

Dark matter, Primordial Gravity Waves and Proton Decay

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C.S. Un



Physics Beyond the Standard Model

- Neutrino Physics: SM + Gravity suggests $m_\nu \lesssim 10^{-5}$ eV
- Electric charge quantization not explained in SM
(Dirac requires monopoles)
- Dark Matter: SM offers no plausible DM candidate
- Origin of matter in the universe
- Inflation (resolve problems of standard big bang cosmology)

Grand Unified Theories (GUTs)

- Unification of SM/MSSM gauge couplings
- Unification of matter/quark-lepton multiplets
- Proton Decay
- Electric charge quantization, Magnetic monopoles predicted (as Dirac wanted)
- Seesaw physics, neutrino oscillations
- Baryogenesis/leptogenesis
- Inflation/gravity waves, $\delta\rho/\rho$

Quark-Lepton Unification

- Pati-Salam $\rightarrow SU(4)_c \times SU(2)_L \times SU(2)_R$:

$$(4, 2, 1) + (\bar{4}, 1, 2)$$

$$\begin{pmatrix} u & u & u & \nu_e \\ d & d & d & \ell \end{pmatrix}_{L,R} \implies 16 \text{ chiral fields};$$

SM neutrinos can have tiny masses via seesaw mechanism(built in)

- Georgi-Glashow $\rightarrow SU(5)$: $10 + \bar{5}$

- 15 chiral fields;
 - Massless neutrinos

- Fritzsch-Minkowski, Georgi $\rightarrow SO(10)$:

$$16 \xrightarrow{SU(5)} 10 + \bar{5} + 1(\nu_R)$$

- E_6

SU(5) x U(1)_{PQ} (Non-SUSY)

Model Contains axion (strong CP + DM),
right-handed neutrinos, and a new scalar
which drives inflation (& breaks U(1)_{PQ})

$SU(5) \times U(1)_{PQ}$

Neutrino masses

Fixes bad mass relations



	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
$SU(5)$	10	5	1	5	5	1	24	45*
PQ symmetry (DFSZ)	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

$$\begin{aligned} \mathcal{L}_{Yuk} = & T_L \cdot \mathbf{Y}_{10} \cdot T_L \cdot H_1 + T_L \cdot \mathbf{Y}_5 \cdot F_L \cdot H_2 + T_L \cdot \mathbf{Y}_{45} \cdot F_L \cdot \chi \\ & F_L \cdot \mathbf{Y}_\nu \cdot \nu_L^c \cdot H_1 + \frac{1}{2} \mathbf{Y}_N \nu_L^c \cdot \nu_L^c \cdot \sigma + \text{h.c.}, \end{aligned}$$



$$M_e = \mathbf{Y}_5 \langle H_2 \rangle + 2\mathbf{Y}_{45} \langle \chi \rangle$$

$$M_d = \mathbf{Y}_5^T \langle H_2 \rangle - 6\mathbf{Y}_{45}^T \langle \chi \rangle$$

$$M_u = 4(\mathbf{Y}_{10} + \mathbf{Y}_{10}^T) \langle H_1 \rangle$$

$$M_\nu \simeq \mathbf{Y}_\nu^T \cdot \mathbf{Y}_N^{-1} \cdot \mathbf{Y}_\nu \frac{\langle H_1 \rangle^2}{\langle \sigma \rangle}$$

$$\mathbf{SU(5) \times U(1)_{PQ}}$$

Inflation with σ

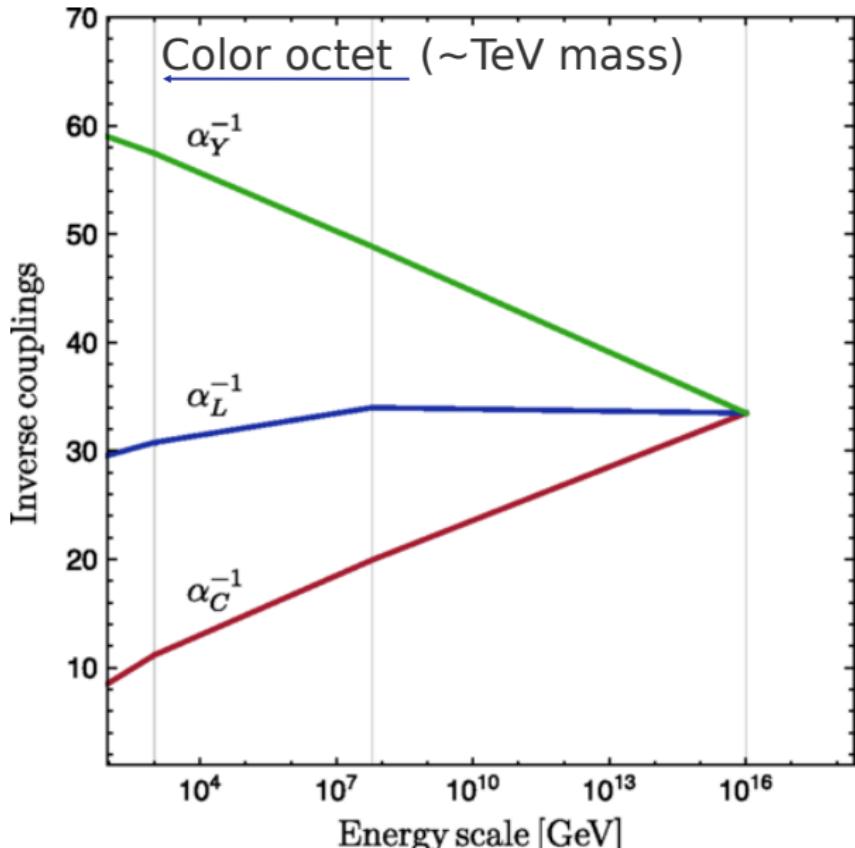
	T_L	F_L	ν_L^c	H_1	H_2	σ	Φ	χ
$SU(5)$	10	5	1	5	5	1	24	45*
$U(1)_{PQ}$	$\alpha/2$	$\alpha/2$	$\alpha/2$	$-\alpha$	$-\alpha$	$-\alpha$	0	$-\alpha$

$$\sigma = \rho e^{ia/f_a}$$

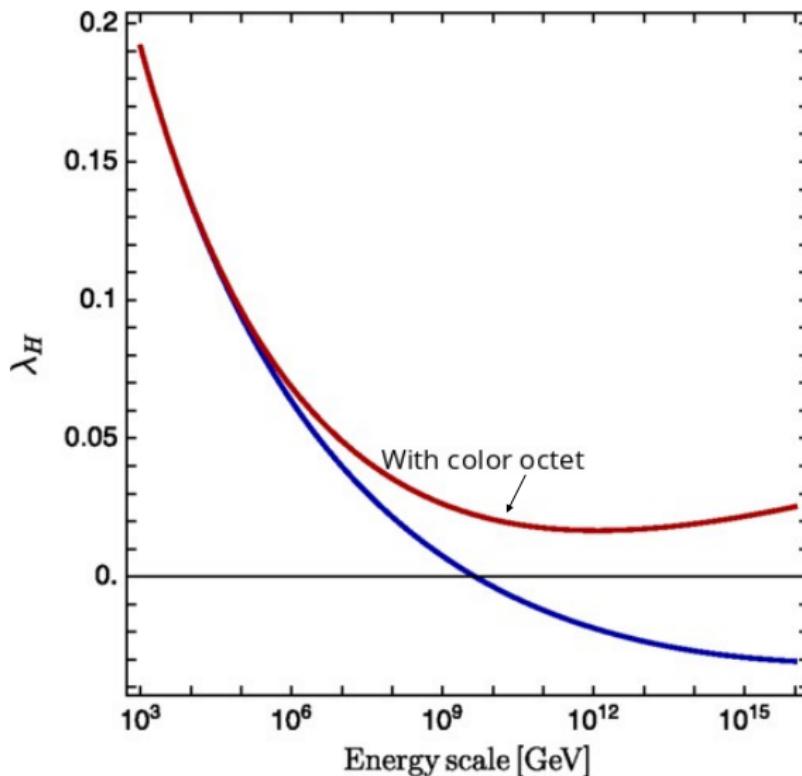
Inflaton

Axion

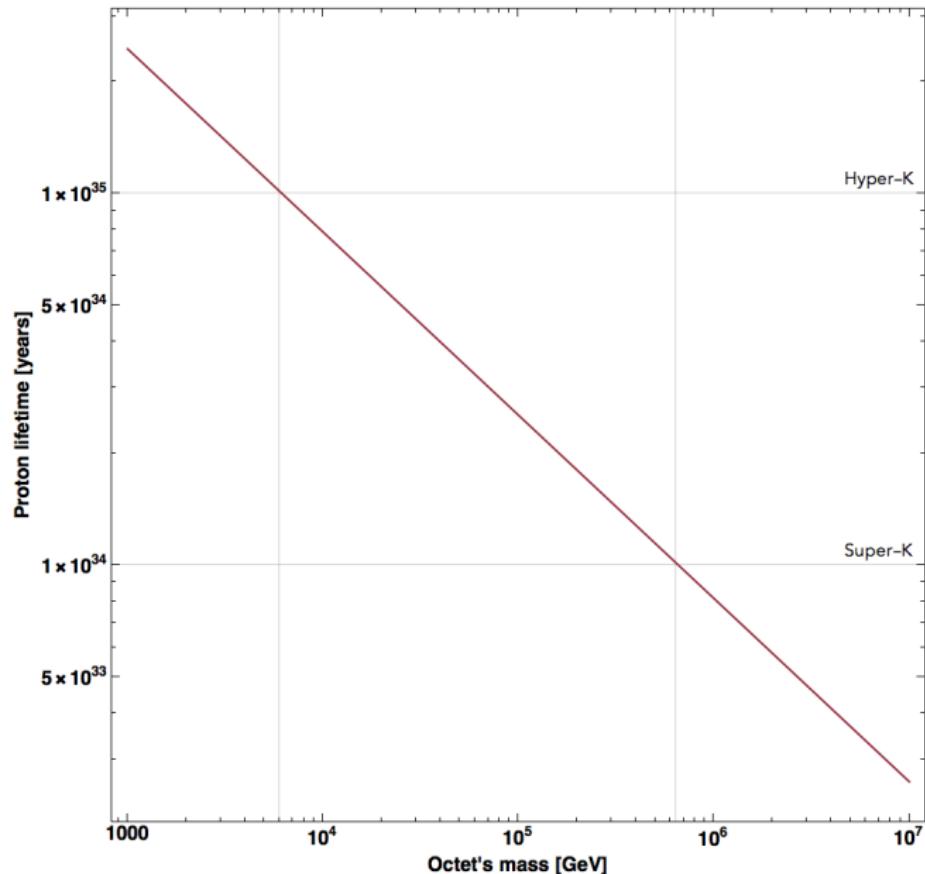
$SU(5) \times U(1)_{\text{PQ}}$



Higgs vacuum is stabilized



Proton Lifetime



Non-SUSY SO(10)

- $G = SO(10)/\text{Spin}(10)$
- $H = SU(3)_c \times U(1)_{e.m.}$
- $\Pi_2(G/H) \cong \Pi_1(H) \Rightarrow$ Monopoles
- $\Pi_1(G/H) \cong \Pi_0(H) = \mathbb{Z}_2 \Rightarrow$ Cosmic Strings, Dark Matter
(provided $G \rightarrow H$ breaking uses only tensor representations)
- $\mathbb{Z}_2 \subset \mathbb{Z}_4$ (center of $SO(10)$)
- Recent work suggests that this Z_2 symmetry can yield plausible cold dark matter candidates.

[Mario Kadastik, Kristjan Kannike, Martti Raidal, Phys.Rev. D81, 015002 (2010), Yann Mambrini, Natsumi Nagata, Keith A. Olive, Jeremi Quevillon, and Jiaming Zheng Phys.Rev. D91 (2015) no.9, 095010 ; Sofiane M. Boucenna, Martin B. Krauss, Enrico Nardi Phys.Lett. B755 (2016) 168-17]

Successful Primordial Inflation should:

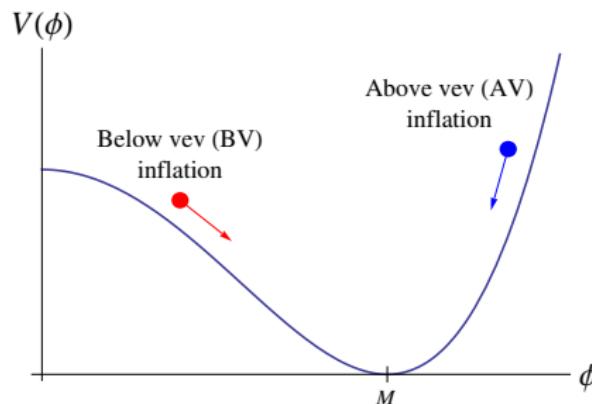
- Explain flatness, isotropy;
- Provide origin of $\frac{\delta T}{T}$;
- Offer testable predictions for n_s, r (gravity waves), $dn_s/d \ln k$;
- Recover Hot Big Bang Cosmology;
- Explain the observed baryon asymmetry;
- Offer plausible CDM candidate;

Inflation with a Higgs Potential [Kallosh and Linde, 07; Rehman, Shafi and Wickman, 08]

- Consider the following Higgs Potential:

$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{M} \right)^2 \right]^2 \quad \leftarrow (\text{tree level})$$

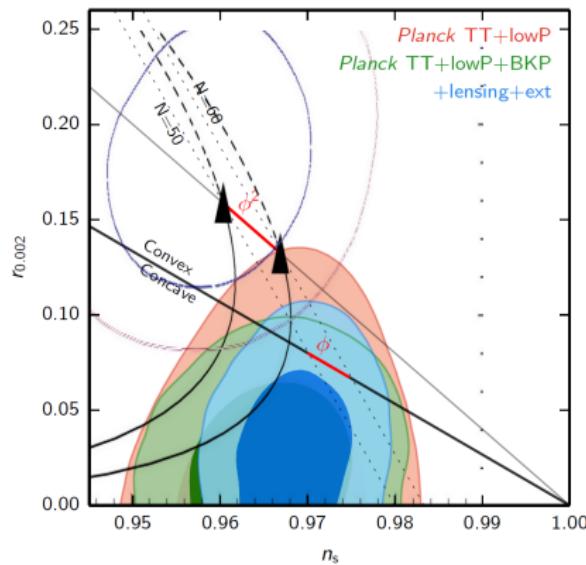
Here ϕ is a gauge singlet field.



- WMAP/Planck data favors BV inflation ($r \lesssim 0.1$).

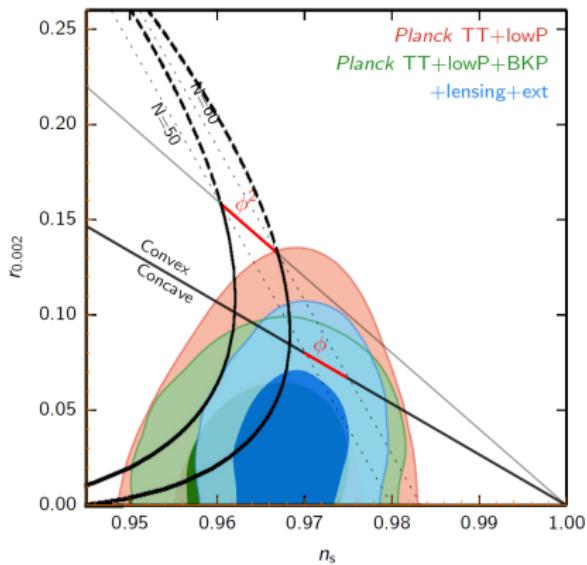
Note: This is for minimal coupling to gravity

Higgs Potential:



n_s vs. r for Higgs potential, superimposed on Planck and Planck+BKP 68% and 95% CL regions taken from arXiv:1502.01589. The dashed portions are for $\phi > v$. N is taken as 50 (left curves) and 60 (right curves).

Coleman–Weinberg Potential:



n_s vs. r for Coleman–Weinberg potential, superimposed on Planck and Planck+BKP 68% and 95% CL regions taken from arXiv:1502.01589. The dashed portions are for $\phi > v$. N is taken as 50 (left curves) and 60 (right curves).

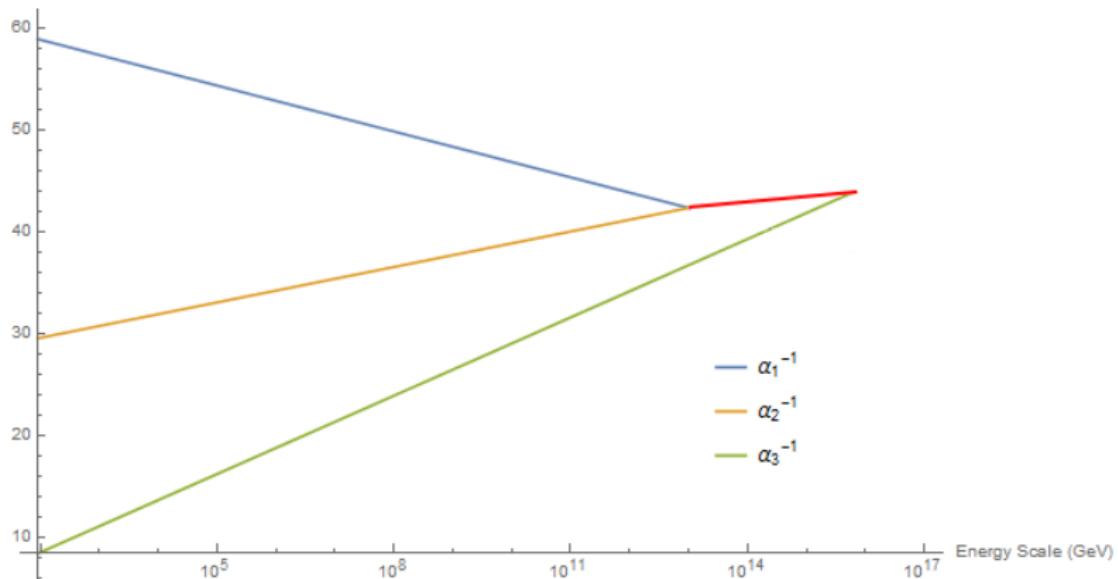
Primordial Monopoles in $\text{SO}(10) \rightarrow 4 - 2 - 2 \rightarrow 3 - 2 - 1$

- Let's consider how much dilution of the monopoles is necessary.
 $M_I \sim 10^{13}$ GeV corresponds to monopole masses of order $M_M \sim 10^{14}$ GeV. For these intermediate mass monopoles the MACRO experiment has put an upper bound on the flux of $2.8 \times 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. For monopole mass $\sim 10^{14}$ GeV, this bound corresponds to a monopole number per comoving volume of $Y_M \equiv n_M/s \lesssim 10^{-27}$. There is also a stronger but indirect bound on the flux of $(M_M/10^{17} \text{ GeV})10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ obtained by considering the evolution of the seed Galactic magnetic field.
- At production, the monopole number density n_M is of order H_x^3 , which gets diluted to $H_x^3 e^{-3N_x}$, where N_x is the number of e -folds after $\phi = \phi_x$. Using

$$Y_M \sim \frac{H_x^3 e^{-3N_x}}{s},$$

where $s = (2\pi^2 g_S/45)T_r^3$, we find that sufficient dilution requires $N_x \gtrsim \ln(H_x/T_r) + 20$. Thus, for $T_r \sim 10^9$ GeV, $N_x \gtrsim 30$ yields a monopole flux close to the observable level.

Gauge Couplings in SM



Stech & Tauartkiladze

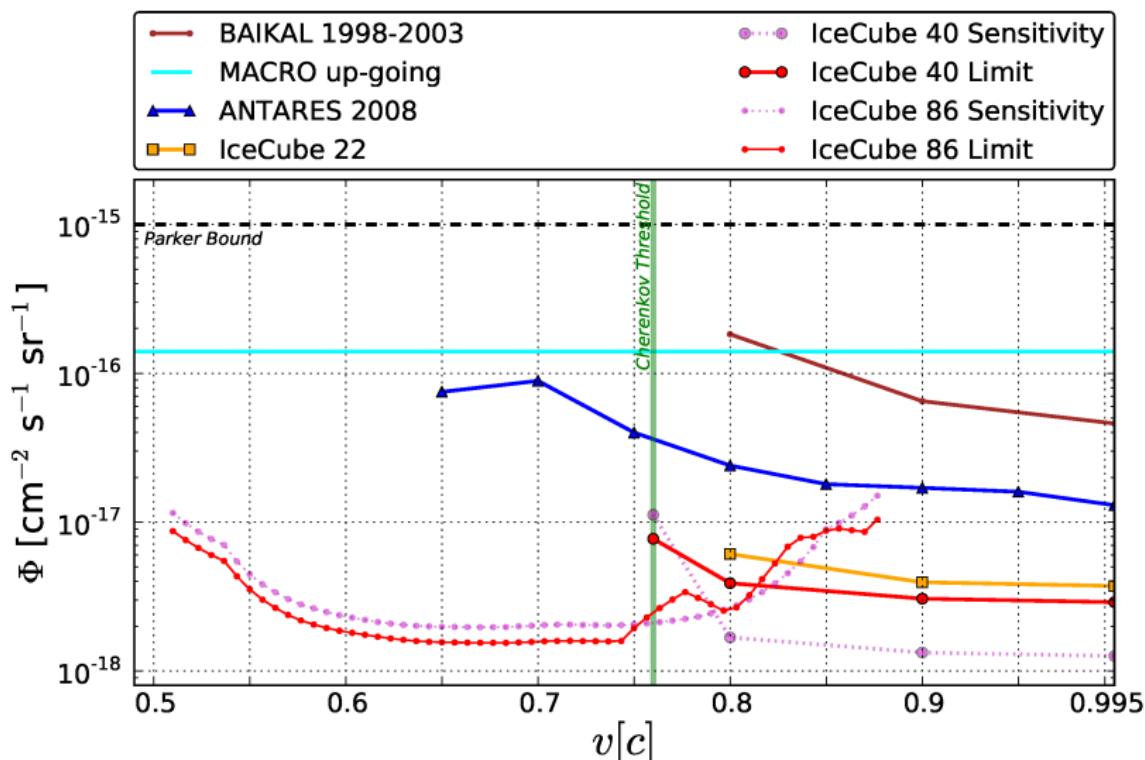
$SU(3)_L \times SU(3)_R$ Monopole

$$E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R \quad (1)$$

$$\xrightarrow{M_I \sim 10^{13} \text{ GeV}} SU(3)_C \times SU(2)_L \times U(1) \quad (2)$$

- Second breaking produces monopoles with three units of magnetic charge
- Since their mass $\sim 10M_I$ some may survive inflation

Relativistic Monopoles at IceCube



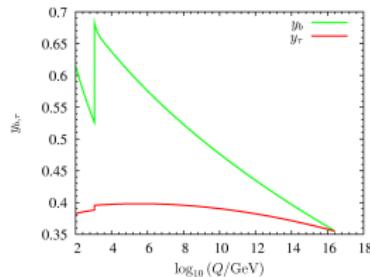
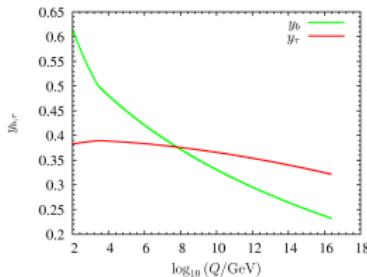
Source: IceCube Collaboration, Eur. Phys. J. C (2016) 76:133

Supersymmetry

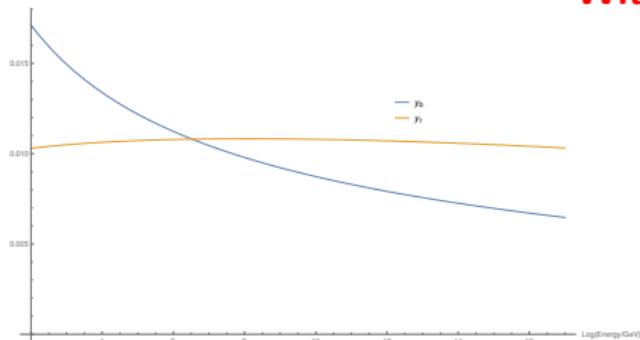
- Unification of the SM gauge couplings at $M_{GUT} \sim 2 \times 10^{16}$ GeV
- Resolution of the gauge hierarchy problem
- Cold dark matter candidate (LSP)
- Compelling inflation models

SUSY Yukawa Unification

b- τ Yukawa coupling unification



Without



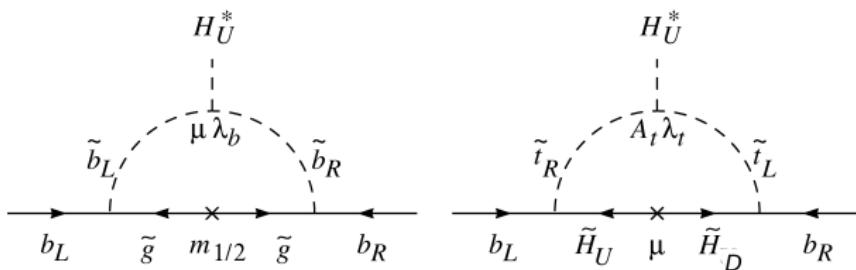
Supersymmetry

b- τ YU and finite threshold corrections ¹

Dominant contributions to the bottom quark mass from the gluino and chargino loop

$$\delta y_b \approx \frac{g_3^2}{12\pi^2} \frac{\mu m_{\tilde{g}} \tan \beta}{m_1^2} + \frac{y_t^2}{32\pi^2} \frac{\mu A_t \tan \beta}{m_2^2} + \dots$$

where $m_1 \approx (m_{\tilde{b}_1} + m_{\tilde{b}_2})/2$ and $m_2 \approx (m_{\tilde{t}_2} + \mu)/2$



where $\lambda_b = y_b$ and $\lambda_t = y_t$

¹L. J. Hall, R. Rattazzi and U. Sarid, Phys. Rev.D 50, 7048 (1994)

$b - \tau$ QYU in $SU(5)$

$$\begin{aligned} 0 &\leq m_{10} \leq 20\text{TeV} \\ 0 &\leq m_5 \leq 20\text{TeV} \\ 0 &\leq M_{1/2} \leq 5\text{TeV} \\ -3 &\leq A_t/m_{10} \leq 3 \\ -20 &\leq A_{b\tau}/m_5 \leq 20 \\ 1.2 &\leq \tan \beta \leq 60 \\ 0 &\leq m_{H_d} \leq 20\text{TeV} \\ 0 &\leq m_{H_u} \leq 20\text{TeV} \end{aligned}$$

$$y_b : y_\tau = (1 - C) : (1 + 3C), \quad |C| \leq 0.2$$

	Point 1	Point 2	Point 3	Point 4	Point 5
m_0	3074	2375	2057	2745	2133
M_1	3941	3607	3350	3557	3387
M_2	5845	5009	4536	5069	4545
M_3	1084	1504	1571	1289	1654
M_{H_d}	615	725	800	609	752
M_{H_u}	1759	2025	2054	2152	2121
$\tan \beta$	44.7	42.9	40.5	44.3	42.3
A_0/m_0	-0.57	-0.62	-0.66	-0.72	-0.65
μ	212.3	333.9	472	699	786
ΔEW	9.8	27.4	48.8	109.6	137.5
m_h	123.2	123.5	123.3	123.6	123.4
m_H	1895	1586	1639	1244	1447
m_A	1883	1576	1629	1236	1437
m_{H^\pm}	1897	1588	1642	1248	1450
$m_{\tilde{\chi}_{1,2}^0}$	207.3, 209.4	326.8, 329.3	460.7, 463.6	688.1, 690.8	769.7, 772.9
$m_{\tilde{\chi}_{3,4}^0}$	1792, 4856	1629, 4138	1509, 3739	1614, 4206	1529, 3749
$m_{\tilde{\chi}_{1,2}^\pm}$	215.7, 4845	338.2, 4120	475.1, 3720	706.2, 4189	789.5, 3728
$m_{\tilde{g}}$	2487	3291	3407	2884	3571
$m_{\tilde{u}_{L,R}}$	5099, 3754	4719, 3713	4460, 3604	4740, 3706	4585, 3762
$m_{\tilde{l}_{1,2}}$	1584, 4189	1939, 3910	2002, 3728	1760, 3845	2171, 3823
$m_{\tilde{d}_{L,R}}$	5100, 3646	4720, 3616	4460, 3513	4740, 3606	4585, 3672
$m_{\tilde{b}_{1,2}}$	2788, 4231	2901, 3936	2923, 3748	2795, 3871	3031, 3838
$m_{\tilde{e}_{e,\mu}}$	4843	4005	3579	4262	3627
$m_{\tilde{\nu}_\tau}$	4582	3798	3407	4008	3432
$m_{\tilde{\epsilon}_{L,R}}$	4838, 3373	4002, 2684	3578, 2357	4258, 3002	3626, 2427
$m_{\tilde{\tau}_{1,2}}$	2447, 4560	1941, 3784	1744, 3397	2131, 3992	1742, 3423
$\sigma_{SI}(\text{pb})$	0.66×10^{-10}	0.10×10^{-09}	0.14×10^{-09}	0.17×10^{-09}	0.23×10^{-09}
$\sigma_{SD}(\text{pb})$	0.12×10^{-05}	0.78×10^{-06}	0.58×10^{-06}	0.28×10^{-06}	0.32×10^{-06}
Ωh^2	0.008	0.02	0.041	0.0914	0.113
$y_{t,b,\tau}(M_{\text{GUT}})$	0.55, 0.30, 0.41	0.54, 0.30, 0.39	0.54, 0.28, 0.36	0.55, 0.32, 0.42	0.54, 0.30, 0.39
C	0.08	0.07	0.07	0.08	0.08

	Point 1	Point 2	Point 3
m_{10}	2325	5805	3299
M_5	4334	5756	4813
$M_{1/2}$	1317	2478	1002
m_{H_d}	1574	6740	1592
m_{H_u}	3698	8052	4206
$\tan \beta$	22.6	13.8	26.7
A_t/m_{10}	-1.73	-1.65	-1.46
$A_{b,\tau}/m_5$	0.29	-2.46	0.05
μ	107.8	714.9	835.4
Δ_{EW}	35.3	117	163
m_h	124.5	126.4	124.1
m_H	1334	6513	946.3
m_A	1326	6471	940.1
m_{H^\pm}	1336	6514	950
$m_{\tilde{\chi}_{1,2}^0}$	102.8, 111.4	701.3, 716.4	441.7 , 783.3
$m_{\tilde{\chi}_{3,4}^0}$	579.9, 1104	1128, 2110	831, 899
$m_{\tilde{\chi}_{1,2}^\pm}$	110.8 , 1093	732.5 , 2088	792, 894
$m_{\tilde{g}}$	2954	5361	2369
$m_{\tilde{u}_{L,R}}$	3420, 3424	7354, 7302	3780, 3839
$m_{\tilde{t}_{1,2}}$	1403, 2569	2797, 5473	1548, 2747
$m_{\tilde{d}_{L,R}}$	3421, 4957	7355, 7187	3781, 5140
$m_{\tilde{b}_{1,2}}$	2572, 4831	5539, 6868	2751, 4958
$m_{\tilde{\nu}_1}$	4457	6007	4902
$m_{\tilde{\nu}_3}$	4411	5852	4822
$m_{\tilde{e}_{L,R}}$	4455, 2246	6002, 5791	4899, 3196
$m_{\tilde{\tau}_{1,2}}$	2053, 4404	5464, 5851	2947, 4816
$\sigma_{SI}(\text{pb})$	0.10×10^{-8}	0.72×10^{-9}	0.20×10^{-8}
$\sigma_{SD}(\text{pb})$	0.82×10^{-4}	0.15×10^{-5}	0.59×10^{-6}
$\Omega_{CDM} h^2$	0.05	0.097	0.098
$y_{t,b,\tau}$	0.50, 0.13, 0.17	0.51, 0.07, 0.1	0.52, 0.16, 0.21
C	0.08	0.08	0.07

	Point 1	Point 2	Point 3	Point 4
m_{10}	2286	928.6	7062	5223
M_5	6884	1558	6005	3.87
$M_{1/2}$	4816	4621	2797	2019
m_{H_d}	12.62	7054	9667	3714
m_{H_u}	5263	5020	8695	6202
$\tan \beta$	27.2	26.7	16	29
A_t/m_{10}	2.36	0.58	-1.41	-1.25
$A_{b,\tau}/m_5$	0.64	4.43	9.2	19.4
μ	765.6	990.4	1757	2237
Δ_{EW}	343.5	416.3	767	1127
m_h	123.7	124.5	126.4	125
m_H	1660	7177	2289	4078
m_A	1649	7130	2572	4051
m_{H^\pm}	1662	7178	2590	4079
$m_{\tilde{\chi}_{1,2}^0}$	759.6, 762.1	980.5, 983.3	1267 , 1738	904.8 , 1684
$m_{\tilde{\chi}_{3,4}^0}$	2186, 4010	2090, 3828	1741, 2366	2183, 2188
$m_{\tilde{\chi}_{1,2}^\pm}$	785.4 , 3953	1009 , 3785	1769, 2330	1684, 2194
$m_{\tilde{g}}$	9582	9128	5936	4383
$m_{\tilde{u}_{L,R}}$	8785, 8465	8273, 7815	8697, 8541	6420, 6413
$m_{\tilde{t}_{1,2}}$	6733, 7958	6012, 7427	4240, 4961	3404, 5096
$m_{\tilde{d}_{L,R}}$	8786, 10627	8273, 7949	8697, 7728	6420, 3468
$m_{\tilde{b}_{1,2}}$	7915, 10350	7406, 7657	3344, 5007	3183, 5106
$m_{\tilde{e}_1}$	7594	3255	6218	1454
$m_{\tilde{e}_3}$	7494	2917	4115	929.5
$m_{\tilde{e}_{L,R}}$	7594, 2629	3269, 2207	6217, 7193	1495, 5159
$m_{\tilde{\tau}_{1,2}}$	1999, 7491	1044 , 2943	2754, 4052	984.6 , 4920
$\sigma_{SI}(\text{pb})$	0.99×10^{-10}	0.12×10^{-9}	0.11×10^{-9}	0.70×10^{-11}
$\sigma_{SD}(\text{pb})$	0.17×10^{-6}	0.14×10^{-6}	0.68×10^{-7}	0.85×10^{-8}
$\Omega_{CDM} h^2$	0.094	0.099	0.12	0.1
$y_{t,b,\tau}$	0.53, 0.15, 0.21	0.53, 0.15, 0.21	0.51, 0.1, 0.12	0.52, 0.16, 0.24
C	0.09	0.1	0.05	0.12

SUSY Higgs (Hybrid) Inflation

[Dvali, Shafi, Schaefer; Copeland, Liddle, Lyth, Stewart, Wands '94]

[Lazarides, Schaefer, Shafi '97][Senoguz, Shafi '04; Linde, Riotto '97]

[Buchmüller, Domcke and Schmitz]

- Attractive scenario in which inflation can be associated with symmetry breaking $G \rightarrow H$
- Simplest inflation model is based on

$$W = \kappa S (\Phi \bar{\Phi} - M^2)$$

S = gauge singlet superfield, $(\Phi, \bar{\Phi})$ belong to suitable representation of G

- Need $\Phi, \bar{\Phi}$ pair in order to preserve SUSY while breaking $G \rightarrow H$ at scale $M \gg \text{TeV}$, SUSY breaking scale.
- R-symmetry

$$\Phi \bar{\Phi} \rightarrow \Phi \bar{\Phi}, \quad S \rightarrow e^{i\alpha} S, \quad W \rightarrow e^{i\alpha} W$$

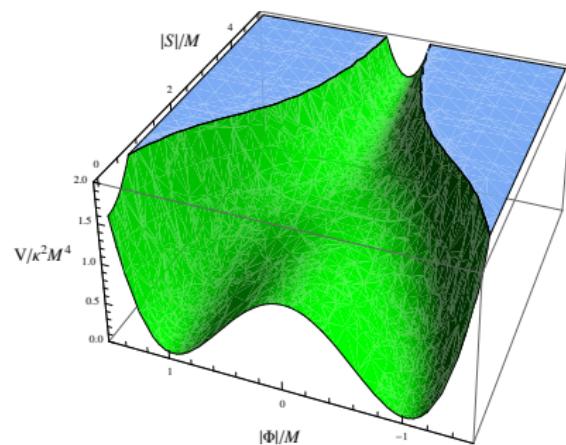
$\Rightarrow W$ is a unique renormalizable superpotential

- Tree Level Potential

$$V_F = \kappa^2 (M^2 - |\Phi^2|)^2 + 2\kappa^2 |S|^2 |\Phi|^2$$

- SUSY vacua

$$|\langle \bar{\Phi} \rangle| = |\langle \Phi \rangle| = M, \langle S \rangle = 0$$



Take into account radiative corrections (because during inflation $V \neq 0$ and SUSY is broken by $F_S = -\kappa M^2$)

- Mass splitting in $\Phi - \bar{\Phi}$

$$m_{\pm}^2 = \kappa^2 S^2 \pm \kappa^2 M^2, \quad m_F^2 = \kappa^2 S^2$$

- One-loop radiative corrections

$$\Delta V_{\text{1loop}} = \frac{1}{64\pi^2} \text{Str}[\mathcal{M}^4(S) (\ln \frac{\mathcal{M}^2(S)}{Q^2} - \frac{3}{2})]$$

- In the inflationary valley ($\Phi = 0$)

$$V \simeq \kappa^2 M^4 \left(1 + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x) \right)$$

where $x = |S|/M$ and

$$F(x) = \frac{1}{4} \left((x^4 + 1) \ln \frac{(x^4 - 1)}{x^4} + 2x^2 \ln \frac{x^2 + 1}{x^2 - 1} + 2 \ln \frac{\kappa^2 M^2 x^2}{Q^2} - 3 \right)$$

Tree level + radiative corrections + minimal Kähler potential yield:

$$n_s = 1 - \frac{1}{N} \approx 0.98.$$

$\delta T/T$ proportional to M^2/M_p^2 , where M denotes the gauge symmetry breaking scale. Thus we expect $M \sim M_{GUT}$ for this simple model. In practice, $M \approx (1 - 5) \times 10^{15}$ GeV

Since observations suggest that n_s lie close to 0.97, there are at least two ways to realize this slightly lower value:

- include soft SUSY breaking terms, especially a linear term in S ;
- employ non-minimal Kähler potential.

Hybrid Inflation & Split SUSY

- $U(1)_R$ -symmetry yields the following unique renormalizable superpotential:

$$W = S \left(\kappa \bar{\Phi} \Phi - \kappa M^2 + \lambda H_u H_d \right)$$

- Include SUSY breaking/SUGRA, the inflationary potential is:

$$V(\phi) = m^4 \left(1 + A \ln \left(\frac{\phi}{\phi_0} \right) \right) - 2\sqrt{2}m_G m^2 \phi$$

$$\phi = \sqrt{2} \operatorname{Re}[S], \quad m \equiv \sqrt{\kappa} M$$

$$A = \frac{1}{4\pi^2} \left(\lambda^2 + \frac{N\phi}{2} \kappa^2 \right)$$

- Successful inflation/gauge symmetry breaking requires $\lambda > \kappa$

Hybrid Inflation & Split SUSY

- MSSM μ -term

$$\mu = \frac{\lambda}{\kappa} m_G \equiv \gamma m_G$$

$$n_s \simeq 1 - \frac{2}{N_0} f(B), \quad B = \frac{2\sqrt{2}m_G\phi_0}{Am^2}$$

- For $N_0 = 60$:

$$1) \quad B = 0 \implies f(B) = 1/2 \implies n_S \simeq 0.98$$

$$2) \quad B = 0.7 \implies f(B) = 1.03 \implies n_S \simeq 0.966$$

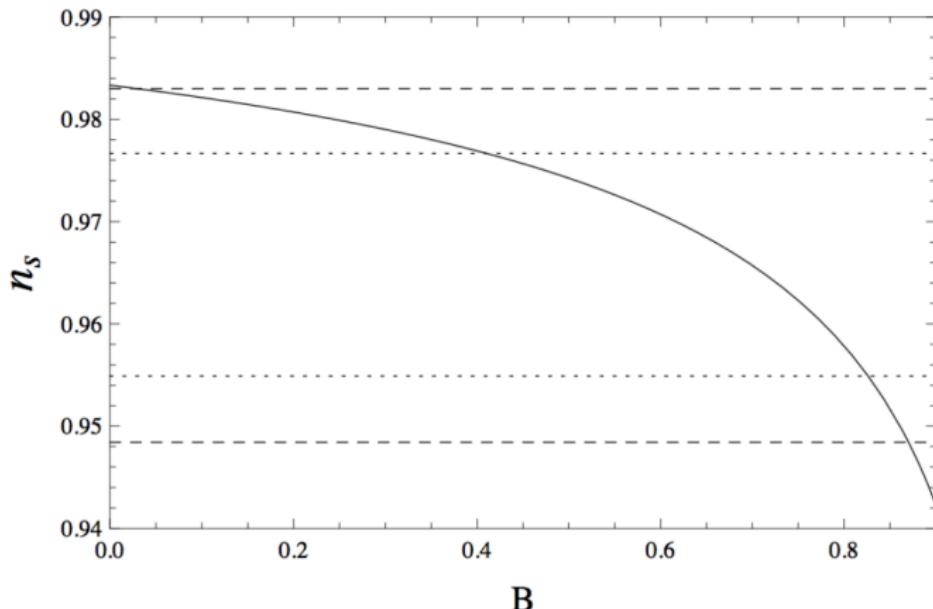


Figure: Spectral index n_s vs. B . The region between the two dotted (dashed) lines corresponds to 1σ (2σ) limit obtained by Planck 2015.

- $\Gamma(\phi \rightarrow \tilde{H}_u \tilde{H}_d) = \frac{\lambda^2}{8\pi} m_\phi \implies T_r \gtrsim 3.2 \times 10^{11} \text{GeV}$
- Cosmology with gravitinos:
 - 1) LSP gravitino not realized.
 - 2) If m_G is sufficiently large, LSP is still in thermal equilibrium when inflaton/gravitino decay

$$\implies m_G \gtrsim (4.6 \times 10^7 \text{GeV}) \left(\frac{m_{\text{LSP}}}{2 \text{TeV}} \right)$$

Minimal scenario yields split SUSY

$m_0 \sim m_G \sim \mu (\implies \tan(\beta) \approx 2, m_h \approx 125\text{GeV})$

$M_{1/2} \sim \text{TeV} \implies \text{Wino dark matter}$

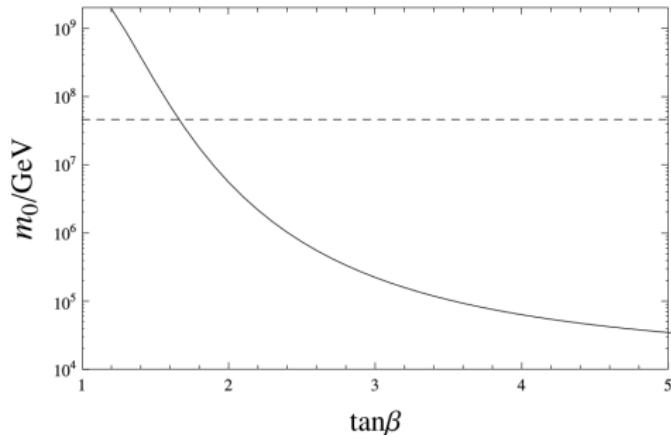


Figure: Soft scalar mass m_0 as a function of $\tan(\beta)$

Summary

- Unification of all forces remains a compelling idea.
- Grand unification explains charge quantization, predicts monopoles and proton decay.
- Also explains tiny neutrino masses via seesaw mechanism.
- Non-SUSY gauge coupling unification require new particles/new physics below M_{GUT} .
- In non-SUSY inflation with Higgs potential, $r \gtrsim 0.02$ (minimal coupling to gravity).
- SUSY models offer plausible dark matter candidates such as TeV mass higgsino.
- Class of SUSY inflation models predict $\frac{\delta T}{T} \propto (\frac{M}{M_P})^2$, with $M \sim 10^{16}$ GeV; $r \lesssim (10^{-3} - 10^{-4})$.
- $b - \tau$ Yukawa Unification can be implemented in SUSY models with particle masses in the TeV range.
- Find dark matter, primordial gravity waves and proton decay.

Thank You!