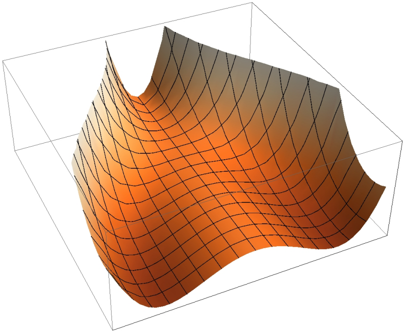
Justice for supersymmetric F-term hybrid inflation

.. in the light of Planck



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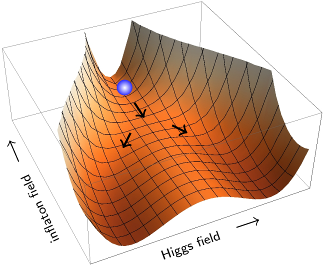
Overview

- a brief introduction to supersymmetric hybrid inflation
- the game-changer: soft supersymmetry breaking
- results and discussion
- conclusion

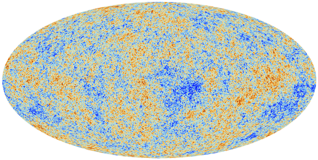
Hybrid Inflation in Pictures

- inflaton field → flat direction, higgs field → ends inflation

scalar potential



- large vacuum energy
  → exponential expansion
- classical trajectory
  → dynamics of inflation
- quantum fluctuations
  → observables A_s, n_s, r



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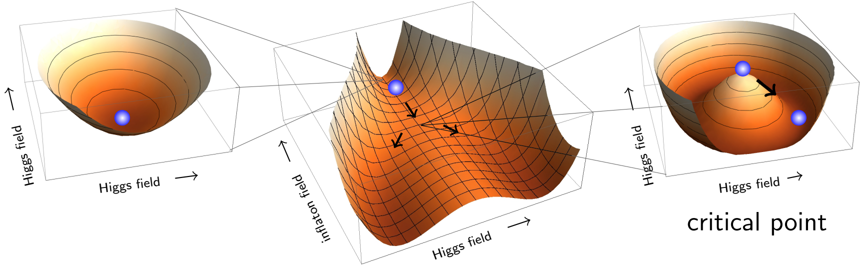

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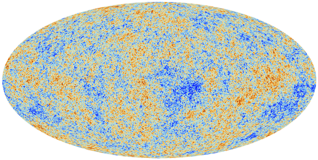


Some Highlights of Susy F-term Hybrid Inflation

$$W = \lambda\Phi(\frac{v^2}{2} - S_+S_-)\,, \quad U(1):\, q(\Phi) = 0,\, q(S_+) = -q(S_-)$$

[Copeland *et al* '94, Dvali *et al* '94]

Particle Physics

- describes spontaneous breaking of a $U(1)$ symmetry, e.g. $U(1)_{B-L}$
- by observation $v \sim$ GUT scale $\rightarrow$ last step of GUT breaking scheme?
- for gauged $U(1)_{B-L}$: Right-handed neutrinos $m_N \sim y \times m_{GUT}$
  $\rightarrow$ small 'SM' neutrino masses via seesaw mechanism

Cosmology

- Observables of Inflation from GUT-scale physics
- Cosmological $U(1)_{B-L}$ PT triggers reheating, leptogenesis
- $\rightarrow$ production of entropy, dark matter, matter-antimatter asymmetry

[Buchmüller, VD, Schmitz '12]

simple, well-motivated and predictive model

Predictions for Observables

Inflationary observables

- are determined by shape of the scalar potential

  $A_s = \frac{V}{24\pi^2 \epsilon M_P^2}\Big|_{\phi_*}, \quad n_s = (1 - 6\epsilon + 2\eta)\Big|_{\phi_*}$

  with $\epsilon = \frac{M_P^2}{2}\frac{V'}{V}, \eta = M_P^2 \frac{V''}{V}; \quad \phi = |\Phi|$

- evaluated at $\phi = \phi_*$, N_* efolds before the end of inflation at $\phi_f \sim v$

  $\rightarrow$ solve eom $3H\dot{\phi} = -V'(\phi)$ with $dN = -H dt$

  $\rightarrow$ solve $N_* = \frac{1}{M_P^2}\int_{\phi_f}^{\phi_*} \frac{V}{V'} d\phi \qquad \rightarrow \phi_*$

.. in the case of hybrid inflation

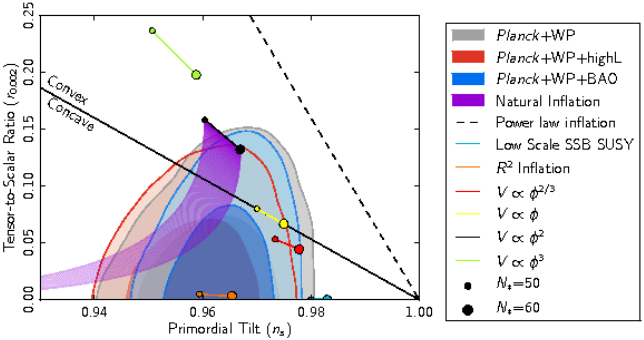
- scalar potential: $V = V_0 + \frac{\lambda^4 v^4}{128\pi^2} f\left(|\phi/v|^2\right)$

  with $f(z) = (z-1)^2 \ln(z-1) + (z+1)^2 \ln(z+1) - 2z^2 \ln(z)$

- consider $\phi_* >> v$: $\rightarrow f'_* \sim (v/\phi_*)^2 \rightarrow \phi_*^2 \sim \frac{\lambda}{4\pi^2} N_*$

  $\rightarrow A_s = \frac{1}{3}\left(\frac{v}{M_P}\right)^4 N_*$ and $n_s = 1 - \frac{1}{N_*} \simeq 0.98$

But . . . Inflation after Planck



[Planck '13]

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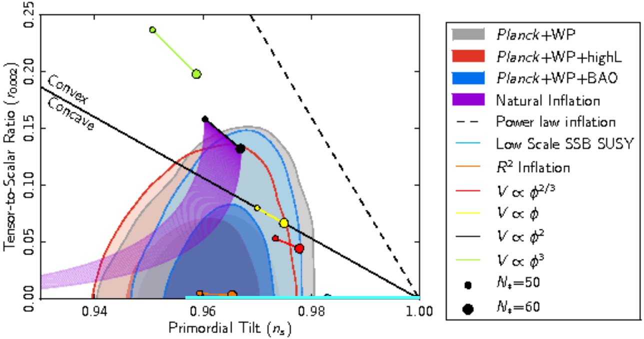


[Planck '13]

⇒ but a closer look will reveal a very different picture !

The role of soft supersymmetry breaking

- F-term supersymmetry breaking, dynamics stabilised during inflation:

$$\langle F_z \rangle \neq 0$$

- F-term scalar potential in supergravity

$$V_F = e^K \left(\underbrace{K^{\alpha\beta} \mathcal{D}_\alpha W \mathcal{D}_\beta \bar{W}}_{\ni |F_z|^2} - 3|W|^2 \right)$$

- Minkowski vacuum after inflation

$$V_F = 0 \to \langle W \rangle = W_0 \neq 0 \,, \qquad m_{3/2}^2 M_P^4 = e^K |W|^2 \sim W_0^2$$

effective description of susy breaking $\to W \mapsto W + \kappa \, m_{3/2} M_P^2$

I won't discuss hidden sector dynamics
I won't solve the cosmological constant problem

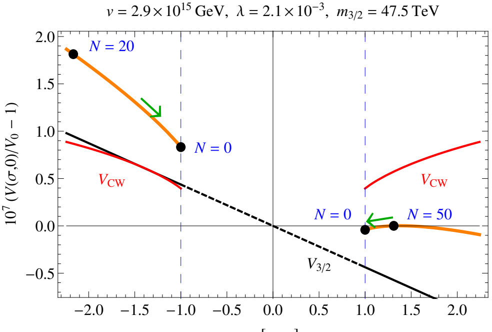
The role of soft supersymmetry breaking

- constant term in W breaks degeneracy in the inflaton phase

$$W = \lambda \Phi (\frac{v^2}{2} - S_+ S_-) + m_{3/2} M_P^2 \quad \to V = V(|\Phi|) - \lambda v^2 m_{3/2} (\Phi + \Phi^*) + \ldots$$

e.g. [Covi, Buchmüller '06]

- scalar potential is 'tilted' in the complex plane $\Phi = (\sigma + i\tau)/\sqrt{2}$



[Yanagida et al '10] [Shafi et al '13]

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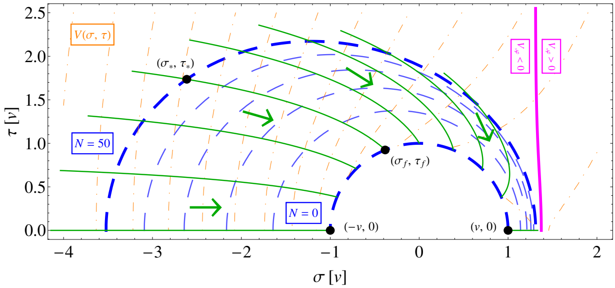
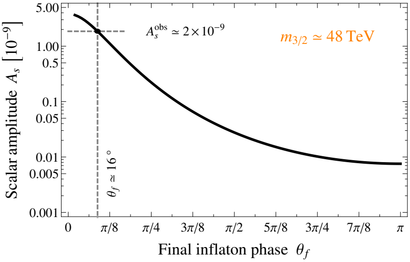
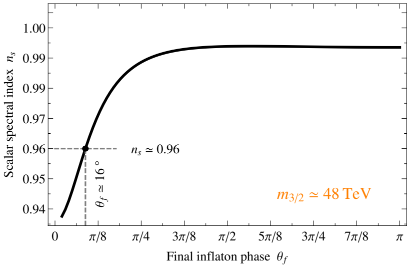


F-term susy hybrid inflation is a two-field model

A two-field inflation model

- calculate observables along different possible trajectories
- predictions depend strongly on choice of trajectory

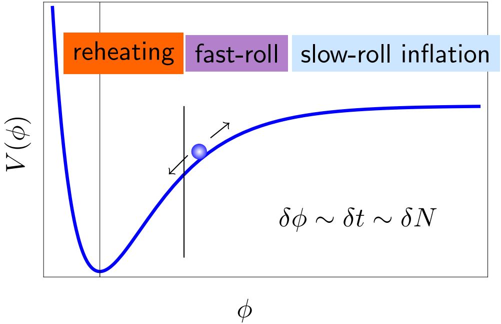




additional parameter θ_f must be taken into account

Calculating predictions in a multi field model

- number of e-folds N gives a time-axis: $dN = -H dt$
- perturbation δN between trajectories $\rightarrow$ primordial fluctuations



observables from

- $V, V_a, V_a^b\big|_{\phi_*}$
- $N_a = \frac{dN}{d\phi_a},\ N_a\big|_{\phi_*}$
- $\rightarrow N(\phi),\ N_a(\phi)$

  [Sasaki *et al* '96]
- $\rightarrow V(N), N_a(N)$

beware of $\delta N \not\parallel \delta\phi$

Calculating predictions in a multi field model

slow-roll inflation

$$A_s = \frac{H^2}{4\pi^2} N_a N^a \Big|_{N_*}$$

$$n_s - 1 = -2 \left(\frac{H'}{H} + \frac{N^a N_a'}{N^b N_b} \right) \Big|_{N_*}$$

with $' = d/dN$:

$$N_a'(N) = -P_a^b(N) N_b(N)$$

where

$$P_a^b = \left(\frac{V_a^b}{V} - \frac{V_a V^b}{V^2} \right)$$

$$N_a(N_0) = N_a^0 + \frac{V}{V_b \Sigma^b} \Sigma_a$$

[Yokoyama *et al* '07/'08, Mazumdar *et al* '08]

fast-roll inflation | (p) reheating

$$N_a^0 = N_a^{FR} + N_a^{PH}$$

obtained by solving eom for ϕ_a:

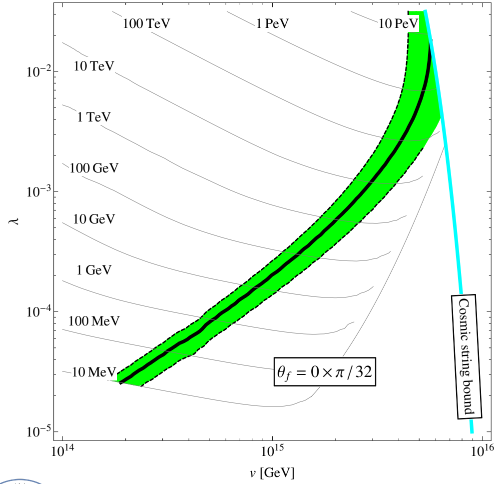
$$\ddot{\phi}_a + 3H\dot{\phi}_a + \partial V / \partial \phi_a^* = 0$$

and integrating solution to obtain $N(\phi)$

Predictions calculated numerically in two-dimensional fieldspace

Preliminary Results

- parameters: $v, \lambda, m_{3/2}, \theta_f \quad \overset{A_s = A_s^{obs}}{\longrightarrow} \quad v, \lambda, \theta_f$



$n_s \sim 0.96$

possible for $\theta_f \lesssim \pi/4$:

$$n_s - 1 \simeq 2\eta \sim 2\frac{M_P^2}{v^2}\frac{\partial^2 V}{V} \sim -\frac{\lambda^2}{4\pi^2}\frac{M_P^2}{|\phi_*|^2}$$

There are regions in parameter space which yield inflation in accordance with the Planck data

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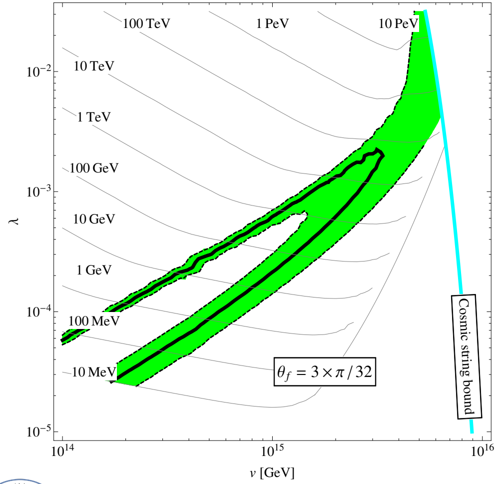

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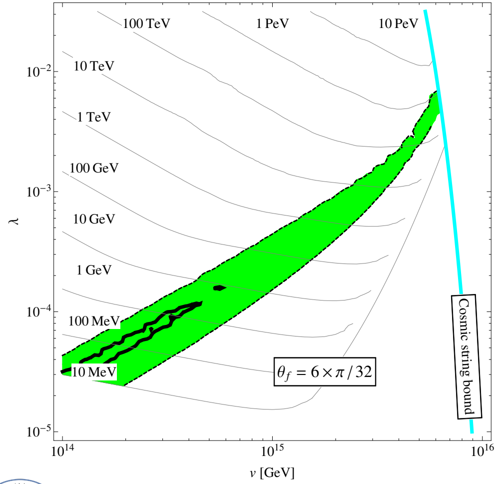

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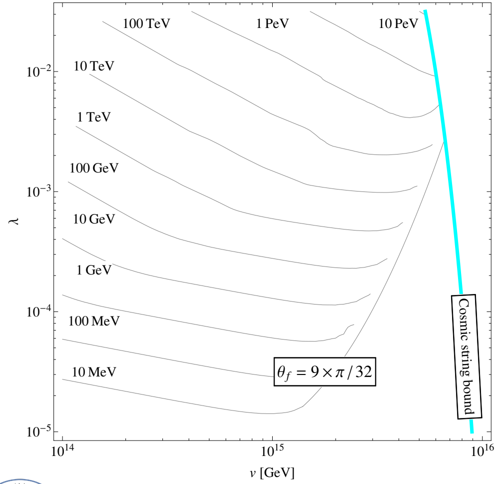

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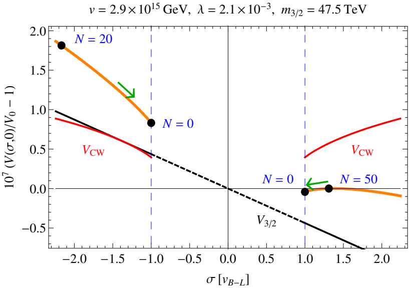
There are regions in parameter space which yield inflation in accordance with the Planck data

The Issue of Initial Conditions

Two problems

- How 'artificial' (i.e. fine-tuned) is the starting point of the inflaton?
- Is it necessary to adjust this value across different Hubble patches?

Recall single-field situation:



- "how did the inflaton end up there ?? "
- $H^2 \sim \frac{\lambda}{4} v^4$ small $\rightarrow$ reintroduces horizon problem

Both problems occur in single-field setup

The Issue of Initial Conditions

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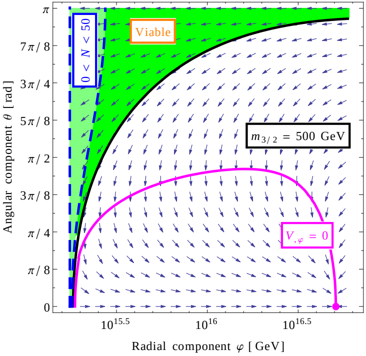
The two-field situation:

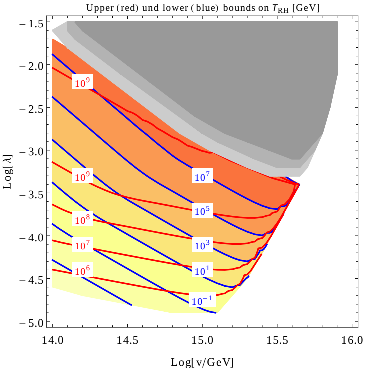


- significant part of parameter space yields successful inflation
- inflation can start at the Planck scale (for $\theta_P \sim \pi$)

Both problems relaxed in the two-field analysis

Gravitino Overproduction?

- gravitinos are produced thermally ($\sim T$) and non-thermally ($\sim 1/T$)
- gravitino LSP $\rightarrow$ over closure of the universe?
- decaying gravitino $\rightarrow$ entropy production in decay after BBN ?



- gravitino LSP, $m_\phi < m_z$
- possible reheating temperatures restricted
- large gravitino masses excluded
- bounds depend on reheating process

[Endo, Hamaguchi, Takahashi '06; Nakaumra, Yamaguchi '06; Kawaski, Takahashi, Yanagida '06; Endo, Takahashi, Yanagida '07/'08; ...]

$m_{3/2} \lesssim 100$ TeV, but loopholes due to
mass hierarchies in susy breaking & reheating, R-parity violation ...

Conclusion and Outlook

- Taking into account F-term susy breaking, hybrid inflation is a two-field model
- The observables then do not only depend on the parameters of the scalar potential, but in particular on the choice of the inflationary trajectory
- Accordance with the Planck data can be achieved in a significant part of the parameter space
- Initial condition problem is relaxed
- Next steps: non-gaussianities, non-minimal Käbler potential