(P)reheating Effects of the Kähler Moduli Inflation I Model

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Cosmology from Home 2022

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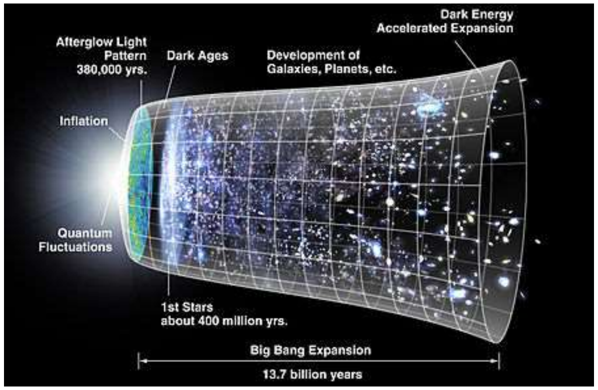
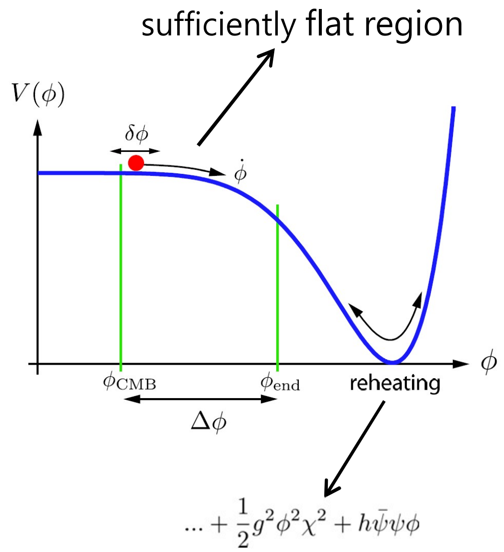
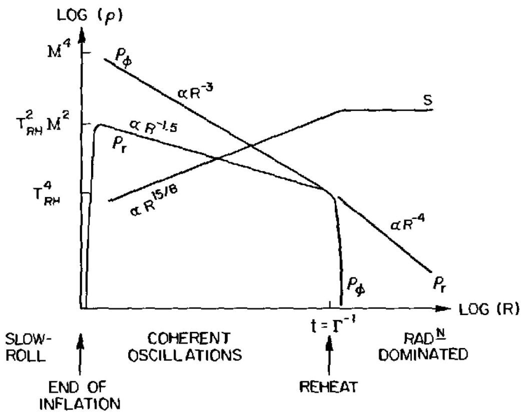
Outline

- Slow-Roll Inflation
- Testing Inflation
- The Model
- MCMC Sampling Analysis
- Reheating Dynamics
- Numerical Lattice Simulations
- Summary & Remarks

Slow-Roll Inflation







Horizon or homogeneity problem

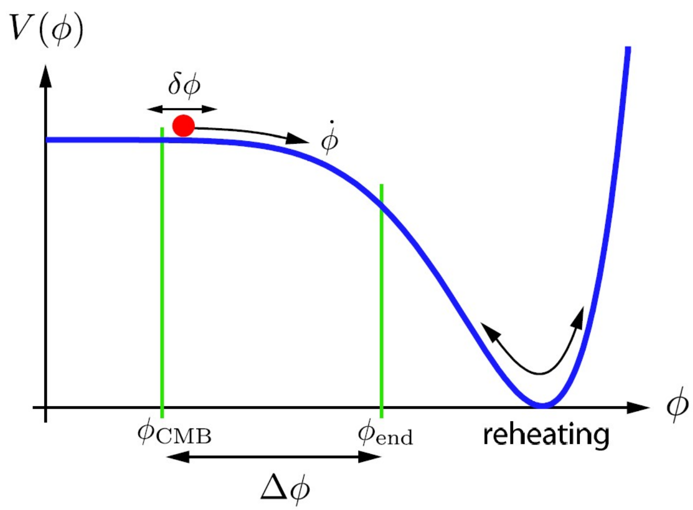
Flatness problem

Structure formation problem

Monopole problem

Image Credit: NASA / WMAP Science Team
Image Credit: arXiv: 1006.0275
Image Credit: E. Kolb & M. Turner

Slow-Roll Inflation Contd.



Slow-Roll Parameters

$$\epsilon = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \qquad \eta = M_{\rm Pl}^2\frac{V''}{V} \qquad \xi = M_{\rm Pl}^4\frac{V'V'''}{V^2}$$

Inflation occurs when

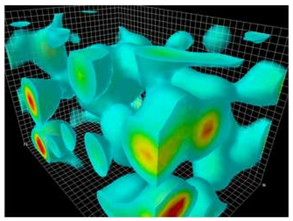
$$\epsilon \ll 1,\ |\eta| \ll 1,\ \text{and}\ \xi \ll \epsilon, \eta$$

Inflation stops when

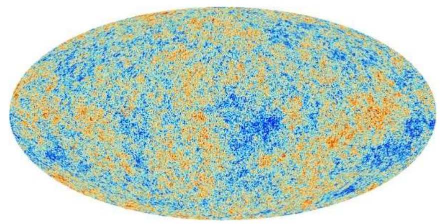
$$\epsilon = 1 \text{ or } |\eta| = 1$$

Image Credit: arXiv: 1006.0275

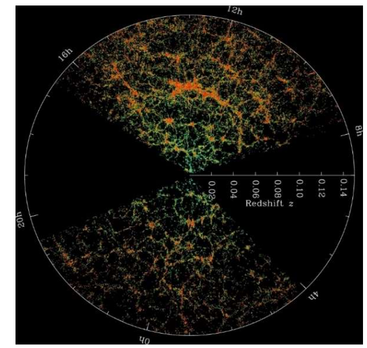
Testing Inflation



Random Quantum fluctuations



Cosmic Microwave Background



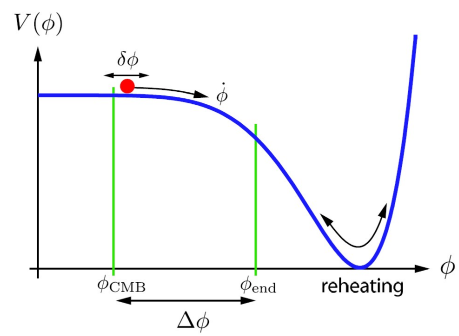
Map of the Universe

Tensor-to-scalar power ratio r

Scalar spectral index n_s

Its running $n_{\rm run} = {\rm d\,ln}n_s/{\rm d\,ln}k$

Scalar power spectrum amplitude A_s



$$r \simeq 16\epsilon$$

$$n_s \simeq 1 - 6\epsilon + 2\eta$$

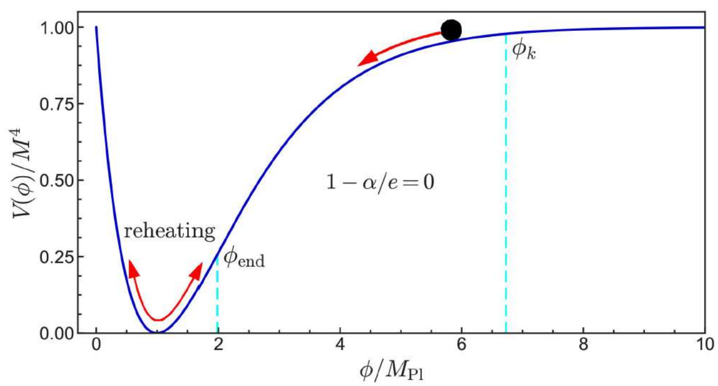
$$n_{\rm run} \simeq 16\epsilon\eta - 24\epsilon^2 - 2\xi$$

$$A_s = \frac{V(\phi_k)}{24\pi^2 M_{\rm Pl}^4 \epsilon}$$

Image Credit: arXiv: 1006.0275
Image Credit: ESA and the Planck Collaboration
Image Credit: Sloan Digital Sky Survey (SDSS)
Image Credit: arXiv: 1312.5672

The Kähler Moduli Inflation I (KMII)

$$V(\phi) = M^4 \left(1 - \alpha \frac{\phi}{M_{\rm Pl}} e^{-\phi/M_{\rm Pl}}\right) + g^2\chi^2\phi^2$$

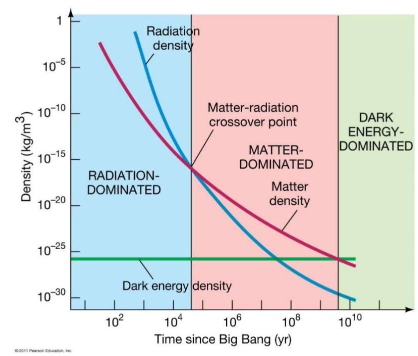


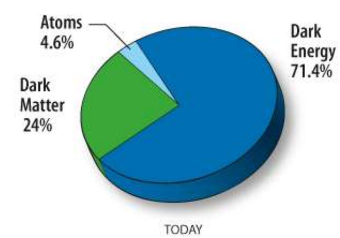
Does the model work?

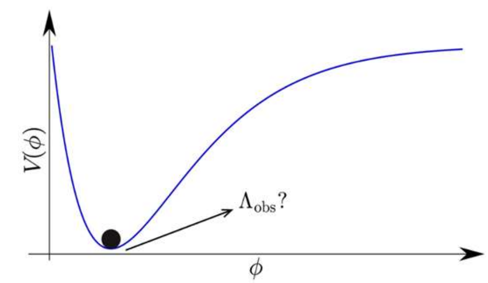
What are the allowed model parameter ranges?

Does it predict anything else that can be observed?

Observed dark energy density $\Lambda_{\rm obs} \sim 10^{-47}\,{\rm GeV}^4$



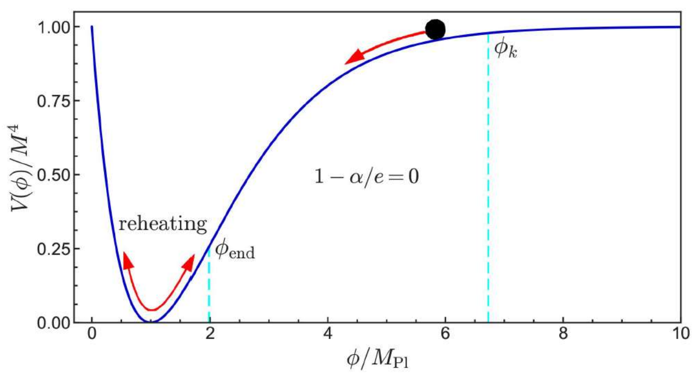




$\Lambda_{\rm obs} = V(\phi)$ at minimum

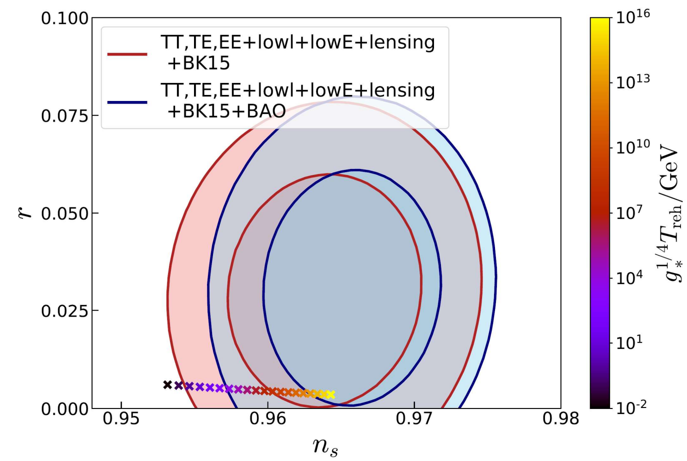
Credit: NASA/WMAP Science Team

Does the Model Work?



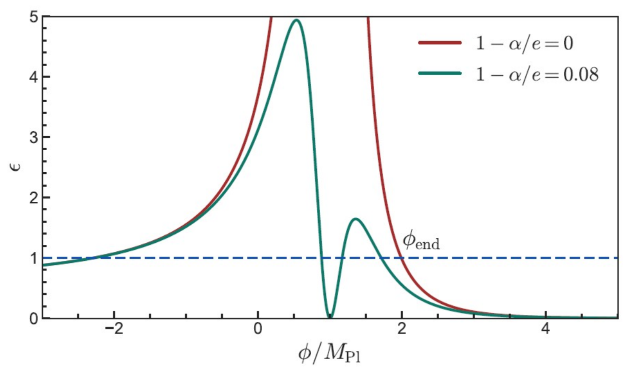
$Planck$ + BK15

$Planck$ + BK15 + BAO



$$r \simeq 16\epsilon$$

$$n_s \simeq 1 - 6\epsilon + 2\eta$$



$$\epsilon = \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\epsilon \ll 1,\ |\eta| \ll 1,\ \text{and}\ \xi \ll \epsilon, \eta$$

$$\epsilon = 1 \text{ or } |\eta| = 1$$

Reheating temperature

$$1\,{\rm MeV} < T_{\rm reh} < 10^{7-9}\,{\rm GeV}$$

$Planck$ + BK15 $\quad T_{\rm reh} \gtrsim 0.3\,{\rm GeV}$

$Planck$ + BK15 + BAO $\quad T_{\rm reh} \gtrsim 3 \times 10^3\,{\rm GeV}$

at 95% CL

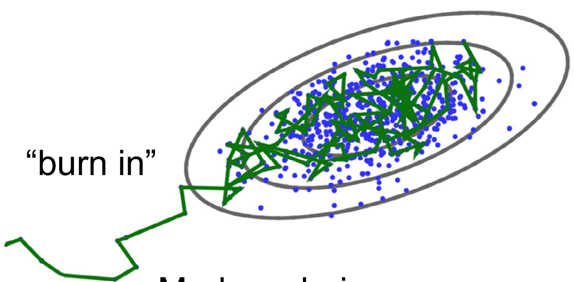
Predictions computed using the ASPIC Library: arXiv:1303.3787

Allowed Model Parameter Ranges

Markov Chain Monte Carlo Sampling[1]

Bayes' Theorem

$$p(\boldsymbol{\theta}|\boldsymbol{z}) = \frac{p(\boldsymbol{\theta})p(\boldsymbol{z}|\boldsymbol{\theta})}{m(\boldsymbol{z})}$$



$$V(\phi) = M^4\left(1 - \alpha\frac{\phi}{M_{\rm Pl}}e^{-\phi/M_{\rm Pl}}\right) + g^2\chi^2\phi^2$$

Model parameters

$$M,\ \alpha, \text{and } g^2$$

$$\downarrow$$

$$A_s, n_s, n_{\rm run}, \text{ and } r$$

(predicted values)

Data

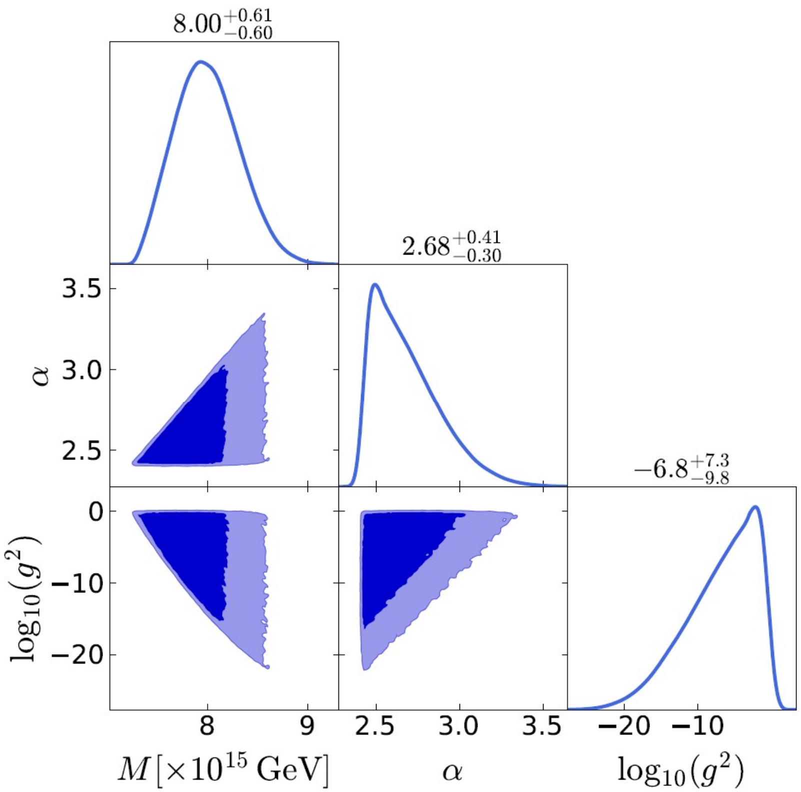
$$A_s, n_s, n_{\rm run}, \text{ and } r$$

$$\textit{Planck} + \text{BK15} + \text{BAO}$$

1. arXiv:1202.3665

Image credit: https://wiki.ubc.ca/

MCMC Sampling Results



Model parameter posteriors

$$7.4 \times 10^{15}\mathrm{GeV} < M < 8.6 \times 10^{15}\mathrm{GeV}$$

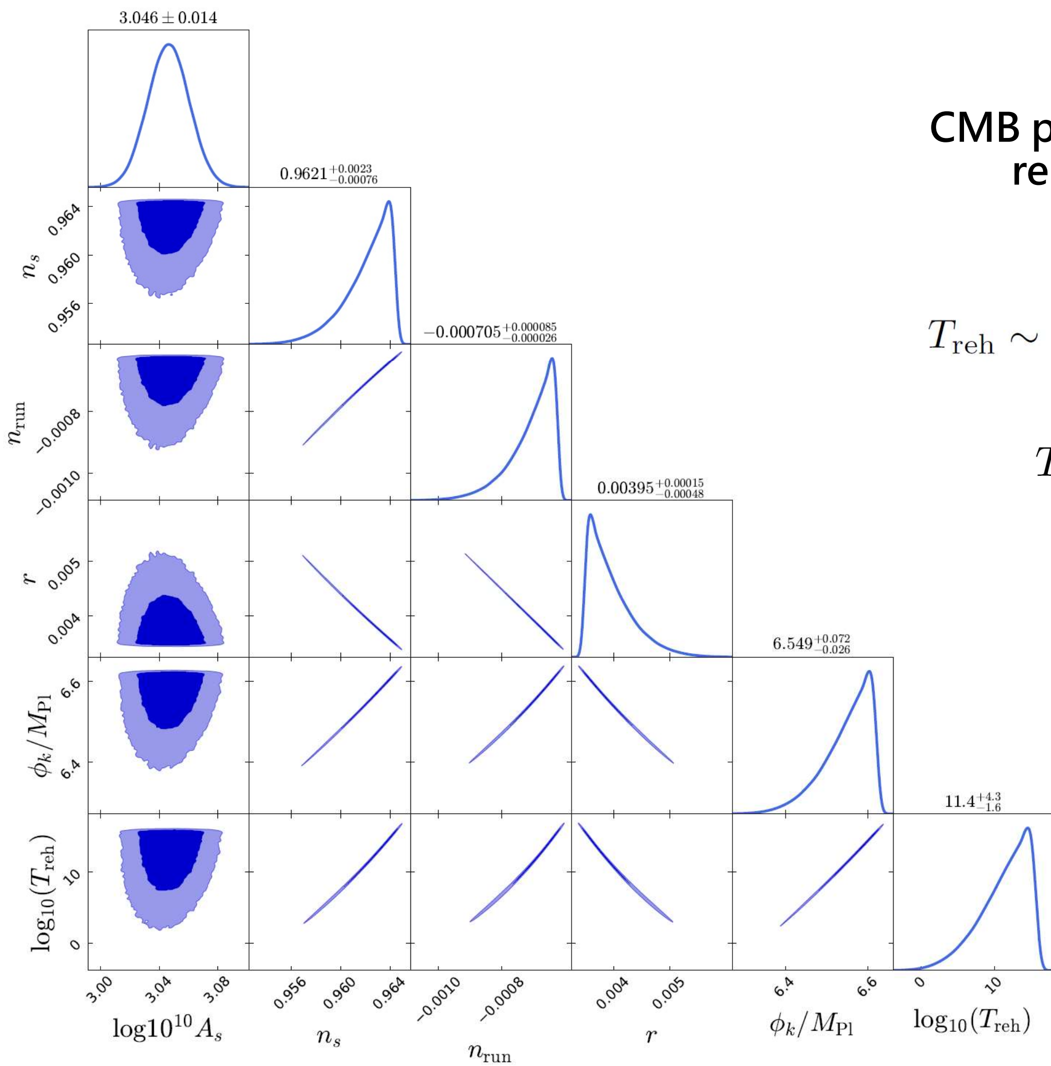
$$2.4 < \alpha < 3.1$$

$$g^2 \gtrsim 2.5 \times 10^{-17}$$

$$m_\phi^2 = \frac{M^4 \alpha}{e M_{\mathrm{Pl}}^2}$$

$$2.1 \times 10^{13}\mathrm{GeV} < m_\phi < 3.2 \times 10^{13}\mathrm{GeV}$$

all at 95% CI



CMB parameter posteriors with reheating temperature

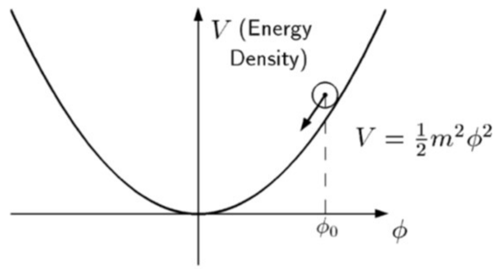
$$T_{\rm reh} \sim \left(\frac{90}{g_* \pi^2}\right)^{1/4} \frac{g^2 M_{\rm Pl}^2}{\sqrt{8\pi} M} \left(\frac{e}{\alpha}\right)^{1/4}$$

$$T_{\rm reh} \gtrsim 1.8 \times 10^3 \text{ GeV}$$

at 95% CI

Does the Model Predict Anything Else?

Reheating after Inflation



$$V(\phi, \chi) = \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\chi^2 + h\bar{\psi}\psi\phi$$

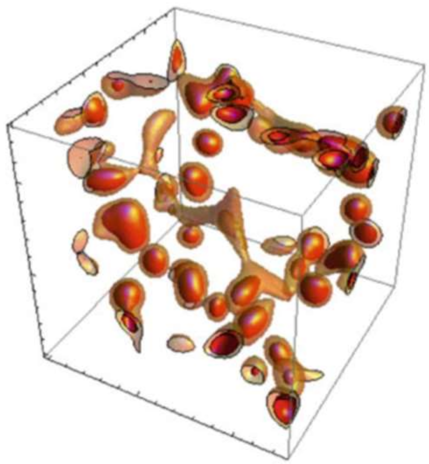
Classical motion of inflaton

$$\ddot{\phi} + V'_\phi \simeq 0$$

Equation of motion of fluctuations

$$\delta\ddot{\phi}_\mathbf{k} + (k^2 + V''_\phi)\delta\phi_\mathbf{k} = 0$$

$$\delta\ddot{\chi}_\mathbf{k} + (k^2 + V''_\chi)\delta\chi_\mathbf{k} = 0$$



Formation of oscillons

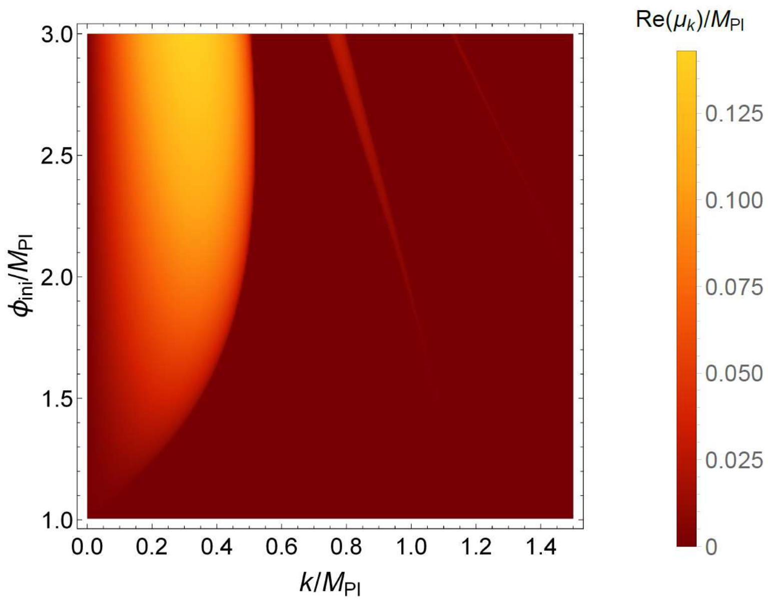
Parametric resonance due to self-interactions (self-resonance)

Parametric resonance due to coupling

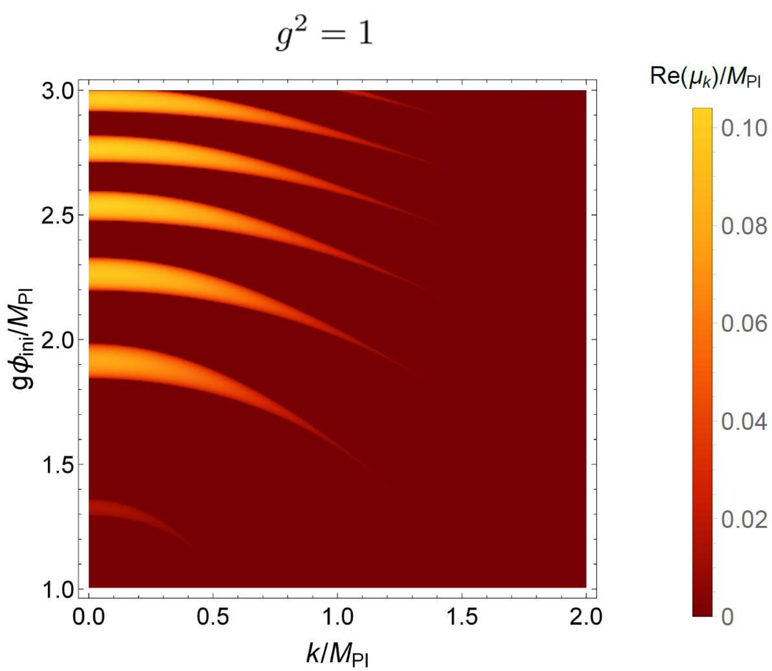
Tachyonic instabilities

Image Credit: arXiv: 1312.5672
Image Credit: arXiv:1907.04402

Floquet Analysis



Parametric resonance due to self-interactions



Parametric resonance due to coupling

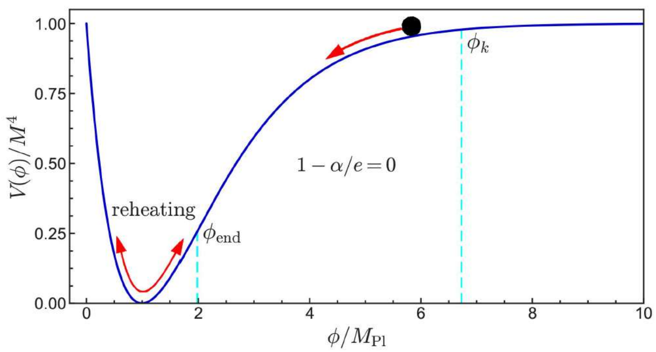
Numerical Lattice Simulations

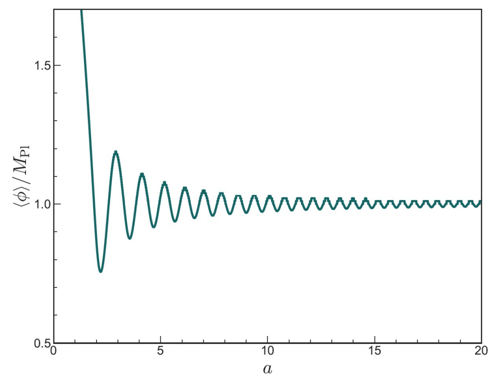
Dark Energy equation of state

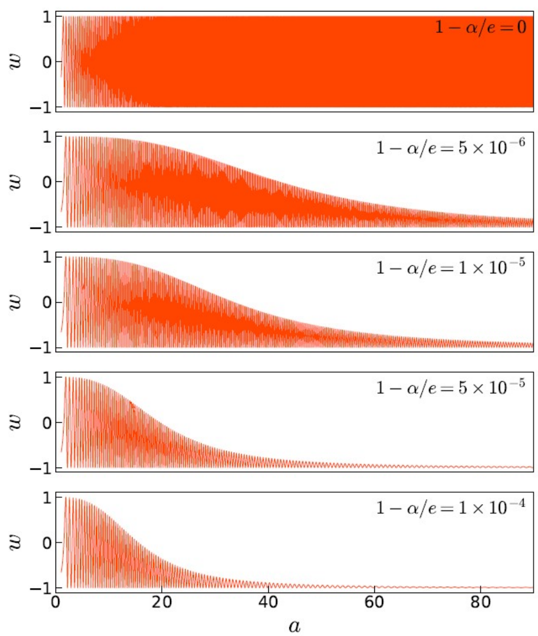
$$w_{DE} \approx -1$$

HLattice code[1]

$$V(\phi) = M^4\left(1 - \alpha\frac{\phi}{M_{\rm Pl}}e^{-\phi/M_{\rm Pl}}\right) + g^2\chi^2\phi^2$$







Box size $= 0.3H_{ini}^{-1}$

Resolution $= 128$

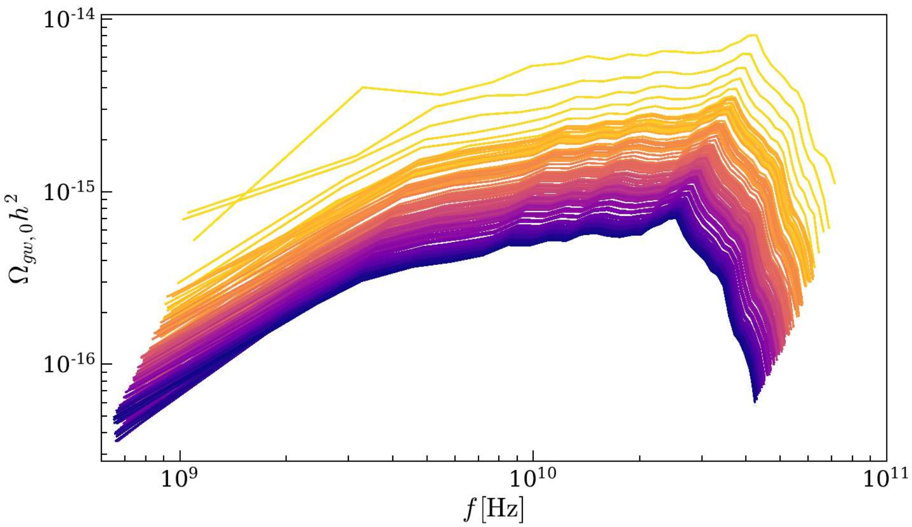
$M = 8.0\times10^{15}$ GeV

$1-\alpha/e = 0$

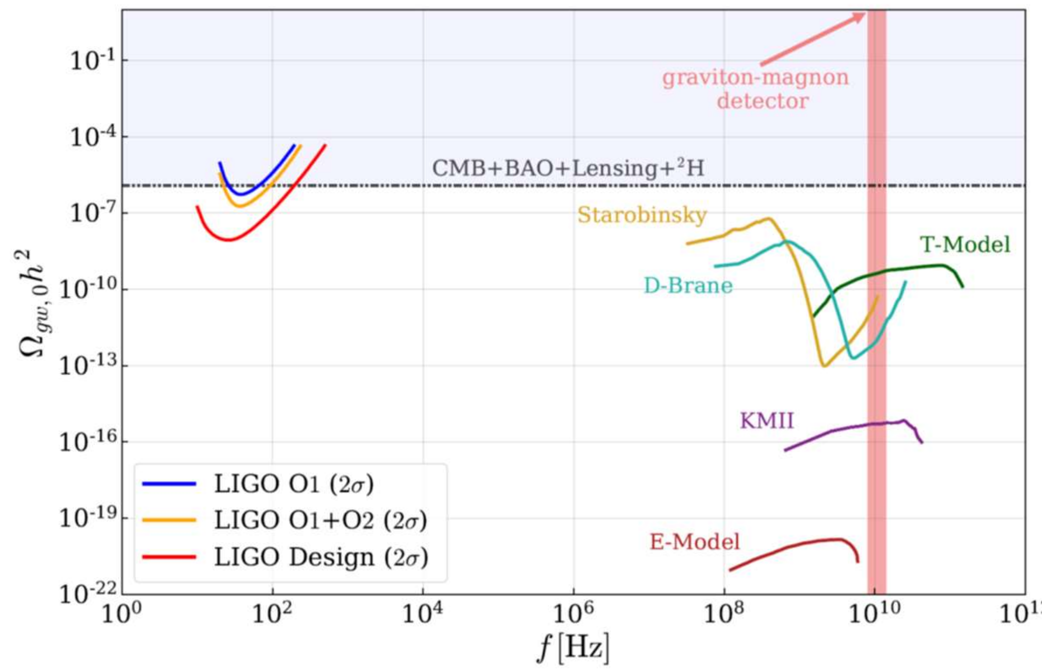
$g^2 = 10^{-4}$

1. arXiv:1102.0227
WSU Kamiak cluster (20 cores)

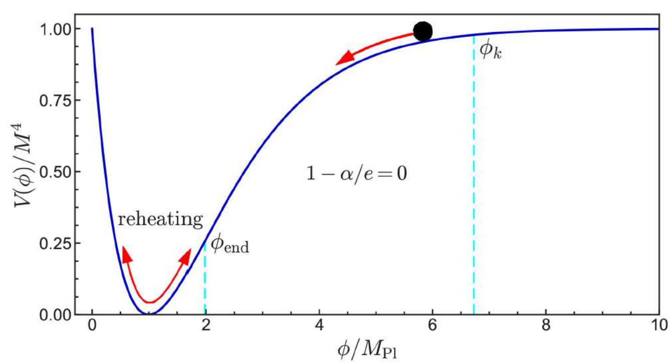
HLattice Results



Stochastic Gravitational Wave Spectra

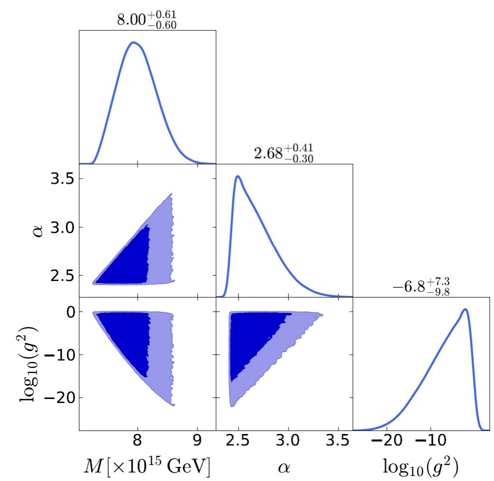


Summary & Remarks



$$V(\phi) = M^4\left(1 - \alpha\frac{\phi}{M_{\rm Pl}}e^{-\phi/M_{\rm Pl}}\right) + g^2\chi^2\phi^2$$

α needs to be fine-tuned to achieve $\Lambda_{\rm obs}$



Mass of inflaton field $m_\phi \sim 10^{13}\,{\rm GeV}$

Predicts a high Reheating Temperature

$T_{\rm reh} \gtrsim 1.8\times 10^3\,{\rm GeV}$ at 95% CI

No oscillon formation/generation of gravitational waves found during preheating

Is $V_{\rm min} = 0$ the most viable?

Is $V_{\rm min} \neq 0$ the most viable?