Lattice Simulations of Axion Inflation

Status and perspectives

Angelo Caravano (He/Him) - Institut d'Astrophysique de Paris

Based on work with: Drew Jamieson, Eiichiro Komatsu, Kaloian D. Lozanov, Marco Peloso, Jochen Weller,…

Roadmap

0) Motivation: why axion inflation? Why simulations?

1) The method: lattice simulations of inflation

2) Results

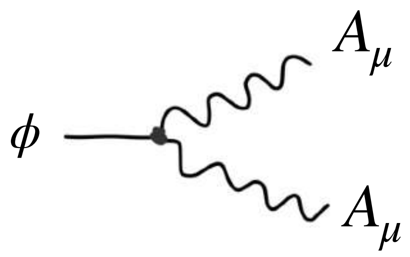
3) Open questions and future directions

Axion inflation

[Freese, Frieman, Olinto (1990)]
[Anber, Sorbo 0908.4089]

Think of the inflaton as an axion-like field

$$\mathscr{L}_{\text{inflation}} \supset \frac{\alpha}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$



In this talk: focus on U(1) gauge field $A_\mu = (A_0, \vec{A})$

Axion-U(1) inflation

[Freese, Frieman, Olinto 1990]
[Turner, Widrow 1988]
[Garretson, Field, Carrol 1992]
[Anber, Sorbo 0908.4089]

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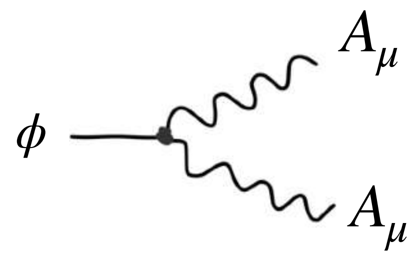
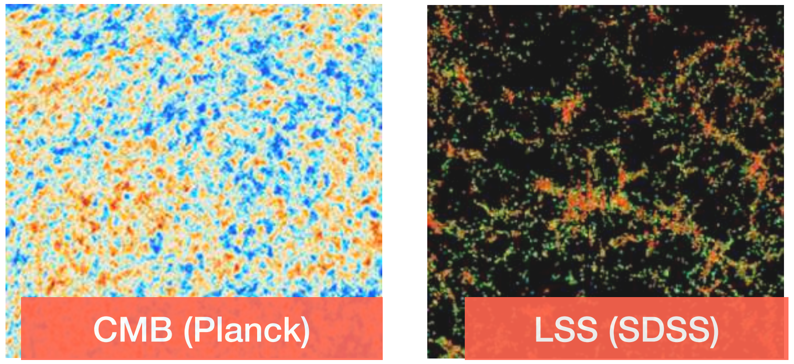


Observational consequences:

1. Production of gauge field → **2.** decay into inflaton perturbations



observable!

Axion-U(1) inflation

...
[Anber, Sorbo 0908.4089]
[Barnaby, Peloso 1011.1500]

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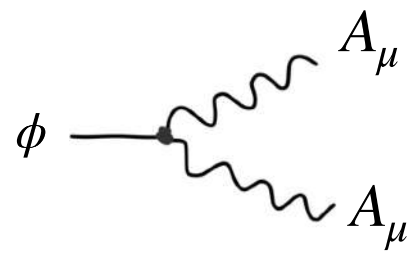


Observational consequences:

1. Production of gauge field → **2.** decay into inflaton perturbations

In math:

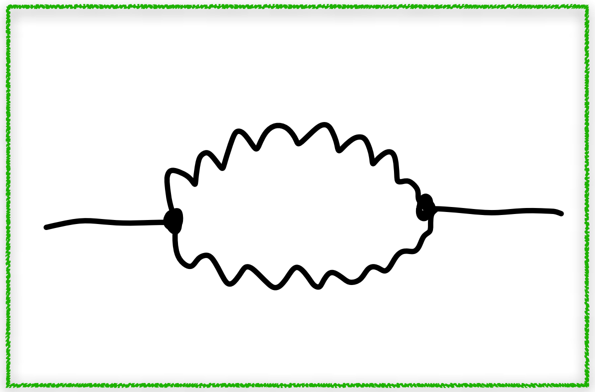
1. $$A_\pm'' + \left(k^2 \pm k\phi' \frac{\alpha}{f}\right) A_\pm = 0$$ one helicity enhanced for $k < \phi' \dfrac{\alpha}{f}$ easy (linear)

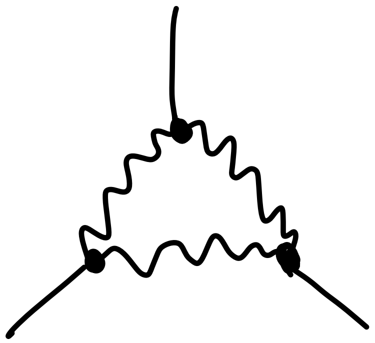
2. $$\left(\frac{\partial^2}{\partial \tau^2} + 2\mathscr{H}\frac{\partial}{\partial \tau} - \nabla^2 + a^2 V''(\phi)\right) \delta\phi(\vec{x}, \tau) = a^2 \frac{\alpha}{f} \left(F_{\mu\nu}\tilde{F}^{\mu\nu}(\vec{x}) - \langle F_{\mu\nu}\tilde{F}^{\mu\nu}\rangle\right)$$ difficult (nonlinear)

Axion inflation

Analytic results

(Green function methods, in-in calculations)





- Power spectrum:

$$\boxed{\mathscr{P}_\zeta(k) \simeq \mathscr{P}_{\mathrm{vac}} + \mathscr{P}^2_{\mathrm{vac}} f_2(\xi) e^{4\pi\xi}}$$

vacuum
(free theory)

sourced

$$\mathscr{P}_{\mathrm{vac}} \simeq \frac{H^4}{(2\pi\dot{\phi})^2}$$

$$\xi = \frac{\alpha\dot{\phi}}{2fH}$$

Axion inflation

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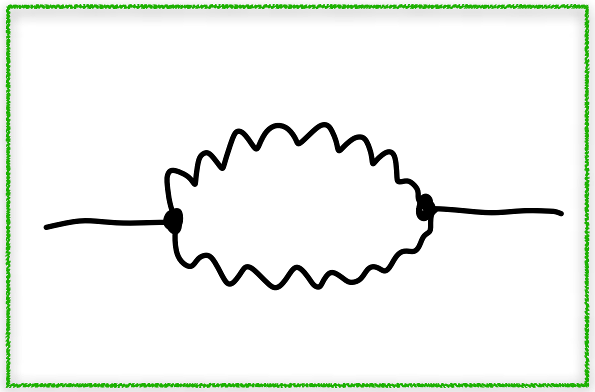

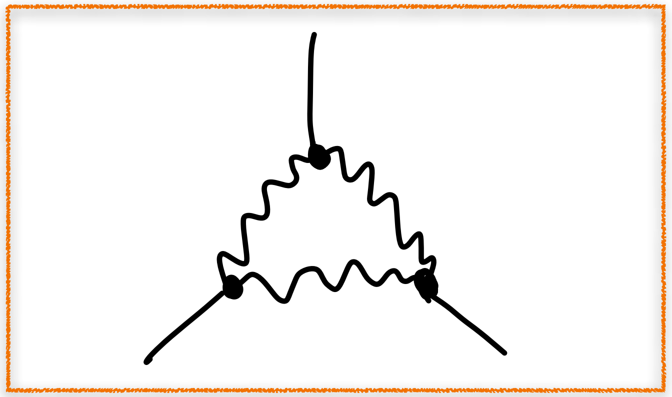

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vacuum
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$$\mathcal{P}_{\text{vac}} = \frac{H^4}{(2\pi\dot{\phi})^2}$$

$$\xi = \frac{\alpha\dot{\phi}}{2fH}$$

- Bispectrum:

$$\boxed{f_{\text{NL}}^{(\text{equil.})}(\xi) \simeq \frac{f_3(\xi)\mathcal{P}_{\text{vac}}^3 e^{6\pi\xi}}{\mathcal{P}_\zeta^2}}$$

Axion inflation

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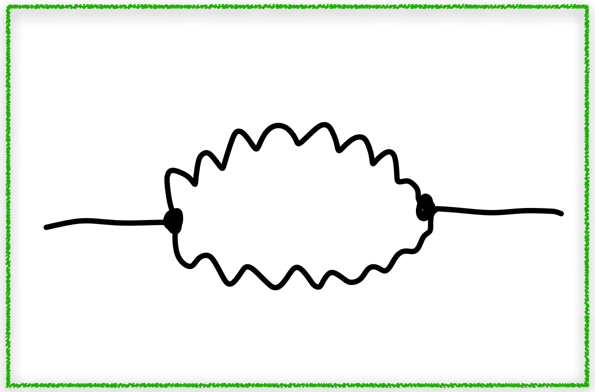
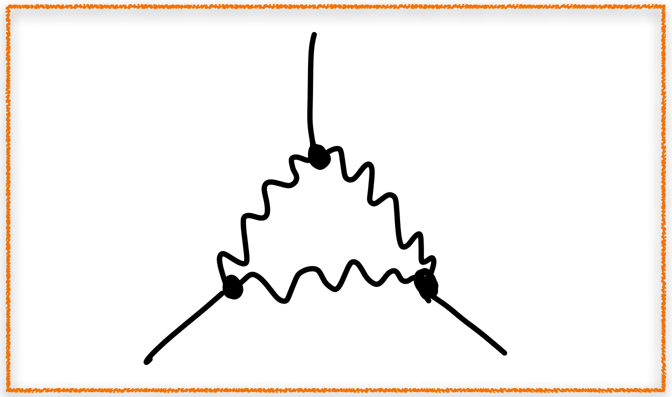
Analytic results

(Green function methods, in-in calculations)





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vacuum
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$$\mathscr{P}_{\rm vac} = \frac{H^4}{(2\pi\dot{\phi})^2}$$

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- Bispectrum:

$$\boxed{f_{\rm NL}^{\rm (equil.)}(\xi) \simeq \frac{f_3(\xi)\mathscr{P}^3_{\rm vac} e^{6\pi\xi}}{\mathscr{P}^2_\zeta}}$$

assuming constant ξ

Axion inflation

[Anber, Sorbo 0908.4089]
[Barnaby, Peloso 1011.1500]
[Sorbo 1011.1525]

Analytic results

(Green function methods, in-in calculations)

- Power spectrum: $$\mathcal{P}_\zeta(k) \simeq \mathcal{P}_{\rm vac} + \mathcal{P}_{\rm vac}^2 f_2(\xi) e^{4\pi\xi}$$ $$\mathcal{P}_{\rm vac} \simeq \frac{H^4}{(2\pi\dot{\phi})^2}$$
- Bispectrum: $$f_{\rm NL}^{\rm (equil.)}(\xi) \simeq \frac{f_3(\xi)\mathcal{P}_{\rm vac}^3 e^{6\pi\xi}}{\mathcal{P}_\zeta^2}$$ $$\xi = \frac{\alpha\dot{\phi}}{2fH}$$
- Directly sourced, **chiral** gravitational waves:

$$\mathcal{P}_{GW}^{L/R} \simeq \frac{H^2}{\pi M_{\rm Pl}^2}\left[1 + \frac{2H^2}{M_{\rm Pl}^2} f_h^{L/R}(\xi) e^{4\pi\xi}\right], \qquad \mathcal{P}_{GW}^{L} \neq \mathcal{P}_{GW}^{R}$$

Axion inflation

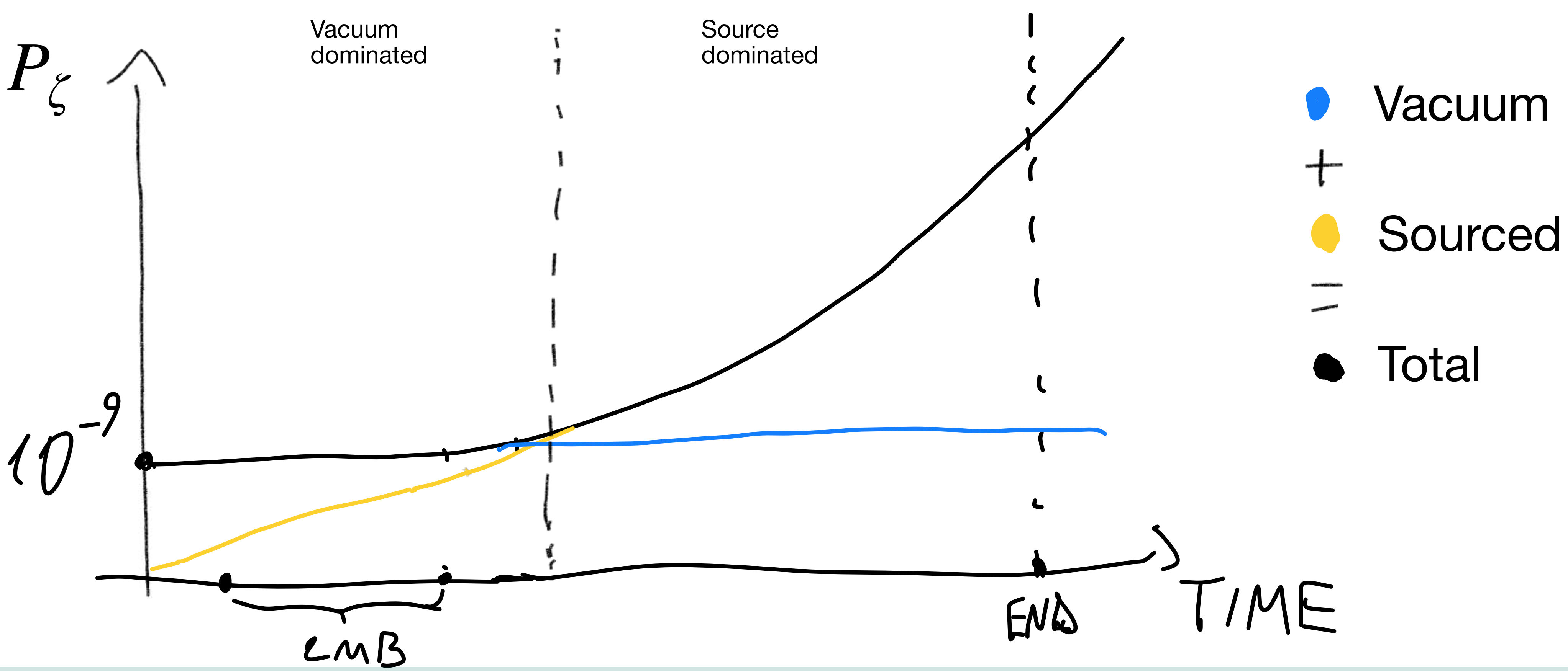
[Cook, Sorbo (2011)]
[Barnaby, Pajer, Peloso (2012)]
[Linde, Mooij, Pajer (2012)]
…

Analytic results

$$\mathcal{P}_\zeta(k) \simeq \mathcal{P}_{\text{vac}} + \mathcal{P}_{\text{vac}}^2 f_2(\xi) e^{4\pi\xi} \qquad \xi = \frac{\alpha\dot{\phi}}{2fH} \propto \sqrt{\epsilon}$$

Scalar perturbations naturally grow on small scales

Very interesting observational consequences: **PBHs, GWs at interpherometer scales**



Axion inflation

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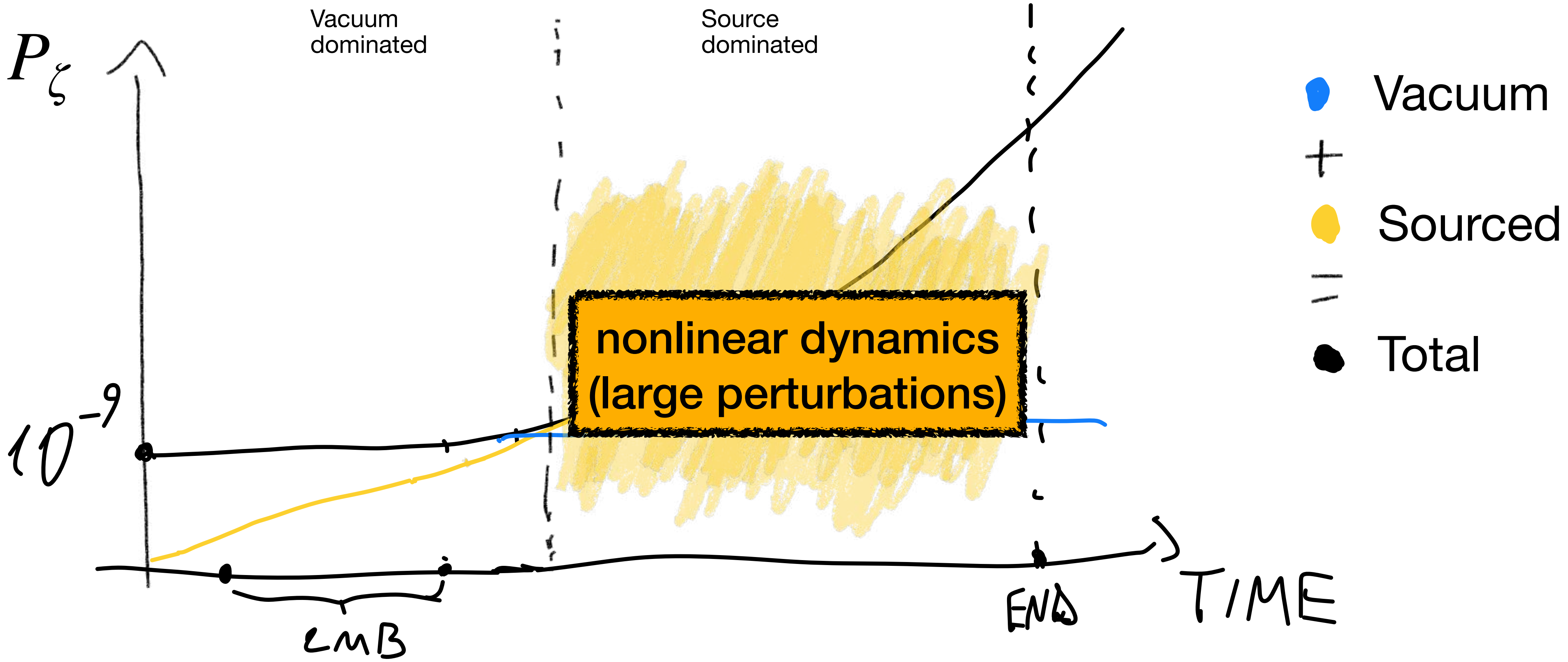
Scalar perturbations naturally grow on small scales

Very interesting observational consequences: **PBHs, GWs at interpherometer scales**

BUT:



Axion inflation

More precisely:

$$\partial_\tau^2 \bar{\phi} + 2\mathscr{H}\partial_\tau \bar{\phi} + a^2 V'(\bar{\phi}) = a^2 \frac{\alpha}{f} \langle F_{\mu\nu} \tilde{F}^{\mu\nu} \rangle$$

If these terms become comparable → **backreaction** → Sort of extra friction, but not so simple (as we will see)

Importantly, this happens when $\dfrac{\langle E^2 \rangle}{2} + \dfrac{\langle B^2 \rangle}{2} \ll V(\phi)$

but $\dfrac{\langle E^2 \rangle}{2} + \dfrac{\langle B^2 \rangle}{2} \sim \dfrac{\langle \dot{\phi}^2 \rangle}{2}$

Roadmap

0) Motivation: why axion inflation? Why simulations?

1) The method: lattice simulations of inflation

2) Results

3) Open questions and future directions

Lattice simulations

- Numerical tool to study non-perturbative cosmological phenomena.
- Examples: reheating phase after inflation, cosmological phase transitions.

Lattice simulations

AC, Komatsu, Lozanov, Weller (2021)
AC (2022), AC (2025)
Jamieson, AC, Komatsu (in prep.)

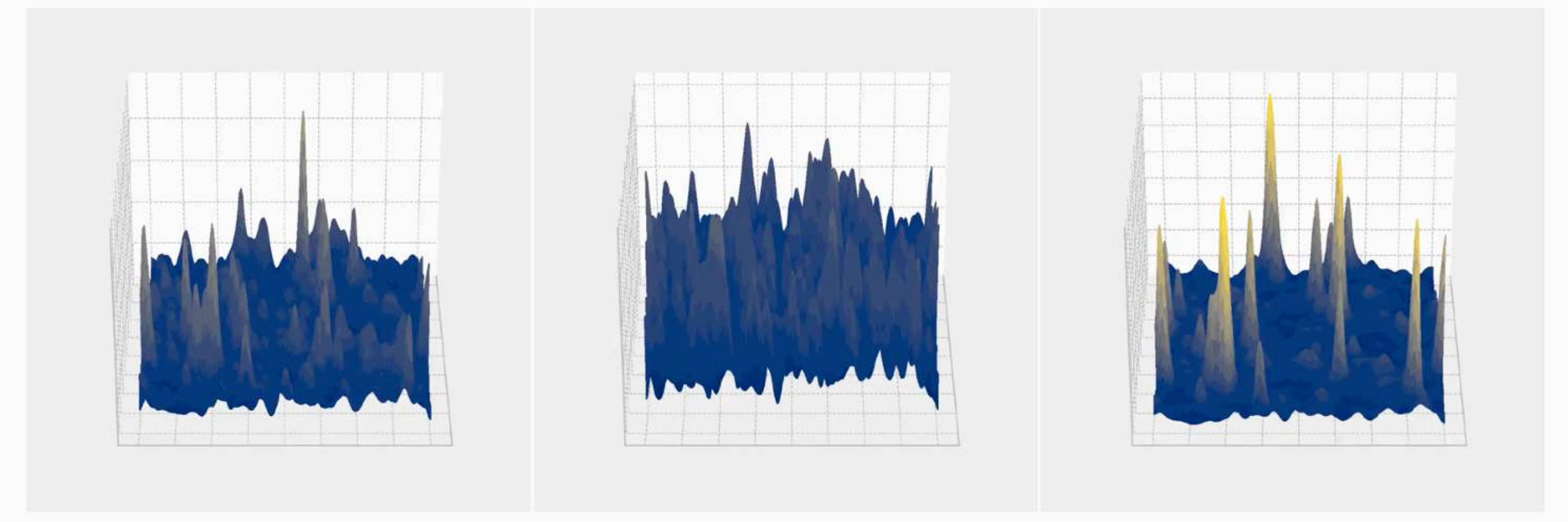
- Numerical tool to study non-perturbative cosmological phenomena.
- Examples: reheating phase after inflation, cosmological phase transitions.

My goal:

Develop lattice techniques for inflation

Recently published a code for single-field inflation:

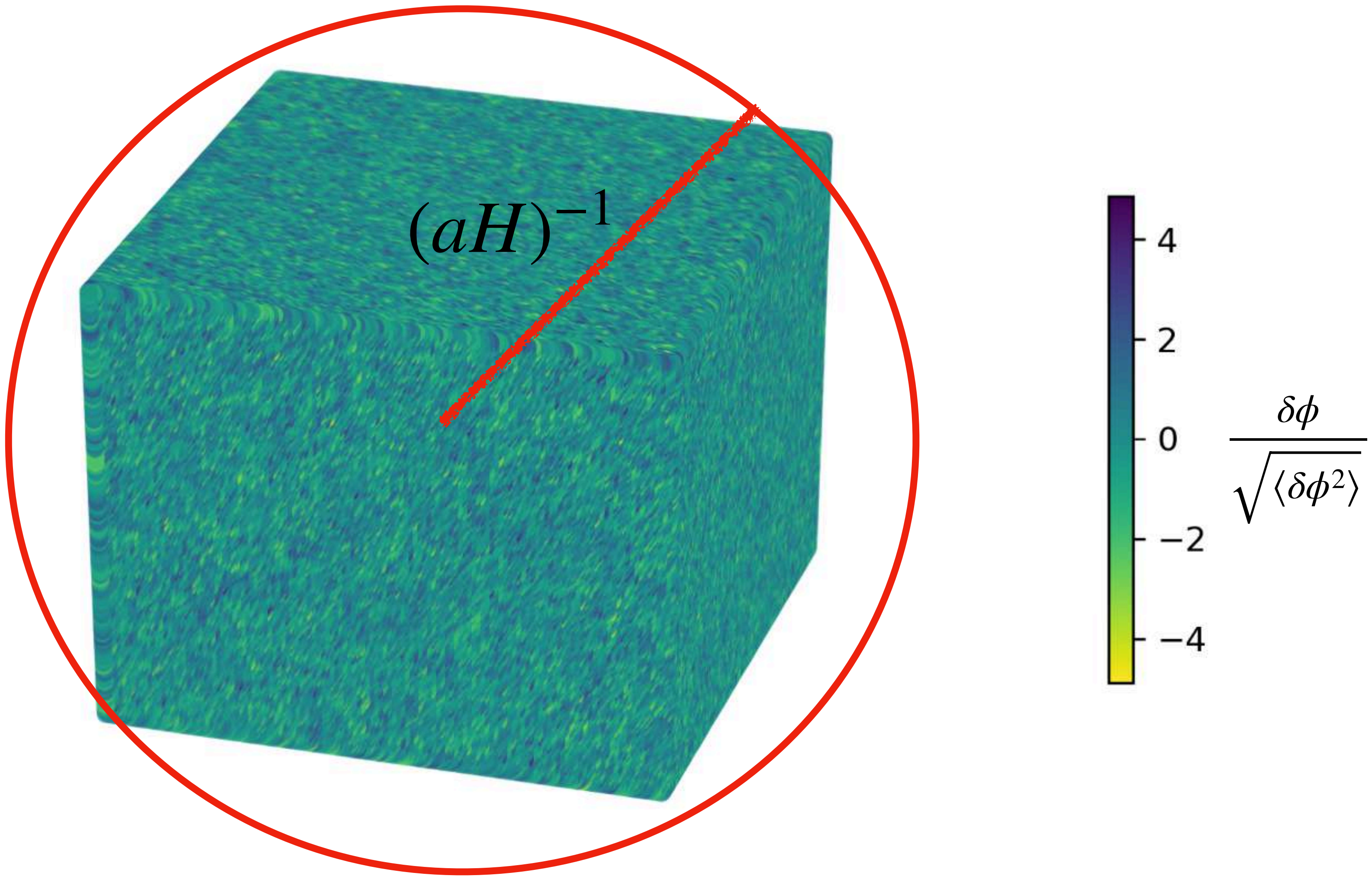
InflationEasy: A C++ Lattice Code for Inflation



Lattice simulations of inflation

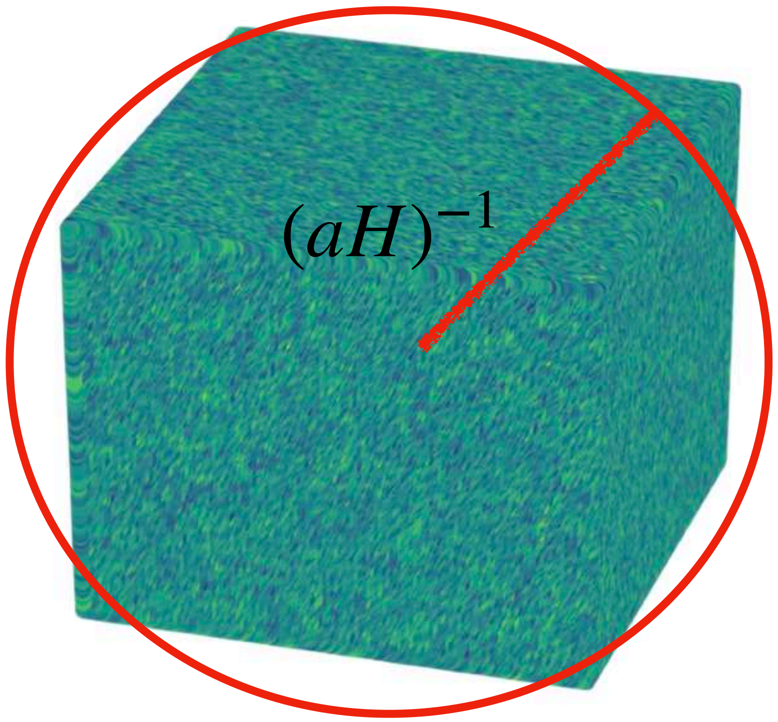
[AC 2209.13616]

Start with quantum fluctuations on sub-horizon box:



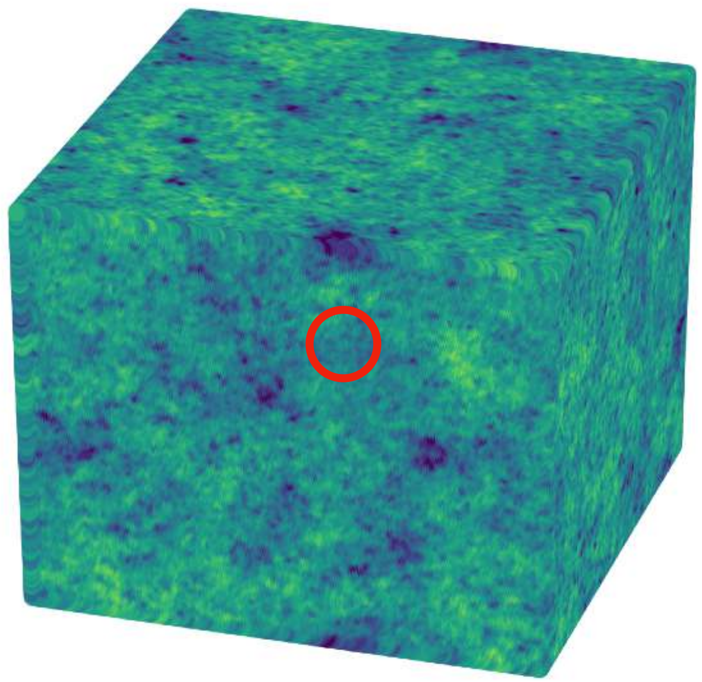
Lattice simulations of inflation

“sub-horizon” box



Nonlinear evolution

“super-horizon” box (frozen)



$$\phi'' + 2H\phi' - \partial_j\partial_j\phi + a^2\frac{\partial V}{\partial\phi} = -\,a^2\frac{\alpha}{4f}F_{\mu\nu}\tilde{F}^{\mu\nu},$$

$$A_0'' - \partial_j\partial_j A_0 = \frac{\alpha}{f}\epsilon_{ijk}\partial_k\phi\partial_i A_j,$$

$$A_i'' - \partial_j\partial_j A_i = \frac{\alpha}{f}\epsilon_{ijk}\phi'\partial_j A_k - \frac{\alpha}{f}\epsilon_{ijk}\partial_j\phi(A_k' - \partial_k A_0)$$

\+ Friedmann equation for scale factor

$$\frac{d^2a}{d\tau^2} = \frac{1}{6}\left(\langle\rho\rangle - 3\langle p\rangle\right)a^3$$

Lattice simulations of inflation

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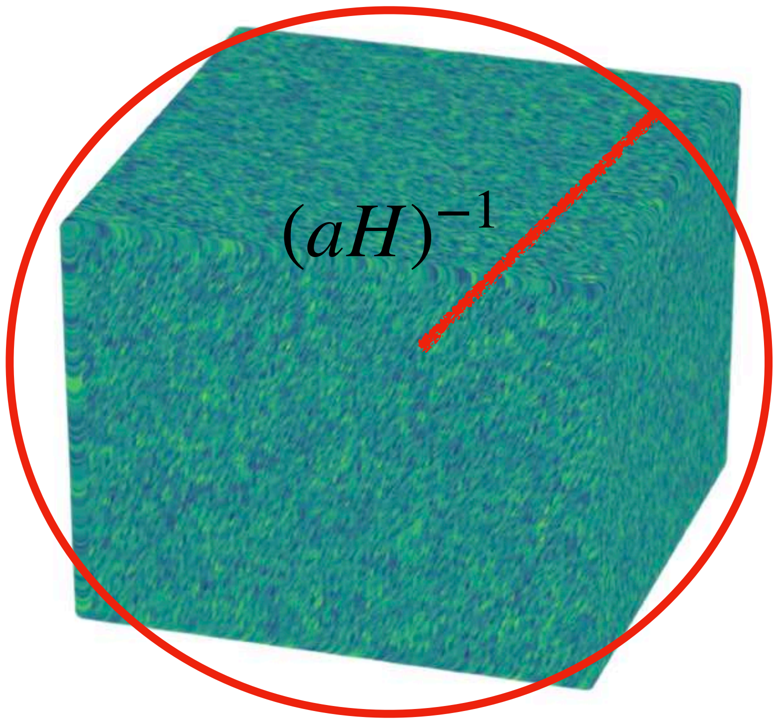
"sub-horizon" box



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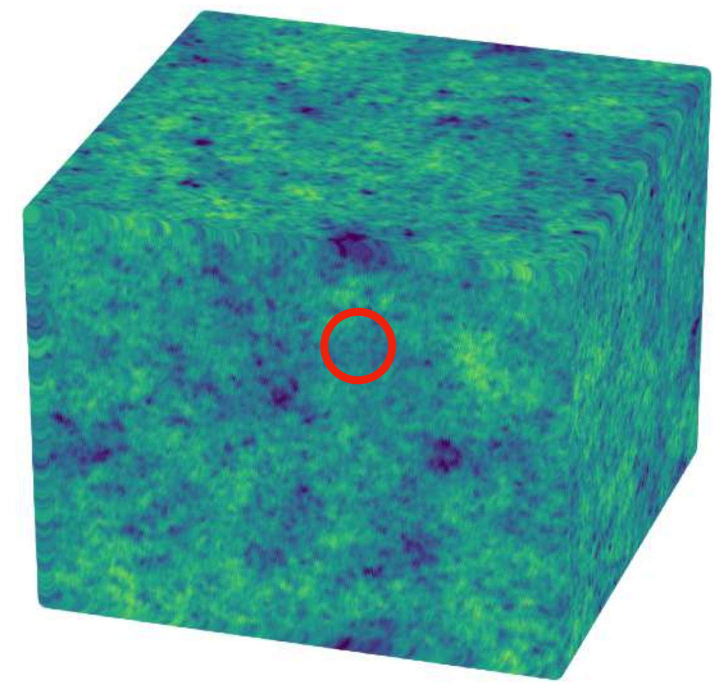

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+ Friedmann equation for scale factor

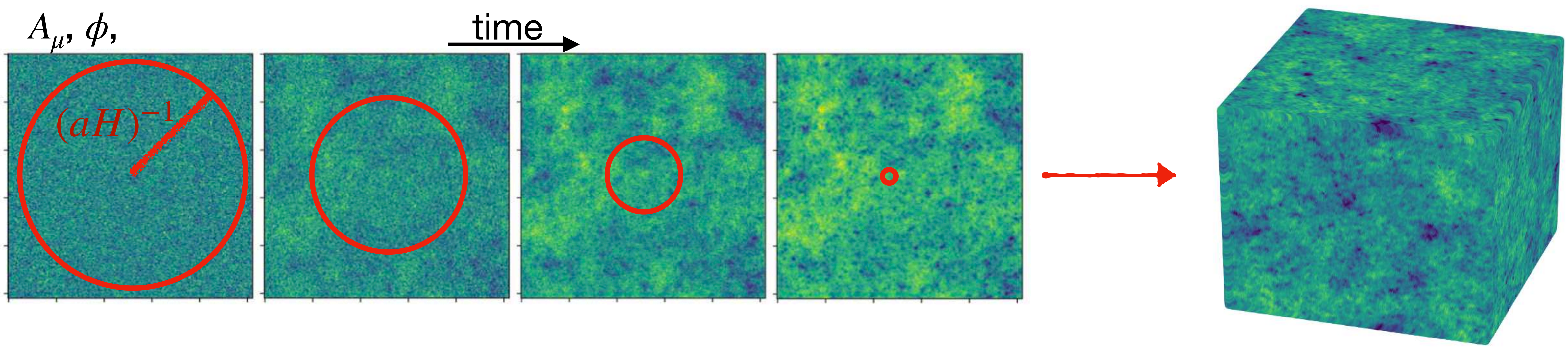
$$\frac{d^2a}{d\tau^2} = \frac{1}{6}\left(\langle\rho\rangle - 3\langle p\rangle\right)a^3$$

Analogous to the approach used for reheating in

Adshead, Gibling, Pieroni, Weiner (2019)

Lattice simulations of Inflation

[AC 2209.13616]



- Key point: non-perturbative $\phi(\vec{x},t) \neq \bar{\phi}(t) + \delta\phi(\vec{x},t)$

- Assumptions: 1) Neglect gravitational interactions

  2) Semi-classical approach (neglect quantum tunneling, interference, etc…)

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Lattice simulation of axion inflation

AC, Komatsu, Lozanov, Weller (2022)
AC (2022)

The first simulation of axion inflation

Results:

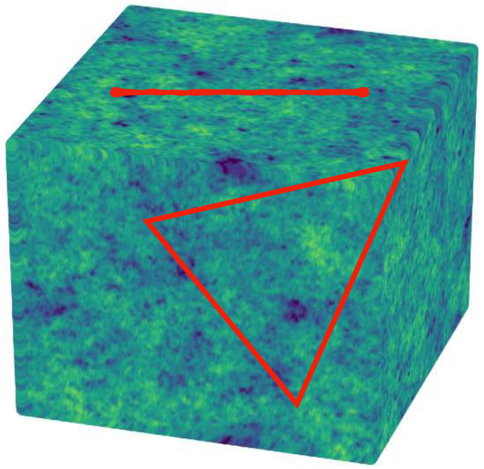
1. Large scales: small $\xi = \frac{\alpha\dot{\phi}}{2fH}$ linear regime

2. Small scales: large $\xi = \frac{\alpha\dot{\phi}}{2fH}$ nonlinear regime

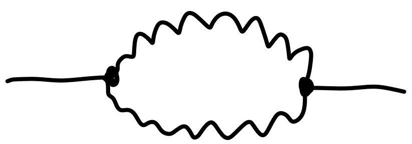
Perturbative regime (large scales)

AC, Komatsu, Lozanov, Weller (2022)

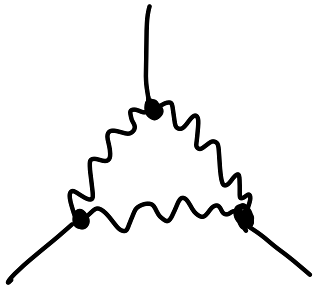
Simulation confirms analytical results (**very nontrivial)**

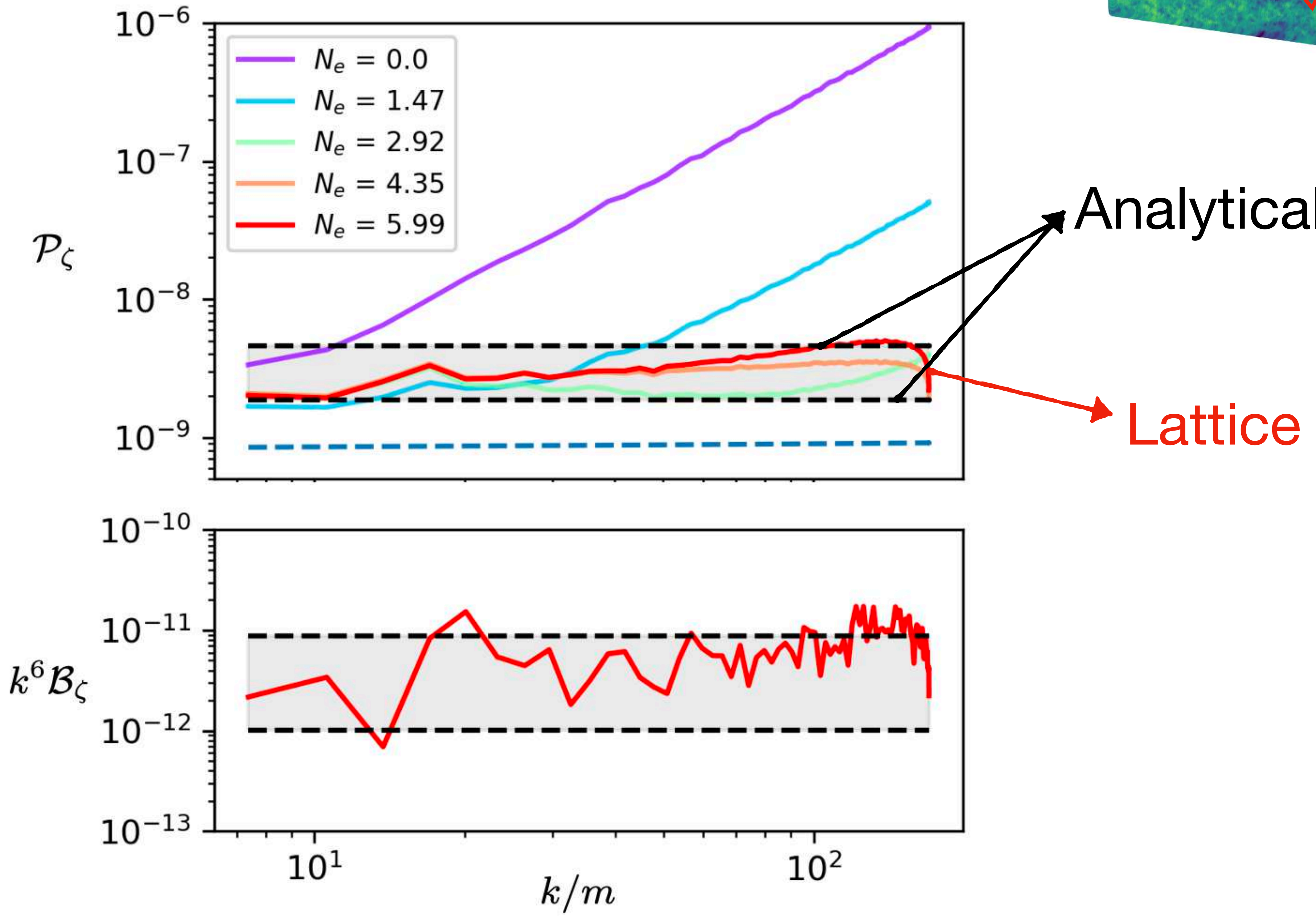


Power spectrum:



Equilater bispectrum:





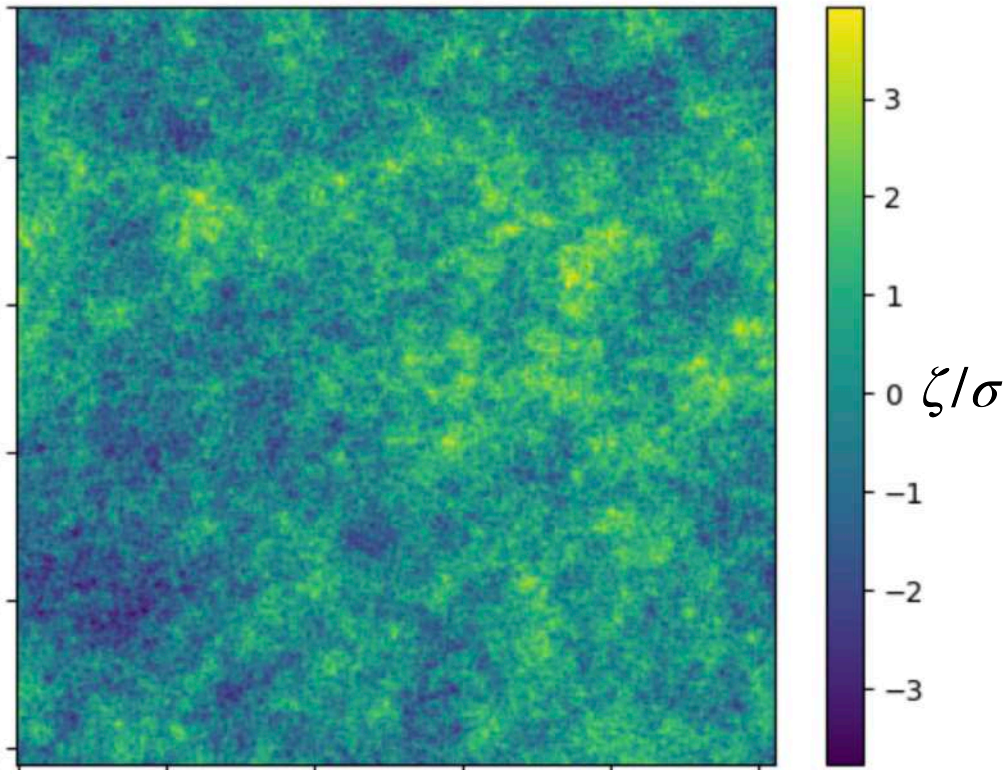
Perturbative regime (large scales)

AC, Komatsu, Lozanov, Weller (2022)

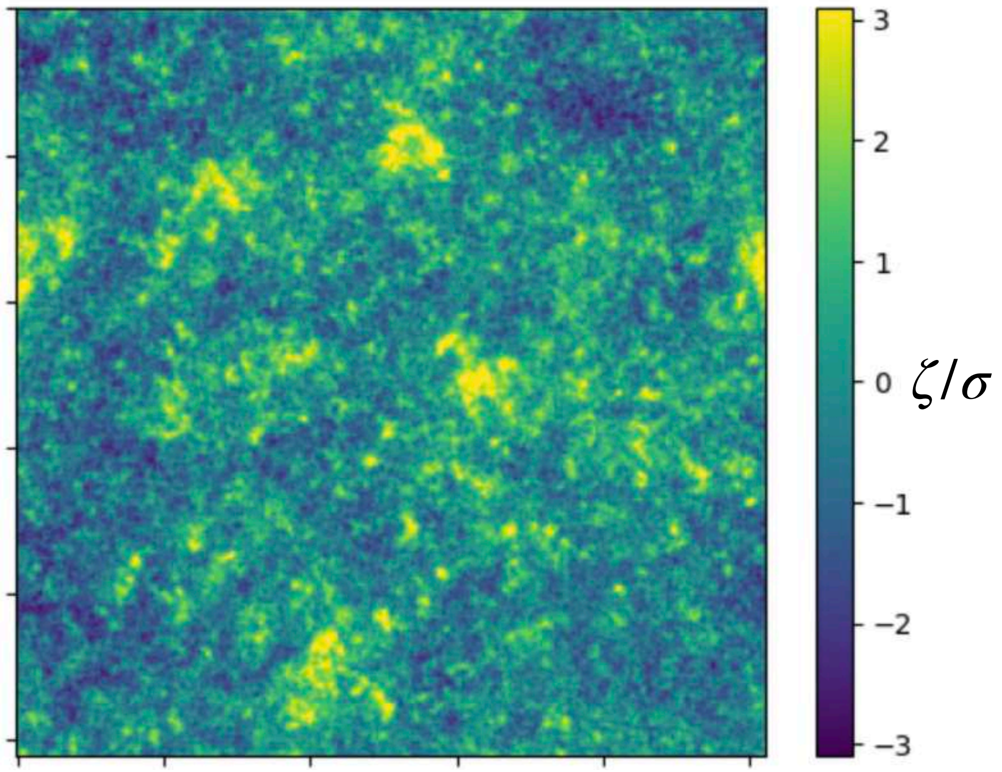
We finally know the full $\zeta(\mathbf{x}, t)$!

Beyond quadratic assumption
$\zeta \simeq \zeta_G + f_{\rm NL} K[\zeta_G, \zeta_G]$

Gaussian (ζ_G)



Non-Gaussian (ζ_{NG})

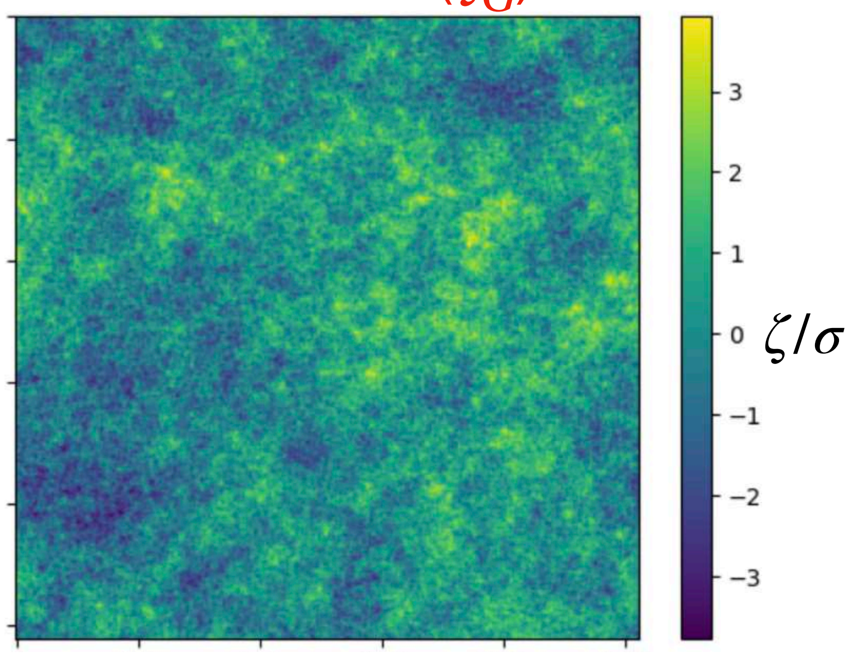


Perturbative regime (large scales)

Thanks to the lattice, we know the full $\zeta(\mathbf{x}, t)$!

Beyond approximations
$\zeta \simeq \zeta_G + f_{\rm NL} K[\zeta_G, \zeta_G]$

Gaussian (ζ_G)



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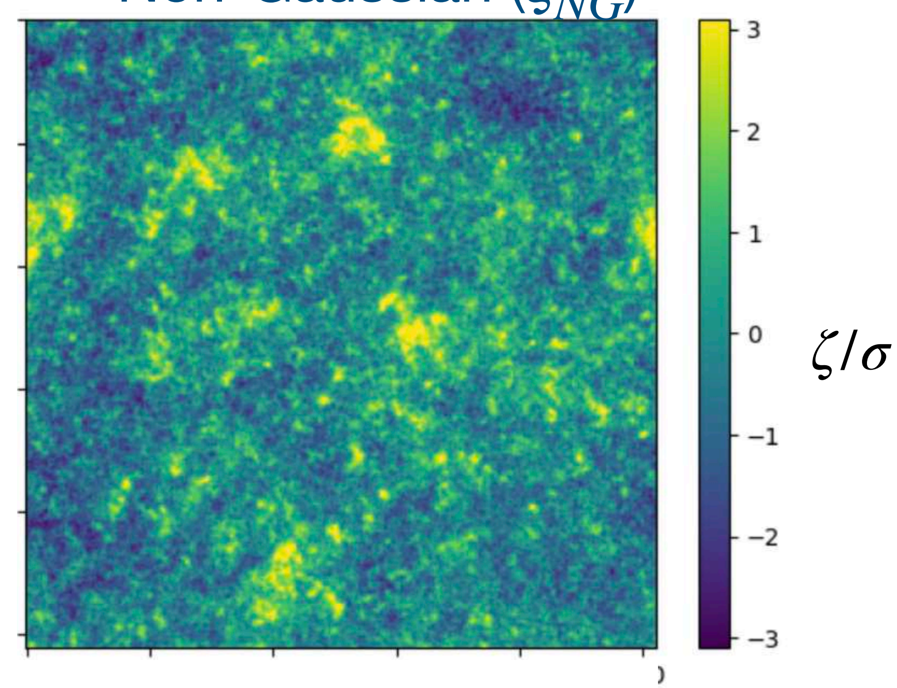
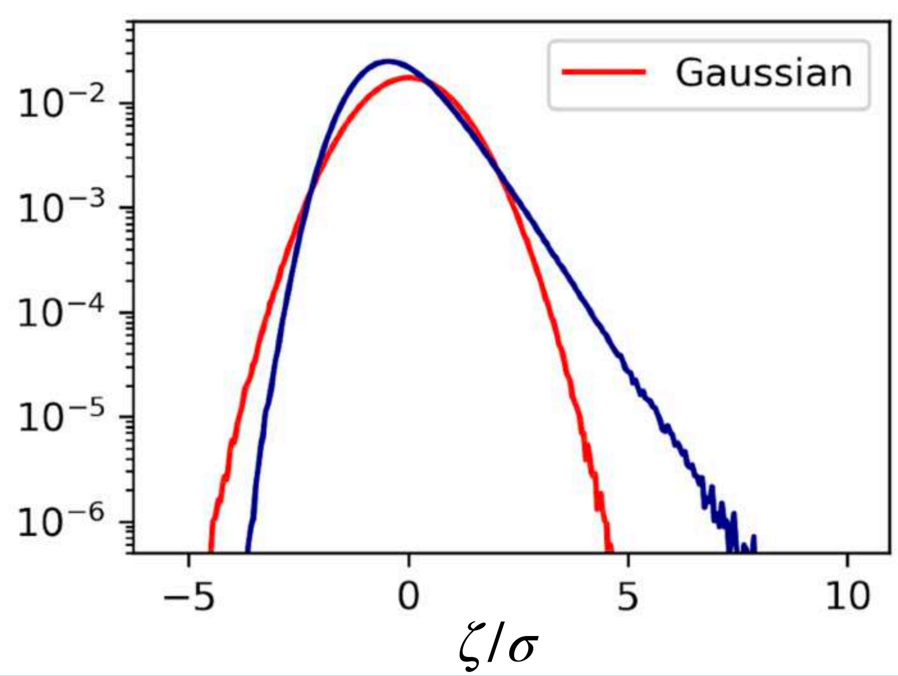


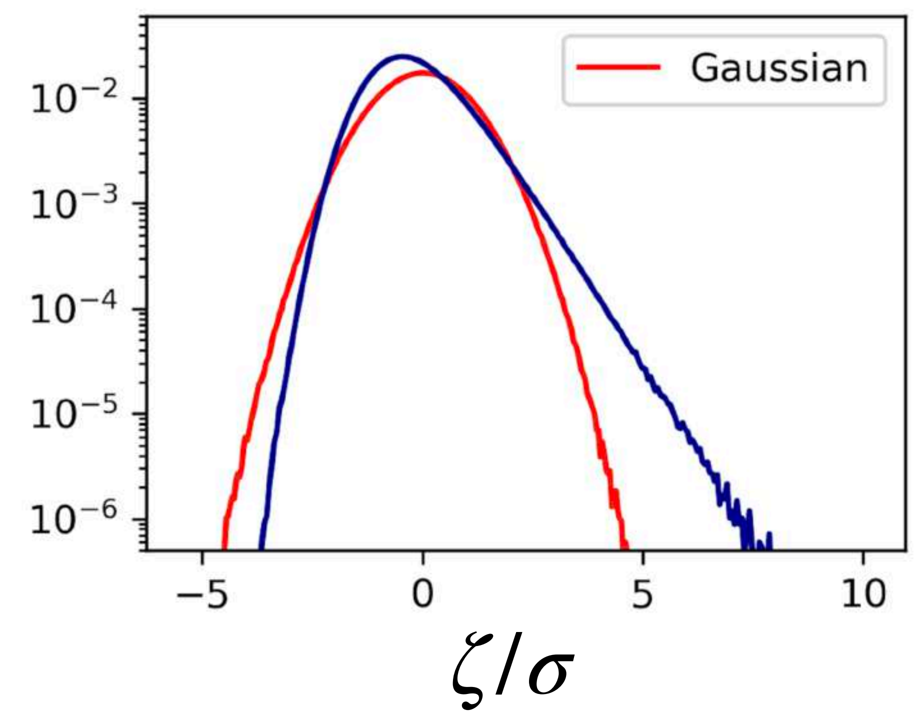


Perturbative regime (large scales)

Define cumulants:

$$\kappa_n = \frac{\langle \zeta^n \rangle_c}{\sigma^n}$$

κ_3 “skewness”, κ_4 “kurtosis”, etc.



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AC, Komatsu, Lozanov, Weller (2022)

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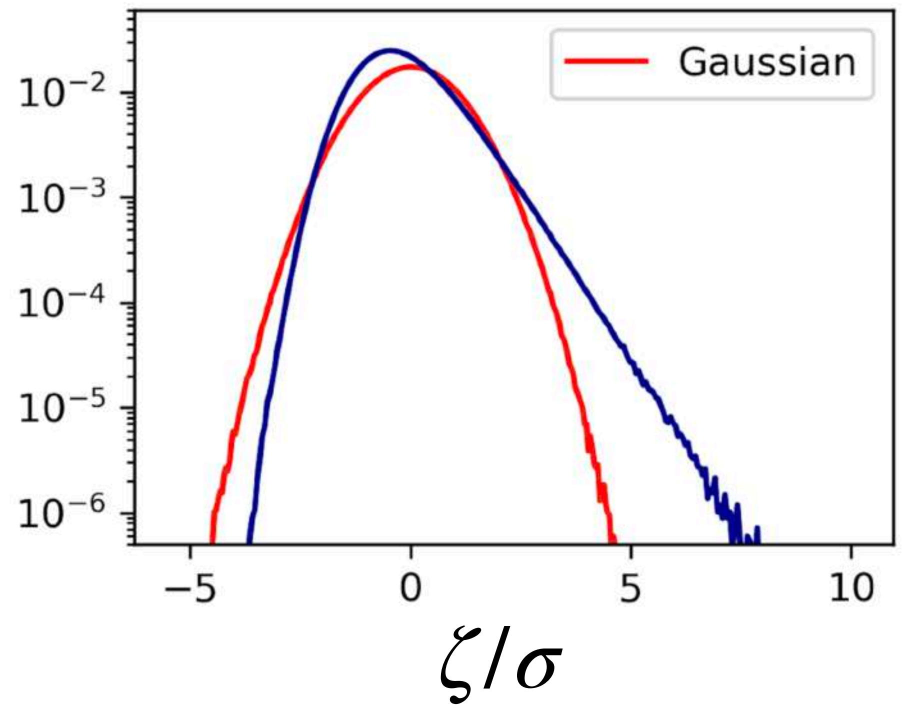

$$\ldots > \kappa_6 > \kappa_5 > \kappa_4 > \kappa_3$$

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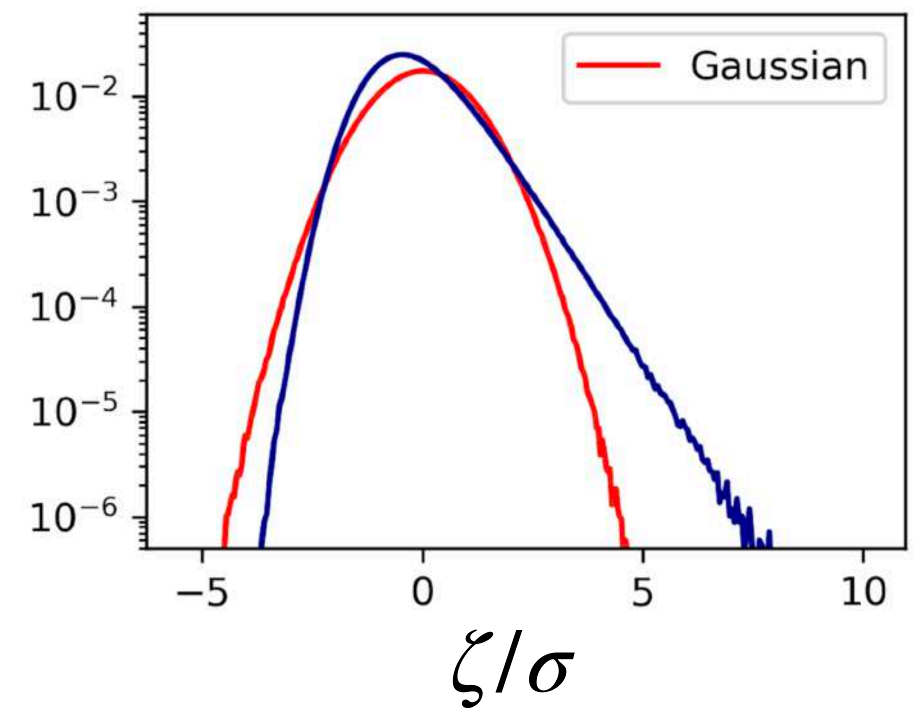

$$\ldots > \kappa_6 > \kappa_5 > \kappa_4 > \kappa_3$$

Higher order polyspectra

Trispectrum

Bispectrum

Perturbative regime (large scales)

AC, Komatsu, Lozanov, Weller (2022)

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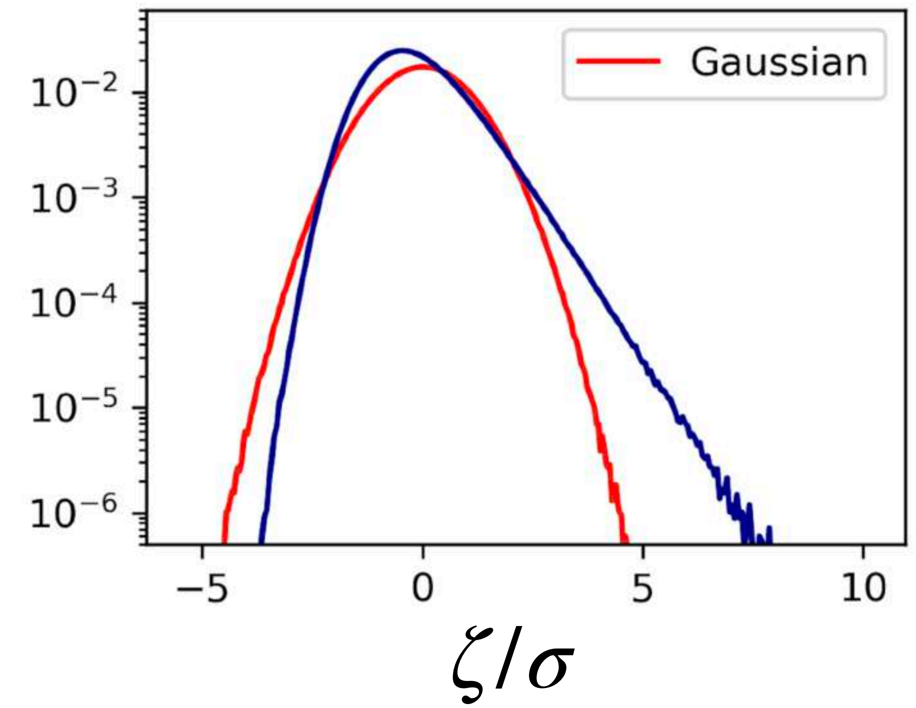


$$\ldots > \kappa_6 > \kappa_5 > \kappa_4 > \kappa_3$$

$$\zeta \neq \zeta_G + f_{\rm NL} K[\zeta_G, \zeta_G]$$

What now?

Lattice simulation of axion inflation

AC, Komatsu, Lozanov, Weller (2022)

AC, E. Komatsu, K. D. Lozanov, J. Weller 2102.06378

AC 2204.12874

The first simulation of axion inflation

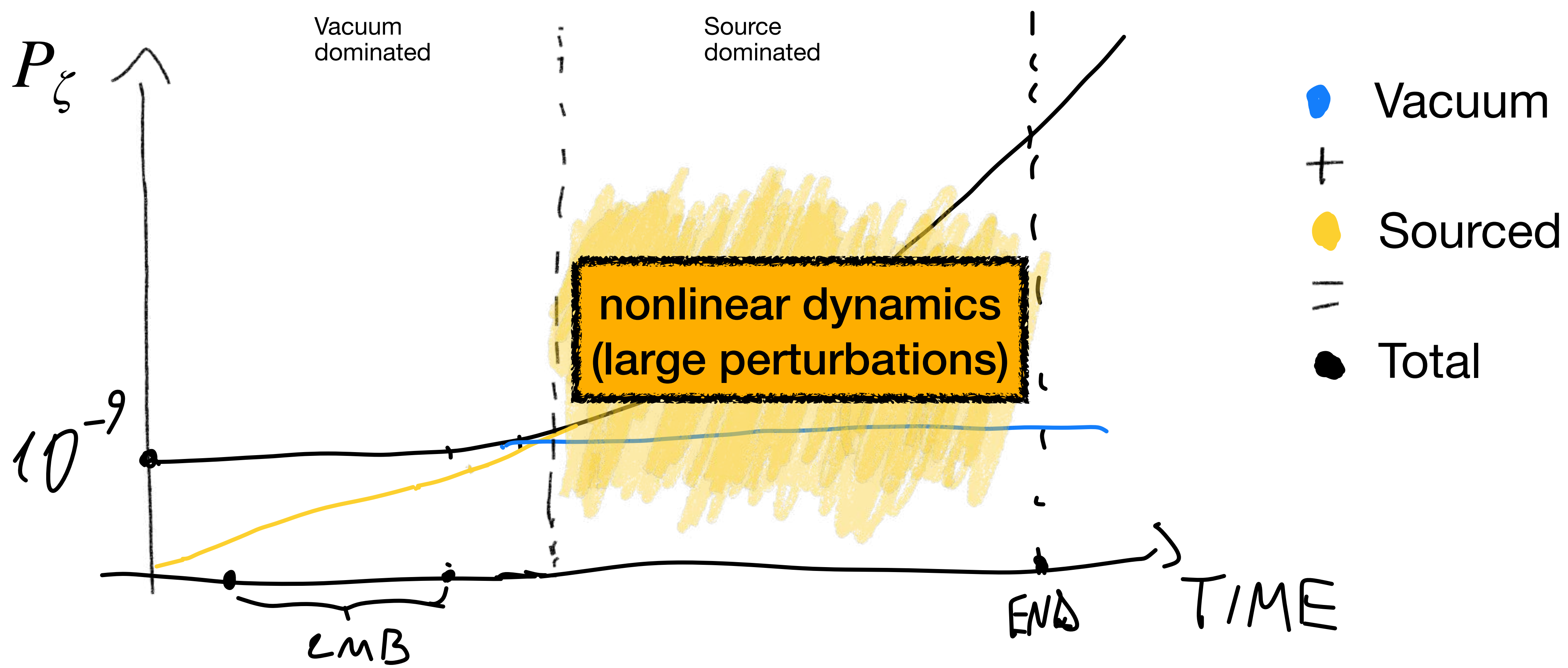
Results:

1. Large scales: small $\xi = \dfrac{\alpha\dot{\phi}}{2fH}$ perturbative regime

2. Small scales: large $\xi = \dfrac{\alpha\dot{\phi}}{2fH}$ non-perturbative regime

Non-perturbative regime (small scales)

AC, Komatsu, Lozanov, Weller (2022)



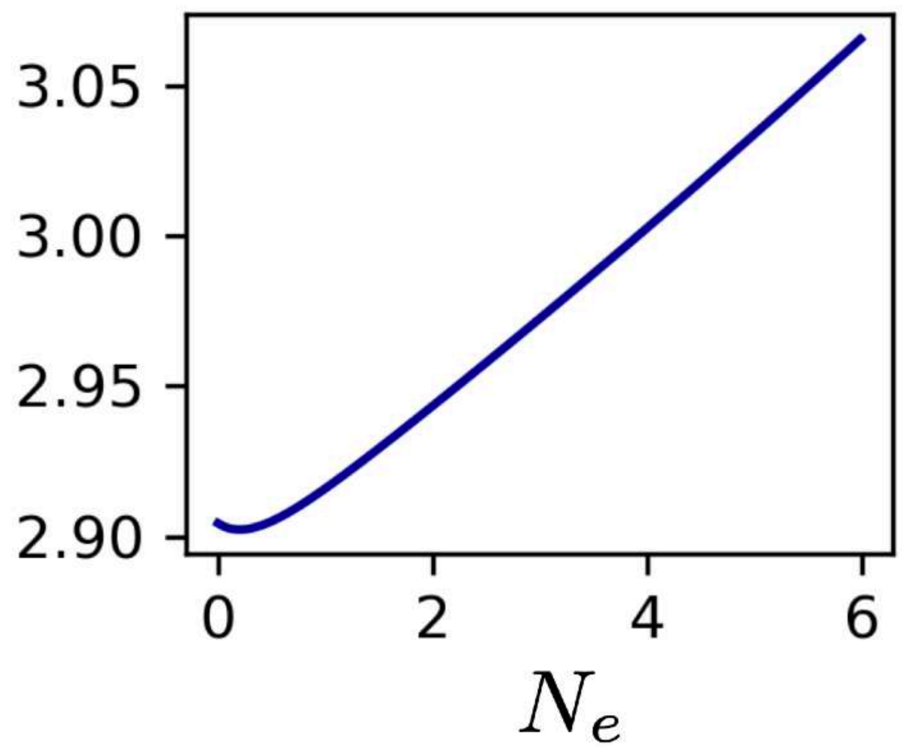
Non-perturbative regime (small scales)

Study transition linear $\longrightarrow$ nonlinear

$$\xi = \frac{\alpha\dot{\phi}}{2fH}$$

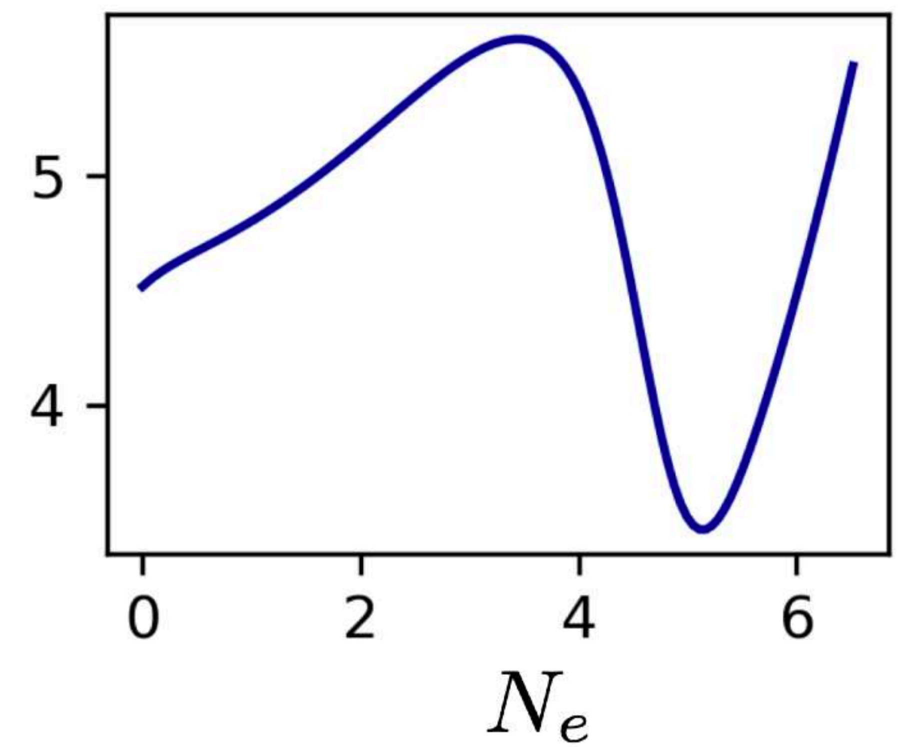
Linear

(no backreaction)



Linear-nonlinear transition

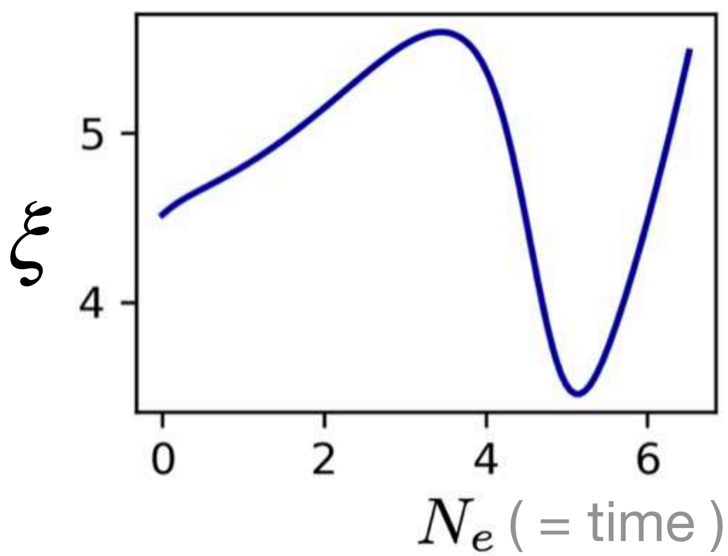
(strong backreaction)

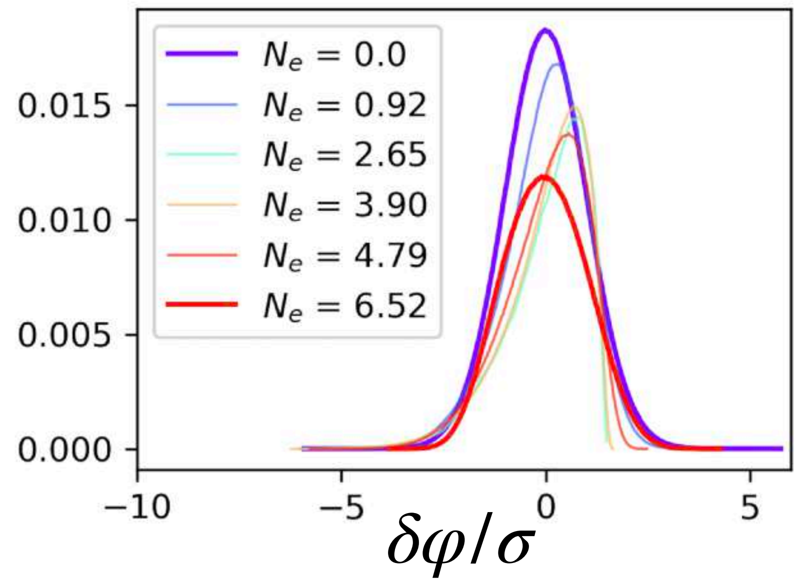


e-folds number (time)

Non-perturbative regime (small scales)

AC, Komatsu, Lozanov, Weller (2022)

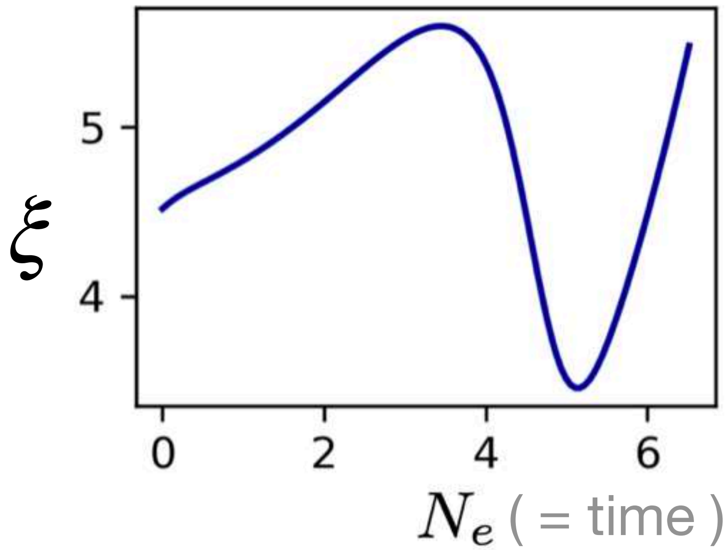


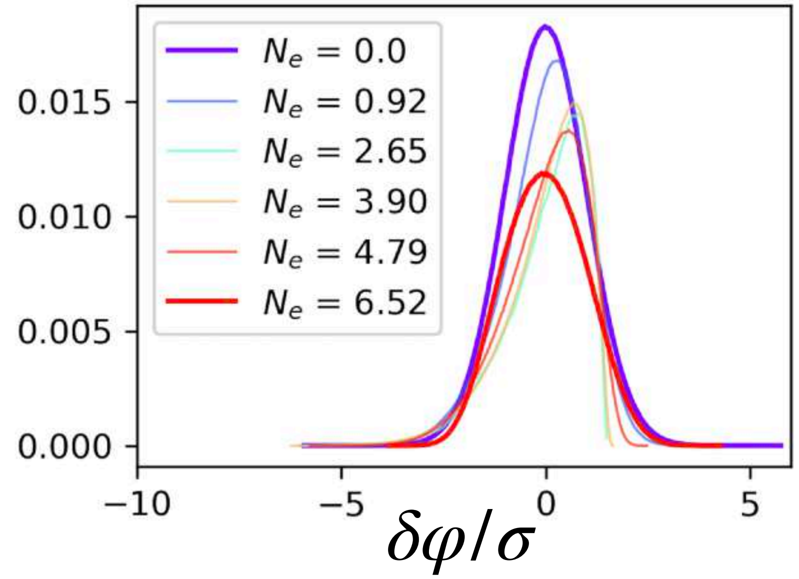


Non-Gaussianity is **<u>suppressed</u>** in the nonlinear regime!

Non-perturbative regime (small scales)

AC, Komatsu, Lozanov, Weller (2022)





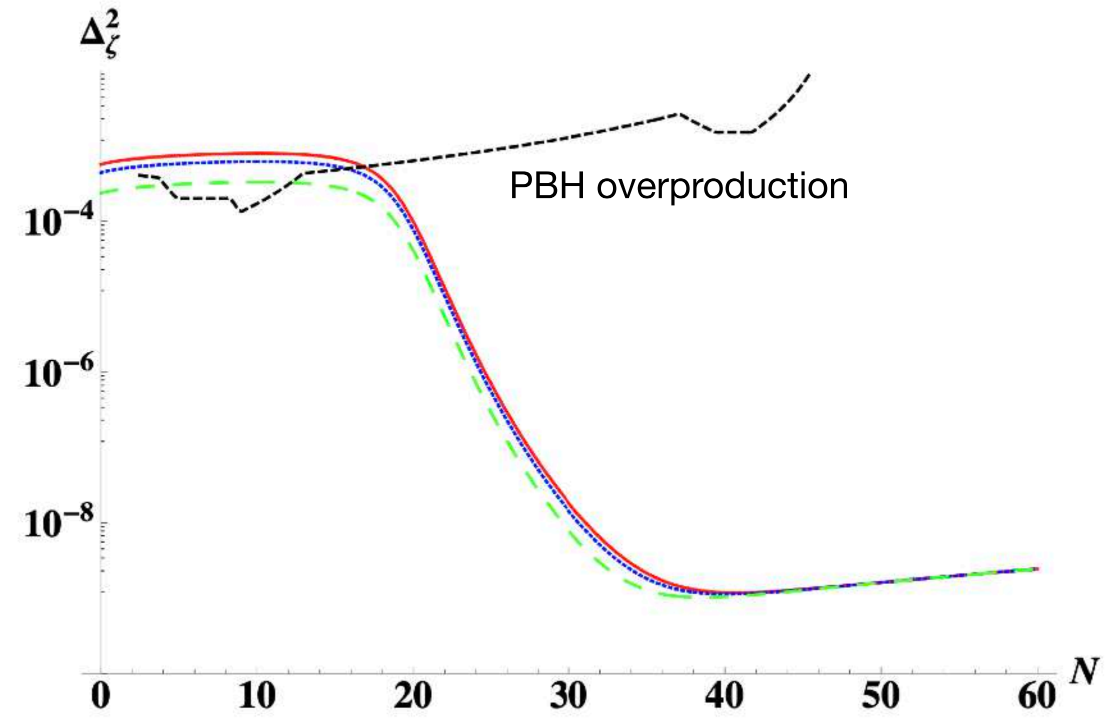
Non-Gaussianity is **suppressed** in the nonlinear regime!

The opposite of what it was believed in the literature:

$$\phi \simeq f_{NL}\phi_g^2$$ → Stringent PBH bound

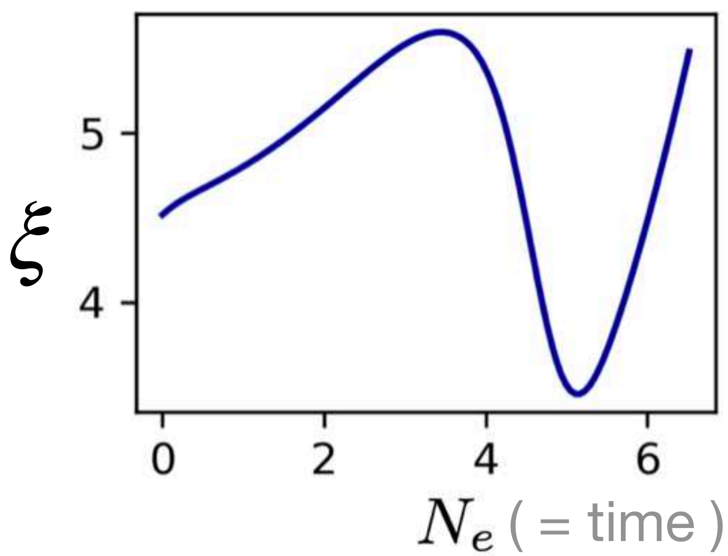
[Linde, Mooij, Pajer (2012)]

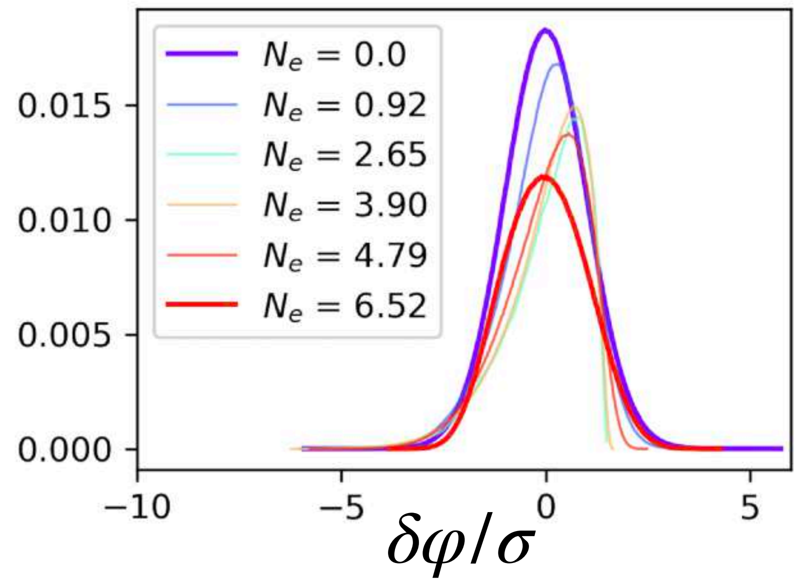
…



Non-perturbative regime (small scales)

AC, Komatsu, Lozanov, Weller (2022)





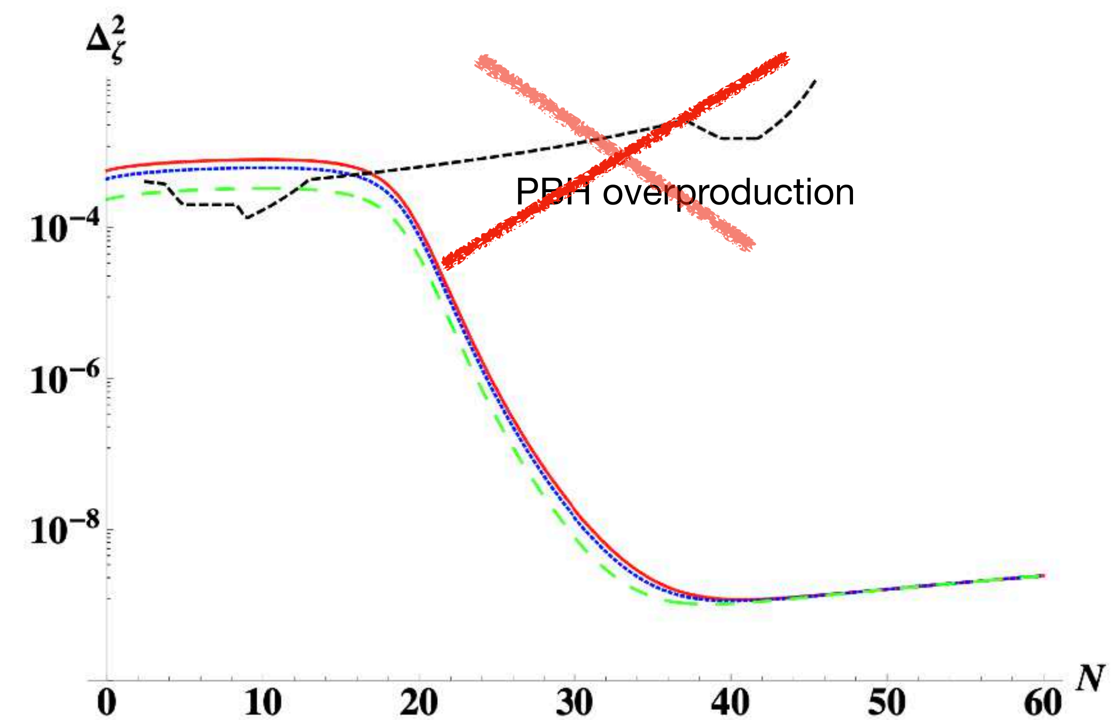
Non-Gaussianity is **suppressed** in the nonlinear regime!

Gaussianization process opens up the parameter space of the model.

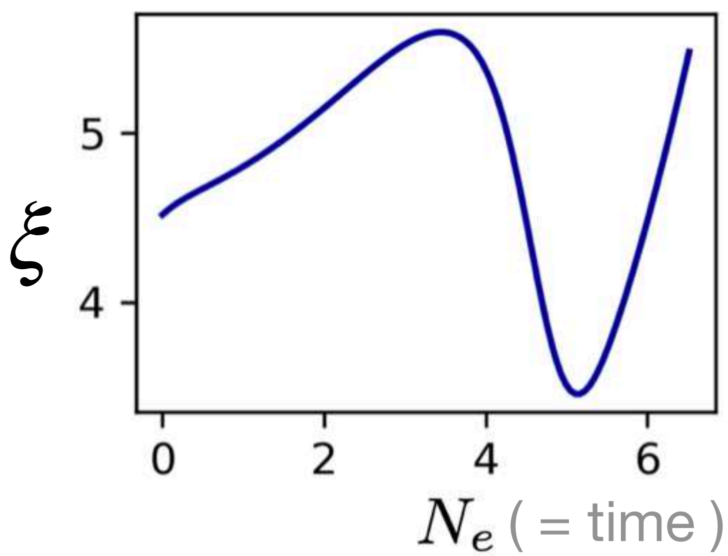
$$\phi \simeq f_{NL}\phi_g^2$$ → ~~Stringent PBH bound~~

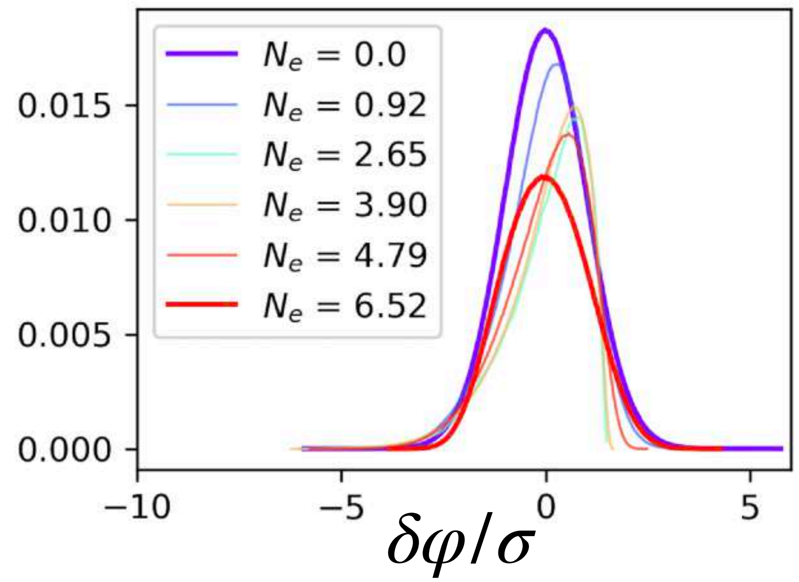
[**Linde, Mooij, Pajer** (2012)]

…



Non-perturbative regime (small scales)





Non-Gaussianity is **suppressed** in the nonlinear regime!

This allows for a sizeable GW signal at PTA

NANOGrav signal from axion inflation

Xuce Niu,[a] and Moinul Hossain Rahat[b]

[a]Institute for Fundamental Theory, Department of Physics, University of Florida, Gainesville, FL 32611, USA
[b]School of Physics & Astronomy, University of Southampton, Southampton SO17 1BJ, UK

E-mail: xuce.niu@ufl.edu, M.H.Rahat@soton.ac.uk

Axion-Gauge Dynamics During Inflation as the Origin of Pulsar Timing Array Signals and Primordial Black Holes

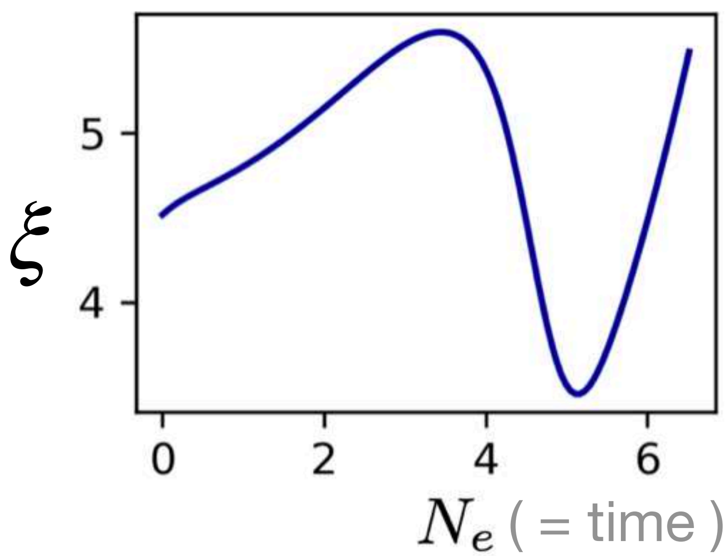
Caner Ünal,[1,2,*] Alexandros Papageorgiou,[3,†] and Ippei Obata[4,‡]

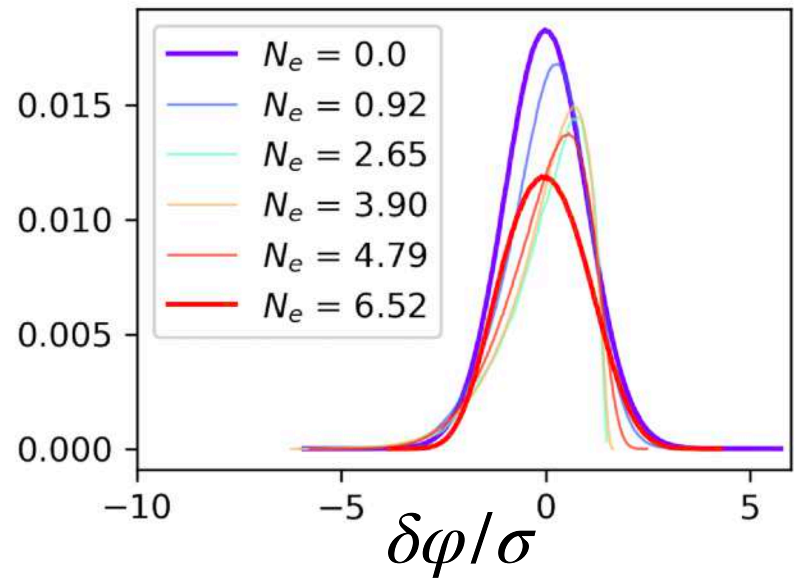
[1]Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel
[2]Feza Gursey Institute, Bogazici University, Cengelkoy, Istanbul, Turkey
[3]Particle Theory and Cosmology Group, Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), 34126 Daejeon, Korea
[4]Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), UTIAS, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8583, Japan

We demonstrate that the recently announced signal for a stochastic gravitational wave background (SGWB) from pulsar timing array (PTA) observations, if attributed to new physics, is compatible with primordial GW production due to axion-gauge dynamics during inflation. More specifically we find that axion-$U(1)$ models may lead to sufficient particle production to explain the signal while simultaneously source some fraction of sub-solar mass primordial black holes (PBHs) as a signature. Moreover there is a parity violation in GW sector, hence the model suggests chiral GW search as a concrete target for future. We further analyze the axion-$SU(2)$ coupling signatures and find that in the low/mild backreaction regime, it is incapable of producing PTA evidence and the tensor-to-scalar ratio is low at the peak, hence it overproduces scalar perturbations and PBHs.

Non-perturbative regime (small scales)

AC, Komatsu, Lozanov, Weller (2022)





Non-Gaussianity is **suppressed** in the nonlinear regime!

Why? central limit theorem!

Look at the source term:

$$\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)(k) = \sum_{k'} F_{\mu\nu}(k')\ \tilde{F}^{\mu\nu}(k-k')\,.$$

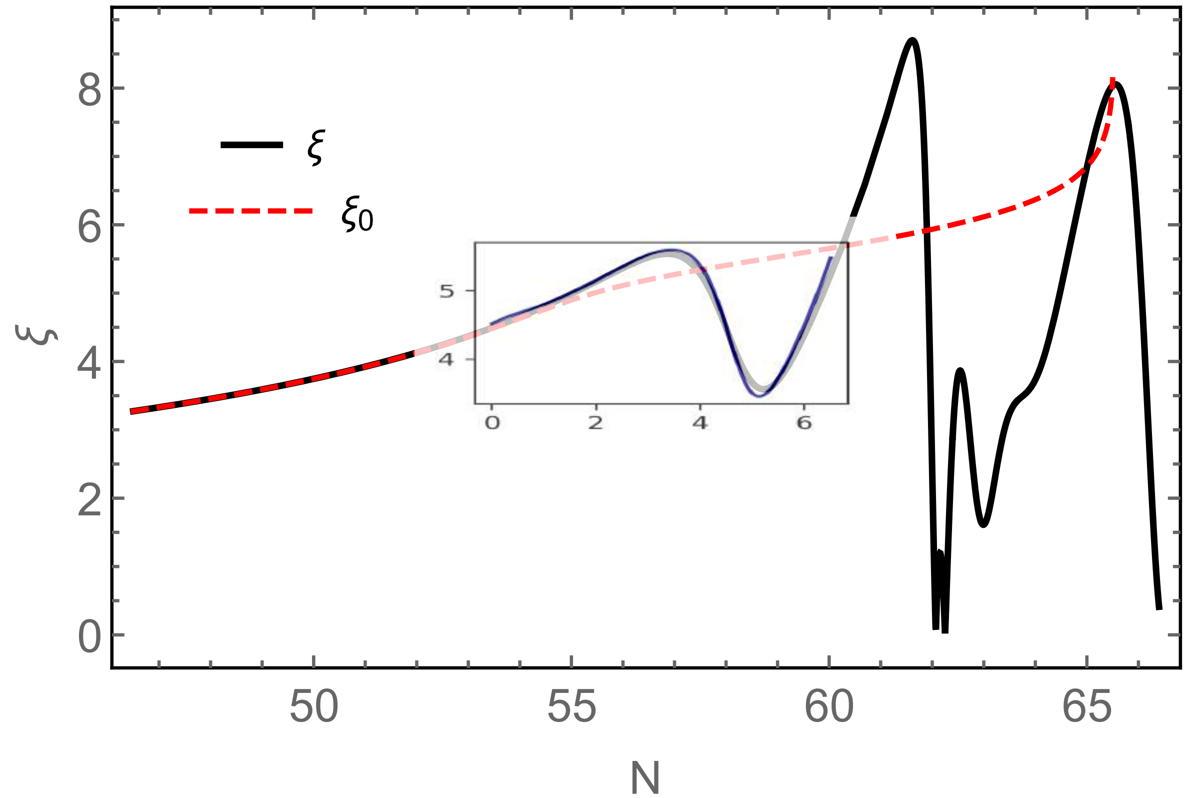
$$\frac{1}{8\xi} < \frac{k'}{aH} < 2\xi \longrightarrow$$ Many terms for large ξ

Analogous to fermion production: [Adshead, Pearce, Peloso, Roberts, Sorbo (2018)]

Backreaction

AC, Komatsu,
Lozanov, Weller
(2022)

Comparison with 2002.02952



Lattice confirmation of semi-analytical methods:

[Domcke, Guidetti, Welling, Westphal arXiv:2002.02952]

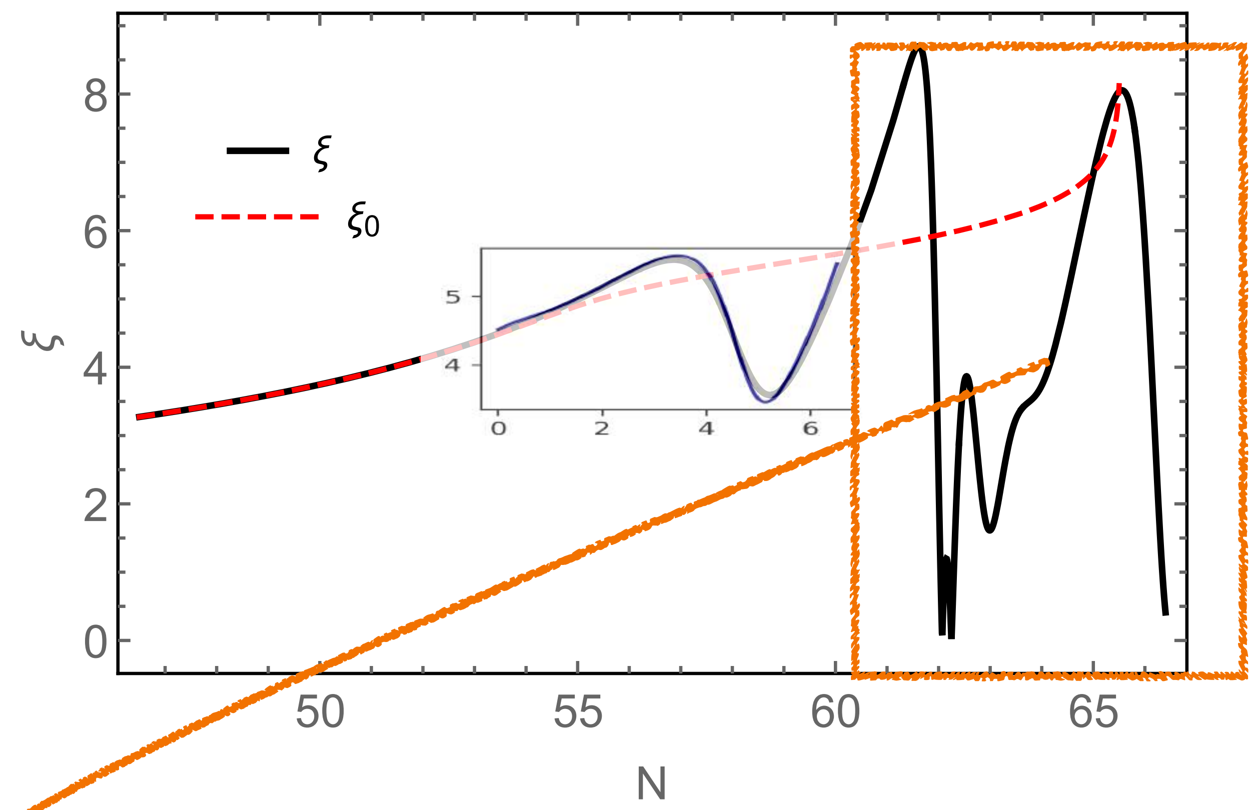
[E.V. Gorbar, K. Schmitz, O. O. Sobol, S. I. Vilchinskii arXiv:2109.01651]

These works solved the "homogeneous backreaction", i.e. assuming $\delta\phi = 0$

Backreaction

AC, Komatsu, Lozanov, Weller (2022)

Comparison with 2002.02952



What happens **here** is under investigation.

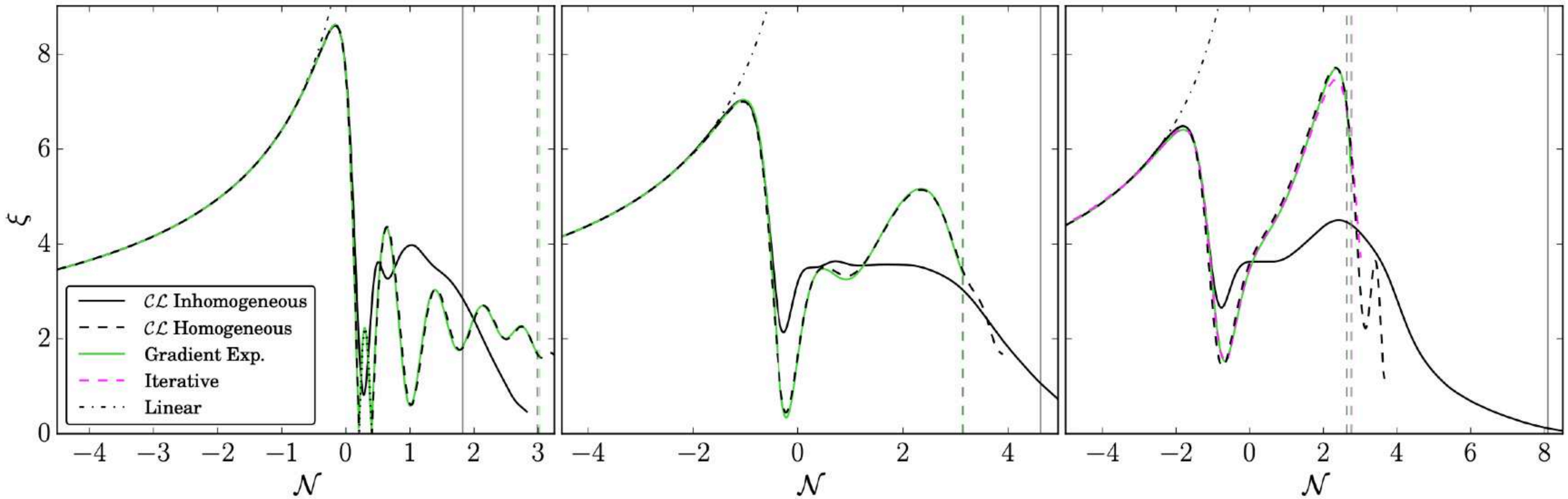
See a non-exclusive list of recent developments:

[Peloso, Sorbo, 2209.08131]	[Figueroa, Lizarraga, Urio, Urrestilla 2303.17436]	[Sharma, Brandeburg, Subramanian, Vikman 2506.20538]	[Iarygina, Sfakianakis, Brandenburg, 2506.20538]
Analytical	Lattice simulation of the end of inflation	Lattice, end of inflation, magnetogenesis	Lattice, end of inflation, with Schwinger pair production

Backreaction

AC, Komatsu, Lozanov, Weller (2022)

Key result in this context: **Axion inhomogeneities matters** [Figueroa, Lizarraga, Urio, Urrestilla (2023)]



See a non-exclusive list of recent developments:

[Peloso, Sorbo, (2022)] → Analytical

[Figueroa, Lizarraga, Urio, Urrestilla (2023)] → Lattice simulation of the end of inflation

[Sharma, Brandeburg, Subramanian, Vikman (2025)] → Lattice, end of inflation, magnetogenesis

[Iarygina, Sfakianakis, Brandenburg, (2025)] → Lattice, end of inflation, with Schwinger pair production

Recent developments

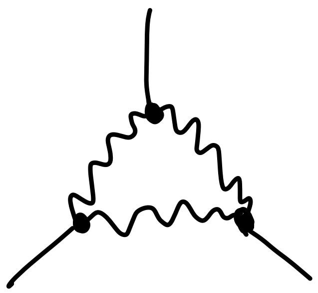
Large scales (weak backreaction)

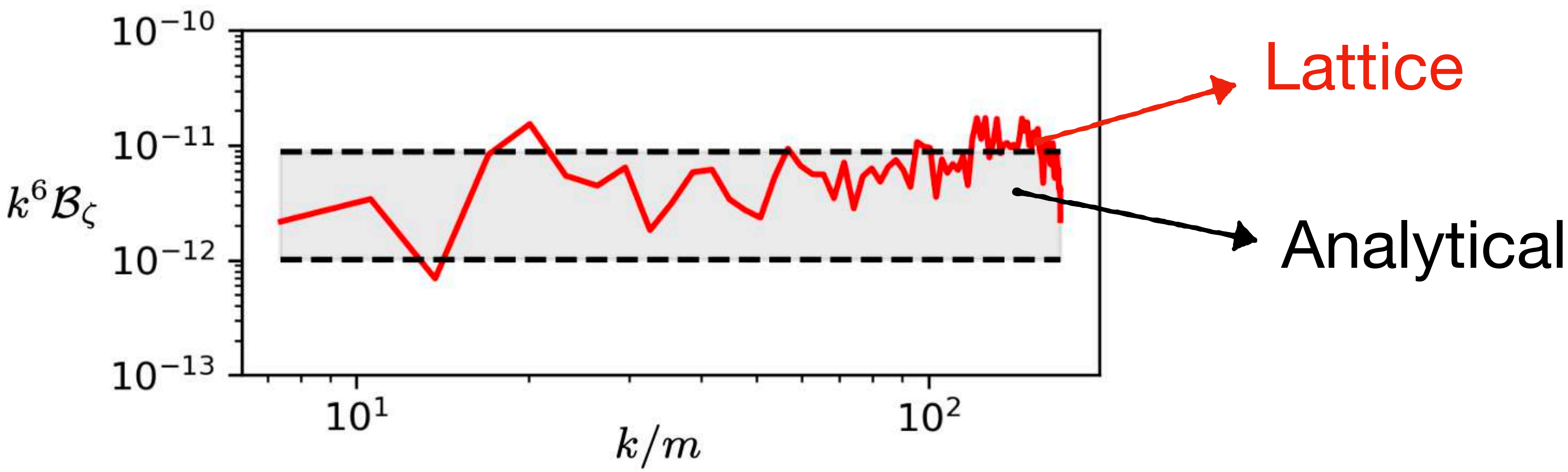
AC, Komatsu, Lozanov, Weller (2022)

No PBH bound → we should look for large-scale signatures

Example, non-Gaussianity:

Equilater bispectrum:





Large scales (weak backreaction)

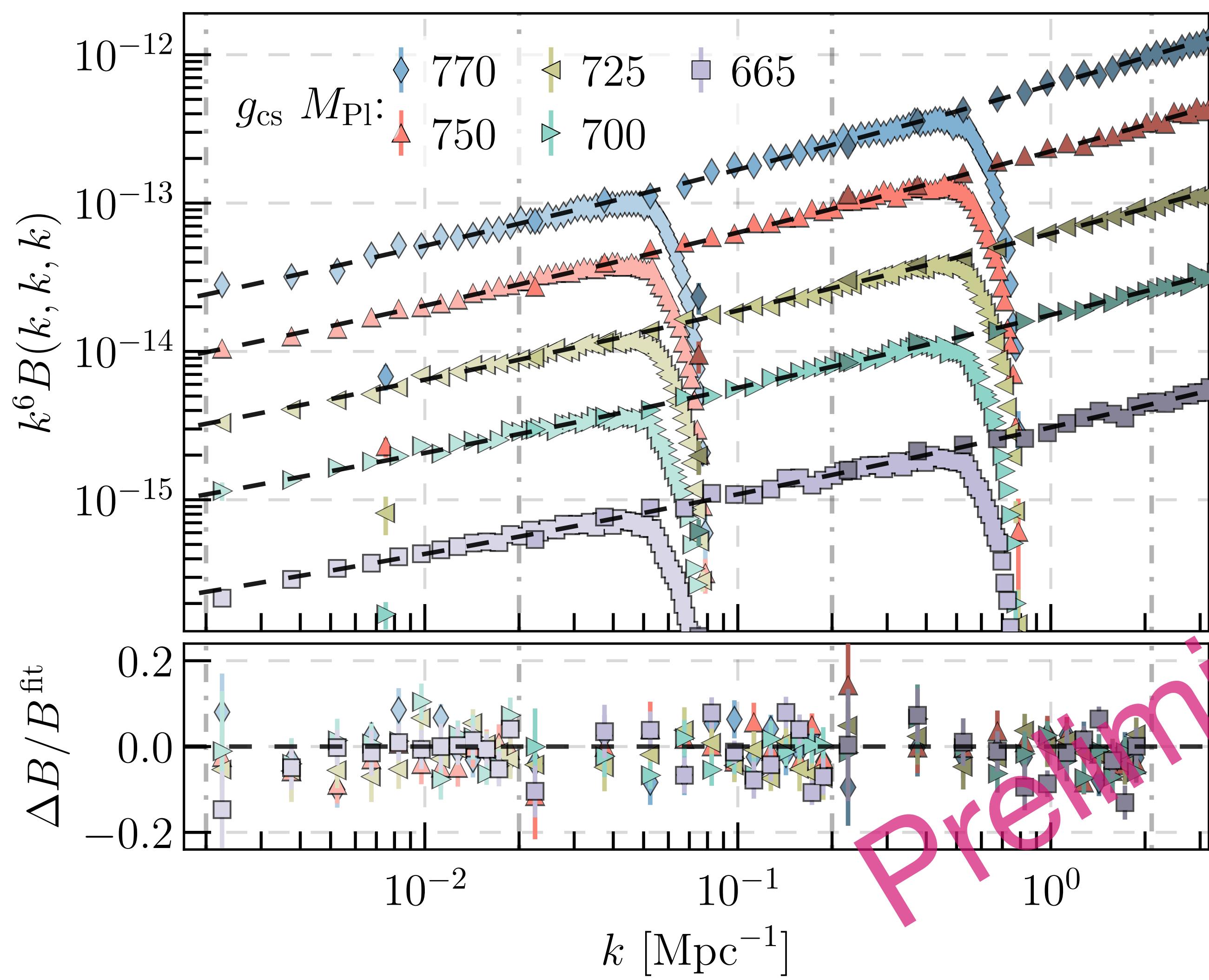
Jamieson, **AC**, Komatsu
(in preparation)

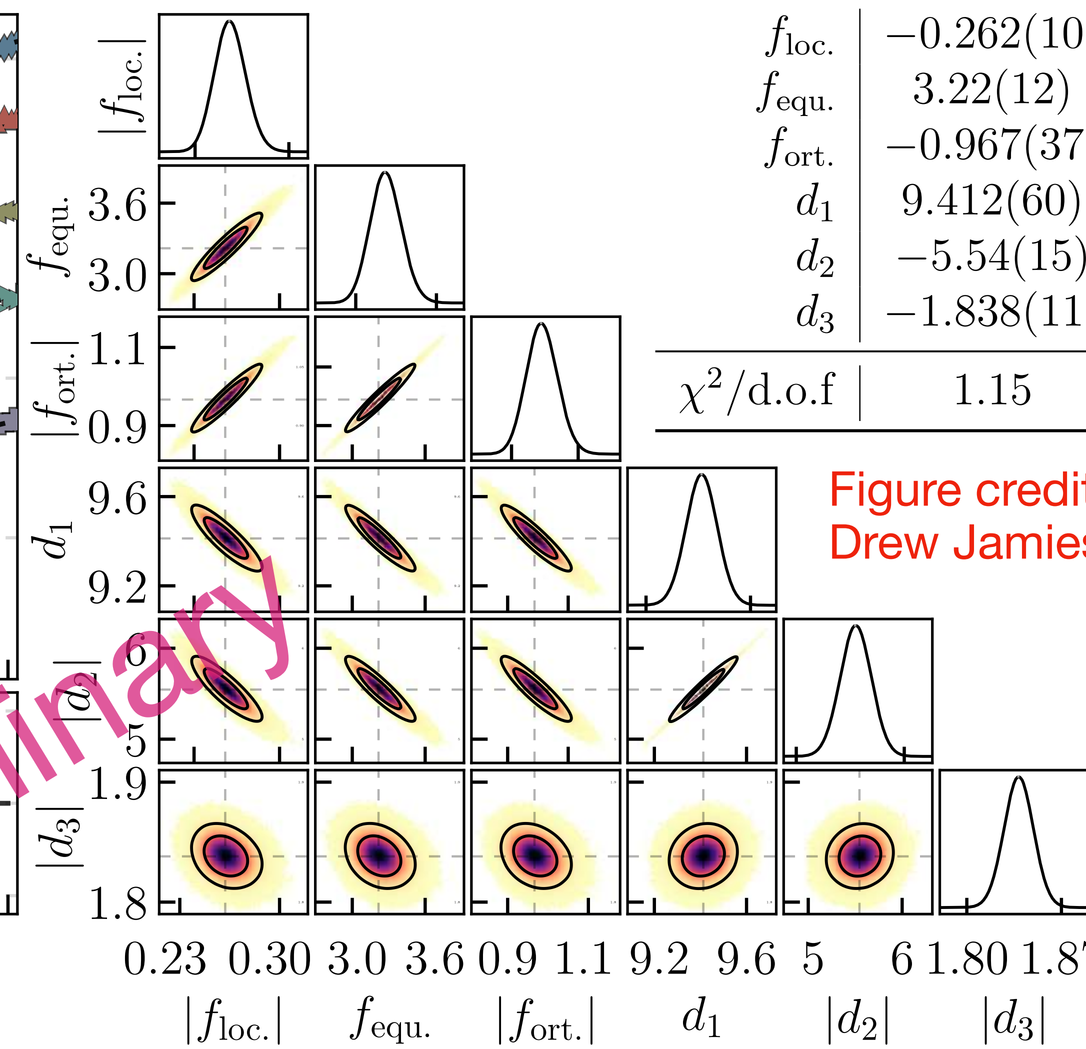
Use the simulation to understand the large-scale signal

First step: full bispectrum beyond constant-ξ approximation

$$B_{\rm fit}(k_1,k_2,k_3) = \quad f_{\rm loc}B_{\rm loc}[P_{\rm eff}](k_1,k_2,k_3) + f_{\rm equ}B_{\rm equ}[P_{\rm eff}](k_1,k_2,k_3) + f_{\rm ort}B_{\rm ort}[P_{\rm eff}](k_1,k_2,k_3)$$

$$P_{\rm eff}(k) = \sqrt{10^7 A_s^3}\left(\frac{k}{k_p}\right)^{\frac{3}{4}(n_s-1)} e^{d_1|\xi(k)|}\,|\,\xi(k)\,|^{d_2}\left(\frac{\xi(k)}{\xi_{\rm p}}\right)^{d_3}.$$





$f_{\rm loc.}$	$-0.262(10)$
$f_{\rm equ.}$	$3.22(12)$
$f_{\rm ort.}$	$-0.967(37)$
d_1	$9.412(60)$
d_2	$-5.54(15)$
d_3	$-1.838(11)$
χ^2/d.o.f	1.15

Figure credit:
Drew Jamieson

Spectator axion-gauge sector

Strong backreaction is challenging because of the large dynamical range

Idea: look at a **more controlled setup**, where the axion is a spectator:

$$\mathscr{L}_{\text{inflation}} \supset \underbrace{-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)}_{\text{Inflaton sector}} \underbrace{-\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - V(\sigma) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{4f}\sigma F_{\mu\nu}\tilde{F}^{\mu\nu}}_{\text{Spectator axion-gauge sector}}$$

Spectator axion-gauge sector

AC, Peloso 2407.13405

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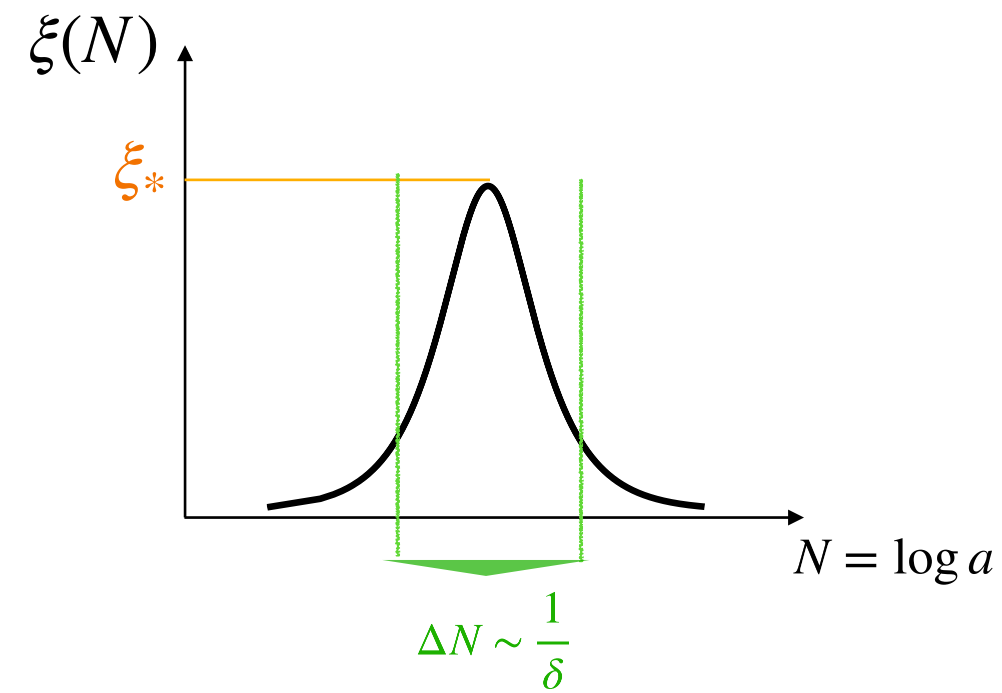
We can freely tune $V(\sigma)$ to roll for a finite time.

$$V(\sigma) = \frac{\Lambda^4}{2}\left[\cos\left(\frac{\sigma}{f}\right) + 1\right]$$

$$\downarrow$$

$$\xi \simeq \frac{2\xi_*}{\left(\frac{a}{a_*}\right)^\delta + \left(\frac{a_*}{a}\right)^\delta}, \qquad \xi_* = \frac{\alpha\delta}{2}, \qquad \delta = \frac{\Lambda^4}{6H^2f^2}$$



Spectator axion-gauge sector

AC, Peloso 2407.13405

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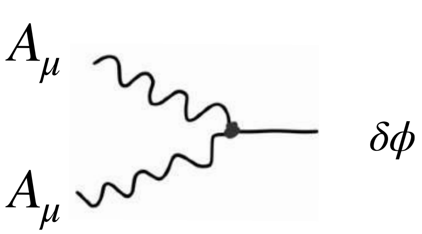
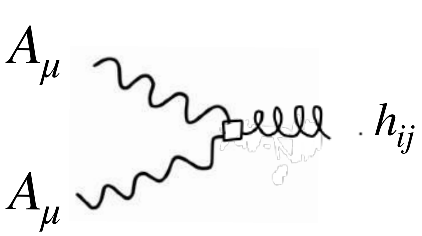
This model was constructed to increase the tensor-to-scalar ratio

[Namba, Peloso, Shiraishi, Sorbo, Unal (2015)]

Minimal axion inflation

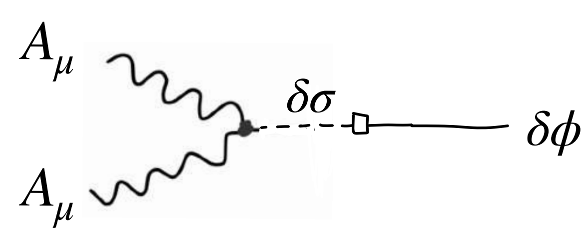


Direct sourcing of inflation fluctuations

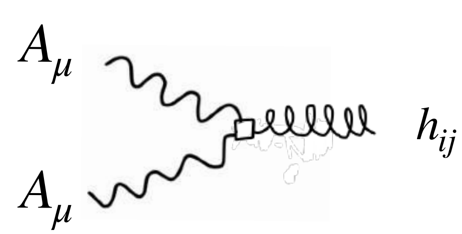


Direct sourcing of gravitational waves

Spectator axion model



Indirect, suppressed sourcing of inflation fluctuations



Direct sourcing of gravitational waves

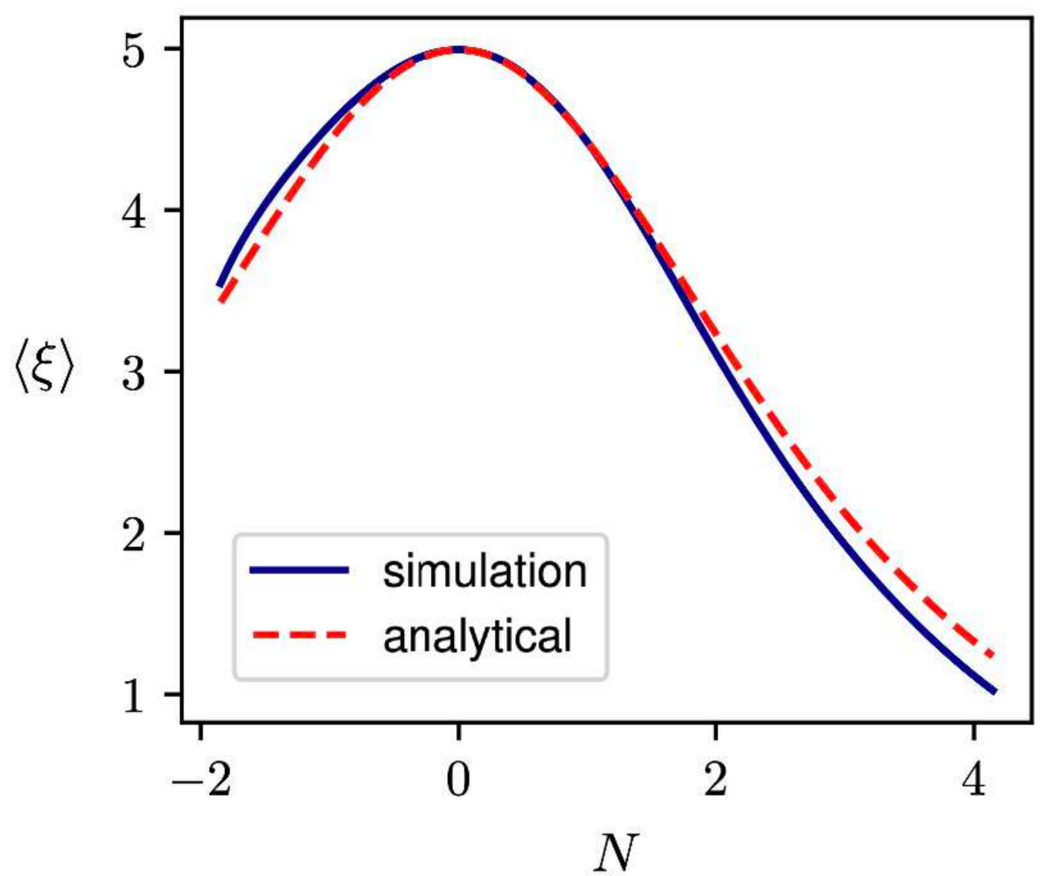
Backreaction: spectator model

AC, Peloso 2407.13405

We performed lattice simulations of this model

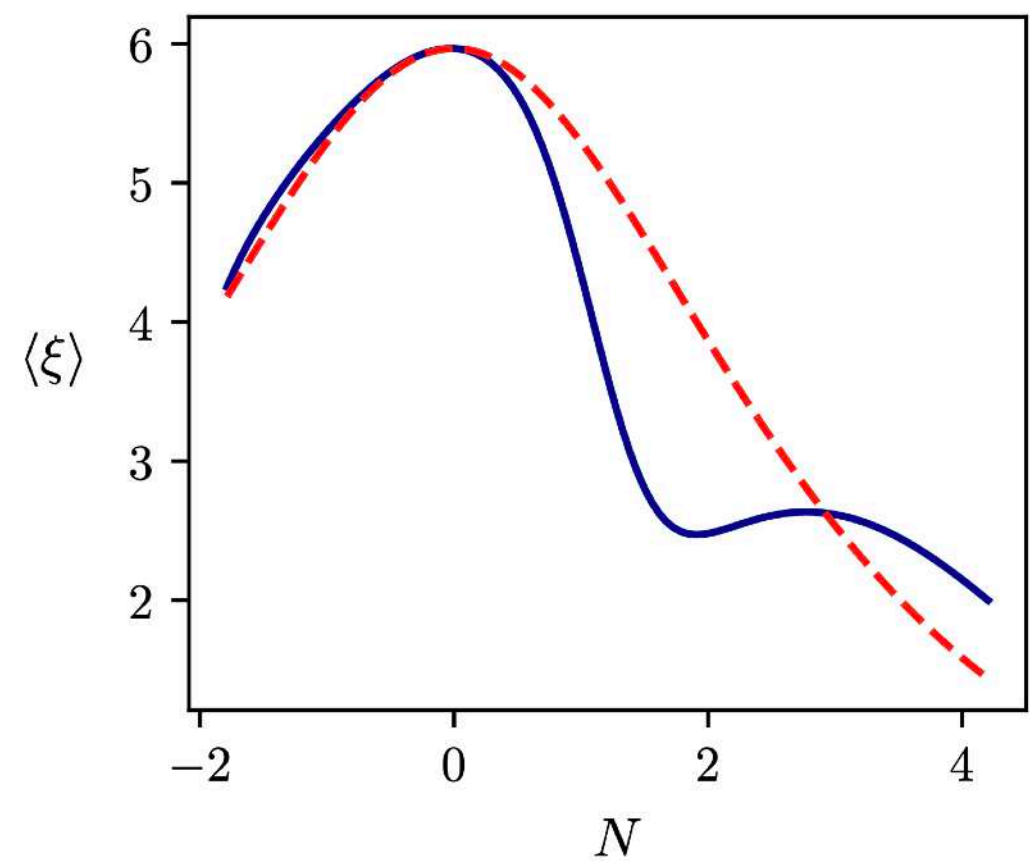
weak backreaction

$\xi_* = 5\,,\ \delta = 0.5\ (\Delta N \sim 2)$



strong backreaction

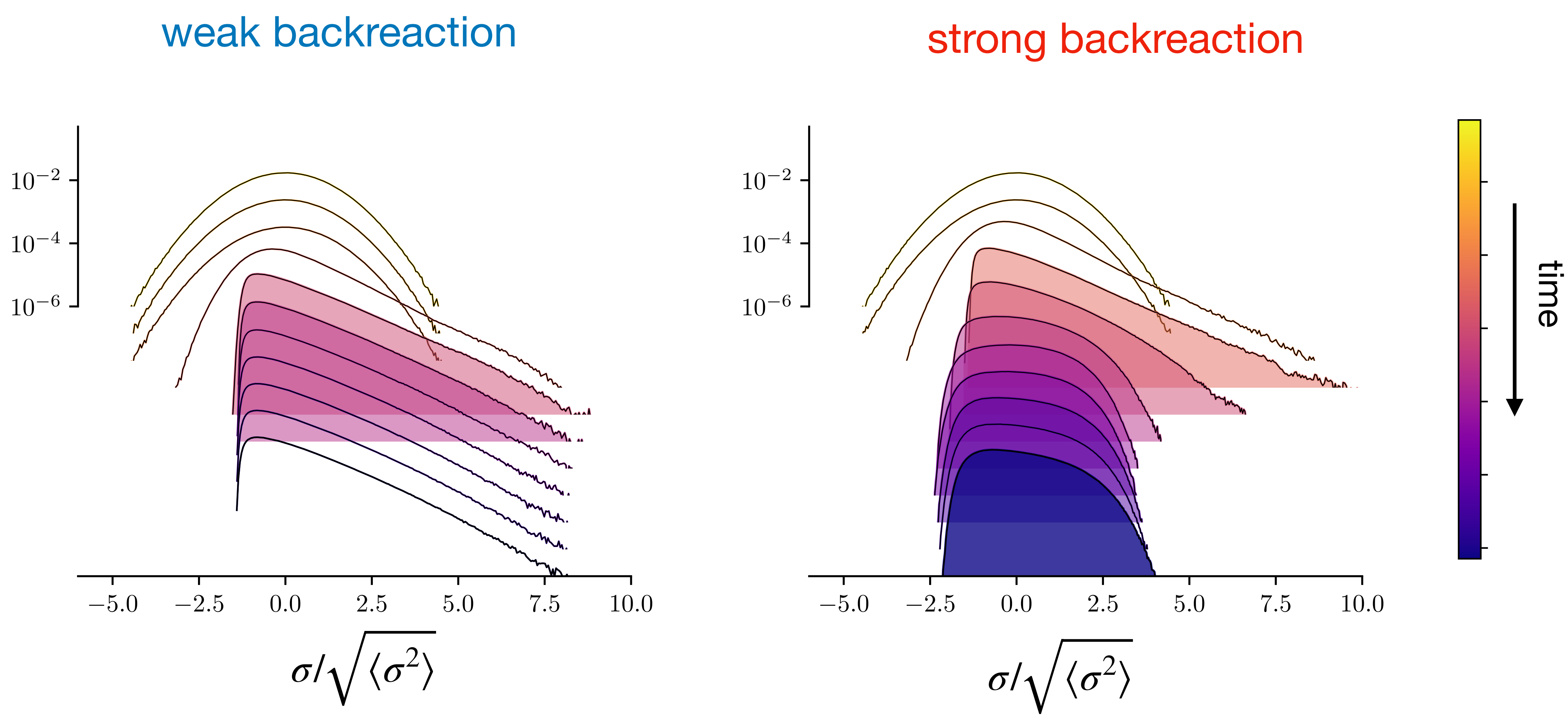
$\xi_* = 6\,,\ \delta = 0.5\ (\Delta N = \sim 2)$



Backreaction: spectator model

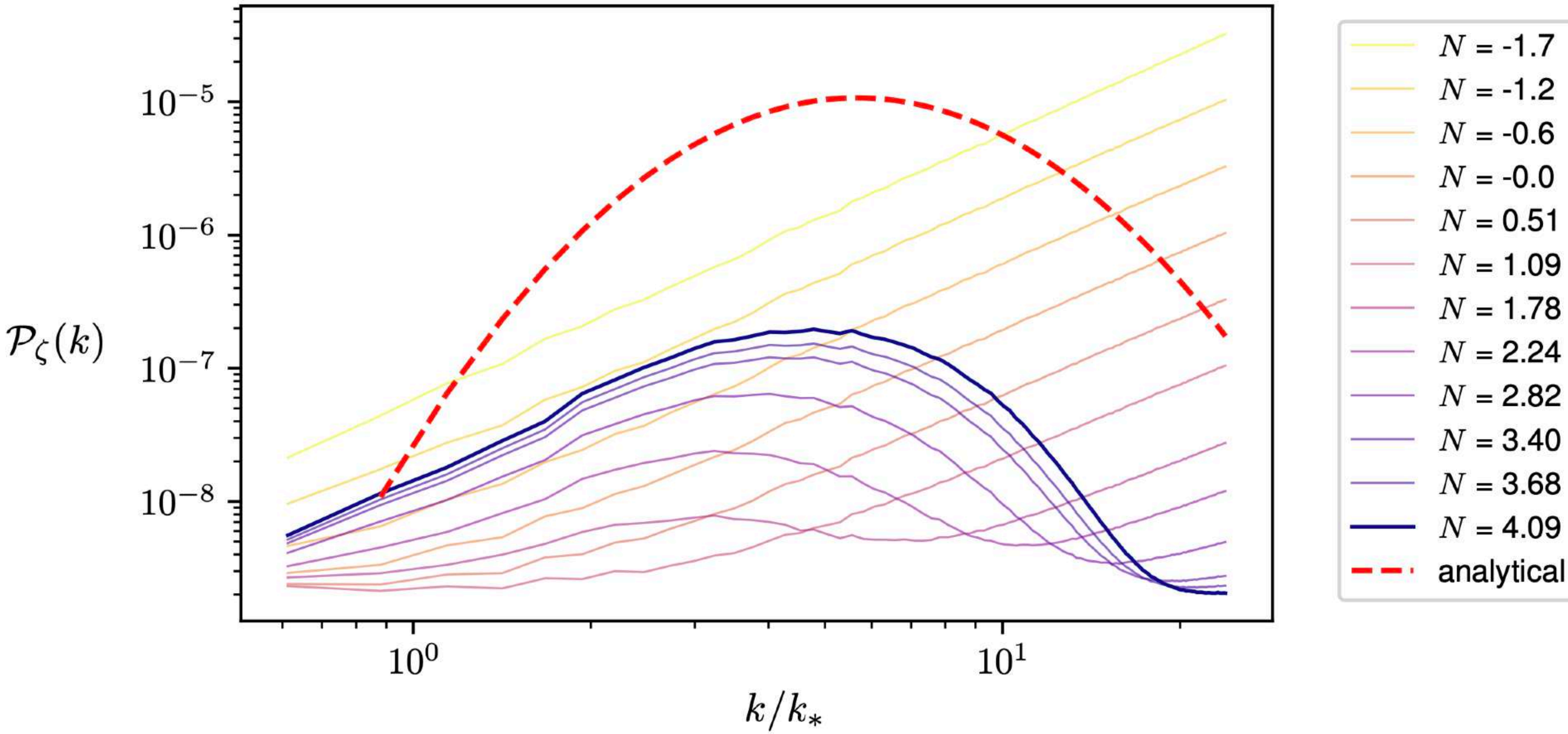
AC, Peloso 2407.13405

Suppression of non-Gaussianity



Backreaction: spectator model

Key result: backreaction is important in the PTA range

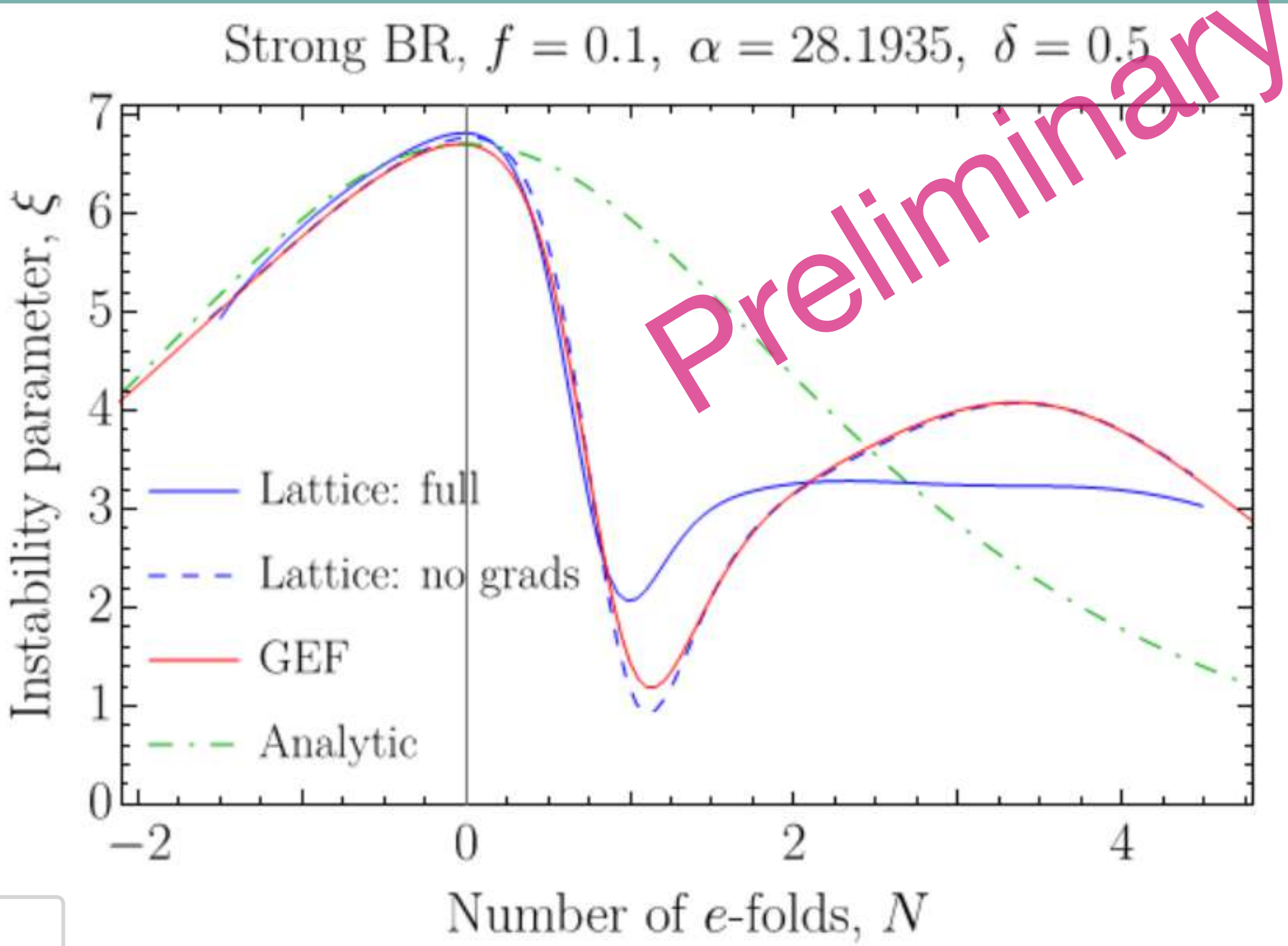


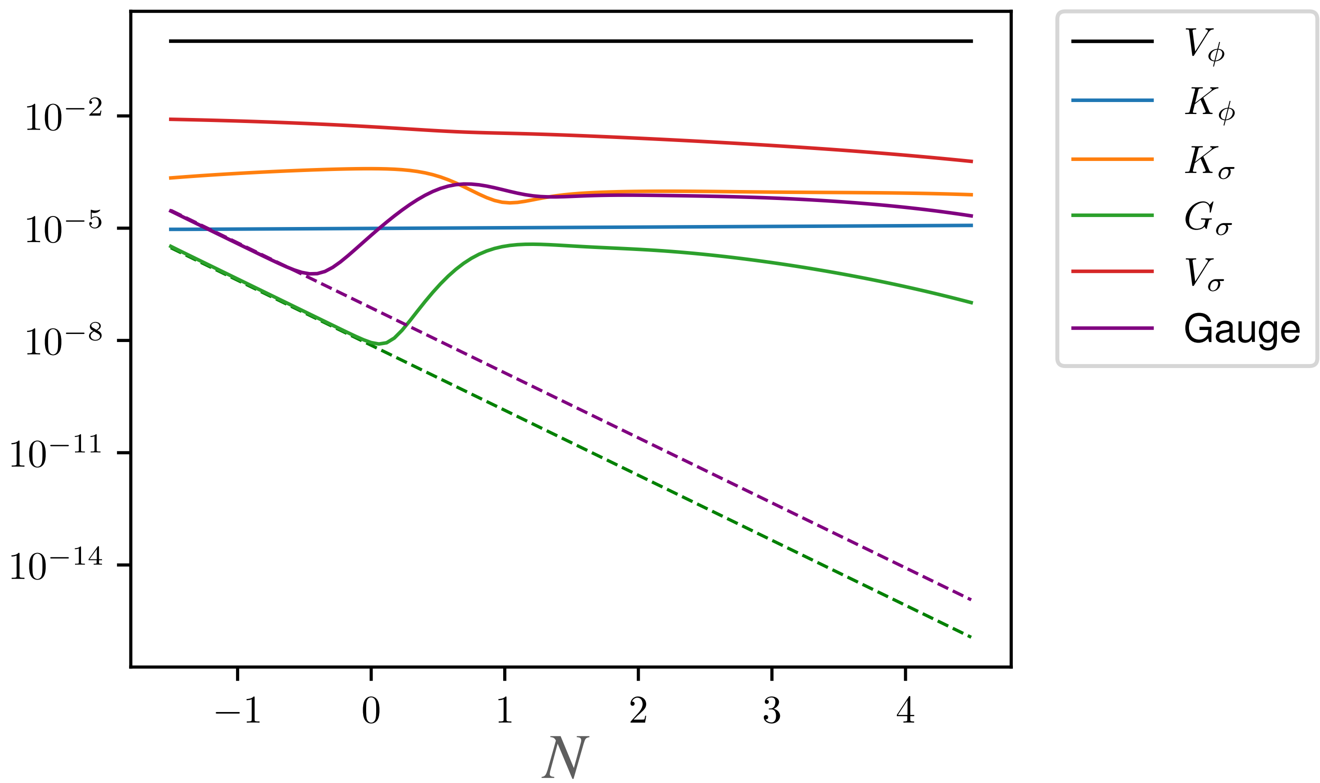
Backreaction: gradients

AC, Peloso 2407.13405

We compared full lattice results with homogeneous backreaction techniques (Gradient Expansion)

[Albouy, **AC**, von Eckardstein, Peloso, Renaux-Petel, Schmitz, Sobol (in prep.)]





Axion gradients are important, even if their energy is subdominant

Summary

- Axion inflation is an interesting model with multi-scale signatures

- Lattice simulations are emerging as a crucial tool in understanding these models:
  - Understanding complicated background dynamics
  - Gaussianization process → relaxes 10+ years old PBH bounds

Next steps:

- Use the simulation to calculate the observables

  (e.g. GW spectra, late-time non-Gaussianity

- Improve on the strong backreaction regime

  New lattice techniques (e.g. zoom-in techniques)

- Look at other models: for example SU(2) gauge fields

- Couple the simulation with analytical understanding