

# Induced GWs with PBHs & Imprints of Primordial NG on GWs

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\*Based mainly on

C. Unal Phys. Rev. D99, 041301 (2019) [ arXiv:1811.09151 ]

J. Garcia-Bellido, M. Peloso, C. Unal JCAP 1709 (2017) 013 [ arXiv:1707.02441 ]

J. Garcia-Bellido, M. Peloso, C. Unal JCAP 1612 (2016) 031 [ arXiv:1610.03763 ]

\*\*Learn a lot from collaboration with De Luca, Franciolini, Garcia-Bellido, Kehagias, Peloso, Riotto



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# Brief Summary for Inflation at CMB

- The dimensionless power spectrums for scalar and tensor sectors

$$\begin{aligned}\langle \zeta_{\vec{k}} \zeta_{\vec{k}'} \rangle &\equiv \frac{2\pi^2}{k^3} P_\zeta(\vec{k}) \delta^{(3)}(\vec{k} + \vec{k}') , \\ \langle h_\lambda(\vec{k}) h_{\lambda'}(\vec{k}') \rangle &= \frac{2\pi^2}{k^3} P_\lambda(k) \delta_{\lambda\lambda'} \delta^{(3)}(\vec{k} + \vec{k}')\end{aligned}\quad (1)$$

- The power spectrum is conventionally parametrized as

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

- The parameters in Planck '18 (for the pivot scale  $k_* = 0.05 \text{Mpc}^{-1}$ )
  - $\mathcal{A}_s = (2.1 \pm 0.03) \cdot 10^{-9}$  (*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

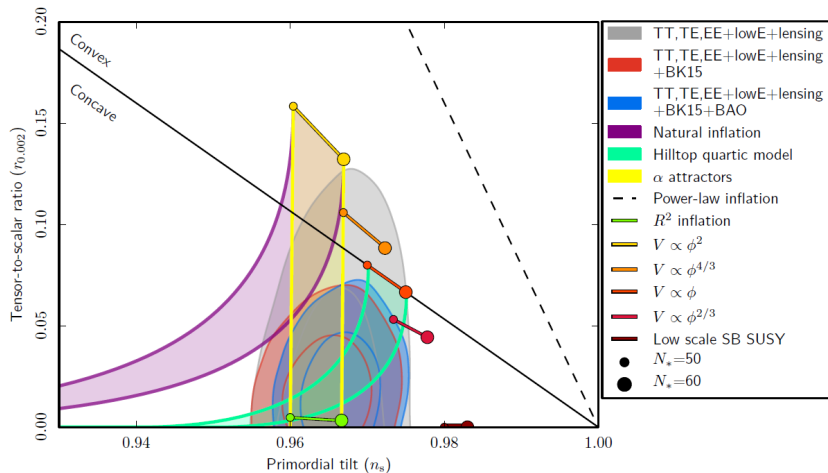


Figure: Predictions of selected inflationary models (taken from Planck '18)

# 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  $10^{-4} \lesssim k/\text{Mpc}^{-1} \lesssim 0.1$ .
- $\mu$ - and  $y$ - distortions extend this range up to  $\sim 10^4 \text{Mpc}^{-1}$ .
- 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!

See also talks of Clesse, Croon, Hooper, Racco, Ramani on PBH

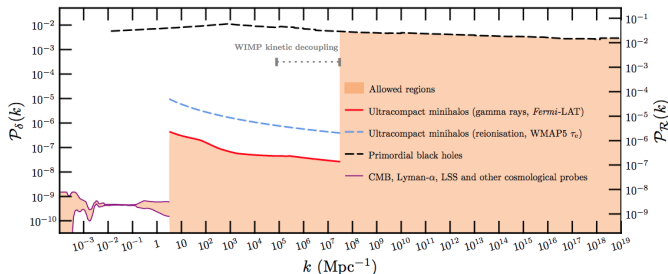


Figure: Density/curvature perturbations, taken from arXiv:1110.2484

# 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! ( See also talk of Racco )
  - (induced) GWs via nonlinear coupling  $\zeta + \zeta \rightarrow h$   
Acquaviva+'02 ; Mollerach, Harari, Matarrese '03, Ananda, Clarkson, Wands '06 ; Baumann+'07

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

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

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

- 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  $2 \rightarrow 1$  and  $3 \rightarrow 1$  processes  
Barnaby, Peloso '10 ; Anber, Sorbo '12 ; Bugaev, Klimai '13 ; Garcia-Bellido, Peloso, Unal '16...
- Let's allow some NG

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

$$P_{\zeta}^G(k) = \mathcal{A} \cdot \exp \left[ -\frac{\ln^2(k/k_*)}{2\sigma^2} \right]$$
$$P_{\zeta}^{NG}(k) = 2f_{NL}^2 \int \frac{dp}{p} \frac{d\Omega}{4\pi} \frac{k^3}{|\mathbf{k} - \mathbf{p}|^3} P_{\zeta}^G(p) P_{\zeta}^G(|\mathbf{k} - \mathbf{p}|) \quad (7)$$

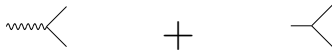
- Effects of NG :Scalar modes peak at a larger frequency, more contraction due to more legs, wider signal due to convolution

# Effects of NG and Contractions of Four Point Function

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

$$= \Omega_{GW}^G + \Omega_{GW}^{NG} \quad (8)$$

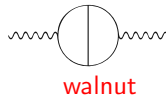
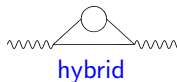
## Contractions



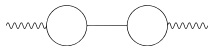
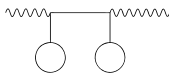
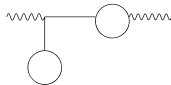
- $\mathcal{O}(f_{NL}^0)$



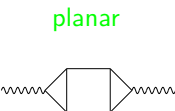
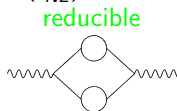
- $\mathcal{O}(f_{NL}^2)$



- Contractions vanishing due to zero momentum propagator or symmetry

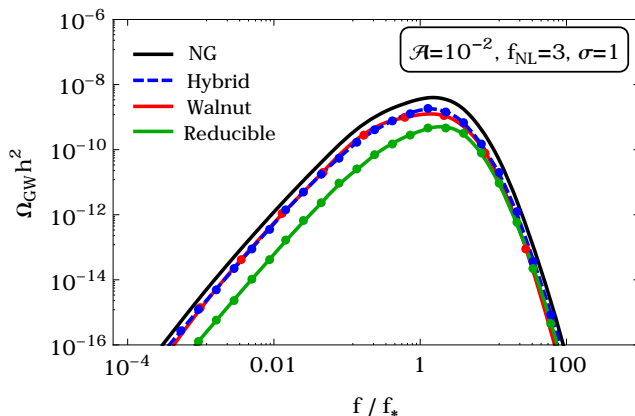


- $\mathcal{O}(f_{NL}^4)$



# Results ( $\sigma \sim \Delta N_{peak} = 1$ ) Unal '19

$\Omega_{GW}^{NG}$  peaks at larger freq + wider + larger amplitude <sup>1</sup>

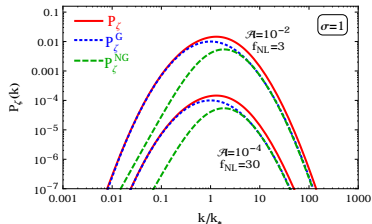
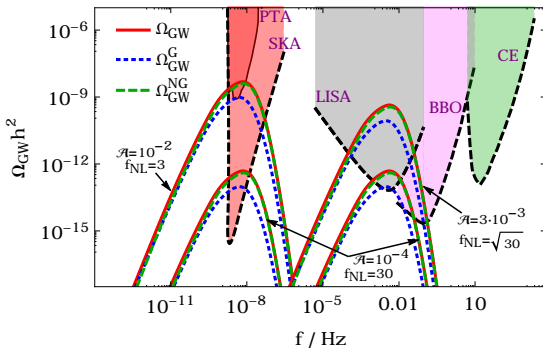


<sup>1</sup>Large NG limit,  $\mathcal{A} \cdot f_{NL}^2 \gg 1$ , was studied by Nakama, Kamionkowski, Silk '17 ; Garcia-Bellido, Peloso, Unal '17 ; Cai, Pi, Sasaki '19



# Results ( $\sigma \sim \Delta N_{peak} = 1$ ) Unal '19

$\Omega_{GW}^{NG}$  peaks at larger freq + wider + larger amplitude



$$\rho_{PBH} \simeq \rho_{DM} (f_{LISA} \rightarrow 10^{-12} M_{\odot})$$

Garcia-Bellido, Peloso, Unal '17

Bartolo, De Luca, Franciolini, Lewis, Peloso, Racco, Riotto '18

# Constraints

Byrnes, Cole, Patil '18 ; Inomata, Nakama '18 ; Kalaja+'19

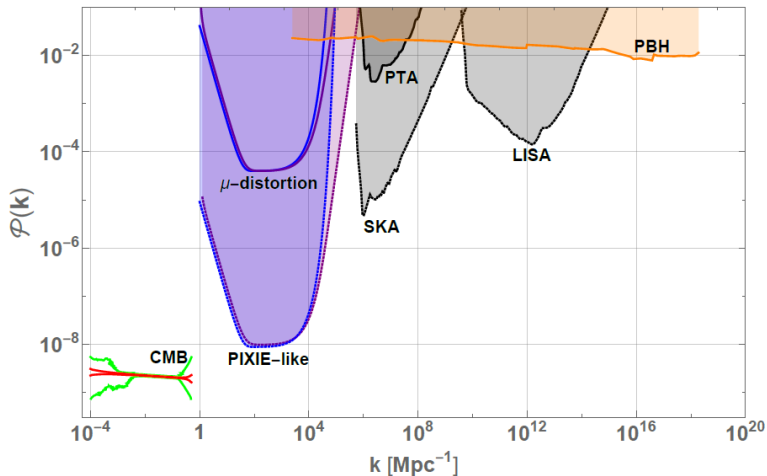


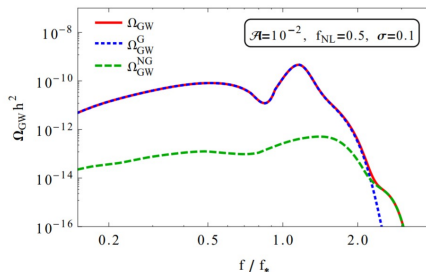
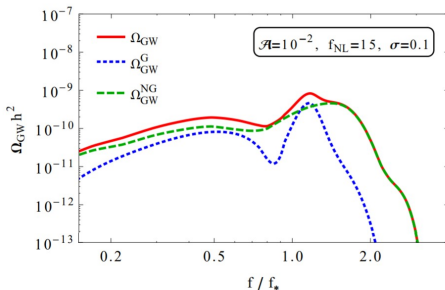
Figure: Constraints on  $P_\zeta$  taken from arXiv:1811.11158

# Observational Signatures for Narrow Spectra Unal '19

Signature 1: A not-very-well-resolved double peak.

Signature 2: A bump in UV tail even if NG component of GW spectrum is completely subdominant.

With PTA and LISA : ( $\Omega_{\text{GW}} h^2 \sim \mathcal{O}(10^{-15})$ ),  $f_{\text{NL}} \sim 0.5$  possible



# 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)

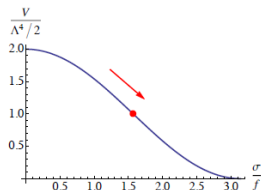
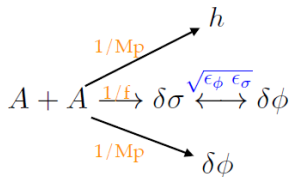
# One Explicit Model with Large Prim. NG ( $\chi^2$ Distribution)

Garcia-Bellido, Peloso, Unal '16, '17

$$\mathcal{L} = \frac{M_p^2}{2} R - \frac{1}{2} (\partial\phi)^2 - V_{\text{inf}}(\phi) - \frac{1}{2} (\partial\sigma)^2 - V(\sigma) - \frac{1}{4} F^2 - \alpha \frac{\sigma}{4f} F \tilde{F} \quad \rho_\phi \gg \rho_\sigma \gg \rho_A$$

Hidden Sector

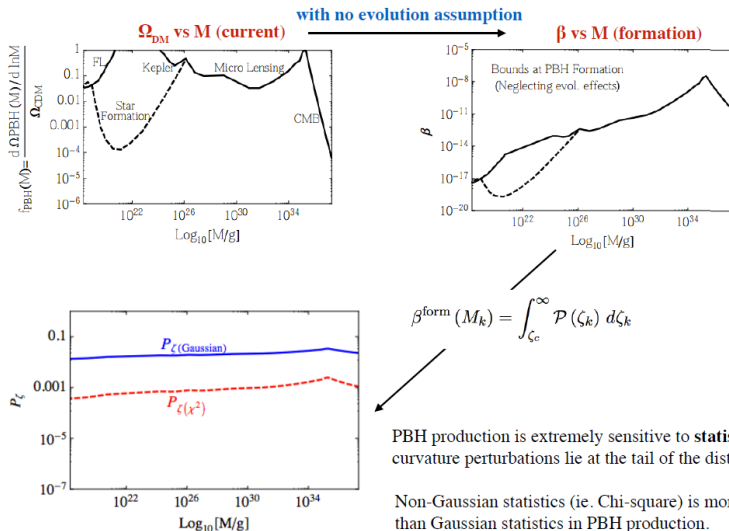
$$A''_{\pm} + \left( k^2 \mp k \frac{\alpha \sigma'}{f} \right) A_{\pm} = 0$$



Enhanced Primordial Scalar+Tensor Modes

Particle Production  
Parameter

$$\xi \equiv \frac{\alpha \dot{\sigma}}{2 f H}$$



## CMB $\mu$ Distortion ( Nakama, Chluba, Kamionkowski '17)

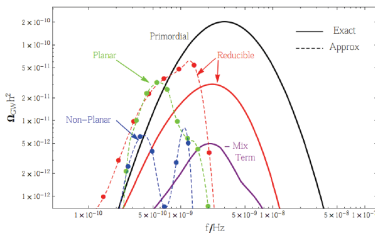
$$\langle \mu \rangle \sim \mathcal{O}(1) \int d \ln k P_\zeta(k) \Rightarrow \langle \mu_{NG} \rangle \ll \langle \mu_G \rangle$$

## Primordial + Induced GWs

Order of Magnitude Estimate of the peak  $\Omega_{\text{GW},0} \sim \mathcal{O}(\text{a few}) \Omega_{\text{Rad},0} P_\zeta^2$  Nakama, Silk, Kamionkowski '16

### Non-Gaussian Rolling Axion ( $\chi^2$ ) Model

Garcia-Bellido, Peloso, Unal '17



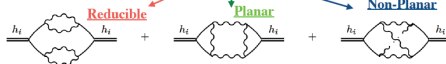
### Primordial Vertex



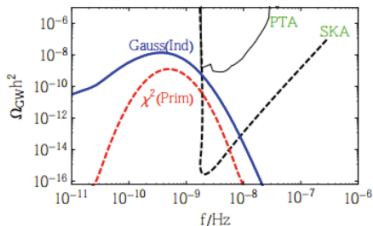
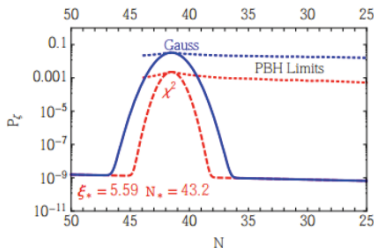
### Primordial

### Mixed

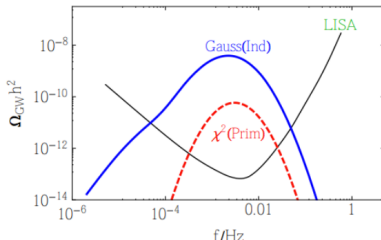
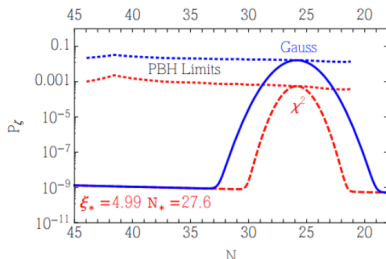
### Induced Vertex



## LIGO GWs & $M_{BH} \sim O(30)M_{\odot}$



## LISA GWs & $M_{BH} \sim O(10^{-12})M_{\odot}$





## GW w/ Non-Trivial Evolution Garcia-Bellido, Peloso, Unal '17

Almost all **previous studies** assume trivial evolution (ie **neglect** gas accretion onto PBH and mergers)

(neglecting GW leakage)

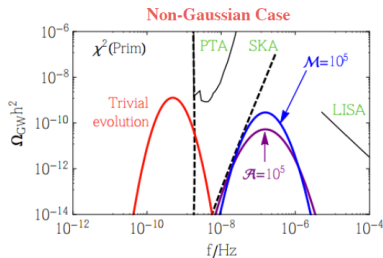
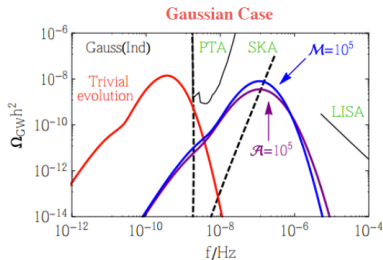
Merging ( $\mathcal{M}$ ) :  $n_{\text{PBH}} \downarrow$   $\rho_{\text{PBH}} \leftrightarrow$

Accretion ( $\mathcal{A}$ ) :  $n_{\text{PBH}} \leftrightarrow$   $\rho_{\text{PBH}} \uparrow$

### Simplest Parametrization

$$M \rightarrow M_{\text{PBH}} \times \mathcal{M} \quad n \rightarrow n_{\text{PBH}} / \mathcal{M}$$

$$M \rightarrow M_{\text{PBH}} \times \mathcal{A} \quad n \rightarrow n_{\text{PBH}}$$



With non-trivial evolution  $\rightarrow$  Smaller  $M_{\text{form}} \rightarrow$  Higher  $f_{\text{form}}$  since  $f \propto M^{-1/2}$

With non-trivial evolution, PBHs form with smaller masses. In result, primordial distortion signal does not enhance