Primordial Non-Gaussianity via Gravitational Waves

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Based mainly on

Juan Garcia-Bellido, Marco Peloso, Caner Unal : JCAP 12 (2016) 031
Juan Garcia-Bellido, Marco Peloso, Caner Unal : JCAP 09 (2017) 013
Caner Unal: Phys.Rev.D 99 (2019) 4, 041301
Caner Unal, Ely D. Kovetz, Subodh P. Patil : Phys.Rev.D 103 (2021) 6, 063519

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How to probe smaller scales?

Inflation is expected to last roughly 60 e-folds depending on post-inflation physics.

- CMB and LSS probe the wavenumbers in the range $10^{-4} \lesssim k/\mathrm{Mpc}^{-1} \lesssim 0.1$.
- $\mu-$ and $y-$ distortions extend this range up to $\sim 10^5\,\mathrm{Mpc}^{-1}$.
- This corresponds only 18 efolds of inflation.

The rest $\sim$ 40 e-folds is unexplored apart from the bounds and potential signatures associated with primordial black holes (PBHs), and the GW signatures!

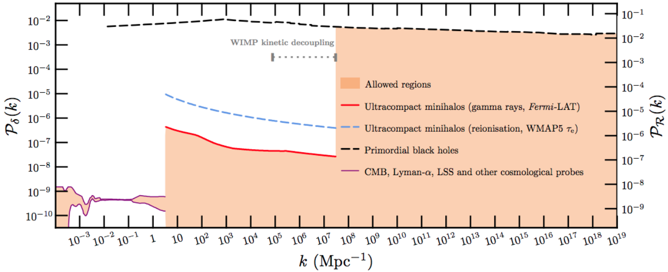


Figure: Density/curvature perturbations, taken from arXiv:1110.2484

Scalar Induced (Secondary) GWs

- Assume amplification in primordial density fluctuations at scales much smaller than CMB modes (not assume a specific mechanism)
  - Inevitable (induced) GWs from enhanced primordial density perturbations via (nonlinear coupling) $\zeta + \zeta \to h$

    Acquaviva+'02 ; Mollerach, Harari, Matarrese '03, Ananda, Clarkson, Wands '06 ; Baumann+'07

$$h''_{\lambda,\,\mathrm{k}}(\eta) + 2\mathcal{H}\, h'_{\lambda,\,\mathrm{k}}(\eta) + \mathrm{k}^2 h_{\lambda,\,\mathrm{k}}(\eta) = 2\mathcal{S}_{\lambda,\,\mathrm{k}}(\eta) \;, \tag{1}$$

$$\mathcal{S}_{\lambda,\,\mathrm{k}}(\eta) \quad \propto \quad \int d^3\mathrm{p}\;\, \partial\,\zeta_{\mathrm{p}} \;\, \partial\,\zeta_{\mathrm{k-p}} \tag{2}$$

$$\Omega_{GW} \propto P_{h_{ind}} \propto \left(\int d\tau\; G \cdot \mathcal{S} \right)^2 \propto \langle \zeta\,\zeta\,\zeta\,\zeta \rangle \tag{3}$$

  - Primordial Black Holes (may or may not be part of DM, but our conclusions are **independent** from that)

- Could we measure these observables so that we can learn more about primordial/high energy universe?
  Possible!

NonGaussianity

- When curvature fluctuations are amplified, they usually come together with non-trivial amount of NG
  - Slowing down the inflaton leads to quantum diffusion
    Pattison+ '17 ; Franciolini+ '17 ; Biagetti+ '18 ; Ezquiaga, Garcia-Bellido '18...
  - Particle production is inherently NG via $2 \to 1$ and $3 \to 1$ processes
    Barnaby, Peloso '10 ; Anber, Sorbo '12 ; Bugaev, Klimai '13 ; Garcia-Bellido, Peloso, Unal '16...

- Let's allow some NG

$$\zeta_{\rm k} = \zeta_{\rm k}^G + f_{NL} \int \frac{d^3 p}{(2\pi)^{3/2}} \zeta_{\rm p}^G \, \zeta_{\rm k-p}^G \, , \qquad \Rightarrow \qquad P_\zeta(k) = P_\zeta^G(k) + P_\zeta^{NG}(k) \quad (4)$$

$$P_\zeta^G(k) = \mathcal{A} \cdot \exp\left[- \frac{\ln^2 (k/k_*)}{2\sigma^2} \right]$$

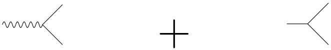
$$P_\zeta^{NG}(k) = 2 f_{\rm NL}^2 \int \frac{dp}{p} \frac{d\Omega}{4\pi} \frac{k^3}{|{\rm k} - {\rm p}|^3} P_\zeta^G(p) \, P_\zeta^G(|{\rm k} - {\rm p}|) \quad (5)$$

- Effects of NG :Scalar modes peak at a larger frequency, more contraction due to more legs, wider signal due to convolution

Induced GWs with Local NG Garcia-Bellido, Peloso, Unal '17 ; Unal '19

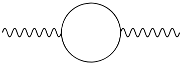
$$\Omega_{GW} \propto P_{h_{ind}} \propto \left(\int d\tau \, G \cdot \mathcal{S} \right)^2 \propto \int d^3p \int d^3q \, \langle \underbrace{\zeta_{\rm p} \quad \zeta_{\rm k-p} \quad \zeta_{\rm q} \quad \zeta_{\rm k'-q}}_{\left(\zeta_G + f_{NL}\zeta_G^2\right)^4} \rangle$$

$$= \Omega_{GW}^{G} + \Omega_{GW}^{NG} \qquad (6)$$

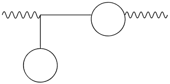


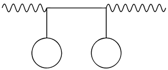
Contractions

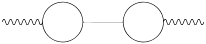
- $\mathcal{O}(f_{NL}^0)$



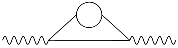
- Contractions vanishing due to zero momentum propagator or symmetry



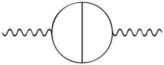




- $\mathcal{O}(f_{NL}^2)$



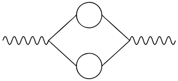
hybrid



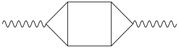
walnut

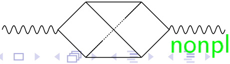
- $\mathcal{O}(f_{NL}^4)$

reducible



planar





nonplanar

Large Primordial NG in Density and Induced GWs

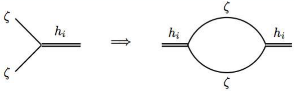
Garcia-Bellido, Peloso, Unal '17

Gaussian Model

Has been studied and well understood

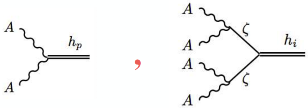
Ananda et al '06, Baumann et al '07

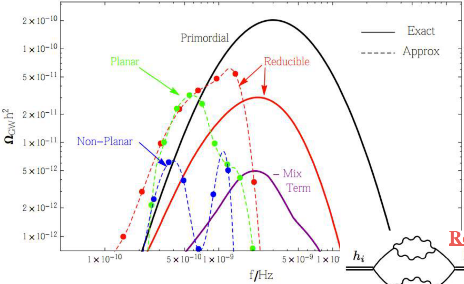
Induced



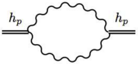
Non-Gaussian Rolling Axion (χ^2) Model

Garcia-Bellido, Peloso, Unal '17

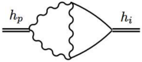




Primordial



Mixed

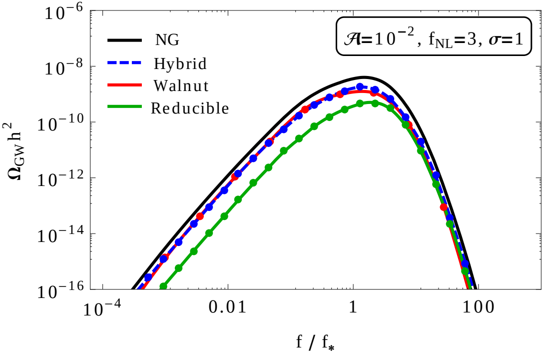


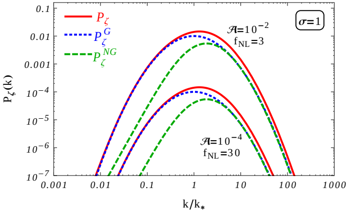
Induced

Reducible

Planar

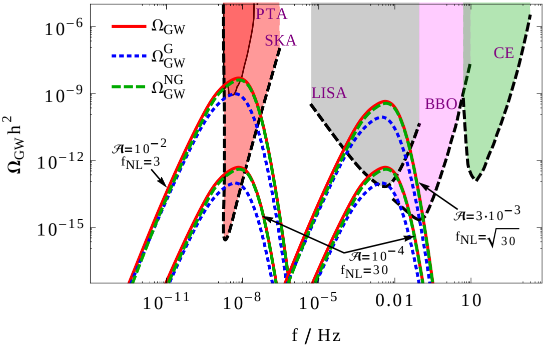
Non-Planar

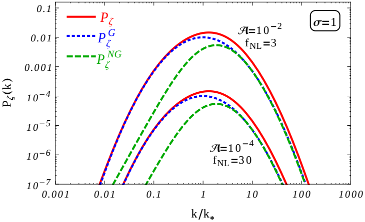




[1]Large f_{NL} limit studied by Nakama, Kamionkowski, Silk '16 ; Garcia-Bellido, Peloso, Unal '17
[2]Also recent works with similar results : Atal, Domenech '21 ; Adshead, Lozanov, Weiner '21

Ω_{GW}^{NG} peaks at larger freq + wider + larger amplitude





$\rho_{PBH} \simeq \rho_{DM}$: 2 intervals!

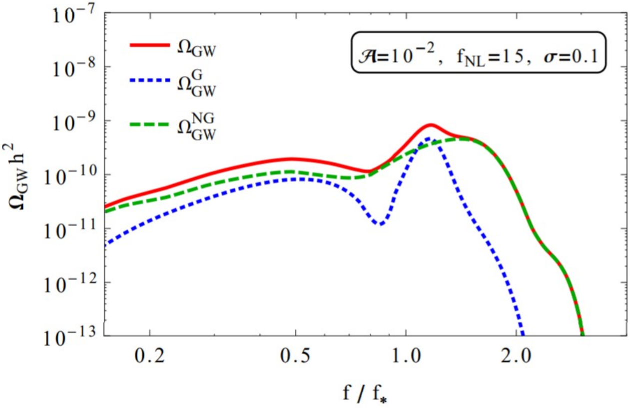
(i) $1 : 100 M_\odot$ Bird+ '16 ; Clesse, Garcia-Bellido '16 ; Sasaki+ '16

$\leftrightarrow f_{PTA}$ Bugaev, Klimai '11 ; Inomata+ '16 ; Garcia-Bellido, Peloso, Unal '16 '17

(ii) $10^{-14} : 10^{-11} M_\odot \leftrightarrow f_{LISA}$ Garcia-Bellido, Peloso, Unal '17 ; Bartolo+ '19 ; Cai, Pi, Sasaki '19

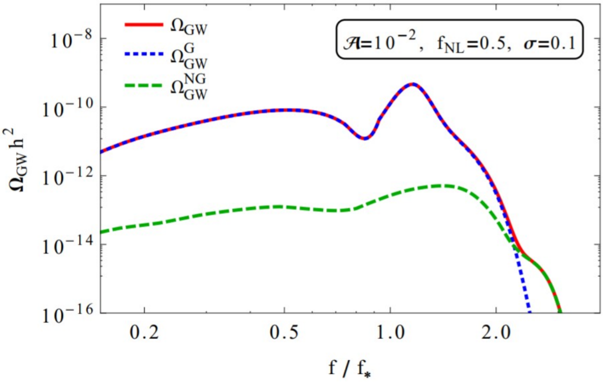
Signatures for Narrow Spectra - I ($\sigma << 1$) Unal '19

Signature 1: A double peak signature



Signatures for Narrow Spectra - II ($\sigma << 1$) Unal '19

Signature 2: A bump in UV tail even if GWs from NG fluctuations are completely subdominant.



With PTA-SKA and LISA, probing $f_{NL} \sim \mathcal{O}(0.1 - 10)$ is possible
(could be better probe than next generation CMB+LSS !)

On Primordial Perturbations, PBHs, SMBH seeds

Unal, Kovetz, Patil '21

7 decades in wavenumber ($k : 1 - 10^7\,\mathrm{Mpc}^{-1}$) $\sim$ 14 decades in PBH ($0.1 - 10^{13}\,M_\odot$)
(i) detect perturbations (GWs or density) and PBH signatures OR
(ii) Robustly constrain perturbations + PBHs $> 0.1 M_\odot$, rule them out as super-massive black hole seeds.
Conclusions are robust to changes in (i) the statistics of primordial density fluctuations, (ii) PBH merger and accretion history and (iii) clustering statistics.