Induced gravitational waves and baryon asymmetry fluctuations from primordial black hole formation

Julián Rey

DESY Theory Group

Introduction

- We will explore the interplay between primordial black holes, gravitational waves, and the baryon asymmetry.
- PBHs are dark matter candidates that do not require physics beyond inflation. They can account for the totality of dark matter if[1]

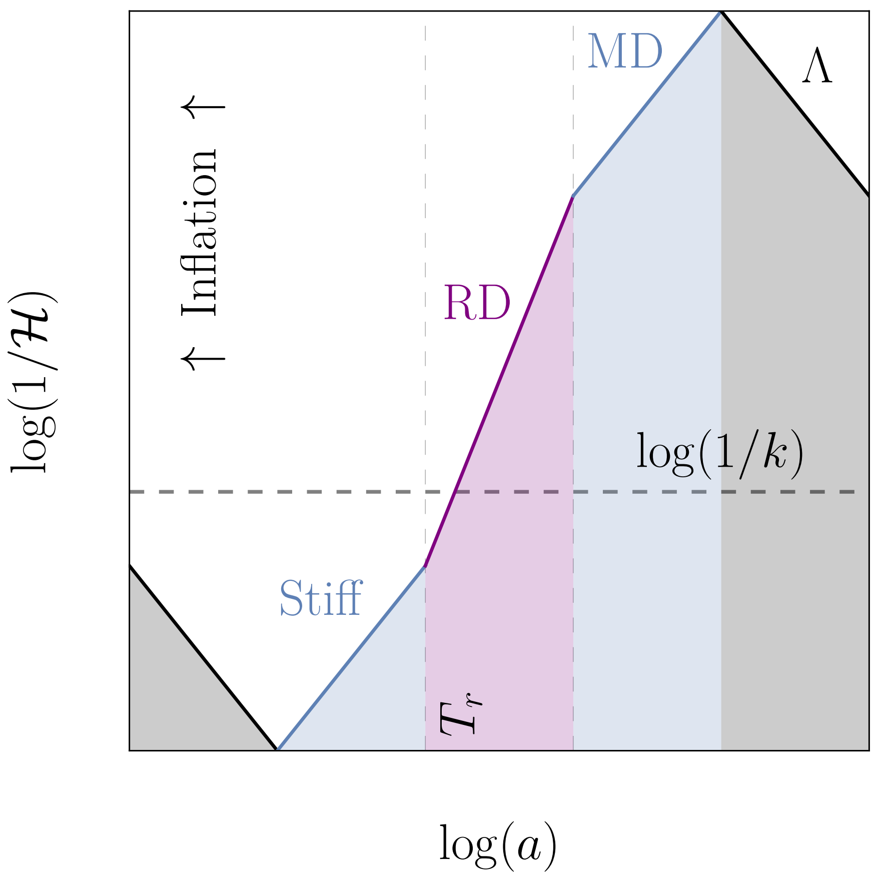
$$10^{-16}\,M_\odot \lesssim M_{\rm PBH} \lesssim 10^{-11} M_\odot .$$

- The simplest way to form PBHs is from the gravitational collapse of large density fluctuations produced during inflation.
- These large density fluctuations seed gravitational wave signals that could be probed within the next few decades.[2]
- These perturbations also act as a source for fluctuations in the baryon asymmetry.

[1] B. Carr, et al. [0912.5297], A. Arbey et al. [1906.04750], H. Niikura et al. [1701.02151], A. Katz et al. [1807.11495]
[2] M. Sasaki et al. [1801.05235]

Primordial black holes

PBHs are formed in the early universe by mechanisms different to stellar collapse. We consider formation from large density fluctuations during an early stiff era.



- Fluctuations are produced during inflation. They induce collapse upon re-entry.
- A significant population requires a large power spectrum,

$$\frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \propto \int_{\delta_c}^{\infty} \exp\left(-\delta^2/2\mathcal{P}_{\mathcal{R}}\right) d\delta.$$

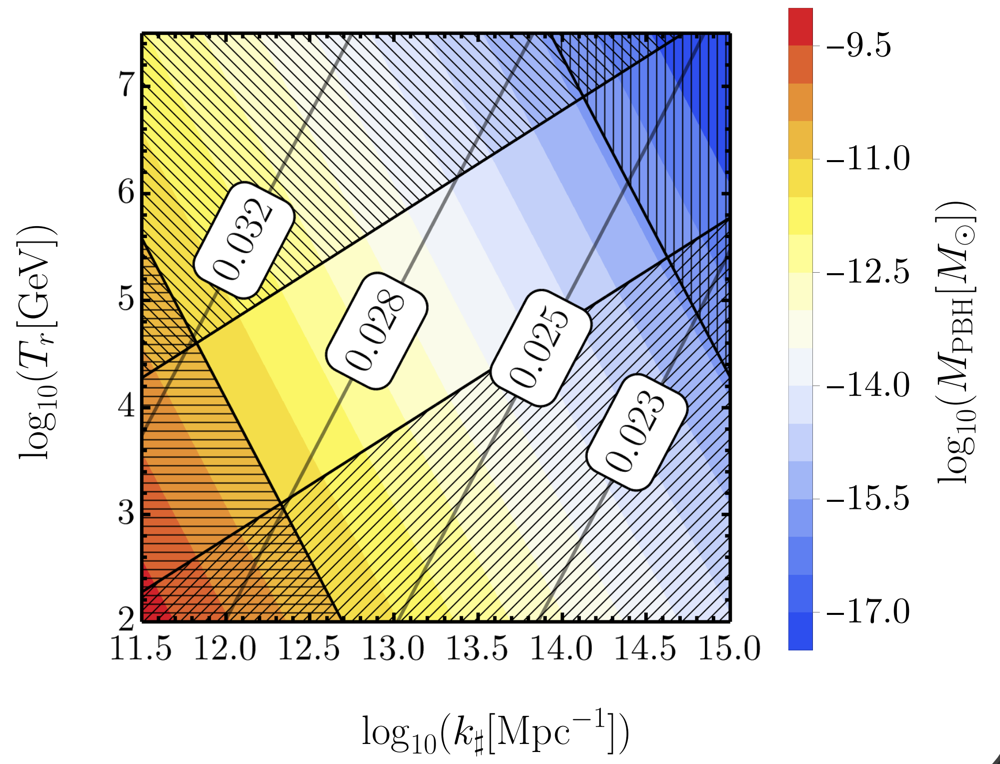
- This can be obtained if the inflaton slows down,

$$\mathcal{P}_{\mathcal{R}} \sim H^4/\dot{\phi}^2.$$

Mass and abundance

We model the power spectrum as flat (CMB) + sharp (PBHs)

$$\mathcal{P}_{\mathcal{R}} = \mathcal{A}_\flat + k_\sharp \mathcal{A}_\sharp \delta(k - k_\sharp)$$

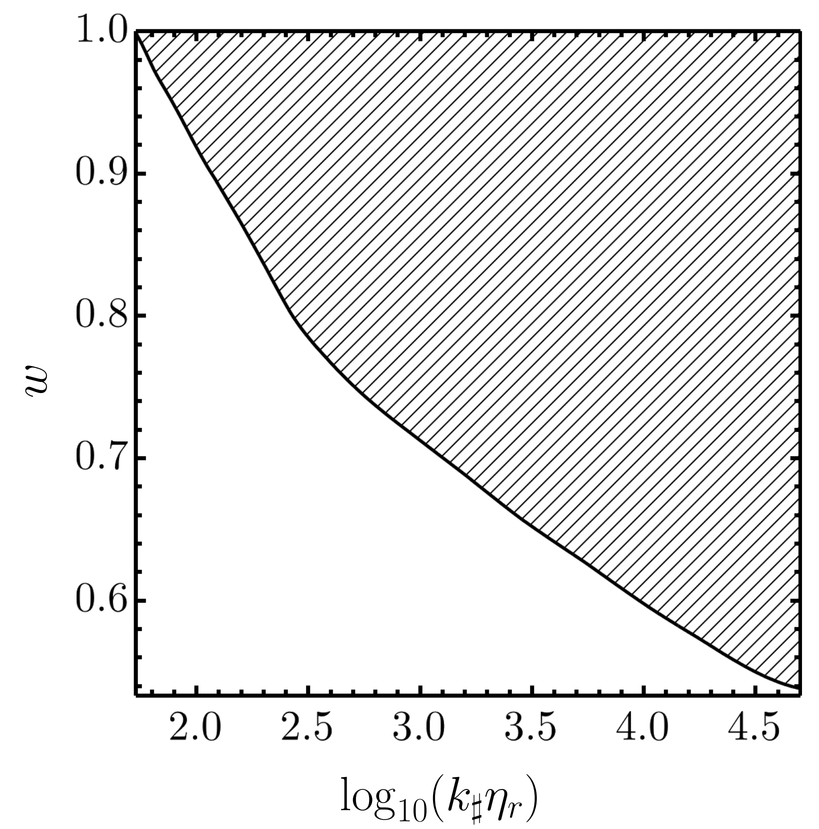


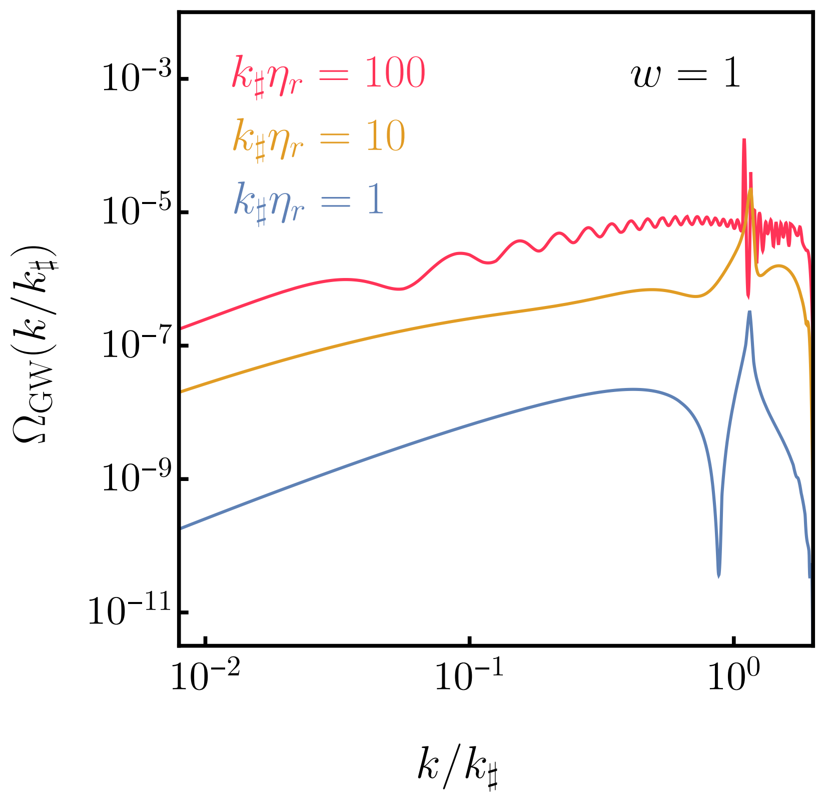
- Mass and abundance depend on w, T_r, and $k_\sharp$.
- We have several constraints,
  1. Unconstrained masses
  2. Collapse must occur before transition
  3. GWs should not be overproduced
- These constraints are relaxed for w closer to 1/3.

Gravitational waves

Large scalar perturbations source gravitational waves,[3]

$$h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} \sim \partial_i\phi\partial_j\phi \qquad \Omega_{\rm GW}h^2 < 1.8\times 10^{-6}$$

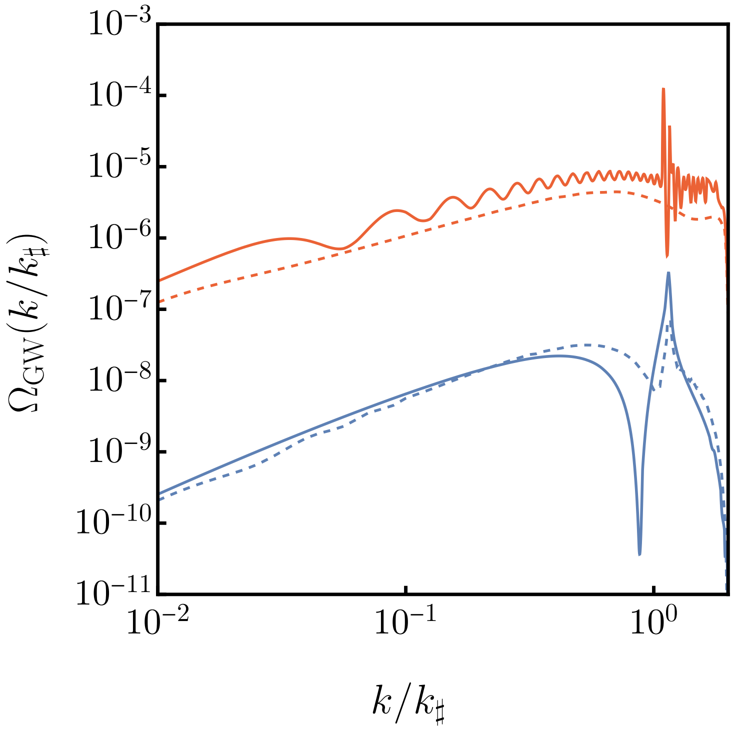




[3] G. Domenech [1912.05583]

Gradual transition

If instead of a sudden transition we take a gradual decay, the resulting spectrum is the same, but features are smoothed out



- We take a smooth energy transfer rate

$$\frac{d\rho_w}{dN} + 3(1+w)\rho_w = -\frac{\Gamma}{H}\rho_w,$$
$$\frac{d\rho_\gamma}{dN} + 4\rho_\gamma = \frac{\Gamma}{H}\rho_w.$$

- The equations for the perturbations are much more complex.
- The plot shows the numerical result for $w = 1$ with $k_\sharp \eta_r = 1$ and $k_\sharp \eta_r = 100$
- We conclude the bound does not depend heavily on this.

Chiral gravitational anomaly

Leptogenesis: *generating a lepton asymmetry at early times, and using* **sphalerons** *(non-perturbative electroweak processes) to convert it to a* **baryon asymmetry**.

The Standard Model, coupled to gravity, contains an anomaly,

$$\nabla_\mu J^\mu_{\mathrm{L}} = -\frac{N_{\mathrm{L-R}}}{24(4\pi)^2} R\tilde{R} \qquad \rightarrow \qquad a^3 n_{\mathrm{L}} = \frac{1}{16\pi^2} \int \epsilon_{ijk} \partial_j \partial_\ell \phi \partial_k h'_{i\ell} d\eta .$$

The mean value of this quantity vanishes $\langle n_{\mathrm{L}} \rangle = 0$, but its variance does not, because inflation is a stochastic process.[4] We expect inflation to generate an asymmetry of order $\sim \langle n_{\mathrm{L}}^2 \rangle^{1/2}$ on different patches. The Sakharov conditions are verified.

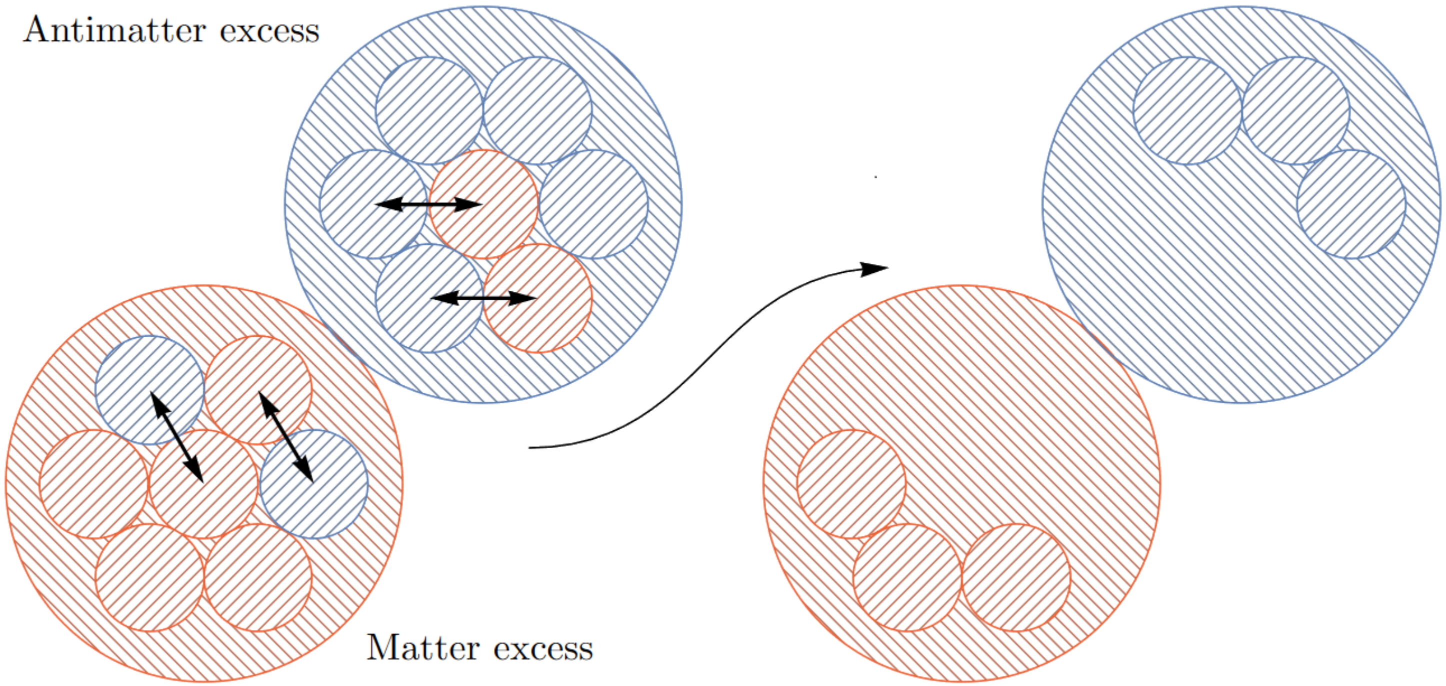
- We are describing a spectrum of fluctuations on top of the observed $n_{\mathrm{L}}/s \sim 10^{-10}$
- Alternatively, one could also consider couplings such as $\varphi R\tilde{R}$ (gravitational leptogenesis).[5]

[4] A. Maroto and A. Miravet. [2207.00465]
[5] M. Peskin et al. [hep-th/0403069]

Annihilation dynamics

Small neighbouring patches with matter and antimatter excesses annihilate. Larger regions remain unaffected, since quarks cannot travel beyond the Silk scale,

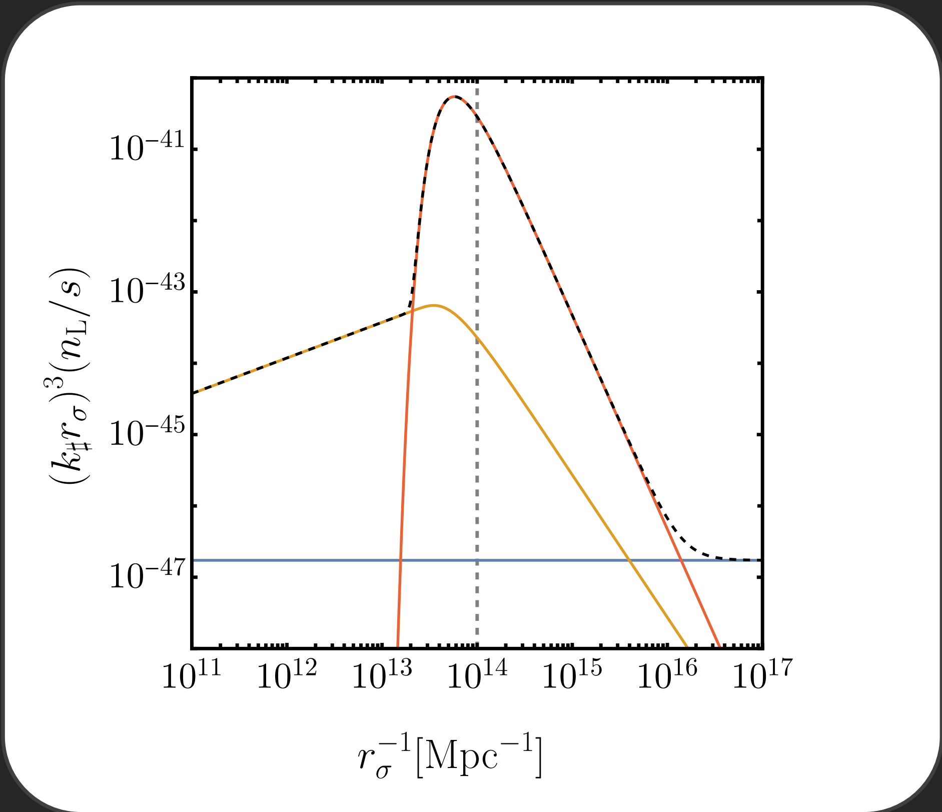
$$r_{\rm S}^2 \simeq \int_0^{t_{\rm QCD}} dt\, \frac{\lambda_{\rm Q}}{a^2} \simeq \left(10^{-17}{\rm Mpc}\right)^2.$$



Baryon asymmetry fluctuations

We compute the variance smoothed over a scale r_σ. Both the flat CMB spectrum and the PBH peak contribute to the variance. Very mild dependence on w and T_r.

$$\langle |n_{\mathrm{L}}|^2 \rangle_{r_\sigma} = \left\langle \left| \int d^3\boldsymbol{r}\, W_{r_\sigma}(r)\, n_{\mathrm{L}}(\boldsymbol{x}+\boldsymbol{r}) \right|^2 \right\rangle$$



- From dimensions and $a^3 n_{\mathrm{L}} \sim \phi h$, and dividing by $s \sim g_{\star s}(T) T^3$,

$$\frac{n_{\mathrm{L}}}{s} \sim \frac{\sqrt{\mathcal{P}_{\mathcal{R}} \mathcal{P}_h}}{g_{\star s}(T_0)(r_\sigma T_0)^3}$$

- Results for a flat scalar/tensor spectrum, a sharp scalar spectrum, and sharp scalar/tensor spectrum.

Future directions

- Constraints on Ω_{GW} for $w \simeq 0$, and the effect of non-Gaussianities.
- Determine the relevant observables: baryon-to-photon ratio η, anisotropies in Ω_b, baryon isocurvature modes...
- Effect of non-Gaussianities on n_{L}/s fluctuations.
- Compute the spectrum in a model of gravitational leptogenesis, such as $f(\varphi)R\tilde{R}$, where the mean value $\langle n_{\mathrm{L}} \rangle_{r_\sigma}$ does not vanish.
- Is there a mechanism to enhance the fluctuations on large scales?

Conclusions

- Black holes can form during an early stiff epoch. The abundance still requires $\mathcal{P}_{\mathcal{R}} \sim 10^{-2}$. The mass depends on w, T_r and $k_\sharp$
- The parameter space is constrained by asking that 1. the masses can explain DM, 2. collapse occurs before the transition and 3. GWs are not overproduced
- We find that a stiff epoch enhances the induced GW spectrum, just like it does for the first-order GWs.
- These large scalar perturbations and GWs also induce fluctuations in the baryon asymmetry via the chiral gravitational anomaly.
- We do not aim to explain the observed value of n_{L}/s. These fluctuations could potentially be used as a new observable to probe PBHs, though they are small.

These fluctuations are present in **any** *model of PBH formation from single-field inflation, assuming only the SM matter content.*

Thank you!


"Scientists have discovered a new kind of Black Hole that has a gravitational field so intense that no treats or dropped food scraps can escape."