No-Scale Inflation

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Cosmology Lunchtime Seminar
26 October 2015

J. Ellis, MG, D.V. Nanopoulos and K.A. Olive, JCAP **1501**, 010 (2015) [arXiv:1409.8197 [hep-ph]]
J. Ellis, MG, D.V. Nanopoulos and K.A. Olive, JCAP **1510**, 003 (2015) [arXiv:1503.08867 [hep-ph]]
J. Ellis, MG, D.V. Nanopoulos and K.A. Olive, JCAP **1507**, 050 (2015) [arXiv:1505.06986 [hep-ph]]

University of Minnesota

Overview

- Introduction
  - Inflation
  - Supersymmetry and supergravity
- No-scale inflation
  - $R+R^2$ inflation in supergravity
  - Multifield effects
- Reheating
  - Perturbative decay of the modulus/matter inflaton
  - Combined CMB + reheating constraints
- Conclusion

The FRW Universe

The homogeneous and isotropic Universe is described by the FRW metric

$$ds^2 = dt^2 - a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right]$$

Modeling its content as an ideal fluid, the Einstein equations and energy-momentum conservation lead to

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_P^2} - \frac{k^2}{a^2} + \frac{\Lambda}{3}$$

$$\dot{\rho} + 3H(\rho + p) = 0$$

$$\Rightarrow \begin{cases} \rho \propto a^{-4}\,, \; a \propto t^{1/2} & \text{(matter)} \\ \rho \propto a^{-3}\,, \; a \propto t^{2/3} & \text{(radiation)} \end{cases}$$

For a density $\rho_c = 3H^2 M_P^2\,,\;\; k = 0$. The density parameter has the present value

$$\Omega = \rho/\rho_c = 1.000 \pm 0.005 \qquad \text{(Planck, 2015)}$$

If the Universe is dominated by a fluid with $p = w\rho$, the particle horizon is

$$L_p = a(t)\int_0^t \frac{dt'}{a(t')} \sim H^{-1} \qquad (\text{ if } \; w > -1/3\,)$$

Why inflation?

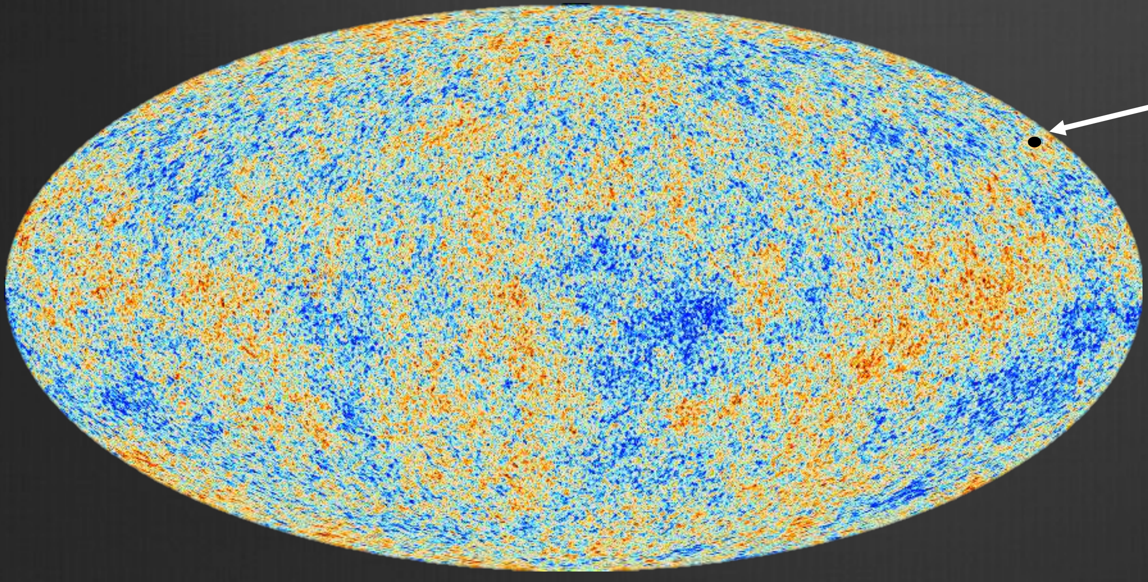
- The flatness problem
  - The condition $\Omega \approx 1$ is unstable. In the radiation dominated universe,

$$\Omega - 1 = \frac{k}{H^2 a^2} = \frac{90 M_P^2 \hat{k}}{g(T) T^2}$$

where $\hat{k} = \frac{k}{a^2 T^2} = (\Omega_0 - 1)\frac{H_0}{T_0} < 10^{-61}$

$$\Rightarrow \ |\Omega - 1|_{\mathrm{GUT}} < 10^{-57}$$

- The horizon problem



Size of particle horizon at recombination

But $\dfrac{\Delta T}{T} \sim 10^{-5}$

Why inflation?

- The relics problem
  - Magnetic monopoles are created when a GUT group is broken
  - They are heavy and stable $\Rightarrow$ may overclose the universe

1 monopole per horizon $\longrightarrow$ $\Omega_M \sim 10^{13}$

- Small scale inhomogeneities
  - There is a plethora of structure on smaller scales (stars, galaxies, clusters,…)
  - At early times, $t \lesssim 10^9 s$, $\lambda_{\rm phys} > H^{-1}$ for galactic scales

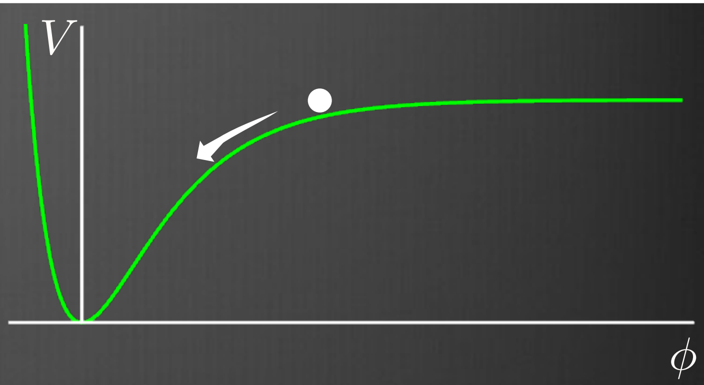
$$\frac{\delta\rho}{\rho} \sim t \qquad \Rightarrow \qquad \left.\frac{\delta\rho}{\rho}\right|_{t=t_P} \lesssim 10^{-57}$$

but random fluctuations predict $\frac{\delta\rho}{\rho} \sim 10^{-40}$

Scalar field inflation

A scalar field slowly rolling in its potential

$$\mathcal{S} = \int d^4x\,\sqrt{-g}\left[\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right]$$



In a flat FRW background, $\phi(\mathbf{x},t) \to \phi(t) + \delta\phi(\mathbf{x},t)$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$H^2 = \frac{1}{3M_P^2}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$

Slow roll is possible if $\epsilon, |\eta| \ll 1$, where $\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2, \quad \eta = M_P^2\left(\frac{V''}{V}\right)$

Scale factor grows exponentially, $a \sim e^{Ht}$. Number of *e-folds* of inflation:

$$N \equiv \ln\left(\frac{a_f}{a_i}\right) = \int_{t_i}^{t_f} H\,dt \simeq -\frac{1}{M_P^2}\int_{\phi_i}^{\phi_f}\frac{V}{V'}\,d\phi$$

Scalar field inflation

Standard cosmological problems are solved:

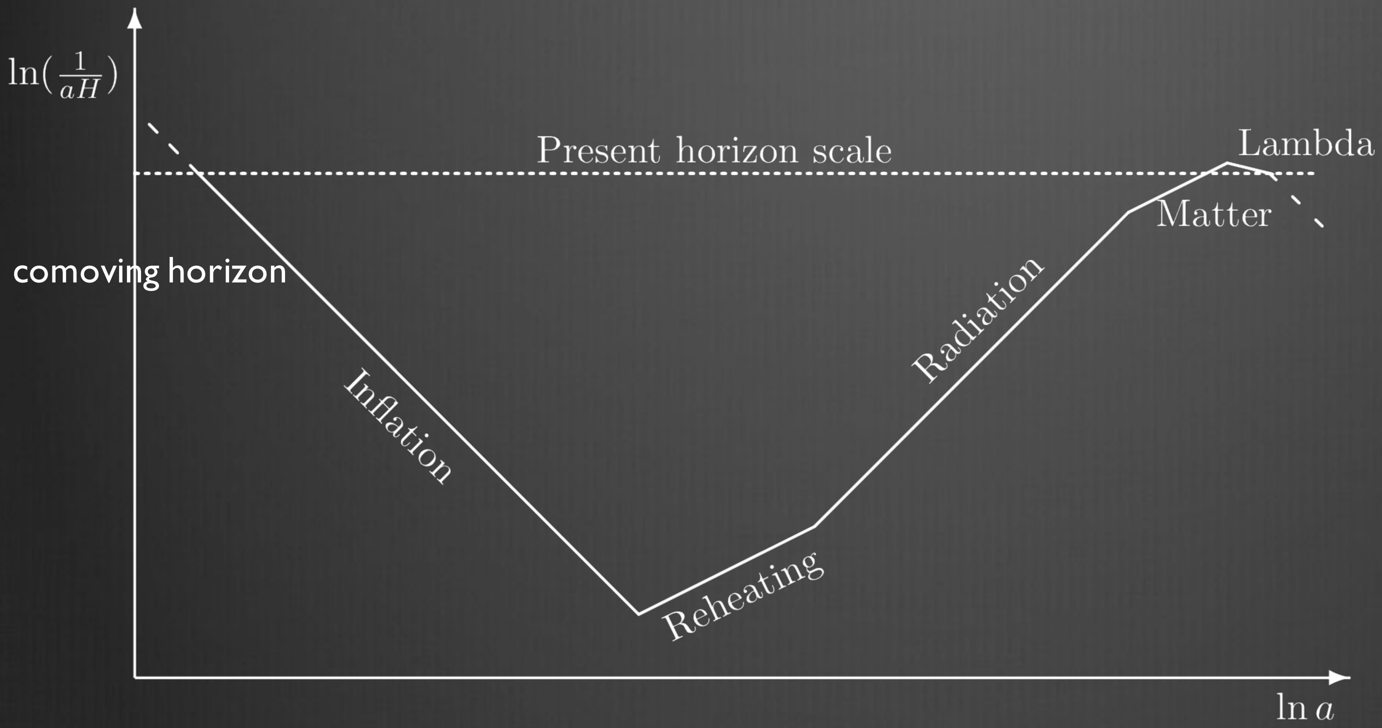
- Flatness: $|\Omega - 1| \propto e^{-2Ht} \quad \Rightarrow \quad N_{\rm tot} \gtrsim 70$
- Horizon: $L_p(t) = H^{-1}(e^{Ht} - 1)$
- Relics: All previous content is diluted away, $\rho \sim e^{-3Ht}$. Matter and radiation are regenerated during *reheating*
- Inhomogeneities:

$$\phi(\mathbf{x}, t) = \phi(t) + \delta\phi(\mathbf{x}, t)$$

$$ds^2 = (1 + 2\Psi)dt^2 - a^2(1 - 2\Psi)d\mathbf{x}^2$$

$$\underbrace{\mathcal{R} = \frac{H}{\dot\phi}\left(\delta\phi + \frac{\dot\phi}{H}\Psi\right)}_{\text{comoving curvature perturbation}} \quad \Rightarrow \quad \mathcal{P}_{\mathcal{R}} = \underbrace{\frac{H^4}{4\pi^2\dot\phi^2}}_{A_S}\left(\frac{k}{aH}\right)^{n_s - 1}$$

Why inflation?



On super-horizon scales,

$$\dot{\mathcal{R}} \simeq 0$$

At horizon reentry,

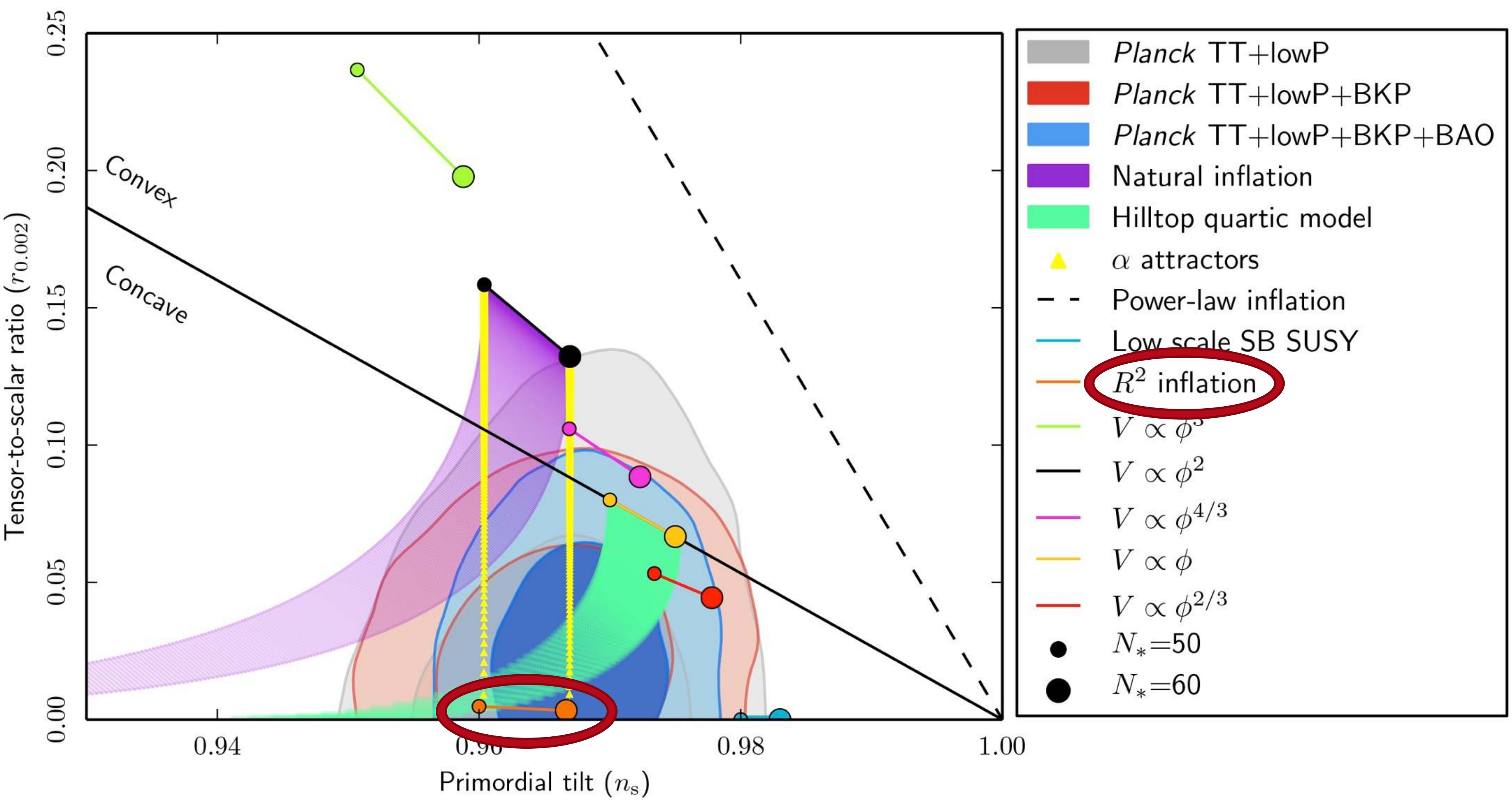
$$\mathcal{R} \sim \frac{\delta\rho}{\rho}$$

Tensor perturbations

$$ds^2 = dt^2 - a^2(\delta_{ij} + h_{ij})dx^i dx^j \quad \Rightarrow \quad \mathcal{P}_T = \underbrace{\frac{2}{\pi^2}H^2}_{A_T}\left(\frac{k}{aH}\right)^{-2\epsilon}$$

Planck 2015 results

$$\ln(10^{10} A_S) = 3.094 \pm 0.034, \qquad n_s \simeq 1 - 6\epsilon + 2\eta\,, \qquad r = \frac{A_T}{A_S}$$



$R+R^2$ (Starobinsky) inflation

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

(Starobinsky, 1980)

$$\downarrow$$

$$\tilde{g}_{\mu\nu} = (1+\phi/3m^2)g_{\mu\nu}\,, \qquad \phi' = \sqrt{\frac{3}{2}}\ln\left(1+\frac{\phi}{3m^2}\right)$$

$$\downarrow$$

$$= \int d^4x\sqrt{-\tilde{g}}\left[\frac{\tilde{R}}{2} + \frac{1}{2}(\partial_\mu\phi')^2 - \underbrace{\frac{3}{4}m^2\left(1-e^{-\sqrt{2/3}\phi'}\right)^2}_{\text{Starobinsky potential}}\right]$$

$$n_s \approx 0.961 - 0.968$$

$$r \approx 0.0030 - 0.0042$$

Why supersymmetry?

Supersymmetry is the spacetime symmetry that relates bosons and fermions. If it is realized in nature, it must be broken.

- It is the single extension of Poincare symmetry

$$\{Q_\alpha, Q_\beta\} = \{\bar{Q}_{\dot\alpha}, \bar{Q}_{\dot\beta}\} = 0\,, \qquad \{Q_\alpha, \bar{Q}_{\dot\alpha}\} = 2\sigma^\mu_{\alpha\dot\alpha} P_\mu$$

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle\,, \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

- Particles are arranged in irreps of the superalgebra (*supermultiplets*)

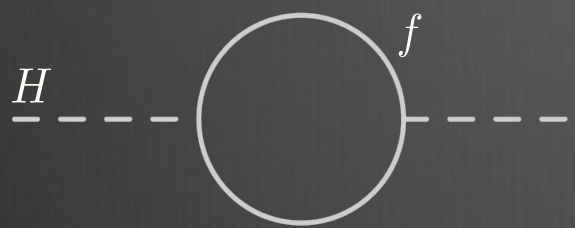
Chiral superfields: SM matter (Higgs) + SUSY partners $\quad \Phi \supset (\phi, \psi, F)$

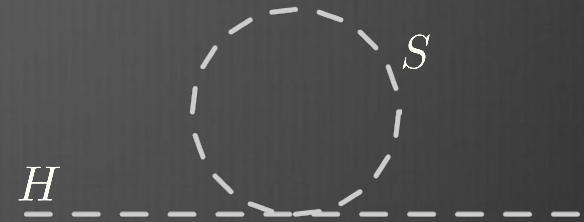
Vector superfields: SM gauge bosons + SUSY partners $\quad V^a \supset (A^a_\mu, \lambda^a, D^a)$

Dark matter candidates $\quad \langle \sigma v \rangle \sim \dfrac{\alpha_{\mathrm{em}}^2}{m_\chi^2}$

Why supersymmetry?

- Provides a solution to the hierarchy problem

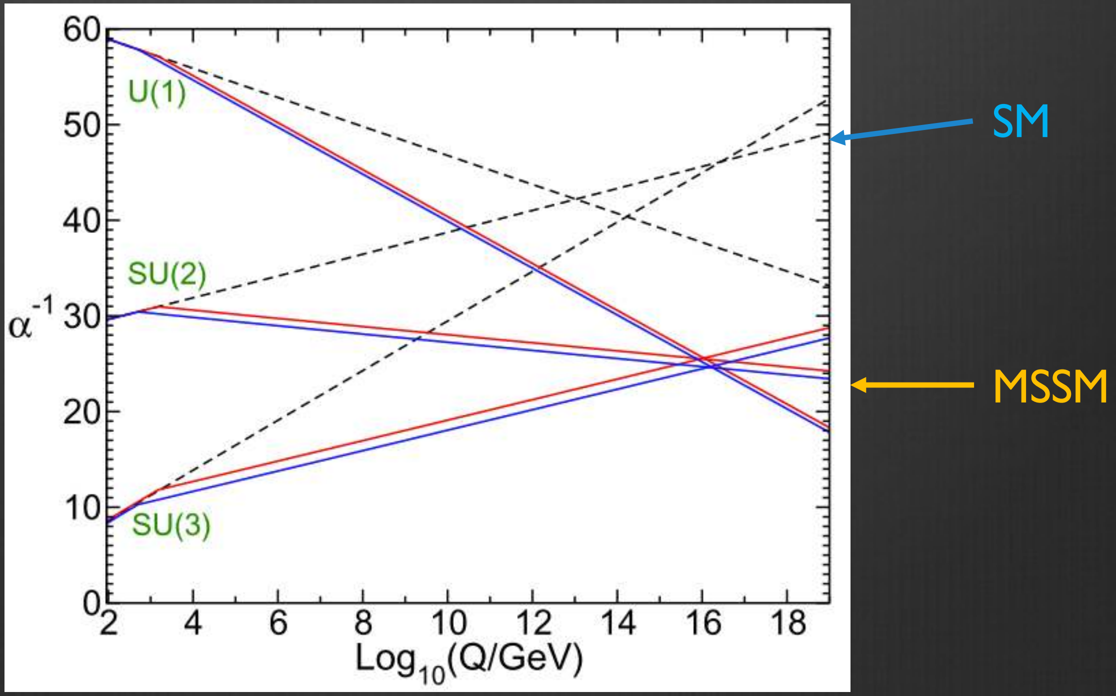




$$\Delta m_H^2 = \frac{\lambda_f^2}{8\pi^2}\left[-\Lambda^2 + 6m_f^2 \ln\left(\frac{\Lambda}{m_f}\right)\right]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda^2 - 2m_S^2 \ln\left(\frac{\Lambda}{m_S}\right)\right]$$

- Allows gauge coupling unification



Supergravity

When supersymmetry is promoted to a local symmetry, it contains GR (*supergravity*)

spin-2 graviton e_μ^a + spin-3/2 gravitino ψ_μ

Coupling of supergravity to matter is in general complicated. It is determined by the (real) Kähler potential $K(\Phi, \bar{\Phi})$ and the (holomorphic) superpotential $W(\Phi)$ and gauge kinetic function $f_{ab}(\Phi)$

Local supersymmetry is spontaneously broken if $m_{3/2} = \langle e^{K/2} W \rangle \neq 0$

The scalar part of the Lagrangian

$$e^{-1}\mathcal{L}_S = K^i_j D_\mu \phi_i D^\mu \bar{\phi}^j$$
$$- \underbrace{e^K}_{\substack{\text{too steep!} \\ (\eta \text{ problem})}} \underbrace{\left[(K^{-1})^j_i (K^i W + W^i)(K_j \bar{W} + \bar{W}_j) - 3|W|^2 \right]}_{\text{generically } V_0 \neq 0}$$

No-scale Supergravity

Consider

$$K = -3\ln\underbrace{\left(T+\bar{T}-|\phi|^2/3+\cdots\right)}_{SU(N,1)\ /\ SU(N)\times U(1)}+\cdots$$

Then,

- The scalar potential is flat, with vanishing cosmological constant
- Supersymmetry is broken with undetermined gravitino mass
- Flatness may be lifted by (mass) parameters in W that break the underlying symmetry
- Small parameters are natural and protected by supersymmetry
- The theory arises as the EFT of compactified string theory
- Inflaton candidates: volume modulus T, singlet matter field ϕ (right handed s-neutrino)

No-scale Supergravity

Consider

$$K = -3\ln\left(T+\bar{T}-|\phi|^2/3+\cdots\right)+\cdots$$

Then,

$$\mathcal{L} = (T+\bar{T}-|\phi|^2/3)^{-1}\,(\partial_\mu\bar{T},\,\partial_\mu\bar{\phi})\begin{pmatrix}3 & -\phi\\ -\bar{\phi} & T+\bar{T}\end{pmatrix}\begin{pmatrix}\partial^\mu\bar{T}\\ \partial^\mu\bar{\phi}\end{pmatrix} - \frac{\hat{V}}{(T+\bar{T}-|\phi|^2/3)^2}$$

$$\hat{V} = |W^\phi|^2+\frac{1}{3}(T+\bar{T})|W^T|^2+\frac{1}{3}\left(W^T(\bar{\phi}\bar{W}_\phi-3\bar{W})+\mathrm{h.c.}\right)$$

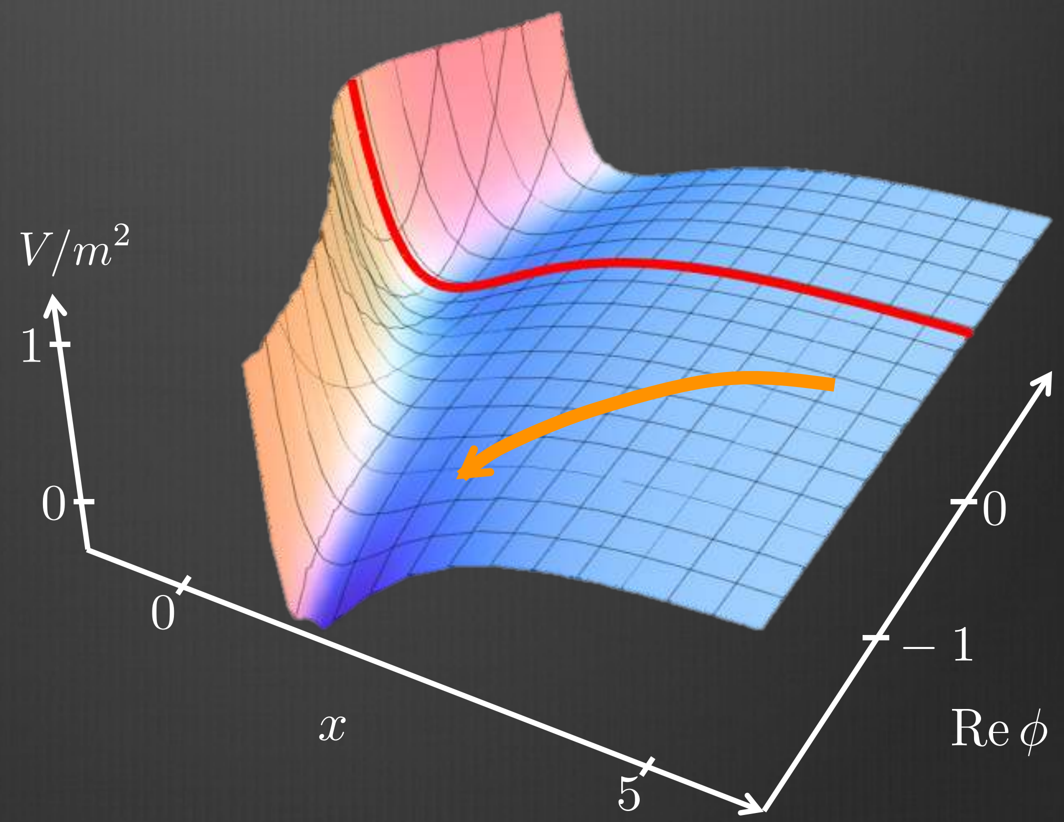
Starobinsky inflation in (no-scale) supergravity

- Cecotti (1987):

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

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

$$\mathrm{Re}\,T = \frac{1}{2}e^{\sqrt{2/3}x}$$



Starobinsky inflation in (no-scale) supergravity

- Cecotti (1987):

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

~~SU(2,1)~~

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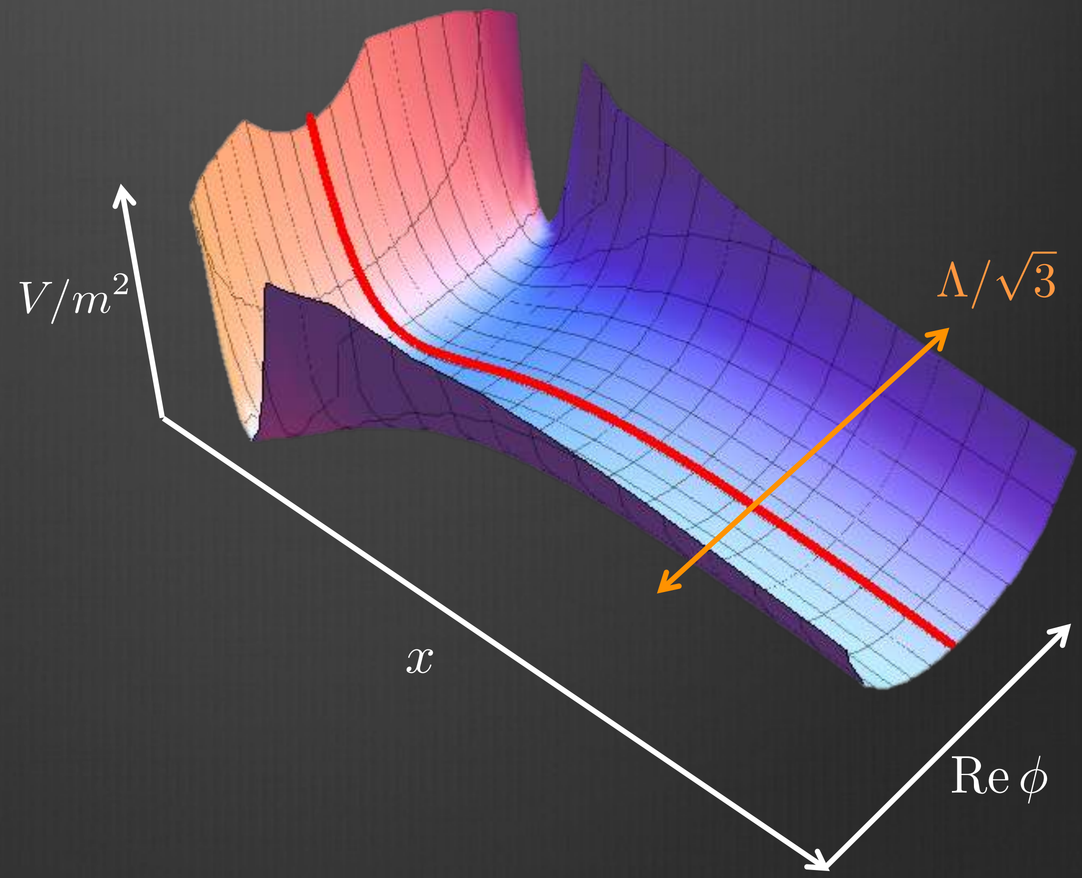


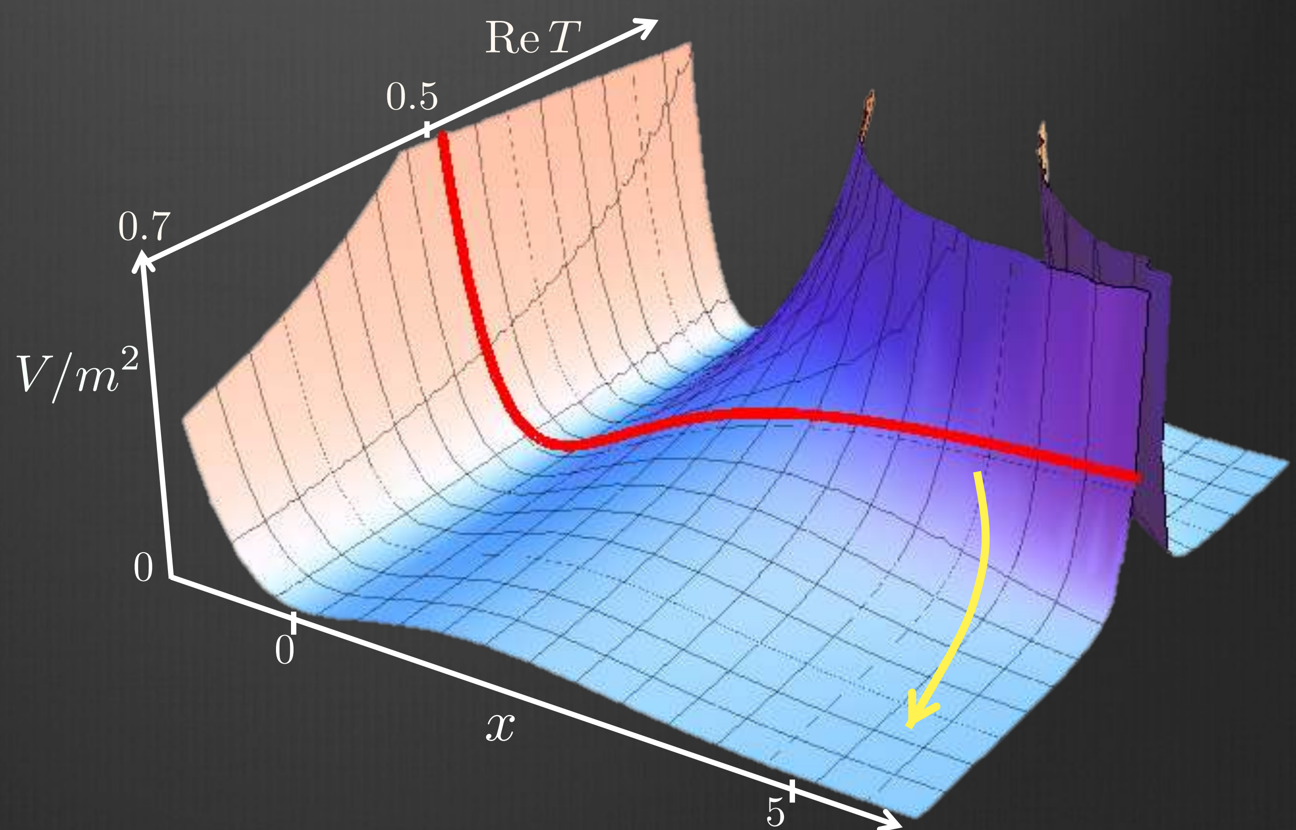
Starobinsky inflation in (no-scale) supergravity

- Ellis, Nanopoulos, Olive (2013):

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

$$W = m \left(\frac{\phi^2}{2} - \frac{\phi^3}{3\sqrt{3}} \right)$$

$$\phi = \sqrt{3} \tanh(x/\sqrt{6})$$



Starobinsky inflation in (no-scale) supergravity

- Ellis, Nanopoulos, Olive (2013):

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

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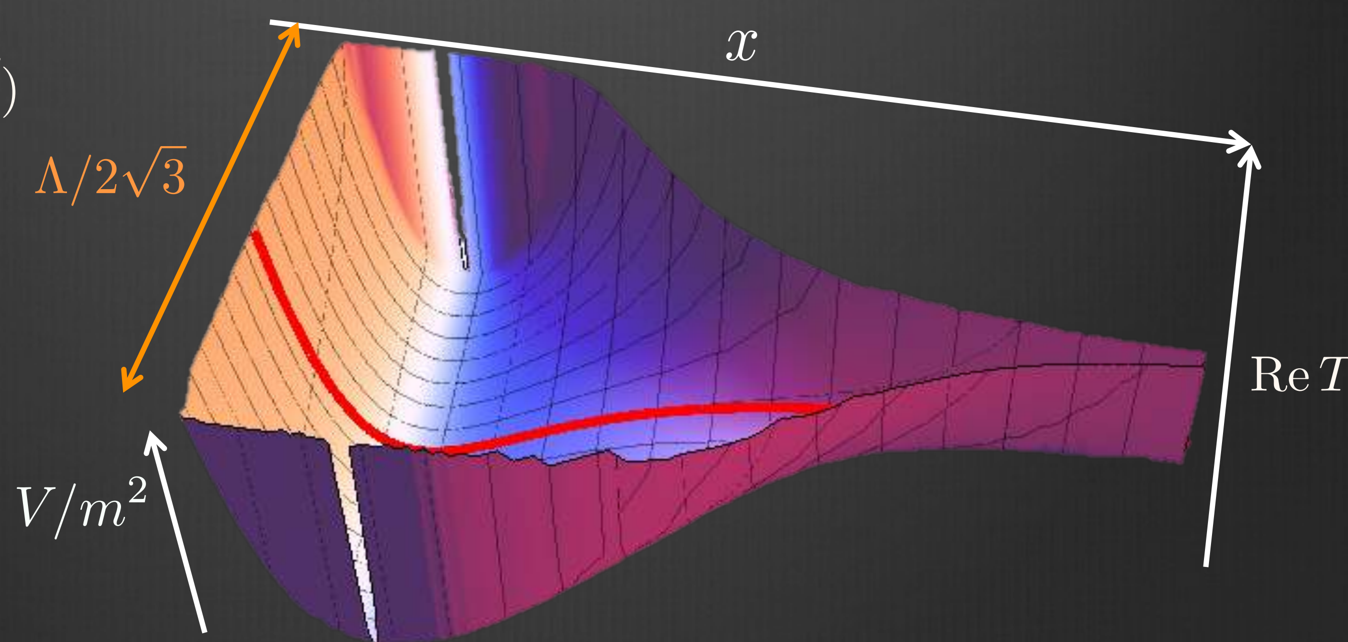


Starobinsky inflation in (no-scale) supergravity

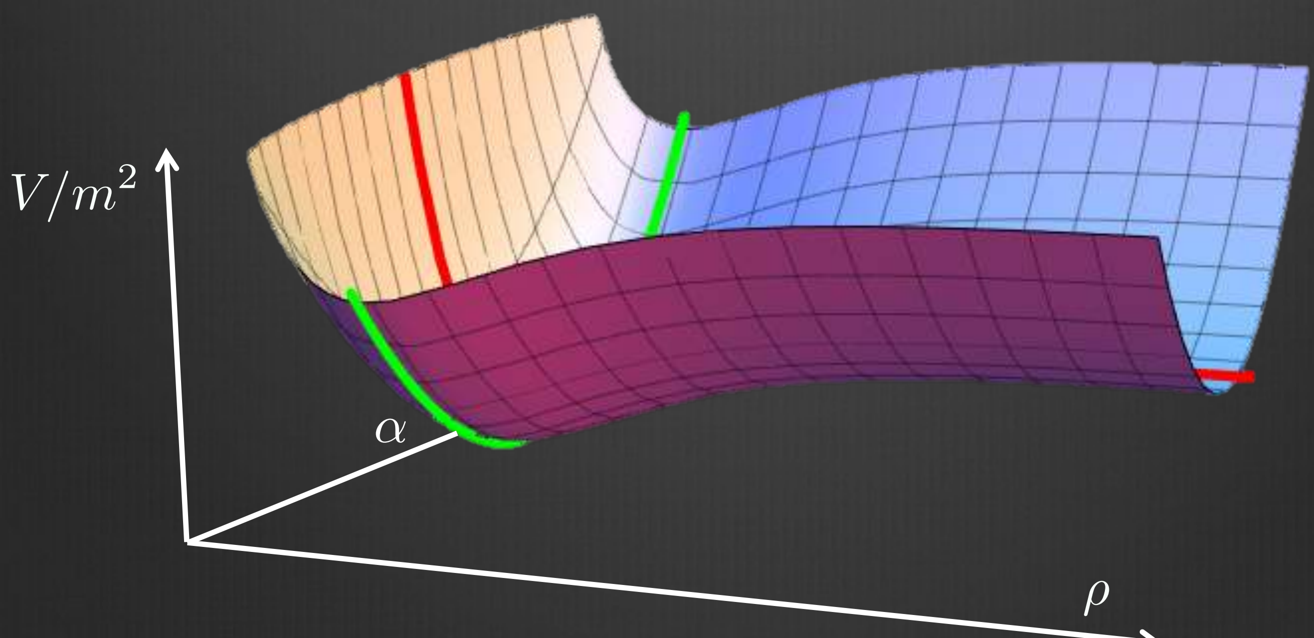
- Ellis, G, Nanopoulos, Olive (2014):

$$K = -3\ln(T+\bar{T}) + \frac{|\varphi|^2}{(T+\bar{T})^3} \,, \qquad T = \frac{1}{2}e^{-\sqrt{2/3}\rho} + \frac{i}{\sqrt{6}}\alpha$$

$$W = \sqrt{3}m\varphi(T-1/2)$$

$$V \propto e^{|\varphi|^2/(T+\bar{T})^3}$$

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



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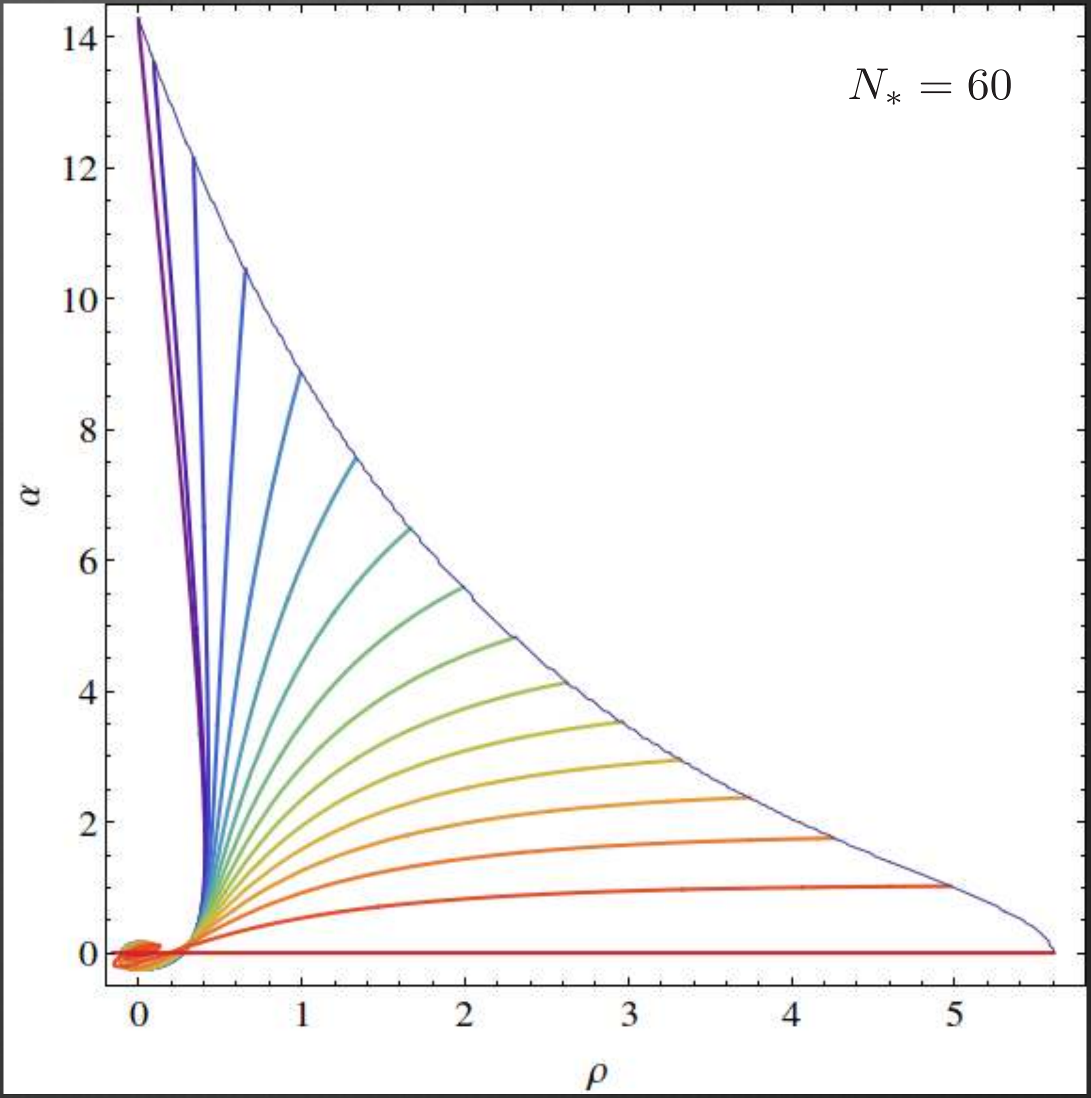

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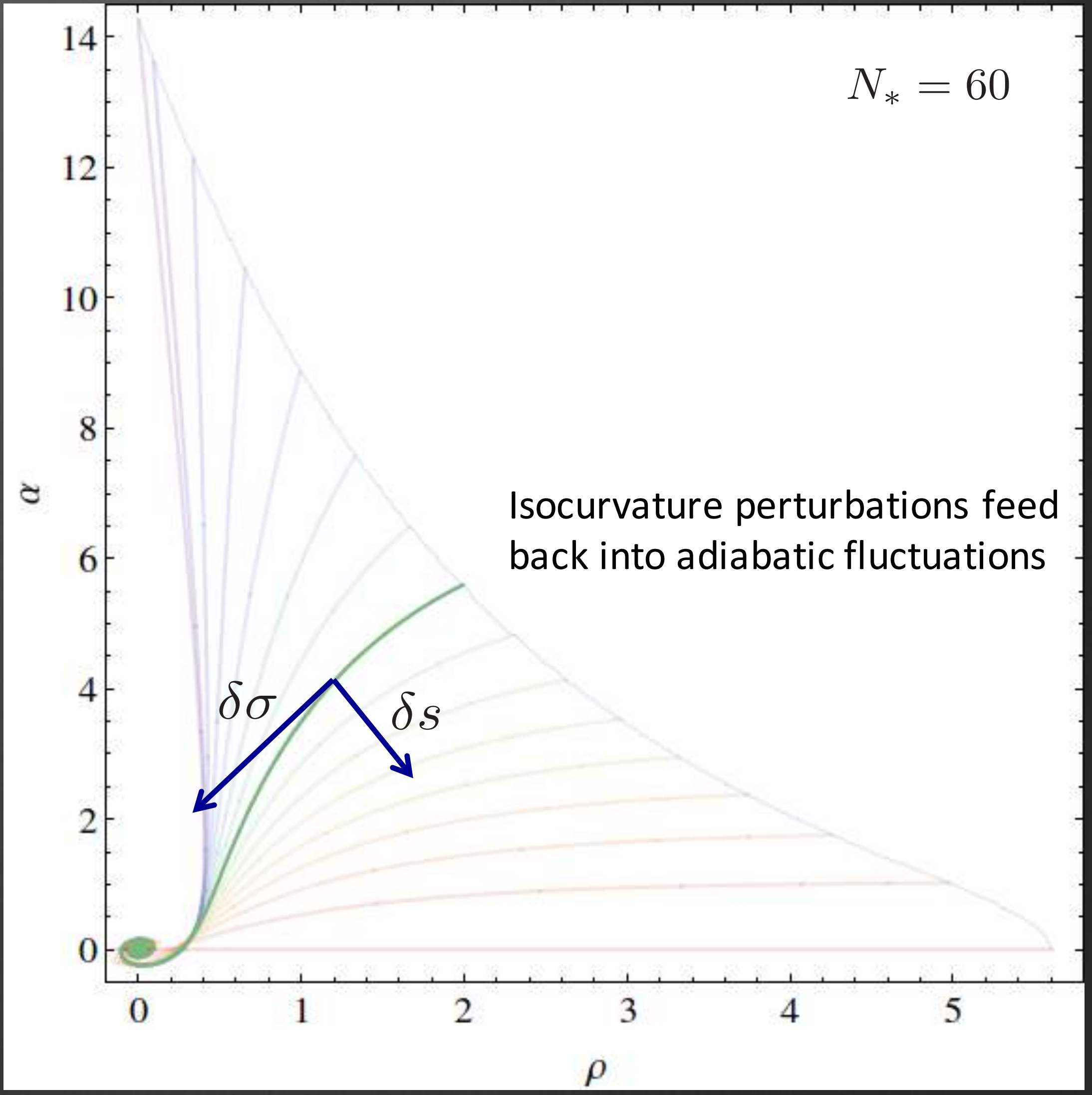


Two-field effects

Rewrite $T = \frac{1}{\sqrt{2}}(\chi + i\zeta)$

$$\mathcal{L}_{\rm kin} \; = \; \frac{1}{2} f(\chi,\zeta) \, \left[(\partial_\mu \chi)^2 + (\partial_\mu \zeta)^2\right] \; = \; \frac{3}{4\chi^2} \left[(\partial_\mu \chi)^2 + (\partial_\mu \zeta)^2\right]$$

Background:

$$\ddot{\chi} + 3H\dot{\chi} + \frac{1}{2} f^{-1} \left[(\dot{\chi}^2 - \dot{\zeta}^2) f_\chi + 2\dot{\chi}\dot{\zeta} f_\zeta\right] + f^{-1} V_{,\chi} \; = \; 0$$

$$\ddot{\zeta} + 3H\dot{\zeta} + \frac{1}{2} f^{-1} \left[(\dot{\zeta}^2 - \dot{\chi}^2) f_\zeta + 2\dot{\chi}\dot{\zeta} f_\chi\right] + f^{-1} V_{,\zeta} \; = \; 0$$

$$H^2 \; = \; \frac{1}{3}\left[\frac{1}{2} f(\dot{\chi}^2 + \dot{\zeta}^2) + V\right]$$

Adiabatic and isocurvature decomposition:

$$\dot{\sigma} = \sqrt{f(\dot{\chi}^2 + \dot{\zeta}^2)} \quad \Rightarrow \quad \begin{aligned} \mathbf{e}_\sigma &= (\dot{\chi}/\dot{\sigma}, \dot{\zeta}/\dot{\sigma}) \\ \mathbf{e}_s &= (\dot{\zeta}/\dot{\sigma}, -\dot{\chi}/\dot{\sigma}) \end{aligned} \quad \Rightarrow \quad \begin{aligned} \delta\sigma &= \frac{f}{\dot{\sigma}}(\chi\delta\chi + \zeta\delta\zeta) \\ \delta s &= \frac{f}{\dot{\sigma}}(\chi\delta\zeta - \zeta\delta\chi) \end{aligned}$$

Two-field effects

Gauge invariant perturbations:

$$Q_\sigma = \delta\sigma + \frac{\dot\sigma}{H}\Psi$$
$$Q_s = \delta s$$

$$\ddot Q_\sigma + 3H\dot Q_\sigma + 2\frac{V_s}{\dot\sigma}\dot Q_s + \left(\frac{k^2}{a^2} + C_{\sigma\sigma}\right) Q_\sigma + C_{\sigma s}Q_s = 0$$
$$\ddot Q_s + 3H\dot Q_s - 2\frac{V_s}{\dot\sigma}\dot Q_\sigma + \left(\frac{k^2}{a^2} + C_{ss}\right) Q_s + C_{s\sigma}Q_\sigma = 0$$

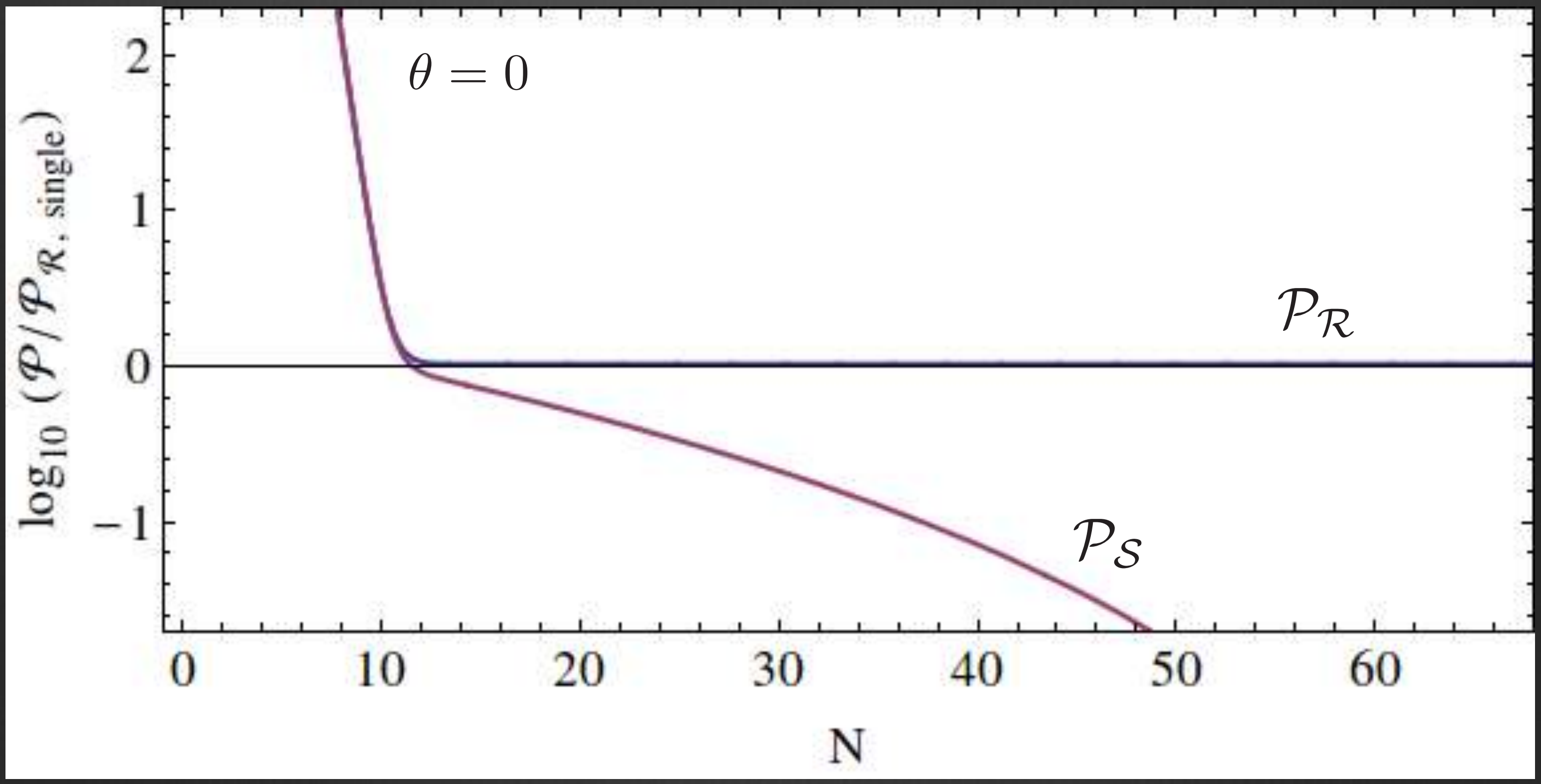
$$C_{\sigma\sigma} = V_{\sigma\sigma} - \left(\frac{V_s}{\dot\sigma}\right)^2 + \frac{2\dot\sigma}{H}V_\sigma + 3\dot\sigma^2 - \frac{\dot\sigma^4}{2H^2} - \frac{f_\chi\dot\chi + f_\zeta\dot\zeta}{2f\dot\sigma}V_\sigma - \frac{f_\zeta\dot\chi - f_\chi\dot\zeta}{2f\dot\sigma}V_s$$
$$C_{\sigma s} = 6H\frac{V_s}{\dot\sigma} + 2\frac{V_sV_\sigma}{\dot\sigma^2} + 2V_{\sigma s} + \frac{\dot\sigma V_s}{H} - \frac{f_\chi\dot\chi + f_\zeta\dot\zeta}{f\dot\sigma}V_s + \frac{f_\zeta\dot\chi - f_\chi\dot\zeta}{f\dot\sigma}V_\sigma$$
$$C_{s\sigma} = -6H\frac{V_s}{\dot\sigma} - 2\frac{V_\sigma V_s}{\dot\sigma^2} + \frac{\dot\sigma V_s}{H}$$
$$C_{ss} = V_{ss} - \left(\frac{V_s}{\dot\sigma}\right)^2 + \frac{f_\chi\dot\chi + f_\zeta\dot\zeta}{2f\dot\sigma}V_\sigma + \frac{f_\zeta\dot\chi - f_\chi\dot\zeta}{2f\dot\sigma}V_s + \frac{\dot\sigma^2}{2f^2}\left(\frac{f_\chi^2}{f} + \frac{f_\zeta^2}{f} - f_{\chi\chi} - f_{\zeta\zeta}\right)$$

Two-field effects

Curvature and entropy perturbations, and power spectrum:

$$\mathcal{R} = \frac{H}{\dot{\sigma}} Q_\sigma \,, \qquad \langle \mathcal{R}(k) \bar{\mathcal{R}}(k') \rangle = \frac{2\pi^2}{k^3} \mathcal{P}_{\mathcal{R}}\, \delta(k - k')$$

$$\mathcal{S} = \frac{H}{\dot{\sigma}} Q_s \,, \qquad \langle \mathcal{S}(k) \bar{\mathcal{S}}(k') \rangle = \frac{2\pi^2}{k^3} \mathcal{P}_{\mathcal{S}}\, \delta(k - k')$$



$$\frac{H^4}{4\pi^2 \dot{\sigma}^2}$$

Two-field effects

Curvature and entropy perturbations, and power spectrum:

$$\mathcal{R} = \frac{H}{\dot\sigma} Q_\sigma \,, \qquad \langle \mathcal{R}(k)\bar{\mathcal{R}}(k')\rangle = \frac{2\pi^2}{k^3}\mathcal{P}_{\mathcal{R}}\,\delta(k-k')$$

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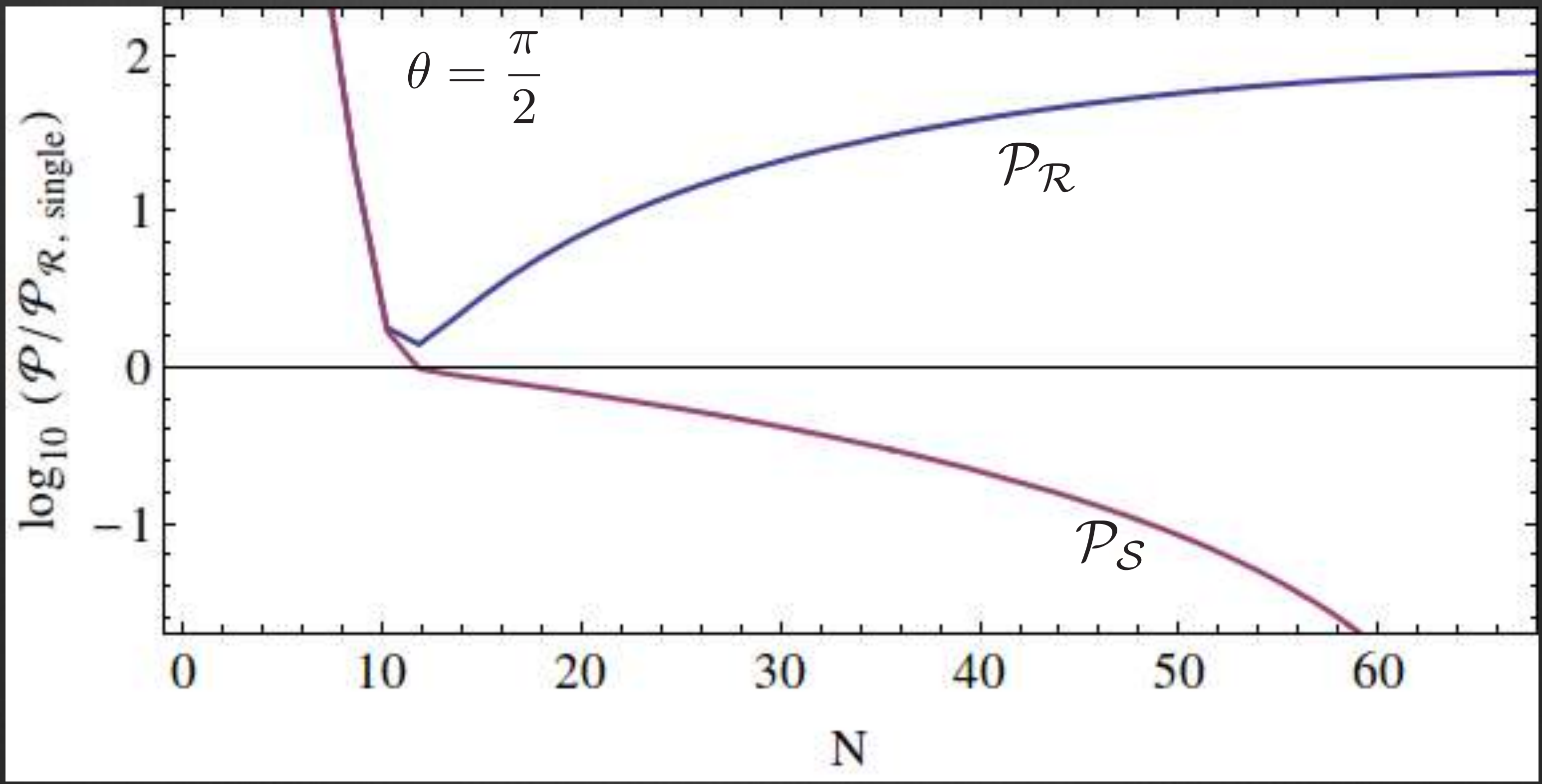
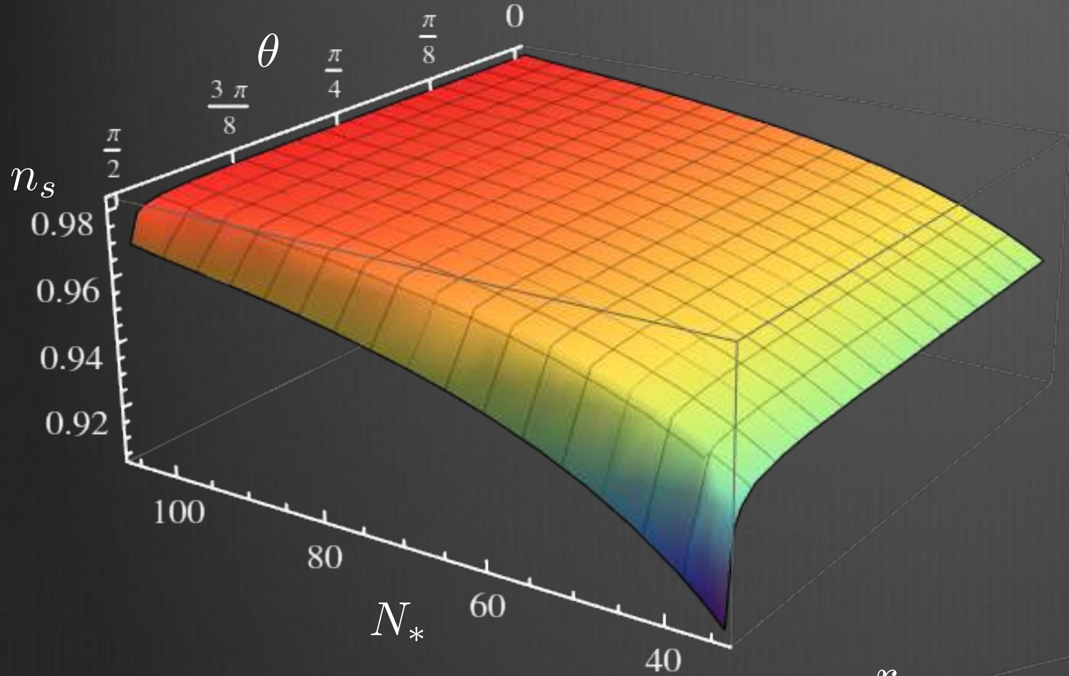


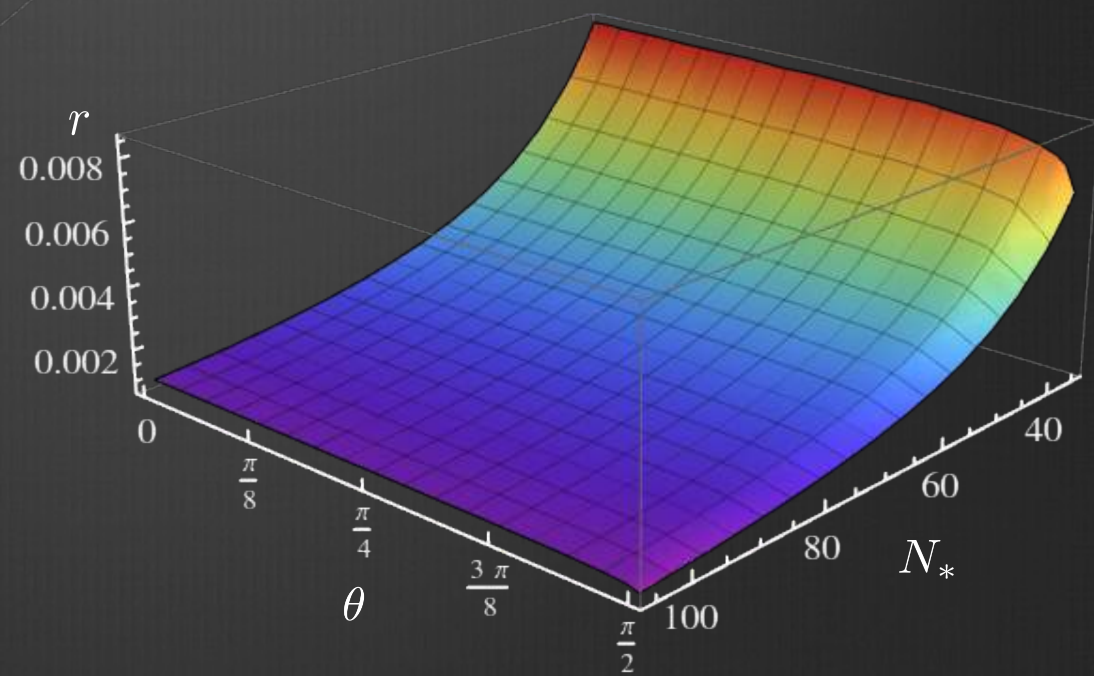
$$\frac{H^4}{4\pi^2\dot\sigma^2}$$

Two-field effects



$$n_s = 1 + \frac{d \log \mathcal{P}_\mathcal{R}}{d \log k}$$

$$r = \frac{\mathcal{P}_T}{\mathcal{P}_\mathcal{R}}$$

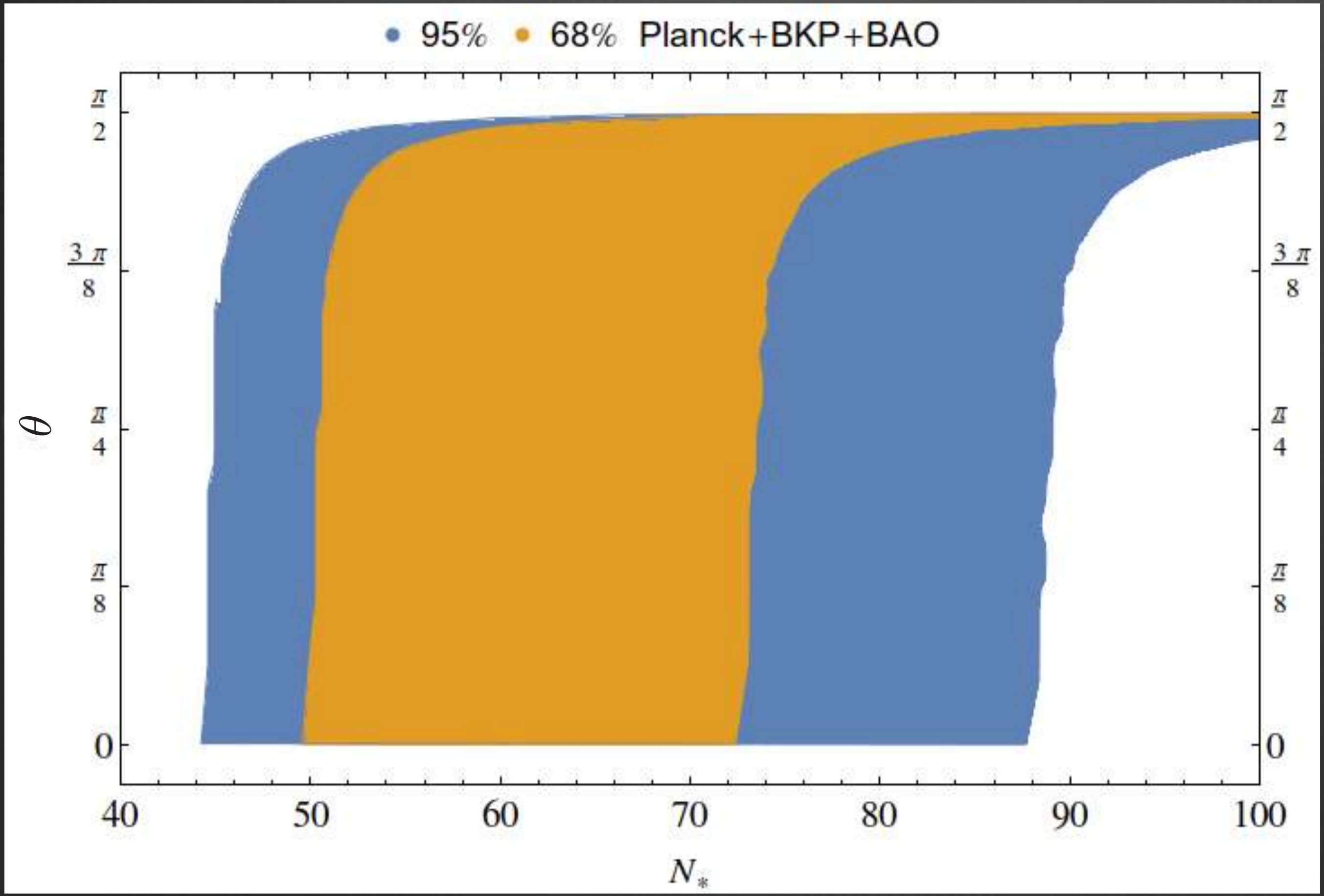


Two-field effects

$$n_s = 1 + \frac{d\log\mathcal{P}_\mathcal{R}}{d\log k}$$

$$r = \frac{\mathcal{P}_T}{\mathcal{P}_\mathcal{R}}$$

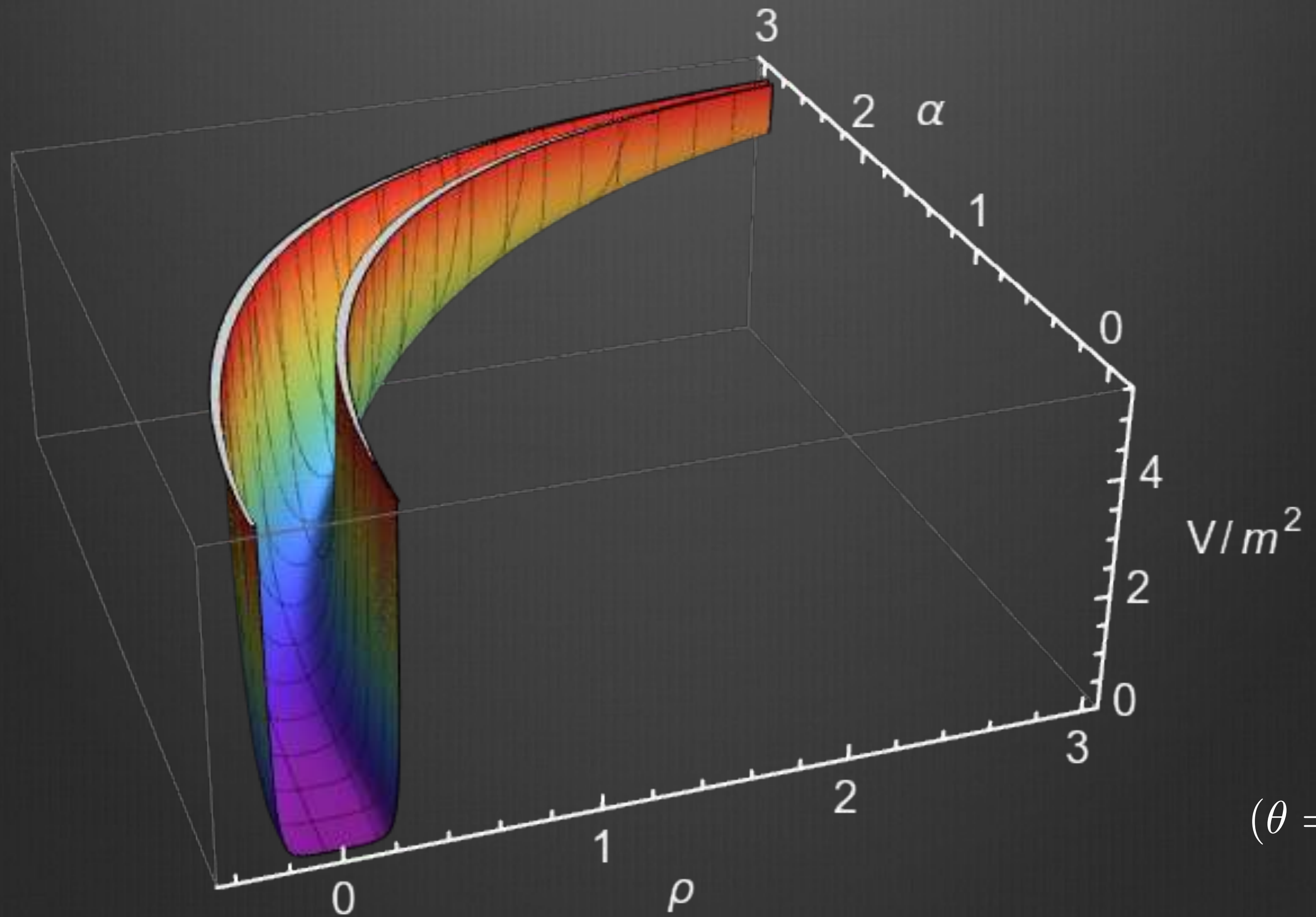
$$|f_{NL}| \lesssim 0.04$$



Two-field effects

The quadratic direction can be recovered via modulus stabilization

$$K = -3\ln\left(T+\bar{T}+c\left[\sin\theta(T+\bar{T}-1)-\cos\theta(T-\bar{T})^2\right]^2\right)+\frac{|\phi|^2}{(T+\bar{T})^3}$$

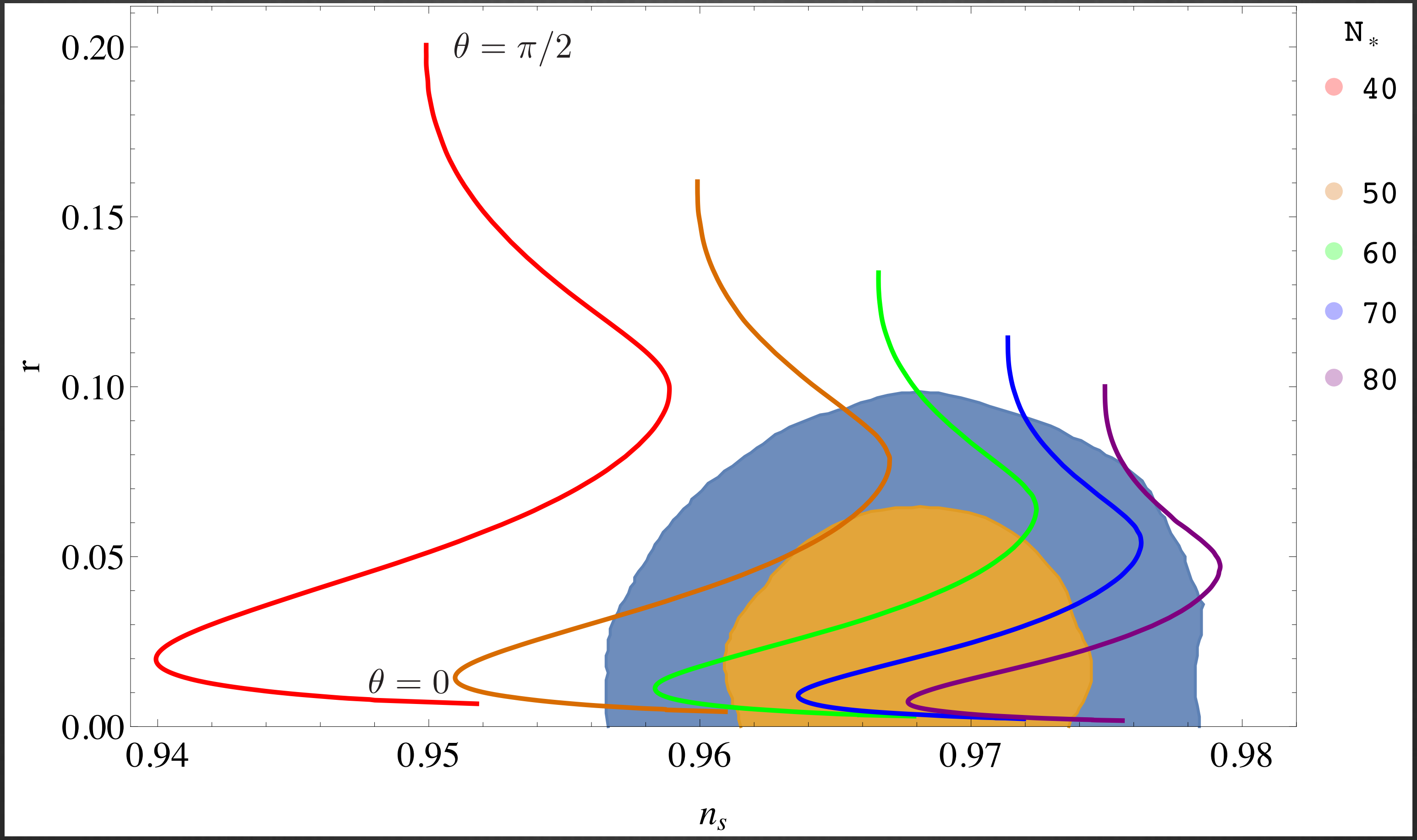


$(\theta = 4\pi/9)$

Two-field effects

The quadratic direction can be recovered via modulus stabilization

$$K = -3\ln\left(T+\bar{T}+c\left[\sin\theta(T+\bar{T}-1)-\cos\theta(T-\bar{T})^2\right]^2\right)+\frac{|\phi|^2}{(T+\bar{T})^3}$$



$(c = 100)$

Inflaton decay in no-scale models

Kähler potential from string compactifications (S, U_j fixed)

$$K = -3\ln\left(T + \bar{T} - \underbrace{\frac{1}{3}\sum_j |\phi_j|^2\Bigg)}_{\text{Untwisted}} + \underbrace{\sum_a \frac{|\varphi_a|^2}{(T+\bar{T})^{n_a}}}_{\text{Twisted}}$$

$\Rightarrow$ inflaton is either T or ϕ_1

Generic superpotential

$$W = W_{\rm inf}(T, \phi_1) + W_M(T, \phi_i, \varphi_a; \mu)$$

with $\mu \sim m_{3/2} \ll m$

Inflaton decay in no-scale models

The supergravity Lagrangian $(G = K + \ln|W|^2)$

$$
\begin{aligned}
\mathrm{e}^{-1}\mathcal{L} = & -\frac{R}{2} + G^i_j D_\mu\phi_i D^\mu\bar\phi^j - e^G(G_i(G^{-1})^i_j G^j - 3) - \frac{1}{4}(\mathrm{Re}\, f_{ab})F_{a\mu\nu}F^{\mu\nu}_b - \frac{1}{4}(\mathrm{Im}\, f_{ab})F_{a\mu\nu}\tilde F^{\mu\nu}_b \\
& - \frac{g^2}{2}(\mathrm{Re}\, f^{-1}_{ab})G^i T_{aij}\phi_j G^k T_{bkl}\phi_l - \frac{\mathrm{e}^{-1}}{2}\epsilon^{\mu\nu\rho\sigma}\bar\psi_\mu\gamma_5\gamma_\nu D_\rho\psi_\sigma + \Bigg[\frac{i}{2}G^i_j\bar\chi_{iR}\gamma^\mu D_\mu\chi^j_R \\
& + \frac{\mathrm{e}^{-1}}{8}\epsilon^{\mu\nu\rho\sigma}\bar\psi_\mu\gamma_\nu\psi_\rho G^i D_\sigma\phi_i + \frac{i}{2}\bar\chi_{iR}\not{D}\phi_j\chi^k_R(-G^{ij}_k + \frac{1}{2}G^i_k G^j) + \frac{i}{\sqrt2}G^j_i\bar\psi_{\mu R}\not{D}\bar\phi^i\gamma^\mu\chi_{jL} \\
& + \frac{1}{2}\mathrm{Re}\, f_{ab}\left(\frac{i}{2}\bar\lambda_a\not{D}\lambda_b + \frac{1}{4}\bar\lambda_a\gamma^\mu\sigma^{\nu\rho}\psi_\mu F_{b\nu\rho} - \frac{i}{2}G^i D^\mu\phi_i\bar\lambda_{aL}\gamma_\mu\lambda_{bL}\right) + \frac{1}{8}\mathrm{Im}\, f_{ab}\ \mathrm{e}^{-1}D_\mu(\mathrm{e}\bar\lambda_a\gamma_5\gamma^\mu\lambda_b) \\
& - \frac{1}{4\sqrt2}(f_{ab})^{,i}\ \bar\chi_{iR}\sigma^{\mu\nu}F_{a\mu\nu}\lambda_{bL} + \frac{i}{2}e^{G/2}\bar\psi_{\mu L}\sigma^{\mu\nu}\psi_{\nu R} + \frac{1}{2}gG^i T_{aij}\phi_j\bar\psi_{\mu R}\gamma^\mu\lambda_{aR} - g\sqrt2 G^j_i T_{ajk}\phi_k\bar\lambda_{aL}\chi^i_R \\
& - \frac{1}{2}e^{G/2}(-G^{ij} - G^i G^j + G^{ij}_k(G^{-1})^k_l G^l)\bar\chi_{iR}\chi_{jL} - \frac{1}{\sqrt2}e^{G/2}G^i\bar\psi_{\mu L}\gamma^\mu\chi_{iL} \\
& + \frac{i}{16}G^j_i\bar\chi_{iL}\gamma_\sigma\chi_{jL}(\epsilon^{\mu\nu\rho\sigma}\bar\psi_\mu\gamma_\nu\psi_\rho - i\bar\psi^\mu\gamma^5\gamma_\sigma\psi_\mu) + \left(\frac{1}{8}G^{ij}_{kl} - \frac{1}{8}G^{ij}_m(G^{-1})^m_n G^n_{kl} - \frac{1}{16}G^i_k G^j_l\right)\bar\chi_{iR}\chi_{jL}\bar\chi^k_L\chi^l_R \\
& + \frac{1}{4}e^{G/2}(\bar f_{ab})_{,j}(G^{-1})^j_k G^k\bar\lambda_{aL}\lambda_{bR} + \frac{g}{\sqrt2}(\mathrm{Re}\, f_{ab})^{-1}(f_{bc})^{,k}G^i T_{aij}\phi_j\bar\chi_{kR}\lambda_{cL} + \frac{3}{32}[(\mathrm{Re}\, f_{ab})\bar\lambda_{aR}\gamma_\mu\lambda_{bR}]^2 \\
& - \frac{1}{32}(G^{-1})^k_l(f_{ab})^{,l}(\bar f_{cd})_{,k}\bar\lambda_{aR}\lambda_{bL}\bar\lambda_{cL}\lambda_{dR} + \frac{i}{4\sqrt2}(f_{ab})^{,i}\left(\bar\chi_{iR}\sigma^{\mu\nu}\lambda_{aL}\bar\psi_{\nu R}\gamma_\mu\lambda_{bR} + \frac{i}{2}\bar\psi_{\mu L}\gamma^\mu\chi_{iL}\bar\lambda_{aL}\lambda_{bL}\right) \\
& + \frac{i}{16}(\mathrm{Im}\, f_{ab})\bar\lambda_a\gamma^\mu\sigma^{\rho\sigma}\psi_\mu\bar\psi_\rho\gamma_\sigma\lambda_b + \frac{1}{16}\bar\psi_{iR}\gamma^\mu\psi^j_R\bar\lambda_{dL}\gamma_\mu\lambda_{cL}\left[G^i_j(\mathrm{Re}\, f_{cd}) + \frac{1}{2}\mathrm{Re}\ \left(f^{-1}_{ab}(f_{ac})^{,i}(\bar f_{bd})_{,j}\right)\right] \\
& - \frac{1}{16}\bar\chi_{iR}\chi_{jL}\bar\lambda_{cR}\lambda_{dL}\left(-2G^{ij}_k(G^{-1})^k_l(f_{cd})^{,l} + 2(f_{cd})^{,ij} - \frac{1}{2}\mathrm{Re}\, f^{-1}_{ab}(f_{ac})^{,i}(\bar f_{bd})_{,j}\right) \\
& - \frac{1}{128}\bar\chi_{iR}\sigma_{\mu\nu}\chi_{jL}\bar\lambda_{cR}\sigma^{\mu\nu}\lambda_{dL}\mathrm{Re}\ \left(f^{-1}_{ab}(f_{ac})^{,i}(f_{fb})^{,j}\right) + \mathrm{h.c.}\Bigg]
\end{aligned}
$$

Inflaton decay in no-scale models

Decay of the untwisted matter inflaton ϕ_1 (WZ):

Segregated inflation and matter sectors, $W_1 = W_{1\alpha} = W_{1\alpha\beta} = \cdots = 0$

$$\Rightarrow \quad \Gamma(\phi_1 \to \mathrm{matter}) = 0$$

No inflaton – modulus mixing, $W_{1TT} = 0$

$$\Rightarrow \quad \Gamma(\phi_1 \to T\,T) = 0$$

$$\Gamma(\phi_1 \to \psi_{3/2}\psi_{3/2}) = 0$$

No gauge kinetic function dependence, $\partial f_{\alpha\beta}/\partial\phi_1 = 0$

$$\Rightarrow \quad \Gamma(\phi_1 \to gg) = \Gamma(\phi_1 \to \tilde{g}\tilde{g}) = 0$$

Inflaton decay in no-scale models

Decay of the untwisted matter inflaton ϕ_1 (WZ):

ϕ_1 as heavy singlet sneutrino, $\Delta W = y_\nu H_u L \phi_1$

$$\Rightarrow \quad \Gamma(\phi_1 \to H_u^0 \tilde{\nu}, H_u^+ \tilde{f}_L) = m \frac{|y_\nu|^2}{16\pi}$$

Inflaton – modulus mixing, $\Delta W = \zeta (T - 1/2)^2 \phi_1$

$$\Rightarrow \quad \Gamma(\phi_1 \to T\,T) = \Gamma(\phi_1 \to \psi_{3/2}\psi_{3/2}) = m \frac{|\zeta|^2}{72\pi}$$

$$\Gamma(\phi_1 \to gg) = (p-3)^2 \frac{|\zeta \cdot f'(T)|^2}{216\pi \langle \mathrm{Re}\, f \rangle^2} \left(\frac{N_G}{12}\right) \left(\frac{m_{3/2}}{m}\right)^2 m$$

$$= \left(\frac{m}{m_{3/2}}\right)^2 \Gamma(\phi_1 \to \tilde{g}\tilde{g})$$

Inflaton decay in no-scale models

Decay of the volume modulus inflaton T (Cecotti, EGNO):

Coupling to matter (untwisted $n_i \equiv 1$),

$$\mathcal{L} = \frac{n_I}{\sqrt{3}}\delta T \Phi_I \partial_\mu \partial^\mu \bar{\Phi}^I - \frac{i n_I}{2\sqrt{3}}\delta T \bar{\chi}_{IL}\gamma^\mu \partial_\mu \chi^I_L$$

$$+\frac{i n_I}{2\sqrt{3}}\bar{\chi}_{IL}(\not{\partial}\delta T)\chi^I_L + \frac{\sqrt{3}}{2}W^{IJ}\,\delta T \bar{\chi}_{IL}\chi_{JR} + \frac{\sqrt{3}}{2}W^{IJK}\,\delta T \Phi_K \bar{\chi}_{IL}\chi_{JK}$$

$$-\frac{B^I_J}{\sqrt{3}}\delta T \Phi_I \bar{\Phi}^J - \frac{B^{IJ}_K}{2\sqrt{3}}\delta T \Phi_I \Phi_J \bar{\Phi}^K - \frac{B^I_{JK}}{2\sqrt{3}}\delta T \Phi_I \bar{\Phi}^J \bar{\Phi}^K$$

$$-\frac{B^{IJK}_L}{6\sqrt{3}}\delta T \Phi_I \Phi_J \Phi_K \bar{\Phi}^L - \frac{B^I_{JKL}}{6\sqrt{3}}\delta T \Phi_I \bar{\Phi}^J \bar{\Phi}^K \bar{\Phi}^L - \frac{B^{IJ}_{KL} + C^{IJ}_{KL}}{4\sqrt{3}}\delta T \Phi_I \Phi_J \bar{\Phi}^K \bar{\Phi}^L$$

$$+\text{h.c.} + \mathcal{O}\left(\frac{m_{3/2}}{m}\right) + \cdots$$

$$B^{I_1 I_2 \ldots}_{J_1 J_2 \ldots} = \left[(n_a - 3)W^{I_1 I_2 \ldots a}\bar{W}_{a J_1 J_2 \ldots} - 2W^{I_1 I_2 \ldots k}\bar{W}_{k J_1 J_2 \ldots}\right]$$

$$C^{IJ}_{KL} = -(3 + (n_I + n_J - 3)(n_K + n_L - 3))W^{IJ}\bar{W}_{KL} + (n_I + n_M - 3)\delta^I_L W^{JM}\bar{W}_{MK}$$

Inflaton decay in no-scale models

Decay of the volume modulus inflaton T (Cecotti, EGNO):

Decays to matter,

$$\Gamma(T \to \bar{\chi}_I \chi_J) = (n_I + n_J - 3)^2 \frac{|W^{IJ}|^2 m}{192\pi M_P^2}$$

$$\Gamma(T \to \Phi_I \bar{\Phi}^J) = (n_I + n_L - 3)^2 \frac{|W^{IL}\bar{W}_{LJ}|^2}{48\pi m M_P^2}$$

$$\Gamma(T \to \Phi_I \bar{\Phi}^J \bar{\Phi}^K) = (n_I + n_L - 3)^2 \frac{|W^{IL}\bar{W}_{LJK}|^2 m}{12(8\pi)^3 M_P^2}$$

$$\boxed{\Gamma(T \to \bar{\chi}_I \chi_J \Phi_K) = (n_I + n_J + n_K - 3)^2 \frac{|W^{IJK}|^2 m^3}{36(8\pi)^3 M_P^2}}$$

$$\Gamma(T \to \Phi_I \Phi_J \bar{\Phi}^K) = (n_I + n_J + n_L - 3)^2 \frac{|W^{IJL}\bar{W}_{LK}|^2 m}{12(8\pi)^3 M_P^2}$$

$$\boxed{\Gamma(T \to \Phi_I \Phi_J \bar{\Phi}^K \bar{\Phi}^M) = (n_I + n_J + n_L - 3)^2 \frac{|W^{IJL}\bar{W}_{LKM}|^2 m^3}{72(8\pi)^5 M_P^2}}$$

Inflaton decay in no-scale models

Decay of the volume modulus inflaton T (Cecotti, EGNO):

Decays to matter,

$$\Gamma(T \to \tilde{t}_R \tilde{t}_L \bar{\tilde{t}}_R \bar{\tilde{t}}_L) = (2n_t + n_H - 3)^2 \frac{|y_t|^4 m^3}{8(8\pi)^5 M_P^2}$$

$$\Gamma(T \to H_u^0 t_L \bar{t}_R,\ \tilde{t}_L \tilde{H}_u^0 \bar{t}_R,\ \bar{\tilde{t}}_R t_L \tilde{H}_u^0) = (2n_t + n_H - 3)^2 \frac{|y_t|^2 m^3}{12(8\pi)^3 M_P^2}$$

T-dependent gauge kinetic function $f_{\alpha\beta} = f(T)\delta_{\alpha\beta}$

$$\Gamma(T \to gg) = \frac{|f'(T)|^2}{32\pi \langle \mathrm{Re}\, f \rangle^2} \left(\frac{N_G}{12} \right) \frac{m^3}{M_P^2}$$

All other rates suppressed by powers of $\frac{m_{3/2}}{m}$

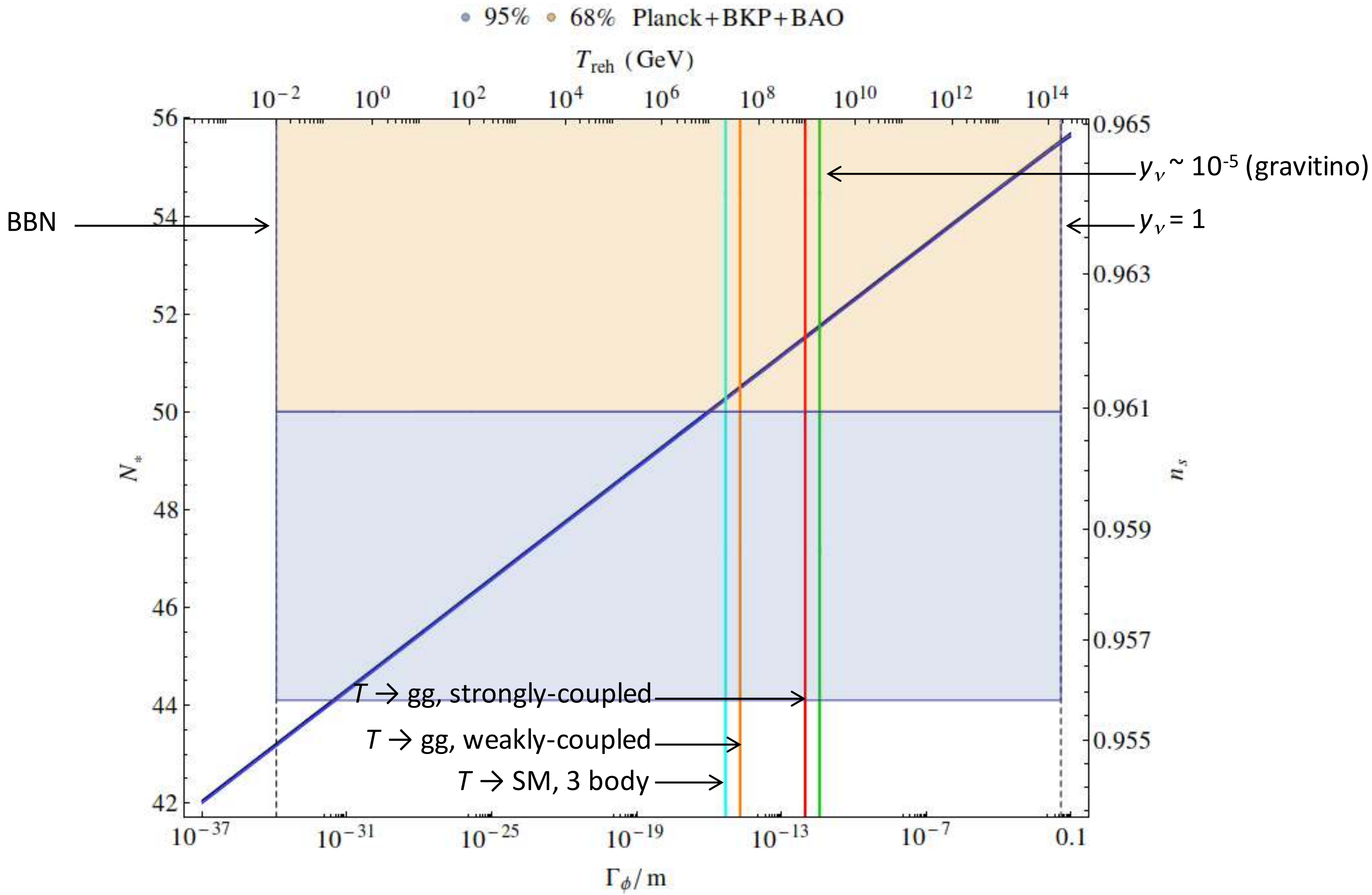
CMB + Reheating for Starobinsky

$$N_* = 66.9 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{M_P^4 \rho_{\rm end}}\right) + \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right) - \frac{1}{12}\ln g_{\rm reh}$$

$$= 68.66 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln(A_{S*}) - \frac{1}{2}\ln\left(N_* - \sqrt{\frac{3}{8}}\frac{\phi_{\rm end}}{M_P} + \frac{3}{4}e^{\sqrt{\frac{2}{3}}\frac{\phi_{\rm end}}{M_P}}\right)$$
$$+ \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\left[2\ln\left(\frac{\Gamma}{m}\right) - 1.832\right] - \frac{1}{12}\ln g_{\rm reh}$$

$$w_{\rm int} = \frac{1}{N_{\rm reh} - N_{\rm end}}\int_{N_{\rm end}}^{N_{\rm reh}} w(n)\, dn \approx \frac{0.743}{\ln(3.40\, m/\Gamma)}$$

CMB + Reheating for Starobinsky



Conclusion

- No-scale supergravity can realize Starobinsky (and quadratic) inflation
- Stabilization not necessary in the presence of twisted matter
- Two-field effects reduce tensor-to-scalar ratio to Planck-compatible values
- Low energy susy phenomenology can be easily integrated (Ellis, G, Nanopoulos, Olive, 2015)
- No-scale reheating lies in the favored range, with

$$\text{(CMB)} \qquad 10^{-16} \lesssim \frac{\Gamma}{m} \lesssim 10^{-12} \qquad \text{(gravitino)}$$

Conclusion

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Thank you