جامعة نيويورك أبوظبي
NYU | ABU DHABI

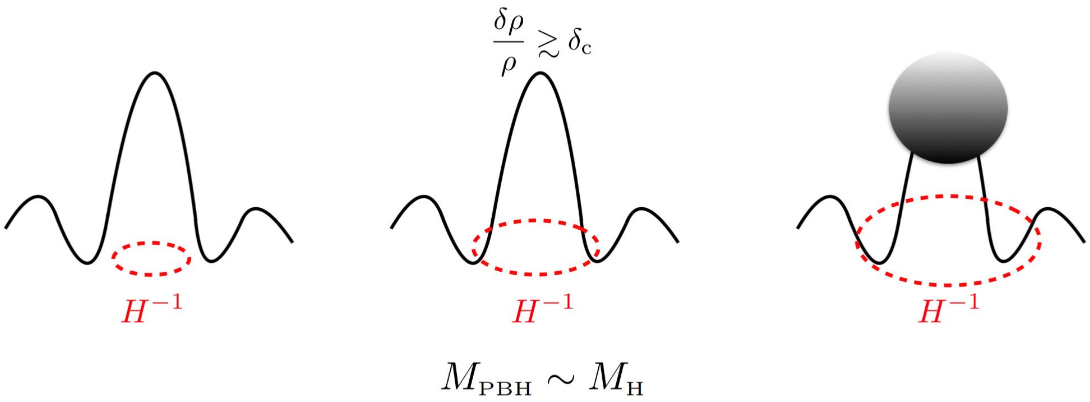
Antonio J. Iovino
PBH and SIGW: Lessons from PTA

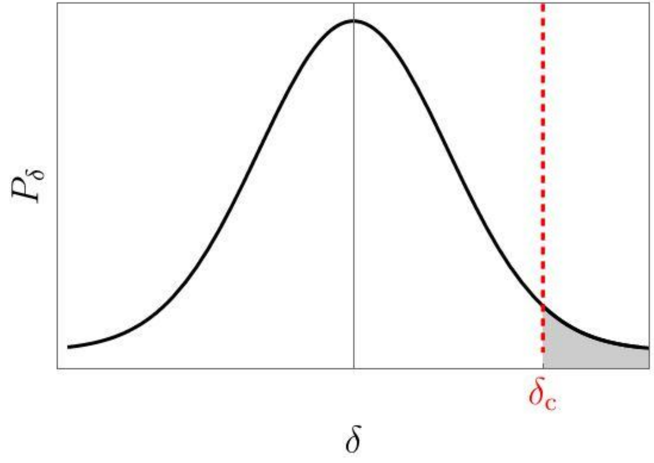
PBHs from collapse of large overdensities

Black holes in the early Universe
B.Carr and S.Hawking
(1974) Mon.Not.Roy.Astron.Soc.

Different from Astro Black holes (gravitational collapse of a star)

- Dark Matter today,
- Some of the events in LVK
- Seed for supermassive black holes and LSS





What we can compute during inflation is the curvature perturbation field ζ (or *R*).
In order to get a sizeable amount of DM $P_\zeta \simeq 0.01$

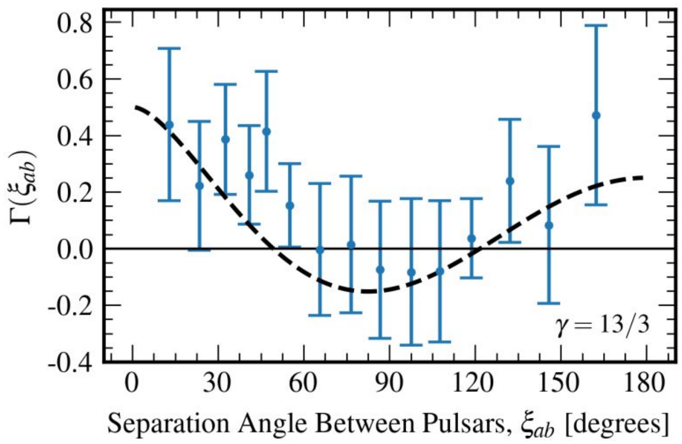
PBH and SIGW

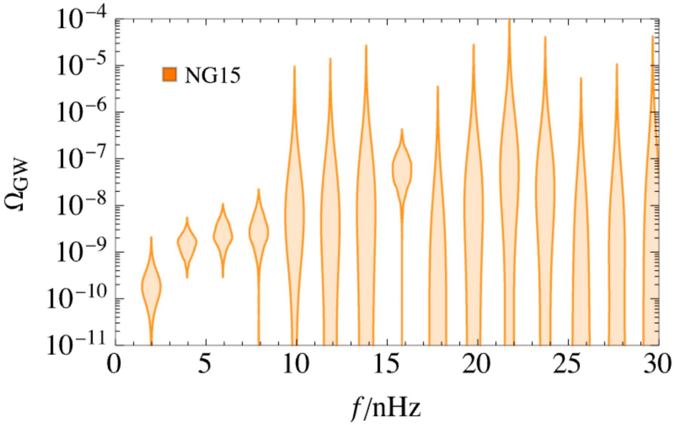
SIGW are produced by a second-order effect when scalar perturbations re-enter the horizon.

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

$$f \simeq 5\,\mathrm{kHz}\left(\frac{m_{\rm H}}{10^{-24}M_\odot}\right)^{-1/2}$$

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

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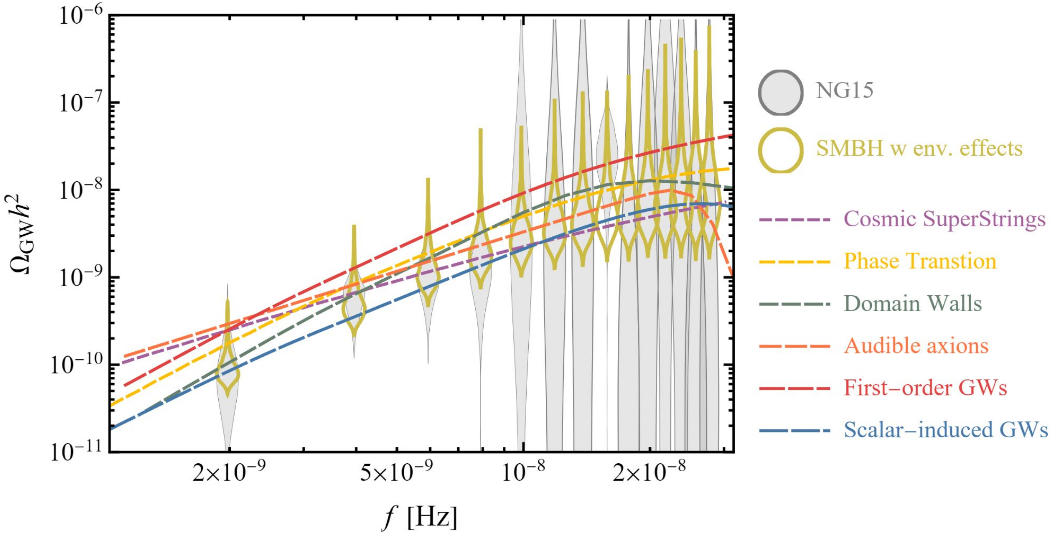


arXiv:2308.08546
J. Ellis et *al (PRD)*

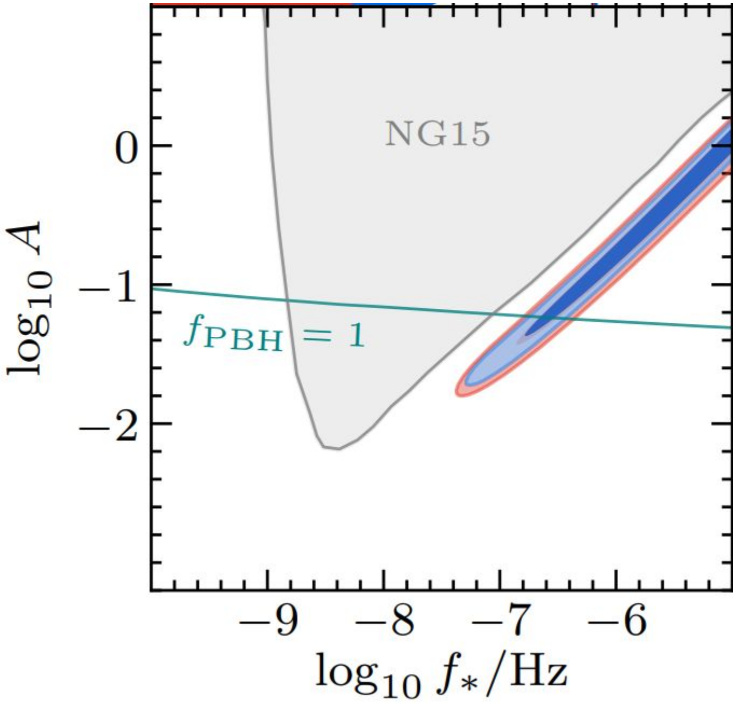
SIGW as a possible explanation for NANOGrav

The NANOGrav 15 yr Data Set: Search for Signals from New Physics. (Astrophys.J.Lett.)
NANOGrav Collaboration ArXiv:2306.16219

"There is no tension between the SIGW explanation of Nanograv and the PBH overproduction"

Simplifications:

1) Gaussian Density contrast
2) Threshold independent from the PS Shape
3) Incorrect use of the window function
4) Omission of QCD impact



Fitting the PTA Datasets

EPTA
– arXiv:2306.16214

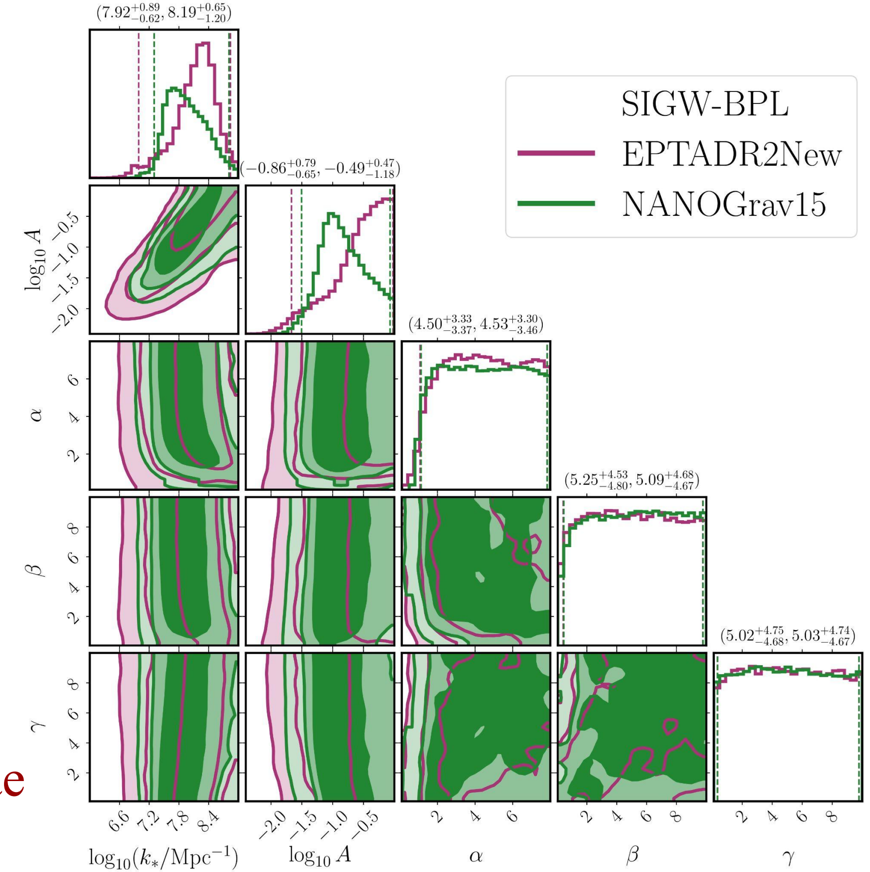
NANOGrav
– arXiv:2306.16213
– arXiv:2306.16219

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, <u>A.J.I.,</u> V. Vaskonen, H. Veermae

Abundance of PBHs: The role of NGs.

Threshold statistics on the compaction function

G.Ferrante, G. Franciolini, **A.J.I**. A.Urbano.
PRD arXiv:2211.01728

NON-LINEARITIES (NL)

$$\delta(\hat{r}) = -\frac{4(1+\omega)}{5+3\omega}\left(\frac{1}{aH}\right)^2 \exp\left(-\frac{5\zeta(r)}{2}\right)\nabla^2 \exp\left(\frac{\zeta(r)}{2}\right)$$

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

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

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

curvaton case

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

Inflection-point (IP or USR) case

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

Quadratic approx.

- The amplitude of the power spectrum
- The shape of the power spectrum (Parameters for the collapse)
- The amount of Non gaussianity (fnl, r_{dec}, and so on…)

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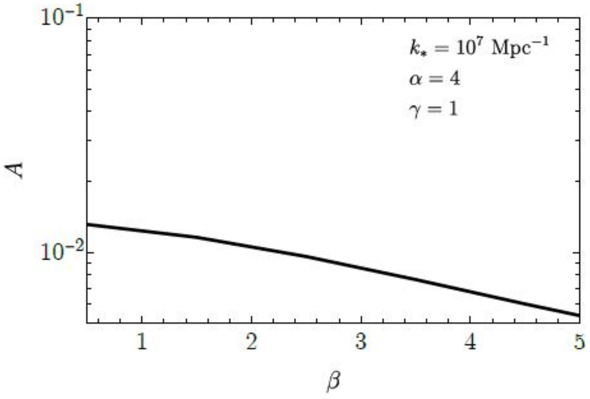
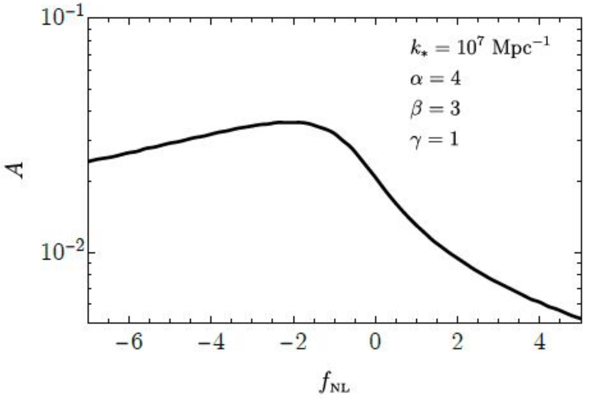
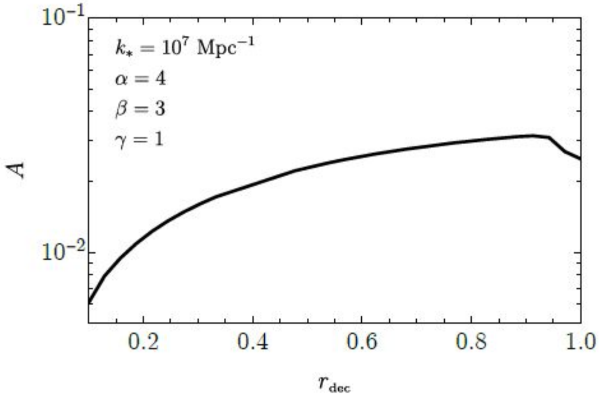


$$\zeta = \zeta_G + \frac{3}{5} f_{NL}\zeta_G^2$$



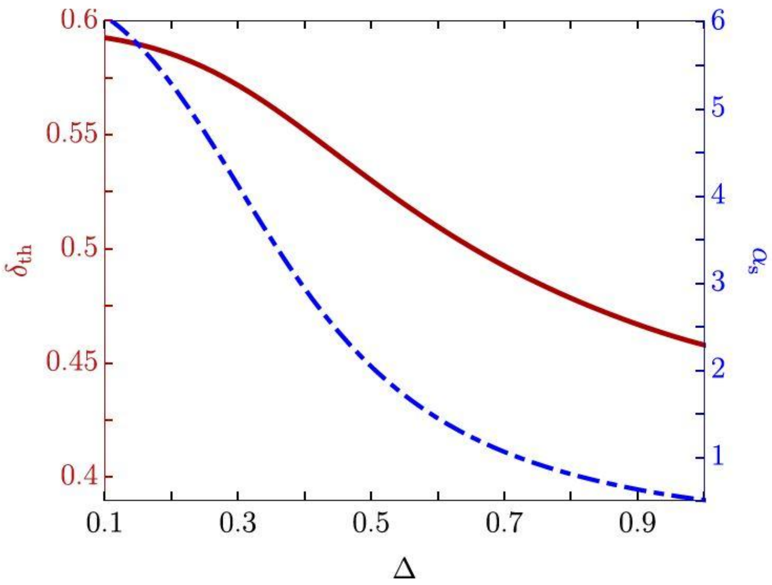
$$\zeta = \log\left[X(r_{dec},\zeta_G)\right]$$



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

Abundance of PBHs: Shape dependencies

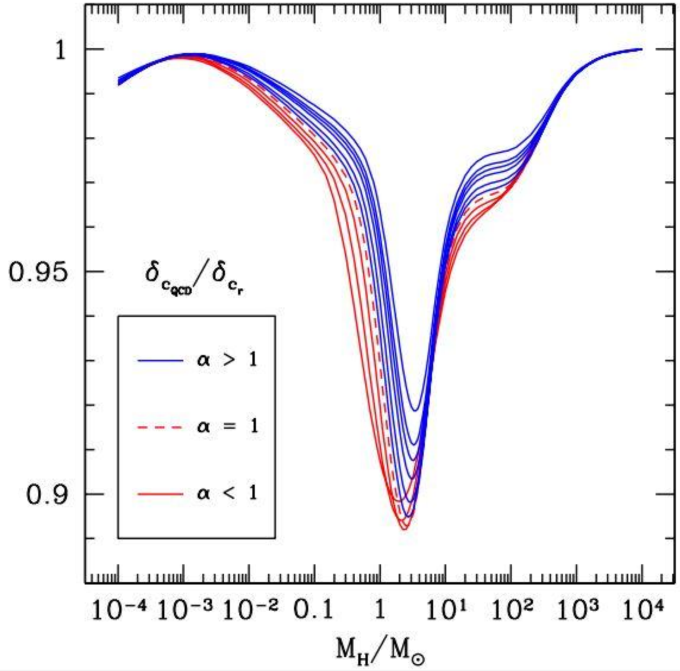
I. Musco,V. De Luca, G. Franciolini, A.Riotto.– arXiv:2011.03014



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

QCD phase transitions

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



Tension between NANOGrav and PBHs

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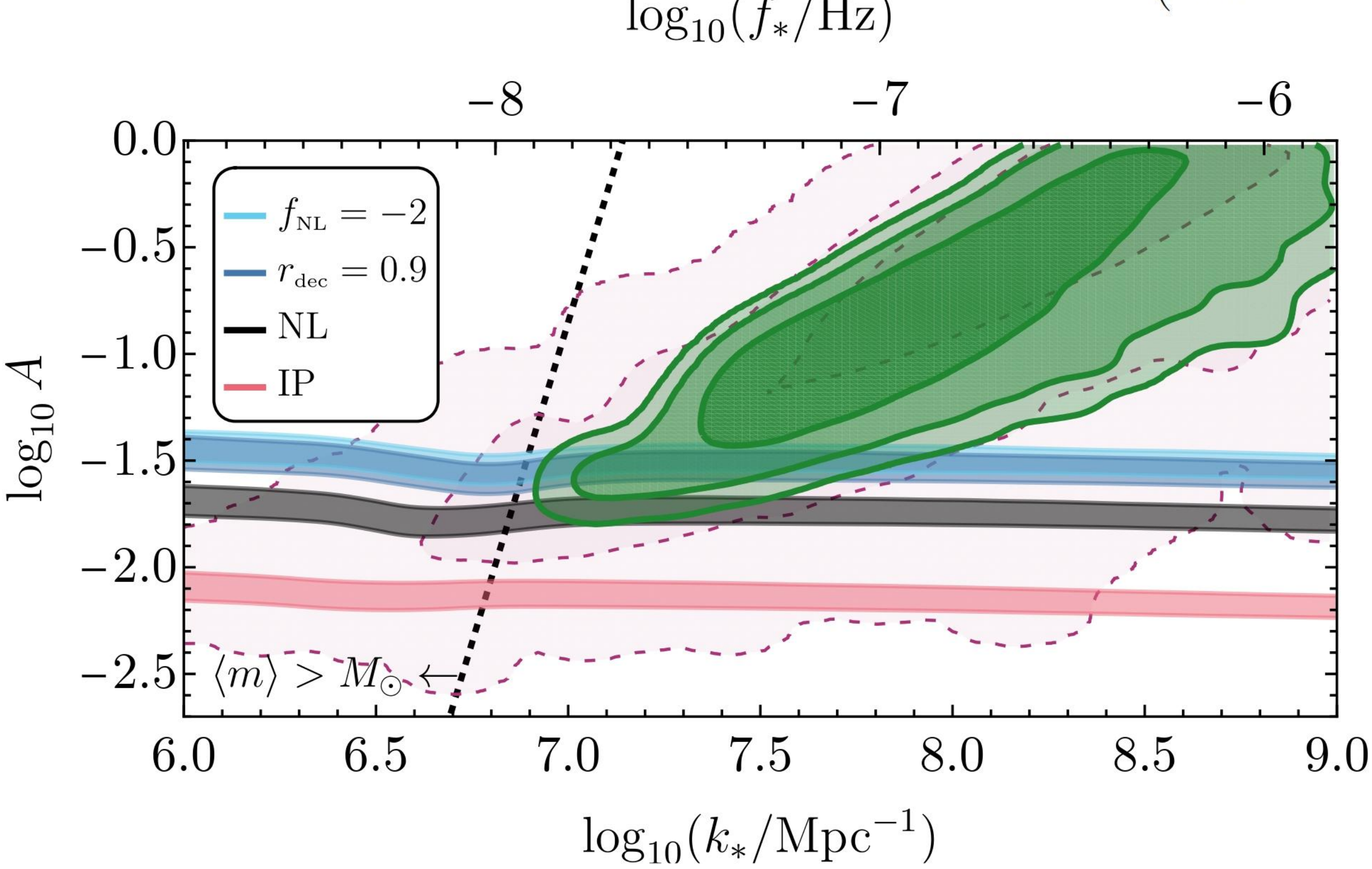
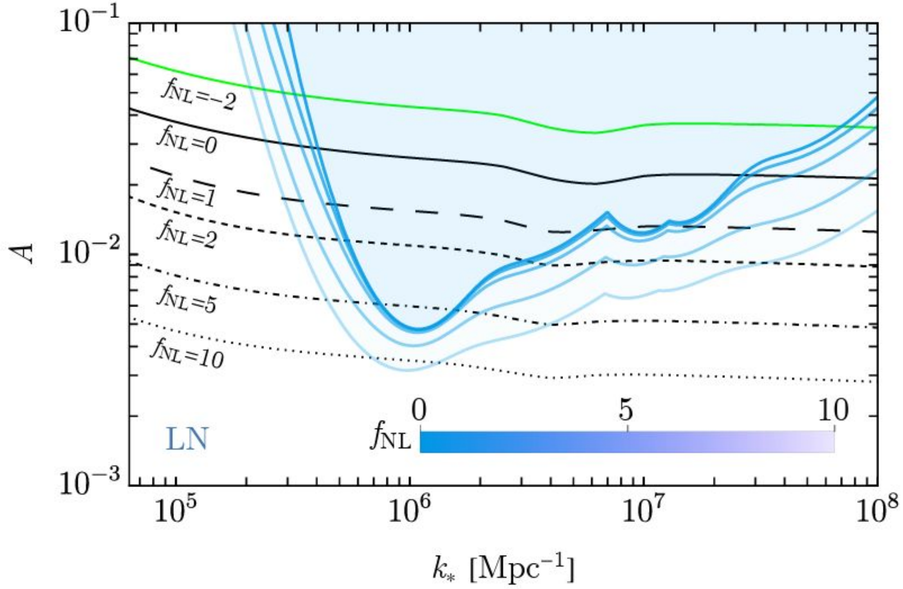
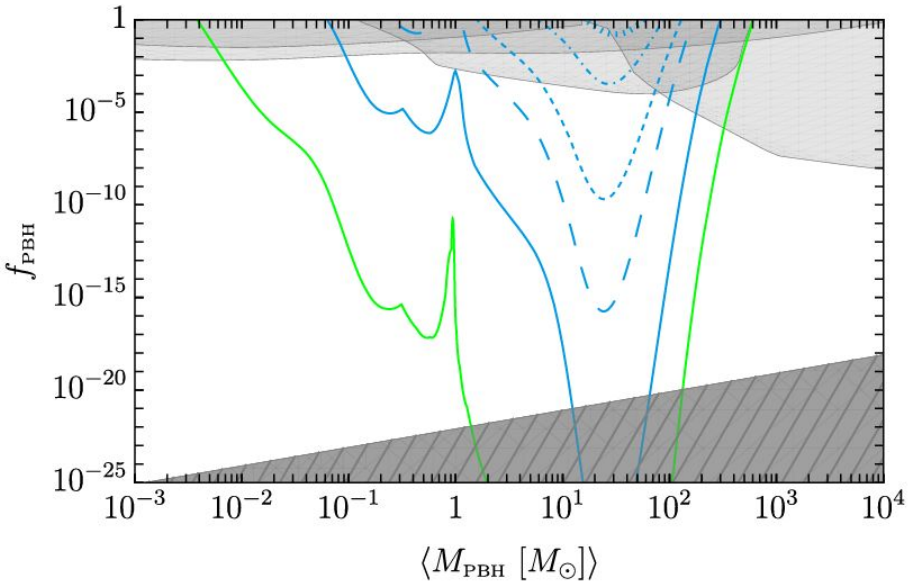


Constraining PBHs with PTAs

A.J. Iovino. G.Perna, A.Riotto and H.Veermae.
arXiv:2406.20089 *JCAP*





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

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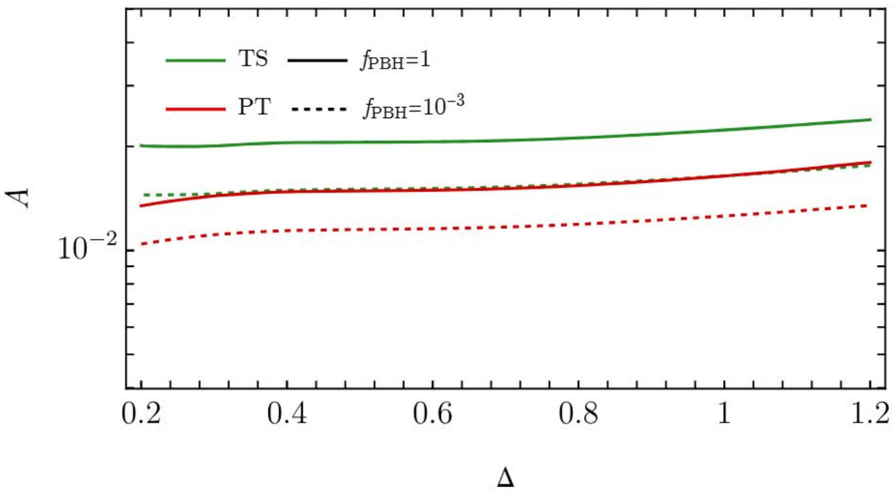

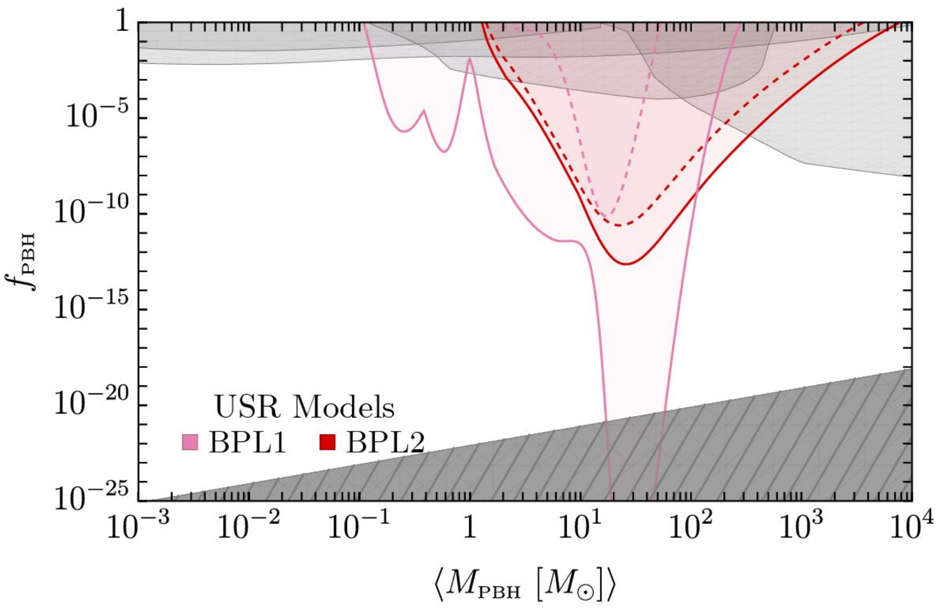

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Projection from future experiments

A.J. Iovino. G.Perna and H.Veermae.

In preparation

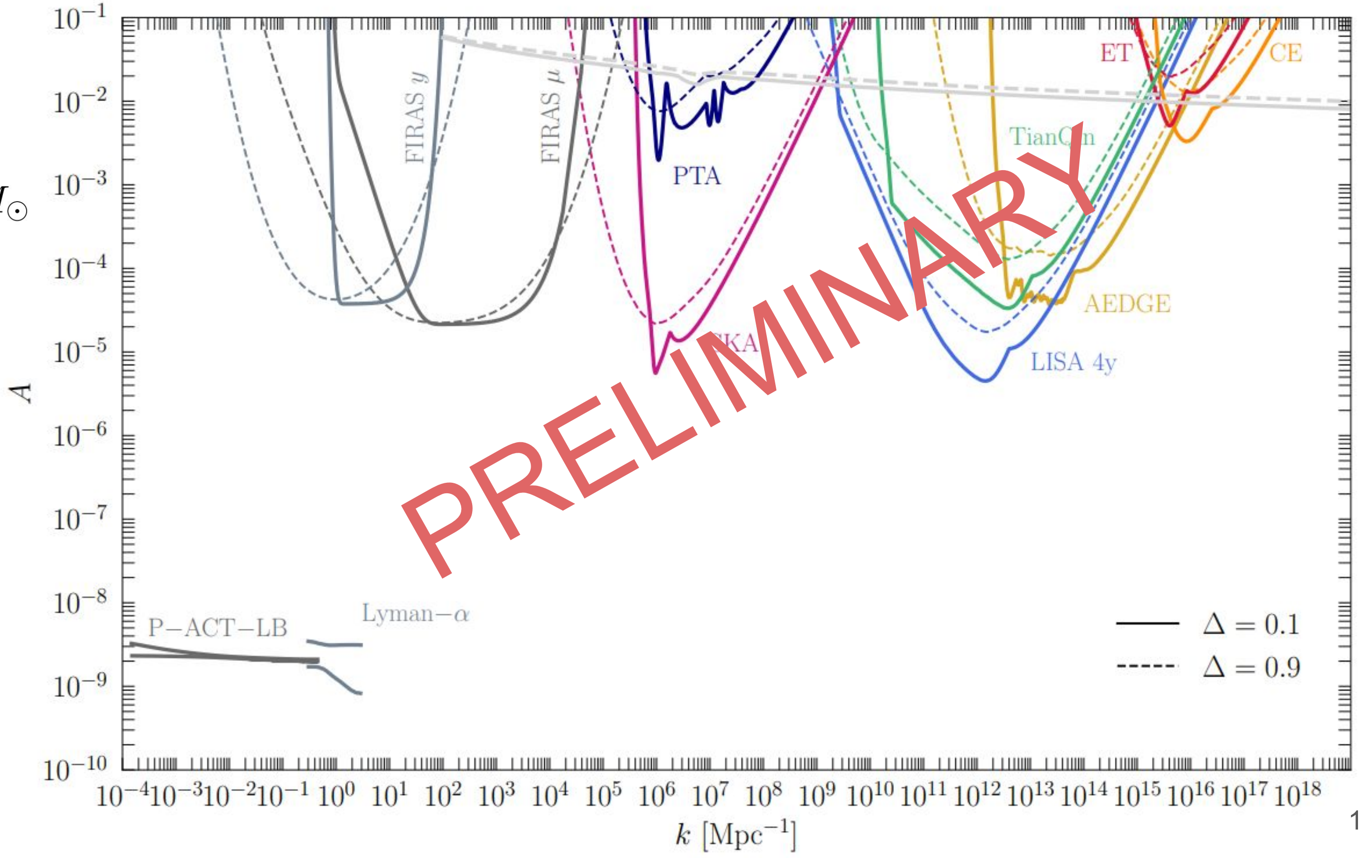
$$M_H(t) \sim \left(\frac{10^{6.5}\mathrm{Mpc}^{-1}}{k}\right)^2 M_\odot$$

PTA: (sub)Solar Range

LISA: Asteroidal Range

Can Lisa close the asteroidal mass range?

Yes but no spoiler…



How strong are these claims? Some potential issues

i) Threshold values (or PBH computations) maybe are not correct?

a) Non-linearities in the transfer function
b) Going beyond the average profile for the compaction function.
c) Role of NGs

ii) Peak theory

a) A discrepancy already at gaussian level.
b) How to deal with NGs
c) Cloud in cloud problem

S. Young, C. T. Byrnes, and M. Sasaki– arXiv:1405.7023
C.M. Yoo, J.O.. Gong,, and S. Yokoyama– arXiv:1906.06790
S. Pi, M. Sasaki, V. Takhistov, J. Wang arXiv: 2501.00295

iii) SIGW and NGs

a) The effects of non-Gaussianity on SIGWs may not always be accurately captured by an expansion around a Gaussian field

arXiv:2412.06764 **A.J.I.**, G. Perna, A. Riotto, A. Ricciardone, S. Matarrese

See Sysky and Jacopo's talks

V. De Luca, A. Kehagias, A. Riotto.– arXiv:2307.13633
arXiv:2402.11033 A.Ianniccari, **A.J.I.**, A. Kehagias, D. Perrone, A. Riotto (PRD)
I. Musco, A. Kehagias, A. Riotto.– arXiv:1906.07135
A. Escrivà, Y. Tada, S. Yokoyama, C. Yoo- arXiv:2202.01028

Conclusions

- *The computation of the abundance of PBHs relies on the formalism and on the presence of primordial non-guassianities (NGs)*

- *NGs plays a fundamental role also on the SIGW*

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

- *Future and current experiments can be used to put constraints on the PBH abundance*

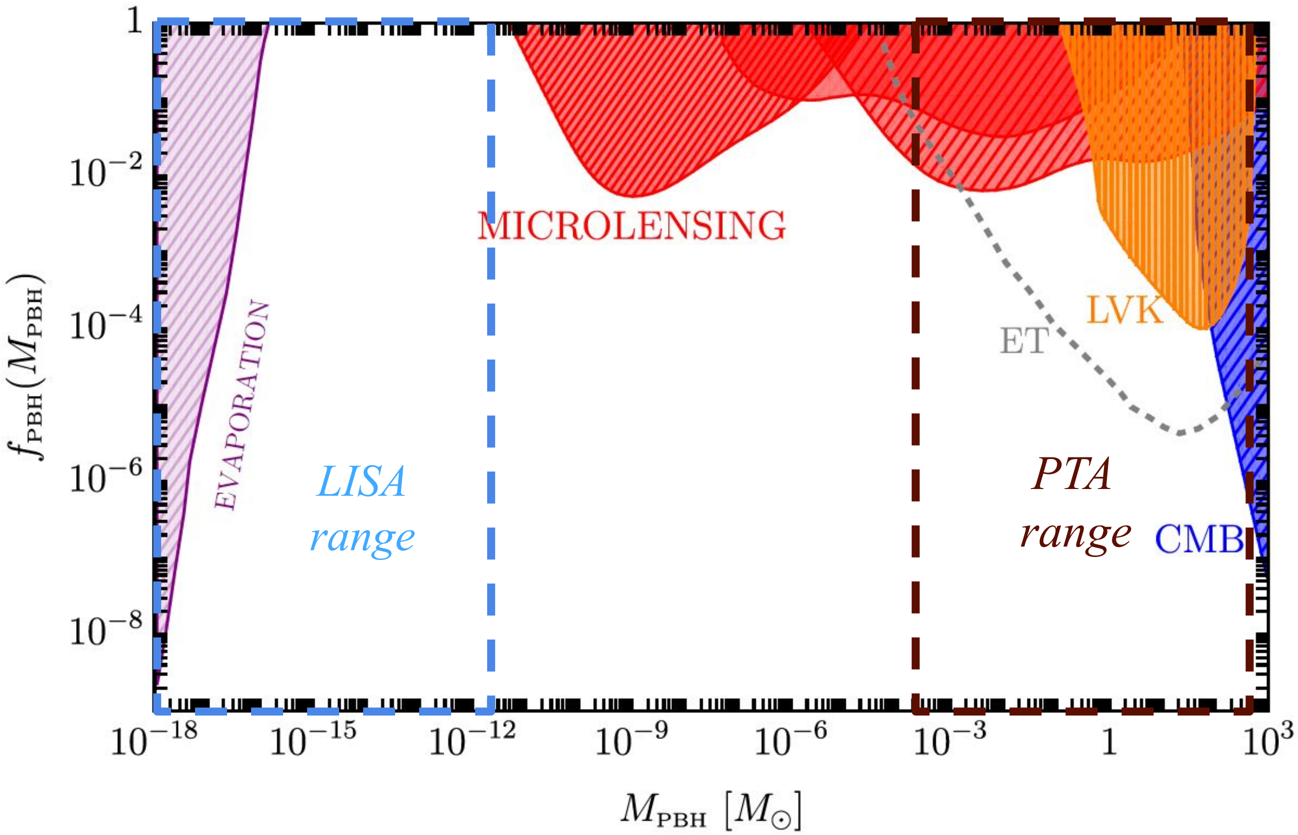
Back up Slides

PBH abundance

Total Abundance

Mass Distribution $$\frac{\mathrm{d} f_{\rm PBH}}{\mathrm{d}\ln M_{\rm PBH}} = \frac{1}{\Omega_{\rm DM}} \int \frac{\mathrm{d}M_k}{M_k}\, \beta_k(M_{\rm PBH}) \left(\frac{M_{\rm eq}}{M_k}\right)^{1/2}$$

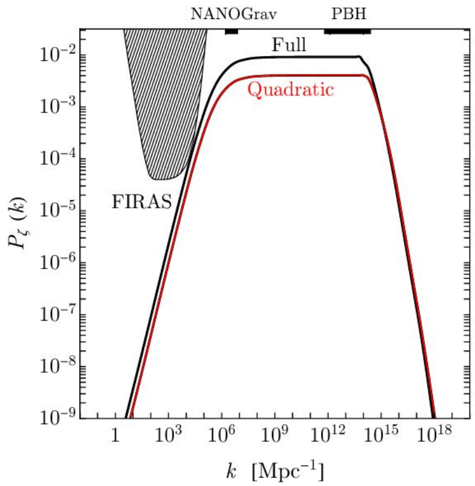
$$f_{\rm PBH} = \int \frac{\mathrm{d}M_{\rm PBH}}{M_{\rm PBH}} \frac{\mathrm{d} f_{\rm PBH}}{\mathrm{d}\ln M_{\rm PBH}}$$

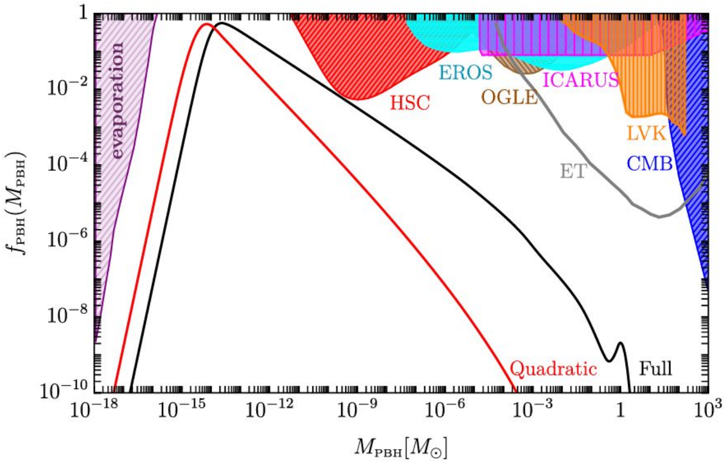


In which way can we determine the mass distribution?

Abundance of PBHs: The role of NGs.

G.Ferrante, G.Franciolini, **A.J.I.**, A.Urbano
arXiv:2305.13382 JCAP





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Fitting the PTA Datasets

Log-likelihood analysis

Fitting the posterior distributions

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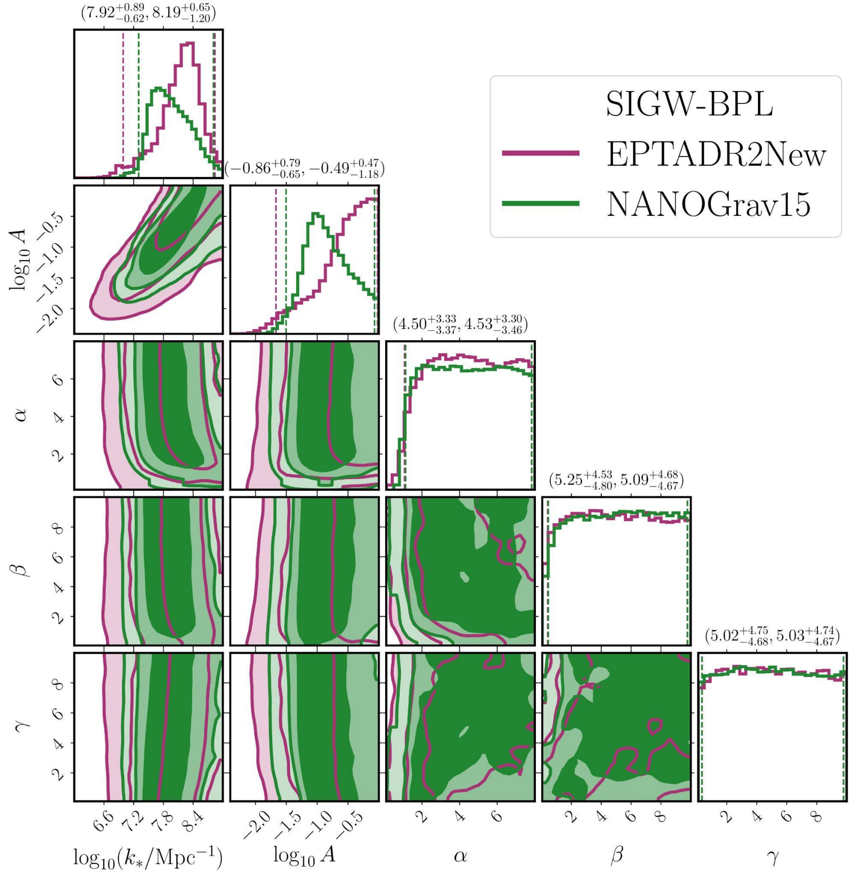
Results:

The causality 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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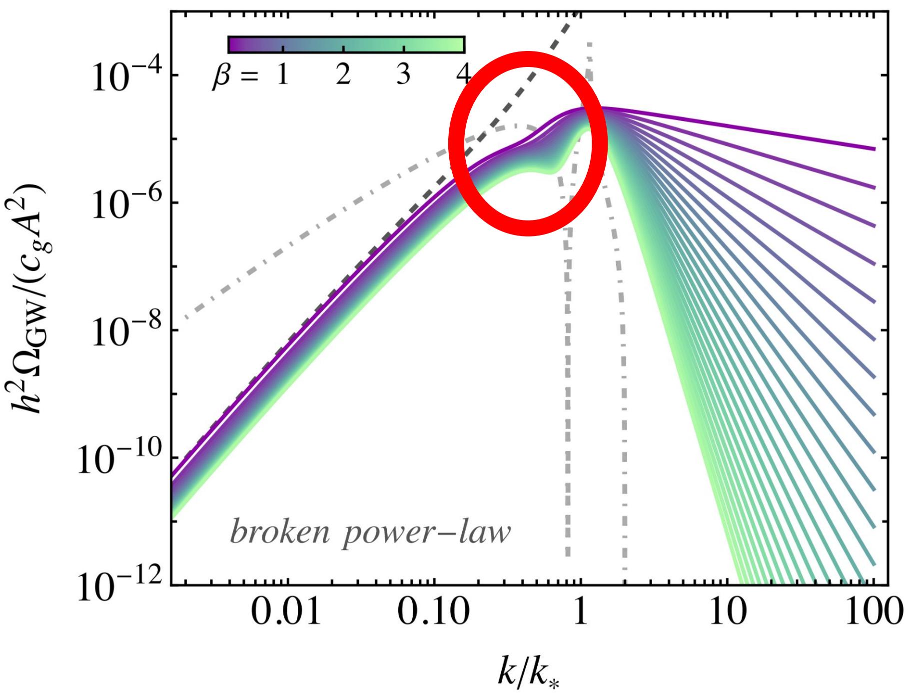

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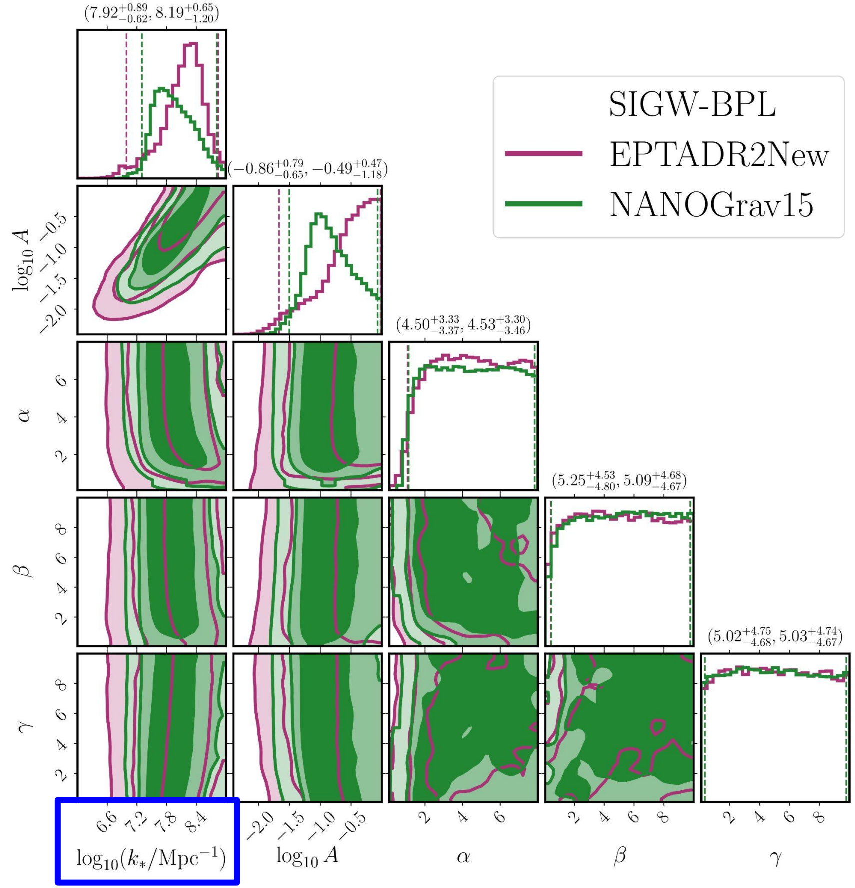
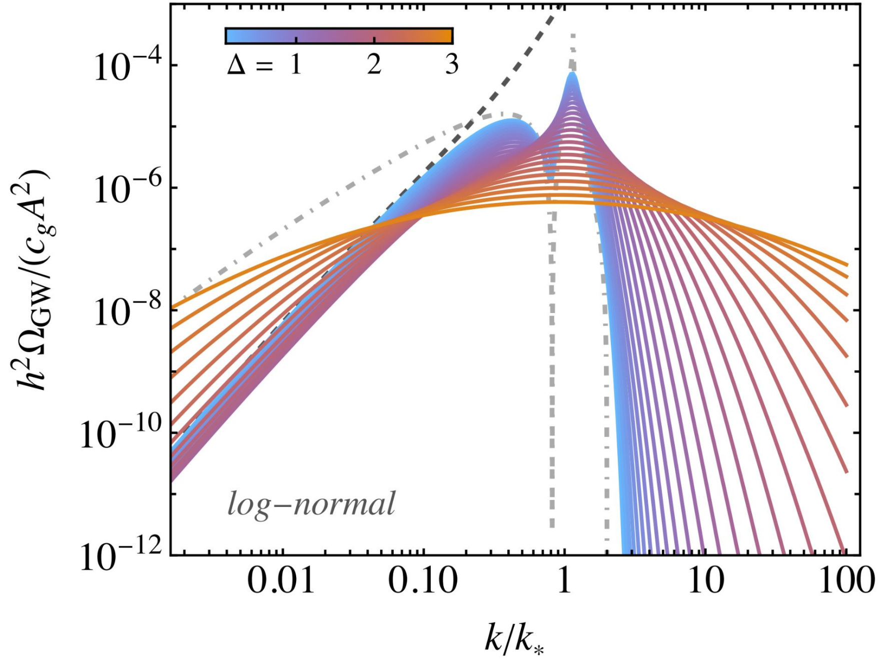
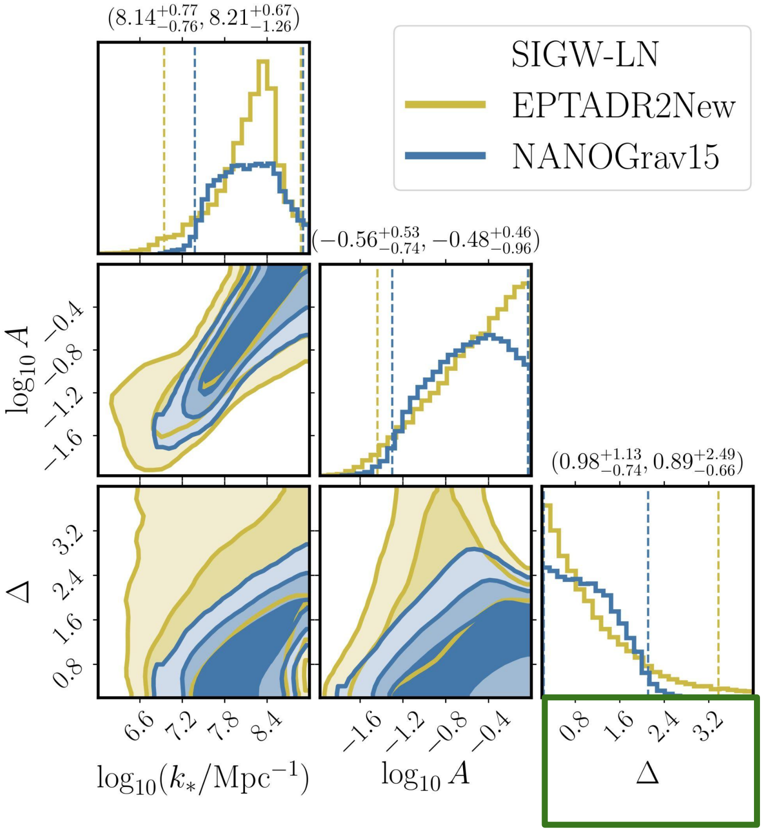


Results:

Position of the peak at higher frequencies.

Broad spectrum does not fit so well.





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Some potential issues on SIGW

A.J.I, S. Matarrese, G. Perna, A. Ricciardone, A.Riotto
ArXiv:2412.06764

The effects of non-Gaussianity on SIGWs may not always be accurately captured by an expansion around a Gaussian field

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

P. Adshead, K. Lozanov, Z. Weiner ArXiv:2105.01659
G. Perna, C. Testini, A. Ricciardone, S. Matarrese ArXiv:2406.20089

$$\zeta = -\mu \ln \left| 1 - \frac{\zeta_{\rm g}}{\mu} \right|$$

$$f_{\rm NL} = 5/(6\mu)$$

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

$$S_{ij} = -\left| 1 - \frac{\zeta_{\rm g}}{\mu} \right|^{2(\mu-1)} \partial_i \zeta_{\rm g} \partial_j \zeta_{\rm g}$$

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$$S_{ij}^{Q} = 4\Phi\partial_i\partial_j\Phi + 2\partial_i\Phi\partial_j\Phi - \partial_i\left(\frac{\dot{\Phi}}{H}+\Phi\right)\partial_j\left(\frac{\dot{\Phi}}{H}+\Phi\right)$$

Tomita-1975
S. Matarrese, O. Pantano, D. Saez-arXiv:astro-ph/9310036.

Sub-horizon

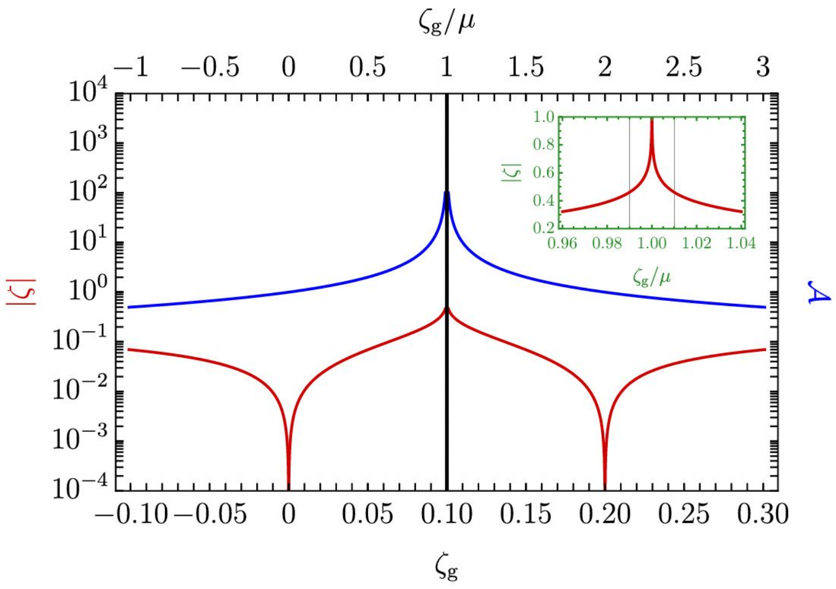
Two Approximations:

1) Non-linear perturbation is in the perturbative regime

$$\Phi(t,\mathbf{k}) \equiv \frac{2}{3}T(k,t)\zeta(\mathbf{k}) \qquad \partial_i\zeta = \frac{1}{\left|1-\frac{\zeta_g}{\mu}\right|}\partial_i\zeta_g,$$

2) The gaussian field with its typical value

$$\left|1-\frac{\zeta_g}{\mu}\right|^{-1} \simeq \left|1-\frac{\pm\langle\zeta_g^2\rangle^{1/2}}{\mu}\right|^{-1} \equiv \mathcal{A},$$



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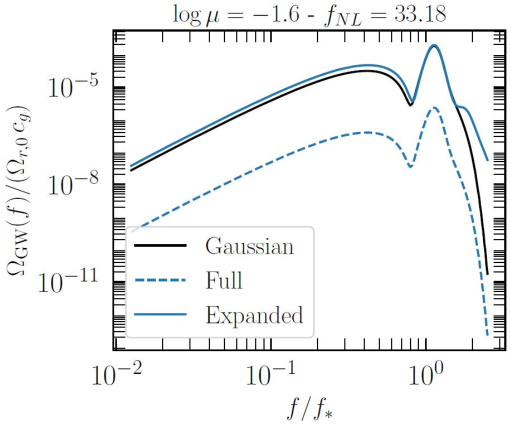

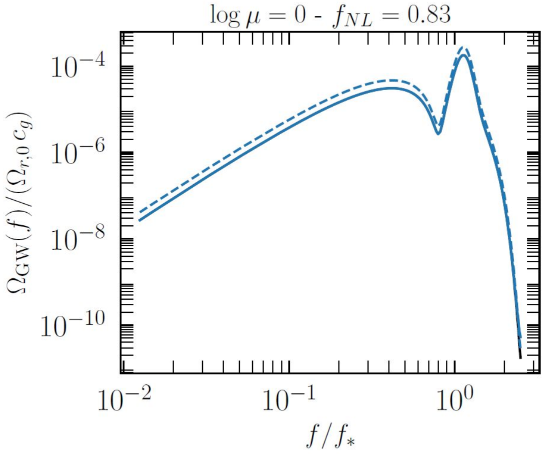

The results for the full expansion are qualitative due to some approximations in the computations
(Feel free to ask after the talk)

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A.J.I, S. Matarrese, G. Perna, A. Ricciardone, A.Riotto
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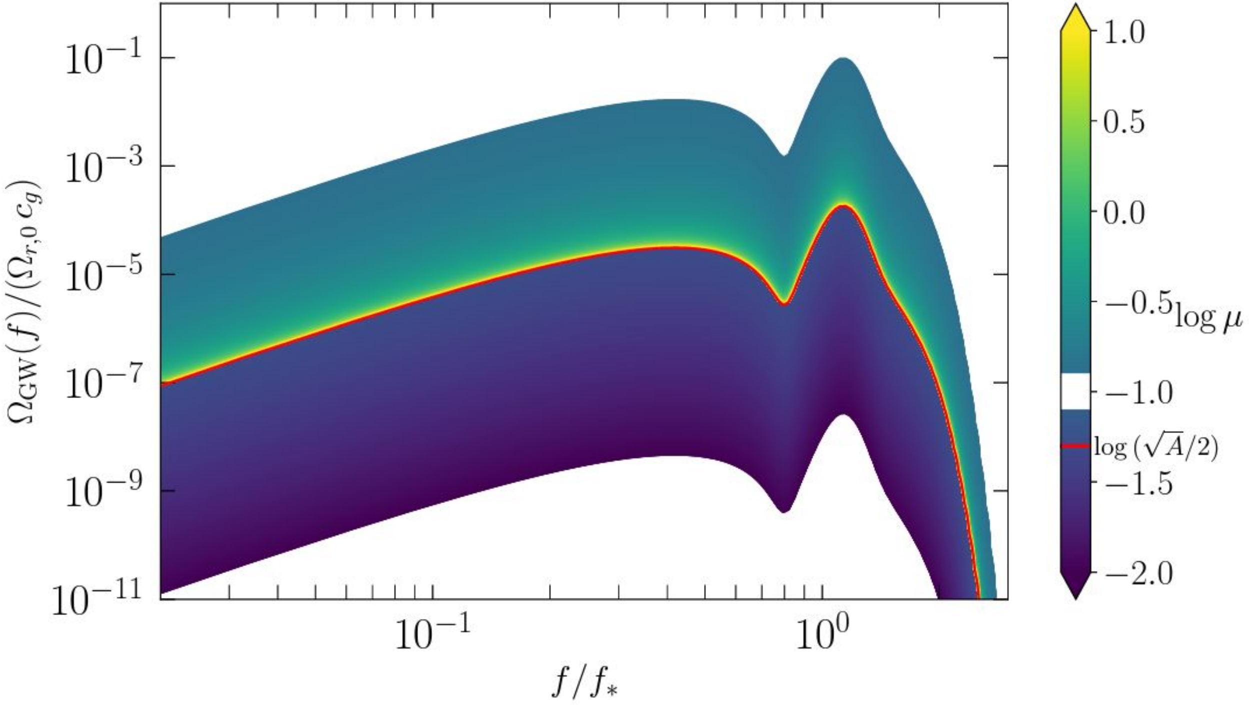

$$\frac{\Omega_{\rm GW}^{\rm New}(f)}{\Omega_{\rm GW}^{\rm Usual}(f)} \sim \mathcal{A}^4$$