New Minimal SO(10) GUT
A Theory for All Epochs

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Plan

- SO(10) MSGUTs : Phylogeny and Structure
- Accurate fits : Susy spectra prediction : Higgs Discovery
- Susy Spectra: Relic density, $\Delta a_\mu, \epsilon_{leptogenesis}$
- Higgs Portal into GUT : $d = 5$ suppression
- Susy Seesaw Inflection failure in NMSGUT
- BICEP enables NMSGUT Inflation
- Dynamical MSGUT Flavour Unification
- Outlook

Target for any GUT

- Data for GUT To Explain : Measured νSM parameters : $(3 + 18)$:
- Gauge couplings $g_{1,2,3}(M_Z)$
- (Yukawa Coupling determined)fermion masses and mixing parameters

$$m_{q,l} : 10^{-4} - 10^{2}\, GeV \quad ; \quad \sin\theta_i^{CKM} \sim .003 - .22$$
$$\delta^{CKM} \sim \pi/3 \quad ; \quad \Delta m_\nu^2 \sim (10\, meV^2)$$
$$\theta_{12,23}^{PMNS} \sim \pi/4 \quad ; \quad \theta_{13}^{PMNS} \sim 8^\circ \pm 4^\circ$$

- **Still Awaited (4) :** $M_\nu \;\; \delta^{PMNS} \;\; \alpha_{1,2}^{PMNS}$

Exotic Process limits and anomalies

- Baryon violation : Proton Lifetime :

$$\tau_P > 10^{34}\mathrm{yrs}$$

- Muon g-2 anomaly :

$$\Delta a_\mu \sim 3 \times 10^{-9}$$

- Quark & Lepton Flavour violation (SUSY$\geq$ SM ! :

$$B.R.(B_s \to \mu\gamma) \sim 3 \times 10^{-4}....$$
$$B.R.(\mu \to e\gamma) <\leq 2.410^{-12}$$

- Leptogenetic CP violation :

$$\epsilon_{CP} \simeq -\frac{3M_1}{8\pi M_2}\frac{Im[(Y_\nu^\dagger Y_\nu)^2]_{12}}{(Y_\nu^\dagger Y_\nu)_{11}} \sim 10^{-7}$$

Hints of Unification

- MSSM Gauge Unification at $M_X^0 \sim 10^{16.25}$ GeV
- $y_t \simeq y_b \simeq \tau(M_X)$ *for* $\tan\beta > 40 - 60 \Rightarrow$ same GUT irrep !
- $10^{1-2} meV = M_{\nu_L} \sim \frac{m_{top}^2}{(10^{-3} M_X^0)} \Rightarrow\Rightarrow M_{\nu_L^c} \sim 10^{-3} M_X^0$ (Type I Seesaw)

New Hints of Unification :Higgs Discovery (2012)

- **2012** : ATLAS/CMS Higgs Mass $\simeq 126 GeV$.

$$\Delta M_H^2 = \frac{3m_t^4}{2\pi^2 v^2 \sin^2\beta}[log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{2M_S^2}(1 - \frac{X_t^2}{6M_S^2})]$$

- $X_f = A_f - \mu(\tan\beta)^{-2T_{3L}}, M_S = \frac{m_{\tilde{t}_1} + m_{\tilde{t}_2}}{2}$

- $\Delta M_H^2 \simeq 36\mathrm{GeV}$ requires large M_S, A_f, μ !
- We found $10 M_S, |A_0|, \mu \sim$ 100 TeV required by NMSGUT fermion fit in 2008 !

New Hints of Unification : BICEP Tensor Mode Discovery (2014)

- BICEP B mode Polarization of CMB measured

$$r = \frac{P_T}{P_S} = 0 \cdot 2 \pm 0.06 \Rightarrow$$

$$V_0^{\frac{1}{4}} \simeq 2 \times 10^{16}\mathrm{GeV} \Rightarrow\Rightarrow$$

$$\phi_0 \geq 10 M_P \qquad (\mathrm{LythBound})$$

VIRTUES OF SO(10)

- $\{(Q_L, L_L, u_L^c, d_L^c, l_L^c) \oplus \nu_L^c\} \equiv 16$: Tight and complete

- Simple Tri-band FM Higgs Channel Spectrum

$$\begin{aligned} 16 \otimes 16 &= 10 \oplus 120 \oplus 126 \Rightarrow (10 + 120 + \overline{126})_H \\ \overline{126} &= (15,2,2) + \Delta_R(10,1,3) + \Delta_L(\overline{10},3,1) + (6,1,1) \end{aligned}$$

- Crucial MSSM R-parity

$$(-)^{3(B-L)} \equiv M_p \subset U(1)_{B-L} \subset G_{LR} \subset G_{PS} \subset SO(10)$$

VIRTUES OF SO(10)

- Only Even B-L vevs $< \Delta_{L,R} > \Rightarrow\Rightarrow R_p\sqrt{}\sqrt{} \Rightarrow\Rightarrow$ Stable LSP

- NATURAL HOME TO BOTH SEESAWS :

$$\text{Type I}: \quad M_{B-L} \sim < \vec{\Delta}_R >_{SM=0} \Rightarrow M_{\nu^c} \Rightarrow M_\nu^I \sim \frac{v_W^2}{M_{B-L}}$$

$$\text{Type II}: \quad < \vec{\Delta}_L >_{Y=2, T_{3L}=-1} \Rightarrow\Rightarrow M_\nu^{II} \sim \frac{v_W^2}{M_{\Delta_L}}$$

TWO SCHOOLS OF SO(10)

Renormalizable SO(10)	NON-REN GUTS
Renormalizable couplings	Non Renorm. couplings
No ad-hoc discrete symmetries	Ad-hoc discrete necessary
Large(126,210,..) few (AS)	Small (10,16,45,54) irreps (AF)
# Parameter minimal	Unlimited # parameters
No Higgs duplication	Duplicates Higgs
$M_p \subset SO(10)$	"string motivated" Z_2
Higgs-Matter distinct	Higgs-Matter mix
Only B-L even vevs $\Rightarrow R_p\surd\surd$	R_p broken
UNSTRUNG !!	STRING INSPIRED !!
a) $210 \oplus 126 \oplus \overline{126}$	$16^n_H \oplus 10^m \oplus 45^l$
b)$54 \oplus 45 \oplus 126 \oplus \overline{126}$	Plethora

New Minimal Supersymmetric Grand Unified Theory

- $3 \times 16_F$, 10_H, $\overline{126}_H$, 126_H, 210_H,120_H, 45_V [1] [2]
- **AM Higgs** : $< 210,\ \overline{126},\ 126 >\ \Rightarrow$ Susy $SO(10) \longrightarrow MSSM$
- **Superpotential**

$$\begin{aligned} W &= m\ 210^2 + \lambda\ 210^3 + M\ 126 \cdot \overline{126} + \eta\ 210 \cdot 126 \cdot \overline{126} \\ &+ 10 \cdot 210(\gamma\ 126 + \bar{\gamma}\ \overline{126}) \\ &+ M_H\ 10^2 + h_{AB}\ 16_A \cdot 16_B + f'_{AB}\ 16_A 16_B \end{aligned}$$

Superpotential Parameters : $((\mathbf{2 \times 7 - 4}) + \mathbf{3} + \mathbf{2 \times 6} = \mathbf{25})$
Minimal [3]

[1] CSA, Mohapatra(1982), Clark, Kuo and Nakagawa (1983)
[2] CSA, Garg(2006)
[3] CSA, Bajc,Melfo,Senjanovic, Vissani(2003)

NMSGUT-SSB

- **GUT scale VEVS** : $SO(10) \to MSSM$

$$\langle (15,1,1)\rangle_{210} \;:\; a \qquad \langle (15,1,3)\rangle_{210} : \omega \qquad \langle (1,1,1)\rangle_{210} \;:\; p$$

$$\langle (10,1,3)\rangle_{\overline{126}} \;:\; \bar{\sigma} \;\;;\;\; \langle (\overline{10},1,3)\rangle_{126} \;: \sigma$$

- D Terms, preserve SUSY :

$$|\sigma| = |\overline{\sigma}| \qquad \Rightarrow \qquad D_{B-L} \equiv 0$$

- F terms : 4 Independent equations for $a, p, w, \sigma = \bar{\sigma}$

NMSGUT-SSB

- SSB completely analyzable Units : $\frac{m}{\lambda}$

$$\tilde{a} = \frac{(x^2+2x-1)}{(1-x)} \quad ; \quad \tilde{p} = \frac{x(5x^2-1)}{(1-x)^2}$$

$$\tilde{\sigma}\tilde{\bar{\sigma}} = \frac{2}{\eta}\frac{\lambda x(1-3x)(1+x^2)}{(1-x)^2}$$

- **EOM reduce to single Cubic in** $x = -\lambda\omega/m$ with a single parameter $\xi = \frac{\lambda M}{\eta m}$:

$$8x^3 - 15x^2 + 14x - 3 = -\xi(1-x)^2$$

- Chiral GUT scale spectra : 52 MSSM multiplet sets, 26 MSSM types : 18 unmixed , 8 mixed : 504 Fields

Opening the Higgs Portal

- 6 pairs of doublets from $\{\mathbf{10}, \overline{\mathbf{126}}, \mathbf{126_H}, \mathbf{210_H}, \mathbf{120}\}_H$ mix into MSSM doublets mix in 6×6 Higgs mass matrix $\mathcal{H}$ of which just one and only one pair pair must be light

- MSSM Higgs is PORTAL into UV completion *through* Consistency Condition(a.k.a Fine tuning) :

$$Det\, \mathcal{H} = 0$$

Opening the Higgs Portal

- Bi-Unitary transformation $\Rightarrow \bar{U}^T \mathcal{H} U$ is diagonal. Left and right Null Eigenvectors of $\mathcal{H}$ define the Higgs Fractions $\alpha_i, \bar{\alpha}_i$:

$$\alpha_i = U_{i1} \quad ; \quad \bar{\alpha}_i = \overline{U}_{i1}$$
$$H = \sum_i \alpha_i^* h_i \quad ; \quad \overline{H} = \sum_i \bar{\alpha}_i^* \bar{h}_i$$
$$L_{eff} : h_i \rightarrow \alpha_i H \quad ; \bar{h}_i \rightarrow \bar{\alpha}_i \overline{H}$$

- $SO(10)\mathrm{MatterYukawas} \oplus \{\alpha_i \bar{\alpha}_i\} \Rightarrow$ MSSM Yukawas $y_{AB}^{u,d,l,\nu}$ and Majorana masses $M_{\bar{\nu}^c}$:

$$\Psi_A.(h_{AB} H + f_{AB} \Sigma + g_{AB} \Theta)\Psi_B \quad \Rightarrow \quad 3 + 12 + 6 = 21 \quad \text{parameters}$$

for the MSSM Yukawas

Achievements of MSGUTs

- Completely realistic fit of all fermion mass mixing data[4]
- Prediction of distinctive MSSM spectra(2008)
  - Normal s-hierarchy ($m_{\tilde{q}_3,\tilde{l}_3} >> m_{\tilde{q}_{1,2},\tilde{l}_{1,2}}$)
  - Heavy stop,sbottom, large A_0 now (2012) *necessary* for $M_H^{Susy} >> M_Z$
  - Large A_0 and μ parameter
  - NMSGUT requires these to survive !
  - Light smuon (muon g-2 and CDM co-annihilation)
- Generic mechanism[5] for suppression of fast SUSY $d = 5$ operator mediated proton decay $\tau_p \sim 10^{27}$yrs upto the Susy Gauge mediated level $\tau_p \sim 10^{36}$yrs

[4] C.S.A. and S. K. Garg, Nucl. Phys.**B**857 (2012)101

[5] C. S.A., I. Garg and C. K. Khosa, **NPB 882** (2014)397

M_S Threshold

- NMSGUT success is Quantum found / *not tree level engineered* : Quantum corrections to Light-Heavy matching resolve difficulties of $b - t - \tau$ unification in NMSGUT.

- Fermion masses : $\overline{\mathbf{126}}$ couplings suppressed to fit $M_\nu \Rightarrow\Rightarrow$
- $\mathbf{10} \oplus \mathbf{120}$ only fits charged fermion masses $y_t \simeq y_b \simeq y_\tau(M_X)$ and $\tan\beta \simeq 50$ IF, MSSM radiative corrections raise $Y_{d,s}^{GUT}$ by 3-4 times while Y_b^{GUT} lowered by 5%.

M_S Threshold

- Precisely at large tan β gluino and chargino loops modify down type quarks sufficiently *provided*
- Light gauginos : $\sim .1 - 1.5$ TeV
- $M_S > 10$ TeV
- $\mu, A_0 \sim 100$ TeV
- *Normal* s-hierarchy $m_{\tilde{3}} >> m_{\tilde{1},\tilde{2}}$

Field	Mass(GeV)
$M_{\tilde{G}}$	1000.14
$M_{\chi^{\pm}}$	569.81, 125591.22
M_{χ^0}	210.10_{LSP}, 569.81, 125591.20, 125591.20
$M_{\tilde{\nu}}$	15308.069, 15258.322, 21320.059
$M_{\tilde{e}}$	1761.89, 15308.29, 211.57_{smuon}, 15258.60, 20674.72, 21419.56
$M_{\tilde{u}}$	11271.80, 14446.76, 11270.63, 14445.80, 24607.51, 40275.87
$M_{\tilde{d}}$	8402.99, 11272.10, 8401.48, 11270.95, 40269.19, 51845.93
M_A	377025.29
$M_{H^{\pm}}$	377025.30
M_{H^0}	377025.28
M_{h^0}	124.00_{h^0}

Table: Large $\mu, B, A_0 \Rightarrow\Rightarrow$ LSP $\simeq \tilde{B}, \tilde{\chi}^{\pm}\tilde{W}_{\pm}$). Light gauginos,Normal Shierarchy $\Rightarrow$ Higgs h^0 as found ,Light smuon ! Other sfermions multi-TeV : Decoupled & Mini-split, large μ, A_0

Baryon Stability on the Higgs Dissolution Edge

$$W^{\Delta B} = L_{ABCD} Q_A Q_B Q_C L_D + R_{ABCD} \bar{U}_A \bar{U}_B \bar{D}_C \bar{L}_D$$

$$(L,R)_{ABCD} \sim \frac{(h/f/g)_{AB}(h/f/g)_{CD}}{M_X}$$

- MSSM Higgs blend of 6 pairs from NMSGUT Higgs $\Rightarrow\Rightarrow$ $\sim 10^3$ heavy fields renormalize light Higgs : *Generically* drive it to "Higgs dissolution edge" :

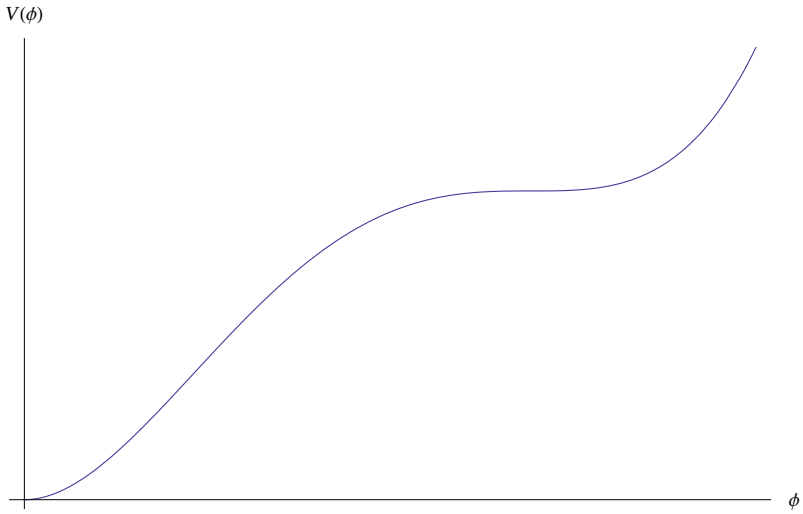
$$Z_{H,\bar{H}} \simeq 0$$

- $\Rightarrow\Rightarrow$

$$Y_{GUT} \sim \sqrt{Z_H} Y^{MSSM}(M_X) << Y^{MSSM}(M_X) < 1$$

- But $\mathcal{A}(\Delta B \neq 0, d = 5) \sim \frac{Y^2_{GUT}}{M_X}$!! $\Rightarrow\Rightarrow$
- $\tau_p >> 10^{27}$ yrs (generic) $\longrightarrow\longrightarrow$ $\tau_p > 10^{34}$ yrs !

Generic Renormalizable Inflection Point Inflation(GRIPI)



Generic Renormalizable Inflection Point Inflation

$$V = \frac{h^2}{12}\phi^4 - \frac{Ah}{6\sqrt{3}}\phi^3 + \frac{M^2}{2}\phi^2$$

TunedforInflection! $A = 4M\sqrt{1-\Delta}$; $\phi_0 = \frac{\sqrt{3}M}{h}(1 -$

$$V(\phi_0) = V_0 = \frac{M^4}{4h^2}(1+4\Delta)$$

GRIPI parameters before BICEP

- GRIPI parameters thought essential before BICEP :

$$N_{COBE} \quad > 50 \Rightarrow \quad : \quad h^2 \sim 10^{-24.95 \pm 0.17}(\frac{M}{GeV})$$

$$\Delta \quad \sim 10^{-28.17 \pm .13}(\frac{M}{GeV})^2 \quad : V_0 \sim 10^{40}(\frac{M}{10^4\,\mathrm{GeV}})^3 GeV^4$$

- Tensor scalar ratio r determines Vacuum energy scale

$$V_0^{1/4} = 2 \times 10^{16}\mathrm{GeV}(\frac{r}{0 \cdot 1})^{1/4}$$

- BICEP : $r \sim .2 \Rightarrow V_0^{1/4} \sim 2 \times 10^{16} \Rightarrow$ GUT scale controlled inflation !!!!

Susy Chiral-Gauge systems and Inflationary Parameters

- Seek the Inflaton among fields of Particle Physics Models !!

- Generically GRIPI in Chiral-Gauge system has from V_D

$$h \sim g \sim 10^{-1} >> h_{inflation}$$

- Composite Inflaton : e.g. LHN *flat direction* nullifies gauge coupling :

$$\tilde{N} = \tilde{\nu} = h_0 = \frac{\varphi}{\sqrt{3}} = \phi e^{i\theta}; \quad \phi \geq 0, \quad \theta \in [0, 2\pi)$$

MSSM Inflations and developments

- MSSM Inflation (Allahverdi,Mazumdar, Raidal et al 2002) MSSM flat direction inflaton e.g. LHN. suppresses gauge contributions to h,
- $A, M \sim 1 - 10\,\mathrm{TeV}$ from soft terms. Highly fine tuned : $\Delta \sim 10^{-20}$!! and unstable.
- Supersymmetric Seesaw Inflation (CSA , Garg 2012) LHN flat direction,

$$M \simeq\sim M_{\nu^c}\ 10^8 - 10^{10}\mathrm{GeV} \quad \Rightarrow \quad V_0 \sim 10^{52} - 10^{58}\,GeV$$

$$r <<< 0 \cdot 1!!$$

- AFTER BICEP :

$$V_0 \simeq 10^{65}\mathrm{GeV} \quad \Rightarrow \quad M_{Infl} > 10^{12.5}\,GeV$$

Susy Chiral-Gauge systems and Inflationary Parameters

- - Superpotential couplings of inflaton components in MSSM inflation or SSI inflation φ should all be $<< 10^{-8}$.
  - Trilinear coupling $A = 4M$.
- Conceivable in factorized gauge model : impossible to Unify.
- NMSGUT embedding of SSI failed !

- $M > 10^{13}\mathrm{GeV} \Rightarrow \Delta \sim 1$ Inflection breaks down, r large reanalyze !

- BICEP : $V_0^{1/4} \sim 10^{16.2} \Rightarrow M > 10^{13}$ GeV : $\Rightarrow \Delta \sim 1$ no Inflection $A <, << M$, acceptable !!

Post BICEP Renormalizable Inflation

- Slow roll still achievable for $10^{12.5} < M < 10^{14}\,GeV$ without inflection.
- For $N_{COBE} > 50$ one requires

$$\omega = \frac{M}{hM_p} \geq 10$$

$$\begin{aligned} V_0 &\simeq 10^2 M^2 M_p^2 \simeq 10^{65}\mathrm{GeV} \quad \Rightarrow \\ M &\simeq 10^{13.5}\mathrm{GeV} \qquad\qquad h \simeq 10^{-6} \end{aligned}$$

- With heavy Higgs contribution $\sim 10^{-3}$ to Inflaton mass $M >> M_{\nu_1^c} \sim 10^7$ GeV easily achievable.

High Hopes on the Higgs Dissolution Edge

- $$h \simeq \sqrt{h_{10}^{\dagger} h_{10} + f_{\overline{126}}^{\dagger} f_{\overline{126}} + g_{120}^{\dagger} g_{120}} \simeq 10^{-6}$$

  Not easy to achieve simultaneously with accurate fits !.
- However:GUT threshold suppression of SO(10) Yukawas sufficient to lower *first generation* SO(10) Yukawas $\sim 10^{-6}$.
- After BICEP revolution in outlook NMSGUT may become first realistic unified matter theory to achieve Inflation and tie Inflaton to specific dynamics !!
- Current search (2 weeks) NMSGUT fits for > 18 target parameters has $\chi \sim 2$ for 18 target parameters *and* successful inflation with measured parameters ! But we hope for better fits.

OUTLOOK

- NMSGUT fits all fermion data
- Focus on Higgs portal highly rewarding :Distinctive Susy spectra predicted to be mini-split decoupled Susy with *normal* s-hierarchy
- A_0, μ, m_0 predicted to be large in 2008as required by Higgs Discovery in 2012.
- $d = 5$ Baryon decay suppressed to tolerable levels near gauge dominated ones.

OUTLOOK

- Light smuon NLSP possible allows Susy resolution of muon g-2 anomaly and relic co-annihilation for correct Bino DM density.
- BICEP revolution may enable NMSGUT to become first realistic Unified theory with parameters compatible with Inflation and Inflaton made from GUT model Fields.
- Higgs mixing with UV completion and $\Delta\mathcal{H} = 0$ consistency condition again crucial : Proton Life time Inflated because universe lives on the Higgs dissolution edge which enable Inflation !
- Natural *renormalizable* MSGUT Yukawon-ification , identifying Horizontal and GUT scales emerges from MSGUT unification via exploitation of Higgs Portal consistency conditions. Predicts Light $\sim 10\mathrm{GeV}$ viable CDM (DAMA/LIBRA).

THANK YOU