Probing primordial features with the SGWB

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with J. Fumagalli and L. Witkowski

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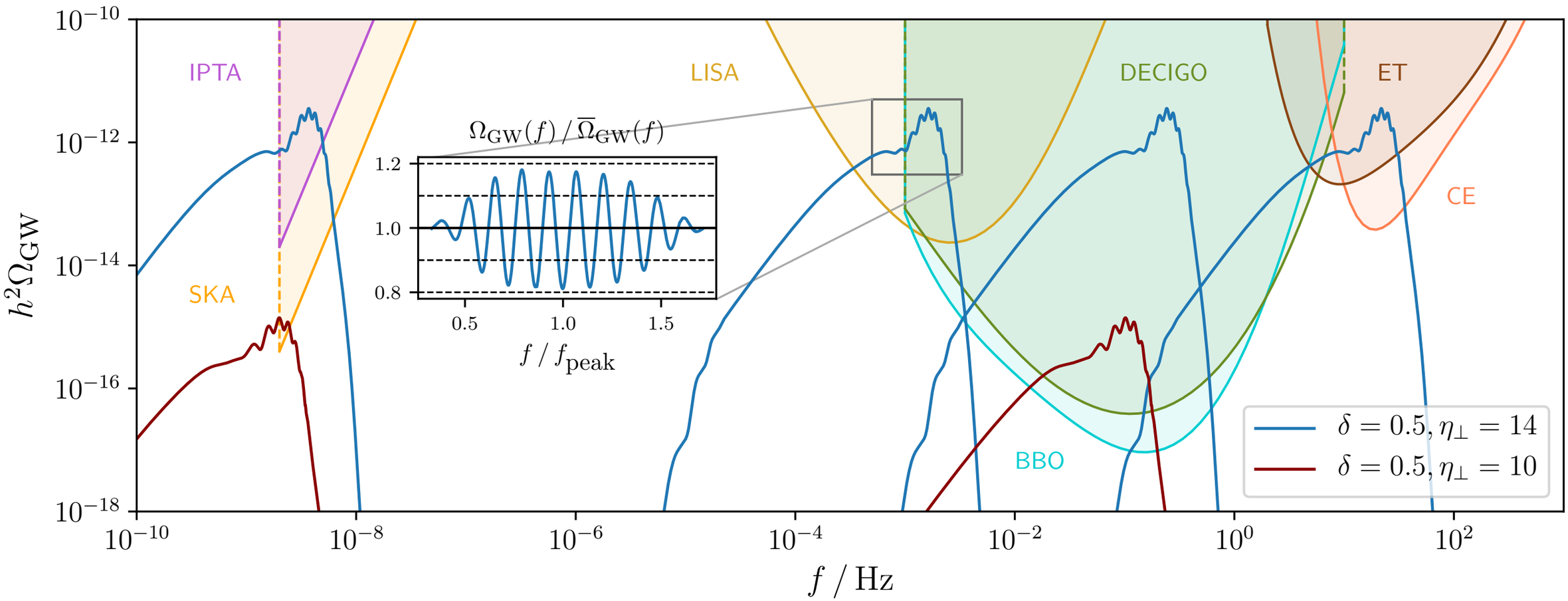
GEODESI

Take-home message

Primordial features invaluable probe of early universe

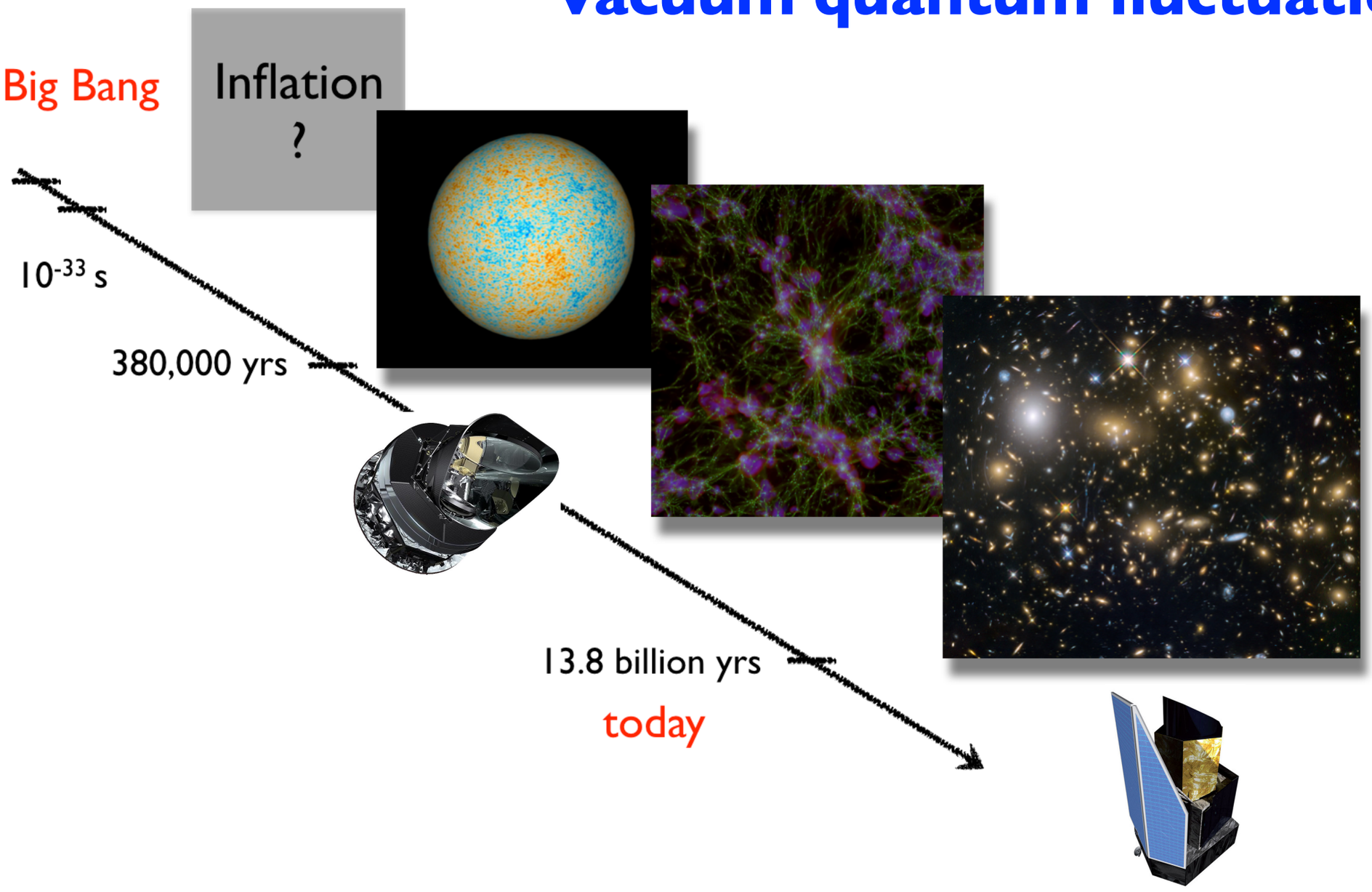
Oscillations in primordial scalar power spectrum ⟶ Oscillations in frequency profile of $\Omega_{\rm GW}(f)$

Precious probe of inflation on small scales

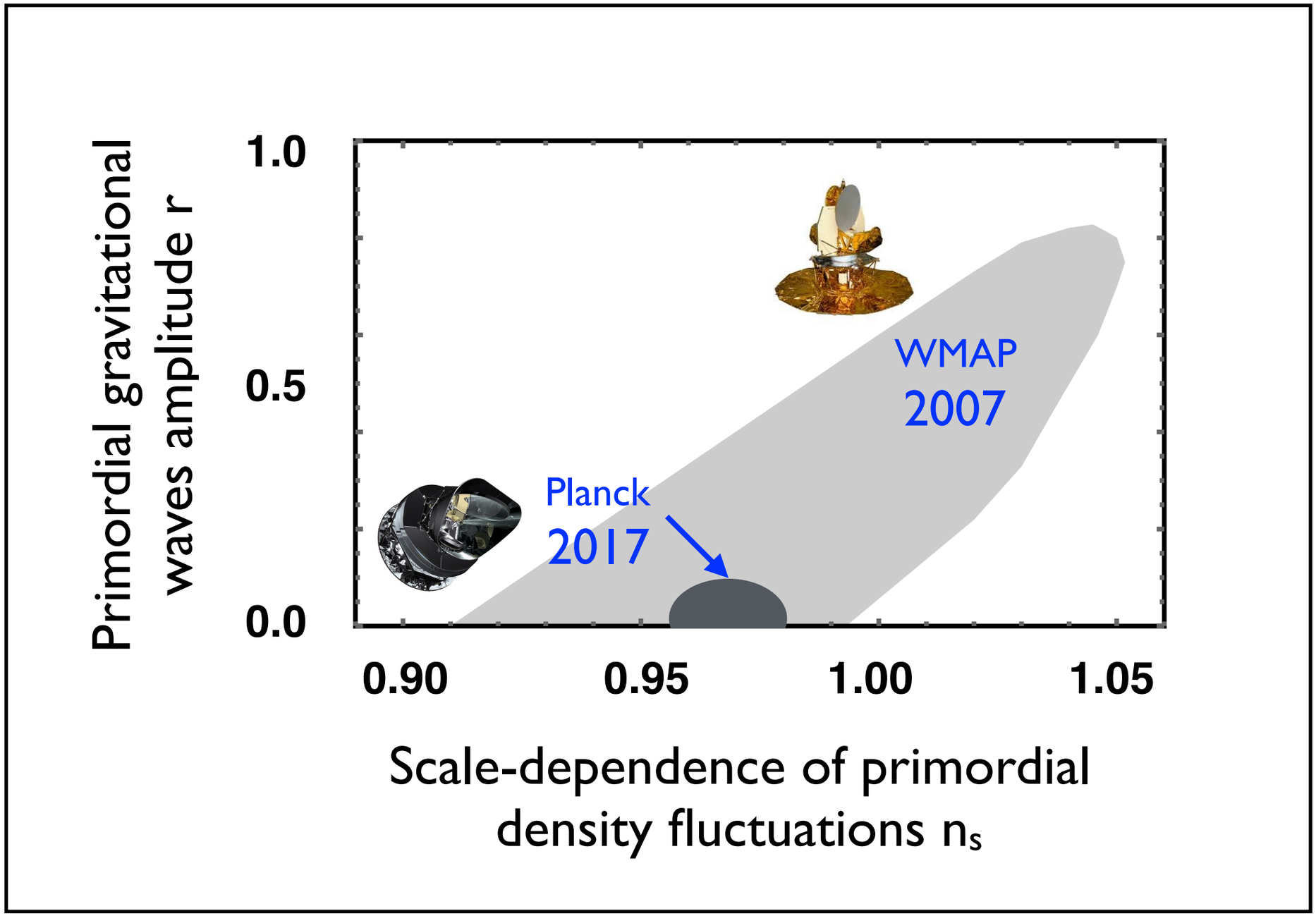


Inflation: a period of accelerated expansion before the radiation era that solves the problems of the Hot Big bang model

Structures in universe emerge from vacuum quantum fluctuations



Observational progress



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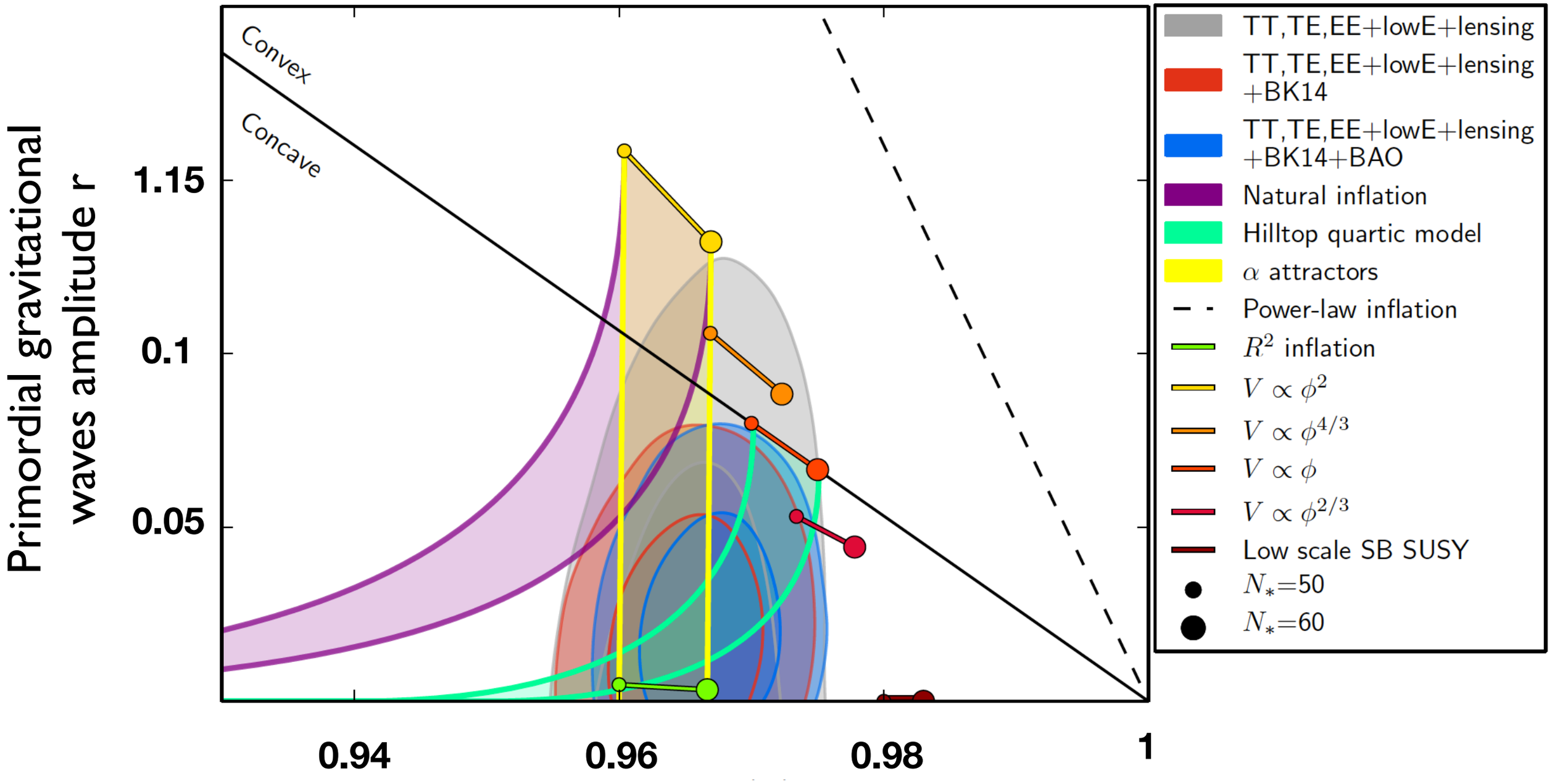
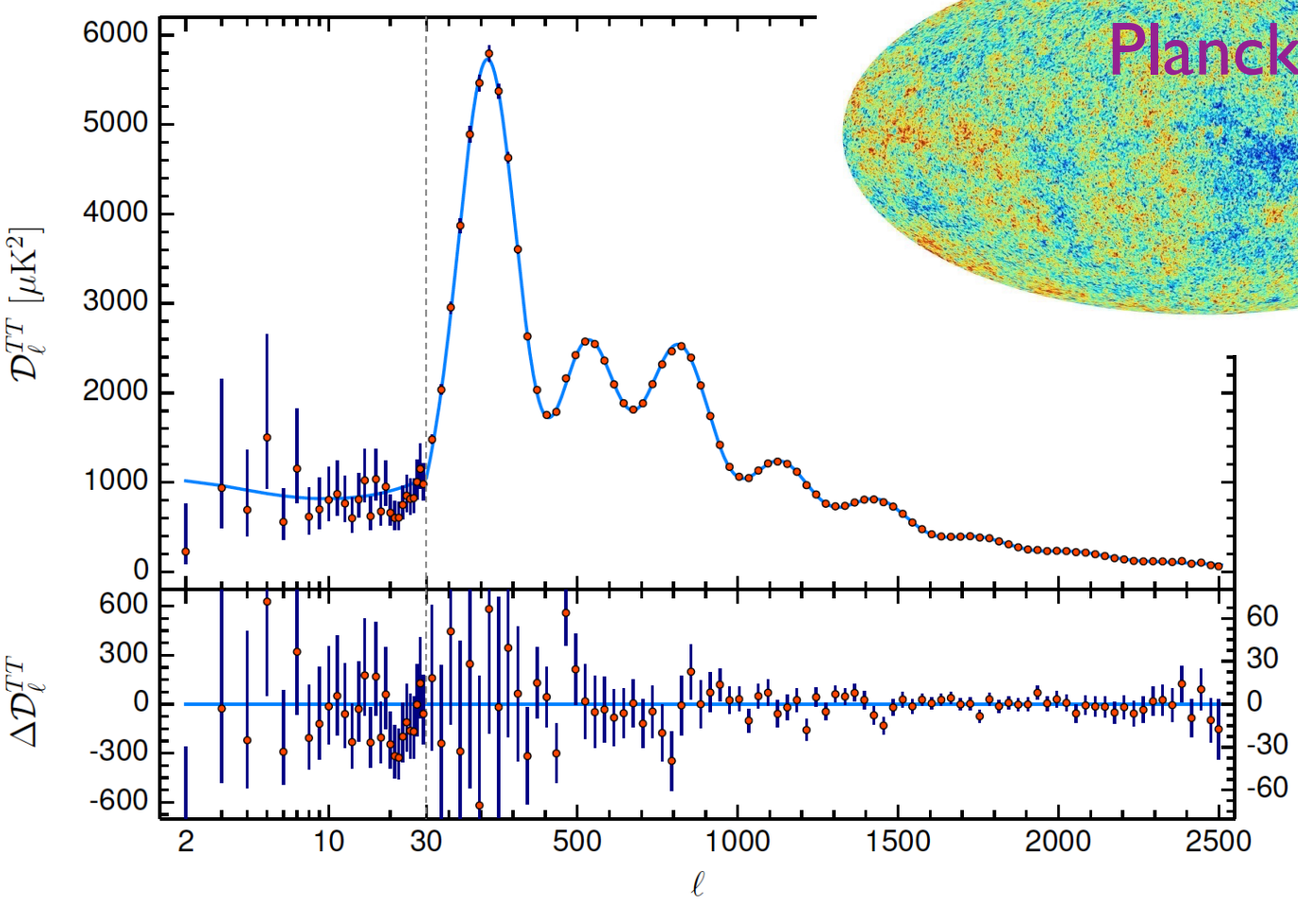
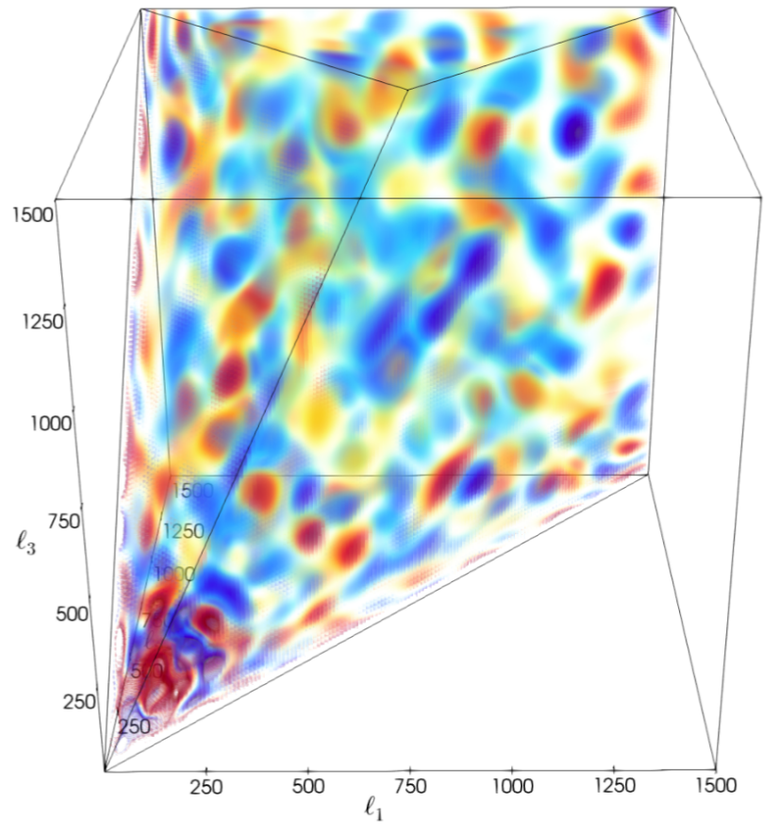


Scale-dependence of primordial density fluctuations n_s

Observational progress





Density fluctuations:

Superhorizon - adiabatic
almost scale-invariant - Gaussian

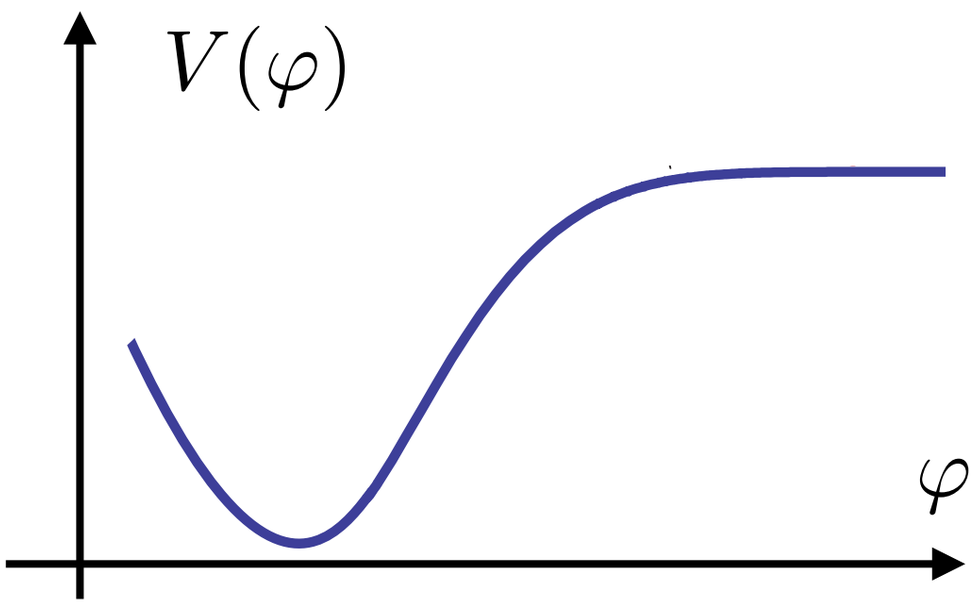
Simplest fit to data: single-field slow-roll inflation

Physics of inflation?

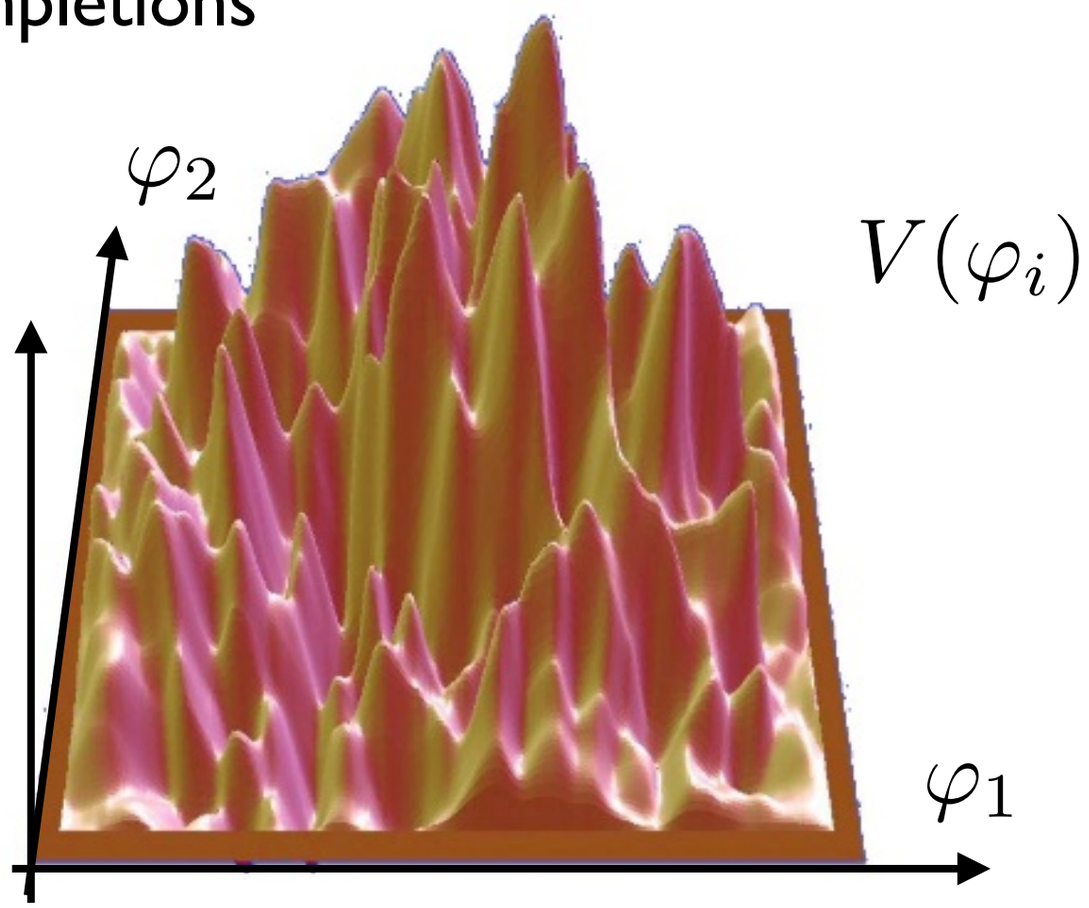
No-one believes single-field slow-roll models
are more than toy models

- decoupled from the rest of physics

- lack UV completions



Hoped



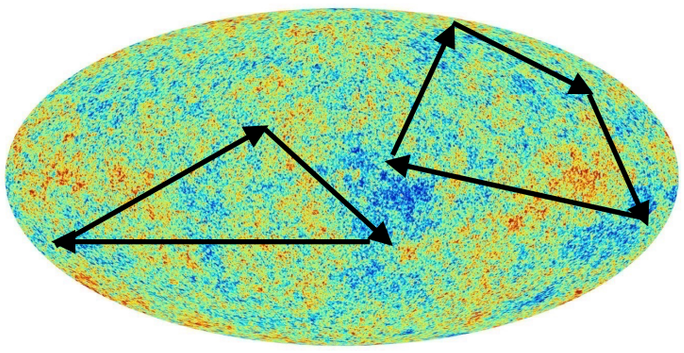
Found

Looking for new physics

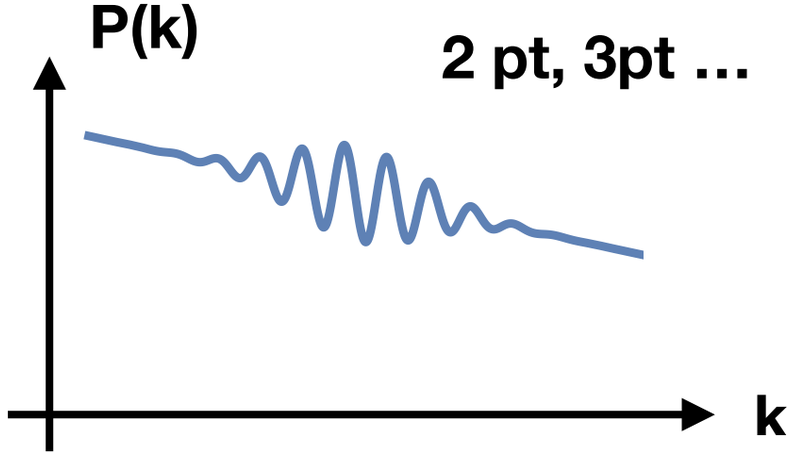
- Single-field slow-roll: at best emergent approximate description
- Cosmologists seek deviations to it in motivated manner

Primordial non-Gaussianities

Primordial features



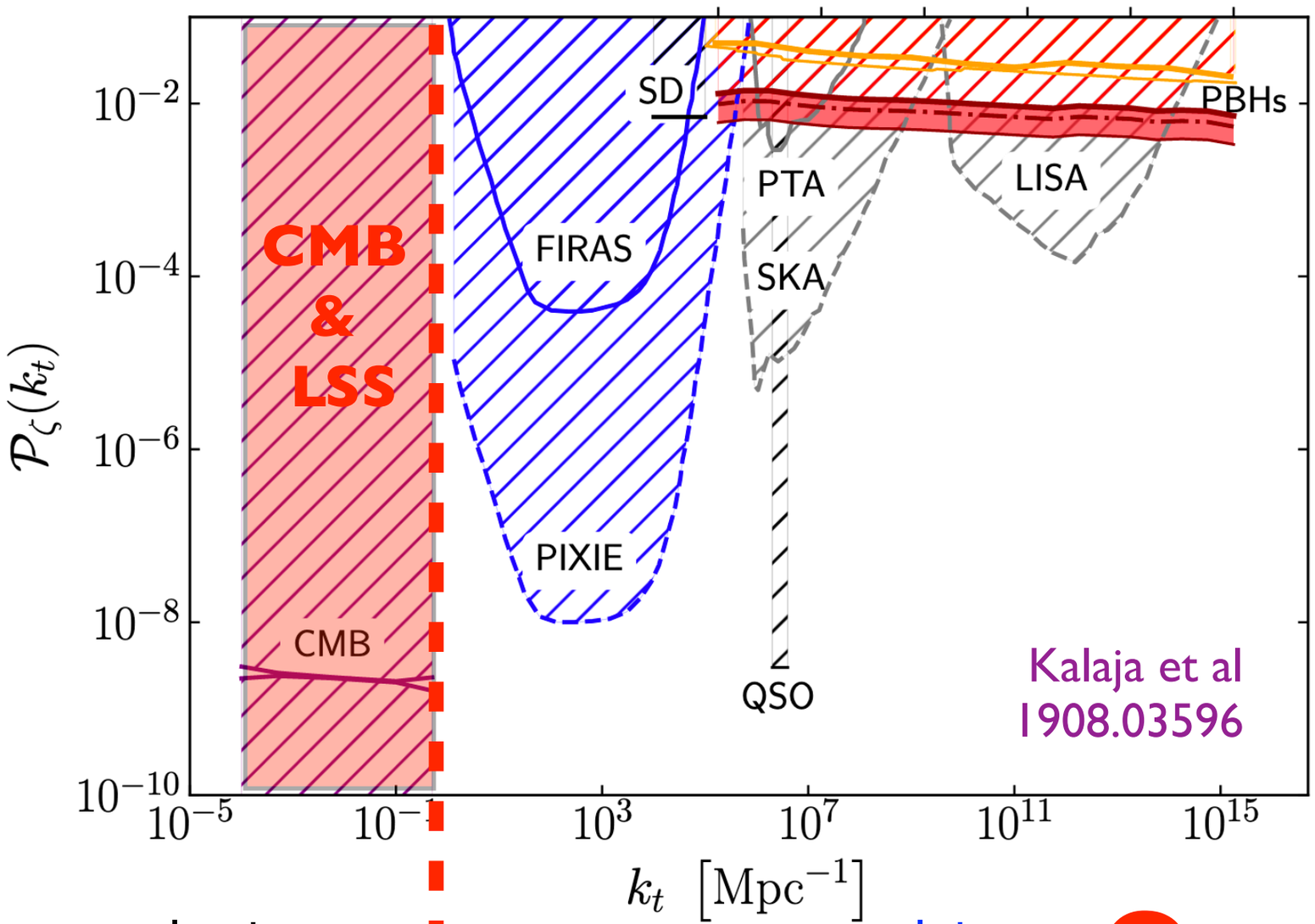
3pt, 4 pt …



Rule out all simplest models,
detection of heavy particles, etc

Studied for CMB, LSS, 21cm

Inflation on small scales?



Spectral distortions

Primordial Black Holes

Stochastic GW background

probed by

early stage of inflation

$\simeq$

Slow Roll + Corrections

later stage

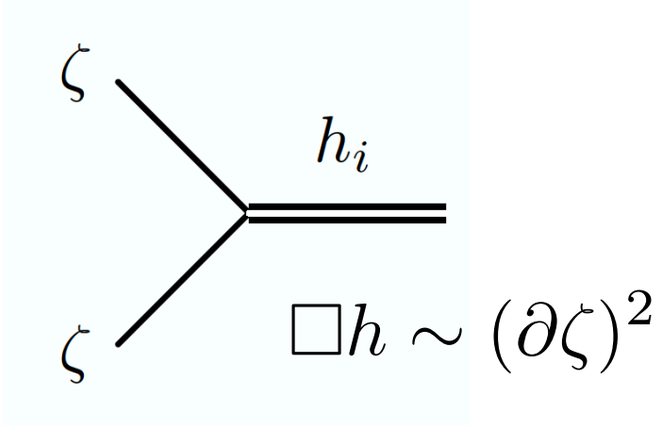
?

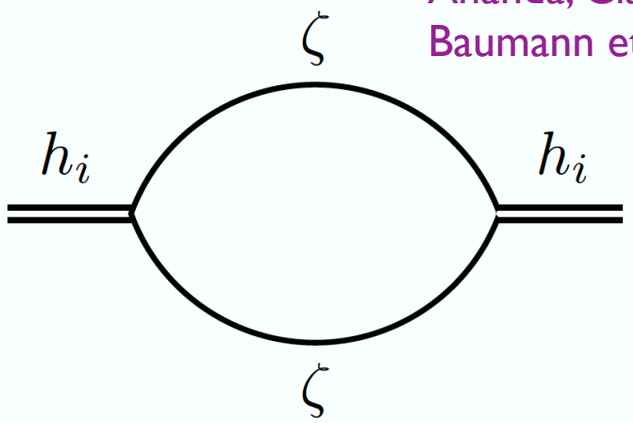
Drastically different?

High-Energy effects to be discovered?

Scalar-induced GWs

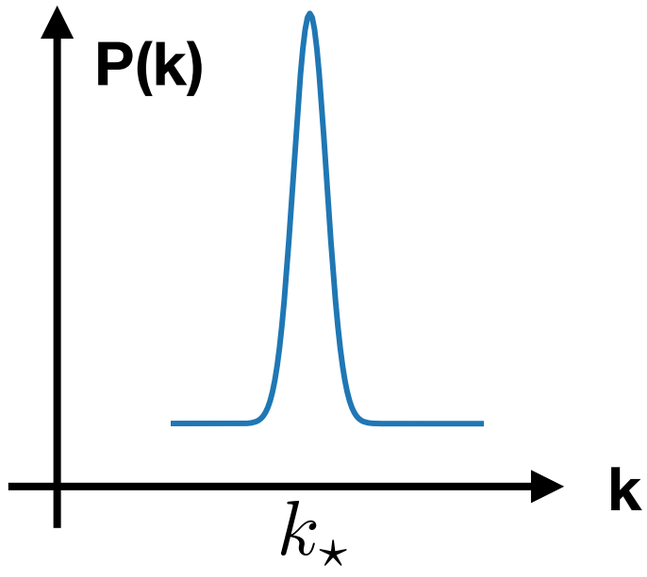
Acquaviva et al. '02
Mollerach, Harari, Matarrese '03
Ananda, Clarkson, Wands '06
Baumann et al. '07 …

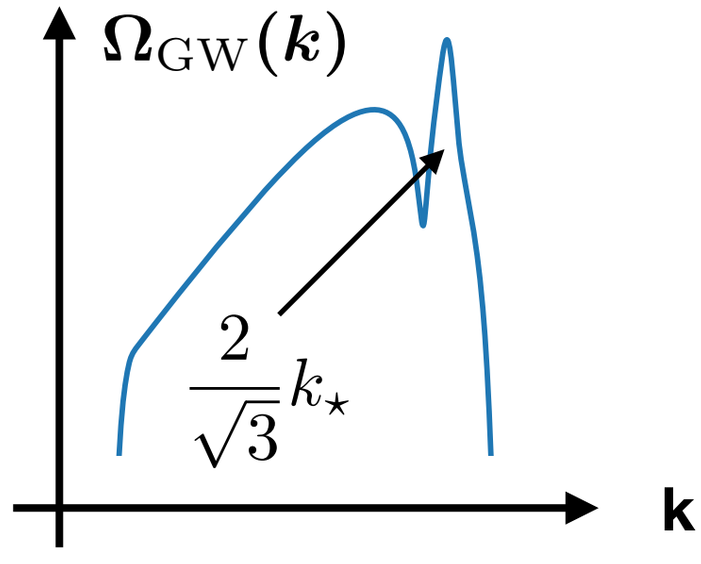




Enhanced $\delta\rho$ → Enhanced GWs at horizon re-entry after inflation

$$\Omega_{\rm GW}(k) = \int\int T(u,v)\mathcal{P}_\zeta(ku)\mathcal{P}_\zeta(kv) \quad \sim 10^{-5}\,\mathcal{P}_\zeta^2$$





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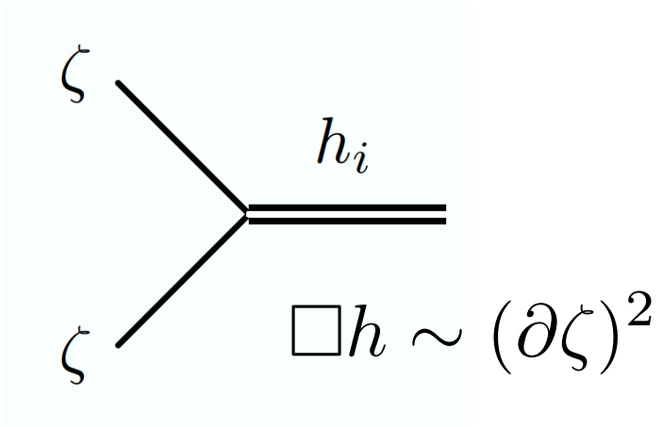

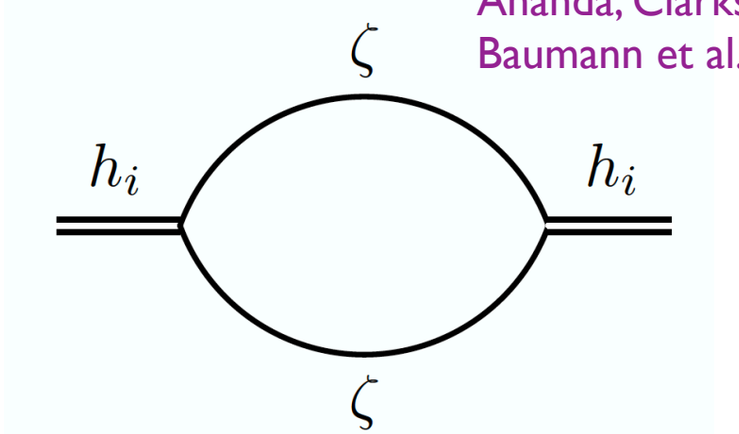

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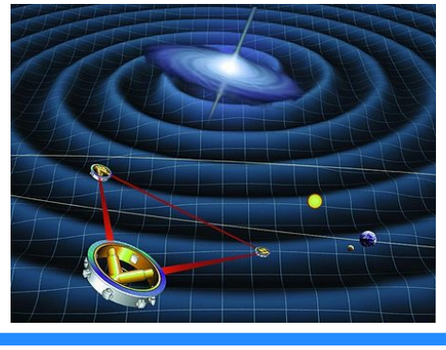
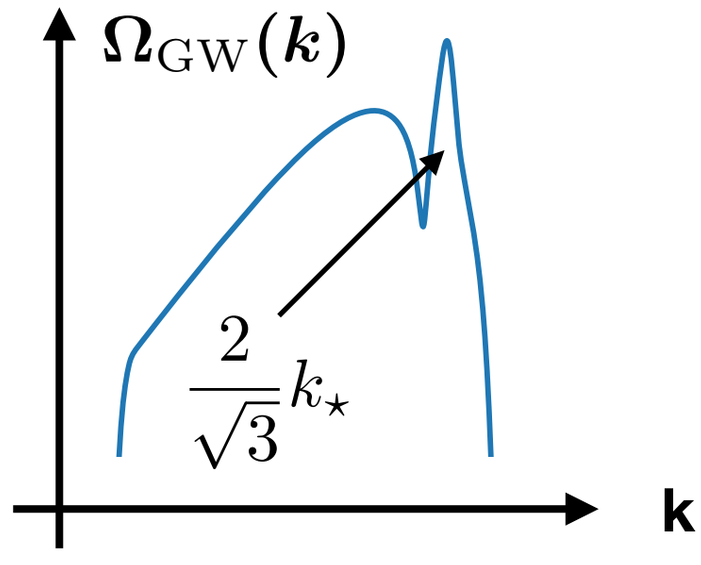
$$\log\left(\frac{f}{10^{-3}\text{Hz}}\right) \simeq \log\left(\frac{k}{10^{12}\text{Mpc}^{-1}}\right) \simeq N_{\text{after CMB}} - 30$$



GW observatories probe inflation on small scales



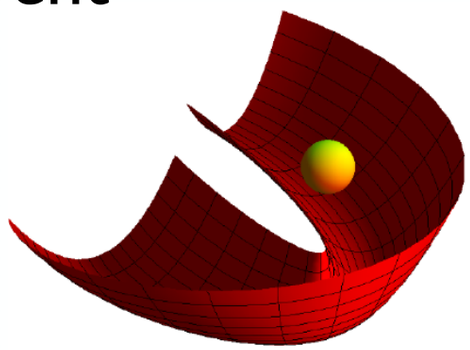
Primordial features

Sharp features

$$\frac{\mathcal{P}_\zeta(k)}{\mathcal{P}_{\rm env}(k)} = \left[1 + A_{\rm lin}\cos\left(\omega_{\rm lin}k + \varphi_{\rm lin}\right)\right]$$

Localized event

step in potential
turn in field space …



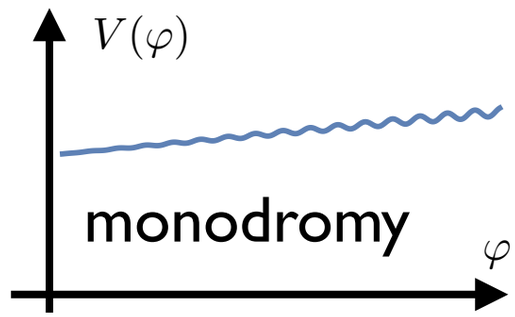
$$e^{-ik\tau_{\rm f}} = e^{ik/k_{\rm f}}$$

selection of
preferred time/scale

Resonant features

$$\left[1 + A_{\rm log}\cos\left(\omega_{\rm log}\log(k/k_\star) + \varphi_{\rm log}\right)\right]$$

Resonance btw
background
oscillations and
quantum modes
oscillations



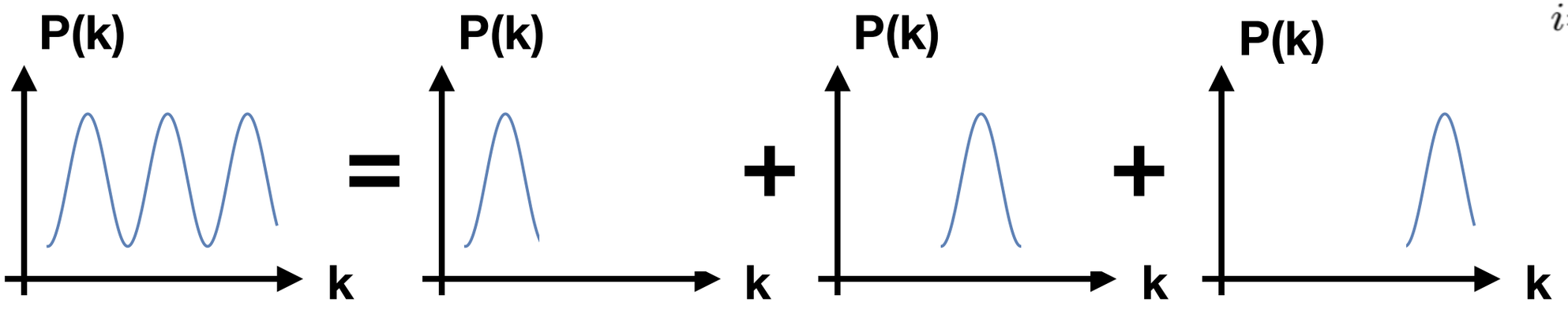
$$e^{iMt} = e^{i\frac{M}{H}N} \longrightarrow e^{i\omega_{\rm log}\log(k/k_\star)}$$

$$k \propto e^{N_k}$$

Intuition

1) Decompose as sum of individual peaks

$$\mathcal{P}_\zeta(k) = \sum_{i=1}^{n_\mathrm{p}} \mathcal{P}_{k_{\star i}}(k)$$



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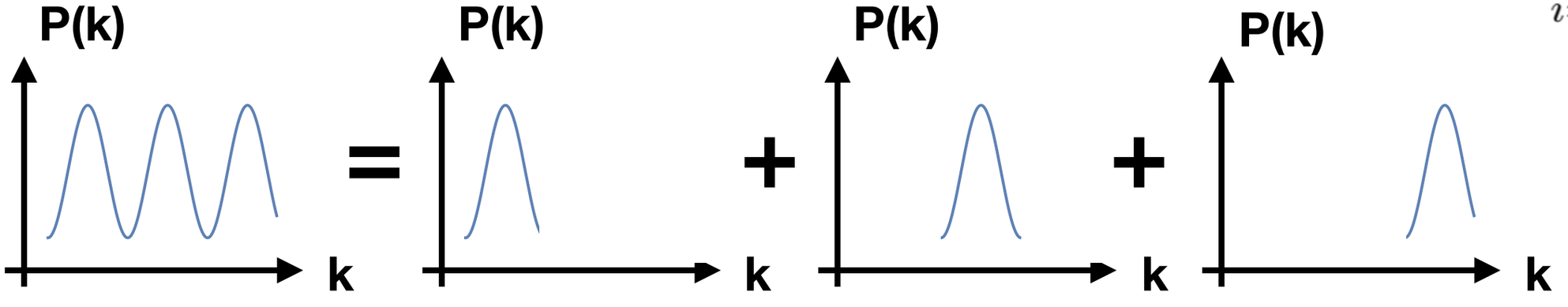

2) $$\Omega_\mathrm{GW} = \sum_{ij} \Omega_\mathrm{GW}(\mathrm{peak}\, i, \mathrm{peak}\, j)$$

Non-linear:

individual peaks

+ interactions between peaks

$$k_{\mathrm{max},ij} = \frac{1}{\sqrt{3}}(k_{\star i} + k_{\star j})\,, \quad \text{with} \quad k_{\mathrm{max},ij} > |k_{\star i} - k_{\star j}|$$

Cai et al, 1901.10152

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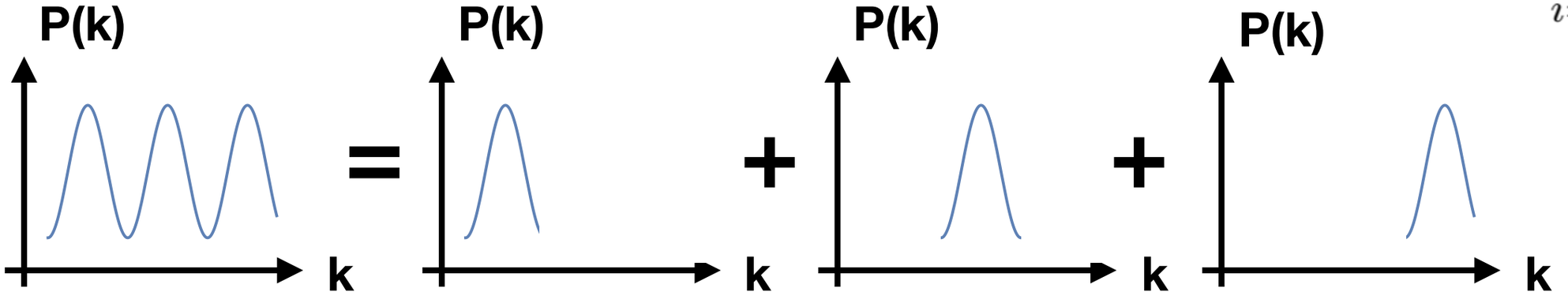

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3) Periodicity Δk $\longrightarrow$ Periodicity $\dfrac{\Delta k}{\sqrt{3}}$

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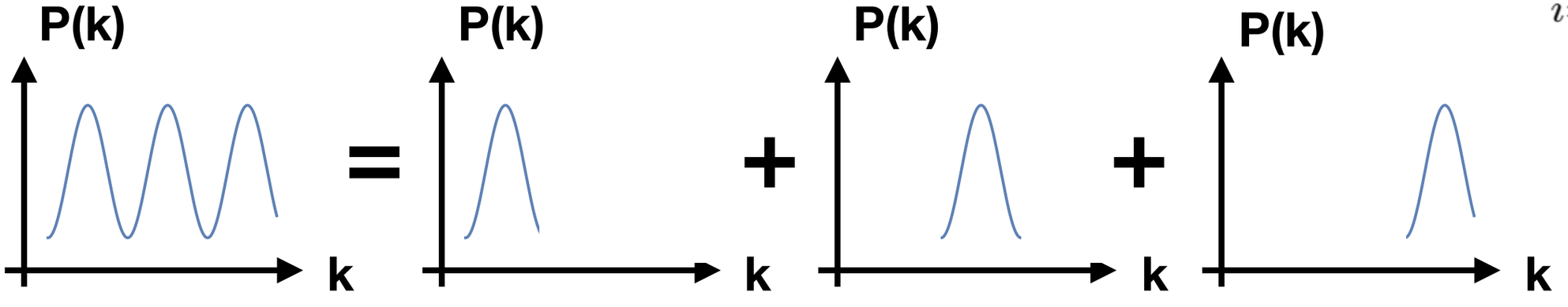

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Cai et al, 1901.10152

3 bis) Periodicity $\Delta \log k$ ⟶ Periodicity $\Delta \log k$

in preparation

+ caveat

SGWB signature of sharp features

$$\mathcal{P}_\zeta(k) = \mathcal{P}_{\rm env}(k) \times \left[1 + A_{\rm lin} \cos\left(\omega_{\rm lin} k + \varphi_{\rm lin}\right)\right]$$

$$\omega_{\rm lin}^{\rm GW} = \sqrt{3}\,\omega_{\rm lin}$$

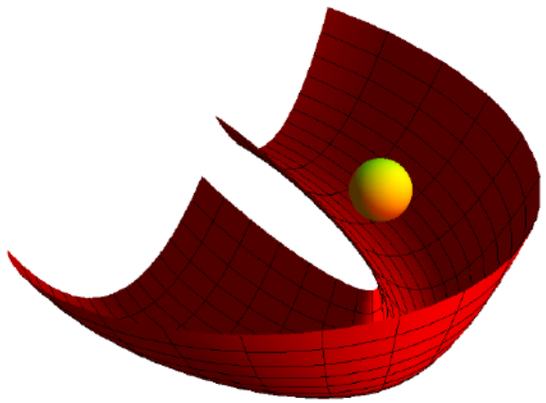
$$\Omega_{\rm GW}(k) \sim \overline{\Omega}_{\rm GW}(k)\left[1 + A\cos(\omega_{\rm lin}^{\rm GW} k + \phi)\right]$$

Overall shape determined by enveloppe of power spectrum

Periodic structure in k ⟶ Periodic structure in k

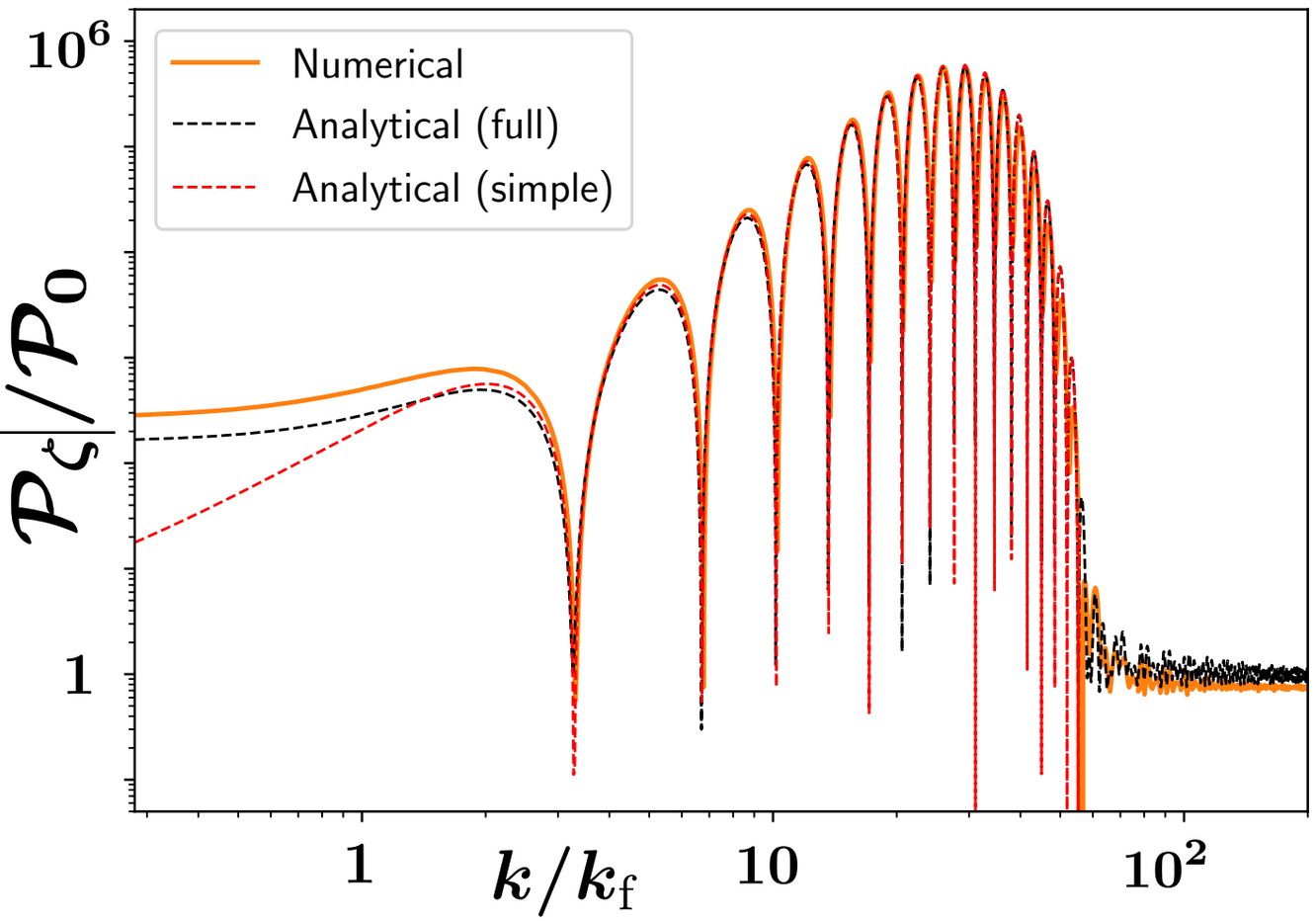
Averaging-out effect: e.g. from 100% modulation to 10%

An explicit example

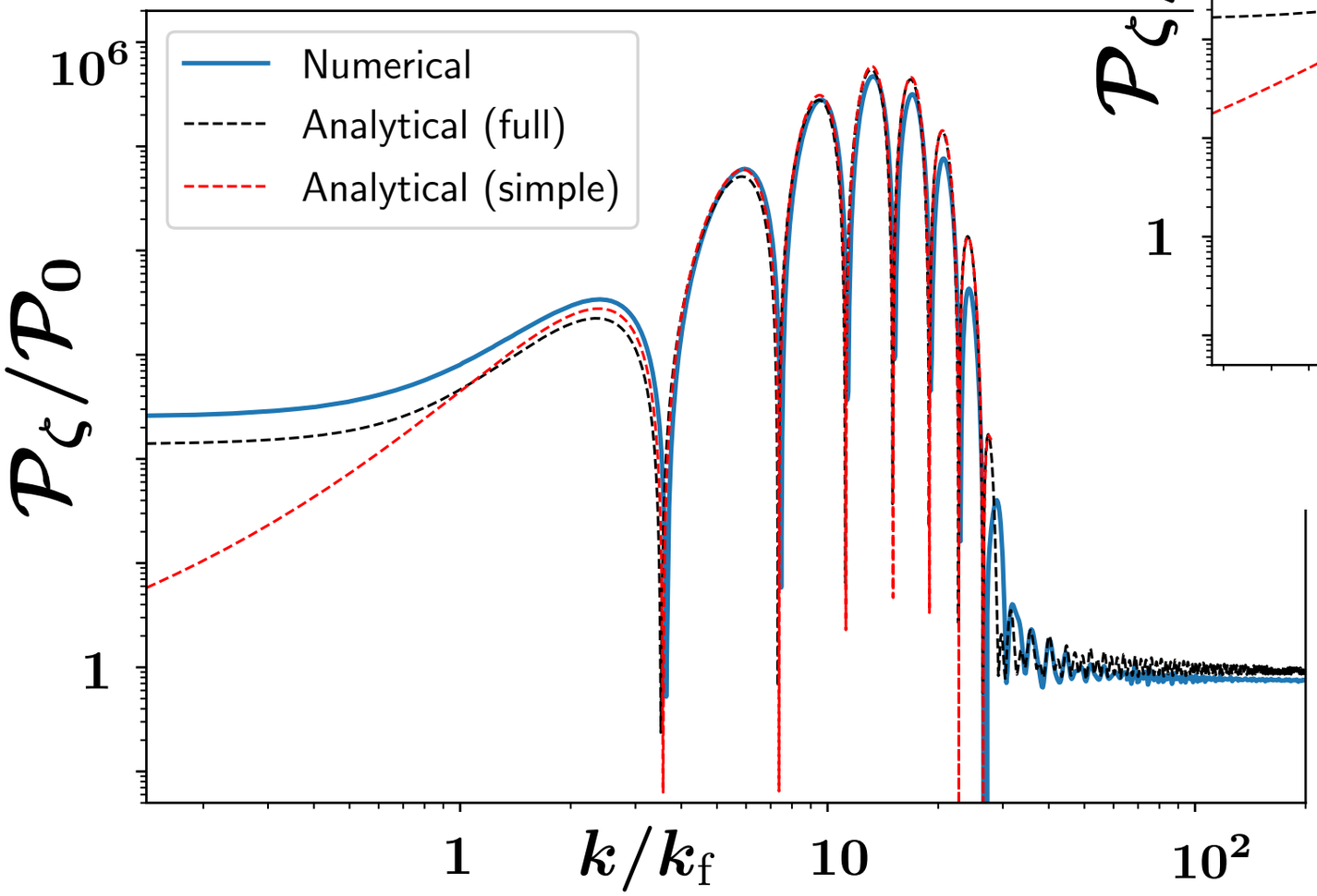


Fumagalli et al
2004.08369, 2012.02761
Palma et al 2004.06106

$\delta = 0.25, \eta_\perp = 28$



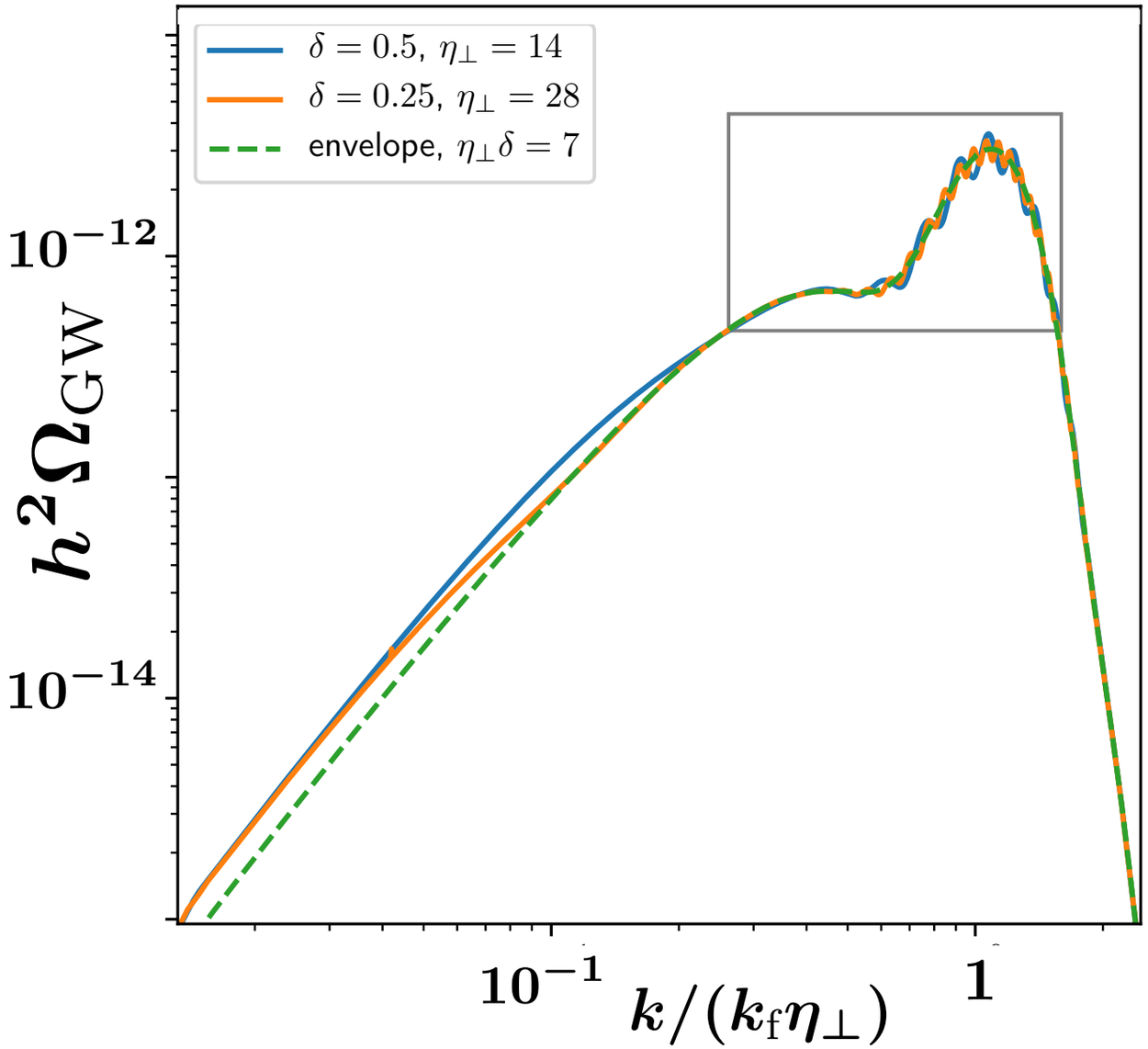
$\delta = 0.5, \eta_\perp = 14$

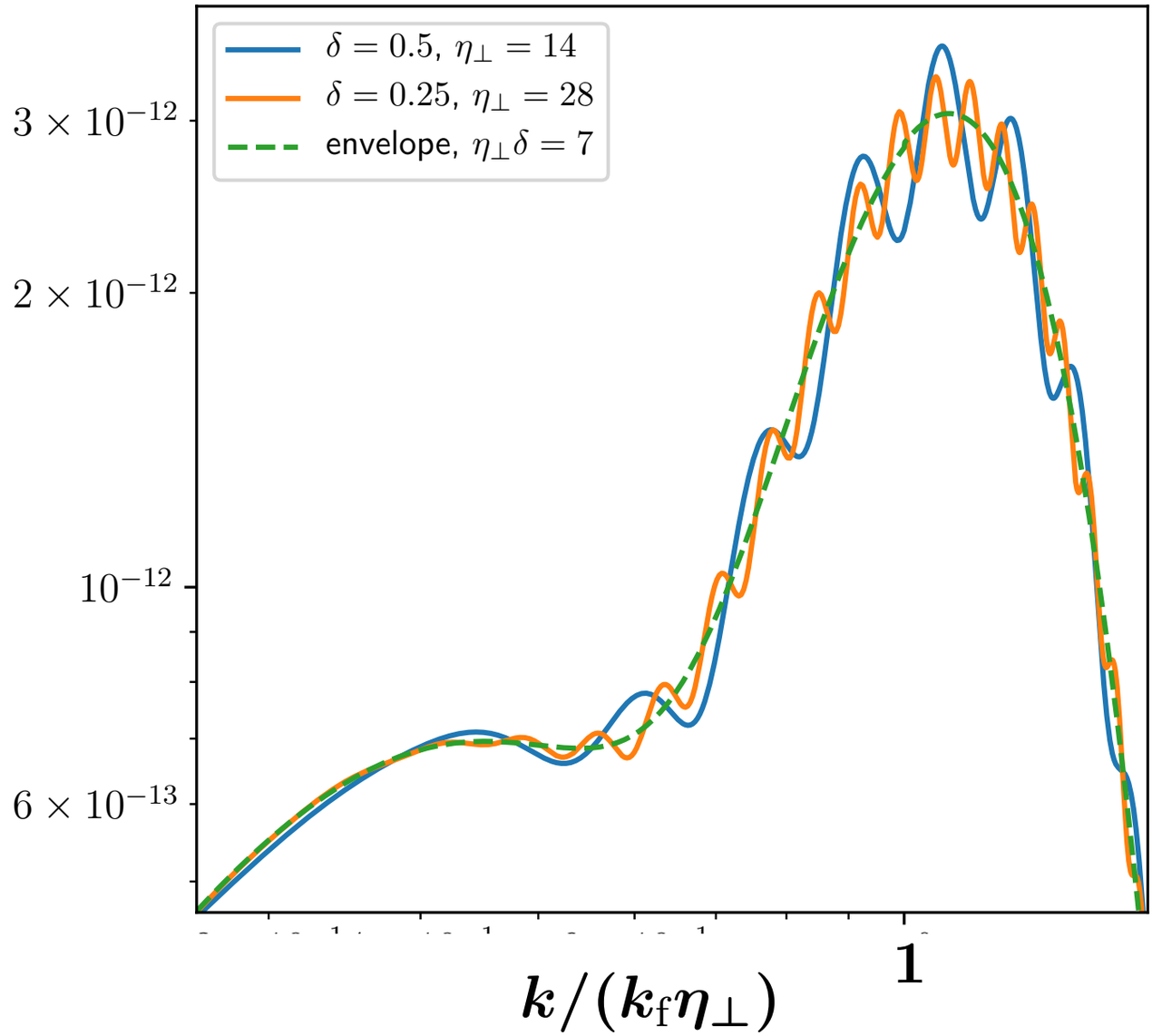


δ duration of turn in e-fold

$\eta_\perp = \dfrac{\Omega}{H}$ importance of turn

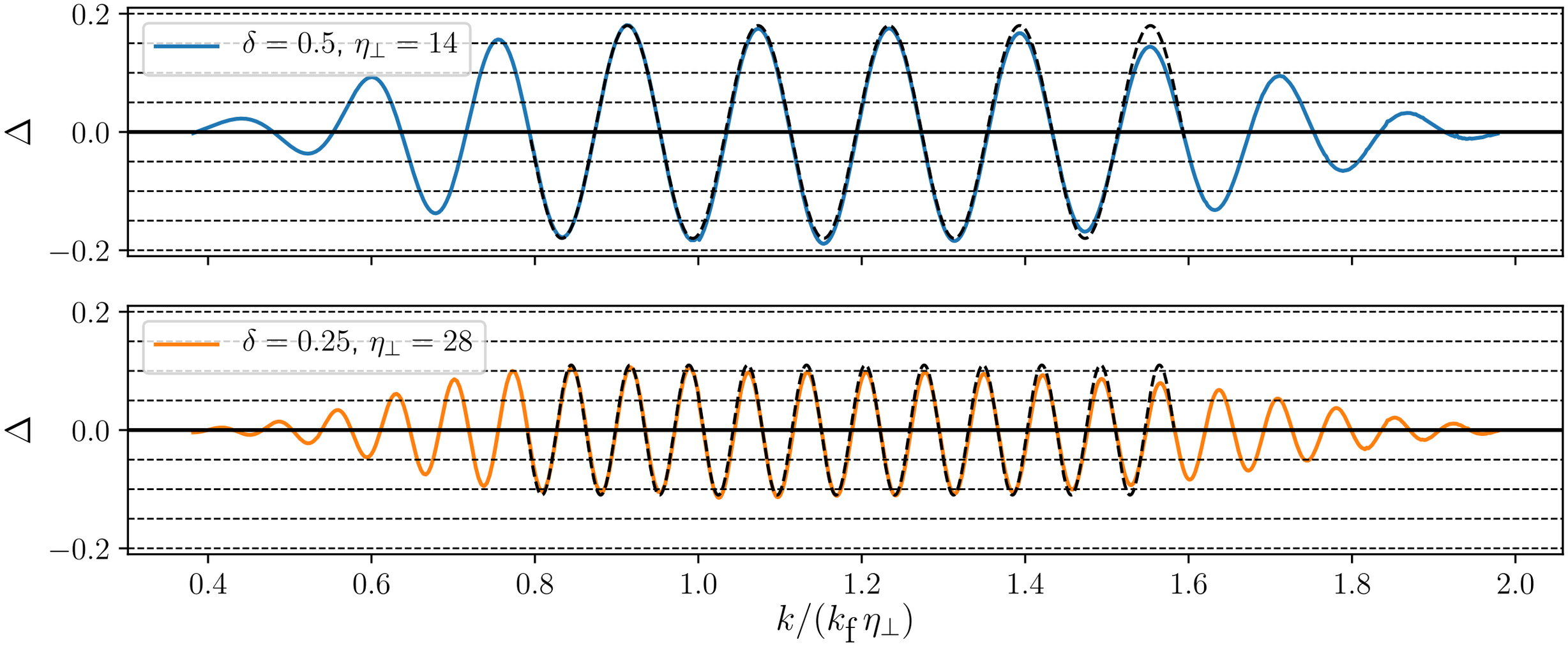
and its SGWB signature





Feature template

$$\Delta(k) \equiv \frac{\Omega_{\rm GW}(k) - \overline{\Omega}_{\rm GW}(k)}{\overline{\Omega}_{\rm GW}(k)} = A\cos(\omega_{\rm lin}^{\rm GW} k + \phi)$$

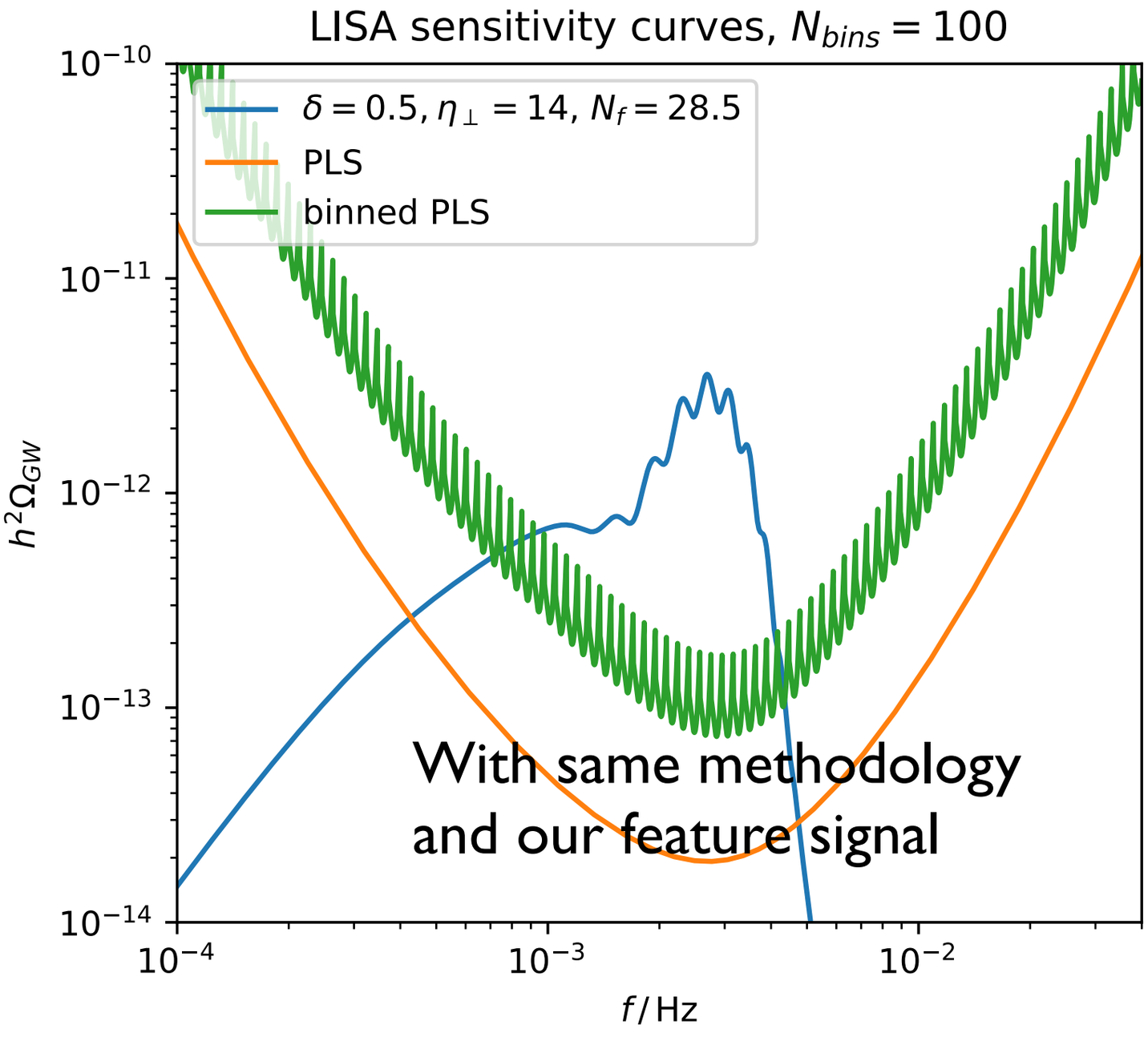


Detectability

Reconstruction of spectral shape with LISA

Caprini et al, LISA CosWG 1906.09244

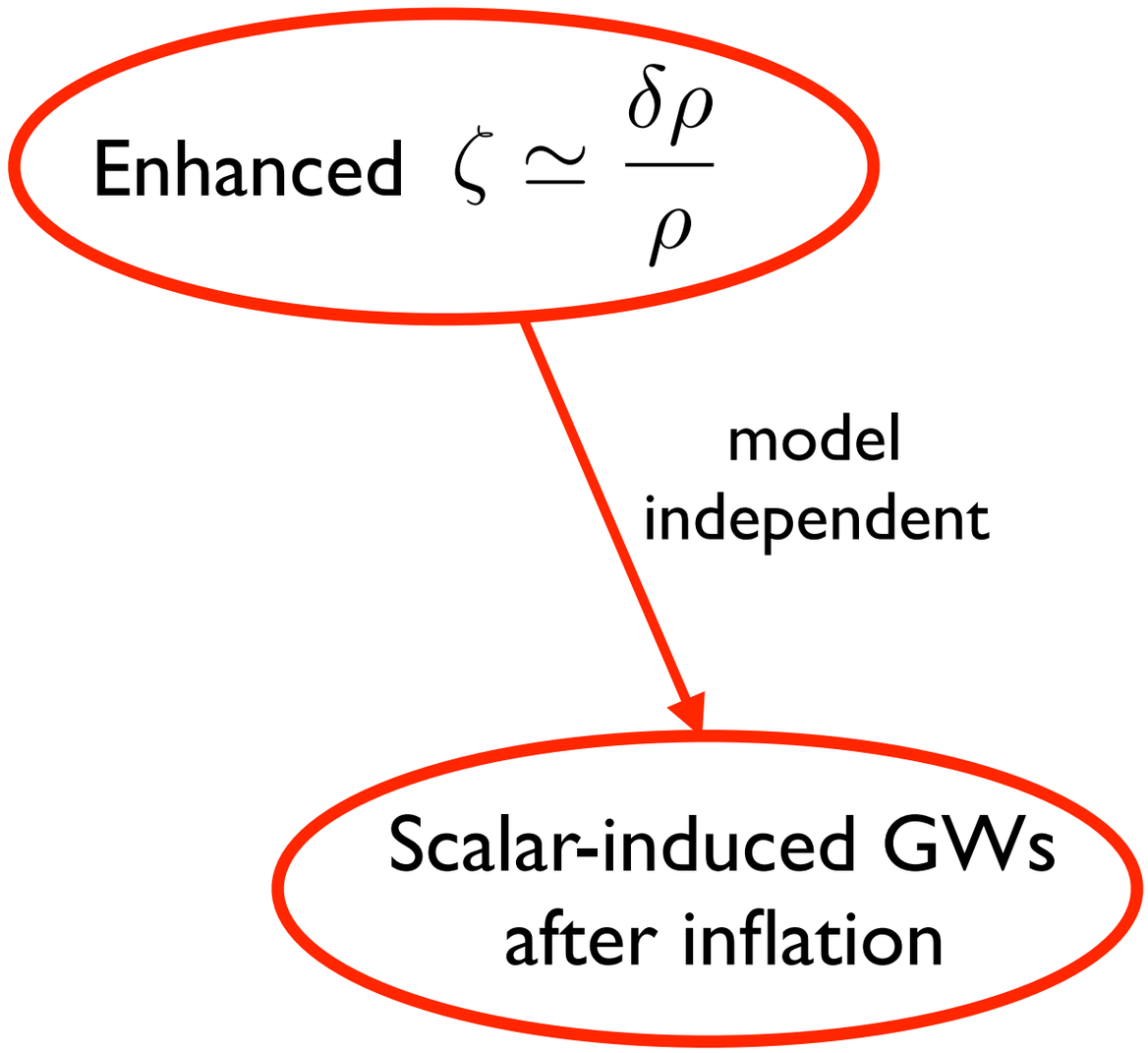
A wiggly signal can be reconstructed (without particular motivation there)



Oscillations resolvable by LISA T=3 years

see also Braglia et al 2012.05821

Theoretical consistency



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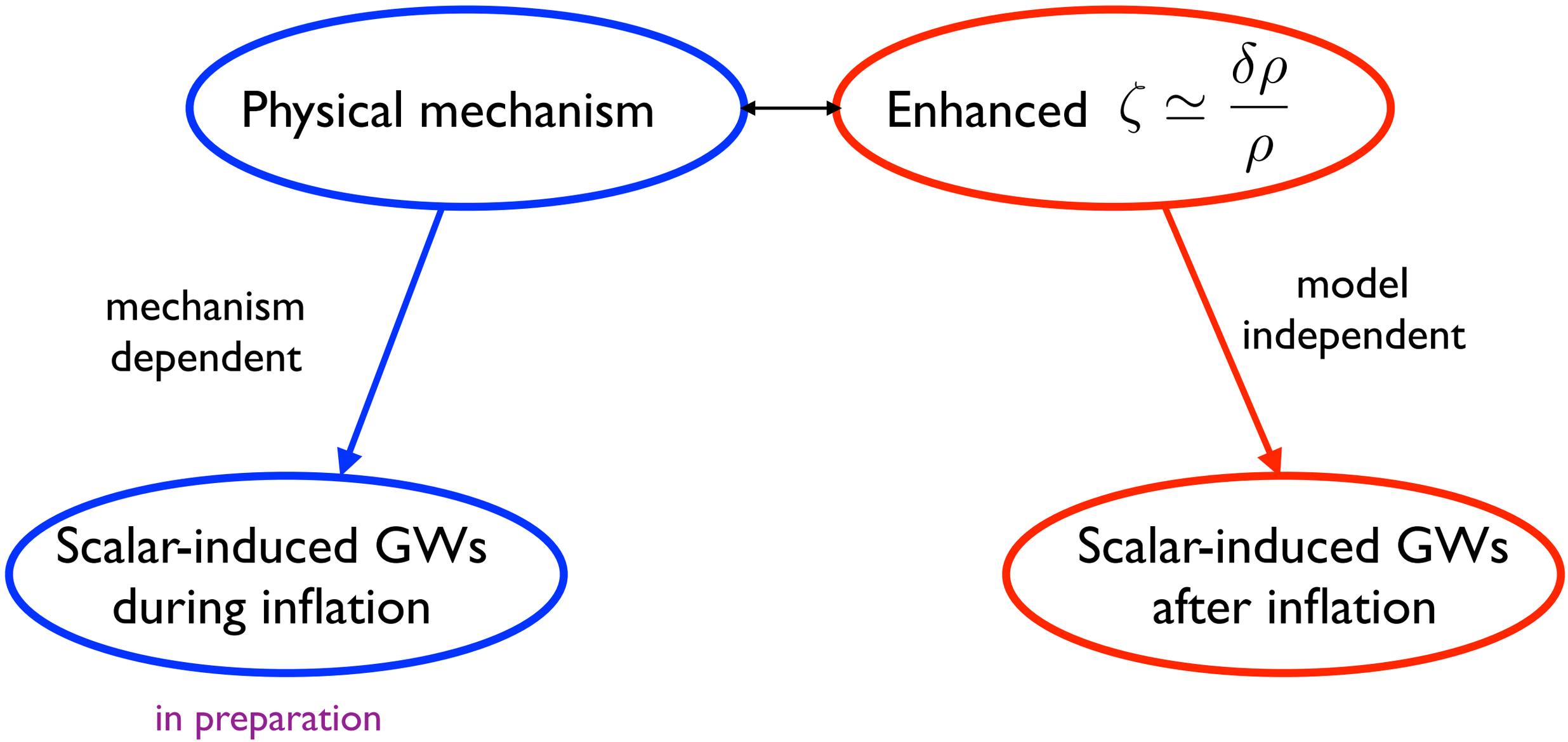

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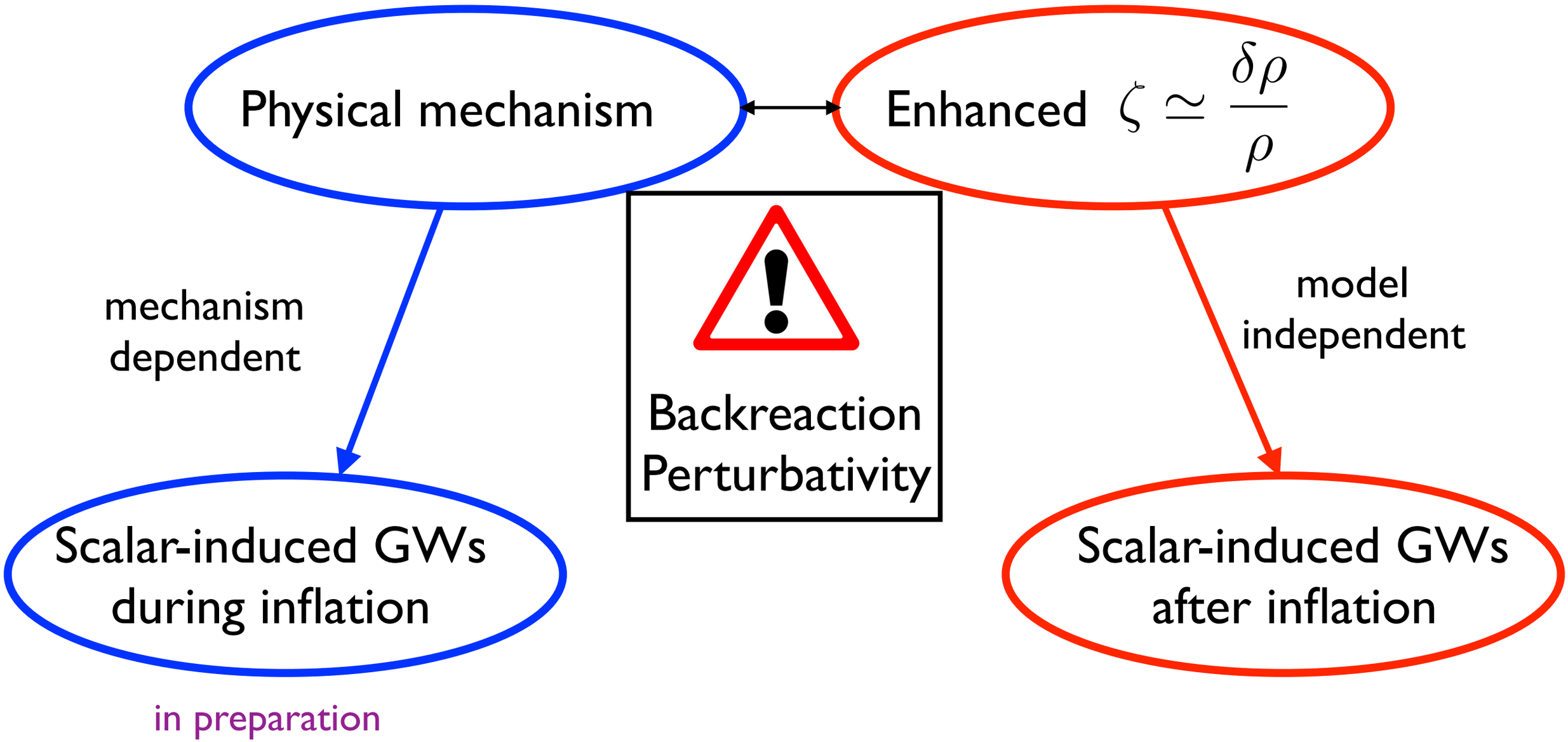

Take-home message

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