Higgs Boson Mass, New Physics and Inflation

Qaisar Shafi

shafi@bartol.udel.edu

Bartol Research Institute

Department of Physics and Astronomy

University of Delaware

Newark, DE 19716, USA

OUTLINE

- Higgs Boson / Seesaw Mechanisms
- Gauge-Higgs Unification
- Inflation
- Conclusion

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

$$130 \text{ GeV} \lesssim m_h \lesssim 170 \text{ GeV}$$

SM Higgs boson mass bounds

From the Higgs potential in the SM,

Higgs quartic coupling determines $\boxed{M_H^2 = \lambda v^2}$ $(v = 246\text{GeV})$

Once Higgs mass is measured, its high energy behavior

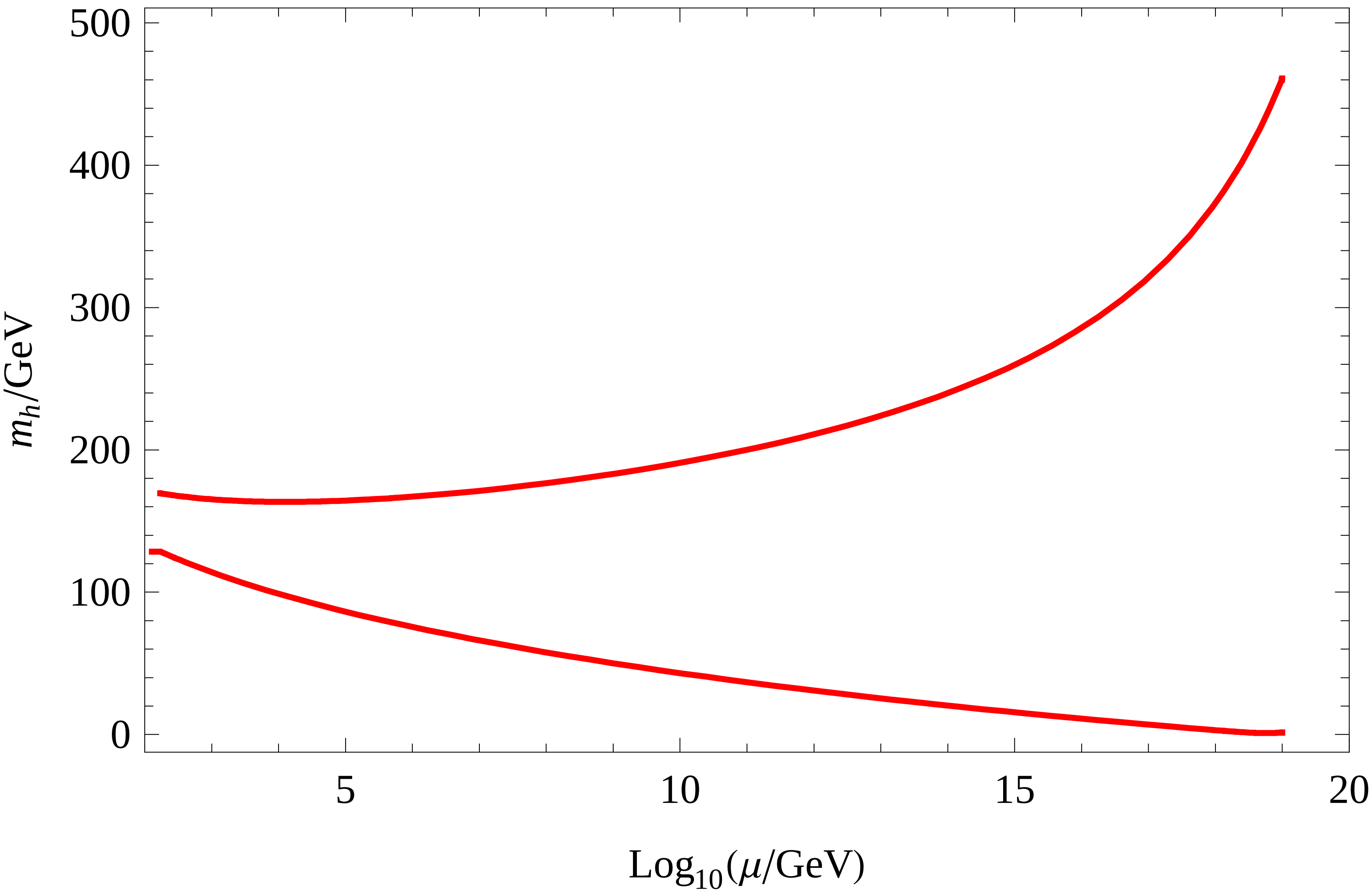
can be understood via RGE running of $\lambda(\mu)$

$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\beta_\lambda^{(1)} + \frac{1}{(16\pi^2)^2}\beta_\lambda^{(2)},$$

top Yukawa is important

$$\left\{\begin{array}{rcl}
\beta_\lambda^{(1)} & = & 12\lambda^2 - \left(\frac{9}{5}g_1^2 + 9g_2^2\right)\lambda + \frac{9}{4}\left(\frac{3}{25}g_1^4 + \frac{2}{5}g_1^2 g_2^2 + g_2^4\right) \underline{+ 12y_t^2\lambda - 12y_t^4}, \\
\beta_\lambda^{(2)} & = & -78\lambda^3 + 18\left(\frac{3}{5}g_1^2 + 3g_2^2\right)\lambda^2 - \left(\frac{73}{8}g_2^4 - \frac{117}{20}g_1^2 g_2^2 + \frac{2661}{100}g_1^4\right)\lambda - 3\lambda y_t^4 \\
& & + \frac{305}{8}g_2^6 - \frac{289}{40}g_1^2 g_2^4 - \frac{1677}{200}g_1^4 g_2^2 - \frac{3411}{1000}g_1^6 - 64g_3^2 y_t^4 - \frac{16}{5}g_1^2 y_t^4 - \frac{9}{2}g_2^4 y_t^2 \\
& & + 10\lambda\left(\frac{17}{20}g_1^2 + \frac{9}{4}g_2^2 + 8g_3^2\right)y_t^2 - \frac{3}{5}g_1^2\left(\frac{57}{10}g_1^2 - 21g_2^2\right)y_t^2 - 72\lambda^2 y_t^2 + 60y_t^6.
\end{array}\right.$$

The Standard Model Higgs



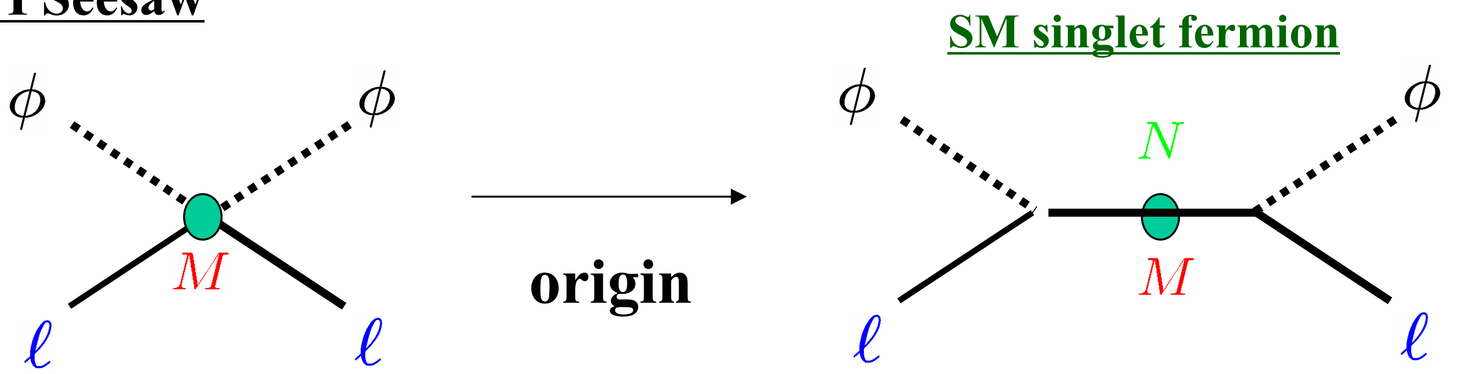
Physics beyond the SM required by:

- Neutrino Oscillations
  $$\left(\Delta m^2_{SM} \underset{\text{dim } 5}{\sim} 10^{-10} eV^2 \ll \Delta m^2_{ATM}, \Delta m^2_{SOL}\right)$$
  $\sum m_{\nu_i} \lesssim 1$ 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

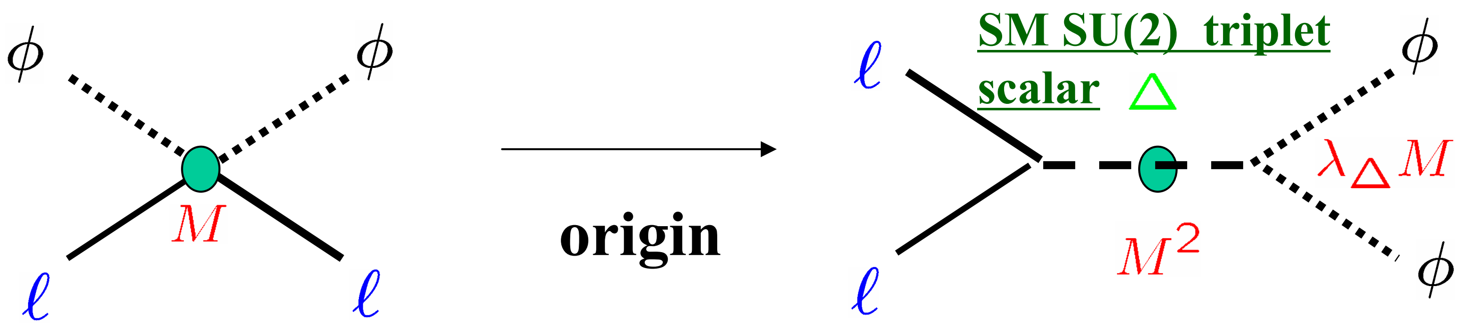
Additional Motivations

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

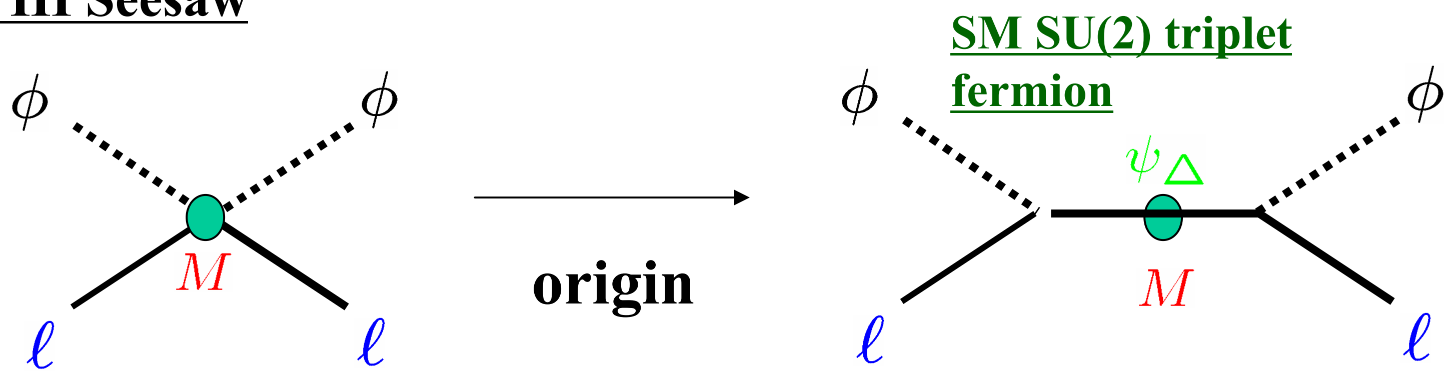
Type I Seesaw



Type II Seesaw



Type III Seesaw

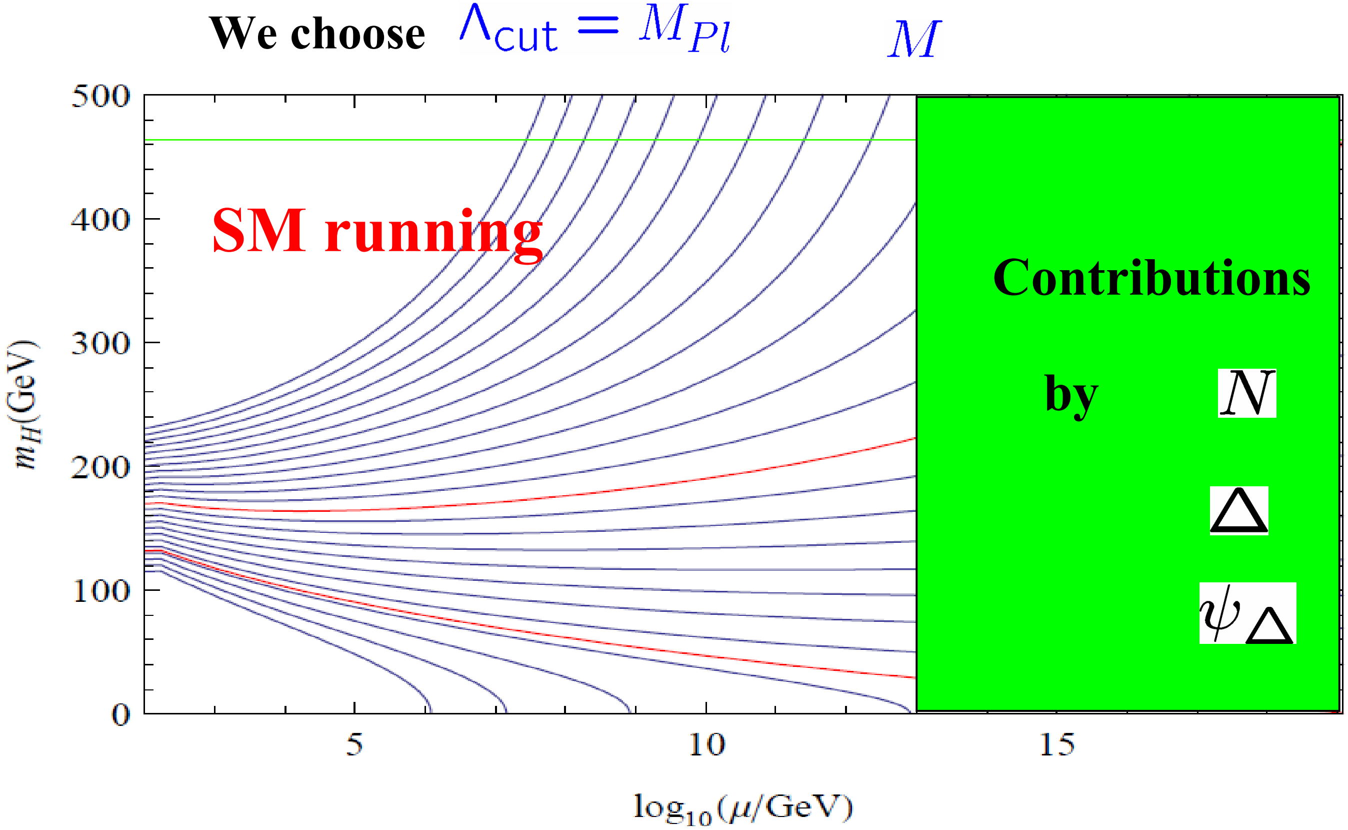


In all seesaw scenarios, new particles couple to Higgs doublet

→ **contribute to Higgs quartic RGE for** $\mu > M$

Running mass: $m_H(\mu) = \sqrt{\lambda} v$

We choose $\Lambda_{\text{cut}} = M_{Pl}$



: type I

: type II

: type III

Type I seesaw

Casas, Clemente, Ibarra & Quiros,

PRD 62, 053005 (2000);

Modification of RGEs in the presence of 3 singlet fermions (Okada, Gogoladze, QS)

with $\mathcal{L}_Y = y_\nu^{ij}\overline{\ell_i}\phi N_j$

For simplicity, we assume 3 degenerate N: $\mathbf{M} = M \times 1_{3\times 3}$

Light neutrino mass matrix: $\mathbf{M}_\nu = -\frac{1}{2}v^2 \mathbf{Y}_\nu^T \mathbf{M}^{-1}\mathbf{Y}_\nu = \frac{v^2}{2M}\mathbf{Y}_\nu^T\mathbf{Y}_\nu$

For $\mu < M$, **SM RGEs**

For $\mu \geq M$,

$$\frac{dy_t}{d\ln\mu} = y_t\left(\frac{1}{16\pi^2}\beta_t^{(1)} + \frac{1}{(16\pi^2)^2}\beta_t^{(2)}\right) \qquad \beta_t^{(1)} \rightarrow \beta_t^{(1)} + \boxed{\mathrm{tr}\,[\mathrm{S}_\nu]}$$

$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\beta_\lambda^{(1)} + \frac{1}{(16\pi^2)^2}\beta_\lambda^{(2)} \qquad \beta_\lambda^{(1)} \rightarrow \beta_\lambda^{(1)} \boxed{+\,4\ \mathrm{tr}[\mathrm{S}_\nu]\lambda - 4\ \mathrm{tr}[{\mathrm{S}_\nu}^2]}$$

$$\boxed{16\pi^2\frac{d\mathrm{S}_\nu}{d\ln\mu} = \mathrm{S}_\nu\left[6y_t^2 + 2\ \mathrm{tr}\,[\mathrm{S}_\nu] - \left(\frac{9}{10}g_1^2 + \frac{9}{2}g_2^2\right) + 3\ \mathrm{S}_\nu\right]} \qquad \mathrm{S}_\nu = \mathbf{Y}_\nu^\dagger\mathbf{Y}_\nu$$

*** We employ 2-loop SM RGEs + 1-loop new RGEs**

Fixing the cutoff scale M_{Pl}, we investigate <u>Higgs mass bounds</u>

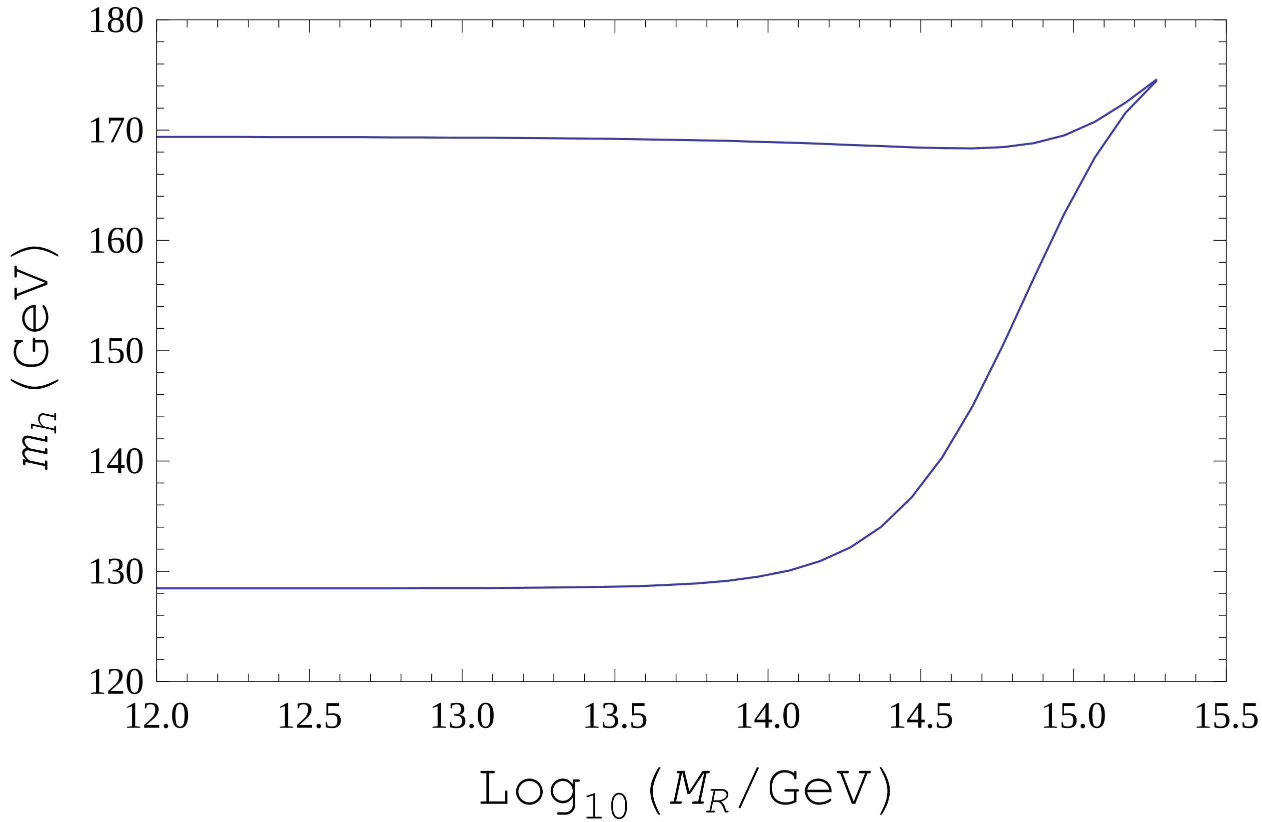
<u>Vacuum stability bound</u>: the lowest Higgs boson mass which satisfies

$\lambda(\mu) \geq 0$ **for any scale between** $M_H \leq \mu \leq M_{Pl}$

<u>Perturbativity bound</u>: the highest Higgs boson mass which satisfies

$\lambda(\mu) \leq \sqrt{4\pi}$ **for any scale between** $M_H \leq \mu \leq M_{Pl}$

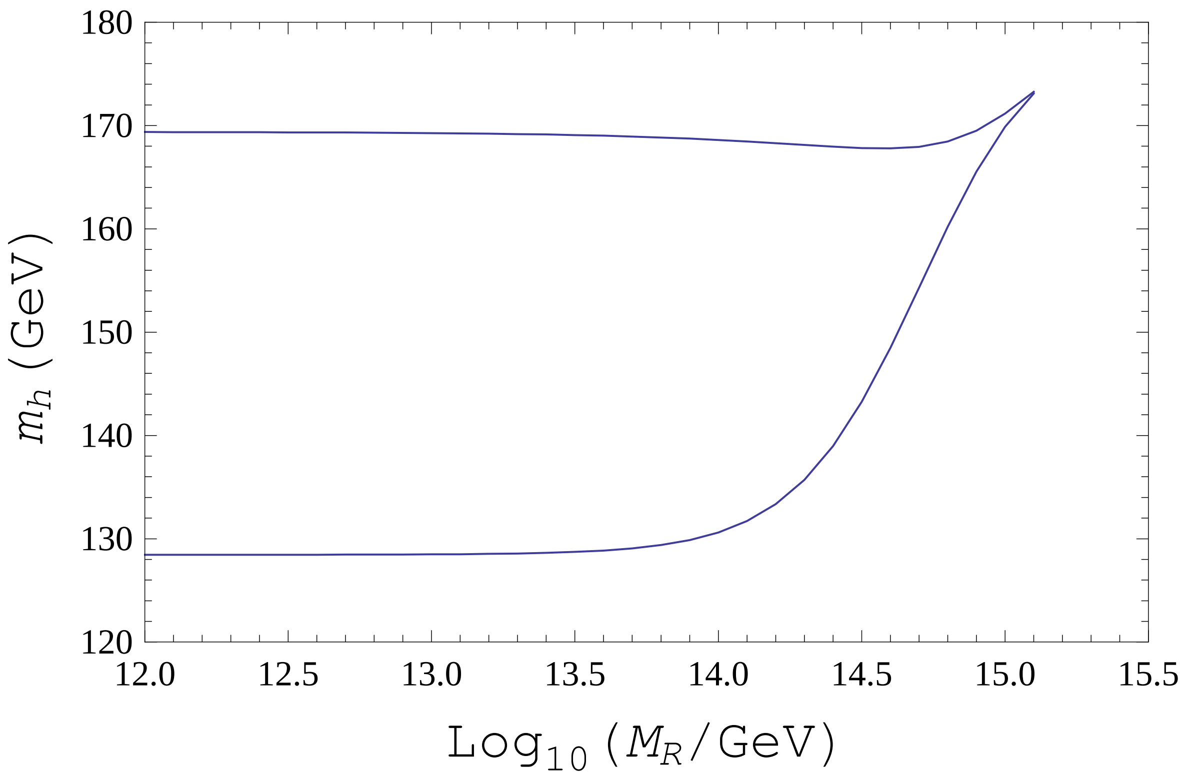
Type I Seesaw and Higgs Mass Bounds



Higgs boson mass bound as a function of M_R in the case with hierarchical mass spectrum. The lower and upper lines correspond to the stability and triviality bounds, respectively. The Higgs boson mass range is closed for $M_R = 1.86 \times 10^{15}$ GeV, where $m_h = 175$ GeV.

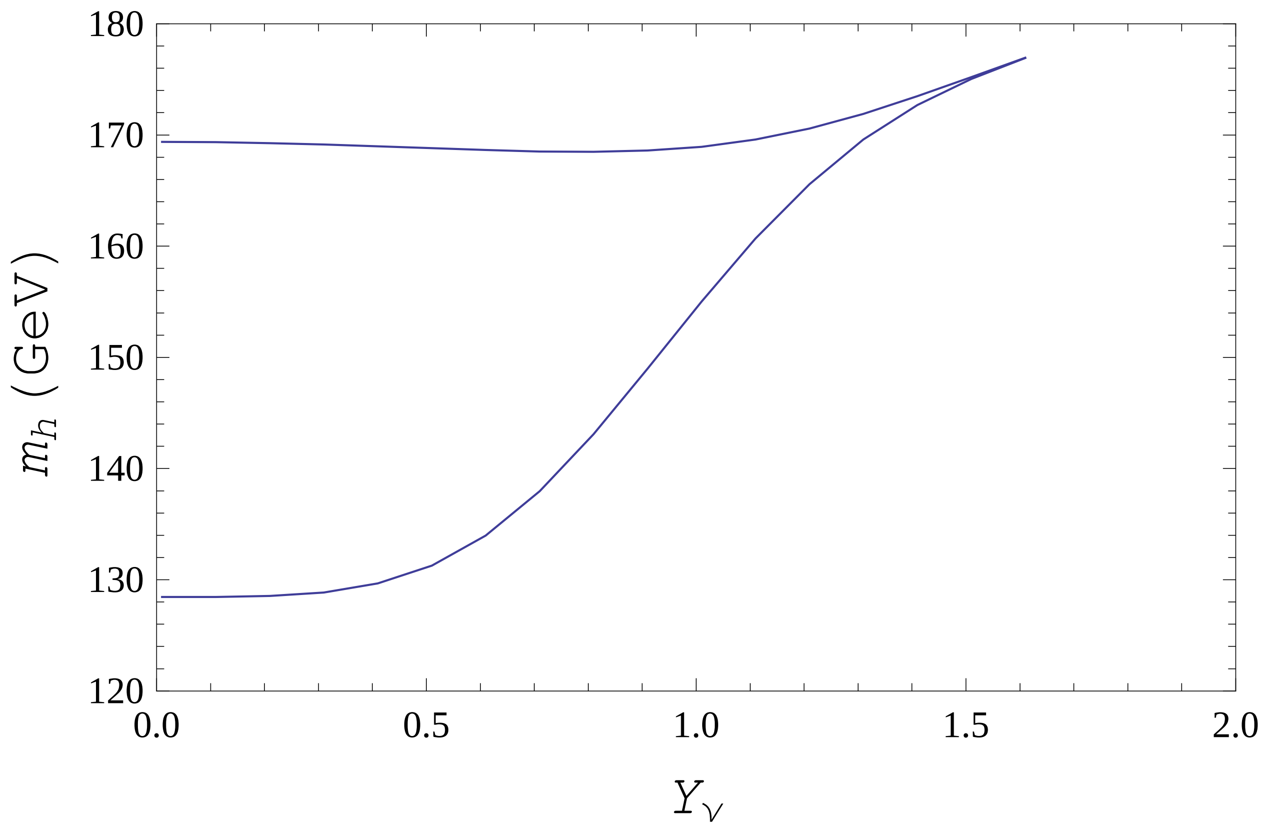
Casas et. al. (hep-ph/9904295); Gogoladze et.al. (unpublished).

Type I Seesaw and Higgs Mass Bounds



Higgs boson mass bound as a function of M_R in the case with inverted-hierarchical mass spectrum. The lower and upper lines correspond to the stability and triviality bounds, respectively. The Higgs boson mass range is closed for $M_R = 1.26 \times 10^{15}$ GeV, where $m_h = 173$ GeV.

Type I Seesaw and Higgs Mass Bounds



Higgs boson mass bound as a function of Y_ν. The lower and upper lines correspond to the stability and triviality bounds, respectively. The limit $Y_\nu = 0$ reproduces the SM result. The Higgs boson mass range is closed for $Y_\nu \simeq 1.6$.

Type II seesaw

Gogoladze, N.O. &Shafi,

arXive: 0802.3257 [hep-ph]

We introduce a triplet scalar field

$$\Delta : (\mathbf{3}, 1) \text{ under } SU(2)_L \times U(1)_Y$$

$$\Delta = \frac{\sigma^i}{\sqrt{2}}\Delta_i = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

Scalar potential

$$\begin{aligned} V(\Delta,\phi) &= -m_\phi^2(\phi^\dagger\phi) + \frac{\lambda}{2}(\phi^\dagger\phi)^2 \\ &+ M_\Delta^2 \mathrm{tr}\left(\Delta^\dagger\Delta\right) + \frac{\lambda_1}{2}\left(\mathrm{tr}\Delta^\dagger\Delta\right)^2 + \frac{\lambda_2}{2}\left[\left(\mathrm{tr}\Delta^\dagger\Delta\right)^2 - \mathrm{tr}\left(\Delta^\dagger\Delta\Delta^\dagger\Delta\right)\right] \\ &+ \lambda_4\phi^\dagger\phi\ \mathrm{tr}\left(\Delta^\dagger\Delta\right) + \lambda_5\phi^\dagger\left[\Delta^\dagger,\Delta\right]\phi + \left[\frac{\Lambda_6}{\sqrt{2}}\phi^T i\sigma_2\Delta^\dagger\phi + \mathrm{h.c.}\right], \end{aligned}$$

Many new couplings: $\lambda_1, \lambda_2, \lambda_4, \lambda_5$

$$\Lambda_6 = \lambda_6 M_\Delta$$

Neutrino Yukawa coupling: $\boxed{\mathcal{L}_\Delta = -\frac{1}{\sqrt{2}} (Y_\Delta)_{ij}\, \ell_L^{Ti} C i\sigma_2 \Delta \ell_L^j + \text{h.c.}},$

$\langle\phi\rangle = \frac{v}{\sqrt{2}}$ → **Tadpole term for the triplet scalar**

→ $\langle\Delta\rangle \sim \frac{\lambda_6 v^2}{M_\Delta}$

Neutrino mass: $\mathrm{M}_\nu = \frac{v^2}{2}\frac{\mathbf{Y}_\Delta \lambda_6}{M_\Delta}$

After integrating out the heavy triplet, we have

$$V(\phi)_{\text{eff}} = -m_\phi^2(\phi^\dagger\phi) + \frac{1}{2}\left(\lambda - \lambda_6^2\right)(\phi^\dagger\phi)^2$$

SM Higgs quartic is defined as $\boxed{\lambda_{\text{SM}} = \lambda - \lambda_6^2}$

Now we solve RGEs in the presence of Type II seesaw

Many free parameters: $\lambda, \lambda_1, \lambda_2, \lambda_4, \lambda_5, \lambda_6, Y_\triangle$

For $\mu < M_\triangle$, **SM RGEs**

For $\mu \geq M_\triangle$,

$$\frac{dg_i}{d\ln\mu} = \frac{b_i}{16\pi^2} g_i^3 + \frac{g_i^3}{(16\pi^2)^2}\left(\sum_{j=1}^{3} B_{ij} g_j^2 - C_i y_t^2\right)$$

$$b_i = \left(\frac{41}{10}, -\frac{19}{6}, -7\right) \rightarrow b_i = \left(\boxed{\frac{47}{10}, -\frac{5}{2}}, -7\right)$$

$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\beta_\lambda^{(1)} + \frac{1}{(16\pi^2)^2}\beta_\lambda^{(2)} \qquad \beta_\lambda^{(1)} \longrightarrow \beta_\lambda^{(1)} \boxed{+ 6\lambda_4^2 + 4\lambda_5^2}$$

with the matching condition: $\boxed{\lambda_{\rm SM} = \lambda - \lambda_6^2}$

*** We employ 2-loop SM RGEs + 1-loop new RGEs**

$$
\begin{aligned}
16\pi^2 \frac{d\lambda_1}{d\ln\mu} &= -\left(\frac{36}{5}g_1^2 + 24g_2^2\right)\lambda_1 + \frac{108}{25}g_1^4 + 18g_2^4 + \frac{72}{5}g_1^2 g_2^2 \\
&\quad +14\lambda_1^2 + 4\lambda_1\lambda_2 + 2\lambda_2^2 + 4\lambda_4^2 + 4\lambda_5^2 + 4\mathrm{tr}\left[\mathrm{S}_\Delta\right]\lambda_1 - 8\mathrm{tr}\left[\mathrm{S}_\Delta^2\right], \\
16\pi^2 \frac{d\lambda_2}{d\ln\mu} &= -\left(\frac{36}{5}g_1^2 + 24g_2^2\right)\lambda_2 + 12g_2^4 - \frac{144}{5}g_1^2 g_2^2 \\
&\quad +3\lambda_2^2 + 12\lambda_1\lambda_2 - 8\lambda_5^2 + 4\mathrm{tr}\left[\mathrm{S}_\Delta\right]\lambda_2 + 8\mathrm{tr}\left[\mathrm{S}_\Delta^2\right], \\
16\pi^2 \frac{d\lambda_4}{d\ln\mu} &= -\left(\frac{9}{2}g_1^2 + \frac{33}{2}g_2^2\right)\lambda_4 + \frac{27}{25}g_1^4 + 6g_2^4 \\
&\quad + \left(8\lambda_1 + 2\lambda_2 + 6\lambda + 4\lambda_4 + 6y_t^2 + 2\mathrm{tr}\left[\mathrm{S}_\Delta\right]\right)\lambda_4 + 8\lambda_5^2 - 4\mathrm{tr}\left[\mathrm{S}_\Delta^2\right], \\
16\pi^2 \frac{d\lambda_5}{d\ln\mu} &= -\frac{9}{2}g_1^2\lambda_5 - \frac{33}{2}g_2^2\lambda_5 - \frac{18}{5}g_1^2 g_2^2 \\
&\quad + \left(2\lambda_1 - 2\lambda_2 + 2\lambda + 8\lambda_4 + 6y_t^2 + 2\mathrm{tr}\left[\mathrm{S}_\Delta\right]\right)\lambda_5 + 4\mathrm{tr}\left[\mathrm{S}_\Delta^2\right].
\end{aligned}
$$

$$
16\pi^2 \frac{d\mathrm{S}_\Delta}{d\ln\mu} = 6\,\mathrm{S}_\Delta^2 - 3\left(\frac{3}{5}g_1^2 + 3g_2^2\right)\mathrm{S}_\Delta + 2\mathrm{tr}[\mathrm{S}_\Delta]\mathrm{S}_\Delta \qquad \mathrm{S}_\Delta = Y_\Delta^\dagger Y_\Delta
$$

RGE of λ_6 is decoupled from other RGEs, but plays an important role through the matching condition

Analysis is quite involved…..

We focus on most important parameters: $\lambda_4, \lambda_5, \lambda_6$

λ_4, λ_5 **appear in Higgs quartic RGE**

λ_6 **shifts Higgs quartic coupling @** $M_\triangle$ **by the matching condition**

We analyze RGEs for various λ_6 **at the cutoff with others fixed**
λ_5

Fixing the cutoff scale M_{Pl}**, we investigate <u>Higgs mass bounds</u>**

<u>Vacuum stability bound</u>: the lowest Higgs boson mass which satisfies

$\lambda(\mu) \geq 0$ **for any scale between** $M_H \leq \mu \leq M_{Pl}$

<u>Perturbativity bound</u>: the highest Higgs boson mass which satisfies

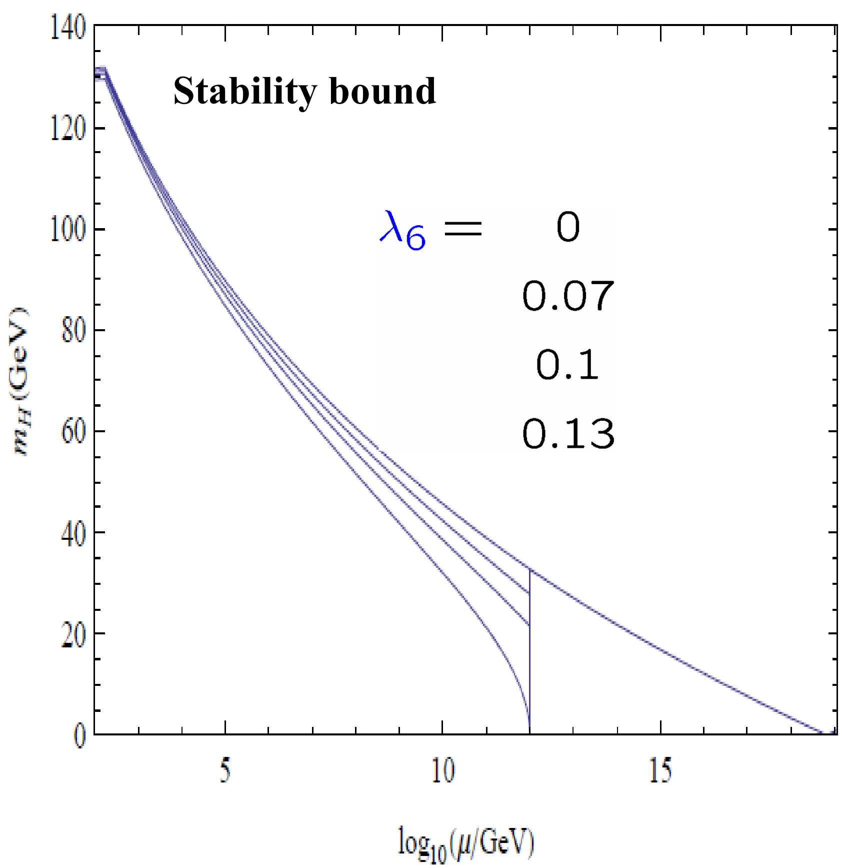
$\lambda(\mu) \leq \sqrt{4\pi}$ **for any scale between** $M_H \leq \mu \leq M_{Pl}$

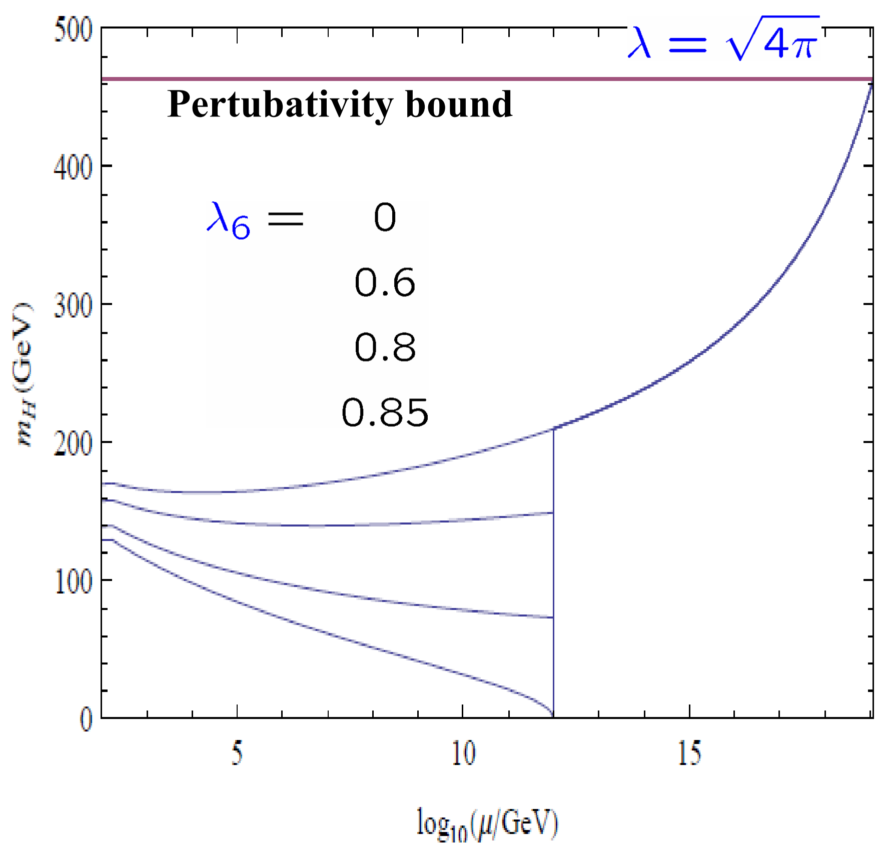
Sample: $\lambda_1 = \sqrt{4\pi}$, $\lambda_2 = -1$, $\lambda_4 = \lambda_5 = 0$ and $Y_\Delta = 0$

$M_\Delta = 10^{12}$ GeV

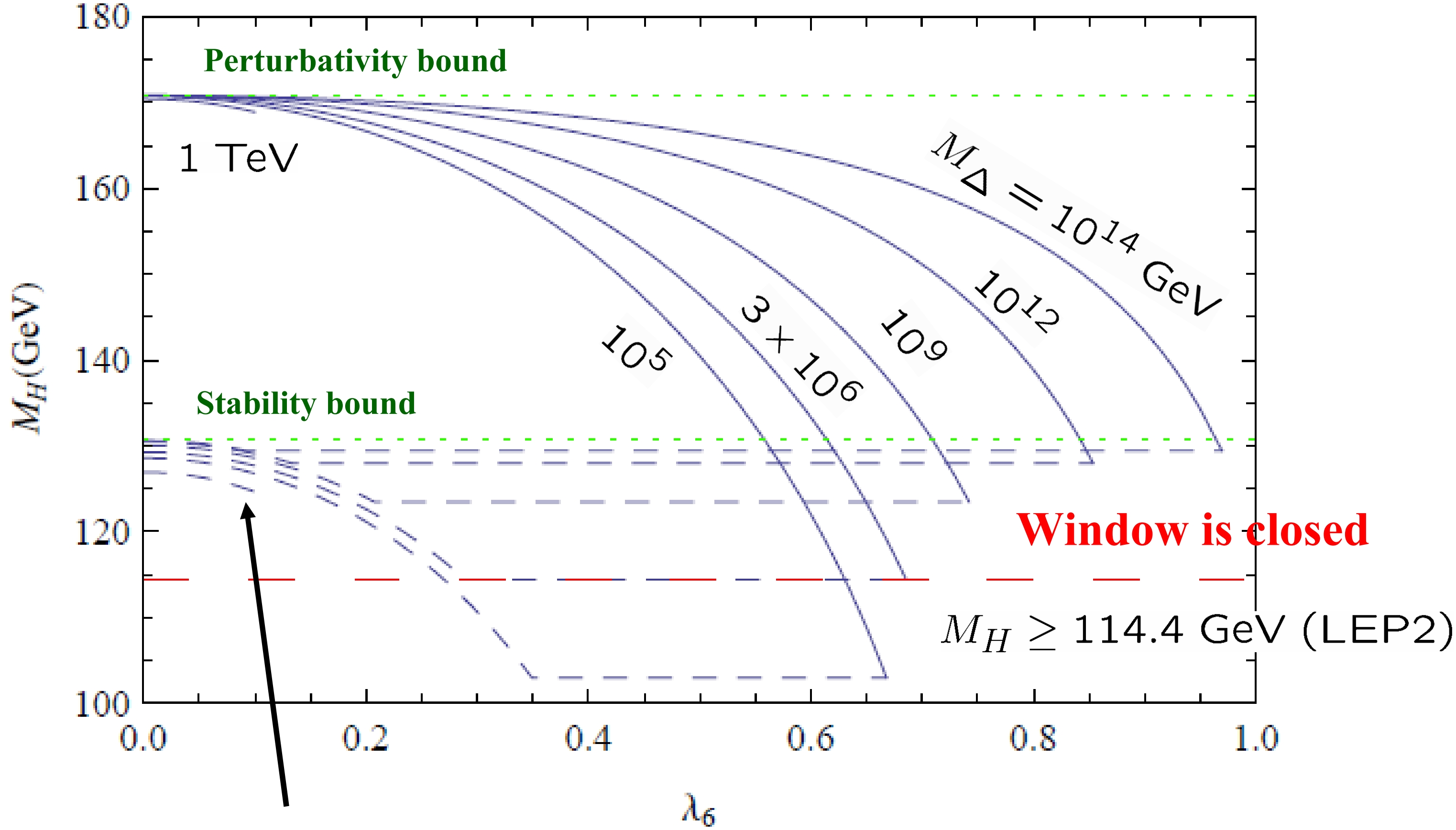
Input: top quark pole mass = 172.6 GeV

Running Higgs mass





Higgs mass bounds versus λ_6 for various M_Δ



ρ parameter constraint

$$\langle\Delta\rangle \sim \lambda_6 v^2/M_\Delta$$

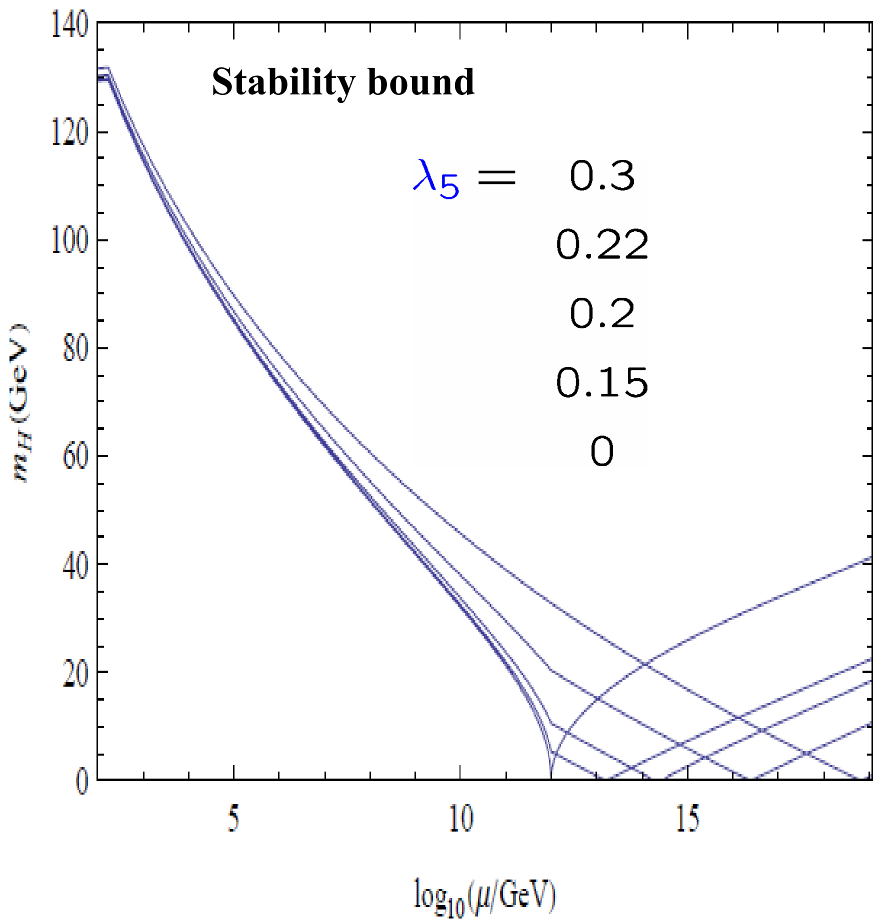
$$\Delta\rho = \rho - 1 \simeq \langle\Delta\rangle/v \lesssim 0.01 \quad \rightarrow \quad \lambda_6 \lesssim 0.01 M_\Delta/v.$$

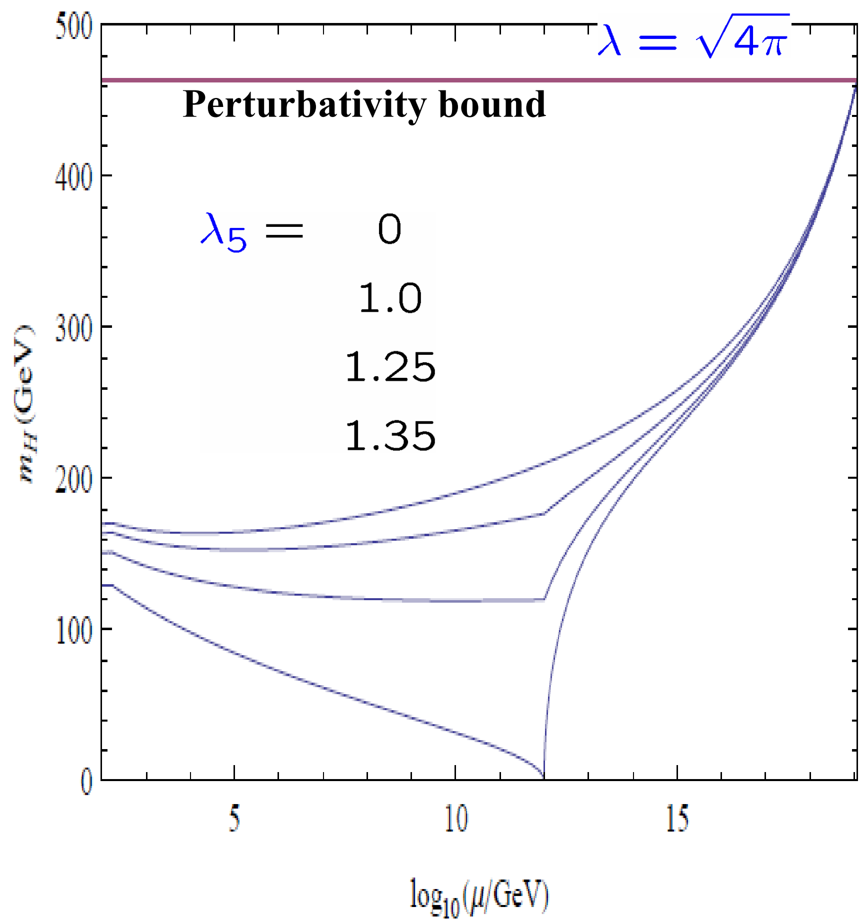
Sample: $\lambda_1 = \sqrt{4\pi},\ \lambda_2 = -1,\ \lambda_4 = 0,\ \Lambda_6 = 0$ and $Y_\Delta = 0.$

$M_\Delta = 10^{12}$ GeV

Input: top quark pole mass = 172.6 GeV

Running Higgs mass





Sample: $\lambda_1 = \sqrt{4\pi},\ \lambda_2 = -1,\ \lambda_4 = 0,\ \Lambda_6 = 0$ and $Y_\Delta = 0.$

$M_\Delta = 10^{12}$ GeV

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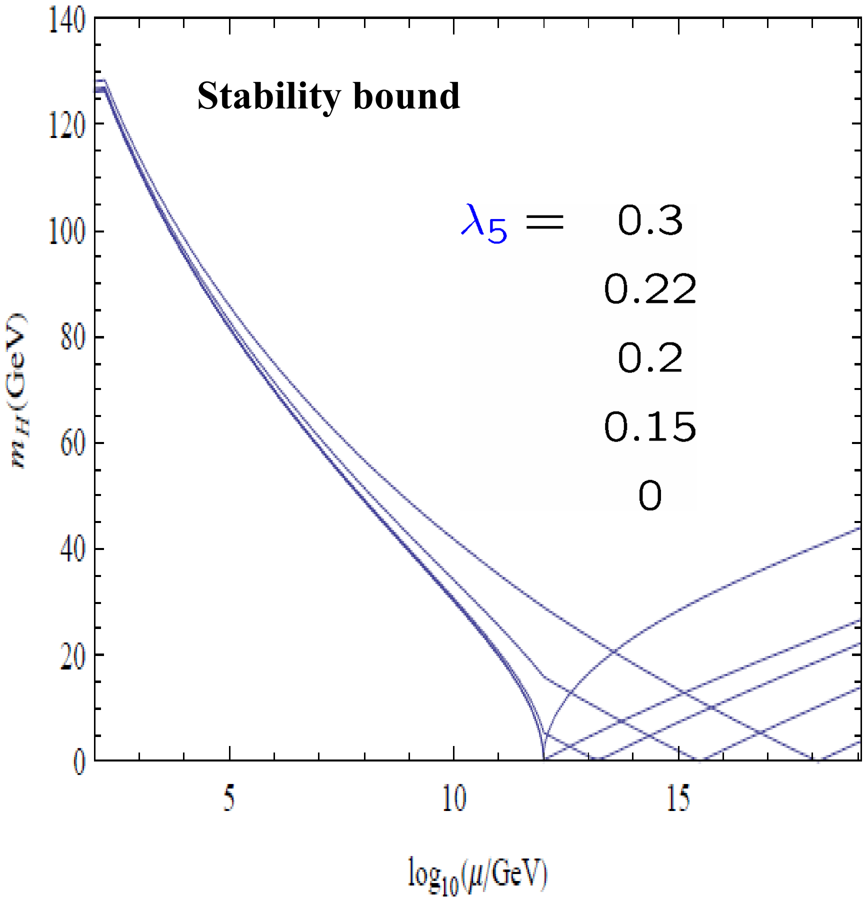
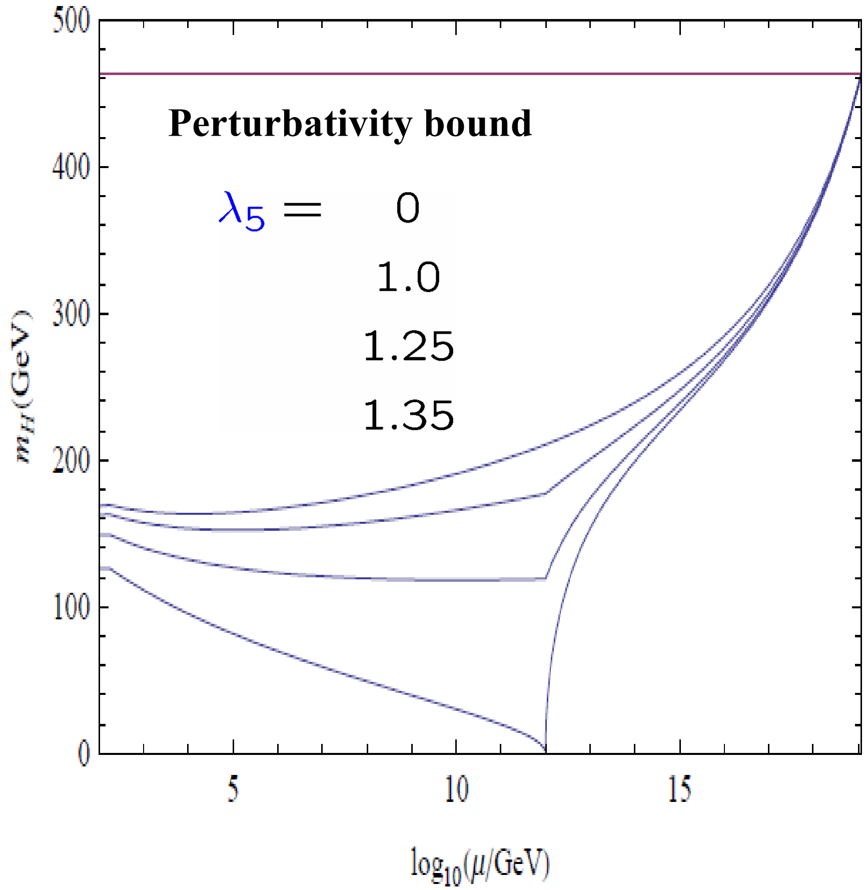
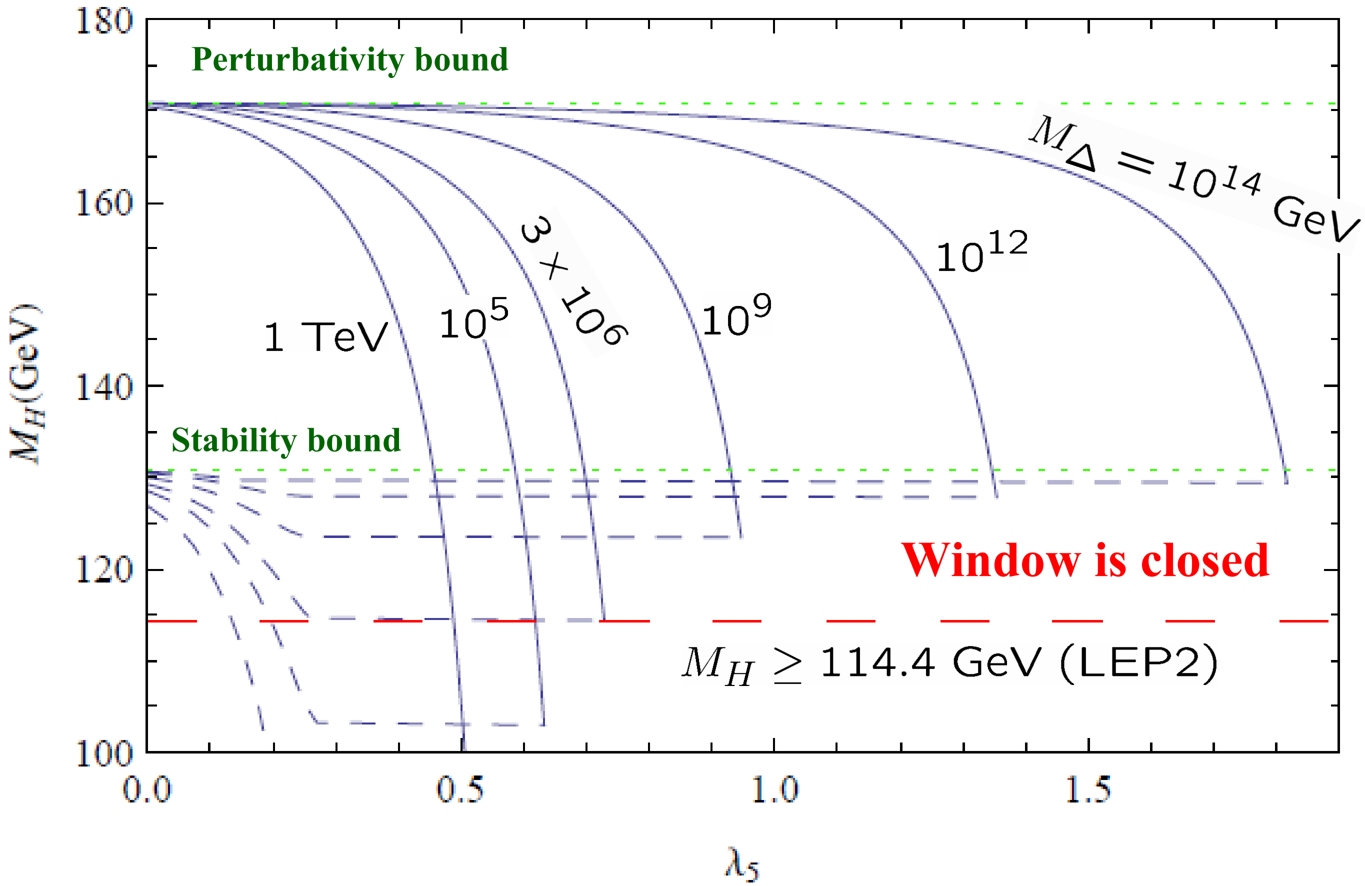
Running Higgs mass





Higgs mass bounds versus λ_5 for various $M_\triangle$



Type III Seesaw and Higgs Mass

- Introduce 3 generations of fermions ψ_i ($i = 1, 2, 3$), which transform as $(\mathbf{3}, 0)$ under the electroweak gauge group SU(2)$_L\times$U(1)$_Y$:

$$\psi_i = \sum_a \frac{\sigma^a}{2}\psi_i^a = \frac{1}{2}\begin{pmatrix} \psi_i^0 & \sqrt{2}\psi_i^+ \\ \sqrt{2}\psi_i^- & -\psi_i^0 \end{pmatrix}.$$

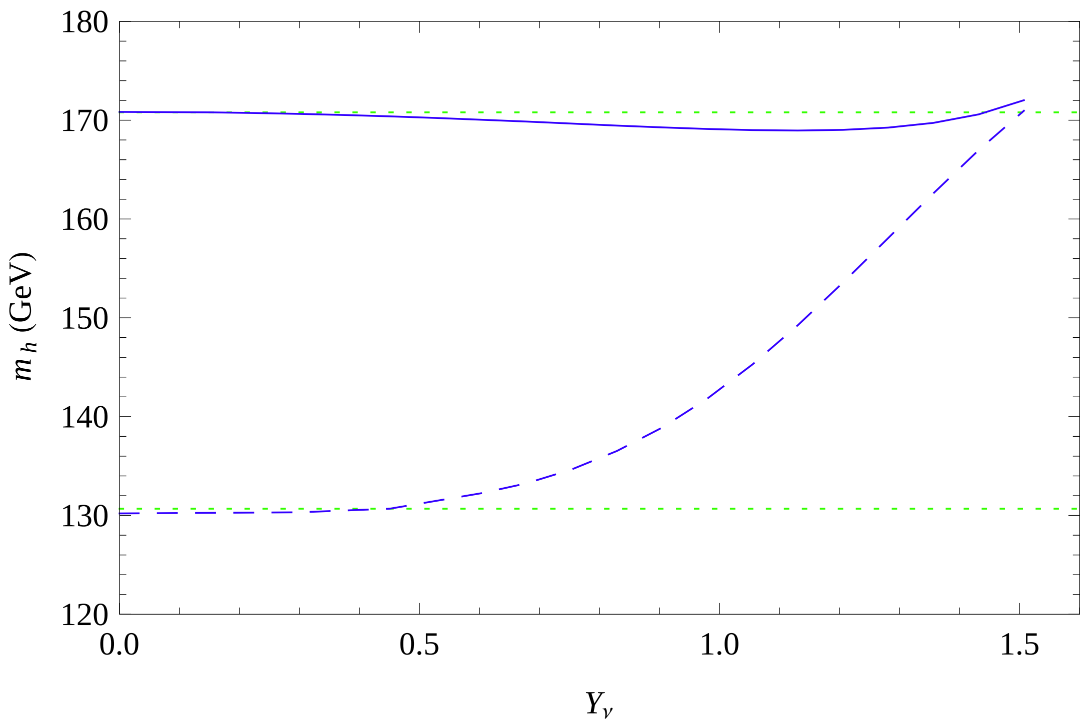
- With canonically normalized kinetic terms for the triplet fermions, we introduce the Yukawa coupling

$$\mathcal{L}_Y = y_{ij}\overline{\ell_i}\psi_j\Phi,$$

where Φ is the Higgs doublet.

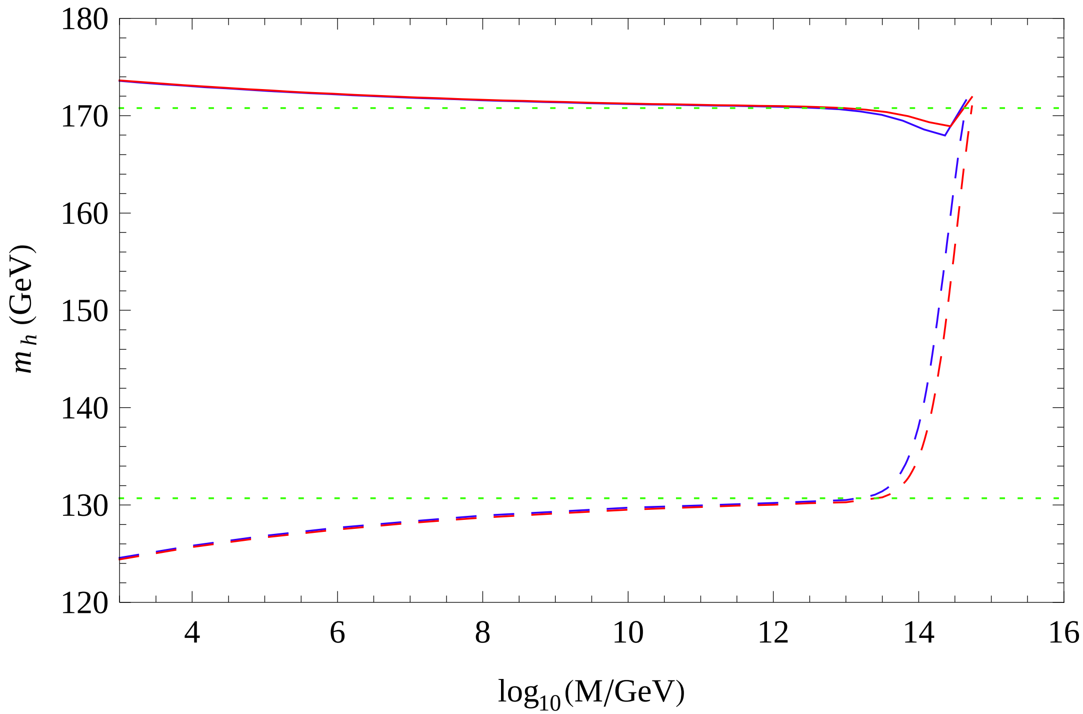
Type III Seesaw and Higgs Mass

Gogoladze, Okada, Q.S



Perturbativity (solid) and vacuum stability (dashed) bounds on the Higgs boson pole mass (m_h) versus Y_ν with the seesaw scale $M = 10^{13}$ GeV. The upper and lower dotted lines respectively show the perturbativity bound ($m_h \simeq$171 GeV) and the vacuum stability bound ($m_h \simeq$131 GeV) in the SM case.

Type III Seesaw and Higgs Mass

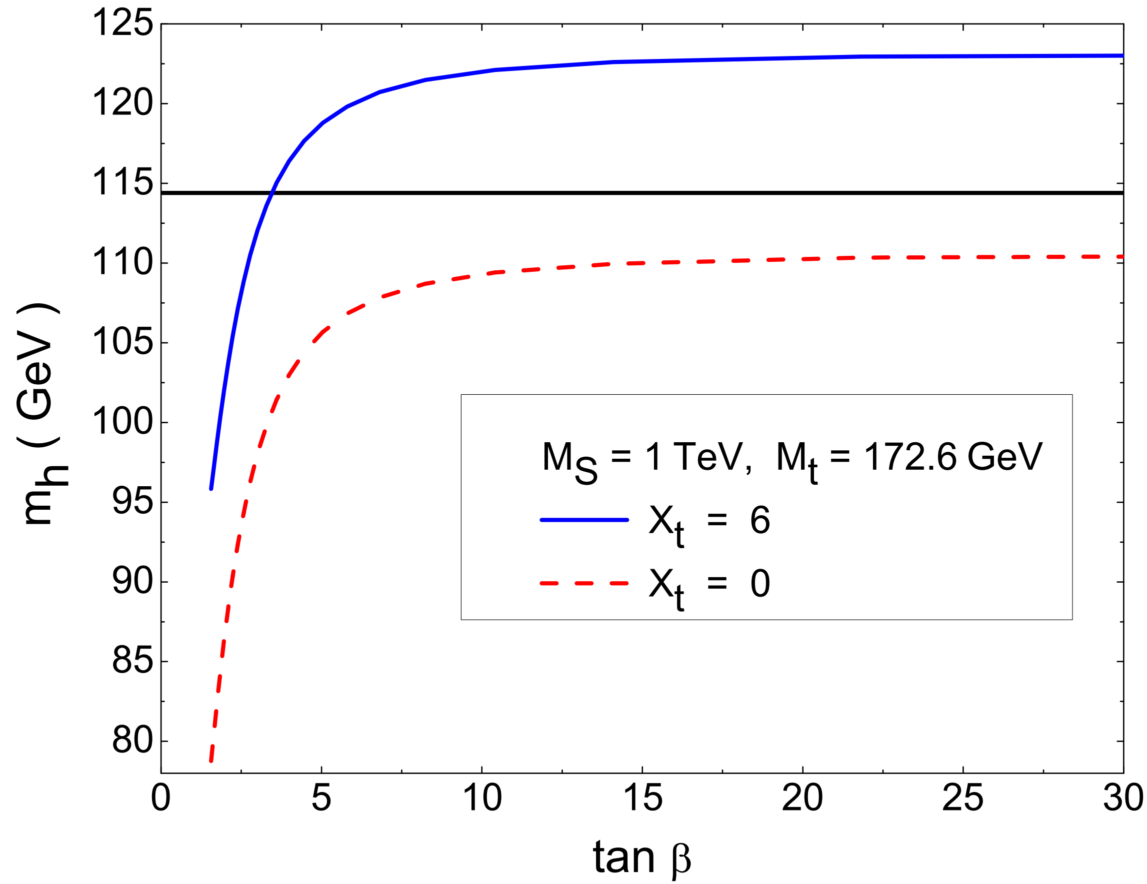


Perturbativity and vacuum stability bounds versus M, with a hierarchical mass spectrum (outer region in red), and an inverted-hierarchical mass spectrum (inner region in blue).

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



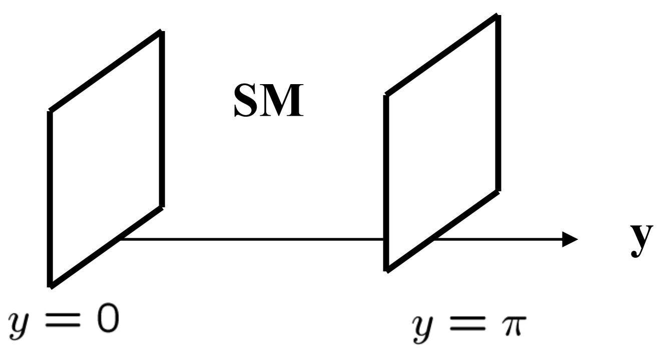
WARPED EXTRA DIMENSION

- 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: $M_P \rightarrow \text{TeV}^2/M_P \; (\sim 10^{-3}\text{eV})$
- KK excitations at LHC?

Gauge-Higgs Unification

Bulk Standard Model

5-dim. theory compactified on orbifold S^1/Z_2



All SM fields reside in the bulk

Higgs boson associated with 5th component of gauge fields in higher dimension

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[9] M. Sakamoto and K. Takenaga, Phys. Rev. D **75**, 045015 (2007).

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[11] For example, see G. Cacciapaglia, C. Csaki and S. C. Park, JHEP **0603**, 099 (2006), and references therein.

$$SU(3) \supset SU(2) \times U(1)$$

$$\text{SU(3) gauge} = \left(\begin{array}{c:c} \begin{array}{c} SU(2) \\ \textbf{adj} \end{array} & \textbf{doublet} \\ \hdashline \textbf{doublet} & \textbf{singlet} \end{array}\right)$$

Impose non-trivial boundary conditions (parity assignment)

$$A_\mu = \left(\begin{array}{c|c} W_\mu + B_\mu & X_\mu \\ \hline X_\mu^\dagger & B_\mu \end{array}\right) \qquad A_5 = \left(\begin{array}{c|c} W_5 + B_5 & H \\ \hline H^\dagger & B_5 \end{array}\right)$$

are Z2 even fields, others odd fields

Zero modes for odd fields are project out,

So SU(3) is broken to SU(2) X U(1) by this parity assignment

5th component of 5dim gauge field → scalar in 4D theories

We identify ``H" as Higgs doublet in the SM → gauge-Higgs unification

$$\mathcal{L}_5^{gauge} = -\frac{1}{4}F^{aMN}F^a_{MN} = -\frac{1}{4}F^{a\mu\nu}F^a_{\mu\nu} + \frac{1}{2}F_5^{a\mu}F^a_{5\mu}$$

$$\frac{1}{2}F_5^{a\mu}F^a_{5\mu} \to (D_\mu H)^\dagger (D_\mu H)$$

$$H : (2, +1/2)$$

Kinetic term for Higgs is included as 5dim SU(3) gauge interaction

5 dimensional gauge symmetry → No mass and quartic coupling @ tree

Phenomenologically interesting observation ``Gauge-Higgs Condition"

→ realization of gauge-Higgs unification at UV

is equivalent to imposing ``vanishing quartic Higgs couping"

at $\Lambda_{cut} = 1/(2\pi R)$

Haba, Matsumoto, N.O.&Yamashita, JHEP 0602, 073 (2006)

Application of the guage-Higgs condition

UV completion of the SM by (5D) gauge-Higgs unification

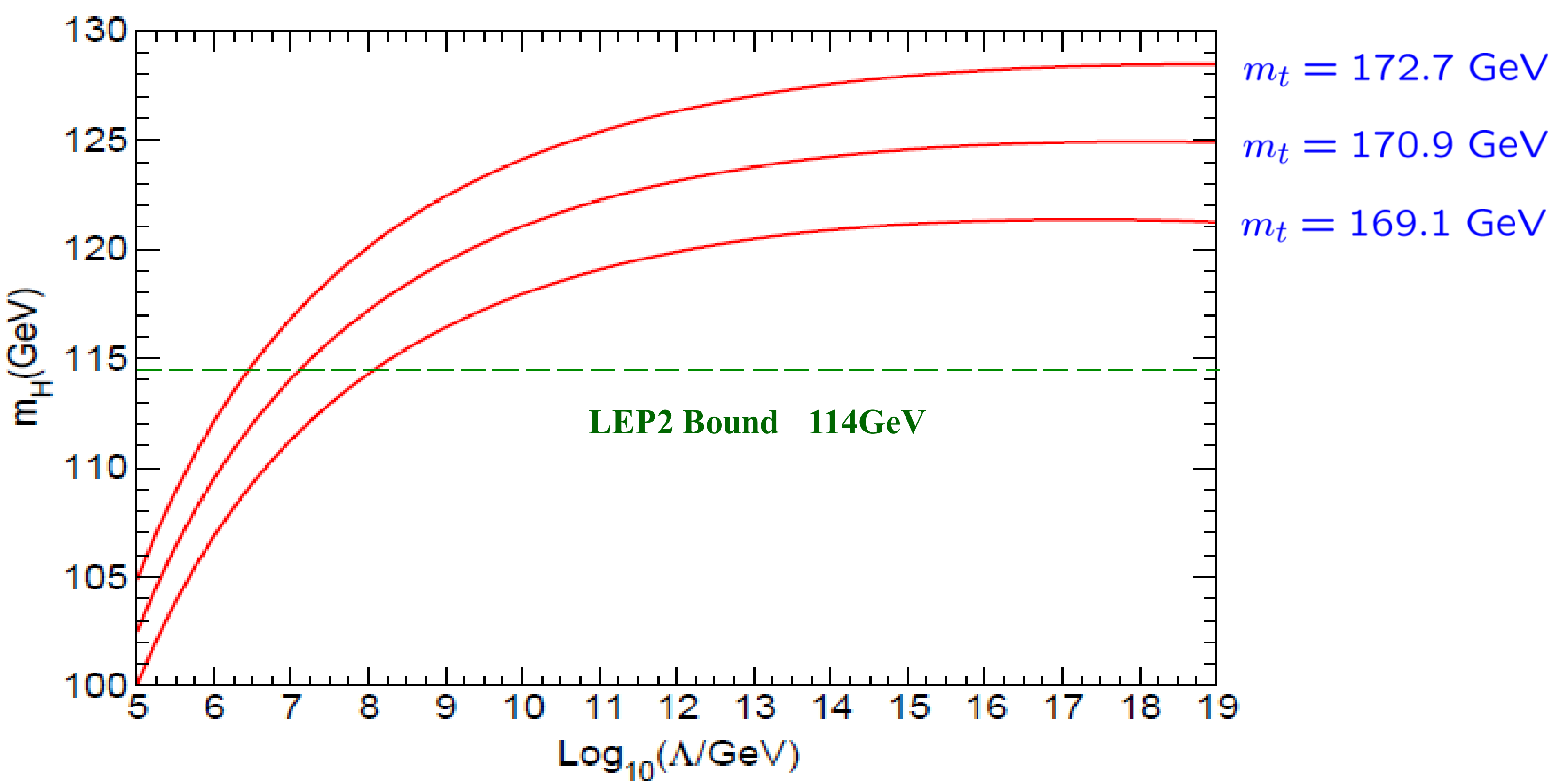
→Higgs boson mass prediction

as a function of the compactification scale

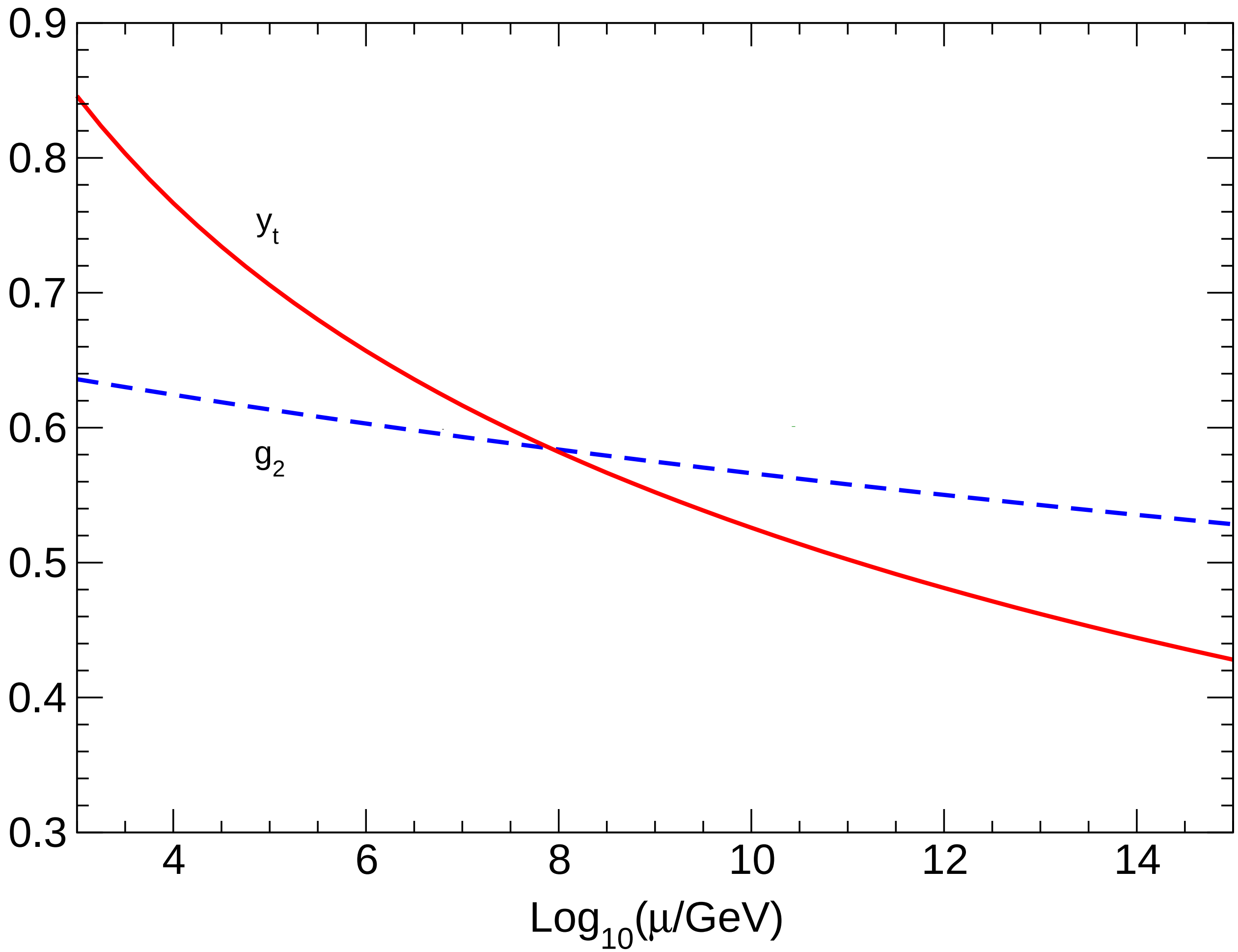
by imposing the condition $\lambda_H(\Lambda) = 0$

Gogoladze, N.O. & Shafi

Phys. Lett. B, 257 (2007)



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

Standard Model (SM) + Einstein' GR

$\Rightarrow$ Hot Big Bang Cosmology

Predictions

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

54-1

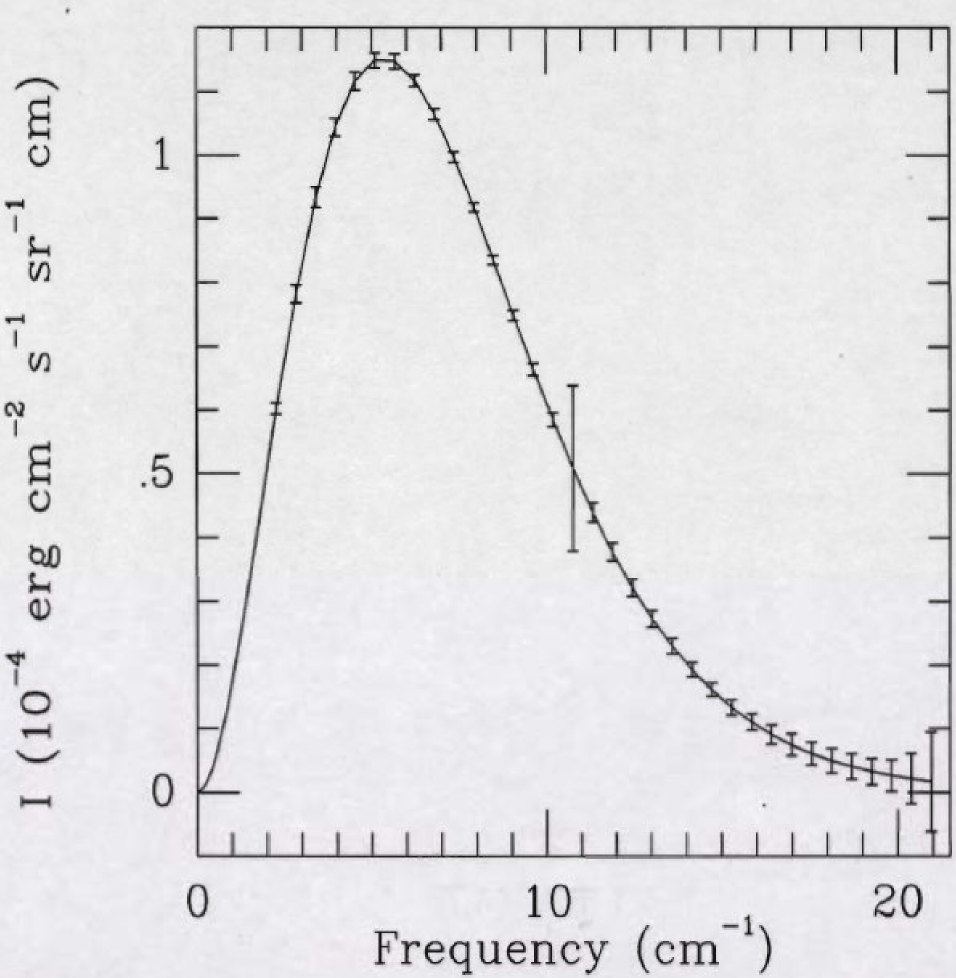
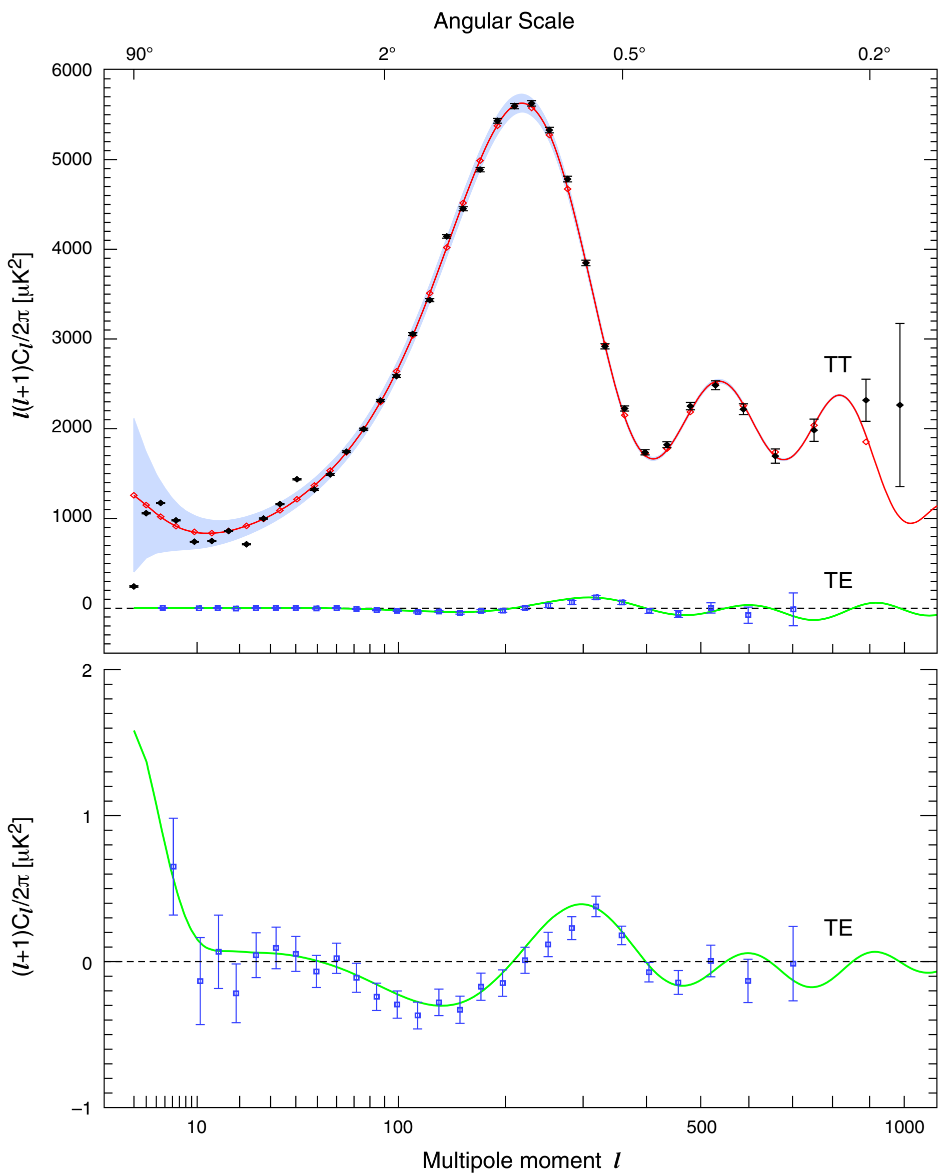


Figure 4: Spectrum of the Cosmic Microwave Background Radiation as measured by the FIRAS instrument on COBE and a black body curve for $T = 2.7277\,\text{K}$. Note, the error flags have been enlarged by a factor of 400. Any distortions from the Planck curve are less than 0.005% (see Fixsen *et al.* ,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


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

Inflationary Cosmology

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

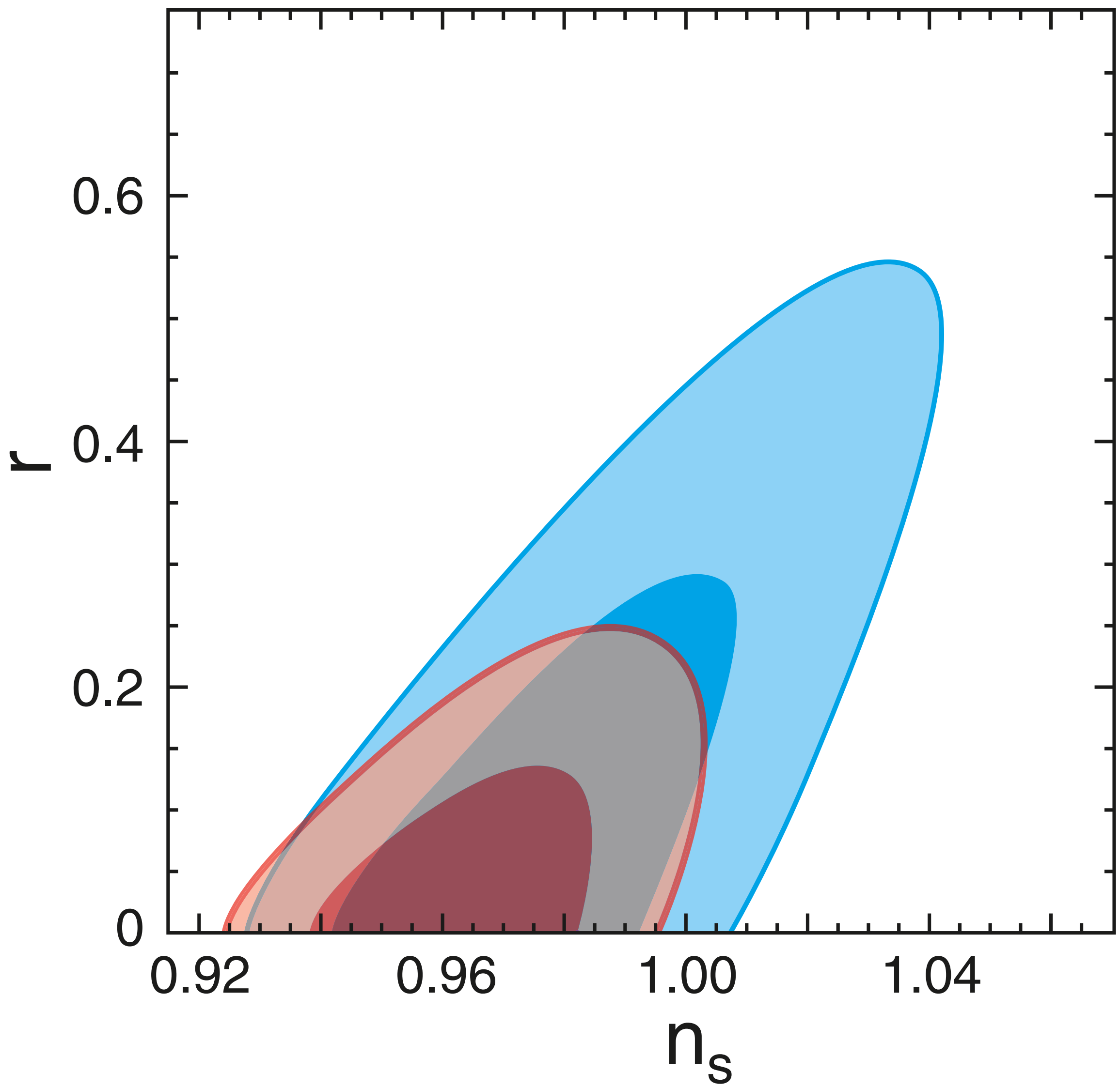
Inflationary Cosmology

- 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-5 yields $n_s = 0.96 \pm 0.014$

(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, Q.S....)
  - Compactification (Arkani Hamed et.al, ..., Schmidt et.al,....)
  - Quintessence/Inflation

Quartic (CW) Potential (non-susy)

Q.S, Vilenkin;Senoguz

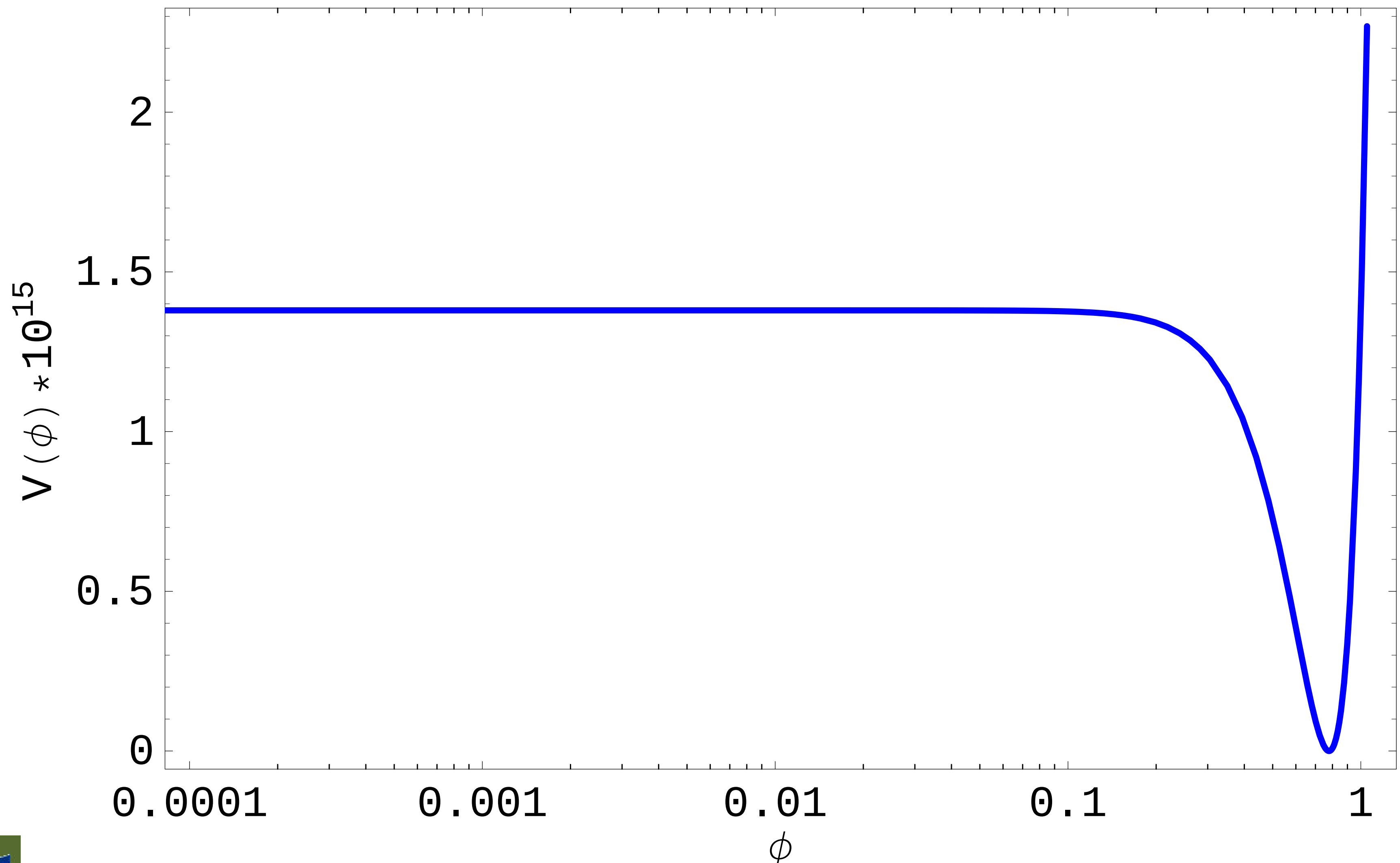
$$V(\phi) = A\phi^4 \left(ln\left(\frac{\phi}{M}\right) - \frac{1}{4}\right) + \frac{AM^4}{4}$$

$\phi =$ 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)



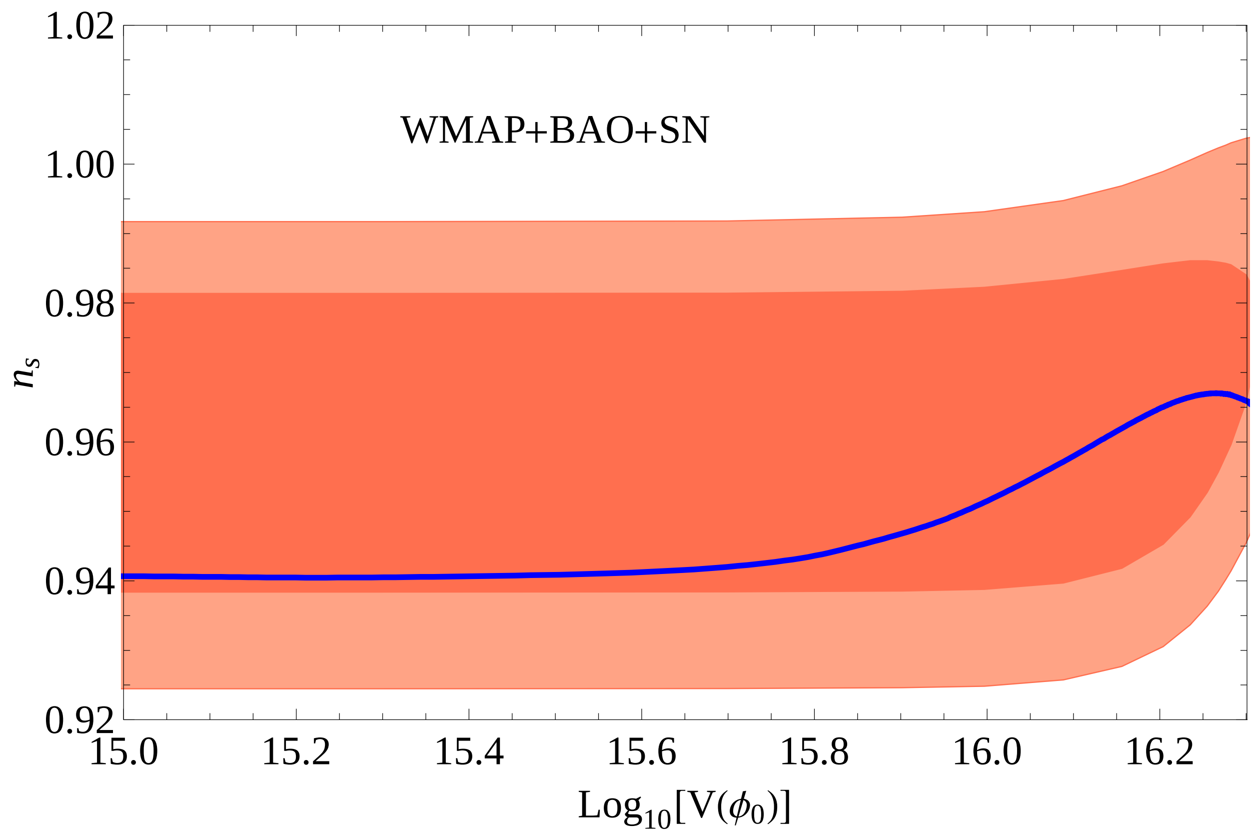
Quartic (CW) Potential (non-susy)

- 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 $k_0 = 0.002 Mpc^{-1}$

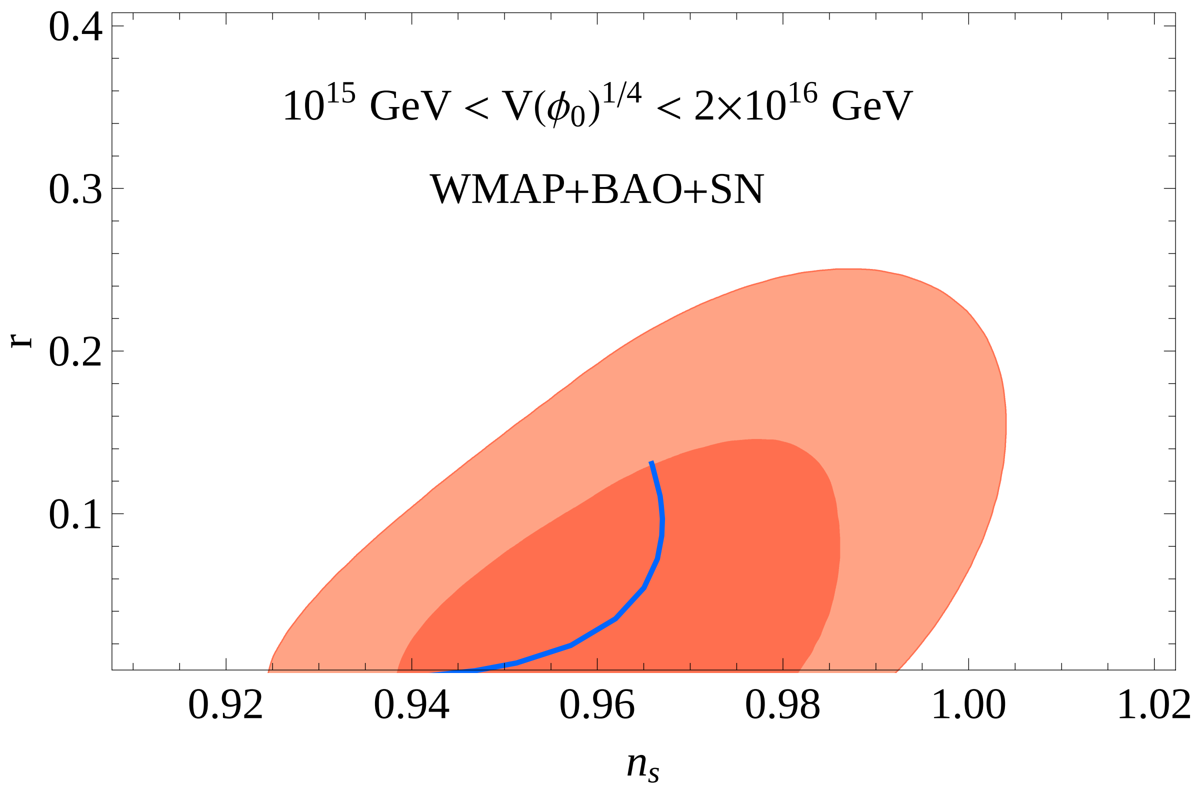
$\left(V_0^{1/4} > 10^5\right.$ GeV to avoid conflict with WMAP$\left.\right)$

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
  $n_s = 1 - \frac{2}{N_0} \simeq 0.96$
  $r \simeq 0.13$
  $\alpha \simeq -0.6 \times 10^{-3}$



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+BAO+SN range for n_s (68% and 95% confidence levels, taken from Komatsu *et al.*, astro-ph/0803.0547).



The tensor to scalar ratio r vs the spectral index n_s for the Coleman-Weinberg potential (blue curve). The WMAP+BAO+SN contours (68% and 95% confidence levels) are taken from Komatsu *et al.*, astro-ph/0803.0547.

$(m_P = 1)$

$V_0^{1/4}$(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

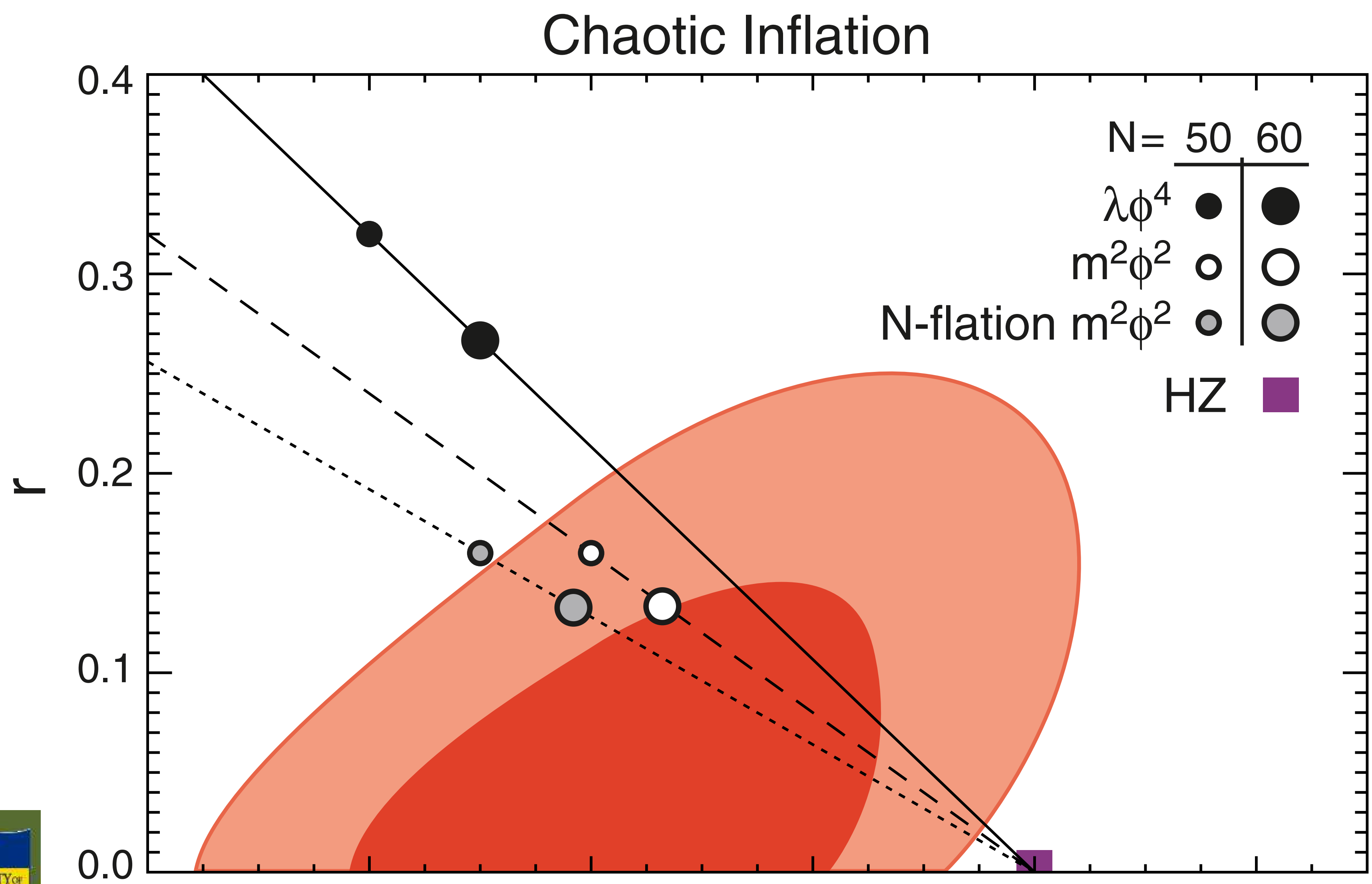
- Consider the quartic coupling $-c\phi^2\chi^\dagger\chi$, with $c \sim (M_c/M)^2$. Here χ vev breaks $4-2-2$ to $3-2-1$ and ϕ is the inflaton.
- Monopole formation occurs when $c\phi^2 \sim H^2$ $\longrightarrow H(t-t_\chi) \equiv \eta \sim 3c/\lambda$.
- Initial monopole number density $\sim H^3$, 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.

Scalar field ϕ with yukawa interactions $\frac{h}{2}\phi N N$.

$$V = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + V_{1-loop},$$

where

$$V_{1-loop} =$$
$$\frac{1}{64\pi^2}\left[\left(m^2 + \frac{\lambda}{2}\phi^2\right)^2 \ln\left(\frac{m^2+(\lambda/2)\phi^2}{\mu^2}\right) - 2\left(h\phi + m_N\right)^4 \ln\left(\frac{h\phi+m_N}{\mu}\right)\right].$$

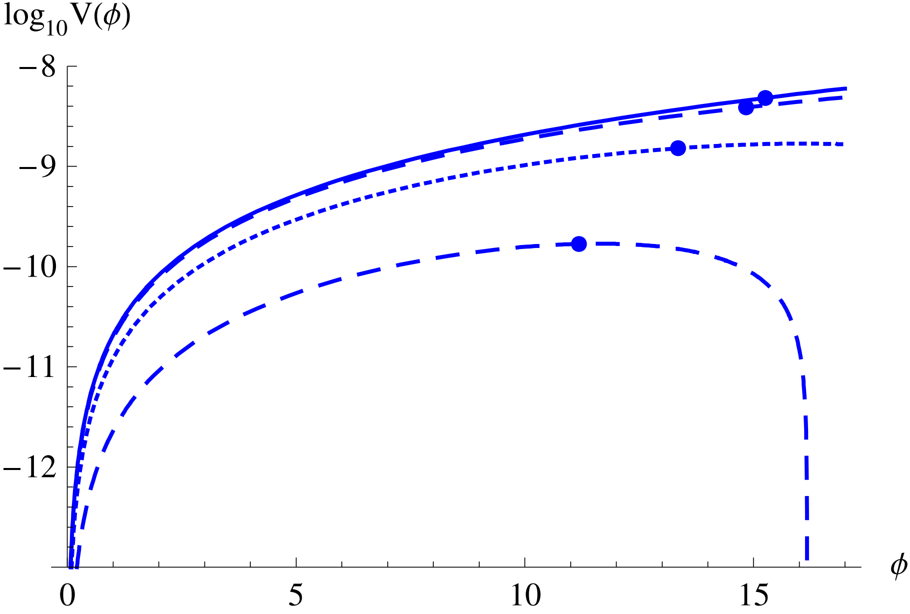


Chaotic Inflation
r
0.4
0.3
0.2
0.1
0.0
N= 50 60
λφ⁴
m²φ²
N-flation m²φ²
HZ

The inflationary parameters for the potential $V = (1/2)m^2\phi^2 - \kappa\phi^4 \ln(\phi/m_P)$

(in units $m_P = 1$)

$\log_{10}(\kappa)$	m (10^{-6})	ϕ_e	ϕ_0	$V(\phi_0)^{1/4}$	N_0	u_0	n_s	r	α (10^{-4})
$V = (1/2)m^2\phi^2$ (assuming $\rho_{\rm reh} = 10^{-16} m^2 m_P^2$)									
	6.437	1.457	15.26	0.008334	58.31		0.9657	0.1349	-5.901
ϕ^2 branch									
-16	6.434	1.457	15.25	0.008322	58.31	319.4	0.9657	0.1341	-5.901
-15	6.383	1.457	15.15	0.008204	58.47	30.2	0.9656	0.1267	-5.853
-14.5	6.245	1.457	14.83	0.007891	58.5	8.355	0.9645	0.1085	-5.647
-14.2	5.798	1.457	14.19	0.007212	58.43	3.165	0.9591	0.07567	-4.423
-14.11	4.917	1.456	13.35	0.006241	58.23	2.067	0.9459	0.04239	-1.254
Hilltop branch									
-14.11	4.917	1.456	13.35	0.006241	58.23	2.067	0.9459	0.04239	-1.254
-14.2	3.628	1.456	12.35	0.005019	57.93	0.3324	0.9219	0.01769	3.196
-14.5	2.146	1.455	11.18	0.003603	57.48	0.1447	0.8852	0.004665	6.022
-15	1.032	1.455	10.04	0.002344	56.88	0.0531	0.8424	0.000826	5.236
-16	0.268	1.453	8.617	0.001103	55.86	0.0102	0.7762	0.000039	2.254



The tree level potential (solid), the ϕ^2 and hilltop solution potentials for $\log_{10}(\kappa) = -14.5$ (dashed), and the potential for $\log_{10}(\kappa) = -14.11$ where the two solutions meet (dotted). The points on the curves denote ϕ_0.

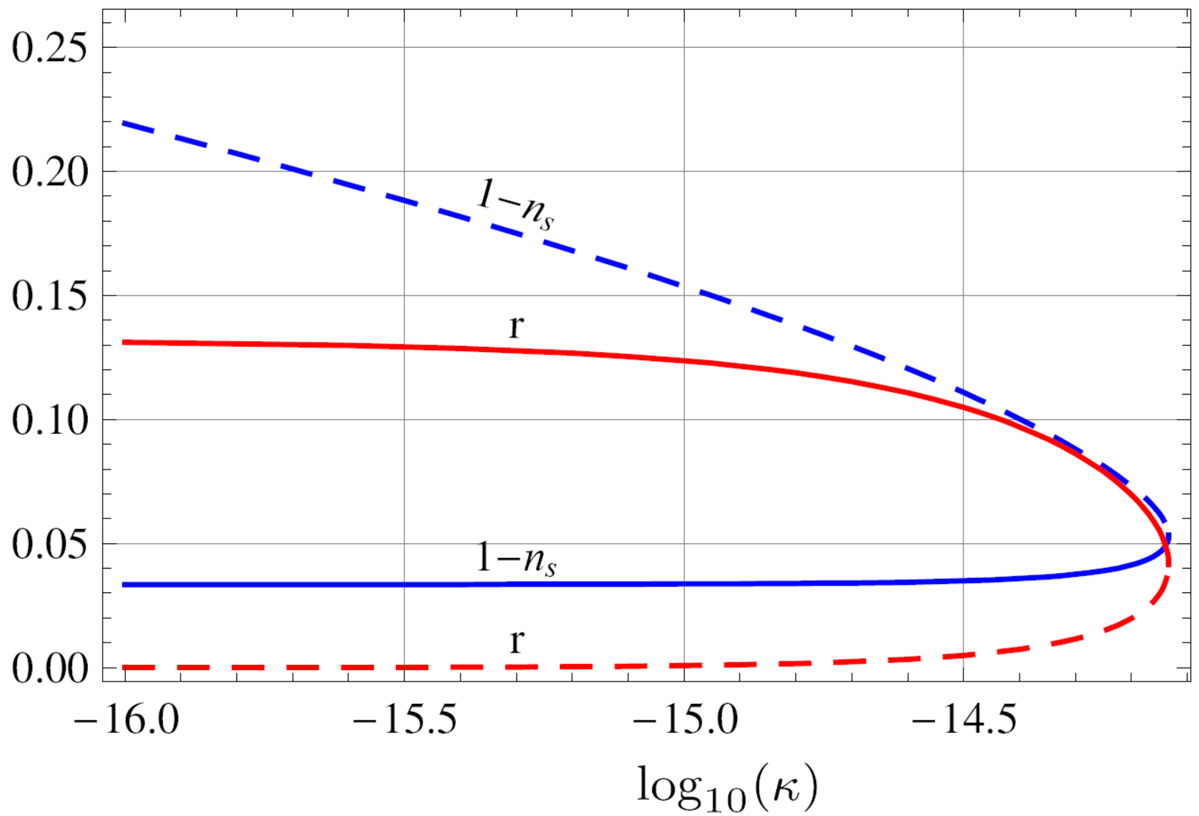
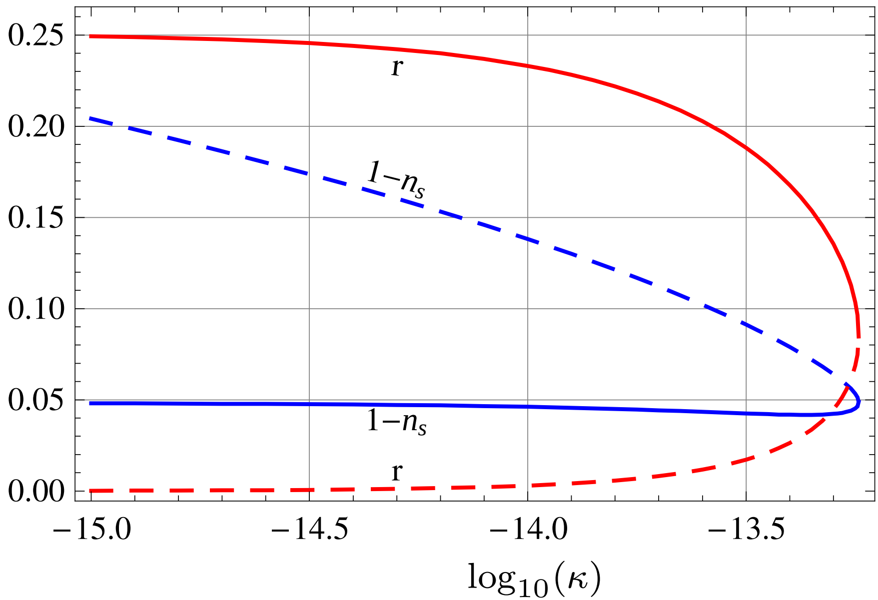


FIG. 2: $1 - n_s$ and r vs. κ for the potential $V = (1/2)m^2\phi^2 - \kappa\phi^4 \ln(\phi/m_P)$. Solid and dashed curves correspond to ϕ^4 and hilltop branches respectively. Note that the curvature perturbation amplitude and number of e-folds require $\kappa \lesssim 7.4 \times 10^{-15}$.

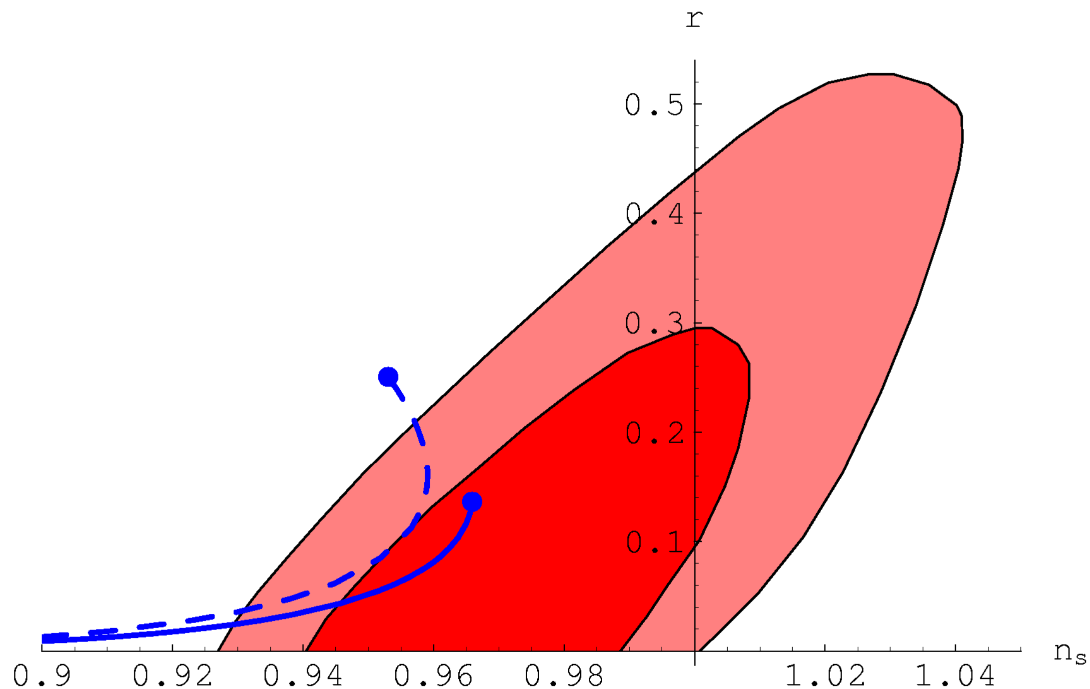
The inflationary parameters for the potential $V = (1/4!)\lambda\phi^4 - \kappa\phi^4 \ln(\phi/m_P)$

(in units $m_P = 1$)

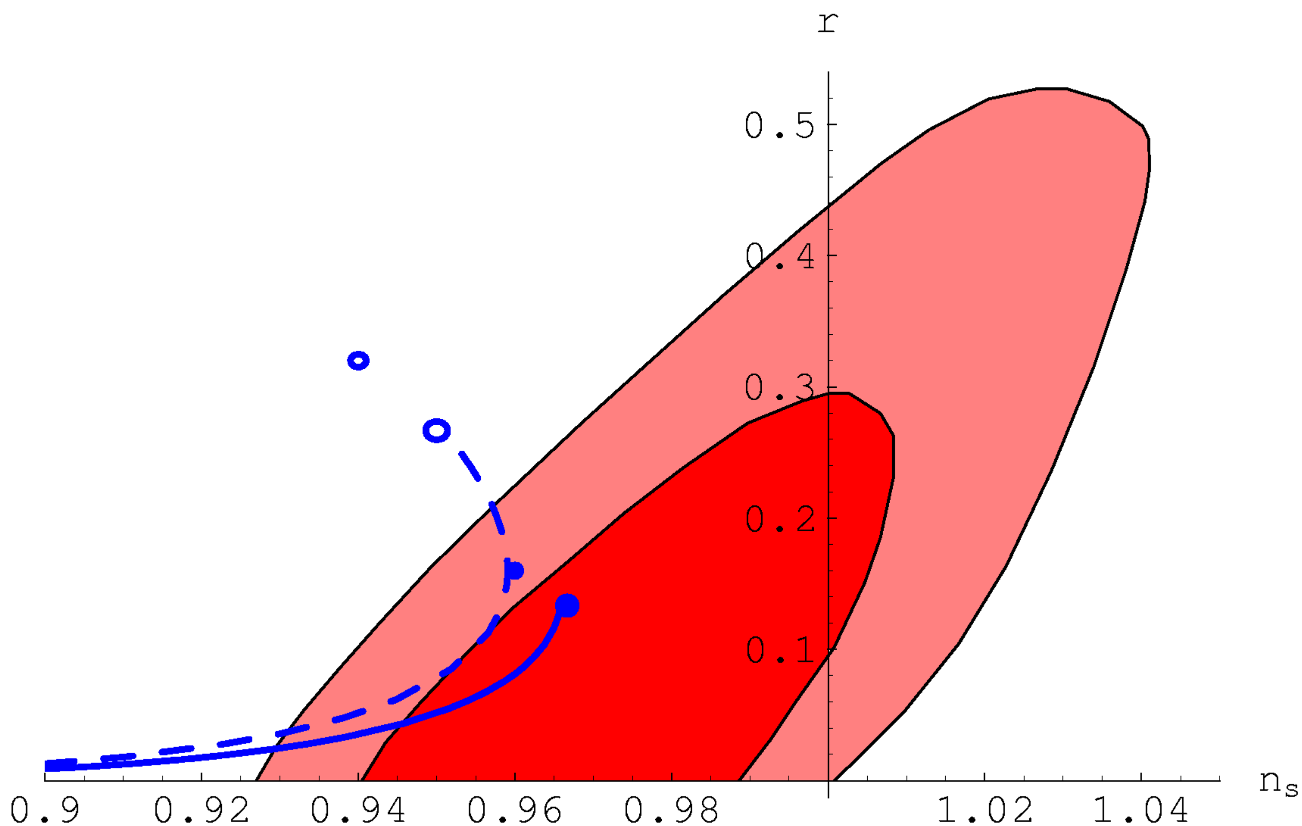
$\log_{10}(\kappa)$	$\log_{10}(\lambda)$	ϕ_e	ϕ_0	$V(\phi_0)^{1/4}$	N_0	v_0	n_s	r	α (10^{-4})
				$V = (1/4!)\lambda\phi^4$					
	-12.07	2.53	22.39	0.009737	62.55		0.9517	0.251	-7.637
				ϕ^4 branch					
-15.	-12.03	2.516	22.31	0.00972	62.54	143.1	0.9519	0.2493	-7.606
-14.	-11.78	2.438	21.69	0.009558	62.43	14.08	0.9539	0.2331	-7.372
-13.5	-11.49	2.369	20.49	0.009058	62.2	3.834	0.9575	0.1881	-7.025
-13.3	-11.36	2.338	19.35	0.008344	61.97	1.762	0.9577	0.1355	-6.261
-13.24	-11.33	2.319	18.23	0.007421	61.74	0.9184	0.9512	0.08476	-3.725
				Hilltop branch					
-13.24	-11.33	2.319	18.23	0.007421	61.74	0.9184	0.9512	0.08476	-3.725
-13.3	-11.41	2.305	17.11	0.006329	61.49	0.4937	0.9359	0.04481	0.9321
-13.5	-11.63	2.292	15.85	0.004985	61.14	0.2391	0.9088	0.01718	6.326
-14.	-12.15	2.276	14.15	0.003225	60.57	0.0799	0.8618	0.002978	8.232
-15.	-13.18	2.256	12.15	0.001534	59.69	0.0151	0.7959	0.000149	4.078



$1 - n_s$ and r vs. κ for the potential $V = (1/4!)\lambda\phi^4 - \kappa\phi^4 \ln(\phi/m_P)$. Solid and dashed curves correspond to ϕ^4 and hilltop branches respectively.



- Tree level Inflation Potential: $V = \frac{1}{2}m^2\phi^2$
  Radiative Corrections: $-\kappa\phi^4$ ln(ϕ/m_P), $\kappa > 0$ (From Yukawa coupling $\frac{h}{2}NN\phi$)
- Tree level Inflation Potential: $V = \frac{\lambda}{4!}\phi^4$
  Radiative Corrections: $-\kappa\phi^4$ ln (ϕ/m_P), $\kappa > 0$


r
0.5
0.4
0.3
0.2
0.1
0.9
0.92
0.94
0.96
0.98
1.02
1.04
n_s

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.