Title: The recent gravitational wave observation by pulsar timing arrays and primordial black holes: the importance of non-gaussianities - VIRTUAL

Speakers: Antonio Iovino

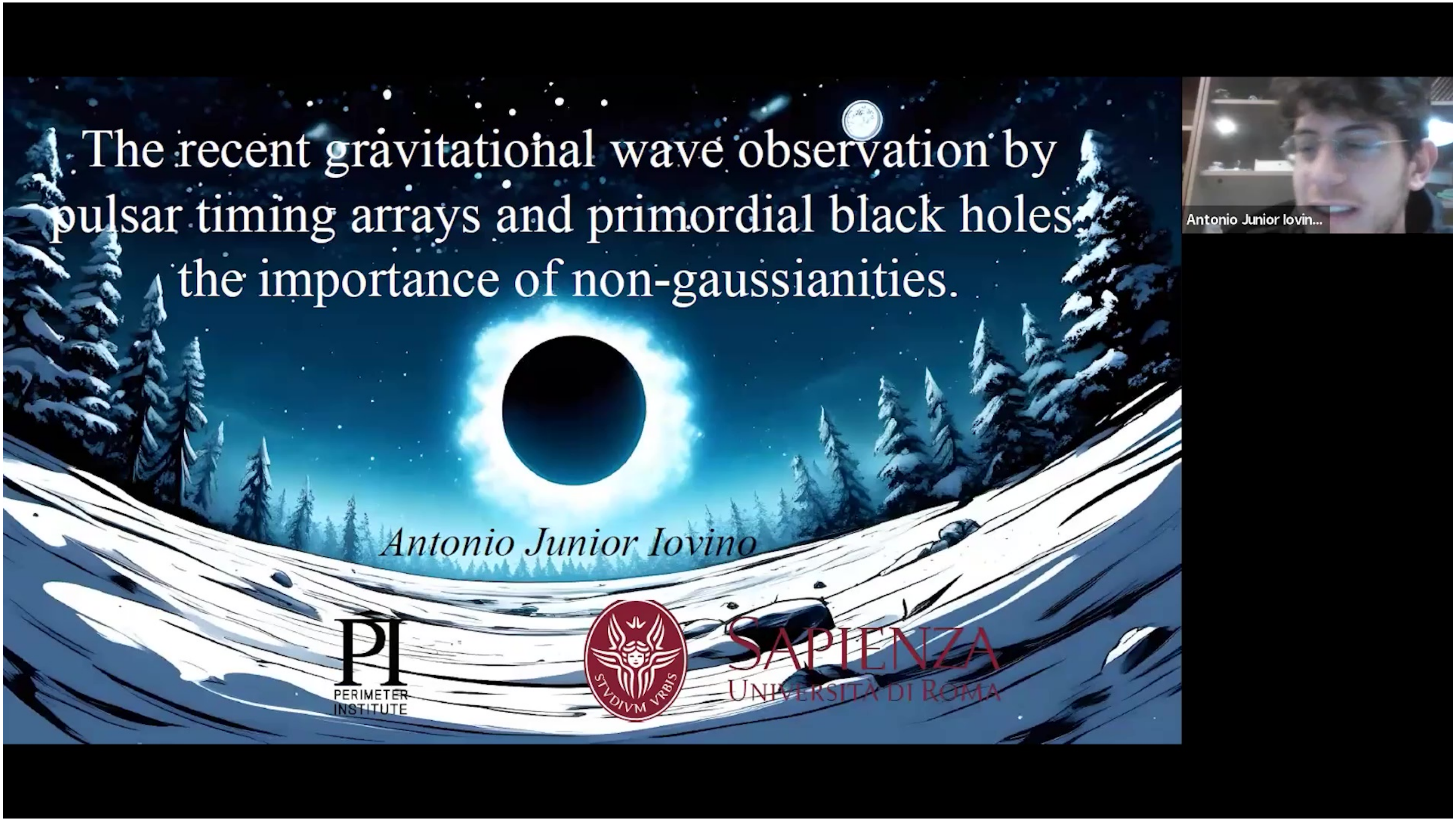
Series: Particle Physics

Date: November 07, 2023 - 1:00 PM

URL: https://pirsa.org/23110050

Abstract: The recent data releases by multiple pulsar timing array (PTA) experiments show evidence for Hellings-Downs angular correlations indicating that the observed stochastic common spectrum can be interpreted as a stochastic gravitational wave background. We study whether the signal may originate from gravitational waves induced by high-amplitude primordial curvature perturbations. Such large perturbations may be accompanied by the generation of a sizable primordial black hole (PBH) abundance. We discuss in which scenarios the inclusion of non-Gaussianities in the computation of the abundance can lead to a signal compatible with the PTA experiments without overproducing PBHs.

Zoom link https://pitp.zoom.us/j/95261778825?pwd=QndRd0xQVFpNVzk0VXpRUkNqR1JXZz09


The recent gravitational wave observation by pulsar timing arrays and primordial black holes: the importance of non-gaussianities.
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SAPIENZA
UNIVERSITÀ DI ROMA
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Primordial Black Holes: outline presentation

REVIEW: A. M. Green and B. J. Kavanagh.– arXiv:2007.10722

PART 1) ABUNDANCE of PBH: The role of NGs

arXiv:2211.01728 (Published on PRD)

G.Ferrante, G.Franciolini, A.J.I., A.Urbano

PART 2) GRAVITATIONAL WAVES: PBH as possible explanation of PTA

arXiv:2306.17149 (To appear on PRL)

G.Franciolini, A.J.I., H. Veermae, V. Vaskonen

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Black Holes: Astro vs Primordial

Astro BH: forms from the gravitational collapse of a star. We know they exist.

$$M > \mathcal{O}(1)\, M_{\odot}$$

PBH: forms in the Early universe through a gravitational collapse of large over densities in the primordial density contrast field δ.
They can still be around as long as they do not evaporate within the age of the universe

$$M > 10^{-18}\, M_{\odot}$$

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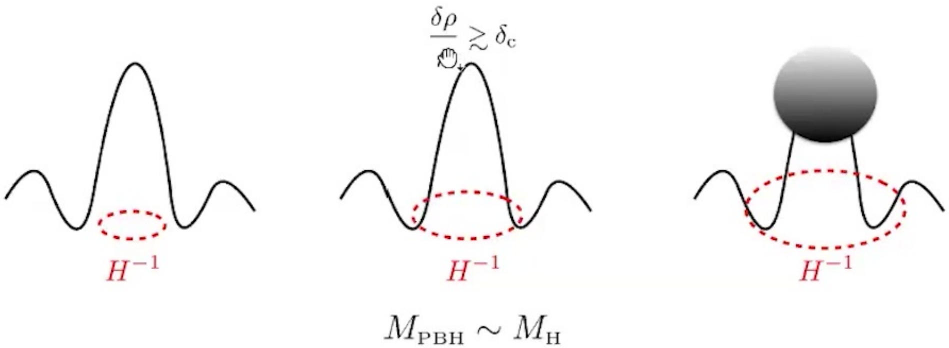
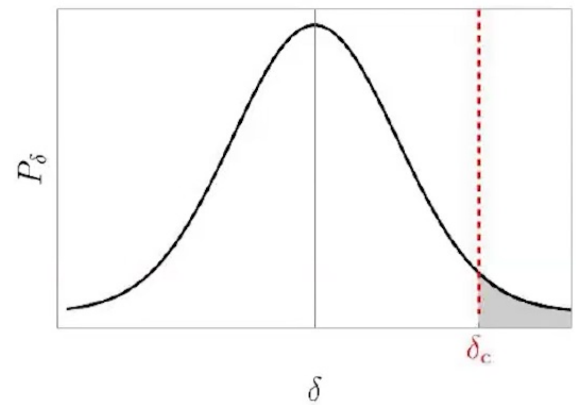
Abundance of PBHs





$$\beta = \int_{\delta_c}^{\infty} \mathcal{K}(\delta - \delta_c)^{\gamma} \, \mathrm{P}_{\delta}(\delta) d\delta$$

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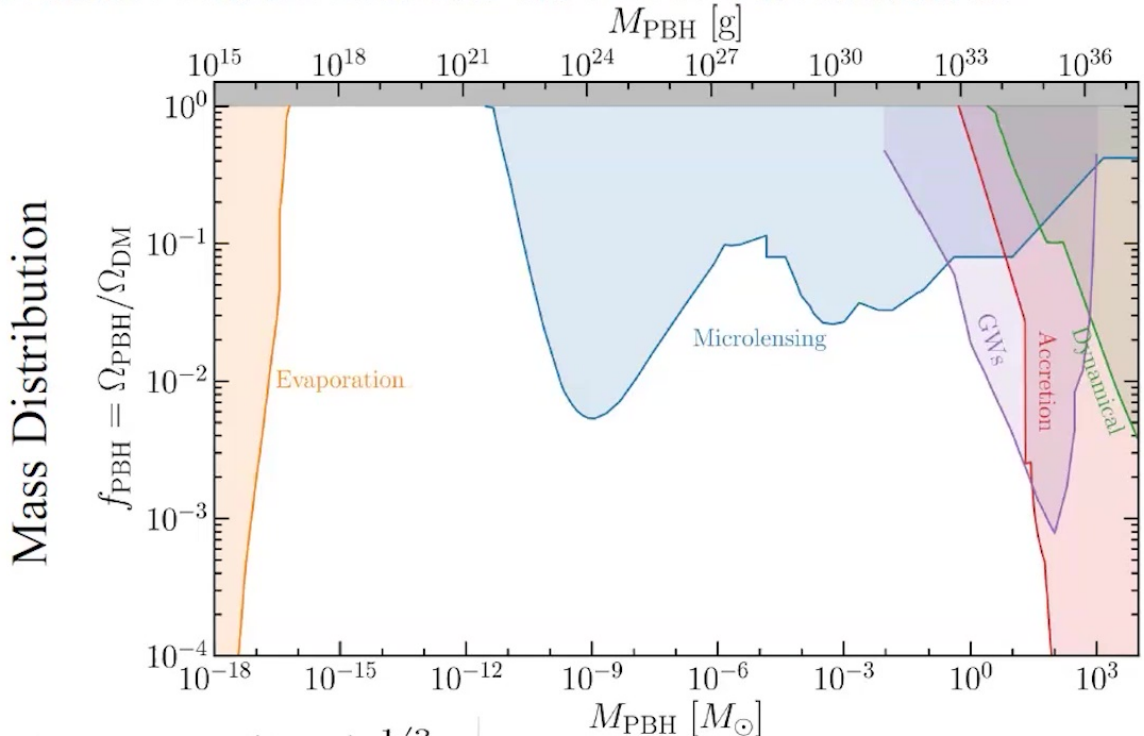
Primordial Black Holes as DM candidates



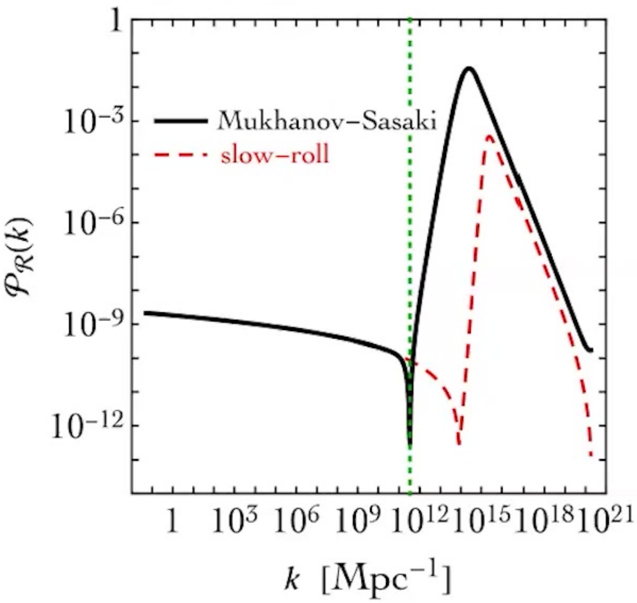
PBH as Dark Matter:

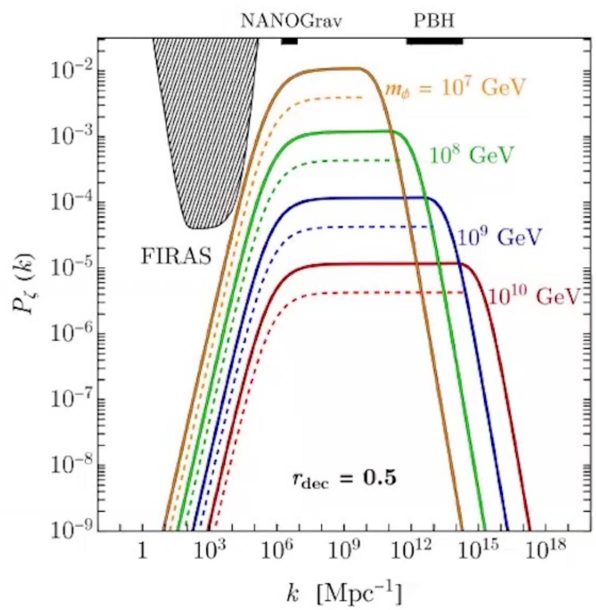
- USR models
- Hybrid inflation
- Curvaton field
- exotic formation mechanisms (bubble collisions and so on)
- And etc etc…

$$\Omega_{\rm PBH} = \int d\log M_H \left(\frac{M_{\rm eq}}{M_H}\right)^{1/2} \beta$$

Primordial Black Holes as DM candidates

What we can compute during inflation is the curvature perturbation field ζ (or R).





PBH as Dark Matter:

- USR models
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- exotic formation mechanisms (bubble collisions and so on)
- And etc etc…

$$M_H \simeq 17 M_\odot \left(\frac{g_\star}{10.75}\right)^{-1/6} \left(\frac{k/\kappa}{10^6 \mathrm{Mpc}^{-1}}\right)^{-2}$$

Abundance of PBHs: The role of Non-Gaussianities (NG).

An exact formalism for the computation of PBHs mass fraction abundance NGs in the curvature perturbation field ζ:

NON-LINEARITIES (NL)

$$\delta(\vec{x},t) = -\frac{2}{3}\Phi\left(\frac{1}{aH}\right)^2 e^{-2\zeta(\vec{x})}\left[\nabla^2\zeta(\vec{x}) + \frac{1}{2}\partial_i\zeta(\vec{x})\partial_i\zeta(\vec{x})\right]$$

T. Harada, C. M. Yoo, T. Nakama and Y. Koga,.– arXiv:1503.03934

PRIMORDIAL NG IN $\zeta = F(\zeta_G)$

$\zeta = F(\zeta_G)$

power-series expansion [28–34, 36–39]
$\zeta = \zeta_G + \frac{3}{5} f_{NL}\zeta_G^2 + \frac{9}{25} g_{NL}\zeta_G^3 + \ldots$

ultra slow-roll with an upward step [50]
$\zeta = -\frac{2}{|h|}\left[\sqrt{1-|h|\zeta_G} - 1\right]$

curvaton [48, 49]
$\zeta = \log\left[X(r_{dec}, \zeta_G)\right]$

ultra slow-roll [42]
$\zeta = -\left(\frac{6}{5}f_{NL}\right)^{-1}\log\left(1 - \frac{6}{5}f_{NL}\zeta_G\right)$

$r_{dec} \equiv \left.\frac{3\rho_\phi}{3\rho_\phi + 4\rho_\gamma}\right|_{\text{curvaton decay}}$

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$r_{\rm dec} \equiv \left.\frac{3\rho_\phi}{3\rho_\phi + 4\rho_\gamma}\right|_{\rm curvaton\ decay}$

Mathematical formulation

By integrating δ over the radial coordinate r we get the compaction function C

$$\mathcal{C}(r) = -2\Phi\, r\, \zeta'(r) \left[1 + \frac{r}{2}\zeta'(r)\right] = \mathcal{C}_1(r) - \frac{1}{4\Phi}\mathcal{C}_1(r)^2\,, \qquad \mathcal{C}_1(r) := -2\Phi\, r\, \zeta'(r)$$

In the presence of NG C_1 takes the form

$$\mathcal{C}_1(r) = -2\Phi\, r\, \zeta'_{\rm G}(r)\, \frac{dF}{d\zeta_{\rm G}} = \mathcal{C}_{\rm G}(r)\, \frac{dF}{d\zeta_{\rm G}}\,, \qquad \text{with} \quad \mathcal{C}_{\rm G}(r) := -2\Phi\, r\, \zeta'_{\rm G}(r)$$

From the two-dimensional joint PDF of ζ_G and C_G, called P_G

Later on confirmed also by A.Gow et al arXiv:2211.08348

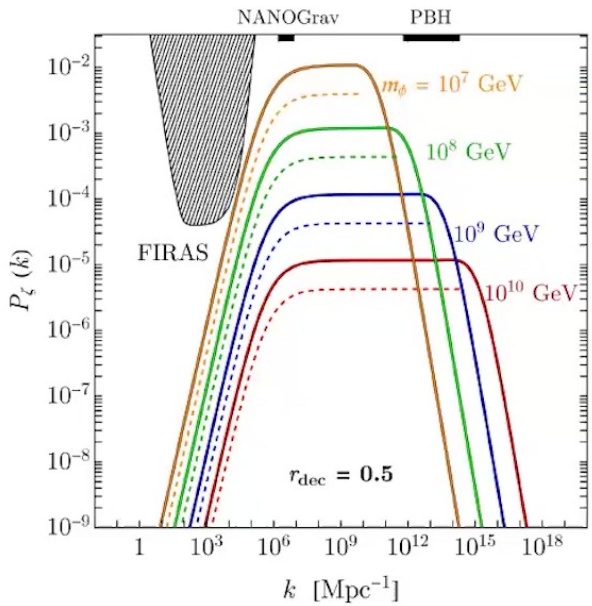
NG PBH mass fraction adopting threshold statistics on the compaction function

$$\beta_{\rm NG} = \int_{\mathcal{D}} \mathcal{K}(\mathcal{C} - \mathcal{C}_{\rm th})^\gamma {\rm P}_{\rm G}(\mathcal{C}_{\rm G}, \zeta_{\rm G}) d\mathcal{C}_{\rm G} d\zeta_{\rm G}\,, \tag{56}$$

$${\rm P}_{\rm G}(\mathcal{C}_{\rm G}, \zeta_{\rm G}) = \frac{1}{(2\pi)\sigma_c\sigma_r\sqrt{1-\gamma_{cr}^2}} \exp\left(-\frac{\zeta_{\rm G}^2}{2\sigma_r^2}\right) \exp\left[-\frac{1}{2(1-\gamma_{cr}^2)}\left(\frac{\mathcal{C}_{\rm G}}{\sigma_c} - \frac{\gamma_{cr}\zeta_{\rm G}}{\sigma_r}\right)^2\right]\,, \tag{57}$$

$$\mathcal{D} = \{\mathcal{C}_{\rm G},\, \zeta_{\rm G} \in \mathbb{R} \;:\; \mathcal{C}(\mathcal{C}_{\rm G}, \zeta_{\rm G}) > \mathcal{C}_{\rm th} \;\wedge\; \mathcal{C}_1(\mathcal{C}_{\rm G}, \zeta_{\rm G}) < 2\Phi\}\,, \tag{58}$$

Mathematical formulation



$$\langle \mathcal{C}_{\rm G}\mathcal{C}_{\rm G}\rangle = \sigma_c^2 = \frac{4\Phi^2}{9}\int_0^\infty \frac{dk}{k}(kr_m)^4 W^2(k,r_m)T^2(k,r_m)P_\zeta(k)\,,$$

$$\langle \mathcal{C}_{\rm G}\zeta_{\rm G}\rangle = \sigma_{cr}^2 = \frac{2\Phi}{3}\int_0^\infty \frac{dk}{k}(kr_m)^2 W(k,r_m)W_s(k,r_m)T^2(k,r_m)P_\zeta(k)\,,$$

$$\langle \zeta_{\rm G}\zeta_{\rm G}\rangle = \sigma_r^2 = \int_0^\infty \frac{dk}{k}W_s^2(k,r_m)T^2(k,r_m)P_\zeta(k)\,,$$

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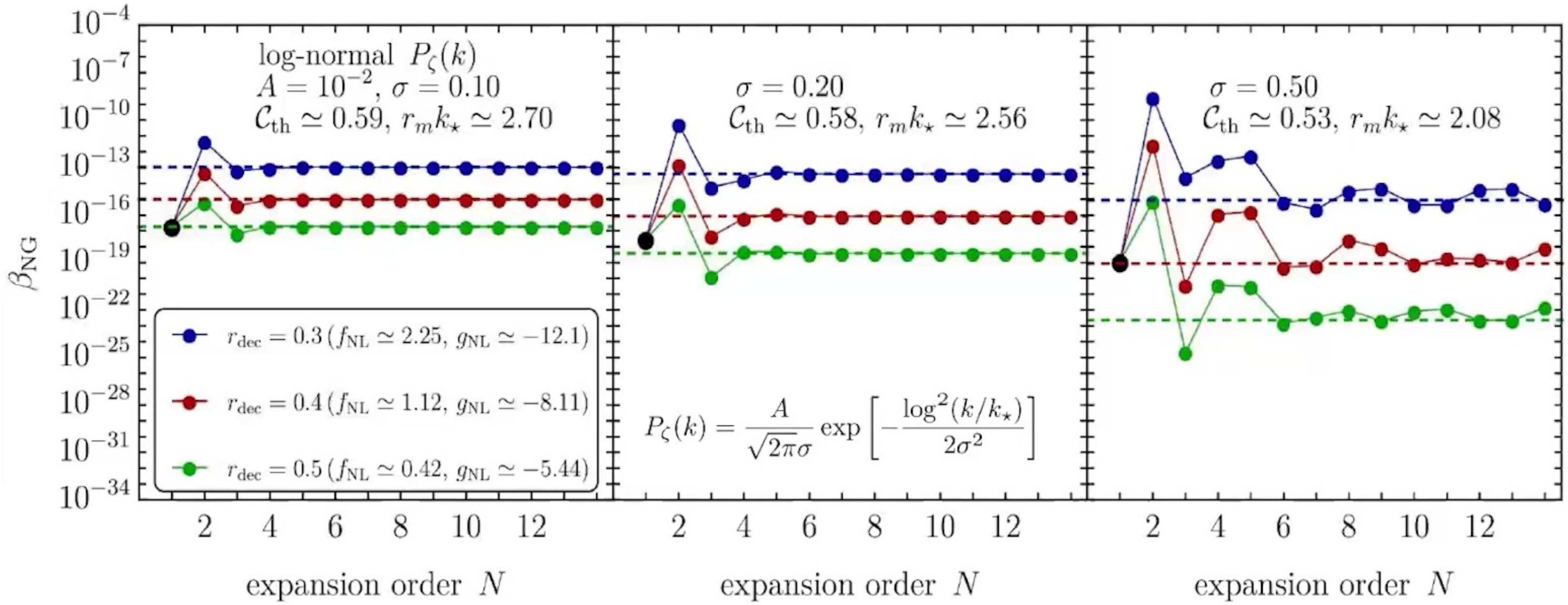
Application to the curvaton model

Failure of the perturbative approach (Narrow)

- - - $\zeta = \log\left[X(r_{\rm dec}, \zeta_{\rm G})\right]$

● $\zeta_N = \sum_{n=1}^{N} c_n(r_{\rm dec})\zeta_{\rm G}^n$



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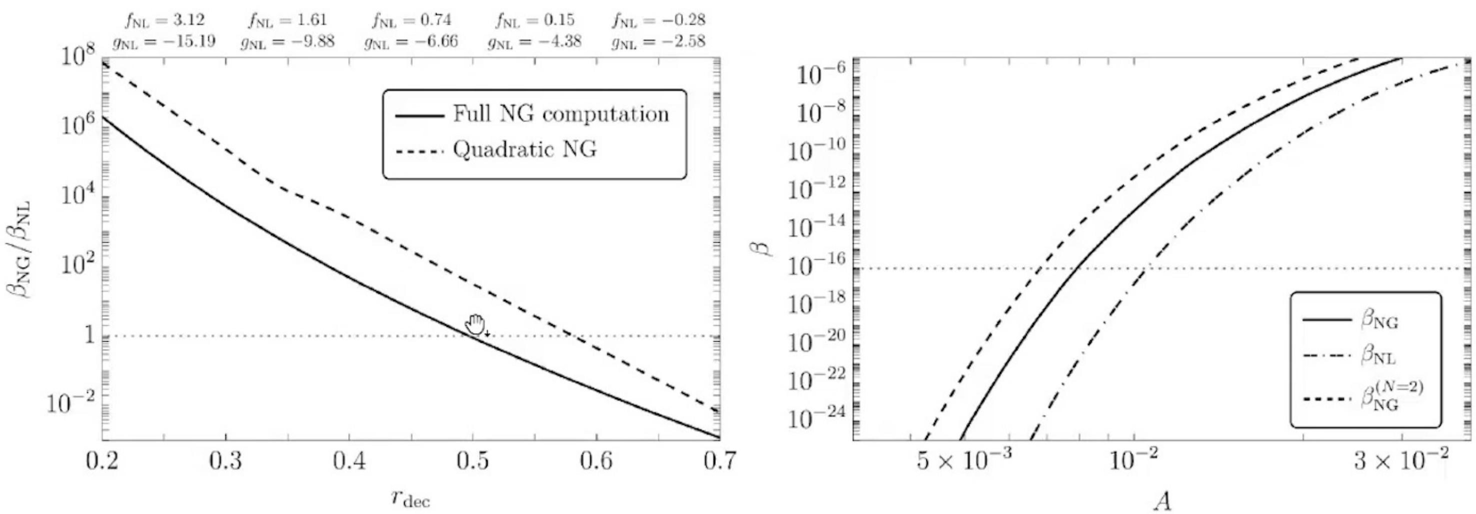
Application to the curvaton model

Quadratic app. overestimates the abundance



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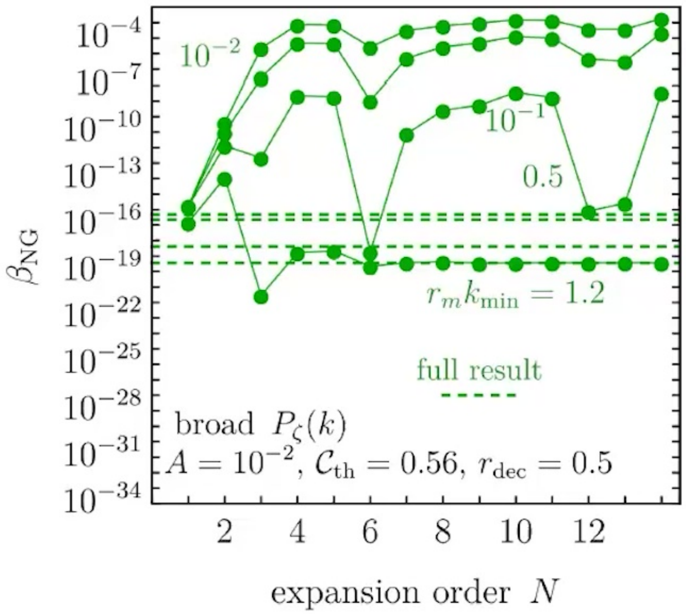
Application to the curvaton model

Failure of the perturbative approach (Broad)

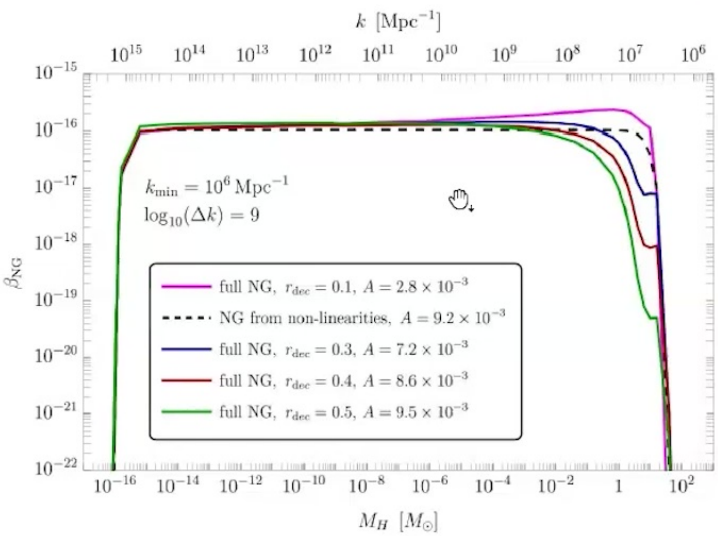


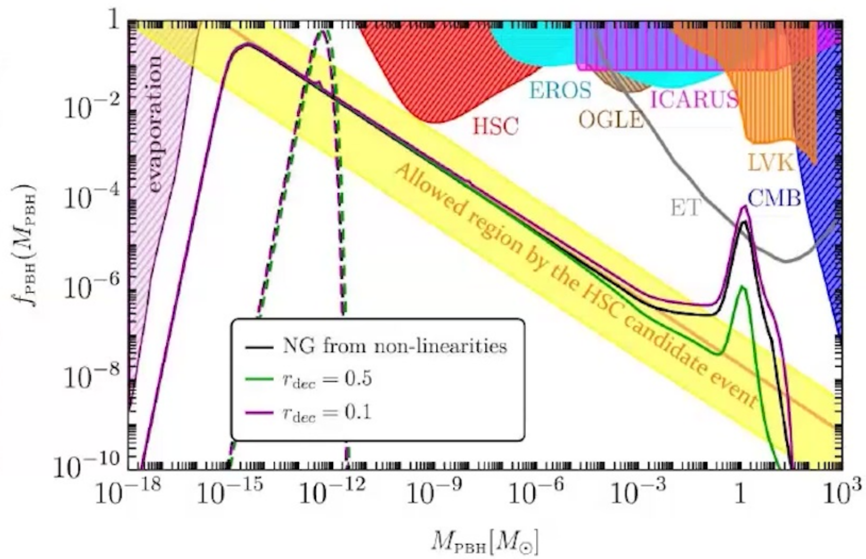
$$P_\zeta(k) = A\,\Theta(k - k_{\rm min})\,\Theta(k_{\rm max} - k)$$

For a broad Power spectrum the power-series expansion is simply wrong and one is forced to use the full result NG.

Application to the curvaton model (2)

Breaking of M_H-Independence





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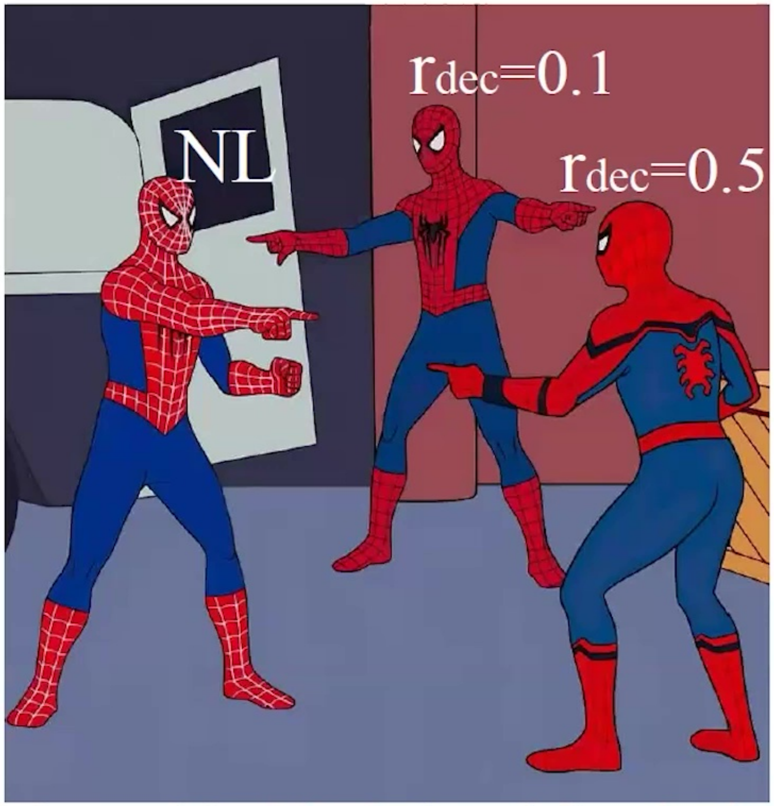


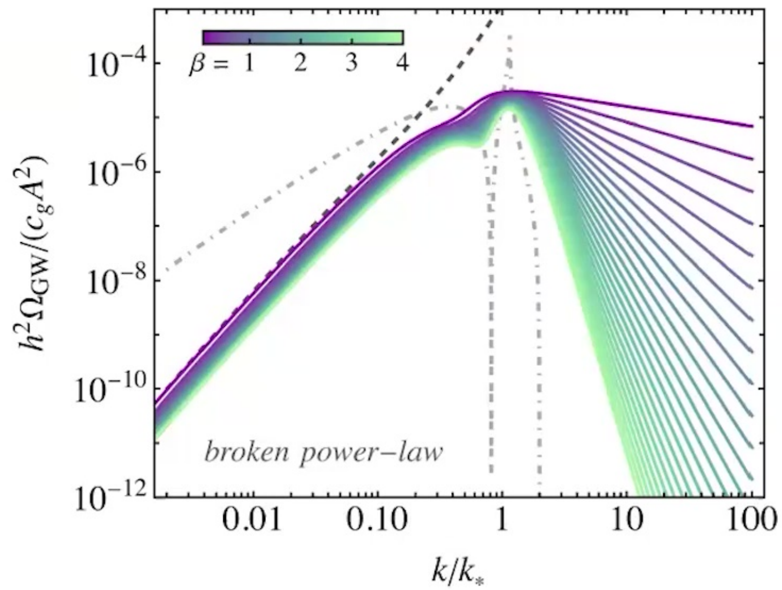
We need another observable: The induced Gravitational waves

PBH and SGWB

SGWB are produced by a second-order effect when scalar perturbations re-enter the horizon.

$$h^2\Omega_{\rm GW}(k) = \frac{h^2\Omega_r}{24}\left(\frac{g_*}{g_*^0}\right)\left(\frac{g_{*s}}{g_{*s}^0}\right)^{-\frac{4}{3}}\mathcal{P}_h(k)$$

$$\mathcal{P}_h(k) \propto \mathcal{P}_\zeta^2(k)$$



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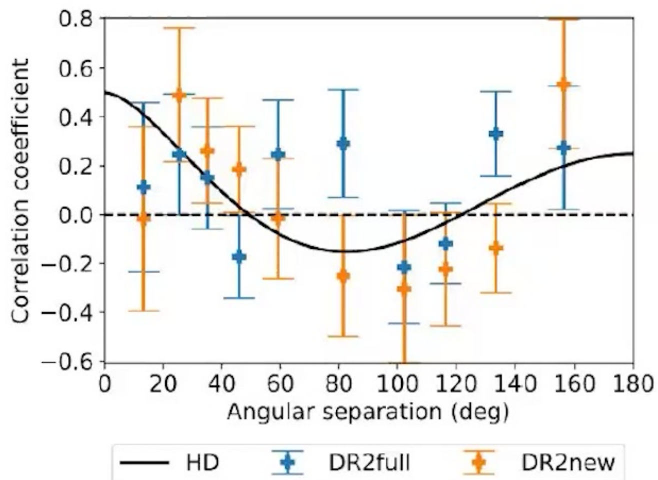
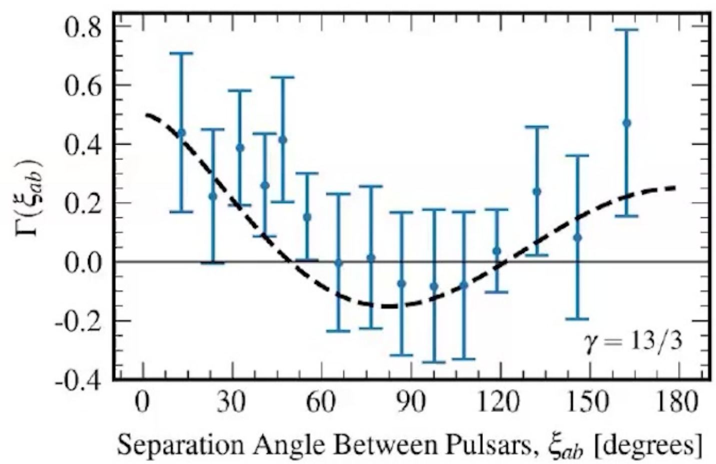
PBH and SGWB

Several PTA collaborations show that the correlations follow the Hellings–Downs pattern expected for a stochastic gravitational-wave background.

NANOGrav – arXiv:2306.16213
arXiv:2306.16219

EPTA – arXiv:2306.16214





16

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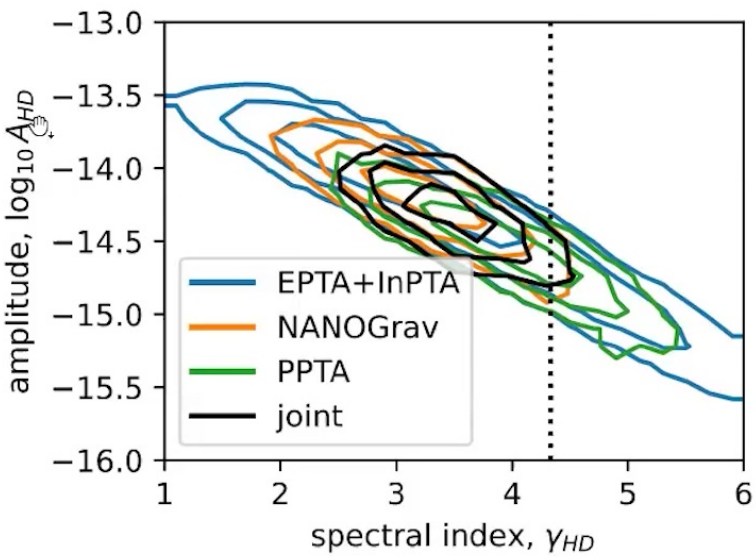
IPTA – arXiv:2309.00693



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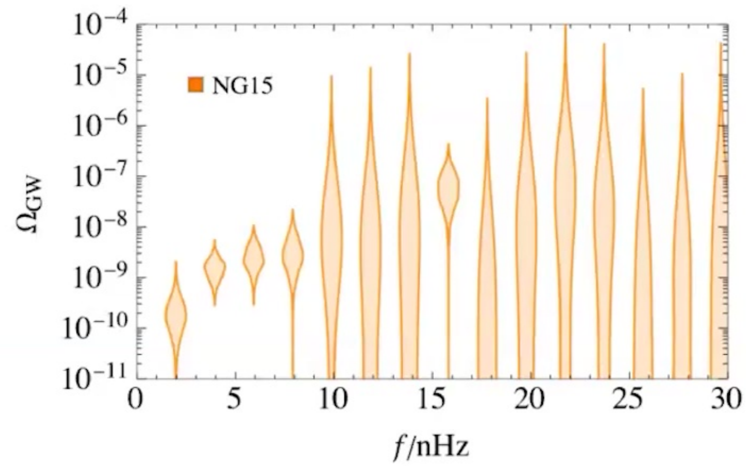

17

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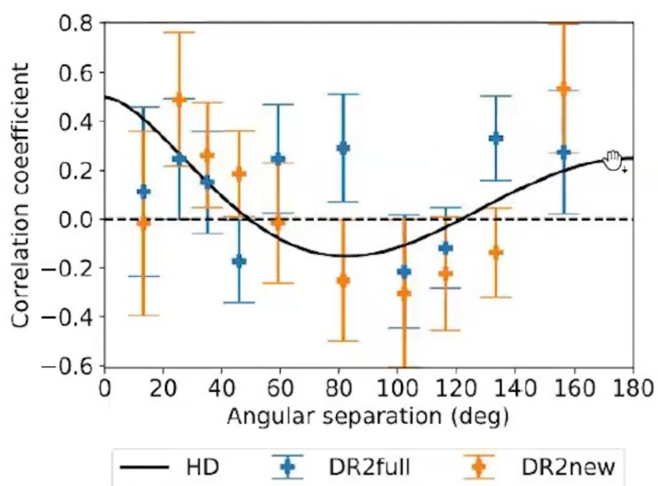

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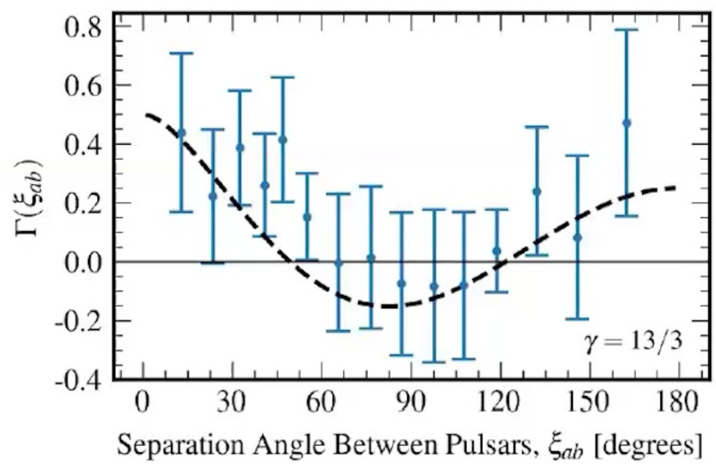


PBH and SGWB

SGWB are produced by a second-order effect when scalar perturbations re-enter the horizon.

Log-likelihood analysis

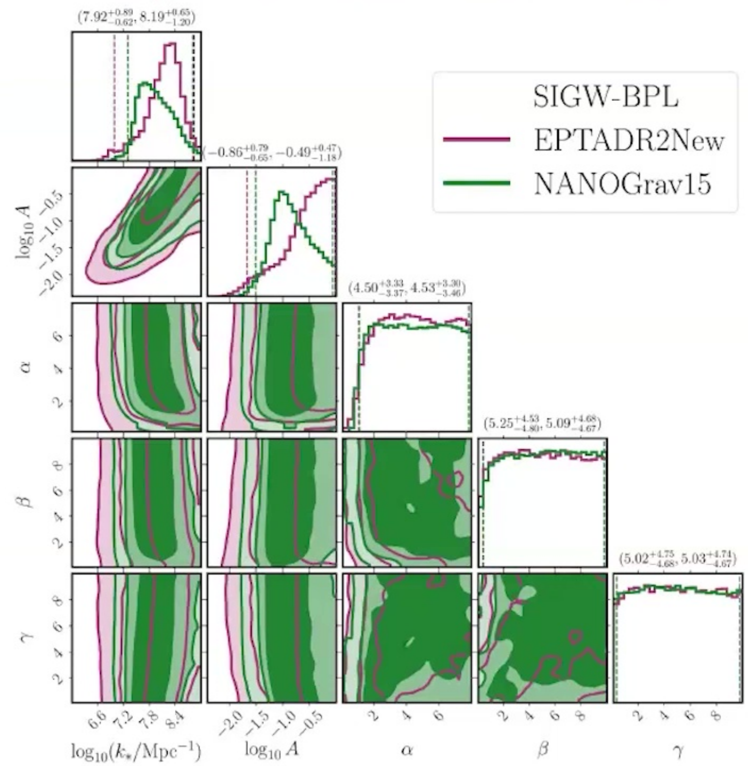
Fitting the posterior distributions

$$\mathcal{P}_\zeta^{\rm BPL}(k) = A\frac{(\alpha+\beta)^\gamma}{\left(\beta\,(k/k_*)^{-\alpha/\gamma}+\alpha\,(k/k_*)^{\beta/\gamma}\right)^\gamma}$$

$$\mathcal{P}_\zeta^{\rm LN}(k) = \frac{A}{\sqrt{2\pi}\Delta}\,\exp\left(-\frac{1}{2\Delta^2}\ln^2(k/k_*)\right)$$

The casuality tail is not good:

$$\Omega_{\rm GW}(k\ll k_*)\propto k^3(1+\tilde{A}\ln^2(k/\tilde{k}))$$



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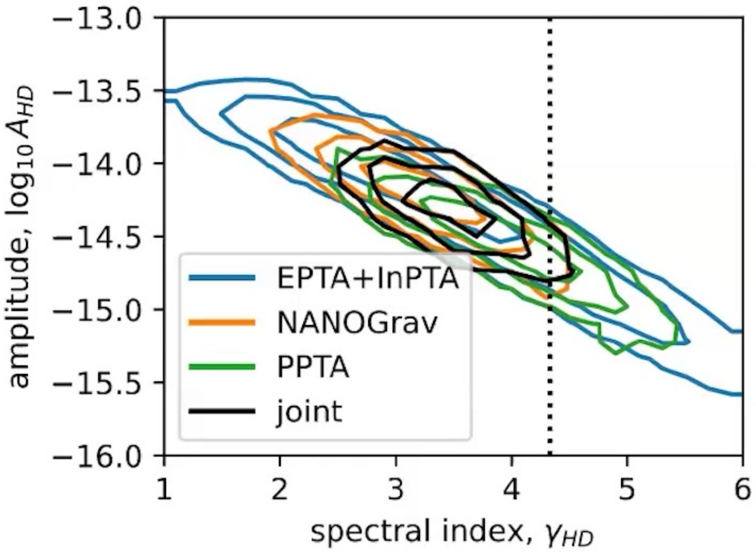

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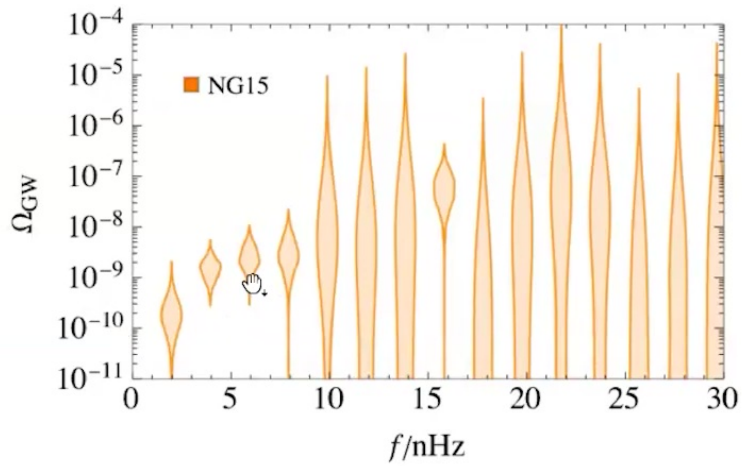

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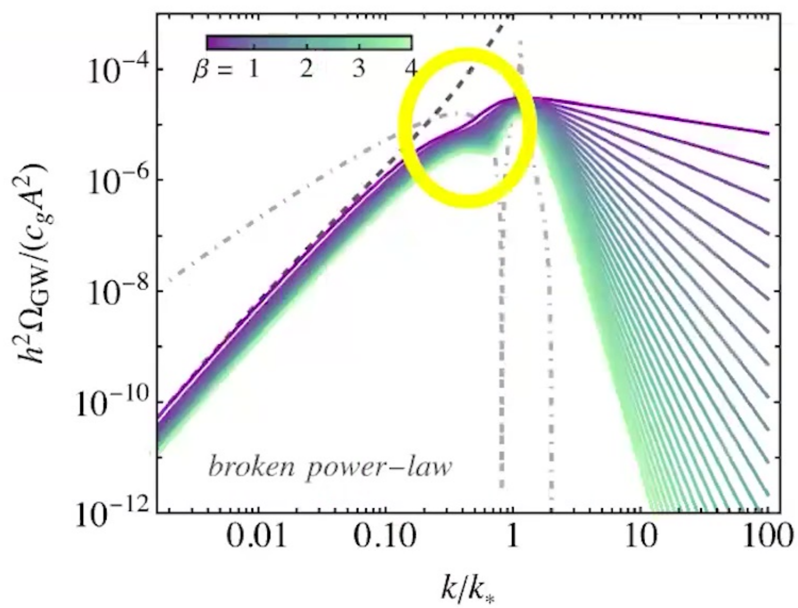

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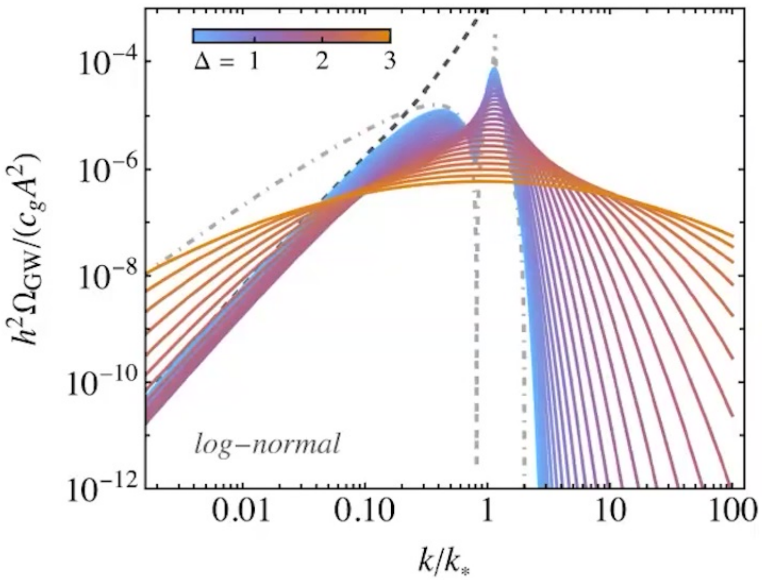
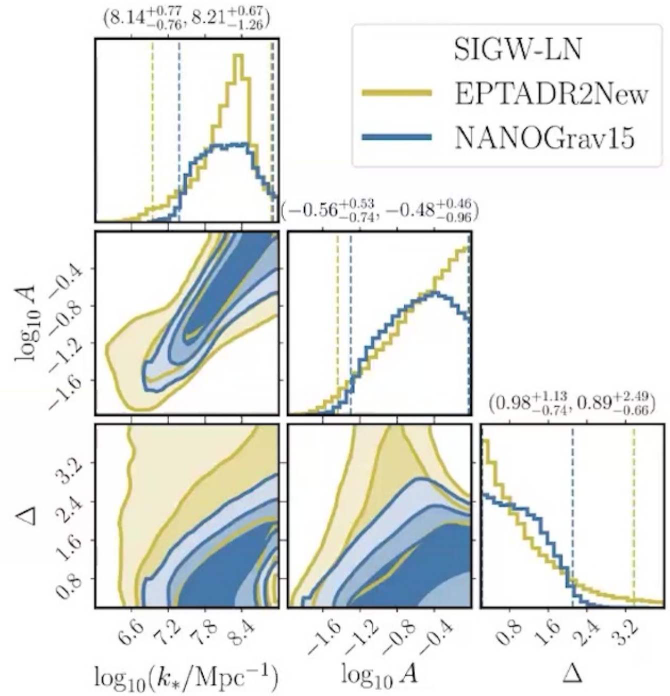


Δ = 1 2 3
$h^2\Omega_{GW}/(c_g A^2)$
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
log−normal
0.01 0.10 1 10 100
k/k_*



$(8.14^{+0.77}_{-0.76}, 8.21^{+0.67}_{-1.26})$
$(-0.56^{+0.53}_{-0.74}, -0.48^{+0.46}_{-0.96})$
$(0.98^{+1.13}_{-0.74}, 0.89^{+2.49}_{-0.66})$
SIGW-LN
EPTADR2New
NANOGrav15
$\log_{10} A$
−0.4 −0.8 −1.2 −1.6
Δ
3.2 2.4 1.6 0.8
6.6 7.2 7.8 8.4
$\log_{10}(k_*/\mathrm{Mpc}^{-1})$
−1.6 −1.2 −0.8 −0.4
$\log_{10} A$
0.8 1.6 2.4 3.2
Δ

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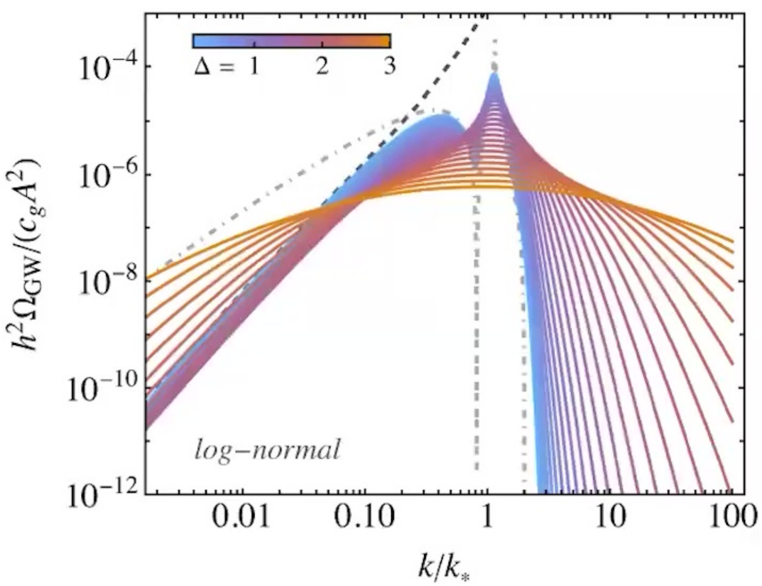
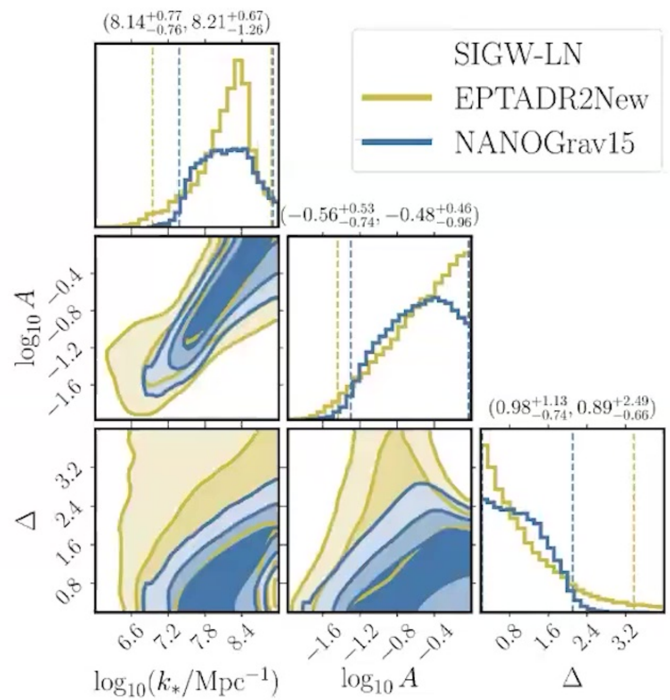

$\Delta = 1 \quad 2 \quad 3$
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$h^2\Omega_{\rm GW}/(c_g A^2)$
log−normal
0.01
0.10
1
10
100
k/k_*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$\log_{10} A$
−0.4
−0.8
−1.2
−1.6
Δ
3.2
2.4
1.6
0.8
6.6
7.2
7.8
8.4
$\log_{10}(k_*/\mathrm{Mpc}^{-1})$
−1.6
−1.2
−0.8
−0.4
$\log_{10} A$
0.8
1.6
2.4
3.2
Δ


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Improvement respect to NANOGrav analysis.

NANOGrav collaboration
arXiv:2306.16219

Power spectrum <> Abundance <> GWs

- Non-Gaussianities in the abundance.
- Dependency of the PBH formation parameters on the PS shape.
- QCD impact on threshold.

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NGs in the abundance: Cases under consideration

NON-LINEARITIES (NL)

$$\delta(\vec{x},t) = -\frac{2}{3}\Phi\left(\frac{1}{aH}\right)^2 e^{-2\zeta(\vec{x})}\left[\nabla^2\zeta(\vec{x}) + \frac{1}{2}\partial_i\zeta(\vec{x})\partial_i\zeta(\vec{x})\right]$$

$$\delta(\vec{x},t) = -\frac{4}{9a^2H^2}\nabla^2\zeta(\vec{x})$$

PRIMORDIAL NG IN $\zeta = F(\zeta_G)$

$$\zeta = \log\left[X(r_{\rm dec},\zeta_{\rm G})\right]$$

curvaton case

$$\zeta = -\frac{2}{\beta}\log\left(1-\frac{\beta}{2}\zeta_{\rm G}\right)$$

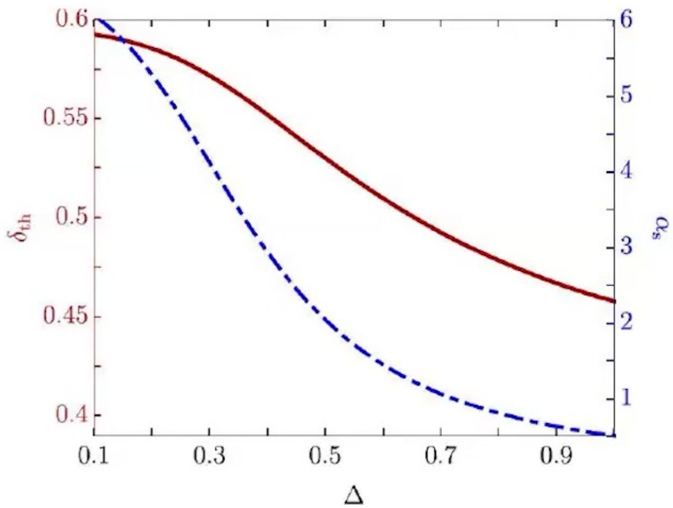
Inflection-point (USR) case

$$\zeta = \zeta_{\rm G} + \frac{3}{5}f_{\rm NL}\zeta_{\rm G}^2$$

Quadratic approx.

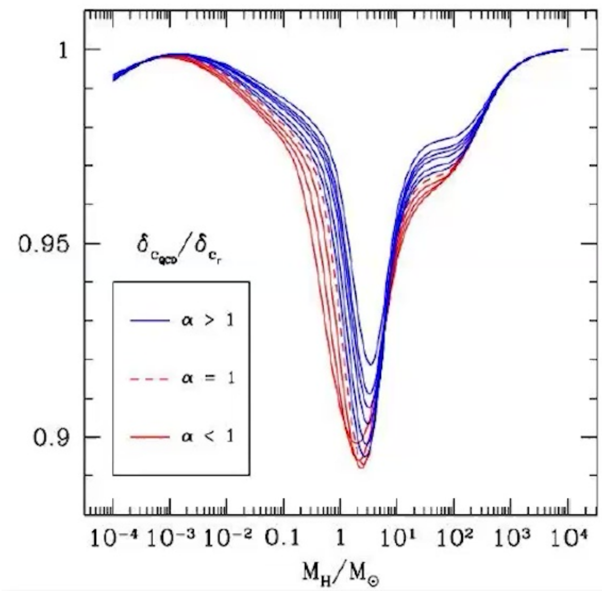
Abundance of PBHs: Shape dependencies

I. Musco,V. De Luca, G. Franciolini, A.Riotto.– arXiv:2011.03014



QCD phase transitions

I. Musco, K.Jedamzik, S.Young.– arXiv:2303.07980



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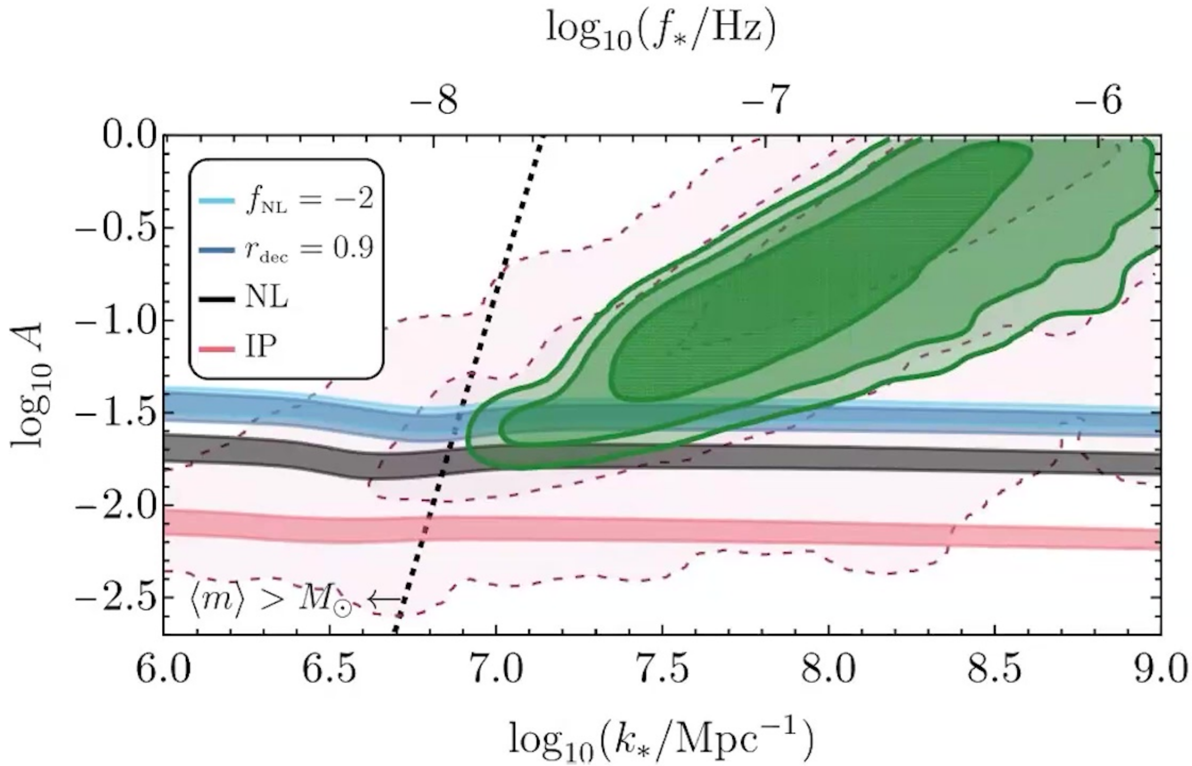
Tension between NANOGrav and PBHs



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Conclusions

- *Fundamental to take into account both kind of NGs in the computation for the abundance.*

- *Negative NGs to alleviate the tension between PTA and PBH overproduction.*

A potential issue

Threshold values maybe are not correct? Different super-horizon threshold conditions may lead to an overestimation of the abundance, due to non-linear effects not included in the linear transfer function. *Next step: we need a new prescription.*

V. De Luca, A. Kehagias, A. Riotto.– arXiv:2307.13633

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