Matter Inflation

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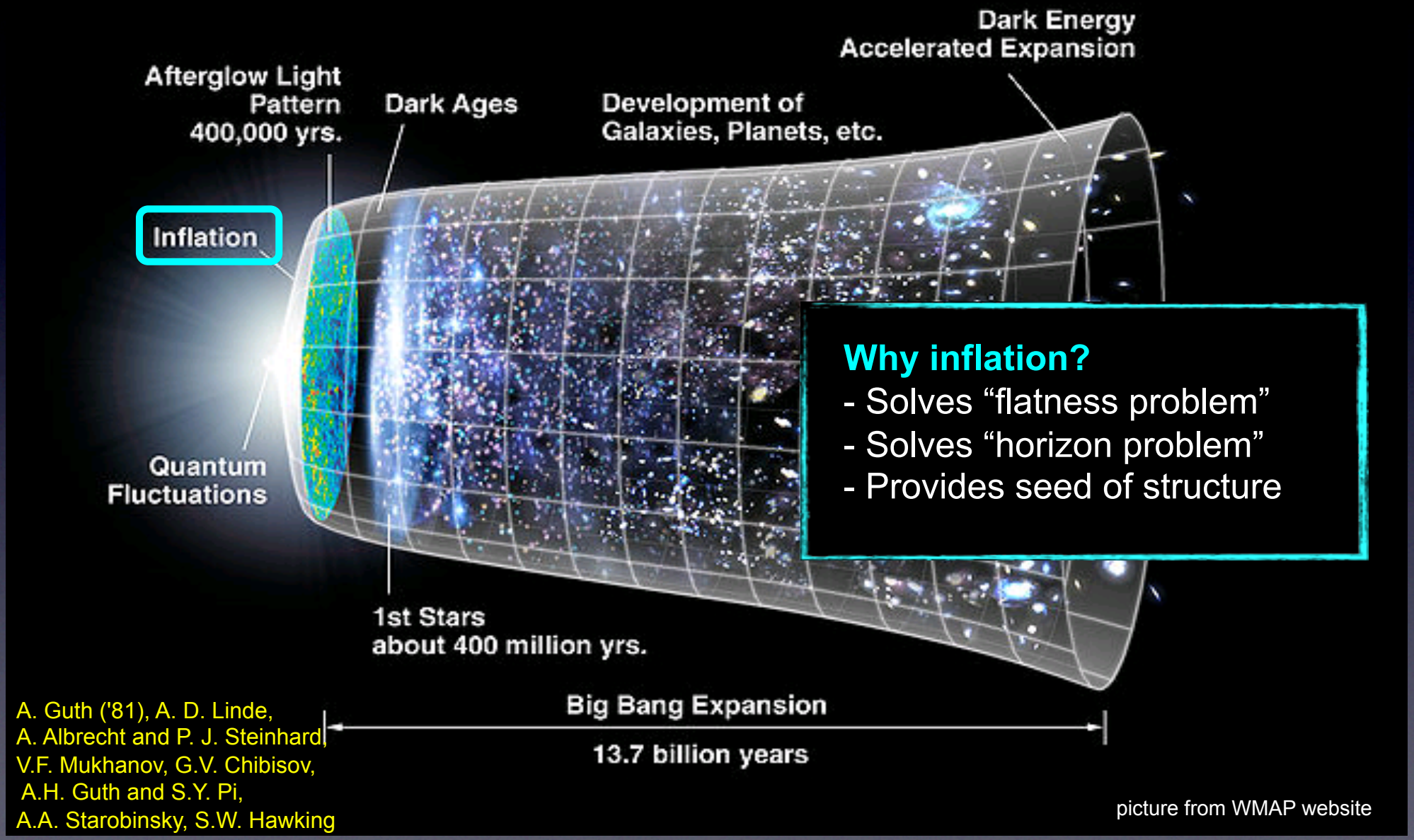
Inflation = Era of accelerated expansion in the very early universe



Why inflation?
- Solves “flatness problem”
- Solves “horizon problem”
- Provides seed of structure

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?

- Simple and attractive 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:

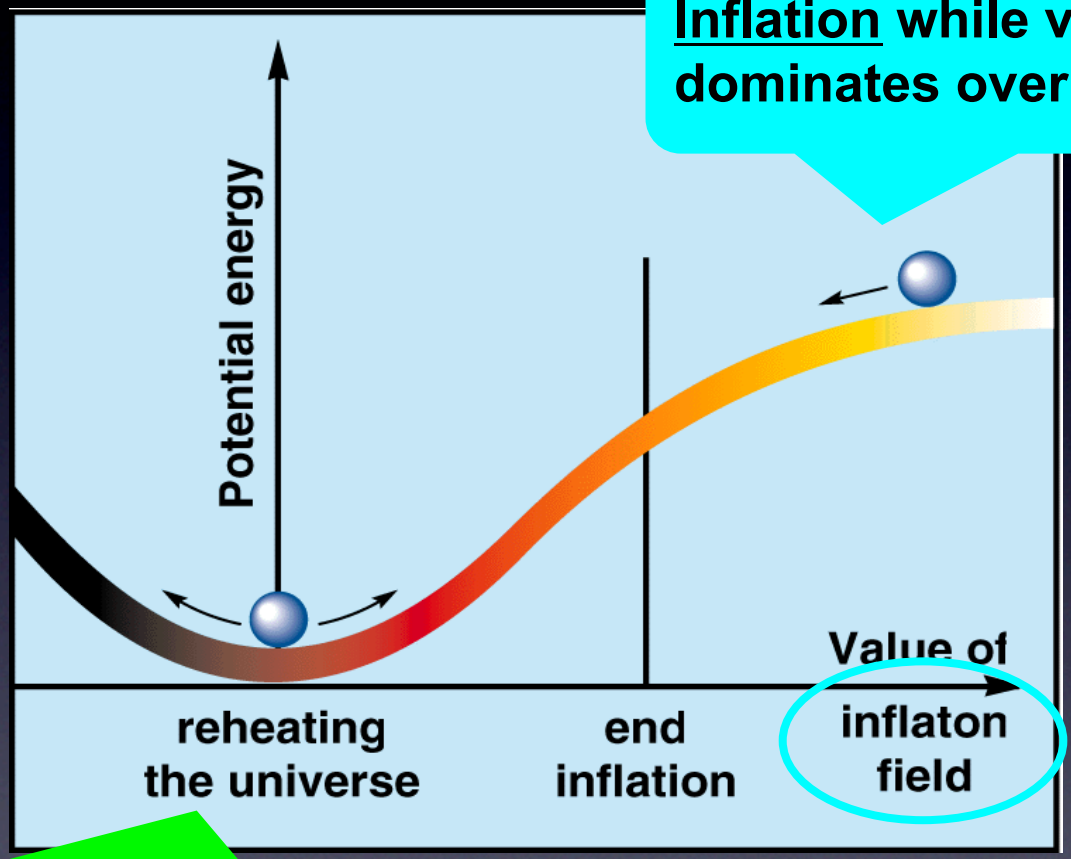
$$\Rightarrow \quad a(t) = \exp\left(\sqrt{\frac{8\pi G_N V(\phi)}{3}}t\right)$$

and the universe “inflates”!

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

Dynamics during and after inflation

Inflation while vacuum energy dominates over kinetic energy



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

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

Two major questions:

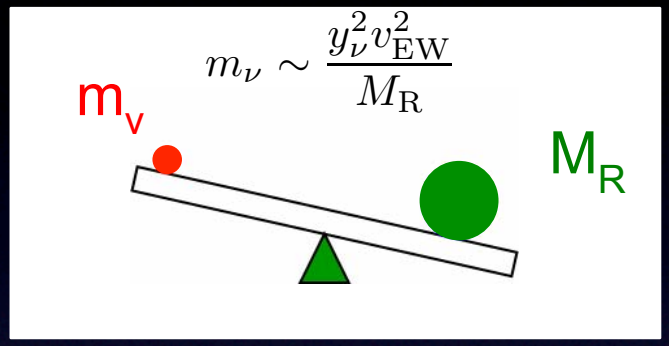
Which particle physics scenario can give rise to successful inflation?

And finally: Who is the inflaton particle?

Matter Inflation (= "Tribrid" Inflation)

A novel framework for realising inflation in the matter sector of SUSY extensions of the SM

One attractive possibility: Seesaw + SUSY →
The RH sneutrino as the inflaton

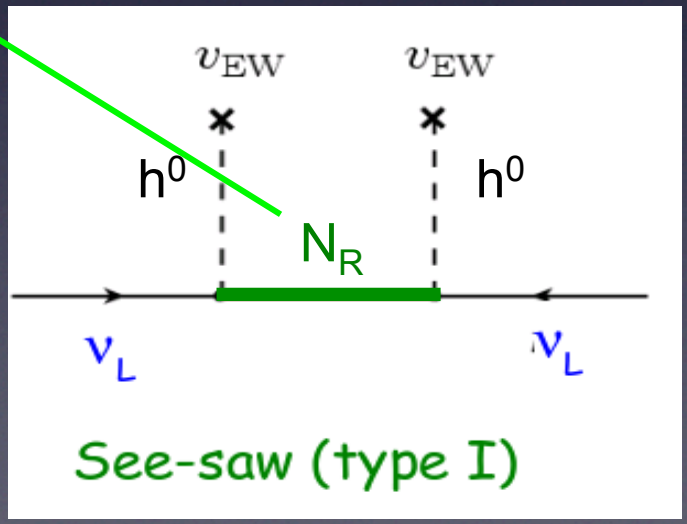


Seesaw mechanism:
P. Minkowski ('77); ...

The right-handed neutrino superfield:

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

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



Framework: local supersymmetry = supergravity

Two possibilities for the origin of the large RH neutrino masses

$\leftrightarrow$

two options for realising inflation with neutrinos

Origin of right-handed neutrino masses

I) Direct mass terms:

$$\mathcal{W}_{M_{\rm R}} = M_{\rm R} \nu_{\rm R} \nu_{\rm R}$$

II) Mass terms from spontaneous symmetry breaking

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

Origin of right-handed neutrino masses

I) Direct mass terms:

$$\mathcal{W}_{M_{\rm R}} = M_{\rm R}\nu_{\rm R}\nu_{\rm R}$$

II) Mass terms from spontaneous symmetry breaking

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

$$\mathcal{W}_{M_{\rm R}} = \frac{\lambda}{M_{\rm Pl}}\nu_{\rm R}\nu_{\rm R}HH$$

For example:

In SO(10) GUTs:

$$\frac{1}{\Lambda}16_i 16_j H_{\overline{16}} H_{\overline{16}}$$

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

$$\frac{1}{\Lambda}\nu_{\rm Ri}\nu_{\rm Rj}\theta^{(i)}\theta^{(j)}$$

Chaotic Sneutrino Inflation

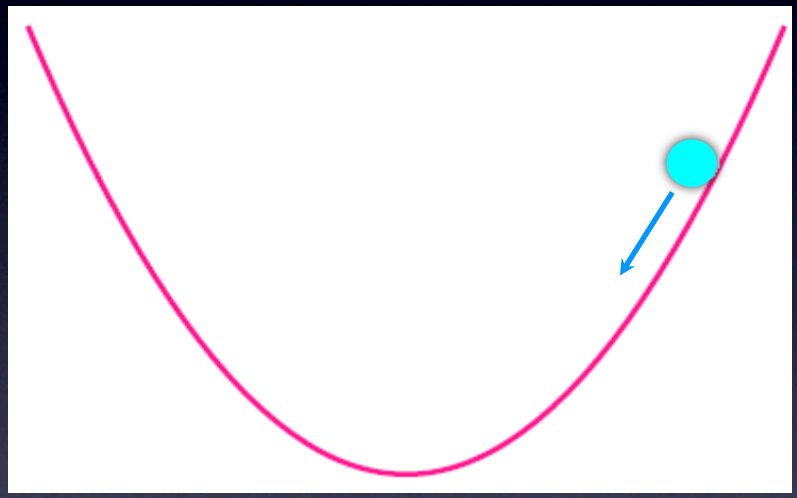
I) Direct mass terms:

Murayama, Suziki, Yanagida, Yokoyama ('93)

$$\mathcal{W}_{M_{\rm R}} = M_{\rm R}\nu_{\rm R}\nu_{\rm R}$$

Inflaton potential from:

$$|F_{\nu_R}|^2 = \left|\frac{\partial W}{\partial \nu_R}\right|_{\theta=0} = |M_R \tilde{N}_R|^2$$



'Large field' (chaotic) sneutrino inflation

Predictions for CMB observables:
$n_s \approx 0.96$, $r \approx 0.16$

Predictions for neutrino physics:
$M_R \sim 10^{13}$ GeV

Note: ν_R has to be a total singlet!

In supergravity:
W + suitable Kähler potential K

Sneutrino Hybrid Inflation

II) Mass term from spontaneous symmetry breaking (SSB)

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

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

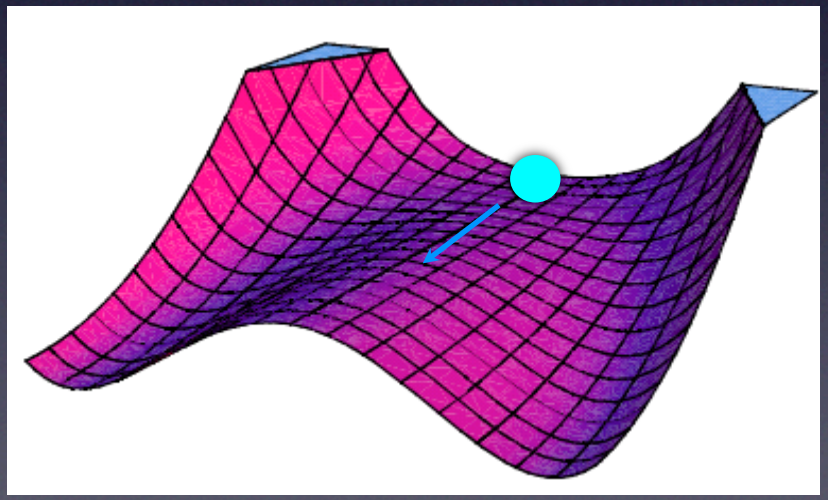
S.A., Baumann, Domcke, Kostka ('10)

i) $\langle \tilde{N}_R \rangle \neq 0$ can stabilise H at $\langle H \rangle = 0$ 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

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

$|F_S|^2 \Rightarrow$

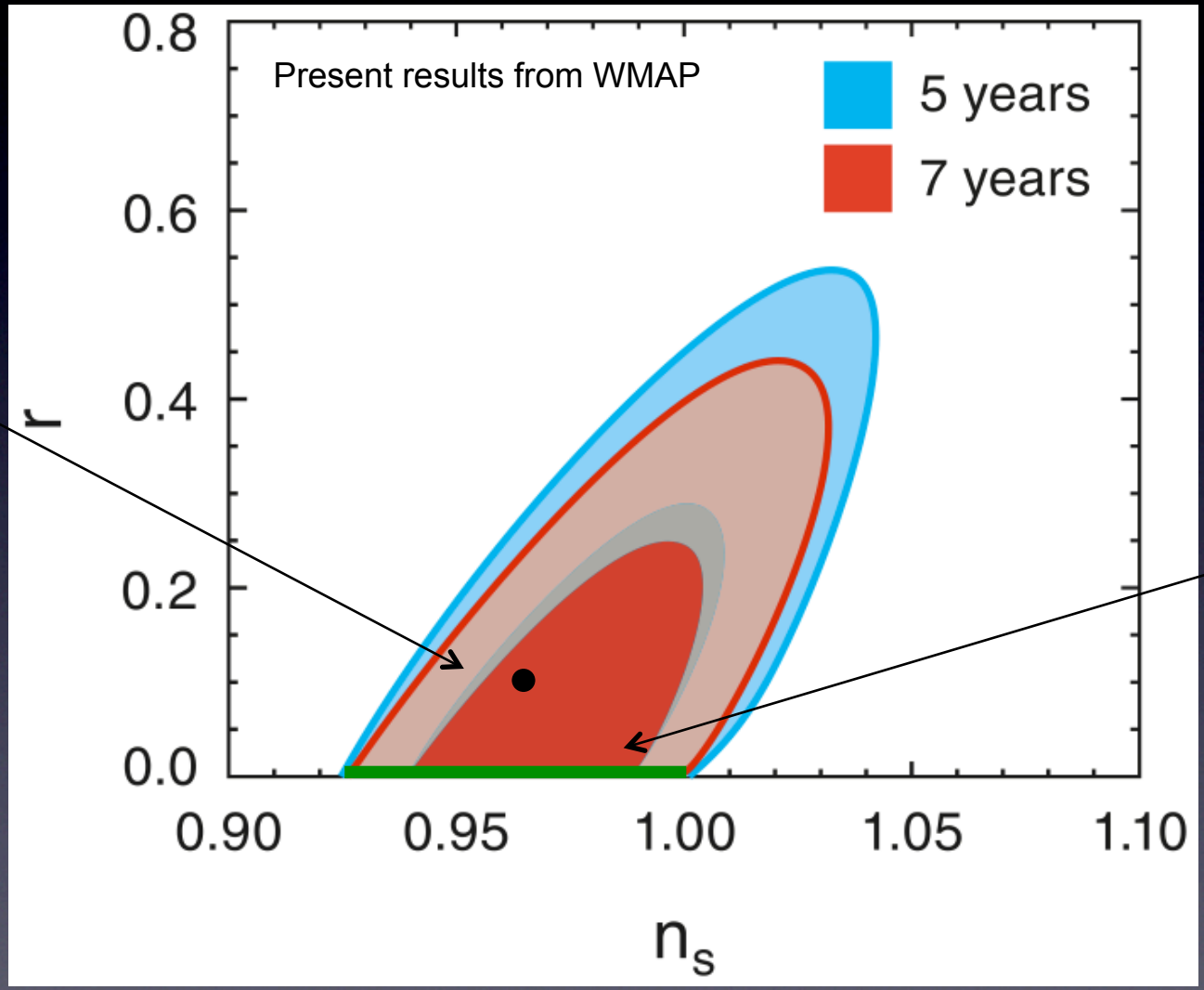


'Hybrid-type' sneutrino inflation

Chaotic ↔ Hybrid models can be well distinguished by the forthcoming CMB observations ...

Prediction of
Chaotic Sneutrino Inflation

Murayama, Suziki, Yanagida, Yokoyama (‘93)



Prediction of
Sneutrino Hybrid Inflation

S.A., Bastero-Gil, King, Shafi (’04)

(WMAP ‘10, WMAP '08)

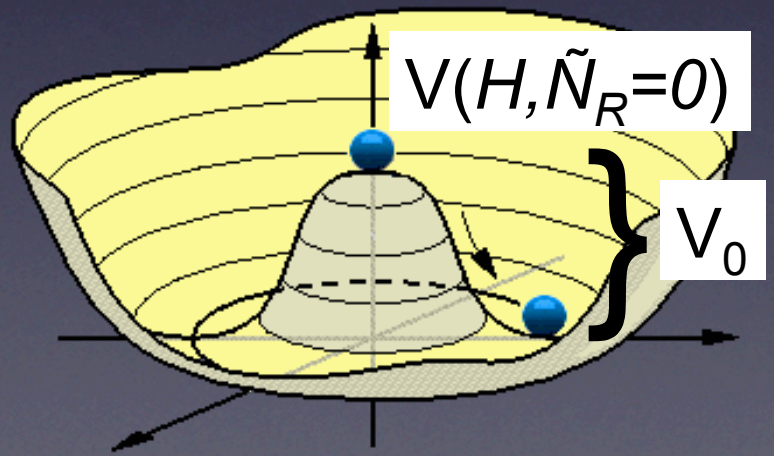
Sneutrino Hybrid Inflation

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

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 2nd order phase transition)

$|F_S|^2 \Rightarrow$



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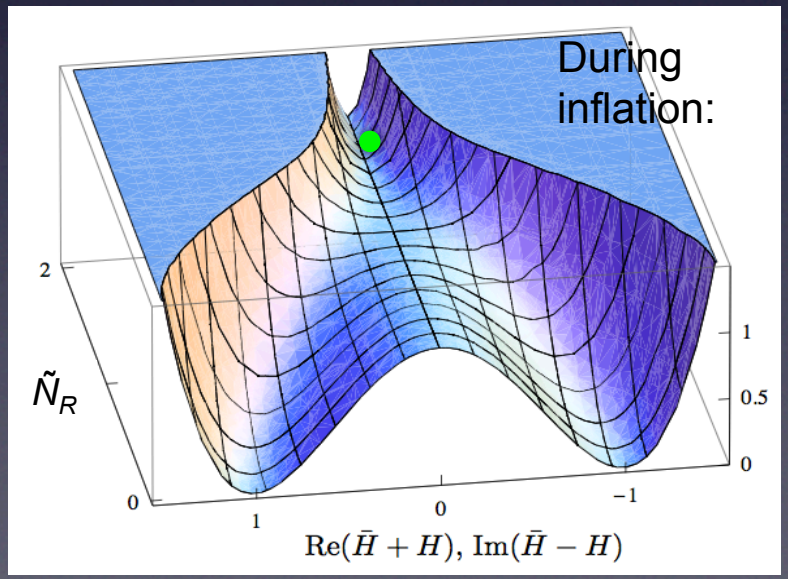
$|F_S|^2 \Rightarrow$

15

<ÑR> > ÑR,crit



Inflaton superfield

(v_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 Hybrid Inflation

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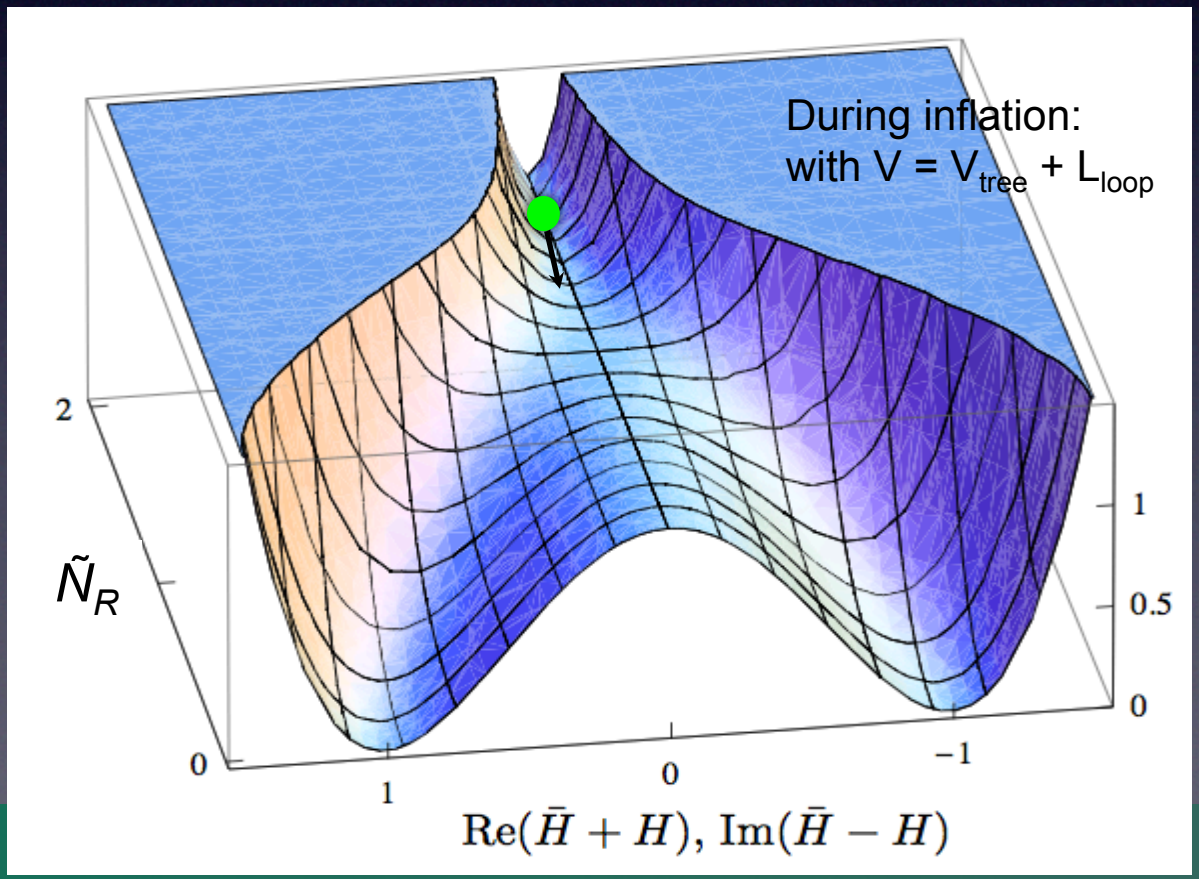

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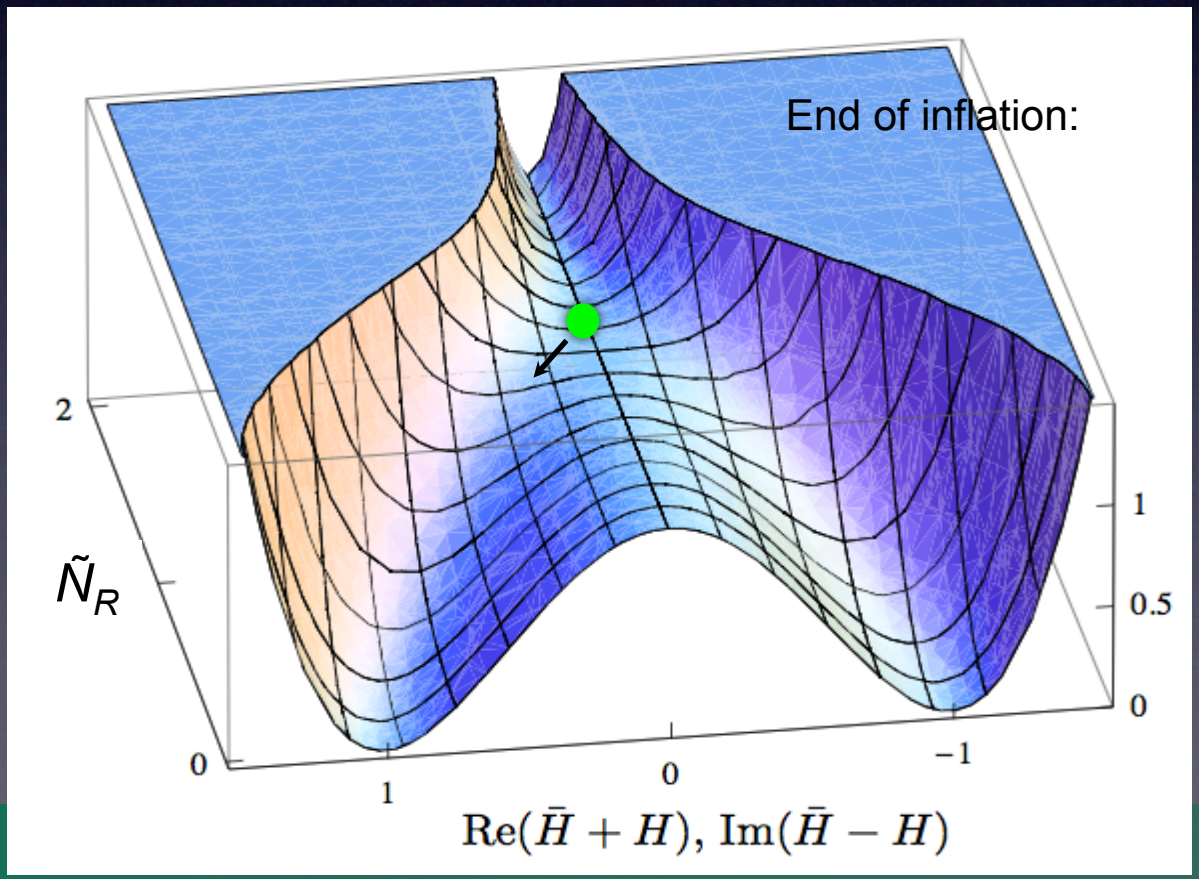

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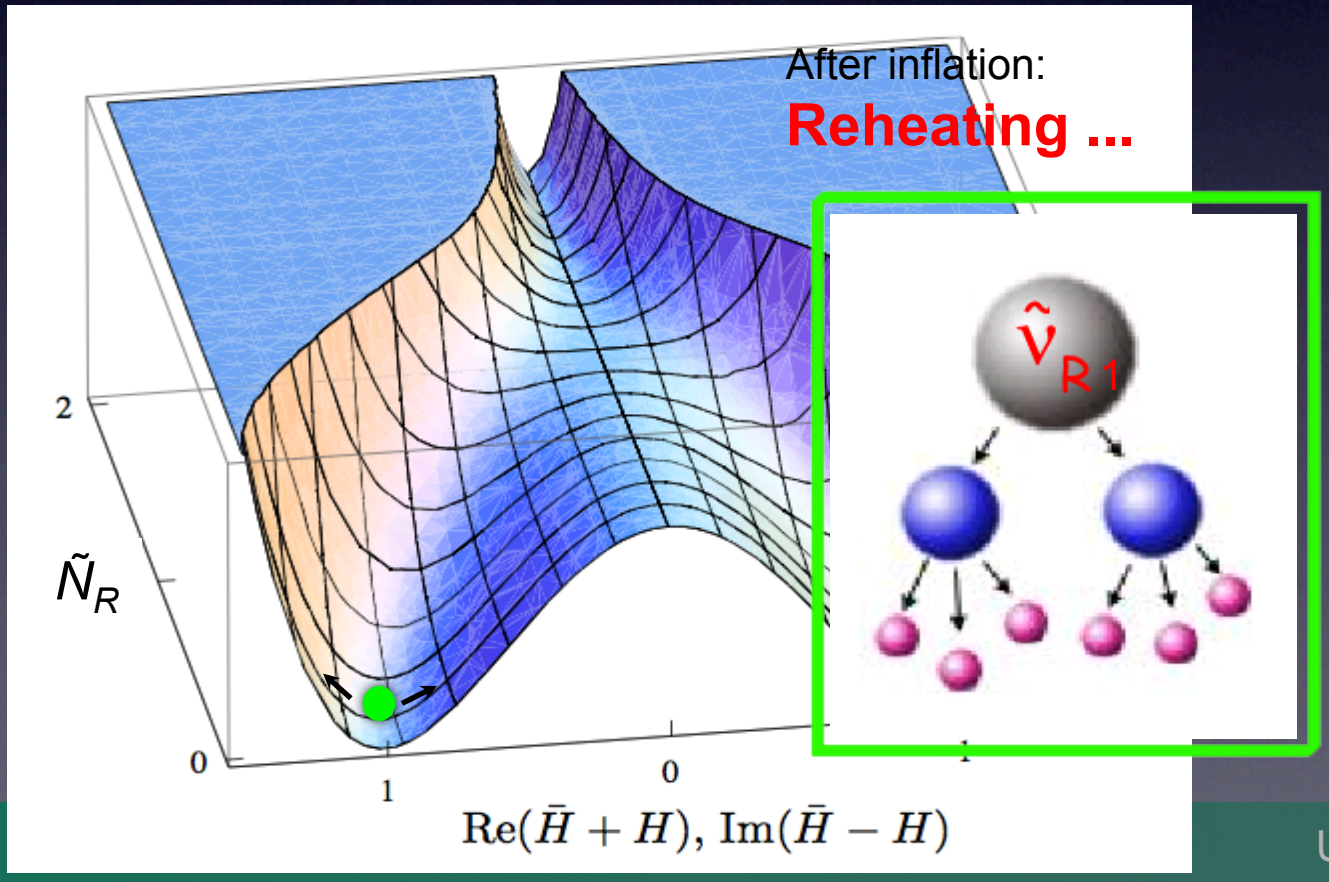
Sneutrino Hybrid Inflation

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

Neutrino Yukawa couplings



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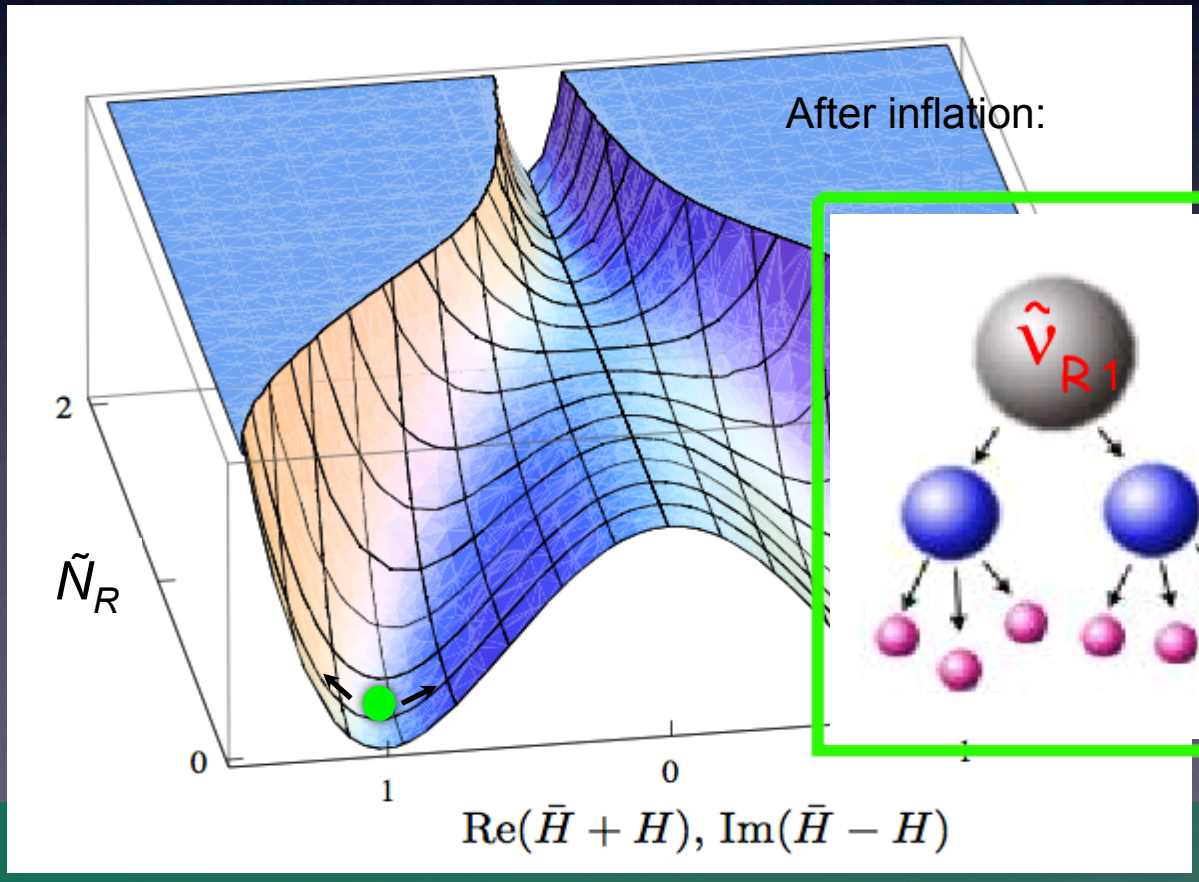
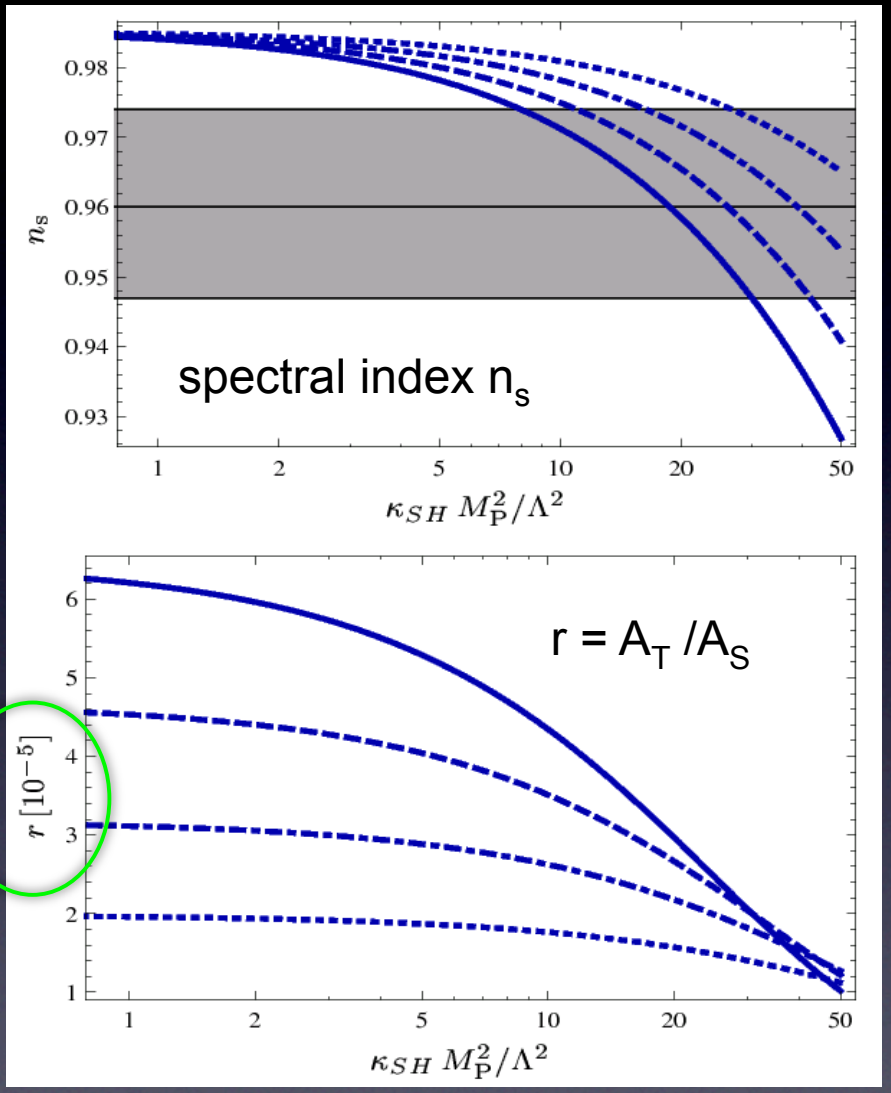


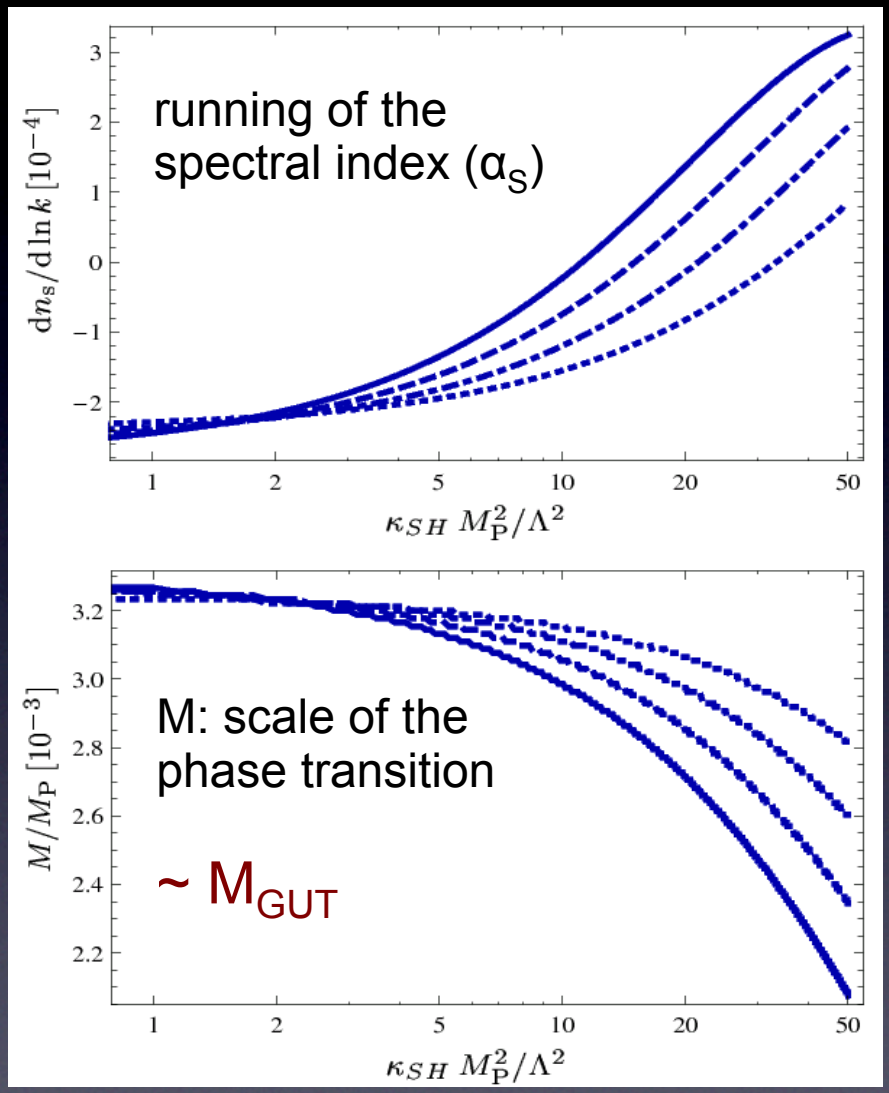
Non-thermal leptogenesis after sneutrino inflation: very efficient way of generating the observed baryon asymmetry!

Recent study:
S.A., Baumann, Domcke, Kostka ('10)

CMB observables



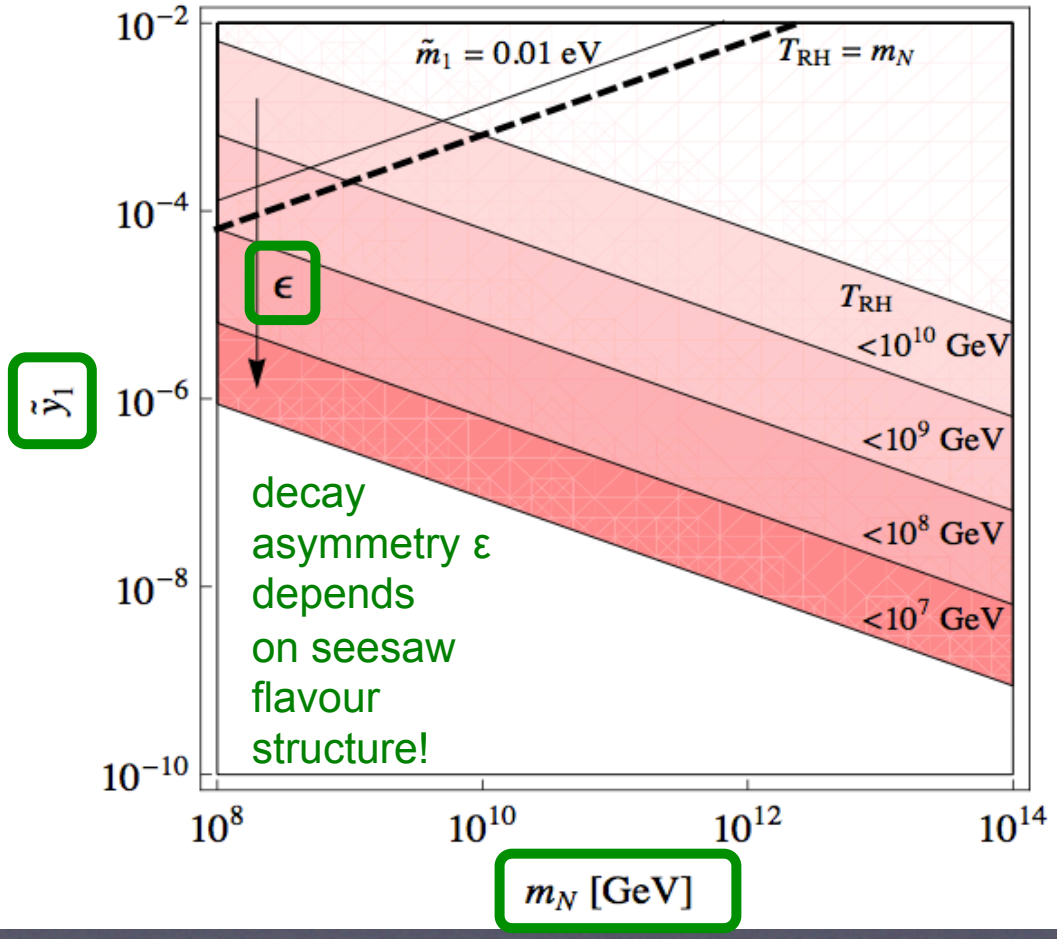
very small
(as typical for Hybrid-type models)



Example: Predictions in a toy model ...

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

Sneutrino hybrid inflation and non-thermal leptogenesis



- Reheating + Leptogenesis

$N_1 \leftrightarrow$ inflaton

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

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

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

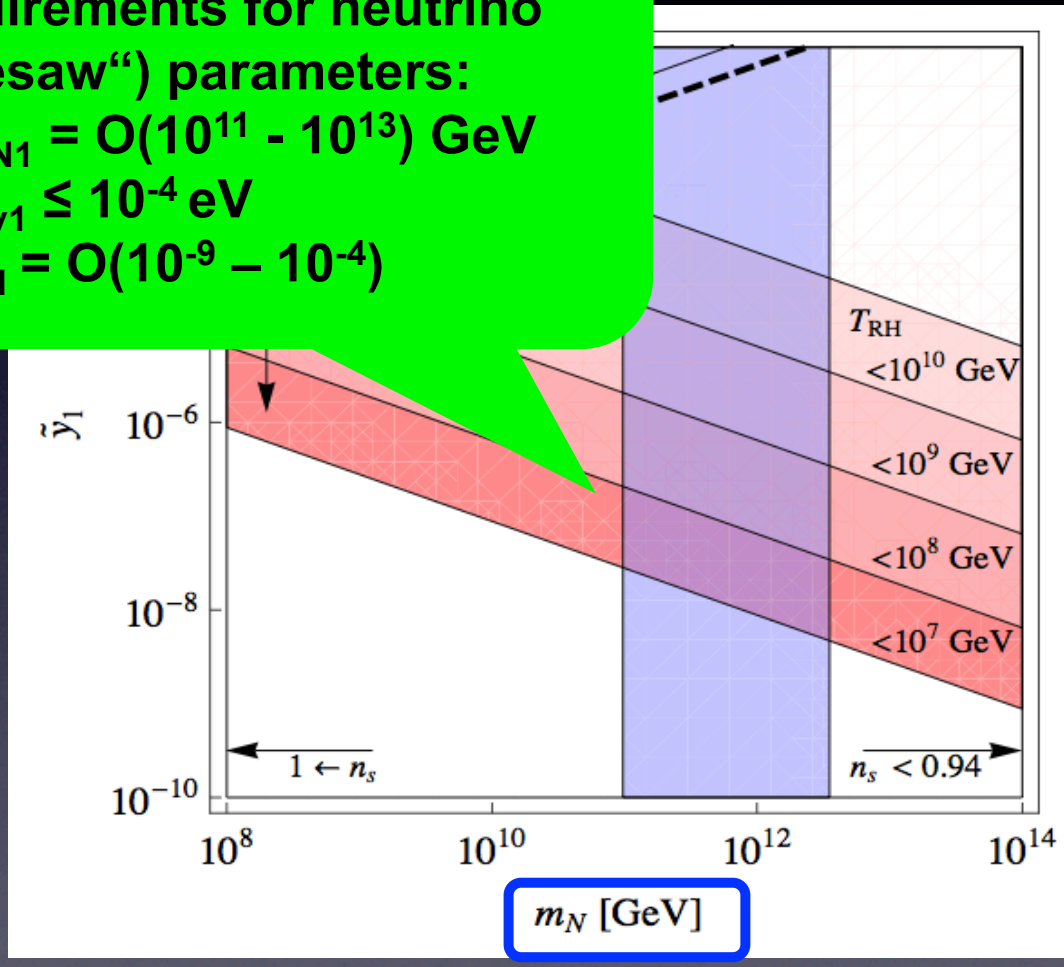
$$\epsilon < \frac{3}{8\pi} \frac{\sqrt{\Delta m^2_{\text{atm}}}\, m_N}{\langle v \rangle^2}$$

[S. Davidson, A. Ibarra '02]

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

Sneutrino hybrid inflation and non-thermal leptogenesis

Requirements for neutrino ("seesaw") parameters:
→ m_{N1} = O(10^{11} - 10^{13}) GeV
→ $m_{\nu 1} \leq 10^{-4}$ eV
→ $y_{\nu 1}$ = O(10^{-9} – 10^{-4})



- Reheating + Leptogenesis
- Inflation

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[S. Davidson, A. Ibarra '02]

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

Sneutrino Hybrid Inflation belongs to a more general class of models: Matter Inflation

$$\mathcal{W} = \kappa S(f(H) - M^2) + g(\phi, H)$$

Driving superfield

Waterfall superfield

Inflaton superfield (resides in the matter sector)

- Also referred to as "Tribrid" inflation, because three fields play a certain role in the superpotential of the models …

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

Further developments & possibilities in Matter Inflation

- Inflaton does not have to be a gauge singlet. It can also be a gauge non-singlet (e.g. a D-flat direction of GUT representations)

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

- The (2^{nd} order) phase transition at the end of inflation can be …
  - ✓ ... a GUT phase transition

    Dvali, Shafi, Schaefer ('94)
  - ✓ ... the breaking of a family symmetry (e.g. A_4, …)

    S. A., King, Malinsky, Velasco-Sevilla, Zavala ('07)

- Possibilites for realising Matter Inflation in Heterotic String Theory ...

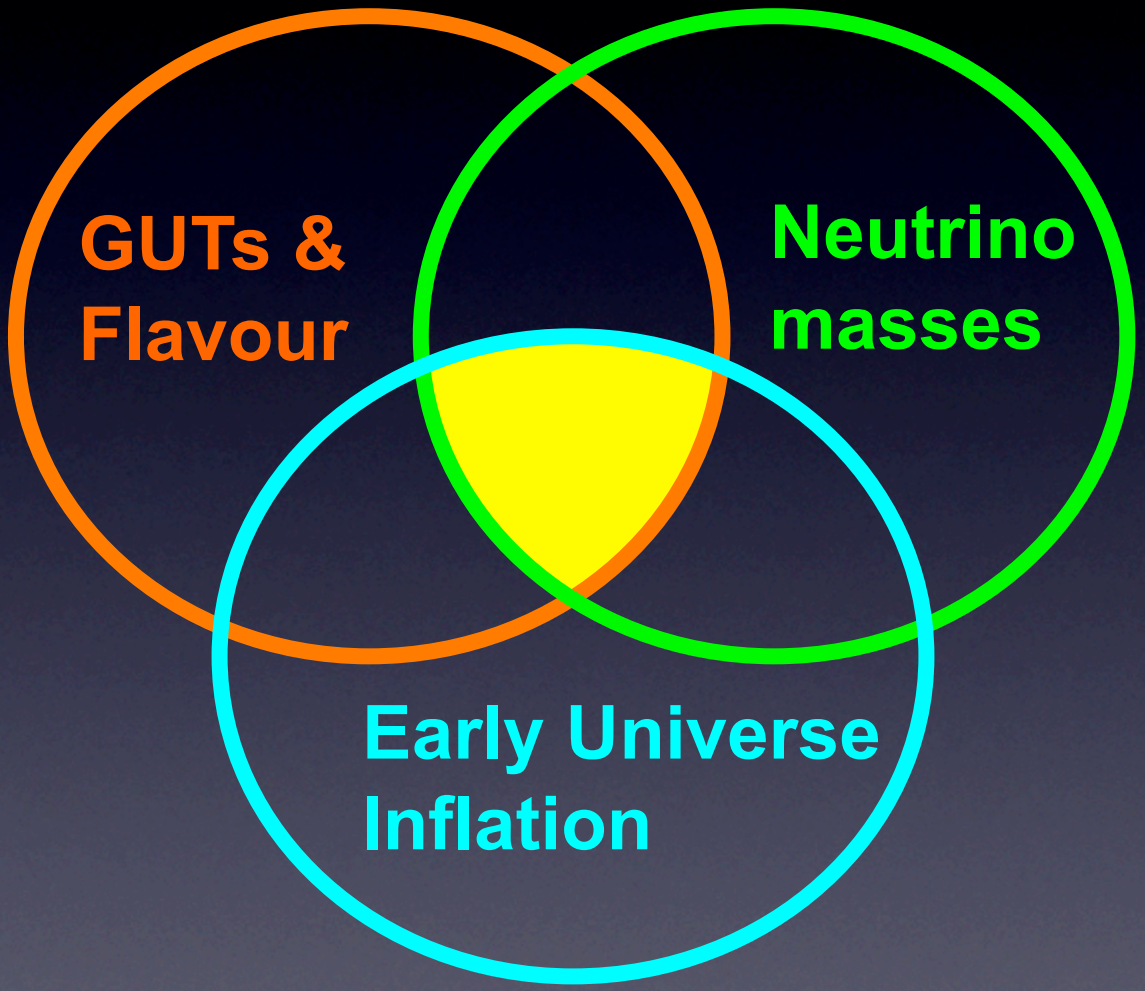
  S. A., Halter, Erdmenger ('11)

Further developments & possibilities in Matter Inflation

- No monopoles are generated at the end of inflation ...
  - ✓ ... if the inflaton is a gauge non-singlet (→ group broken during inflation) S.A., Bastero-Gil, Baumann, Dutta, King, Kostka (‘10)
  - ✓ ... if a family symmetry is broken at the end of inflation (as in “flavon inflation”) S. A., King, Malinsky, Velasco-Sevilla, Zavala (‘07)
  - ✓ ... in “pseudosmooth” versions of tribrid inflation S.A., Nolde, Ur Rehman (‘12)

- ✓ The η-problem (→ “flatness problem” of the inflaton potential) can be solved in SUGRA by symmetry (e.g. by a Heisenberg or shift symmetry in the Kähler potential) S.A., M. Bastero-Gil, K. Dutta, S. F. King, P. M. Kostka (‘08) S.A., K. Dutta, P. M. Kostka ('09)

Summary and conclusions



- The RH sneutrino is an attractive candidate for the Inflation: Chaotic vs Hybrid-like (= "Tribrid")
- In Sneutrino "Tribrid" Inflation: The end of inflation can be associated with GUT or family symmetry breaking
- Sneutrino "Tribrid" Inflation belongs to a novel class of inflation models where the inflaton resides in the matter sector (→ Matter Inflation)