Primordial Black Hole Dark Matter

Based on Phys.Rev.Lett. 120(2018)191102 done with S. Wang, Y.F. Wang and T. Li
arXiv:1910.07397 done with Y.F. Wang, T. Li and S. Liao
ApJ 864(2018)61 and arXiv:1904.02396 done with Z.C. Chen
ApJ 871(2019)97 done with Z.C. Chen and F. Huang
Phys.Rev.D 100(2019)081301(R) & arXiv:1910.09099 & 1910.12239 done with Z.C. Chen and C. Yuan

LISA
Taiji
TianQin

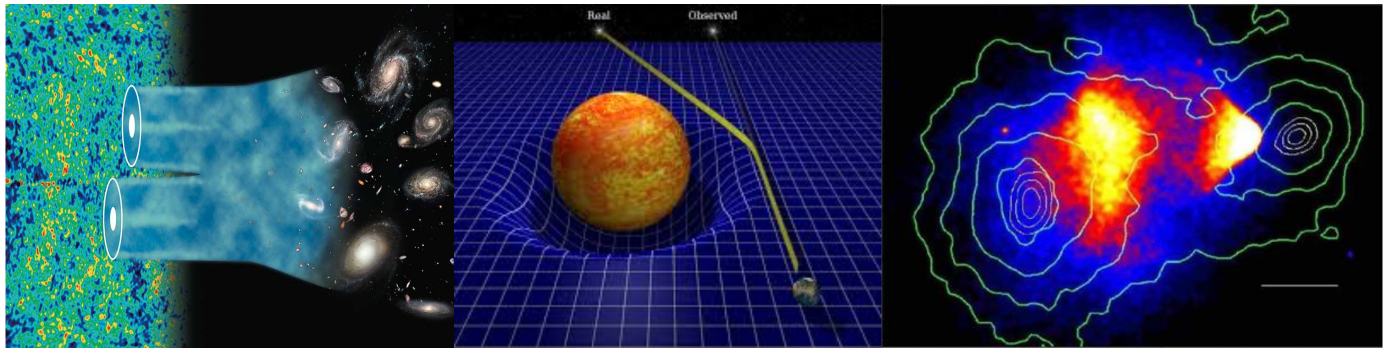
PPTA
IPTA
FAST
SKA

LIGO
Virgo
KAGRA

Qing-Guo Huang
Institute of theoretical physics, CAS

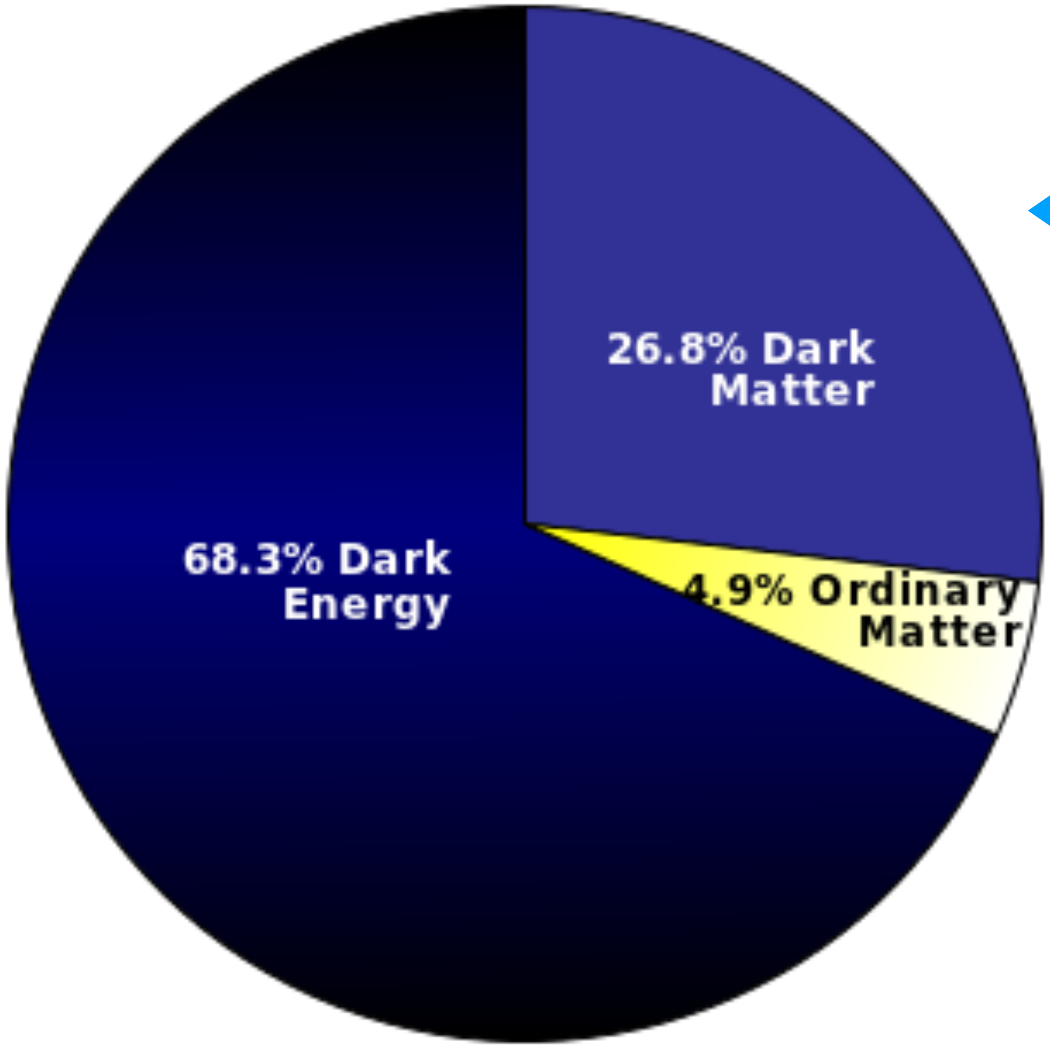
The nature of

Dark Matter



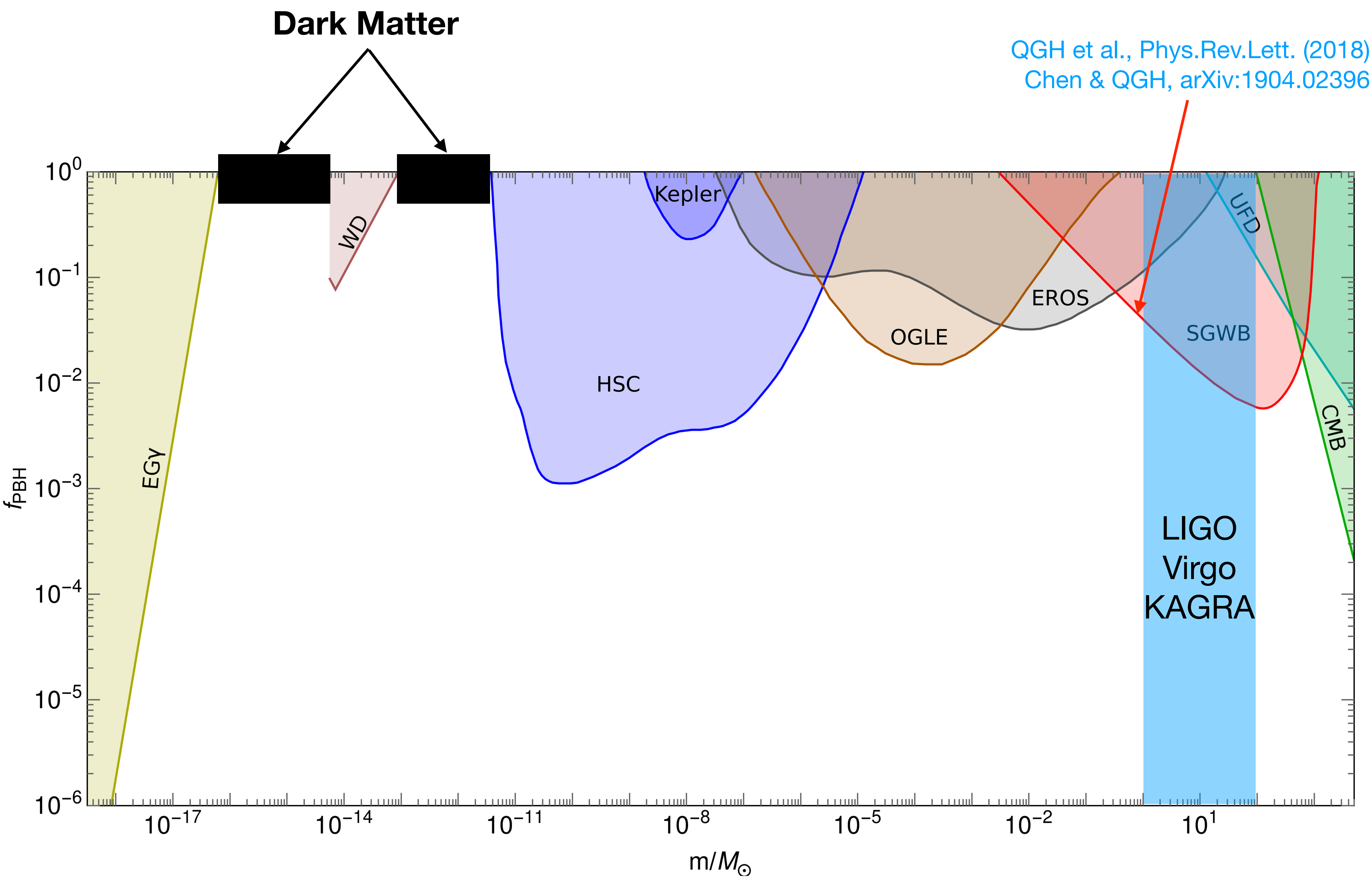
Planck 18 (CMB only): $\Omega_c h^2$ =0.1200±0.0012 (100σ)

Planck 18+BAO: $\Omega_c h^2$ =0.11933±0.00091 (131σ)



Primordial Black Hole

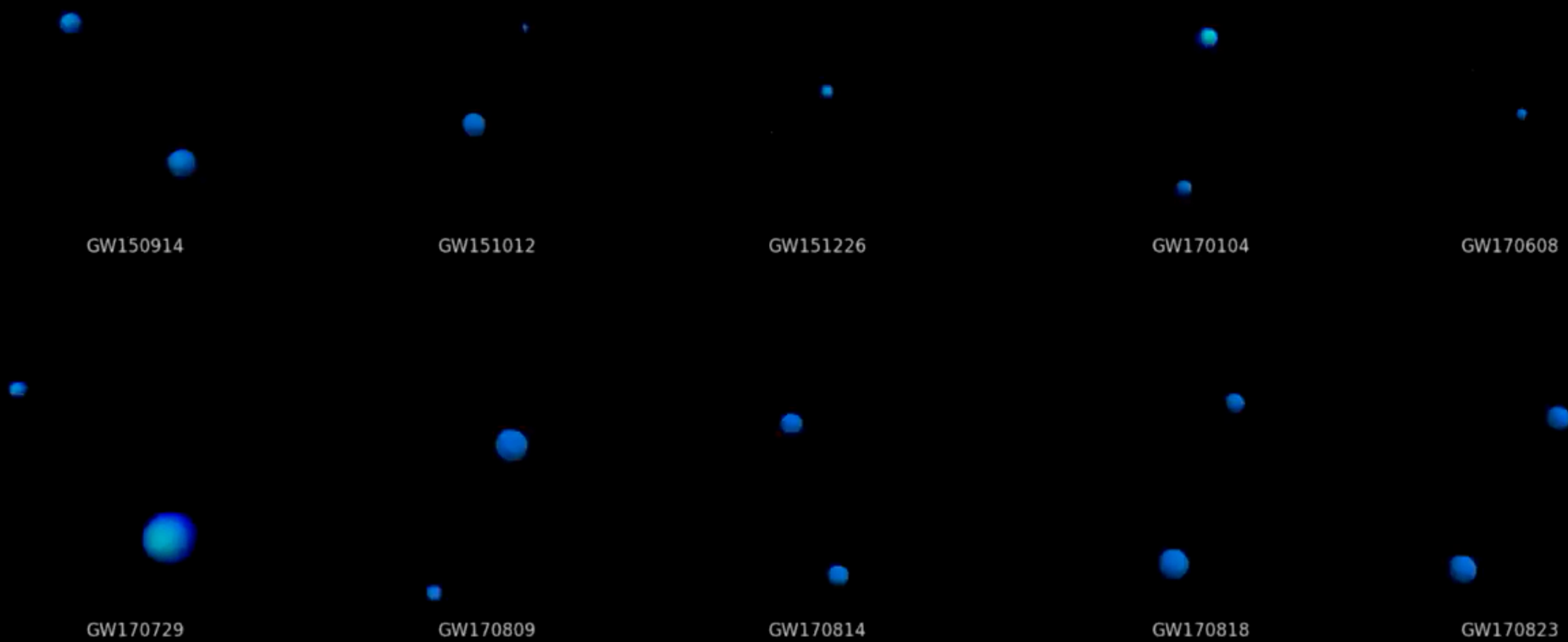
$$f_{\rm pbh} = \frac{\Omega_{\rm pbh}}{\Omega_{CDM}}$$



Dark Matter
QGH et al., Phys.Rev.Lett. (2018)
Chen & QGH, arXiv:1904.02396
Kepler
WD
HSC
OGLE
EROS
UFD
SGWB
CMB
EGγ
LIGO
Virgo
KAGRA
f_{PBH}
$m/M_{\odot}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-17}
10^{-14}
10^{-11}
10^{-8}
10^{-5}
10^{-2}
10^{1}

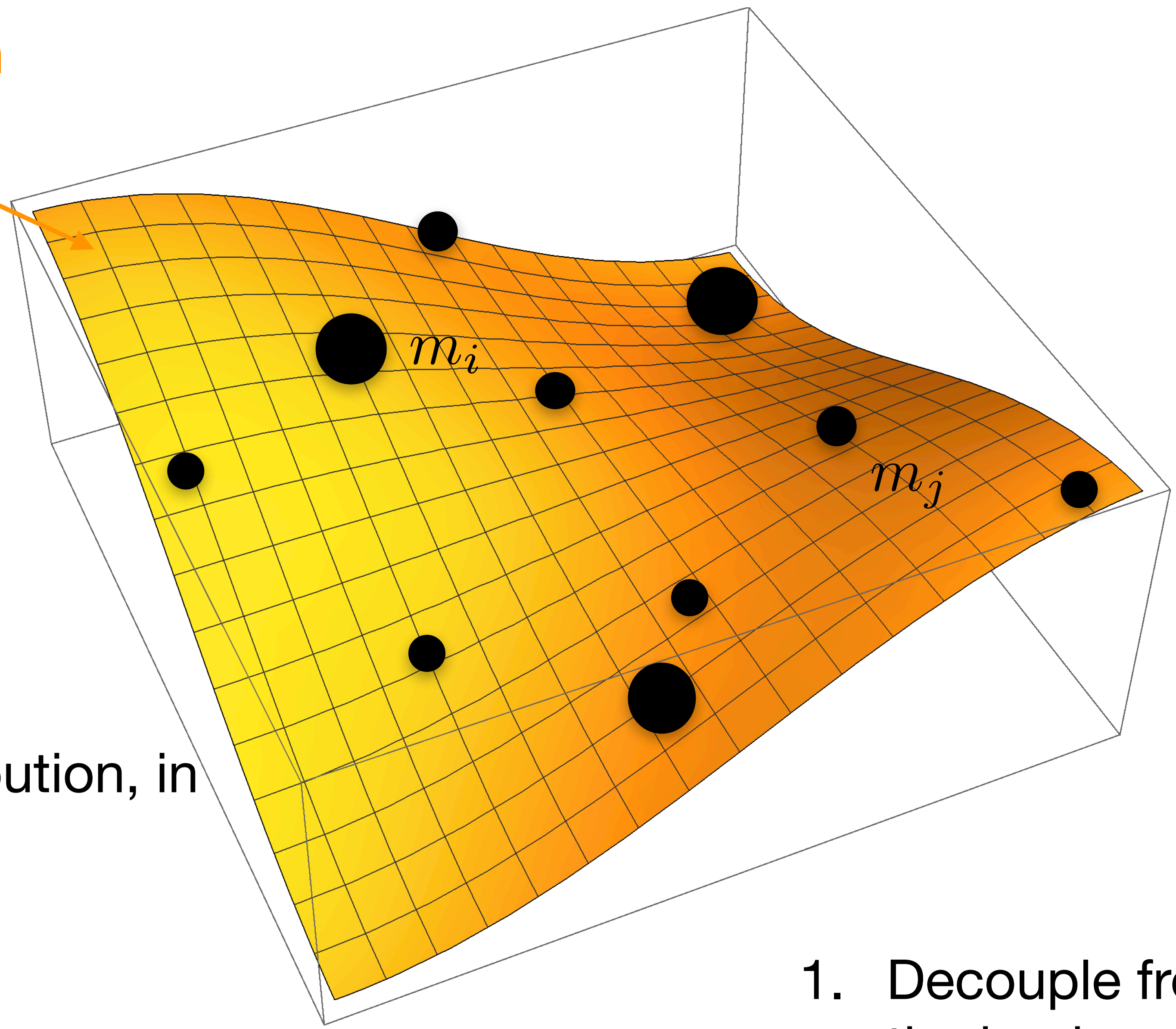
LIGO VIRGO SXS

Time: -0.63 seconds



Merger rate distribution [Chen & QGH, ApJ (2018); Chen, Huang & QGH, ApJ (2019); Chen & QGH, arXiv:1904.02396]

Density Perturbation

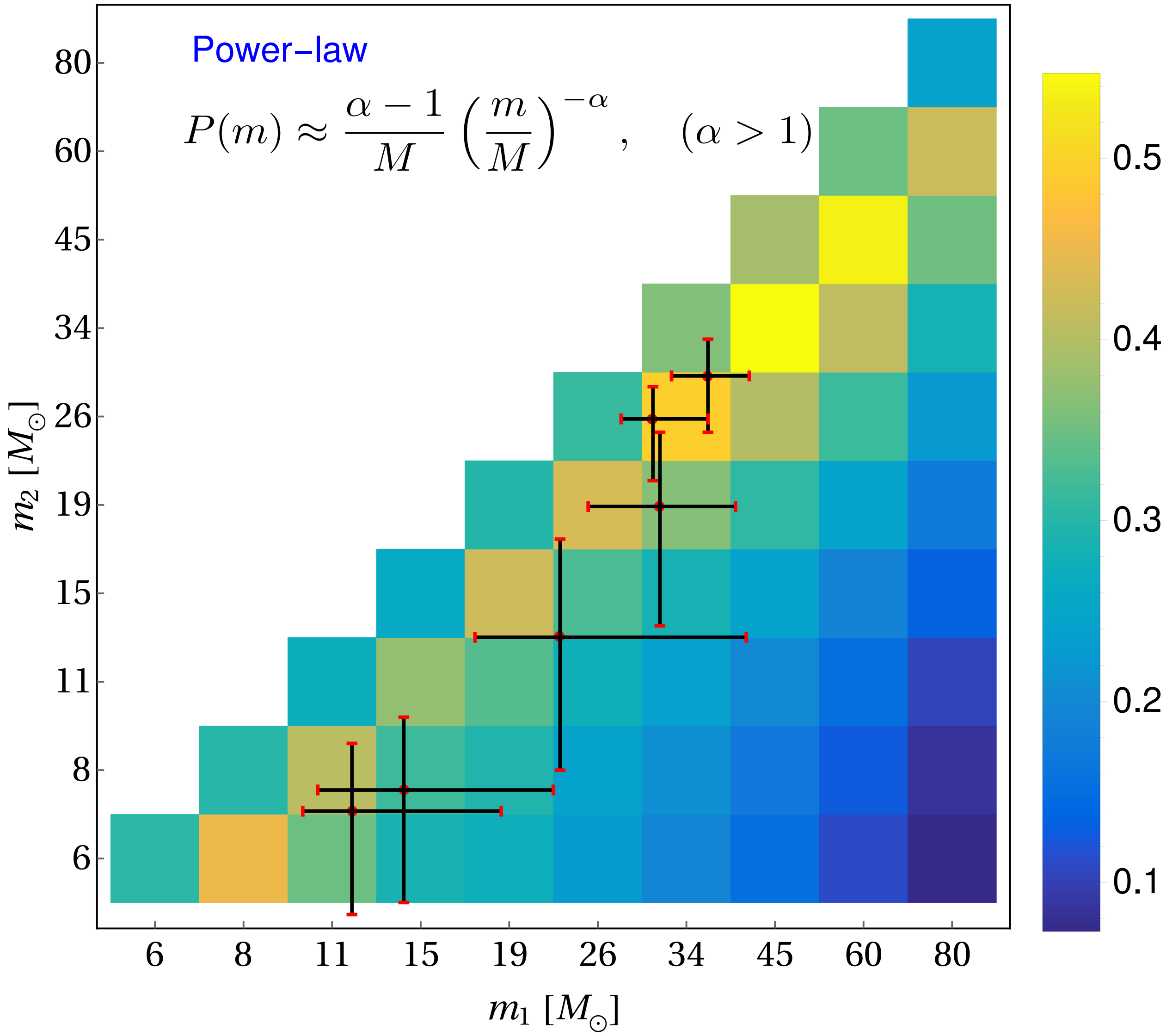


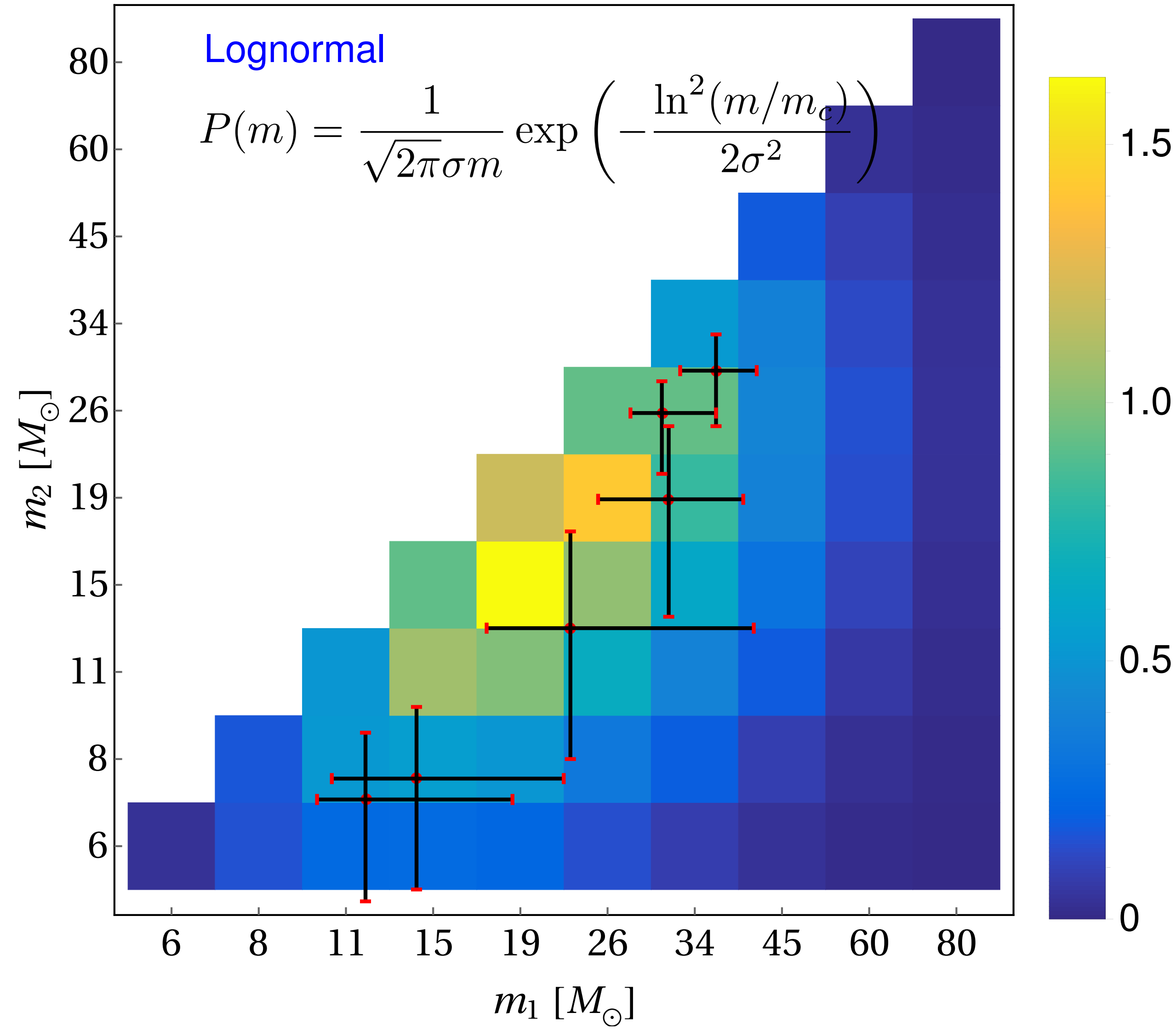
The merger rate distribution, in unit of **Gpc**$^{-3}$**yr**$^{-1}$

$$R_{ij}(t) = \mathcal{R}_{ij}\Delta^2$$

$$\mathcal{R}_{ij} \simeq 3.9 \cdot 10^6 \times \frac{\rho_m}{\rho_m^0}\left(\frac{t}{t_0}\right)^{-\frac{34}{37}} f^2(f^2+\sigma_{eq})^{-\frac{21}{74}} \times \min\left(\frac{P(m_i)}{m_i}, \frac{P(m_j)}{m_j}\right)\left(\frac{P(m_i)}{m_i}+\frac{P(m_j)}{m_j}\right) \times (m_i m_j)^{\frac{3}{37}}(m_i+m_j)^{\frac{36}{37}}$$

1. Decouple from the expansion of the background
2. Torques by all other PBHs and density perturbations provides an initial angular momentum
3. Coalescence due to GW radiations



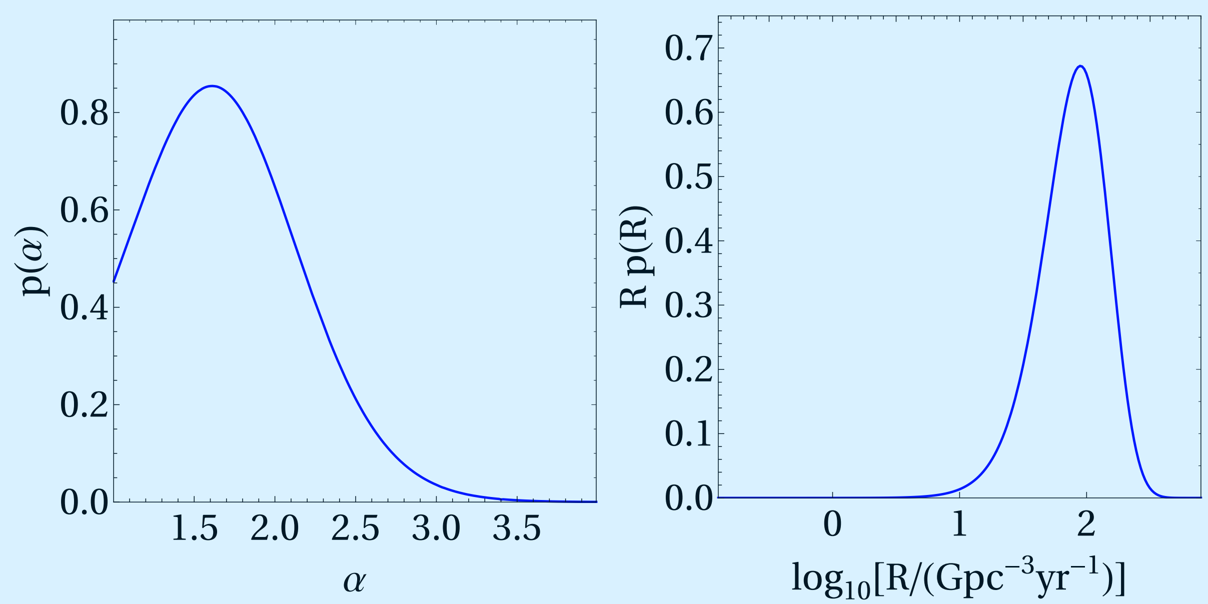


Averaged sensitive spacetime volume of LIGO

$$\Lambda_{ij} = \int_0^1 R_{ij}\frac{d\langle VT\rangle}{dz}dz$$

LIGO O1

$$P(m) = \frac{\alpha - 1}{M_{\min}} \left(\frac{m}{M_{\min}} \right)^{-\alpha} \quad \text{for } M_{\min} = 5 M_\odot$$

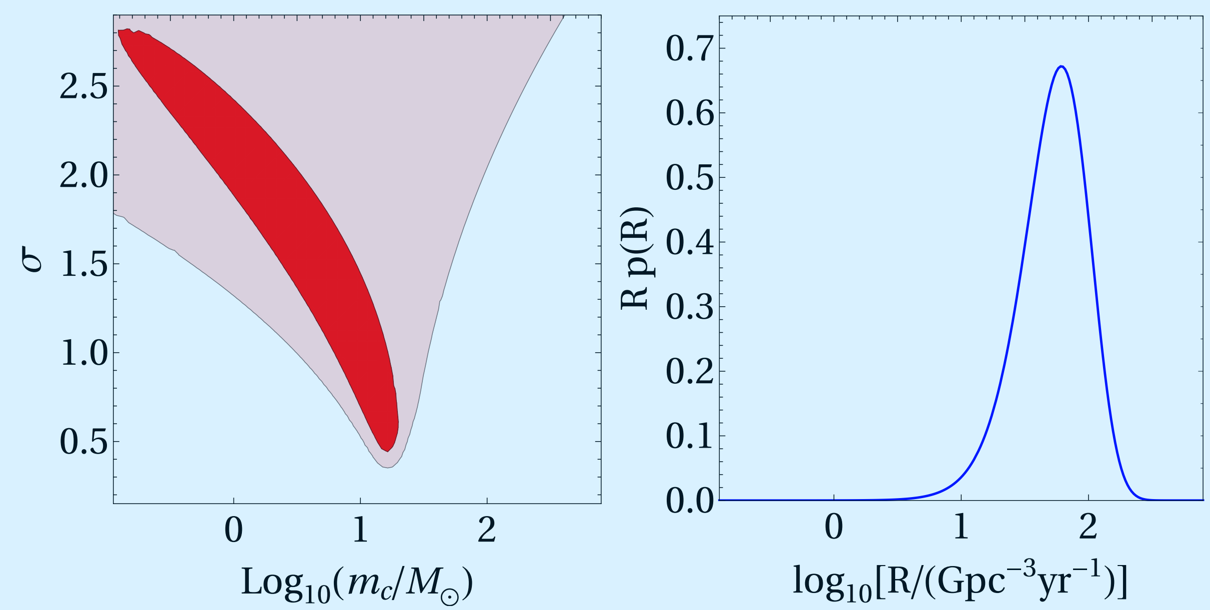


$$\alpha = 1.61 \text{ (best fit value)}$$

$$R = 80^{+108}_{-56} \text{ Gpc}^{-3}\text{yr}^{-1}$$

$$f_{pbh} = 3.8^{+2.3}_{-1.8} \times 10^{-3}$$

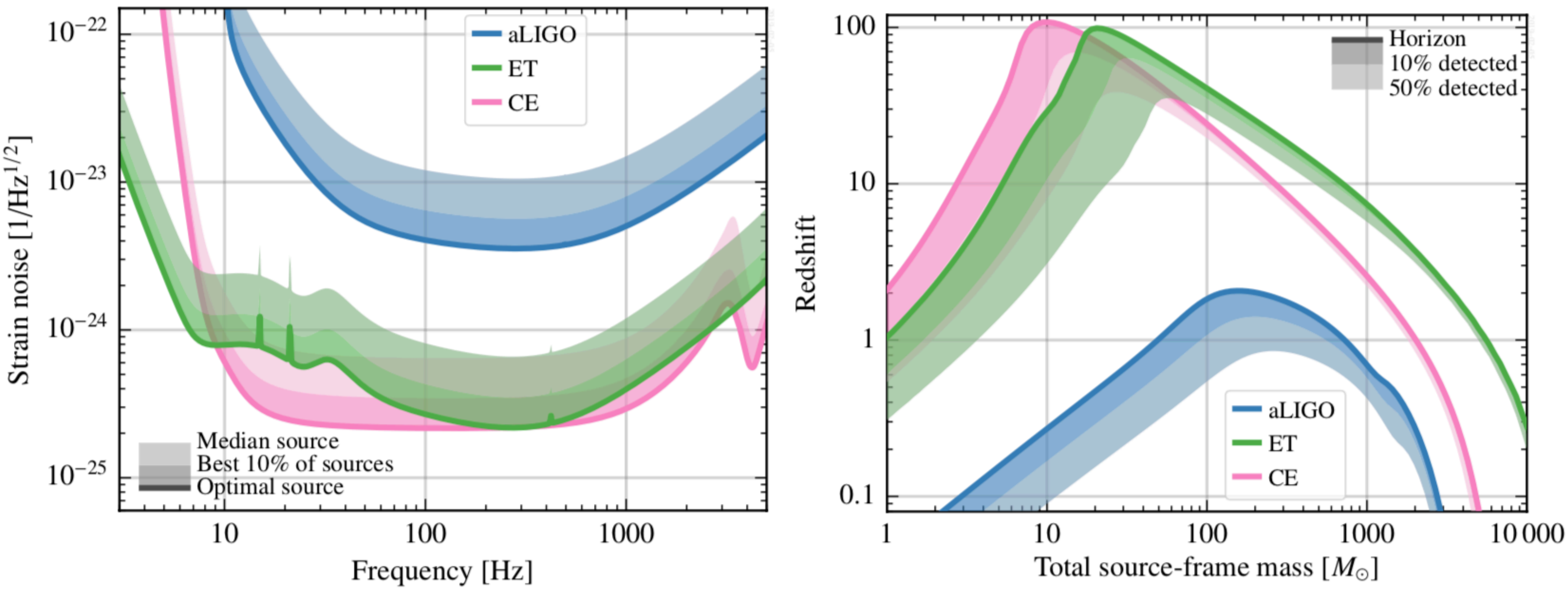
$$P(m) = \frac{1}{\sqrt{2\pi}\sigma m} \exp\left(-\frac{\log^2(m/m_c)}{2\sigma^2} \right)$$

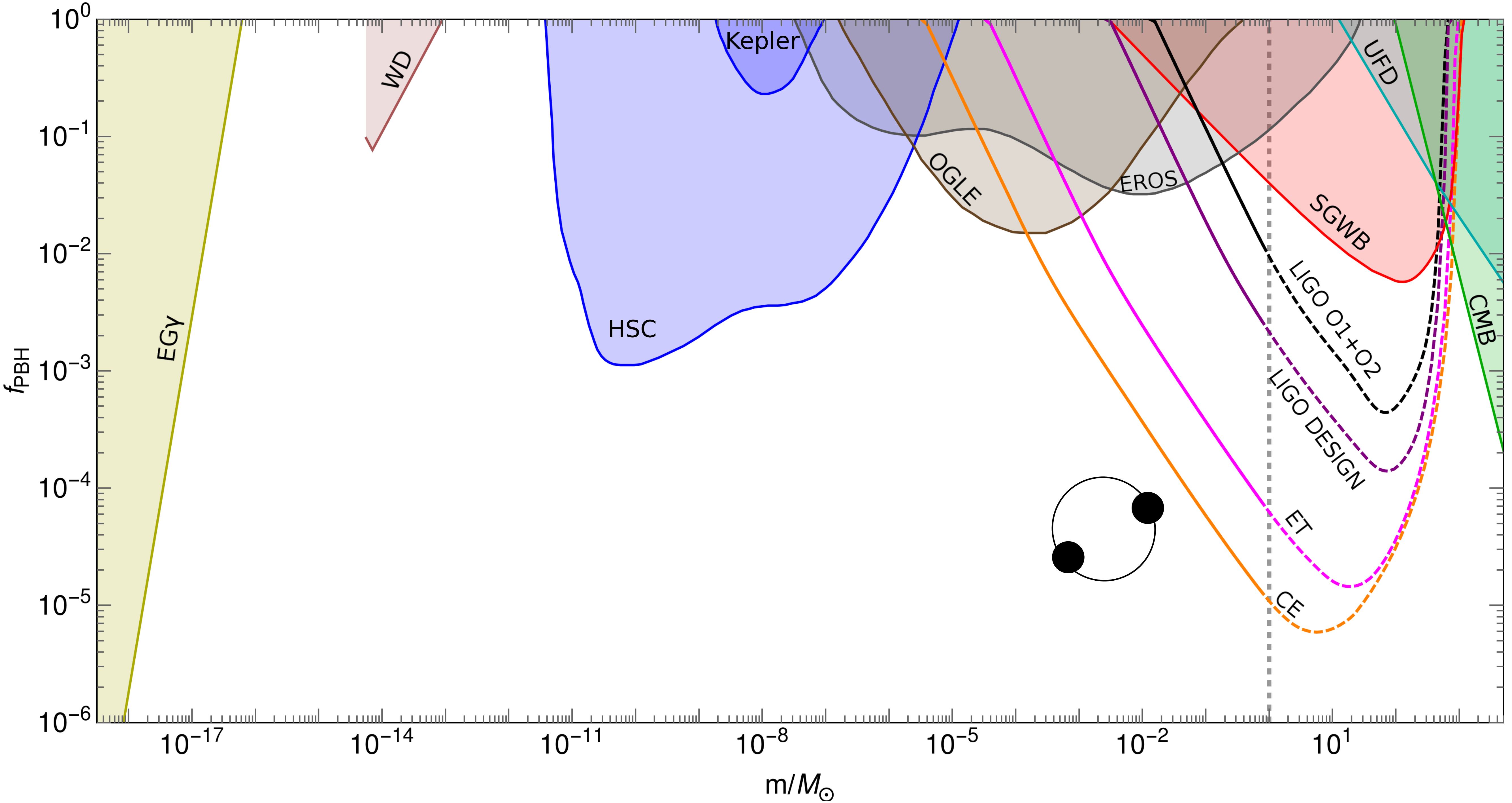


$$m_c = 14.8 M_\odot, \ \sigma = 0.65 \text{ (best fit value)}$$

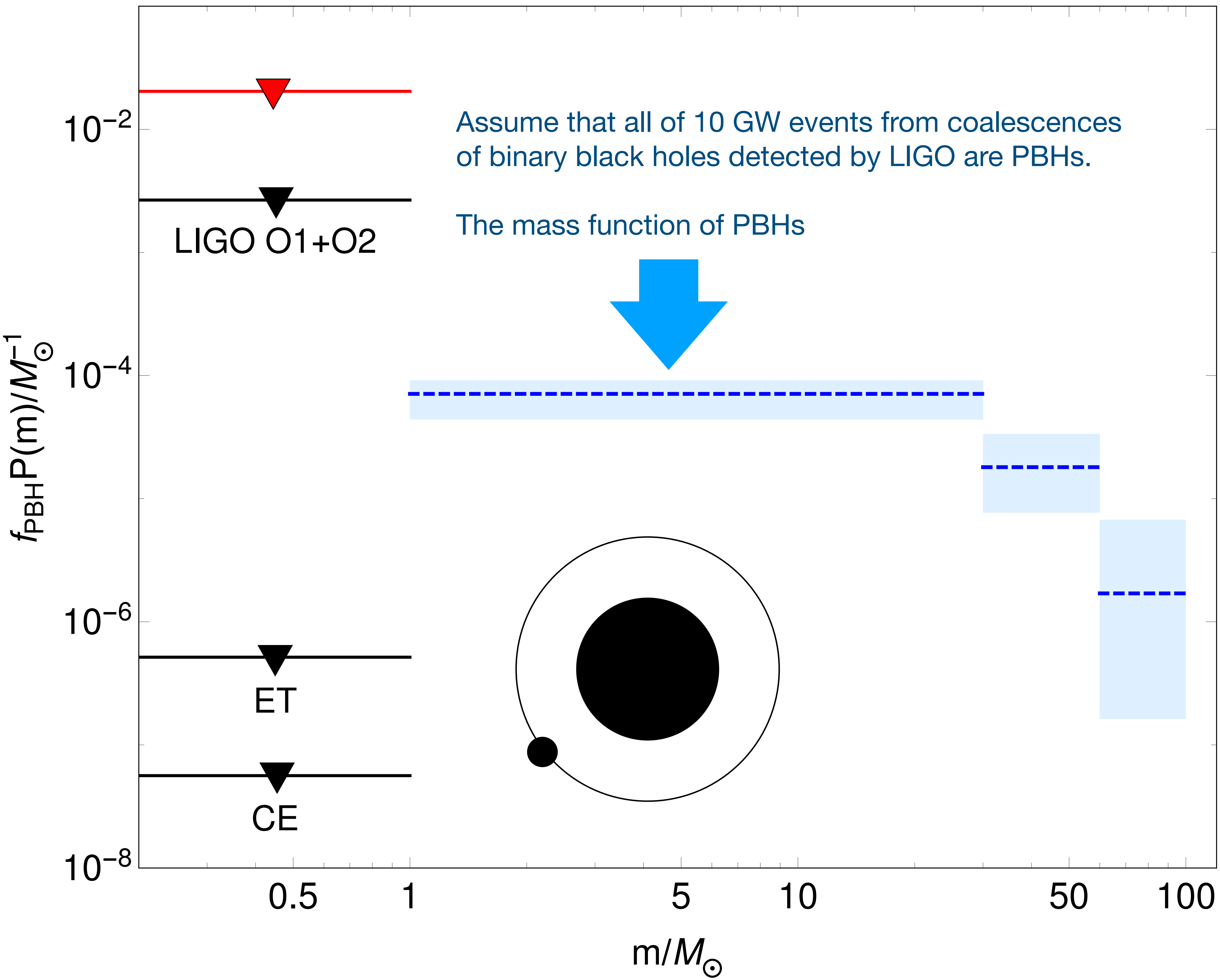
$$R = 55^{+74}_{-38} \text{ Gpc}^{-3}\text{yr}^{-1}$$

$$f_{pbh} = 2.8^{+1.6}_{-1.3} \times 10^{-3}$$


aLIGO
ET
CE
Median source
Best 10% of sources
Optimal source
Strain noise [1/Hz$^{1/2}$]
Frequency [Hz]
Horizon
10% detected
50% detected
Redshift
Total source-frame mass [$M_\odot$]

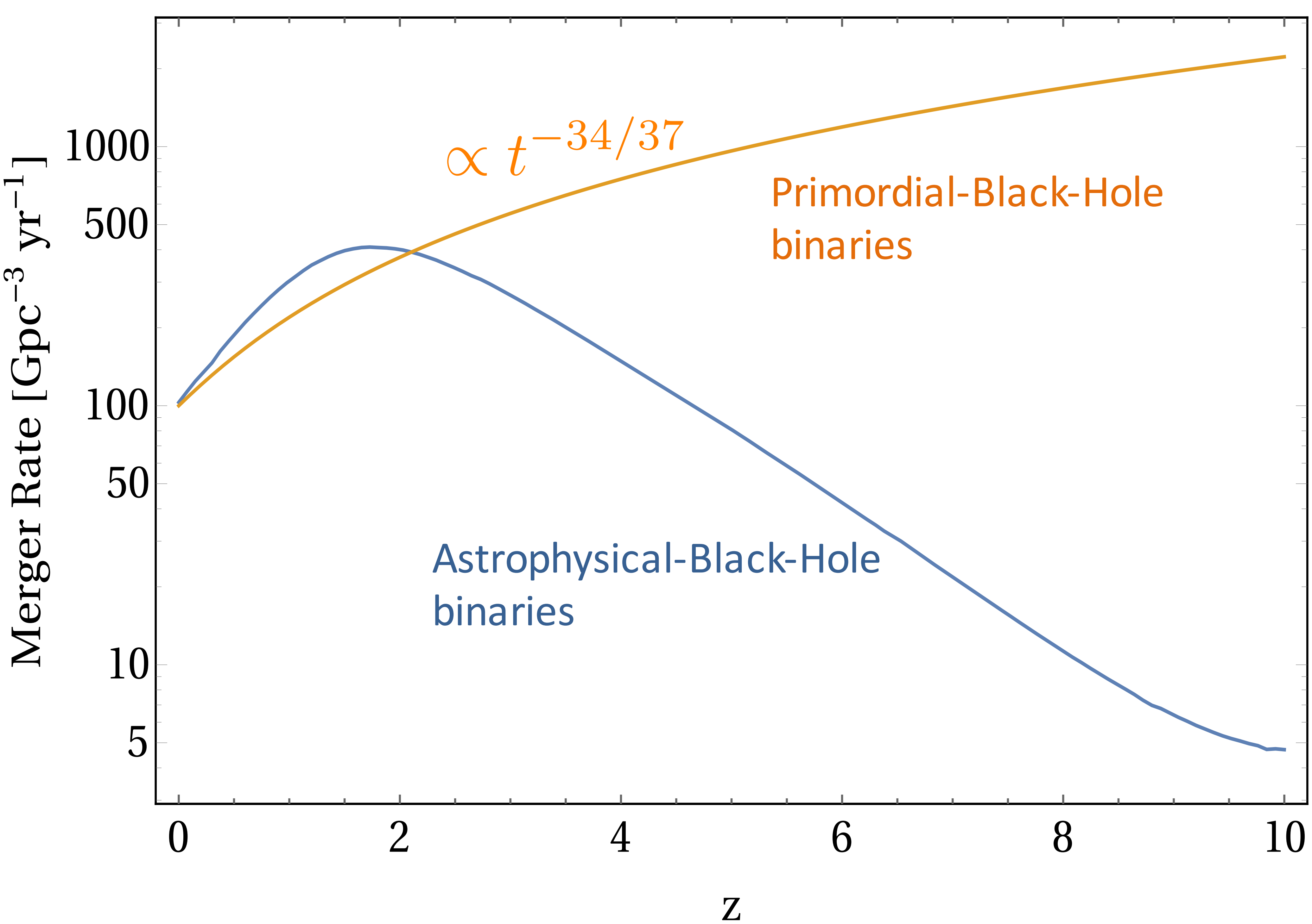


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$f_{\rm PBH}$
10^{-17}
10^{-14}
10^{-11}
10^{-8}
10^{-5}
10^{-2}
10^{1}
$m/M_\odot$
EGγ
WD
HSC
Kepler
OGLE
EROS
SGWB
UFD
CMB
LIGO O1+O2
LIGO DESIGN
ET
CE

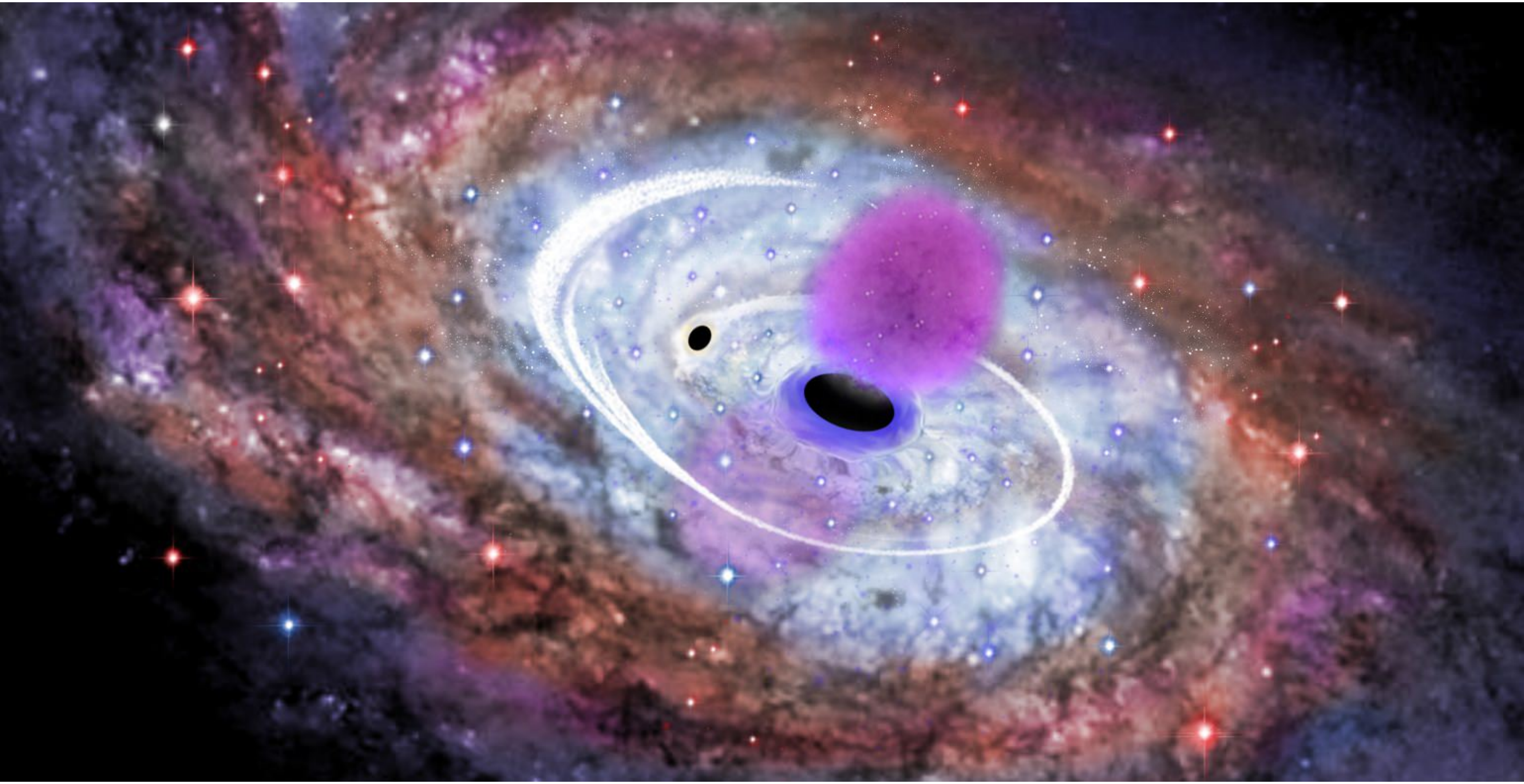


Assume that all of 10 GW events from coalescences of binary black holes detected by LIGO are PBHs.
The mass function of PBHs
LIGO O1+O2
ET
CE
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$f_{\rm PBH}P(m)/M_\odot^{-1}$
0.5
1
5
10
50
100
$m/M_\odot$

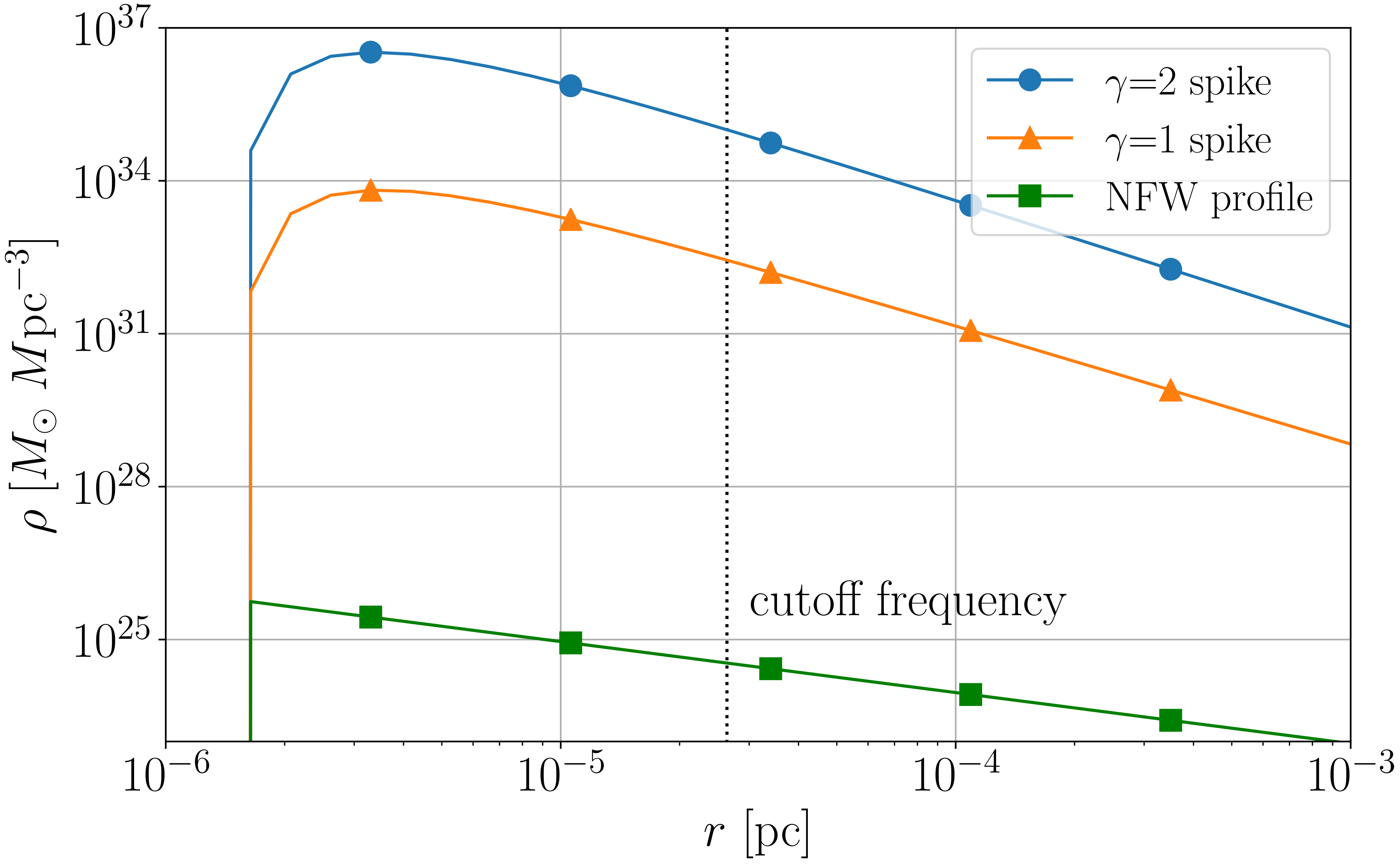
$$\mathcal{R}_{ij} \simeq 3.9 \cdot 10^6 \times \frac{\rho_m}{\rho_m^0} \left(\frac{t}{t_0}\right)^{-\frac{34}{37}} f^2 (f^2 + \sigma_{eq})^{-\frac{21}{74}}$$
$$\times \min\left(\frac{P(m_i)}{m_i}, \frac{P(m_j)}{m_j}\right) \left(\frac{P(m_i)}{m_i} + \frac{P(m_j)}{m_j}\right)$$
$$\times (m_i m_j)^{\frac{3}{37}} (m_i + m_j)^{\frac{36}{37}}$$



PBHs in the center of galaxies [Y.F. Wang, QGH, T. Li and S. Liao, arXiv:1910.07397]



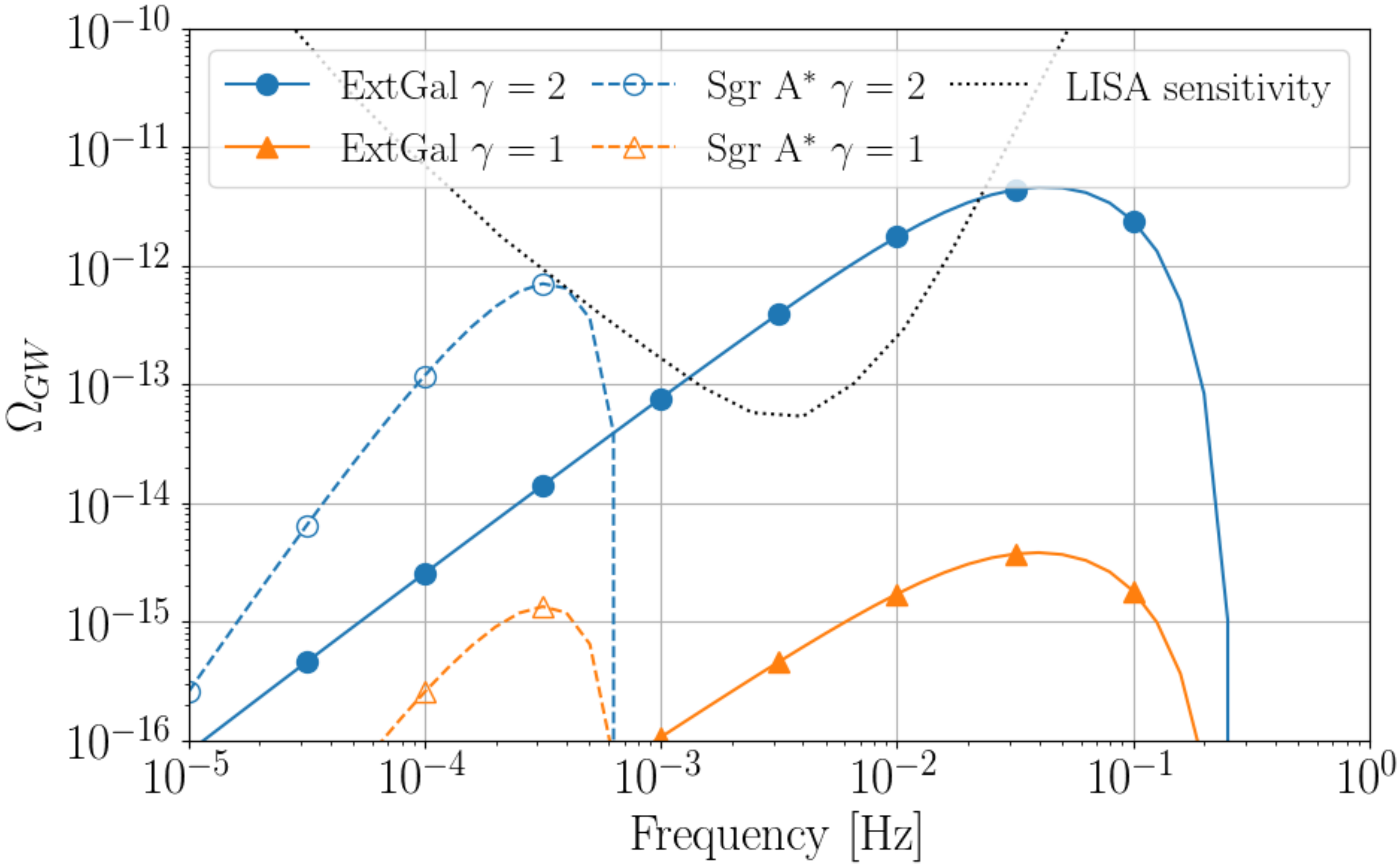
Matter distribution in the center of galaxies



$$\rho_{sp} = \rho_R \left(1 - \frac{4R_s}{r}\right)^3 \left(\frac{R_{sp}}{r}\right)^{\gamma_{sp}}$$

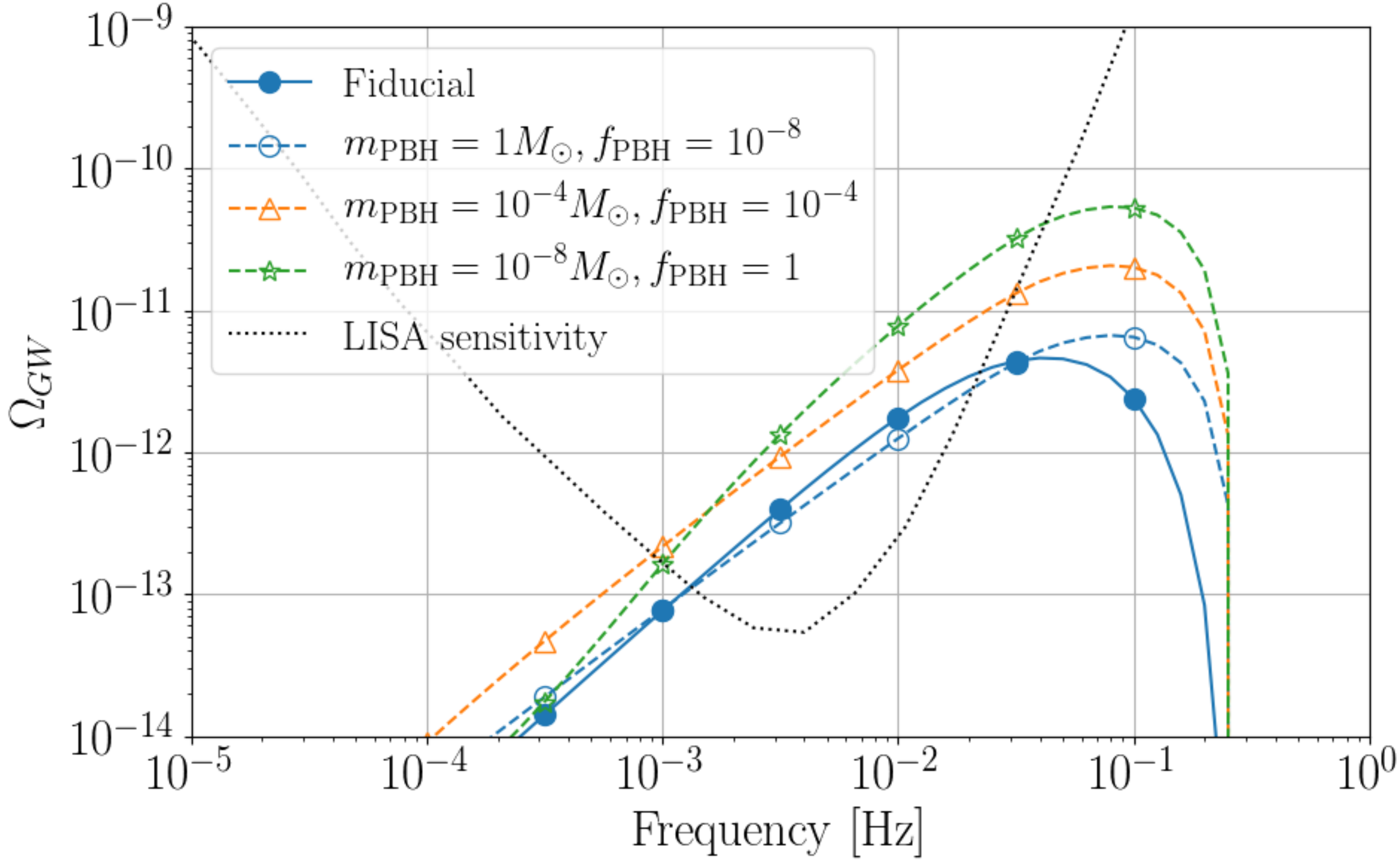
$$\gamma_{sp} = (9 - 2\gamma)/(4 - \gamma)$$

SGWB from PBHs surrounding Sgr A* and in the extragalactic massive BHs

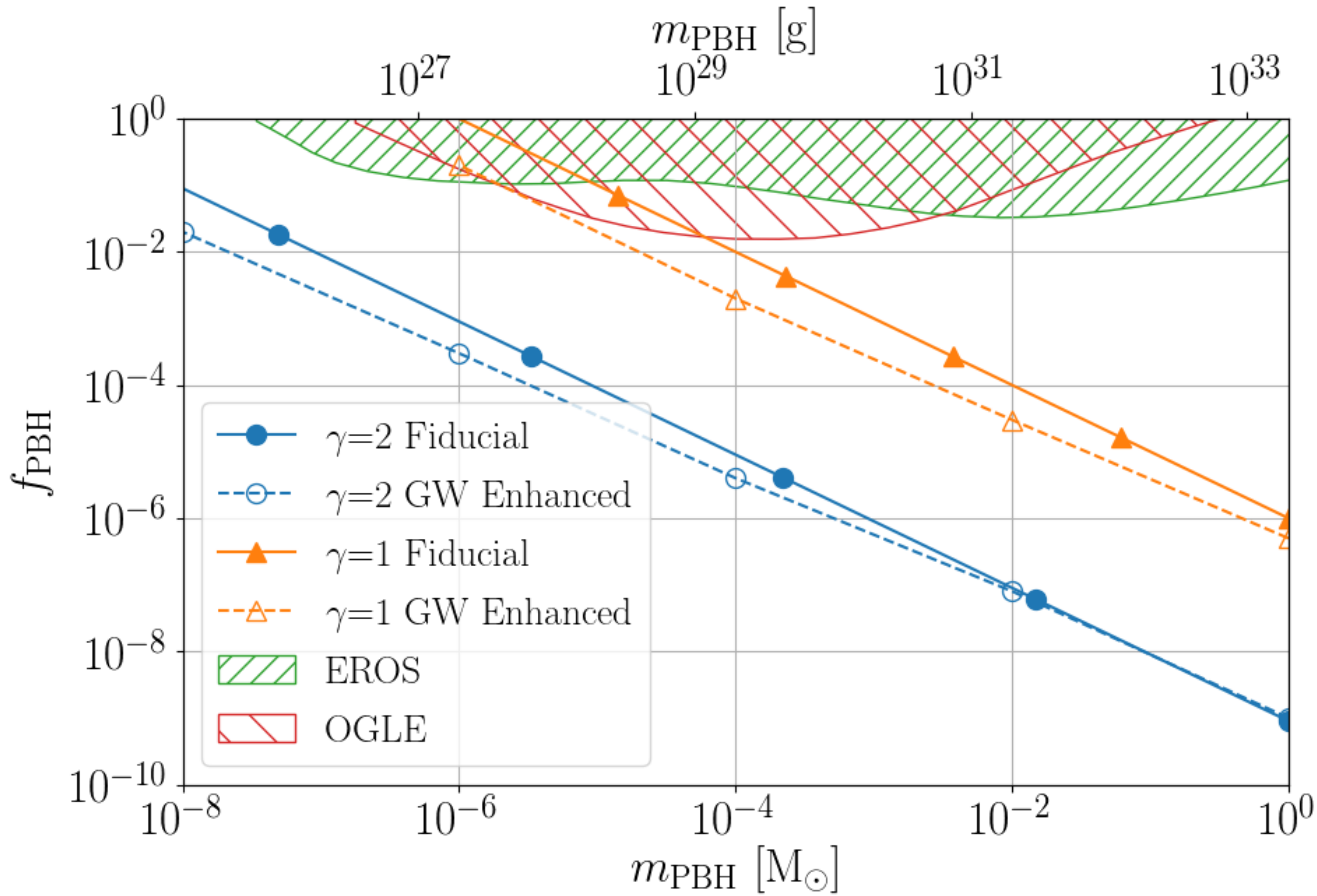


$(m_{PBH} = 1M_{\odot}, f_{PBH} = 10^{-8})$

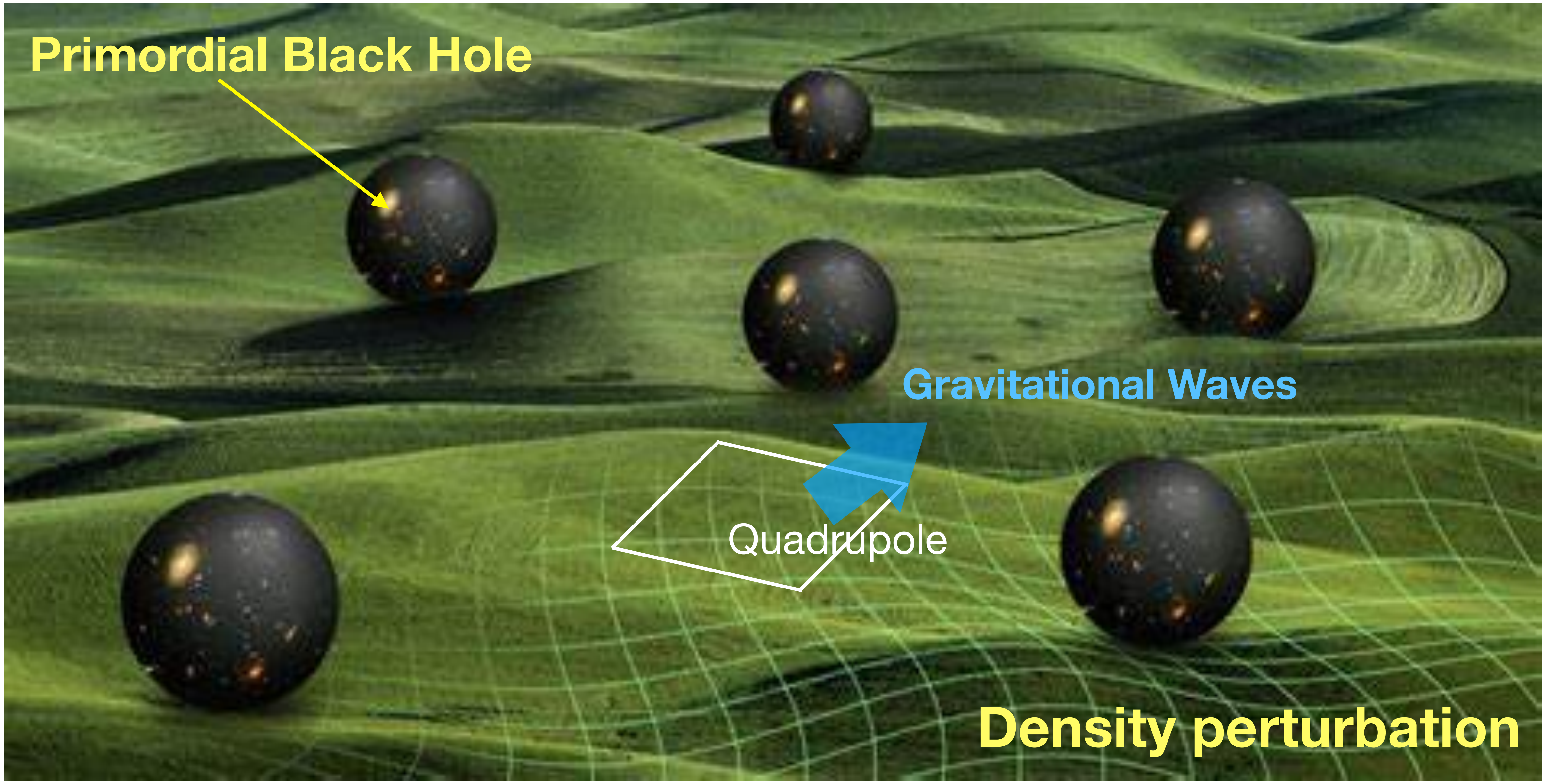
Enhancement due to GW dissipation



The projected constraints on PBH abundance in DM



Scalar induced GWs (SIGW) [Yuan, Chen & QGH, Phys.Rev.D (Rapid Communication) (2019) & arXiv:1910.09099; Chen, Yuan & QGH, arXiv:1910.12239]



$$\mathrm{d}s^2 = a^2 \left\{ -(1+2\phi)\mathrm{d}\eta^2 + \left[(1-2\phi)\delta_{ij} + \frac{h_{ij}}{2} \right] \mathrm{d}x^i \mathrm{d}x^j \right\}$$

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4\mathcal{T}_{ij}^{\ell m} S_{\ell m}$$

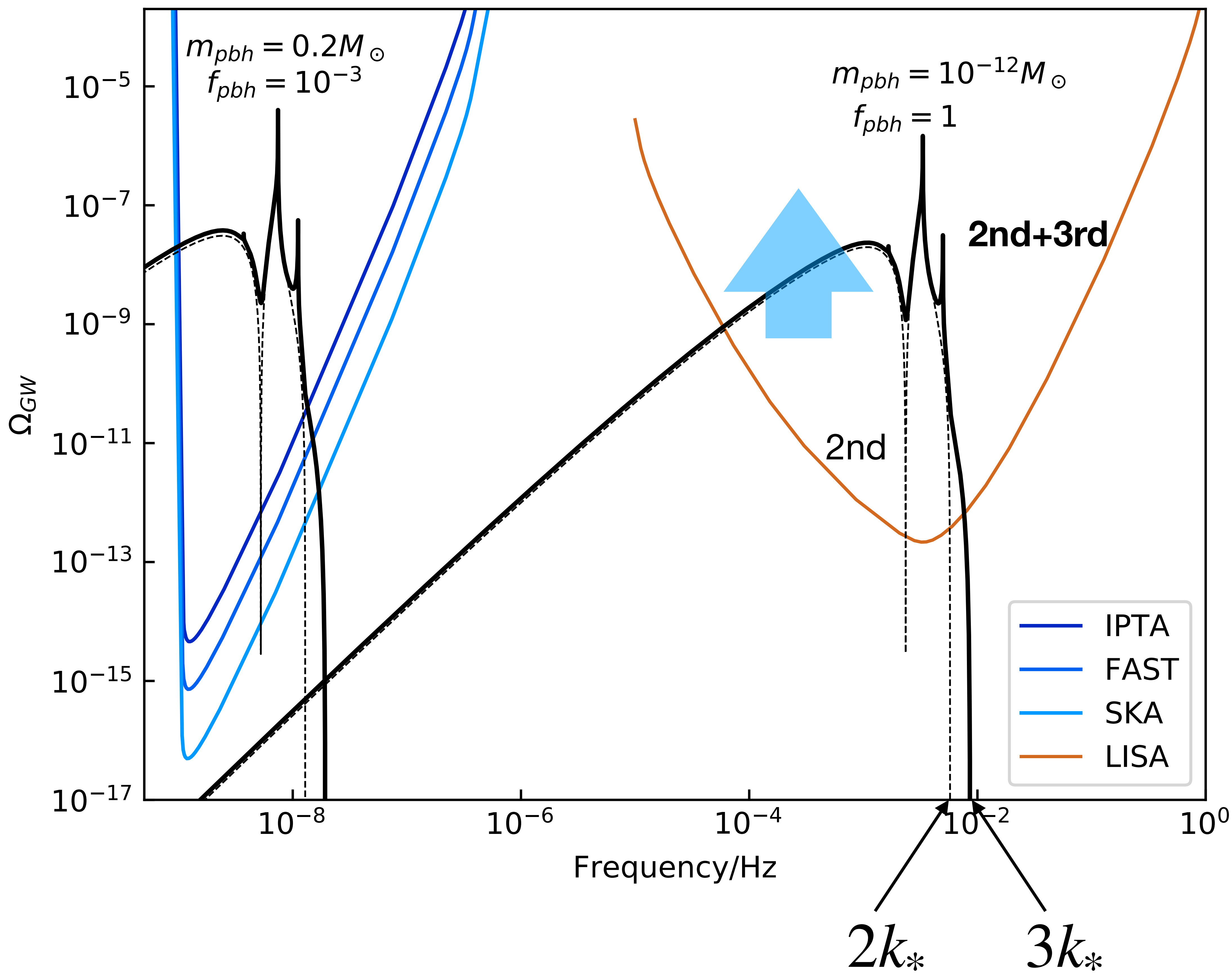
$$S_{ij}^{(2)} = 4\phi\partial_i\partial_j\phi + 2\partial_i\phi\partial_j\phi - \frac{1}{\mathcal{H}^2}\partial_i(\mathcal{H}\phi + \phi')\partial_j(\mathcal{H}\phi + \phi')$$

$$S = S^{(2)}(\phi^2) + S^{(3)}(\phi^3) + S^{(4)}(\phi^4)$$

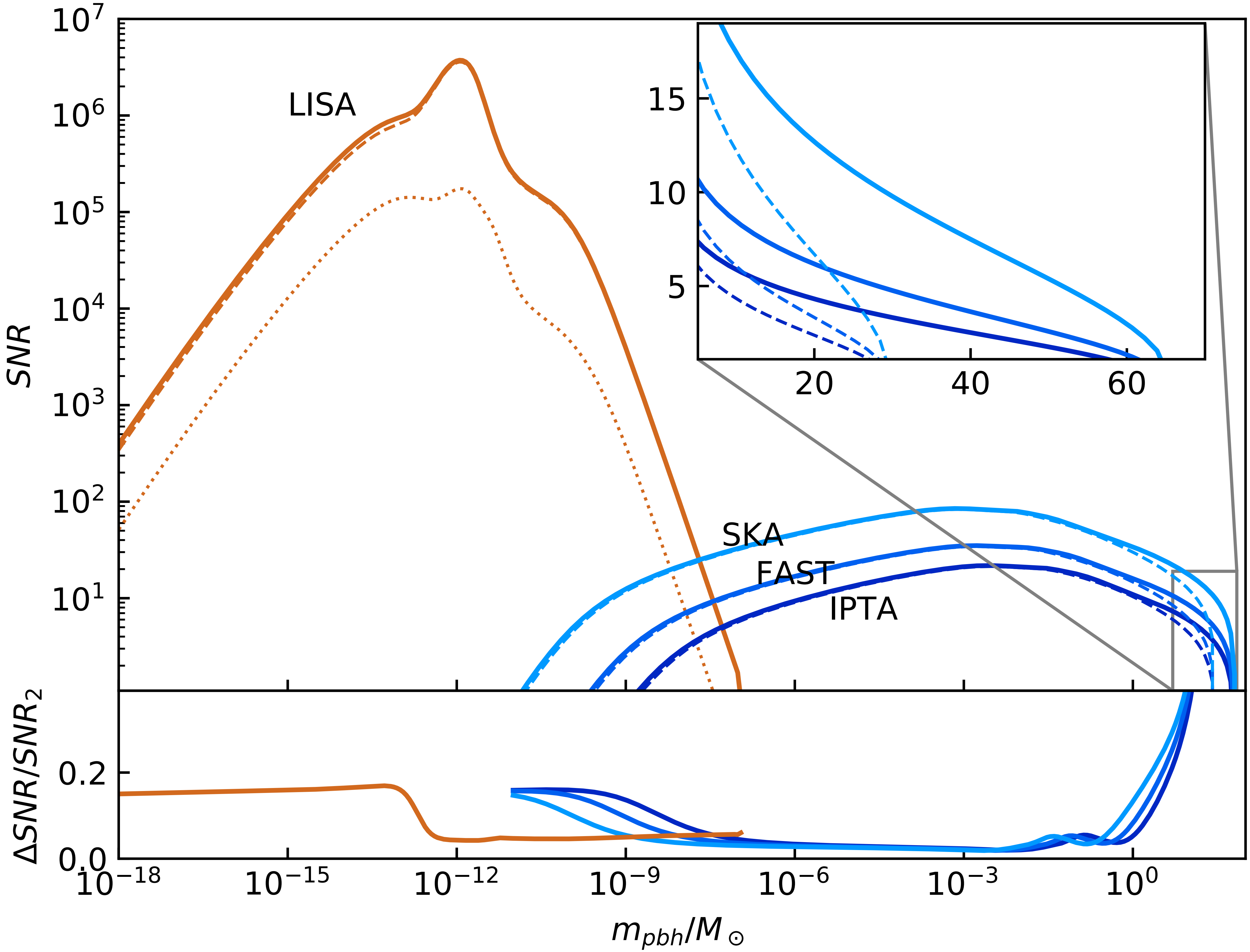
$$\Omega_{GW} = \frac{1}{\rho_c}\frac{d\rho_{GW}}{d\ln f} \sim \langle S^{(2)}S^{(2)}\rangle + \langle S^{(3)}S^{(3)}\rangle + \langle S^{(2)}S^{(4)}\rangle$$

$$\begin{aligned}
S_{ij}^{(3)} =& \frac{1}{\mathcal{H}}\left(12\mathcal{H}\phi - \phi'\right)\partial_i\phi\partial_j\phi - \frac{1}{\mathcal{H}^3}\left(4\mathcal{H}\phi - \phi'\right)\partial_i\phi'\partial_j\phi' \\
&+ \frac{1}{3\mathcal{H}^4}\left(2\partial^2\phi - 9\mathcal{H}\phi'\right)\partial_i\left(\mathcal{H}\phi + \phi'\right)\partial_j\left(\mathcal{H}\phi + \phi'\right),
\end{aligned}$$

$$\begin{aligned}
S_{ij}^{(4)} =& 16\phi^3\partial_i\partial_j\phi + \frac{1}{3\mathcal{H}^3}\Big[2\phi'\partial^2\phi - 9\mathcal{H}\phi'^2 - 8\mathcal{H}\phi\partial^2\phi \\
&\qquad + 18\mathcal{H}^2\phi\phi' + 96\mathcal{H}^3\phi^2\Big]\partial_i\phi\partial_j\phi \\
&+ \frac{2}{3\mathcal{H}^5}\Big[-\phi'\partial^2\phi + 3\mathcal{H}\phi'^2 + 4\mathcal{H}\phi\partial^2\phi \\
&\qquad + 3\mathcal{H}^2\phi\phi' - 12\mathcal{H}^3\phi^2\Big]\partial_i\phi'\partial_j\phi' \\
&+ \frac{1}{36\mathcal{H}^6}\Big[-16(\partial^2\phi)^2 - 3\partial_k\phi'\partial^k\phi' + 120\mathcal{H}\phi'\partial^2\phi \\
&\qquad - 6\mathcal{H}\partial_k\phi\partial^k\phi' + 144\mathcal{H}^2\phi\partial^2\phi - 180\mathcal{H}^2\phi'^2 \\
&\qquad + 33\mathcal{H}^2\partial_k\phi\partial^k\phi - 504\mathcal{H}^3\phi\phi' - 144\mathcal{H}^4\phi^2\Big] \\
&\qquad \times \partial_i\left(\mathcal{H}\phi + \phi'\right)\partial_j\left(\mathcal{H}\phi + \phi'\right).
\end{aligned}$$

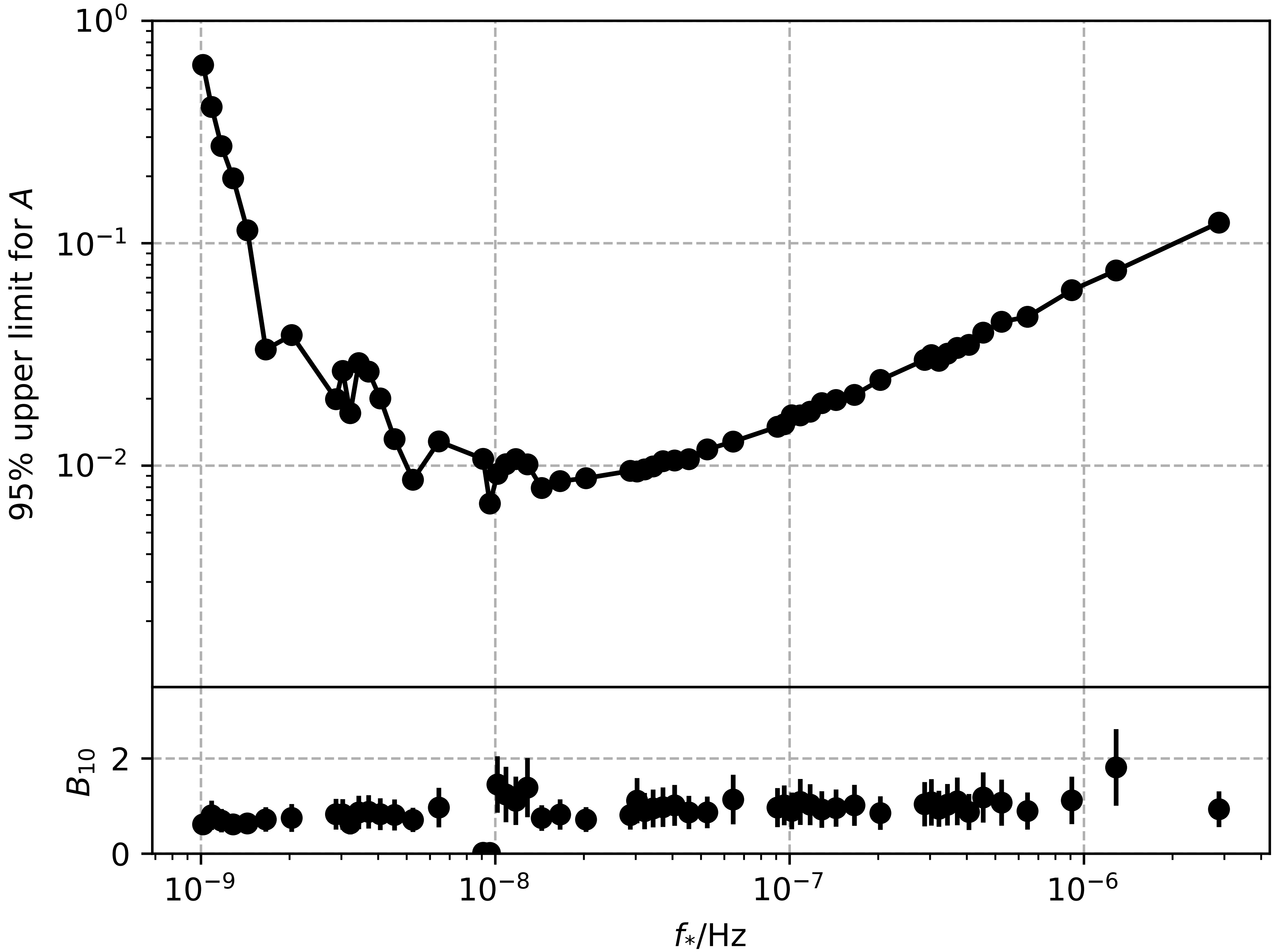


$m_{pbh} = 0.2M_\odot$
$f_{pbh} = 10^{-3}$
$m_{pbh} = 10^{-12}M_\odot$
$f_{pbh} = 1$
2nd+3rd
2nd
IPTA
FAST
SKA
LISA
Ω_{GW}
Frequency/Hz
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
$2k_*$
$3k_*$



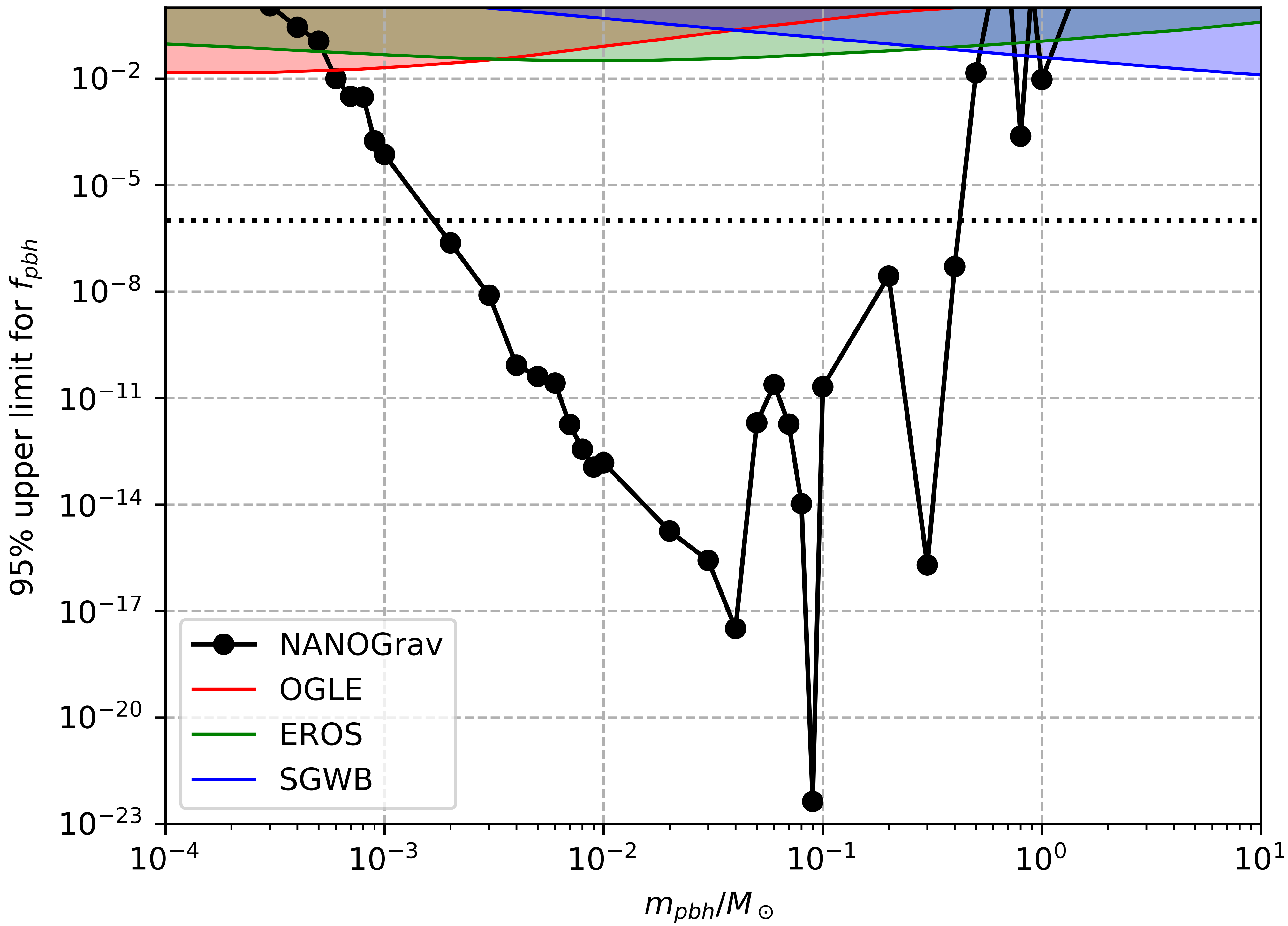
LISA
SKA
FAST
IPTA
SNR
ΔSNR/SNR_2
m_pbh/M_⊙
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.2
0.0
10^-18
10^-15
10^-12
10^-9
10^-6
10^-3
10^0
15
10
5
20
40
60

Current constraints from NanoGRAV

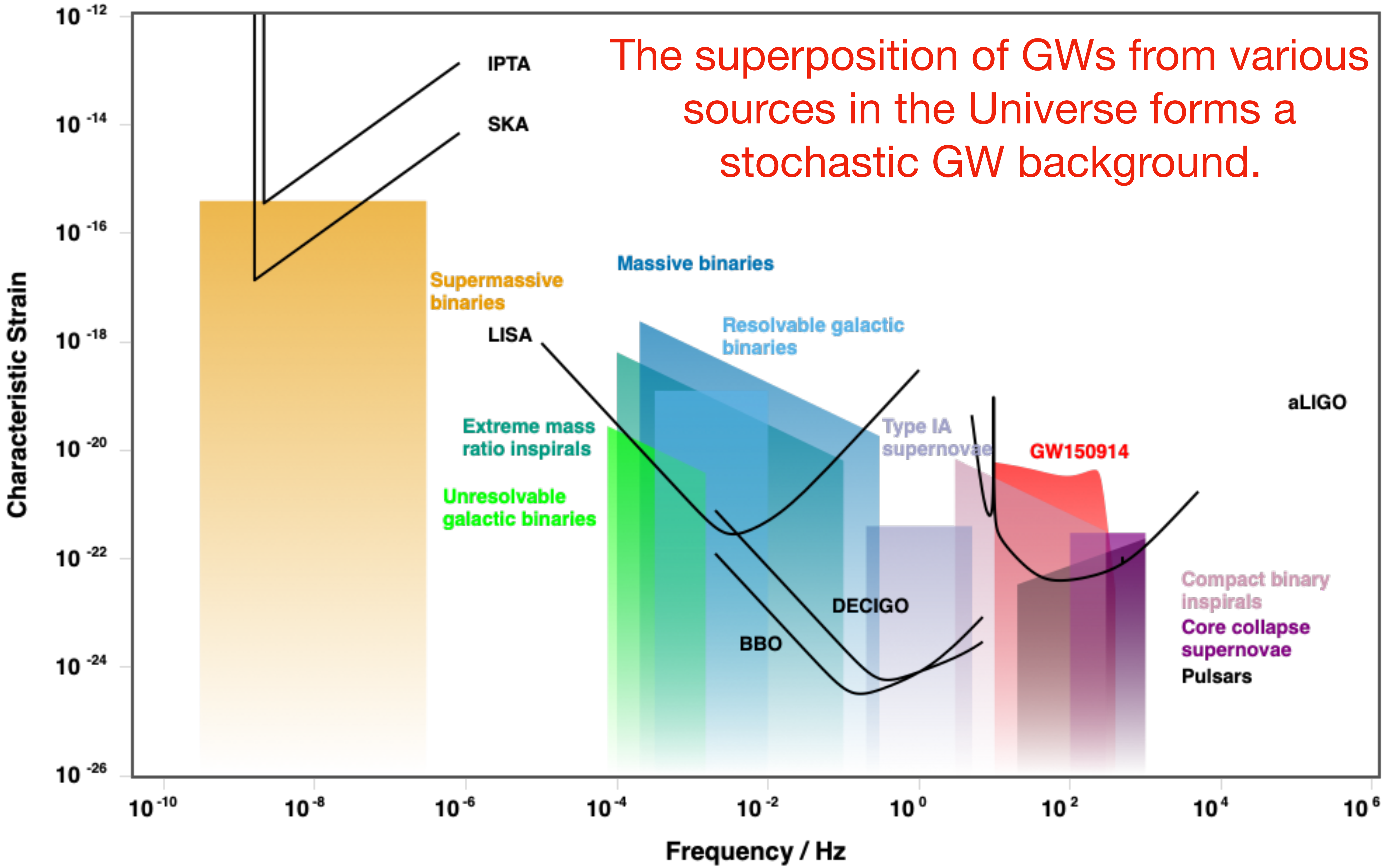


$$P_\phi(k) = A f_* \delta(f - f_*)$$

$$\frac{m_{\rm pbh}}{M_\odot} \simeq 2.3 \times 10^{18} \left(\frac{H_0}{f_*}\right)^2$$



$$f_{\rm pbh} \simeq 1.9 \times 10^7 \left(\zeta_c^2/A - 1\right) e^{-\frac{\zeta_c^2}{2A}} \left(\frac{m_{\rm pbh}}{M_\odot}\right)^{-1/2}$$


The superposition of GWs from various sources in the Universe forms a stochastic GW background.
Characteristic Strain
Frequency / Hz
10 -12
10 -14
10 -16
10 -18
10 -20
10 -22
10 -24
10 -26
10 -10
10 -8
10 -6
10 -4
10 -2
10 0
10 2
10 4
10 6
IPTA
SKA
Supermassive binaries
Massive binaries
LISA
Resolvable galactic binaries
Extreme mass ratio inspirals
Unresolvable galactic binaries
Type IA supernovae
GW150914
aLIGO
DECIGO
BBO
Compact binary inspirals
Core collapse supernovae
Pulsars

slope

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{d\log\rho_{\rm GW}}{d\log f} = \frac{\pi^2}{3H_0^2}f^3 S_h(f) \propto f^{n_{\rm GW}}$$

GW spectral energy density

spectral density

$$n_{\rm GW} = 2/3$$

Compact Binary Coalescences

$$n_{\rm GW} = n_t + \alpha_t \ln(f/f_{\rm CMB})/2$$

Primordial Gravitational Waves

$$n_{\rm GW} = 0$$

Scale-invariant Energy

……

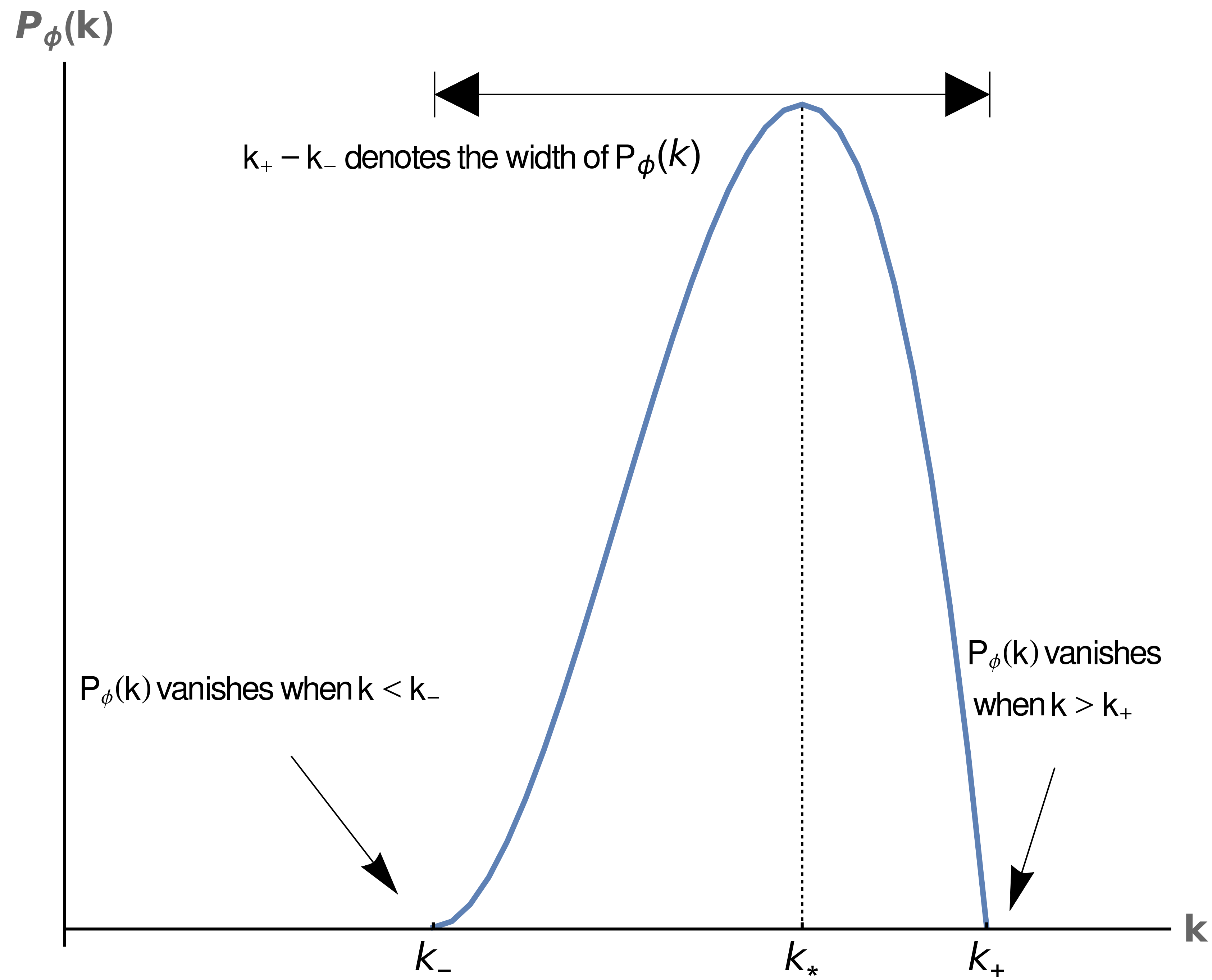
Power spectrum of scalar curvature perturbation is enhanced at small scales.

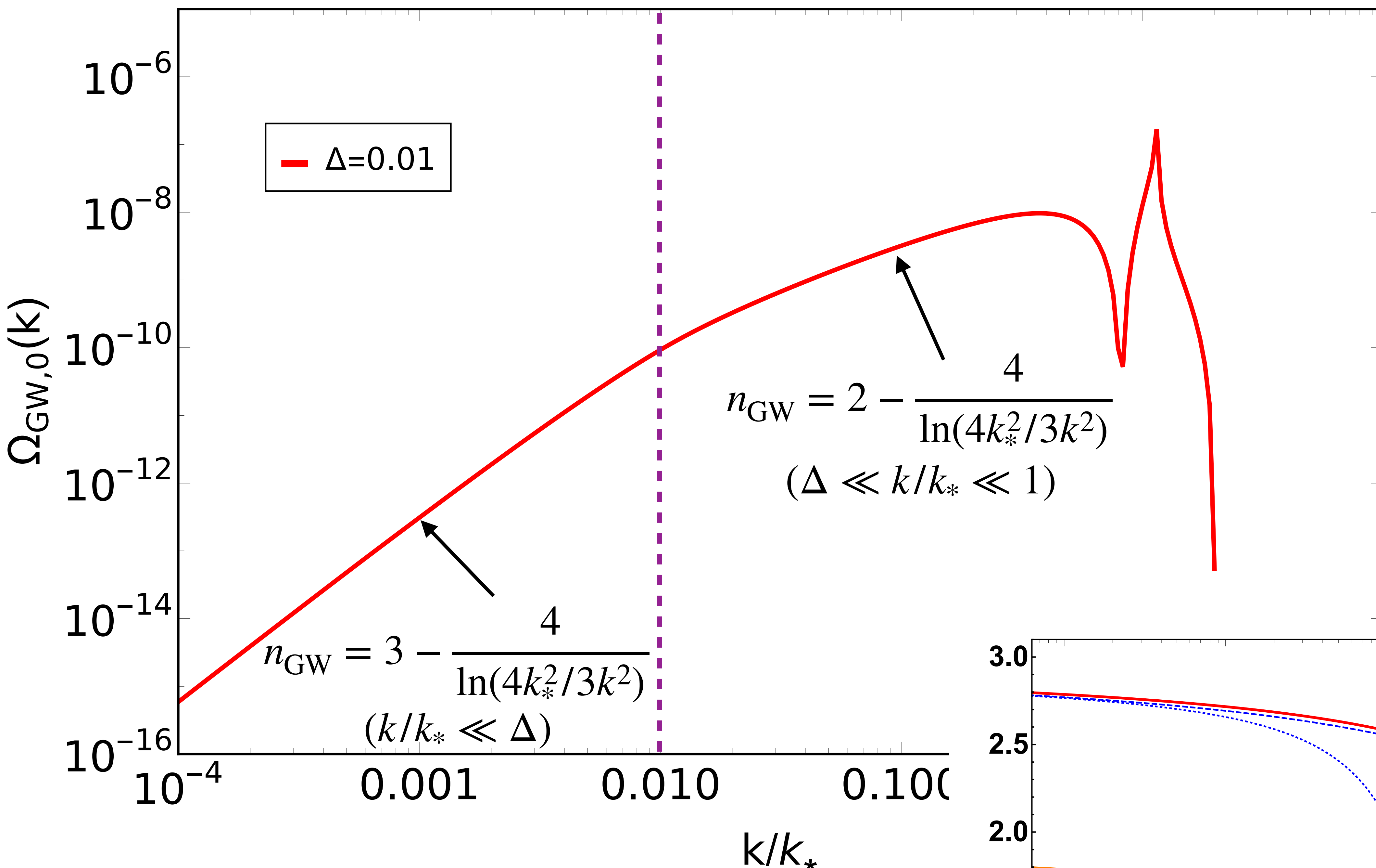
Dimensionless width parameter

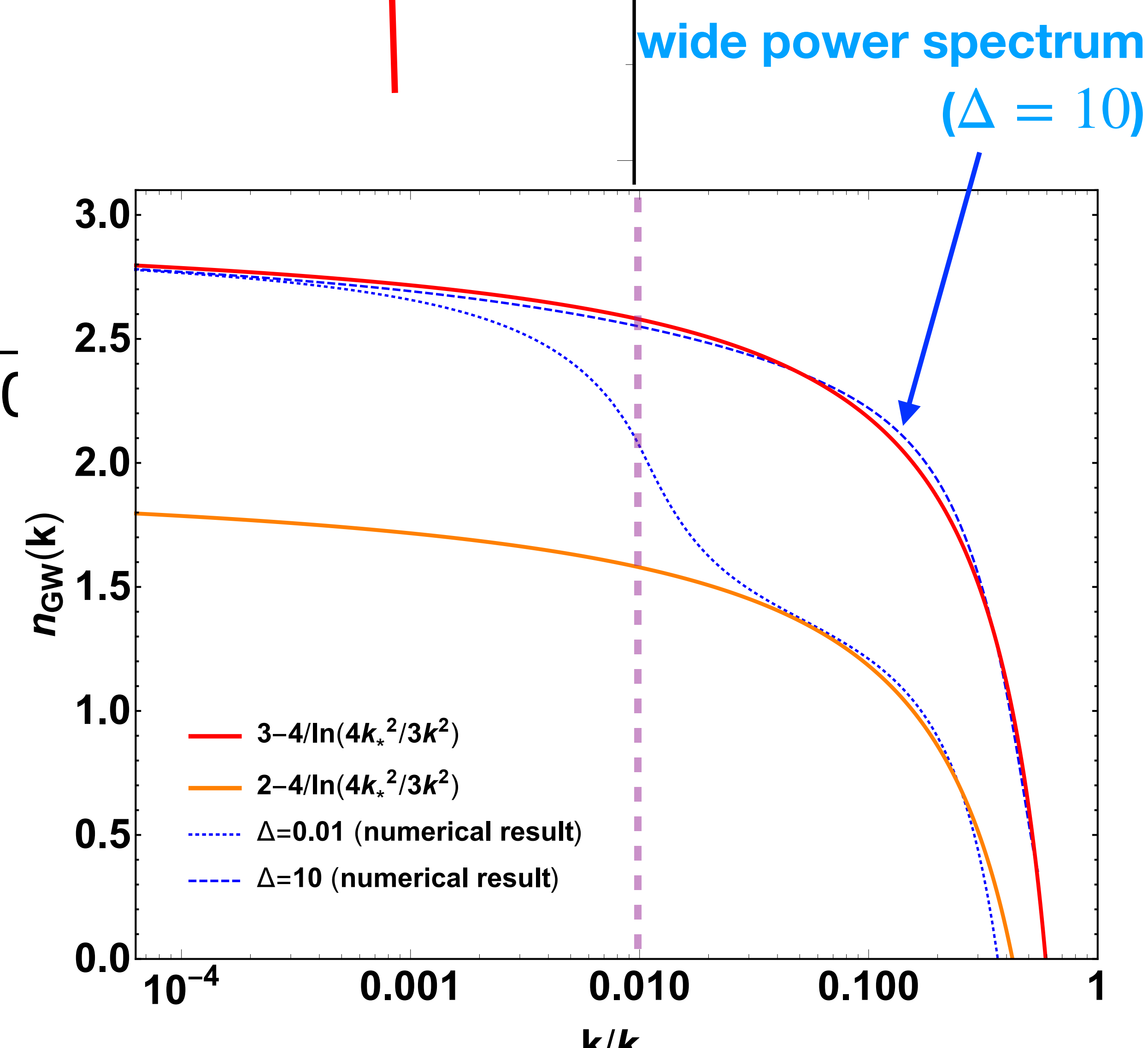
$$\Delta = \frac{k_+ - k_-}{k_*}$$

For a narrow power spectrum

$$\Delta \ll 1$$







In the infrared limit,

$$\Omega_{GW}(k \to 0) \propto k^3$$

slope

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{d\log\rho_{\rm GW}}{d\log f} = \frac{\pi^2}{3H_0^2} f^3 S_h(f) \propto f^{n_{\rm GW}}$$

GW spectral energy density

spectral density

$$n_{\rm GW} = 2/3$$

Compact Binary Coalescences

$$n_{\rm GW} = n_t + \alpha_t \ln(f/f_{\rm CMB})/2$$

Primordial Gravitational Waves

$$n_{\rm GW} = 0$$

Scale-invariant Energy

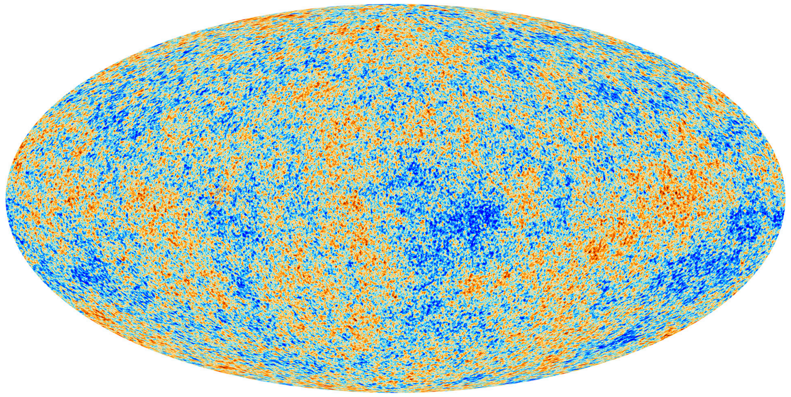
$$n_{\rm GW} = 3 - 2/\ln(f_c/f)$$

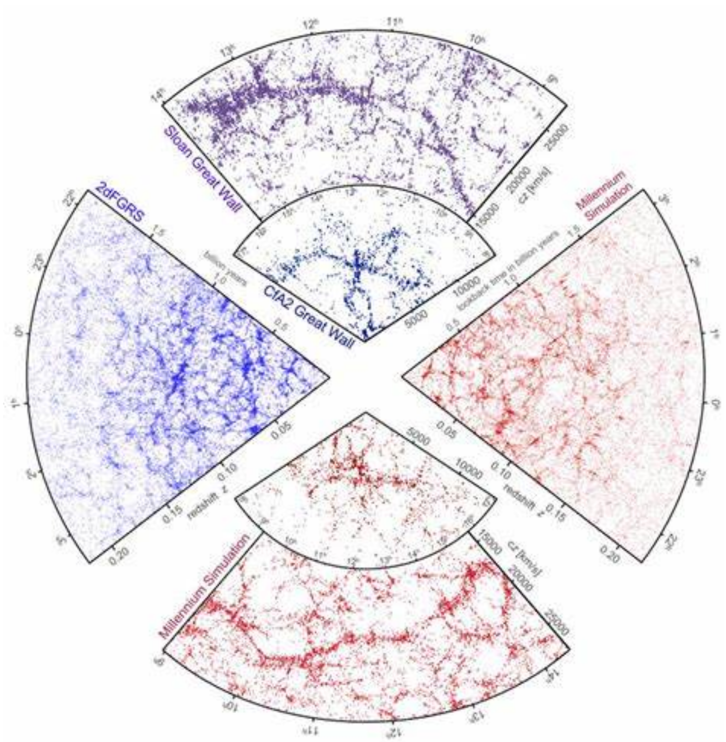
Scalar induced GWs
inevitably accompanying the
formation of PBHs

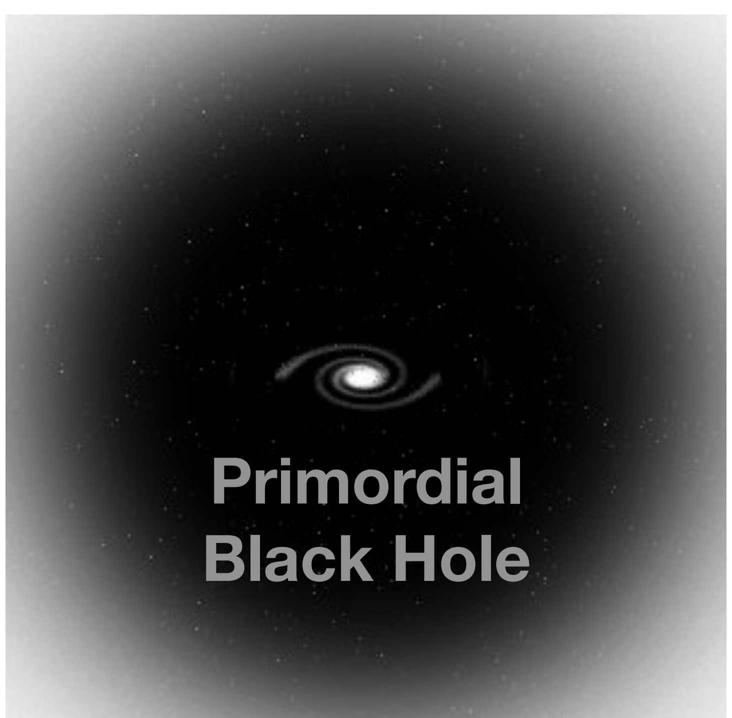
The postulation of

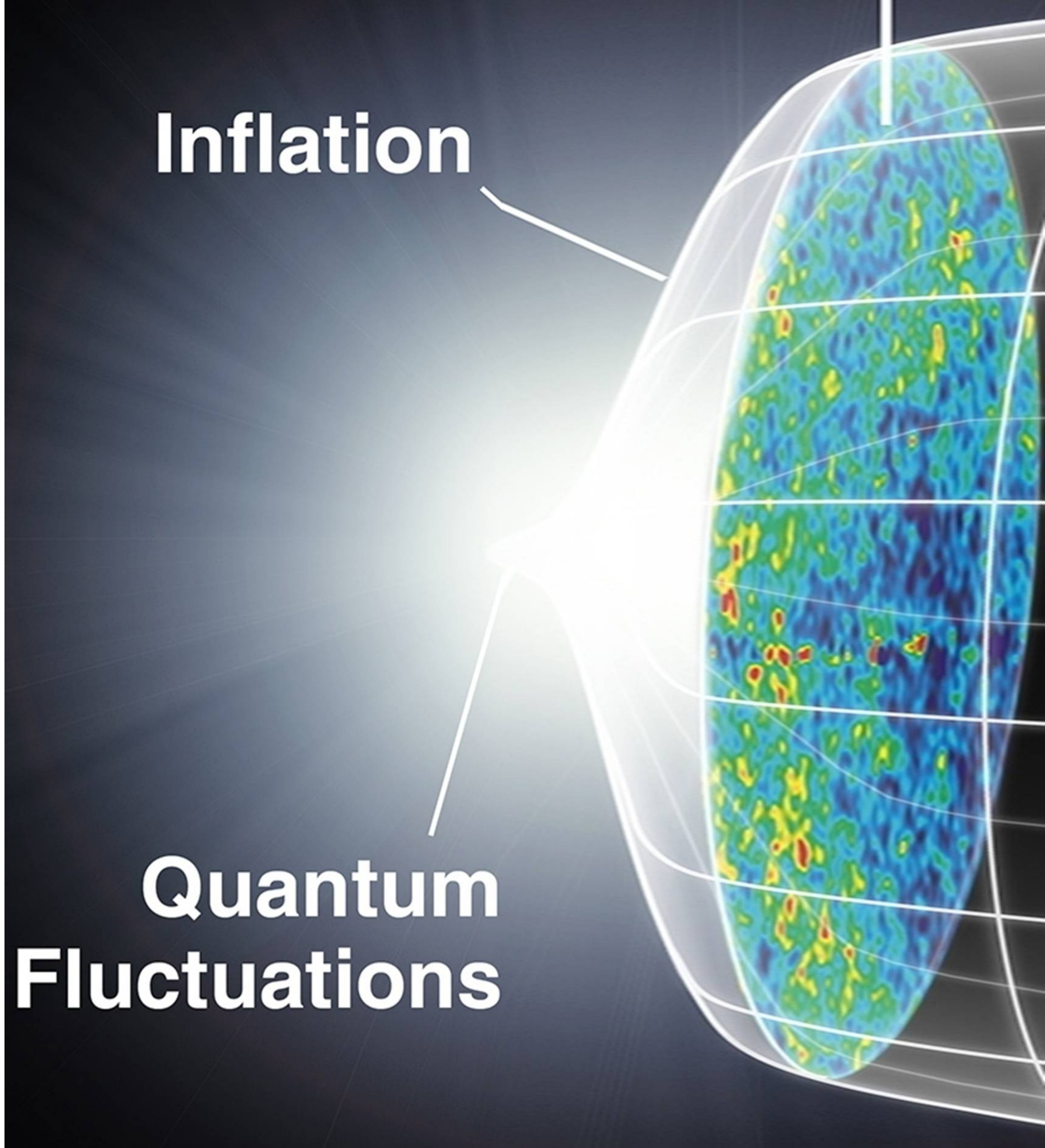
Primordial Black Hole Dark Matter

is testable
for
the next generation GW detectors.




Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
Millennium Simulation


Primordial Black Hole


Inflation
Quantum Fluctuations

Thank You!