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A boosted gravitational wave background for primordial black holes with broad mass distributions and thermal features

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The GWB from black hole mergers

A **gravitational-wave background** (GWB) is a random gravitational signal produced by the incoherent superposition of many sources

Dimensionless quantity characterizing the GWB

$$\Omega_{\rm GW} \equiv \frac{1}{\rho_{\rm c}} \frac{{\rm d}\rho_{\rm GW}}{{\rm d}\log f}$$

$\rho_{\rm GW}$: GW energy density

$\rho_{\rm c}$: critical density today

The **GW energy spectrum** is a superposition of redshifted GW radiation coming from merging BH binaries over the whole cosmic history

$$\Omega_{\rm GW}(f)h^2 = \frac{(\pi G)^{2/3}h^2}{3\,c^2\,\rho_{\rm c}}\, f^{2/3} \int_0^\infty \frac{{\rm d}z}{(1+z)^{4/3}H(z)} \times \int\!\!\int {\rm d}\ln m_1\, {\rm d}\ln m_2\, \tau_{\rm merg}(m_1, m_2, z)\, M_{\rm c}^{5/3}$$

$\tau_{\rm merg}$: merger rate (per unit of logarithmic mass)

$H(z)$: Hubble parameter

$M_{\rm c}$: chirp mass of the binary system

Broad PBH mass function with thermal features

The **thermal history** of the early Universe induces a reduction in the EoS parameter w

↓

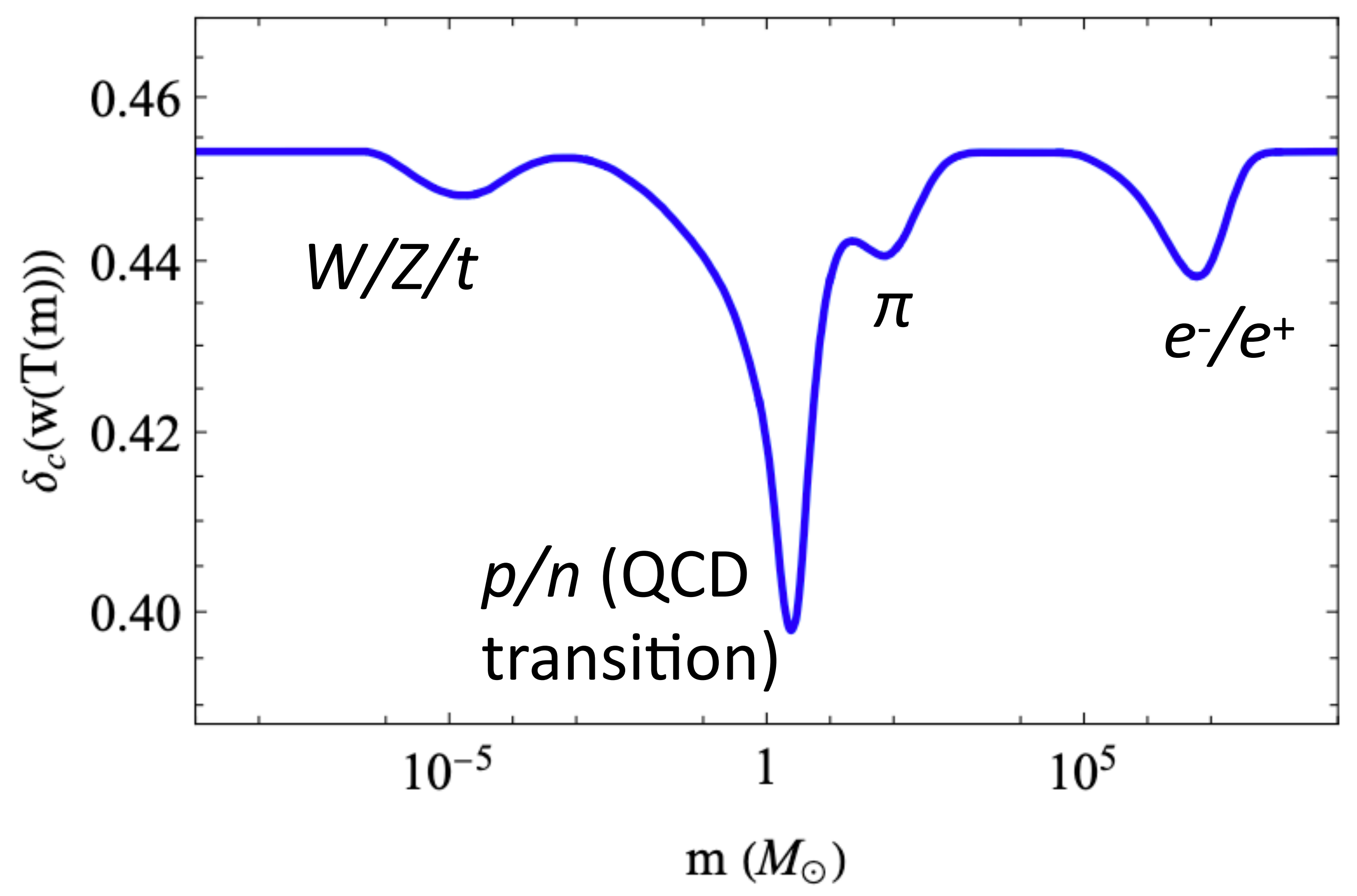
This reduction decreases the value of the critical overdensity threshold δ_c for PBH formation

↓

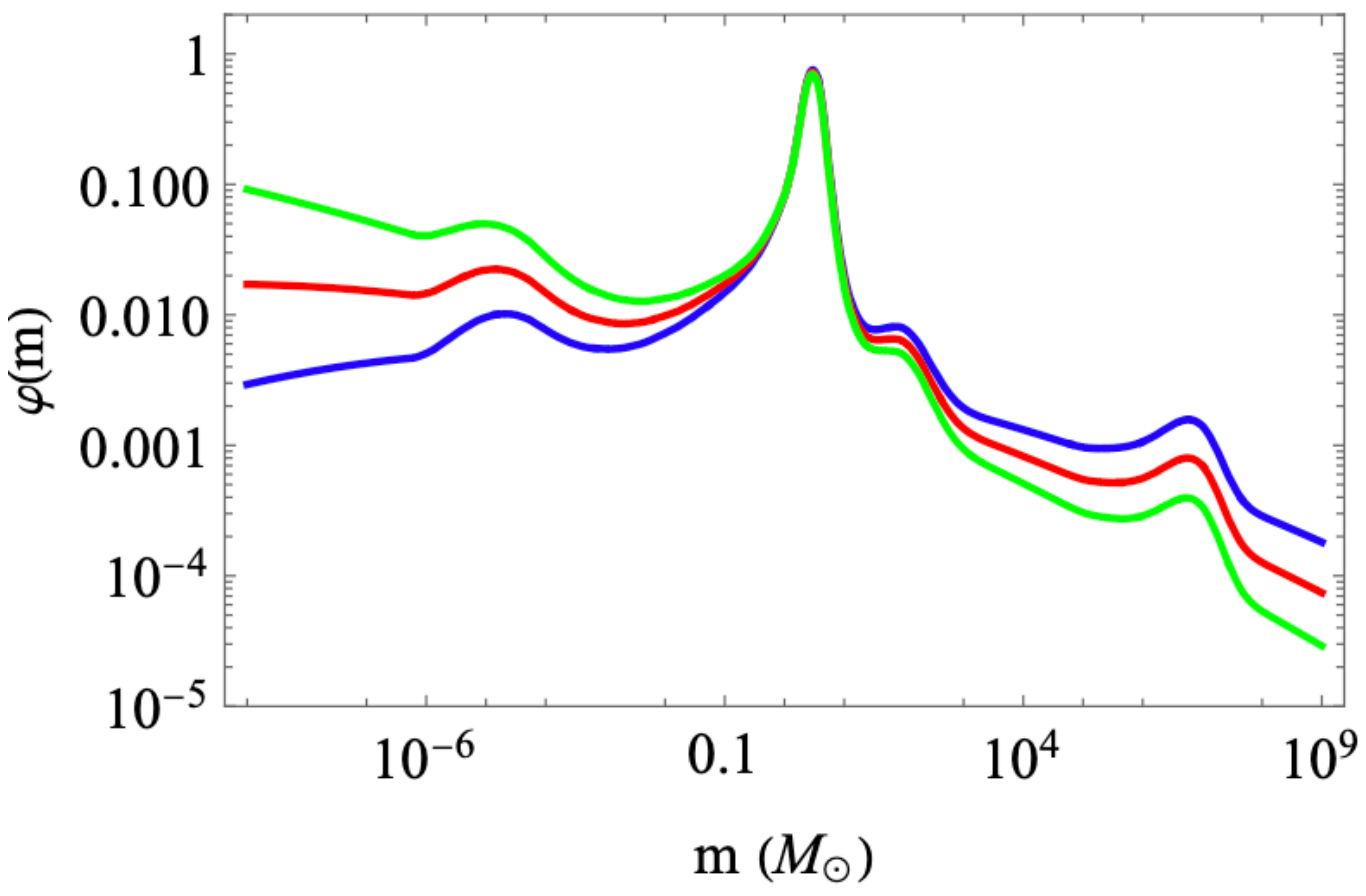
PBHs would have formed at different times in the early Universe, with different masses

A primordial origin would imply an extended mass function

Variation of the threshold δ_c with the Horizon mass



Broad PBH mass function



PBH merger rates

PBH binary formation channels

- Late-time 2-body capture in dense PBH clusters

$$\frac{\mathrm{d}\tau_{\mathrm{clust}}}{\mathrm{d}\ln m_1 \mathrm{d}\ln m_2} \propto \phi(m_1)\phi(m_2) \times \frac{(m_1+m_2)^{10/7}}{(m_1 m_2)^{5/7}} \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$$

- Formation in the early Universe

$$\frac{\mathrm{d}\tau_{\mathrm{prim}}}{\mathrm{d}\ln m_1 \mathrm{d}\ln m_2} \propto f_{\mathrm{sup}}(m_1,m_2,z) \times \phi(m_1)\phi(m_2) \left[\frac{t(z)}{t_0}\right]^{-34/37} \times \left(\frac{m_1+m_2}{M_\odot}\right)^{-32/37} \left[\frac{m_1 m_2}{(m_1+m_2)^2}\right]^{-34/37} \mathrm{yr}^{-1}\mathrm{Gpc}^{-3}$$

- Enhanced clustering is expected due to **isocurvature perturbations** induced by Poisson fluctuations in the PBH distribution
- PBHs should be **clustered** into subhaloes
- If most PBH are regrouped in clusters, **microlensing constraints** on their abundance **can be evaded**, allowing $f_{\mathrm{PBH}} = 1$

- f_{sup} takes into account effects that lead to early binary **disruption** and induce **rate suppression**
- τ_{prim} depends on the **redshift** via the function $t(z)$ since early binary dynamics can be modified throughout the cosmic history

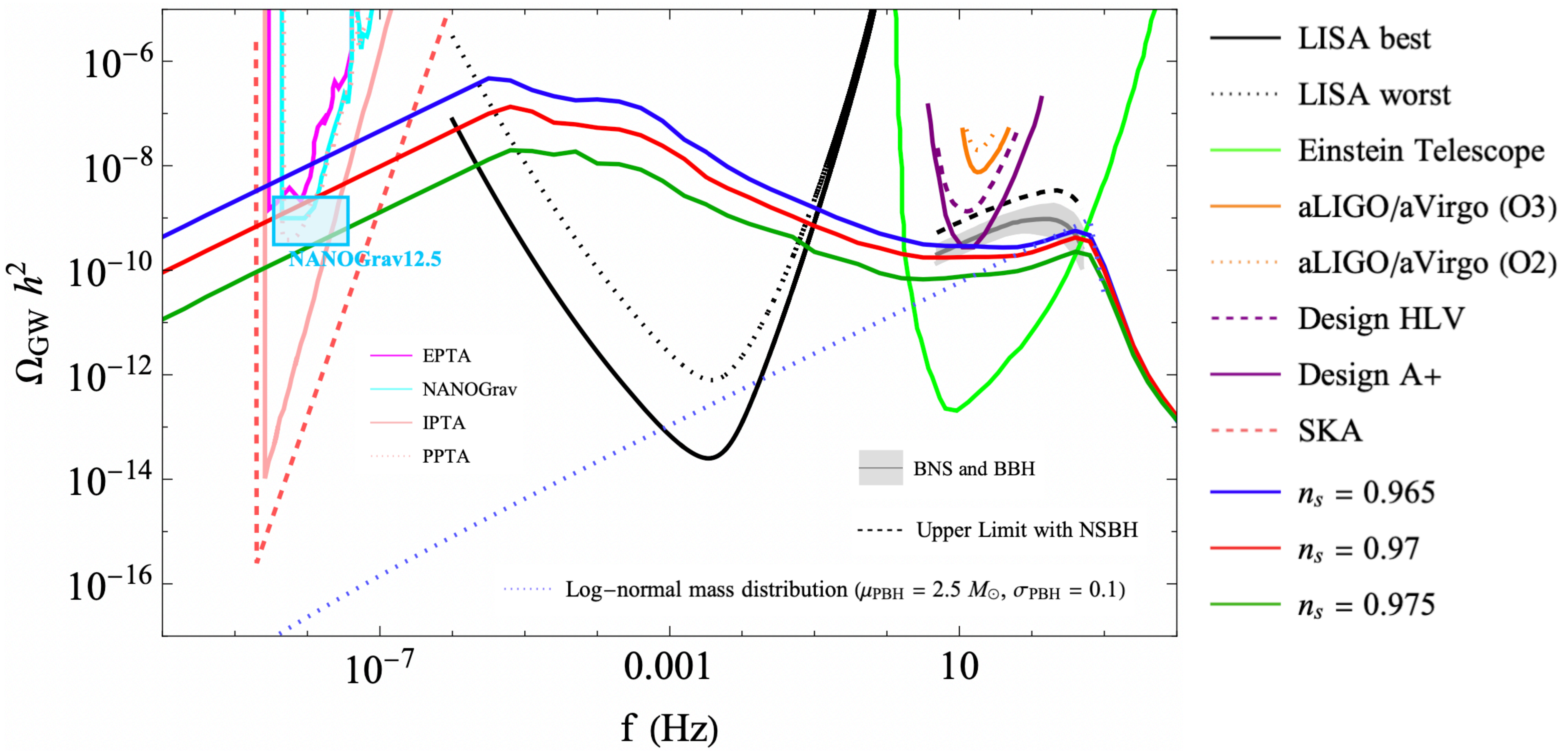
Results and detectability of the GWB

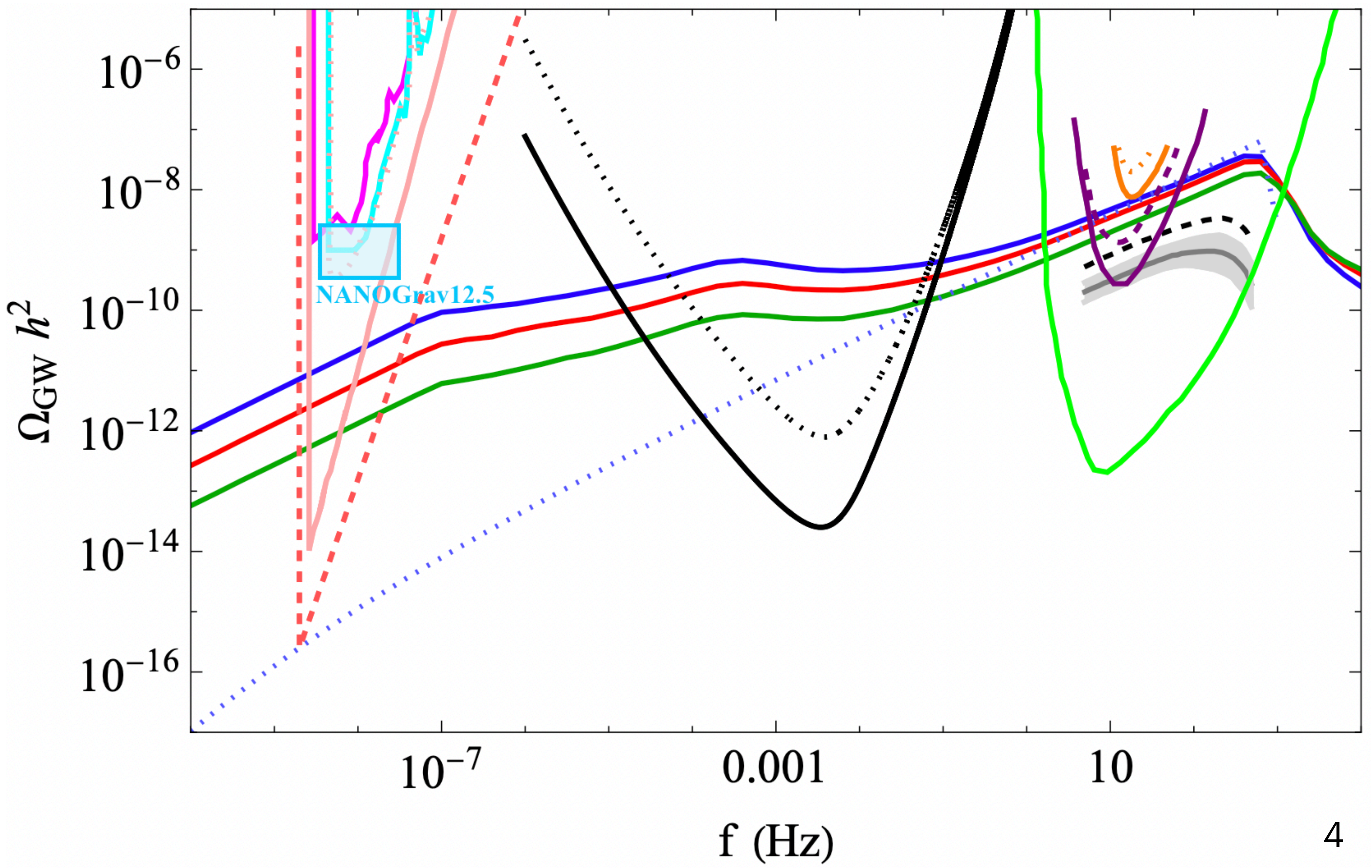
GWB from late PBH binaries in clusters

- ☑ The GWB amplitude is boosted below 10 Hz due to low mass ratio binaries
- ☑ The GWB coincides with a signal from NANOGrav12.5
- ☑ Ground-based detectors will allow us to distinguish between an astrophysical and a primordial origin because of the different background spectral index

GWB from early PBH binaries

- ☑ The GWB typically dominates the one from late and astrophysical binaries at high frequency
- ☑ The shape of the GWB could provide information on the PBH mass function and the background spectral index could help differentiate the late and early PBH binaries
- ☑ The GWB could potentially be detected in the next observing runs of LV





Thank you!

Backup Slides

Spectrum of the root-mean-square amplitude of the Gaussian inhomogeneities from which the PBHs have formed:

$$\delta_{\rm rms}(m) = A_{\rm s} \left(\frac{m}{M_\odot} \right)^{(1-n_{\rm s})/4}$$

n_s : small-scale scalar spectral index

A_s : spectrum amplitude

Fraction of the Universe that collapses to form PBHs of mass m at formation :

$$\beta(m) = \mathrm{erfc}\left(\frac{\delta_{\rm c}}{\sqrt{2}\delta_{\rm rms}(m)} \right)$$

δ_c : critical overdensity threshold leading to PBH formation

Broad PBH mass function :

$$\phi(m) \equiv \frac{1}{\rho_{\rm DM}} \frac{\mathrm{d}\rho_{\rm PBH}}{\mathrm{d}\ln m} \approx \frac{3.8}{f_{\rm PBH}} \left(\frac{M_{\rm eq}}{m} \right)^{1/2} \beta(m)$$

$M_{\rm eq} \simeq 2.8 \cdot 10^{17} M_\odot$

: Hubble mass at matter-radiation equality

GW amplitude as a function of the masses m_1 and m_2

Late PBHs binaries in clusters | Early PBHs binaries

At LIGO frequencies

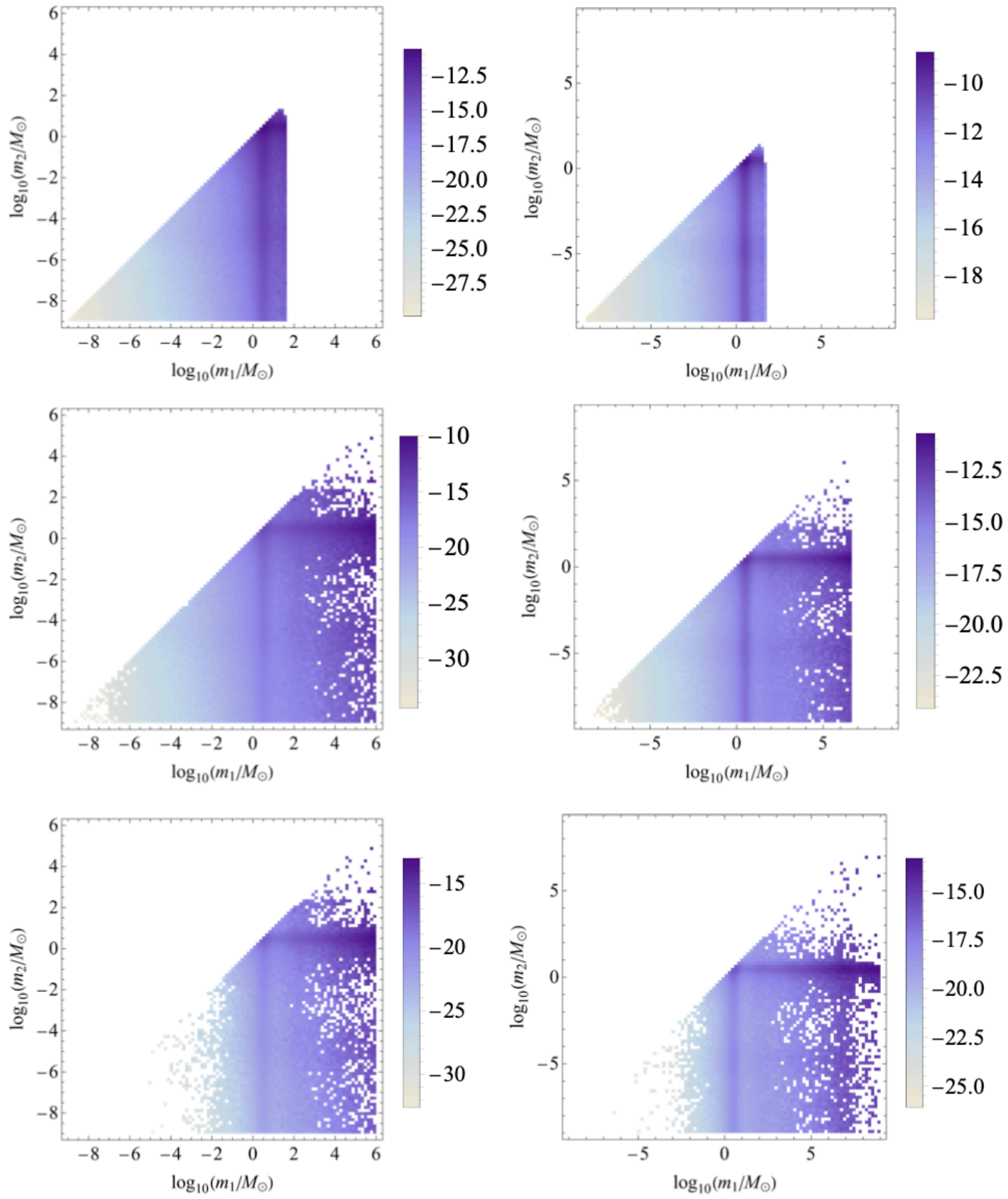
Contribution of subsolar and solar-mass binaries

At LISA and PTA frequencies

Contribution of solar and intermediate-mass binaries

In general

Binaries with very low mass ratios contribute importantly to the GWB



$f = 100$ Hz

$f = 10^{-3}$ Hz

$f = 10^{-8}$ Hz