectrum
  - Enhanced possibility of EW baryogenesis (Kang, Liu, PL, Li)

# Exotics

- $L$-singlets
- $R$-doublets
- Standard model singlets
- Extra Higgs doublets
- Fractional charges (e.g., 1/2)
- Ordinary/hidden sector mixing
- Higgs/lepton mixing

# Flat directions

- Two SM singlets charged under $U(1)'$

$$V(S_1, S_2) = m_1^2 |S_1^2| + m_2^2 |S_2^2| + \frac{g'^2 Q'^2}{2} (|S_1^2| - |S_2^2|)^2$$

Break at EW scale for $m_1^2 + m_2^2 > 0$, at intermediate scale for $m_1^2 + m_2^2 < 0$ (stabilized by loops or HDO)

- Small Dirac (or other fermion) masses from

$$W \sim \hat{H}_2 \hat{L}_L \hat{\nu}_L^c \left( \frac{\hat{S}}{\mathcal{M}} \right)^{P_D}$$

- Possible cosmological implications

# Family Structure/Fermions

- Differences in embeddings for third family? (Family symmetries in 4d effective field theory vs string dynamics)
  - Hierarchy of masses
  - Mixings?
  - FCNC
- Sources/magnitudes of CP phases. Strong CP.
- Majorana neutrino masses? Diagonal terms?
- WYSINWYG
  - Some particles may be composite (e.g., intersecting brane construction)
  - Family disappearance under vacuum restabilization

# Asymptotic freedom in quasi-hidden sector

- SUSY breaking/moduli stabilization
- Motivated parametrizations of SUSY breaking
- Compositeness
- Fractional charge confinement

# Conclusions

- Standard Model extremely successful, but is clearly incomplete
- Most aspects tested. Precision electroweak points towards decoupling types of new physics (e.g., SUSY, unification)
- Superstring/M theory extremely promising theoretical direction
- Need vigorous bottom-up experimental and theoretical probes to test SM/MSSM and search for alternatives
- Need vigorous top-down program to connect to experiment and suggest new TeV scale physics
- May be much beyond MSSM at TeV scale