Cosmic Inflation meets Particle Physics

Stefan Antusch

based on collaborations with:
Mar Bastero-Gil, Jochen P. Baumann, Koushik Dutta, Philipp Kostka and Steve F. King

arXiv:0808.2425, 0902.2934, 0905.0905, 1002,xxx

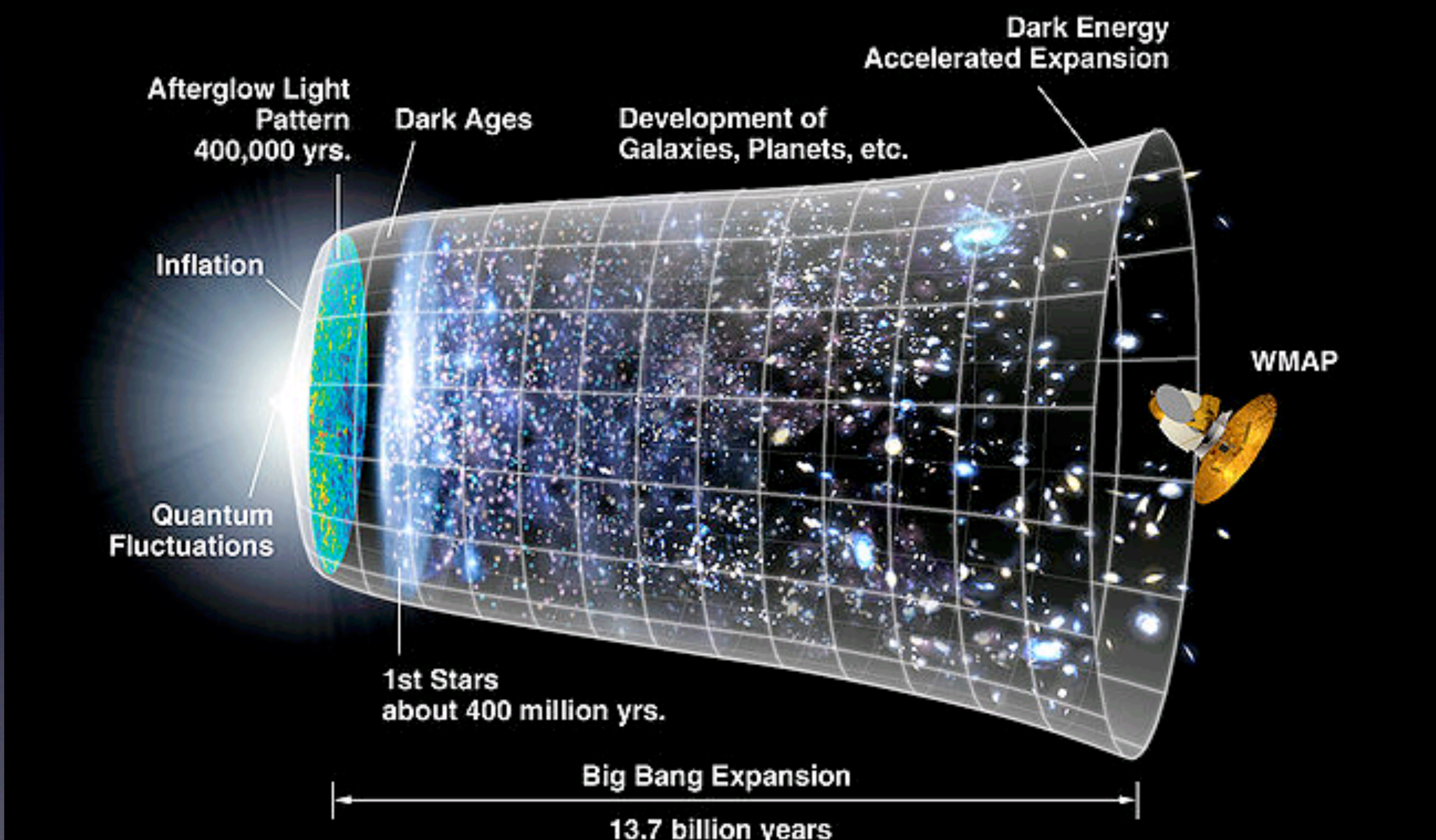
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Overview

- Inflation in supergravity (symmetry solutions to the η-problem)
- Classes of particle physics models of inflation
  (New class: Tribrid inflation)
- 'Matter inflation' in Grand Unified Theories
  (Tribrid inflation with a gauge non-singlet inflaton)

Disclaimer:
Not a complete review of models;
I will focus on 'high-scale' inflation;
GR not modified ...

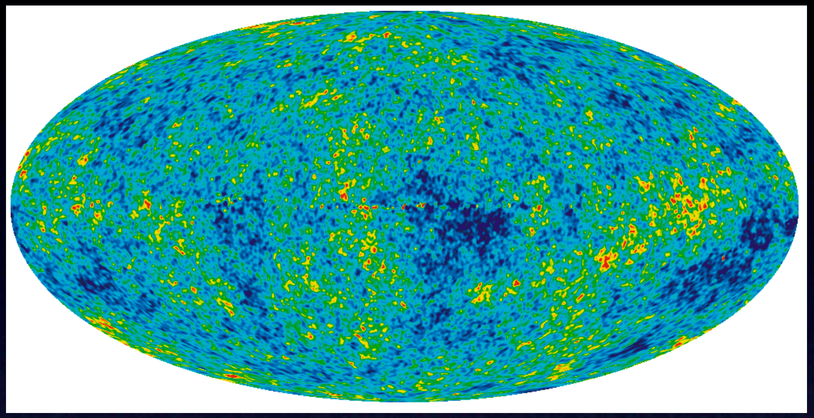
Inflation = Era of accelerated expansion in the very early universe



picture from WMAP website

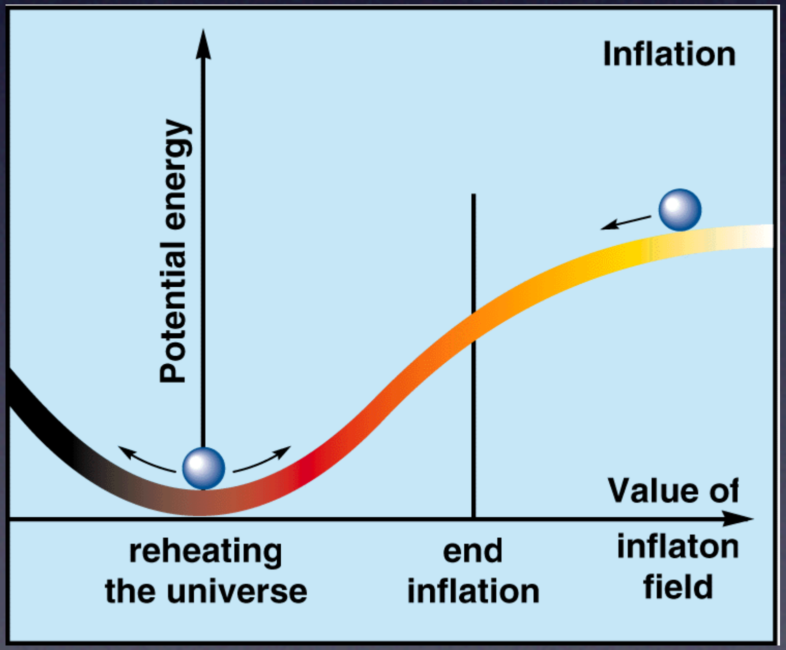
The paradigm of cosmic Inflation

- Inflation provides a successful paradigm for explaining why the universe is rather flat, homogenous and isotropic on large scales (with inhomogeneities on smaller scales) and free of relic species (monopoles, ...)



- Condition for inflation: Vacuum energy (fluid with $p < -\rho/3 \leftrightarrow w < -1/3$) dominates ...

- Simplest realization: Minimally coupled 'slowly rolling' scalar field ...



- Inflationary perturbations can be the seed for $\delta T/T$ of the CMB and of structure in the universe ...

A. Guth ('81), A. D. Linde ('82),
A. Albrecht and P. J. Steinhard ('82), ...

Slow roll parameters and inflationary perturbations

- Approximate calculation for 'slow roll inflation' yields (*may not always be accurate enough!*):

$$\varepsilon = \frac{m_P^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\eta = m_P^2 \frac{V''}{V}$$

$$\xi = m_P^4 \frac{V V'''}{V^2}$$

$$\Rightarrow$$

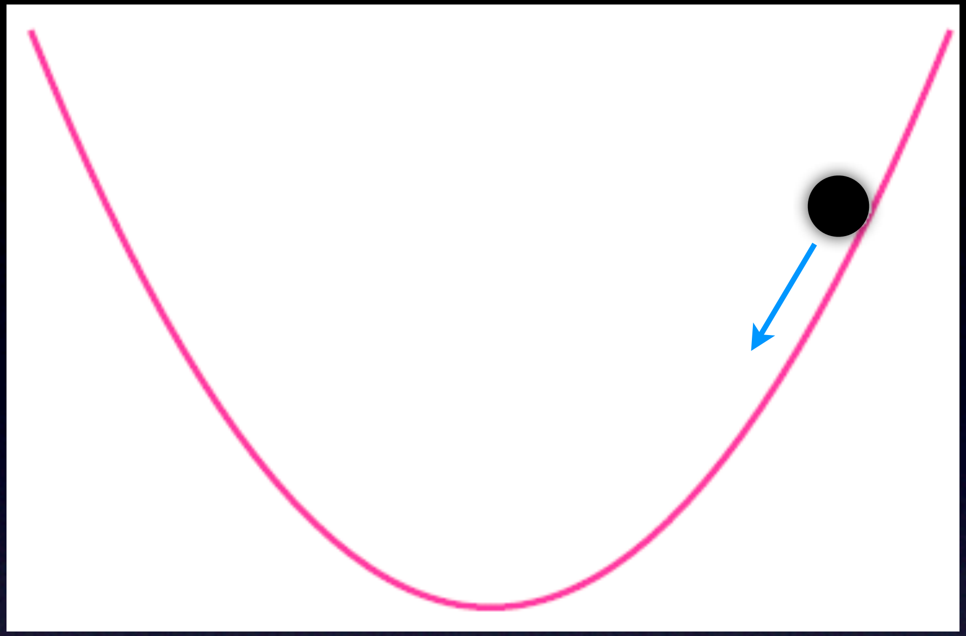
$$\left.\begin{aligned} A_S &\approx \frac{H^2}{\varepsilon\pi} \\ A_T &\approx \frac{16H^2}{\pi} \end{aligned}\right\} \quad r = \frac{A_T}{A_S} \approx 16\,\varepsilon$$

$$\begin{aligned} n_S &\approx 1 - 6\varepsilon + 2\eta \\ \alpha_S &\approx -2\xi - 24\varepsilon^2 + 16\varepsilon\eta \\ n_T &\approx -2\varepsilon \end{aligned}$$

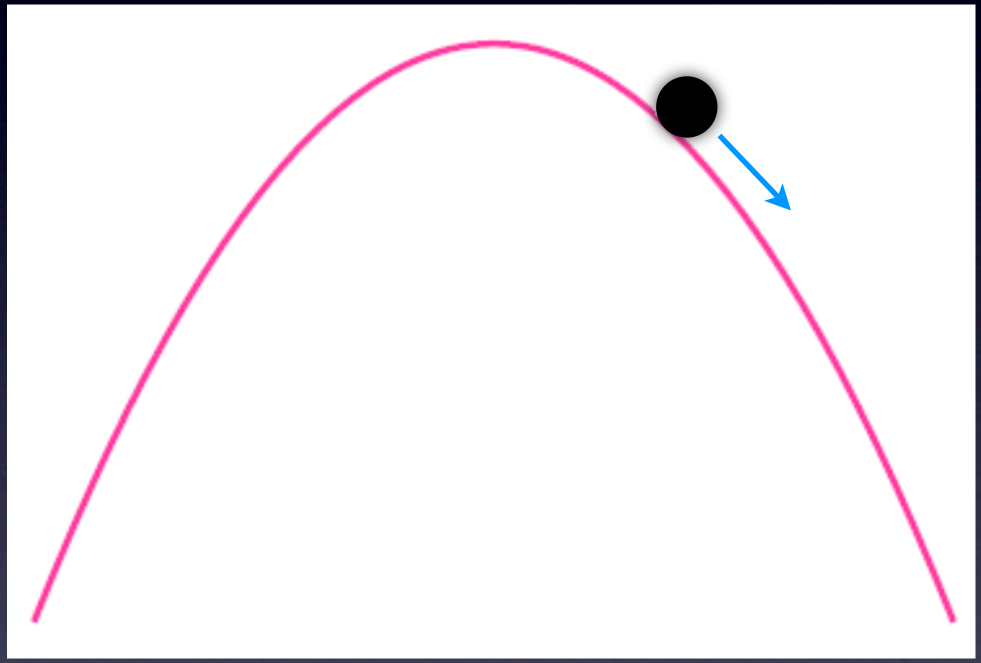
r: tensor-to-scalar ratio

Slow roll inflation: ε, η, ξ << 1 !

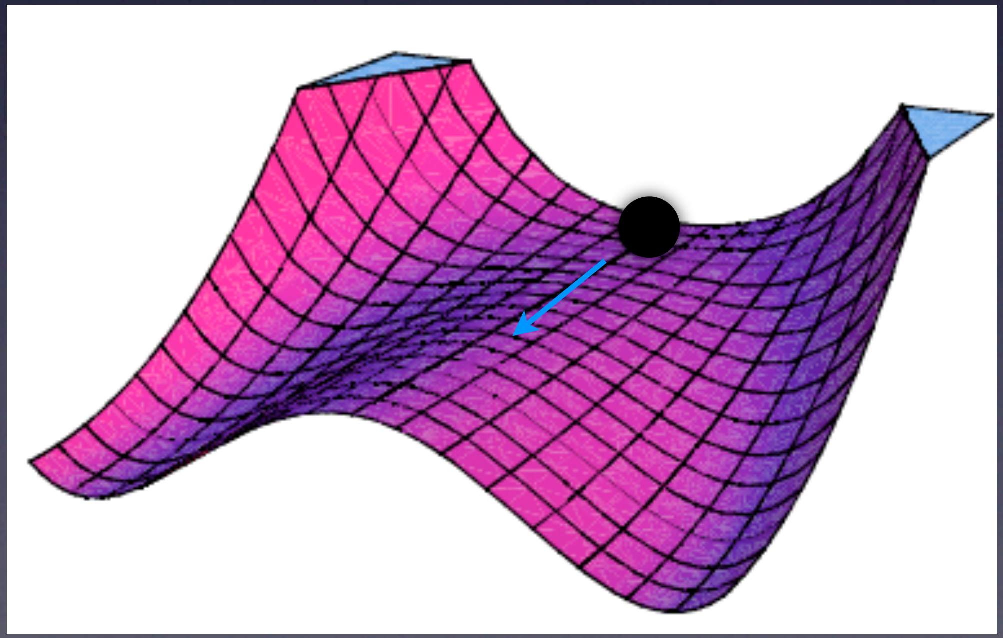
Basic types of inflation models



'Large field' (chaotic) inflation



'Small field' (new) inflation



'Hybrid' inflation

... many variants of scalar field potentials can lead to inflation ...

Observations consistent with simplest slow roll inflationary models

- From WMAP 5-year data (+ SN + BAO):
  - Hints that $n_S < 1$:

    $$n_s = 0.960 \pm 0.013$$

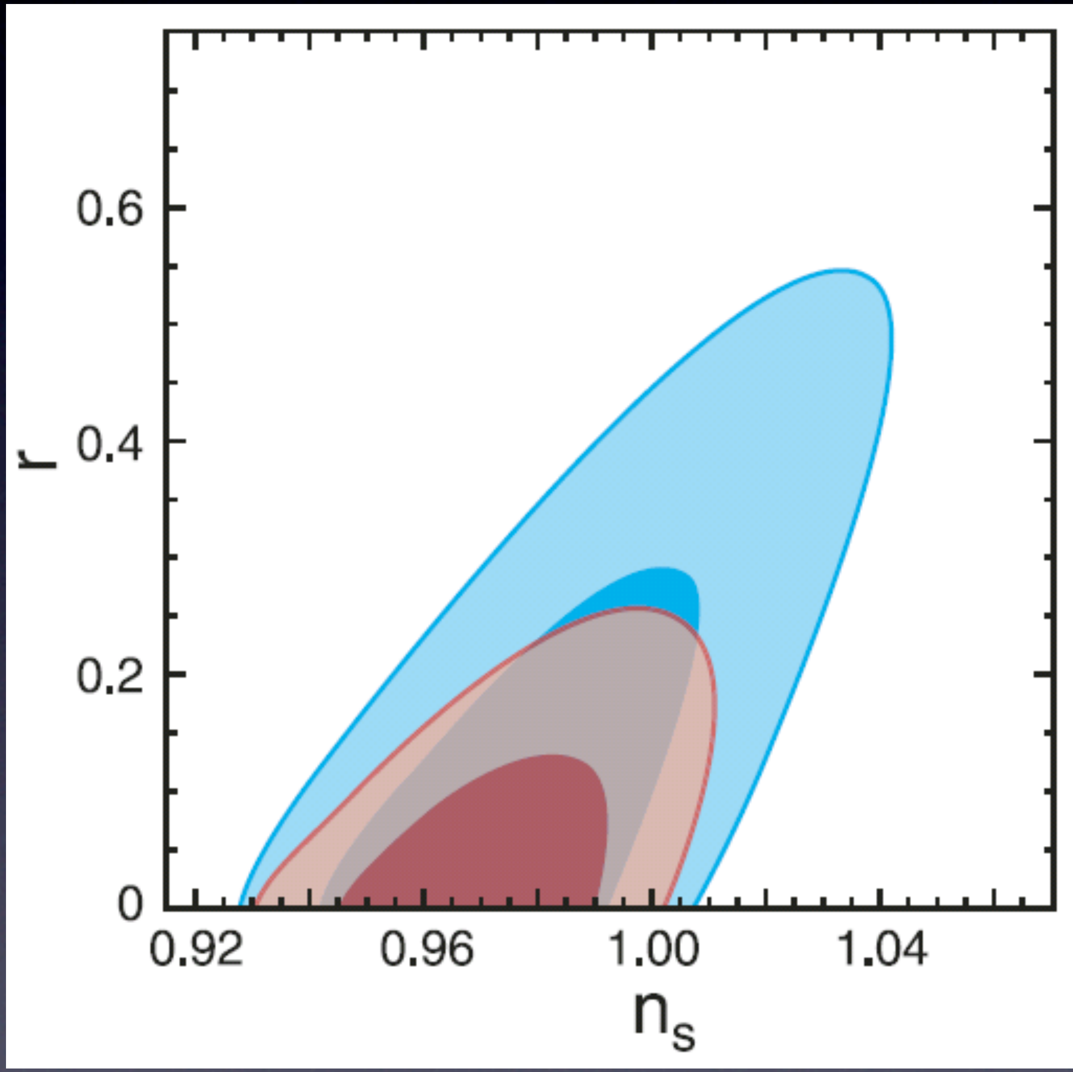
  - No signs for gravitational waves:

    $$r < 0.22 \ (95\% \ \mathrm{CL})$$

  - Amplitude A_S (Cobe '92):

    $$A_S^{1/2} = 5.0\ (\pm 0.1) \times 10^{-5}$$

  - No clear signs for running of the spectral index
  - Compatible with adiabatic and Gaussian primordial perturbations



(WMAP '08,,
WMAP '08 + SN + BAO)

Future: The PLANCK satellite

- PLANCK (launched on 14th of May 2009)
  - will measure n_S more precisely
    → Is n_S really ≠ 1? Important prediction of inflation!
  - will be sensitive to r up to 0.01 ... 0.1
    → r ≠ 0 would be smoking gun signal of inflation; results will help to discriminate between (classes of) inflation models
  - will more precisely test the adiabaticity and Gaussianity of the perturbations

    → Could rule out slow roll inflation by one single field (if deviations found)

Inflation and models of particle physics

- ... often: Scalar field (= inflaton) is introduced 'ad hoc', without any connection to models of particle physics.

- Question:

How is inflation connected to theories of particle physics ?

A typical problem ...

Inflation (typically taking place at high energies $\Lambda \sim M_{GUT}$)

new physics
@ Λ induces ...

**Hierarchy problem:
quantum corrections ⇒
$\delta m_H^2 \sim \Lambda^2$**

A typical problem ...

Inflation (typically taking place at high energies $\Lambda \sim M_{GUT}$)

new physics
@ Λ induces ...

Hierarchy problem: quantum corrections $\Rightarrow$

$\delta m_H^2 \sim \Lambda^2$

solution seems
to suggest ...

Supersymmetry
(as local symmetry: supergravity = SUGRA)

A typical problem ...

Inflation (typically taking place at high energies $\Lambda \sim M_{GUT}$)

new physics @ Λ induces ...

Hierarchy problem: quantum corrections ⇒ $\delta m_H^2 \sim \Lambda^2$

solution seems to suggest ...

Supersymmetry (as local symmetry: supergravity = SUGRA)

SUGRA typically induces ...

Mass of the inflaton: $m_f \sim H \Rightarrow \eta \sim 1$

would spoil slow roll inflation!

V(ϕ) from K & W:

$$V_F = e^K \left[K^{ij^*} \mathcal{D}_i W \, \mathcal{D}_{j^*} W^* - 3\,|W|^2 \right]$$

η-problem of SUGRA inflation!

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

A typical problem ...

Inflation (typically taking place at high energies $\Lambda \sim M_{GUT}$)

new physics @ Λ induces ...

Hierarchy problem: quantum corrections $\Rightarrow$ $\delta m_H^2 \sim \Lambda^2$

solution seems to suggest ...

Supersymmetry (as local symmetry: supergravity = SUGRA)

... one has to solve the 'η-problem'

~~Mass of the inflaton:~~
$\cancel{m_\phi \sim H \Rightarrow \eta \sim 1}$

Challenge: How can inflation be realised in supergravity theories?

Possible approaches to solve the η-problem: 3 strategies

- **Expansion of K in fields/M_P:**

requires tuning of parameters

$$K = \sum_{i,j,k} \left(|X_i|^2 + \frac{\alpha_i}{M_P^2}|X_i|^4 + \frac{\beta_{ij}}{M_P^2}|X_i|^2|X_j|^2 + \mathcal{O}\left(\frac{|X_{i,j,k}|^6}{M_P^4}\right)\right)$$

- **'Shift' symmetry:**

$N \to N + i\,\alpha$

$K = f(N + N^*)$

protects Im[N] from obtaining a SUGRA mass by symmetry!

(used by many authors ...)

- **'Heisenberg' symmetry:**

$$T \to T + i\mu \qquad T \to T + \alpha^* N + |\alpha|^2/2 \qquad N \to N + \alpha$$

T: 'modulus field', which has to be stabilised

$K = f(\rho)$ $\qquad \rho = T + T^* - |N|^2$

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

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

Other possibility: 'D-term Hybrid inflation' (not discussed in this talk)

Particle physics models of inflation in supergravity

- ... to illustrate/address both issues, let us look at the following example for a typical superpotential:

Schematically:

$$W = S\,(H^2 - M^2) + g(N,H))$$

Remark: Less simple potentials in practice! Also other possibilities ...

S: 'Driving field'
$|F_S|^2 \rightarrow$ provides vacuum energy if <H>=0

phase transition:
<H>=0 → <H>=M

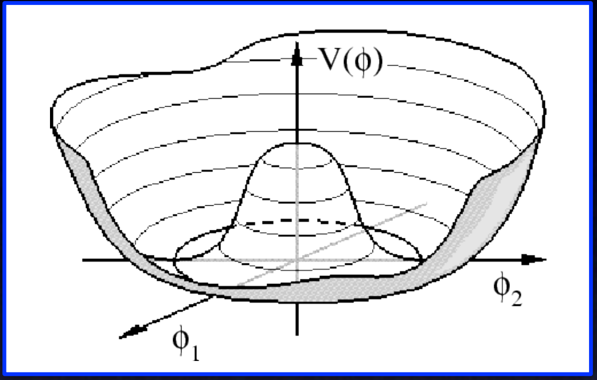
N: Matter field
i) get mass when <H>=M
ii) direct mass from W

H: Higgs field
<H>=0 (false vacuum)
<H>=M (true vacuum)

Can S, H or N act as the inflaton field?

Particle physics models of inflation in supergravity

- <u>In principle</u>, any of the three types of fields can be the inflaton
  → link to particle physics!



$$W = S\,(H^2 - M^2) + g(N,H))$$

H: Higgs field
<H>=0 (false vacuum)
<H>=M (true vacuum)

'New Inflation'-type of model

(Remark: typically $H^2 \rightarrow f(H,\bar{H})$, with $\bar{H}$ in the conjugate representation)

Phase transition may be the one of

- **GUT symmetry breaking**
  (inflation ↔ GUTs: many works)
- **Flavour symmetry breaking**
  (can be below GUT phase transition)
  S.A., S.F. King, M. Malinsky, L. Velasco-Sevilla, I. Zavala ('08)

Particle physics models of inflation in supergravity

- In principle, any of the three types of fields can be the inflaton
  → link to particle physics!

$$W = S\,(H^2 - M^2) + g(N,H))$$

S: 'Driving field'
$|F_S|^2$ → provides vacuum energy if <H>=0

Phase transition may be the one of

- **GUT symmetry breaking**
- **Flavour symmetry breaking (can be below GUT phase transition)**

'Hybrid Inflation'-type of model

(H = 'waterfall field' for ending inflation)

Particle physics models of inflation in supergravity

- In principle, any of the three types of fields can be the inflaton $\rightarrow$ link to particle physics!

$m_\nu \sim v_{EW}^2/m_N$

$$W = S\,(H^2 - M^2) + g(N,H))$$

N: Matter field
i) get mass when
<H>=M

Attractive candidate for N:

- **right-handed sneutrino = superpartner of ν_R from the seesaw mechanism**
  S.A., Bastero-Gil, King, Shafi ('04)
- **Phase transition (GUT, flavour, ...) gives its large mass after inflation**

New variant of 'Hybrid Inflation'
$\rightarrow$ 'Tribrid Inflation'
(S for V_0, H ends inflation, N=inflaton)

Particle physics models of inflation in supergravity

- In principle, any of the three types of fields can be the inflaton $\rightarrow$ link to particle physics!

$$W = S\,\cancel{(H^2 - M^2)} + g(N,H))$$

N: Matter field
ii) direct mass from W

'Large field (chaotic)'-type of inflation model

Attractive candidate for N:

- **right-handed sneutrino = superpartner of n_R from the seesaw mechanism**
  Murayama, Suzuki, Yanagida, Yokoyama ('93)
- **for simplest superpotential $W = m_N N^2$, $m_N \sim 10^{13}$ GeV would be in the right range for seesaw and for inflation!**

Solutions to the η-problem in classes of models

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

	K expansion + tuning	Shift symmetry	Heisenberg symmetry
S is the inflaton ('Hybrid inflation')	(yes) Copeland et al; Dvali, Shafi, Schaefer ('94)	X*	X
H is the inflaton ('New inflation')	(yes) Shafi, Senoguz ('04)	X (?)	X (?)
New! N is the inflaton ('Tribrid inflation')	(yes) S.A. et al ('04)	yes S.A. et al ('09) Postma, Mooij ('10)	yes S.A. et al ('08)
Large field 'chaotic' inflation	X	yes Kawasaki et al ('00)	yes S.A. et al ('09)

'Tribrid inflation': New class of models; very suitable for solving the η-problem by symmetry! ... + other attractive features!

Note: ... incomplete table!

Can the inflaton field be a gauge non-singlet in SUGRA inflation?

	K expansion + tuning	Shift symmetry	Heisenberg symmetry	Non-singlet Inflaton
S is the inflaton ('Hybrid inflation')	(yes) Copeland et al; Dvali, Shafi, Schaefer ('94)	X*	X	X
H is the inflaton ('New inflation')	(yes) Shafi, Senoguz ('04)	X (?)	X (?)	yes (?)
N is the inflaton ('Tribrid inflation')	(yes) S.A. et al ('04)	yes S.A. et al ('09) Postma, Mooij ('10)	yes S.A. et al ('08)	yes S.A. et al (in preparation)
Large field 'chaotic' inflation	X	yes Kawasaki et al ('00)	yes S.A. et al ('09)	X

Note: ... incomplete table!

Tribrid inflation with gauge non-singlet inflaton field

- Basic idea:

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

Driving field
(its F-term provides the vacuum energy)

Waterfall fields
(= Higgs fields that give mass to the matter fields)

Inflaton field(s)
(are here gauge non-singlets)

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka
(in preparation; arXiv:1002.xxx)

Tribrid inflation with gauge non-singlet inflaton field

- Basic idea:

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

Driving field
(its F-term provides the vacuum energy)

Waterfall fields
(= Higgs fields that give mass to the matter fields)

Inflaton field(s)
(are here gauge non-singlets)

Example: SO(10) GUTs

F_i in representation 16 of $\mathrm{SO}(10)$
$\bar{F}$ in representation $\overline{16}$ of $\mathrm{SO}(10)$
$i = (1,...,4)$

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka
(in preparation; arXiv:1002.xxx)

Tribrid inflation with gauge non-singlet inflaton field

- Basic idea:

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

Driving field
(its F-term provides the vacuum energy)

Waterfall fields
(= Higgs fields that give mass to the matter fields)

Inflaton field(s)
(are here gauge non-singlets)

✓ Inflation can proceed in D-flat valley: sneutrino direction viable trajectory

Other example: Pati-Salam unified theories

$$F_1 = \begin{pmatrix} 0 & 0 & 0 & \nu^c \\ 0 & 0 & 0 & 0 \end{pmatrix}, \qquad \bar{F} = \begin{pmatrix} 0 & 0 & 0 & \bar{\nu}^c \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka (in preparation; arXiv:1002.xxx)

Tribrid inflation with gauge non-singlet inflaton field

- Basic idea:

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

Driving field
(its F-term provides the vacuum energy)

Waterfall fields
(= Higgs fields that give mass to the matter fields)

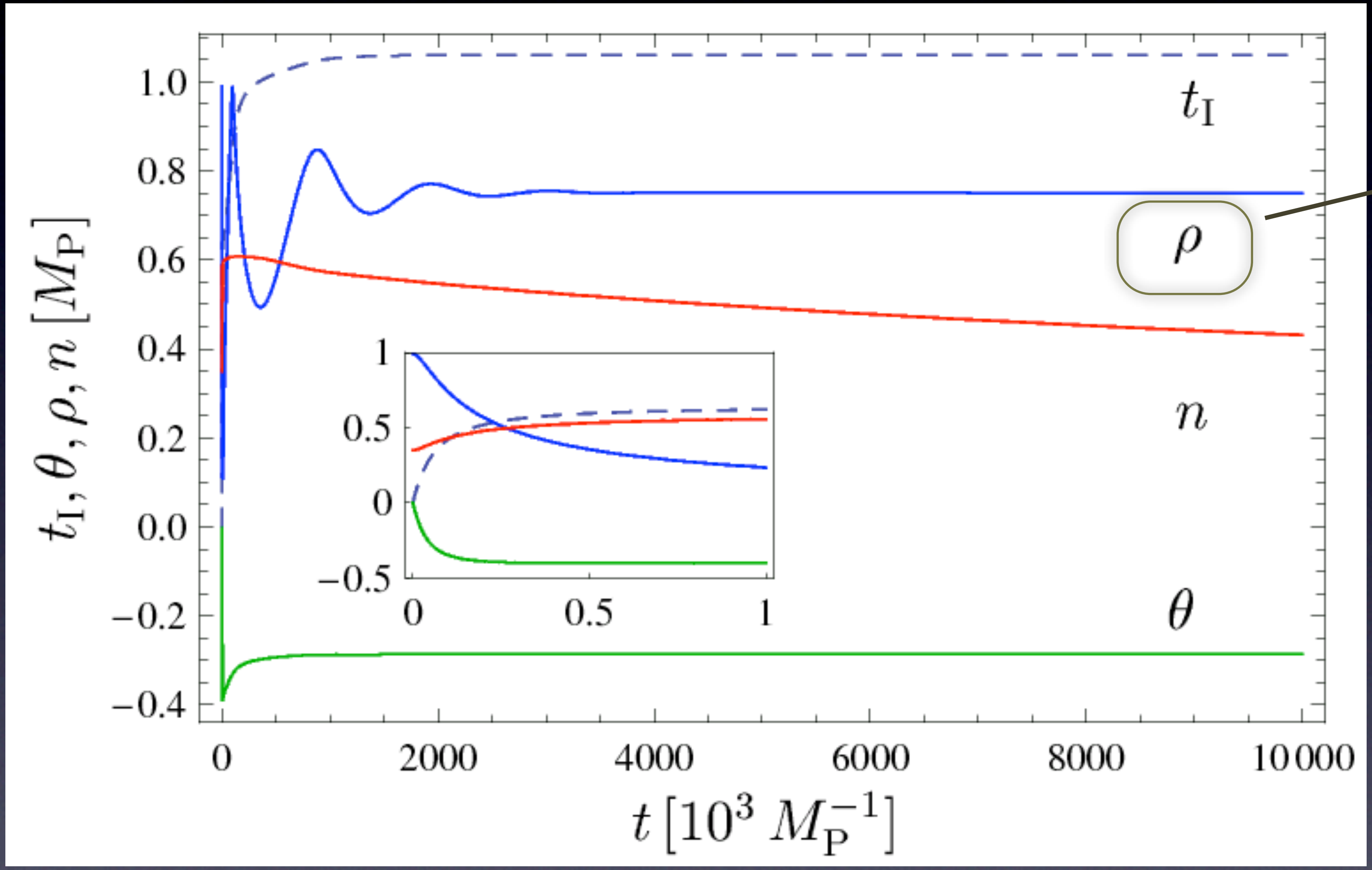
Inflaton field(s)
(are here gauge non-singlets)

✓ SUGRA η-problem can be solved by Heisenberg symmetry:

$$K = f(\rho)\,, \quad \rho = T + T^* - \sum_i |F_i|^2 - |\bar{F}|^2$$

✓ Modulus ρ stabilized by large vacuum energy V_0 during inflation

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka (in preparation; arXiv:1002.xxx)



Modulus field ρ gets stabilized quickly with the help of the large vacuum energy during inflation!

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

Tribrid inflation with gauge non-singlet inflaton field

- Basic idea:

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

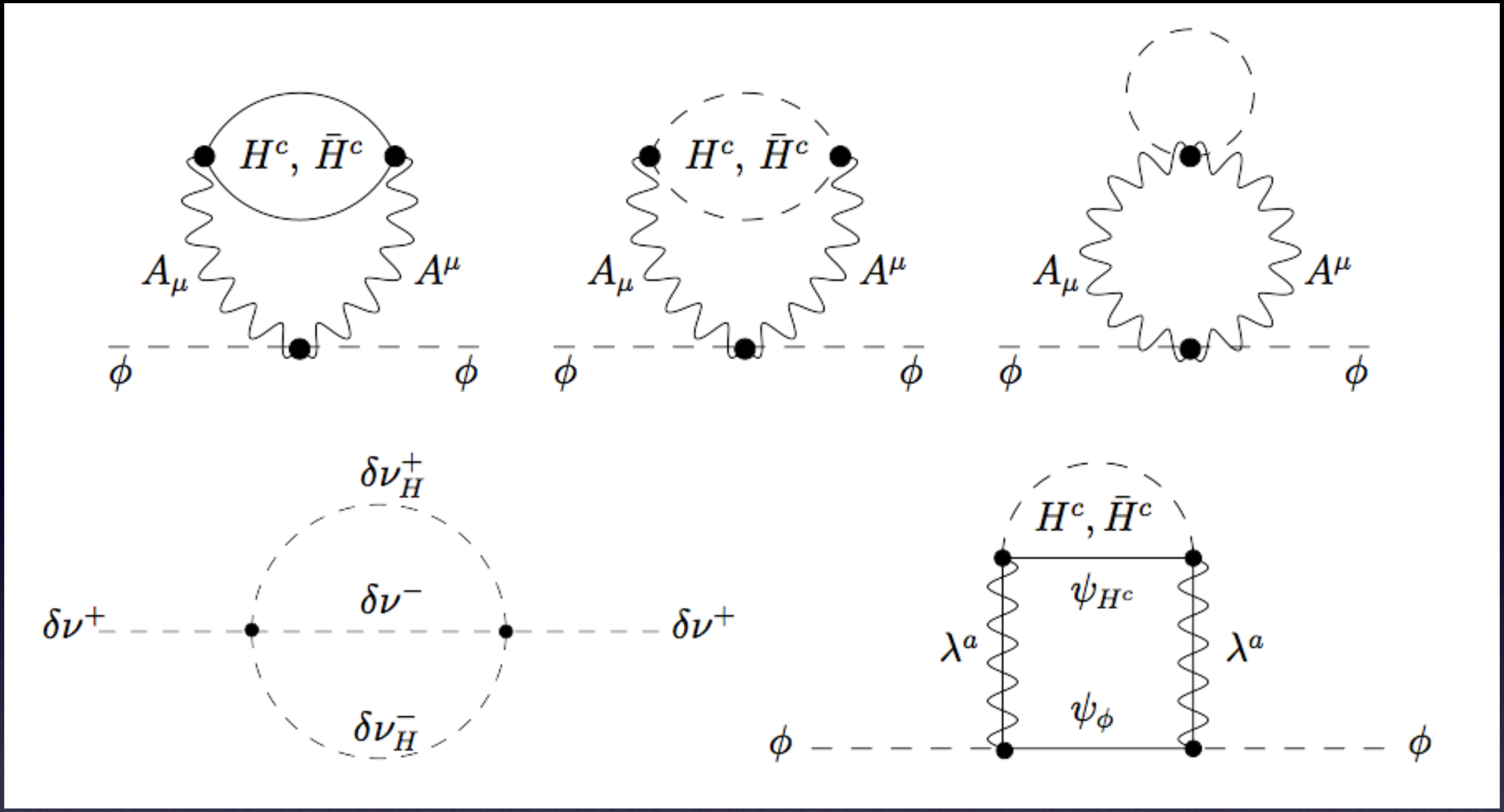
Driving field
(its F-term provides the vacuum energy)

Waterfall fields
(= Higgs fields that give mass to the matter fields)

Inflaton field(s)
(are here gauge non-singlets)

✓ '2-loop gauge η-problem' (Dvali '95) automatically solved as well ...

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka (in preparation; arXiv:1002.xxx)



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!

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

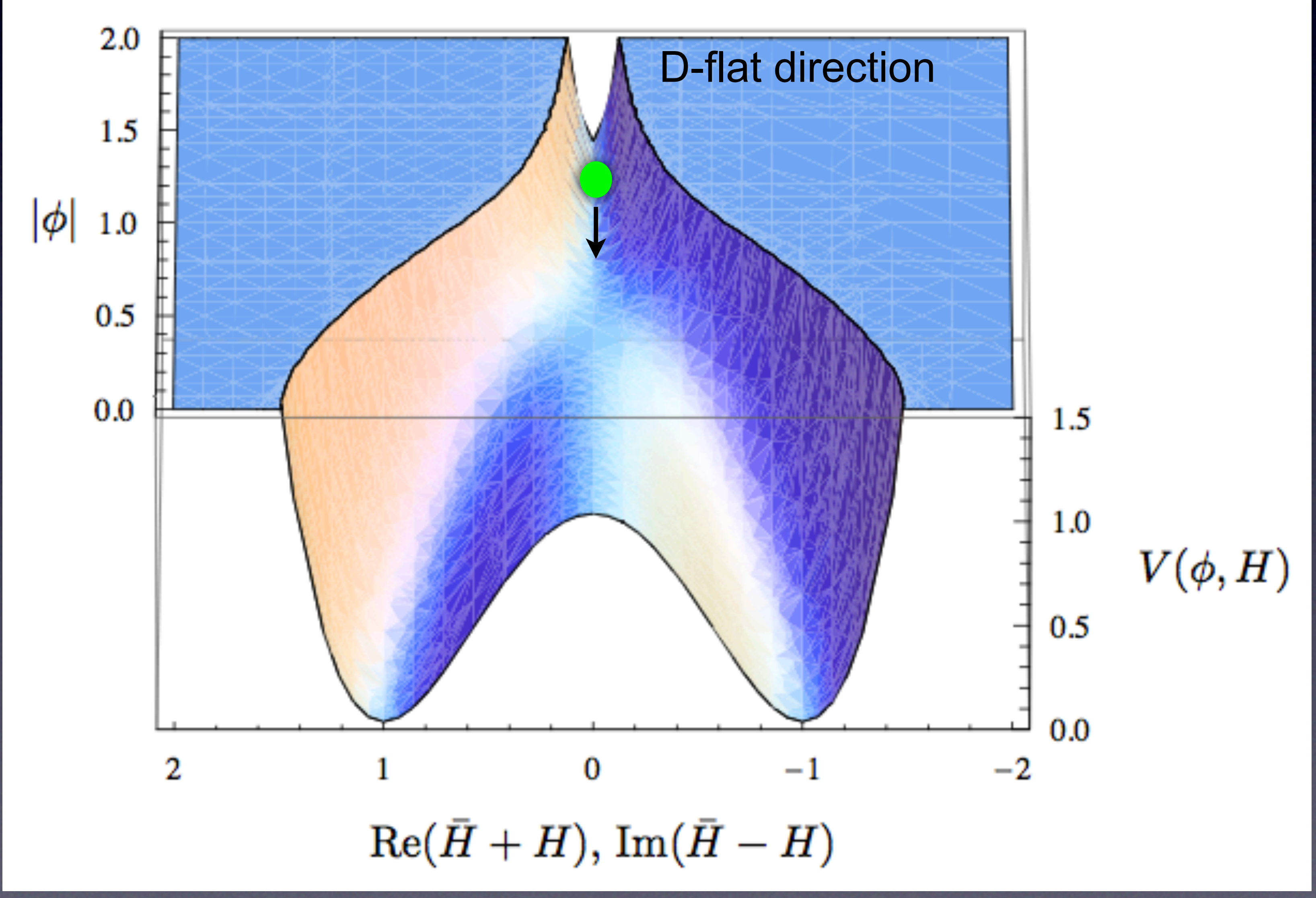
suppressed by large gauge boson mass !

S.A., M. Bastero-Gil, J. Baumann, K. Dutta, S. F. King, P. M. Kostka (in preparation; arXiv:1002.xxx)

Tribrid inflation with gauge non-singlet inflaton field

- During inflation:
  - <S> = 0, <H> = 0

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

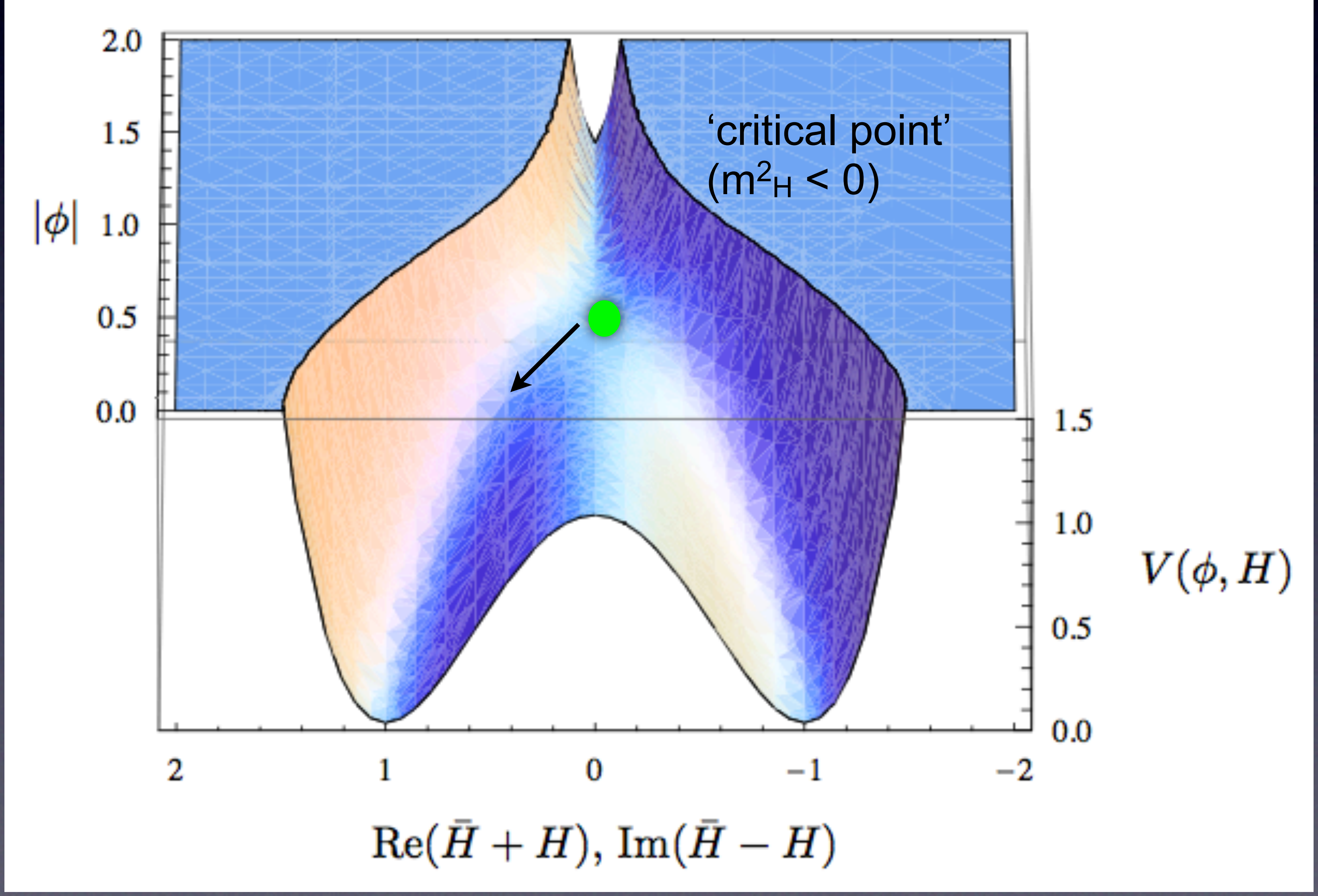


Inflaton potential:
flat at tree-level;
slope generated by
radiative corrections

Tribrid inflation with gauge non-singlet inflaton field

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

- End of inflation:
  - critical point: m^2_H becomes < 0
  - H moves quickly to true vacuum <H> ~ M ('waterfall')

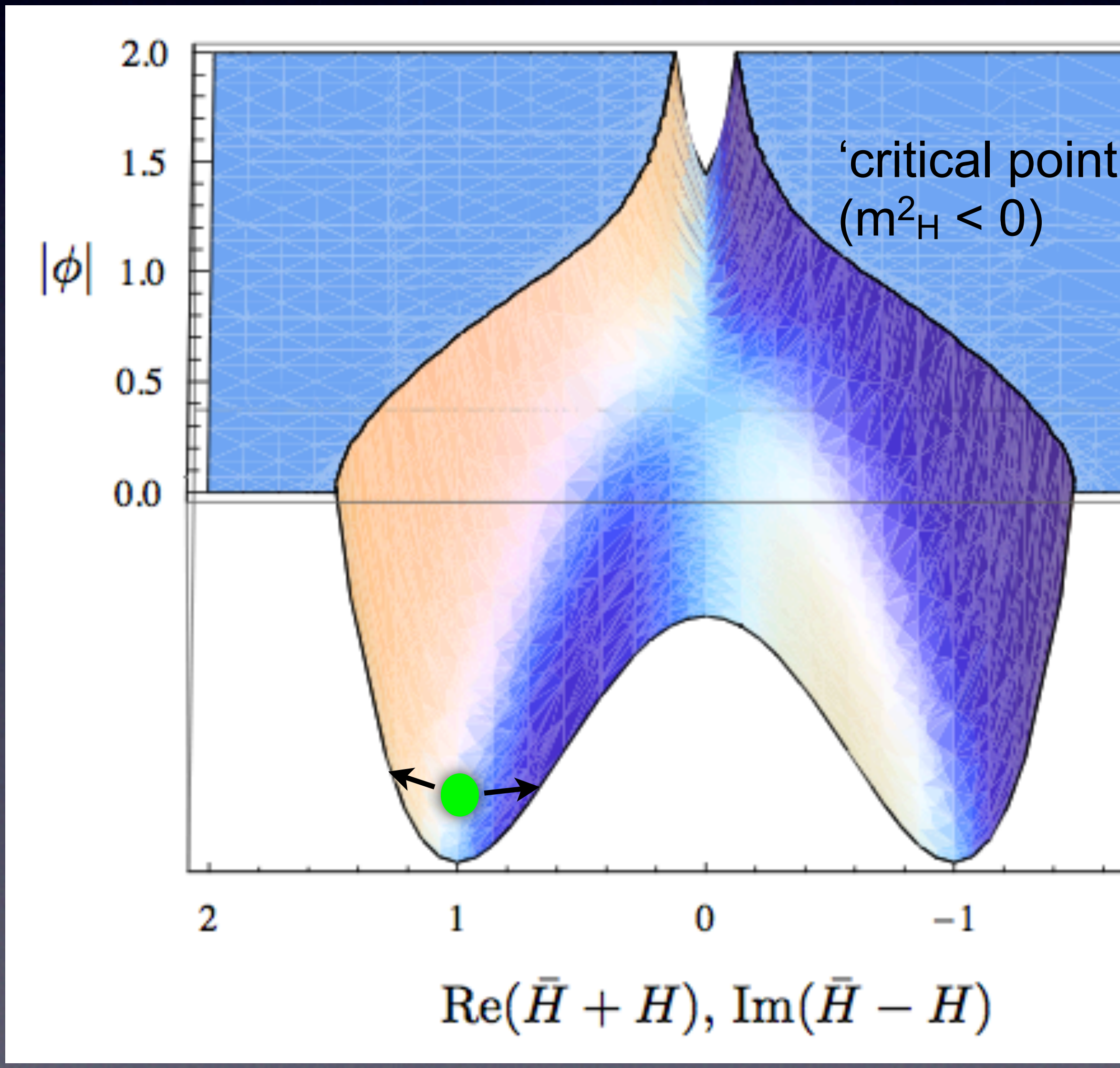


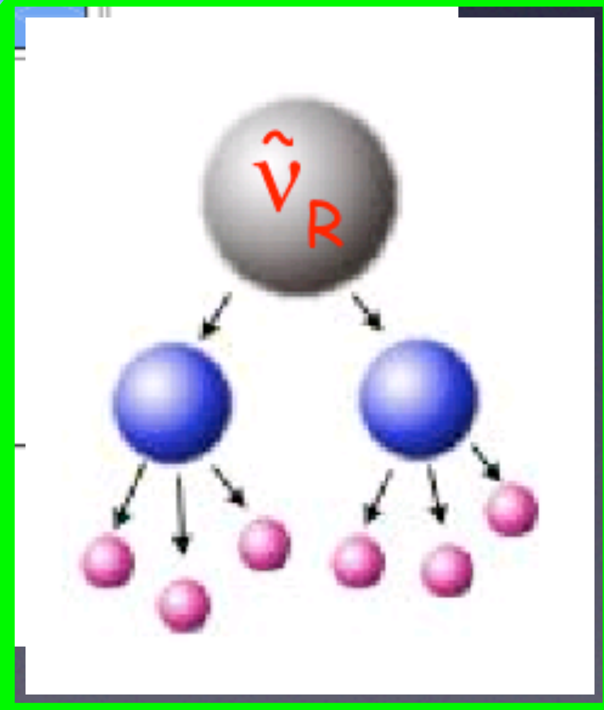
After inflation, when H is in its true vacuum, some field directions get a large mass ~ M; 3 generations remain light (SM fields)! (general: # F - # $\bar{F}$ light)

Tribrid inflation with gauge non-singlet inflaton field

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

- After inflation:
  - fields oscillate in the minima of their potential
  - their decay reheats the universe and produce SM particles ...

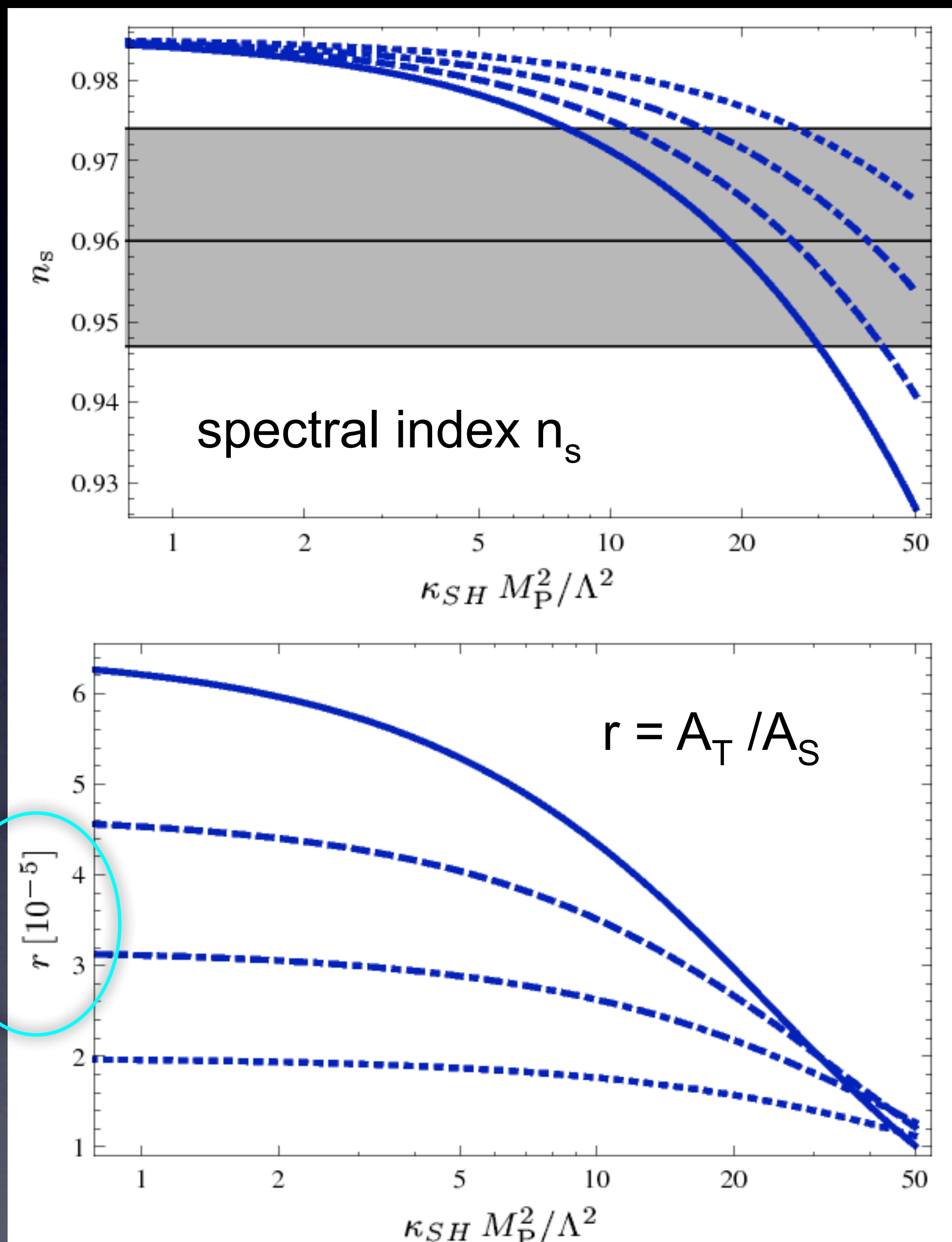




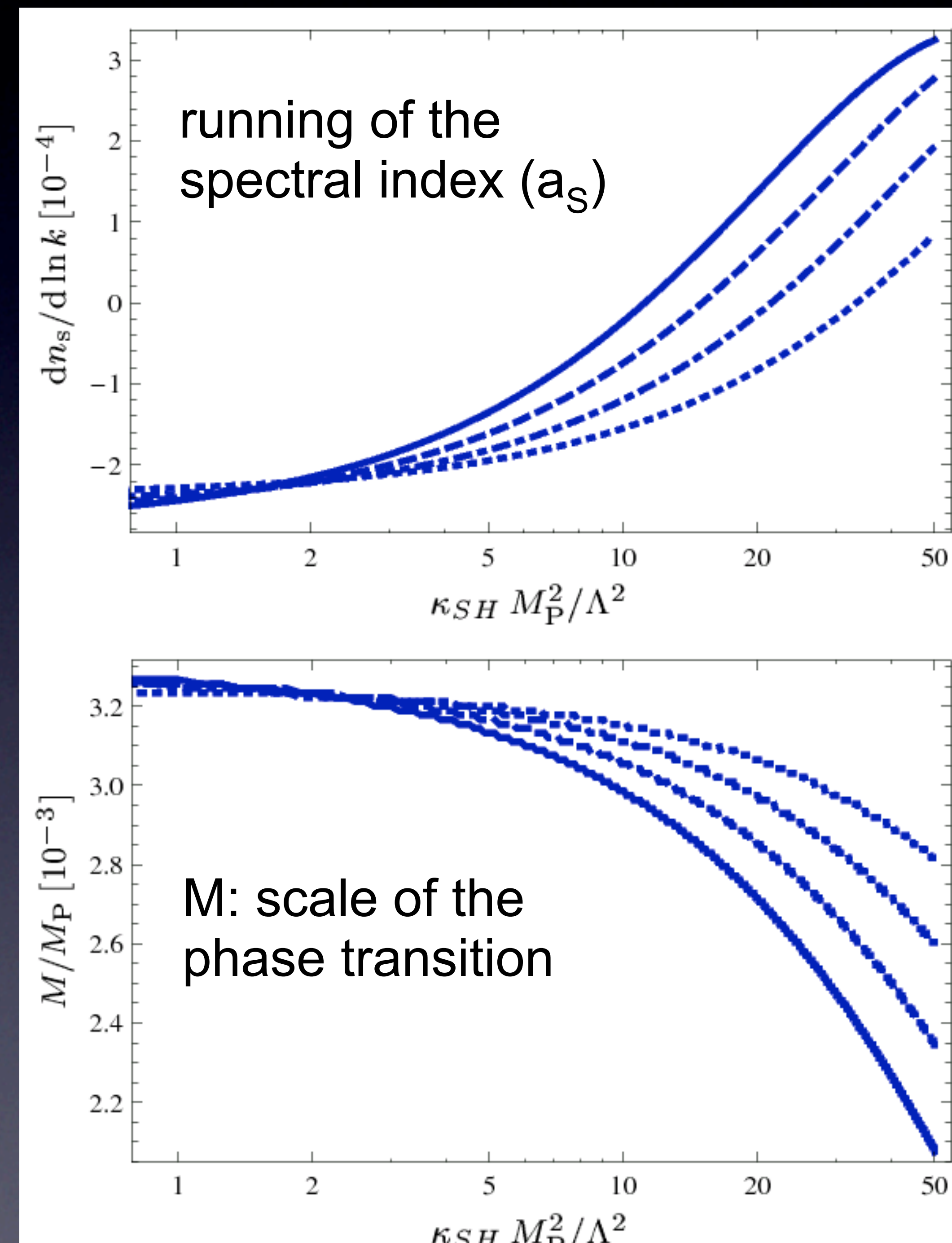
Non-thermal leptogenesis after sneutrino inflation:
very efficient way of generating the observed baryon asymmetry!

In an explicit model: calculation of the predictions for CMB observables ...

S.A., K. Dutta, P. M. Kostka ('09)



very small
(as typical for Hybrid models)



Example: predictions in toy model of 'Tribrid inflation'

Summary and Conclusions

- Inflation solves flatness, horizon & monopole problems and it can provide the seed of $\delta T/T$ in the CMB and of structure in the universe
- Many open questions, for instance:
  - How is inflation linked to theories of particle physics? How can inflation be realised in supergravity theories?
- Attractive new class of inflation models in supergravity: 'Tribrid Inflation'
- Temperature anisotropies of the CMB are a powerful probe of inflation
  $\rightarrow$ results from PLANCK satellite may allow to discriminate between inflationary models