NANOGrav 12.5-yr Result and the Planet-mass PBHs

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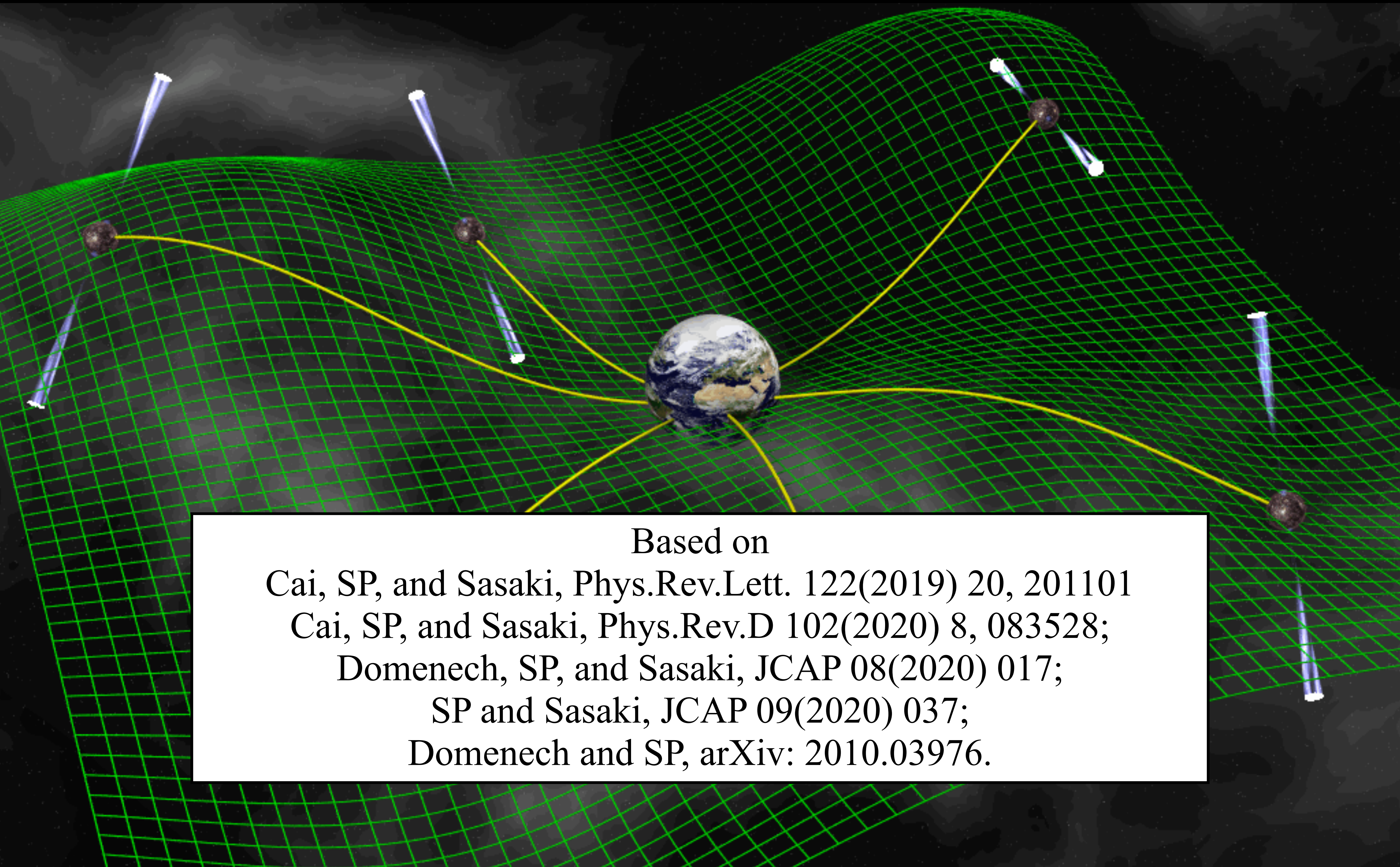
Gravitational Wave Primordial Cosmology, IAP, France
2021-5-19



Based on
Cai, SP, and Sasaki, Phys.Rev.Lett. 122(2019) 20, 201101
Cai, SP, and Sasaki, Phys.Rev.D 102(2020) 8, 083528;
Domenech, SP, and Sasaki, JCAP 08(2020) 017;
SP and Sasaki, JCAP 09(2020) 037;
Domenech and SP, arXiv: 2010.03976.

PTA discovered SGWB?

The NANOGrav 12.5-year Data Set: Search For An Isotropic Stochastic Gravitational-Wave Background

ABSTRACT

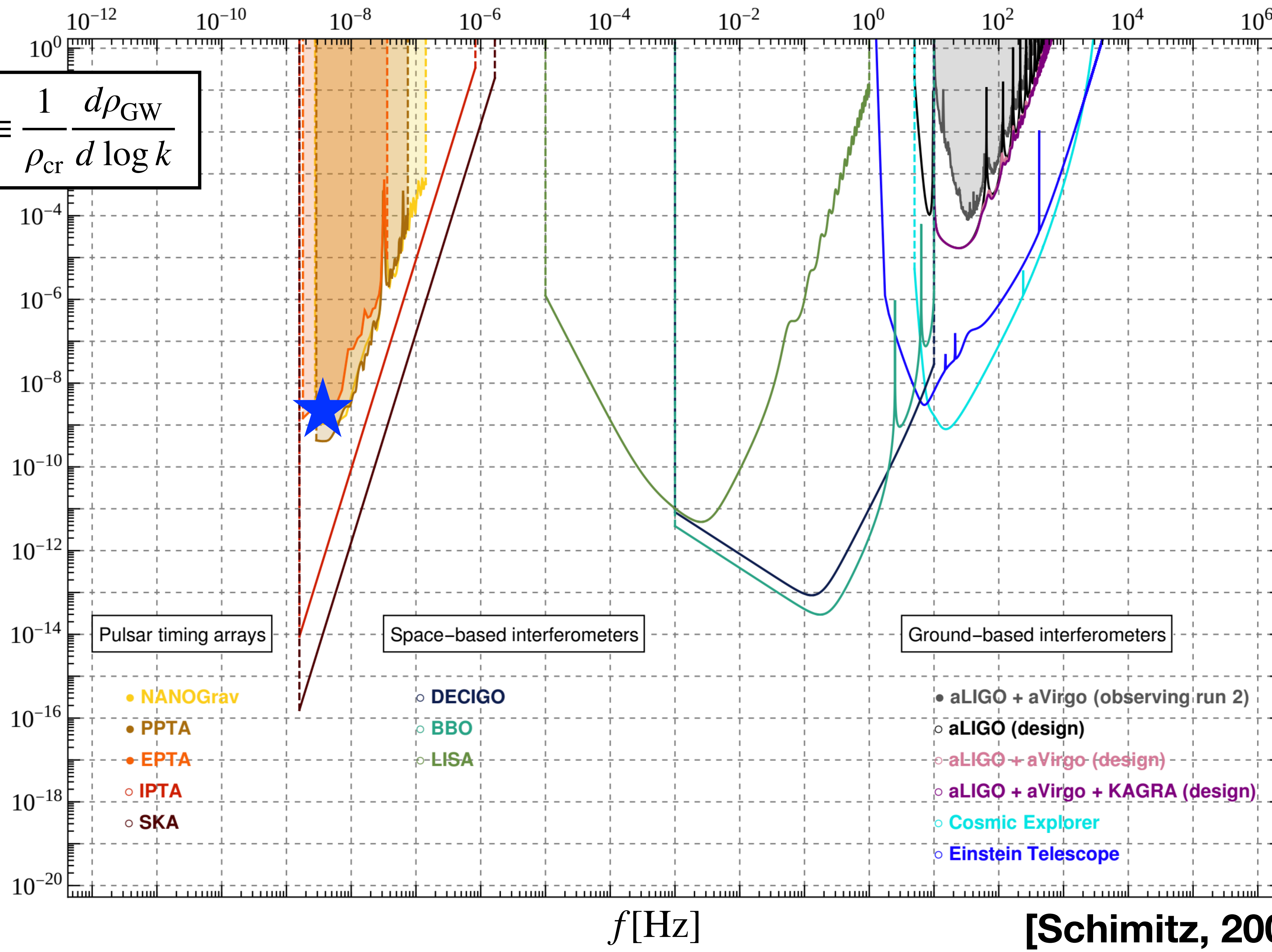
We search for an isotropic stochastic gravitational-wave background (GWB) in the 12.5-year pulsar timing data set collected by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav). Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars. The Bayesian posterior of the amplitude for a $f^{-2/3}$ power-law spectrum, expressed as characteristic GW strain, has median 1.92×10^{-15} and 5%–95% quantiles of $1.37\text{–}2.67 \times 10^{-15}$ at a reference frequency of $f_{\rm yr} = 1\ {\rm yr}^{-1}$. The Bayes factor in favor of the common-spectrum process versus independent red-noise processes in each pulsar exceeds $10,000$. However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with General Relativity. We find that the process has neither monopolar nor dipolar correlations, which may arise from, for example, reference clock or solar-system ephemeris systematics, respectively. The amplitude posterior has significant support above previously reported upper limits; we explain this in terms of the Bayesian priors assumed for intrinsic pulsar red noise. We examine potential implications for the supermassive black hole binary population under the hypothesis that the signal is indeed astrophysical in nature.

[NANOGrav, 2009.04496]

$$\Omega_{\rm GW}(f_{\rm yr}) = 2.33 \times 10^{-9}, \quad f_{\rm yr} = 3.17 \times 10^{-8} {\rm Hz}$$

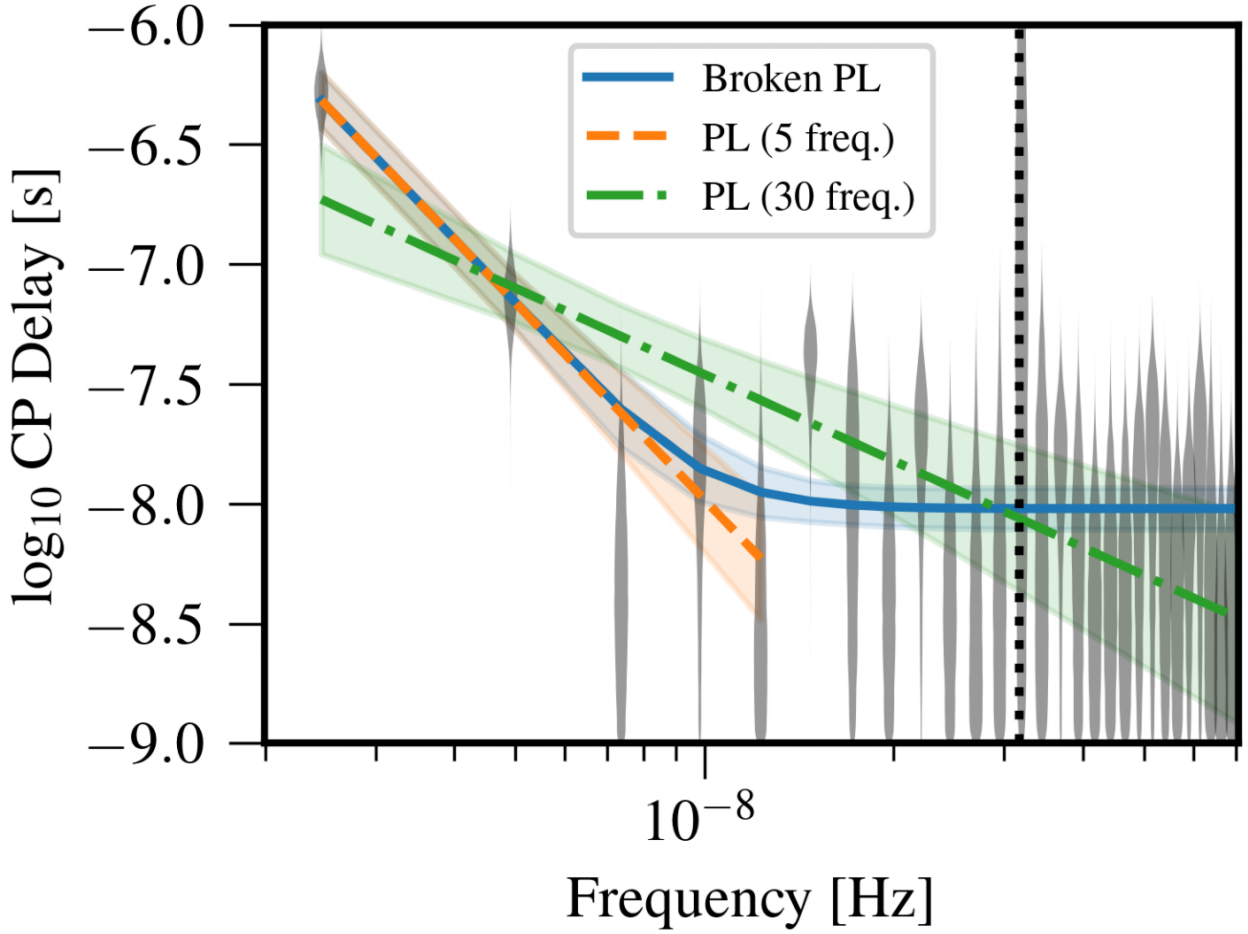
PTA discovered SGWB?

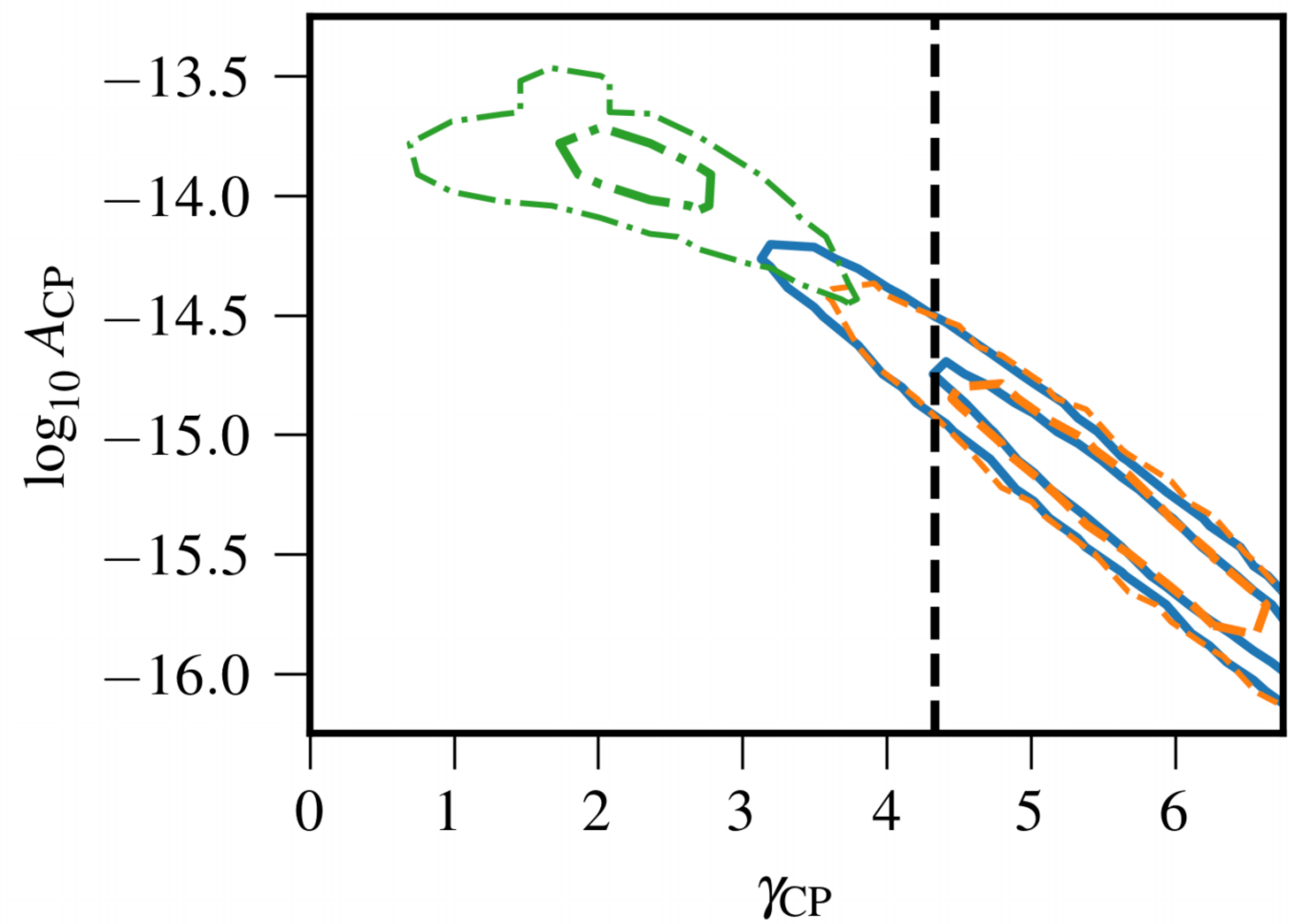
$$\Omega_{\rm GW} \equiv \frac{1}{\rho_{\rm cr}} \frac{d\rho_{\rm GW}}{d \log k}$$



[Schimitz, 2002.04615]

PTA discovered SGWB?





$$\Omega_{\rm GW} = \frac{2\pi^2 f_{\rm yr}^2}{3H_0^2} A_{\rm SGWB}^2 \left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma}$$

$$f_{\rm yr} = 3.17 \times 10^{-8}\ {\rm Hz}\,.$$

[NANOGrav, 2009.04496]

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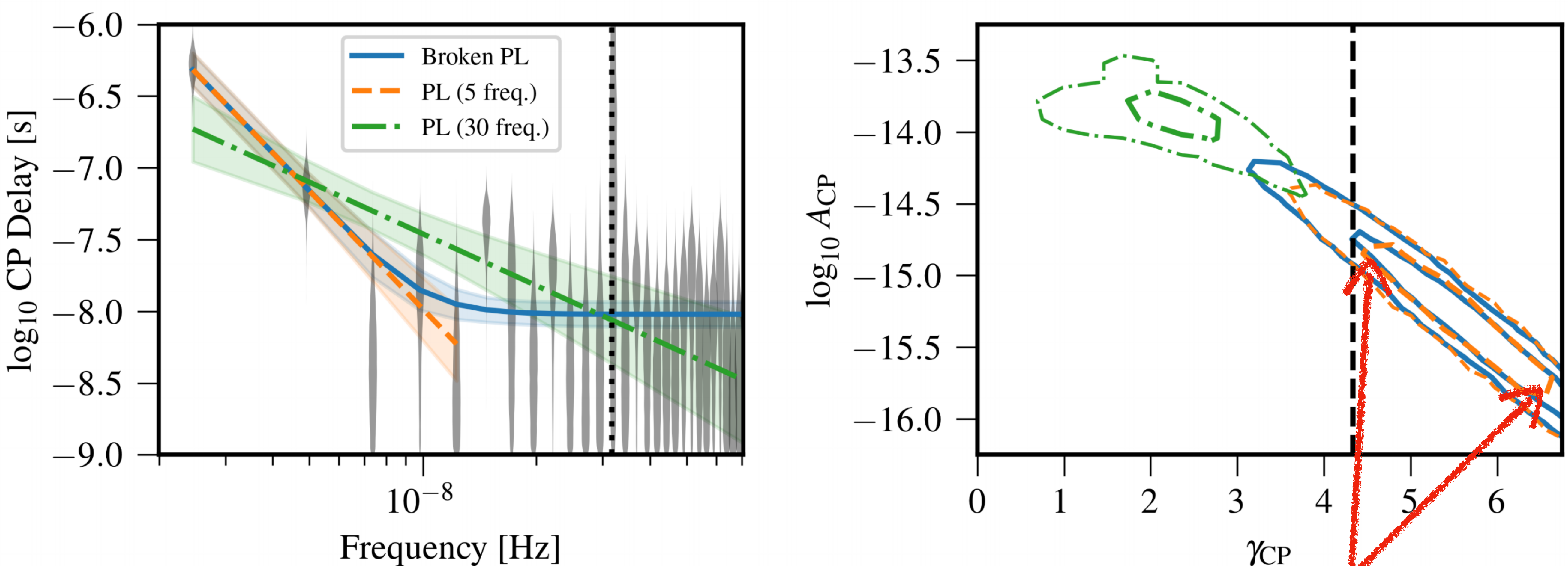

$\Omega_{\rm GW} \propto f^{-3/2\sim 1/2}$

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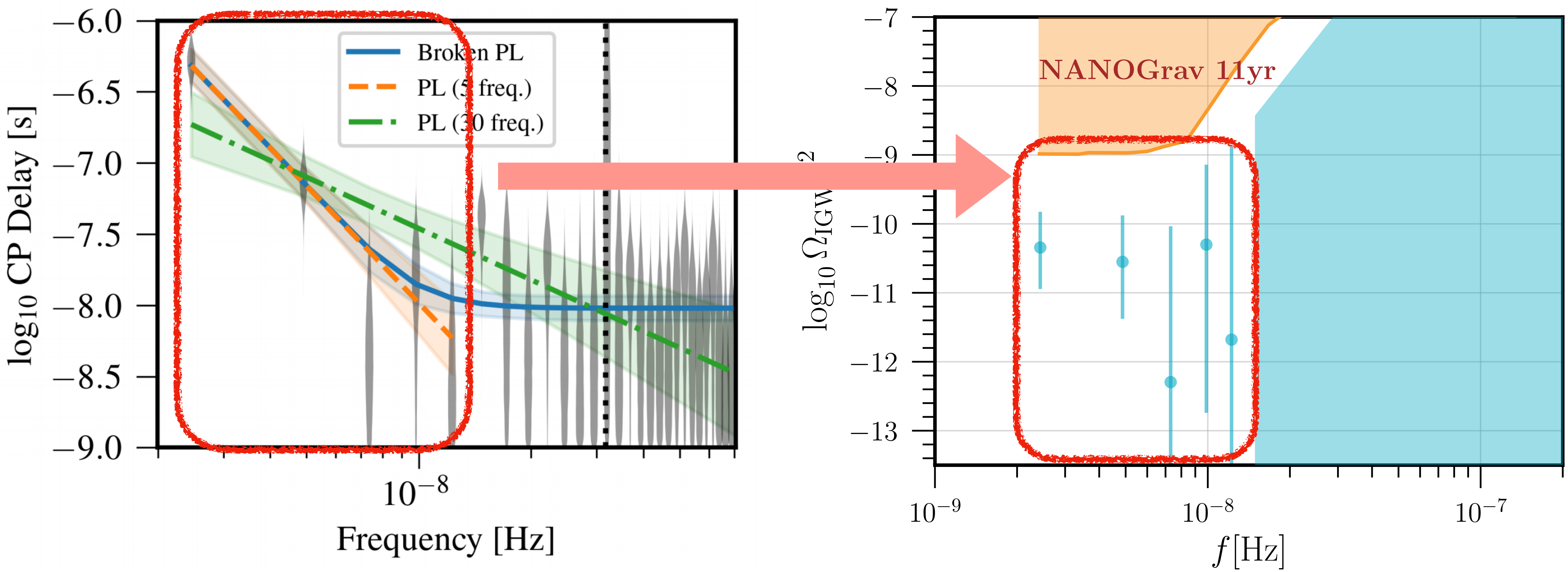

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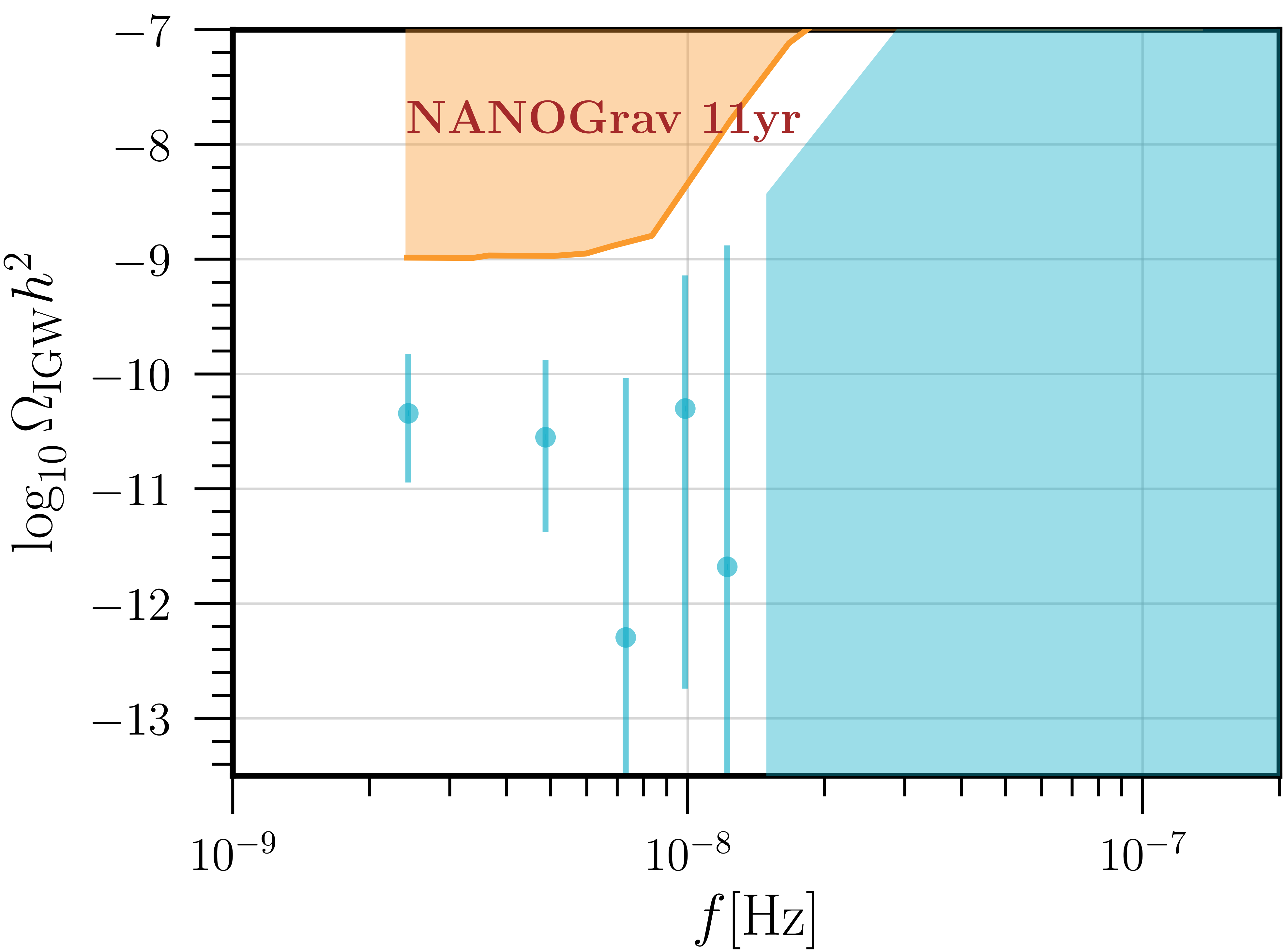

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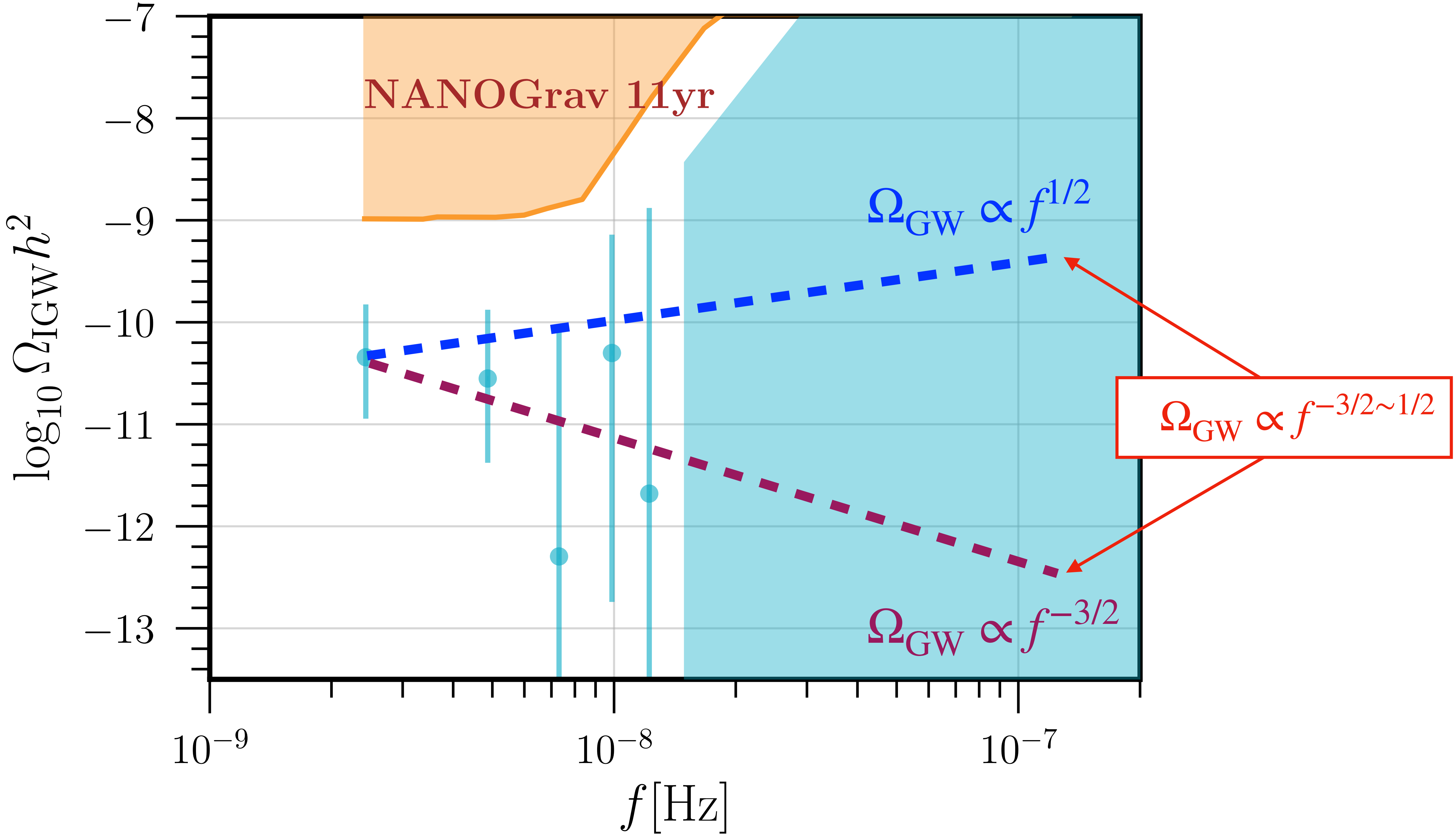

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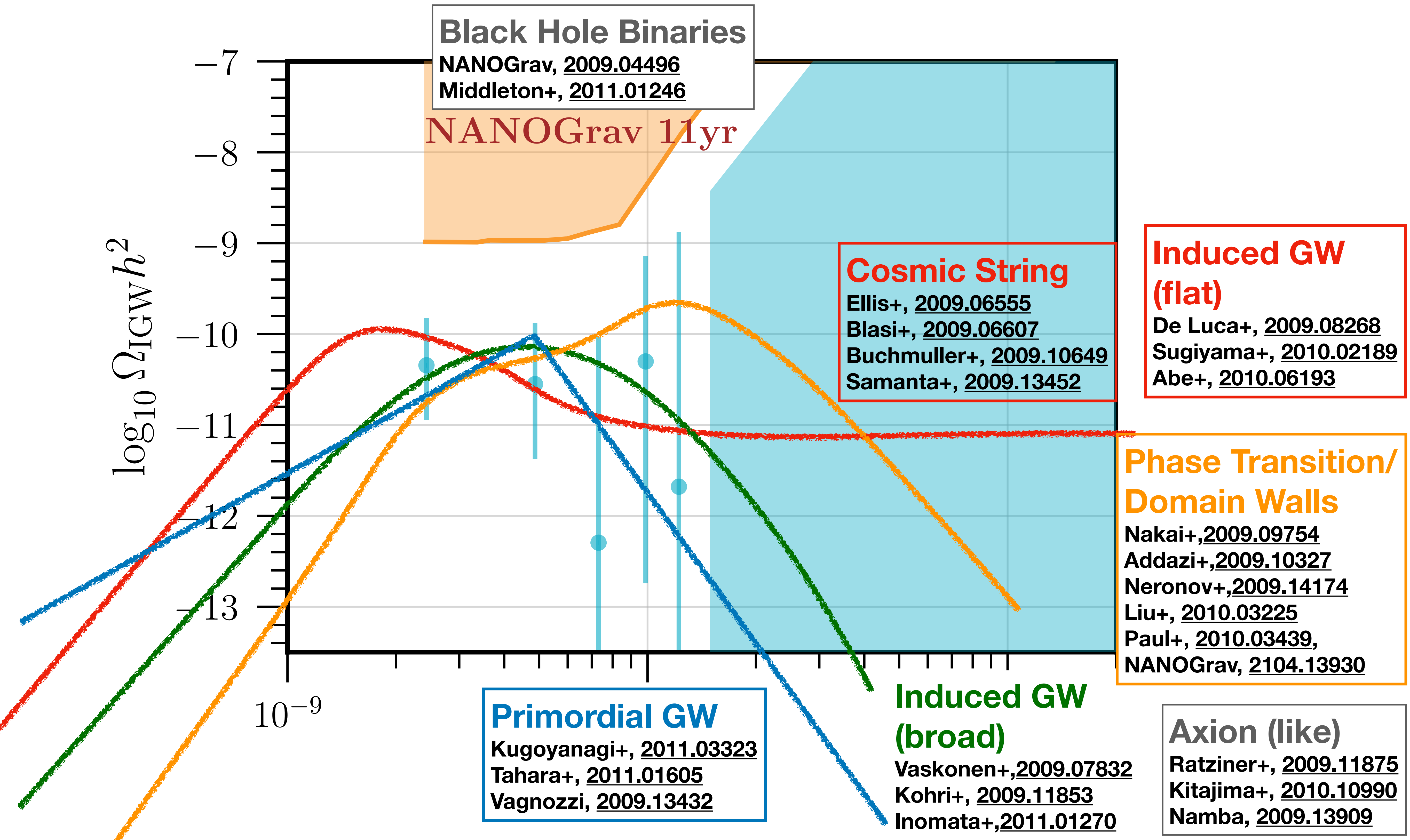
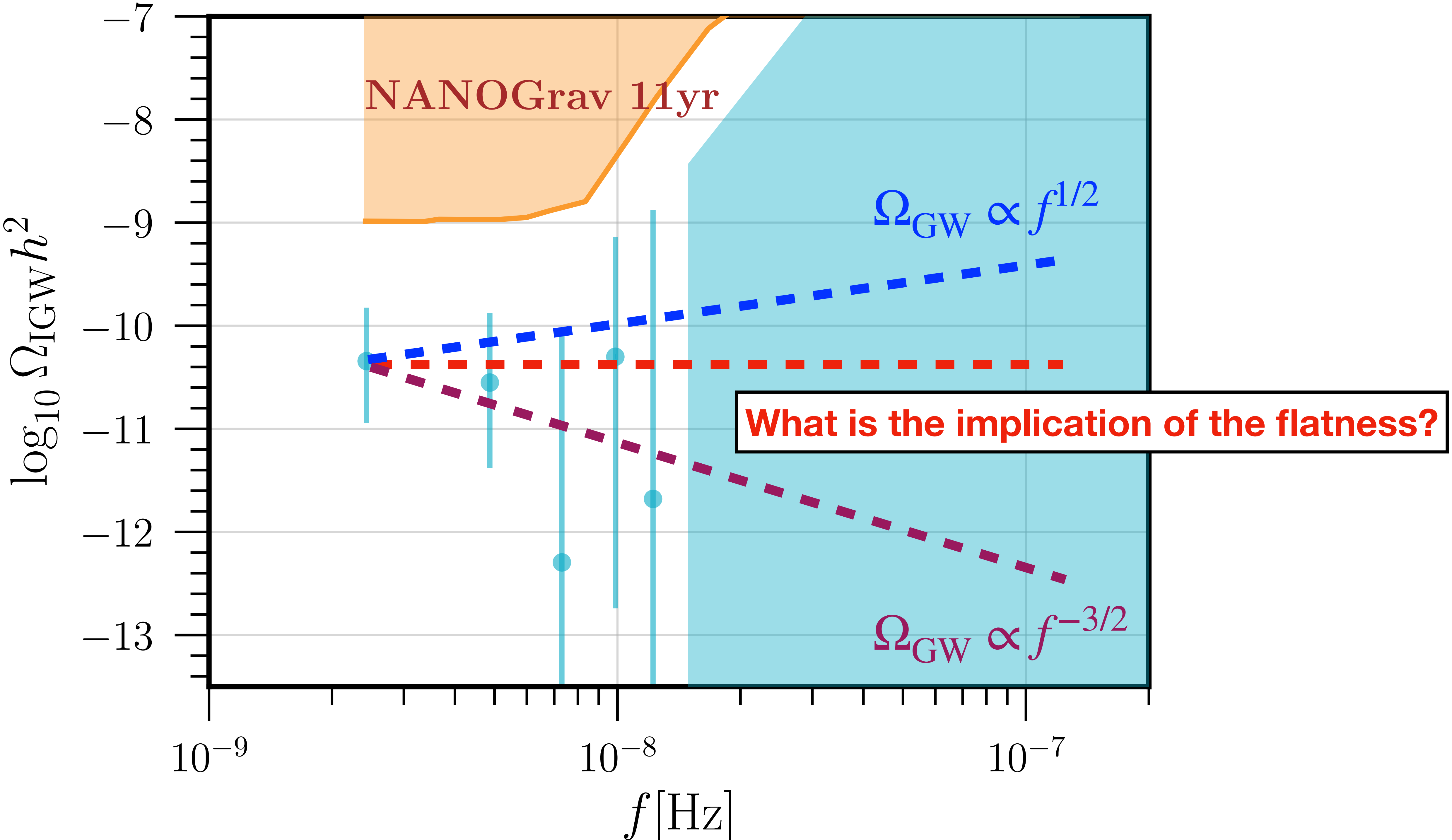


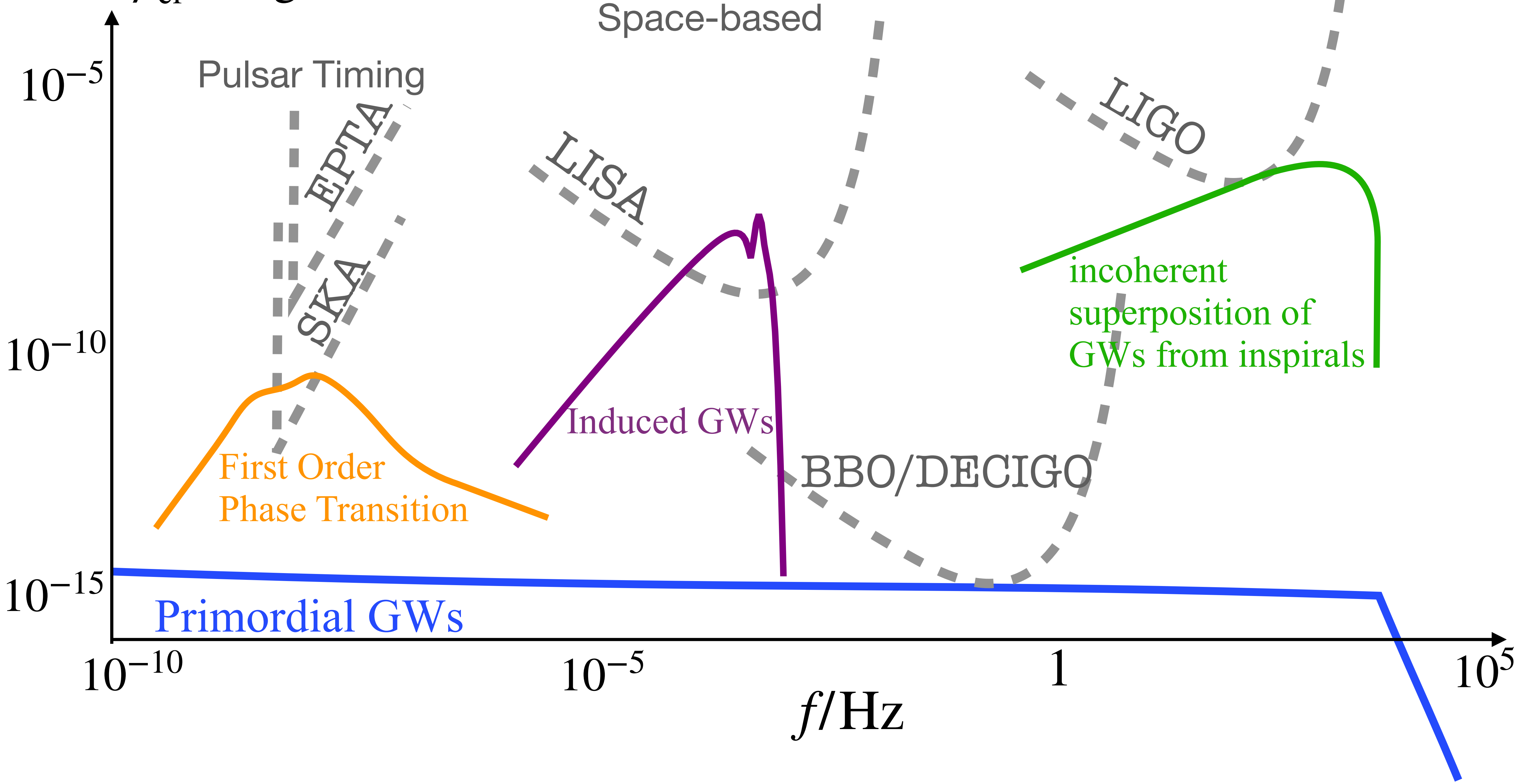
Spectral Shape of SGWB



[Domènech and SP, 2010.03976]

Spectral Shape of SGWB

$$\Omega_{\rm GW} \equiv \frac{1}{\rho_{\rm cr}} \frac{d\rho_{\rm GW}}{d \log k}$$



Spectral Shape of SGWB

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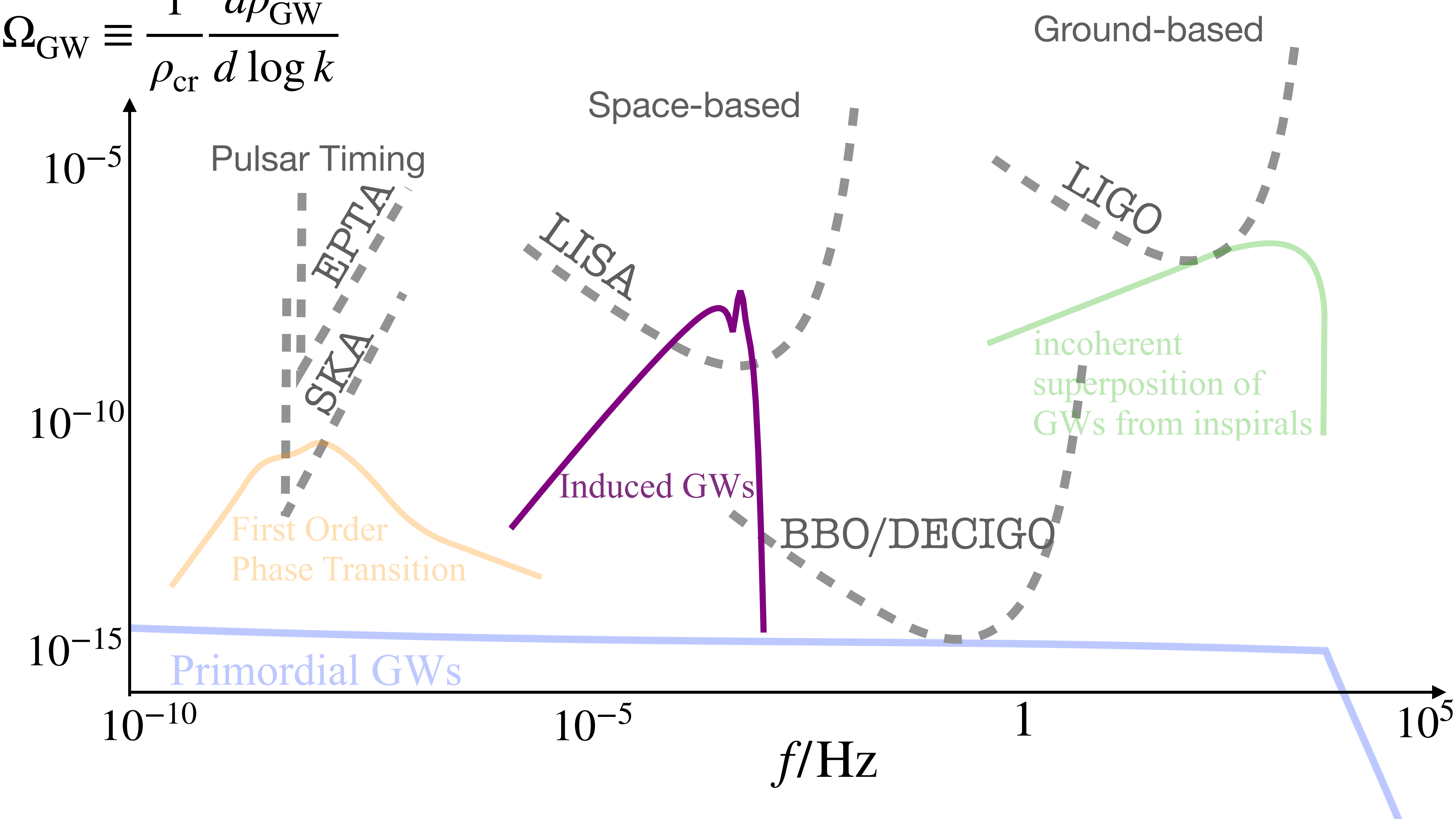
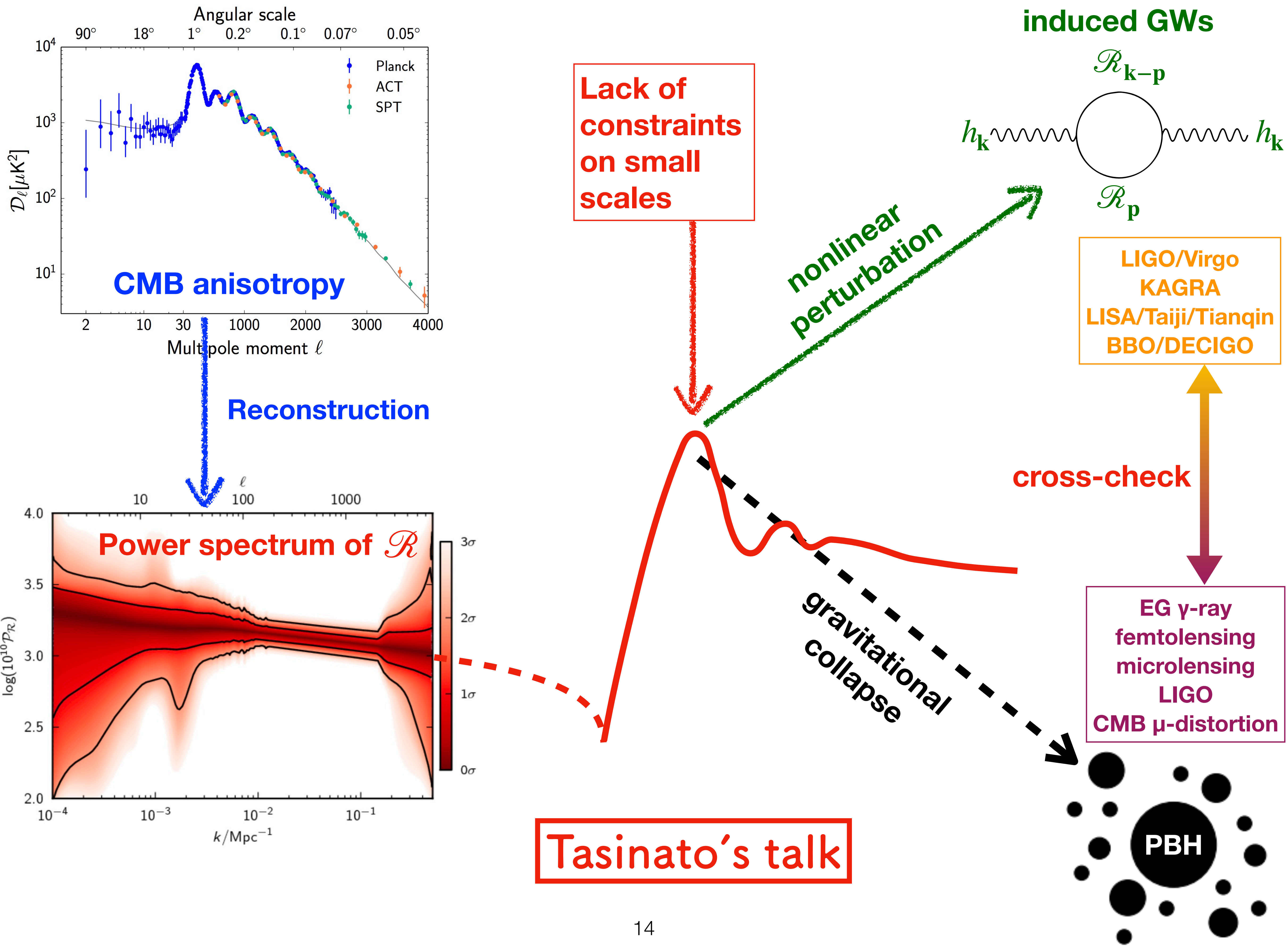
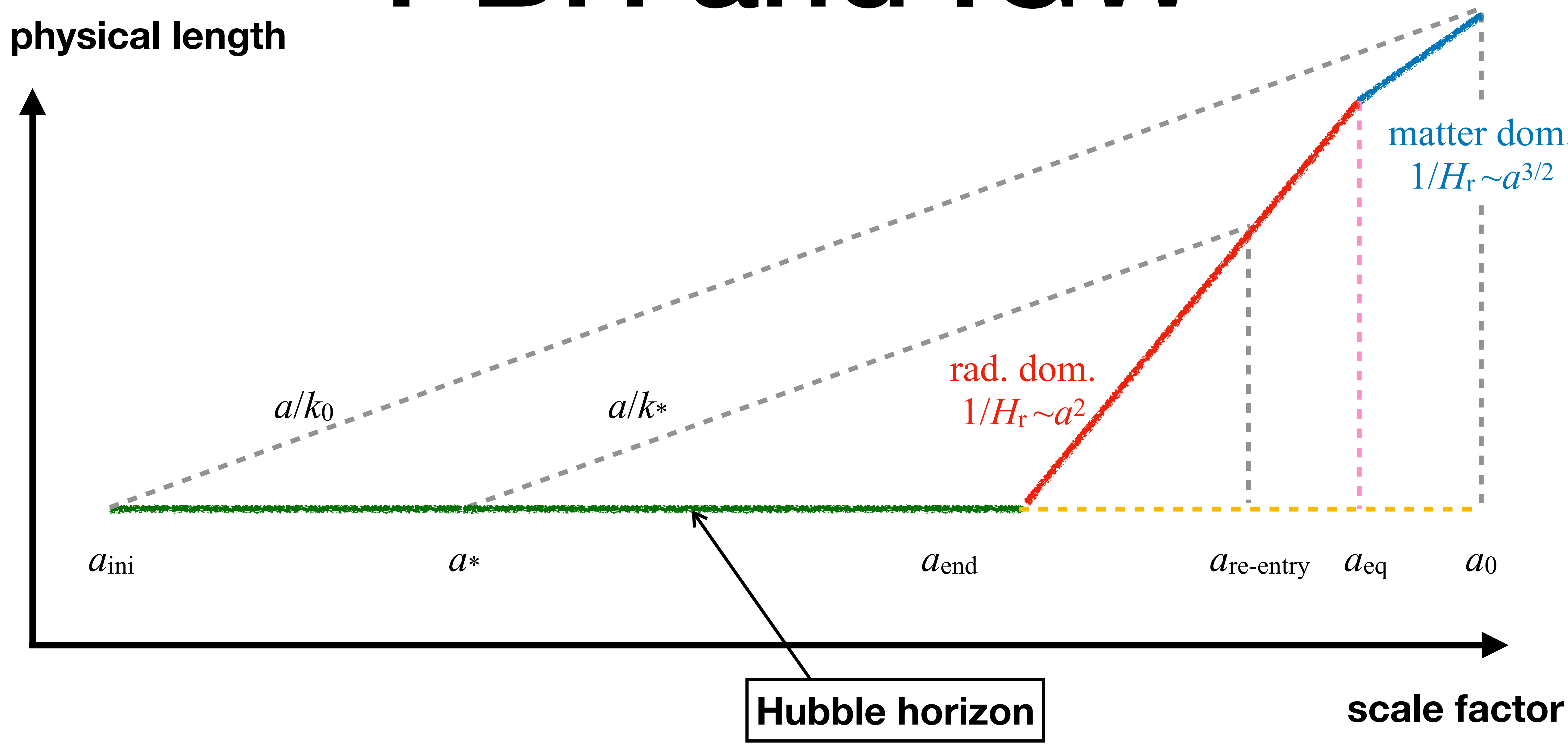


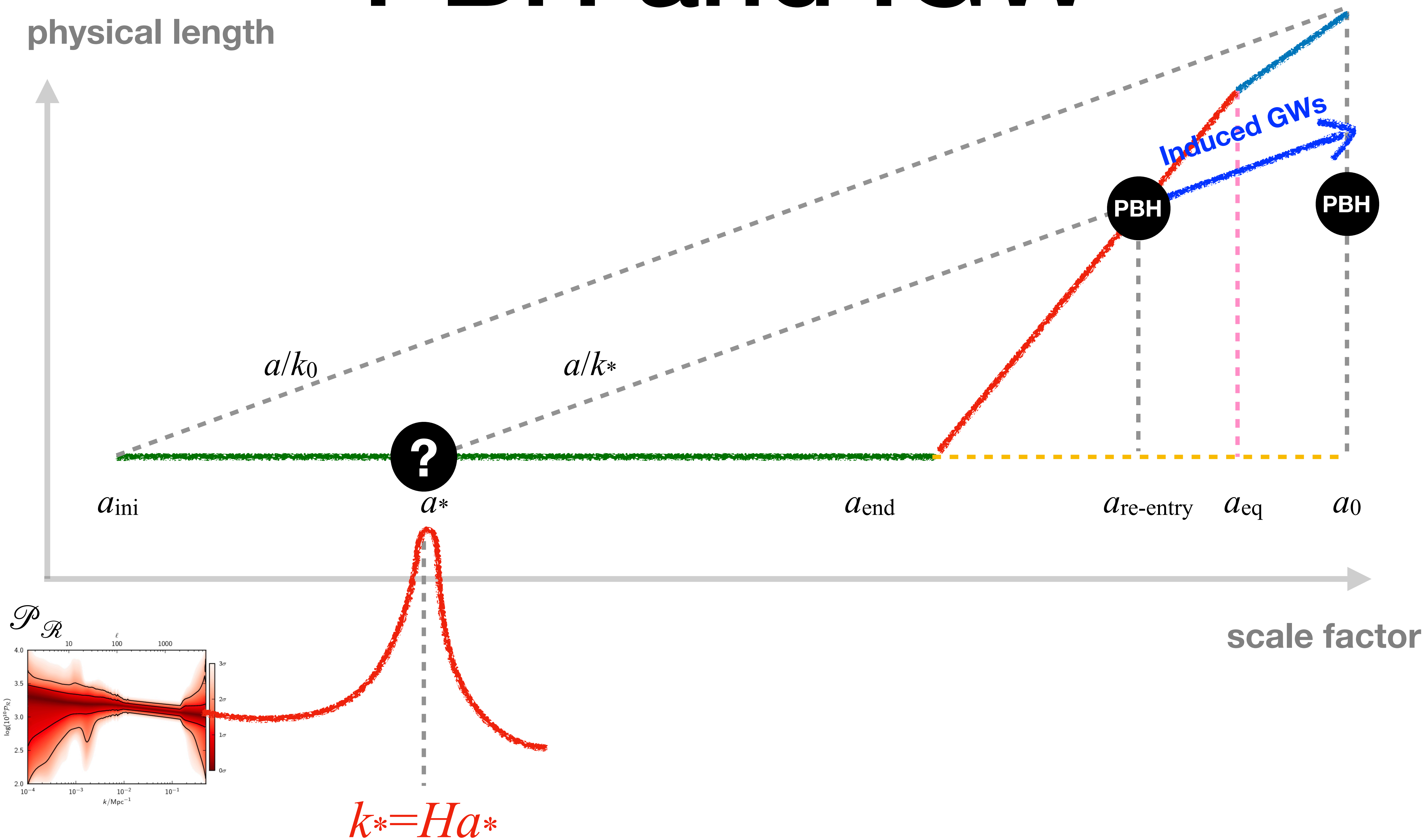


Angular scale
90° 18° 1° 0.2° 0.1° 0.07° 0.05°
Planck
ACT
SPT
$\mathcal{D}_\ell [\mu K^2]$
CMB anisotropy
Multipole moment ℓ
Reconstruction
Power spectrum of $\mathscr{R}$
$\log(10^{10}\mathcal{P}_{\mathcal{R}})$
k/Mpc^{-1}
3σ 2σ 1σ 0σ
Lack of constraints on small scales
nonlinear perturbation
gravitational collapse
induced GWs
$\mathscr{R}_{\mathbf{k}-\mathbf{p}}$
$h_{\mathbf{k}}$
$h_{\mathbf{k}}$
$\mathscr{R}_{\mathbf{p}}$
LIGO/Virgo
KAGRA
LISA/Taiji/Tianqin
BBO/DECIGO
cross-check
EG γ-ray
femtolensing
microlensing
LIGO
CMB μ-distortion
PBH
Tasinato's talk

PBH and IGW


physical length
matter dom.
$1/H_r \sim a^{3/2}$
rad. dom.
$1/H_r \sim a^2$
a/k_0
a/k_*
a_{ini}
a_*
a_{end}
$a_{re\text{-}entry}$
a_{eq}
a_0
Hubble horizon
scale factor

PBH and IGW



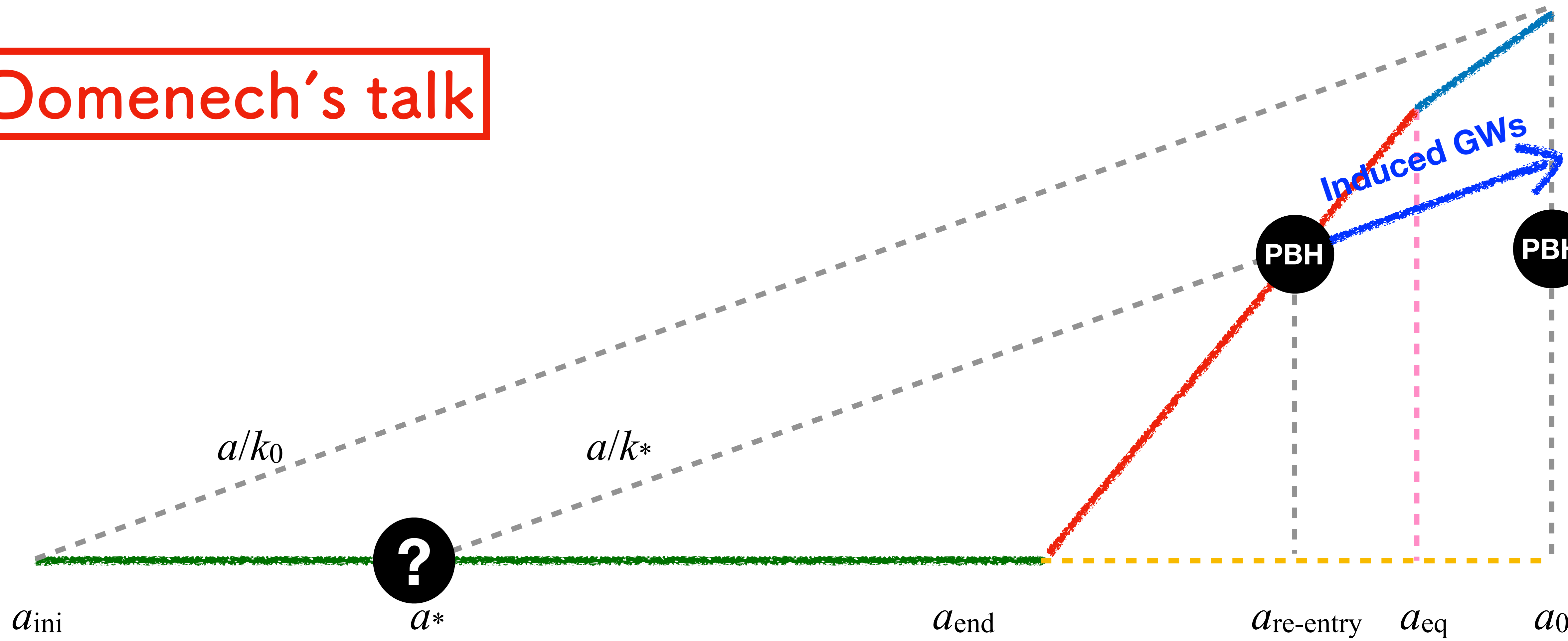
physical length
a/k_0
a/k_*
Induced GWs
PBH
PBH
?
$a_{\rm ini}$
a_*
$a_{\rm end}$
$a_{\rm re\text{-}entry}$
$a_{\rm eq}$
a_0
scale factor
$\mathscr{P}_{\mathscr{R}}$
$k_*=Ha_*$

$$h_{\mathbf{k}} \sim \int d\eta \times (\text{Green function}) \int d^3p \times (\text{Transfer function}) \times \Phi_{\mathbf{p}}\Phi_{\mathbf{k-p}}\,.$$

$$\Omega_{\rm GW} \sim \Omega_r \langle hh \rangle \sim \Omega_r \langle \Phi\Phi\Phi\Phi \rangle \sim \Omega_r \mathscr{P}_\Phi^2 \sim 10^{-6} \mathscr{P}_{\mathscr{R}}^2$$

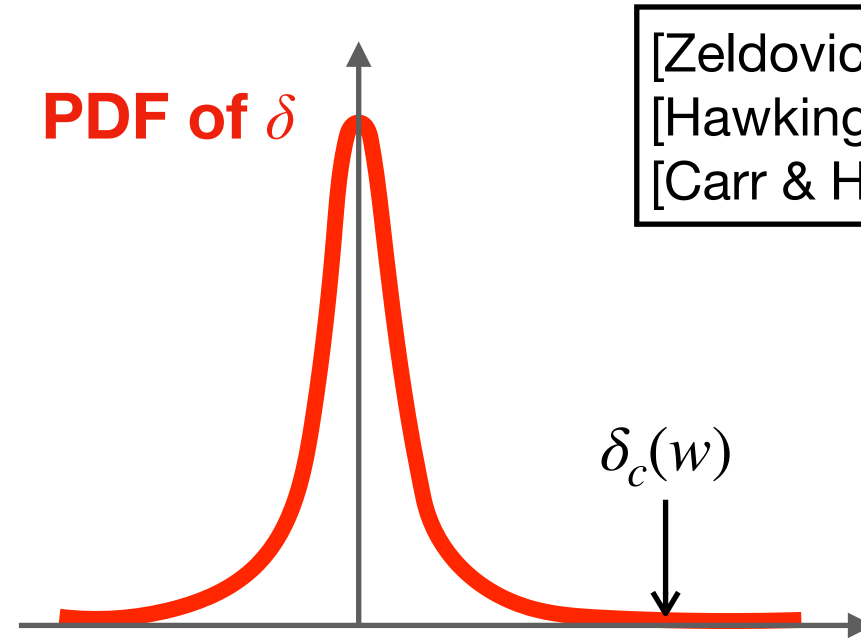
[Matarrese+, 1997]
[Ananda+, 2007]
[Baumann+, 2007]

Domenech's talk



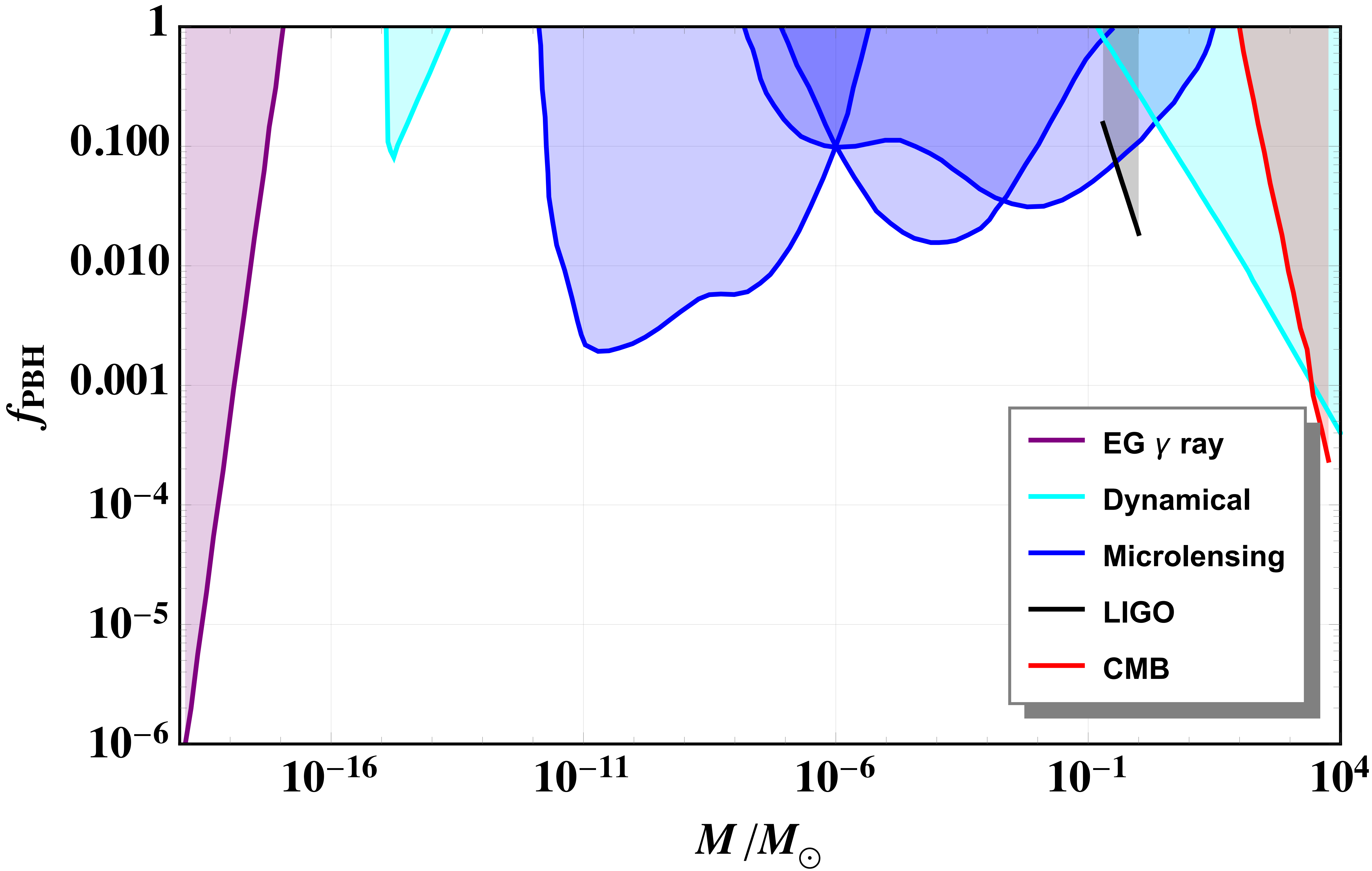
$$\beta \sim \text{erfc}\left(\frac{\mathscr{R}_c}{2\sqrt{\mathscr{P}_{\mathscr{R}}}}\right)$$

$$f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}} = 4.11 \times 10^8 \beta(M) \left(\frac{M}{M_\odot}\right)^{-1/2}$$

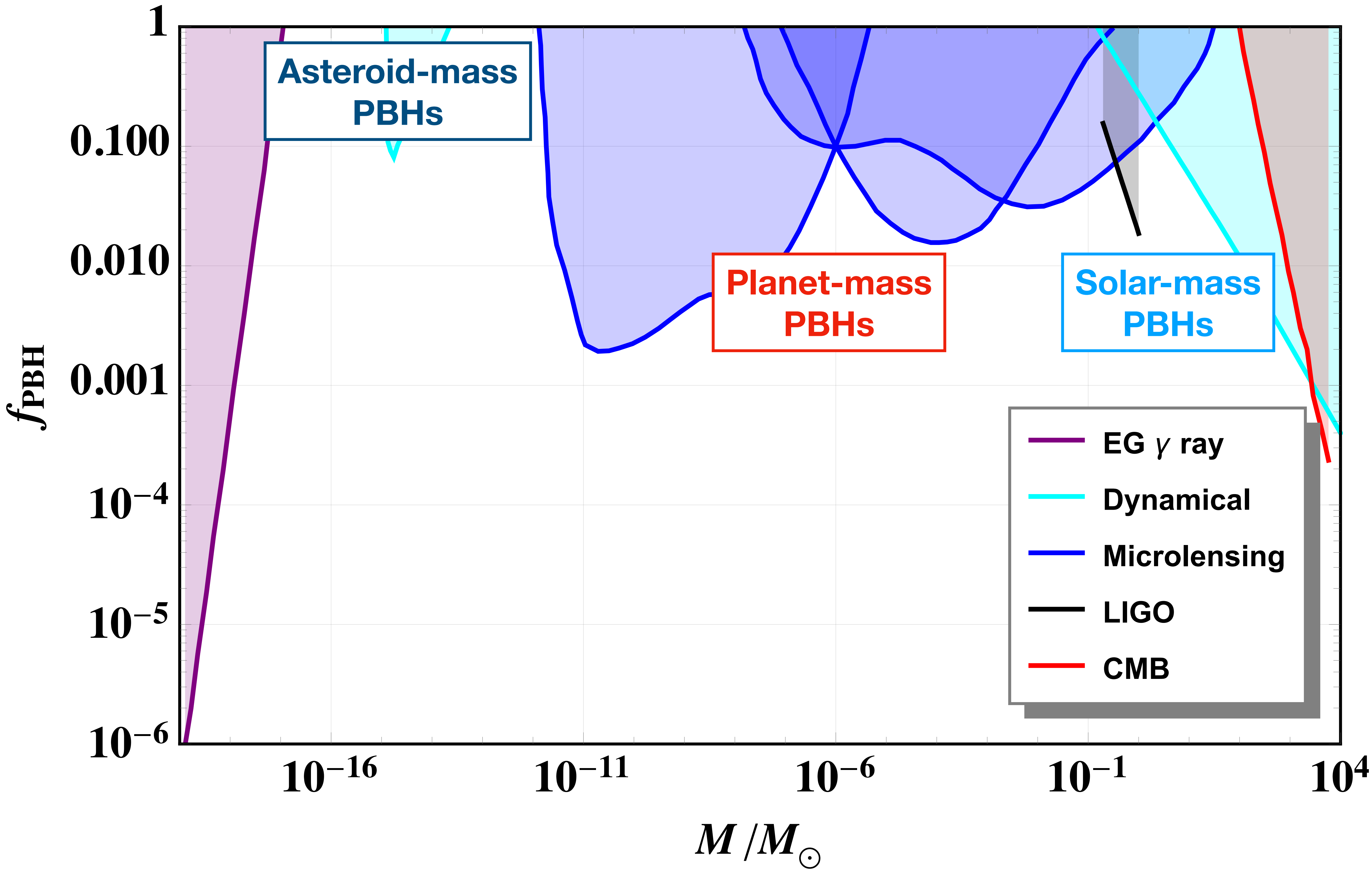


[Zeldovich & Novikov 1966]
[Hawking 1971]
[Carr & Hawking 1974]

Constraints on f_{PBH}



Constraints on f_{PBH}



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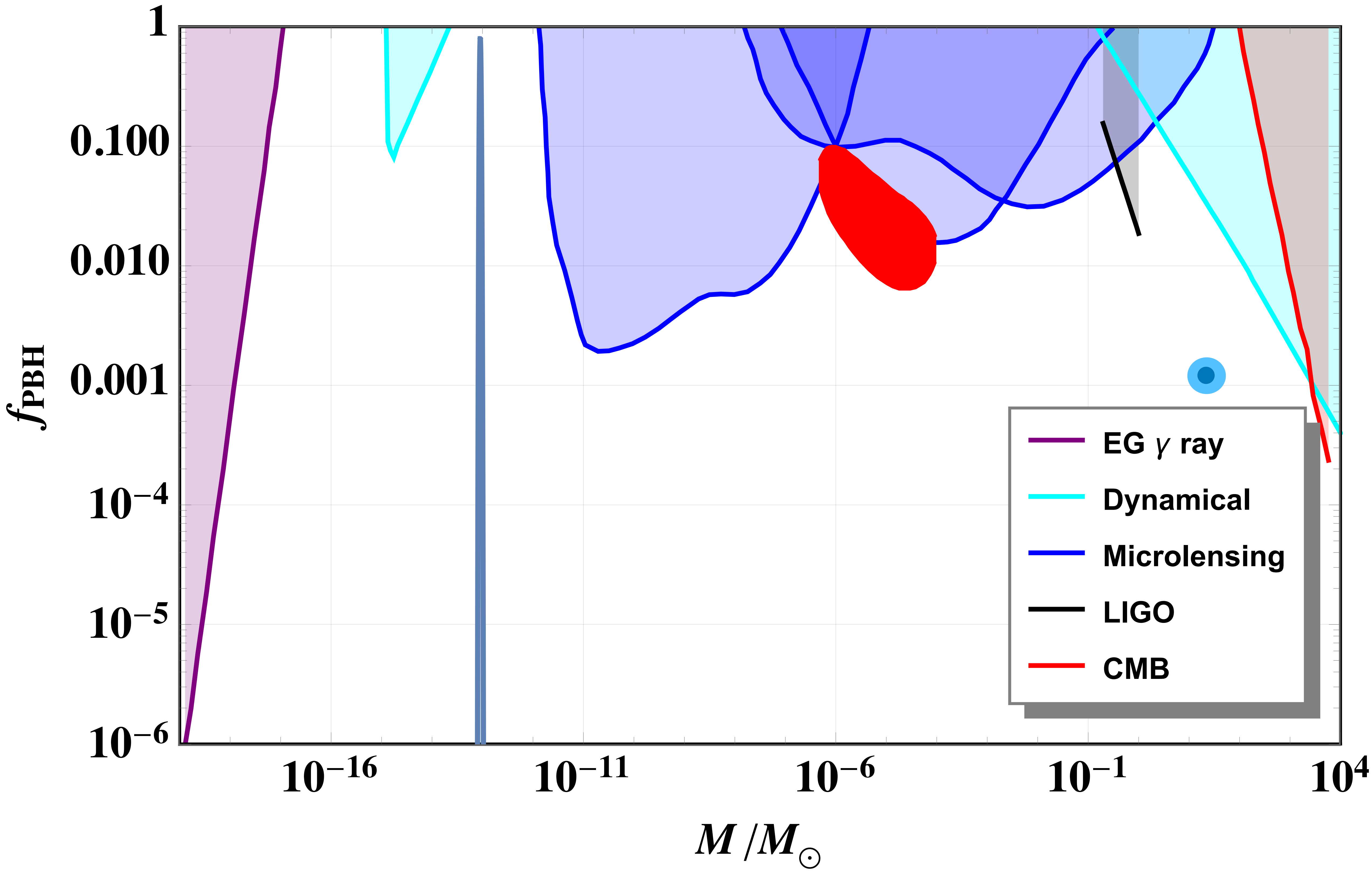
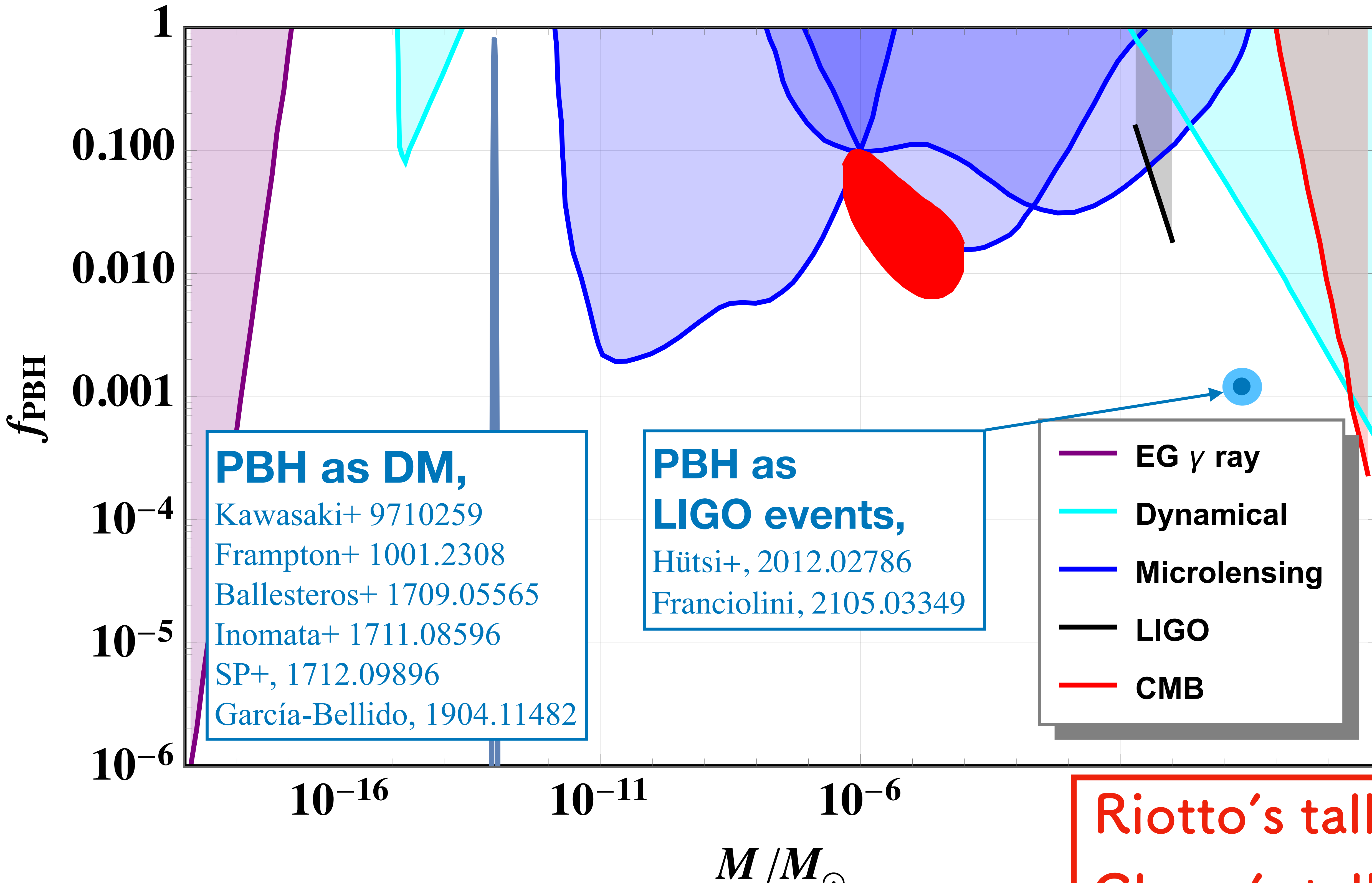


Constraints on f_{PBH}



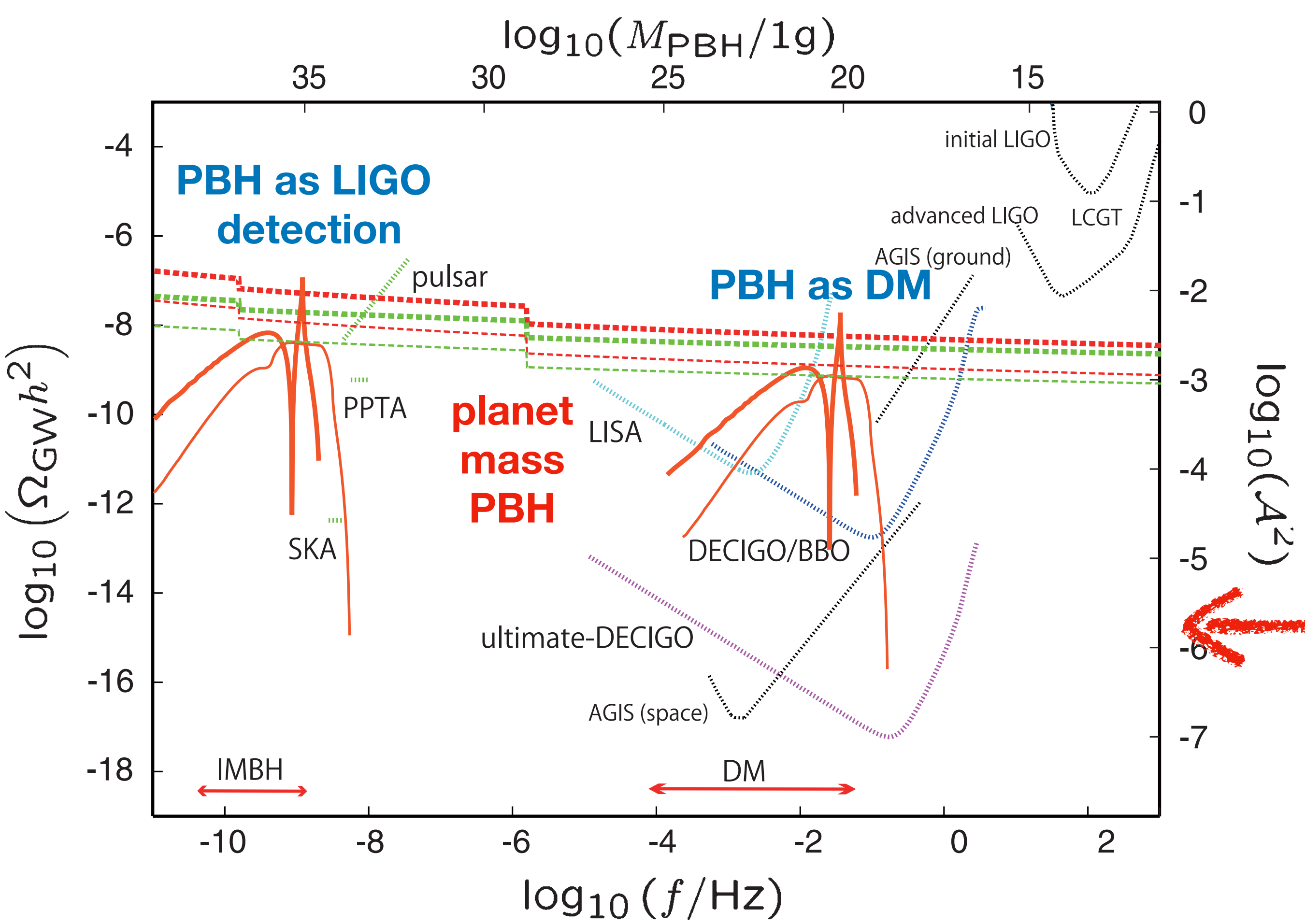
Riotto's talk
Clesse's talk

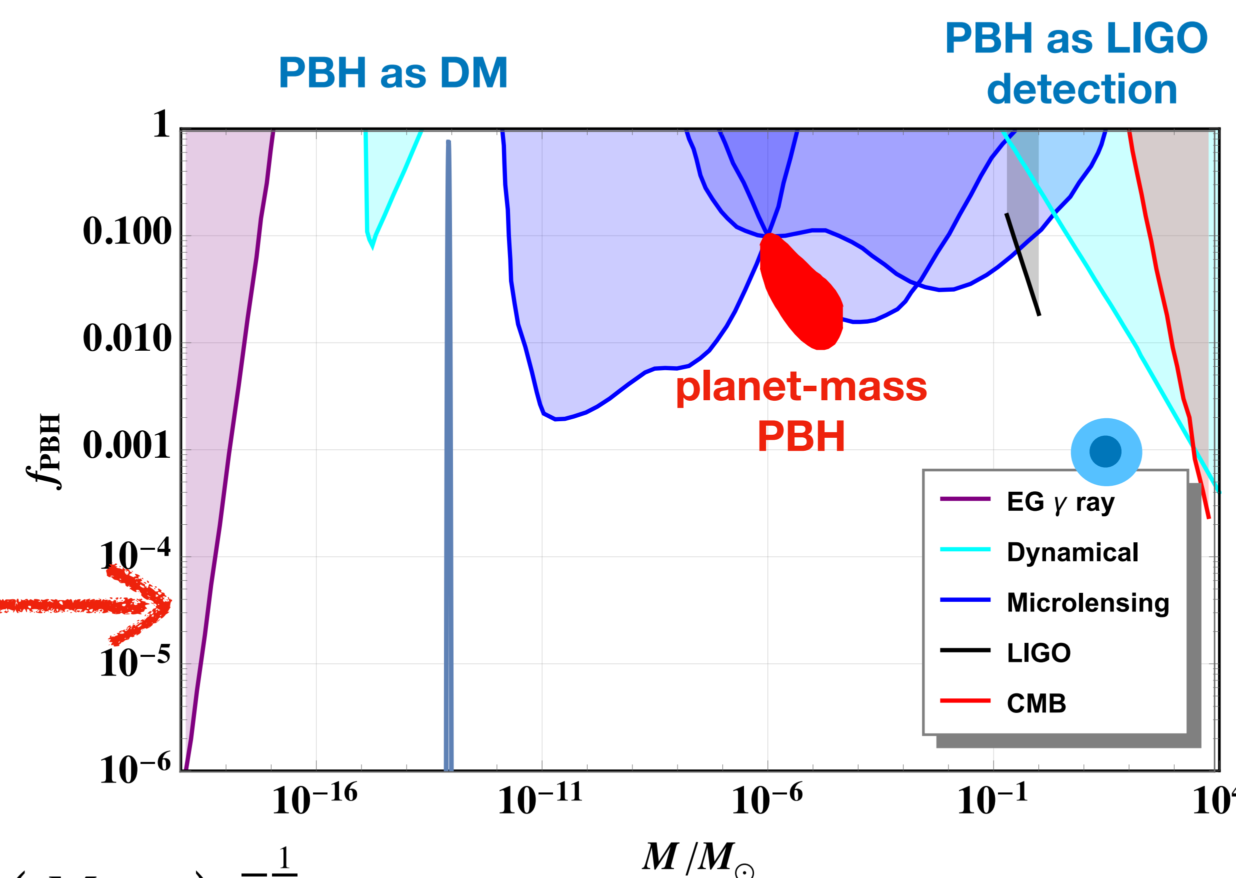
Induced GWs

$$\Omega_{\rm GW} \sim \langle hh \rangle \sim \langle \Phi\Phi\Phi\Phi \rangle \sim \mathscr{P}_\Phi^2 \sim \mathscr{P}_\mathscr{R}^2$$

PBH abundance

$$f_{\rm PBH} \sim 4.11 \times 10^8 \beta(M) \left(\frac{M}{M_\odot}\right)^{-1/2}, \qquad \beta \sim \mathrm{erfc}\left(\frac{\mathscr{R}_c}{2\sqrt{\mathscr{P}_\mathscr{R}}}\right)$$





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

Saito & Yokoyama 0812.4339

Induced GWs

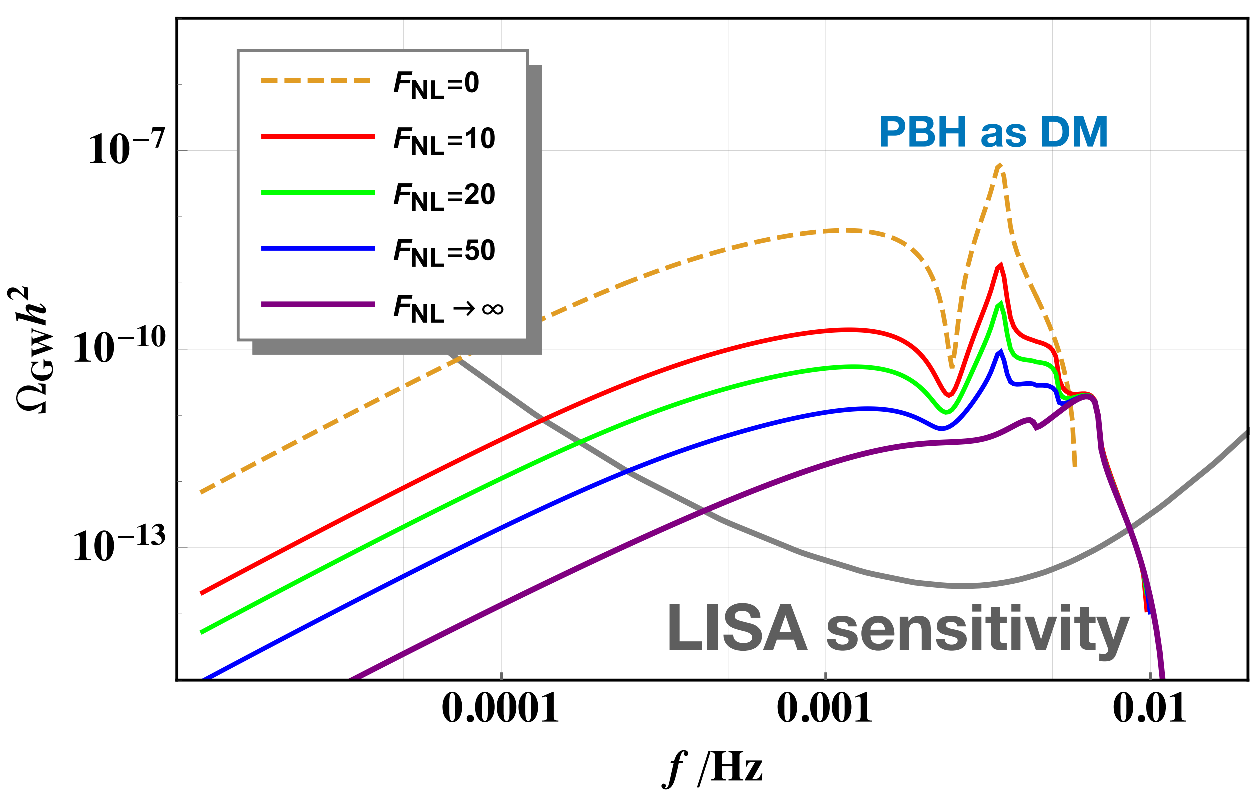
$$\Omega_{\rm GW} \sim \mathcal{P}^2_{\mathcal{R},\rm G} + F^2_{\rm NL}\mathcal{P}^3_{\mathcal{R},\rm G} + F^4_{\rm NL}\mathcal{P}^4_{\mathcal{R},\rm G}$$

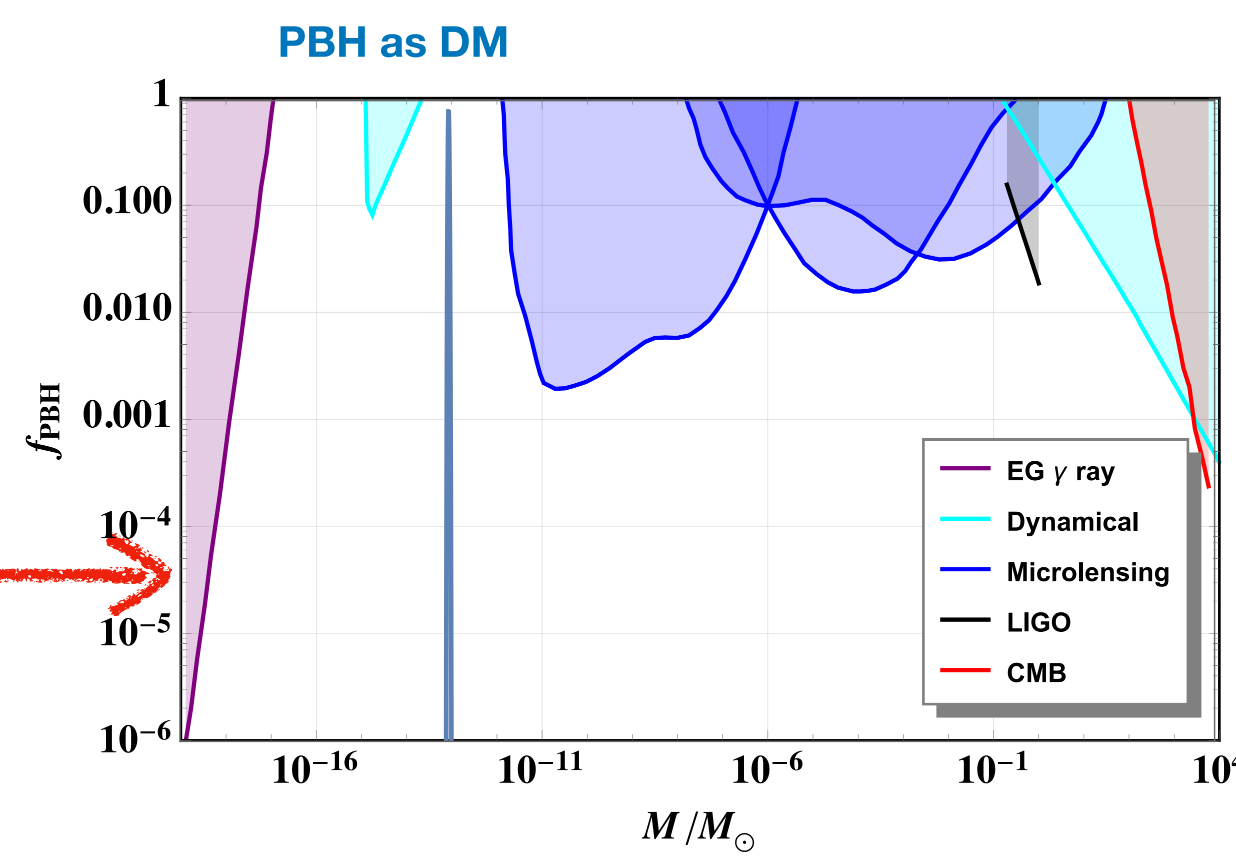
PBH abundance

$$\mathcal{R}_{g\pm}(\mathcal{R}_c) = \frac{1}{2F_{\rm NL}}\left(-1 \pm \sqrt{1 + 4F_{\rm NL}\left(F_{\rm NL}\mathcal{P}_{\mathcal{R},G} + \mathcal{R}_c\right)}\right).$$

$$\beta = \frac{1}{2}{\rm erfc}\left(\frac{\mathcal{R}_{g+}(\mathcal{R}_c)}{\sqrt{2\mathcal{P}_{\mathcal{R},G}}}\right) + \frac{1}{2}{\rm erfc}\left(-\frac{\mathcal{R}_{g-}(\mathcal{R}_c)}{\sqrt{2\mathcal{P}_{\mathcal{R},G}}}\right); \quad f_{\rm NL} > 0.$$

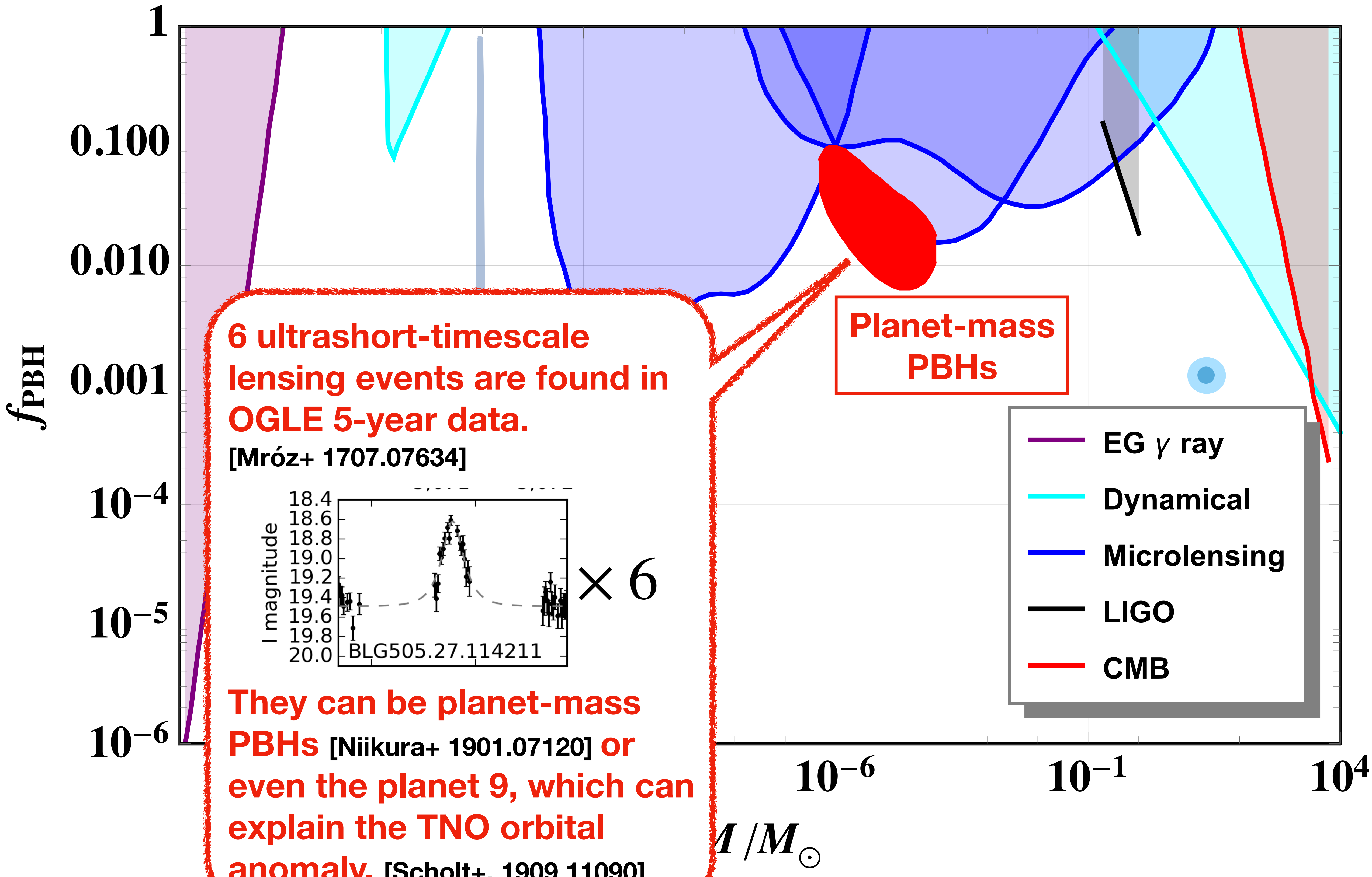
Cai, SP, and Sasaki, 1810.11000
Ünal, 1811.09151
Ünal+, 2008.11184





Ünal's talk

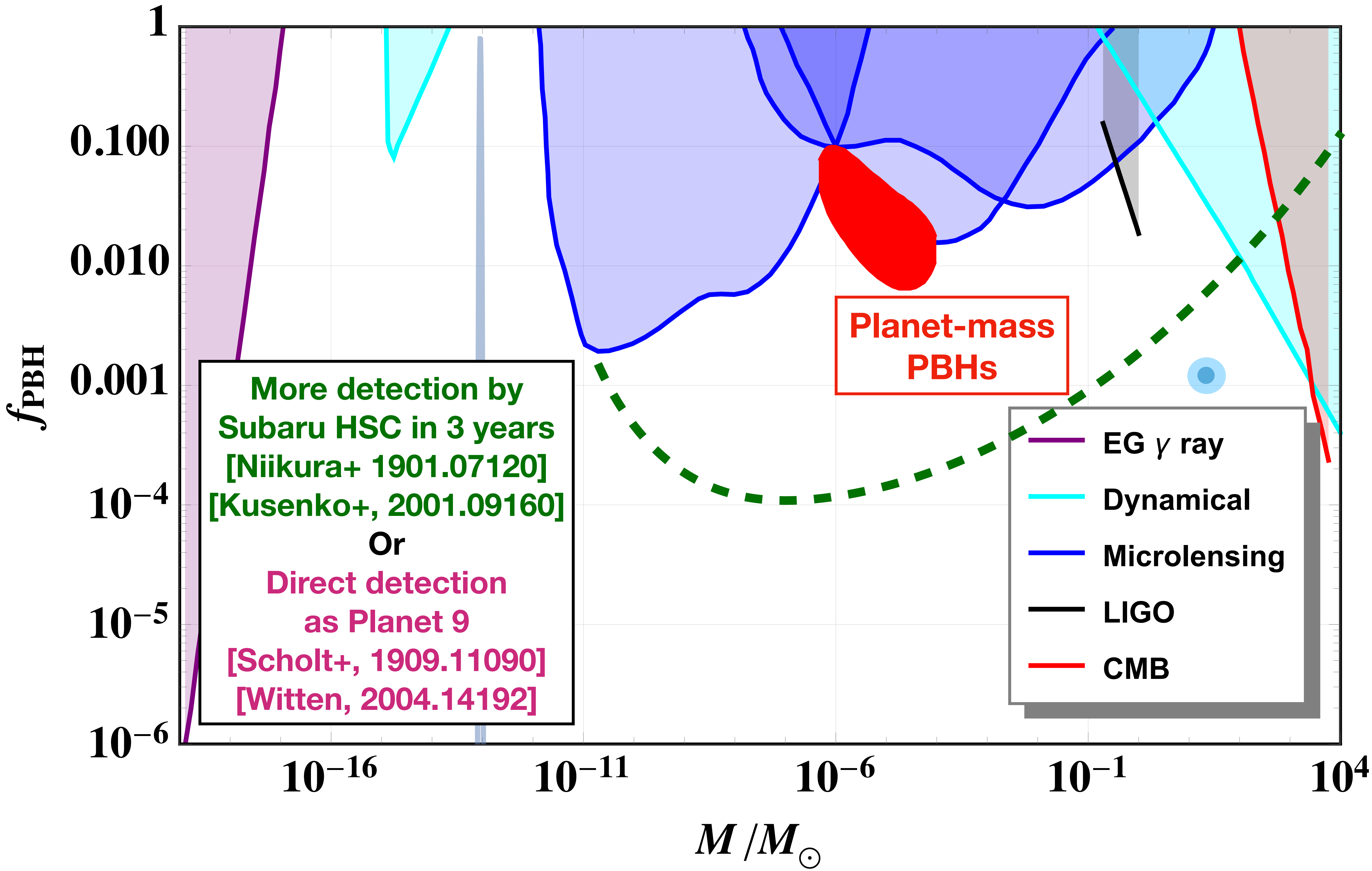
Constraints on f_{PBH}



6 ultrashort-timescale lensing events are found in OGLE 5-year data. [Mróz+ 1707.07634]

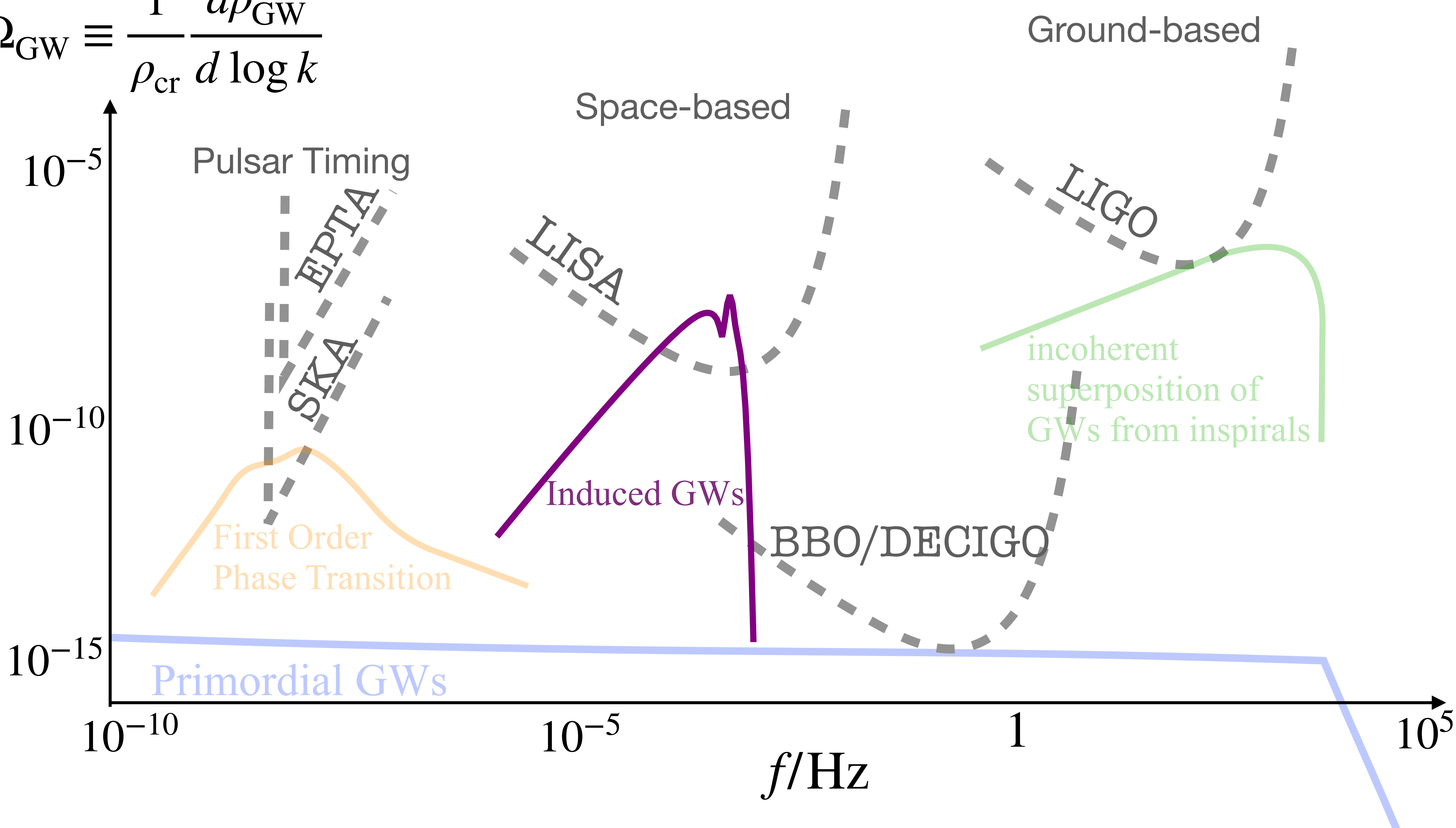
They can be planet-mass PBHs [Niikura+ 1901.07120] or even the planet 9, which can explain the TNO orbital anomaly. [Scholt+, 1909.11090]

Constraints on f_{PBH}

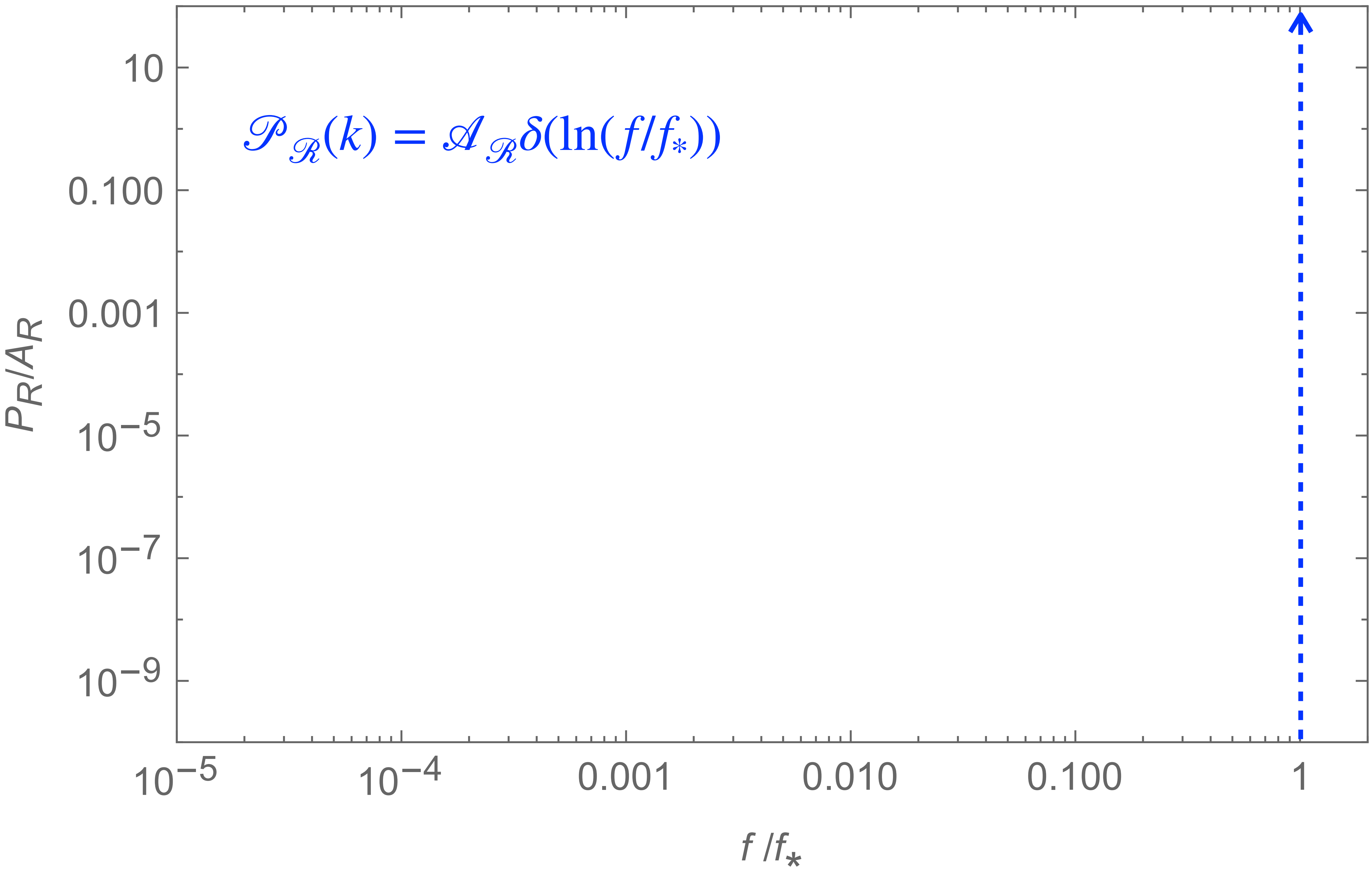


Shape of $\Omega_{\rm IGW}$

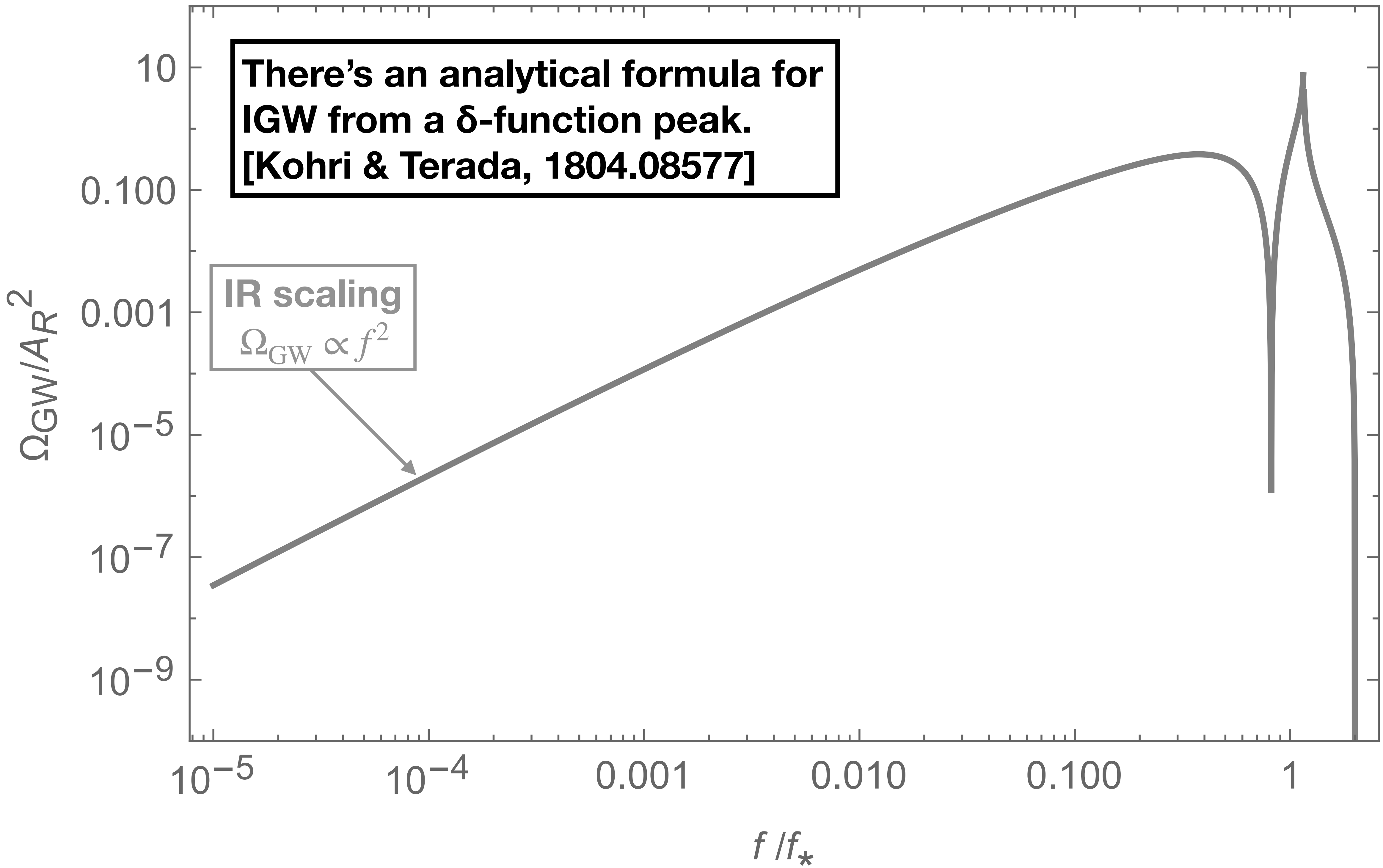
$$\Omega_{\rm GW} \equiv \frac{1}{\rho_{\rm cr}} \frac{d\rho_{\rm GW}}{d\log k}$$



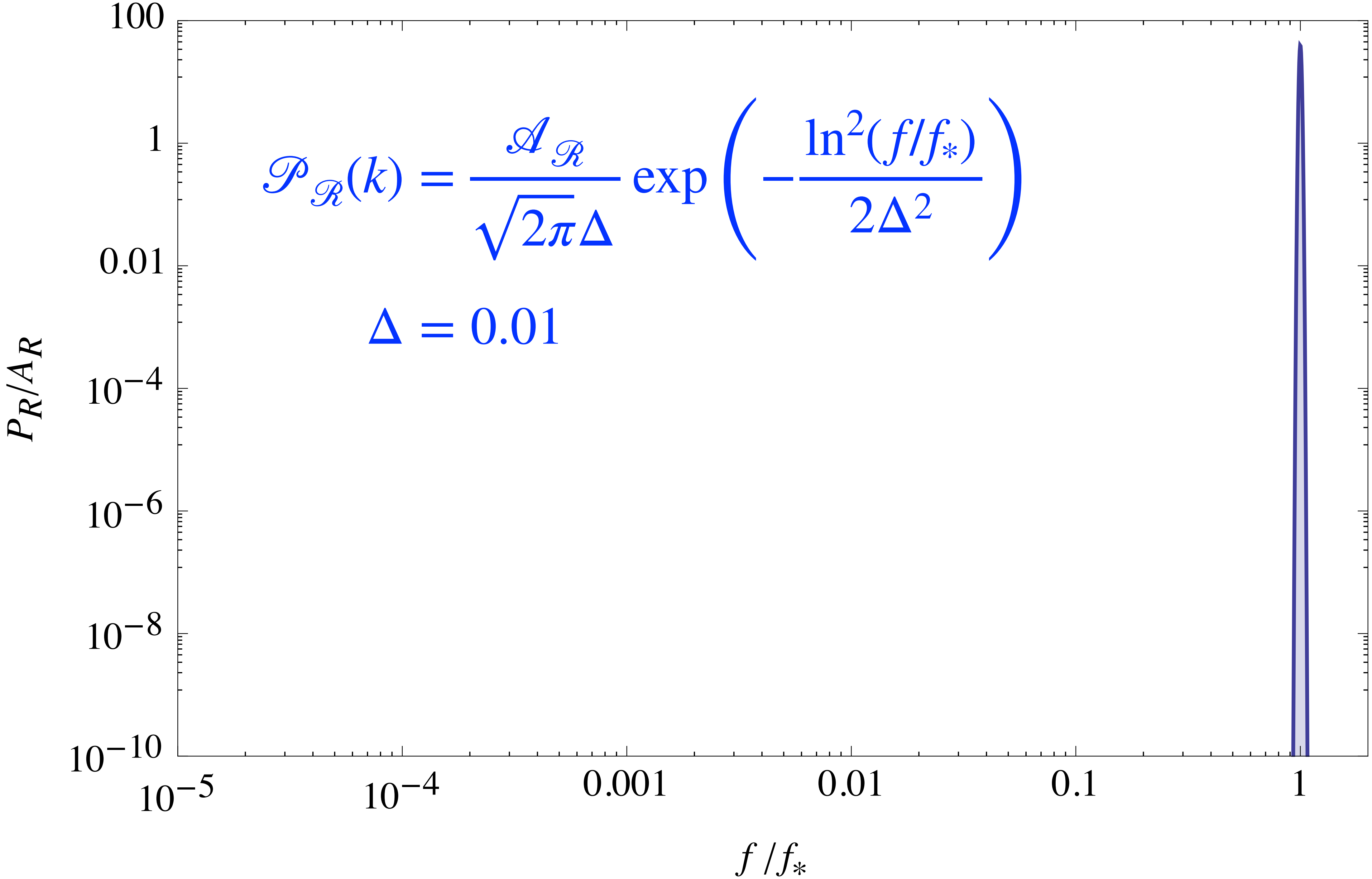
Shape of Ω_{IGW}



Shape of Ω_{IGW}



Shape of $\Omega_{\rm IGW}$



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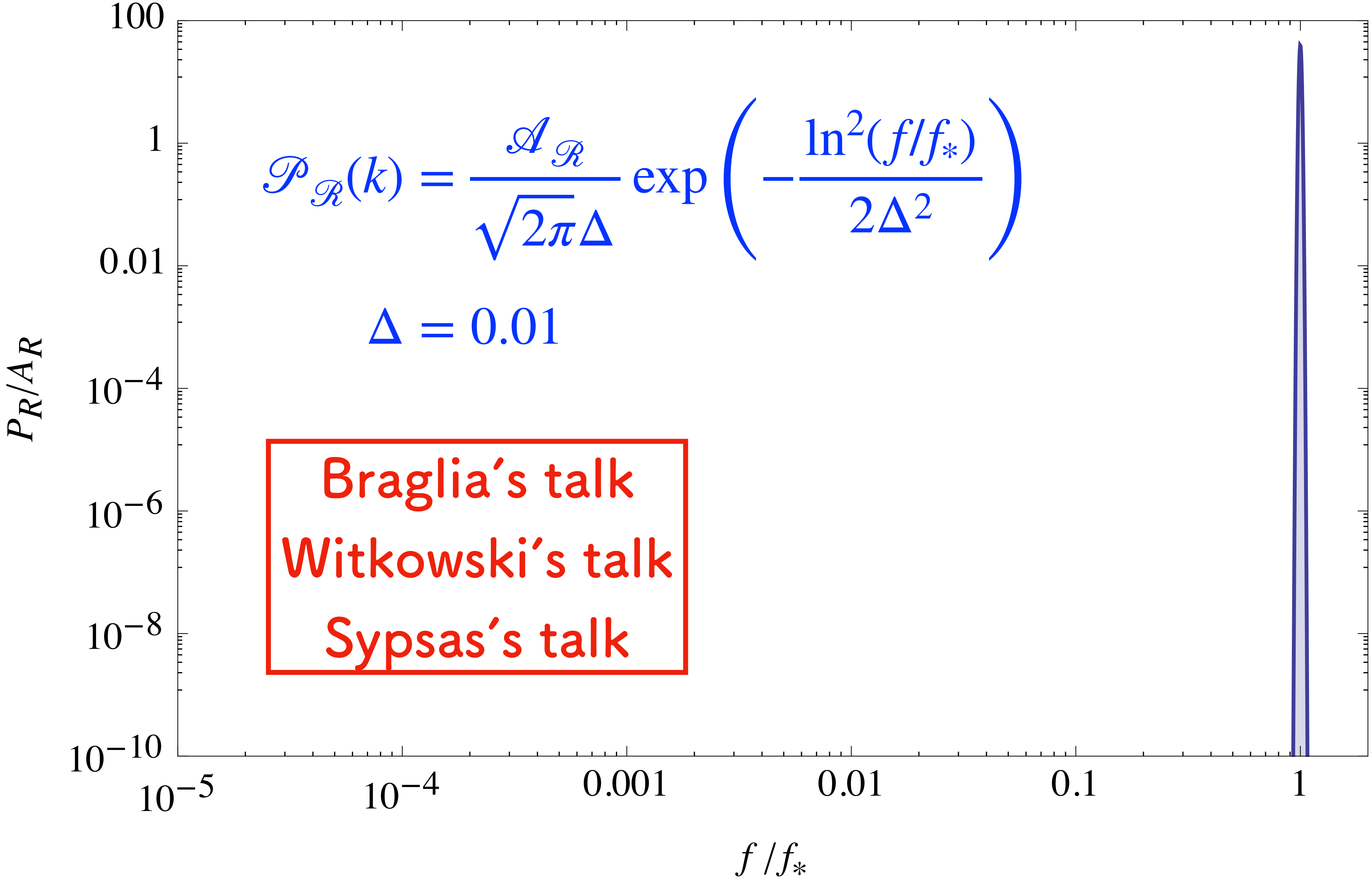

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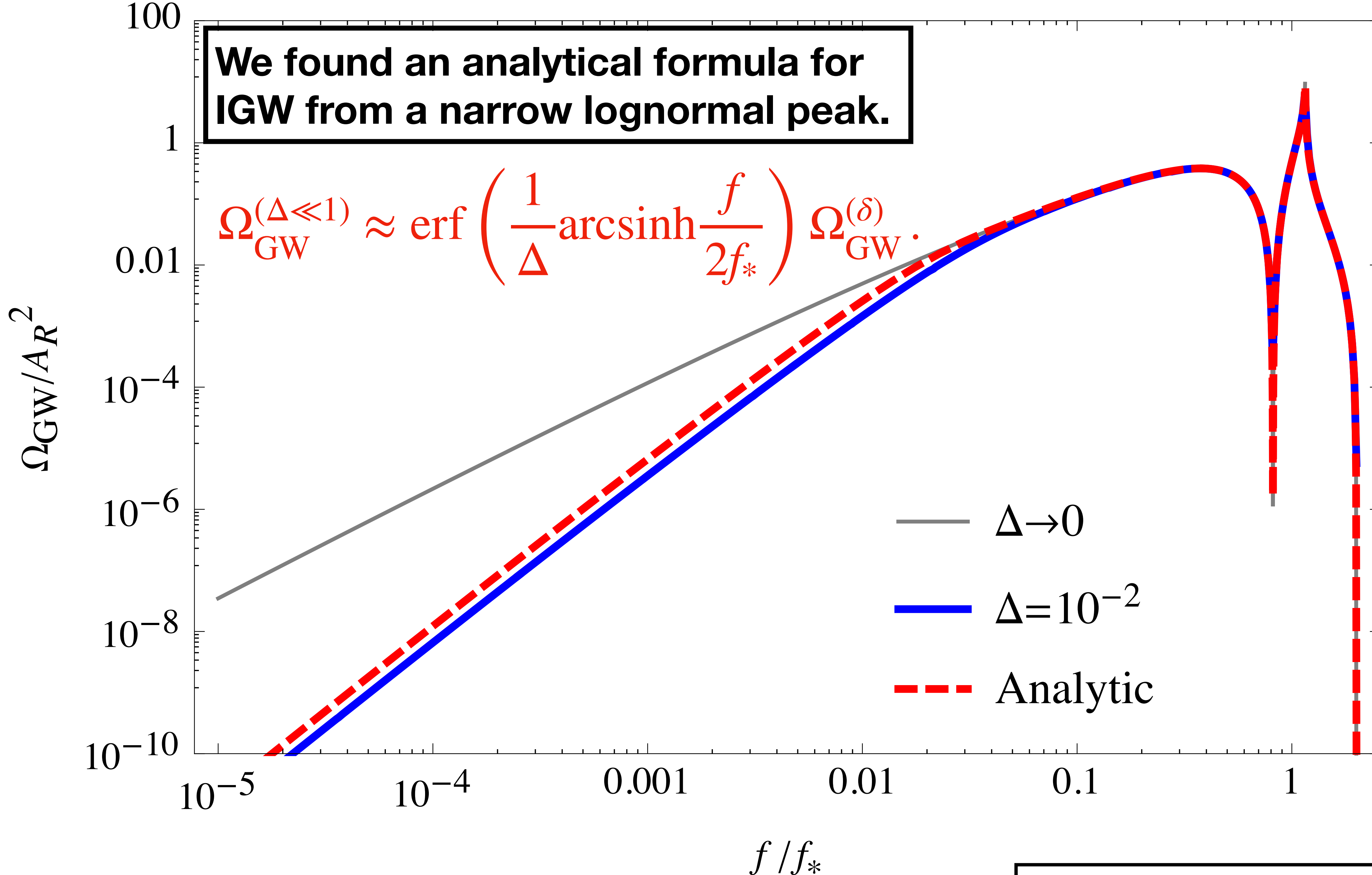
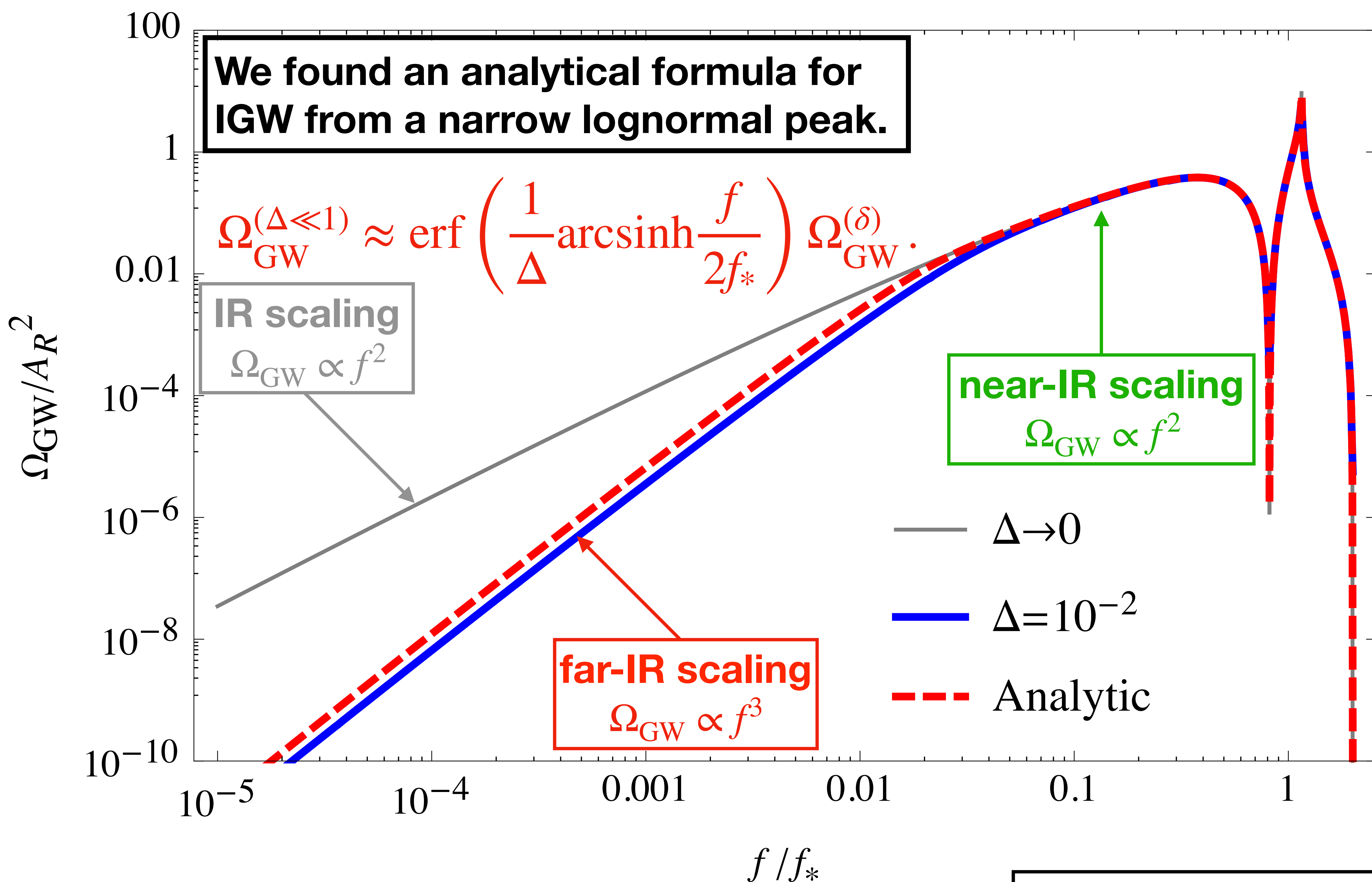


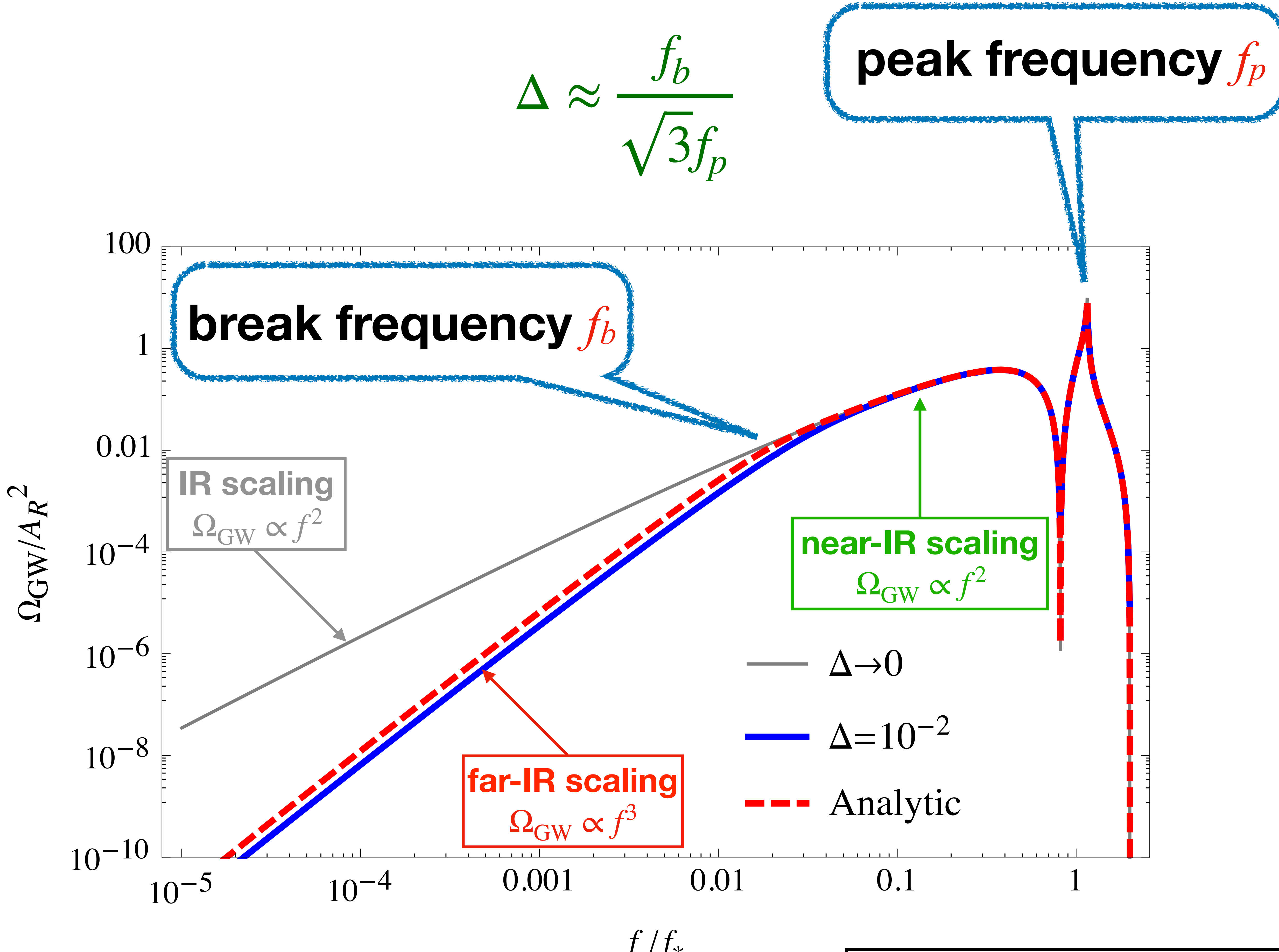
SP and Sasaki, 2005.12306

Shape of $\Omega_{\rm IGW}$



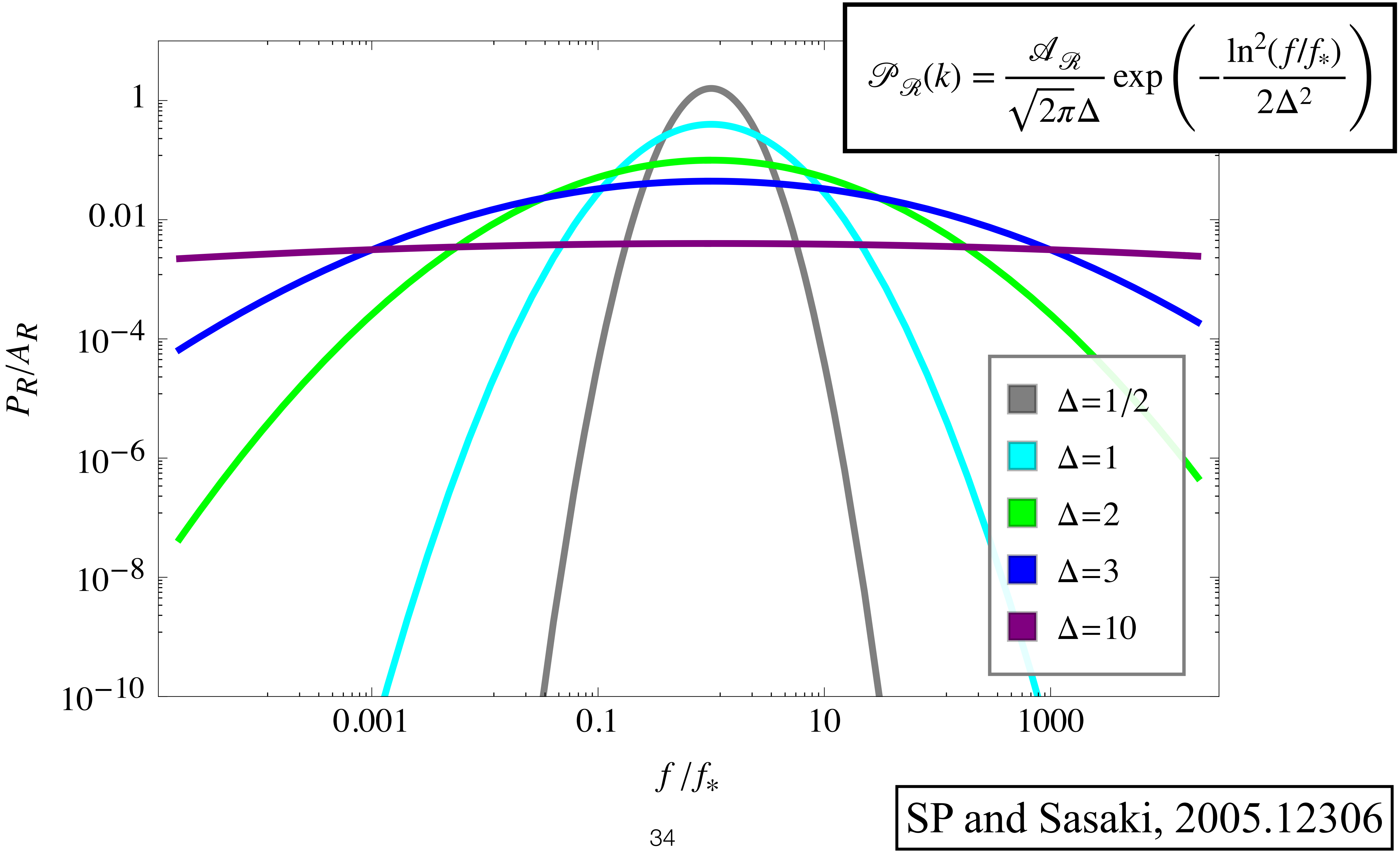
SP and Sasaki, 2005.12306

$$\Delta \approx \frac{f_b}{\sqrt{3} f_p}$$

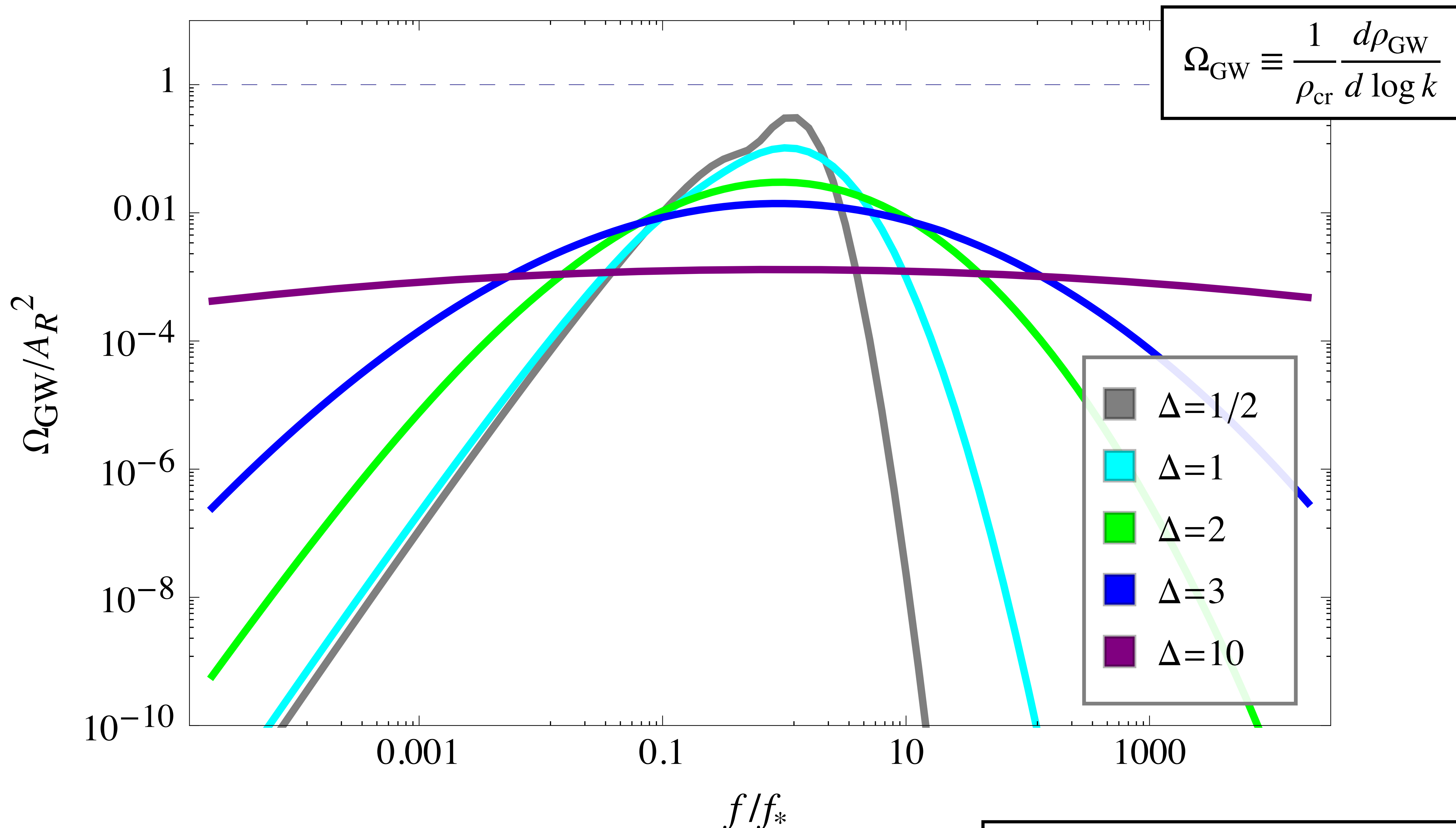


SP and Sasaki, 2005.12306

Shape of $\Omega_{\rm IGW}$

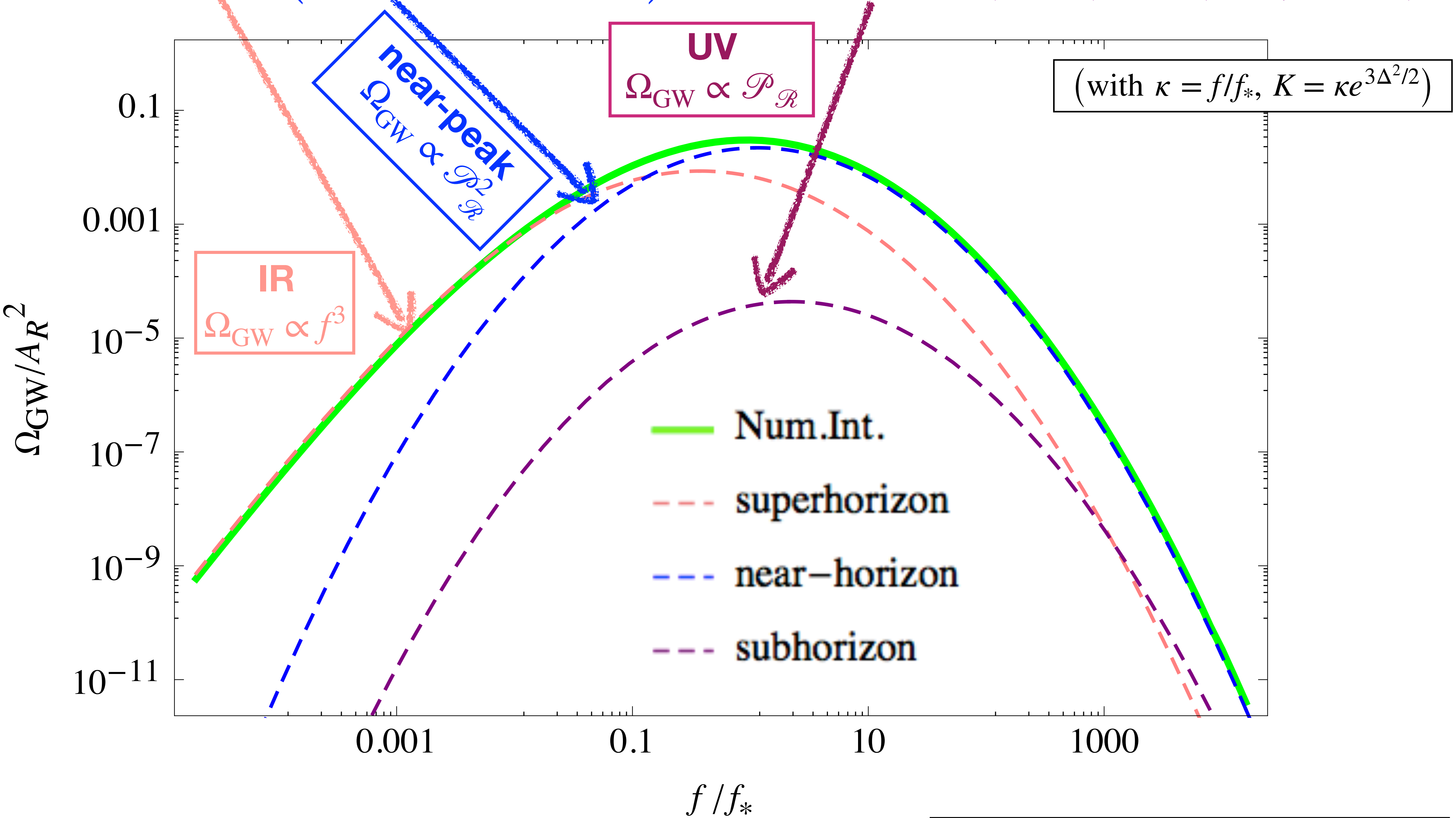


Shape of Ω_{IGW}



SP and Sasaki, 2005.12306

$$\frac{\Omega_{\rm GW}}{\mathscr{A}_{\mathscr{R}}^2} \approx \frac{4}{5\sqrt{\pi}}\kappa^3 \frac{e^{\frac{9\Delta^2}{4}}}{\Delta}\left[\left(\ln^2 K + \frac{\Delta^2}{2}\right)\mathrm{erfc}\left(\frac{\ln K + \frac{1}{2}\ln\frac{3}{2}}{\Delta}\right) - \frac{\Delta}{\sqrt{\pi}}\exp\left(-\frac{\left(\ln K + \frac{1}{2}\ln\frac{3}{2}\right)^2}{\Delta^2}\right)\left(\ln K - \frac{1}{2}\ln\frac{3}{2}\right)\right]$$
$$+\frac{0.0659}{\Delta^2}\kappa^2 e^{\Delta^2}\exp\left(-\frac{\left(\ln\kappa + \Delta^2 - \frac{1}{2}\ln\frac{4}{3}\right)^2}{\Delta^2}\right) + \frac{1}{3}\sqrt{\frac{2}{\pi}}\kappa^{-4}\frac{e^{8\Delta^2}}{\Delta}\exp\left(-\frac{\ln^2\kappa}{2\Delta^2}\right)\mathrm{erfc}\left(\frac{4\Delta^2 - \ln(\kappa/4)}{\sqrt{2}\Delta}\right)$$

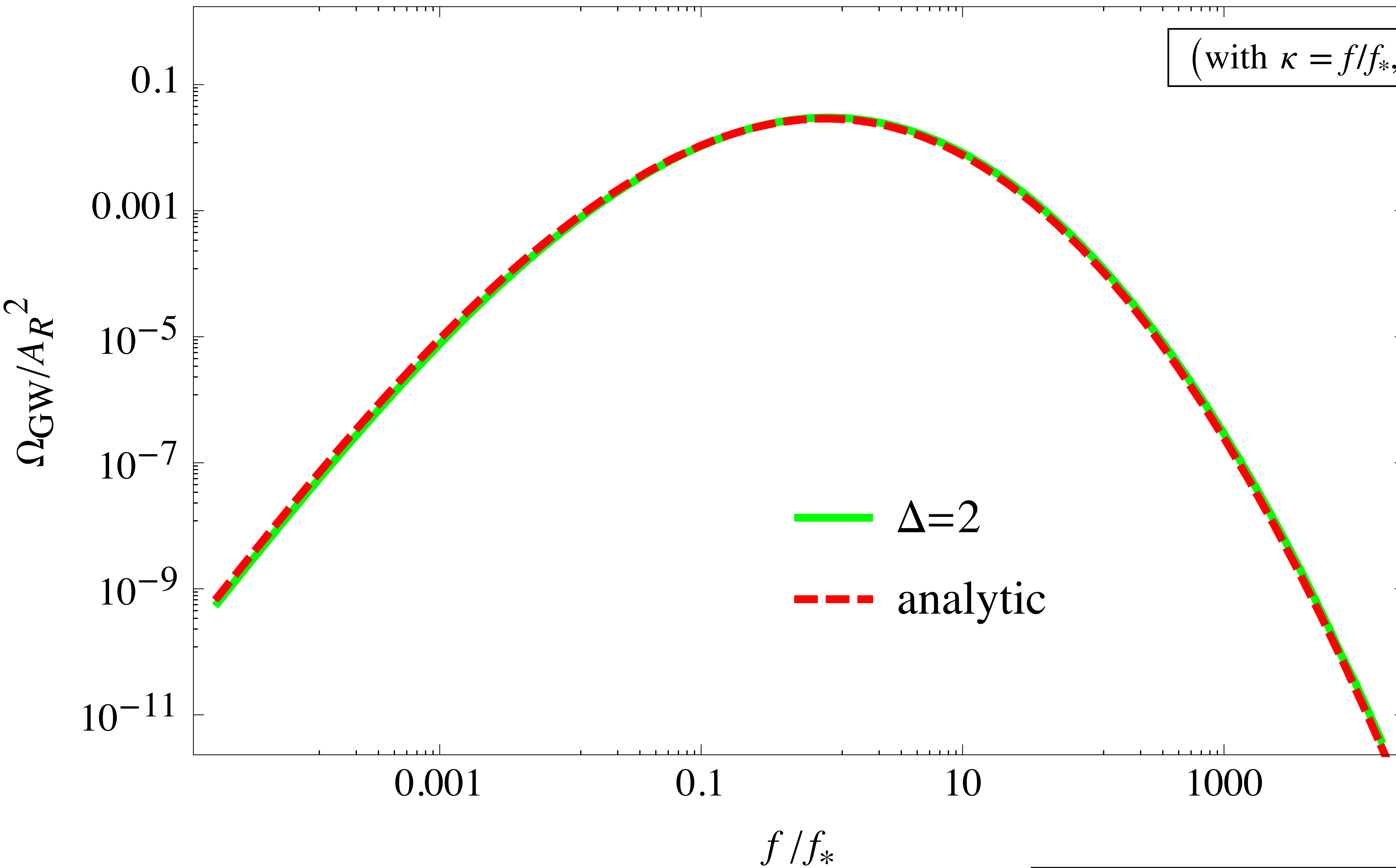


SP and Sasaki, 2005.12306

$$\frac{\Omega_{\rm GW}}{\mathcal{A}_{\mathcal{R}}^2} \approx \frac{4}{5\sqrt{\pi}}\kappa^3 \frac{e^{\frac{9\Delta^2}{4}}}{\Delta}\left[\left(\ln^2 K + \frac{\Delta^2}{2}\right)\mathrm{erfc}\left(\frac{\ln K + \frac{1}{2}\ln\frac{3}{2}}{\Delta}\right) - \frac{\Delta}{\sqrt{\pi}}\exp\left(-\frac{\left(\ln K + \frac{1}{2}\ln\frac{3}{2}\right)^2}{\Delta^2}\right)\left(\ln K - \frac{1}{2}\ln\frac{3}{2}\right)\right]$$

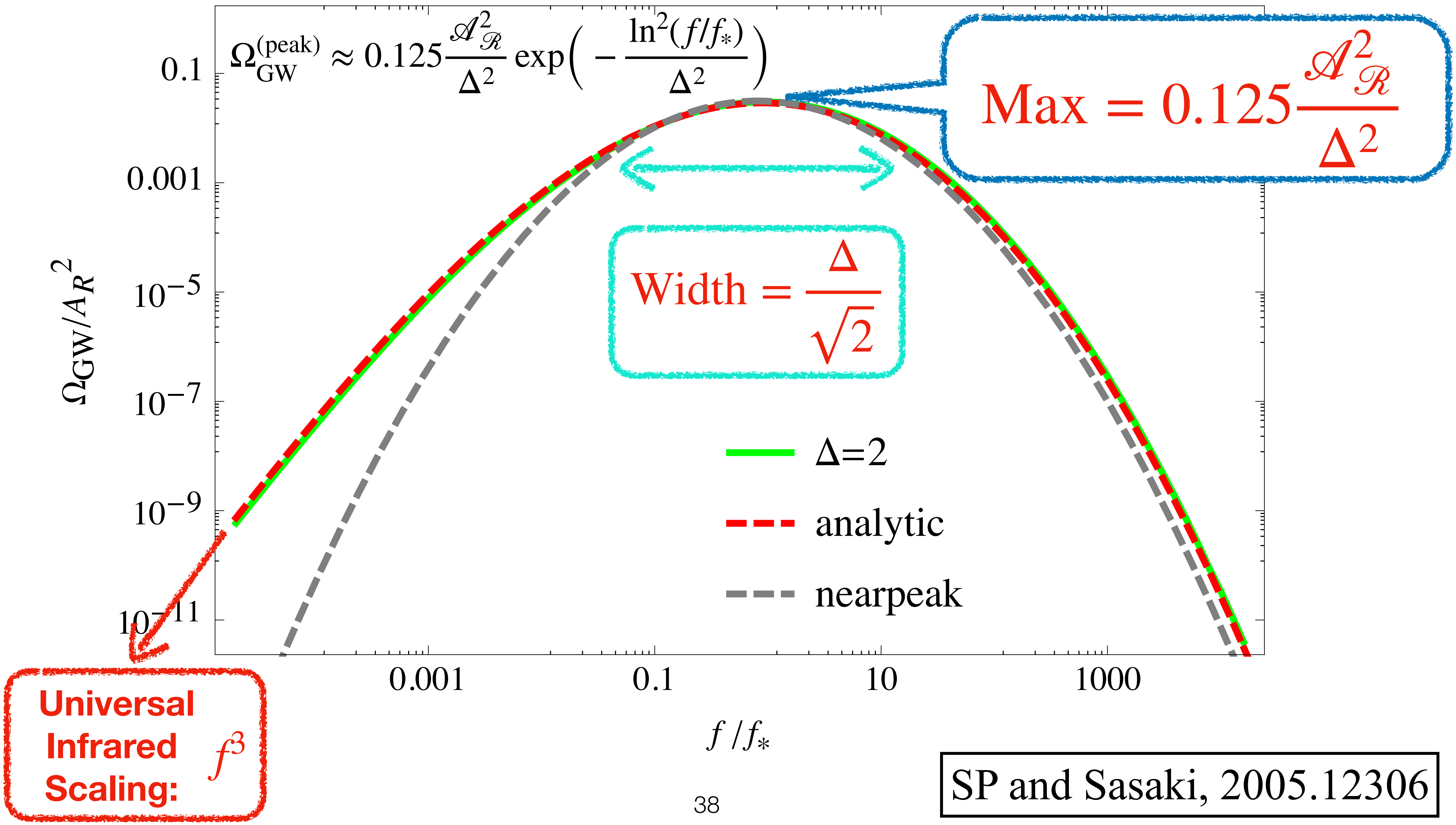
$$+\frac{0.0659}{\Delta^2}\kappa^2 e^{\Delta^2}\exp\left(-\frac{\left(\ln\kappa + \Delta^2 - \frac{1}{2}\ln\frac{4}{3}\right)^2}{\Delta^2}\right) + \frac{1}{3}\sqrt{\frac{2}{\pi}}\kappa^{-4}\frac{e^{8\Delta^2}}{\Delta}\exp\left(-\frac{\ln^2\kappa}{2\Delta^2}\right)\mathrm{erfc}\left(\frac{4\Delta^2 - \ln(\kappa/4)}{\sqrt{2}\Delta}\right)$$

(with $\kappa = f/f_*$, $K = \kappa e^{3\Delta^2/2}$)



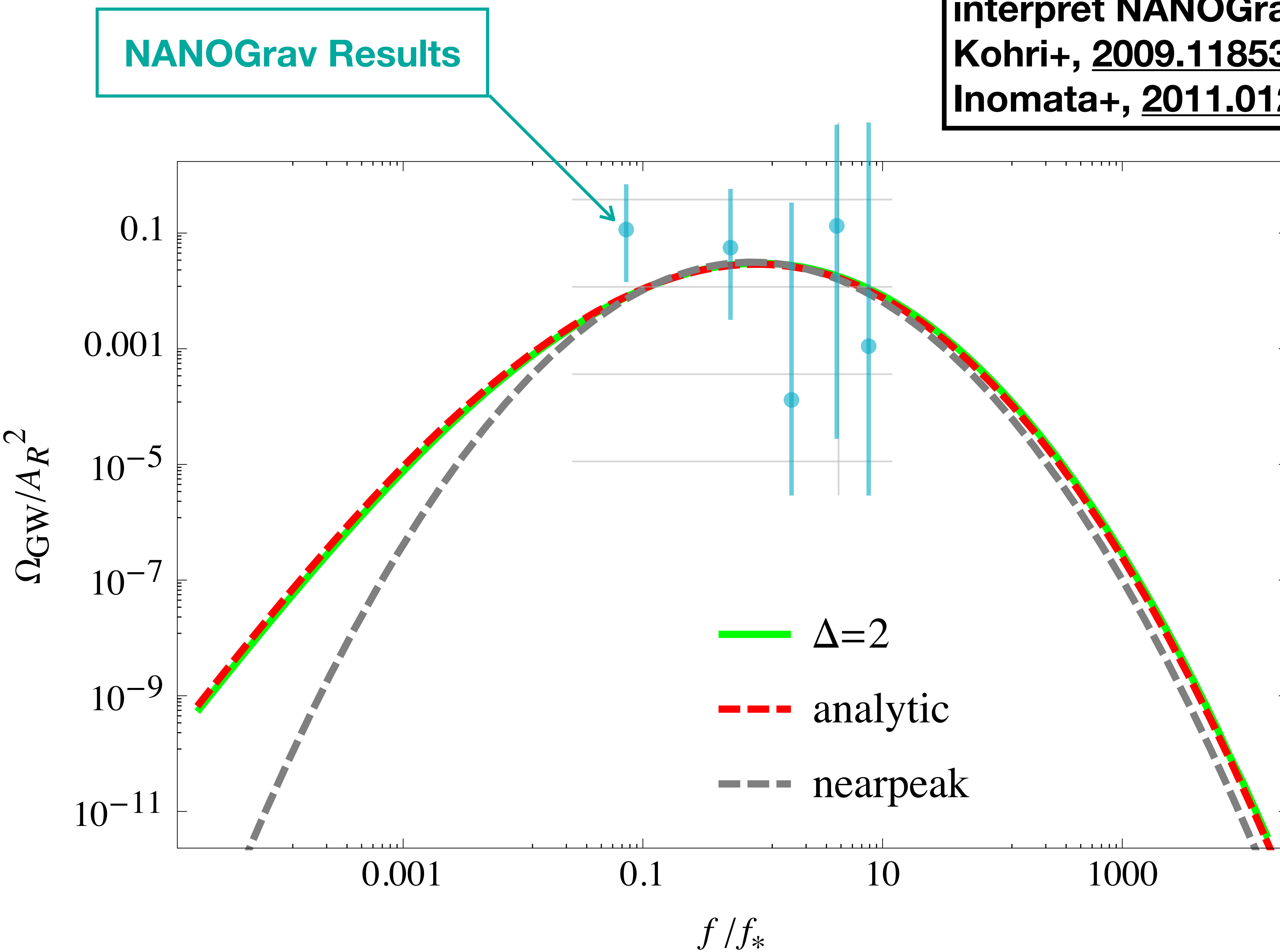
SP and Sasaki, 2005.12306

Shape of $\Omega_{\rm IGW}$

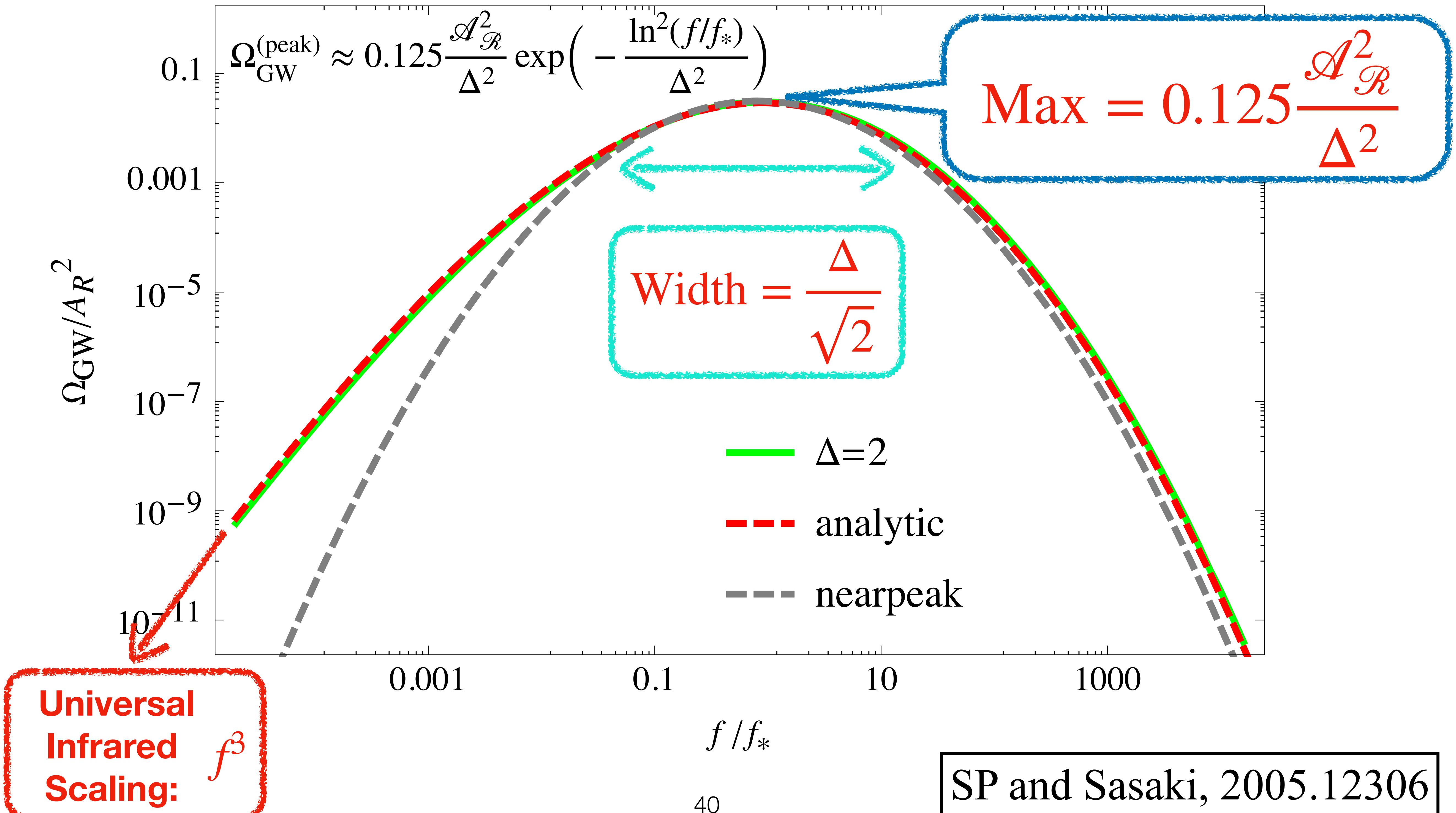


SP and Sasaki, 2005.12306

The flat near-peak spectrum can be used to interpret NANOGrav result.
Kohri+, 2009.11853
Inomata+, 2011.01270



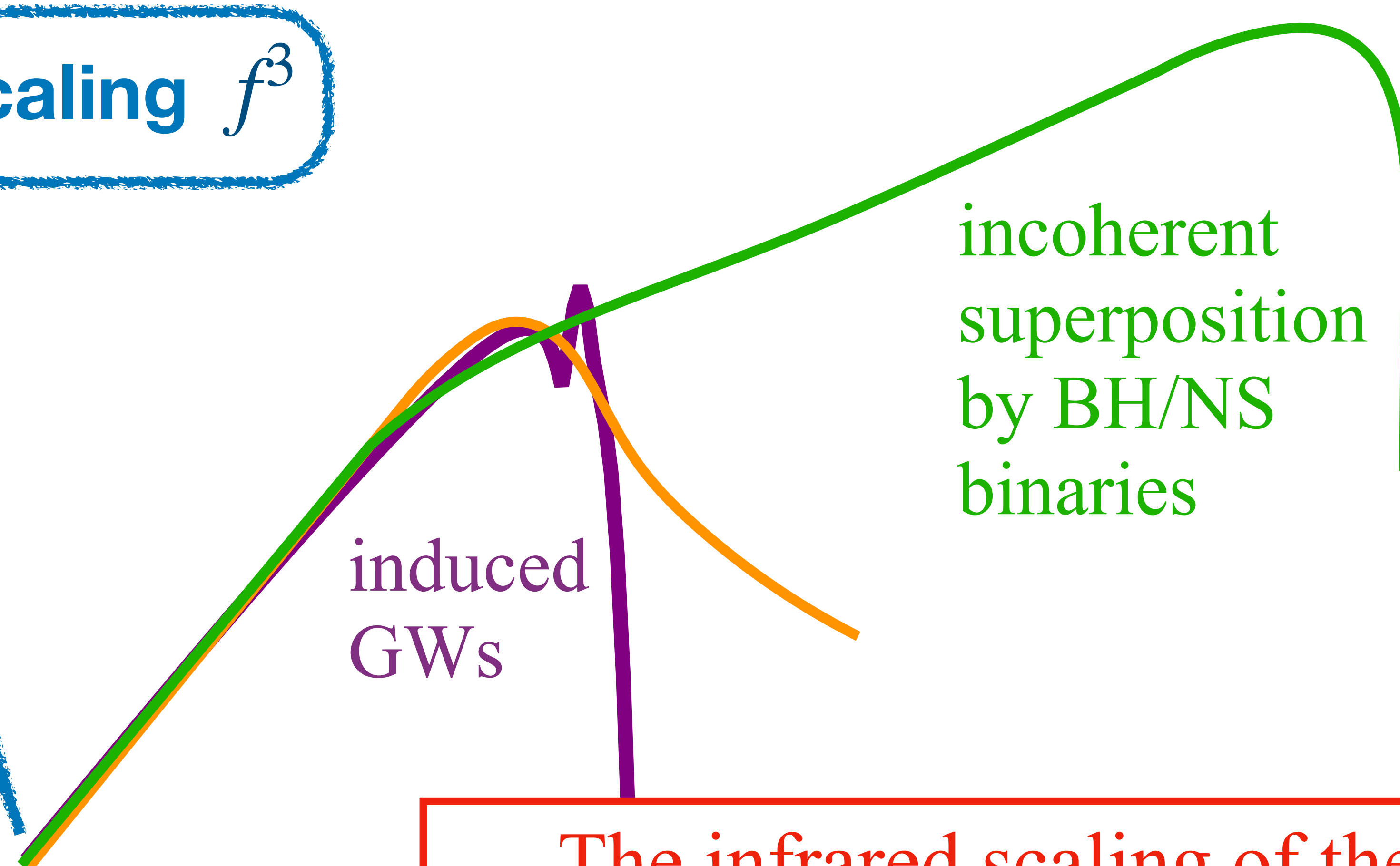
Infrared scaling of $\Omega_{\rm IGW}$



SP and Sasaki, 2005.12306

Infrared scaling of $\Omega_{\rm IGW}$

Universal infrared scaling f^3



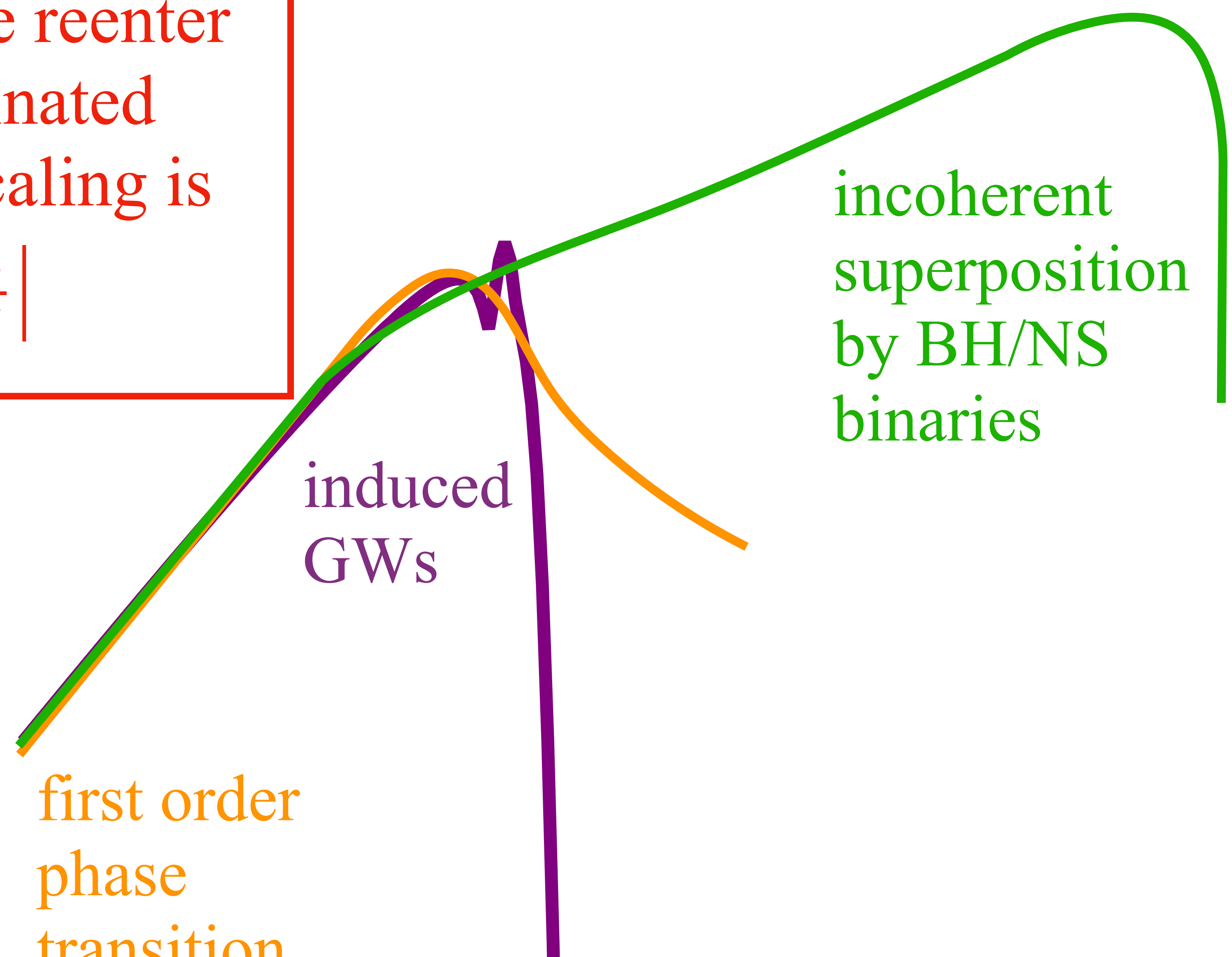
The infrared scaling of the GW spectrum is k^3, as (1) k is smaller than all the scales of the source term; and (2) k-mode reenter the horizon in the radiation dominated universe.

Cai, SP, and Sasaki, 1909.13728
Domènech, 1912.05583
Domènech, SP, and Sasaki, 2005.12314

Infrared scaling of $\Omega_{\rm IGW}$

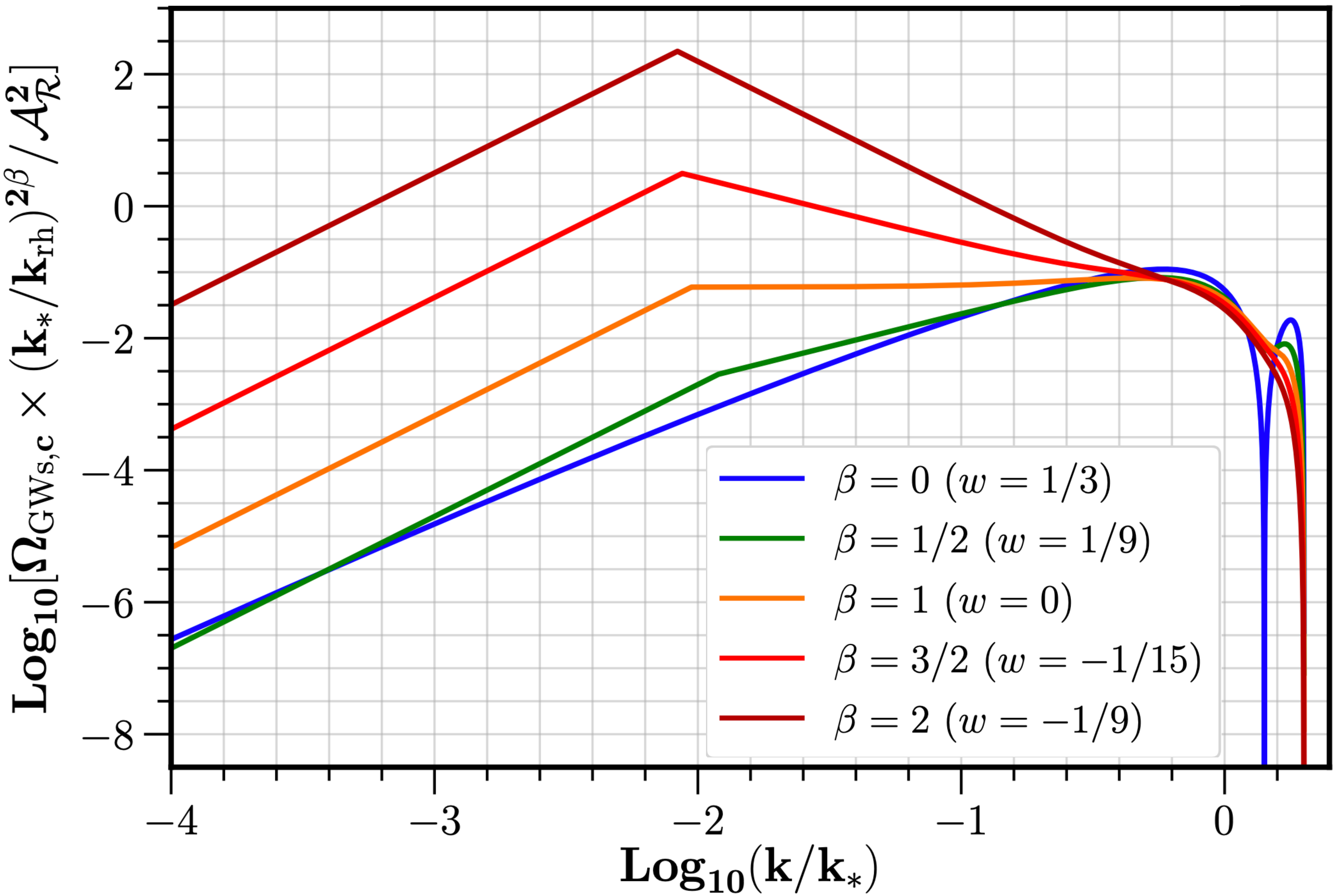
When the infrared mode reenter the horizon in a *w*-dominated universe, the infrared scaling is

$$\Omega_{\rm GW} \propto f^{3-2\left|\frac{1-3w}{1+3w}\right|}$$



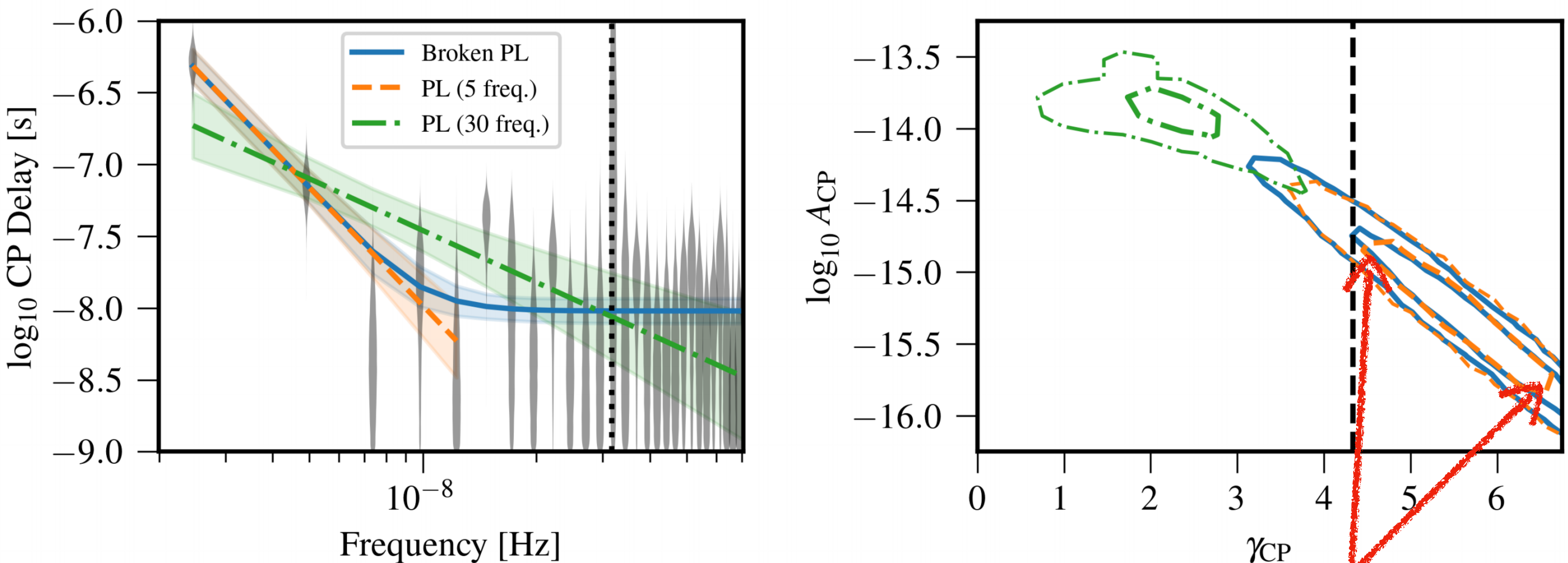
Cai, SP, and Sasaki, 1909.13728
Domènech, 1912.05583
Domènech, SP, and Sasaki, 2005.12314

Infrared scaling of Ω_{IGW}



Domènech, SP, and Sasaki, 2005.12314

Back to NANOGrav



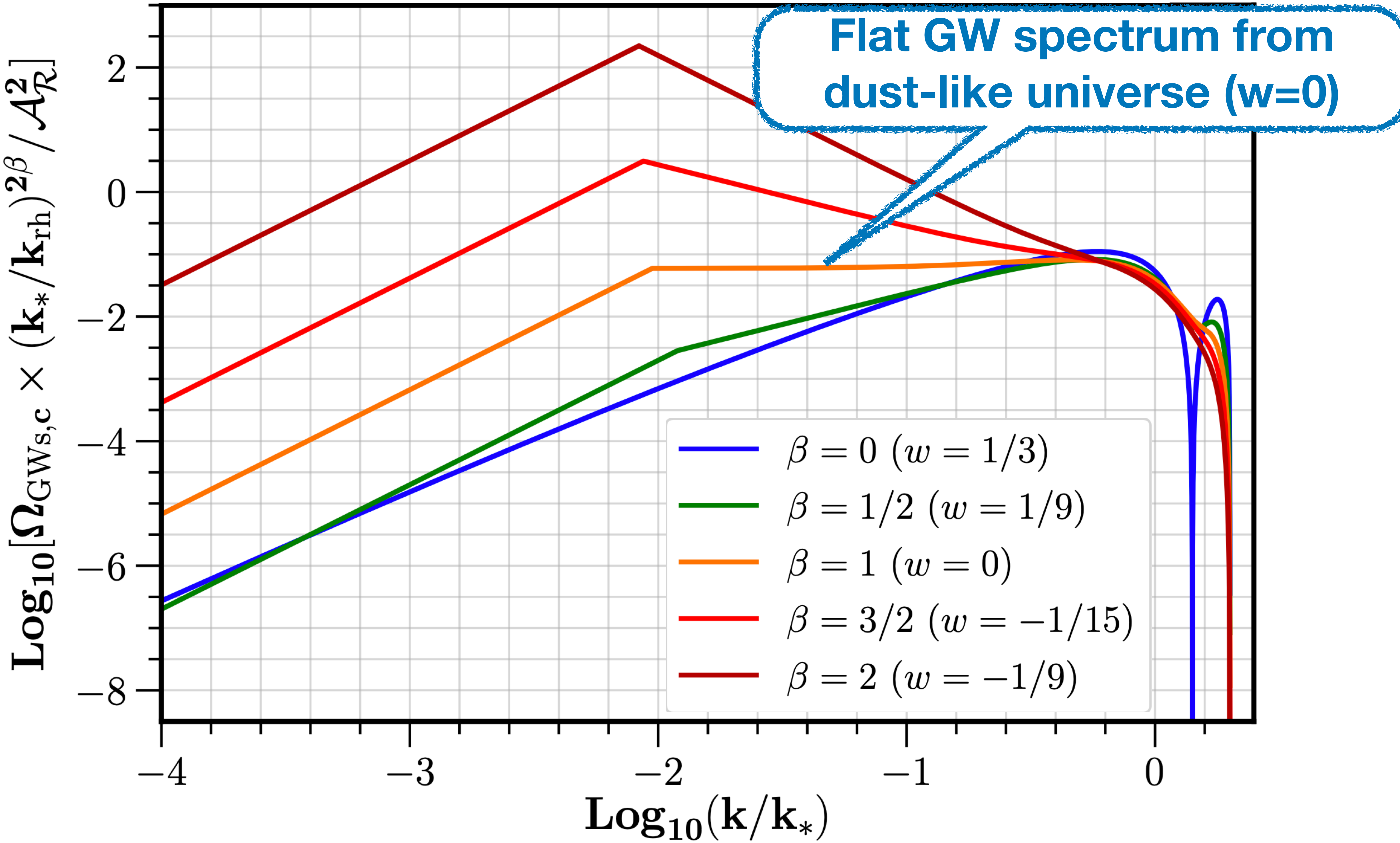
$\Omega_{GW} \propto f^{-3/2\sim 1/2}$

$$\Omega_{\rm GW} = \frac{2\pi^2 f_{\rm yr}^2}{3H_0^2} A_{\rm SGWB}^2 \left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma}$$

$$f_{\rm yr} = 3.17 \times 10^{-8}\ {\rm Hz}\,.$$

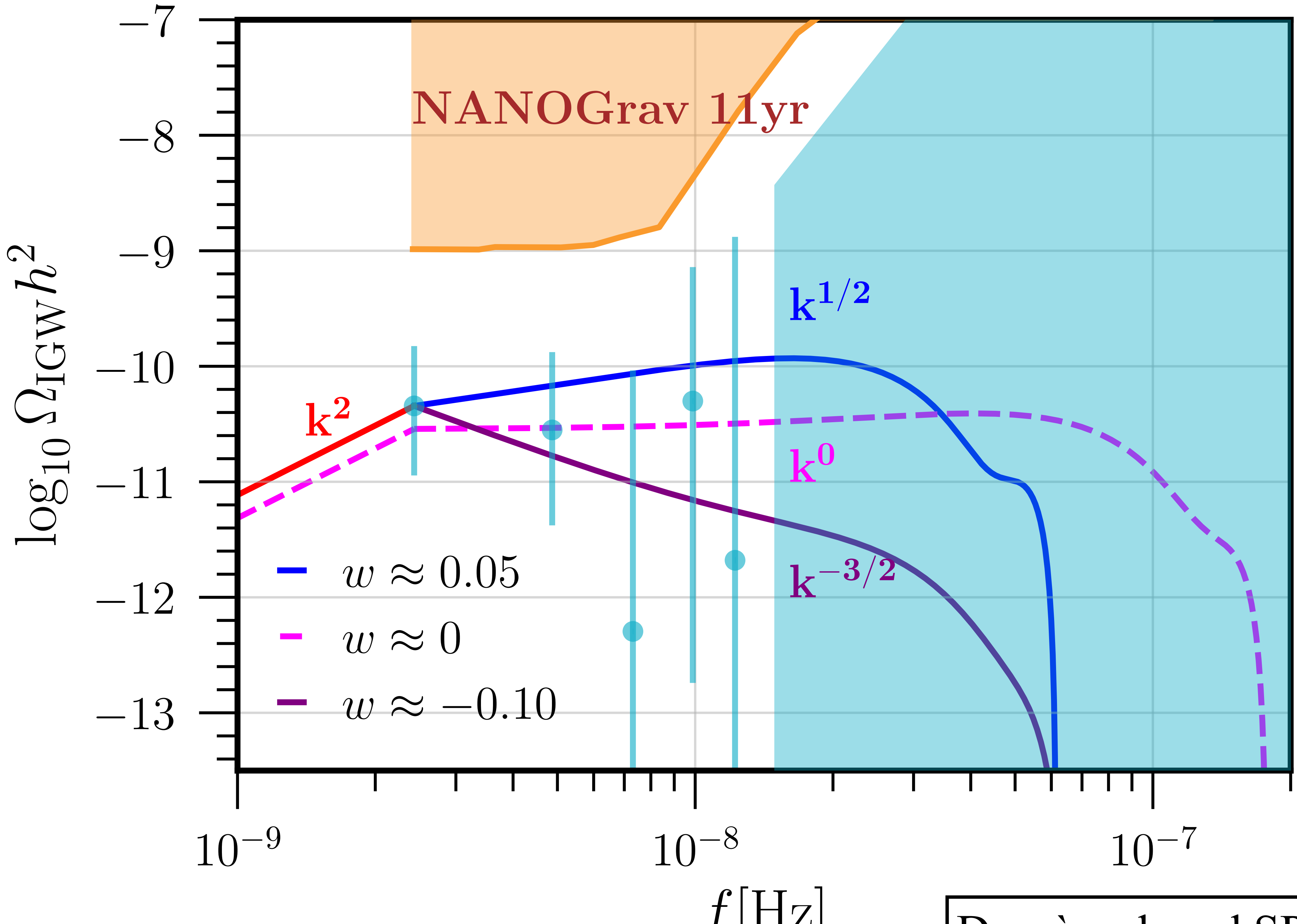
[NANOGrav, 2009.04496]

Infrared scaling of $\Omega_{\rm IGW}$



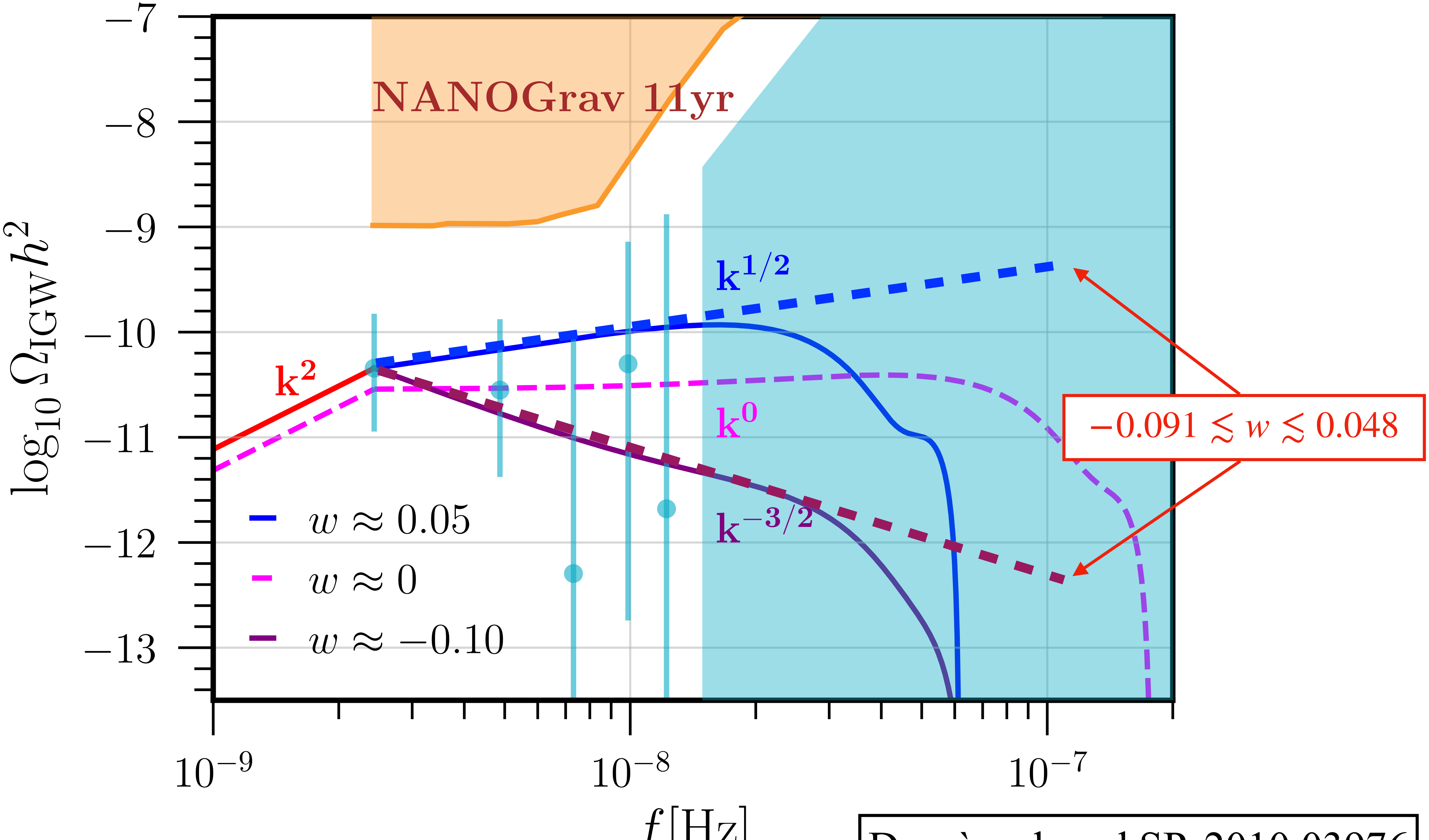
Domènech, SP, and Sasaki, 2005.12314

NANOGrav PBHs



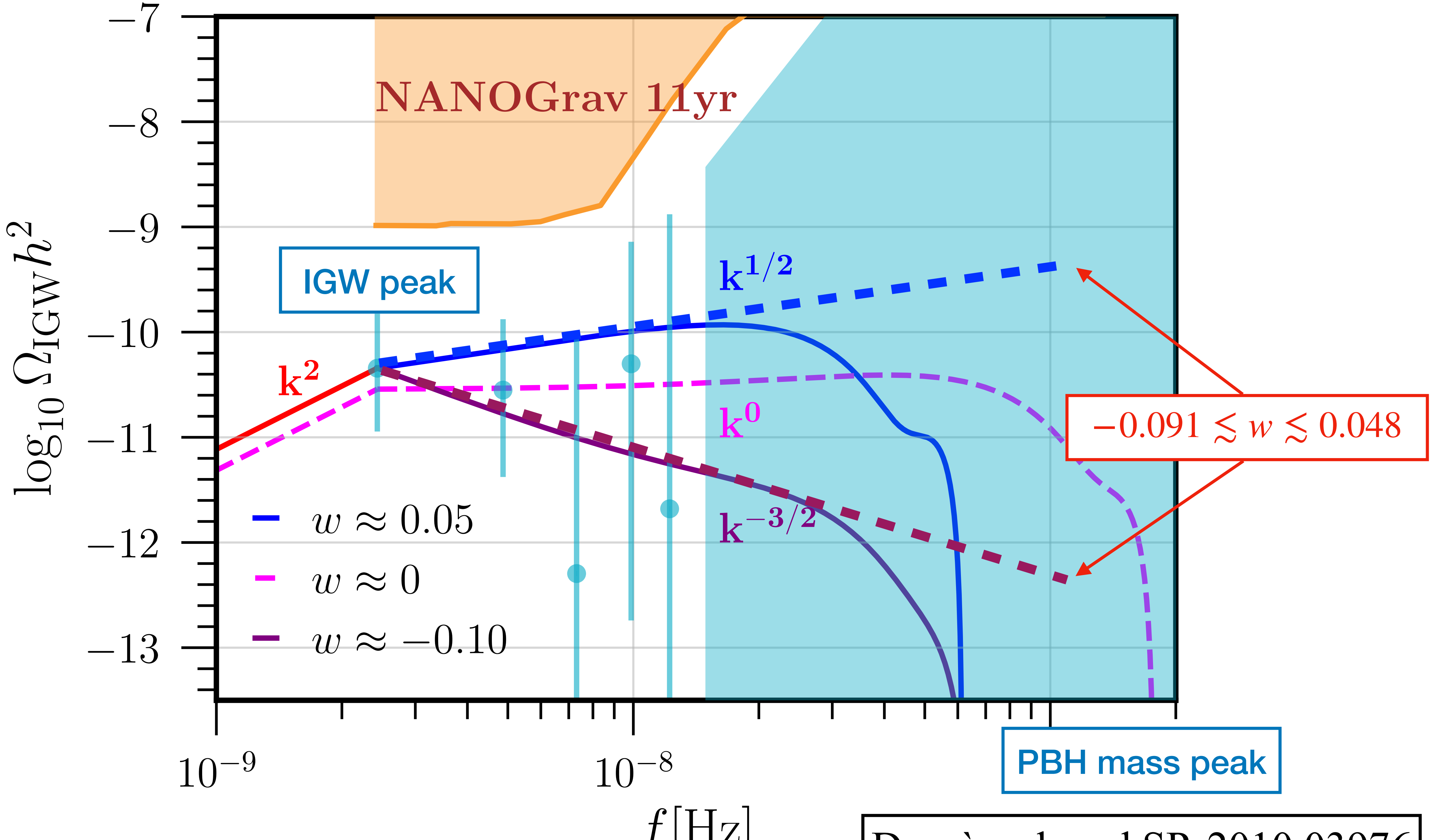
Domènech and SP, 2010.03976

NANOGrav PBHs



Domènech and SP, 2010.03976

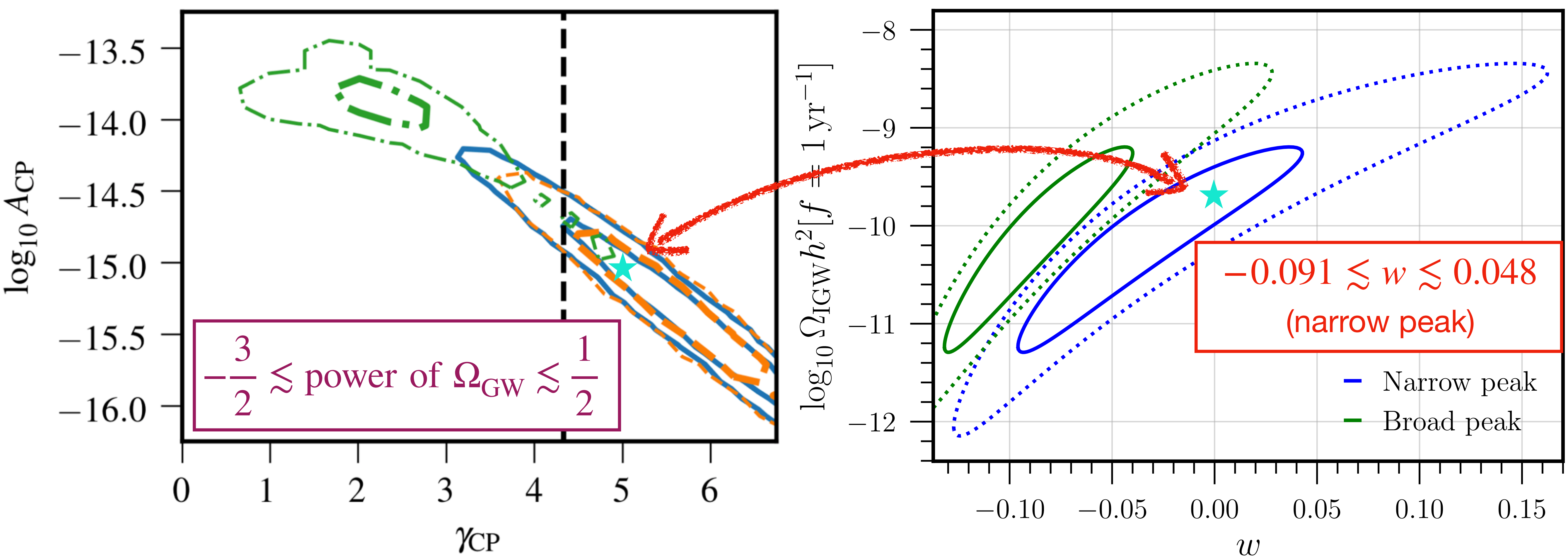
NANOGrav PBHs



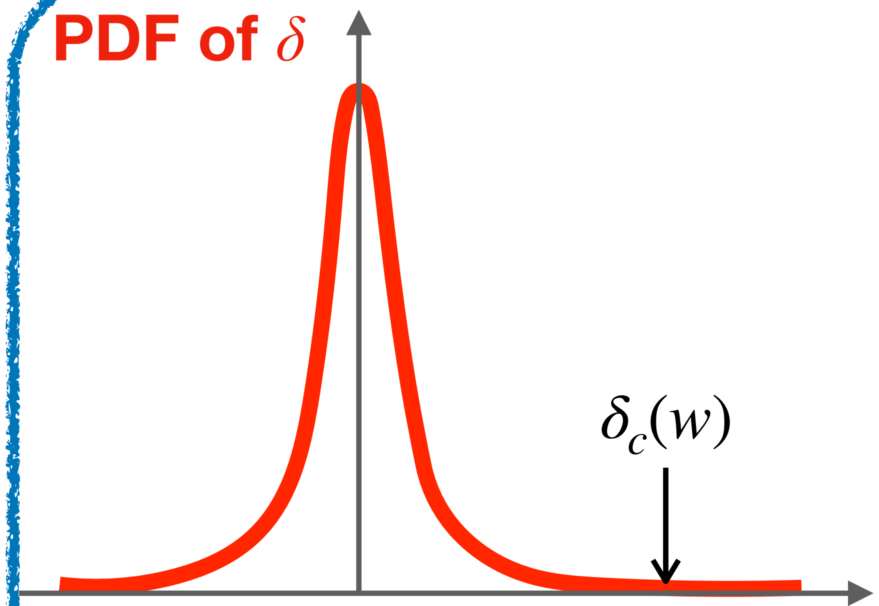
Domènech and SP, 2010.03976

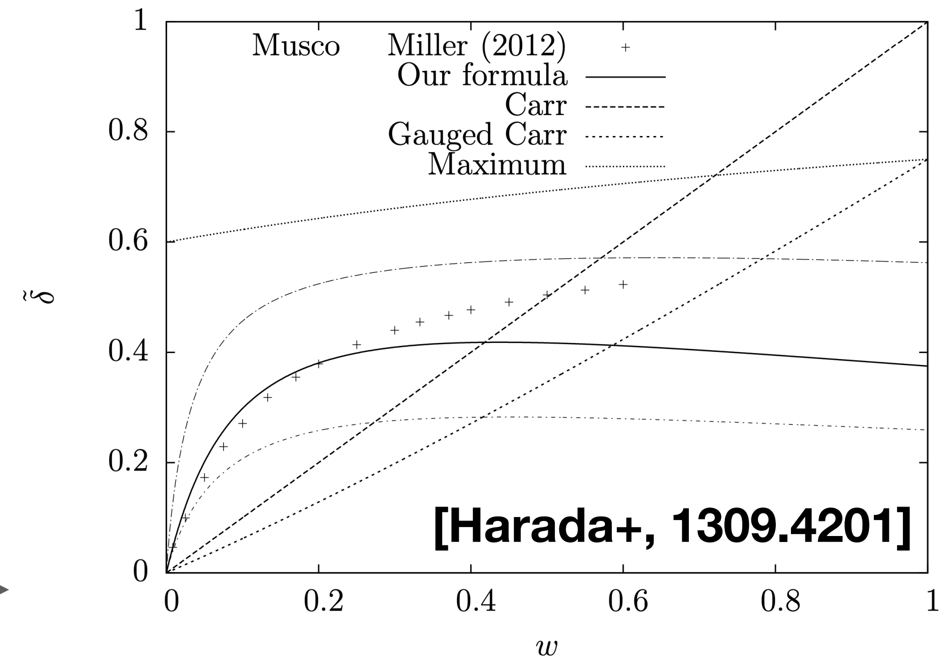
NANOGrav PBHs

$$\Omega_{\rm GW} = \frac{2\pi^2 f_{\rm yr}^2}{3H_0^2} A_{\rm SGWB}^2 \left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma_{\rm CP}}$$

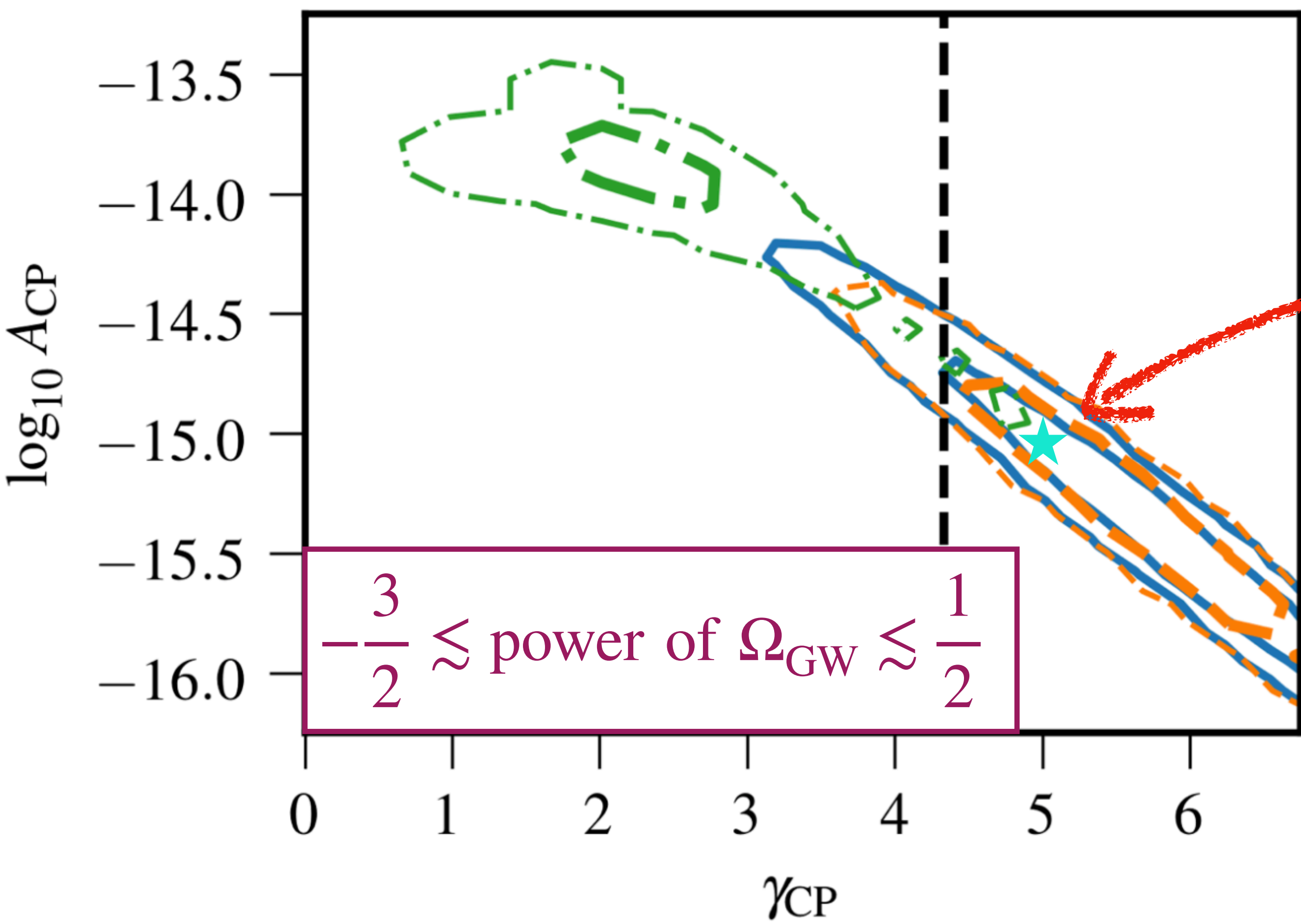


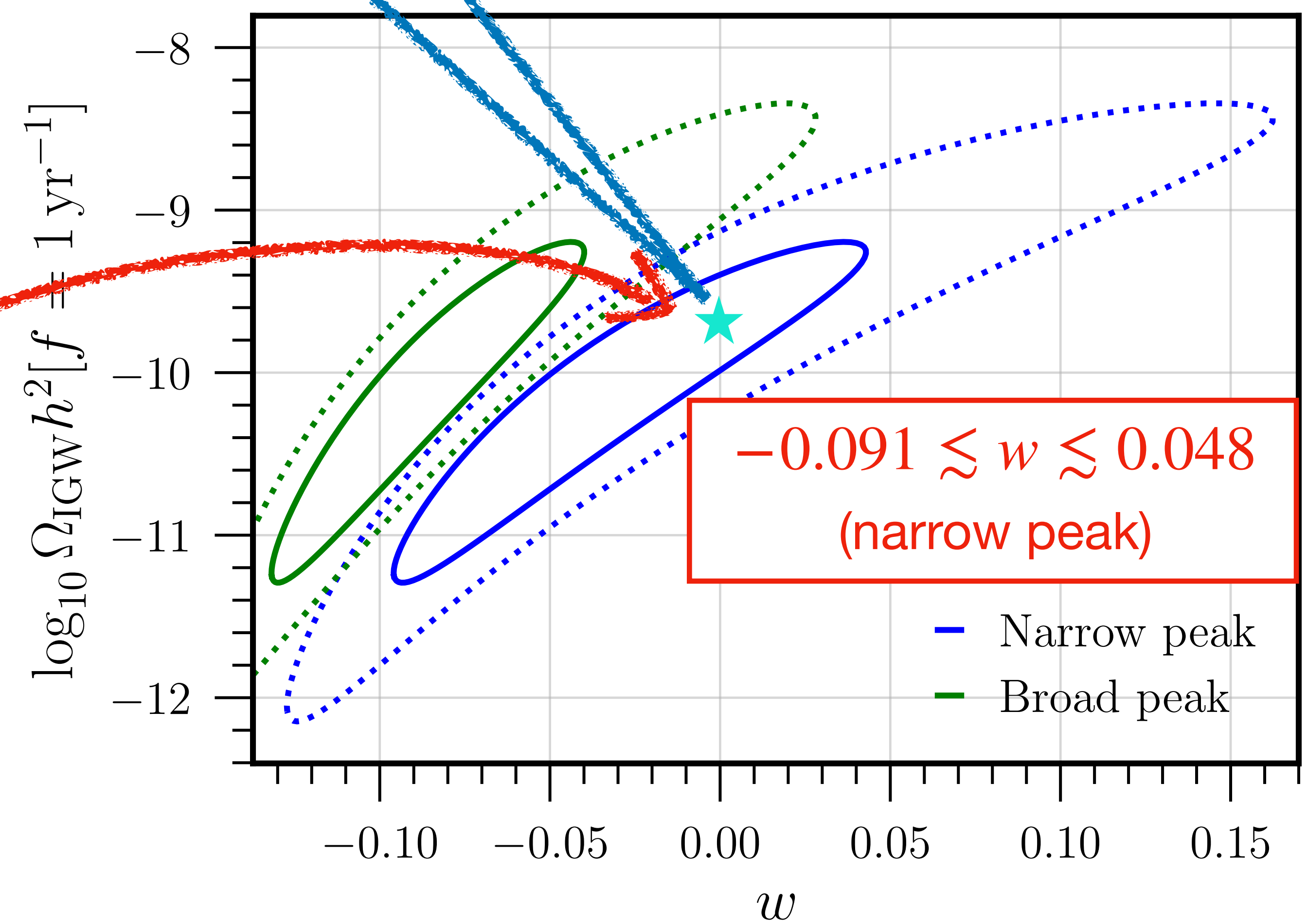
Domènech and SP, 2010.03976





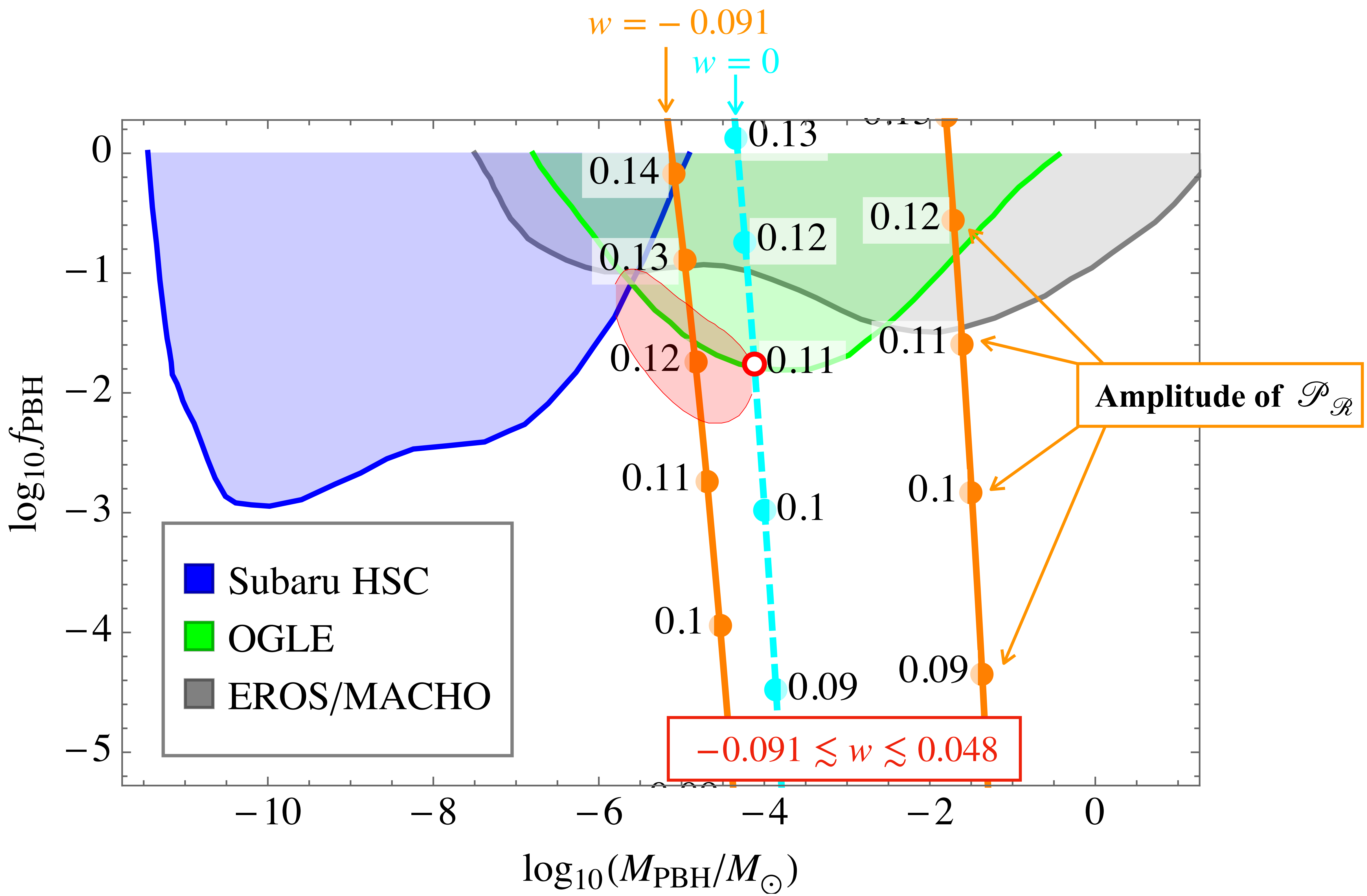
Softening of EoS can decrease δ_c, which enhances the PBH abundance.
We use a scalar-field dominated universe with exponential potential to avoid instability of $w<0$.





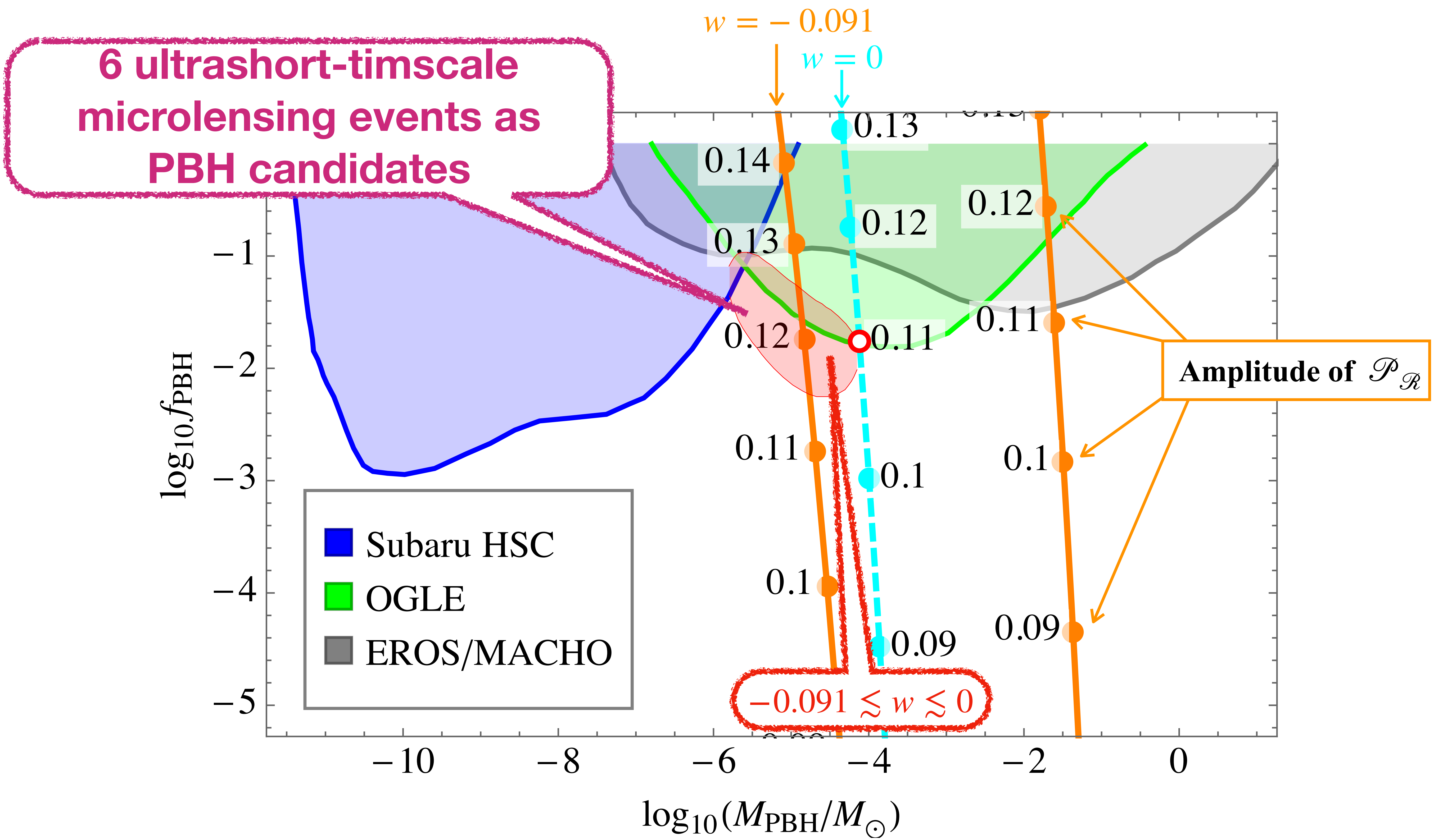
Domènech and SP, 2010.03976

NANOGrav PBHs



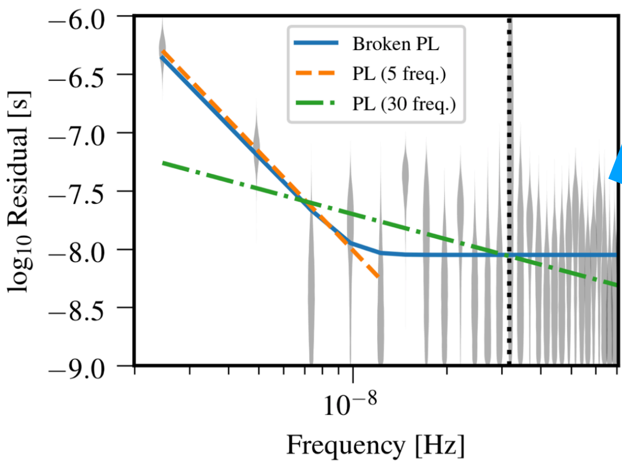
Domènech and SP, 2010.03976

NANOGrav PBHs

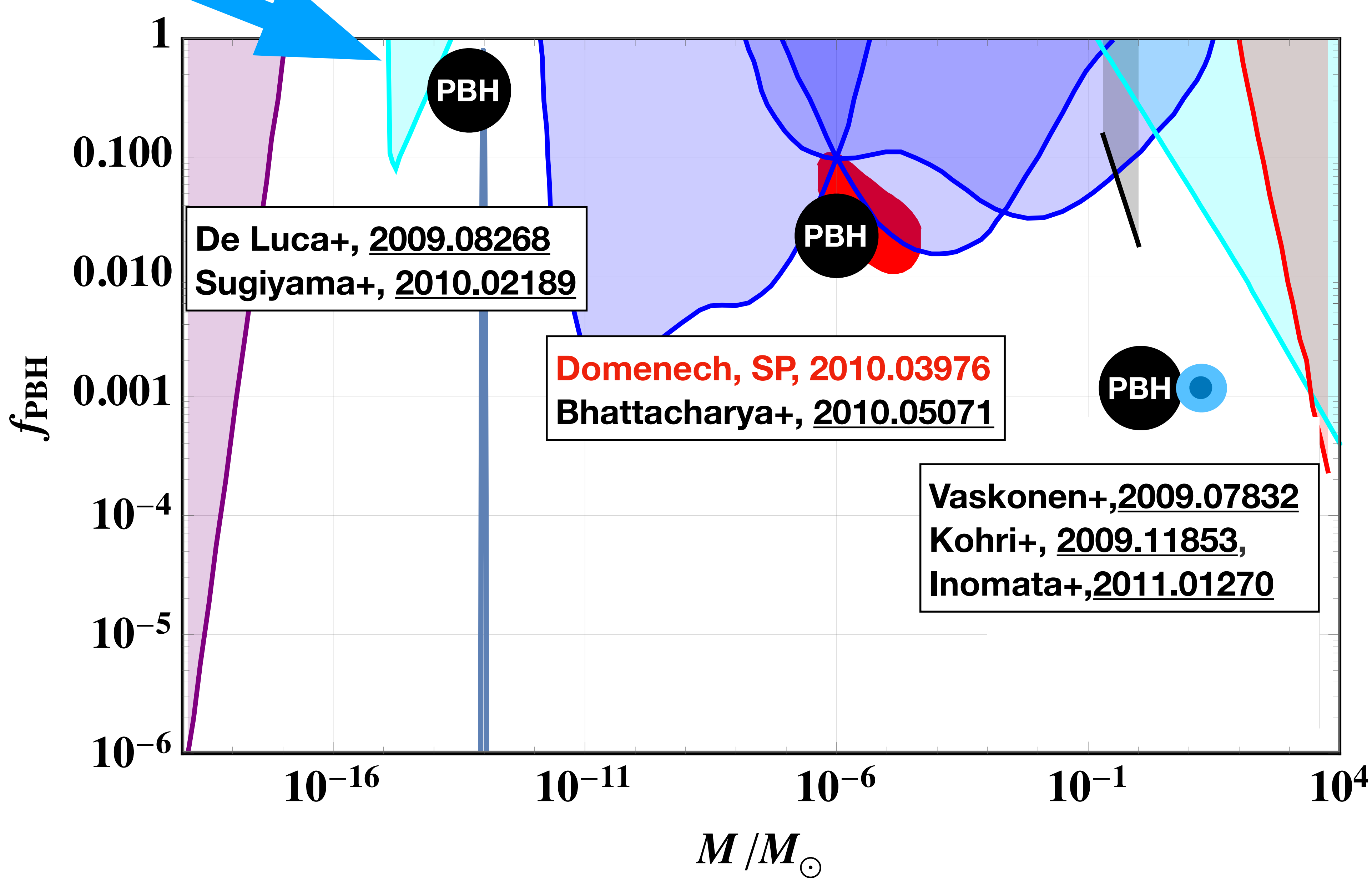


Domènech and SP, 2010.03976

Summary



Broken PL
PL (5 freq.)
PL (30 freq.)
−6.0
−6.5
−7.0
−7.5
−8.0
−8.5
−9.0
log10 Residual [s]
10−8
Frequency [Hz]



PBH
PBH
PBH
De Luca+, 2009.08268
Sugiyama+, 2010.02189
Domenech, SP, 2010.03976
Bhattacharya+, 2010.05071
Vaskonen+,2009.07832
Kohri+, 2009.11853,
Inomata+,2011.01270
1
0.100
0.010
0.001
10−4
10−5
10−6
fPBH
10−16
10−11
10−6
10−1
104
M /M⊙

Summary

- Infrared scaling can help us probe the thermal history of the universe and the energy scale of the source.

- Shape of IGW: The most crucial factor is the width of the peak of the scalar spectrum. We found analytical formulas for lognormal peaks (for RD), which is useful for signal searching in the future.

- NANOGrav result and planet-mass PBH: Possible detection of SGWB by NANOGrav can be connected to the recently reported planet-mass PBHs, if there is a dust-like era before ~150 MeV.

Thank you !