Constraining axion inflation with gravitational waves across 29 decades in frequency

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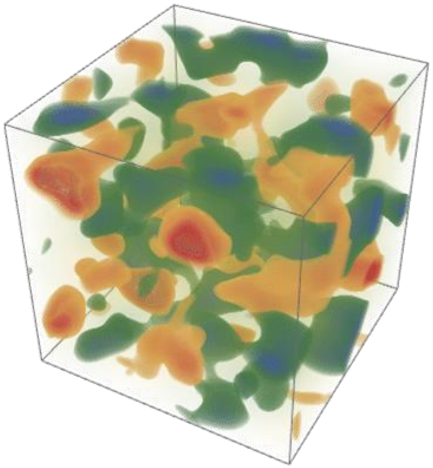

arXiv: 1909.12842 and 1909.12843
with Peter Adshead, Tom Giblin, and Mauro Pieroni

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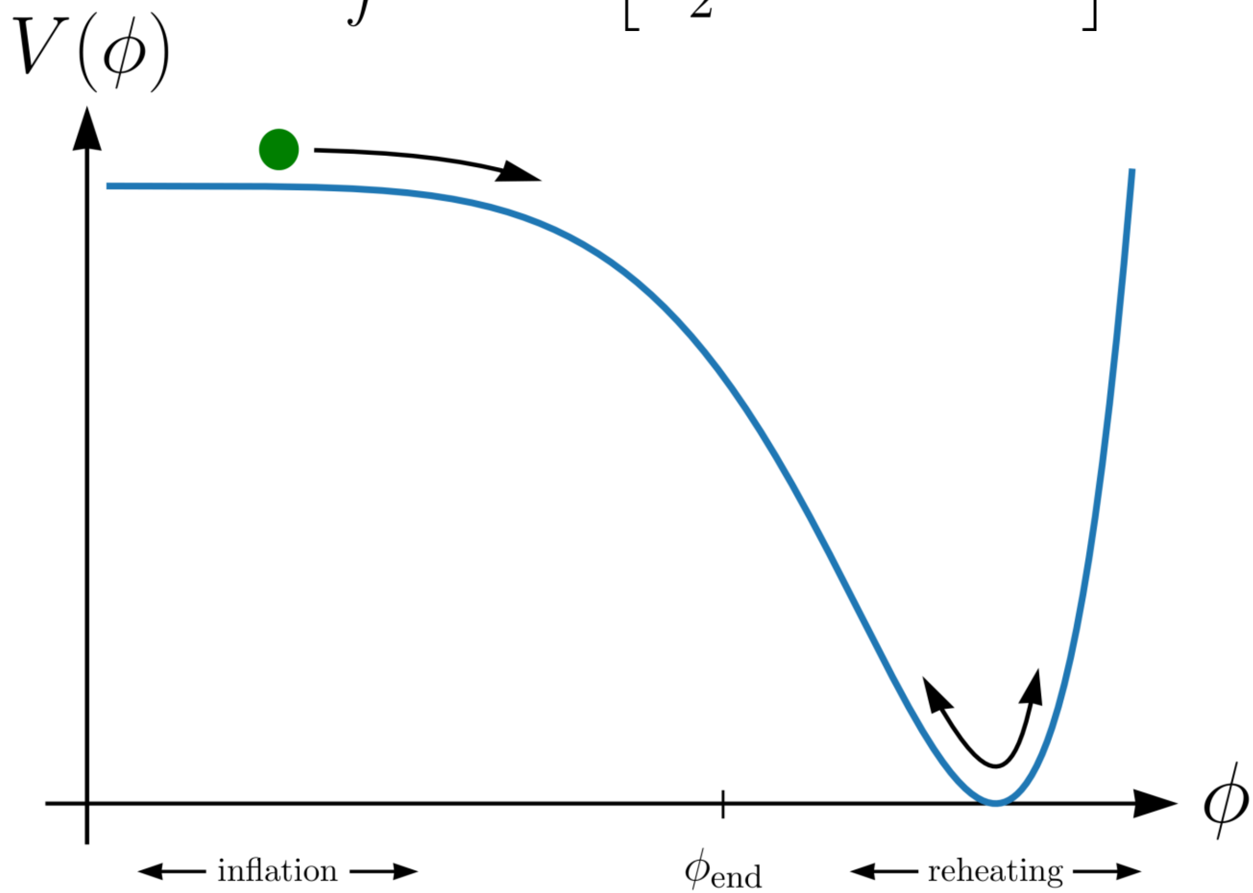
DOE CSGF

Why (p)reheating?

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



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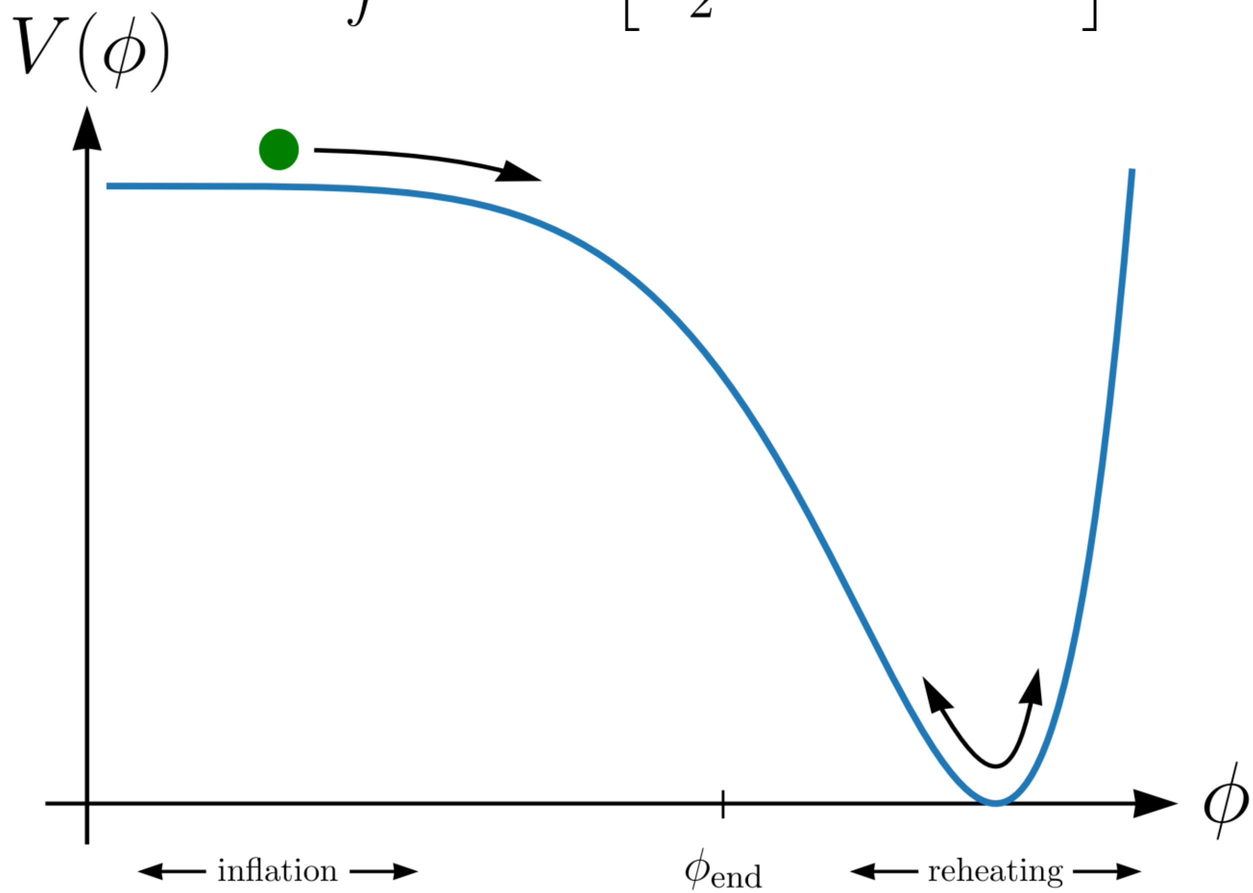

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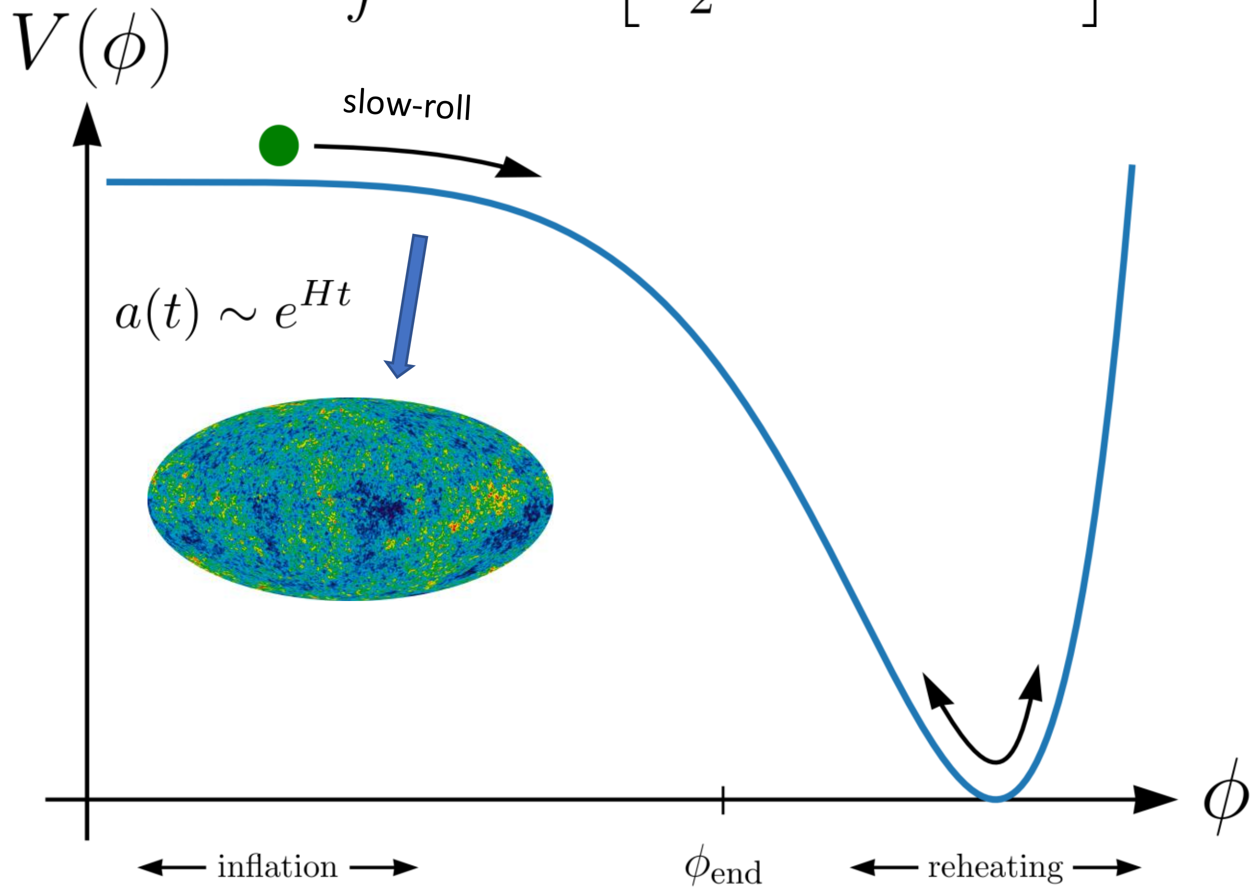

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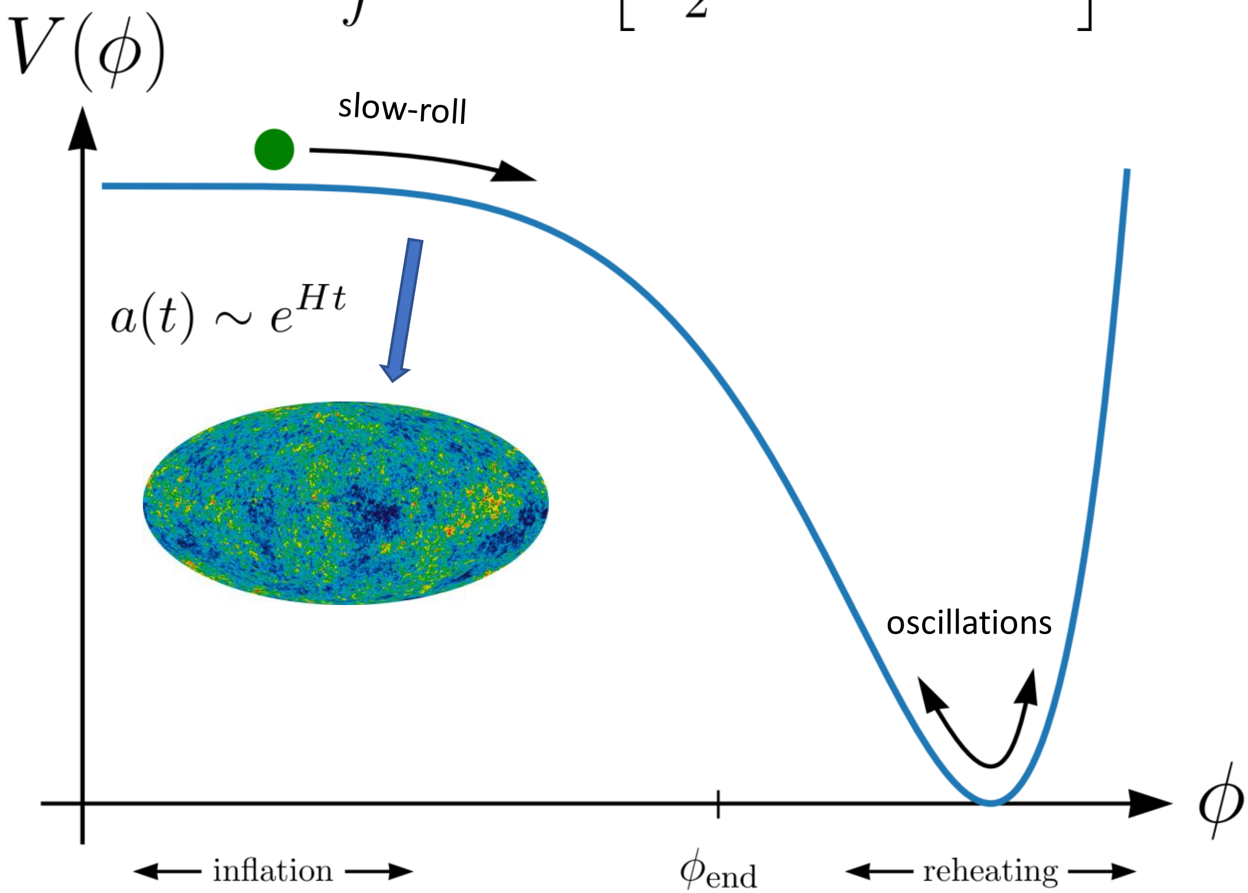

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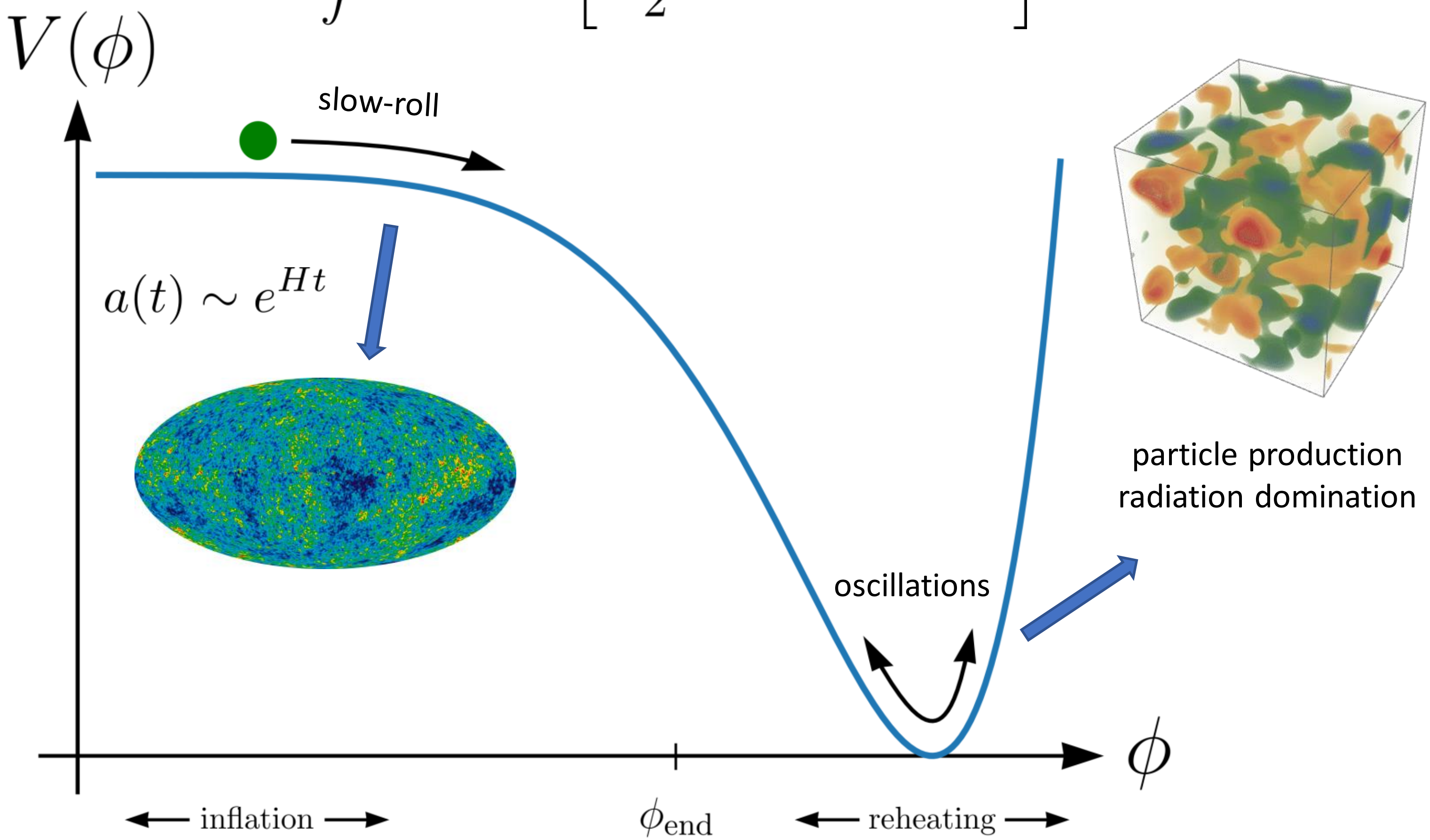

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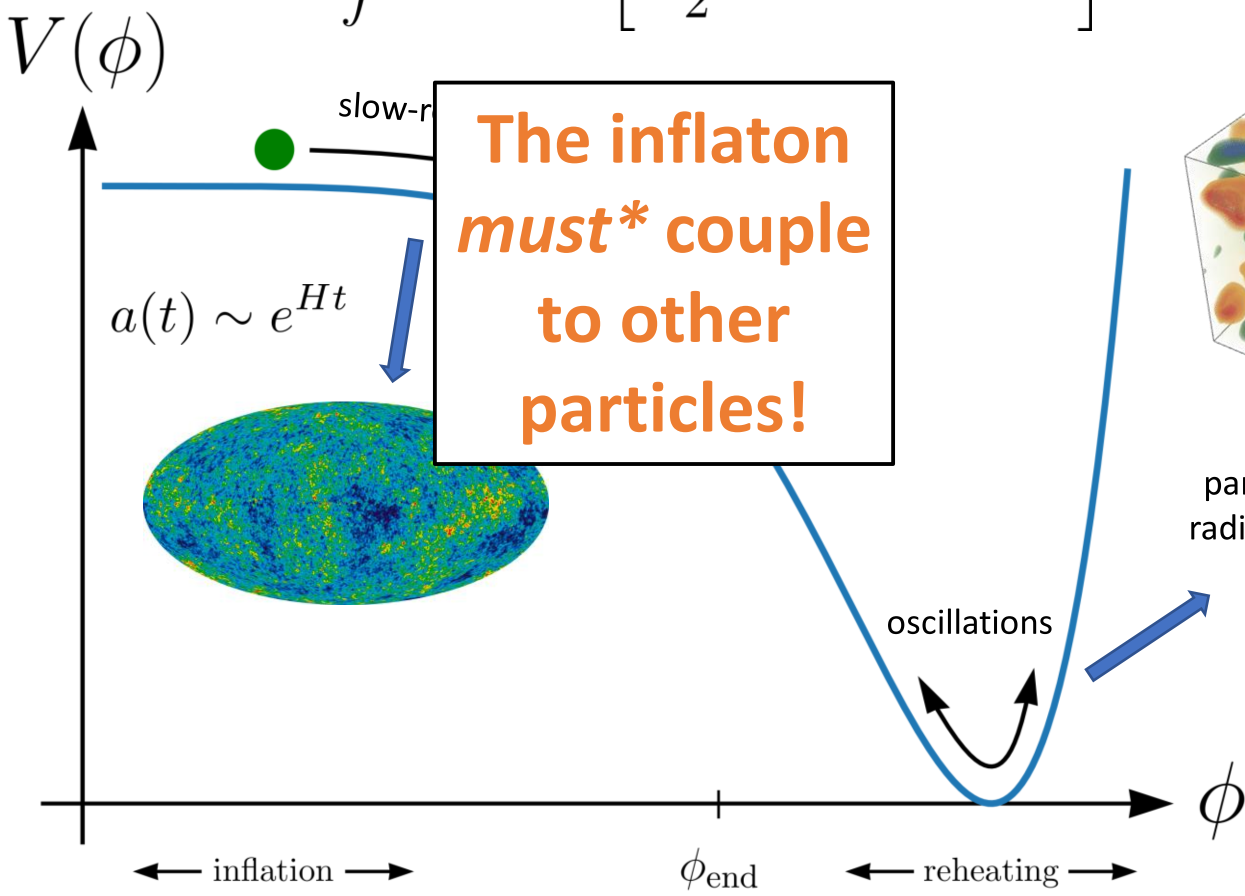
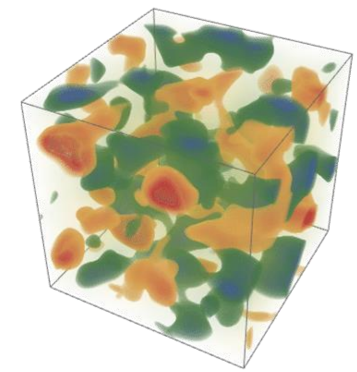


The inflaton *must couple to other particles!**



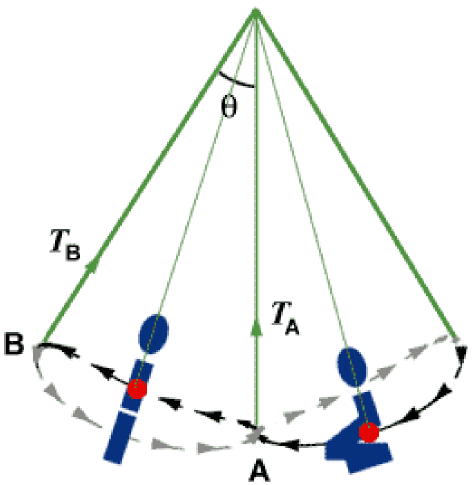
particle production
radiation domination

Reheating via perturbative decay

- Couple the inflaton to some other field, compute its decay rate
- The Universe is reheated once decay becomes efficient
  - I.e., the lifetime is shorter than the Hubble time
- Limitations:
  - Ignores coherent nature of inflaton
  - Misses possible *non*perturbative and nonlinear effects

Preheating after inflation

- Perturbative reheating may be preceded by a phase of nonperturbative preheating
  - Exponential particle production, i.e., exponential growth of Fourier modes
  - Are induced by various types of resonances from the homogeneous oscillation of the inflaton
- Analogous to a child on a swing: pumping legs amplifies the amplitude of swinging



http://www.hk-phy.org/articles/swing/swing_e.html

Tachyonic resonance

- Schematically: interaction of the form

$$V_{\mathrm{int}} = \frac{1}{2}\lambda\phi\chi^2$$

  leads to the mode equation

$$\chi_k'' + \left(k^2 + \lambda\phi\right)\chi_k = 0$$

- Modes exhibit exponential growth whenever their squared effective frequency is negative:

$$k^2 + \lambda\phi_0 \sin(m_\phi t) < 0$$

Reality check

- The Universe expands
  - Homogeneous inflaton is a damped harmonic oscillator
  - Momenta redshift in and out of instability bands
- The inflaton itself will fragment
  - χ particles can backreact onto the inflaton
- Need to eventually populate Standard Model (or SM-like) degrees of freedom

Axial coupling to gauge fields

- Pseudoscalar axion ϕ coupled to gauge fields:

$$\mathcal{L}_{\mathrm{gauge}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \underbrace{\frac{\alpha}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}}_{\frac{\alpha}{f} \phi \mathbf{E} \cdot \mathbf{B}}$$

- System of equations:

$$\phi'' - \partial_i \partial_i \phi + 2\mathcal{H}\phi' + a^2 \frac{\mathrm{d}V}{\mathrm{d}\phi} = -a^2 \frac{\alpha}{4f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$A_i'' - \partial_j \partial_j A_i - \frac{\alpha}{f} \epsilon^{ikl} \phi' \partial_k A_l + \frac{\alpha}{f} \epsilon^{ikl} \partial_k \phi \left(A_l' - \partial_l A_0 \right) = 0$$

Tachyonic production of gauge bosons

- Linearized EOM of gauge-field polarizations:

$$A_\pm'' + \underbrace{\left(k^2 \mp \frac{\alpha}{f} k \phi'\right)}_{} A_\pm = 0$$

one polarization: negative effective frequency → exponential growth for $k < \frac{\alpha}{f}|\phi'|$

- Controlled by instability parameter, $\xi \equiv \frac{\alpha}{f}\frac{\phi'}{2aH}$:

$$A_-(k) \sim e^{|\xi|}$$

even during inflation!

Inflationary dynamics

- Gauge fields backreact onto inflaton background:

$$\bar{\phi}'' + 2\mathcal{H}\bar{\phi}' + a^2 \frac{\mathrm{d}V}{\mathrm{d}\bar{\phi}} = \frac{\alpha}{f} a^2 \langle \mathbf{E} \cdot \mathbf{B} \rangle$$

- In de Sitter limit,

$$\langle \mathbf{E} \cdot \mathbf{B} \rangle \simeq -2.4 \times 10^{-4} \mathrm{sign}\left(\phi'\right) \frac{H^4}{\xi^4} e^{2\pi|\xi|}$$

opposes inflaton's velocity → friction!

Phenomenology during inflation

- Exponential enhancement of gauge fields during axion inflation leads to
  - Polarized electromagnetic fields
  - Non-Gaussianity
  - Chiral gravitational waves
  - Primordial black holes
- Also (in principle) can realize warm inflation

Preheating after axion inflation

- Important nonperturbative dynamics during inflation set the stage for preheating

- Nonlinear effects quickly become important

$$\phi'' - \partial_i \partial_i \phi + 2\mathcal{H}\phi' + a^2 \frac{\mathrm{d}V}{\mathrm{d}\phi} = -a^2 \frac{\alpha}{4f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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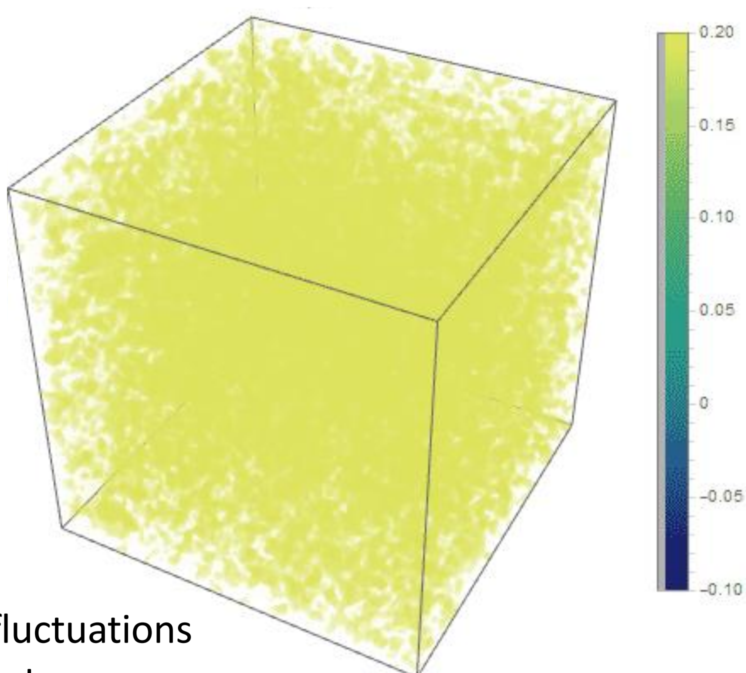
Lattice simulations of preheating

classical fields: PDE initial-value problem

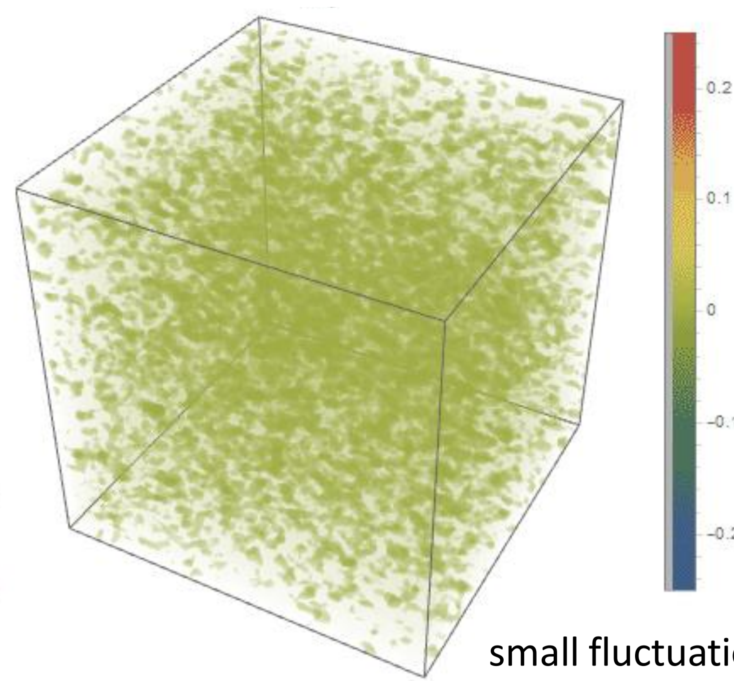
discretize onto a 3D grid

inflaton



small fluctuations
about mean

coupled field



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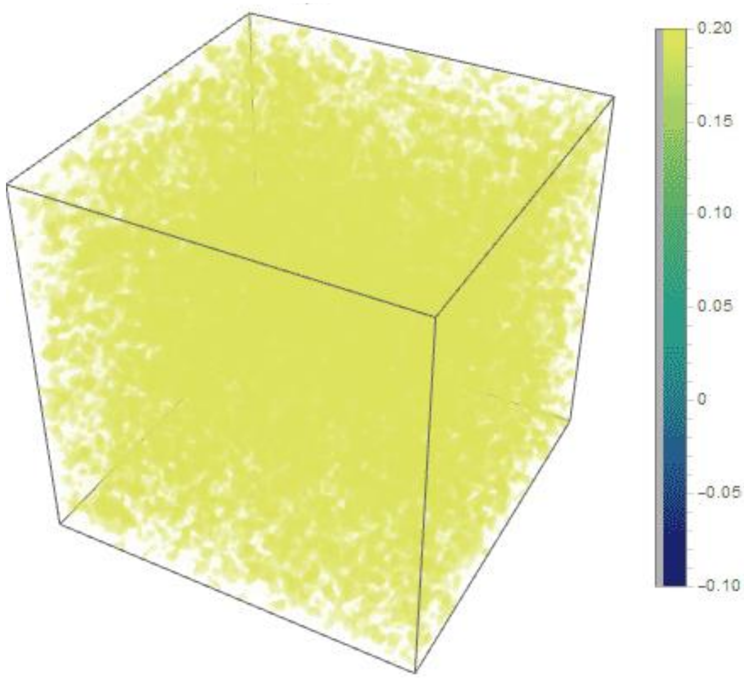

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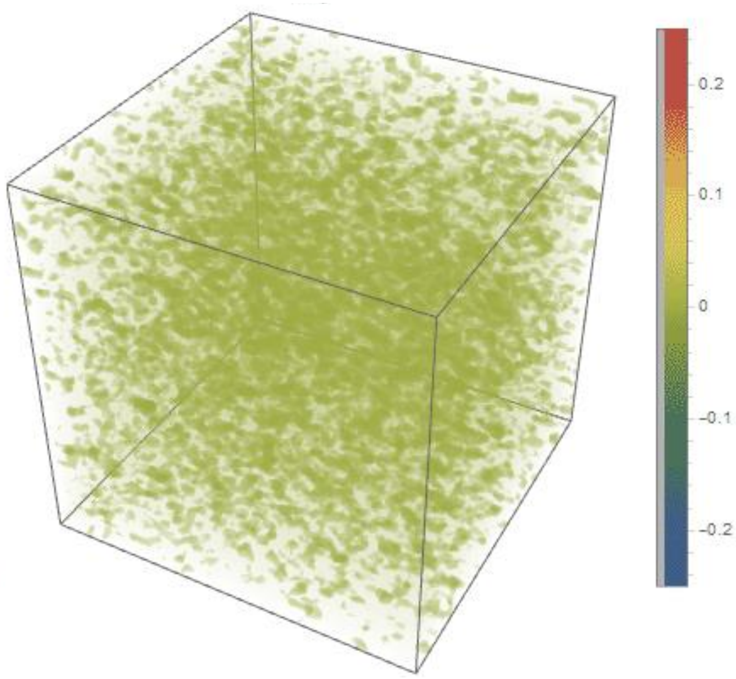

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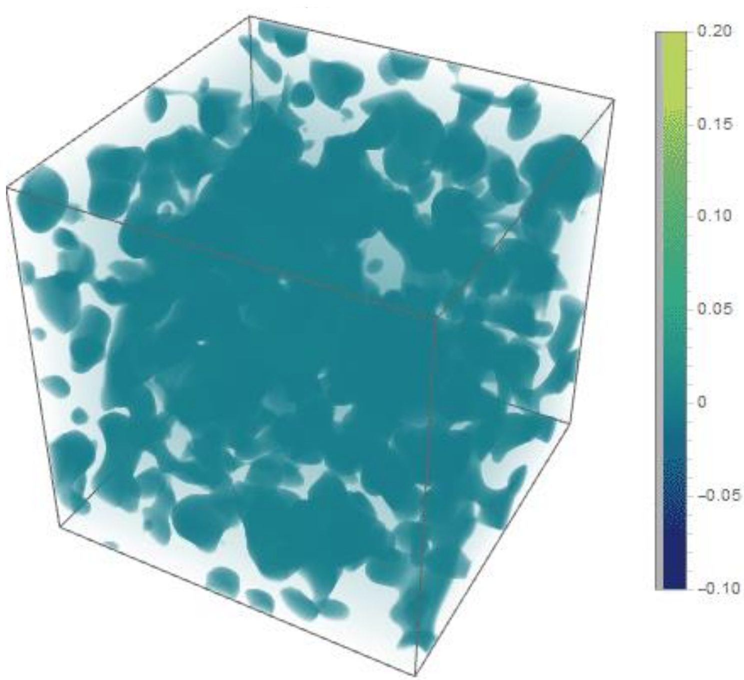

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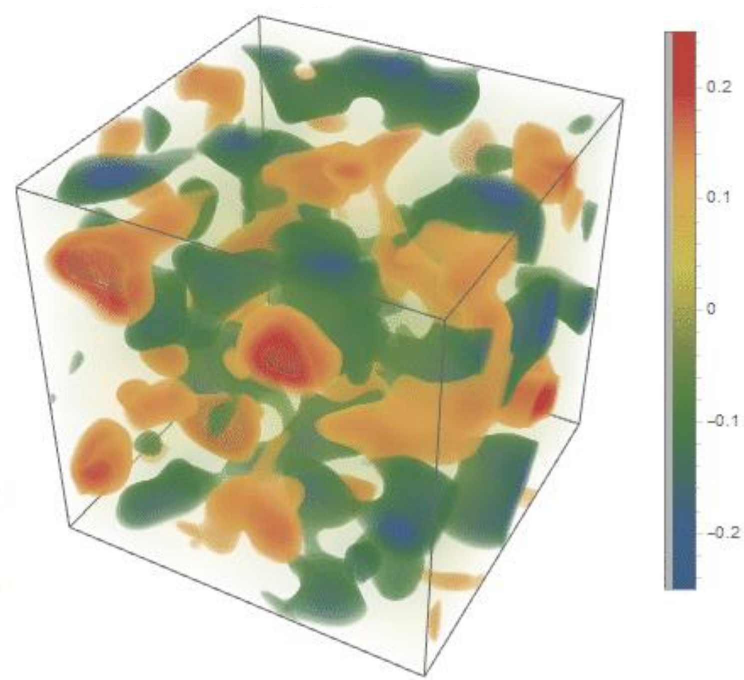
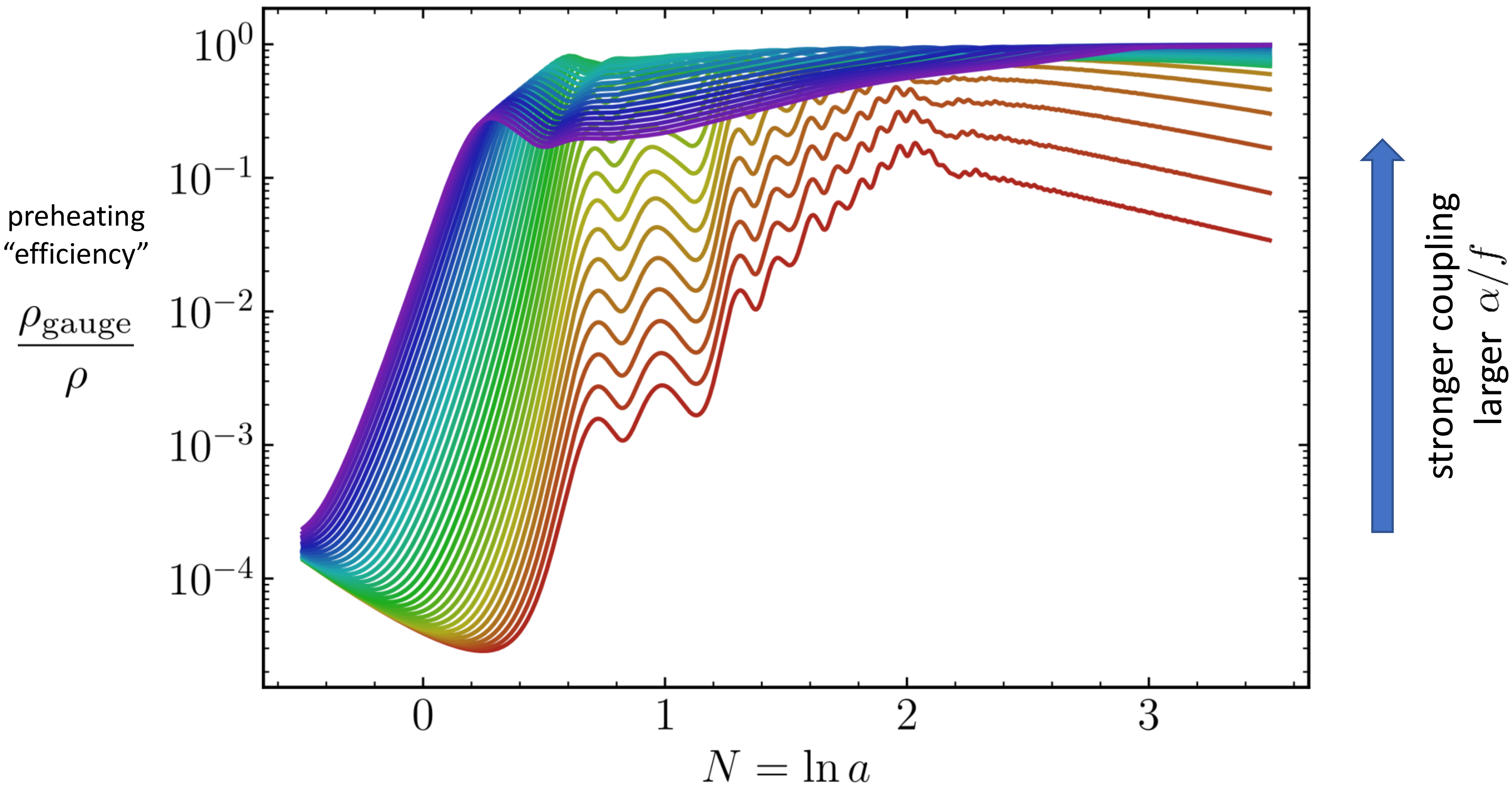
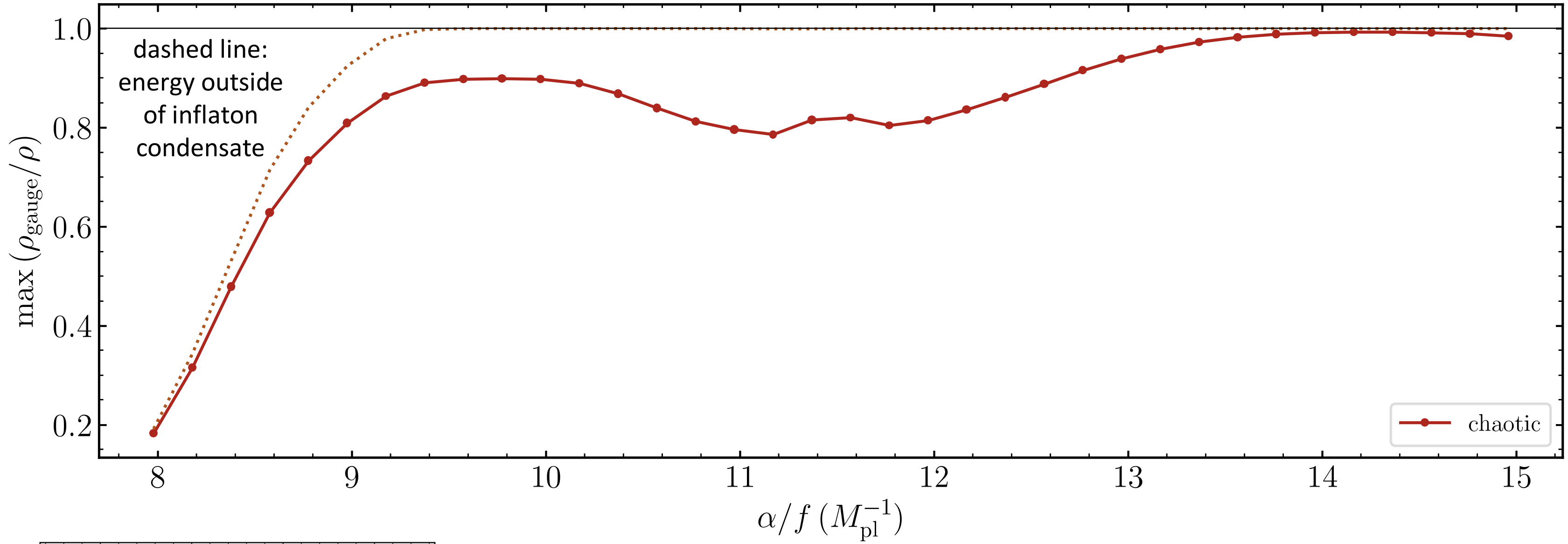


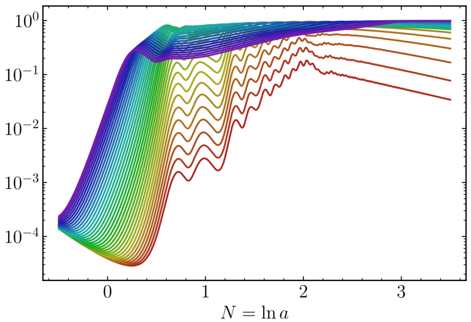
Gauge preheating after inflation



Efficiency of preheating

$$A_i'' - \partial_j \partial_j A_i - \frac{\alpha}{f} \epsilon^{ikl} \phi' \partial_k A_l + \frac{\alpha}{f} \epsilon^{ikl} \partial_k \phi \left(A_l' - \partial_l A_0 \right) = 0$$





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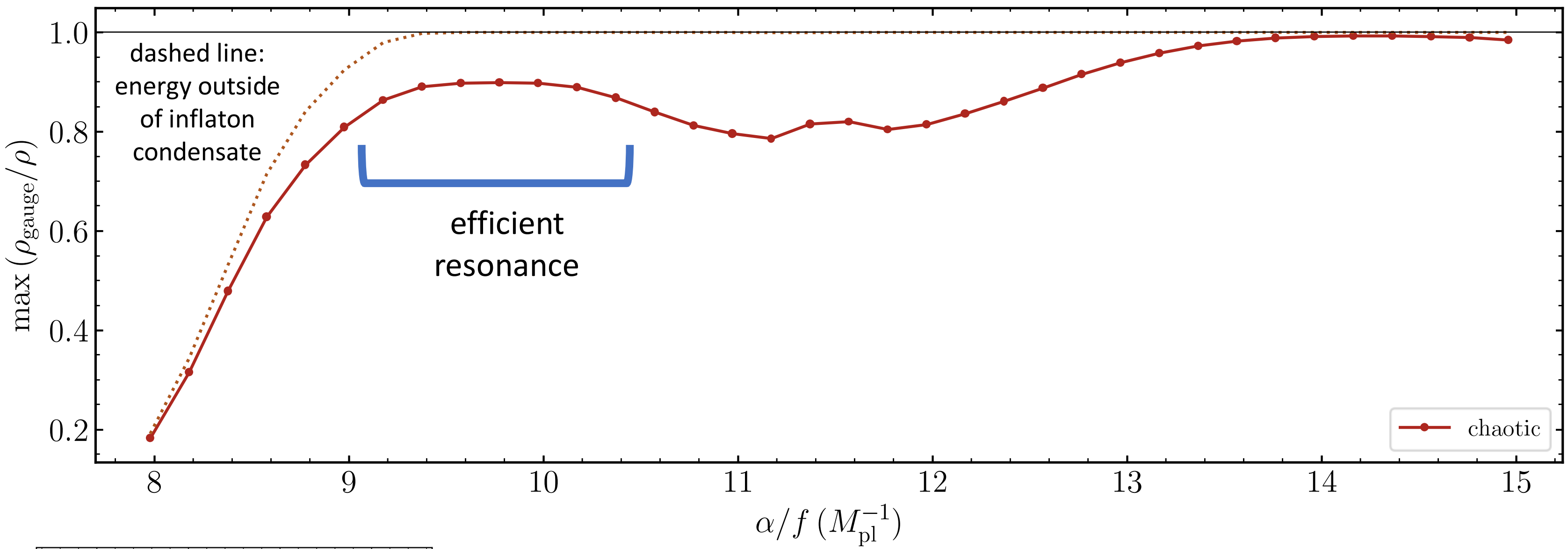

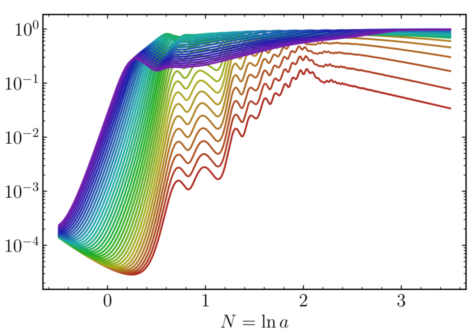

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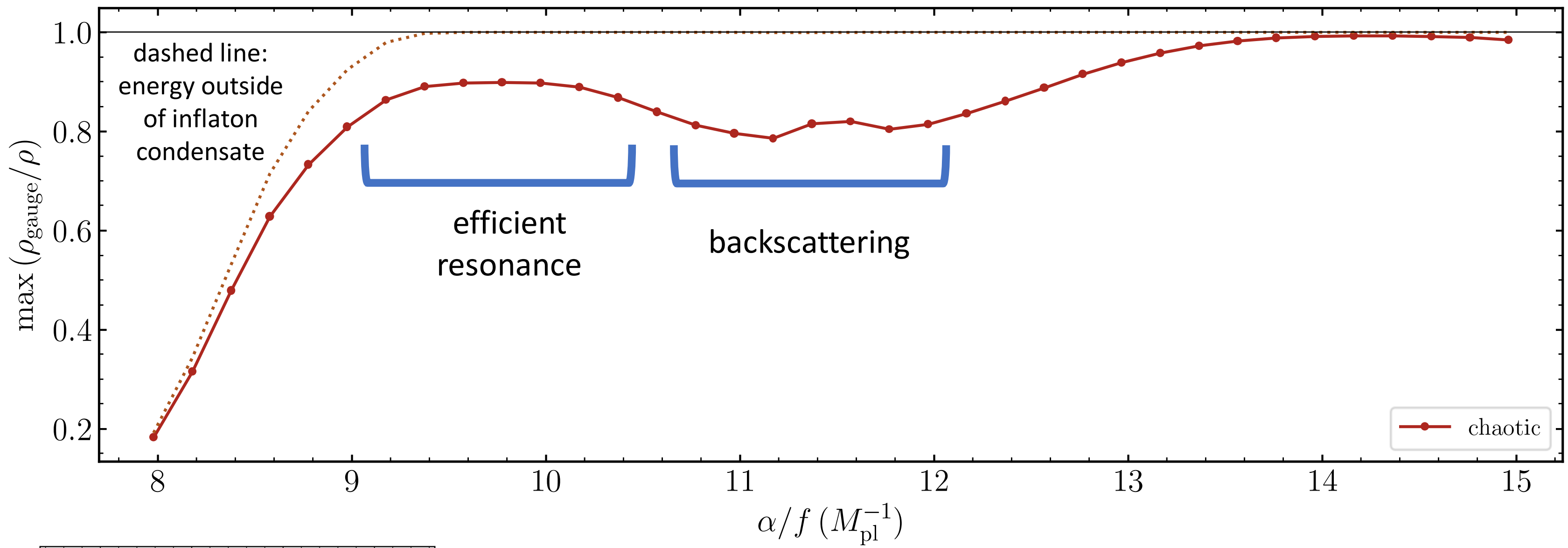

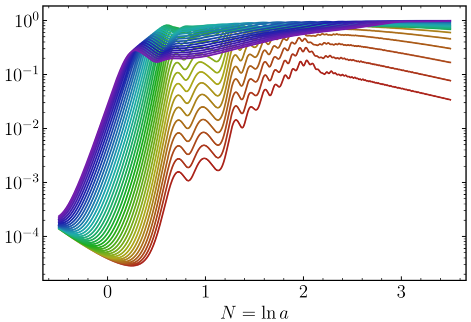

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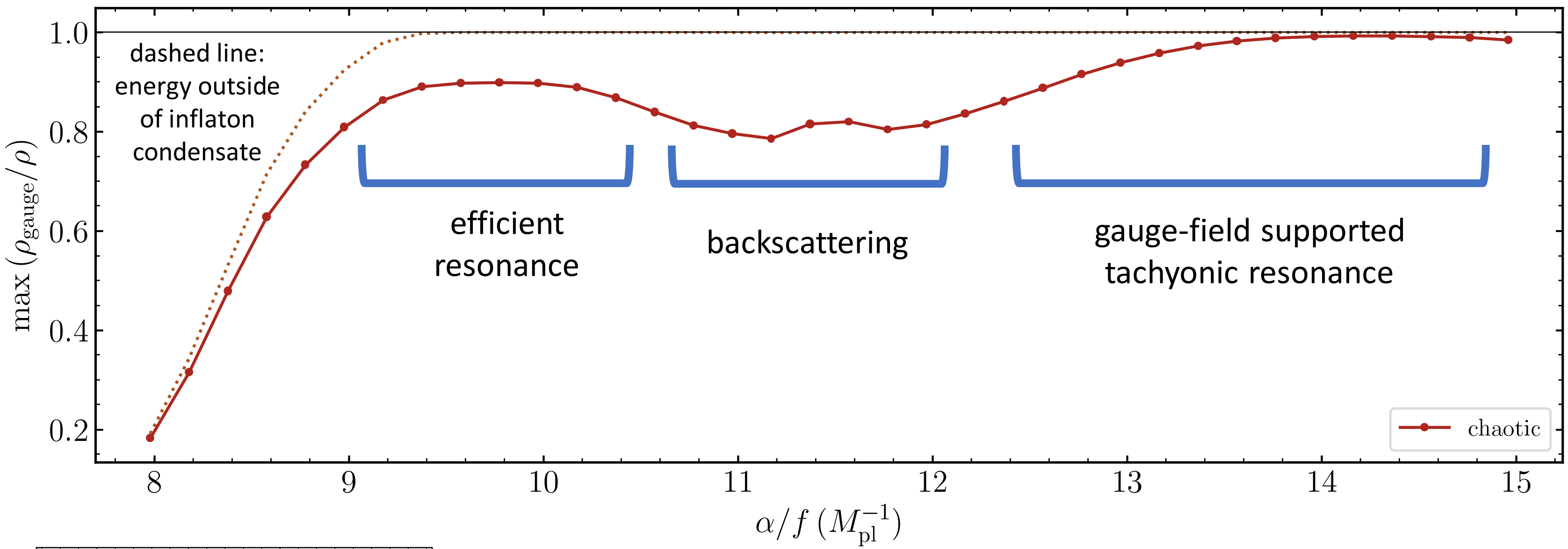
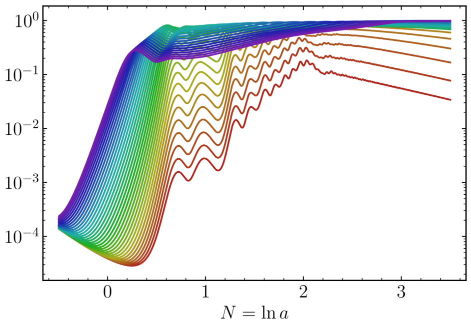
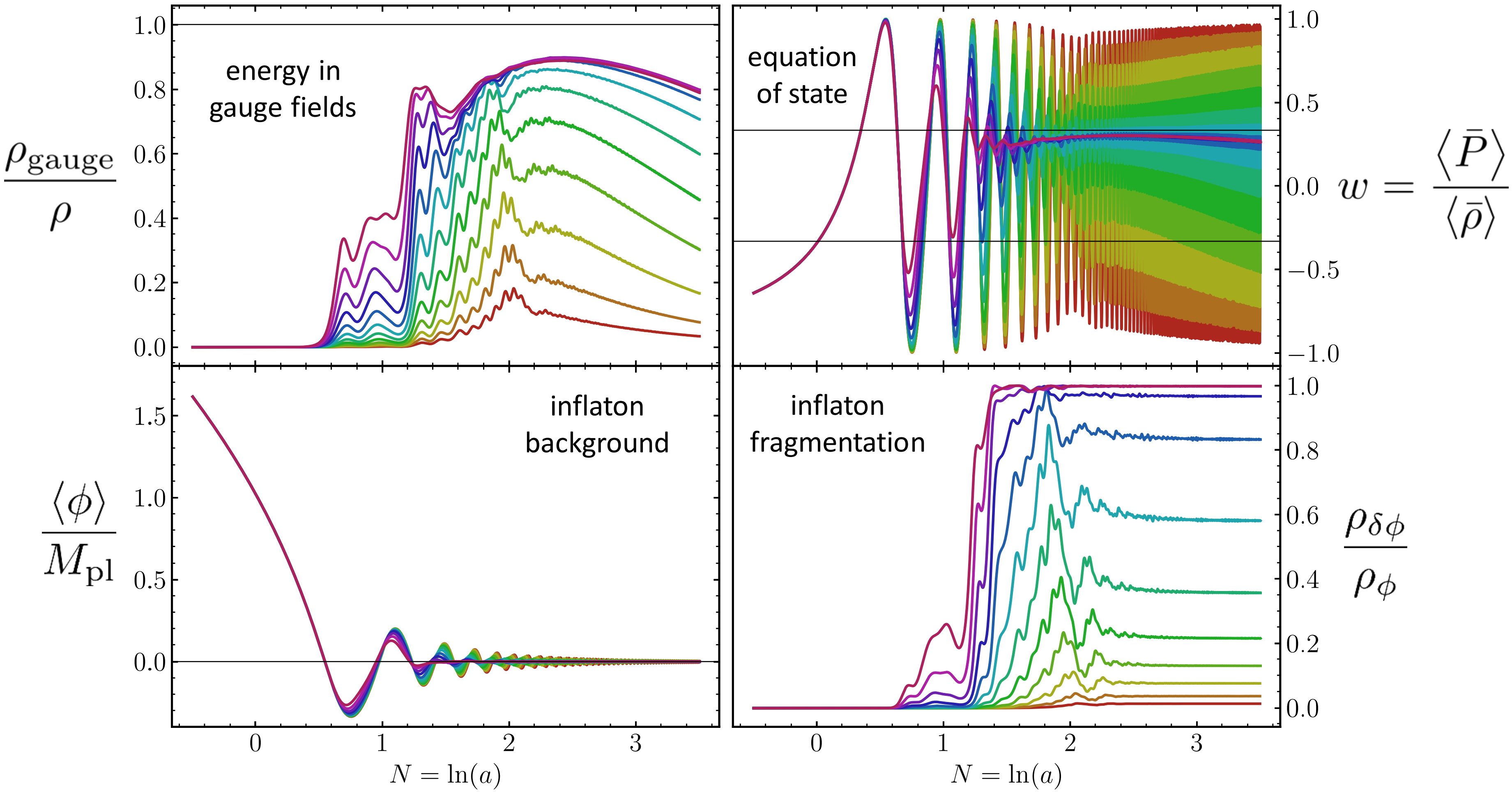
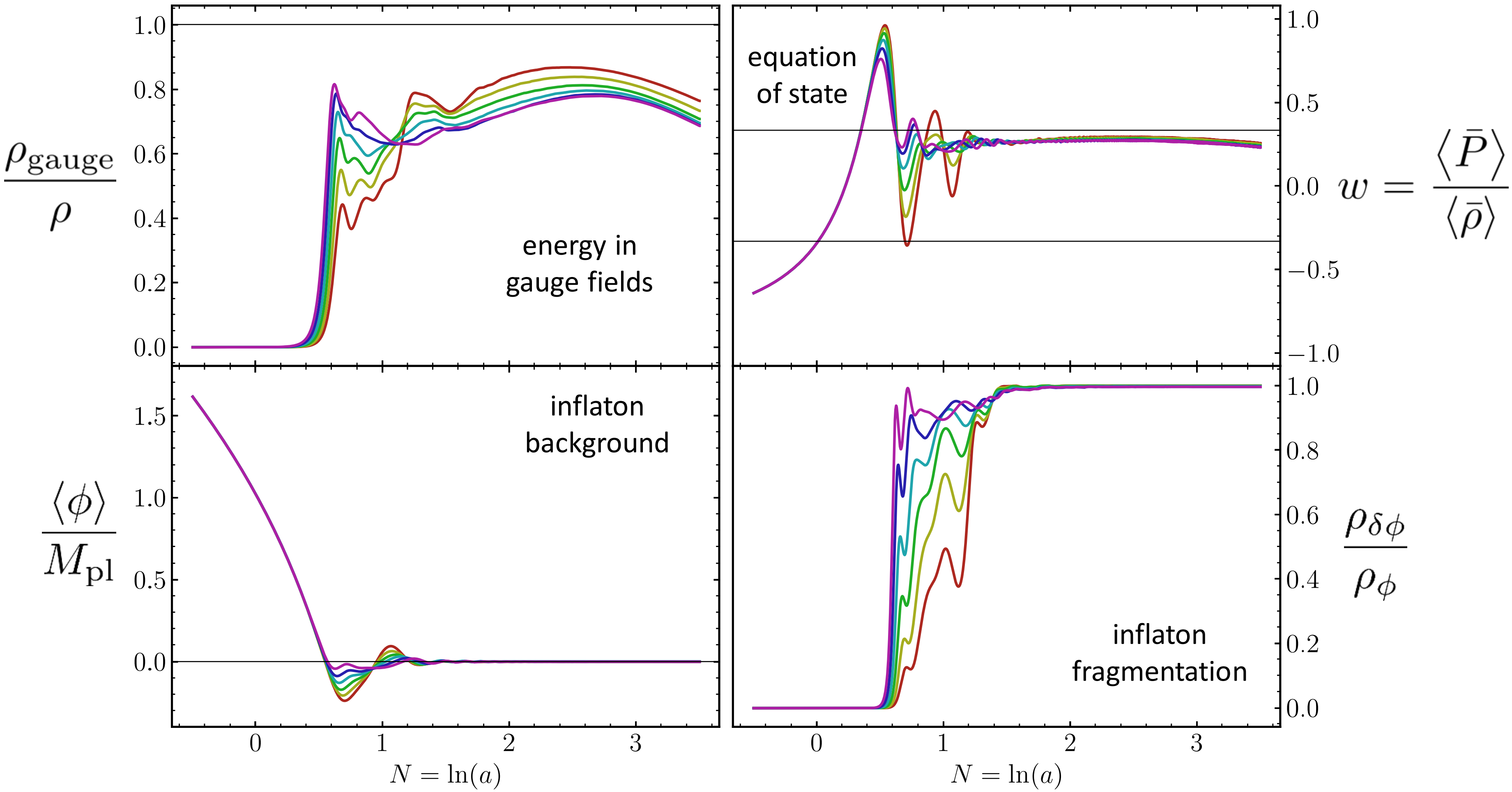




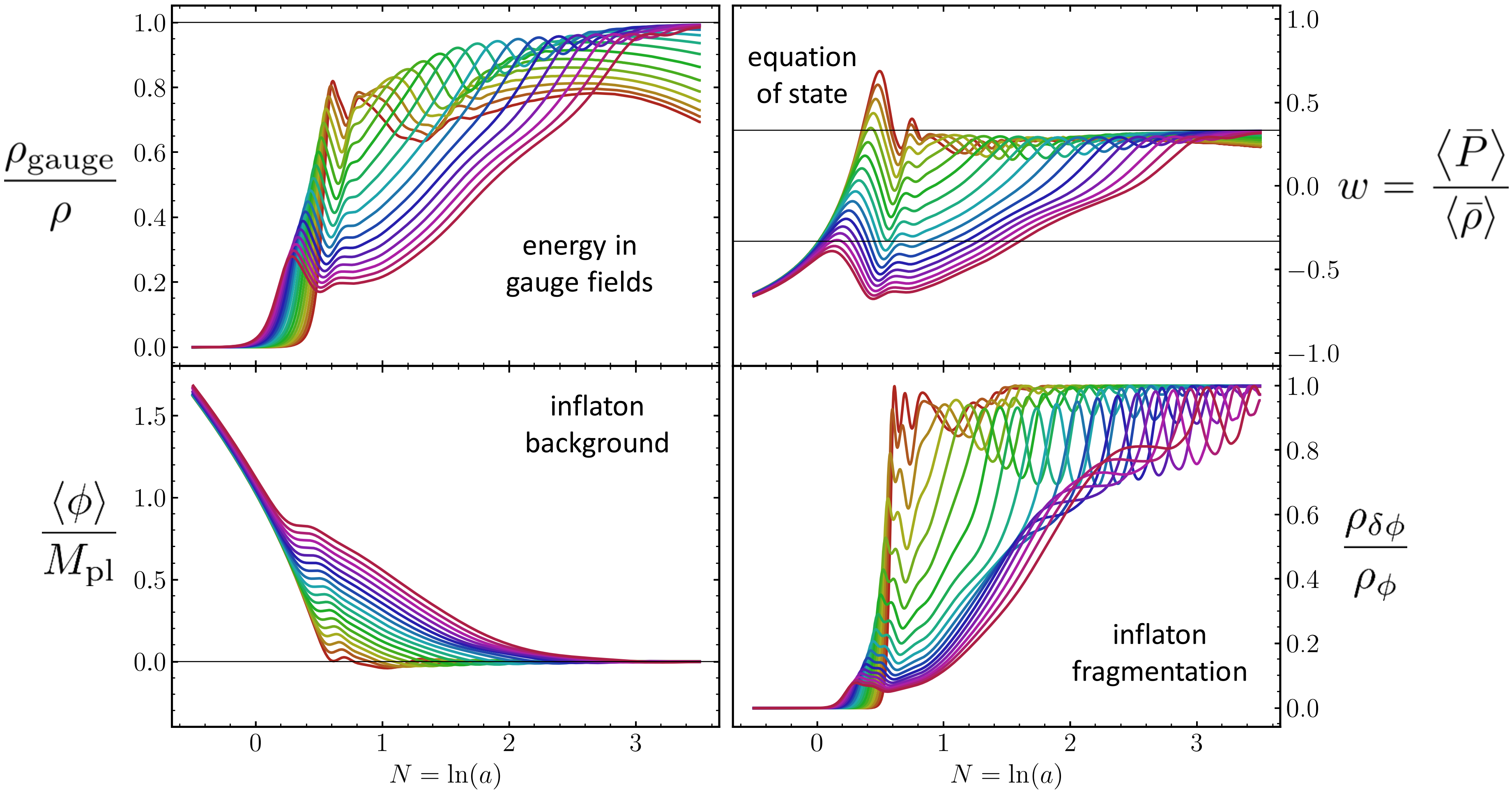
Low coupling: efficient resonance



Moderate coupling: backreaction



High coupling: gauge-field supported tachyonic resonance



Generation of gravitational waves

- Preheating generates anisotropic stress

$$T_{ij}^{A} = -\frac{1}{a^2}\left[E_i E_j + B_i B_j + \frac{\delta_{ij}}{2}\left(\mathbf{E}^2 + \mathbf{B}^2\right)\right]$$

$$T_{ij}^{\phi} = \partial_i \phi \partial_j \phi - a^2 \delta_{ij}\left(\frac{1}{2}\partial_\mu \partial^\mu \phi + V(\phi)\right)$$

which sources gravitational waves

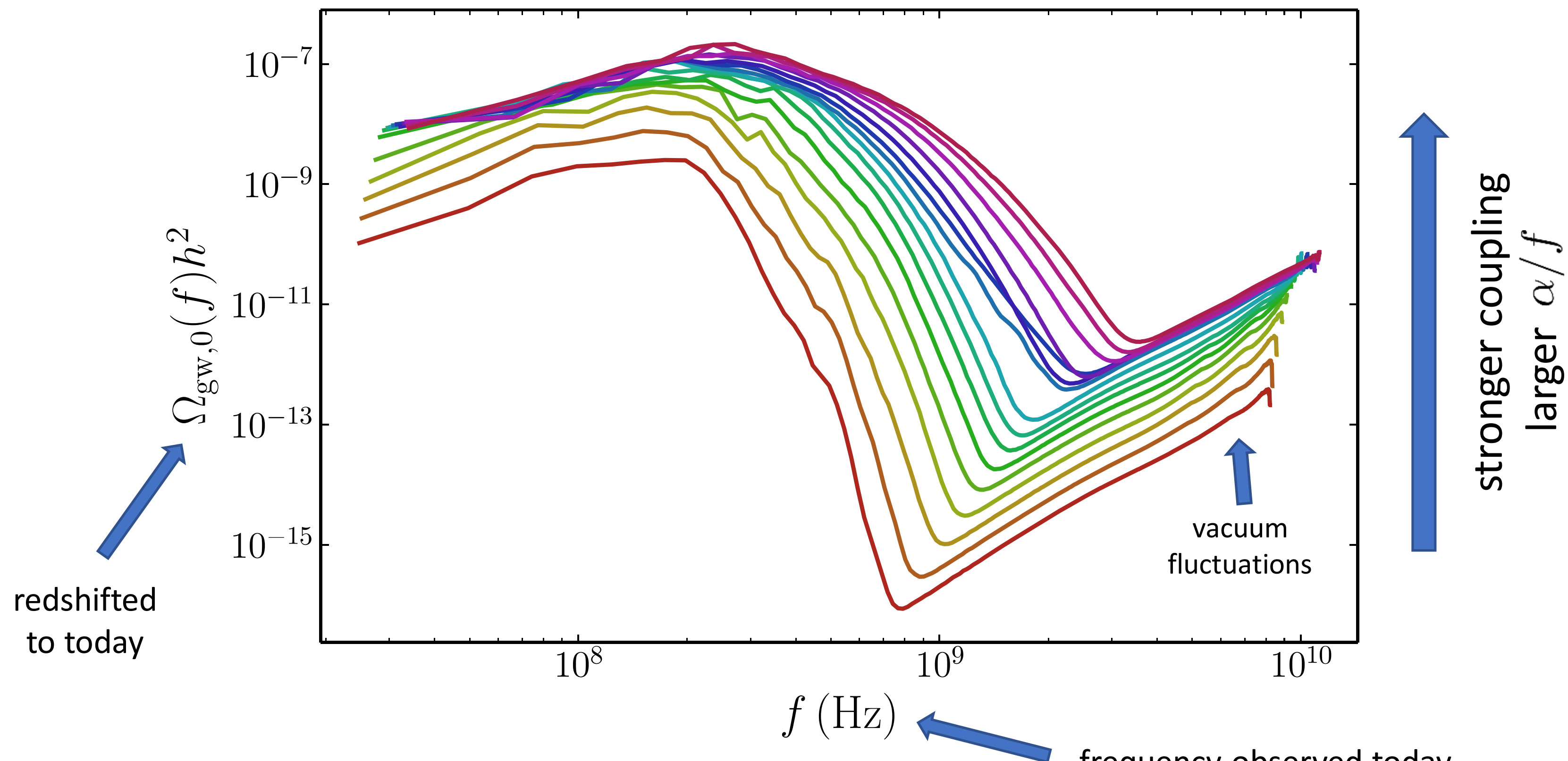
$$h_{ij}'' - \nabla^2 h_{ij} + 2\mathcal{H} h_{ij}' = \frac{2}{M_{\mathrm{pl}}^2} T_{ij}^{\mathrm{TT}}$$

linear, inhomogeneous PDE

transverse-traceless projection of the stress tensor

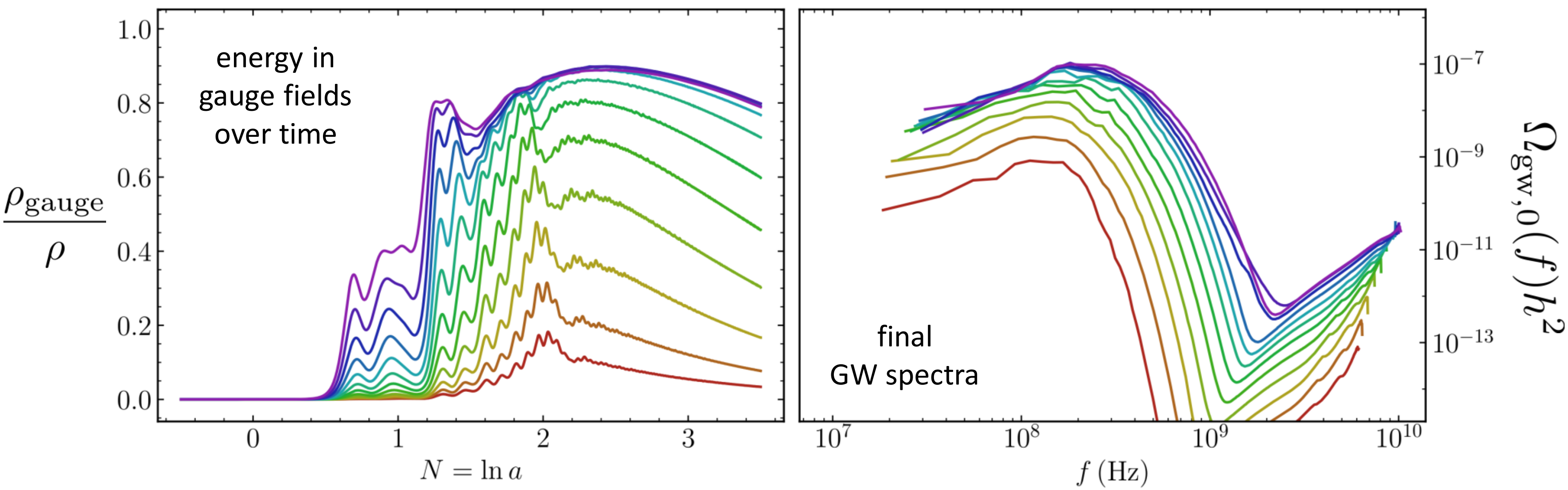
Generation of gravitational waves

$$\Omega_{\rm gw}(k) \equiv \frac{1}{\rho}\frac{\mathrm{d}\rho_{\rm gw}}{\mathrm{d}\ln k} = \frac{1}{24\pi^2 L^3}\frac{k^3}{\mathcal{H}^2}\sum_\lambda \left|h_k^{\lambda\prime}(\tau))\right|^2$$



$\sim \rho^{1/4}$

Low coupling: efficient resonance



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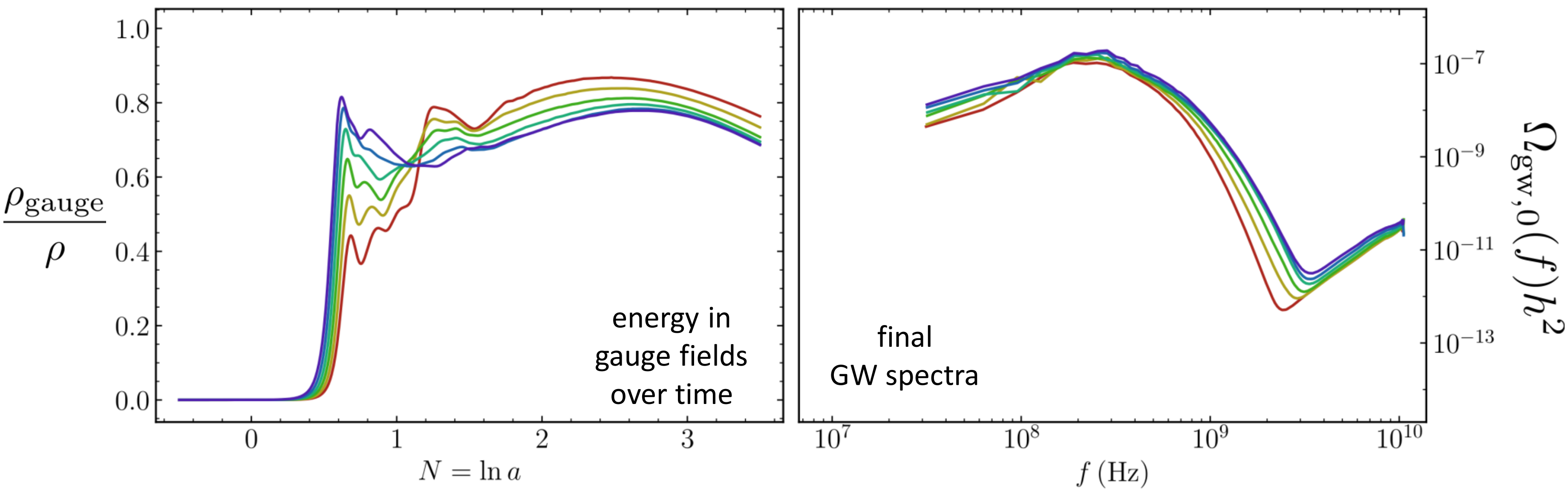

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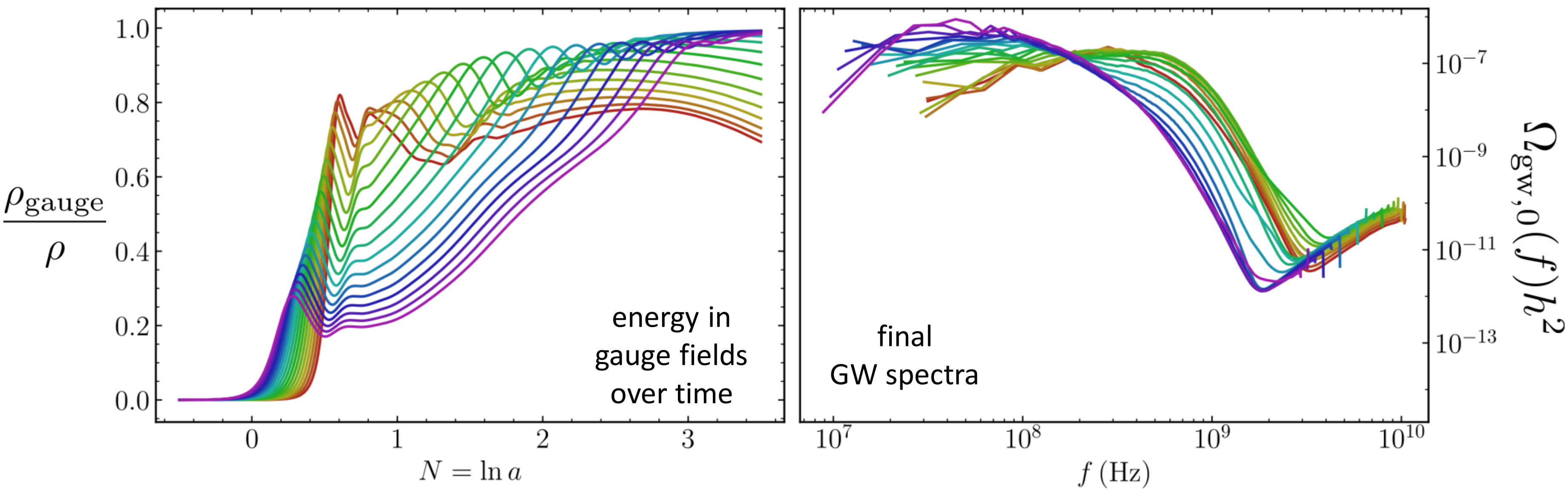


Constraints from $N_{\rm eff}$

- As radiation, GWs contribute to the effective number of relativistic degrees of freedom:

$$\frac{\Omega_{\rm gw,0} h^2}{\Omega_{\gamma,0} h^2} = \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \Delta N_{\rm eff}$$

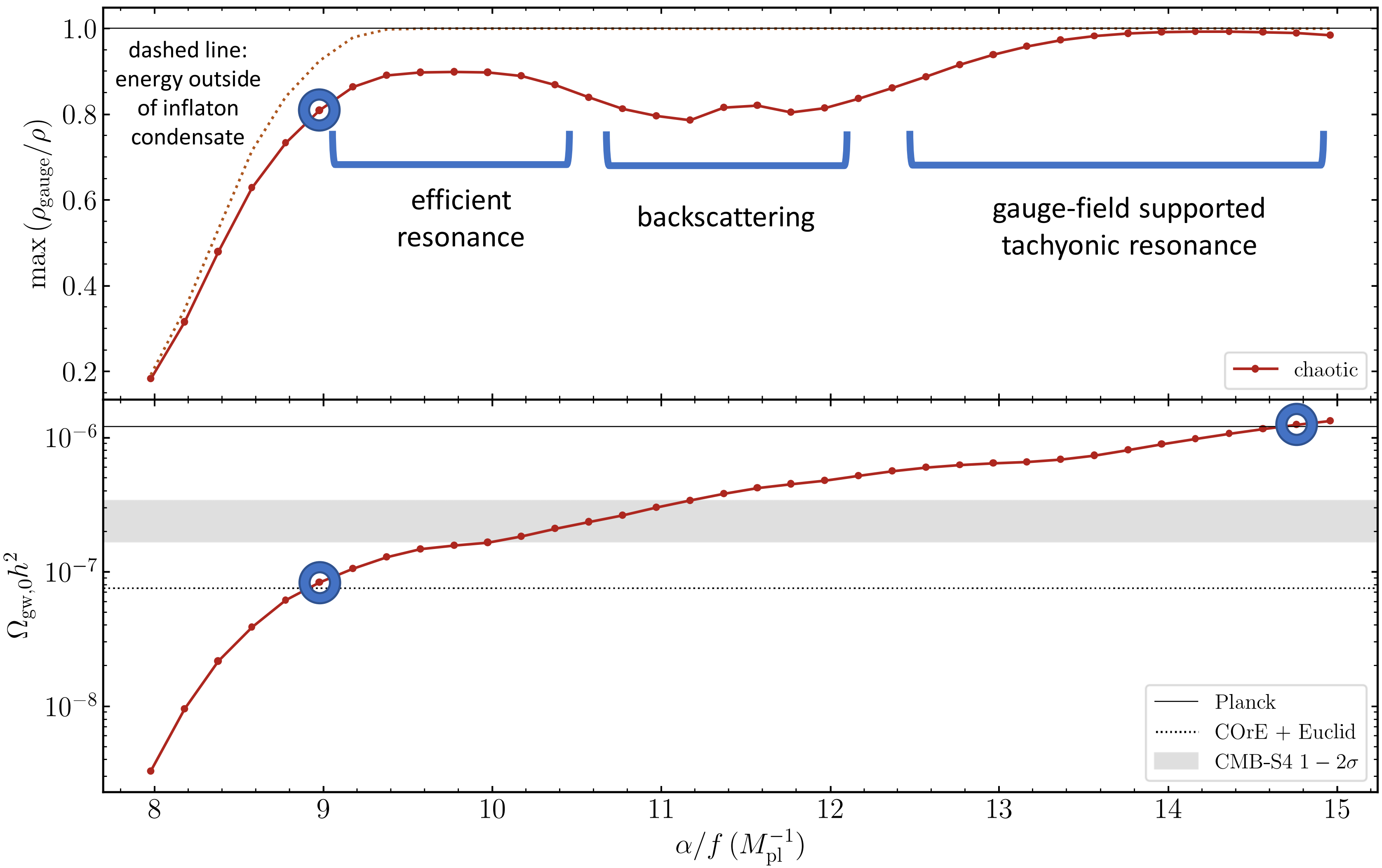
- CMB-S4 will probe $\Delta N_{\rm eff}$ to a level that would constrain*

$$\Omega_{\rm gw,0} h^2 \lesssim 7.6 \times 10^{-8}$$

$$\left(\Omega_{\rm radiation,0} h^2 \sim 10^{-5} \right)$$

*arXiv:1508.02393

Efficiency of GW production



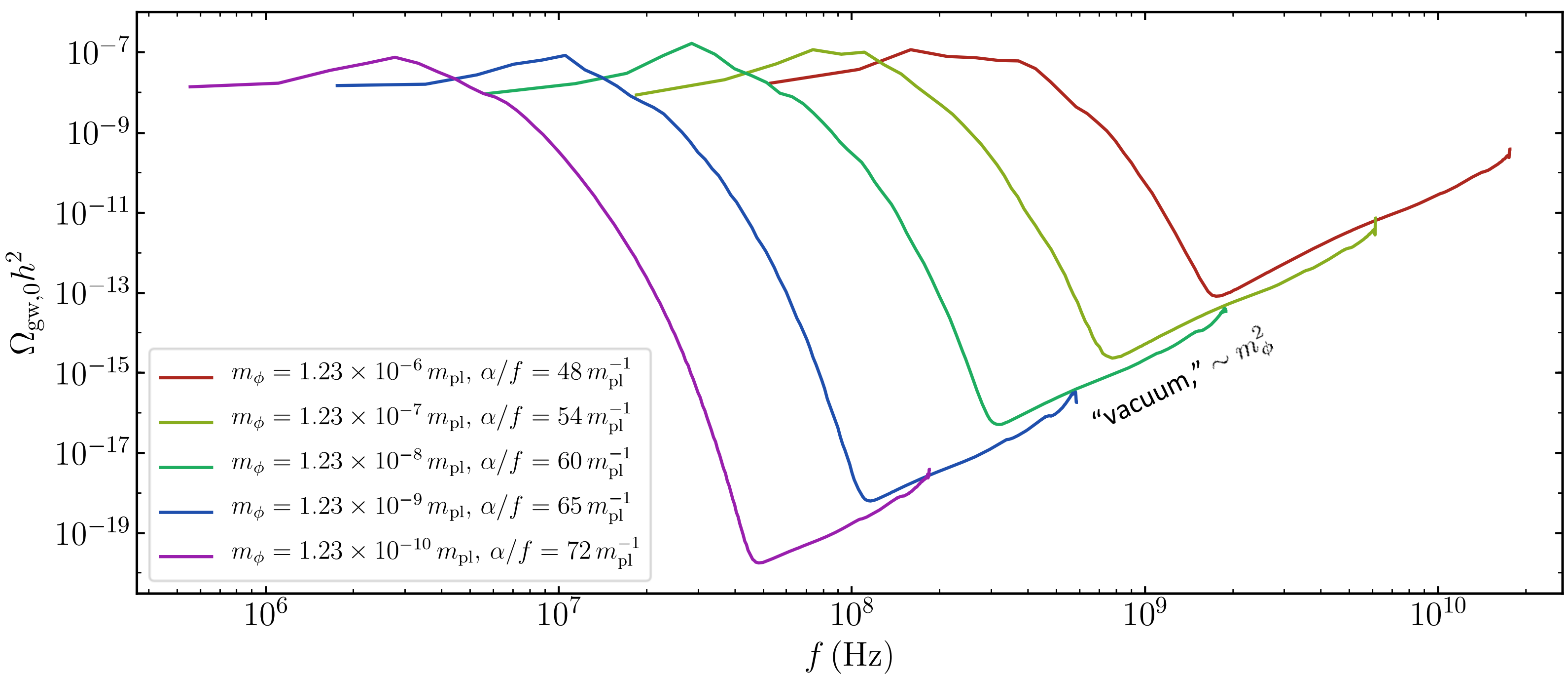
Dependence on the potential?

- Planck 2018, 68% CL:

$$n_s \simeq 0.9649 \pm 0.0042$$
$$r < 0.1$$

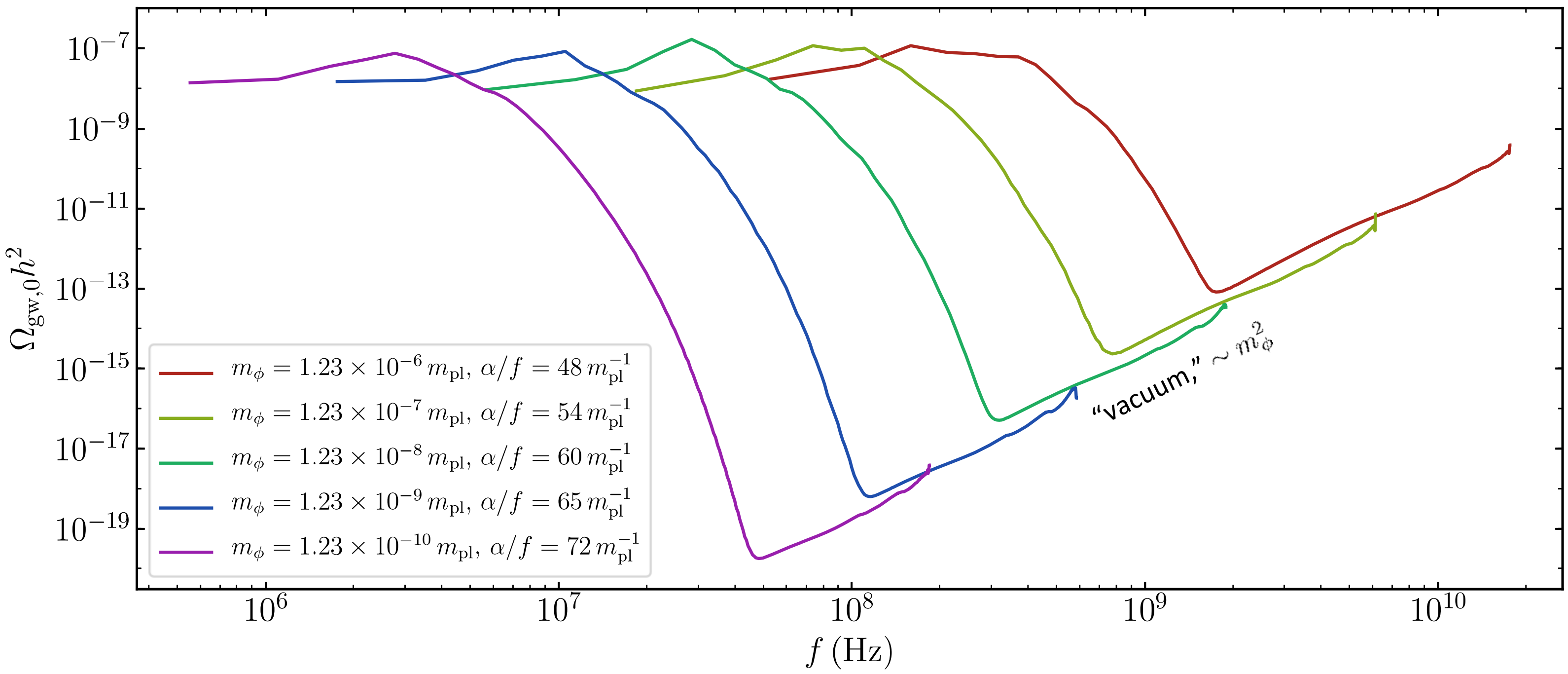
- Chaotic inflation is in fact disfavored at the 95% CL
- Quadratic potential models oscillations about a generic potential's minimum to leading order
  - Does the true shape of the potential matter?
- Does the inflationary energy scale have an effect?

Scaling of the GW spectrum



$$\sim \sqrt{m_\phi m_{\mathrm{pl}}}$$

Scaling of the GW spectrum

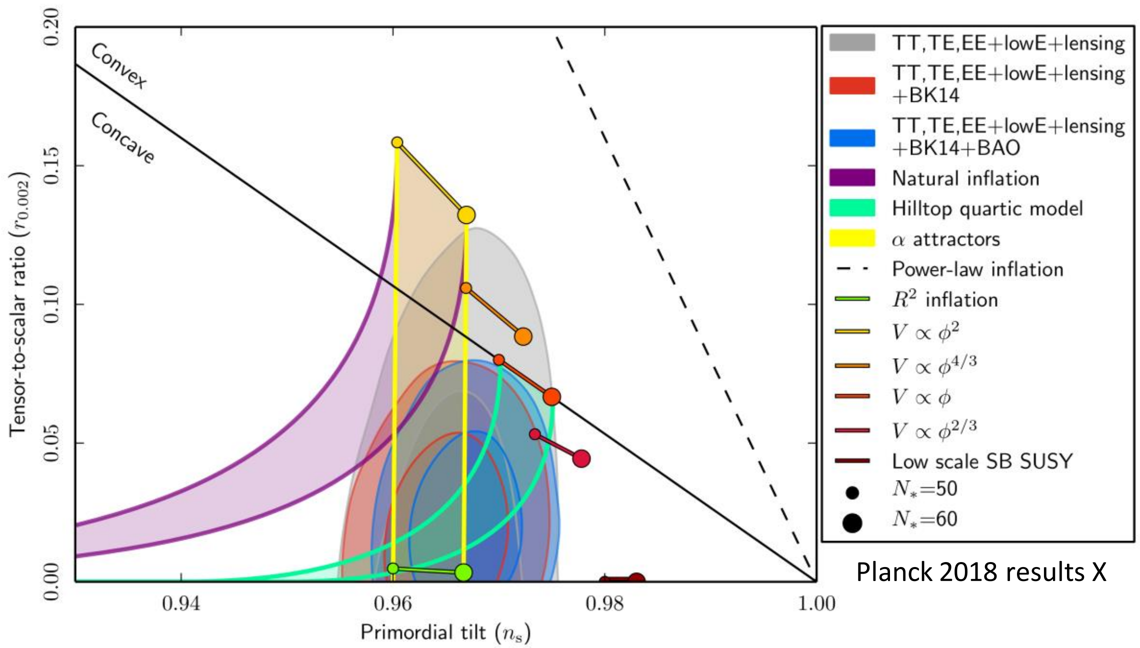


$$\sim \sqrt{m_\phi m_{\mathrm{pl}}}$$

direct detection?
=(

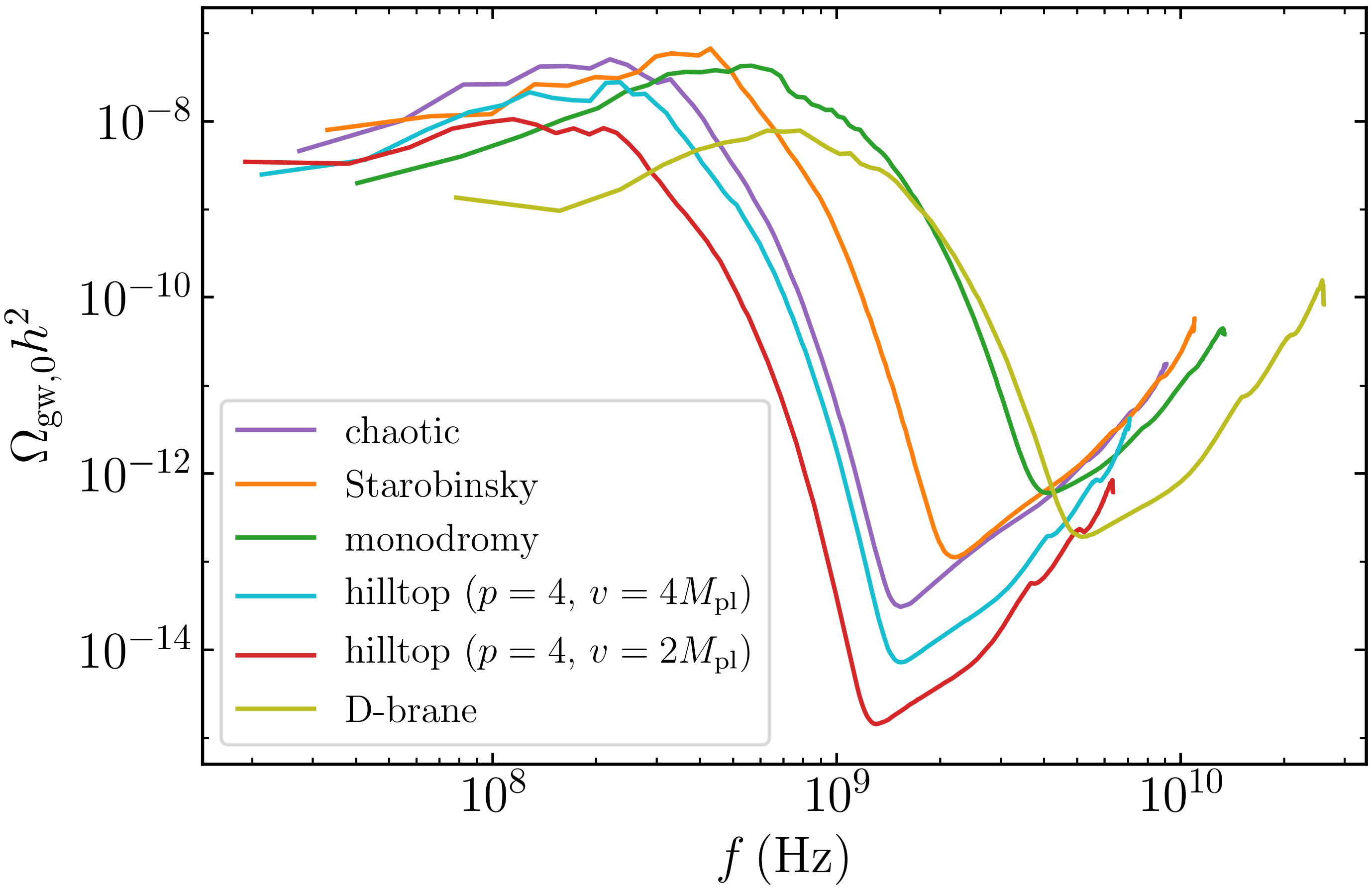
What about the shape of the potential?

- Models are characterized by predicted scalar tilts and tensor-to-scalar ratios
- Is there a connection to preheating/GW production?



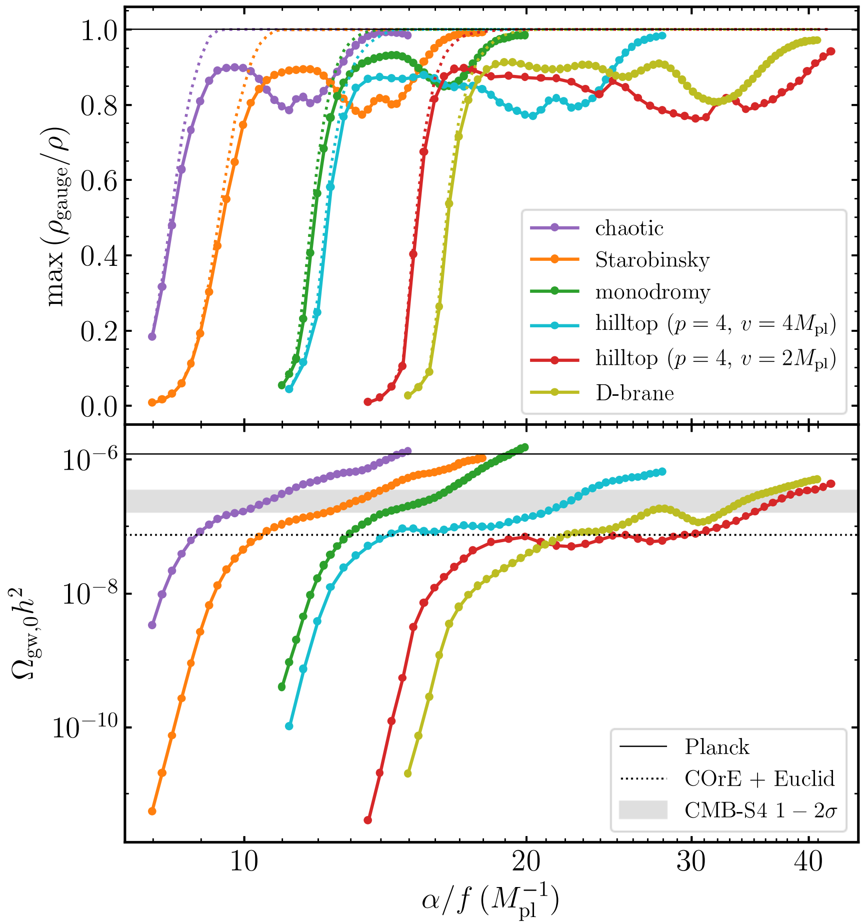
Planck 2018 results X

Gravitational wave signals



In all cases: preheating is 85% efficient

Dependence on potential shape



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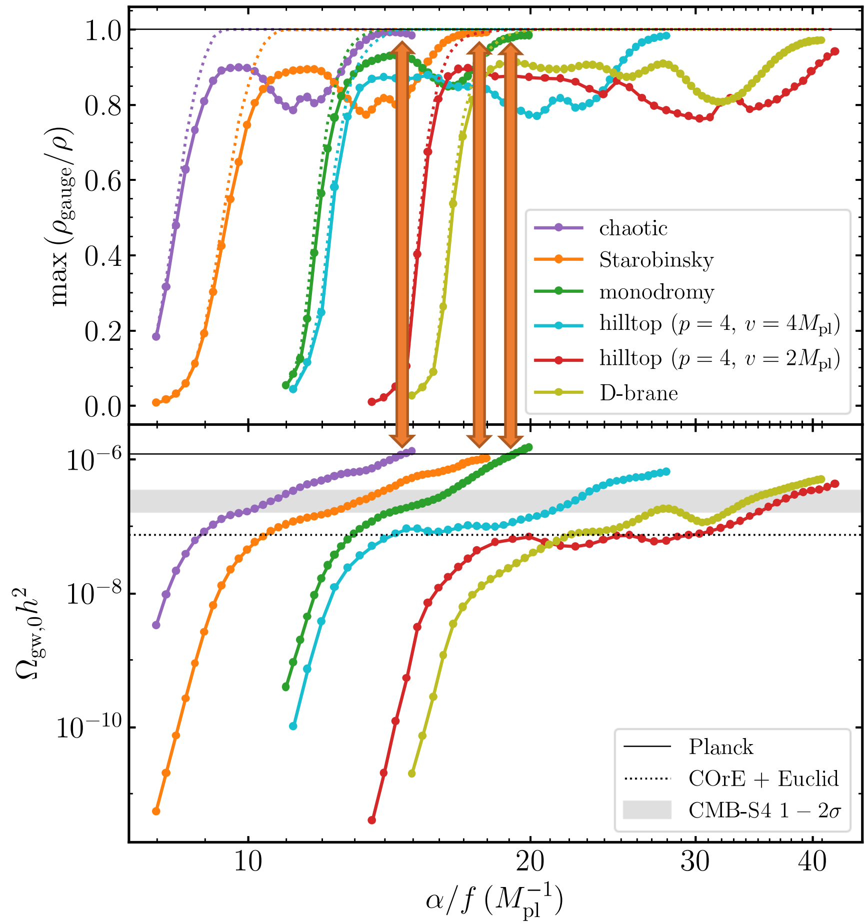

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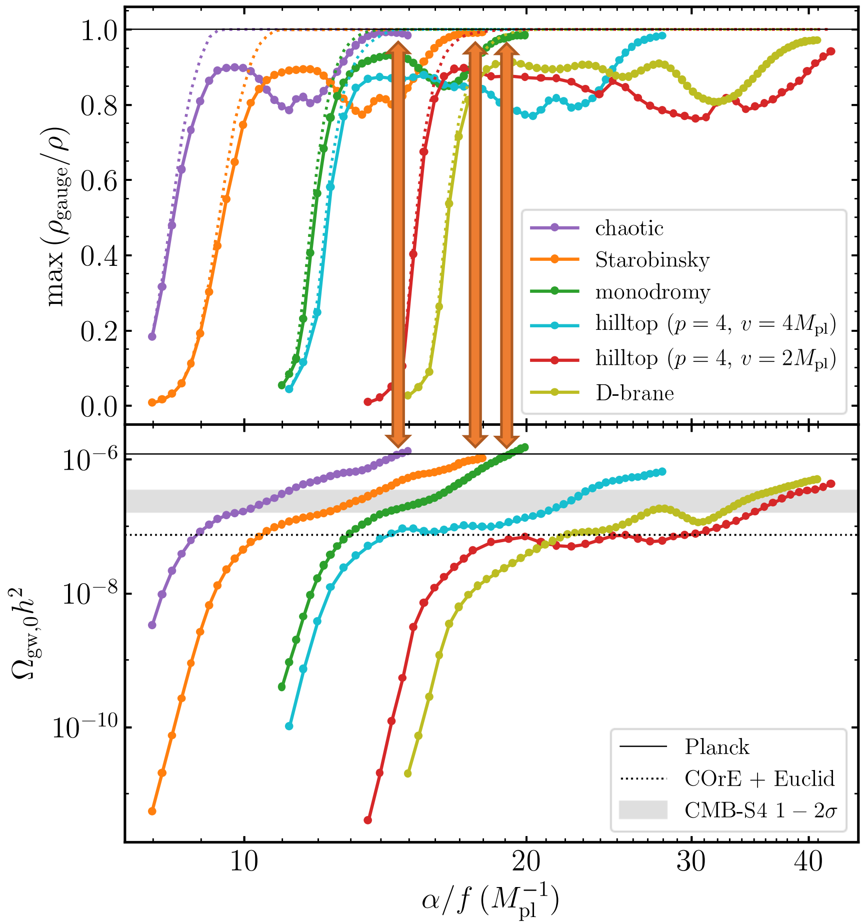

Now: constrain coupling for high-scale inflation models

Dependence on potential shape

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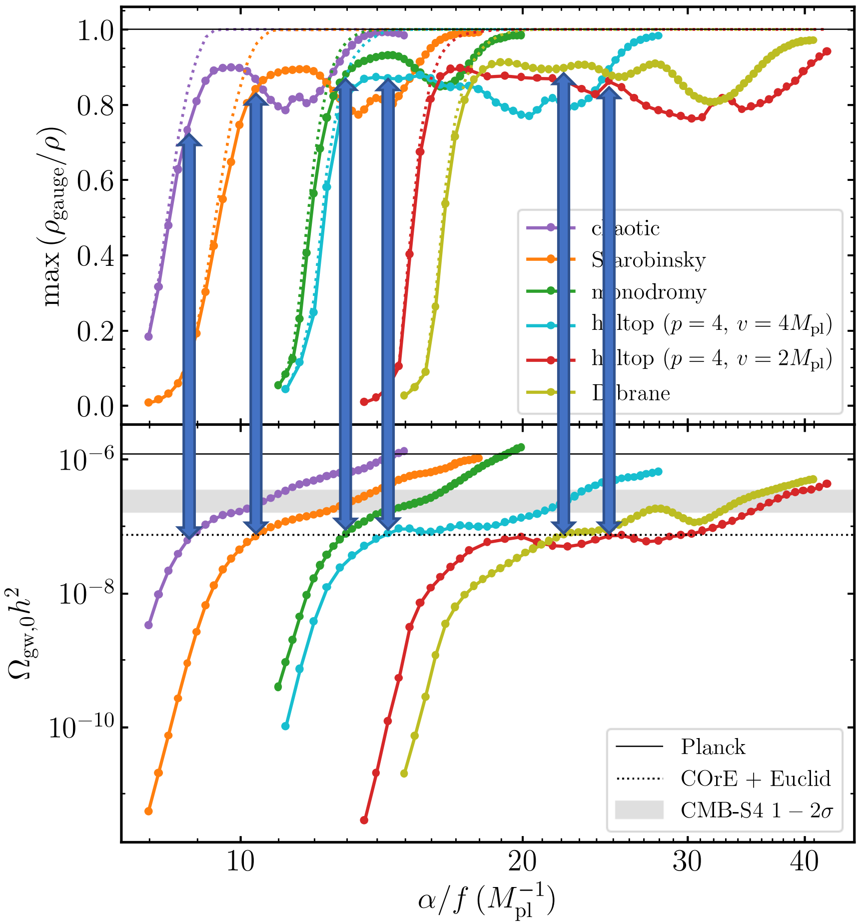

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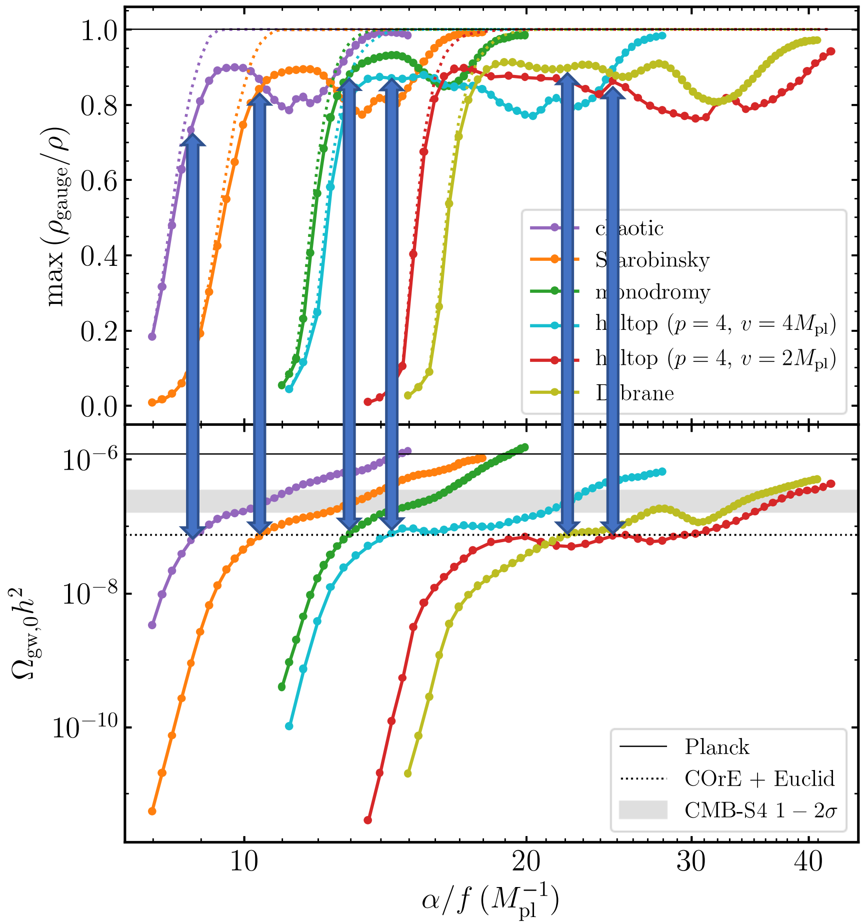
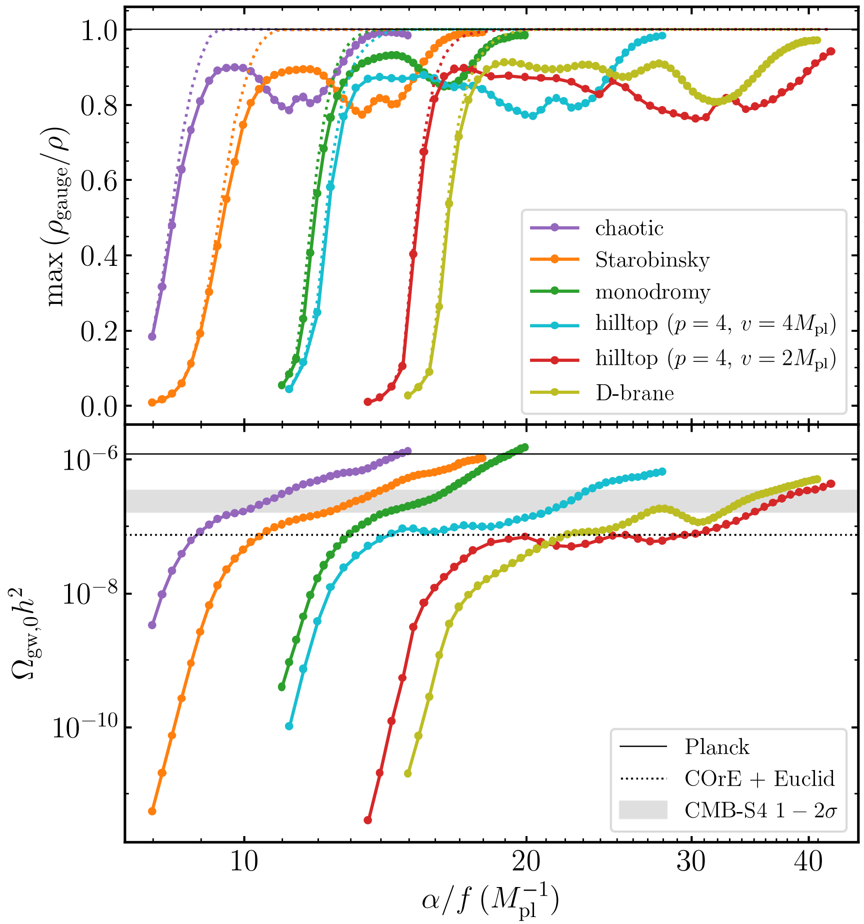


Now: constrain coupling for high-scale inflation models

In the future: probe/rule out regime of complete preheating

Dependence on potential shape

constraints are strongest for high-scale inflation (→ large tensor-to-scalar ratio)



observe $r \gtrsim 10^{-3}$ and nonzero $\Delta N_{\rm eff}$ → consistent with large scale inflaton coupled to gauge fields

Conclusions

- Inflaton couplings to gauge fields: compelling models, observable phenomenology
- Complete preheating in these models results in a (possibly) detectable relic gravitational wave background via CMB measurements of ΔN_{eff}
  - Places strongest current bounds on coupling strength
  - Could probe or rule out entire regime of gauge preheating after high scale inflation
- Future considerations
  - Primordial black hole (over)production?
  - Metric backreaction?
  - Plasma effects?