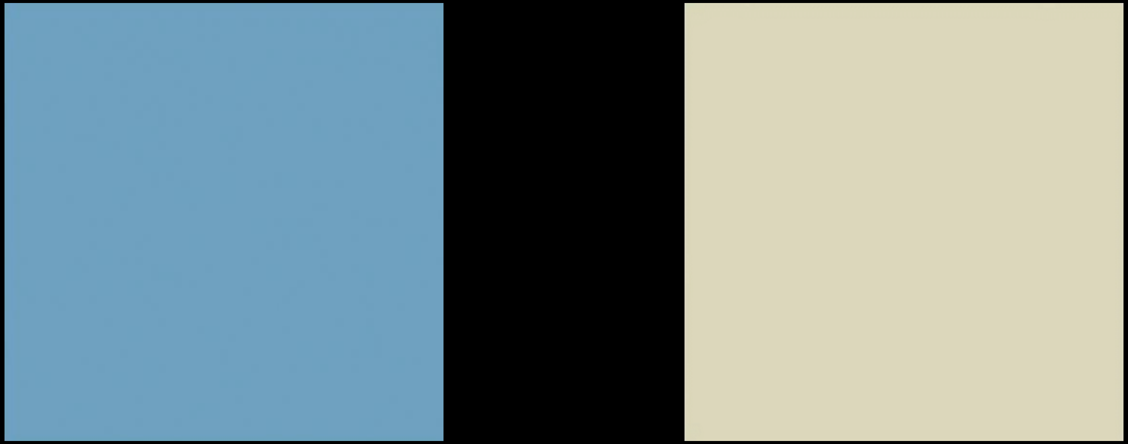

Lattice simulations of inflation and reheating

Kaloian Lozanov

UIUC, Cosmology and HEPheno

The equation of state after inflation

KL and M. Amin (2017, 18, 19)

What is w after inflation?

$$w = \frac{\text{pressure}}{\text{energy density}}$$

$$S = \int d^4x\sqrt{-g}\Big[\frac{1}{16\pi G}\mathcal{R} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\Big]$$

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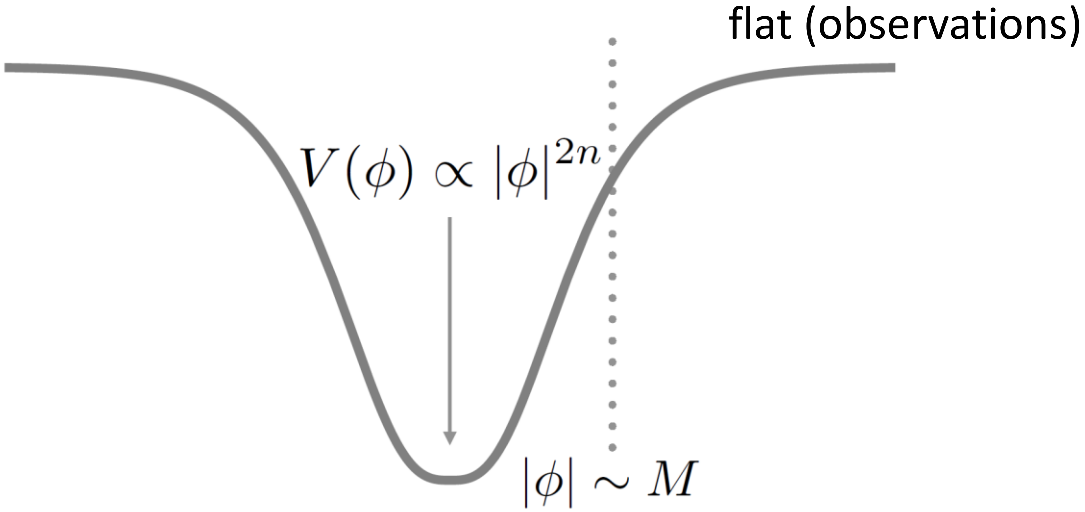

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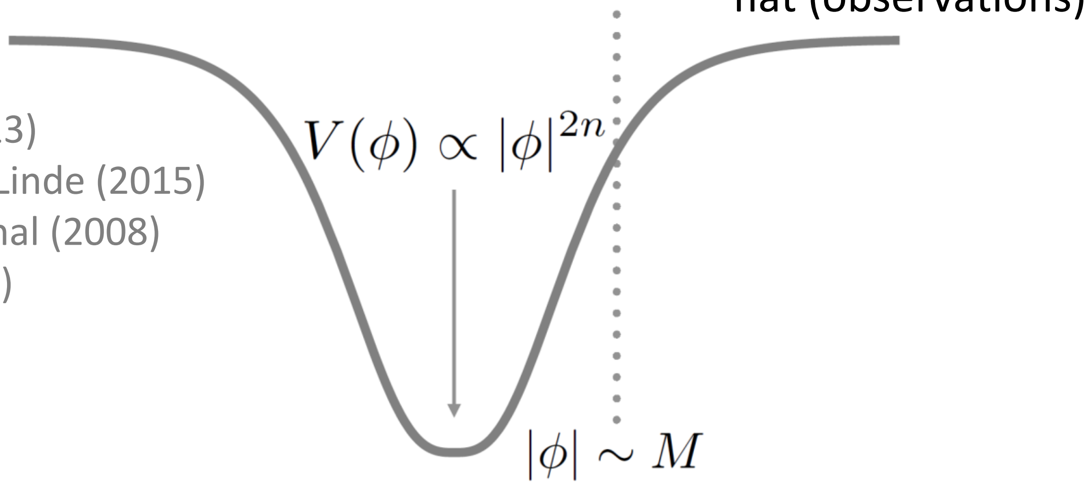

Kallosh and Linde (2013)
Carrasco, Kallosh and Linde (2015)
Silverstein and Westphal (2008)
McAllister, et al. (2014)

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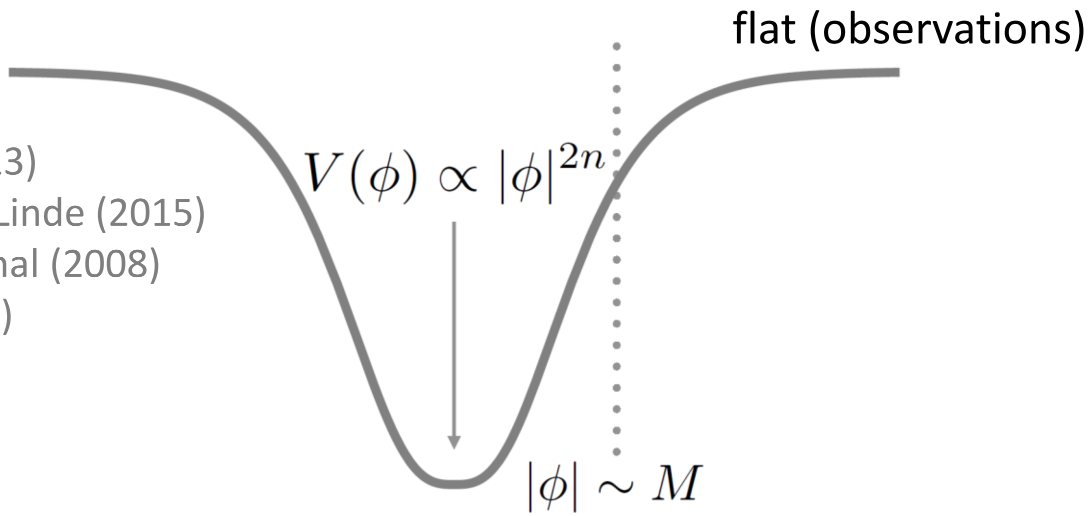


Kallosh and Linde (2013)
Carrasco, Kallosh and Linde (2015)
Silverstein and Westphal (2008)
McAllister, et al. (2014)

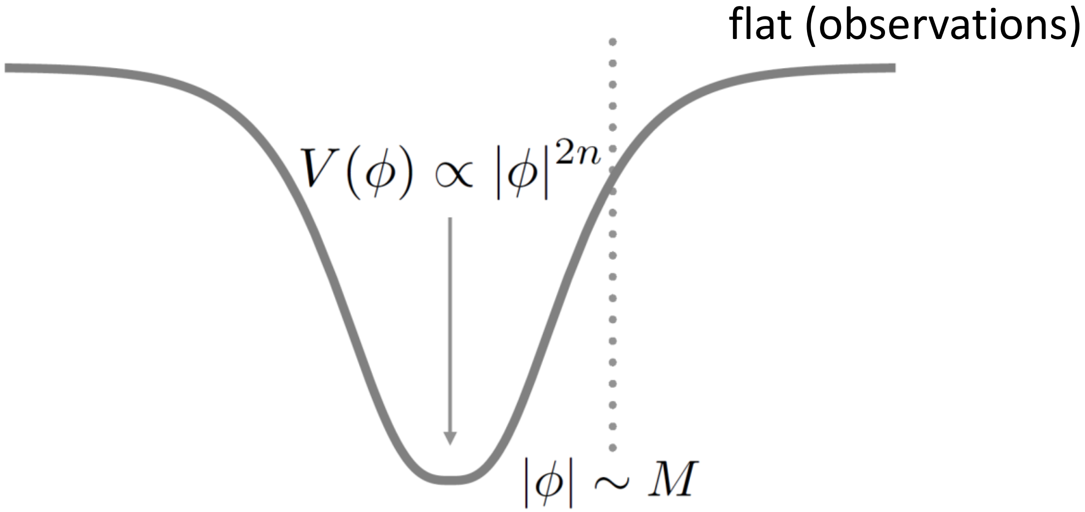
assumption: self-couplings dominate over others

What is w after inflation?

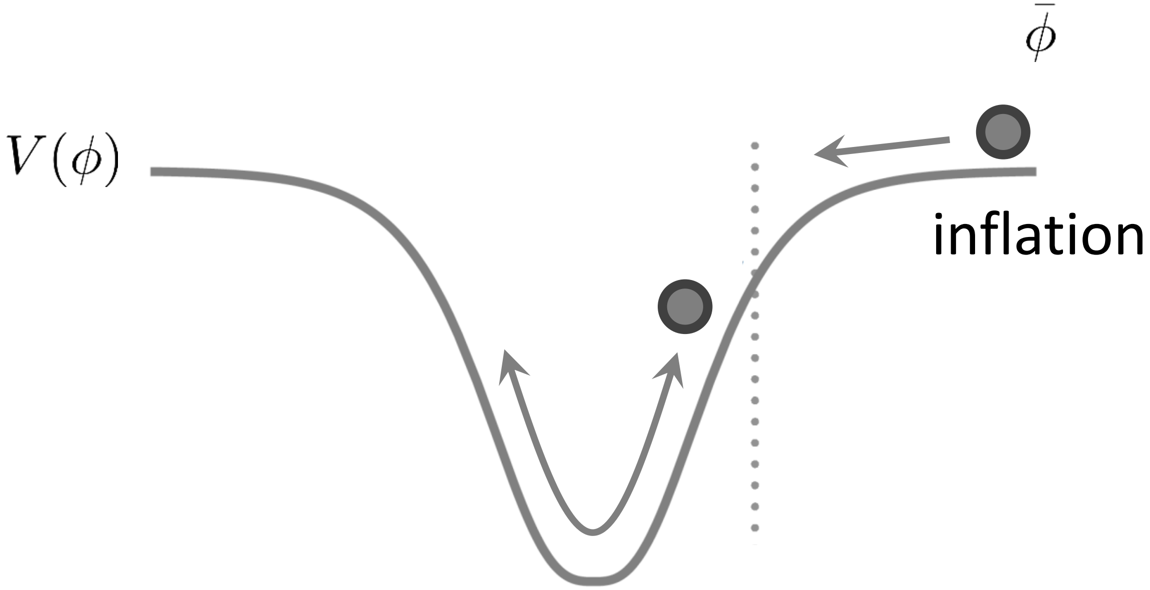
at sufficiently late times:

$$\boxed{w = \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}}$$

(even without couplings to other fields!)



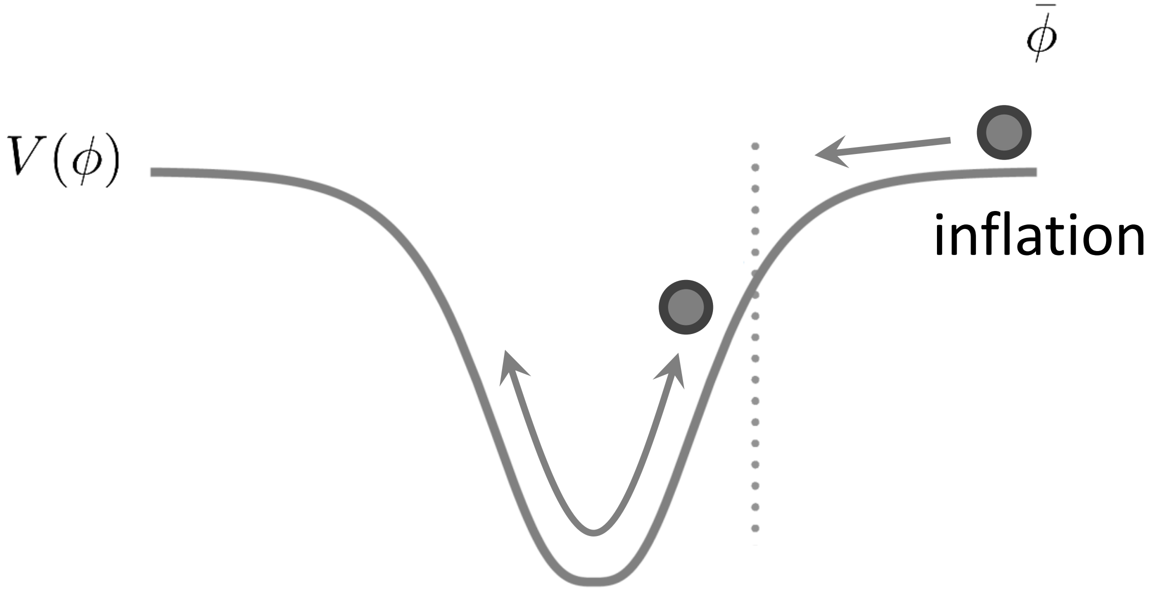
Inflaton dynamics



inflation

inflation ends:
oscillatory phase

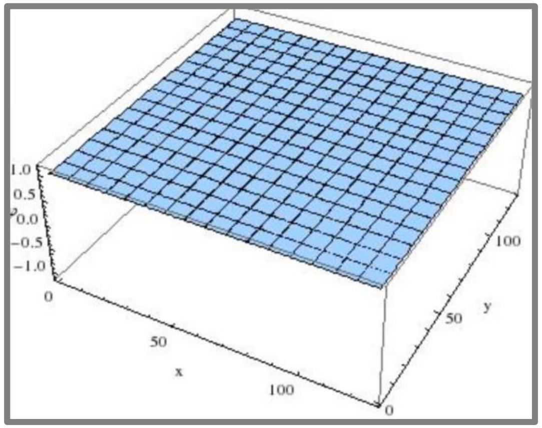
Inflaton (homogeneous) dynamics



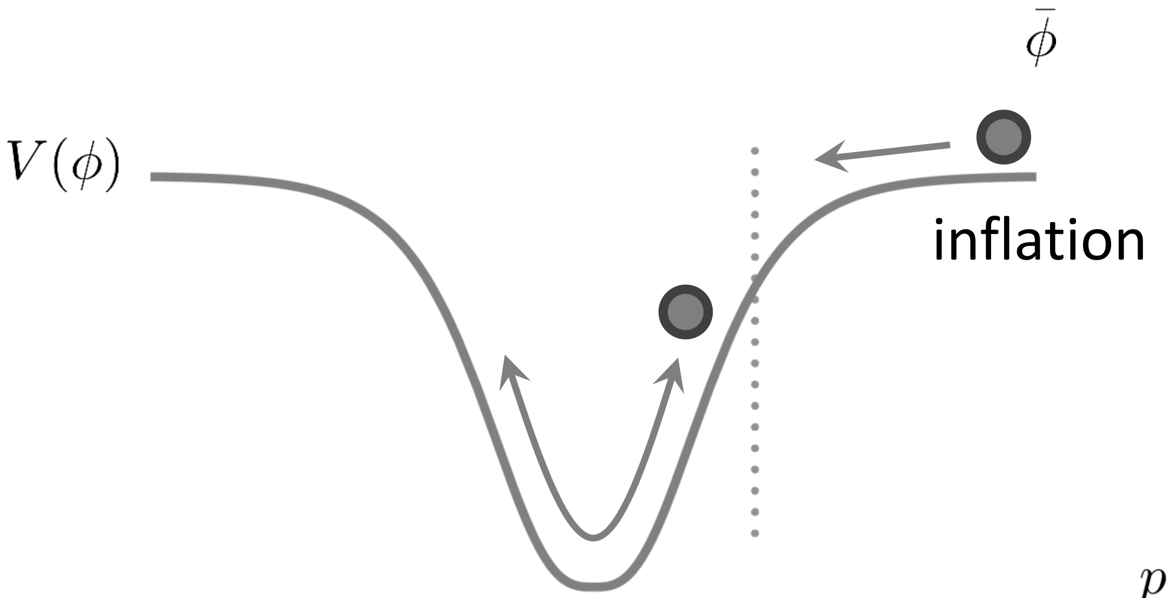
inflation ends:
oscillatory phase

$$\bar{\phi}(t) \propto a(t)^{-3/(n+1)}$$

$$\phi \times a^{3/(n+1)}$$



Inflaton (homogeneous) dynamics

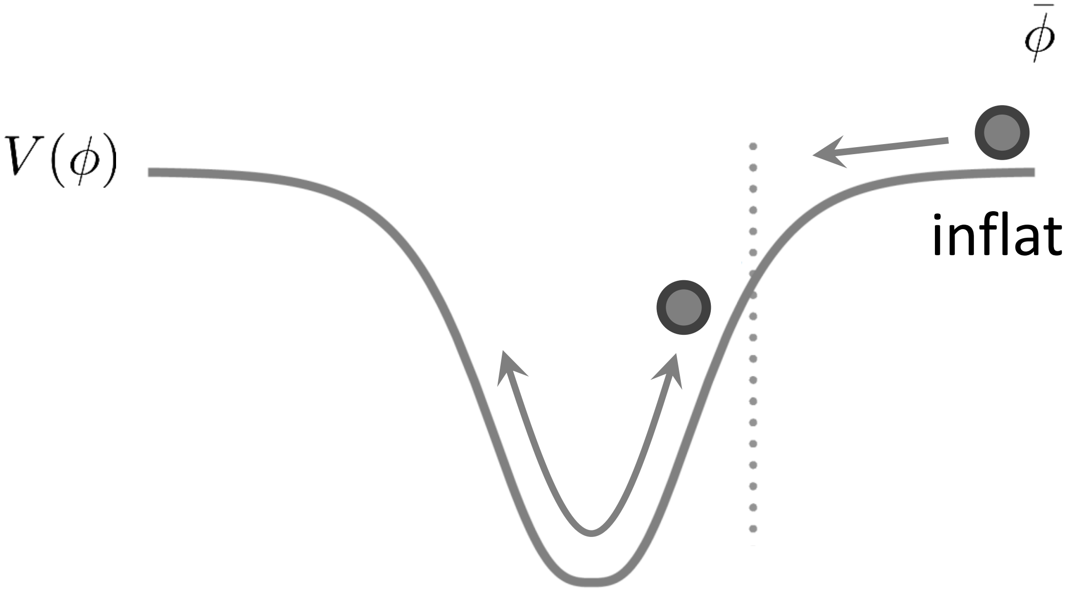


$$w \equiv \frac{p}{\rho} = \frac{\dot{\phi}^2/2 - (\nabla\phi)^2/6 - V(\phi)}{\dot{\phi}^2/2 + (\nabla\phi)^2/2 + V(\phi)}$$

inflation ends:
oscillatory phase

$$\bar{\phi}(t) \propto a(t)^{-3/(n+1)}$$

Inflaton (homogeneous) dynamics

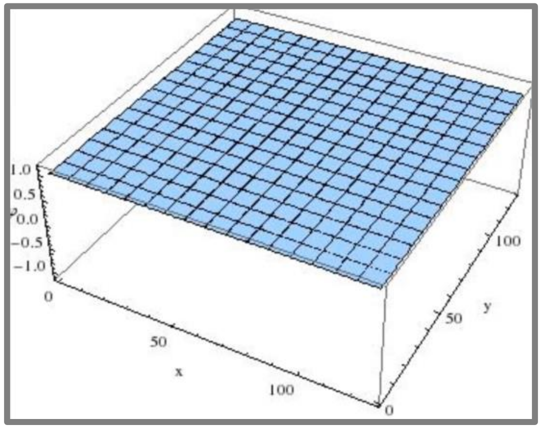


inflation

inflation ends:
oscillatory phase

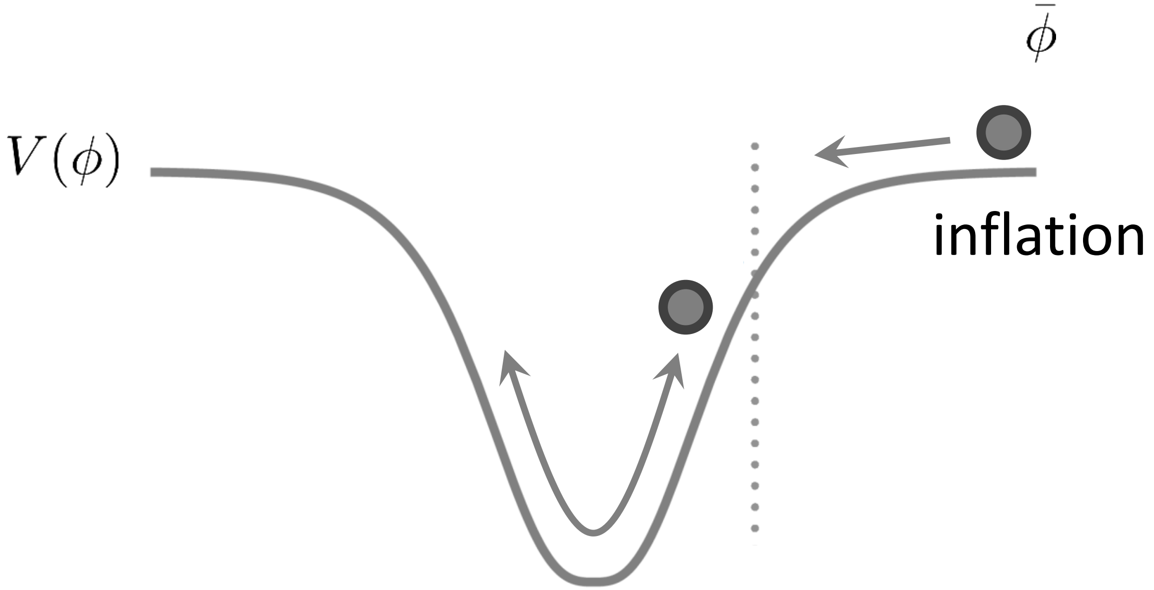
$$w_{\text{hom}} = \frac{n-1}{n+1}$$

$\phi \times a^{3/(n+1)}$



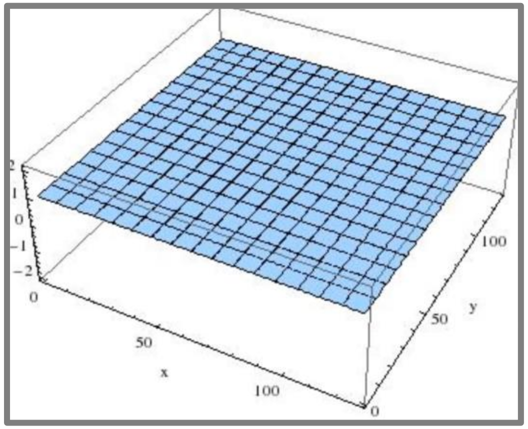
Turner (1983)

Inflaton (actual) dynamics



inflation ends:
oscillatory phase

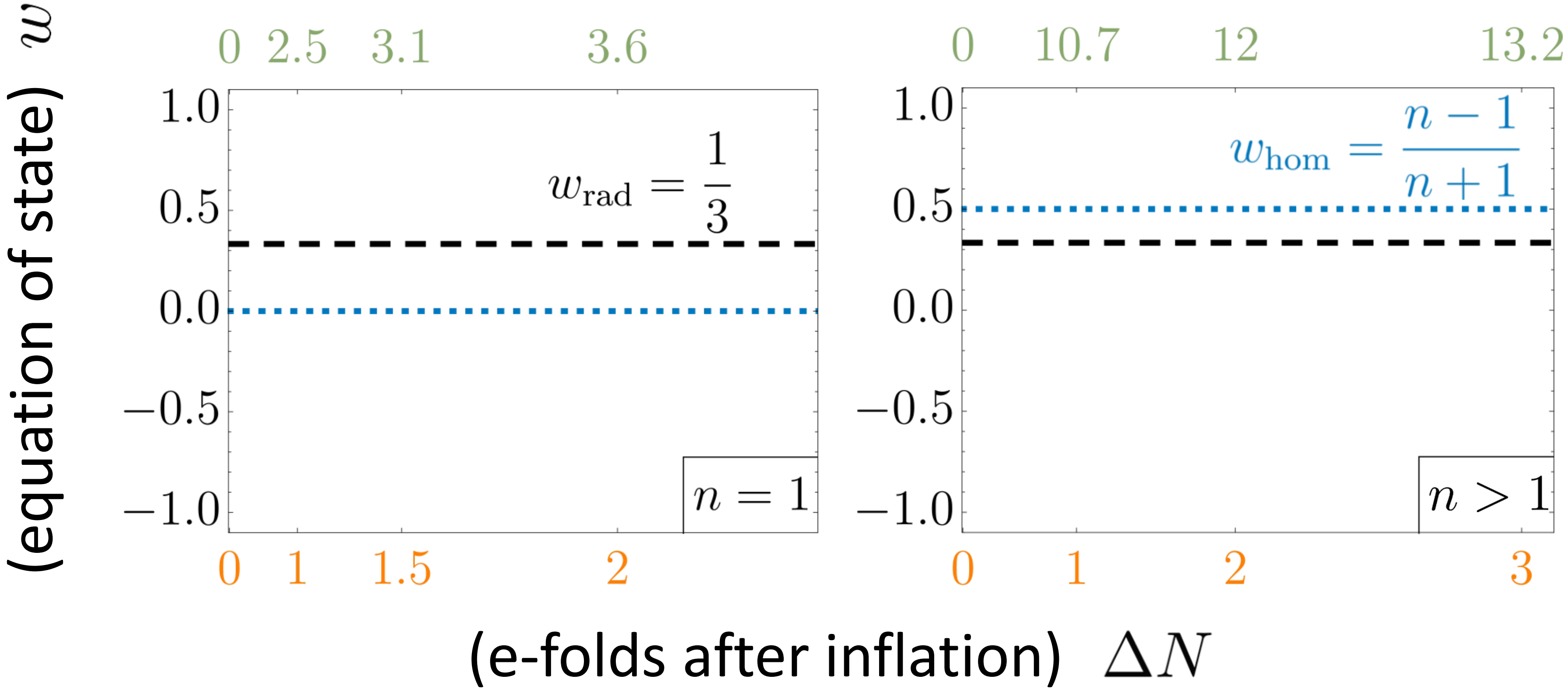
$\phi \times a^{3/(n+1)}$



- parametric resonance of $\delta\phi(t, \mathbf{x})$
- $\bar{\phi}$ fragments

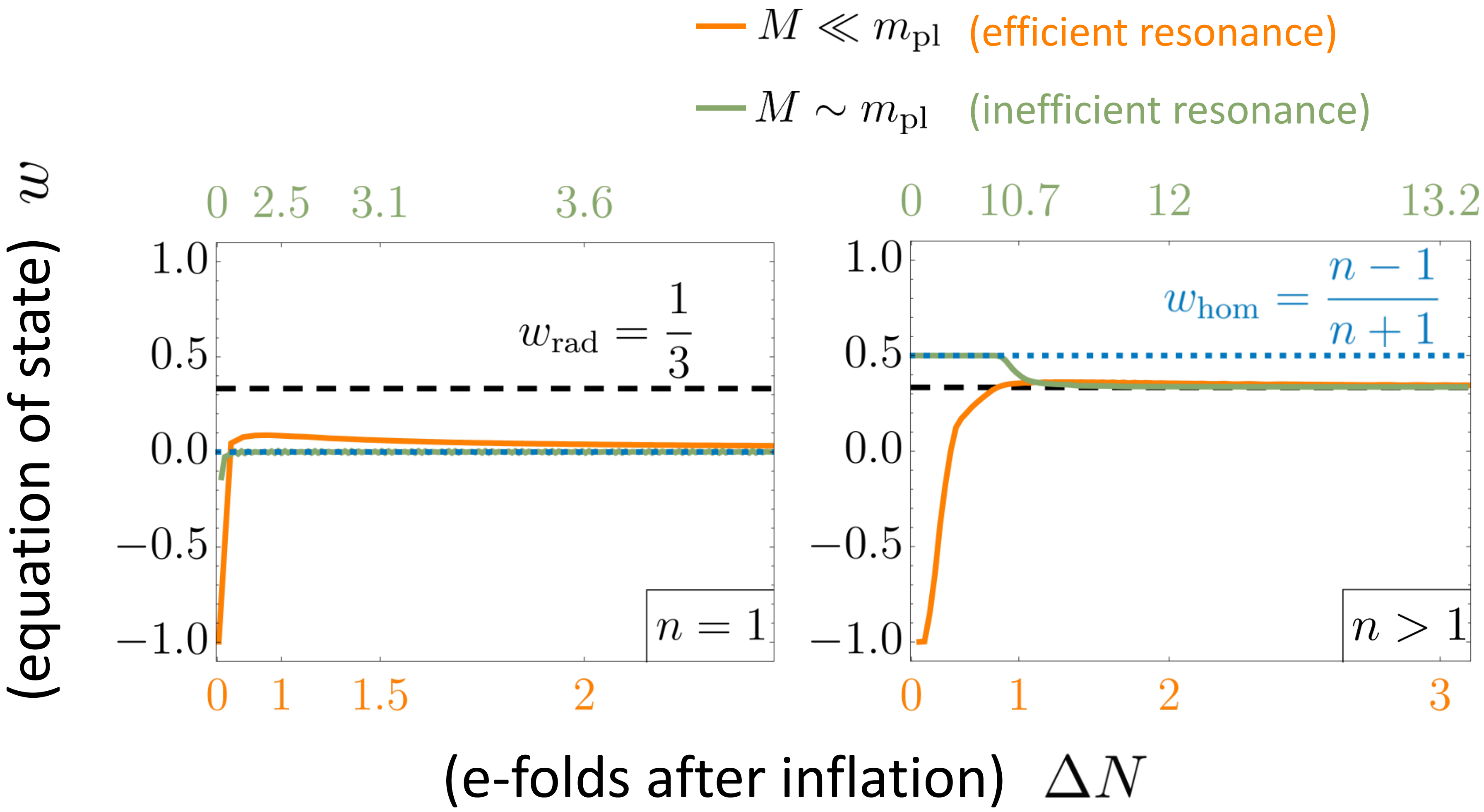
KL and M. Amin (2017)
KL and M. Amin (2018)

Equation of state



$$\Delta N \equiv \int_{a_{\text{end}}}^{a} d \ln a$$

Equation of state



$$\Delta N \equiv \int_{a_{\rm end}}^{a} d\ln a$$

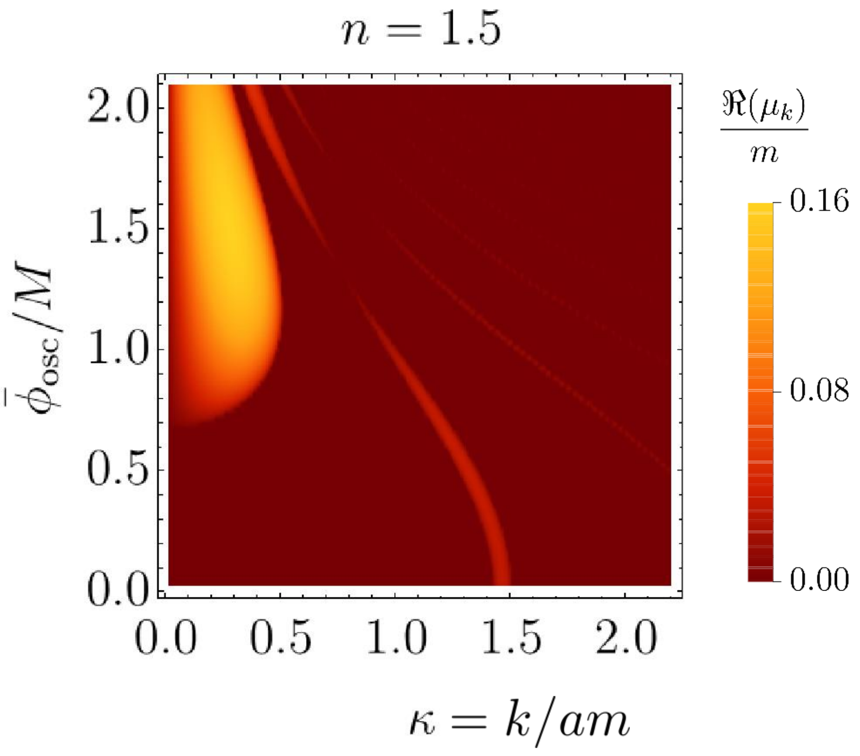
Towards radiation domination

$$n > 1$$

Towards radiation domination

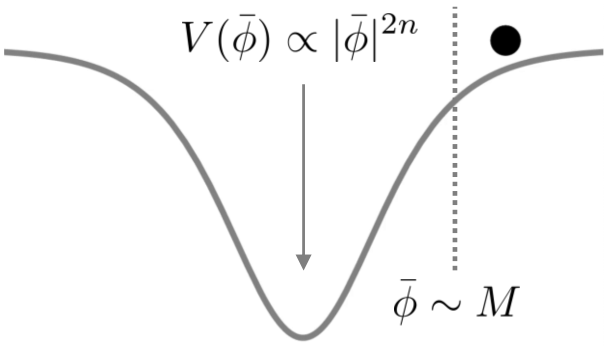
$$n > 1$$

Non-perturbative decay (parametric self-resonance)



inflaton vev amplitude

inflaton field wavenumber



$$\delta\phi_k \propto \exp(\pm\mu_k t)$$

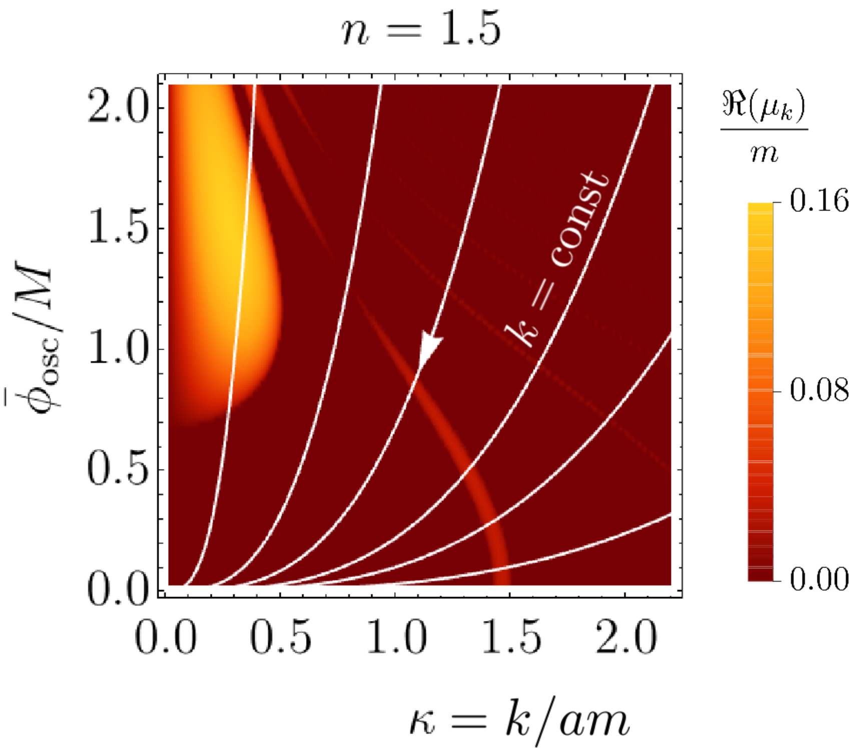
$m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$

Towards radiation domination

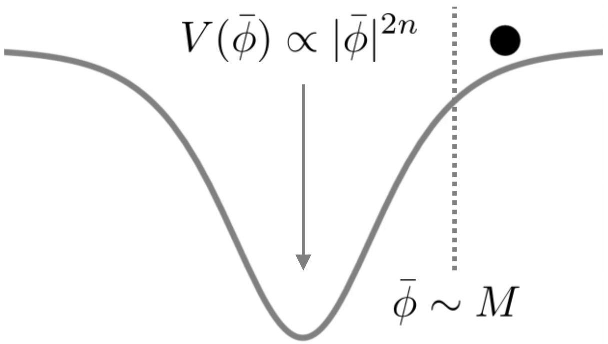
$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



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Towards radiation domination

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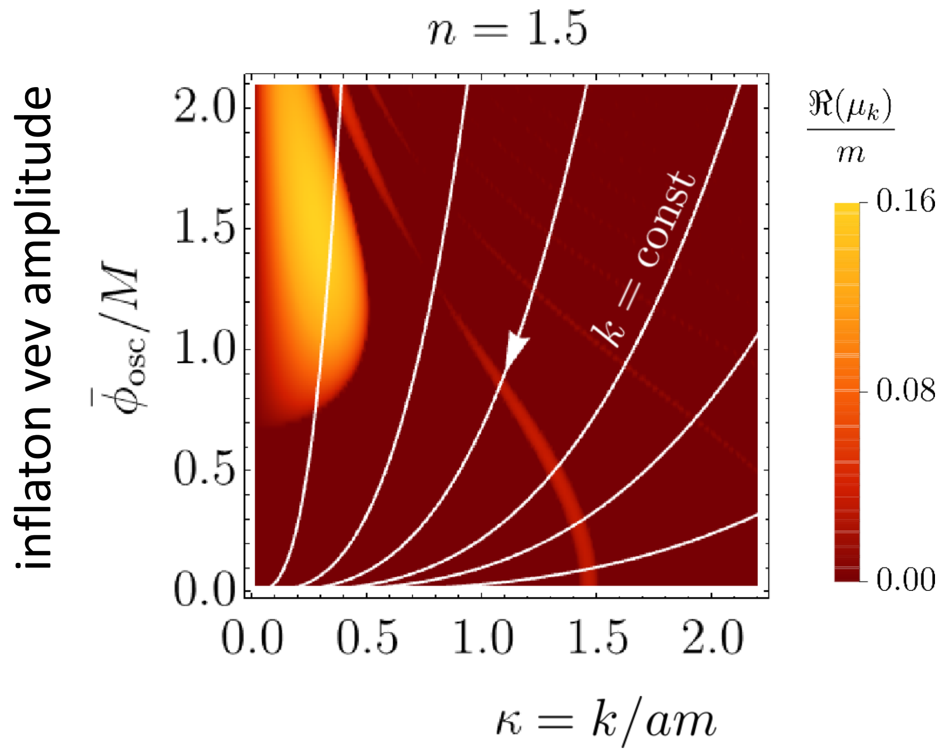
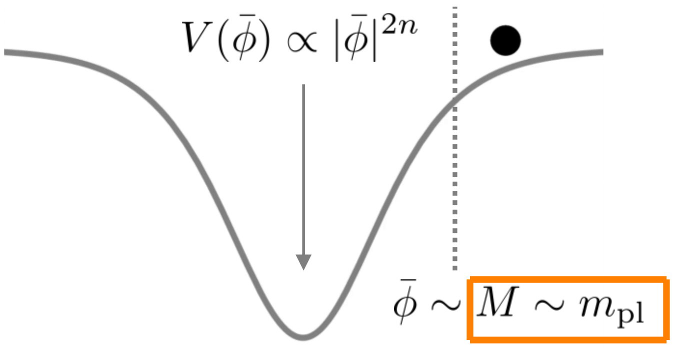


inflaton field wavenumber



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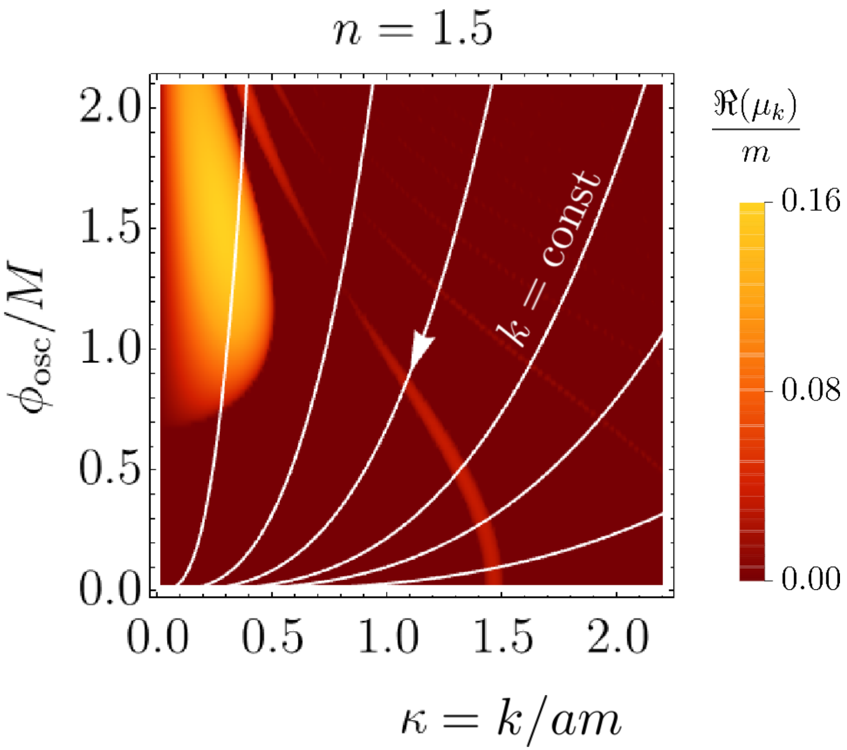

inflaton vev amplitude

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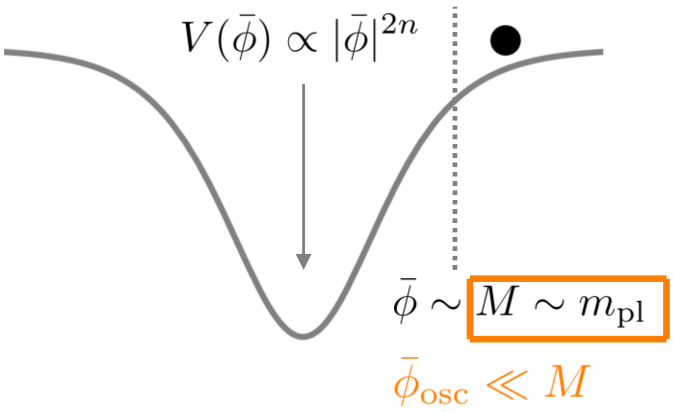

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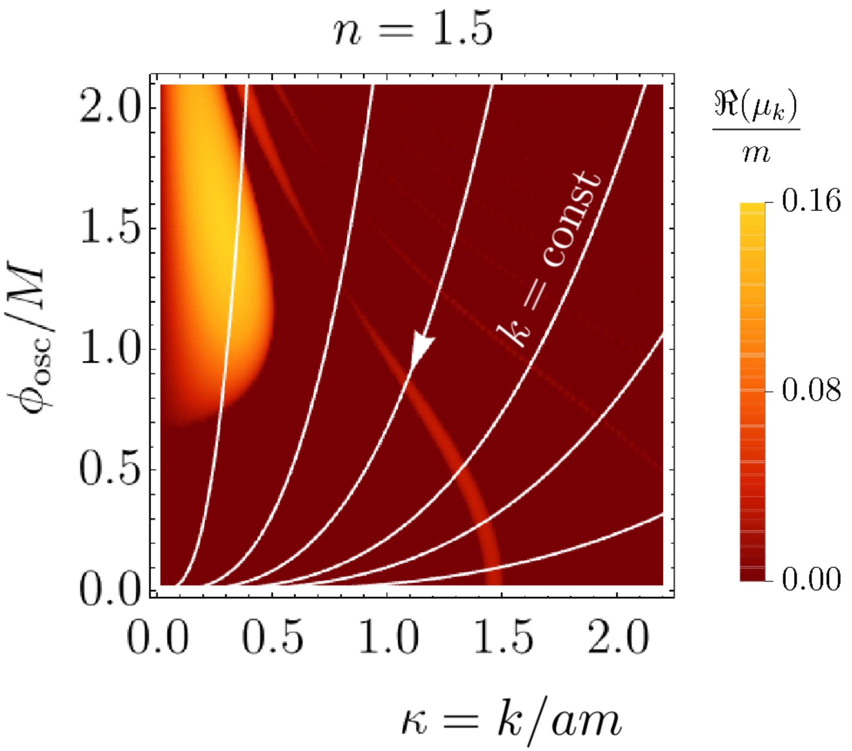
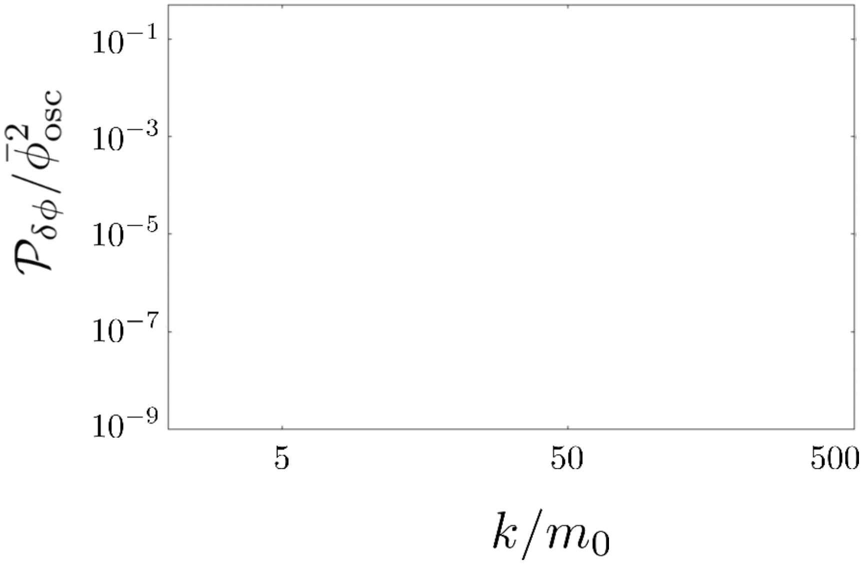


inflaton vev amplitude

inflaton field wavenumber

Power spectrum:

$$\langle \delta\phi(x)^2 \rangle \equiv \int \mathcal{P}_{\delta\phi}\, d\ln k$$

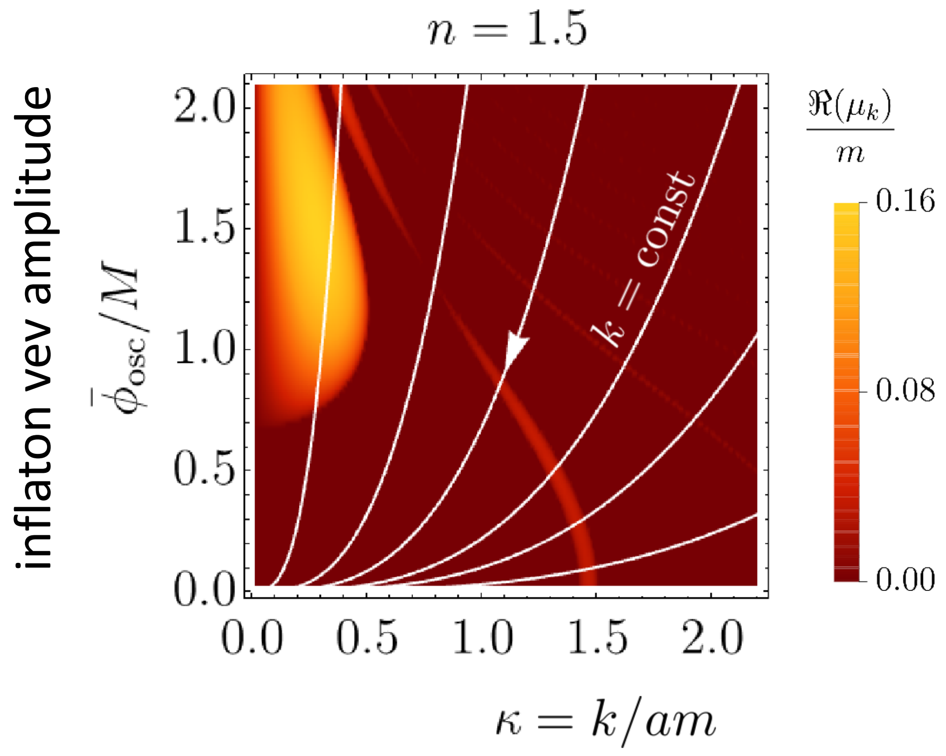


comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)



inflaton field wavenumber

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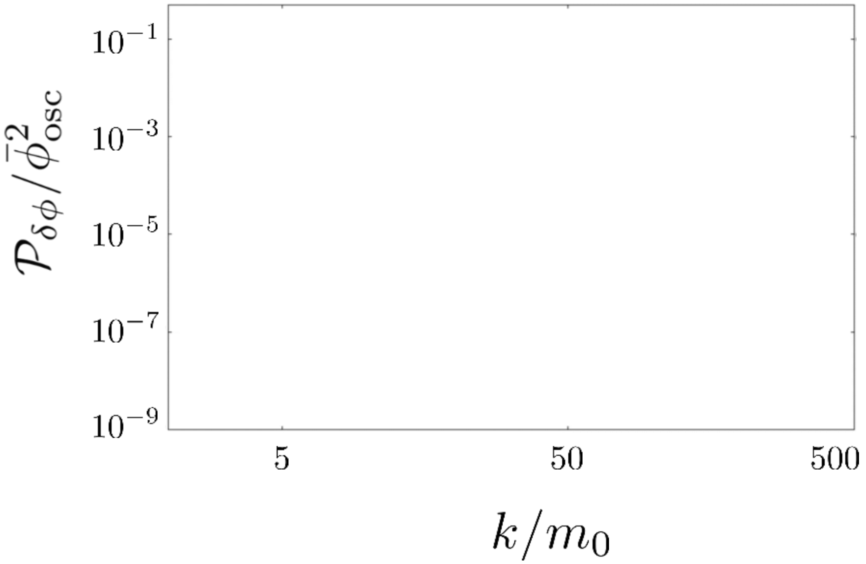

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Towards radiation domination

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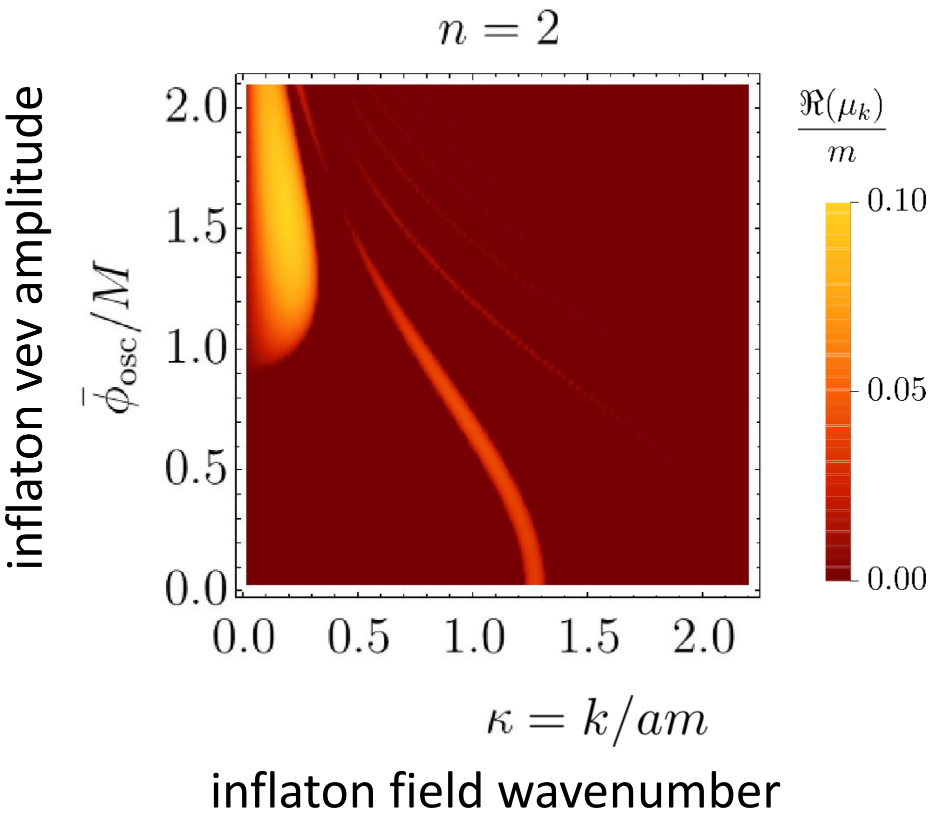

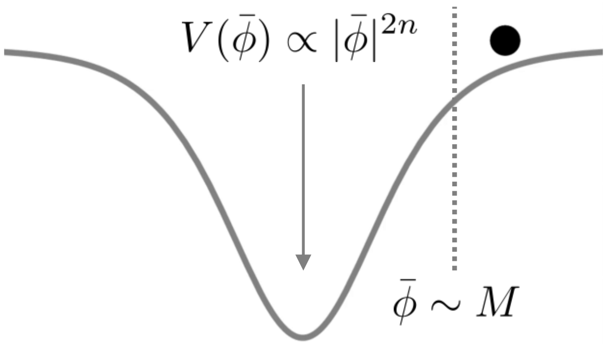

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Towards radiation domination

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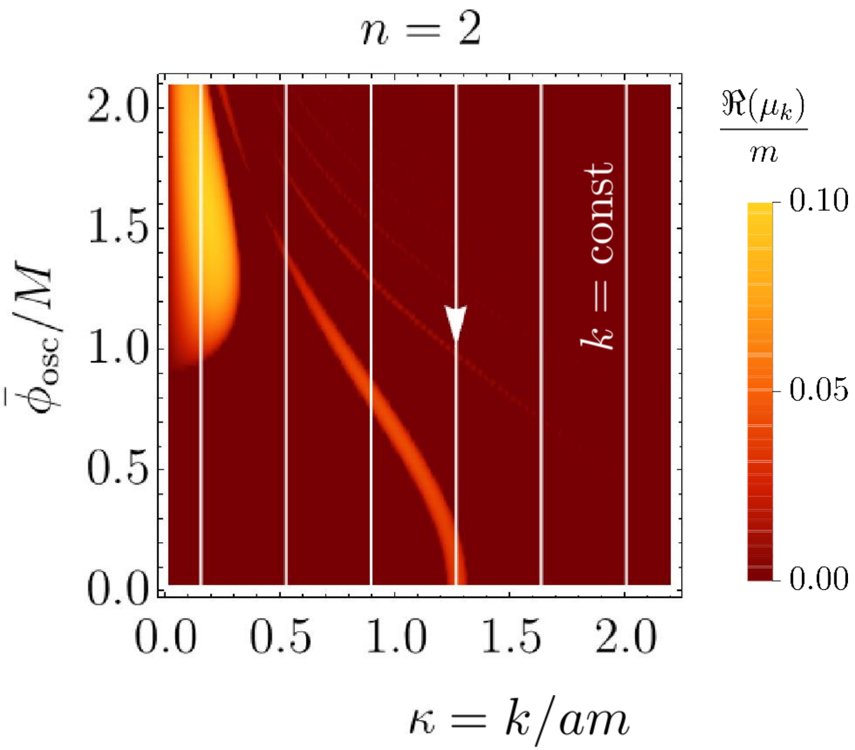
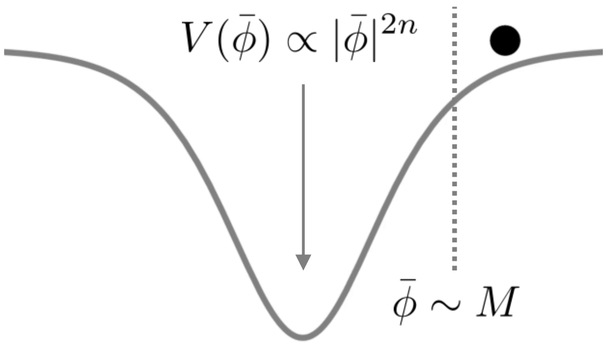
Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



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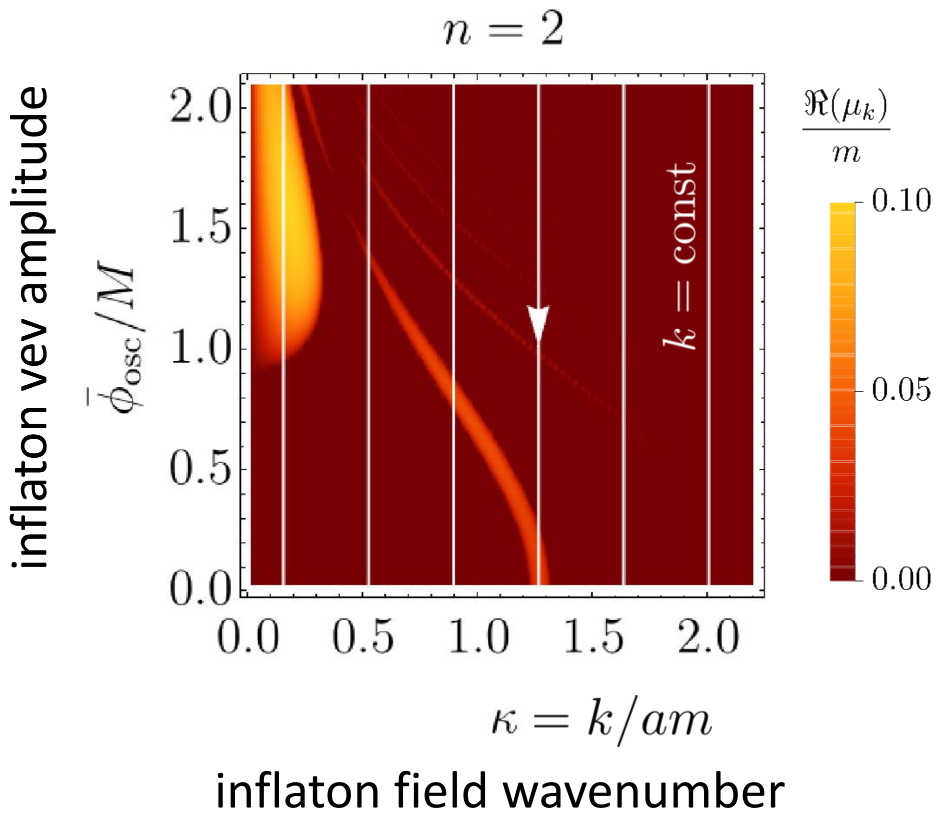

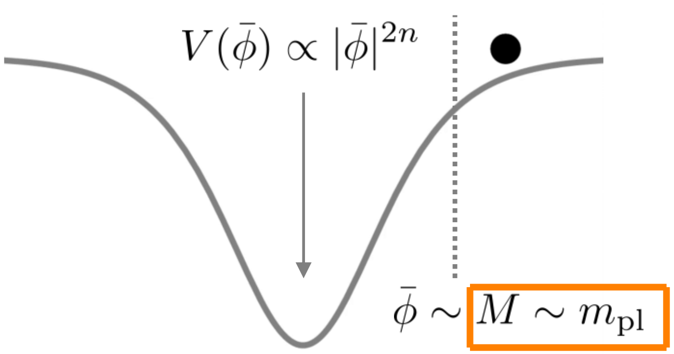

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Towards radiation domination

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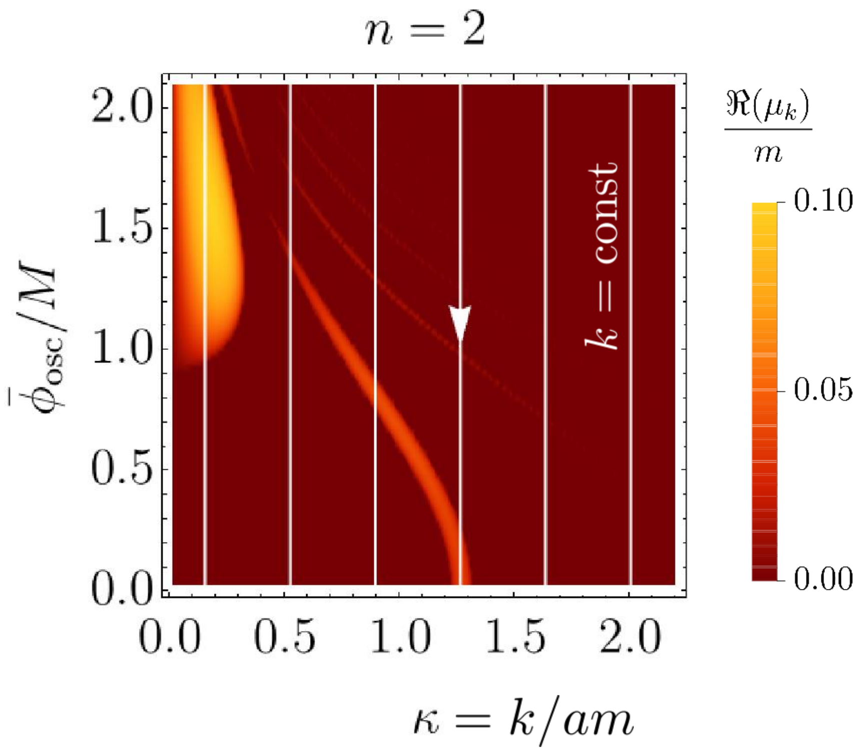
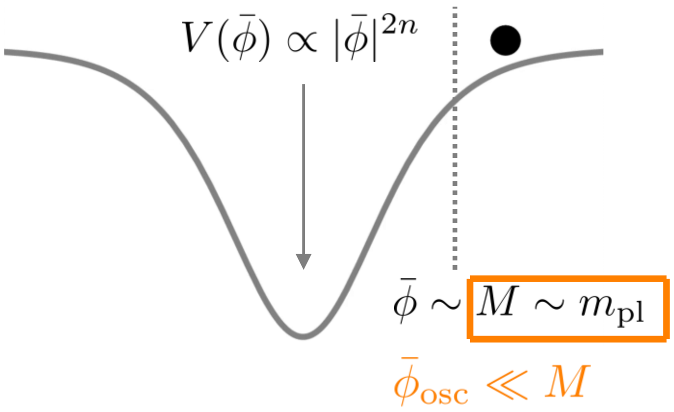


inflaton field wavenumber



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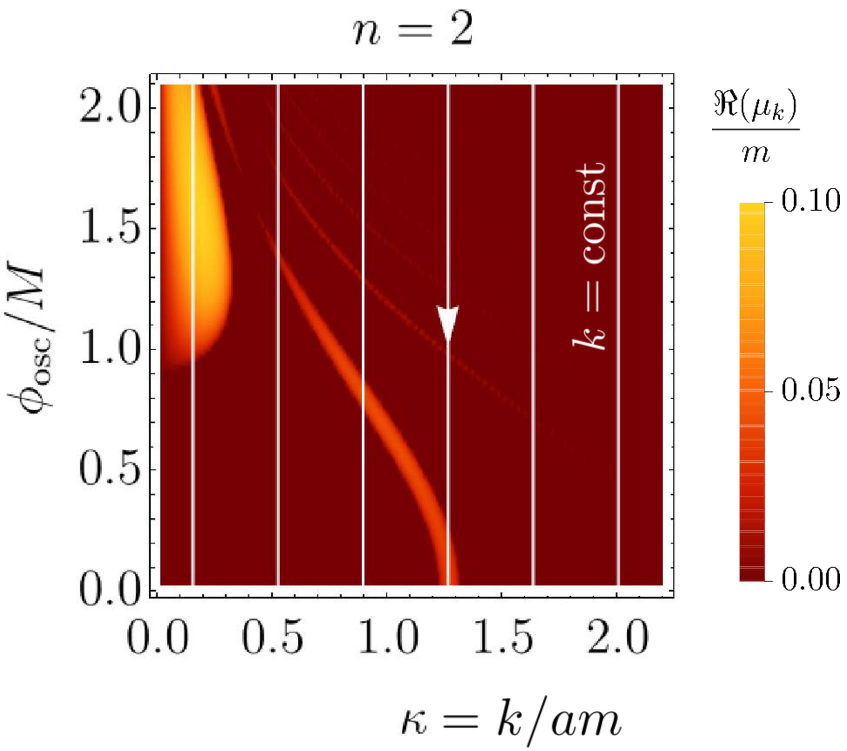
Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

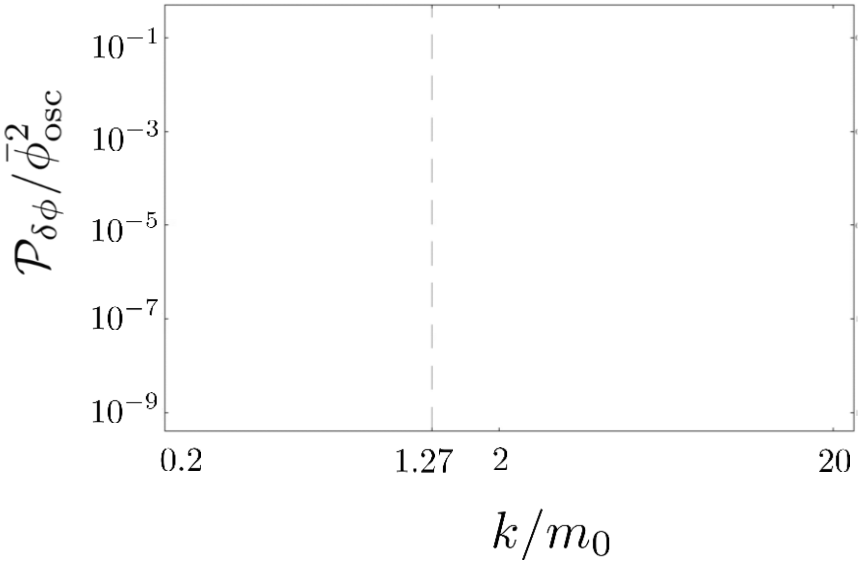
inflaton vev amplitude



inflaton field wavenumber

Power spectrum:

$$\langle \delta\phi(x)^2 \rangle \equiv \int \mathcal{P}_{\delta\phi}\, d\ln k$$



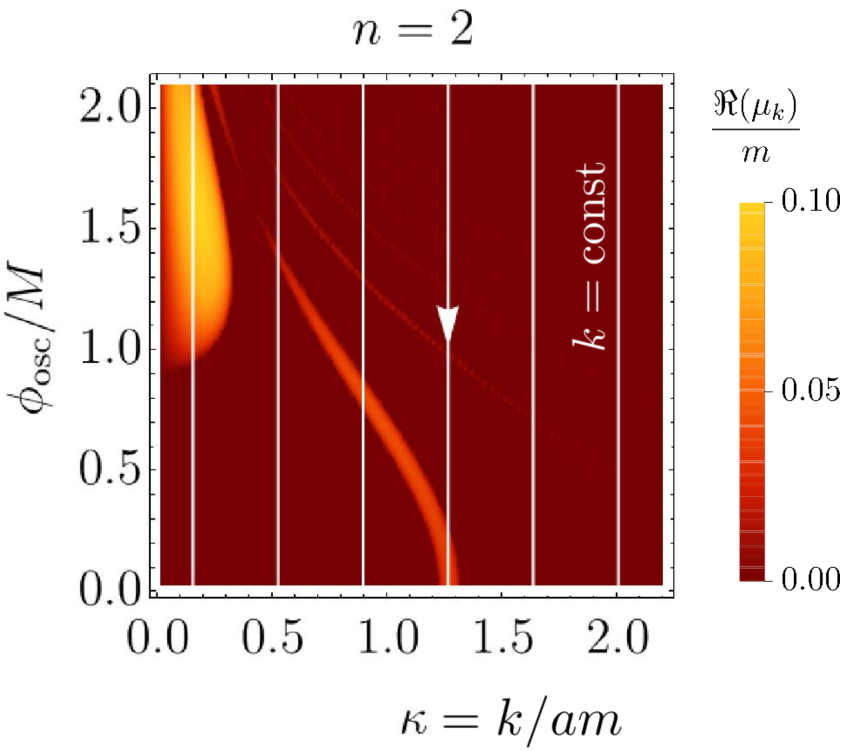
comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



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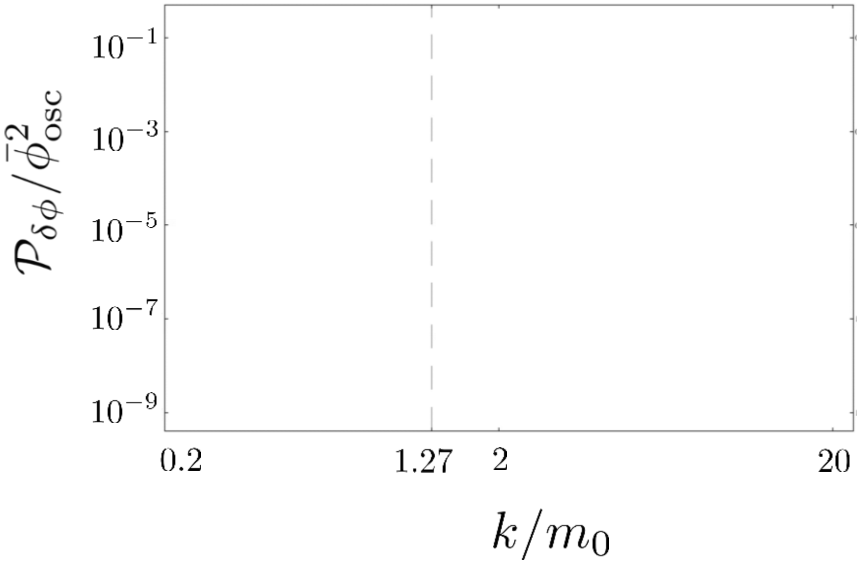


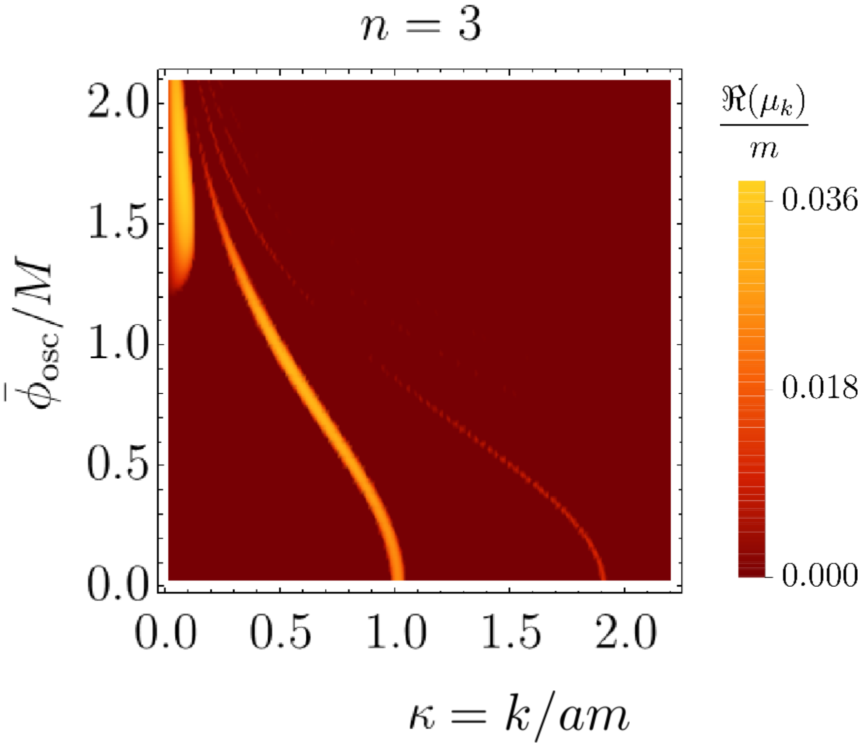
comoving wavenumber

Towards radiation domination

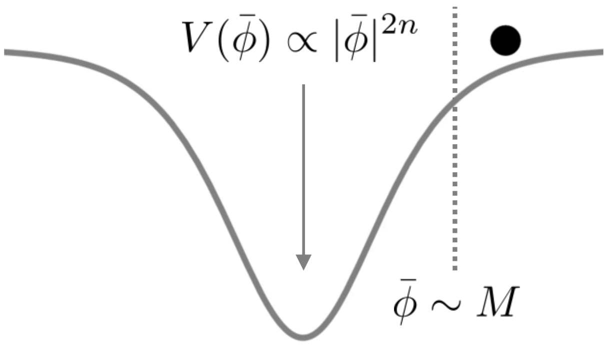
$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



$$\delta\phi_k \propto \exp(\pm\mu_k t)$$

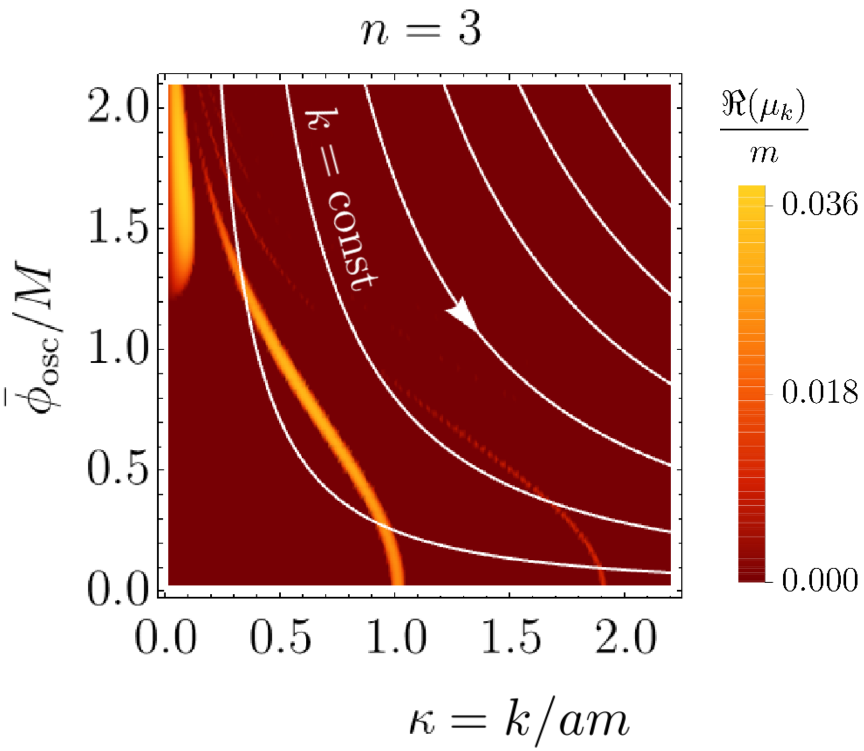
$$m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$$

Towards radiation domination

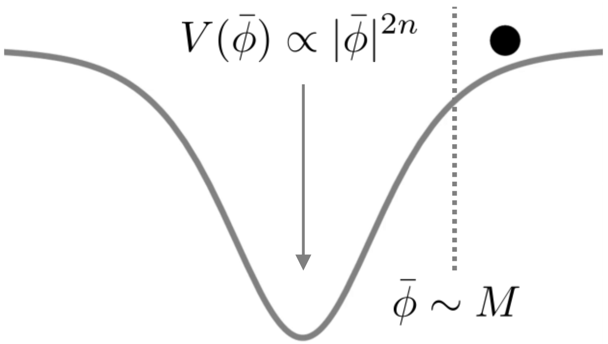
$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



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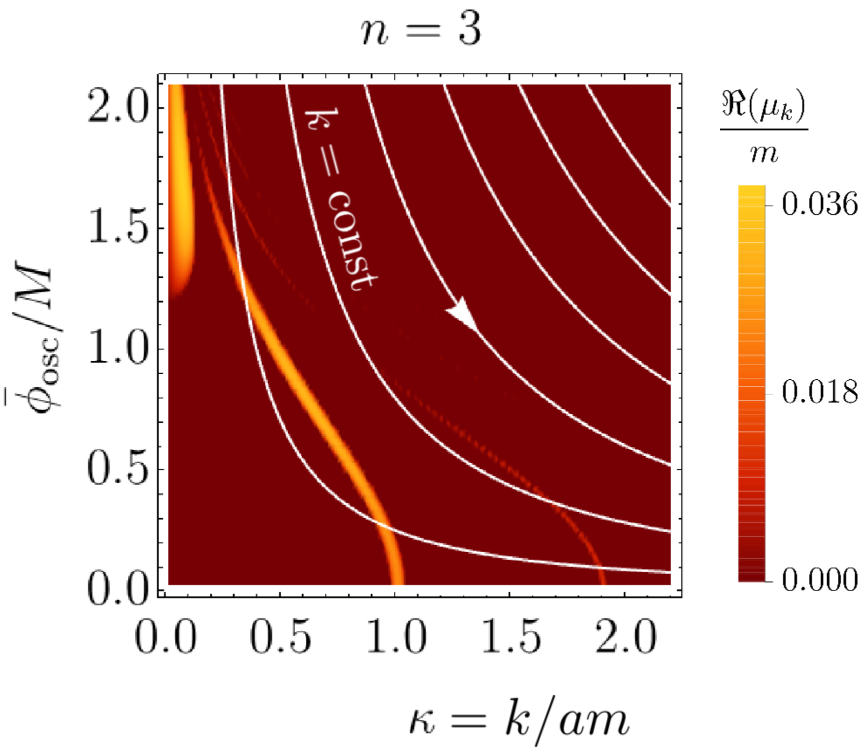
Towards radiation domination

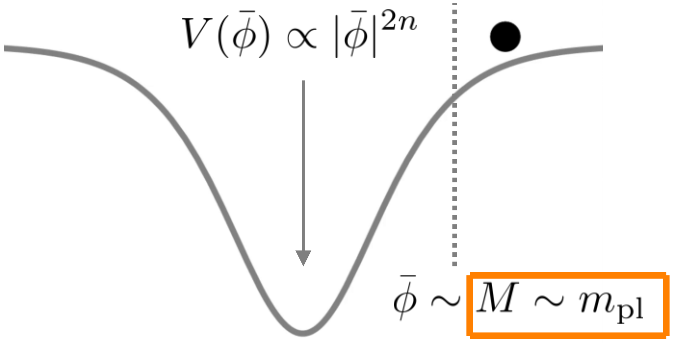
$$n > 1$$

Non-perturbative decay (parametric self-resonance)



inflaton vev amplitude

inflaton field wavenumber



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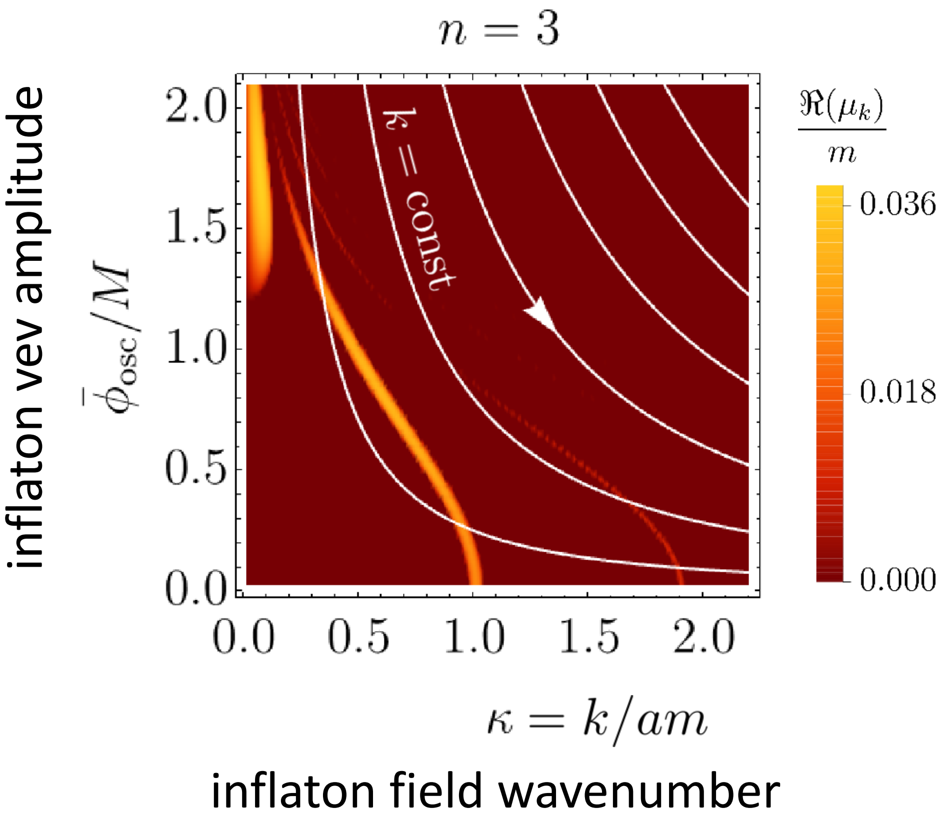
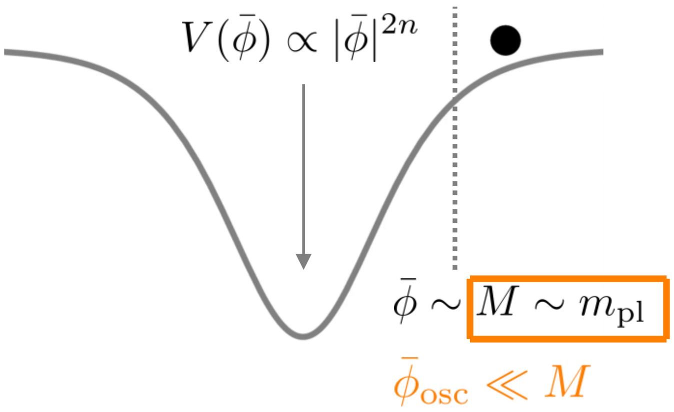
Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)





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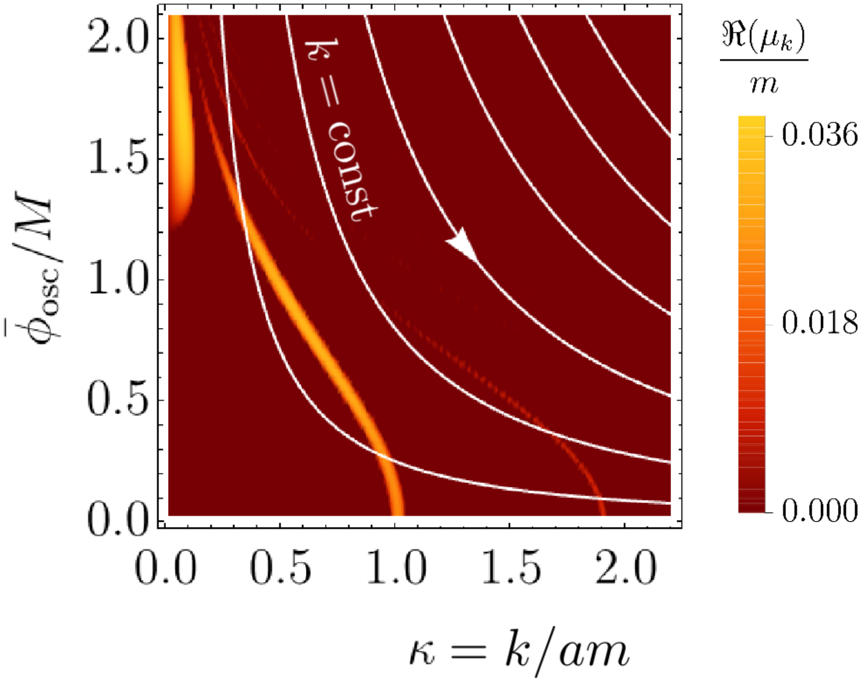
Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

$n = 3$

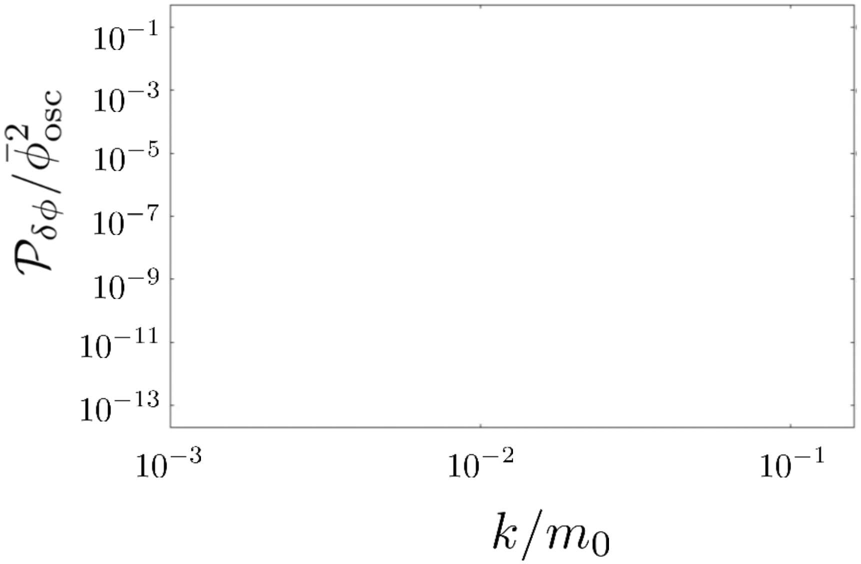


inflaton vev amplitude

inflaton field wavenumber

Power spectrum:

$$\langle \delta\phi(x)^2 \rangle \equiv \int \mathcal{P}_{\delta\phi}\, d\ln k$$



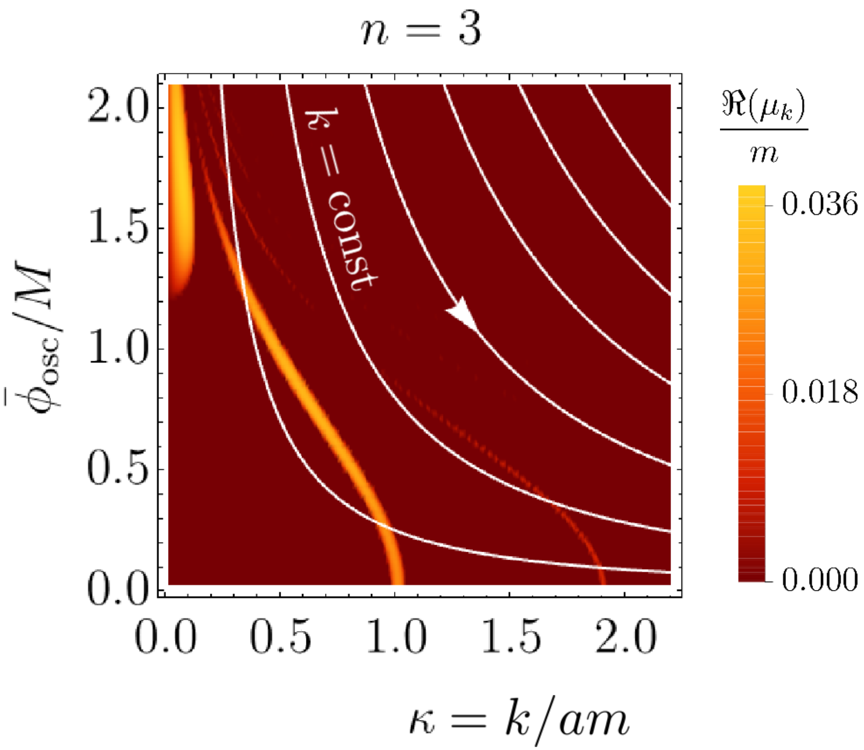
comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber

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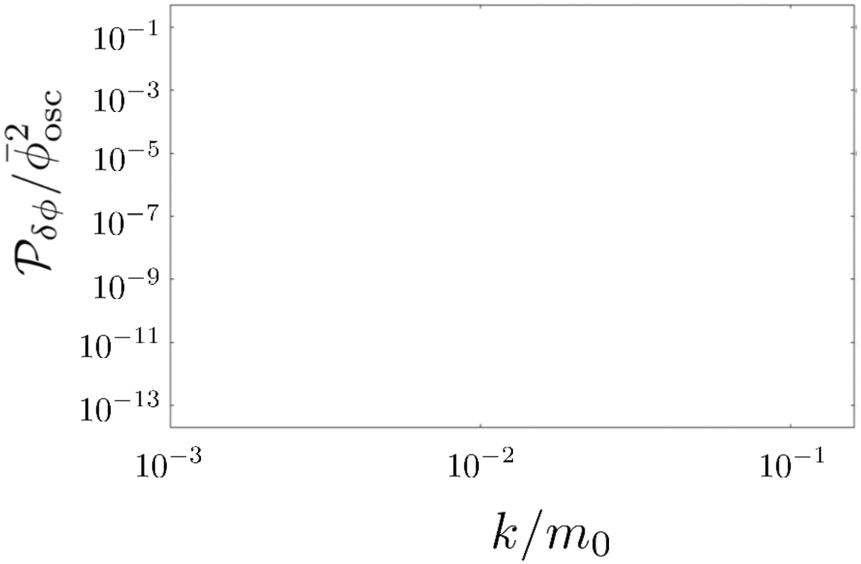
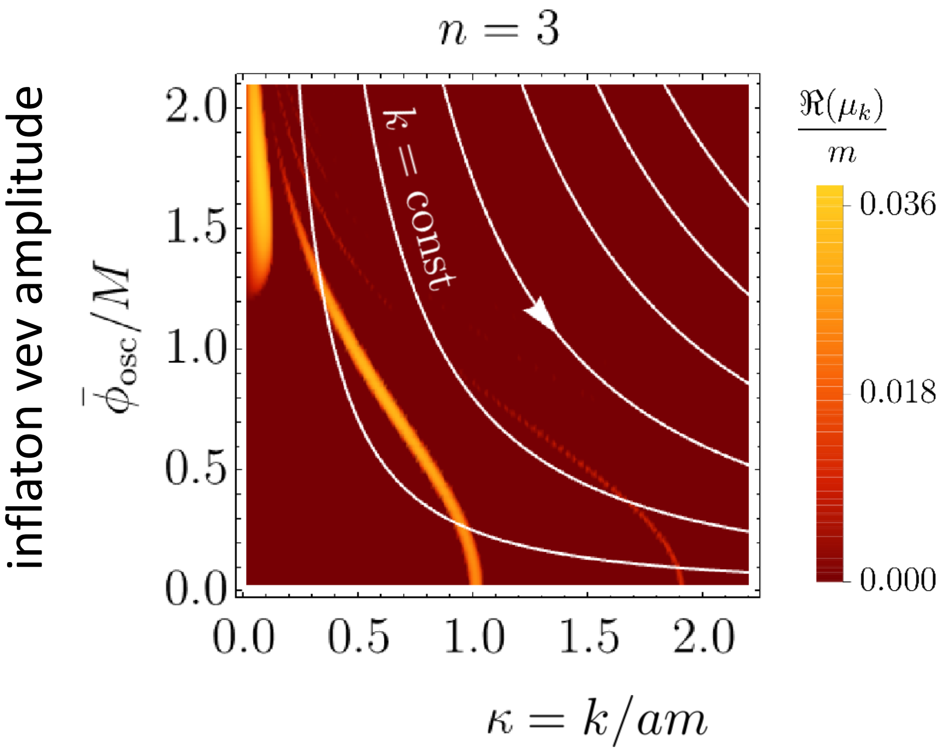


comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)



inflaton vev amplitude

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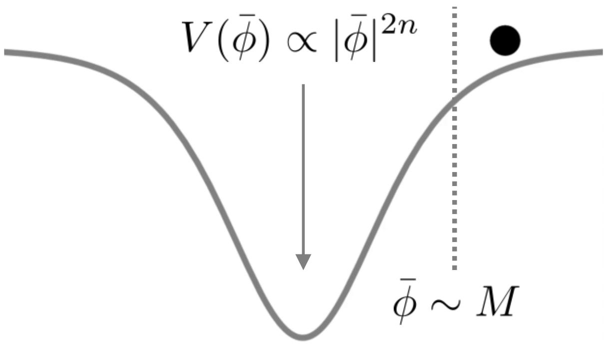


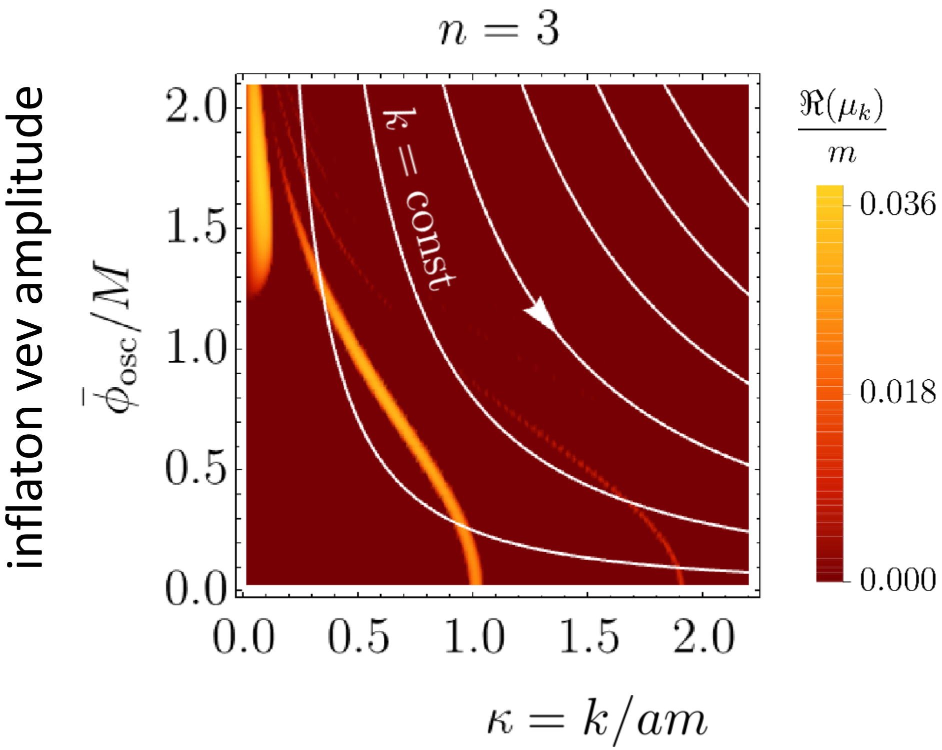
$$\delta\phi_k \propto \exp(\pm\mu_k t)$$

$$m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$$

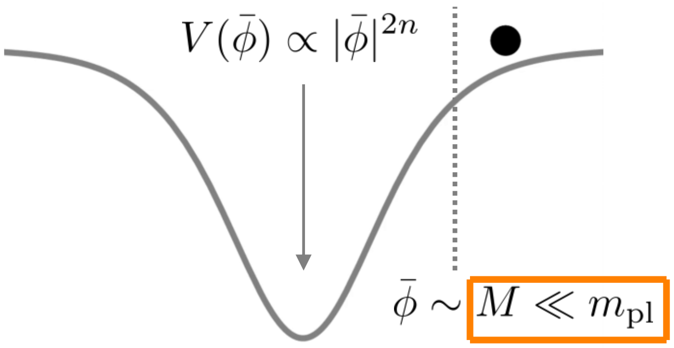
Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)



inflaton field wavenumber



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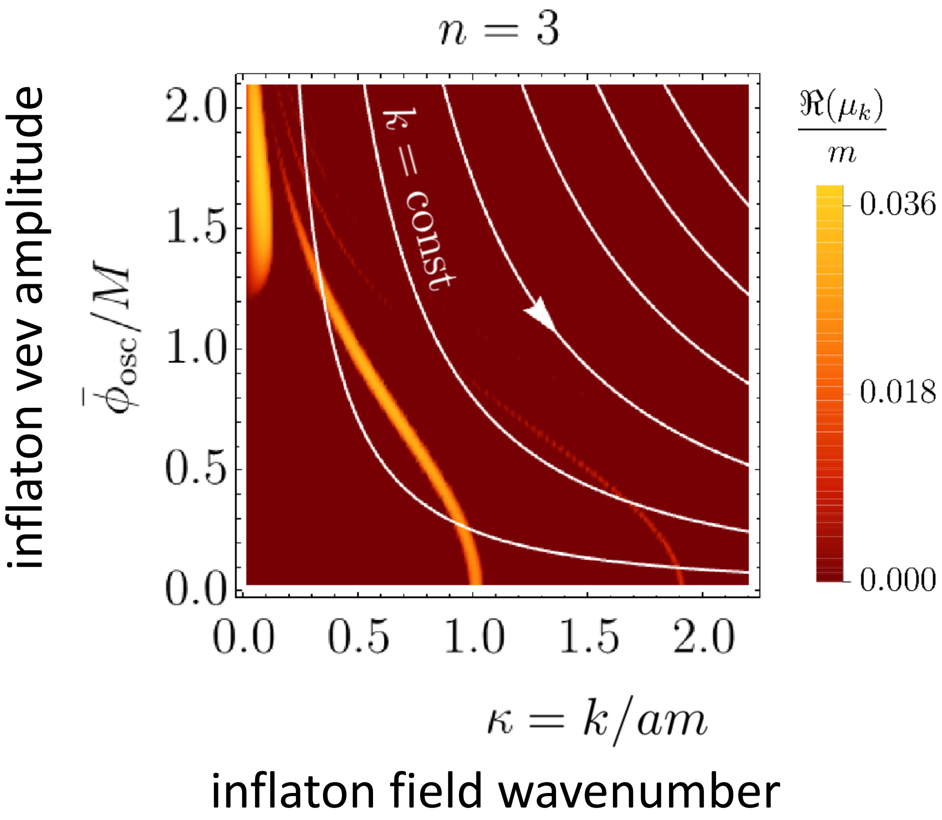

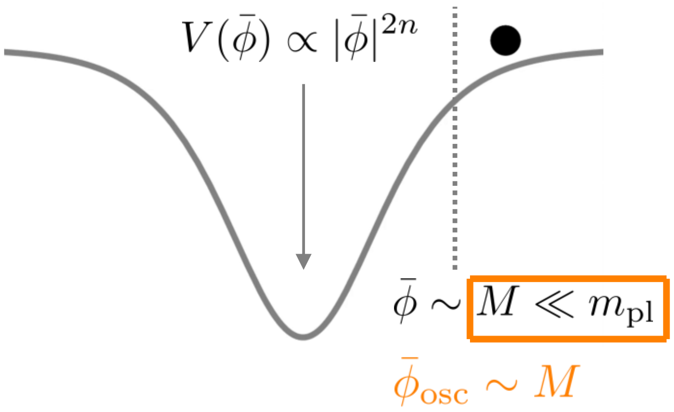

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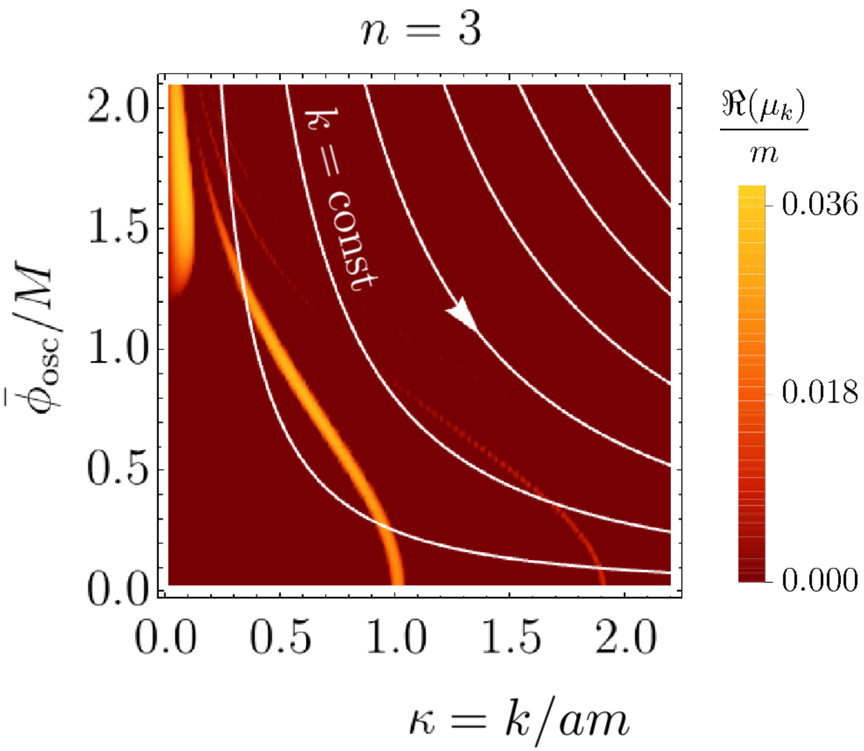
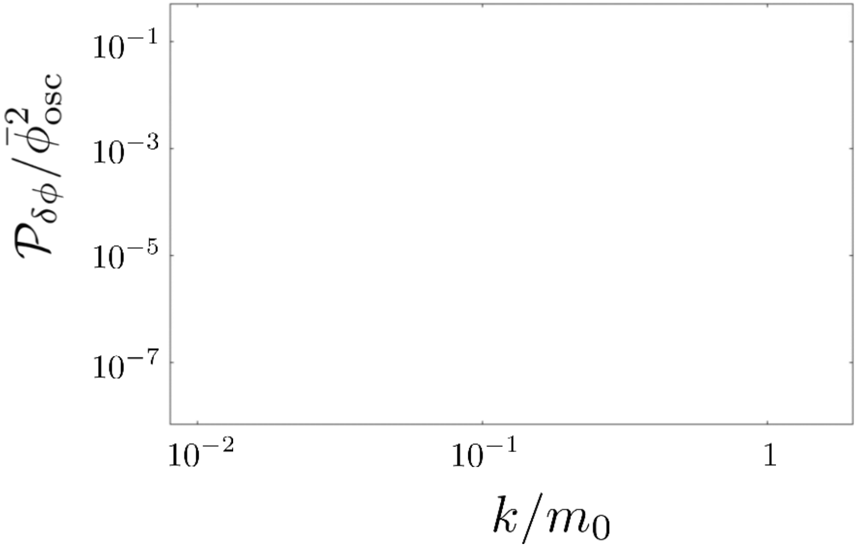
inflaton vev amplitude



inflaton field wavenumber

Power spectrum:

$$\langle \delta\phi(x)^2 \rangle \equiv \int \mathcal{P}_{\delta\phi}\, d\ln k$$



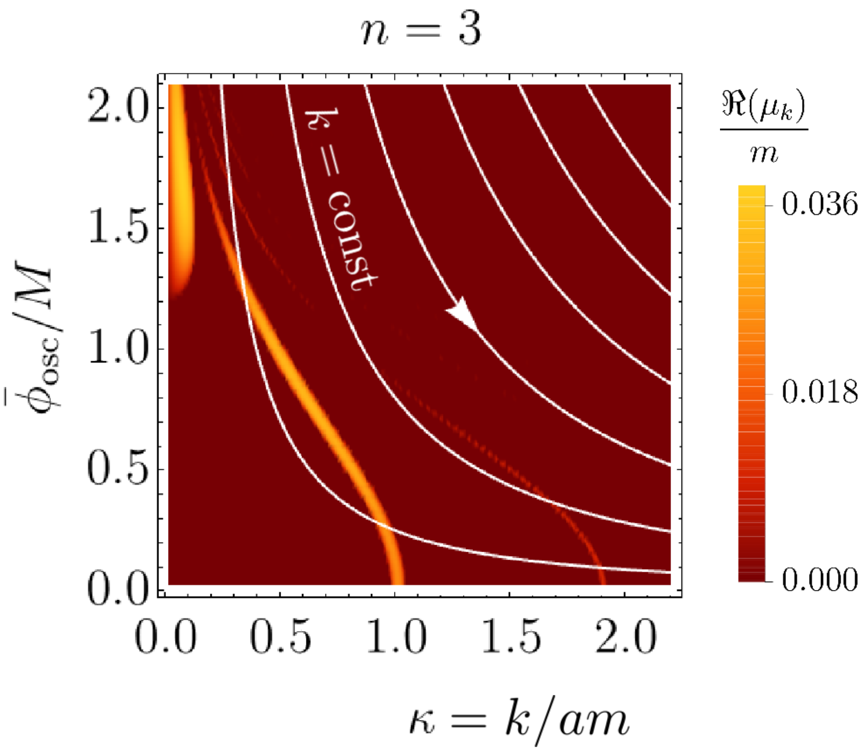
comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



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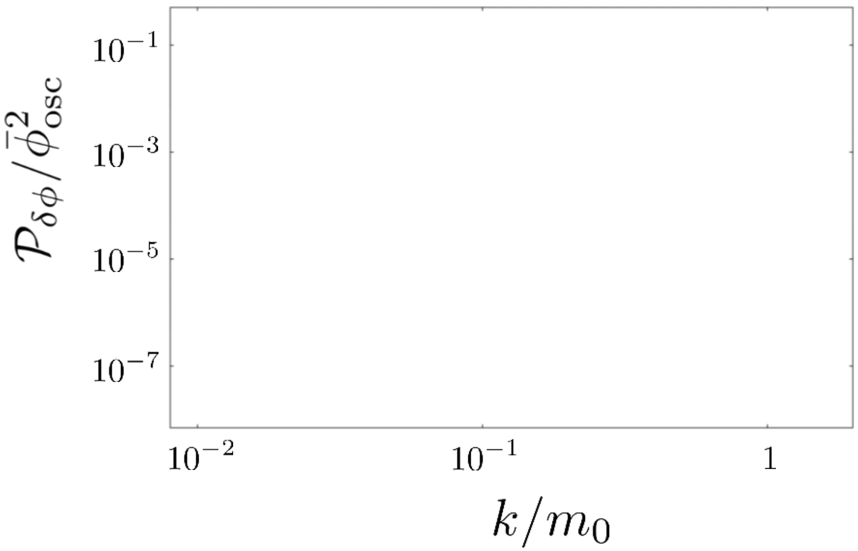
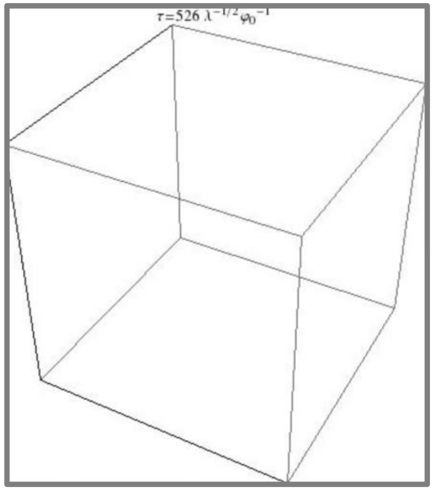


comoving wavenumber

Towards radiation domination

$$n > 1$$

$$M \ll m_{\rm pl}$$



- $\bar{\phi}$ fragments quickly

$$M \sim m_{\rm pl}$$

- slow production of $\delta\phi(t,\mathbf{x})$
- $\bar{\phi}$ fragments gradually

$$\Delta N_{\rm fr} \approx \frac{n+1}{3}\ln\left(10^3\frac{M}{m_{\rm pl}}\right)$$

at sufficiently late times:

ϕ virialized + turbulent $\rightarrow w = \dfrac{1}{3}$

Expansion history effects

Expansion history effects

Spectral index: n_s

Tensor-to-scalar ratio: r

Expansion history effects

Spectral index: $n_{\mathrm{s}} = n_{\mathrm{s}}(M, n, N_*)$

Tensor-to-scalar ratio: $r = r(M, n, N_*)$

Expansion history effects

Spectral index: $n_{\rm s} = n_{\rm s}(M, n, N_*)$

Tensor-to-scalar ratio: $r = r(M, n, N_*)$??

Expansion history effects

Spectral index: $n_\mathrm{s} = n_\mathrm{s}(M, n, N_*)$

Tensor-to-scalar ratio: $r = r(M, n, N_*)$??

$$50 \leq N_* \leq 60$$

Planck Collaboration (2015)

Expansion history effects

Spectral index: $n_{\mathrm{s}} = n_{\mathrm{s}}(M, n, \enclose{circle}{N_*})$

Tensor-to-scalar ratio: $r = r(M, n, \enclose{circle}{N_*})$ ✓

$$\xcancel{50 \leq N_* \leq 60}$$

KL and M. Amin (2017 and 2018)

Expansion history effects

Spectral index: $n_{\rm s} = n_{\rm s}(M, n, N_*)$

Tensor-to-scalar ratio: $r = r(M, n, N_*)$ ✓

$$\boxed{N_* = 66.89 - \frac{1}{12}\ln g_{\rm th} + \frac{1}{4}\ln\frac{V_*^4}{m_{\rm pl}^4\rho_{\rm end}} - \ln\frac{k_*}{a_0 H_0} + \frac{3\bar{w}_{\rm int} - 1}{4}\Delta N_{\rm rad}}$$

$$\Delta N_{\rm rad} \equiv \int_{a_{\rm end}}^{a_{\rm rad}} d\ln a$$

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$$\Delta N_{\rm rad} \equiv \int_{a_{\rm end}}^{a_{\rm rad}} d\ln a$$

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$$\Delta N_{\rm fr} = \begin{cases} 1 & \text{if} \quad M \ll m_{\rm pl} \\ \frac{n+1}{3}\ln\left(10\frac{\kappa}{\Delta\kappa}\frac{M}{m_{\rm pl}}\right) & \text{if} \quad M \sim m_{\rm pl} \end{cases}$$

$\Delta N_{\rm rad} \equiv \int_{a_{\rm end}}^{a_{\rm rad}} d\ln a$

KL and M. Amin (2017 and 2018)

Expansion history effects

Spectral index: $n_{\rm s} = n_{\rm s}(M, n, N_*)$

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$$w_{\rm int}(\Delta N) = \begin{cases} \frac{n-1}{n+1} & \text{if} \quad 0 < \Delta N < \Delta N_{\rm rad} \\ \frac{1}{3} & \text{if} \quad \Delta N > \Delta N_{\rm rad} \end{cases}$$

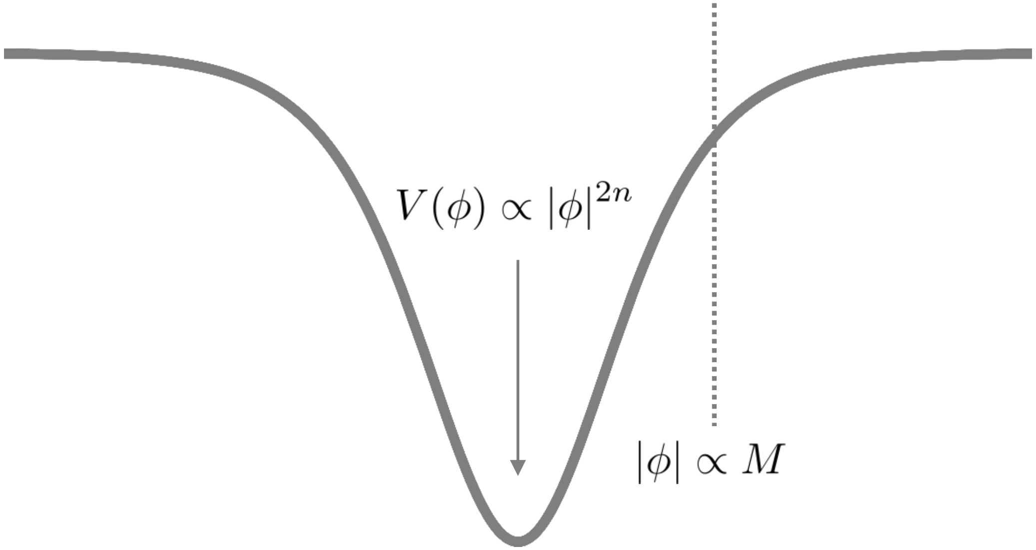
$$\Delta N_{\rm rad} \equiv \int_{a_{\rm end}}^{a_{\rm rad}} d\ln a$$

KL and M. Amin (2017 and 2018)

Expansion history effects

$$V(\phi) \propto \tanh^{2n}\left(\frac{|\phi|}{M}\right)$$

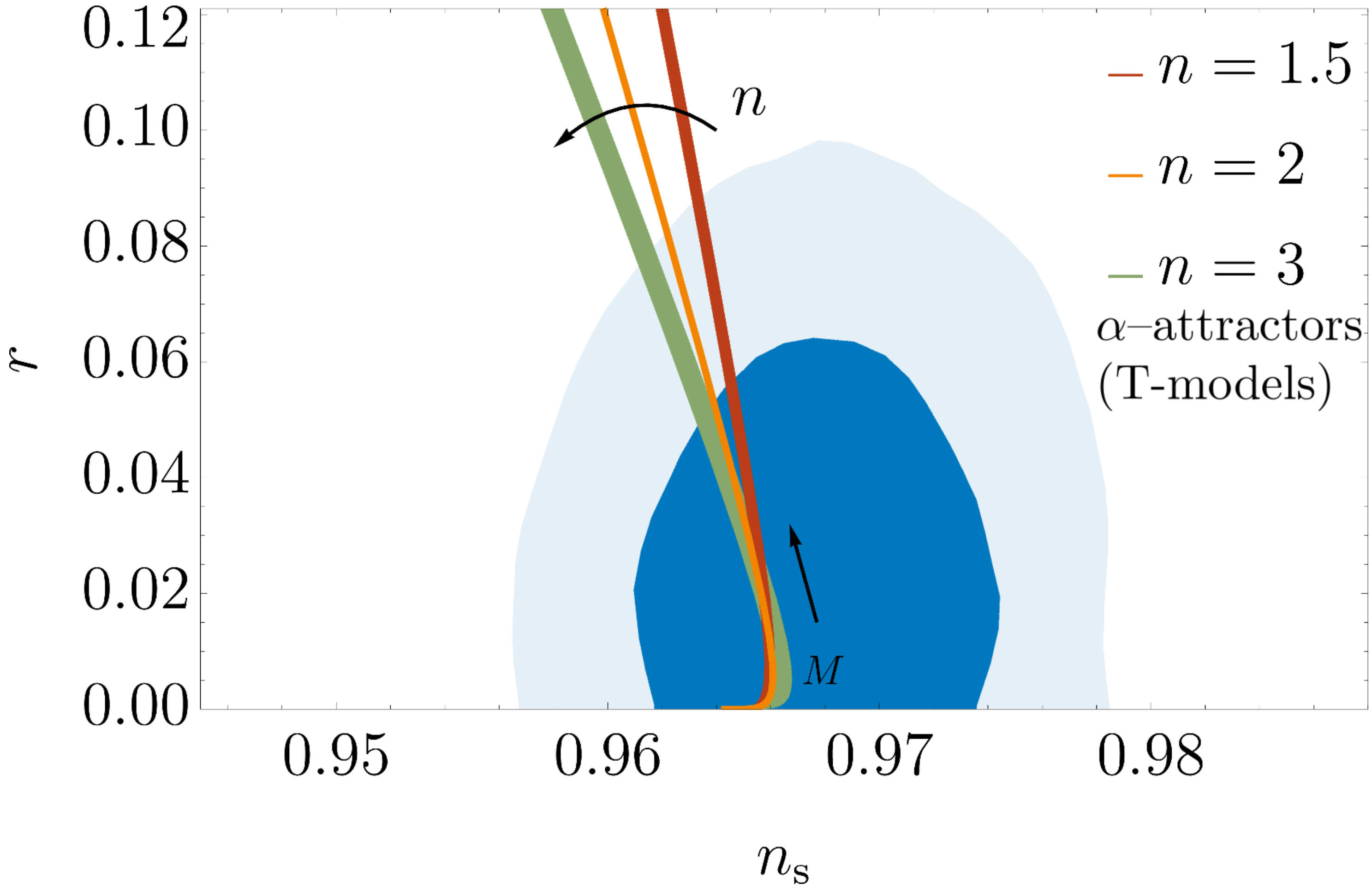
α–attractors
(T-models)



Kallosh and Linde (2013)
Carrasco, Kallosh and Linde (2015)

Expansion history effects

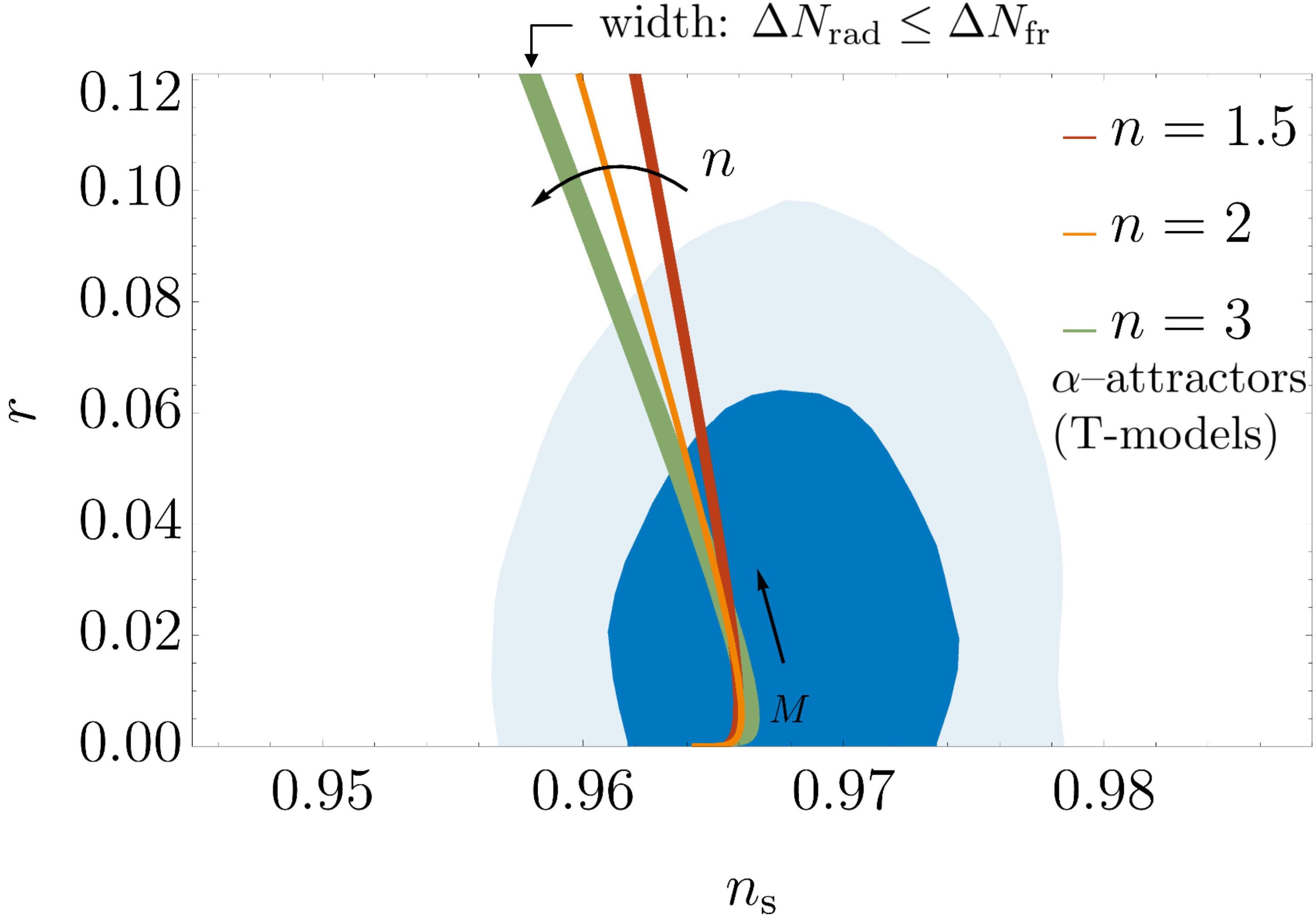
tensor-to-scalar ratio



spectral index

KL and M. Amin (2018)
Planck Collaboration (2015)

Expansion history effects



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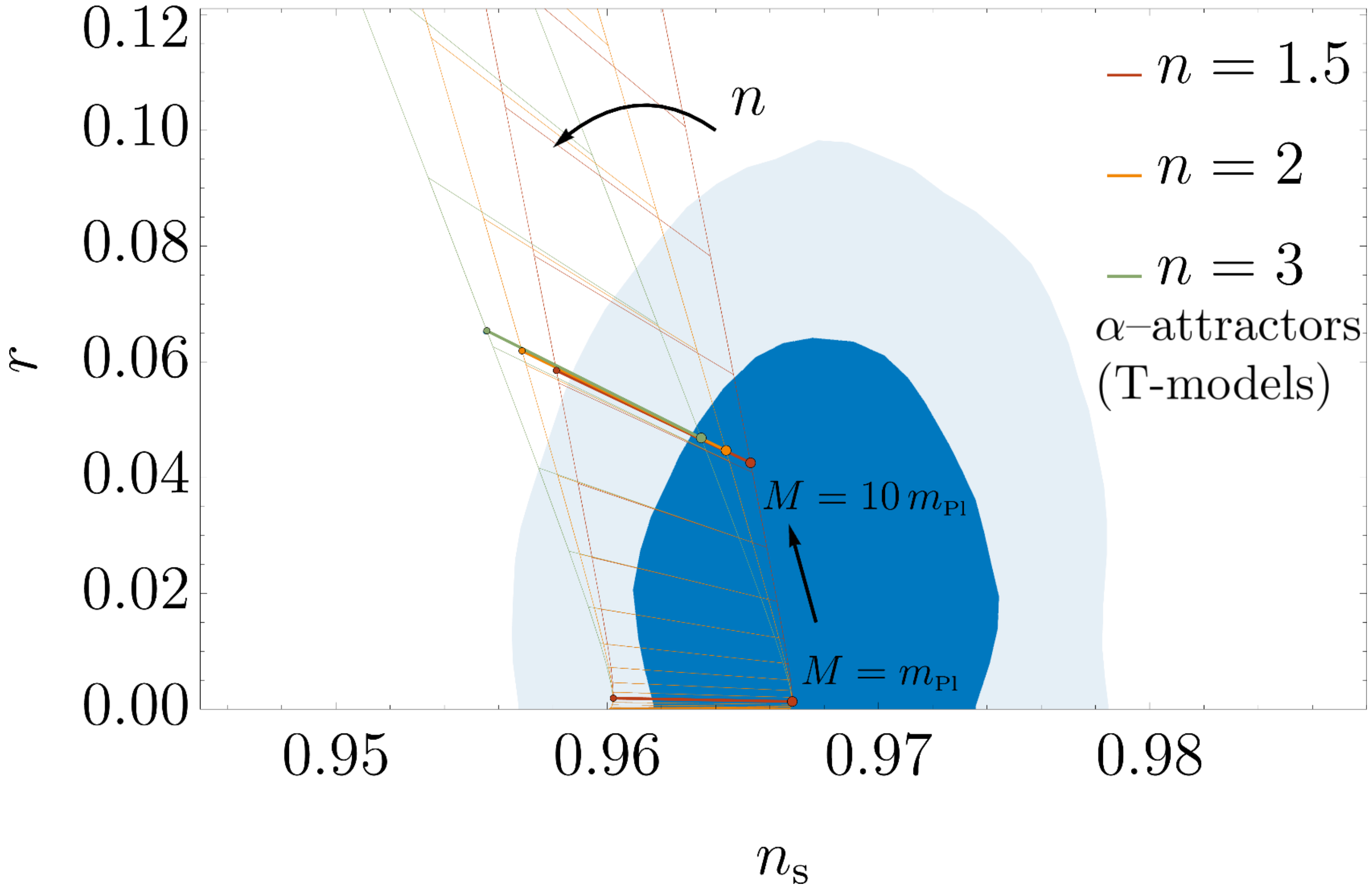

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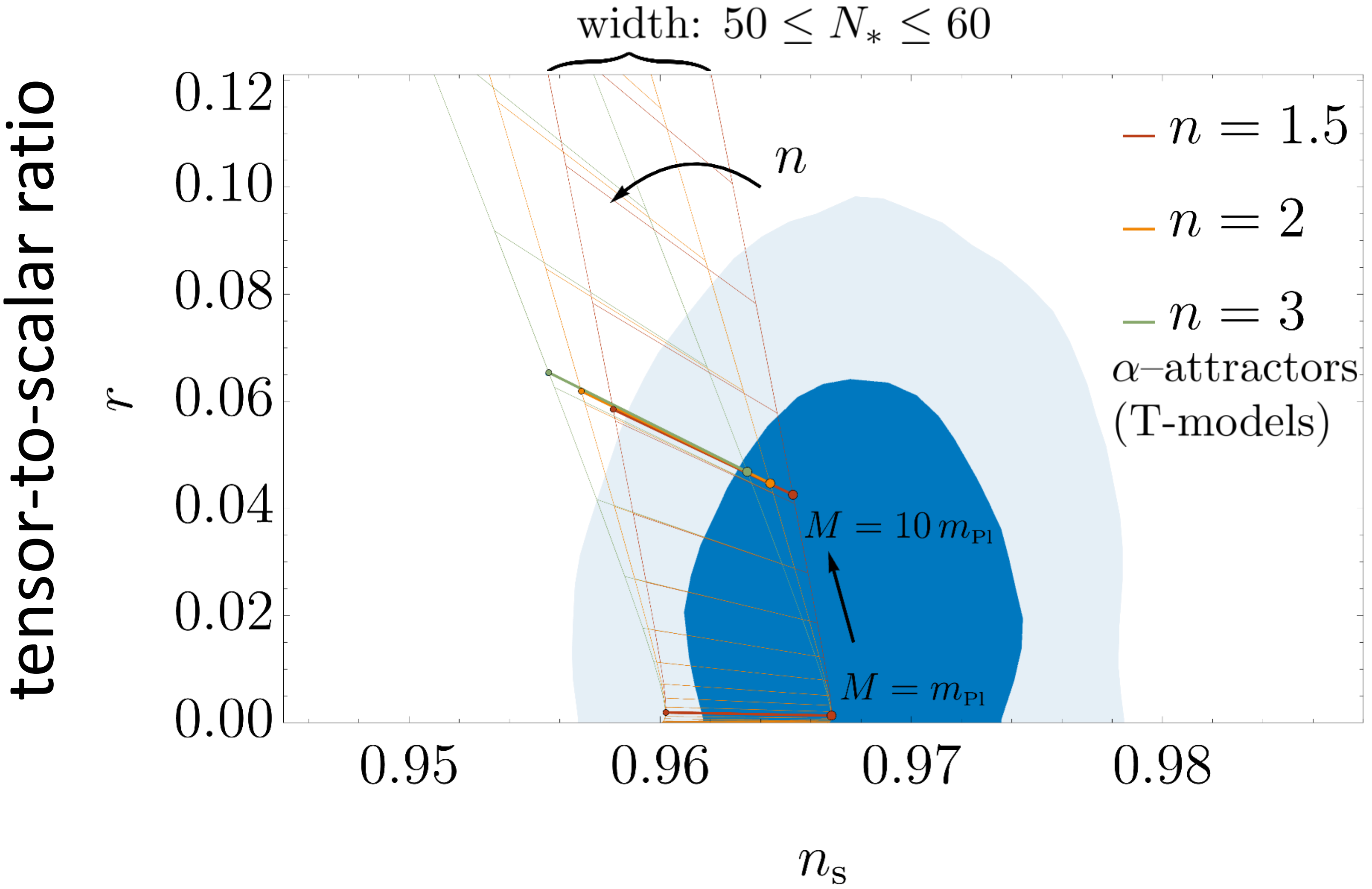

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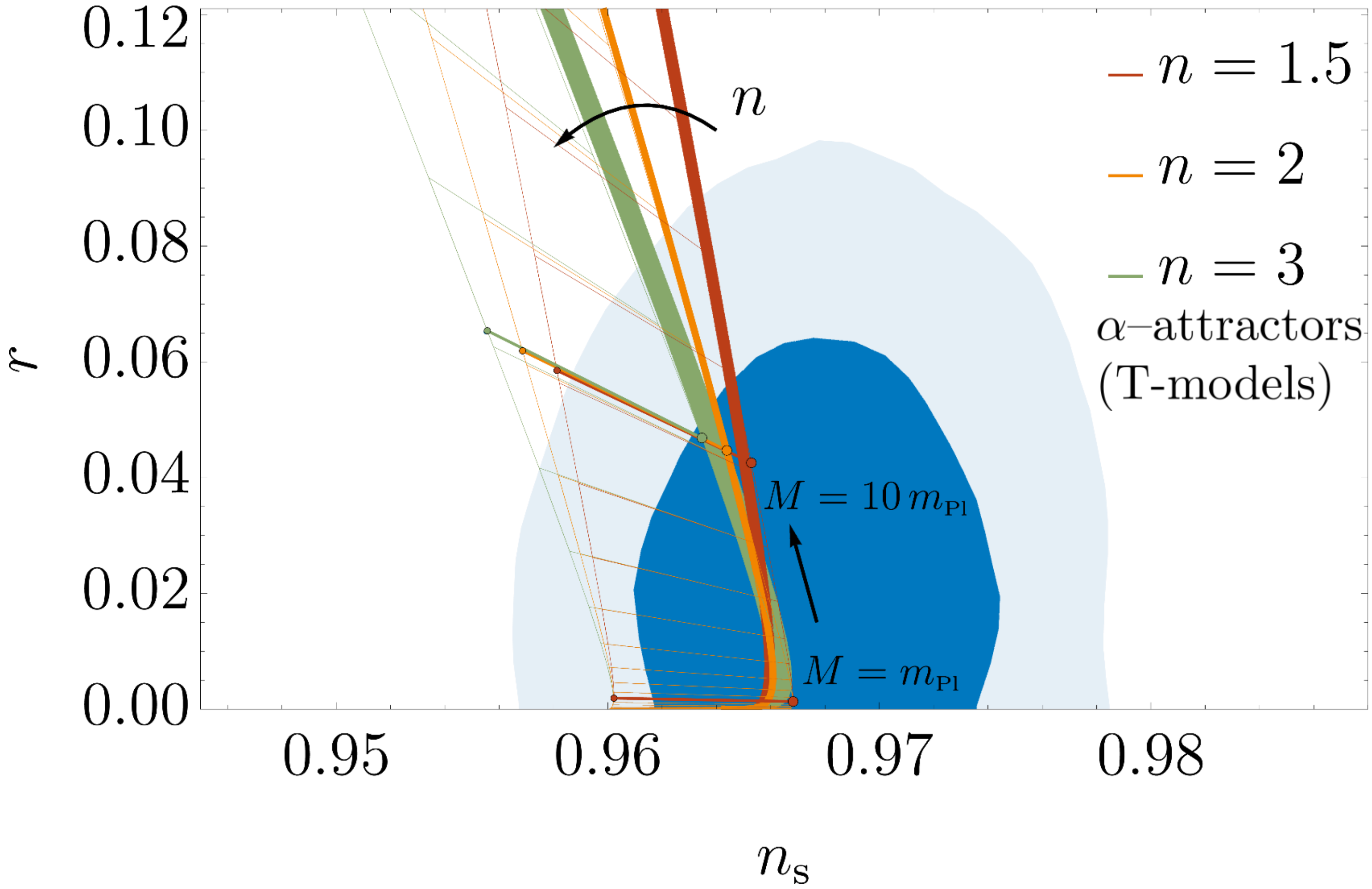


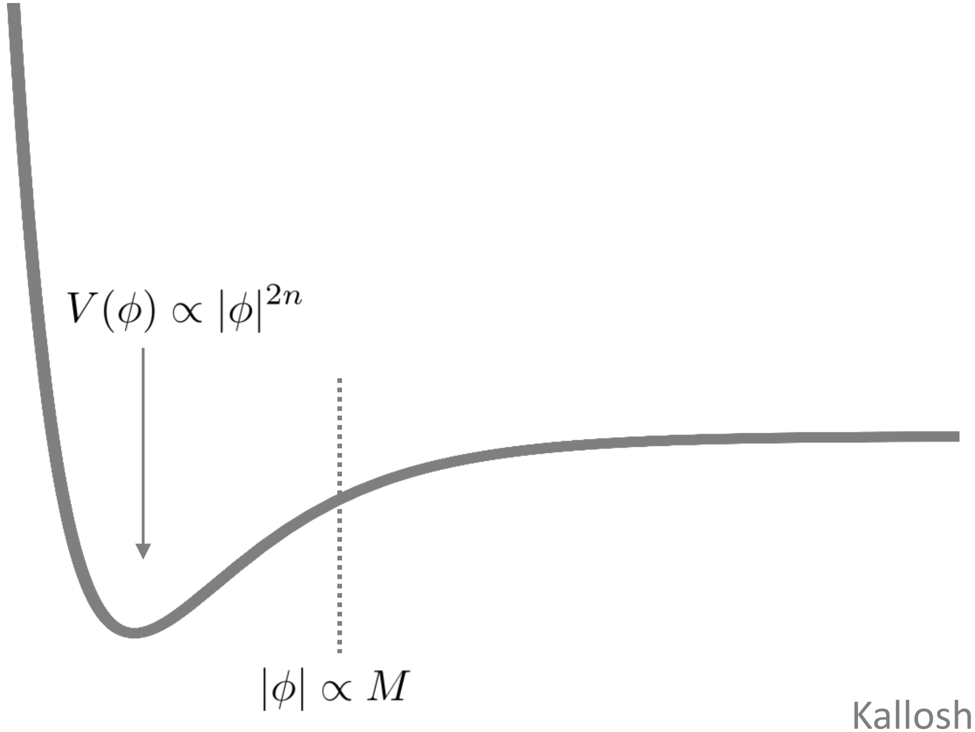
spectral index

KL and M. Amin (2018)
Planck Collaboration (2015)

Expansion history effects

$$V(\phi) \propto \left|1 - e^{-\phi/M}\right|^{2n}$$

α–attractors
(E-models)



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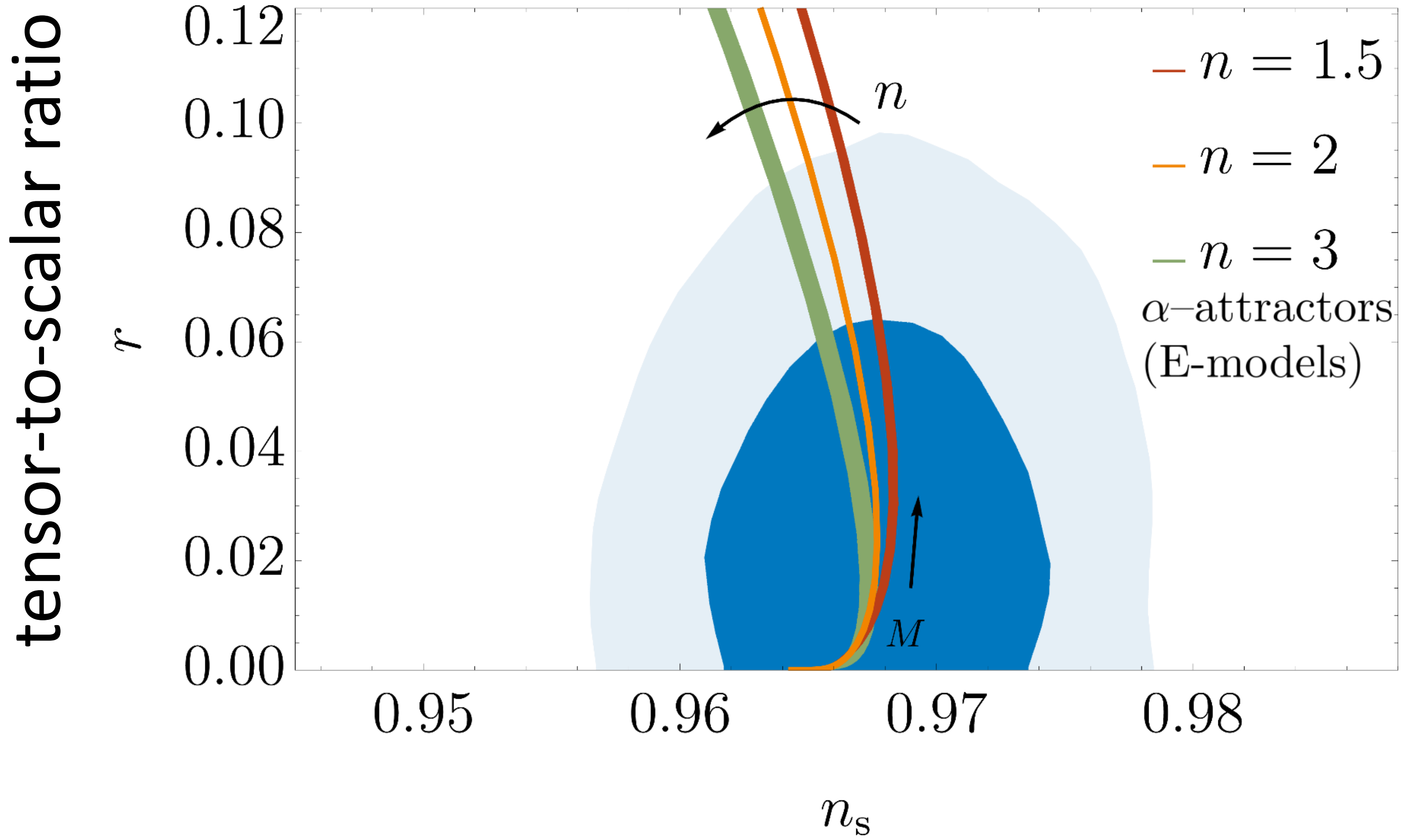

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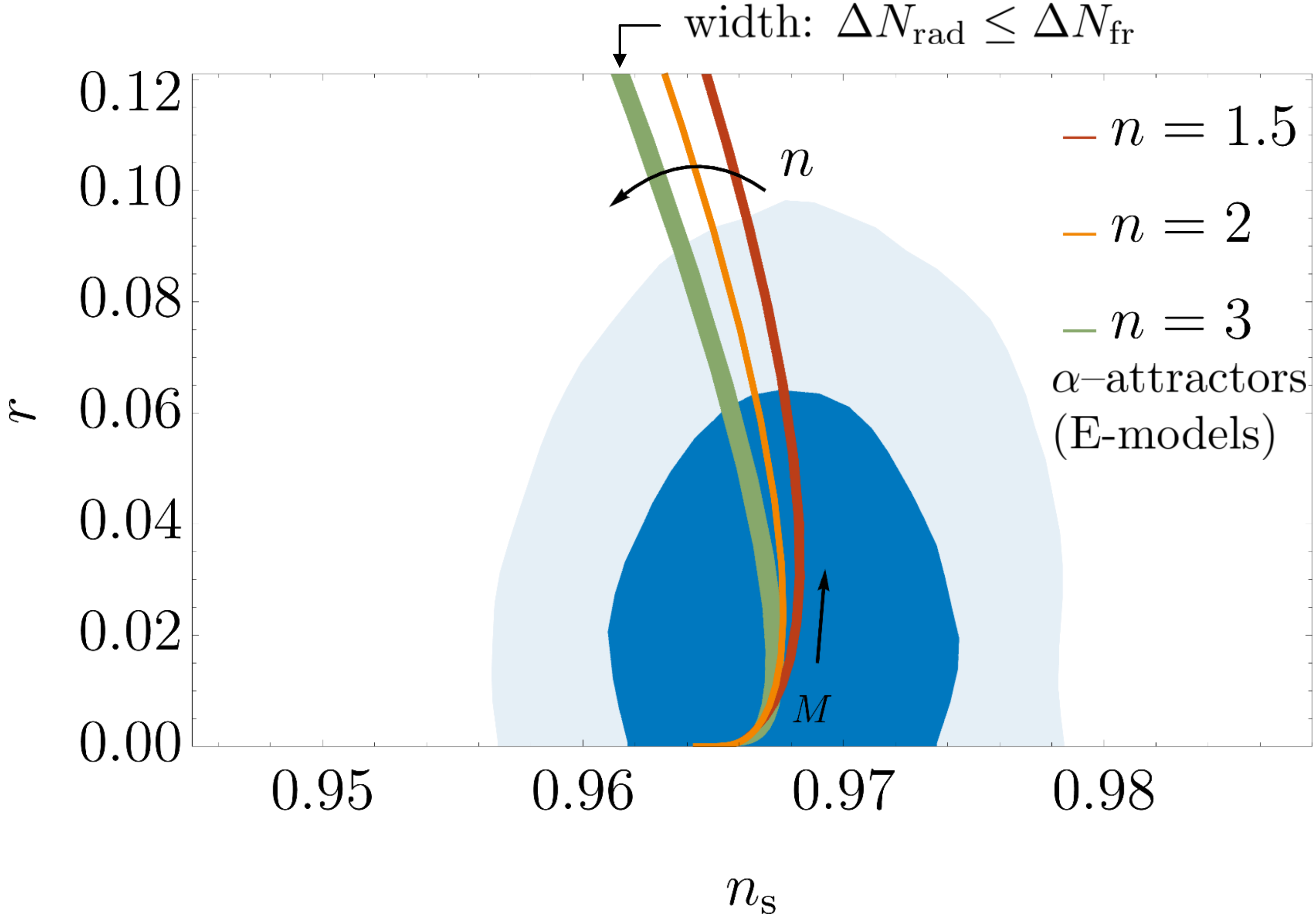

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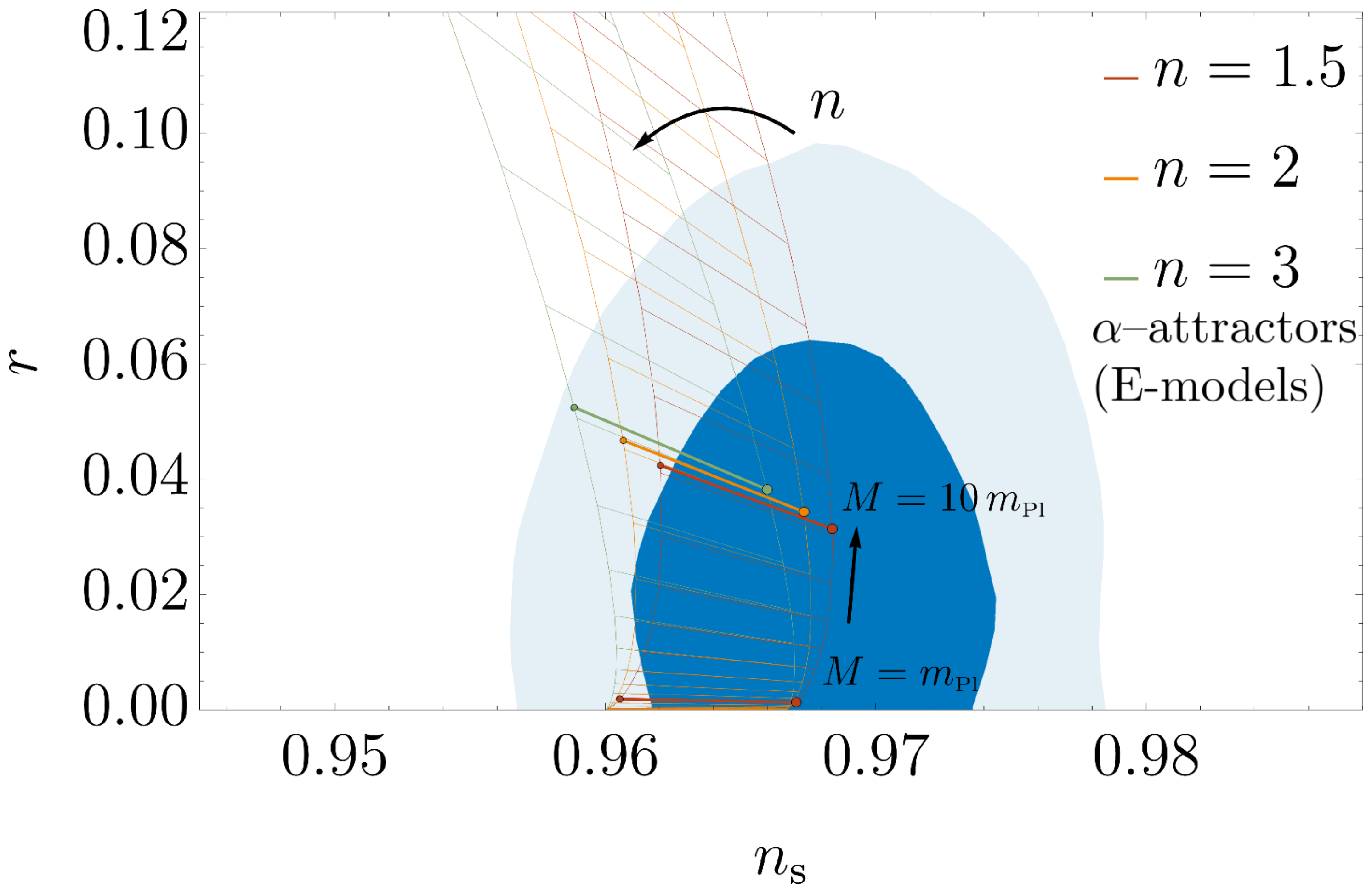

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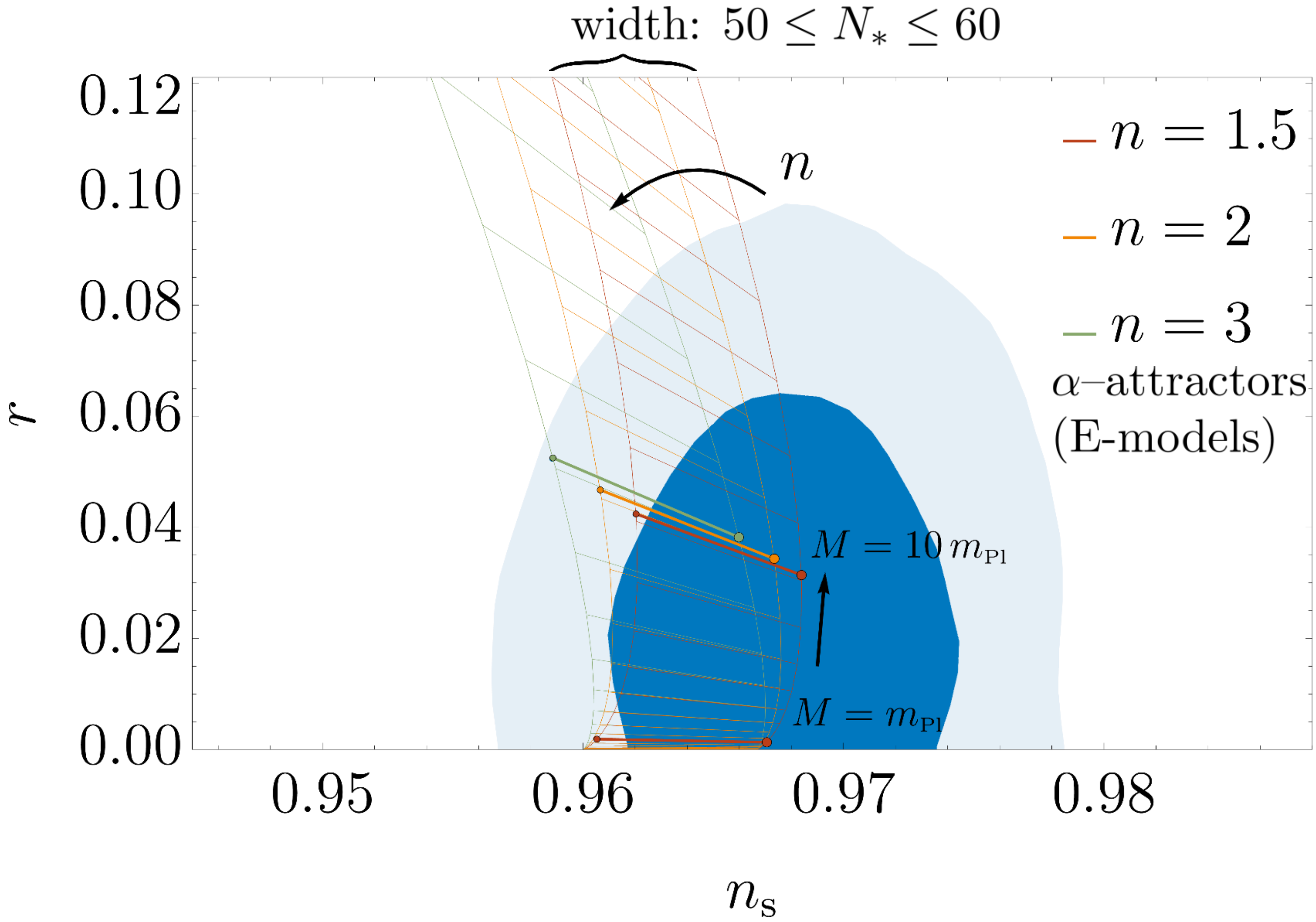

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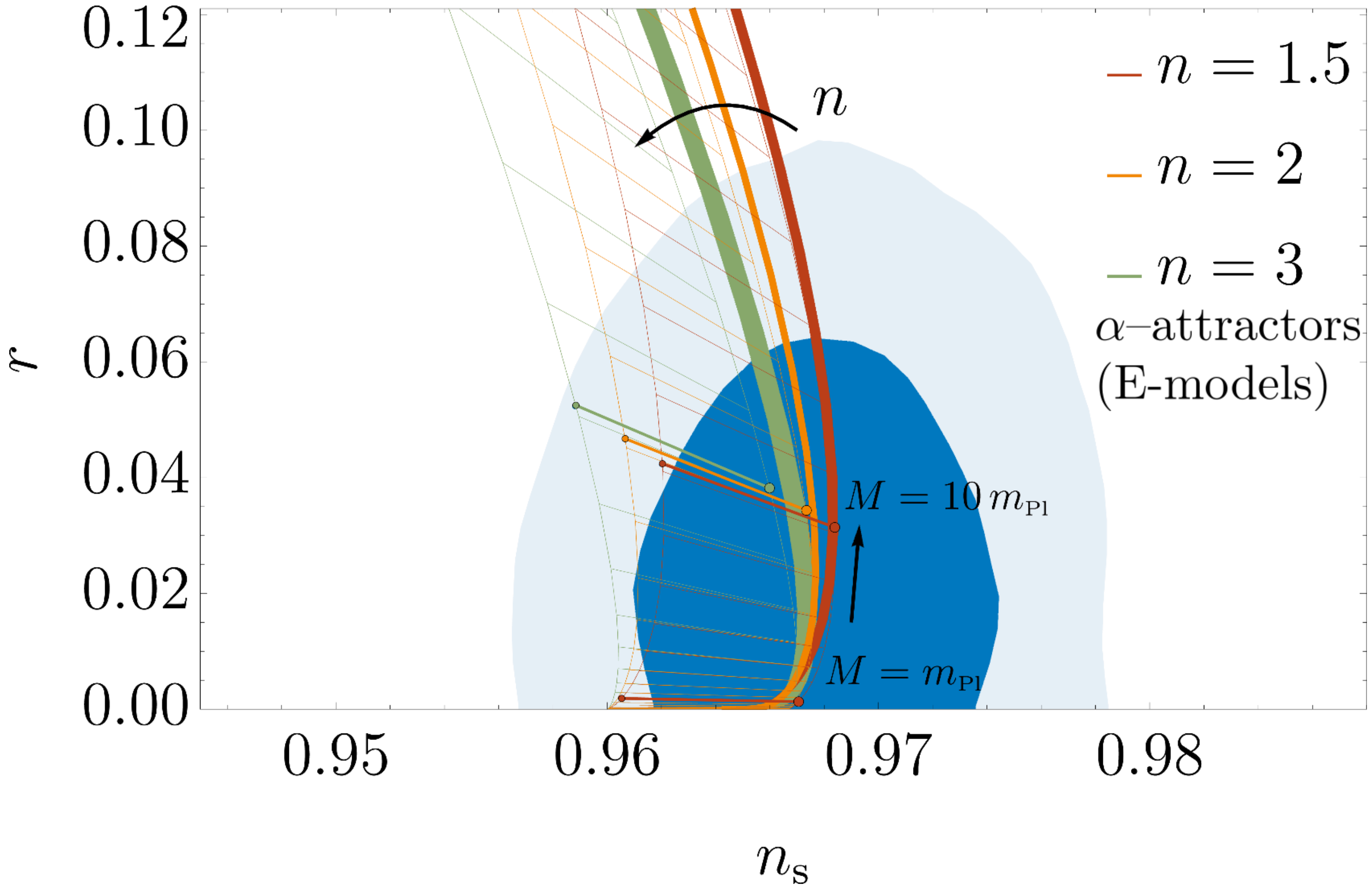


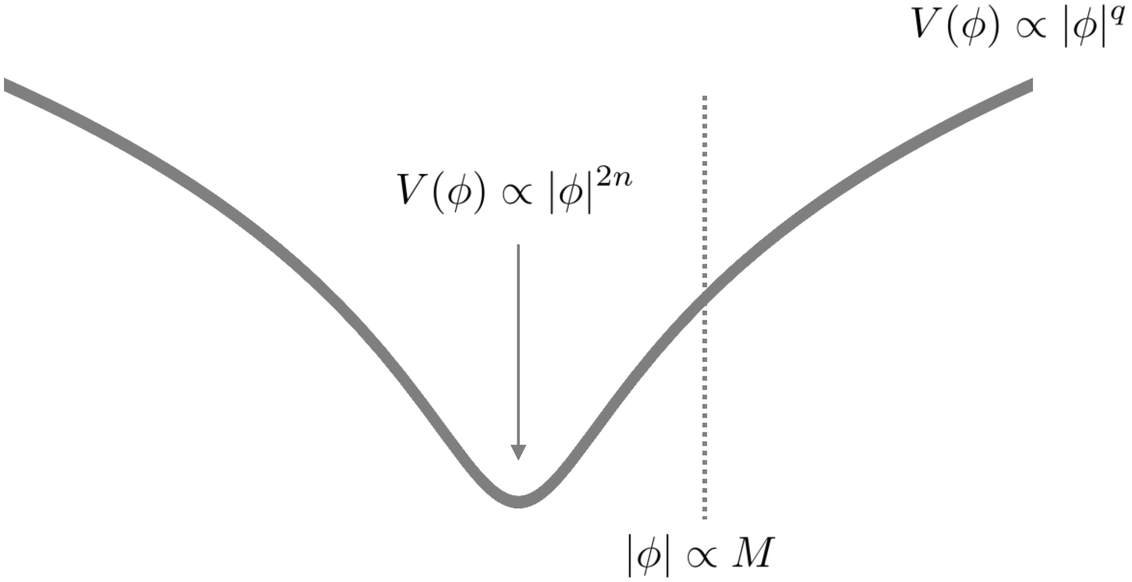
spectral index

KL and M. Amin (2018)
Planck Collaboration (2015)

Expansion history effects

$$V(\phi) \propto \left[1 + \left|\frac{\phi}{M}\right|^{2n}\right]^{\frac{q}{2n}} - 1$$

Monodromy

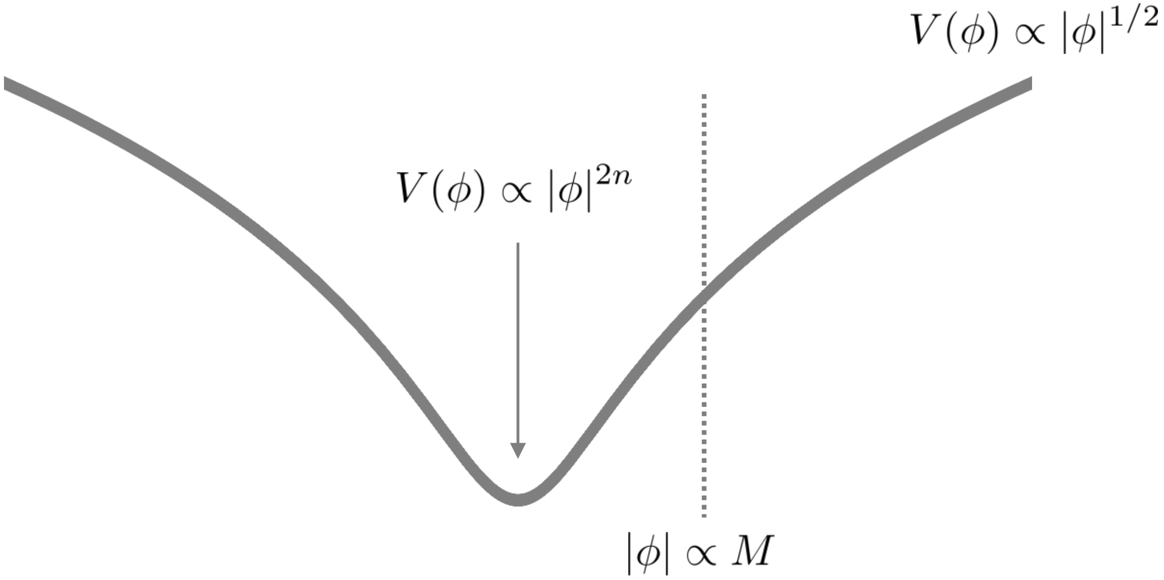


Silverstein and Westphal (2008)
McAllister, et al. (2014)

Expansion history effects

$$V(\phi) \propto \left[1 + \left|\frac{\phi}{M}\right|^{2n}\right]^{\frac{1}{4n}} - 1$$

Monodromy
$q = 1/2$



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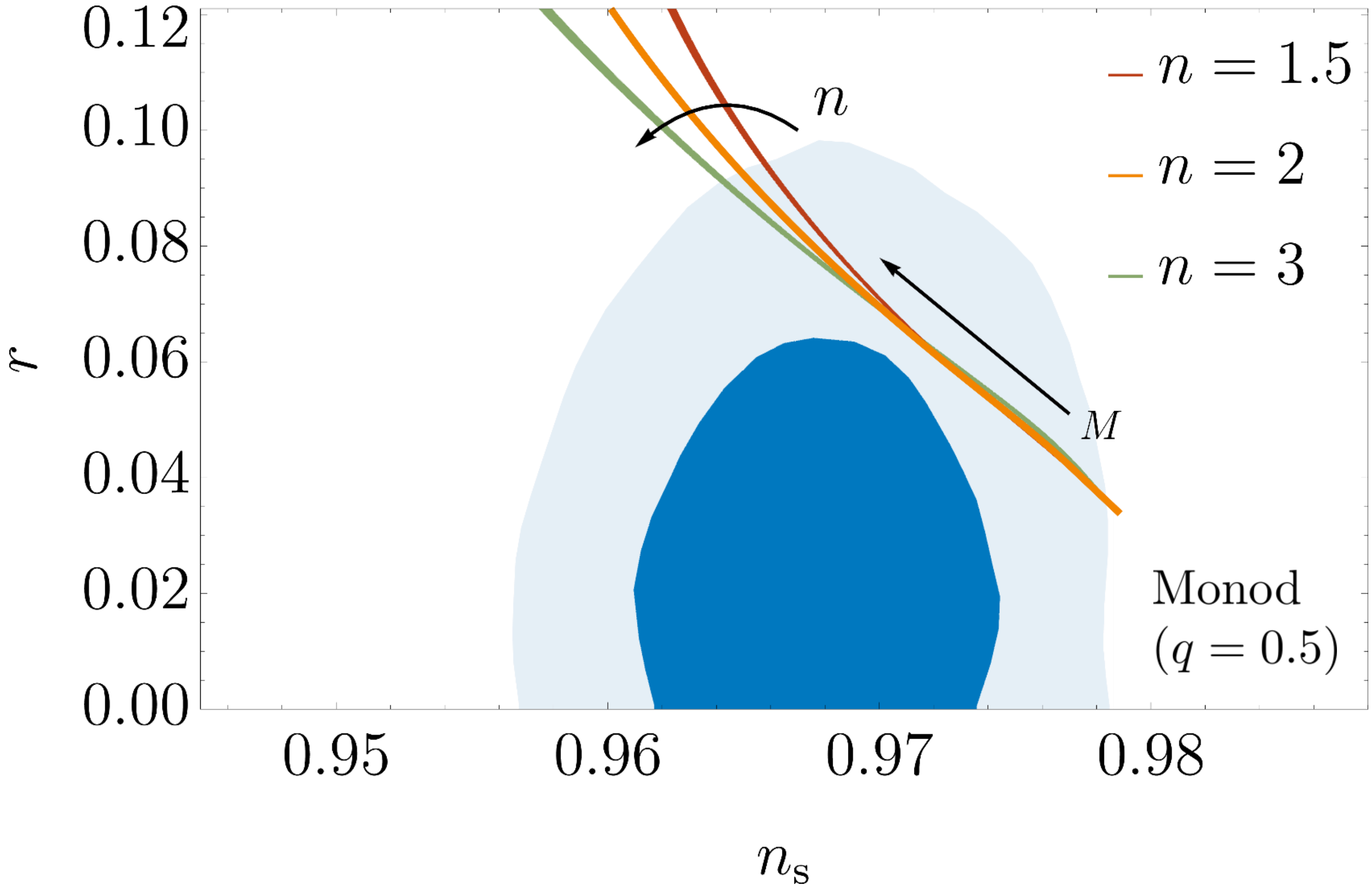

tensor-to-scalar ratio

spectral index

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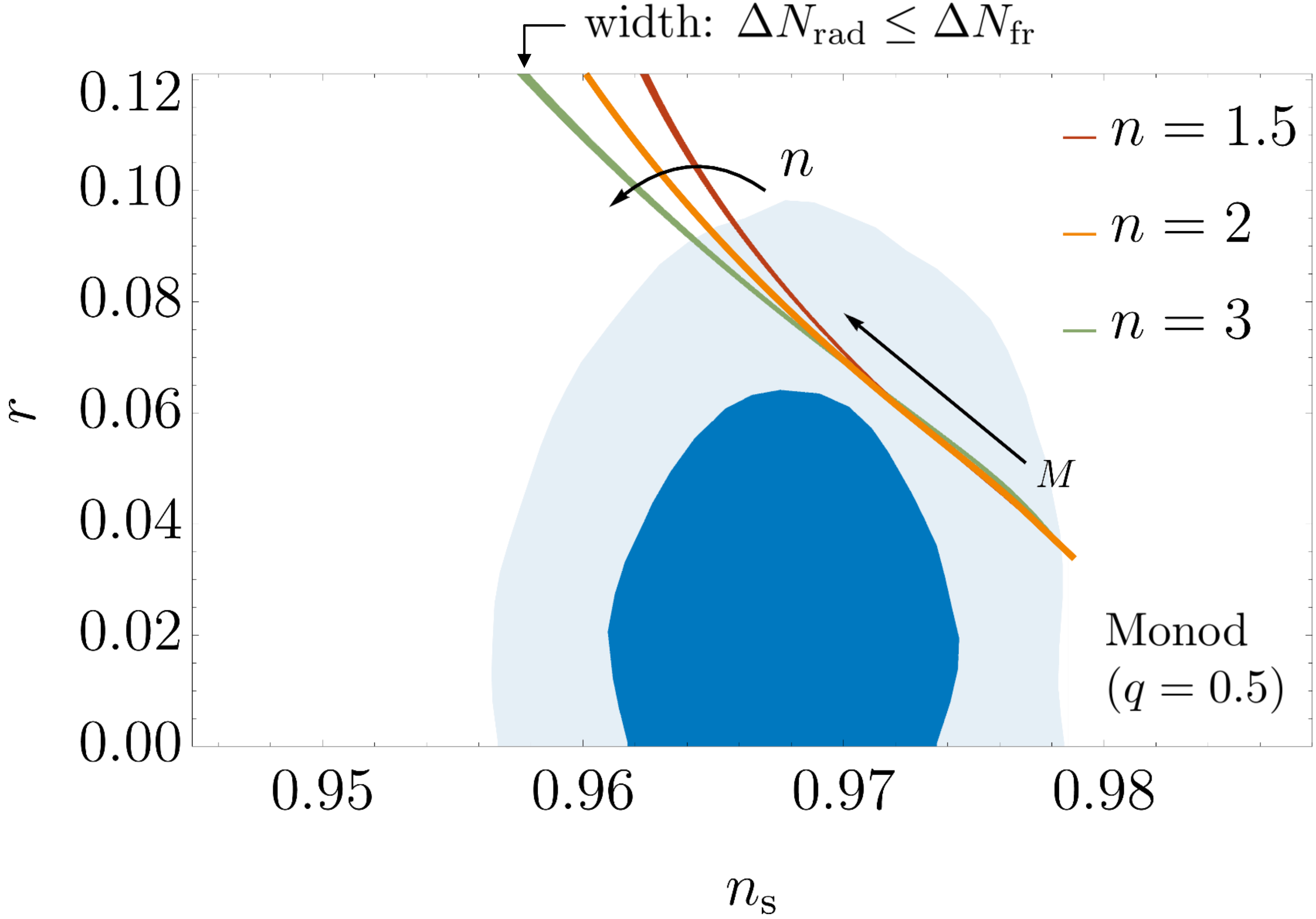
Planck Collaboration (2015)

Expansion history effects

tensor-to-scalar ratio



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Expansion history effects

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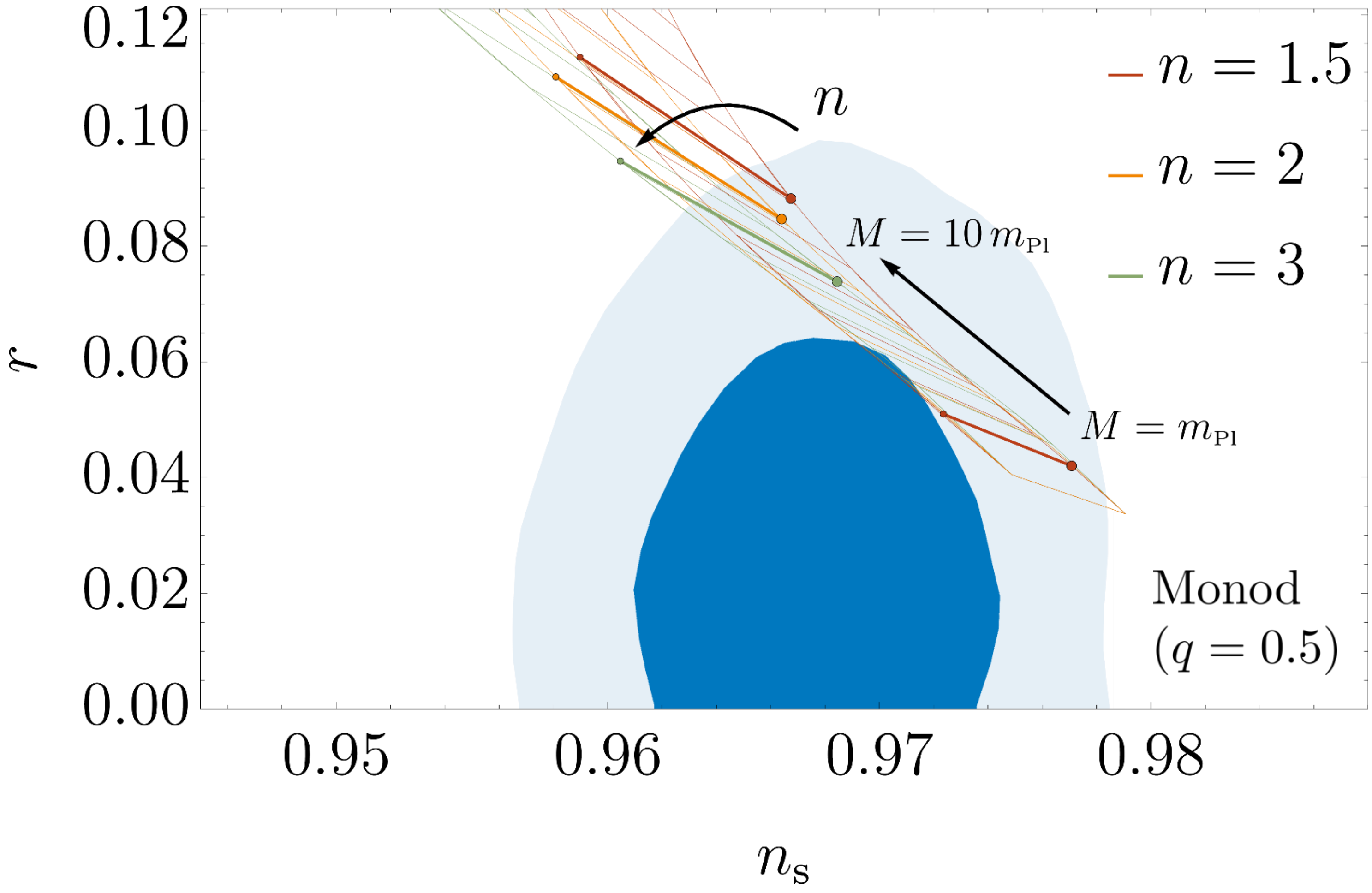

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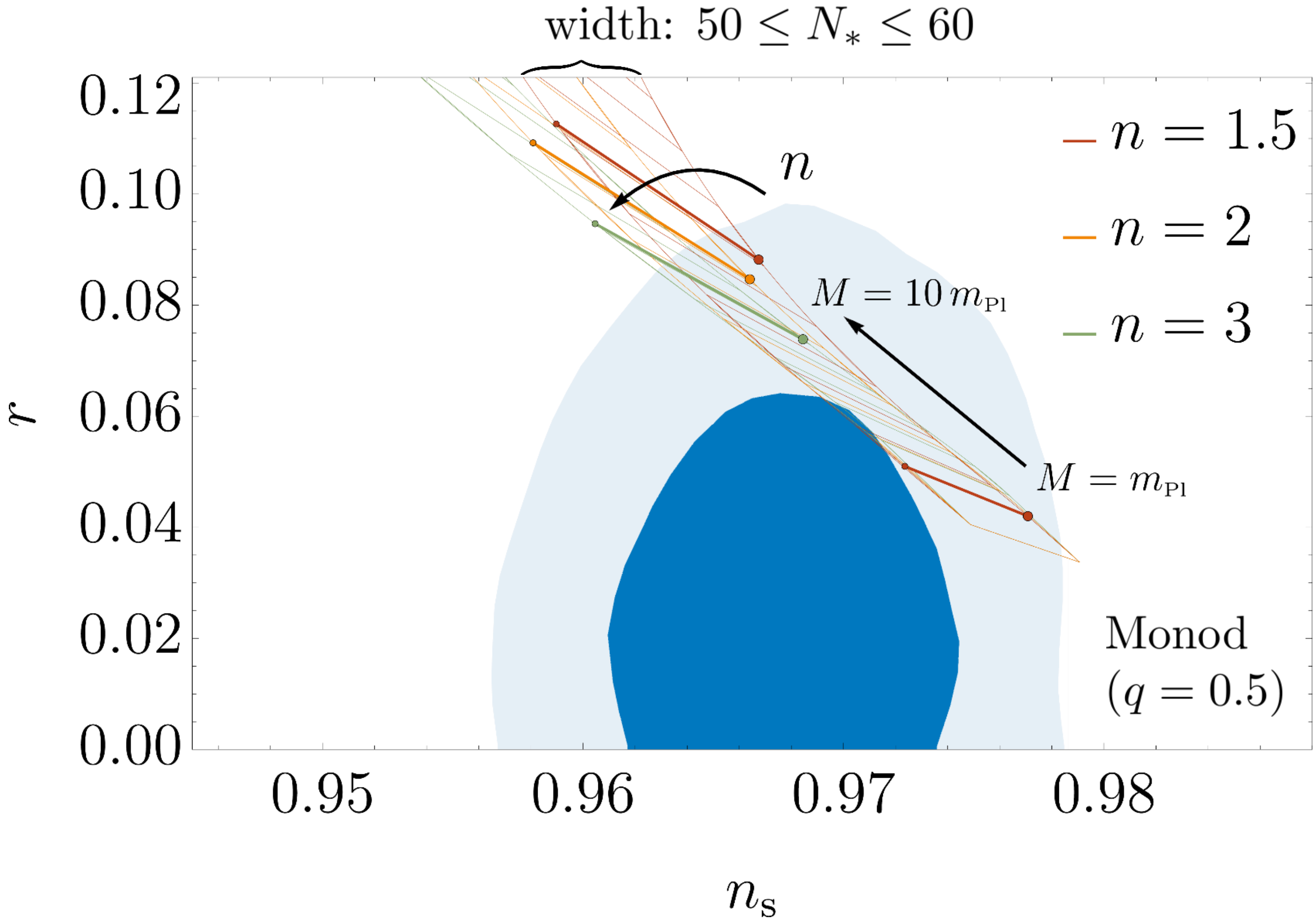

tensor-to-scalar ratio

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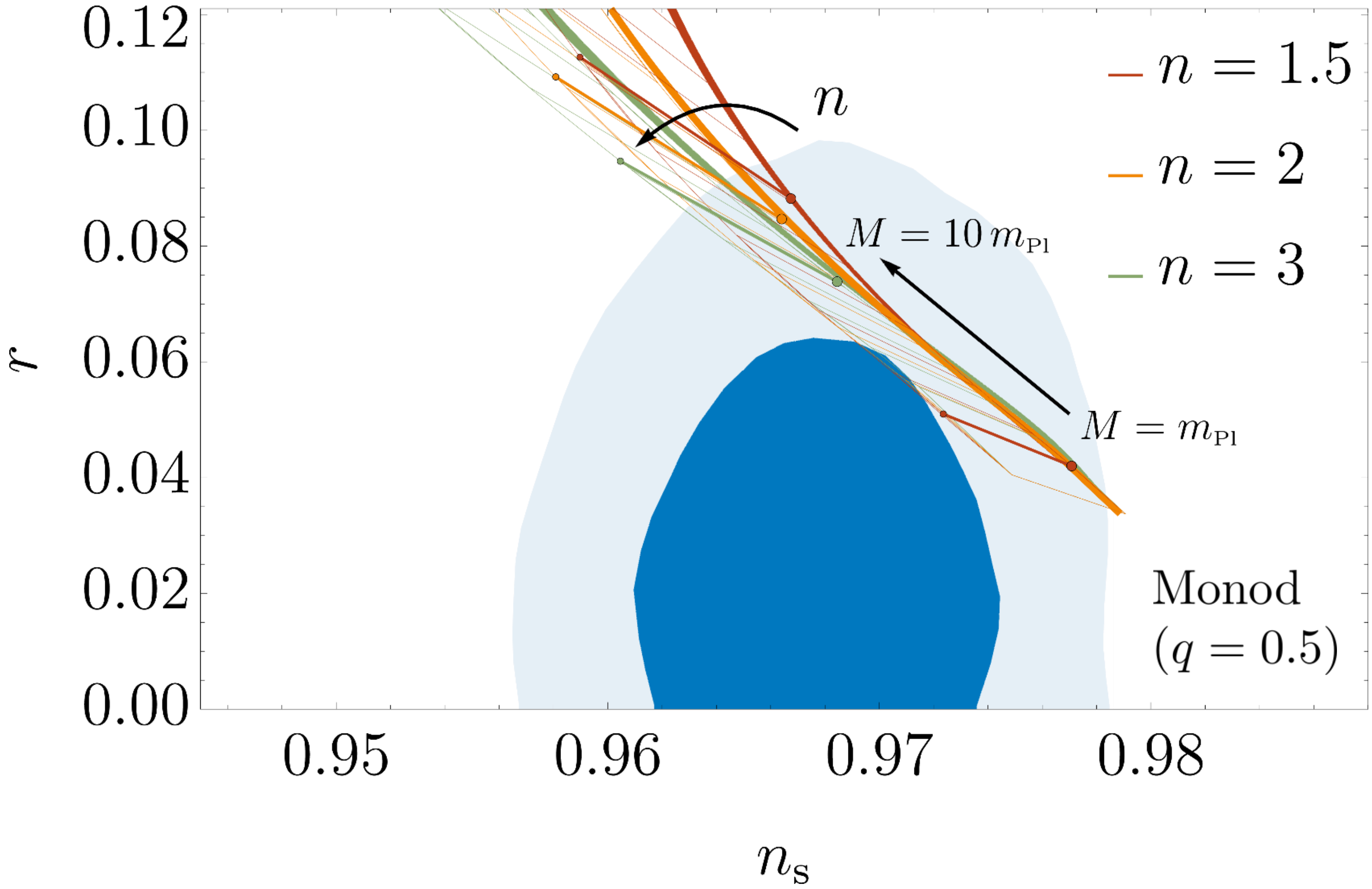
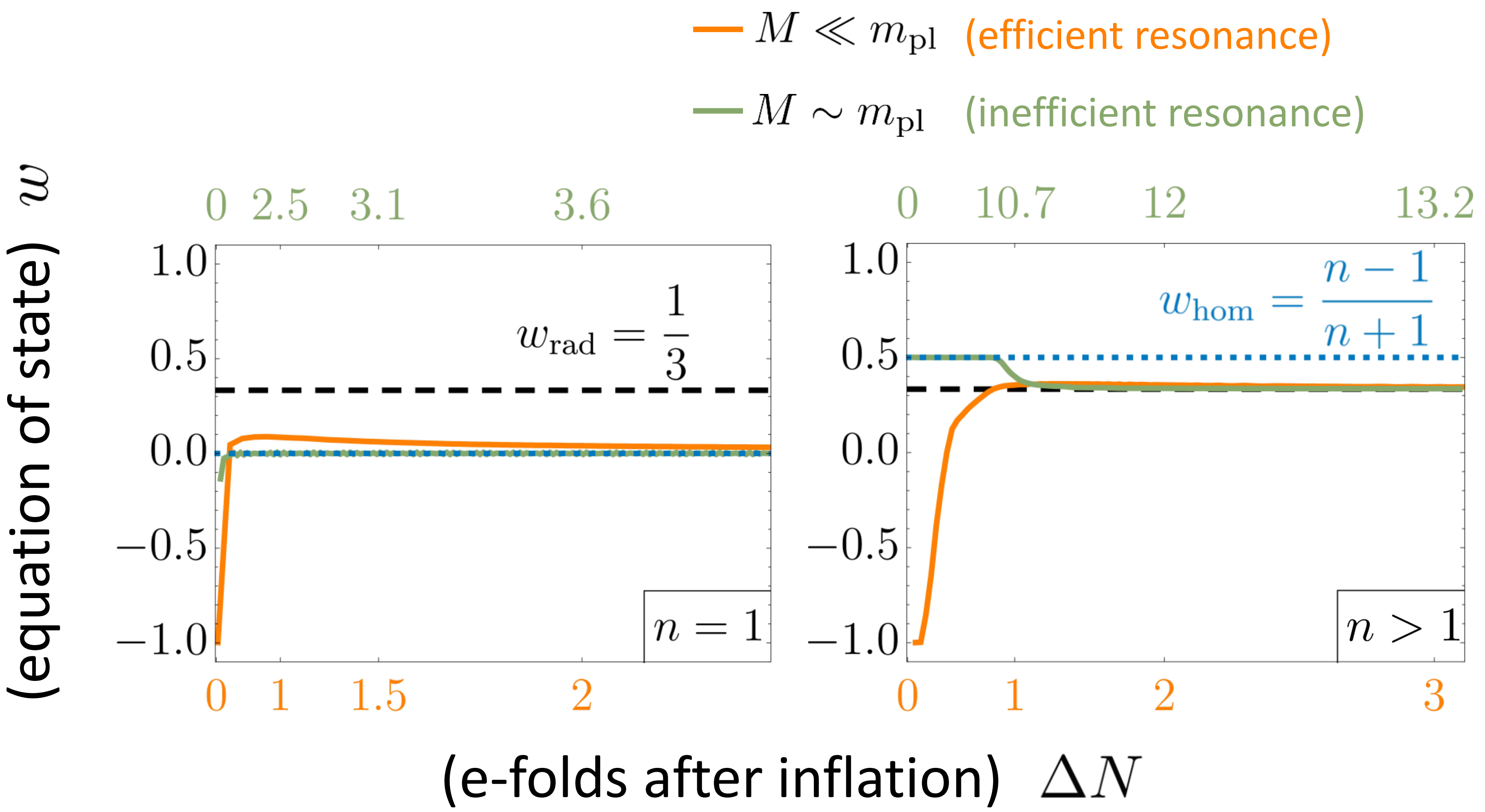


spectral index

KL and M. Amin (2018)
Planck Collaboration (2015)

Equation of state



$$\Delta N \equiv \int_{a_{\rm end}}^{a} d\ln a$$

Matter domination?

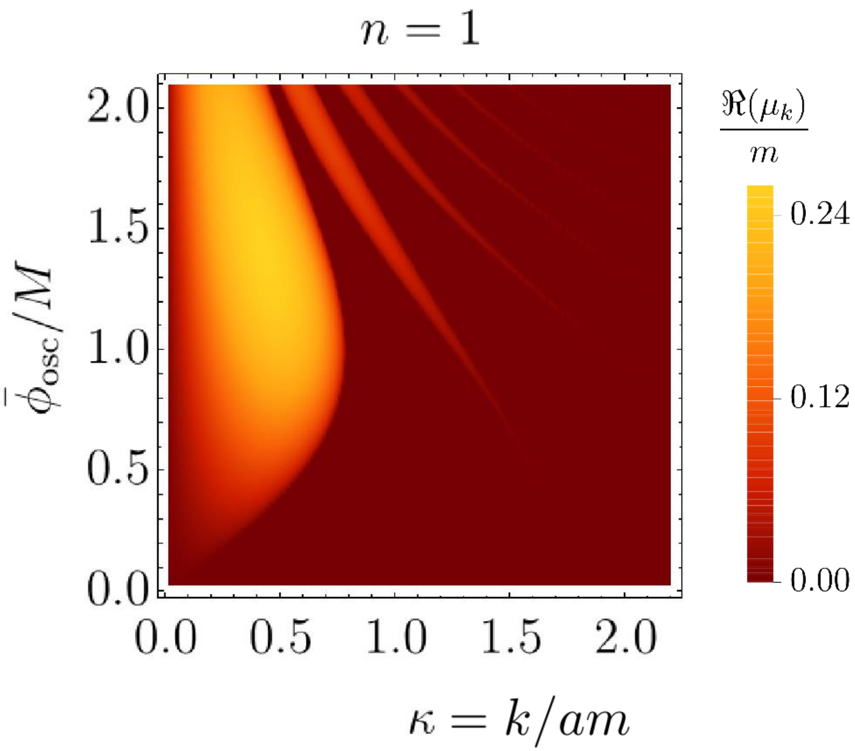
$$n = 1$$

Matter domination?

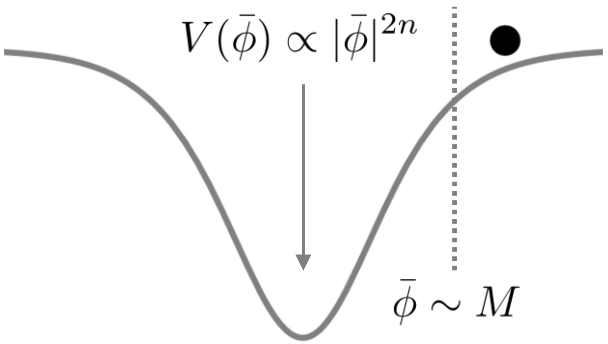
$$n = 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



$$\delta\phi_k \propto \exp(\pm\mu_k t)$$

$$m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$$

Matter domination?

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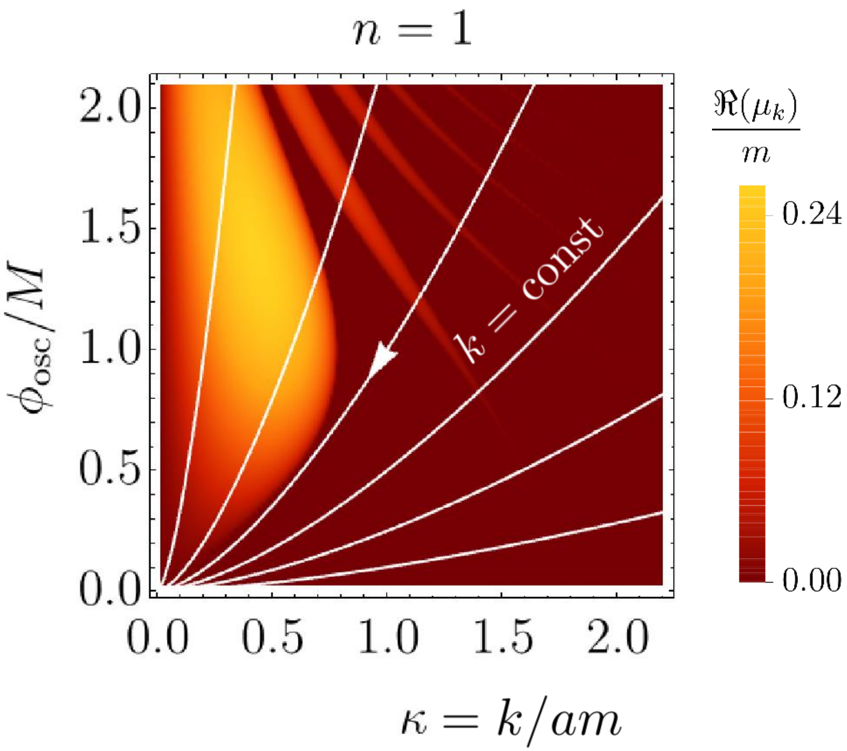

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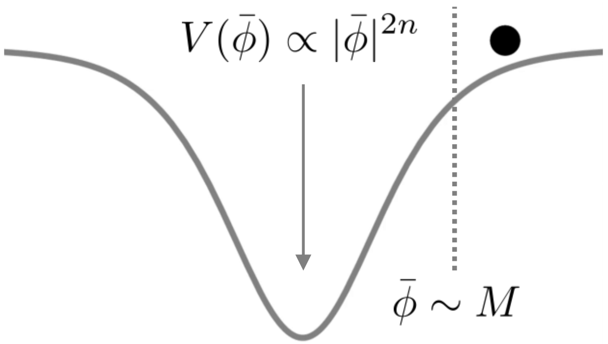

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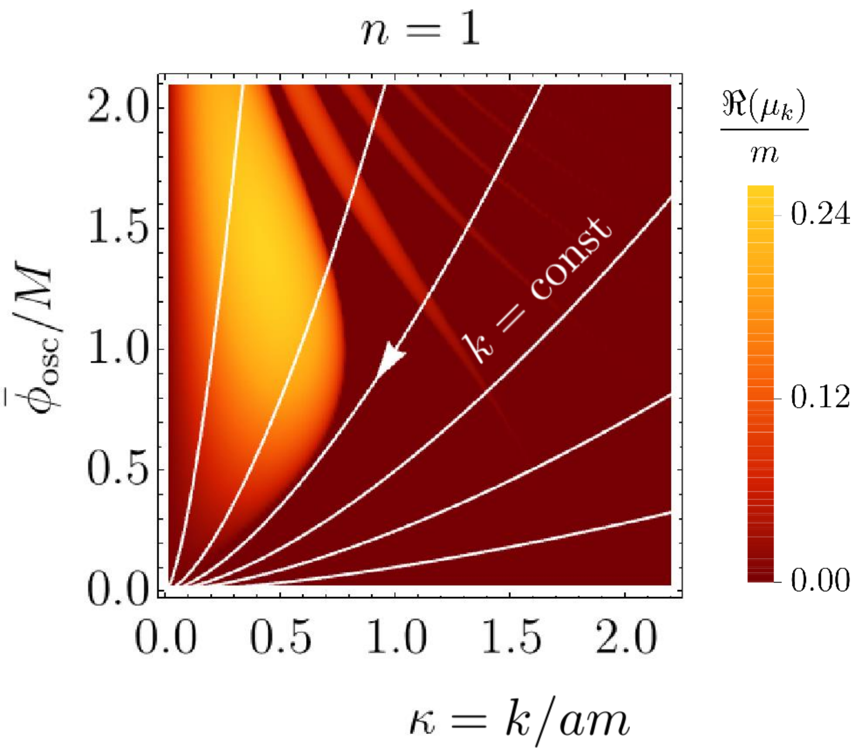

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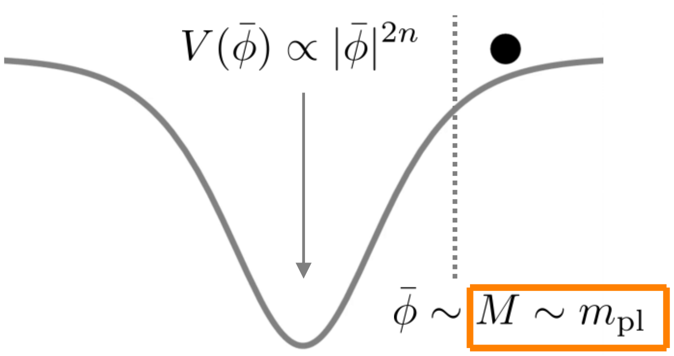

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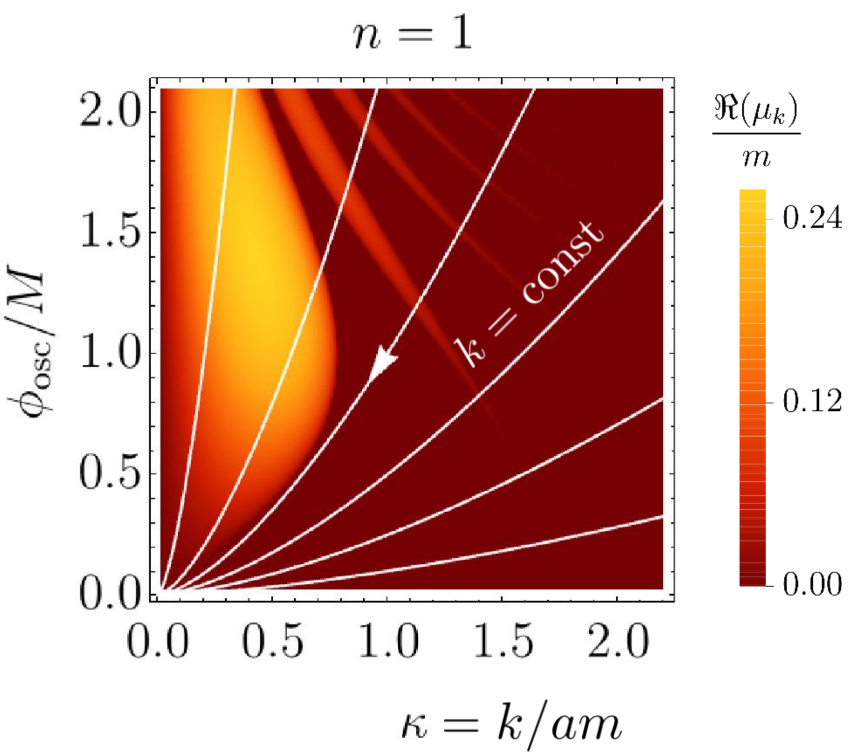

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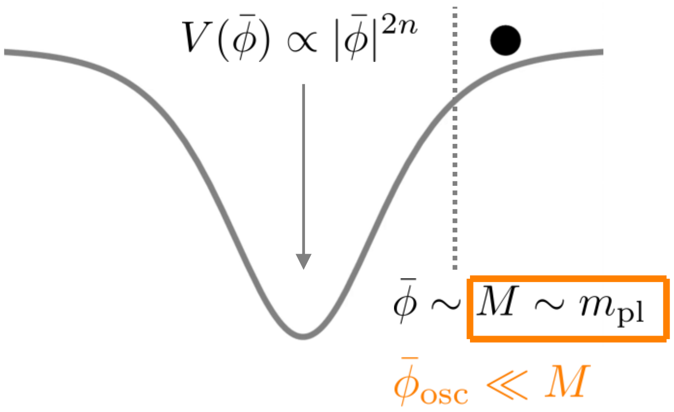

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Matter domination?

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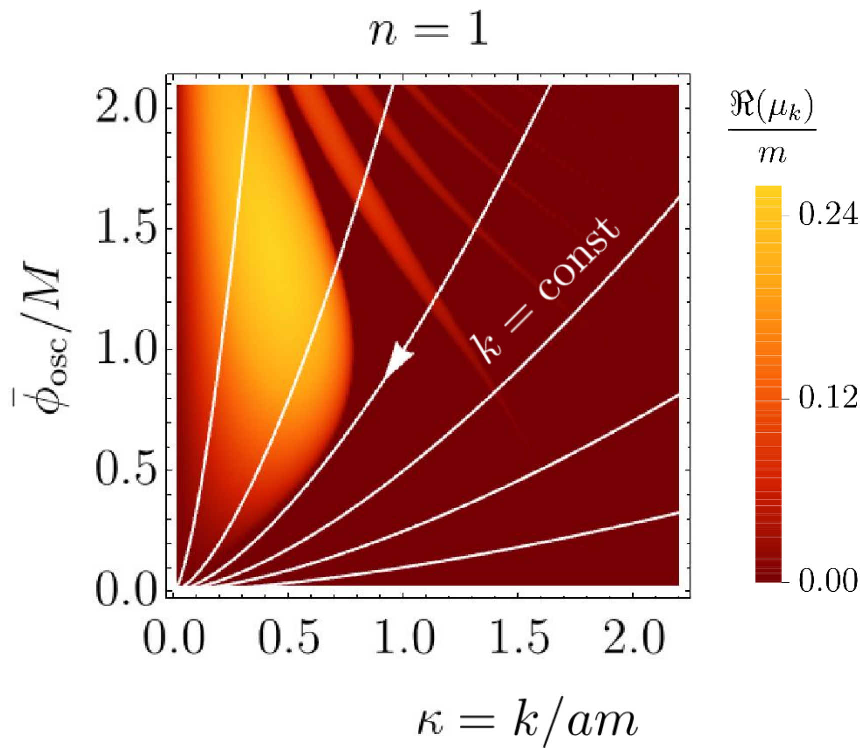
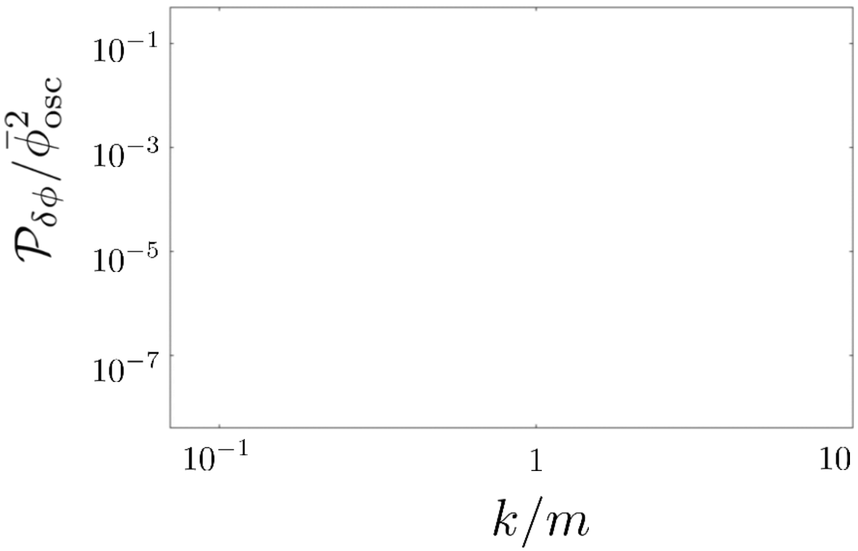


inflaton vev amplitude

inflaton field wavenumber

Power spectrum:

$$\langle \delta\phi(x)^2 \rangle \equiv \int \mathcal{P}_{\delta\phi}\, d\ln k$$

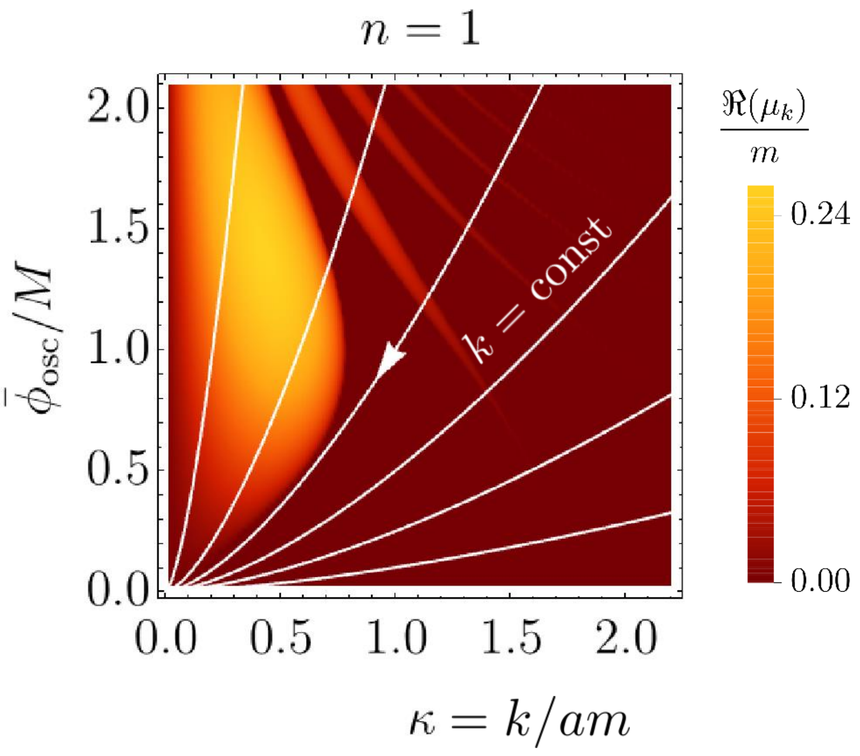


comoving wavenumber

Matter domination?

$$n = 1$$

Non-perturbative decay (parametric self-resonance)

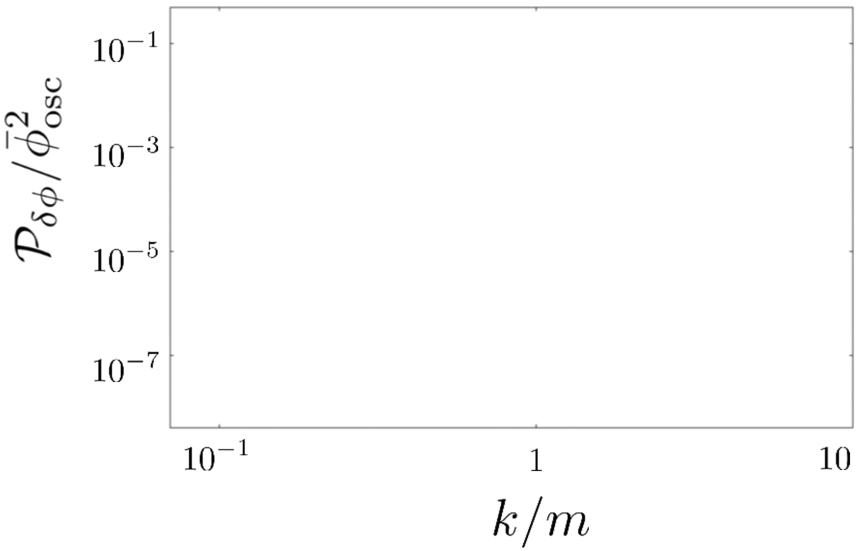


inflaton vev amplitude

inflaton field wavenumber

Power spectrum:

$$\left\langle \delta\phi(x)^2 \right\rangle \equiv \int \mathcal{P}_{\delta\phi}\, d\ln k$$



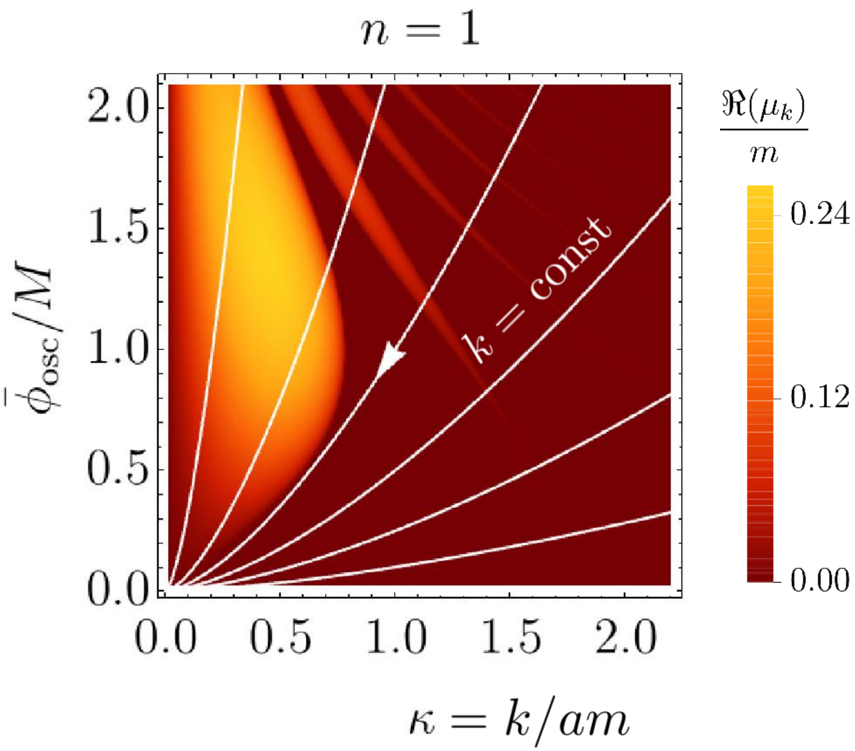
comoving wavenumber

Matter domination?

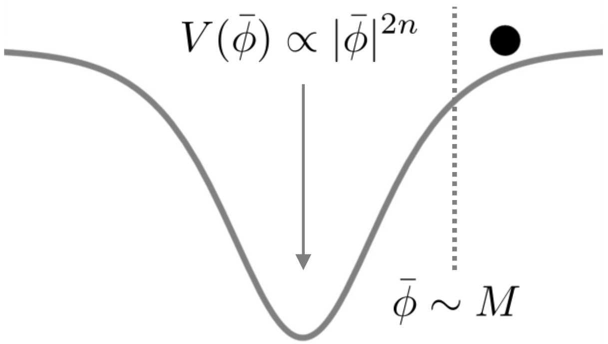
$$n = 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



$$\delta\phi_k \propto \exp(\pm\mu_k t)$$

$$m^2 \equiv V'(\bar{\phi}_{\text{osc}})/\bar{\phi}_{\text{osc}}$$

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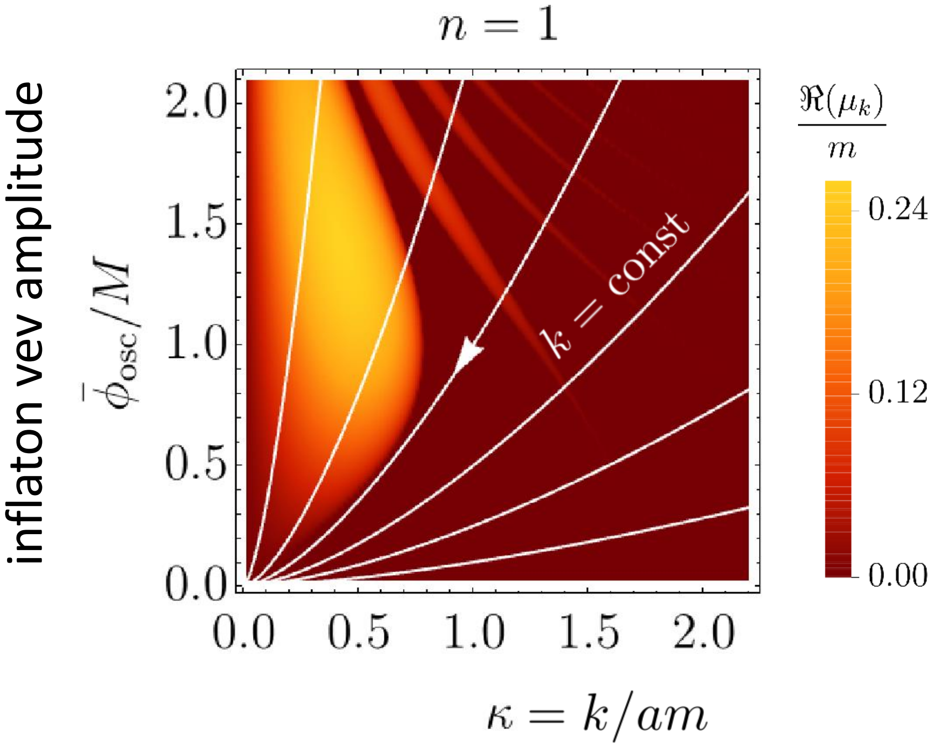

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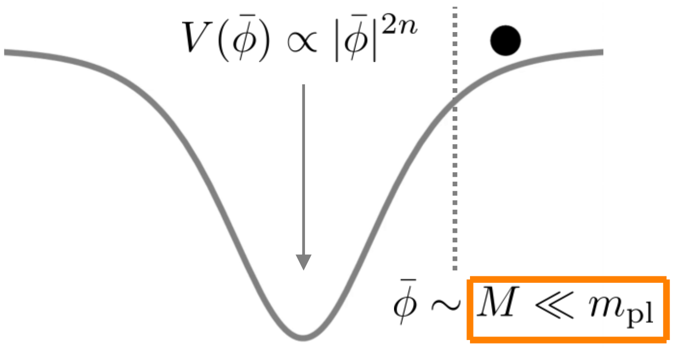

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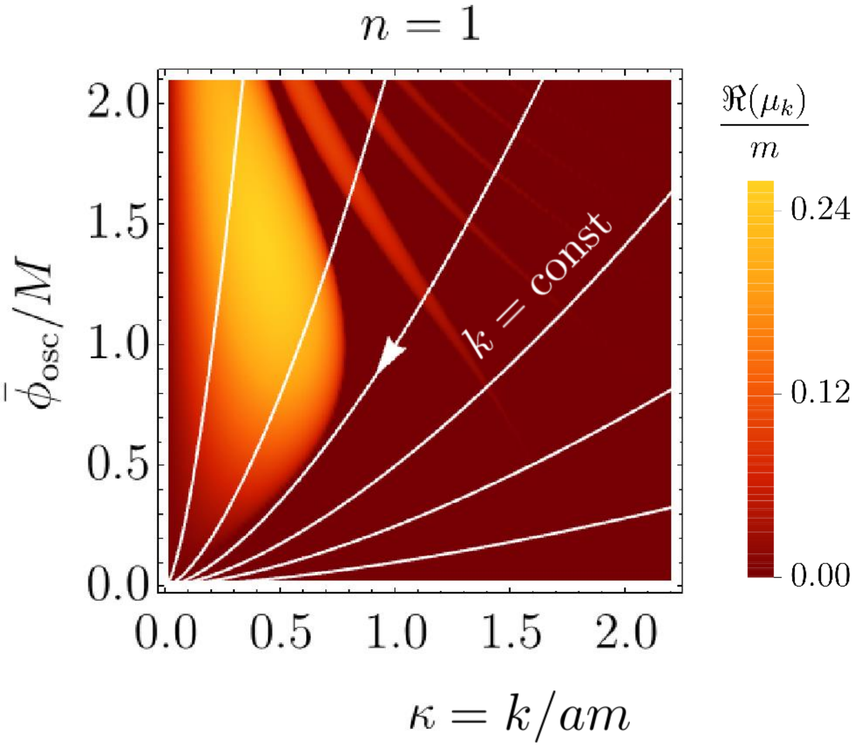

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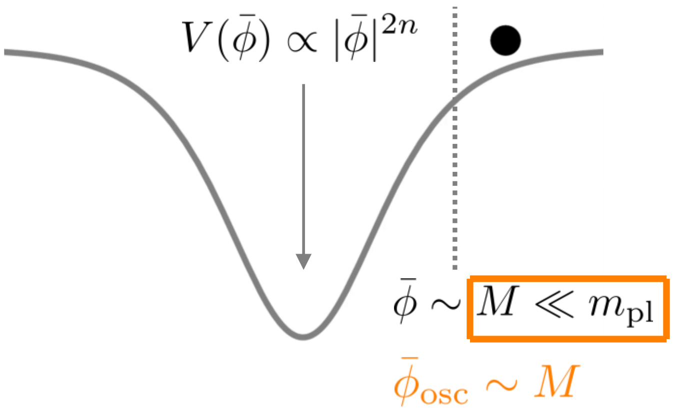

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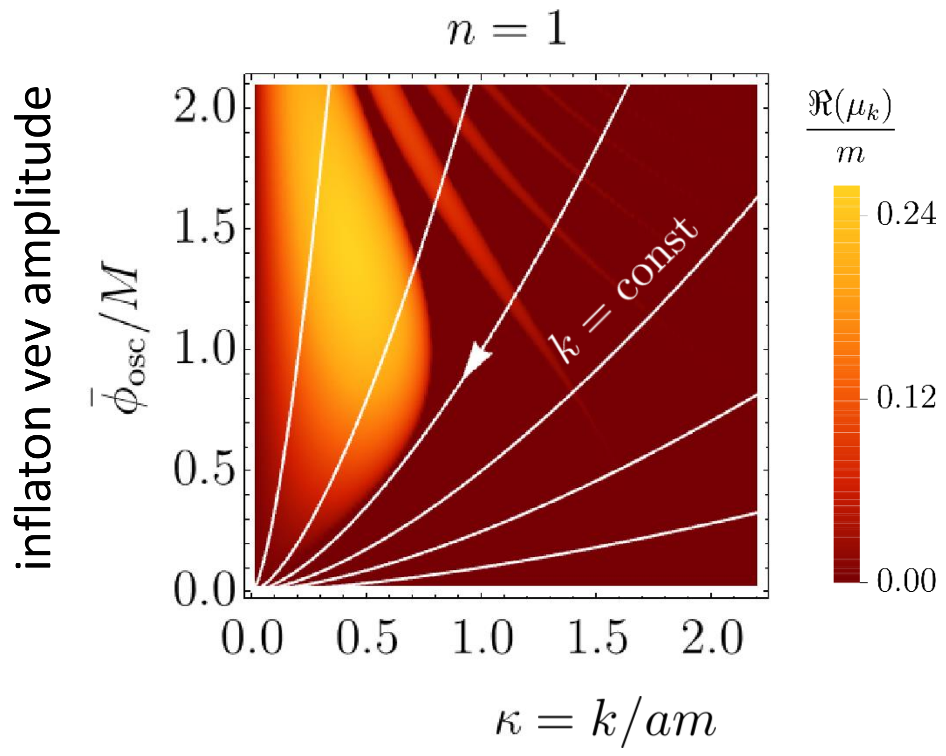

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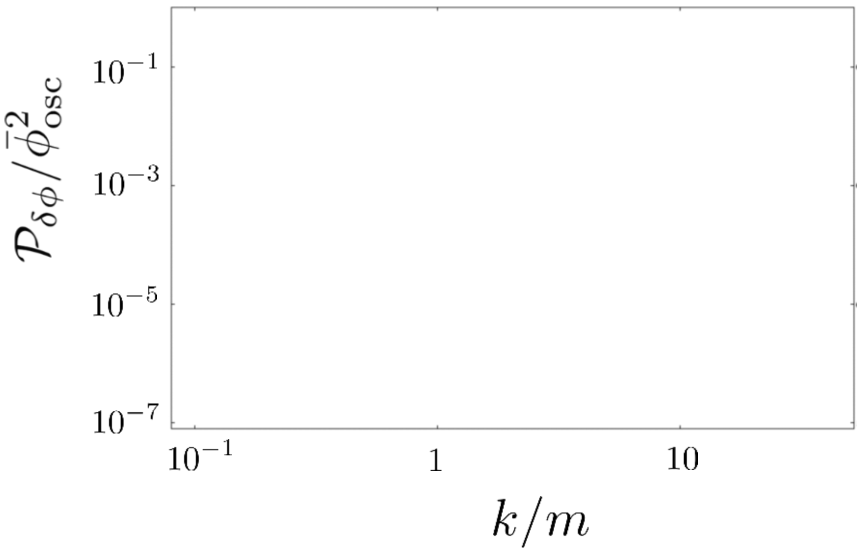

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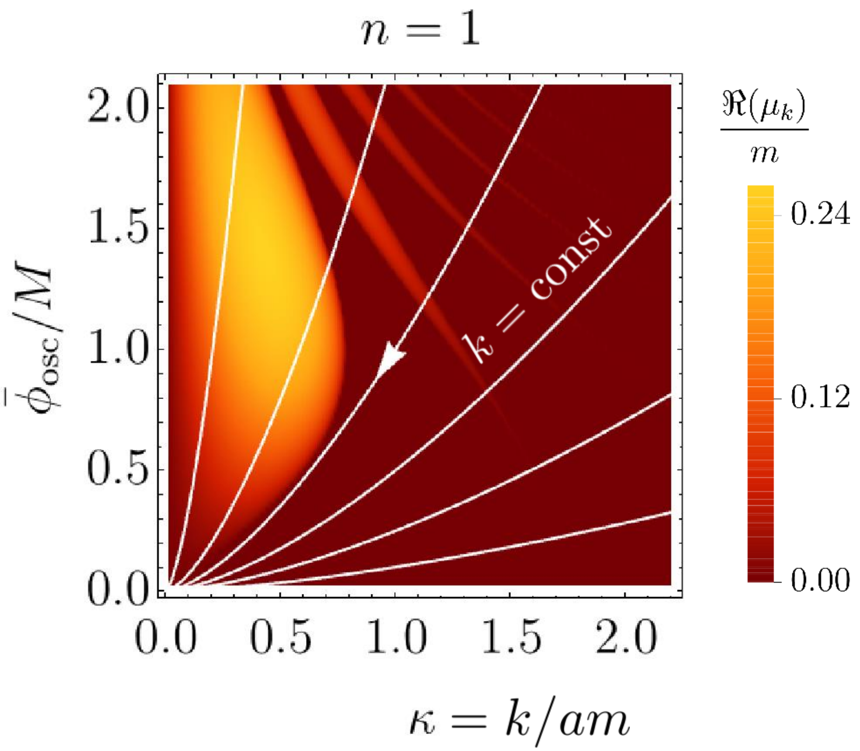

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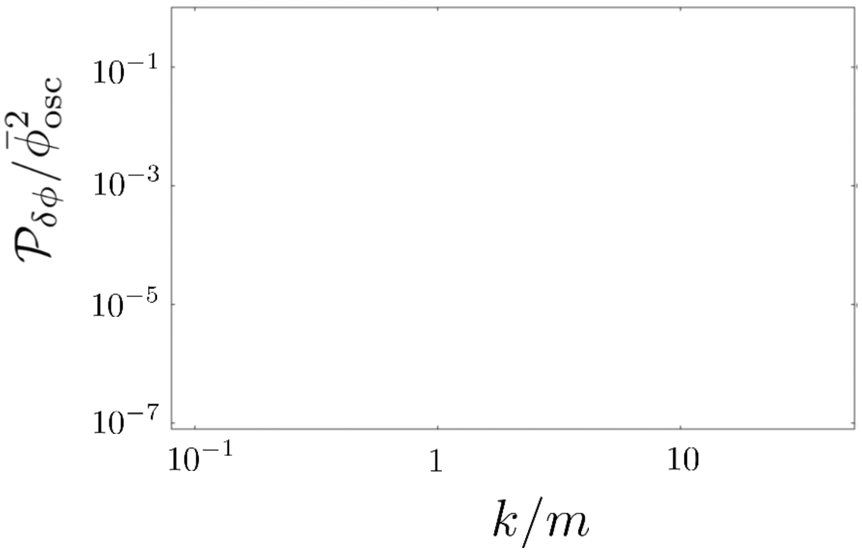
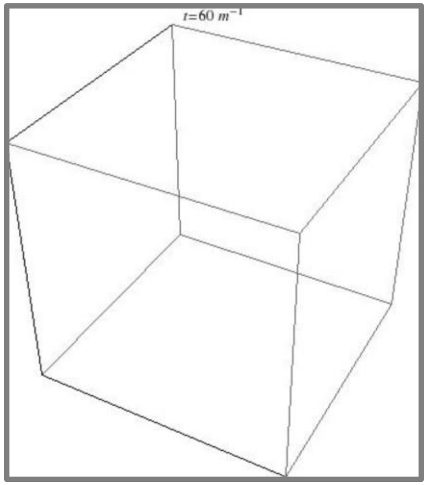


comoving wavenumber

Matter domination?

$$n = 1$$

$M \ll m_{\rm pl}$



- $\bar{\phi}$ forms oscillons (stable)

KL and Amin (2017, 18, 19)

See also Amin, Easther, Finkel, Flauger, Hertzberg (2011)

$M \sim m_{\rm pl}$

- $\delta\phi(t, \mathbf{x})$ production shut off
- $\bar{\phi}_{\rm osc}(t) =$ pressureless dust

matter-like eos: $w = 0$

couplings to other fields?

See also Antusch, Figueroa, Marschall, Torrenti (2020)

Antusch, Marschall, Torrenti (2022)

Other connections …

Other connections …

- stochastic GWs from fragmentation KL and M. Amin (2019)

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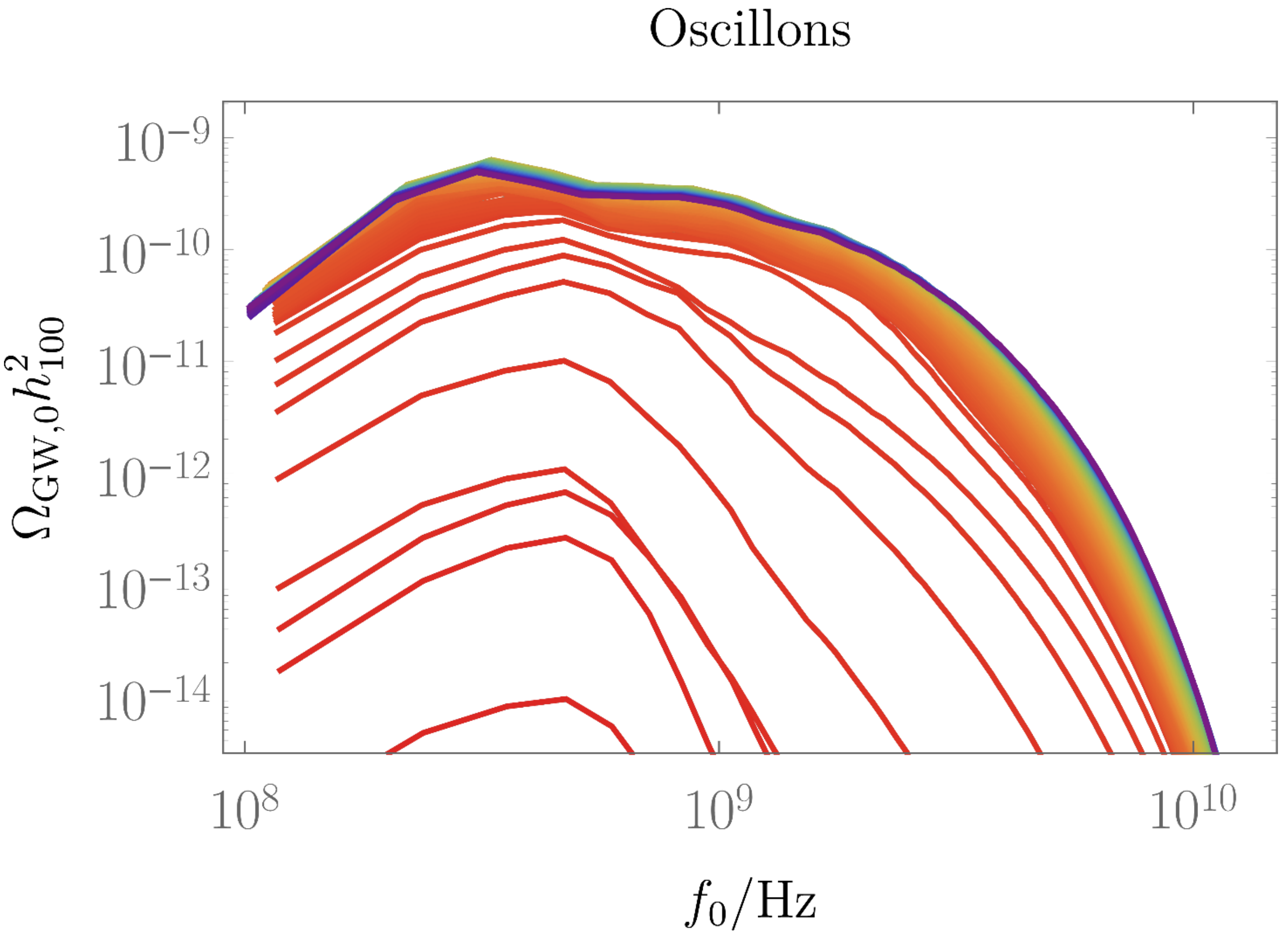

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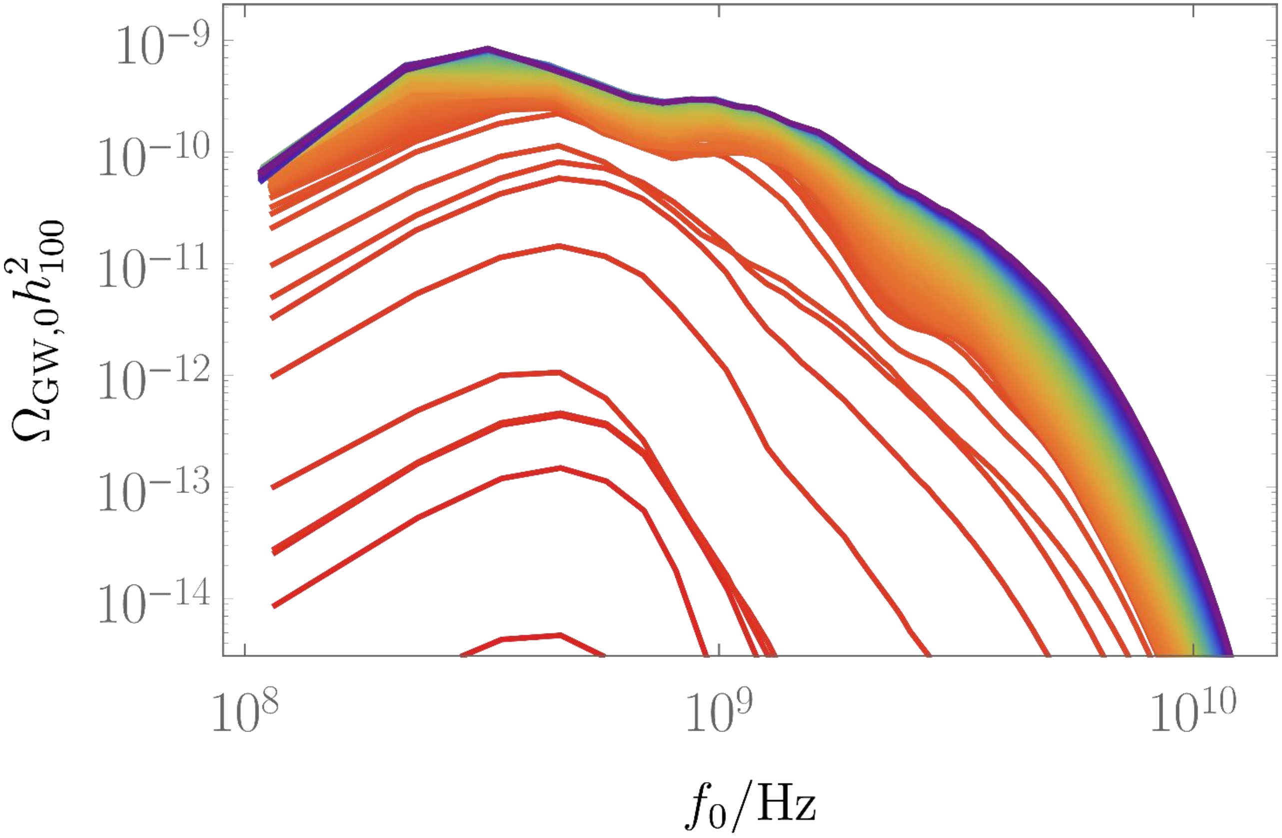
Transients



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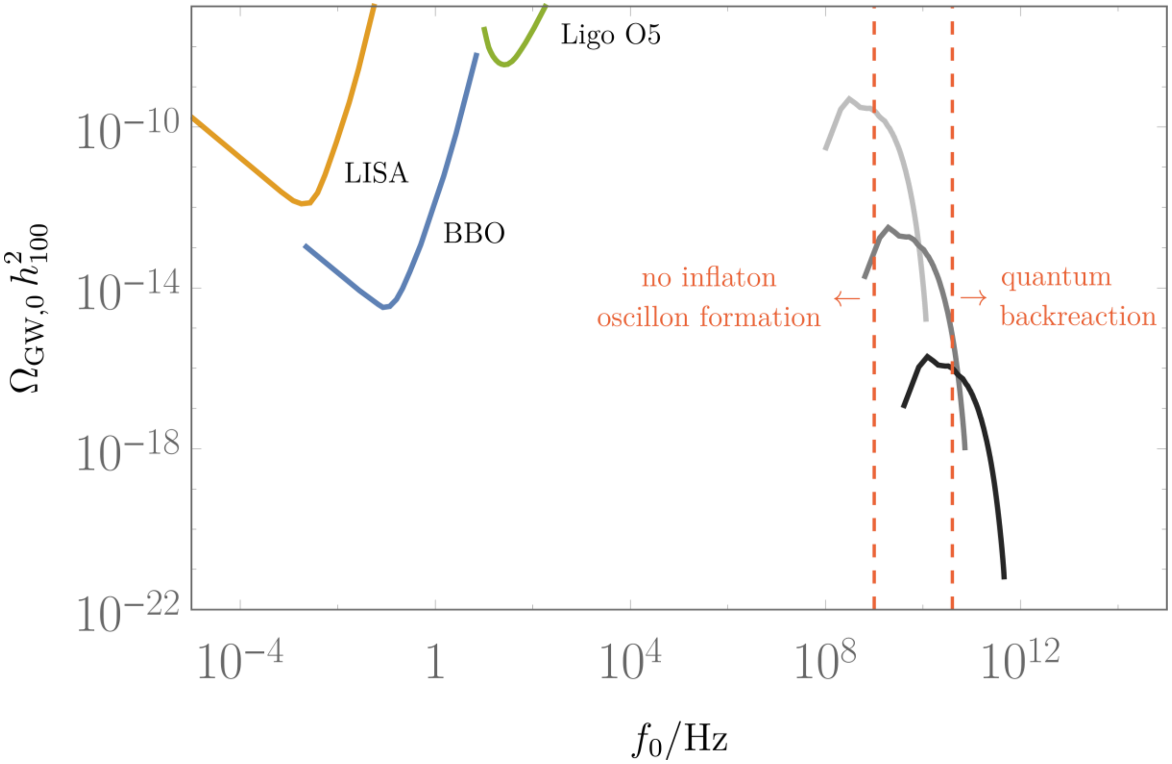
INFLATON oscillons



See also Adshead, Giblin, Pieroni, Weiner (2019a, 2019b)
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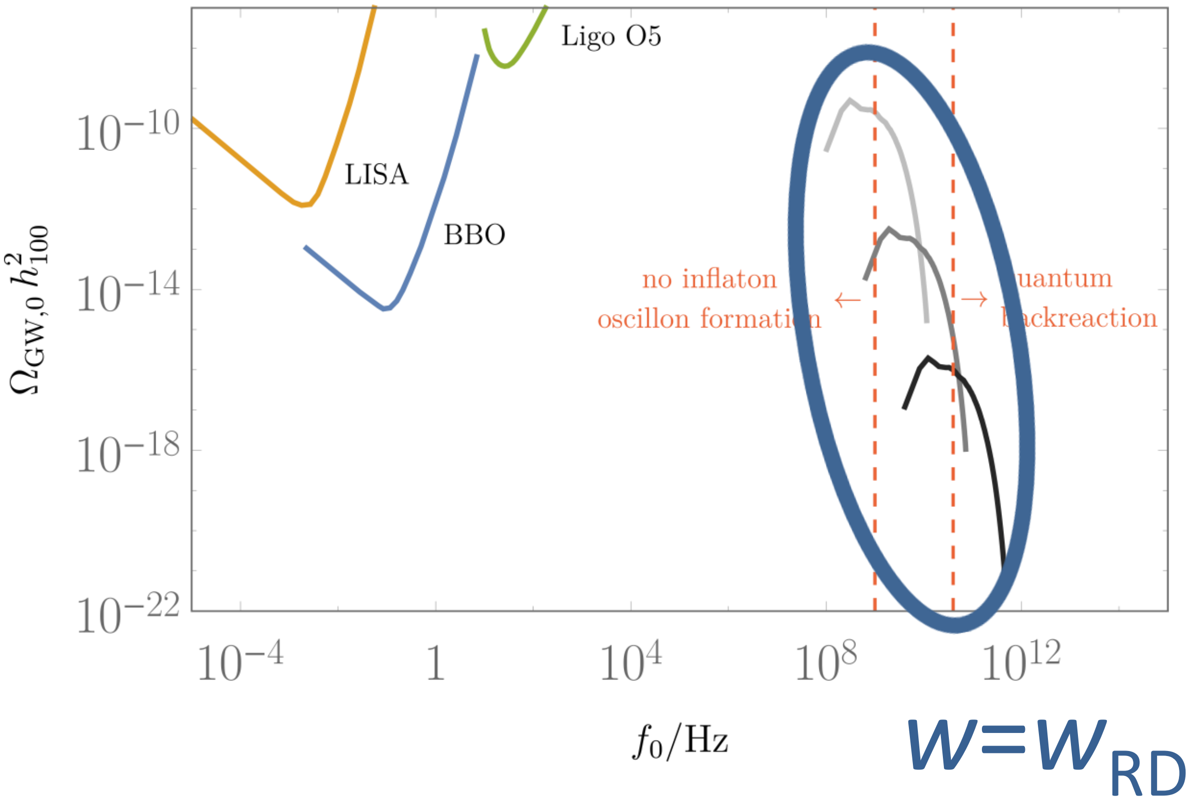

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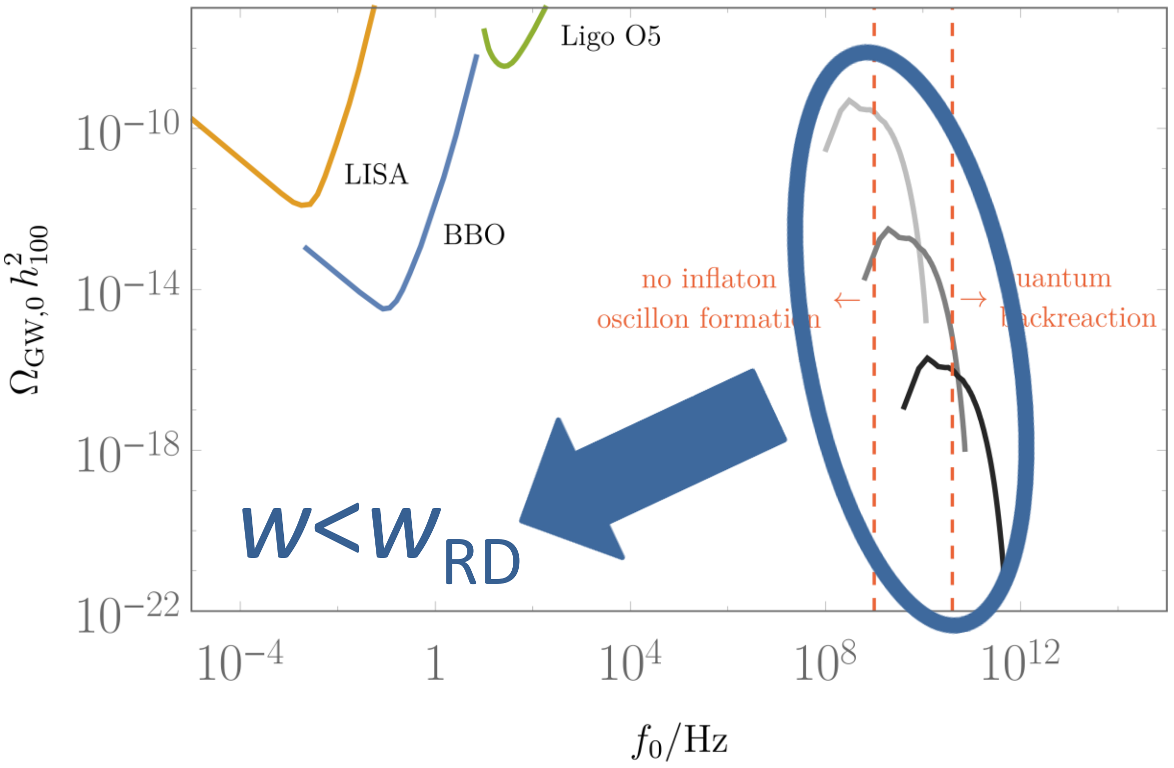

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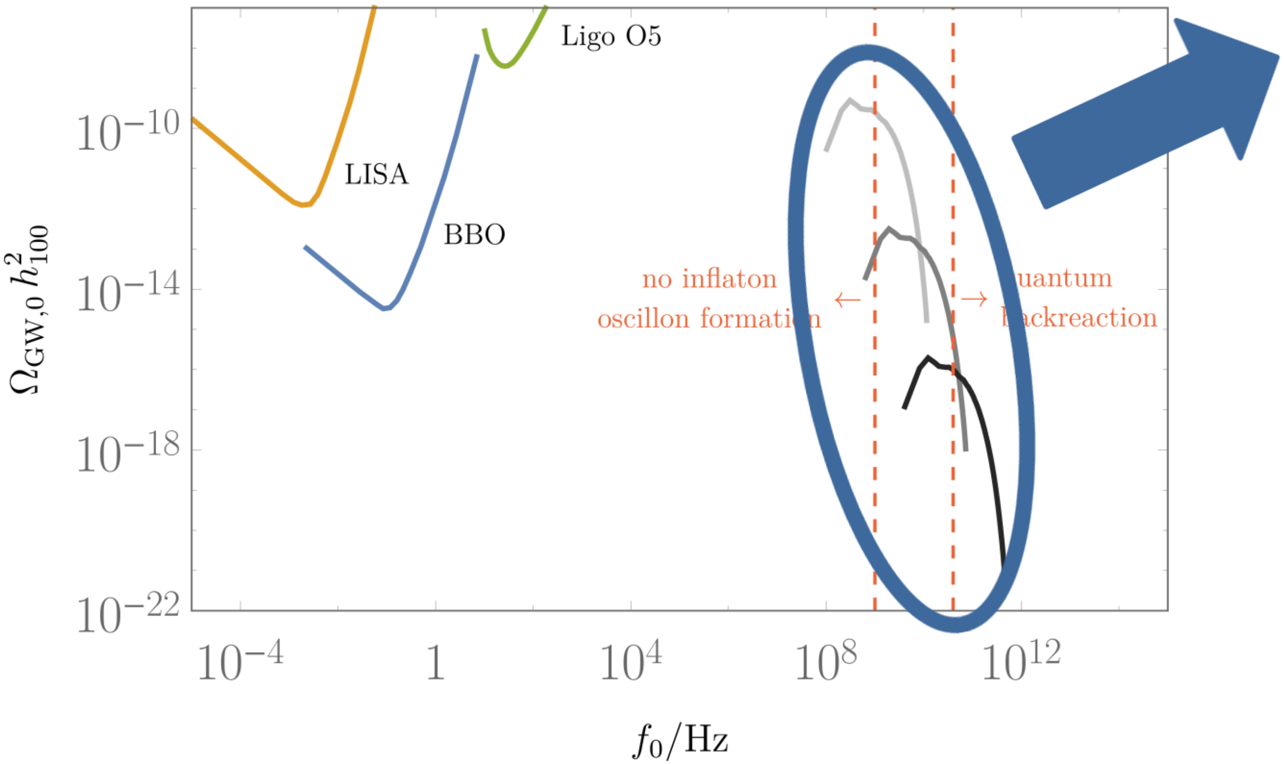

$w>w_{\mathrm{RD}}$

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Other connections …

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- (early) dark energy (n=2)

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Weiner, Adshead, Giblin (2020)
M. Amin, KL and T. Smith (in progress)

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Kusenko and Shaposhnikov (1997)

Other connections …

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- dark matter (n=1 oscillons → Q-balls) Kusenko and Shaposhnikov (1997)
- matter-antimatter asymmetry… KL and M. Amin (2014)

Oscillons & baryogenesis

KL and M. Amin, PRD 90, 083528 (2014)

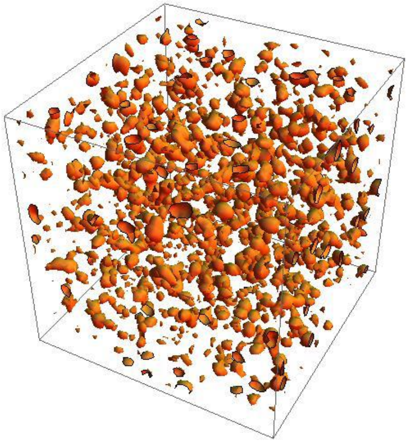
complex
inflaton ϕ
+ ~~U(1)~~

dynamics at the end of inflation

inflaton/anti-inflaton
asymmetry

decay

matter-antimatter
asymmetry
$\eta \approx 6 \times 10^{-10}$



very different dynamics from homogeneous case!

Gauge fields, inflation & reheating

KL and M. Amin, JCAP 1606 032 (2016)

$$S = \int d^4x\sqrt{-g}\Big[\frac{1}{16\pi G}\mathcal{R} - (D_\mu\phi)^\dagger D^\mu\phi - V(|\phi|) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\Big]$$

See also Figueroa, Garcia-Bellido, Torrenti, (2015, 16)

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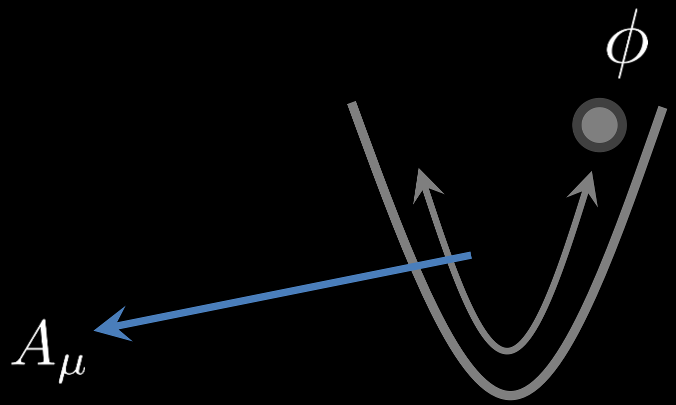

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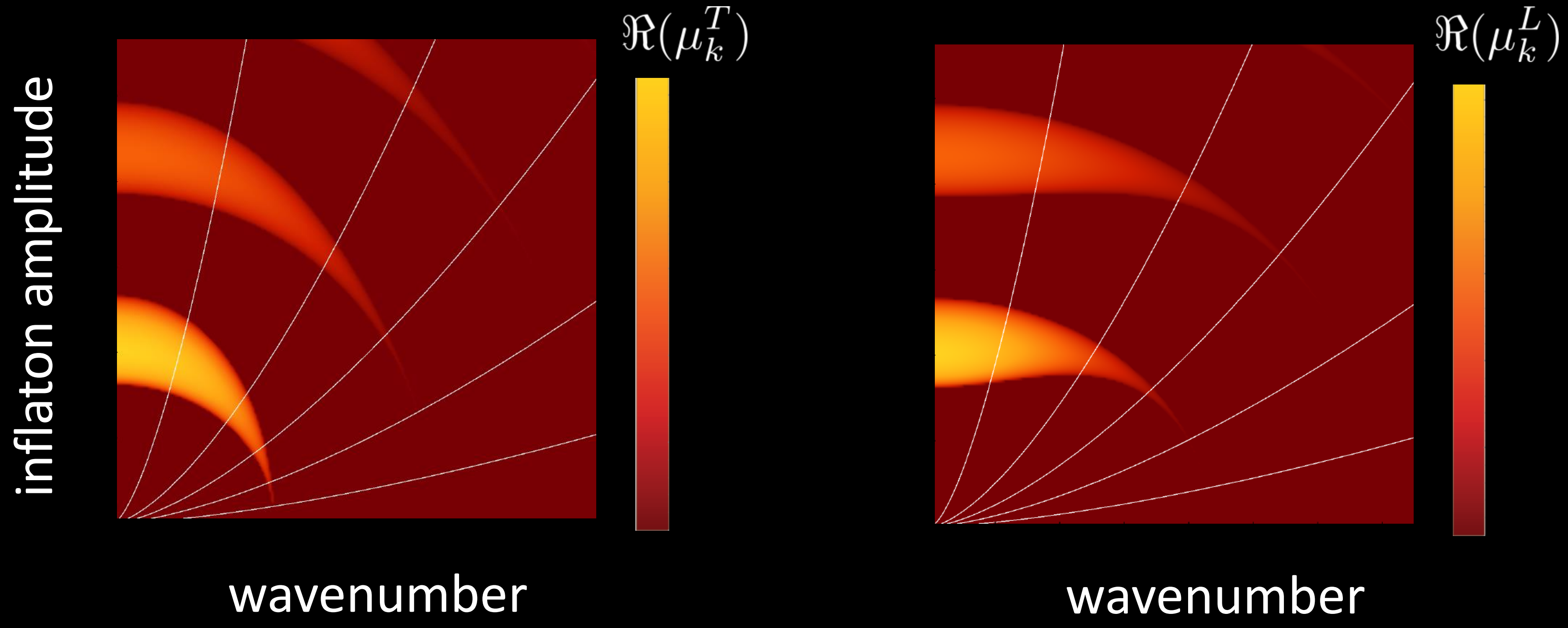
$A_k^T \propto \exp(\pm\mu_k^T t)$ $A_k^L \propto \exp(\pm\mu_k^L t)$



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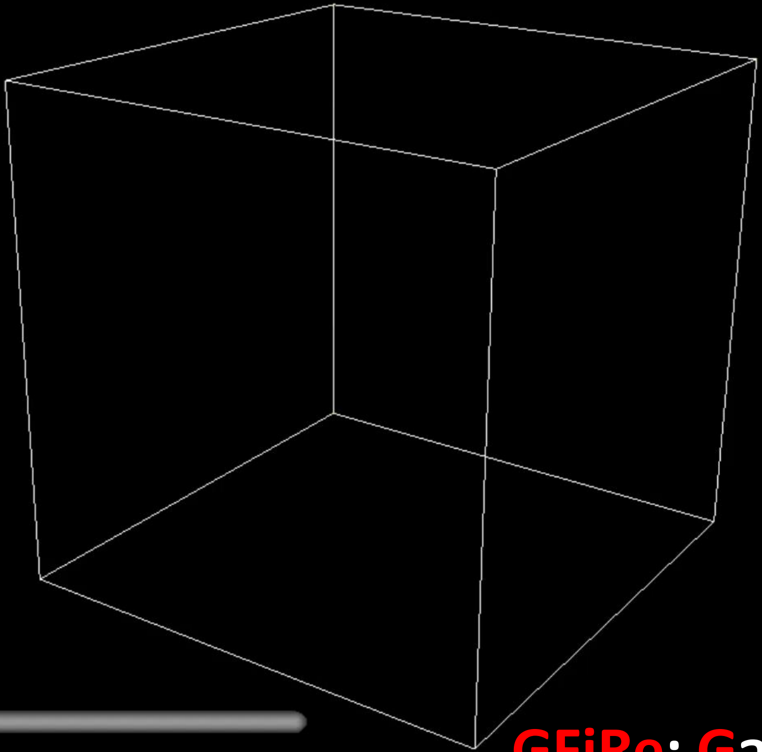
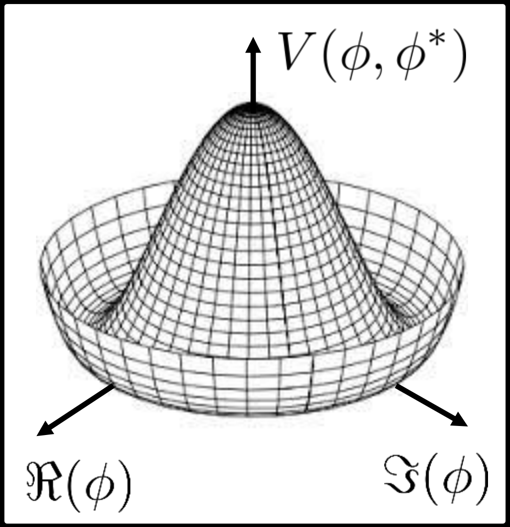
Non-Abelian code in collaboration with M. Amin, A. Caravano, KL, E. Komatsu… (in progress)





Abelian code: KL, M. Amin (2020)

GFiRe: Gauge Field integrator for Reheating

NEW LATTICE CODE!!! JCAP 058 04 (2020)

See also Figueroa, Florio, Torrenti, Valkenburg (2020, 2021)

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Weak δA_μ Backreaction

$\xi \gg 1$

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Linde, Mooij and Pajer (2013)
Garcia-Bellido, Peloso and Unal (2016)
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Lattice theory: Angelo Caravano, Komatsu, KL, Weller (2021a,b, 2022)

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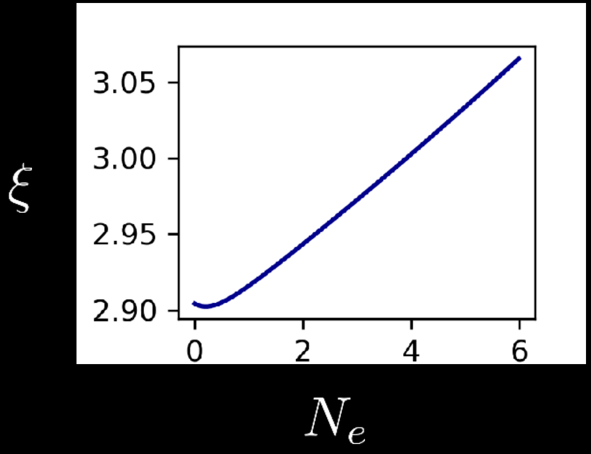

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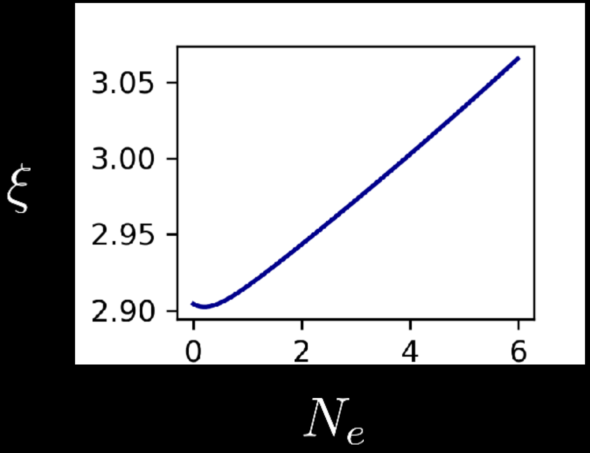

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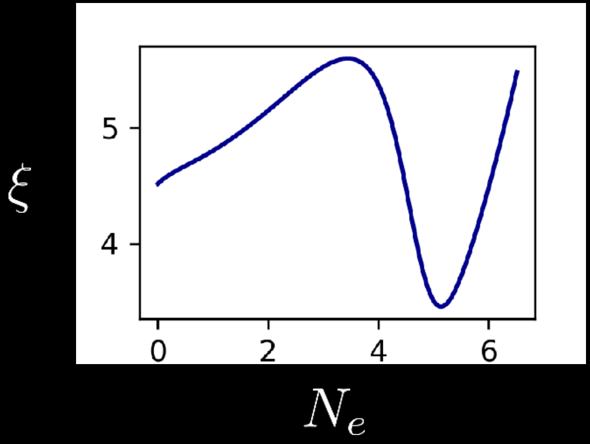

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Weak δA_μ Backreaction

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Strong δA_μ Backreaction

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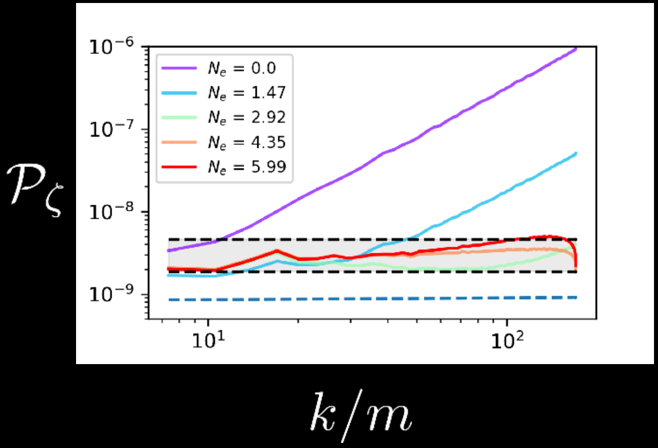

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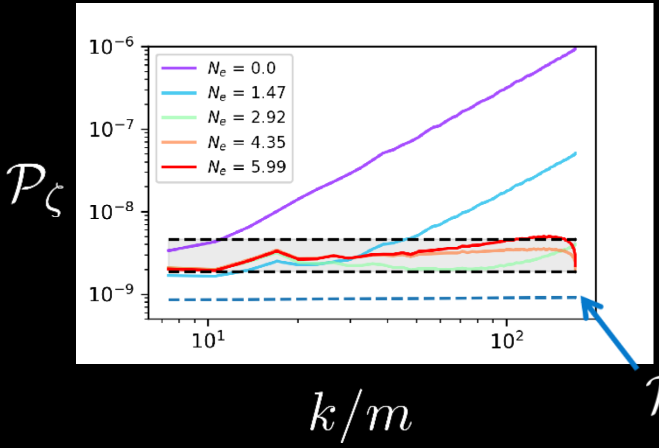

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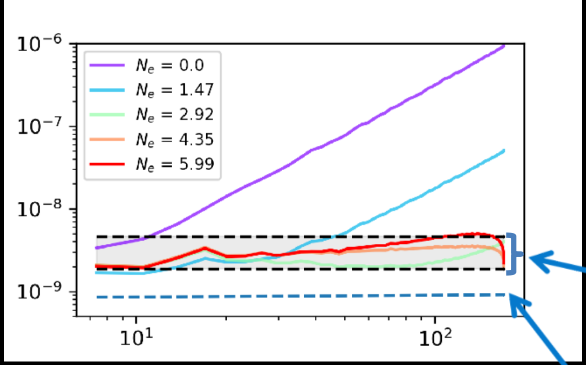

$$\mathcal{P}_\zeta^a = \mathcal{P}_{\rm vac} + \mathcal{P}_{\rm vac}^2 f(\xi)e^{4\pi\xi}$$

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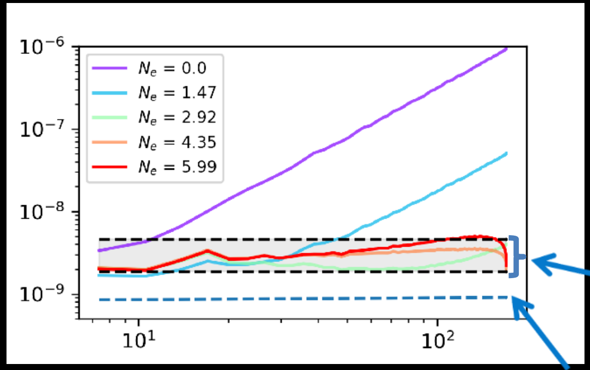

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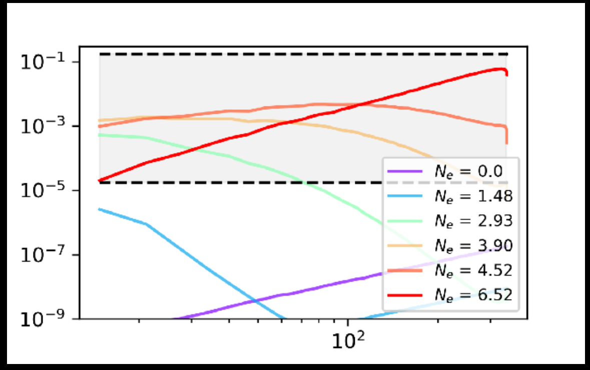

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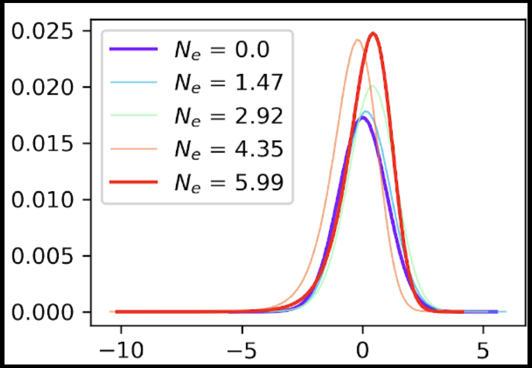

ζ/σ

$\xi \gg 1$

Strong δA_μ Backreaction

$$\sigma^2 = \langle\zeta^2\rangle$$

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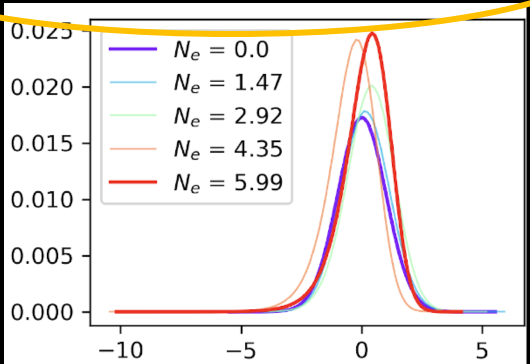

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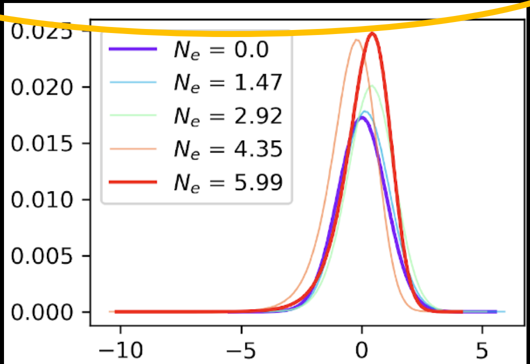

ζ/σ

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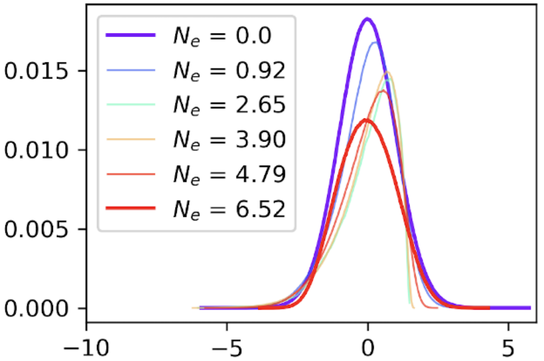

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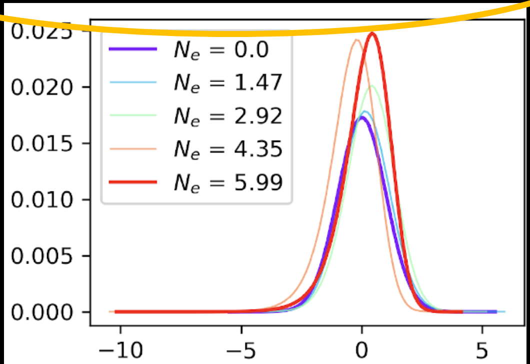

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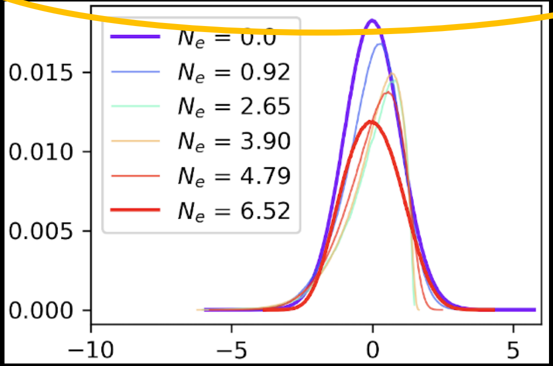

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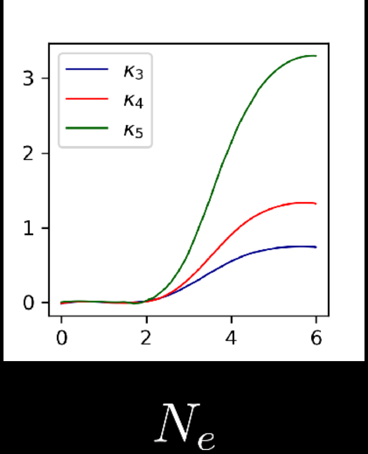

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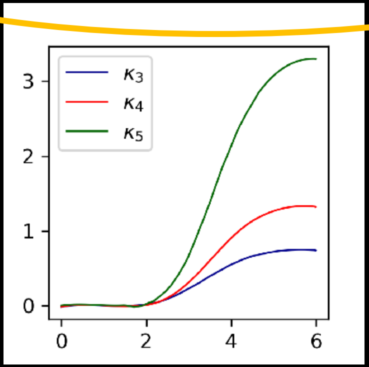

N_e

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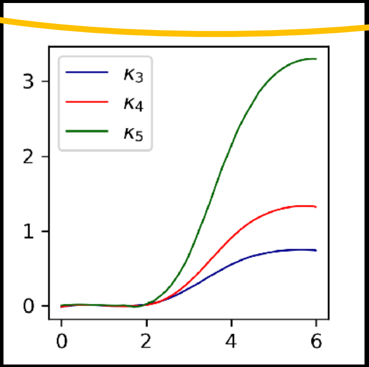

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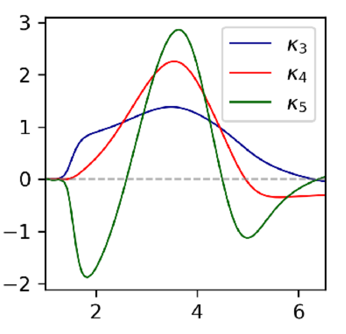

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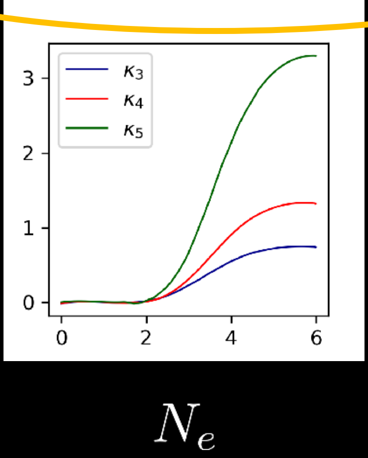

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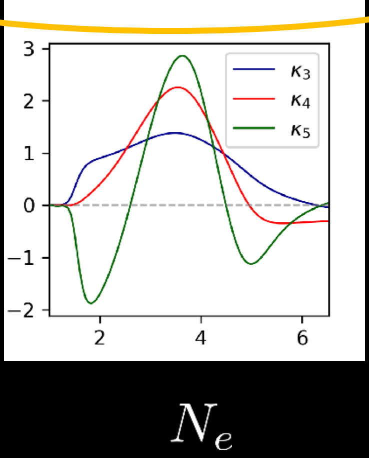

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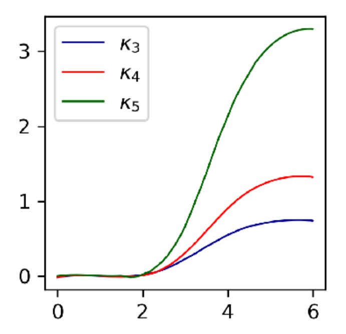

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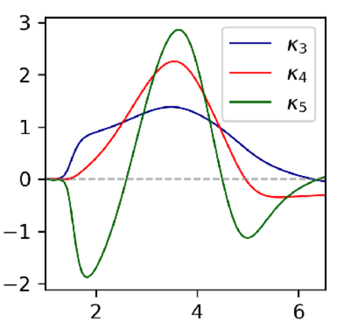

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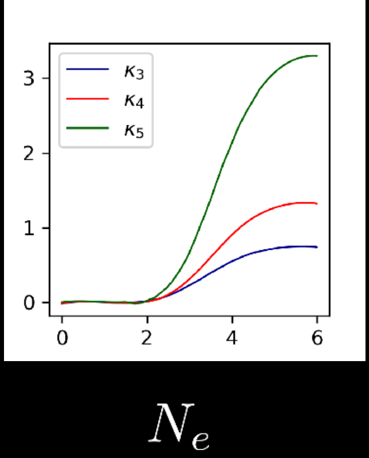
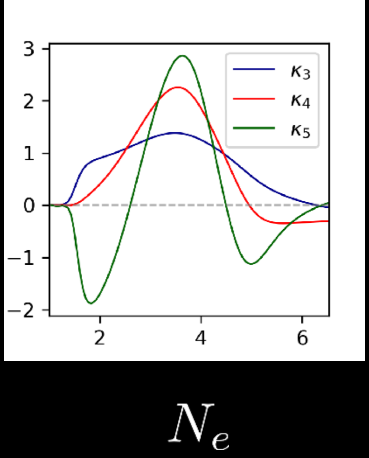


$$\phi''_k + 2\mathcal{H}\phi'_k + k^2\phi_k = a^2\frac{\alpha}{4f}\int d^3q\, F_{\mu\nu q}\tilde{F}^{\mu\nu}_{k-q}$$



Gauge fields, inflation & reheating

Anber and Sorbo (2010), Barnaby and Peloso (2011)
Angelo Caravano, Komatsu, KL, Weller (2021a,b, 2022)

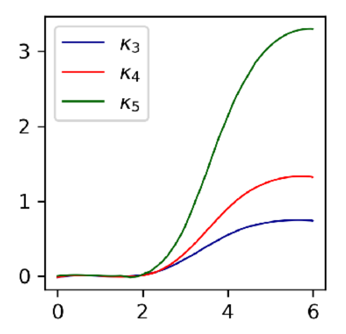
$$S = \int d^4x\sqrt{-g}\Big[\frac{1}{16\pi G}\mathcal{R} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha\phi}{4f}F_{\mu\nu}\tilde{F}^{\mu\nu}\Big]$$

Axion inflaton: $\phi(\mathbf{x},t) = \overline{\phi}(t) + \delta\phi(\mathbf{x},t)$

$$\xi = \alpha\dot{\overline{\phi}}/(2fH)\,, \quad \zeta = -H\delta\phi/\dot{\overline{\phi}}$$

$\xi \gtrsim 1$

Weak δA_μ Backreaction



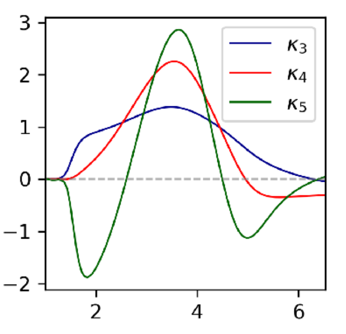
N_e

$$\phi_k'' + 2\mathcal{H}\phi_k' + k^2\phi_k = a^2\frac{\alpha}{4f}\int d^3q\, F_{\mu\nu q}\tilde{F}^{\mu\nu}_{k-q}$$

$$q/\mathcal{H} \lesssim \xi$$

$\xi \gg 1$

Strong δA_μ Backreaction



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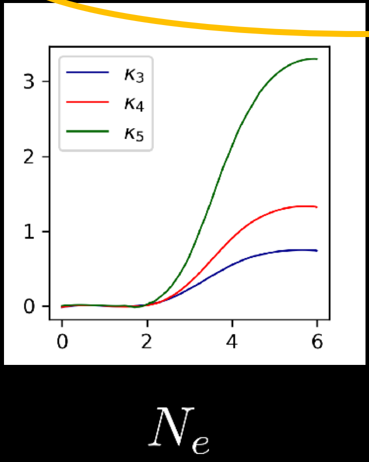
Axion inflaton: $\phi(\mathbf{x},t)=\bar{\phi}(t)+\delta\phi(\mathbf{x},t)$

$$\xi=\alpha\dot{\bar{\phi}}/(2fH)\,,\quad \zeta=-H\delta\phi/\dot{\bar{\phi}}$$

$\xi\gtrsim 1$ **non-Gaussianity**

Weak δA_μ Backreaction



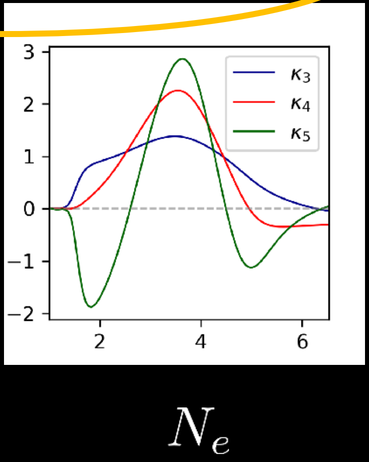
$$\phi_k''+2\mathcal{H}\phi_k'+k^2\phi_k=a^2\frac{\alpha}{4f}\int d^3q\,F_{\mu\nu q}\tilde{F}^{\mu\nu}_{k-q}$$

$$q/\mathcal{H}\lesssim\xi$$

$\xi\gg 1$ **Gaussianity!**

Strong δA_μ Backreaction

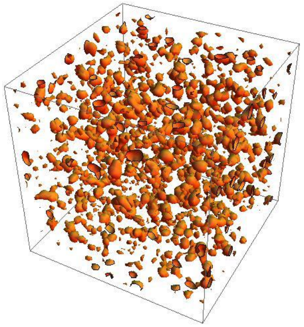
CLT



Conclusions

Reheating at the end of inflation:

- very rich dynamics



Future plans:

- more realistic models (e.g. gauge fields)

- observational signatures
  -expansion history, relics, GWs