New probe of non-Gaussianities with primordial black hole induced gravitational waves

Based on [2403.00660, T. Papanikolaou, X. C. He, X.-Ha. Ma, Y. F. Cai., E. N. Saridakis, M. Sasaki]

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ΕΥΡΩΠΑΪΚΟΥ ΠΟΛΙΤΙΣΜΟΥ
ΙΔΡΥΤΕΣ ΝΙΚΟΣ ΚΑΙ ΛΥΝΤΙΑ ΤΡΙΧΑ

Introduction

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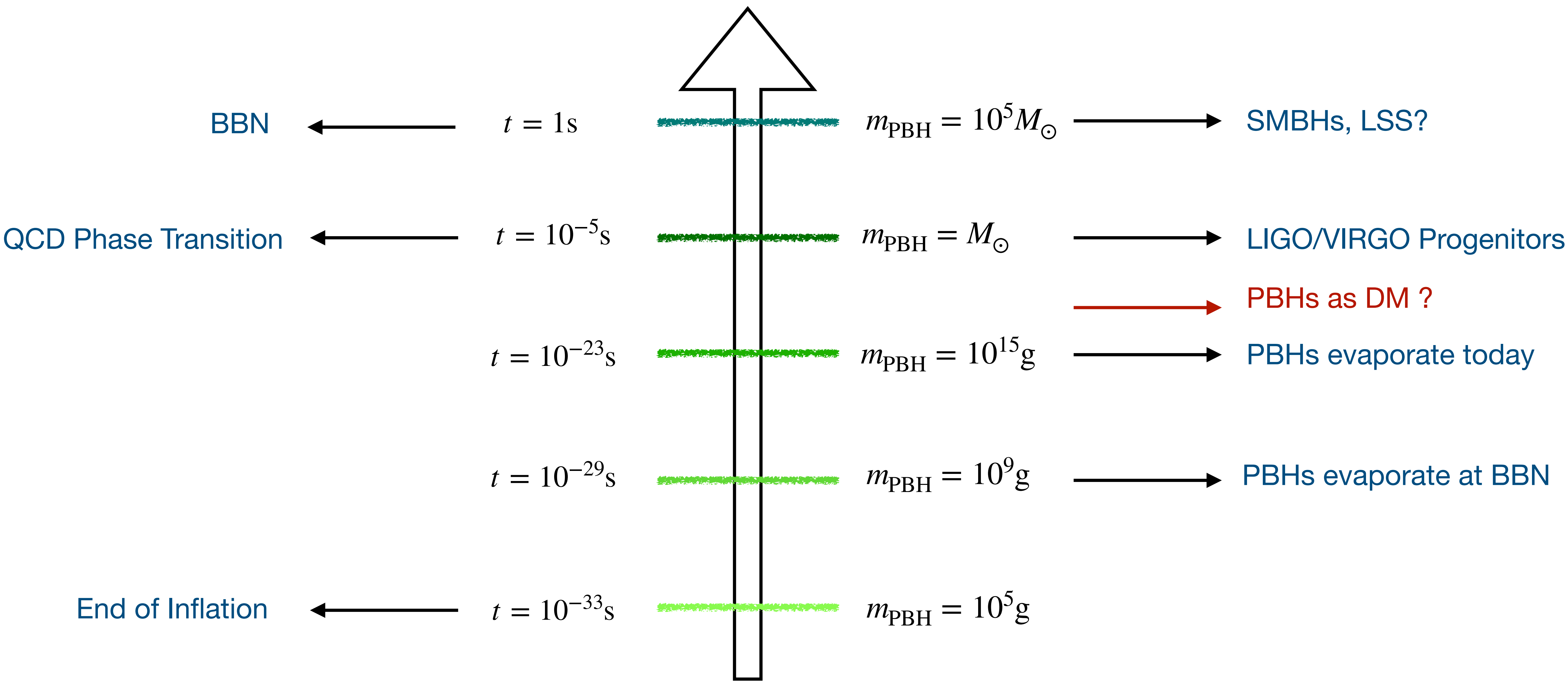
$$m_{\rm PBH} = \gamma M_{\rm H} \propto H^{-1} \text{ where } \gamma \sim {\rm O}(1)$$



See for reviews in [Carr et al.- 2020, Sasaki et al - 2018, Clesse et al. - 2017]

PBHs and GWs

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- 4) **GWs induced** at second order **by PBH energy density fluctuations** [Papanikolaou et al. - 2020].

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- Evaporation of light PBHs can also **produce naturally the baryon asymmetry** through CP violating out-of-equilibrium decays of Hawking evaporation products [J. D. Barrow et al. - 1991, T. C. Gehrman et al. - 2022, N. Bhaumik et al. - 2022].

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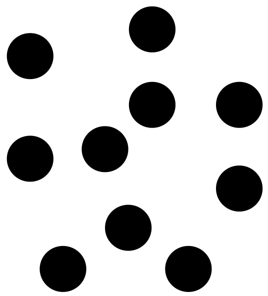
- **GWs induced by PBH energy density fluctuations can interpret** in a very good agreement **the recently released PTA GW data** [Lewicki et al. - 2023, Basilakos et al. - 2023]

The PBH Matter Field



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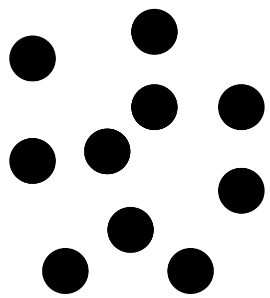

Poisson Statistics [Desjacques & Riotto - 2018, Ali-Haimoud - 2018]

Same mass [Dizgah, Franciolini & Riotto - 2019]

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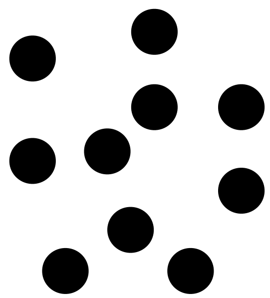

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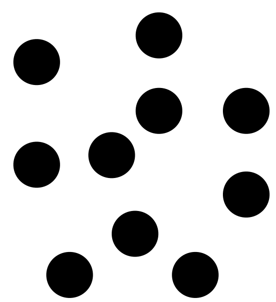

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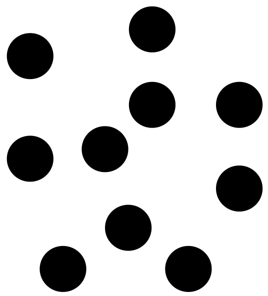

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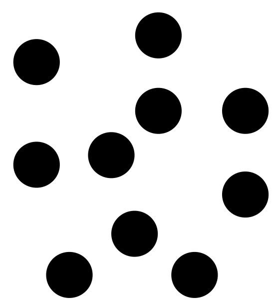

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This **isocurvature perturbation,** $\delta_{\rm PBH}$ generated during the RD era **will convert** during the PBHD era **to a curvature perturbation** $\zeta_{\rm PBH}$, associated to a PBH gravitational potential Φ.

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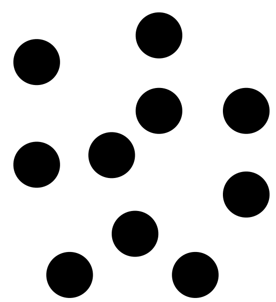

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$$\mathcal{P}_{\Phi}(k) = S_{\Phi}^2(k)\left(5 + \frac{4}{9}\frac{k^2}{k_{\rm d}^2}\right)^{-2} \mathcal{P}_{\delta_{\rm PBH},{\rm Poisson}}(k), \text{ where } S_{\Phi}(k) \equiv \left(\frac{k}{k_{\rm evap}}\right)^{-1/3}$$

Scalar Induced Gravitational Waves

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- The equation of motion for the Fourier **2nd order modes** $h_{\vec{k}}$, read as:

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- The source term, $S_{\vec{k}}$ can be recast as:

$$S^s_{\vec{k}} = \int \frac{\mathrm{d}^3\vec{q}}{(2\pi)^{3/2}} e^s_{ij}(\vec{k}) q_i q_j \left[2\Phi_{\vec{q}}\Phi_{\vec{k}-\vec{q}} + \frac{4}{3(1+w)}(\mathscr{H}^{-1}\Phi'_{\vec{q}} + \Phi_{\vec{q}})(\mathscr{H}^{-1}\Phi'_{\vec{k}-\vec{q}} + \Phi_{\vec{k}-\vec{q}})\right].$$

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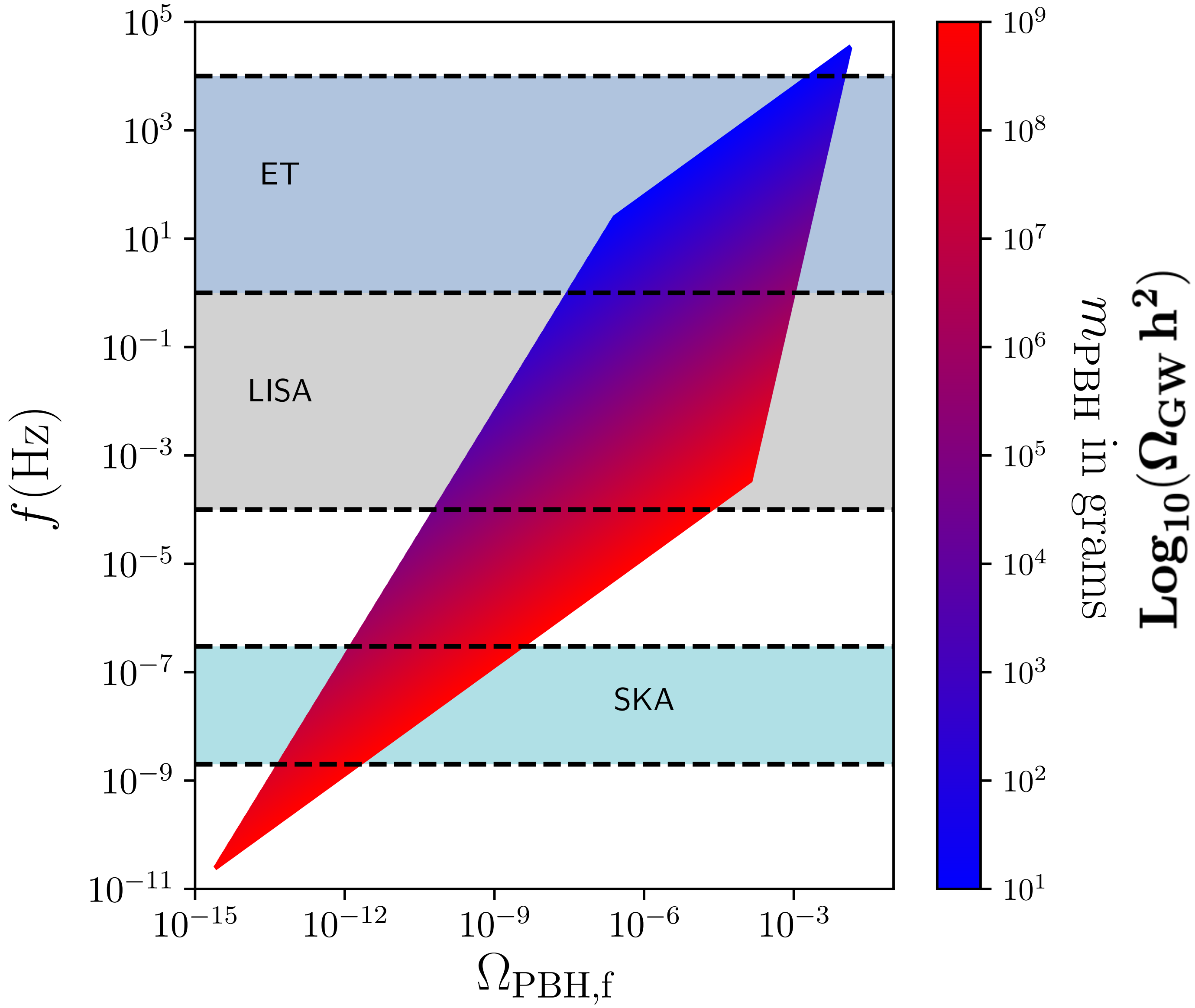
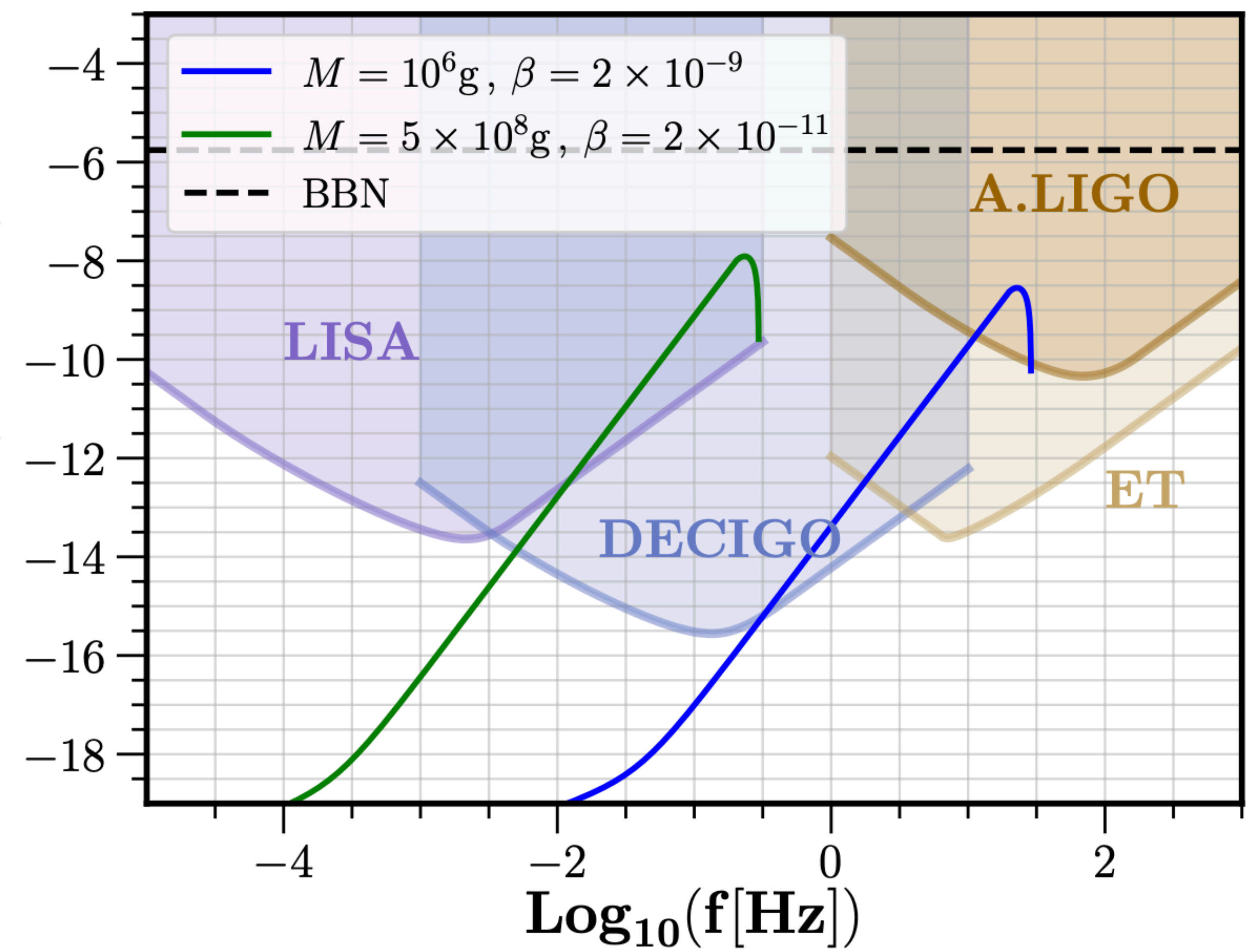
$$\Omega_{\rm GW}(\eta, k) \equiv \frac{1}{\rho_{\rm tot}} \frac{\mathrm{d}\rho_{\rm GW}}{\mathrm{d}\ln k} = \frac{1}{24} \left(\frac{k}{a(\eta)H(\eta)} \right)^2 \mathscr{P}_h(\eta, k),$$

$$\text{with} \quad \mathscr{P}_h(\eta, k) \equiv \frac{k^3 |h_k|^2}{2\pi^2} \propto \int \mathrm{d}v \int \mathrm{d}u \left(\int f(v, u, k, \eta) \mathrm{d}\eta \right)^2 \mathscr{P}_\Phi(kv) \mathscr{P}_\Phi(ku) \,.$$

GW Detectability



[Papanikolaou et al. - 2020]



[Domenech et al. - 2020]

- By accounting on BBN bounds on the GW amplitude at $k \sim k_{\mathrm{UV}}$, one can set upper bound constraints on the $\Omega_{\mathrm{PBH,f}}$ readings as

$$\boxed{\Omega_{\mathrm{PBH,f}} < 10^{-6}\left(\frac{M_{\mathrm{PBH}}}{10^4\mathrm{g}}\right)^{-17/24}.}$$

The effect of local-type non-Gaussianities

Primordial non-Gaussianities of local type

$$
\begin{aligned}
\langle \mathcal{R}(\boldsymbol{k_1})\mathcal{R}(\boldsymbol{k_2})\rangle &\equiv (2\pi)^3\delta^{(3)}(\boldsymbol{k_1}+\boldsymbol{k_2})P_{\mathcal{R}}(k) \\
\langle \mathcal{R}(\boldsymbol{k_1})\mathcal{R}(\boldsymbol{k_2})\mathcal{R}(\boldsymbol{k_3})\rangle &\equiv (2\pi)^3\delta^{(3)}(\boldsymbol{k_1}+\boldsymbol{k_2}+\boldsymbol{k_3}) \\
&\quad \times \frac{6}{5} f_{\rm NL}\left[P_{\mathcal{R}}(k_1)P_{\mathcal{R}}(k_2) + 2\text{ perms}\right] \\
\langle \mathcal{R}(\boldsymbol{k_1})\mathcal{R}(\boldsymbol{k_2})\mathcal{R}(\boldsymbol{k_3})\mathcal{R}(\boldsymbol{k_4})\rangle &\equiv (2\pi)^3\delta^{(3)}(\boldsymbol{k_1}+\boldsymbol{k_2}+\boldsymbol{k_3}+\boldsymbol{k_4}) \\
&\quad \times \left\{ \frac{54}{25} g_{\rm NL}\left[P_{\mathcal{R}}(k_1)P_{\mathcal{R}}(k_2)P_{\mathcal{R}}(k_3) + 3\text{ perms}\right] \right. \\
&\qquad \left. + \tau_{\rm NL}\left[P_{\mathcal{R}}(k_1)P_{\mathcal{R}}(k_2)P_{\mathcal{R}}(|\boldsymbol{k_1}+\boldsymbol{k_3}|) + 11\text{ perms}\right] \right\}
\end{aligned}
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Primordial non-Gaussianities of local type

$$\langle \mathcal{R}(\boldsymbol{k_1})\mathcal{R}(\boldsymbol{k_2})\rangle \equiv (2\pi)^3\delta^{(3)}(\boldsymbol{k_1}+\boldsymbol{k_2})P_{\mathcal{R}}(k)$$

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[Path integral formalism for n-point correlation functions (galaxy halo bias)]

[S. Matarrese et al. - 1986, S. Matarresse and L. Verde - 2008]

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$$\mathscr{P}_{\delta_{\rm PBH}}(k) \simeq \mathscr{P}_{\mathscr{R}}(k)\nu^4 \left(\frac{4}{9\sigma_R}\right)^4 \int \frac{\mathrm{d}^3p_1\mathrm{d}^3p_2}{(2\pi)^6}\tau_{\rm NL}(p_1,p_2,p_1,p_2)W^2_{\rm local}(p_1)W^2_{\rm local}(p_2)P_{\mathscr{R}}(p_1)P_{\mathscr{R}}(p_2)$$
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[Suyama & Yokoyama - 2019]

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The non-Gaussian PBH matter power spectrum

$$\text{Ansatz 1}: \mathscr{P}_{\mathscr{R}} = \mathscr{P}_{\mathscr{R}}(k_\mathrm{f})e^{-\frac{1}{2\sigma^2}\ln^2\left(\frac{k}{k_\mathrm{f}}\right)} + 2.2\times10^{-9}\left(\frac{k}{0.05\mathrm{Mpc}^{-1}}\right)^{0.965-1}, \text{ with } \mathscr{P}_{\mathscr{R}}(\mathrm{k_f}) \simeq 10^{-2}$$

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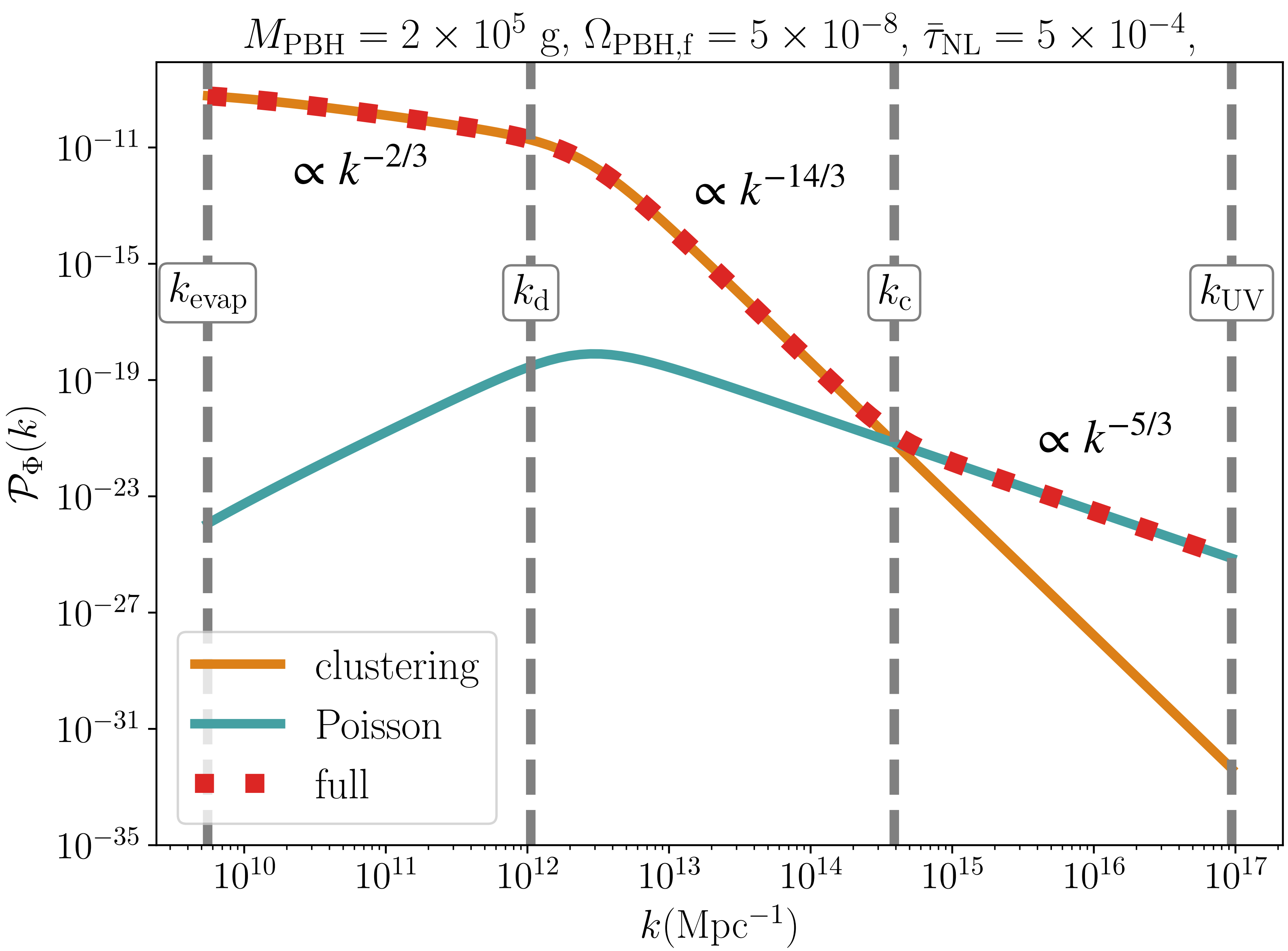

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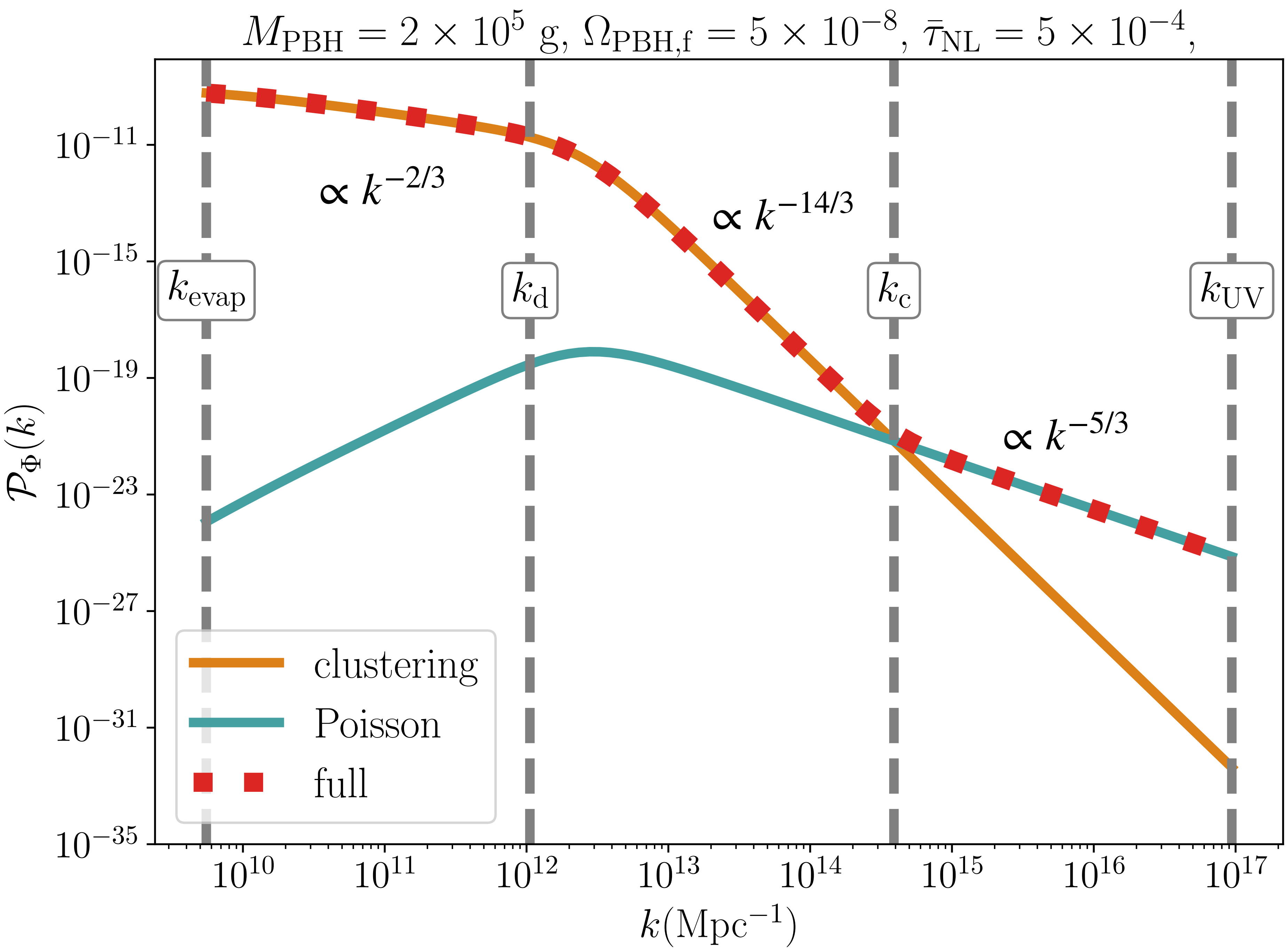
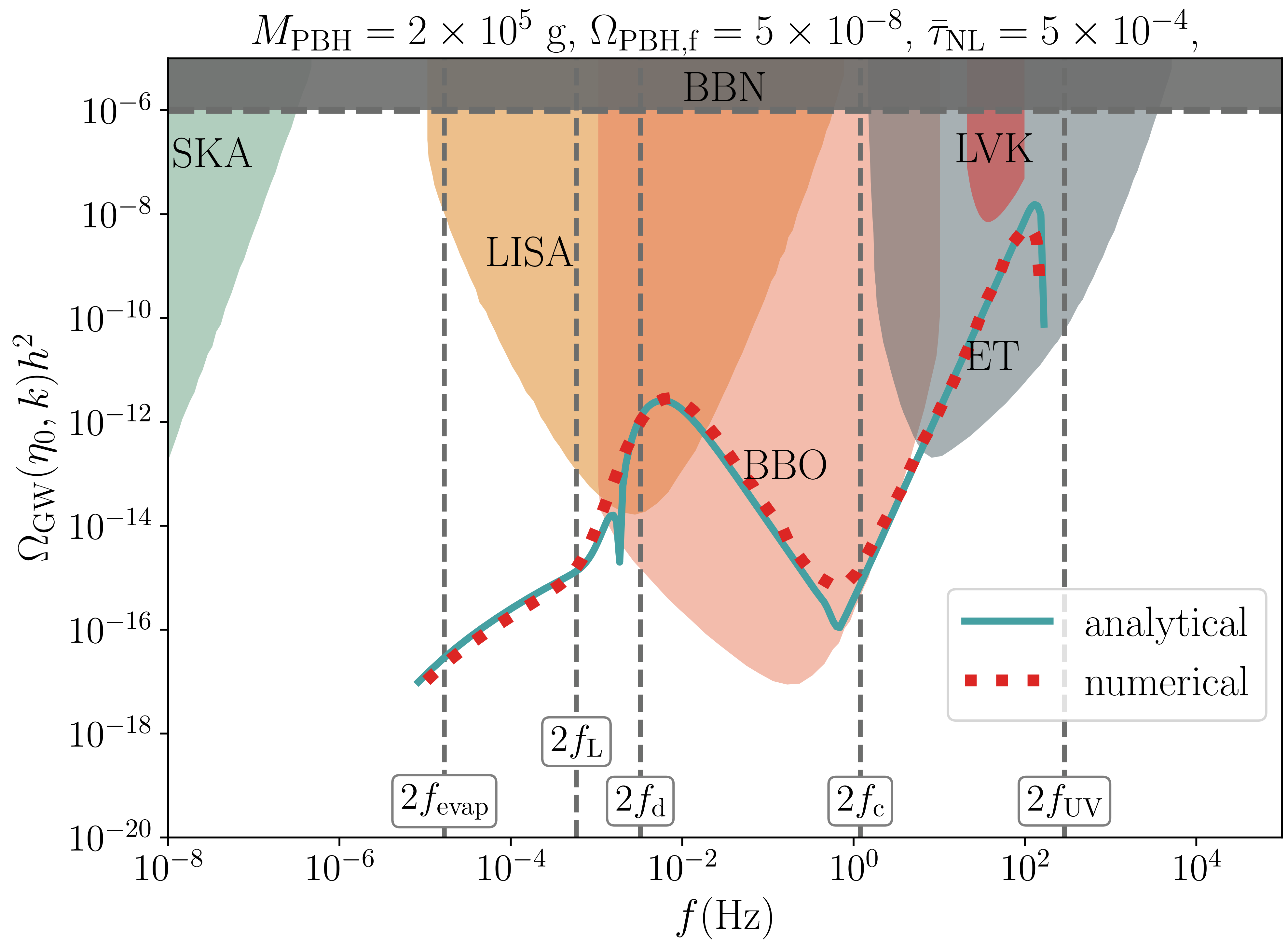
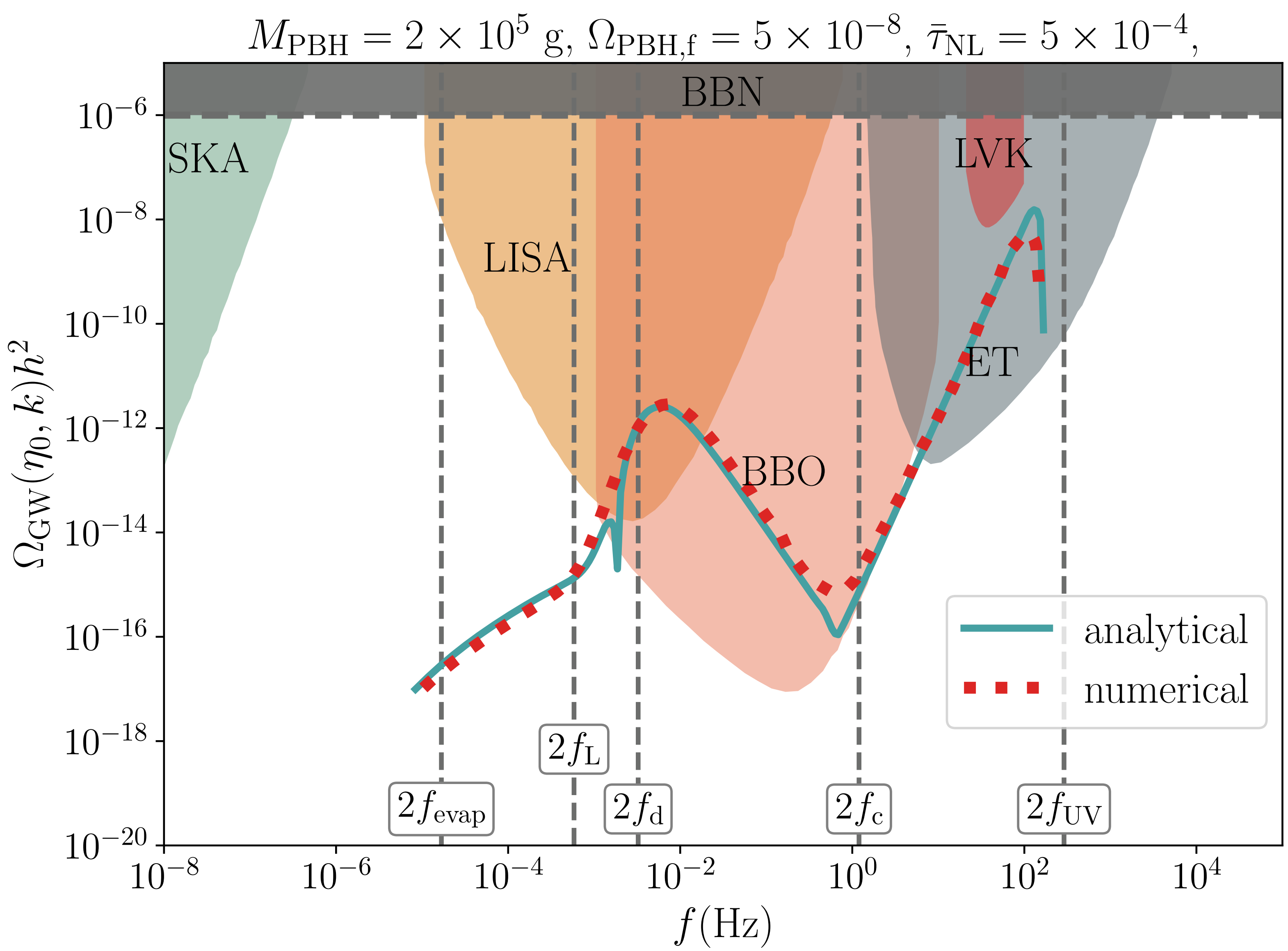


$$\boxed{\text{Scale Hierarchy : } 10^5\mathrm{Mpc}^{-1} < k_{\rm evap} < k_{\rm d} < k_{\rm c} < k_{\rm UV} \ll k_{\rm f} \sim 1/R}$$

Non-Gaussian Induced GWs



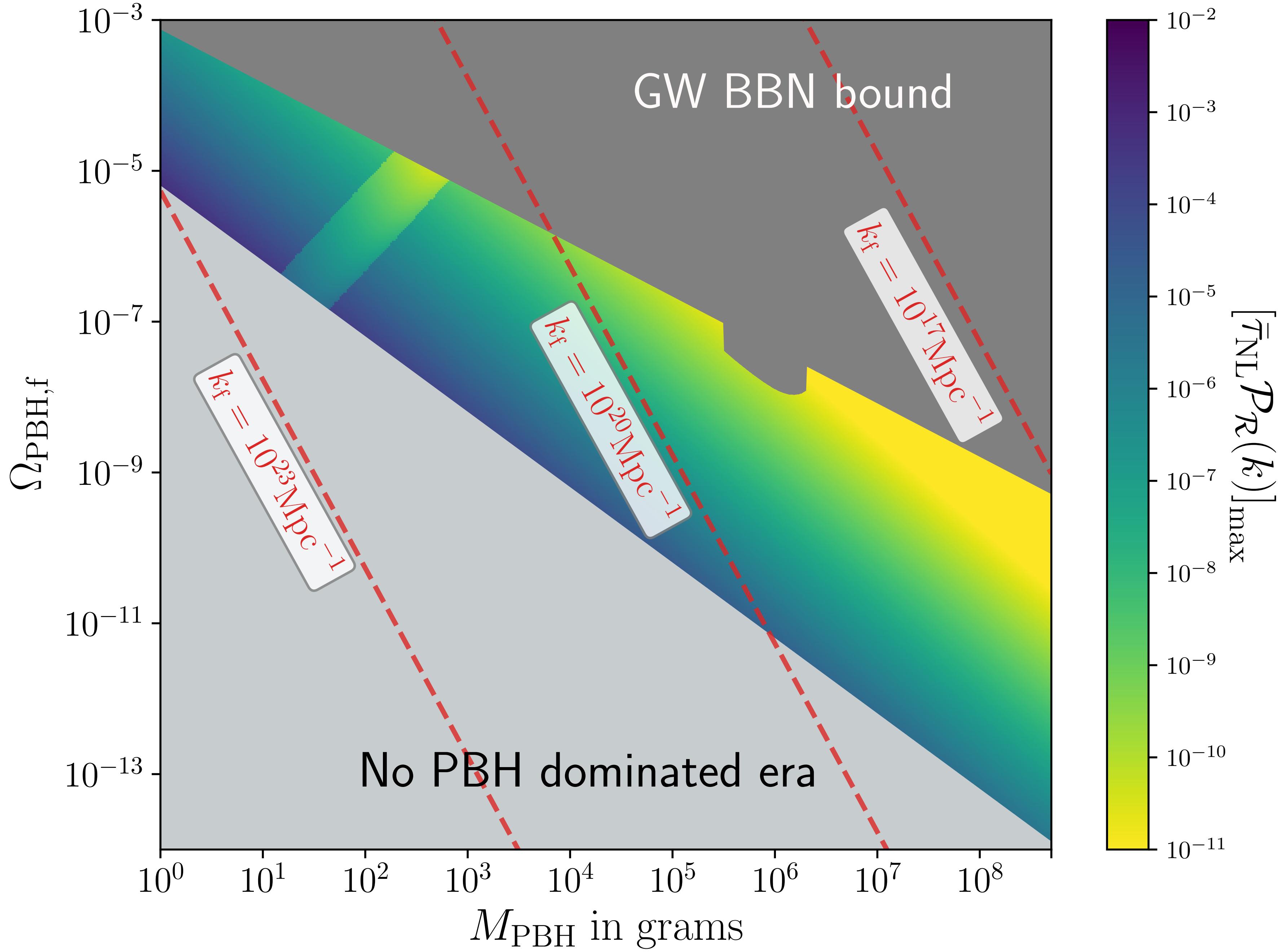
Non-Gaussian Induced GWs



$$\Omega_{\rm GW}(\eta_0,k)h^2 \simeq \begin{cases} 3\times10^{-80}\left(\dfrac{k}{10^4{\rm Mpc}^{-1}}\right)^{11/3}\left(\dfrac{M_{\rm PBH}}{10^4{\rm g}}\right)^{41/6}\left(\dfrac{\Omega_{\rm PBH,f}}{10^{-10}}\right)^{16/3} & 2k_{\rm c}<k<2k_{\rm UV} \\ 5\times10^{-13}\left(\dfrac{k}{10^4{\rm Mpc}^{-1}}\right)^{-7/3}\left(\dfrac{M_{\rm PBH}}{10^4{\rm g}}\right)^{11/6}\left(\dfrac{\Omega_{\rm PBH,f}}{10^{-10}}\right)^{16/3}\left(\dfrac{\bar{\tau}_{\rm NL}\mathcal{P}_\mathcal{R}}{10^{-15}}\right)^{2} & 2k_{\rm d}<k<2k_{\rm c} \\ 4\times10^{-75}\left(\dfrac{k}{10^4{\rm Mpc}^{-1}}\right)^{17/3}\left(\dfrac{M_{\rm PBH}}{10^4{\rm g}}\right)^{17/2}\left(\dfrac{\bar{\tau}_{\rm NL}\mathcal{P}_\mathcal{R}}{10^{-15}}\right)^{2} & \\ \quad +10^{-39}\left(\dfrac{k}{10^4{\rm Mpc}^{-1}}\right)\left(\dfrac{M_{\rm PBH}}{10^4{\rm g}}\right)^{4}\left(\dfrac{\Omega_{\rm PBH,f}}{10^{-10}}\right)^{22/9}\left(\dfrac{\bar{\tau}_{\rm NL}\mathcal{P}_\mathcal{R}}{10^{-15}}\right)^{2} & 2k_{\rm evap}<k<2k_{\rm d} \end{cases}$$

Constraining non-Gausianities

$$\Omega_{\rm GW}(2k_{\rm d},\eta_0) \le 10^{-6} \Rightarrow \bar{\tau}_{\rm NL}\mathscr{P}_{\mathscr{R}}(k) \le 4\times 10^{-20}\Omega_{\rm PBH,f}^{-17/9}\left(\frac{M_{\rm PBH}}{10^4{\rm g}}\right)^{-17/9}$$



Conclusions

- **GWs** induced by **PBH isocurvature perturbations** can be abundantly produced in **eMD eras before BBN** driven by PBHs and give us access to the early Universe given their **potential detectability by GW experiments.**

- In particular, by requiring not to have GW overproduction at the end of BBN one can set **constraints on the abundances of ultralight PBHs** with $m_{\mathrm{PBH}} < 10^{9}\mathrm{g}$ which are **otherwise unconstrained** by other observational probes.

- Incorporating in the analysis **the effect of local-type primordial non-Gaussianities on PBH clustering** we found a **bi-peaked structure of the induced GW signal** with the l**ow frequency peak being related to the** τ_{NL} **parameter.**

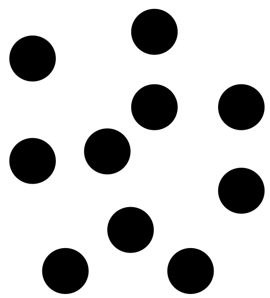
- Accounting finally for BBN bounds on the GW amplitude we set **constraints on primordial non-Gaussianities on very small scales** $k > 10^{5}\mathrm{Mpc}^{-1}$, otherwise unconstrained by current CMB and LSS probes.

- The portal of **PBH induced GWs** can serve as a **new messenger from the early Universe.**

Thanks for your attention!

Appendix

The PBH Matter Field



Poisson Statistics [Desjacques & Riotto - 2018, Ali-Haimoud - 2018]

Same mass [Dizgah, Franciolini & Riotto - 2019]

$$P_{\delta_{\rm PBH}}(k) \equiv \langle |\delta_k^{\rm PBH}|^2 \rangle = \frac{4\pi}{3}\left(\frac{\bar{r}}{a}\right)^3 = \frac{4\pi}{3k_{\rm UV}^3}, \quad \text{where} \quad k < k_{\rm UV} = \frac{a}{\bar{r}}$$

$$S = \frac{\delta\rho_{\rm PBH}}{\rho_{\rm PBH}} - \frac{3}{4}\frac{\delta\rho_{\rm r}}{\rho_{\rm r}}$$

$$\rho_{\rm PBH,f} \ll \rho_{\rm r,f}$$

$$\delta\rho_{\rm PBH,f} + \delta\rho_{\rm r,f} = 0$$

$$S_{\rm f} \simeq \delta_{\rm PBH} \equiv \frac{\delta\rho_{\rm PBH}}{\rho_{\rm PBH}} \simeq \frac{\delta n_{\rm PBH}}{n_{\rm PBH}}$$

[Isocurvature perturbation]