Signals of primordial black holes at gravitational wave interferometers

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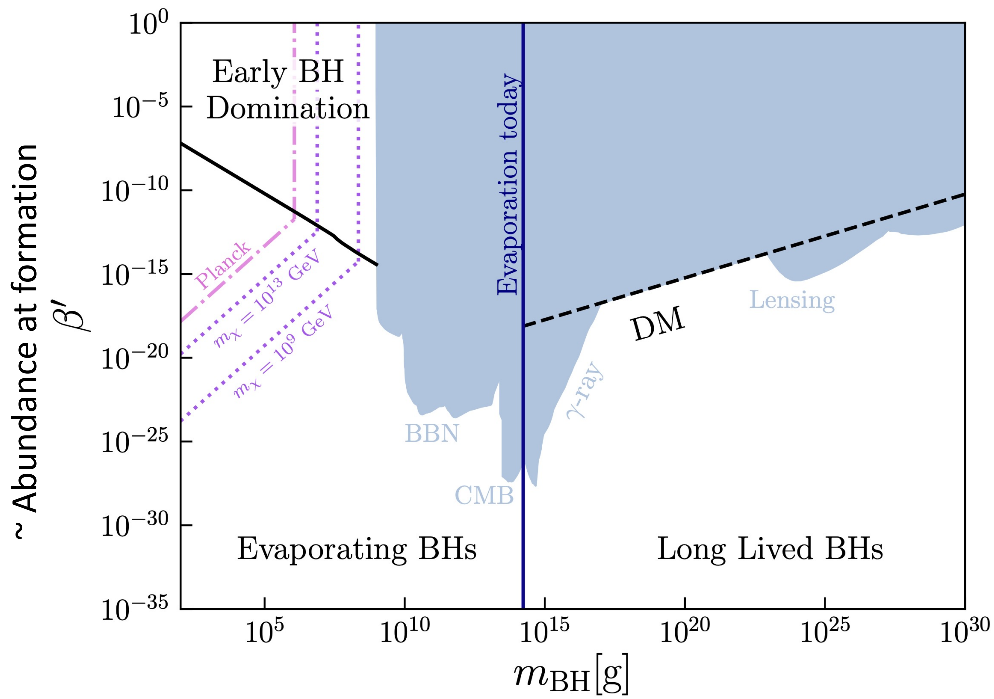
Background and Motivation

Constraints from
B. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, (2020), arXiv:2002.12778,
D. Hooper, G. Krnjaic, and S. D. McDermott, JHEP08, 001 (2019), arXiv:1905.01301

Primordial black holes –> Dark Matter

- Long lived – PBHs themselves constitute a component of DM
- Short lived – Hawking evaporation produces particle DM, stable Planck-scale relics?



Mean black hole mass

Interesting cosmology, early black hole domination?

Goal: Investigate this parameter space through gravitational waves

PBH Formation

A. D. Gow, C. T. Byrnes, P. S. Cole, and S. Young, JCAP02, 002 (2021), arXiv:2008.03289

Inflation may generate large primordial curvature perturbations at small scales

- These curvature perturbations induce large overdensities that will form primordial black holes (PBHs)

$$\mathcal{P}(k) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\log^2(k/k_\star)}{2\sigma^2}\right)$$

$$\beta = \frac{\rho_{\mathrm{BH},\star}}{\rho_{r,\star}} \qquad m_{\mathrm{BH}} \propto \frac{4\pi}{3}\rho_{r,\star}H_\star^{-3}$$

PBH mass and abundance

↕

Curvature perturbation amplitude, scale, width

- PBH mass ~ Horizon mass at $k_\star$
- Abundance ↔ curvature perturbation amplitude + width

Ex:

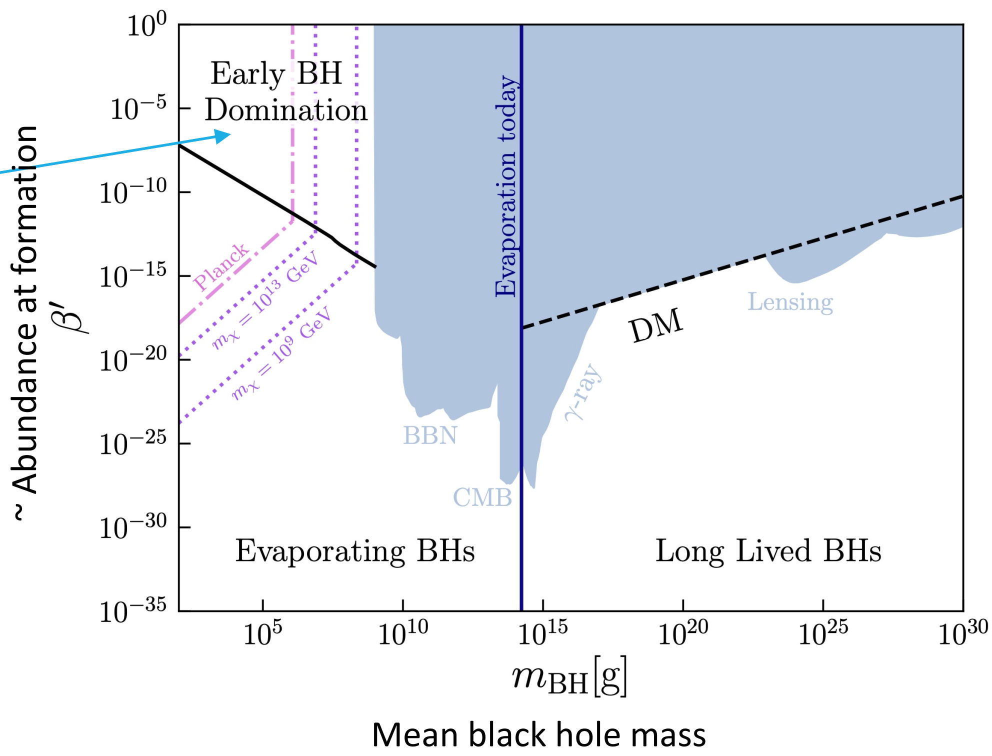
$$A = 0.016,\ \sigma = 1 \rightarrow \beta = 10^{-7}$$
$$A = 0.0029, \sigma = 1 \rightarrow \beta = 10^{-35}$$

PBH parameter space

Gravitational waves indirectly probe deviations to standard cosmology

- Matter density grows with scale factor
- RD era –> PBH dominated era –> RD –> Usual MD

$$\frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{r}}} \propto a$$



- GWs from primordial perturbations at formation
- GWs from early PBH fluid

Predicted GWs at second order

Formalism due to
K. Kohri and T. Terada, Phys. Rev. D97, 123532 (2018), arXiv:1804.08577,
T. Papanikolaou, V. Vennin, and D. Langlois, arXiv:2010.11573v2

We want to calculate the GW spectrum today from early curvature perturbations

$$h''_{\mathbf{k}}(\eta) + 2\mathcal{H}h'_{\mathbf{k}}(\eta) + k^2 h_{\mathbf{k}}(\eta) = 4S_{\mathbf{k}}(\eta)$$

$$S_{\mathbf{k}}(\eta) \sim \int d^3q(\Phi_{\mathbf{q}}\Phi_{\mathbf{k}-\mathbf{q}} + \text{quadratic terms in } \Phi, \Phi')$$

$$\mathcal{P}_{\rm GW}(\eta,k)\delta^3(\mathbf{k}+\mathbf{k}') = \frac{k^3}{2\pi^2}\langle h_{\mathbf{k}}(\eta)h_{\mathbf{k}'}(\eta)\rangle,$$
$$\mathcal{P}(\eta,k)\delta^3(\mathbf{k}+\mathbf{k}') = \frac{k^3}{2\pi^2}\langle \Phi_{\mathbf{k}}(\eta)\Phi_{\mathbf{k}'}(\eta)\rangle.$$

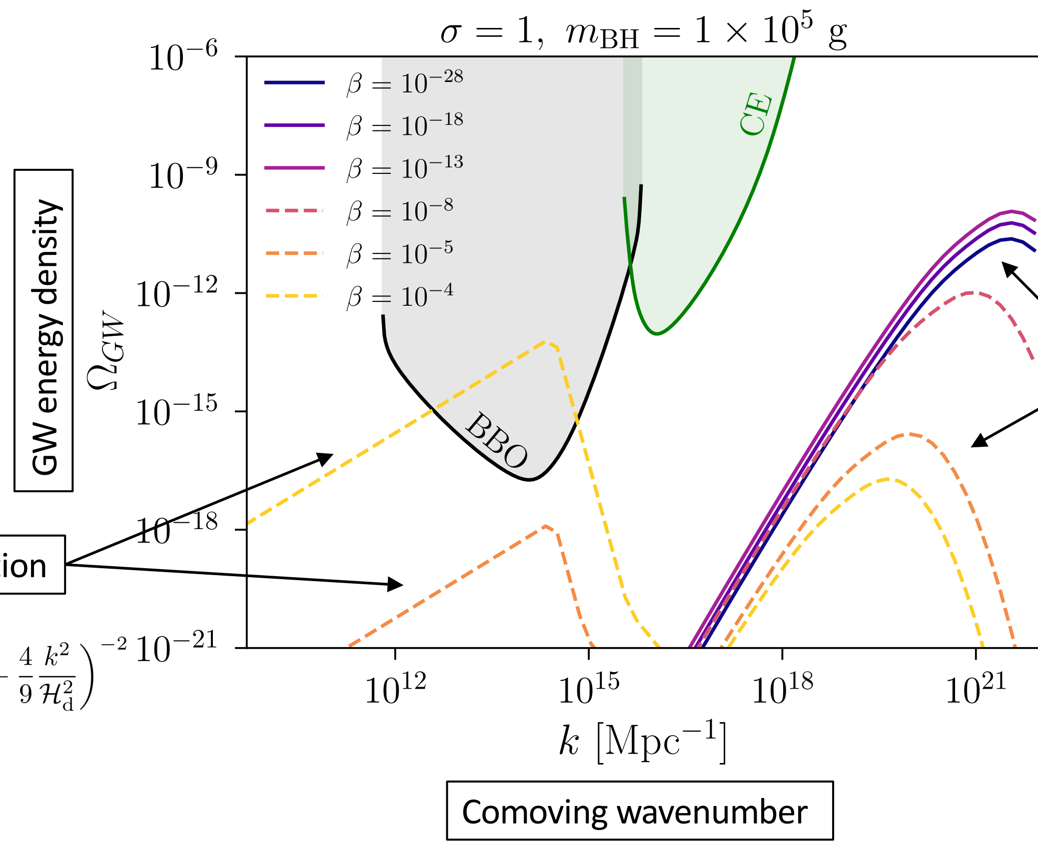
Initial curvature perturbation in PBH dominated era:

$$\mathcal{P}_{\rm MD}(k) = \frac{2}{3\pi}\left(\frac{k}{k_{\rm UV}}\right)^3\left(5+\frac{4}{9}\frac{k^2}{\mathcal{H}_{\rm d}^2}\right)^{-2}$$

Primordial curvature perturbation entering horizon during RD:

$$\mathcal{P}(k) = \frac{A}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{\log^2(k/k_\star)}{2\sigma^2}\right)$$

Resulting GW spectra today



$$\mathcal{P}_{\rm MD}(k) = \frac{2}{3\pi}\left(\frac{k}{k_{\rm UV}}\right)^3\left(5+\frac{4}{9}\frac{k^2}{\mathcal{H}_{\rm d}^2}\right)^{-2}$$

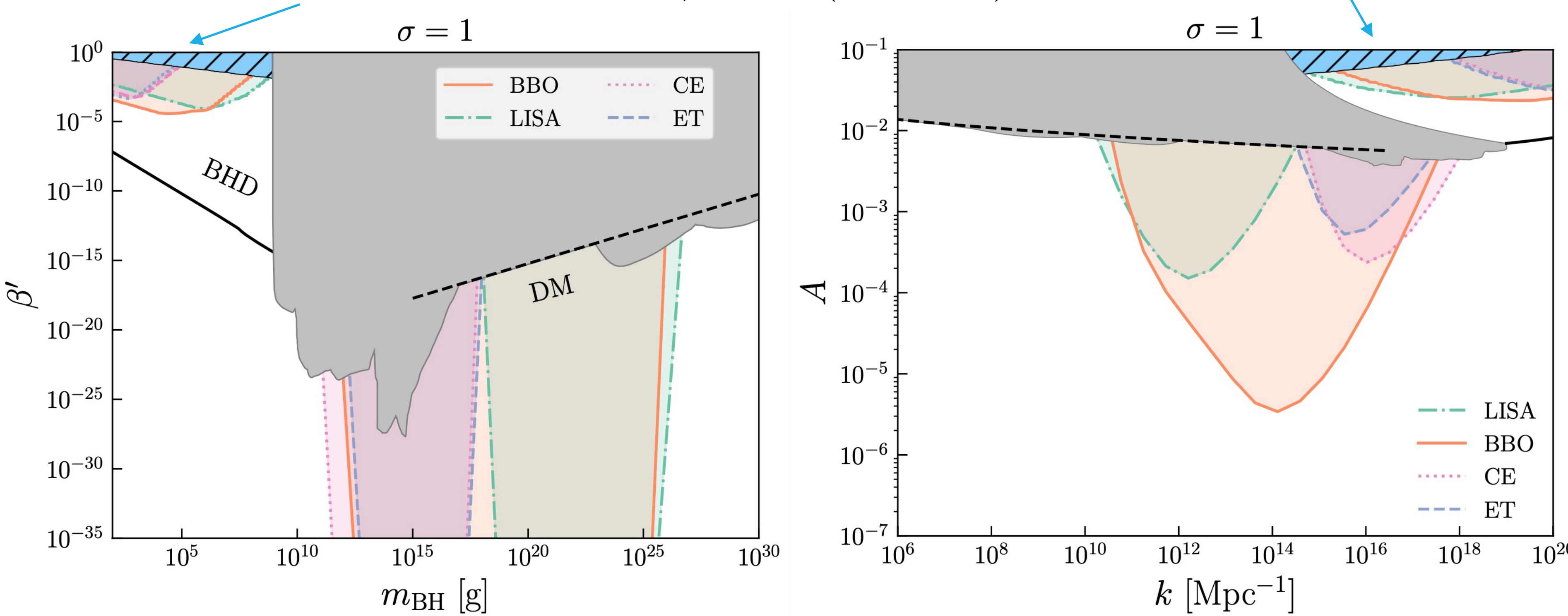
$$\mathcal{P}(k) = \frac{A}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{\log^2(k/k_\star)}{2\sigma^2}\right)$$

Detector Sensitivity
E. Thrane and J. D. Romano, Phys. Rev. D81, 124032(2013), arXiv:1310.5300,
K. Schmitz, J. High Energ. Phys., 97 (2021), arXiv:2002.04615v3

$$\mathcal{P}(k) = \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{\log^2(k/k_\star)}{2\sigma^2}\right)$$

GW overclosure

GW overclosure



Existing bounds, reaches in black hole mass – abundance plane

Existing bounds, reaches in curvature perturbation peak frequency – amplitude plane

Observation Time = 1 yr
SNR = 1

Assuming perfect
subtraction of foreground

Conclusions

Next generation GW observatories may indirectly PBHs in the early universe

These observatories will indirectly detect long-lived black holes in almost the entire allowed parameter space (depending on the primordial curvature perturbation shape)

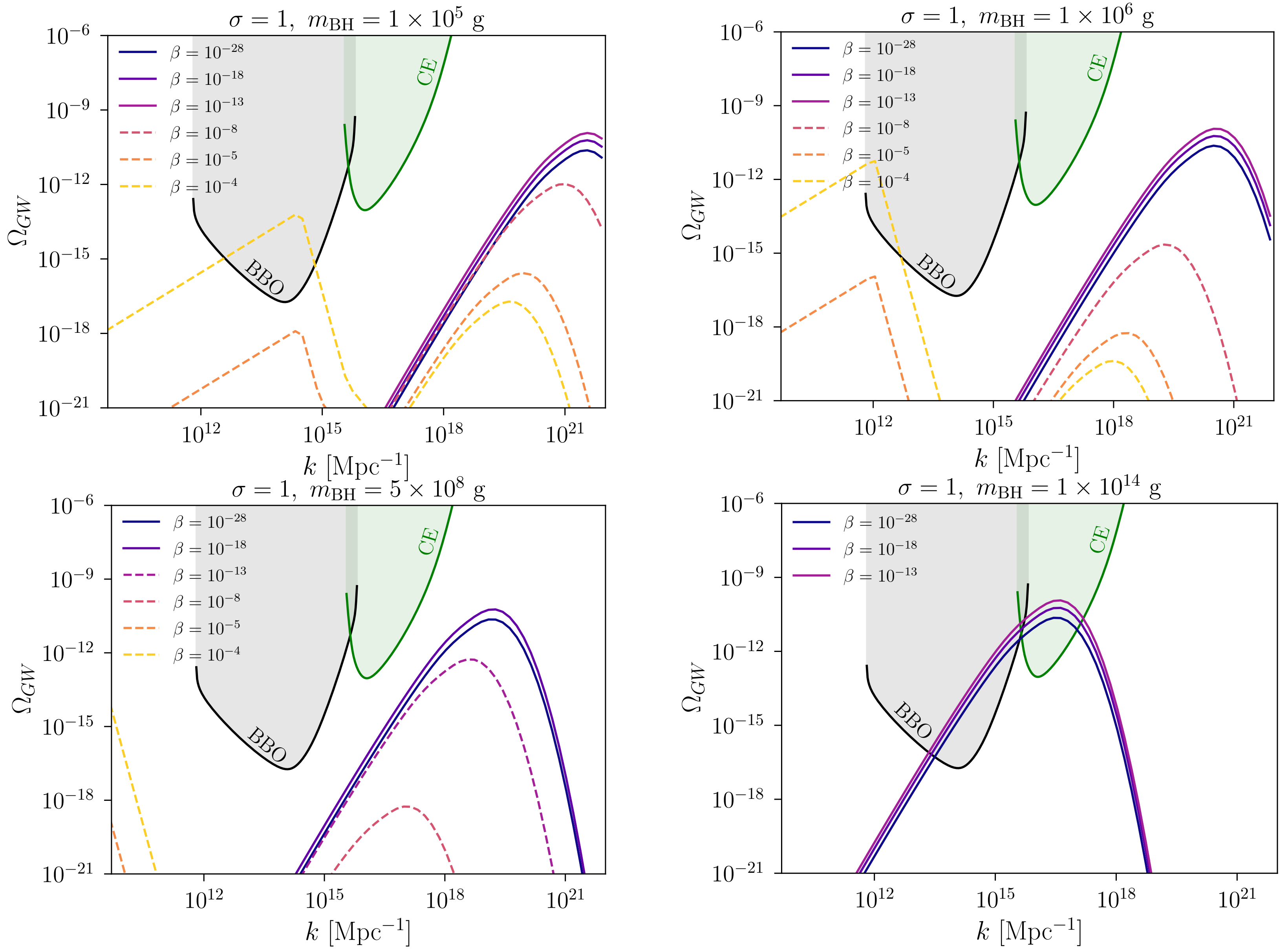
Black hole parameter space

Primordial curvature perturbation parameter space

Existing bounds from BBN, EGB, etc. (current observational bounds on long lived black holes) can be used to indirectly bound the parameter space of primordial curvature perturbations

We can also probe primordial perturbations at small scales and high amplitude, *because of the induced black hole dominated* era.

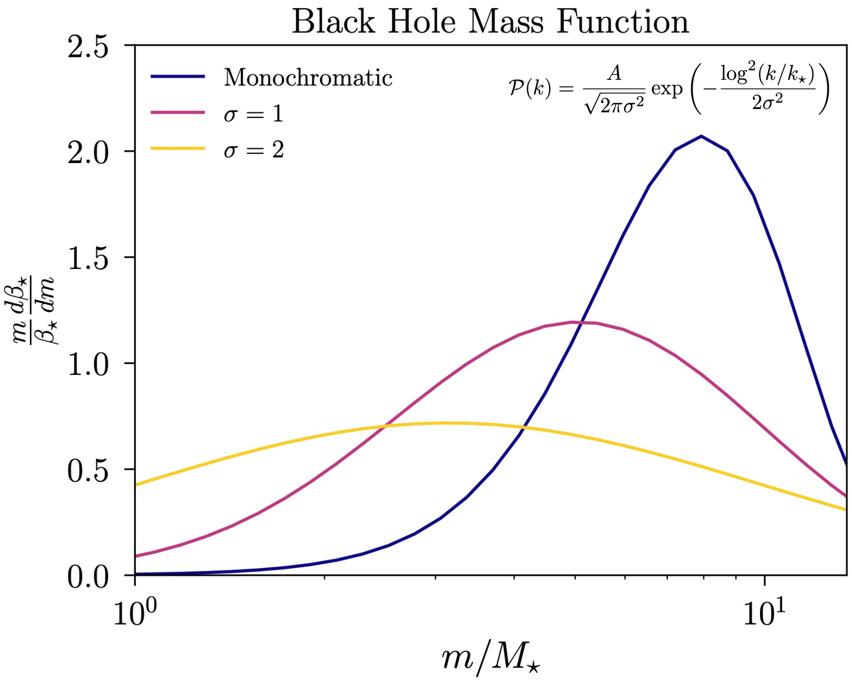
Extras



$\sigma = 1,\ m_{\rm BH} = 1\times10^{5}$ g
$\sigma = 1,\ m_{\rm BH} = 1\times10^{6}$ g
$\sigma = 1,\ m_{\rm BH} = 5\times10^{8}$ g
$\sigma = 1,\ m_{\rm BH} = 1\times10^{14}$ g
$\beta = 10^{-28}$
$\beta = 10^{-18}$
$\beta = 10^{-13}$
$\beta = 10^{-8}$
$\beta = 10^{-5}$
$\beta = 10^{-4}$
BBO
CE
Ω_{GW}
k [Mpc^{-1}]
10^{-6} 10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21}
10^{12} 10^{15} 10^{18} 10^{21}

Primordial Black Hole Formation

We work in the Press-Schechter formalism – PBHs are formed when the density contrast exceeds a certain threshold (various papers have calculated this numerically)

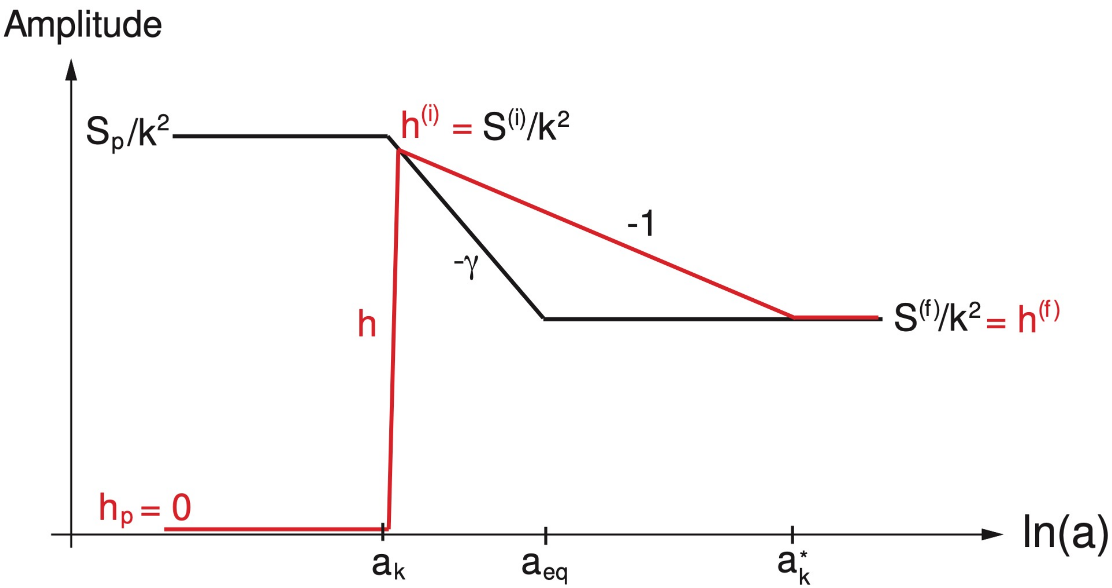


$$m_{\rm BH} \propto \frac{4\pi}{3}\rho_{r,\star}H_\star^{-3}$$

$$\beta \propto A^b \mathrm{Erfc}\left[\frac{c}{\sqrt{A}}\right]$$

A monochromatic curvature perturbation with $A = 0.01$ gives an abundance of $\beta = 4 \times 10^{-5}$

Evolution of the source term



$$\Phi''_{\mathbf{k}}(\eta) + \frac{6(1+w)}{(1+3w)\eta}\Phi'_{\mathbf{k}}(\eta) + wk^2\Phi_{\mathbf{k}}(\eta) = 0$$

In RD: $\Phi \sim \frac{1}{(k\eta)^2}$

In MD: $\Phi \sim \mathrm{const.}$

Second order perturbation theory

$$h''_{\mathbf{k}}(\eta) + 2\mathcal{H}h'_{\mathbf{k}}(\eta) + k^2 h_{\mathbf{k}}(\eta) = 4S_{\mathbf{k}}(\eta)$$

$$S_{\mathbf{k}} = \int \frac{\mathrm{d}^3 q}{(2\pi)^{3/2}} e_{ij}(\mathbf{k}) q_i q_j \left(2\Phi_{\mathbf{q}}\Phi_{\mathbf{k}-\mathbf{q}} + \frac{4}{3(1+w)} \left(\mathcal{H}^{-1}\Phi'_{\mathbf{q}} + \Phi_{\mathbf{q}}\right) \left(\mathcal{H}^{-1}\Phi'_{\mathbf{k}-\mathbf{q}} + \Phi_{\mathbf{k}-\mathbf{q}}\right) \right)$$

$$\Phi''_{\mathbf{k}}(\eta) + \frac{6(1+w)}{(1+3w)\eta}\Phi'_{\mathbf{k}}(\eta) + wk^2\Phi_{\mathbf{k}}(\eta) = 0.$$

$$\mathcal{P}_h(\eta, k) = 4\int_0^\infty \mathrm{d}v \int_{|1-v|}^{1+v} \mathrm{d}u \left(\frac{4v^2 - \left(1 + v^2 - u^2\right)^2}{4vu} \right)^2 I^2(v, u, x)\mathcal{P}_\zeta(kv)\mathcal{P}_\zeta(ku)$$

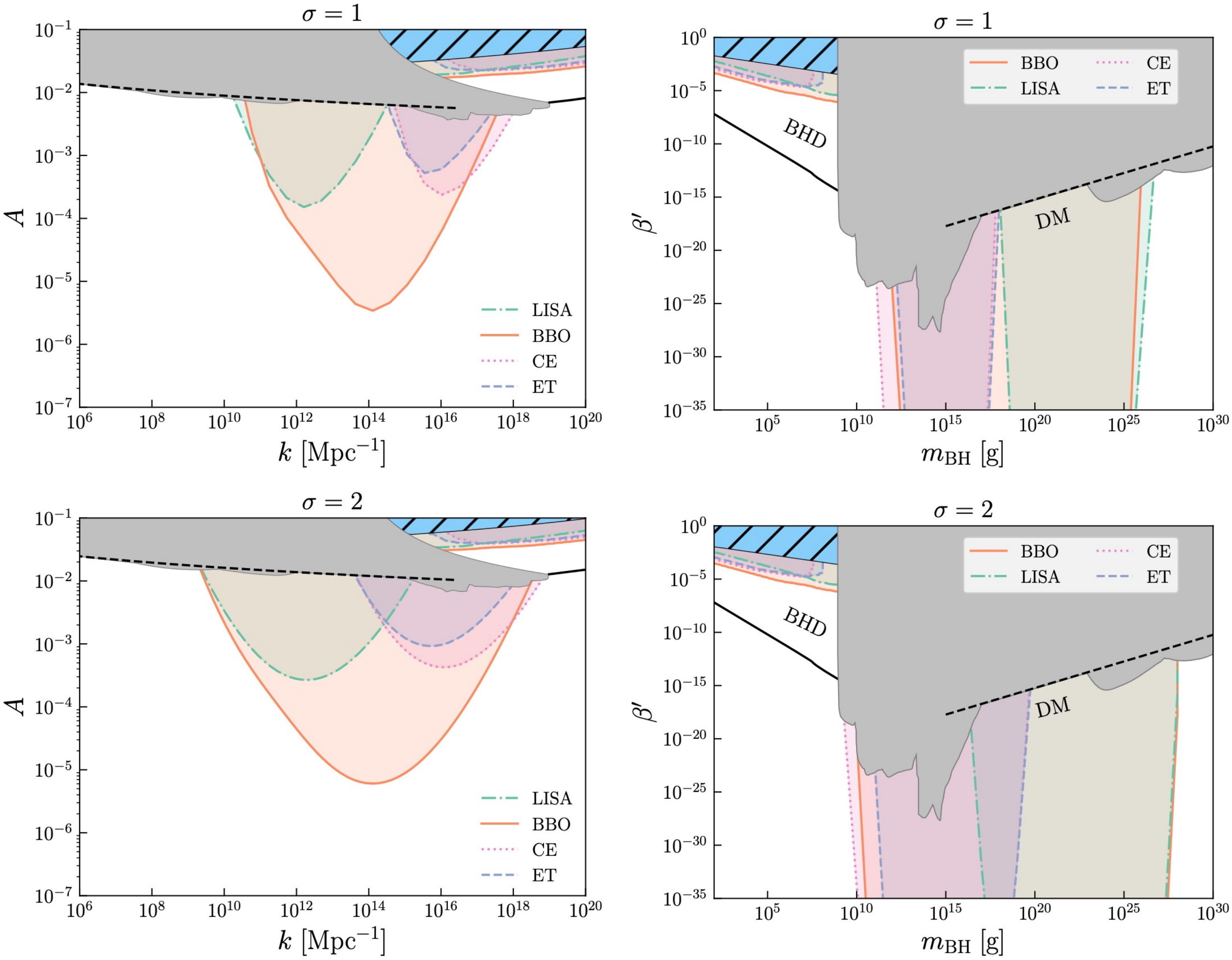
$$\Omega_{\mathrm{GW}}(\eta, k) = \frac{\rho_{\mathrm{GW}}(\eta, k)}{\rho_{\mathrm{tot}}(\eta)} = \frac{1}{24}\left(\frac{k}{a(\eta)H(\eta)}\right)^2 \overline{\mathcal{P}_h(\eta, k)}$$

Nonlinearities from MD era

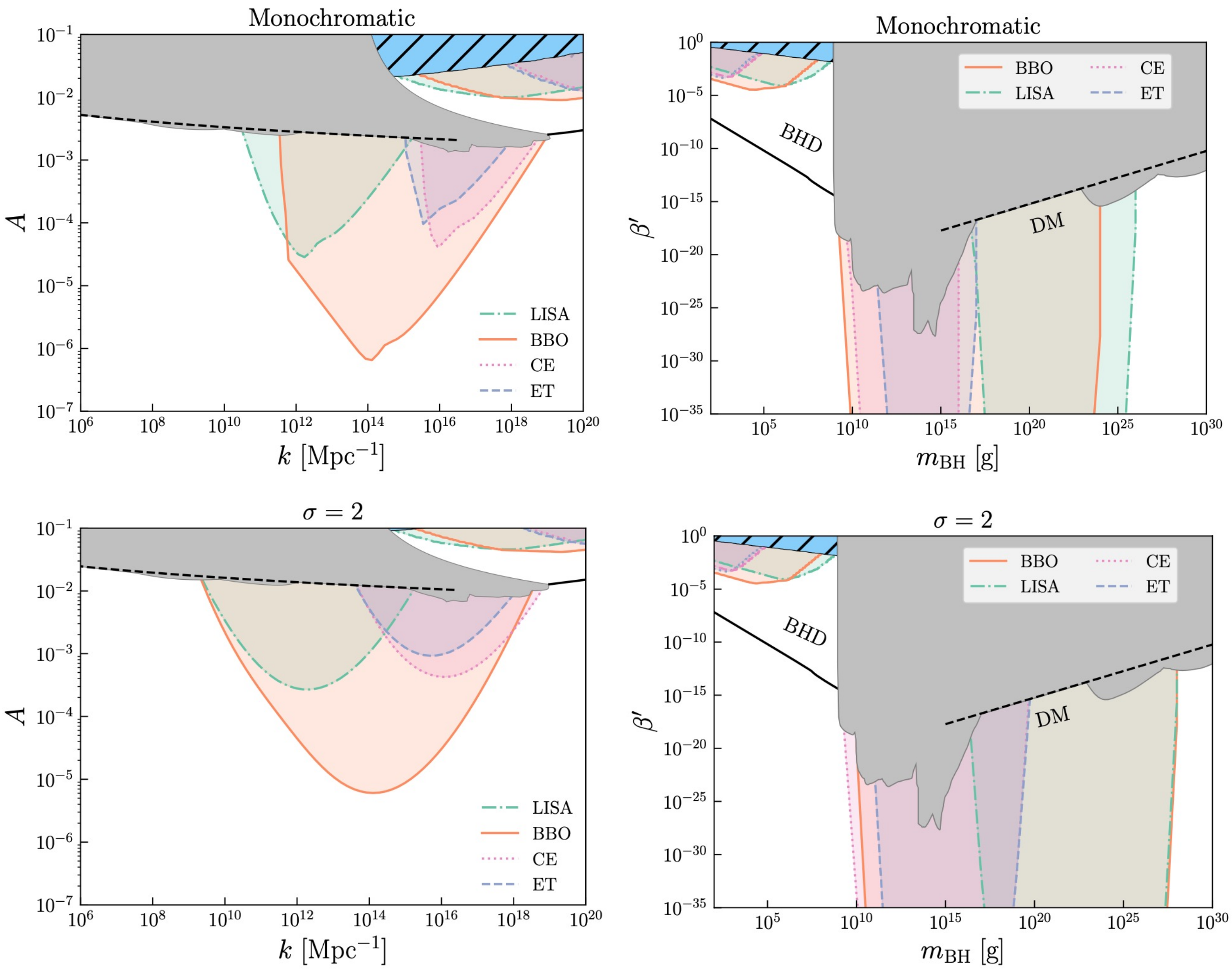
Since matter density perturbations grow with the scale factor, in a long enough MD era, they will eventually become non-linear, what happens then?

- Possible clustering effects, PBHs form halos and transfer power to smaller scales?

In our results, we apply a conservative estimate: apply a cutoff to the source when the matter perturbations become nonlinear.



Reaches without non-linear cutoff

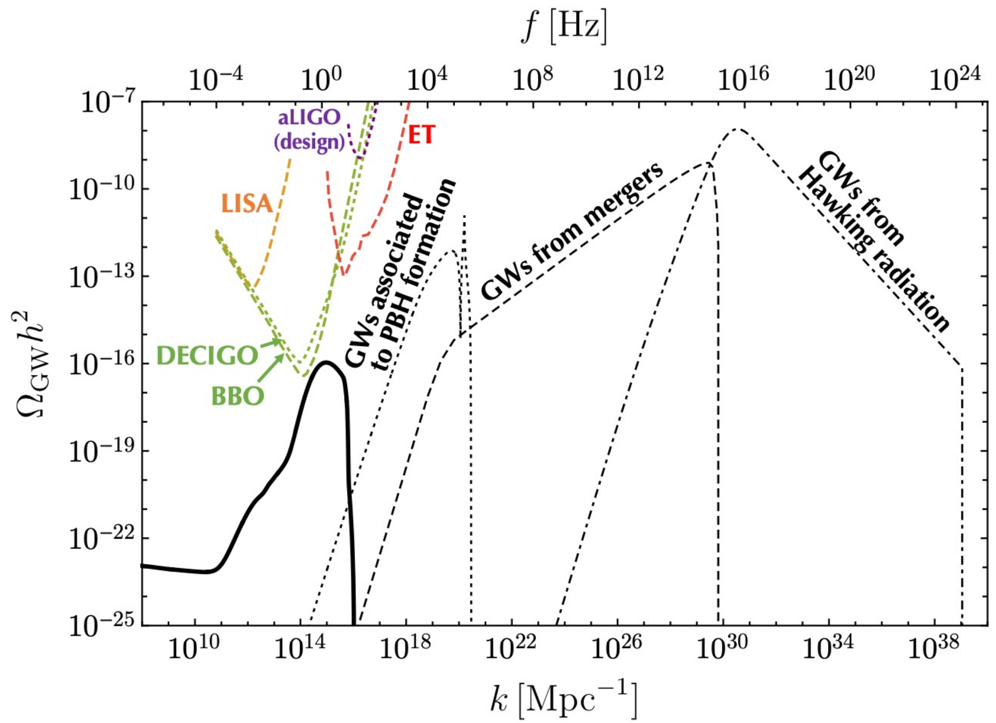


With NL cutoff, monochromatic and $\sigma = 2$ widths

Note that the relationship between amplitude and abundance is highly dependent on the curvature perturbation width

Additional Sources of GWs

- Mergers
- Hawking radiation
- Rapid reheating from black hole dominated –> radiation dominated



We don't take into account the mergers + Hawking radiation, as the scales are too small to appear in our reaches.

Rapid reheating also requires a very narrow mass function, so we don't consider this case