Imprints of Primordial non-Gaussianity on GWs

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**Collaboration with: De Luca, Franciolini, Garcia-Bellido, Kehagias, Peloso, Riotto

Brief Summary for Inflation at CMB

- The dimensionless power spectrums for scalar and tensor sectors

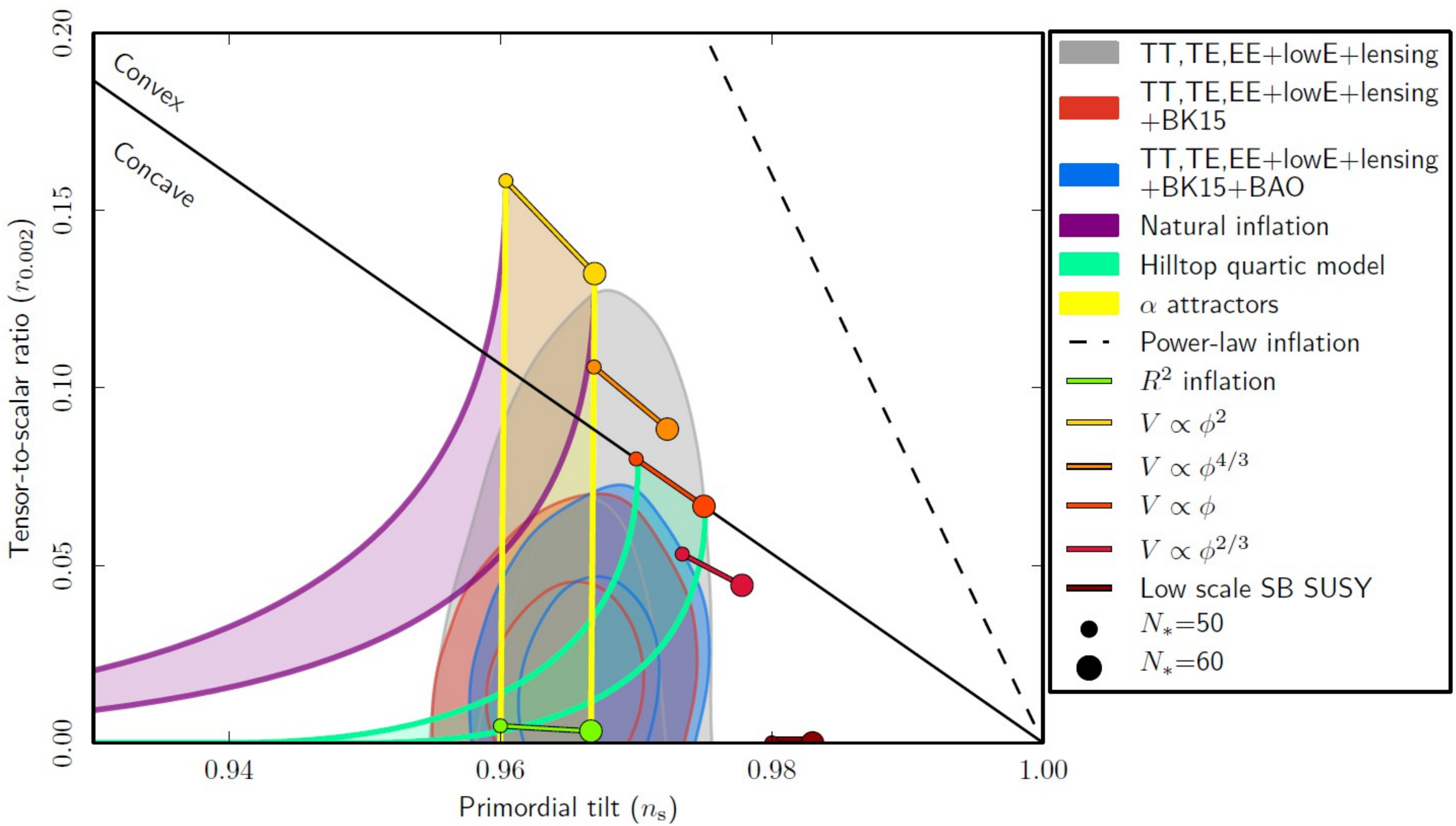
$$\langle \zeta_{\vec{k}}\, \zeta_{\vec{k}'} \rangle \equiv \frac{2\pi^2}{k^3} P_\zeta(\vec{k})\, \delta^{(3)}(\vec{k}+\vec{k}') \,,$$
$$\left\langle h_\lambda(\vec{k})\, h_{\lambda'}(\vec{k}') \right\rangle = \frac{2\pi^2}{k^3} P_\lambda(k) \delta_{\lambda\,\lambda'}\, \delta^{(3)}(\vec{k}+\vec{k}') \qquad (1)$$

- The power spectrum is conventionally parametrized as

$$P_\zeta(k) = \mathcal{A}_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln(k/k_*)} \,, \qquad P_{\rm gw} = \frac{2H^2}{\pi^2 M_p^2} \left(\frac{k}{k_*}\right)^{n_T} \qquad (2)$$

- The parameters in Planck '18 (for the pivot scale $k_* = 0.05\mathrm{Mpc}^{-1}$)
  - $\mathcal{A}_s = (2.1 \pm 0.03) \cdot 10^{-9}$ (*Planck TT, TE, EE + lowE + lensing*) , 68% CL
  - $n_s = 0.9649 \pm 0.0042$ (*Planck TT, TE, EE + lowE + lensing*), 68% CL
  - $\alpha_s = -0.0045 \pm 0.0067$ (*Planck TT, TE, EE + lowE + lensing*) , 68% CL

Inflationary models



Planck '18

How to probe smaller scales?

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

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

Domcke, Dvorkin for stochastic GWs

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!

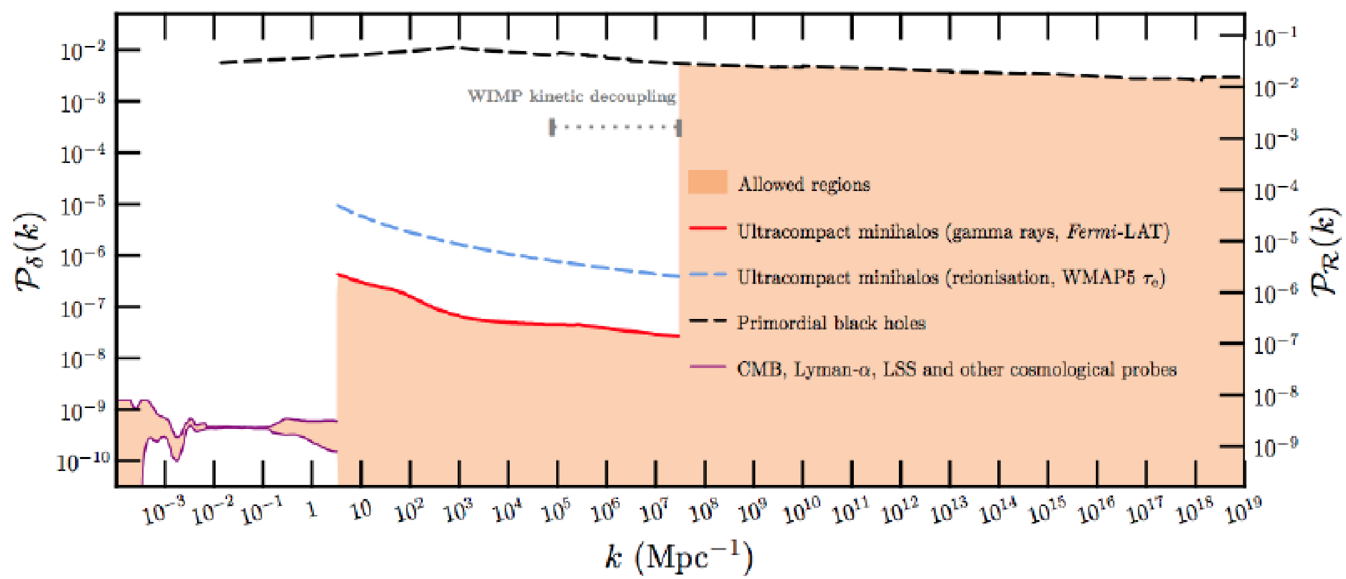


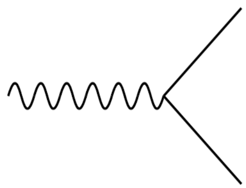
Figure: Density/curvature perturbations, taken from arxiv 1110.2484

Byrnes' talk for PBH review, De Luca's talk for PBH spin

See also Primordial GWs at small scales Maleknejad, Dimastrogiovanni, Fassiello, ...

Basic Assumptions and Observational Signatures

- Let's assume an increase in scalar fluctuations at scales much smaller than CMB bump (not assume a specific mechanism to produce this feature) Inevitable consequences!
  - (induced) GWs via nonlinear coupling $\zeta + \zeta \to h$ Mollerach etal '03
    Ananda etal '06 and Baumann etal '07



$$h''_{\lambda,\mathbf{k}}(\eta) + 2\mathcal{H}\, h'_{\lambda,\mathbf{k}}(\eta) + \mathbf{k}^2 h_{\lambda,\mathbf{k}}(\eta) = 2\mathcal{S}_{\lambda,\mathbf{k}}(\eta) \,, \tag{3}$$

$$\mathcal{S}_{\lambda,\mathbf{k}}(\eta) \propto \int d^3\mathbf{p}\, \zeta_{\mathbf{p}}\, \zeta_{\mathbf{k}-\mathbf{p}} \tag{4}$$

$$\Omega_{GW} \propto P_{h_{ind}} \propto \left(\int d\tau\, G \cdot \mathcal{S}\right)^2 \propto \langle \zeta\, \zeta\, \zeta\, \zeta \rangle \tag{5}$$

Racco and Franciolini's talks for GWs from PBH
Inomata and Terada's talks for induced GWs

  - 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 etal '17, Biagetti etal '18, Ezquiaga etal '18
  - Particle production is inherently NG via $2 \to 1$ and $3 \to 1$ processes Anber etal '09, Bugaev etal '13, Garcia-Bellido etal '16 (+Unal)

- Let's allow some NG

$$\zeta_{\mathbf{k}} = \zeta^G_{\mathbf{k}} + f_{NL} \int \frac{d^3 p}{(2\pi)^{3/2}} \zeta^G_{\mathbf{p}}\, \zeta^G_{\mathbf{k}-\mathbf{p}} \,, \qquad \Rightarrow \qquad P_\zeta(k) = P^G_\zeta(k) + P^{NG}_\zeta(k) \quad (6)$$

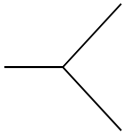
$$P^G_\zeta(k) \;=\; \mathcal{A} \cdot \exp\left[-\frac{\ln^2(k/k_*)}{2\sigma^2}\right]$$

$$P^{NG}_\zeta(k) \;=\; 2 f^2_{\rm NL} \int \frac{dp}{p} \frac{d\Omega}{4\pi} \frac{k^3}{|\mathbf{k}-\mathbf{p}|^3} P^G_\zeta(p)\, P^G_\zeta(|\mathbf{k}-\mathbf{p}|) \qquad (7)$$

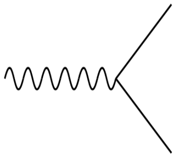
- Effects of NG :Scalar modes peak at a larger frequency, more contraction due to more legs, wider signal due to convolution

Effects of NG and Contractions of Four Point Function

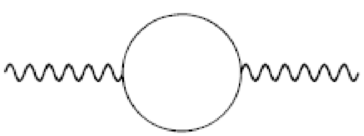
$$\begin{aligned}\Omega_{GW} \propto P_{h_{ind}} \quad &\propto \quad \left(\int d\tau\, G \cdot \mathcal{S}\right)^2 \propto \int d^3p \int d^3q \,\langle\, \underbrace{\zeta_{\mathbf{p}} \quad \zeta_{\mathbf{k}-\mathbf{p}} \quad \zeta_{\mathbf{q}} \quad \zeta_{\mathbf{k}'-\mathbf{q}}}_{(\zeta_G + f_{NL}\zeta_G^2)^4} \,\rangle \\ &= \quad \Omega_{GW}^{G} + \Omega_{GW}^{NG} \qquad (8)\end{aligned}$$



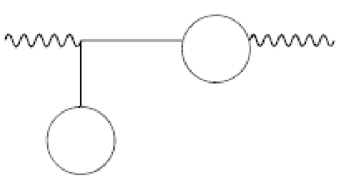
Contractions

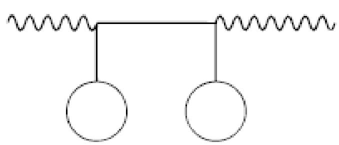


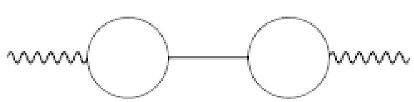
- $\mathcal{O}(f_{NL}^0)$



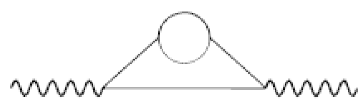
- Contractions vanishing due to zero momentum propagator or symmetry



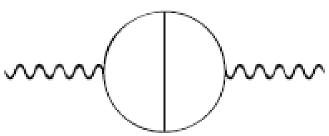




- $\mathcal{O}(f_{NL}^2)$

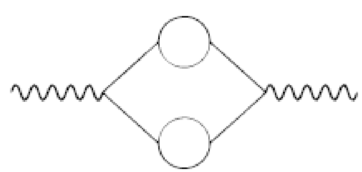


hybrid

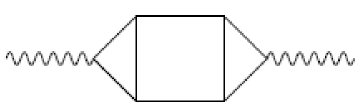


walnut

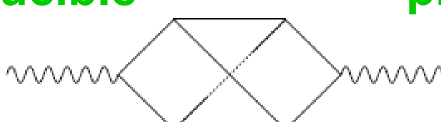
- $\mathcal{O}(f_{NL}^4)$



reducible



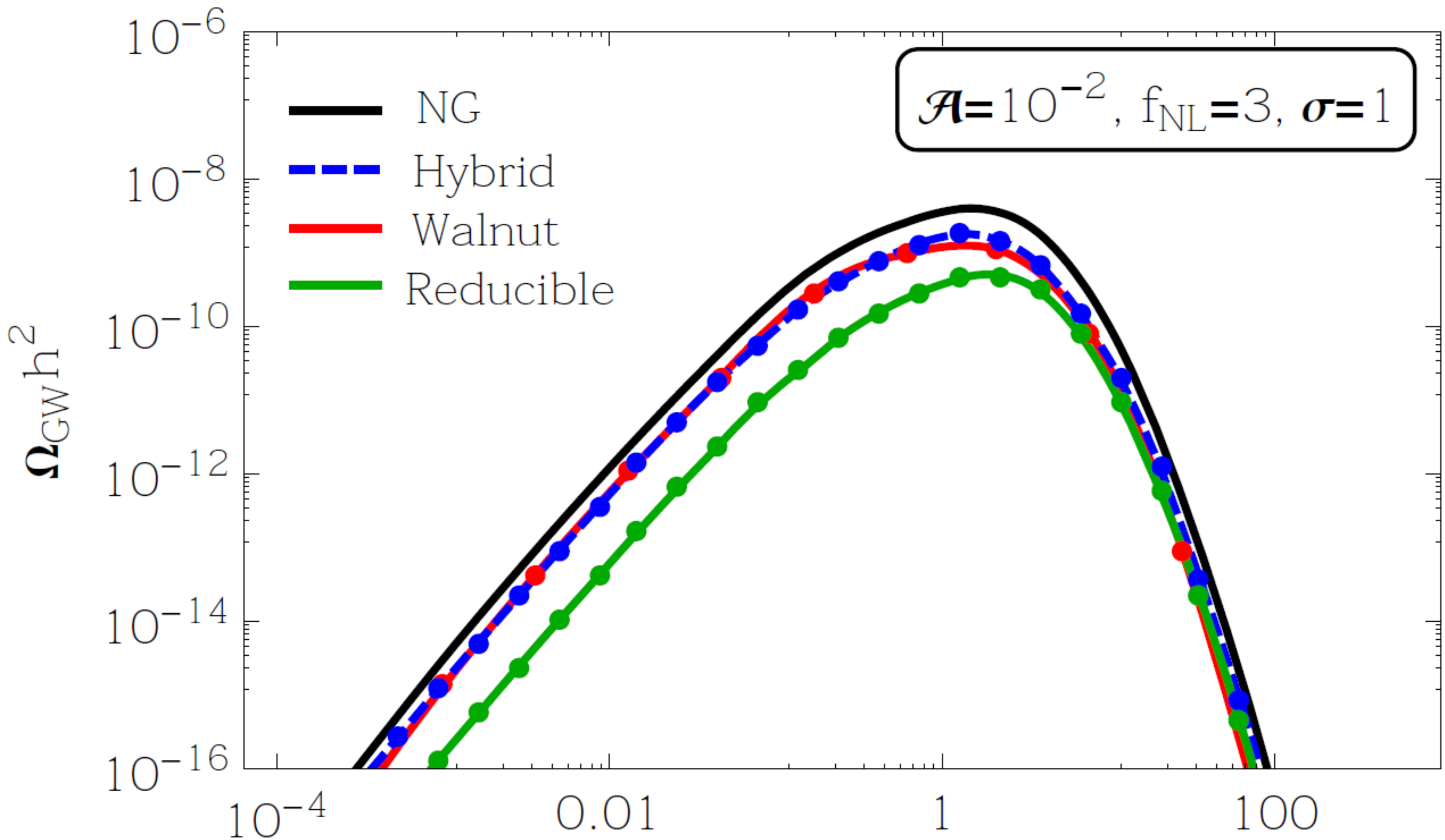
planar



Non-planar

Results ($\sigma \sim \Delta N_{peak} = 1$)

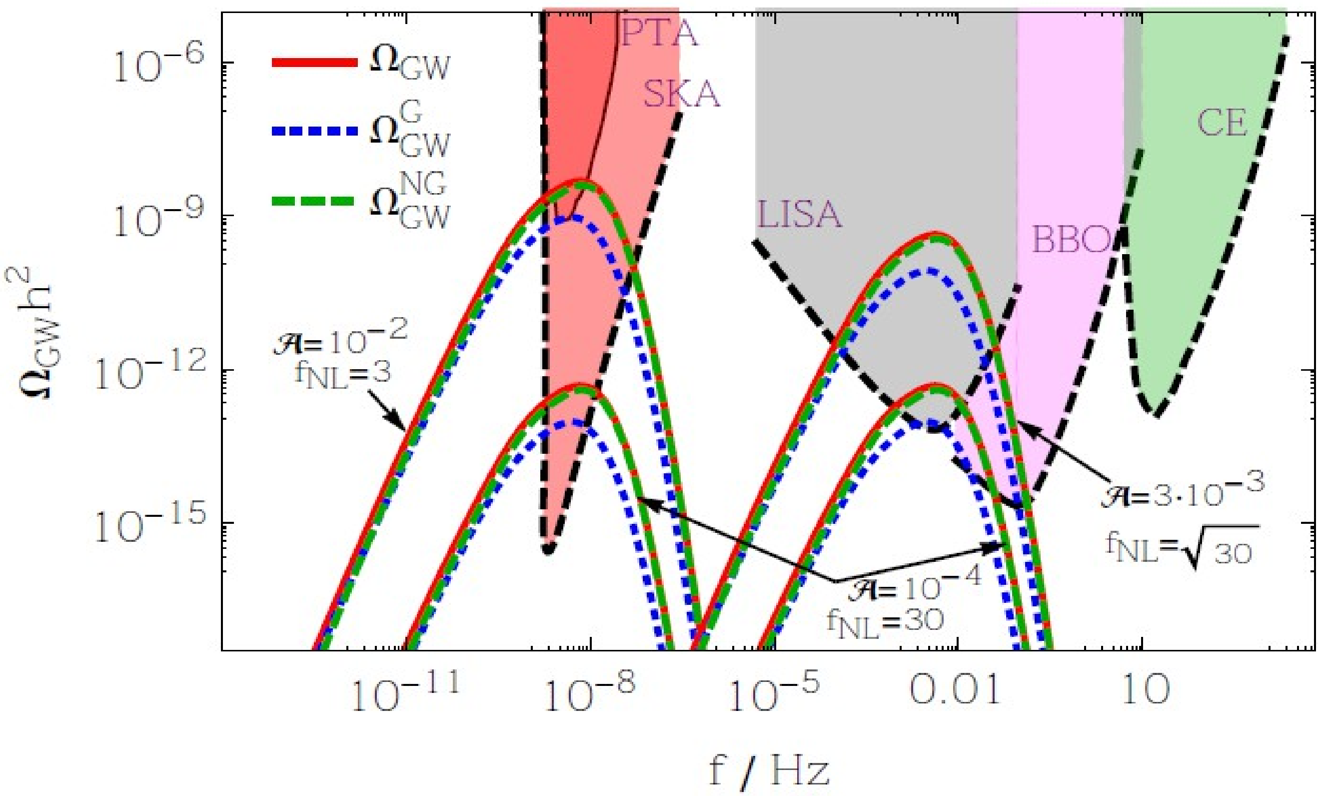
Unal '18 [1]



[1] Large f_{NL} limit has been studied by Nakama etal '16, Garcia-Bellido etal '17, Cai etal '18 (+Unal)

Results ($\sigma \sim \Delta N_{peak} = 1$)

Ω_{GW}^{NG} peaks at larger freq + wider + larger amplitude Unal '18

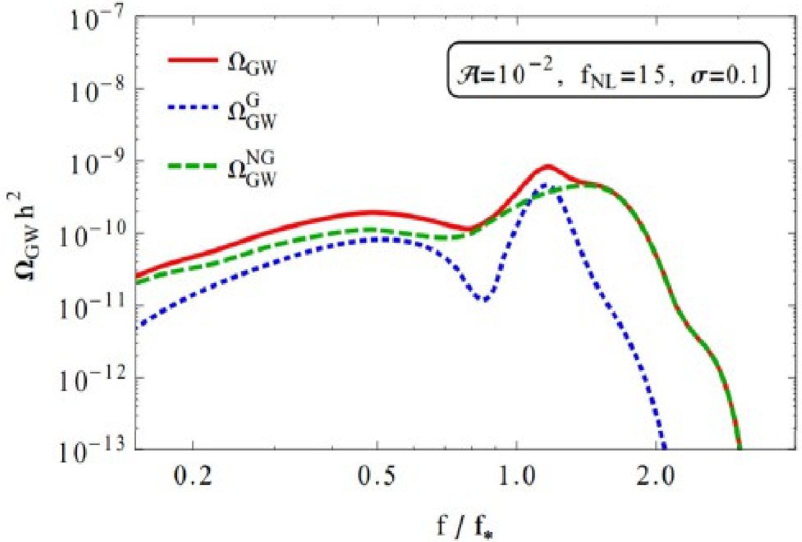


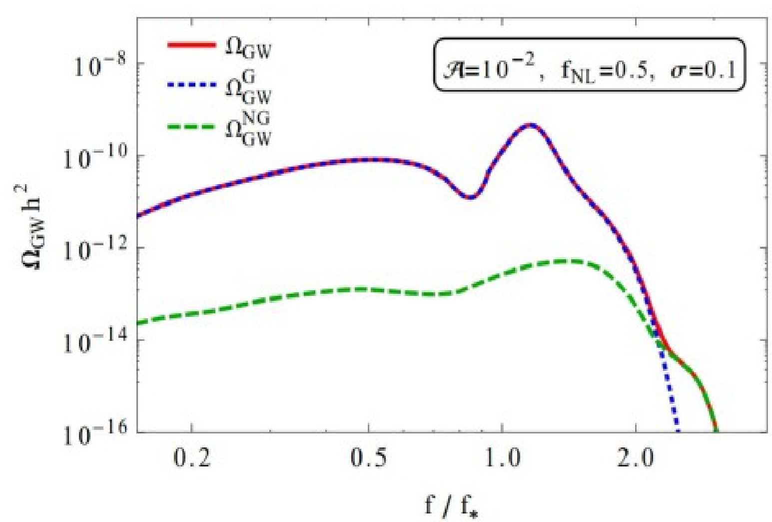
Larger signals produce $\rho_{PBH} \simeq \rho_{DM}$ ($f_{PTA} \to 10M_\odot$ and $f_{LISA} \to 10^{-12}M_\odot$)

Observational Signatures for Narrow Spectra

S1: A not-well-resolved double peaks.
S2: A bump in UV tail even if NG component of GW spectrum is completely subdominant

Unal '18





Summary

- Enhanced small scale perturbations (usually contain NG component) lead PBH and induced GWs
- GW spectrum (2-pt function) can probe the statistical properties of the small scales of inflation and indirectly effective operators
- With PTA and LISA sensitivity, $f_{NL} \sim 0.5$ possible
- Interesting coincidence: two future most powerful interferometers will probe the mass range for PBH allowing them to be DM(still under debate)