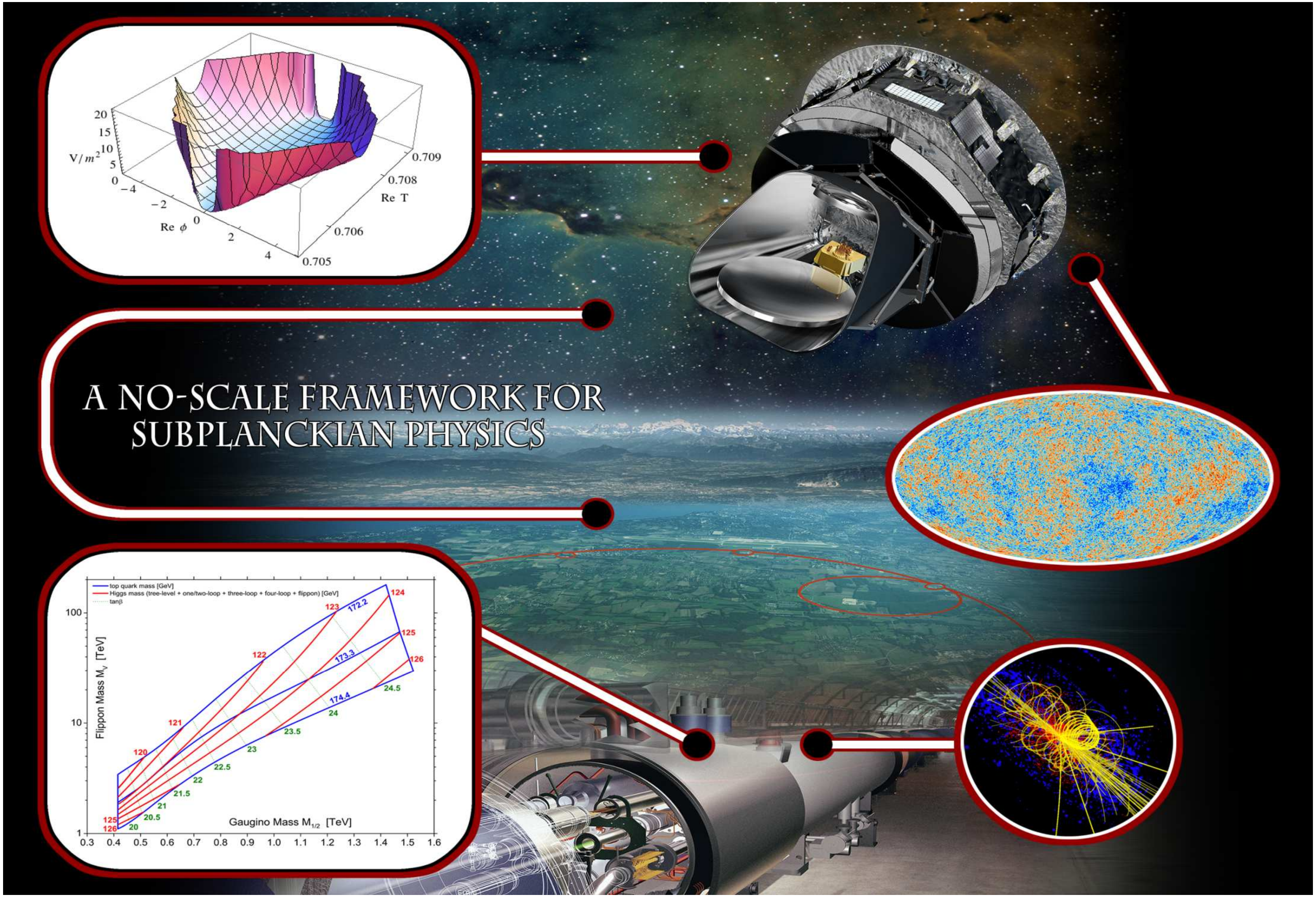
A NO-SCALE FRAMEWORK FOR SUBPLANCKIAN PHYSICS



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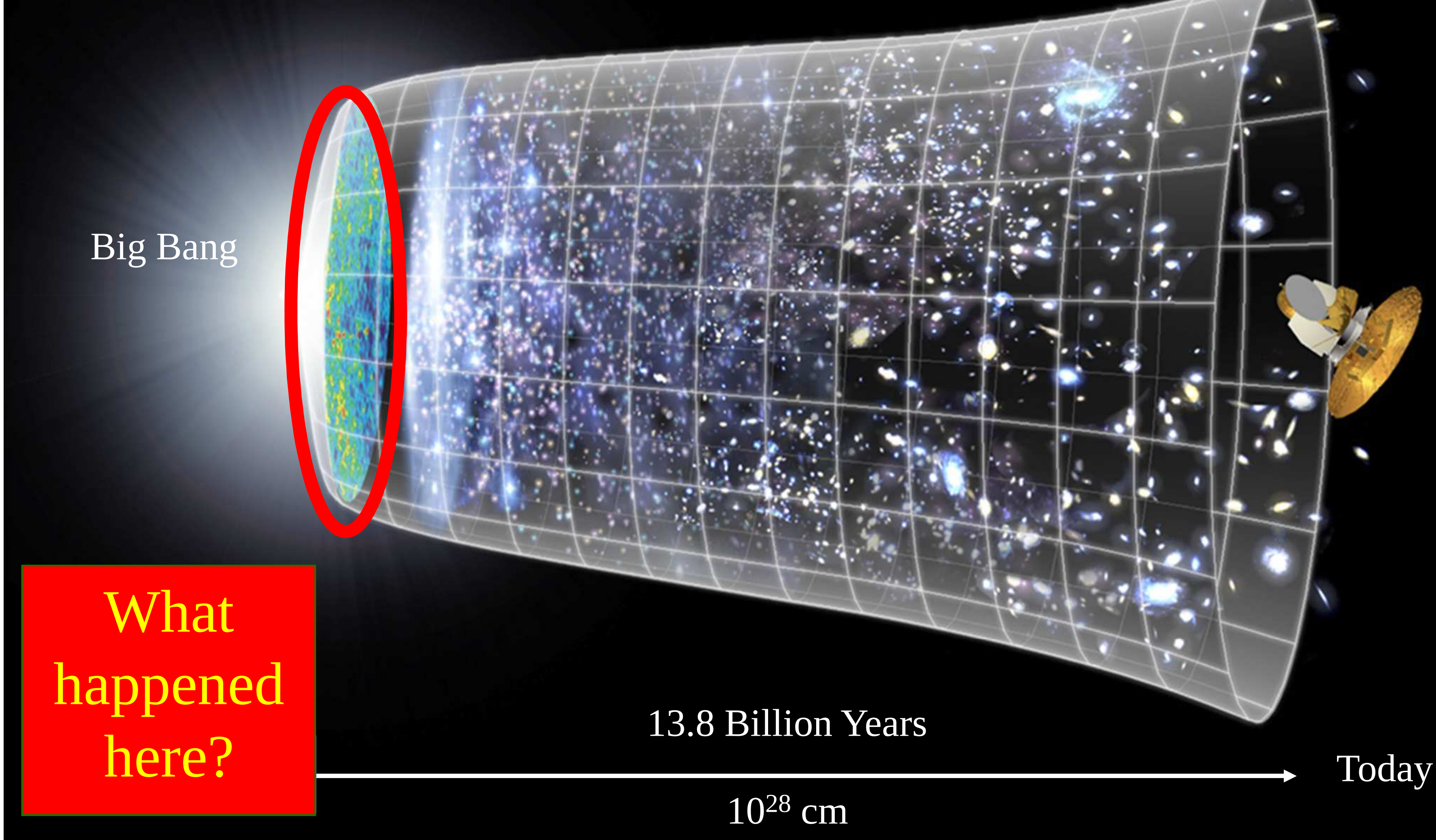
TEXAS A&M UNIVERSITY

ACADEMY OF ATHENS

Echo from the Big Bang

Inflation in Light of Planck & BICEP2



Some Big Questions

- Why is the Universe so big and old?
- Why is it (almost) homogeneous on large scales?
- Why is its geometry (almost) Euclidean?
- What is the origin of structures in the Universe?

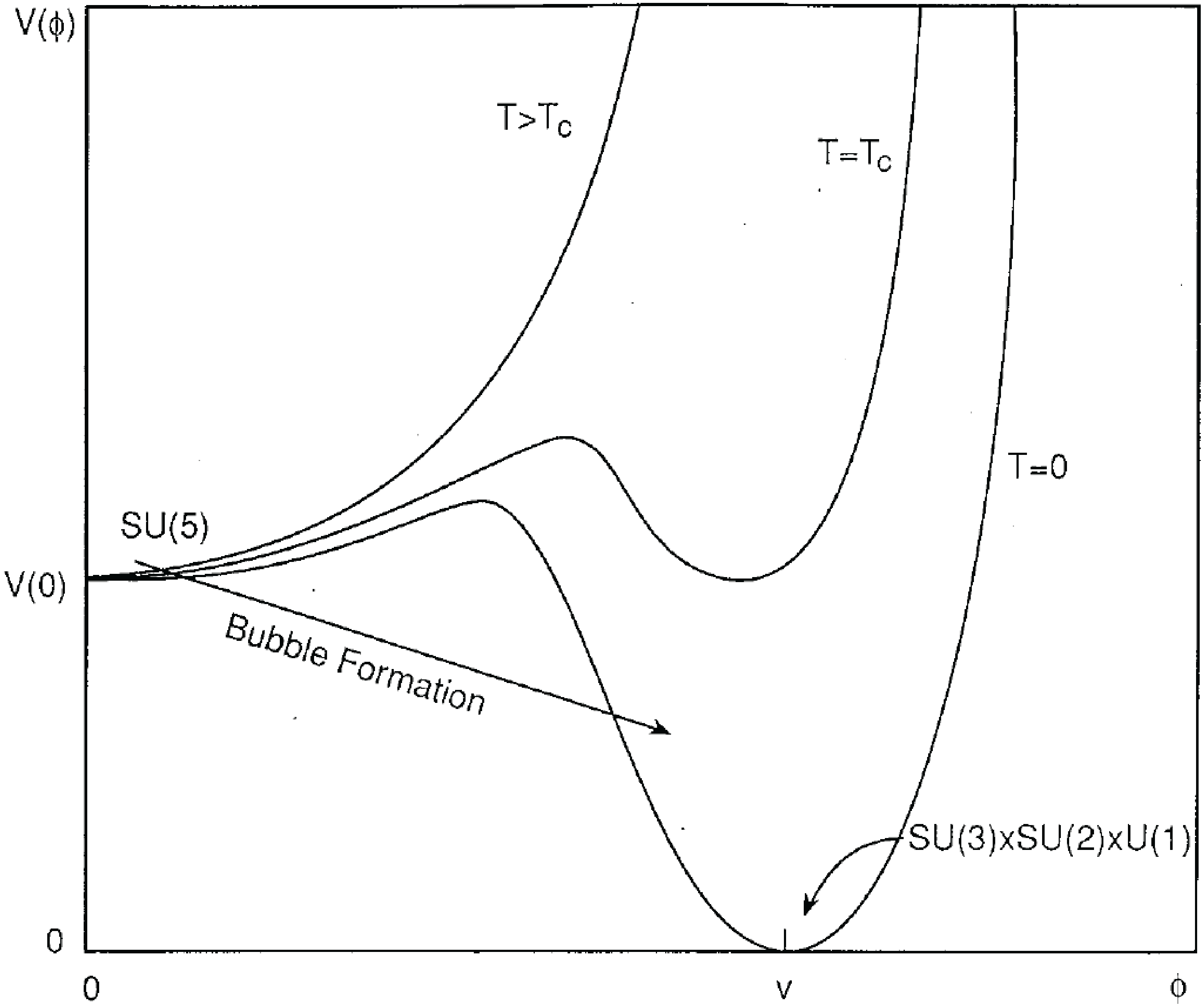
A possible answer:

Cosmological inflation

- What do the Planck and BICEP2 data tell us?
- Models of inflation

Inflation

- Standard cosmology assumes an adiabatically expanding Universe, $R \sim 1/T$
- Phase transitions can violate this condition
- Expect several phase transitions in the Early Universe
  - GUTS: SU5 $\rightarrow$ SU(3) x SU(2) x U(1)
  - SM: SU(2) x U(1) $\rightarrow$ U(1)
  - possibly other non-gauged symmetry breakings
- Entropy production common result
- Type of inflation will depend on the order of the phase transition


V(ϕ)
T>Tc
T=Tc
T=0
SU(5)
V(0)
Bubble Formation
SU(3)xSU(2)xU(1)
0
0
v
ϕ

Inflation

$$\Lambda = 8\pi G_N V_0$$

For $\varrho \ll V_0$,

$$H^2 = \frac{\dot{R}^2}{R^2} \approx \frac{8\pi G_N V_0}{3} = \frac{\Lambda}{3}$$

or

$$\frac{\dot{R}}{R} \approx \sqrt{\frac{\Lambda}{3}} \qquad R \sim e^{Ht}$$

For $H\tau > 65$, curvature problem solved

When the transition is over, the Universe reheats to $T < V_0^{1/4} \sim T_i$, but $R \gg R_i$

Old New Inflation

Great idea based on 1-loop corrected SU(5) potential for the adjoint:

$$V(\sigma) = A\sigma^4(\ln\frac{\sigma^2}{v^2} - \frac{1}{2}) \qquad A = \frac{5625}{1024\pi^2} g_5^4$$

Linde; Albrecht, Steinhardt

Problems:

- Vacuum structure
- destabilization through quantum fluctuations
- fine tuning (require curvature to be << M_X)
- density fluctuations - $\delta\rho/\rho \sim 100\, g_5^2$

How SUSY can help

Exact Susy - $V_{1\text{-loop}} = 0$

$$A = \frac{1}{64\pi^2 v^4}(\sum_B g_B m_B^4 - \sum_F g_F m_F^4) = 0$$

Broken Susy - $A = \dfrac{75}{32\pi^2 v^2} g_5^2 m_s^2$

fixes fine-tuning, $\delta\rho/\rho$, etc. -
but isn't really a model

Ellis,
Nanopoulos,
Olive,
Tamvakis

Supergravity

Start with a Kähler Potential

$$G = K + \ln|W|^2$$

Minimal N=1 defined by K = $\phi^i\phi_i^*$

and scalar potential

$$V = e^G\left[G_i(G^{-1})^i_j G^j - 3\right] + \mathrm{D-terms}$$

or

$$V = e^{\phi^i\phi_i^*}\left[|\frac{\partial W}{\partial\phi^i} + \phi_i^* W|^2 - 3|W|^2\right] + \mathrm{D-terms}$$

for minimal N=1

Typically, $m^2 \sim H^2$

η-problem!

Supergravity

Constructing Models $W = \mu^2 \sum_n \lambda_n \phi^n$

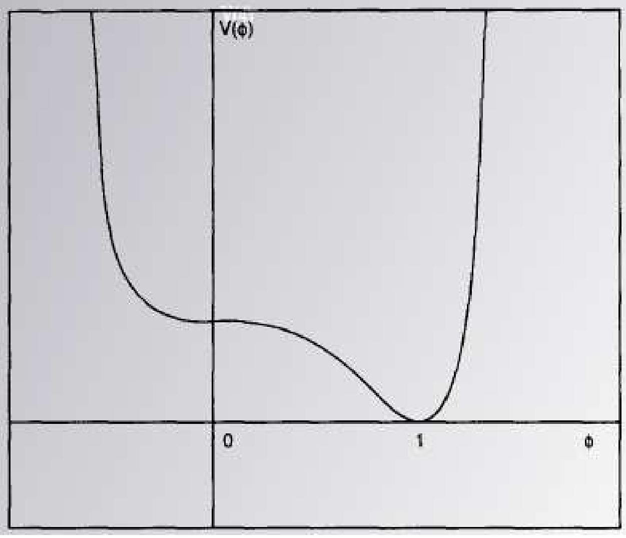
Nanopoulos, Olive, Srednicki, Tamvakis

μ^2 fixed by amplitude of density fluctuations, $\lambda_n \sim \mathcal{O}(1)$

Simplest example, $W = \mu^2(1-\phi)^2$

Holman, Ramond, Ross

$$\begin{aligned} V &= \mu^4 e^{|\phi|^2}\Big[1 + |\phi|^2 - (\phi^2 + \phi^{*2}) - 2|\phi|^2(\phi + \phi^*) \\ &\quad +5|\phi^2|^2 + |\phi|^2(\phi^2 + \phi^{*2}) - 2|\phi^2|^2(\phi + \phi^*) + |\phi^3|^2\Big] \\ &\simeq \mu^4(1 - 4\phi^3 + \frac{13}{2}\phi^4 + \cdots \end{aligned}$$



No-Scale Supergravity

Natural vanishing of cosmological constant (tree level) with the supersymmetry scale not fixed at lowest order. (Also arises in generic 4d reductions of string theory.)

$$K = -3\ln(T + T^* - \phi^i {\phi_i}^*/3)$$

$$V = e^{\frac{2}{3}K} \left|\frac{\partial W}{\partial \phi^i}\right|^2$$

Globally supersymmetric potential once K (canonical) picks up a vev

No Scale SUGRA: A Case Study in Reductionism

There is a function called the Kähler potential which must be specified by the model builder in order to fix the metric of superspace, and determine the scalar potential. It is not fixed by the symmetries of the theory. There is however a particularly natural choice.

$$K = -3 \ln (T + T^* - \Sigma \varphi_i^* \varphi_i)$$

$$V_{SUGRA} = 0$$

The scalar potential is flat and vanishing. Supersymmetry is BROKEN, and there is no cosmological constant. This is all desirable at the ***Tree Level***.

CONSTRAINT: $m_0 = 0$, $A = 0$, $B = 0$ $m_{1/2} \neq 0$ for SUSY breaking

The gaugino mass $m_{1/2}$ remains undetermined at the classical level.

All soft-terms though, are dynamically evolved in terms of only the single parameter ($m_{1/2}$), which may itself be determined by radiative corrections to the potential !

E. Cremmer, S. Ferrara, C. Kounnas and D. V. Nanopoulos, Phys. Lett. B 133, 61 (1983)
J. R. Ellis, A. B. Lahanas, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B 134, 429 (1984)
J. R. Ellis, C. Kounnas and D. V. Nanopoulos, Nucl. Phys. B 241, 406 (1984)
A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. 145, 1 (1987)

No-scale Supergravity (nSUGRA)

Choose a specific form for the Kähler potential:

$$K = -3\ln(T + T^* - \Sigma\varphi_i^*\varphi_i)$$

$$V_{SUGRA} = 0$$ At the tree-level

Furthermore the gaugino mass $m_{1/2}$ remains undetermined. Thus, the soft terms are not fixed (at the classical level) close to the Planck scale.

So, $m_{1/2} = m_{1/2}(T_i)$

with $\langle T_i \rangle$ determined by radiative corrections.

$m_{1/2}$, $m_0 = 0$, $A_0 = 0$, $B = 0$

Thus, in principle all soft-terms may be determined in terms of only **one-parameter**, $m_{1/2}$ → **The One-Parameter Model**

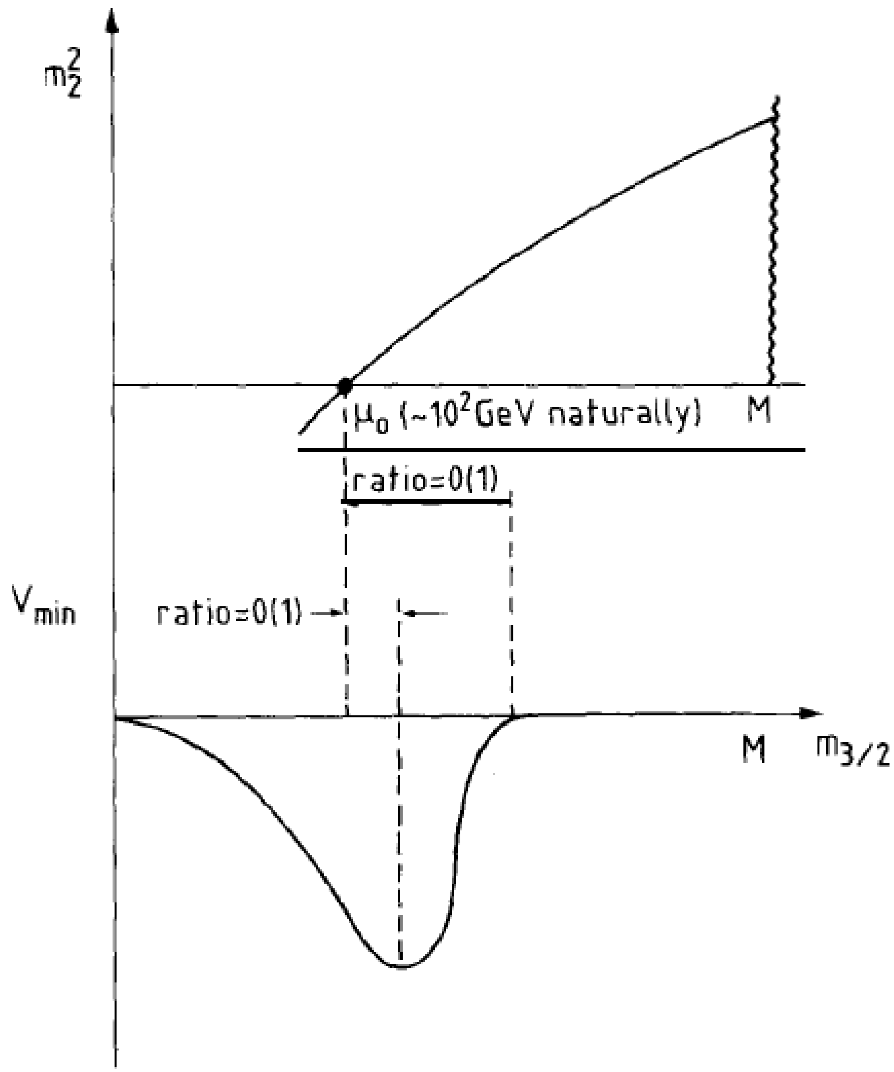


Fig. 14. V_{min} as a function of the floating gravitino mass $m_{3/2}$. V_{min} becomes deepest at $m_{3/2} = O(1)\ \mu_0$ with μ_0 the critical scale at which m_2^2 vanishes (m_3^2 has been taken as zero) (from ref. [90]).

Relation to String Theory

The no-scale structure emerges naturally as the infrared limit of string theory.

In particular,

- Heterotic M-theory compactifications
- Type IIB flux compactifications – **Flipped SU(5)**
- F-theory compactifications (non-pertubative limit of Type IIB)

The nSUGRA 'One-Parameter Model'

Strict No-scale Moduli Scenario: $m_0 = A = B = 0$

Special Dilaton Scenario:

$$m_0 = \frac{m_{1/2}}{\sqrt{3}} \qquad A = -m_{1/2} \qquad B = \frac{2\, m_{1/2}}{\sqrt{3}}$$

These ansatz combined with the no-scale condition define the so-called **one-parameter model** since the soft-terms are now all defined in terms $m_{1/2}$

Subset of the mSUGRA parameter space $\longrightarrow$ Highly constrained, but predictive!

Ellis, Kounnas, and DVN, **Nucl.Phys.B247:373-395,1984**
Lopez, DVN, and Zichichi, **Phys.Lett.B319:451-456,1993**
Lopez, DVN, and Zichichi, **Int.J.Mod.Phys.A10:4241-4264,1995**
Lopez, DVN, and Zichichi, **Phys.Rev.D52:4178-4182,1995**

No-Scale Supergravity

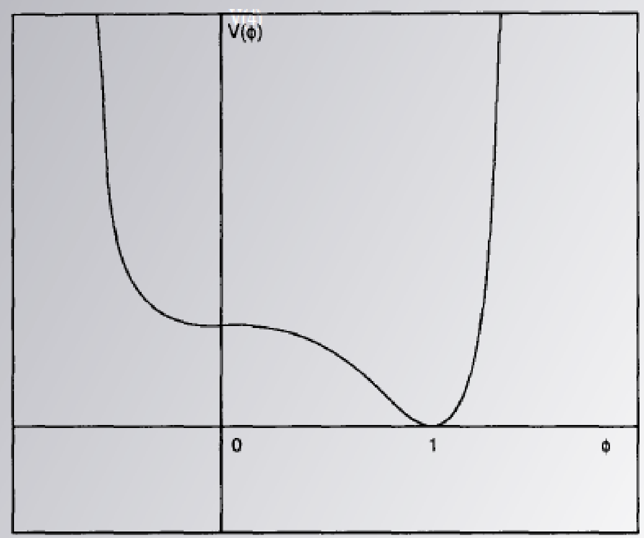
Constructing Models $W = \mu^2 \sum_n \lambda_n \phi^n$

Ellis, Enqvist, Nanopoulos, Olive, Srednicki

μ^2 fixed by amplitude of density fluctuations, $\lambda_n \sim \mathcal{O}(1)$

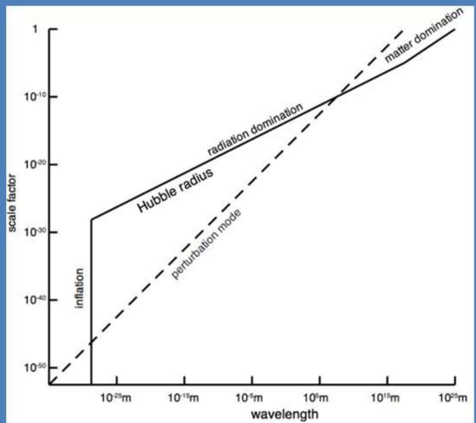
Simplest example, $W = \mu^2(\phi - \phi^4/4)$

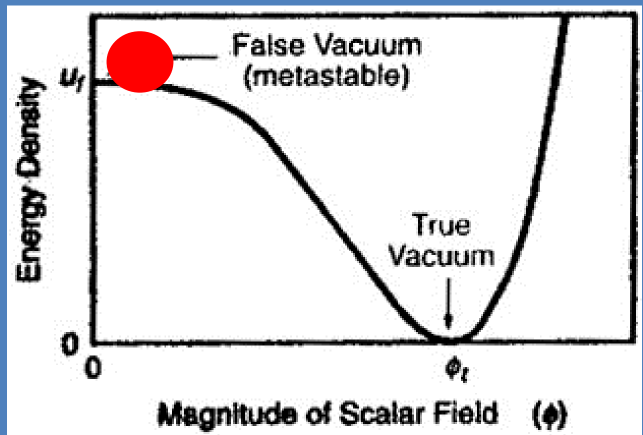
$$V = \mu^4 |1 - \phi^3|^2$$



Primordial Perturbations

- "Cosmological constant" due to vacuum energy in "inflaton" field ϕ: $\Lambda \sim V(\phi) \neq 0$
- Quantum fluctuations in ϕ cause perturbations in energy density (scalar) and metric (tensor)
- (Almost) independent of scale size





- Visible in cosmic microwave background (CMB)

Inflationary Perturbations in a Nutshell

- Universe expanding like de Sitter
- Horizon → information loss → mixed state
- Effective 'Hawking temperature' $H/2\pi$
- Expect quantum fluctuations:

$$\langle\phi\phi\rangle, \qquad \langle hh\rangle \sim H^2$$

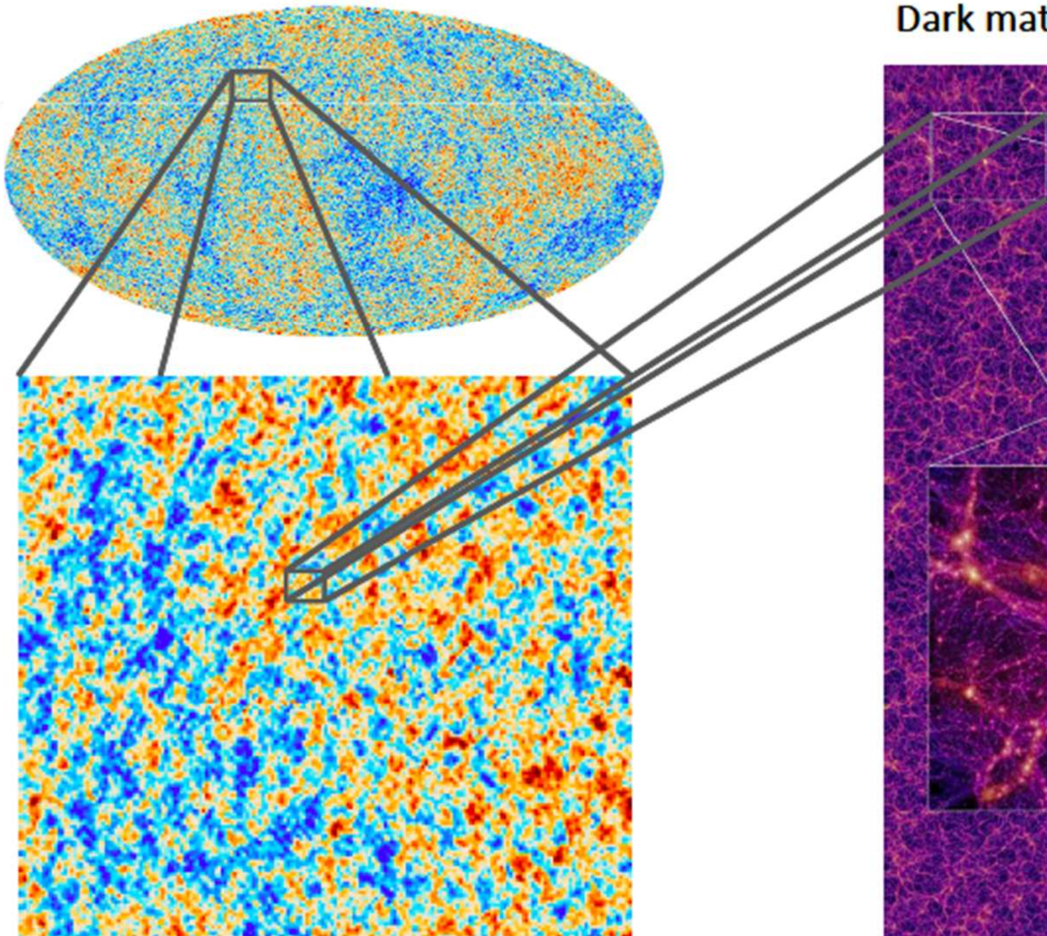
(inflaton, gravitational field: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$)

Scalar (density), tensor perturbations

- Should have thermal spectrum
- Scalars enhanced by evolution of ϕ → $r \sim \varepsilon$

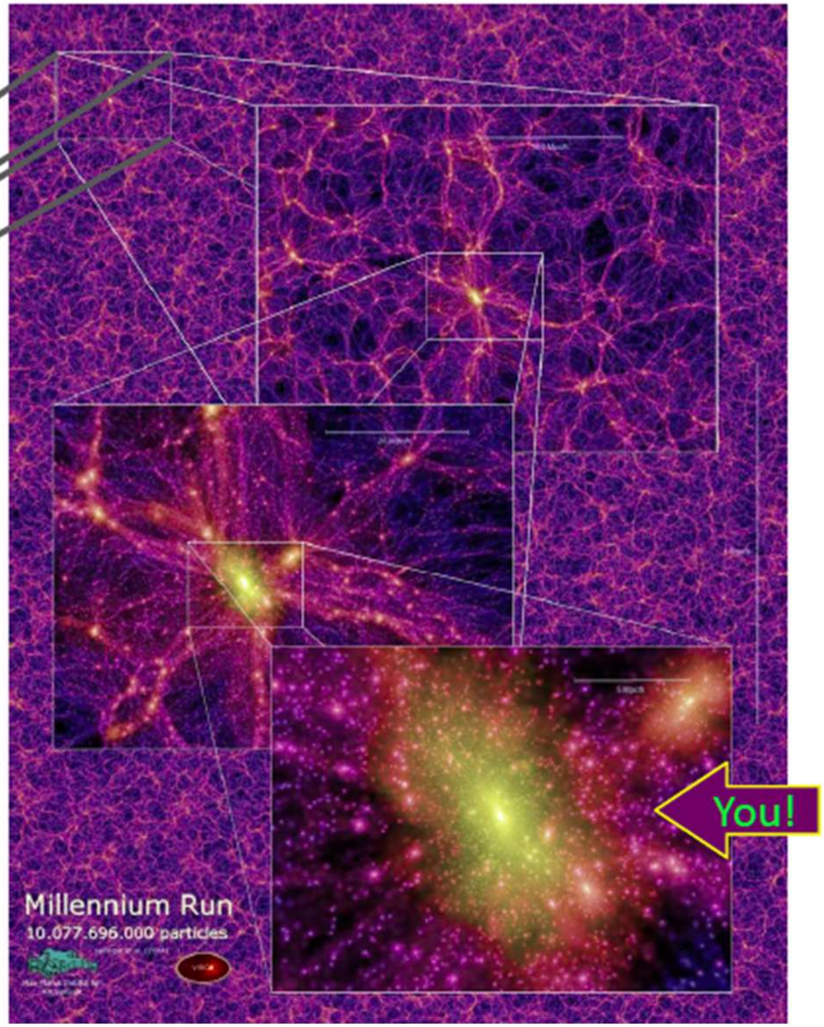
Perturbations Generate Structures

Planck

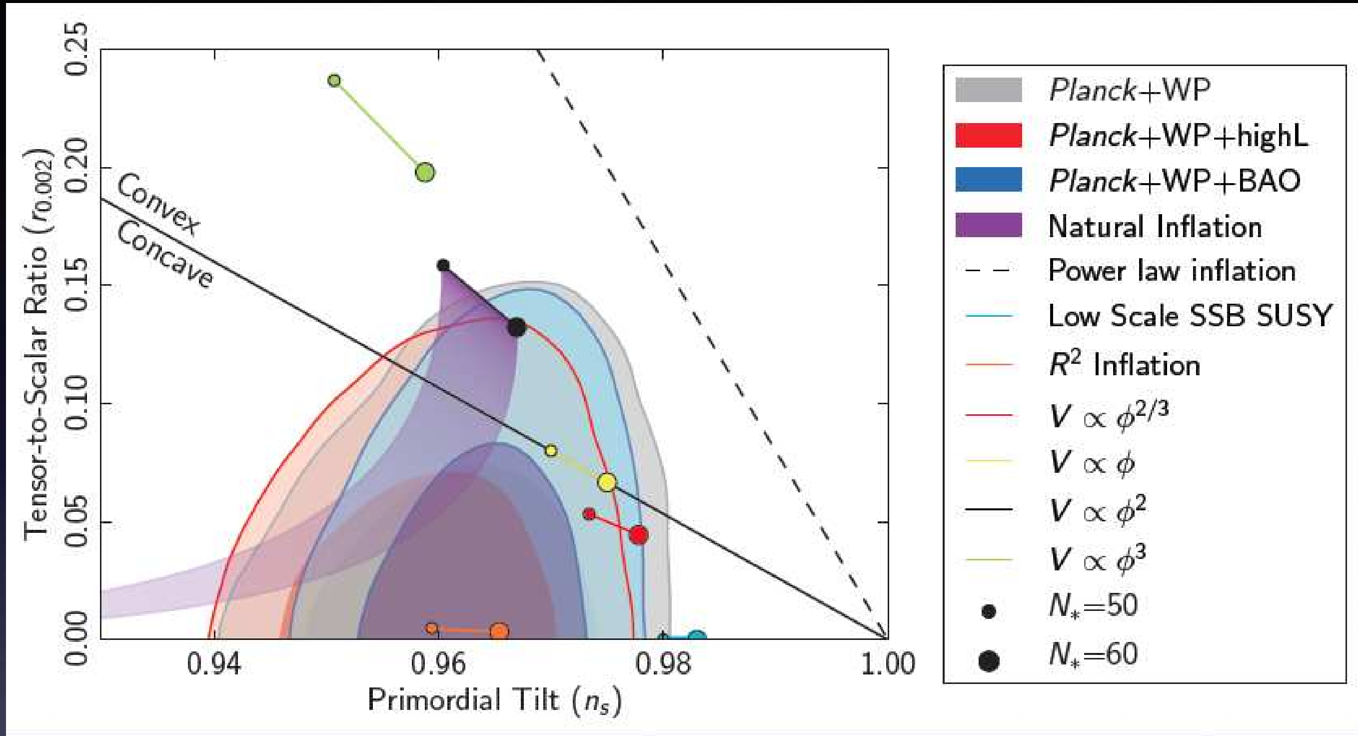


Primordial quantum perturbations as seen in the Cosmic Microwave Background

Dark matter distribution today (simulated)



Planck Results



$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \qquad \eta = \frac{V''}{V} \qquad n_s = 1 - 6\epsilon + 2\eta \qquad r = 16\epsilon$$

Trouble for simple supergravity and no-scale models:

$$\epsilon \simeq \frac{1}{72N^4} \ll 1 \quad \cancel{\text{OK}}$$

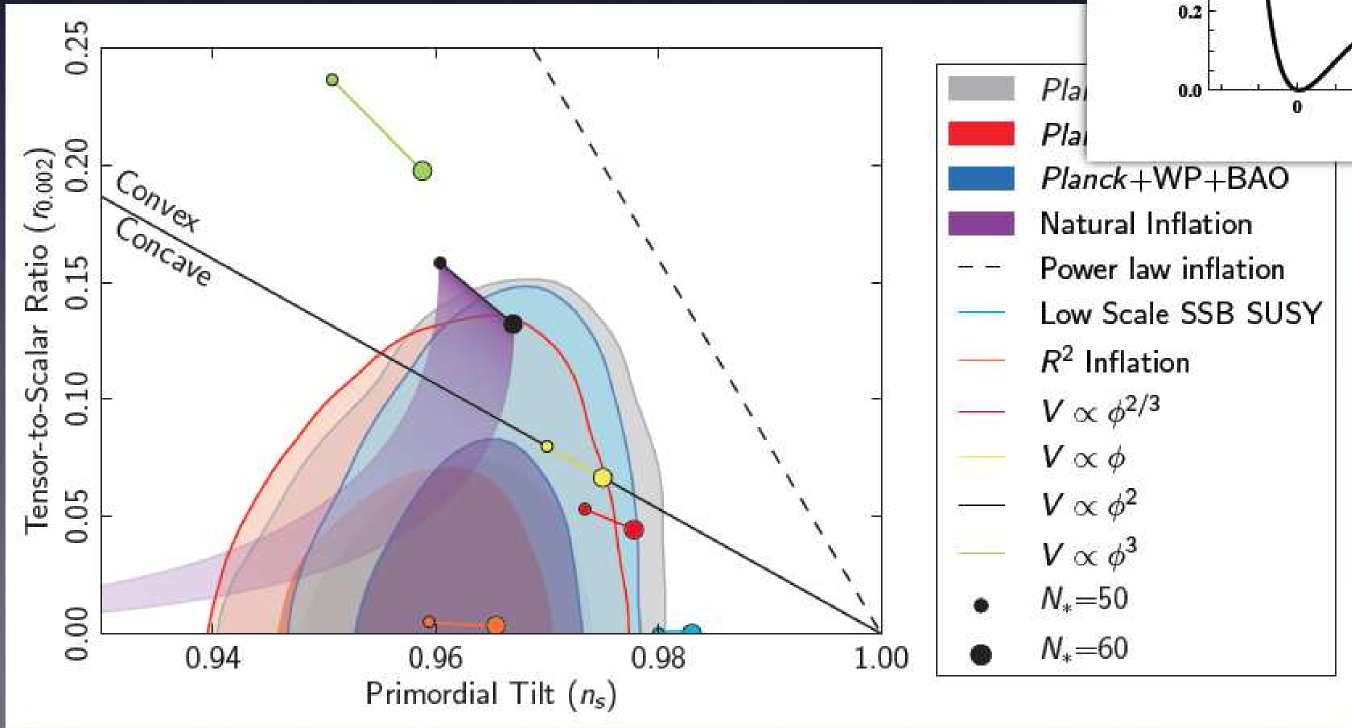
$$\eta \simeq -\frac{1}{2N} \quad \text{not OK}$$

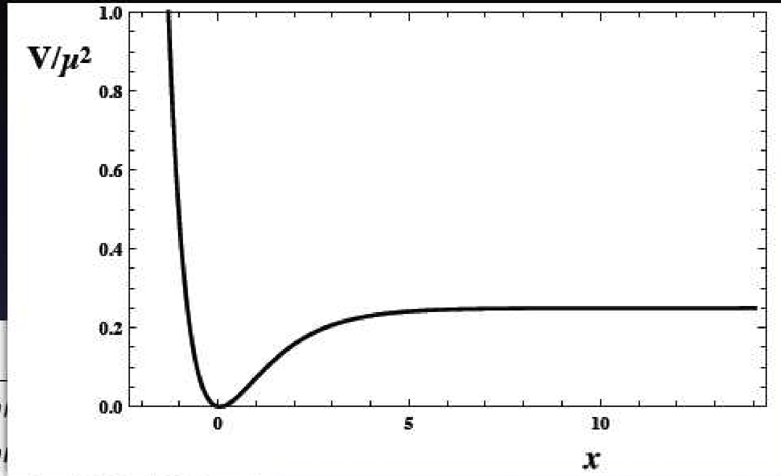
$$n_s \sim .933$$

Planck-friendly Models

R+R^2 Inflation

For N=55, n_s = 0.965; r = .0035

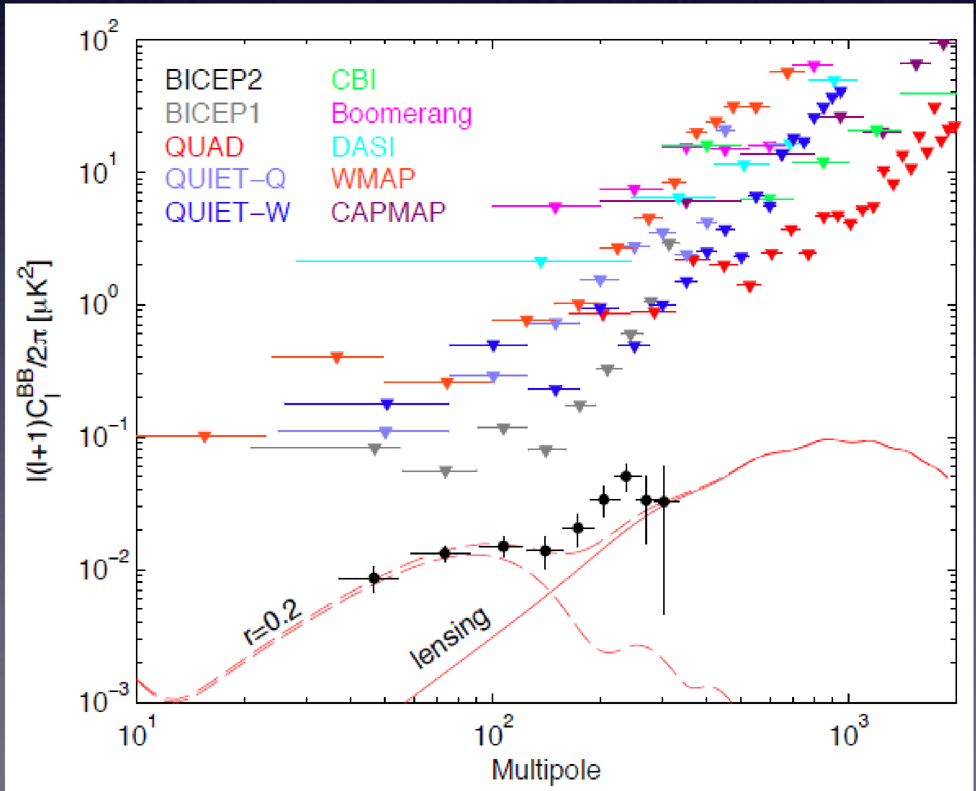




Bicep-friendly Models

Quadratic Chaotic Inflation

For N=55, $n_s = 0.964$; $r = .145$



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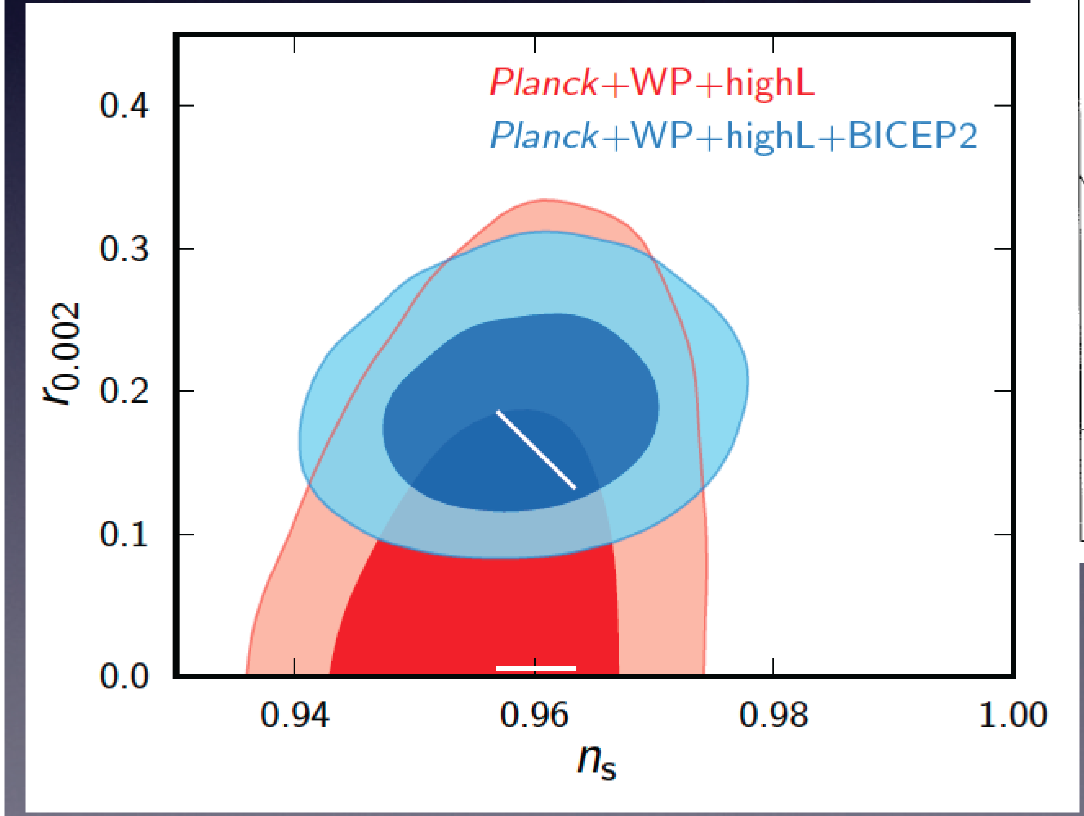
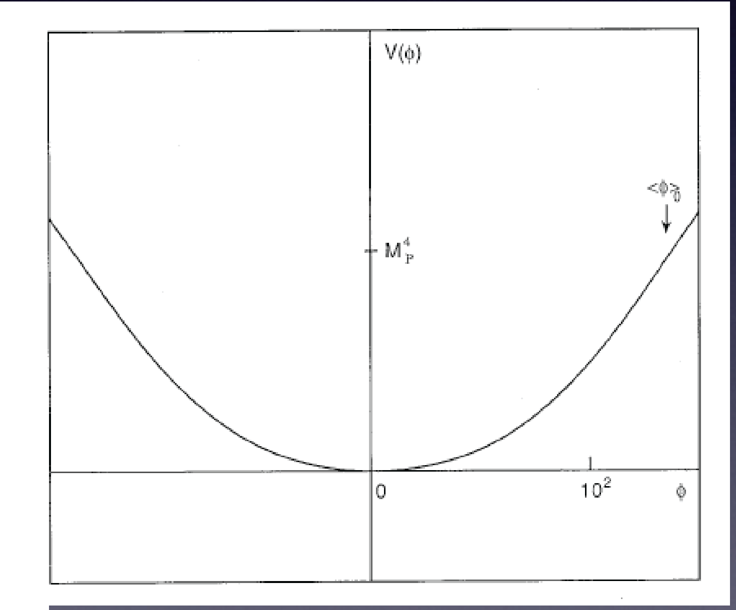




Includes running of the spectral index

No-Scale models revisited

Can we find a model consistent with Planck? Ellis, Nanopoulos, Olive

Start with WZ model: $$W = \frac{\hat{\mu}}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$$

Assume now that T picks up a vev: 2<Re T> = c

$$\mathcal{L}_{eff} = \frac{c}{(c-|\phi|^2/3)^2}|\partial_\mu \phi|^2 - \frac{\hat{V}}{(c-|\phi|^2/3)^2}$$

Redefine inflaton to a canonical field χ $$\hat{V} = |W_\Phi|^2$$

$$\phi = \sqrt{3c}\tanh\left(\frac{\chi}{\sqrt{3}}\right)$$

No-Scale models revisited

The potential becomes:

$$V = \mu^2 \left| \sinh(\chi/\sqrt{3}) \left(\cosh(\chi/\sqrt{3}) - \frac{3\lambda}{\mu} \sinh(\chi/\sqrt{3}) \right) \right|^2$$

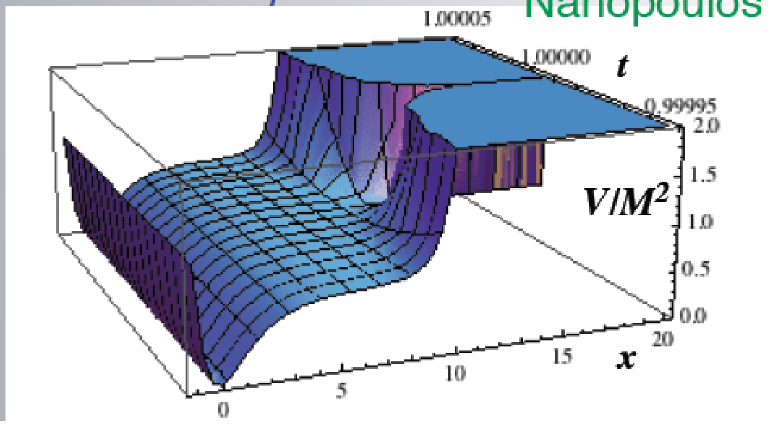
For λ=μ/3, this is exactly the R + R² potential
and Starobinsky model of inflation

$$V = \mu^2 e^{-\sqrt{2/3}x} \sinh^2(x/\sqrt{6})$$

Have so far *assumed* a vev for one of the two fields

$$K = -3\ln\left(T + T^* - \frac{|\phi|^2}{3} + \frac{(T+T^*-1)^4 + d(T-T^*)^4}{\Lambda^2}\right)$$

Ellis, Kounnas, Nanopoulos



No-Scale models revisited

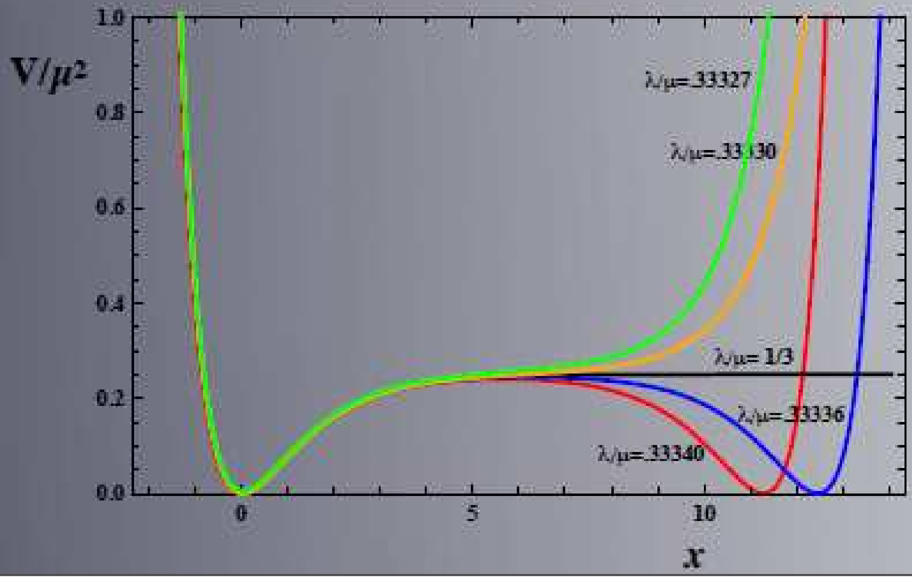
The potential becomes:

$$V = \mu^2 \left| \sinh(\chi/\sqrt{3}) \left(\cosh(\chi/\sqrt{3}) - \frac{3\lambda}{\mu} \sinh(\chi/\sqrt{3}) \right) \right|^2$$

$$\hat{\mu} = \mu\sqrt{(c/3)}$$

For $\lambda=\mu/3$, this is exactly the $R + R^2$ potential

$$V = \mu^2 e^{-\sqrt{2/3}x} \sinh^2(x/\sqrt{6})$$



$$\chi = (x + iy)/\sqrt{2}$$

Classes of R+R^2 in No-Scale Supergravity

So is the inflaton T or ϕ?

1) T-fixed (ϕ-inflaton)

Starobinsky potential found when

$$\hat{V} = M^2|\phi|^2|1-\phi/\sqrt{3}|^2$$

Ellis, Nanopoulos, Olive

$$W = M\left[\frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}}\right]$$

2) ϕ-fixed (T-inflaton)

Starobinsky potential found when

$$\hat{V} = 3M^2|T-1/2|^2$$

Cecotti; Kallosh, Linde

$$W = \sqrt{3}M\phi(T-1/2)$$

Phenomenology with No-Scale (WZ) Inflation

$$K = -3\ln\left(1 - \frac{|y_1|^2 + |y_2|^2}{3} + \frac{|y_2|^4}{\Lambda^2}\right),$$

Solves Polonyi issues

$$W = M\left[\frac{y_1^2}{2}\left(1 + \frac{y_2}{\sqrt{3}}\right) - \frac{y_1^3}{3\sqrt{3}}\right]$$

y_2 - Polonyi like field

y_1 - Inflaton

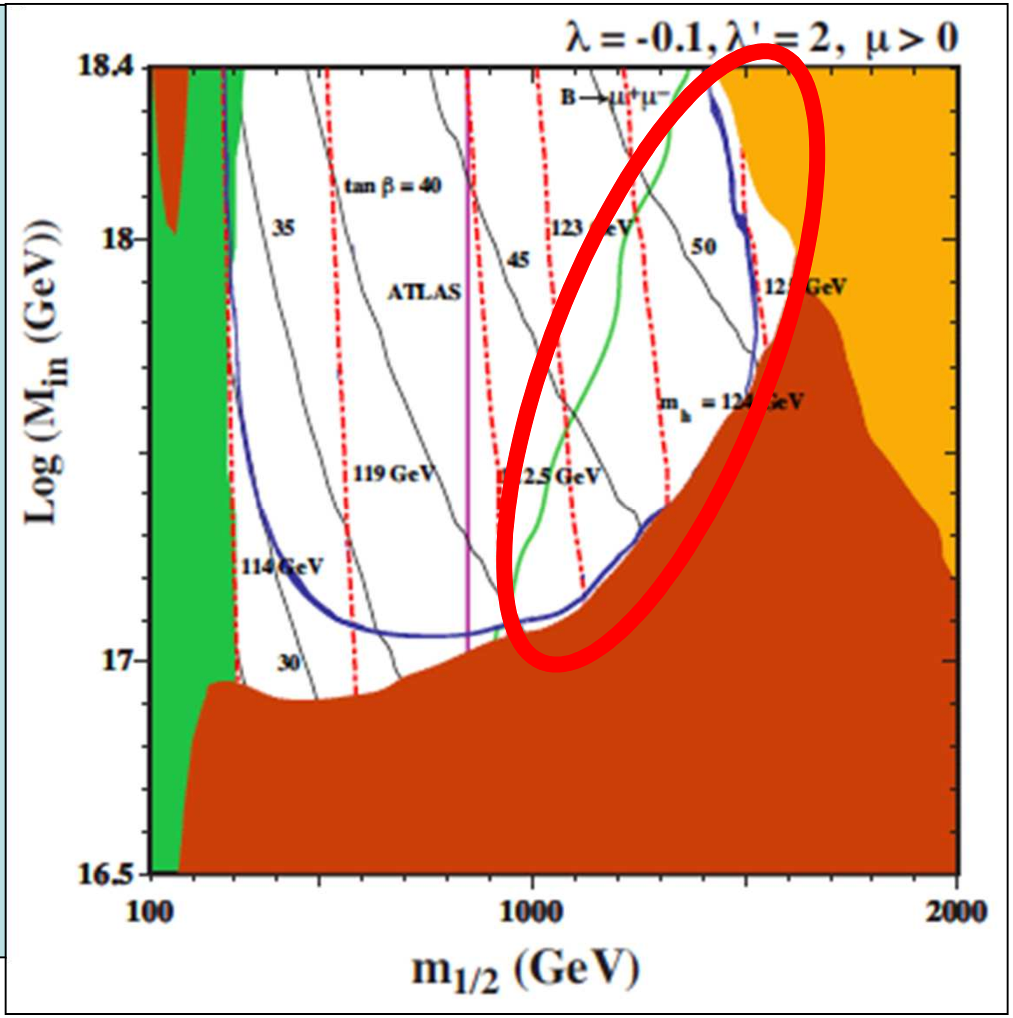
Add: $W_Y = \lambda H_2^i L_i y_1$

y_1 now interpreted as a right handed sneutrino with mass $M = 10^{-5}\, M_P$

Neutrino see-saw $m_\nu = \dfrac{\lambda^2 v^2}{M}$

No-Scale Framework for Particle Physics & Dark Matter

- Incorporating Starobinsky-like inflation, leptogenesis, neutrino masses, LHC constraints, supersymmetric dark matter,
- Stringy origin…?



JE, Nanopoulos & Olive, arXiv:1310.4770

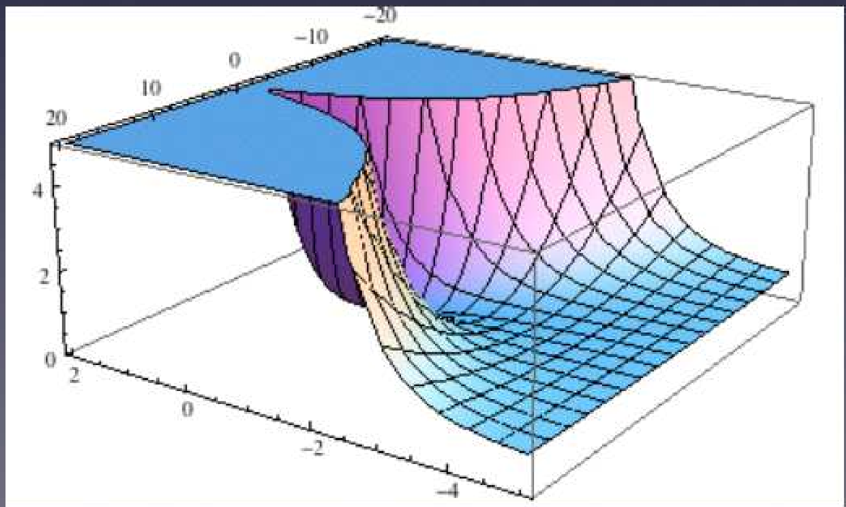
Qadratic Chaotic Inflation:

with $$W = \sqrt{3}M\phi(T - 1/2)$$

Cecotti

write $$T = \frac{1}{2}\left(e^{-\sqrt{\frac{2}{3}}\rho} + i\sqrt{\frac{2}{3}}\sigma\right)$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\rho\partial^\mu\rho + \frac{1}{2}e^{2\sqrt{\frac{2}{3}}\rho}\partial_\mu\sigma\partial^\mu\sigma - \frac{3}{4}m^2\left(1 - e^{-\sqrt{\frac{2}{3}}\rho}\right)^2 - e^{2\sqrt{2/3}\rho}\frac{1}{2}m^2\sigma^2\,,$$



Ferrara, Kehagias, Riotto

Qadratic Chaotic Inflation:

with $W = \sqrt{3} M \phi (T - 1/2)$

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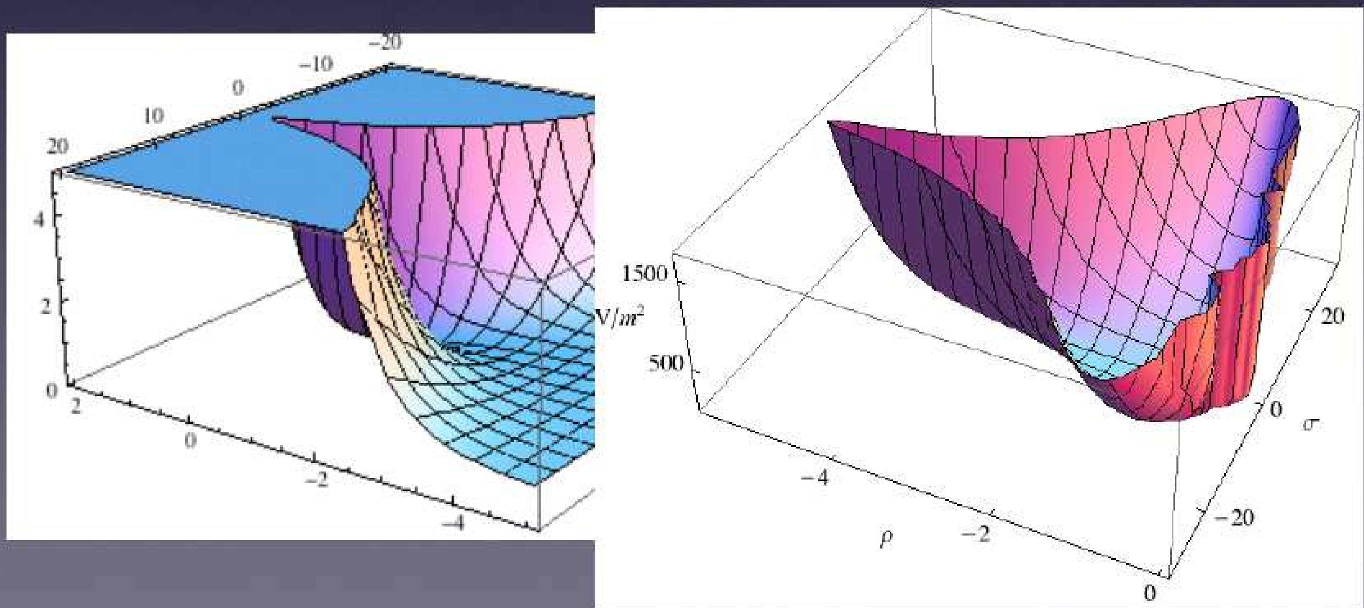
write $T = \frac{1}{2}\left(e^{-\sqrt{\frac{2}{3}}\rho} + i\sqrt{\frac{2}{3}}\sigma\right)$

$$\mathcal{L} = \frac{1}{2}\partial_\mu\rho\partial^\mu\rho + \frac{1}{2}e^{2\sqrt{\frac{2}{3}}\rho}\partial_\mu\sigma\partial^\mu\sigma - \frac{3}{4}m^2\left(1 - e^{-\sqrt{\frac{2}{3}}\rho}\right)^2 - e^{2\sqrt{2/3}\rho}\frac{1}{2}m^2\sigma^2 ,$$



Ferrara, Kehagias, Riotto

Ellis, Garcia, Nanopoulos, Olive

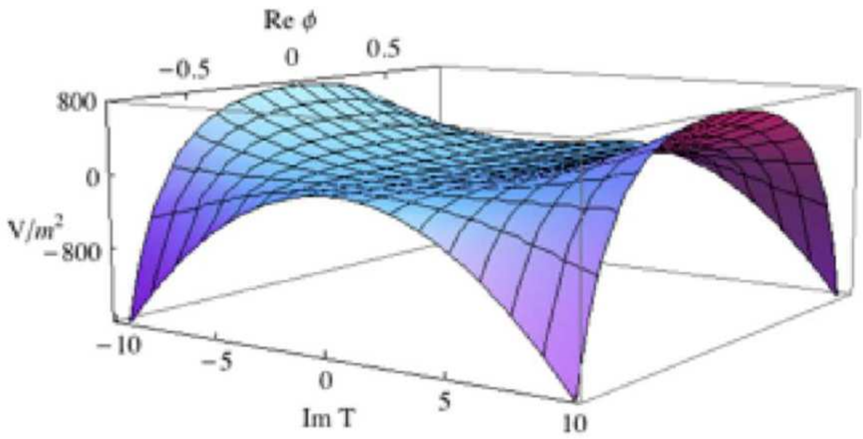


Figure 2: *The scalar potential of the model (30, 33) projected onto the* $(\mathrm{Im}\,T, \mathrm{Re}\,\phi)$ *plane with fixed values* $\mathrm{Re}\,T = 1/2$ *and* $\mathrm{Im}\,\phi = 0$.

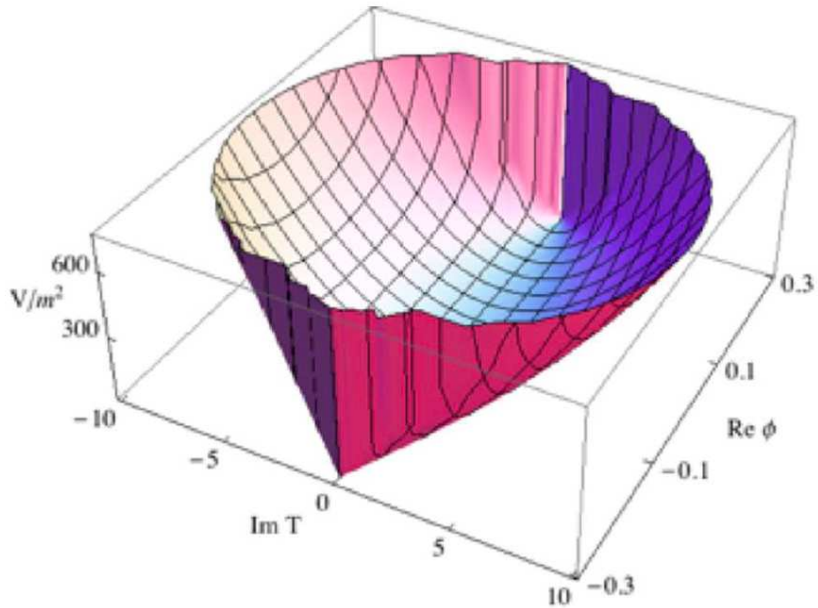


Figure 4: *As in Fig. 2, but for the scalar potential of the model (30, 34).*

SU(1,1)/U(1) models

Ellis, Garcia, Nanopoulos, Olive

$$K = -3\ln(T+\bar{T}) + \frac{|\phi|^2}{(T+\bar{T})^w}$$

with $W = \sqrt{3}M\phi(T-1/2)$

$$V \propto e^{|\phi|^2/(T+\bar{T})^w} \simeq e^{|\phi|^2}$$

$$V = 3m^2|T-1/2|^2(T+T^*)^{(w-3)}$$

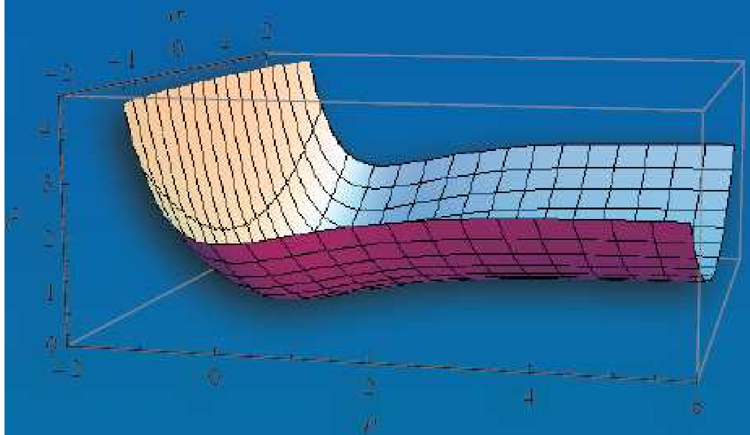
choose $w = 3$

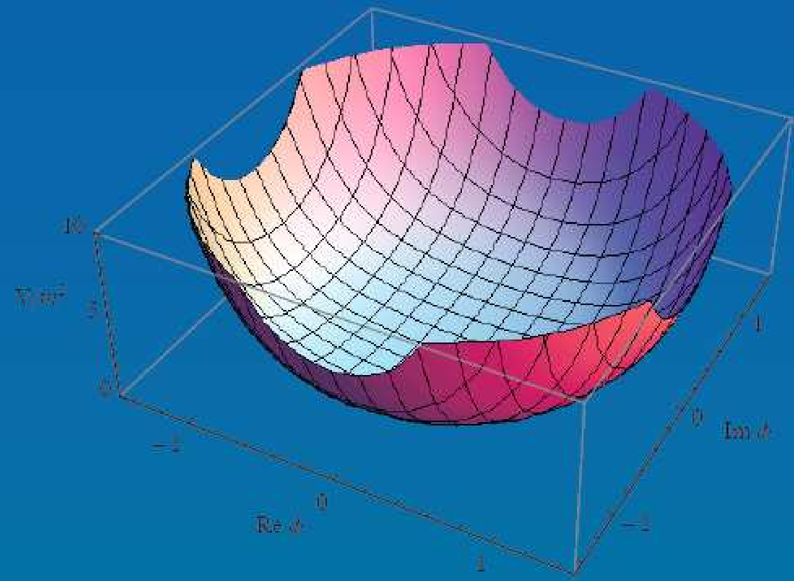
One No-Scale Model to Fit Them All

Ellis, Garcia, Nanopoulos, Olive

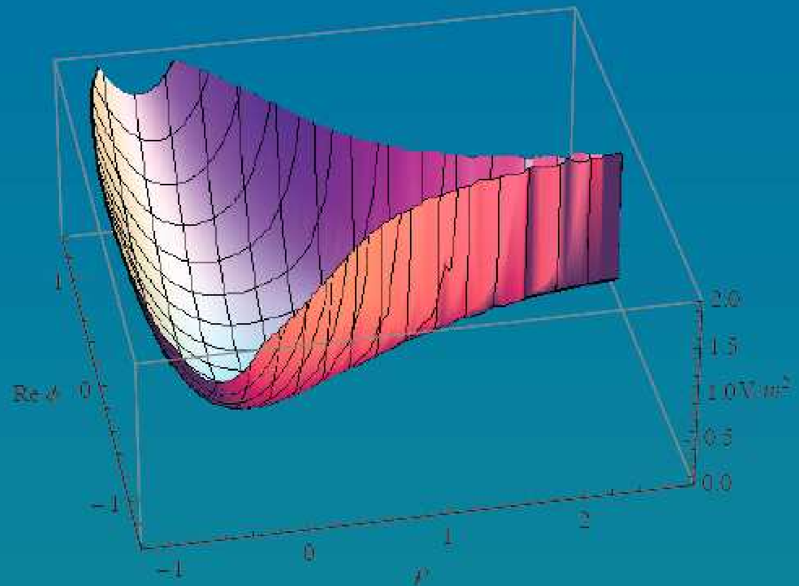
again write $T = \frac{1}{2}\left(e^{-\sqrt{\frac{2}{3}}\rho} + i\sqrt{\frac{2}{3}}\,\sigma\right)$

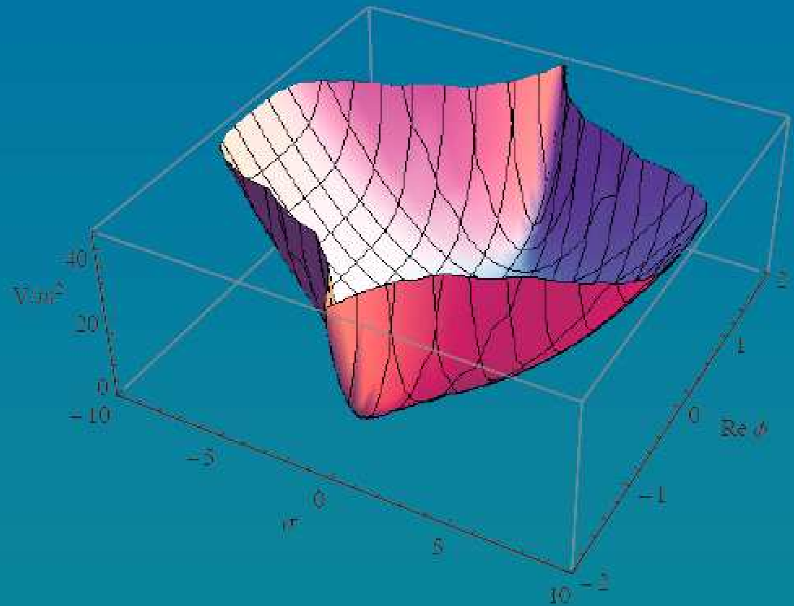
$$\mathcal{L} = \frac{1}{2}\partial_\mu\rho\partial^\mu\rho + \frac{1}{2}e^{2\sqrt{\frac{2}{3}}\rho}\partial_\mu\sigma\partial^\mu\sigma - \frac{3}{4}m^2\left(1 - e^{-\sqrt{\frac{2}{3}}\rho}\right)^2 - \frac{1}{2}m^2\sigma^2$$





The Potential





$$K = -3\log\left(T+T^* - c(\cos\theta(T+T^*-1) - i\sin\theta(T-T^*))^4\right) + \frac{|\phi|^2}{(T+T^*)^3}\,.$$

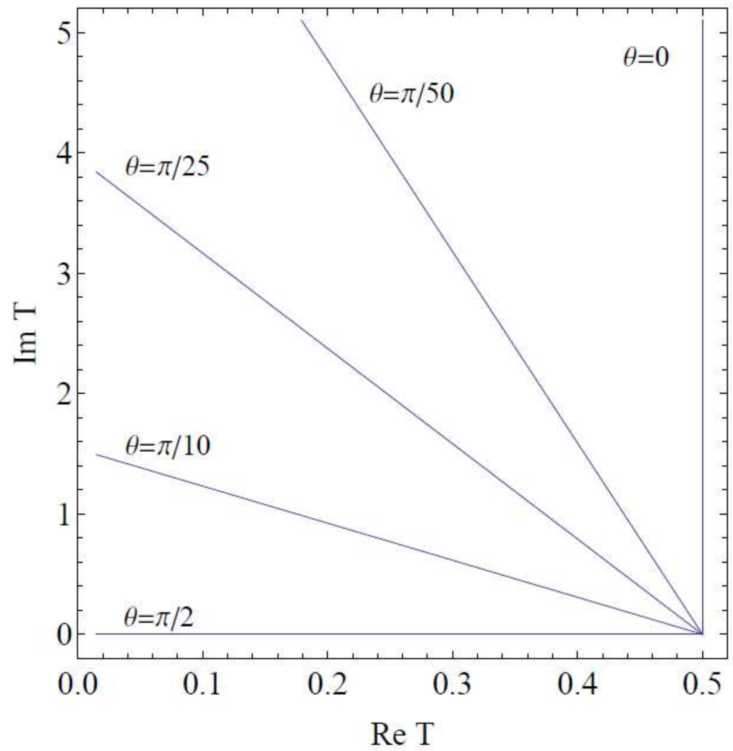


Figure 2: *Inflationary directions in the* $(\mathrm{Re}\,T, \mathrm{Im}\,T)$ *plane, labeled by the stabilization angle* θ*.*

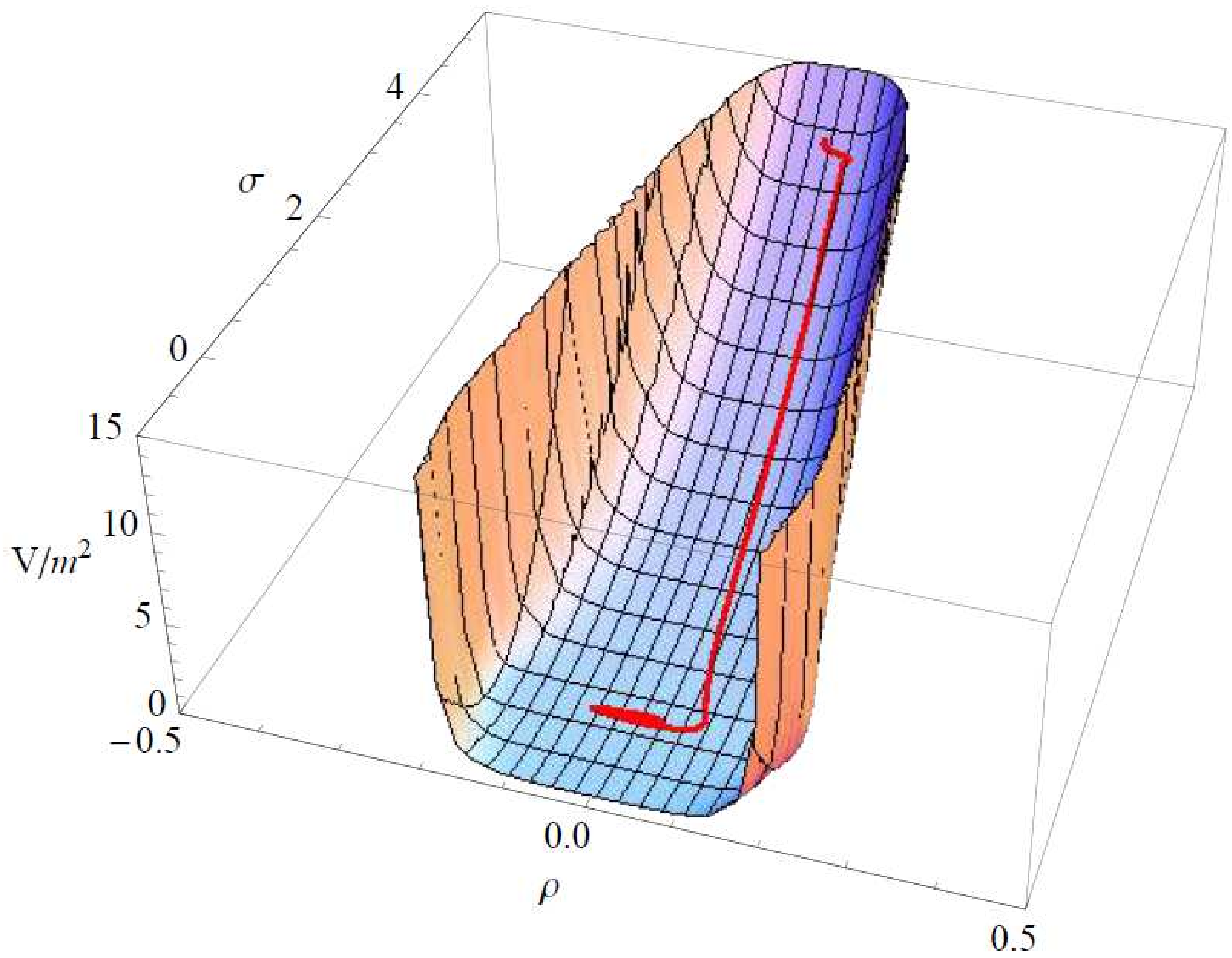


Figure 4: *Numerical solution for $\theta = 0$, $c = 1000$, with initial conditions $\rho_0 = 0$, $\sigma_0 = 5$ and $\phi_0 = 0$: 'circling the drain'.*

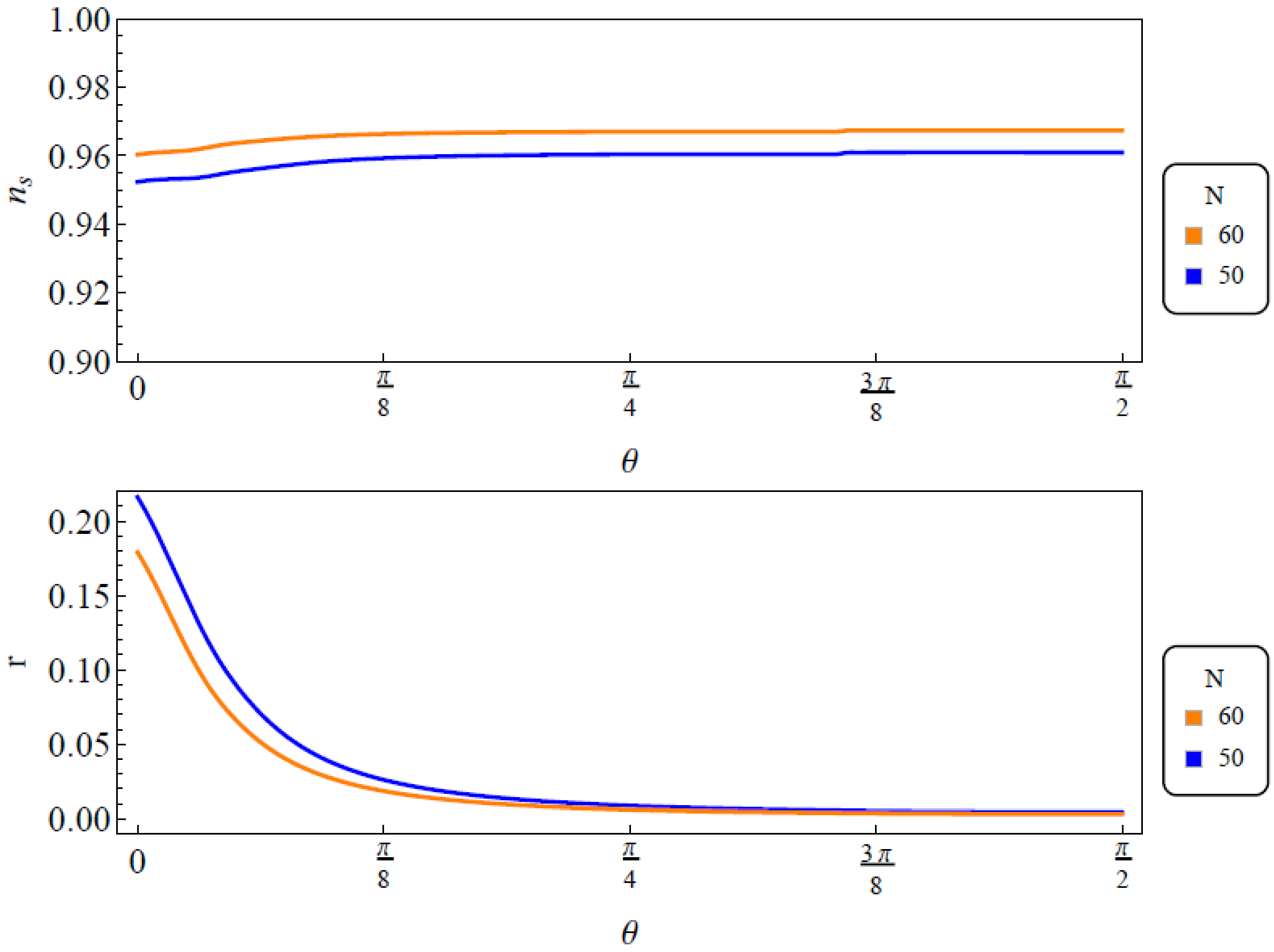


Figure 9: *Upper panel: The scalar tilt as function of θ. Lower panel: The tensor-to-scalar ratio as function of θ.*

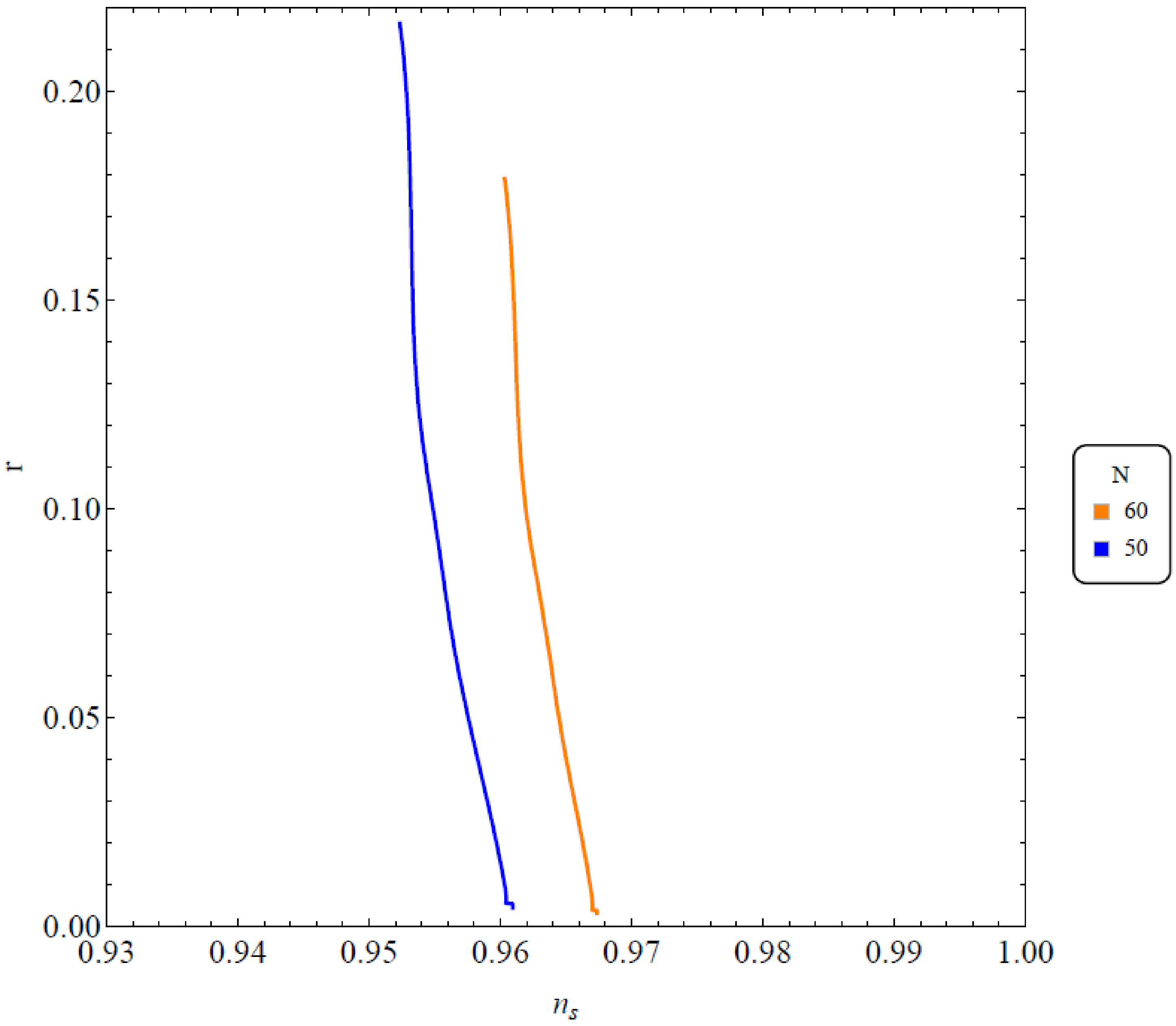


Figure 10: *The parametric curve* $(n_s(\theta), r(\theta))$.

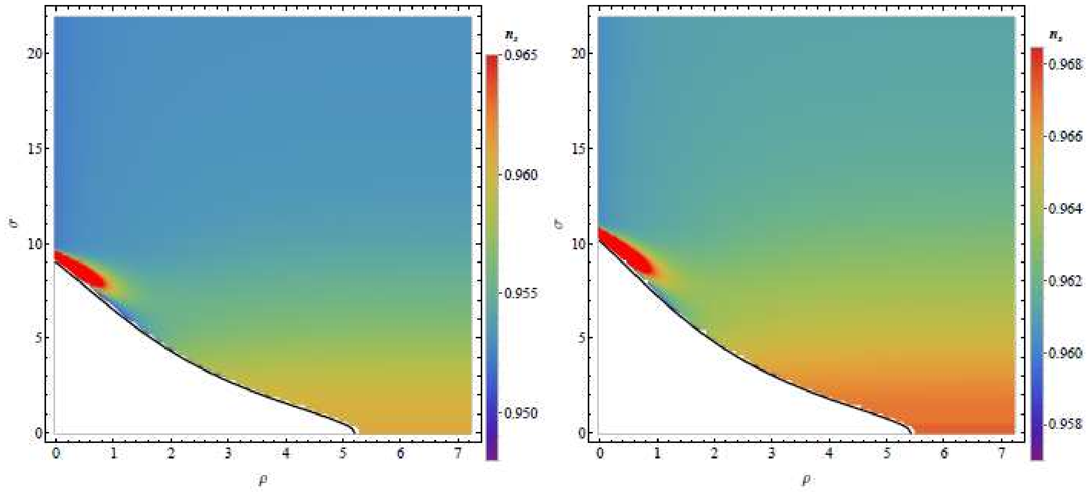


Figure 13: *The scalar tilt n_s with stationary initial conditions at arbitrary points in the (ρ, σ) plane for $\phi_0 = 0$, $c = 10$. Left panel: The case of $N = 50$ e-foldings. Right panel: The case of $N = 60$ e-foldings. In each case, the solid curve is the boundary for the specified value of N.*

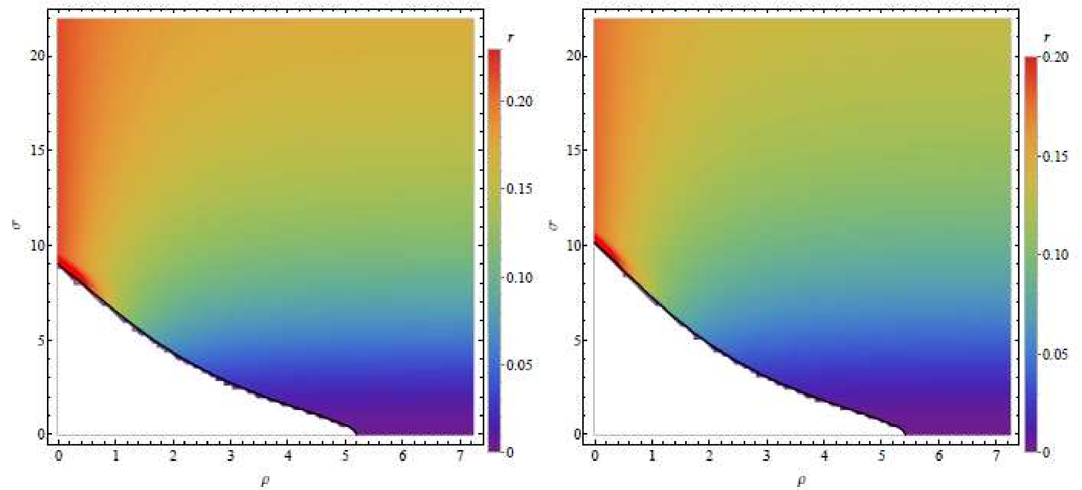
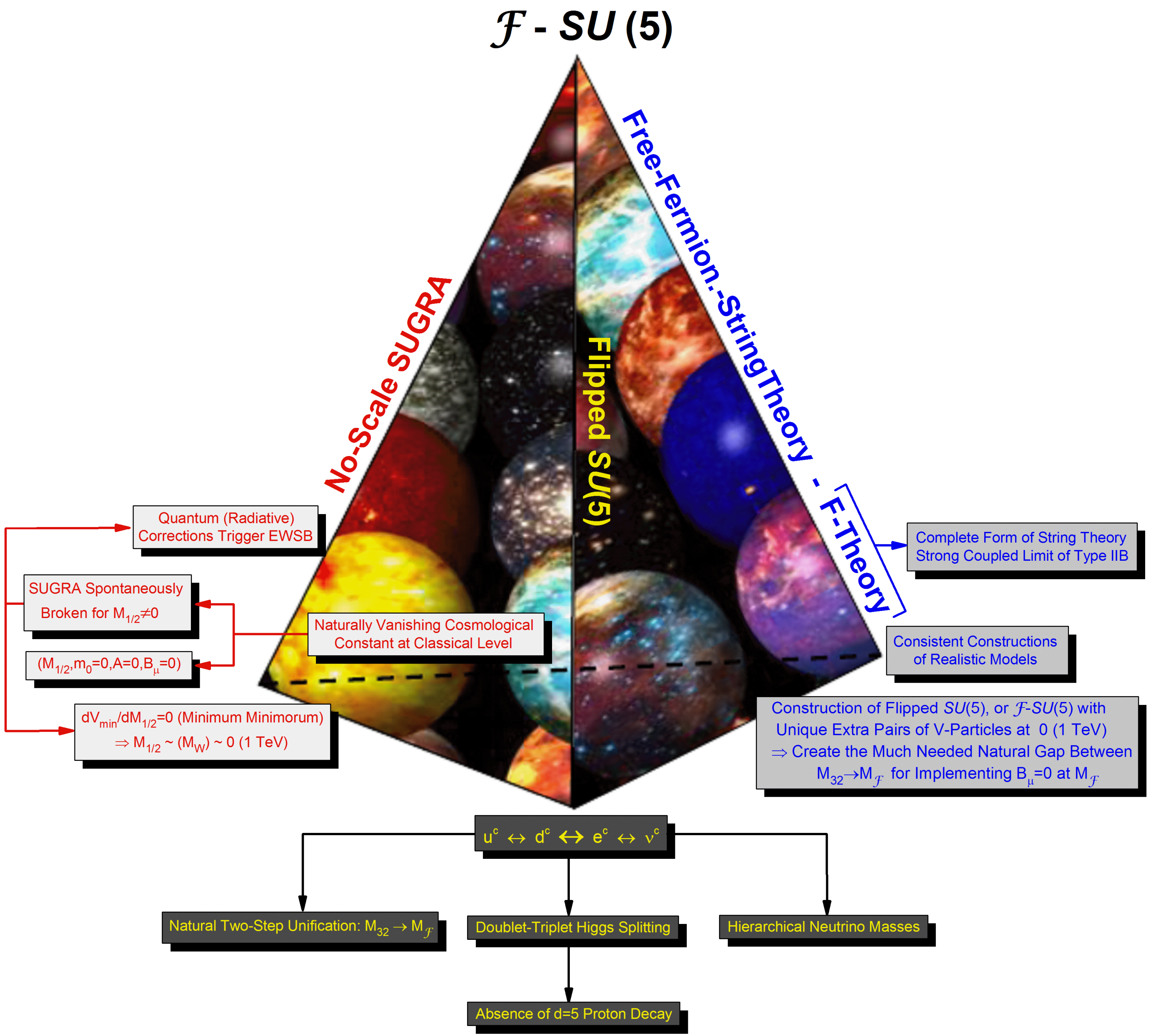
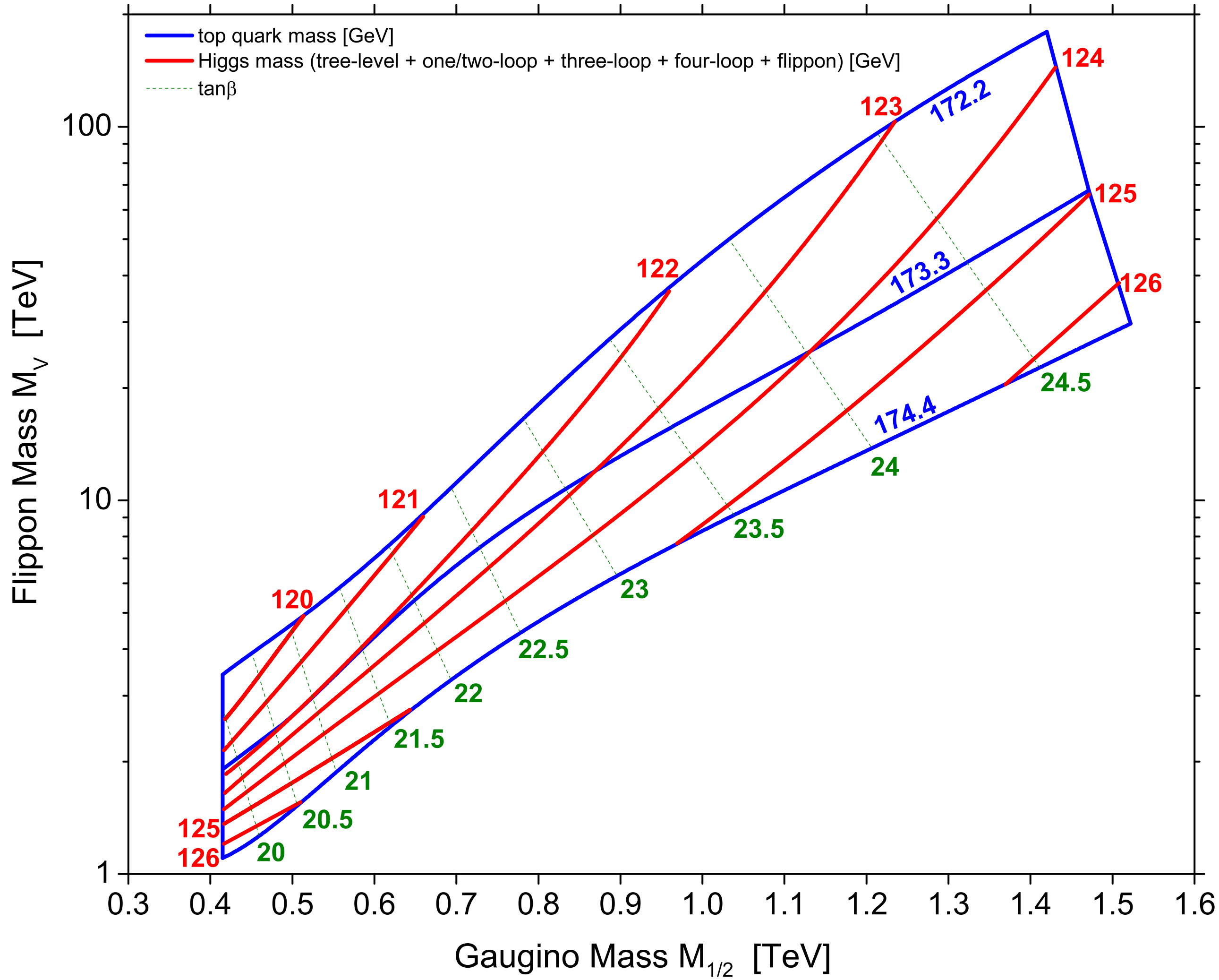


Figure 14: *The tensor-to-scalar ratio r with stationary initial conditions at arbitrary points in the (ρ, σ) plane for $\phi_0 = 0$, $c = 10$. Left panel: The case of $N = 50$ e-foldings. Right panel: The case of $N = 60$ e-foldings. In each case, the solid curve is the boundary for the specified value of N.*

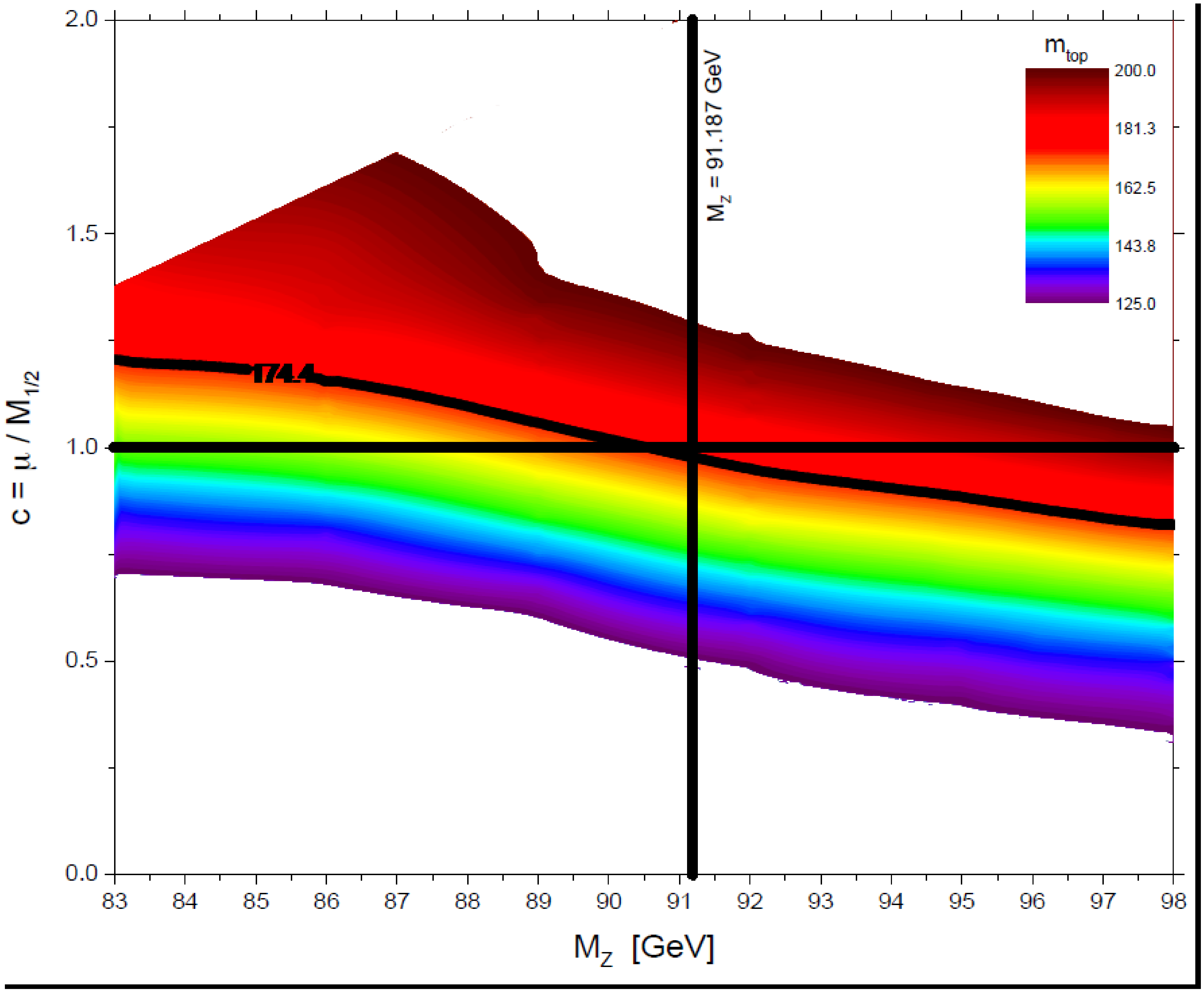


ℱ - SU (5)
No-Scale SUGRA
Flipped SU(5)
Free-Fermion.-StringTheory - F-Theory
Quantum (Radiative) Corrections Trigger EWSB
SUGRA Spontaneously Broken for $M_{1/2}\neq 0$
Naturally Vanishing Cosmological Constant at Classical Level
$(M_{1/2}, m_0=0, A=0, B_\mu=0)$
$dV_{min}/dM_{1/2}=0$ (Minimum Minimorum)
$\Rightarrow M_{1/2} \sim (M_W) \sim 0$ (1 TeV)
Complete Form of String Theory
Strong Coupled Limit of Type IIB
Consistent Constructions of Realistic Models
Construction of Flipped SU(5), or ℱ-SU(5) with Unique Extra Pairs of V-Particles at 0 (1 TeV)
$\Rightarrow$ Create the Much Needed Natural Gap Between $M_{32} \to M_{\mathcal{F}}$ for Implementing $B_\mu=0$ at $M_{\mathcal{F}}$
$u^c \leftrightarrow d^c \leftrightarrow e^c \leftrightarrow \nu^c$
Natural Two-Step Unification: $M_{32} \to M_{\mathcal{F}}$
Doublet-Triplet Higgs Splitting
Hierarchical Neutrino Masses
Absence of d=5 Proton Decay

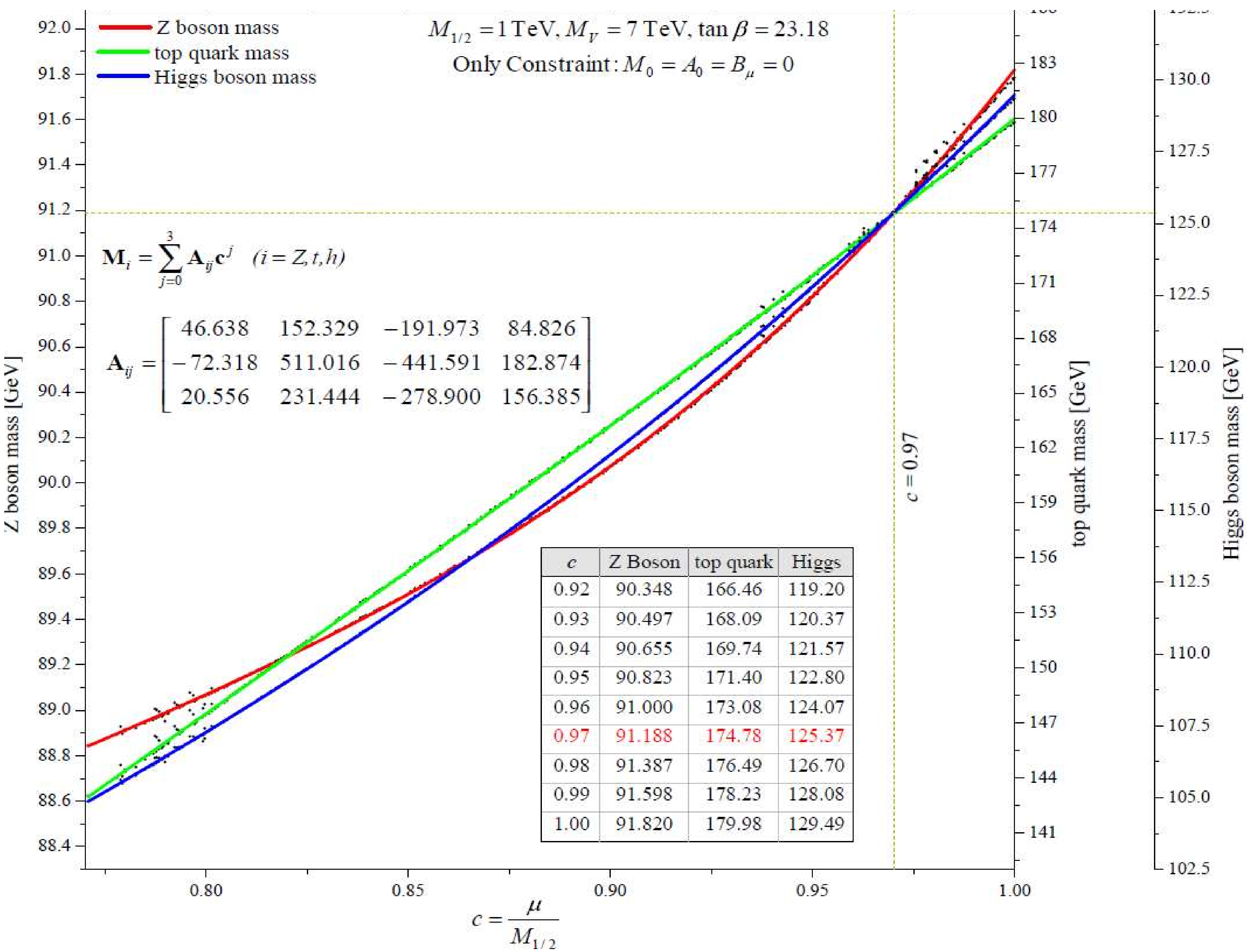
Part II of The Golden Point Saga, as Featured in arXiv: 1007.5100
Also Starring: Tianjun Li, James A. Maxin & Joel W. Walker
D.V. NANOPOULOS
THE GOLDEN STRIP
of Correlated Top Quark, Gaugino, and Vectorlike Mass In No-Scale, No Parameter
F-SU(5)
George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University
Houston Advanced Research Center (HARC)
Academy of Athens



Constrained model space of No-Scale F-SU(5) as a function of the gaugino mass $M_{1/2}$ and flippon mass M_V . The thick lines demarcate the total Higgs boson mass gradients, including the tree-level plus one/two-loop (as computed by the SuSpect 2.34 codebase), the three-loop plus four-loop contributions, and the flippon contribution. The thin dashed lines represent gradients of tanβ, while the upper and lower exterior boundaries are defined by a top quark mass of m_t = 173.3± 1.1 GeV. The left edge is marked by the LEP constraints, while the right edge depicts where the Planck relic density can no longer be maintained due to an LSP and light stau mass difference less than the on-shell tau mass. All model space within these boundaries satisfy the Planck relic density constraint Ωh^2 = 0.1199 ± 0.0027 and the No-Scale requirement Bμ = 0.



2.0
1.5
1.0
0.5
0.0
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
M_Z [GeV]
$c = \mu / M_{1/2}$
$M_Z = 91.187$ GeV
174.4
m_{top}
200.0
181.3
162.5
143.8
125.0



c	Z Boson	top quark	Higgs
0.92	90.348	166.46	119.20
0.93	90.497	168.09	120.37
0.94	90.655	169.74	121.57
0.95	90.823	171.40	122.80
0.96	91.000	173.08	124.07
0.97	91.188	174.78	125.37
0.98	91.387	176.49	126.70
0.99	91.598	178.23	128.08
1.00	91.820	179.98	129.49

Summary

- Inflation ingrained in Standard Cosmology.
- The Starobinsky model of inflation can be realized in no-scale supergravity with either modulus T or 'matter' field ϕ with a simple WZ superpotential.
- The latter lends itself nicely to equating the inflaton with a right-handed sneutrino
- Can construct a simple potential which interpolates between the Planck-friendly (small r) solution, or the BICEP-friendly (large r) solution
- Can easily integrate low energy susy phenomenology