Antonio Junior Iovino

Timekeepers of the Universe: The recent gravitational wave observation by PTA and PBH

SAPIENZA
UNIVERSITÀ DI ROMA

NEHOP
NEW HORIZONS IN PRIMORDIAL BLACK HOLE PHYSICS

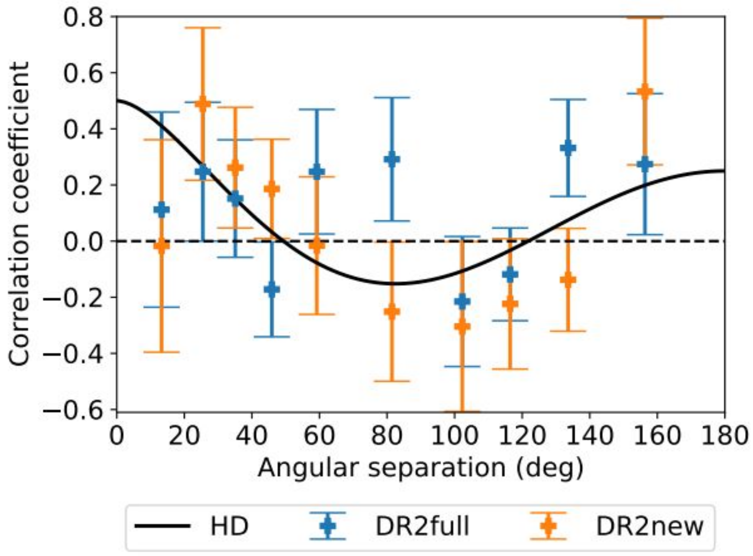
UNIVERSITÉ DE GENÈVE

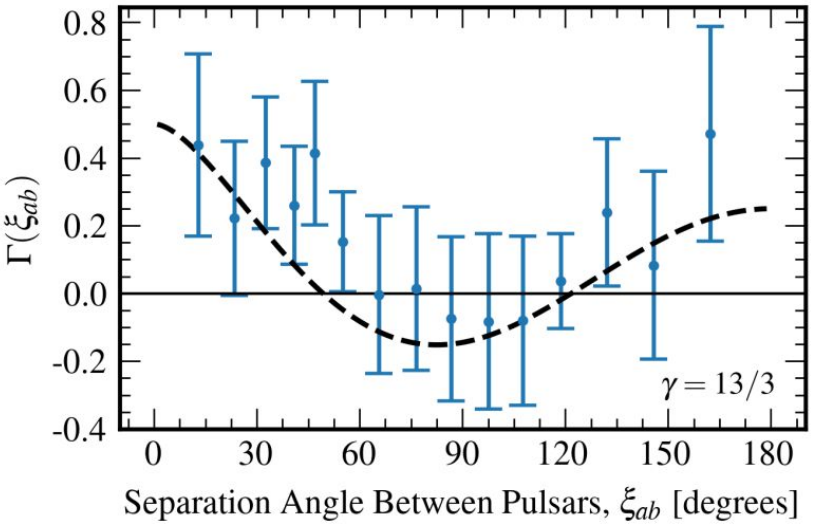
PBH and SGWB

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

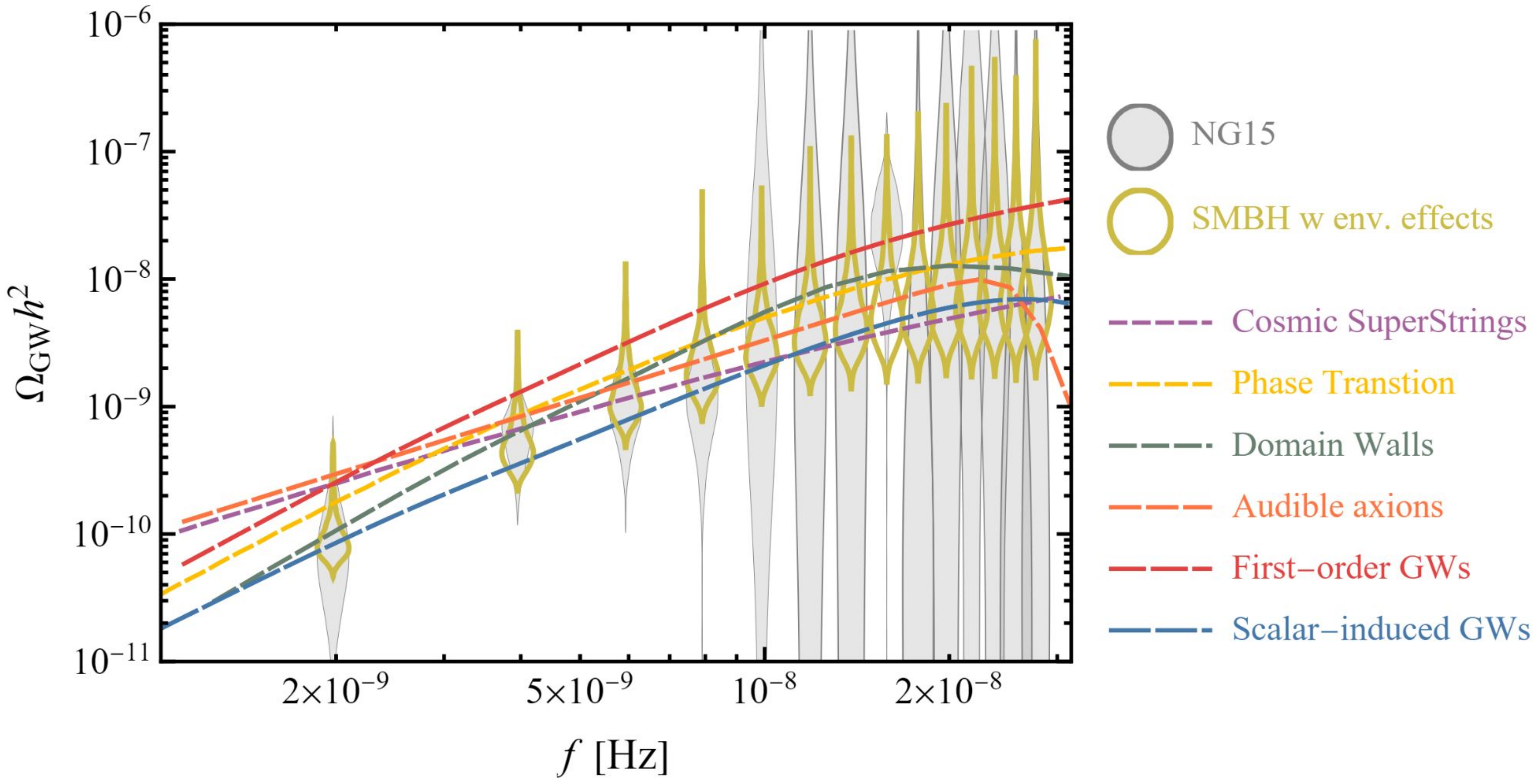




What is the PTA source?

arXiv:2308.08546 J. Ellis A.J.I. et *al (PRD)*

All the PTA possible sources: Astro vs Cosmo



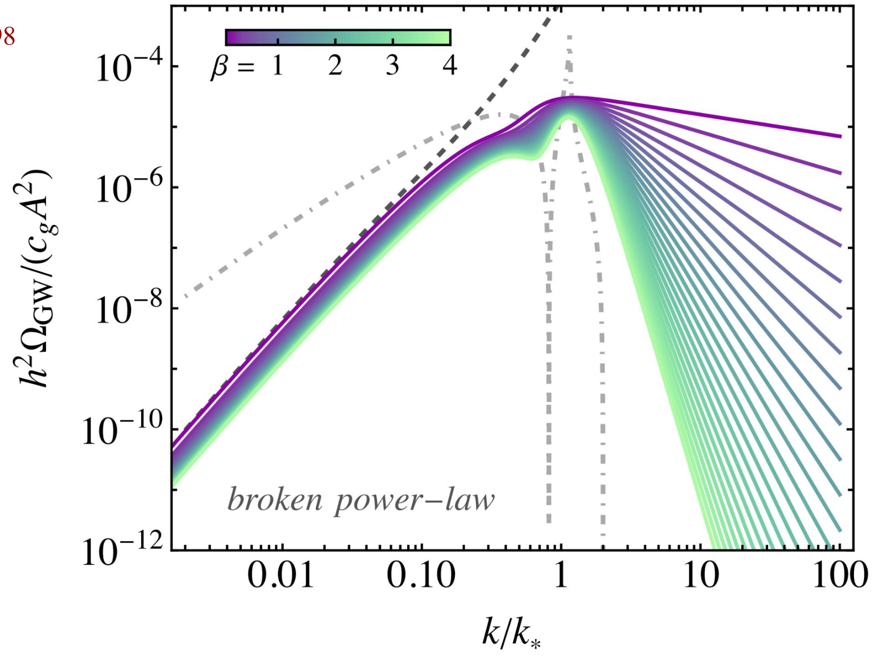
PBH and SGWB

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

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

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

REVIEW G. Domenech– arXiv:2109.01398



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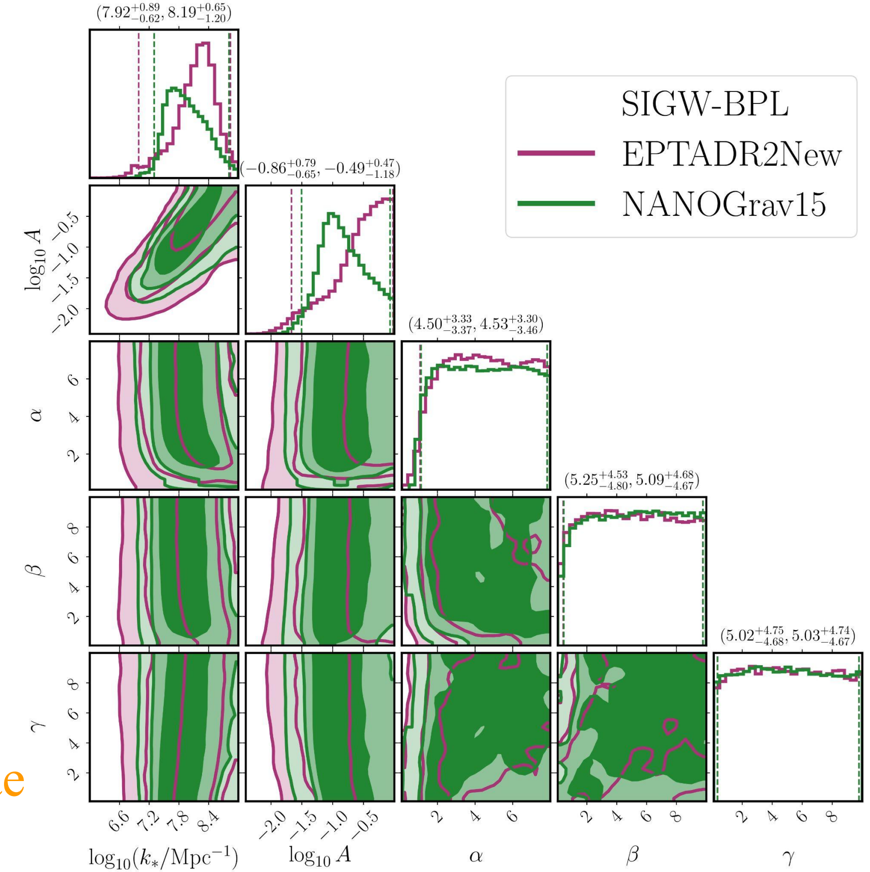
Log-likelihood analysis

Fitting the posterior distributions

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

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



arXiv:2306.17149 *(PRL)*

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

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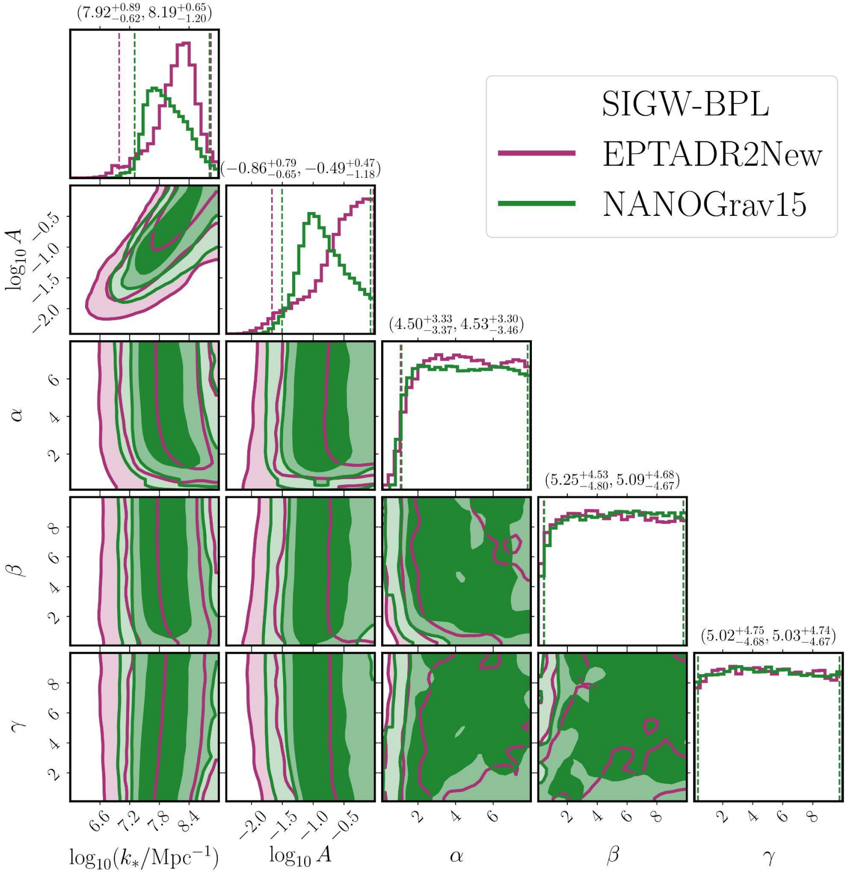
Results:

The casuality tail is not good:

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



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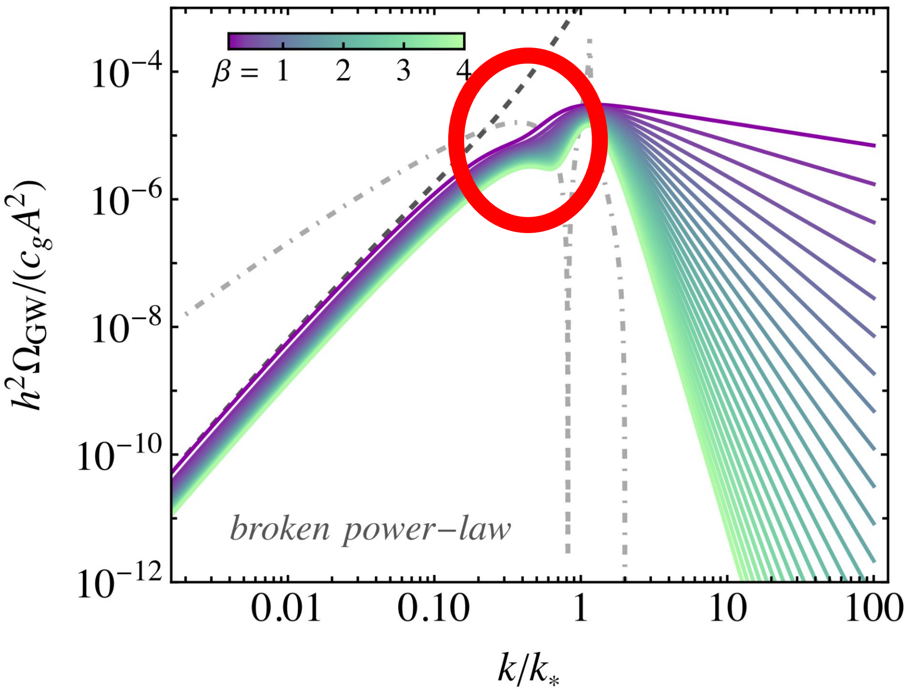

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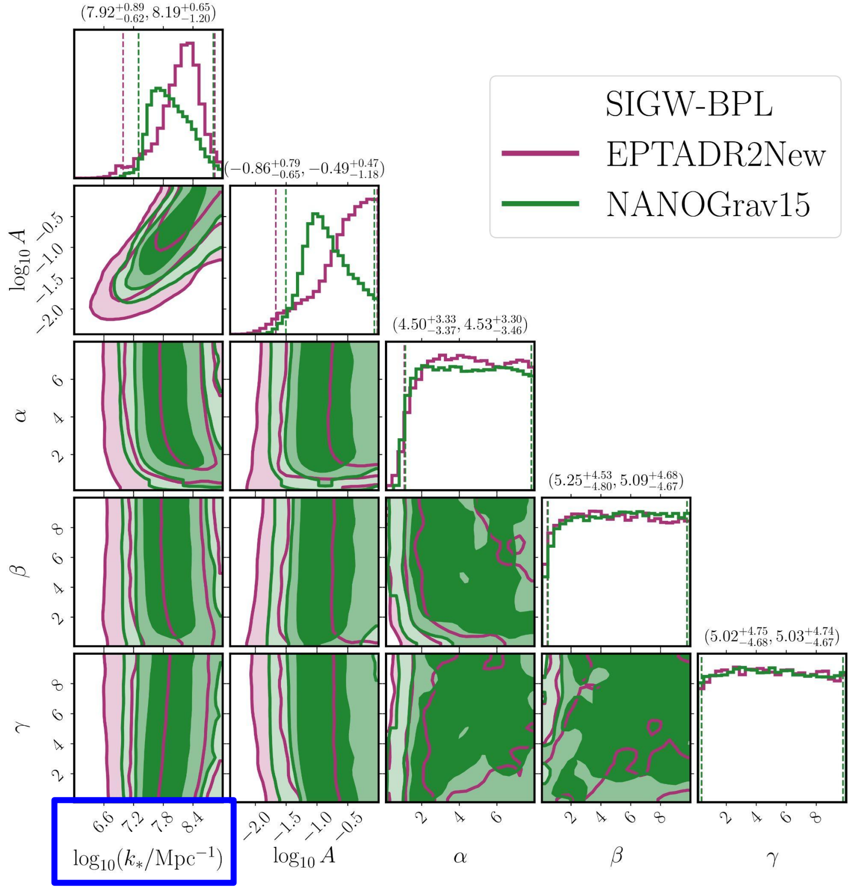
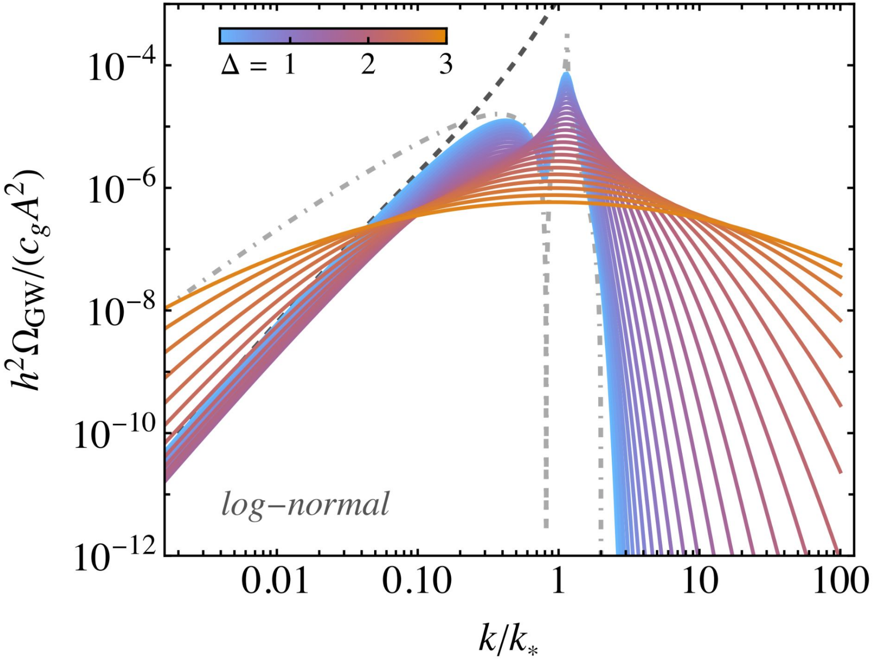
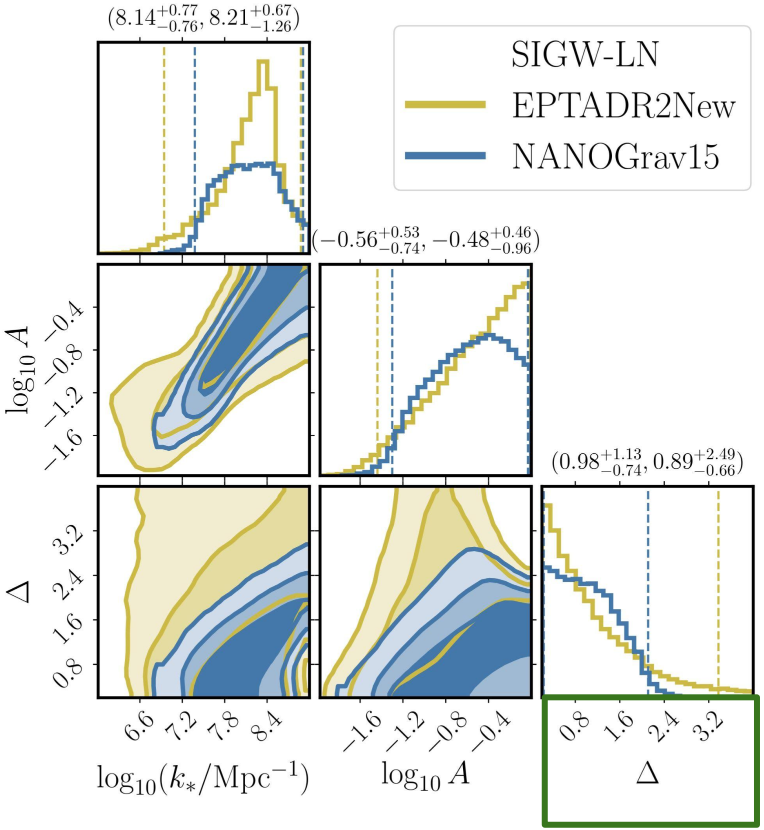
Results:

Position of the peak at higher frequencies.

Broad spectrum does not fit so well.







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

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.

Abundance of PBHs: The role of NGs.

Threshold statistics on the compaction function

G.Ferrante, G. Franciolini, A.J.I. A.Urbano.–arXiv:2211.01728
A.Gow *et al*– arXIv:2211:08348

NON-LINEARITIES (NL)

$$\delta(r,t) = -\frac{2}{3}\Phi\left(\frac{1}{aH}\right)^2 e^{-2\zeta(r)}\left[\zeta''(r) + \frac{2}{r}\zeta'(r) + \frac{1}{2}\zeta'(r)^2\right]$$

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

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

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

curvaton case

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

Inflection-point (IP or USR) case

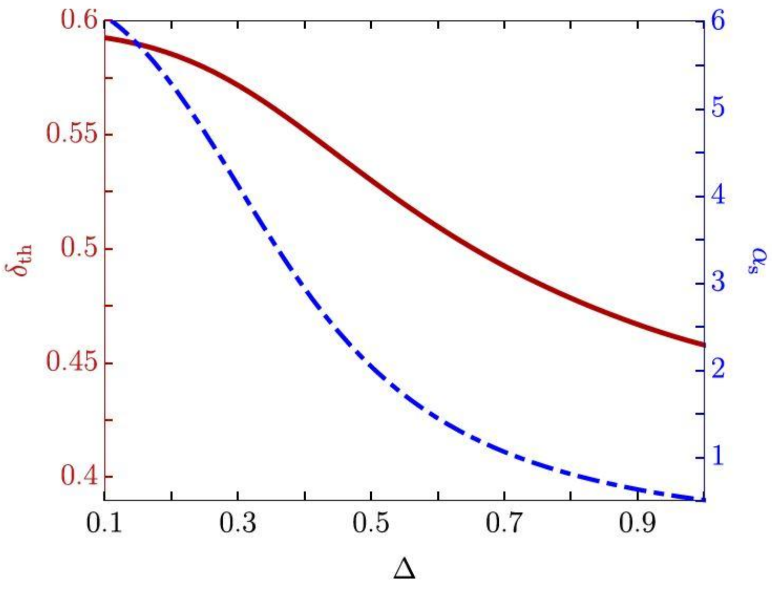
$$\zeta = \zeta_G + \frac{3}{5} f_{\rm NL}\zeta_G^2$$

Quadratic approx.

Abundance of PBHs: Shape dependencies

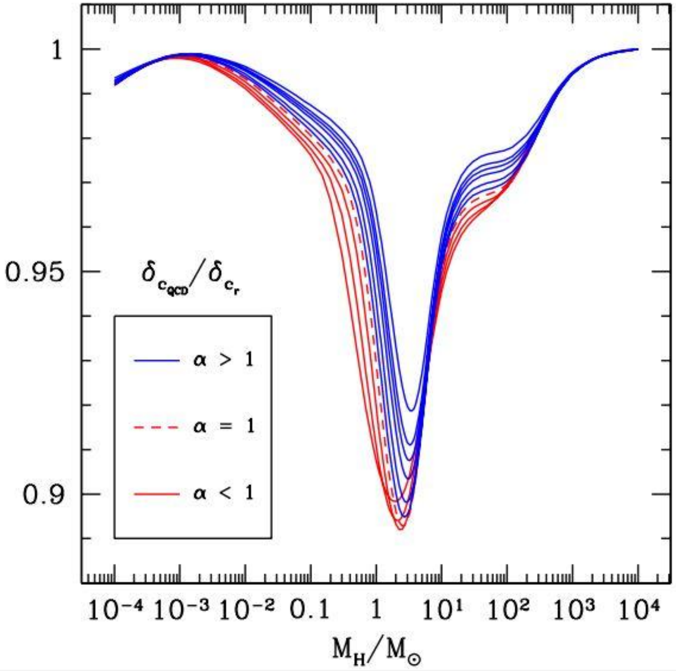
See Musco's Talk

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



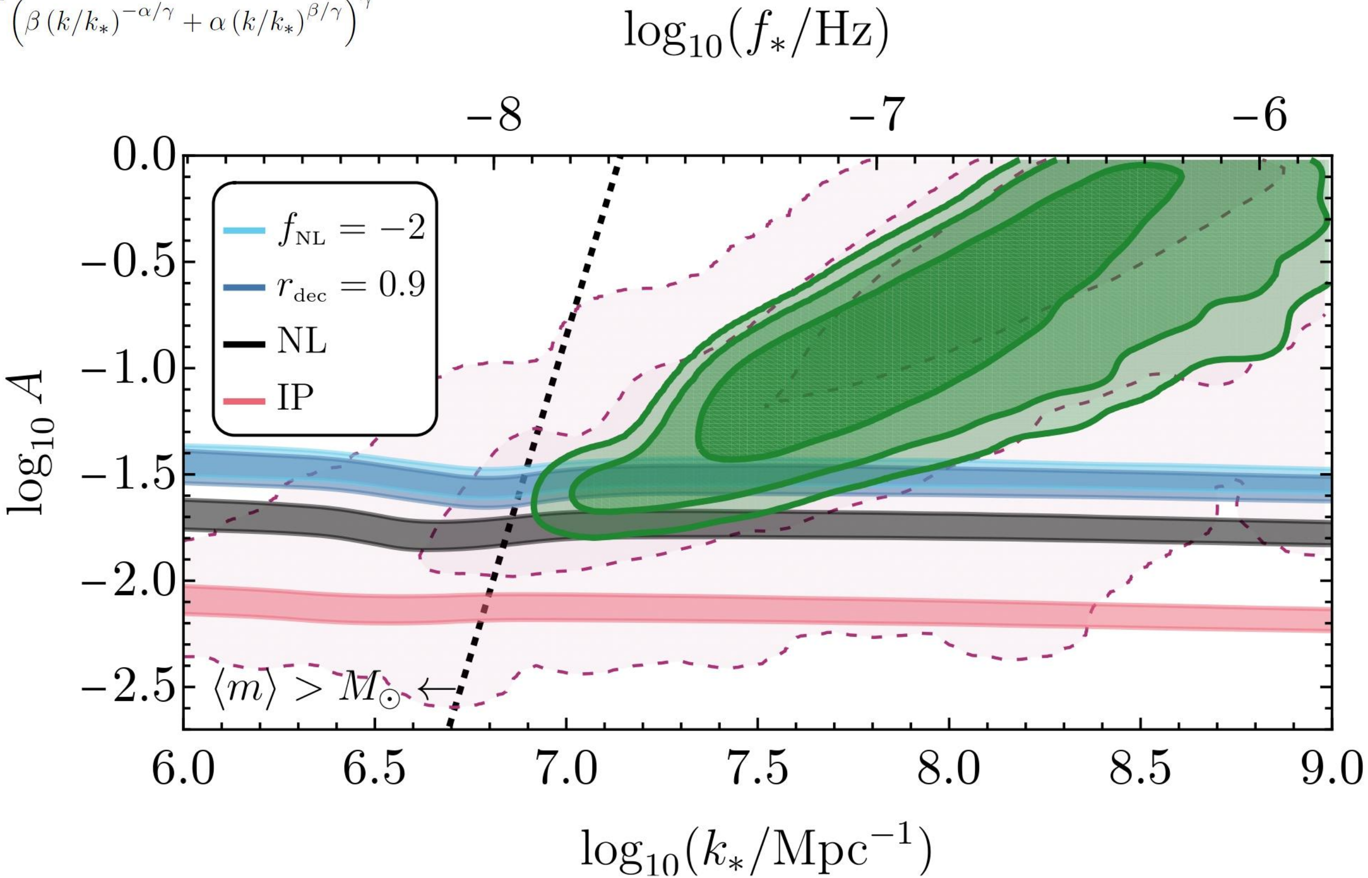
QCD phase transitions

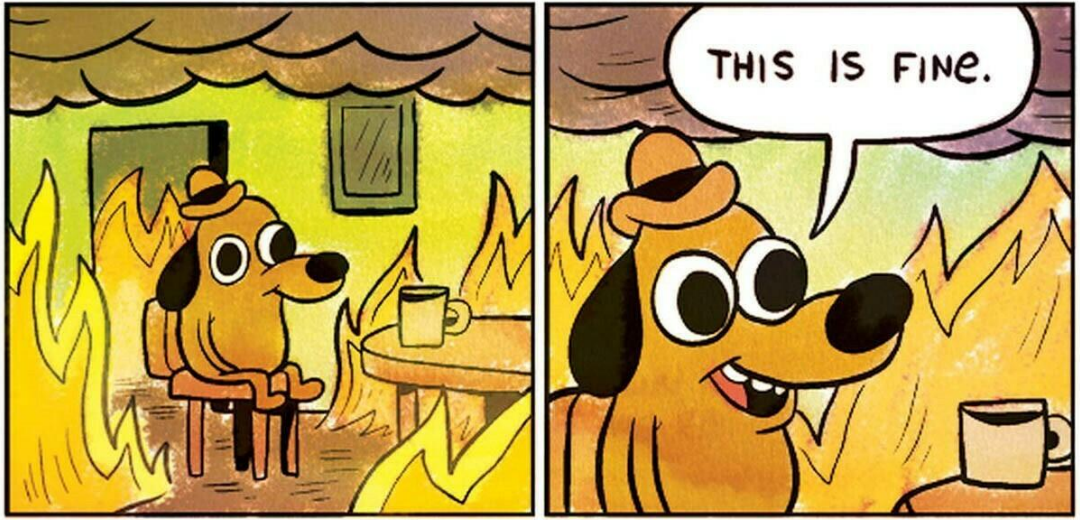
I. Musco, K.Jedamzik, S.Young.– arXiv:2303.07980

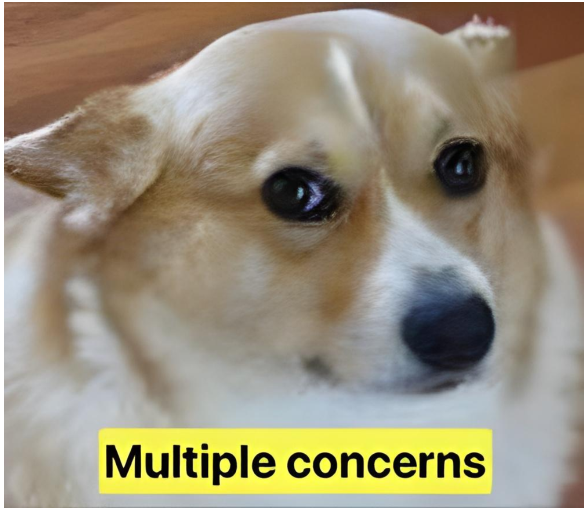


Tension between NANOGrav and PBHs

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







A potential issue

When we compute the threshold using the average value for the compaction, non-linear effects not included in the linear transfer function lead to different super-horizon threshold conditions.

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

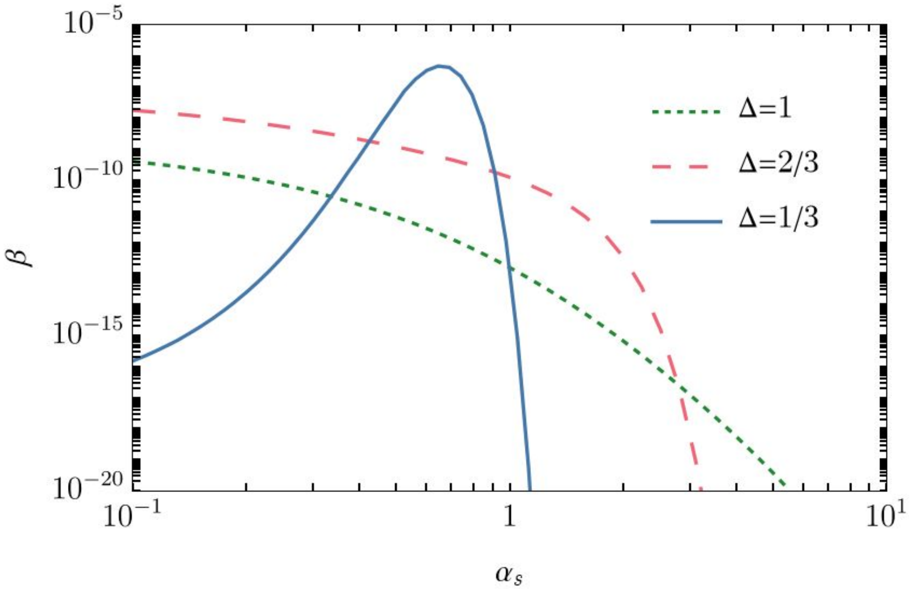
Going beyond the average profile

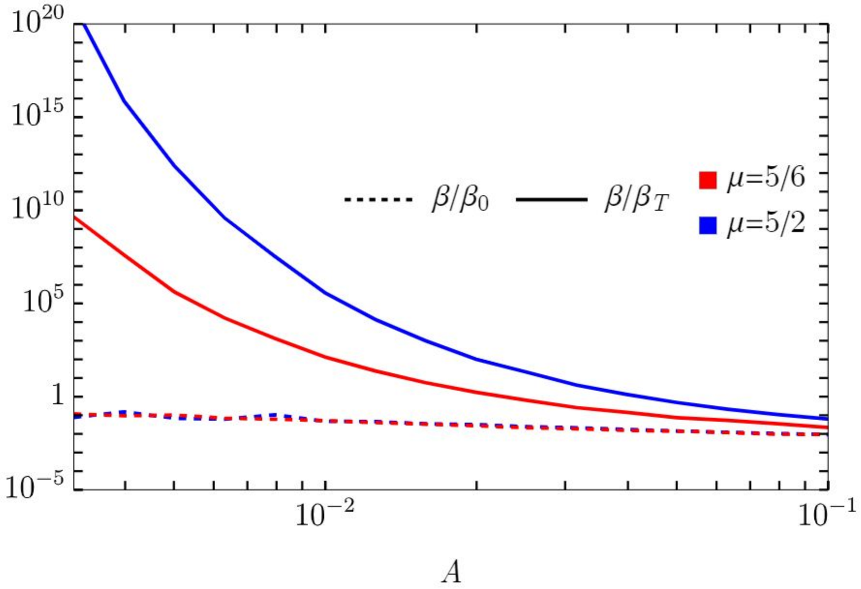
arXiv:2402.11033 A.Ianniccari, A.J.I., A. Kehagias, D. Perrone, A. Riotto (PRD)

In realistic cases, threshold is determined by the broadest possible compaction function.

$$\mathcal{P}_{\rm g}(k) = \frac{A}{\sqrt{2\pi}\Delta}\exp\left[-\ln^2(k/k_\star)/2\Delta^2\right]$$

$$\zeta(\mathbf{x}) = -\mu_\star \ln\left(1 - \frac{\zeta_{\rm g}(\mathbf{x})}{\mu_\star}\right)$$





We need to reduce the amplitude of a factor O(2-3), so PTA-PBH tension is exacerbated

Conclusions

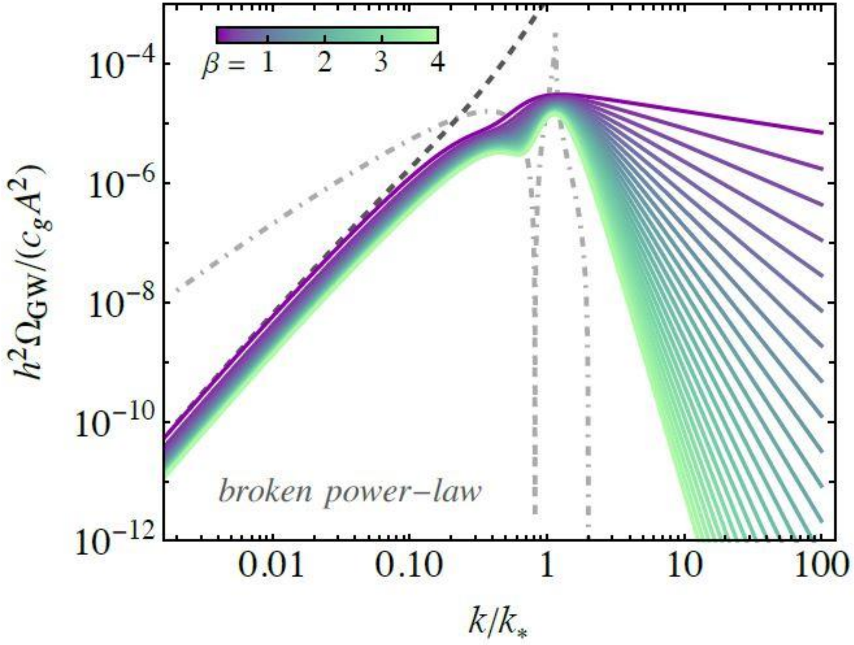
Negative NGs to alleviate the tension between PTA and PBH overproduction.

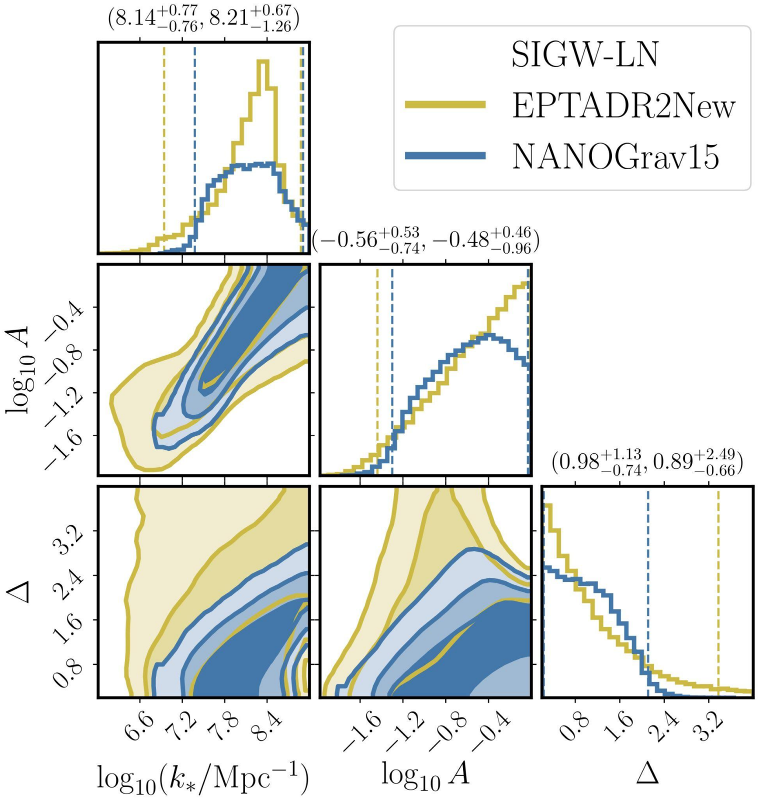
There is still a lot of uncertainties in the way we compute the PBH abundance and on the possibility that they maybe the PTA explanation .*

**A.J.I.*, *G.Perna, A. Riotto and H. Veermae to appear*

Thank you

Back-up slides





Threshold statistics on the Compaction: 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

NG PBH mass fraction-distribution adopting threshold statistics on the compaction function

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

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

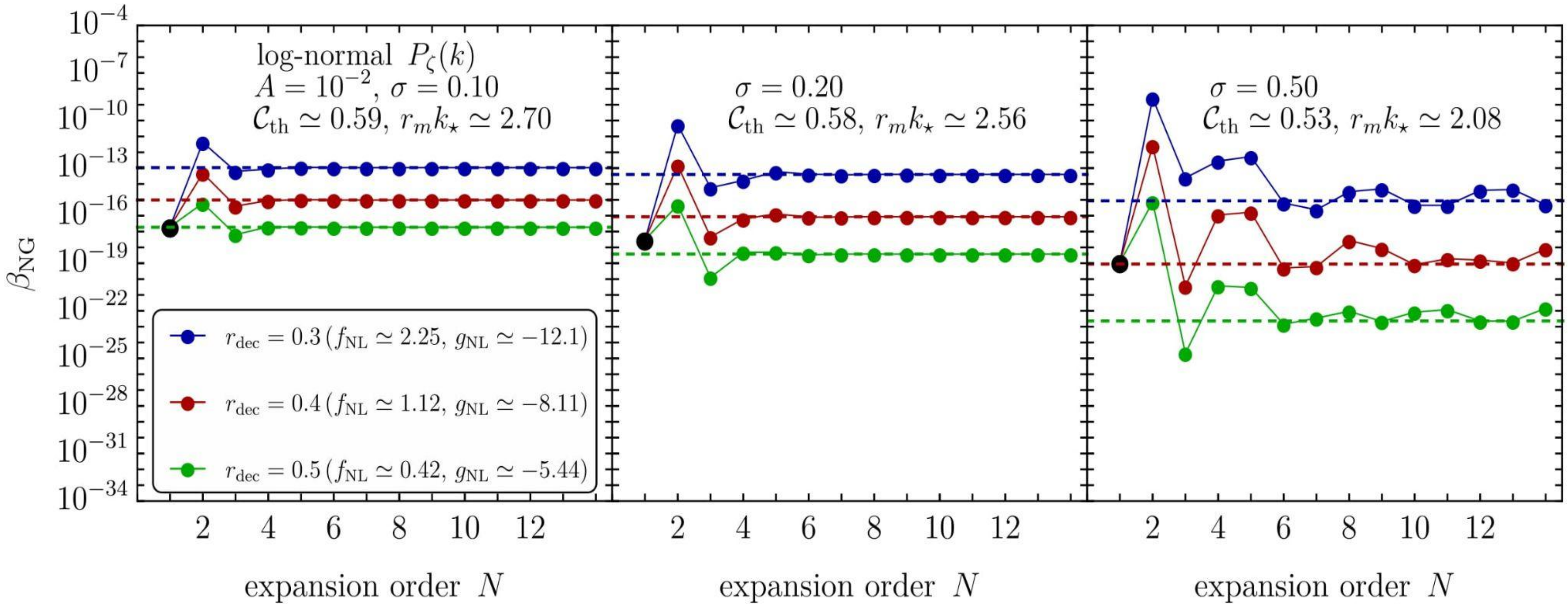
$$f_{\rm PBH}(M_{\rm PBH}) = \frac{1}{\Omega_{\rm DM}} \int_{M_{\rm H}^{\rm min}(M_{\rm PBH})} d\log M_{\rm H} \left(\frac{M_{\rm eq}}{M_{\rm H}}\right)^{1/2} \left[1 - \frac{\mathcal{C}_{\rm th}}{\Phi} - \frac{1}{\Phi}\left(\frac{M_{\rm PBH}}{\mathcal{K} M_H}\right)^{1/\gamma}\right]^{-1/2} \frac{\mathcal{K}}{\gamma} \left(\frac{M_{\rm PBH}}{\mathcal{K} M_{\rm H}}\right)^{\frac{1+\gamma}{\gamma}}$$
$$\times \int d\zeta_{\rm G} P_{\rm G}(\mathcal{C}_{\rm G}(M_{\rm PBH}, \zeta_{\rm G}), \zeta_{\rm G} | M_{\rm H}) \left(\frac{dF}{d\zeta_{\rm G}}\right)^{-1}.$$

Quadratic gives wrong result

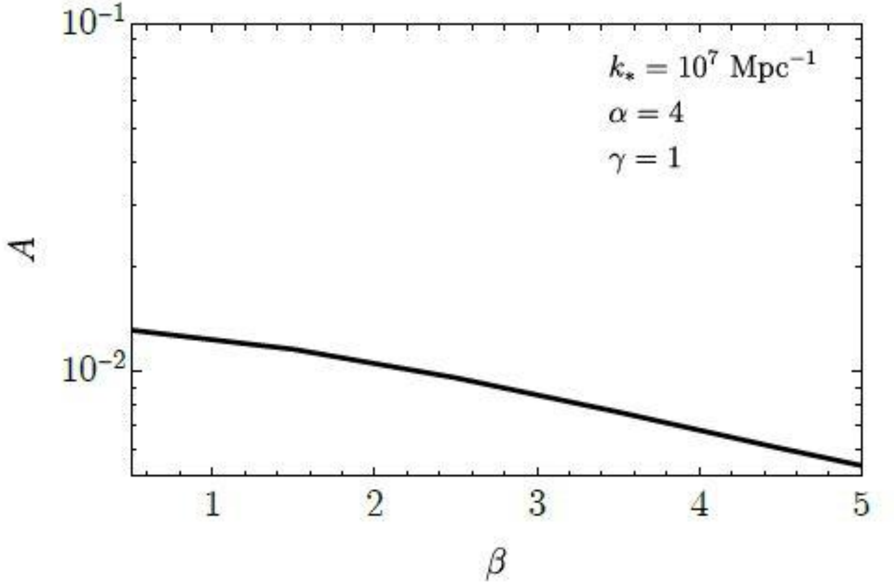
Failure of the perturbative approach (Narrow)

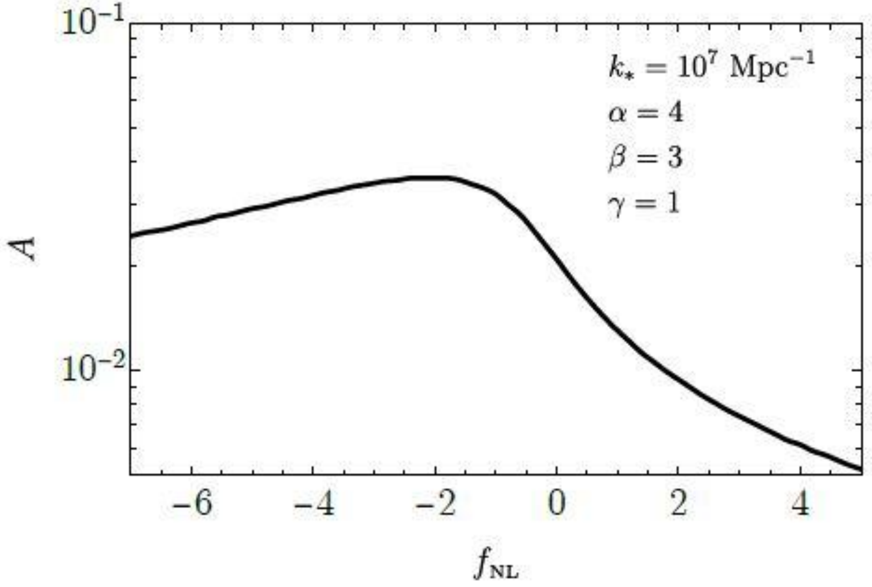
- - - - $\zeta = \log[X(r_{\rm dec}, \zeta_{\rm G})]$

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



NG generic features





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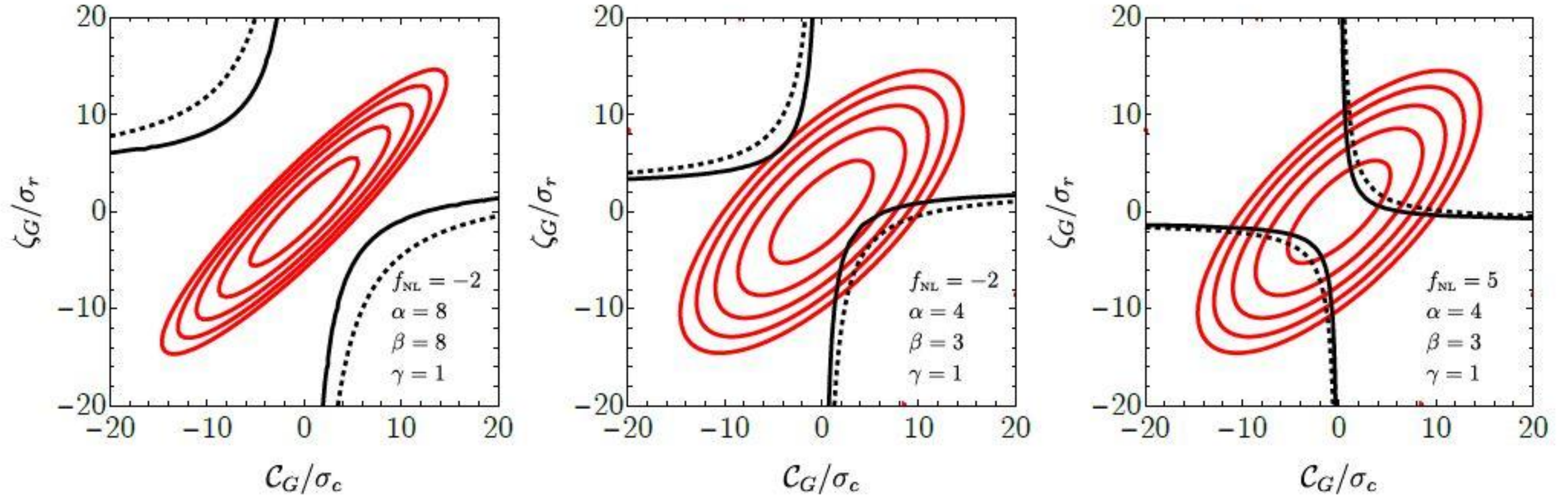

FIG. S4. Two dimensional PDF as a function of $(\mathcal{C}_G, \zeta_G)$ compared to the over-threshold condition $\mathcal{C} > \mathcal{C}_{th}$. In all panels, we considered the BPL power spectrum with an amplitude $A = 0.05$. The red lines indicates the contour lines corresponding to $\log_{10}(P_G) = -45, -35, -25, -15, -5$. The collapse of type-I PBHs take place between the black solid and dashed lines (see more details in Ref. [195]). *Left panel:* Example of a very narrow power spectrum with $\alpha = \beta = 8$. The abundance is suppressed in the presence of negative f_{NL} by the strong correlation between $\mathcal{C}_G$ and ζ_G obtained for narrow spectra. *Center panel:* Example of negative non-Gaussianity and representative BPL spectrum. The PBH formation is sourced by regions of small ζ_G and positive $\mathcal{C}_G$ or both negative $\mathcal{C}_G$ and ζ_G. *Right panel:* Example with positive f_{NL}, showing the region producing PBHs populates the correlated quadrants of the plot, at odds with that is found in the other panels.

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NANOGrav – arXiv:2306.16213
arXiv:2306.16219

IPTA – arXiv:2309.00693