GRAVITATIONAL WAVE CONSTRAINTS ON PRIMORDIAL BLACK HOLES

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Based on:
G. Domènech, S. Pi, **AW**, J. N. Wang 2402.18965
G. Domènech, K. Pardo, S. Pi, **AW**, J. N. Wang in preparation
W. C. Hong, S. Kuroyanagi, S. Pi, **AW**, Z. Y. Zhang in preparation

05.12.2025 at DESY

PBH: WHAT?

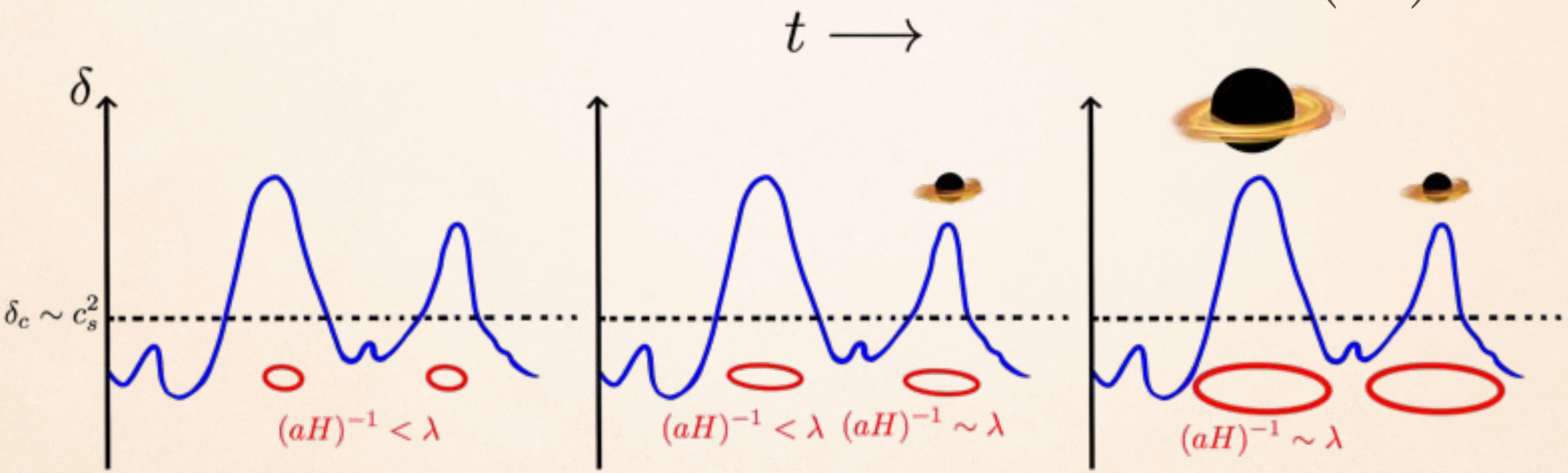
$1 M_\odot = 2 \times 10^{33} g$

Y. B. Zel'dovich & I. D. Novikov 1967

S. W. Hawking 1971

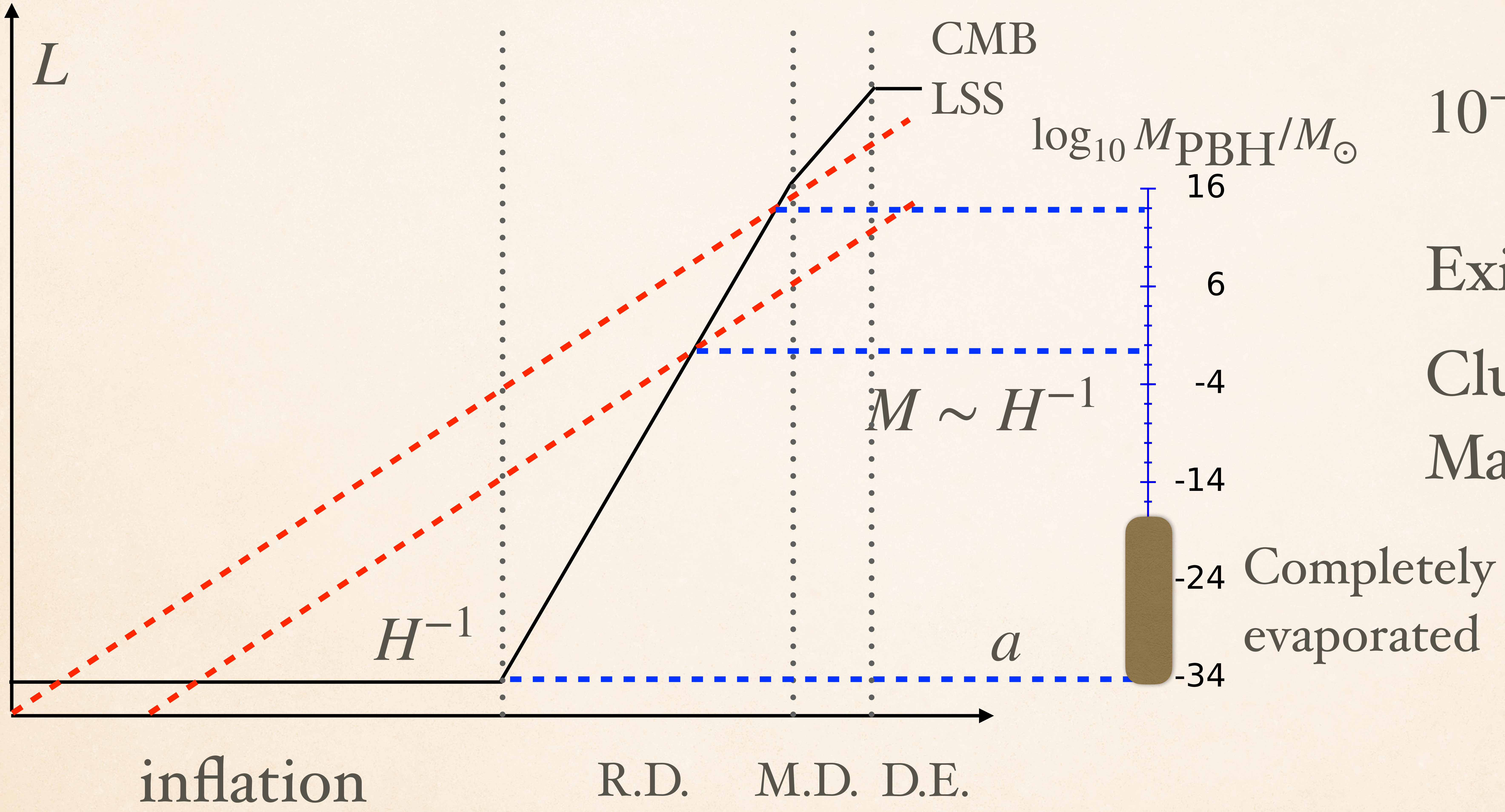
B. Carr & S. W. Hawking 1974

$$M \approx 2.03 \times 10^5 \gamma_c \left(\frac{t}{1s}\right) M_\odot$$



P. Villanueva-Domingo et al. 2021

PBH: WHY?



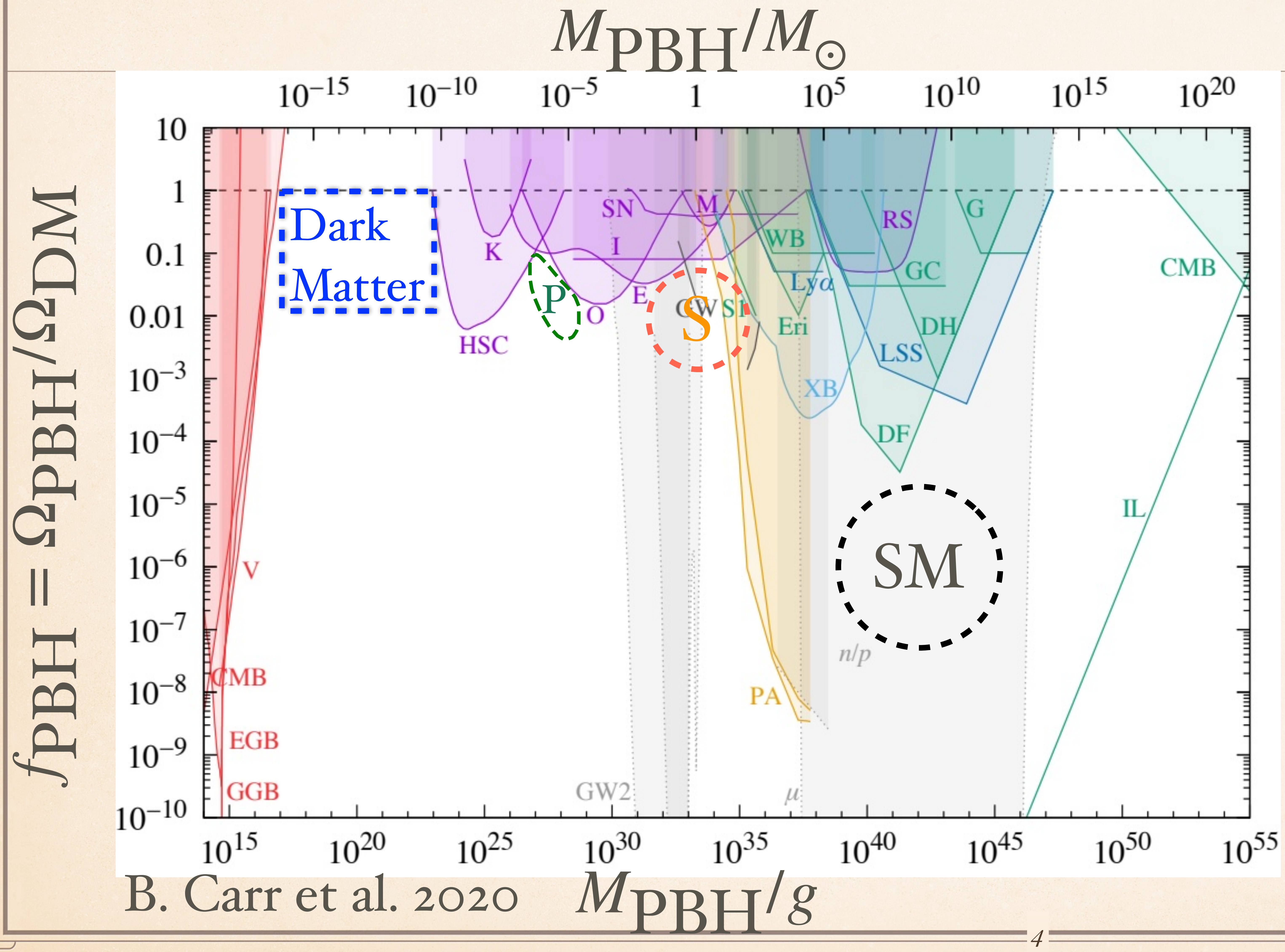
$10^{-18} - 10^{14} M_\odot$

Existence

Clustering

Mass function

PBH: WHY?



B. Carr et al. 2020

Asteroid: Dark Matter

Planet: Micro-lensing
Niikura et al. 2019

Solar: LVK binary

Super -Massive

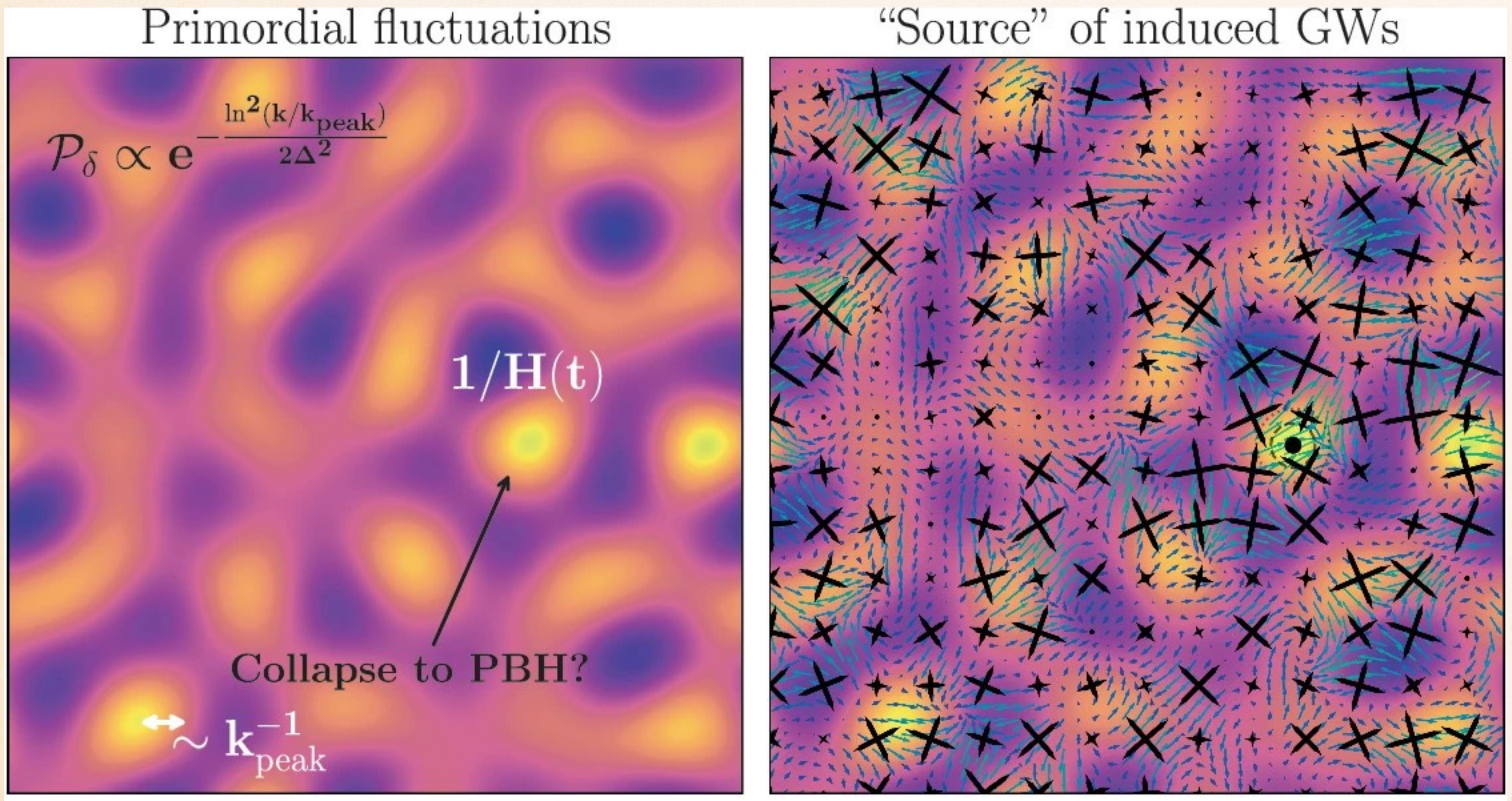
MECHANISM TO PRODUCE

Early Universe	Ultra Slow-Roll	W. H. Kinney 2005
	Parameter Resonance	Y. F. Cai et al. 2018
	Hybrid Inflation	A. Linde 1993
	…	
Late Universe	Phase Transition	M. Crawford & D. N. Schwann 1982
	Curvaton	M. Kawasaki et al. 2012
	…	

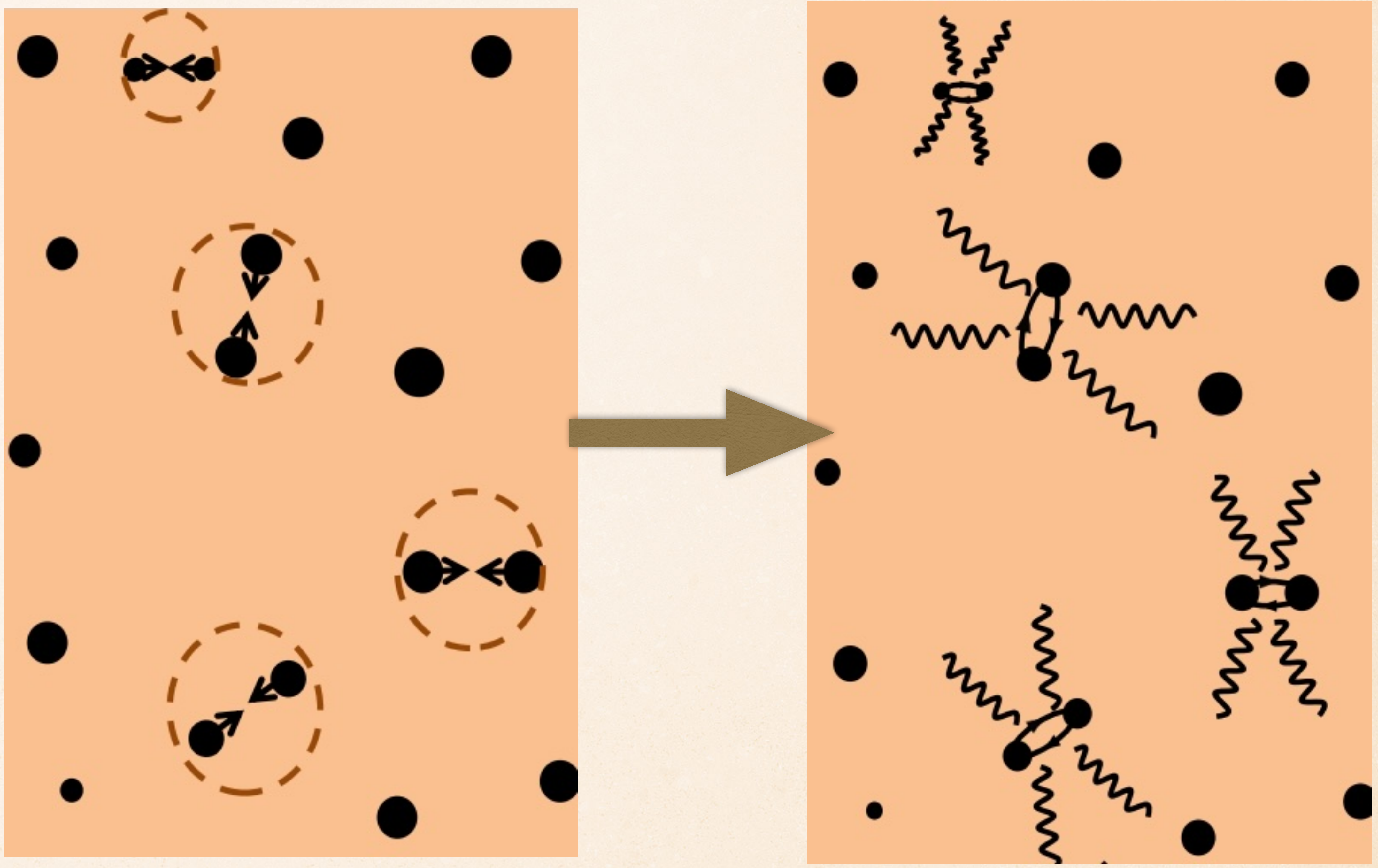
ASSOCIATED GW

$$\ddot{h}_{ij} \sim \Lambda^{\mu\nu}_{ij}\partial_i\zeta\partial_j\zeta \longrightarrow \Omega_{\rm GW} \sim \mathscr{P}^2_\zeta$$

$$\Omega_{\rm GW}(f) \sim \int dz \mathscr{R}(z)\frac{dE}{d\ln f}$$



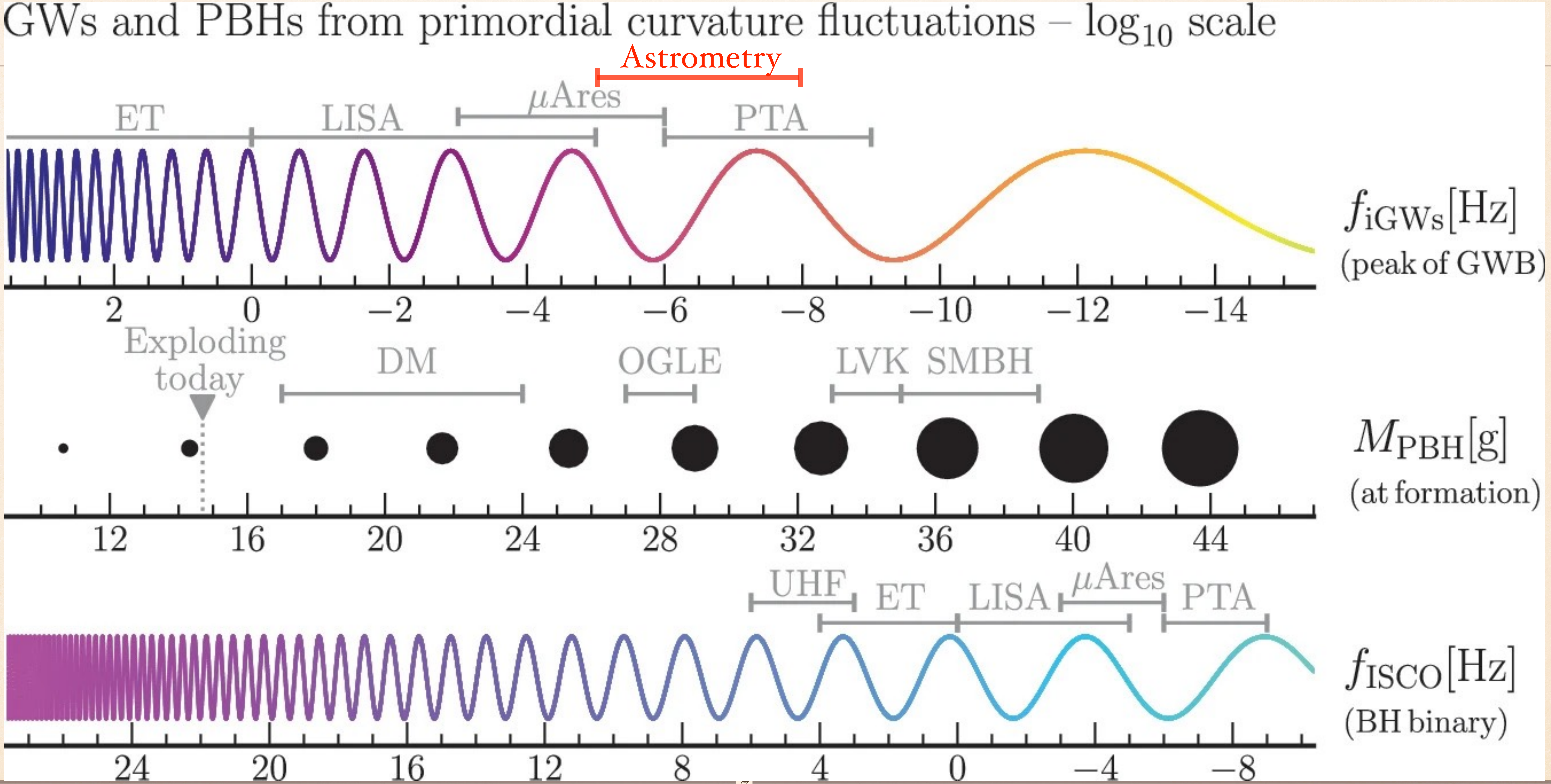
G. Domènech 2025



M. Sasaki et al. 2018

ASSOCIATED GW

G. Domènech 2025



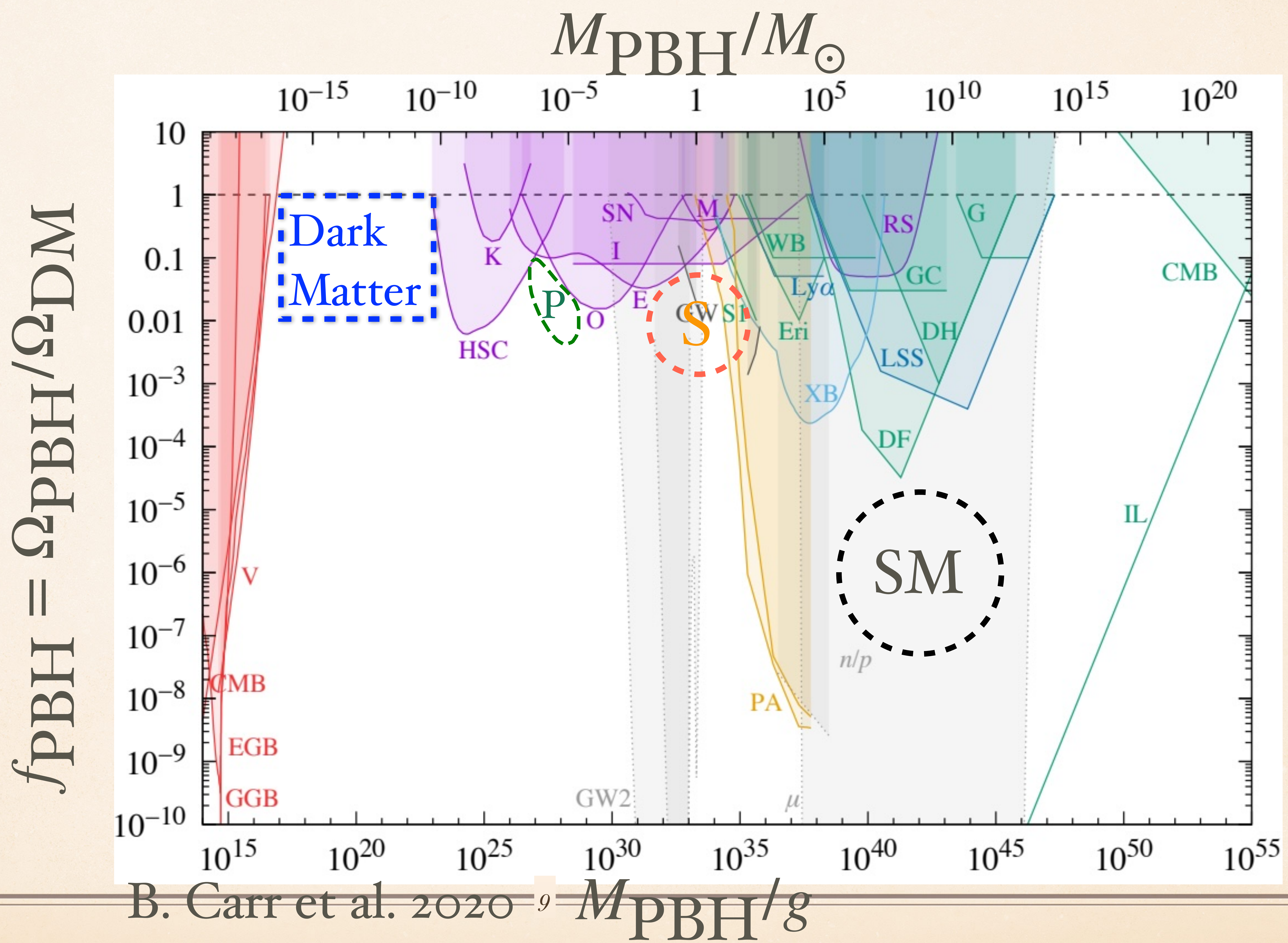
OUTLINE

- nHz GW (Pulsar Timing Array)
- μHz GW (Astrometry)

Planet $10^{-6} - 10^{-4} M_{\odot}$

- mHz GW (Space-based Laser Interferometer) Asteroid $10^{-16} - 10^{-10} M_{\odot}$

PLANETARY MASS WINDOW

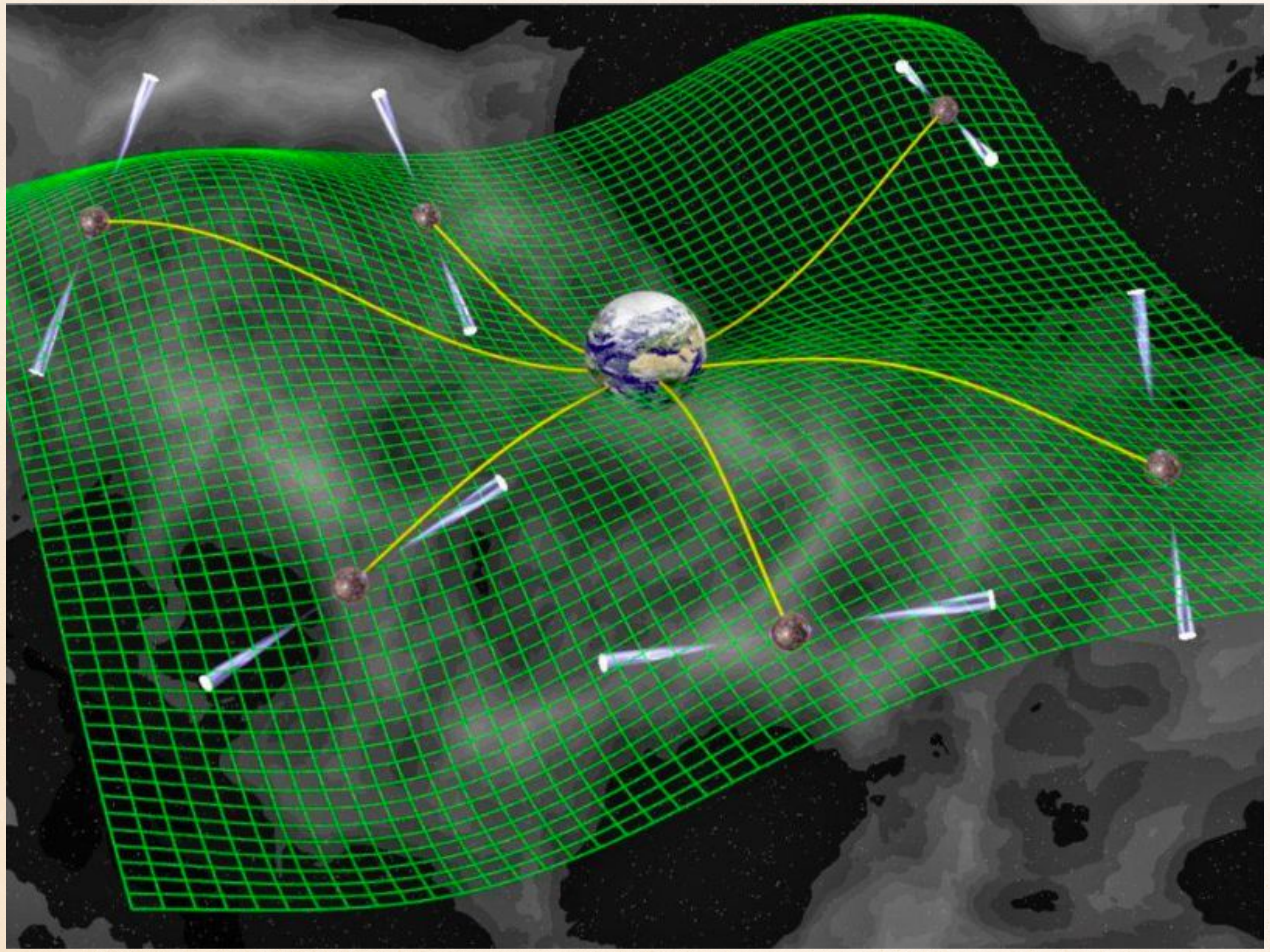


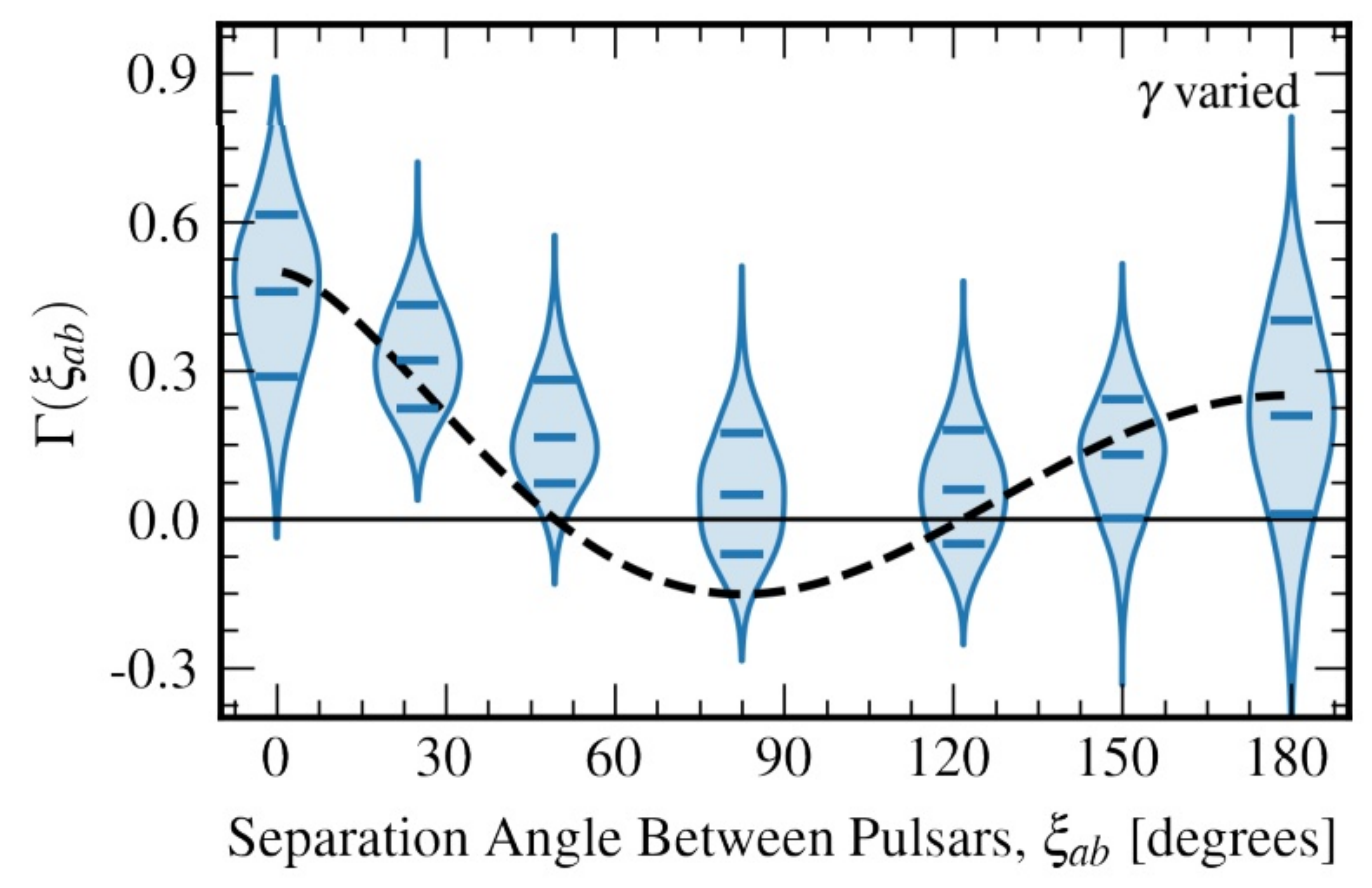
B. Carr et al. 2020

PULSAR TIMING ARRAY

Hellings-Downs Curve

$$\Phi_{ab,i} = \Gamma_{\mathrm{HD}}\left(\xi_{ab}\right)\Phi_{\mathrm{HD},i}$$





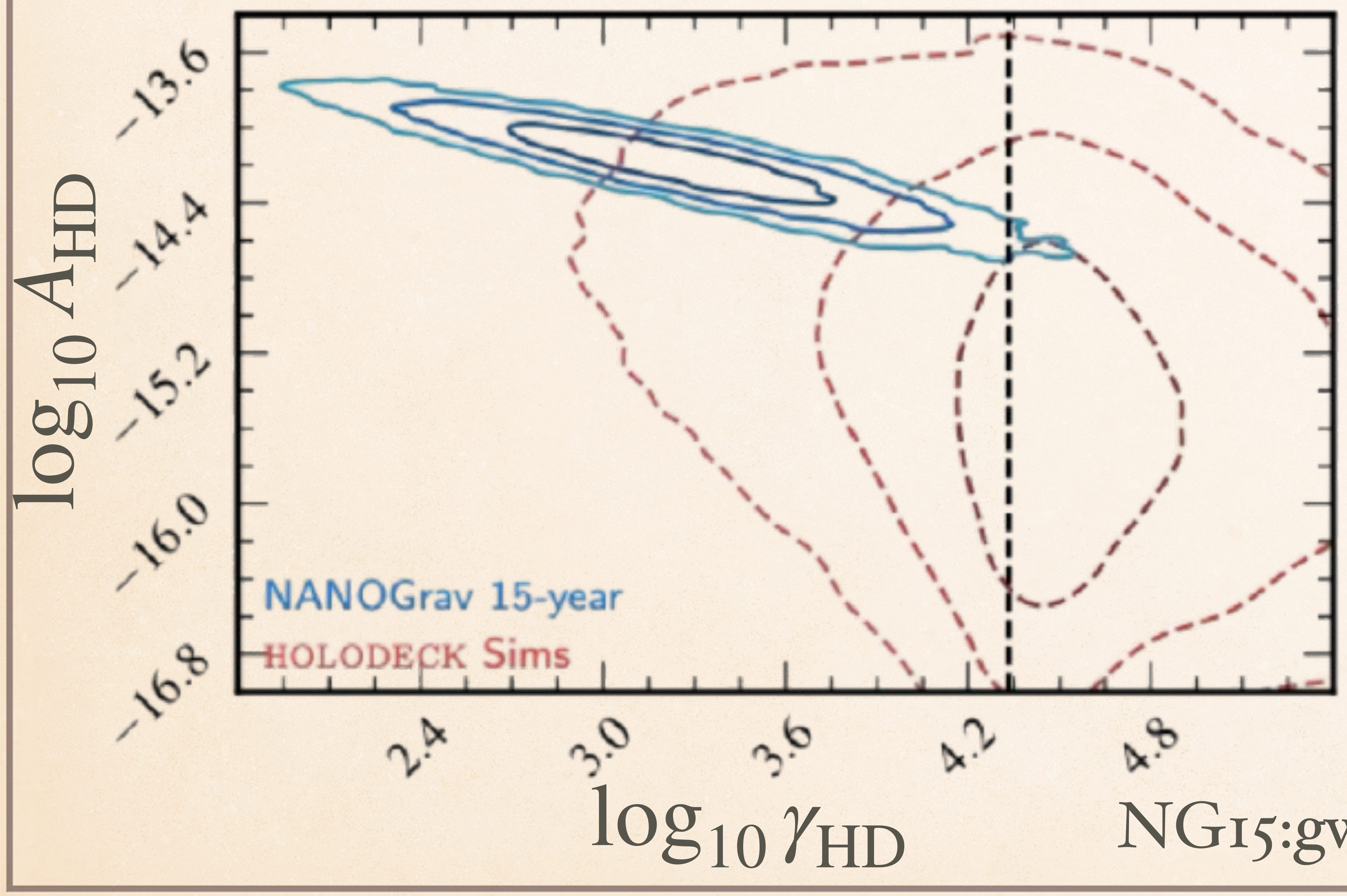
Credit: David J. Champion

NG15:gwb

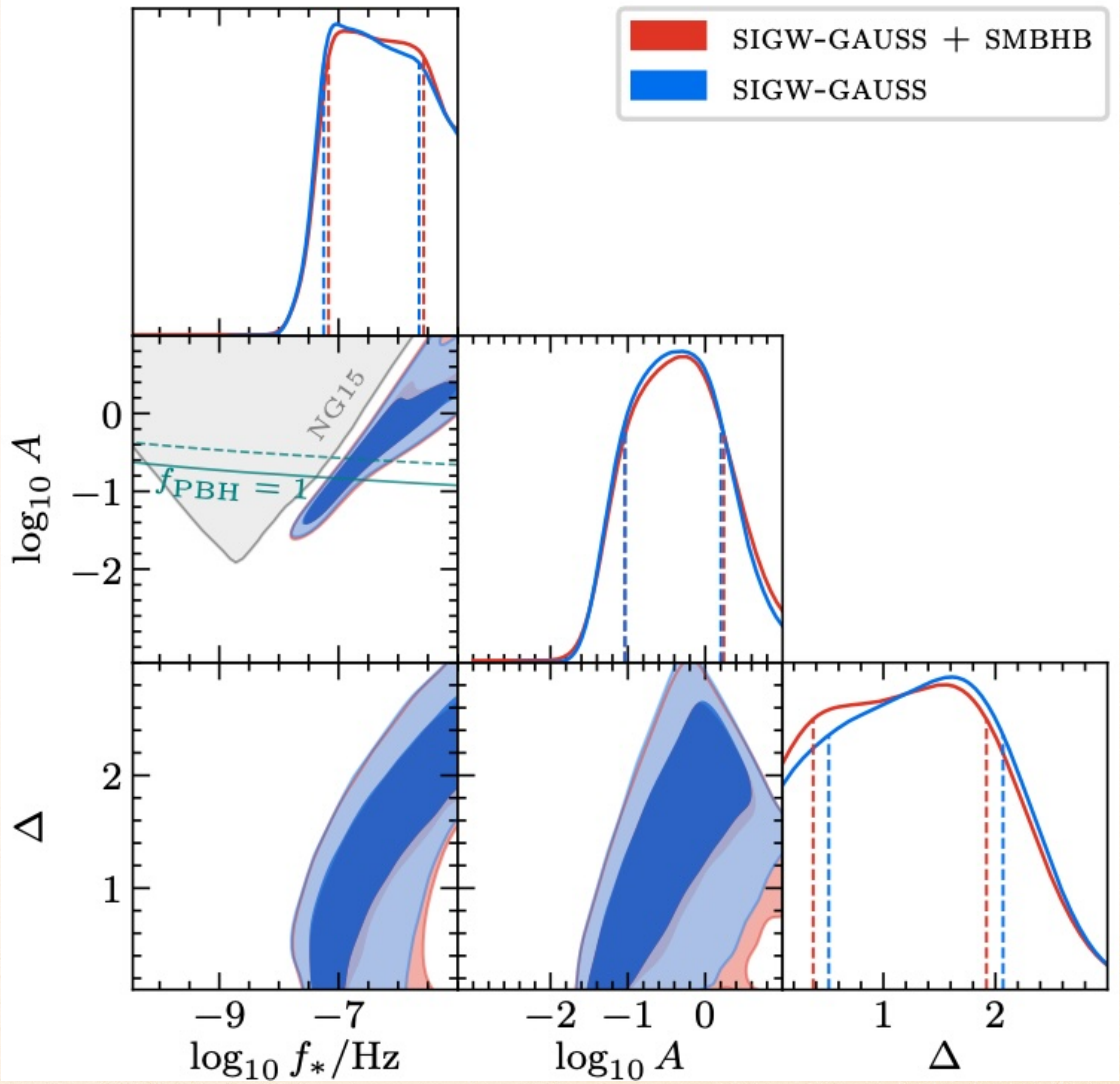
PULSAR TIMING ARRAY

NG15:new_phy

$$\Phi_{\mathrm{HD},i} = \frac{A_{\mathrm{HD}}^2}{12\pi^2}\frac{1}{T}\left(\frac{f_i}{f_{\mathrm{ref}}}\right)^{-\gamma_{\mathrm{HD}}} f_{\mathrm{ref}}^{-3}$$

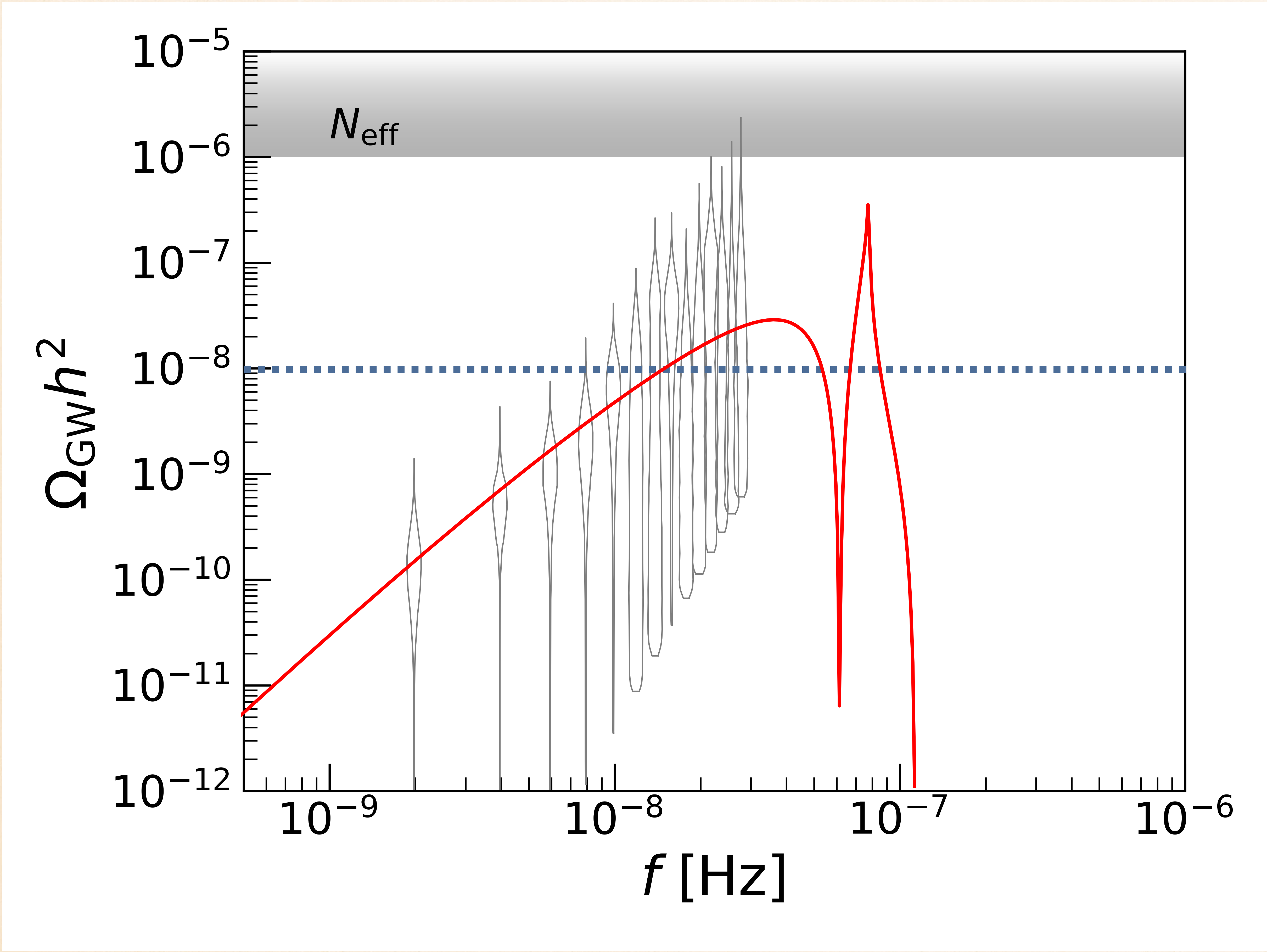


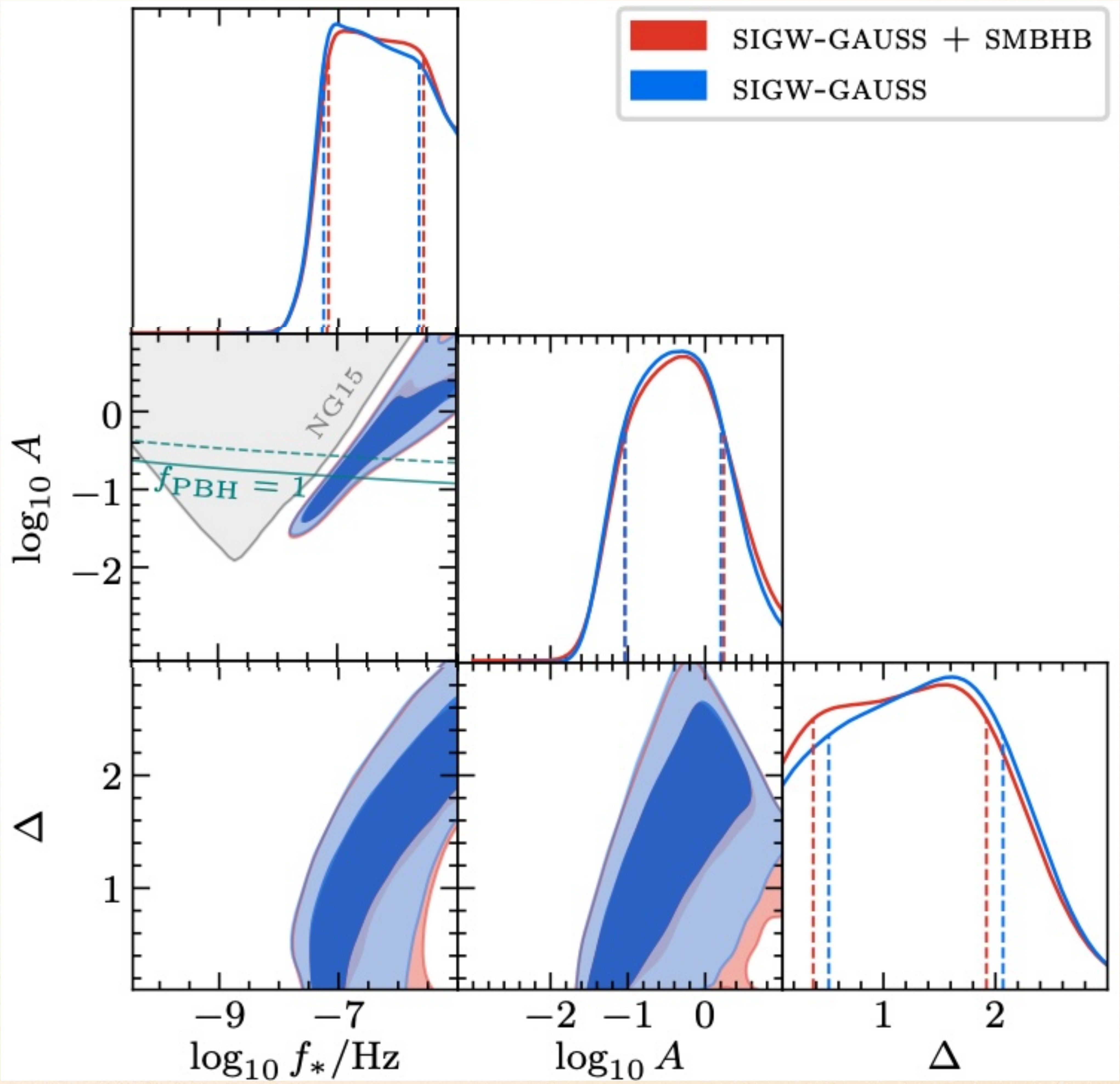
NG15:gwb



PULSAR TIMING ARRAY

NG15:new_phy





$$\Omega_{{\rm GW},0}h^2 = 3.4 \times 10^{-5}\Omega_{\rm GW} \longrightarrow 0.02 \lesssim \mathscr{A}_\zeta \lesssim 0.2$$

PULSAR TIMING ARRAY

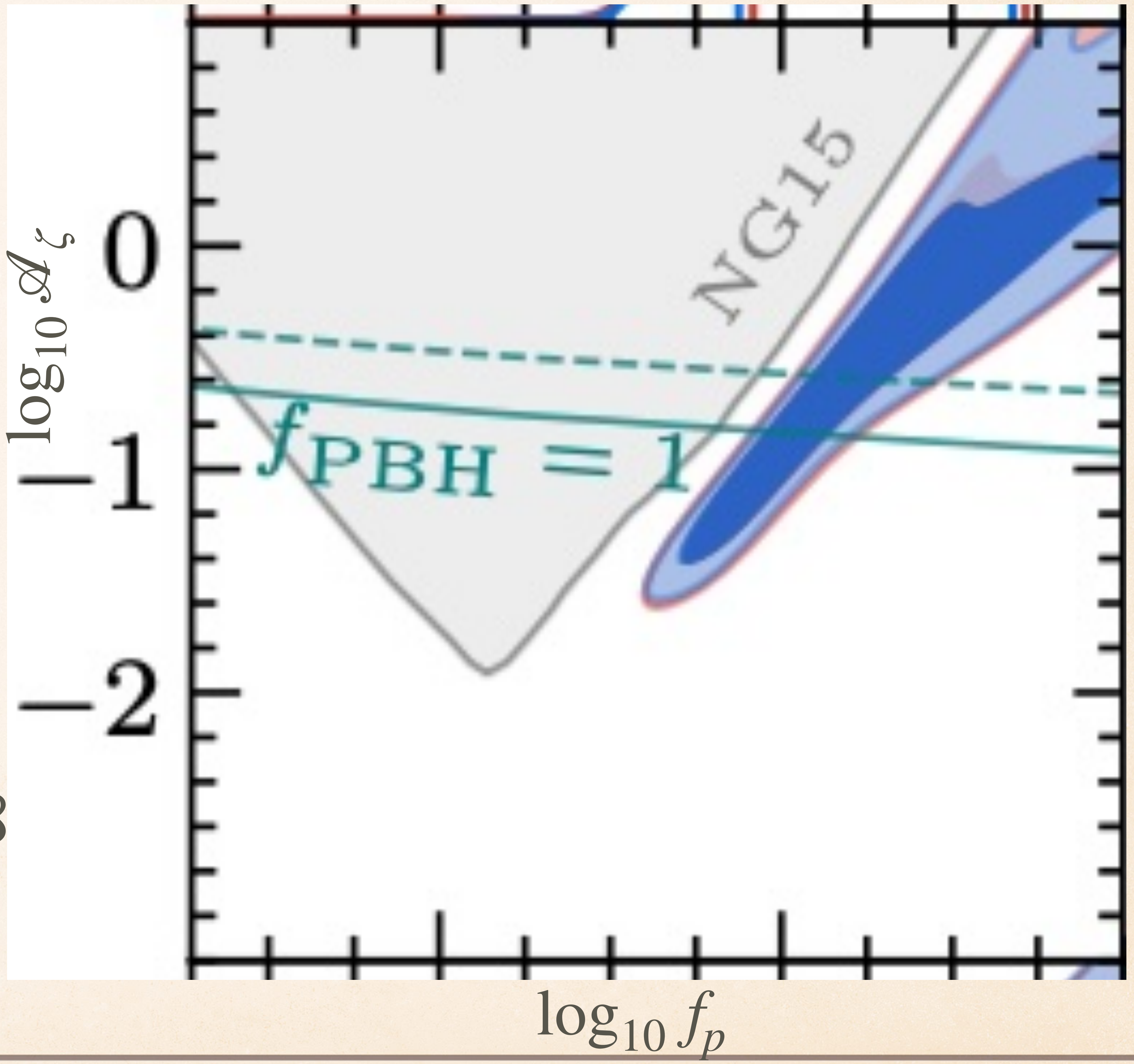
NG15:new_phy

$$f_{\rm PBH} \sim 10^{11} \left(\frac{M_{\rm PBH}}{10^{-5} M_\odot} \right)^{-1/2} \frac{\delta_c}{\sqrt{\pi}\sigma} \exp\left(-\frac{\delta_c^2}{2\sigma^2} \right)$$

$$f_{\rm PBH} < 1 \longrightarrow \sigma < 0.2\delta_c \sim 0.1$$

$$\sigma^2(M(k)) = \begin{cases} 1.06 A_\zeta & \text{(real-space top-hat)} \\ 0.0867 A_\zeta & \text{(Gaussian)} \\ 0.0472 A_\zeta & \text{(k-space top-hat).} \end{cases}$$

K. Ando et al. 2018



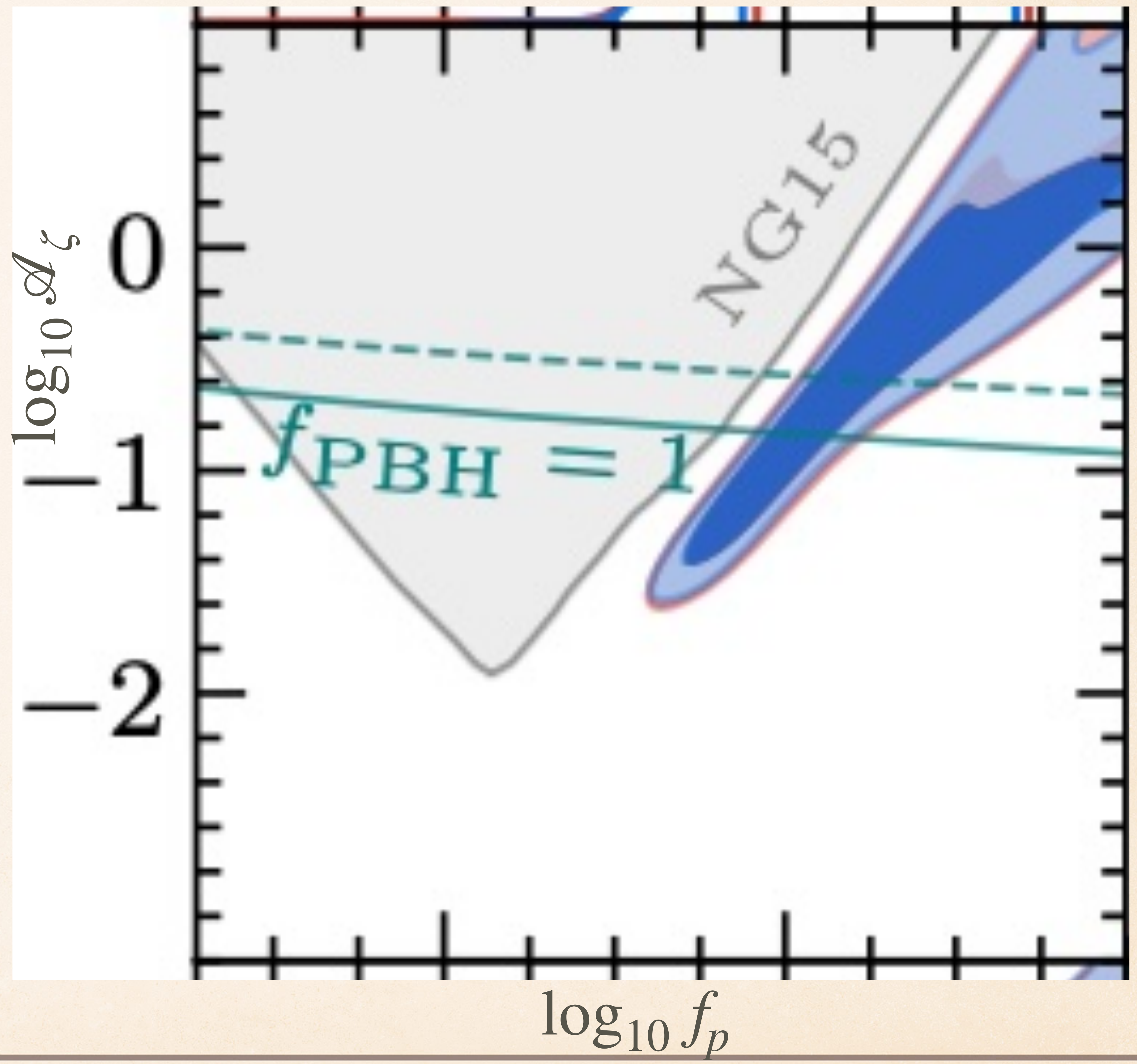
$\mathcal{A}_\zeta \lesssim 0.01$ $\quad 0.02 \lesssim \mathcal{A}_\zeta \lesssim 0.2$

PULSAR TIMING ARRAY

NG15:new_phy

PBH Overproduction

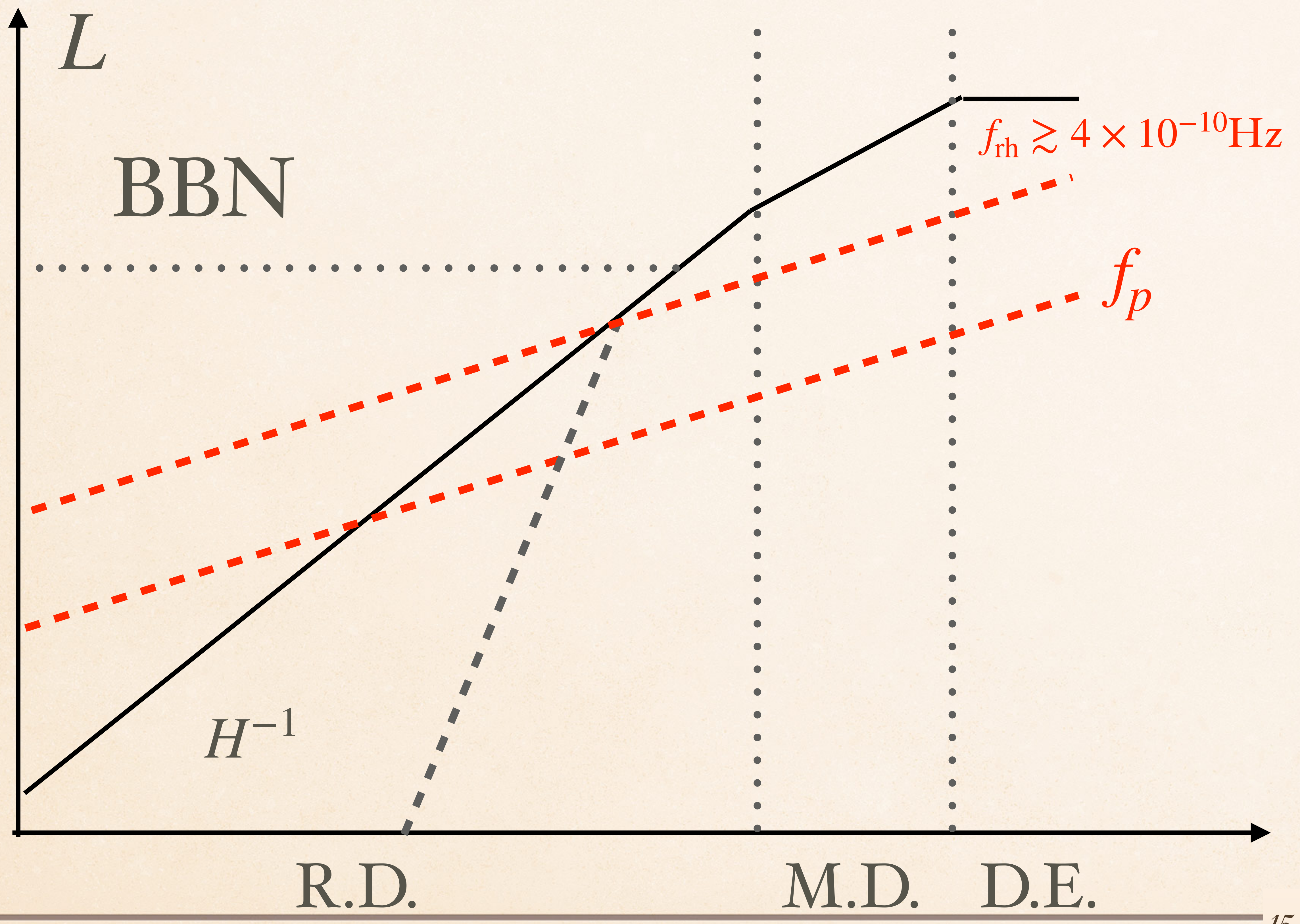
- Negative non-Gaussianity
- Stiff stage
- Wider power spectrum

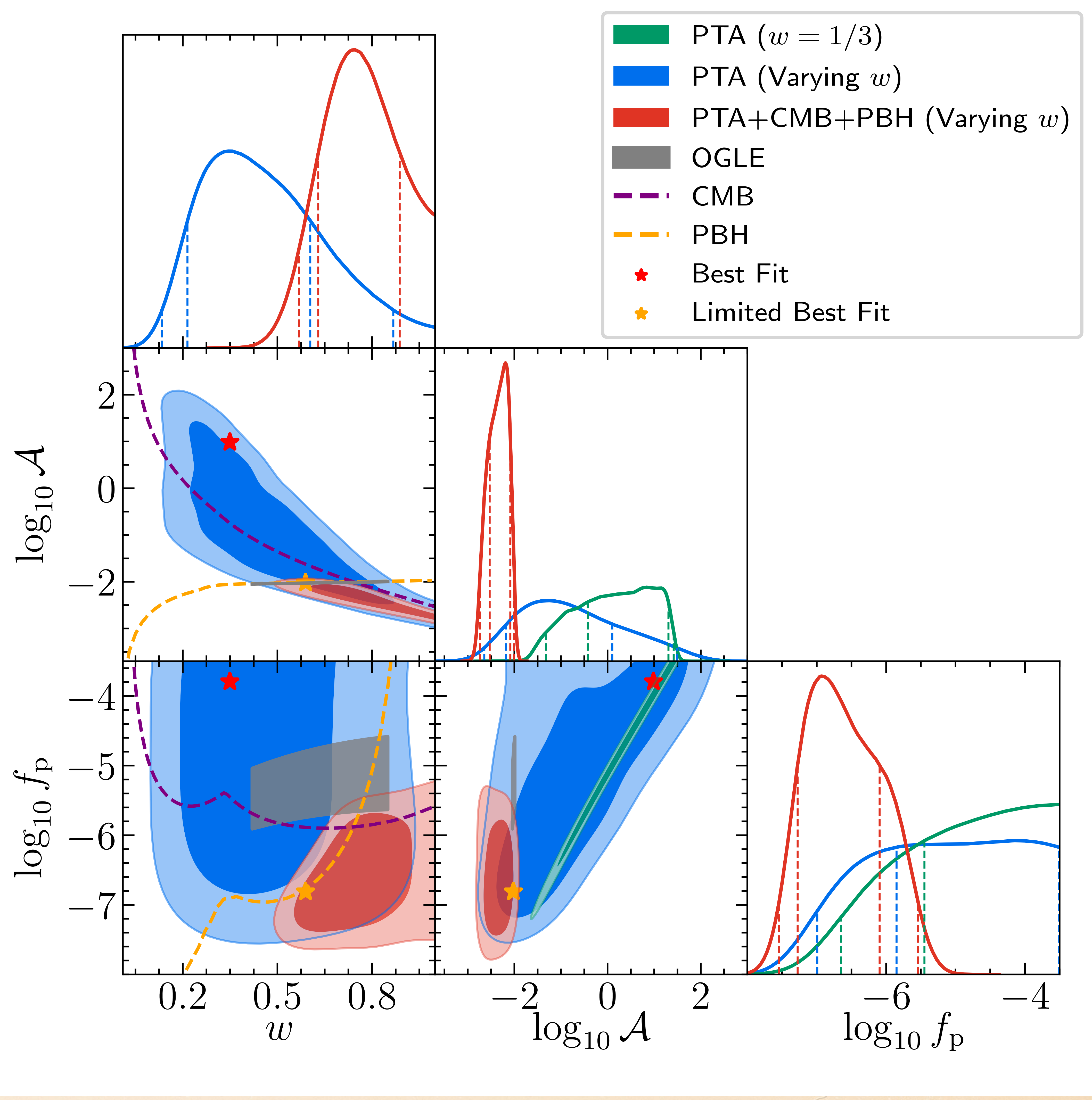


STIFF STAGE

G. Domènech, S. Pi, **AW**, J. N. Wang 2024

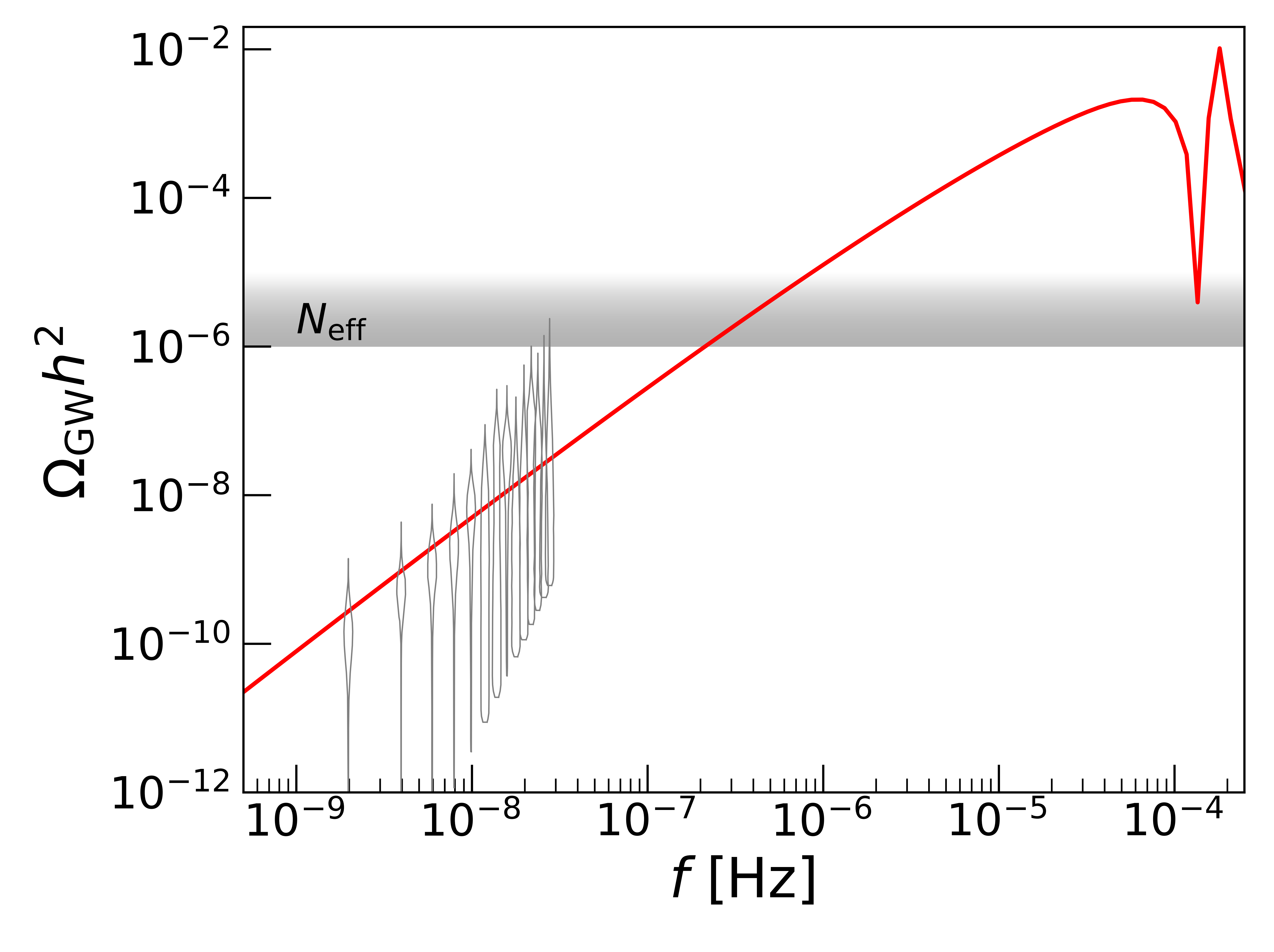
$$V(\phi) \propto \phi^{2n}, \quad w_{\rm eff} = \frac{n-1}{n+1}$$

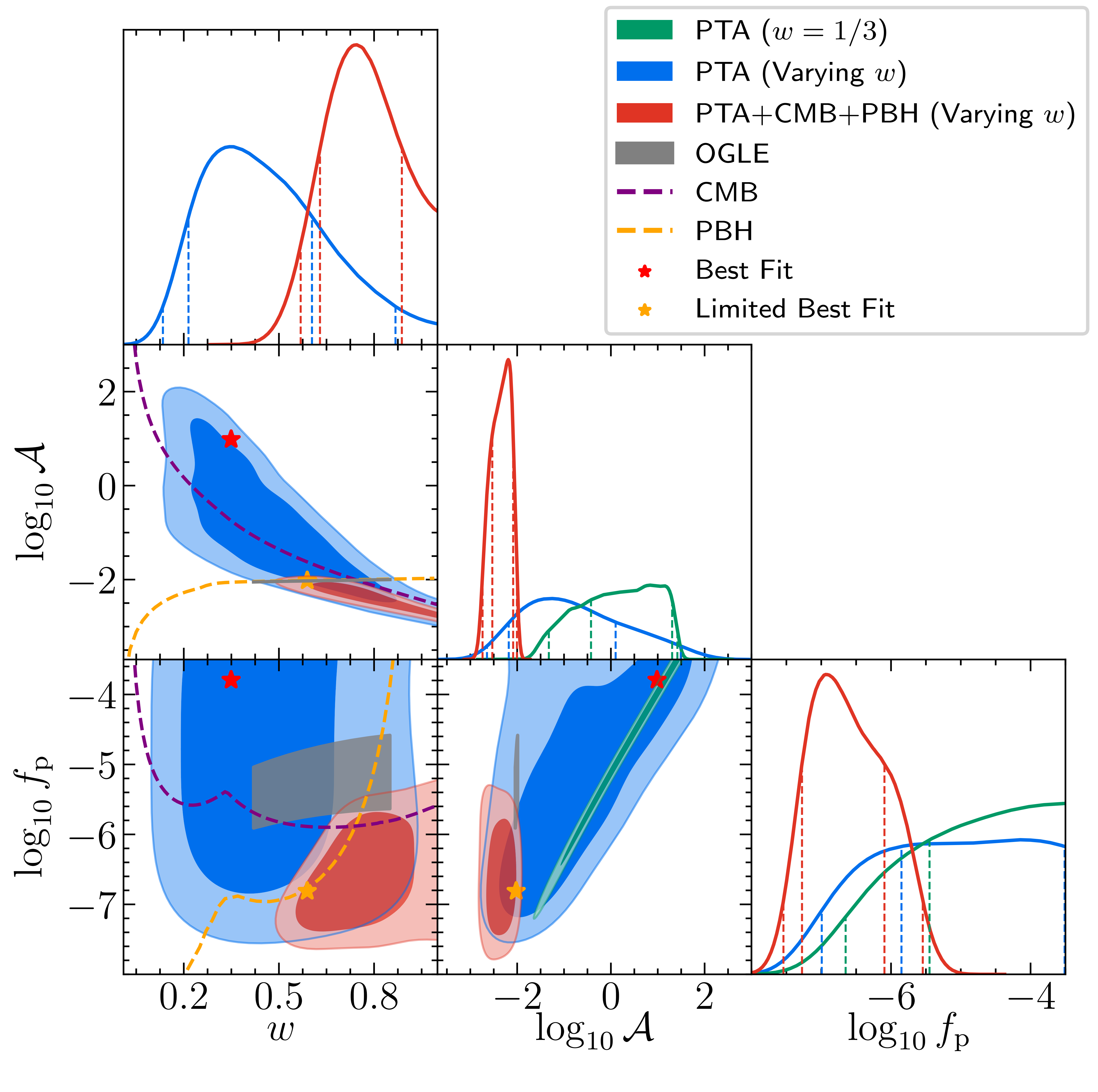




STIFF STAGE

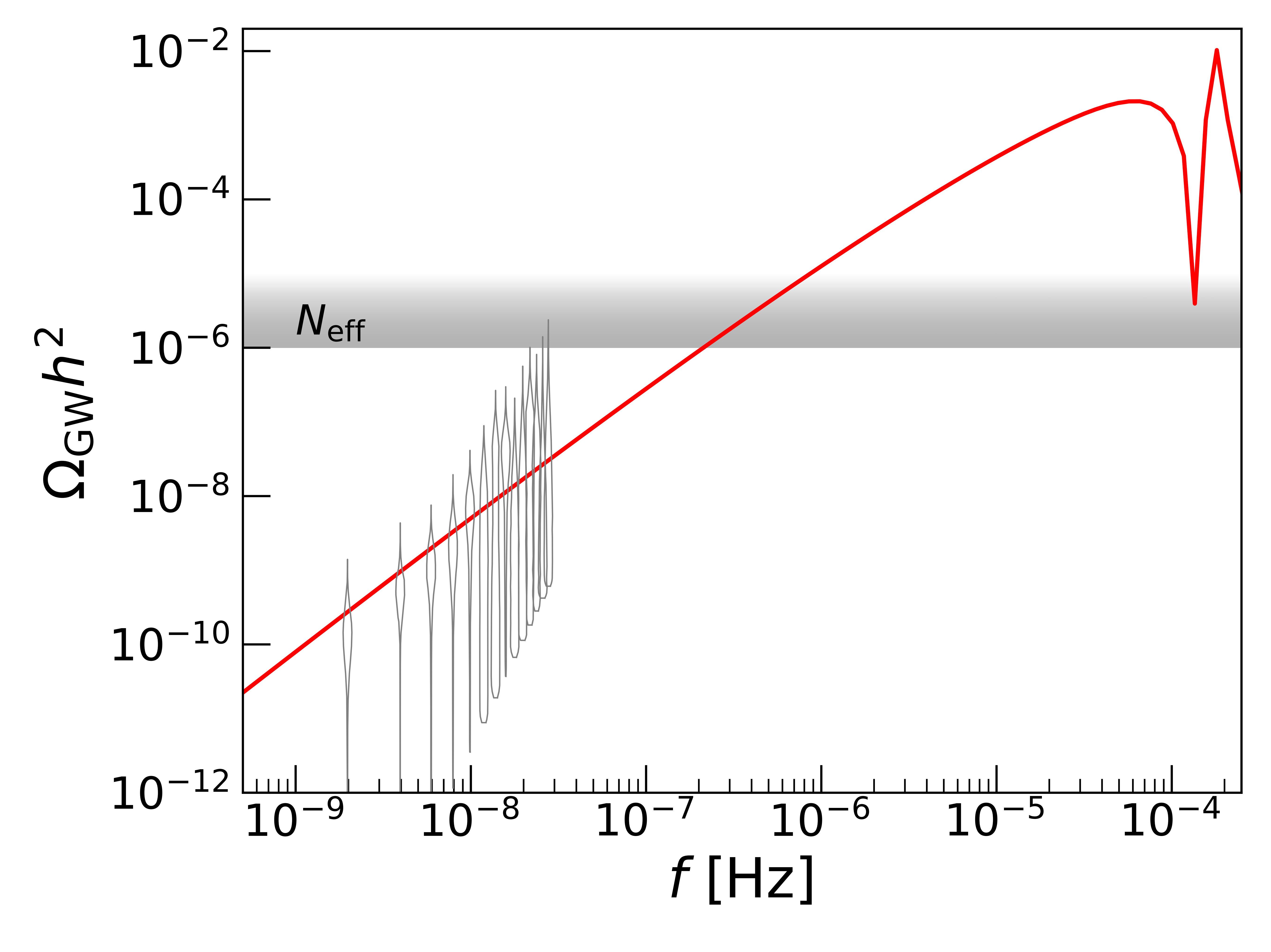
G. Domènech, S. Pi, **AW**, J. N. Wang 2024

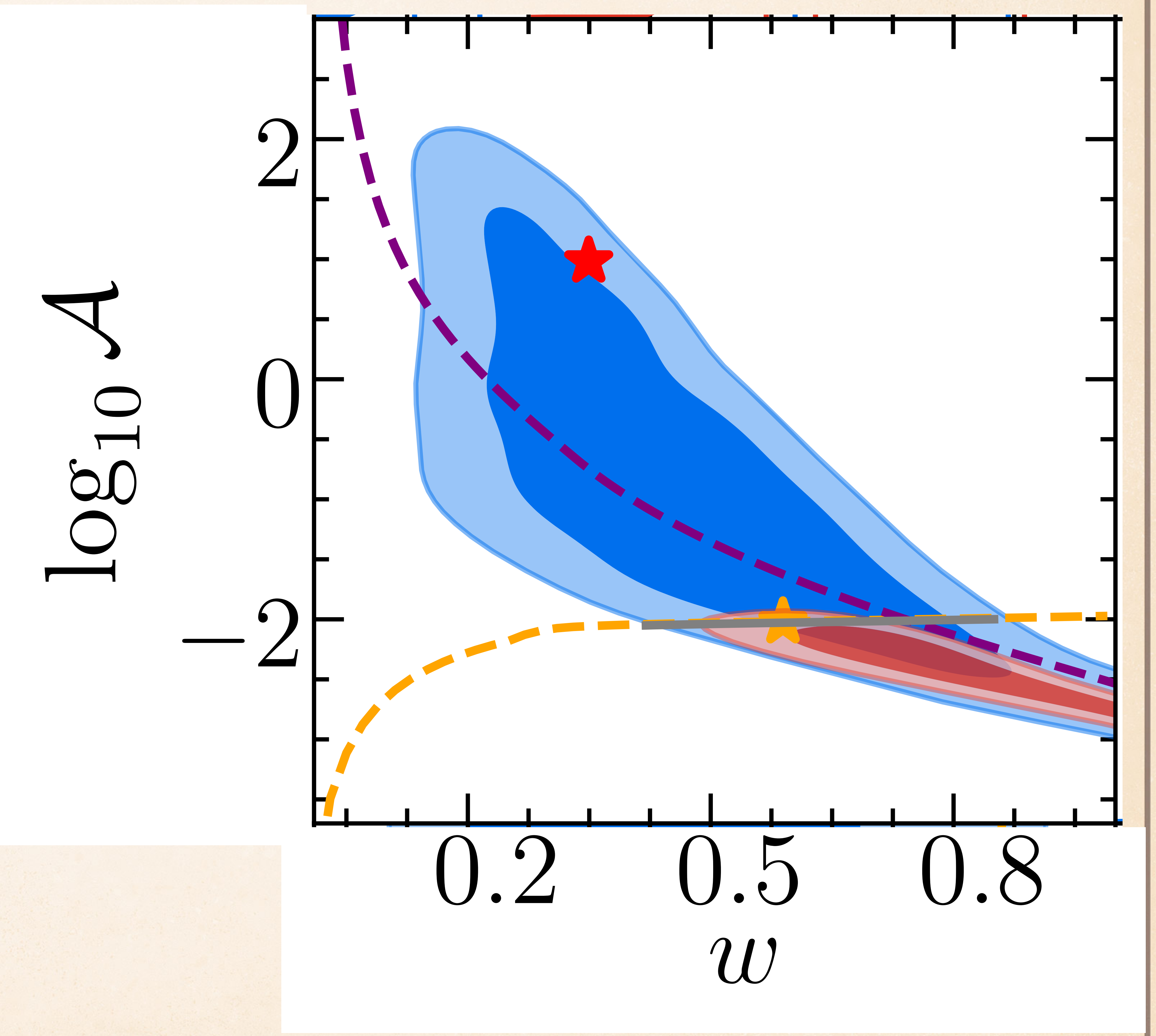




STIFF STAGE

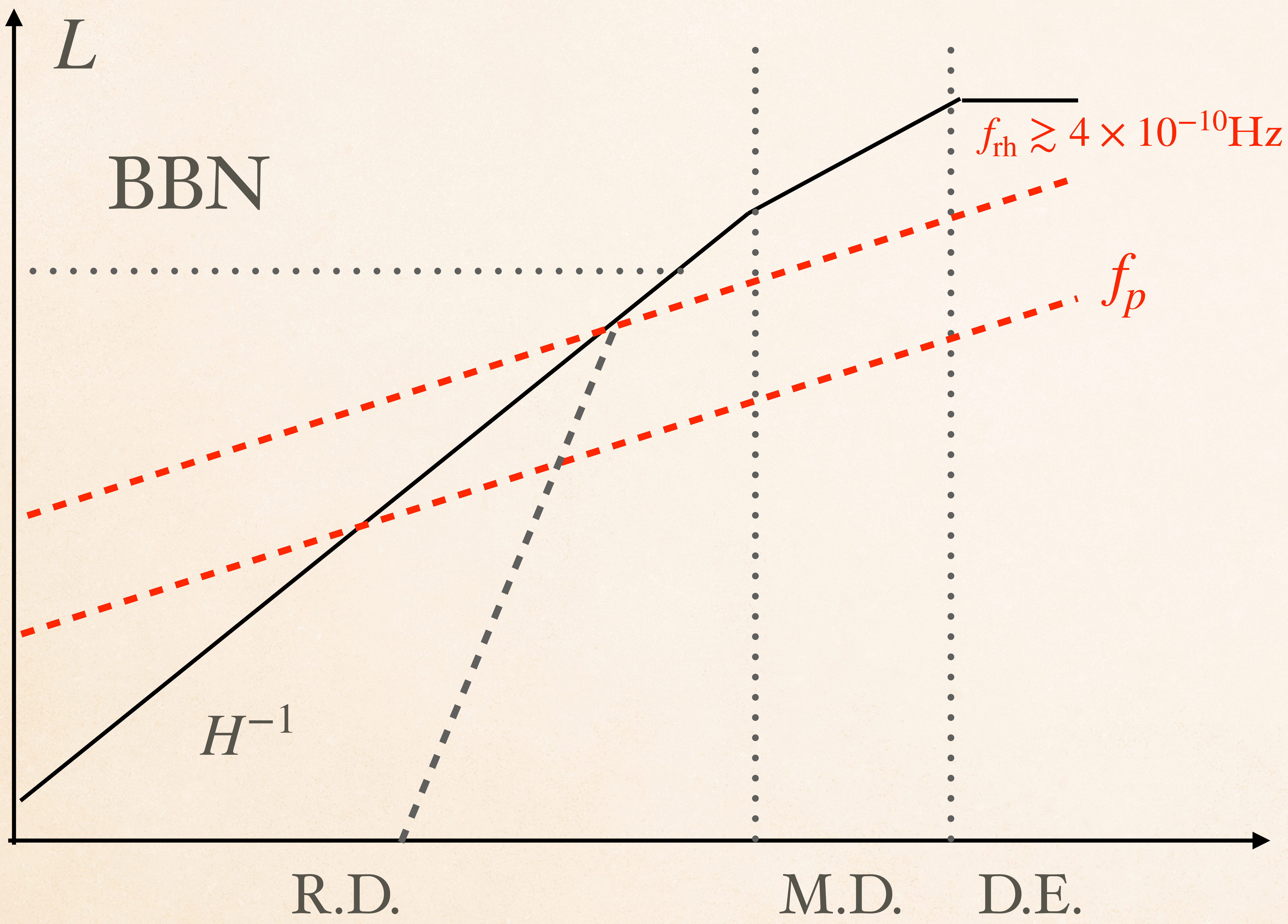
G. Domènech, S. Pi, **AW**, J. N. Wang 2024

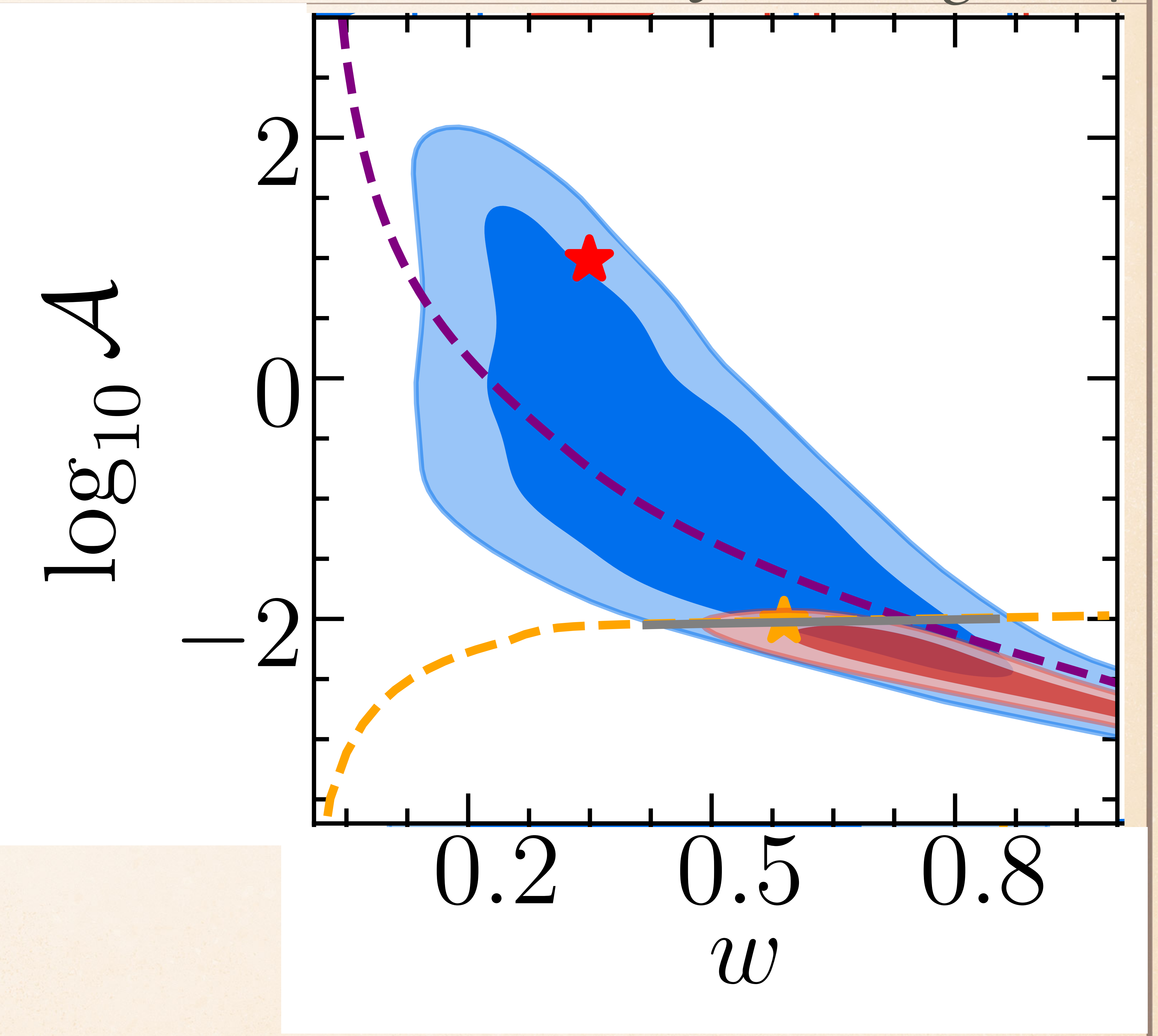




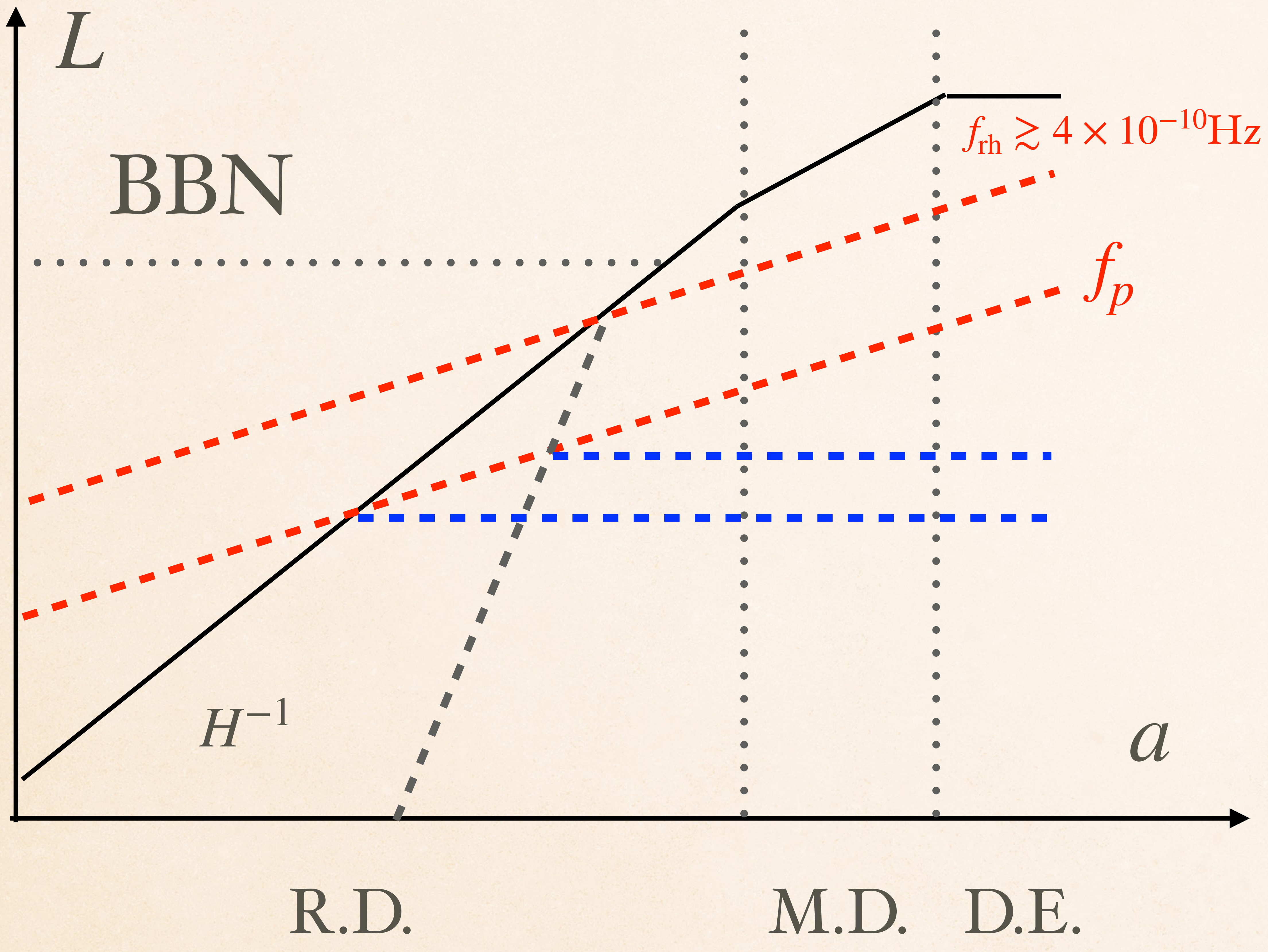
STIFF STAGE

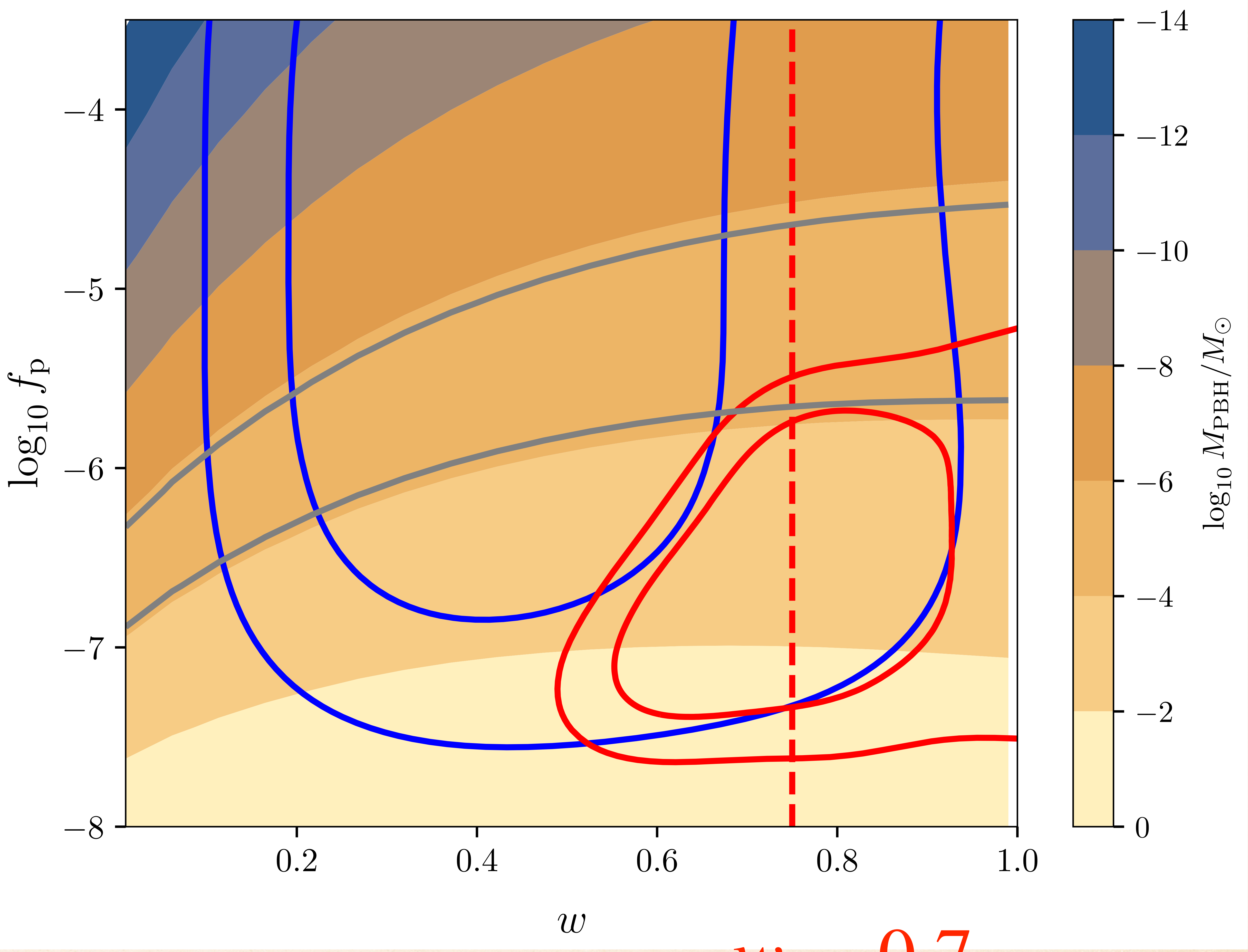
G. Domènech, S. Pi, **AW**, J. N. Wang 2024





STIFF STAGE





$w \sim 0.7$

PULSAR TIMING ARRAY

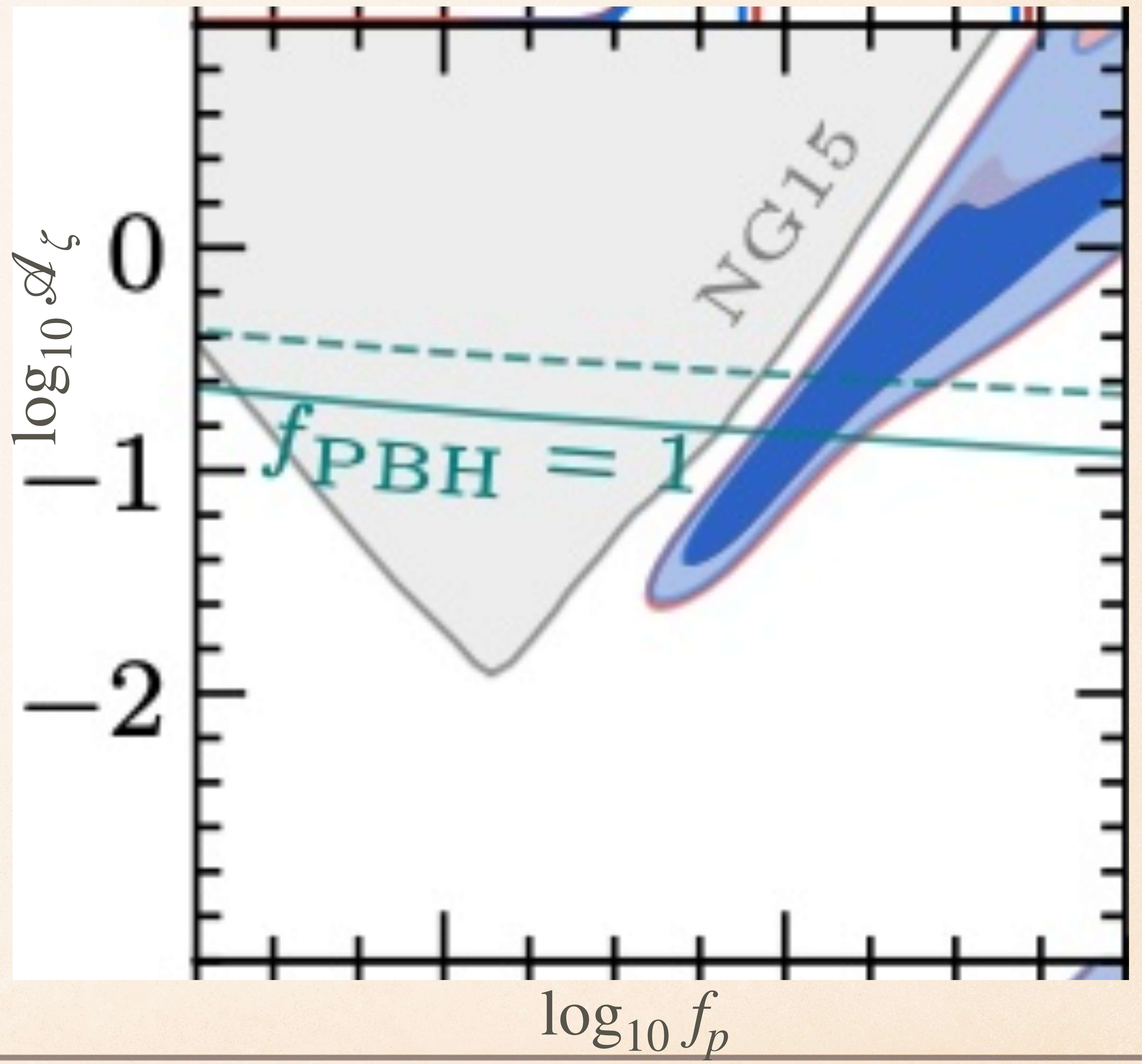
NG15:new_phy

PBH Overproduction

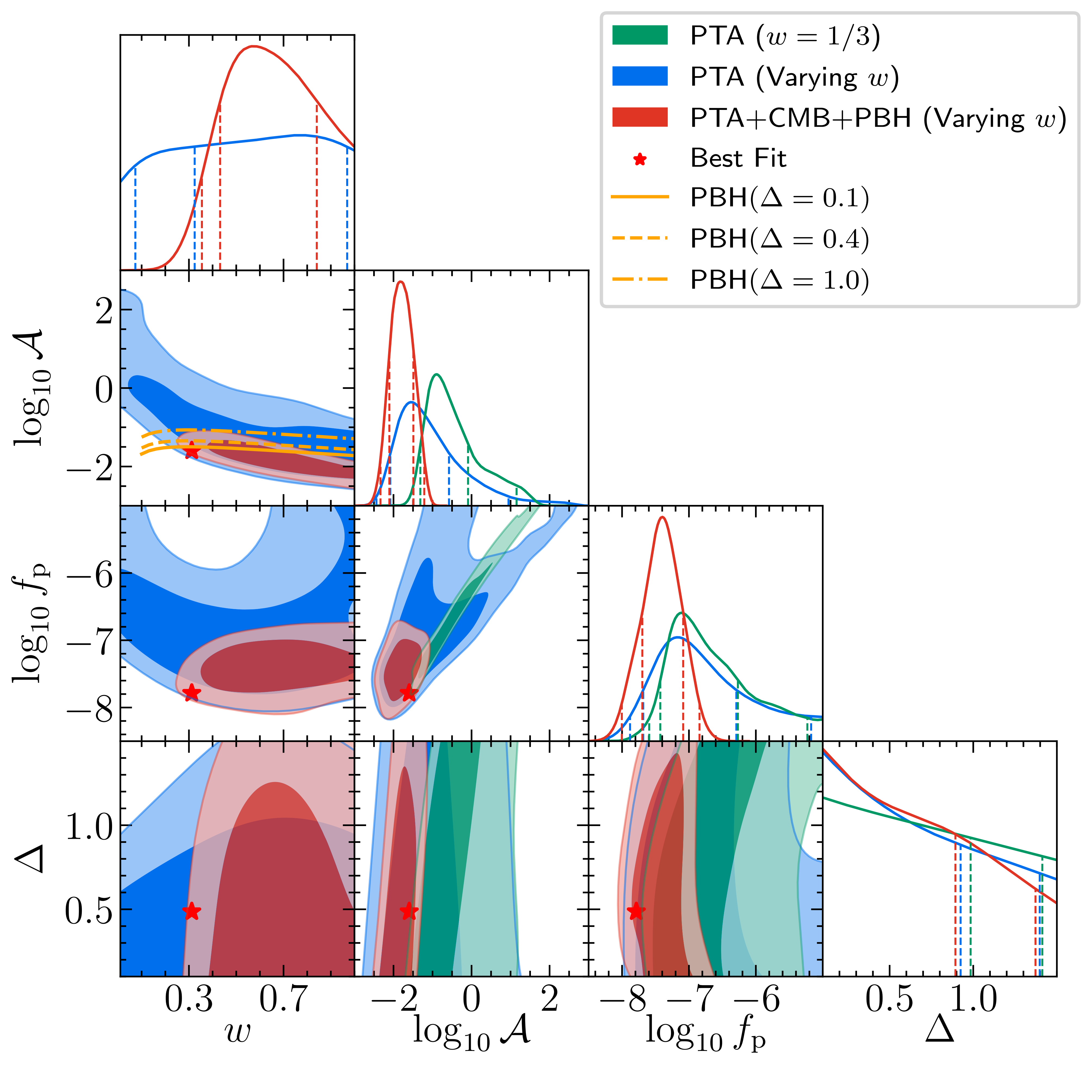
Negative non-Gaussianity

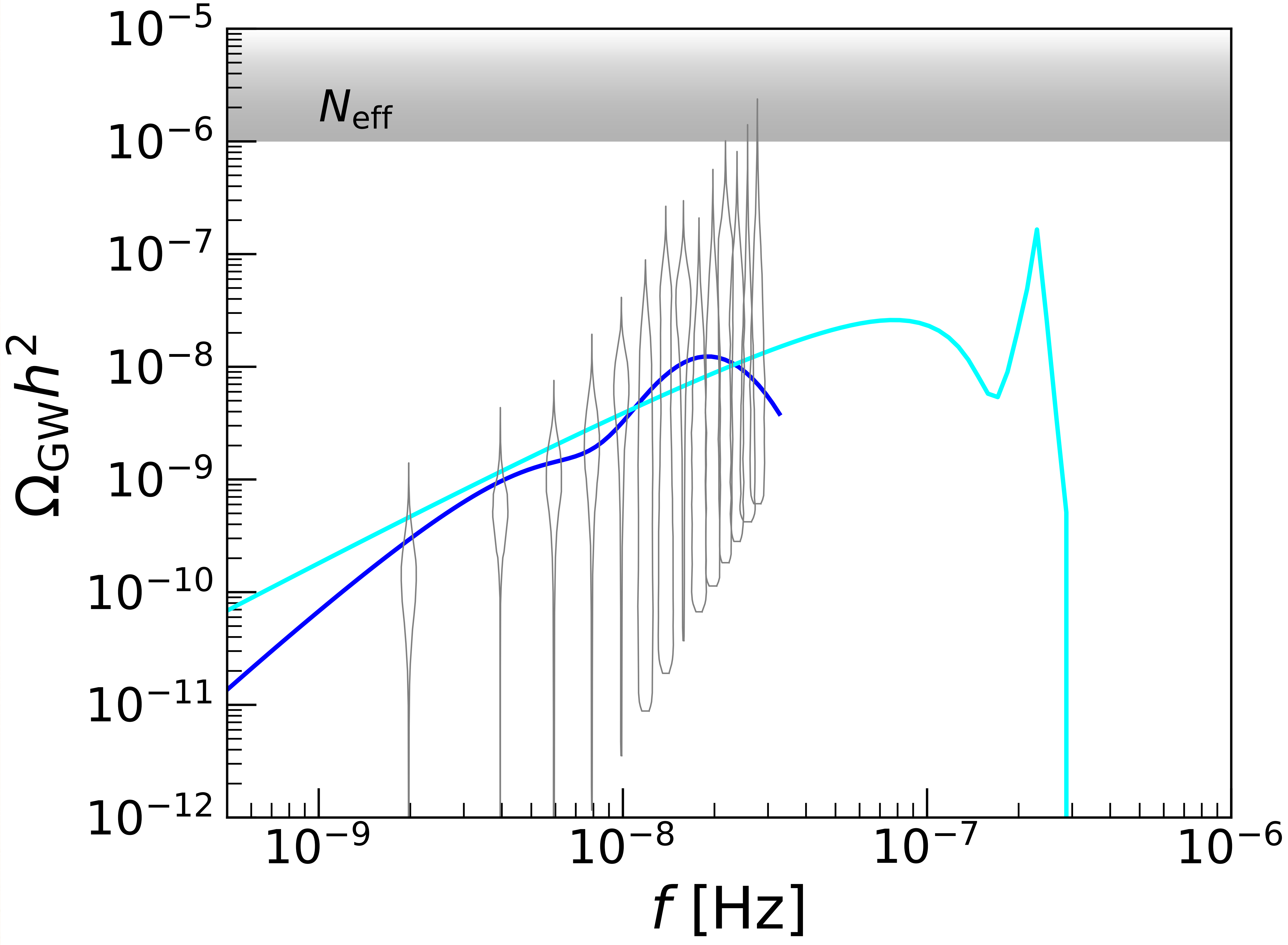
Stiff stage

Wider power spectrum



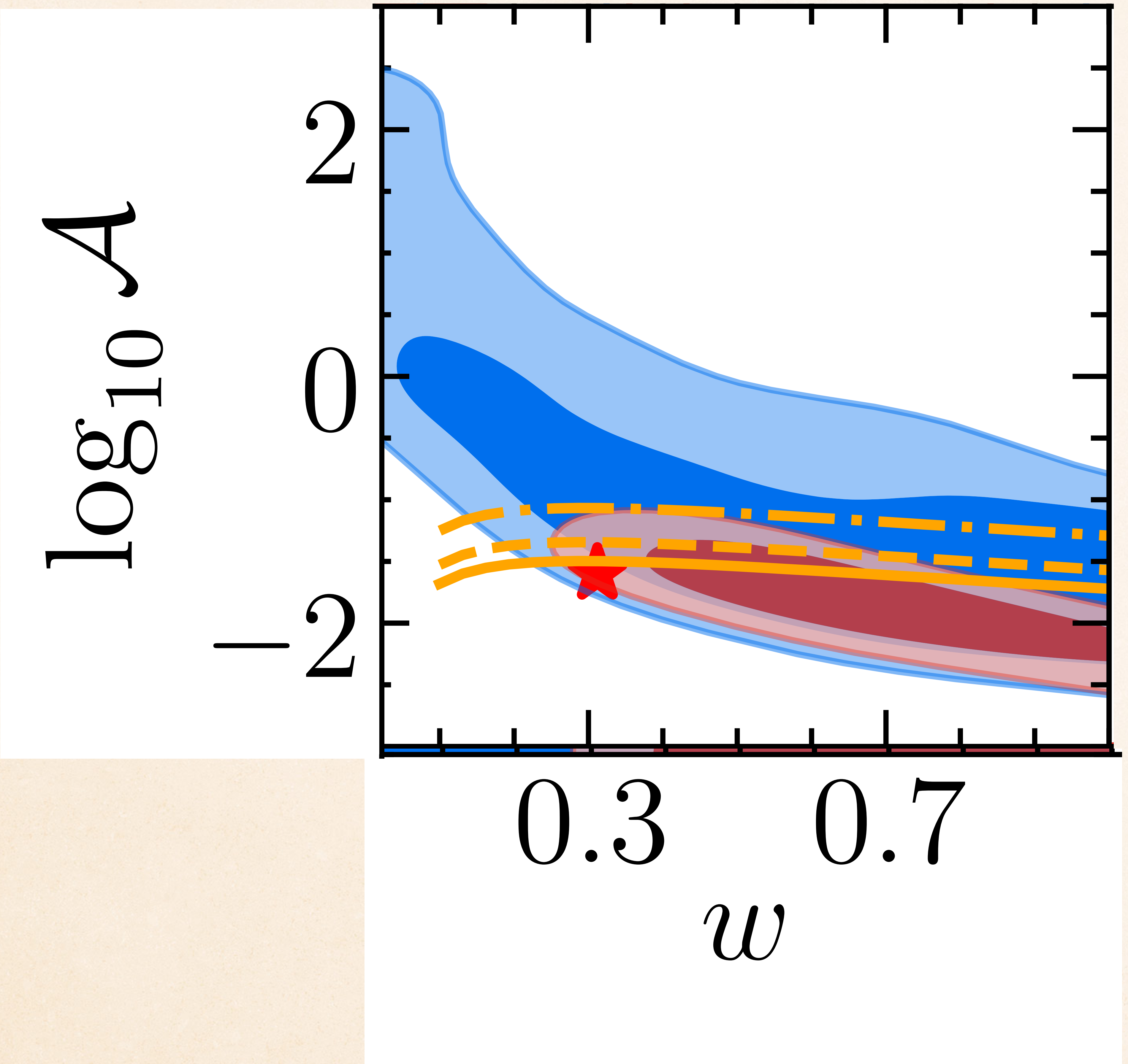
WIDER POWER SPECTRUM

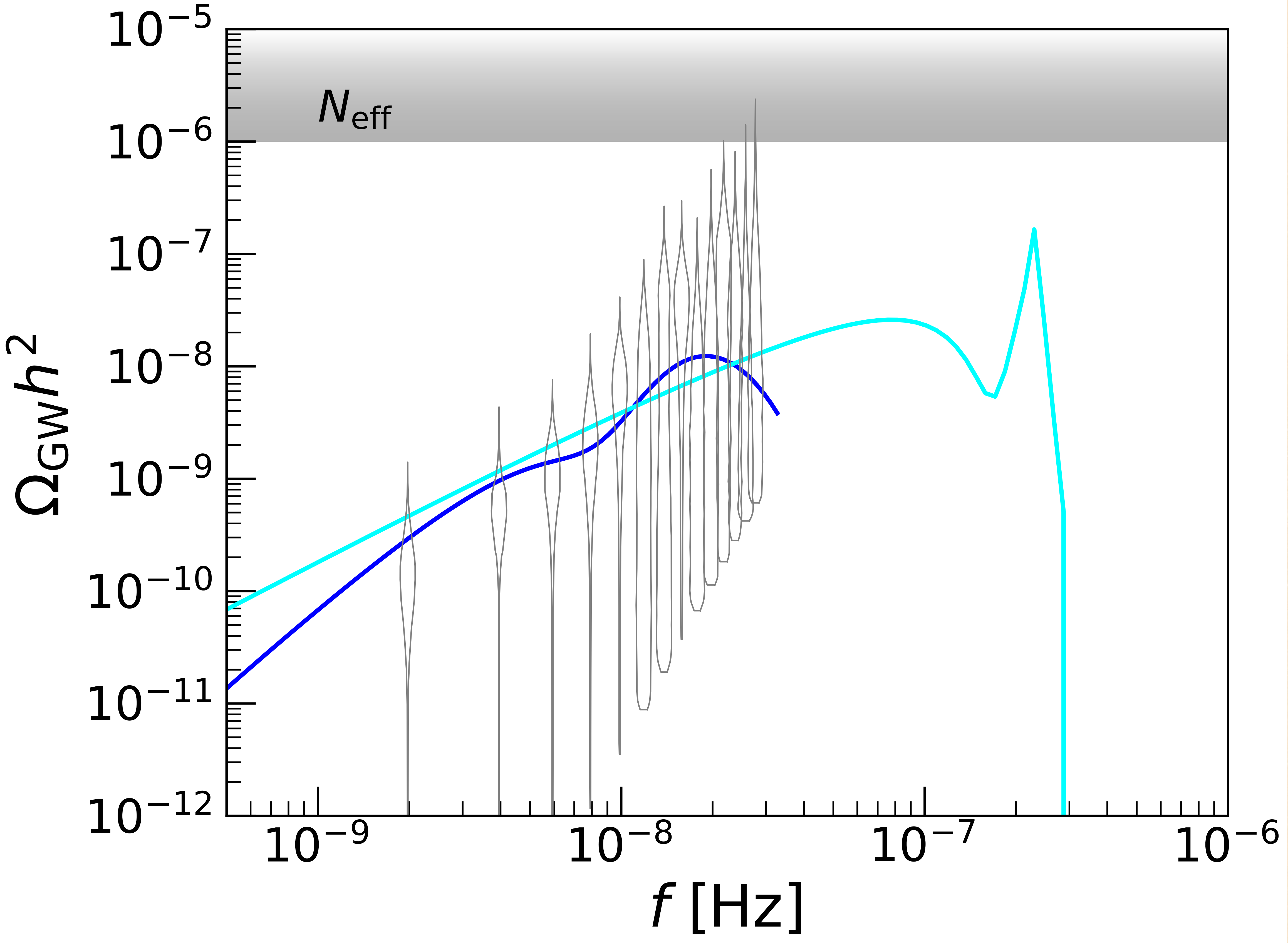




$$\Delta \approx 0.49, \quad f_p \approx 1.6 \times 10^{-8} \text{Hz}$$

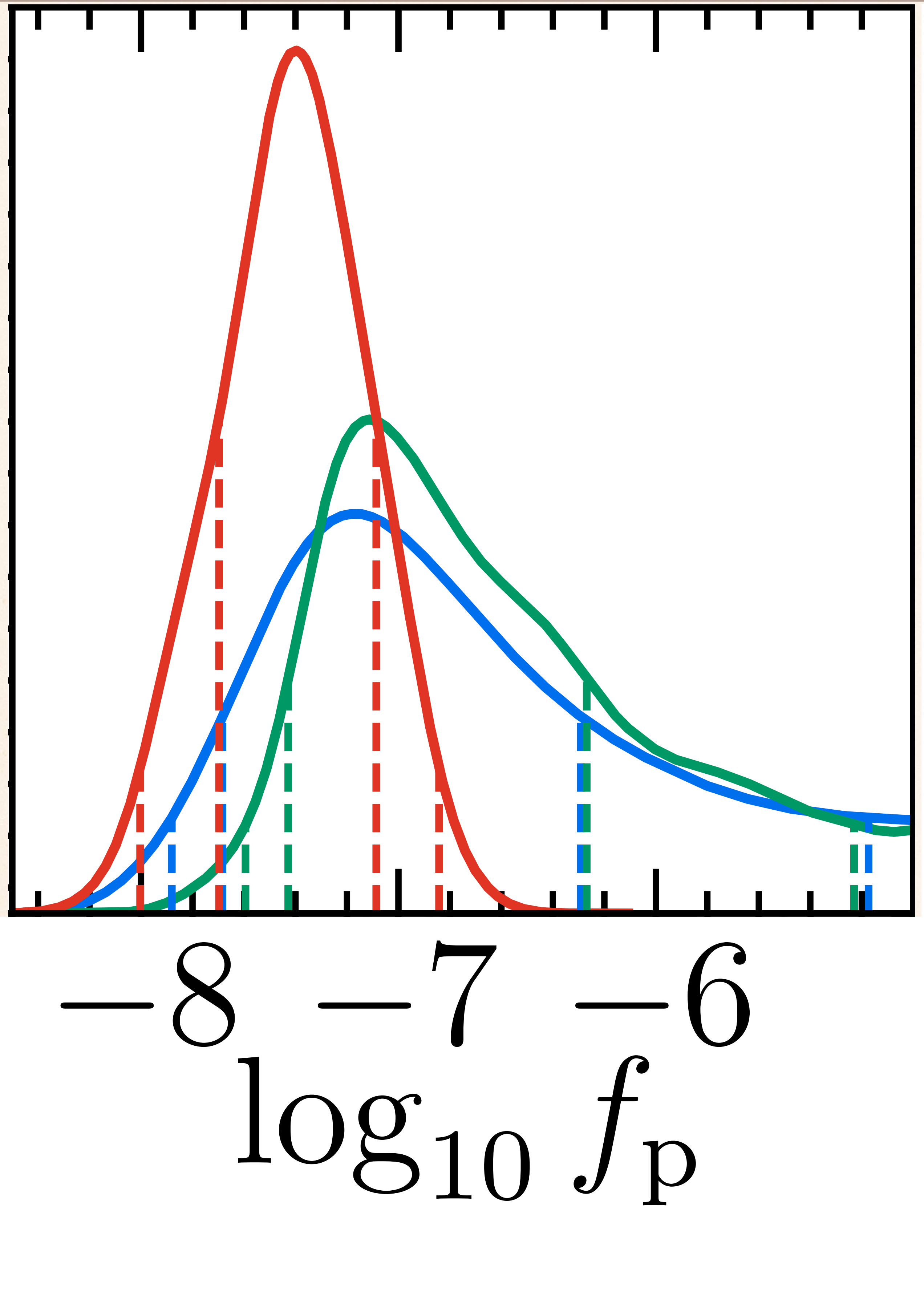
WIDER POWER SPECTRUM

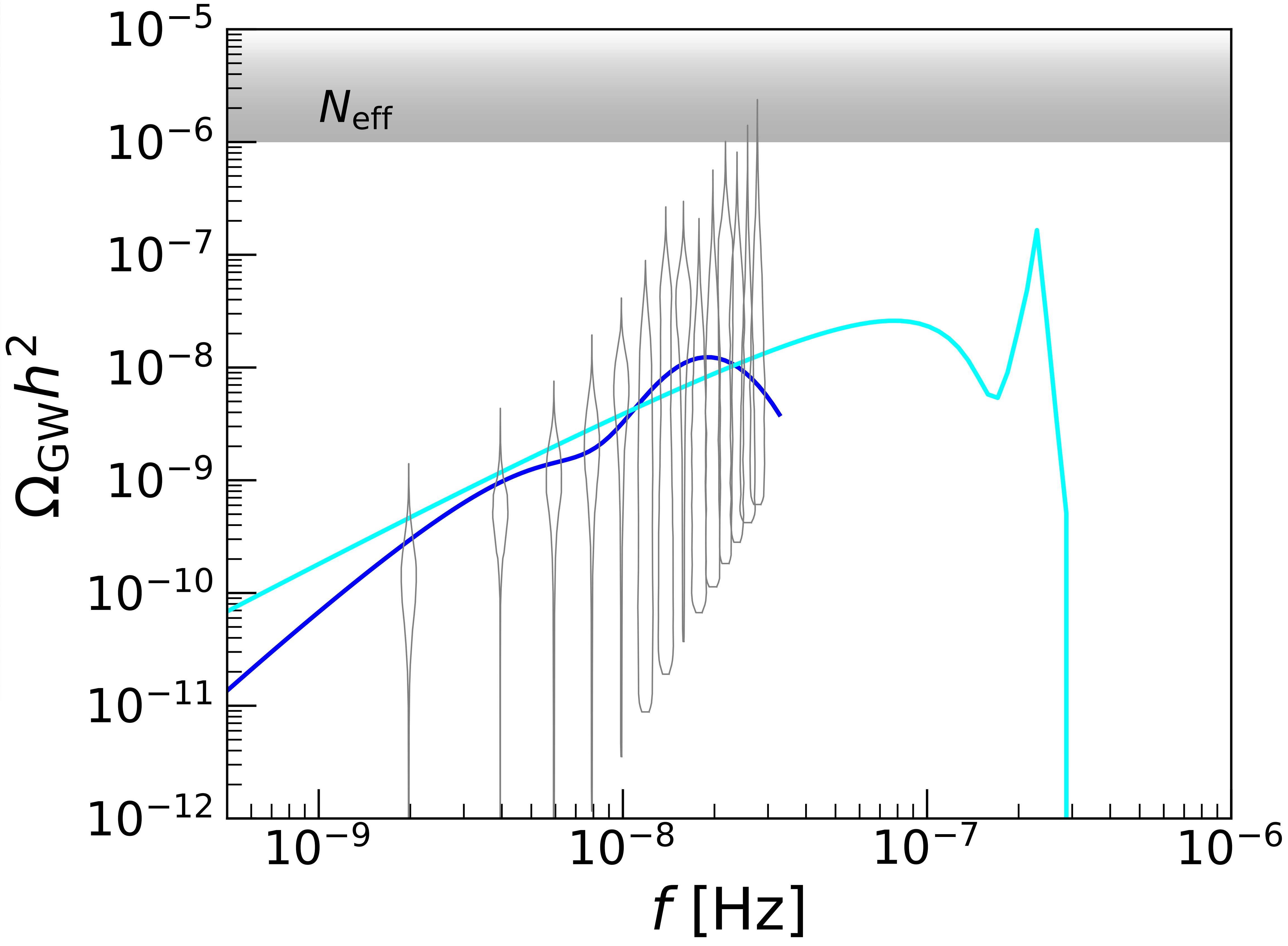




WIDER POWER SPECTRUM

$f_p \lesssim 10^{-7}\mathrm{Hz}$





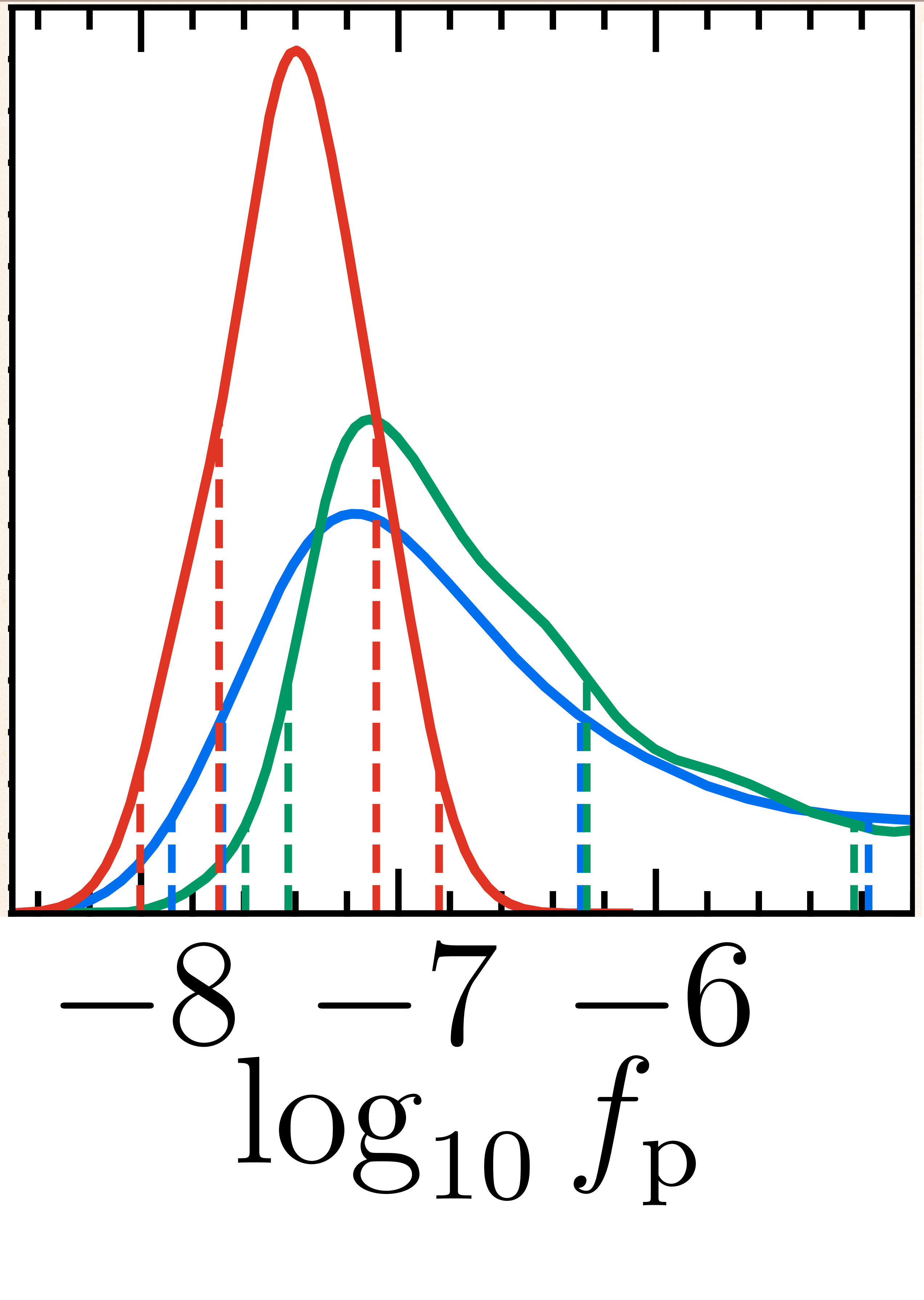
$\Delta \approx 0.49, \quad f_p \approx 1.6 \times 10^{-8}\mathrm{Hz}$

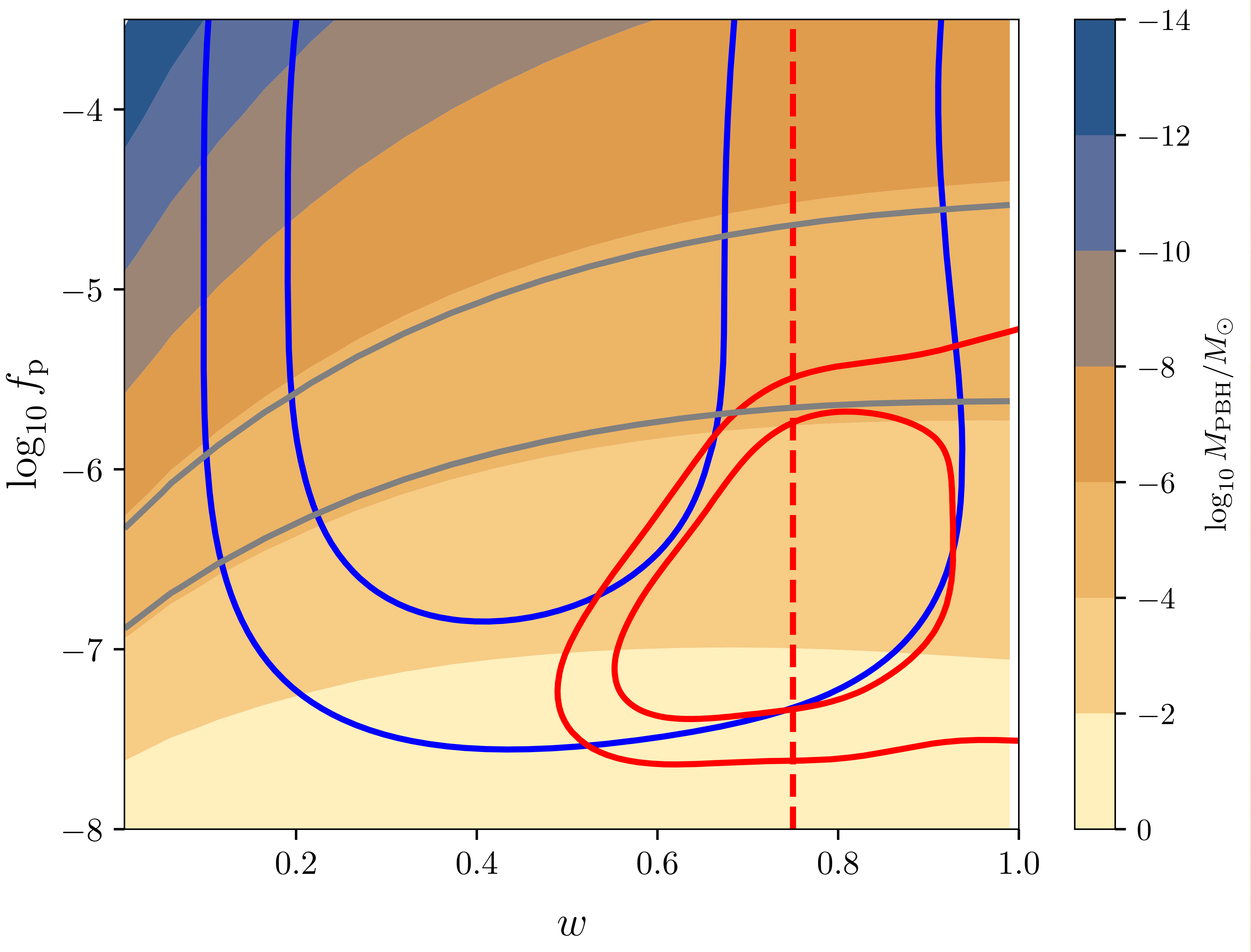
WIDER POWER SPECTRUM

$f_p \lesssim 10^{-7}\mathrm{Hz}$

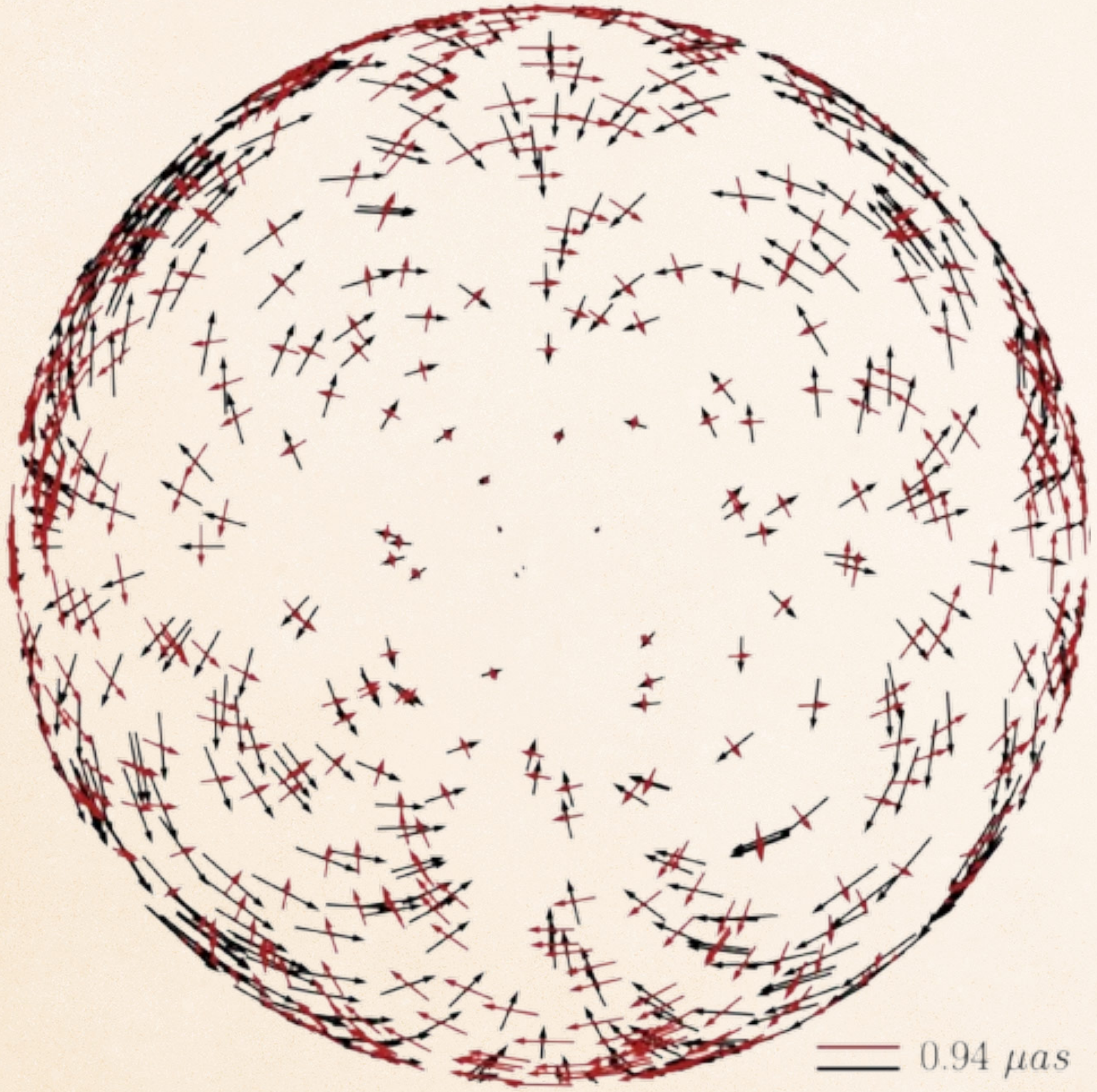
↓

$M \gtrsim 10^{-4} M_\odot$

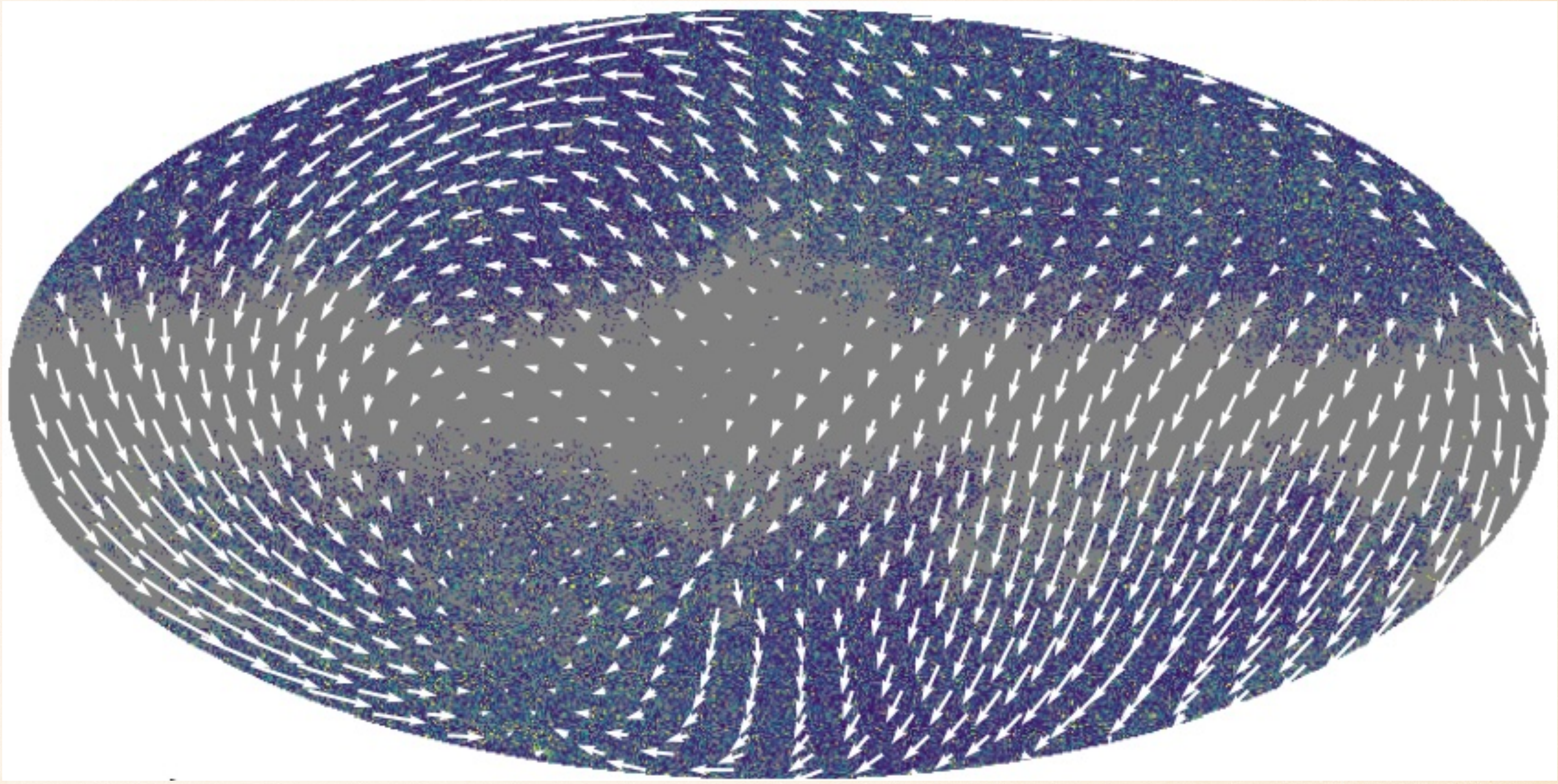




ASTROMETRY



Y. Wang, K. Pardo, T-C Chang & O. Doré 2020

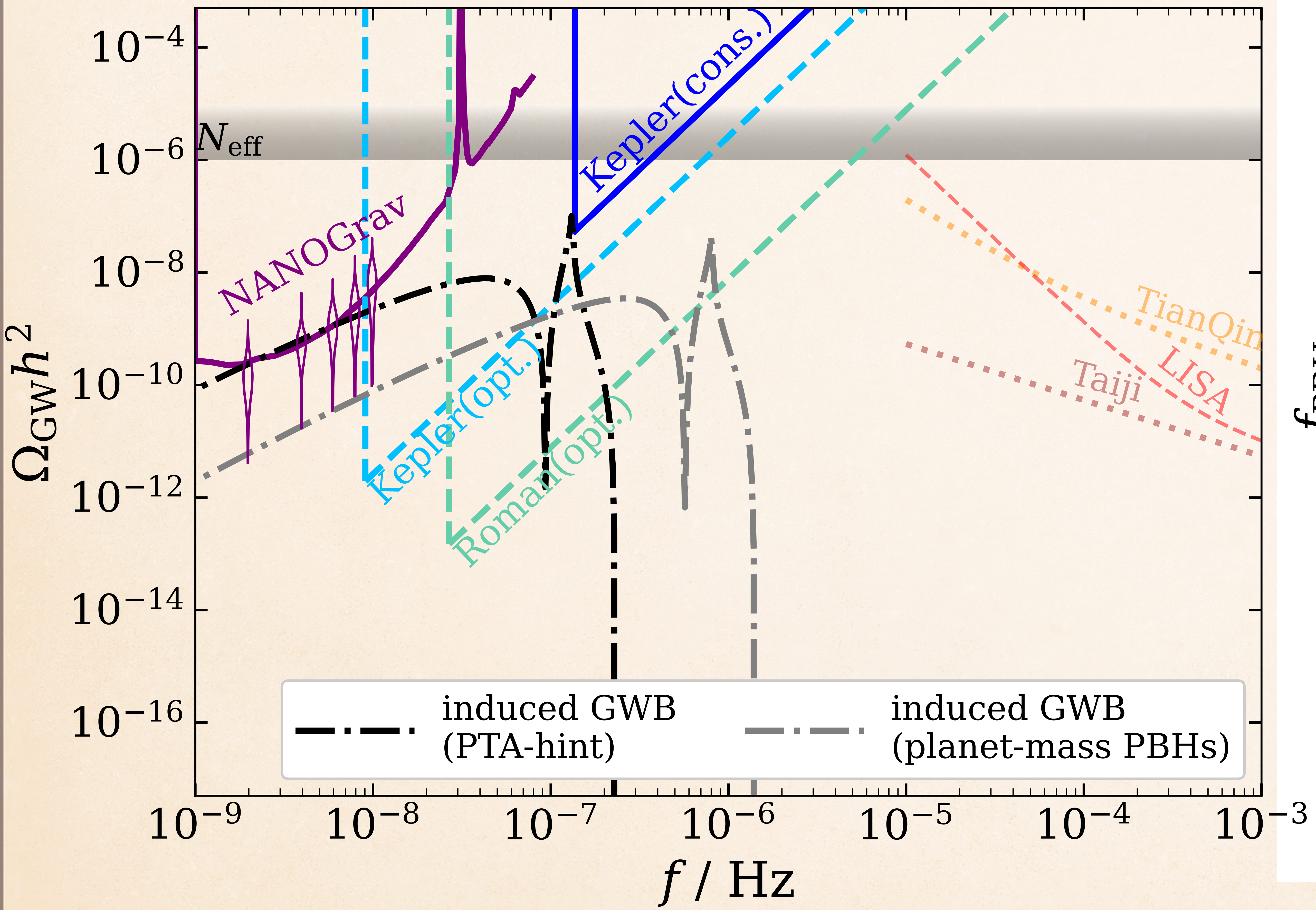


$$\int_{4/2\times10^{-18}}^{1.1\times10^{-8}} h^2\Omega_{\rm GW} d\ln f \lesssim 0.087$$

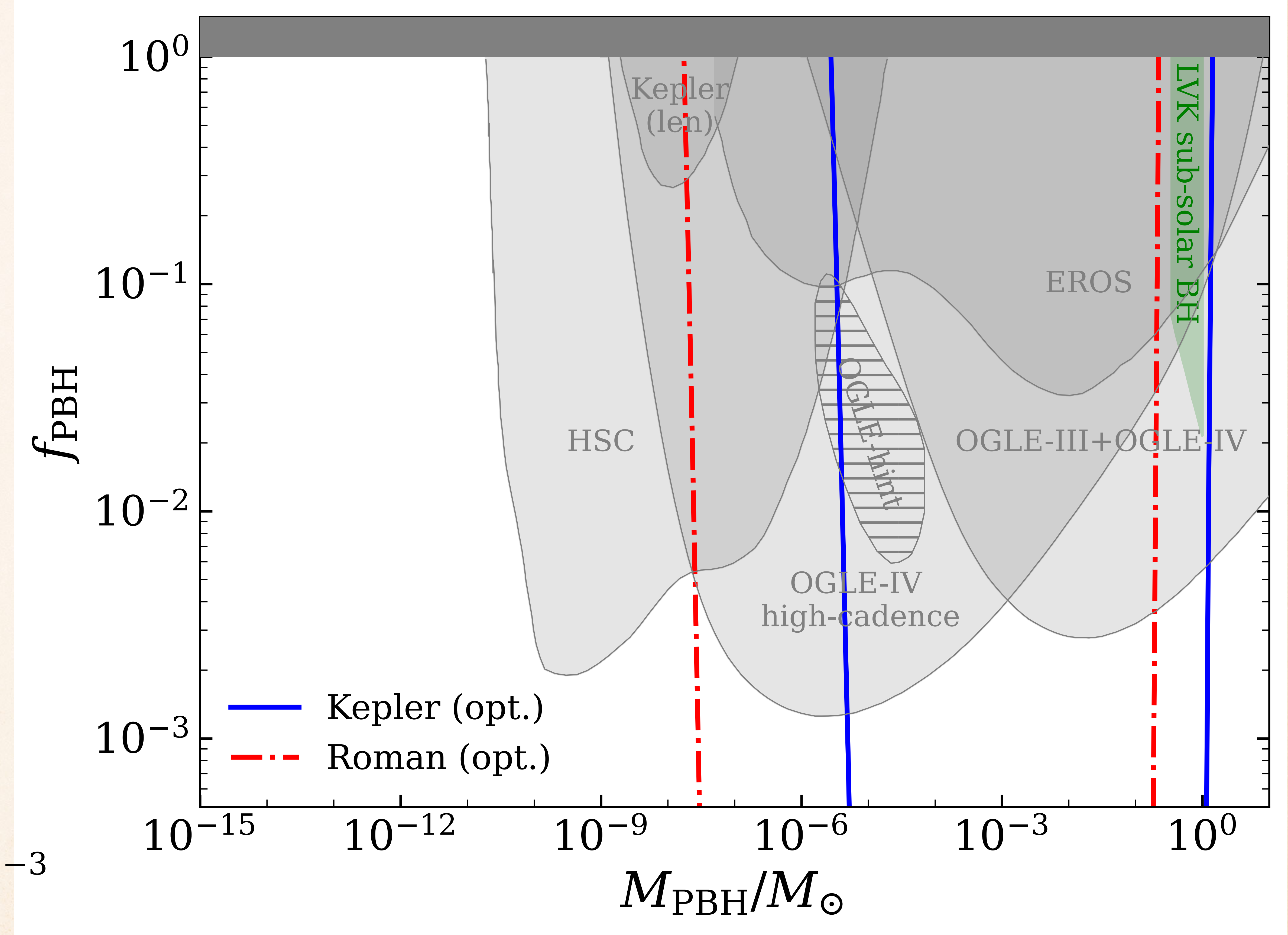
Gaia DR3

S. Jaraba et al. 2023

ASTROMETRY

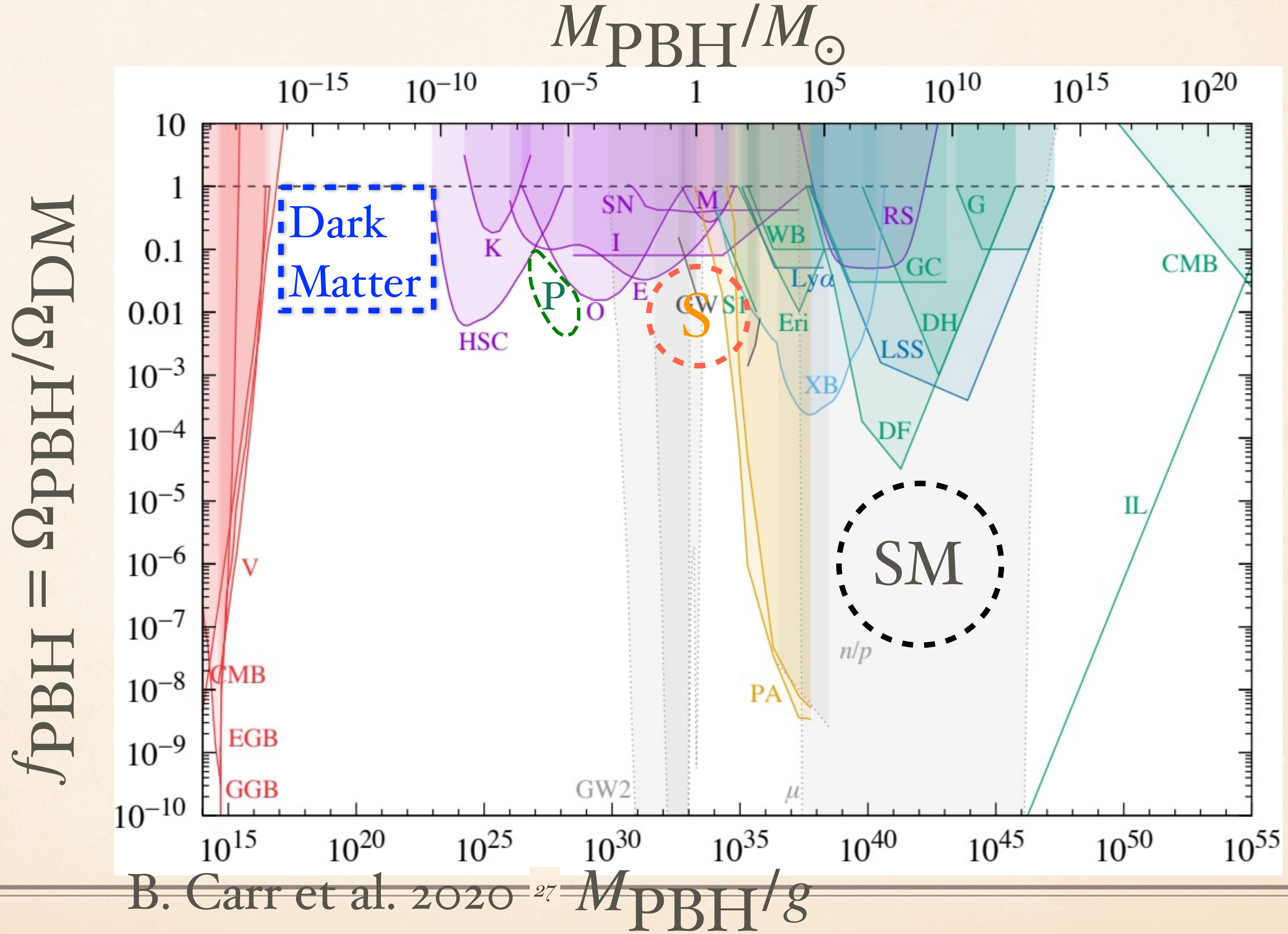


10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\Omega_{\rm GW}h^2$
$N_{\rm eff}$
NANOGrav
Kepler(cons.)
Kepler(opt.)
Roman(opt.)
TianQin
LISA
Taiji
induced GWB (PTA-hint)
induced GWB (planet-mass PBHs)
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
f / Hz



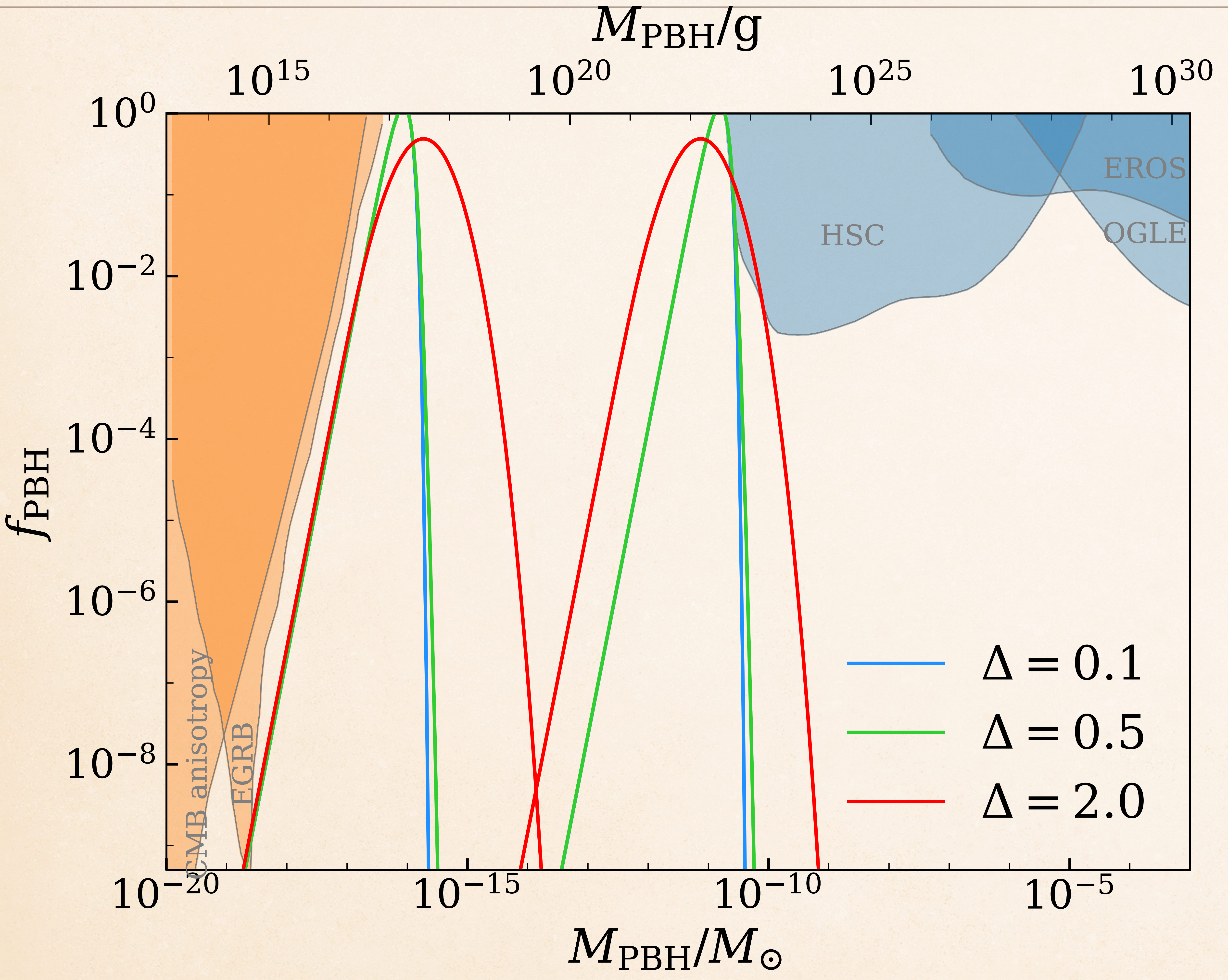
10^{0}
10^{-1}
10^{-2}
10^{-3}
$f_{\rm PBH}$
Kepler (len)
LVK sub-solar BH
EROS
HSC
OGLE-hint
OGLE-III+OGLE-IV
OGLE-IV high-cadence
Kepler (opt.)
Roman (opt.)
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
$M_{\rm PBH}/M_\odot$

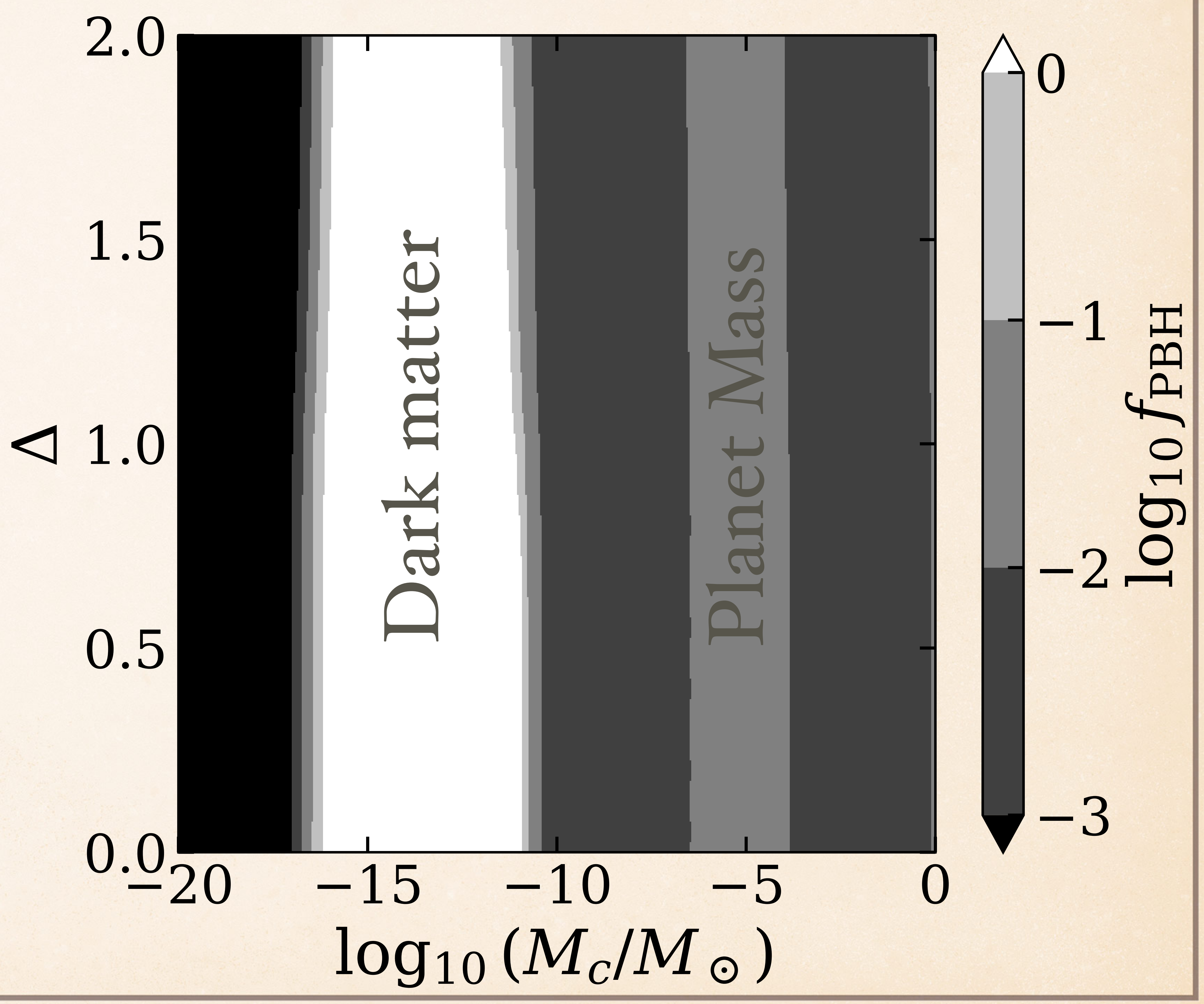
ASTEROID MASS WINDOW



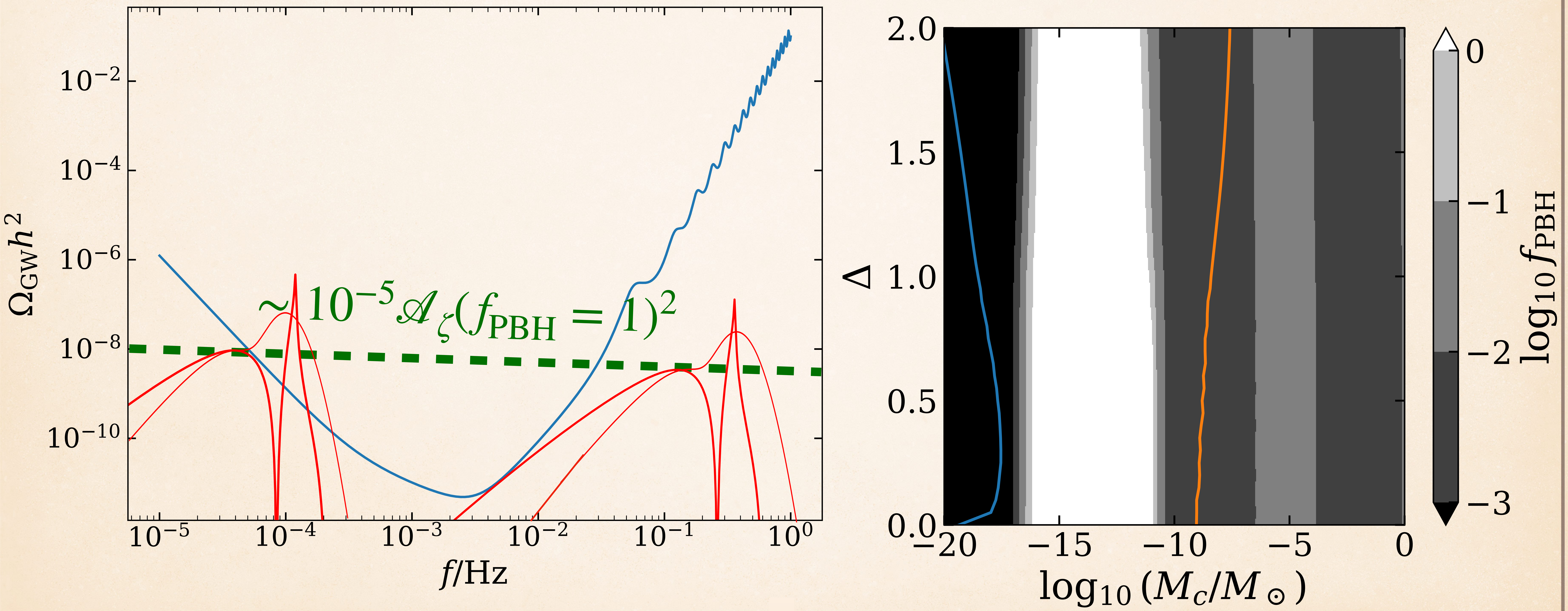
B. Carr et al. 2020

SPACE-BASED DETECTOR

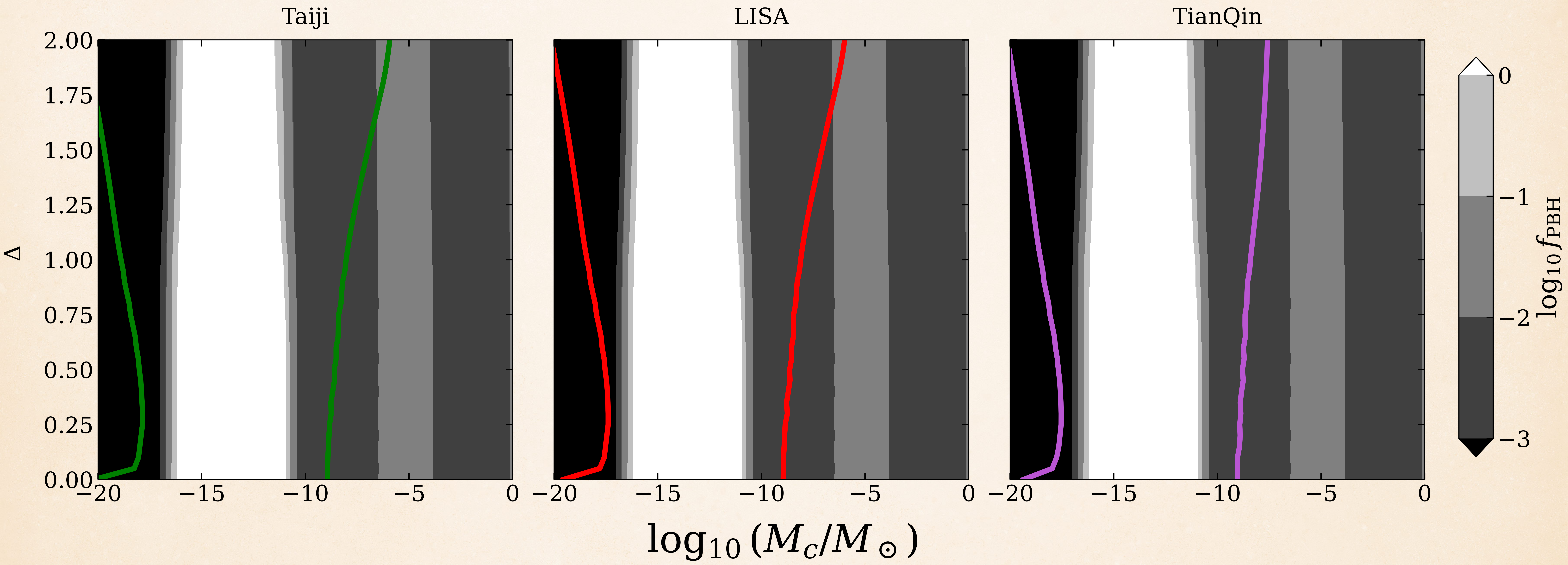




SPACE-BASED DETECTOR



SPACE-BASED DETECTOR



SUMMARY

- **PBHs** can naturally form in the early universe.
- They can serve as probes of inflation and the universe's thermal history.
- **Induced GWs** are a potential signature of PBHs.
- **PTA** and **astrometric observations** can detect planetary-mass or sub-solar-mass PBHs and constrain the thermal history.
- **Space-based GW detectors** can help confirm the PBH interpretation of DM.

THANK YOU FOR ATTENDING