Particle physics models of inflation and reheating

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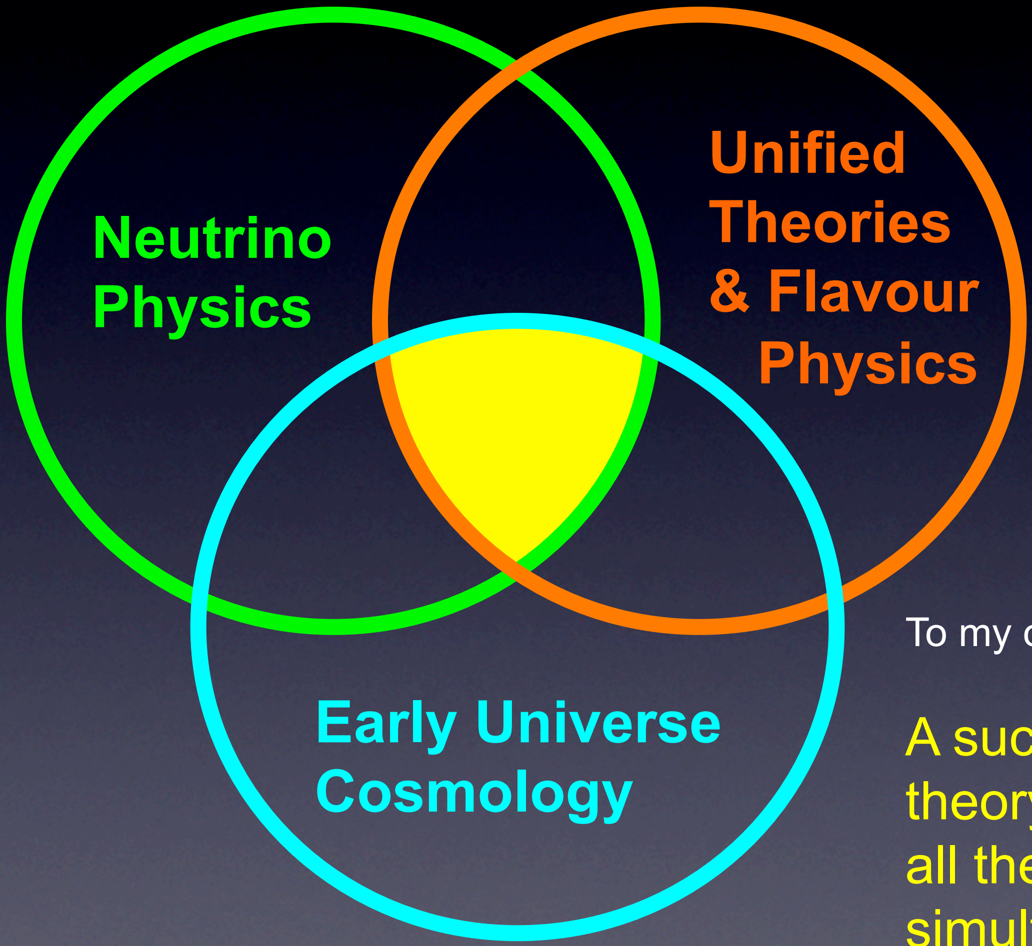
Goal: More fundamental model of particle physics & cosmology

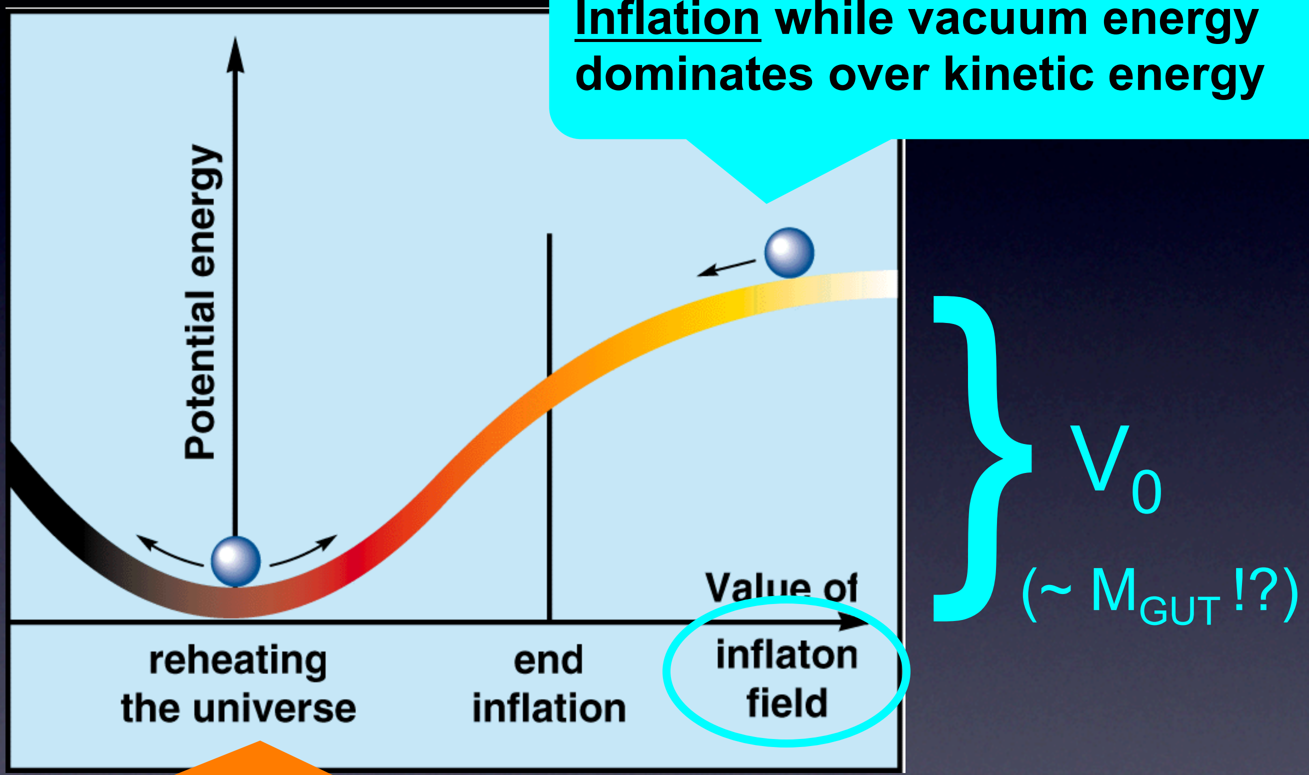


To my opinion:

A successful particle theory has to master all these challenges simultaneously!

Dynamics during and after inflation

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



<u>Reheating/Preheating</u>: Inflaton transfers energy to other fields → matter & antimatter, and possibly their asymmetry get produced!

Outline

- Some classes of particle physics models of inflation in supergravity
  - Hybrid-like models ("tribrid-inflation")
  - Hilltop-like ("plateau") inflation

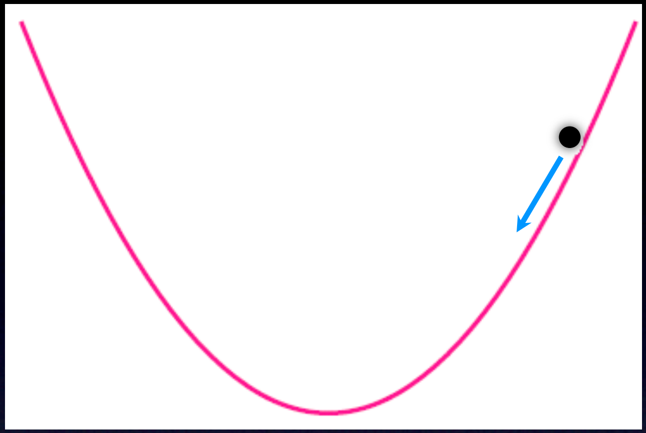
- Briefly: Solutions to the η-problem

- Particle physics connections I: Tribrid inflation and flavour models (Examples: RH sneutrino or LH_u flat direction as inflaton)

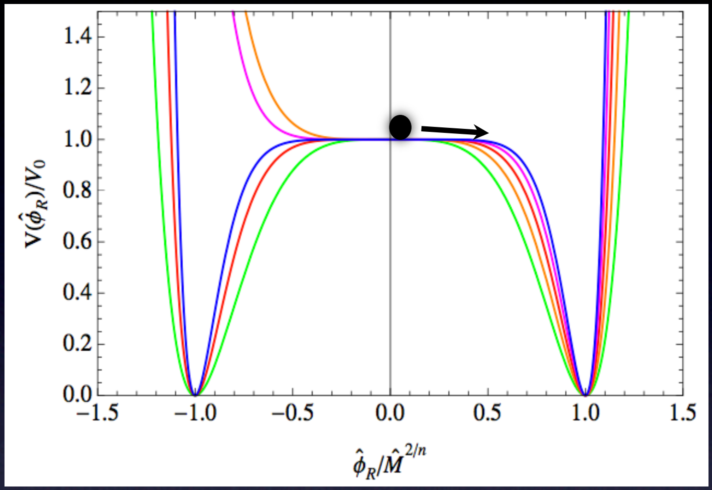
- Particle physics connections II: Hilltop inflation & flavour models ("flavon inflation")

- (P)reheating after hilltop inflation

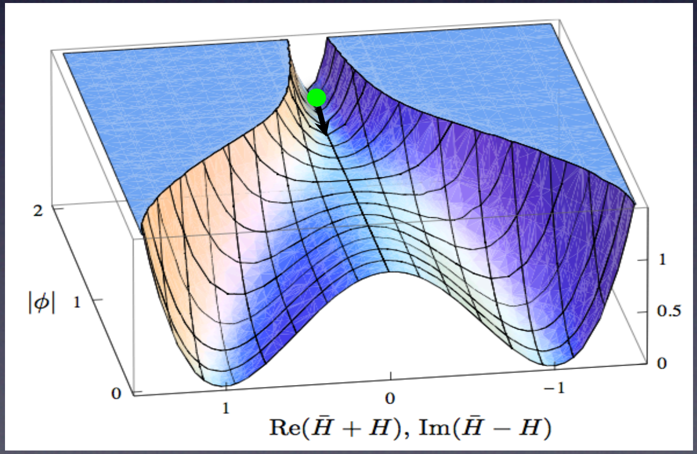
Basic types of inflation models



'Large field' (chaotic) inflation

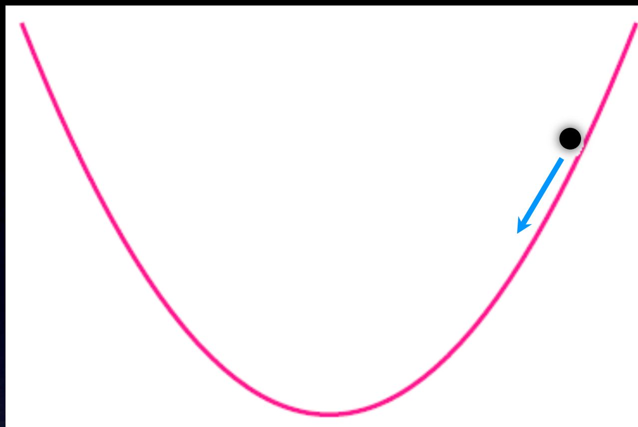


'Small field' hilltop inflation

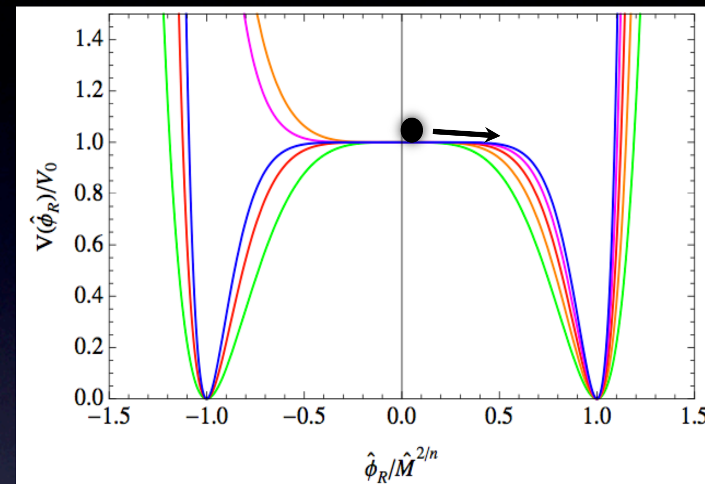


'Hybrid-type' inflation models

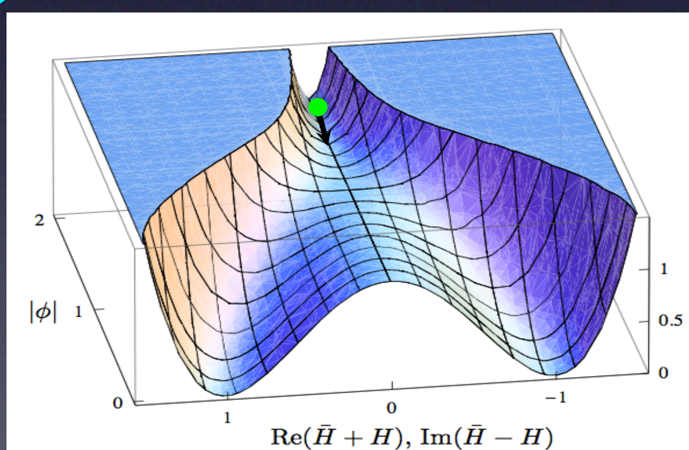
Basic types of inflation models



'Large field' (chaotic) inflation



'Small field' hilltop inflation



'Hybrid-type' inflation models

Possible connections to a (2nd order particle physics phase transitions at very high energies (~ M_{GUT})

Some classes of particle physics models of inflation in supergravity

Particle physics models of inflation in supergravity

Note: I can cover here of course only a subset of model building possibilities!

- ... to illustrate possible connections to particle physics, let us look at the following example for a typical superpotential:

Schematically:

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

phase transition: $\langle H\rangle=0 \rightarrow \langle H\rangle^n=M^2$

Remark: Less simple potentials in practice! (using: Planck units)

Particle physics models of inflation in supergravity

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Remark: Less simple potentials in practice! (using: Planck units)

phase transition:
<H>=0 → $\langle H\rangle^n = M^2$

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

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

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

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

Particle physics models of inflation in supergravity

- In principle, any of the three types of fields can be the inflaton …
  → different links to particle physics …

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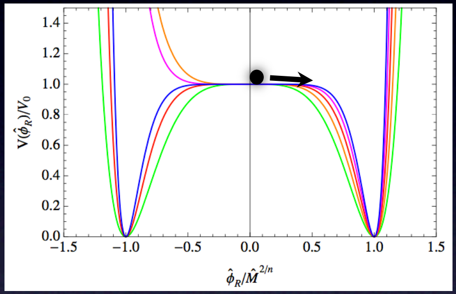


$$W = S\,(H^n - M^2) + f(N,H))$$

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

'Small field hilltop'-type model

E.g.: Linde ('82), Izawa, Yanagida ('96), …
In Sugra: Senoguz, Shafi ('04), …

(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

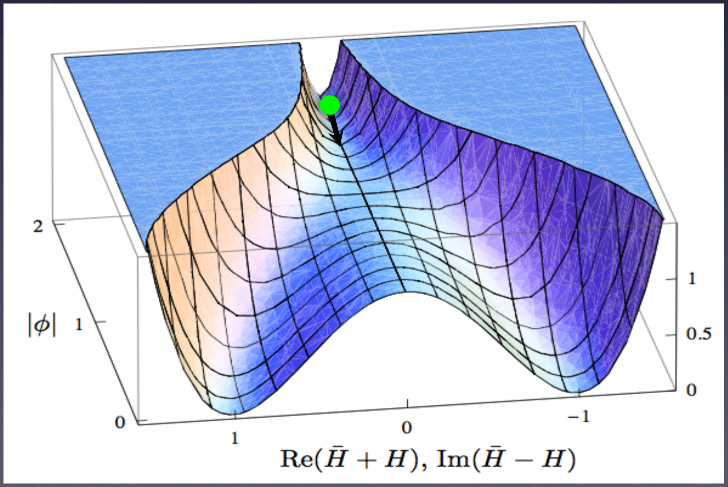
- In principle, any of the three types of fields can be the inflaton
  → different links to particle physics …

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

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

'Standard' SUSY Hybrid Inflation model

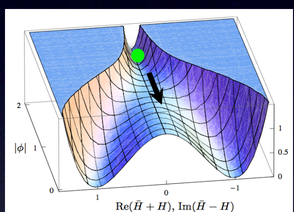
Copeland et al ('94); Dvali, Shafi, Schaefer ('94), Linde, Riotto ('97)



(H = 'waterfall field' for ending inflation)

Particle physics models of inflation in supergravity

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



During inflation: S = 0, H = 0

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

Example: $f(N,H) = N^2\,H^2$

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

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

Attractive candidate for N:

- **right-handed sneutrino = superpartner of ν_R from the seesaw mechanism** S.A., Bastero-Gil, King, Shafi ('04)
- **D-flat direction in GUTs** S.A., Baumann, Bastero-Gil, Dutta, King, Kostka, Shafi ('10)
- **Phase transition (GUT, flavour, ...) can give large mass to N after inflation**

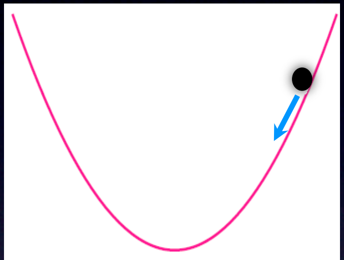
Variant of 'Hybrid Inflation'
→ 'Tribrid Inflation'

S.A., Bastero-Gil, King, Shafi ('04); S.A., Dutta, Kostka ('09)

(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
  → different links to particle physics …



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

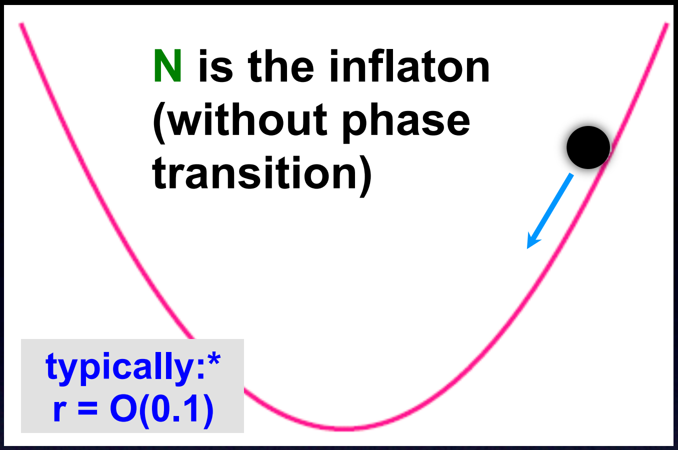
N: Matter field
ii) direct mass from W

'Large field (chaotic)'-type of inflation model *Linde ('83)*

Attractive candidate for N:

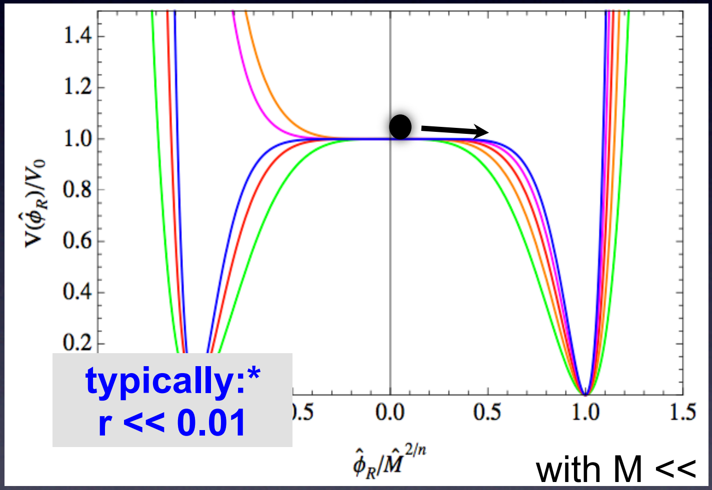
- **right-handed sneutrino = superpartner of ν_R from the seesaw mechanism**
  Murayama, Suzuki, Yanagida, Yokoyama ('93)
  Ellis, Raidal, Yanagida ('04)
- **for a simple superpotential $W = m_N N^2$, $m_N \sim 10^{13}$ GeV would be in the right range for seesaw and for inflation!**

Classes of models ↔ Tensor perturbations

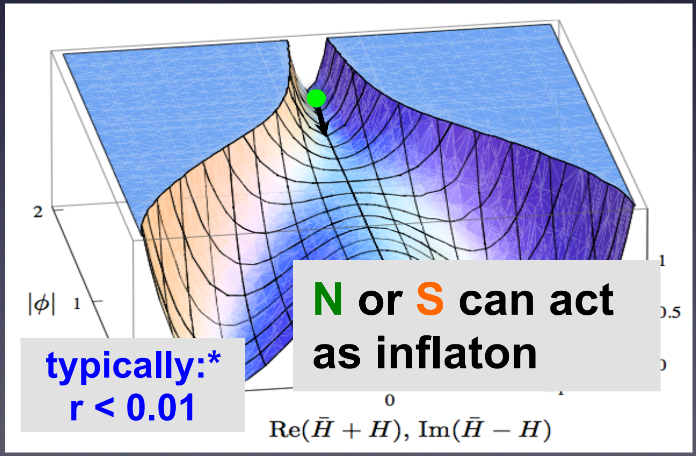


'Large field' (chaotic) inflation

H is the inflaton



'Small field' hilltop inflation



'Hybrid-type' inflation models

Solutions to the “η-problem”?

Approaches to solve the η-problem: 3 strategies in supergravity

- Expansion of K in fields/M_P:

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

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

- 'Shift' symmetry:

$$\phi \to \phi + i\alpha$$

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

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

used in many works, e.g.:
Kawasaki, Yamaguchi, Yanagida ('00), … ;
without SUGRA: Freese, Frieman Olinto ('90), …

- 'Heisenberg' symmetry:

can solve the η-problem for |ϕ| by symmetry!

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

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

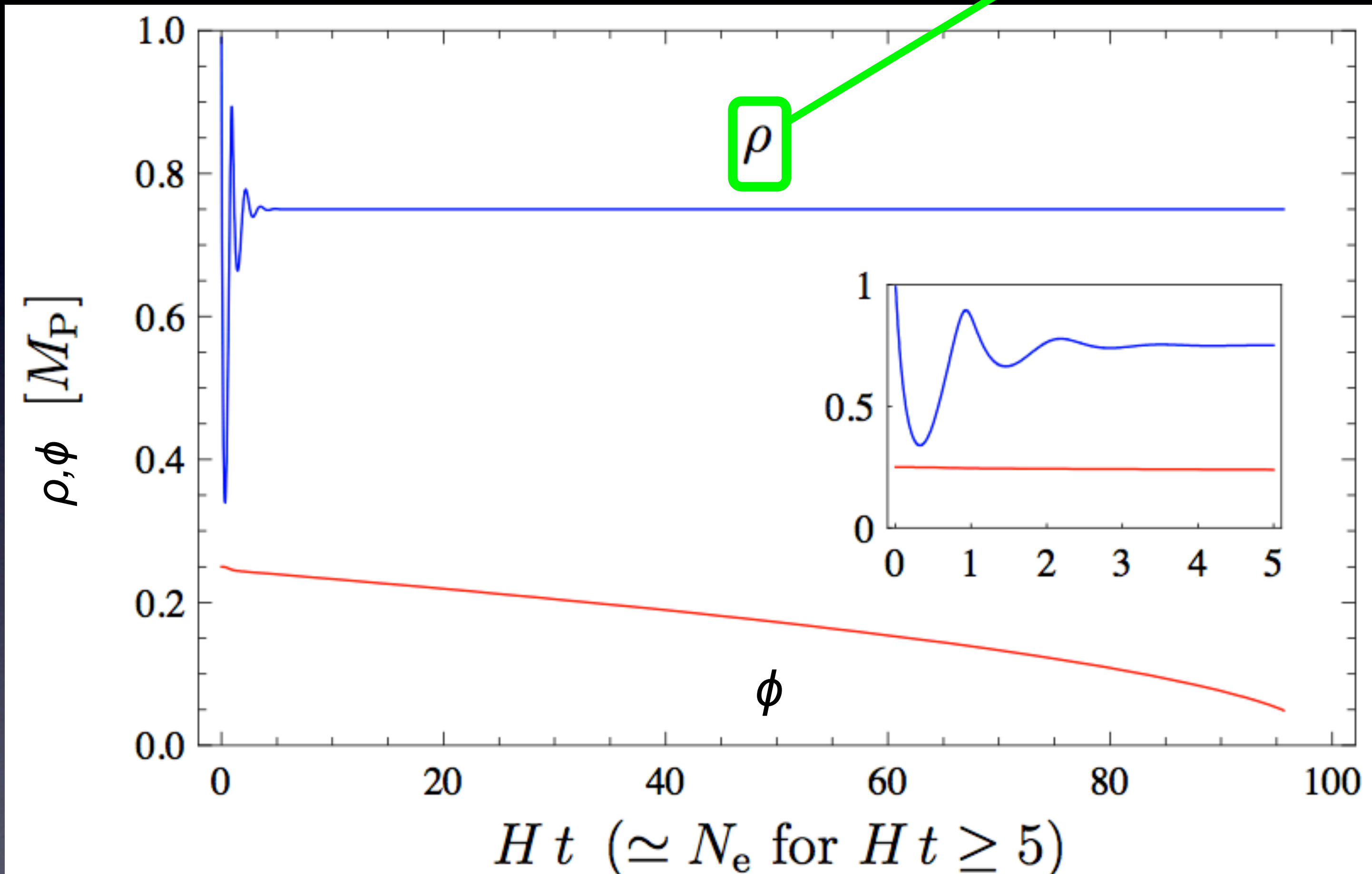
T: 'modulus field' → has to be stabilised

Gaillard, Murayama, Olive ('95),
S.A., Bastero-Gil, Dutta, King, Kostka ('08,'09)
S.A., Dutta, Erdmenger, Halter ('11),
S.A., Cefala, ('13)

The modulus field can get successfully stabilized …

The field combination ρ (which contains T) can get stabilized quickly with the help of the large V_0. The universe inflates for >> 60 e-folds.

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



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

Extra stabilisation during inflation: S.A., K. Dutta, S. Halter ('11)

Solutions to the η-problem in classes of models

Note: ... incomplete table!

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

**) not very useful, would require singlet inflaton (cannot break anysymmetry)

	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 ('Hilltop inflation')	(yes) Shafi, Senoguz ('04)	X**	yes S.A., Cefala ('13)
N is the inflaton in 'Tribrid inflation'	(yes) S.A. Bastero-Gil, King, Shafi ('04)	yes S.A., Dutta, Kostka ('09) Postma, Mooij ('10)	yes S.A., Dutta, Bastero-Gil, King, Kostka ('08)
N is the inflaton in 'Chaotic' inflation	X	yes Kawasaki, Yamaguchi, Yanagida ('00), ...	yes S.A., Dutta, Bastero-Gil, King, Kostka ('09)

Example for connection to particle physics:

Tribrid inflation in flavour models

S. A., D. Nolde (arXiv:1306.3501)

Typical situation in flavour models ...

- Flavour structure generated by VEVs of flavons Θ_i, e.g. (in SUSY):
(in natural units where M_{pl} = 1)

$$W_m = \lambda_i \Theta_i \cdot L H_u N_i \qquad W_m = \gamma_i N_i^2 \Theta_i^2$$

Flavons

- Flavon VEVs break a family symmetry G_F in certain directions, e.g.:

$$\langle \Theta_1 \rangle = c_1 \begin{pmatrix} 0 \\ 1 \\ \pm 1 \end{pmatrix} \qquad \langle \Theta_2 \rangle = c_2 \begin{pmatrix} \pm 1 \\ \pm 1 \\ 1 \end{pmatrix}$$

Typical situation in flavour models ...

- Flavon VEVs (in SUSY) from superpotentials of the form:

$$W_{\text{fl}} = S_i \left([\Theta_i]^{\ell_i} - \mu_i^2 \right) + \ldots$$

combination of flavons invariant under family symmetry group G_F

Combining W_m and W_{fl} we obtain superpotentials which are suitable for realising inflation in close connection to particle physics' (e.g. via 'tribrid inflation')

→ $\Theta_i = 0 \Rightarrow$ large vacuum energy $O(\mu_i^4)$

Examples: Matter inflation in flavour models

- Example 1: Inflation along L H_u – direction: Connection to neutrino Yukawa coupling

$$W_{\text{inf}} = S_i\left([\Theta_i]^{\ell_i} - \mu_i^2\right) + \lambda_i \Theta_i \cdot \underbrace{LH_u}_{\equiv \Phi^2} N_i + \ldots$$

$$y_\phi = \lambda_i \frac{\langle \Theta_i \rangle}{M_{\text{Pl}}}$$

Neutrino Yukawa coupling

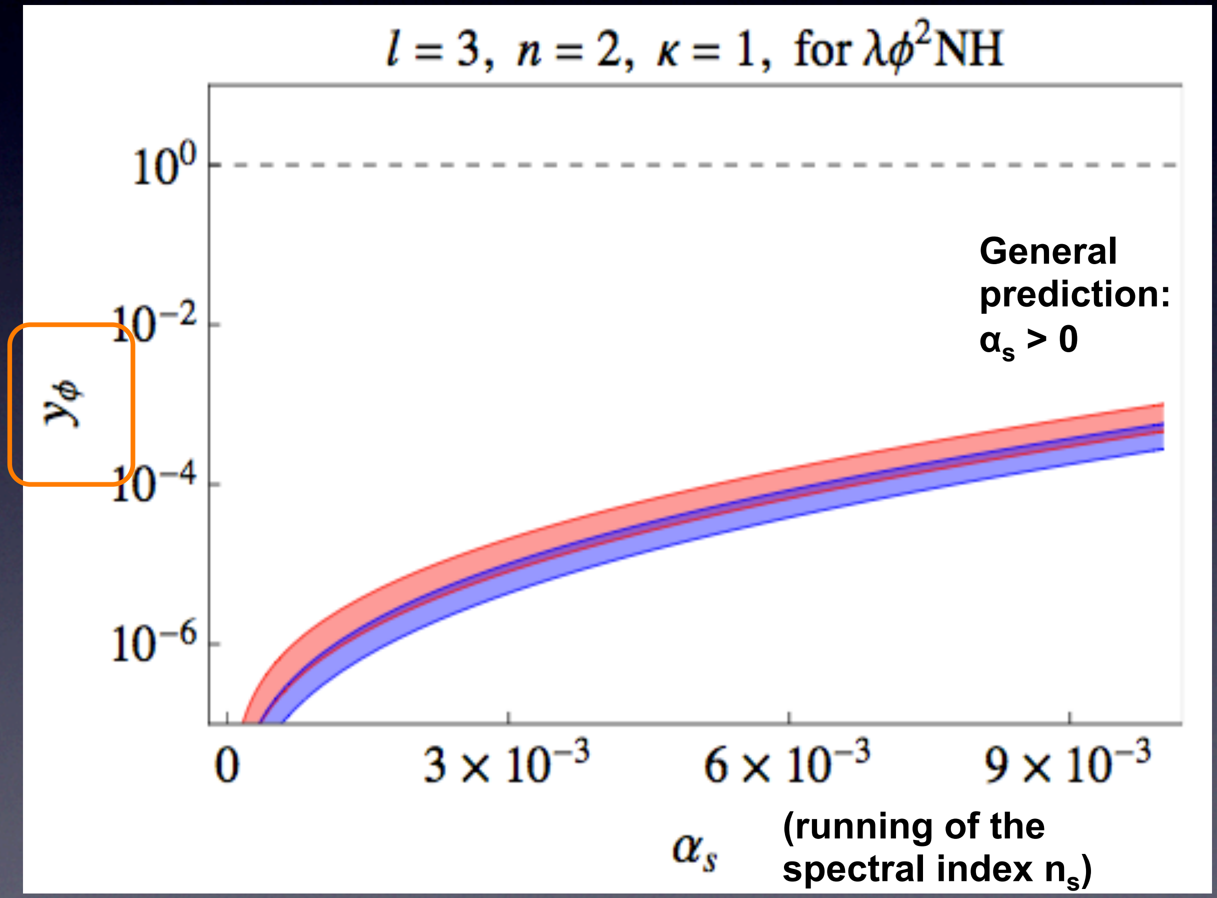
Inflaton field direction

S. A., D. Nolde (arXiv:1306.3501)

Neutrino Yukawa coupling predicted as function of α_s (running of spectral index)

- In example 1:

S. A., D. Nolde (arXiv:1306.3501)



Examples: Matter inflation in flavour models

S. A., D. Nolde (arXiv:1306.3501)

- Example 2: Inflation along RH sneutrino direction:
  Connection to mass of the RH (s)neutrino

$$W_{\text{inf}} = S_i\left([\Theta_i]^{\ell_i} - \mu_i^2\right) + \gamma_i \underbrace{N_i^2}_{\equiv \Phi^2} \Theta_i^2 + \ldots$$

RH neutrino mass (γ_i)

Inflaton field direction (N_i^2)

$$m_\Phi = 2\gamma_i \frac{\langle \Theta_i \rangle^2}{M_{\text{Pl}}}$$

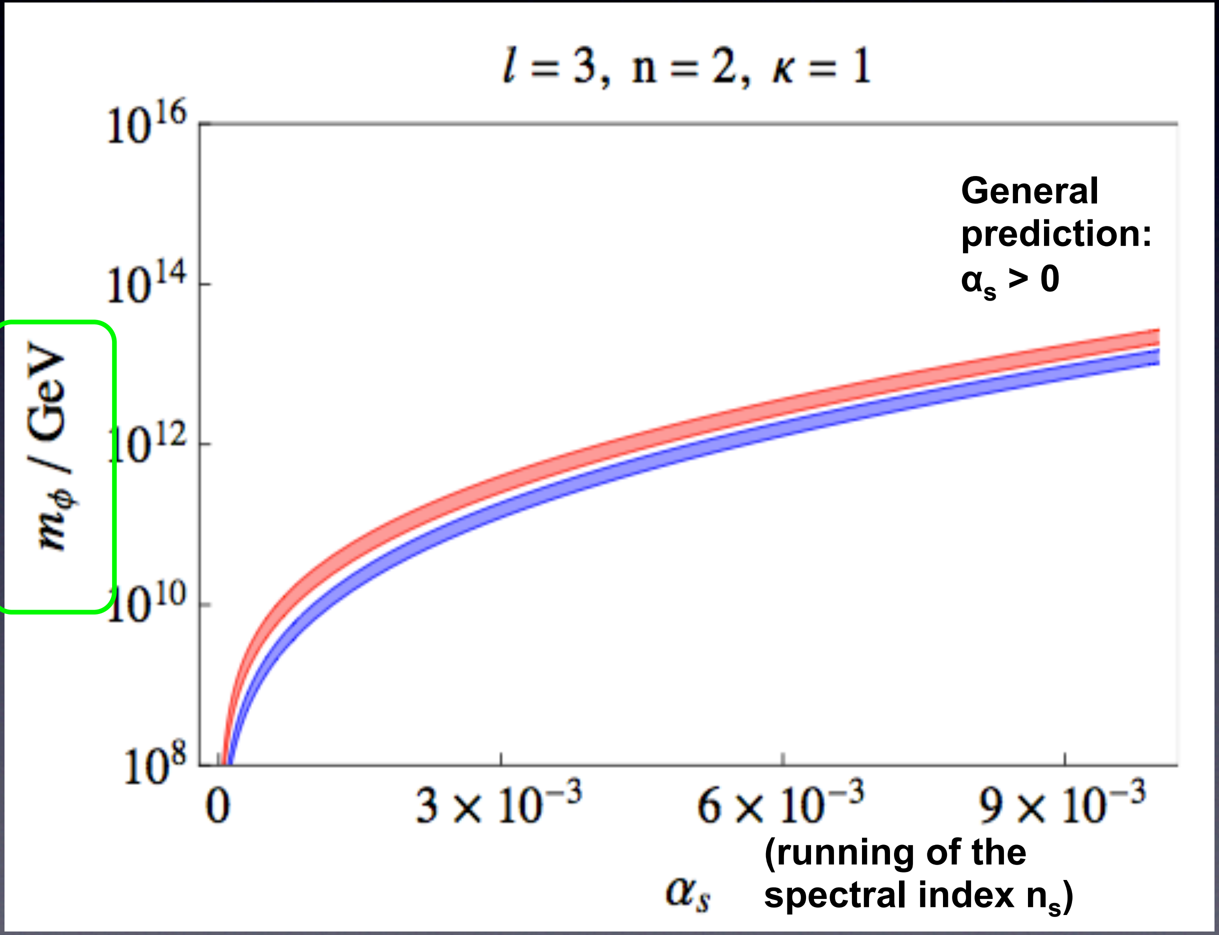
RH sneutrinos as inflaton in hybrid/tribrid inflation, see also: S.A., M. Bastero Gil, S.F. King, Q. Shafi ('04)
S.A., J. P. Baumann, V. Domcke, P. Kostka ('10)

RH sneutrinos as inflaton in chaotic inflation: Murayama, Suziki, Yanagida, Yokoyama ('93)

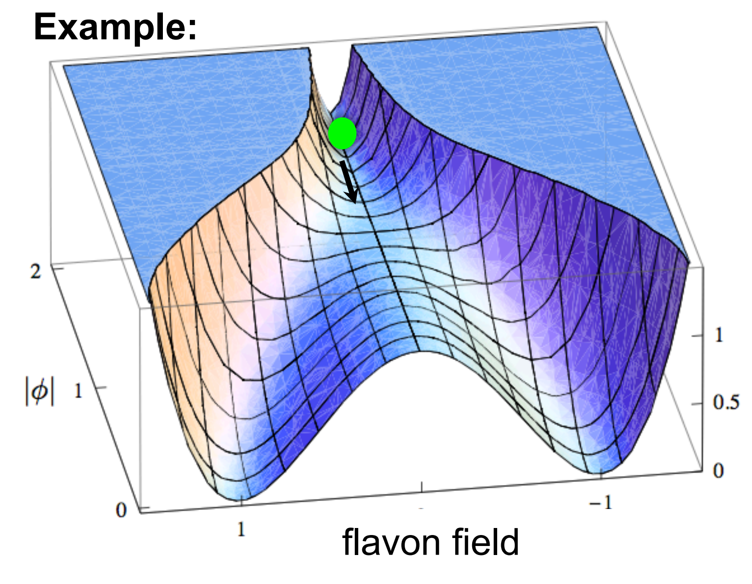
RH neutrino mass predicted as function of α_s (running of spectral index)

- In example 2:

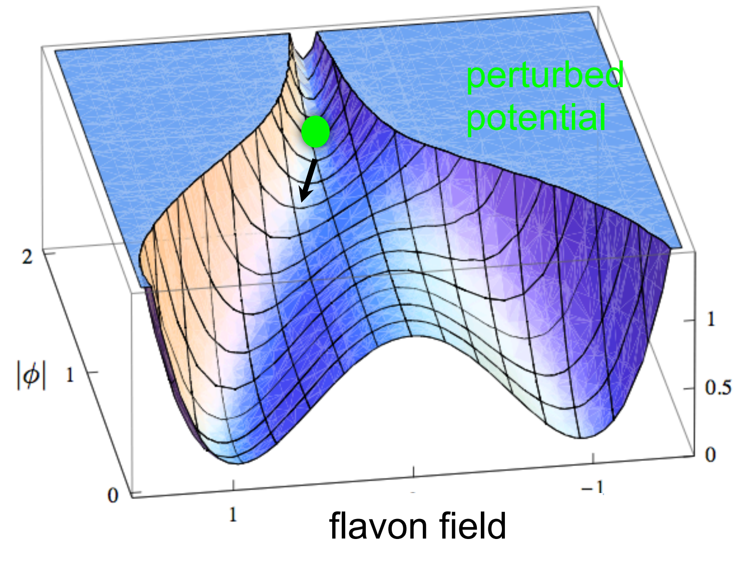
S. A., D. Nolde (arXiv:1306.3501)



As in hybrid inflation, inflation ends by a 2nd order phase transition

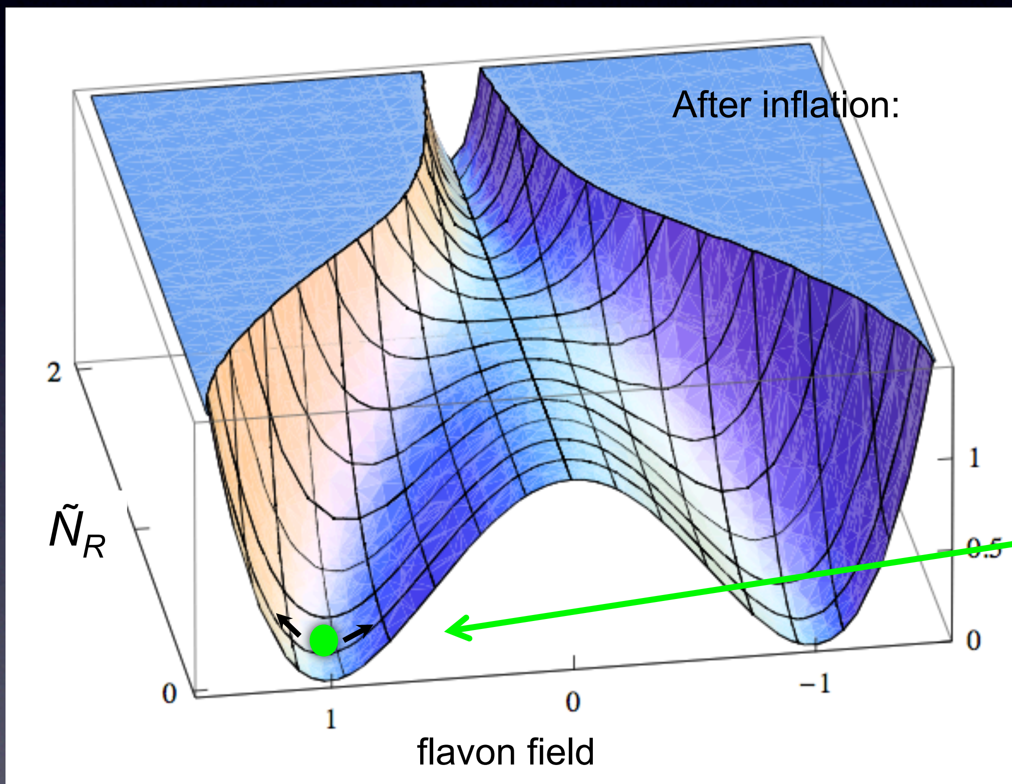


Interesting feature:
Deformations in the potential.
*(e.g. in a model with A4 family symmetry, **arXiv:1306.3501**)*

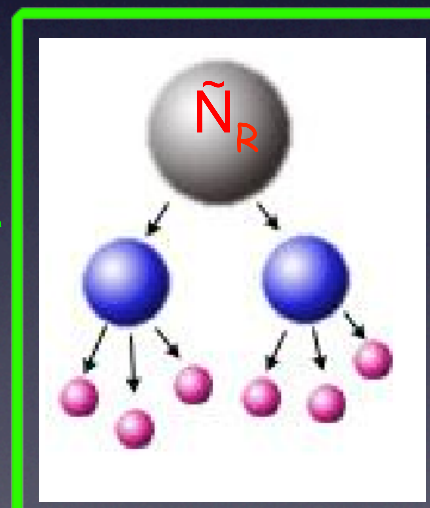


→ Topological defect production after inflation automatically avoided!

After inflation: Reheating, baryogenesis ...



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



Hilltop inflation and flavour models: "Flavon inflation"

“Flavon inflation”

The flavons themselves can also act as inflaton fields in so-called ‘new inflation’:

S. A., S.F. King, M. Malinsky, L. Velasco Sevilla, I. Zavala (arXiv:0805.0325)

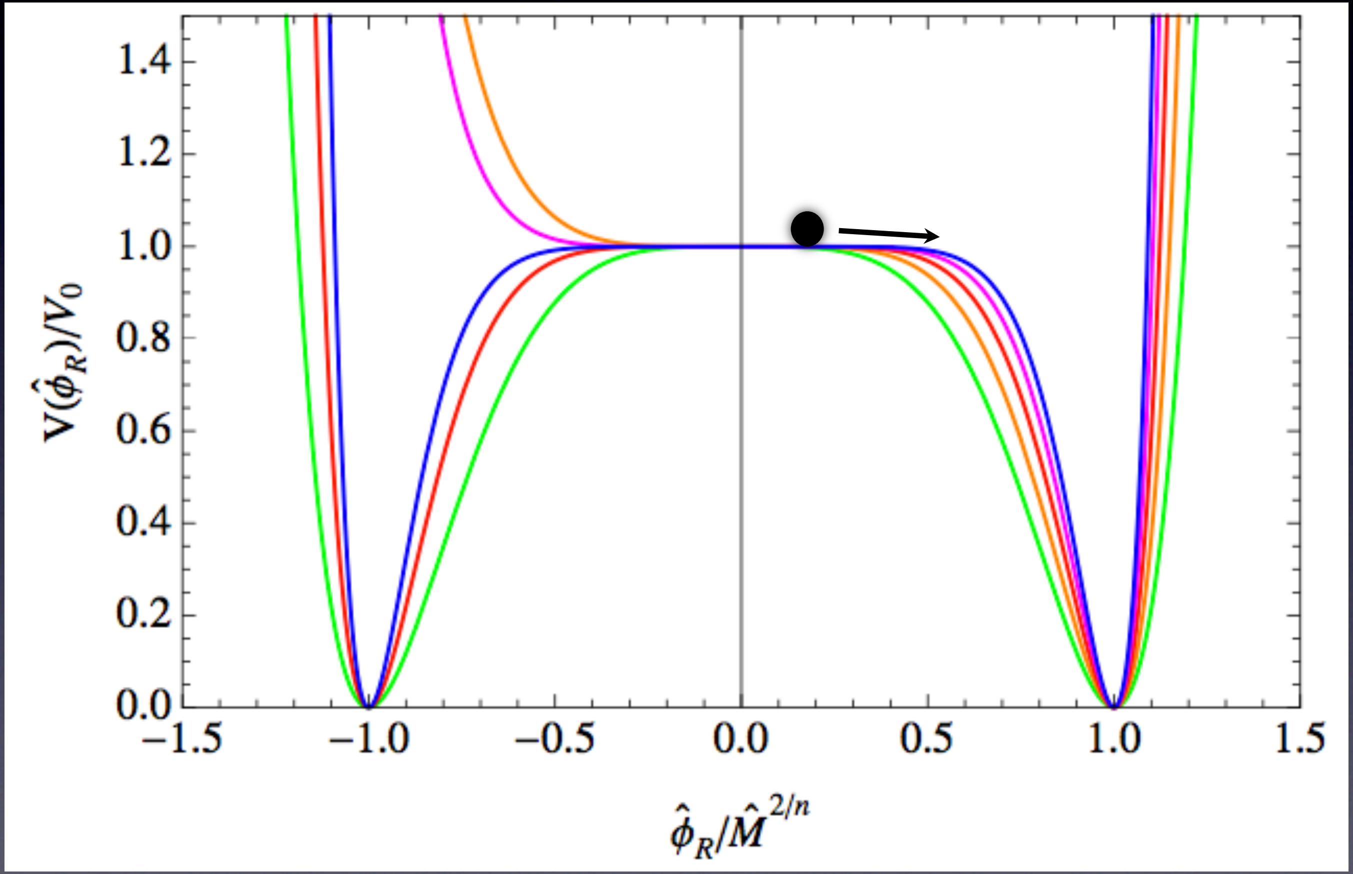
$$W_{\mathrm{fl}} = S_i \left([\Theta_i]^n - \mu_i^2 \right) + \ldots$$

Flavon = Inflaton field

Hilltop inflation: inflaton potential

Inflaton potential: "Plateau" for small Φ

$$V(\phi) \simeq V_0 \left(1 - \frac{\phi^p}{v^p}\right)^2$$



Early "hilltop-type" scenarios:
Linde ('82); Izawa, Yanagida ('96); Izawa, Kawasaki, Yanagida ('97)

Supergravity formulation:
Senoguz, Shafi ('04), S. A., F. Cefala ('03)

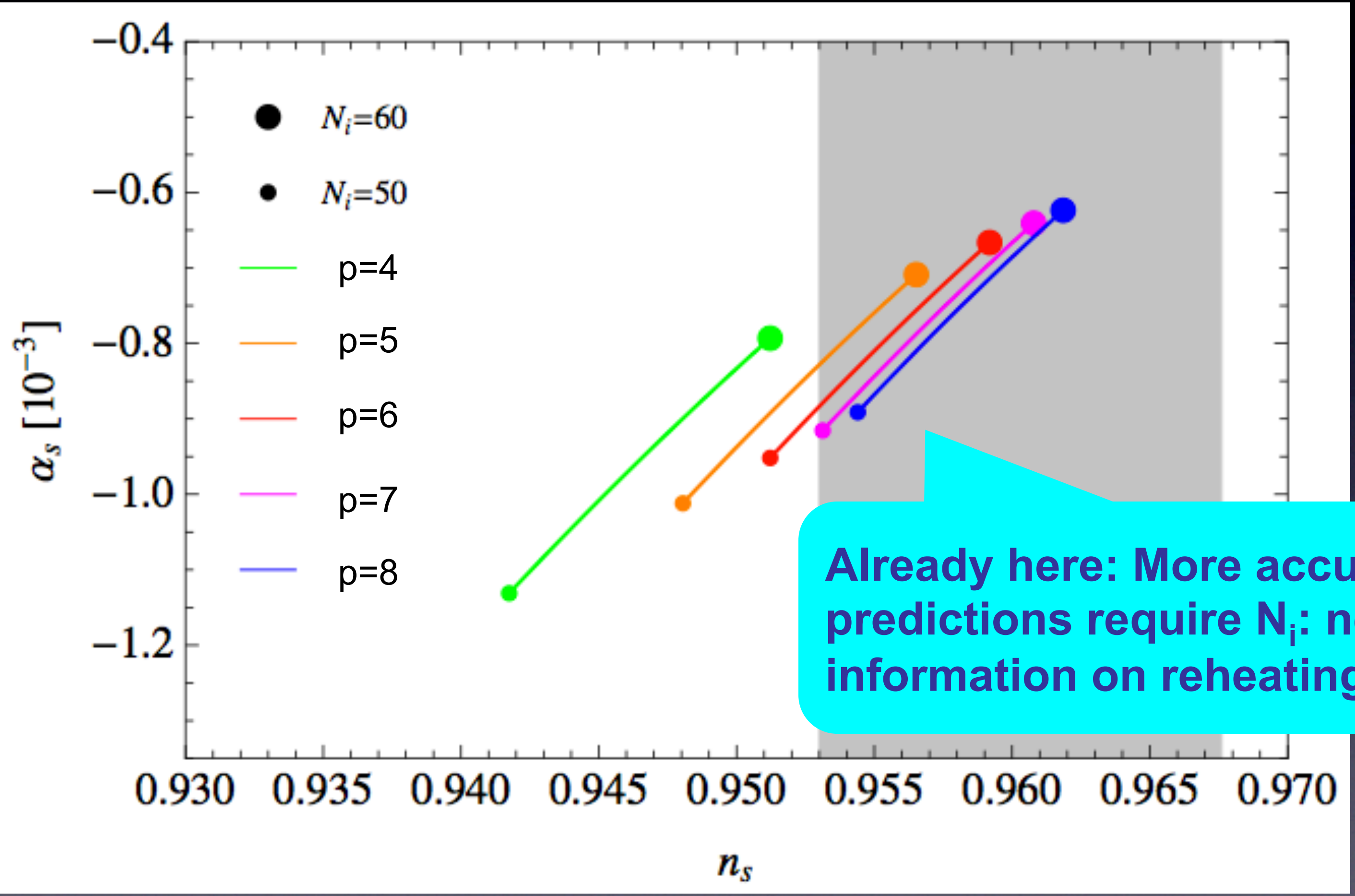
Shown in the plot: Potential for p=4,5,6,7,8

Very predictive in SUGRA with Heisenberg symmetry! S. A., F. Cefala ('03)

Hilltop inflation: inflationary predictions

Predictions for n_s and α_s: using single field slow roll formulae ...

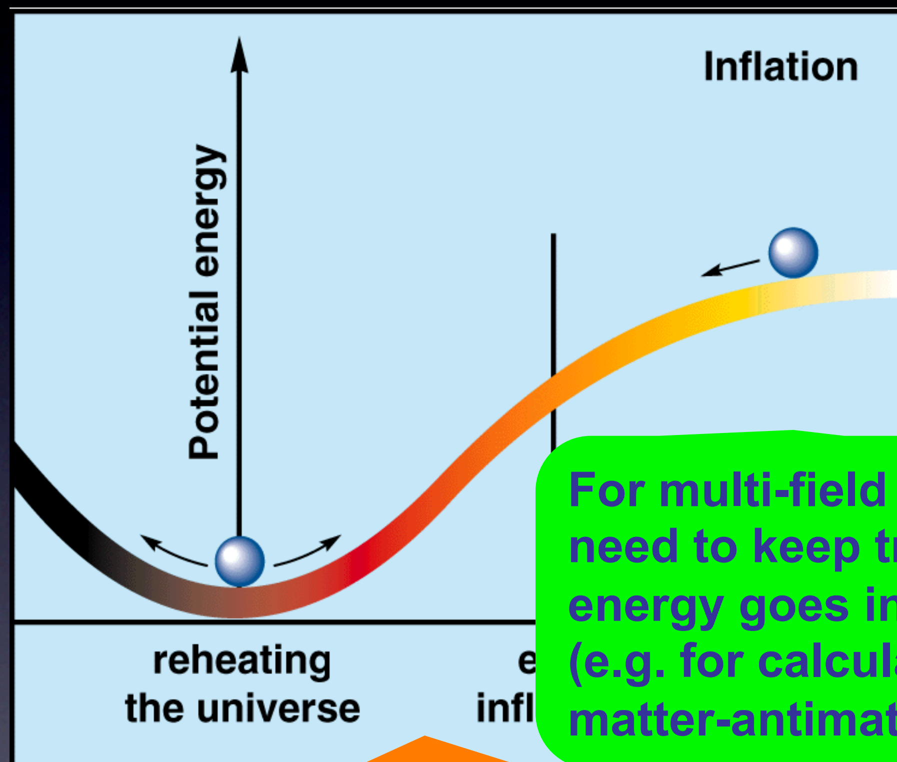
(Small field, $\Phi << m_{pl}$)



Already here: More accurate predictions require N_i: needs information on reheating phase!

(P)reheating after Hilltop inflation

Reheating requires the inflaton field to couple to other fields ➔ particle physics



For multi-field models: We need to keep track how much energy goes into each field! (e.g. for calculating the matter-antimatter asymmetry)

<u>Reheating</u>: Inflaton transfers energy to other fields → ends when radiation dominated universe (in thermal eq.) is reached → link to "standard big bang cosmology"

A simple example model: hilltop inflation with reheating & explained initial conditions

Φ: inflaton field

$$W = \Lambda^2 \hat{S} \left(\frac{4\hat{\Phi}^6}{\mu^6} - 1 \right) + \lambda_i \hat{\Phi}^2 \hat{X}_i^2 + y_{ji} \hat{L}_j \hat{H}_u \hat{X}_i$$

Generates inflaton potential of the hilltop form (with p=6)

$$V(\phi) \simeq V_0 \left(1 - \frac{\phi^p}{v^p} \right)^2$$

S. A., D. Nolde, S. Orani (arXiv:1402.5328)

A simple example model: hilltop inflation with reheating & explained initial conditions

X: RH sneutrino

$$W = \Lambda^2 \hat{S} \left(\frac{4\hat{\Phi}^6}{\mu^6} - 1 \right) + \lambda_i \hat{\Phi}^2 \hat{X}_i^2 + y_{ji} \hat{L}_j \hat{H}_u \hat{X}_i$$

(i) Explains initial conditions (large mass for Φ before inflation)
(ii) Generates large mass for X (= RH sneutrino) after inflation

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

S. A., D. Nolde, S. Orani (arXiv:1402.5328)

A simple example model: hilltop inflation with reheating & explained initial conditions

S. A., D. Nolde, S. Orani (arXiv:1402.5328)

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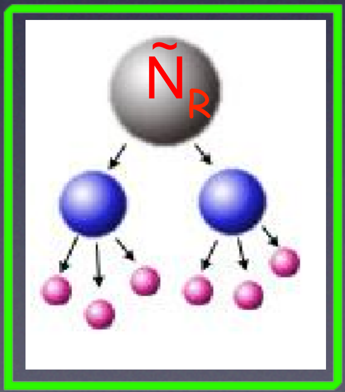
X: RH sneutrino



Decays of X into SM fields & their superpartners

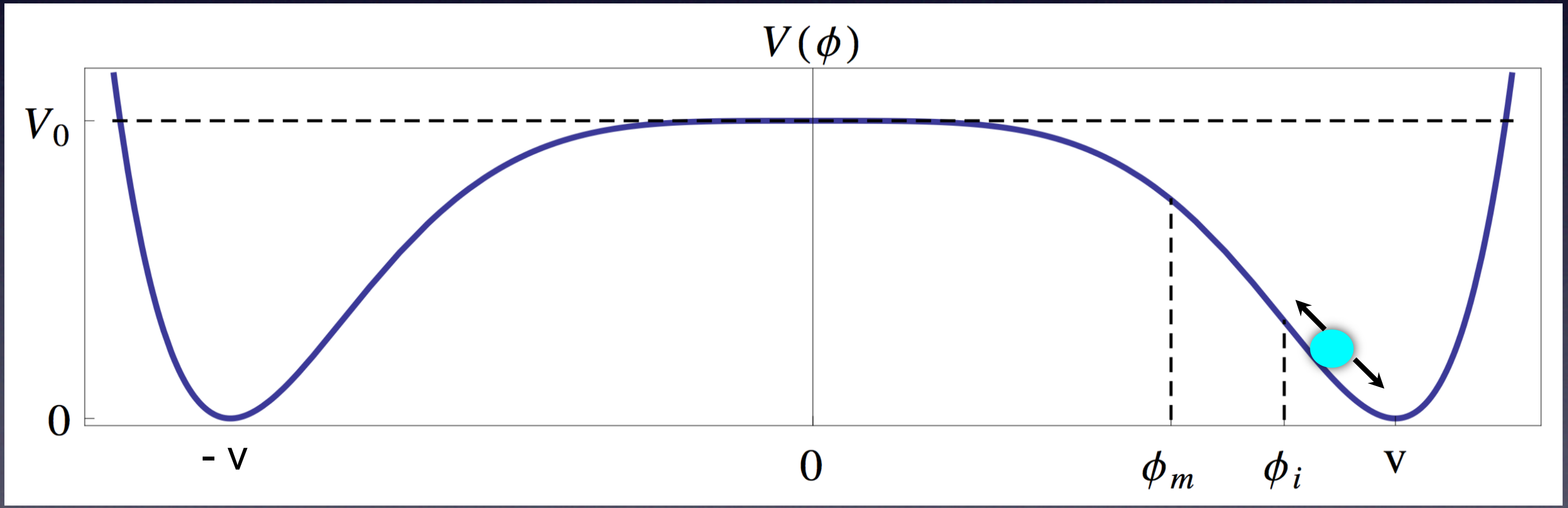
Attractive possibility: Matter-antimatter asymmetry via “leptogenesis” mechanism

Reheating after hilltop inflation

For a more detailed overview, see:
S. A., D. Nolde, S. Orani (arXiv:1503.06075)

Preheating:

- Phase I: Tachyonic preheating (V_0 into fluctuations of Φ)
- Phase II: Tachyonic oscillations of (V_0 into fluctuations of Φ)
- Phase III (potentially): Parametric resonances (Φ into fluctuations of X)

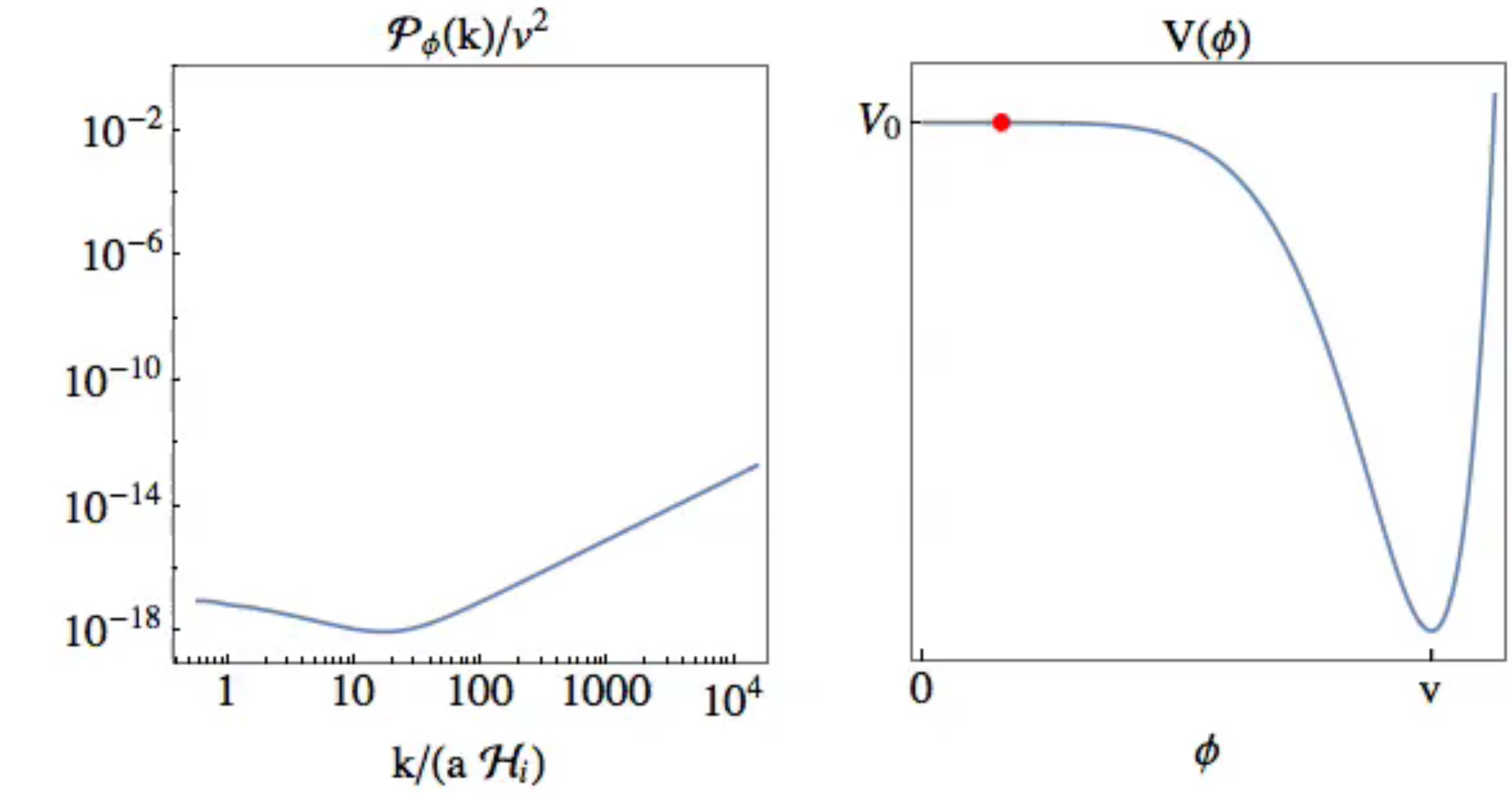


Afterwards:

Perturbative Reheating (pert. decays of Φ and X and thermalization)

Phases I and II: linear analysis

p=6

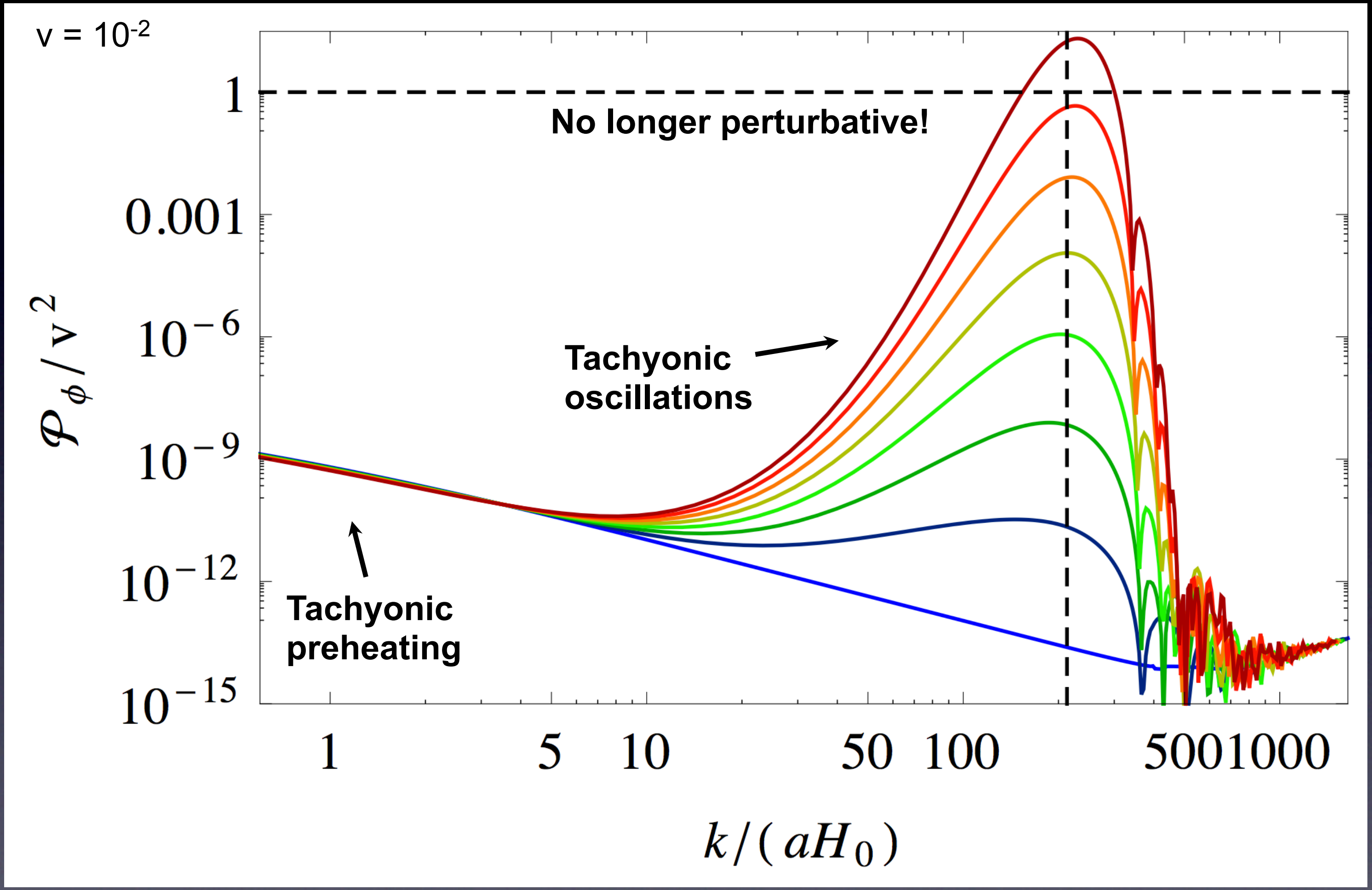


$$\mathcal{P}_\phi(t,k) = \frac{k^3}{2\pi^2}\left|\phi_k(t)\right|^2$$

Movie by Francesco Cefala

Phases I and II: *linear analysis*

p=4



$$\mathcal{P}_\phi(t,k) = \frac{k^3}{2\pi^2} |\phi_k(t)|^2$$

from: S. A., D. Nolde, S. Orani (arXiv:1503.06075)

What happens after the system becomes non-linear ... ? Lattice simulations!

S. A., D. Nolde, S. Orani (arXiv:1503.06075)

- From linear analysis: Fields fluctuate so strong that they may overshoot to the wrong vacuum
  ➔ does this (re)introduce "domain walls"?

We found:
Hill-crossing of the inflaton field to the "wrong vacuum" indeed happens! However, no (stable) domain walls are created. Instead, "hill-crossing oscillons" are formed.

[oscillons = localized and remarkably stable fluctuations of the inflaton field which can form after inflation under suitable conditions] **Copeland, Gleiser, Muller ('95), Amin et al. ('11)**

Analysis of preheating: inhomogeneous field equations on the lattice

For early preheating: Linearized equations in k-space (sometimes possible)

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left(V''(\bar{\phi}) + \frac{k^2}{a^2}\right)\phi_k = 0$$

Initial conditions: Bunch-Davis vacuum at early times

Lattice: Non-linear equations for all fields f(t,x) (using LATTICEEASY)

$$\ddot{f}(t,\bar{x}) + 3H\dot{f}(t,\bar{x}) - \frac{1}{a^2}\bar{\nabla}^2 f(t,\bar{x}) + \frac{\partial V}{\partial f} = 0\,,$$

$$H^2 \equiv \frac{\langle\rho\rangle}{3m_{\rm pl}^2} = \frac{1}{3m_{\rm pl}^2}\left\langle V + \sum_f \left(\frac{1}{2}\dot{f}^2 + \frac{1}{2a^2}\left|\bar{\nabla} f\right|^2\right)\right\rangle$$

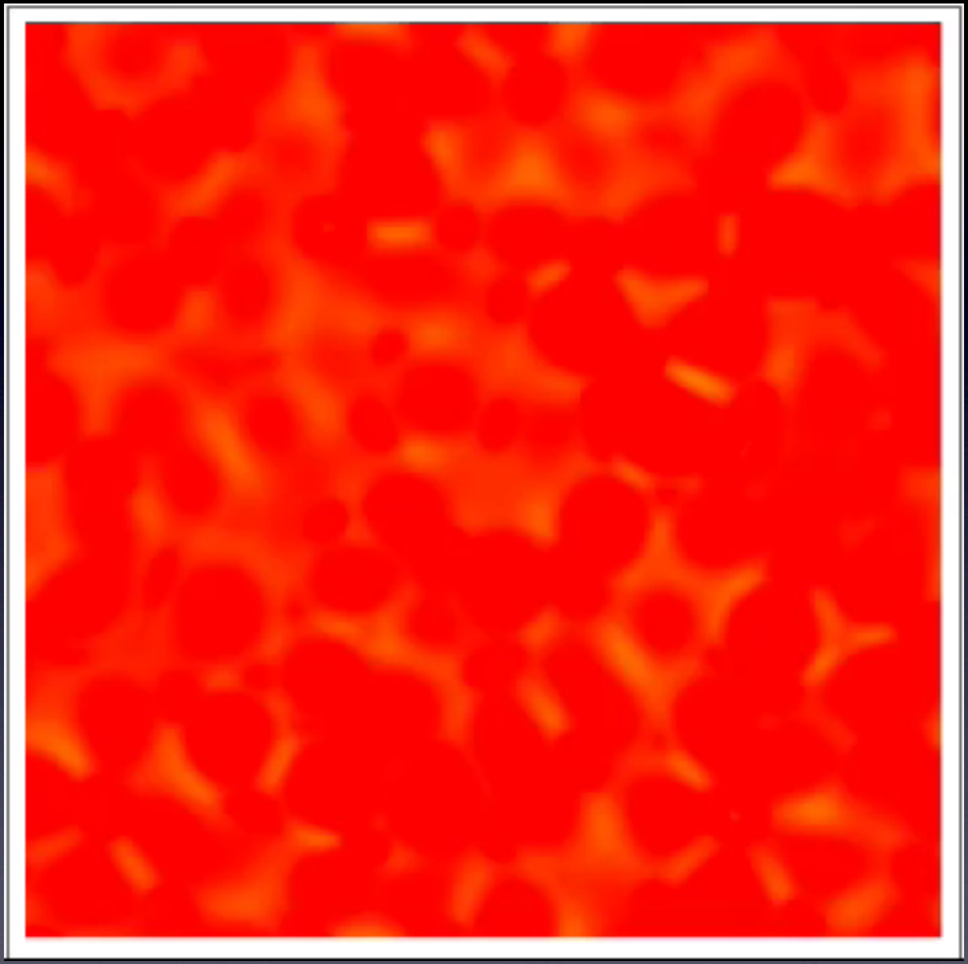
https://particlesandcosmology.unibas.ch/files/hilltop_preheating.html

Hill-crossing oscillons

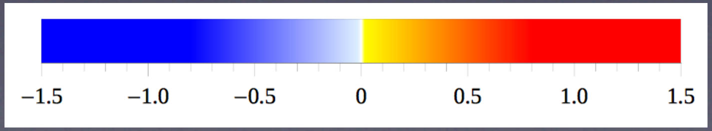
2D lattice simulation

$v = 10^{-2}$

So far: only Φ field considered



Φ/v:



Movie by Stefano Orani

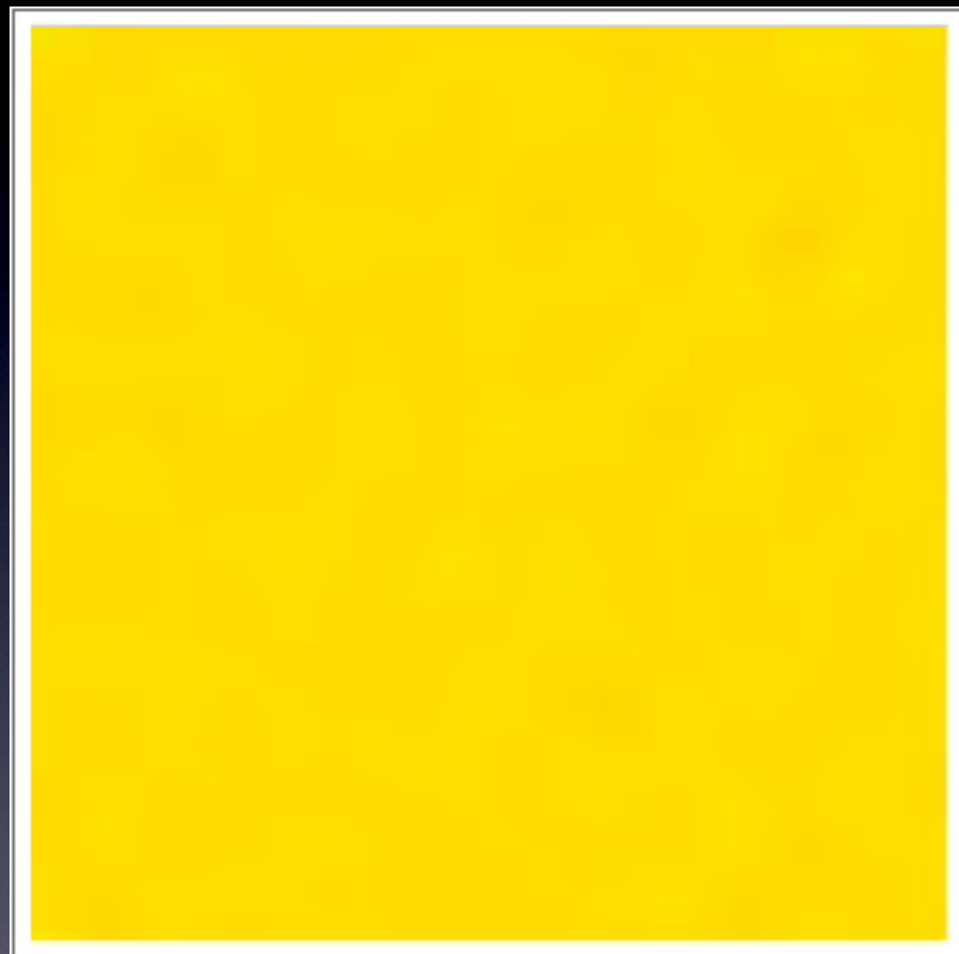
S. A., D. Nolde, S. Orani arXiv:1503.06075 https://particlesandcosmology.unibas.ch/files/hilltop_preheating.html

Hill-crossing oscillons

2D lattice simulation

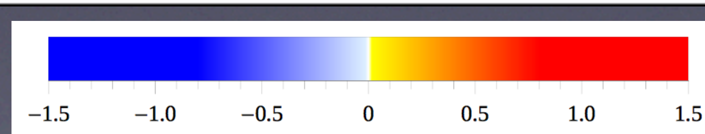
$v = 10^{-5}$

So far: only Φ field considered



Movie by
Stefano Orani

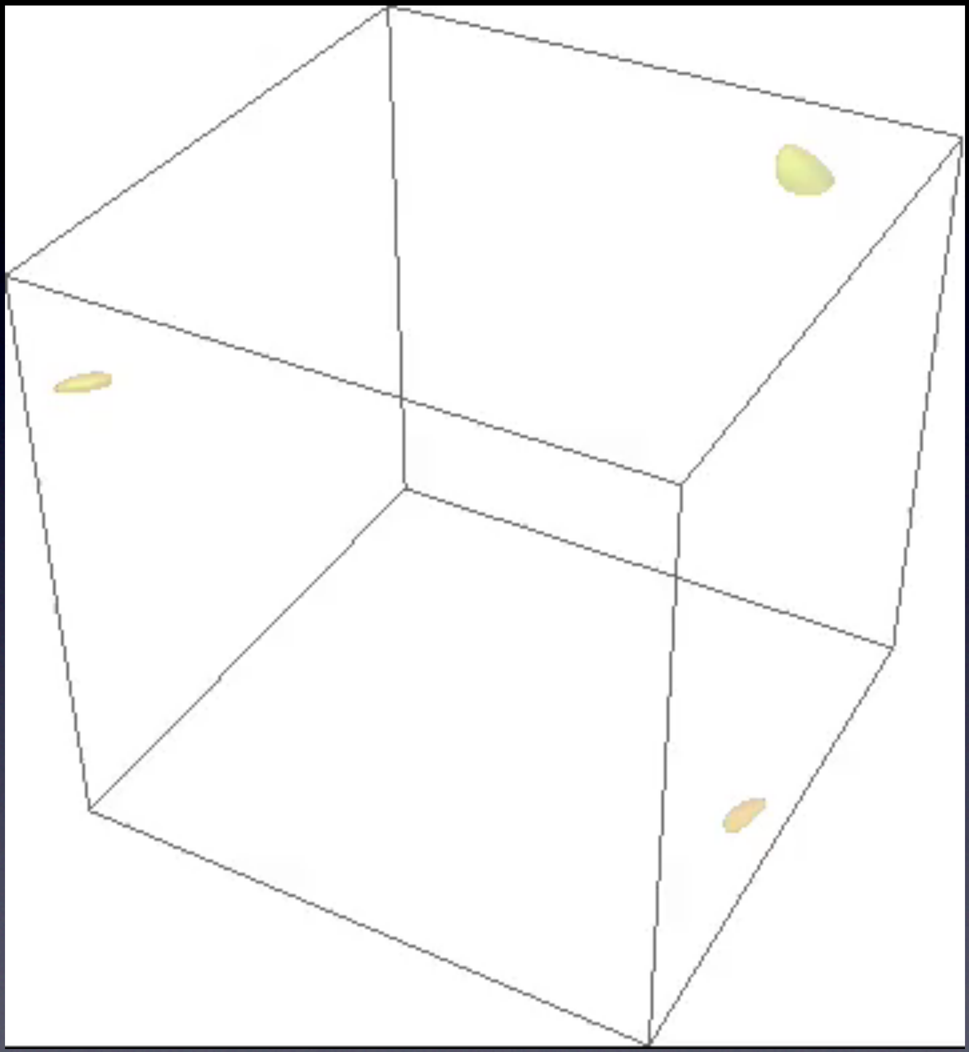
Φ/v:



S. A., D. Nolde, S. Orani
arXiv:1503.06075

Hill-crossing oscillons

So far: only Φ field considered



3D lattice simulation

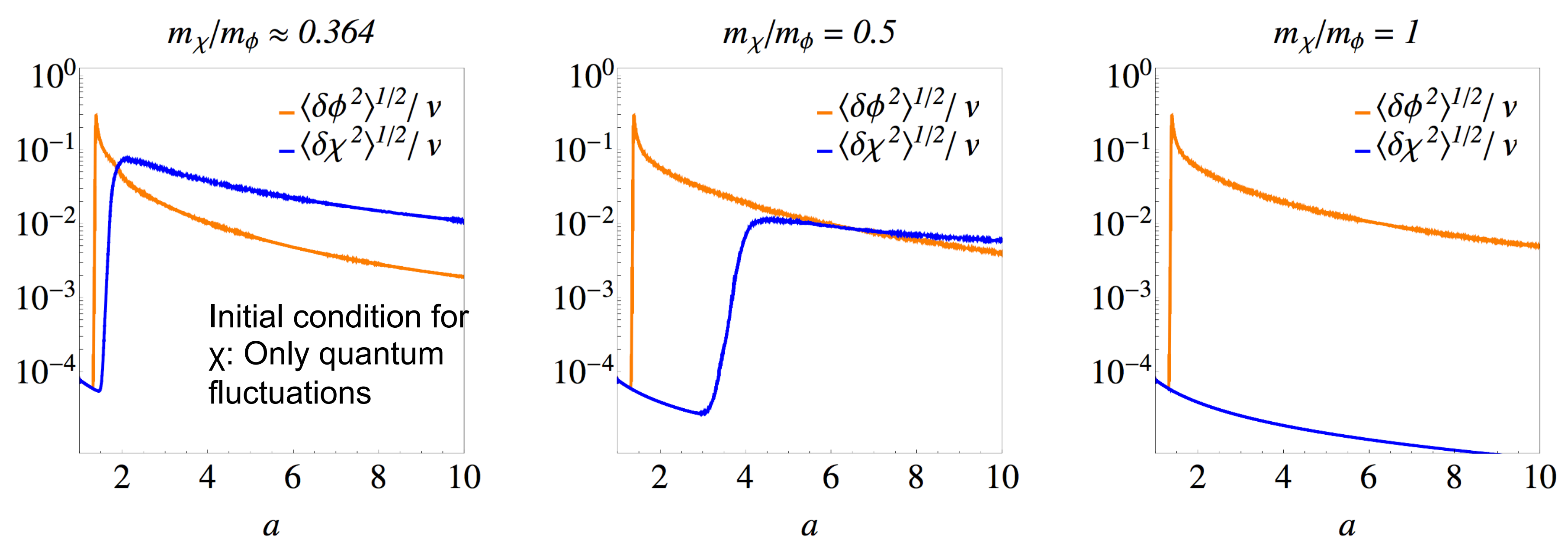
$v = 10^{-2}$

Movie by Stefano Orani

S. A., D. Nolde, S. Orani arXiv:1503.06075

Phase III: What happens to the other scalar field X (e.g. RH sneutrino)?

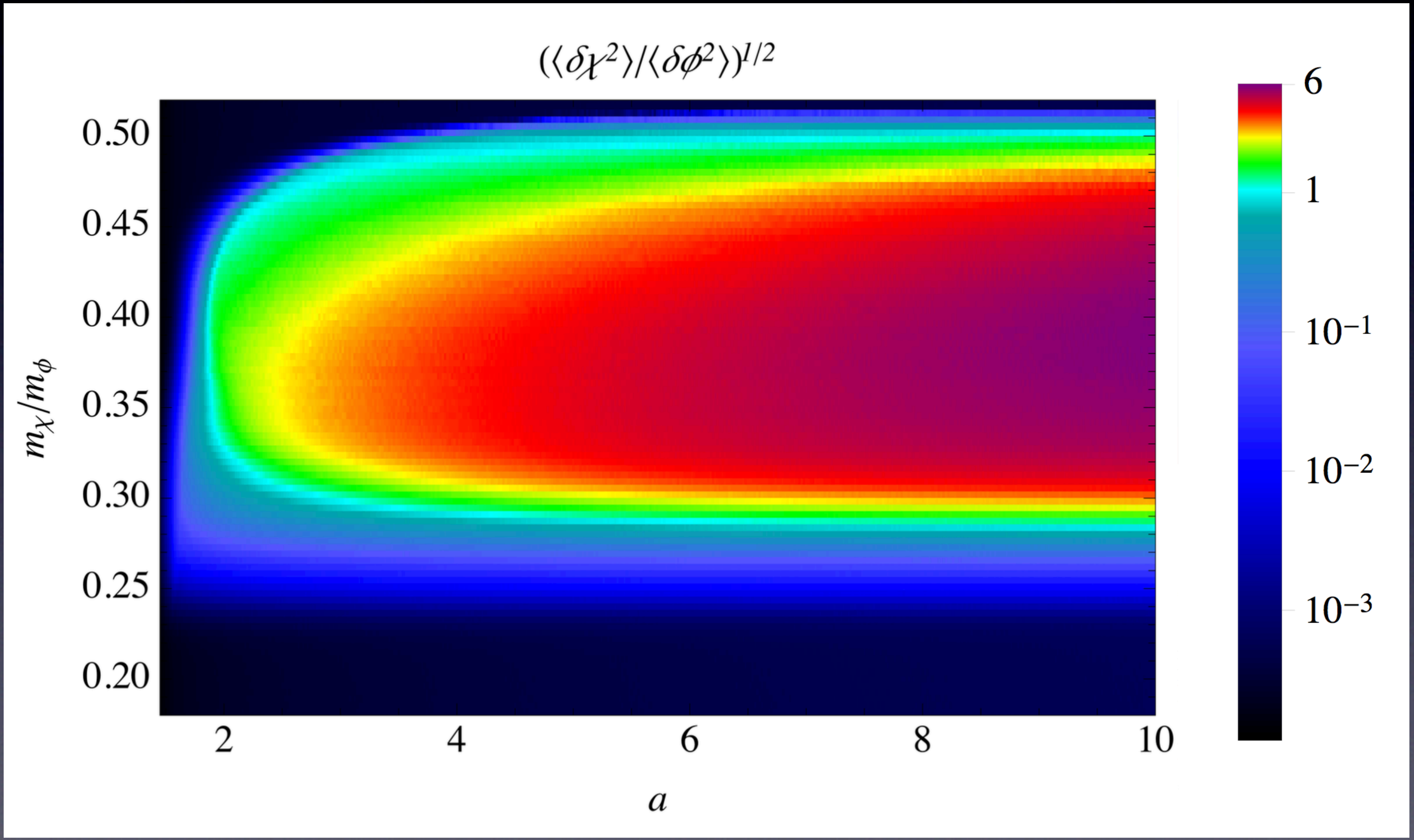
S. A., F. Cefala, D. Nolde, S. Orani (arXiv:1510.04856)



<u>We found using lattice simulations:</u>
The other scalar field can get resonantly enhanced despite the inflaton field being highly inhomogeneous
➔ "parametric resonance from inhomogeneous inflaton field"

Phase III: What happens to the other scalar field X (e.g. RH sneutrino)?

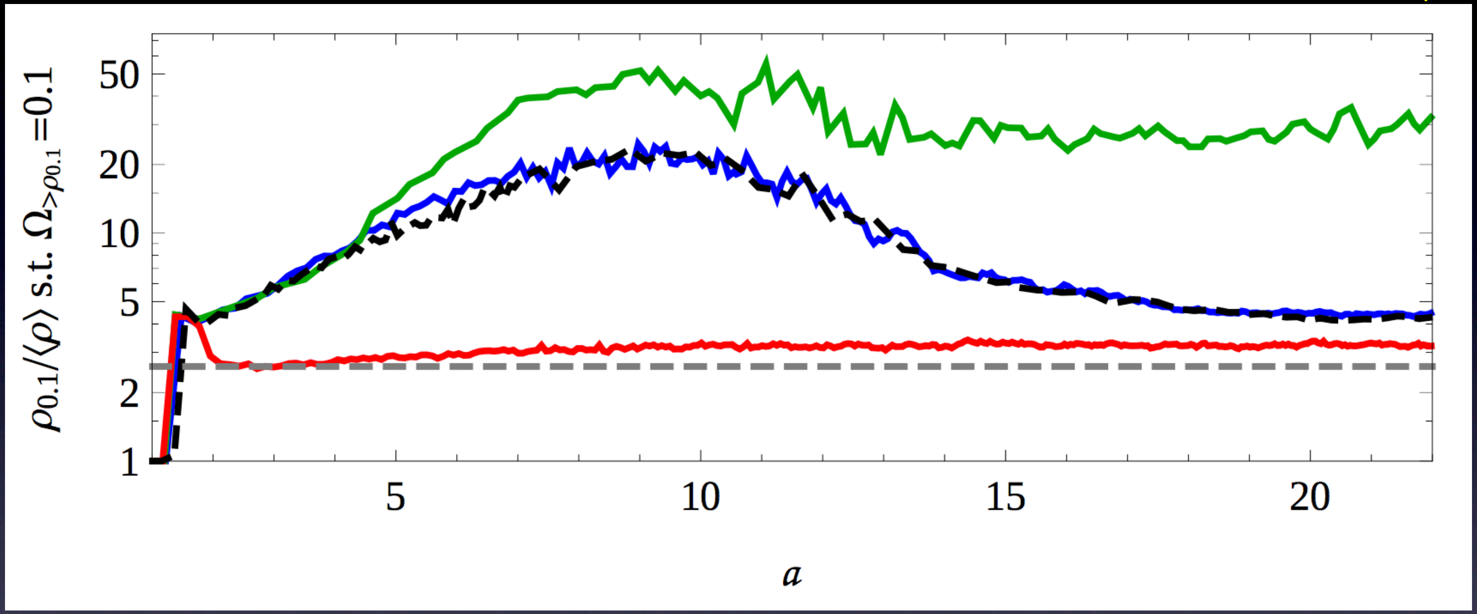
Resonance band (lattice result): S. A., F. Cefala, D. Nolde, S. Orani (arXiv:1510.04856)

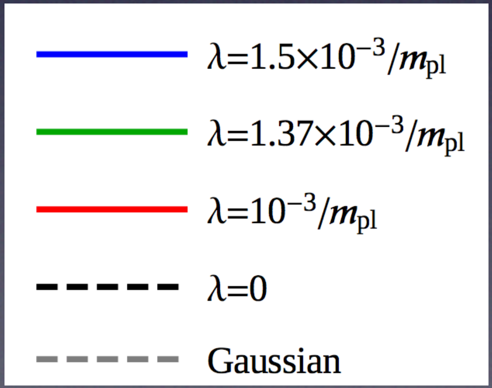


Also: Analytical understanding of via generalized Floquet analysis

How does the parametric resonance of X affect the oscillons?

S. A., S. Orani (arXiv:1511.02336)





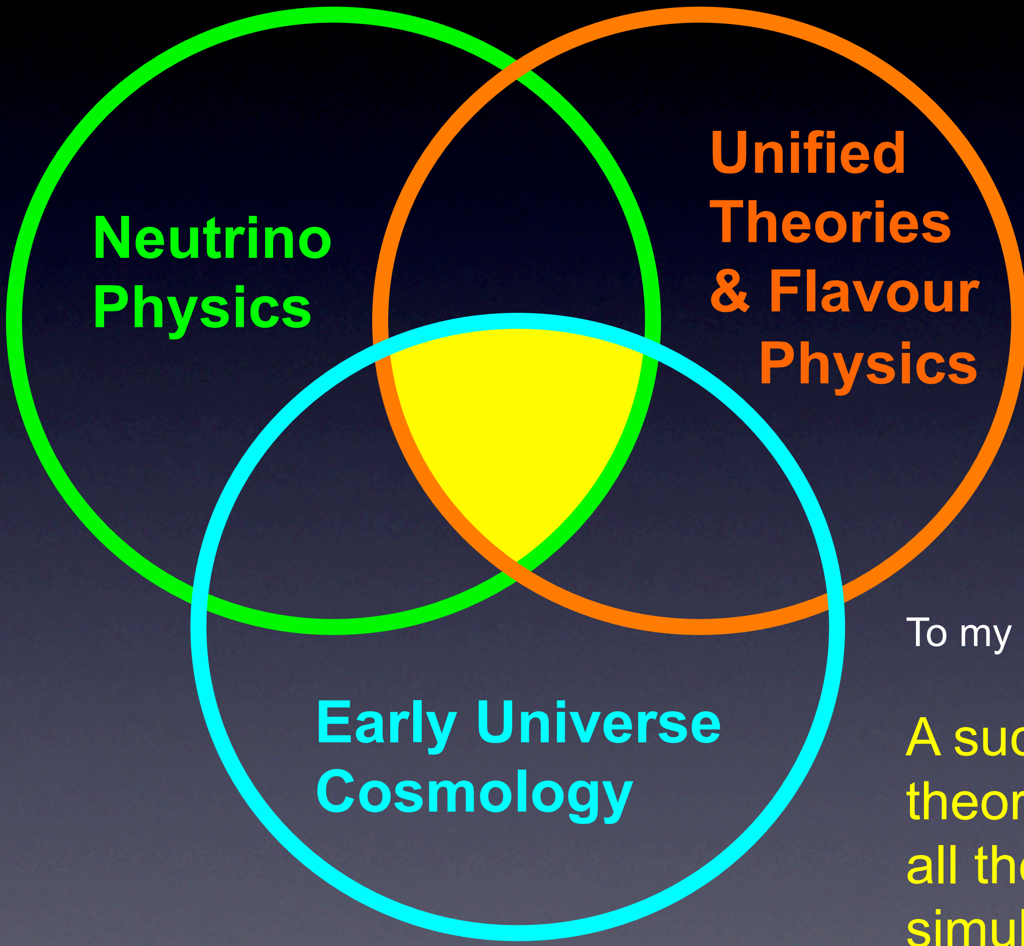
Three cases: depending on whether X gets enhanced

- No effect on oscillons when X stays subdominant
- Strong and fast enhancement of X: oscillons suppressed
- Weaker and delayed enhancement: Oscillons imprinted on X field; stabilisation of the oscillon system!

Next steps ...

- Lifetime of the oscillons?
- (P)reheating after "tribrid inflation"
- Gravitational waves from oscillons
- Baryogenesis/Leptogenesis
- …

Goal: More fundamental model of particle physics & cosmology



To my opinion:

A successful particle theory has to master all these challenges simultaneously!

Thanks for your attention!