The physical mass scales of multi-field preheating

Based on:

[OI, E. Sfakianakis, D.G. Wang, A. Achucarro: JCAP 1906, no. 06, 027(2019) [arXiv:1810.02804]
[OI, E. Sfakianakis, D.G. Wang, A. Achucarro: arXiv:2005.00528 (2020)]

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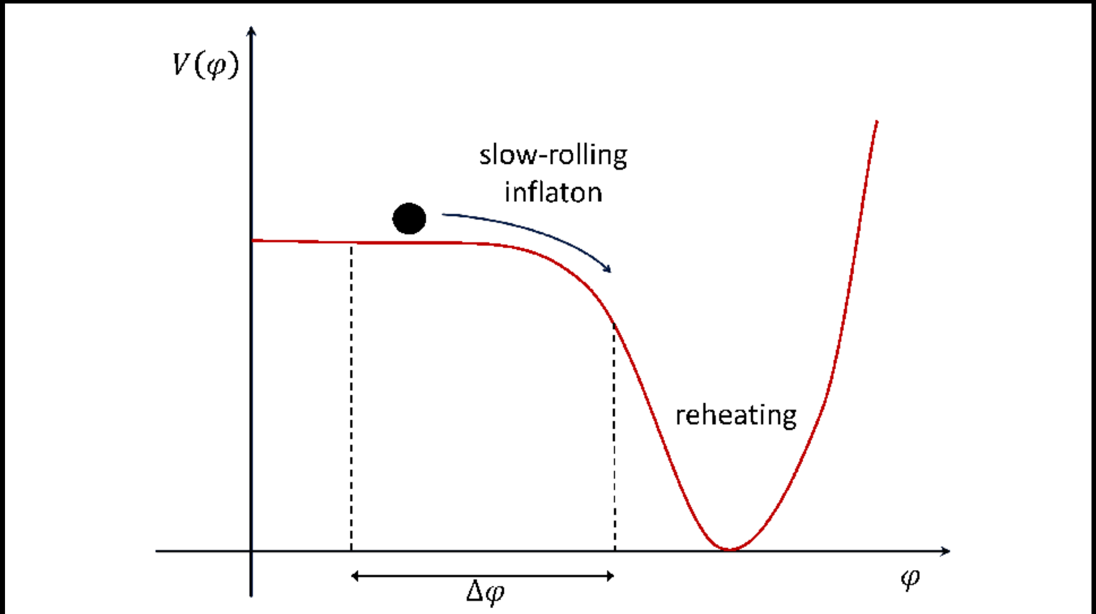
Outline:

- Why do we need to know the physics of (p)reheating?
- Why multi-field?
- Scaling relations in multi-field alpha-attractors
- What’s new in asymmetric alpha attractors?

In the beginning, there was (probably) inflation

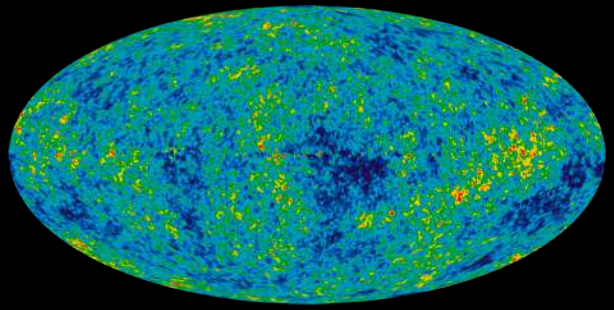
A simple mechanism: scalar field with a flat potential.



- ✓ Solves horizon, flatness problems
- ✓ Explains fluctuations as stretched quantum perturbations → seeds for all structure
- ✓ Predicts a nearly scale invariant spectrum together with Gaussian perturbations

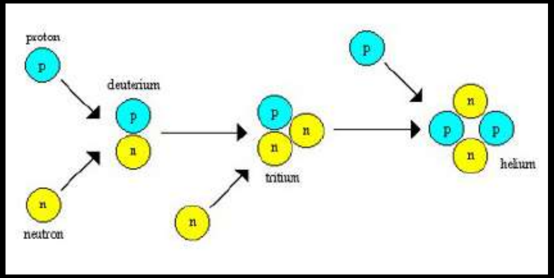
Motivation

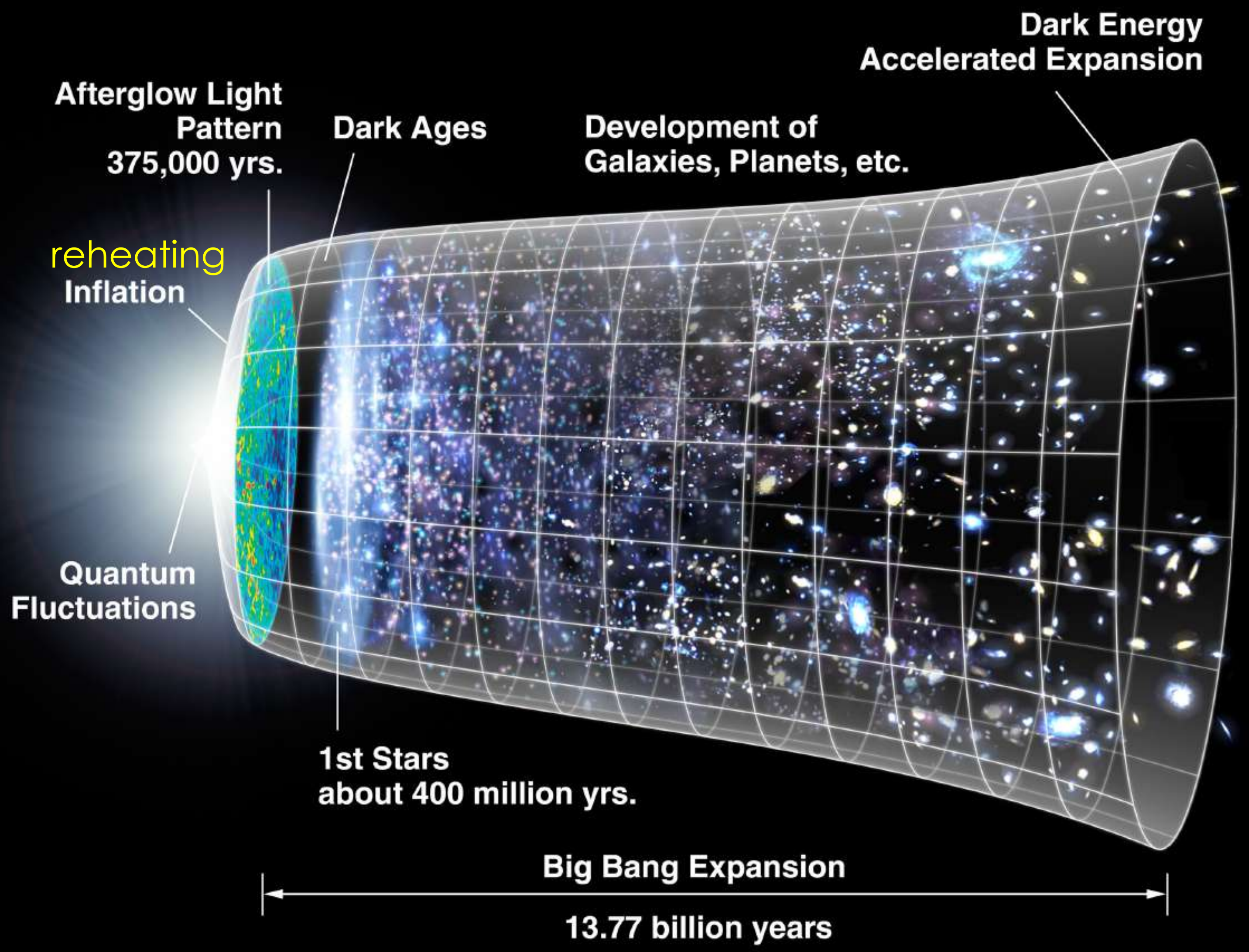
CMB



The reheating era is
poorly explored and constrained

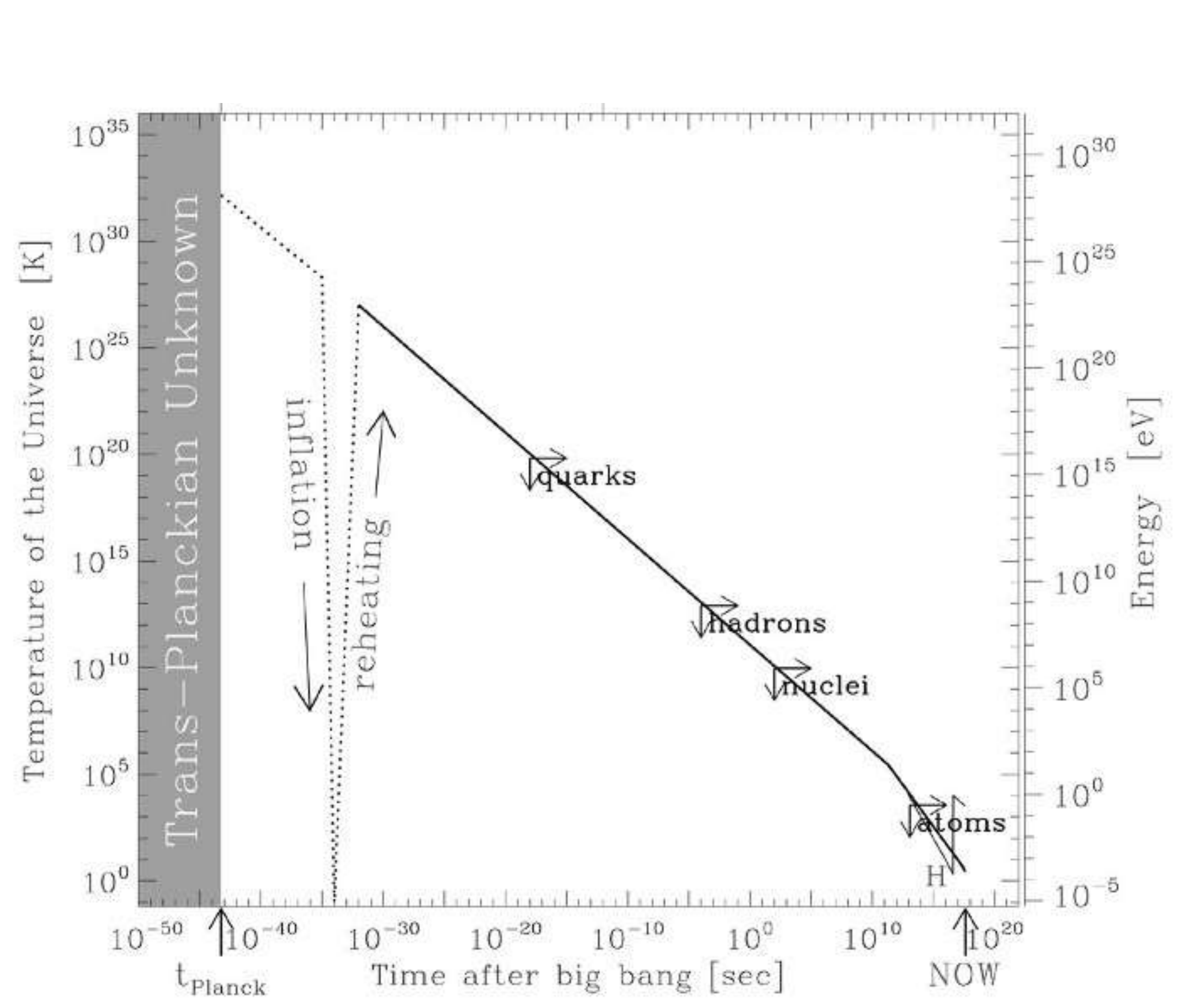
Big Bang nucleosynthesis





Why reheating is important?

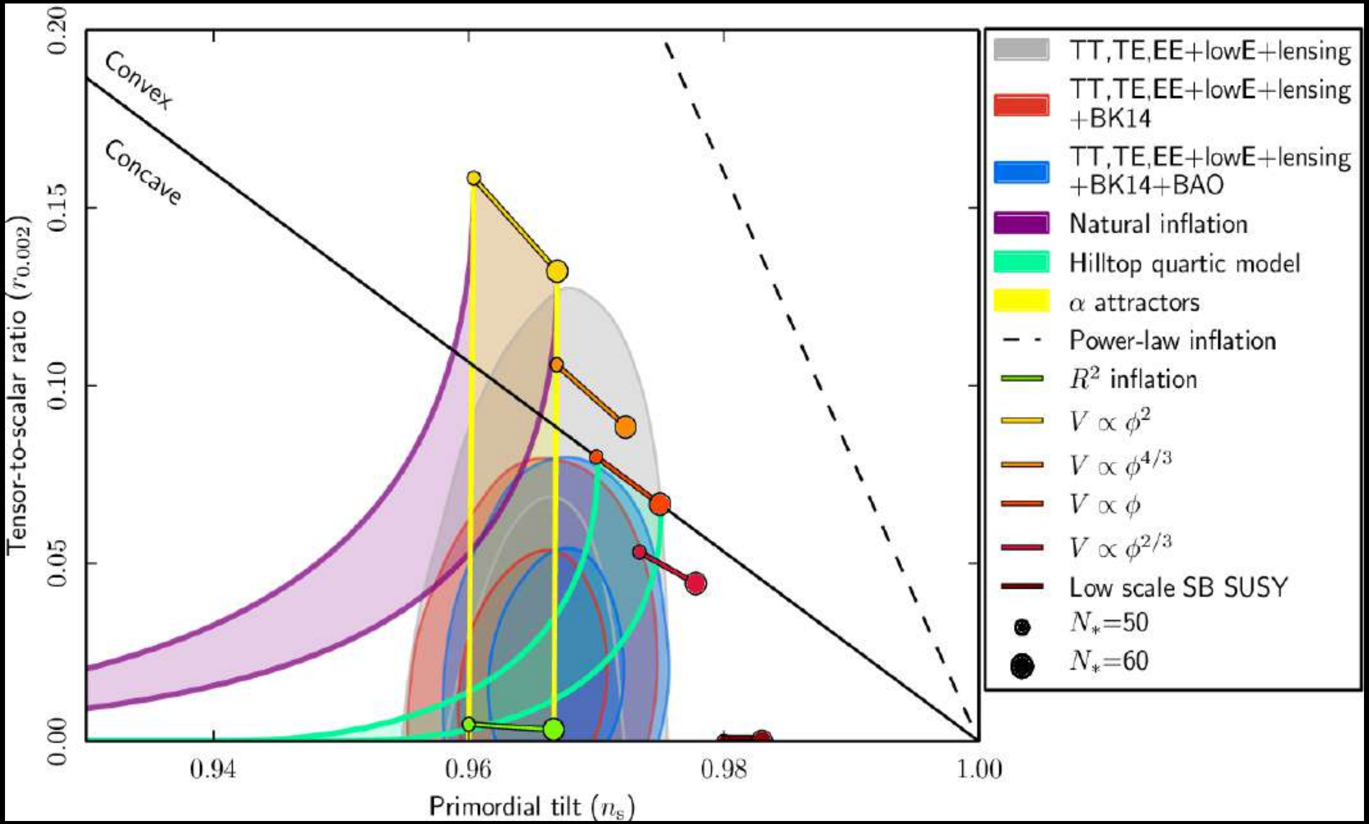
- heats the Universe



[Lineweaver (2003)]

Why reheating is important?

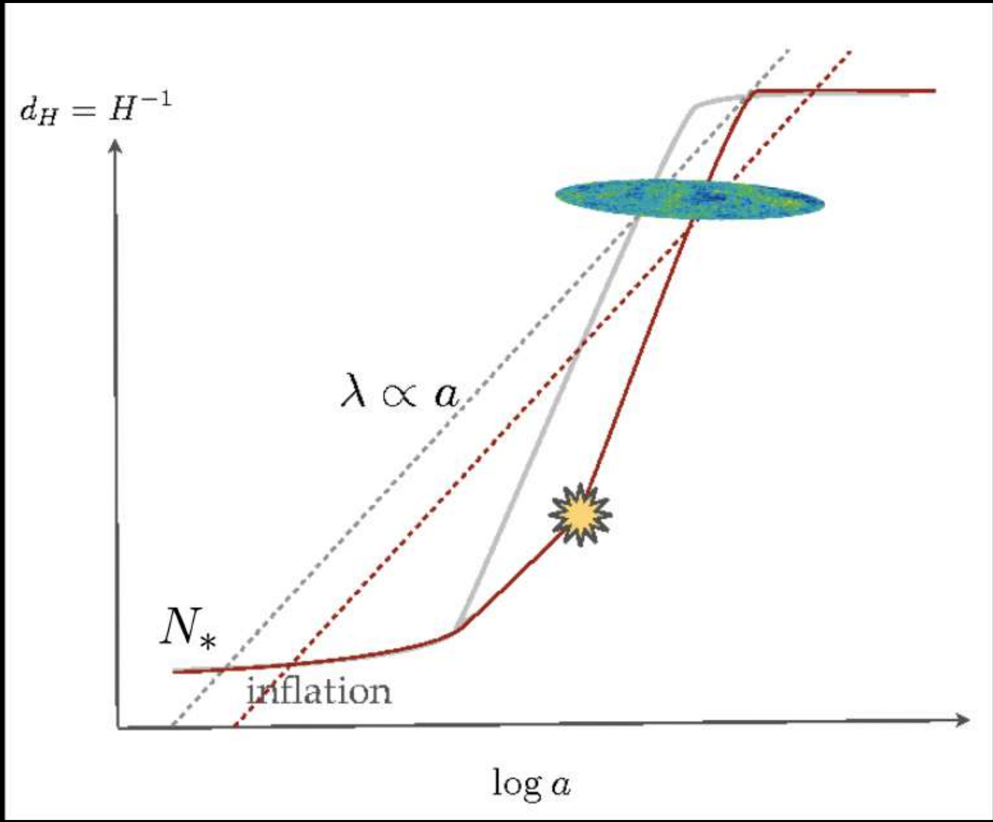
- It is an important source of theoretical uncertainty: $50 < N_* < 60$



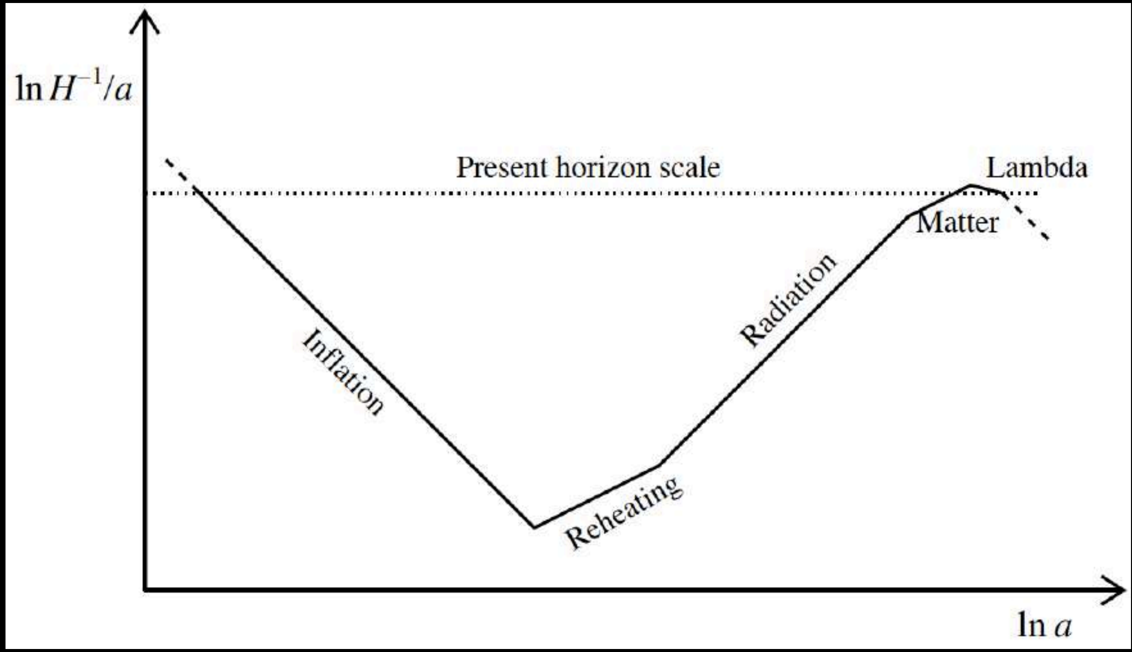
[Planck 2018 results]

Why reheating is important?

- inefficient preheating can lead to prolonged matter-dominated phase after inflation, changing the time during inflation when the CMB modes exit the horizon



[M. Amin at al (2014)]



[A. Liddle, S. Leach (2003)]

Why reheating is important?

- The duration of reheating shifts CMB predictions thus breaking the degeneracy of inflation models

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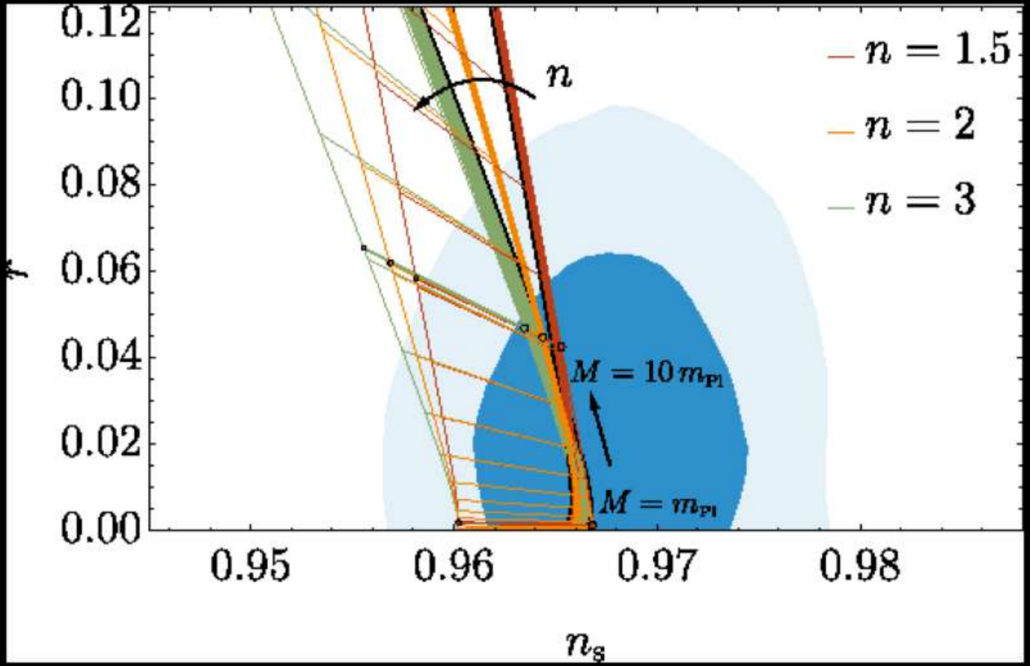

[K. D. Lozanov, M. A. Amin (2017)]

$$\frac{k_*}{a_0 H_0} = e^{-N_*} \frac{a_{\rm end}}{a_{\rm reh}} \frac{a_{\rm reh}}{a_{\rm eq}} \frac{H_*}{H_{\rm eq}} \frac{a_{\rm eq} H_{\rm eq}}{a_0 H_0}$$

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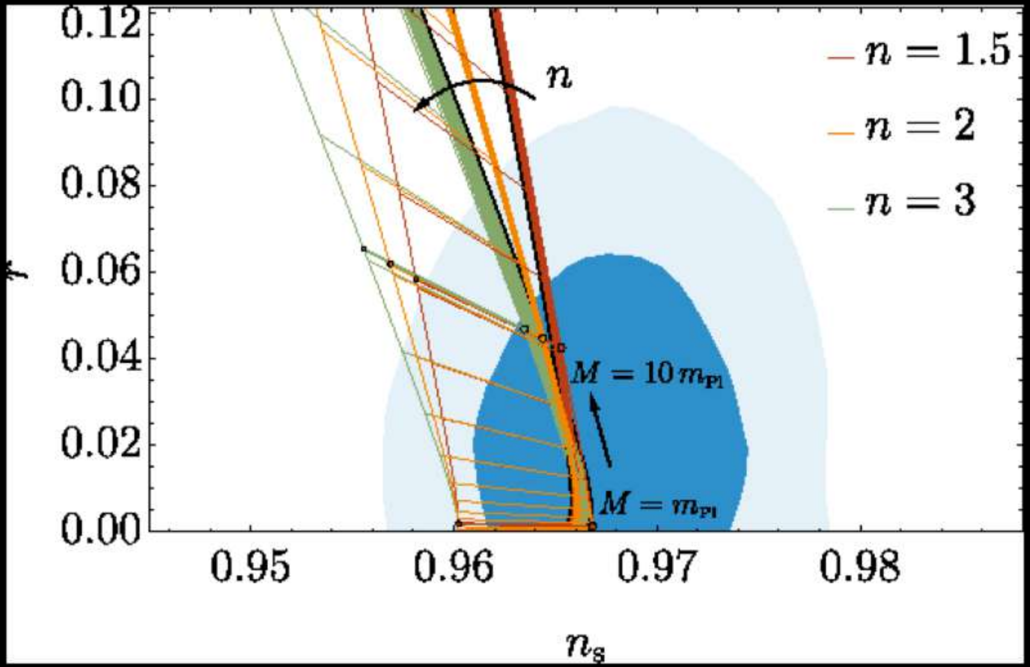

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determined by model of inflation

The basics of (p)reheating

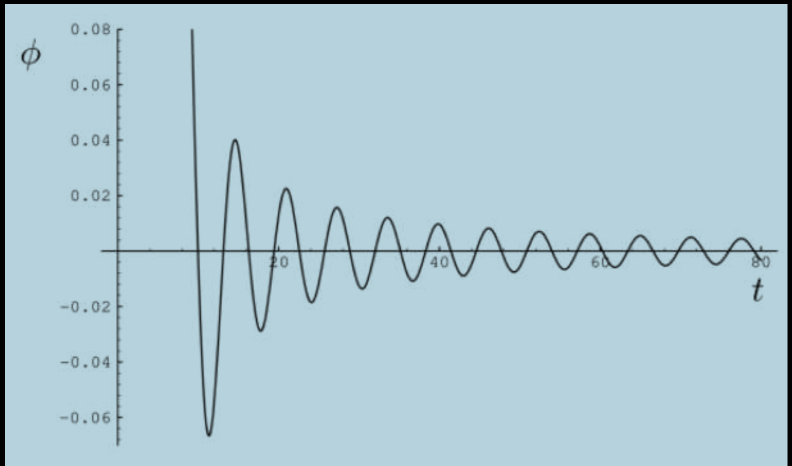
Reheating

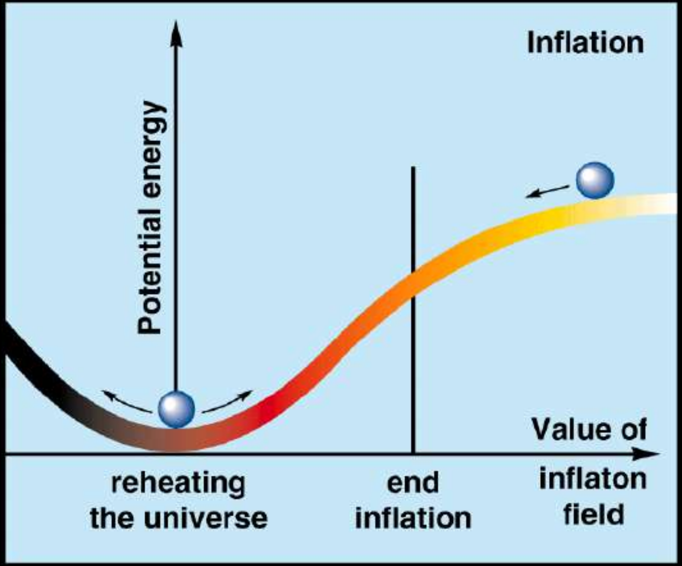
Perturbative single-body decays

$$\ddot{\bar{\phi}} + (3H + \Gamma_{\rm tot})\dot{\bar{\phi}} + m^2\bar{\phi} = 0\,, \quad \Gamma_{\rm tot} \equiv \Gamma_{\phi\to\chi\chi} + \Gamma_{\phi\to\bar{\psi}\psi} + \cdots$$

particle production becomes effective when $H \lesssim \Gamma_{\rm tot}$

- Not fast enough
- Fails for large couplings
- Doesn't take into account collective effects





[J. Gavrcia-Bellido (1999)]

The basics of (p)reheating

Reheating

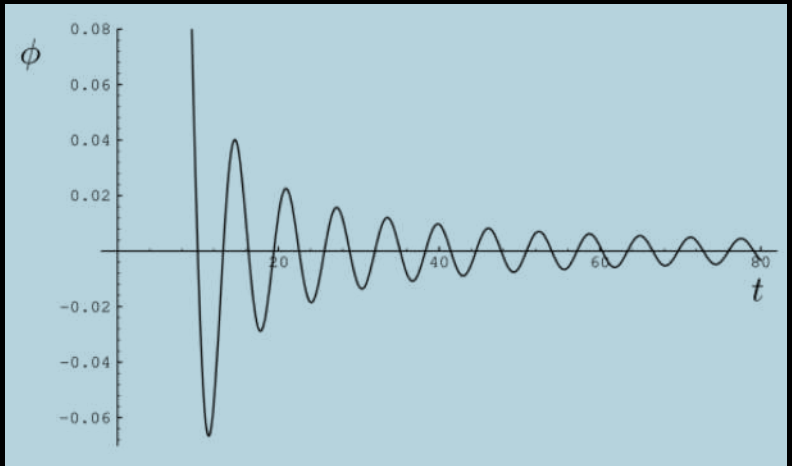
Perturbative

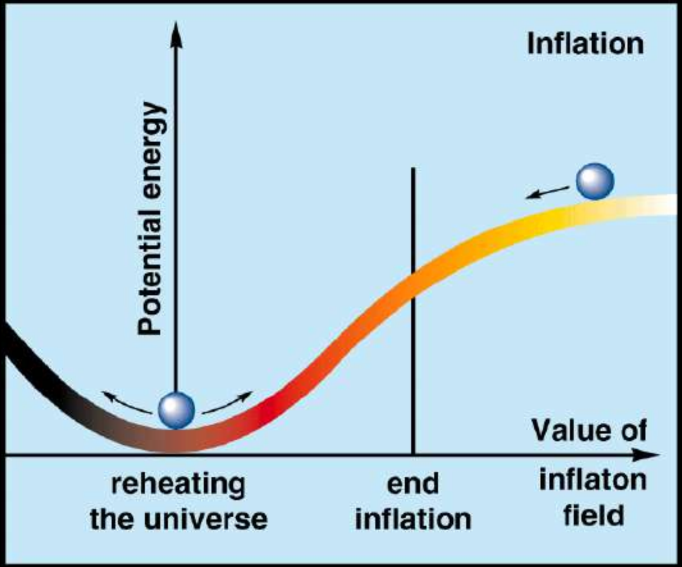
- Fails for large couplings
- Doesn't take into account collective effects
- Not fast enough

Preheating

Non-perturbative

- Parametric resonance
- Tachyonic resonance





[J. Gavrcia-Bellido (1999)]

Parametric resonance

Mode functions of quantized perturbations obey:

$$\partial_t{}^2 \chi_k + \omega^2(k,t)\chi_k = 0$$

$$\chi_k(t) = e^{\mu_k t}\mathcal{P}_{k+}(t) + e^{-\mu_k t}\mathcal{P}_{k-}(t) \quad ,$$

$$\mathcal{P}_{k\pm}(t) = \mathcal{P}_{k\pm}(t+T)$$

$$\mathcal{R}e(\mu_k) \neq 0$$

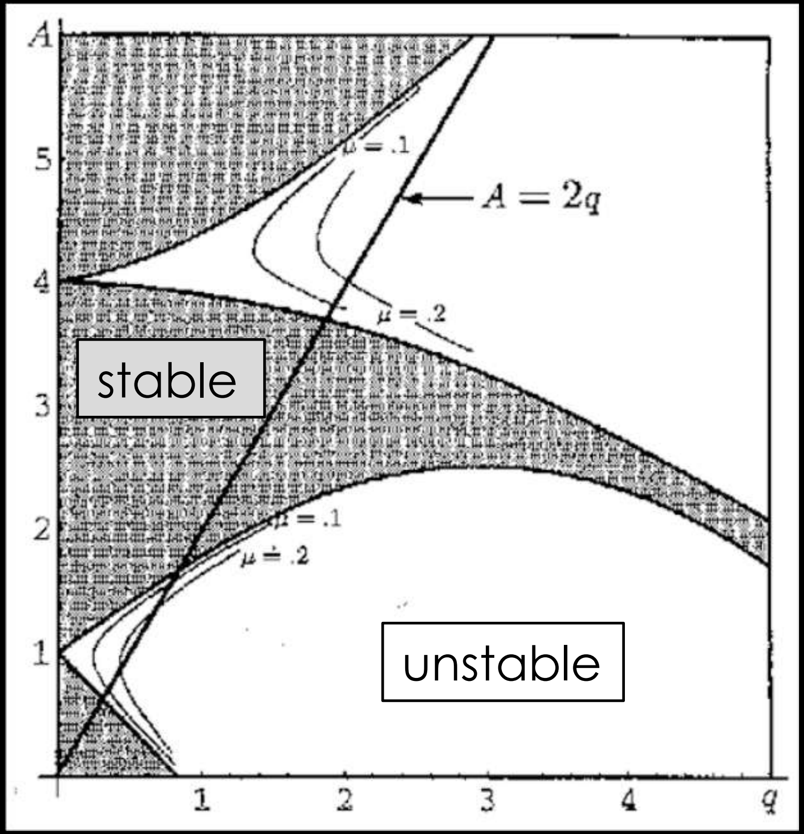
If $\omega^2(k,t)$ evolves harmonically

$$\partial_\tau{}^2 \chi_k + (A_k - 2q\cos 2\tau)\chi_k = 0$$

the Mathieu equation

static universe approximation

instability chart



[L. Kofman at al (1994)]

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$$\boxed{\mathcal{R}e(\mu_k) \neq 0}$$ exponential amplification

If $\omega^2(k,t)$ evolves harmonically

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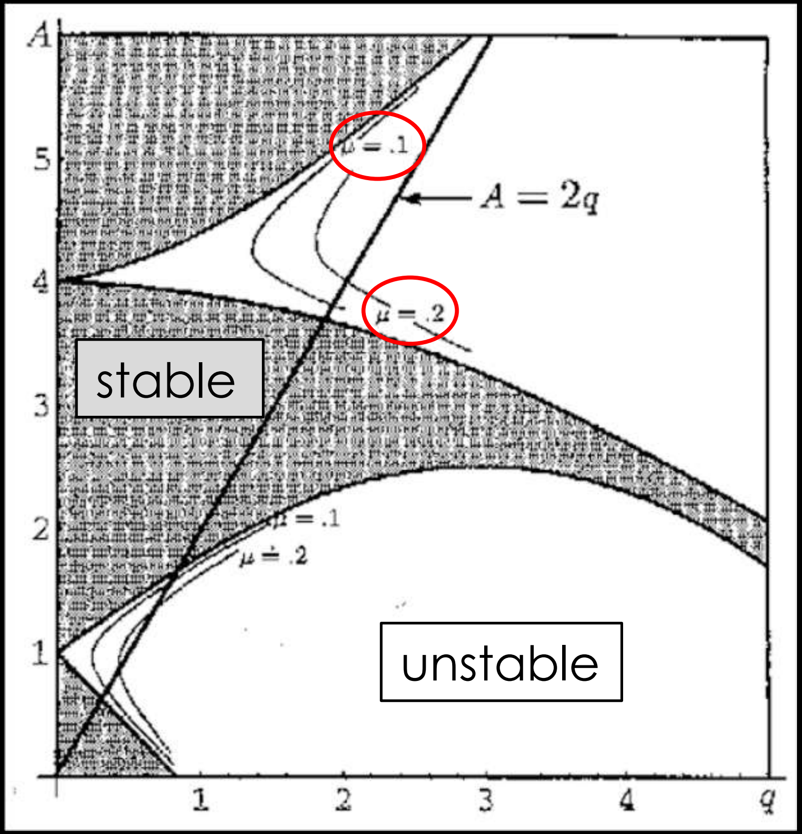

[L. Kofman at al (1994)]

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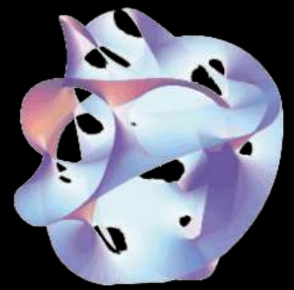
Multi-field inflation

Energy scale of the very early universe could be as high as $10^{15}\mathrm{GeV}$.



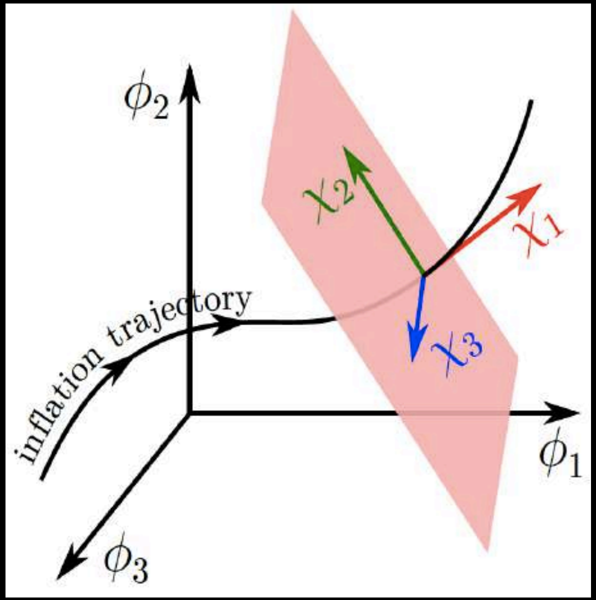
Could contain multiple scalar fields to participate in inflationary dynamics.

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R - \frac{1}{2}\mathcal{G}_{\mathcal{IJ}}(\phi^K)g^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^J - V(\phi^I)\right]$$

field-space metric — potential

Two types of perturbations:

- Adiabatic (curvature)
- Non-Adiabatic (isocurvature)



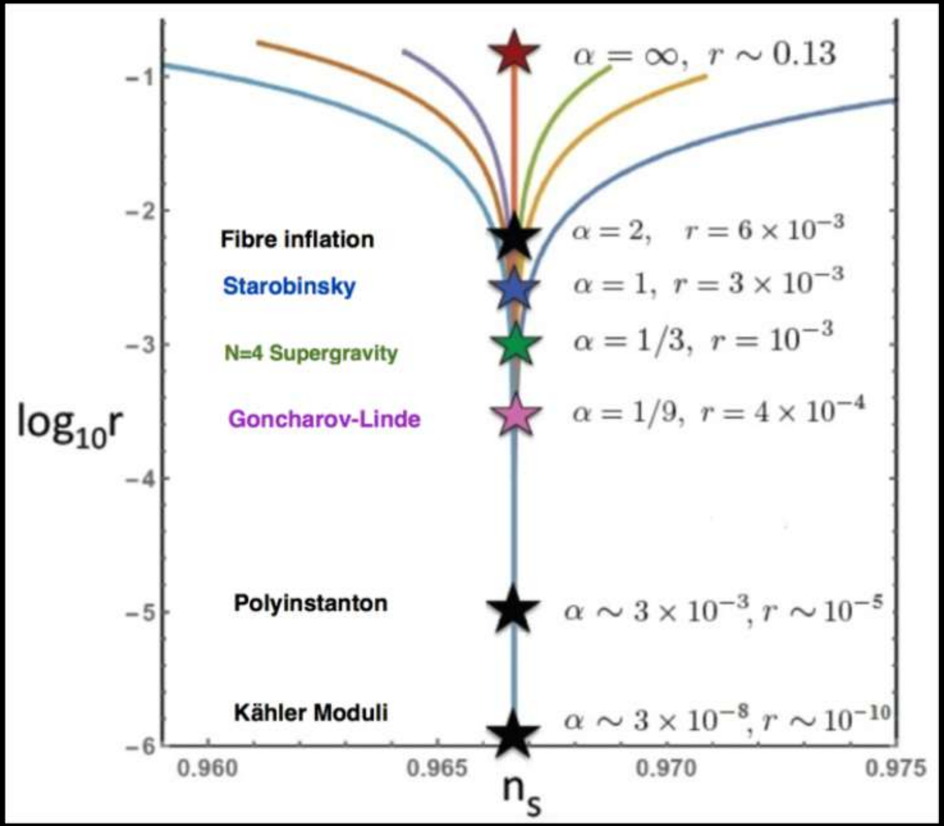
[figure courtesy Yi Wang]

Derivative interaction/random trajectory turns:
couple the fluctuations and modify their dispersion relations and correlators.

Hyperbolic manifolds from UV completions

[R. Kallosh, A. Linde (2013)]
[S. Ferrara, R. Kallosh, A. Linde and M. Porrati (2013)]
[J. J. M. Carrasco, R. Kallosh, A. Linde and D. Roest (2015)]

- ✓ Supergravity
- ✓ String theory compactification: Fibre inflation
- ✓ …



$$V \approx V_0 \left(1 - 2e^{-\sqrt{2}\phi/\sqrt{3\alpha}} + \ldots\right)$$

Flattening of the potential is due to hyperbolic manifolds

$$n_s = 1 - \frac{2}{N_*} \qquad r = \frac{12\alpha}{N_*^2}$$

alpha-attractors provide universal inflationary predictions

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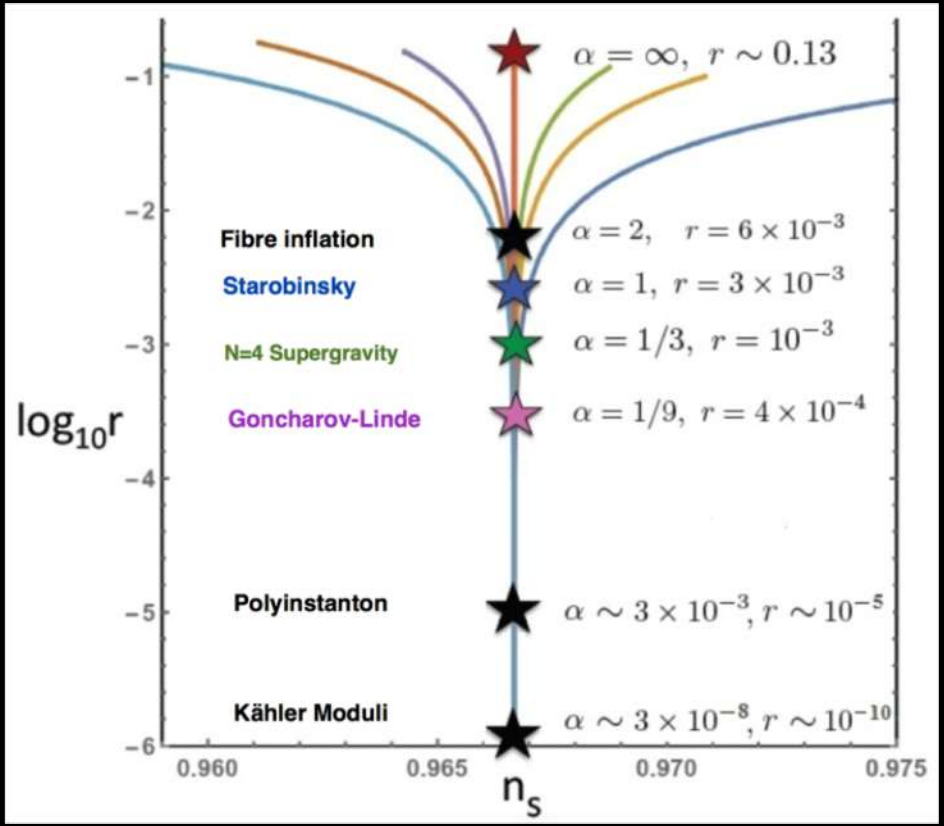

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alpha-attractors provide universal inflationary predictions

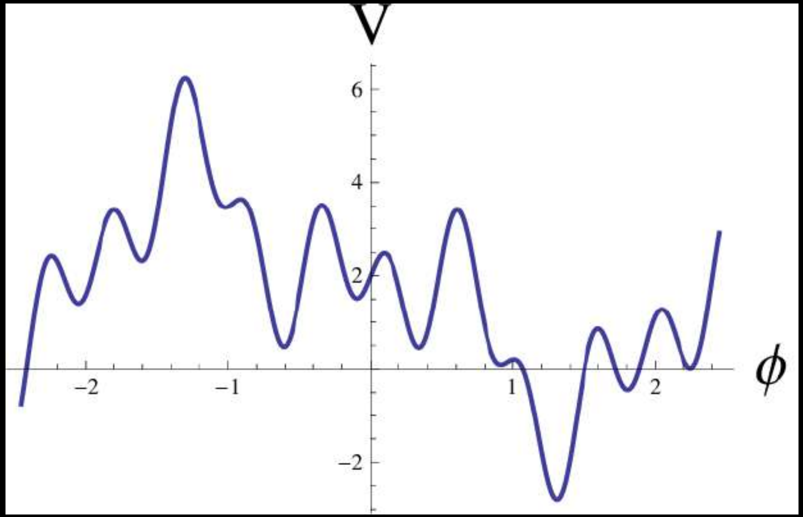
Alpha-attractors as plateau models of inflation

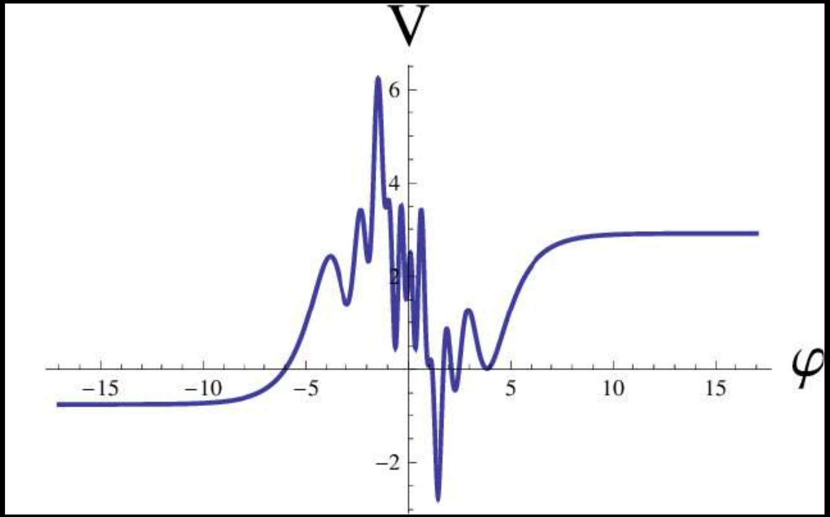
[R. Kallosh, A. Linde (2013)]

The inflationary plateau appears because of the exponential stretching of the growing branch.

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{(\partial\phi)^2}{(1-\frac{\phi^2}{6\alpha})^2} - V(\phi)$$

$$\frac{\partial\phi}{(1-\frac{\phi^2}{6\alpha})} = \partial\varphi \qquad \phi = \sqrt{6\alpha}\tanh\frac{\varphi}{\sqrt{6\alpha}} \qquad V_{dS} = V(\phi)\big|_{\phi=\pm\sqrt{6\alpha}}$$





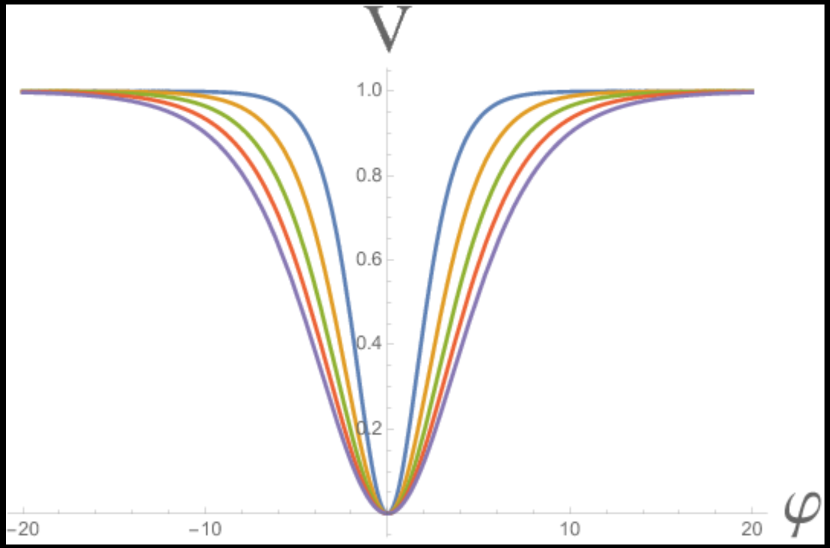
Oksana Iarygina, Leiden University

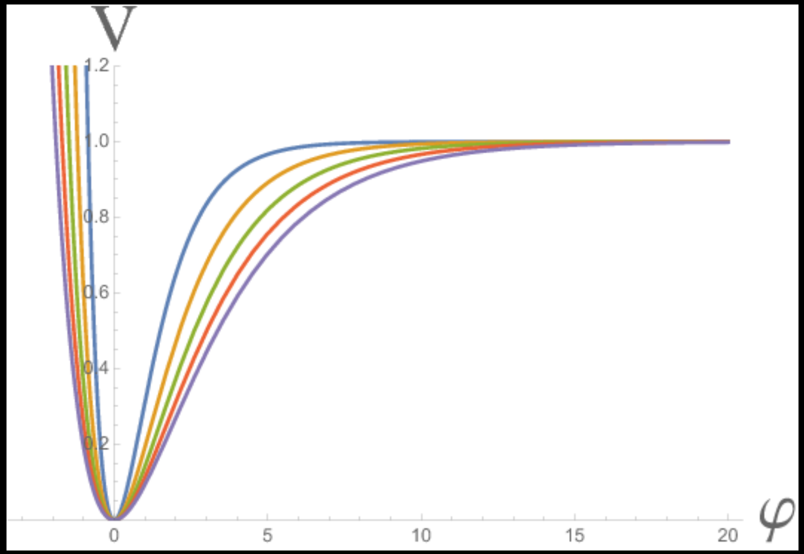
T- and E-models as the prototypical workhorses

[J. J. M. Carrasco, R. Kallosh, A. Linde (2015)]

$$V_T = \alpha\mu^2 \tanh^{2n} \frac{\phi}{\sqrt{6\alpha}}$$

$$V_E = \alpha\mu^2 \left(1 - e^{-\sqrt{2}\phi/\sqrt{3\alpha}}\right)^{2n}$$





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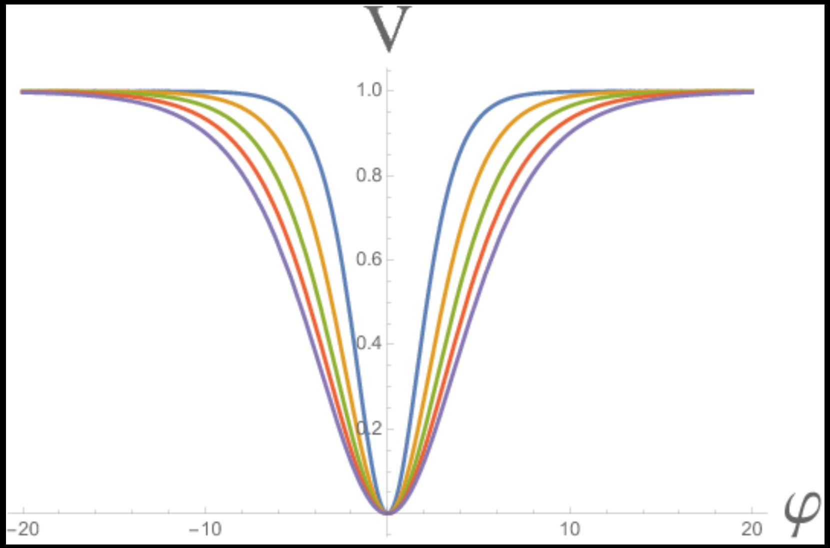

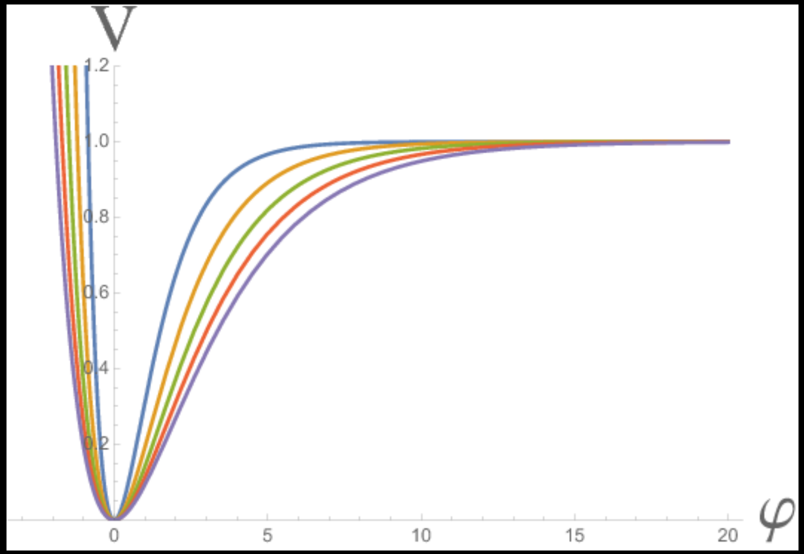

α field-space curvature $^{-1}$

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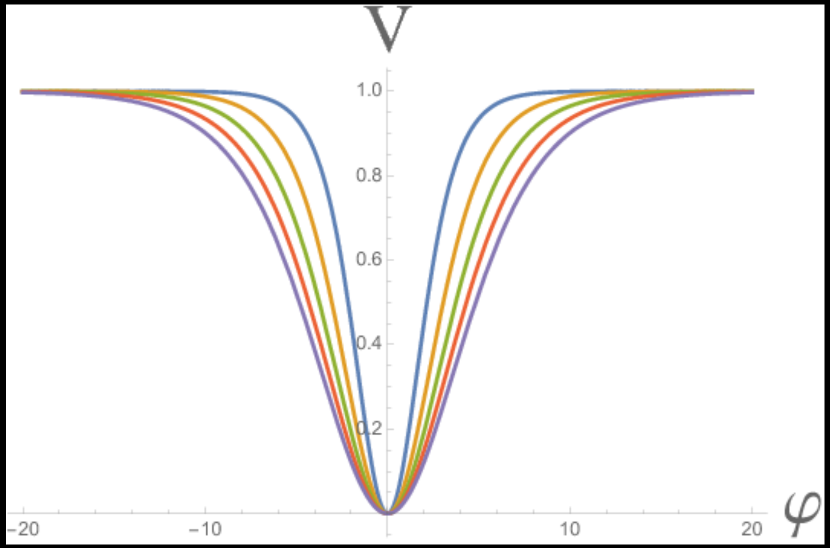
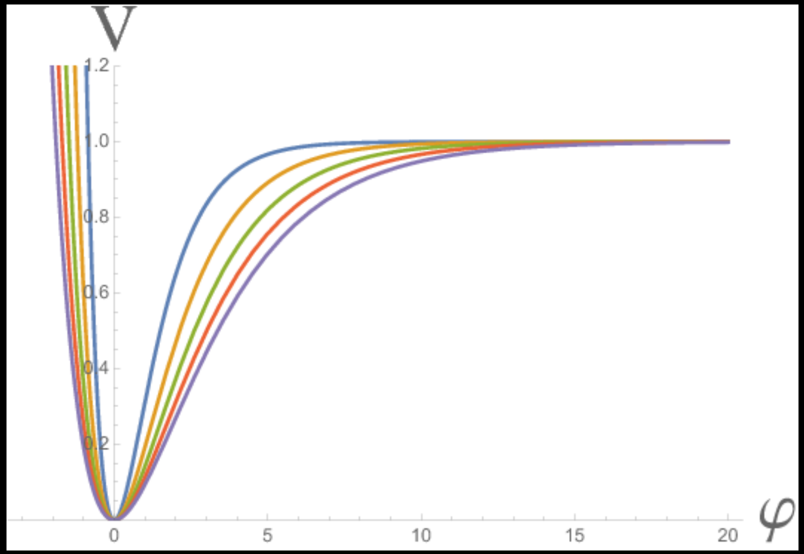




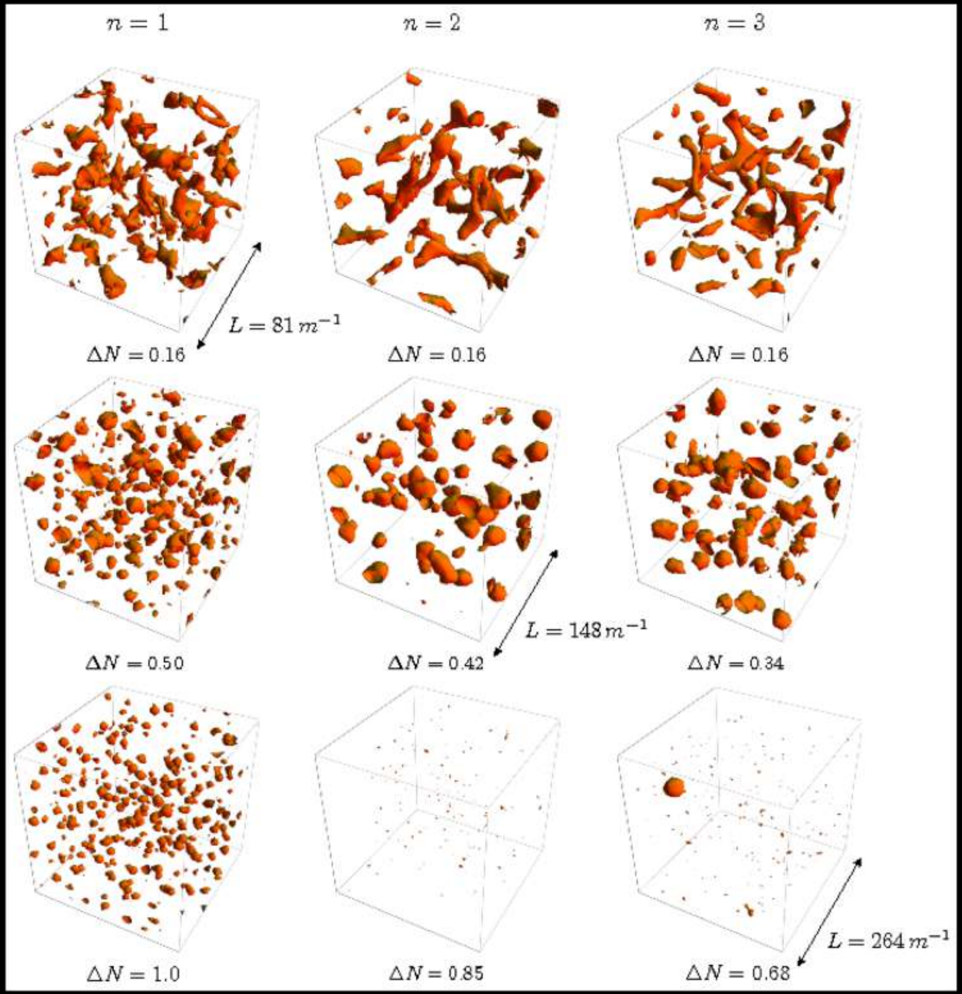
α field-space curvature $^{-1}$

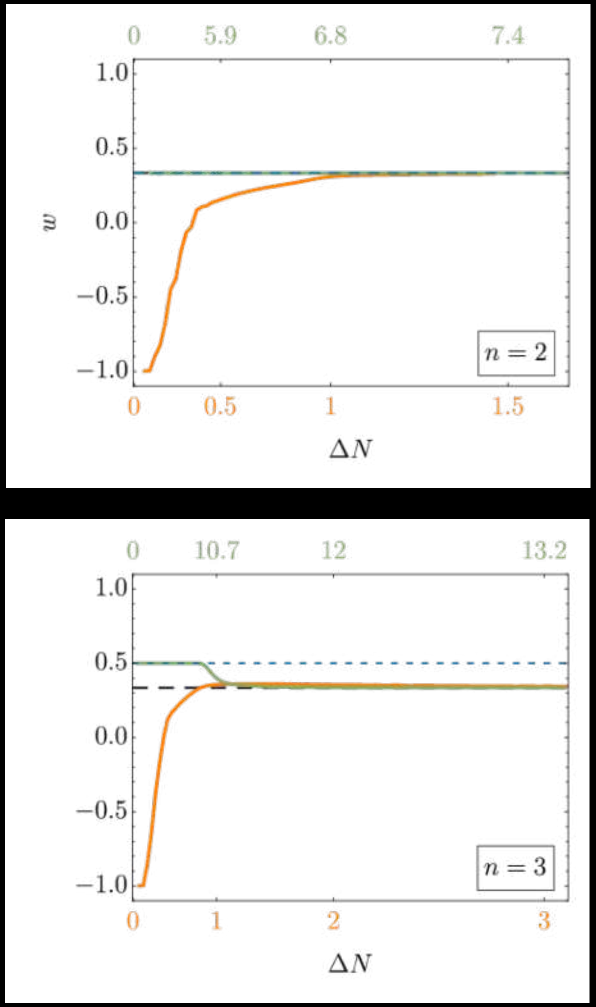
n potential steepness

Lattice simulations for single field alpha attractors

[K. D. Lozanov, M. A. Amin (2017)]

efficient preheating through inflaton self-resonance





Alpha-attractors are intrinsically multi-field models

[J. J. M. Carrasco, R. Kallosh, A. Linde (2015)]

N = 1 Supergravity embedding:

the super-potential

$$W_H = \sqrt{\alpha}\mu\, S\, F(Z)$$

T-model

$$F(Z) = Z^n$$

$$\cos(\beta\theta) = \frac{1}{\cosh(\beta\chi)}$$

$$Z = \tanh\left(\frac{\phi + i\theta}{\sqrt{6\alpha}}\right)$$

$$V(\phi,\chi) = \alpha\mu^2 \left(\frac{\cosh(\beta\phi)\cosh(\beta\chi) - 1}{\cosh(\beta\phi)\cosh(\beta\chi) + 1}\right)^n (\cosh(\beta\chi))^{2/\beta^2}$$

E-model

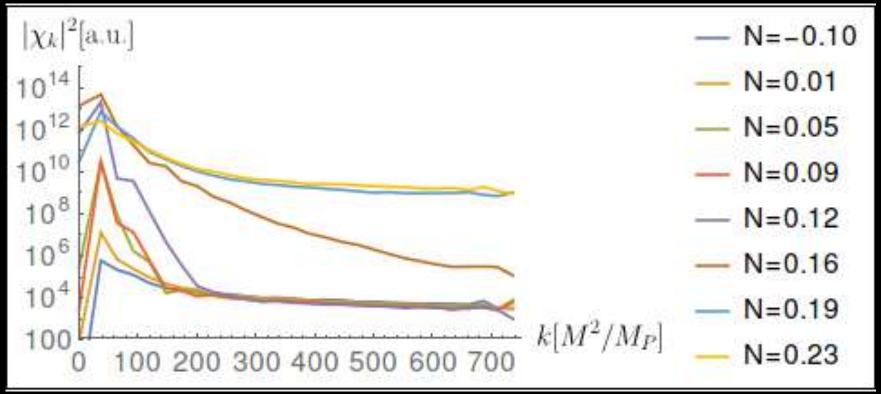
$$F(Z) = \left(\frac{2Z}{Z+1}\right)^n$$

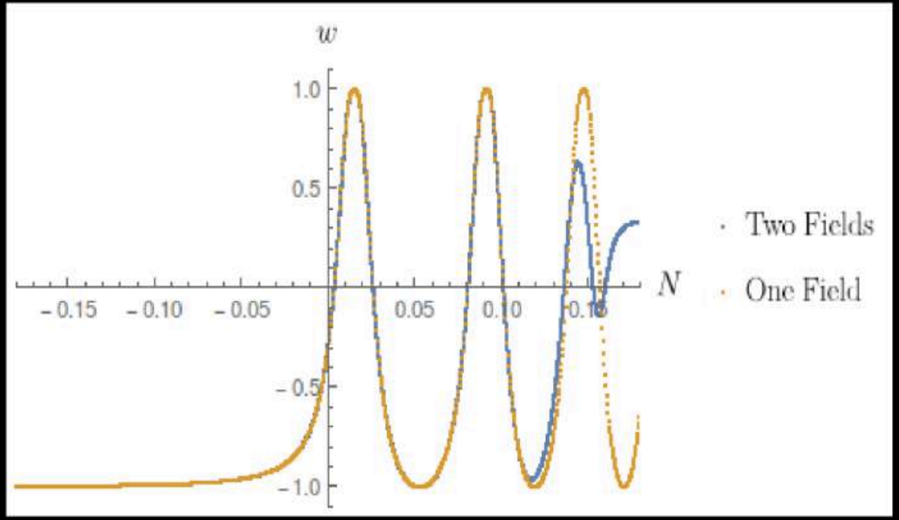
$$\beta = \sqrt{\frac{2}{3\alpha}}$$

$$V(\phi,\chi) = \alpha\mu^2 \left(1 - \frac{2e^{-\beta\phi}}{\cosh(\beta\chi)} + e^{-2\beta\phi}\right)^n (\cosh(\beta\chi))^{2/\beta^2}$$

Lattice simulations for two-field alpha attractors

[T. Krajewski, K. Turzynski, M. Wieczorek (2018)]





showed very efficient preheating with the presence of spectator field

- Why do we need to know the physics of (p)reheating? ✓
- Why multi-field? ✓
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Two-field system on a hyperbolic manifold

[OI, E. Sfakianakis, D.G. Wang, A. Achucarro (2020)]
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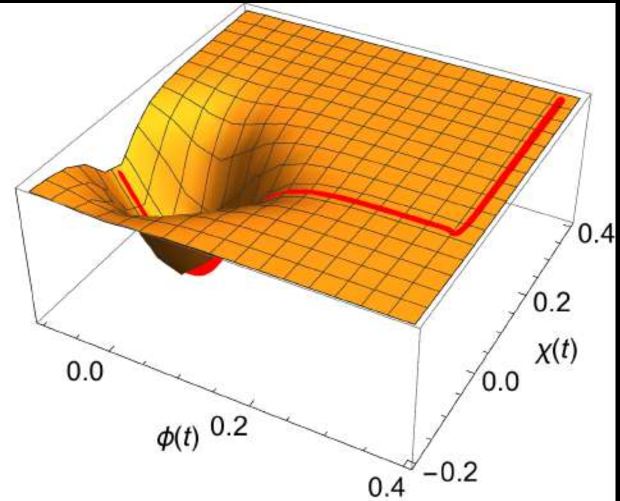
$$\mathcal{L} = -\frac{1}{2}\left(\partial_\mu\chi\partial^\mu\chi + e^{2b(\chi)}\partial_\mu\phi\partial^\mu\phi\right) - V(\phi,\chi)$$

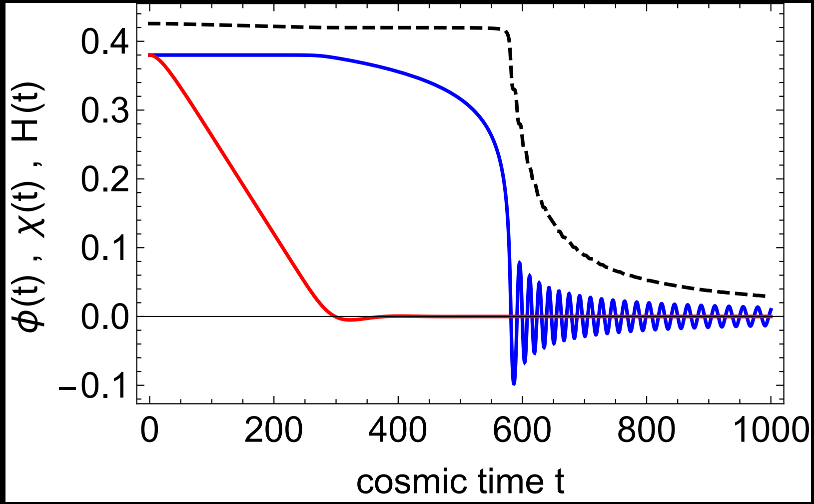
$$b(\chi) = \log\left(\cosh(\beta\chi)\right)$$

$$\beta = \sqrt{2/3\alpha} \quad , \quad \mathcal{R} = -\frac{4}{3\alpha}$$

$$V(\phi,\chi=0) = \alpha\mu^2\left(\tanh^2(\beta\phi/2)\right)^n$$

- The two-stage inflation leading to single-field motion at $\chi = 0$
- The same single-field attractor for broad IC's





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curvature of the field-space

$$V(\phi,\chi=0) = \alpha\mu^2\left(\tanh^2(\beta\phi/2)\right)^n$$

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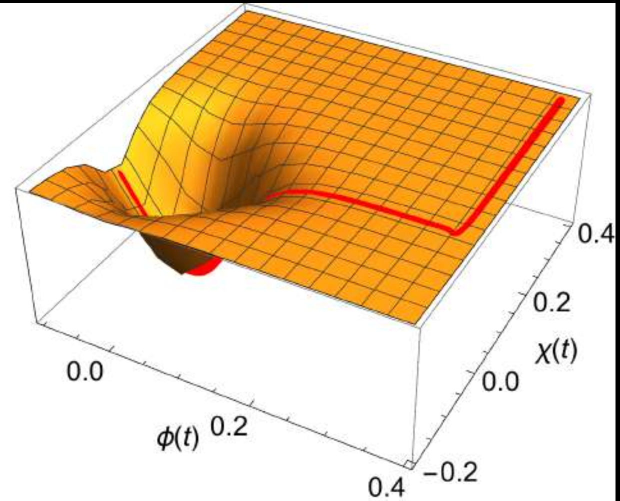

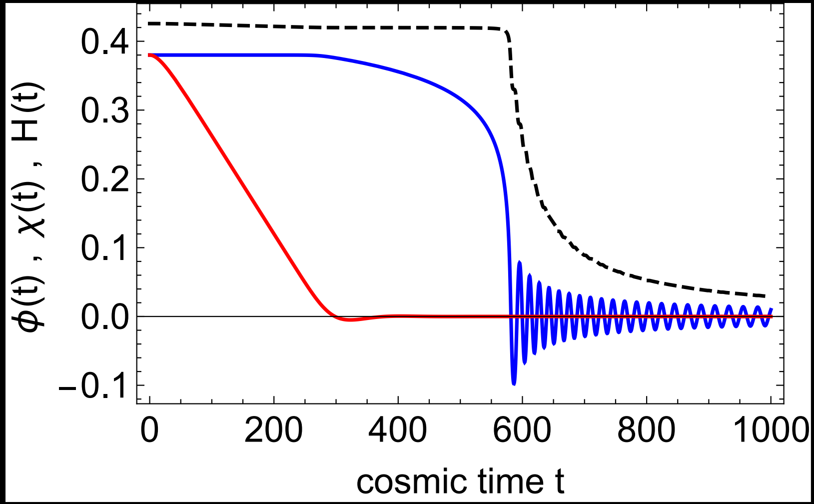

Scaling relations for background quantities

[OI, E. Sfakianakis, D.G. Wang, A. Achucarro (2020)]
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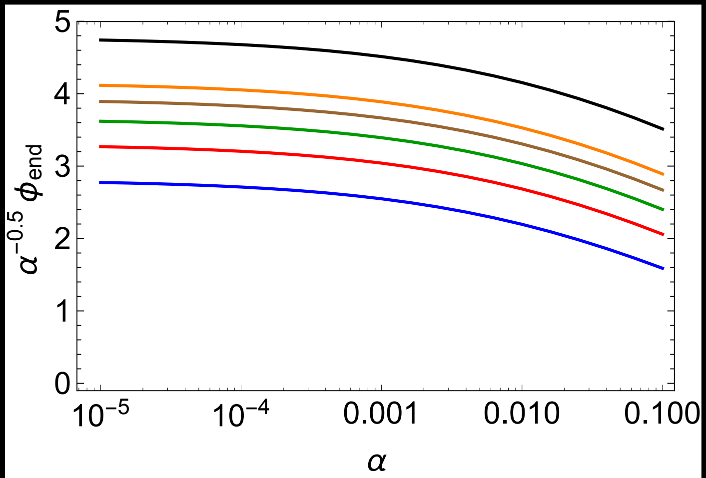
α field-space curvature $^{-1}$
n potential steepness

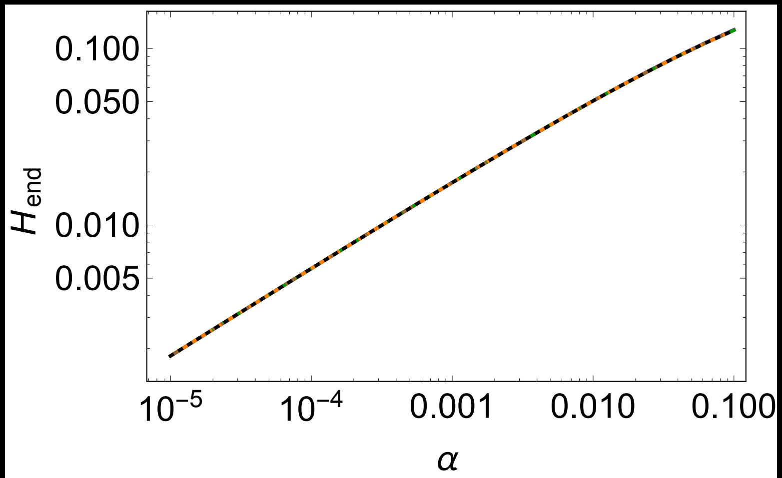
- in the slow-roll approximation and for $\phi \gg \sqrt{\alpha}$:

$$3H^2 \simeq \frac{\alpha}{M_{\rm Pl}^2}\mu^2 \qquad \epsilon \equiv -\frac{\dot{H}}{H^2} \simeq \frac{3\alpha}{4N^2}$$

$$N = \frac{3\alpha}{8n}e^{\beta\phi} \qquad \eta \equiv \frac{\dot{\epsilon}}{\epsilon H} \simeq \frac{2}{N}$$

$$\boxed{\phi_{\rm end} = \mathcal{O}(1)\sqrt{\alpha}} \qquad \boxed{H_{\rm end}^2 = \mathcal{O}(1)\,\alpha\mu^2}$$





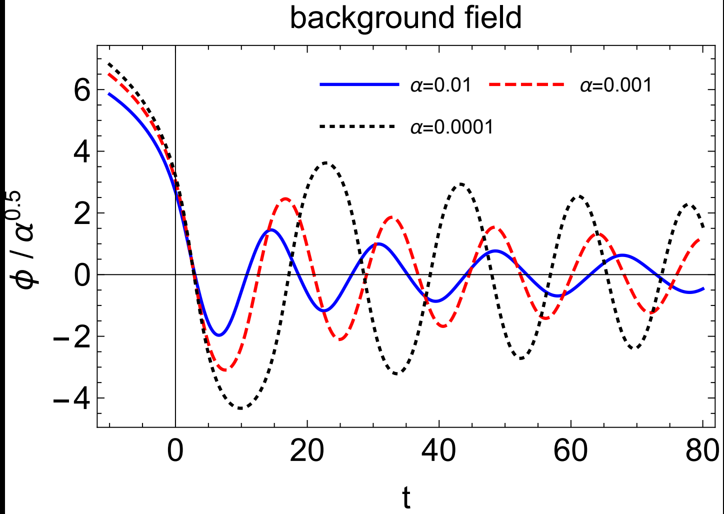
$n = 1, 1.5, 2, 2.5, 3, 5$ (bottom to top)

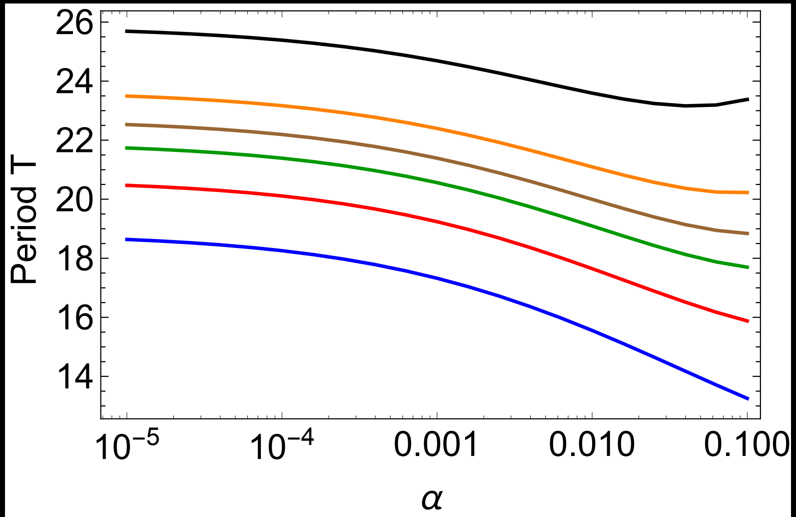
The scale hierarchy

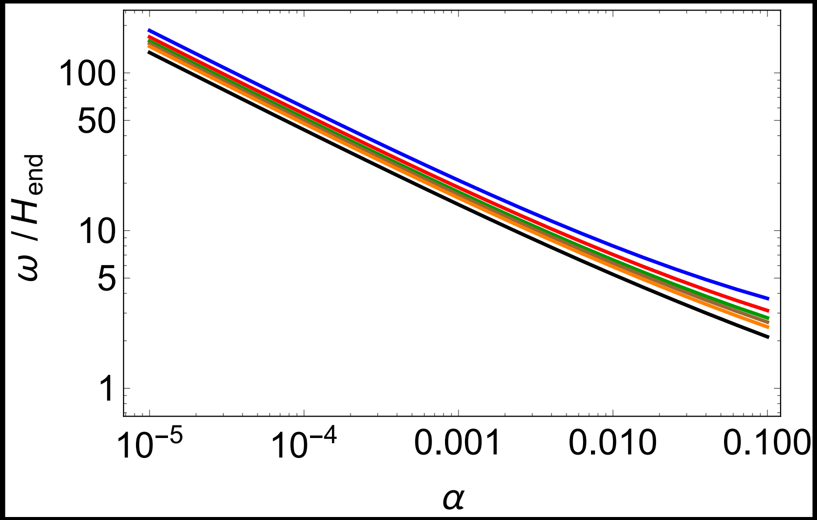
- More background oscillations occur per Hubble time for smaller values of alpha.
- For small alphas the Hubble scale can be neglected, as it takes a large number of background oscillations for any considerable red-shifting to occur.

$T \simeq 20$

$\omega \propto H_{\text{end}}/\sqrt{\alpha}$







$n = 1, 1.5, 2, 2.5, 3, 5$ (bottom to top)

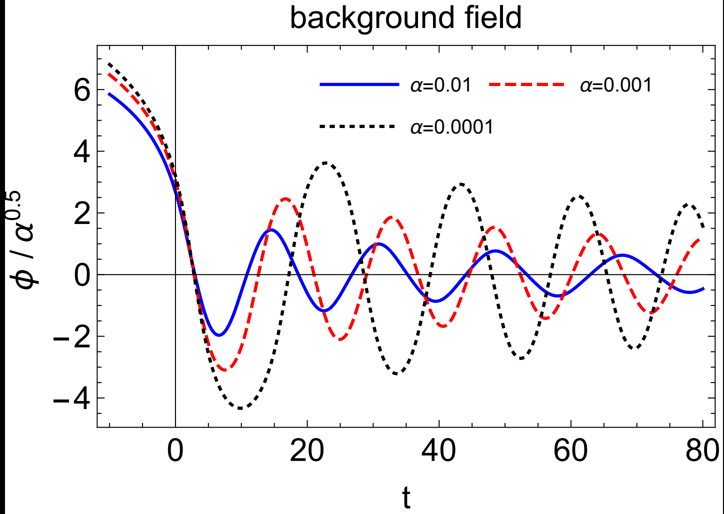
The scale hierarchy

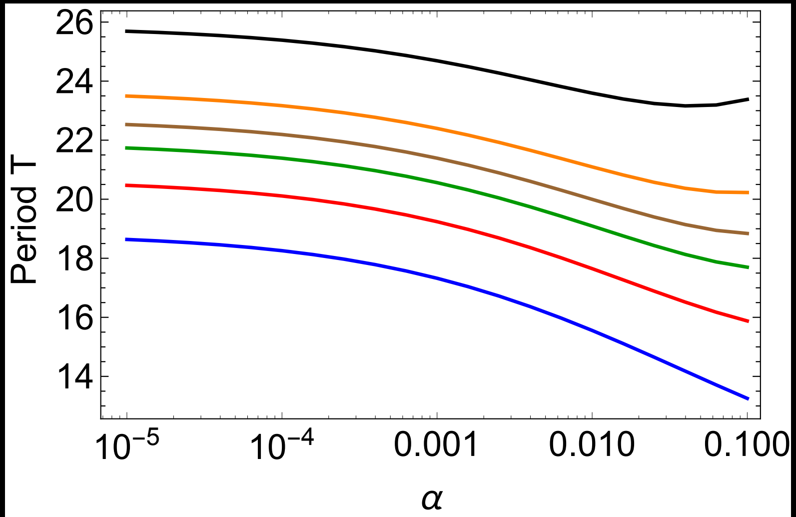
- More background oscillations occur per Hubble time for smaller values of alpha.
- For small alphas the Hubble scale can be neglected, as it takes a large number of background oscillations for any considerable red-shifting to occur.

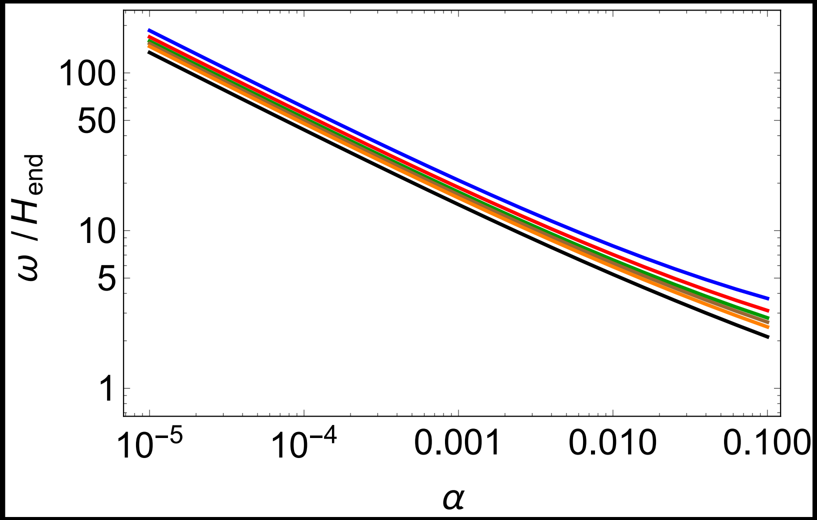
amplification factor per oscillation?

$T \simeq 20$

$\omega \propto H_{\rm end}/\sqrt{\alpha}$







$n = 1, 1.5, 2, 2.5, 3, 5$ (bottom to top)

Additional mass scale for multi-field perturbations

[H. Kodama and M. Sasaki (1984)]
[M. Sasaki, E. D. Stewart (1995)]
[D. Langlois and S. Renaux-Petel (2008)]
[D. I. Kaiser, E. A. Mazenc, and E. I. Sfakianakis (2013)]

Background fields:

$$\mathcal{D}_t\dot{\phi}^I + 3H\dot{\phi}^I + \mathcal{G}^{IK}V_{,K} = 0$$

Perturbaations:

$$\phi^I(x^\mu) = \varphi^I(t) + \delta\phi(x^\mu) \qquad Q^I \equiv \delta\phi^I + \frac{\dot{\phi}^I}{H}\psi$$

$$\mathcal{D}_t^2 Q^I + 3H\mathcal{D}_t Q^I + \left[\frac{k^2}{a^2}\delta^I{}_J + \mathcal{M}^I{}_J\right]Q^J = 0$$

$$\boxed{\mathcal{M}^I{}_J \equiv \mathcal{G}^{IK}(\mathcal{D}_I\mathcal{D}_K V) - \mathcal{R}^I_{LMI}\dot{\varphi}^L\dot{\varphi}^M - \frac{1}{M_{\rm pl}^2 a^3}\mathcal{D}_t\left(\frac{a^3}{H}\dot{\varphi}^I\dot{\varphi}_J\right)}$$

potential + field-space + kinematical effects

Evolution of fluctuations

$$\mathcal{G}_{IJ}(\chi = 0) = \delta_{IJ}$$
$$\Gamma^I_{JK} = 0$$

$$u^\phi \equiv v$$
$$u^\chi \equiv z$$

Quantization:

$$Q^I(x^\mu) \to X^I(x^\mu)/a(t) \qquad \hat{X}^I = \int \frac{d^3k}{(2\pi)^{3/2}} \left[u^I(k,\eta)\hat{a}e^{ik\cdot x} + u^{I*}(k,\eta)\hat{a}^\dagger e^{-ik\cdot x} \right]$$

$$\partial^2_\eta v_k + (k^2 + a^2 m^2_{\mathrm{eff},\phi})v_k = 0$$

$$\partial^2_\eta z_k + (k^2 + a^2 m^2_{\mathrm{eff},\chi})z_k = 0$$

$$m^2_{\mathrm{eff},I} = \mathcal{G}^{IK}(\mathcal{D}_I\mathcal{D}_K V) - \mathcal{R}^I_{LMI}\dot{\varphi}^L\dot{\varphi}^M - \frac{1}{M^2_{\mathrm{pl}}a^3}\delta^I_K\delta^J_I\mathcal{D}_t\left(\frac{a^3}{H}\dot{\varphi}^K\dot{\varphi}_J\right) - \frac{1}{6}R$$

potential + field-space + kinematics + space-time

Evolution of fluctuations

$$m^2_{1,\phi} = V_{\phi\phi}\,, \quad m^2_{1,\chi} = V_{\chi\chi}$$

$$m^2_{2,\chi} = \frac{1}{2} R \dot{\phi}^2$$

$$m^2_{3,\phi} = -\frac{1}{M^2_{\rm Pl} a^3} \mathcal{D}_t \left(\frac{a^3}{H} \dot{\phi}^2 \right)$$

$$m^2_{4,\phi} = m^2_{4,\chi} = -\frac{1}{6} R$$

$$\partial^2_\eta v_k + (k^2 + a^2 m^2_{\text{eff},\phi}) v_k = 0$$

$$\partial^2_\eta z_k + (k^2 + a^2 m^2_{\text{eff},\chi}) z_k = 0$$

$$m^2_{\text{eff},I} = \mathcal{G}^{IK}(\mathcal{D}_I \mathcal{D}_K V) - \mathcal{R}^I_{LMI} \dot{\varphi}^L \dot{\varphi}^M - \frac{1}{M^2_{\rm pl} a^3} \delta^I_K \delta^J_I \mathcal{D}_t \left(\frac{a^3}{H} \dot{\varphi}^K \dot{\varphi}_J \right) - \frac{1}{6} R$$

$$m^2_{\text{eff},\phi} = m^2_{1,\phi} + m^2_{2,\phi} + m^2_{3,\phi} + m^2_{4,\phi}$$

$$m^2_{\text{eff},\chi} = m^2_{1,\chi} + m^2_{2,\chi} + m^2_{3,\chi} + m^2_{4,\chi}$$

Effective mass terms and scaling

$$m_{1,\phi}^2 = V_{\phi\phi}\,, \quad m_{1,\chi}^2 = V_{\chi\chi}$$

$$m_{2,\chi}^2 = \frac{1}{2} R \dot{\phi}^2$$

$$m_{3,\phi}^2 = -\frac{1}{M_{\rm Pl}^2 a^3} \mathcal{D}_t \left(\frac{a^3}{H} \dot{\phi}^2 \right)$$

$$m_{4,\phi}^2 = m_{4,\chi}^2 = -\frac{1}{6} R$$

$$\partial_\eta^2 v_k + (k^2 + a^2 m_{\text{eff},\phi}^2) v_k = 0$$

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$$m_{\text{eff},I}^2 = \mathcal{G}^{IK} (\mathcal{D}_I \mathcal{D}_K V) - \mathcal{R}^I_{LMI} \dot{\varphi}^L \dot{\varphi}^M - \frac{1}{M_{\rm pl}^2 a^3} \delta^I_K \delta^J_I \mathcal{D}_t \left(\frac{a^3}{H} \dot{\varphi}^K \dot{\varphi}_J \right) - \frac{1}{6} R$$

$$m_{\text{eff},\phi}^2 = m_{1,\phi}^2 + \cancel{m_{2,\phi}^2} + m_{3,\phi}^2 + m_{4,\phi}^2$$

$$m_{\text{eff},\chi}^2 = m_{1,\chi}^2 + m_{2,\chi}^2 + \cancel{m_{3,\chi}^2} + m_{4,\chi}^2$$

$$m_{3,\chi}^2 = 0 = m_{2,\phi}^2$$

Effective mass terms and scaling

$$m^2_{1,\phi} = V_{\phi\phi}\,, \quad m^2_{1,\chi} = V_{\chi\chi}$$

$$m^2_{2,\chi} = \frac{1}{2} R \dot{\phi}^2$$

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$$m^2_{4,\phi} = m^2_{4,\chi} = -\frac{1}{6} R$$

$$\partial_\eta^2 v_k + (k^2 + a^2 m^2_{{\rm eff},\phi}) v_k = 0$$

$$\partial_\eta^2 z_k + (k^2 + a^2 m^2_{{\rm eff},\chi}) z_k = 0$$

$$m^2_{{\rm eff},I} = \mathcal{G}^{IK}(\mathcal{D}_I \mathcal{D}_K V) - \mathcal{R}^I_{LMI} \dot{\varphi}^L \dot{\varphi}^M - \frac{1}{M_{\rm pl}^2 a^3} \delta^I_K \delta^J_I \mathcal{D}_t \left(\frac{a^3}{H} \dot{\varphi}^K \dot{\varphi}_J \right) - \frac{1}{6} R$$

$$R = 6(2-\epsilon) H^2$$

$$m^2_{{\rm eff},\phi} = m^2_{1,\phi} + m^2_{2,\phi} + m^2_{3,\phi} + m^2_{4,\phi}$$

$$m^2_{{\rm eff},\chi} = m^2_{1,\chi} + m^2_{2,\chi} + m^2_{3,\chi} + m^2_{4,\chi}$$

$$m^2_{3,\chi} = 0 = m^2_{2,\phi}$$

$$m^2_{3,\phi} \sim \mu^2 \sqrt{\tilde{\alpha}}$$

$$m^2_{4,\phi} = m^2_{4,\chi} \sim \mu^2 \tilde{\alpha}$$

vanish for $\alpha \ll 1$

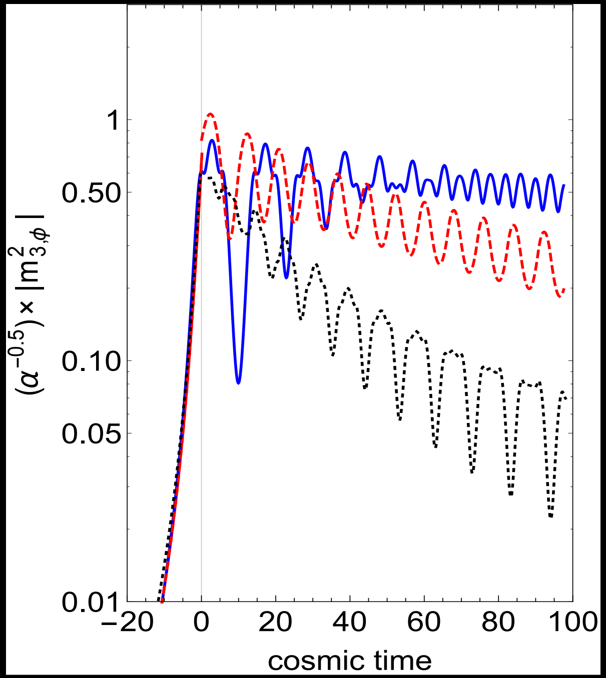
Effective mass terms and scaling

$$m^2_{\mathrm{eff},\phi} = m^2_{1,\phi} + m^2_{2,\phi} + m^2_{3,\phi} + m^2_{4,\phi}$$

$$m^2_{\mathrm{eff},\chi} = m^2_{1,\chi} + m^2_{2,\chi} + m^2_{3,\chi} + m^2_{4,\chi}$$

$$m^2_{3,\phi} \sim \mu^2 \sqrt{\tilde{\alpha}}$$

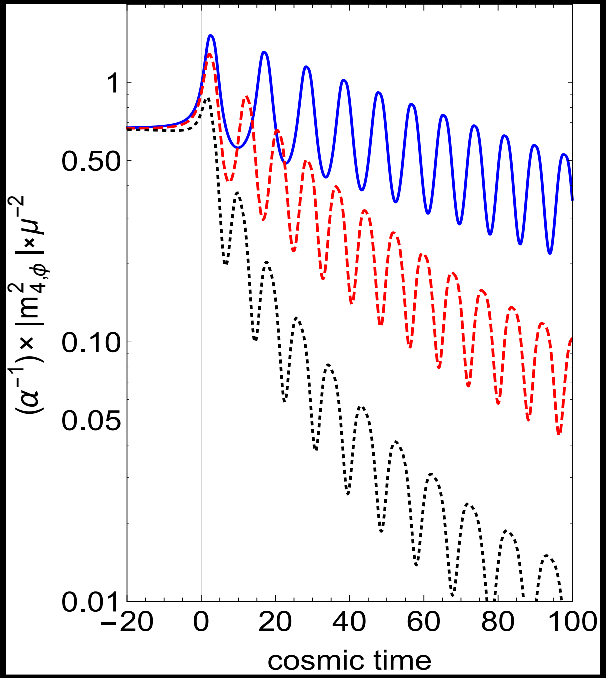
$$m^2_{4,\phi} = m^2_{4,\chi} \sim \mu^2 \tilde{\alpha}$$



$\alpha = 10^{-4}$

$\alpha = 10^{-3}$

$\alpha = 10^{-2}$



Oksana Iarygina, Leiden University

Effective mass terms and scaling for hyperbolic manifolds

Our focus: fluctuations $\delta\chi$ can undergo tachyonic excitation, more efficient than parametric amplification and is a truly multi-field phenomenon with a crucial dependence on the field-space geometry.

$$\rho_k^{(\phi)} = \frac{1}{2}\left[|v_k'|^2 + \left(k^2 + a^2 m_{\text{eff},\phi}^2\right)|v_k|^2\right]$$

$$\rho_k^{(\chi)} = \frac{1}{2}\left[|z_k'|^2 + \left(k^2 + a^2 m_{\text{eff},\chi}^2\right)|z_k|^2\right]$$

$$m_{\text{eff},\phi}^2 \simeq V_{\phi\phi}(\chi = 0)$$

$$m_{\text{eff},\chi}^2 \simeq V_{\chi\chi}(\chi = 0) + \frac{1}{2}\mathcal{R}\dot{\phi}^2$$

$$\mathcal{R} = -4/3\alpha$$

the field space
Ricci curvature scalar

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$$\rho_k^{(\chi)} = \frac{1}{2}\left[|z_k'|^2 + \left(k^2 + a^2 m_{\text{eff},\chi}^2\right)|z_k|^2\right]$$

$$m_{\text{eff},\phi}^2 \simeq V_{\phi\phi}(\chi = 0)$$

$$m_{\text{eff},\chi}^2 \simeq V_{\chi\chi}(\chi = 0) + \frac{1}{2}\mathcal{R}\dot{\phi}^2$$

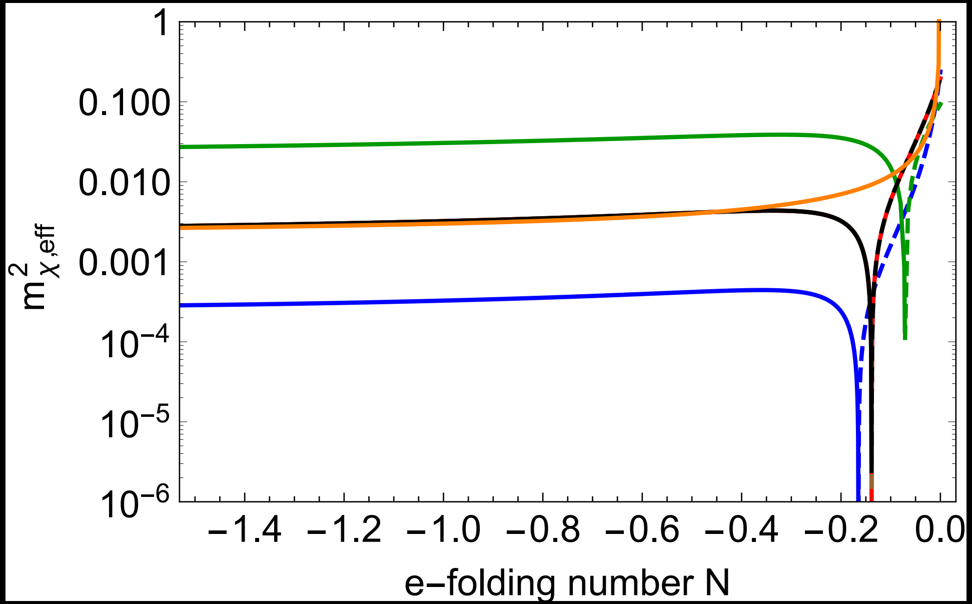
$$\mathcal{R} = -4/3\alpha$$

tachyonic vs parametric resonance

Geometrical destabilization

[S. Renaux-Petel and K. Turzynski (2016)]

Alpha-attractors are safe against geometric destabilization effects until close to the end of inflation.



During inflation the effective super-horizon isocurvature mass in the slow-roll approximation

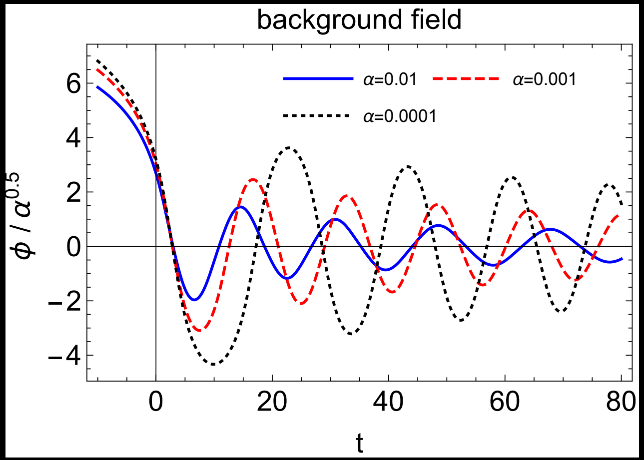
$$m^2_{\chi,\mathrm{eff}} \simeq \left(2 + \frac{1}{N}\right)\alpha$$

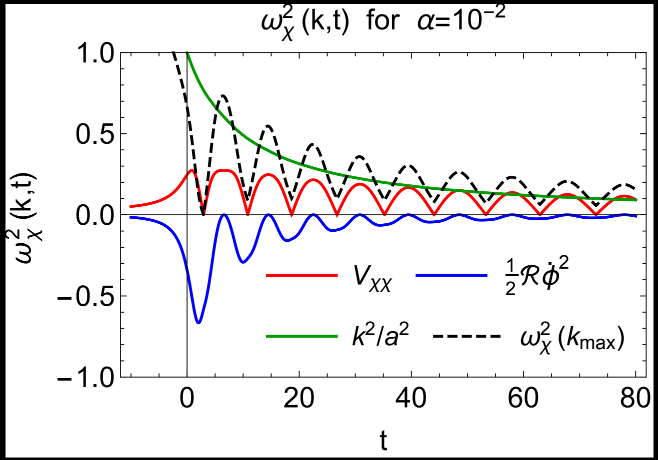
- Inflationary background is safe
- Geometrical destabilization leads to efficient preheating

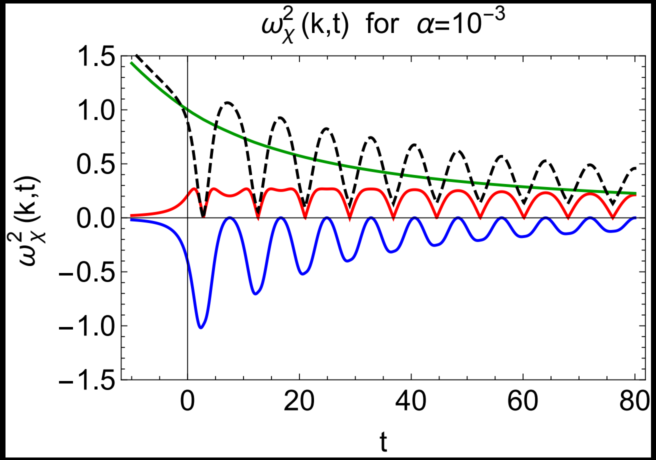
Effective frequency

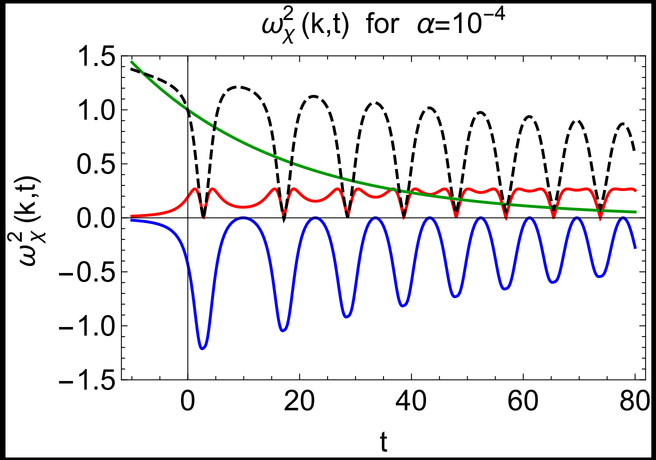
$$\omega_\chi{}^2(k,t) = \frac{k^2}{a^2} + V_{\chi\chi}(\chi=0) + \frac{1}{2}\mathcal{R}\dot{\phi}^2$$

$$\frac{1}{2}\mathcal{R}\dot{\phi}^2 \propto -\frac{1}{\alpha} \times \left(\frac{\sqrt{\alpha}}{\mathcal{O}(1)}\right)^2 = -\mathcal{O}(1)$$









WKB approximation

$$\partial_t^2 \chi_k + \omega_\chi^2(k,t)\,\chi_k = 0$$

$$\Omega_k^2(t) = -\omega_k^2(t)$$

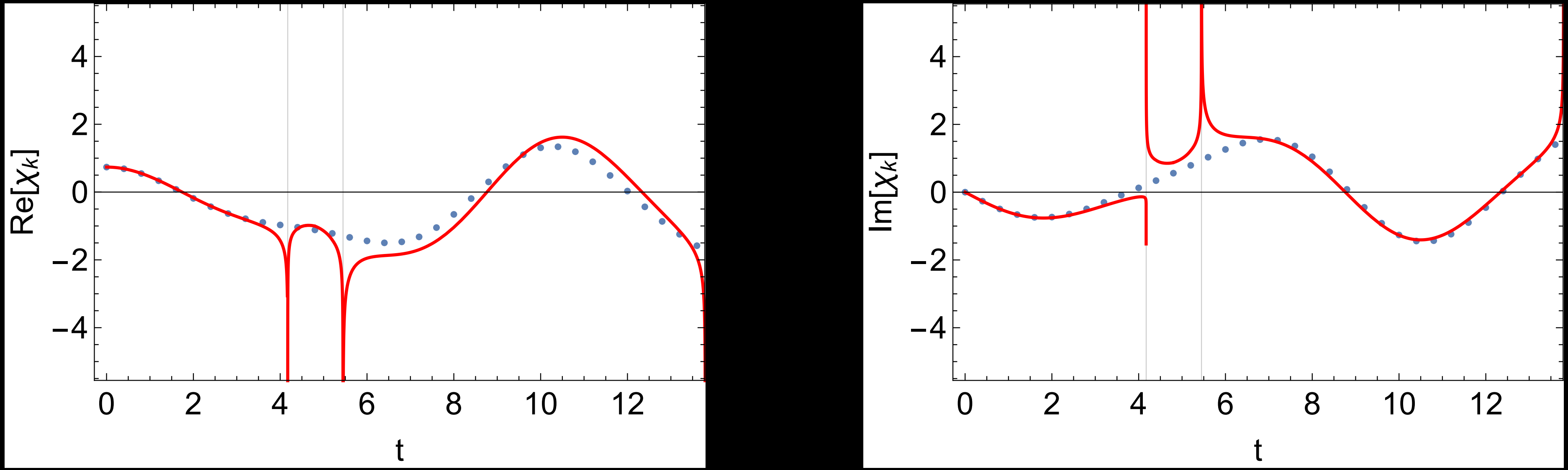
amplification factor
after the first tachyonic region

$$A_k = e^{\int_{t_-}^{t_+} \Omega_k(t)dt}$$

$$\chi_k^I = \frac{\alpha^n}{\sqrt{2\omega_k(t)}} e^{-i\int \omega_k(t)dt} + \frac{\beta^n}{\sqrt{2\omega_k(t)}} e^{i\int \omega_k(t)dt}$$

$$\chi_k^{II} = \frac{a^n}{\sqrt{2\Omega_k(t)}} e^{-\int \Omega_k(t)dt} + \frac{b^n}{\sqrt{2\Omega_k(t)}} e^{\int \Omega_k(t)dt}$$

$$\chi_k^{III} = \frac{\alpha^{n+1}}{\sqrt{2\omega_k(t)}} e^{-i\int \omega_k(t)dt} + \frac{\beta^{n+1}}{\sqrt{2k}} e^{i\int \omega_k(t)dt}$$



WKB (red) before, during and after a tachyonic transition

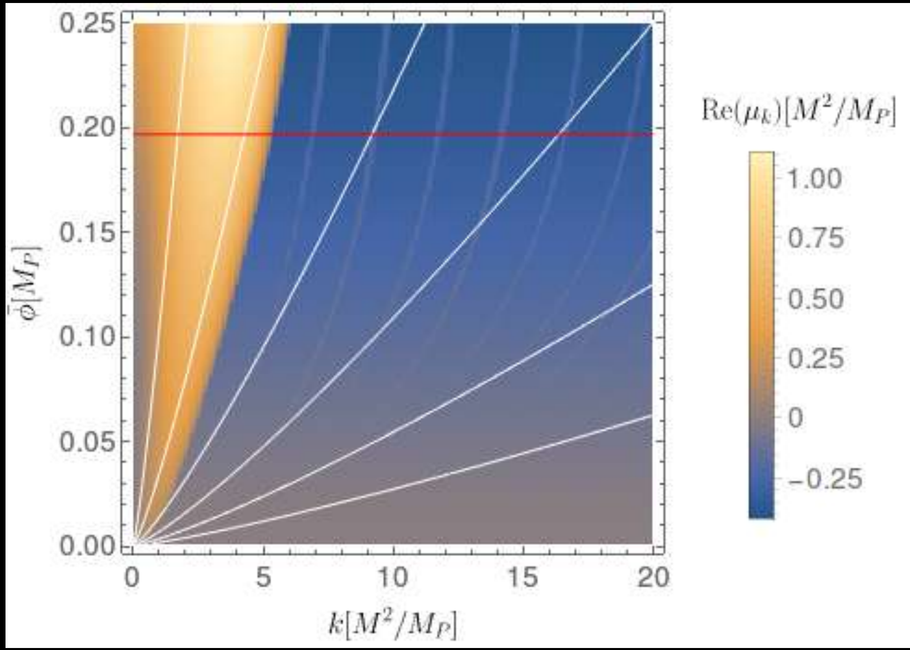
Floquet charts

[T. Krajewski, K. Turzyński, M. Wieczorek (2018)]

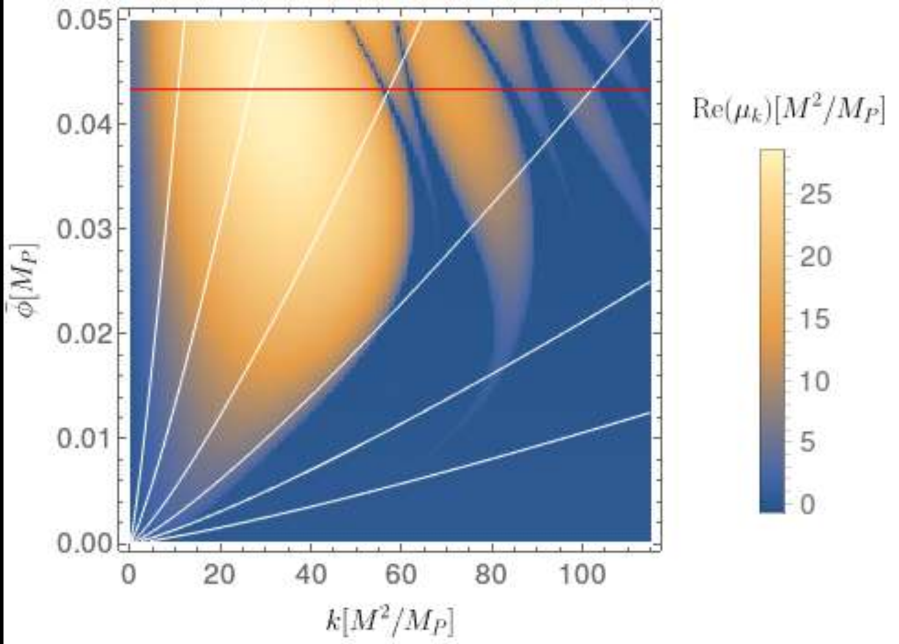
$$\partial_t^2 \chi_k + \omega_\chi^2(k,t)\,\chi_k = 0$$

$$\chi_k(t) \sim e^{\mu_k t} P(t)$$

The resonance structure looks very different!



$\alpha = 10^{-2}$



$\alpha = 10^{-4}$

Floquet charts

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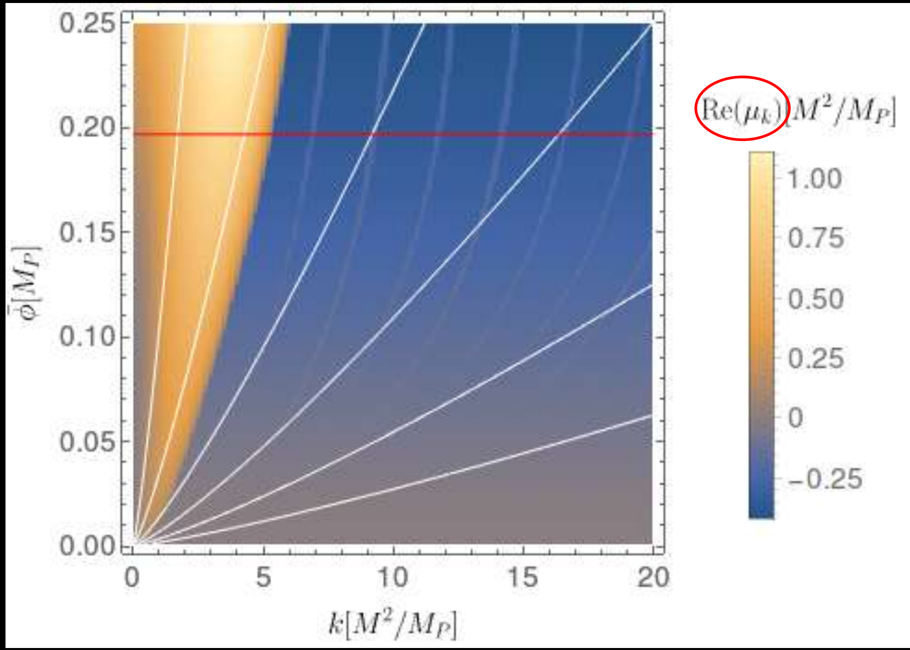

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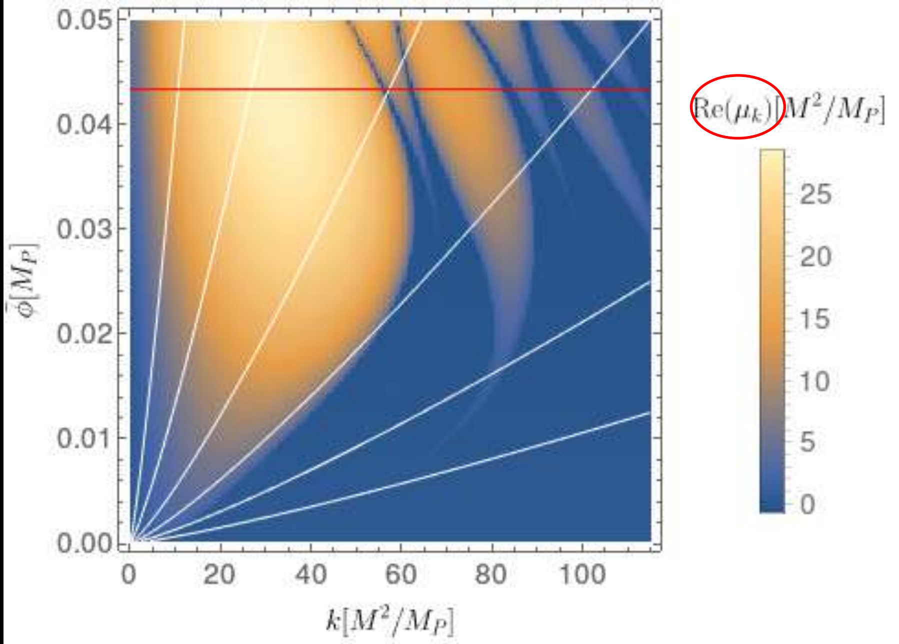
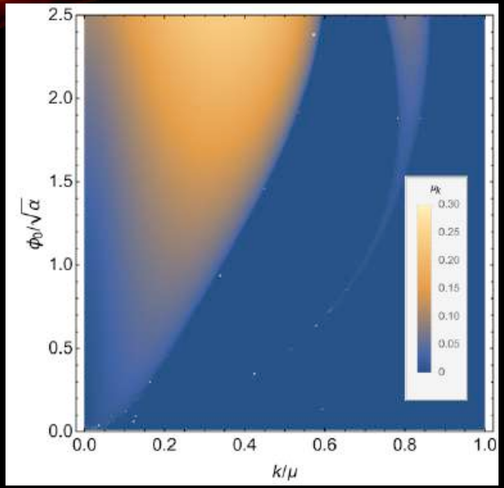
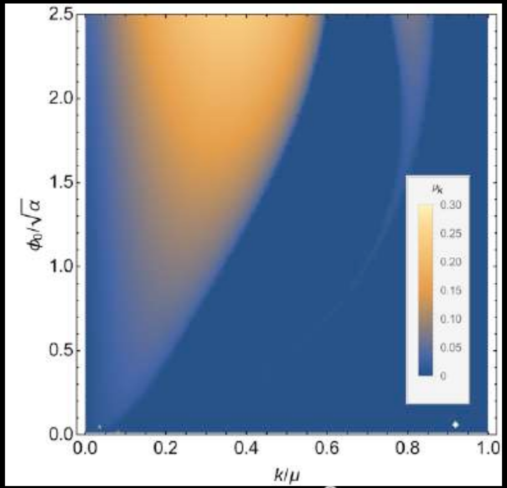


$\alpha = 10^{-4}$

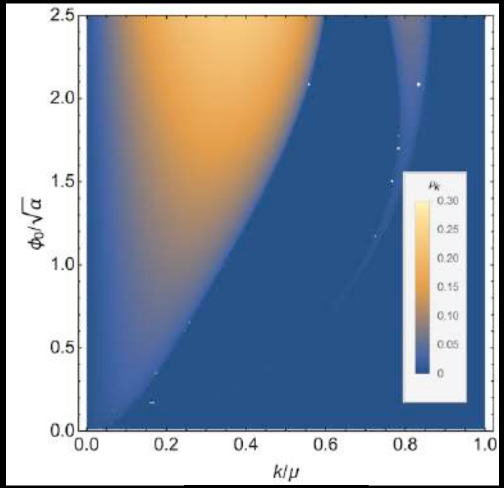
"Master" Floquet diagram



$\alpha = 10^{-2}$



$\alpha = 10^{-3}$



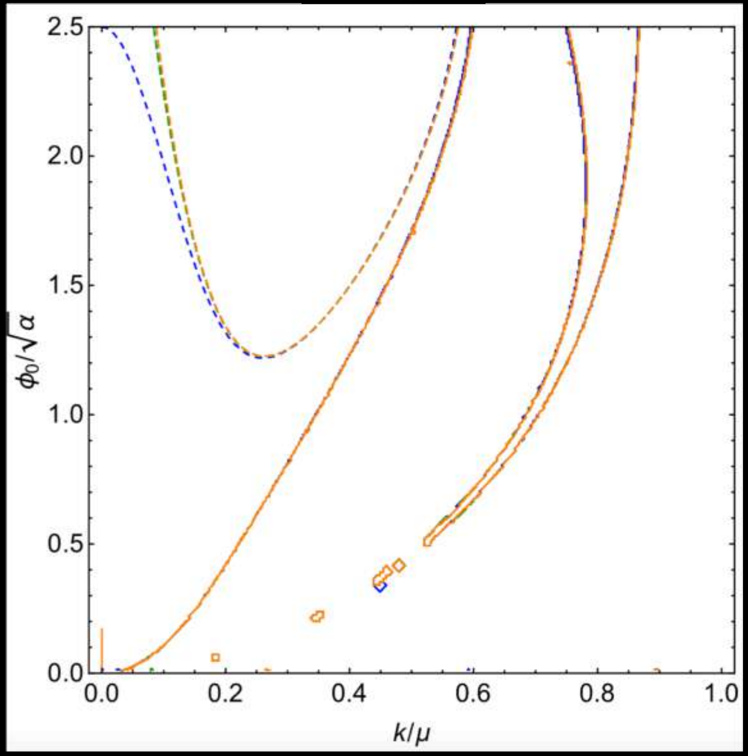
$\alpha = 10^{-4}$

With a proper rescaling

$$\phi_0 \sim \sqrt{\alpha}$$

emerges a unifying picture

"master diagram"

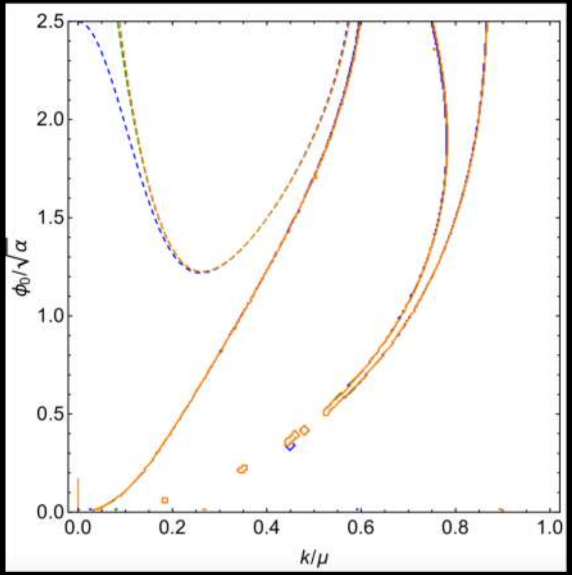


the resonance structure is identical, regardless of the exact value of the field-space curvature

The sum up of the scaling results

For $\boxed{\alpha \ll 1}$:

- The amplification factor during each tachyonic regime is approximately the same
- There are $\mathcal{O}\left(1/\sqrt{\alpha}\right)$ oscillations per Hubble time
- We can ignore the slow red-shifting of the background



↓

The amplification per Hubble time grows as $\mathcal{O}\left(1/\sqrt{\alpha}\right)$

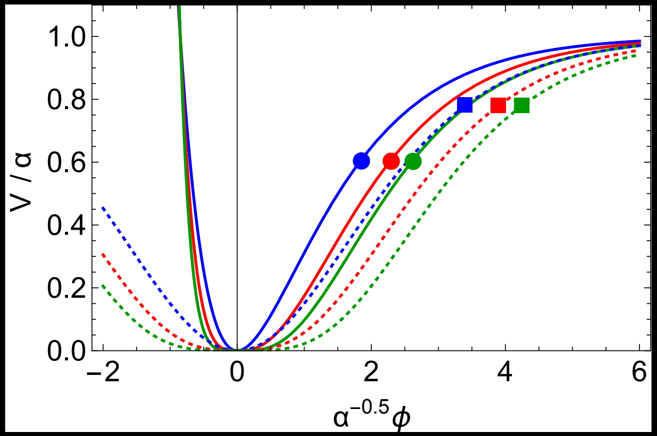
For $\alpha \lesssim 10^{-3}$ preheating is instantaneous

The Floquet chart is "universal" and can be scaled between different values of alpha.

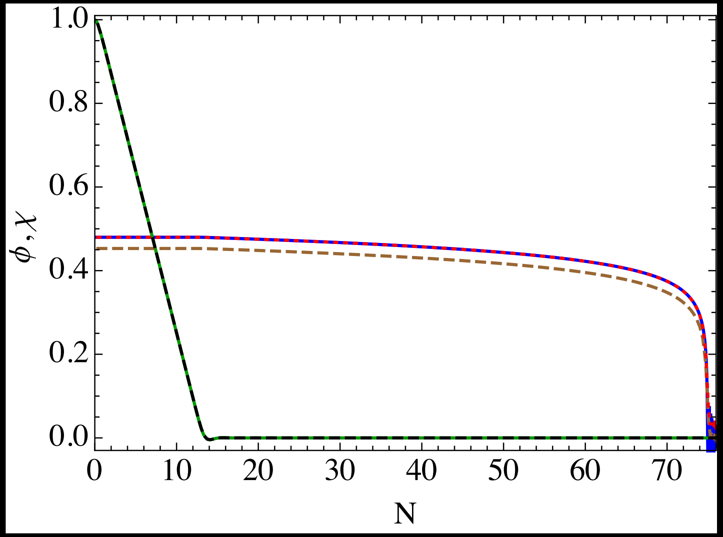
- Why do we need to know the physics of (p)reheating? ✓
- Why multi-field? ✓
- Scaling relations in multi-field alpha-attractors ✓
- What’s new in asymmetric alpha attractors?

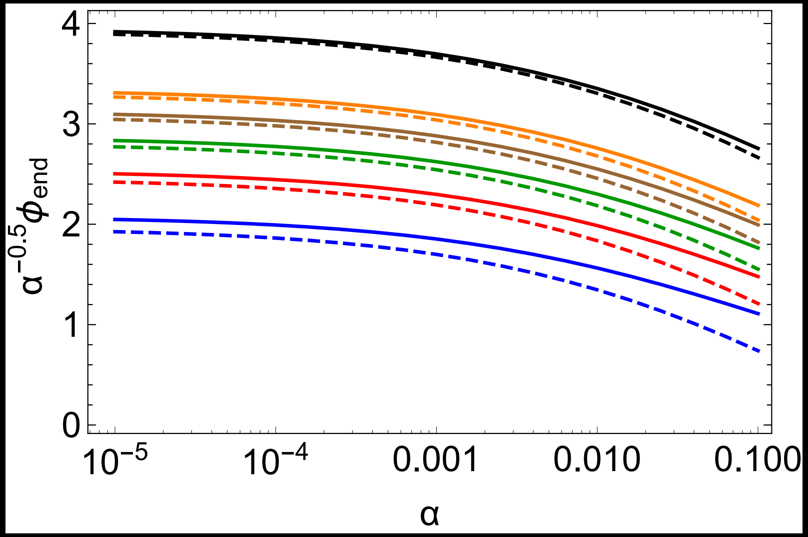
What's new in asymmetric alpha attractors?

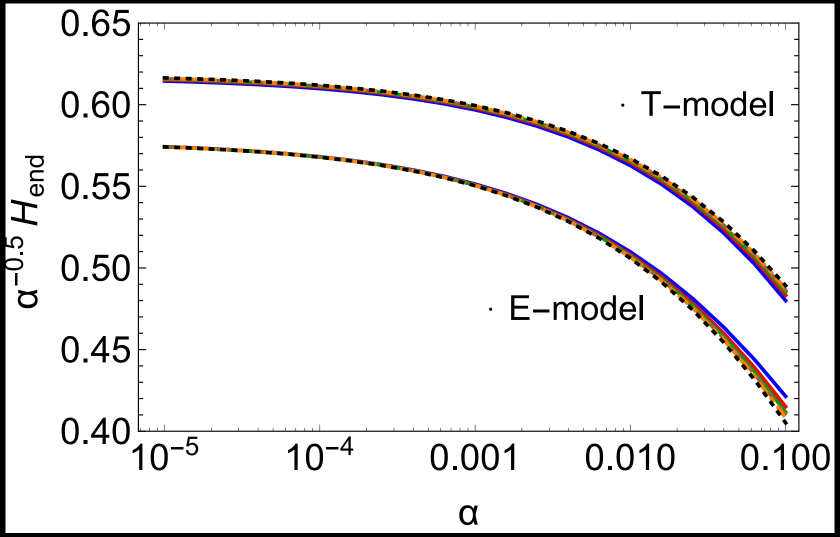
$$V(\phi,\chi) = \alpha\mu^2 \left(1 - \frac{2e^{-\beta\phi}}{\cosh(\beta\chi)} + e^{-2\beta\phi}\right)^n (\cosh(\beta\chi))^{2/\beta^2}$$



Comparison with the T-model showed identical two-field motion during inflation, analytically and numerically.



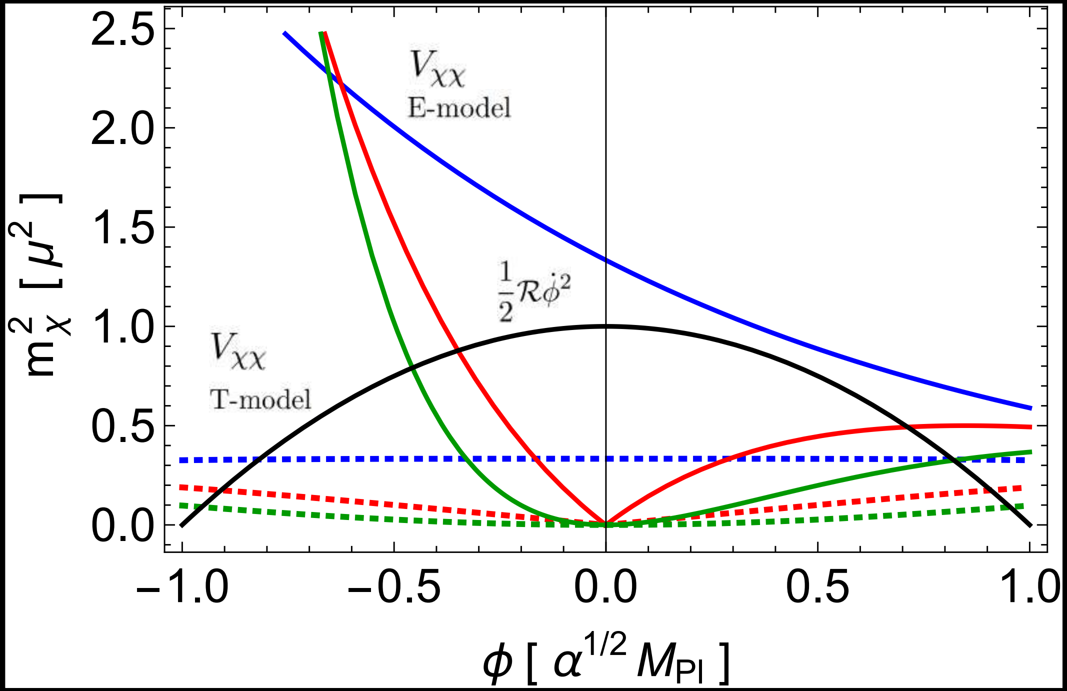




Preheating for symmetric vs asymmetric potentials

$$m^2_{\text{eff},\chi} \simeq V_{\chi\chi}(\chi = 0) + \frac{1}{2}\mathcal{R}\dot{\phi}^2$$

In the E-model with n = 1 the potential term can dominate over the tachyonic field-space curvature



$n = 1, 3/2, 2$ (blue,red green)

Effective mass

$$V_{\chi\chi}(\chi=0) \simeq \frac{4}{3} n e^{-\beta\phi} \left(\left(1 - e^{-\beta\phi}\right)^2 \right)^{n-1}$$

$$m^2_{\mathrm{eff},\chi} \simeq V_{\chi\chi}(\chi=0) + \frac{1}{2}\mathcal{R}\dot{\phi}^2$$

no tachyonic resonance in massive E-model!

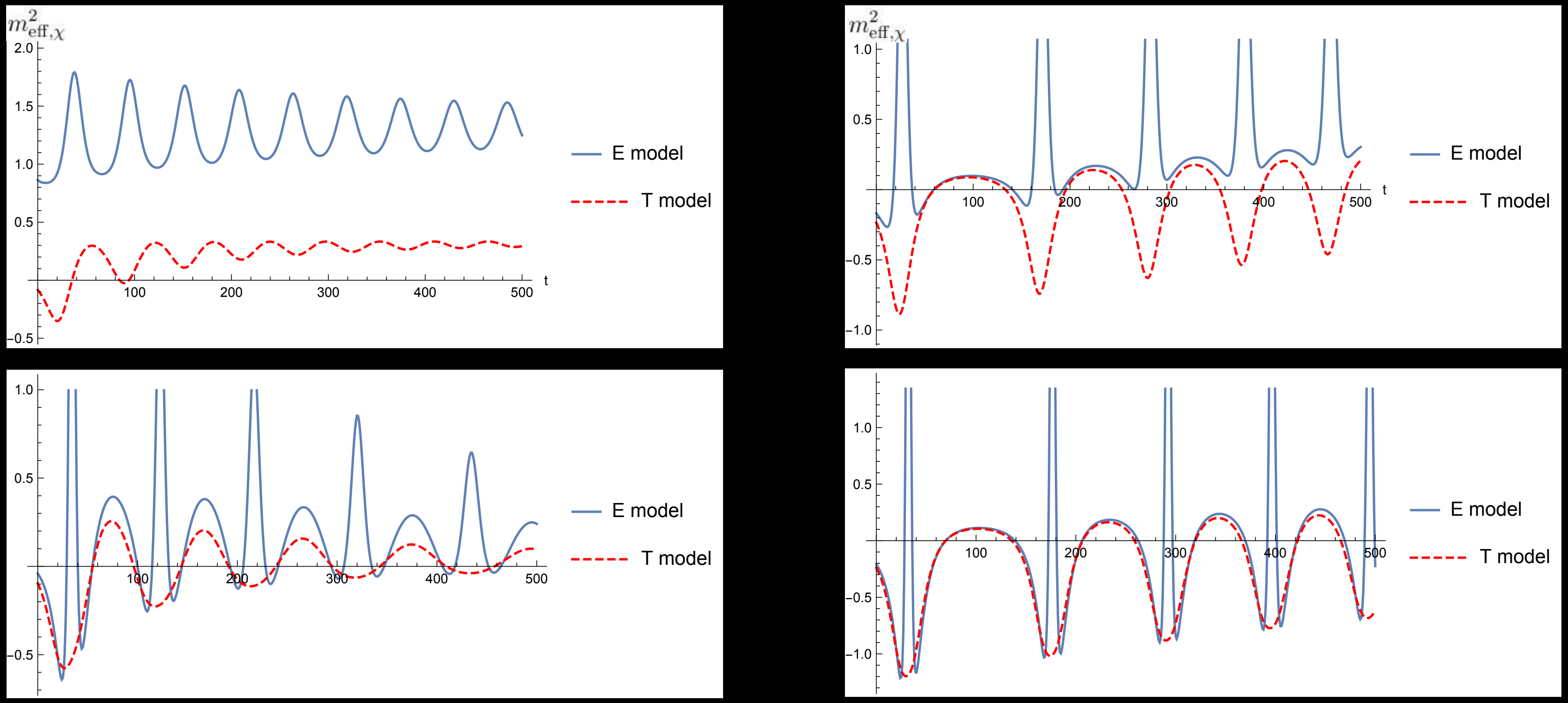
potential steepness:

$n = 1$

massive case

$n > 1$

massless case



$\alpha = 10^{-2}$

$\alpha = 10^{-4}$

Oksana Iarygina, Leiden University

Effective mass

$$V_{\chi\chi}(\chi=0) \simeq \frac{4}{3} n e^{-\beta\phi} \left(\left(1 - e^{-\beta\phi} \right)^2 \right)^{n-1}$$

$$m^2_{\mathrm{eff},\chi} \simeq V_{\chi\chi}(\chi=0) + \frac{1}{2}\mathcal{R}\dot{\phi}^2$$

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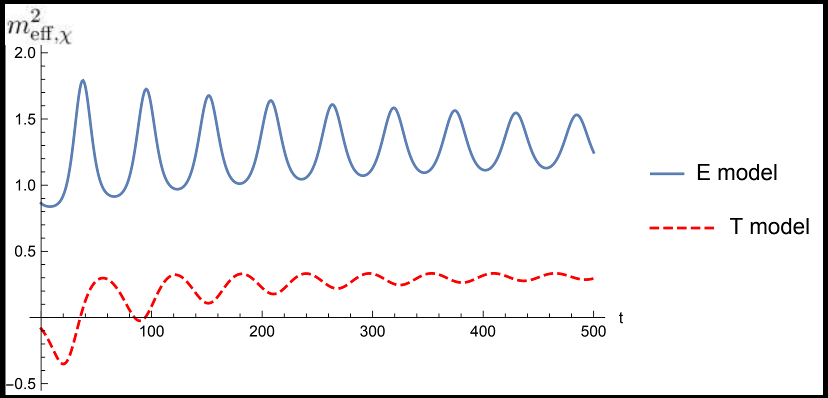
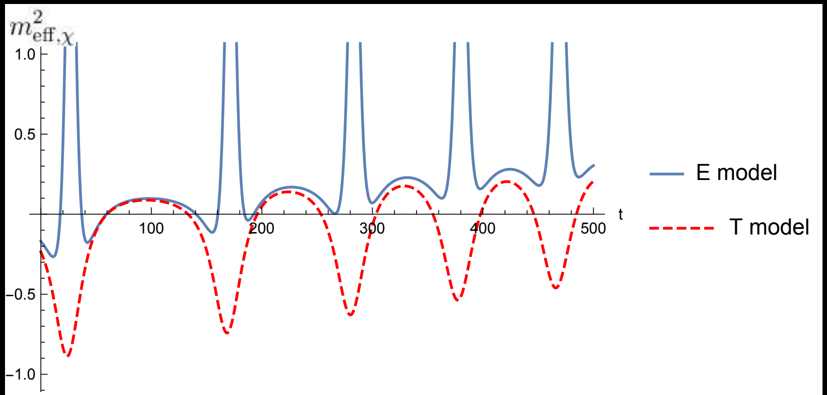
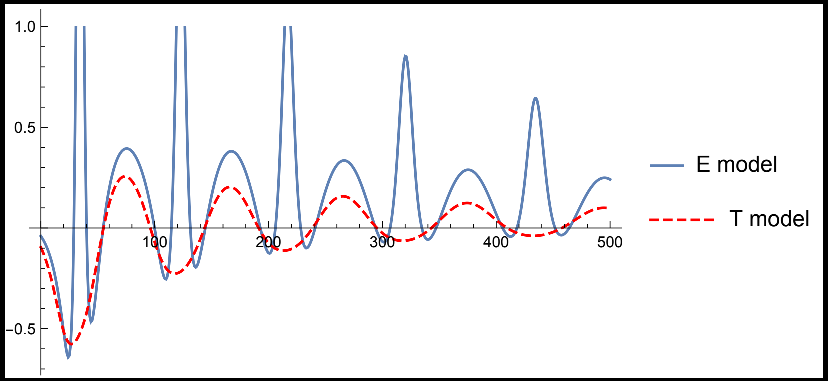
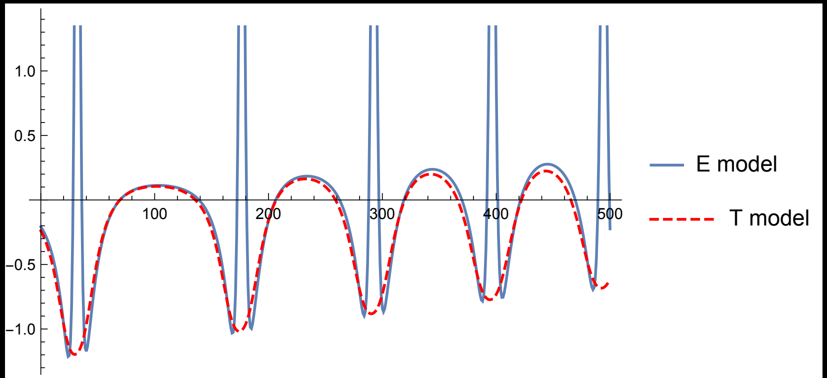




$n > 1$

massless case





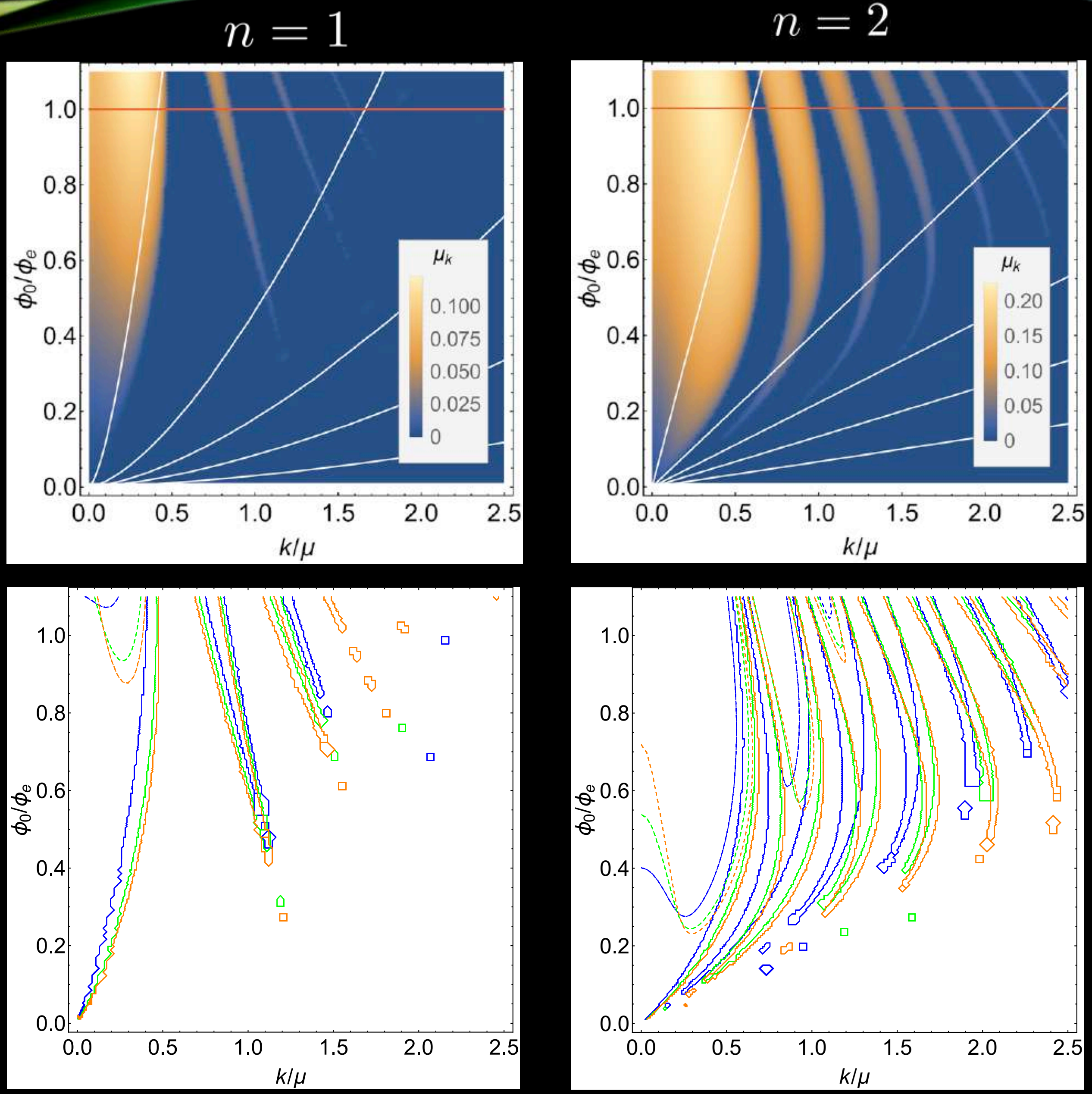
$\alpha = 10^{-2}$ $\alpha = 10^{-4}$

Floquet charts E-model

The E-model has a richer resonance structure during (p)reheating, due to competing mass scales

$$m^2_{\text{eff},\chi} \simeq V_{\chi\chi}(\chi=0) + \frac{1}{2}\mathcal{R}\dot{\phi}^2$$

$$\phi_{\text{end}} = \mathcal{O}(1)\sqrt{\alpha}$$



Preheating efficiency for massive fields

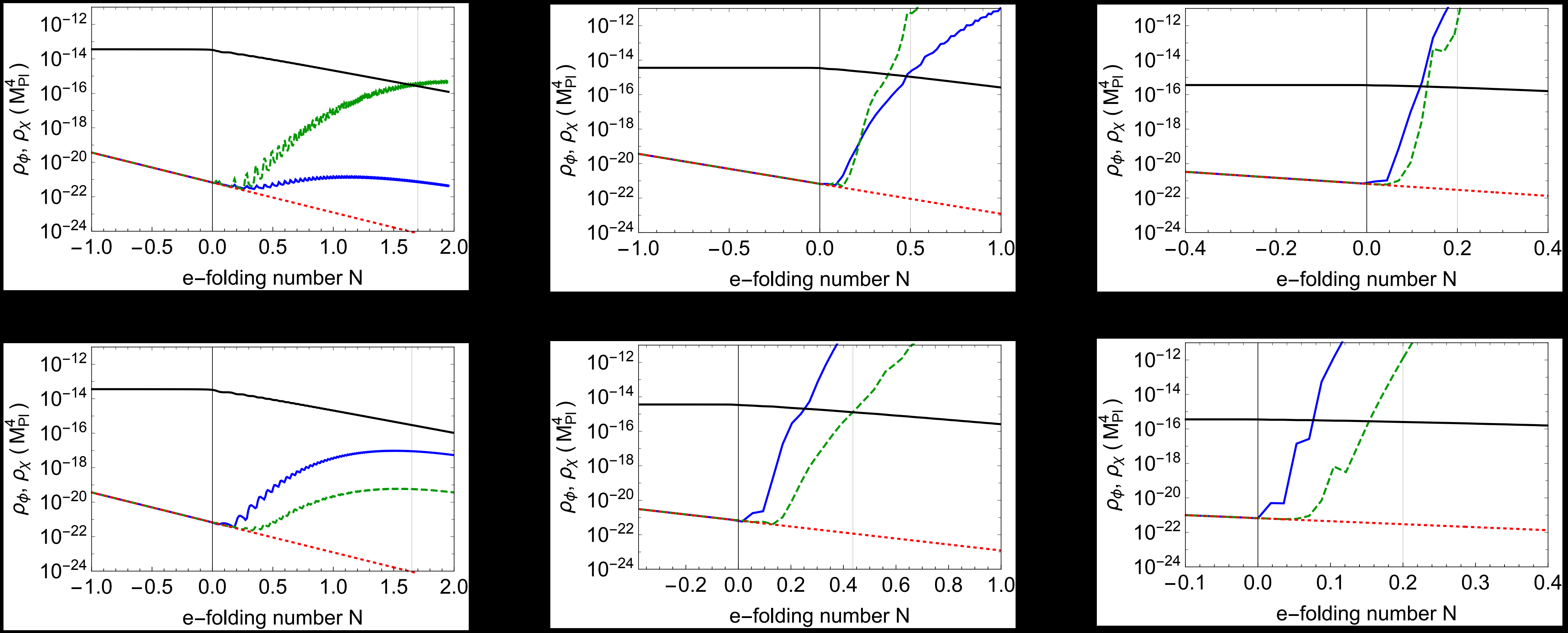
The E-model can preheat through ϕ resonance, when the T-model cannot.

$n = 1$

$\alpha = 10^{-3}$ | $\alpha = 10^{-4}$ | $\alpha = 10^{-5}$

E-model

T-model

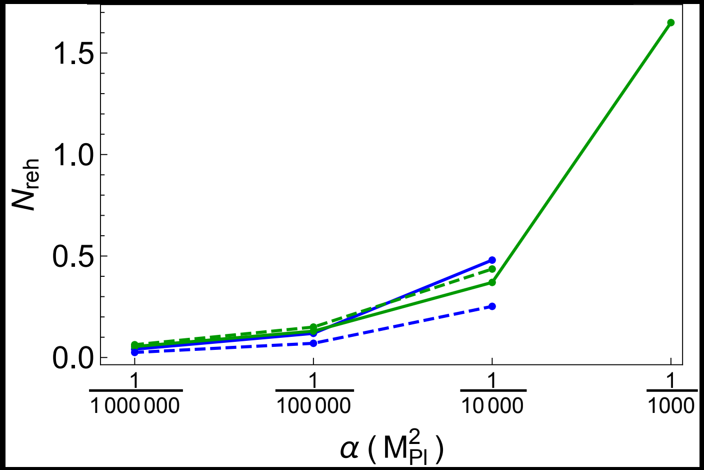


Energy density in ϕ and χ fluctuations (green-dashed and blue)

Oksana Iarygina, Leiden University

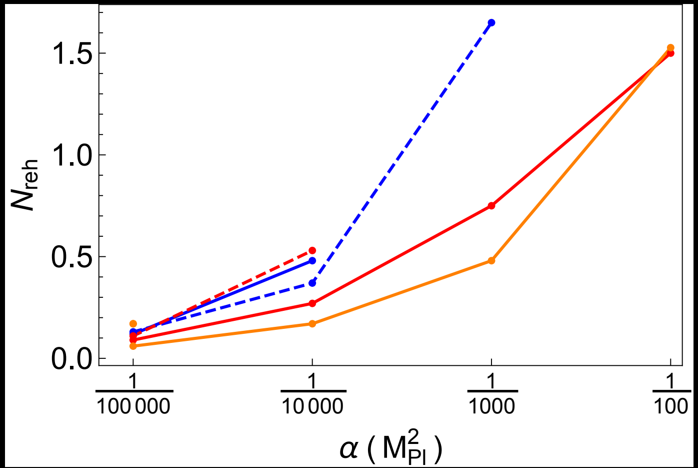
E-T preheating efficiency

ϕ (green) and χ (blue) fluctuations



T-model (dashed), E-model (solid) $n = 1$

ϕ (dashed) and χ (solid) modes



$n = 1, 3/2, 6$ (blue, red, orange)

Massive fields $n = 1$

- The T-model: tachyonic resonance of the χ field for $\alpha \lesssim 10^{-4}$
- The E-model: self-resonance of the ϕ field for $\alpha \approx 10^{-3}$, while the T-model does not preheat!

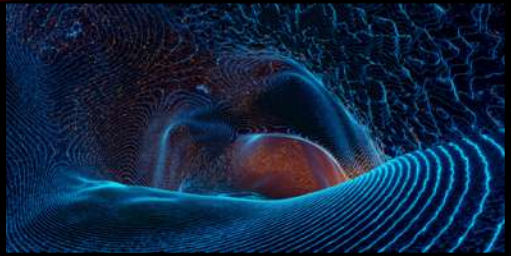
Massless fields and steeper potentials $n > 1$

- tachyonic resonance of a spectator χ field, starting at $\alpha \approx 10^{-3}$

For alphas $\alpha \lesssim 10^{-4}$ preheating is practically instantaneous for any n .

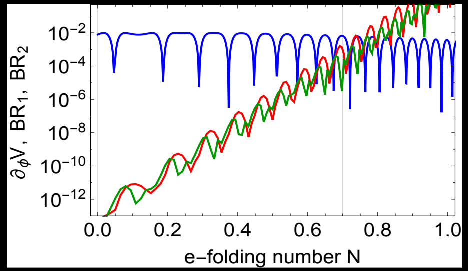
Outlook

- Gravitational waves

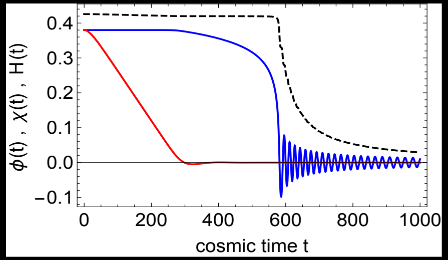


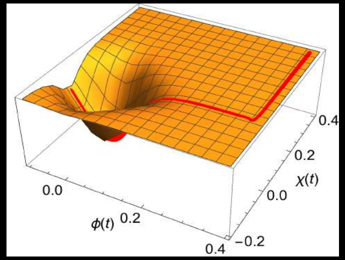
$$f \simeq 2.7 \cdot 10^{10} \frac{k_{\rm phys}}{\sqrt{M_{\rm Pl} H}}\,{\rm Hz} \qquad f \sim \frac{10^7}{\alpha^{1/4}}\,{\rm Hz}$$

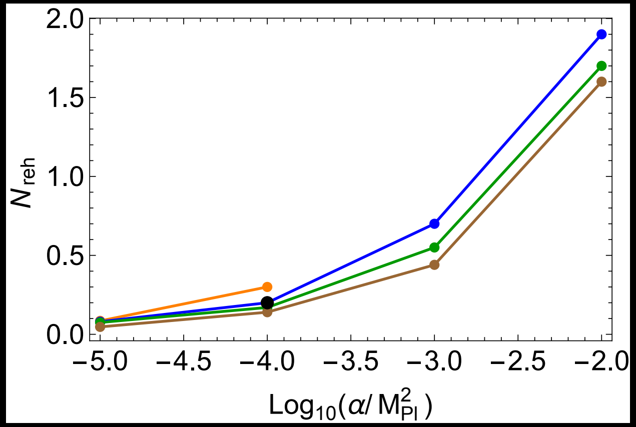
- Non-linear effects and backreaction, oscillon formation?



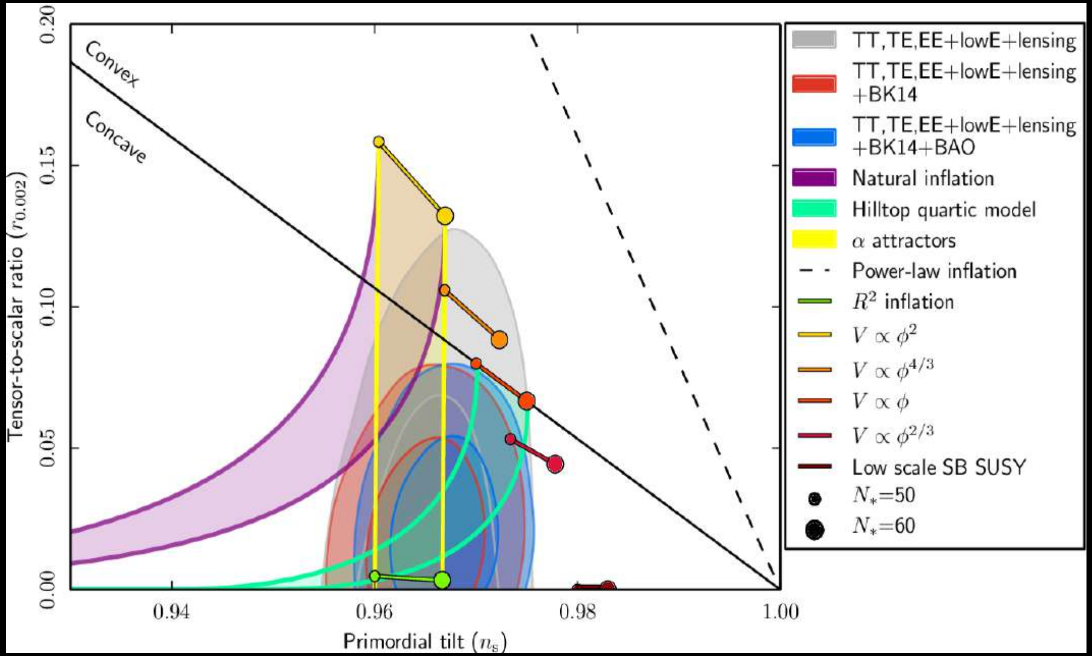
- Inflation along spectator direction and turning around horizon crossing can have observational consequences







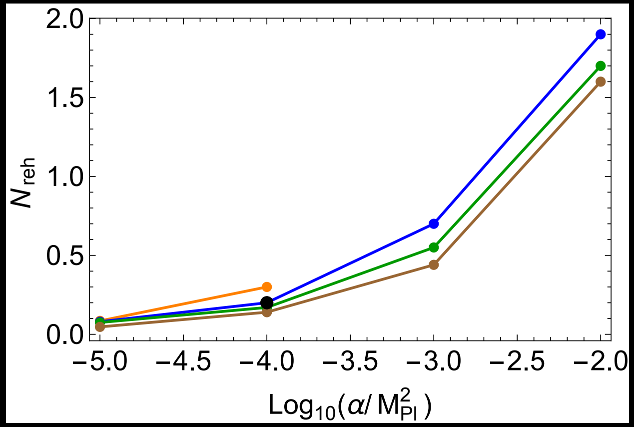
Single-field simulations are unable to capture the most important time-scales, which control the tachyonic growth of the spectator field.

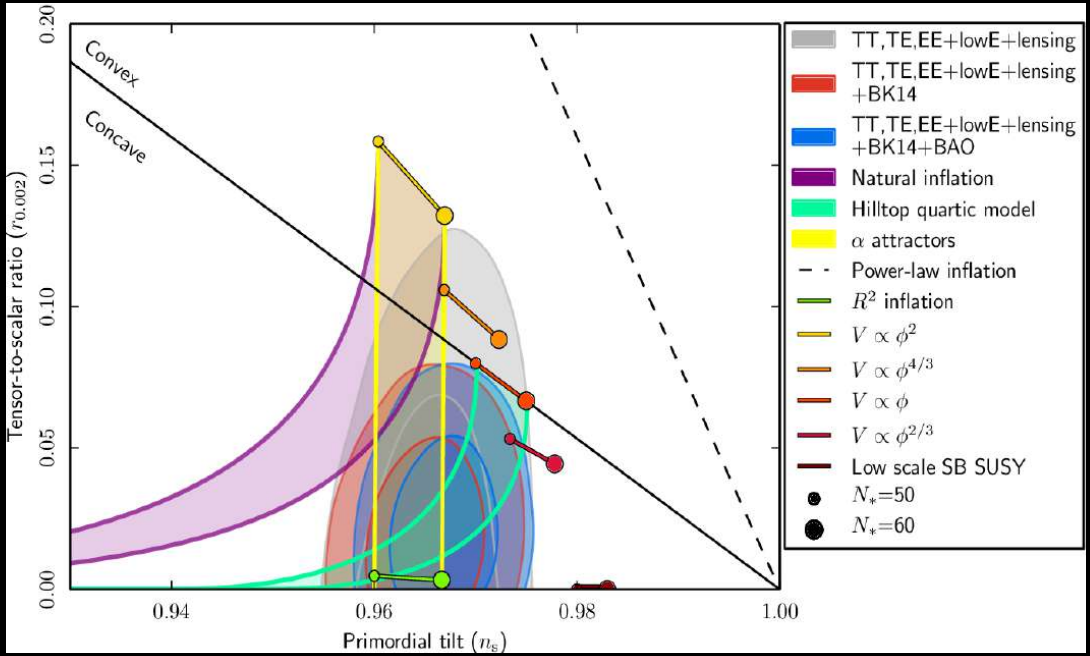


Effective field theory of preheating leads to reducing of error bars of the $n_s - r$ plot.

Thank you!

Single-field simulations are unable to capture the most important time-scales, which control the tachyonic growth of the spectator field.





Effective field theory of preheating leads to reducing of error bars of the $n_s - r$ plot.