Did LIGO Hear the Coalescence of Primordial Black Holes?

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

$$r_{BH} = 2GM$$

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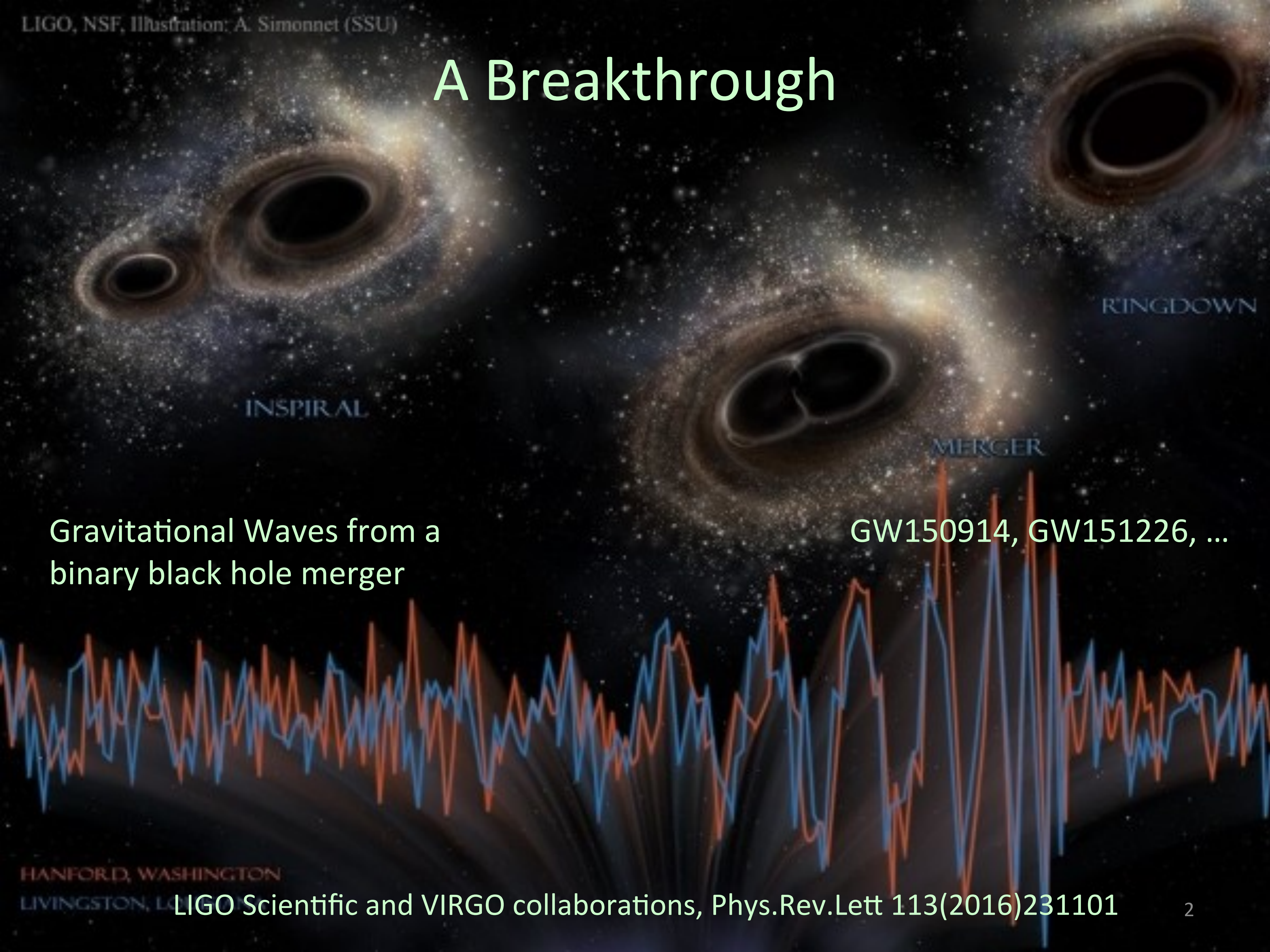
based on arXiv:1608.02174 [JCAP 12(2016) 044] done with L. Chen and K. Wang
and arXiv:1610.08725 done with S. Wang, Y.F. Wang and T. Li

A Breakthrough

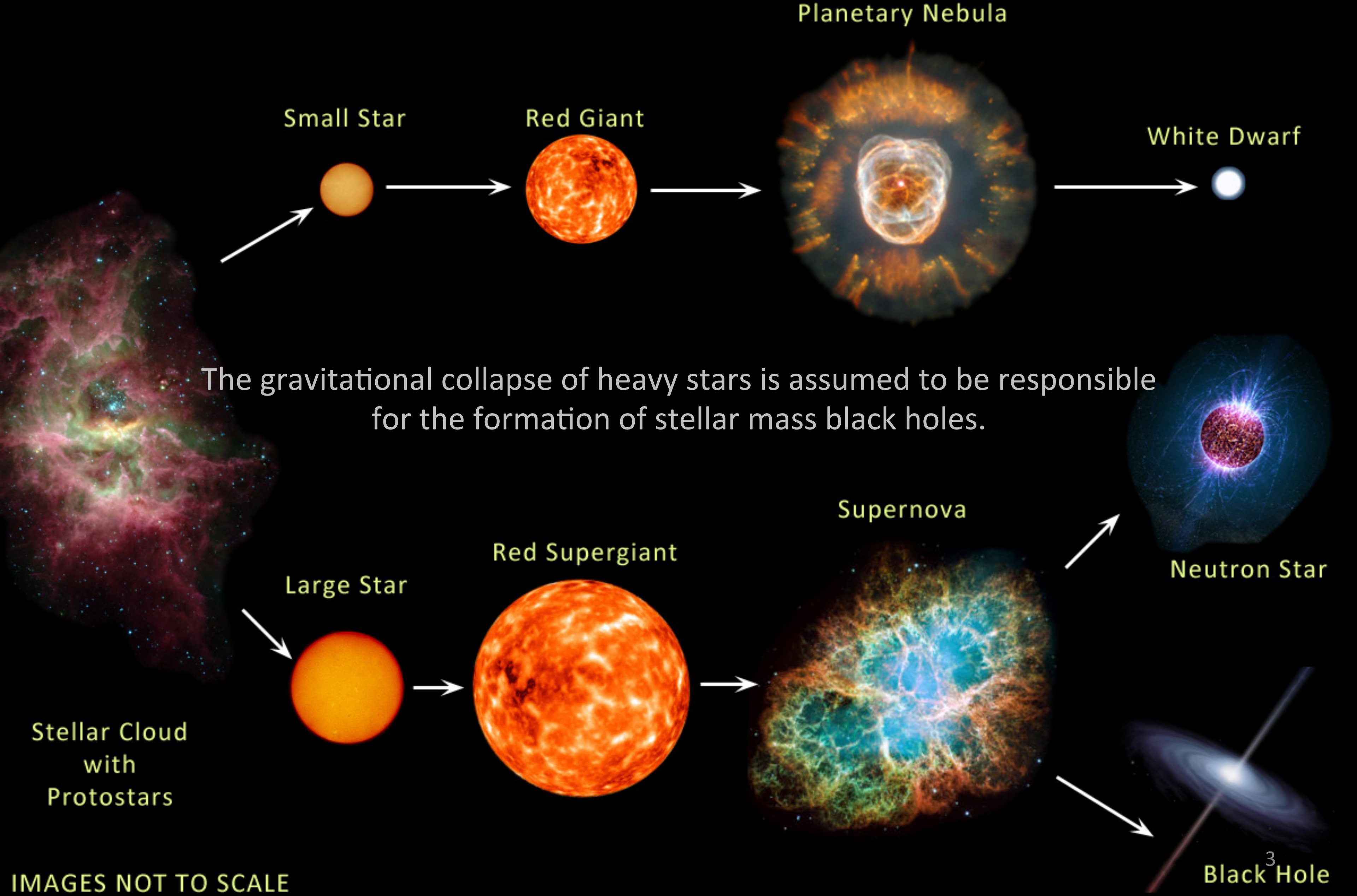


Gravitational Waves from a binary black hole merger

GW150914, GW151226, …

LIGO Scientific and VIRGO collaborations, Phys.Rev.Lett 113(2016)231101

EVOLUTION OF STARS

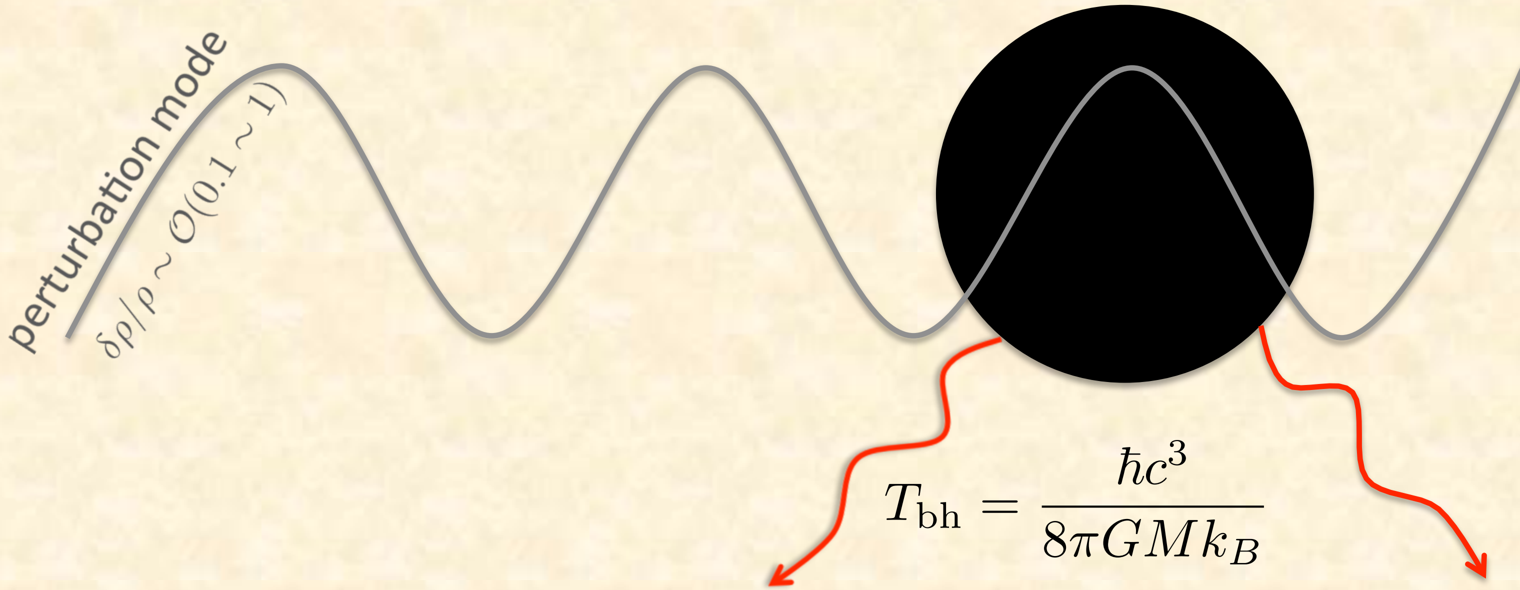


The gravitational collapse of heavy stars is assumed to be responsible for the formation of stellar mass black holes.

IMAGES NOT TO SCALE

Formation of PBHs in the early universe (Hawking, 71'; Carr, Hawking, 74')

$$M_{\rm pbh} \sim \frac{c^3 t}{G} \sim 10^5 \left(\frac{t}{1\ {\rm s}}\right) M_\odot$$



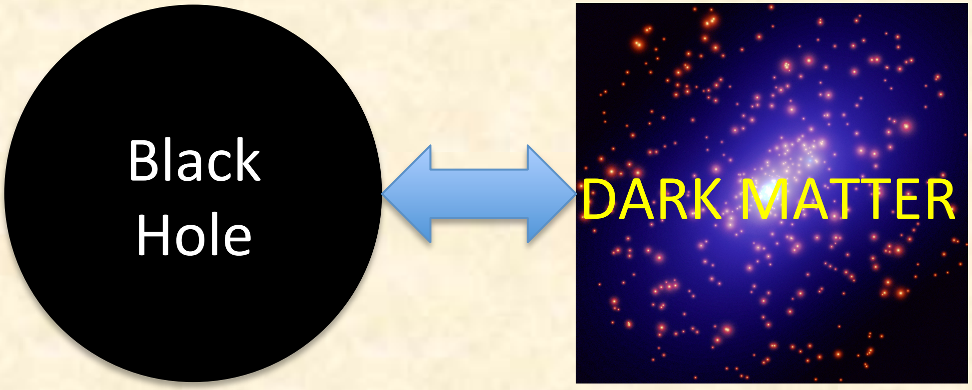
$$T_{\rm bh} = \frac{\hbar c^3}{8\pi G M k_B}$$

$$M_{\text{non-eva,pbh}} > 10^{15}{\rm g} \sim 10^{-18} M_\odot$$

$$\tau_{\rm eva}(M_{\rm bh}) \sim \frac{G^2 M_{\rm bh}^3}{\hbar c^4} \sim 10^{64} \left(\frac{M_{\rm bh}}{M_\odot}\right)^3 \ {\rm yr}$$

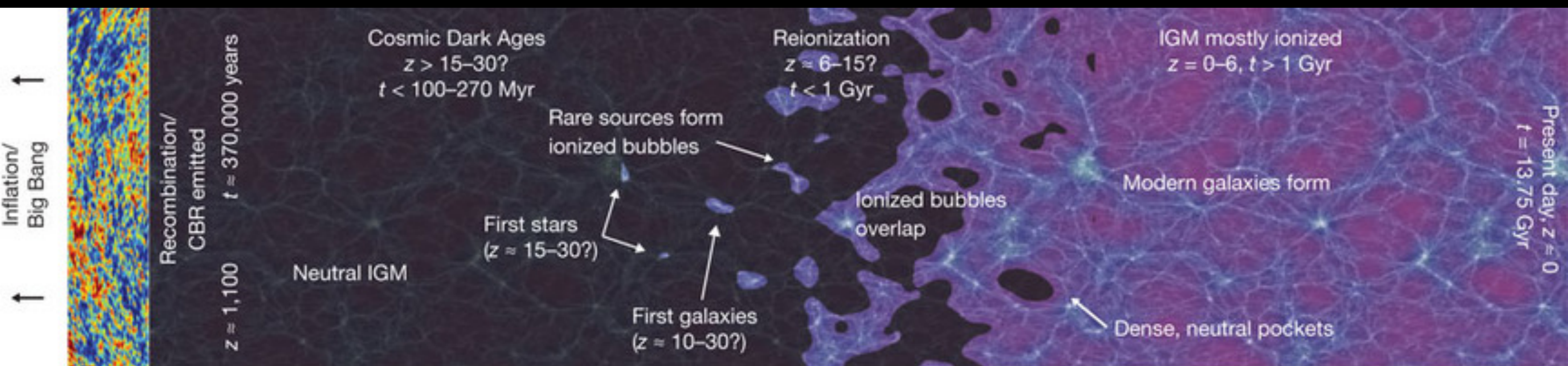
What is the origin of the black holes detected by aLIGO?

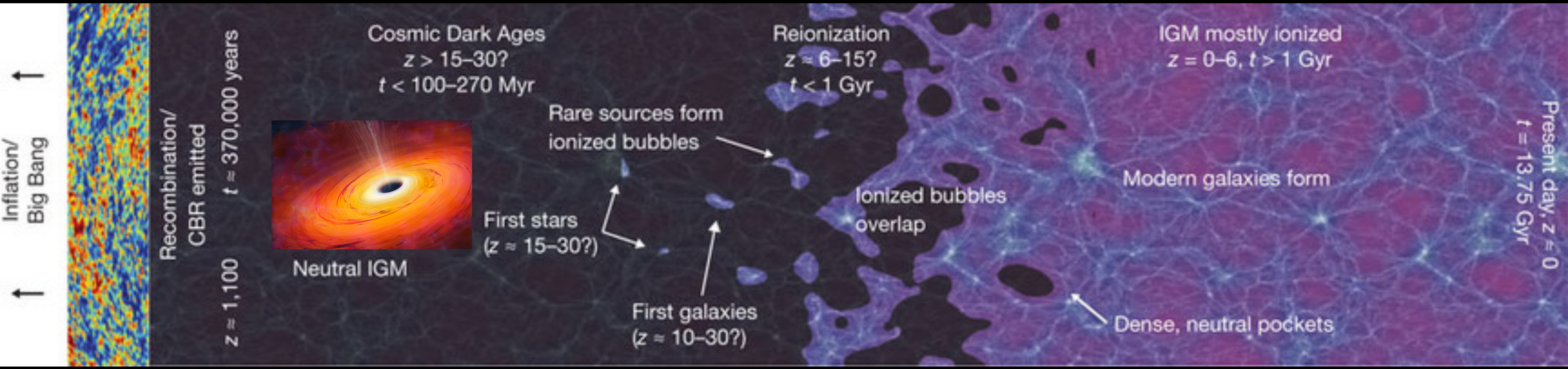
Astrophysical/Primordial ones?



The abundance of primordial black holes in dark matter:

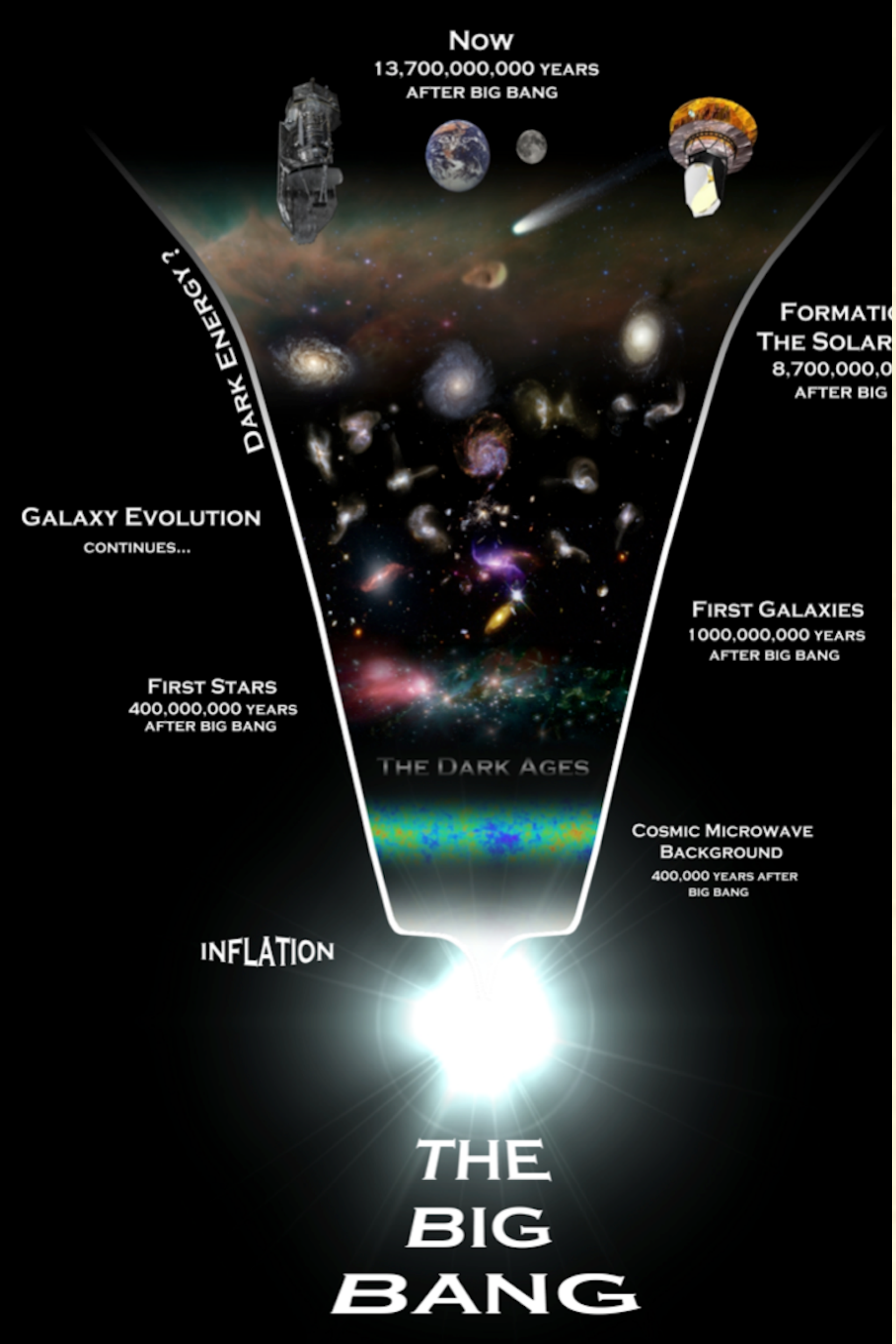
$$f_{\rm pbh} \equiv \frac{\Omega_{\rm pbh}}{\Omega_{\rm CDM}}$$

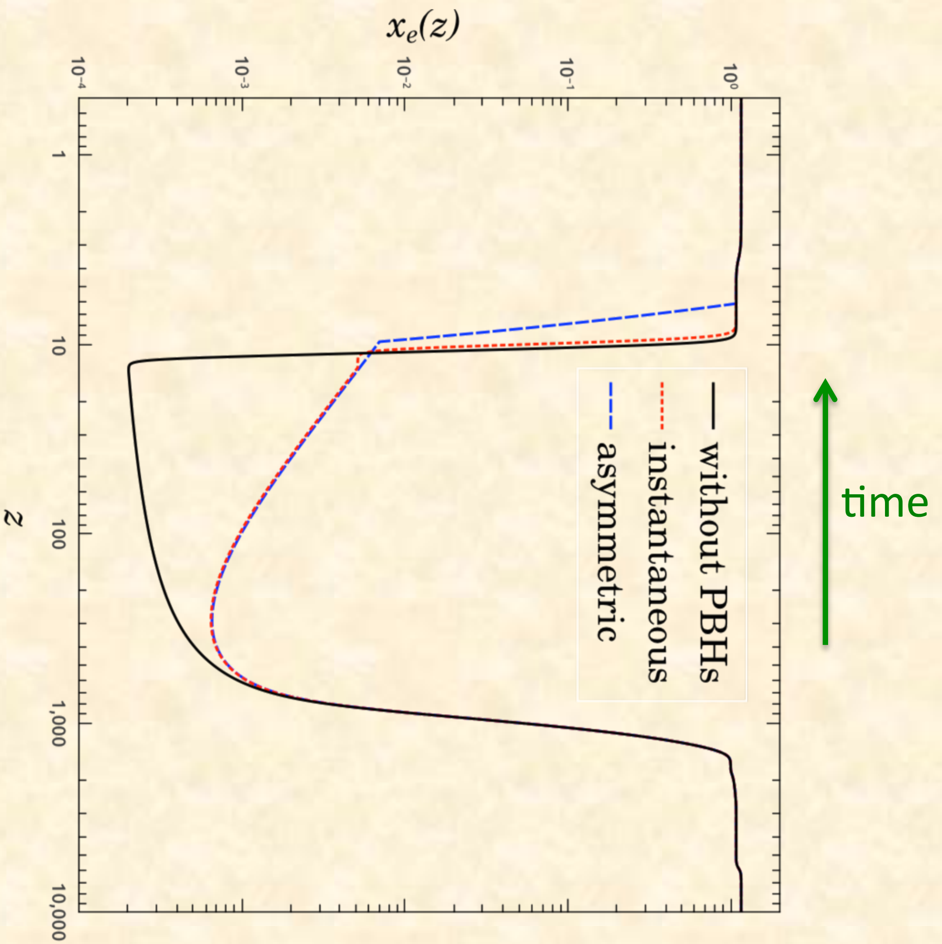

Inflation/
Big Bang
Recombination/
CBR emitted
t ≈ 370,000 years
z ≈ 1,100
Cosmic Dark Ages
z > 15–30?
t < 100–270 Myr
Neutral IGM
Rare sources form
ionized bubbles
First stars
(z ≈ 15–30?)
First galaxies
(z ≈ 10–30?)
Reionization
z ≈ 6–15?
t < 1 Gyr
Ionized bubbles
overlap
IGM mostly ionized
z = 0–6, t > 1 Gyr
Modern galaxies form
Dense, neutral pockets
Present day, z ≈ 0
t = 13.75 Gyr

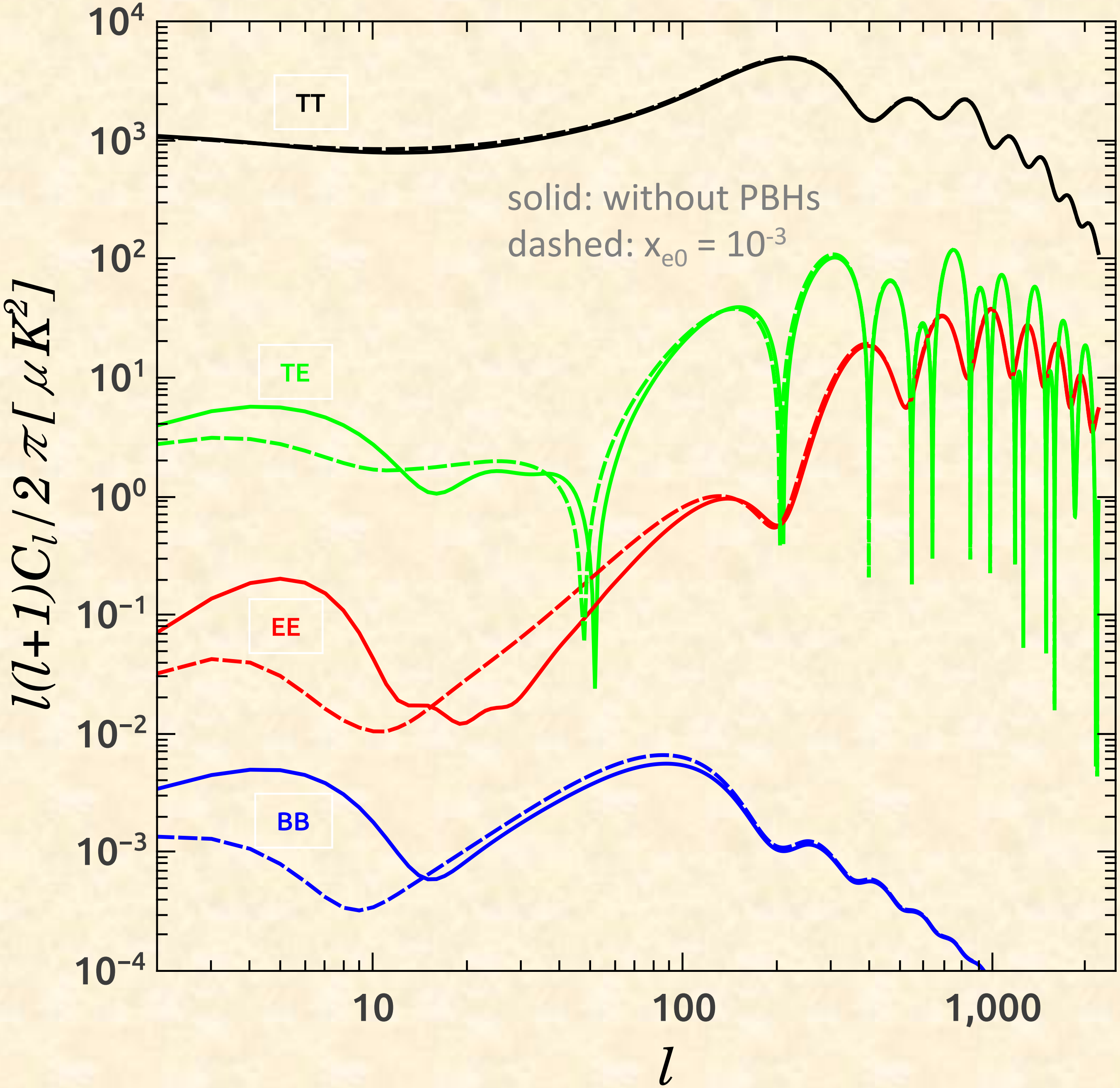

Inflation/
Big Bang
Recombination/
CBR emitted
$t \approx 370{,}000$ years
$z \approx 1{,}100$
Cosmic Dark Ages
$z > 15$–30?
$t < 100$–270 Myr
Neutral IGM
Rare sources form
ionized bubbles
First stars
($z \approx 15$–30?)
First galaxies
($z \approx 10$–30?)
Reionization
$z \approx 6$–15?
$t < 1$ Gyr
Ionized bubbles
overlap
IGM mostly ionized
$z = 0$–6, $t > 1$ Gyr
Modern galaxies form
Dense, neutral pockets
Present day, $z = 0$
$t = 13.75$ Gyr

Ionization fraction $x_e = n_e/n_H$
(Ricotti, Ostriker and Mark, 2007):

$$x_{\rm e,pbh}(z) = \min\left[x_{e0}\left(\frac{1+z}{10^3}\right)^{-1}, 0.1\right]$$

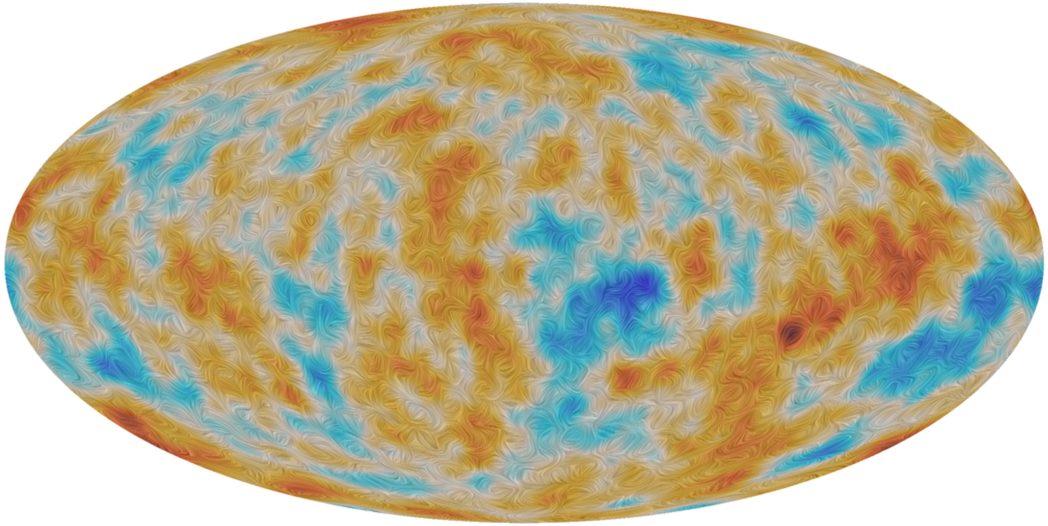


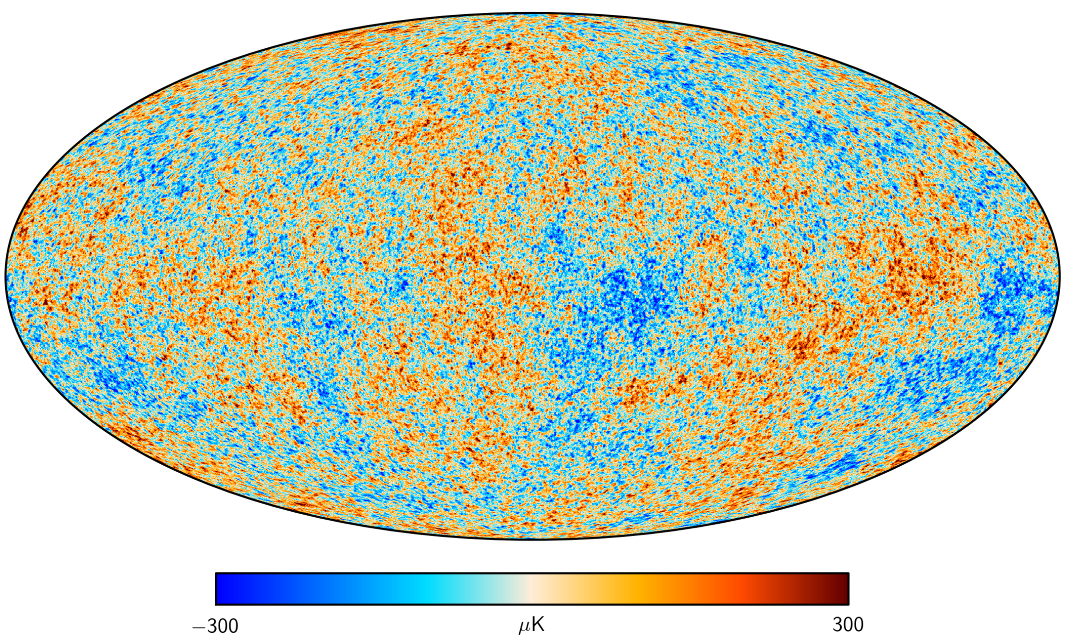




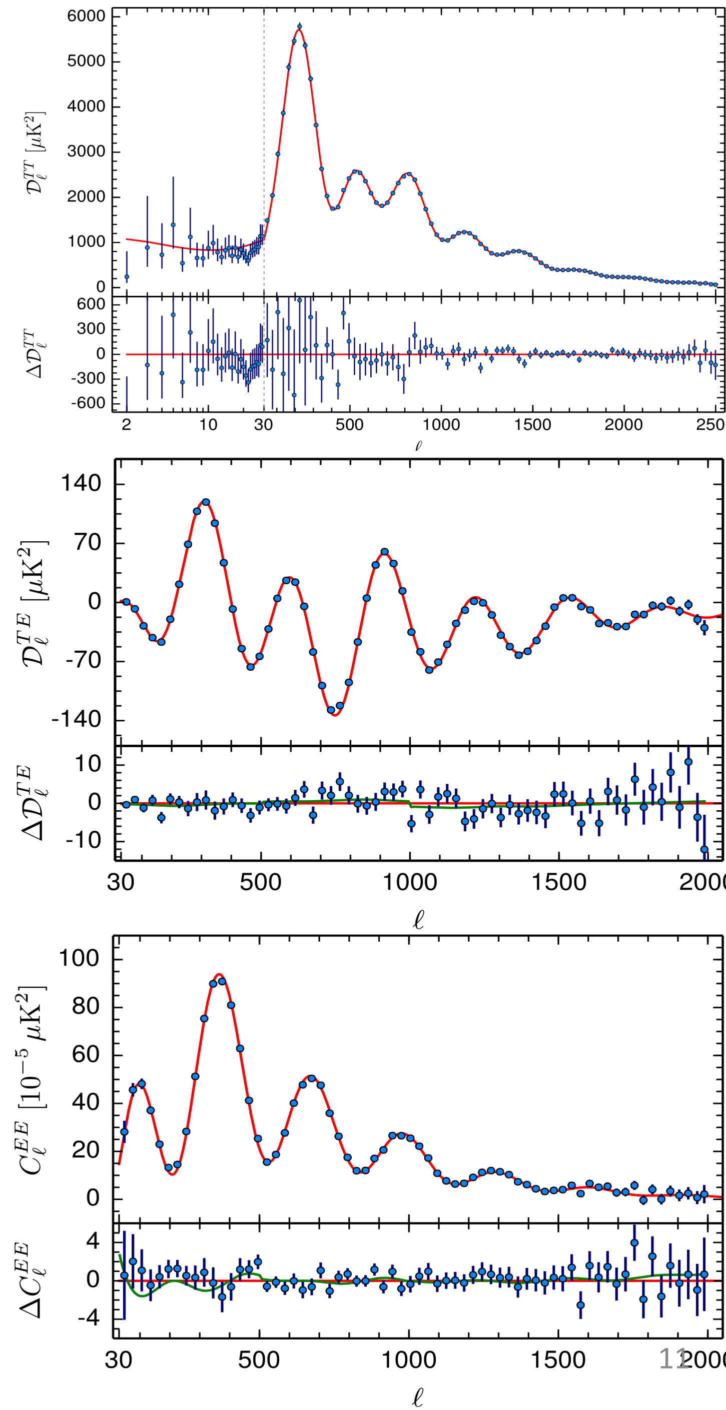
TT
TE
EE
BB
solid: without PBHs
dashed: x_{e0} = 10^{-3}
$l(l+1)C_l/2\pi[\mu K^2]$
l
10
100
1,000
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}

PLANCK 2015

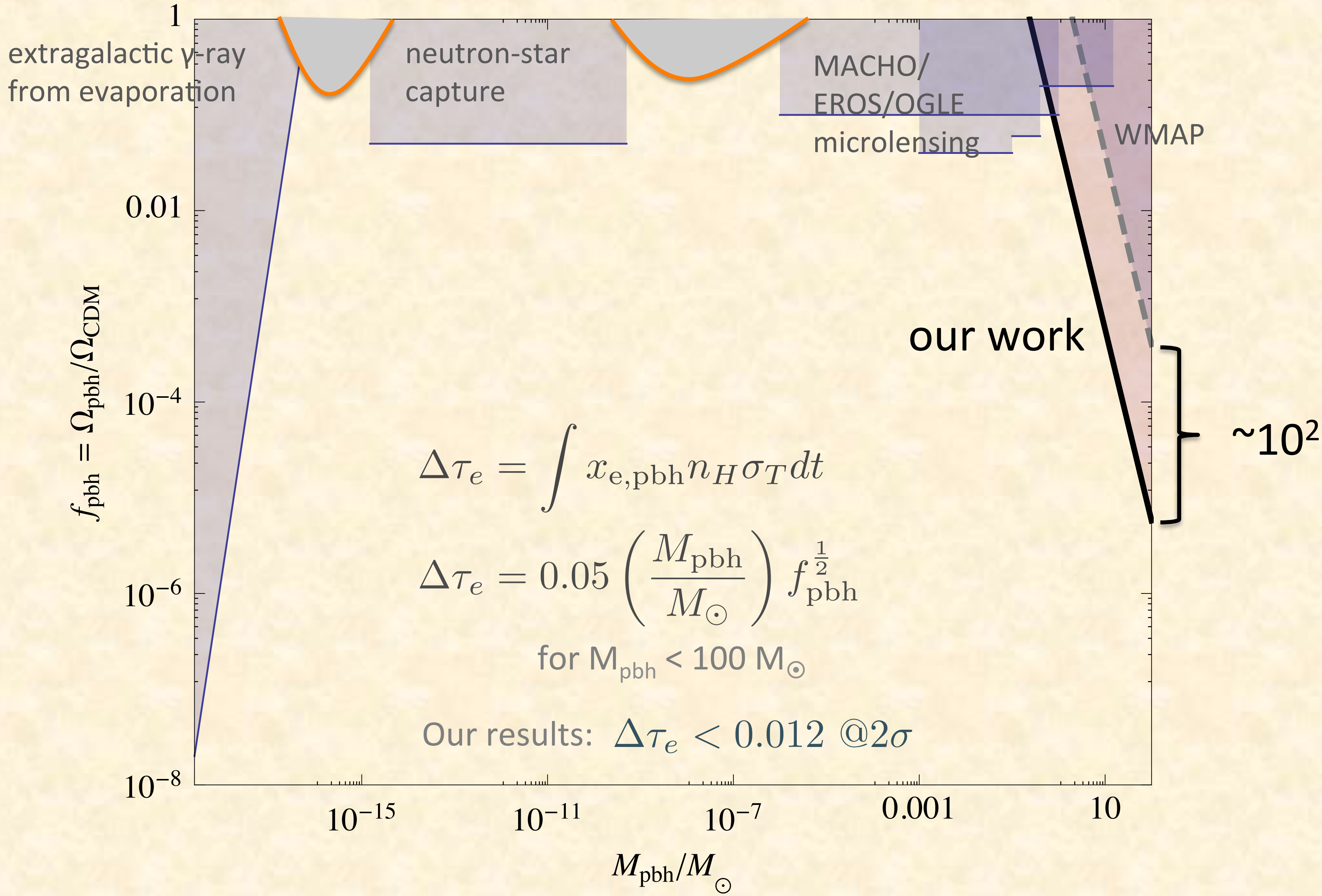




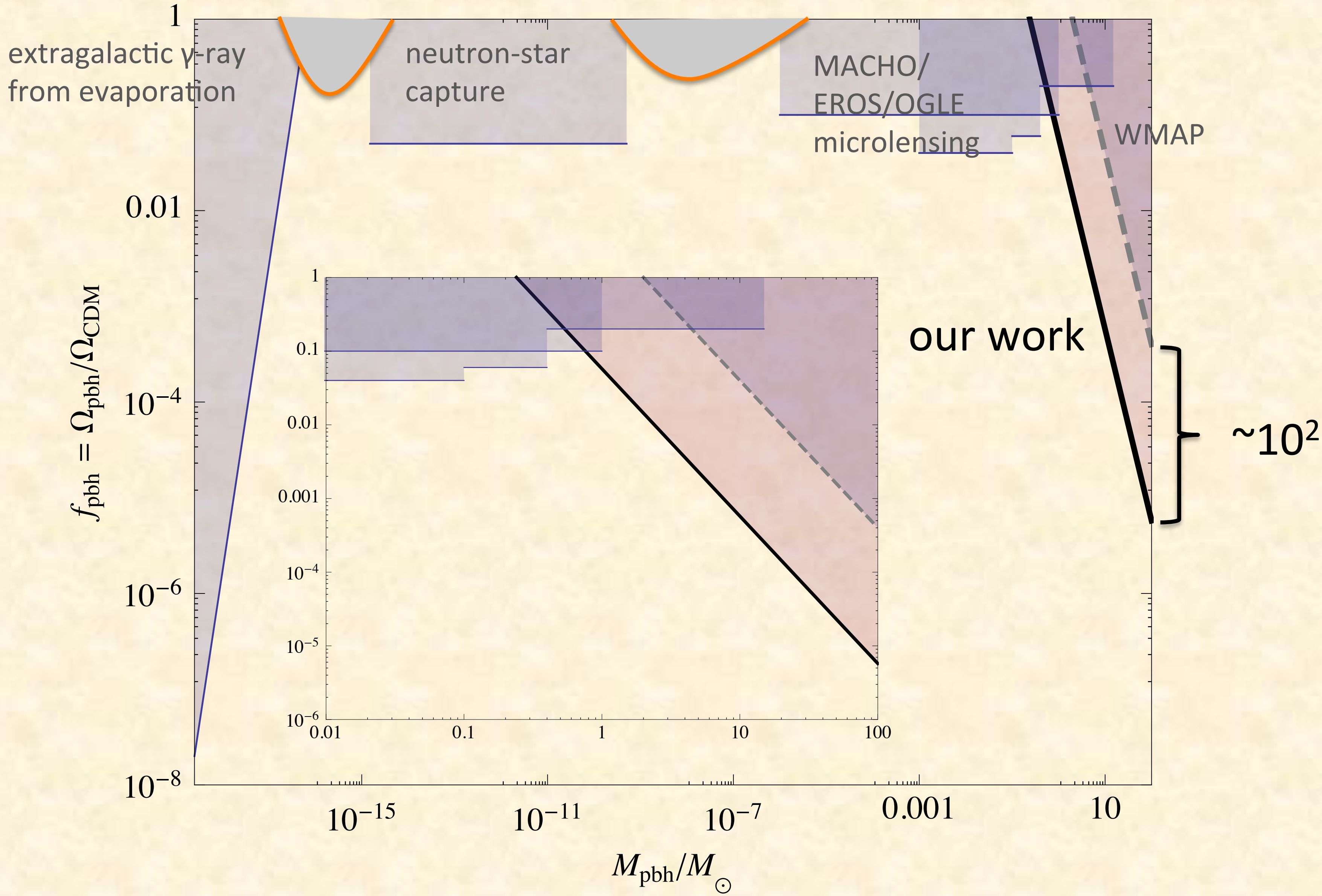
−300
μK
300



$\mathcal{D}_\ell^{TT}\ [\mu\mathrm{K}^2]$
$\Delta\mathcal{D}_\ell^{TT}$
$\mathcal{D}_\ell^{TE}\ [\mu\mathrm{K}^2]$
$\Delta\mathcal{D}_\ell^{TE}$
$C_\ell^{EE}\ [10^{-5}\,\mu\mathrm{K}^2]$
ΔC_ℓ^{EE}
ℓ



extragalactic γ-ray from evaporation
neutron-star capture
MACHO/ EROS/OGLE microlensing
WMAP
our work
~10²
$\Delta\tau_e = \int x_{\mathrm{e,pbh}} n_H \sigma_T dt$
$\Delta\tau_e = 0.05 \left(\frac{M_{\mathrm{pbh}}}{M_\odot}\right) f_{\mathrm{pbh}}^{\frac{1}{2}}$
for $M_{\mathrm{pbh}} < 100\ M_\odot$
Our results: $\Delta\tau_e < 0.012$ @2σ
$f_{\mathrm{pbh}} = \Omega_{\mathrm{pbh}}/\Omega_{\mathrm{CDM}}$
$M_{\mathrm{pbh}}/M_\odot$
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-15}
10^{-11}
10^{-7}
0.001
10



extragalactic γ-ray from evaporation
neutron-star capture
MACHO/ EROS/OGLE microlensing
WMAP
our work
~10²
1
0.01
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁵
10⁻¹¹
10⁻⁷
0.001
10
$f_{\rm pbh} = \Omega_{\rm pbh}/\Omega_{\rm CDM}$
$M_{\rm pbh}/M_\odot$
0.1
0.001
10⁻⁵
0.01
1
100

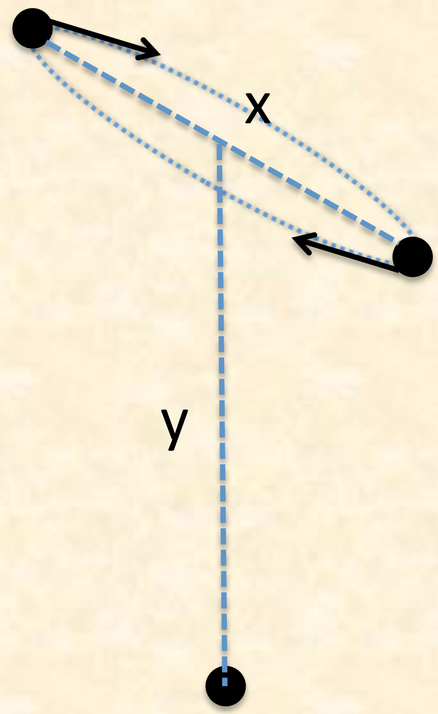
Formation of PBH binary (Nakamura, Sasaki, Tanaka and Thorne, 97')

- The pair of PBHs is supposed to decouple from the expansion of the Universe and forms a gravitational bound system if the average energy density of PBHs over the volume is larger than the background cosmic energy density.

- They just coalesce to a single black hole on the free fall time scale if the motion of these two PBHs is not disturbed.

- The tidal force from neighboring black holes provides enough angular momentum to keep the black holes from colliding with each other, and then the PBH binaries were formed.

- The PBH binary gradually shrinks due to gravitational radiations and finally coalesces.



(x, y are comoving distances at $z=z_{eq}$)

Event Rate (ER) (Nakamura, Sasaki, Tanaka and Thorne, 97'; Sasaki, Suyama, Tanaka and Yokoyama, 2016)

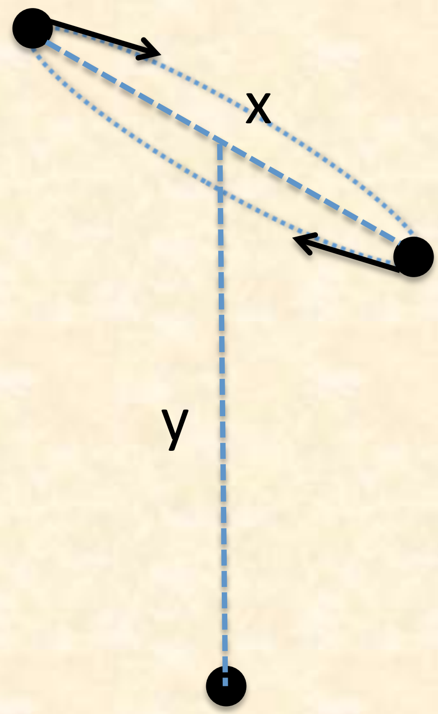
✧ Assuming the uniform probability distribution both for x and y in three dimensional space, the ER of mergers of PBH binaries at the time of t is

$$\mathrm{ER}(t) = \frac{f_{\rm pbh}\Omega_{\rm CDM}\rho_{\rm crit}}{M_{\rm pbh}}\frac{3}{58}$$

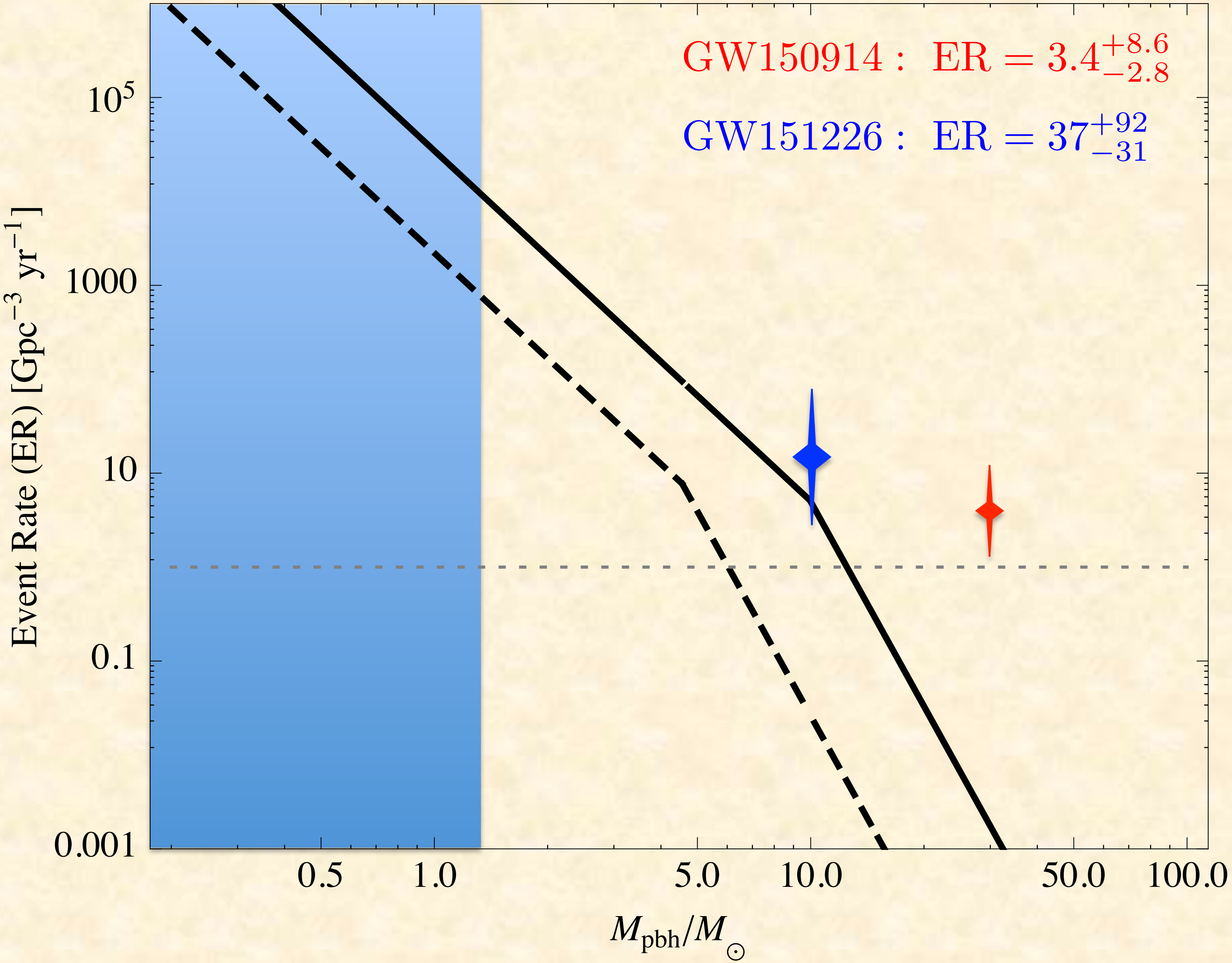
$$\times \begin{cases} \left[-\left(\frac{t}{T}\right)^{\frac{3}{8}} + \left(\frac{t}{T}\right)^{\frac{3}{37}}\right]\frac{1}{t}, & \text{for } t < t_c, \\ \left(\frac{t}{T}\right)^{\frac{3}{8}}\left[-1 + \left(\frac{t}{t_c}\right)^{-\frac{29}{56}} f^{-\frac{29}{8}}\right]\frac{1}{t}, & \text{for } t \geq t_c, \end{cases}$$

$$t_c = Q\bar{x}^4 f_{\rm pbh}^{25/3}$$

$$T = \bar{x}^4 Q / f_{\rm pbh}^4$$



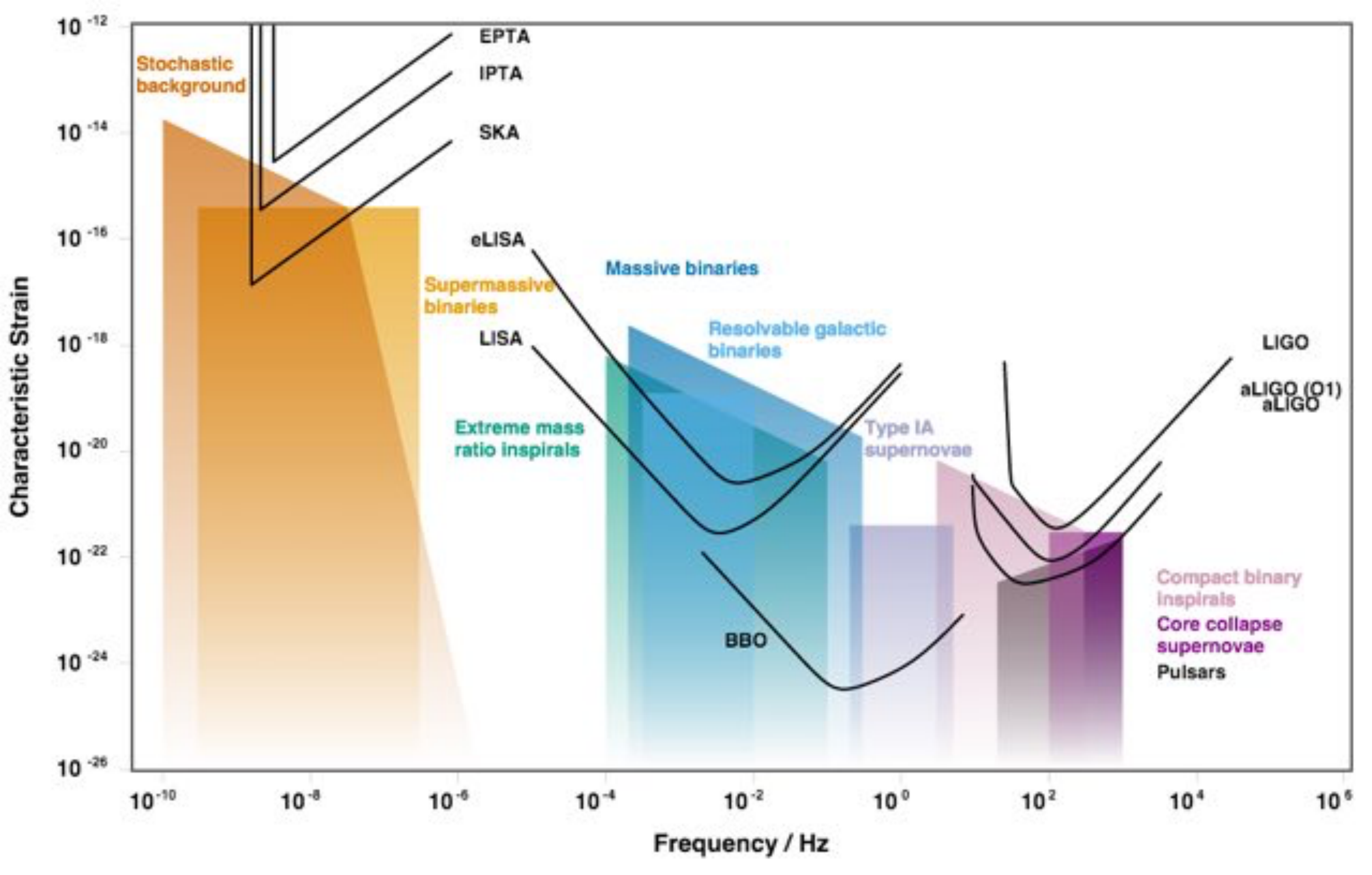
(x, y are comoving distances at $z=z_{eq}$)



$\mathrm{GW150914:\ ER} = 3.4^{+8.6}_{-2.8}$
$\mathrm{GW151226:\ ER} = 37^{+92}_{-31}$
10^5
1000
10
0.1
0.001
Event Rate (ER) [$\mathrm{Gpc^{-3}\ yr^{-1}}$]
0.5
1.0
5.0
10.0
50.0
100.0
$M_{\mathrm{pbh}}/M_{\odot}$

Stochastic Gravitational Wave Background

Many astrophysical and cosmological phenomena are expected to contribute to a stochastic gravitational wave background.



$$\Omega_{\mathrm{GW}}(\nu) = \frac{2\pi^2}{3H_0^2}\nu^2 h_c^2(\nu) = \frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\ln\nu}$$

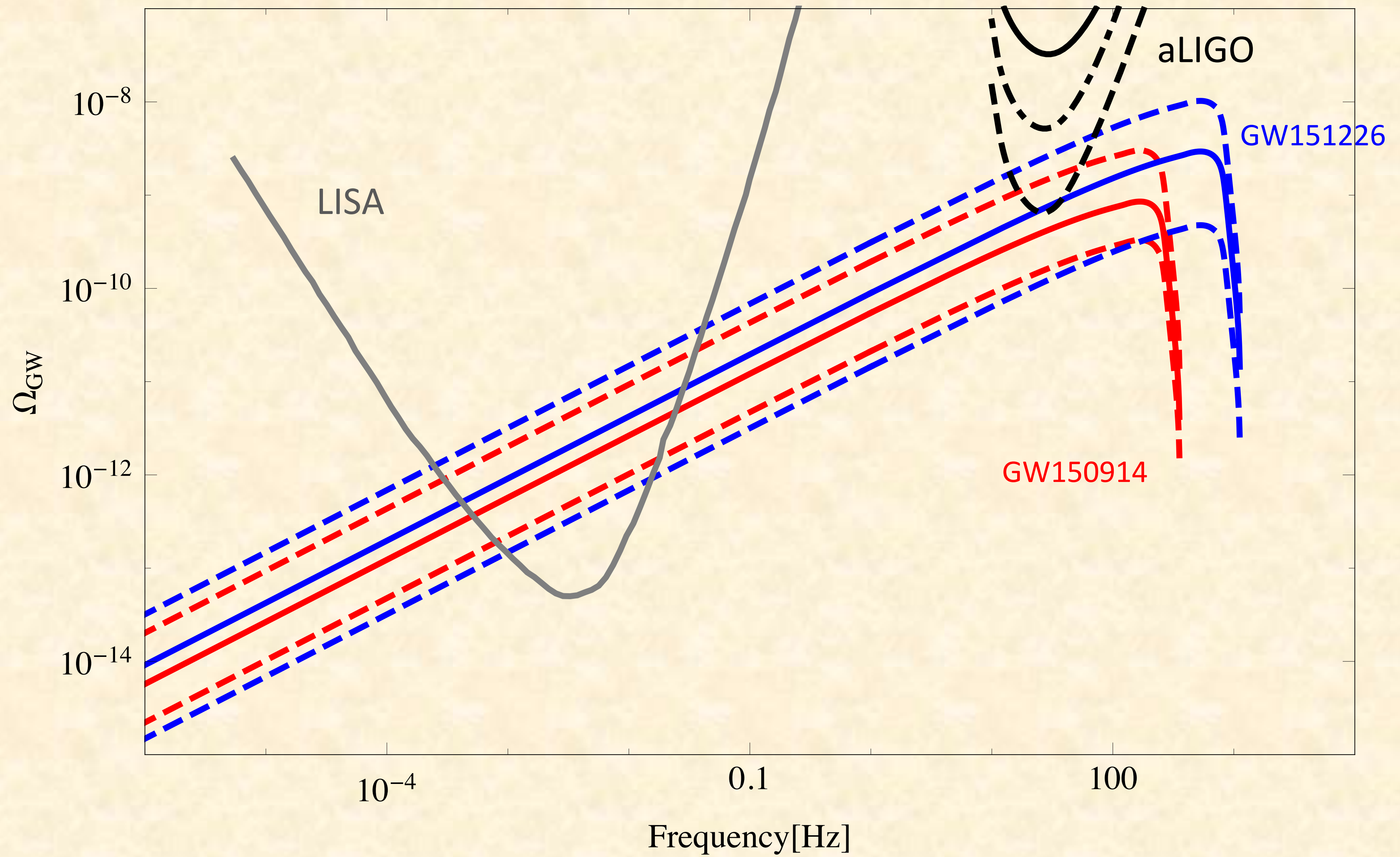
Inspiral-merger-ringdown energy spectrum of Primordial Black holes

$$z_{\mathrm{sup}} = \min(z_{\max}, \nu_{\mathrm{cut}}/\nu - 1)$$

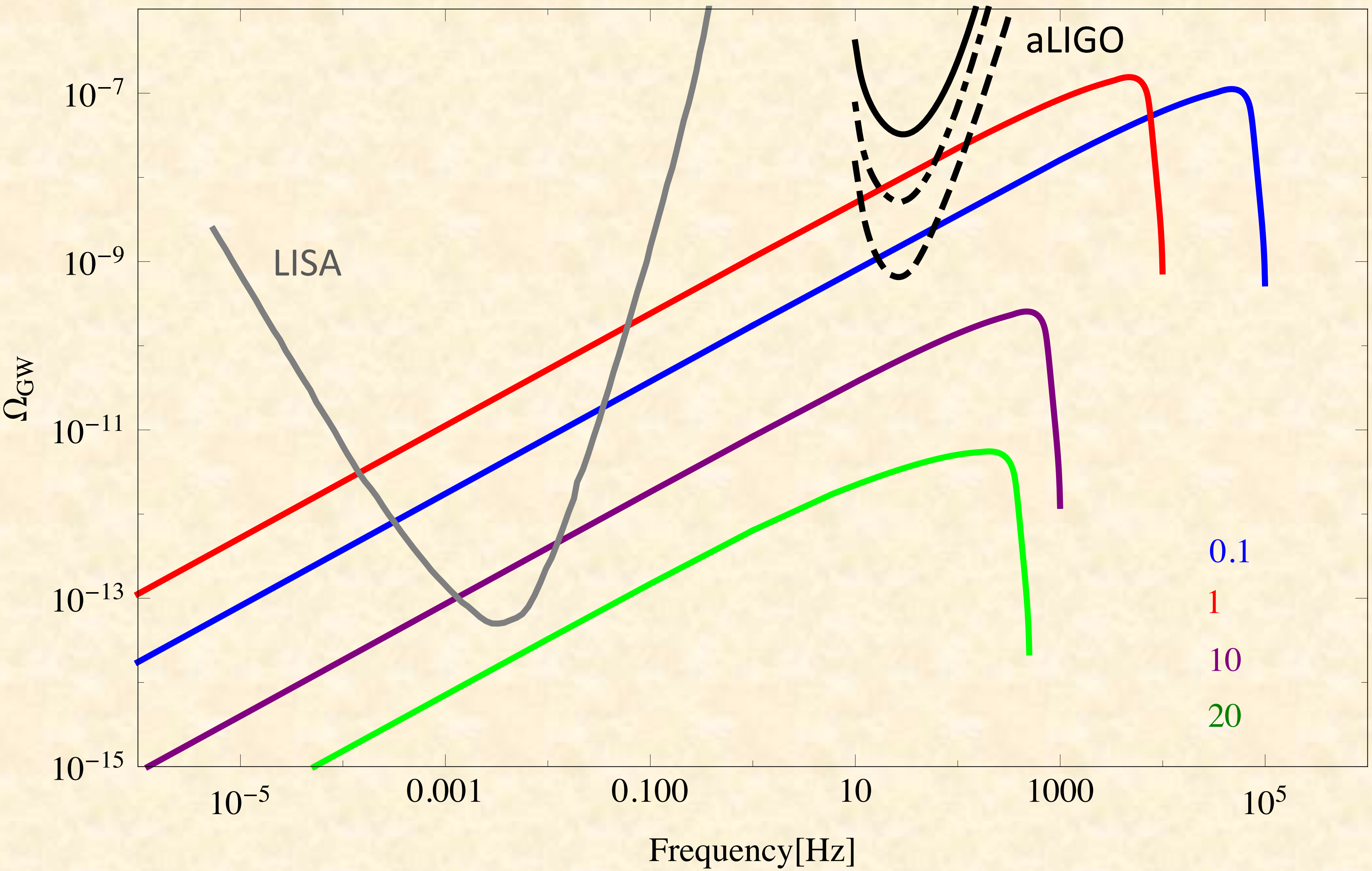
$$\Omega_{\mathrm{GW}}(\nu) = \frac{\nu}{\rho_c H_0}\int_0^{z_{\mathrm{sup}}} \frac{\mathrm{ER}(z)}{(1+z)E(z)}\frac{dE_{\mathrm{GW}}}{d\nu_s}(\nu_s)dz$$

frequency in source frame

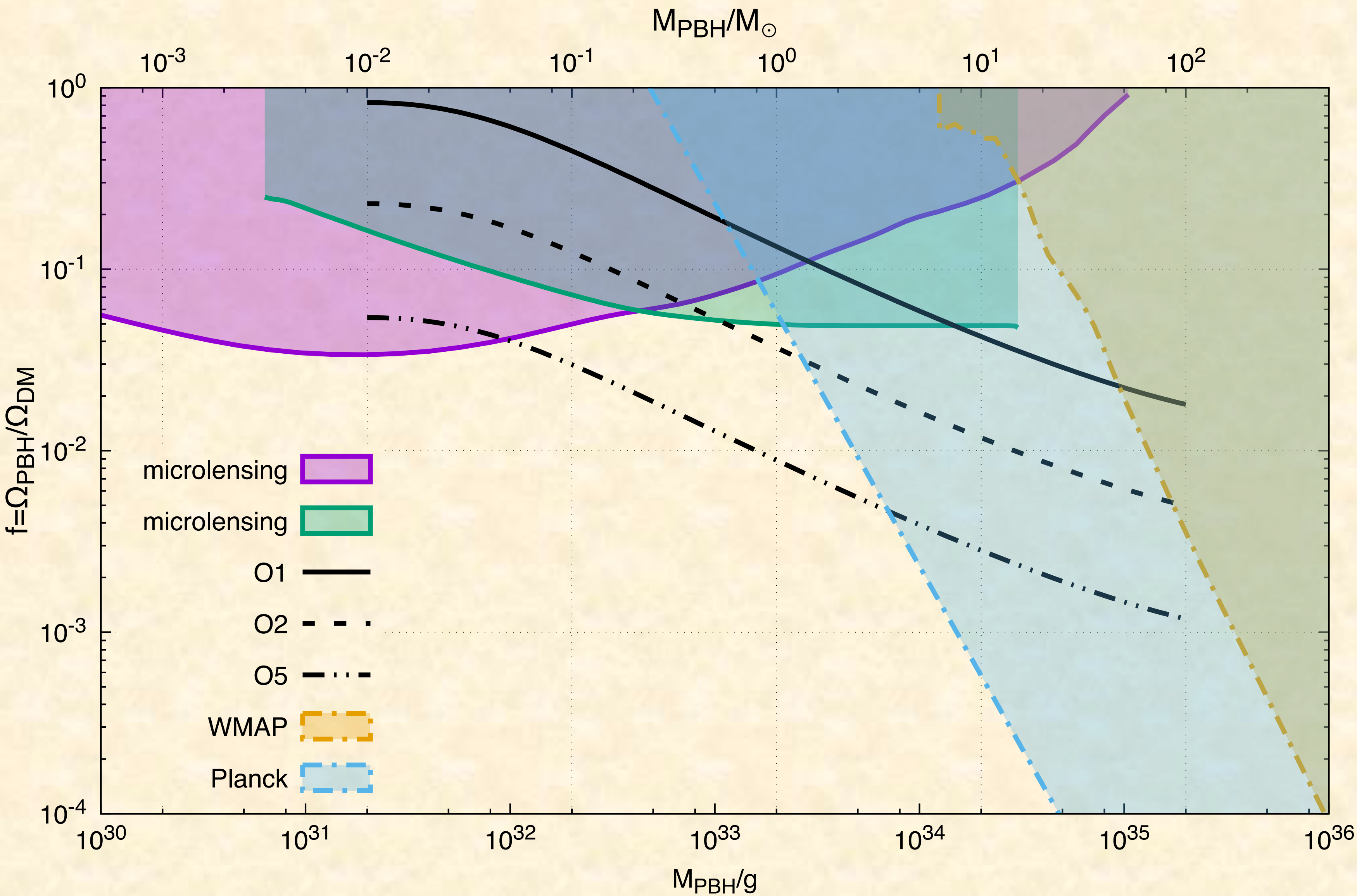
$$E(z) \equiv H(z)/H_0 = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$



aLIGO
GW151226
LISA
GW150914
10^{-8}
10^{-10}
10^{-12}
10^{-14}
Ω_{GW}
10^{-4}
0.1
100
Frequency[Hz]



aLIGO
LISA
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
Ω_{GW}
10^{-5}
0.001
0.100
10
1000
10^5
Frequency[Hz]
0.1
1
10
20



$M_{PBH}/M_{\odot}$
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$f=\Omega_{PBH}/\Omega_{DM}$
microlensing
microlensing
O1
O2
O5
WMAP
Planck
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
M_{PBH}/g

Summary and Discussion

- We give the tightest constraint on the abundance of PBHs with mass not less than one solar-mass from the CMB data.
- GW150914 seems quite unlikely produced by the merger of a PBH binary, but GW151226 can still be interpreted by the coalescence of two PBHs. And we still have large opportunities to detect the coalescences of solar-mass PBHs.
- The Stochastic Gravitational Wave Background generated by mergers of PBH binaries, in particular solar-mass PBHs, may be detected by aLIGO and LISA even if we take into account the most stringent constraints on the abundance of PBHs in the literature. On the other hand, the non-detection of SGWB will put a tighter constraint on the abundance of PBHs with around one solar-mass.
- A more comprehensive analysis for the effects on the CMB from the PBHs is still needed.

Thank you!