Primordial Nano BHs

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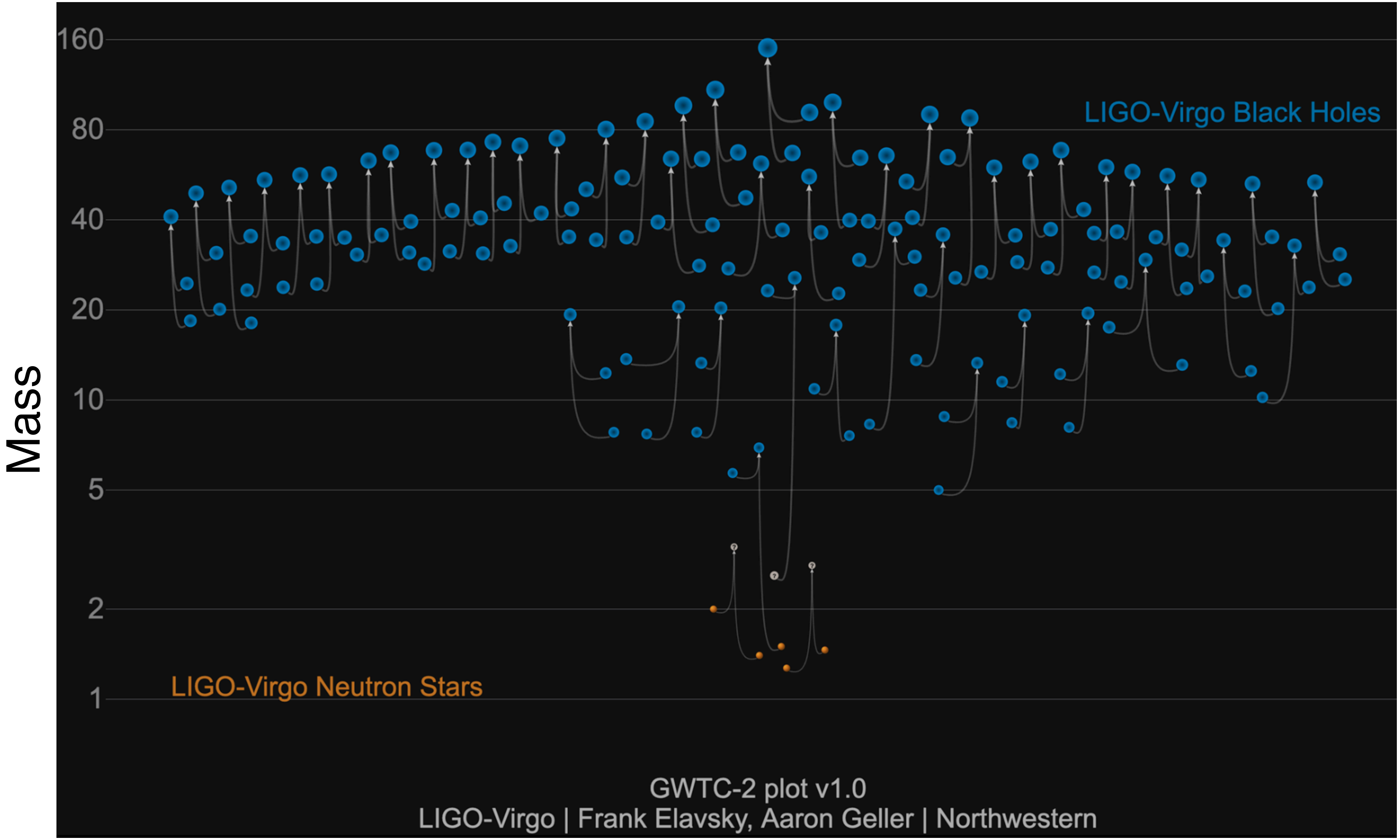
Plan of the talk

- NANOGrav 12.5 yr signal consistent with the PBH scenario. If so, PBHs may comprise the totality of the dark matter

In collaboration with V. De Luca, G. Franciolini, PRL (2021)

Motivation



160
80
40
20
10
5
2
1
Mass
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Black Holes

- Astrophysical BHs forms from the gravitational collapse of a star. We know they exist. Their mass must be above the Chandrasekhar limit,

$$M > \mathcal{O}(1)\, M_\odot$$

- PBHs are formed in the early universe. Their mass can be small and they can still be around as long as they do not evaporate within the age of the universe

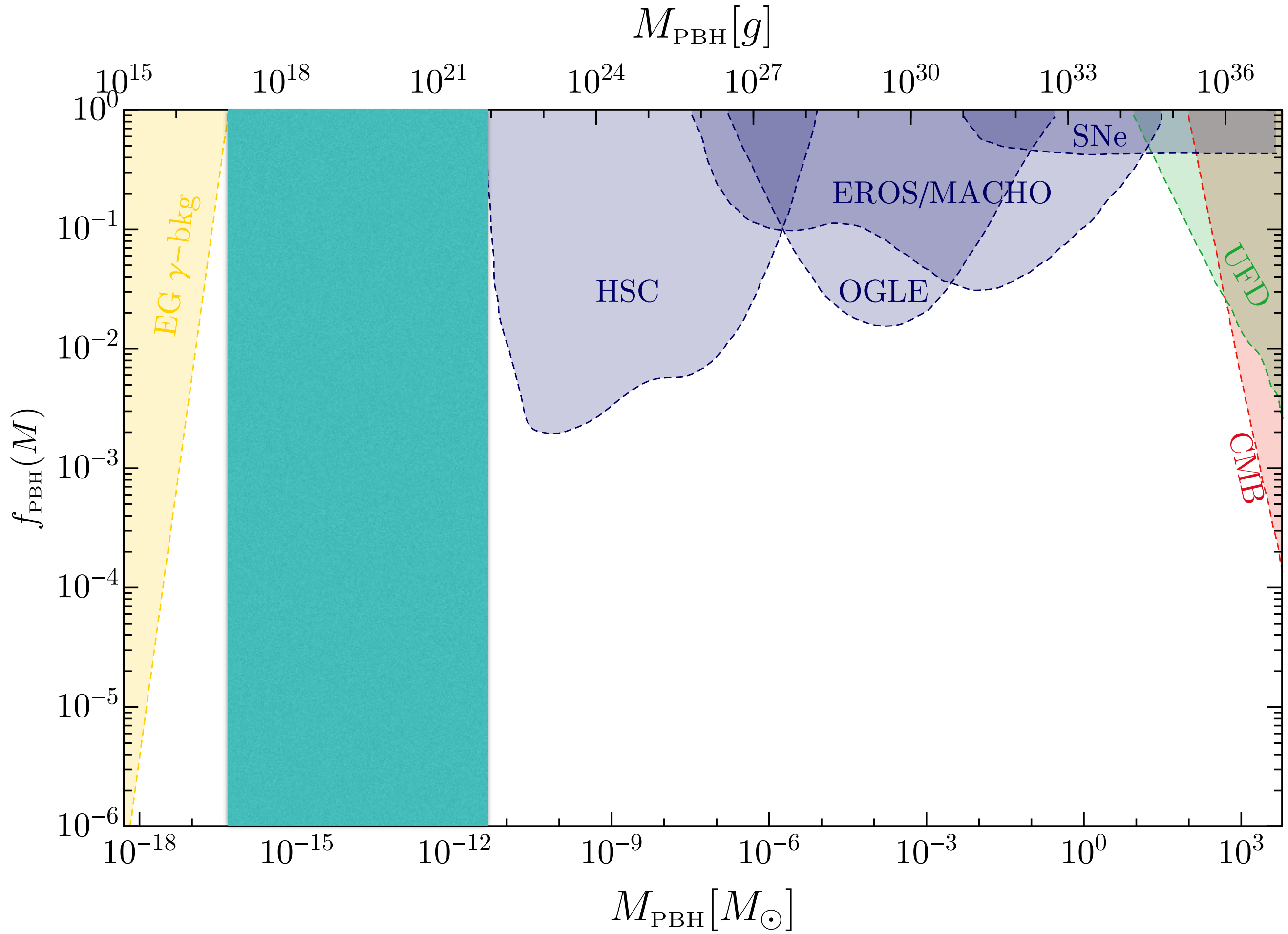
$$M > 10^{-18}\, M_\odot$$

- Can PBHs account for some of the LIGO/Virgo events?
- How to distinguish PBHs from astrophysical BHs?
- Can PBHs be the dark matter?

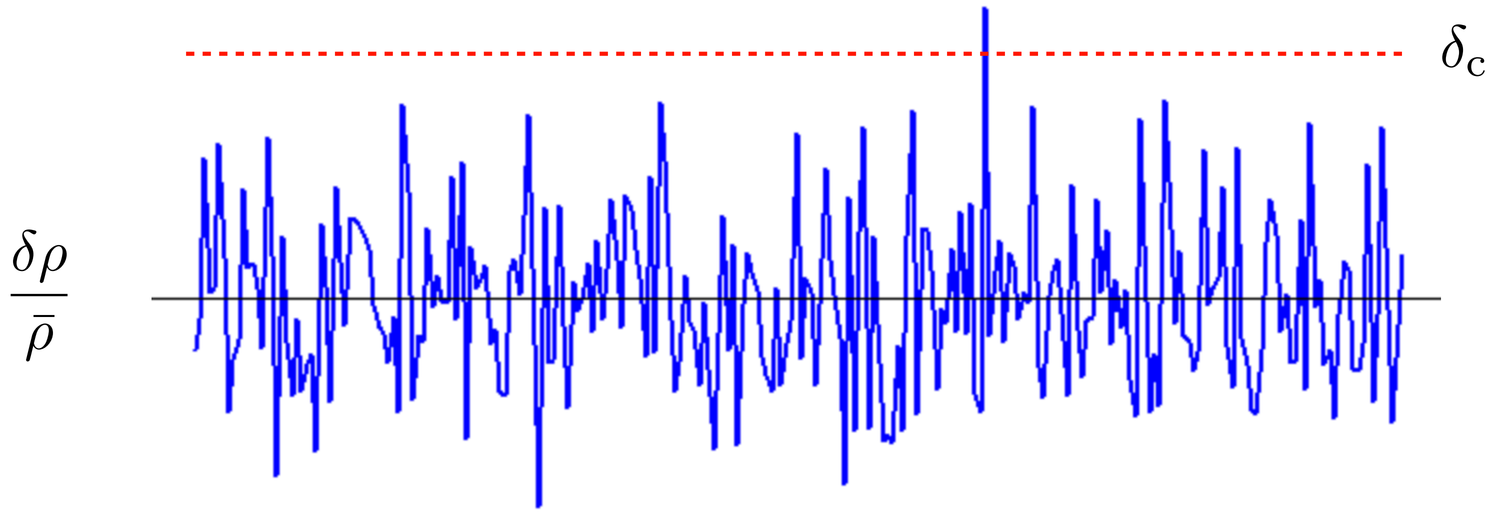
PBHs

Primordial black holes can compose all the dark matter (or a fraction of it)

$$f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$$



PBHs may be originated from peaks of the density contrast

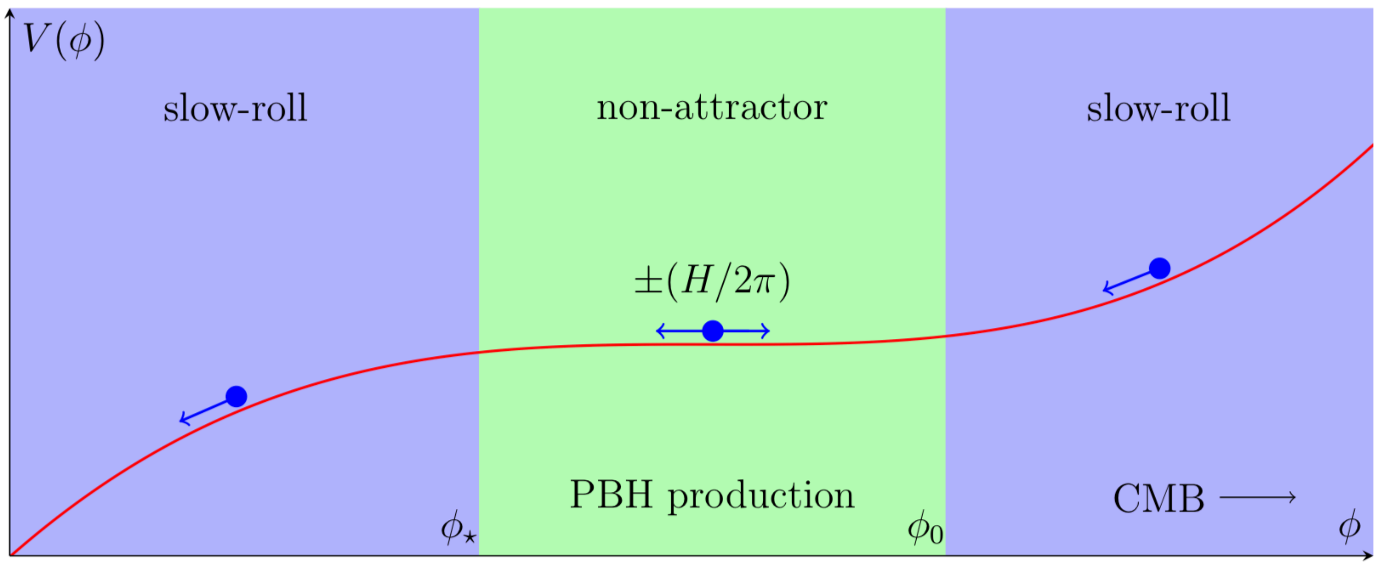


$$\frac{\delta\rho}{\bar{\rho}} \sim \frac{\nabla^2\zeta}{a^2H^2}$$

PBHs are rare events, tail of the distribution

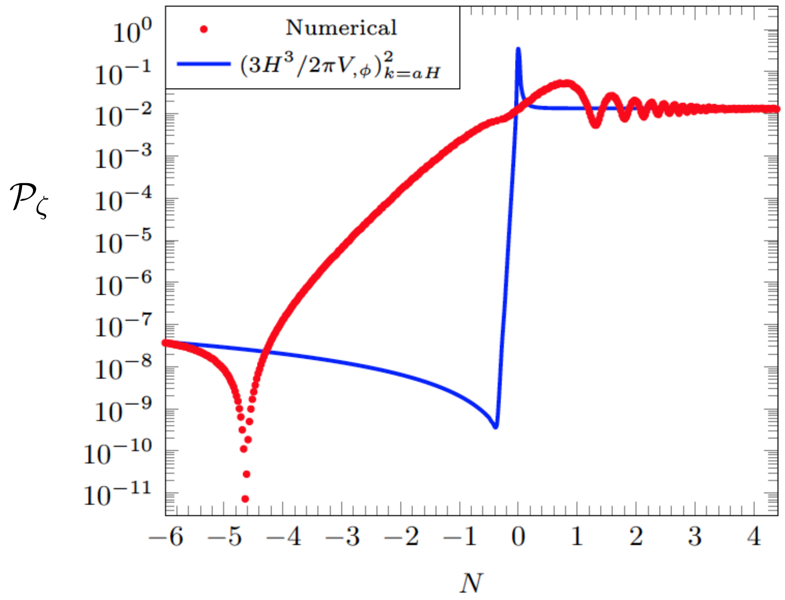
One possible mechanism: large fluctuations from inflation

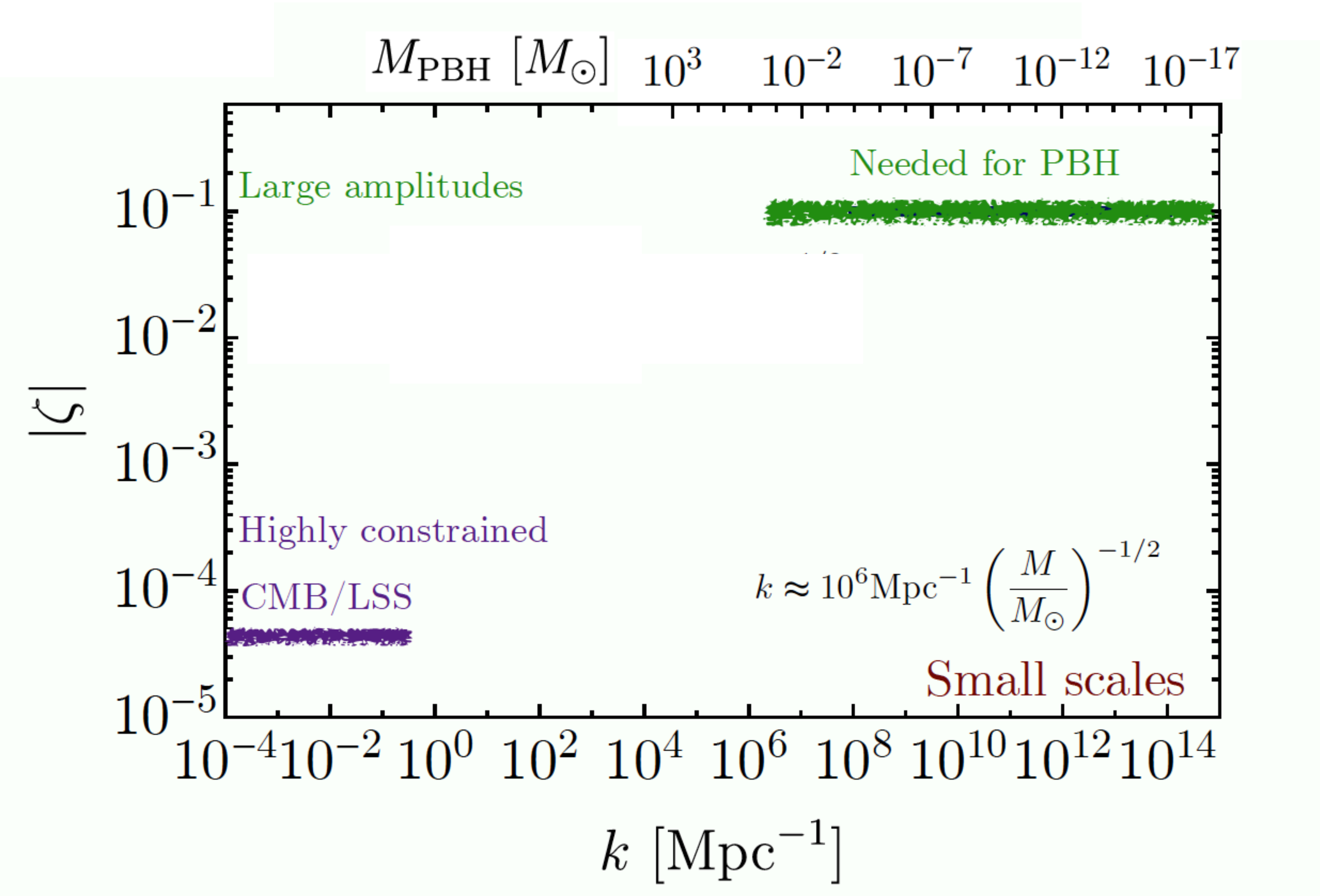
Ultra-slow-roll during inflation



$$\mathcal{P}_\zeta^{1/2} = \frac{H^2}{2\pi|\dot{\phi}|}$$

$$\frac{\mathrm{d}\phi}{\mathrm{d}N} \sim e^{-3N} \Rightarrow \mathcal{P}_\zeta^{1/2} \sim e^{3N}$$

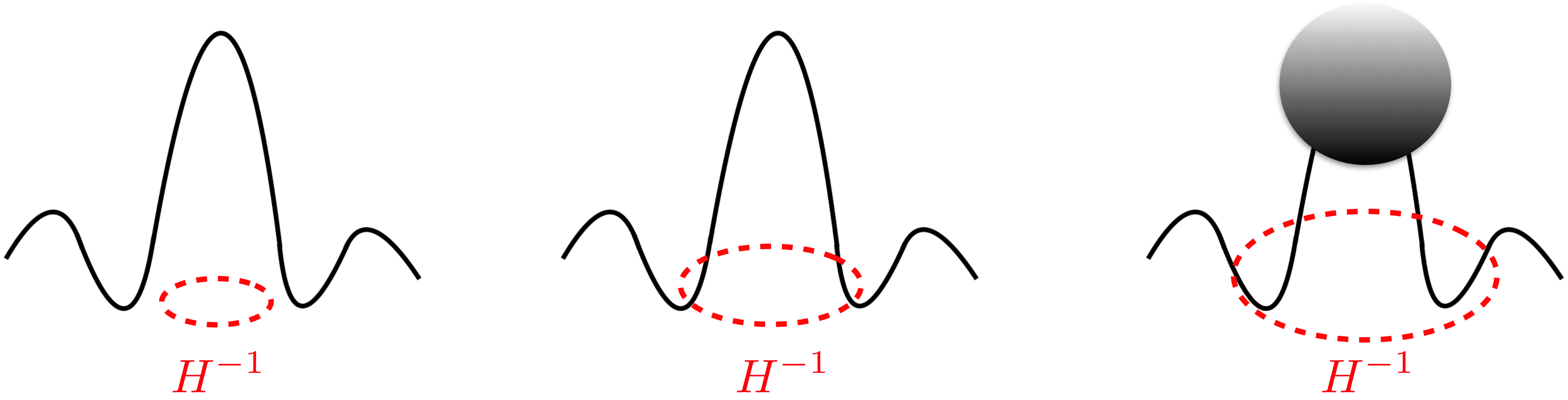




$M_{\rm PBH}\ [M_\odot]$
10^{3} 10^{-2} 10^{-7} 10^{-12} 10^{-17}
Needed for PBH
Large amplitudes
Highly constrained
CMB/LSS
$k \approx 10^6 \mathrm{Mpc}^{-1} \left(\frac{M}{M_\odot}\right)^{-1/2}$
Small scales
$|\zeta|$
10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5}
10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14}
$k\ [\mathrm{Mpc}^{-1}]$

PBHs are originated from peaks of the density contrast

$$\frac{\delta\rho}{\rho} \gtrsim \delta_c \qquad \frac{\delta\rho}{\bar{\rho}} \sim \frac{\nabla^2\zeta}{a^2H^2} \qquad M_{\rm PBH} \sim M_{\rm H}$$



$$\beta(M) = \int_{\delta_c}^{\infty} \frac{{\rm d}\delta}{\sqrt{2\pi}\sigma_\delta} e^{-\delta^2/2\sigma_\delta^2} \qquad \sigma_\delta^2 = \int_0^\infty {\rm d}\ln k W^2(k, R_H)\mathcal{P}_\delta(k)$$

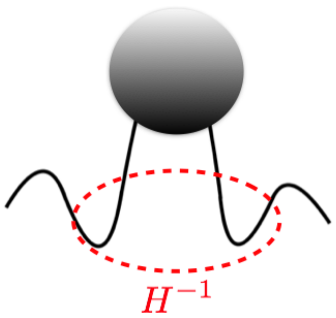
In fact, many non-Gaussian effects
in the threshold and in the non-linear mapping going from
the inflaton fluctuations to the curvature perturbation and to the density contrast

Musco et al. (2020), Biagetti et al. (2021)

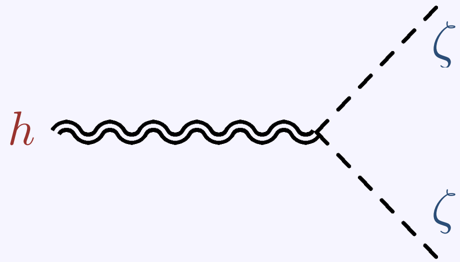
GWs from PBHs

The same curvature perturbations giving rise to PBHs are unavoidably a source for GWs at *second-order* in perturbation theory

$$\frac{\delta\rho}{\bar{\rho}} \sim \frac{\nabla^2\zeta}{a^2H^2}$$

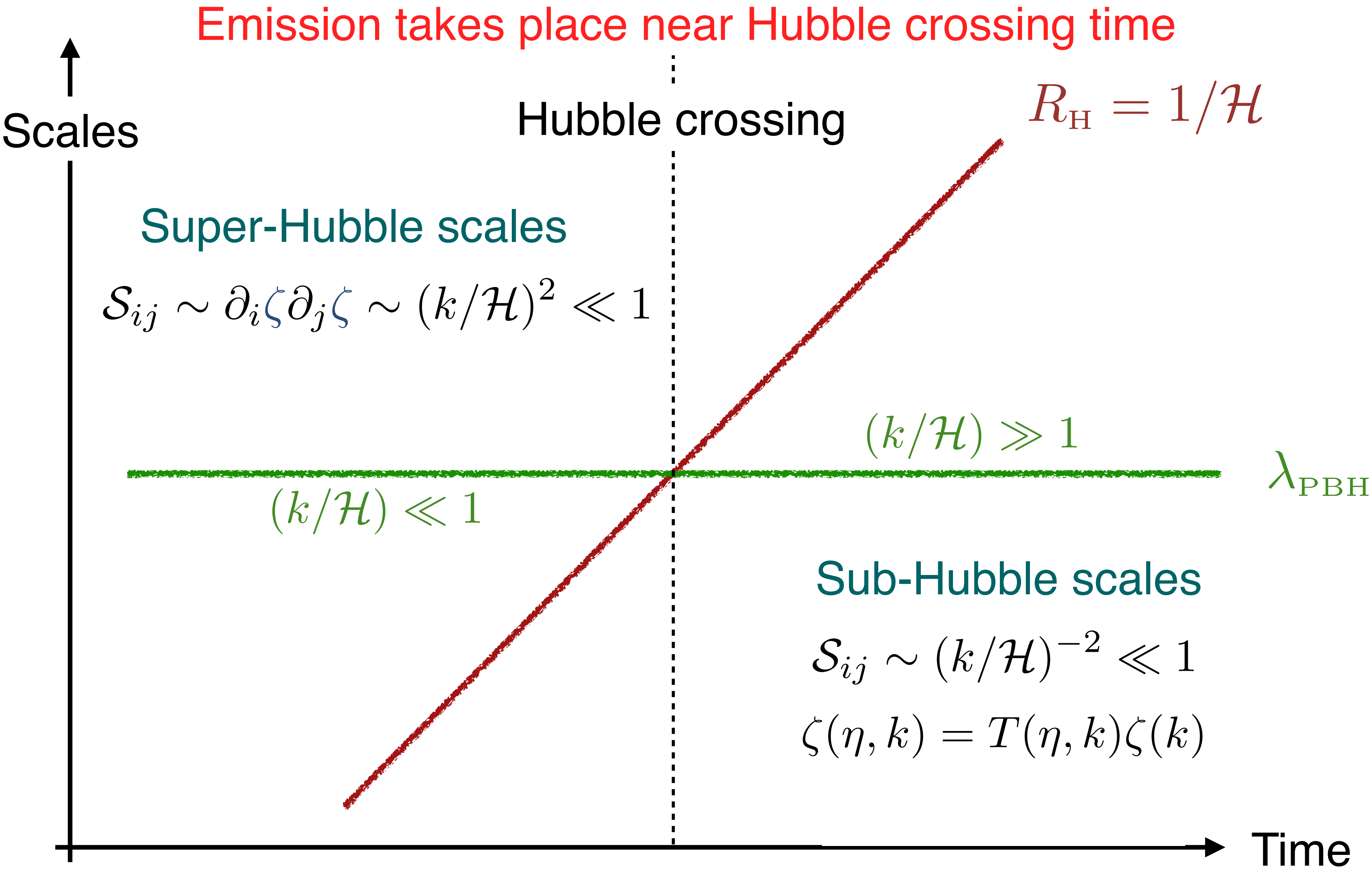


$$h''_{ij} + 2\mathcal{H}h''_{ij} - \nabla^2 h_{ij} = \mathcal{O}(\partial_i\zeta\partial_j\zeta)$$



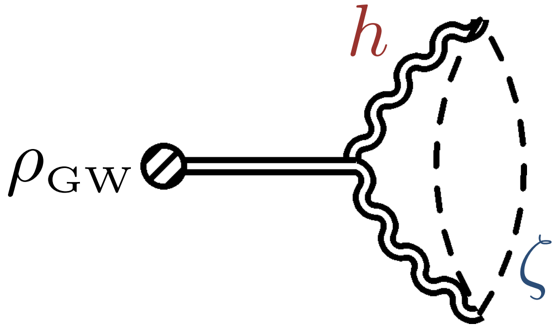
Potentially observable at current and future GW observatories

GWs from PBHs at second-order



GW abundance

The energy density of GWs is given by
the time average over several cycles

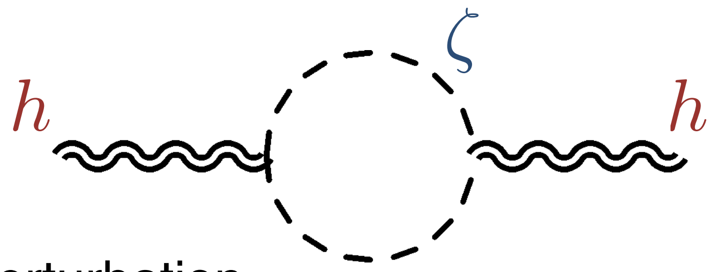


$$\Omega_{\rm GW}(\eta, \vec{x}) = \frac{\rho_{\rm GW}(\eta, \vec{x})}{\overline{\rho}(\eta)} = \frac{M_p^2}{4a^2\overline{\rho}(\eta)} \left\langle h'_{ab}\left(\eta,\, \vec{x}\right) h'_{ab}\left(\eta,\, \vec{x}\right)\right\rangle_{\rm t.a.}$$

GW Power Spectrum

Power spectrum of GWs:

$$\left\langle h^{\lambda_1}(\eta, \vec{k}_1) h^{\lambda_2}(\eta, \vec{k}_2) \right\rangle' \approx \mathcal{P}_\zeta \mathcal{P}_\zeta$$

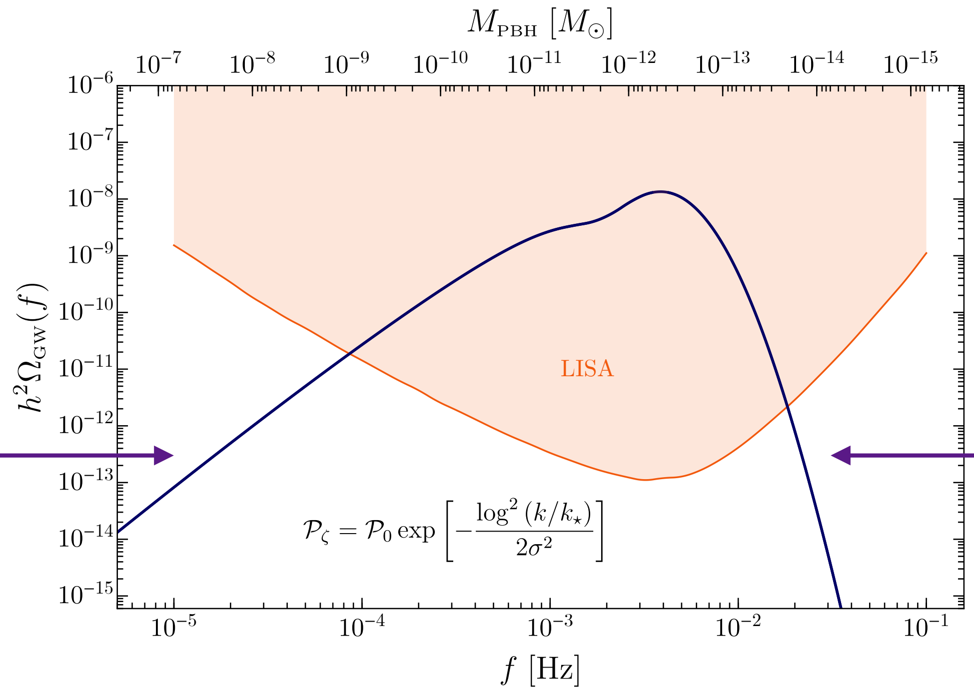


At second order in comoving curvature perturbation,

after averaging over the fast oscillating pieces

$$\Omega_{\rm GW}(\eta, k) = \frac{\pi^2}{243 \mathcal{H}^2 \eta^2} \int \frac{d^3p}{(2\pi)^3} \frac{p^4 \left[1-\mu^2\right]^2}{p^3 |\vec{k}-\vec{p}|^3} \mathcal{P}_\zeta(p) \mathcal{P}_\zeta\left(|\vec{k}-\vec{p}|\right) \mathcal{I}^2\left(\vec{k}, \vec{p}\right)$$

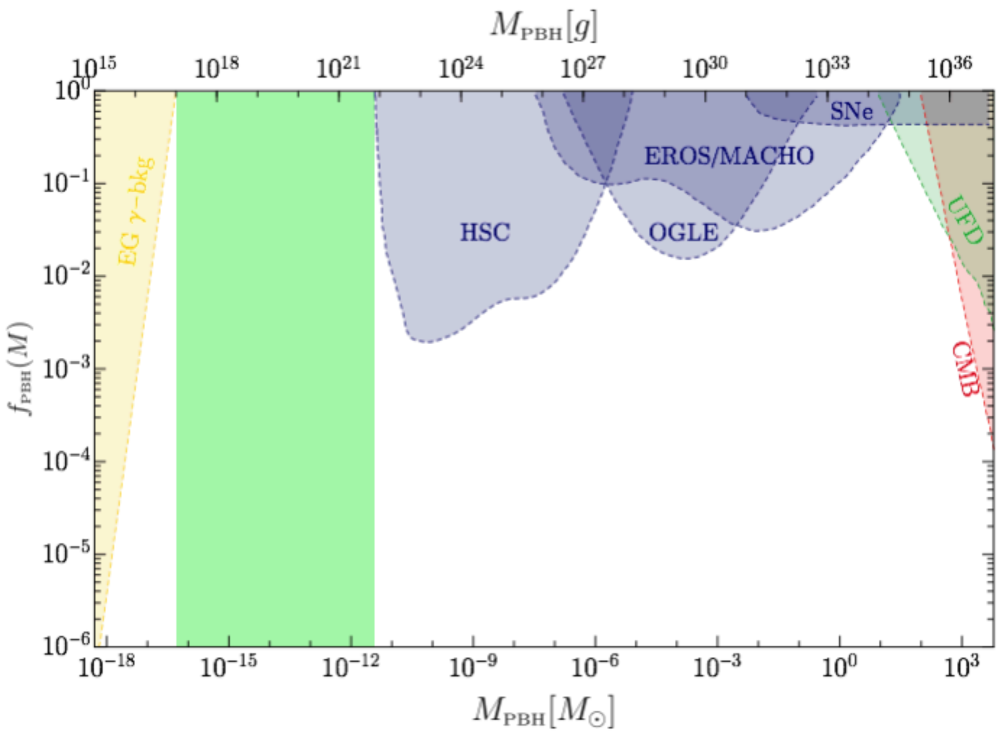
$\propto k^3$

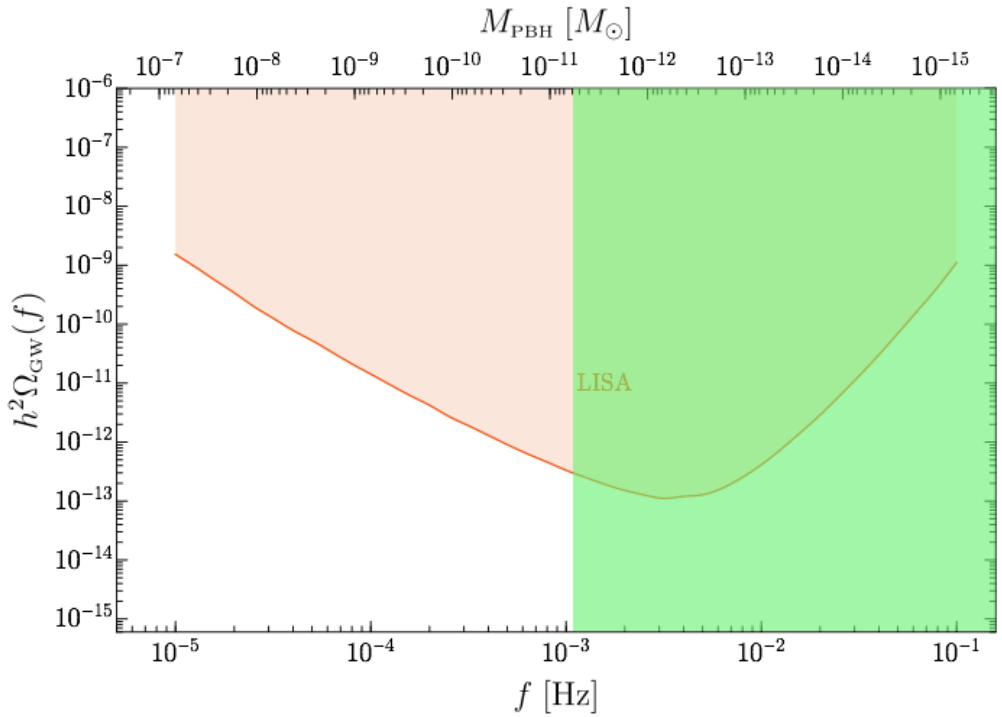


$\propto \mathcal{P}_\zeta^2(k \gg k_*)$

Espinosa et al. (2018)

The PBH dark matter-LISA serendipity





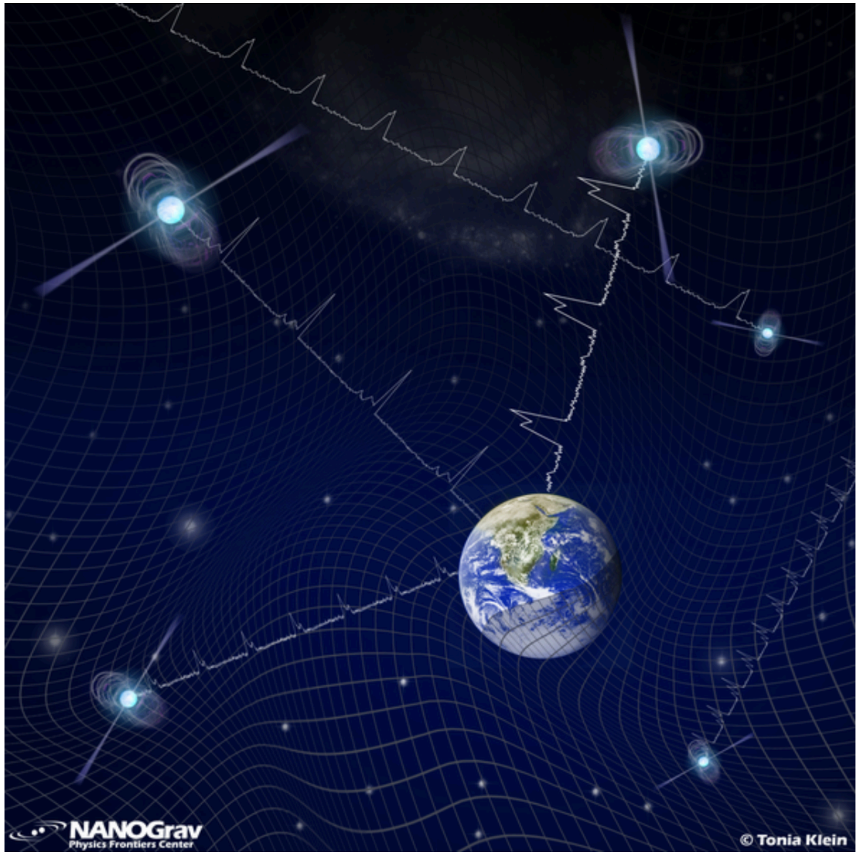
$$M \simeq 10^{-12} M_\odot \left(\frac{f_{\rm LISA}}{f}\right)^2$$

$$f_{\rm LISA} = 3.4 \text{ mHz}$$

$$M \approx 10^{-12} M_\odot$$

Bartolo et al. PRL (2019)

Nano-Grav 12.5 year



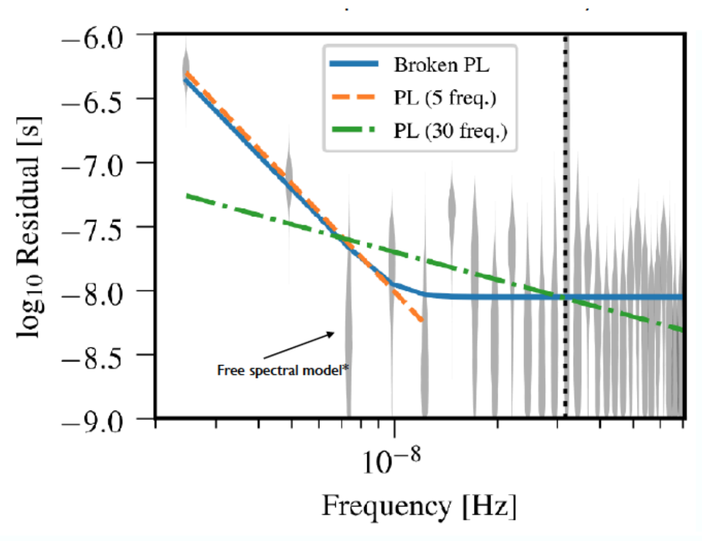
Millisecond pulsars whose signal sensitive to the stochastic GW background

Cross-correlation of timing residuals

$$S_{ab} = \Gamma_{ab} \frac{h_c^2}{12\pi^2 f^3}$$

Nano-Grav 12.5 year

Strong evidence for a stochastic common process across 45 pulsars



$$\Omega(f) = \frac{2\pi^2}{3H_0^2} A^2 f_{\rm yr}^2 \left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma}$$

Possible flat spectrum with amplitude $\Omega(f) \sim 5 \cdot 10^{-10}$

Nano-Grav 12.5 year

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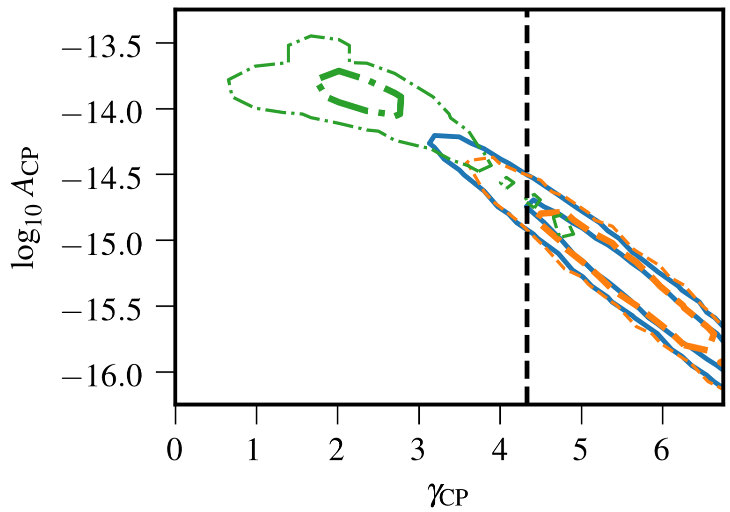
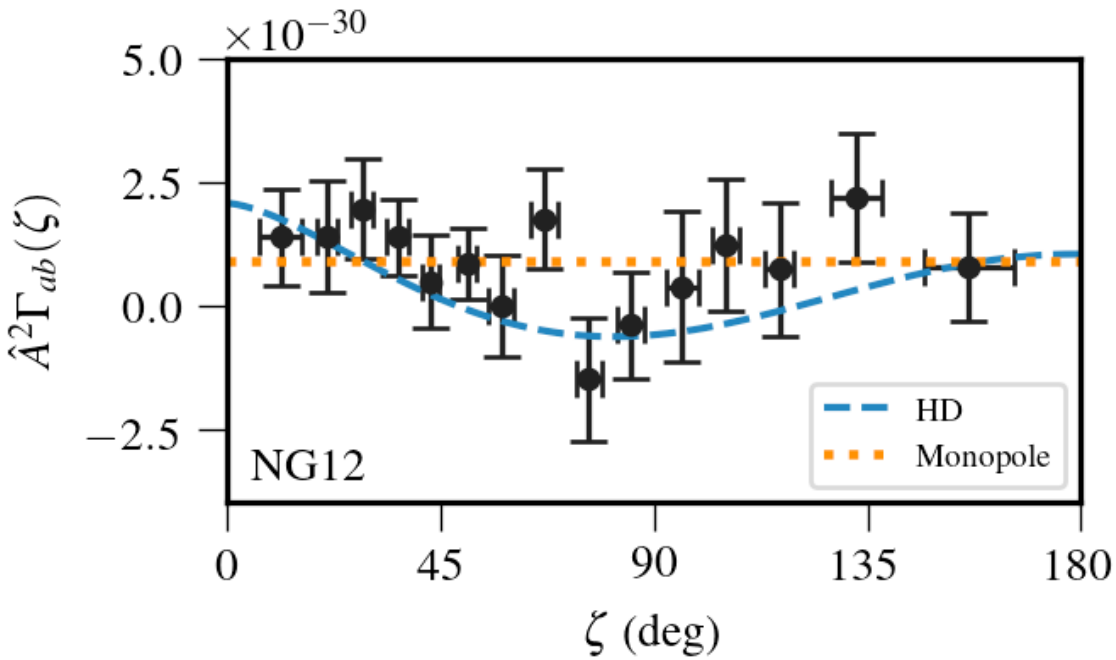


Possible flat spectrum with amplitude $\Omega(f) \sim 5 \cdot 10^{-10}$

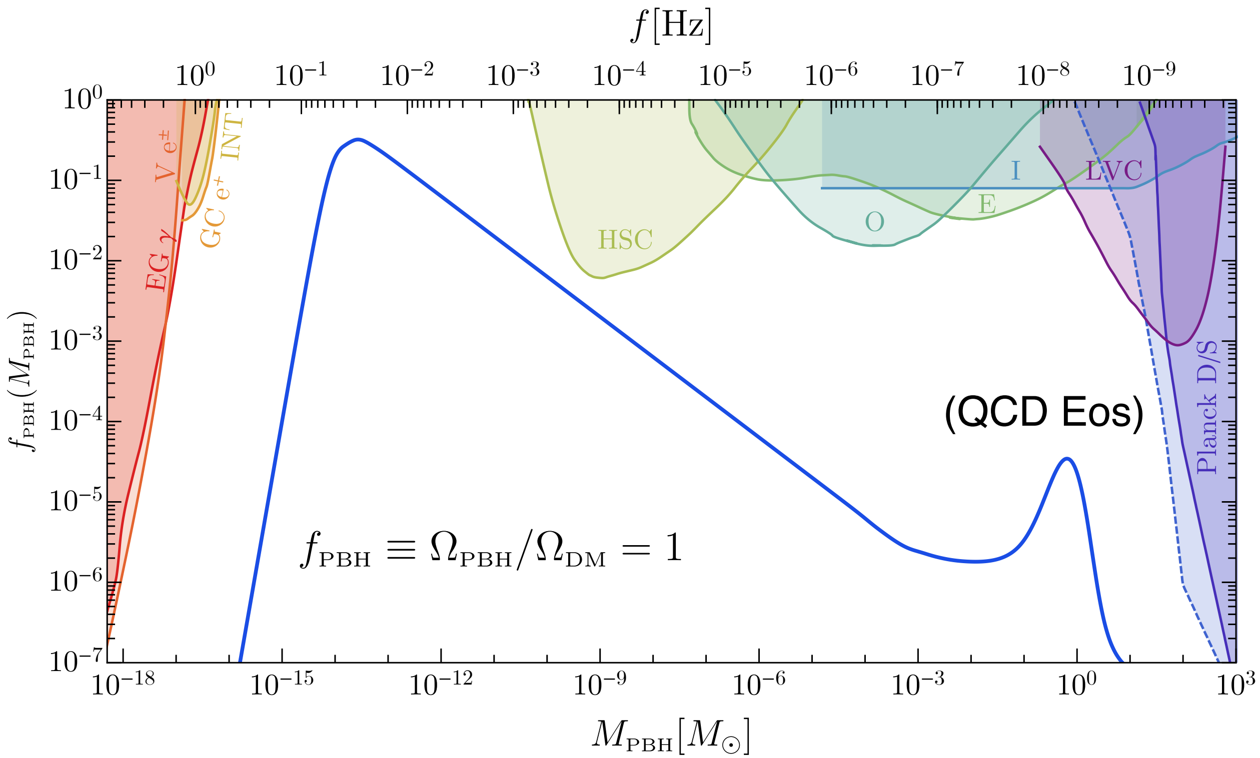
Nano-Grav 12.5 year

Non-conclusive evidence for quadrupolar
Hellings-Downs (HD) correlation pattern (GW footprint)



Need to wait for more data (two years on)

Can be consistent with a PBH = DM scenario



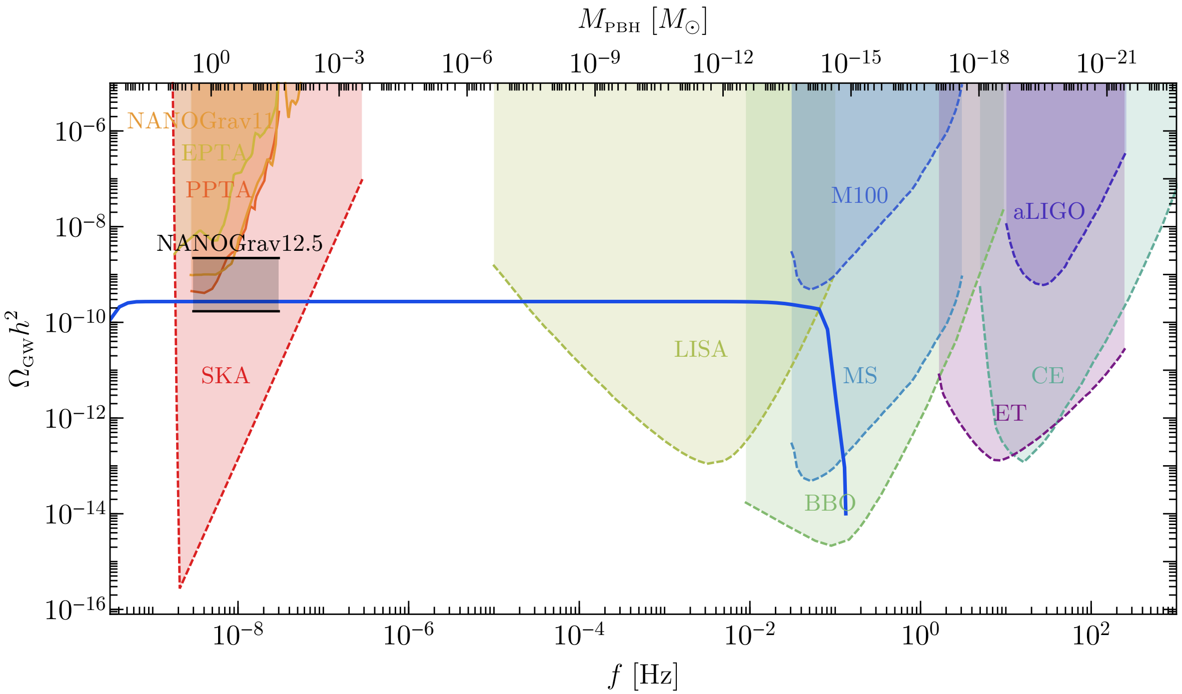
From flat curvature power spectrum

$$\mathcal{P}_\zeta(k) = A_\zeta \Theta(k_s - k)\Theta(k - k_l) \quad k_s \gg k_l$$

PBH mass peaked at the shortest scale

De Luca et al. PRL (2021)

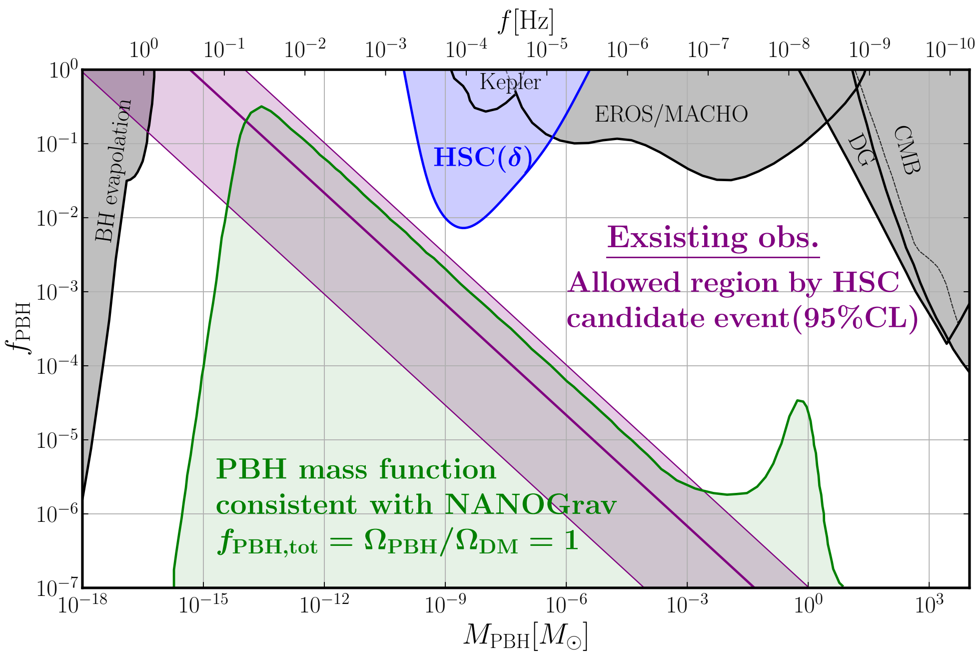
Can be consistent with a PBH = DM scenario



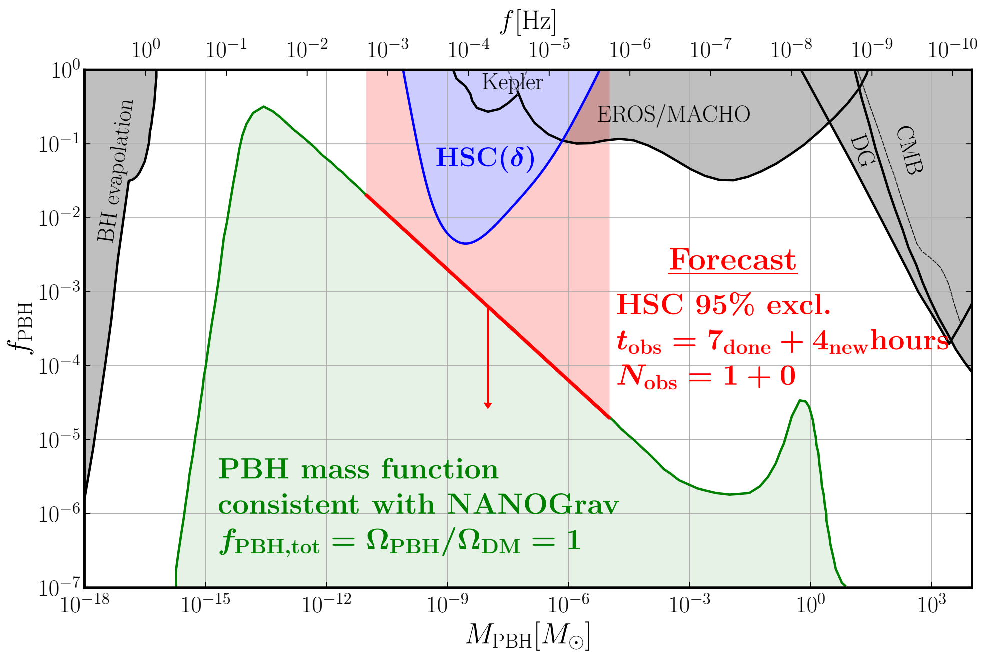
May be confirmed by LISA

Can be consistent with the HSC event

Hyper-Supreme Camera searches for microlensing
of light from the Andromeda galaxy (M31)



Allowed region allowed assuming
a power-law mass function



Forecast with longer
observation time assuming null detection

Sugiyama et al. (2020)

Conclusions

NANOGrav 12.5 yr signal consistent with the PBH scenario.

If so, PBHs may comprise the totality of the dark matter.