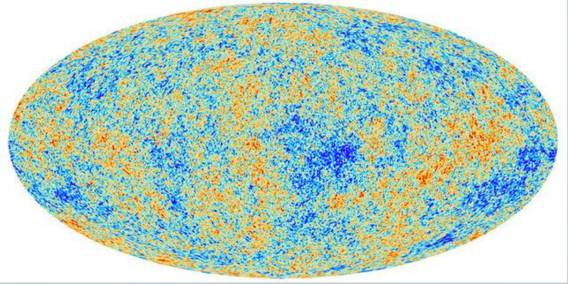
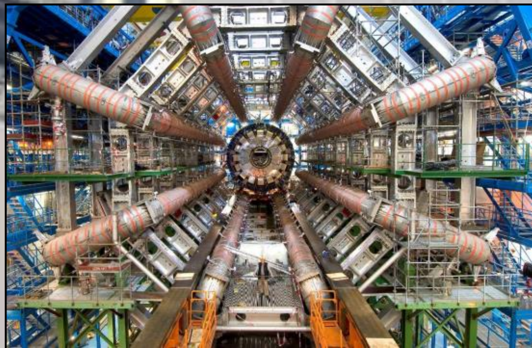


Models of Cosmological Inflation

a Bridge between String Theory and Particle Physics?



The Hypothesis of Cosmological Inflation

- Why is the Universe so big?
- Why is the Universe so homogeneous (on large scales)?
- Why is geometry (approximately) Euclidean **($\Omega_{Tot} \sim 1$)?**
- What is the origin of the structures in the Universe?
- **A possible answer:**
- The Universe grew very rapidly just after the Big Bang
- Pushed by energy in empty space, similar to the Higgs field

(Perhaps it was the Higgs field itself?)

- Structures due to quantum fluctuations?

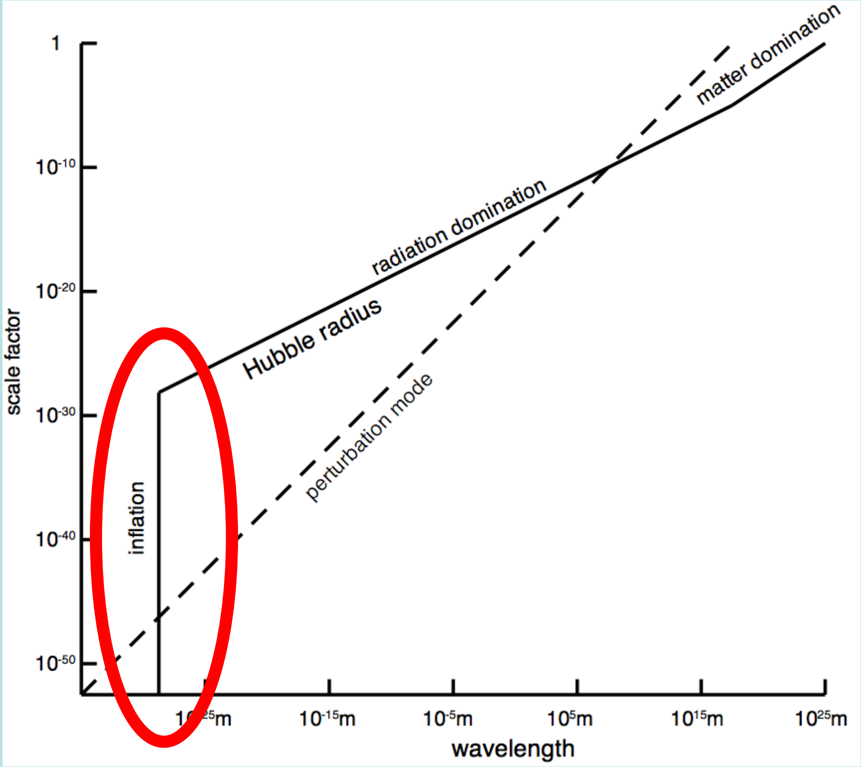
Cosmological Inflation

- Expansion driven by cosmological constant:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3}$$

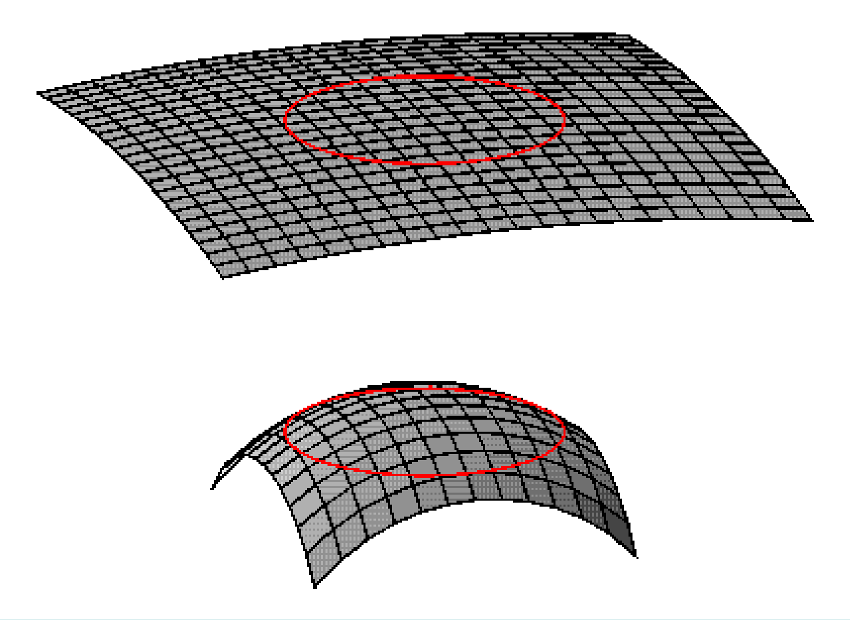
(a = scale size)

- Exponential expansion
- All the visible Universe was once very small
- In close contact: (almost) homogeneous
- Geometry ~ flat



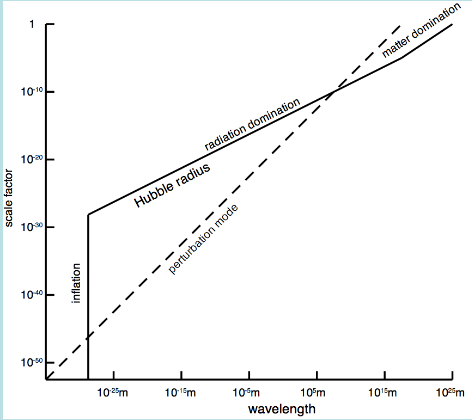
The Hypothesis of Cosmological Inflation

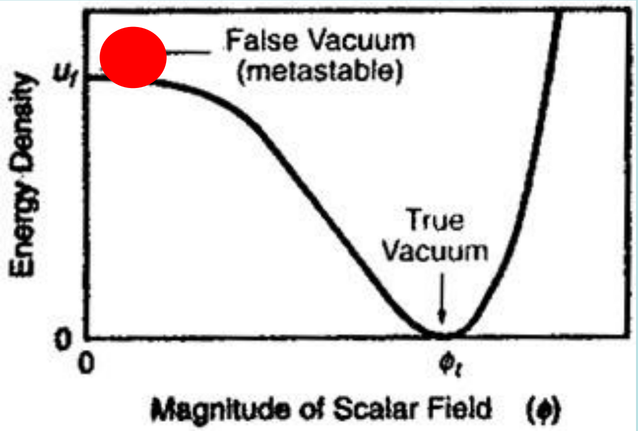
- All the visible Universe started in very small region
- Then it blew up very quickly, like a kid's ballon
- In this way its geometry became almost flat
- Structures originated from quantum fluctuations



Primordial Perturbations

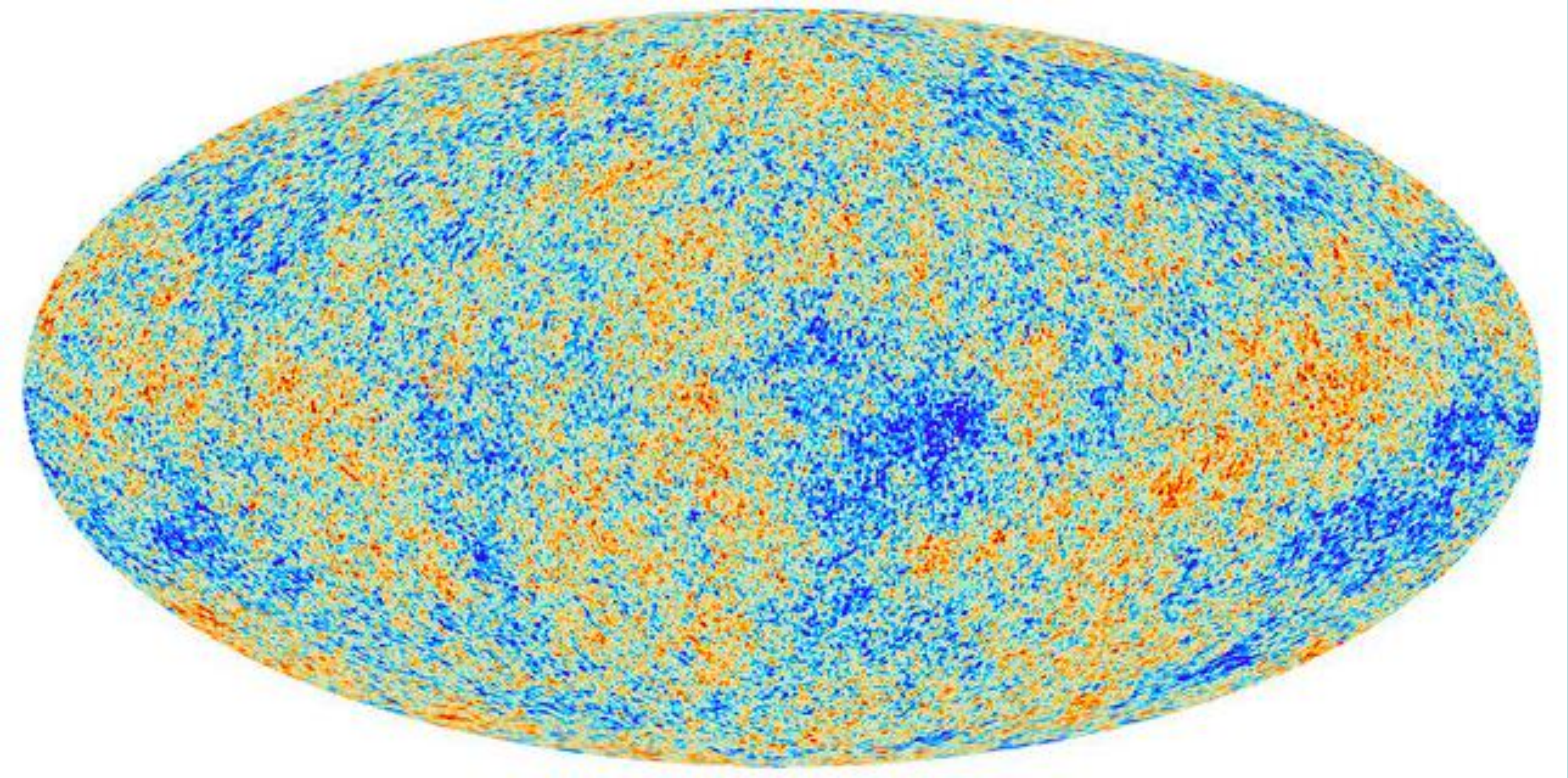
- “Cosmological constant” due to vacuum energy in “inflaton” field ϕ: $\Lambda \sim V(\phi) \neq 0$
- Quantum fluctuations in ϕ cause perturbations in energy density (scalar) and metric (tensor)
- (Almost) independent of scale size





- Visible in cosmic microwave background (CMB)

Cosmological Inflation in Light of Planck



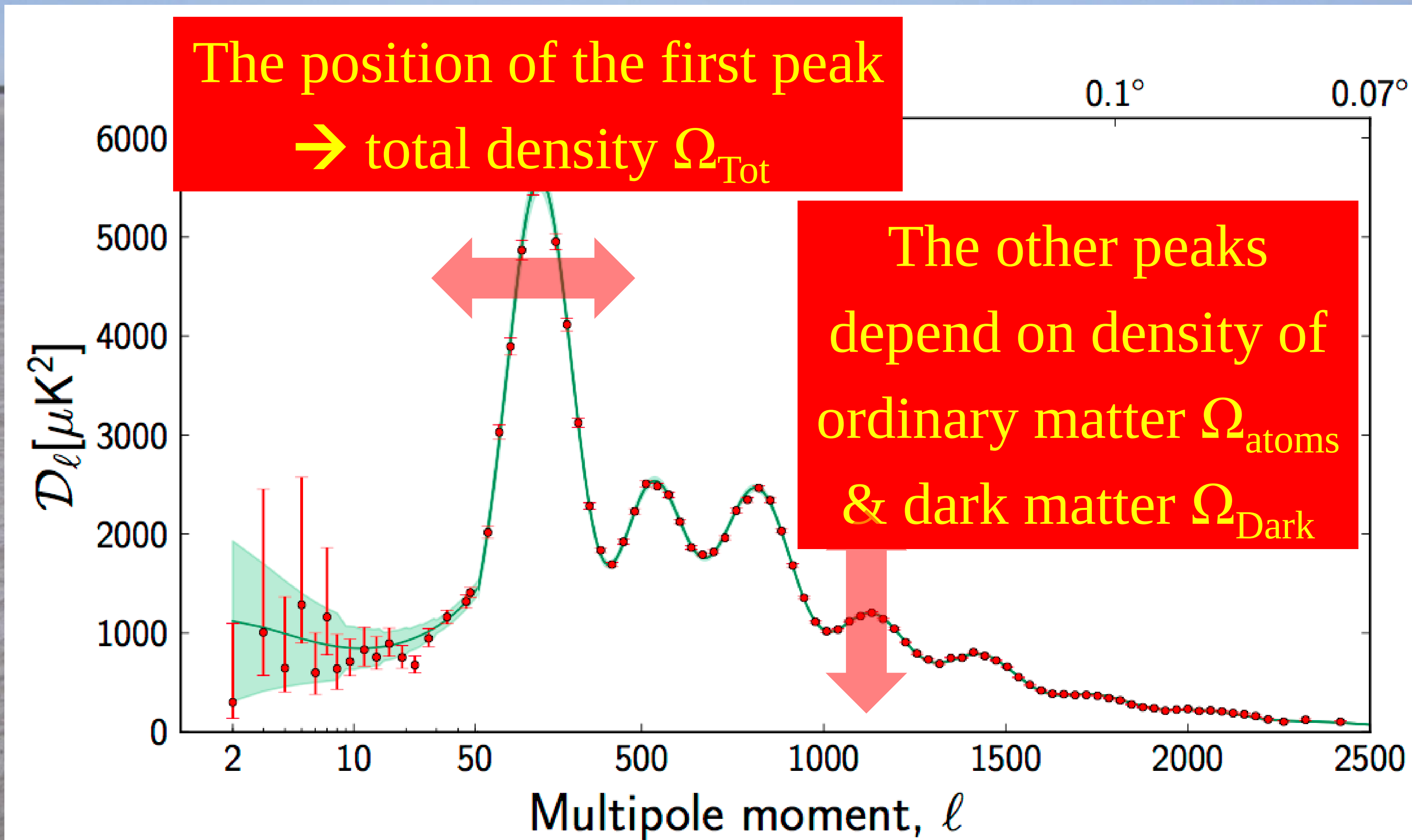
A scalar in the sky? Supersymmetry/supergravity?

CMB: Opportunity & Challenge

- Unique probe of (very) high-energy scale
- Close to string scale?
- Detailed measurements

  ➔ Many probes of models of inflation
- Connection with collider physics via pattern of inflaton decay?
- Use string-motivated framework to construct models of inflation
- **No-scale supergravity (+ flipped unification)**

The Spectrum of Fluctuations in the Cosmic Microwave Background



Slow-Roll Inflation

- Expansion driven by cosmological constant:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3}$$

- Getting small density perturbations requires a "small" potential: $\left(\frac{V}{\epsilon}\right)^{\frac{1}{4}} = 0.0275 \times M_{Pl}$

- That is almost flat: $\epsilon = \frac{1}{2}M_{Pl}^2\left(\frac{V'}{V}\right)^2$, $\eta = M_{Pl}^2\left(\frac{V''}{V}\right)$ small

  so as to get sufficient e-folds of expansion:

$$N = \frac{v^2}{M_{Pl}^2}\int_{x_i}^{x_e}\left(\frac{V}{V'}\right)dx$$

Inflationary Perturbations in a Nutshell

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

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

(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 → $r \sim \varepsilon$

Main CMB Observables

- Scalar and tensor perturbations
- Tilt in scalar spectrum (running down hill)

$$n_s = 1 - 6\epsilon + 2\eta$$

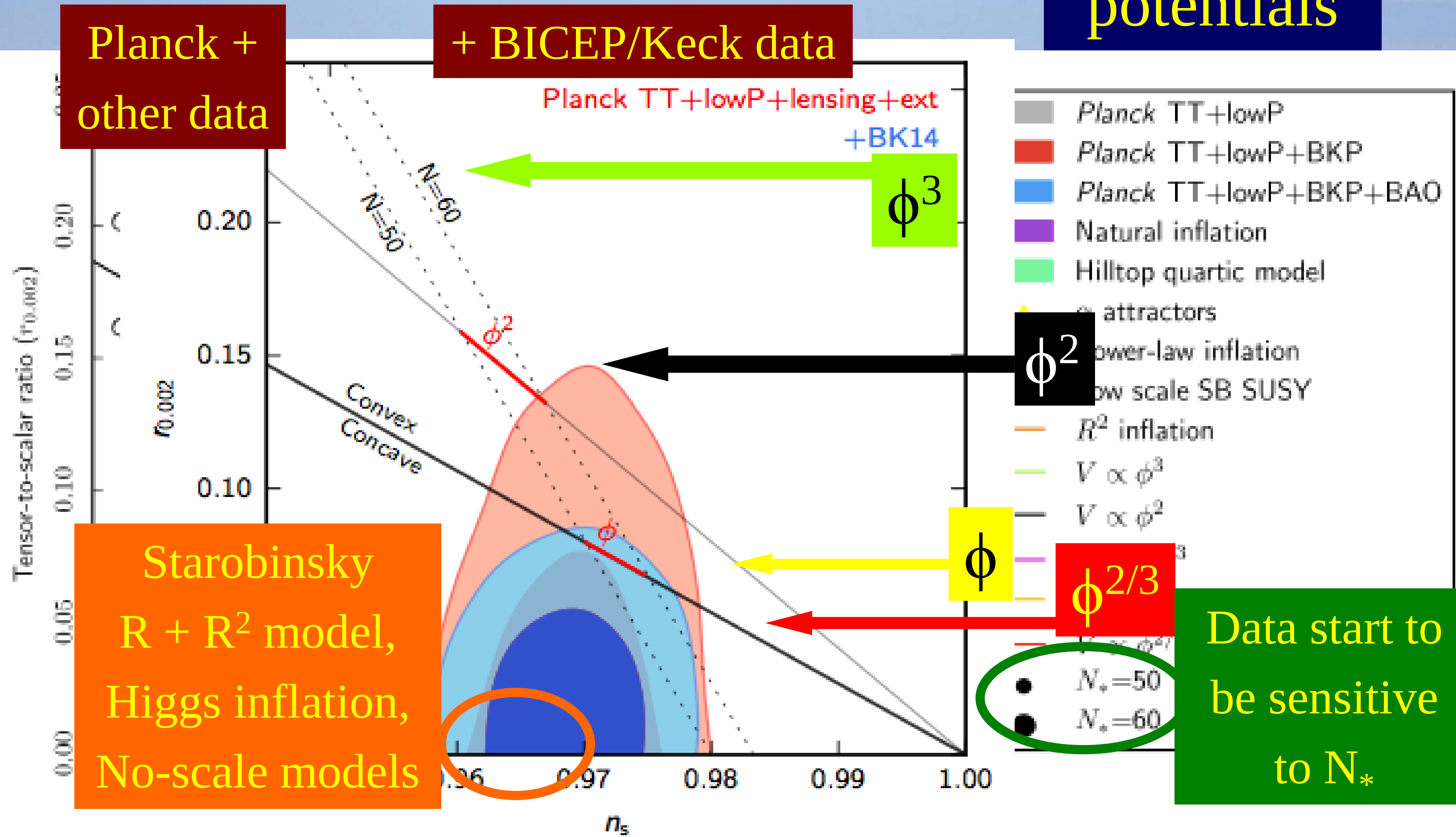
- Tensor perturbations = gravitational waves of quantum origin
- Tensor/scalar ratio:

$$r = 16\epsilon$$

- Are perturbations ~ Gaussian?
  - Look for deviations, e.g., f_{NL}
- Expected to be small in slow-roll models

Inflationary Landscape

Monomial Single-field potentials



Challenges for Inflationary Models

- Links to low-energy physics?
  - Only SM candidate for inflaton is Higgs
    - **BUT** negative potential, ….
- Link to other physics?
  - SUSY partner of RH (singlet) neutrino?
  - Some sort of axion?
- Links to Planck-scale physics?
  - Inflaton candidates in string theory?
  - Inflaton candidates in compactified string models?

Starobinsky Model

- Non-minimal general relativity (singularity-free cosmology):

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)$$

Starobinsky, 1980

- **No scalar!?**
- **Conformally equivalent to scalar field model:**

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2\right]$$

Stelle; Whitt, 1984

- Inflationary interpretation, calculation of perturbations:

Mukhanov & Chibisov, 1981

$$\delta S_b = \frac{1}{2}\int d^4x\left[\phi'^2 - \nabla_a\phi\nabla^a\phi + \left(\frac{a''}{a} + M^2a^2\right)\phi^2\right]$$

Higgs Inflation: a Single Scalar?

Bezrukov & Shaposhnikov, arXiv:0710.3755

- Standard Model with non-minimal coupling to gravity:
$$S_J = \int d^4x\sqrt{-g}\left\{ -\frac{M^2+\xi h^2}{2}R + \frac{\partial_\mu h \partial^\mu h}{2} - \frac{\lambda}{4}\left(h^2-v^2\right)^2 \right\}$$
- Consider case $1 \ll \sqrt{\xi} \lll 10^{17}$: in Einstein frame
$$S_E = \int d^4x\sqrt{-\hat{g}}\left\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - U(\chi) \right\}$$
- With potential: $U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$

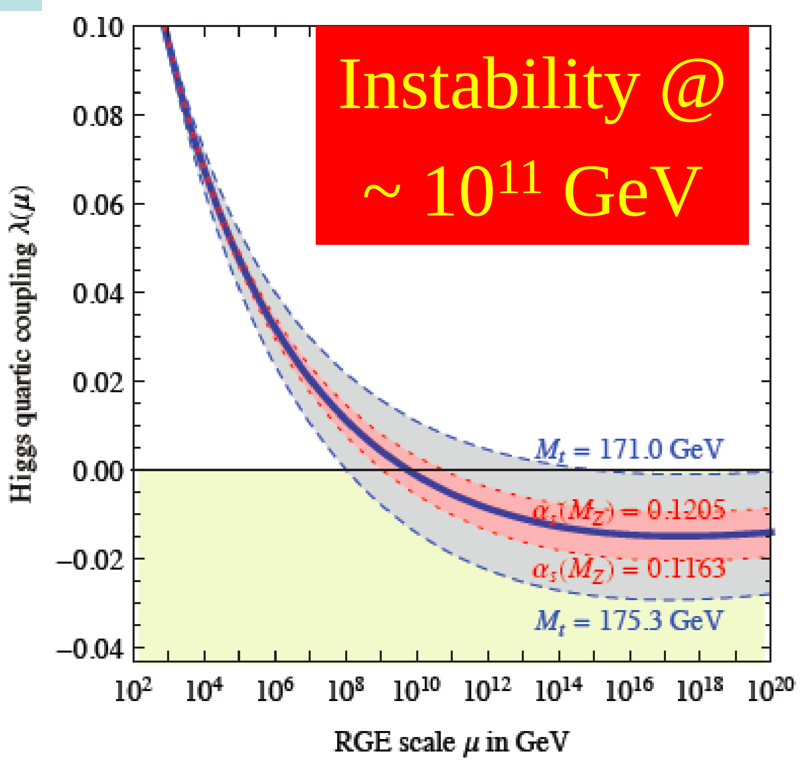
  Similar to Starobinsky, but not identical
- Successful inflationary potential at $\chi \gg M_P$

Problem for Higgs Inflation

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$



Instability @ ~ 10^{11} GeV

- Small M_h: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- **Negative potential not suitable for inflation**
- **Problem avoided with supersymmetry**

What lies beyond the Standard Model?

Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

Inflation Cries out for Supersymmetry

- Want "elementary" scalar field
  (at least looks elementary at energies << M_P)
- To get right magnitude of perturbations
  prefer mass << M_P
  (~ 10^{13} GeV in simple φ^2 models)
- And/or prefer small self-coupling λ << 1
- **Both technically natural with supersymmetry**

JE, Nanopoulos, Olive & Tamvakis 1983

Inflation cries out for Supergravity

- Stabilize ‘elementary’ scalar inflaton
  (needs mass << m_P and/or small coupling)
- **Supersymmetry**
- The only good symmetry is a local symmetry
  (cf, gauge symmetry in Standard Model)
- **Local supersymmetry = supergravity**
- Early Universe cosmology needs gravity
- **Supersymmetry + gravity = supergravity**

No-Scale Supergravity Inflation

- **Supersymmetry + gravity = Supergravity**
- Include conventional matter?
- Potentials in generic supergravity models have 'holes' with depths $\sim - M_P^4$
- Exception: **no-scale supergravity**

Cremmer, Ferrara, Kounnas & Nanopoulos, 1983

- **Appears in compactifications of string**

Witten, 1985

- Flat directions, scalar potential ~ global model + controlled corrections

JE, Enqvist, Nanopoulos, Olive & Srednicki, 1984

JE, Nanopoulos & Olive, arXiv:1305.1247, 1307.3537, …

Old No-Scale Supergravity Model of Inflation

Volume 152B, number 3,4 PHYSICS LETTERS

SU(N, 1) INFLATION

John ELLIS, K. ENQVIST, D.V. NANOPOULOS
CERN, Geneva, Switzerland

K.A. OLIVE
Astrophysics Theory Group, Fermilab, Batavia, IL 60510, USA

and

M. SREDNICKI
Department of Physics, University of California, Santa Barbara, CA 93106, USA

Received 7 December 1984

We present a simple model for primordial inflation in the context of SU(N, 1) no-scale $n = 1$ supergravity. Because the model at zero temperature very closely resembles global supersymmetry, minima with negative cosmological constants do not exist, and it is easy to have a long inflationary epoch while keeping density perturbations of the right magnitude and satisfying other cosmological constraints. We pay specific attention to satisfying the thermal constraint for inflation, i.e. the existence of a high temperature minimum at the origin.

- No ‘holes’ in effective potential with negative cosmological constant

JE, Enqvist, Nanopoulos, Olive & Srednicki, 1984

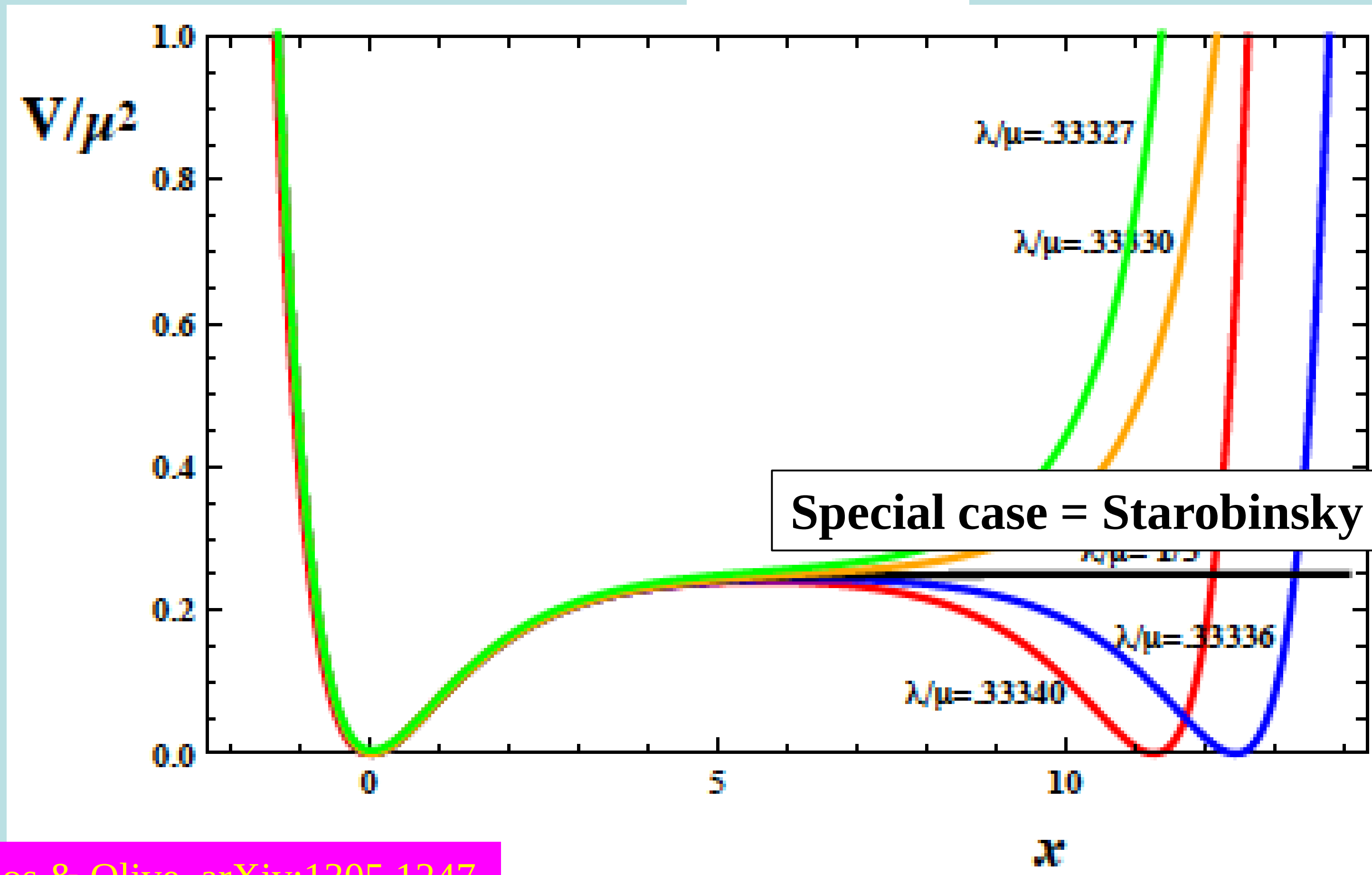
No-Scale Supergravity Inflation Revived

JE, Nanopoulos & Olive, arXiv:1305.1247

- Simplest SU(2,1)/U(1) example:
- Kähler potential: $K = -3\ln(T + T^* - |\phi|^2/3)$
- Wess-Zumino superpotential: $W = \frac{\mu}{2}\Phi^2 - \frac{\lambda}{3}\Phi^3$
- Assume modulus *T = c/2* fixed by 'string dynamics'
- Ef $\mathcal{L}_{eff} = \frac{c}{(c - |\phi|^2/3)^2}|\partial_\mu \phi|^2 - \frac{\hat{V}}{(c - |\phi|^2/3)^2}$ $\hat{V} \equiv \left|\frac{\partial W}{\partial \phi}\right|^2$:
- Modifications to globally supersymmetric case
- Good inflation possible …

No-Scale Supergravity Inflation

- Inflationary potential for $\lambda \simeq \mu/3$



JE, Nanopoulos & Olive, arXiv:1305.1247

Is there more profound connection?

- Starobinsky model:

$$S = \frac{1}{2}\int d^4x\sqrt{-g}(R + R^2/6M^2)$$

- After conformal transformation:

$$S = \frac{1}{2}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} + (\partial_\mu\varphi')^2 - \frac{3}{2}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2\right]$$

- Effective potential: $V = \frac{3}{4}M^2(1 - e^{-\sqrt{2/3}\varphi'})^2$
- Identical with the no-scale Wess-Zumino model for the case $\lambda = \mu/3$

… it actually IS Starobinsky

Cecotti, 1987

JE, Nanopoulos & Olive, arXiv:1305.1247

See also …

- Nakayama, Takahashi & Ya
- Kallosh & Linde – arXiv:13
- Buchmuller, Domcke & Ka
- Kallosh & Linde – arXiv:13
- Farakos, Kehagias and Riot
- Roest, Scalisi & Zavala – ar
- Kiritsis – arXiv:1307.5873
- Ferrara, Kallosh, Linde & P
- **… over 100 papers**

Review

arXiv:1507.02308v1 [hep-ph] 8 Jul 2015

No-Scale Inflation

John Ellis
Department of Physics, King's College London, London WC2R 2LS, UK;
Theory Division, CERN, CH-1211 Geneva 23, Switzerland
E-mail: John.Ellis@cern.ch

Marcos A. G. Garcia
William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
E-mail: garciagarcia@physics.umn.edu

Dimitri V. Nanopoulos
George P. and Cynthia W. Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA; Astroparticle Physics Group, Houston Advanced Research Center (HARC), Mitchell Campus, Woodlands, TX 77381, USA; Academy of Athens, Division of Natural Sciences, Athens 10679, Greece
E-mail: dimitri@physics.tamu.edu

Keith A. Olive
William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
E-mail: olive@physics.umn.edu

July 2015

Abstract. Supersymmetry is the most natural framework for physics above the TeV scale, and the corresponding framework for early-Universe cosmology, including inflation, is supergravity. No-scale supergravity emerges from generic string compactifications and yields a non-negative potential, and is therefore a plausible framework for constructing models of inflation. No-scale inflation yields naturally predictions similar to those of the Starobinsky model based on $R + R^2$ gravity, with a tilted spectrum of scalar perturbations: $n_s \sim 0.96$, and small values of the tensor-to-scalar perturbation ratio $r < 0.1$, as favoured by Planck and other data on the cosmic microwave background (CMB). Detailed measurements of the CMB may provide insights into the embedding of inflation within string theory as well as its links to collider physics.

KCL-PH-TH/2015-28, LCTS/2015-20, CERN-PH-TH/2015-144
ACT-05-15, MI-TH-1521, UMN-TH-3442/15, FTPI-MINN-15/32

Beyond Starobinsky

- Exponential approach to constant potential:

$$V = A\left(1 - \delta e^{-Bx} + \mathcal{O}(e^{-2Bx})\right)$$

- Relations between observables:

$$\begin{aligned} n_s &= 1 - 2B^2\delta e^{-Bx}\,, \\ r &= 8B^2\delta^2 e^{-2Bx}\,, \\ N_* &= \frac{1}{B^2\delta} e^{+Bx}\,. \end{aligned}$$

$$n_s = 1 - \frac{2}{N_*}\,,\; r = \frac{8}{B^2 N_*^2}$$

- E.g., multiple no-scale moduli:

$$K \ni -\Sigma_i N_i \ln(T_i + T_i^*) : \quad N_i > 0, \;\; \Sigma_i N_i = 3$$

- Characteristic of generic string compactifications
- Tensor/scalar ratio may be < prediction of Starobinsky model:

$$B = \sqrt{\left(\frac{2}{N_i}\right)}$$

$$r = \frac{4 N_i}{N_*^2}\,.$$

- **String phenomenology via the CMB?**

JE, Nanopoulos & Olive, arXiv:1307.3537

Ferrara, Kallosh, Linde & Porrati – arXiv:1307.7696

How many e-Folds of Inflation?

- General expression:

JE, García, Nanopoulos & Olive, arXiv:1505.06986

$$N_* = 67 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{M_P^4 \rho_{\rm end}}\right) + \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right) - \frac{1}{12}\ln g_{\rm th}$$

- In no-scale supergravity models:

$$N_* = 68.659 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(A_{S*}\right) - \frac{1}{4}\ln\left(N_* - \sqrt{\frac{3}{8}}\frac{\phi_{\rm end}}{M_P} + \frac{3}{4}e^{\sqrt{\frac{2}{3}}\frac{\phi_{\rm end}}{M_P}}\right)$$
$$+ \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\left(2.030 + 2\ln\left(\Gamma_\phi/m\right) - 2\ln(1+w_{\rm eff}) - 2\ln(0.81 - 1.10\ln\delta)\right)$$
$$- \frac{1}{12}\ln g_{\rm th},$$

Amplitude of perturbations

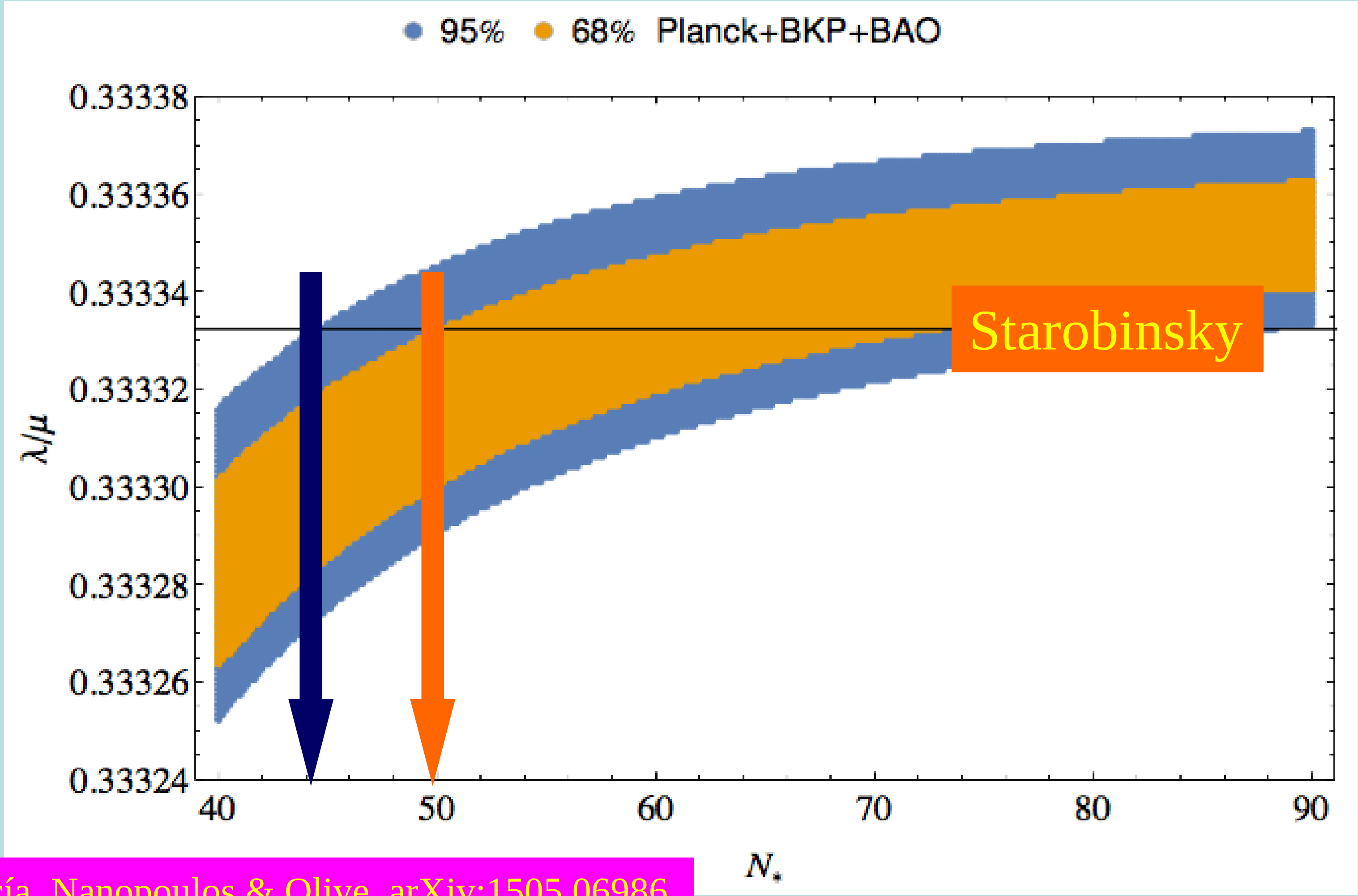
Equation of state during inflaton decay

Inflaton decay rate

- **Prospective constraint on inflaton models?**

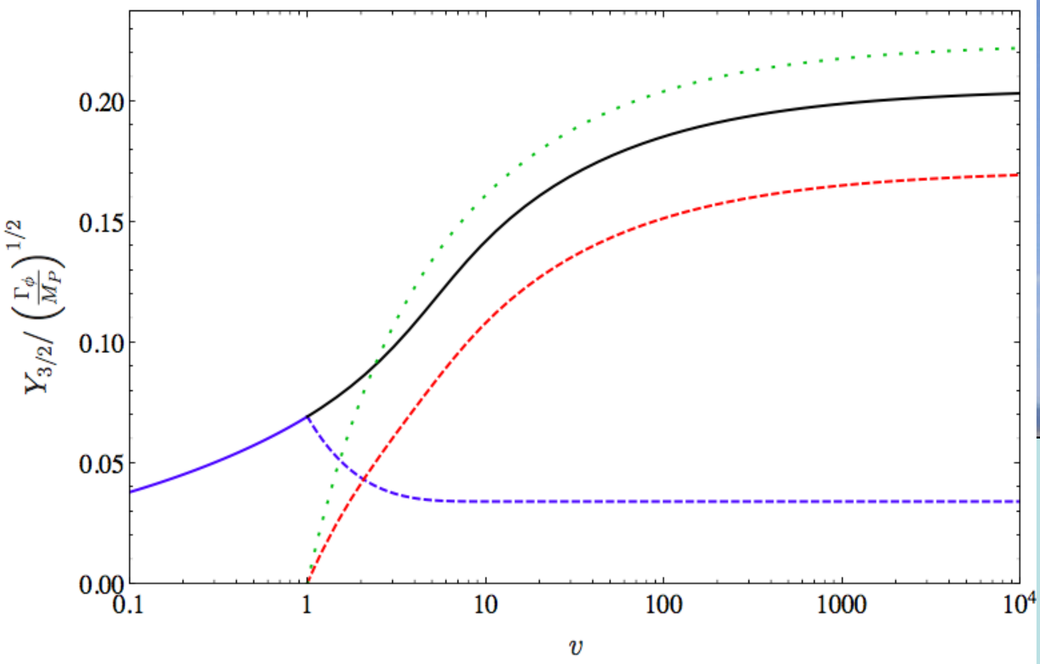
Planck Constraints on # of e-Folds

- Starobinsky-like no-scale models



JE, García, Nanopoulos & Olive, arXiv:1505.06986

Gravitino Constraints on Inflaton Decays



- Production related to inflaton decay rate
- Constraint from success of Big-Bang nucleosynthesis:

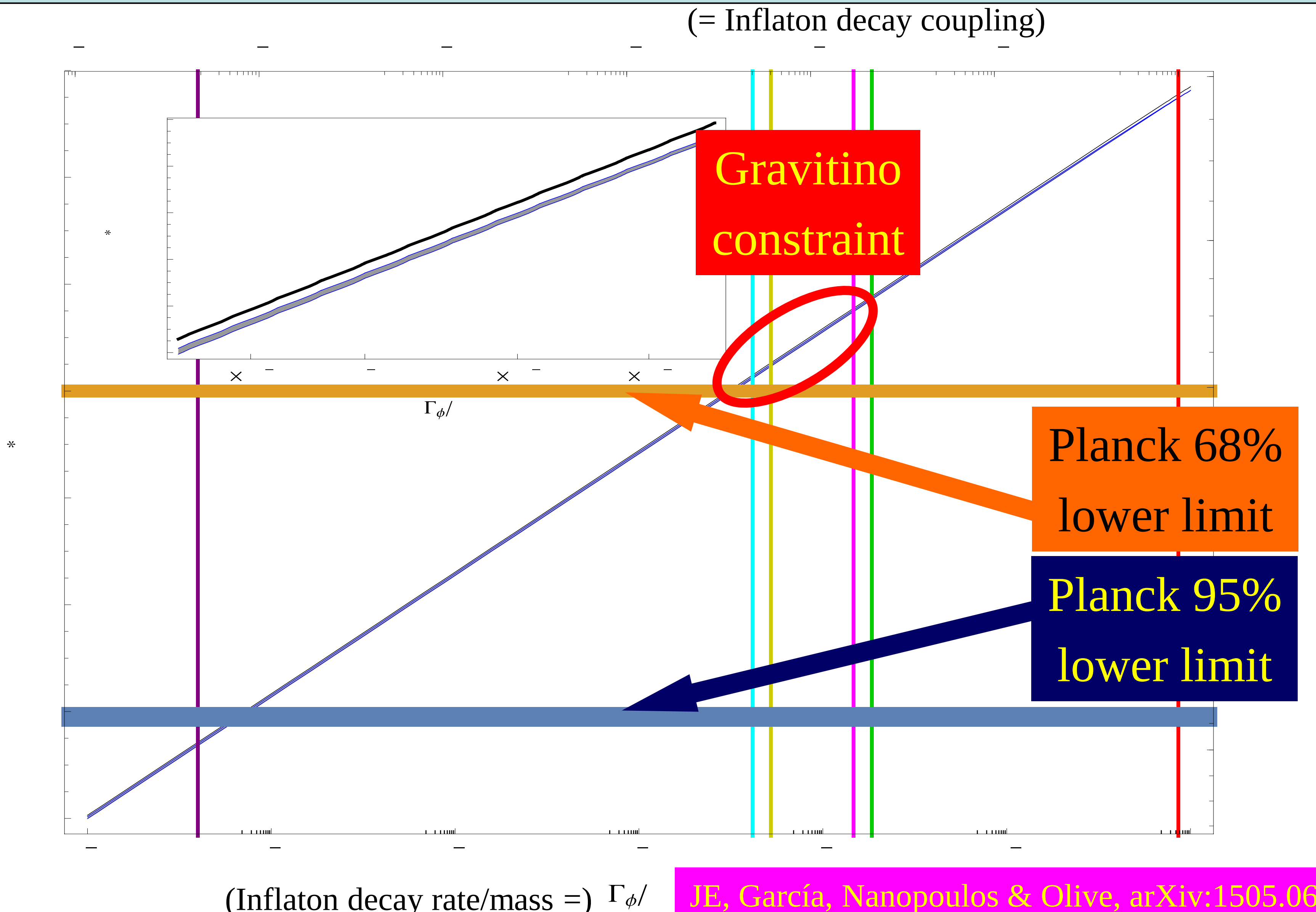
$$|y| \lesssim \left(1 + 0.56\,\frac{m_{1/2}^2}{m_{3/2}^2}\right)^{-1} \begin{cases} 2.9 \times 10^{-9} & \text{for} \quad m_{3/2} = 3 \text{ TeV} \\ 1.5 \times 10^{-6} & \text{for} \quad m_{3/2} = 6 \text{ TeV} \end{cases}$$

- Constraint from dark matter abundance:

$$|y| < 2.7 \times 10^{-5} \left(1 + 0.56\,\frac{m_{1/2}^2}{m_{3/2}^2}\right)^{-1} \left(\frac{100\text{GeV}}{m_{\rm LSP}}\right)$$

JE, García, Nanopoulos, Olive & Peloso, arXiv:1512.05701

Planck Constraints on # of e-Folds

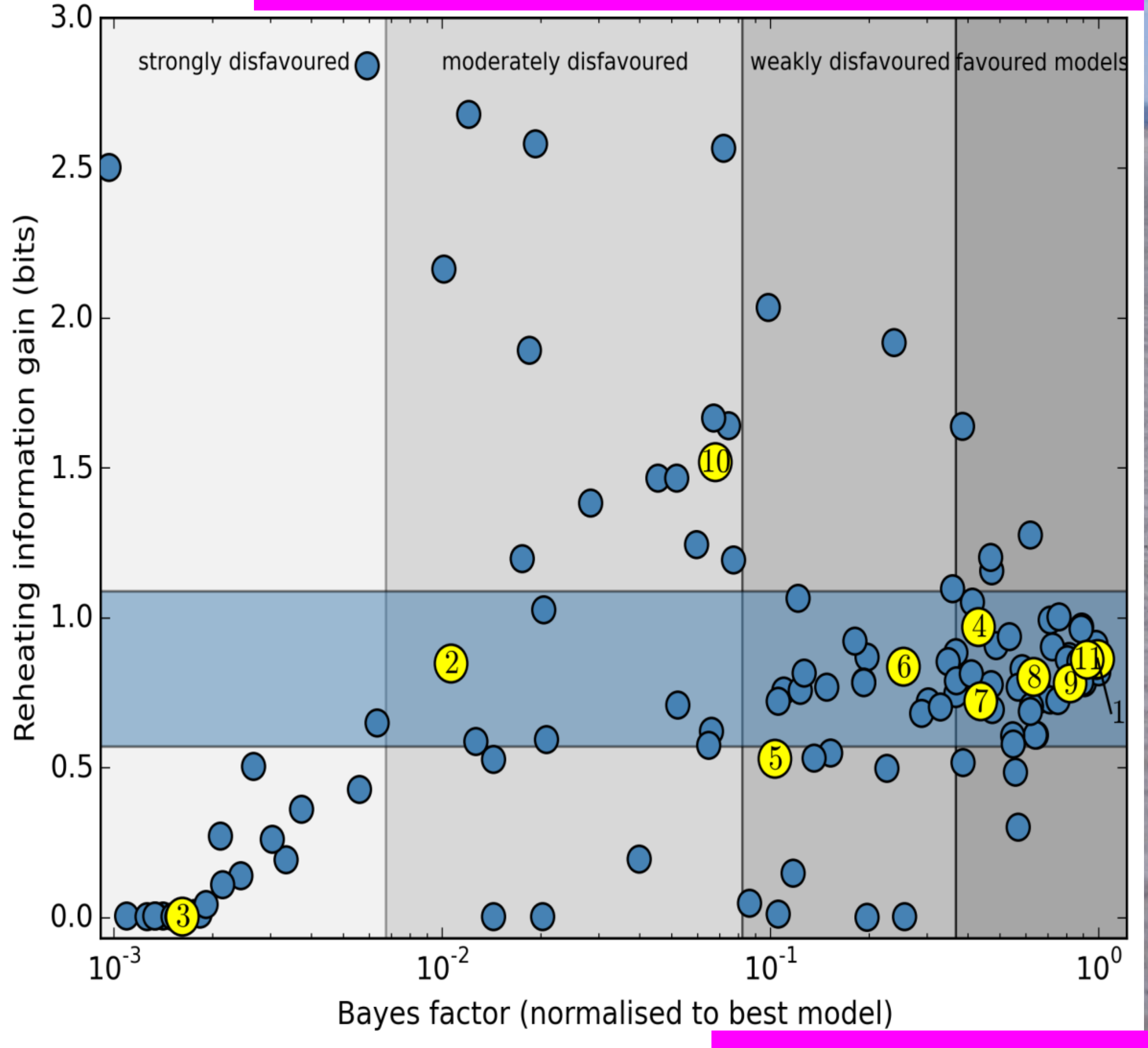


JE, García, Nanopoulos & Olive, arXiv:1505.06986

General Analysis of Reheating

- Selected models:
  - 1): R^2, Higgs
  - 2): Φ^2
  - 3): Φ^4
  - 4): $\Phi^{2/3}$
  - 5): Φ^p, p in [0.2, 6]
  - 6), 7), 8): hilltop
  - 9): brane
  - 10): natural
  - 11): α attractors

Vennin, adapted from Martin, Ringeval & Vennin



JE & Wands, PDG 2016

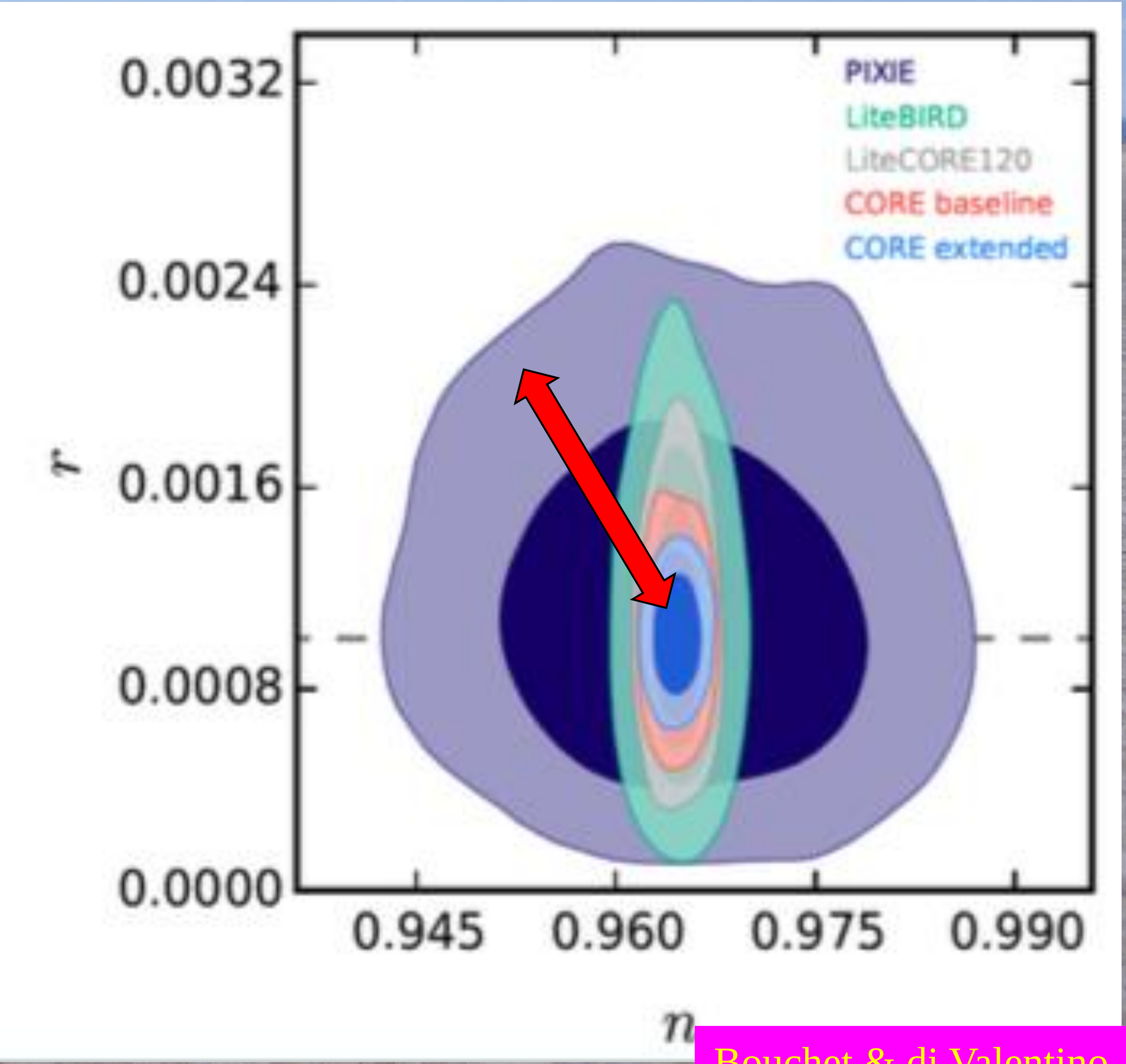
Inflationary Dream

- String-inspired inflationary model with inflation by a Kähler modulus:

$$K \ni -\Sigma_i N_i \ln(T_i + T_i^*)$$

$$n_s = 1 - \frac{2}{N_*}, r = \frac{8}{B^2 N_*^2}$$

- $N_i = 1$
- N_* in [44, 59]

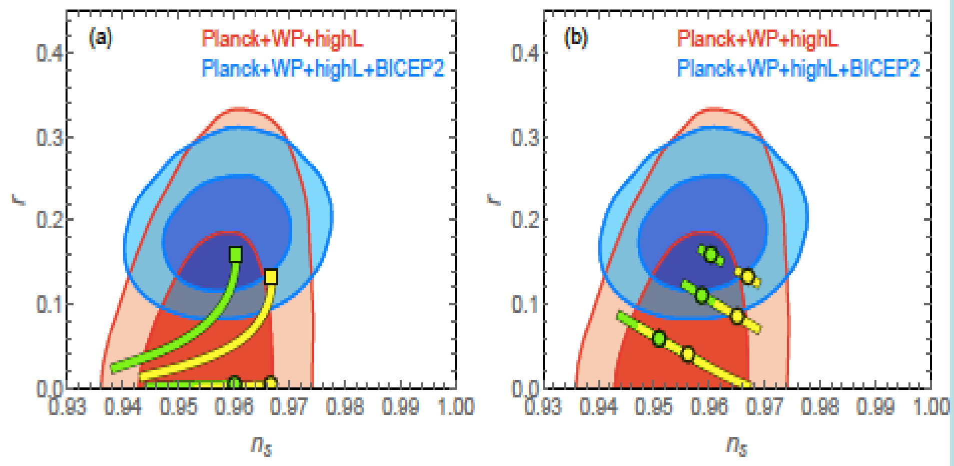


Bouchet & di Valentino

New Higgs Inflation in No-Scale SUSY GUT: I

JE, He & Xianyu, arXiv:1411.5537

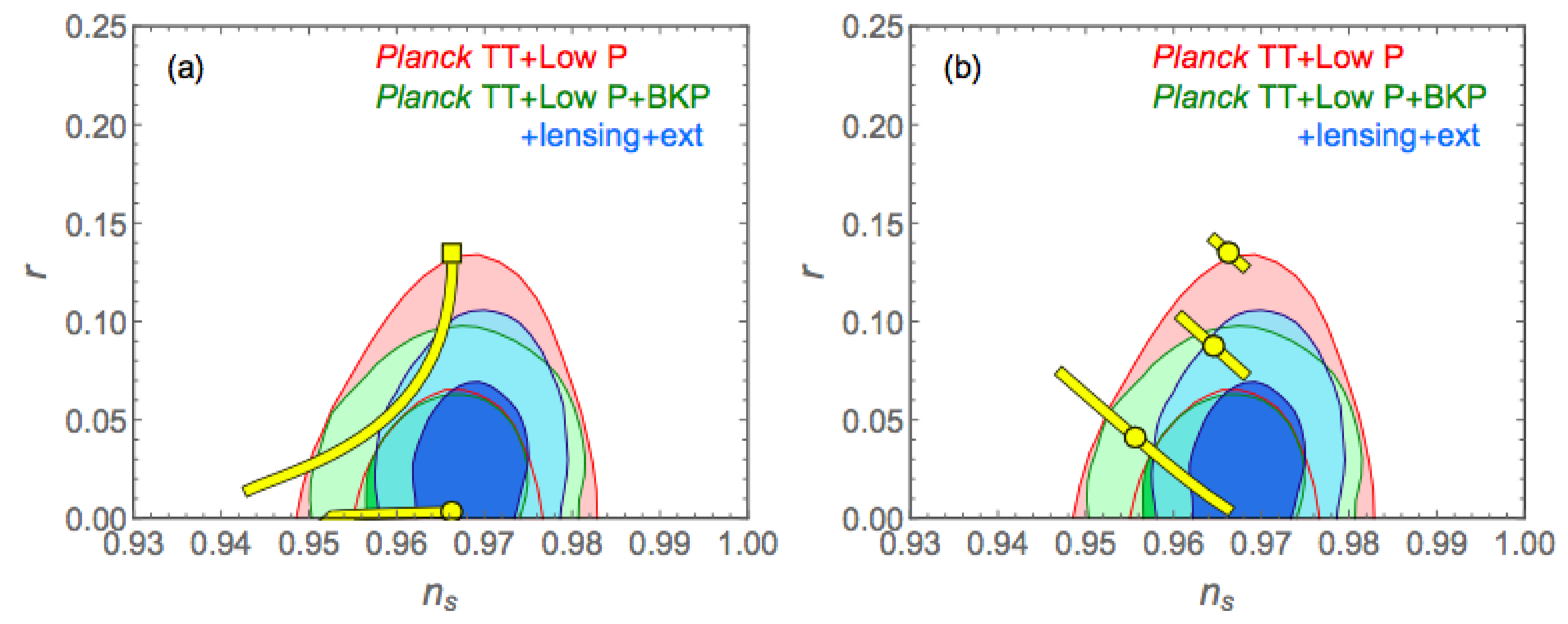
- Grand Unification within SU(5)
- Embed in no-scale supergravity
- Inflation via a combination of **5, 5*** Higgs fields
- Avoids the problems of the original Higgs inflation model: potential positive
- Interpolates between the Starobinsky model (Planck) and a quadratic potential (BICEP2)



New Higgs Inflation in No-Scale SUSY GUT: II

JE, He & Xianyu, arXiv:1606.02202

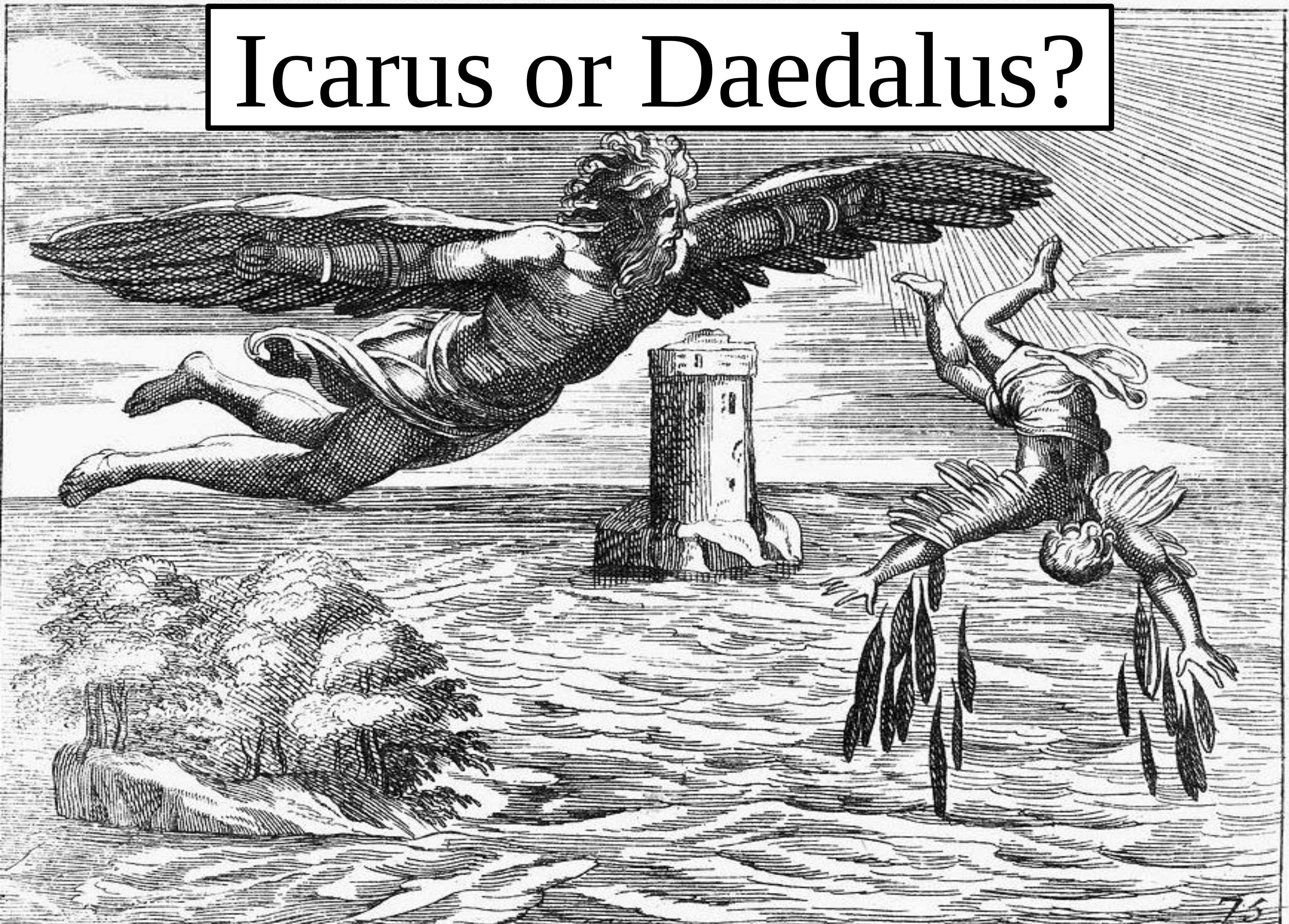
- Grand Unification within flipped SU(5), Pati-Salam
- Can be Starobinsky-like, not necessarily



- Also SO(10) model …

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1609.05849

Icarus or Daedalus?



DEDALE PERD SON FILS ICARE

Flipped

Almost

A Model of Everything

Below the Planck Scale

- Simple GUT models (SU(5), SO(10)) not obtained from weakly-coupled string
  – They need adjoint Higgs, …
- **Flipped SU(5) × U(1) derived**, has advantages
  – Small (5-, 10-dimensional) Higgs representations
  – Long-lived proton, neutrino masses, leptogenesis, …
- Construct model of Starobinsky-like inflation within flipped SU(5) × U(1) framework

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

Flipped SU(5) × U(1) GUT Model

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Fields:
  - Matter: $F_i = (\mathbf{10}, 1)_i \ni \{d^c, Q, \nu^c\}_i$, $\bar{f}_i = (\bar{\mathbf{5}}, -3)_i \ni \{u^c, L\}_i$, $\ell_i^c = (\mathbf{1}, 5)_i \ni \{e^c\}_i$,
  - Higgs: $H = (\mathbf{10}, 1)$, $\bar{H} = (\overline{\mathbf{10}}, -1)$, $h = (\mathbf{5}, -2)$, $\bar{h} = (\bar{\mathbf{5}}, 2)$,
  - Singlets: $\phi_a = (\mathbf{1}, 0),\ a = 0, \ldots, 3.$
- Superpotential:

$$W = \lambda_1^{ij} F_i F_j h + \lambda_2^{ij} F_i \bar{f}_j \bar{h} + \lambda_3^{ij} \bar{f}_i \ell_j^c h + \lambda_4 H H h + \lambda_5 \bar{H} \bar{H} \bar{h} + \lambda_6^{ia} F_i \bar{H} \phi_a + \lambda_7^a h \bar{h} \phi_a + \lambda_8^{abc} \phi_a \phi_b \phi_c + \mu^{ab} \phi_a \phi_b ,$$

- No-scale Kähler potential:

$$K = -3 \ln \left[T + \bar{T} - \frac{1}{3} \left(|\phi_a|^2 + |\ell^c|^2 + f^\dagger f + h^\dagger h + \bar{h}^\dagger \bar{h} + F^\dagger F + H^\dagger H + \bar{H}^\dagger \bar{H} \right) \right]$$

- D-terms: $D^a D^a = \left(\frac{3}{10} g_5^2 + \frac{1}{80} g_X^2 \right) \left(|\tilde{\nu}_i^c|^2 + |\tilde{\nu}_H^c|^2 - |\tilde{\nu}_{\bar{H}}^c|^2 \right)^2$
- Symmetry breaking: $\mathrm{SU}(5) \times \mathrm{U}(1) \to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
- Proton lifetime: $\tau_p = 4.6 \times 10^{35} \times \left(\frac{M_{32}}{10^{16}\ \mathrm{GeV}} \right)^4 \times \left(\frac{0.0374}{\alpha_5(M_{32})} \right)^2\ \mathrm{yrs}$

Starobinsky-Like Inflation

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Need superpotential: $W \supset m\left(\frac{S^2}{2} - \frac{S^3}{3\sqrt{3}}\right)$
- Identify inflaton S with some combination of Φ_a, consider 2 scenarios:
- **1) Hierarchy of scalars*** with one light eigenstate Φ_0^D:

$$\mu_D^{ab} = \mathrm{diag}\left(m/2, \mu_D^{11}, \mu_D^{22}, \mu_D^{33}\right)\ , \qquad \mu_D^{ab} \leq M_{\rm GUT} \quad : \quad \det \mu^{ab} \ll M_{\rm GUT}^4$$

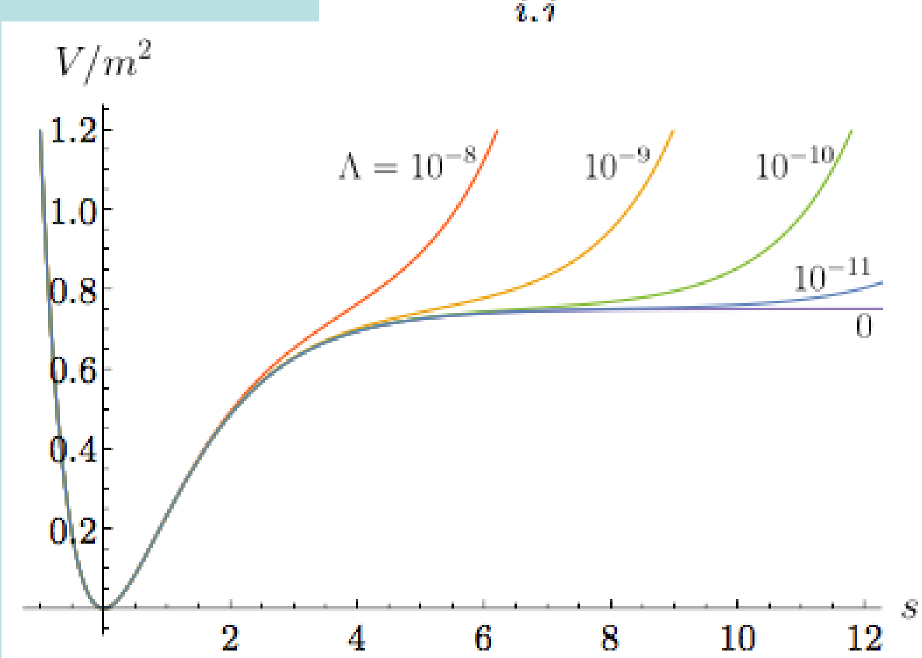
- "Starobinsky" condition: $-3\sqrt{3}\,\lambda_{8,D}^{000} = m$

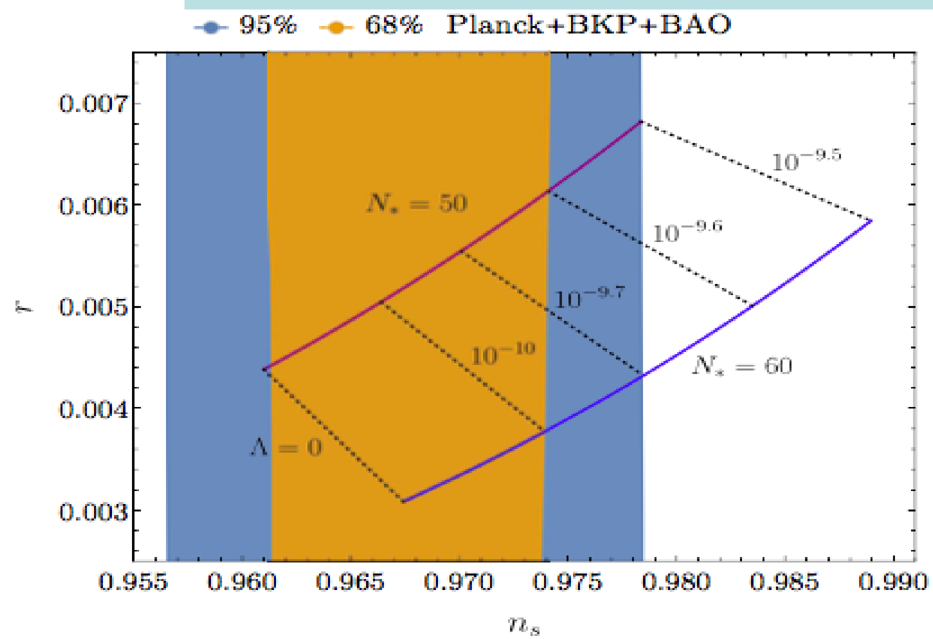
$$V_F \simeq \frac{3}{4}m^2\left(1 - e^{-\sqrt{2/3}\,s}\right)^2 + \frac{3}{4}\sinh^2(\sqrt{2/3}\,s)\sum_i |\lambda_6^{i0}|^2\left(|\tilde{\nu}_{\bar{H}}^c|^2 + |\tilde{\nu}_i^c|^2\right) + \frac{1}{8}m^2 e^{\sqrt{2/3}s}\left(|\tilde{\nu}_{\bar{H}}^c|^2 + \sum_i |\tilde{\nu}_i^c|^2\right) + \cdots .$$

* Consider later scenario **2) no scalar mass hierarchy**

Starobinsky-Like Inflation in Scenario (1)

- Consider case of (relatively) large λ: $\lambda_8^{0ij} \gtrsim \mu^{ij}$
- Potential $\simeq \frac{3}{4} m^2 \left(1 - e^{-\sqrt{2/3}\, s}\right)^2 + \frac{27\sqrt{3}}{4} m \Lambda\, e^{-s/\sqrt{6}} \sinh^3(s/\sqrt{6})$
- Where $\Lambda \equiv -\sum_{i,j} (\lambda_8^{0ij})^{-1} \lambda_8^{00i} \lambda_8^{00j} + \text{h.c.}$





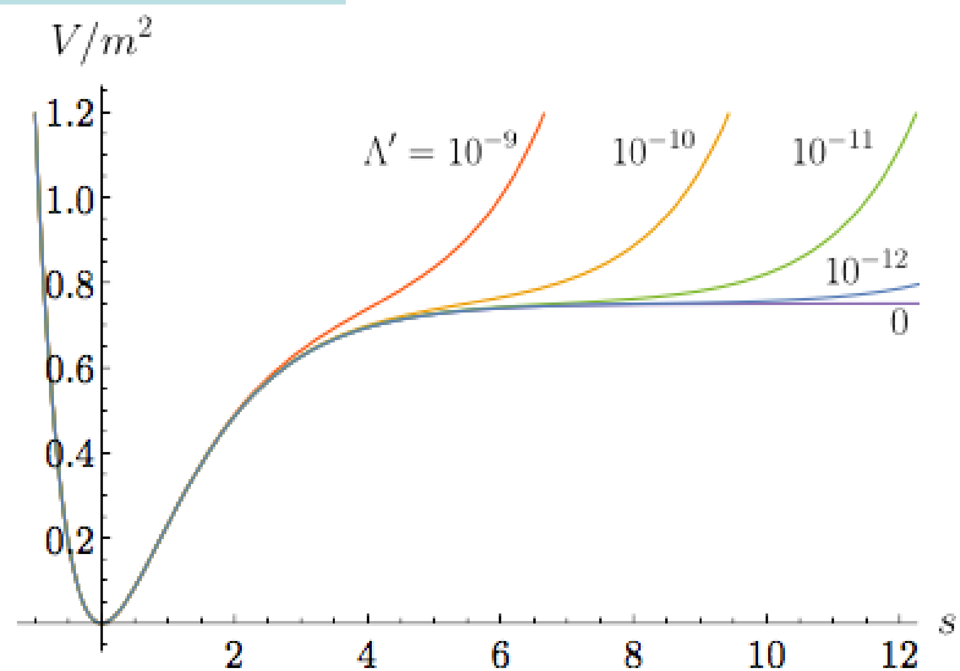
- Starobinsky-like for small Λ: main constraint n_s

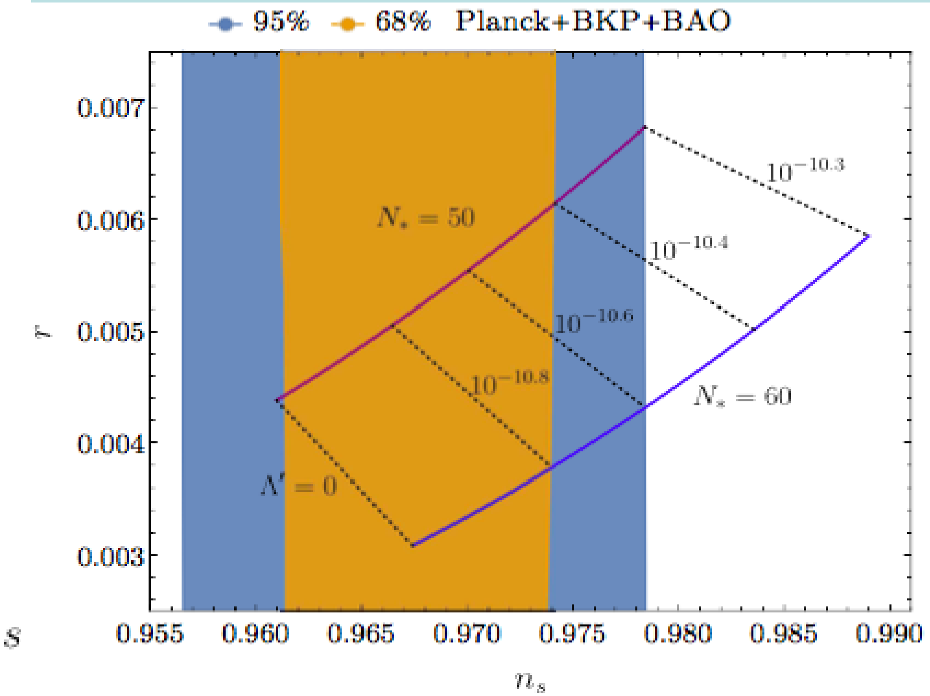
Starobinsky-Like Inflation in Scenario (1)

- Consider case of (relatively) small λ: $\lambda_8^{0ij} \lesssim \mu^{ij}$

$$V_{\rm inf} \simeq \frac{3}{4}m^2\left(1-e^{-\sqrt{2/3}\,s}\right)^2 + 81\,m\,\sinh^4(s/\sqrt{6})\left(\tanh(s/\sqrt{6})-1\right)\sum_i\left[\mu_i^{-1}(\lambda_8^{00i})^2+\text{h.c.}\right]$$

where $\Lambda' = -\sum_a \mu_i^{-1}(\lambda_8^{00i})^2 + \text{h.c.}$



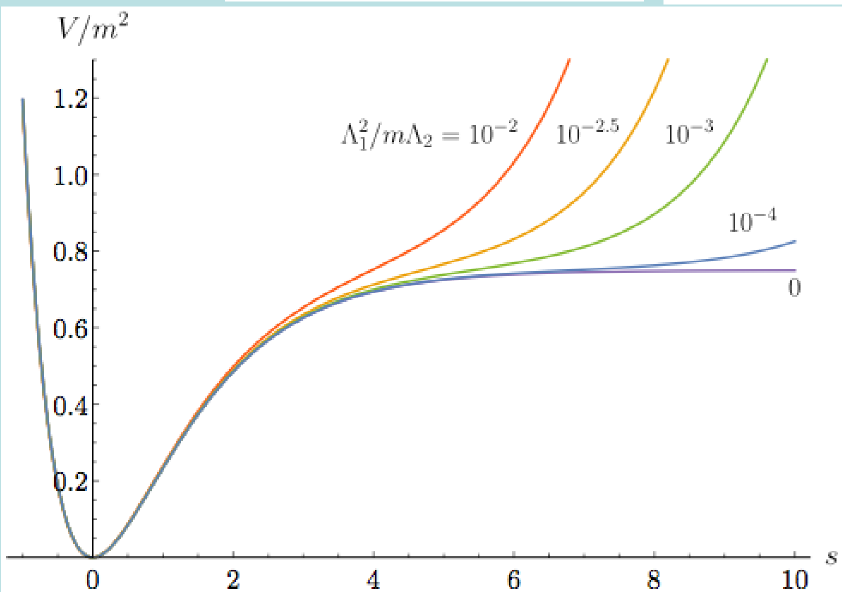


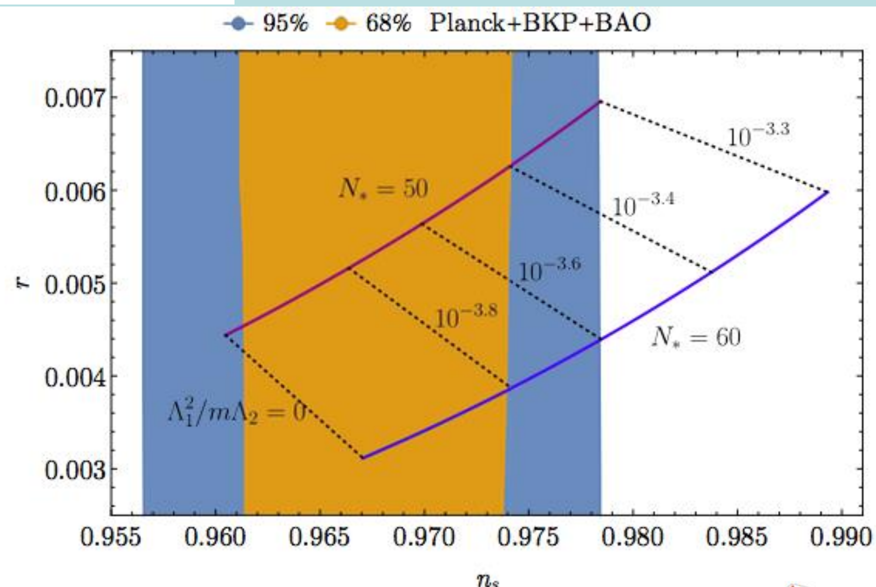
- Starobinsky-like for small Λ’: main constraint n_s

Starobinsky-Like Inflation in Scenario (2)

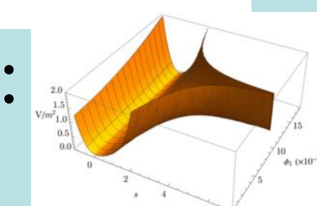
- Multiple light singlet states: correction to Starobinsky potential: $\Delta V_{\text{inf}} \sim \dfrac{\sqrt{3}\, m \sinh(\sqrt{2/3}\, s)}{2(1+\tanh(s/\sqrt{6}))} \dfrac{\Lambda_1^2}{\Lambda_2} \sim m \dfrac{\sqrt{3}\Lambda_1^2}{8\Lambda_2} e^{\sqrt{2/3}\, s}$

  where $\lambda_8^{00i} S \sim \mu^{0i} \sim \Lambda_1$ $\lambda_8^{0ij} S \sim \mu^{ij} \sim \Lambda_2$



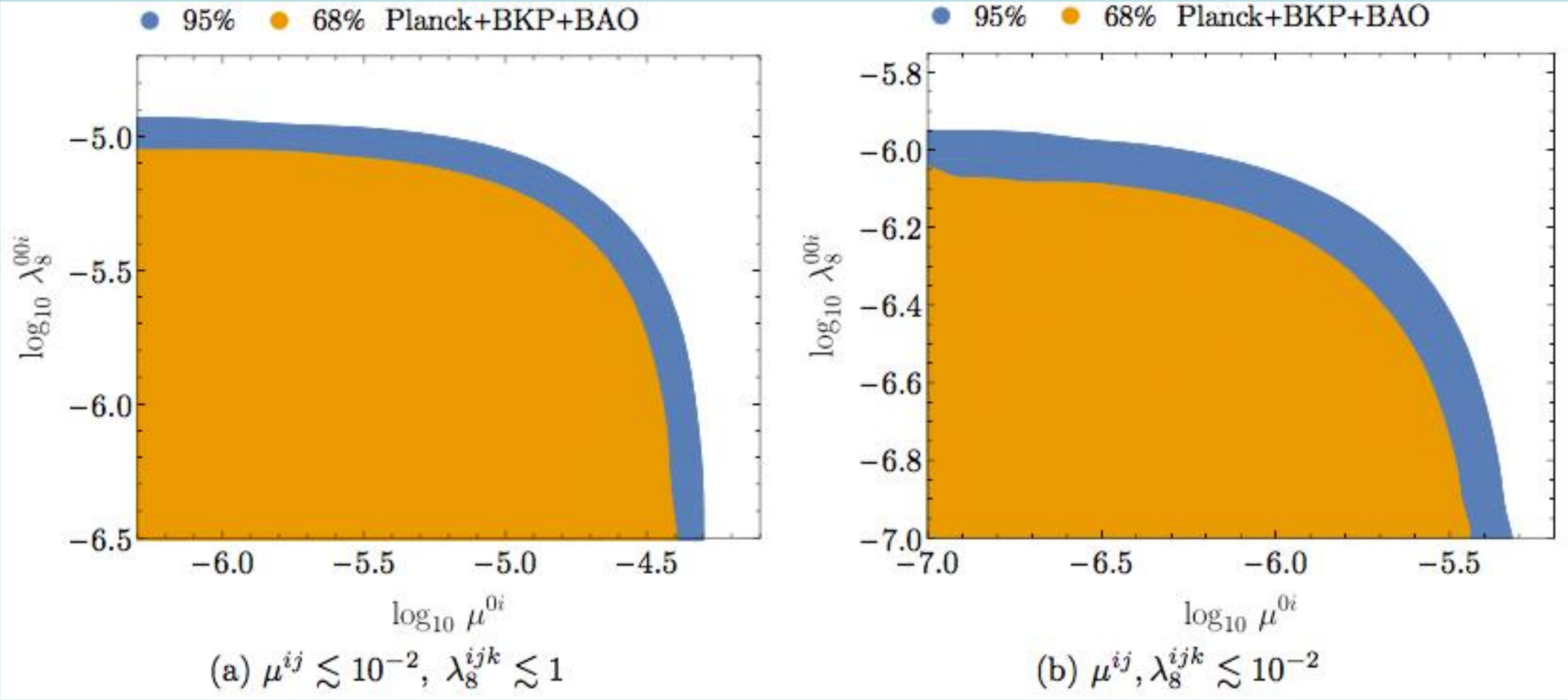


- Multi-field effects not a problem, steep valley:



Full Numerical Calculations

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331



- Constraints including numerical calculations of evolution of inflaton and other scalar fields

Neutrino Masses & Mixing

- Consider 2 options:
- (A) Inflaton decouples from neutrinos
  - Inflaton decays to Higgs(inos): leptogenesis difficult
- (B) Inflaton couples to neutrinos

$$\mathcal{L}^{(i')}_{\rm mass} = -\frac{1}{2}\begin{pmatrix}\nu_{i'} & \nu^c_{i'} & \tilde{S}\end{pmatrix}\begin{pmatrix} 0 & \lambda_2^{i'i'}\langle\bar{h}_0\rangle & 0 \\ \lambda_2^{i'i'}\langle\bar{h}_0\rangle & 0 & \lambda_6^{i'0}\langle\tilde{\nu}^c_{\bar{H}}\rangle \\ 0 & \lambda_6^{i'0}\langle\tilde{\nu}^c_{\bar{H}}\rangle & m \end{pmatrix}\begin{pmatrix}\nu_{i'} \\ \nu^c_{i'} \\ \tilde{S}\end{pmatrix} + {\rm h.c.}$$

- Double seesaw mass matrix, 2 heavy states, couplings

$W = \lambda_2^{i'j}\left(\cos\theta N_{i'1} - \sin\theta N_{i'2}\right) L_j h_u$ where $\tan 2\theta = -\frac{2\lambda_6^{i'0}\langle\tilde{\nu}^c_{\bar{H}}\rangle}{m}$

- Constraints from neutrino data, easier leptogenesis

Neutrino Masses & Inflaton Coupling

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- To avoid overproduction of dark matter via gravitinos if no later entropy $$|y| < 2.7 \times 10^{-5} \left(1 + 0.56 \frac{m_{1/2}^2}{m_{3/2}^2}\right)^{-1} \left(\frac{100\,\mathrm{GeV}}{m_{\mathrm{LSP}}}\right)$$
- With entropy factor Δ, if inflaton couples to neutrinos:

$$|\lambda_2^{i'j} \sin\theta| \lesssim 10^{-5}\Delta$$

- Normal neutrino mass hierarchy preferred

$$m_{\nu_1} \simeq 10^{-9} \times \left(\frac{|\lambda_6^{10}|}{10^{-3}}\right)^{-2} \left(\frac{|\langle \tilde{\nu}_{\bar{H}}^c \rangle|}{10^{16}\ \mathrm{GeV}}\right)^{-2} \mathrm{eV}$$

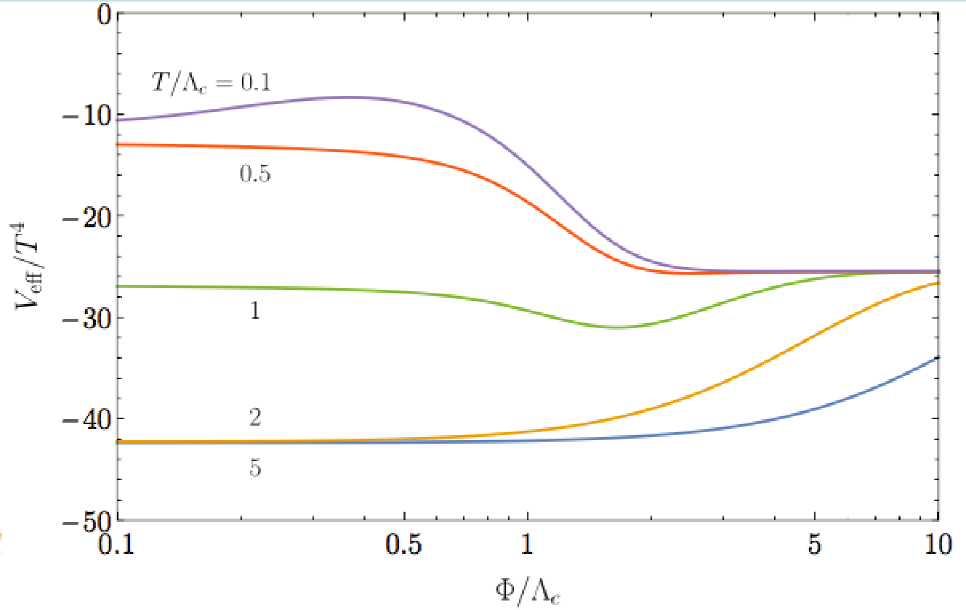
$$m_{\nu_2} \simeq |\delta m^2|^{\frac{1}{2}} \simeq 9 \times 10^{-3}\ \mathrm{eV}$$
$$m_{\nu_3} \simeq |\Delta m^2|^{\frac{1}{2}} \simeq 5 \times 10^{-2}\ \mathrm{eV}$$

- Weak or strong reheating? Too much extra entropy?

The GUT Phase Transition

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- At the end of inflation, flipped SU(5) × U(1) unbroken
- At lower scales, α_5 increases, condensates form breaking SU(5): $g^2(\Lambda_c)\Delta C \equiv g^2(\Lambda_c)(C_c - C_1 - C_2) \simeq 4, \qquad \alpha_c \equiv \alpha(\Lambda_c) \simeq \frac{1}{\pi \Delta C}$
- Typical condensation scale: $\Lambda_c \simeq 4 \times 10^{-7}\, M_{\rm GUT} \simeq 5 \times 10^9$ GeV
- Temperature-dependent effective potential
- Possibility of trapping at origin, excessive entropy release: avoid if $T_{\rm reh} \gtrsim \Lambda_c$



Entropy Release & Baryogenesis

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

- Entropy release

$$\boxed{\Delta \simeq 8\times 10^3}\,\lambda_{1,2,3,7}^{-2}\left(\frac{g_{d\Phi}}{43/4}\right)^{1/4}\left(\frac{915/4}{g_{\rm dec}}\right)\left(\frac{\langle\Phi\rangle}{5\times 10^{15}\,{\rm GeV}}\right)\left(\frac{10\,{\rm TeV}}{m^2_{F,\bar f,\ell^c,\tilde\phi_a}/|m_\Phi|}\right)^{1/2}$$

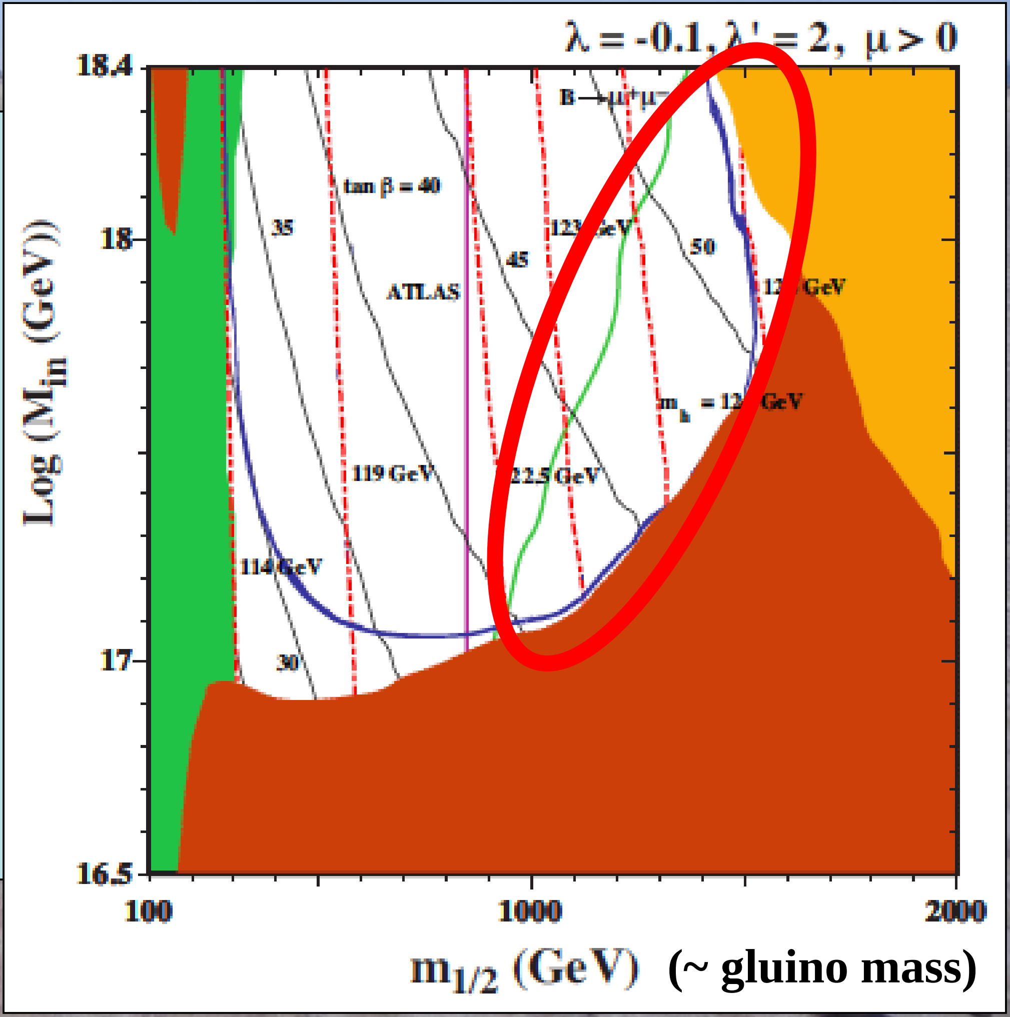
- Relaxes gravitino production constraint, little effect on number of inflationary e-folds: $\Delta N_*^{\rm max} \simeq -4\times 10^{-3}\ln\Delta$
- Standard leptogenesis if inflaton couples to neutrinos:

$$\epsilon \simeq -\frac{3}{4\pi}\frac{1}{\left(U^\dagger_{\nu^c}(\lambda_2^D)^2U_{\nu^c}\right)_{11}}\sum_{i=2,3}{\rm Im}\left[\left(U^\dagger_{\nu^c}(\lambda_2^D)^2U_{\nu^c}\right)^2_{i1}\right]\frac{m}{M_i}$$

$$\boxed{\frac{n_B}{s}\simeq 3.8\times 10^{-11}}\,\delta f\,\lambda_{1,2,3,7}^2\lambda_6^{-2}\left(\frac{43/4}{g_{d\Phi}}\right)^{1/4}\left(\frac{915/4}{g_{\rm reh}}\right)^{1/4}\left(\frac{g_{\rm dec}}{915/4}\right)\left(\frac{y}{10^{-5}}\right)$$
$$\times\left(\frac{5\times 10^{15}\,{\rm GeV}}{\langle\Phi\rangle}\right)^2\left(\frac{m^2_{F,\bar f,\ell^c,\tilde\phi_a}/|m_\Phi|}{10\,{\rm TeV}}\right)^{1/2}\left(\frac{m}{3\times 10^{13}{\rm GeV}}\right)^{1/2}$$

No-Scale Framework for Particle Physics & Dark Matter

- Incorporating **LHC constraints**, **Higgs mass**, **flavour**, **supersymmetric dark matter**, Starobinsky-like inflation, leptogenesis, neutrino masses, …



JE, Nanopoulos & Olive, arXiv:1310.4770

Flipped Almost

A Model of Everything

Below the Planck Scale

- Starobinsky-like inflation can be embedded within flipped SU(5) × U(1) model
- Inflaton coupling to neutrinos preferred for baryogenesis – implications for neutrino masses
- Prefer strong reheating after inflation for same reason
- Example how inflation can connect string theory (no-scale supergravity, GUT derived from string) with particle physics accessible to experiment (neutrinos, dark matter, proton decay, LHC, …)

JE, Garcia, Nagata, Nanopoulos & Olive, arXiv:1704.07331

Summary

- Inflation may solve some of the biggest problems in cosmology: age, size, homogeneity, flatness, …
- Open season for building inflationary models
- Inflation cries out for supersymmetry
- Cosmology requires supergravity
- **Natural framework: no-scale supergravity**
- Derived from string theory
- CMB data can constrain models of particle physics
- **Will the LHC discover supersymmetry?**