Primordial Black Holes: Gravitational Waves Signatures

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Based on

Gravitational Waves from Hyperbolic Encounters of Primordial Black Holes in Dwarf Galaxies
JCAP03(2026)082 [arXiv:2509.19462]

Hierarchical Merger of Primordial Black Holes in Dwarf Galaxies
JCAP09(2022)034 [arXiv:2205.08906]

Outline

Primordial Black Holes

Definition

A PBH is a type of black hole that is **not** formed by the gravitational collapse of a star, but by the extreme density of matter present during the Universe's early expansion.

PBHs properties

Mass: $M_{\rm BH} = 10^{15} \left(\frac{t}{10^{-23}\,{\rm s}} \right)\,{\rm g}$

$M_\odot \simeq 2 \times 10^{33}\,{\rm g}$

Temperature: $T_{\rm BH} \approx 10^{-7} \left(\frac{M}{M_\odot} \right)^{-1}\,{\rm K}$

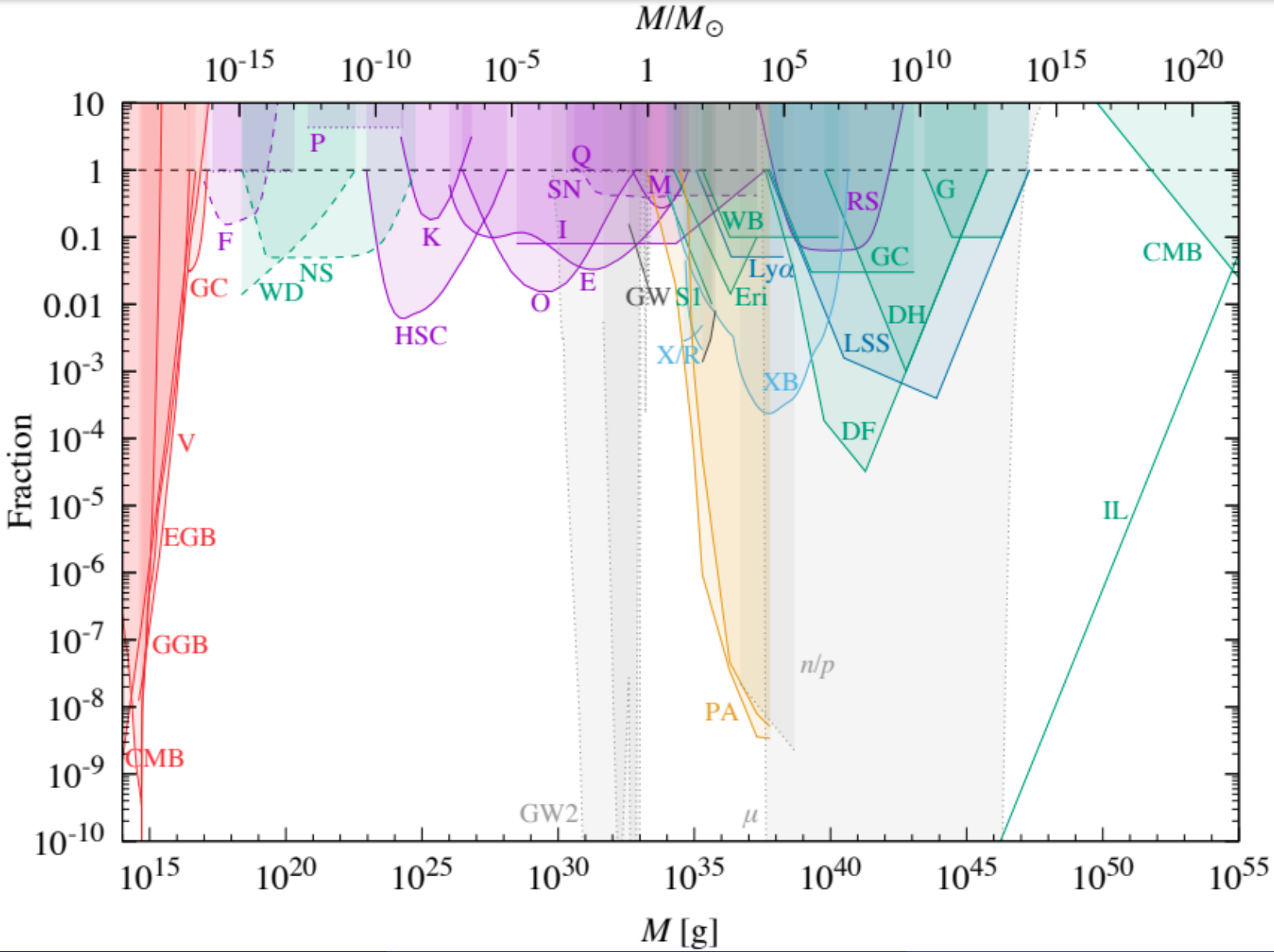
Lifetime: $\tau_{\rm BH} \approx 10^{64} \left(\frac{M}{M_\odot} \right)^{3}\,{\rm y}$

$M_{\rm BH}$	$\tau_{\rm BH}$
$10^{15}\,{\rm g}$	$10^{10}\,{\rm y}$
Sun	$10^{66}\,{\rm y}$

Why PBHs are useful?

- PBHs as a probe of the early Universe $\left(M < 10^{15}\,\mathrm{g}\right)$
- PBHs as a probe of gravitational collapse $\left(M > 10^{15}\,\mathrm{g}\right)$ ✓
  DM candidates $\Omega^0_{\mathrm{PBH}} \lesssim \Omega^0_{\mathrm{CDM}} (= 0.23)$
  source of gravitational waves
- PBHs as a probe of High Energy Physics $\left(M \sim 10^{15}\,\mathrm{g}\right)$
- PBHs as a probe of quantum gravity $\left(M \sim 10^{-5}\,\mathrm{g}\right)$
  (DM candidates)

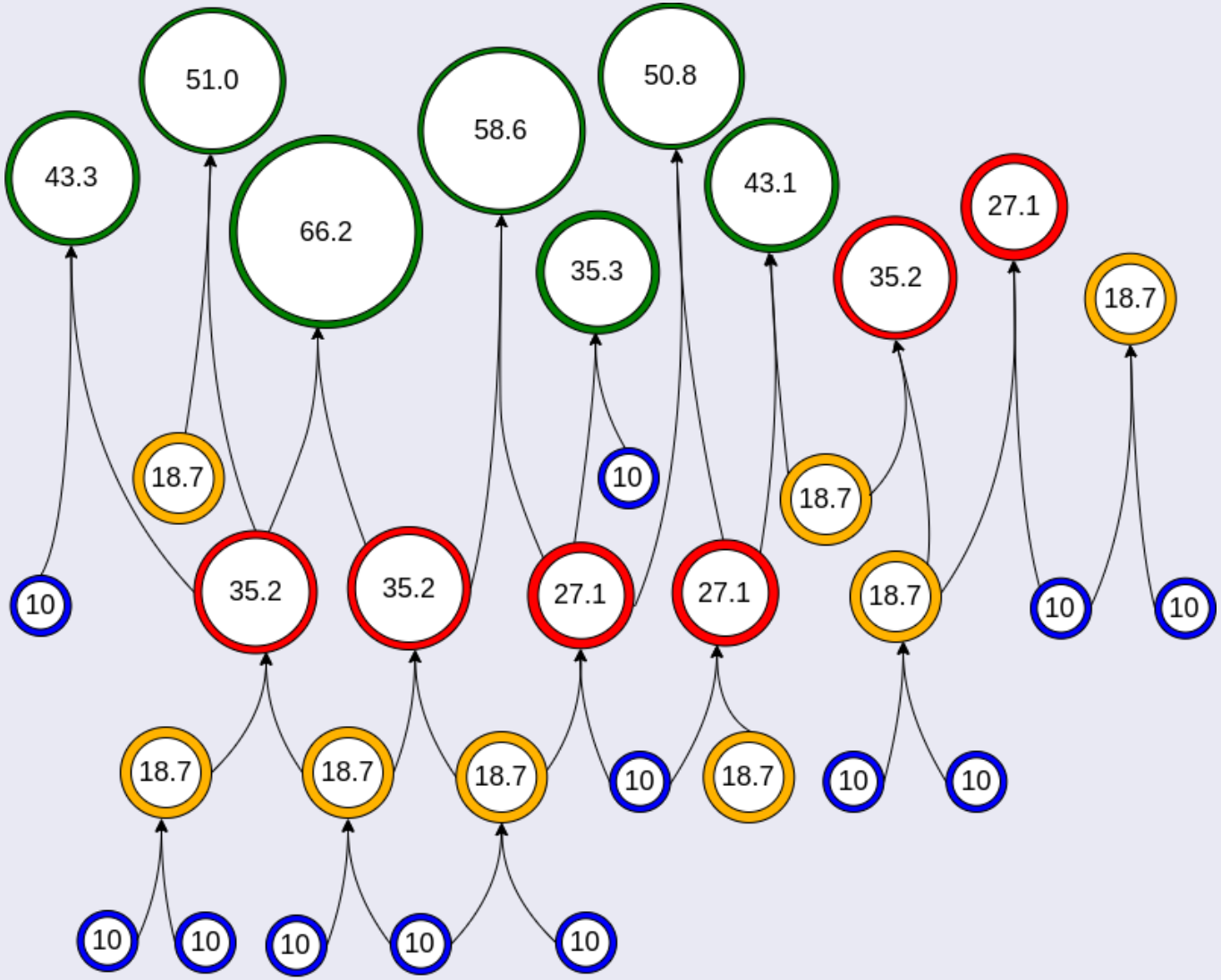
$$\beta \simeq 3.7 \times 10^{-9}\, \gamma^{-1/2} \left(\frac{g_{*,i}}{10.75}\right)^{1/4} \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{1/2} f_{\rm PBH}, \quad f_{\rm PBH} \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$



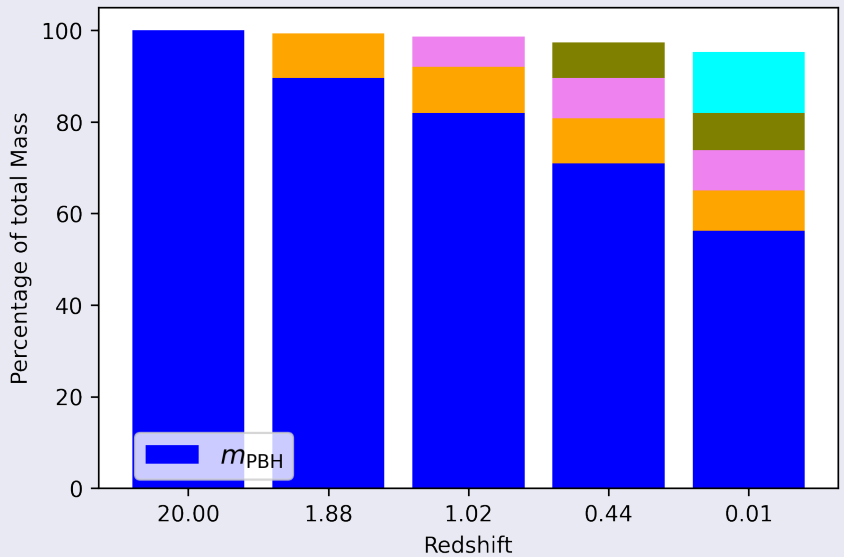
GW from PBHs in Dwarf Galaxies

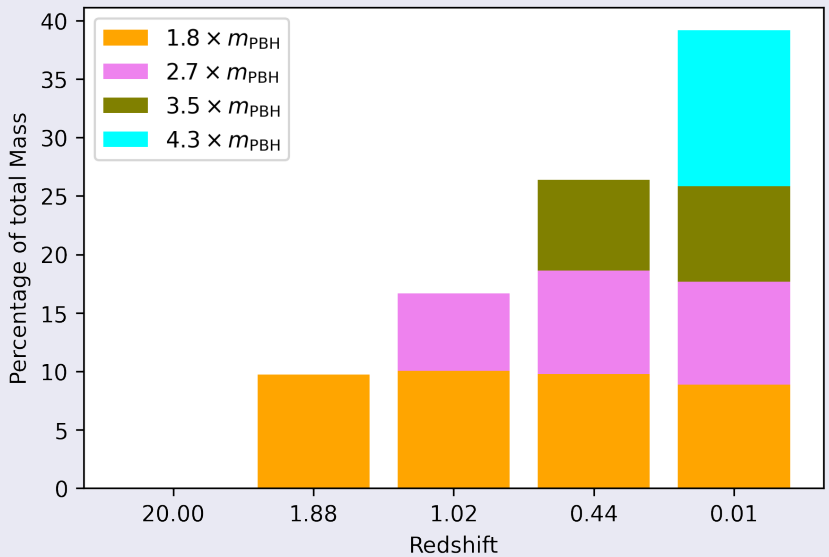
Dwarf Galaxies (DGs) with mass-to-light ratios $\sim 1000\, M_\odot/L_\odot$

Mass: $M = 10^9\, M_\odot$, $M_{\rm core} = 10^5\, M_\odot$ Radius: $R \sim 10$ pc, $R_{\rm core} = 0.9$ pc



First Epoch $(z = 20 - 1.88)$											
m_i	10										
N_i	10^4										
v_i	~ 13										
Second Epoch $(z = 1.88 - 1.02)$											
m_i	10	**18.7**									
N_i	6434	1783									
v_i	~ 10.6	~ 7.5									
Third Epoch $(z = 1.02 - 0.44)$											
m_i	10	18.7	**27.1**	**35.2**							
N_i	4955	994	1092	43							
v_i	~ 9	~ 5.6	~ 7	~ 1.5							
Fourth Epoch $(z = 0.44 - 0.0)$											
m_i	10	18.7	27.1	35.2	**35.3**	**43.1**	**43.3**	**50.8**	**51.0**	**58.6**	**66.2**
N_i	3154	266	526	12	833	281	19	12	17	7	~ 0
v_i	~ 7.5	~ 2.8	~ 4.8	~ 1	~ 6.8	~ 4.4	~ 1.1	~ 1	~ 1.1	~ 0.77	-





GWs from Merger of PBHs

$$\left\langle \frac{dE}{dt} \right\rangle = -\frac{32}{5} \frac{G^4 (m_i m_j)^2 (m_i + m_j)}{a^5} F(e)$$

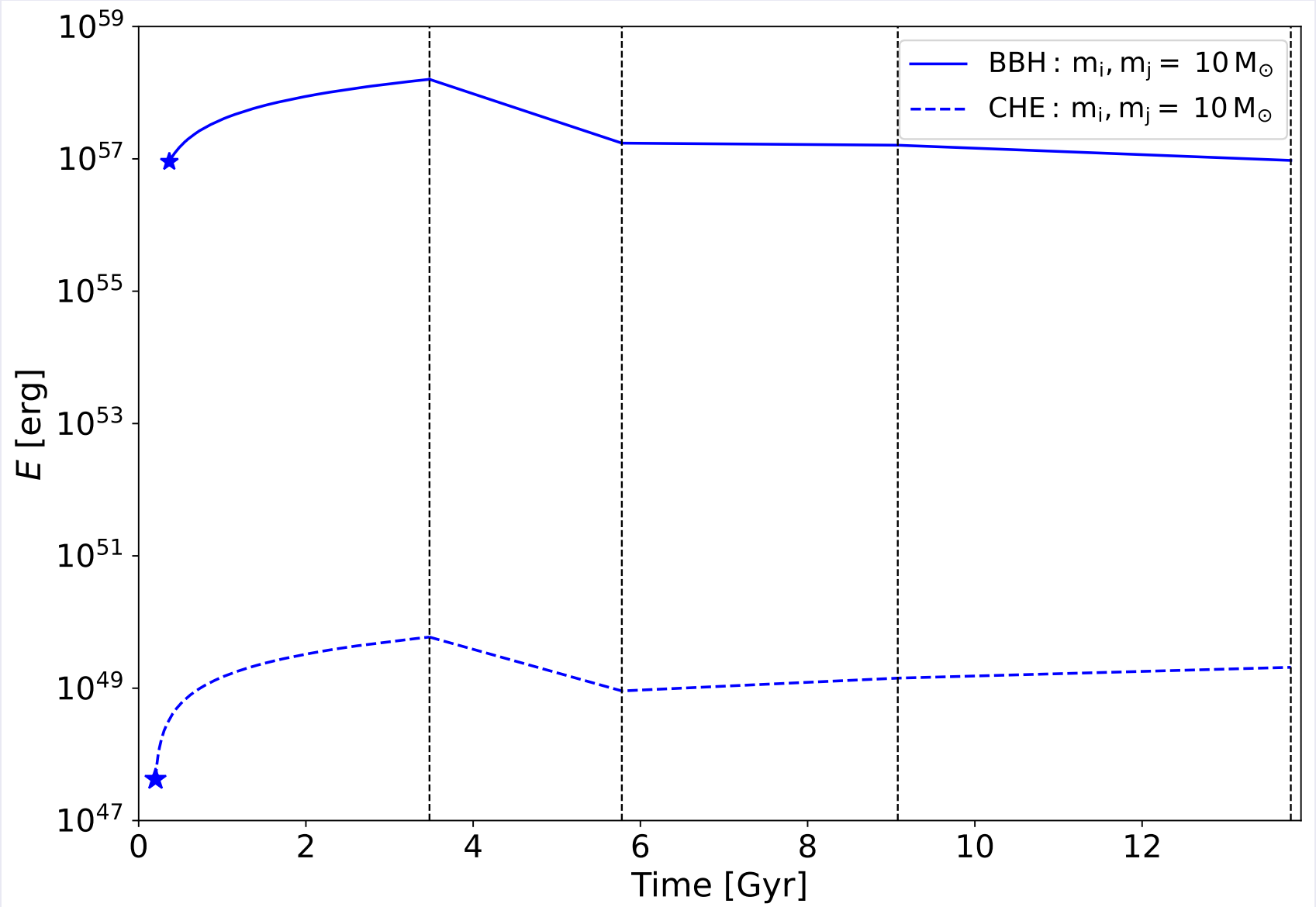
$$F(e) = \frac{1}{(1-e^2)^{7/2}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4 \right)$$

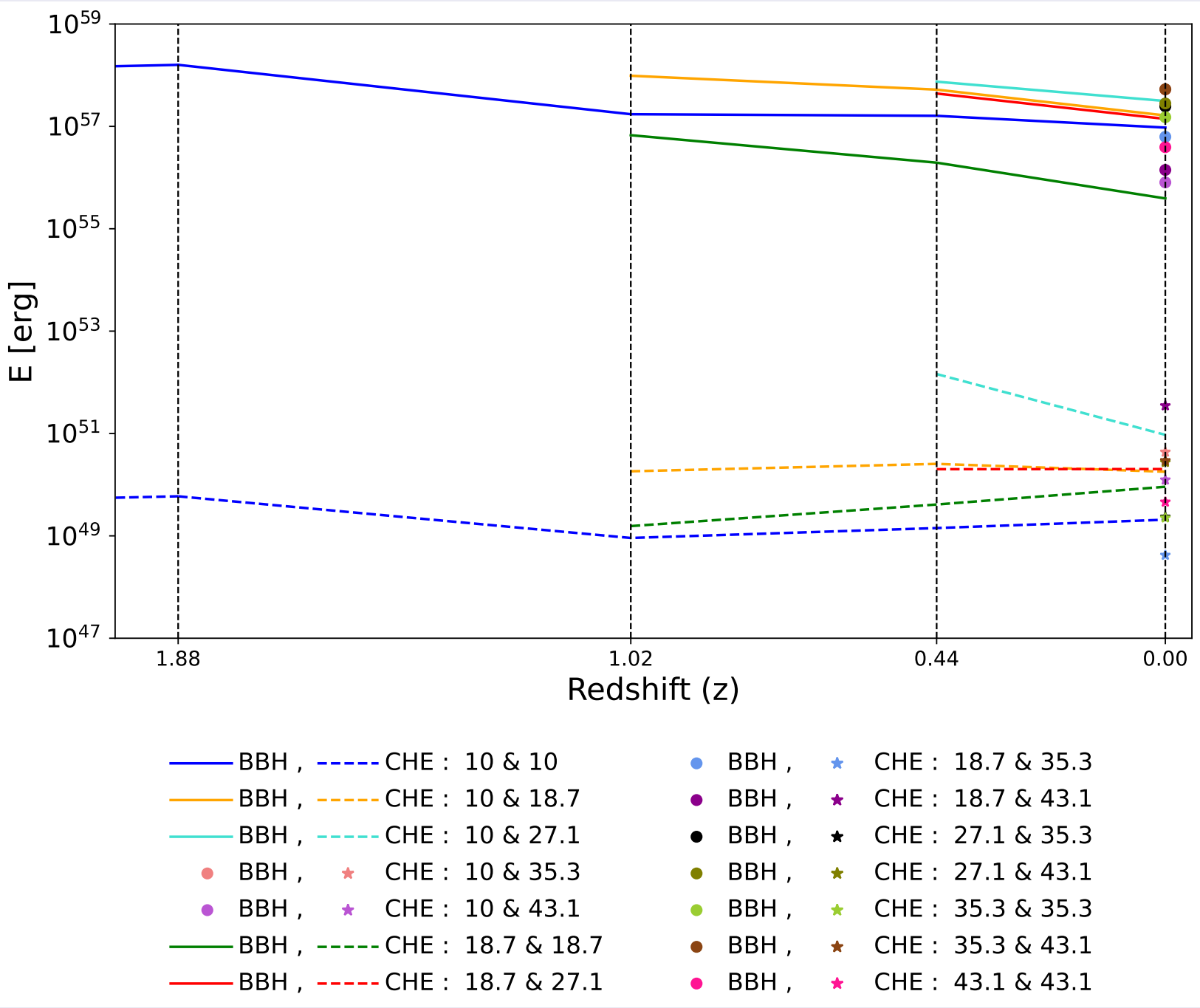
$$\Delta E_{\rm BBH} = \frac{1}{2} m_i m_j \left(\frac{1}{a_{\rm merge}} - \frac{1}{a_{\rm i}} \right)$$

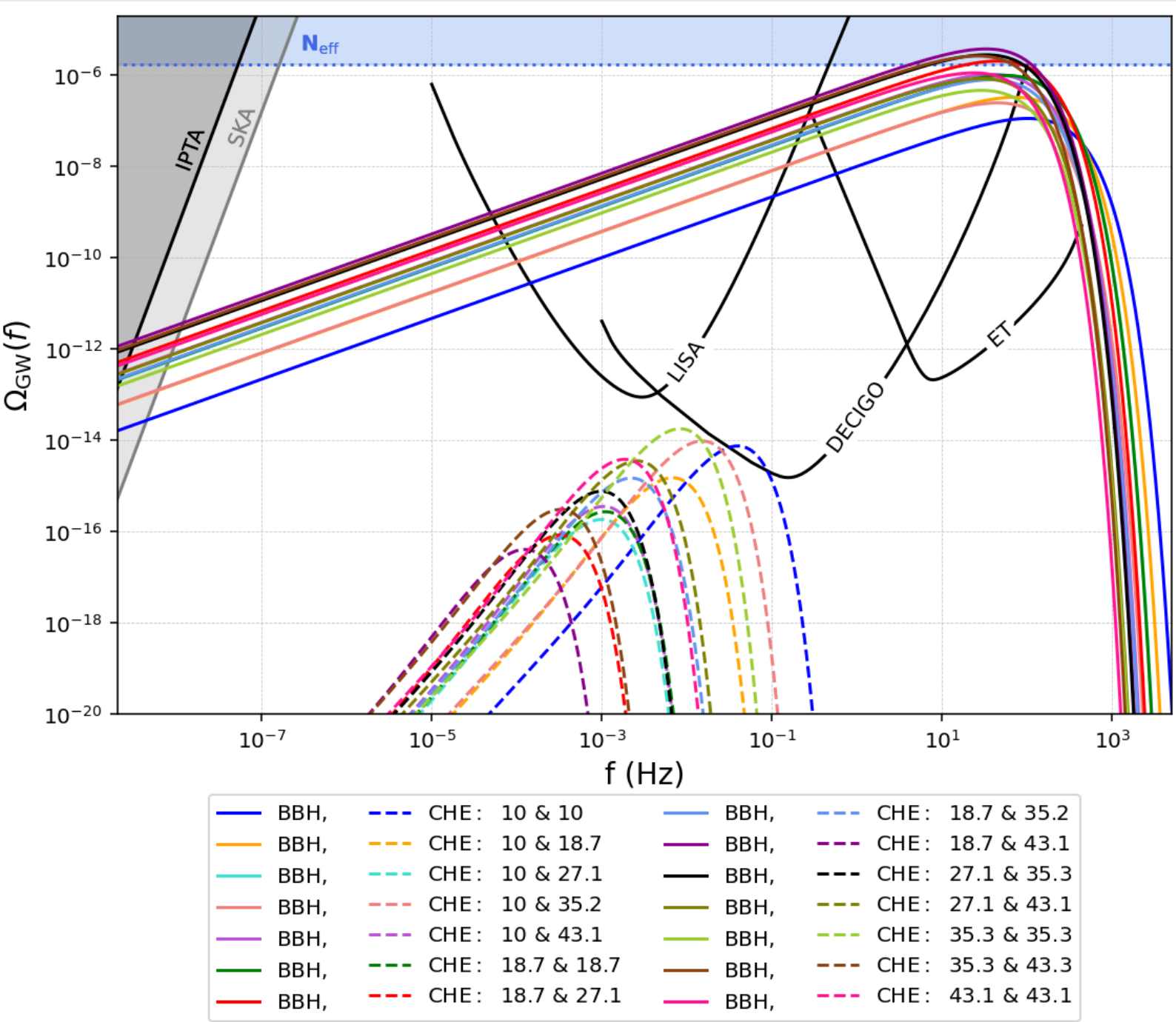
GWs from Close Hyperbolic Encounters of PBHs

$$\sigma_{\rm CHE}(m_i,\, m_j) = \pi b^2 = \pi \left(\frac{G\,(m_i + m_j)}{v_0^2} \right)^2 (e^2 - 1)$$

$$\Delta E_{\rm CHE} = -\frac{8}{15} \frac{G^{7/2}}{c^5} \frac{(m_i + m_j)^{1/2} m_i^2 m_j^2}{r_{\rm min}^{7/2}} f(e)$$


BBH : $m_i, m_j = 10\,M_\odot$
CHE : $m_i, m_j = 10\,M_\odot$
E [erg]
10^{59}
10^{57}
10^{55}
10^{53}
10^{51}
10^{49}
10^{47}
0
2
4
6
8
10
12
Time [Gyr]


10^{59}
10^{57}
10^{55}
10^{53}
10^{51}
10^{49}
10^{47}
E [erg]
1.88
1.02
0.44
0.00
Redshift (z)
BBH , CHE : 10 & 10
BBH , CHE : 10 & 18.7
BBH , CHE : 10 & 27.1
BBH , CHE : 10 & 35.3
BBH , CHE : 10 & 43.1
BBH , CHE : 18.7 & 18.7
BBH , CHE : 18.7 & 27.1
BBH , CHE : 18.7 & 35.3
BBH , CHE : 18.7 & 43.1
BBH , CHE : 27.1 & 35.3
BBH , CHE : 27.1 & 43.1
BBH , CHE : 35.3 & 35.3
BBH , CHE : 35.3 & 43.1
BBH , CHE : 43.1 & 43.1


N_{eff}
IPTA
SKA
LISA
DECIGO
ET
$\Omega_{GW}(f)$
f (Hz)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
BBH, CHE: 10 & 10
BBH, CHE: 10 & 18.7
BBH, CHE: 10 & 27.1
BBH, CHE: 10 & 35.2
BBH, CHE: 10 & 43.1
BBH, CHE: 18.7 & 18.7
BBH, CHE: 18.7 & 27.1
BBH, CHE: 18.7 & 35.2
BBH, CHE: 18.7 & 43.1
BBH, CHE: 27.1 & 35.3
BBH, CHE: 27.1 & 43.1
BBH, CHE: 35.3 & 35.3
BBH, CHE: 35.3 & 43.3
BBH, CHE: 43.1 & 43.1


mount Everest mass ~ 10^{15} g
Thank you