

# Gravitational Wave Signatures of Inflationary Models from Primordial Black Hole (PBH) Dark Matter (DM)

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Paris, COSMO-17, 2017 Aug

- PBH Basics and PBH DM
- PBH production from Perturbations obeying different statistics
- Distinct GW Backgrounds at small scales
- Evolution of PBH from GW

Talk is based mainly on

“Gravitational Wave signatures of inflationary models from Primordial Black Hole Dark Matter “  
J. Garcia-Bellido, M. Peloso, C. Unal [ accepted for publication at JCAP, arXiv: 1707.02441 ]

Axion Model is based on

”Scale dependent Gravitational Waves and Non-Gaussianity from rolling axion”,  
R. Namba, M. Peloso, M. Shiraishi, L. Sorbo, C. Unal [ JCAP 1601:041 ]

# PBH Basics and PBH DM

See also talks of **Kuhnel, Sasaki, Wands, Tenkanen, Vaskonen** on PBH

- Many ways to produce PBH : Primordial perturbations, topological defects, bubble collisions, etc

- $\zeta > \zeta_c$  collapse in re-entry in rad. dom.  $\beta^{\text{form}}(M_k) = \int_{\zeta_c}^{\infty} \mathcal{P}(\zeta_k) d\zeta_k$



- Only a small fraction of regions ( $\beta^{\text{form}}$ ) collapse but  $\rho_{\text{PBH}}$  grows w/  $a(t)$  since PBH is NR matter

- Mass of BH  $\sim$  the horizon mass  $\sim M \simeq 20 \gamma M_{\odot} \left( \frac{k}{10^6 \text{ Mpc}^{-1}} \right)^{-2} \simeq 50 \gamma M_{\odot} \left( \frac{10^{-9} \text{ Hz}}{f} \right)^2$  PTA-LIGO  
correspondence  
(later)

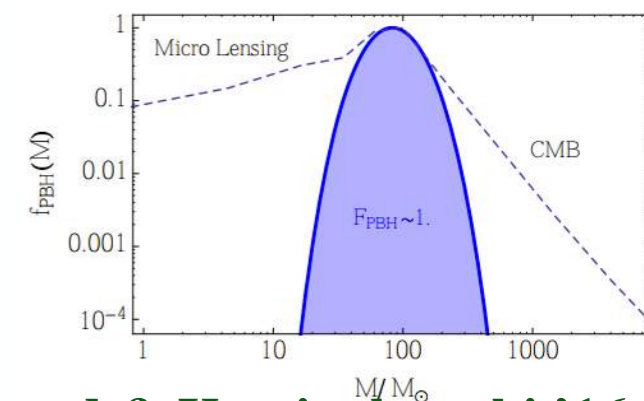
**Garcia-Bellido, Peloso, Unal '16**

**Motivation:** Bird et al '16 | Clesse & Garcia-Bellido '16 | Sasaki et al '16

i) No DM yet (+ No low energy SUSY sign yet)

ii) Detected binaries at LIGO are somehow heavier than BH with astrophysical origin

iii) Revised distortion constraints on PBH for masses larger than solar mass **Ali-Hamoud & Kamionkowski '16**



PBH DM scenario has many distinctive EM and GW Signatures (scale dependent) :

Early initialization of star formation, IMBH/SMBH, Induced GW spectrum from primordial scalar modes,

Stochastic GW spectrum from collision of PBH during cosmic history, distortion due to energy injection, etc.

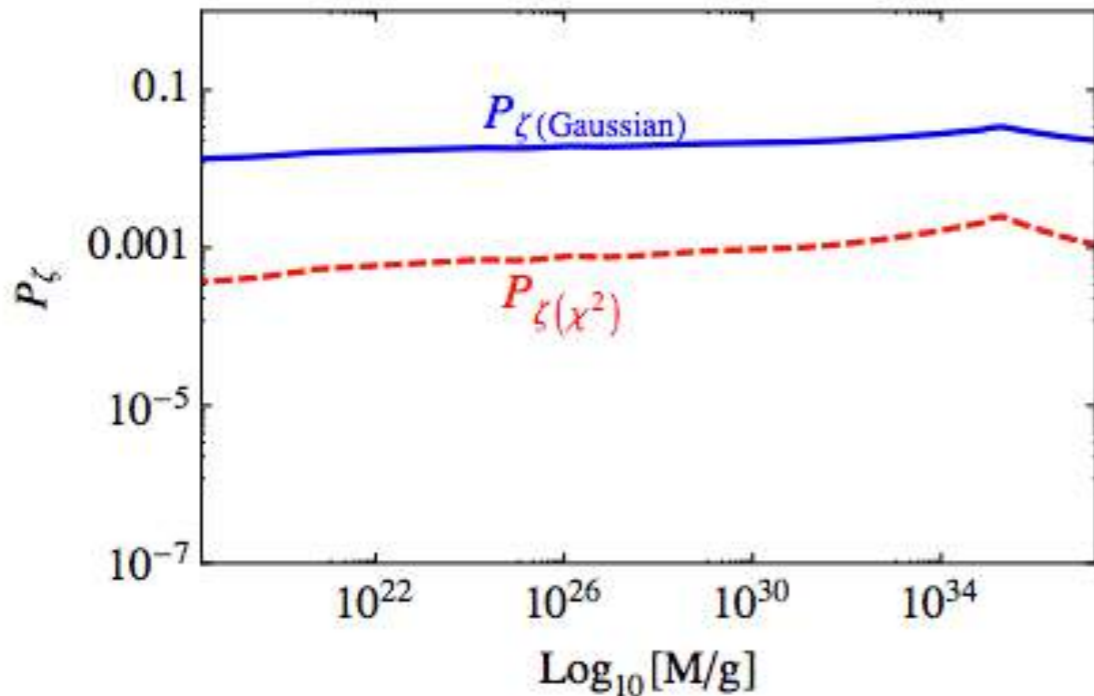
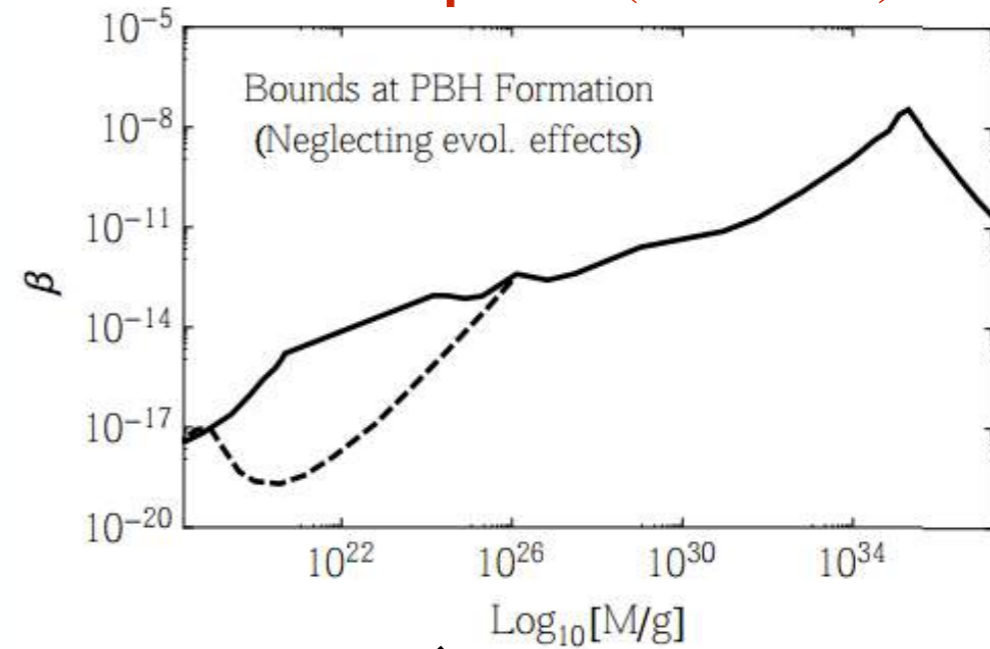
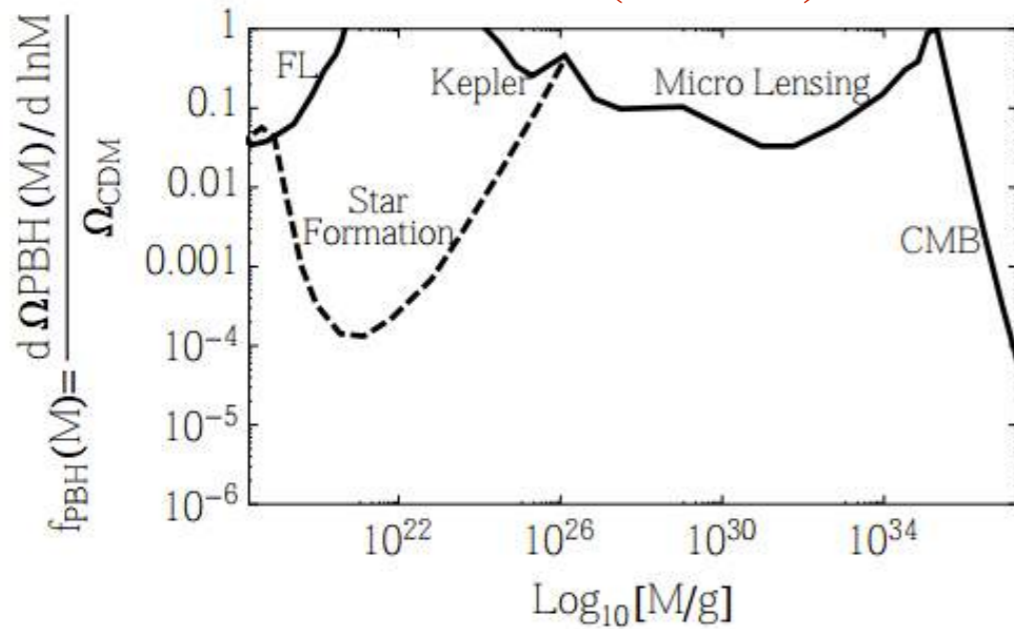
**Garcia-Bellido 1702.08275**

# Bounds and Statistics

with no evolution assumption

$\Omega$  vs  $M$  (current)

$\beta$  vs  $M$  (formation)



$$\beta^{\text{form}}(M_k) = \int_{\zeta_c}^{\infty} \mathcal{P}(\zeta_k) d\zeta_k$$

PBH production is extremely sensitive to both **standard deviation (amplitude)** and **statistics** (large curvature perturbations lie at the tail of the distribution!)

Non-Gaussian statistics (ie. Chi-square) is more efficient than Gaussian statistics in PBH production.

# Models for PBH DM

## Gaussian Model

To assess the relevance of these two features

- Enhanced Primordial Scalar Modes
- Scalar modes obey Gaussian distribution
- NOT enhanced Primordial Tensor Modes
- Enhancement can be due to various methods

!Quantum diffusion effects need more understanding

**Pattison et al '17**

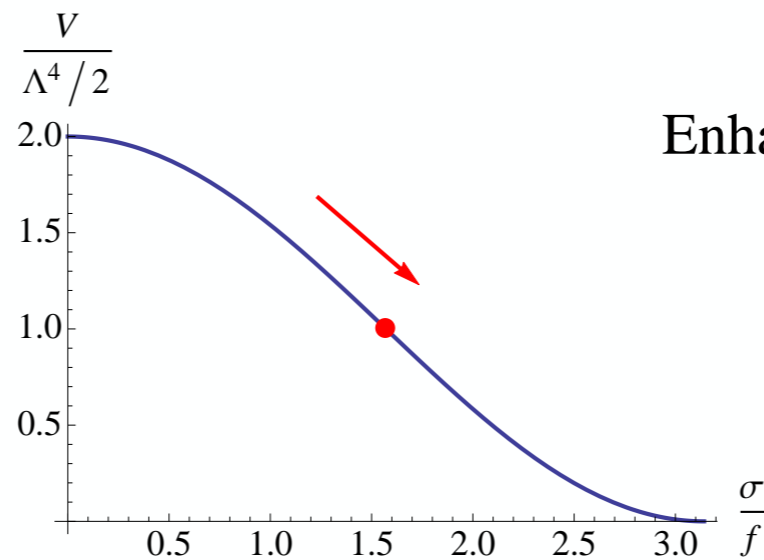
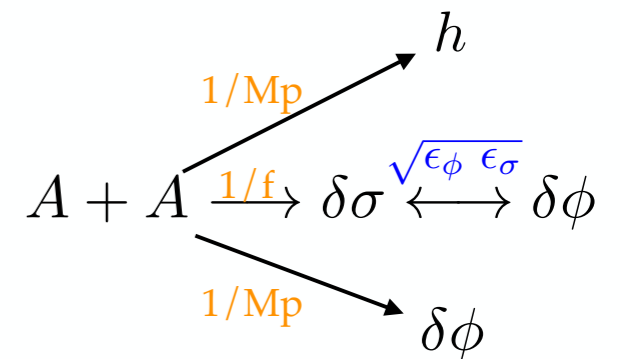
## Non-Gaussian Rolling Axion ( $\chi^2$ ) Model

- Enhanced Primordial Scalar+Tensor Modes (via same mechanism)
- Scalar modes obey  $\chi^2$  distribution

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

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**

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

For details please see

**Namba, Shiraishi, Peloso, Sorbo, Unal '15**

See also talks of **Fujita, Namba, Notari** on axion inflation

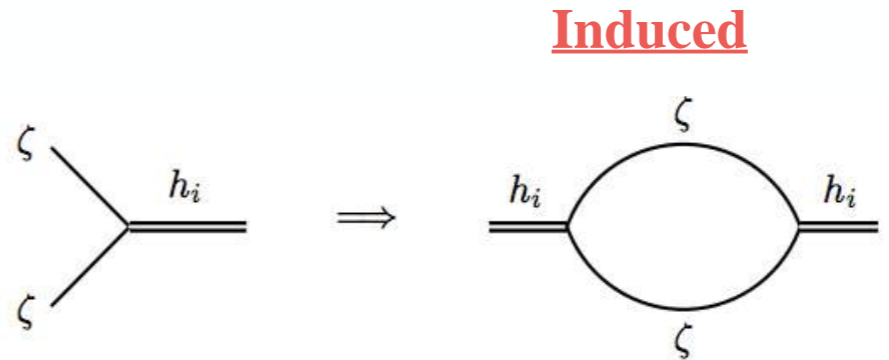
# GW Backgrounds (Induced + Primordial)

Induced GW: Large  $\zeta \rightarrow$  PBH and unavoidably source tensor modes as  $\zeta + \zeta \rightarrow h_i$

## Gaussian Model

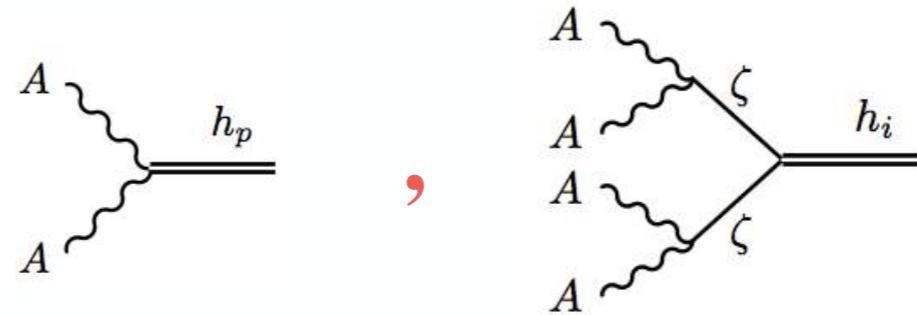
Has been studied and well understood

Ananda et al '06, Baumann et al '07

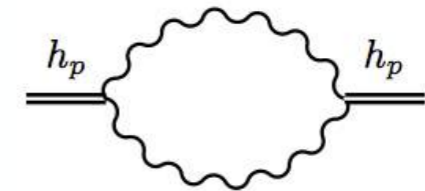


## Non-Gaussian Rolling Axion ( $\chi^2$ ) Model

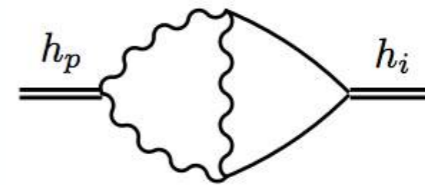
Garcia-Bellido, Peloso, Unal '17



## Primordial

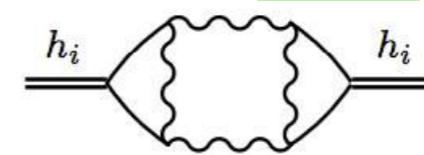


## Mixed

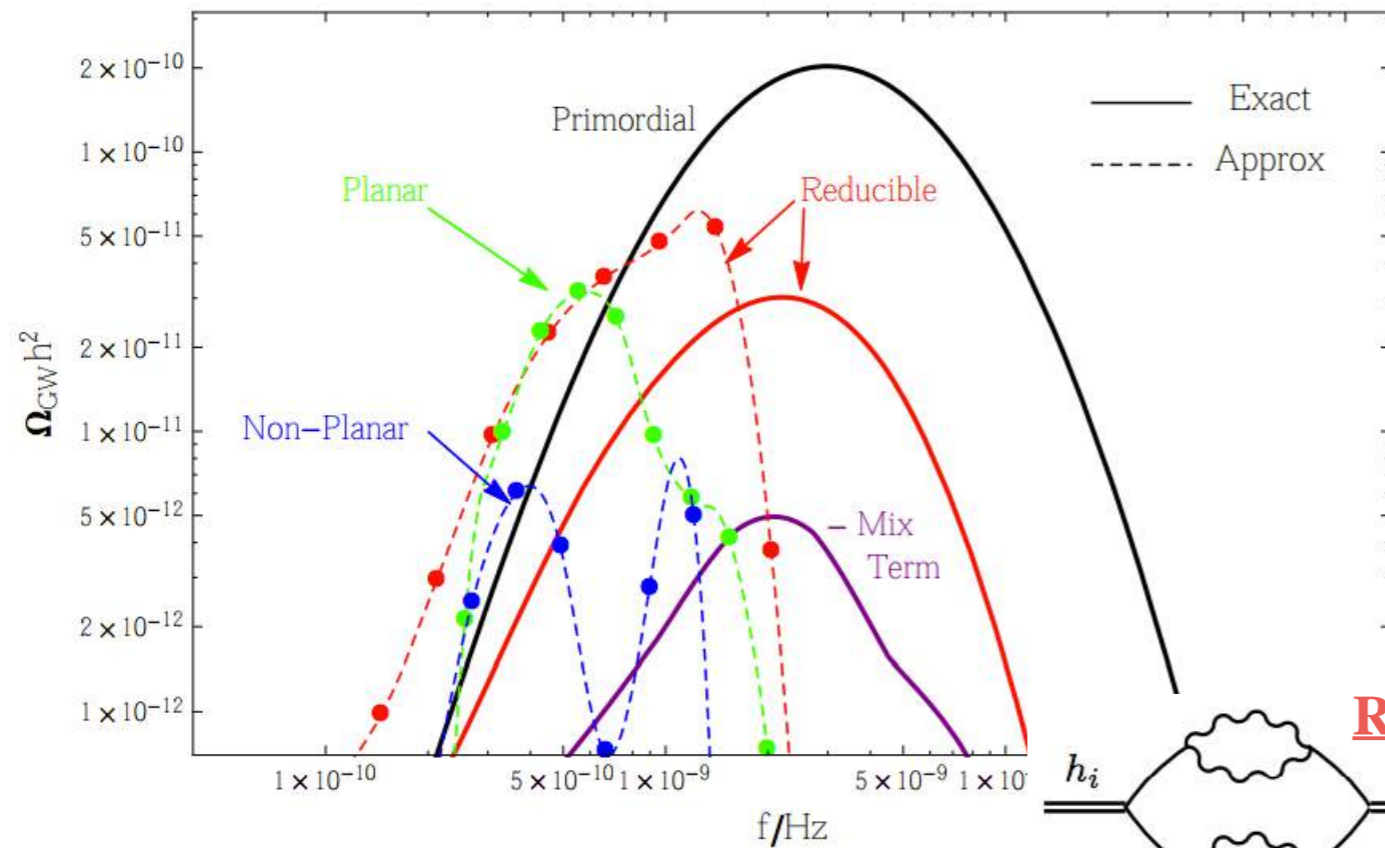
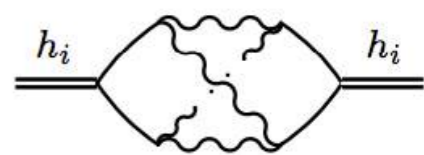


## Induced

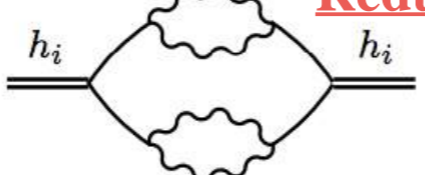
### Planar



### Non-Planar



## Reducible



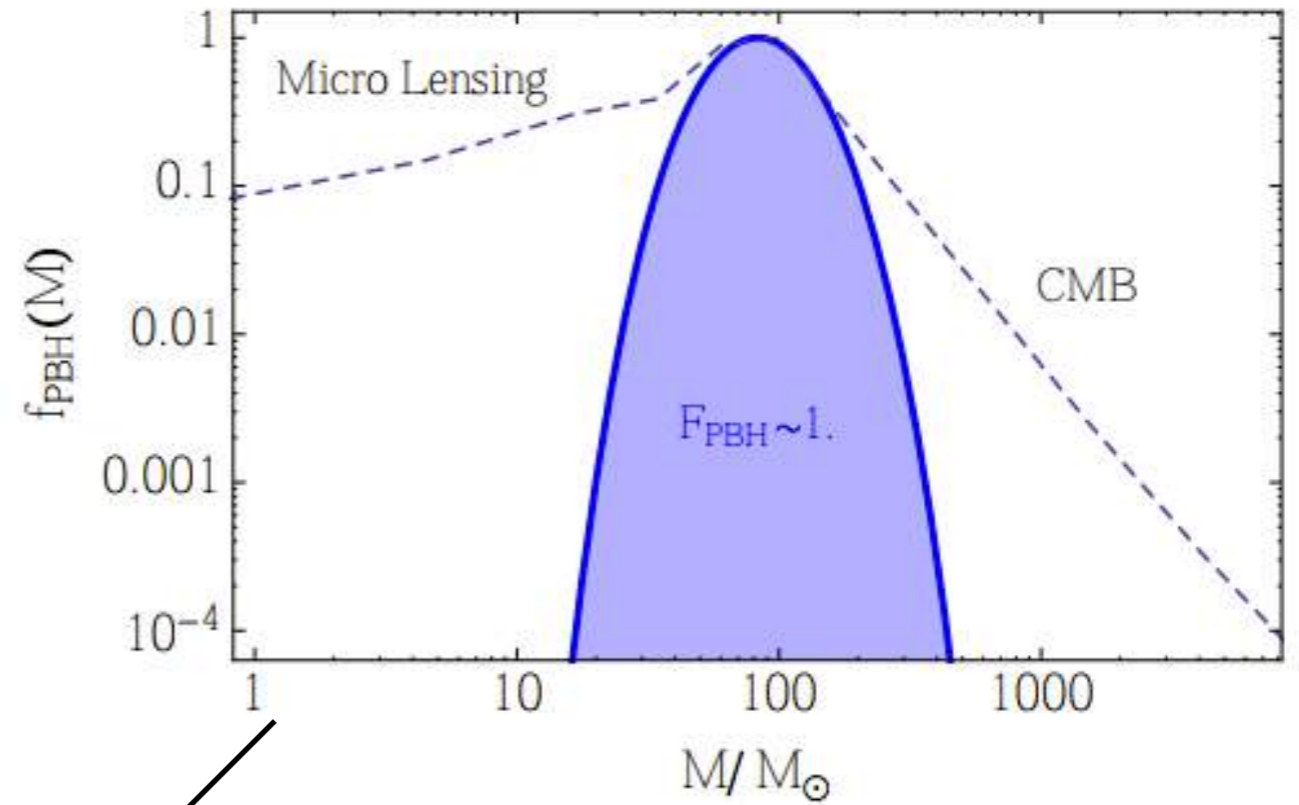
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# GW w/ Different Statistics

$$F_{\text{PBH}} \equiv \int \frac{dM}{M} f_{\text{PBH}}(M) = 1$$



## CMB $\mu$ Distortion

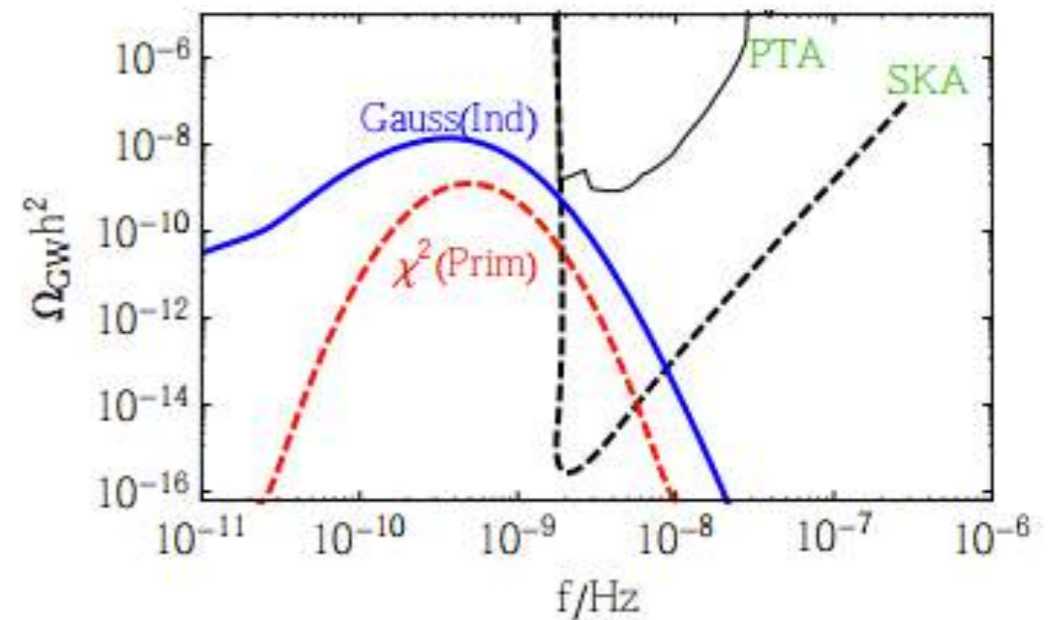
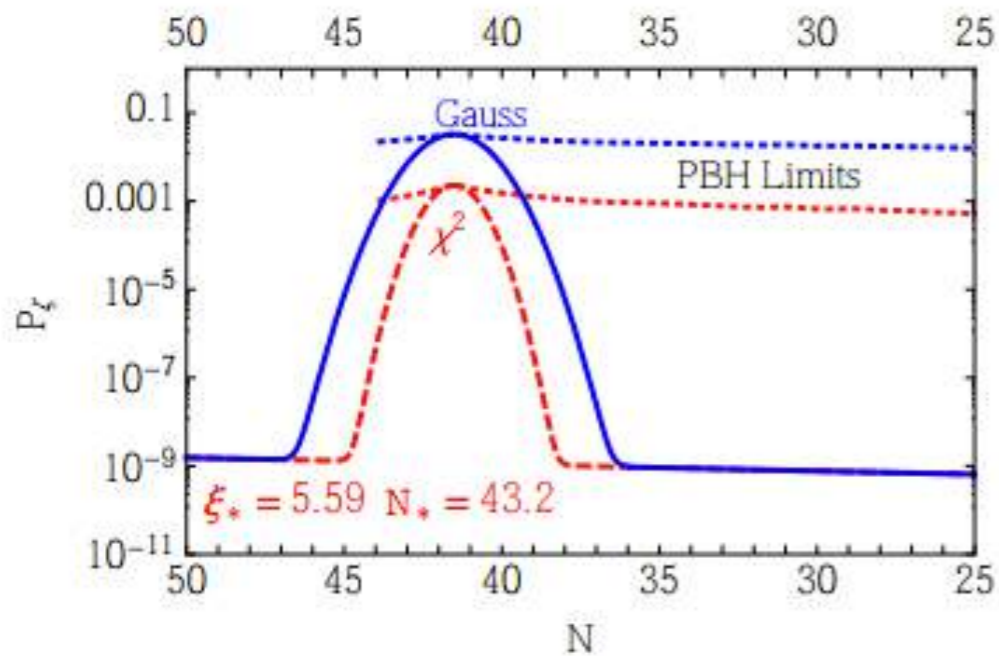
(Using Nakama, Chluba & Kamion. '17)

$$\mu_G \sim 4 \times 10^{-5}$$

$$\mu_{\text{NG}} \sim 3 \times 10^{-8}$$

$$\zeta_c = 1$$

$$f \sim \text{nHz} \sqrt{\frac{10 M_\odot}{M_{\text{PBH}}}} \quad \text{PTA-LIGO correspondence!!!}$$



No detection  $\rightarrow \zeta_c < 0.05$ ; This rules out PBH DM if there is no extreme evolutionary effects

All **previous studies** assume trivial evolution (**neglect** gas accretion onto PBH and PBH mergers)

Both induced and primordial GW spectra carry information about **formation time** not current time.

So **compare** it with **current BH mass function!**

(neglecting GW leakage)

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

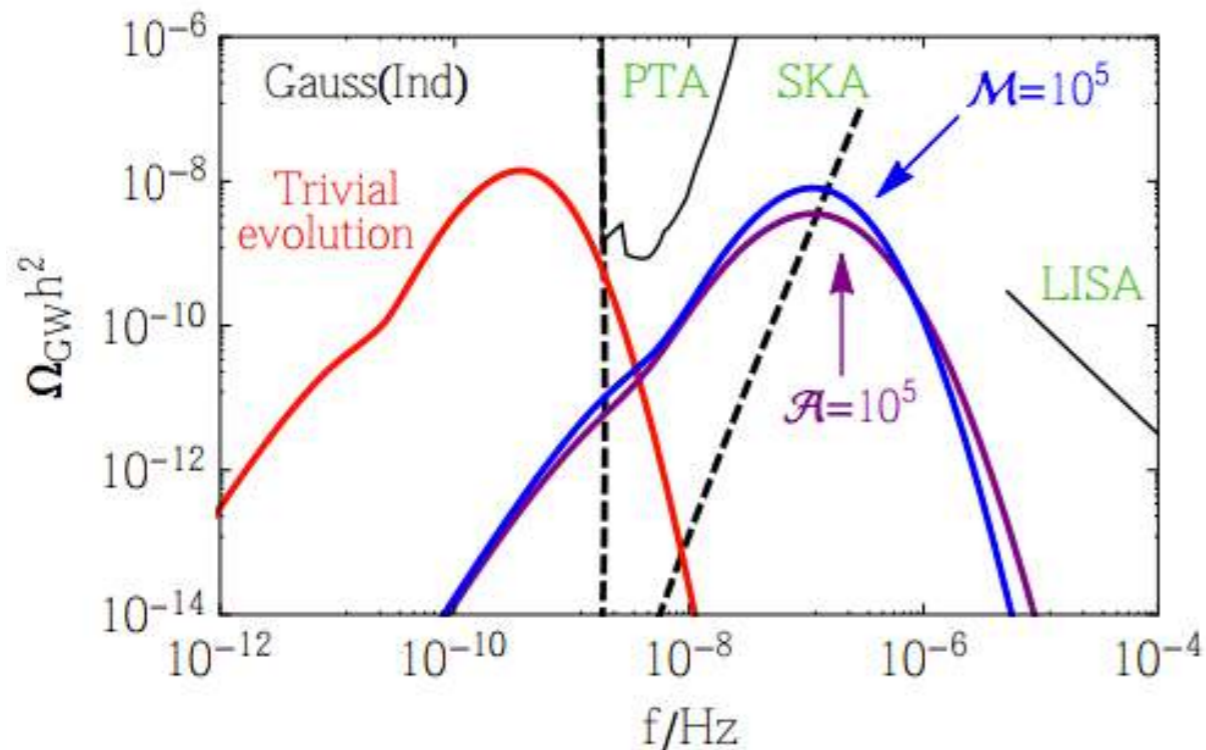
Accretion ( $\mathcal{A}$ ) :  $n_{\text{PBH}} \leftrightarrow$        $\rho_{\text{PBH}} \uparrow$

### Simple Mass Independent Parametrization

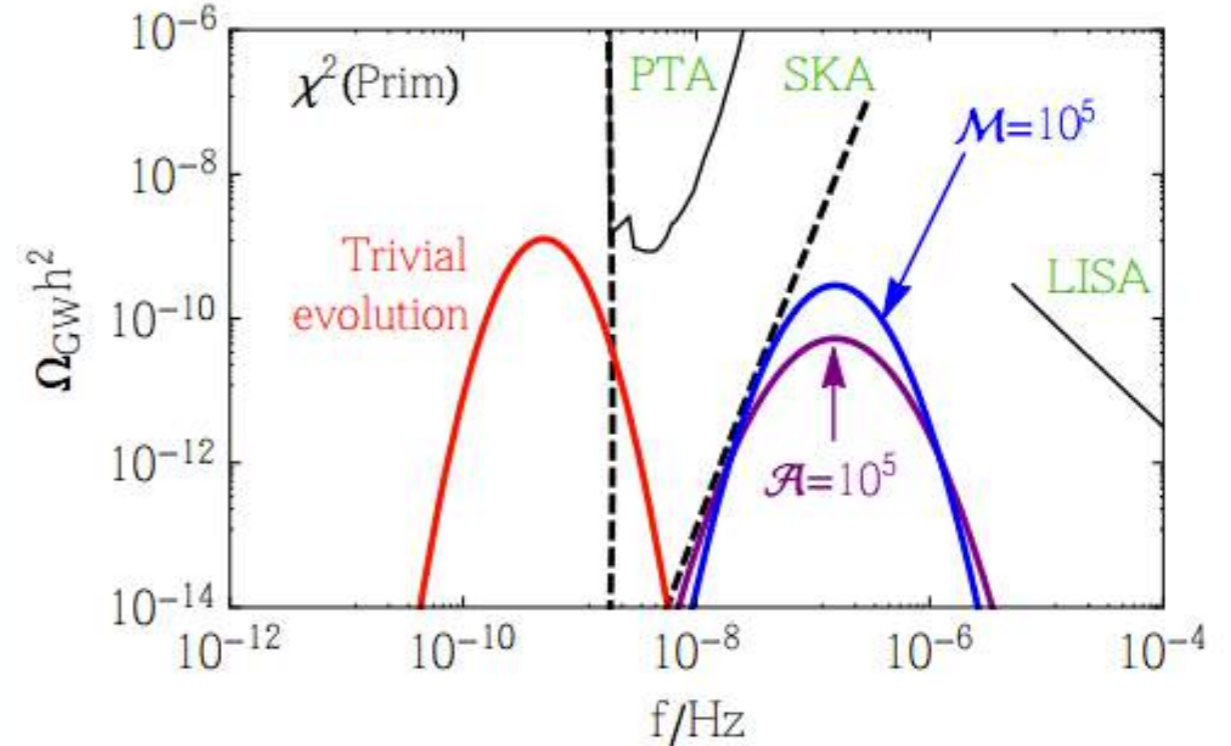
$$M \rightarrow M_{\text{PBH}} \times \mathcal{M} \quad n \rightarrow n_{\text{PBH}} / \mathcal{M}$$

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

### Gaussian Case



### Non-Gaussian Case



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

# Conclusions and Questions

- GW astronomy era has started
- PBH DM is a compelling scenario with distinct predictions
- There exists an interesting correspondence between PTA scales stochastic GW backgrounds and LIGO scales BH coalescences
- We can learn much more about small scales signatures (late times of inflation) via GW

Thanks for your attention and questions