

Reheating from a curved target space

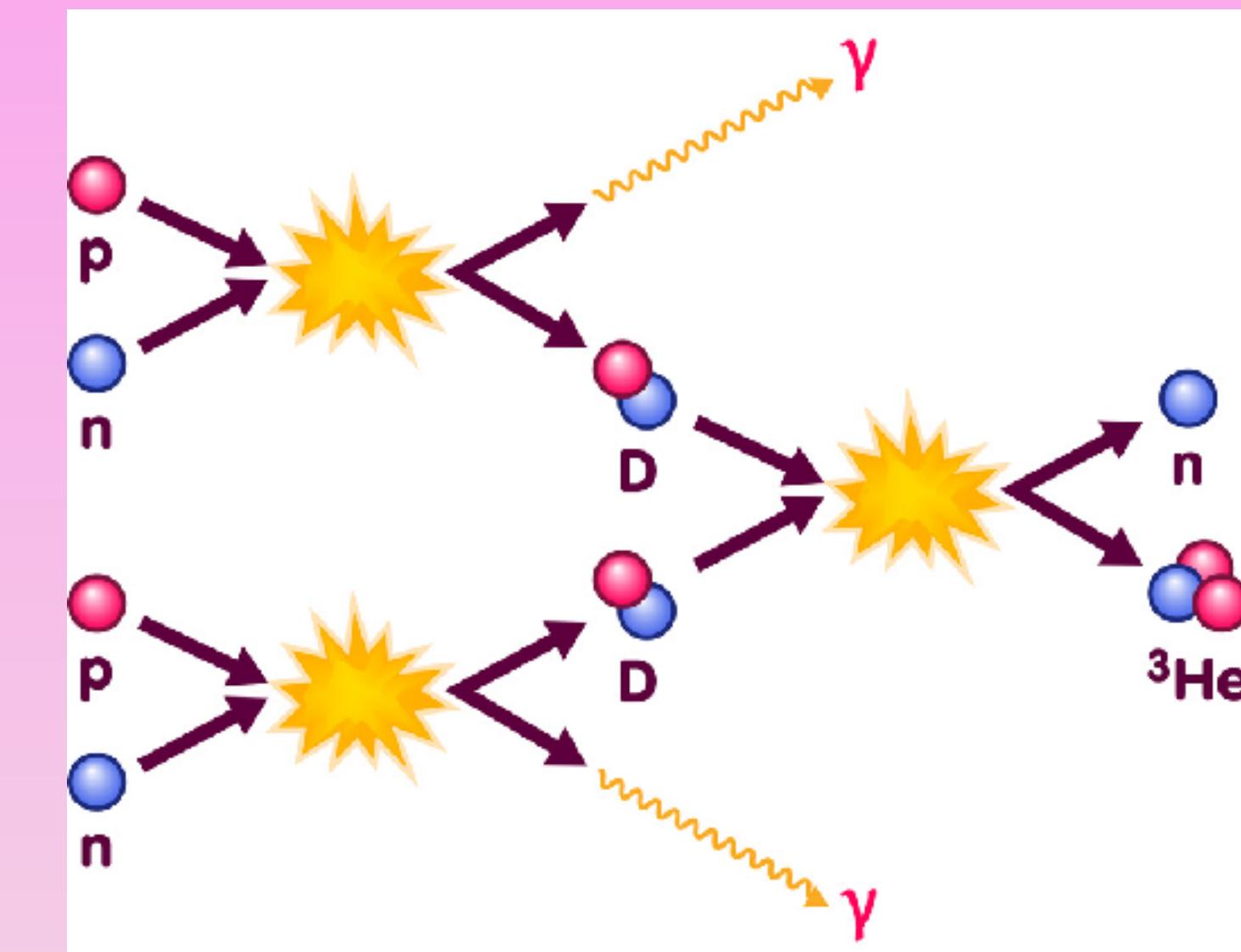
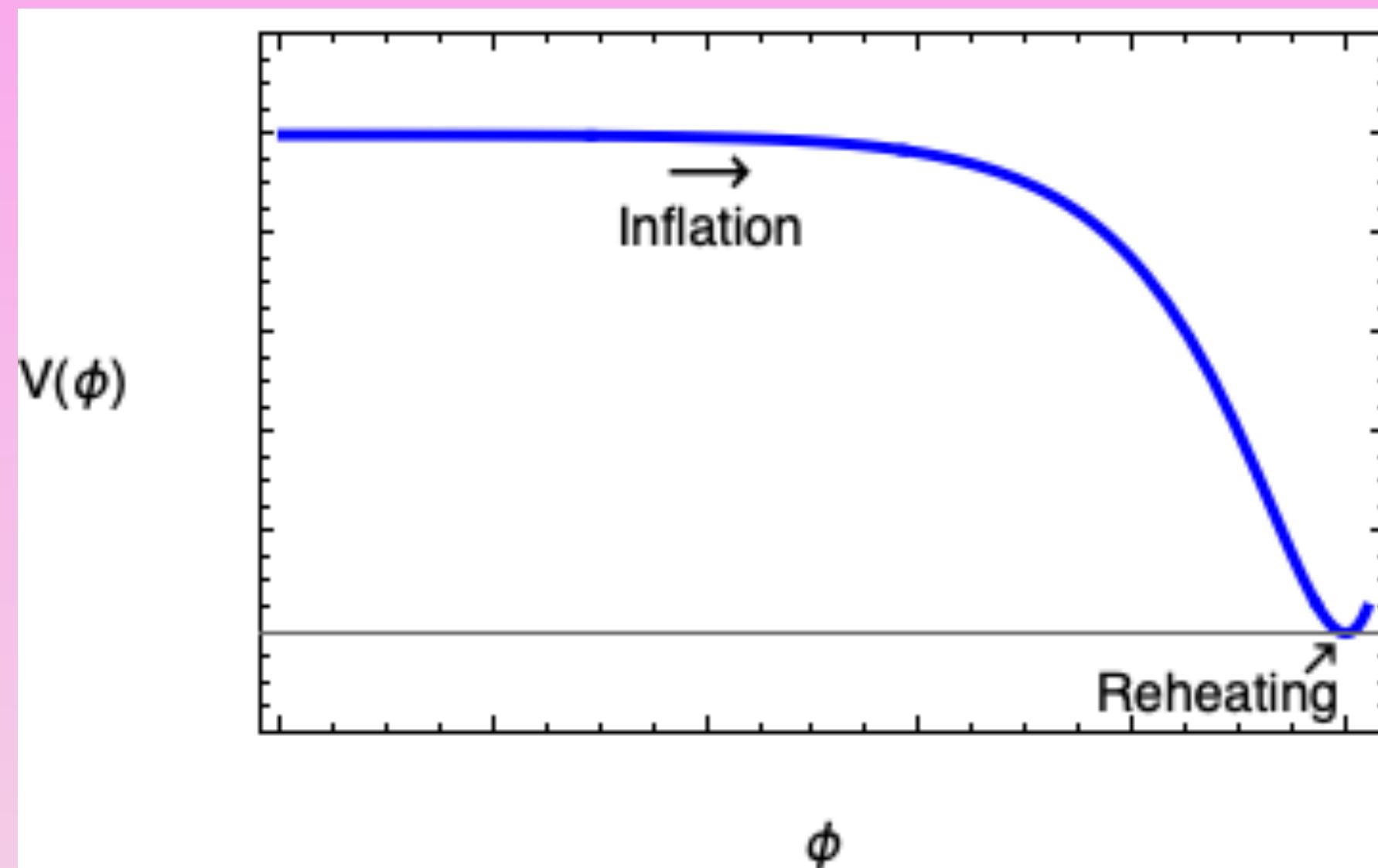
Jorinde van de Vis



Y. Ema, R. Jinno, K. Nakayama, JvdV: *Phys.Rev.D* 103 (2021) 10, 103536
ArXiv: 2102.12501

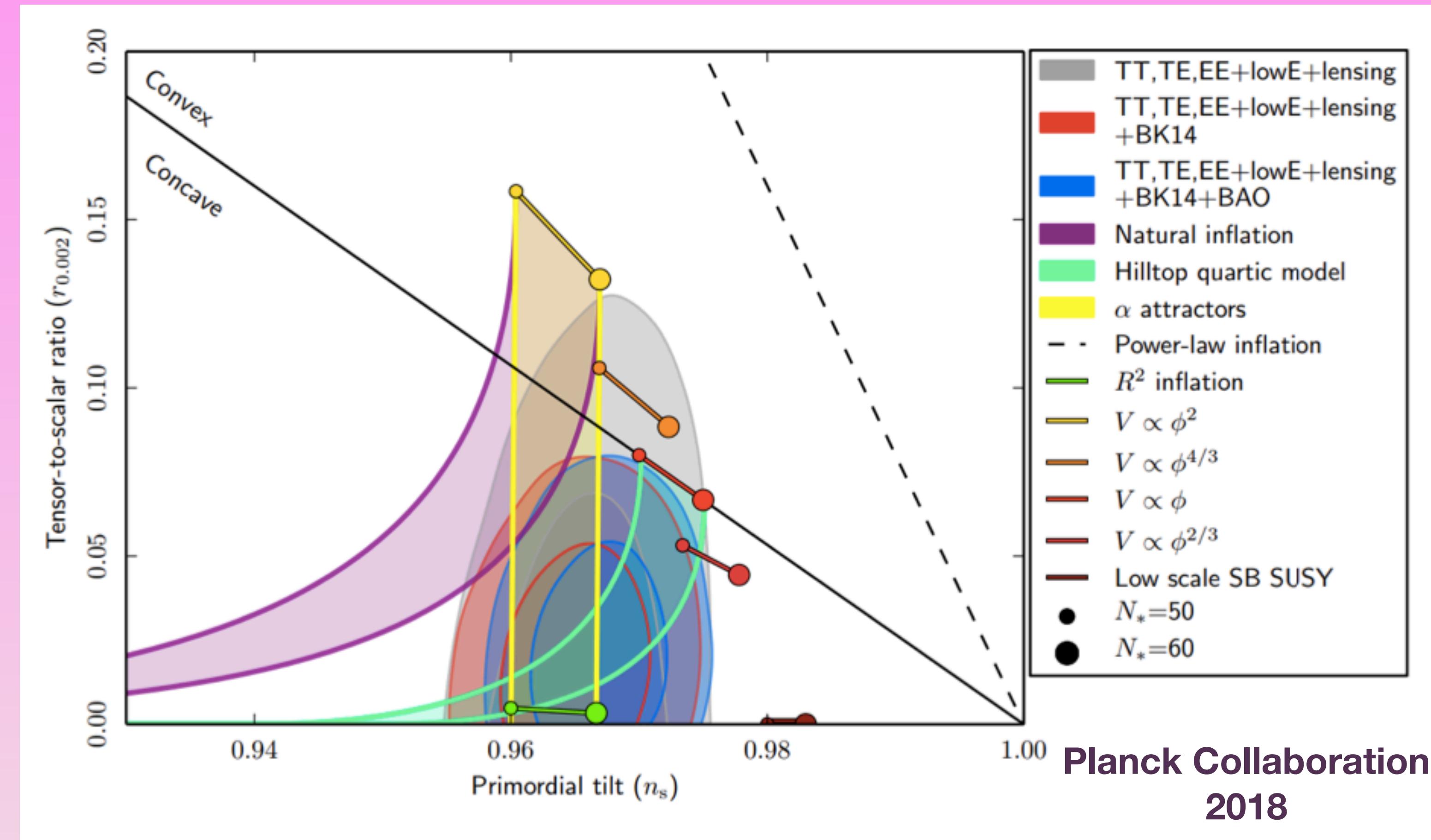
Motivation: reheating

Transition phase between inflation and hot big bang cosmology



Motivation: reheating

Uncertainty in CMB prediction



Motivation: reheating

Reheating catastrophes



Motivation: reheating

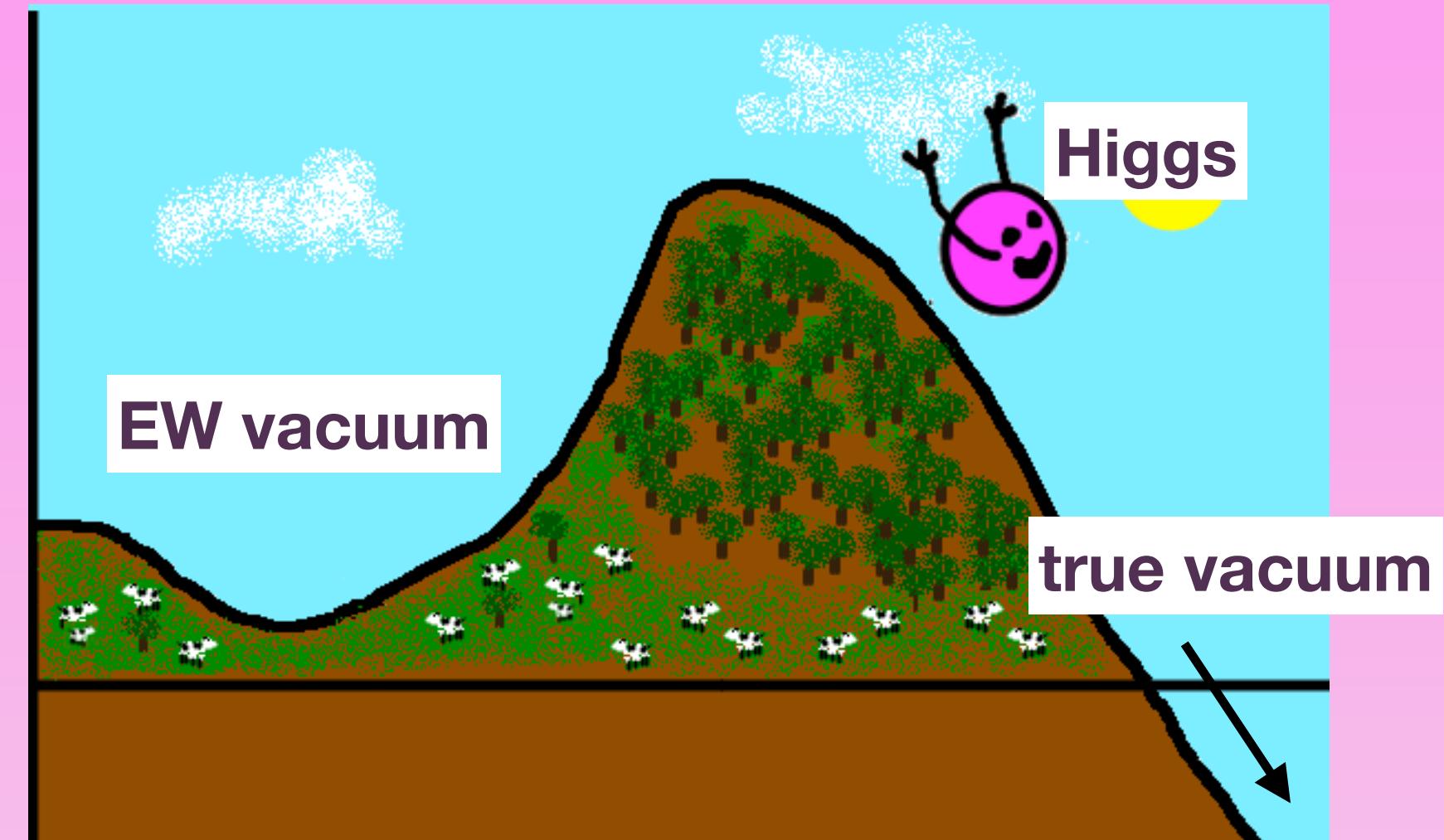
Reheating catastrophes

- Electroweak vacuum decay

Herranen, Markkanen, Nurmi, Rajantie 2015
Ema, Mukaida, Nakayama 2016
Kohri, Matsui 2016
Postma, JvdV 2017

- Unitarity violation (of Higgs inflation)

DeCross, Kaiser, Prabhu, Prescod-Weinstein, Sfakianakis 2016
Ema, Jinno, Mukaida, Nakayama 2016
Sfakianakis, van de Vis 2018



Motivation: reheating

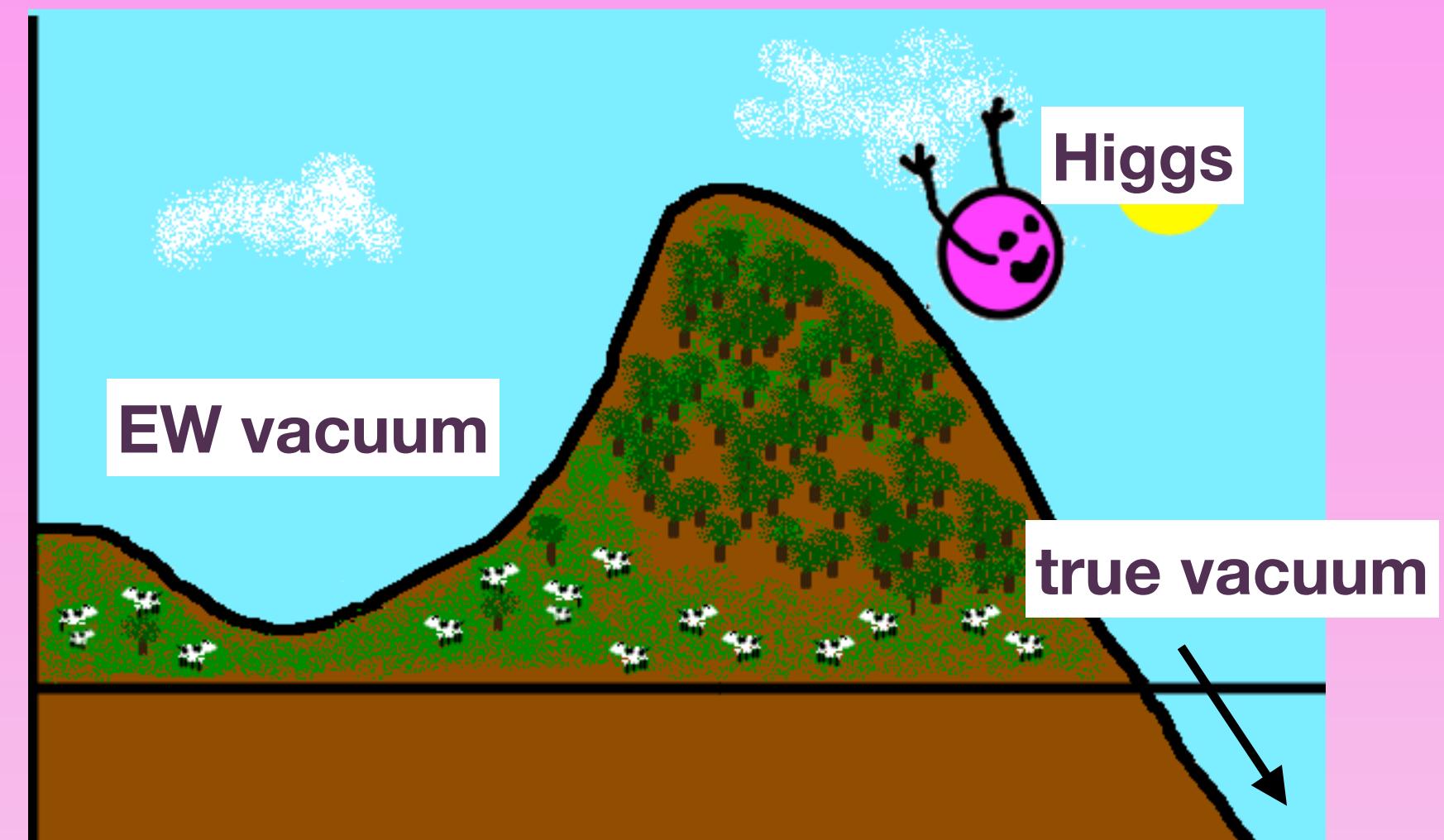
Reheating catastrophes

- Electroweak vacuum decay

Herranen, Markkanen, Nurmi, Rajantie 2015
Ema, Mukaida, Nakayama 2016
Kohri, Matsui 2016
Postma, JvdV 2017

- Unitarity violation (after Higgs inflation)*

DeCross, Kaiser, Prabhu, Prescod-Weinstein, Sfakianakis 2016
Ema, Jinno, Mukaida, Nakayama 2016
Sfakianakis, van de Vis 2018



* Discussion on unitarity issue of Higgs inflation:

Barbon, Casas, Elias-Miro, Espinosa 2015
Burgess, Patil, Trott 2014
Fumagali, Postma 2016

Attitude of this talk: preheating provides an *additional* argument of unitarity breakdown

Motivation: curved target space

- E.g. from Supergravity/multiple fields with nonminimal couplings

- $$S_E = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R + \frac{1}{2} h_{ab} \partial_\mu \phi^a \partial^\mu \phi^b - V \right] \text{ (in Einstein frame)}$$

- Higgs inflation, α -attractors, running kinetic inflation

‘Spiky’ mass - efficient reheating

- $$S_E = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R + \frac{1}{2} h_{ab} \partial_\mu \phi^a \partial^\mu \phi^b - V \right]$$

- Covariant formalism

Sasaki, Stewart 1996

Peterson, Tegmark 2010

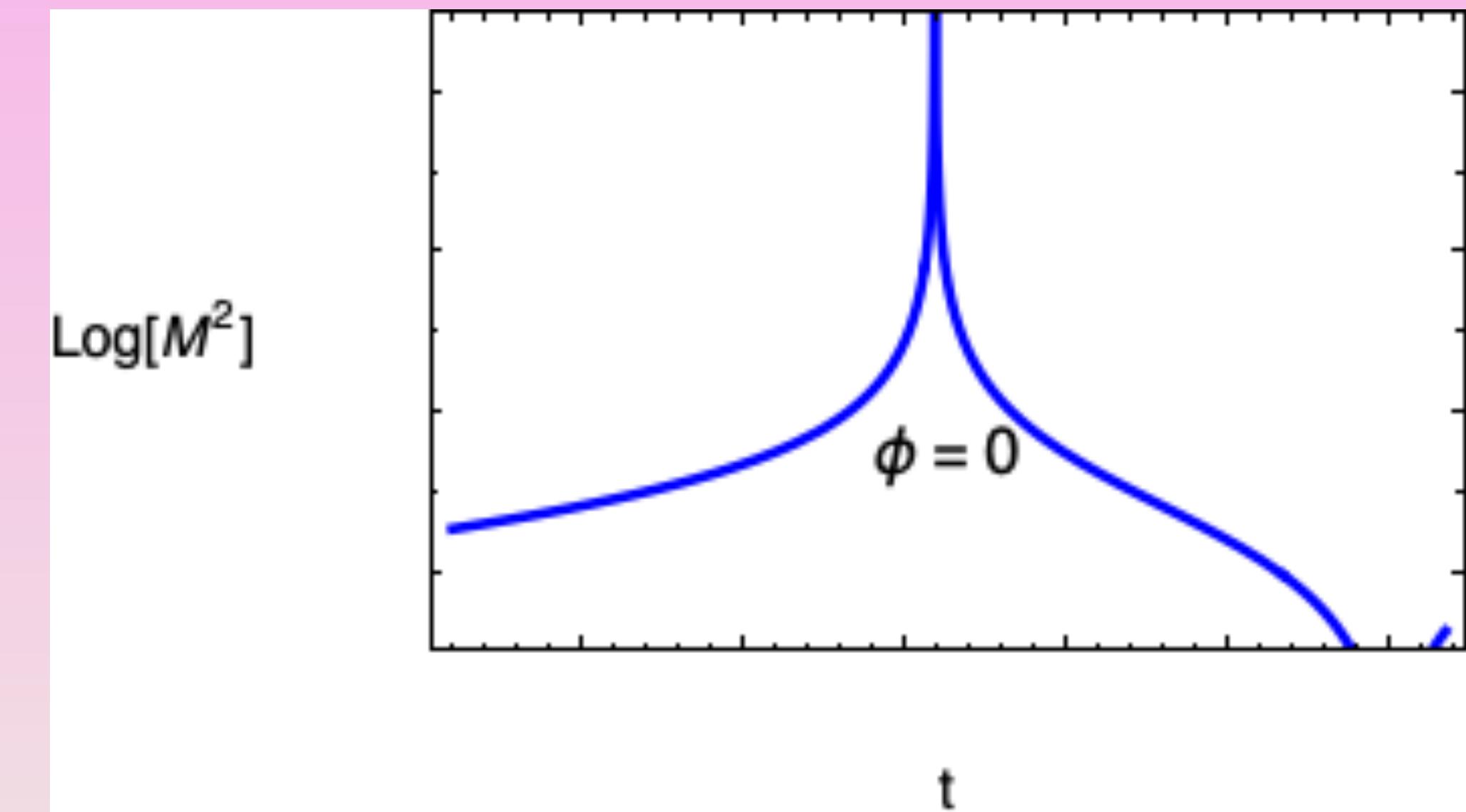
Groot Nibbelink, Van Tent 2001&2002

Gong, Tanaka 2011

Langlois, Renaux-Petel 2008

Kaiser, Mazenc, Sfakianakis 2013

- $$M_{ab} \supset -\dot{\phi}_0^c \phi_0^d R_{abcd}$$

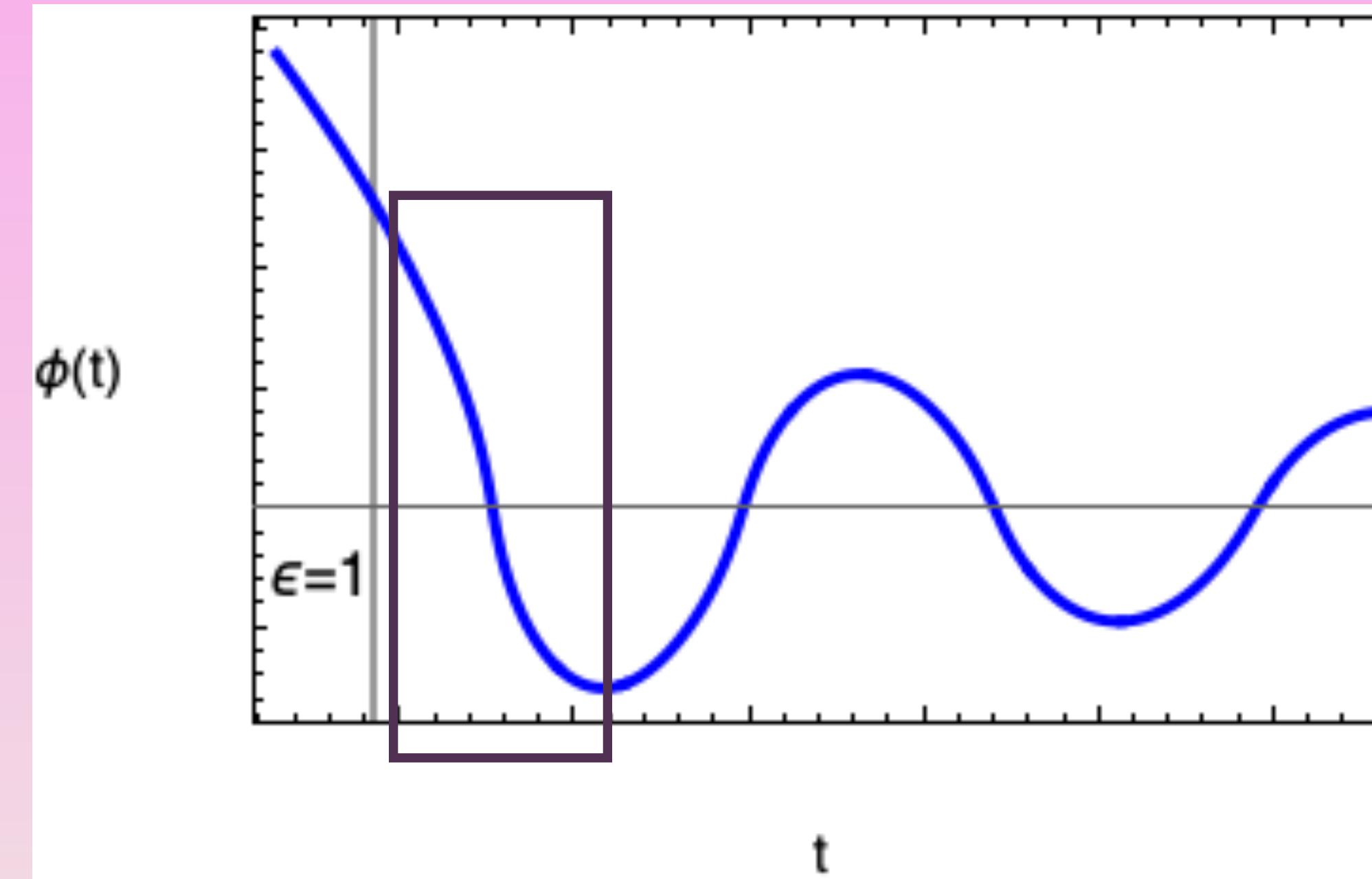


Part I

Semi-analytical computation of particle number

Part I

Semi-analytical computation of particle number



Particle production

- Mixing of positive and negative frequency modes: Bogoliubov coefficients

$$\dot{\alpha}_k = \frac{1}{4\omega_k^2} \frac{d\omega_k^2}{dt} \beta_k e^{2i \int^t dt' \omega_{k'}} , \quad \dot{\beta}_k = \frac{1}{4\omega_k^2} \frac{d\omega_k^2}{dt} \alpha_k e^{-2i \int^t dt' \omega_{k'}}$$

- Initial condition: $\alpha_k = 1, \quad \beta_k = 0$

- Particle number $f_k = |\beta_k|^2$

Particle production

- Mixing of positive and negative frequency modes: Bogoliubov coefficients

$$\dot{\alpha}_k = \frac{1}{4\omega_k^2} \frac{d\omega_k^2}{dt} \beta_k e^{2i \int^t dt' \omega_{k'}} , \quad \dot{\beta}_k = \frac{1}{4\omega_k^2} \frac{d\omega_k^2}{dt} \alpha_k e^{-2i \int^t dt' \omega_{k'}}$$

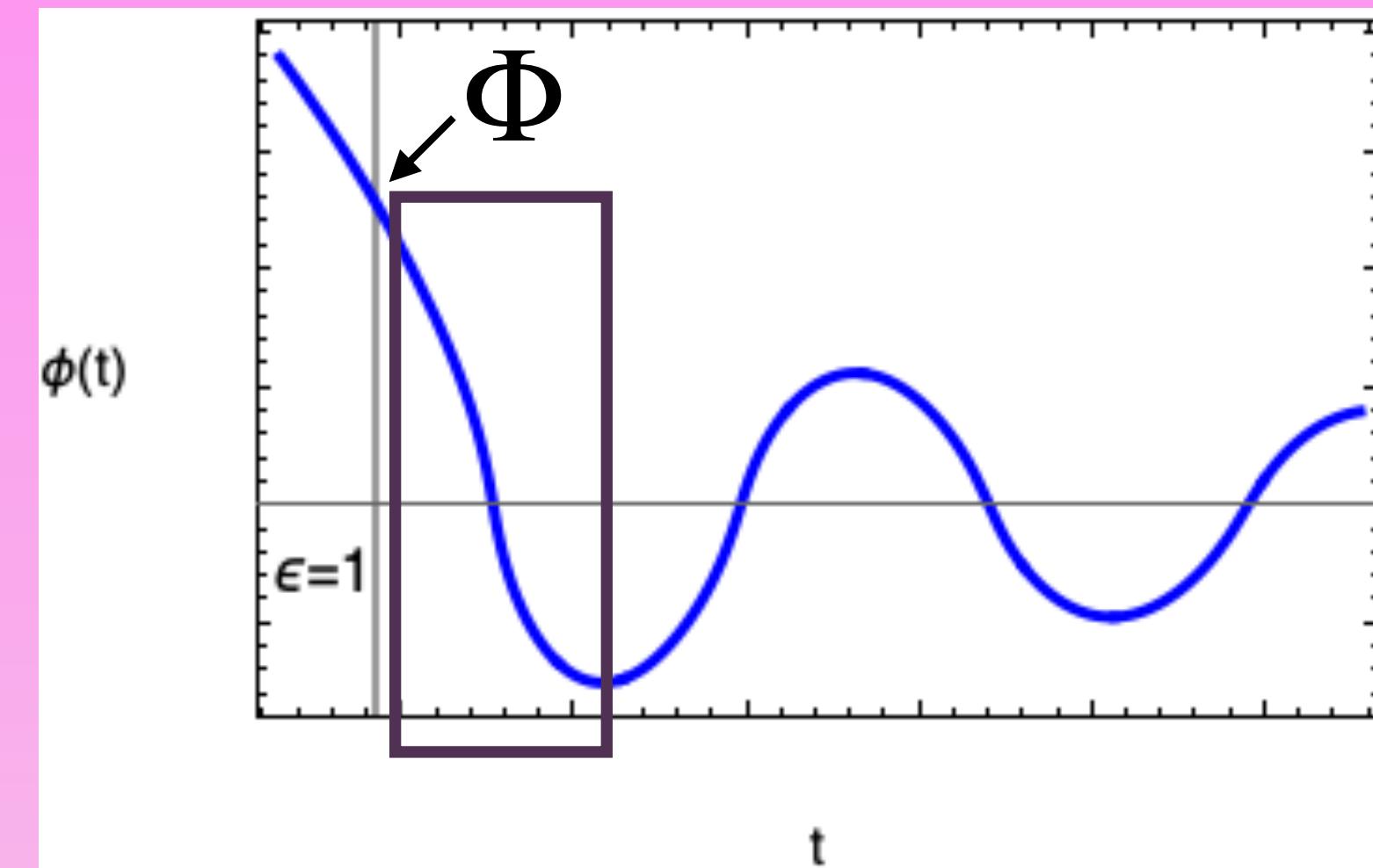
- Initial condition: $\alpha_k = 1, \quad \beta_k = 0$

- Particle number $f_k = |\beta_k|^2$

- Born approximation: $\alpha_k \sim 1$

Our trick: $t \rightarrow \phi$

- $f_k \simeq \left| \int_{-\Phi}^{\Phi} \frac{d\phi}{4} \frac{1}{\omega_k^2} \frac{d\omega_k^2}{d\phi} \exp \left(-2i \int^{\phi} d\phi \frac{\omega_k}{\dot{\phi}} \right) \right|^2$

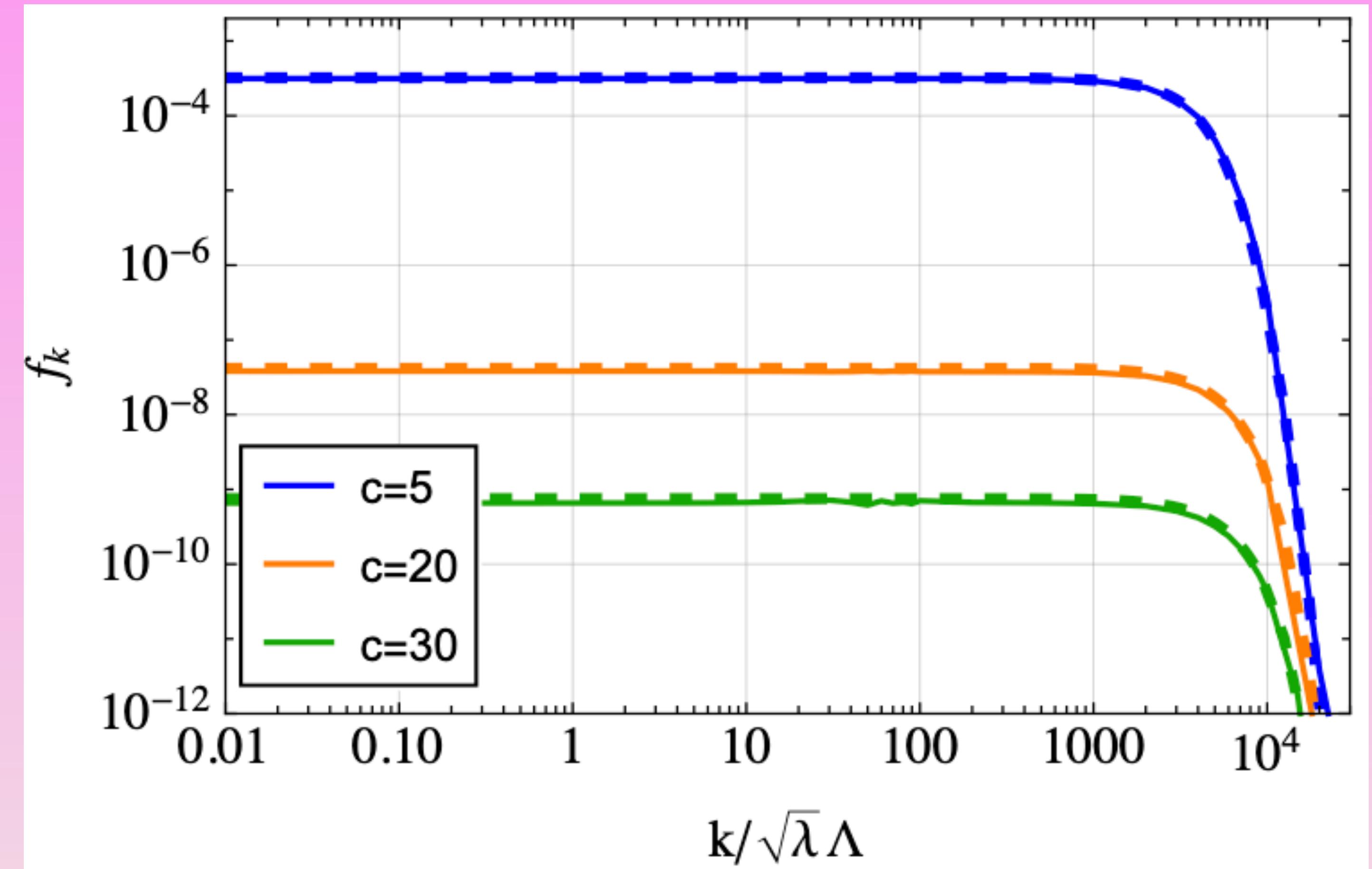


- Limit: $\Phi \rightarrow \infty$

- Cauchy: $f_k \simeq \frac{\pi^2}{4} \left| \sum_{\phi_\otimes} \text{Res}_{\phi=\phi_\otimes} \left[\frac{1}{\omega_k^2} \frac{d\omega_k^2}{d\phi} \exp \left(-2i \int_0^\phi d\phi \frac{\omega_k}{\dot{\phi}} \right) \right] \right|^2$

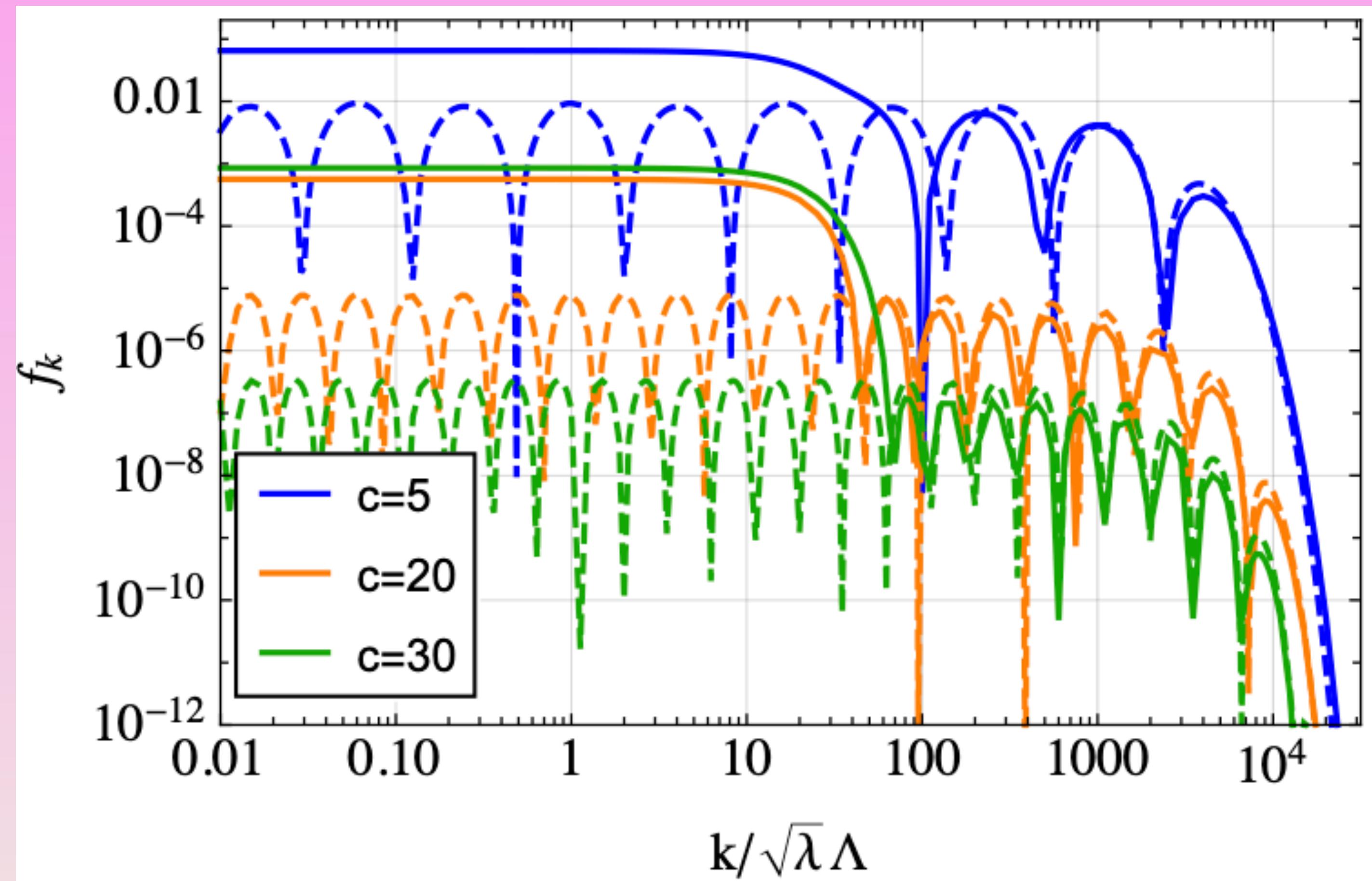
Mass with single pole

- $m_\chi^2 \simeq 2c \frac{V(\Phi)}{\Lambda^2} \frac{1}{1 + \phi^2/\Lambda^2}$



Mass with double pole

- $m_\chi^2 \simeq 2c \frac{V(\Phi)}{\Lambda^2} \frac{1}{(1 + \phi^2/\Lambda^2)^2} + 2\tilde{c} \frac{V(\phi)}{\Lambda^2}$



Limitations

- Born approximation only valid for small particle number
- Validity of $\Phi \rightarrow \infty$
- Other resonances

Part II

Particle production in specific inflationary models

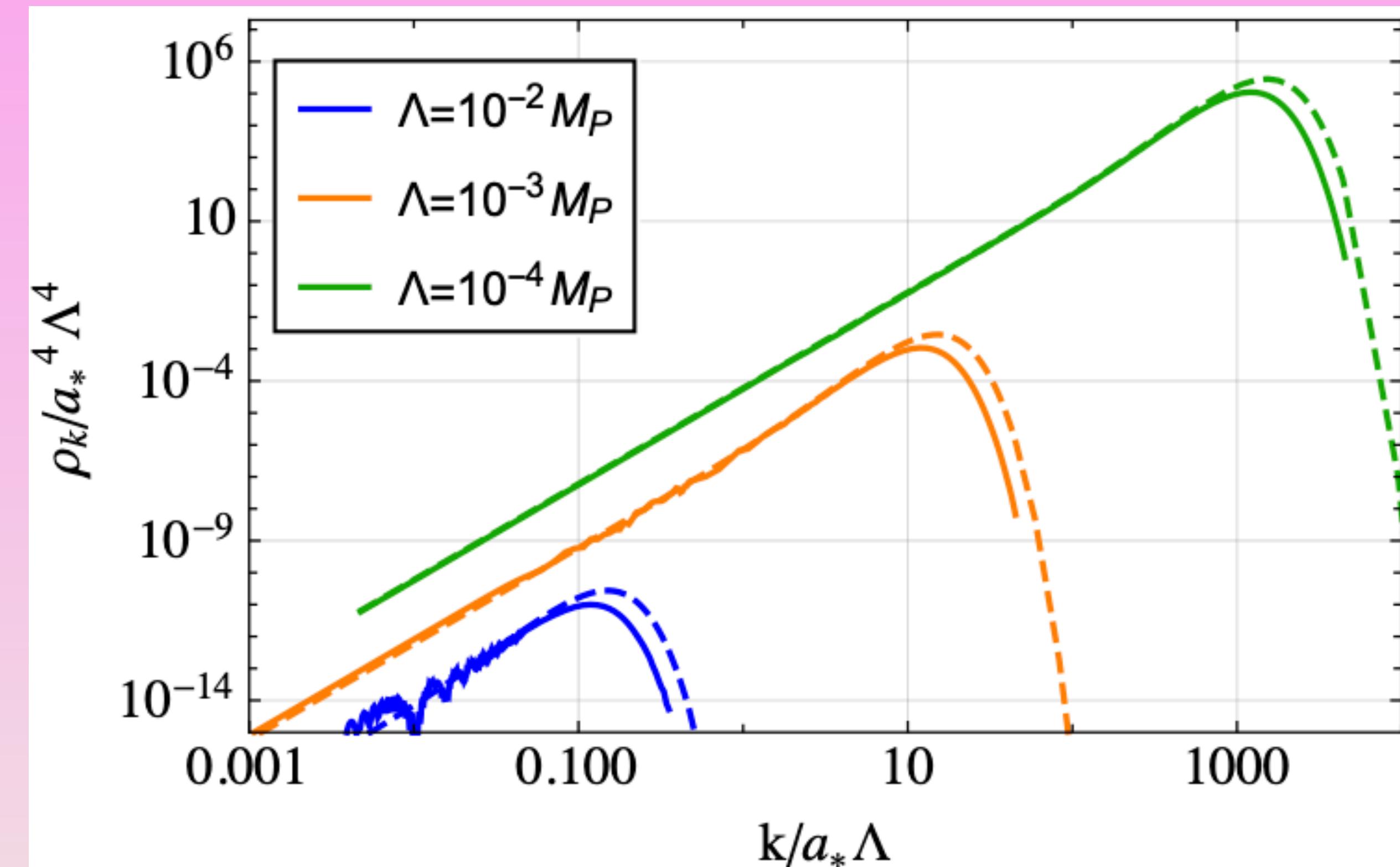
Running kinetic inflation

Takahashi 2010
Nakayama, Takahashi 2010

- $S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R + \frac{1}{2} \left(1 + \frac{\phi^2}{\Lambda^2} - c_K \frac{\chi^2}{\Lambda^2} \right) (\partial\phi)^2 + \frac{1}{2} (\partial\chi)^2 - \left(1 + c_V \frac{\chi^2}{\Lambda^2} \right) \frac{\lambda \phi^4}{4} \right]$

- Spike mass

$$m_\chi^2 \simeq \frac{c_K}{\Lambda^2} \frac{\lambda}{2} \frac{\Phi^4}{1 + \phi^2/\Lambda^2}$$



$$\begin{aligned} c_K &= 10 \\ c_V &= 0.1 \end{aligned}$$

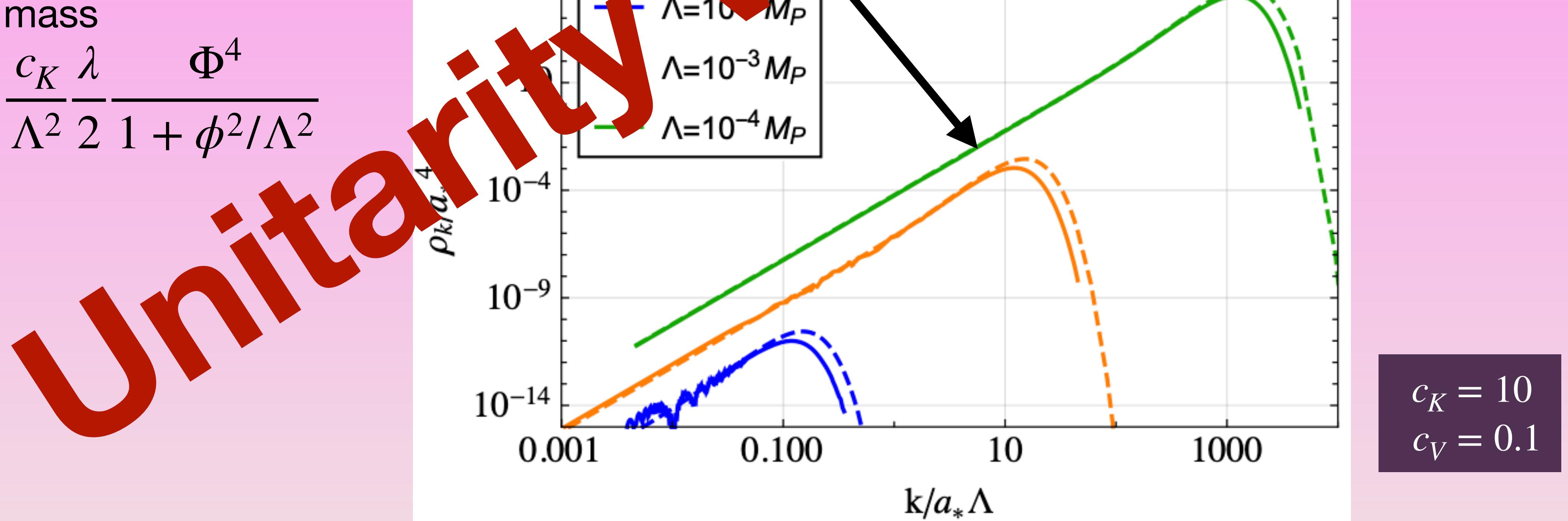
Running kinetic inflation

Takahashi 2009
Nakayama-Takahashi 2010

- $S = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R + \frac{1}{2} \left(1 + \frac{\phi^2}{\Lambda^2} - c_K \frac{\chi^2}{\Lambda^2} \right) (\partial\phi)^2 + \frac{1}{2} (\partial\chi)^2 - \left(1 + c_V \frac{\chi^2}{\Lambda^2} \right) \frac{\lambda \phi^4}{4} \right]$

- Spike mass

$$m_\chi^2 \simeq \frac{c_K}{\Lambda^2} \frac{\lambda}{2} \frac{\Phi^4}{1 + \phi^2/\Lambda^2}$$



Higgs inflation

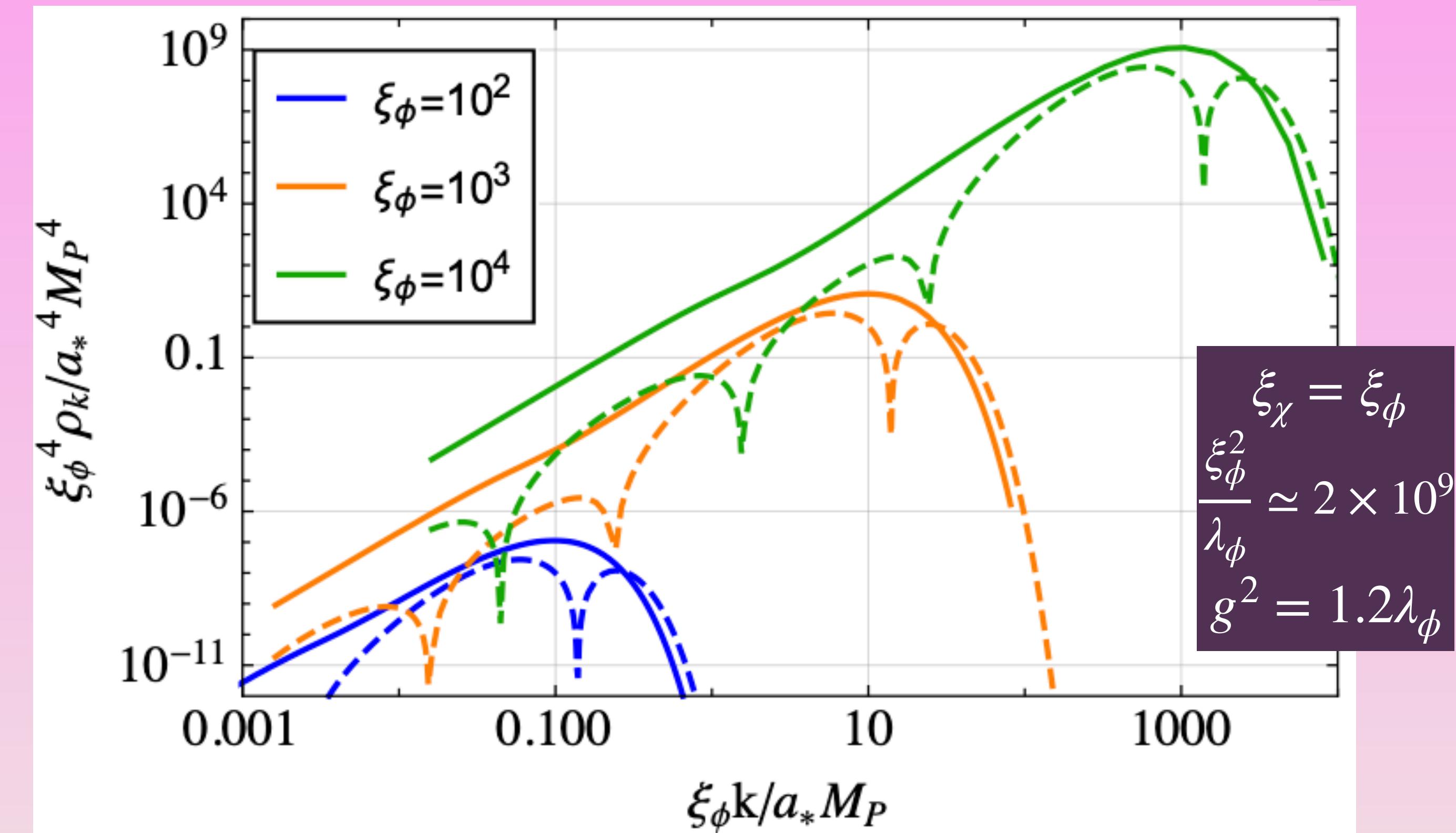
Bezrukov, Shaposhnikov 2007

- $S_J = \int d^4x \sqrt{-g} \left[\left(1 + \frac{\xi_\phi \phi^2 + \xi_\chi \chi^2}{M_P^2} \right) \frac{M_P^2}{2} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi^a \partial_\nu \phi^a - \left(\frac{\lambda_\phi}{4} \phi^4 + \frac{g^2}{2} \phi^2 \chi^2 + \frac{\lambda_\chi}{4} \chi^4 \right) \right]$

- Spike mass

$$m_\chi^2 \simeq \frac{\xi_\chi}{\xi_\phi} \frac{6\xi_\phi^2 \lambda_\phi}{M_P^2} \frac{\tilde{\Phi}^4}{2 \left(1 + 6\xi_\phi^2 \phi^2 / M_P^2 \right)^2}$$

$$\tilde{\Phi}^4 = \frac{\Phi^4}{\left(1 + \xi_\phi \Phi^2 / M_P^2 \right)^2}$$



Higgs inflation

Bezrukov, Shaposhnikov 2007

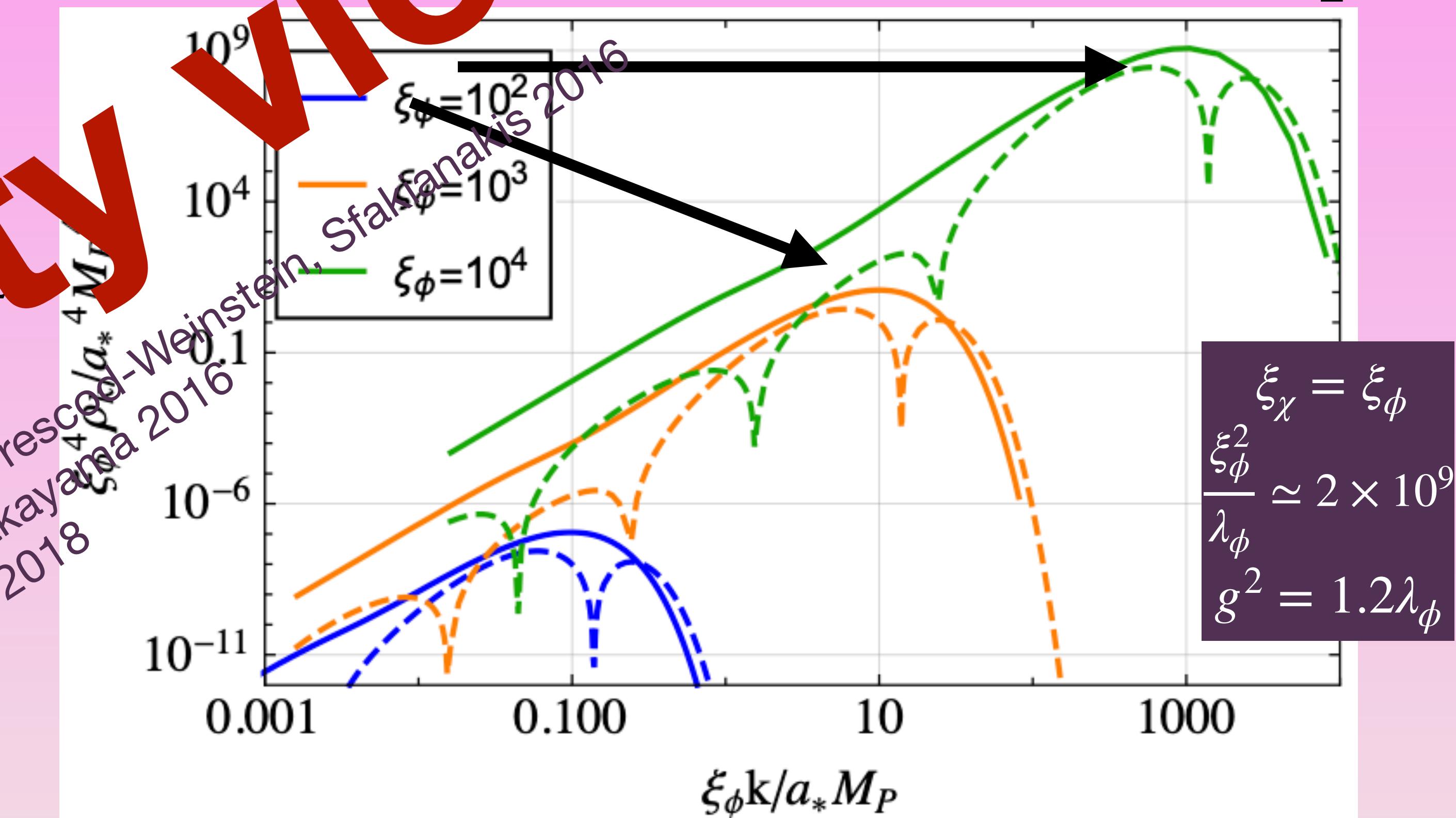
- $S_J = \int d^4x \sqrt{-g} \left[\left(1 + \frac{\xi_\phi \phi^2 + \xi_\chi \chi^2}{M_P^2} \right) \frac{M_P^2}{2} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi^a \partial_\nu \phi^a - \left(\frac{\lambda_\phi}{4} \phi^4 + \frac{g^2}{2} \phi^2 \chi^2 + \frac{\lambda_\chi}{4} \chi^4 \right) \right]$

- Spike mass

$$m_\chi^2 \sim \frac{\xi_\chi}{\xi_\phi} \frac{6\xi_\phi^2 \lambda_\phi}{M_P^2} \frac{\tilde{\Phi}^4}{2} \left(1 + 6\xi_\phi^2 \lambda_\phi / M_P^2 \right)$$

$$\tilde{\Phi}^4 = \frac{\Phi^4}{\left(1 + \xi_\phi \xi_\chi^2 / M_P^2 \right)^2}$$

DeCross, Kaiser, Prabhu, Prescod-Weinstein, Sfakianakis 2016
 Ema, Jinno, Mukaida, Nakayama 2016
 Sfakianakis, van de Vis 2018



Palatini Higgs inflation and α -attractors

- No unitarity violation!
- Palatini Higgs inflation
Bauer, Demir 2008&2010
Rubio, Tomberg 2019
- α -attractors
Krajewski, Turzyński, Wieczorek 2018
Iarygina, Sfakianakis, Wang, Achúcarro 2018&2020

Momentum of produced particles

- Λ : typical mass scale of curved target space.
coincides with unitarity cut-off

- Typical momentum of produced particles $\left(\frac{k}{a_*}\right)_{\max} \sim \frac{\dot{\phi}}{\Lambda}$

- Momentum conservation $\dot{\phi}^2|_{|\phi| \lesssim \Lambda} \sim V(\Phi)$

- Unitarity violated when $\left(\frac{k}{a_*}\right)_{\max} \gtrsim \Lambda$

- Condition for unitarity violation: $V(\Phi) \gtrsim \Lambda^4$

Momentum of produced particles

- Λ : typical mass scale of curved target space.
coincides with unitarity cut-off

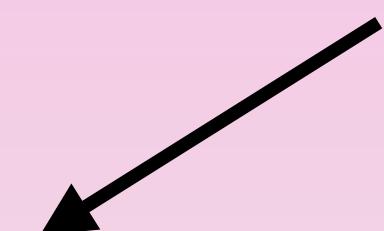
- Typical momentum of produced particles $\left(\frac{k}{a_*}\right)_{\max} \sim \frac{\dot{\phi}}{\Lambda}$

- Momentum conservation $\dot{\phi}^2|_{|\phi| \lesssim \Lambda} \sim V(\Phi)$

- Unitarity violated when $\left(\frac{k}{a_*}\right)_{\max} \gtrsim \Lambda$

- Condition for unitarity violation: $V(\Phi) \gtrsim \Lambda^4$

**Only satisfied for Higgs inflation
and Running Kinetic inflation**



Summary

- Models with curved target space: spiky mass → efficient reheating
- Semi-analytic estimate of particle number after first zero-crossing
- Running kinetic inflation and Higgs inflation violate unitarity
- Palatini Higgs inflation and α -attractors do not
- Condition for unitarity violation: $V(\Phi) \gtrsim \Lambda^4$