Inflation and Unification

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OUTLINE

- Introduction
- Higgs Boson
- Supersymmetry
- Extra Dimension(s)
- Gauge-Higgs Unification
- Orbifold GUTs
- Inflation
- Topological Defects
- Conclusion

SM Predictions (Confirmed)

- Weak Neutral Currents
- Parity Violation in Atoms
- $W^{\pm},\ Z$ gauge bosons, Gluon Jets
- Asymptotic Freedom
- $c,\ t,\ b$ quarks; CP violation; B physics
- Numerous other tests (Stable proton $\tau_p \geq$ few $\times\ 10^{33}$yrs)

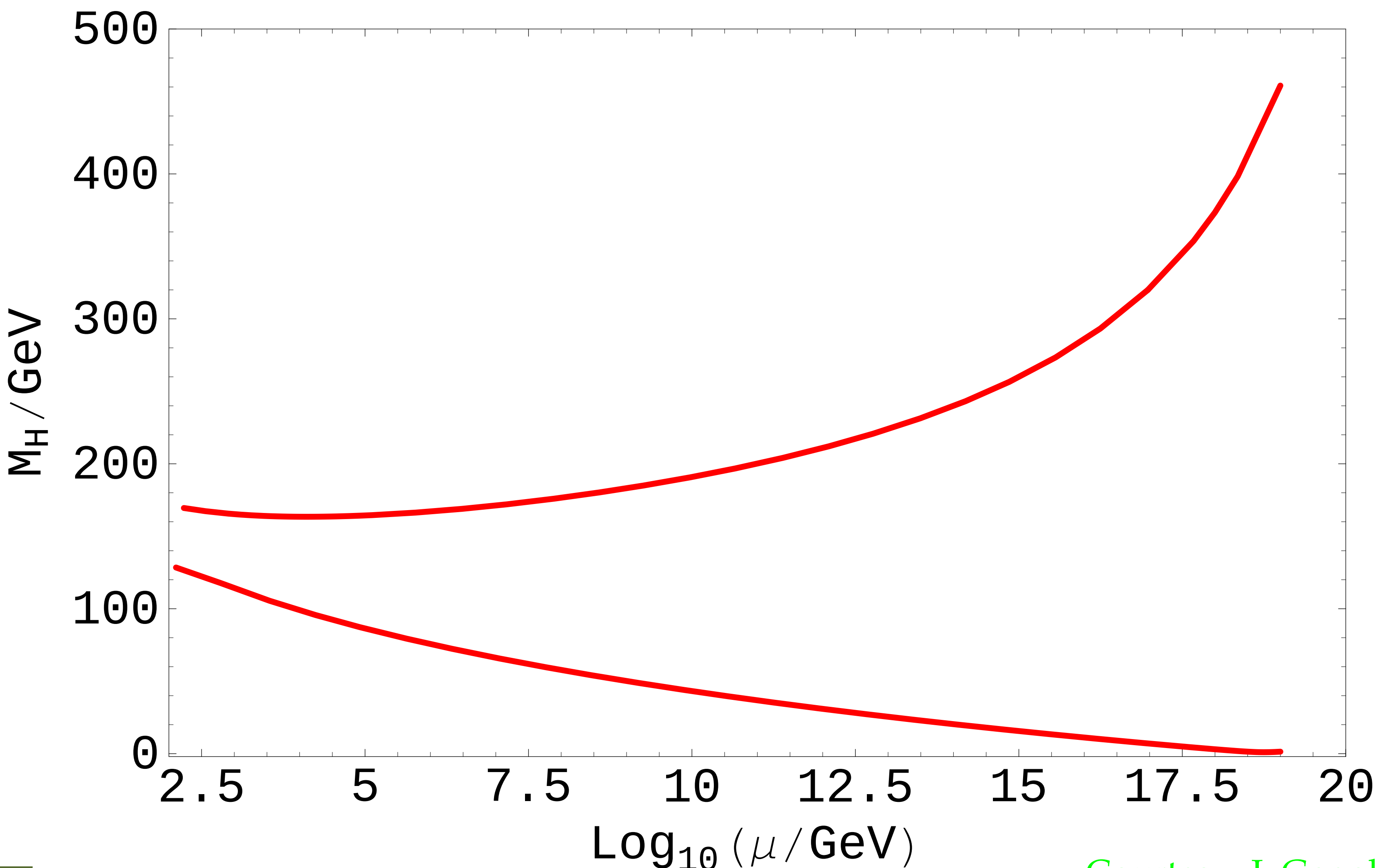
Where is the SM Higgs Boson?

- From arguments based on vacuum stability and perturbativity, and with no new physics between M_Z and M_{Planck}, one finds

$$\begin{aligned} 0.8 &\lesssim \lambda \lesssim 1.1 \\ \Longrightarrow \quad 130 &\ \text{GeV} \lesssim m_h \lesssim 180 \ \text{GeV} \end{aligned}$$

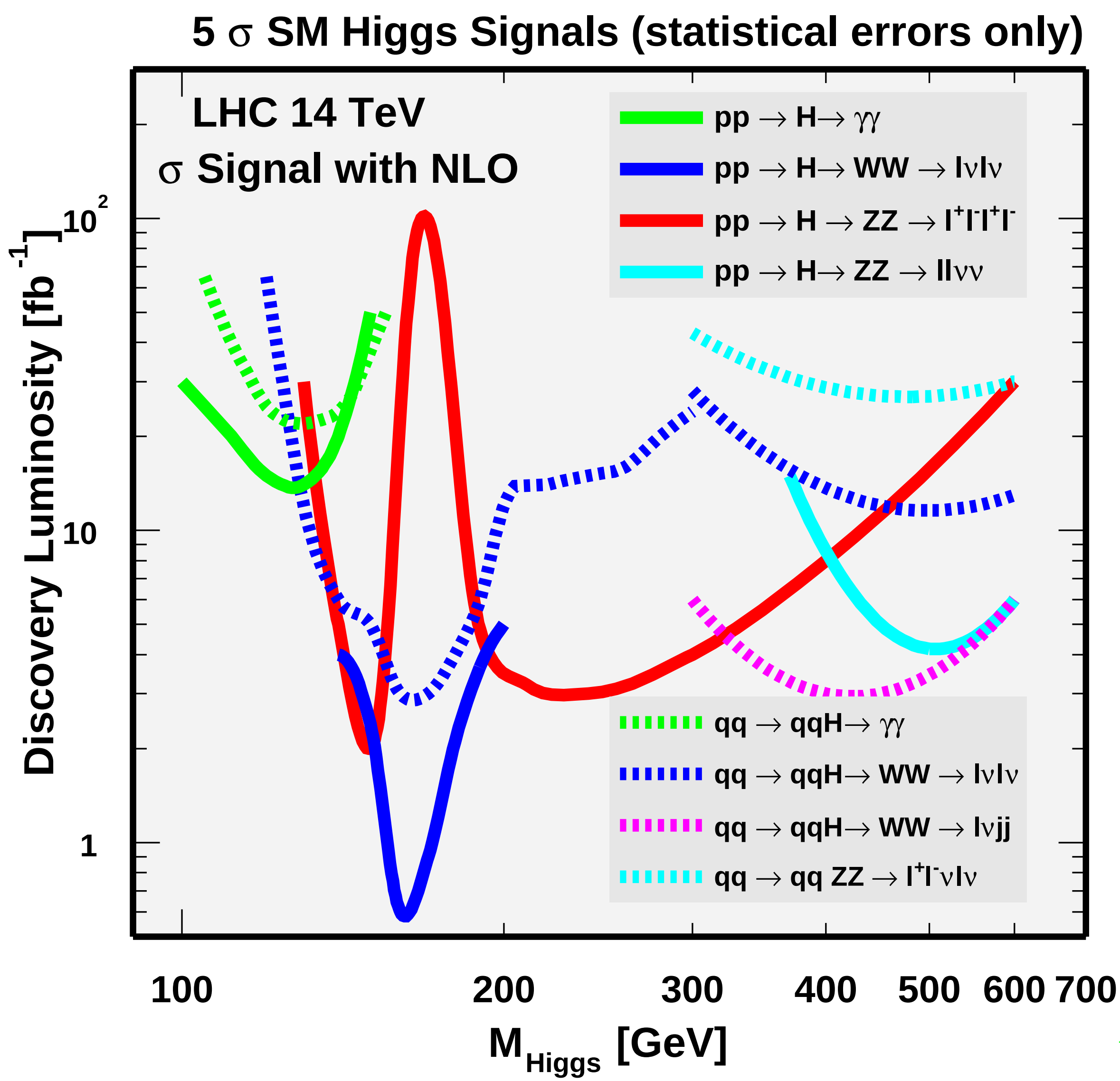
where λ is the quartic coupling.

The Standard Model Higgs



Courtesy: I. Gogoladze

The Standard Model Higgs

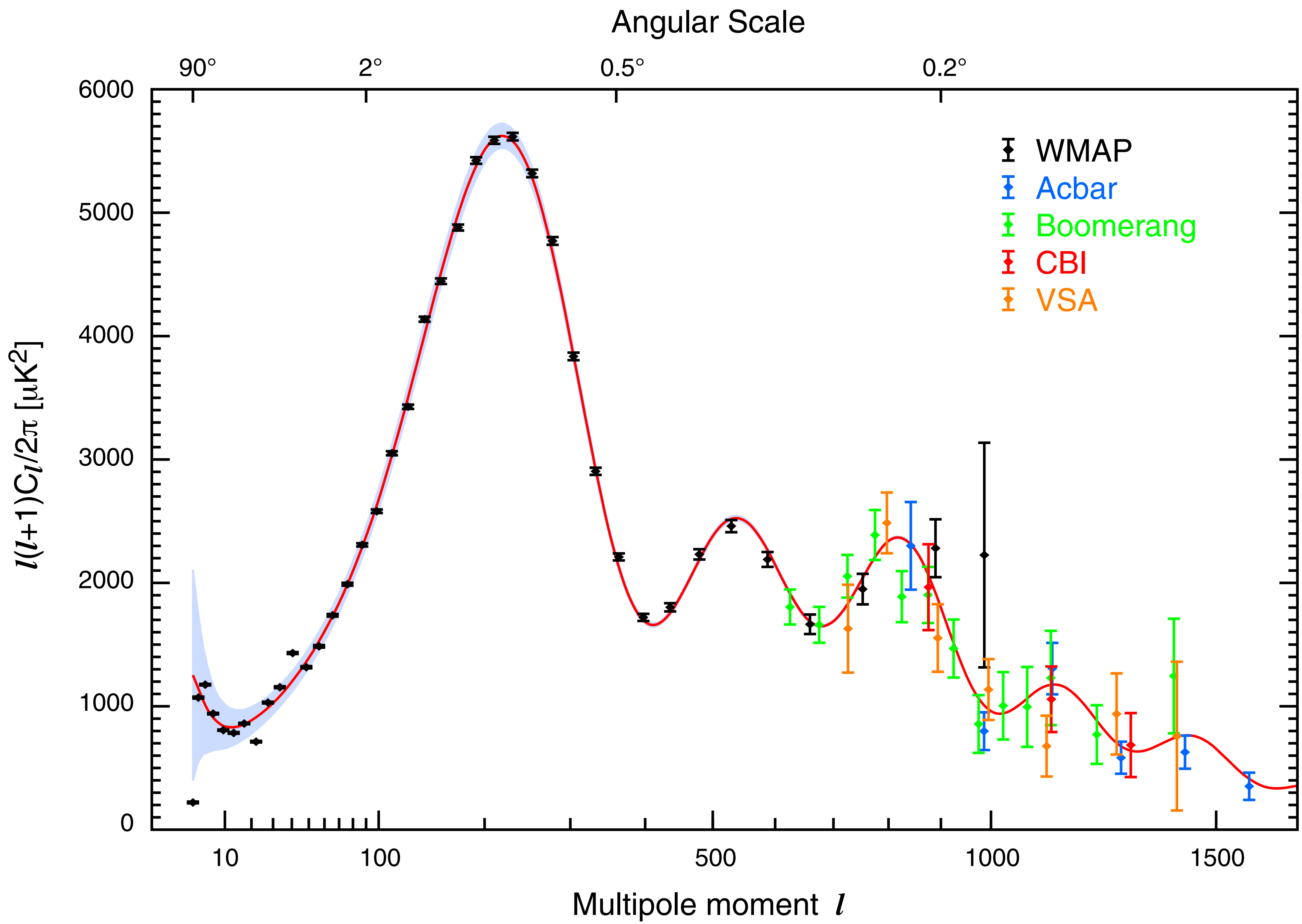


Djouadi *et al.* 2004.

Physics beyond the SM required by:

- Neutrino Oscillations
  $\left(\Delta m^2_{SM} \underset{\text{dim } 5}{\sim} 10^{-10} eV^2 \ll \Delta m^2_{ATM}, \Delta m^2_{SOL}\right)$
  $\sum m_{\nu_i} \lesssim 1 \text{ eV}$
- $\frac{\delta T}{T}$ (Inflation) $\sim 10^{-5}$
- Non-baryonic DM $(\Omega_{CDM} \approx 0.25)$
- Baryon Asymmetry $\left(n_B/s \sim 10^{-10}\right)$, with $\Omega_B \approx 0.05$
- Dark Energy

CMB Angular Power Spectrum



Additional Motivations

- Gauge Hierarchy Problem; $(M_W \ll M_P)$
- Fermion Masses & Mixings;
- Unification with Gravity (?)
- Family Replication
- Charge Quantization
- Origin of Parity Violation

Low Energy Supersymmetry

- Resolution of the gauge hierarchy problem;
- Unification of the SM gauge couplings at $M_{GUT} \sim 2 \times 10^{16}$ GeV;
- Cold dark matter candidate (LSP);
- Predicts new particles accessible at the LHC;
  Other good reasons:
- Radiative electroweak breaking;
- String theory requires susy .
  Leading candidate is the MSSM (Minimal Supersymmetric Standard Model).

The MSSM Higgs Boson

Minimal Supersymmetric Standard Model: Two Higgs Doublet

- h, H, A and $H^{\pm}$

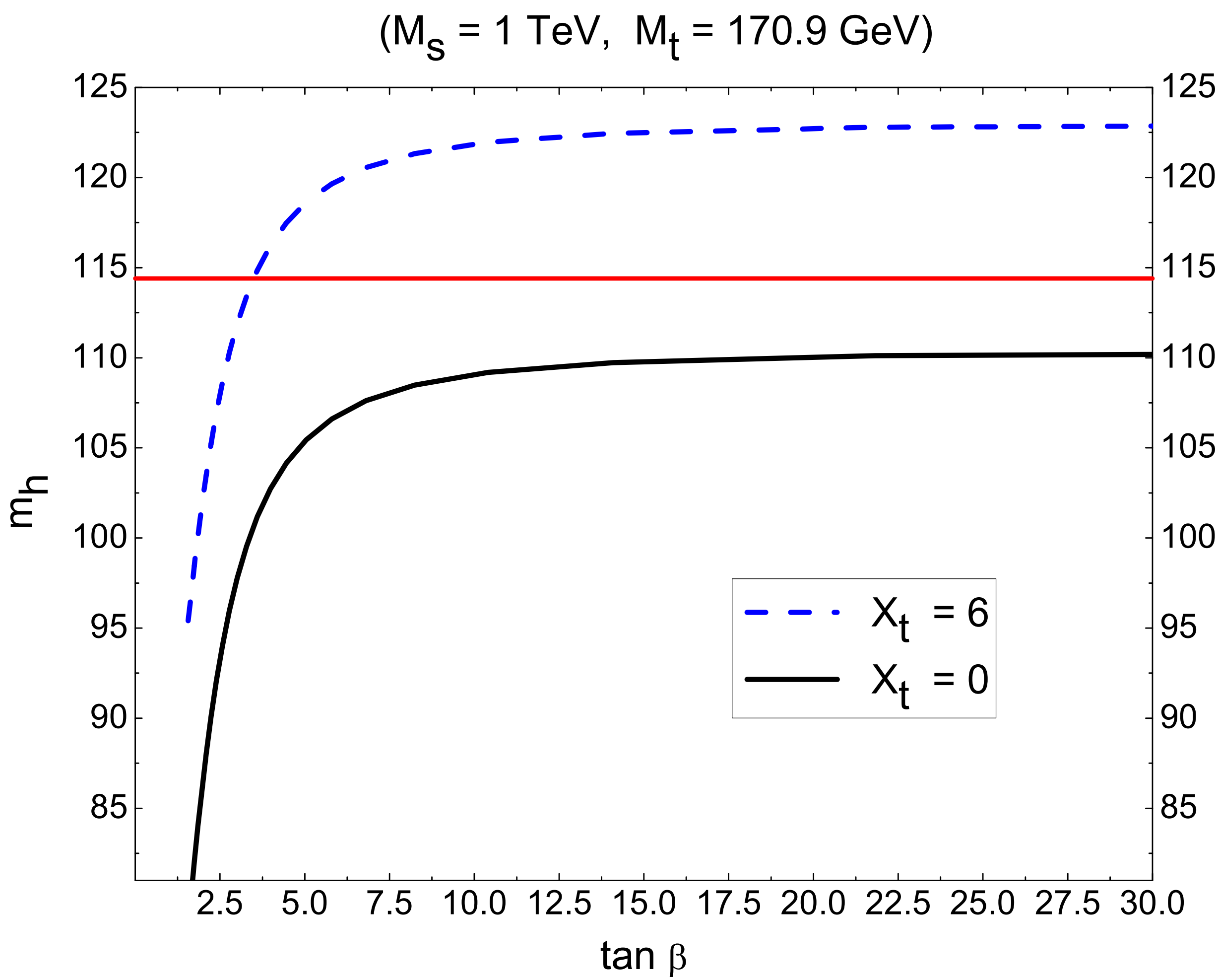
$$m_h^2 \simeq M_Z^2 \cos^2 2\beta \left(1 - \frac{3}{8\pi^2}\frac{m_t^2}{v^2}t\right) + \frac{3}{4\pi^2}\frac{m_t^4}{v^2} \times \left[\frac{1}{2}X_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_s\right)\left(X_t t + t^2\right)\right]$$

The MSSM Higgs Boson

where

$$
\begin{aligned}
t &= \log \frac{M_{\rm susy}^2}{m_t^2}, \widetilde{A}_t = A_t - \mu \cot \beta \\
X_t &= \frac{2\widetilde{A}_t^2}{M_{\rm susy}^2}\left(1 - \frac{\widetilde{A}_t^2}{12 M_{\rm susy}^2}\right)
\end{aligned}
$$

The MSSM Higgs Boson



CMSSM

Chamseddine *et al.* 1982, Barbieri *et al.* 1982, . . .

$m_0, \quad m_{1/2}, \quad A_0, \quad \tan\beta, \quad \mathrm{sign}\mu$

- $m_0 =$ Universal soft SUSY breaking scalar mass
- $m_{1/2} =$ Universal SSB gaugino mass
- $A_0 =$ Universal SSB trilinear interaction
- $\tan\beta = \frac{v_u}{v_d}$
- $\mu =$ Supersymmetric bilinear Higgs parameter

Scanning Procedure

Particle Physics Constraints

- *LEP2 Direct Searches:* $m_{\widetilde{W}_1} > 103.5$ GeV, $m_{\tilde{\tau}_1} > 98.8$ GeV, $m_{\tilde{\tau}_1} - m_{\widetilde{Z}_1} > 10$ GeV
- *Muon Anomalous Magnetic Moment*: Miller *et al.* 2007
  $3.34 \times 10^{-10} \leq \Delta a_\mu \leq 55.6 \times 10^{-10} (3\sigma)$
- $b \longrightarrow s\gamma$ *decay:*
  $2.85 \times 10^{-4} \leq Br(b \longrightarrow s\gamma) \leq 4.24 \times 10^{-4} (2\sigma)$
- $B_s \longrightarrow \mu^+\mu^-$ *decay:*
  $BF(B_s \longrightarrow \mu^+\mu^-) < 1.0 \times 10^{-7} (95\%\text{CL})$

Scanning Procedure

Particle Physics Constraints Contd.

- *Cold Dark Matter Constraint:* $\Omega_{\rm CDM} h^2 = 0.11^{+0.011}_{-0.015} (2\sigma)$

Spergel *et al.* **WMAP** Collaboration, 2006

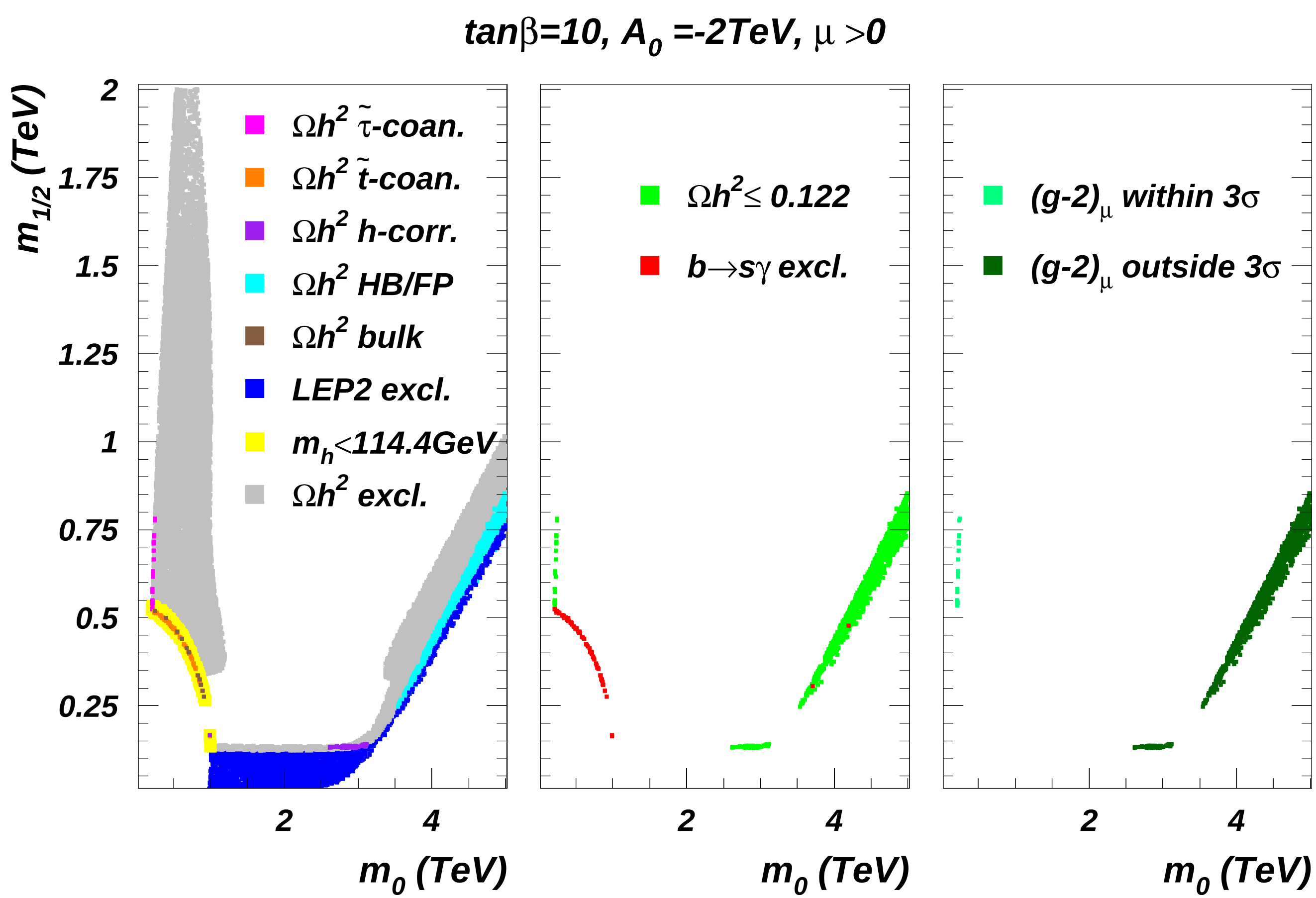
Input Parameters

$$0 \leq m_0 \leq 5 \text{ TeV}, \; 0 \leq m_{1/2} \leq 2 \text{TeV}$$

$$A_0 = 0.5, \; 0, \; -1 \text{ TeV}, \; -2 \text{ TeV},$$

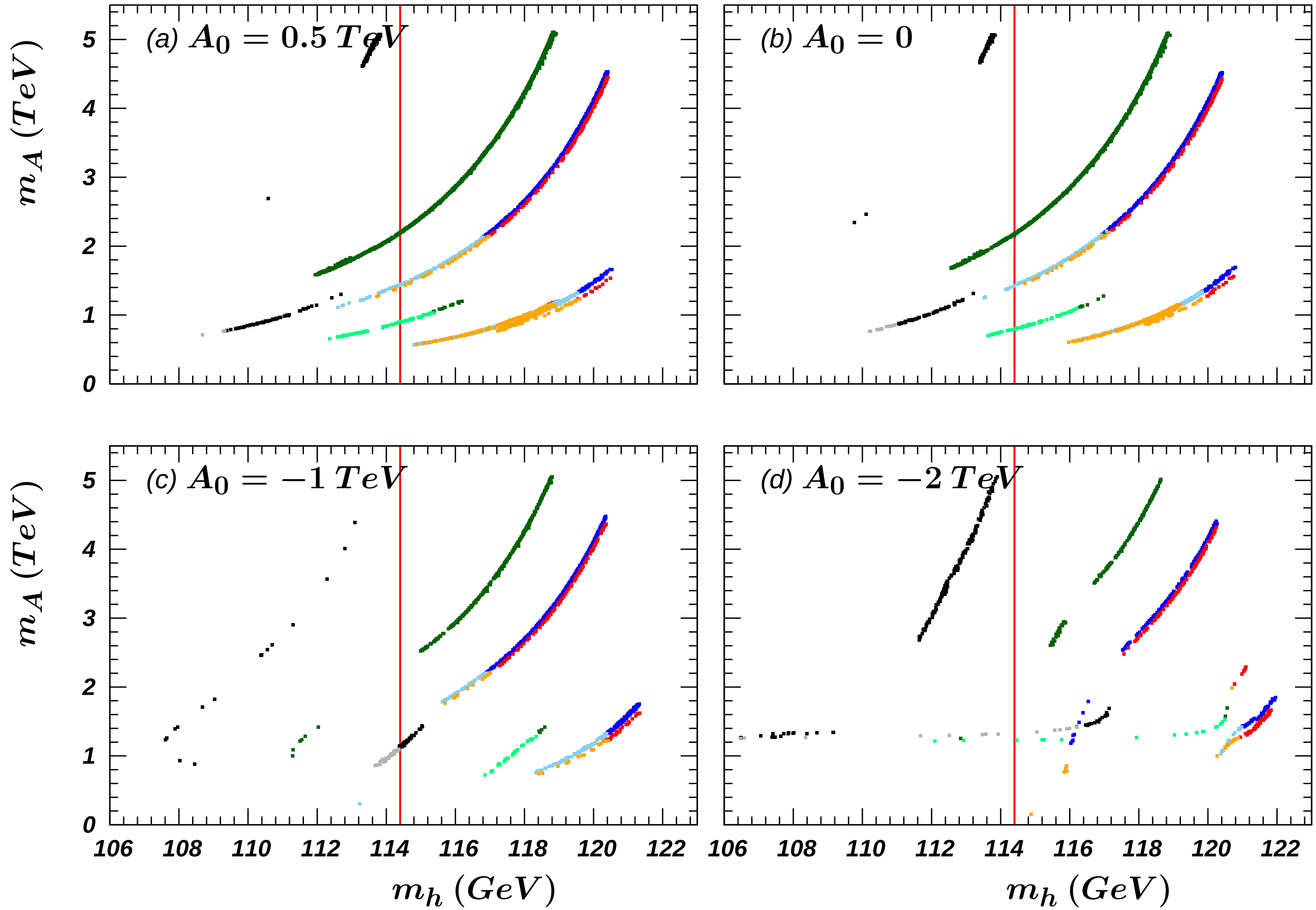
$$\tan\beta = 5, \; 10, \; 50 \text{ and } 53$$

Results: Effect of DM Constraint

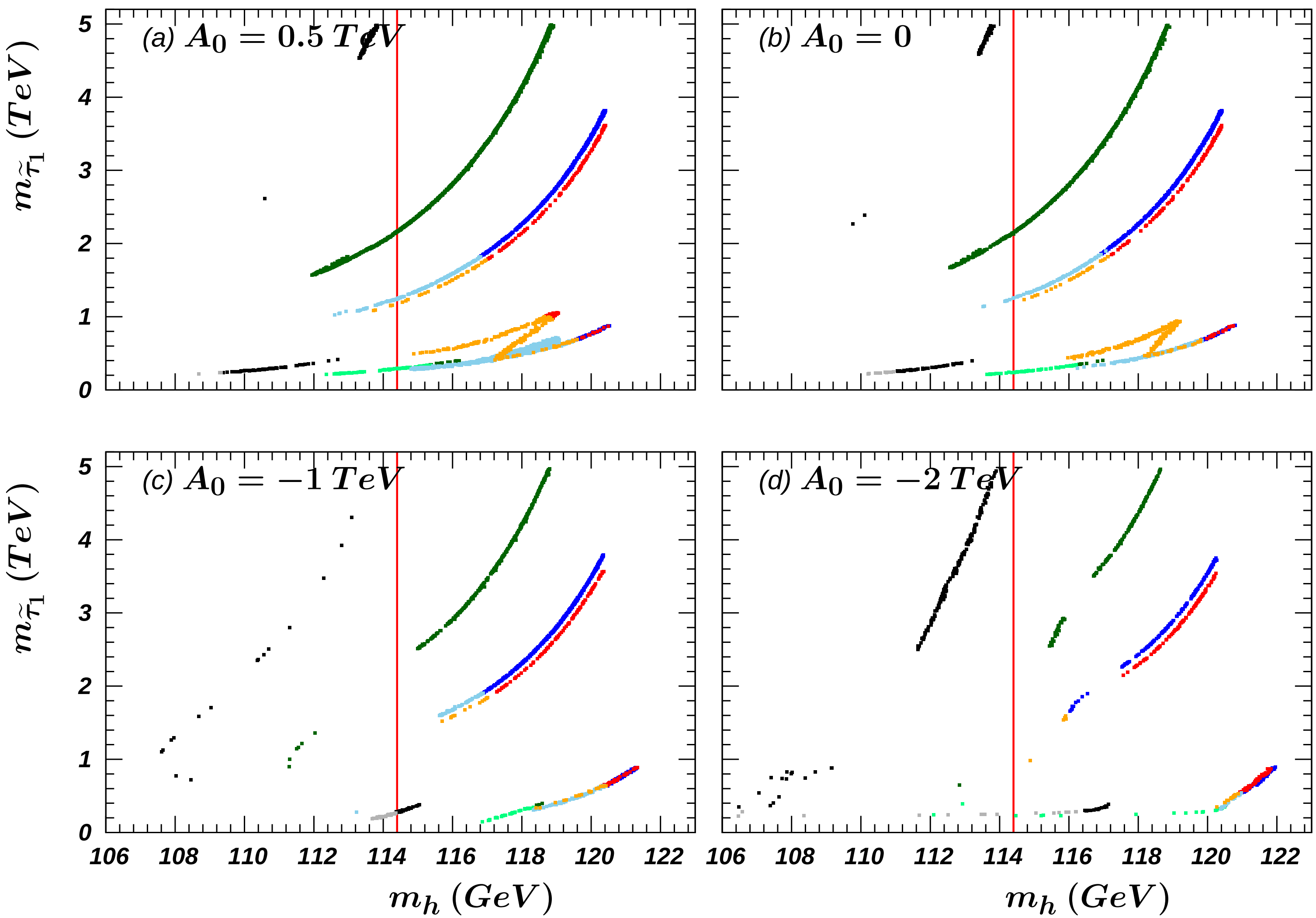


Results: Allowed region for m_A

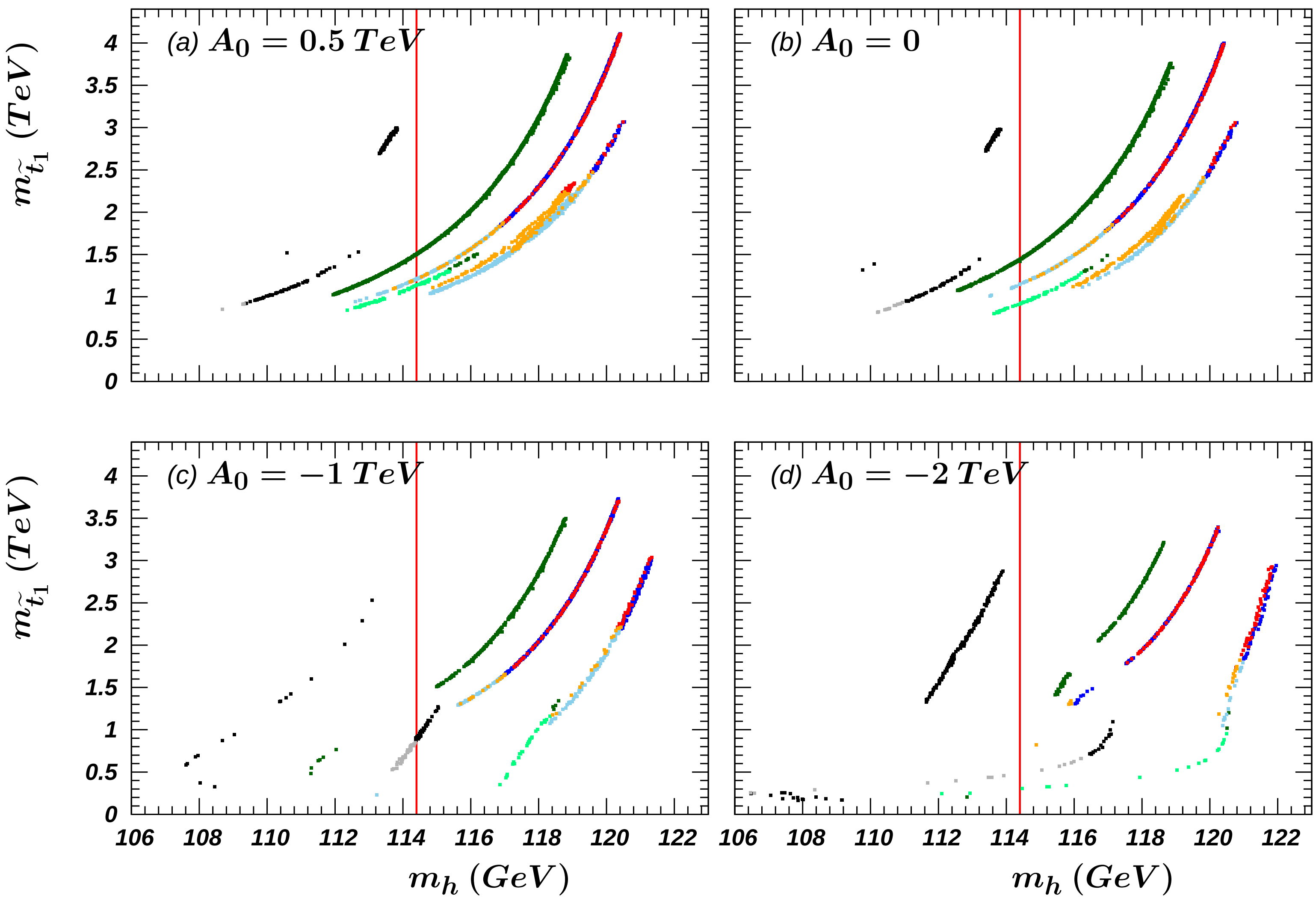
Q.S et al arXiv:0712.1049



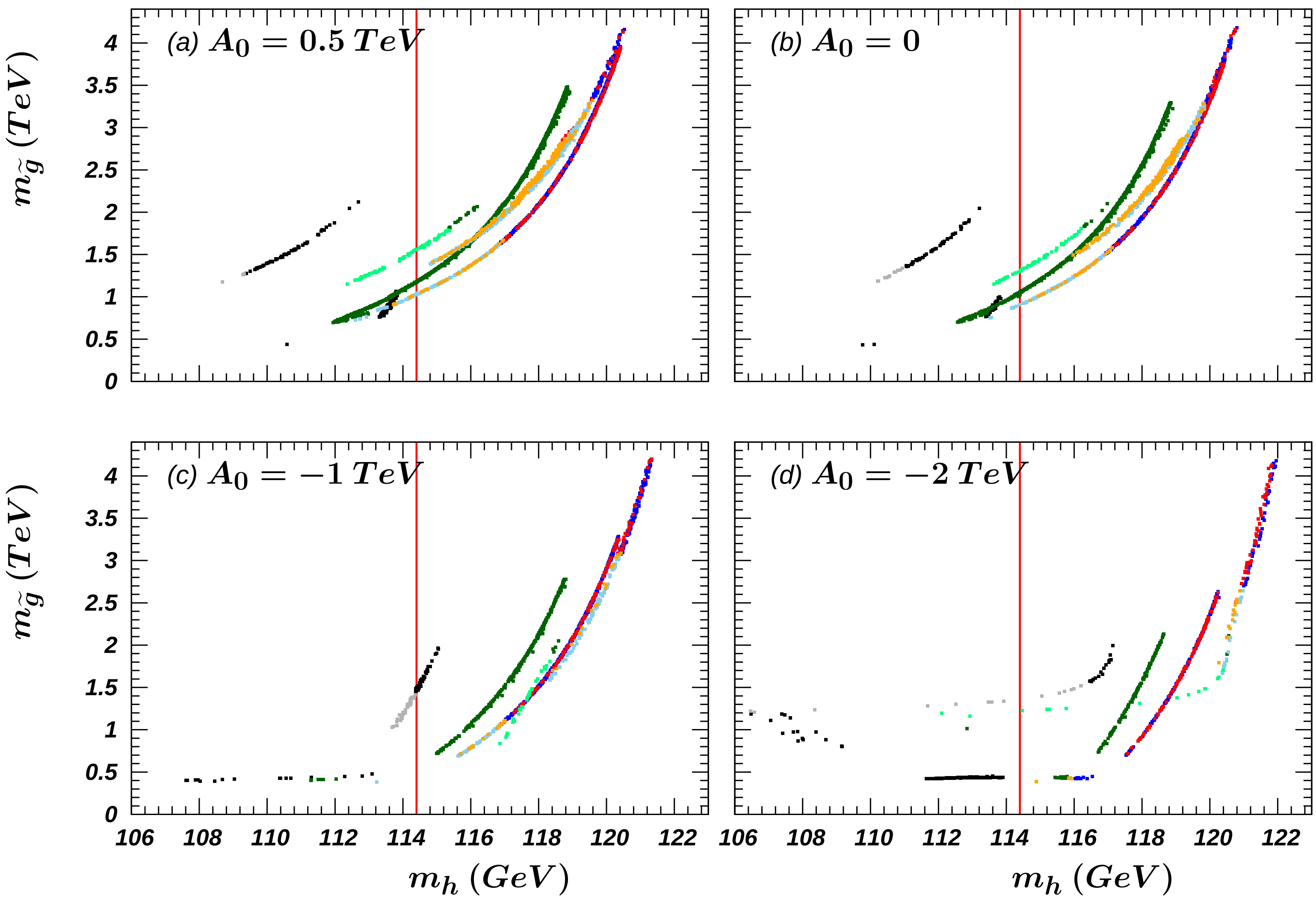
Allowed region for stau mass



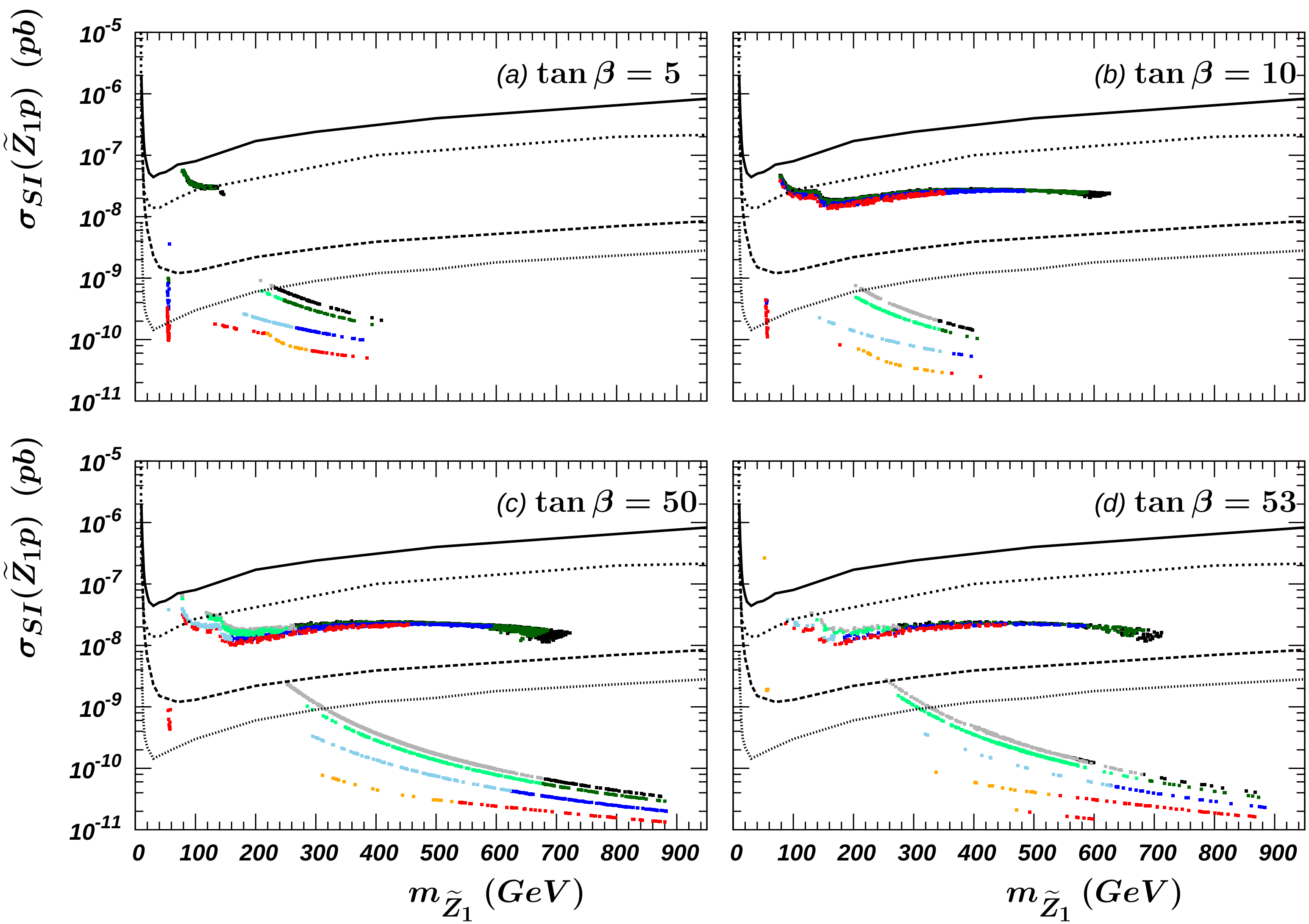
Allowed region for top squark mass



Allowed region for gluino mass



Direct Detection Cross Section



EXTRA DIMENSION(S)

WHO NEEDS THEM ?

- Unification of forces (Kaluza-Klein) Consider
  5 dimensional gravity
  metric tensor $\rightarrow g_{AB}$, $A, B = 0, 1, ..., 4$
  Dimensional reduction to $M_4 \times S^1$:

$g_{\mu\nu}$,	$g_{\mu 4} \sim A_\mu$,	g_{44}
$\uparrow$	$\uparrow$	$\uparrow$
graviton	EM field(!)	scalar
$(\mu, \nu = 0, ..., 3)$		

EXTRA DIMENSION(S)

- Electric charge quantized
- Monopoles
- 'Higgs' mechanism
- Tower of new states (esp. graviton)

EXTRA DIMENSION(S)

- M-Theory

  Presumably 11 dimensional;
  Low energy limit may be 11-d supergravity;
  (graviton, gravitino, A_{MNP})

  $$\left.\begin{array}{c}\text{Contains all known}\\ \text{superstring theories;}\end{array}\right\}\begin{array}{c}\text{Unification of matter}\\ \text{\& gauge forces?}\end{array}$$

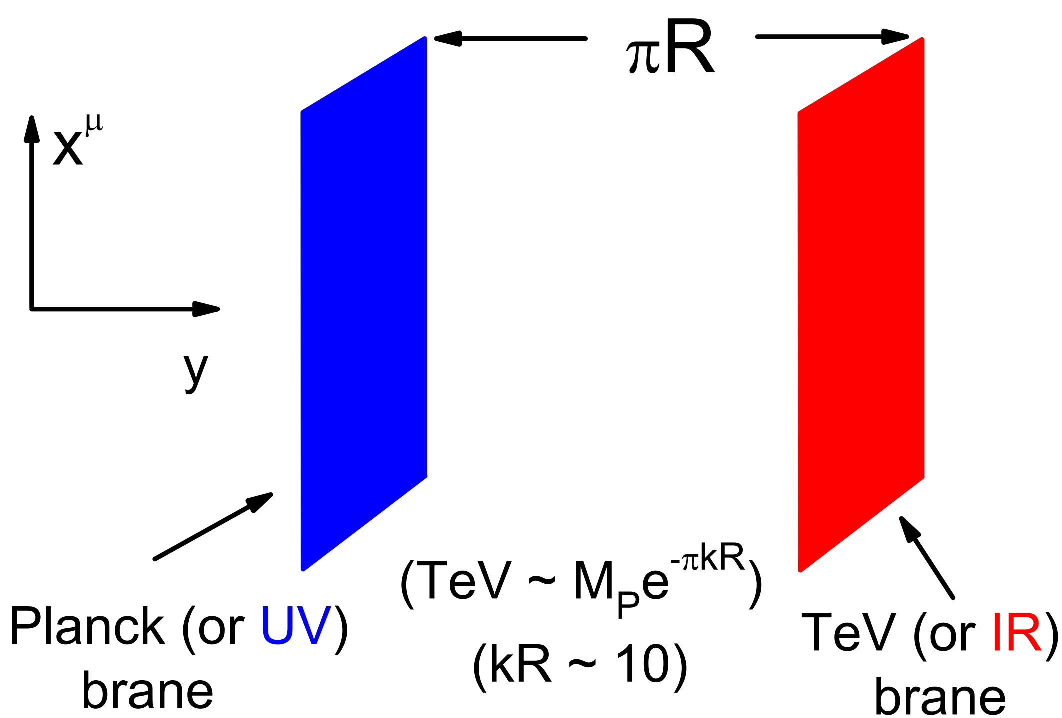
- Large extra dimension(s)

WARPED EXTRA DIMENSION

- Resolution of the gauge hierarchy problem (without invoking susy);
- ν Oscillations may be accommodated using dim 5 SM operators;
- ν could be Dirac or Majorana
- may be consistent with GUTS;
- may generate even 'smaller' scales: $M_P \to \mathrm{TeV}^2/M_P$ $(\sim 10^{-3}\mathrm{eV})$
- KK excitations at LHC?

WARPED EXTRA DIMENSION

Masses scales red-shifted as we move away from the Planck brane (also called "warping")



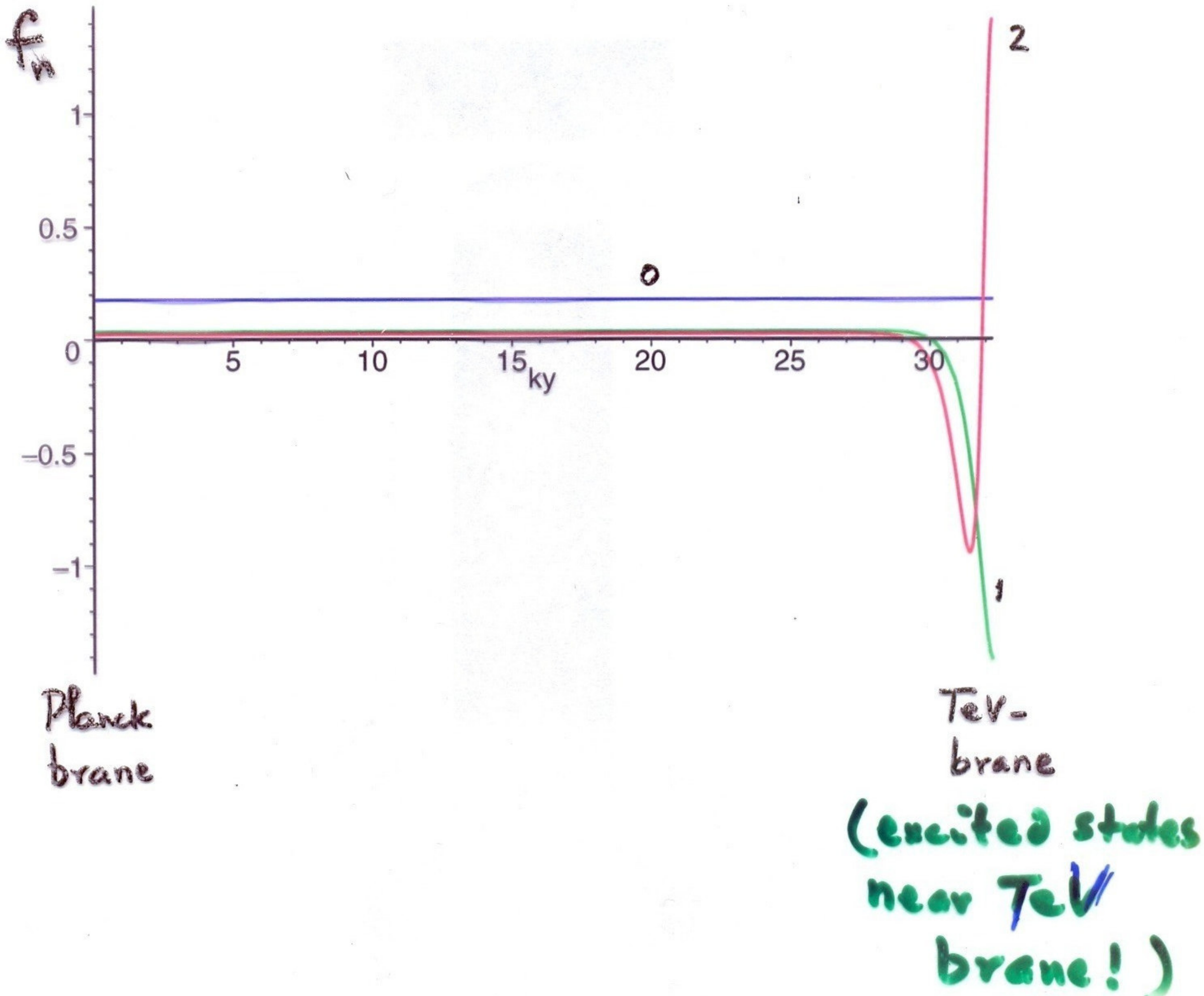
TWO SCENARIOS

- Gravity propagates in bulk;

  SM (especially Higgs) fields reside on TeV brane.

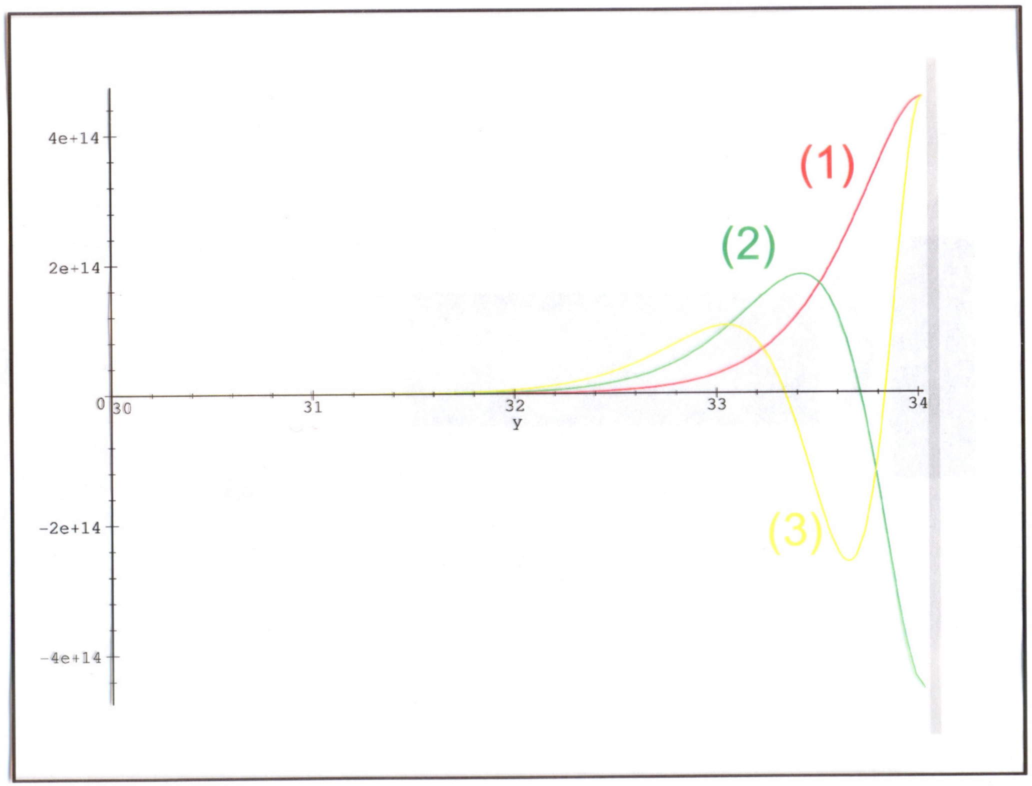
- "All" fields allowed to propagate in bulk (except Higgs?) $\Rightarrow$ many interesting consequences.

SM fields in Bulk (e.g. gauge bosons)



Graviton wave functions

IR-brane



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WARPED DIRAC EQUATION

- Dirac equation in curved spacetime:

$$E_a^M \gamma^a i(\partial_M + \omega_M)\Psi - m_\Psi \Psi = 0$$

$\gamma^a = (\gamma^\mu, \gamma^5) \leftarrow$ 'flat' gamma

vielbein : $E_a^M = e^{k|y|}\eta_a^\mu + \delta_{a5}\delta^{M5}$

spin connection: $\omega_M = \left(\frac{k}{2}e^{-k|y|}\,sgn(y)\gamma_5\gamma_\mu, 0\right)$

$$\Rightarrow \left[e^{2k|y|}\partial_\mu\partial^\mu + \partial_5^2 - k\,sgn(y)\partial_5 - m_\Psi^2\right]e^{-2k|y|}\Psi = 0$$

- KK decomposition:

$$\Psi(x^\mu, y) = \frac{1}{(2\pi R)^{1/2}}\sum_{n=0}^{\infty}\psi^n(x^\mu)e^{2k|y|}f_n(y)$$

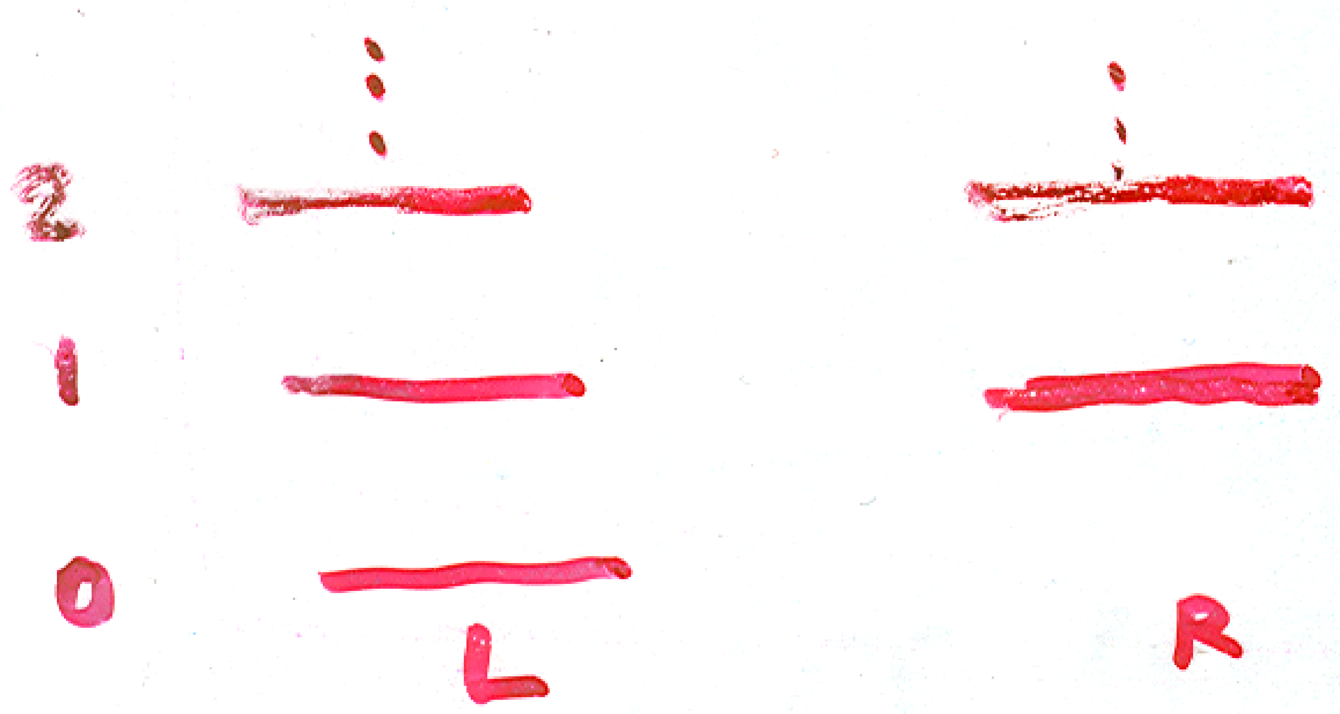
$$\Rightarrow \left(-\partial_5^2 + k\,sgn(y)\partial_5 + m_\psi^2\right)f_n = e^{2k|y|}m_n^2 f_n$$

B.C. at $y = 0, \pi R \longrightarrow$ determine m_n, f_n.

SM fermions arise as 'zero' modes of the KK decomposition.

5d Dirac mass $m_\psi = c\,k\,\varepsilon(y)$

Grossmann
Neubert
Huber + QS
Gherghetta
Pomarol



(Note: $\psi(-y) = \pm\gamma_5 \psi(y)$)

$m_n \sim n\pi k\, e^{-\pi k R}$ ← excited states

For $c > \frac{1}{2}$: zero mode localized (exponential) → Planck brane

$c < \frac{1}{2}$: zero mode → TeV-brane

Fermion mass hierarchy: Determined by the overlap between the fermion wave functions and Higgs (on TeV brane)

E.g.: $c(e) = 0.68$, $c(\mu) = 0.59$, $c(\tau) = 0.54$

Zero modes

$$\phi^{(0)}(y) \sim e^{(1-\alpha)k|y|}$$

[$m_\phi^2 = ak^2$; $\alpha = \sqrt{4+a}$]

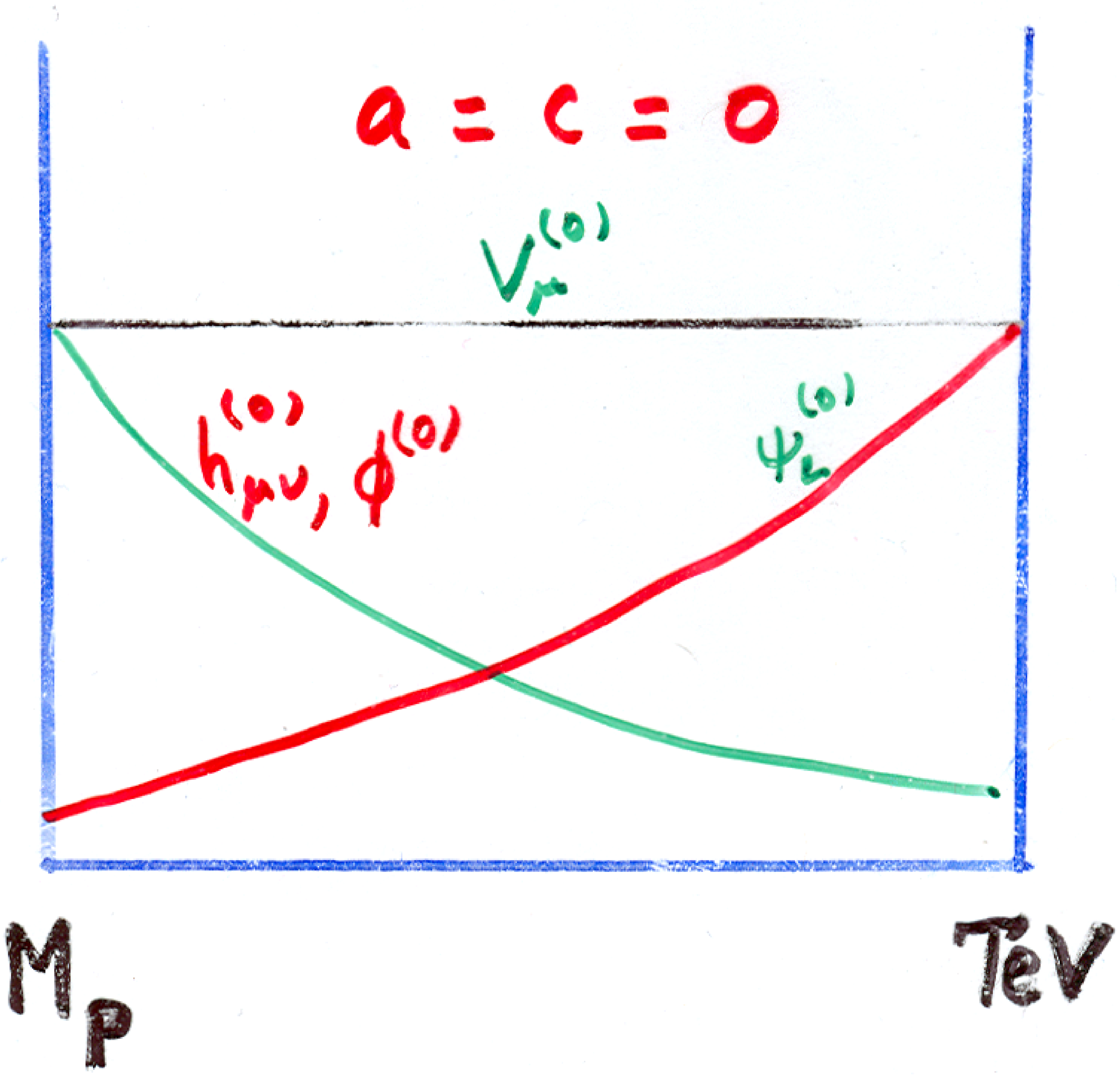
$$\Psi_L^{(0)}(y) \sim e^{(\frac{1}{2}-c)k|y|}$$

[$m_\Psi = ck\,\varepsilon(y)$]

↑ 5D bulk mass

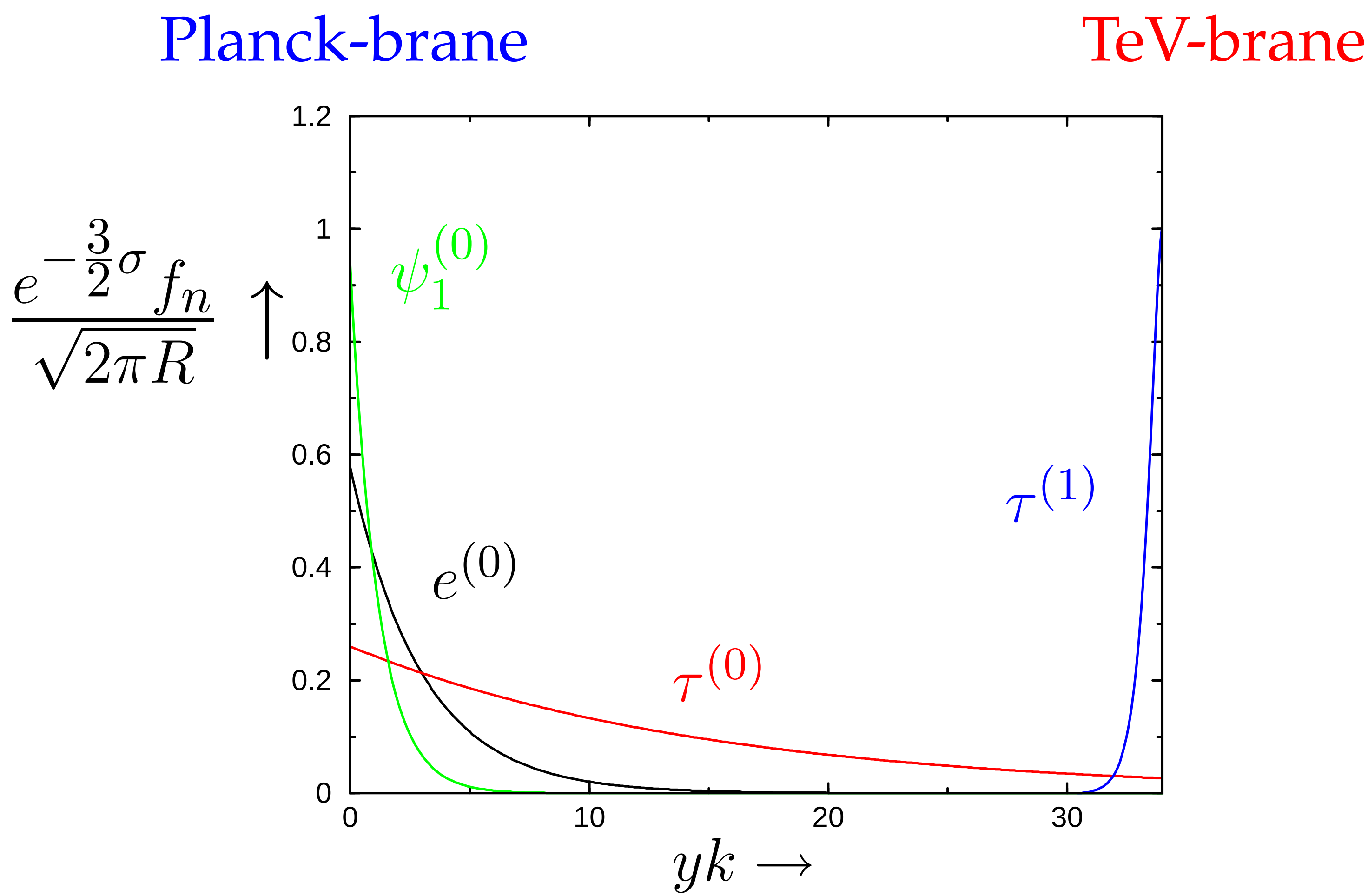
$$V_\mu^{(0)}(y) \sim \text{indep. of } y$$

$$h_{\mu\nu}^{(0)}(y) \sim e^{-k|y|}$$



$\phi^{(0)}, \Psi_L^{(0)}$ can localise on either brane (depends on a & c)

Fermion Wave Function



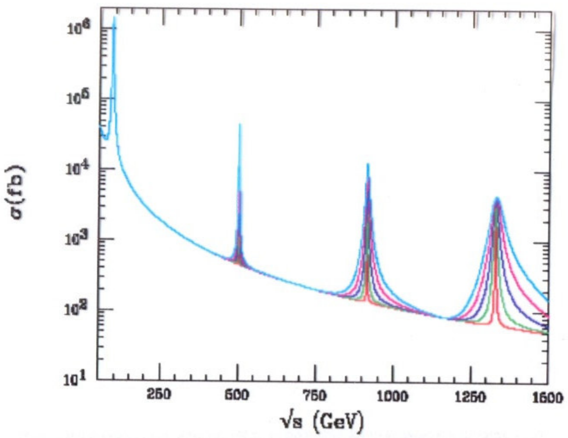


Figure 4: The cross section for $e^+e^- \to \mu^+\mu^-$ including the exchange of a KK tower of gravitons in the Randall-Sundrum model with $m_1 = 500$ GeV. The curves correspond to $k/\overline{M}_{Pl} =$ in the range $0.01 - 0.05$.

[Davoudiasl, Hewett, Rizzo
hep-ph/0006041]

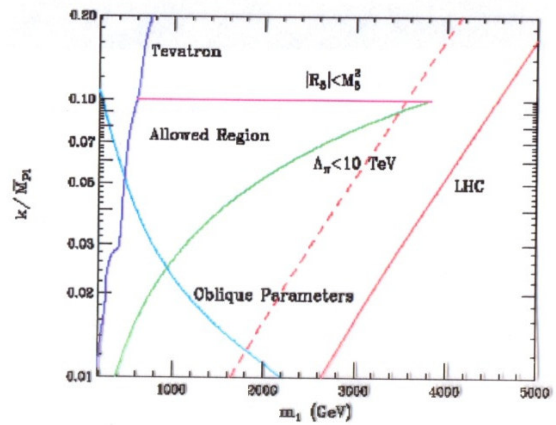


Figure 6: Summary of experimental and theoretical constraints on the Randall-Sundrum model in the two-parameter plane $k/\overline{M}_{Pl} - m_1$, for the case where the Standard Model fields are constrained to the TeV-brane. The allowed region lies in the center as indicated. The LHC sensitivity to graviton resonances in the Drell-Yan channel is represented by the diagonal dashed and solid curves, corresponding to 10 and 100 fb^{-1} of integrated luminosity, respectively.

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Assuming 5D Yukawa couplings to be of order unity :

Quark locations:

$c(Q_1) = 0.64$, $c(D_1) = 0.64$, $c(U_1) = 0.67$

$c(Q_2) = 0.58$, $c(D_2) = 0.60$, $c(U_2) = 0.53$

$c(Q_3) = 0.32$, $c(D_3) = 0.60$, $c(U_3) = -0.46$

Leptons :

$c(L_1) = 0.63$, $c(E_1) = 0.73$

$c(L_2) = 0.57$, $c(E_2) = 0.59$

$c(L_3) = 0.57$, $c(E_3) = 0.50$

Neutrino Oscillations in RS

Majorana Case Consider the dimension five operator

$$\int d^4x \int dy \sqrt{-g}\, \frac{l_{ij}}{M_5^2}\, H^2\, \Psi_i\, C\, \Psi_j$$

$$\equiv \int d^4x\, M_{ij}^{(\nu)}\, \Psi_i^{(0)}\, C\, \Psi_j^{(0)},$$

$$M_{ij}^{(\nu)} = \int_{-\pi R}^{+\pi R} \frac{dy}{2\pi R}\, \frac{l_{ij}}{M_5^2}\, e^{-4\sigma(y)}\, H^2(y)\, f_{0i}^{(\nu)}(y)\, f_{0j}^{(\nu)}(y)$$

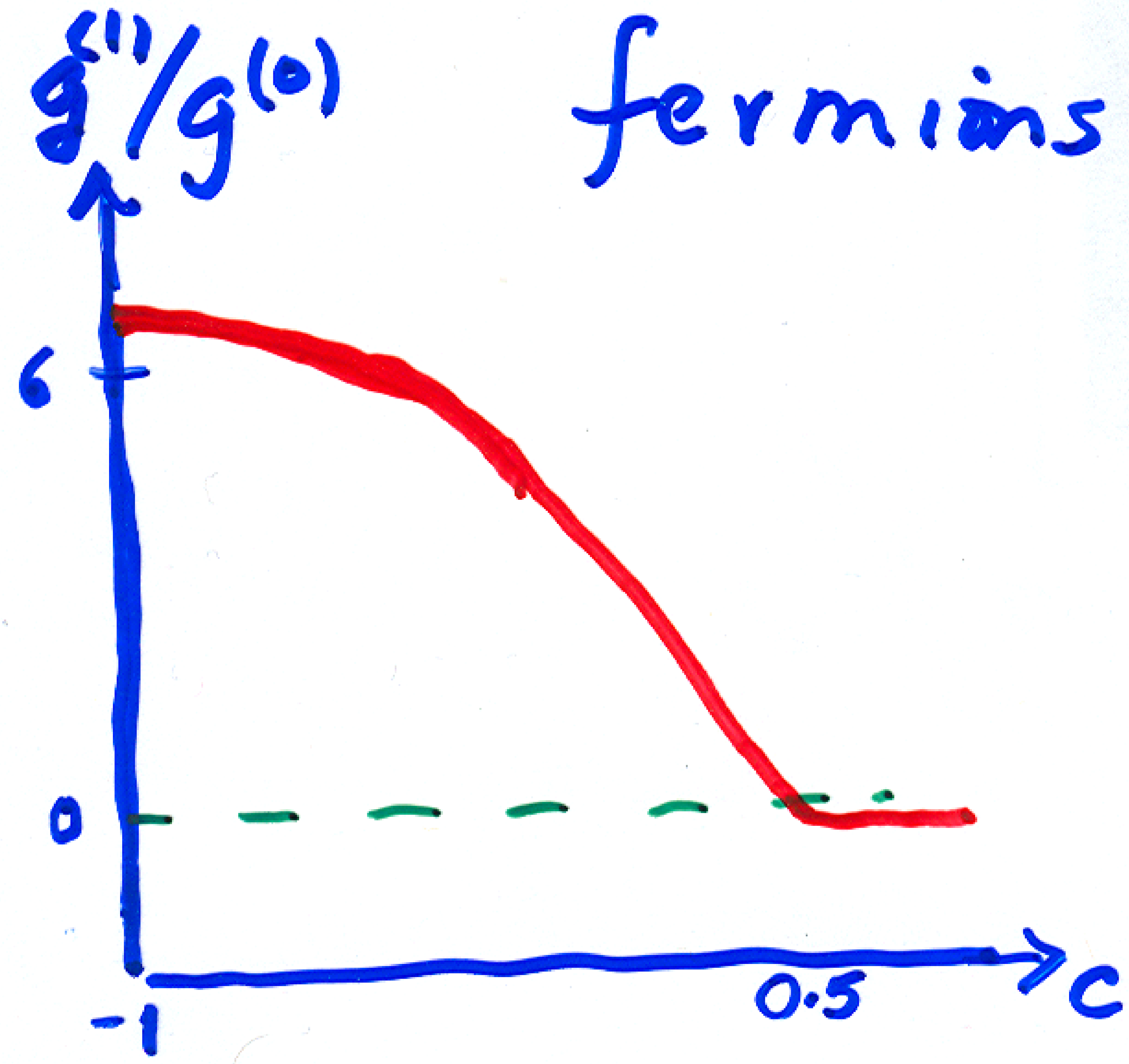
KK gauge bosons display non-universal couplings.

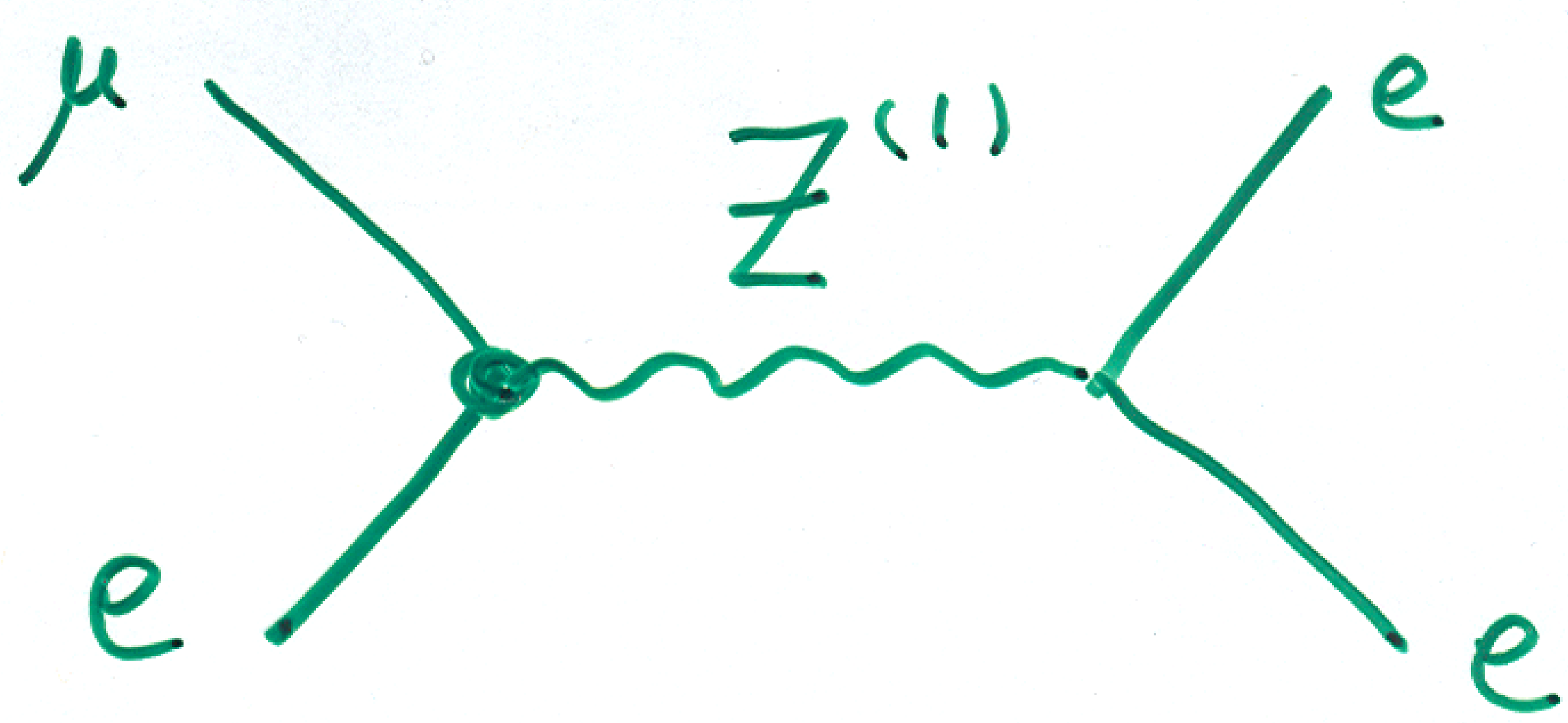
For $g = \mathrm{diag}(g_e, g_\mu, g_\tau)$,

- $G = U^\dagger g U$ (in mass basis)

  $\Rightarrow$ flavour non-diagonal couplings,

- couplings almost universal for $c > 1/2$, where the light fermions are localized;





SUMMARY (Warped SM)

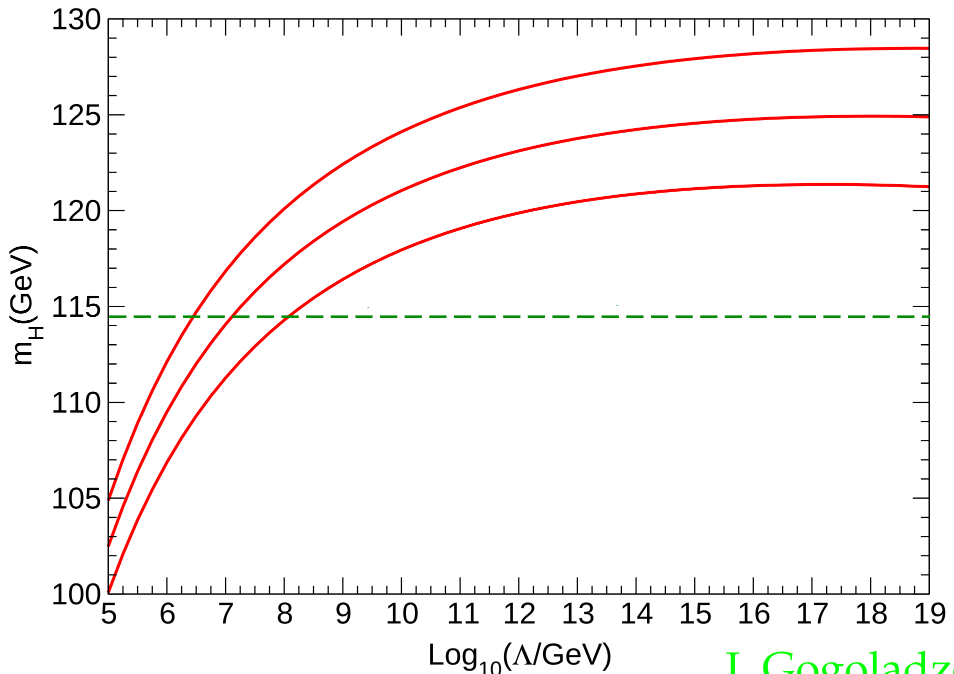
- Bulk SM fields;
- Higgs on the TeV Brane;
- Neutrinos could be Dirac or Majorana
- Dirac Neutrinos: Introduce SM singlet fermion, (eliminate dim 5 Majorana masses by imposing some symmetry, say lepton number), $\Longrightarrow p$ stable; But $n - \overline{n}$ possible; Also $\mu \rightarrow e\gamma$, etc.
- Smoking Gun: KK excitations at the LHC.

5D Gauge – Higgs Unification

In 5D we have non-SUSY $SU(3)_C \times SU(3)_w \times U(1)$ gauge symmetry.

Fifth dimension compactified on the orbifold S^1/Z_2.

SM Higgs Boson arises from the 'internal' components of the 5D gauge field.

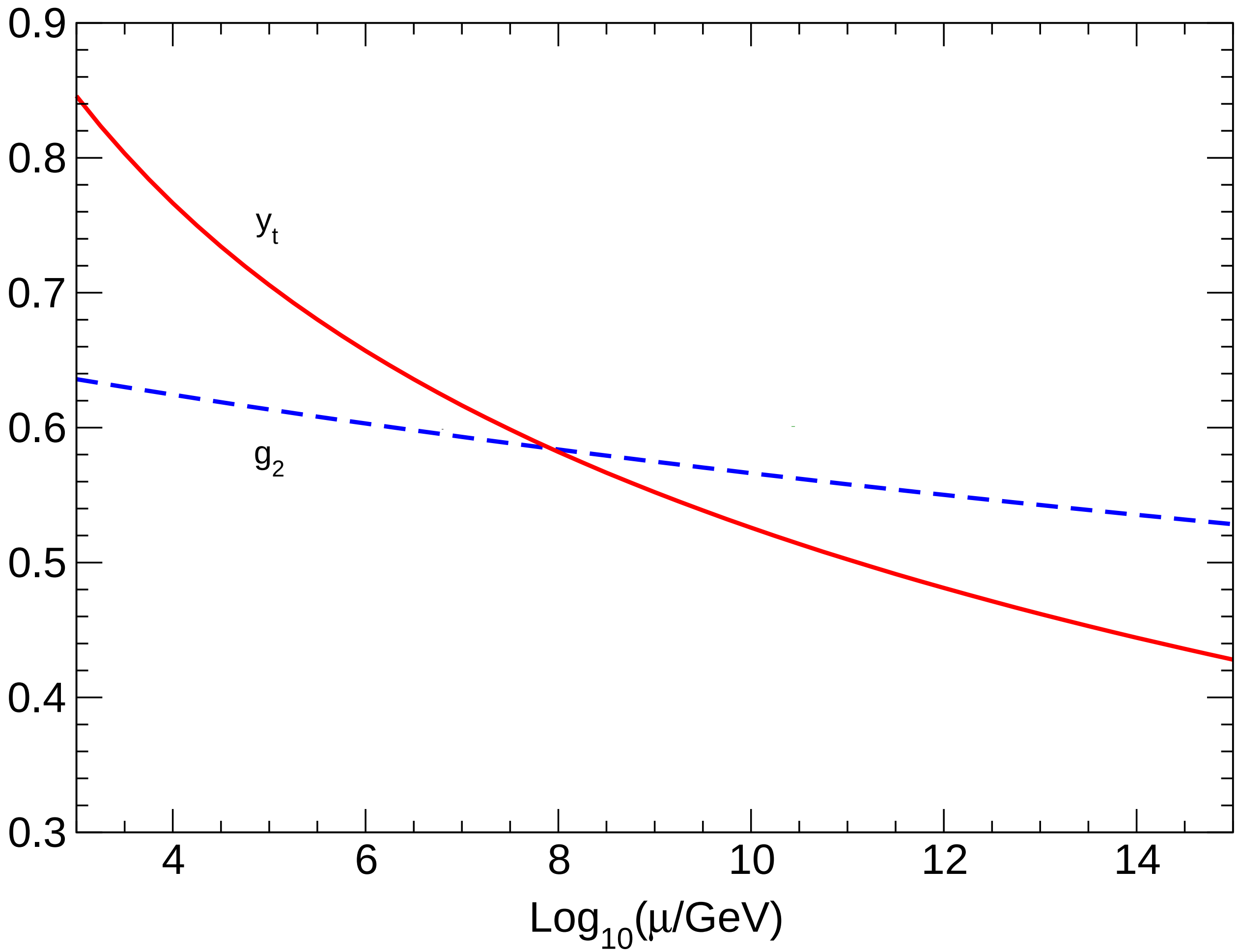


I. Gogoladze, N. Okada, Q.S.

From 5D theory with Gauge Higgs unification condition:

$114.5\ \mathbf{GeV} \leq m_h \leq 125\ \mathrm{GeV}$

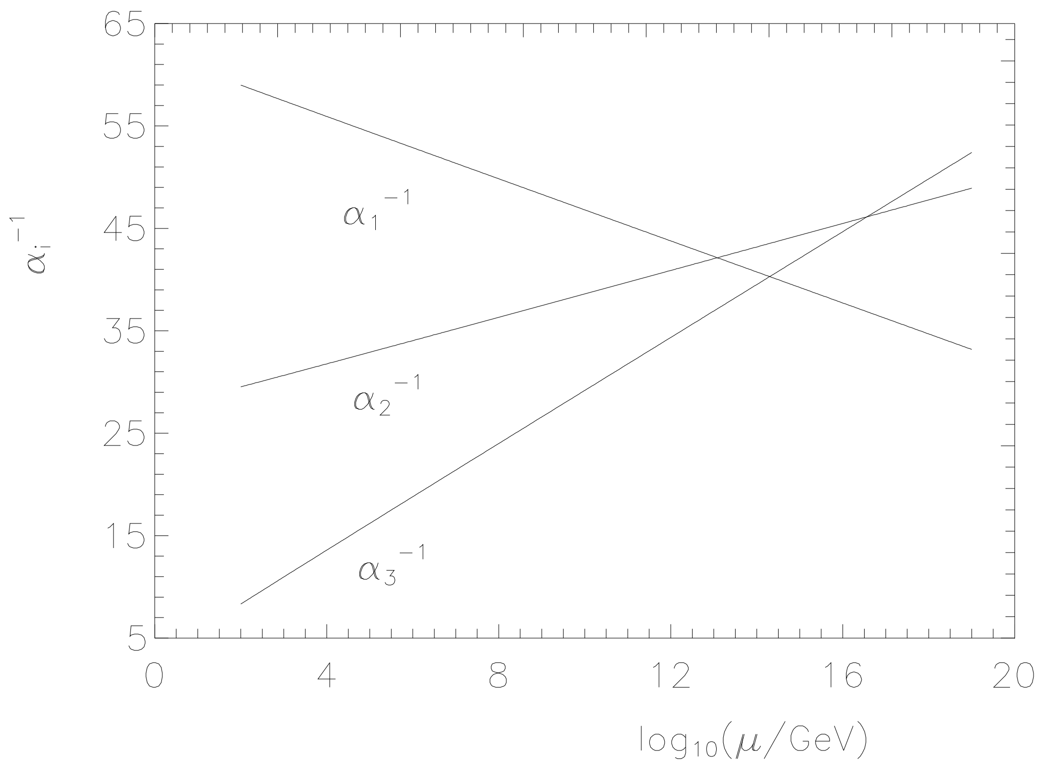
Gauge and top Yukawa Unification



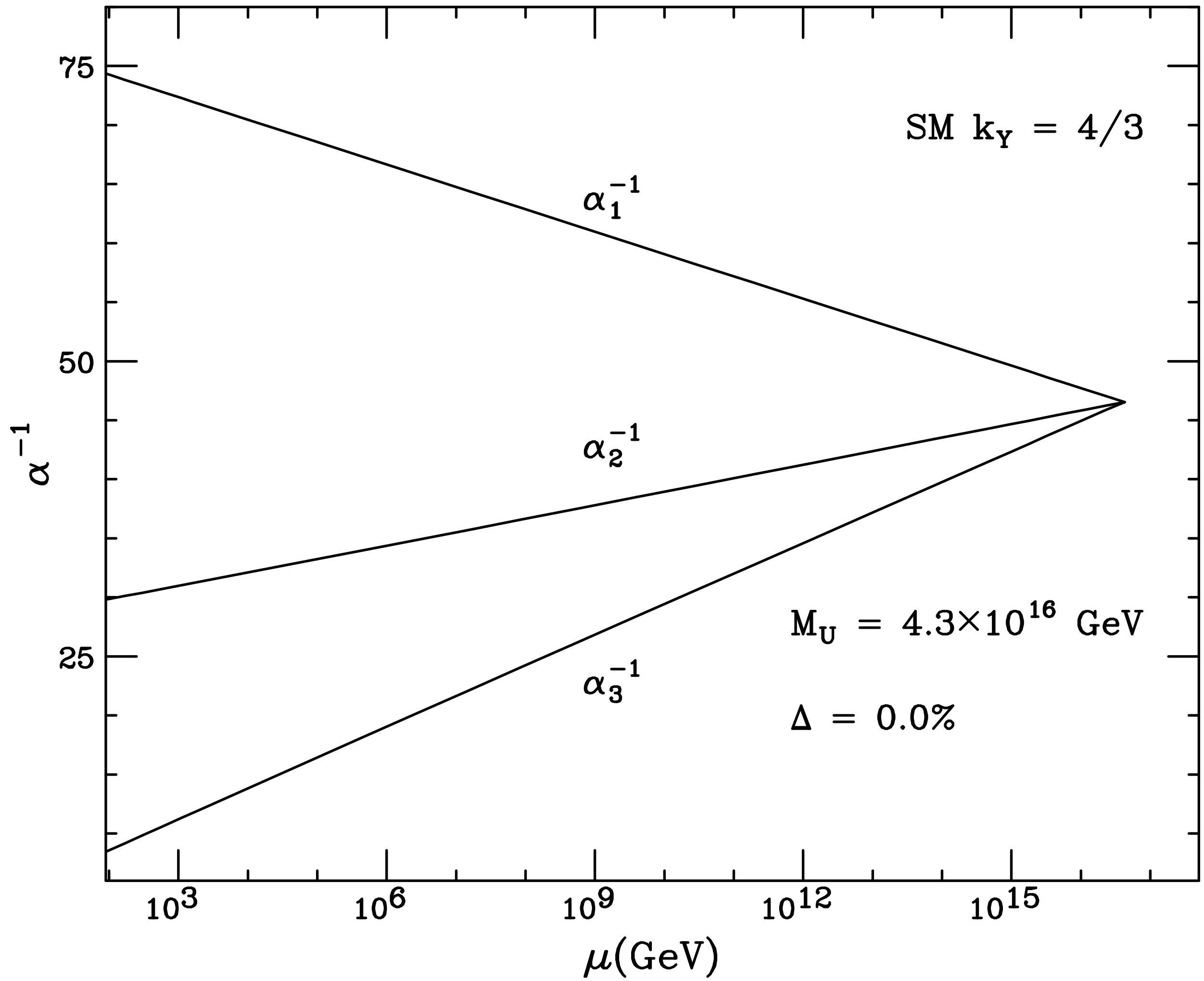
Gauge and top Yukawa Unification

	$M_t = 169.1$	$M_t = 170.9$	$M_t = 172.8$
Λ	3.26×10^7	8.41×10^7	2.34×10^8
m_h	112.9	117.0	121.1

Orbifold GUTs, $U(1)_Y$ and Higgs Mass



V. Barger, J. Jiang, P. Langacker and T. Li, Nucl. Phys. B 726 (2005) 149, have shown that in orbifold GUT it is possible to have non-canonical normalization for $U(1)_Y$ hypercharge, which provides gauge coupling unification within the SM framework.



75
50
25
α^{-1}
SM k_Y = 4/3
α_1^{-1}
α_2^{-1}
α_3^{-1}
M_U = 4.3×10^{16} GeV
Δ = 0.0%
10^3
10^6
10^9
10^{12}
10^{15}
μ(GeV)

$SU(7)$ orbifold model

I.Gogoladze, T.Li, Q.S.

- $\mathcal{N}=1$ SUSY in 7D corresponds to $\mathcal{N}=4$ SUSY in 4D. The bulk gauge supermultiplet is decomposed under 4D $\mathcal{N}=1$ SUSY into a gauge vector multiplet V and three chiral multiplets Σ_1, Σ_2 and Σ_3 in the adjoint representation.
- The bulk action in the Wess-Zumino gauge and in 4D N=1 SUSY notation contains:

$$\mathcal{S} \;=\; \int d^7x \; \mathrm{Tr}\left(\int d^2\theta \left(\frac{1}{kg^2}\Sigma_1[\Sigma_2,\Sigma_3]\right)\right) + h.c.$$

7D $\mathcal{N}=1$ SUSY $SU(7)$ gauge theory is compactified on the orbifold $T^2/Z_6 \times S^1/Z_2$.

$$R_{\Gamma_T} \ = \ \text{diag}\left(+1,+1,+1,\omega^{n_1},\omega^{n_1},\omega^{n_1},\omega^{n_2}\right)$$

$$R_{\Gamma_S} \ = \ \text{diag}\left(+1,+1,+1,+1,+1,-1,-1\right)$$

where n_1 and n_2 are positive integers, and $n_1 \neq n_2$.

$$\{SU(7)/R_{\Gamma_T}\} = SU(3)_C \times SU(3) \times U(1) \times U(1)'$$

$$\{SU(7)/R_{\Gamma_S}\} = SU(5) \times SU(2) \times U(1)$$

$$\mathbf{SU(7)} \Rightarrow \mathbf{SU(3)_C} \times \mathbf{SU(2)_L} \times \mathbf{U(1)_Y} \times \mathbf{U(1)}_\alpha \times \mathbf{U(1)}_\beta$$

$$\left(\begin{array}{cccc} (\mathbf{8},\mathbf{1})_{Q00} & (\mathbf{3},\bar{\mathbf{2}})_{\mathbf{Q12}} & (\mathbf{3},\mathbf{1})_{Q13} & (\mathbf{3},\mathbf{1})_{Q14} \\ (\bar{\mathbf{3}},\mathbf{2})_{Q21} & (\mathbf{1},\mathbf{3})_{Q00} & (\mathbf{1},\mathbf{2})_{\mathbf{Q23}} & (\mathbf{1},\mathbf{2})_{Q24} \\ \{(\bar{\mathbf{3}},\mathbf{1})_{\mathbf{Q31}} & (\mathbf{1},\bar{\mathbf{2}})_{\mathbf{Q32}} & (\mathbf{1},\mathbf{1})_{Q00} & (\mathbf{1},\mathbf{1})_{Q34} \\ (\bar{\mathbf{3}},\mathbf{1})_{Q41} & (\mathbf{1},\bar{\mathbf{2}})_{Q42} & (\mathbf{1},\mathbf{1})_{Q43} & (\mathbf{1},\mathbf{1})_{Q00} \end{array}\right)$$

Gauge and Top Yukawa Unification

$$R_{\Gamma_T} = \text{diag}\left(+1, +1, +1, \omega^5, \omega^5, \omega^5, \omega^2\right)$$

$$R_{\Gamma_S} = \text{diag}\left(+1, +1, +1, +1, +1, -1, -1\right)$$

$$\begin{aligned} \mathbf{T}_{\mathbf{U(1)_Y}} &\equiv \frac{\mathbf{1}}{\mathbf{6}}\text{diag}\left(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{0}, \mathbf{0}, -\mathbf{3}, \mathbf{0}\right) \\ &+ \frac{\sqrt{\mathbf{14}}}{\mathbf{42}}\text{diag}\left(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}, -\mathbf{6}\right), \end{aligned}$$

Gauge and Top Yukawa Unification

$$\mathbf{T}_{\mathbf{U(1)}_\alpha} \equiv -\frac{\sqrt{\mathbf{14}}}{\mathbf{2}}\,\mathrm{diag}\,(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{0},\mathbf{0},-\mathbf{3},\mathbf{0}) + \mathrm{diag}\,(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},-\mathbf{6})$$

$$\mathbf{T}_{\mathbf{U(1)}_\beta} \equiv \mathrm{diag}\,(\mathbf{1},\mathbf{1},\mathbf{1},-\mathbf{2},-\mathbf{2},\mathbf{1},\mathbf{0})$$

$\mathrm{tr}[T^2_{U(1)_Y}] = 2/3$. From $k_Y g^2_Y = g^2_2 = g^2_3$ condition we are getting $\mathbf{k_Y = 4/3}$.

Zero modes from the chiral multiplets

$$\mathbf{\Sigma_1 \to Q_3 : \left(3, 2, \frac{1}{6}, 3, -\frac{\sqrt{14}}{2}\right)}$$

$$\mathbf{\Sigma_2 \to H_u : \left(1, 2, \frac{1}{2}, -3, -\frac{3\sqrt{14}}{2}\right)}$$

$$\mathbf{+H_d : \left(1, 2, -\frac{1}{2}, 3, \frac{3\sqrt{14}}{2}\right)}$$

$$\mathbf{\Sigma_3 \to t^c : \left(\bar{3}, 1, -\frac{2}{3}, 0, 2\sqrt{14}\right)}$$

Zero modes from the chiral multiplets

from the trilinear term in the 7D bulk action

$$\int \mathbf{d^7x} \left[\int \mathbf{d^2}\theta \, \mathbf{g_7 Q_3 t^c H_u + h.c.} \right],$$

$$\mathbf{g_1 = g_2 = g_3 = y_t = g_7/\sqrt{V}},$$

1. The brane localized gauge and Yukawa interaction can be negligible.
2. The zero modes are not localized at different points on the orbifold.
3. The four dimensional fields are not heavily mixed with other brane localized fields.

Higgs Sector

$$\mathbf{H} \equiv -\cos\beta\, \mathbf{i}\sigma_{\mathbf{2}}\, \mathbf{H}_{\mathbf{d}}^{*} + \sin\beta\, \mathbf{H}_{\mathbf{u}}$$

$$\mathbf{h_t} = \mathbf{y_t} \sin\beta$$

The quartic Higgs coupling is determined at M_{GUT} by the supersymmetric D-term

$$\lambda = \frac{\frac{3}{4}\mathbf{g_1^2}(\mathbf{M}_{\mathrm{GUT}}) + \mathbf{g_2^2}(\mathbf{M}_{\mathrm{GUT}})}{\mathbf{4}} \cos^{\mathbf{2}} \mathbf{2}\beta$$

$$\mathbf{m_h} = \sqrt{\lambda}\mathbf{v}$$

Results

Compactification scale, SUSY and additional gauge symmetry breaking scale $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\alpha \times U(1)_\beta \Rightarrow SM$ are all of order M_{GUT}.
Below M_{GUT} scale we have the SM particle content with:

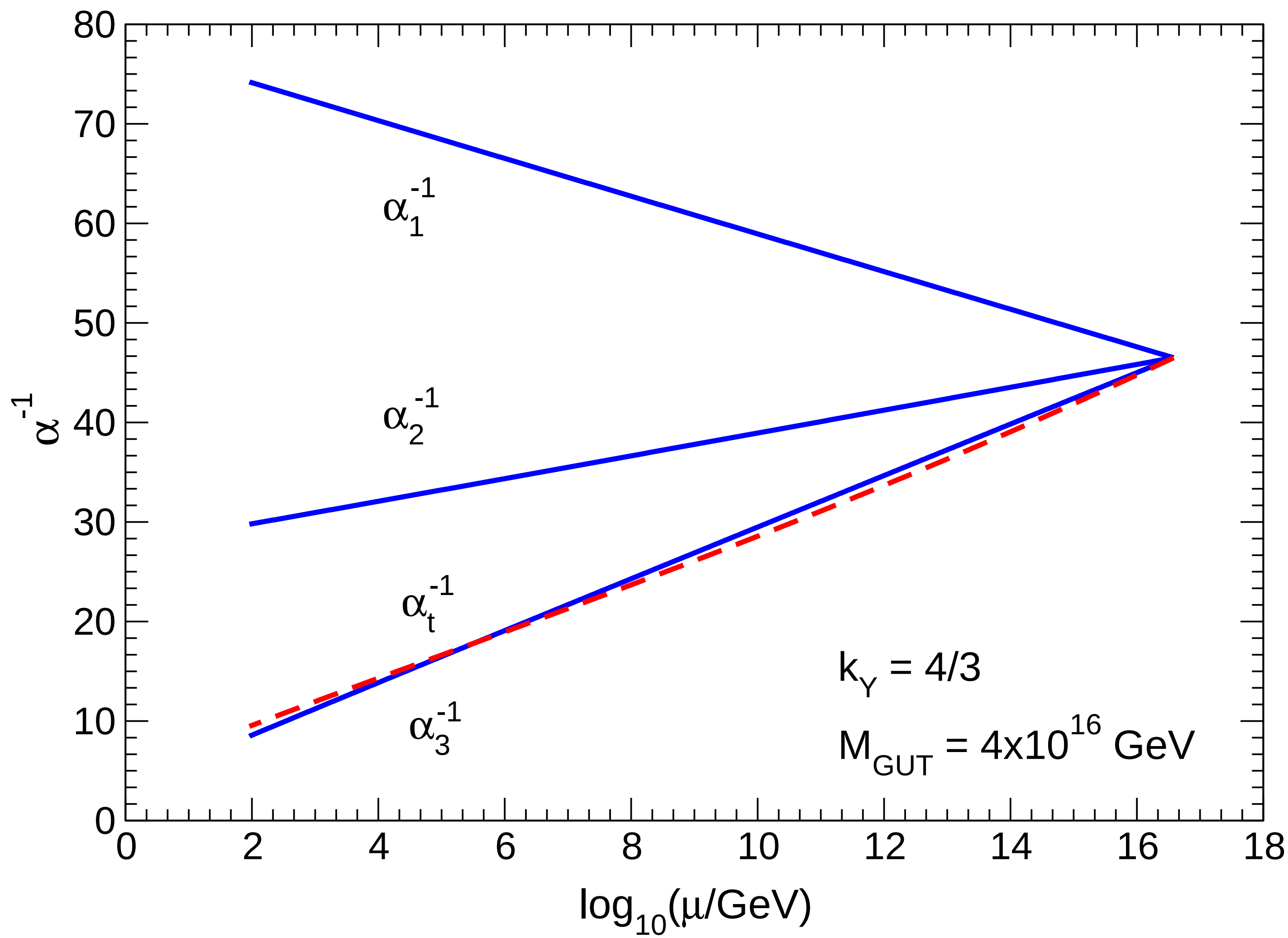
$$\mathbf{g_1 = g_2 = g_3 = y_t}, \quad \mathbf{h_t = y_t} \sin\beta$$

Input parameters:

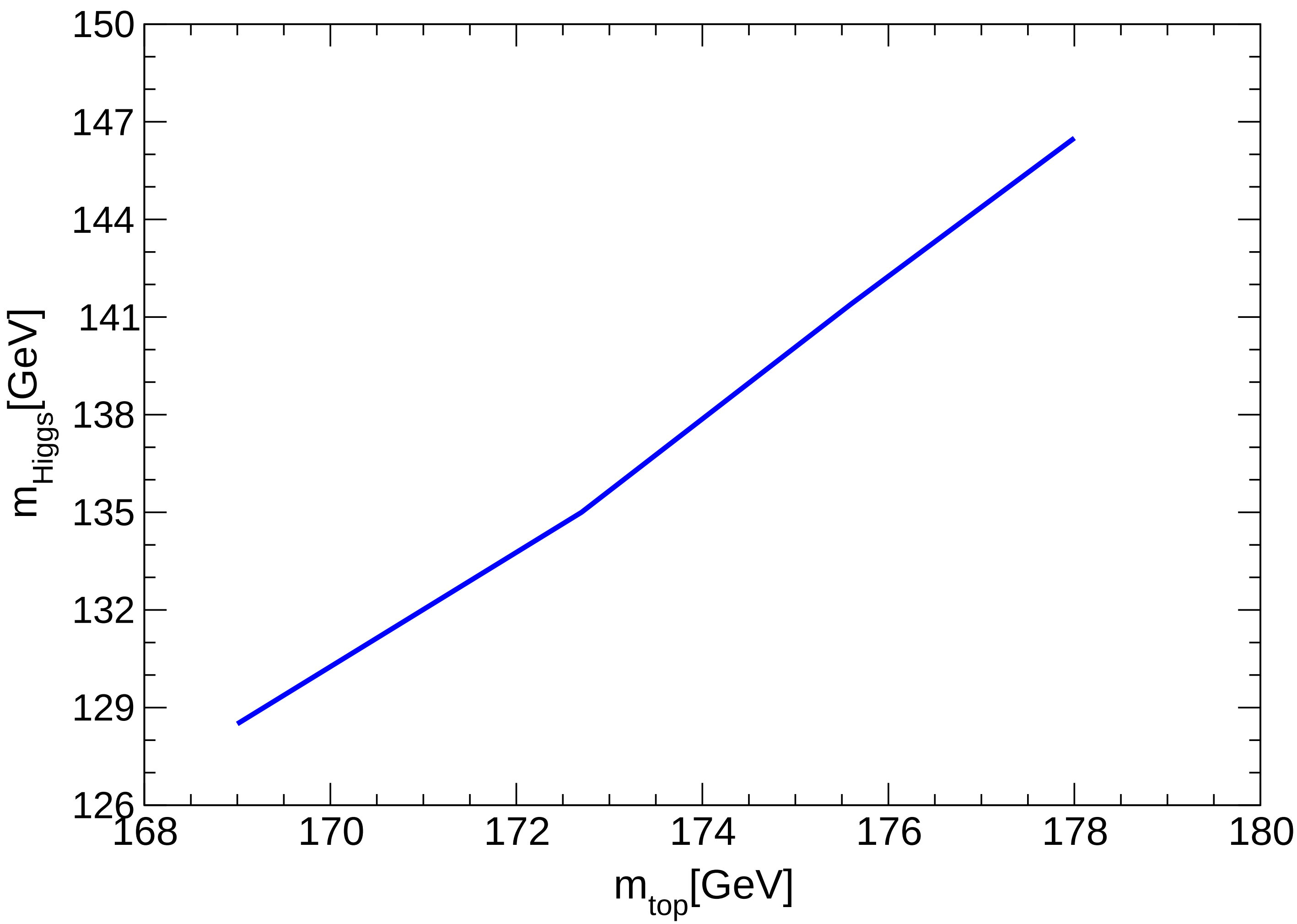
$$\alpha_{EM} = \mathbf{127.92 \pm 0.02}, \quad \mathbf{m_t = 170.9GeV}$$
$$\sin^2\theta_w = \mathbf{0.2311 \pm 0.0001},$$

Prediction: $\alpha_{\mathbf{3}}(\mathbf{M_Z}) = \mathbf{0.118}, \quad \mathbf{m_h = 131GeV}$

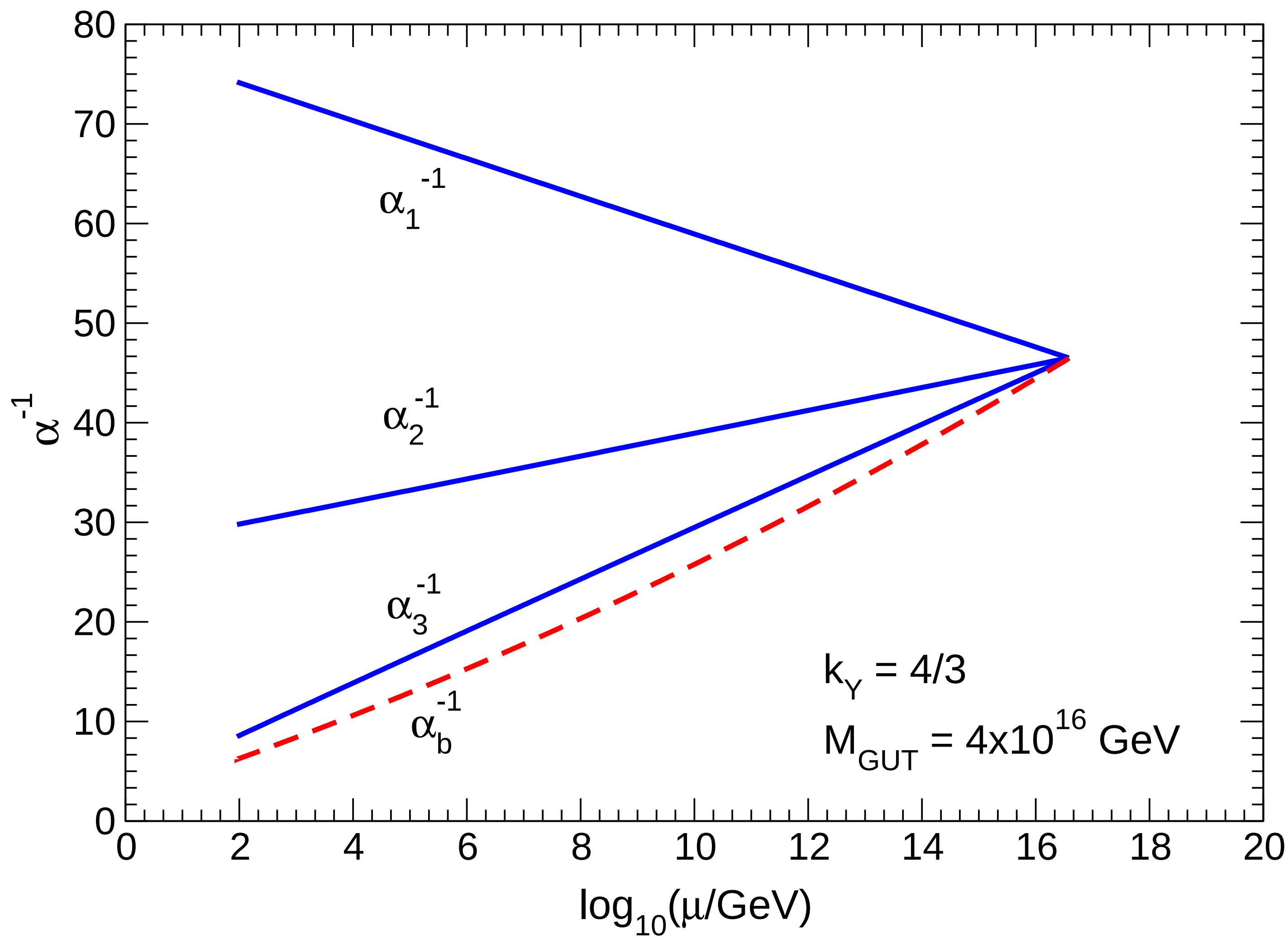
Gauge and Top Yukawa Unification



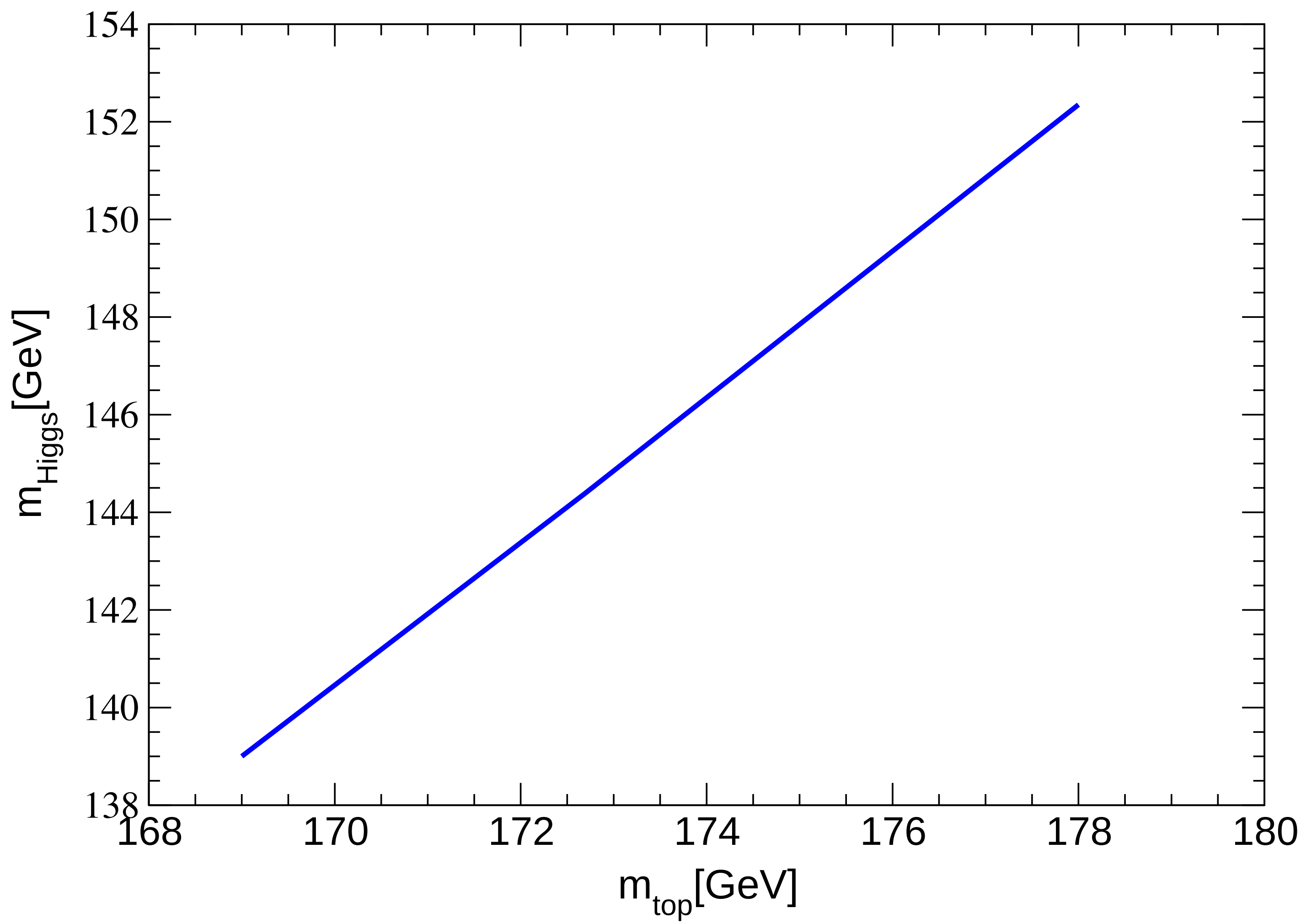
Gauge and Top Yukawa Unification



Gauge & Bottom Yukawa Unification



Gauge & Bottom Yukawa Unification



Standard Model (SM) + Einstein' GR

$\Rightarrow$ Hot Big Bang Cosmology

Predictions

- Existence of CMB;
- Redshift (Galaxies);
- Primordial Nucleosynthesis.

54-1

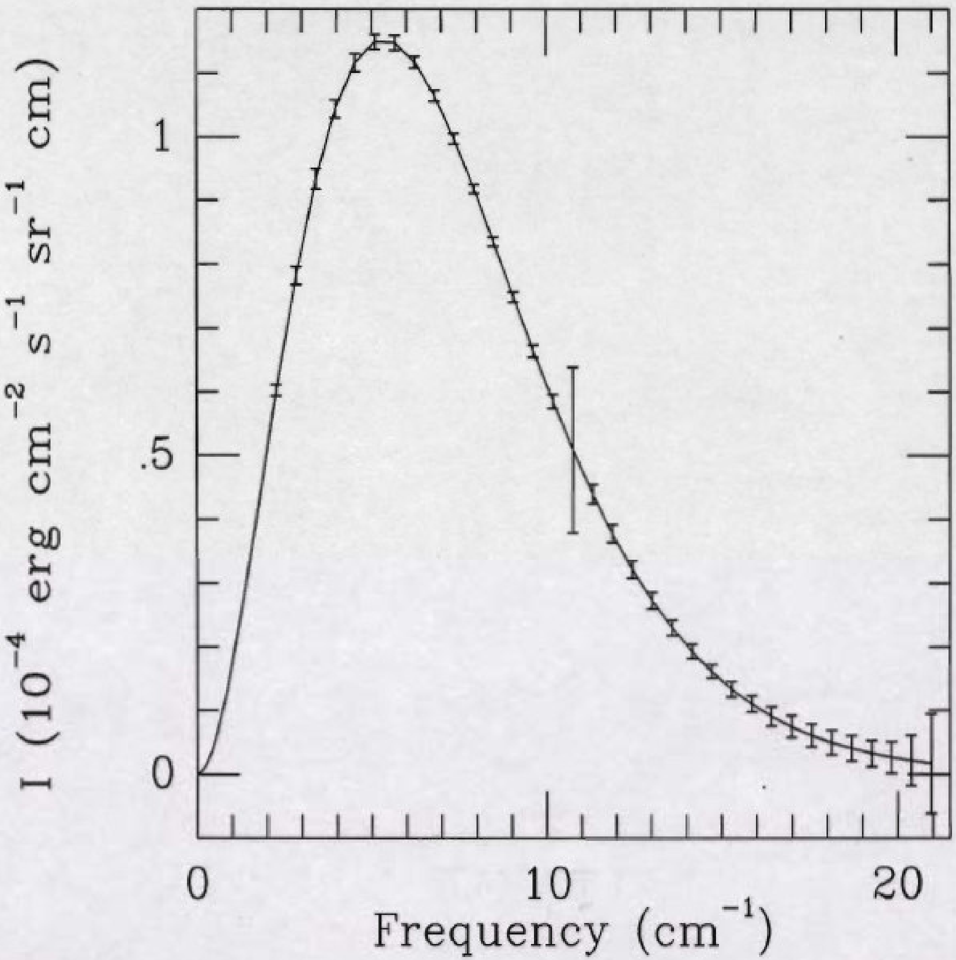
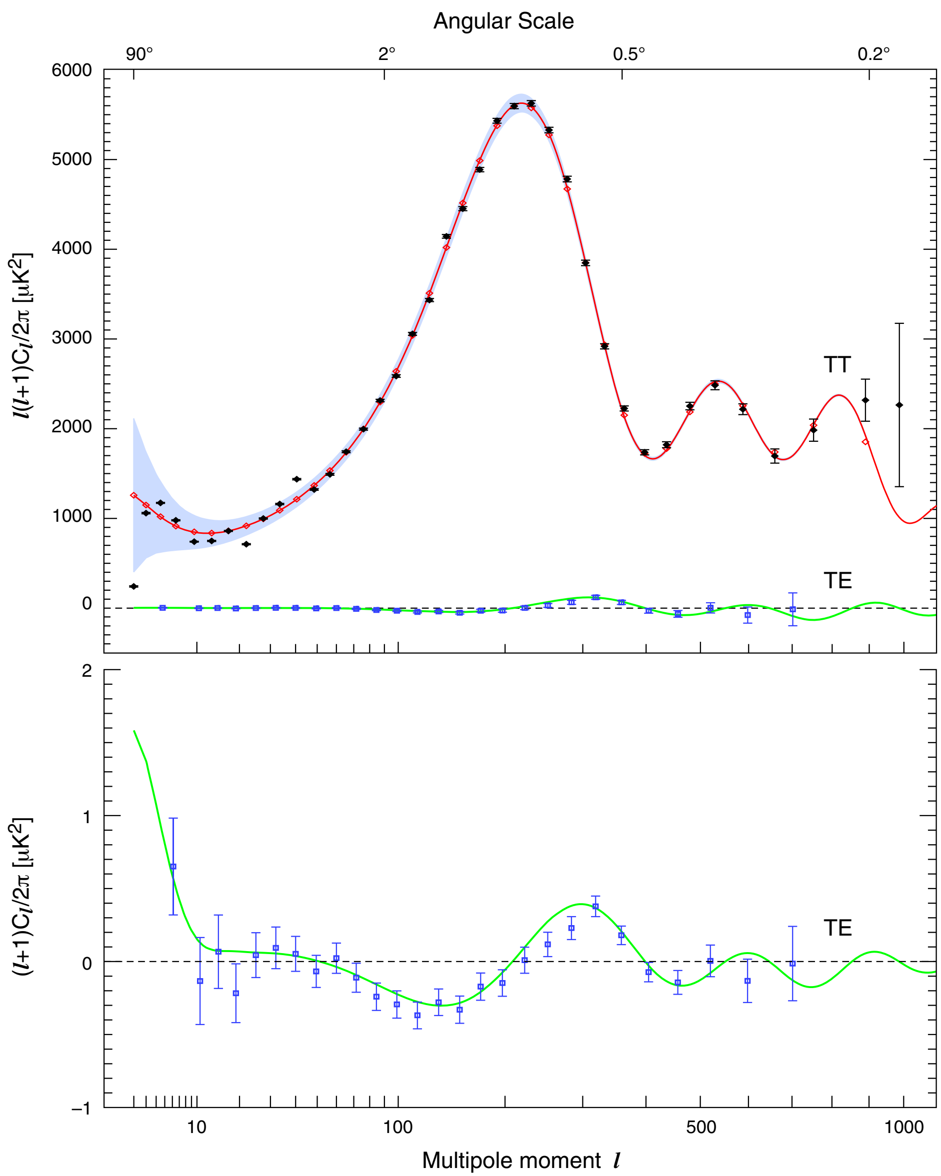


Figure 4: Spectrum of the Cosmic Microwave Background Radiation as measured by the FIRAS instrument on COBE and a black body curve for $T = 2.7277\,\mathrm{K}$. Note, the error flags have been enlarged by a factor of 400. Any distortions from the Planck curve are less than 0.005% (see Fixsen *et al.* , 1996).


Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
l(l+1)Cl/2π [μK²]
TT
TE
2
1
0
−1
(l+1)Cl/2π [μK²]
TE
10
100
500
1000
Multipole moment l

Standard Model (SM) + Einstein' GR

Hot Big Bang Cosmology fails to explain

1) Observed Isotropy of CMB(COBE)

2) Origin of $\frac{\delta T}{T}$ -COBE,..., WMAP

3) $\Omega_{total} = 1$ (critical density)

4) $\Omega_{CDM} = 0.22$ (non-baryonic DM)

5) $n_b/n_\gamma = 10^{-10}$ (baryon asymmetry)

- If GR stays intact, an extension of the SM is needed.

(Dark Energy?)

Standard Model (SM) + Einstein' GR

6) Indeed Neutrino Oscillations also require an extension of the SM:

Atmospheric ν Oscillations:

$\Rightarrow |\Delta m_{ATM}| \approx 0.05$ eV,

Solar ν Oscillations:

$\Rightarrow |\Delta m_{SOLAR}| \approx 0.01$ eV;

But $|\Delta m_{\nu}| \approx 0.00001$ eV;

(Dim 5 Ops. (LH) ^{2})

Inflationary Cosmology

- Inflationary Cosmology can take care of (1), (2), (3) and an inflation model can be called "realistic" if it can explain (4)$\rightarrow$ CDM and (5) $\rightarrow n_b/n_\gamma$. Some Models also provide a link with (6)$\rightarrow$ neutrino physics.
- Testable predictions?

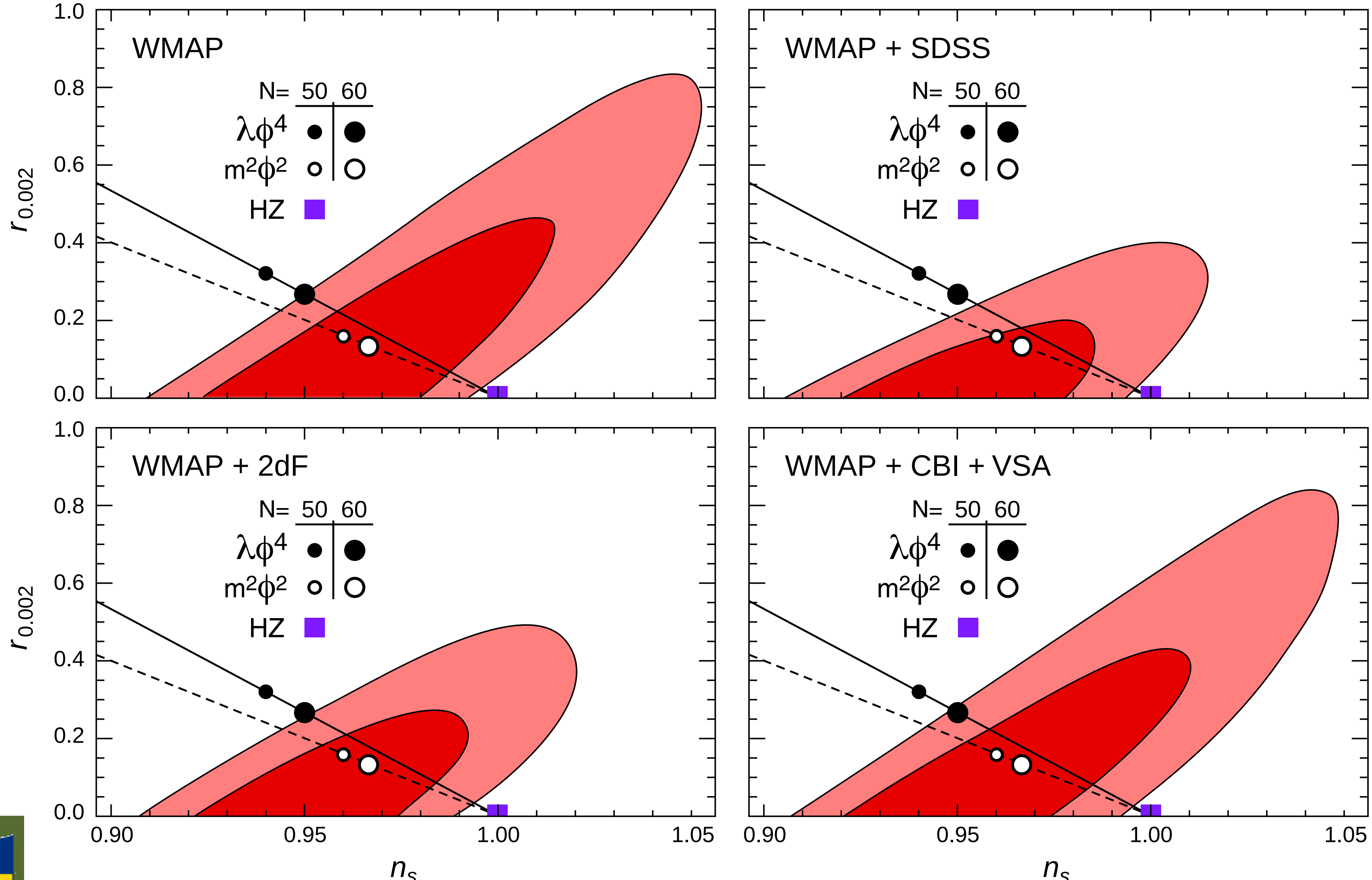
Inflationary Cosmology

- One key parameter in cosmology is the scalar spectral index n_s. According to Harrison and Zeldovich (HZ), $n_s = 1$ is the most 'natural' value, referred to as the scale invariant value.
- The most recent analysis from WMAP yields $n_s \approx 0.95 \pm 0.03$

(WMAP 1 : $n_s \approx 0.99 \pm 0.04$)

A far more precise determination of n_s is crucial for distinguishing inflation models.

Inflationary Cosmology



Inflationary Cosmology

- Inflation model come in variety of flavors. These include:
  - Chaotic Inflation (Linde, ..., Murayama, ..., Yanagida)
  - New Inflation (Linde, Albrecht, Steinhardt,..., Senoguz,....)
  - Hybrid Inflation (non-susy , susy)
  - Supergravity Inflation
  - Brane Inflation (Dvali, Tye, ...)
  - Compactification (Arkani Hamed et.al, ..., Schmidt et.al,....)
  - Quintessence/Inflation

Inflation

In this talk I will assume that inflation is associated with some symmetry breaking (phase transition) in the early universe. This is motivated as follows:

- SM gives rise to phase transitions:
  Electroweak ($T_c \sim 100$ GeV) $SU(2) \times U(1) \rightarrow U(1)_{em}$
  QCD ($T_c \sim 100$ MeV) $\rightarrow$ Confinement
- SM gauge symmetry is a part of some larger symmetry. Examples:
  $SU(5)$, L←R models, Extra dimensions;
  Global Symmetries (U(1)$_{axions}$, ...)

Inflation

Senoguz, Q.S

To keep the discussion as simple as possible, consider $U(1)_{B-L}$, an accidental global symmetry of the SM. (Similar discussion holds if $U(1)_{B-L} \to U(1)_{axion}$)

- We require that $U(1)_{B-L}$ is spontaneously broken and introduce the coupling $y_{ij} N_i N_j \phi$; Here $< \phi >$ breaks $U(1)_{B-L}$ and also provides masses for the right-handed neutrino N_i.
- ϕ is going to be the inflaton and, since it couples to N_i , the observed baryon asymmetry arises via leptogenesis.

Quartic (CW) Potential (non-susy)

Q.S, Vilenkin; Pi; Linde

$$V(\phi) = A\phi^4 \left(ln \left(\frac{\phi}{M} \right) - \frac{1}{4} \right) + \frac{AM^4}{4}$$

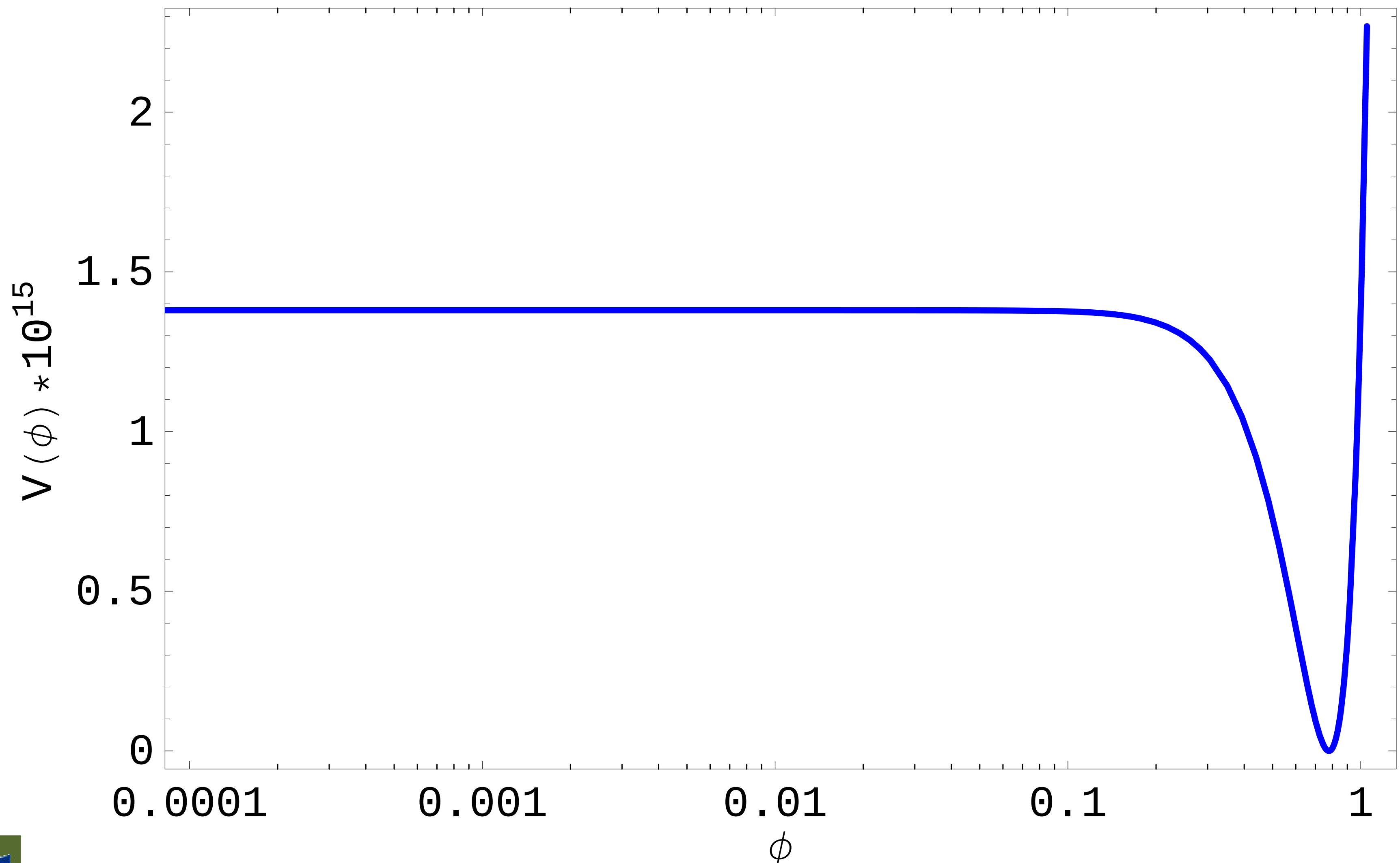
$$\uparrow$$

$\phi =$ gauge singlet

$$V(\phi = M) = 0; V(\phi = 0) = \frac{AM^4}{4} \equiv V_0$$

$$V(\phi << M) = \frac{AM^4}{4} - b\phi^4$$

Quartic (CW) Potential (non-susy)



Quartic (CW) Potential (non-susy)

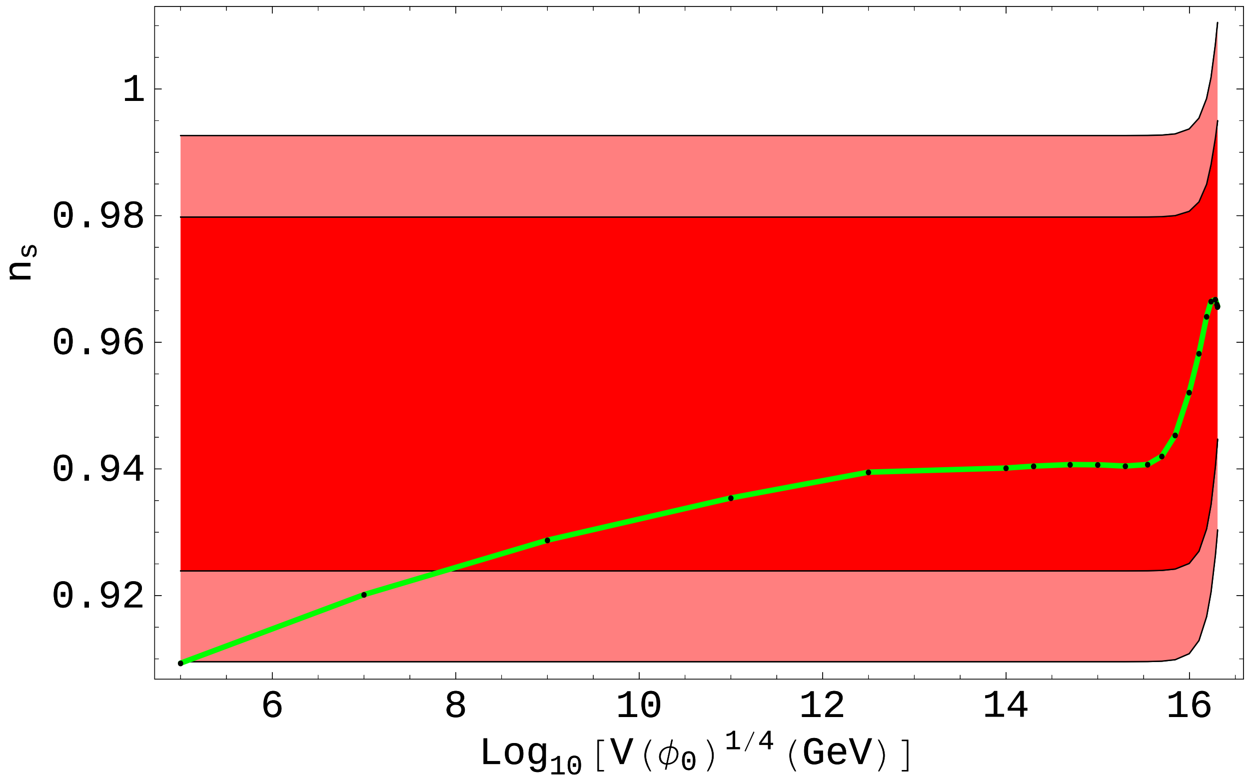
- For $V_0^{1/4} < 10^{16}$ GeV,
  $\phi < m_P$ ($\simeq 2.4 \times 10^{18}$ GeV)
  $V \simeq V_0 \left(1 - (\phi/M)^4\right)$
  $n_s \simeq 1 - \frac{3}{N_0}, \qquad \alpha \simeq (n_s - 1)/N_0$
  $\uparrow$
  e-folds for $k_0 = 0.002 Mpc^{-1}$

$\left(V_0^{1/4} > 10^5 \text{ GeV to avoid conflict with WMAP}\right)$

From New to Large Field Inflation

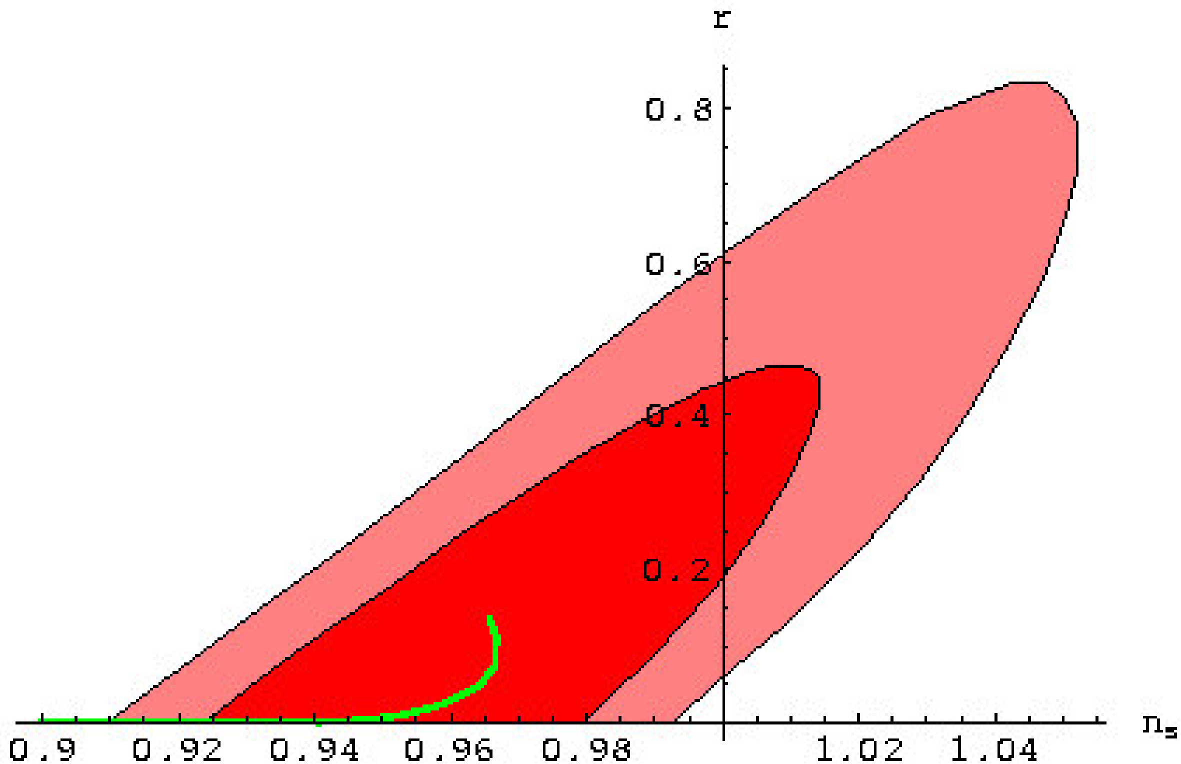
- For $V_0^{1/4} \gtrsim 10^{16}$ GeV, $\phi > m_P$ during observable inflation . Predictions approach that of ϕ^2 potential, with
  $n_s = 1 - \frac{2}{N_0} \simeq 0.96$
  $r \simeq 0.13$
  $\alpha \simeq -0.6 \times 10^{-3}$

From New to Large Field Inflation



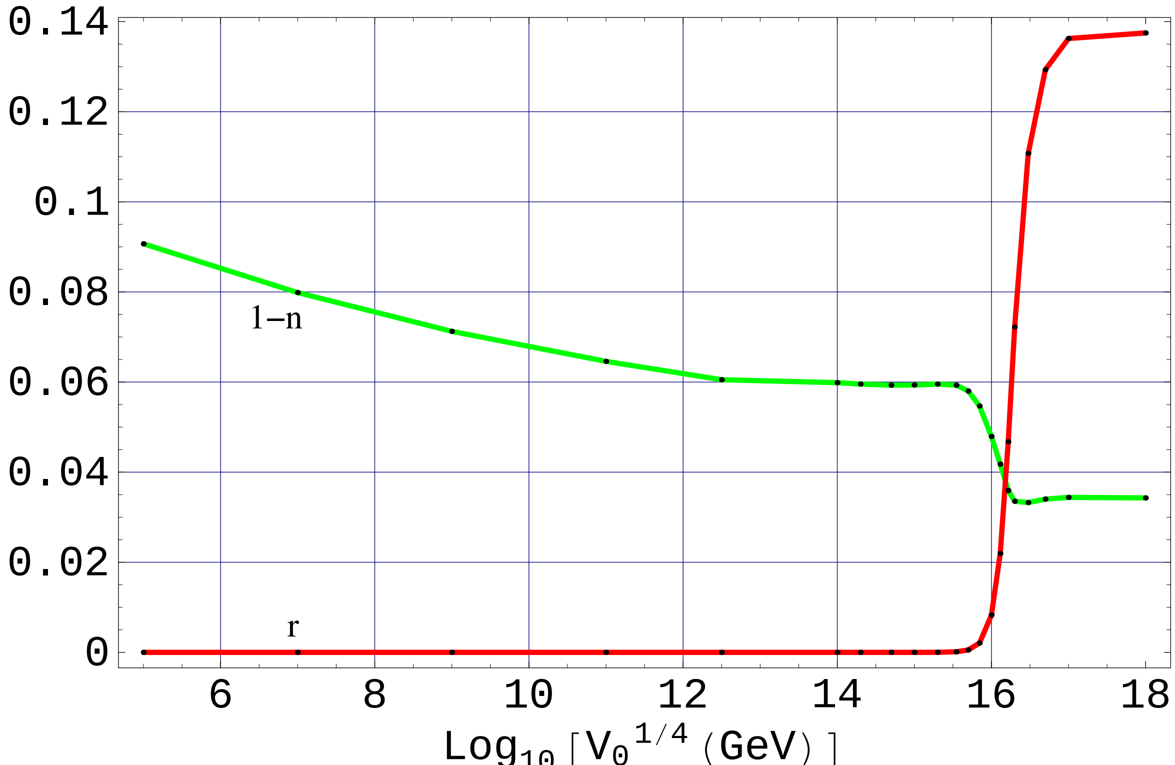
The spectral index n_s vs $\log[V(\phi_0)^{1/4}\ (\mathrm{GeV})]$ for the Coleman-Weinberg potential (green curve), compared with the WMAP range for n_s (68% and 95% confidence levels, taken from Spergel *et al.*, astro-ph/0603449). Note that the tensor to scalar ratio $r \approx 0$ for $V(\phi_0)^{1/4} \ll 10^{16}$ GeV and $r \approx 0.14$ for $V(\phi_0)^{1/4} \approx 2 \times 10^{16}$ GeV.

From New to Large Field Inflation



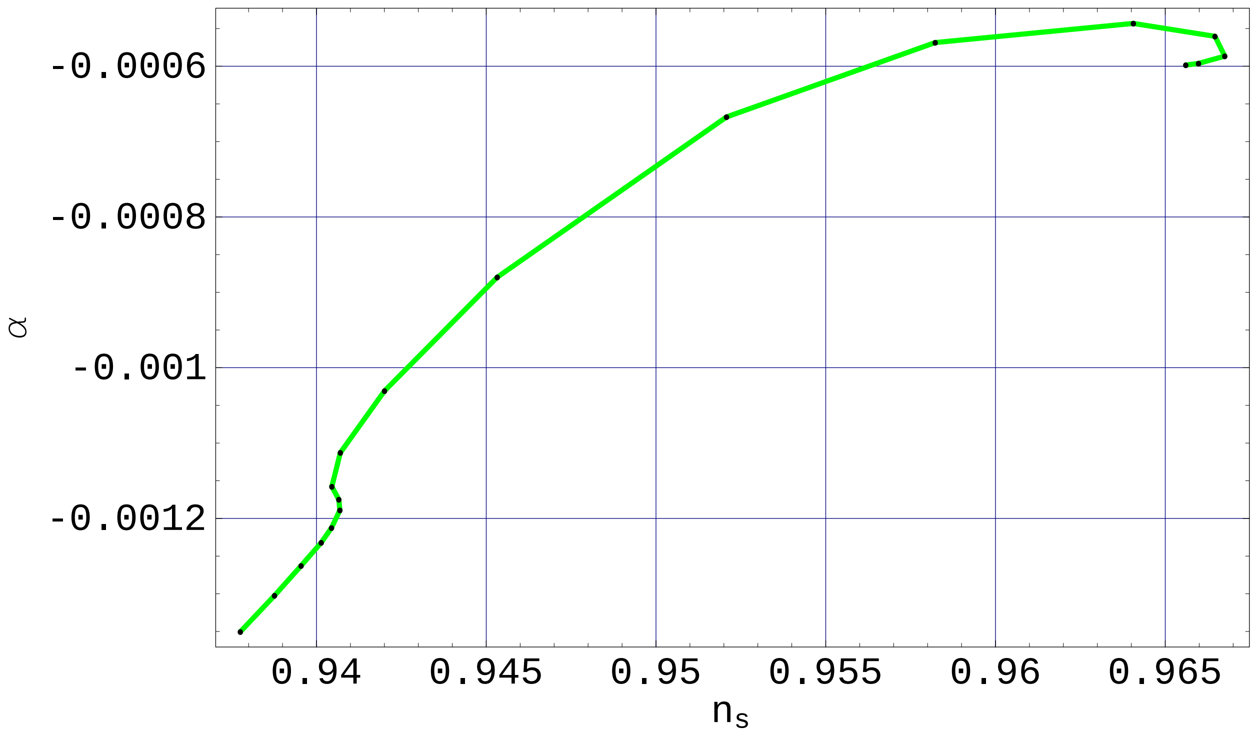
The tensor to scalar ratio r vs the spectral index n_s for the Coleman-Weinberg potential (green curve). The WMAP contours (68% and 95% confidence levels) are taken from Spergel *et al.*, astro-ph/0603449.

From New to Large Field Inflation



$1 - n_s$ and r vs. $\log[V_0^{1/4}\,(\mathrm{GeV})]$ for the Coleman-Weinberg potential.

From New to Large Field Inflation



$\alpha \equiv \frac{dn_s}{d \ln k}$ vs. n_s for the Coleman-Weinberg potential.

$V_0^{1/4}$(GeV)	$A(10^{-14})$	M	ϕ_e	ϕ_0	$V(\phi_0)^{1/4}$(GeV)	n_s	$\alpha(-10^{-3})$	r
10^{13}	1.0	0.018	0.010	3.0×10^{-6}	$\approx V_0^{1/4}$	0.938	1.4	9×10^{-15}
5×10^{13}	1.2	0.088	0.050	7.5×10^{-5}	$\approx V_0^{1/4}$	0.940	1.3	5×10^{-12}
10^{14}	1.3	0.17	0.10	3.0×10^{-4}	$\approx V_0^{1/4}$	0.940	1.2	9×10^{-11}
5×10^{14}	1.9	0.79	0.51	7.5×10^{-3}	$\approx V_0^{1/4}$	0.941	1.2	5×10^{-8}
10^{15}	2.3	1.5	1.1	0.030	$\approx V_0^{1/4}$	0.941	1.2	9×10^{-7}
5×10^{15}	4.8	6.2	5.1	0.71	$\approx V_0^{1/4}$	0.942	1.0	5×10^{-4}
10^{16}	5.2	12	10	3.2	9.9×10^{15}	0.952	1.0	8×10^{-3}
2×10^{16}	1.1	36	35	23	1.7×10^{16}	0.966	0.6	0.07
3×10^{16}	.17	86	85	72	1.9×10^{16}	0.967	0.6	0.11
10^{17}	.001	1035	1034	1020	2.0×10^{16}	0.966	0.6	0.14

Magnetic Monopoles and Inflation

- Consider the breaking

$$SO(10) \longrightarrow 4-2-2 \longrightarrow 3-2-1$$

First breaking produces superheavy monopoles carrying one unit of Dirac charge

$$\pi_2(SO(10)/4-2-2) = Z_2;$$

The second breaking at scale M_c produces monopoles which carry two units of Dirac magnetic charge. These are intermediate mass monopoles and they may survive inflation .

Magnetic Monopoles and Inflation

- Consider the quartic coupling $-c\phi^2\chi^\dagger\chi$, with $c \sim (M_c/M)^2$. Here χ vev breaks $4-2-2$ to $3-2-1$ and ϕ is the inflaton.
- Monopole formation occurs when $c\phi^2 \sim H^2$ $\longrightarrow H(t - t_\chi) \equiv \eta \sim 3c/\lambda$.
- Initial monopole number density $\sim H^3$, which gets diluted by inflation down to $H^3\exp(-3\eta)$; thus, $r_M = n_M/T_R^3 \sim (H/T_R)^3\exp(-3\eta) \lesssim 10^{-30}$.
- Roughly 25- 30 e-folds can yield a flux close to or below the Parker bound.

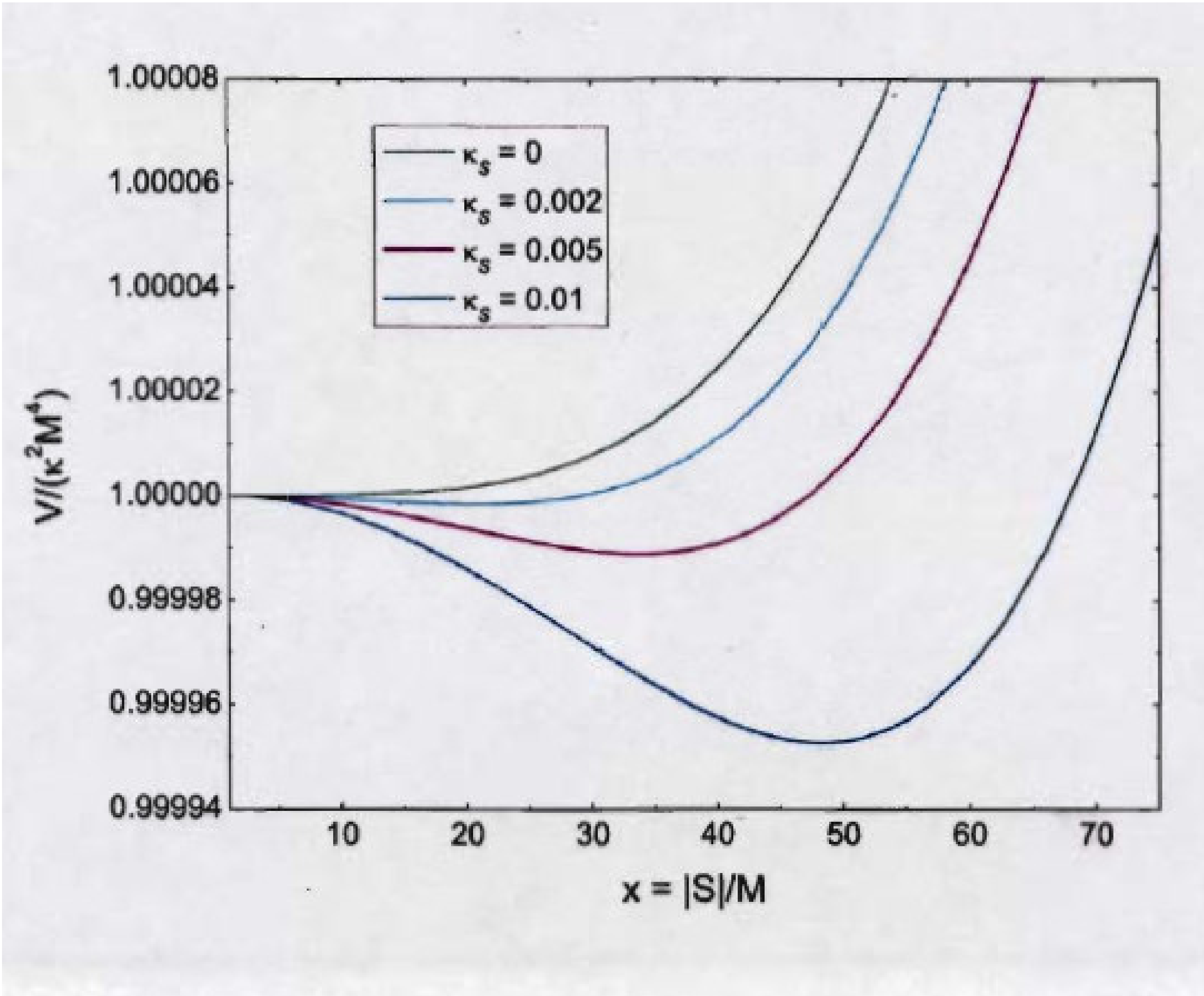
Non-minimal Models King, Bastero Gil, Q.S

$$K = |S|^2 + |\phi|^2 + |\overline{\phi}|^2 + |N|^2 \longleftarrow \text{right-handed sneutrino}$$
$$+\kappa_S \frac{|S|^4}{4m_P^2} + \kappa_{S\phi}\frac{|S|^2|\phi|^2}{m_P^2} + \kappa_{SN}\frac{|S|^2|N|^2}{m_P^2} + ...$$

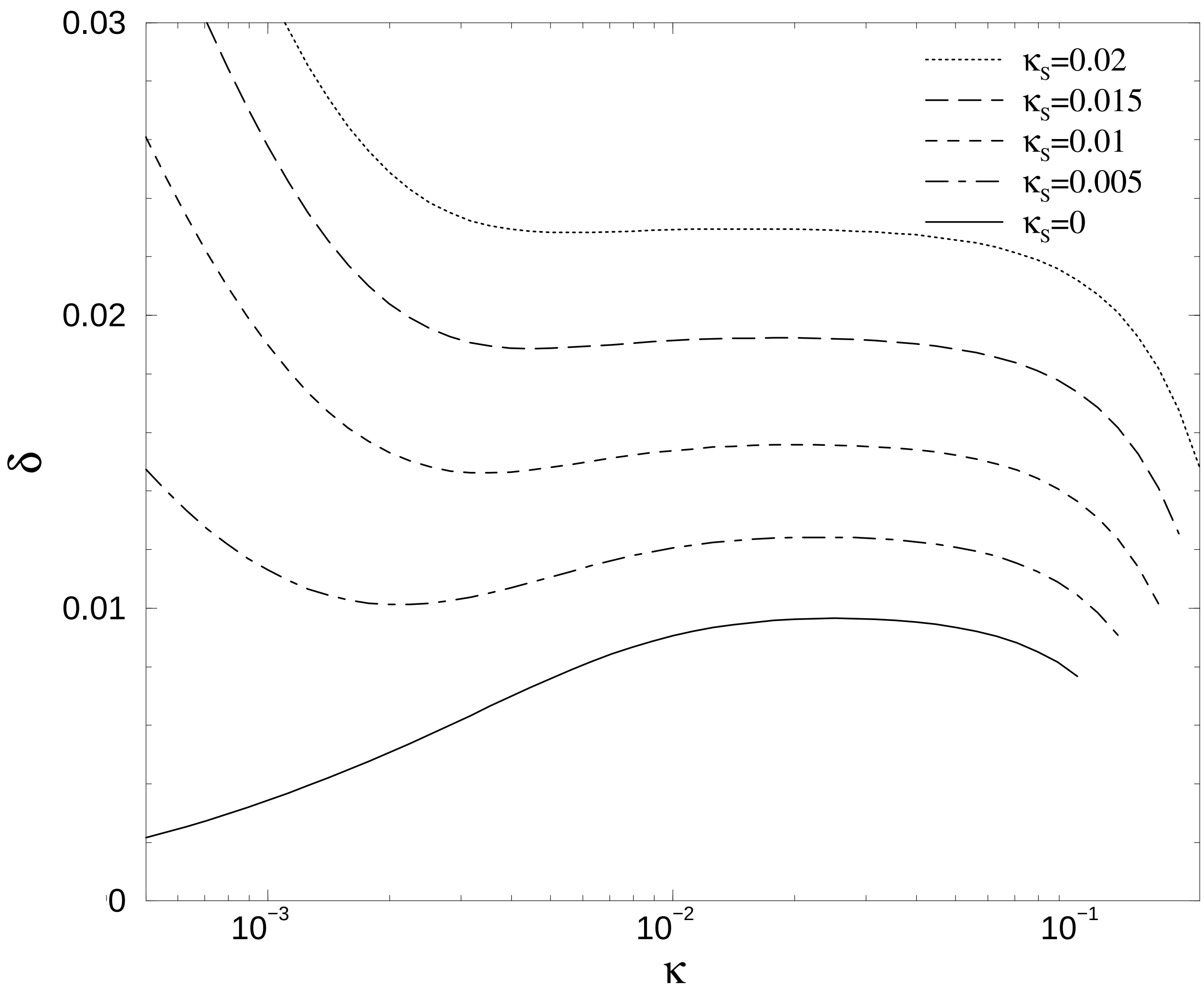
- 'regular' hybrid inflation with ϕ and N at origin during inflation , but $V_{\inf l}$ picks up a term $(-\kappa_S)\,\kappa^2 M^4 \frac{S^2}{m_P^2}$, such that

$$n_s \simeq 1 - 2\delta - 2\kappa_S$$
$$\nearrow \qquad\qquad \nwarrow$$

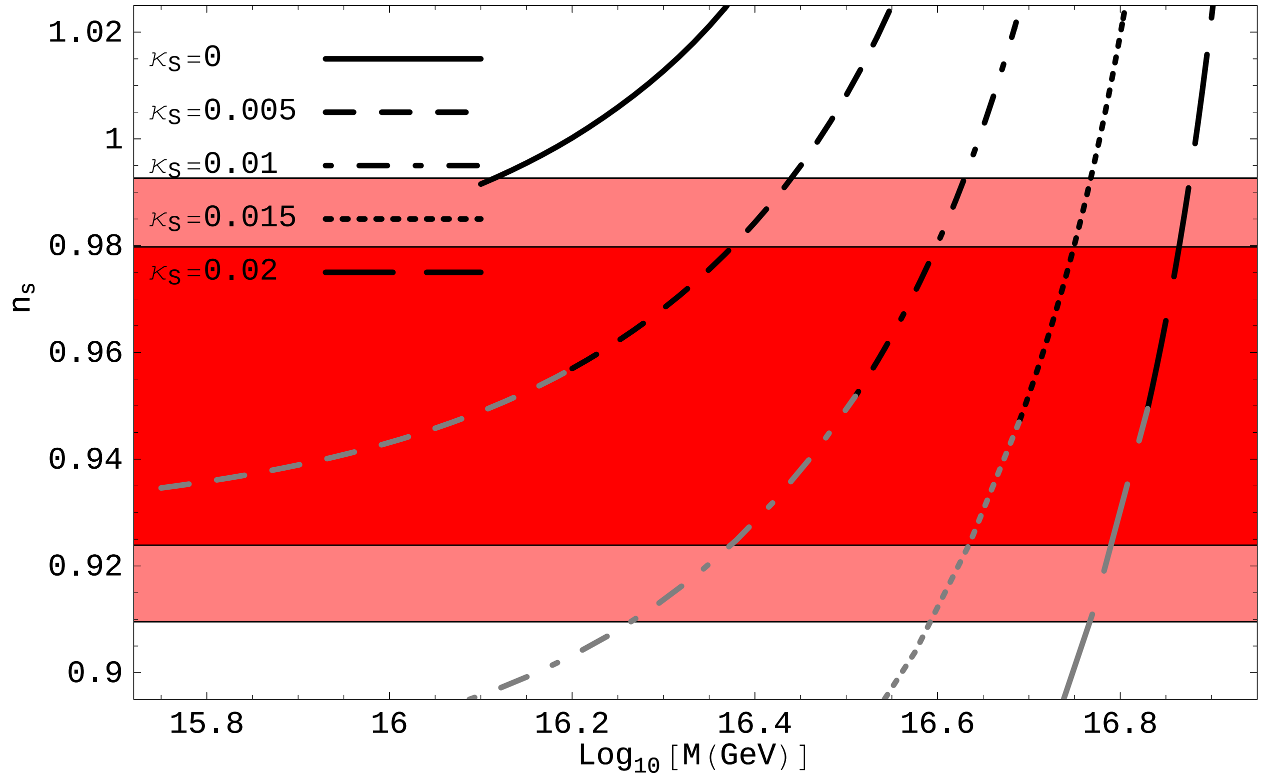
radiative correction non-minimal contribution



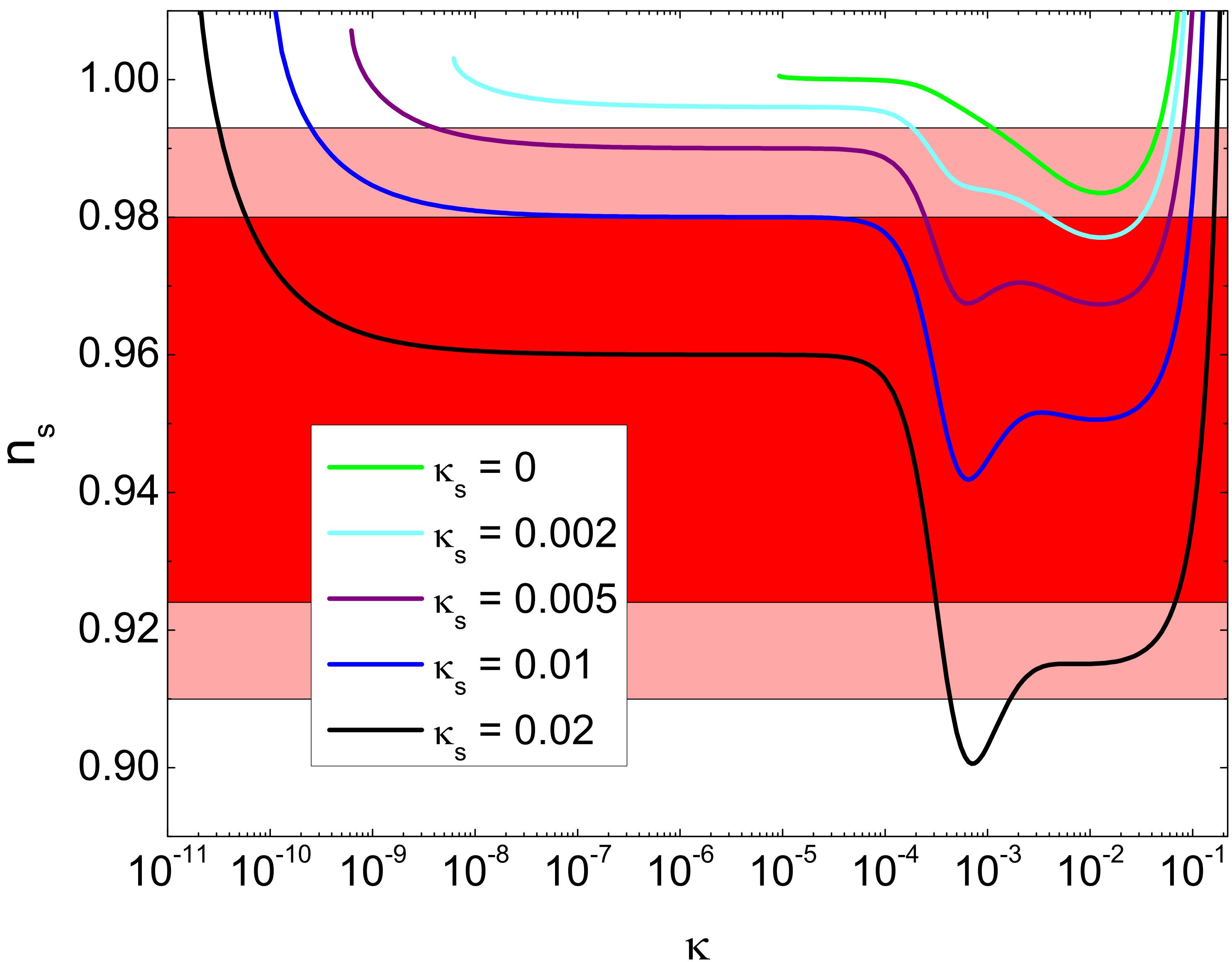
1.00008
1.00006
1.00004
1.00002
1.00000
0.99998
0.99996
0.99994
$V/(\kappa^2 M^4)$
10
20
30
40
50
60
70
$x = |S|/M$
$\kappa_S = 0$
$\kappa_S = 0.002$
$\kappa_S = 0.005$
$\kappa_S = 0.01$



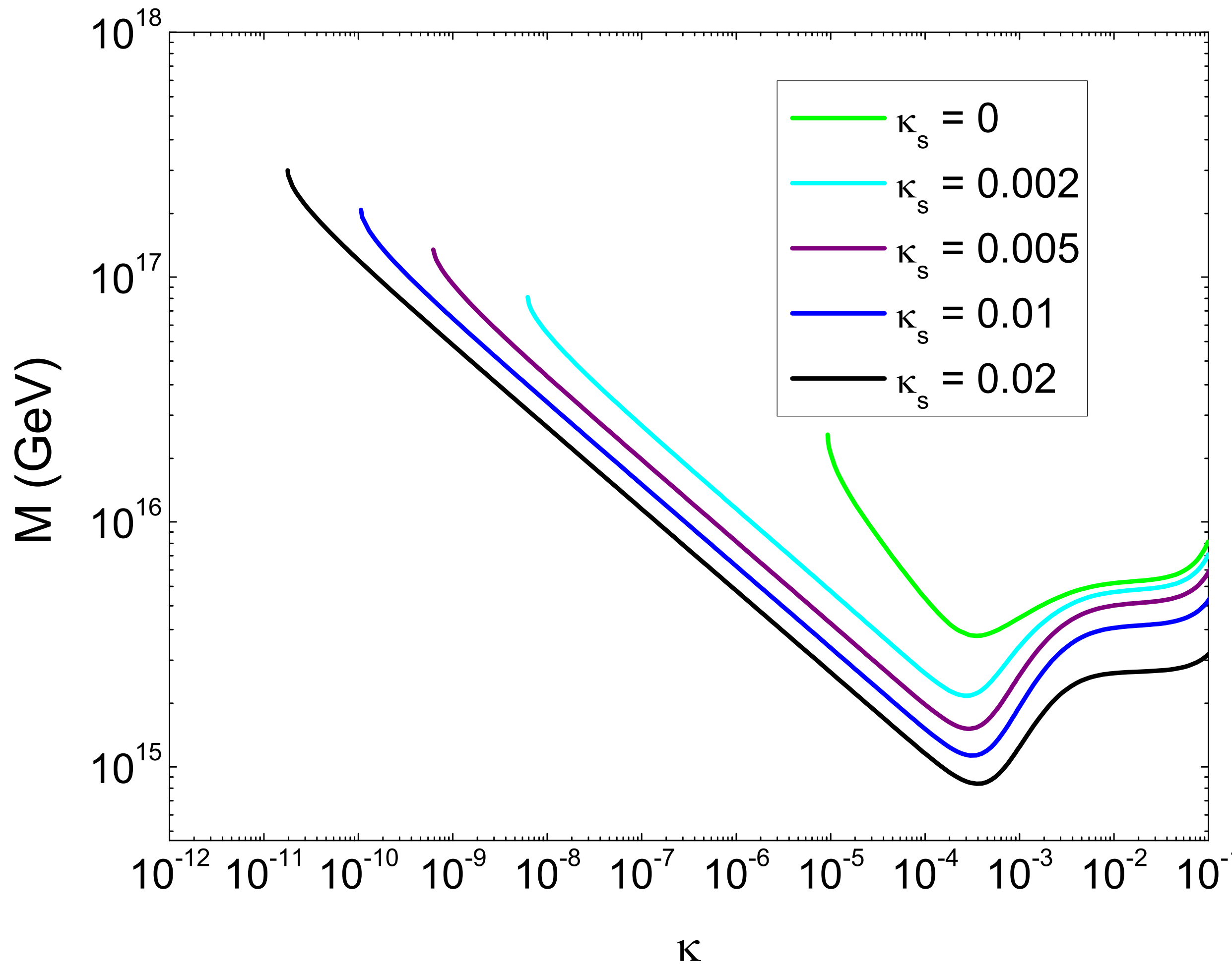
0.03
0.02
0.01
0
δ
10^{-3}
10^{-2}
10^{-1}
κ
κ_S=0.02
κ_S=0.015
κ_S=0.01
κ_S=0.005
κ_S=0



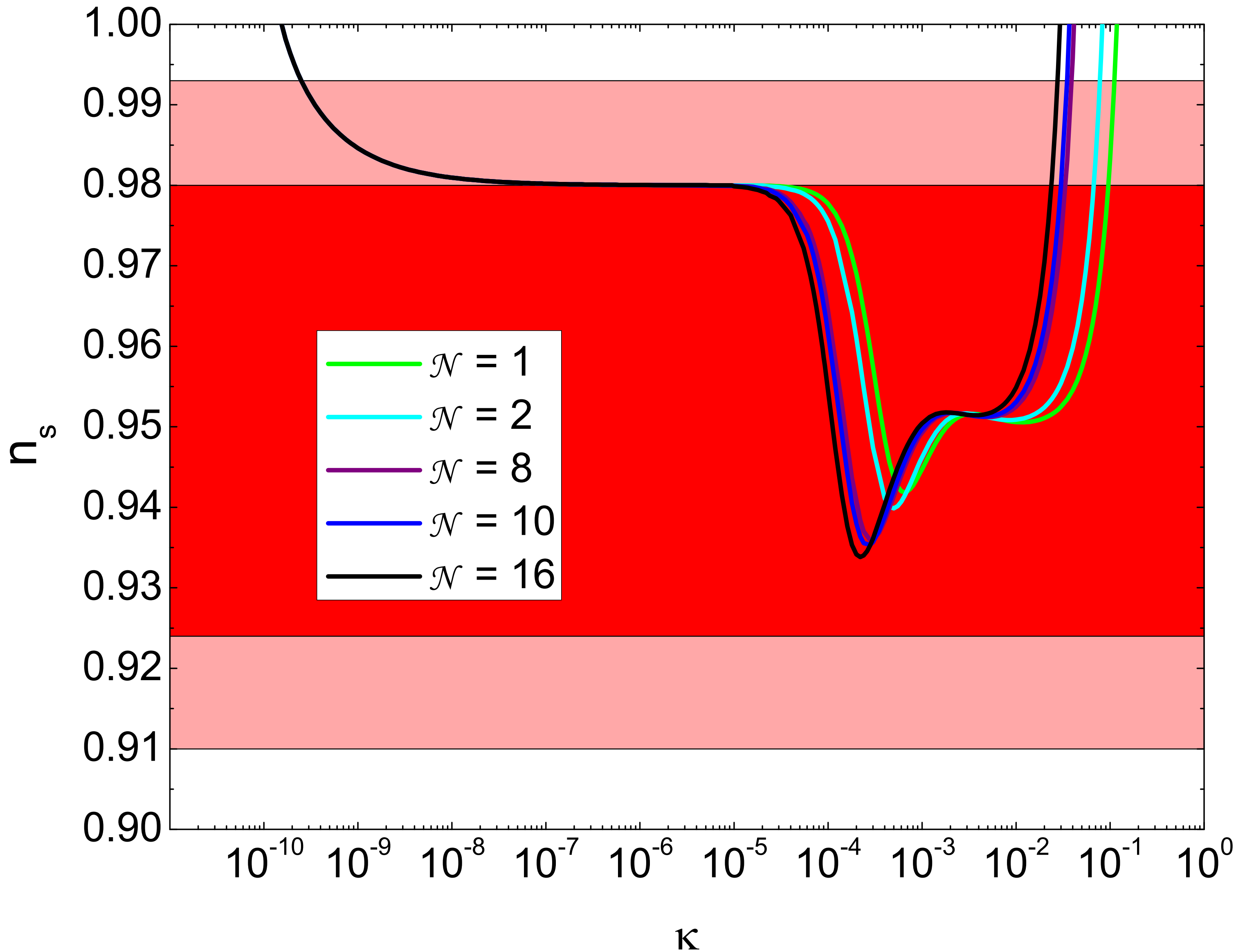
The spectral index n_s as a function of the gauge symmetry breaking scale M for smooth hybrid inflation , compared with the WMAP range for n_s (68% and 95% confidence levels, taken from Spergel *et al.*, astro-ph/0603449). The gray sections indicate that the field is initially close to a local maximum.



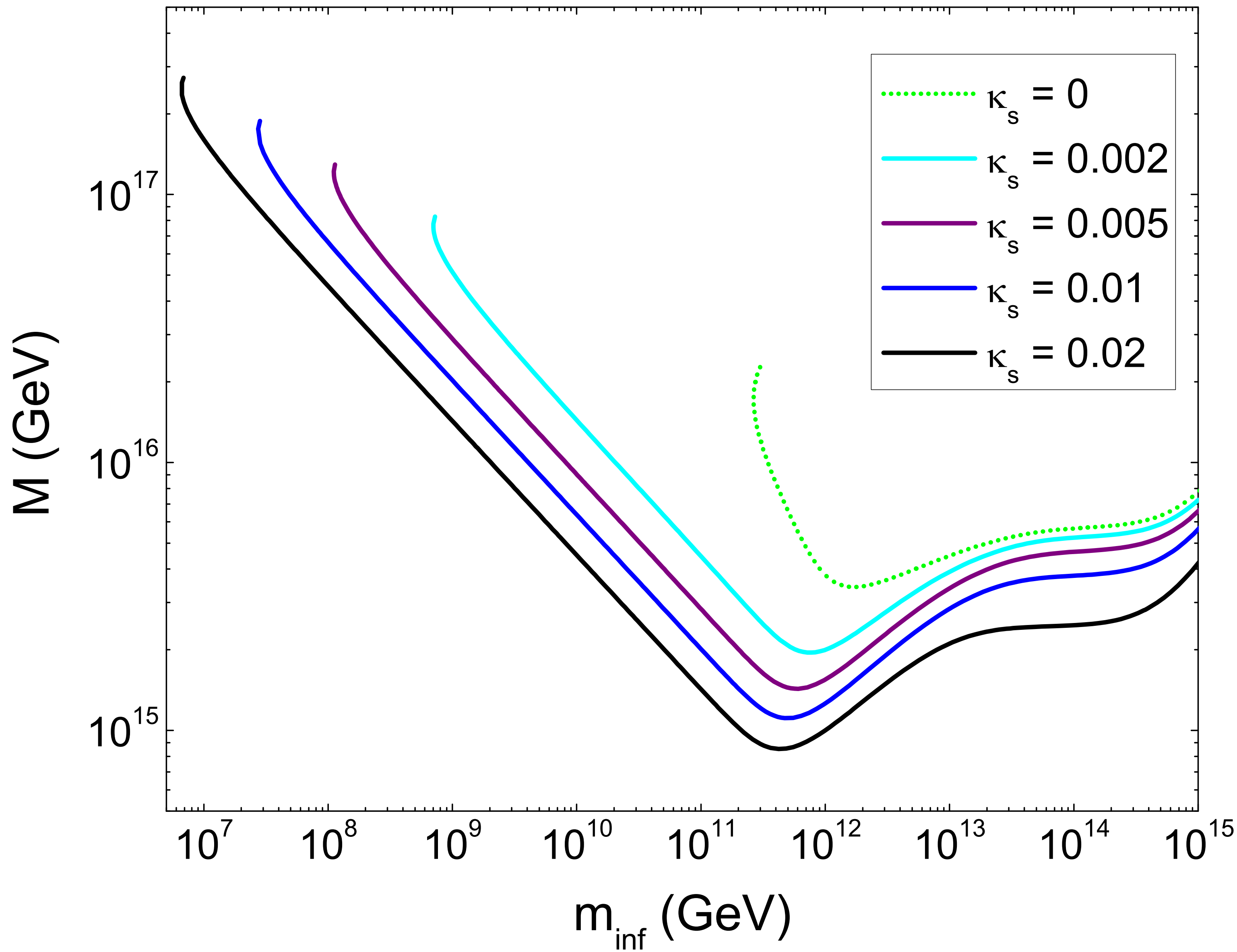
1.00
0.98
0.96
0.94
0.92
0.90
n_s
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
κ
$\kappa_s = 0$
$\kappa_s = 0.002$
$\kappa_s = 0.005$
$\kappa_s = 0.01$
$\kappa_s = 0.02$



M is symmetry breaking scale (Inflation 'scale'$\sim \kappa^{1/2} M$)



1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.90
n_s
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
κ
$\mathcal{N}$ = 1
$\mathcal{N}$ = 2
$\mathcal{N}$ = 8
$\mathcal{N}$ = 10
$\mathcal{N}$ = 16



M (GeV)
10^{17}
10^{16}
10^{15}
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
m_{inf} (GeV)
$\kappa_s = 0$
$\kappa_s = 0.002$
$\kappa_s = 0.005$
$\kappa_s = 0.01$
$\kappa_s = 0.02$

New Inflation (Kawasaki et al,Senoguz,Q.S,..)

Here S and N stay at zero during inflation now driven by ϕ ($W = S\left(-\mu^2 + \frac{(\phi\phi)^m}{M_*^{2m-2}}\right)$)

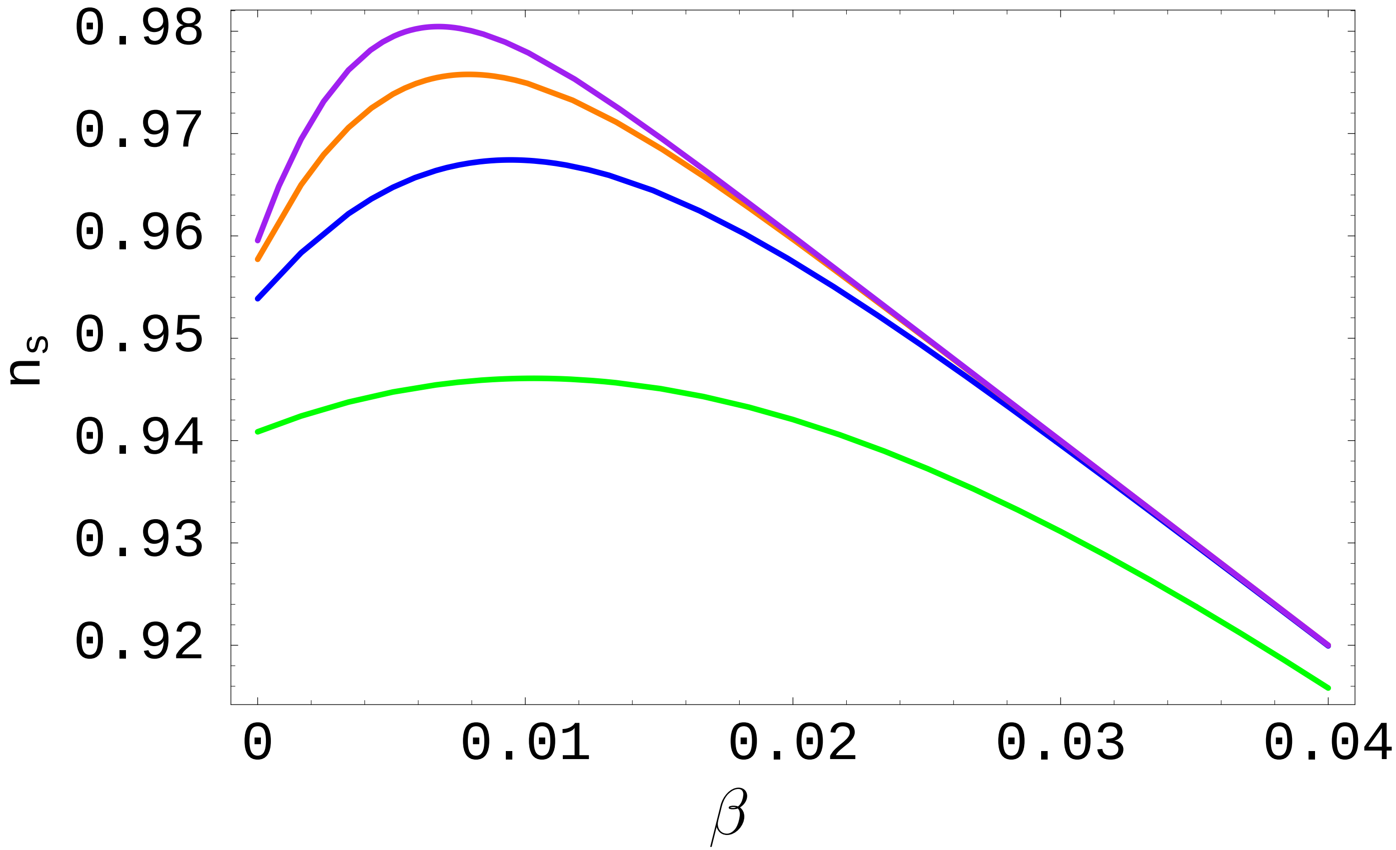
During Inflation,

$V \simeq \mu^4 \left(1 - \frac{\beta}{2}\frac{\phi^2}{m_P^2} + ...\right)$

(with $\beta \equiv \kappa_{S\phi} - 1 \geq 0.$)

$n_s \simeq 1 - 2\beta$, for $\beta \gg 1/\left[(2m-2)\, N_l\right]$

$\simeq 1 - \left[2\,(2m-1)\,/\,(2m-2)\, N_l\right]$, for $\beta \approx 0$.



The spectral index n_s vs. β, for $m = 2$ (green), $m = 3$ (blue), $m = 4$ (orange) and $m = 5$ (purple).

Sneutrino Hybrid Inflation

(Antusch et al)

Here the right-handed sneutrino is the inflaton (cf: Chaotic case).

$$n_s \simeq 1 - 2\gamma \; (\gamma \equiv \kappa_{SN} - 1)$$

$$r \ll \gamma^2$$

$$dn_s/d\ln\kappa \lesssim -\gamma \left(N^2/m_P^2\right)$$

For $\gamma \approx 0.02$, the model is consistent with WMAP 3.

$Z^{'}$ and Cosmic Strings

- Consider the breaking

$$E_6 \longrightarrow SO(10) \times U(1) \longrightarrow 3-2-1 \times U(1)$$

- If the additional $U(1)$ symmetry is broken in the TeV range one predicts not only an additional neutral gauge boson but also topologically stable strings, with mass per unit length μ of order TeV^2.
- These strings are expected to be display superconductivity because of fermions in the $10 + \overline{1}0$ representations of $SO(10)$.

$Z^{'}$ and Cosmic Strings

- Can we see them at the LHC ?
- How about their cosmic counterparts?
- LIGO/ LISA require $G\mu \geqslant 10^{-12}10^{-14}$. In other words, $\mu \gtrsim 10^{11} - 10^{12}$ GeV.

Brane Inflation and Cosmic Strings

Tye et. al.

- In some of the simplest models, inflation is driven by an attractive potential between, say, a D-brane and anti-D-brane, separated by some distance in the extra dimensions. As the branes move closer together, the three large space like dimensions expand exponentially. Eventually they collide, annihilate, and reheat the universe. The separation between the branes plays the role of the inflaton field. (Note: Presumably some branes survive if the SM lives on a stack of branes.)
- In the simplest models the scalar spectral index n_s is close to 0.97, but values close to 0.95 are also possible.

Brane Inflation and Cosmic Strings

- Prior to brane annihilation the associated gauge symmetry is $U(1) \times U(1)$. One linear combination gives rise to D-strings, while the orthogonal combination is associated with F (fundamental)-strings.
- It has been argued that a substantial fraction of energy of the annihilating branes is used up in the production of a network of cosmic D and F strings.
- If one assumes that brane inflation gives rise to the observed inhomogeneities, estimates suggest that

$$10^{-11} \lesssim G\mu \lesssim 10^{-6}.$$

- With some(?) luck it may be possible to observe these primordial strings with LIGO/LISA.

Conclusion

There is some experimental support for ideas underlying grand/partial unification:

- Quantization of electric charge;
- Unification of gauge couplings (SUSY $SU(5)$)
- Neutrino Oscillations ($4-2-2/SO(10)$ models in particular)

But many far reaching predictions are still unverified. These include:

- Proton Decay (mediated, in particular, by superheavy gauge bosons)
- Magnetic monopoles

Conclusion

- Exotic processes /states such as:
  1. $n - \overline{n}$ oscillations;
  2. Rare decays
  3. Color singlet states carrying fractional electric charge (4-2-2, 3-3-3, winding strings)
  4. Topological defects such as cosmic strings
  5. Axion

Clearly, very large scale detectors must be built to continue searching for proton decay and magnetic monopoles. ICE CUBE can look for monopoles, especially if they are not too heavy. They can find monopoles if the flux is not too far below the Parker bound ($\sim 10^{-16} \mathrm{cm}^{-2} \mathrm{sec}^{-1} \mathrm{sr}^{-1}$ for GUT mass monopoles).

Conclusion

The importance of the LHC for the future of high energy physics cannot be overemphasized. Important topics include:

- Nature of Electroweak Symmetry Breaking
- Supersymmetry
- Dark Matter (LSP)
- Extra Dimensions (Kaluza Klein excitations)
- Spontaneous Parity Violation (New gauge bosons, other TeV scale particles)
- TeV Scale Quantum Gravity (Black holes,...)
- Exotic States (Magnetic Monopoles, Fractionally charged color singlets, Z flux tubes, Leptoquarks, diquarks, unparticle physics...).

Conclusion

- Precision Cosmology will play an important role in the search for new physics beyond the SM.
- Challenge for PLANCK and other ongoing/future expts: Determine n_s, n_T, $dn_s/d\ln k$, r, w_{DE}, ... to a high degree of precision
- Find DARK MATTER
  (LSP, axion, majoran, KK,...)
  $\Rightarrow$ help discover standard model of inflation .