Matter Inflation in Supergravity

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Motivation: How can inflation be realised in close contact to particle physics models?

Outline

- Tribrid Inflation (= Matter Inflation): New class of SUSY inflation models where the inflaton resides in the matter sector

- New class very suitable for applying symmetry solutions to the η-problem, e.g.: Heisenberg symmetry with stabilised modulus

- Interesting inflaton candidates:
  - Right-handed Sneutrino: SUSY partner of the right-chiral neutrino
    (Alternative to “chaotic sneutrino inflation” of Murayama, Suziki, Yanagida, Yokoyama (‘93))
  - D-flat direction of gauge non-singlet (GUT) fields

- Other aspects: Matter inflation in string theory? After inflation: Reheating, non-thermal leptogenesis, moduli stabilisation, ...

Tribrid Inflation (= Matter Inflation)

- Superpotential of the following form

$$W = X\left(f(H) - M^2\right) + g(H, \phi)$$

Driving superfield
(<u>not</u> the inflaton!)

Waterfall superfield

Inflaton superfield
(from matter sector)

- Three fields, X, H and Φ relevant for the model → Tribrid Inflation
- The inflaton can reside in the matter sector → Matter Inflation

First model of this type in: S.A., Bastero-Gil, King, Shafi ('04)
"Tribrid Inflation" model class in SUGRA: S.A., Dutta, Kostka ('09);
S.A., M. Bastero-Gil, K. Dutta, S. F. King, P. M. Kostka ('08)

Tribrid Inflation (= Matter Inflation)

- Superpotential of the following form

$$W = X\left(f(H) - M^2\right) + g(H,\phi)$$

Driving superfield (not the inflaton!)

Waterfall superfield

Inflaton superfield (from matter sector)

- Features:

→ Inflaton Φ is a (global SUSY) F-flat and D-flat direction (@ tree-level)

→ End of inflation via "waterfall mechanism" (as in Hybrid Inflation)

Tribrid Inflation (= Matter Inflation)

- Superpotential of the following form

$$W = X\left(f(H) - M^2\right) + g(H,\phi)$$

Driving superfield (<u>not</u> the inflaton!)

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Inflaton superfield (from matter sector)

- Features:

→ The field X gets heavy from SUGRA corrections (→ X = 0)

.... Kähler potential will be discussed later!

→ For the inflaton, symmetry solutions to the η-problem can be applied (useful properties: $W_{inf} = 0$, $W_{inf,\Phi} = 0$; c.f. Ewan D. Stewart ('94))

A simple example of Tribrid Inflation

- Simple example (singlet fields, global SUSY to start with):

$$W = X(H^2 - M^2) + \frac{1}{\Lambda} H^2 \Phi^2$$

Driving superfield (X) — Waterfall superfield (H) — Inflaton superfield (Φ)

A simple example of Tribrid Inflation

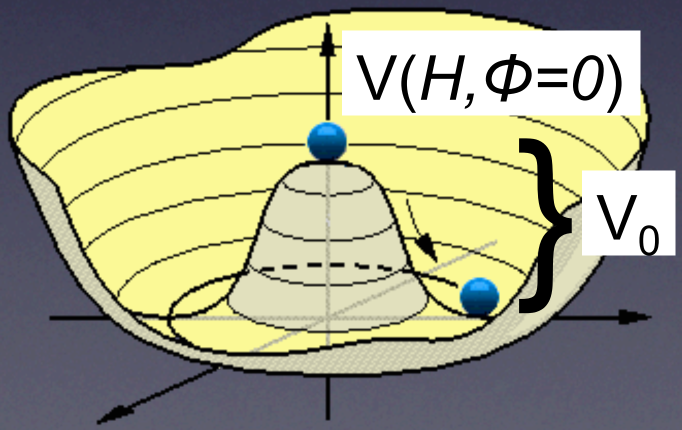
- Simple example (singlet fields, global SUSY to start with):

$$W = X(H^2 - M^2) + \frac{1}{\Lambda} H^2 \Phi^2$$

Driving superfield
(its F-term generates the potential for H and provides the vacuum energy V_0; During and after inflation: $\langle X \rangle = 0$.)

Waterfall superfield
(contains the "waterfall field" (e.g. GUT- or Flavour-Higgs field) that ends inflation by a 2nd order phase transition)

$|F_X|^2 \Rightarrow$



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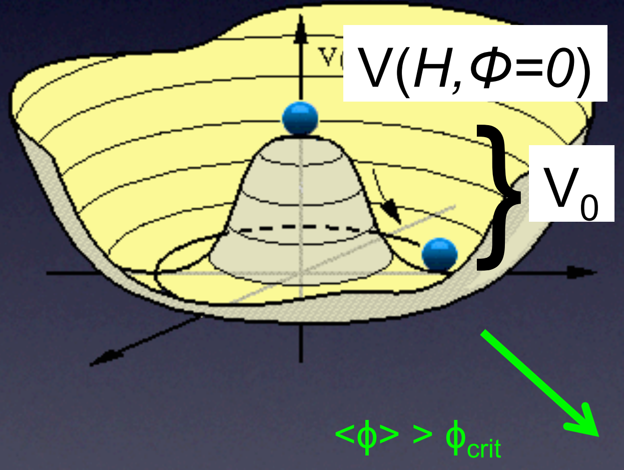
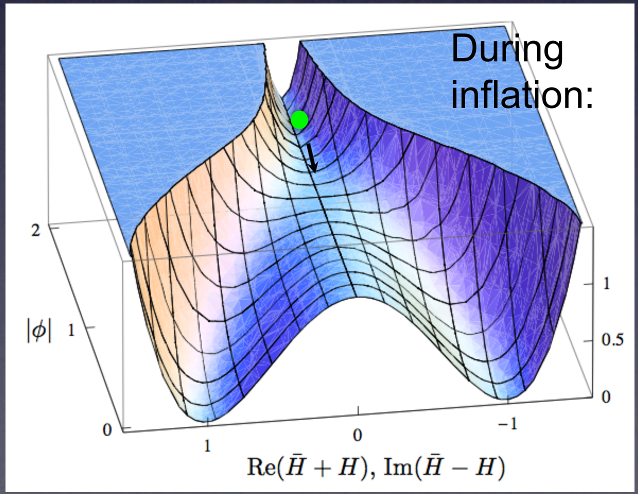




Inflaton superfield
(contains the inflaton field as scalar component; For $<\phi> > \phi_{crit}$ it stabilises H at <H> = 0)

→ Shape of the potential resembles hybrid inflation (Andrei Linde ('91), ...)

The η-problem

- Challenge for realising inflation: Flat enough potential, $m_\phi << \mathcal{H}$

$$\mathcal{H} = \frac{\sqrt{V}}{\sqrt{3} M_P}$$

  - Generic (effective field theory)

$$V \subset V_0 \frac{\phi^\dagger \phi}{M_P^2} \Rightarrow m_\phi \sim \mathcal{H} \leftrightarrow \eta \sim 1$$

  - In supergravity (with K = ϕ*ϕ and V_0 from F-term)

$$V_F = \mathrm{e}^{K/M_P^2} \left(K^{i\bar{j}} D_i W \, D_{\bar{j}} W^* - \frac{3|W|^2}{M_P^2} \right)$$

$$V_F \sim \left(1 + \frac{\phi^\dagger \phi}{M_P^2} + \dots \right) V_0$$

with $D_i W := W_i + K_i W$

E.J Copeland, A.R. Liddle, D.H. Lyth, E.D. Stewart, D. Wands ('94)

Approaches to solve the η-problem: 3 strategies

- Expansion of K in fields/M_P:

requires tuning of parameters! (at 1%-level)

$$K = |\phi|^2 + \frac{\lambda_\phi}{M_P^2}|\phi|^4 + \frac{\lambda_{\phi i}}{M_P^2}|\phi|^2|X_i|^2 + \dots$$

- 'Shift' symmetry: $\phi \rightarrow \phi + i\alpha$

$$K = f(\phi + \phi^*)$$

protects Im[ϕ] from obtaining a SUGRA mass by symmetry!
(used in many works, e.g. Freese, Frieman, Olinto ('90); ...)

- Heisenberg symmetry:

solves the η-problem for |ϕ| by symmetry!

$$T \rightarrow T + \mathrm{i}\,\beta\,, \quad T \rightarrow T + \alpha^*\,\phi + |\alpha|^2/2\,, \quad \phi \rightarrow \phi + \alpha$$

$$K = f(\rho)\,, \ \text{with} \quad \rho = T + T^* - |\phi|^2$$

T: 'modulus field'

Gaillard, Murayama, Olive ('95),
S.A., Bastero-Gil, Dutta, King, Kostka ('08,'09)

Approaches to solve the η-problem: 3 strategies

- Expansion of K in fields/M_P:

- 'Shift' symmetry:

- Heisenberg symmetry:

Remark:
Symmetries have to be broken to allow for slope of V(ϕ)!
→ approximate symmetries

Simple models of inflation in supergravity

Note: ... incomplete list!

- "Standard" SUSY Hybrid Inflation
  (Inflaton scalar component of ϕ)

$$W = \phi(H^2 - M^2)$$

Copeland, Liddle, Lyth, Stewart, Wands ('94);
Dvali, Shafi, Schaefer ('94), Linde, Riotto ('97), ...

- New Inflation

$$W = X\left(\frac{\phi^{2n}}{\Lambda^{2n-2}} - M^2\right)$$

Izawa, Yanagida ('96), Asaka, Hamaguchi,
Kawasaki, Yanagida ('00); Shafi, Senoguz ('04), ...

- Tribrid "Matter" Inflation
  (example model)

$$W = X\left(H^2 - M^2\right) - \frac{1}{\Lambda}H^2\phi^2$$

S.A., Bastero-Gil, King, Shafi ('04),
S.A., M. Bastero-Gil, K. Dutta, S. F. King, P. M. Kostka ('08), ...

- Large Field Chaotic Inflation
  (with quadratic potential)

$$W = mX\phi$$

Kawasaki, Yamaguchi, Yanagida ('00), ...
Recently, generalisations: Kallosh, Linde, Olive, Rube ('10,'11)
Demozzi, Linde, Mukhanov ('10)

Symmetry solutions to the η-problem?

Note: ... incomplete table!

*) problems pointed out e.g. by
Brax et al ('06), Davis, Postma ('08), ...

	K expansion + tuning	Shift symmetry	Heisenberg symmetry	Gauge Non-singlet Inflaton
'Standard' SUSY Hybrid Inflation	(yes) Copeland et al; Dvali, Shafi, Schaefer ('94), ...	X*	X	X
H is the inflaton in New Inflation	(yes) Asaka et al ('00); Shafi, Senoguz ('04)	X	X	yes
Matter field inflaton in Tribrid Inflation	(yes) S.A., Bastero-Gil, King, Shafi ('04)	yes S.A., Dutta, Kostka ('09) Postma, Mooij ('10)	yes S.A., Bastero-Gil, Dutta, King, Kostka ('08)	yes S.A., Bastero-Gil, Baumann Dutta, King, Kostka ('10)
Singlet large field Chaotic Inflation	X	yes Kawasaki, Yamaguchi, Yanagida ('00), ...	yes S.A., Bastero-Gil, Dutta, King, Kostka ('09)	X

Note: Only minimal scalar-curvature coupling cosidered here.

Heisenberg symmetry solution to the η-problem

- Example for K (assuming suitable W with $W_{inf} = 0$, $W_{inf,\Phi} = 0$):

$$K = \underbrace{-3 \ln \rho}_{} + |X|^2 + \kappa_\rho \frac{\rho |X|^2}{M_P} + \ldots , \text{ with } \rho = T + T^* - |\phi|^2$$

Example: No-scale form; More general: f(ρ)

K invariant under Heisenberg symmetry

→ Parameter κ_ρ: Couples ρ to V_0

S.A., M. Bastero-Gil, K. Dutta, S. F. King, P. M. Kostka ('08)

Heisenberg symmetry solution to the η-problem

- Calculate L_{kin} and V_F:

  ✓ In the the (ϕ,ρ)-basis: no kinetic mixing between ϕ and ρ

$$\mathcal{L}_{\rm kin} = \frac{f''(\rho)}{4}\left(\partial_\mu \rho\right)^2 - \frac{f'(\rho)}{2}\left(\partial_\mu \phi\right)^2$$

  ✓ The F-term scalar potential depends only on ρ (and not on ϕ)

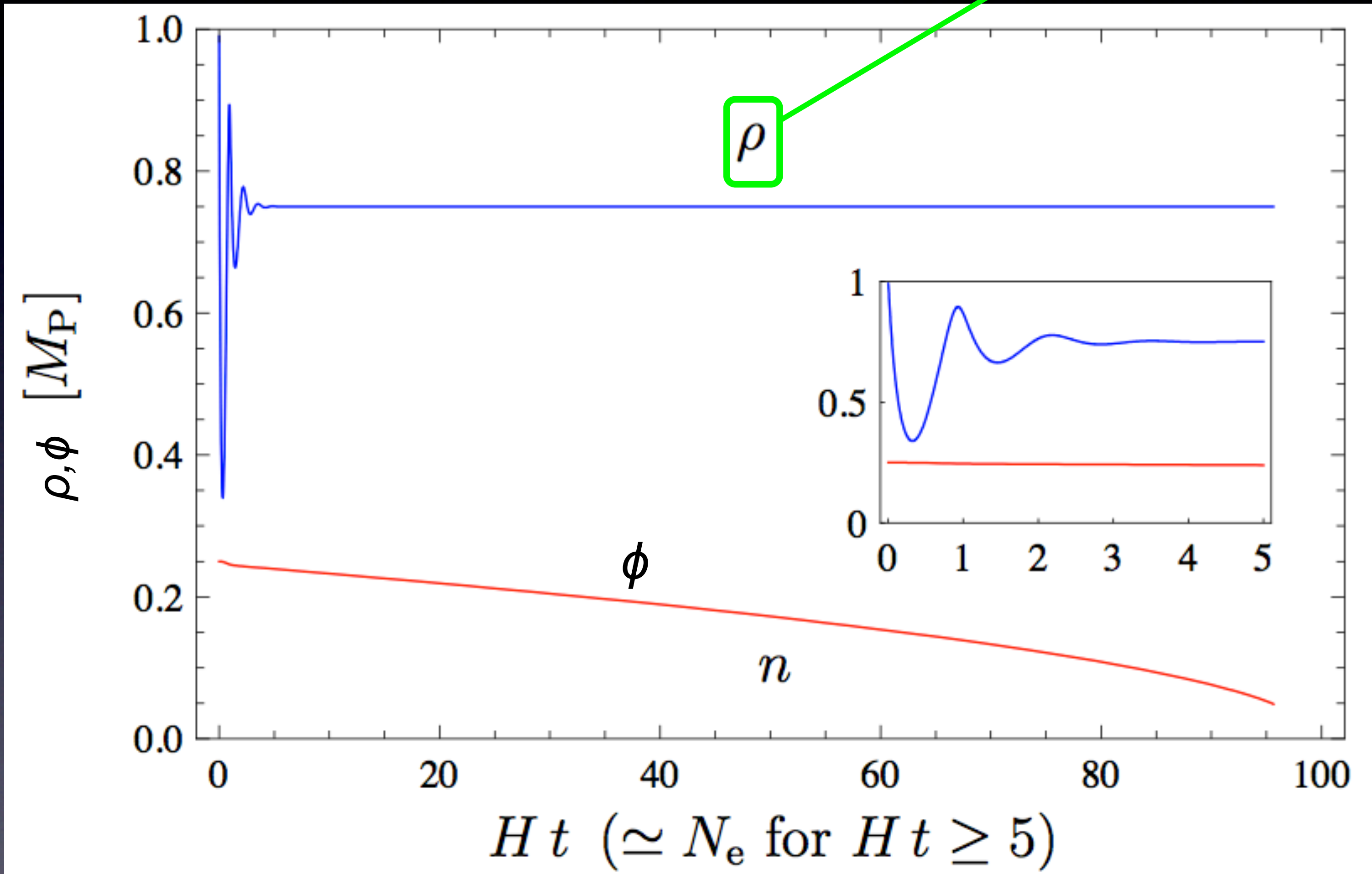
$$V_F \sim \frac{V_0}{\rho^3(1+\kappa_\rho \rho)}$$

→ η-problem solved!

→ ρ can be stabilsed by large V_0

With V = V_{tree} + V_{loop}

Modulus field ρ gets stabilized quickly and allows for >> 60 e-folds of inflation!



S.A., M. Bastero-Gil, K. Dutta, S. F. King, P. M. Kostka ('08)

Note: After inflation, a different stabilisation mechanism is required!

Simple example model of Tribrid (Matter) inflation in Supergravity

- Example model in SUGRA:

$$W = X(H^2 - M^2) + \frac{1}{\Lambda} H^2 \Phi^2$$

breaks the Heisenberg symmetry

$$K = -3 \ln \rho + |X|^2 + \kappa_\rho \frac{\rho |X|^2}{M_P} + \ldots , \text{ with } \rho = T + T^* - |\phi|^2$$

K invariant under Heisenberg symmetry

→ η-problem solved:

✓ Flat potential for ϕ at tree-level

✓ Slope from $V_{1\text{-loop}}$

S.A., M. Bastero-Gil, K. Dutta, S. F. King, P. M. Kostka (‘08)

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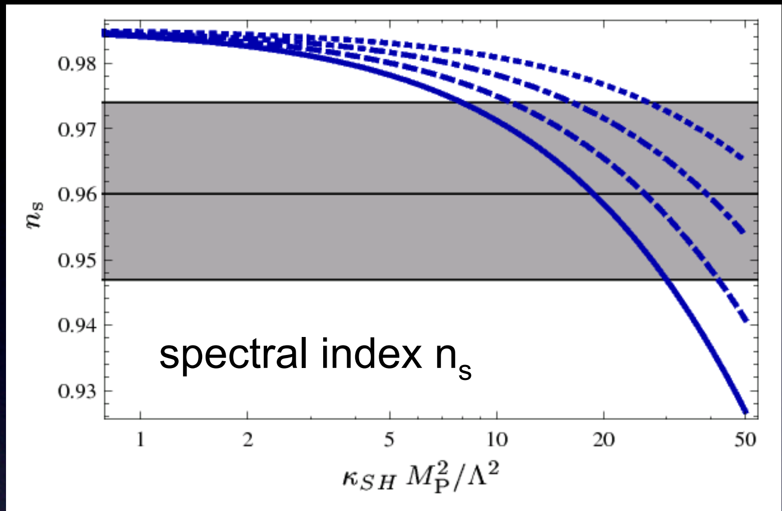
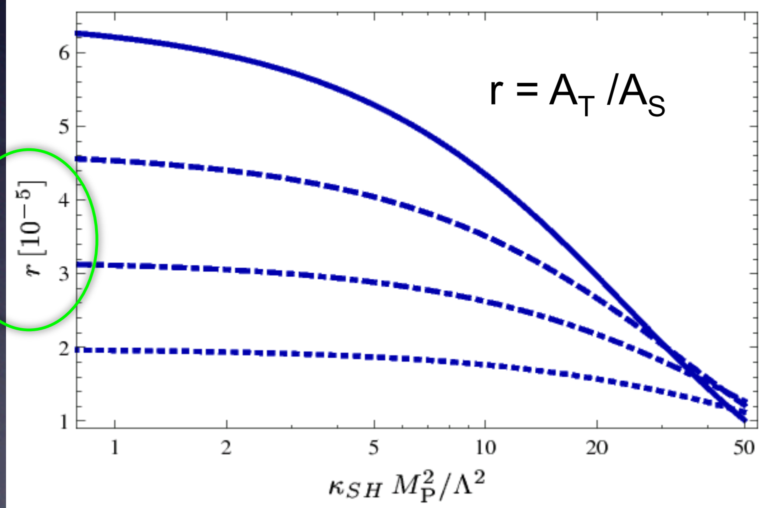
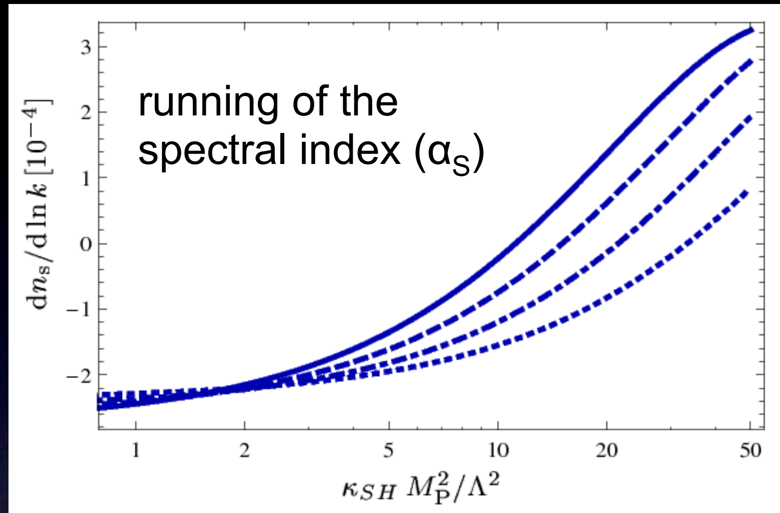
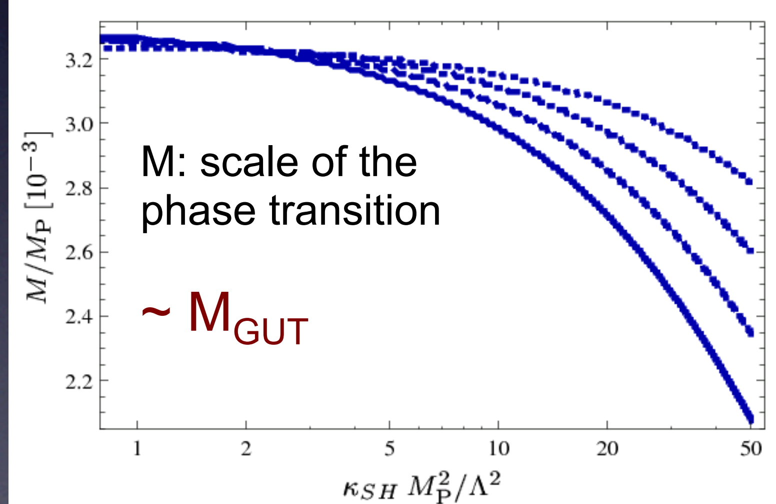




very small
(as typical for Hybrid-type models)





Example: Predictions in a toy model ...

Can the inflaton be a Gauge Non-Singlet?

- Example model of gauge non-singlet inflation in SUGRA:

$$W = X(\bar{H}H - M^2) + \frac{1}{\Lambda}(\bar{F}F_i)(\bar{H}H)$$

$$K = -3\ln\rho + \kappa_\rho \frac{\rho\,|X|^2}{M_P} + \ldots\,, \text{ with } \rho = T + T^* - \sum_i |F_i|^2 - |\bar{F}|^2$$

✓ Several additional challenges for GNS inflation ... all resolved!

Example: SO(10) GUTs

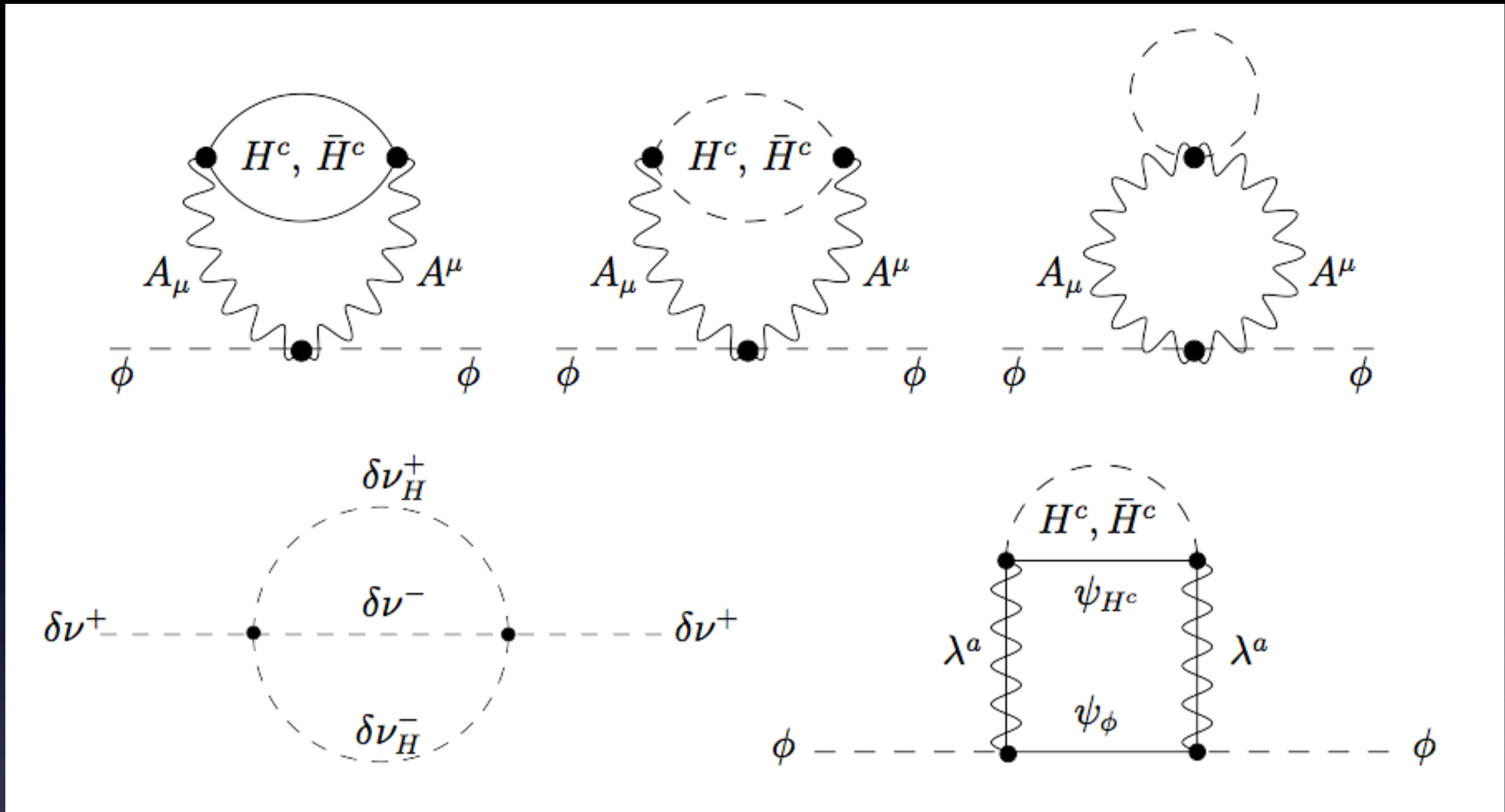
F_i in representation 16 of SO(10)

$\bar{F}$ in representation $\overline{16}$ of SO(10)

i = (1,...,4)

$$\mathbf{16}_i = \begin{pmatrix} q_L & u_R^c & e_R^c & d_R^c & \ell_L & \nu_R^c \end{pmatrix}_i$$

S.A., Bastero-Gil, Baumann, Dutta, King, Kostka ('10)



Typical problem: 2-loop mass contribution for non-singlets

$$\delta m^2 \sim \frac{g^4}{(4\pi)^4} \frac{|W_S|^2}{m_F^2} > \mathcal{H}^2$$

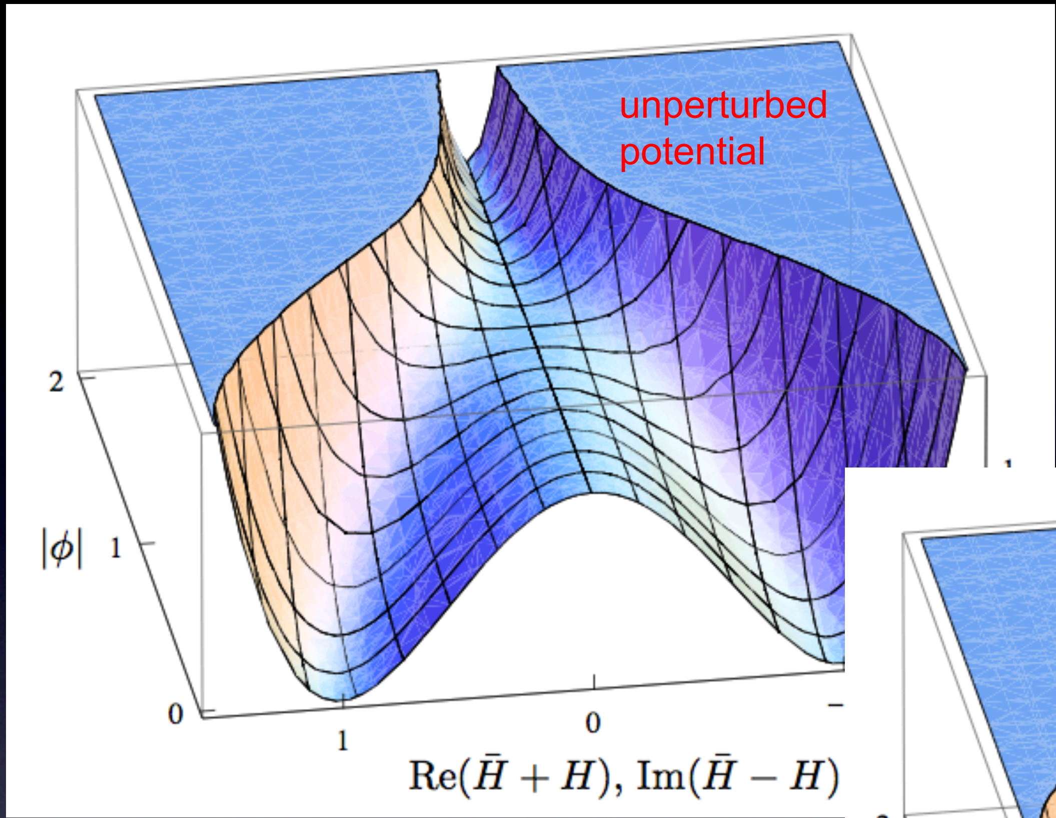
would spoil slow-roll inflation! Dvali '95

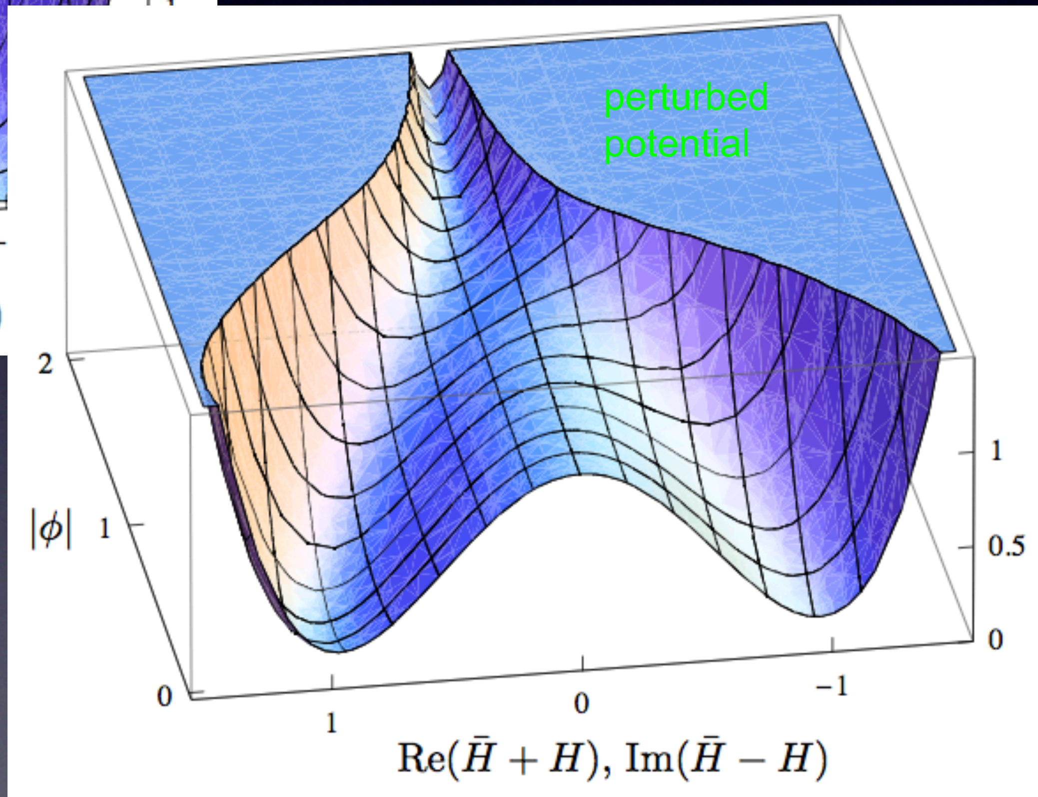
However in our class of models: gauge symmetry broken in the inflaton direction!

$$\delta m^2 \sim \frac{g^4}{(4\pi)^4} \frac{\mu^4}{M_g^2} \ll \mathcal{H}^2$$

suppressed by large gauge boson mass !

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka ('10)





✓ Monopole problem can be avoided:

- "Preferred waterfall direction"
- Breaking SO(10) via a Minimal LR model (→ cosmic strings only)

Other aspects

- “Towards Matter Inflation in Heterotic String Theory”:

  S.A., Dutta, Erdmenger, Halter (‘11)

  - In heterotic string theory, Heisenberg symmetry is a property of the tree-level potential of untwisted matter fields (in the limit $g \to 0$).

- Nonthermal leptogenesis after Tribrid “Matter” Inflation?

  S.A., Baumann, Domcke, Kostka (‘10)

  ✓ If the inflaton is a RH sneutrino (or contains it as a component): “maximally efficient” non-thermal leptogenesis possible ...

Other aspects

- Moduli stabilisation after inflation?
  - ✓ In tribrid inflation + shift symmetry: Postma, Mooij ('10)
  - ✓ In tribrid inflation + Heisenberg symmetry: work in progress ...

Summary and Conclusions

- Tribrid Inflation (= Matter Inflation): New class of SUSY inflation models where the inflaton resides in the matter sector

- New class very suitable for applying symmetry solutions to the η-problem, e.g.: Heisenberg symmetry with stabilised modulus

- Interesting inflaton candidates:
  - Right-handed Sneutrino: SUSY partner of the right-chiral neutrino
  - D-flat direction of gauge non-singlet (GUT) fields

- Other aspects under investigation: Matter inflation in string theory? After inflation: Leptogenesis, moduli stabilisation, ...?