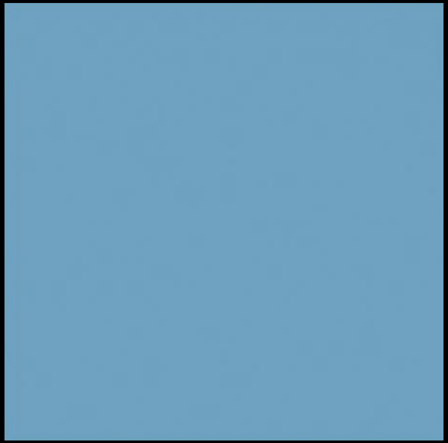

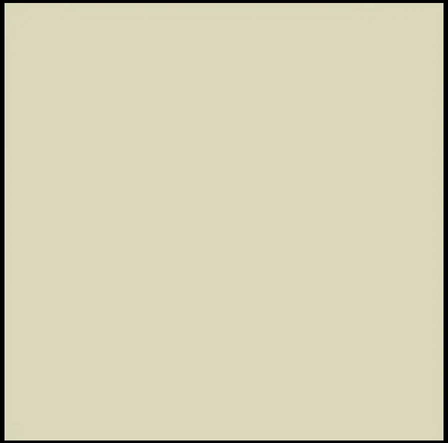

The equation of state after Inflation

Kaloian Lozanov

MPA, Physical Cosmology Group

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Astrophysik

Collaborators: Eiichiro Komatsu, Mustafa Amin, Azadeh Maleknejad, Leila Mirzagoli, Matt Reece, Jiji Fan

Outline

1.) The equation of state after inflation **KL** and M. Amin (2016,17,19)

2.) Oscillons and baryogenesis **KL** and M. Amin (2014)

3.) Gauge fields, inflation and reheating **KL** and M. Amin (2016)
KL, A. Maleknejad and E. Komatsu (2018)
L. Mirzagoli, A. Maleknejad and **KL** (2019)

4.) Cosmology of fine-tuning (in particle physics)
M. Amin, J. Fan, **KL** and M. Reece (2019)

The equation of state after inflation

KL and M. Amin, arXiv:1902.06736
KL and M. Amin, PRD 97 023533 (2017)
KL and M. Amin, PRL 119 061301 (2016)

What is w after inflation?

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

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

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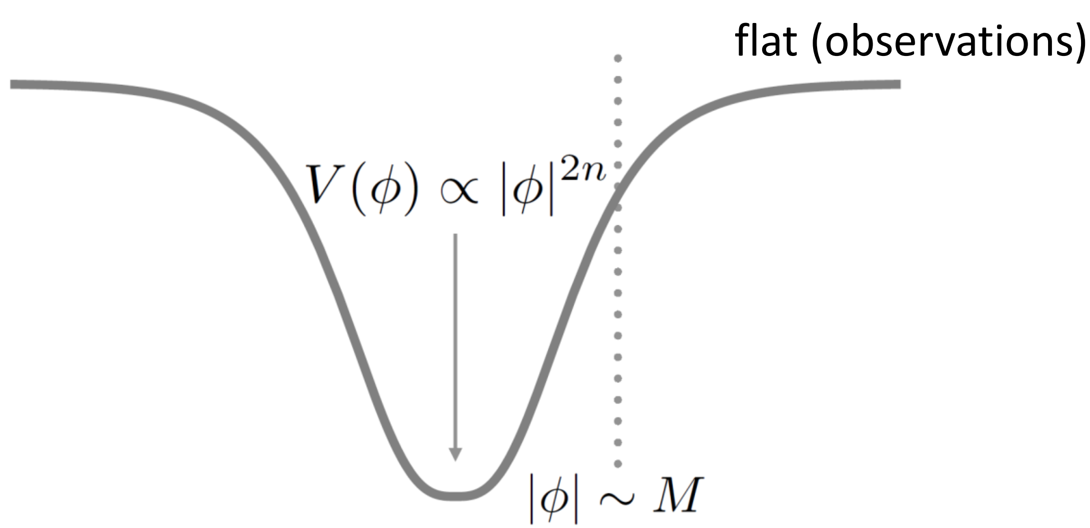

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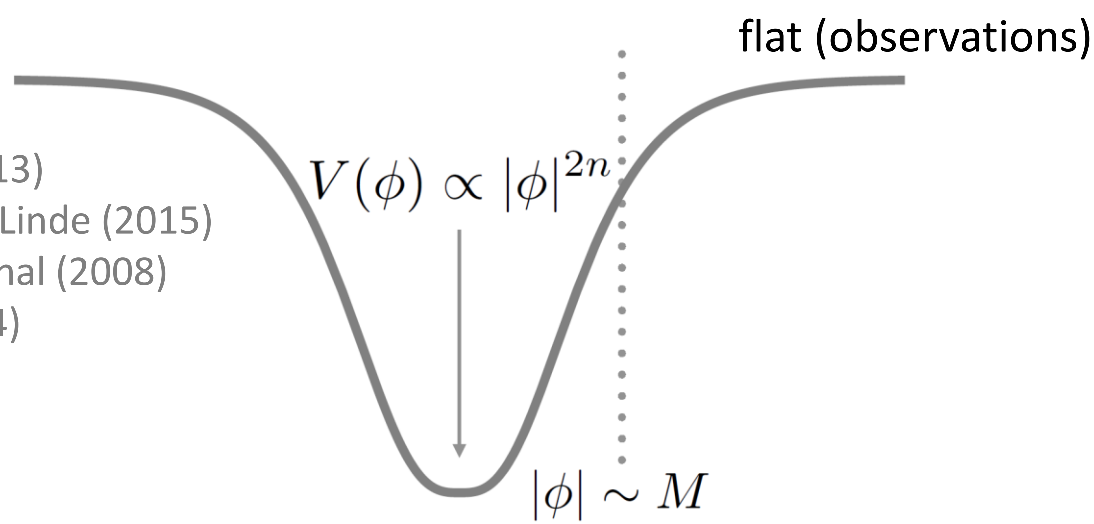

Kallosh and Linde (2013)
Carrasco, Kallosh and Linde (2015)
Silverstein and Westphal (2008)
McAllister, et al. (2014)

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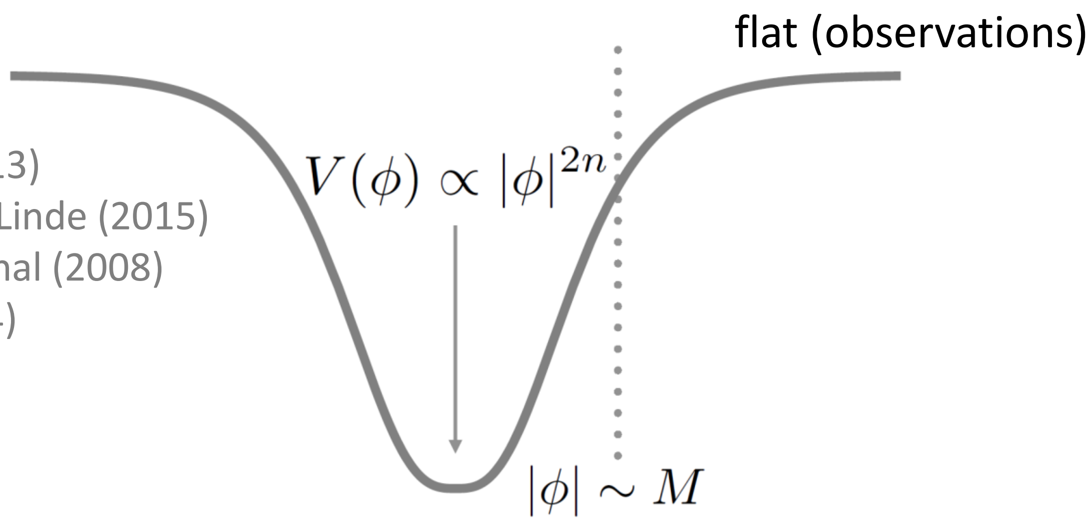


Kallosh and Linde (2013)
Carrasco, Kallosh and Linde (2015)
Silverstein and Westphal (2008)
McAllister, et al. (2014)

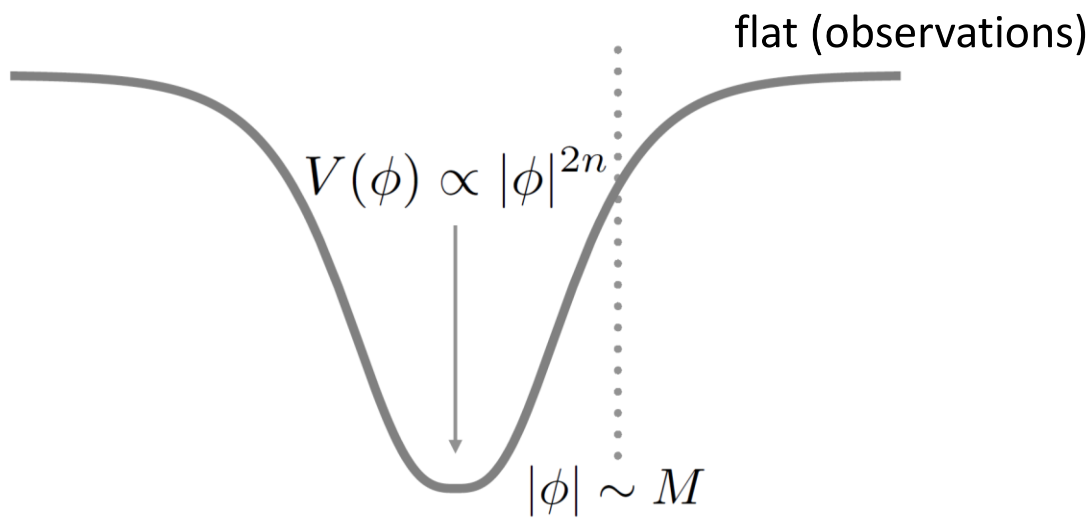
assumption: self-couplings dominate over others

What is w after inflation?

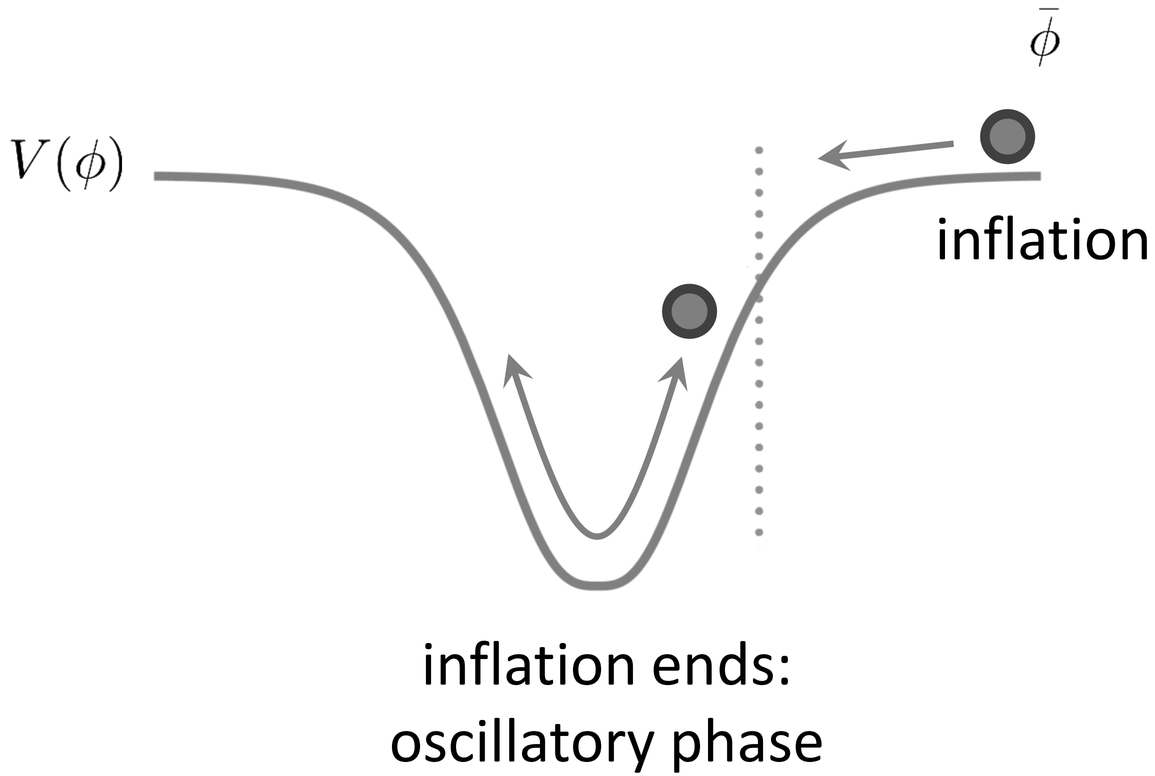
at sufficiently late times:

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

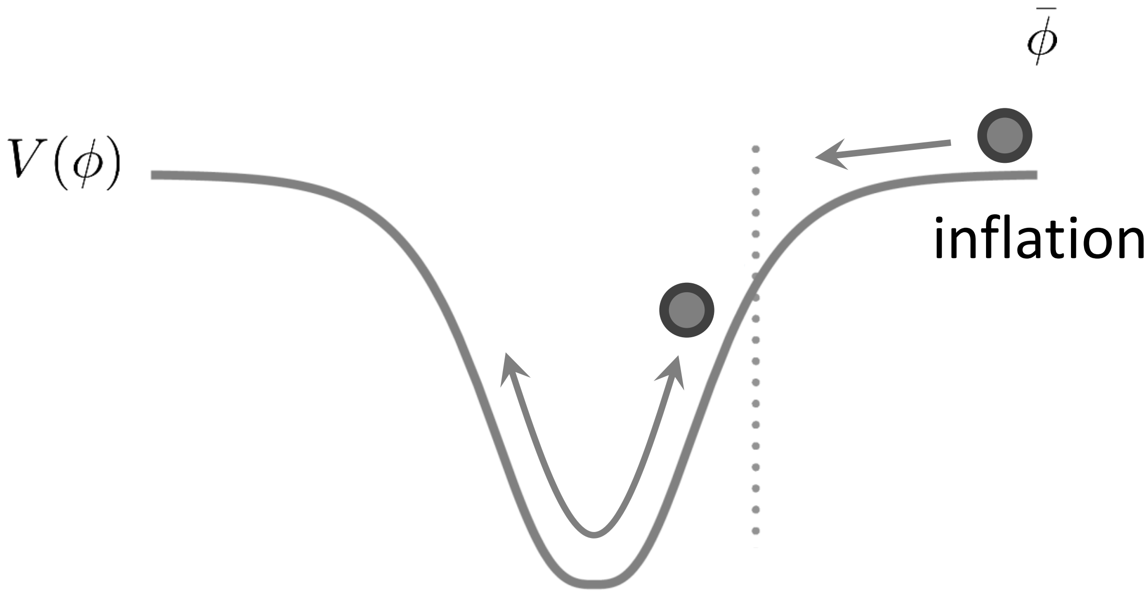
(even without couplings to other fields!)



Inflaton dynamics



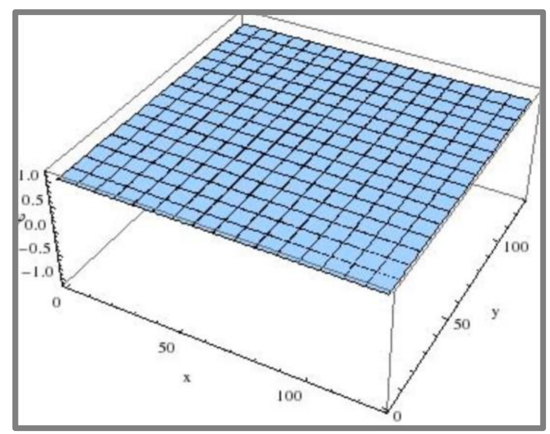
Inflaton (homogeneous) dynamics



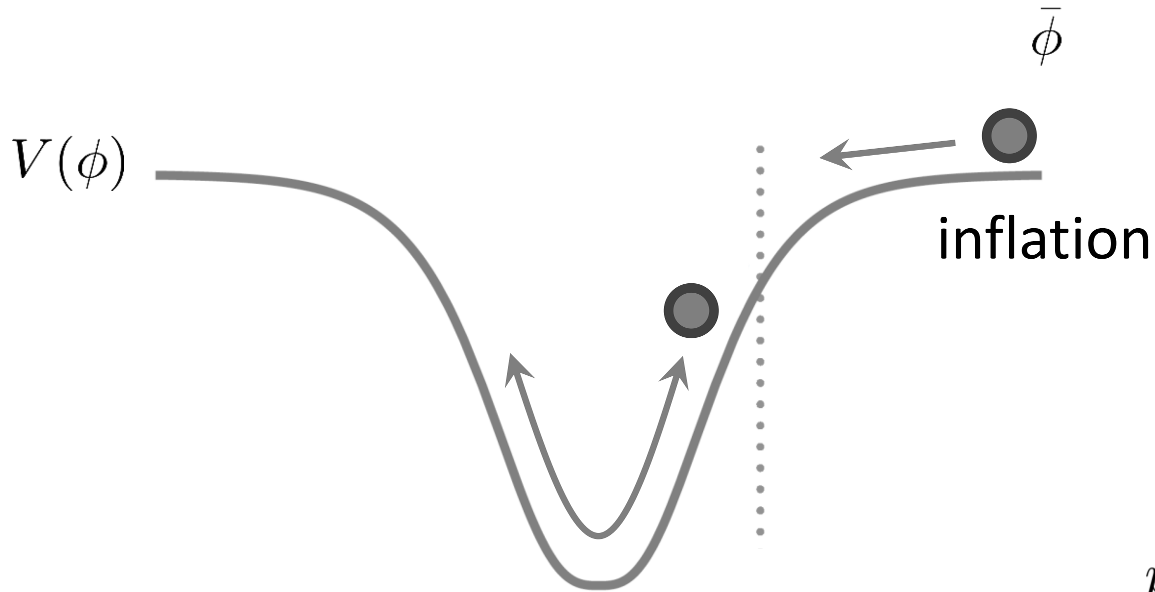
inflation ends:
oscillatory phase

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

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



Inflaton (homogeneous) dynamics

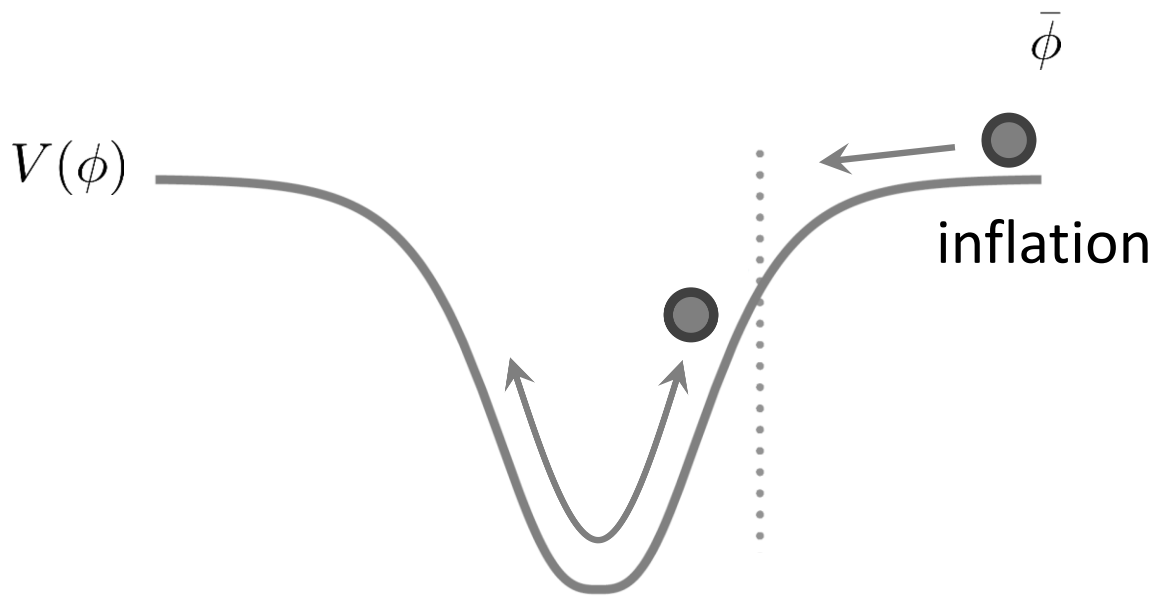


$$w \equiv \frac{p}{\rho} = \frac{\dot{\phi}^2/2 - (\nabla\phi)^2/6 - V(\phi)}{\dot{\phi}^2/2 + (\nabla\phi)^2/2 + V(\phi)}$$

inflation ends:
oscillatory phase

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

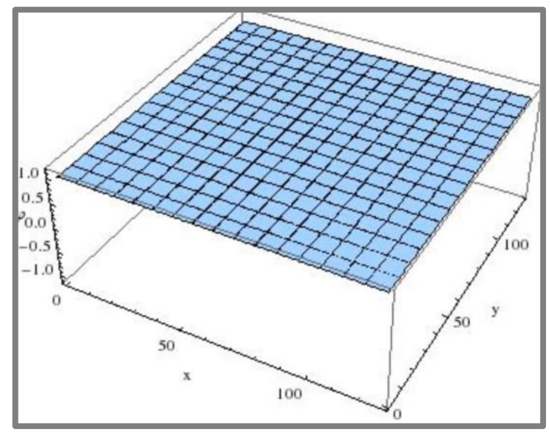
Inflaton (homogeneous) dynamics



inflation ends:
oscillatory phase

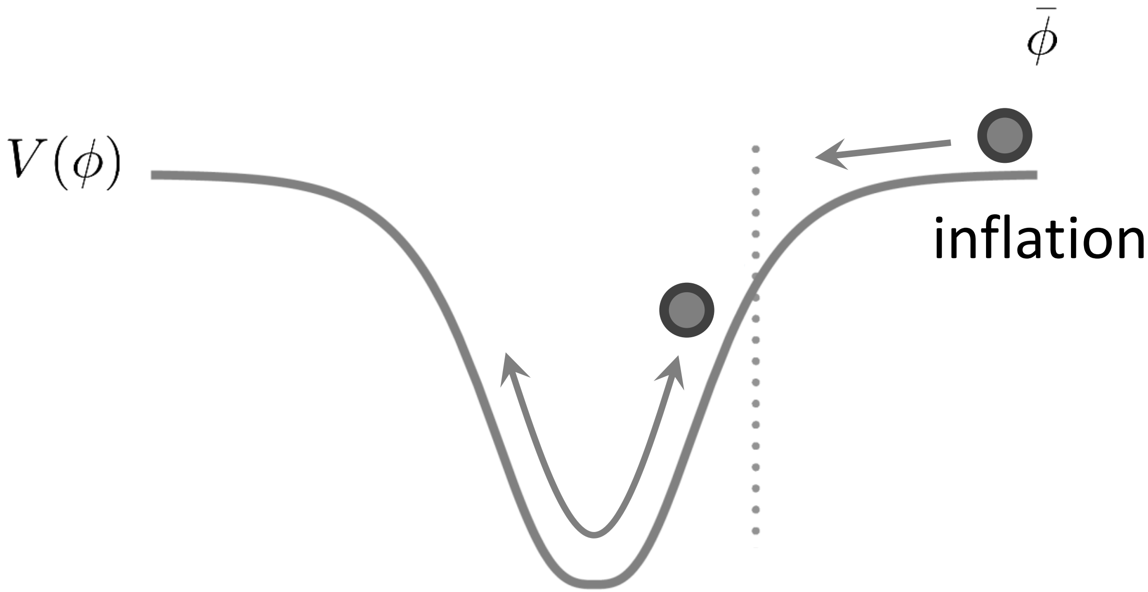
$$w_{\rm hom} = \frac{n-1}{n+1}$$

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



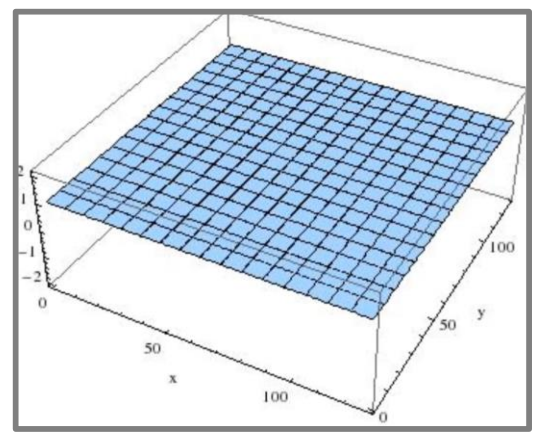
Turner (1983)

Inflaton (actual) dynamics



inflation ends:
oscillatory phase

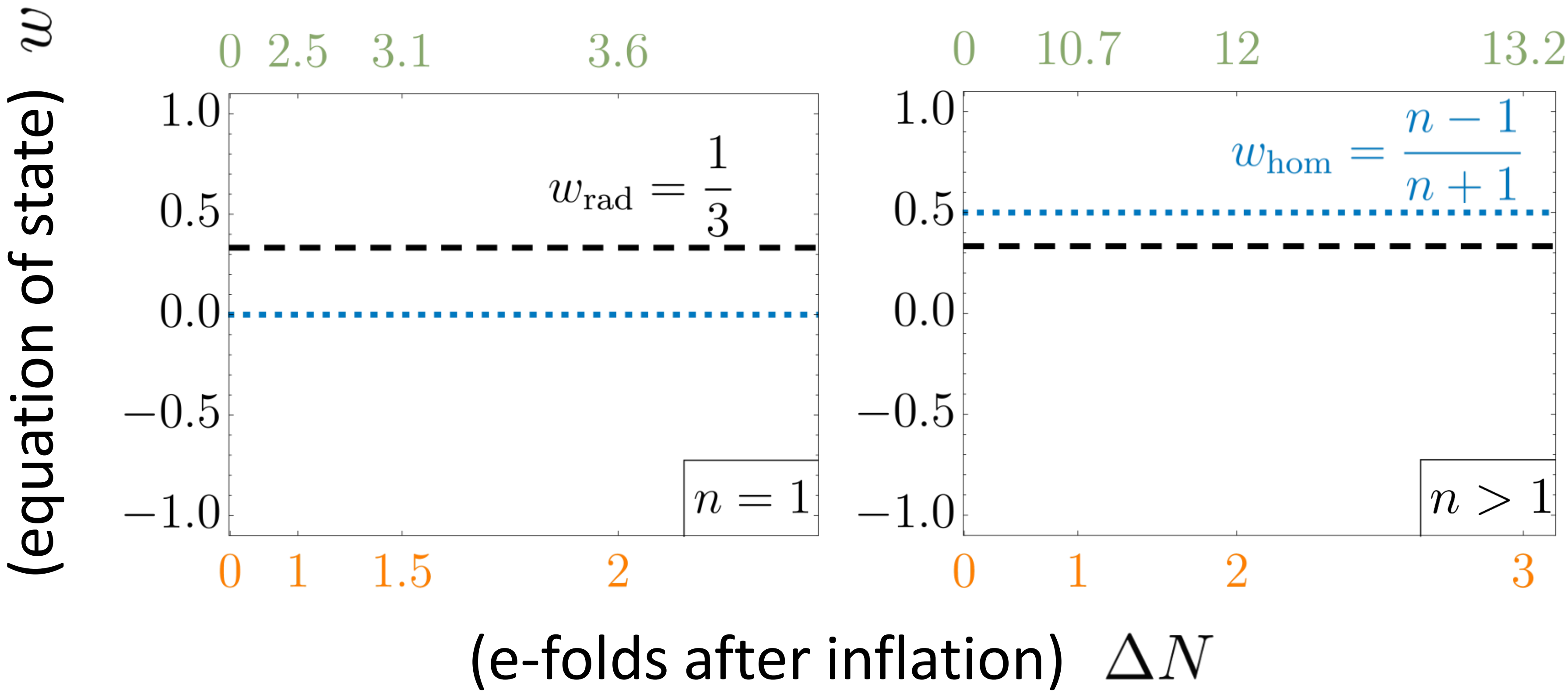
$\phi \times a^{3/(n+1)}$



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

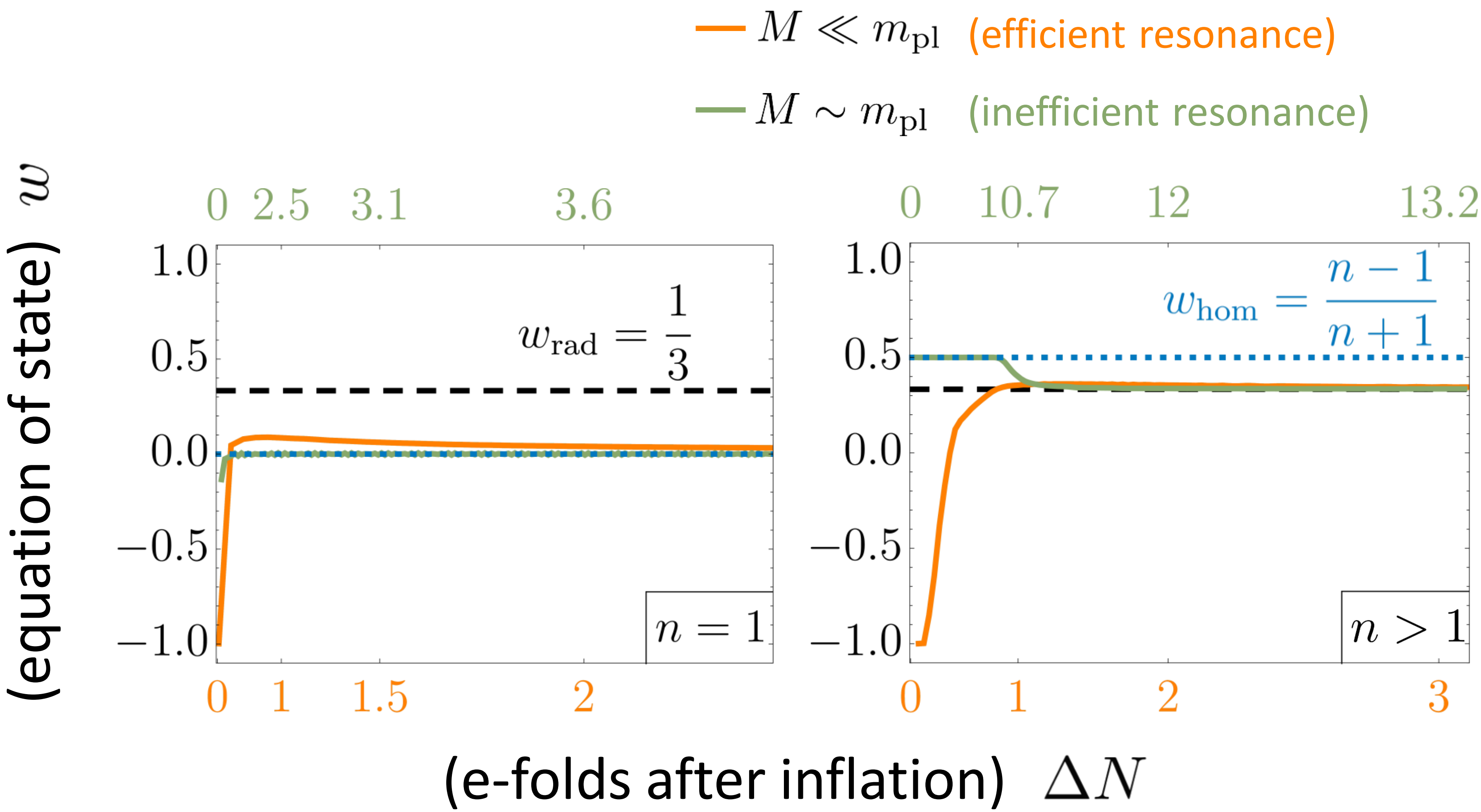
KL and M. Amin (2016)
KL and M. Amin (2017)

Equation of state



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

Equation of state



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

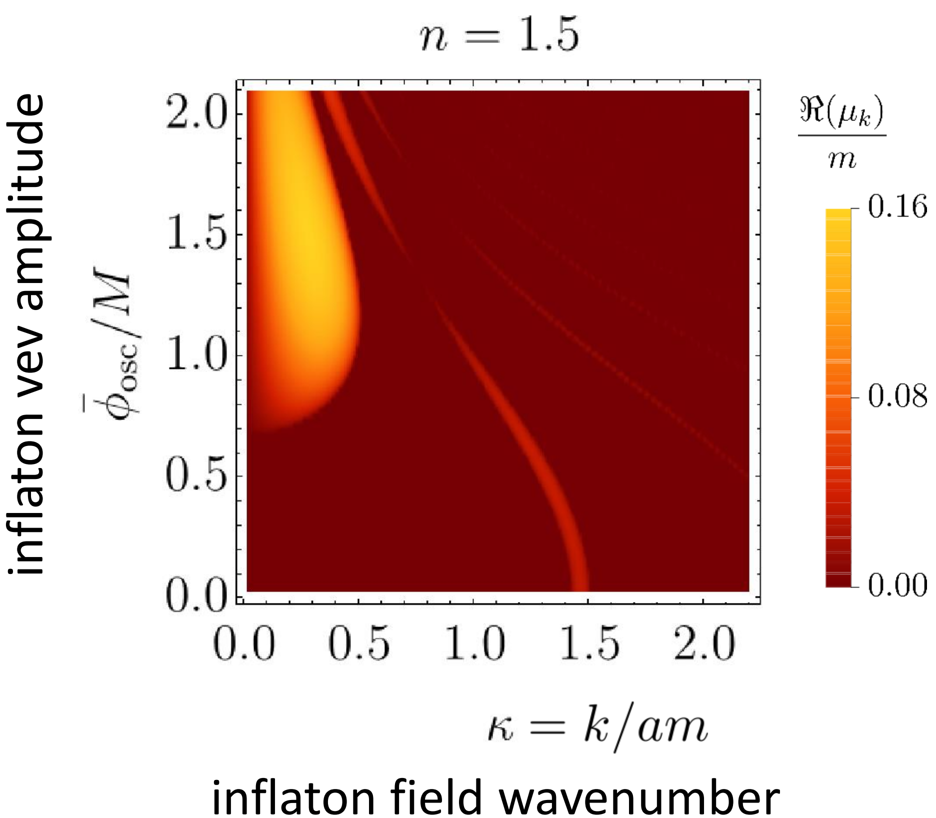
Towards radiation domination

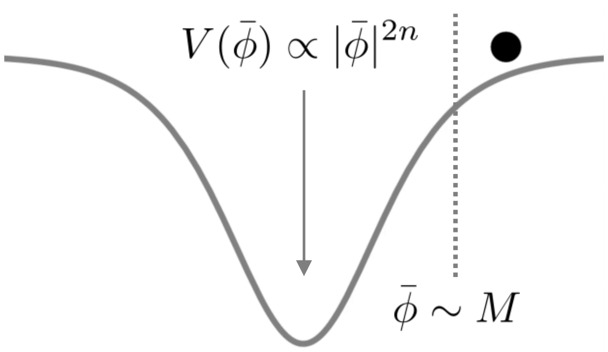
$$n > 1$$

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)





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

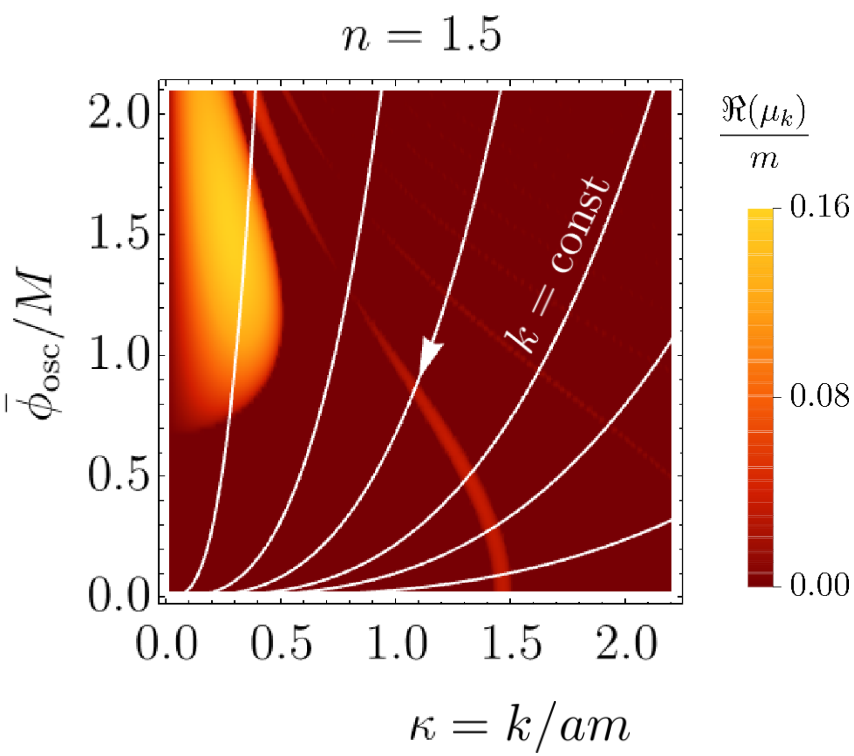
$m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$

Towards radiation domination

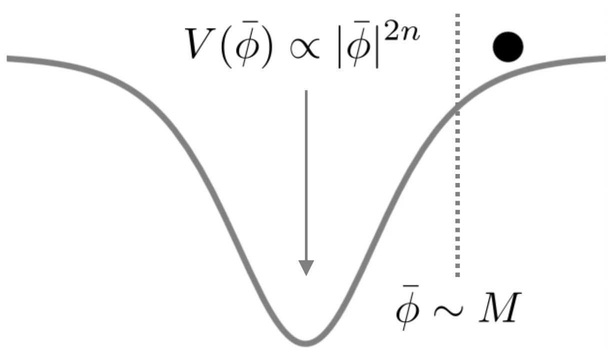
$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



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Towards radiation domination

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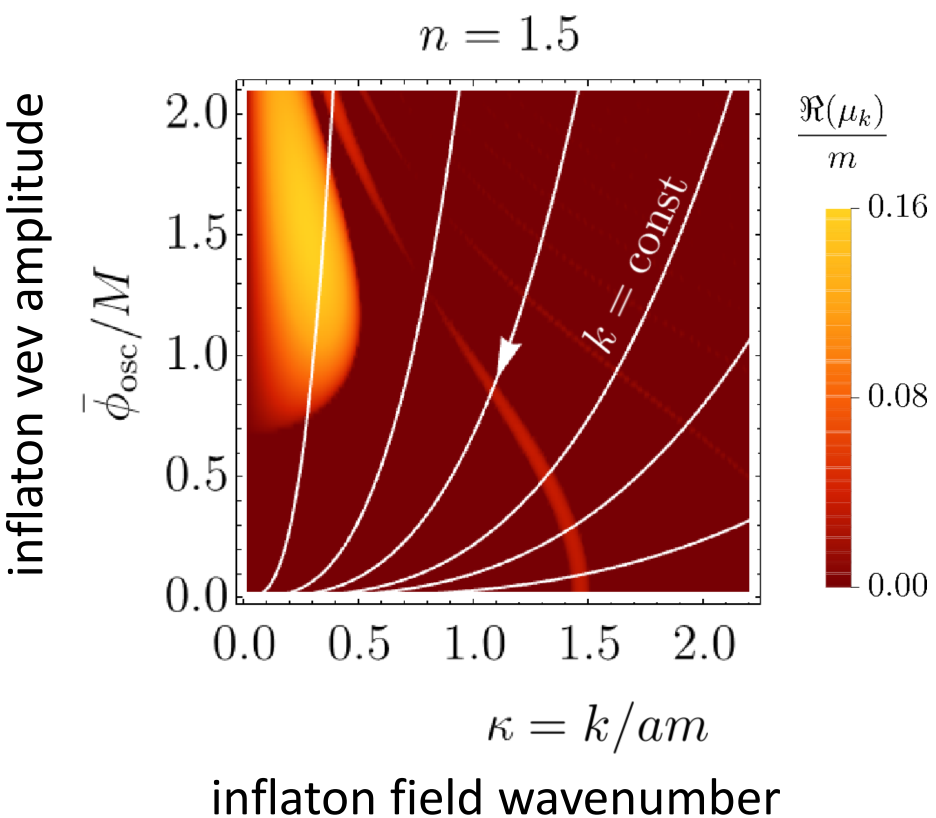

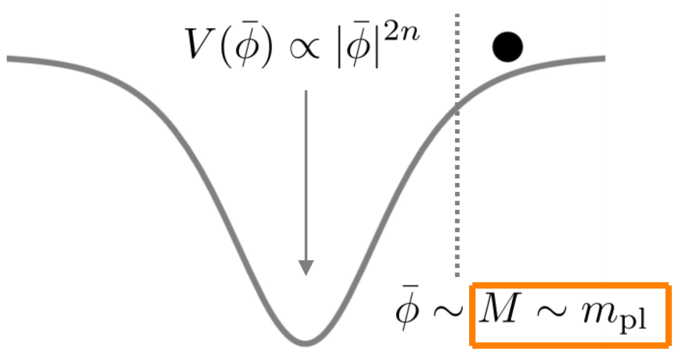

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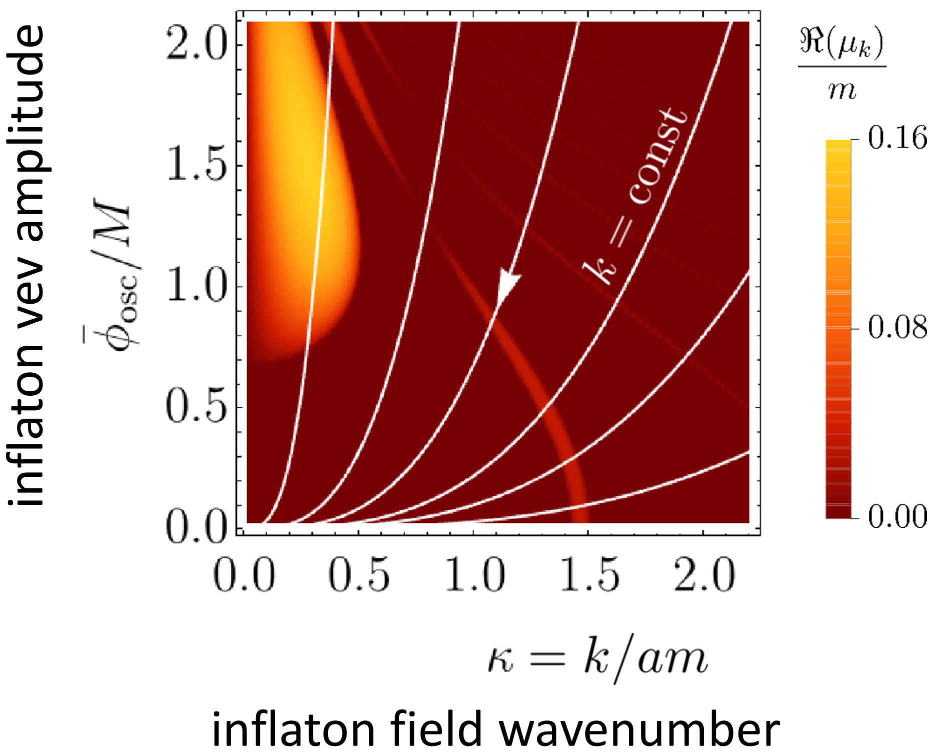
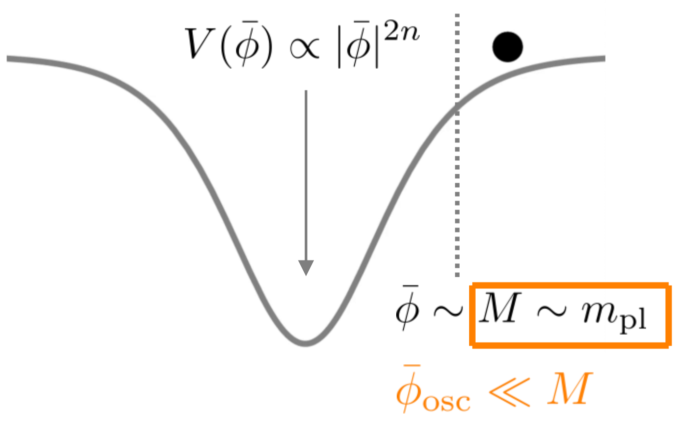
Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

$n = 1.5$





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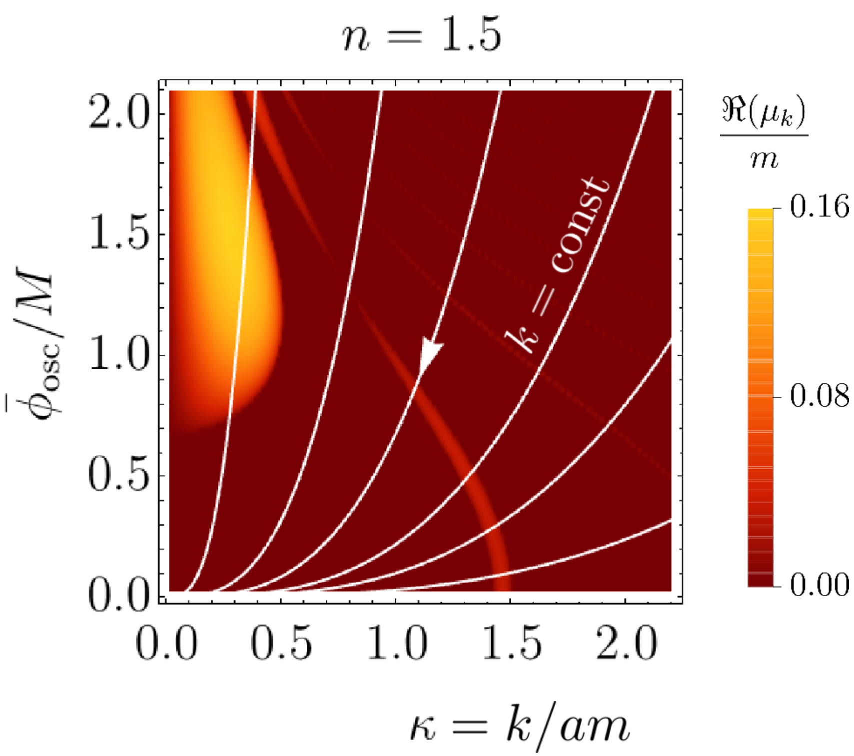
Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

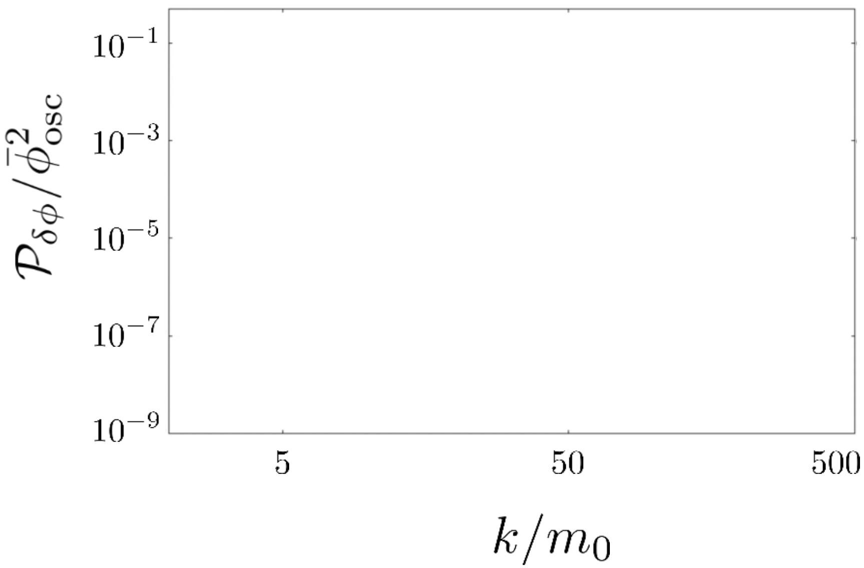
inflaton vev amplitude



inflaton field wavenumber

Power spectrum:

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

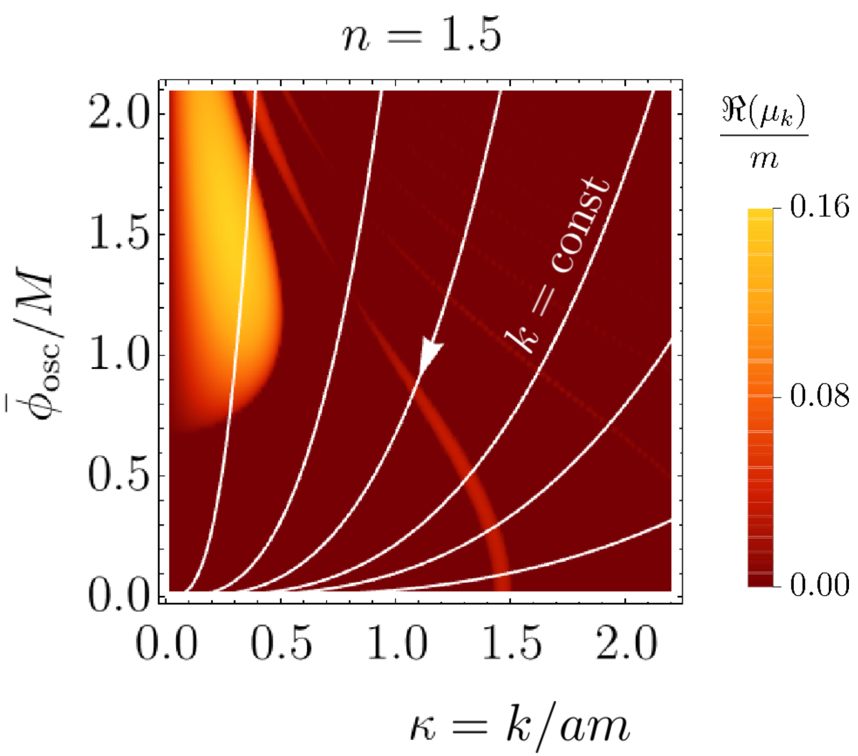


comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)



inflaton vev amplitude

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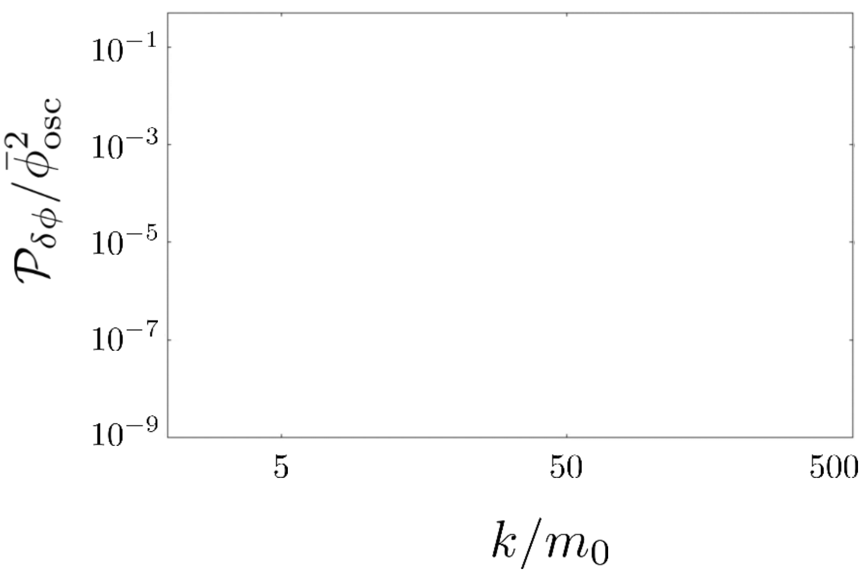


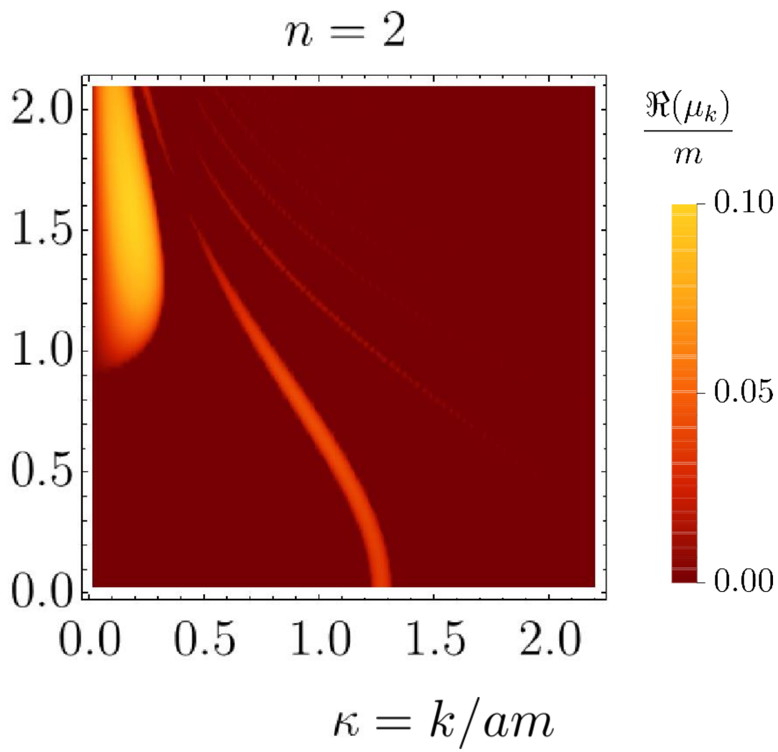
comoving wavenumber

Towards radiation domination

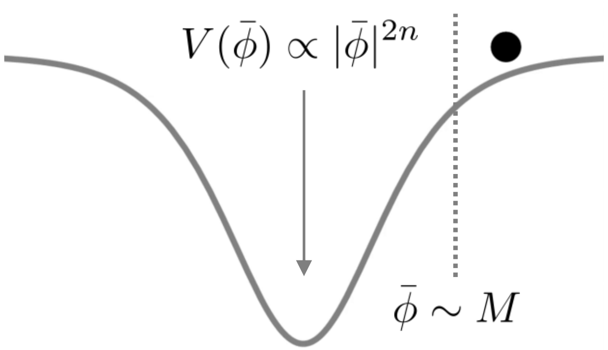
$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



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

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Towards radiation domination

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Non-perturbative decay (parametric self-resonance)

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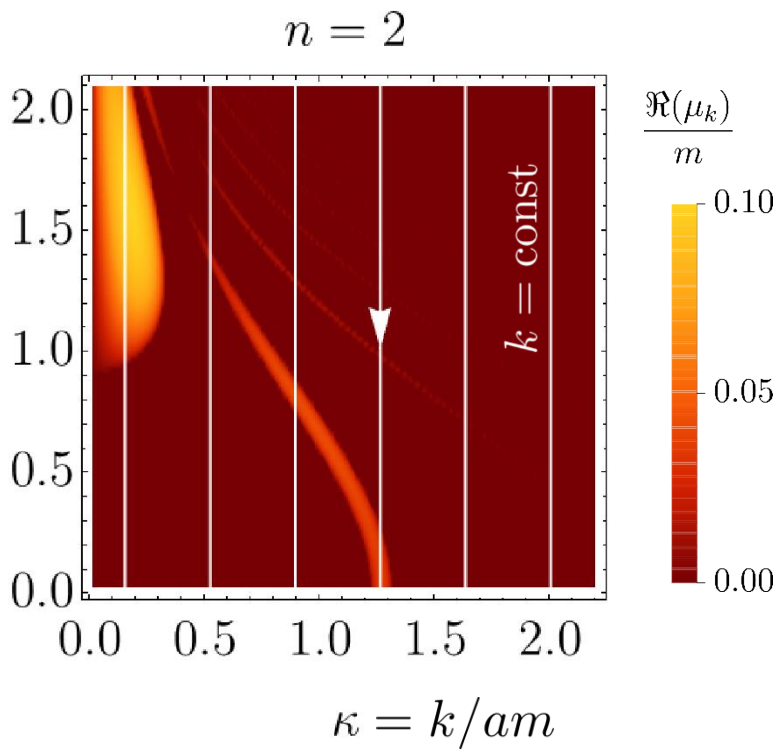

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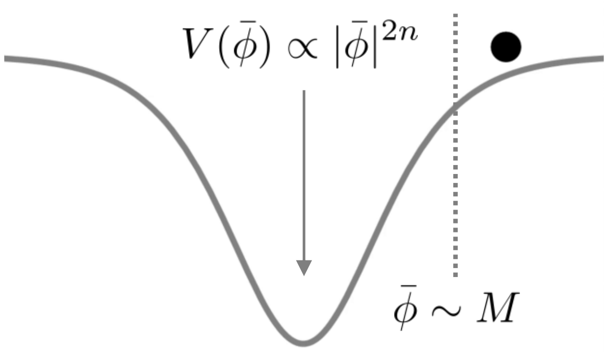

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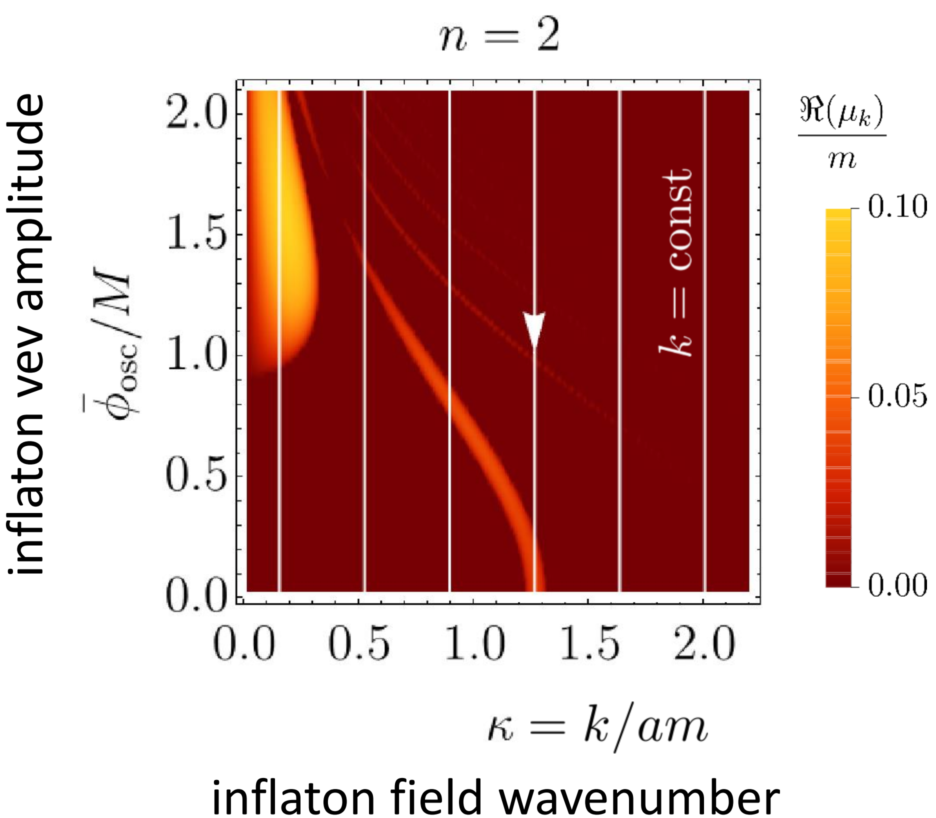

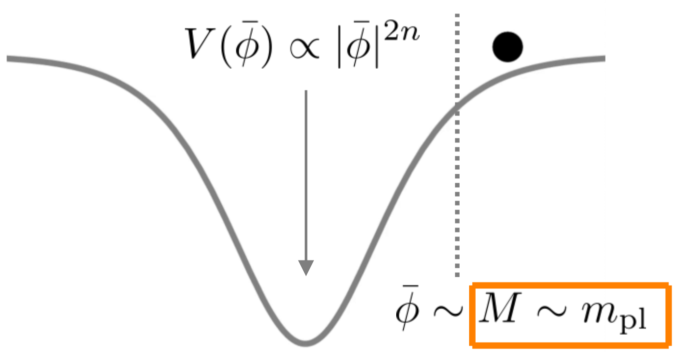

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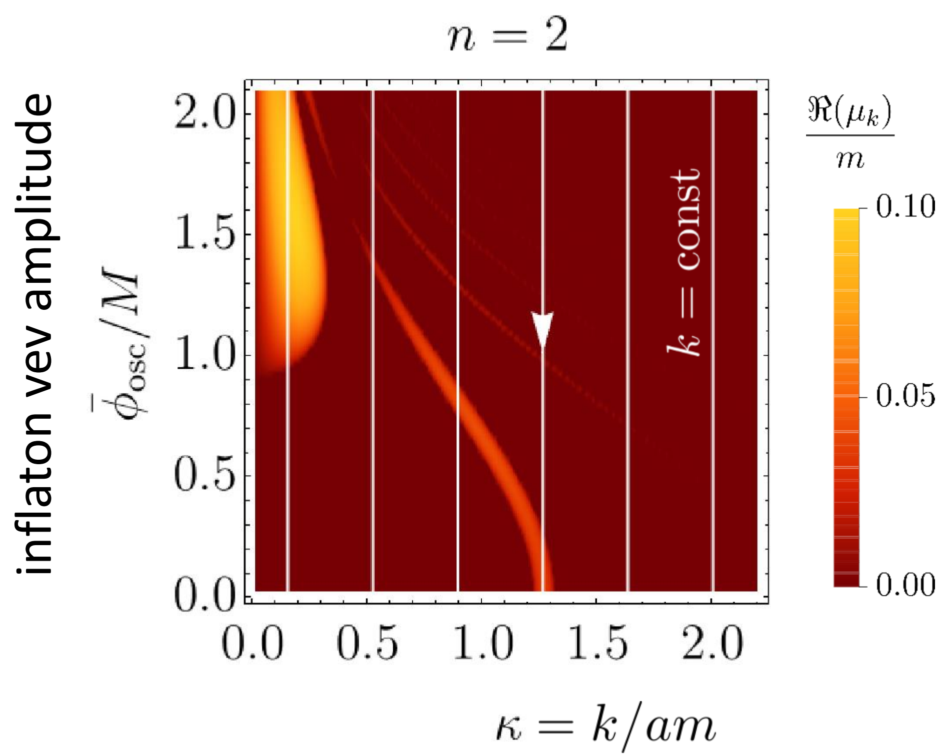
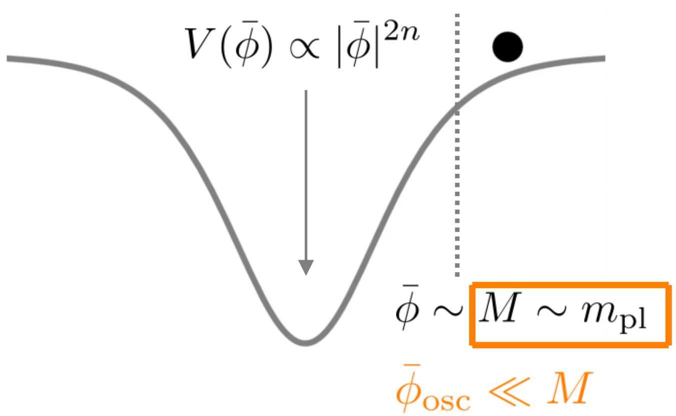


inflaton field wavenumber



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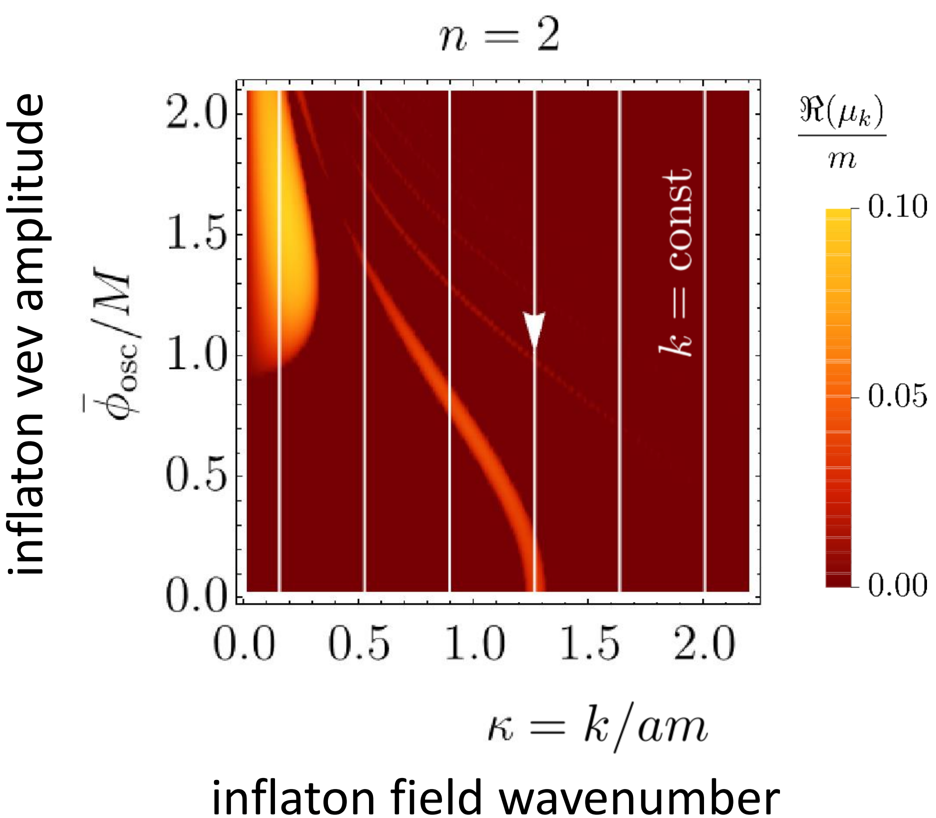
Towards radiation domination

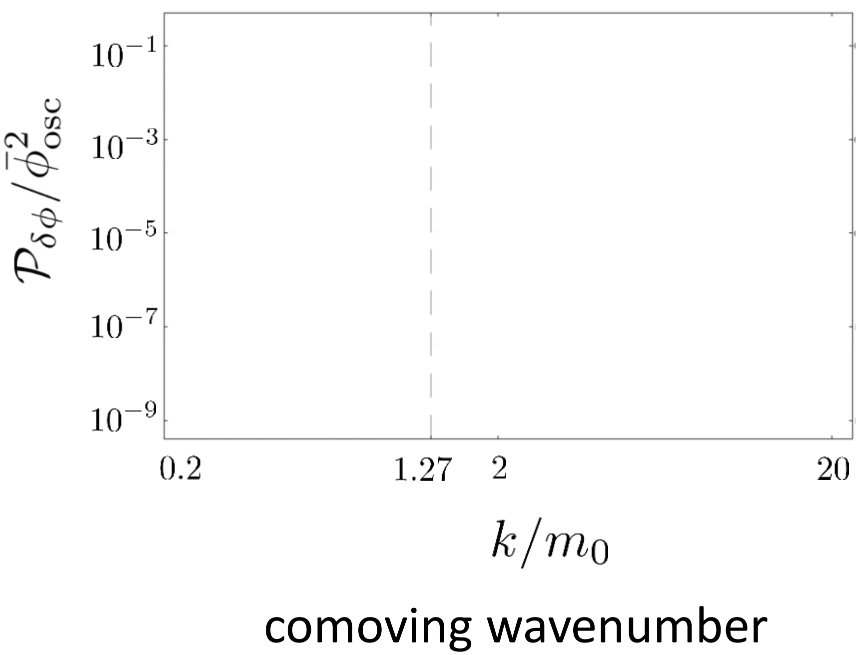
$$n > 1$$

Non-perturbative decay (parametric self-resonance)



Power spectrum:

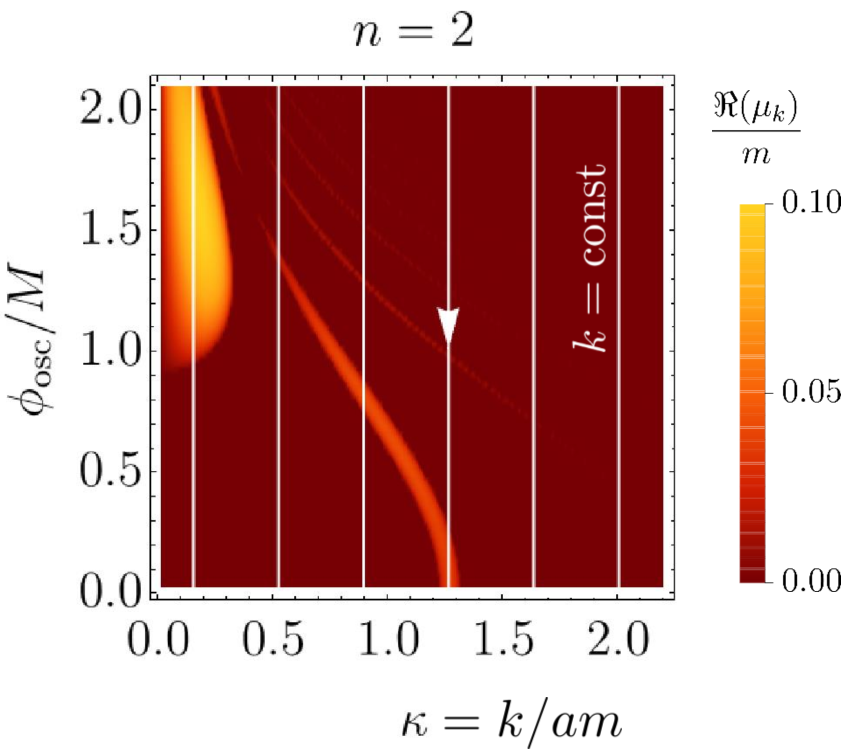
$$\langle \delta\phi(x)^2 \rangle \equiv \int \mathcal{P}_{\delta\phi}\, d\ln k$$



Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)



inflaton vev amplitude

inflaton field wavenumber

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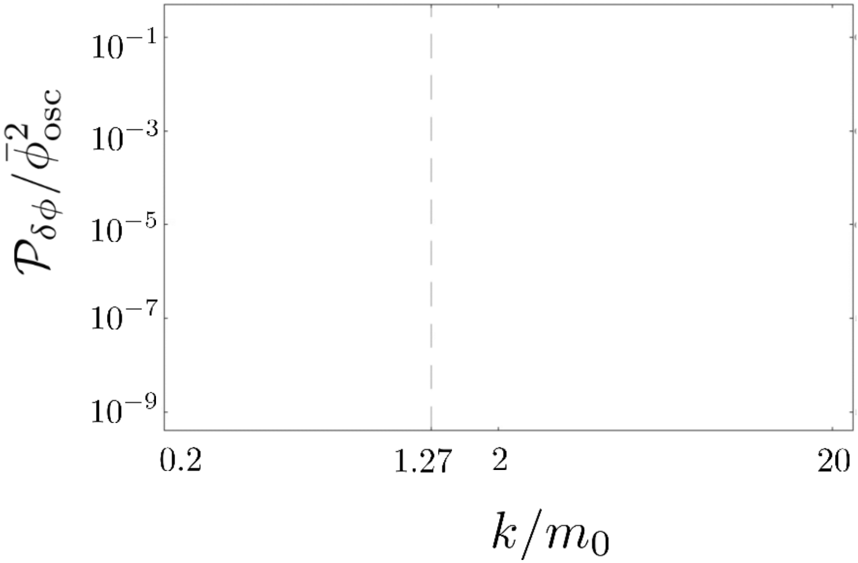
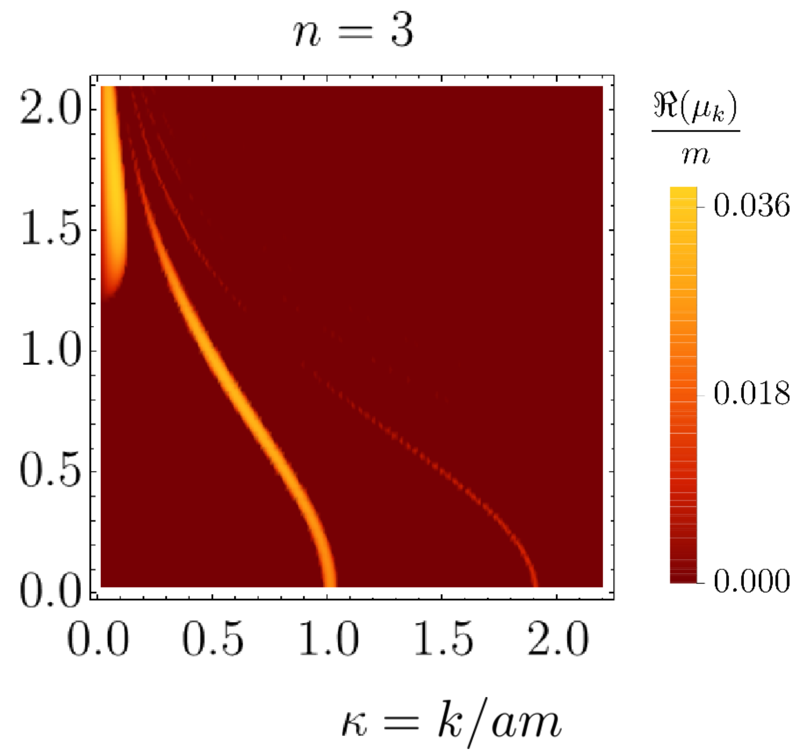


comoving wavenumber

Towards radiation domination

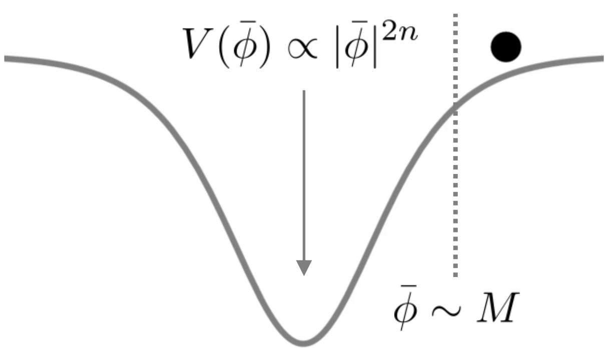
$$n > 1$$

Non-perturbative decay (parametric self-resonance)



inflaton vev amplitude

inflaton field wavenumber



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

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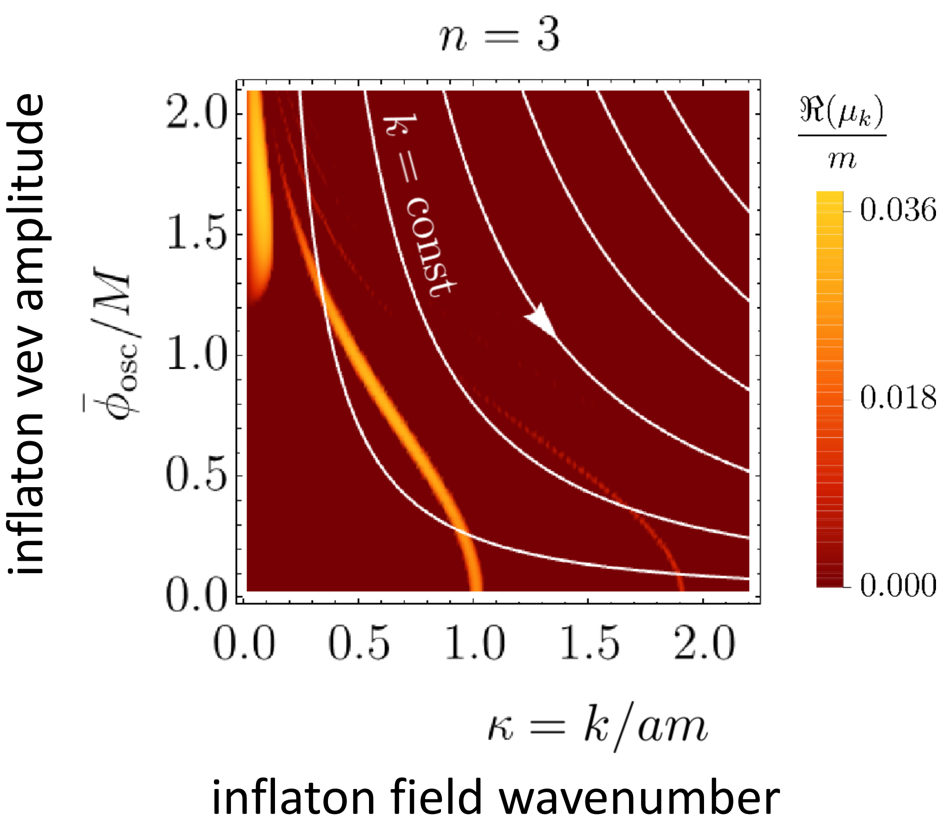
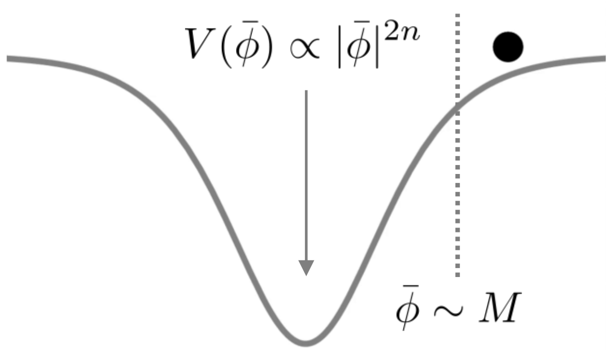
Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)





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Towards radiation domination

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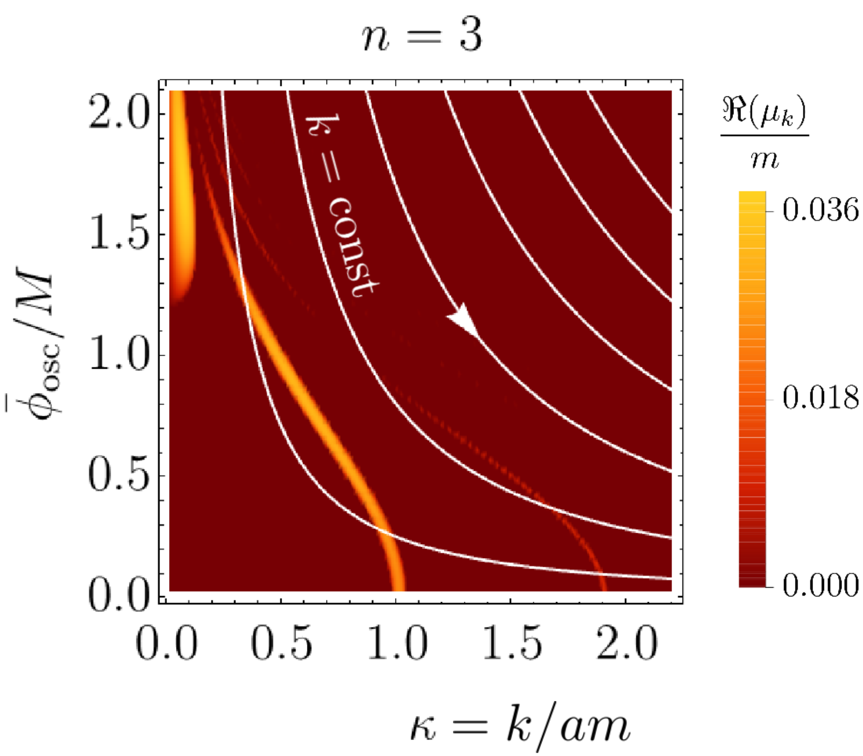
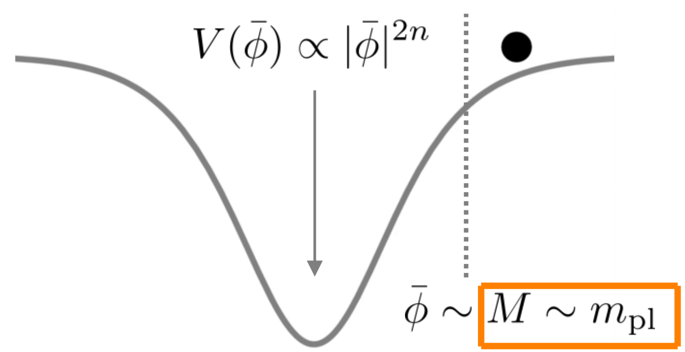


inflaton vev amplitude

inflaton field wavenumber



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Towards radiation domination

$$n > 1$$

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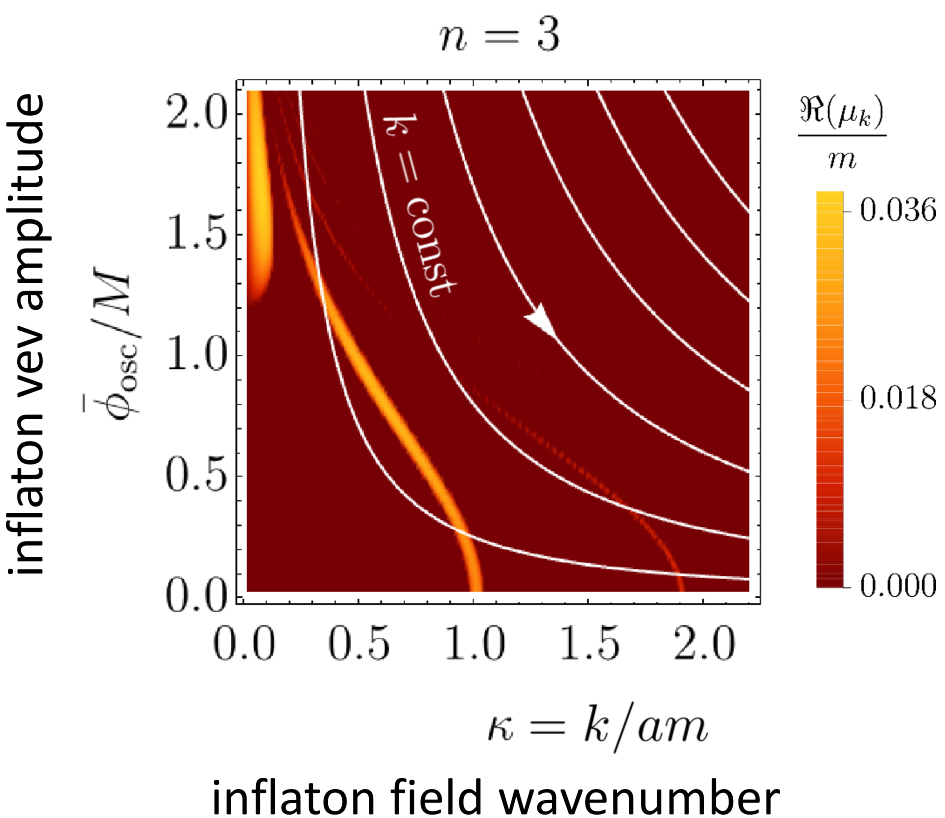

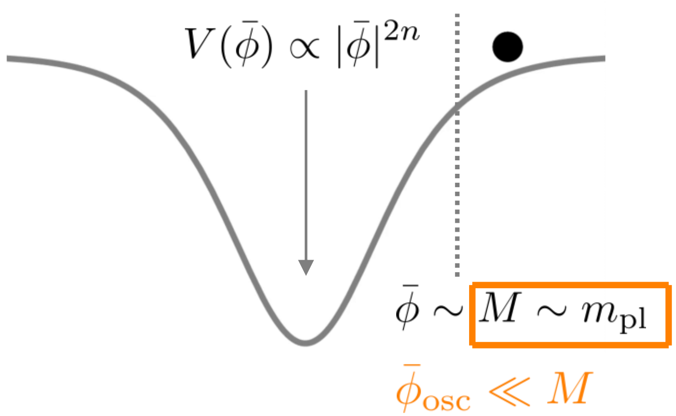

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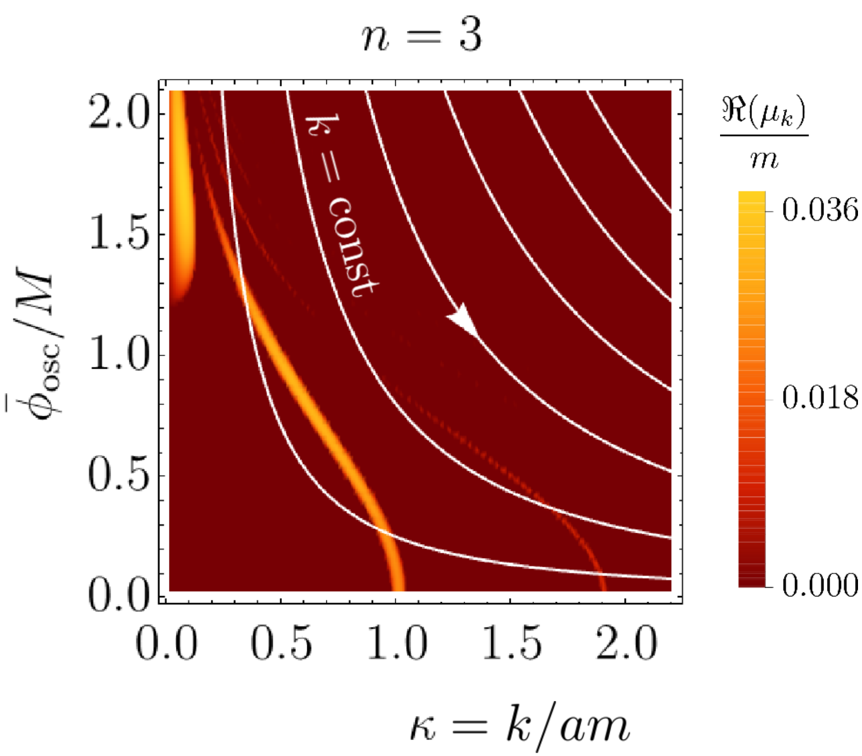
Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber

Power spectrum:

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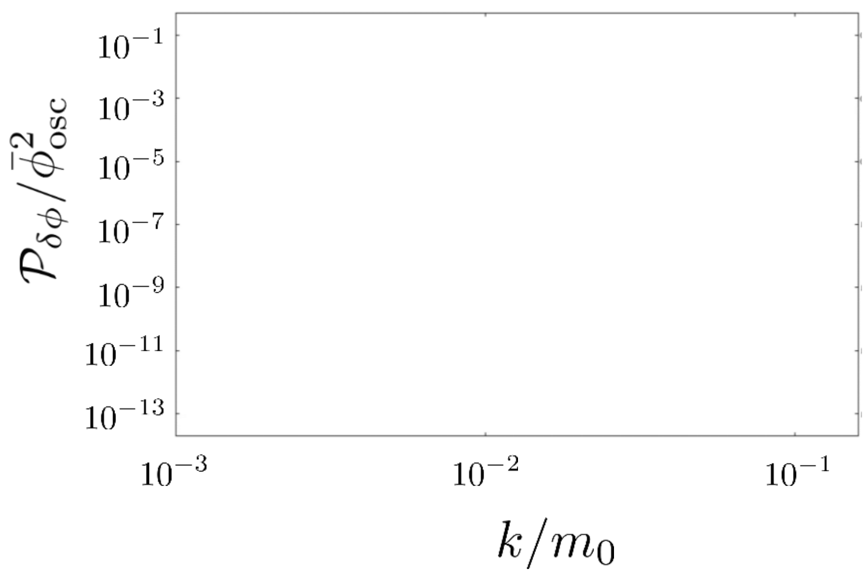


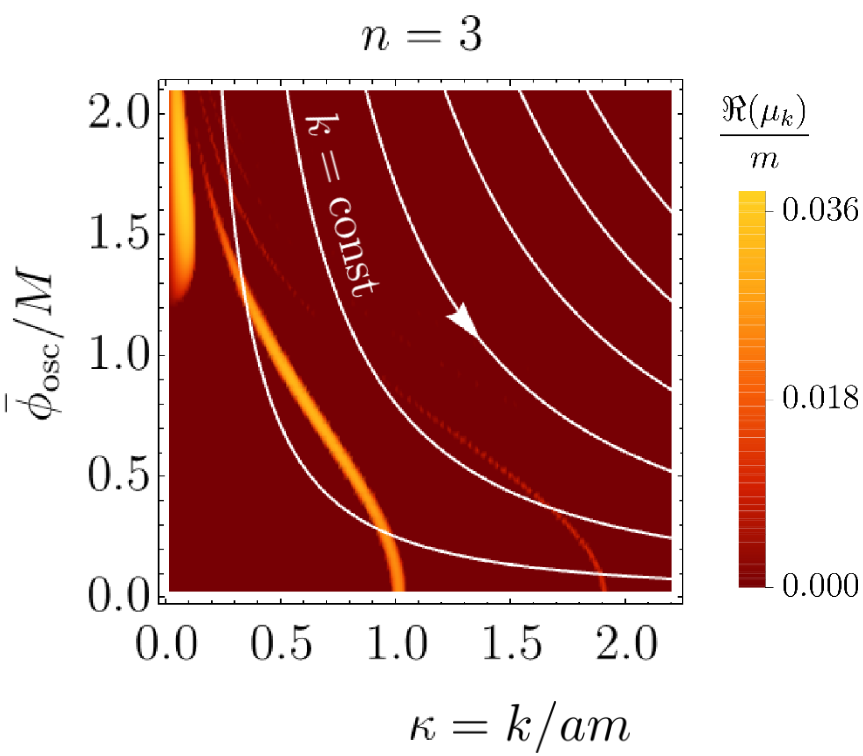
comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber

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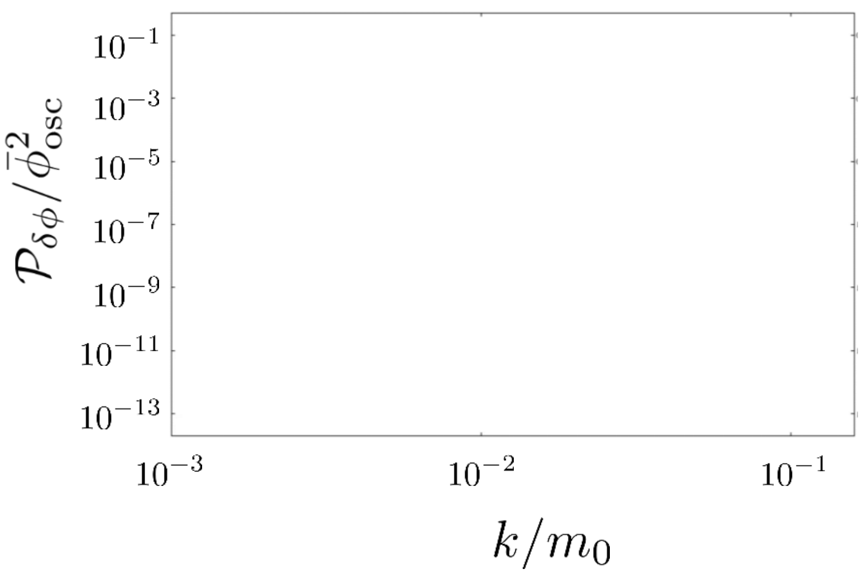
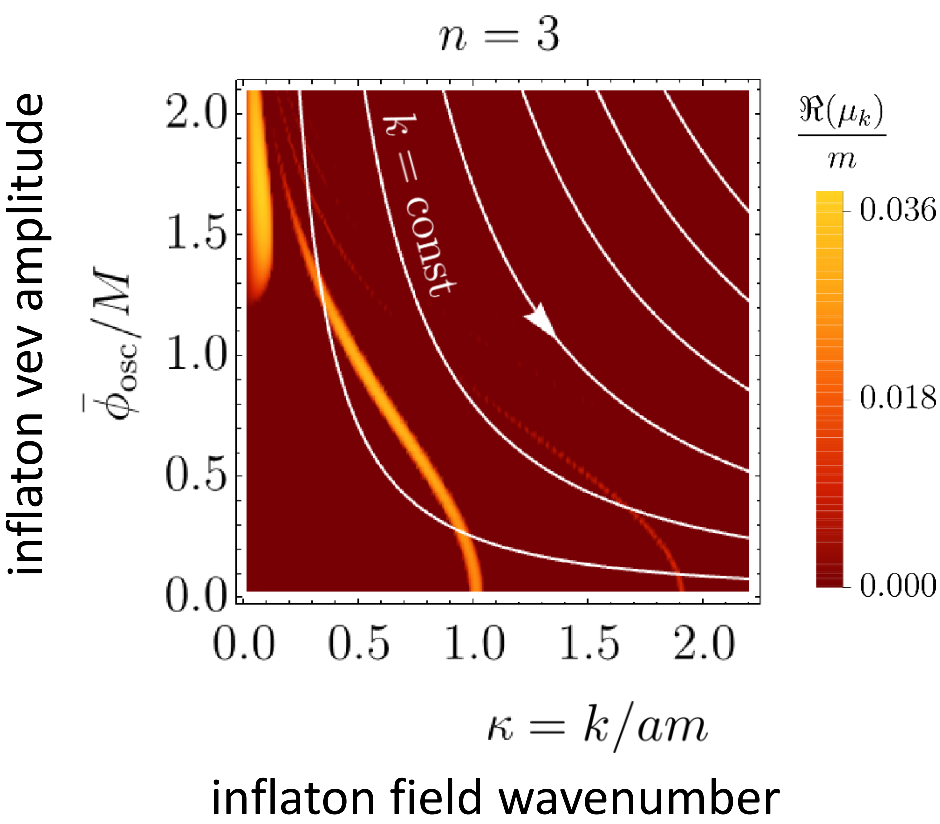


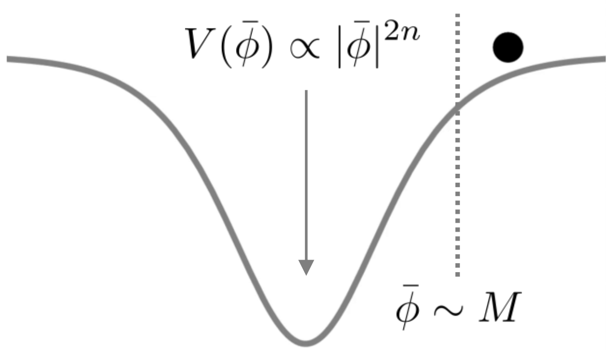
comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric <u>self</u>-resonance)





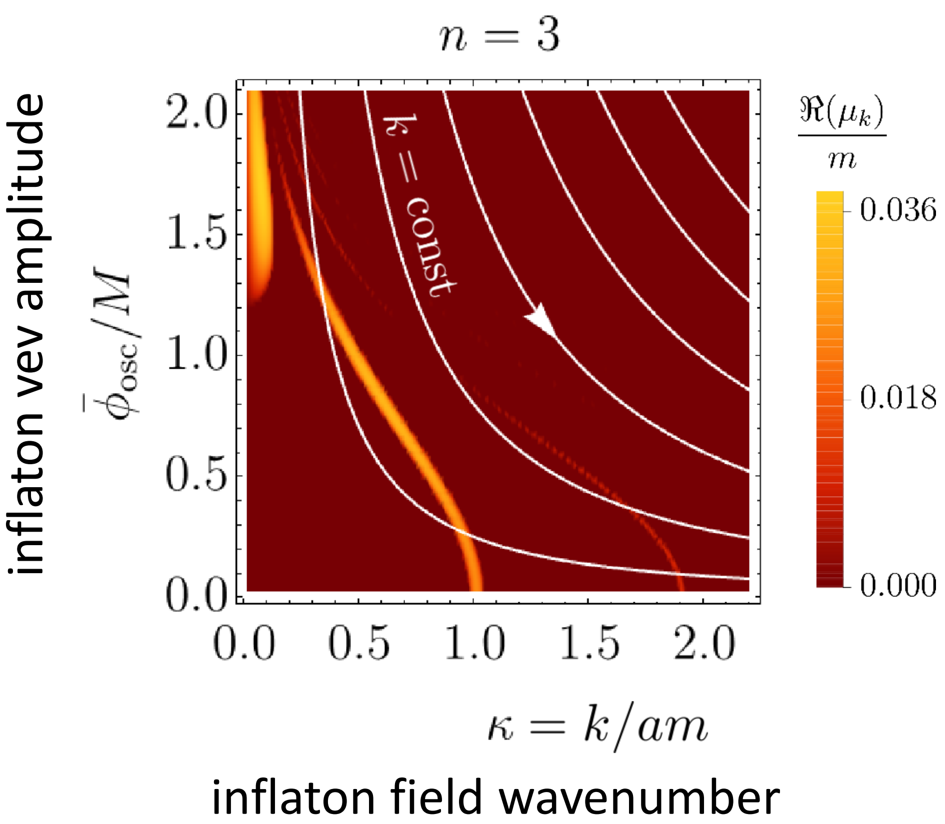
$$\delta\phi_k \propto \exp(\pm\mu_k t)$$

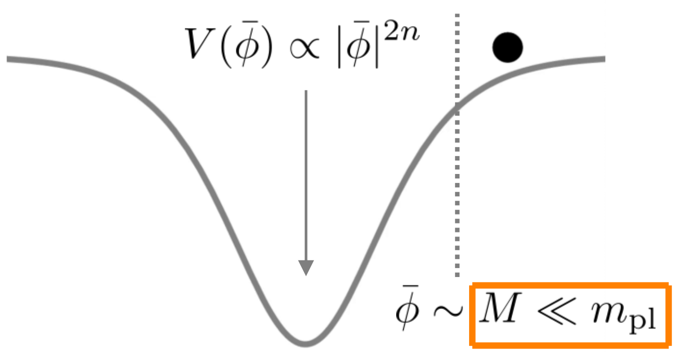
$m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)





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Towards radiation domination

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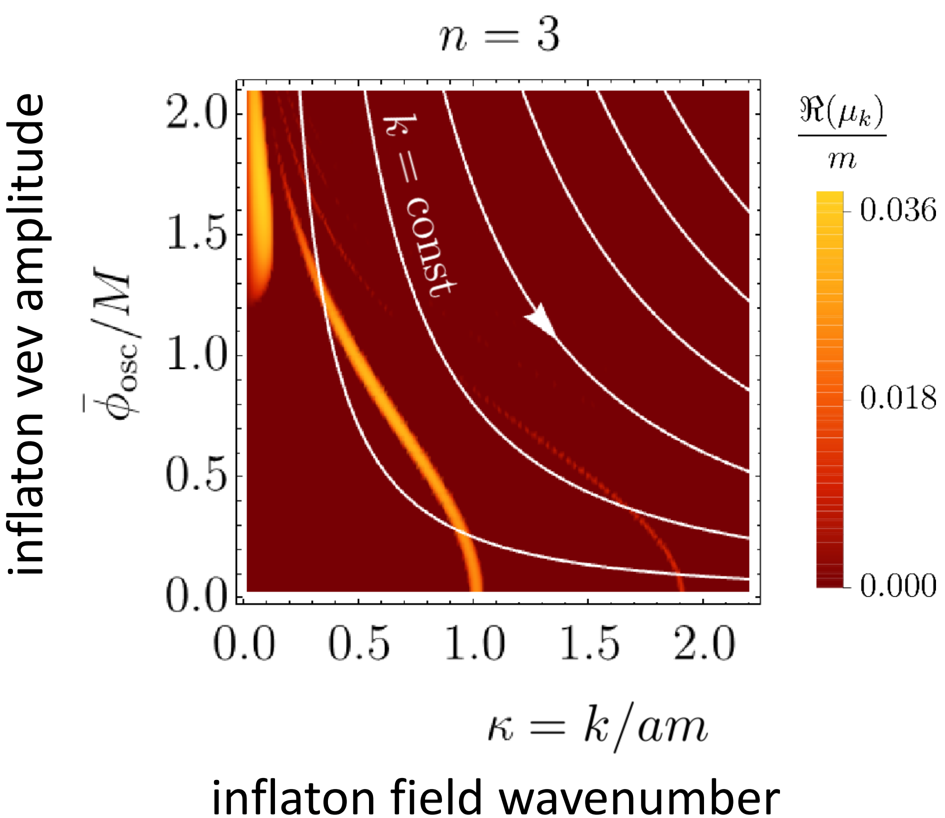

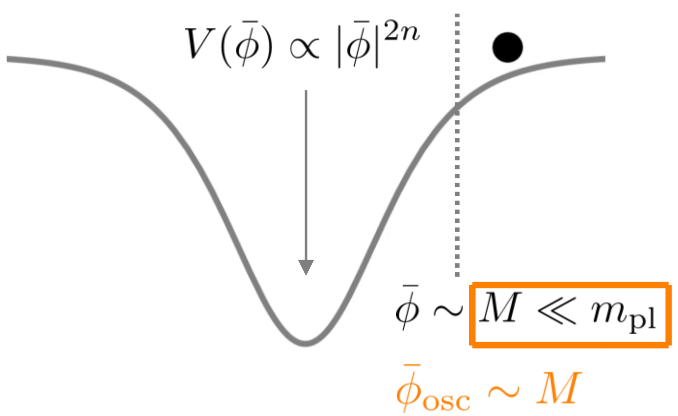

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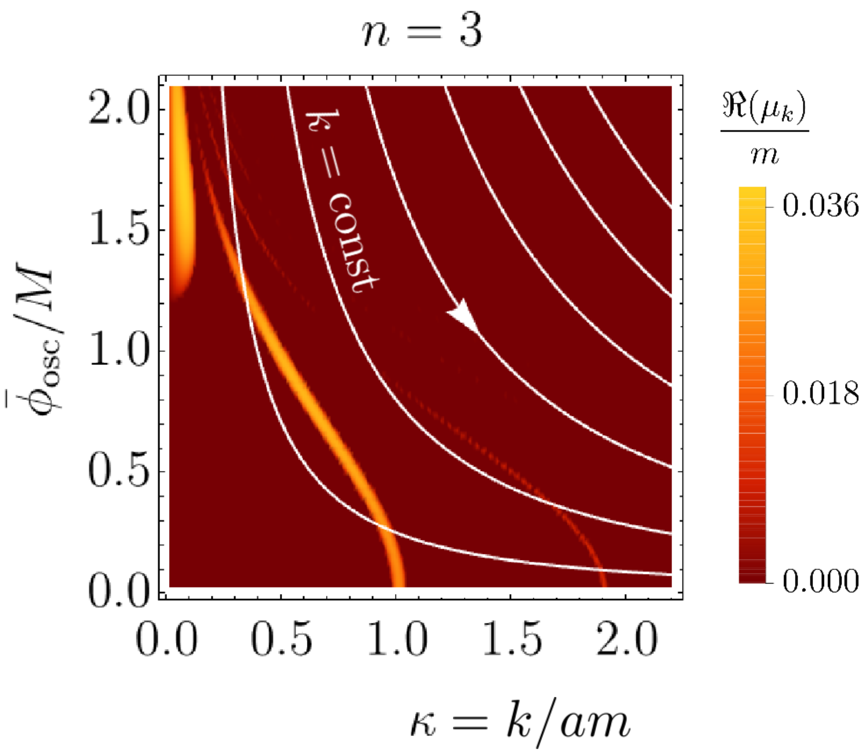
$m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

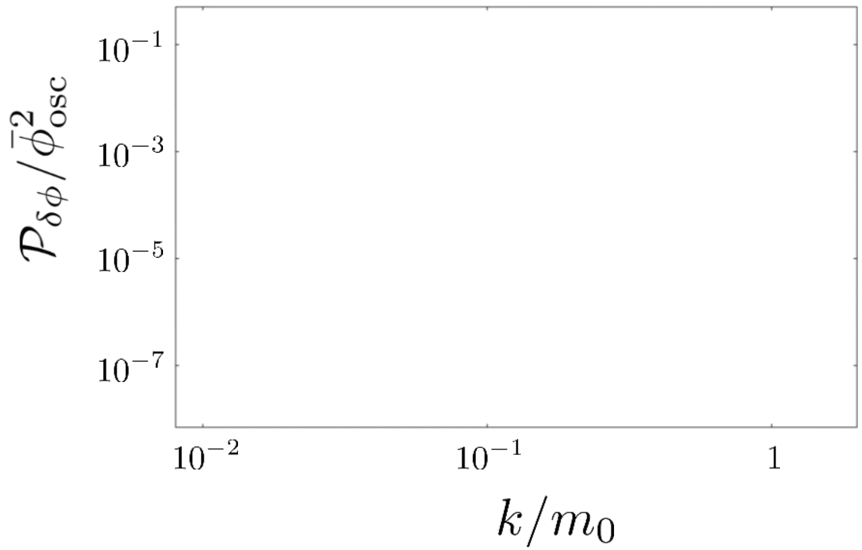
inflaton vev amplitude



inflaton field wavenumber

Power spectrum:

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

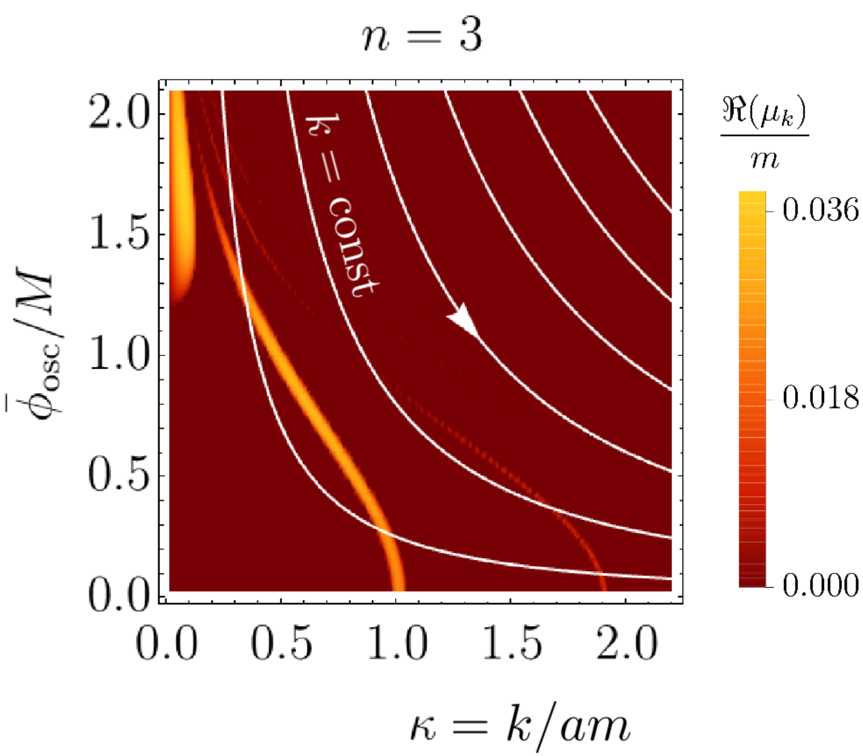


comoving wavenumber

Towards radiation domination

$$n > 1$$

Non-perturbative decay (parametric self-resonance)

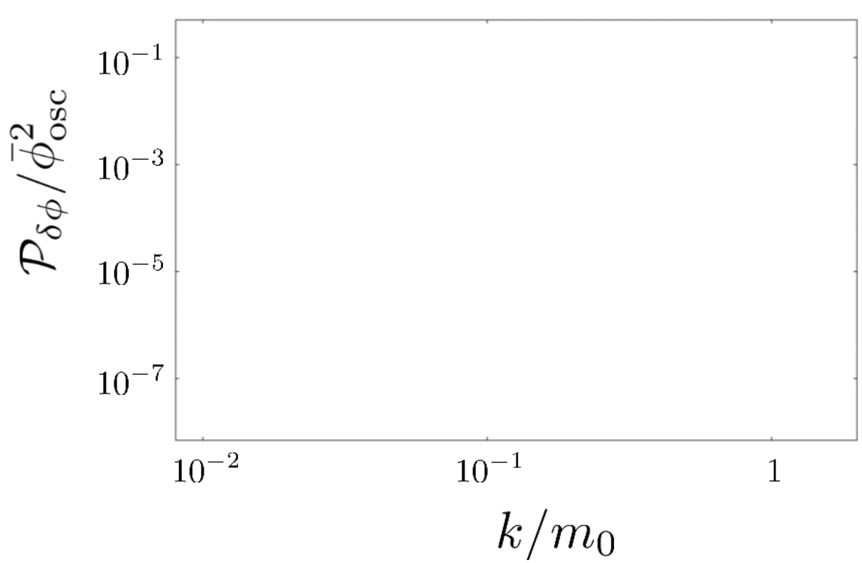


inflaton vev amplitude

inflaton field wavenumber

Power spectrum:

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

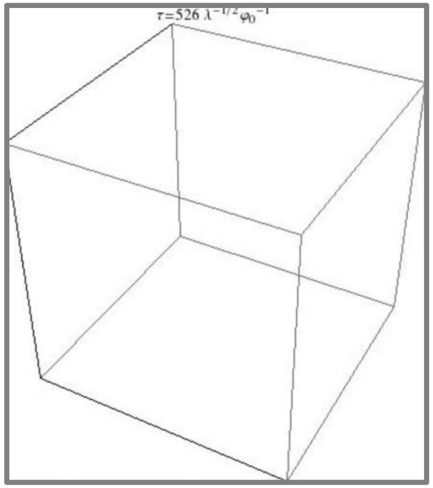


comoving wavenumber

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

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Expansion history effects

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

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

Planck Collaboration (2015)

Expansion history effects

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

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

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

KL and M. Amin (2016 and 2017)

Expansion history effects

Spectral index: $n_s = n_s(M, n, N_*)$

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

$$N_* = 66.89 - \frac{1}{12}\ln g_{\rm th} + \frac{1}{4}\ln\frac{V_*^4}{m_{\rm pl}^4\rho_{\rm end}} - \ln\frac{k_*}{a_0H_0} + \frac{3\bar{w}_{\rm int}-1}{4}\Delta N_{\rm rad}$$

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

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reheating

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

KL and M. Amin (2016 and 2017)

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

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

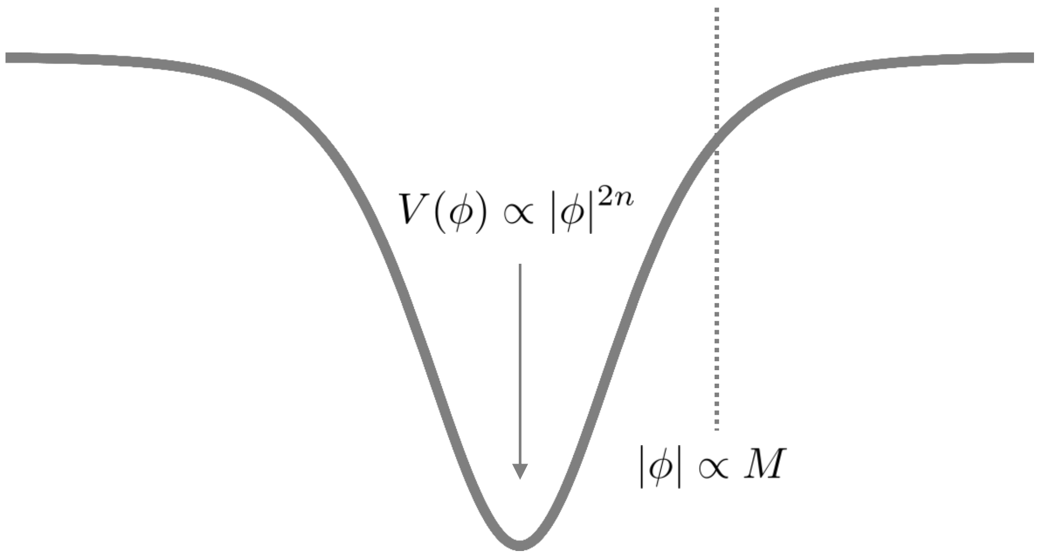
$$\Delta N_{\rm rad} \equiv \int_{a_{\rm end}}^{a_{\rm rad}} d\ln a$$

KL and M. Amin (2016 and 2017)

Expansion history effects

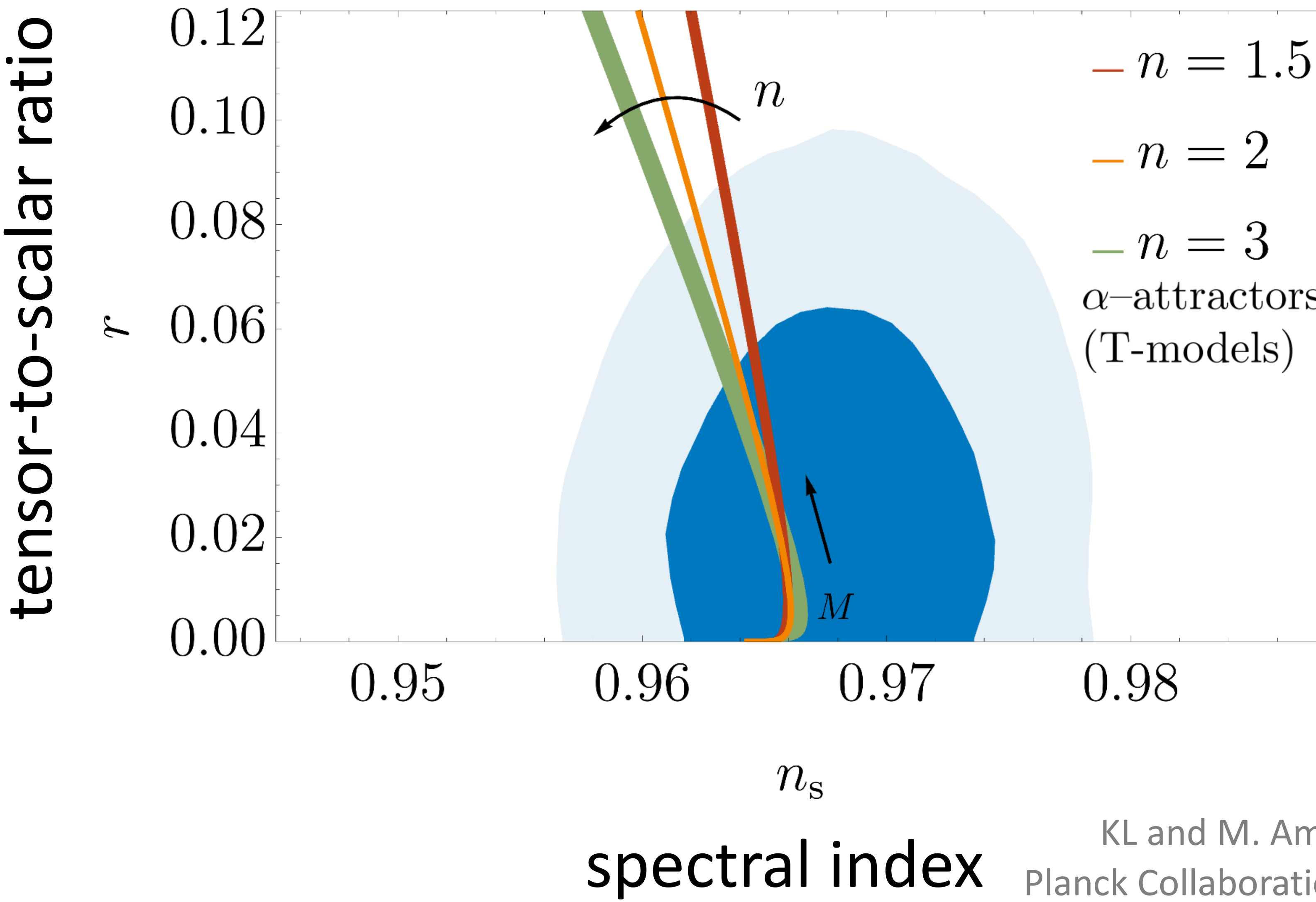
$$V(\phi) \propto \tanh^{2n}\left(\frac{|\phi|}{M}\right)$$

α–attractors
(T-models)



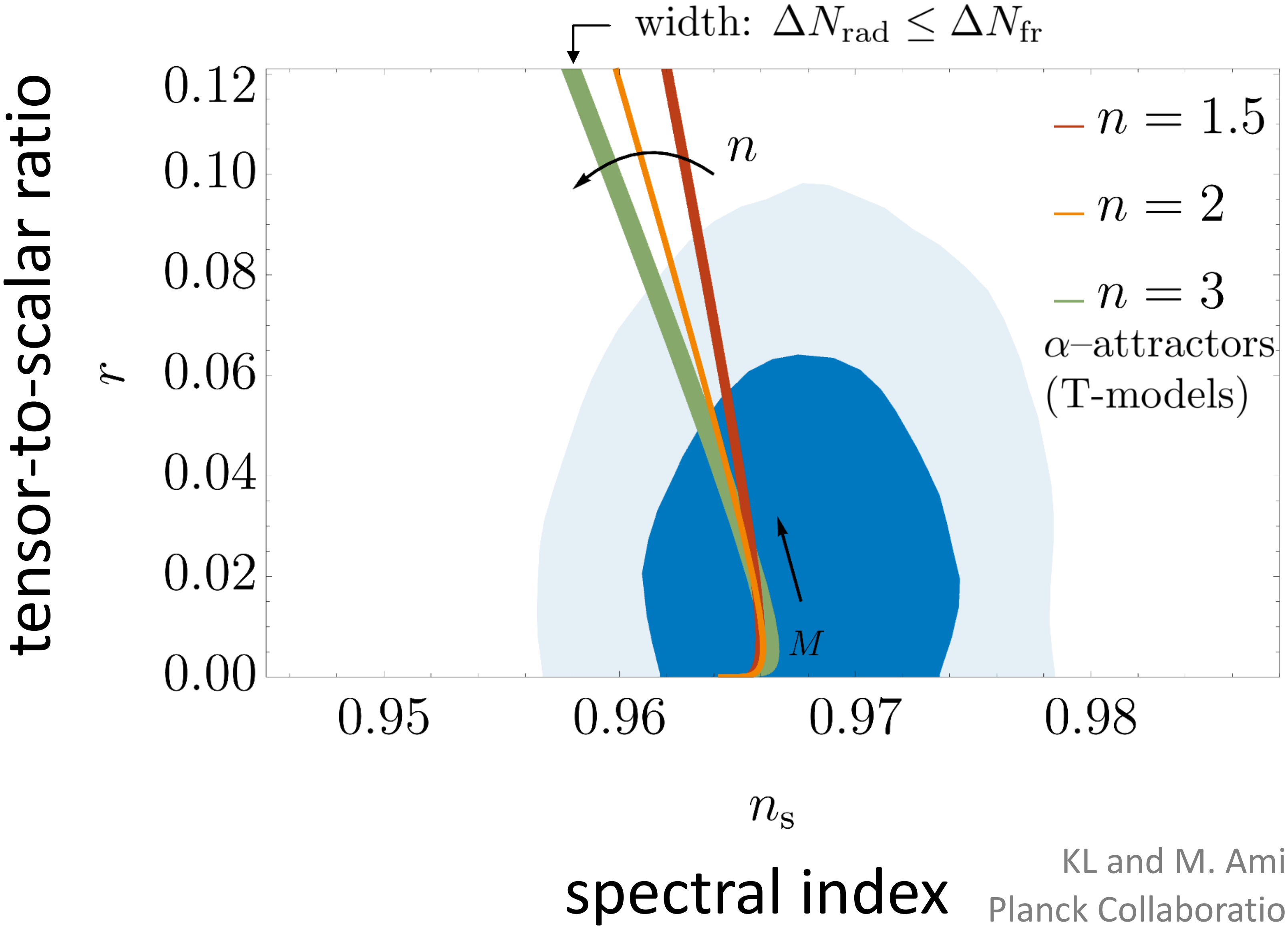
Kallosh and Linde (2013)
Carrasco, Kallosh and Linde (2015)

Expansion history effects



KL and M. Amin (2016)
Planck Collaboration (2015)

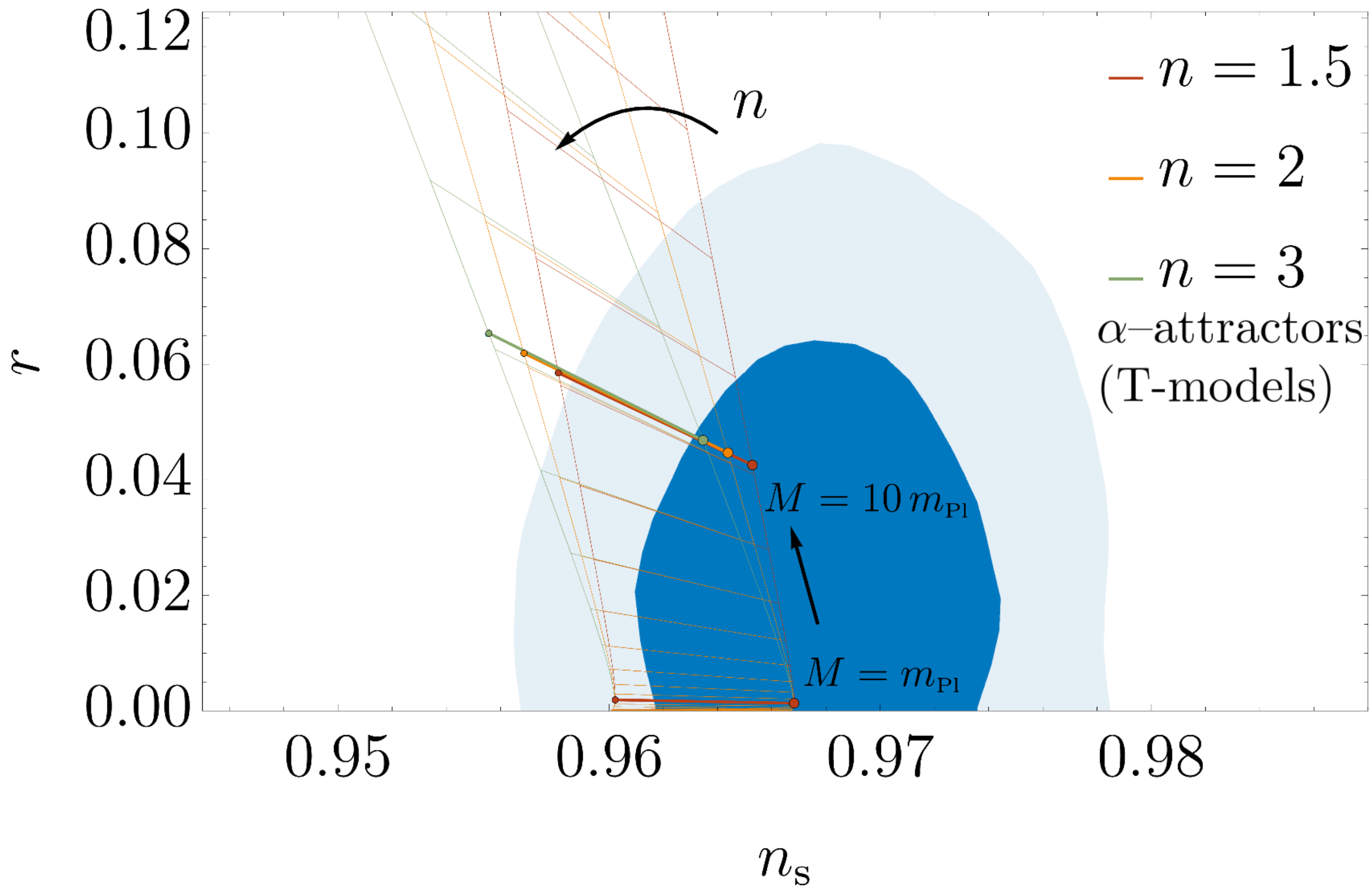
Expansion history effects



KL and M. Amin (2016)
Planck Collaboration (2015)

Expansion history effects

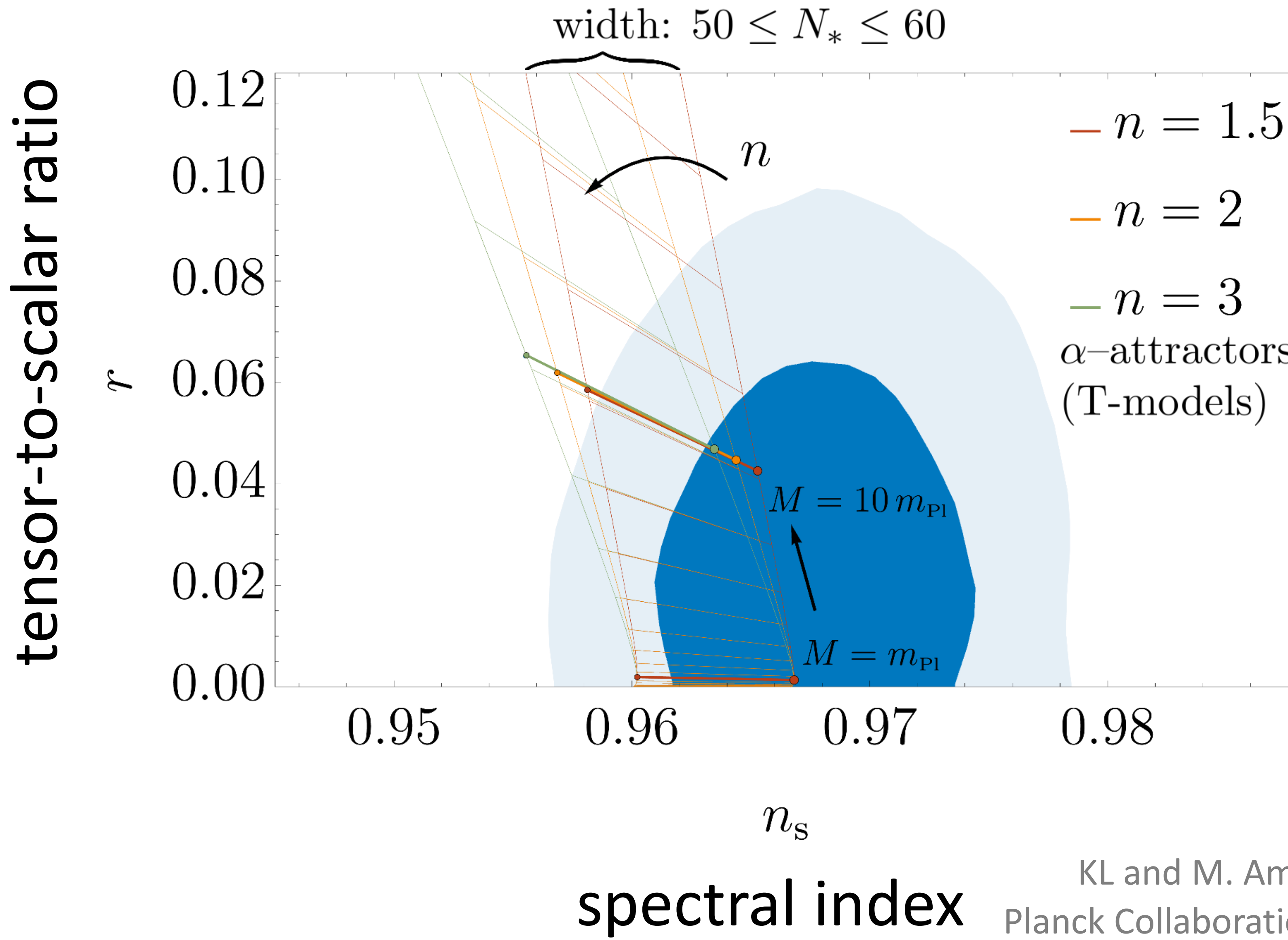
tensor-to-scalar ratio



spectral index

KL and M. Amin (2016)
Planck Collaboration (2015)

Expansion history effects



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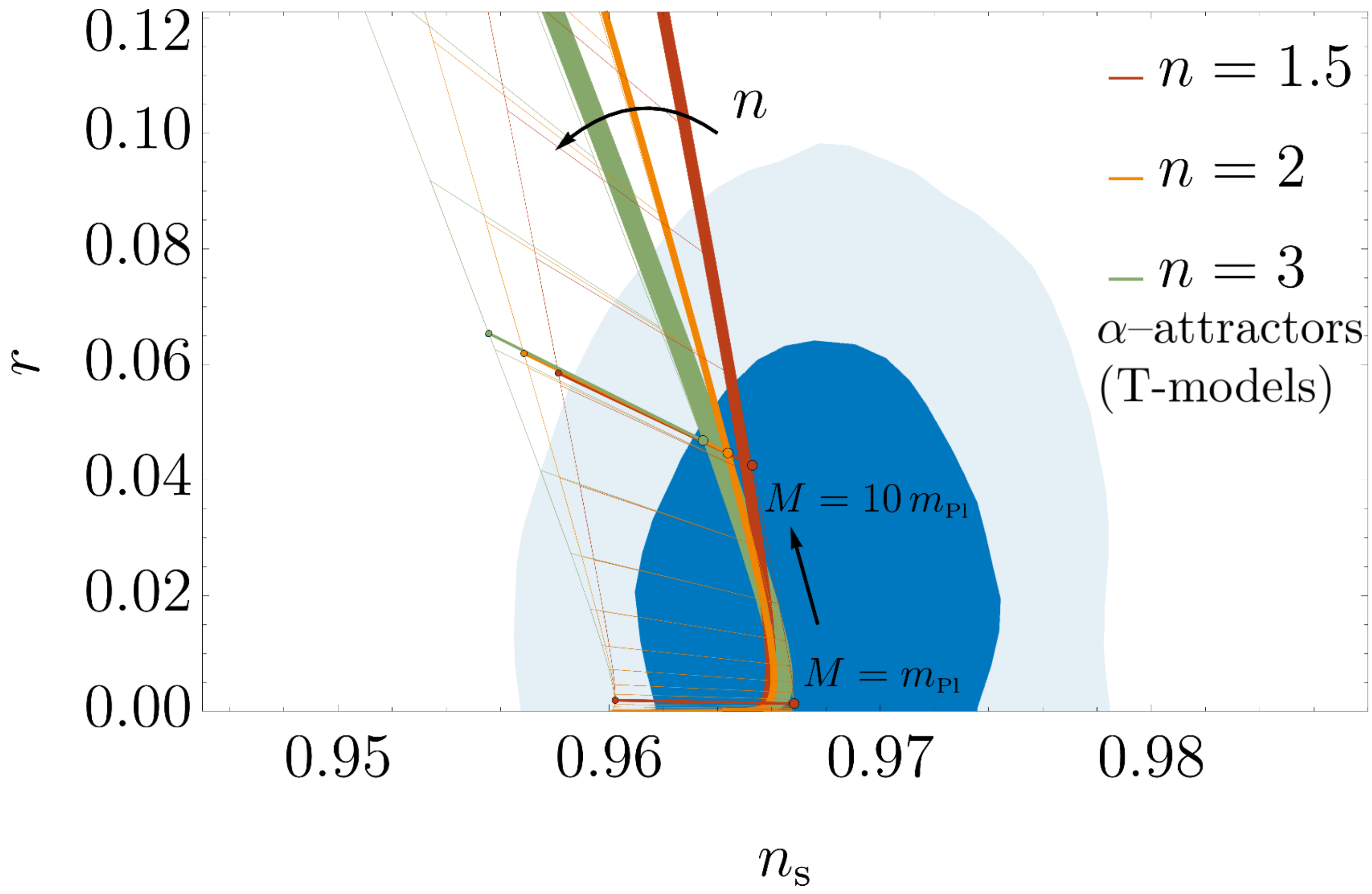
Planck Collaboration (2015)

Expansion history effects

tensor-to-scalar ratio



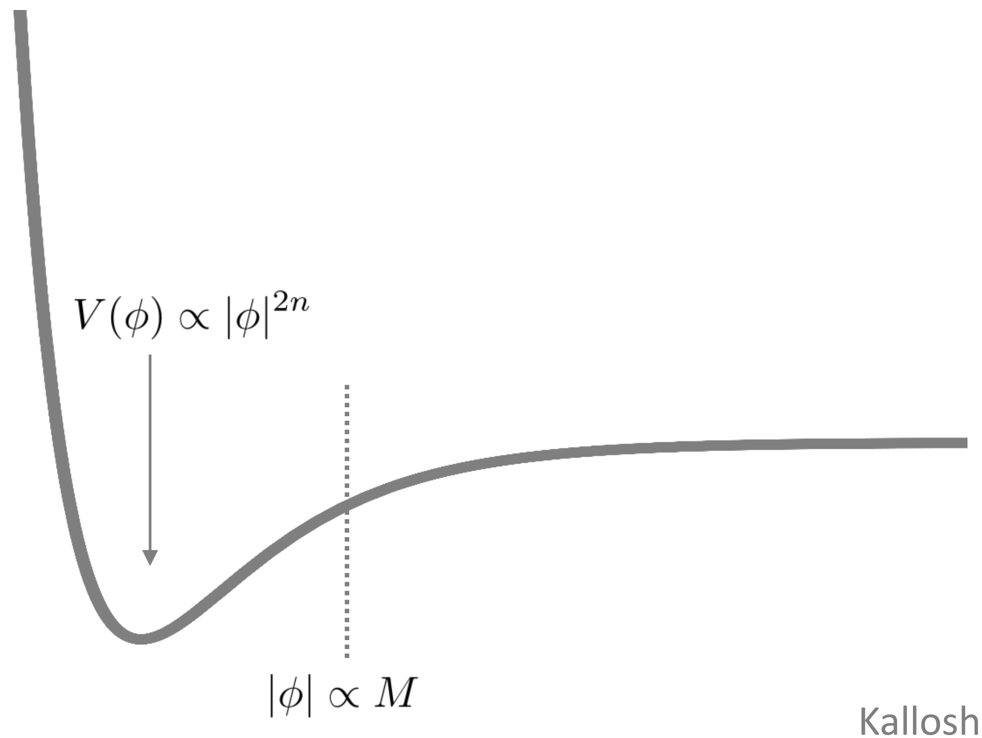
spectral index

KL and M. Amin (2016)
Planck Collaboration (2015)

Expansion history effects

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

α–attractors
(E-models)



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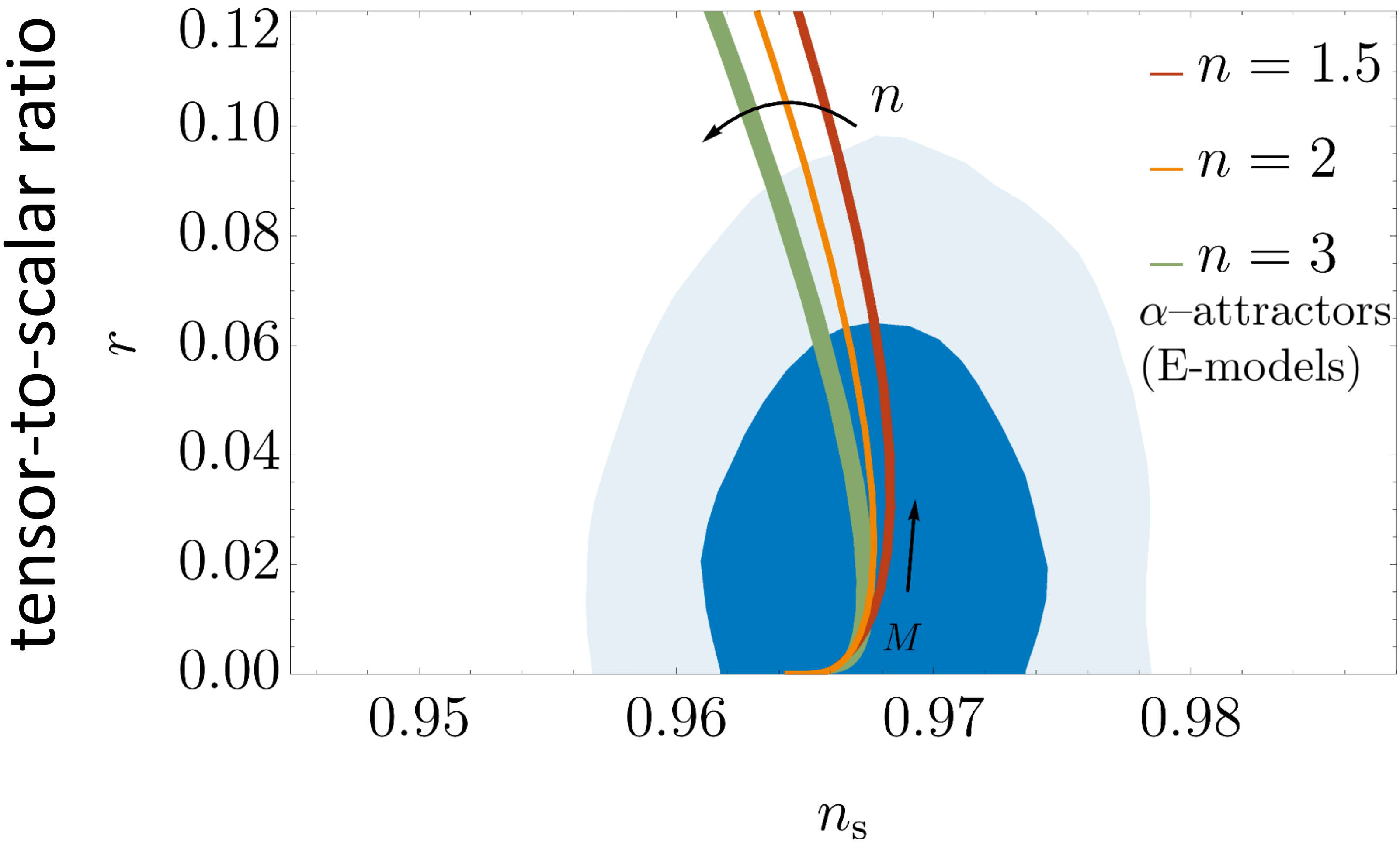

spectral index

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Planck Collaboration (2015)

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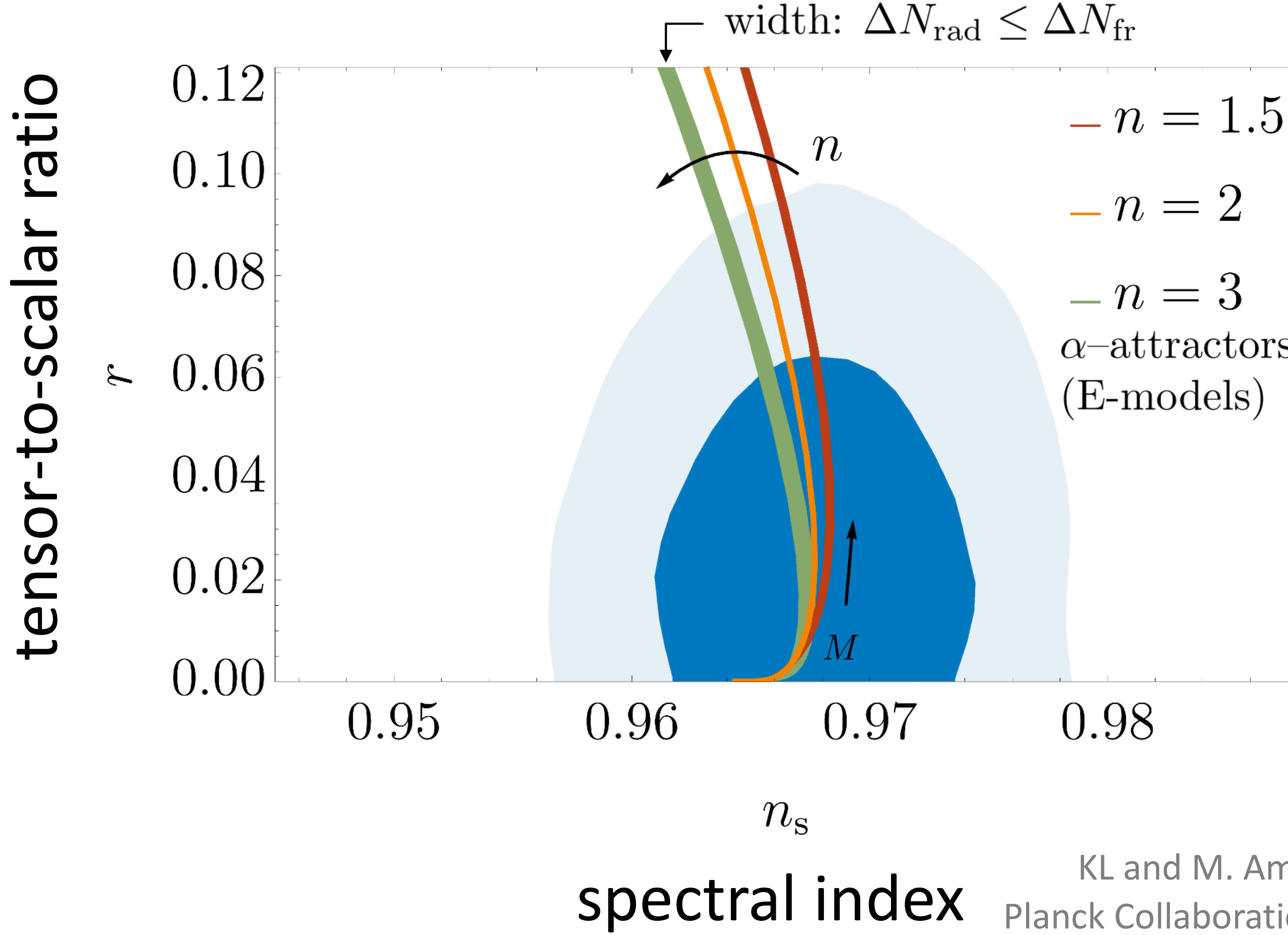

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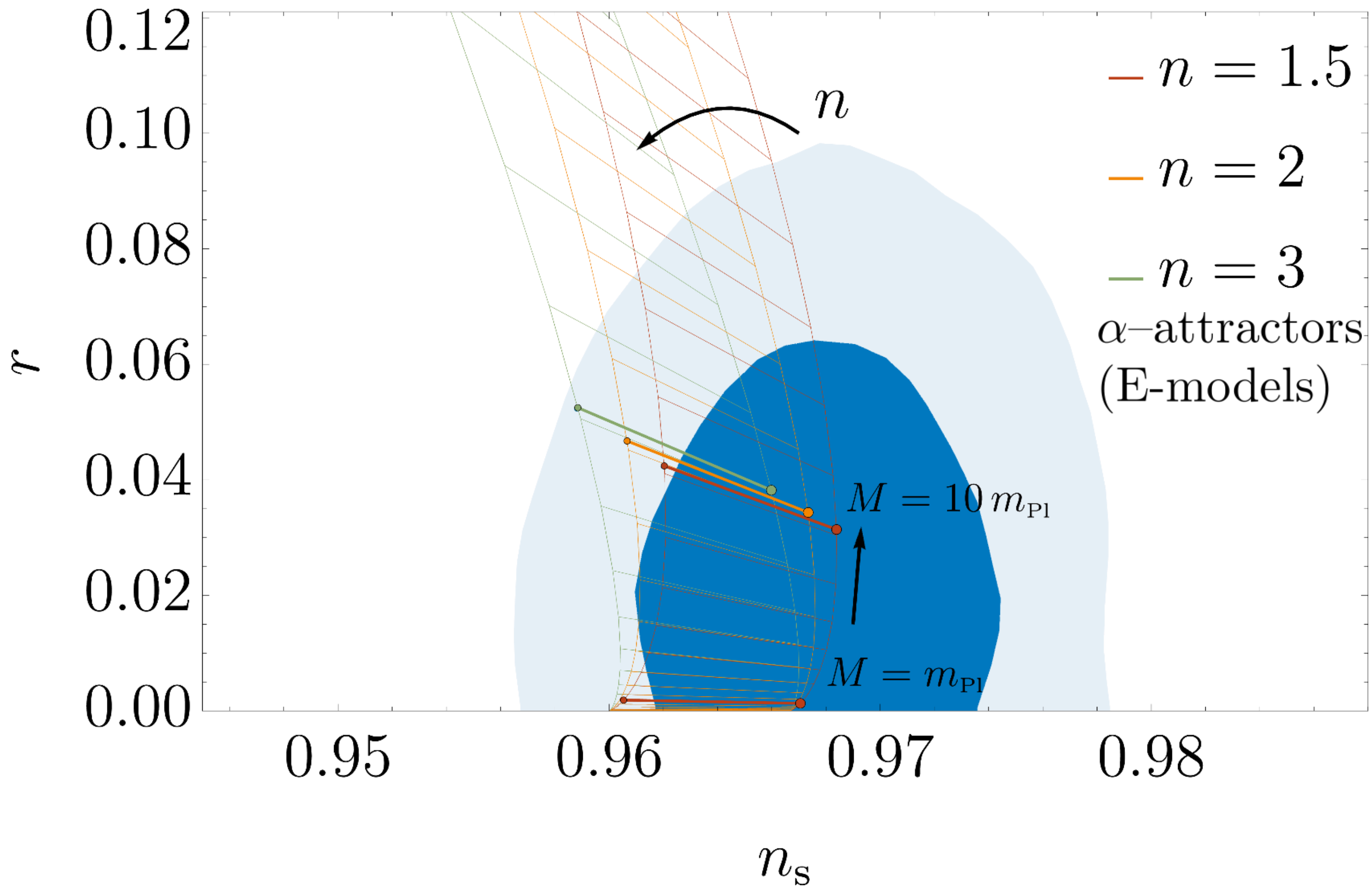
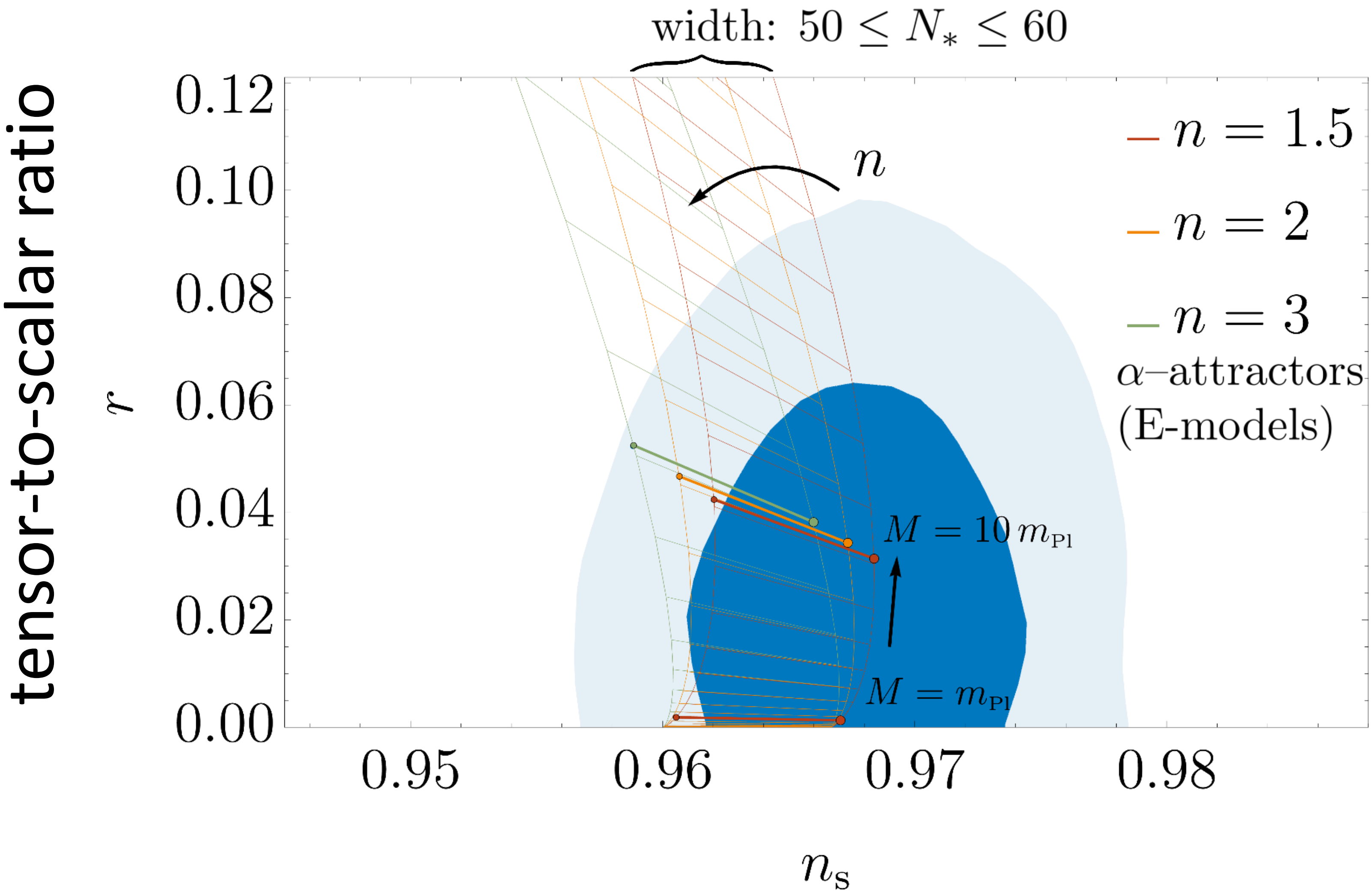


tensor-to-scalar ratio

spectral index

KL and M. Amin (2016)
Planck Collaboration (2015)

Expansion history effects



spectral index

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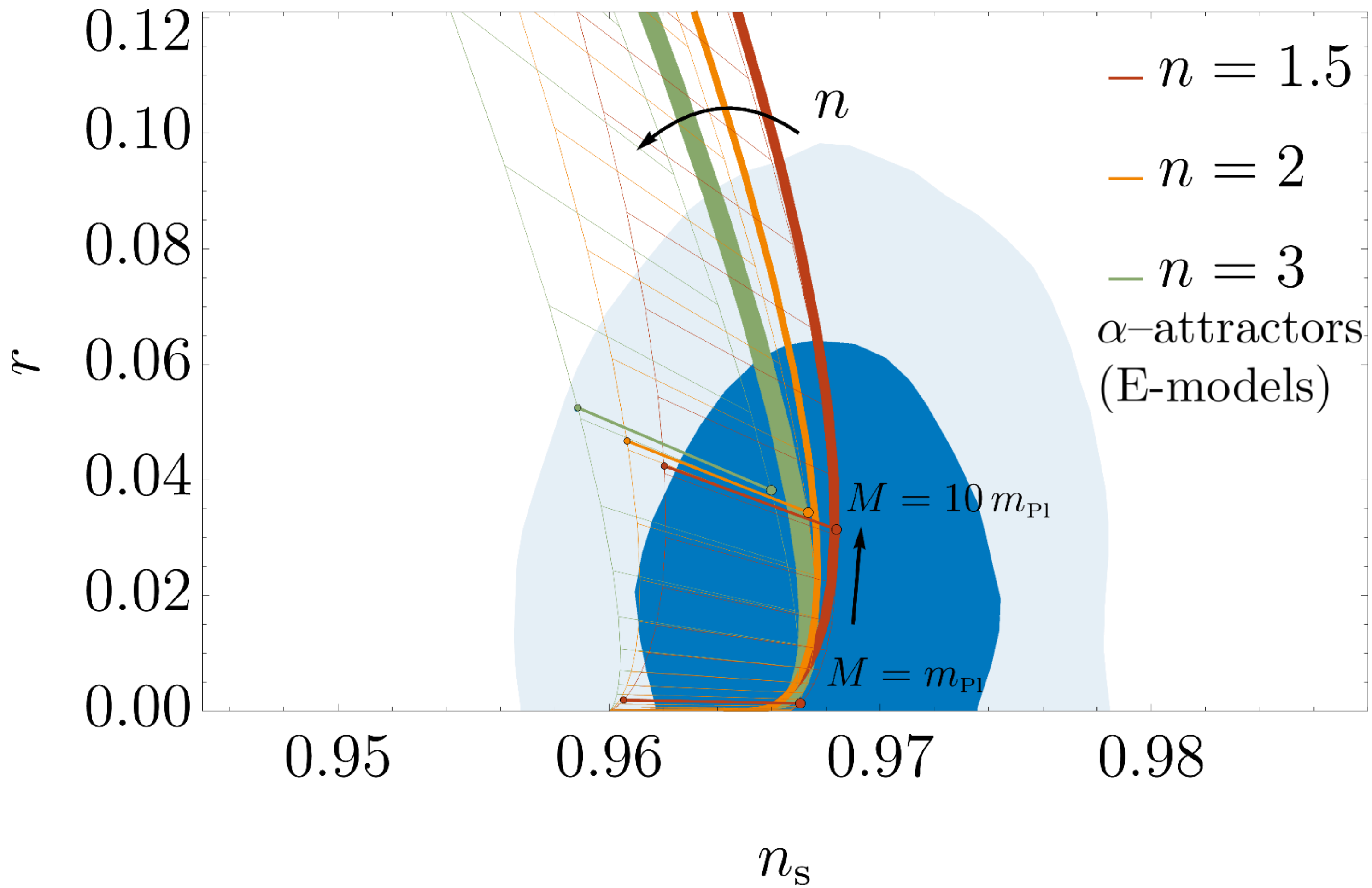


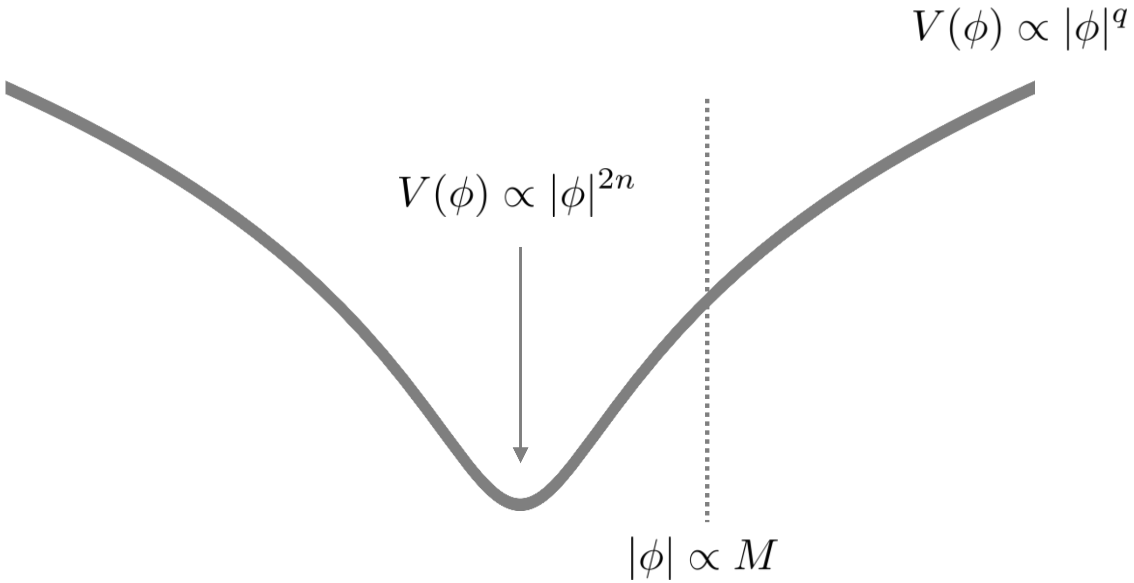
tensor-to-scalar ratio

spectral index

KL and M. Amin (2016)
Planck Collaboration (2015)

Expansion history effects

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

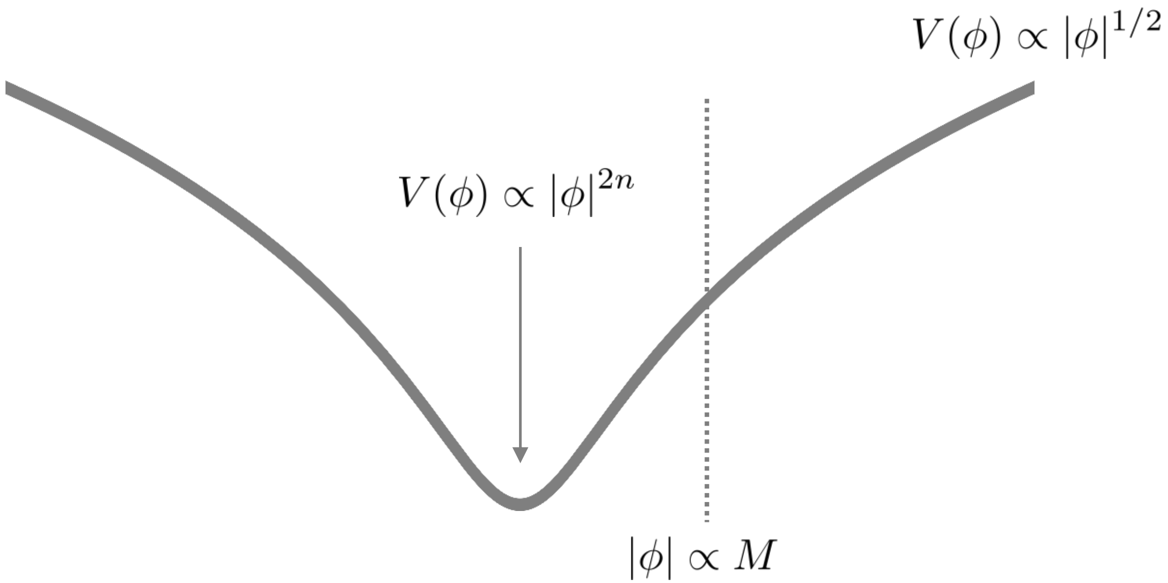


Silverstein and Westphal (2008)
McAllister, et al. (2014)

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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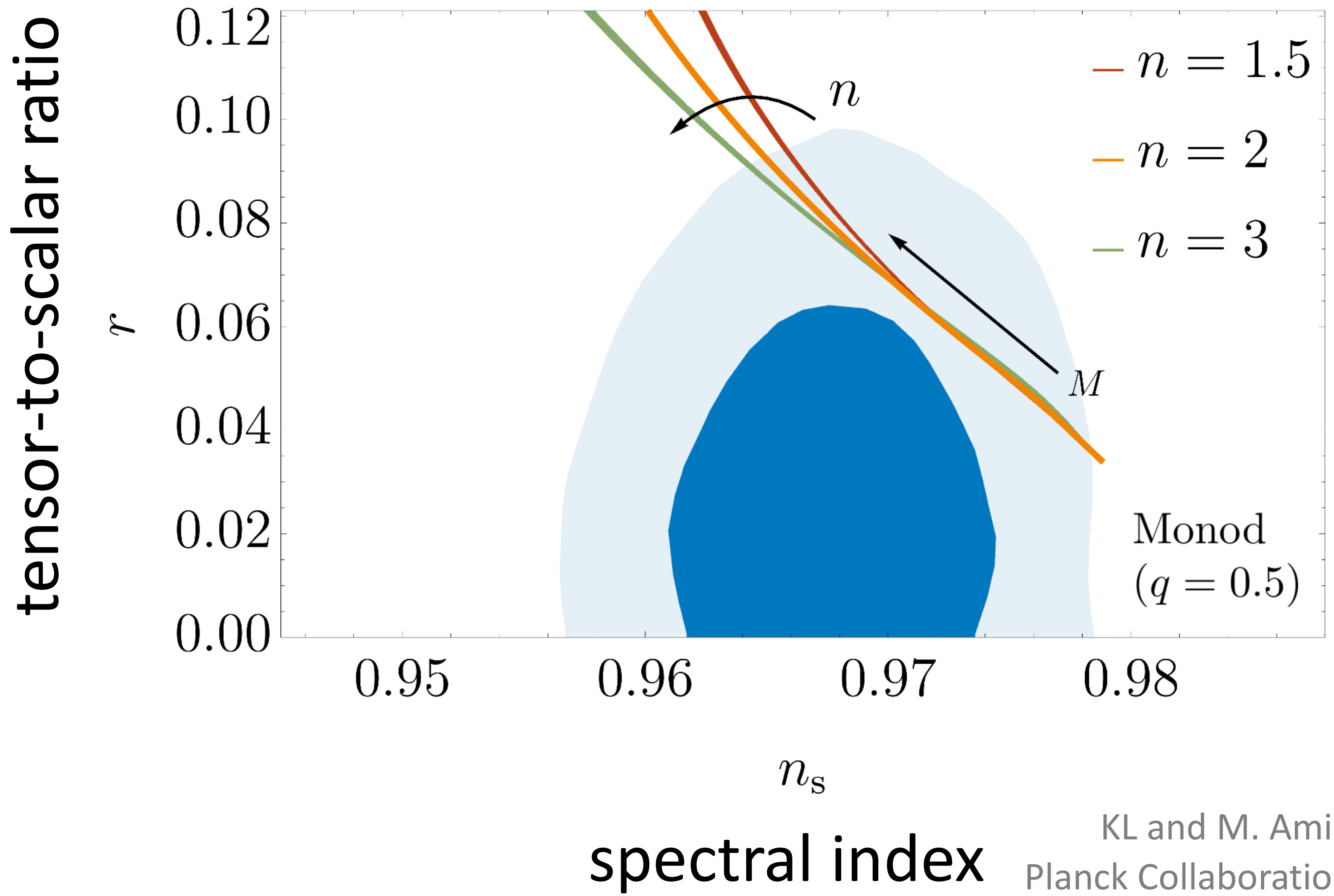

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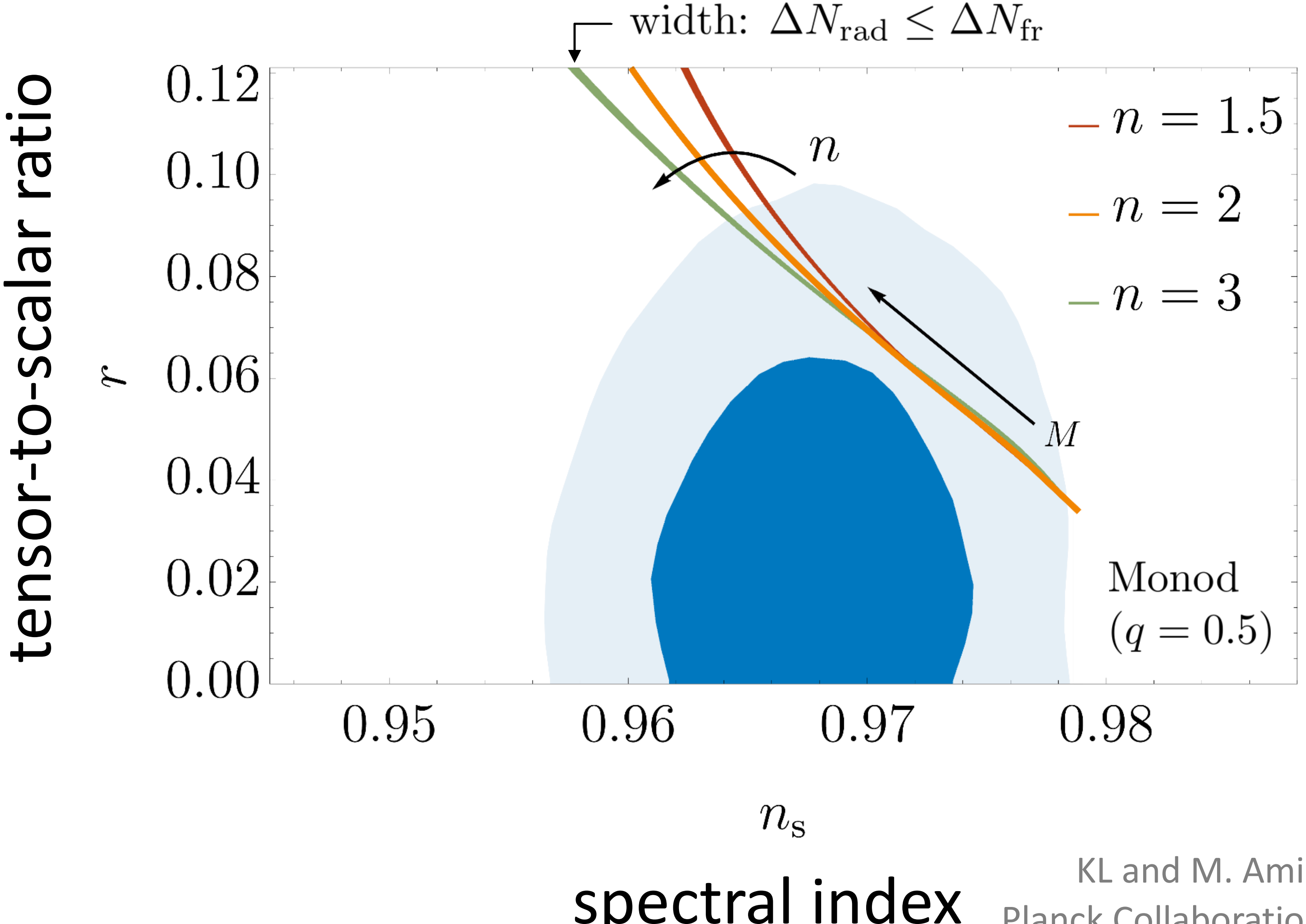
Expansion history effects



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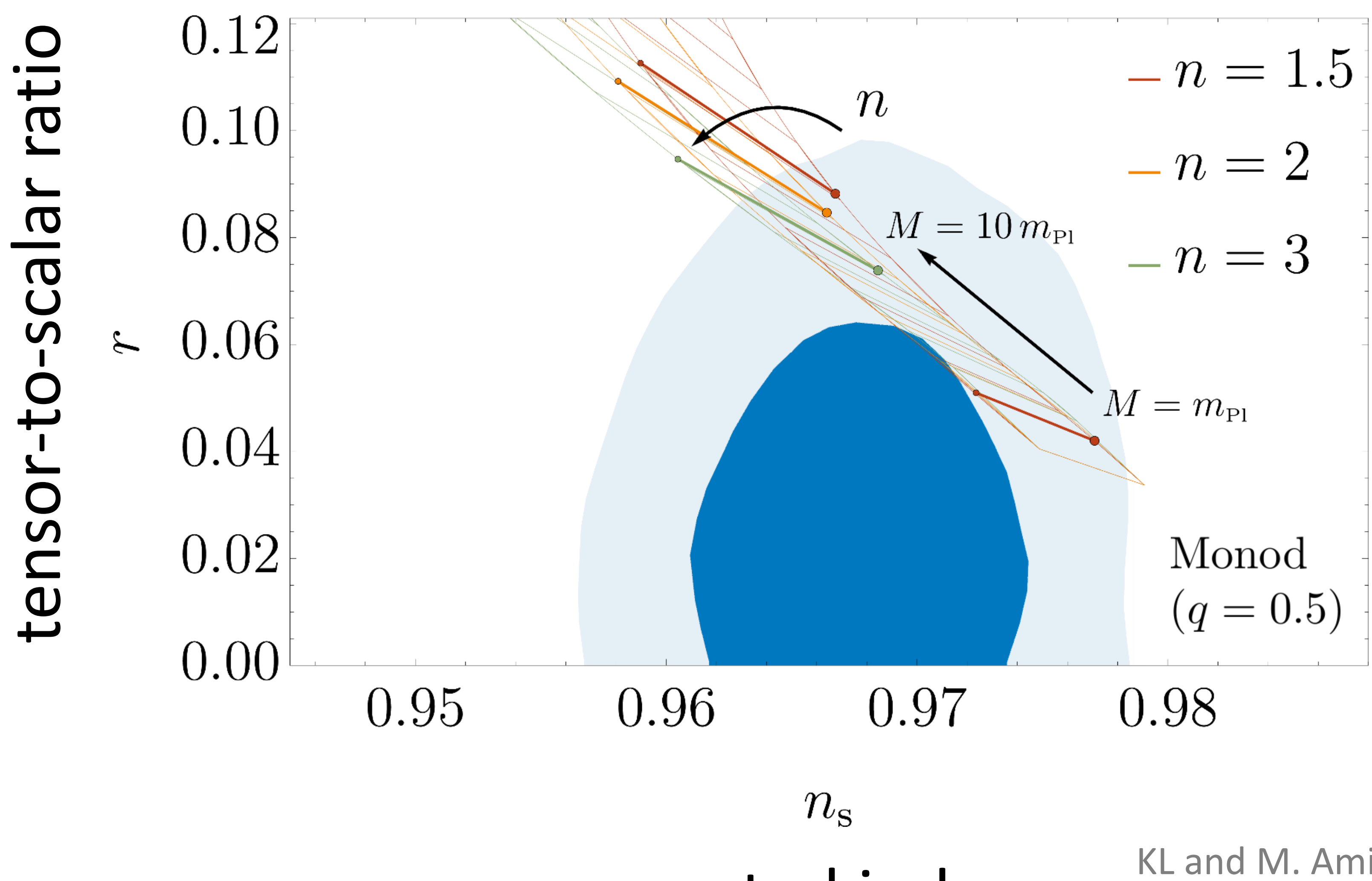

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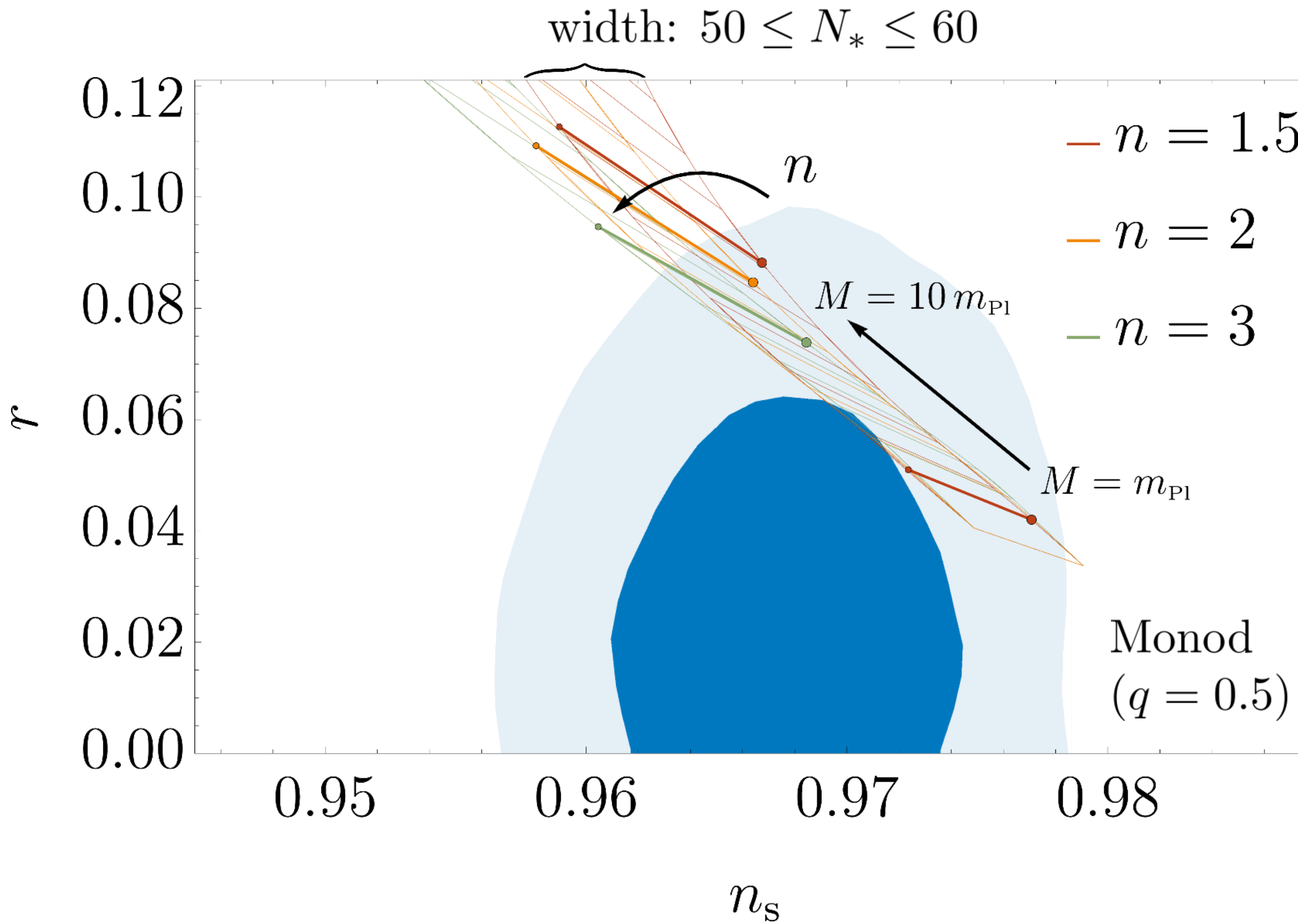

tensor-to-scalar ratio

spectral index

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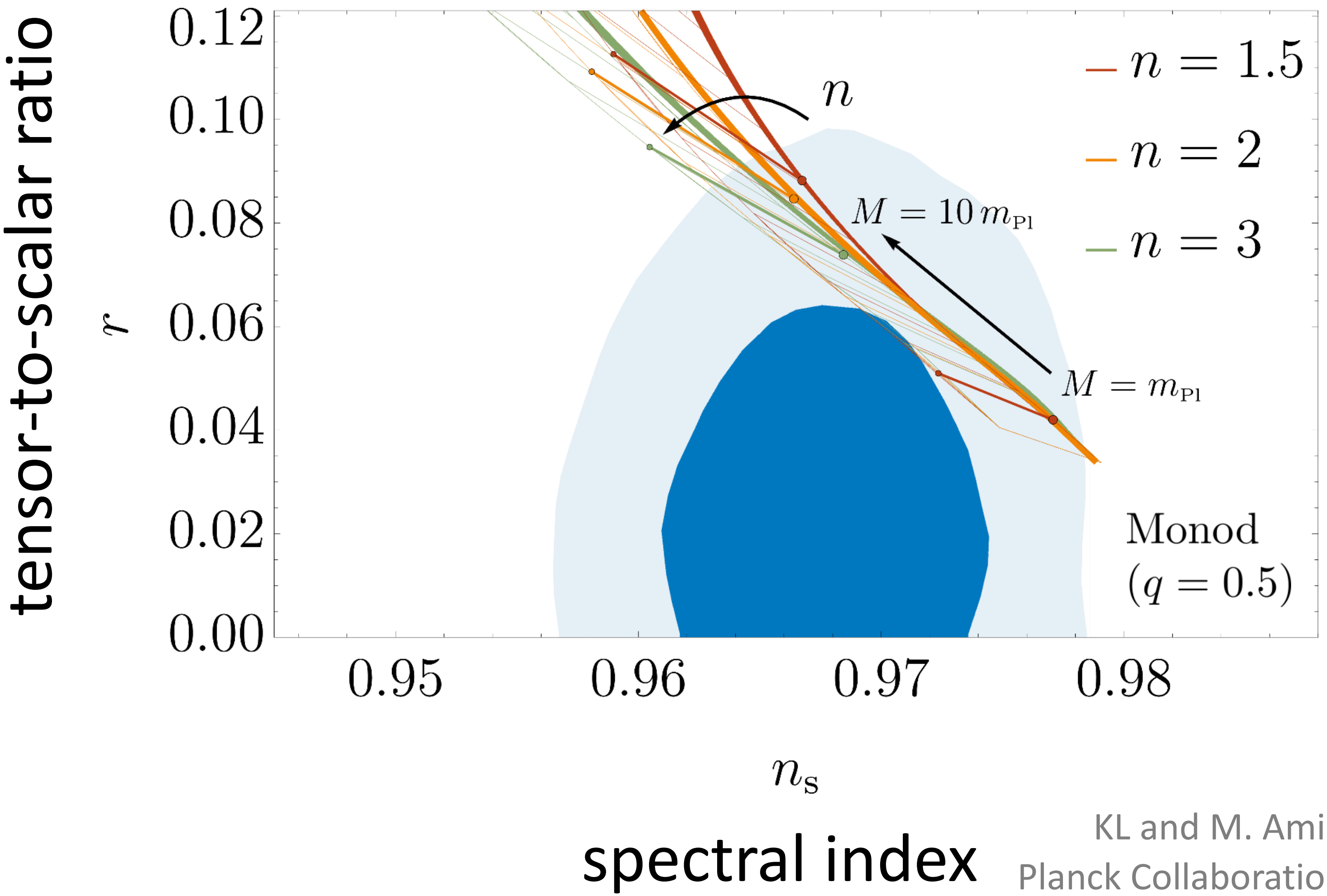
Expansion history effects

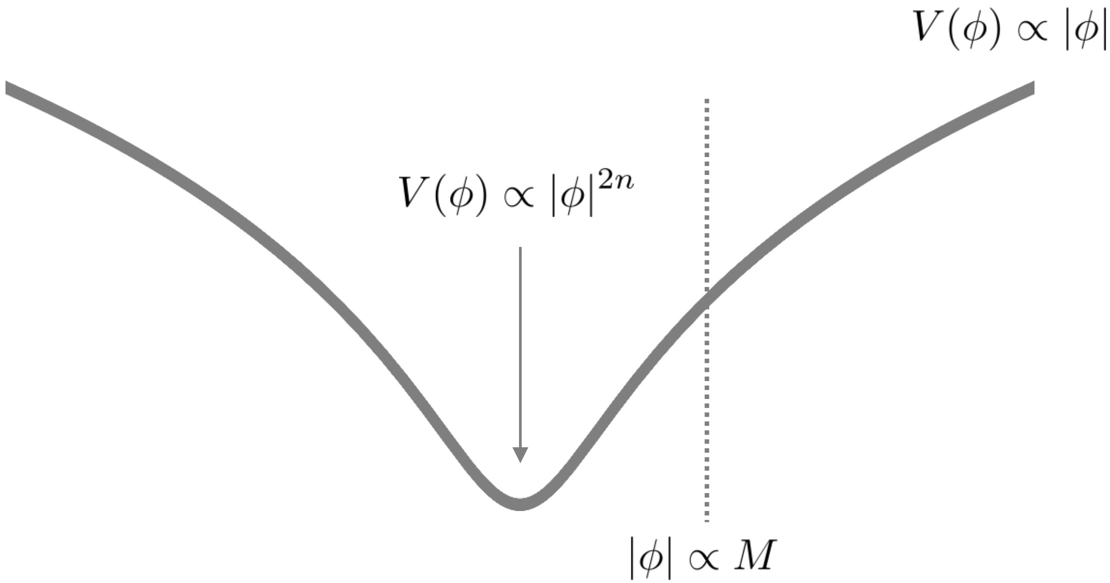


KL and M. Amin (2016)
Planck Collaboration (2015)

Expansion history effects

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

Monodromy
$q = 1$



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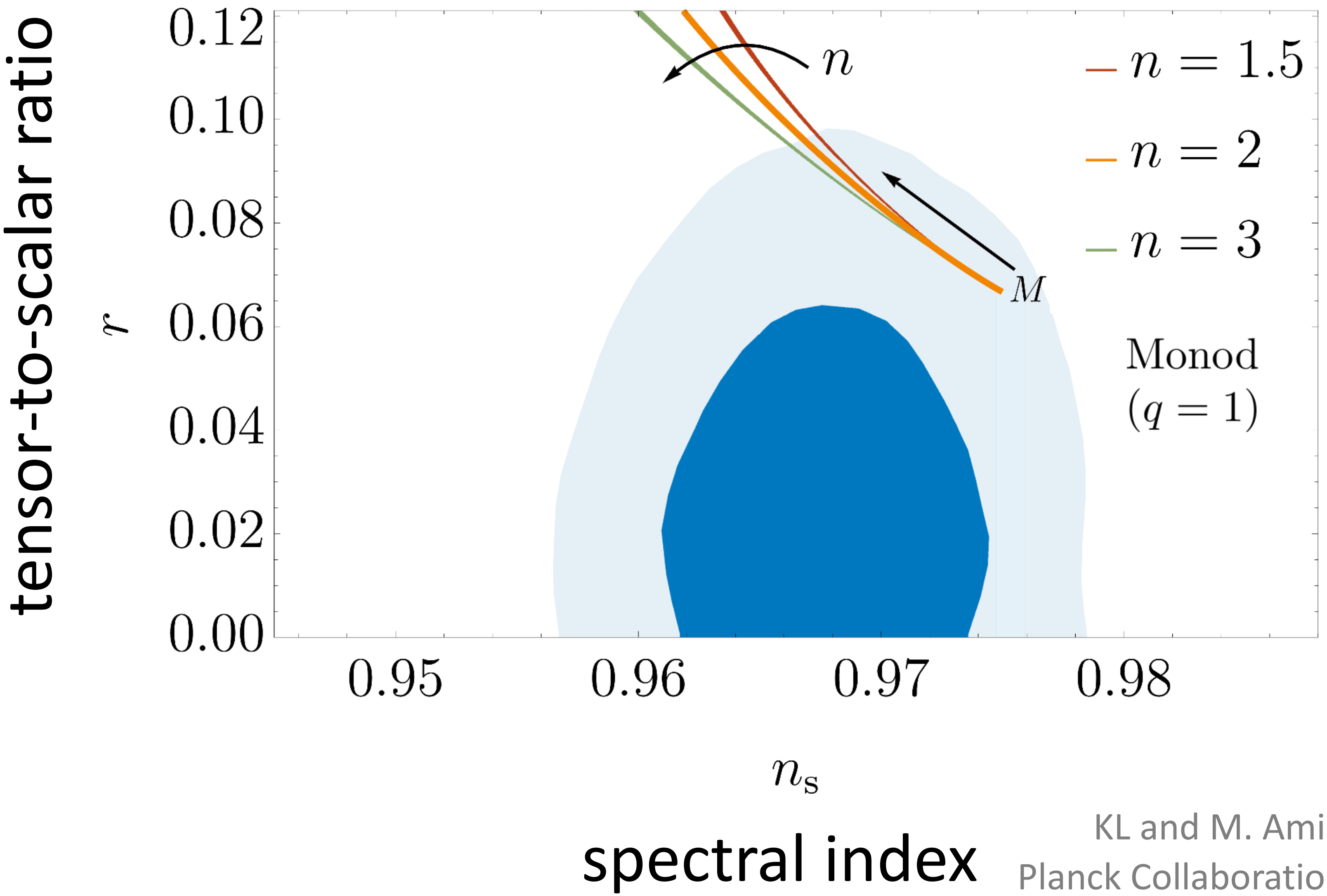

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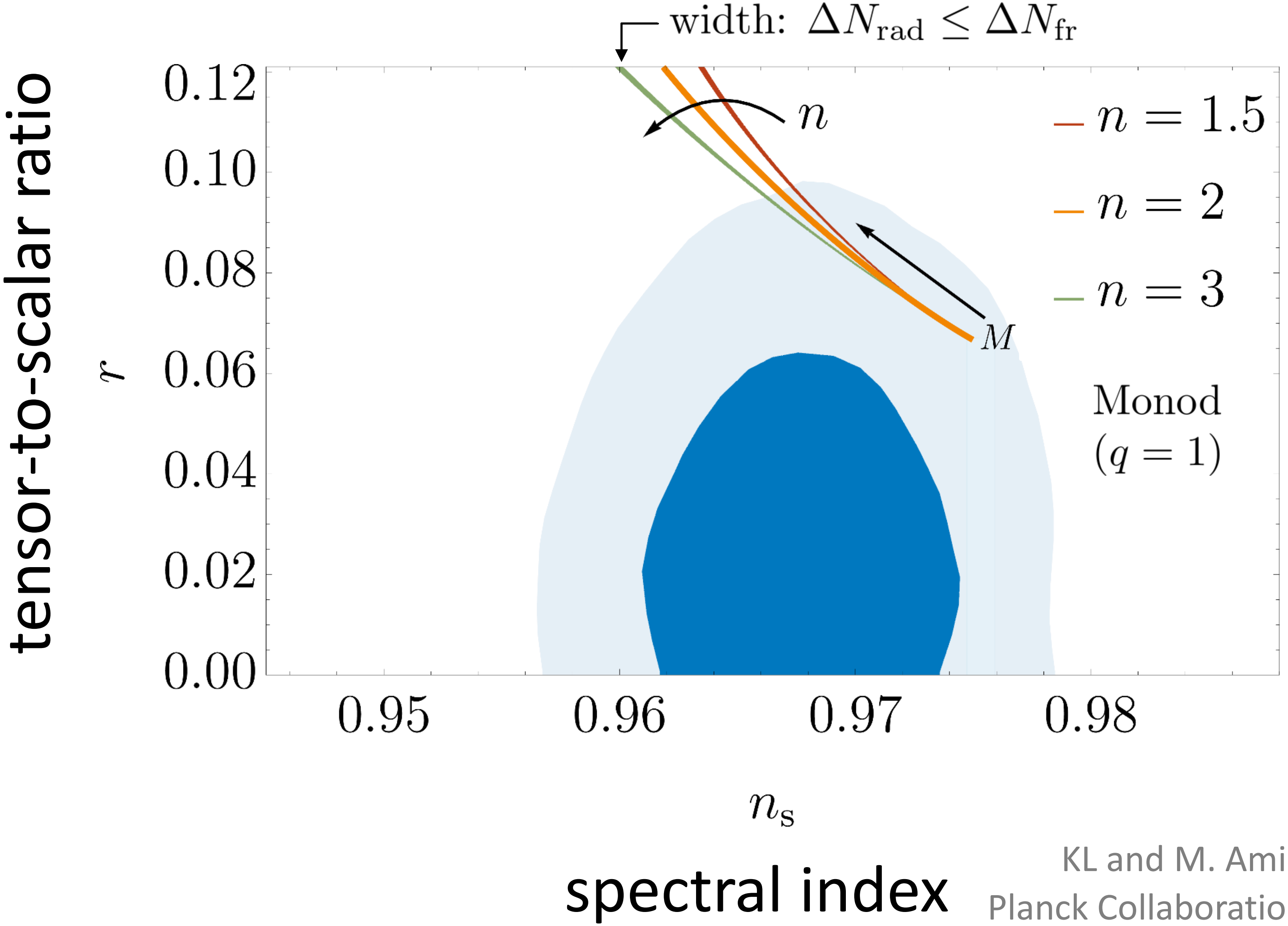

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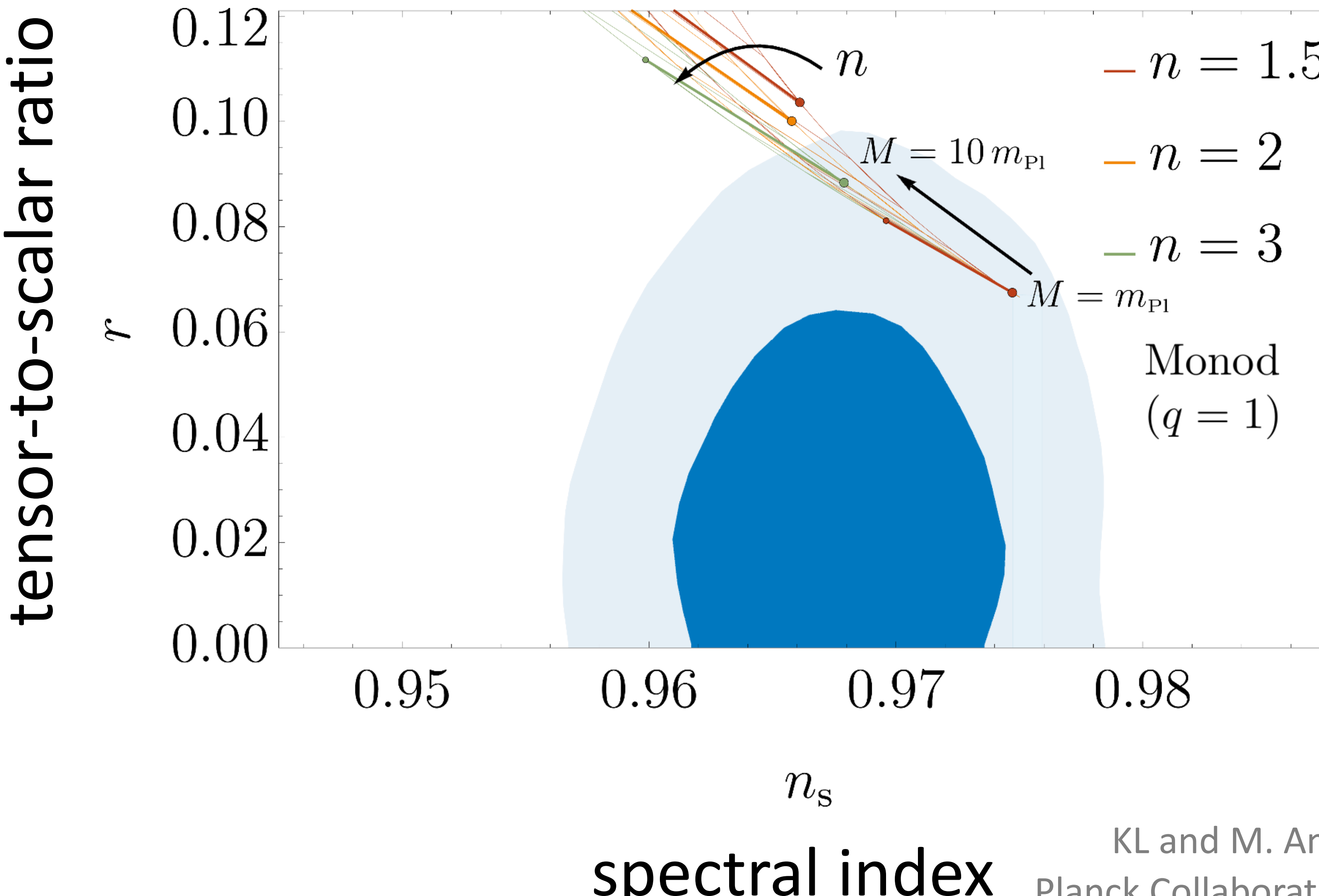

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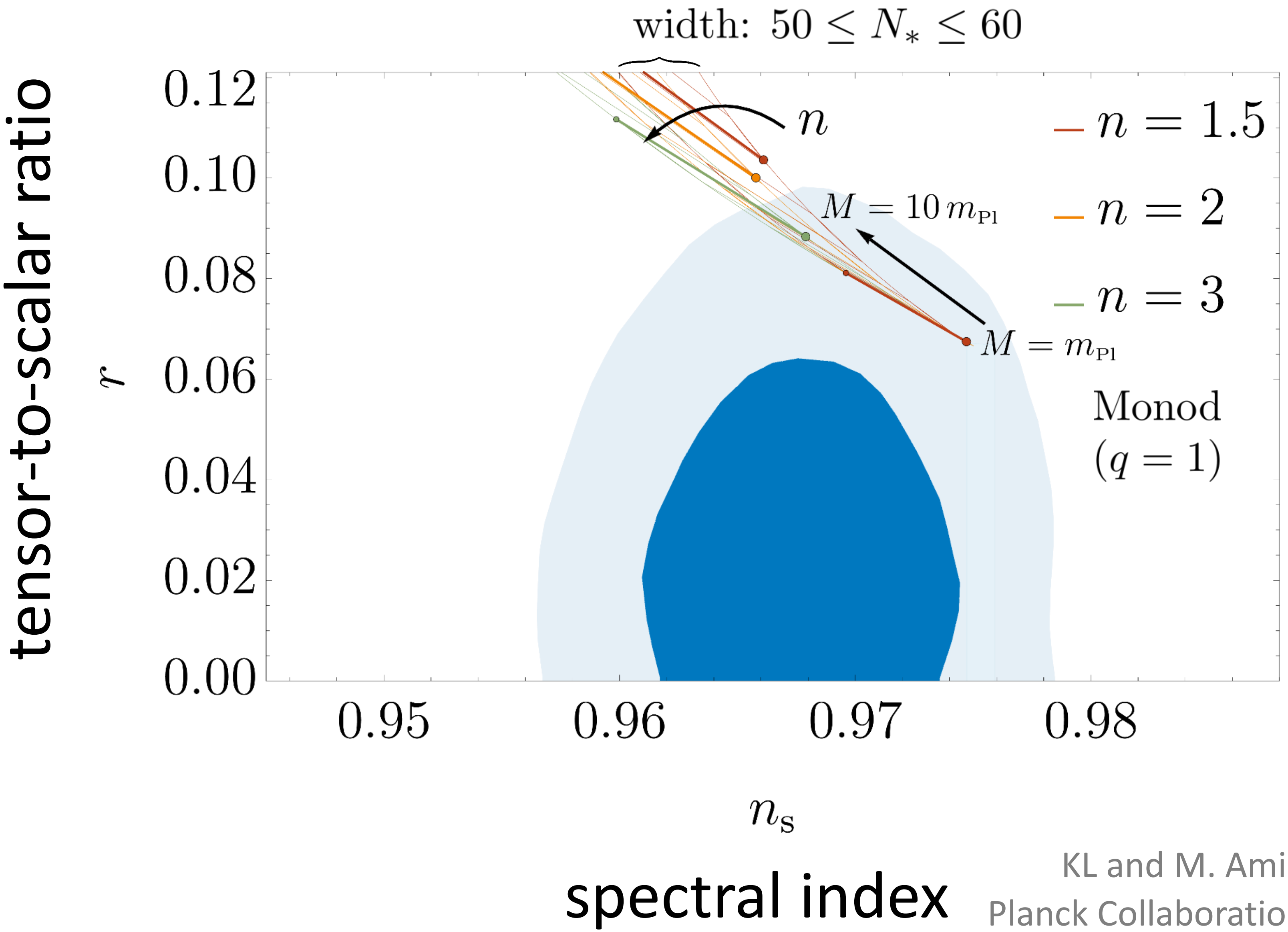

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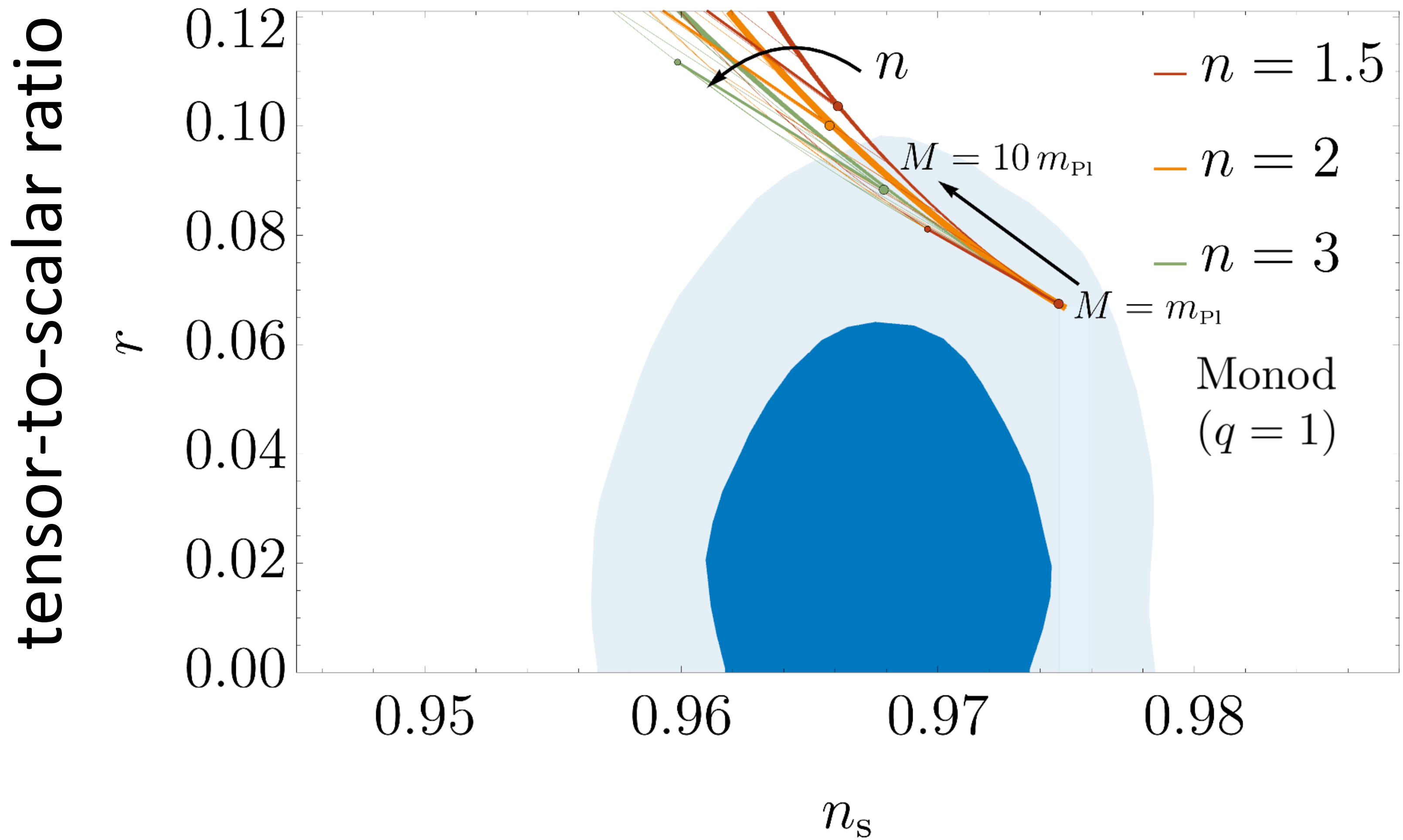
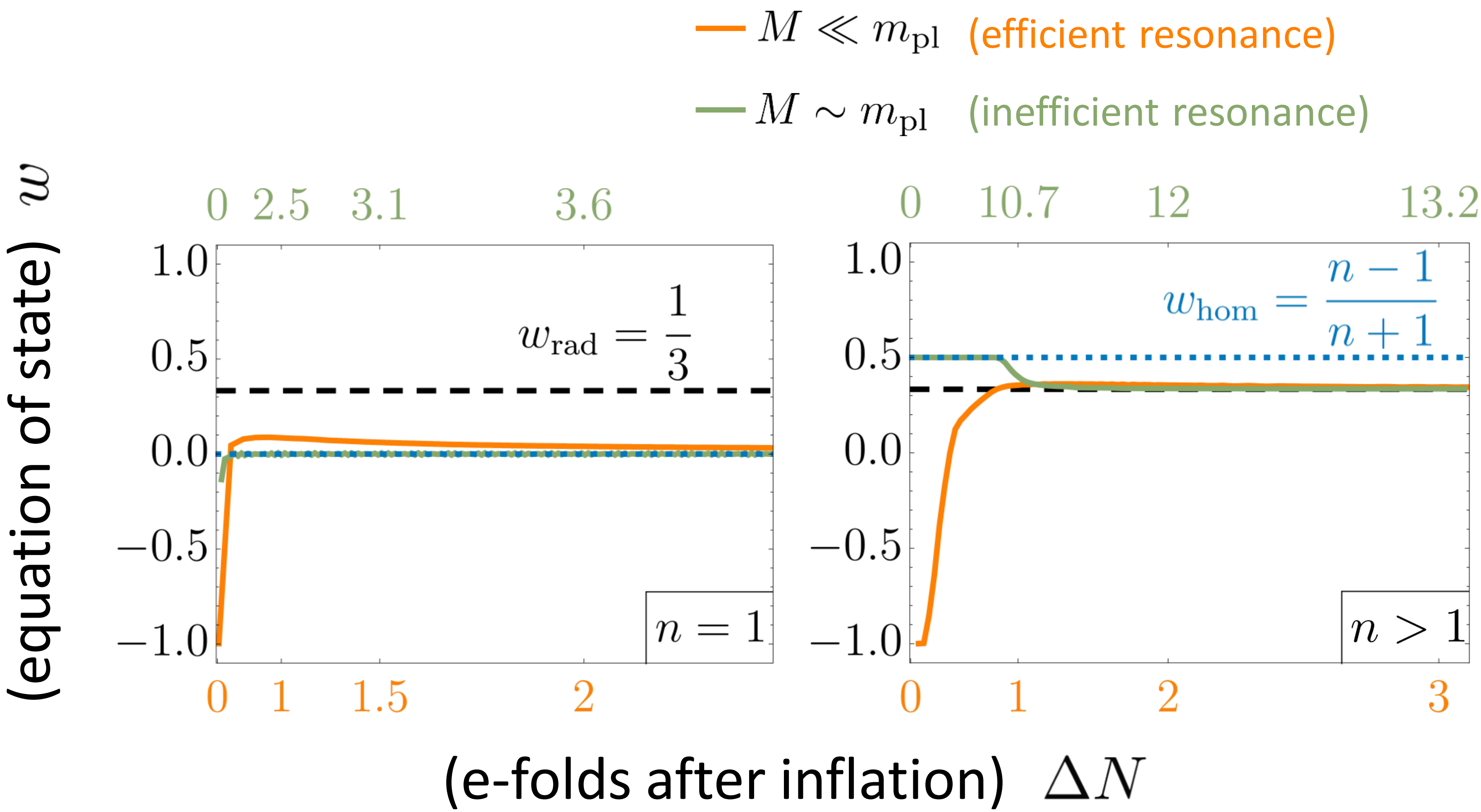


spectral index

KL and M. Amin (2016)
Planck Collaboration (2015)

Equation of state



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

Matter domination?

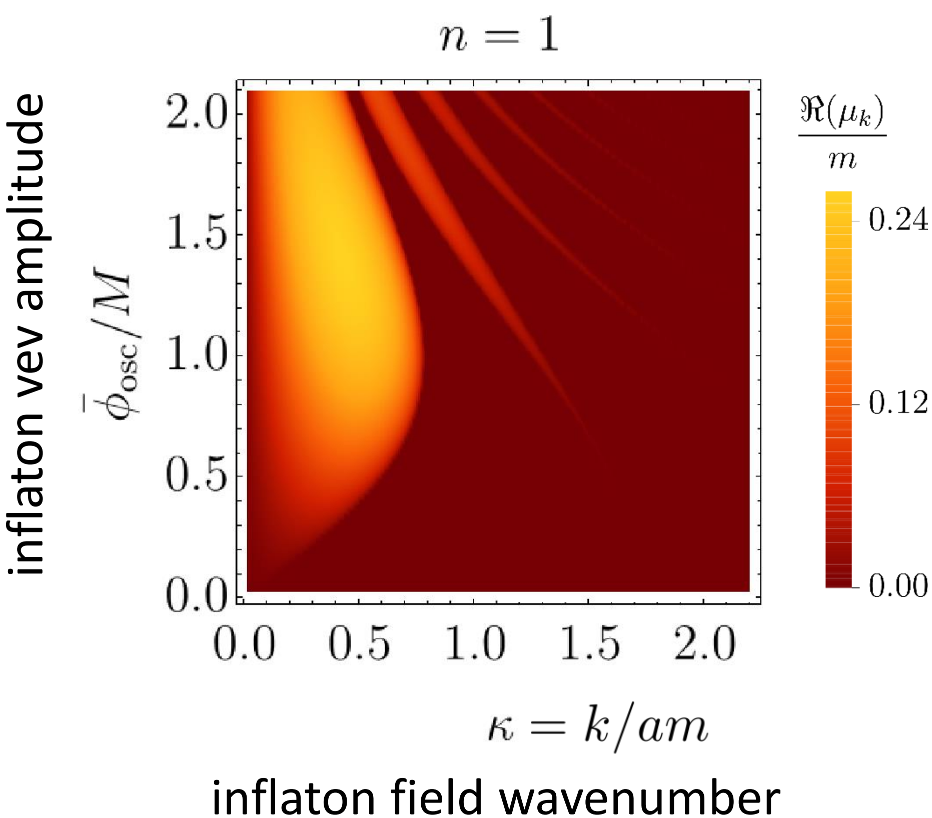
$$n = 1$$

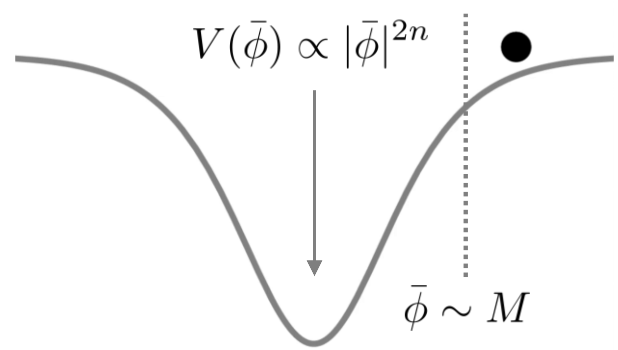
Matter domination?

$$n = 1$$

KL and M. Amin (2016)

Non-perturbative decay (parametric self-resonance)





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

See also Amin, Hertzberg + (2011), Fukunaga, Kitajima and Urakawa (2019) $m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$

Matter domination?

$$n = 1$$

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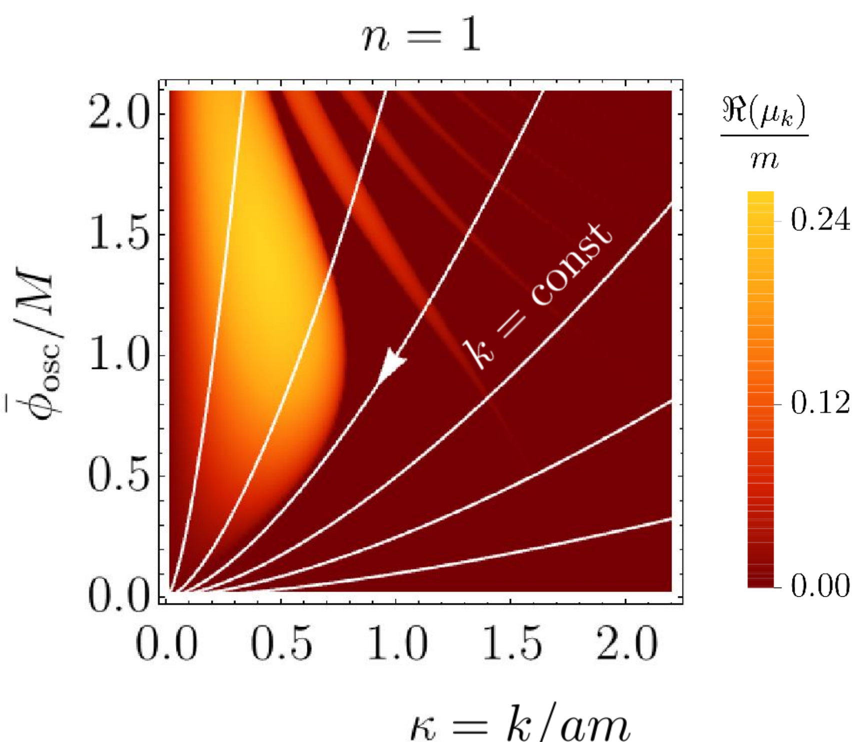
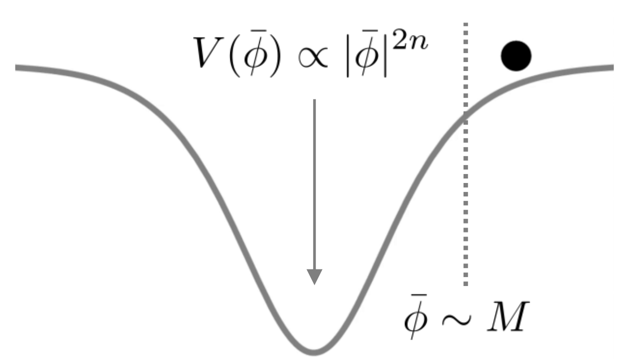
Non-perturbative decay (parametric self-resonance)

inflaton vev amplitude



inflaton field wavenumber



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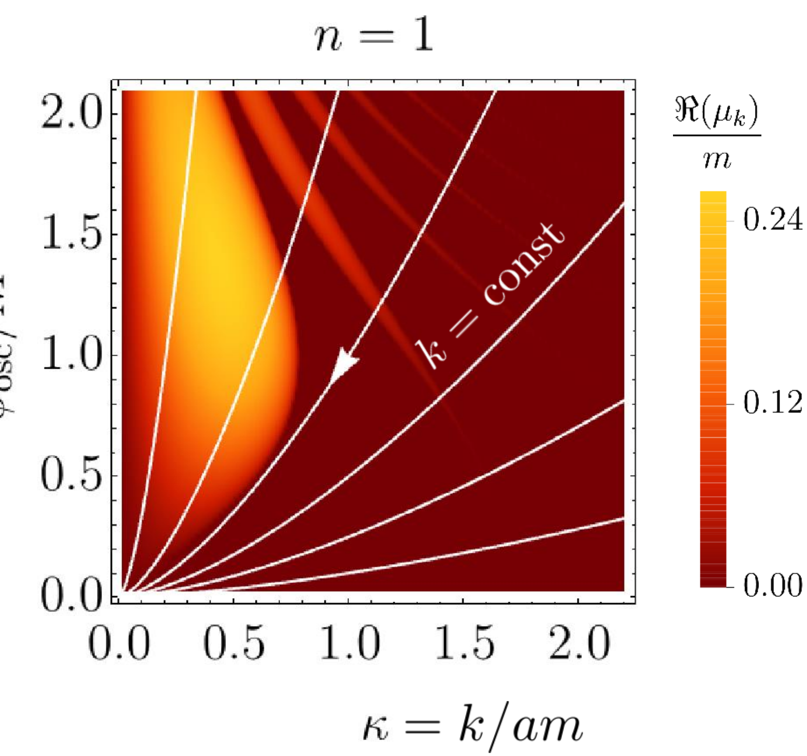
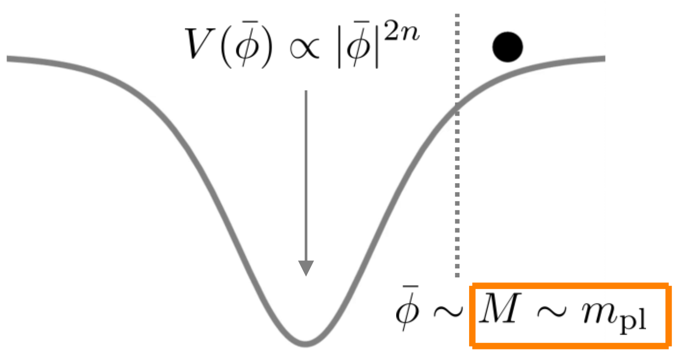


inflaton field wavenumber



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

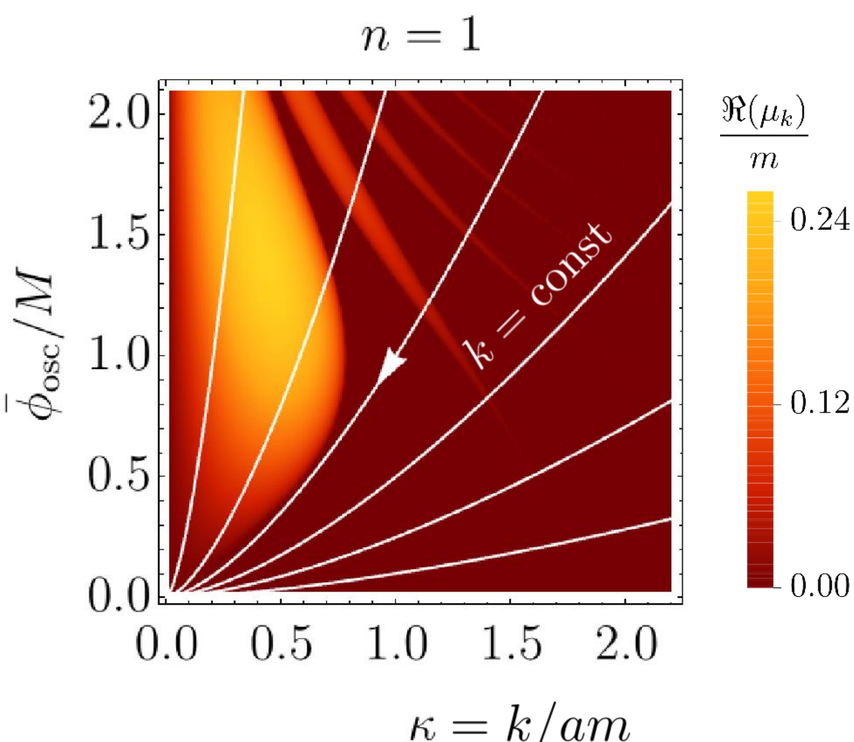
See also Amin, Hertzberg + (2011), Fukunaga, Kitajima and Urakawa (2019) $m^2 \equiv V'(\bar{\phi}_{\rm osc})/\bar{\phi}_{\rm osc}$

Matter domination?

$$n = 1$$

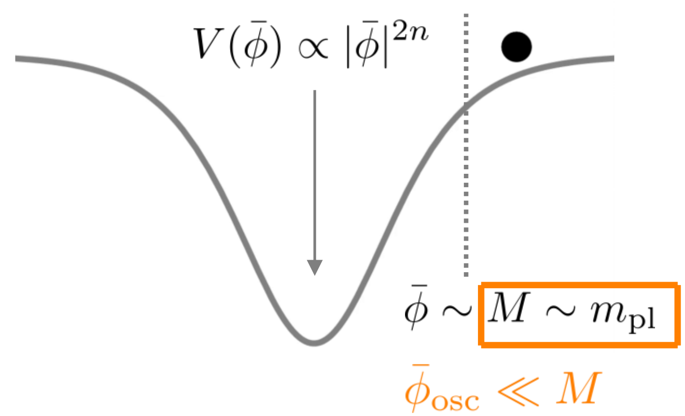
KL and M. Amin (2016)

Non-perturbative decay (parametric self-resonance)



inflaton vev amplitude

inflaton field wavenumber



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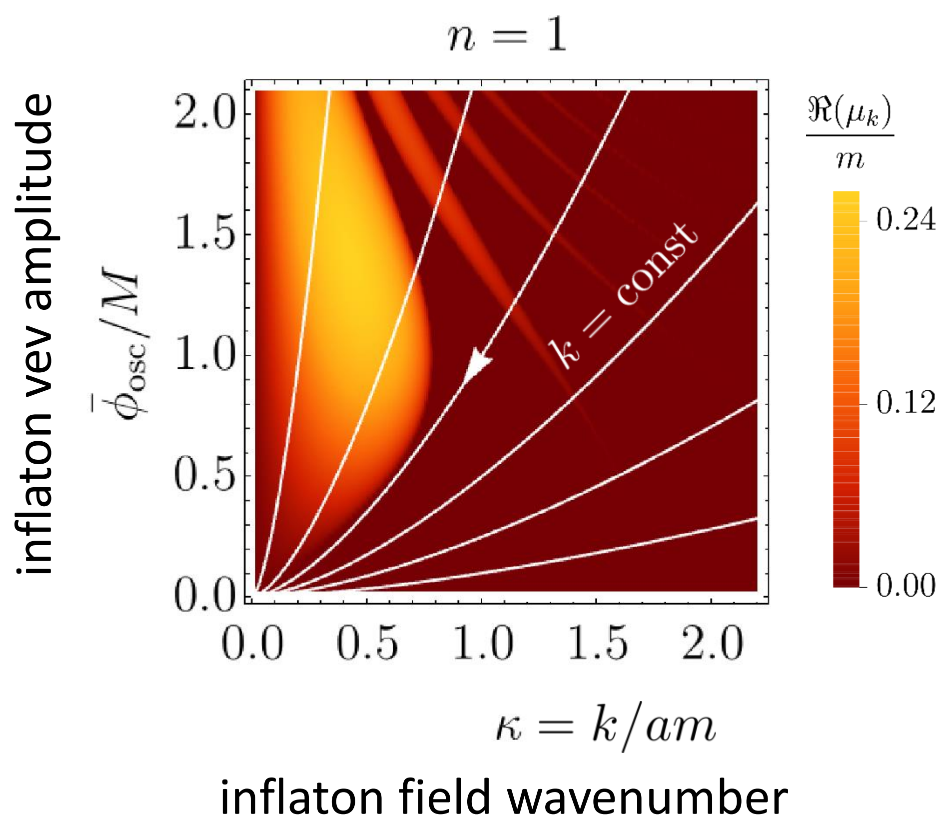
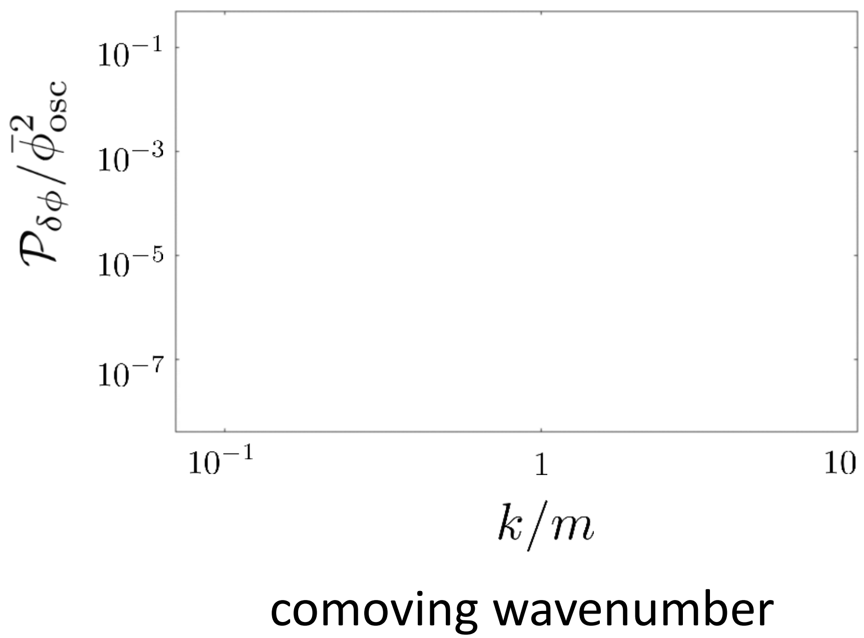


Power spectrum:

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



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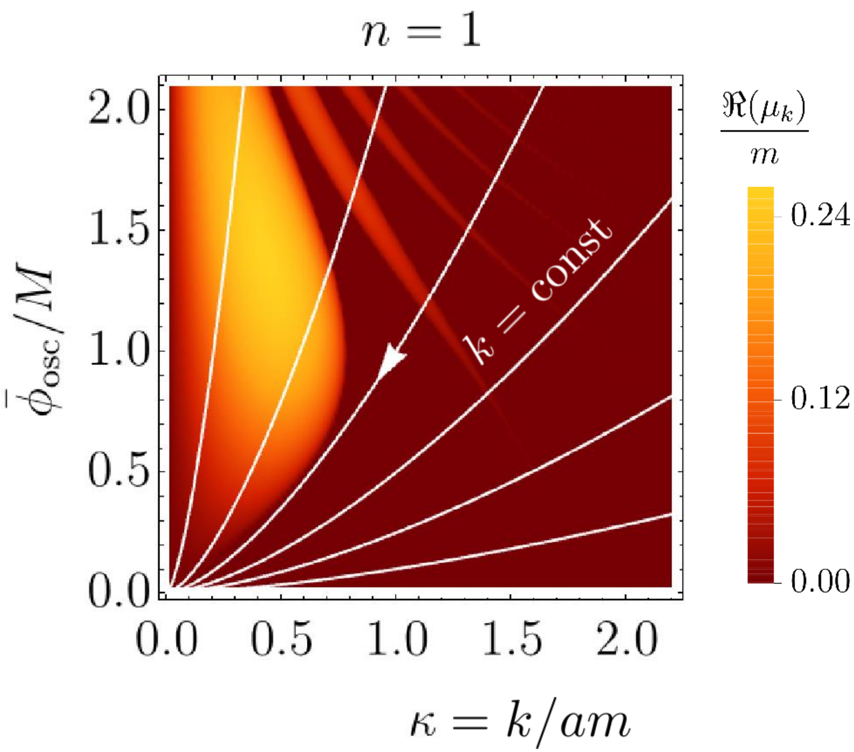

inflaton field wavenumber

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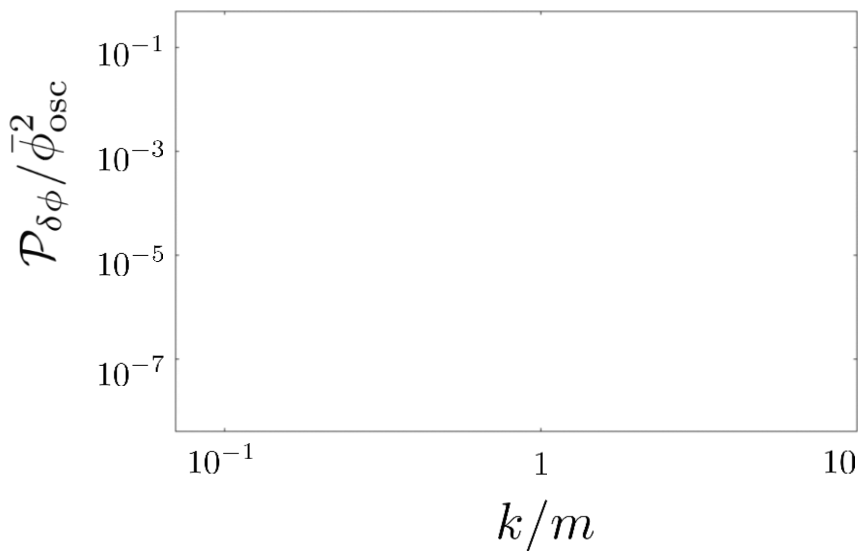

comoving wavenumber

Matter domination?

$$n = 1$$

KL and M. Amin (2016)

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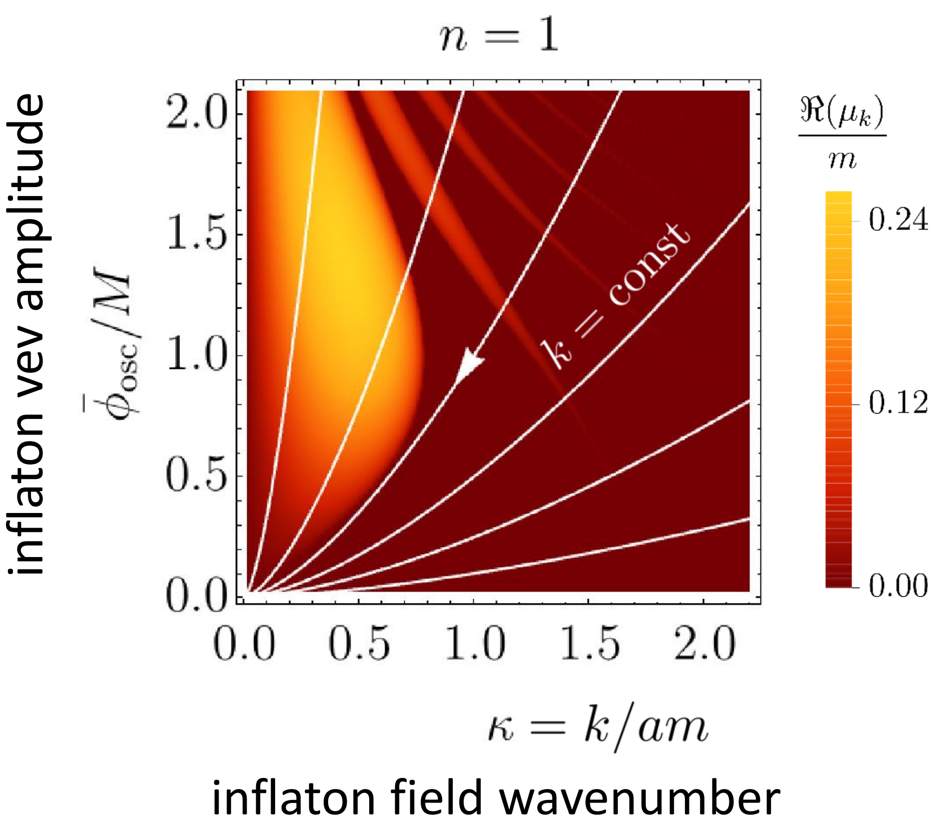

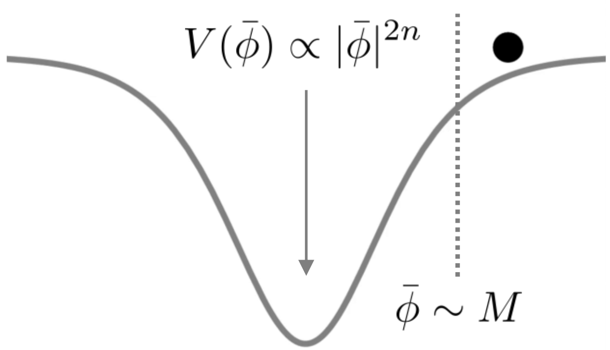

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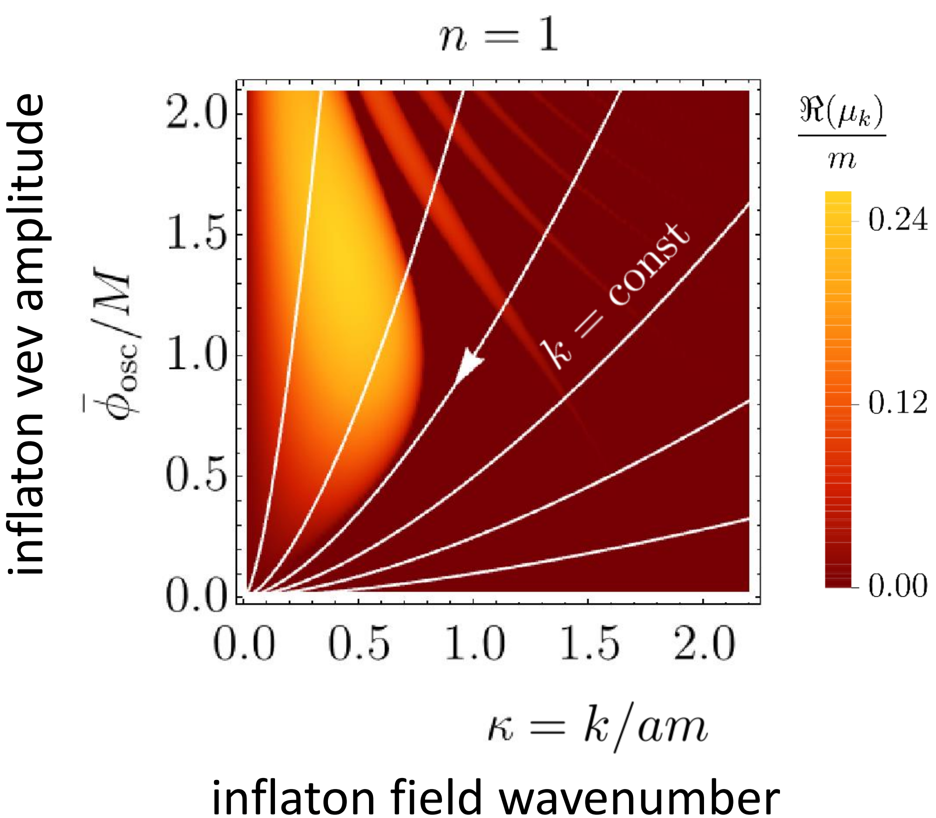

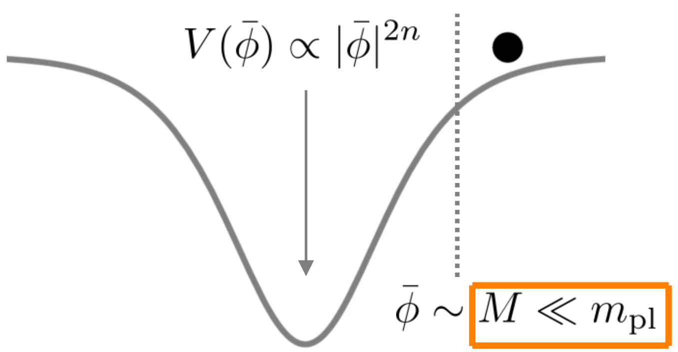

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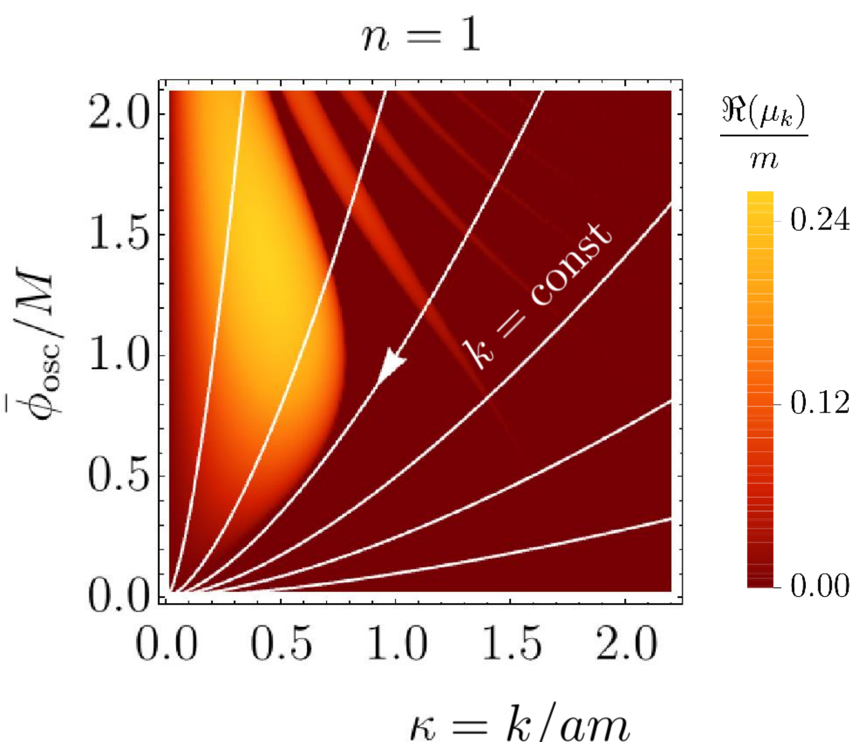
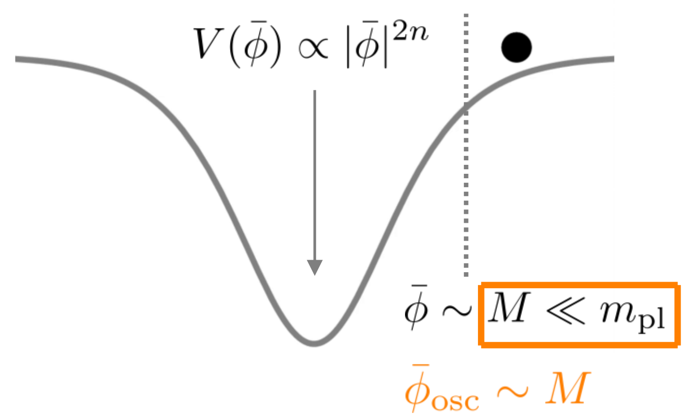


inflaton field wavenumber



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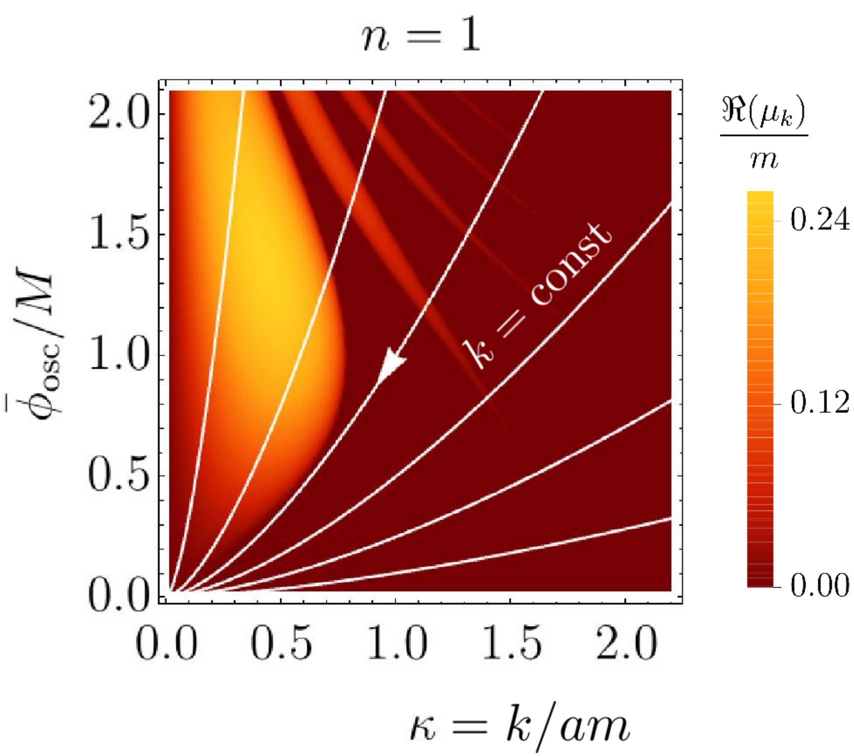

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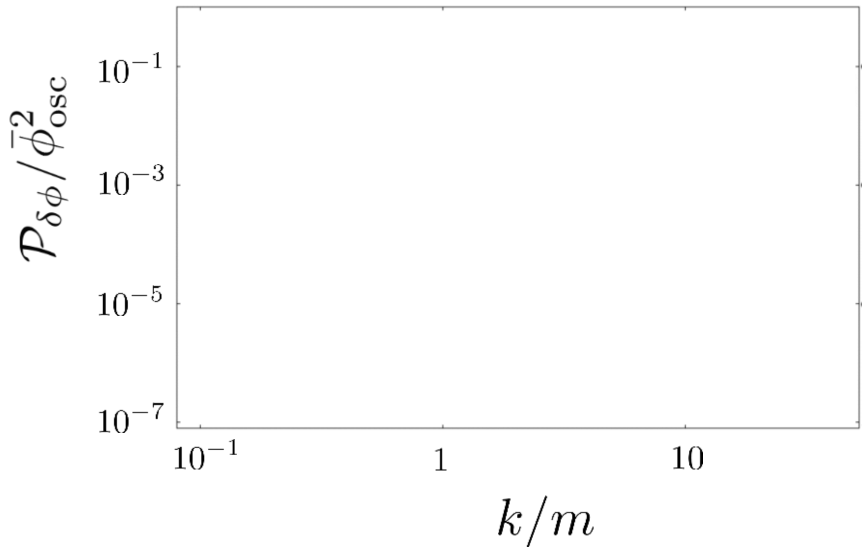

comoving wavenumber

Matter domination?

$$n = 1$$

KL and M. Amin (2016)

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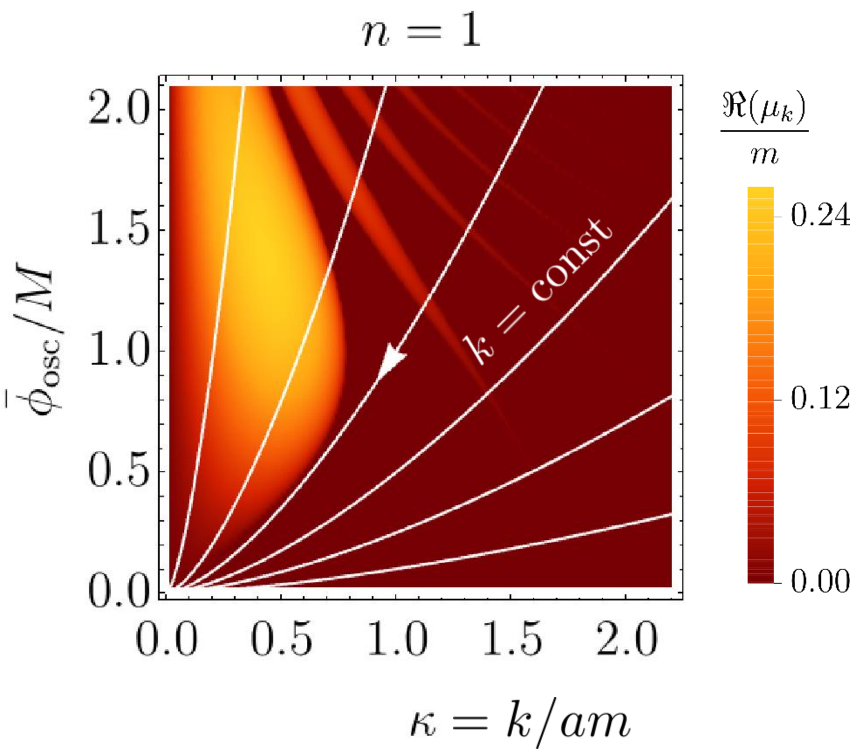
inflaton vev amplitude



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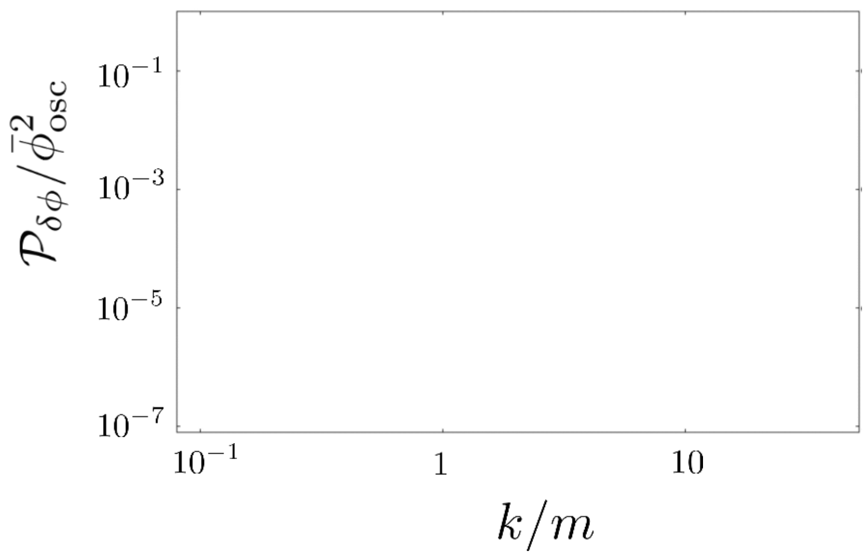
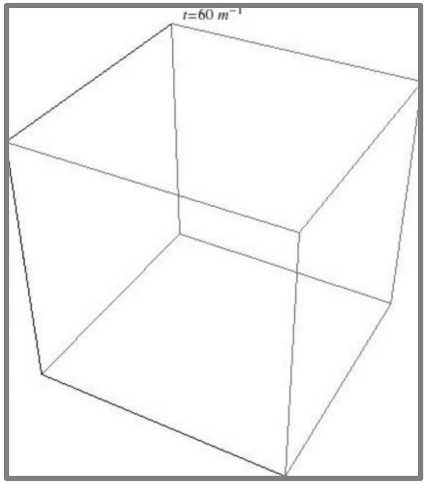


comoving wavenumber

Matter domination?

$$n = 1$$

$M \ll m_{\rm pl}$



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

  See also Amin, Hertzberg et al (2011),
  Urakawa's talk, Kitajima's talk, Torrenti's talk

$M \sim m_{\rm pl}$

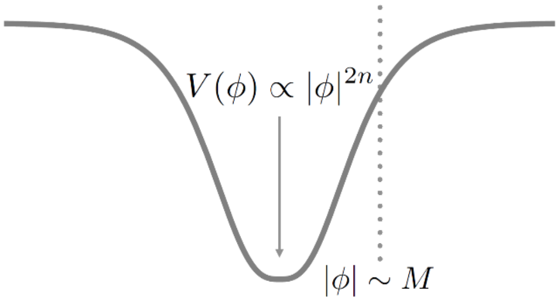
- $\delta\phi(t, \mathbf{x})$ production shut off
- $\bar{\phi}_{\rm osc}(t) =$ pressureless dust

matter-like eos: $w = 0$

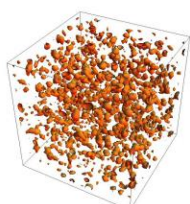
couplings to other fields?

See also Hertzberg (2010), Adshead et al (2015)

Summary



observationally
favored $V(\phi)$



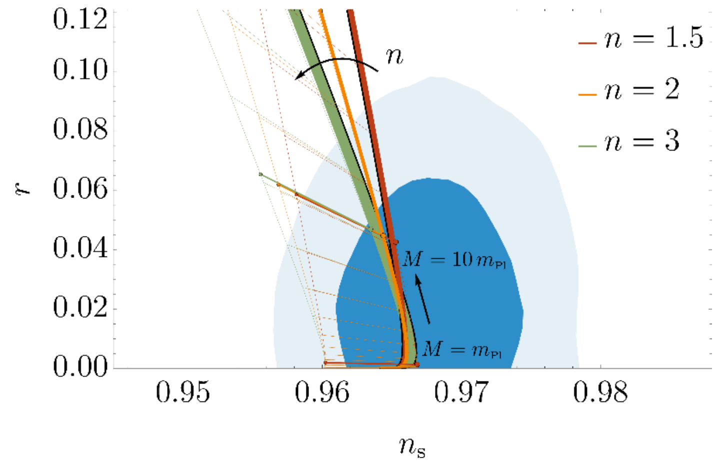
simple result

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

(even without couplings to other fields!)

(at sufficiently late times)

KL and M. Amin, PRD 97 023533 (2017)
KL and M. Amin, PRL 119 061301 (2016)



Reduction in
theoretical uncertainty of
inflationary models

Other connections …

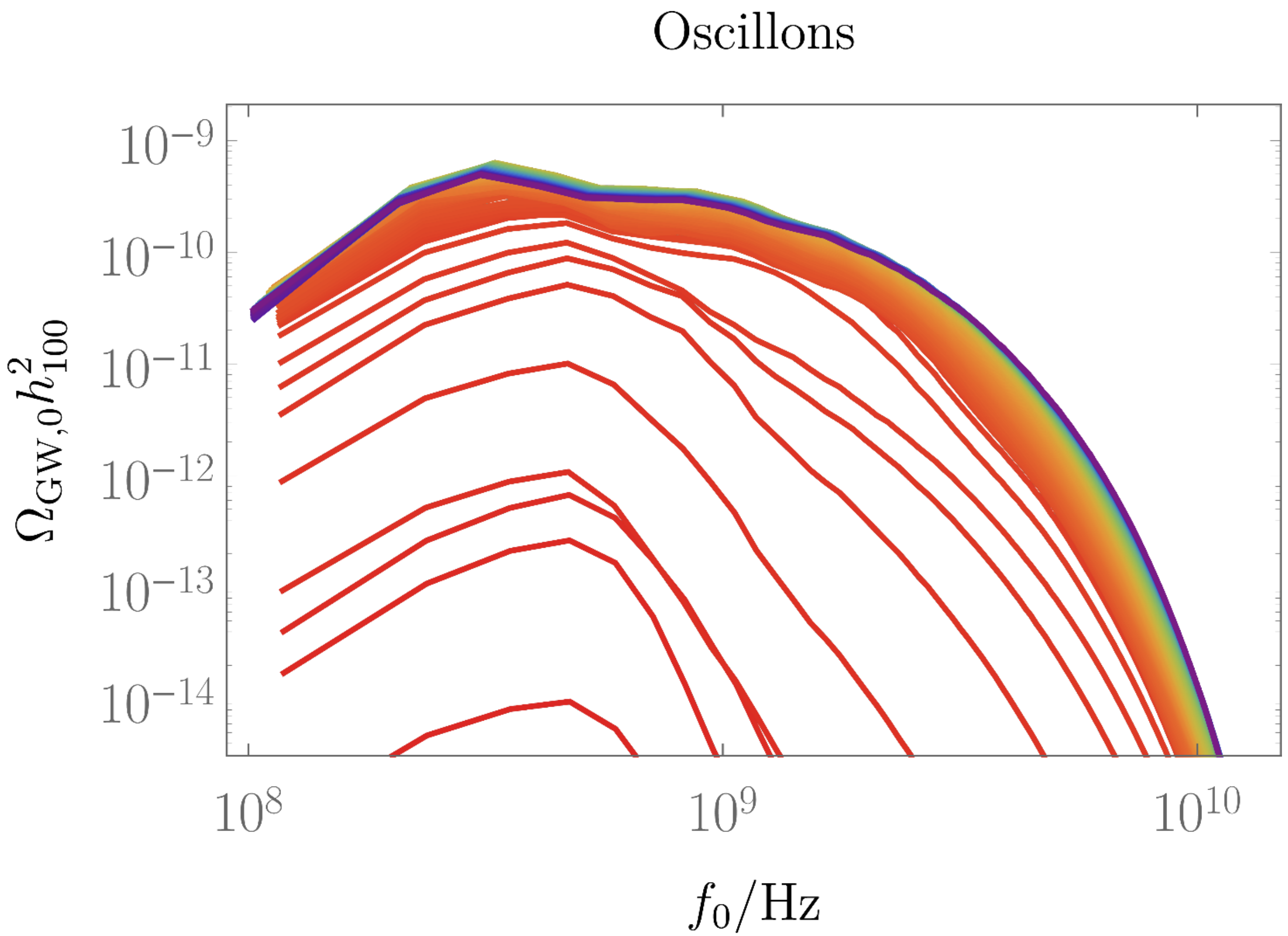
Other connections …

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

Other connections …

- stochastic GWs from fragmentation

KL and M. Amin (2019)



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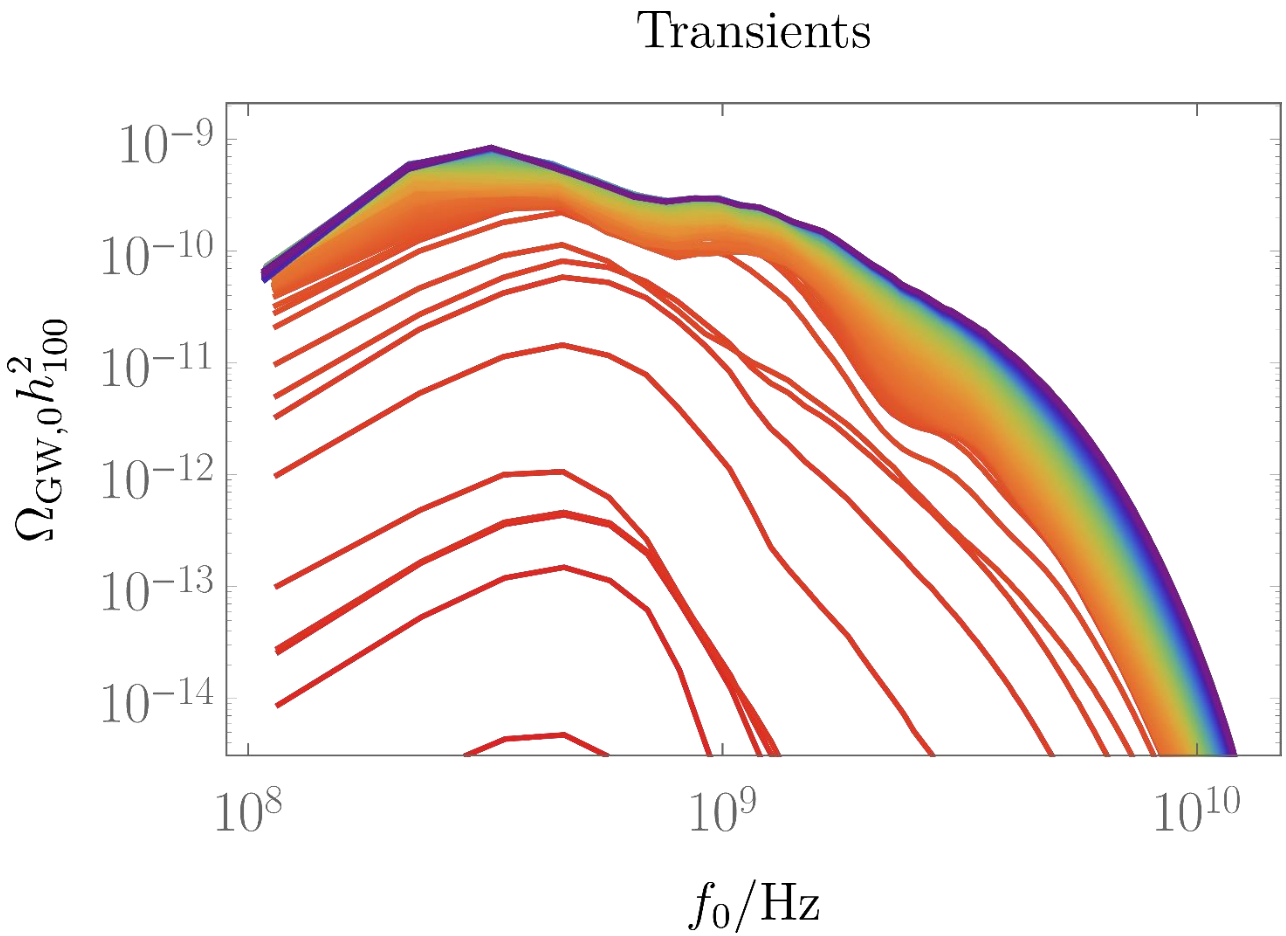

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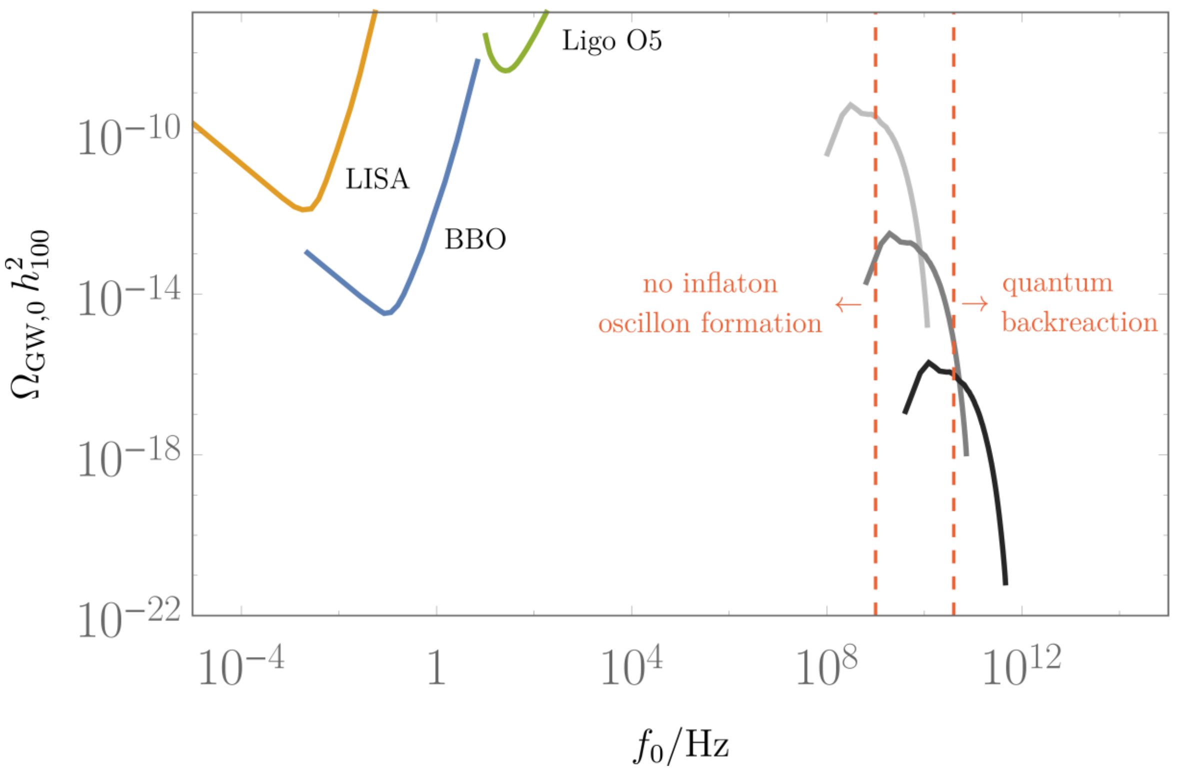
INFLATON oscillons



See also Antusch et al (2016), Soda and Urakawa (2017), Kitajima, Soda and Urakawa (2018)

Other connections …

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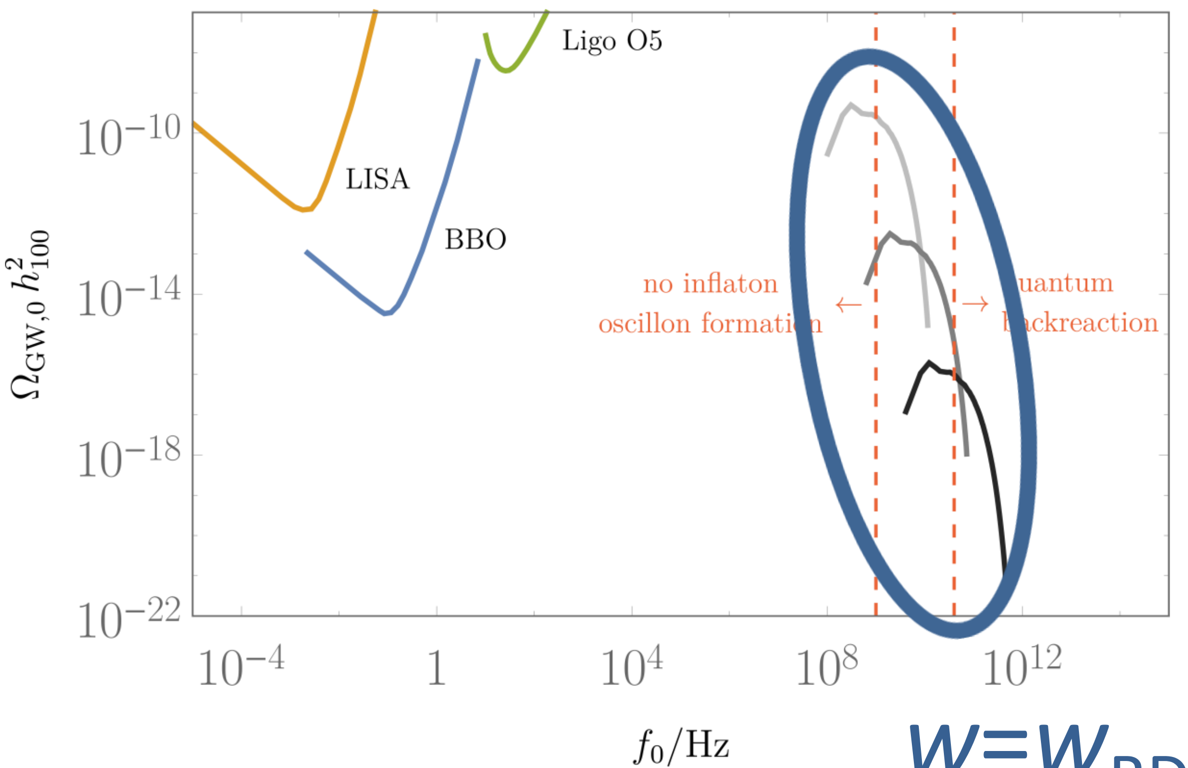
INFLATON oscillons



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

See also Antusch et al (2016), Soda and Urakawa (2017), Kitajima, Soda and Urakawa (2018)

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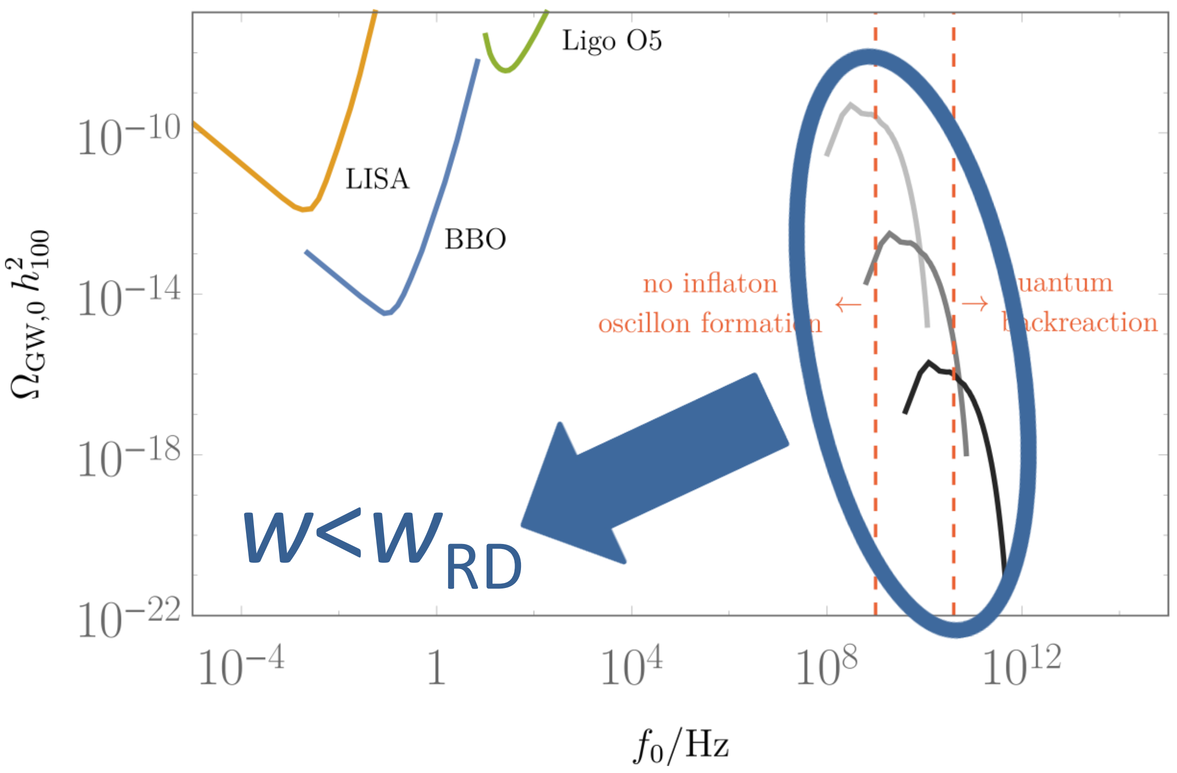
INFLATON oscillons



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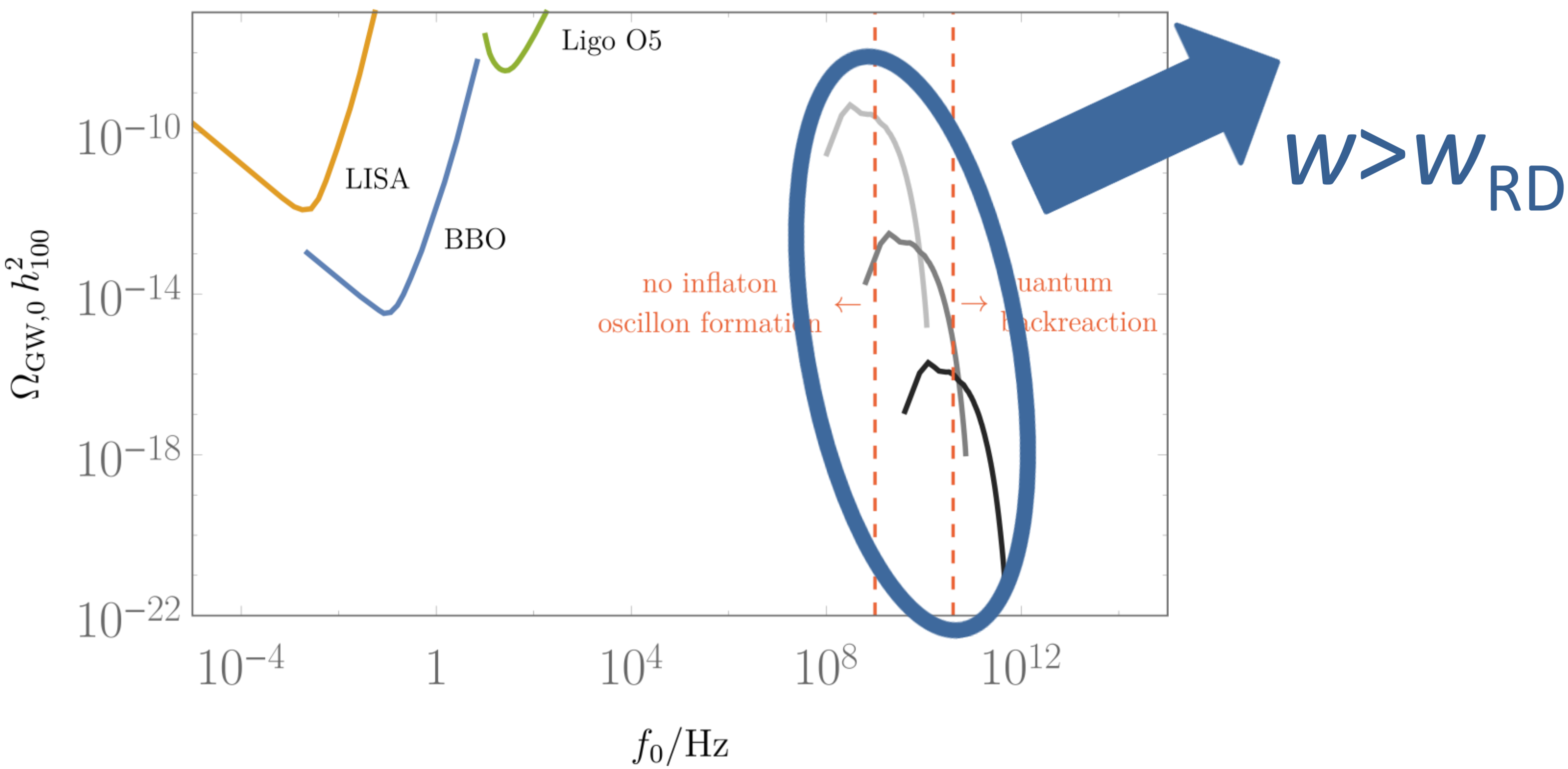

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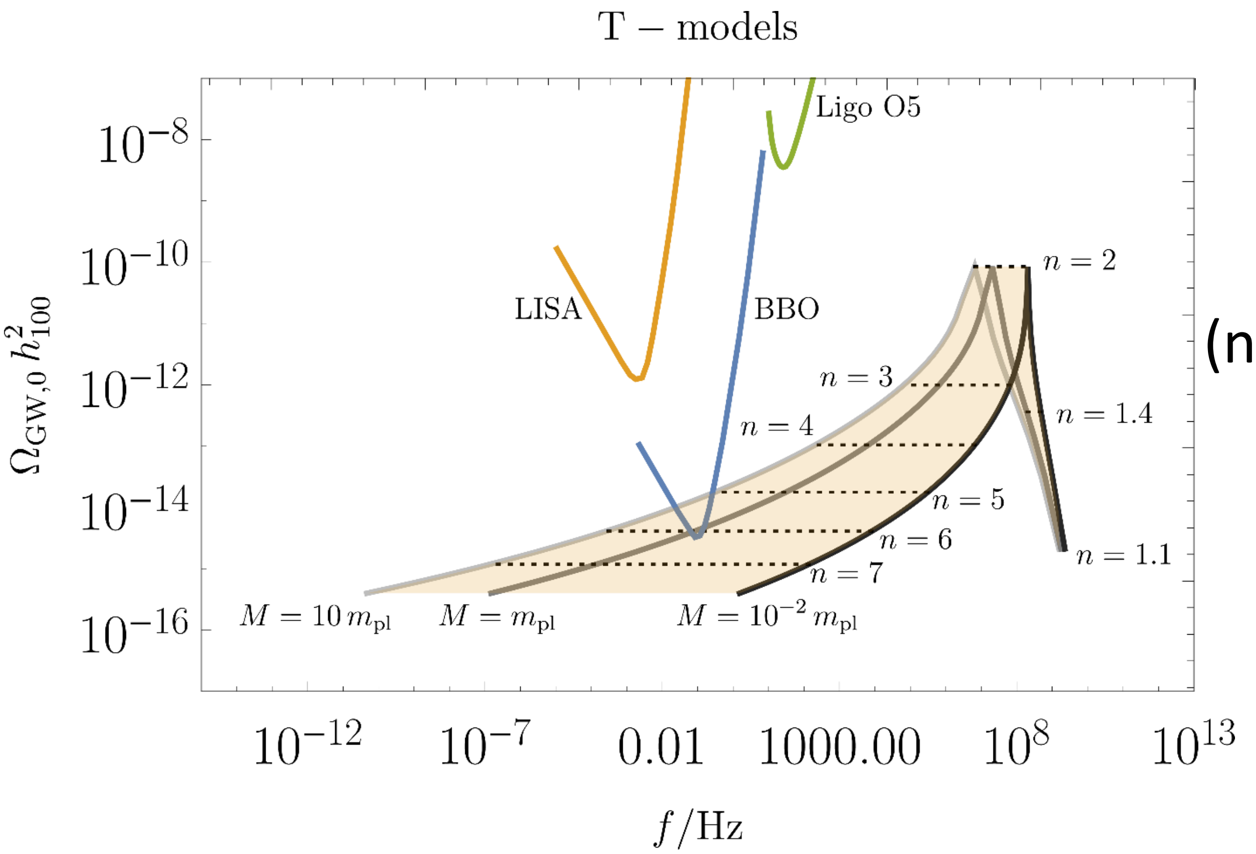
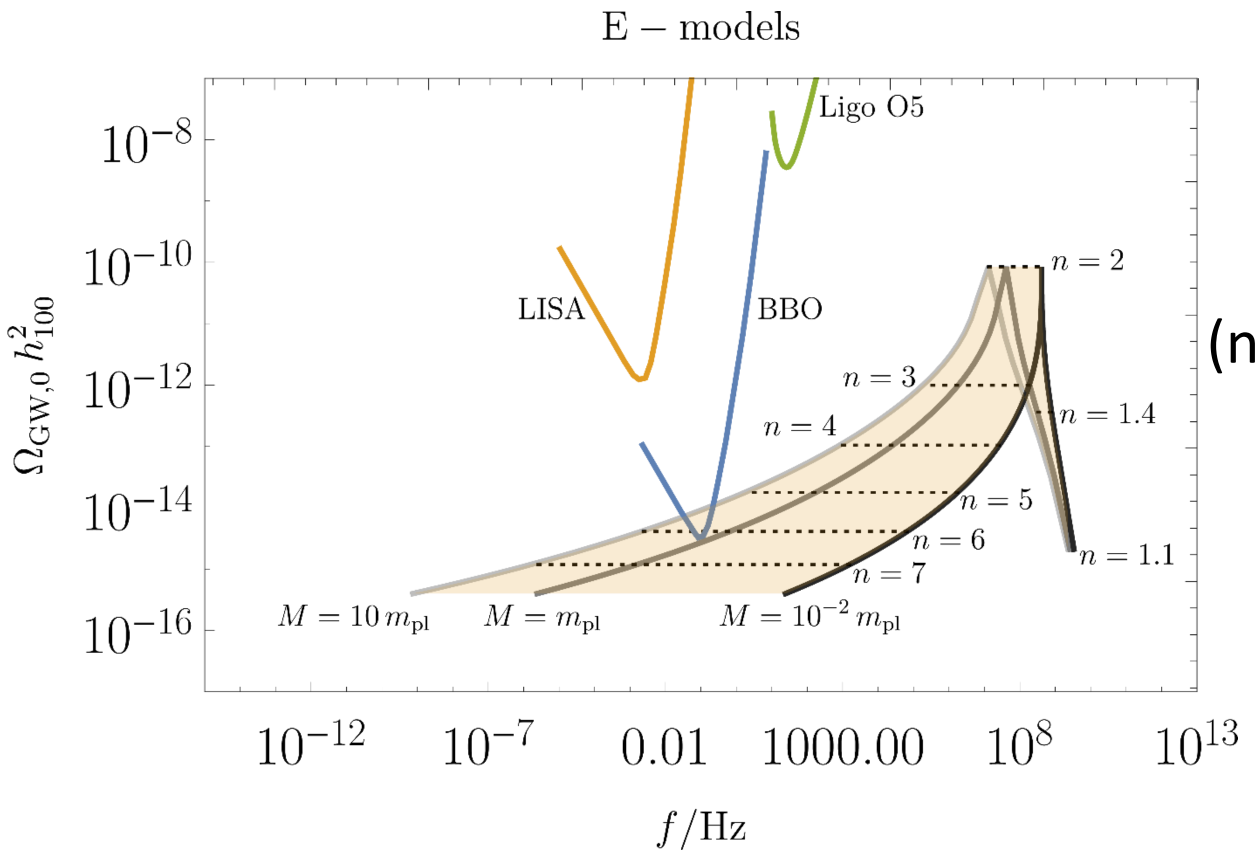


(narrow band)

Other connections …

- stochastic GWs from fragmentation

KL and M. Amin (2019)



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Other connections …

- stochastic GWs from fragmentation

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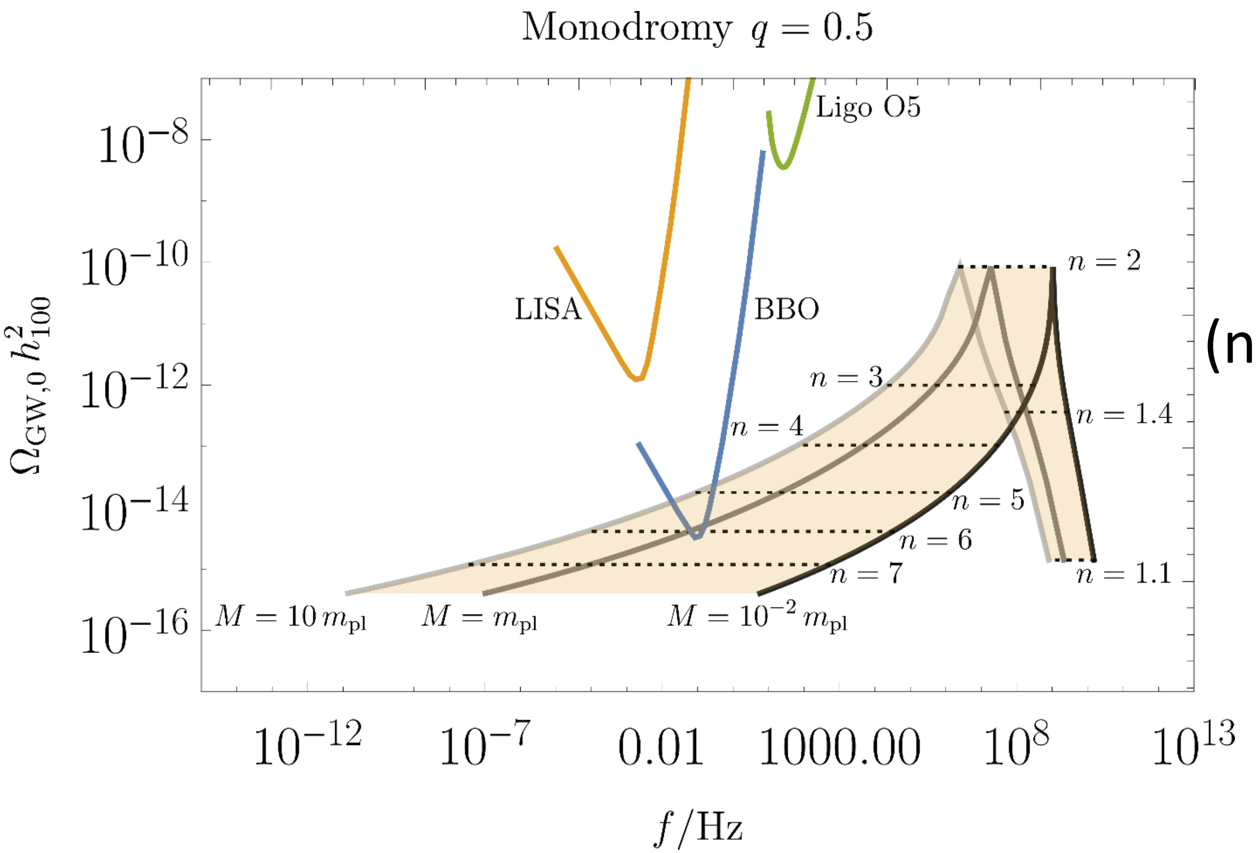

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Other connections …

- stochastic GWs from fragmentation

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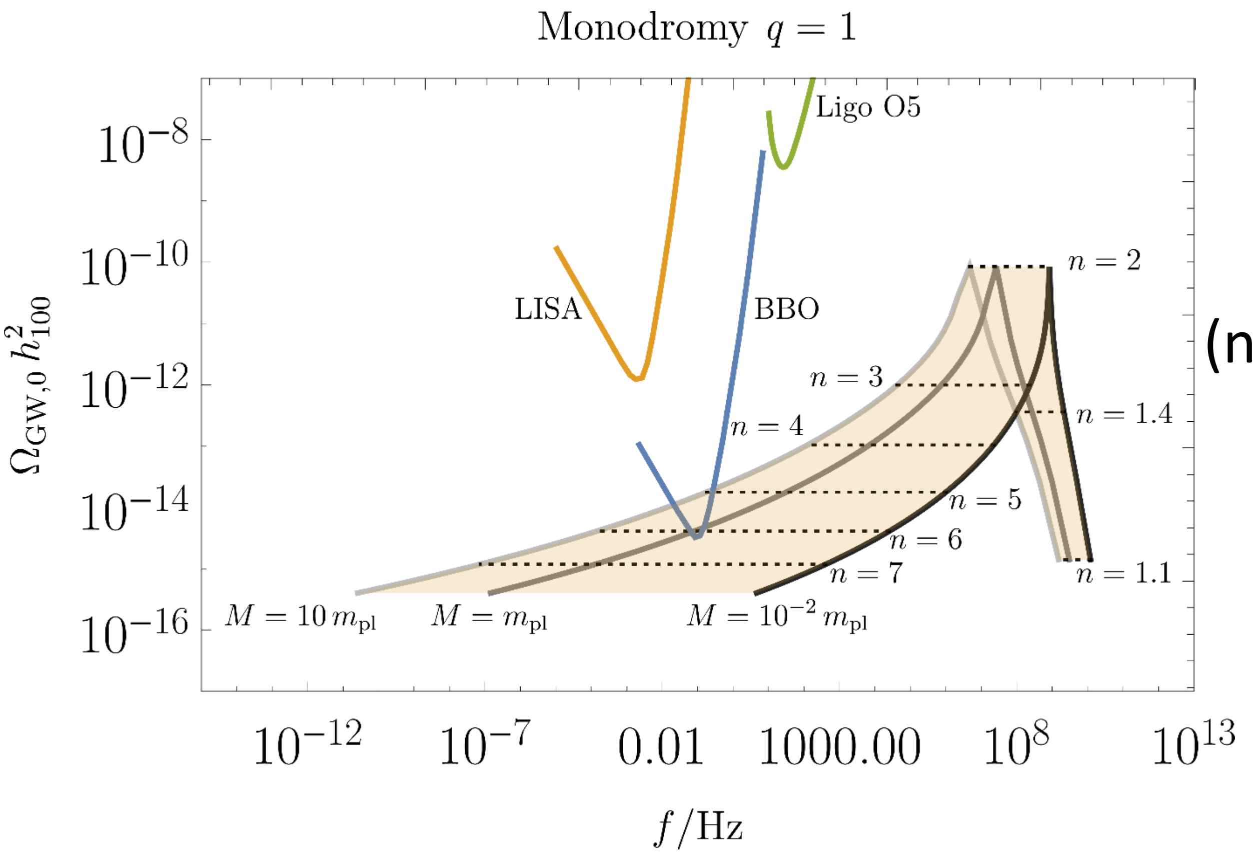


(narrow band)

Other connections …

- stochastic GWs from fragmentation — KL and M. Amin (2019)
- dark energy — P. Agrawal, L. Randall, et al (2019)

Other connections …

- stochastic GWs from fragmentation KL and M. Amin (2019)
- dark energy P. Agrawal, L. Randall, et al (2019)
- dark matter

Other connections …

- stochastic GWs from fragmentation — KL and M. Amin (2019)
- dark energy — P. Agrawal, L. Randall, et al (2019)
- dark matter
- matter-antimatter asymmetry… — KL and M. Amin (2014)

Oscillons and matter-antimatter asymmetry

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

Main idea

complex
inflaton ϕ
+ ~~U(1)~~

↓ dynamics at the end of inflation

inflaton/anti-inflaton
asymmetry

↓ decay

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

The model

A variation of the Affleck-Dine Mechanism (1985)
Hertzberg & Karouby (2013, 2014)

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} \mathcal{R} + |\partial\phi|^2 - V(\phi, \phi^*) \right]$$

$$V(\phi, \phi^*) = V_{\mathrm{s}}(|\phi|) + V_{\mathrm{b}}(\phi, \phi^*)$$

respects U(1) symmetry

responsible for inflation

breaks U(1) symmetry

responsible for generating inflaton/antiinflaton asymmetry

$$V_{\mathrm{b}}(\phi, \phi^*) = \frac{c_n}{n}(\phi^n + \phi^{*n})$$

“small” symmetry breaking

- technically natural
- small during inflation
- small long after inflation

Inflaton asymmetry – baryon asymmetry

$$\Delta N_\phi = N_\phi - N_{\bar\phi} = i\int d^3x a^3(\phi^*\dot\phi - \dot\phi^*\phi)$$

inflaton number (**not conserved!**)

- generated at end of inflation

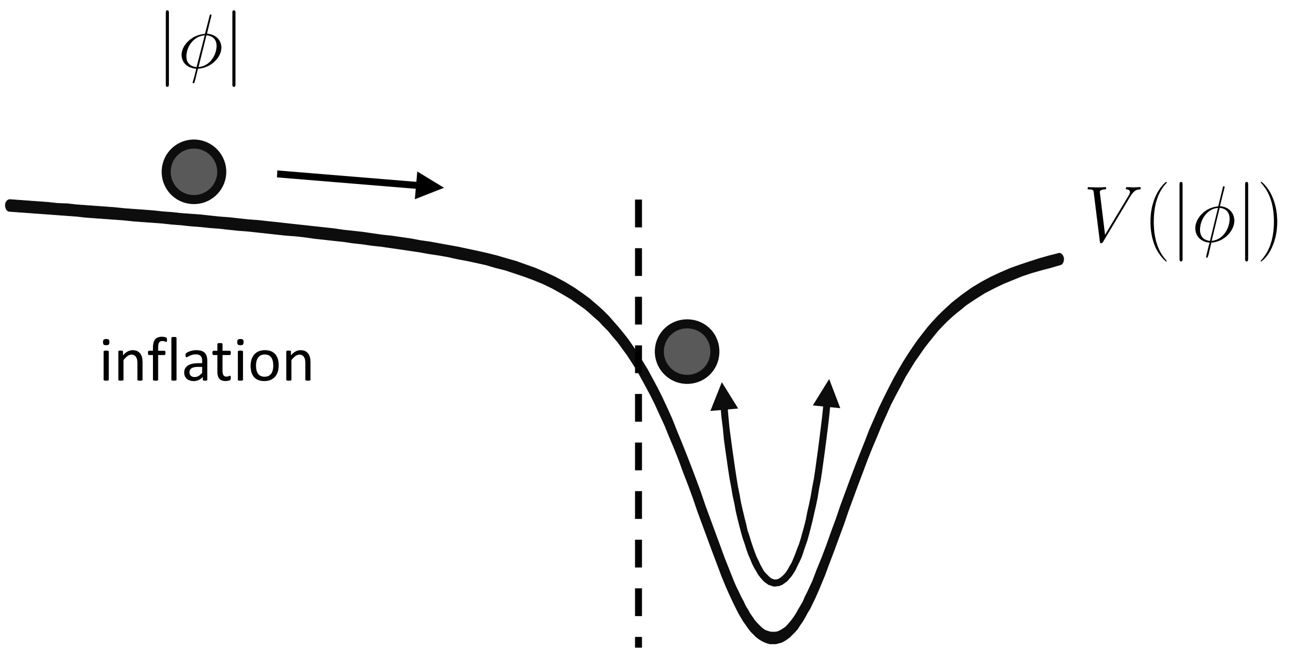
$$\phi \to b$$

decay

$$N_b - N_{\bar b} = b_\phi(N_\phi - N_{\bar\phi})$$

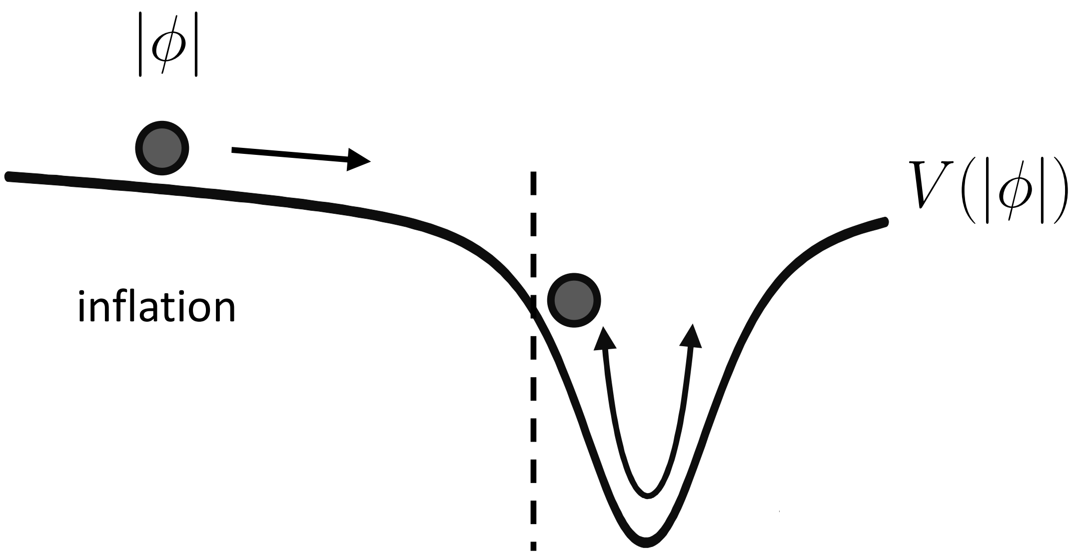
baryon number

Inflaton dynamics



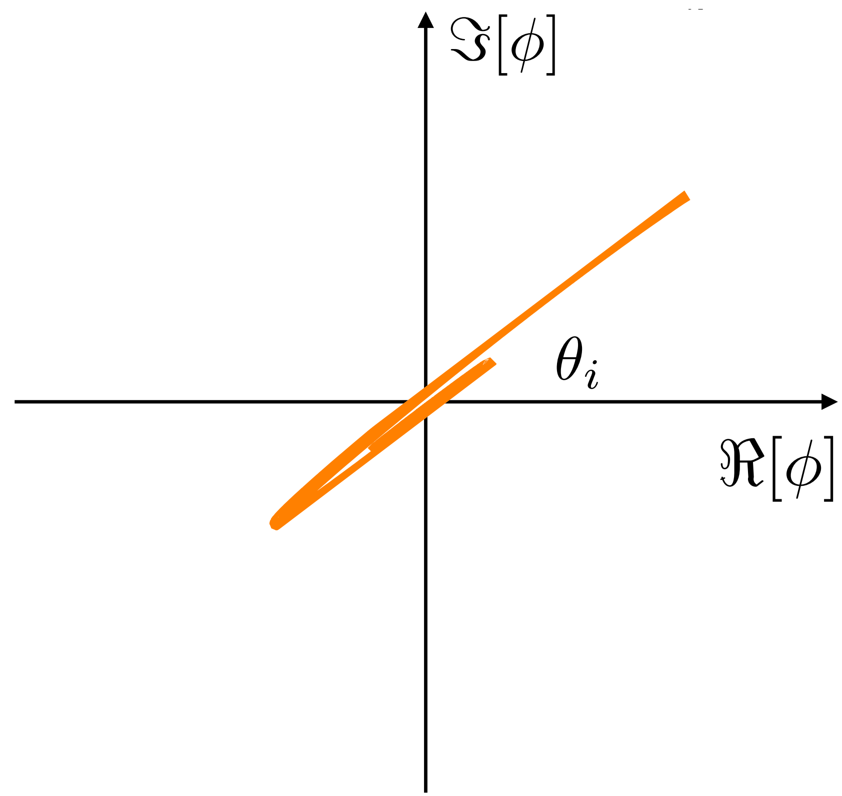
inflation ends:
oscillatory phase

Inflaton (homogeneous) dynamics

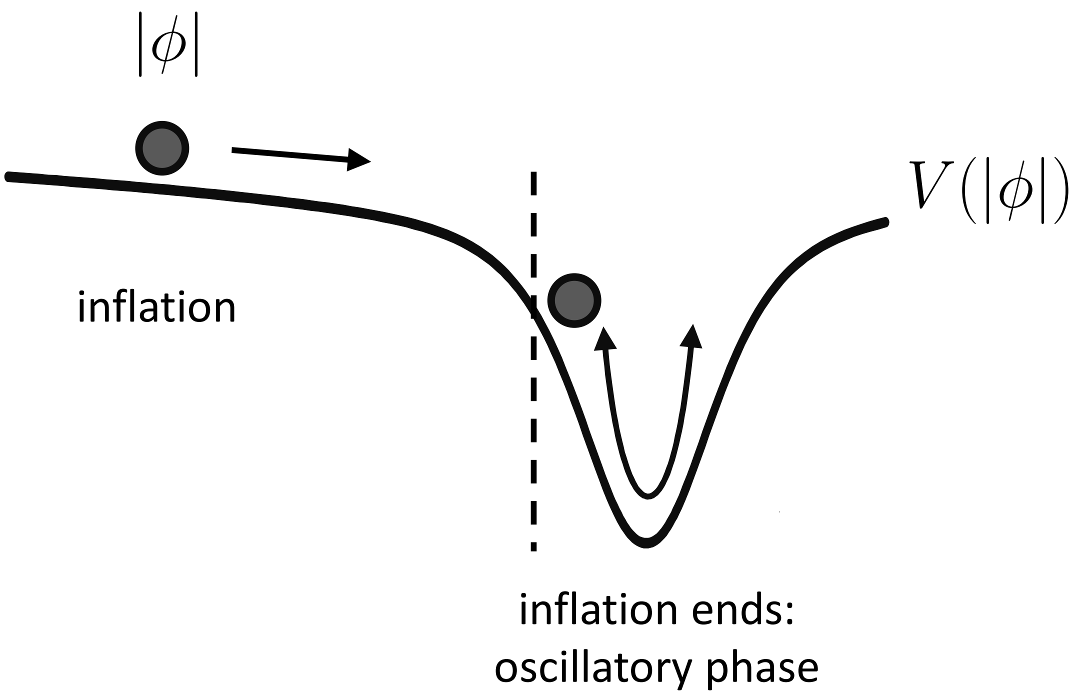


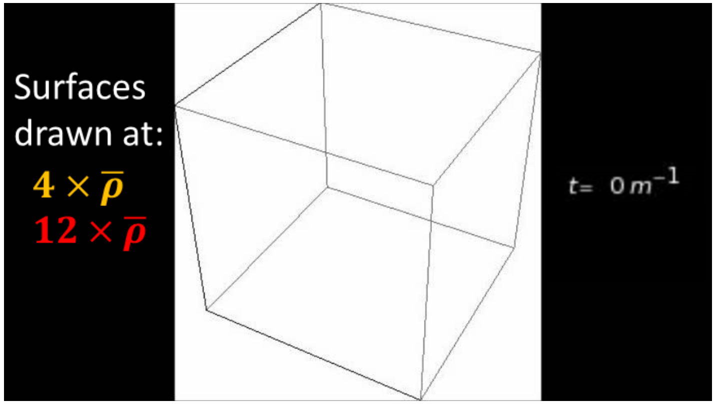
inflation ends:
oscillatory phase

$$|\phi(t)| \approx \frac{|\phi_0|}{a(t)^{3/2}} \sin(mt)$$



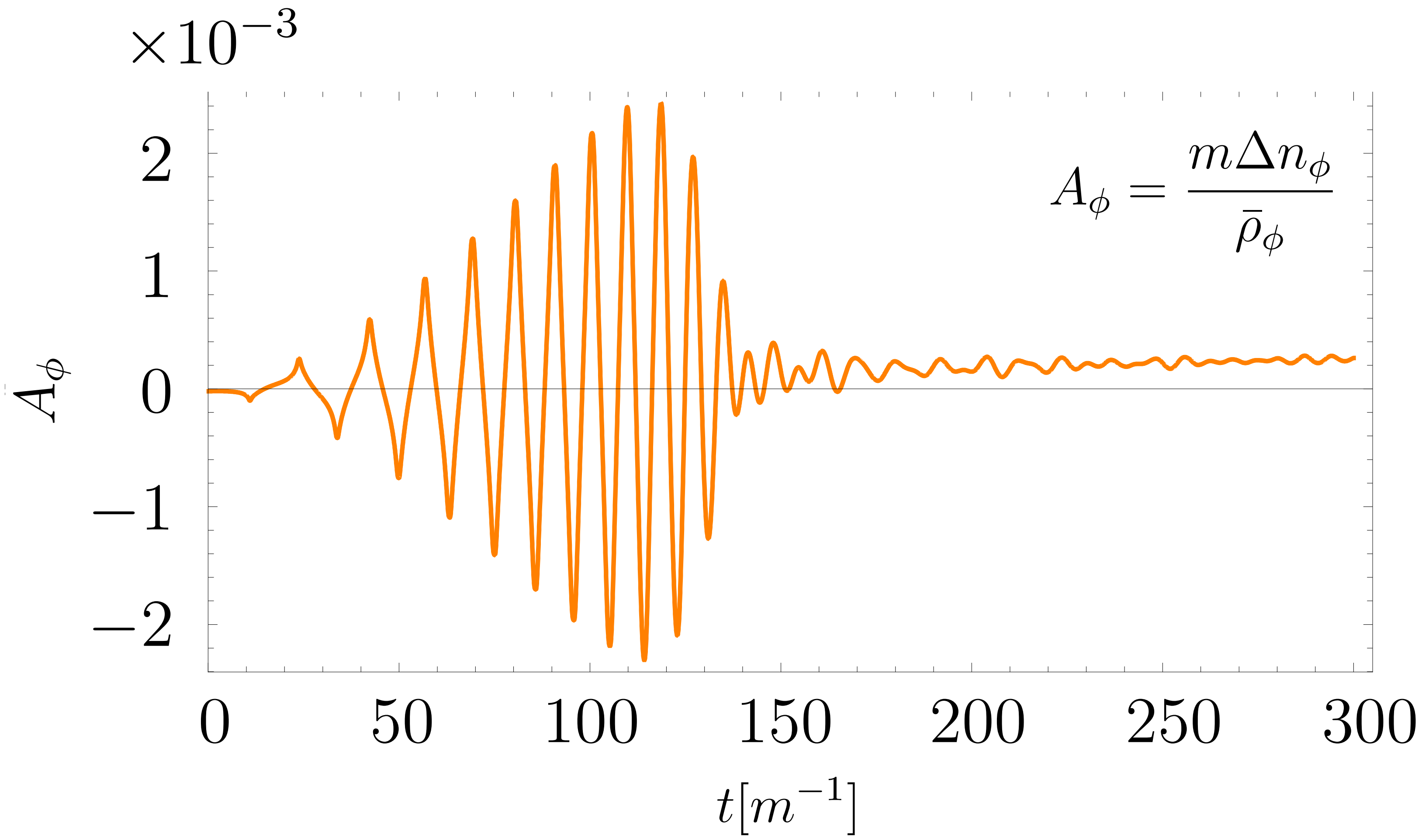
Inflaton (actual) dynamics





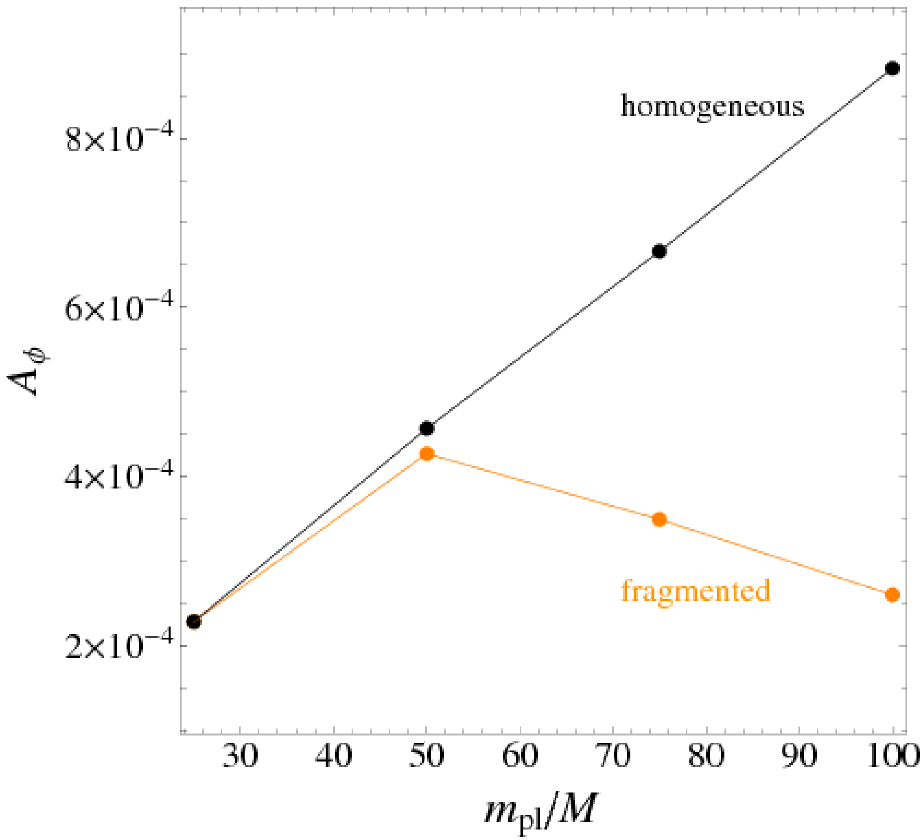
- parametric resonance of $\delta\phi$
- ϕ fragments
- forms oscillons

Inflaton asymmetry

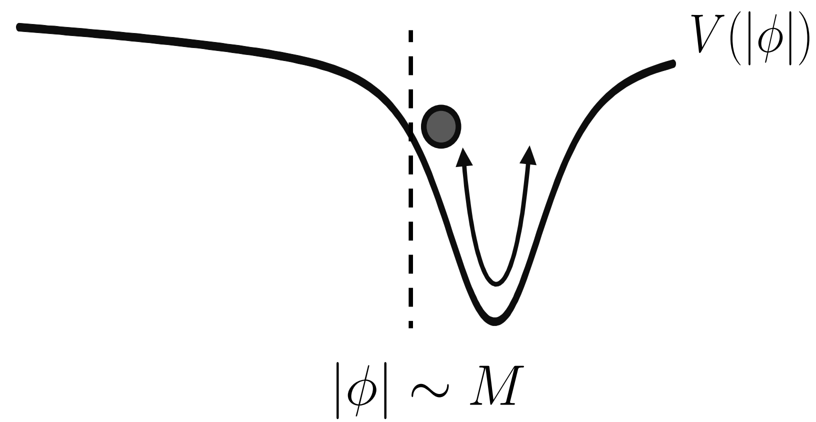


Asymmetry-fragmentation

Non-linear structures DO AFFECT inflaton/anti-inflaton ASYMMETRY!

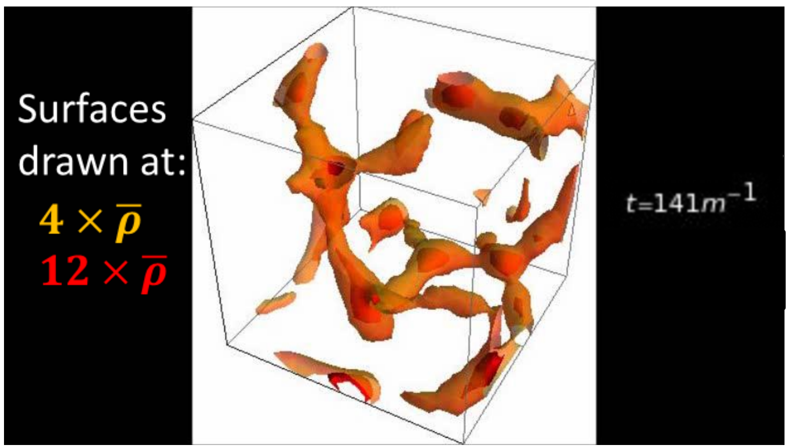


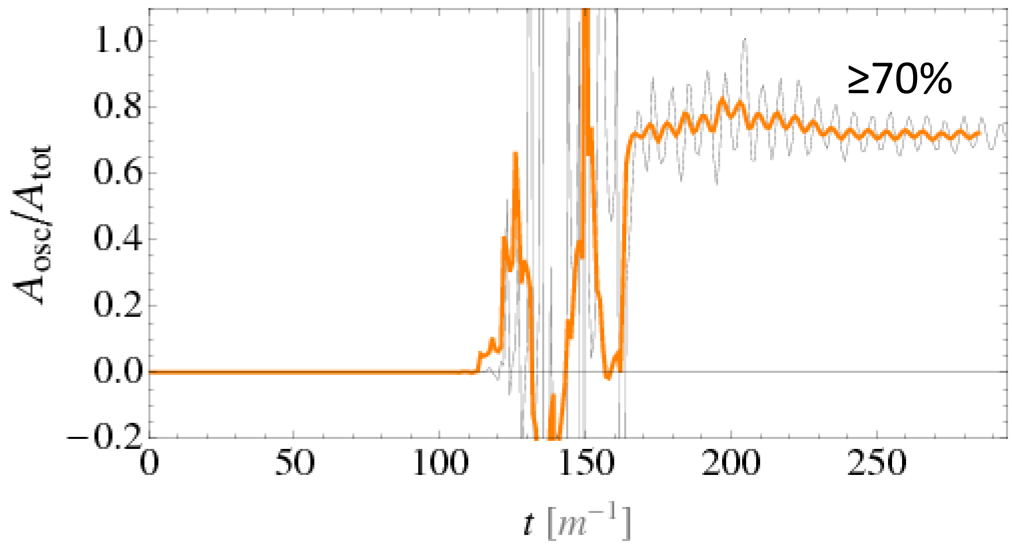
efficiency of fragmentation



where the potential changes shape

Where is the inflaton/anti-inflaton ASYMMETRY?



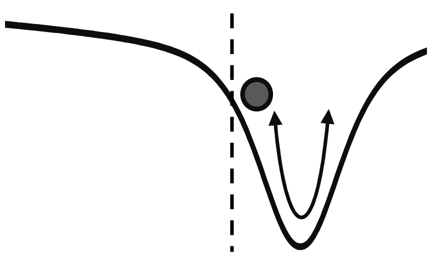


More than 70% of ASYMMETRY locked in oscillons!

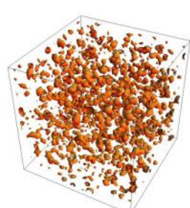
Inflaton asymmetry – parameter dependence

$$A_\phi \sim \mathcal{O}(10^2) \times \left(\frac{M}{m_{\rm Pl}}\right) c_3^2 \sin 3\theta_i$$

(inverse) strength of instability



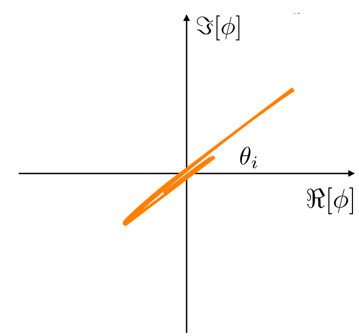
$|\phi| \sim M$



symmetry breaking

$$V_{\rm b}(\phi, \phi^*) = \frac{c_3}{3}\left(\phi^3 + \phi^{*3}\right)$$

initial conditions-inflation



$$c_3 \ll 1,\ M \ll m_{\rm Pl}$$

Inflaton to baryons (qualitative)

$$\eta \sim \mathcal{O}(10^2) \times A_\phi \left(\frac{T_{\rm reh}}{m}\right)$$

from end of inflation

decay rate to baryons

caveats: uncertainty here!! particle physics details, inhomogeneous decay…

Inflaton to baryons (qualitative)

$$\eta \sim \mathcal{O}(10^2) \times A_\phi \left(\frac{T_{\rm reh}}{m} \right) \sim 10^{-9}$$

from end of inflation

decay rate to baryons

sample numbers: $A_\phi \sim 10^{-4},\ T_{\rm reh} \sim 10^7\,{\rm GeV},\ m \sim 10^{14}\,{\rm GeV}$

caveats: uncertainty here!! particle physics details, inhomogeneous decay…

Summary

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

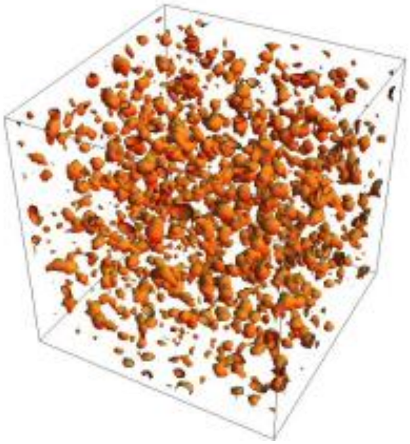
complex
inflaton ϕ
+ ~~U(1)~~

↓ 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)

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

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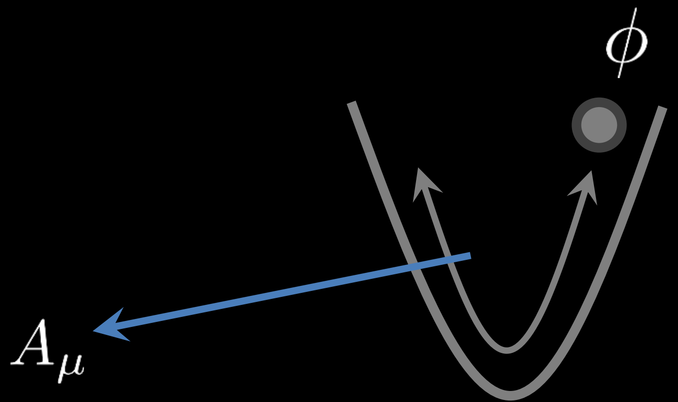

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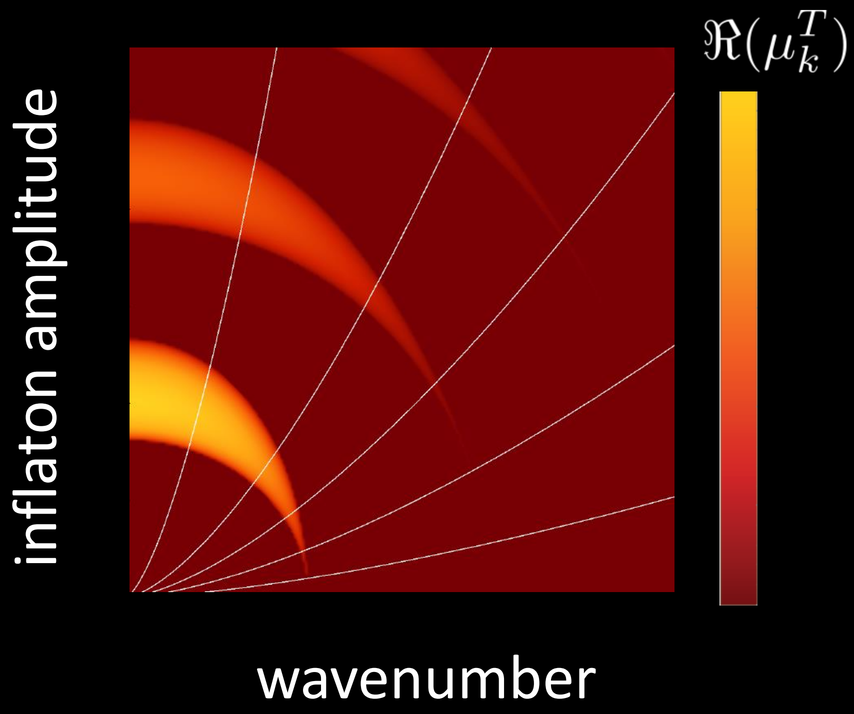
$$A_k^T \propto \exp(\pm \mu_k^T t)$$



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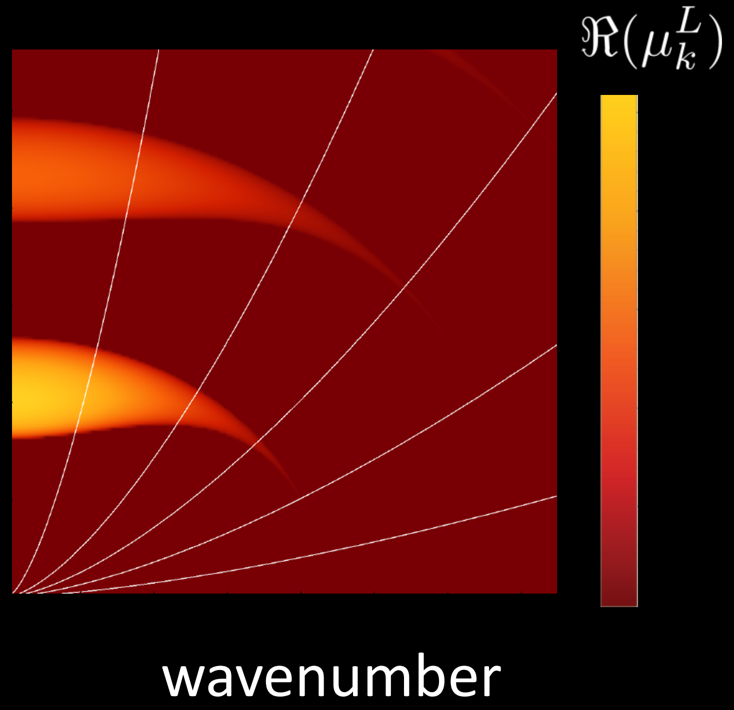
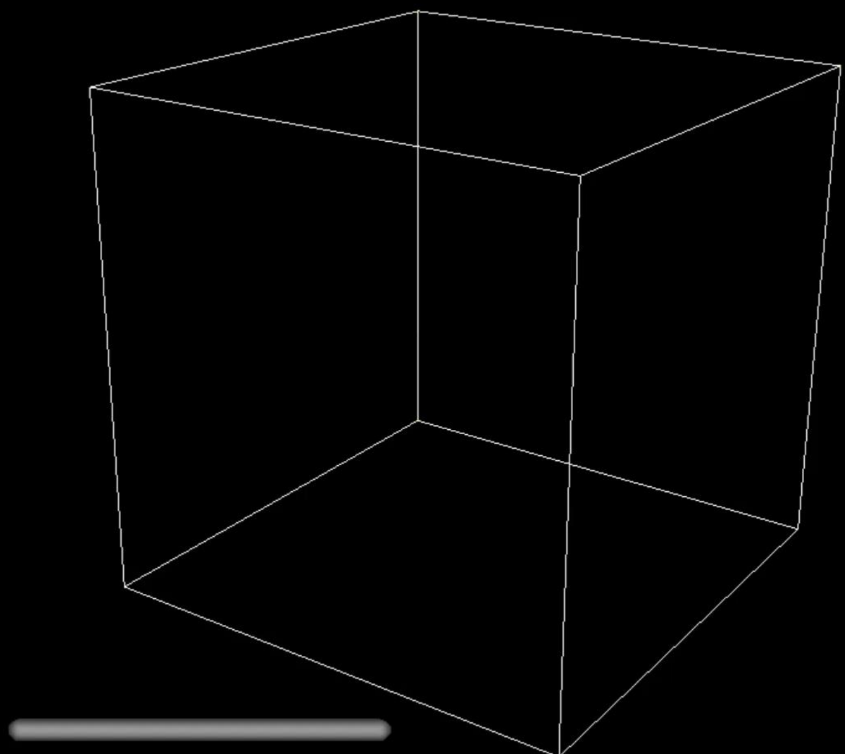


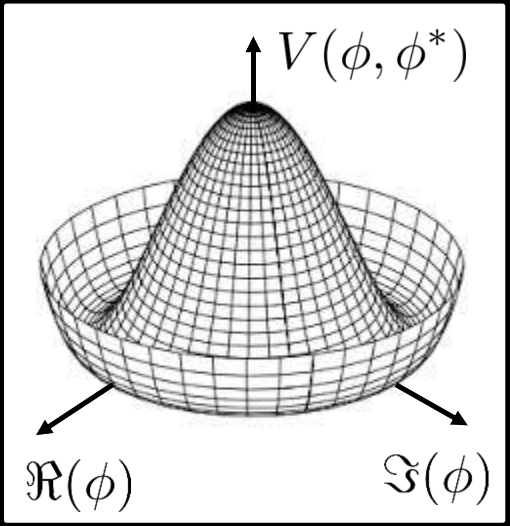
Gauge fields, inflation & reheating

KL and M. Amin, JCAP 1606 032 (2016),
see also Yamaguchi's and Torrenti's talks

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

(in progress)





with Eiichiro Komatsu and Mustafa Amin

Gauge fields, inflation & reheating

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Gauge fields, inflation & reheating

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Gauge fields, inflation & reheating

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Spectator sector

Dimastrogiovanni et al (2016)
Maleknejad (2016, 2018)
Adshead et al (2017)
Agrawal, Komatsu et al (2017, 2018)
Soda and Urakawa (2017)
Kitajima et al (2018)

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Linear coupling between Gauge Fields and GWs!

Gauge fields, inflation & reheating

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δA^b_i and h_{ij}

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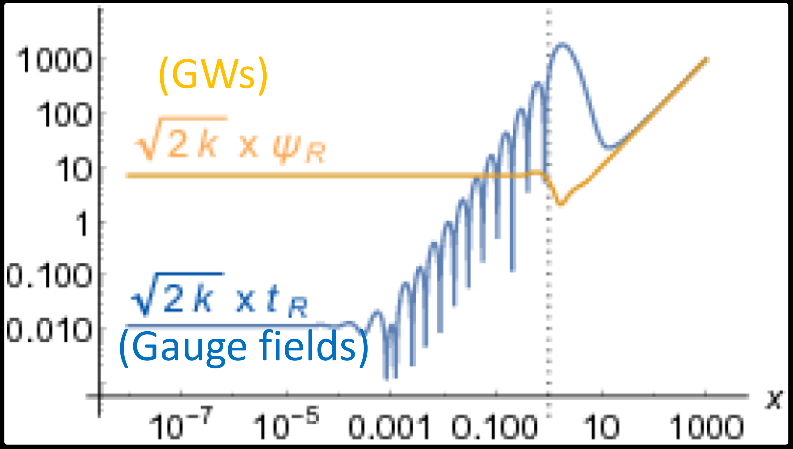

Figure from Dimastrogiovanni et al. arXiv:1608.04216

Gauge fields, inflation & reheating

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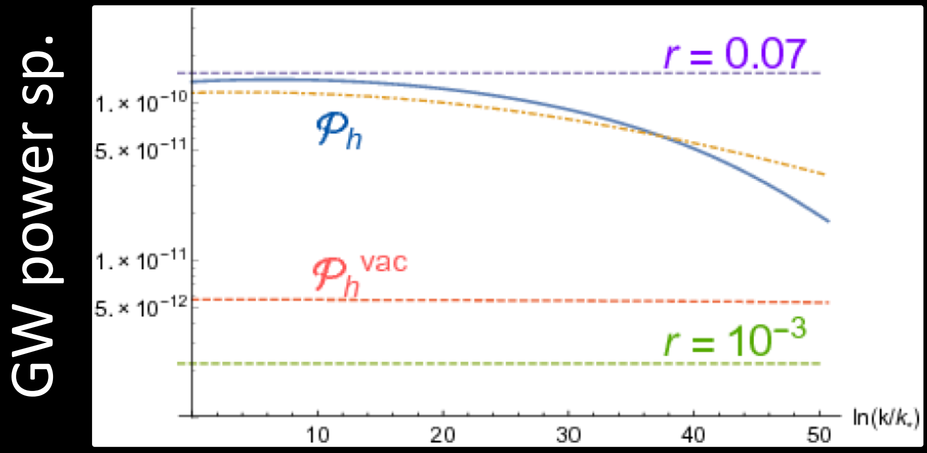

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See also Domcke et al (2018), Adshead et al (2015, 2018, 2019)

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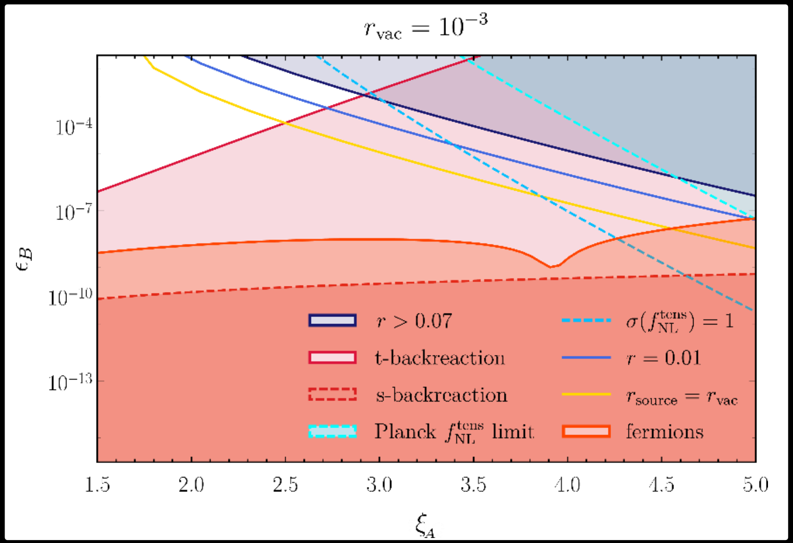
Fraction of energy in Gauge Fields



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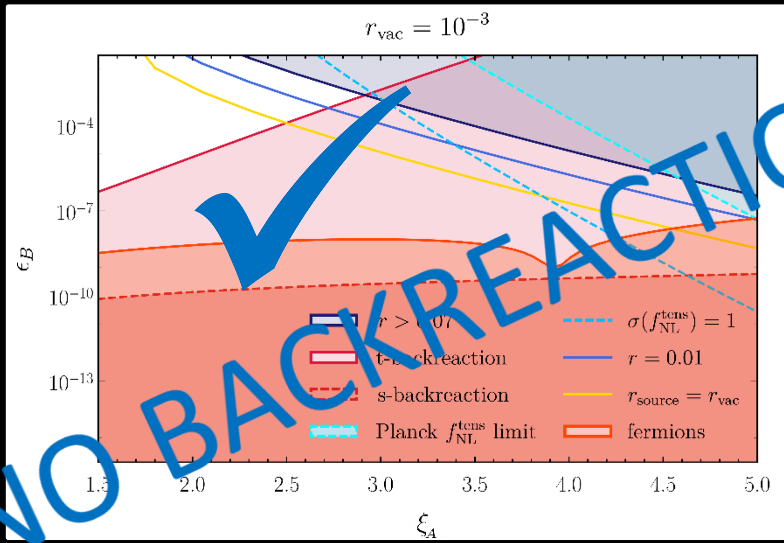

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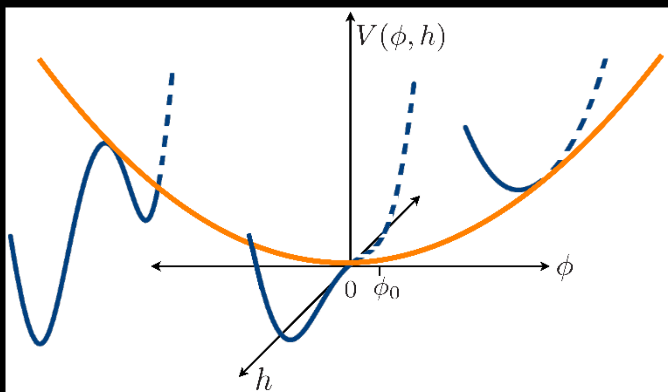
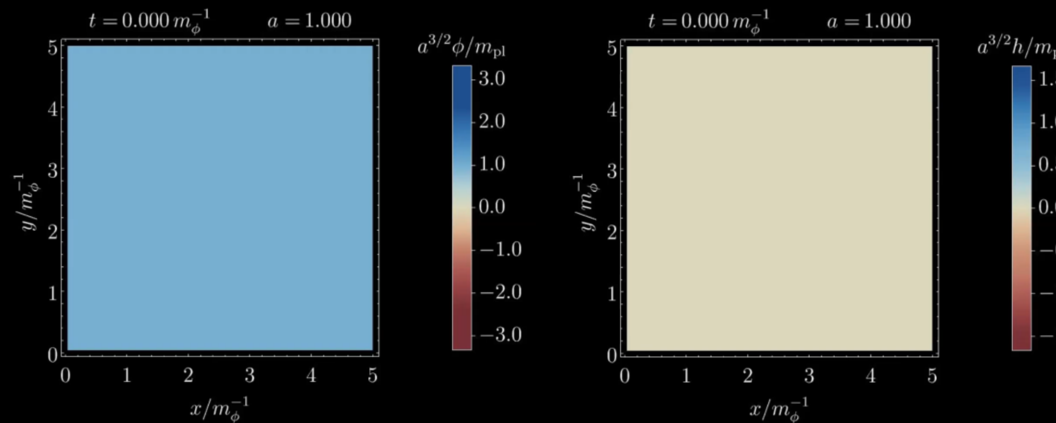
Cosmology of a Fine-Tuned Higgs

Mustafa Amin, JiJi Fan, KL and Matthew Reece, PRD 99 035008 (2019)



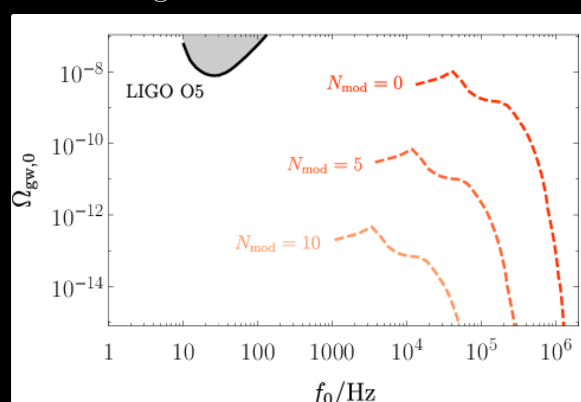


$$\frac{1}{2}m_\phi^2\phi^2 + \frac{M^2}{f}(\phi - \phi_0)\left(h^\dagger h - \frac{v^2}{2}\right) + \lambda(h^\dagger h)^2$$

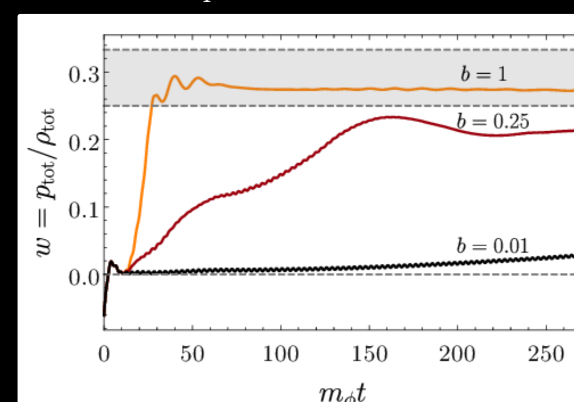
$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \to 1 \Leftrightarrow \text{rapid fragmentation}$$

$$\text{fine tuning} \Leftrightarrow \frac{\phi_0}{f} \ll 1$$

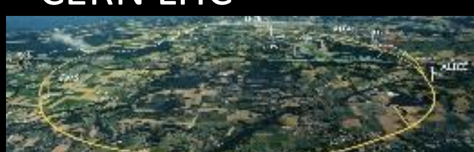
stochastic gravitational waves



non-trivial eq. of state



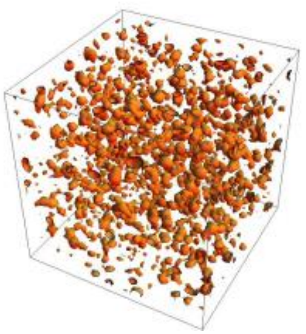
CERN LHC



Conclusions

Reheating at the end of inflation:

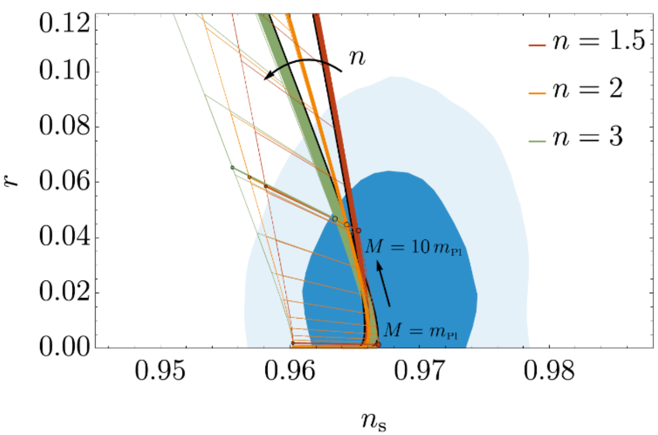
- very rich dynamics



Future plans:

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

- observational signatures
  -expansion history, relics, GWs



Strings

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