Gravitational wave backgrounds from coalescing BH binaries at cosmic dawn

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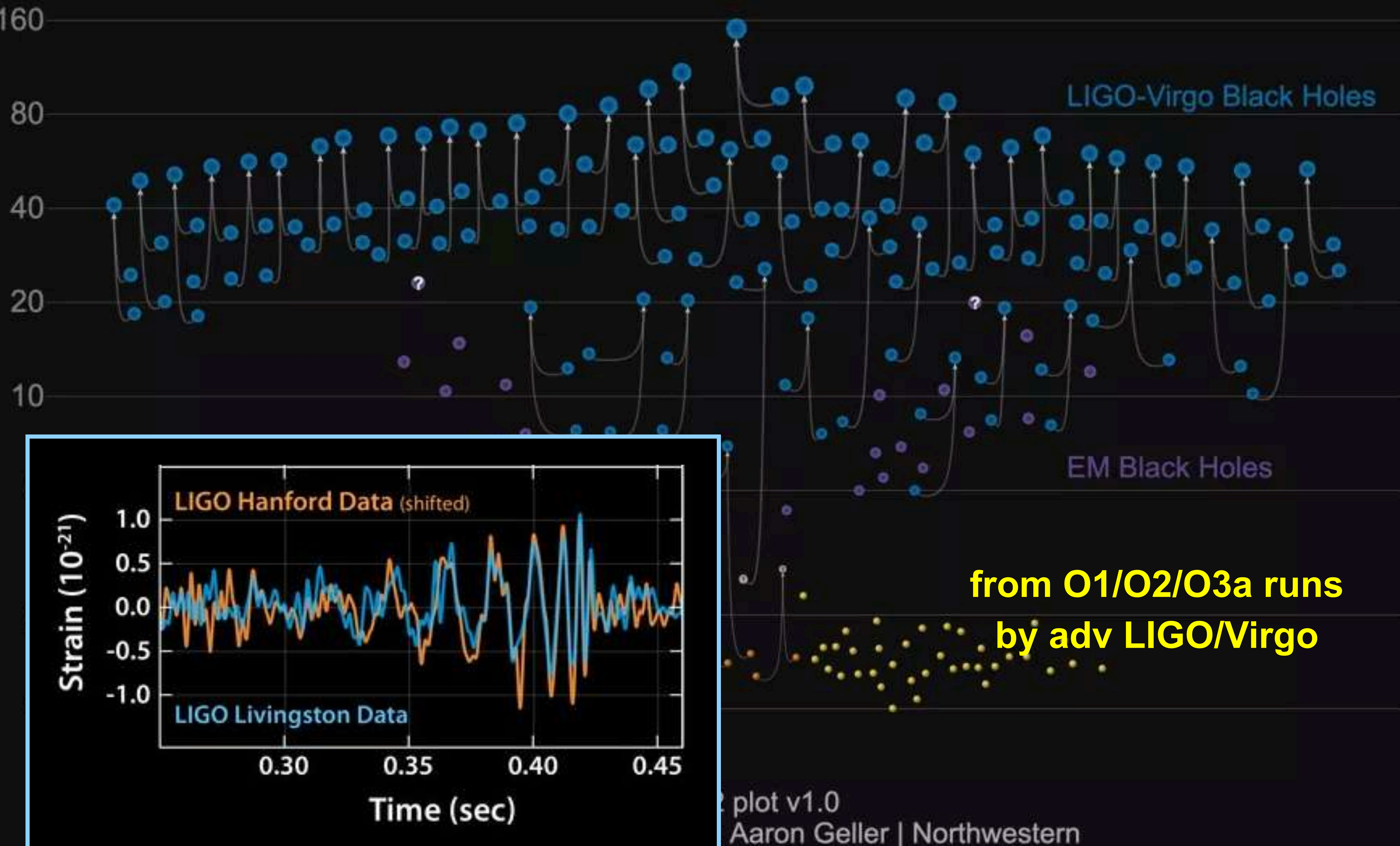
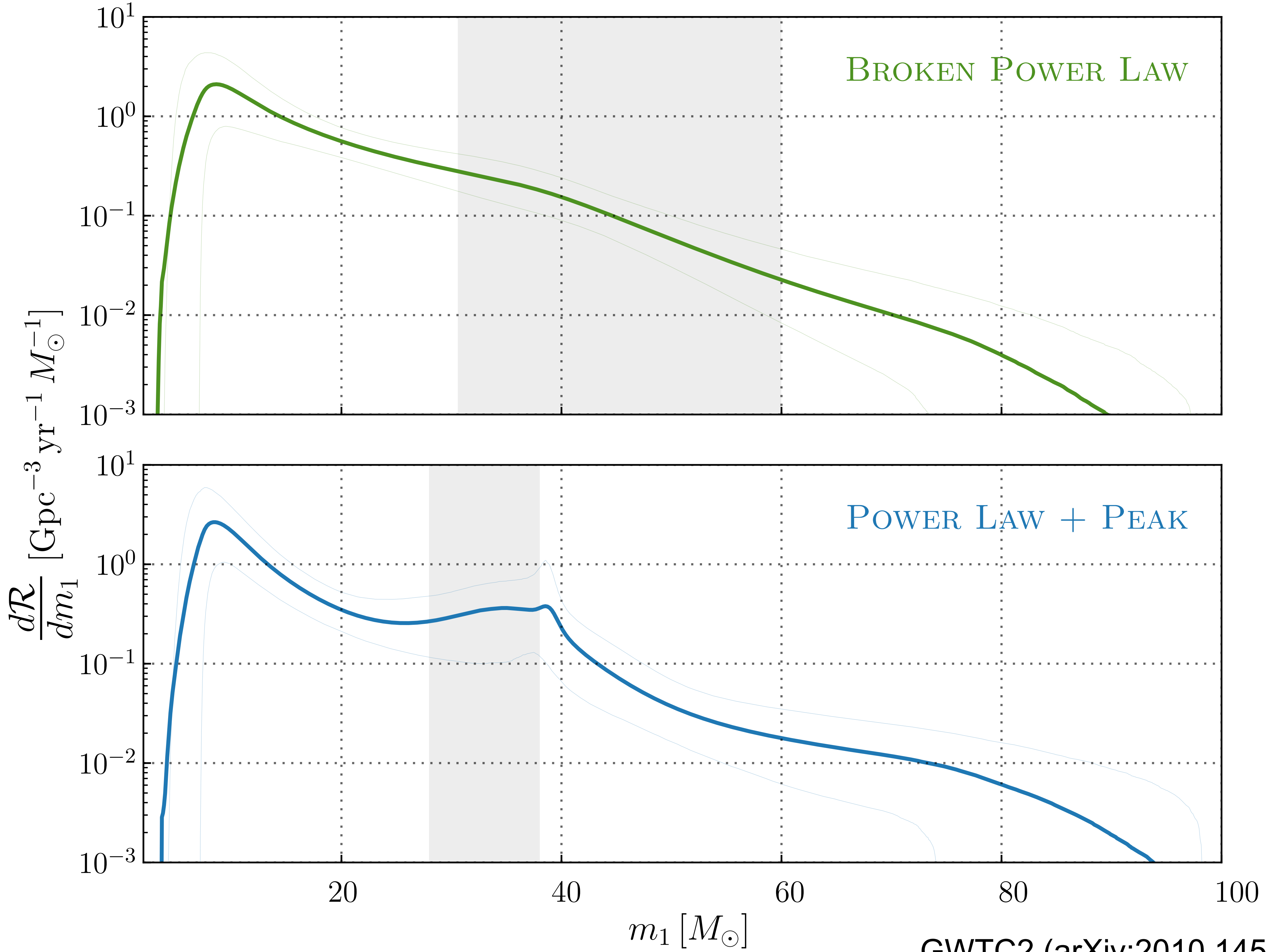
YITP-OzGrav WS "Nuclear burning in massive stars"

GW events from merging BBHs



from O1/O2/O3a runs by adv LIGO/Virgo

Mass function of BBH mergers



GWTC2 (arXiv:2010.14533)

Formation channels

- isolated field massive binaries

  metal-poor stars (PopII; $Z \sim 0.1 Z_{sun}$)

  (e.g., Belczynski 2004, Dominik et al. 2012, Belczynski et al. 2016)

  primordial stars (PopIII; $Z \sim 0$)

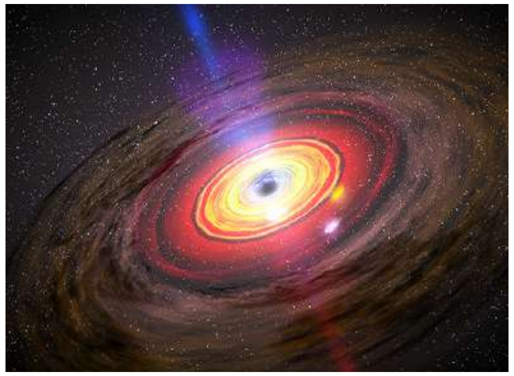
  (e.g., Kinugawa et al. 2014, 2016, 2020, Inayoshi et al. 2016, 2017, Hartwig et al. 2016, Liu & Bromm 2020, Tanikawa et al. 2020, 2021)

- dynamical formation in dense clusters

  (e.g., Portegies Zwart & McMillan 2000, O'Leary, Meiron & Kocsis 2009, Rodriguez et al. 2016, Antonini et al. 2016)

- formation in compact AGN disks

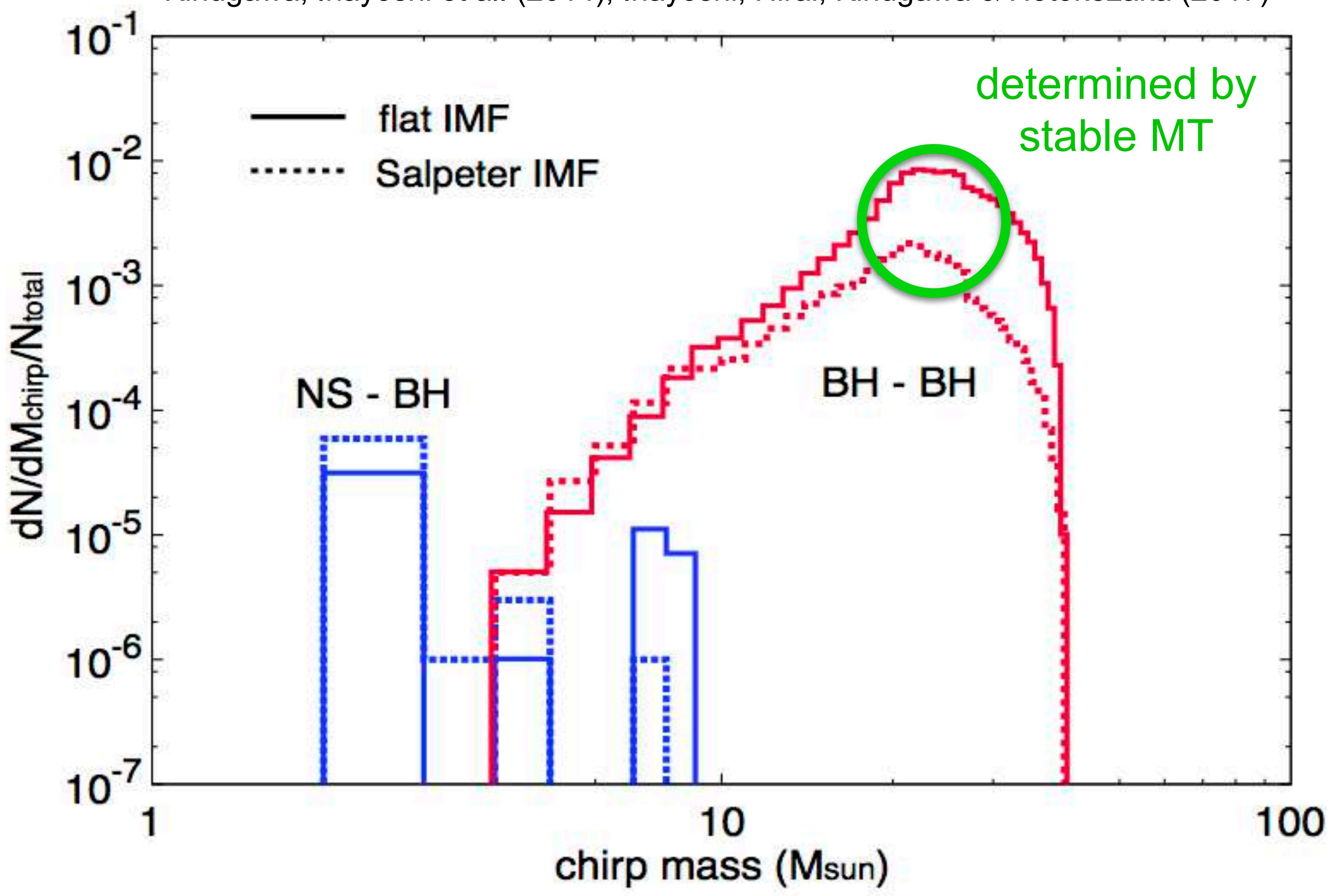
  (Stone et al. 2016, Bartos et al. 2016, Tagawa et al. 2020)



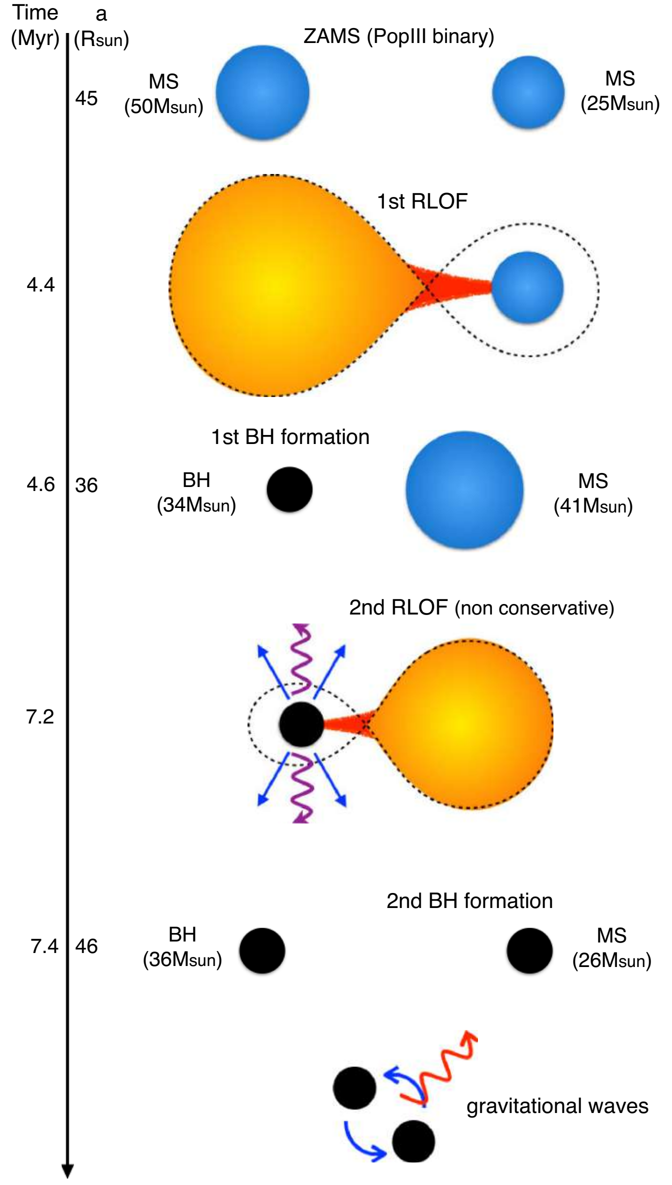
Massive BH formation would favor
low metallicity environments
(top-heavy IMF & weak mass loss)

Population III star origins?

Kinugawa, Inayoshi et al. (2014); Inayoshi, Hirai, Kinugawa & Hotokezaka (2017)



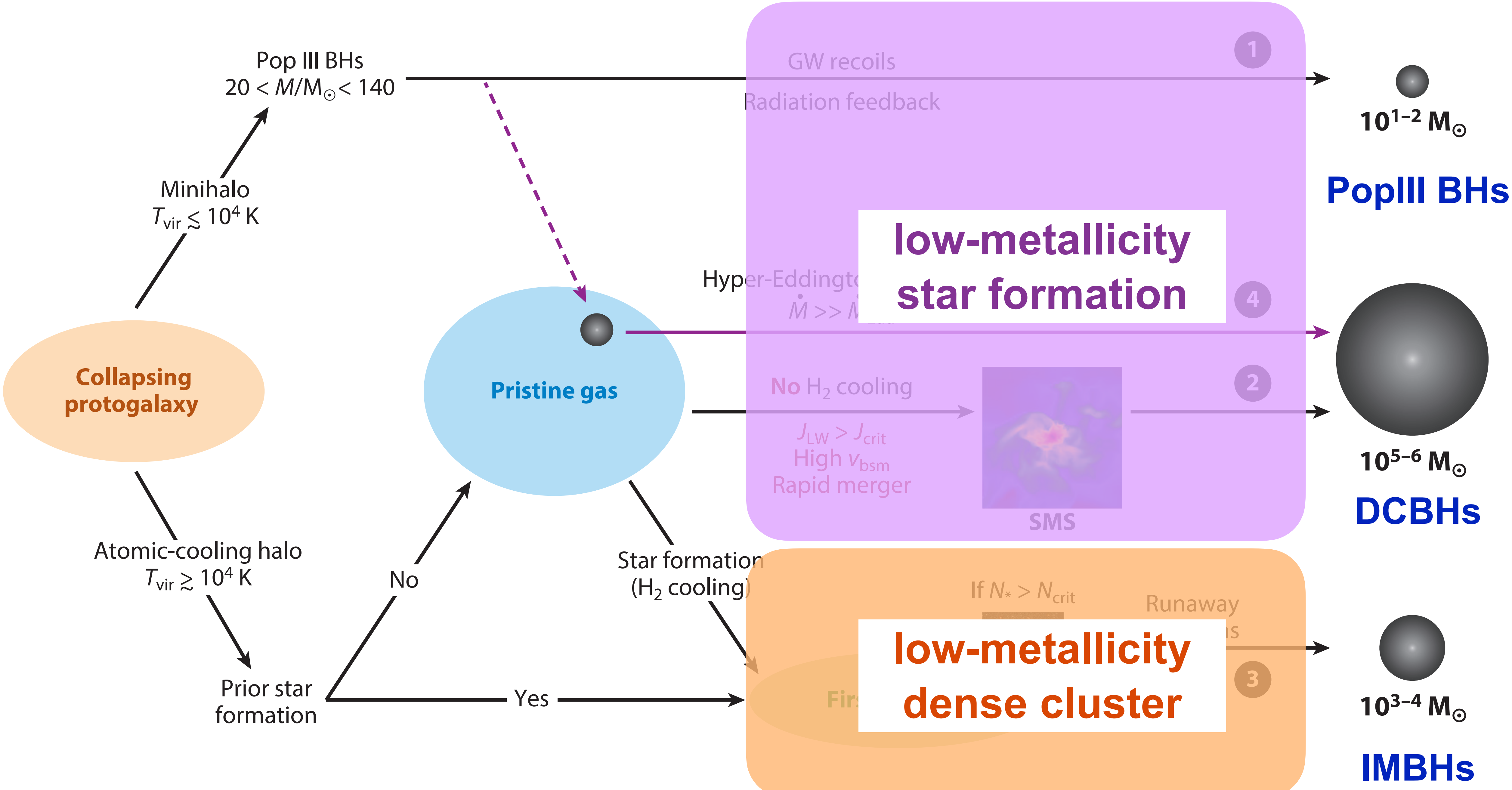
PopIII binary evolution
with MESA code



Typical mass of merging PopIII BBHs ~ **$30+30M_{sun}$**

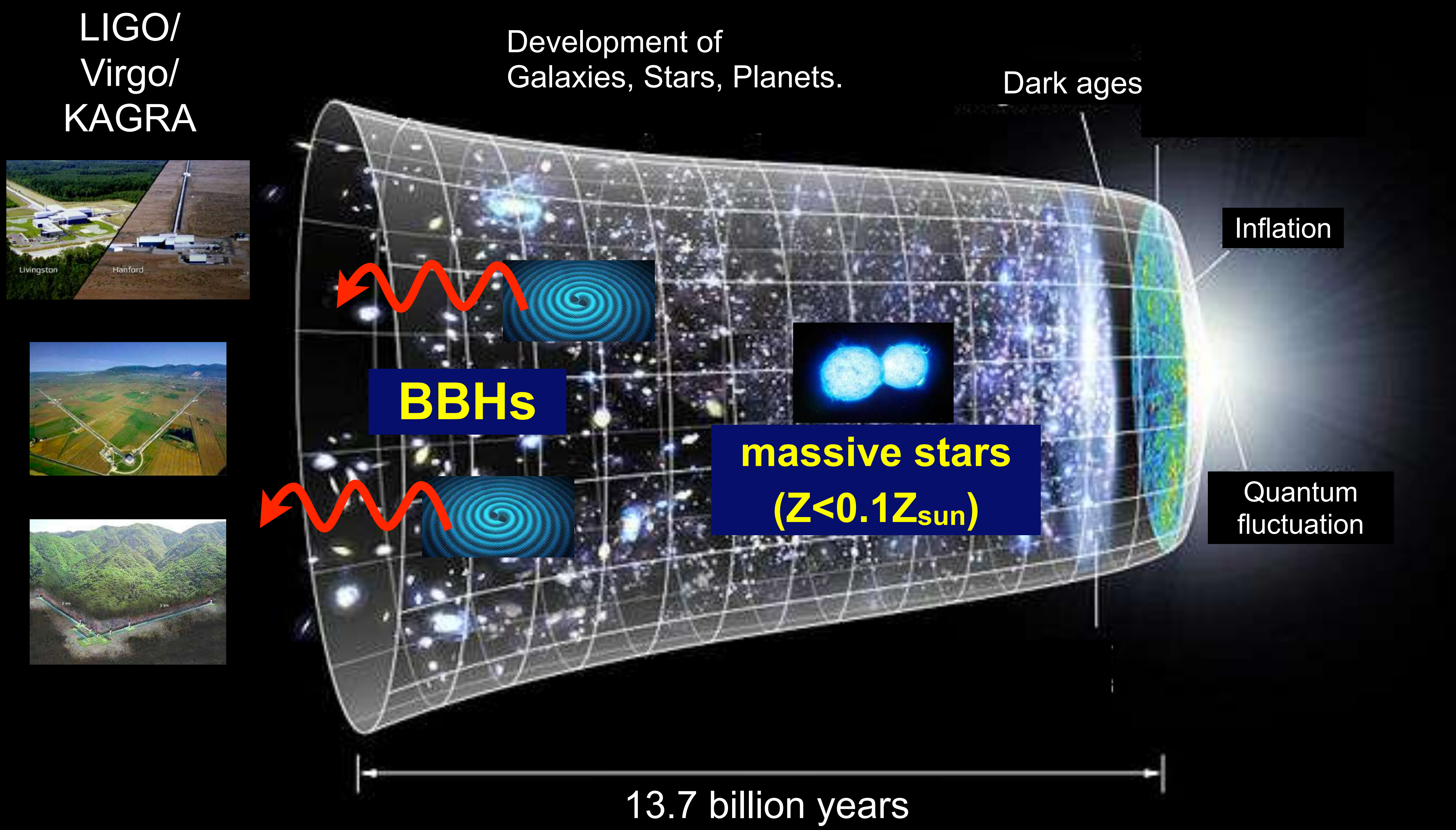
Formation of early SMBHs

from stellar-mass BHs to IMBHs (basically similar but scale-up)

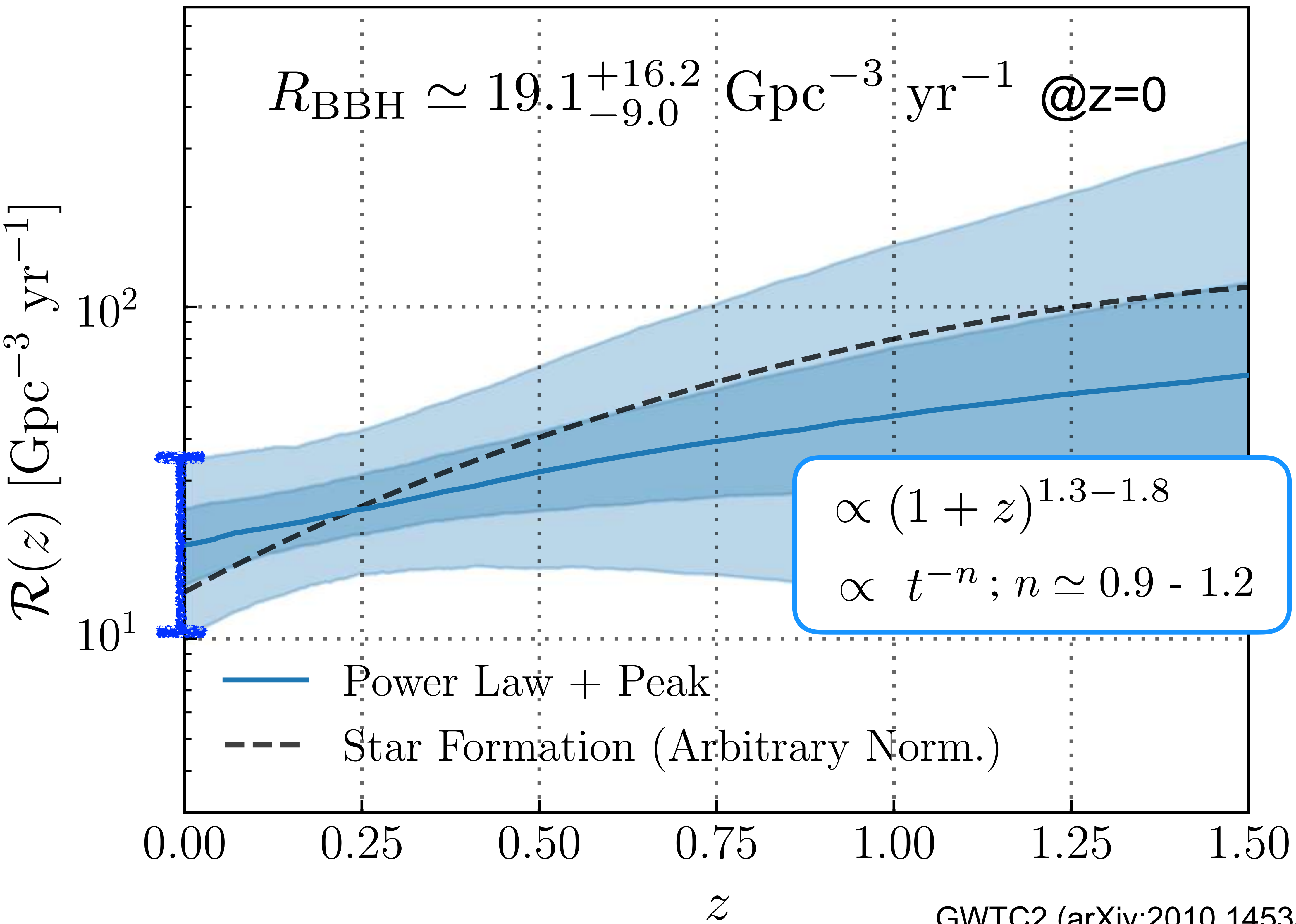


Inayoshi, Visbal & Haiman (2020) ARA&A

low metallicity ≈ high redshift

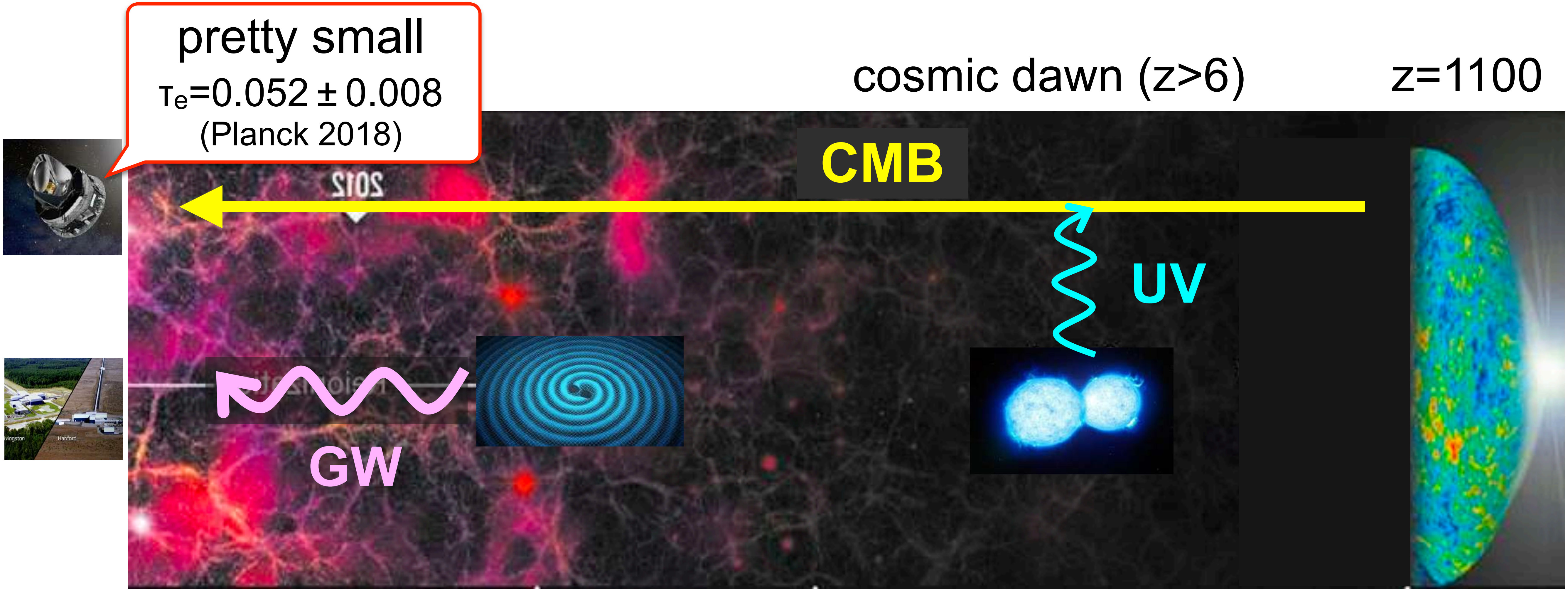


Cosmic BBH merger rate



GWTC2 (arXiv:2010.14533)

Relation between GW & CMB



"Metal-poor massive stars"

high SFR

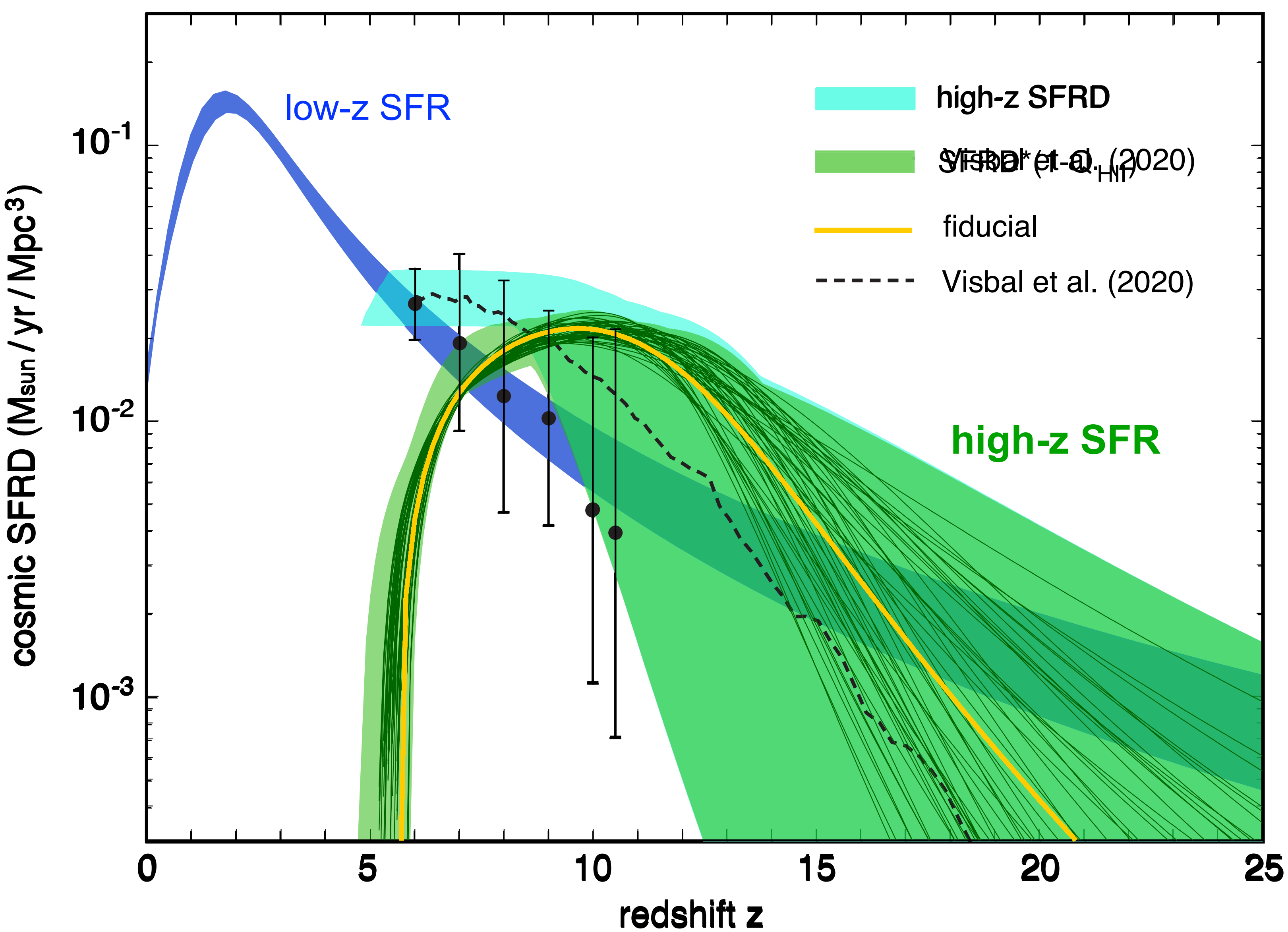
top heavy IMF

→

stronger **GW** from cosmic dawn

higher **CMB optical depth** due to stellar **UV radiation**, but…

SFRD consistent with reionization



Given SFR, f_{esc}, and η_{ion}

$$\dot{n}_{\rm ion} = \frac{f_{\rm esc}\eta_{\rm ion}\dot{\rho}_\star(z)}{m_{\rm p}}$$

ionization history $Q_{HII}(z)$

$$\frac{dQ_{\rm H_{II}}}{dt} = \frac{\dot{n}_{\rm ion}}{\langle n_{\rm H}\rangle} - \frac{Q_{\rm H_{II}}}{t_{\rm rec}}$$

optical depth $\tau_e(z)$ & z_{reion}

the total mass budget used for BBH formation

Planck (2018)

$$\rho_\star \simeq 10^7\ M_\odot\ {\rm Mpc}^{-3} \left(\frac{f_{\rm esc}}{0.1}\right)^{-1.2} \left(\frac{\eta_{\rm ion}}{4\times 10^3}\right)^{-1.2} \left(\frac{\tau_{\rm e}}{0.06}\right)^{0.68}$$

BBH merger rates

- BBH merger rate

$$R_{\rm BBH}(z) = \frac{1}{\langle M_{\rm tot,b}\rangle}\int_0^{t(z)} \dot{\rho}_{\rm BBH}(t')\Psi(t-t')dt'$$

- Merger delay-time distribution

$$\Psi(t) = \frac{dN}{da}\frac{da}{dt} \propto t^{-1+\frac{\gamma+1}{4}}$$

$$\Rightarrow \frac{\Psi_0}{t_{\rm min}}\left(\frac{t}{t_{\rm min}}\right)^{-n}$$

binary separation distribution

$$\frac{dN}{da} \propto a^{\gamma}$$

Öpik's law

$$\gamma = -1$$

cf. n=1 for type Ia SNe

- if SF activity terminates at high-z…

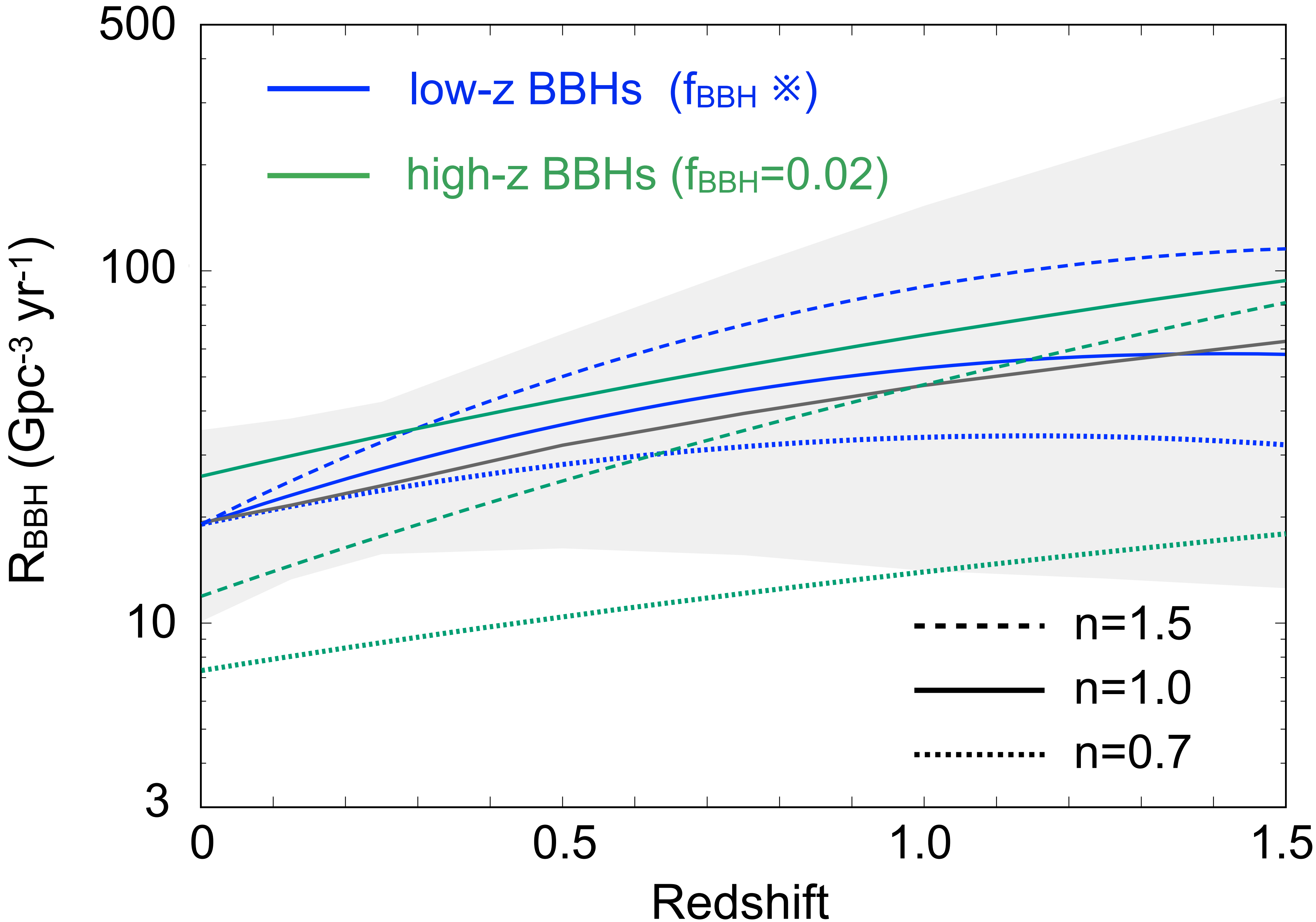
$$R_{\rm BBH} \simeq \frac{f_{\rm BBH}\rho_\star}{\langle M_{\rm tot,b}\rangle}\cdot\frac{1}{t}$$

BBH formation efficiency

$$f_{\rm BBH} \simeq 0.02$$

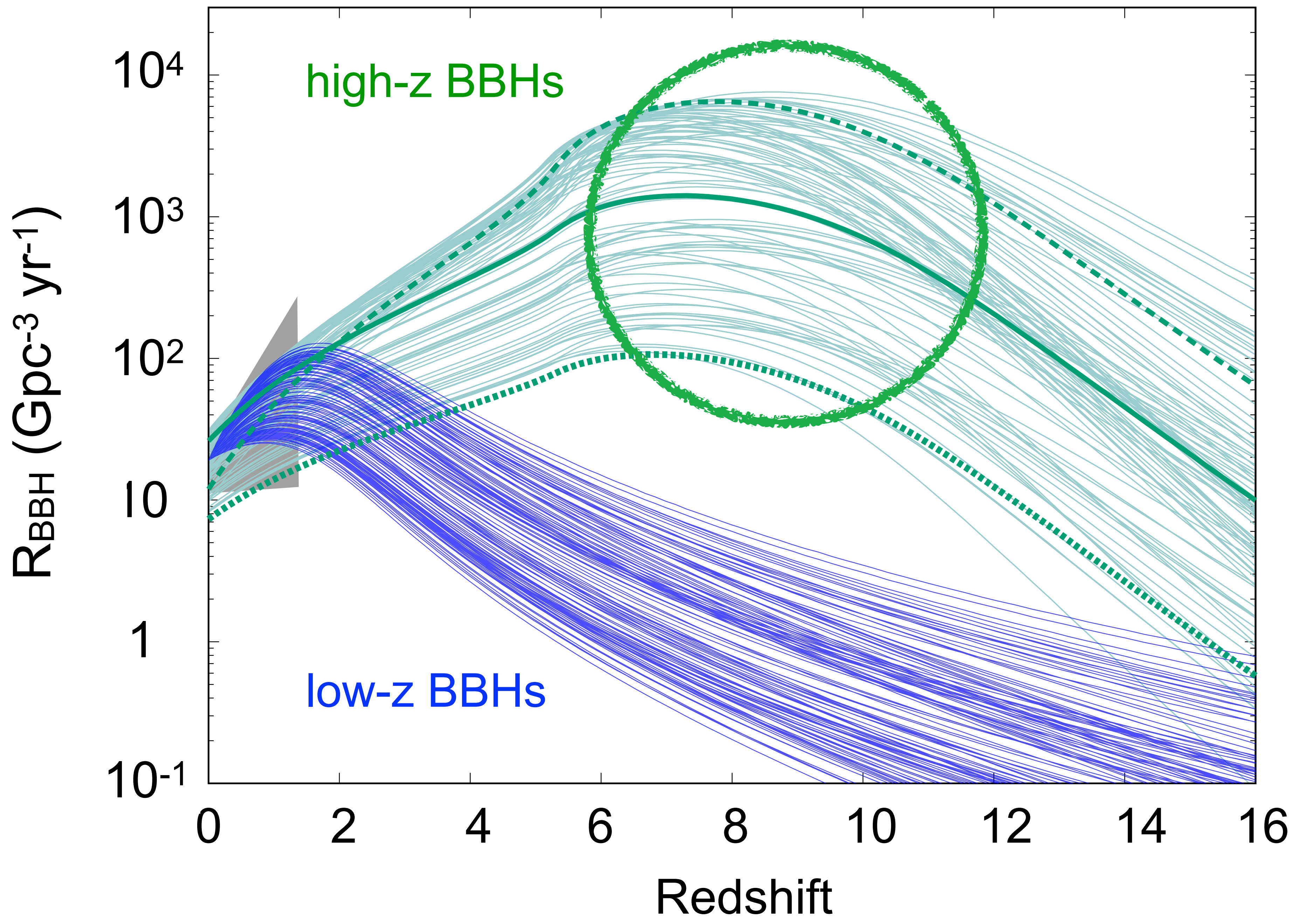
(Salpeter IMF; 0.1-100$M_{\rm sun}$)

BBH merger rates



※ for low-z BBHs, $R_{BBH}(z=0)$ is normalized to be the observed rate

BBH merger rates



individually unresolved GW sources (BBHs) → **GW background**

Gravitational wave background

- GWB energy density (Phinney 2001)

$$\rho_c c^2 \Omega_{gw}(f) = \int_{z_{min}}^{\infty} \int_{M_{min}}^{M_{max}} \frac{d\mathcal{R}_{BBH}}{dM_1} \left(f_r \frac{dE_{gw}}{df_r} \right) \frac{dt}{dz} \frac{dM_1 dz}{1+z}$$

merging rate (our model)
mass function (O3a)

GW spectrum from each BBH

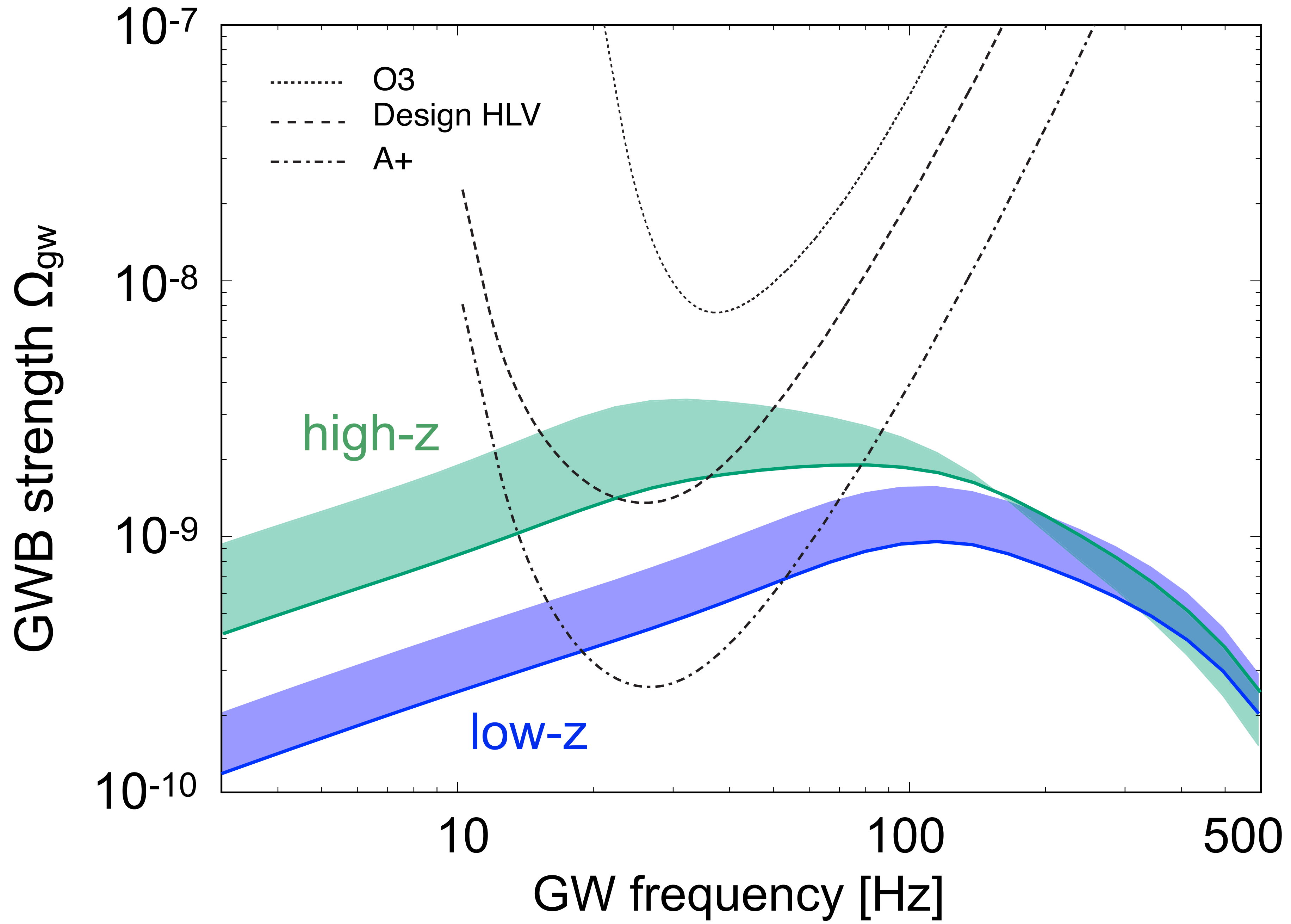
$$\frac{dE_{gw}}{df_r} = \frac{(\pi G)^{2/3} M_{chirp}^{5/3}}{3} \begin{cases} f_r^{-1/3} \mathscr{F}_{PN} & f_r < f_1, \\ \omega_m f_r^{2/3} \mathscr{G}_{PN} & f_1 \le f_r < f_2, \\ \frac{\omega_r \sigma^4 f_r^2}{[\sigma^2 + 4(f_r - f_2)^2]^2} & f_2 \le f_r < f_3, \end{cases}$$

if GW emission due to inspiral phases dominates at f

$$\Omega_{gw}(f) \propto f^{2/3}$$

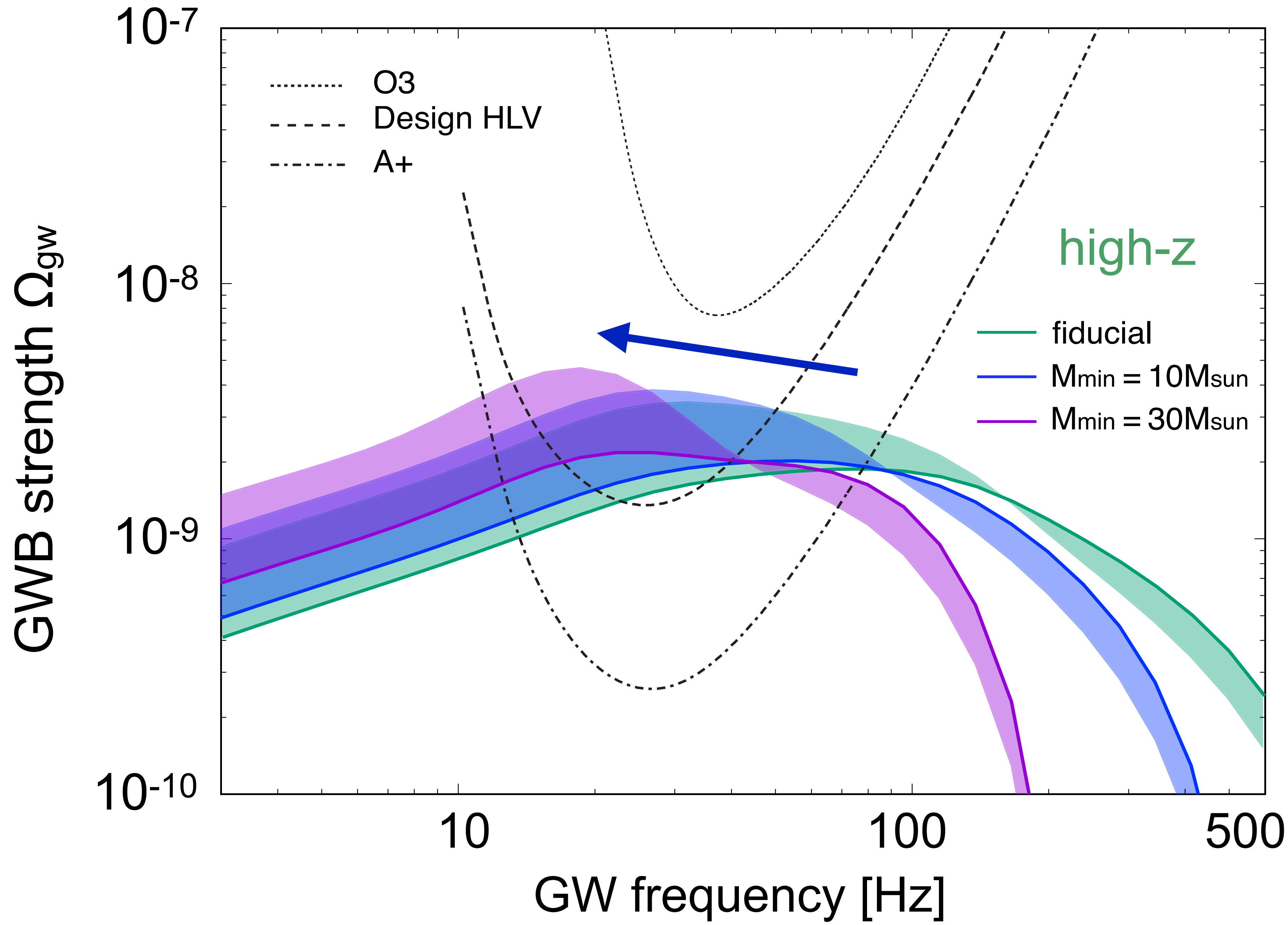
power-law with
an index of **2/3**

GWB: low-z vs. high-z BBHs



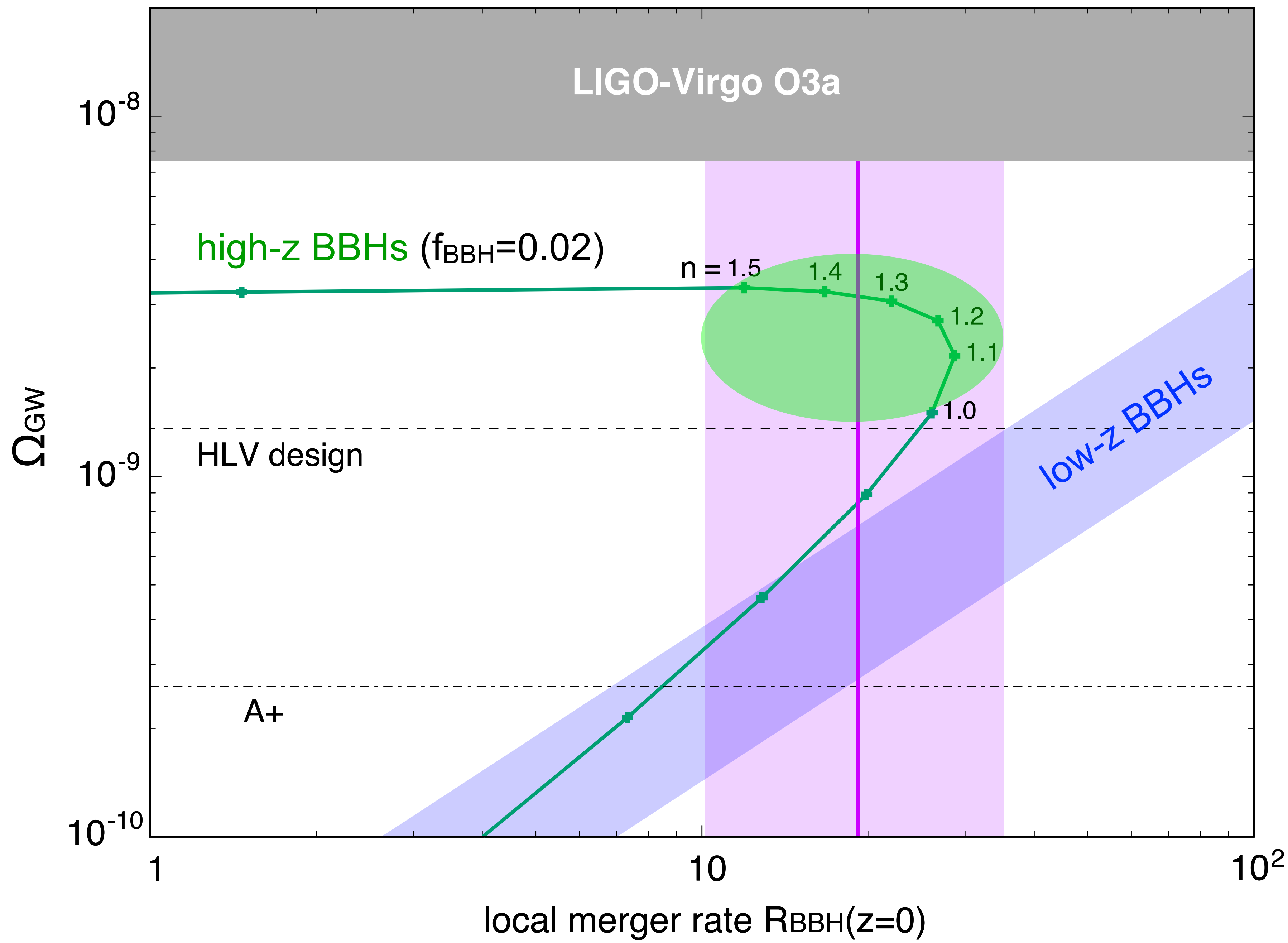
detectable & flatter GWB spectra ⟷ high-z BBH population

GWB: top-heavy BBH MFs



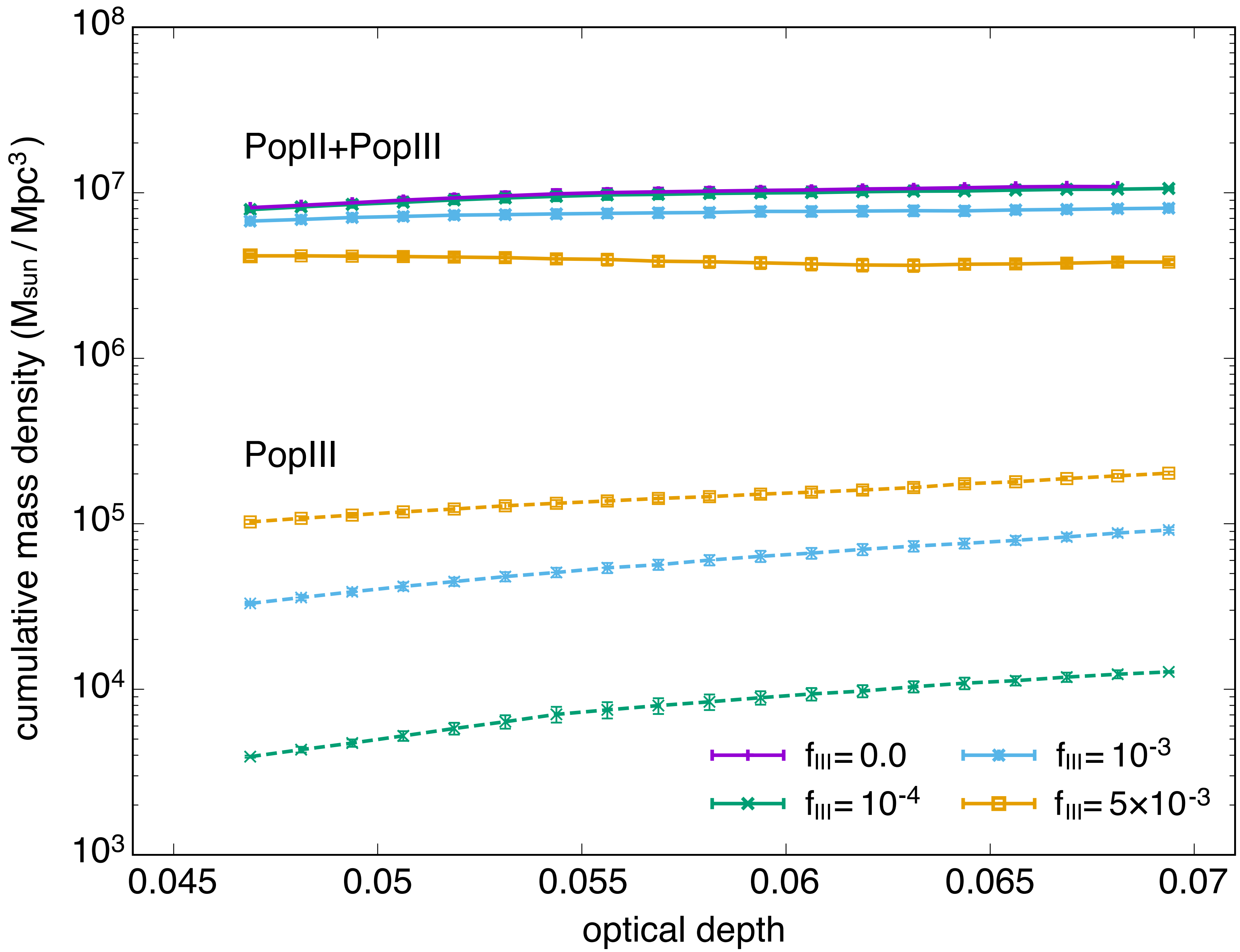
more top-heavy BBH mass function ⟷ the peak is skewed to lower frequencies

Relation between R_{BBH} & Ω_{gw}



high-z BBH GWB
$\Omega_{gw} > 10^{-9}$
→
major contribution
to the local rate

PopIII contributions?



PopIII stellar mass limit

Planck 2015
(Inayoshi et al. 2016)

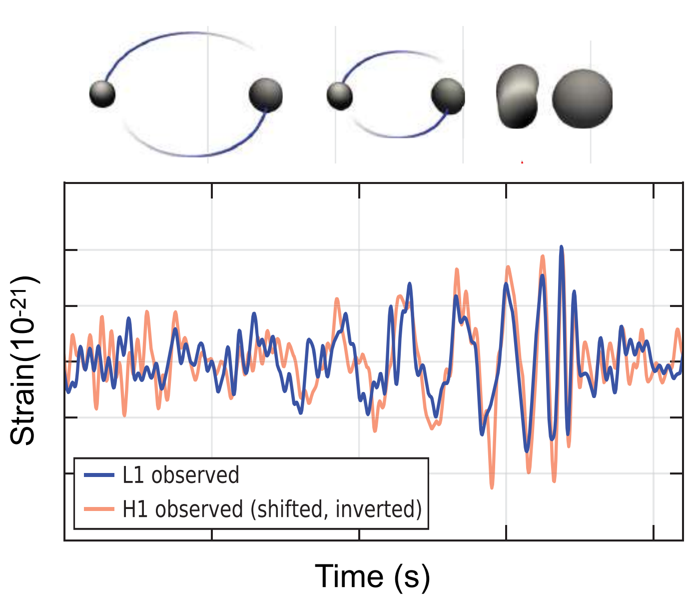
Planck 2018
(this work)

PopIII stars(Z~0), rarer but more effective UV sources

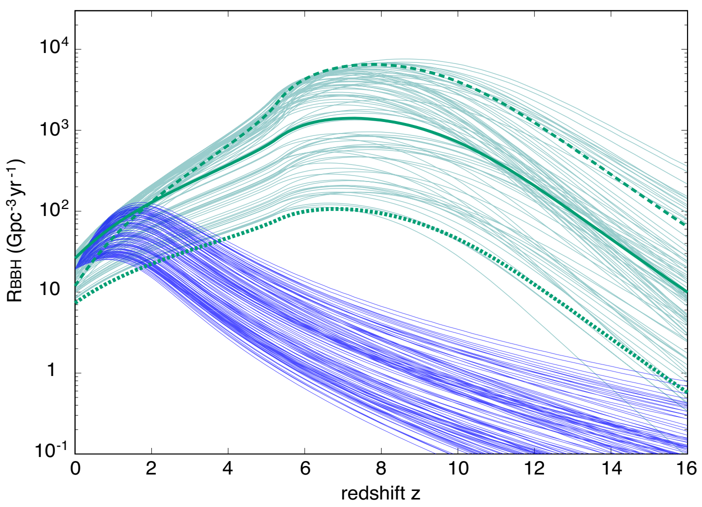
$\rho_{\star,\mathrm{III}} \lesssim 10^5\ M_{\odot}\ \mathrm{Mpc}^{-3}$ **~ 1% of the total mass budget**

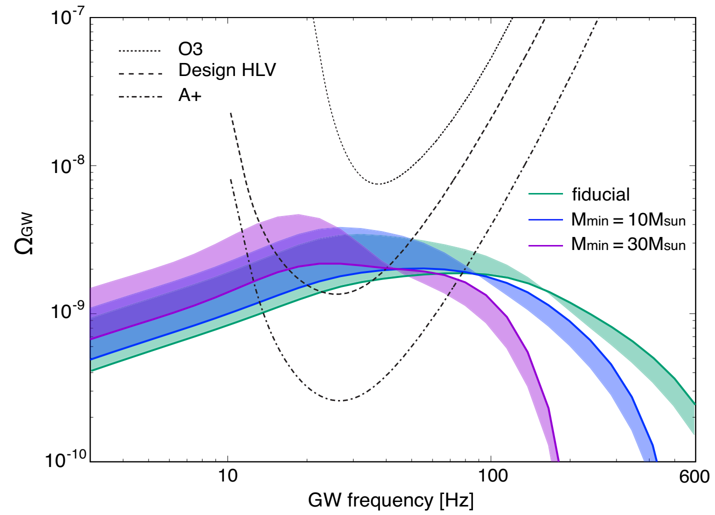
Summary

- Low-metallicity star formation ($Z < 0.1Z_{sun}$) is required for massive BBH formation but without violating the Planck
- Their massive BBH populations at cosmic dawn would contribute to the production of a GW background significantly
- The amplitude of the GWB is strong enough to be detected at the design sensitivity and its spectrum is flattened from the canonical 2/3 power-law



Refs) Inayoshi, Kashiyama, Visbal & Haiman (2016,2021)

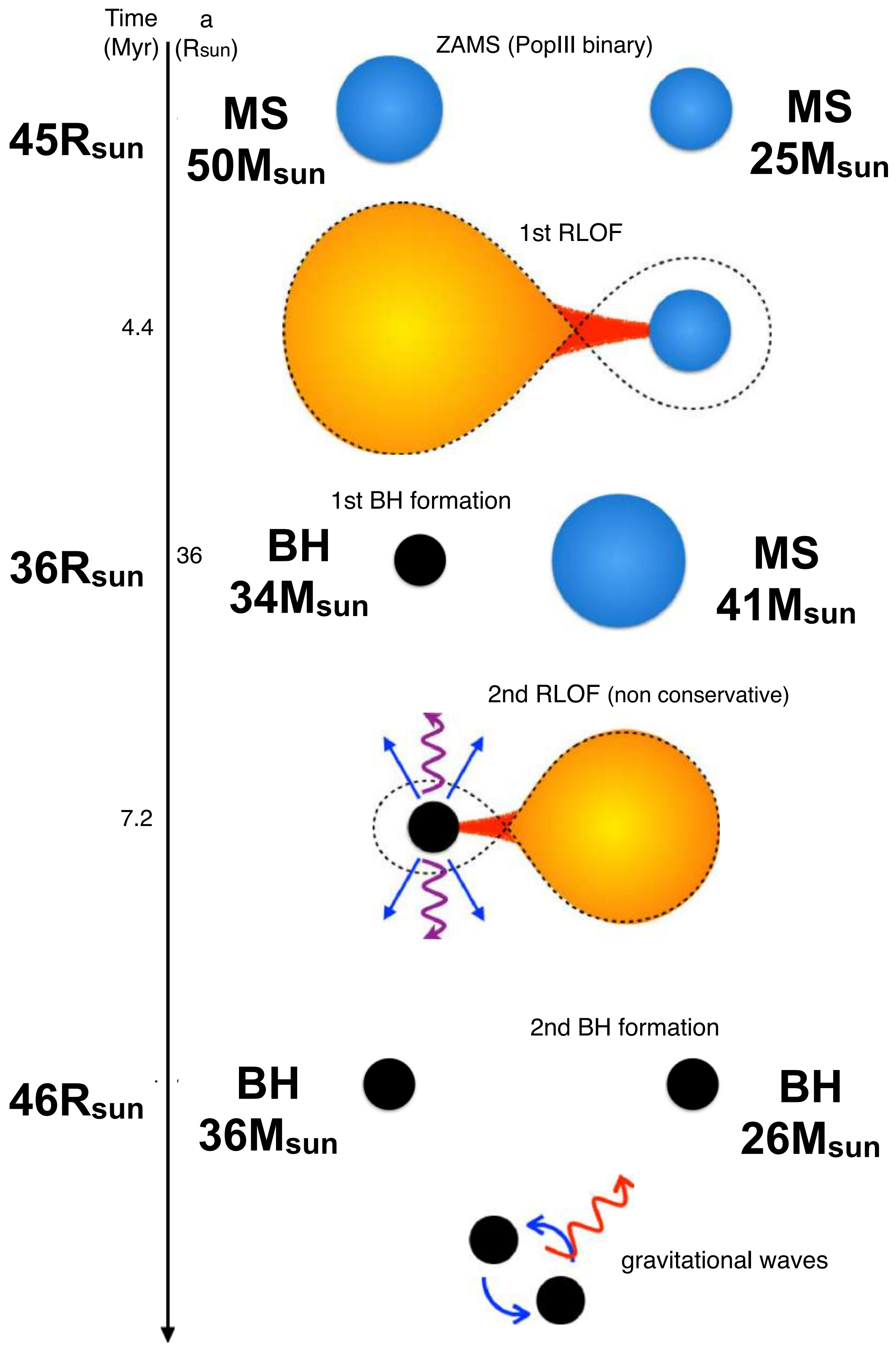


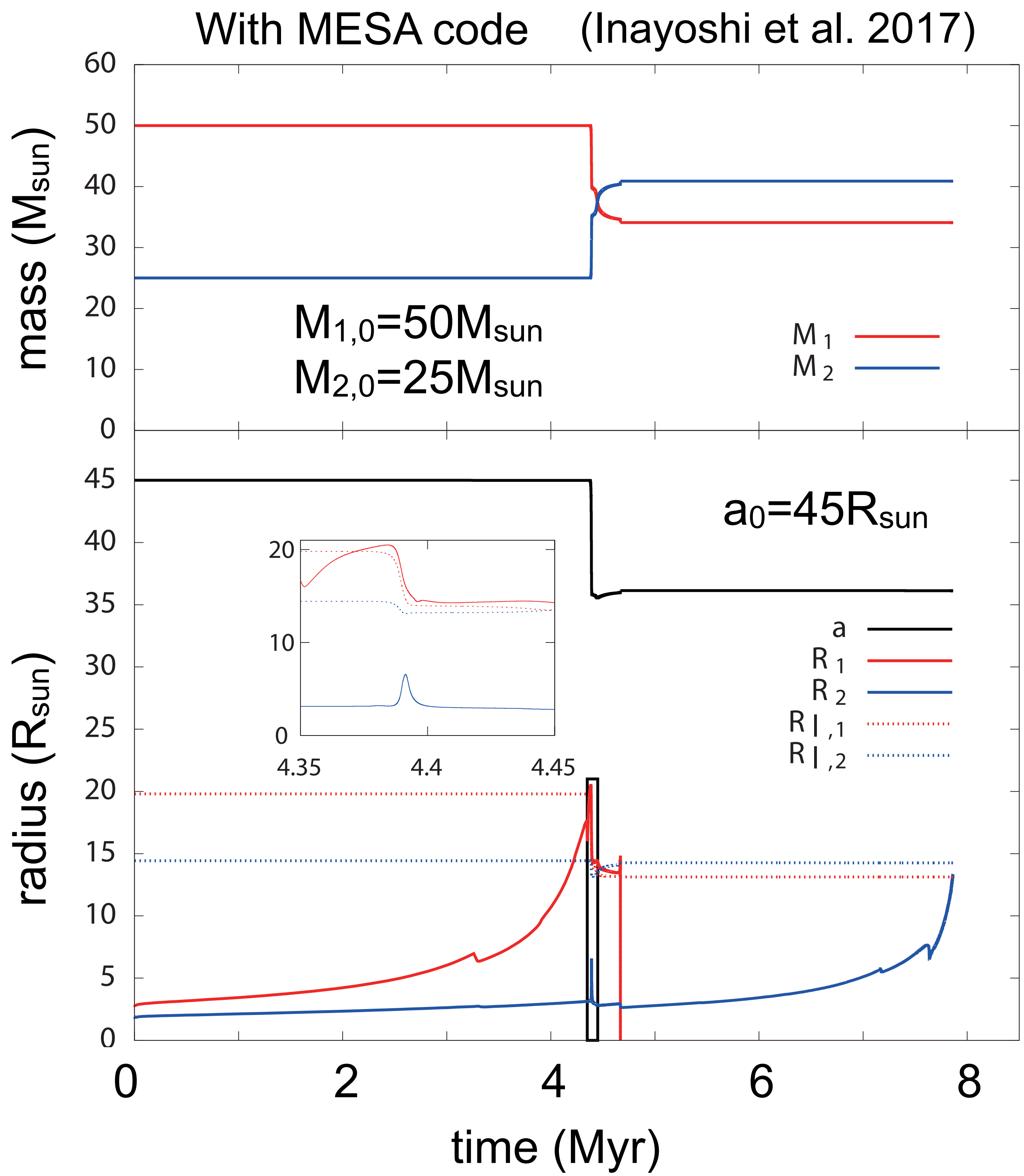


Thank you !!

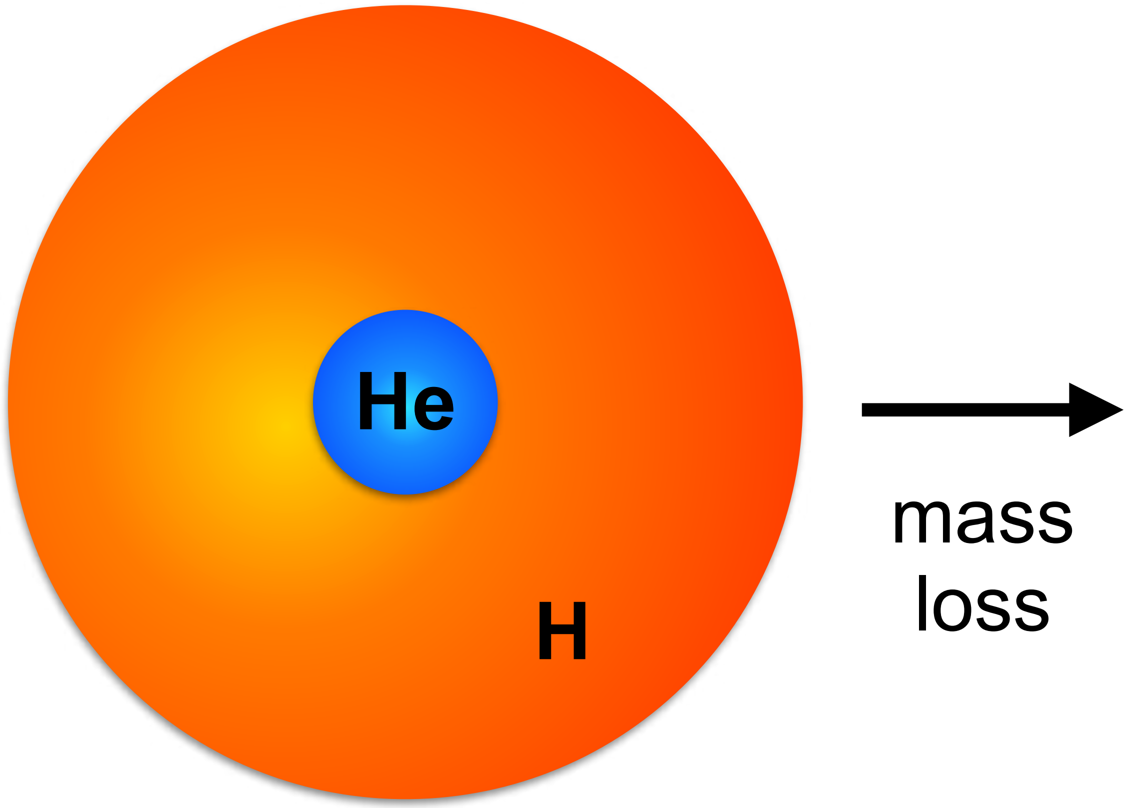
Appendix

PopIII binary evolution





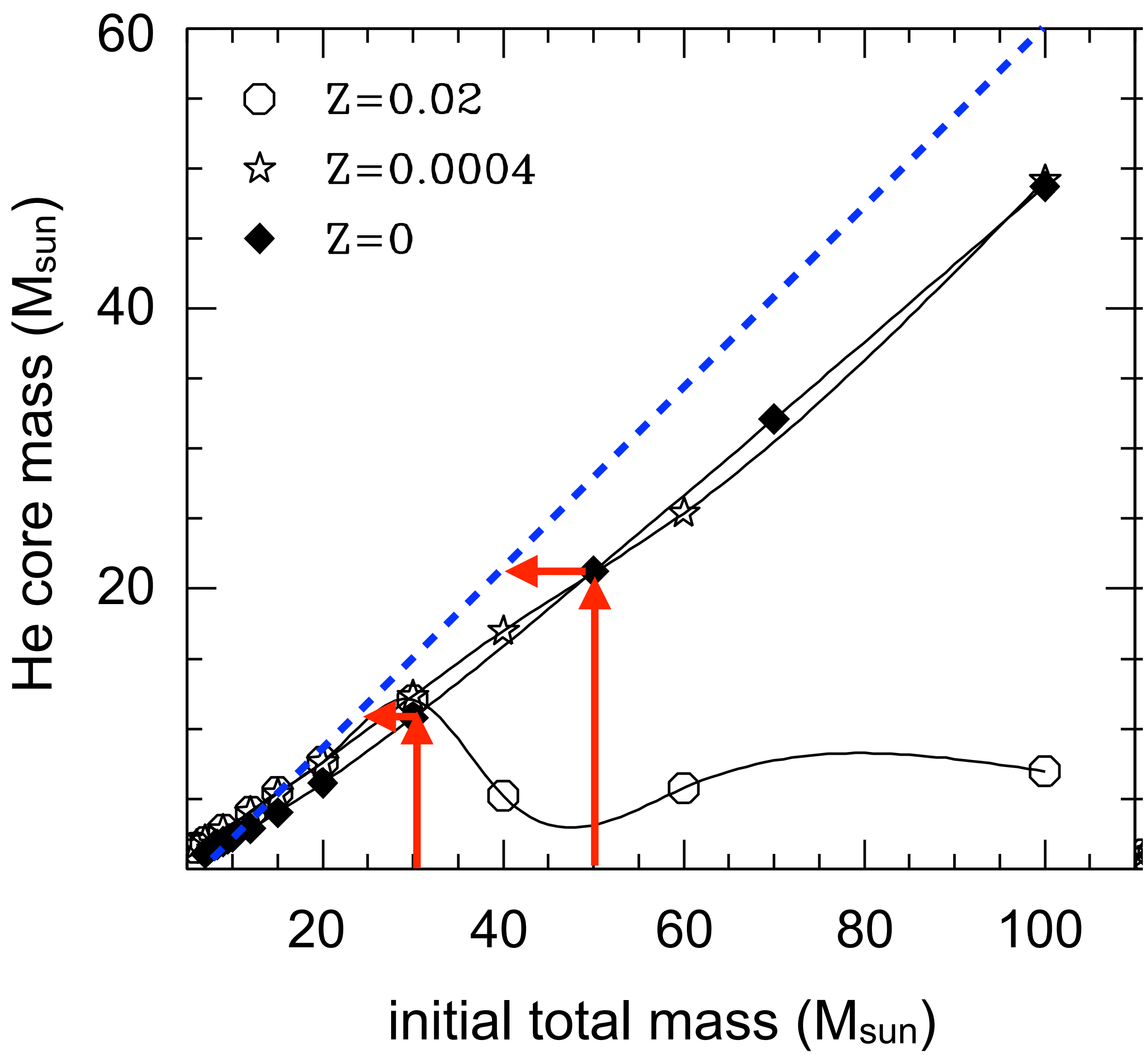
Termination of stable MT



1. mass loss by MT
2. the mass ratio of He core to the total mass increases
3. reach the critical ratio

$$q_{He} \sim 0.6$$

Termination of stable MT



1. mass loss by MT
2. the mass ratio of He core to the total mass increases
3. reach the critical ratio

q_{He} ~ 0.6

Typical mass of BHs in PopIII binaries **~ 30M_{sun}**

GWB from PopIII BBHs