Tribrid inflation

- A framework for connecting inflation with particle physics

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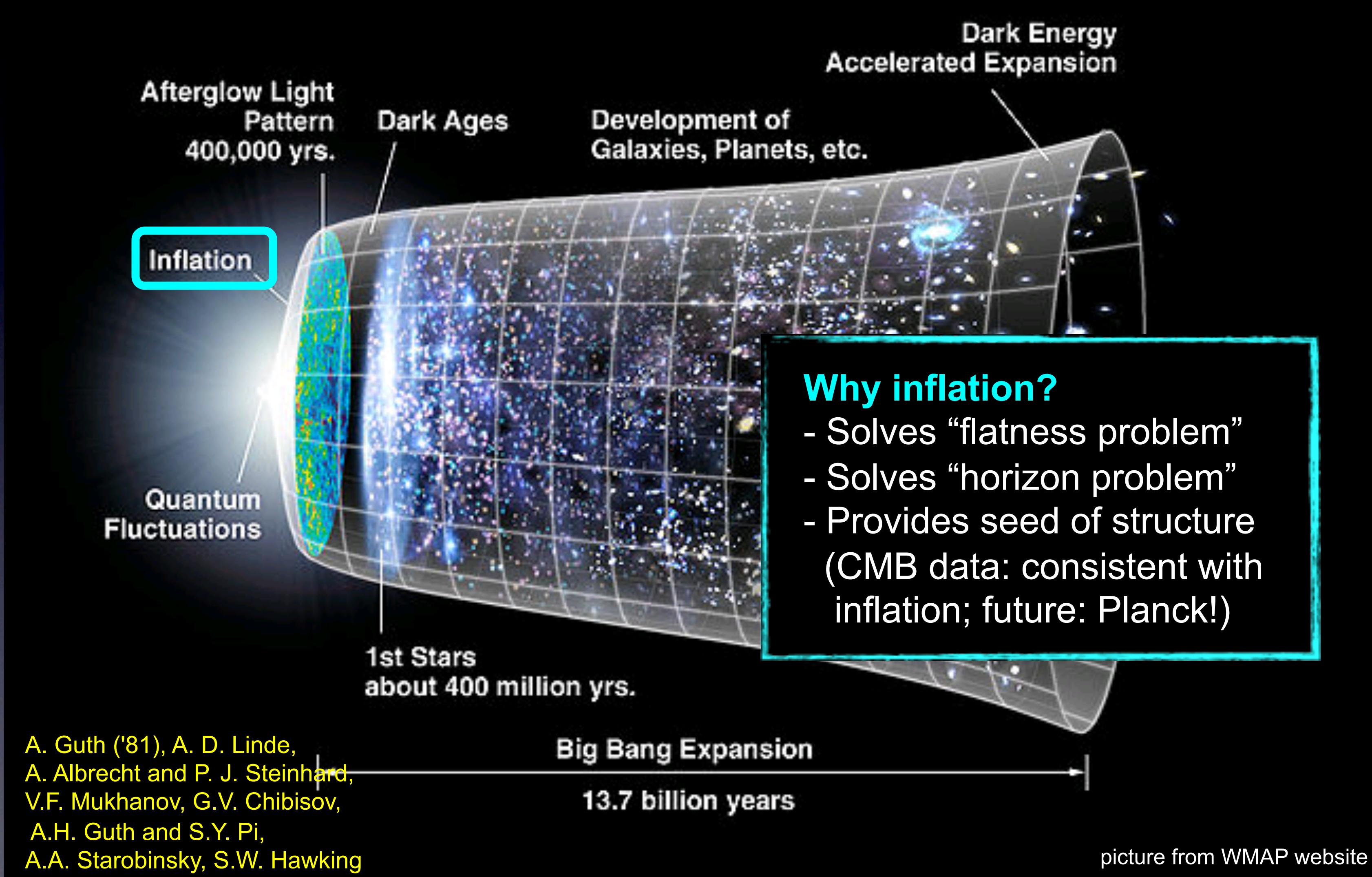
Inflation = Era of accelerated expansion in the very early universe



Why inflation?

- Solves "flatness problem"
- Solves "horizon problem"
- Provides seed of structure
  (CMB data: consistent with inflation; future: Planck!)

A. Guth ('81), A. D. Linde,
A. Albrecht and P. J. Steinhard,
V.F. Mukhanov, G.V. Chibisov,
A.H. Guth and S.Y. Pi,
A.A. Starobinsky, S.W. Hawking

picture from WMAP website

How can inflation be realised?

- Starting point: Einstein's equations of General Relativity

Λ: Cosmological constant

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Metric $g_{\mu\nu}$: Gravity ↔ geometry of space-time

Energy momentum tensor: Represents particle theory

How can inflation be realised?

- Simple possibility: Slowly rolling scalar field ϕ (minimally coupled to gravity)

$$T_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi - g_{\mu\nu} \left(\frac{1}{2} \partial_\rho \phi \partial_\rho \phi + V(\phi) \right)$$

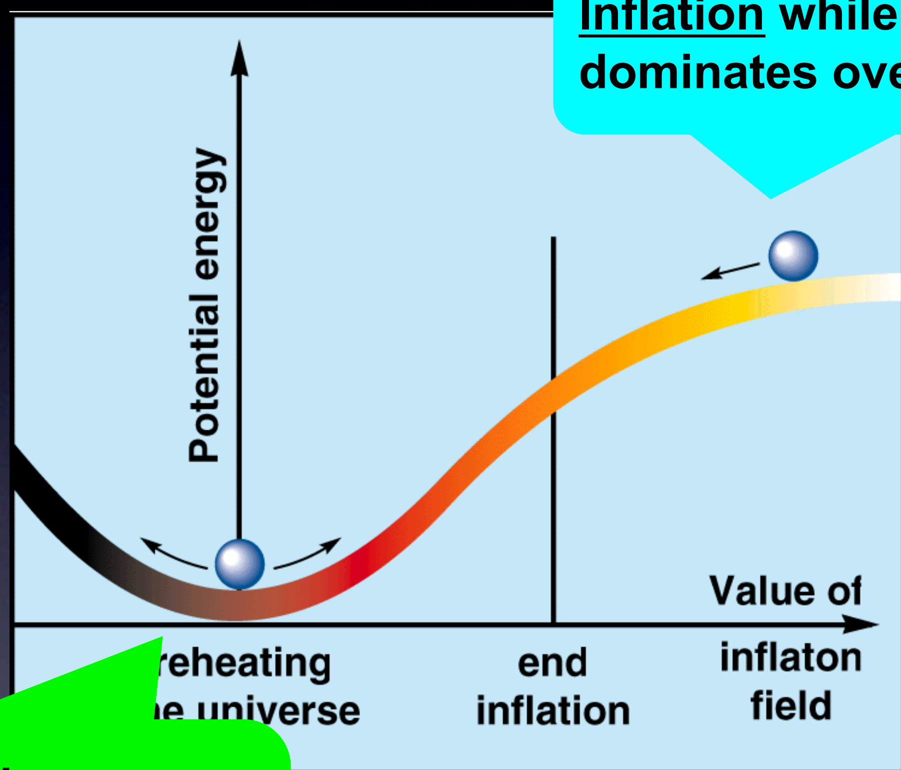
If the vacuum energy V(ϕ) dominates:

$$\Rightarrow \quad a(t) = \exp \left(\sqrt{\frac{8\pi G_N V(\phi)}{3}} t \right)$$

and the universe “inflates”!

Important: The field ϕ is dynamical ⇒ inflation can end!

Dynamics during and after inflation

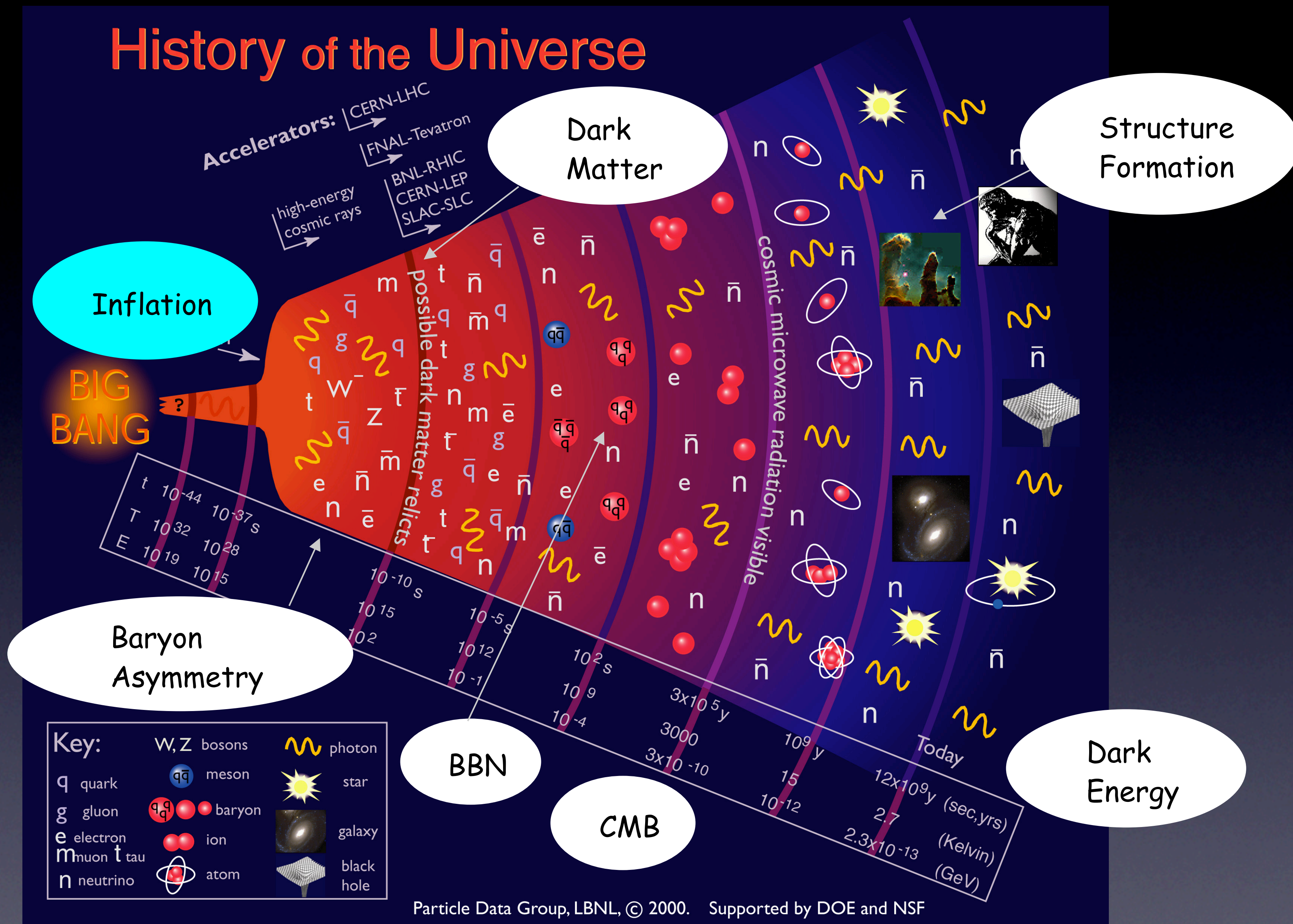


<u>Inflation</u> while vacuum energy dominates over kinetic energy

V_0

<u>Decays of the inflaton</u>:
→ matter & antimatter, and possibly their asymmetry get produced!

Vacuum energy during inflation:
$(V_0)^{1/4} \sim 10^{16}$ GeV $\sim M_{GUT}$



Inflation can successfully set the right initial conditions for the evolution of the universe ...

Open question:

How is inflation connected to 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 $\Rightarrow$ $\delta m_h^2 \sim \Lambda^2$

attractive solution provided by ...

Supersymmetry (as local symmetry: supergravity = SUGRA)

Particle physics models of inflation in supergravity?

Basic types of inflation models

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

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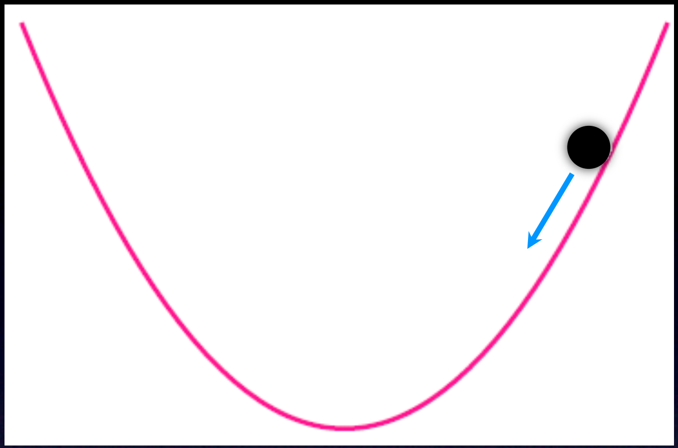
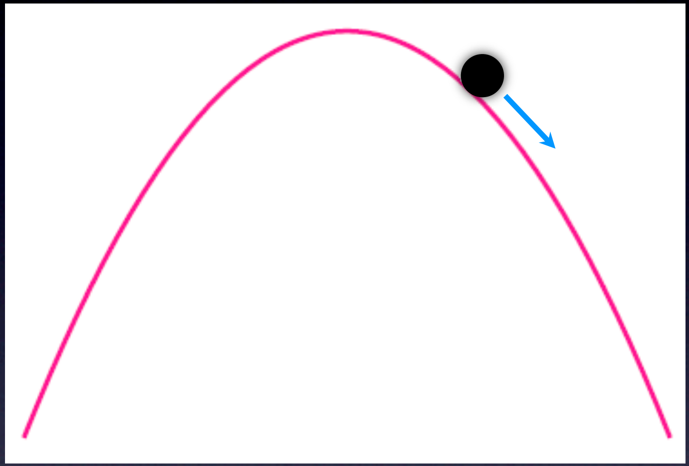
... many variants of scalar field potentials can lead to inflation ...



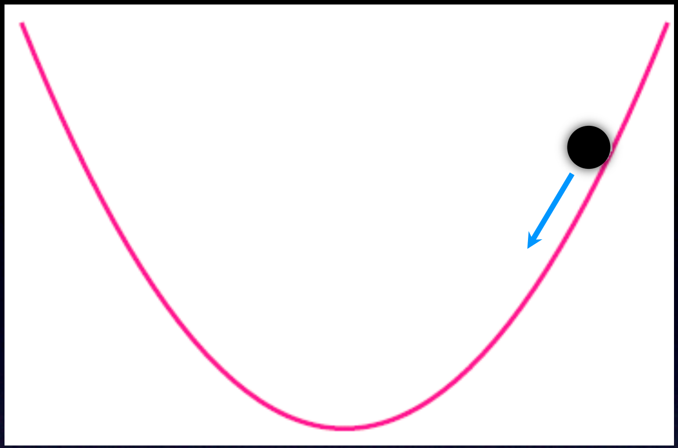
'Large field' (chaotic) inflation



'Small field' (new) inflation

Basic types of inflation models

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



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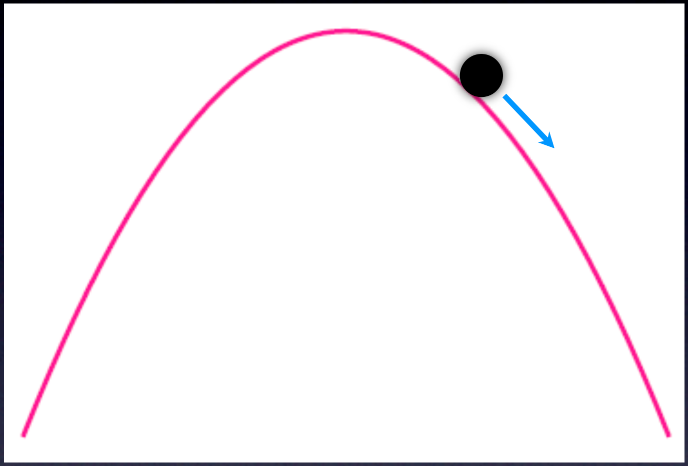
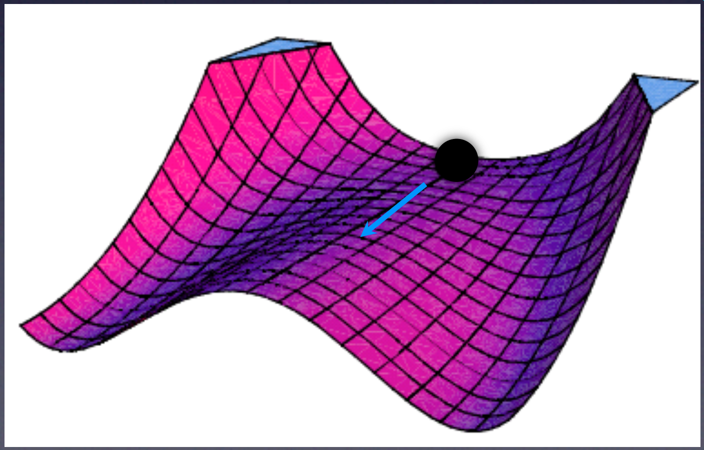


'Small field' (new) inflation



'Hybrid-type' inflation models

... in Hybrid inflation: connection to a 2nd order phase transition at high energies (~ M_{GUT})

Example: “Standard SUSY Hybrid Inflation“

- The “standard” way to realise hybrid inflation SUSY/SUGRA introduces a singlet superfield Φ ...

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

Example: "Standard SUSY Hybrid Inflation"

- The "standard" way to realise hybrid inflation SUSY/SUGRA introduces a singlet superfield Φ ...

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

Inflaton superfield
(has to be a <u>total singlet</u>, apart from possible R symmetry)

Waterfall superfield

Fields are superfields: (index S dropped!)

$$\phi = \phi_S + \sqrt{2}\theta\phi_F + \theta\theta F_\phi$$

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

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

Example: "Standard SUSY Hybrid Inflation"

- Scalar potential (for simplicity: global SUSY, gauge singlet H)

$$\boxed{V_F = \sum_i |F_i|^2 = \sum_i \left|\frac{\partial W}{\partial \Phi_i}\right|^2_{\theta=0}}$$

$$V_F = |F_\phi|^2 + |F_H|^2 \text{ with } \begin{cases} |F_\phi|^2 = |\kappa|^2 |H^2 - M^2|^2 \\ |F_H|^2 = |\kappa|^2 |2 H \phi|^2 \end{cases}$$

Example: "Standard SUSY Hybrid Inflation"

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$$\boxed{V_F = \sum_i |F_i|^2 = \sum_i \left|\frac{\partial W}{\partial \Phi_i}\right|^2_{\theta=0}}$$

"Mexican hat" potential for H

$$V_F = |F_\phi|^2 + |F_H|^2 \text{ with } \begin{cases} \boxed{|F_\phi|^2} = |\kappa|^2 |H^2 - M^2|^2 \\ |F_H|^2 = |\kappa|^2 |2 H \phi|^2 \end{cases}$$

Total m^2 for H (at <H>=0):

$m^2_H|_{<H>=0} = - \kappa^2 M^2 + 4 \kappa^2 |<\Phi>|^2 > 0$

$\Rightarrow$ H=0 stable for $|<\Phi>| > \Phi_c = M^2/4$

For stable <H> = 0:
Large $V_0 = \kappa^2 M^4$, Φ is a "F-flat" direction ... suitable for inflation

Example: "Standard SUSY Hybrid Inflation"

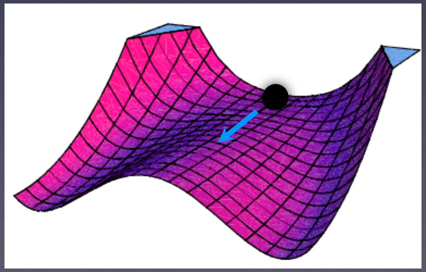
- Scalar potential (for simplicity: global SUSY, gauge singlet H)

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

Inflaton superfield

Waterfall superfield

⇒ Hybrid potential for singlet inflaton field



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

Tribrid Inflation: Hybrid-like inflation with non-singlet inflaton field

Tribrid Inflation from Generalized Superpotential

- Tribrid Inflation: Three fields play a role ...

<u>Note:</u> in Planck units, somewhat simplified ... (e.g. $\Phi^n \to \Phi_1\Phi_2\Phi_3...$)

$$W = \kappa S (H^\ell - M^2) + \lambda H^m \Phi^n$$

Driving superfield
(here: <S> = 0 during and after inflation; S not the inflaton! Vacuum energy V_0 from $|F_S|^2$, m_S > Hubble from Kähler potential operator ~ $|S|^4$)

Waterfall superfield

<u>Inflaton superfield</u>
(D-flat combination of fields from the matter sector; fields <u>can be charged under the symmetry of the theory</u>!)

$$V_D = \frac{1}{2}\sum_a g^2 \left(\phi_i^\dagger \mathcal{T}^a \phi_i\right)^2 \stackrel{!}{=} 0$$

S.A., Bastero-Gil, King, Shafi ('04), S.A., Bastero-Gil, Dutta, King, Kostka ('08), S.A., Ur-Rehmann, Nolde ('12)

Effective Supergravity Framework

- Inflaton field values $\Phi < M_P \Rightarrow$ effective field theory approach possible, Kähler potential can be written as

$$\boxed{K = \text{general expansion in } \frac{\phi}{M_p}, \frac{H}{M_p}, \frac{S}{M_p}}$$

- Explicitly, in Planck units:

$$K = |\Phi|^2 + |H|^2 + |S|^2 + \sum_{i+j+k\geq 2} \kappa_{ijk} |\Phi|^{2i} |H|^{2j} |S|^{2k}$$

- In general: Parameters have to be chosen carefully in order to maintain a flat enough inflaton potential (η-problem)

Tribrid Inflation: Scalar potential

- Scalar potential (for simplicity: global SUSY, gauge singlet H)

$$\boxed{V_F = \sum_i |F_i|^2 = \sum_i |\frac{\partial W}{\partial \Phi_i}|^2_{\theta=0}}$$

$$V_F = \sum_i |F_i|^2 \text{ with } \begin{cases} |F_S|^2 = |\kappa|^2 |H^\ell - M^2|^2 \\ |F_H|^2 = |\cancel{\kappa \ell H^{\ell-1} S} \\ \qquad +\lambda m H^{m-1} \phi^n|^2 \\ |F_\phi|^2 = |\kappa n \lambda H^m \phi^{n-1}|^2 \end{cases}$$

Tribrid Inflation: Scalar potential

- Scalar potential (for simplicity: global SUSY, gauge singlet H)

Generalized “Mexican hat”-like potential for H

$$V_F = \sum_i |F_i|^2 \text{ with } \begin{cases} \boxed{|F_S|^2} = |\kappa|^2 |H^\ell - M^2|^2 \\ |F_H|^2 = |\cancel{\kappa \ell H^{\ell-1} S} \\ \qquad + \lambda m H^{m-1} \phi^n|^2 \\ |F_\phi|^2 = |\kappa n \lambda H^m \phi^{n-1}|^2 \end{cases}$$

For <Φ> ≠ 0: Additional terms
for the potential of H; can stabilize <H> = 0

Tribrid Inflation: Scalar potential

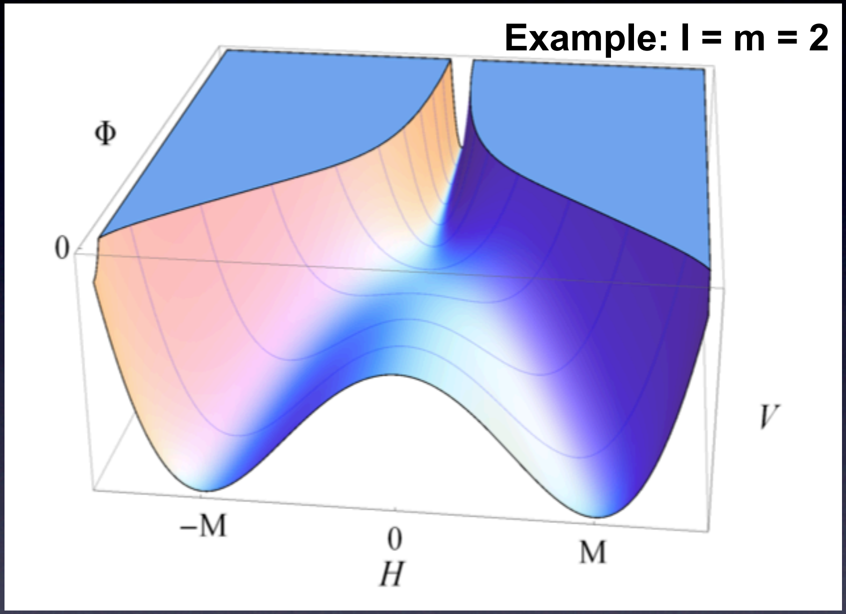
- Scalar potential (for simplicity: global SUSY, gauge singlet H)

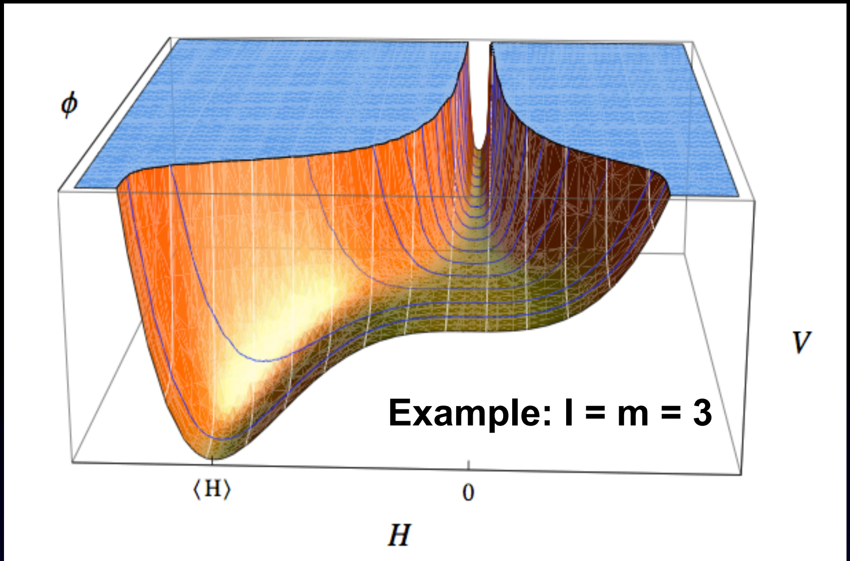
$$V_F = \sum_i |F_i|^2 \text{ with } \begin{cases} |F_S|^2 = |\kappa|^2 |H^\ell - M^2|^2 \\ |F_H|^2 = |\cancel{\kappa \ell H^{\ell-1} S} \\ \qquad +\lambda m H^{m-1} \phi^n|^2 \\ |F_\phi|^2 = |\kappa n \lambda H^m \phi^{n-1}|^2 \end{cases}$$

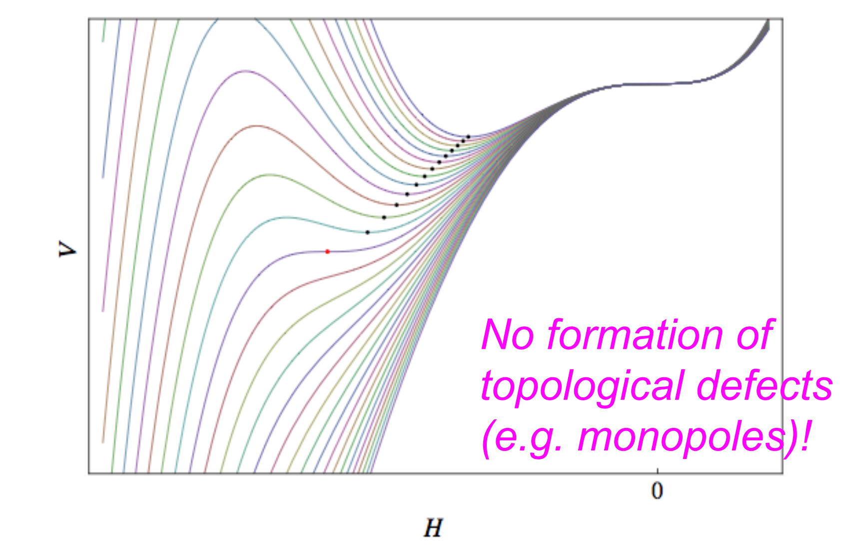
For stable <H> = 0:
Large $V_0 = \kappa^2 M^4$; Φ is a "F-flat" direction ... suitable for inflation

Shape of the potential depends on l, m and n ... different types of potentials for tribrid inflation ...

Tribrid Inflation: Types of potentials ...





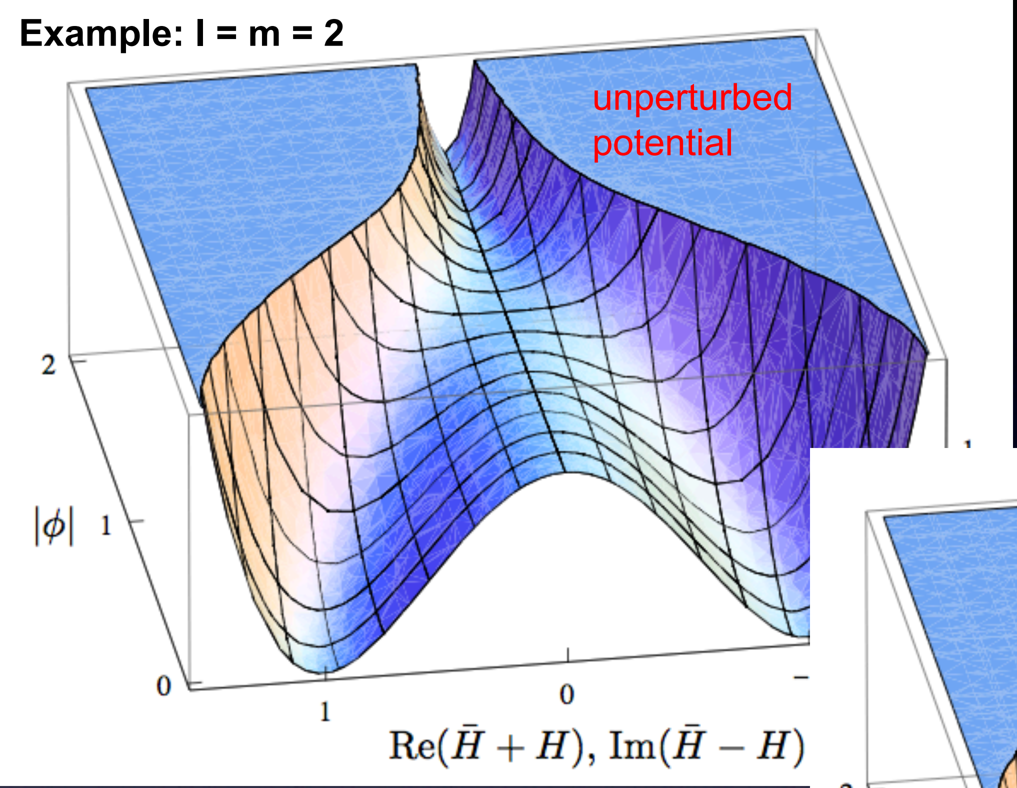


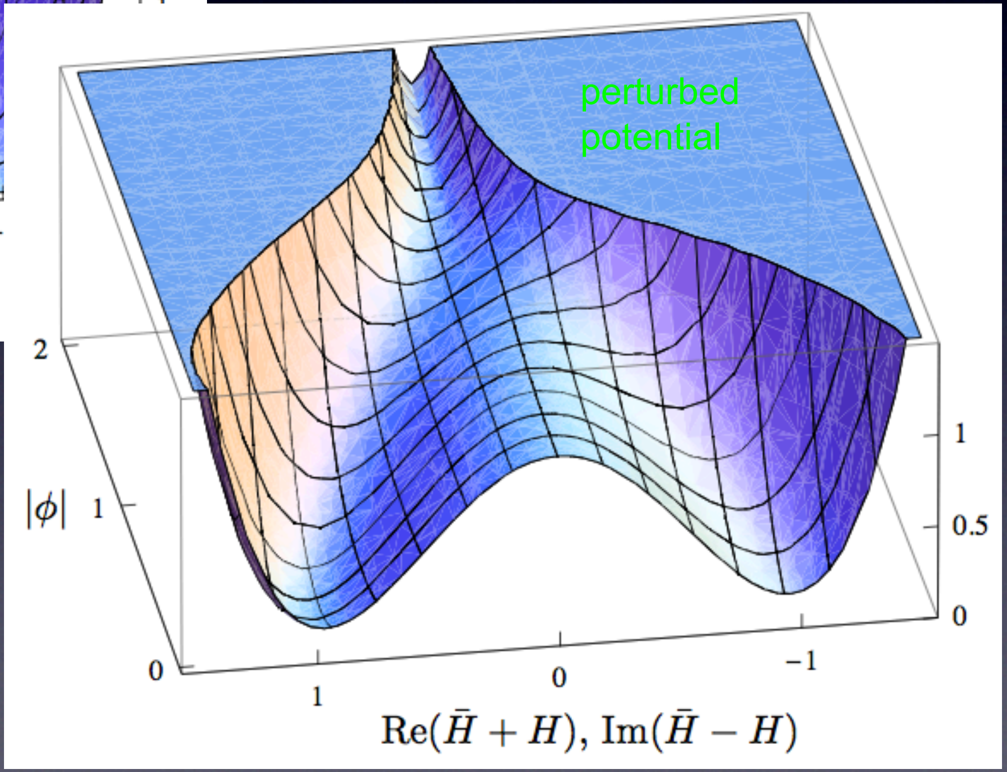
No formation of topological defects (e.g. monopoles)!

<u>Pseudosmooth:</u> Mixture between models with a “waterfall” and models of “smooth” inflation ...

S.A., Nolde, Ur Rehman (’12)

... can avoid topological defects





In addition:
With inflaton field(s) charged under the symmetry, higher-dimensional operators are expected to deform the potential slightly → vacuum can be "preselected"; monopole production after inflation avoided!

Tribrid Inflation: Slope for the inflaton potential

$$W = \kappa \boxed{S}(\boxed{H^\ell} - M^2) + \lambda \boxed{H^m}\boxed{\Phi^n}$$

Inflaton

So far, the inflaton was introduced as tree-level D-flat & F-flat direction of the potential ...

Slope of the inflaton potential can come from:

1. loop corrections (Coleman-Weinberg potential)
2. Planck-suppressed operators from the Kähler potential
3. small $\langle H \rangle \neq 0$ already during inflation (only for $m > 2$)
   (happens in pseudosmooth potentials)

$\rightarrow$ different regimes depending on which contribution dominates

"Regimes" of Tribrid Inflation

S.A., Nolde, Ur Rehman ('12)
S.A., Nolde ('12)

$$W = \kappa S(H^\ell - M^2) + \lambda H^m \Phi^n$$

Inflaton

	$m = 2$	$m = 3$	$m = 4$
$\ell = 2$	Kähler-driven or loop-driven	not possible	not possible
$\ell = 3$	Kähler-driven or loop-driven	pseudosmooth	not possible
$\ell = 4$	Kähler-driven or loop-driven	pseudosmooth or smooth	pseudosmooth

Tribrid Inflation: Possible connection to particle physics models ...

$$W = \kappa S(H^\ell - M^2) + \lambda H^m \Phi^n$$

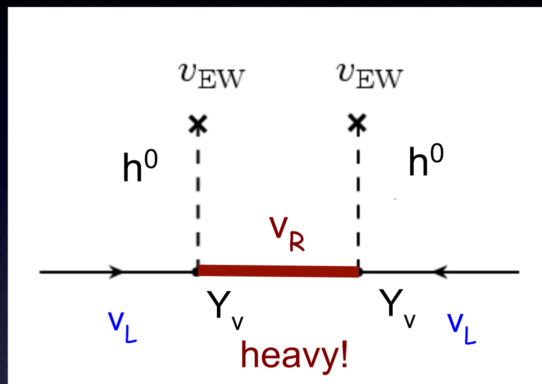
Inflaton

n = 2 ⇒ Mass for a matter field after inflation
n = 3 ⇒ Yukawa coupling after inflation

Phase transition around the GUT scale:
- GUT symmetry? - Family symmetry? ...

Explicit example: Sneutrino Inflation from a Tribrid Superpotential

Origin of neutrino masses? Here: Seesaw mechanism ...



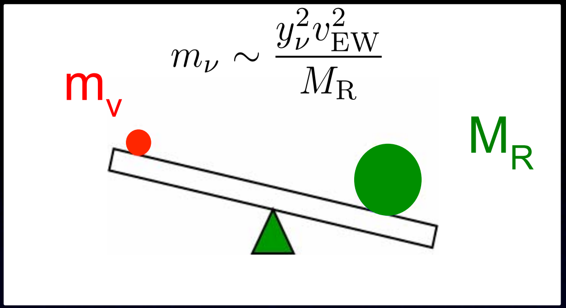
$$\boxed{m_{\rm LL}^{\rm I} \approx -\frac{v_u^2}{2}\, Y_\nu^T M_{\rm RR}^{-1}\, Y_\nu}$$

P. Minkowski ('77), Gell-Mann, Glashow, Mohapatra, Ramond, Senjanovic, Slanski, Yanagida ('79/'80)

The Seesaw mechanism:

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

Seesaw + SUSY → The RH sneutrino as the inflaton

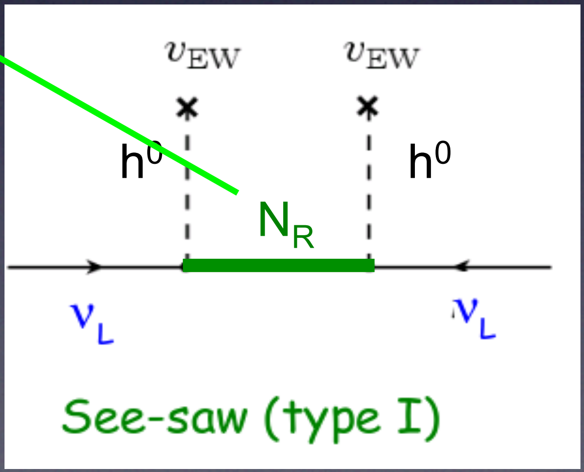


The right-handed neutrino superfield:

$$\boxed{\nu_\mathrm{R} = \widetilde{N}_\mathrm{R} + \sqrt{2}\theta N_\mathrm{R} + \theta\theta F_{N_\mathrm{R}}}$$

P. Minkowski ('77), Mohapatra, Senjanovic, Yanagida, Gell-Mann, Ramond, Slansky, Schechter, Valle, ...

The right-handed sneutrinos, i.e. the scalar superpartners of the RH neutrinos
→ possible candidates for acting as the inflaton field!



Framework: local supersymmetry = supergravity

Two possibilities for the origin of the large RH neutrino masses

$\longleftrightarrow$

two options for realising inflation with right-handed sneutrinos

Origin of right-handed neutrino masses

I) Direct mass terms:

$$\boxed{\mathcal{W}_{M_\mathrm{R}} = \tfrac{1}{2} M_\mathrm{R} \nu_\mathrm{R} \nu_\mathrm{R}}$$

II) Mass terms from spontaneous symmetry breaking

$$\boxed{\mathcal{W}_{M_\mathrm{R}} = \frac{\lambda}{M_\mathrm{Pl}} \nu_\mathrm{R} \nu_\mathrm{R} H H}$$

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I) Direct mass terms:

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II) Mass terms from spontaneous symmetry breaking

… more in the spirit of LR-symm. GUTs and family symmetry models

$$\boxed{\mathcal{W}_{M_\mathrm{R}} = \frac{\lambda}{M_\mathrm{Pl}} \nu_\mathrm{R} \nu_\mathrm{R} H H}$$

For example:

In SO(10) GUTs:

$$\frac{1}{M_\mathrm{Pl}} 16_i 16_j H_{\overline{16}} H_{\overline{16}}$$

In some A_4 flavour models (with $\theta^{(i)}$ flavons in 3 of A_4):

$$\frac{1}{\mathrm{M}_\mathrm{Pl}} \nu_{\mathrm{R}i} \nu_{\mathrm{R}j} \theta^{(i)} \theta^{(j)}$$

Large Field (Chaotic) Sneutrino Inflation

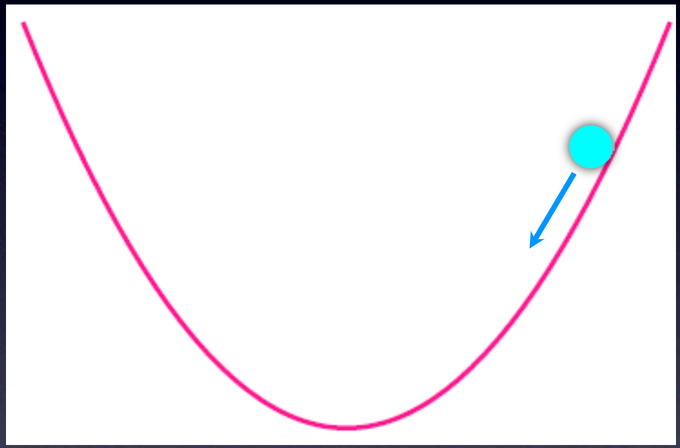
I) Direct mass terms:

Murayama, Suziki, Yanagida, Yokoyama ('93)

$$\boxed{\mathcal{W}_{M_\mathrm{R}} = \frac{1}{2} M_\mathrm{R} \nu_\mathrm{R} \nu_\mathrm{R}}$$

Inflaton scalar potential:

$$V_F = \left|F^2_{\nu_\mathrm{R}}\right|^2 = \sum_i \left|\frac{\partial W}{\partial \nu_\mathrm{R}}\right|^2_{\theta=0} = \left|M_\mathrm{R} \widetilde{N}_\mathrm{R}\right|^2$$



'Large field' (chaotic) sneutrino inflation

In supergravity:
W+ suitable Kähler potential K

Sneutrino Tribrid Inflation

II) Mass term from spontaneous symmetry breaking (SSB)

$$\boxed{\mathcal{W} = \qquad\qquad\qquad \frac{\lambda}{M_{\mathrm{Pl}}}\nu_{\mathrm{R}}\nu_{\mathrm{R}}HH}$$

S.A., Bastero-Gil, King, Shafi ('04);
S.A., Baumann, Domcke, Kostka ('10)

Second term of the Tribrid superpotential, here with m = n = 2

Sneutrino Tribrid Inflation

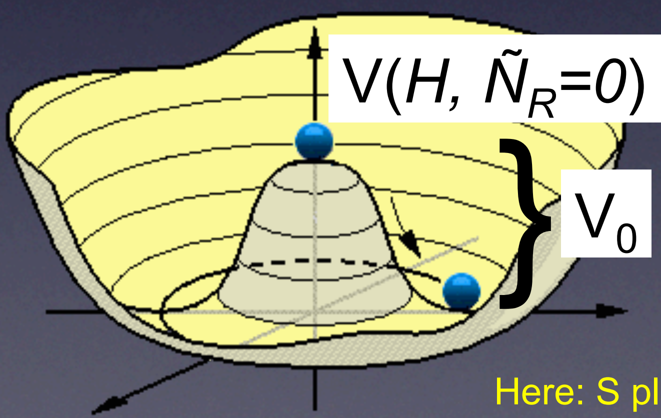
II) Mass term from spontaneous symmetry breaking (SSB)

$$\boxed{\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\mathrm{Pl}}} \nu_{\mathrm{R}} \nu_{\mathrm{R}} H H}$$

S.A., Bastero-Gil, King, Shafi ('04);
S.A., Baumann, Domcke, Kostka ('10)

Additional term in W is just a SUSY version of a SSB potential

$|F_S|^2 \Rightarrow$



Here: S plays no role for the inflationary dynamics! <S>=0 during & after inflation.

Sneutrino Tribrid Inflation

S.A., Bastero-Gil, King, Shafi ('04);
S.A., Baumann, Domcke, Kostka ('10)

II) Mass term from spontaneous symmetry breaking (SSB)

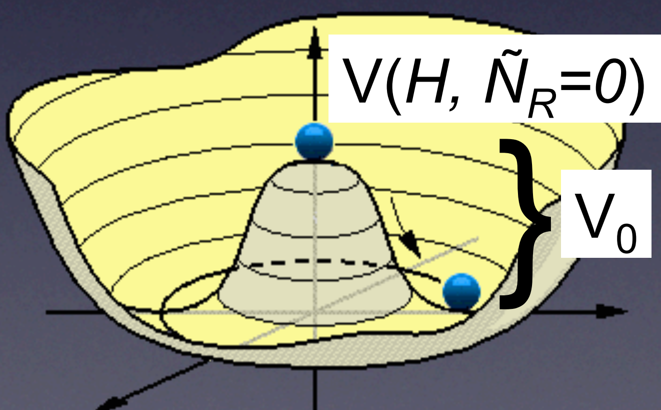
$$\boxed{\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\rm Pl}} \nu_{\rm R} \nu_{\rm R} H H}$$

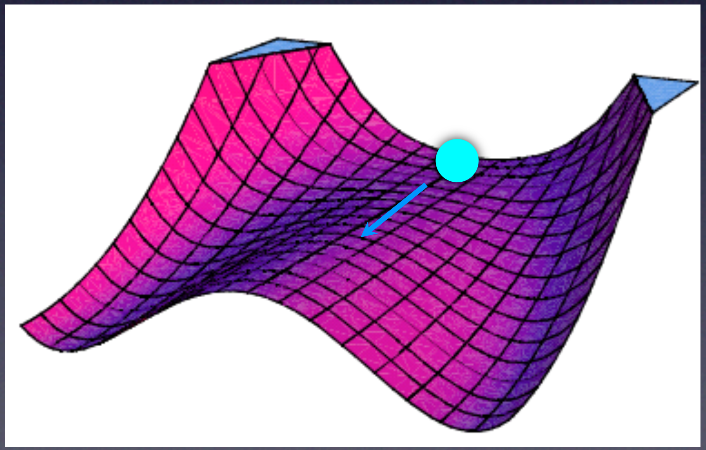
Additional term in W is just a SUSY version of a SSB potential

i) $<\tilde{N}_R> \neq 0$ can stabilise H at $<H> = 0$ and leads to large vacuum energy $V_0 \sim M$

ii) Large masses for the RH (s)neutrinos when H gets a vev after inflation

$|F_S|^2 \Rightarrow$





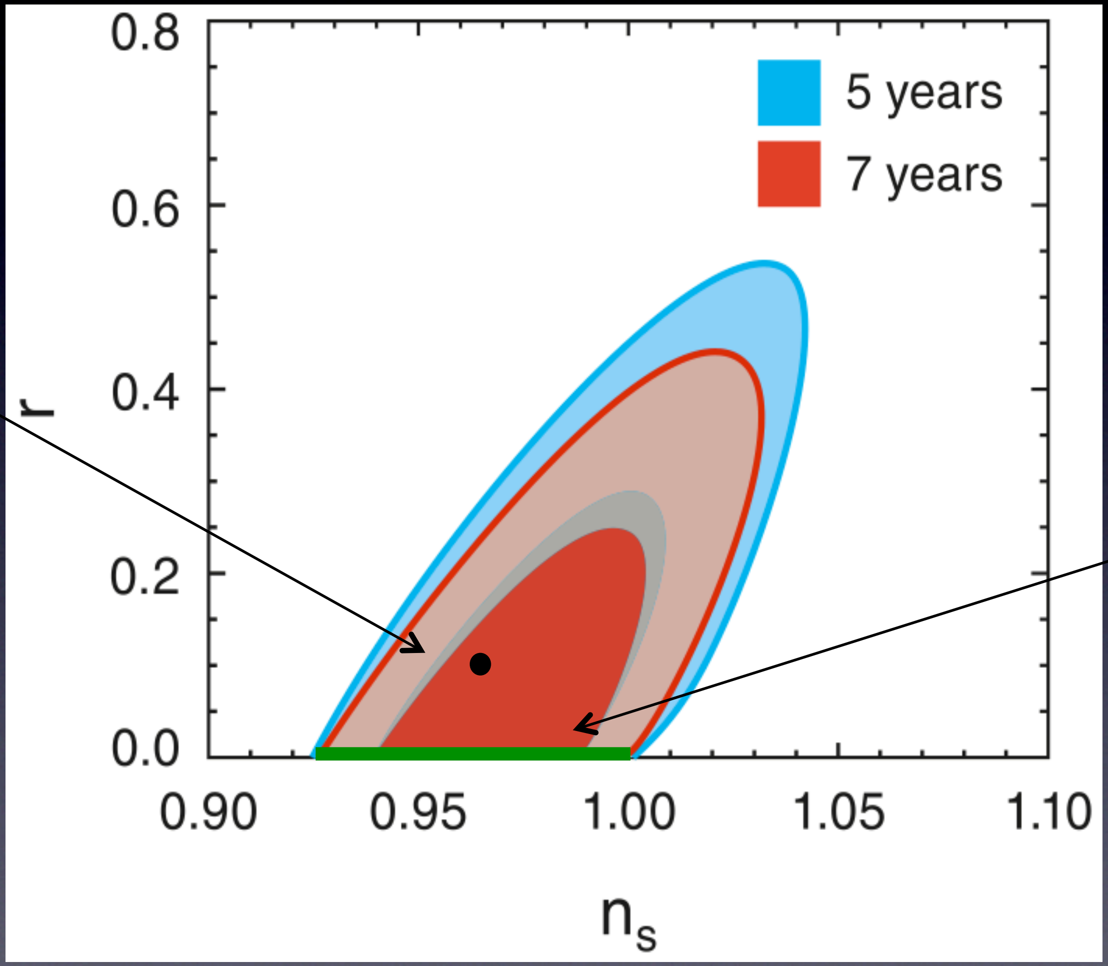
In supergravity:
W+ suitable Kähler potential K

'Hybrid-type' sneutrino inflation

Chaotic ↔ Hybrid models can be distinguished by the results of the Planck satellite

Prediction of
Chaotic Sneutrino Inflation

Murayama, Suziki, Yanagida, Yokoyama ('93)



Prediction of
Sneutrino Tribrid Inflation

S.A., Bastero-Gil, King, Shafi ('04)

(WMAP '10, WMAP '08)

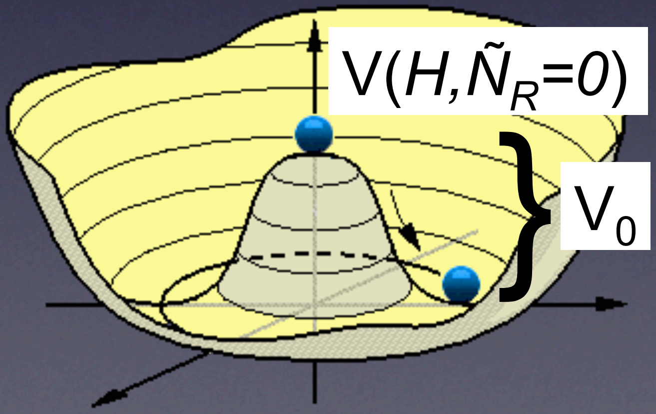
Sneutrino Tribrid Inflation

$$\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\rm Pl}} \nu_{\rm R} \nu_{\rm R} H H$$

Driving superfield
(its F-term generates the potential for H and provides the vacuum energy V_0; During and after inflation: <S> = 0.)

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

$|F_S|^2 \Rightarrow$



In supergravity:
W + suitable
Kähler potential K

Sneutrino Tribrid Inflation

$$\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\rm Pl}} \nu_{\rm R}\nu_{\rm R} H H$$

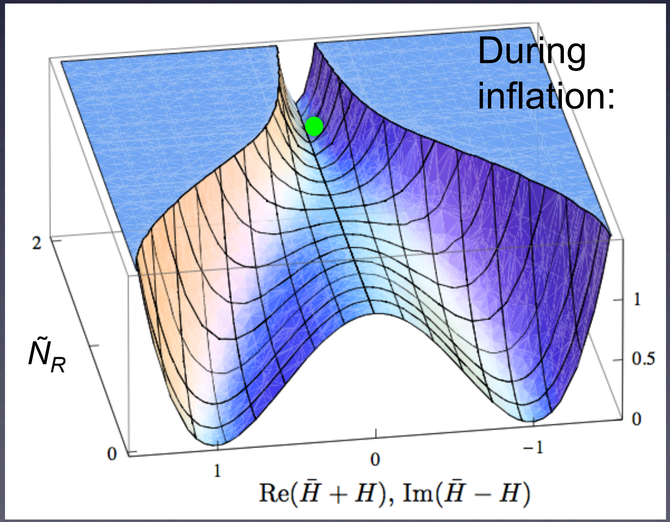
$|F_S|^2 \Rightarrow$

Inflaton superfield

(ν_R contains the inflaton field $\tilde{N}_R$ as scalar component; For $\langle\tilde{N}_R\rangle > \tilde{N}_{R,crit}$ it stabilises H at $\langle H\rangle = 0$)

41

$\langle\tilde{N}_R\rangle > \tilde{N}_{R,crit}$



Sneutrino Tribrid Inflation

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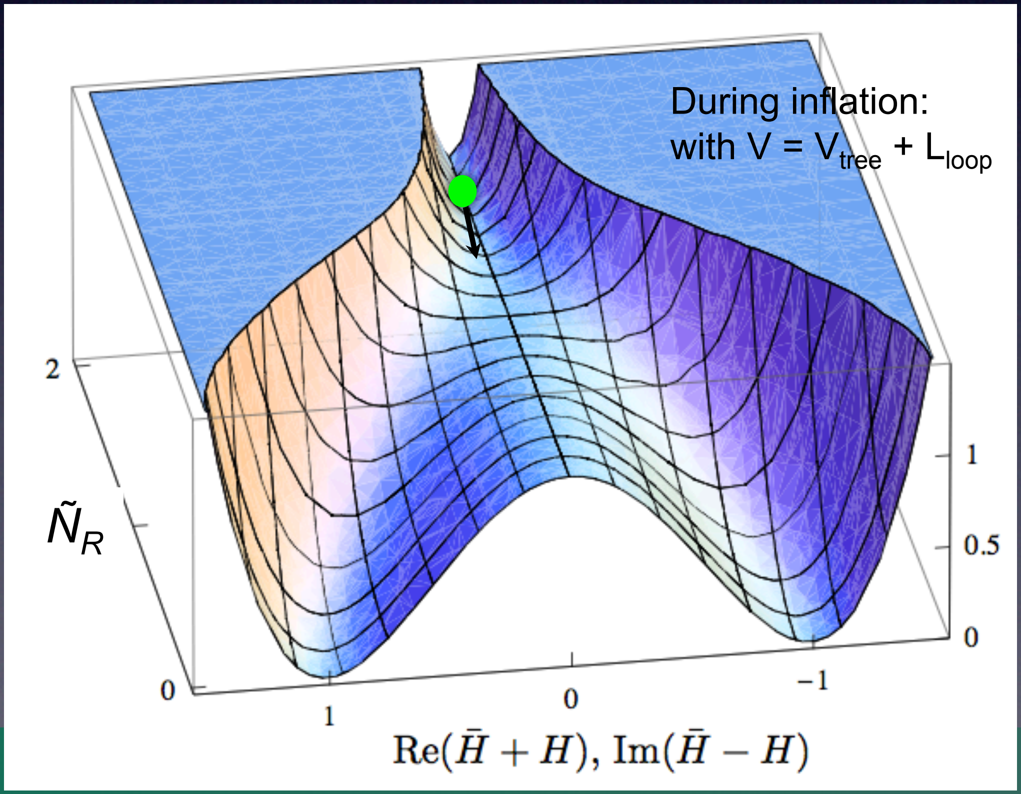


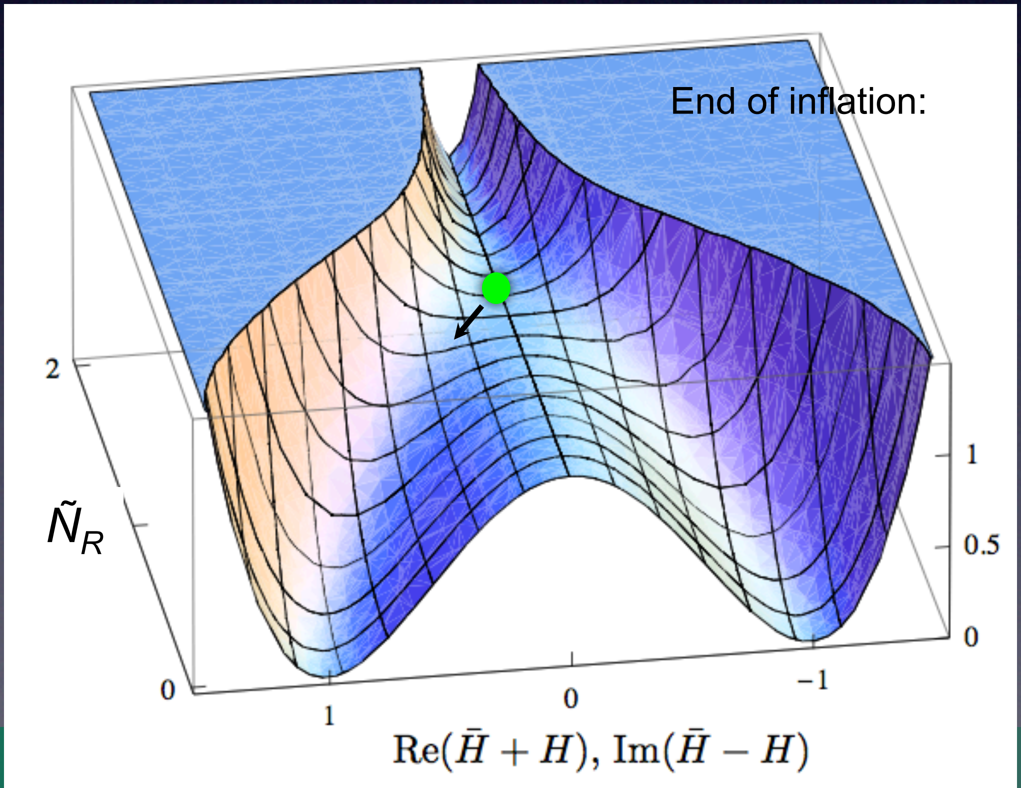
Inflaton superfield

(ν_R contains the inflaton field $\tilde{N}_R$ as scalar component; For $\langle\tilde{N}_R\rangle > \tilde{N}_{R,crit}$ it stabilises H at $\langle H\rangle = 0$)

Note: Inflaton field values still sufficiently below M_P for effective field theory treatment!

Sneutrino Tribrid Inflation

$$\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\rm Pl}} \nu_{\rm R}\nu_{\rm R} H H$$



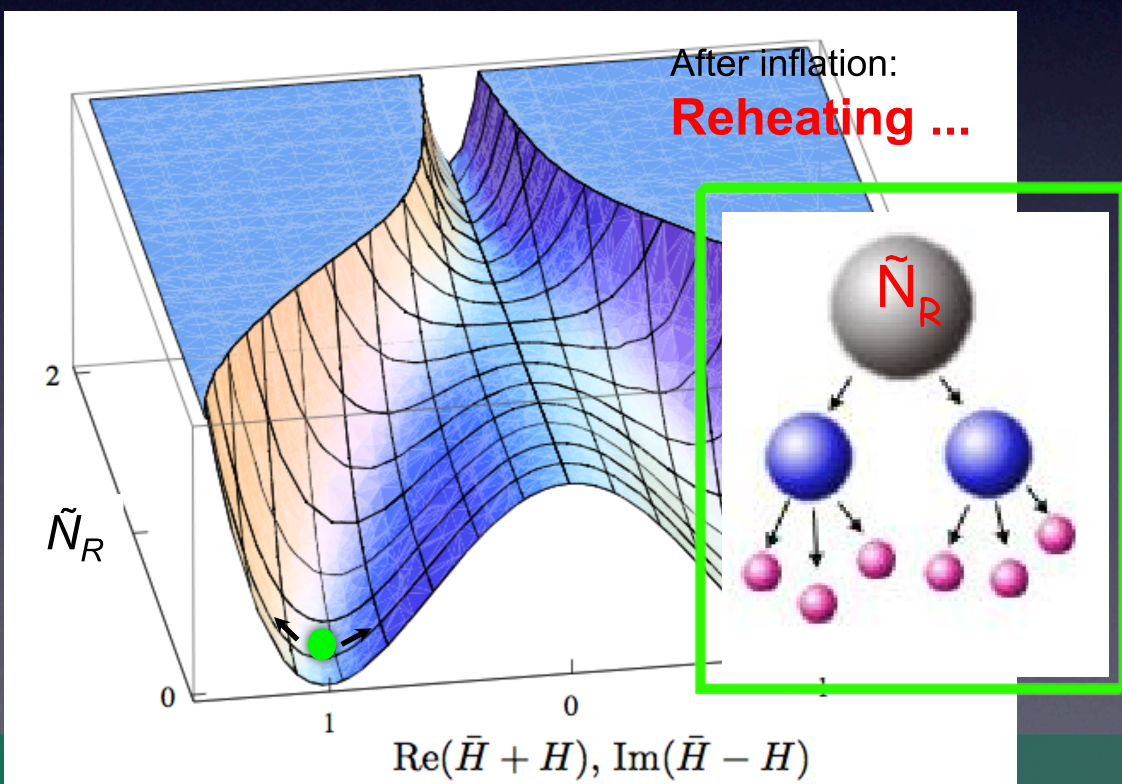
Inflaton superfield

(ν_R contains the inflaton field $\tilde{N}_R$ as scalar component; For $\langle\tilde{N}_R\rangle > \tilde{N}_{R,crit}$ it stabilises H at $\langle H\rangle = 0$)

Sneutrino Tribrid Inflation

$$\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\mathrm{Pl}}}\nu_{\mathrm{R}i}\nu_{\mathrm{R}i}HH + (y_\nu)_{ij}\nu_{\mathrm{R}i}hL_j$$

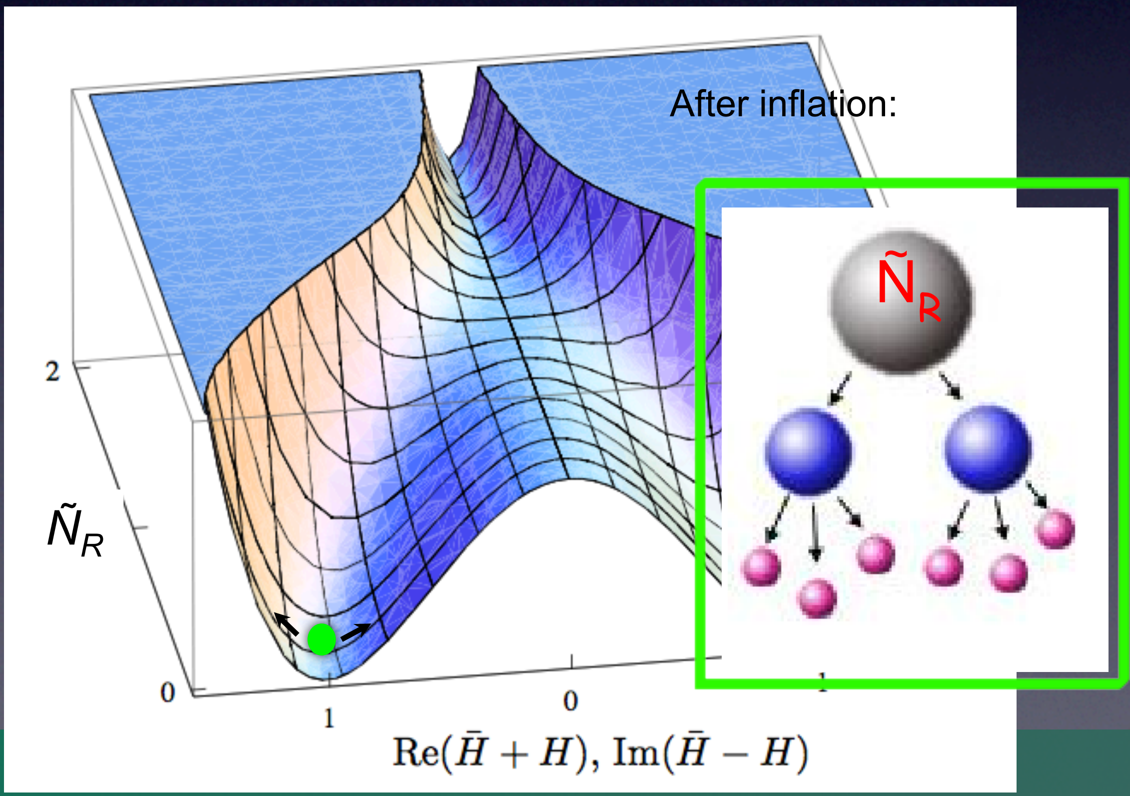
Neutrino Yukawa couplings



Sneutrino Tribrid Inflation

$$\mathcal{W} = \kappa S(H^2 - M^2) + \frac{\lambda}{M_{\rm Pl}} \nu_{\mathrm{R}i}\nu_{\mathrm{R}i} H H + (y_\nu)_{ij}\nu_{\mathrm{R}i} h L_j$$

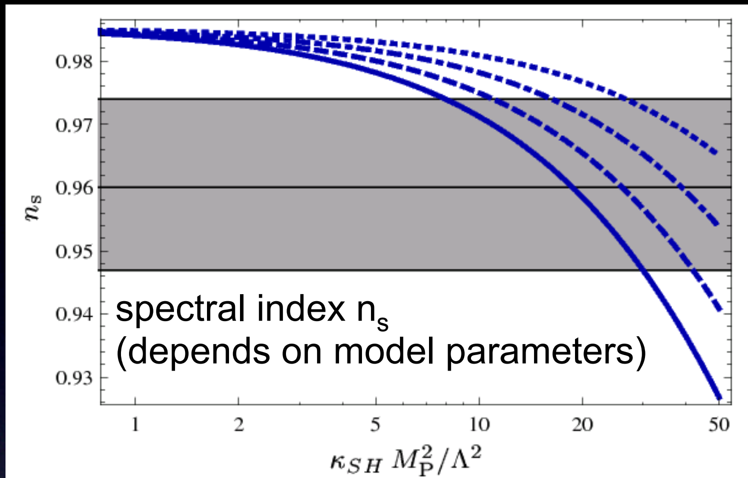
Neutrino Yukawa couplings

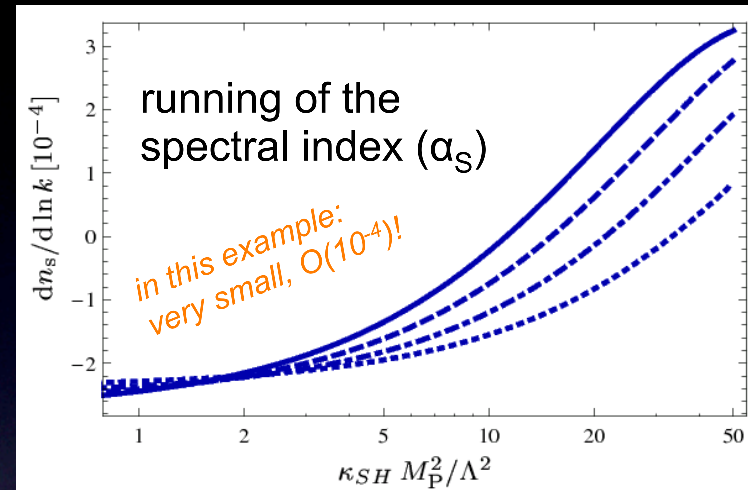


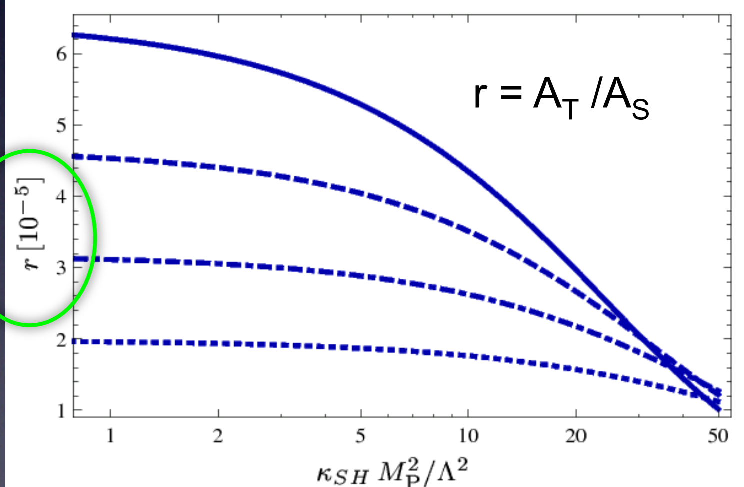
Non-thermal leptogenesis after sneutrino inflation: very efficient way of generating the observed baryon asymmetry!

In Sneutrino Hybrid Inflation:
S.A., Baumann, Domcke, Kostka ('10)

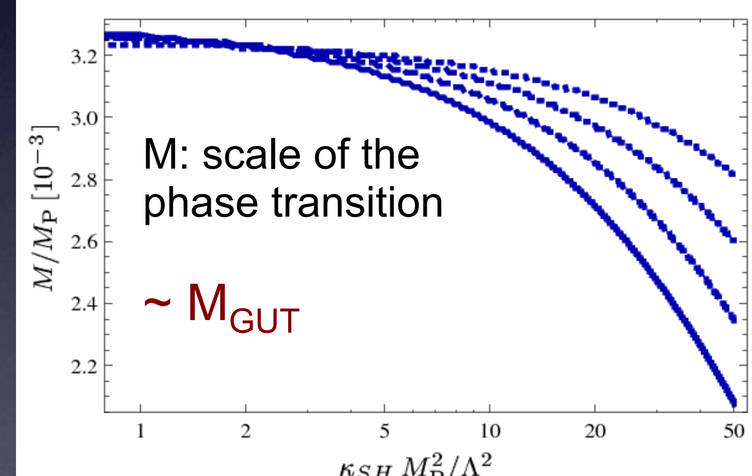
CMB observables







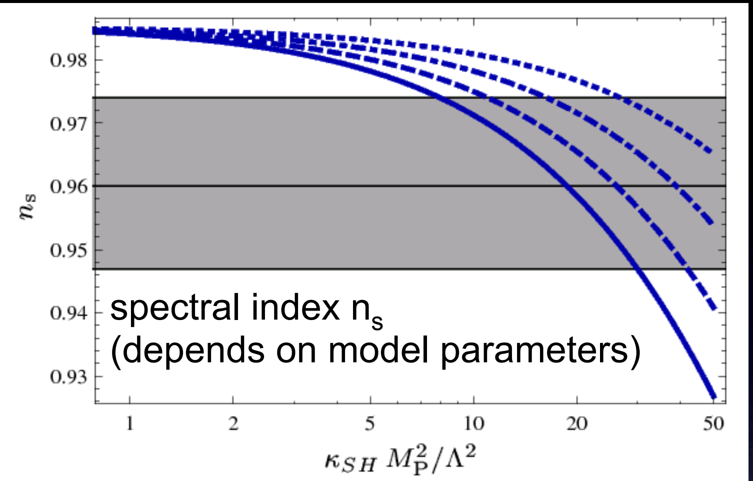
very small
(as typical for Hybrid-type models)

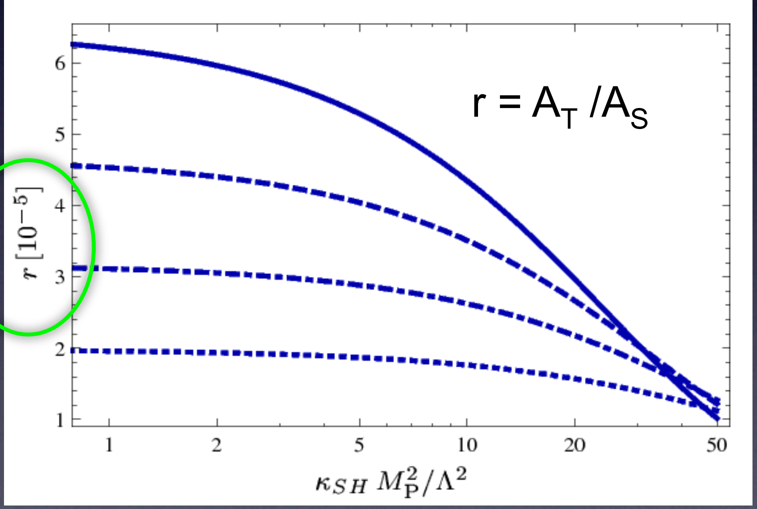


S.A., K. Dutta, P. M. Kostka ('09)

Example: Predictions in a toy model (here: slope from loops) ...

CMB observables





very small
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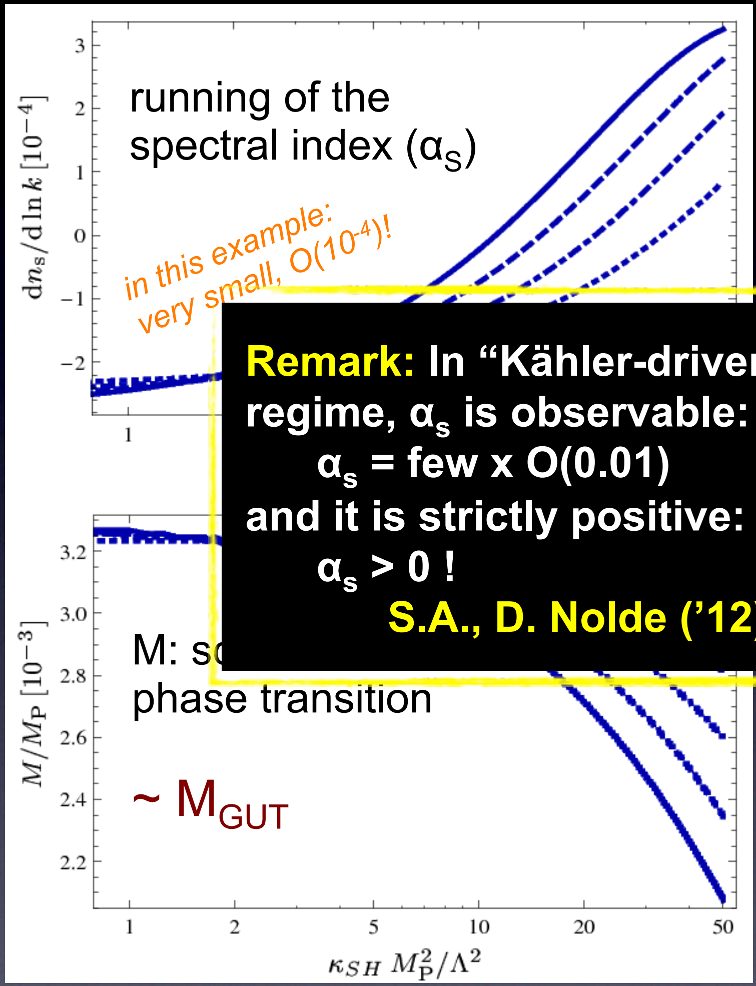
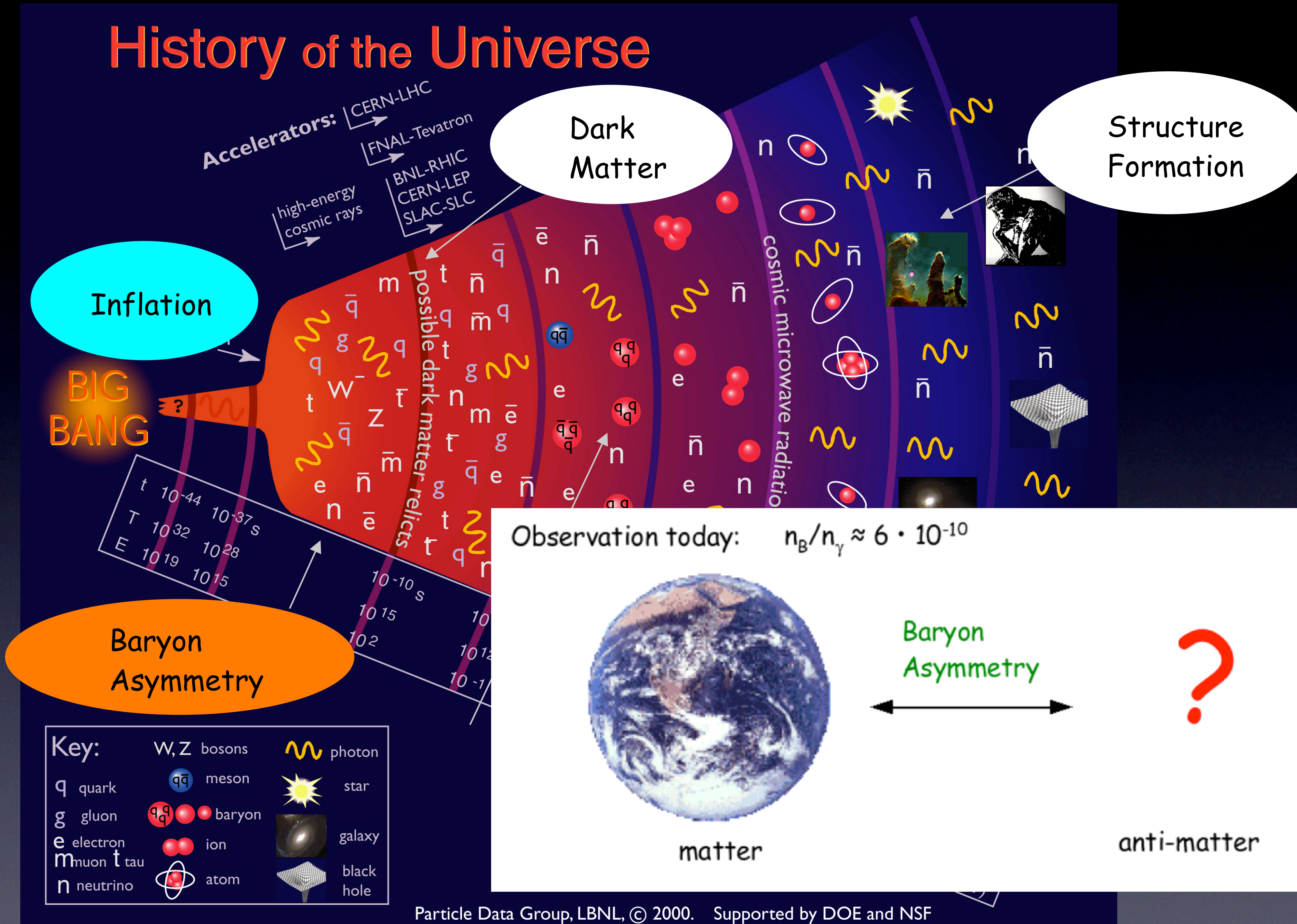


Remark: **In "Kähler-driven" regime, α_s is observable:**
α_s = few x O(0.01)
and it is strictly positive:
$\alpha_s > 0$!
S.A., D. Nolde ('12)

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

Example: Predictions in a toy model (here: slope from loops) ...

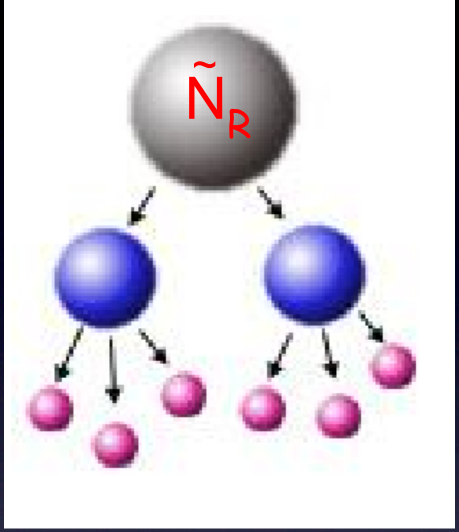
Sneutrino Tribrid Inflation and Non-thermal Leptogenesis



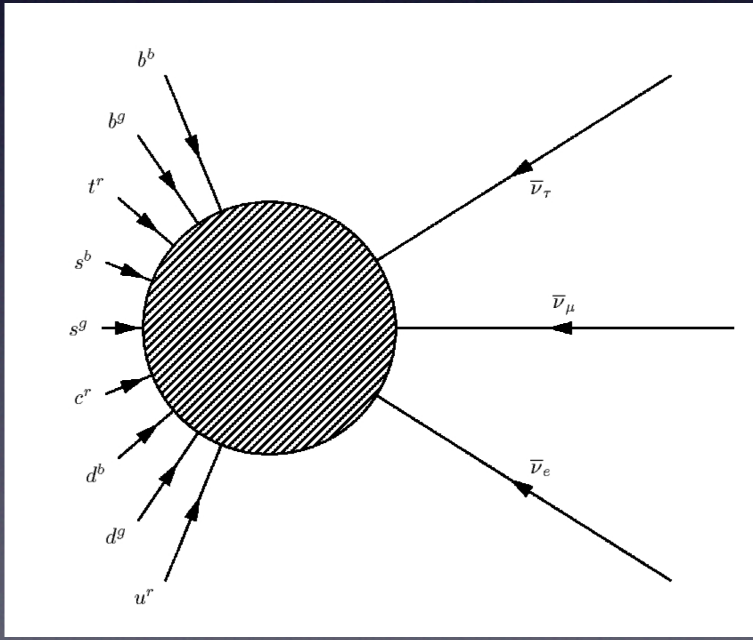
At some stage in the early universe, a small abundance of matter over antimatter has to be generated … otherwise we would not exist!

Non-thermal Leptogenesis after Sneutrino Tribrid Inflation

Step 1 (here):
The right-handed sneutrinos $\tilde{N}_R$ dominate the universe after inflation. No thermal production necessary! Their decays produce a lepton asymmetry ΔL ...



Leptogenesis mechanism: Fukugita, Yanagida ('86)

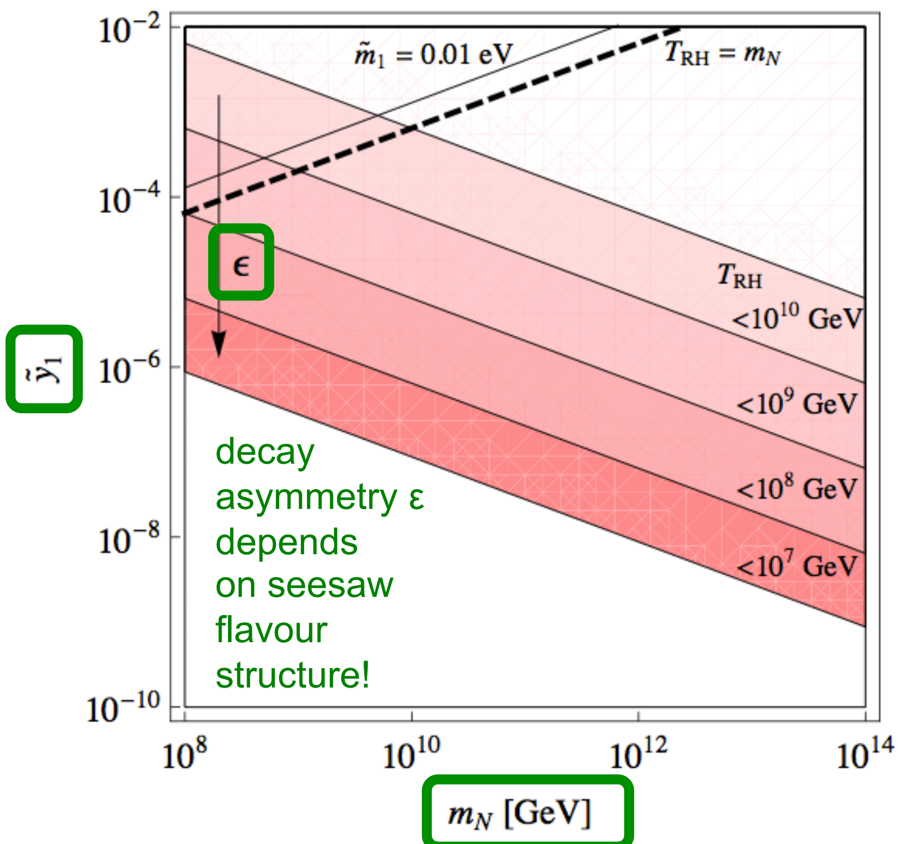


Step 2:
Sphaleron processes (conserve B-L but violate B and L) partly convert the lepton asymmetry ΔL into a baryon asymmetry ΔB

Kuzmin, Rubakov, Shaposhnikov ('85)

Successful Inflation & Leptogenesis

In our toy model of Sneutrino Tribrid Inflation:



- Reheating + Leptogenesis

$N_1 \leftrightarrow$ inflaton

$$\tilde{y}_1 \equiv \sqrt{(y_\nu y_\nu^\dagger)_{11}}$$

$$m_N = \text{(s)neutrino mass}$$

$$\tilde{m}_1 = \tilde{y}_1^2 \langle v \rangle^2 / m_N$$

$$\epsilon < \frac{3}{8\pi} \frac{\sqrt{\Delta m^2_{atm}} m_N}{\langle v \rangle^2}$$

[S. Davidson, A. Ibarra '02]

S.A., Baumann, Domcke, Kostka ('10)

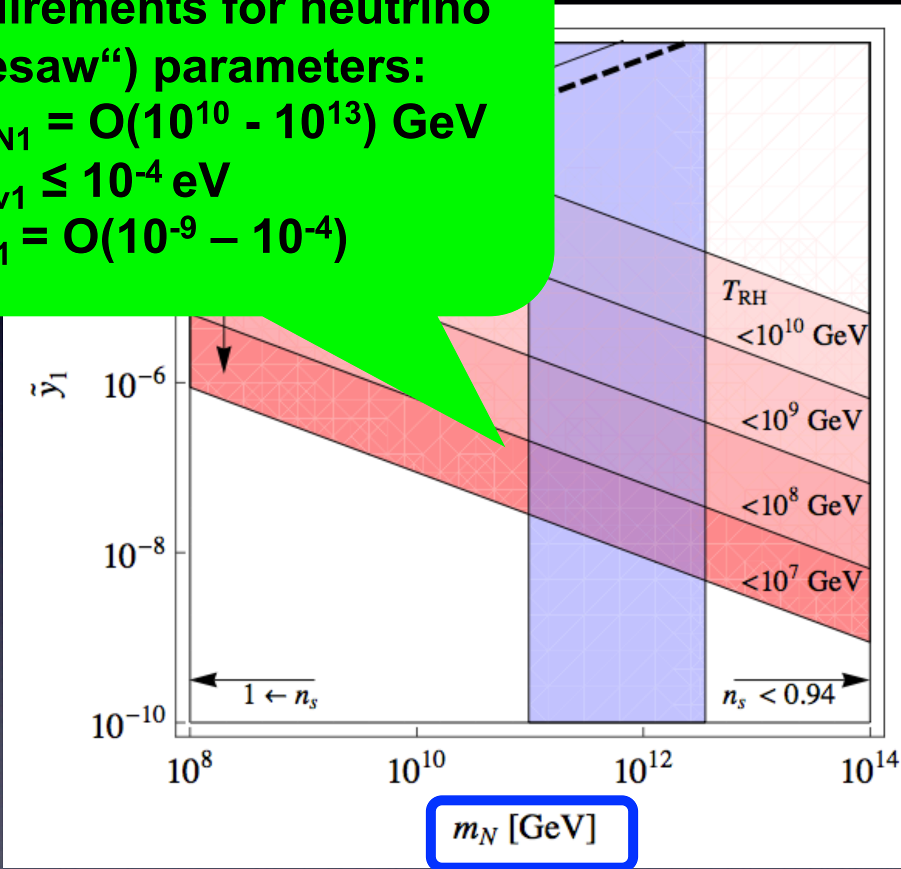
Successful Inflation & Leptogenesis

Requirements for neutrino ("seesaw") parameters:

→ $m_{N1} = O(10^{10} - 10^{13})$ GeV

→ $m_{\nu 1} \lesssim 10^{-4}$ eV

→ $y_{\nu 1} = O(10^{-9} – 10^{-4})$



- Reheating + Leptogenesis
- Inflation

$$\tilde{y}_1 \equiv \sqrt{(y_\nu y_\nu^\dagger)_{11}}$$
$$m_N = \text{(s)neutrino mass}$$
$$\tilde{m}_1 = \tilde{y}_1^2 \langle v \rangle^2 / m_N$$
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[S. Davidson, A. Ibarra '02]

S.A., Baumann, Domcke, Kostka ('10)

Tribrid Inflation and the η-problem ...

Inflationary epoch in the early universe

- Requirements for “slow roll“ inflation
  - “Slow roll parameters” small: ε, $|\eta|$, ξ << 1, V ~ V_0 dominates

$$\epsilon = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 , \quad \eta = M_P^2 \left(\frac{V''}{V}\right) , \quad \xi = M_P^4 \left(\frac{V' V'''}{V^2}\right)$$

“slope of V” “inflaton mass”

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)

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

  - In supergravity (with K = $\phi^*\phi$ and V_0 from F-term)

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

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

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 the η-problem: 3 strategies in supergravity

- Expansion of K in fields/M_P:

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

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

- 'Shift' symmetry:

$$\boxed{\phi \to \phi + i\alpha}$$

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

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

(used in many works ...)

- ‘Heisenberg’ symmetry:

solves the η-problem for $|\phi|$ by symmetry!

$$\boxed{T \to T + \mathrm{i}\,\beta\,, \;\; T \to T + \alpha^*\phi + |\alpha|^2/2\,, \;\; \phi \to \phi + \alpha}$$

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

T: 'modulus field’ → can be stabilised using V_0

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

Approaches 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 in 'Tribrid inflation'	(yes) S.A. et al ('04)	yes S.A. et al ('09) Postma, Mooij ('10)	yes S.A. et al ('08)
N is the inflaton in 'Chaotic' inflation	X	yes Kawasaki, Yamaguchi, Yanagida ('00), ...	yes S.A. et al ('09)

Note: ... incomplete table!

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

Note: ... incomplete table!

	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 ('10)
N is the inflaton in 'Chaotic' inflation	X	yes Kawasaki, Yamaguchi, Yanagida ('00), ...	yes S.A. et al ('09)	X

Gauge Non-Singlet Inflaton field possible!

Heisenberg symmetry solution to the η-problem

Heisenberg symmetry solution to the η-problem

- Example for K:

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

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

K invariant under Heisenberg symmetry

- Field X: Provides the vacuum energy V_0 by $|F_X|^2$ during inflation
- Consider suitable W with (i) $W_{inf} = 0$, $W_\phi = 0$ during inflation and (ii) which yields a tree-level ϕ-flat potential in global SUSY limit
- 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

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

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

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

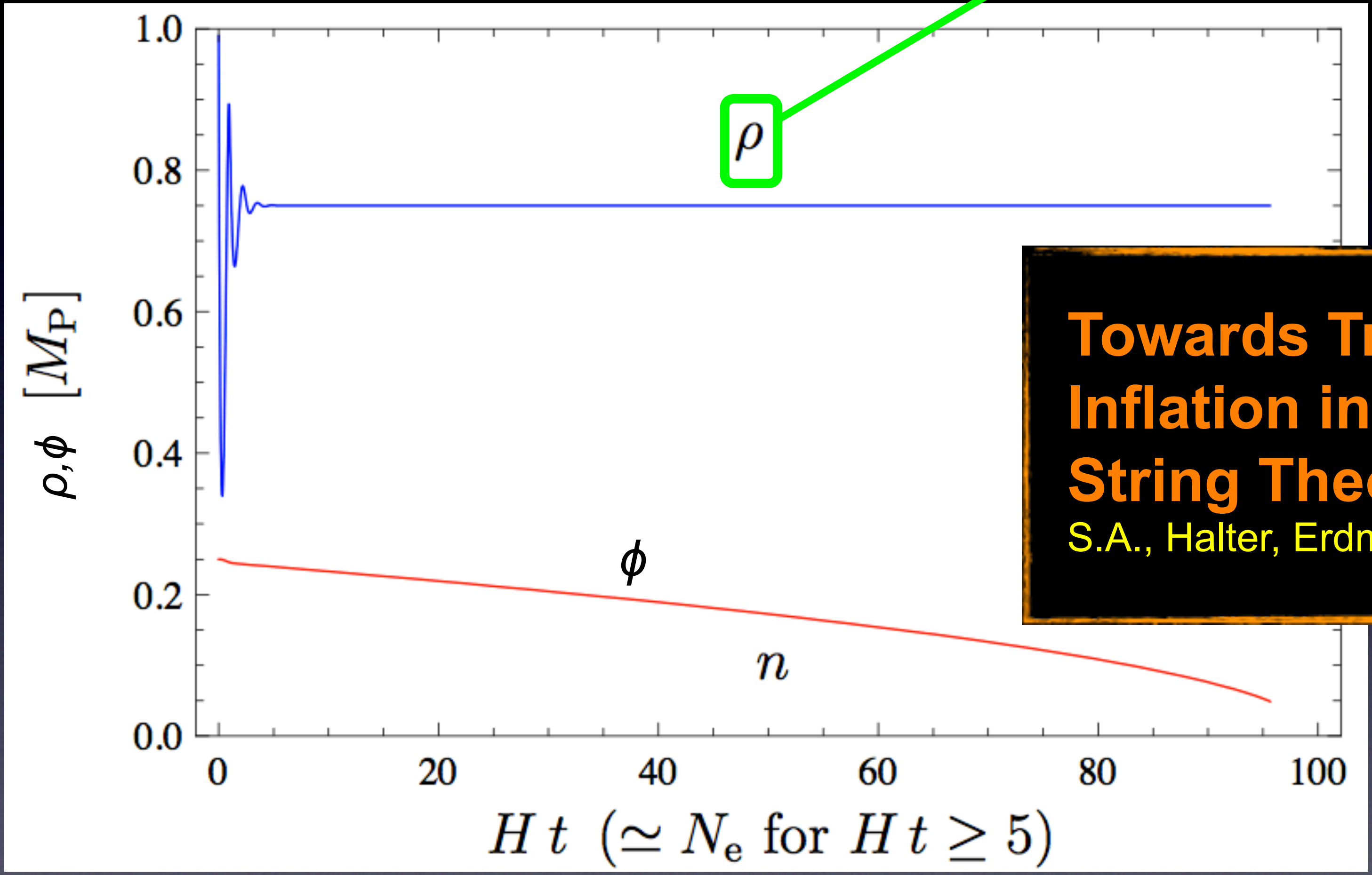
→ no η-problem

→ ρ can be stabilised by large V_0

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

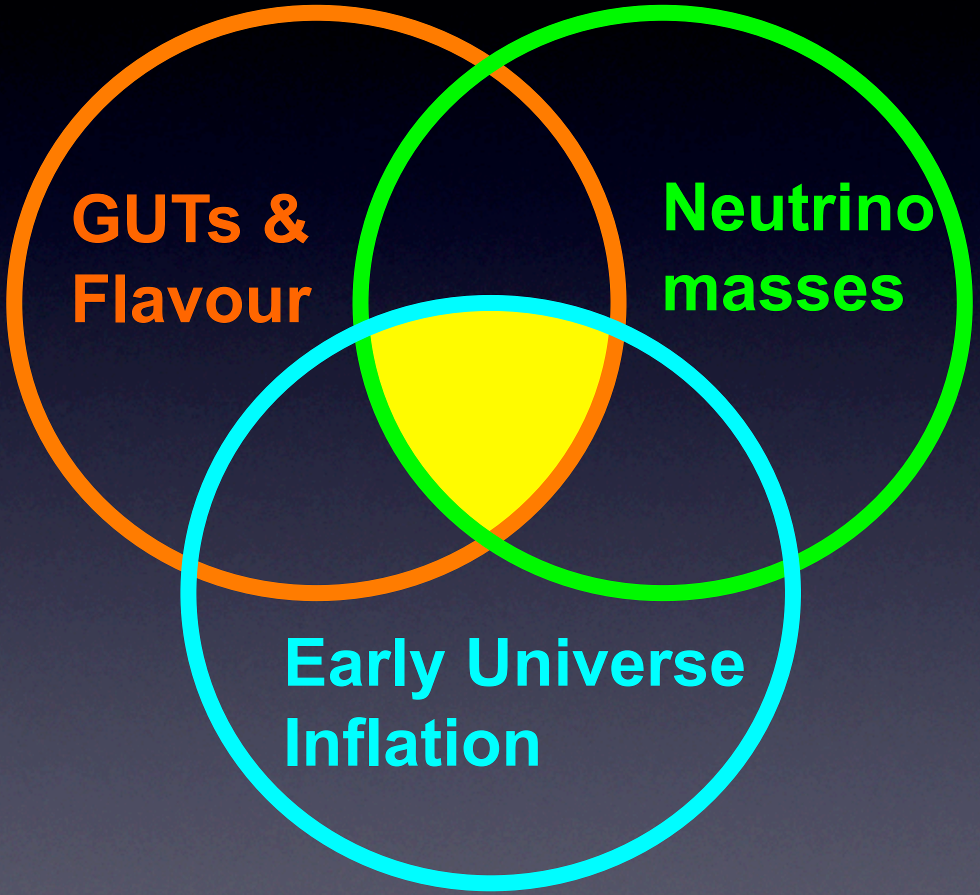
Modulus field ρ gets stabilized quickly and allows for >> 60 e-folds of inflation!

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



Towards Tribrid Inflation in String Theory:
S.A., Halter, Erdmenger ('11)

Summary and conclusions



- Tribrid Inflation is a novel class of models for connecting inflation with particle physics ...
  with various attractive features
- Goal: Inflation as a substantial part of a more fundamental theory of particles & cosmology
- Temperature anisotropies of the CMB are a powerful probe of inflation → PLANCK satellite (First cosmology results: 1/2013)