Theoretical consistency with enhanced density fluctuations

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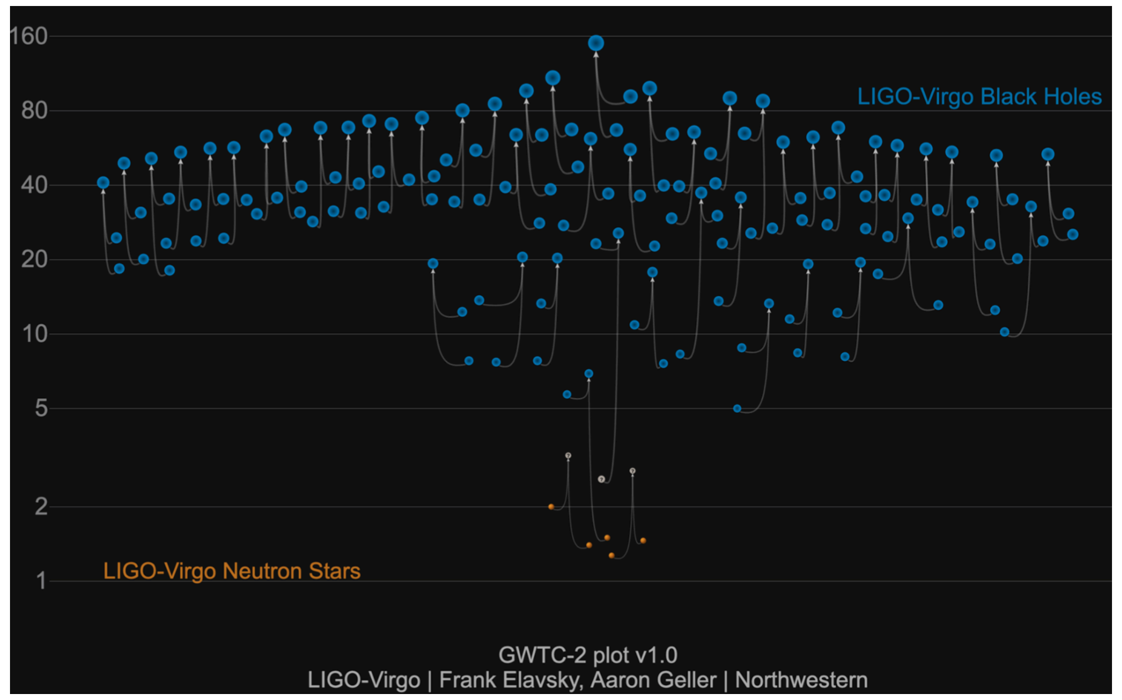
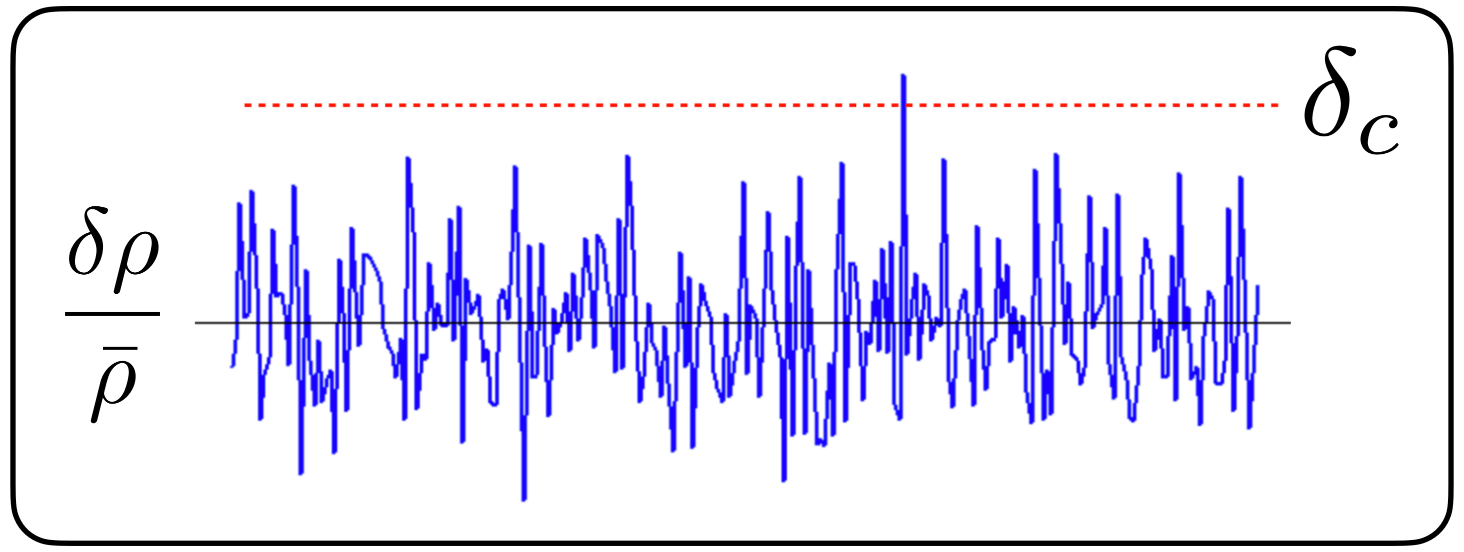
Context: GW astronomy



Have **Primordial Black Holes** been already detected? Data will tell

recent PBH review in LISA CosWG
2310.19857

Large primordial overdensities

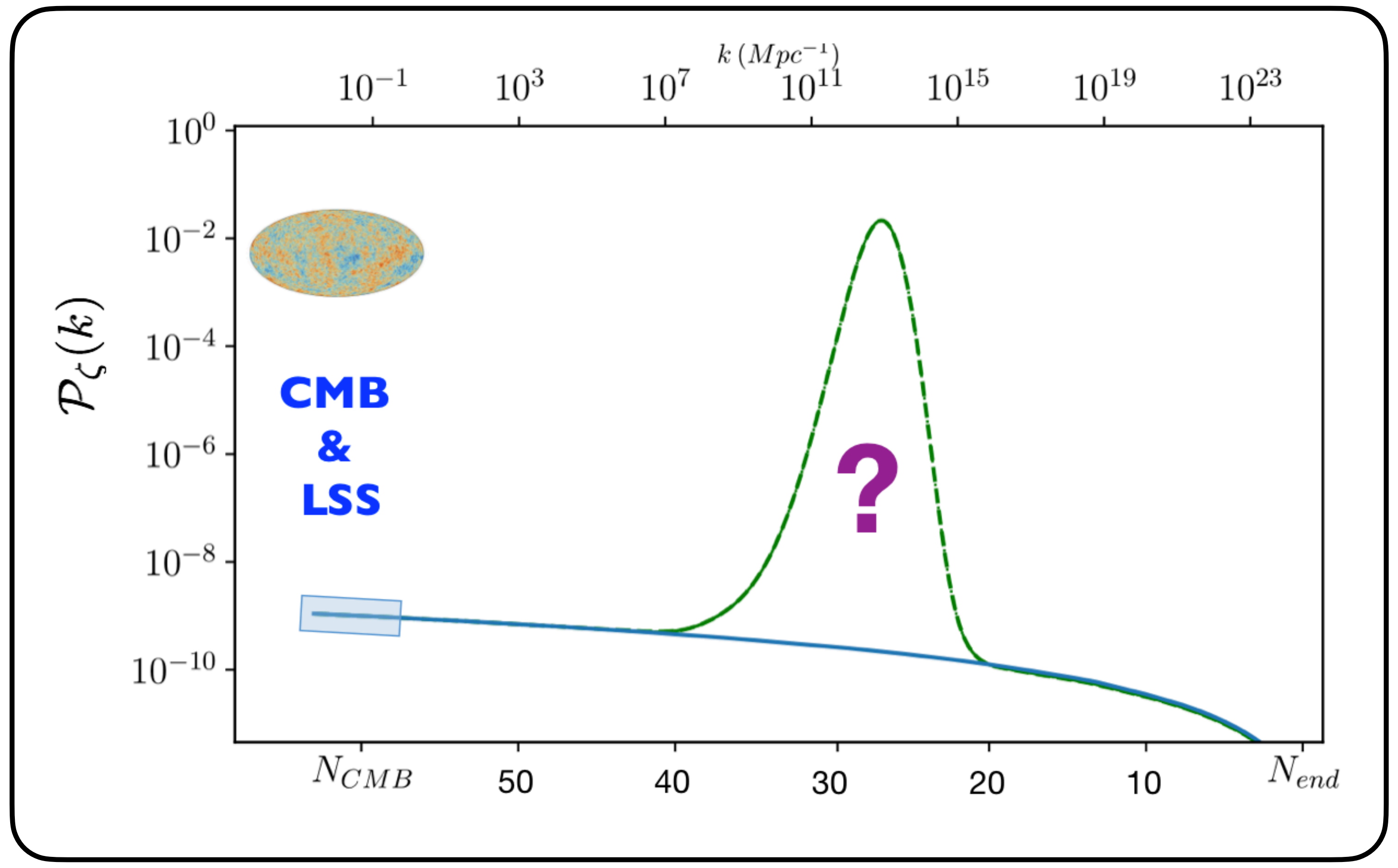


Large power spectrum on small scales and **nontrivial dynamics of inflation**

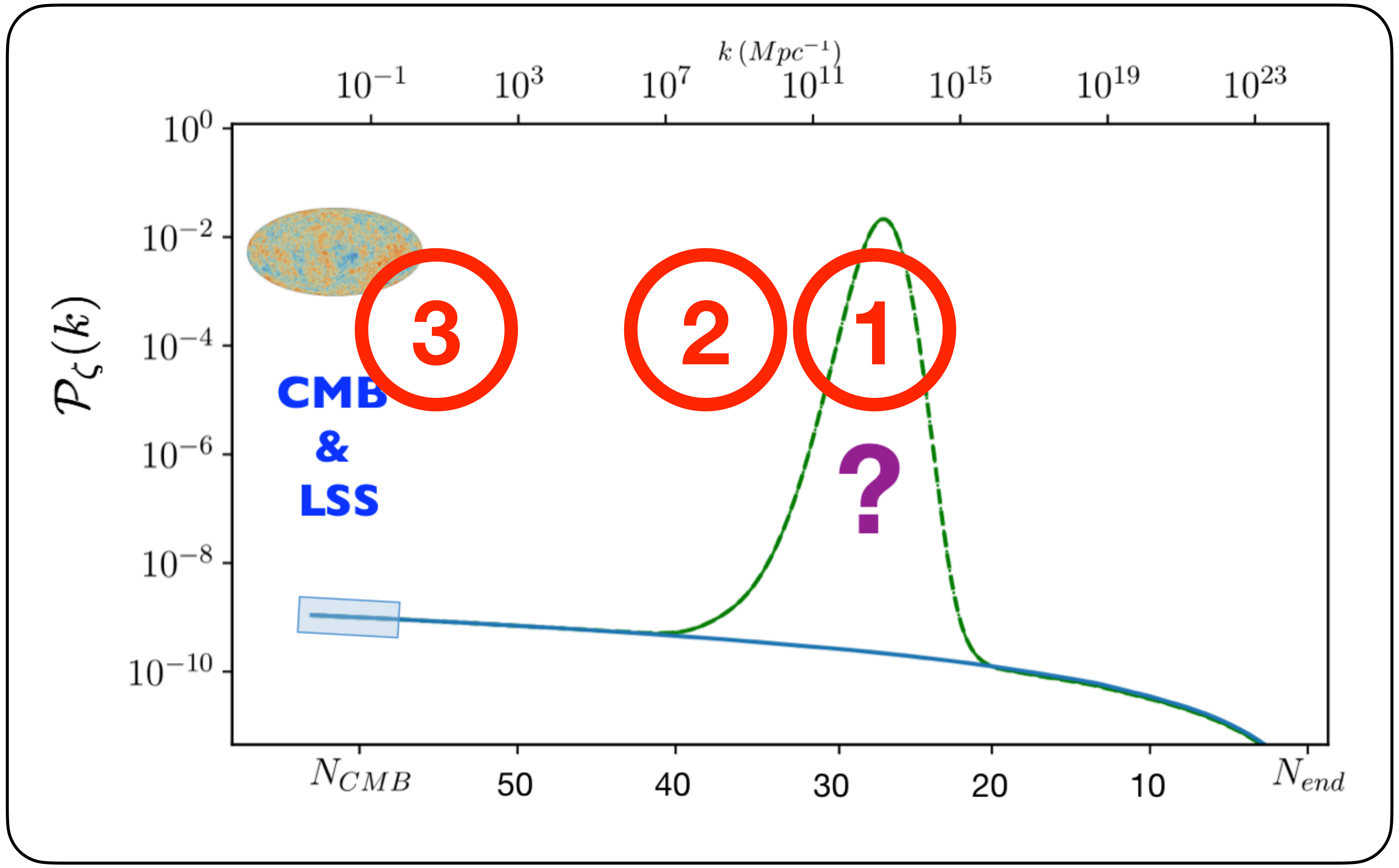
Scalar-induced **SGWB**

$$M \simeq 10^{-12} M_\odot \left(\frac{f_{\rm LISA}}{f}\right)^2$$

Bartolo et al 2019



A tale of three scales



1 slow-roll violation
particle production
enhanced fluctuations …

→

theoretical consistency?

2 Infrared rescattering

3 Effects on CMB scales

Questions

slow-roll violation, particle production, enhanced fluctuations…

↓

Validity of standard perturbation theory?

(distinct questions)

Backreaction?

Loss of perturbative control?

Backreaction

Transfer of energy

Fluctuations ⟷ Background

Energy in fluctuations comes from background!

Typically slows down the inflaton

Retro-action on dynamics of fluctuations

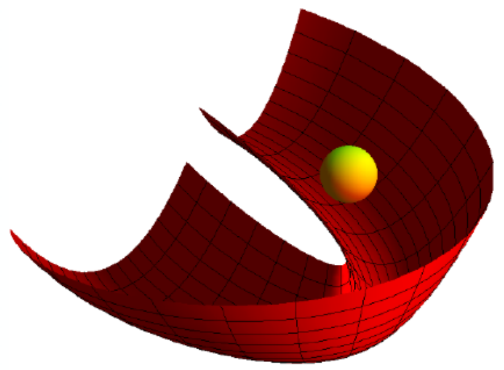
N.B: comparison point:
background kinetic energy

Non-trivial but within scope of analytical methods

Particle production

Sharp feature

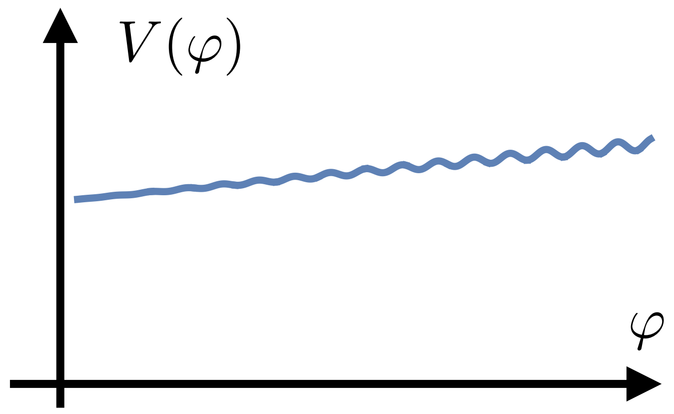
step in potential,
turn in field space …



$$\Delta t \ll H^{-1} \longrightarrow \omega \sim 1/\Delta t \gg H$$

Resonant feature

Resonance btw
background oscillations
and quantum modes oscillations



$$\omega \gg H$$

Excitation of
sub-Hubble modes

$\longrightarrow$

Langage and intuition
of particles useful

Particle production

The produced particles carry energy (and pressure)

Backreaction

$$\zeta \sim \alpha\, \zeta^{\rm BD} + \beta\, \zeta^{*\rm BD}$$

$$\rho = \frac{1}{a^4} \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^3} k|\beta_k|^2$$

energy density of
relativistic particles

Homan, Tolley, 2007
Fumagalli, RP, Witkowski, 2012.02761

Gravitational waves

$$\Box h_{ij} = T_{ij}^{\rm TT}$$

amount of GW bounded
by backreaction / energy conservation

Inomata, 2109.06192

Fumagalli, Palma, RP, Sypsas,
Witkowski, Zenteno, 2111.14664,

Loss of perturbative control (some generic spirit)

Time-dependent coupling in EFT of inflation $M(t)$ characteristic time scale of variation Δt

Governs structure of interactions

$$M(t+\pi) = M(t) + \pi \dot{M}(t) + \ldots$$

↑

Goldstone boson of broken time-diff invariance

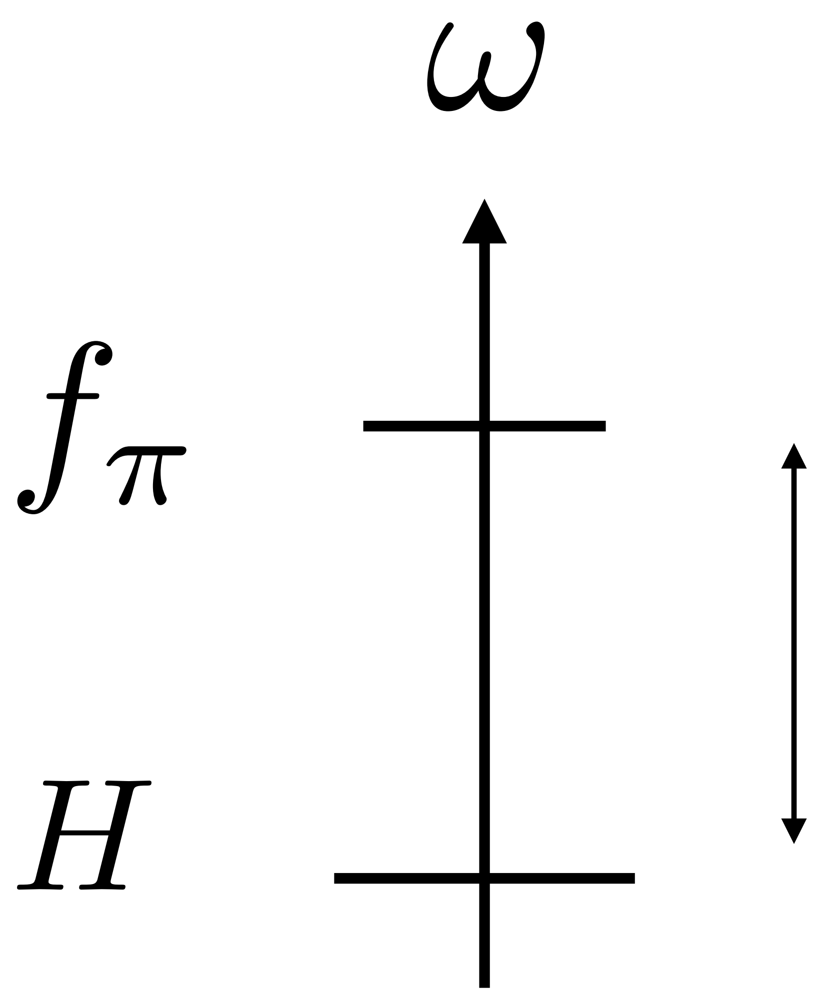
expansion ok if $\pi < \Delta t$ at energy $\omega \sim 1/\Delta t$ excited by time-dependence

Loss of perturbative control (some generic spirit)

e.g., canonical single-field inflation

$$\mathcal{L}/a^3 = \frac{f_\pi^4}{2}\dot{\pi}^2 + \dots \quad \text{with} \quad f_\pi^4 = 2M_{\rm Pl}^2|\dot{H}|$$

$\longrightarrow$ $\Delta t > 1/f_\pi$



$$\mathcal{P}_\zeta \sim \left(\frac{H}{f_\pi}\right)^4$$

the higher $\mathcal{P}_\zeta$ the smaller f_π/H

the easier perturbation theory breaks down

see, e.g., Bartolo, Cannone, Matarrese 13,14
Adshead, Hu, 14

Breakdown of perturbation theory

$$\mathcal{L} \sim (\delta\varphi)^2 + (\delta\varphi)^3 + (\delta\varphi)^4 + \dots$$

2 diagnostic tools

non-Gaussianity

$$\frac{\mathcal{L}_3}{\mathcal{L}_2} \sim f_{\rm NL}\mathcal{P}_\zeta^{1/2} \sim \quad 1$$

useful tools:

PyTransport
CppTransport

nonlinear sigma models

see Iacconi's talk and 2304.14260

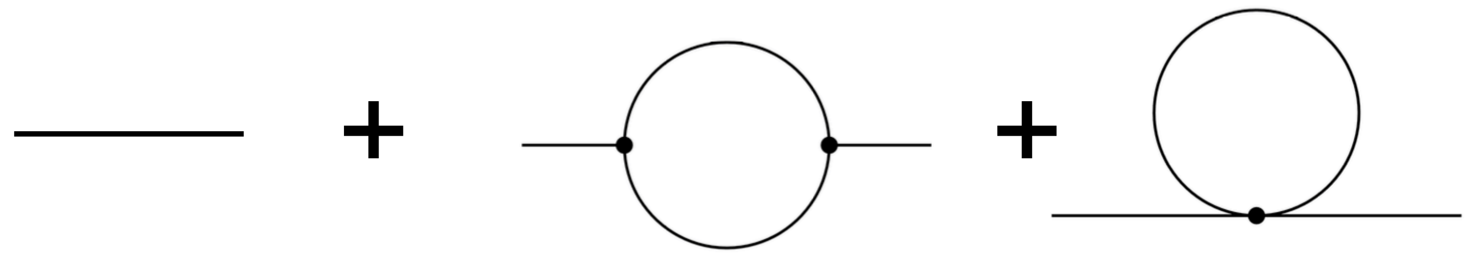
CosmoFLow

EFT based approach

Werth, Pinol, RP, 2302.00655 and to appear

loops

$$\langle \delta\phi^2 \rangle =$$

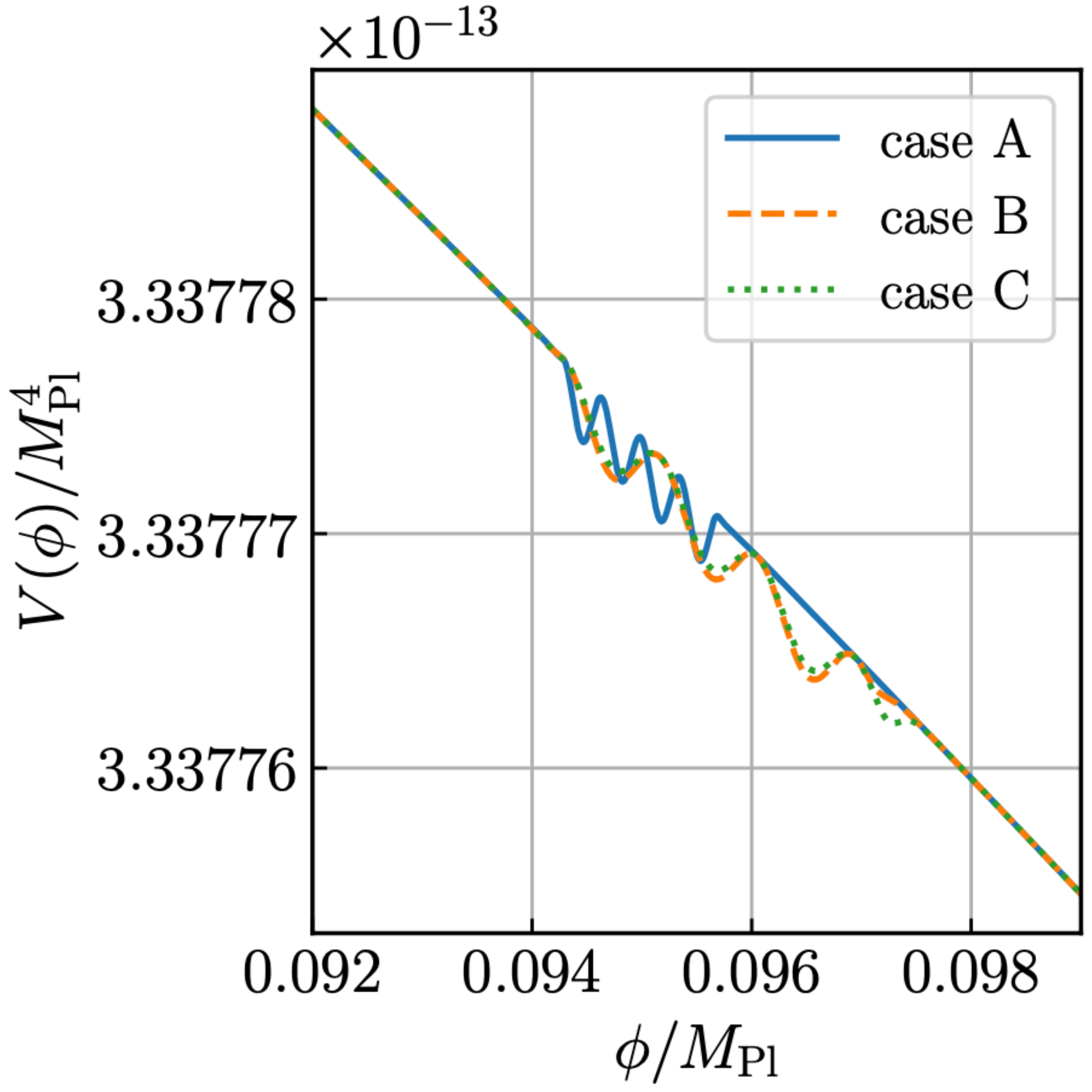


$+ \quad \dots$

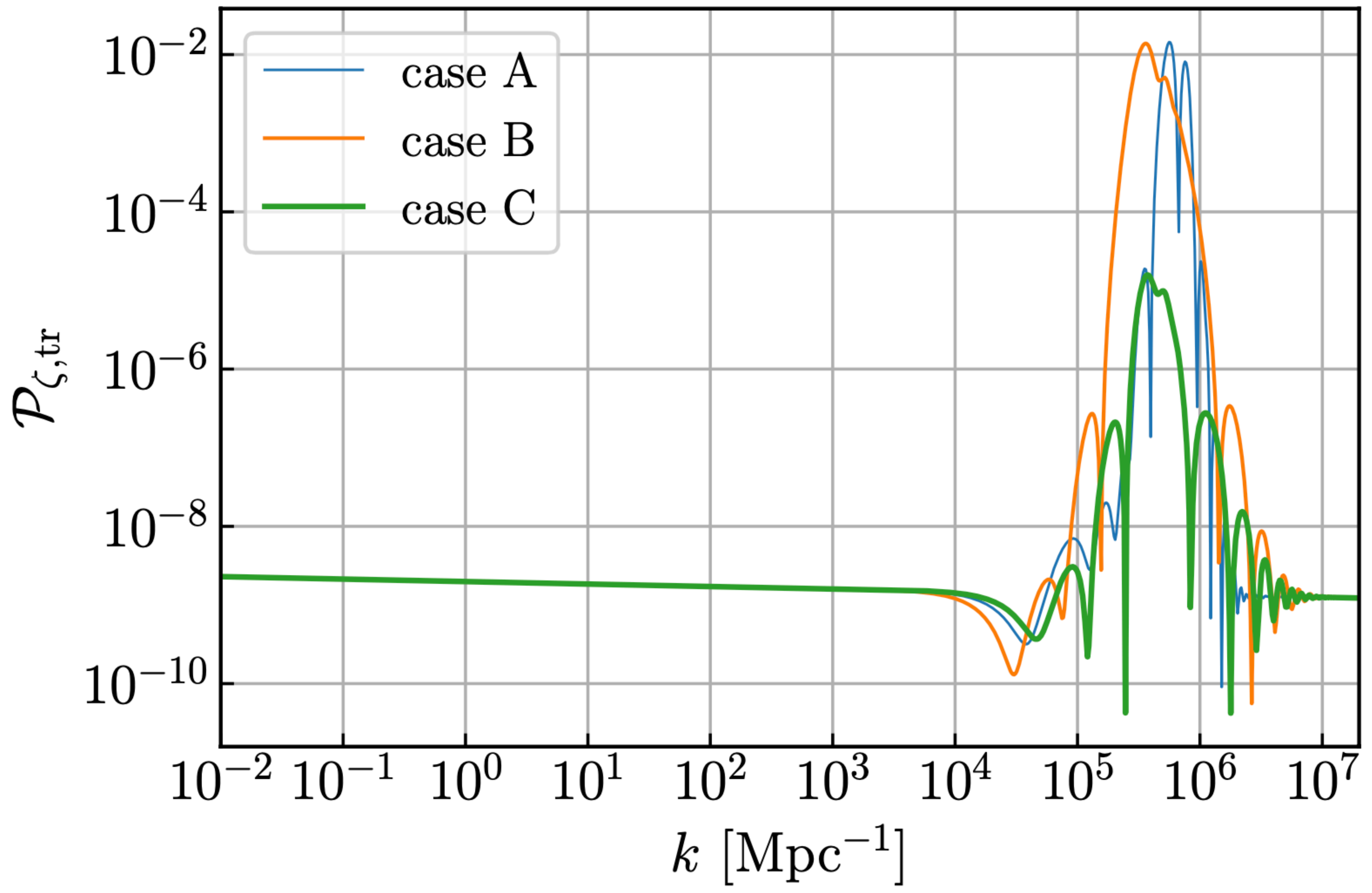
$\mathcal{P}_{\rm tree}$ $\qquad$ $\mathcal{P}_{\rm 1\text{-}loop}$

Inomata, Braglia, Chen, RP, 2211.02586

Example of Resonant Amplification



Floquet-type resonance

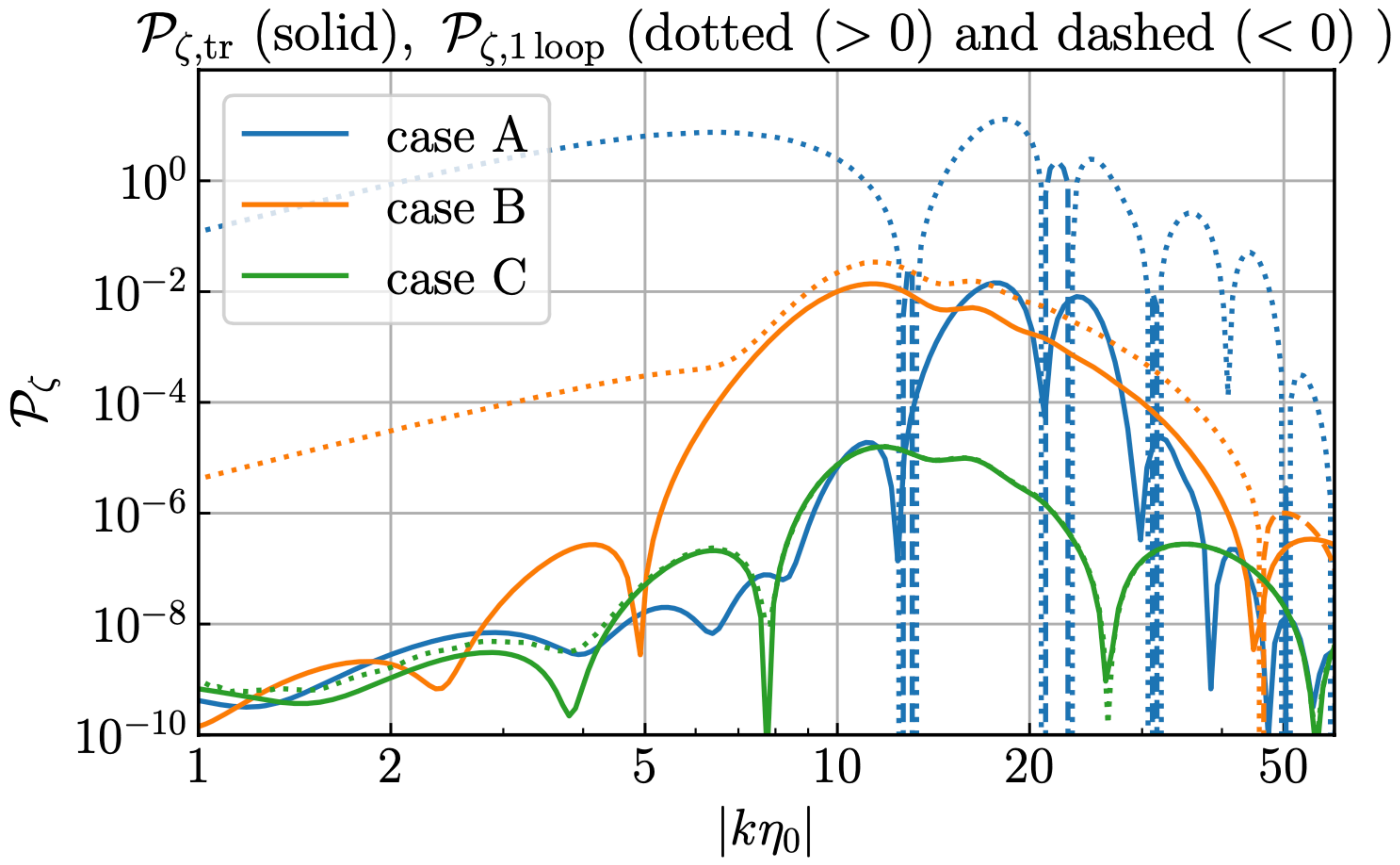


slow-roll + transient periodic modulations
(resonant NG setup)

Tree-level power spectrum

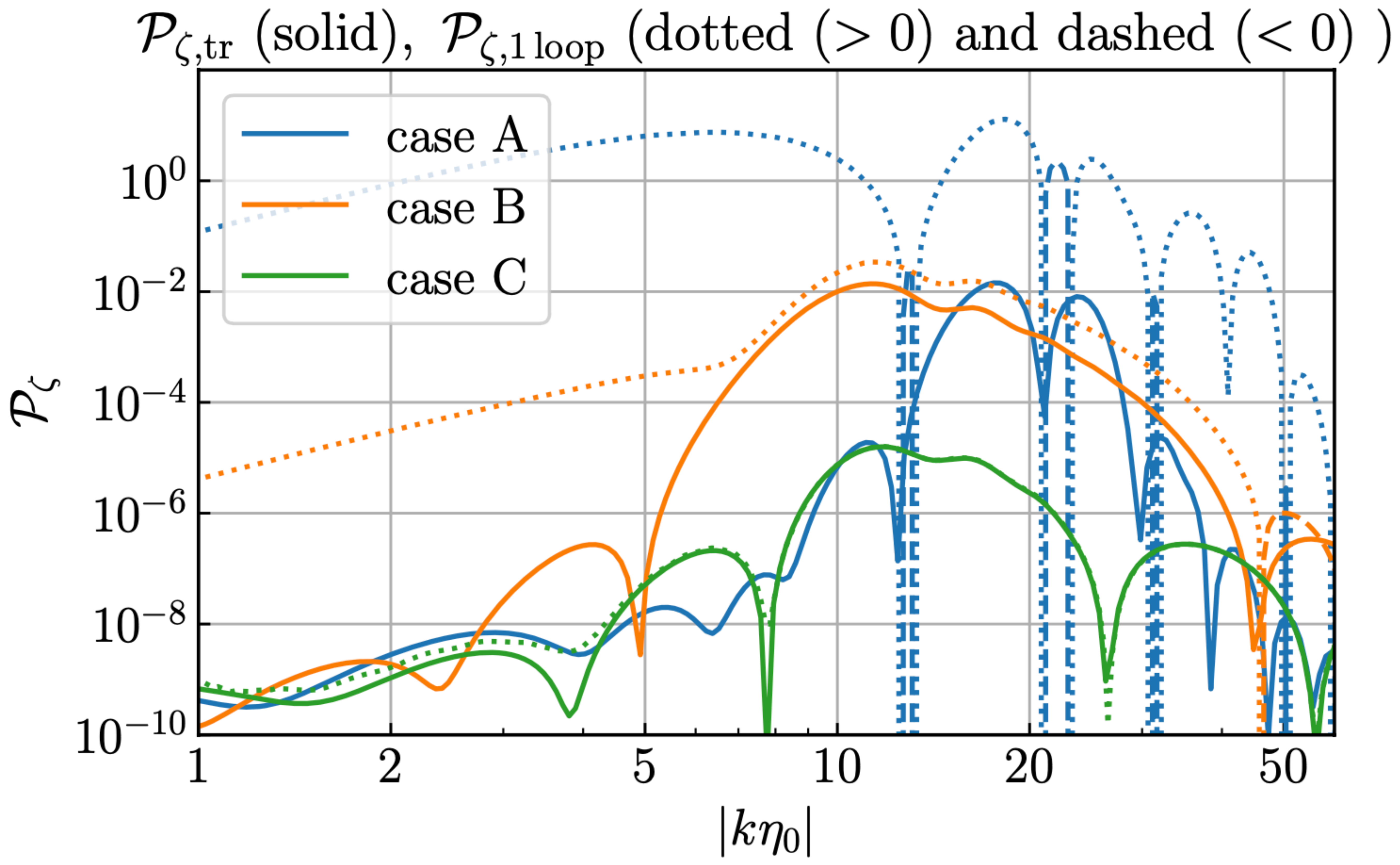
Inomata, Braglia, Chen, RP, 2211.02586

(first) First-principles numerical 1-loop computation



Standard background + numerical mode functions + numerical computations of loop integrals (natural cutoffs)

(first) First-principles numerical 1-loop computation



Standard Perturbation Theory

C: under control

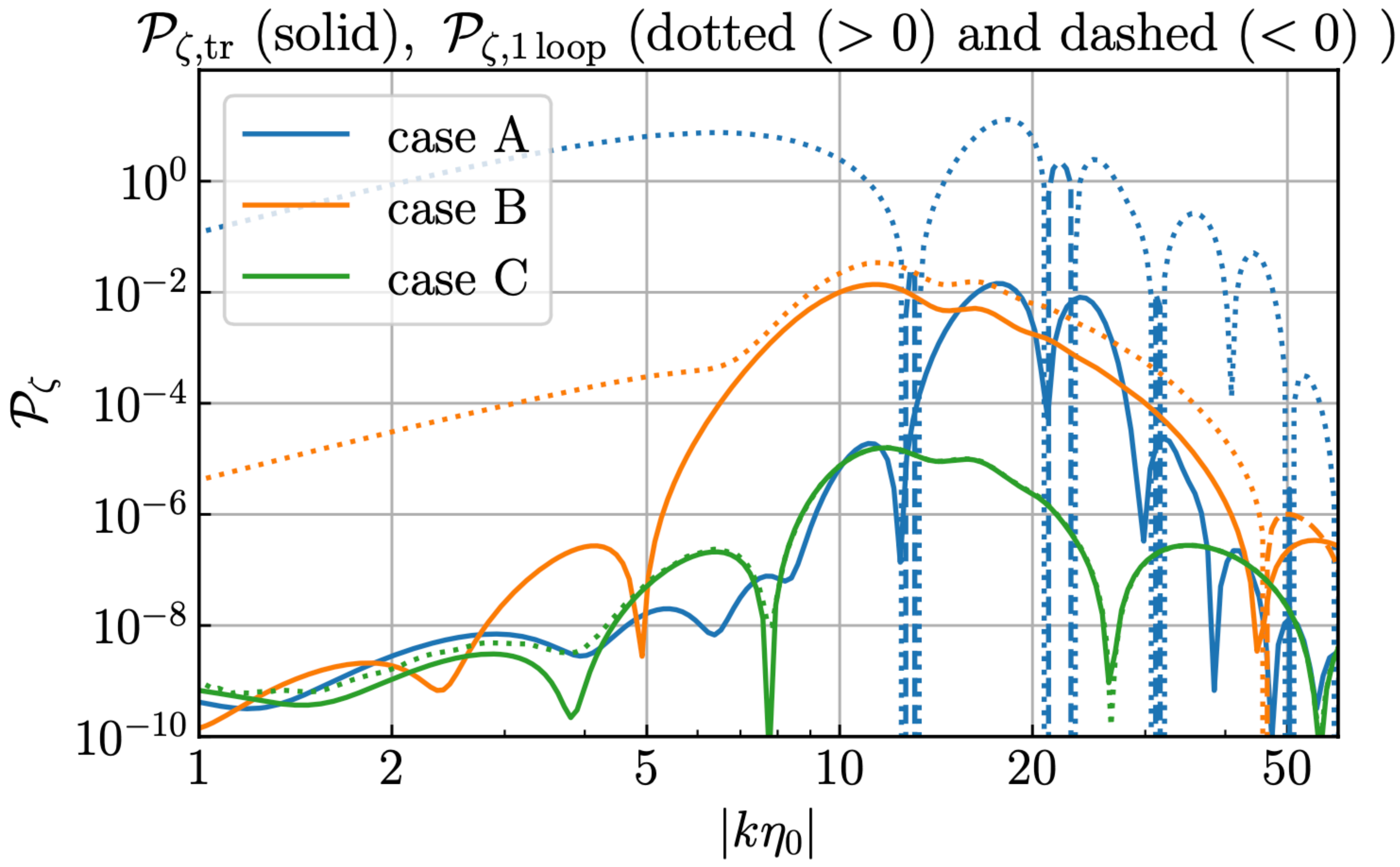
B: marginal

A: out of control

Models with PBH always out of control (in our study!)

Standard background + numerical mode functions + numerical computations of loop integrals (natural cutoffs)

(first) First-principles numerical 1-loop computation



Qualitative analytical understanding as well

Cases A and B: backreaction also an issue

Standard background + numerical mode functions + numerical computations of loop integrals (natural cutoffs)

Lattice simulations to the rescue

Not ultimate answers to all questions (classical vs quantum) but

Extremely useful approach

Fully nonlinear eom
for scalar fields

in (almost) FLRW background
sourced by average
full energy density and pressure

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Backreaction

see Angelo Caravano's review talk, and **preliminary results for resonant amplification setup**

Infrared rescattering

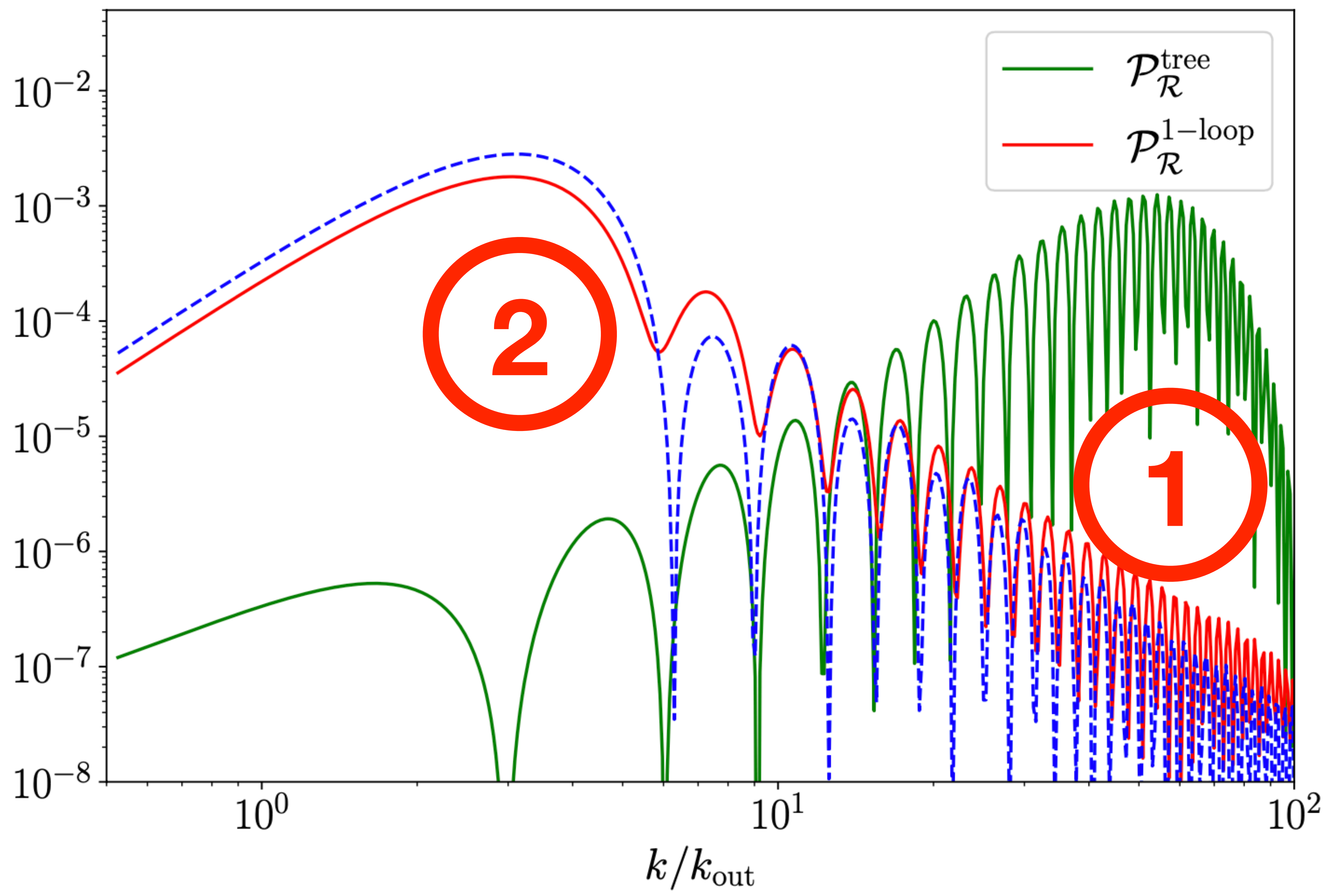
Is $\mathcal{P}_{\text{1-loop}} > \mathcal{P}_{\text{tree}}$ always a problem for SPT?

No! Depends on which scales we discuss

Short reason: some phenomena start at loop level

$$\mathcal{P}_{\text{2-loop}} < \mathcal{P}_{\text{1-loop}}$$

enough then

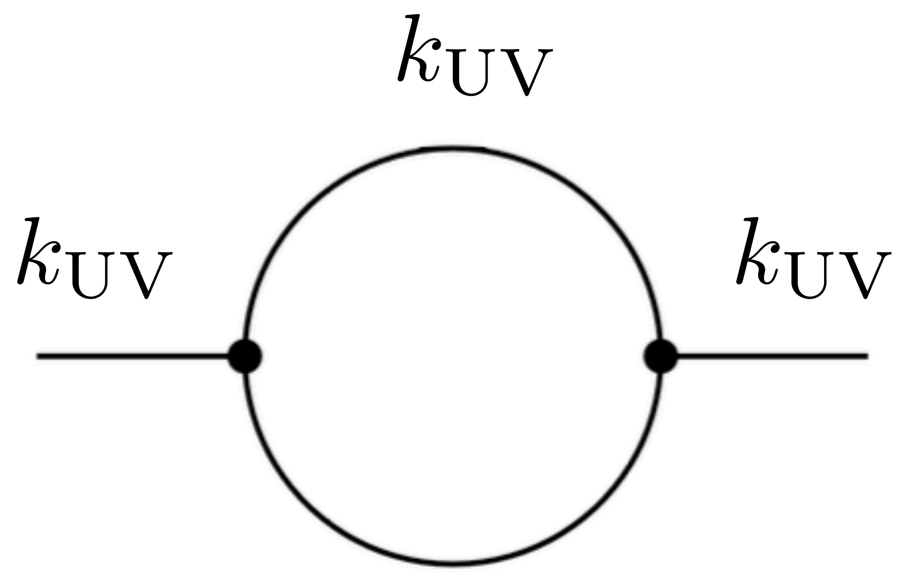


2307.08358, Fumagalli, Bhattacharya, Peloso, RP, Witkowski

Infrared rescattering

see Jacopo Fumagalli's talk

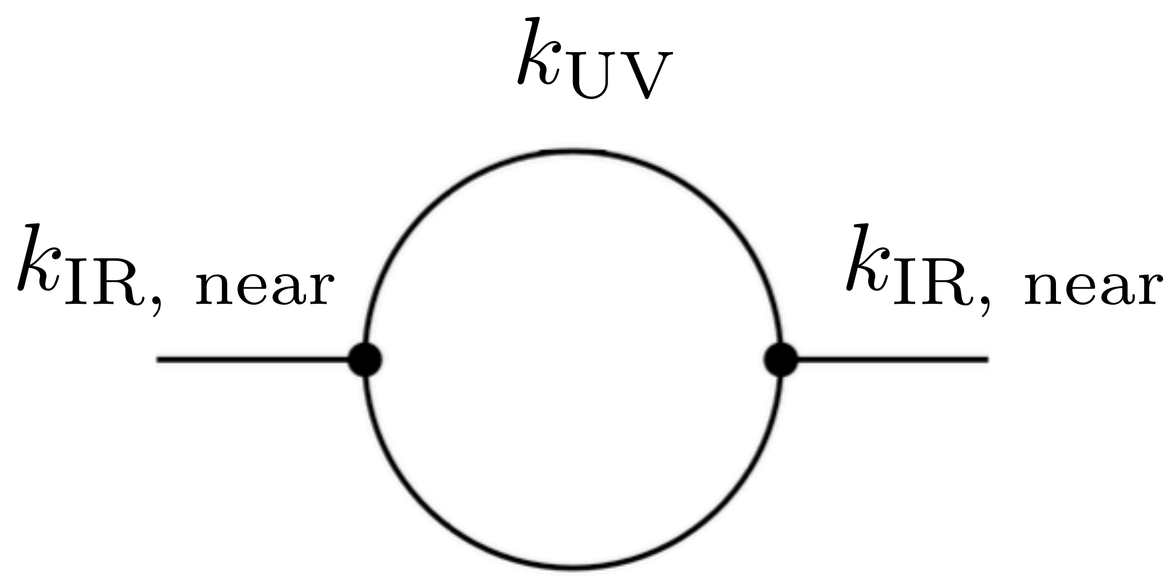
1



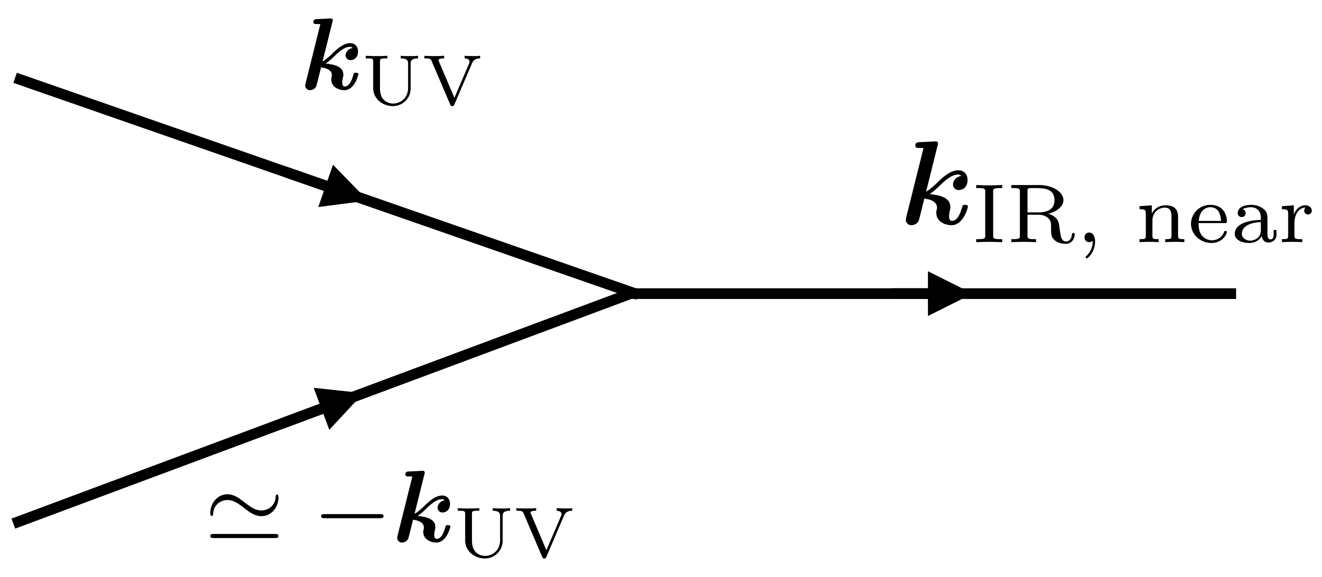
better be under control

vs

2



Particles created inside the horizon



Interact and quickly decay into modes with $\lambda \sim H^{-1}$

Generic analytical results (single-field, spectator, multi-field)

Universal: relevant even with gravitational interactions

2307.08358, Fumagalli, Bhattacharya, Peloso, RP, Witkowski

Similar effect for GW production

2111.14664, Fumagalli, Palma, RP Sypsas, Witkowski, Zenteno

Conclusions

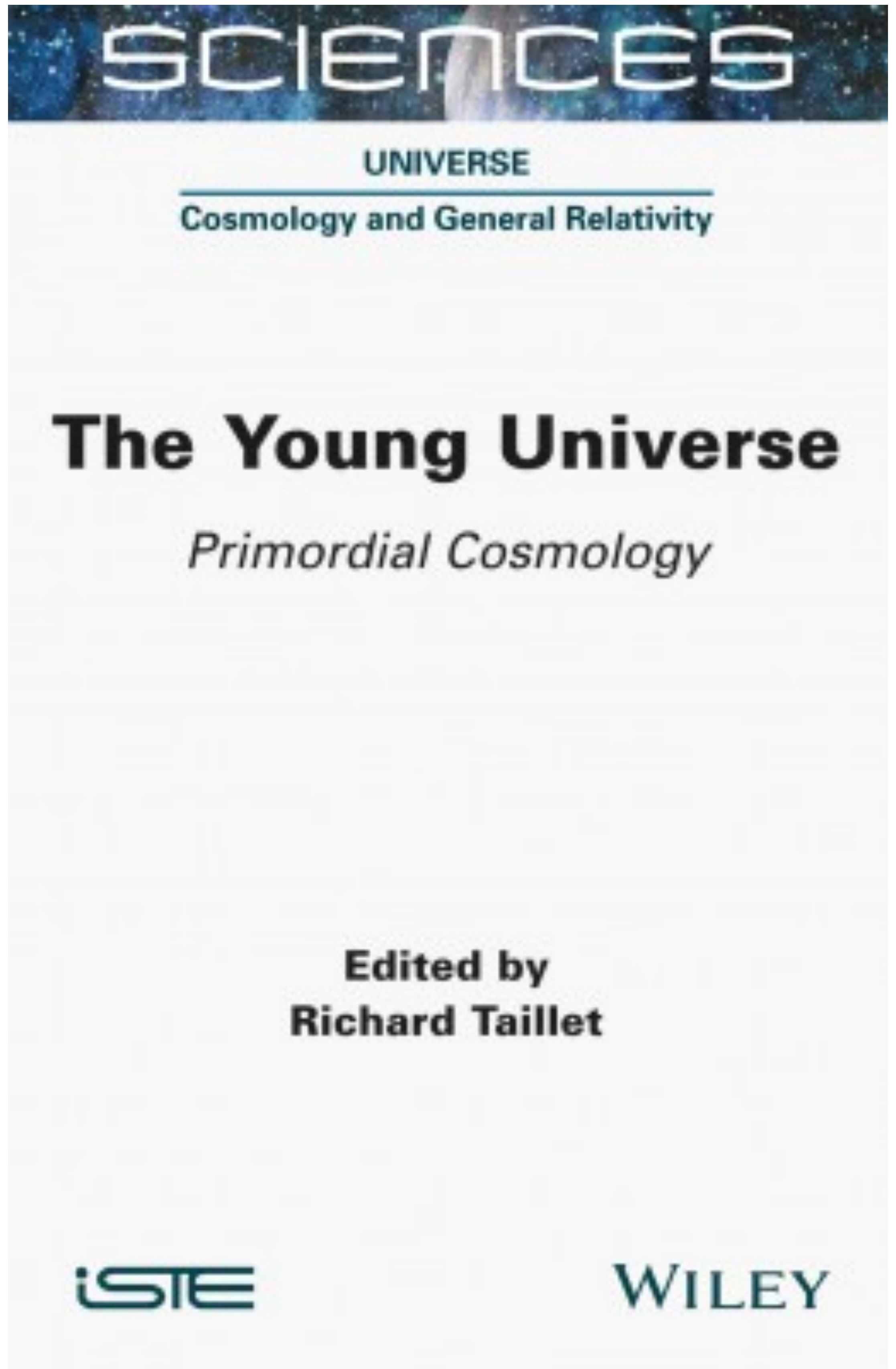
- Backreaction (ok, compute) and perturbative control (more tricky): ever-present threats in models with enhanced fluctuations

- First-principle numerical computations of loop effects with enhanced fluctuations (perturbative control always problematic for setups with PBH)

- First lattice simulation of it: way beyond standard perturbation theory!

- Infrared rescattering: IR cascade of power. Generic effect, of relevance for PBH

Thank you!



Oct 22, 348 pages

undergraduate & graduate textbook, 4 authors :

1. A Thermal History of the Universe and Primordial Nucleosynthesis, Pierre Salati.

2. Cosmological Microwave Background, Julien Lesgourgues.

3. Cosmological Inflation, Sébastien Renaux-Petel.

4. Dark Matter, Richard Taillet.