Probing the primordial universe with GWs

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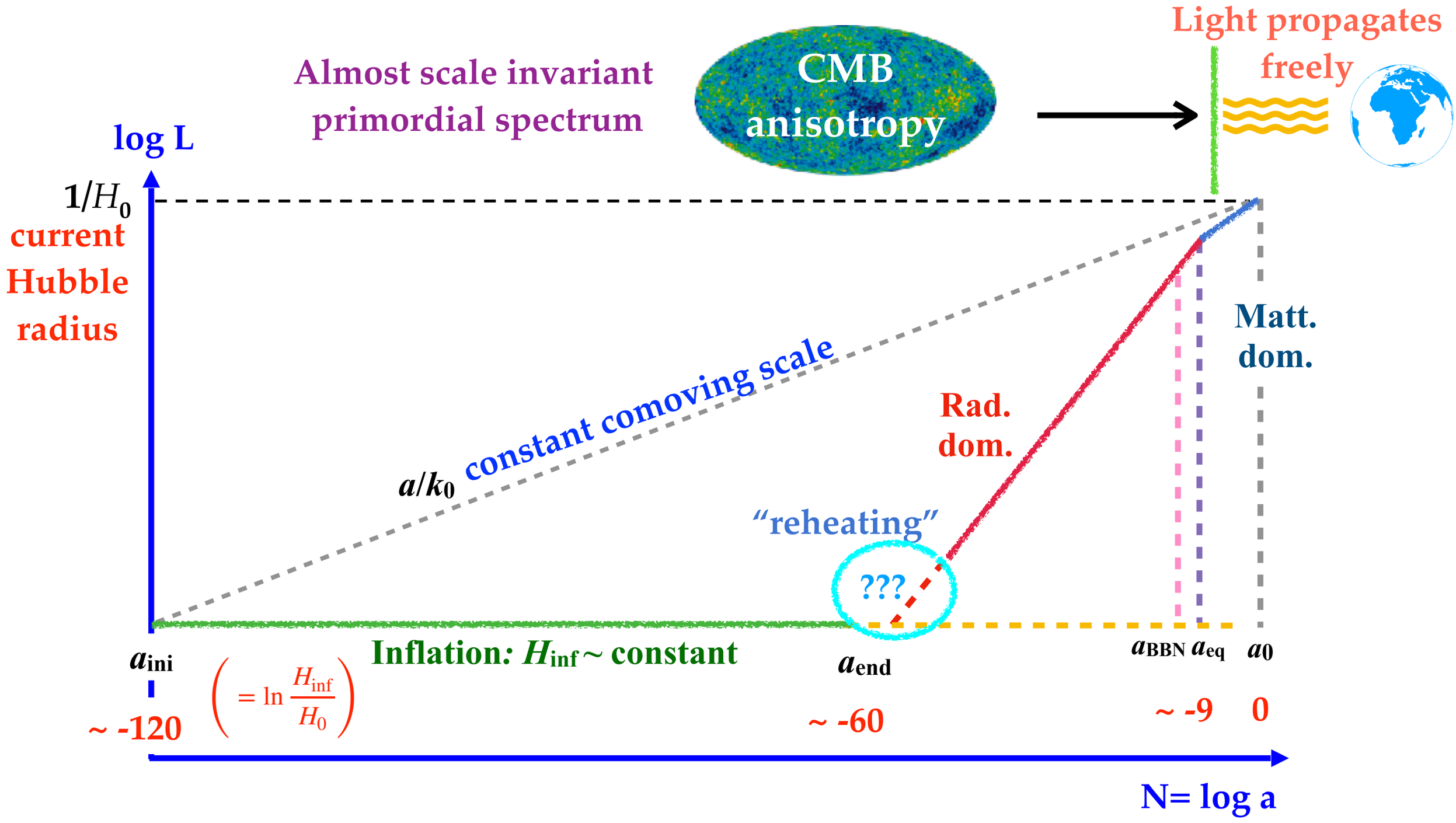
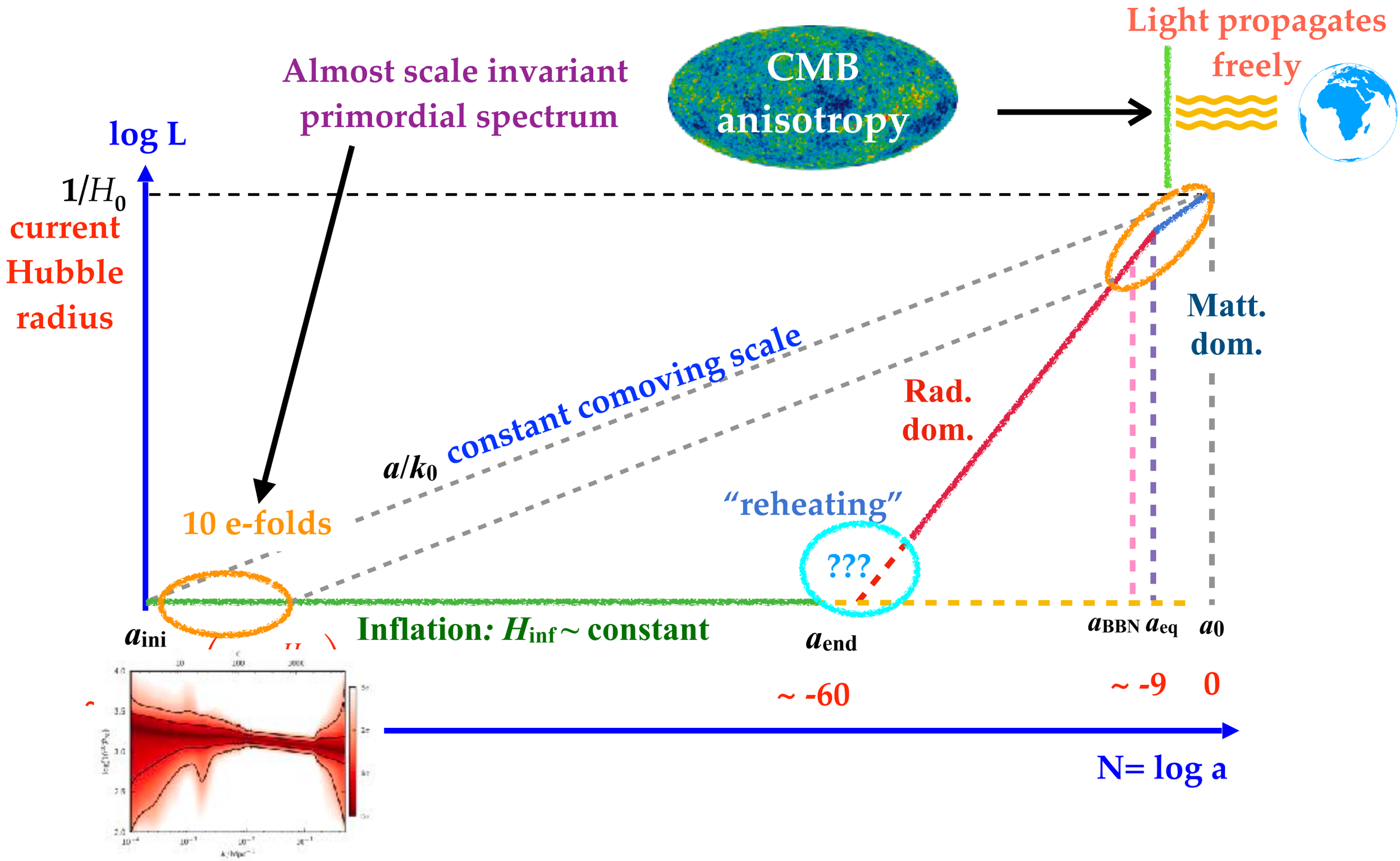
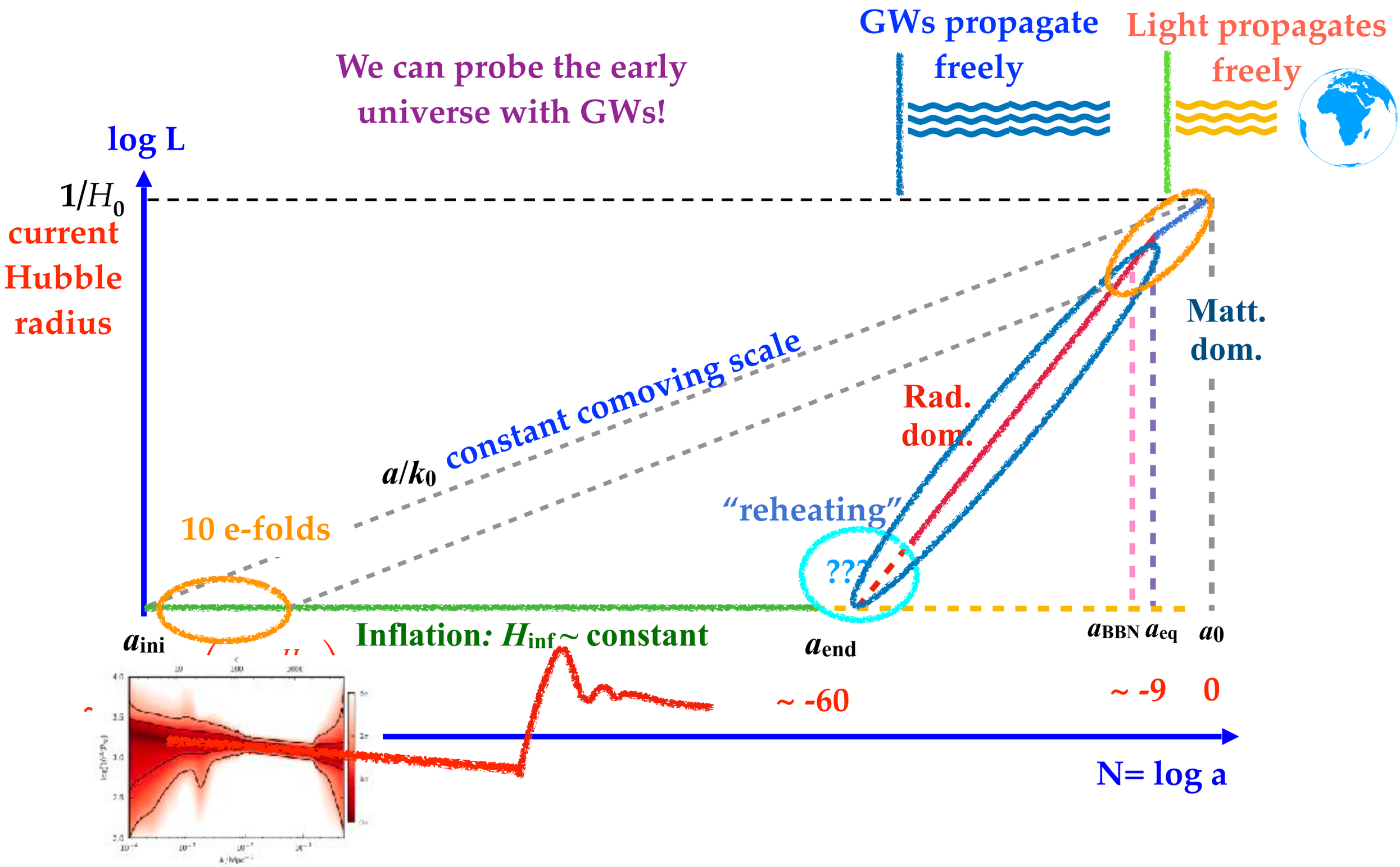
Cosmic spacetime diagram



Cosmic spacetime diagram



Cosmic spacetime diagram



Cosmological SGWB = New physics

New physics before BBN (and after inflation):

Phase transitions:
- **Strong first order phase transitions**
- **Topological defects like cosmic strings**

(QCD axions?)

Preheating and reheating:
- **Parametric resonances**

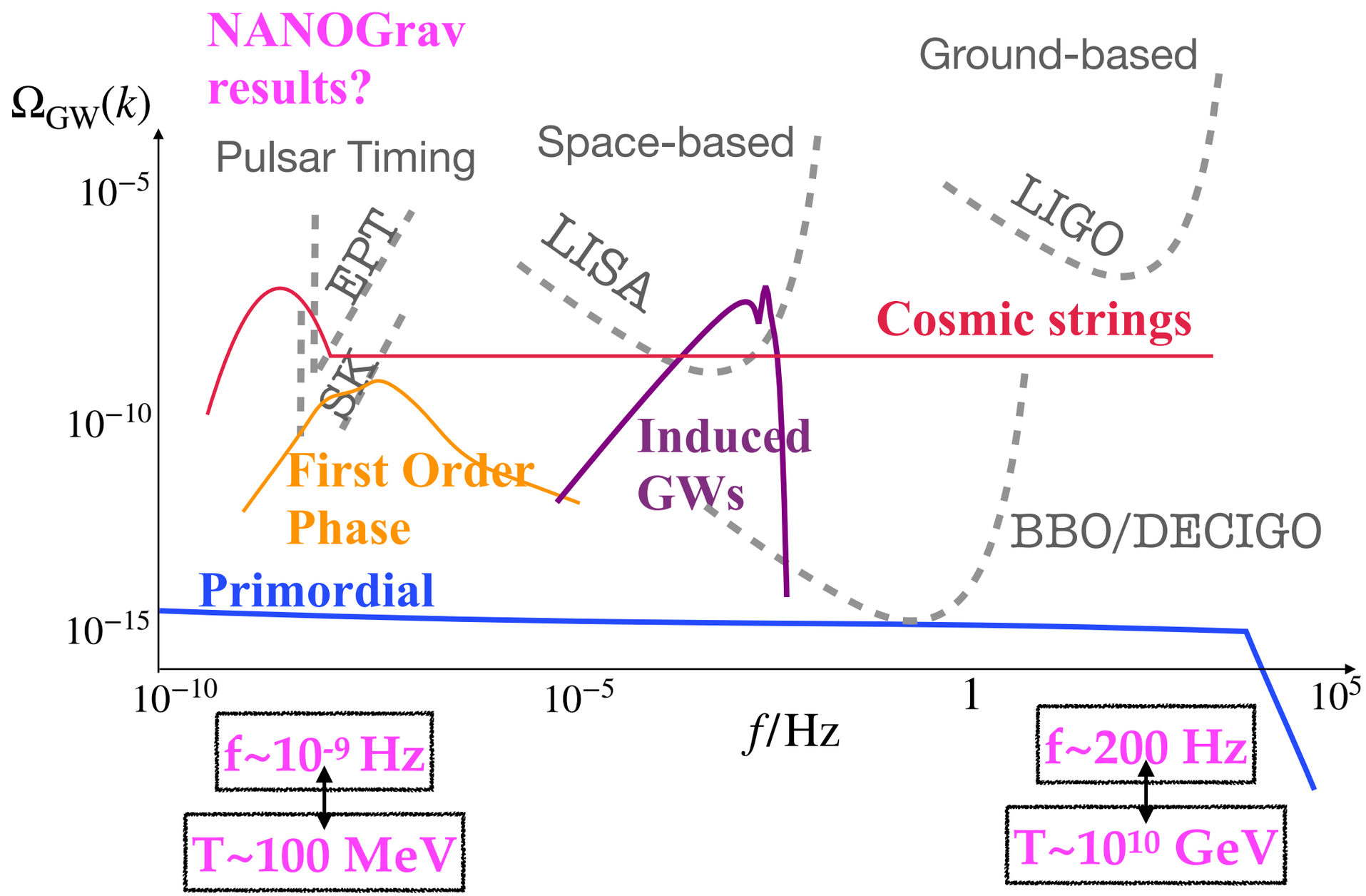
New physics during inflation:

Quantum fluctuations:
- **Enhanced primordial tensor spectrum**
- **Enhanced primordial scalar spectrum**

After inflation →
- **PBHs (dark matter?)**
- **Induced GWs**

Additional sources:
- **SU(2) gauge fields**
- **Axion fields**

Cosmological Stochastic GW background



Induced GWs are very interesting!

1. Probe the primordial spectrum:

Inomata & Nakama: 1812.00674

Byrnes et al. 2008.03289

Absence = upper bound! $\mathscr{P}_{\mathscr{R}} \lesssim 10^{-5}$

2. Probe the shape of inflationary potential [V.Atal & GD: 2103.01056]

UV tail of GW spectrum sensitive to inflationary model

3. Probe the expansion history: [GD, S.Pi, M.Sasaki, 2005.12314]

[GD, 1912.05583]

GW spectrum sensitive to equation of state parameter

$$\frac{d\Omega_{\rm GW}^{\rm induced}({\rm IR})}{d\log k} \sim 3 - 2\frac{1-3w}{1+3w}$$

4.Constrain reheating by PBH:

Papanikolau et al. 2010.11573

[GD, C.Lin & M.Sasaki, 2012.08151]

Strongly constrain the initial fraction of PBH

$$\beta_{\rm PBH} < 10^{-4} - 10^{-12}$$
$$M_{\rm PBH} \sim 1 - 10^{9}\,{\rm g}$$

5.Might explain the NANOGrav results (and some PBH)

[GD and S.Pi, 2010.03976] Vaskonen+, Kohri+, Inomata+, De Luca+, Sugiyama+

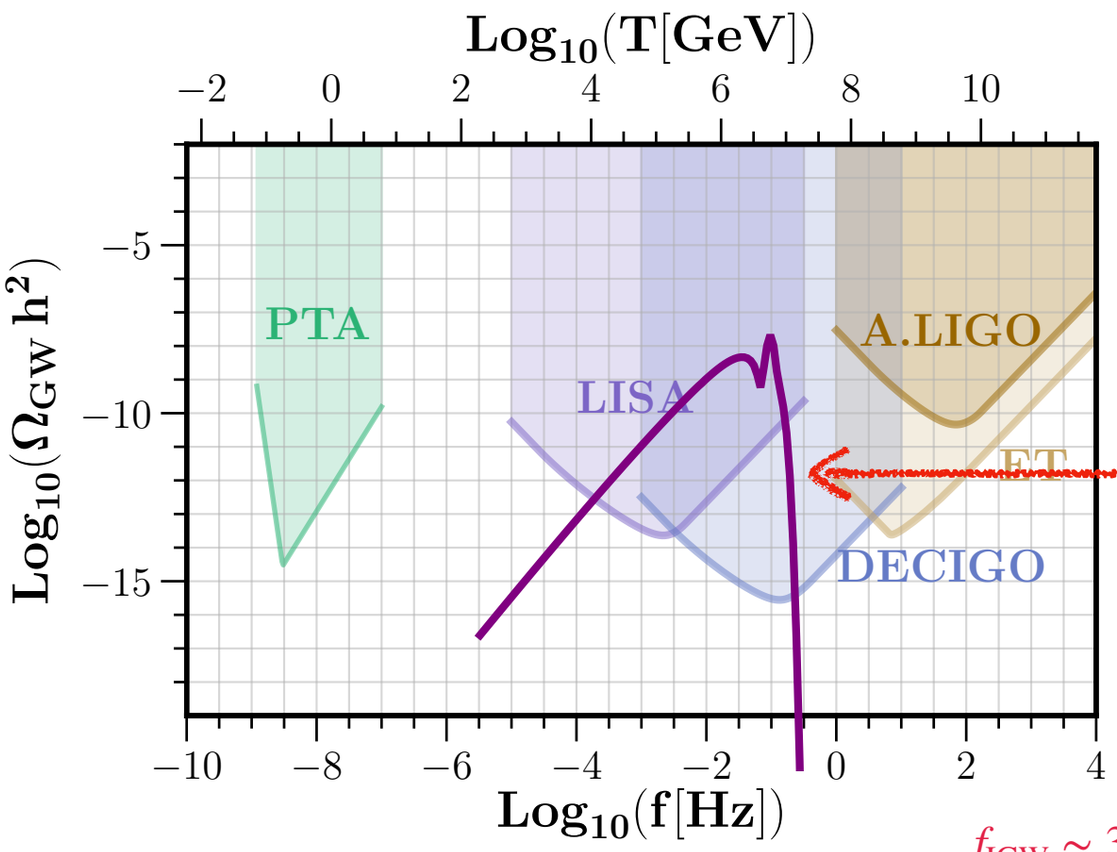
Induced GWs and PBH

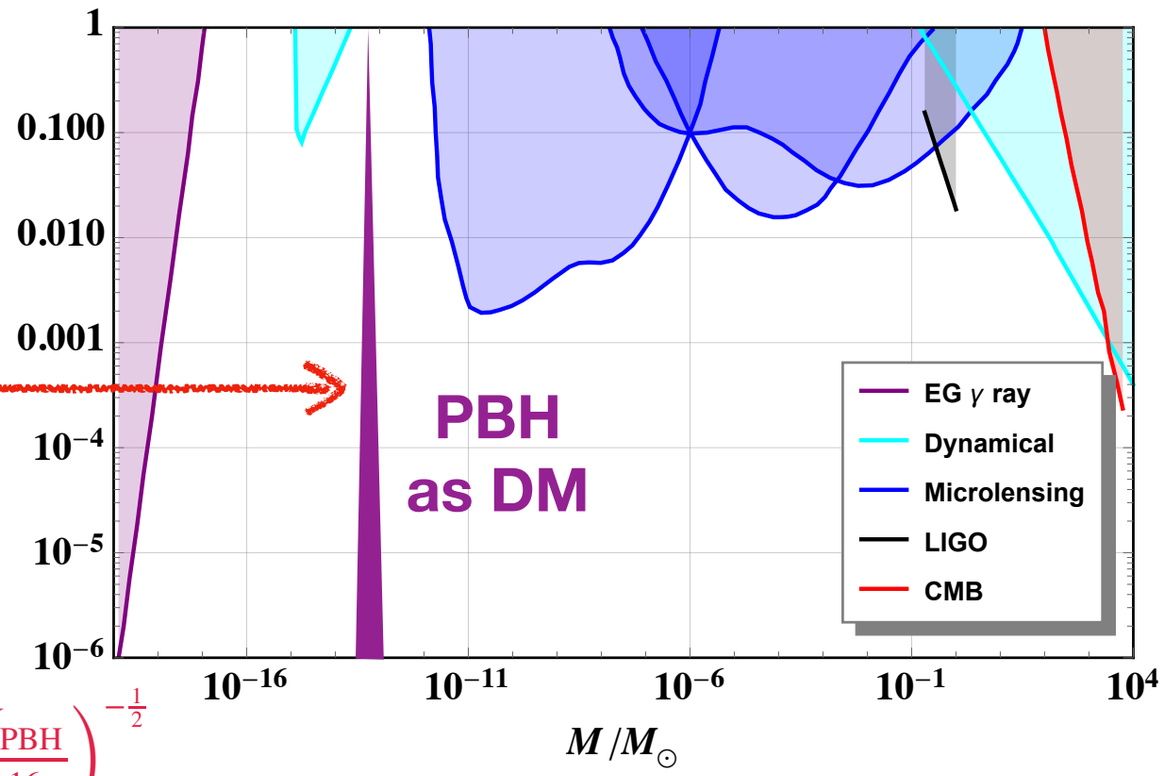
Amount of GWs

$$\Omega_{\rm GW}^{\rm induced} \sim \frac{1}{12}\Omega_{r,0}\mathscr{P}_{\mathscr{R}}^{2}$$

Amount of PBH

$$\beta \sim \mathrm{erfc}\left(\frac{\mathscr{R}_c}{2\mathscr{P}_{\mathscr{R}}^{1/2}}\right)$$





$$f_{\rm IGW} \sim 3\mathrm{Hz}\left(\frac{M_{\rm PBH}}{10^{16}\mathrm{g}}\right)^{-\frac{1}{2}}$$

Future directions/issues

1. Induced GW spectrum gauge dependent??

[GD and M.Sasaki, 1709.09804 & 2012.14016]

Unknown gauge invariant energy density of GWs in cosmology

$$\rho_{\rm GW} \sim \left\langle \dot{h}^{ij}\dot{h}_{ij} \right\rangle \qquad \tau \to \tau + T \qquad h_{ij} \to h_{ij} - \widehat{TT}^{ab}_{ij}\left[\partial_a T \partial_b T\right]$$

Things work well on small scales and reasonable coordinates.

What is the observed energy density at second order?

What is the detector response at second order?

2. Are the IR scalings common to other sources?

Radiation domination $\Omega_{\rm GW} \sim k^3$ Cai, Pi & Sasaki 1909.13728 **Other cosmologies?**

3. Impact of modified gravity to induced GWs?

Is the spectrum of induced GWs affected?

Are there any distinct signatures?

4. Explore PBH <-> IGWs relation in general cosmologies