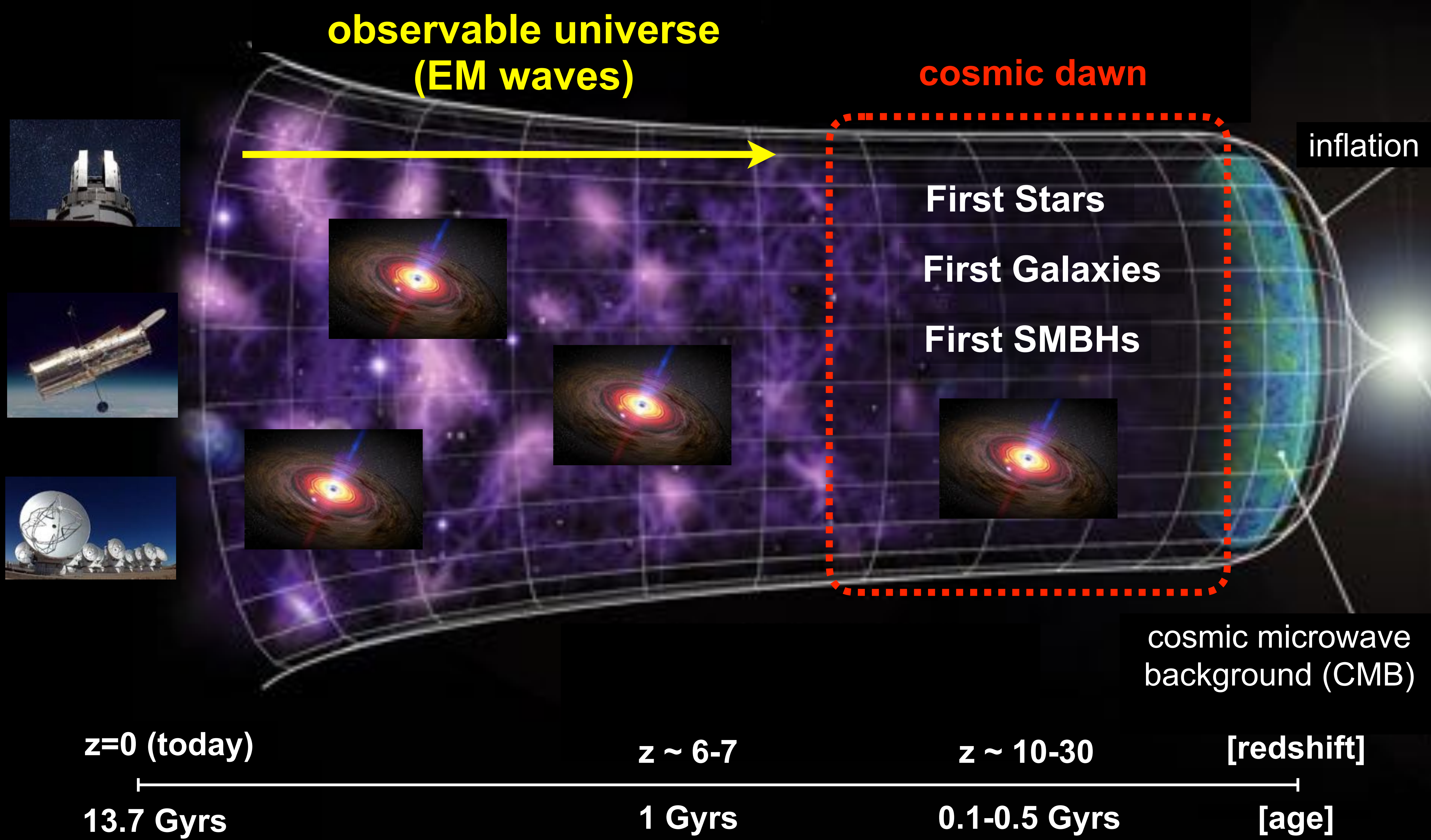
Supermassive Black Holes in the Early Universe and Prospects with Tianqin Observations

Kohei Inayoshi

Peking University
Kavli Institute for Astronomy & Astrophysics

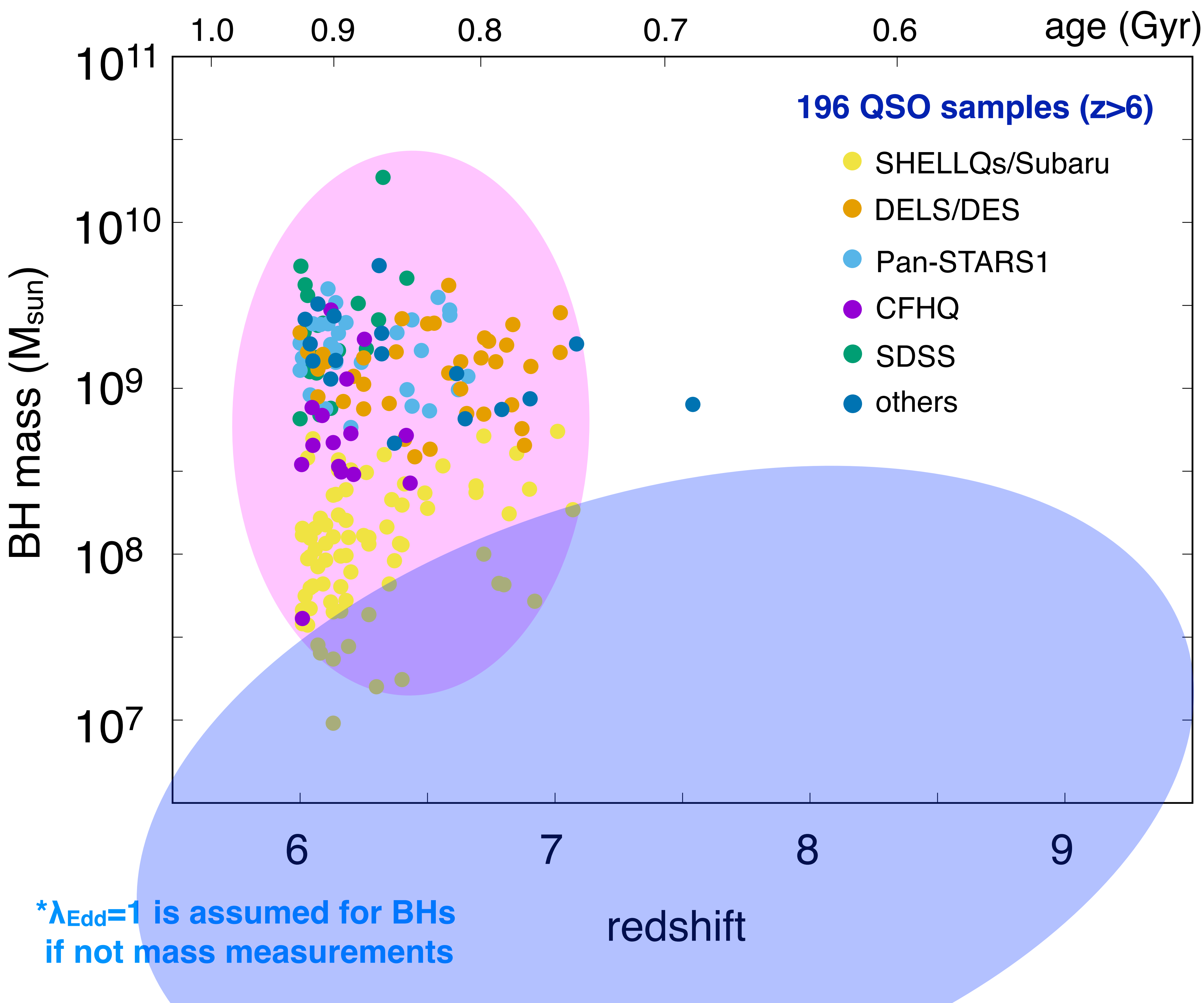
Introduction

History of the universe



High-z SMBH population

Compilation from KI, Visbal & Haiman (2020), ARA&A

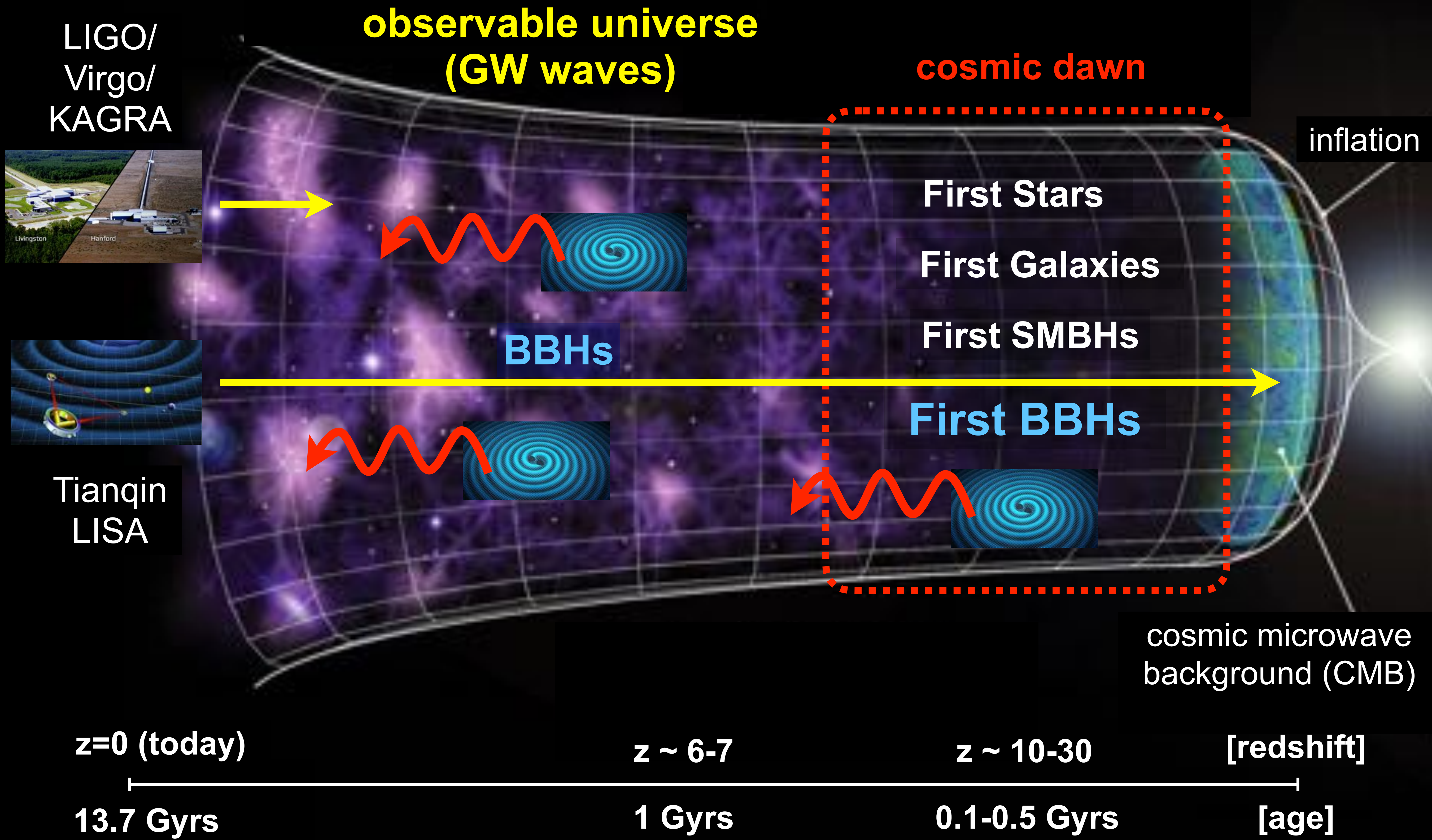


*λ_{Edd}=1 is assumed for BHs if not mass measurements

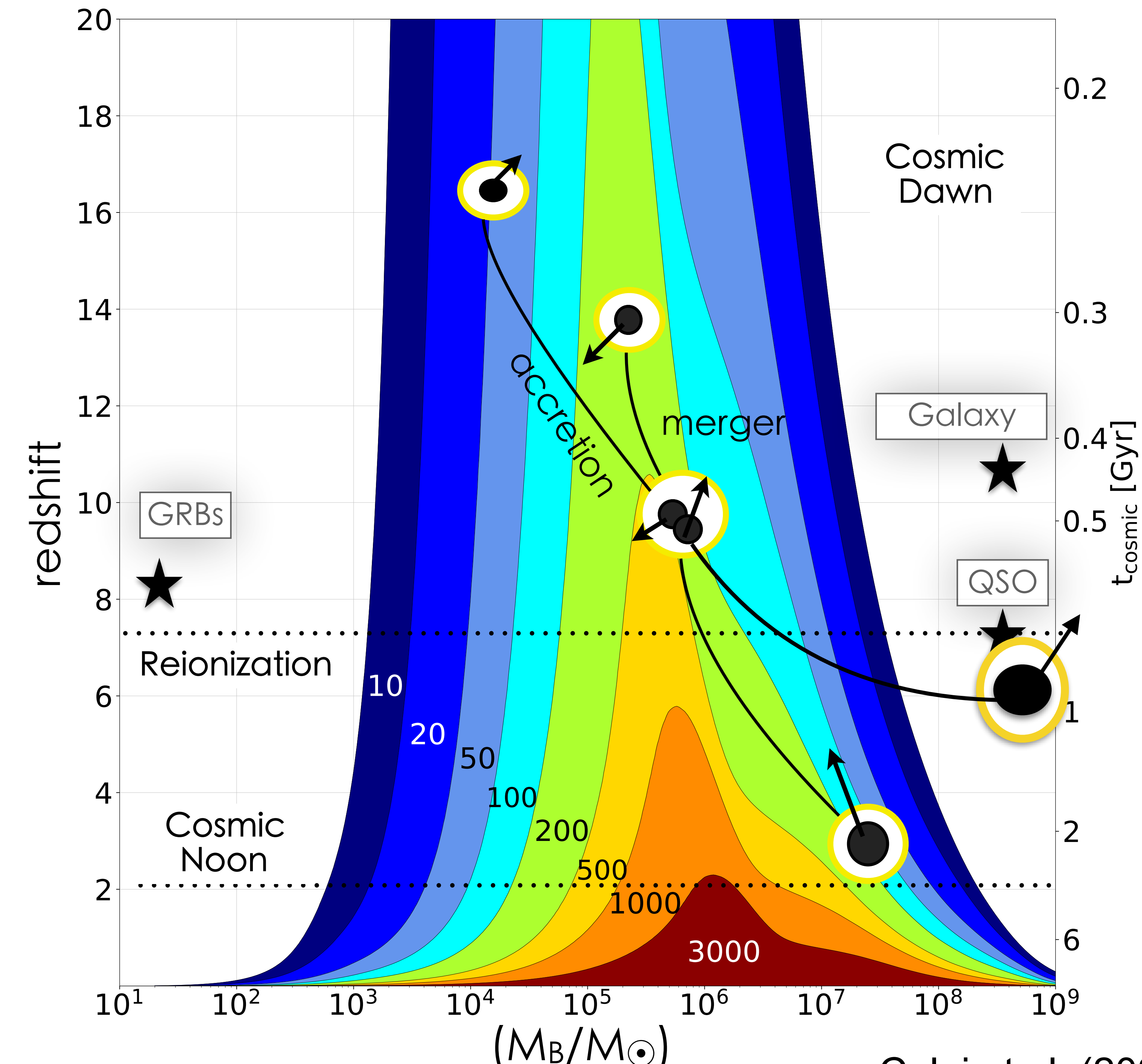
Tips of iceberg

Underlying / dominant BH population

History of the universe

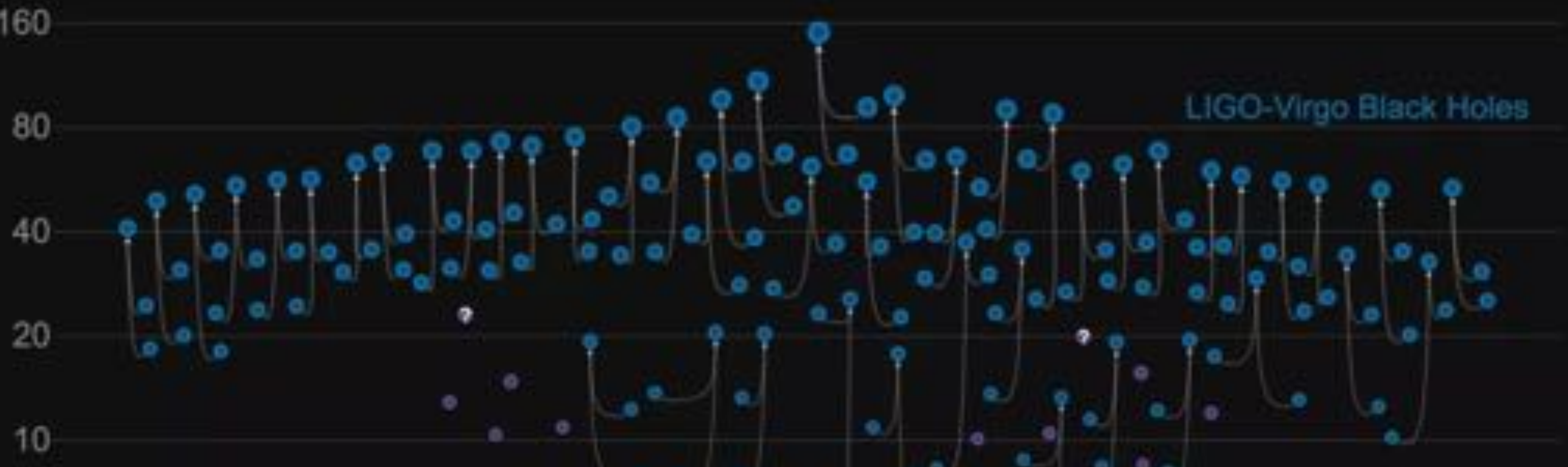


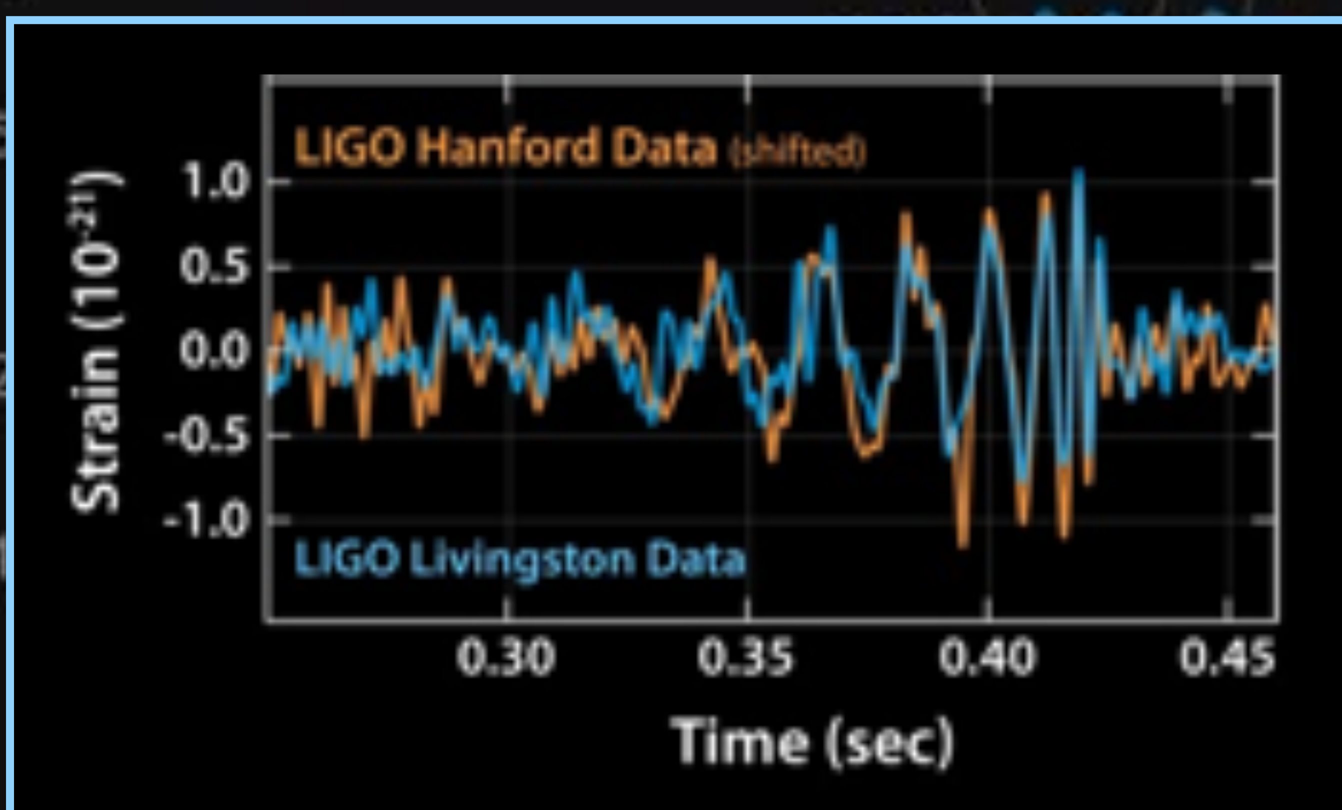
Synergy btw EM & GW observations

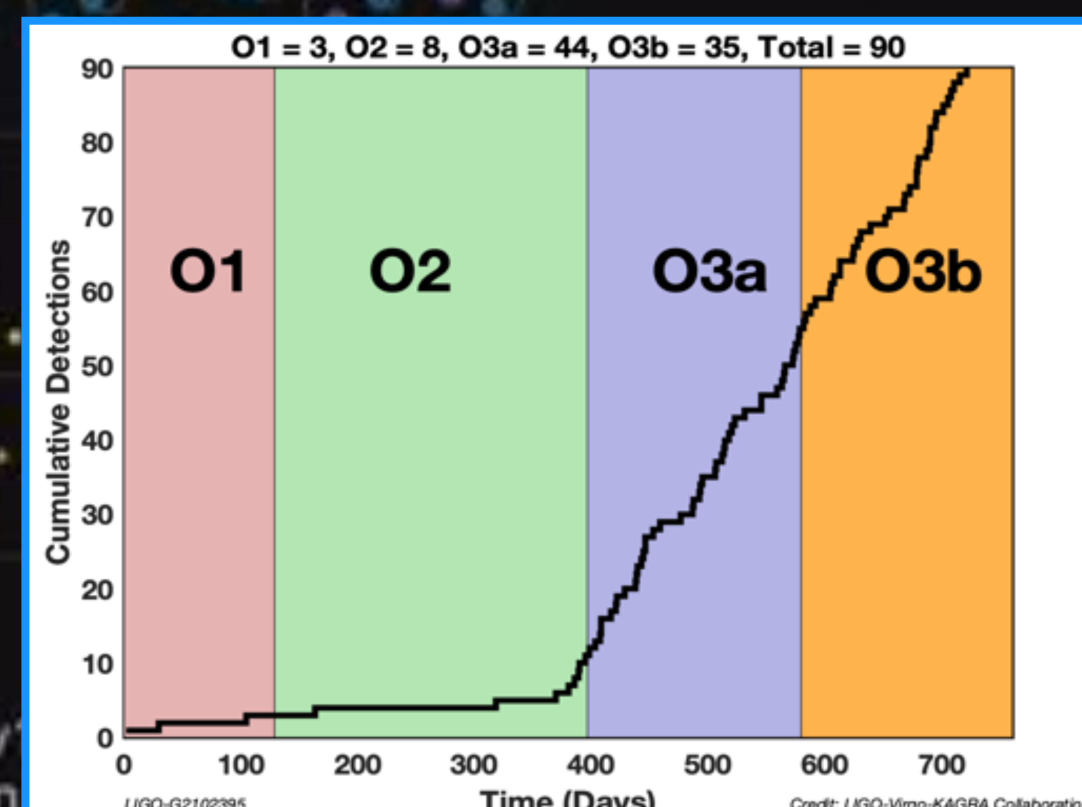


Colpi et al. (2021), Astro2020

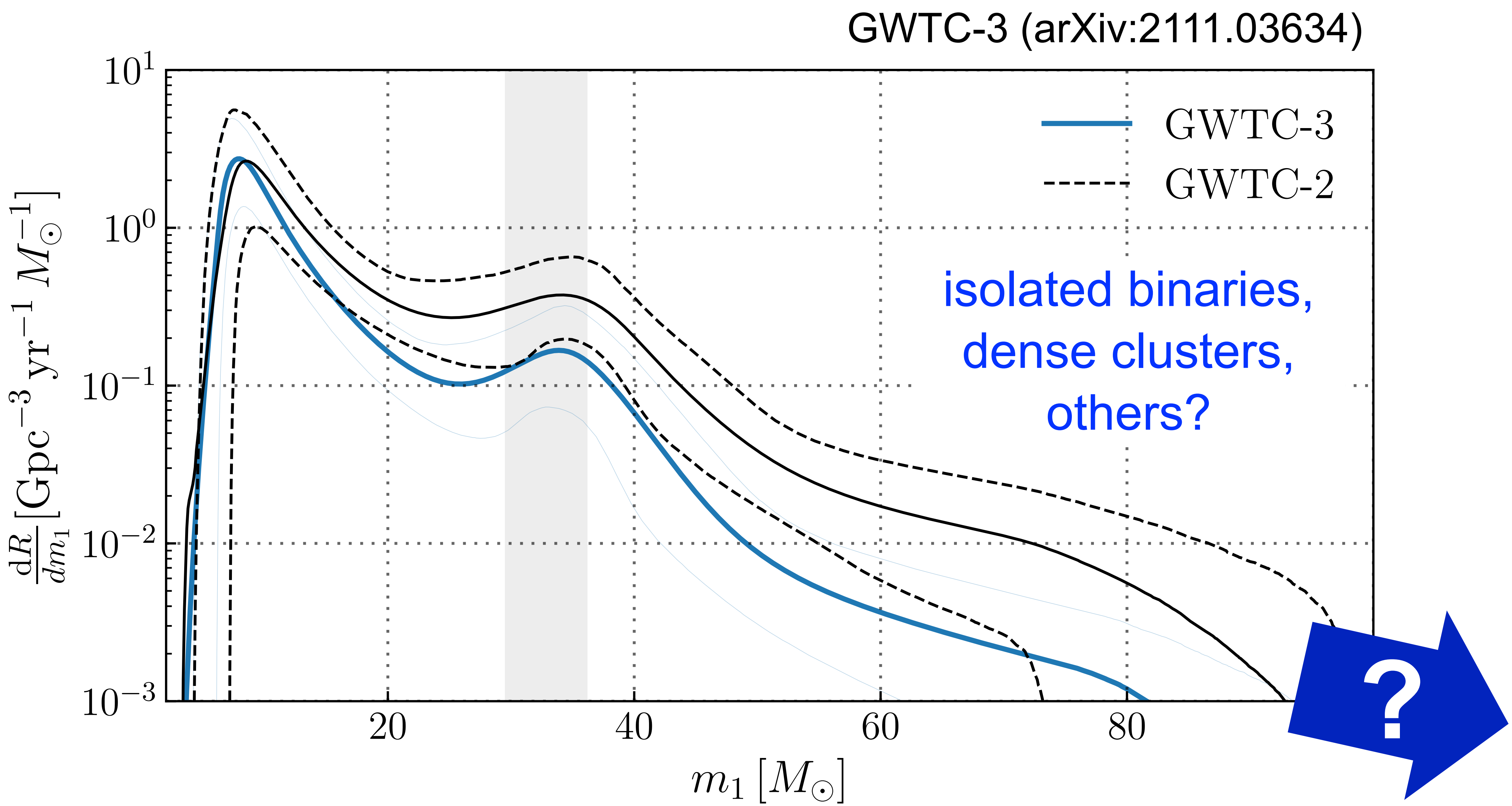
GW events from merging BBHs







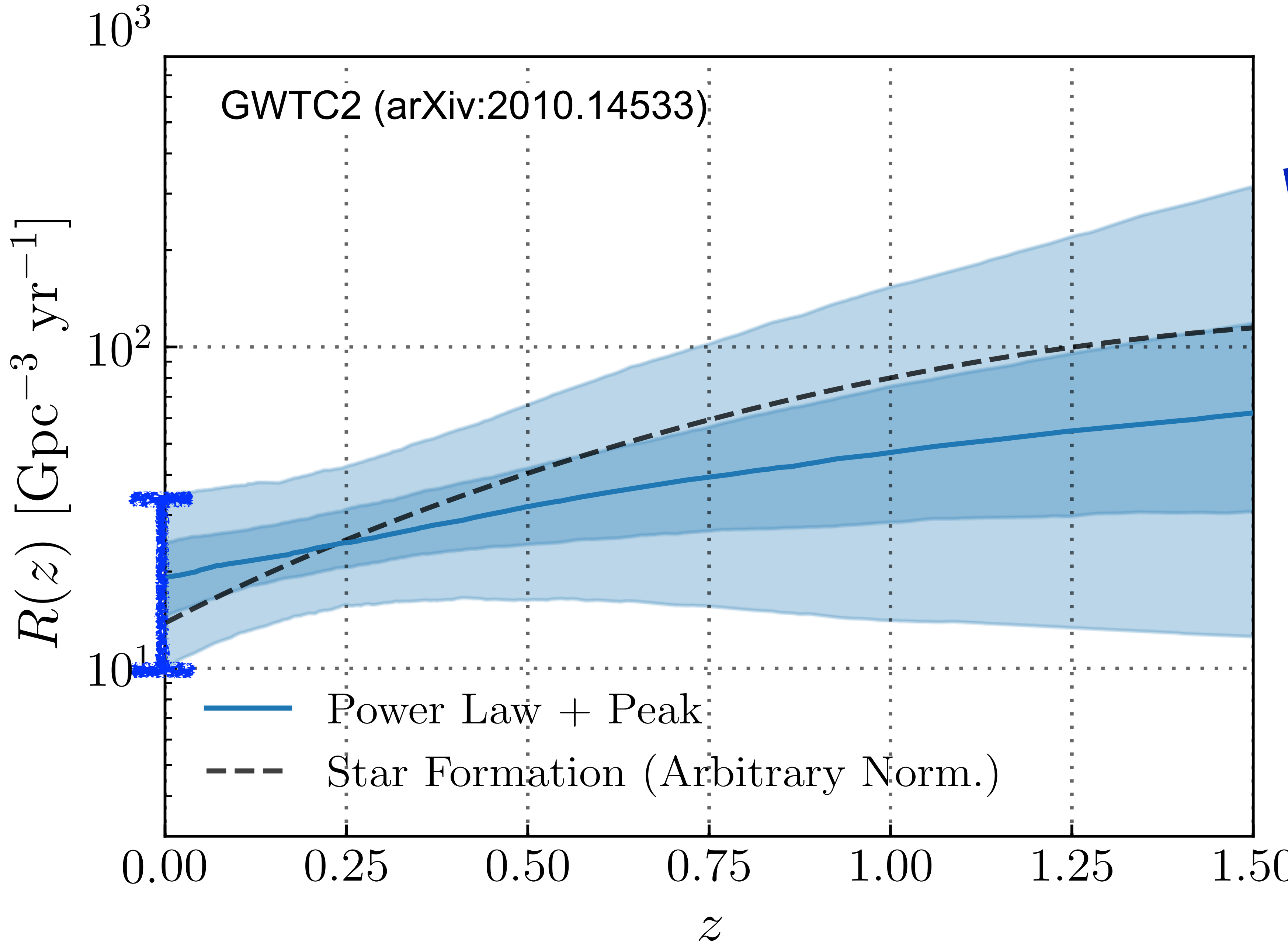
Mass function of BBH mergers



Massive BHs form in **low metallicity environments**

(top-heavy IMF & weak mass loss)

Cosmic BBH merger rate

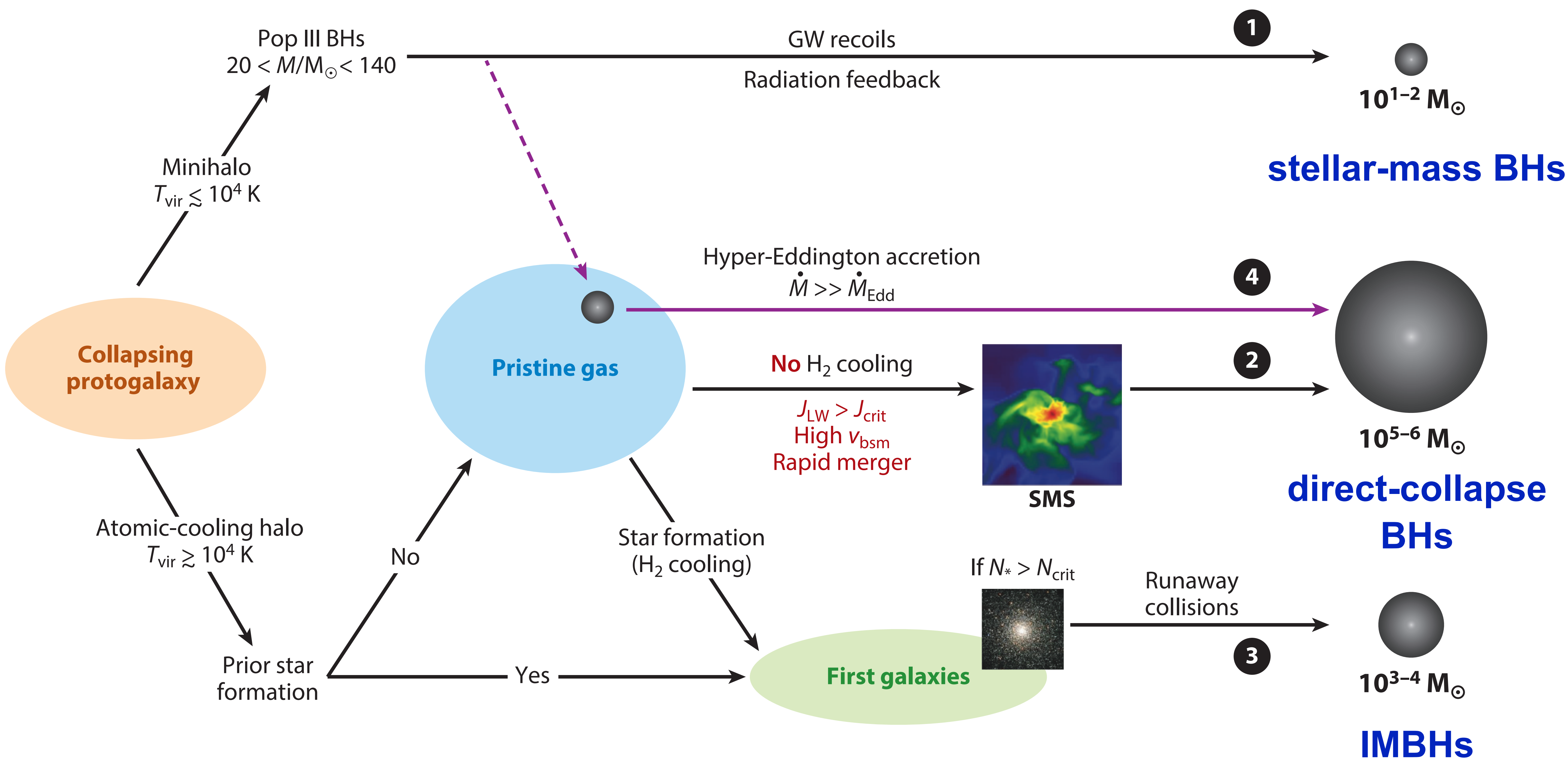


A larger number of BBH merger at **higher redshifts**

$$R(z) \propto (1+z)^{\kappa} \propto t^{-2\kappa/3} \; ; \qquad \kappa = 1.9^{+1.7}_{-1.8}$$

Formation of the earliest BHs

from stellar-mass BHs to IMBHs in low-metallicity environments



Inayoshi, Visbal & Haiman (2020) ARA&A

See also Mayer & Bonoli (2019)

Massive BH formation in the early universe

Basics of star formation

- mass inflow rate in collapsing gas

$$\dot{M} \sim \frac{M_{\rm J}}{t_{\rm ff}} \simeq \frac{c_{\rm s}^3}{G} \quad \propto T^{3/2}$$

if highly turbulent…

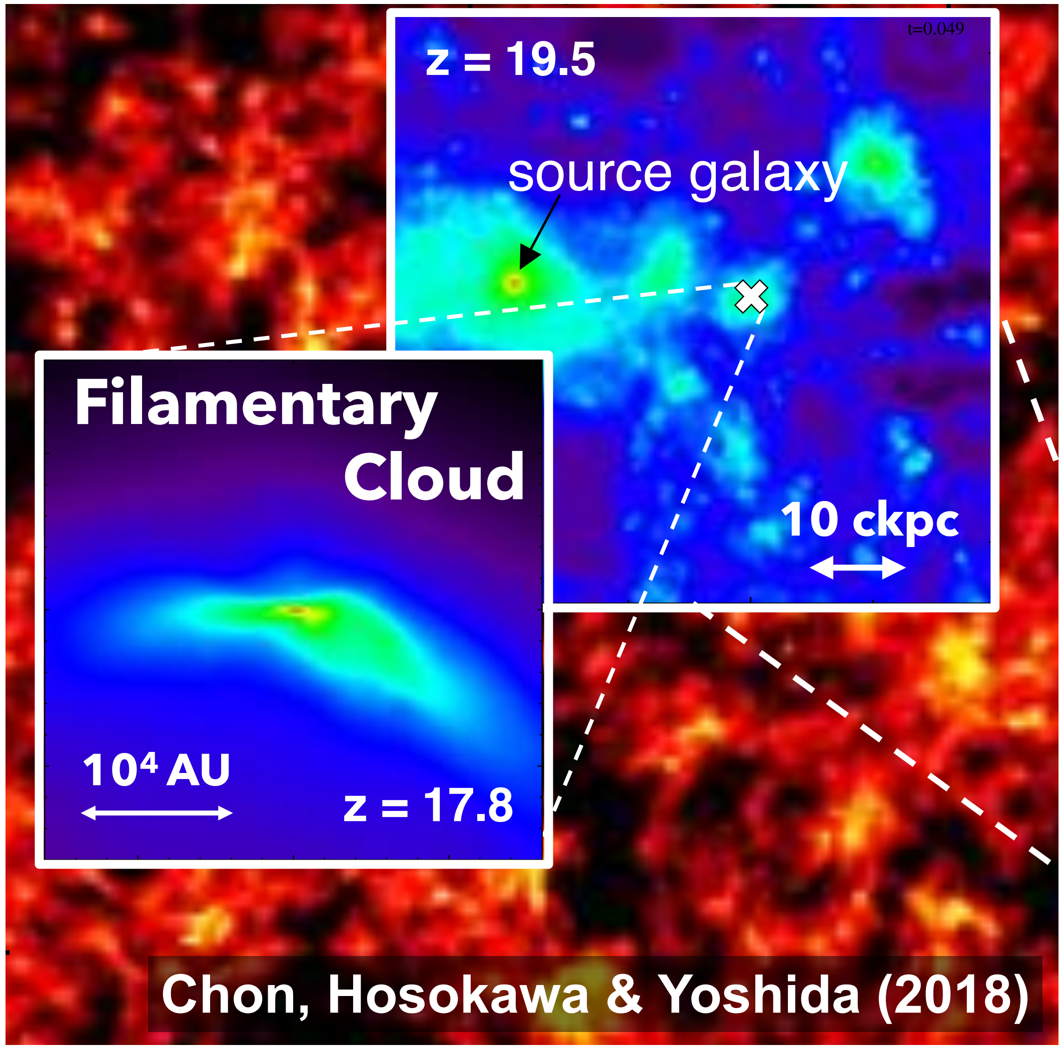
$$c_{\rm eff} = (c_{\rm s}^2 + v_{\rm tur}^2)^{1/2} \gg c_{\rm s}$$

$$t_{\rm ff} \sim (G\rho)^{-1/2}$$

"Warmer" gas hardly collapses by its self-gravity,
but once it happens, the inflow rate becomes **higher**

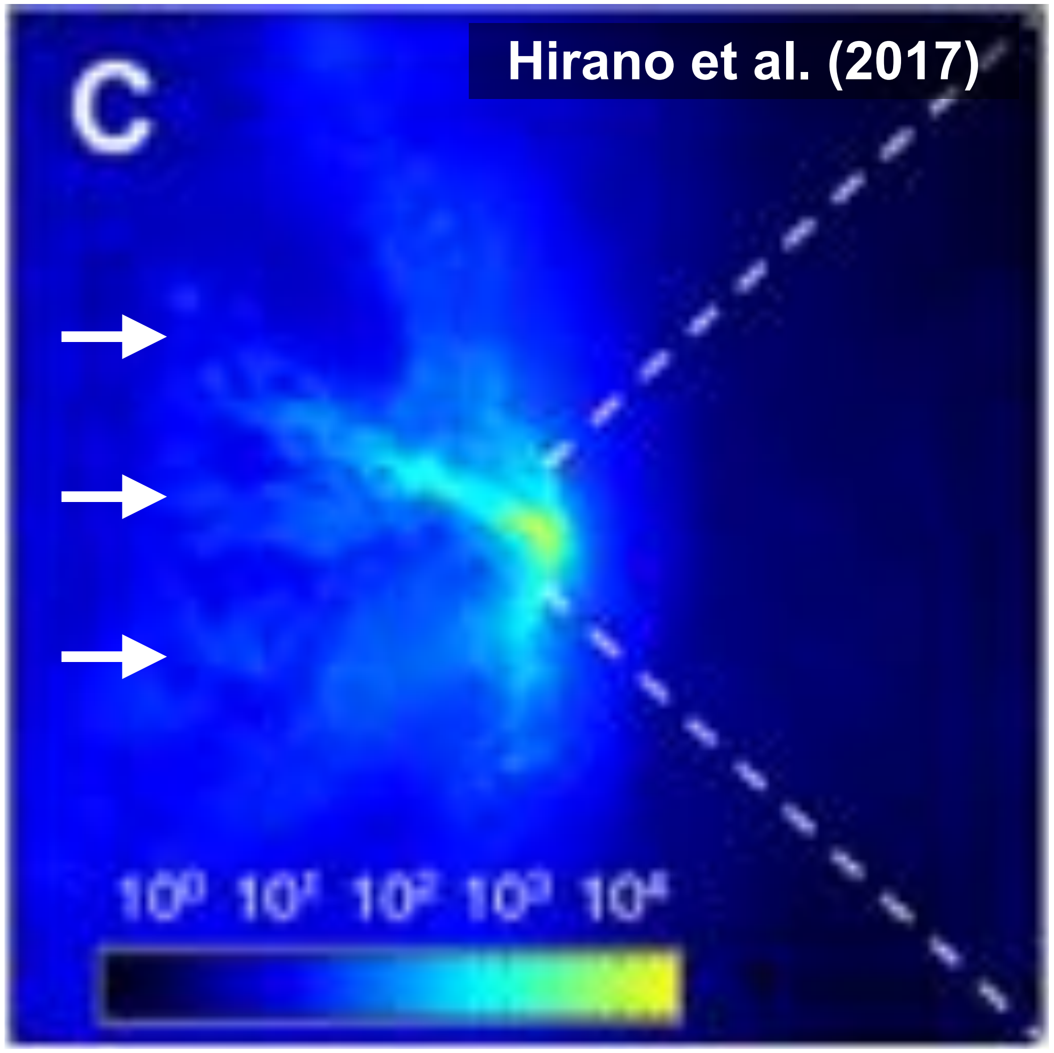
Seed formation ≈ H_2 suppression

Lyman-Werner irradiation



$$H_2 + \gamma_{LW} \rightarrow 2\ H$$

Dynamical heating



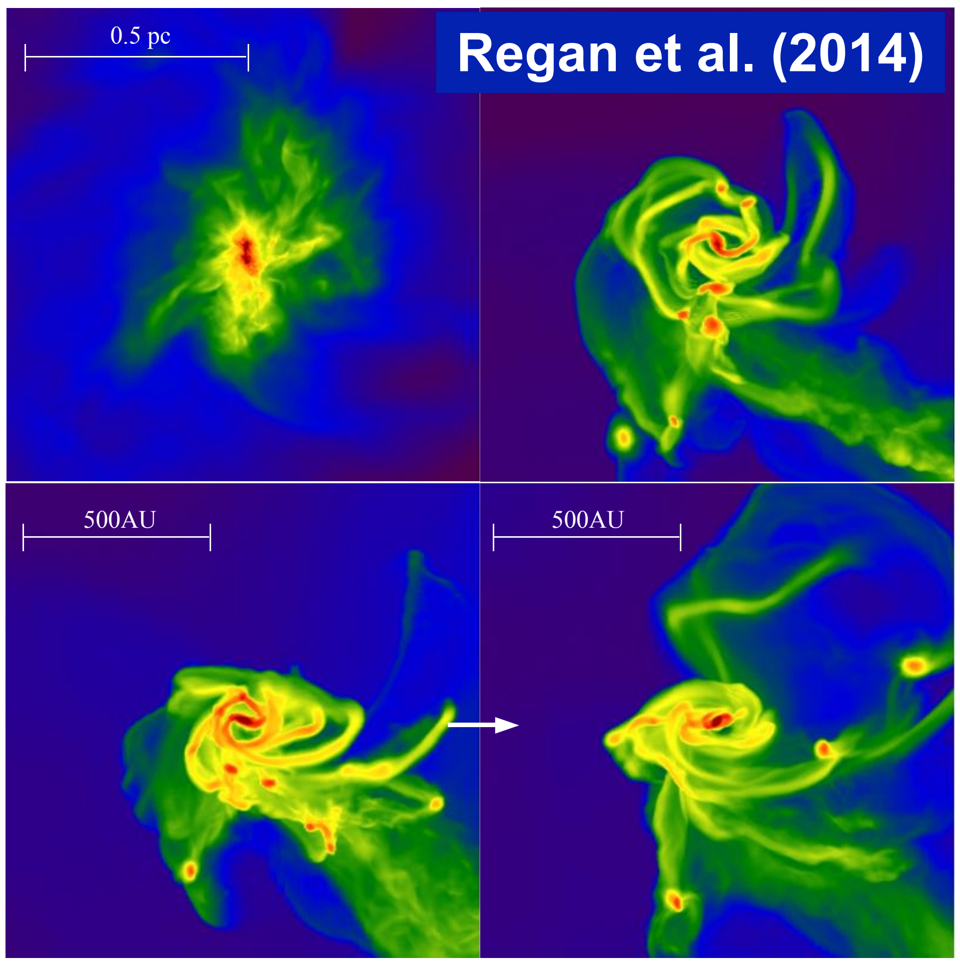
$$c_{\rm eff}^2 = c_s^2 + \boxed{v_{\rm tur}^2}$$

Bromm & Loeb 2003; Shang +2010; Latif +2013; Johnson +(2013); Regan +2014; Inayoshi +2014; Sugimura + 2014; Visbal +2015; Latif +2016; Chon+2016; Hirano+2018; Inayoshi+2018; Wise +2019; Luo+2019 etc…

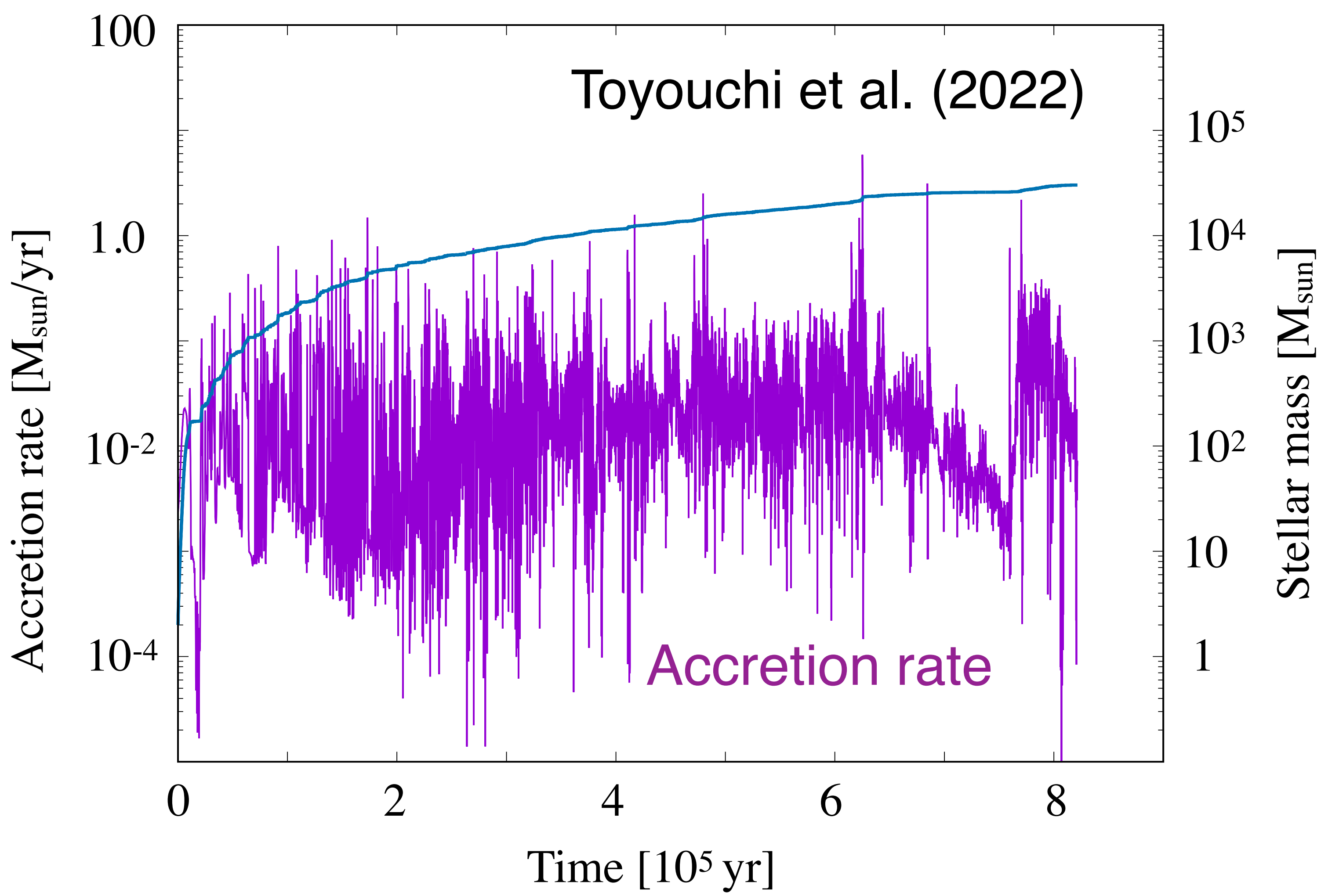
leaving behind **massive seed BHs**?

High acc. Rate & Massive star

- 3D (radiation) hydrodynamical simulations



accretion disk

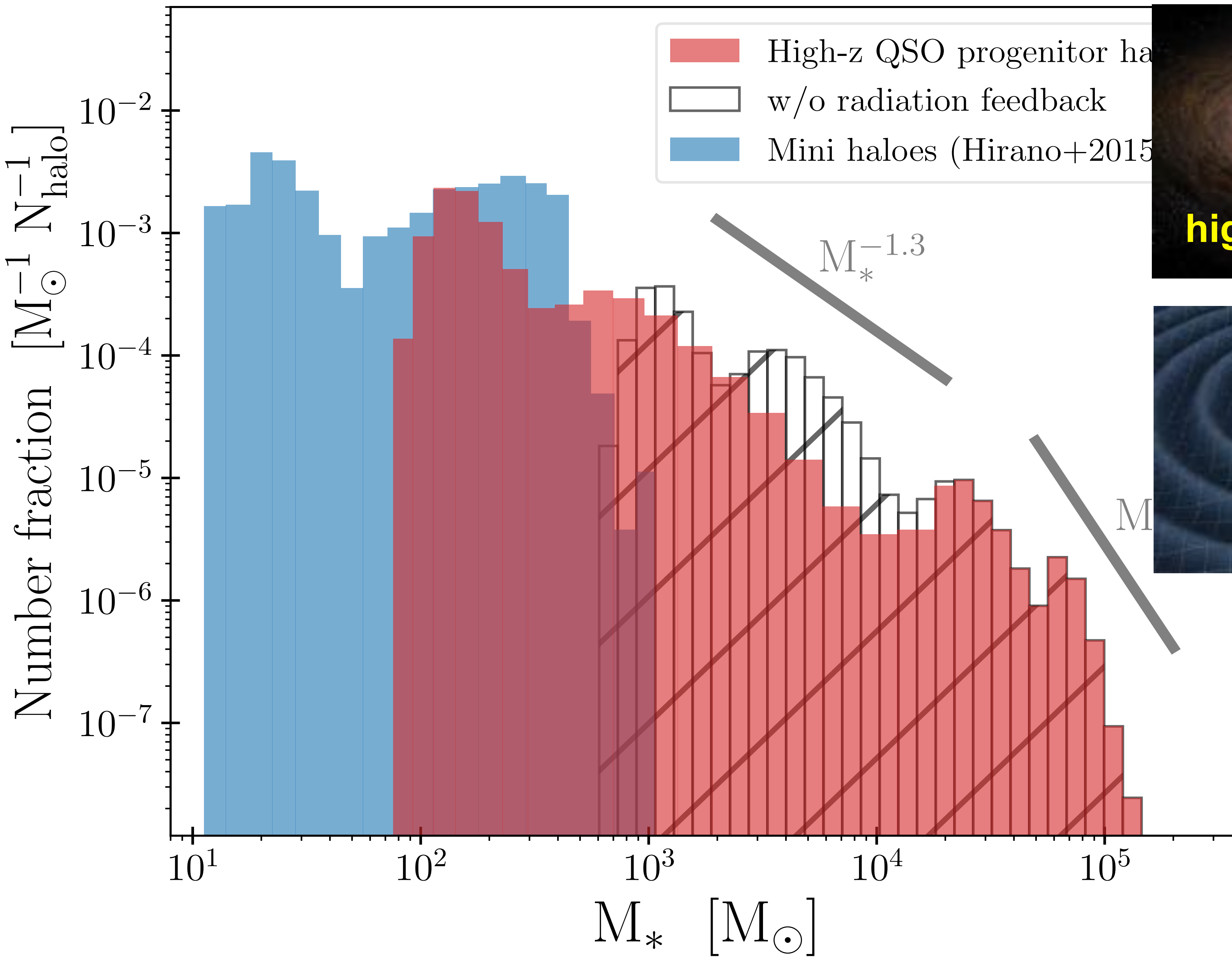


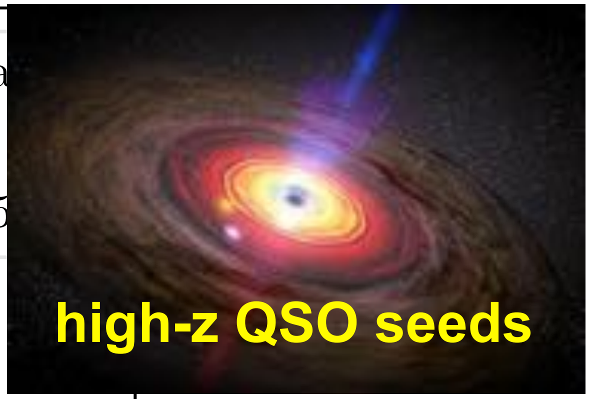
- no/weak fragmentation
- high accretion rate

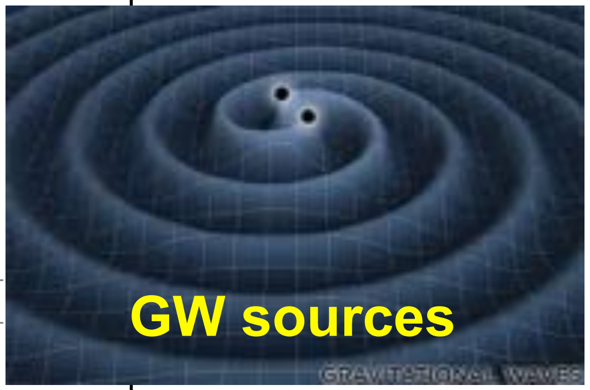
massive seed BHs

$M_\star \simeq 3 \times 10^4\ M_\odot$

BH mass function in QSO host galaxies



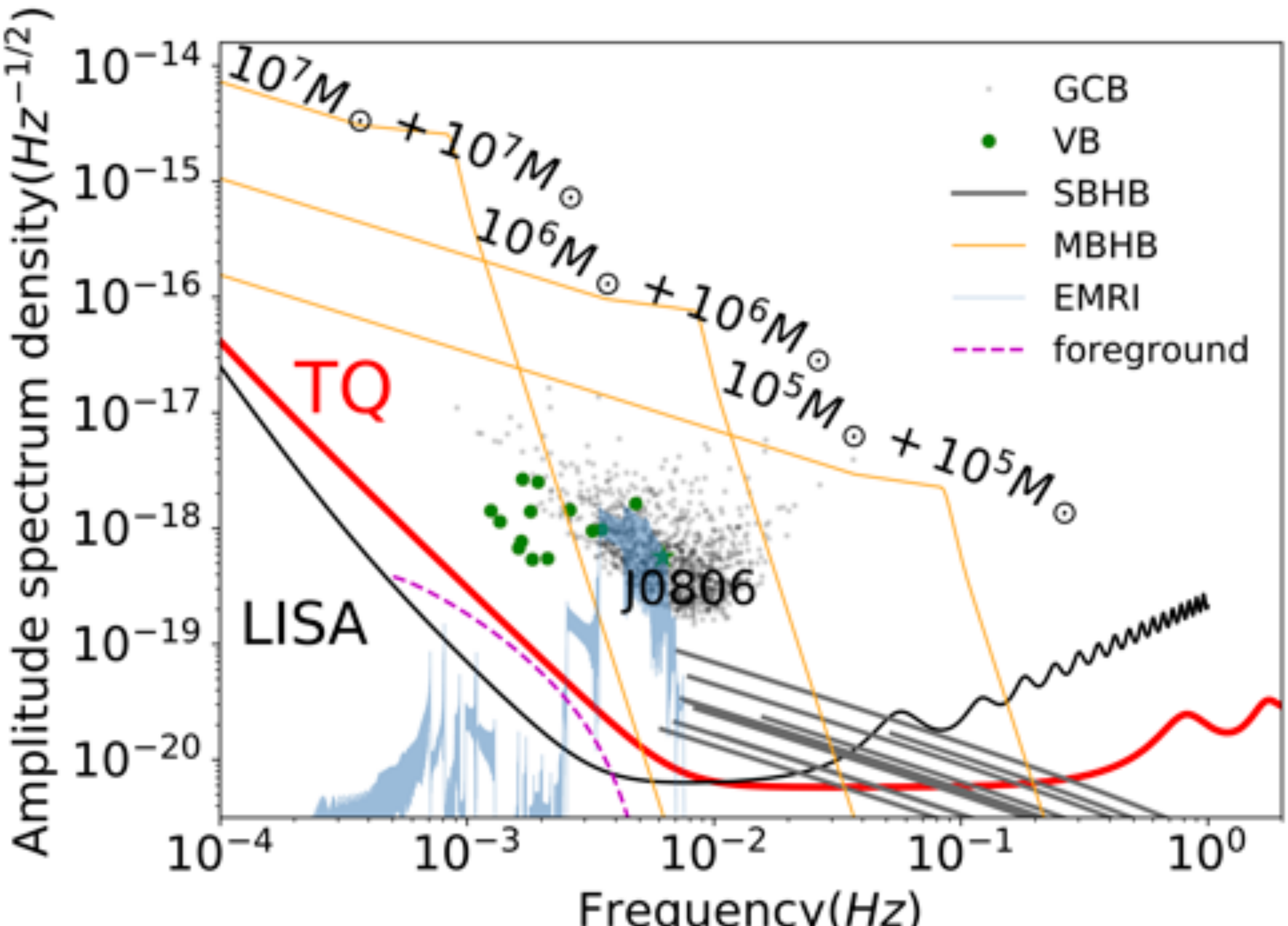




RHD simulations + semi-analytical model for BH seeding

(Li et al. 2021; Toyouchi et al. 2022; see also Sassano et al. 2021)

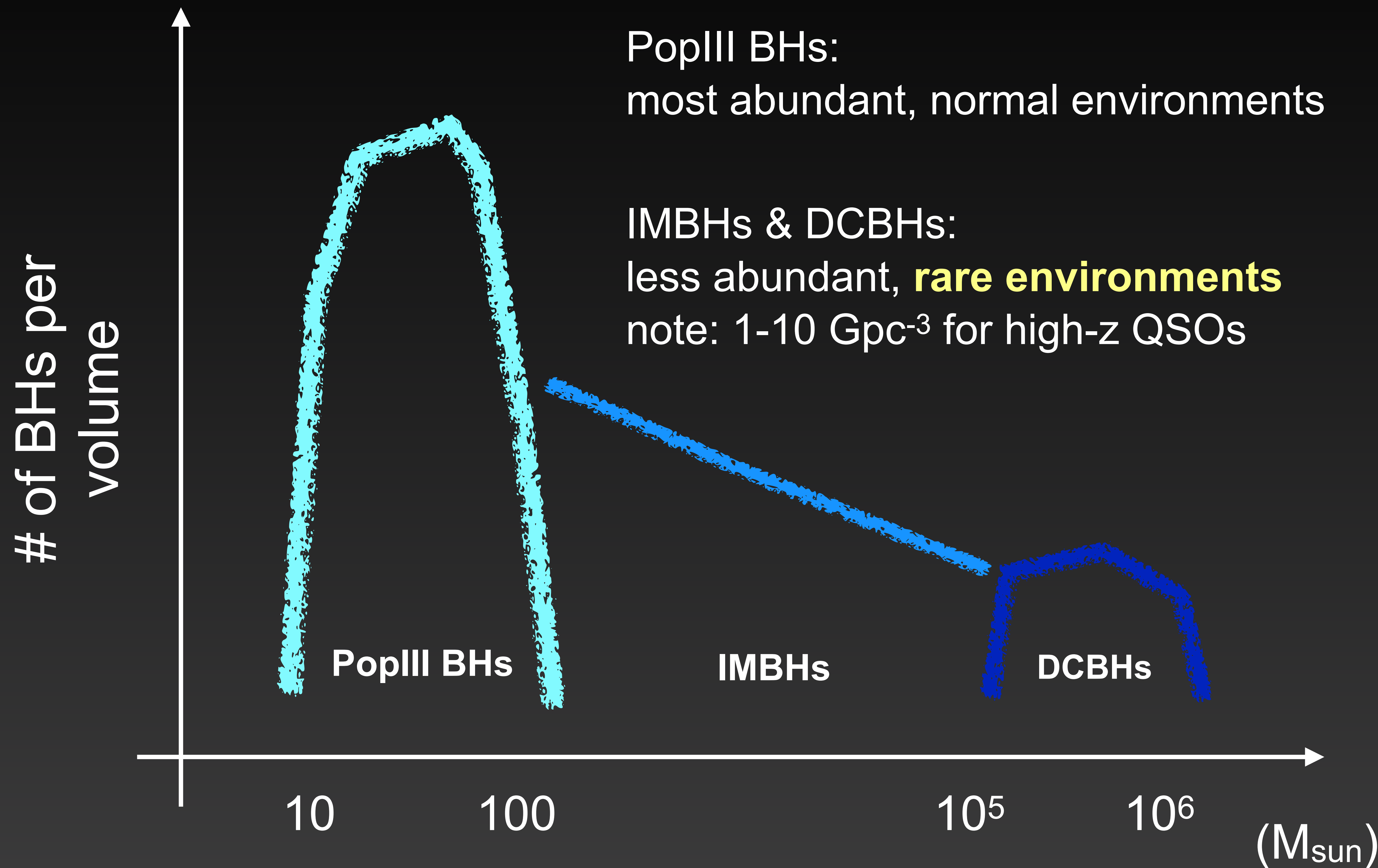
Low-f GW landscapes



BH mass function @ high-z

PopIII BHs:
most abundant, normal environments

IMBHs & DCBHs:
less abundant, **rare environments**
note: 1-10 Gpc^{-3} for high-z QSOs



Discussion

(mainly random thoughts)

BH mass budget & merger rates

BBH merger rates

- BBH merger rate

BBH formation rate

$$R_{\rm BBH}(z) = \underbrace{\frac{1}{\langle M_{\rm tot,b}\rangle}}_{\text{mean mass}} \int_0^{t(z)} \underbrace{\dot{\rho}_{\rm BBH}(t')}_{\text{BBH formation rate}} \underbrace{\Psi(t-t')}_{\text{delay-time distribution}} dt'$$

mean mass

delay-time distribution

- Merger delay-time distribution (DTD)

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

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

binary separation distribution

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

Öpik's law

$\gamma = -1$

cf. n~1 for type Ia SNe

n : DTD index

$t_{\rm min}$: minimum delay time

See more details in Inayoshi+2021

BBH merger rates

- BBH merger rate

BBH formation rate

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

if BBH formation activity terminates at high-z… and n>1

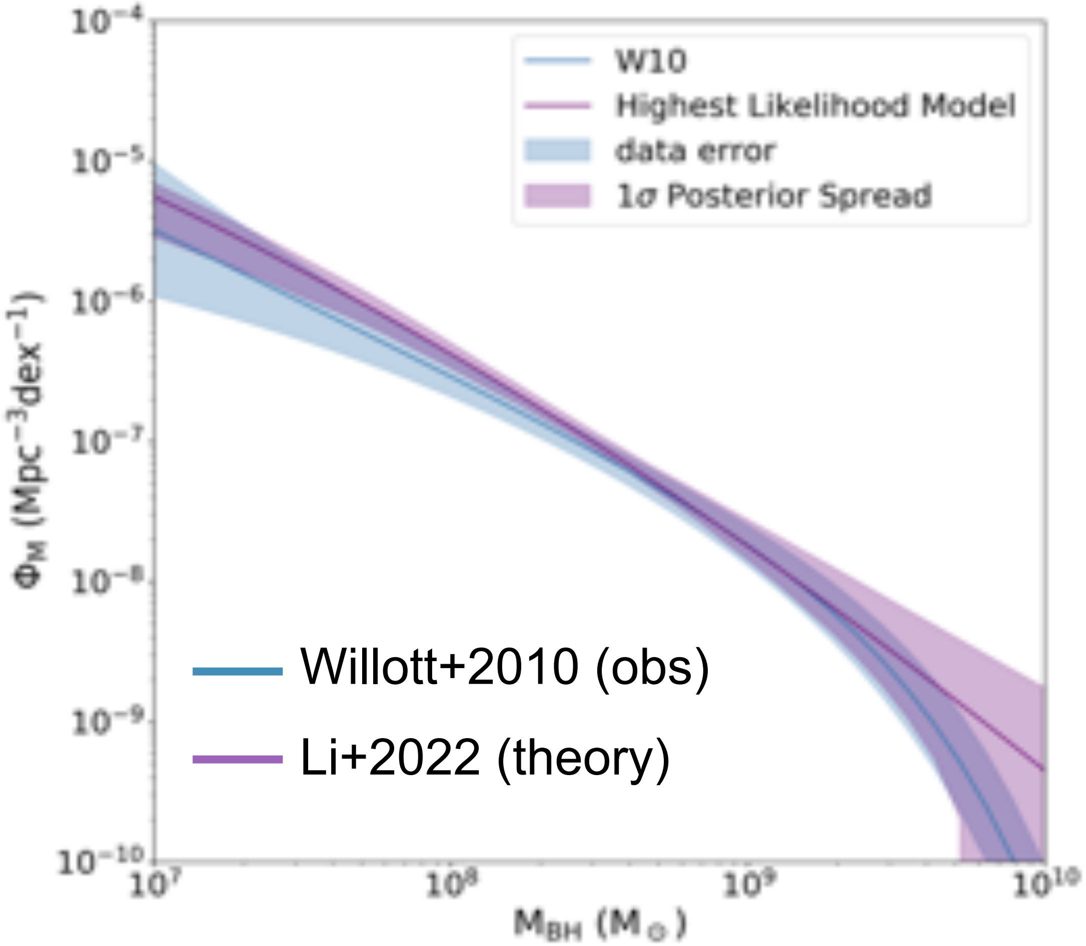
$$R_{\rm BBH} \simeq \frac{n \cdot f_{\rm bin}\ \rho_\bullet}{\langle M_{\rm tot,b}\rangle\ t_{\rm min}} \left(\frac{t}{t_{\rm min}}\right)^{-n} \longrightarrow \frac{f_{\rm bin}\ \rho_\bullet}{\langle M_{\rm tot,b}\rangle\ t_{\rm min}}$$

$\rho_\bullet$: cumulative mass density of BBHs formed at $z>z_0$

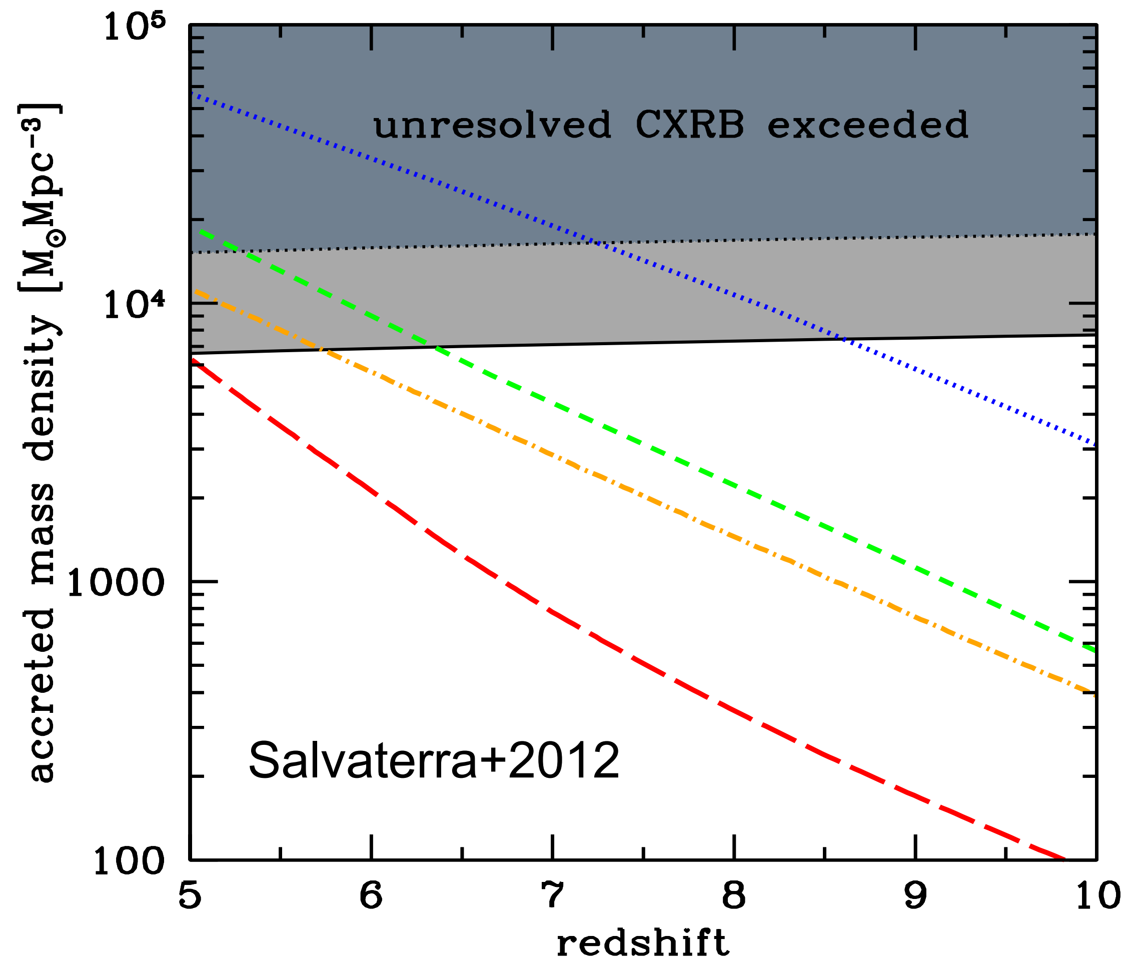
in the limit where **ALL** the available BHs merge at a certain redshift z_0

BH mass budgets @ high-z

BHMF in z~6 QSOs



upper bound from CXRBs



$\rho_\bullet \sim 100\ M_\odot\ \mathrm{Mpc}^{-3}$ (observed BHs)

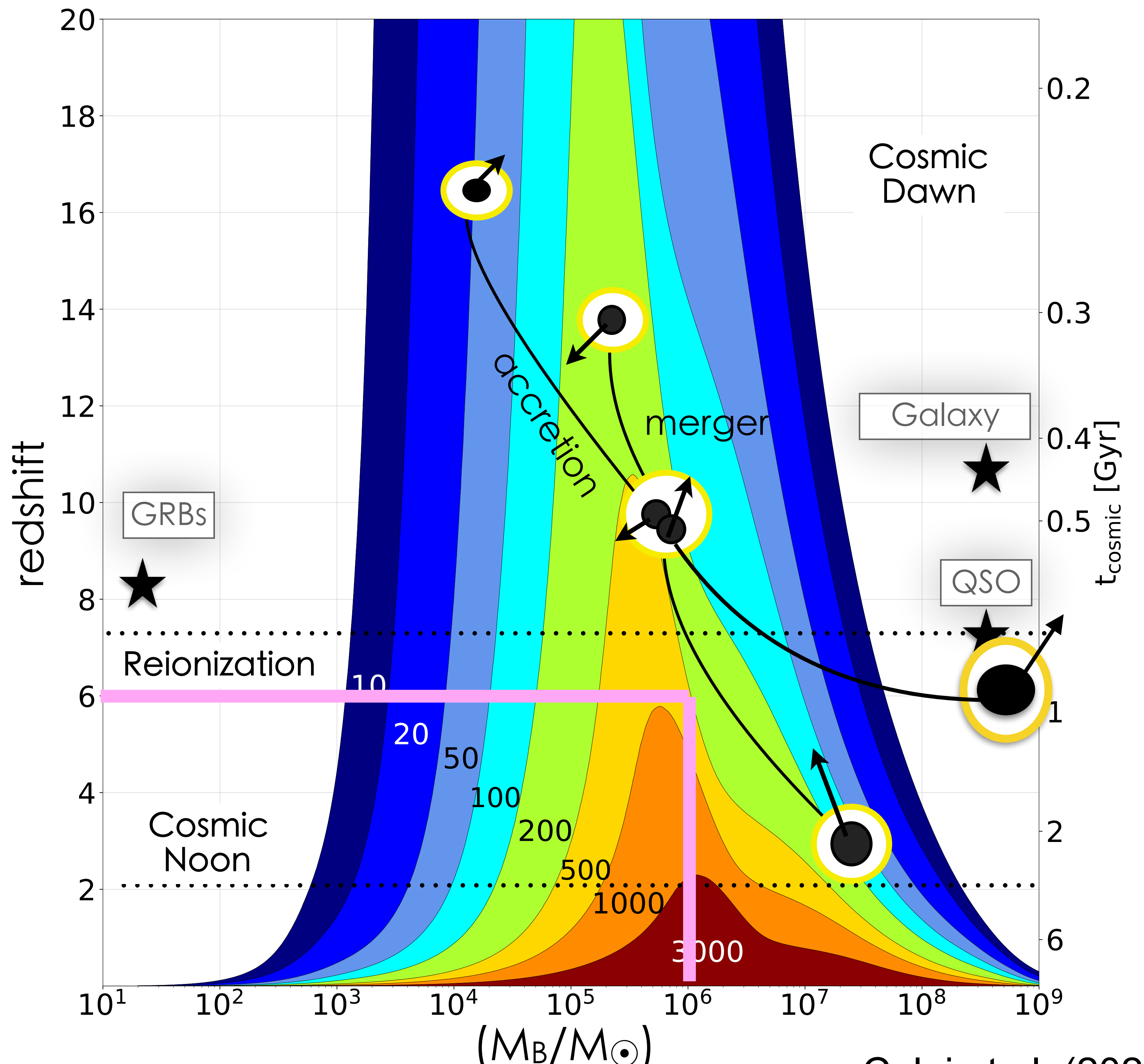
$\rho_\bullet \sim 10^3\ M_\odot\ \mathrm{Mpc}^{-3}$ (inc. obscured BHs)

for $\sim 10^{6-7}\ M_\odot$ BHs

$\rho_{\bullet,\mathrm{acc}} < 10^4\ M_\odot\ \mathrm{Mpc}^{-3}$

if no X-rays from accreting BHs, the limit would be mild

Synergy btw EM & GW observations



Colpi et al. (2021), Astro2020

BBH merger rates

$$R_{\rm BBH} \simeq \frac{f_{\rm bin}\ \rho_\bullet}{\langle M_{\rm tot,b}\rangle\ t_{\rm min}}$$

@z~6

$$\simeq 10^{-1}\ {\rm yr}^{-1}\ {\rm Gpc}^{-3}\ f_{\rm bin}\left(\frac{\rho_\bullet}{10^4\ M_\odot\ {\rm Mpc}^{-3}}\right)\left(\frac{\langle M_{\rm tot,b}\rangle}{10^6\ M_\odot}\right)^{-1}\left(\frac{t_{\rm min}}{100\ {\rm Myr}}\right)^{-1}$$

$$\times \frac{\Delta V_{\rm c}}{1+z}$$

note: coming volume at 5.5<z<6.5 is $\Delta V_c \sim 400\ {\rm Gpc}^3$

$$\frac{d^2N}{dtdz} \sim 6\ f_{\rm bin}\ \rho_{\bullet,4}\ M_{\bullet,6}^{-1}\ t_{\rm min,100}^{-1}\ {\rm events/yr}$$

(observer's frame)

optimistic choices…?

note: ~0.3 merger for a DM halo per redshift (Δt ~ 170Myr @z~6)

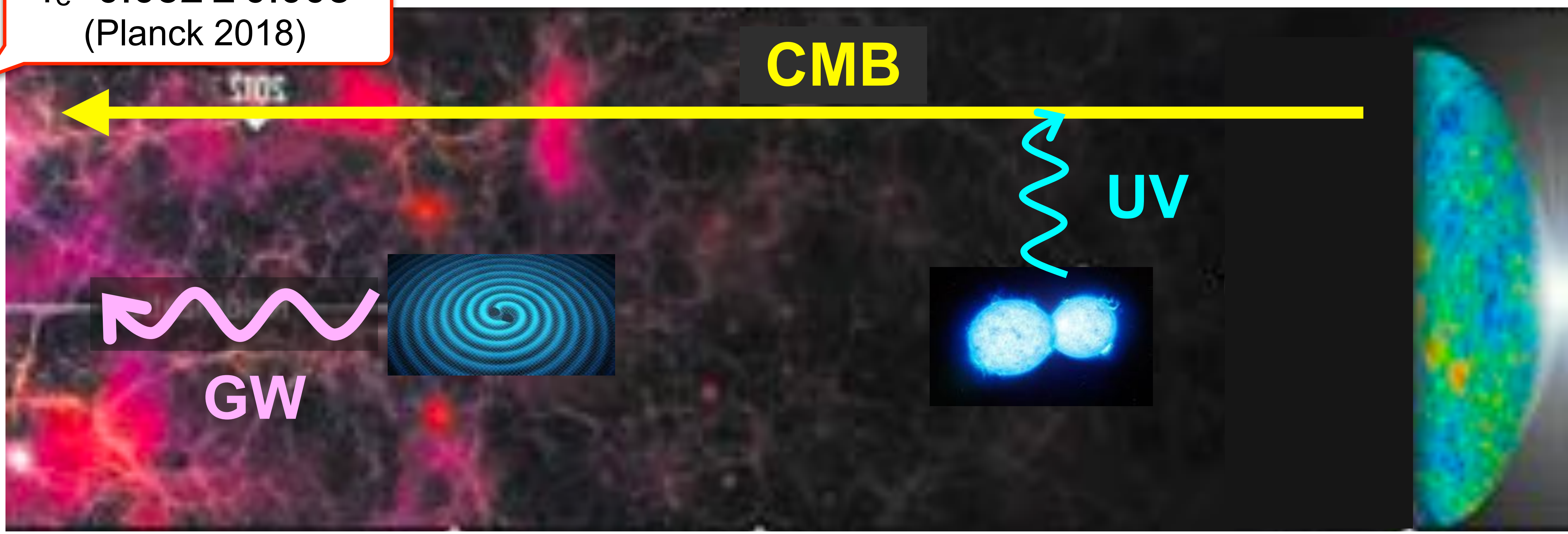
If Tianqin/LISA will observe >1 event / year, those GW sources (BBH mergers) are hidden populations (not quasars)??

Stochastic GW background

Relation between GW & CMB

pretty small
$\tau_e = 0.052 \pm 0.008$
(Planck 2018)

cosmic dawn (z>6)　　z=1100



"Metal-poor massive stars"

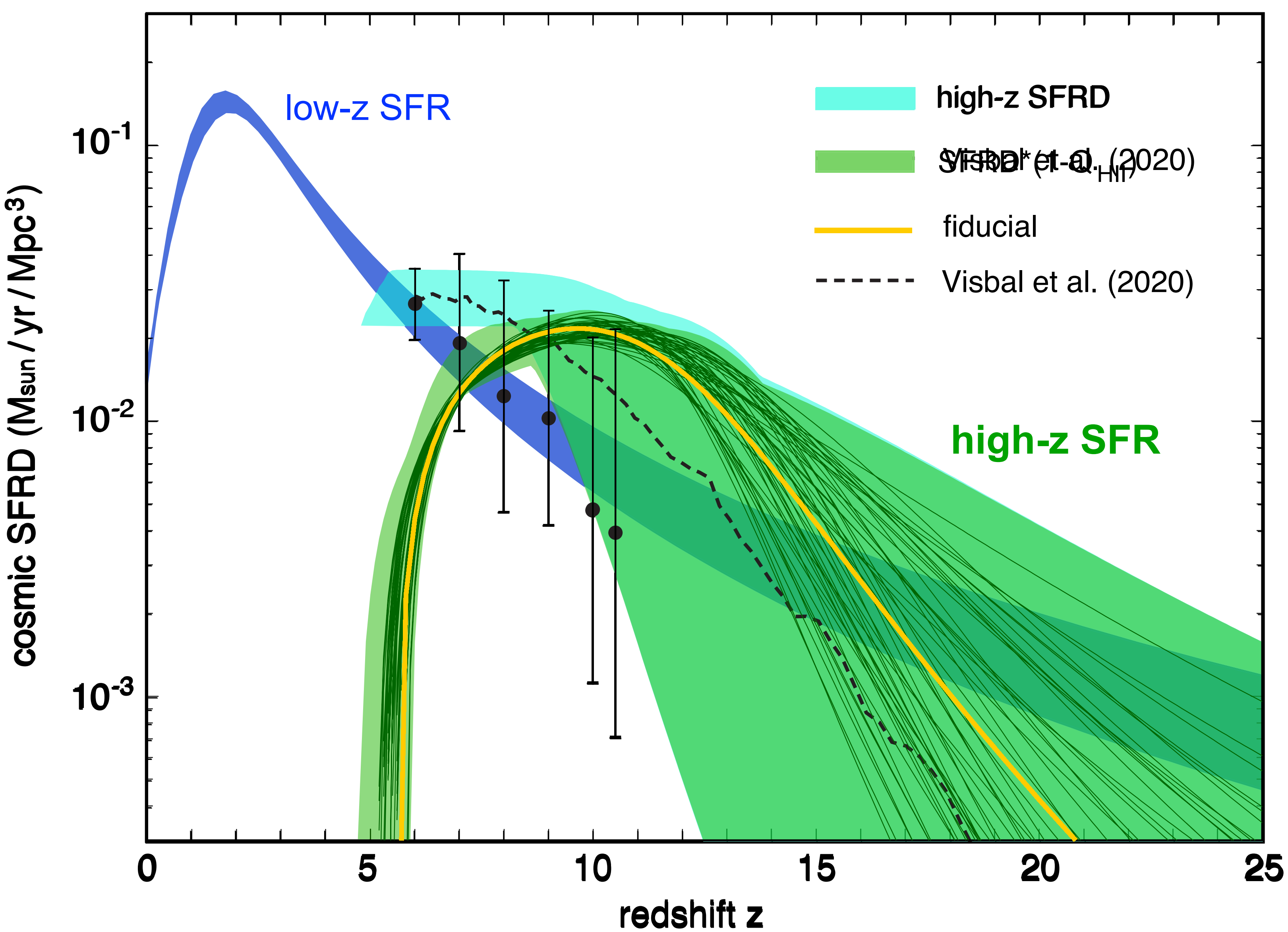
high SFR

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 $Q_{HII}(z)$

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

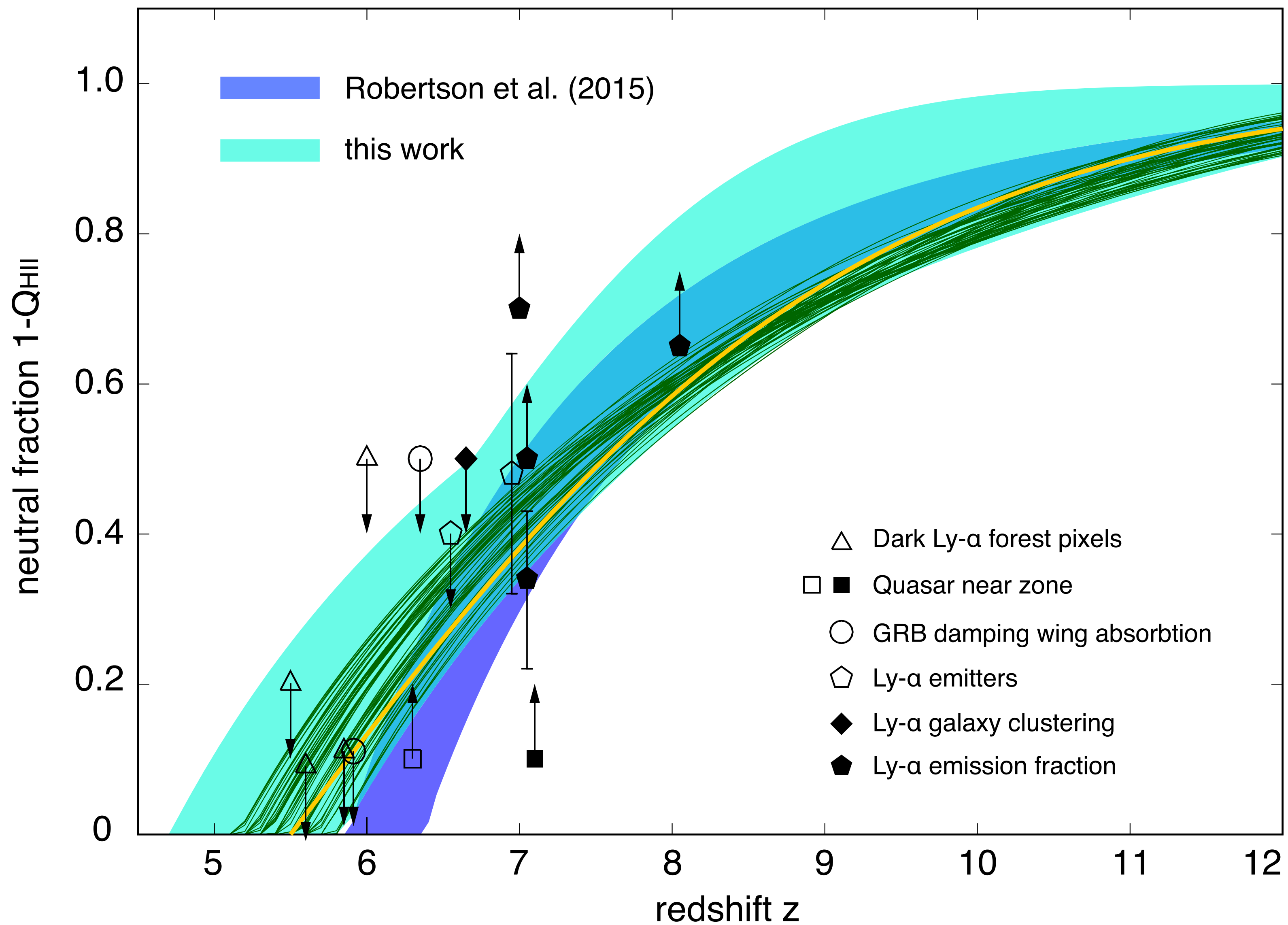
optical depth $\tau_e(z)$ & z_{reion}

the total **stellar** mass budget used for BBH formation

Planck (2018)

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

SFRD consistent with reionization



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BBH merger rates

- BBH merger rate

low-z or high-z BBH

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

- 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…

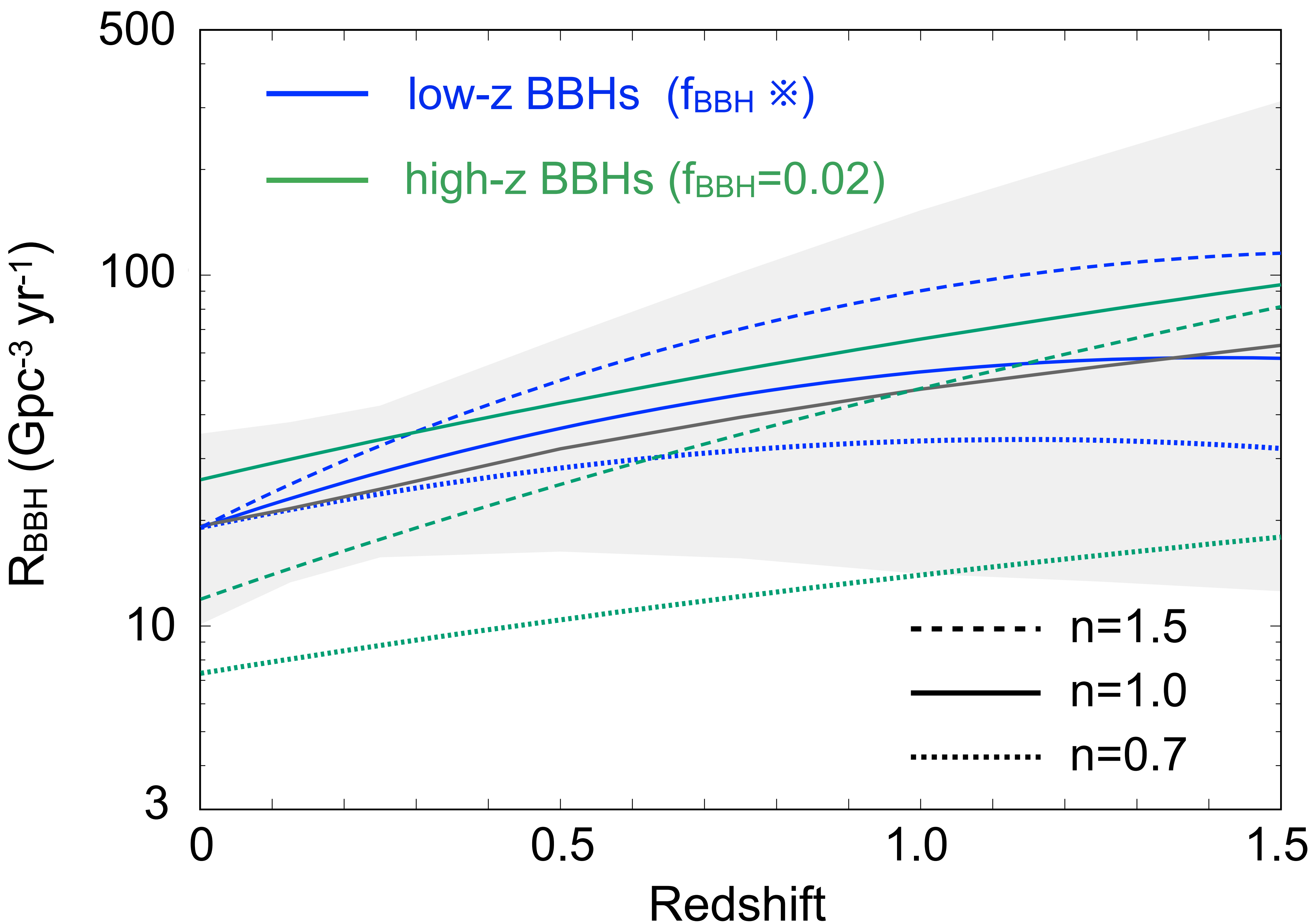
$$R_{\rm BBH} \simeq \alpha_n \frac{f_{\rm BBH}\,\rho_\star}{\langle M_{\rm tot,b}\rangle} t^{-n}$$

BBH formation efficiency

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

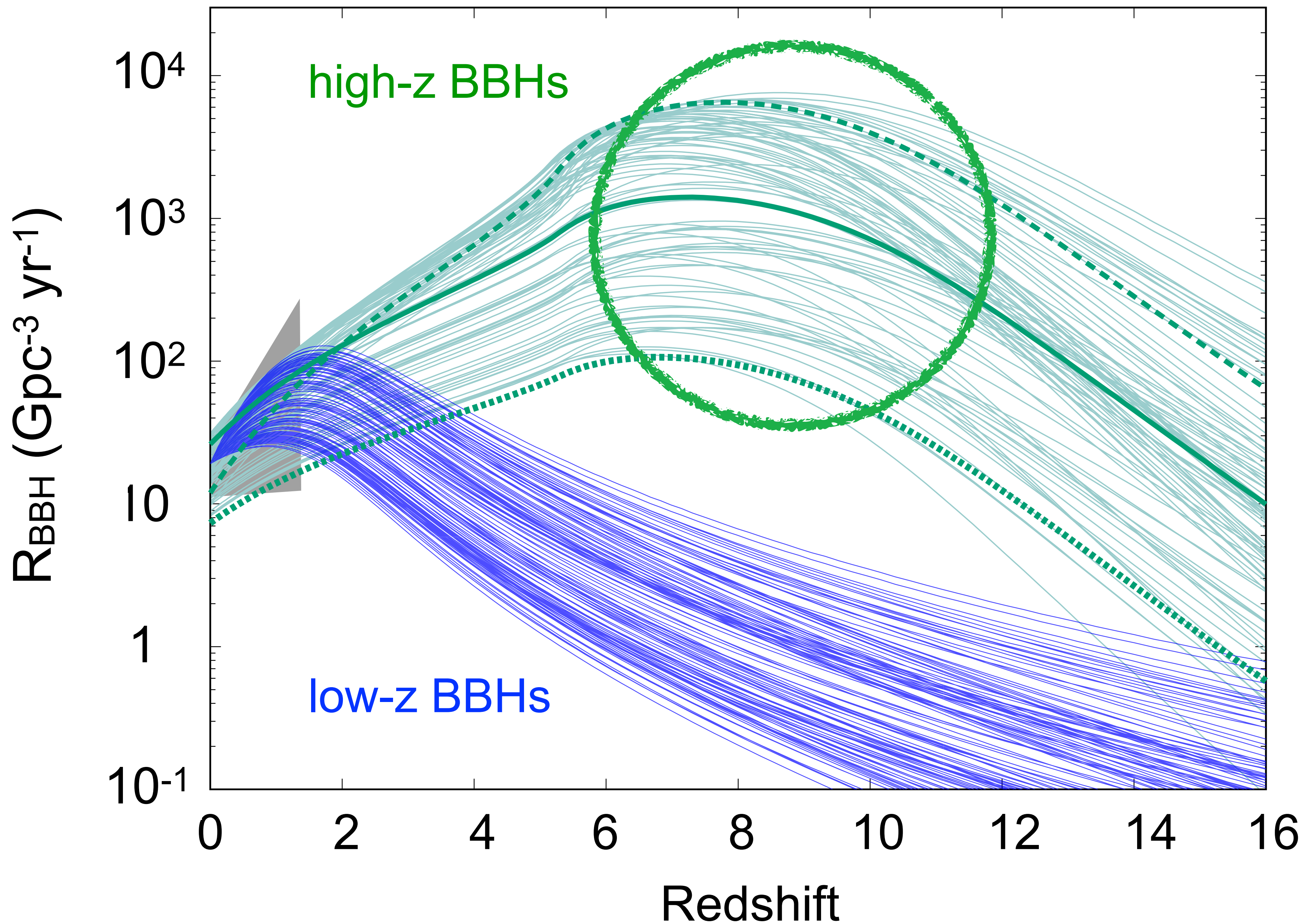
(Salpeter IMF; 0.1-100$M_{\rm sun}$)

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

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

Gravitational wave background

- GWB energy density (Phinney 2001)

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

merging rate (our model)
mass function (O3a)

GW spectrum from each BBH

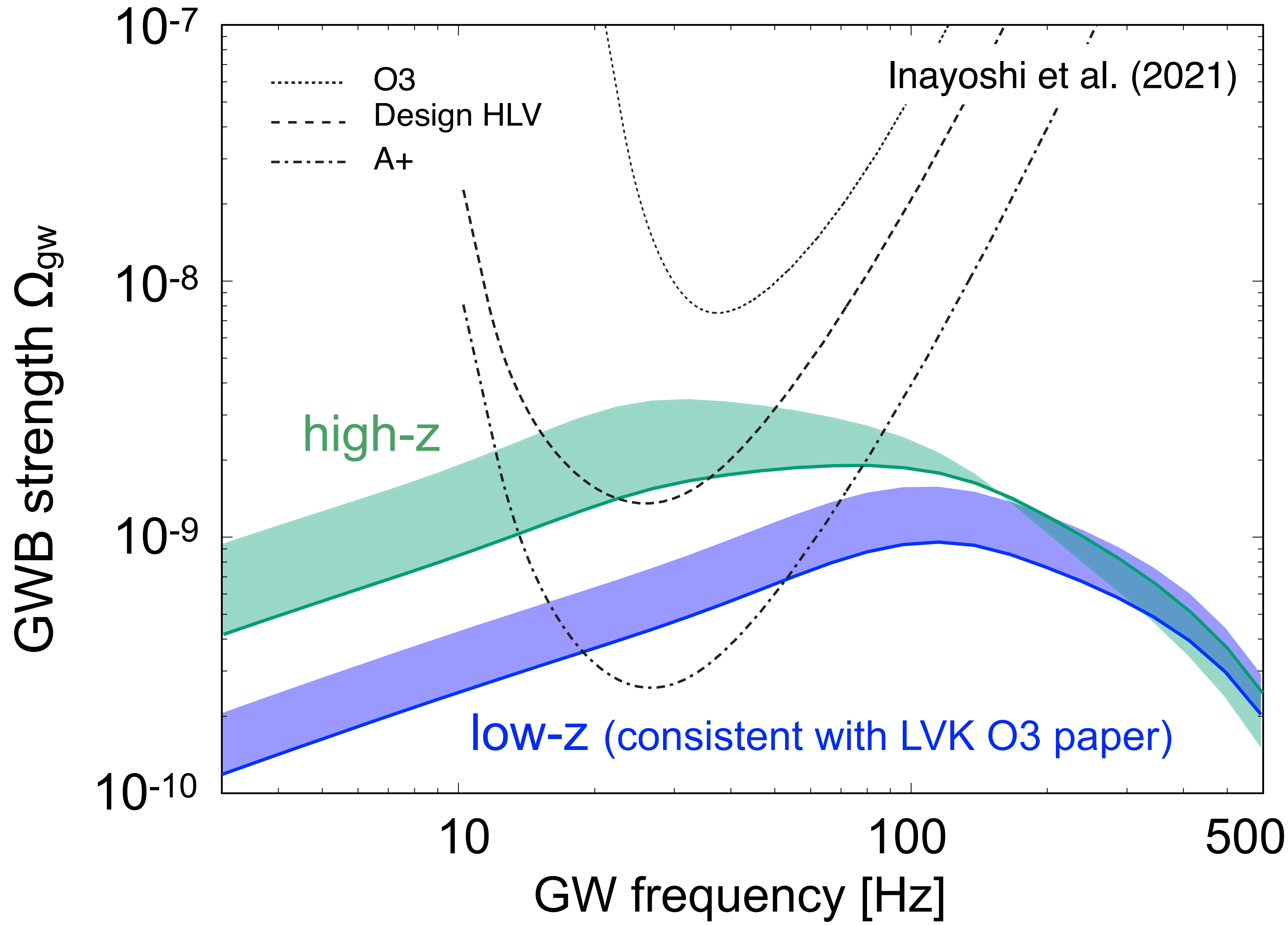
$$\frac{\mathrm{d}E_{\rm gw}}{\mathrm{d}f_r} = \frac{(\pi G)^{2/3} M_{\rm chirp}^{5/3}}{3} \begin{cases} f_r^{-1/3} \mathscr{F}_{\rm PN} & f_r < f_1, \\ \omega_{\rm m} f_r^{2/3} \mathscr{G}_{\rm PN} & f_1 \le f_r < f_2, \\ \frac{\omega_{\rm r} \sigma^4 f_r^2}{[\sigma^2 + 4(f_r - f_2)^2]^2} & f_2 \le f_r < f_3, \end{cases}$$

if GW emission due to inspiral phases dominates at f

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

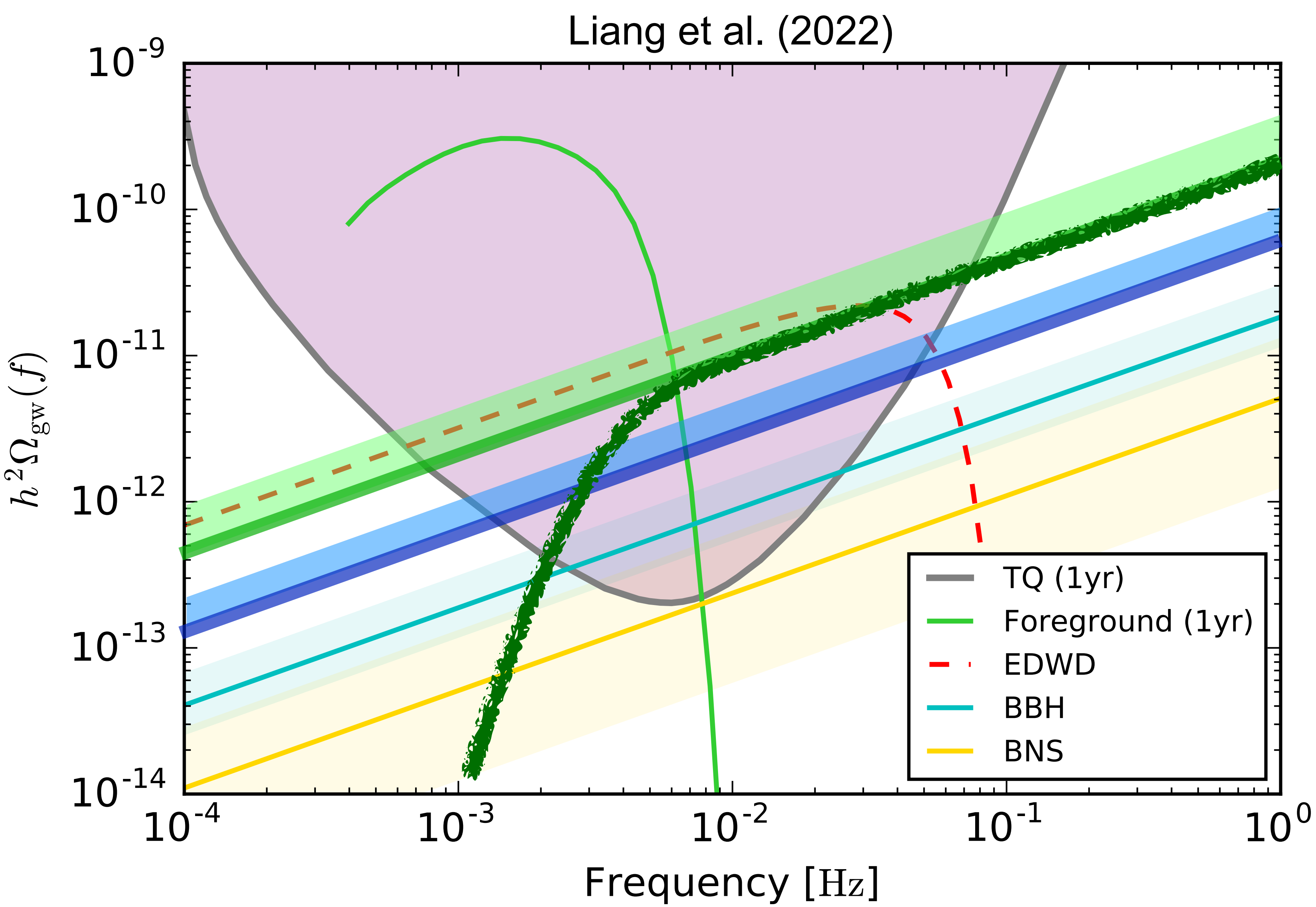
power-law with an index of **2/3**

GWB: low-z vs. high-z BBHs



detectable & flatter GWB spectra ⟺ high-z BBH population

GWB: top-heavy BBH MFs



low-z or **high-z**
stellar-mass BBH

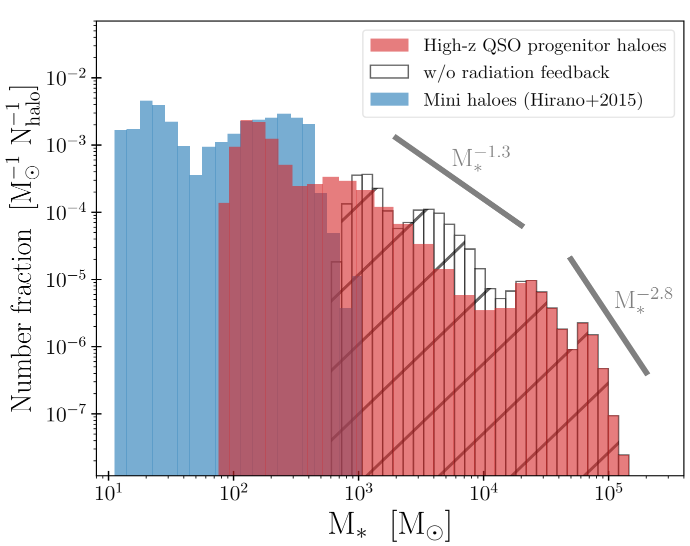
※ simple extrapolation to lower frequencies as $f^{2/3}$

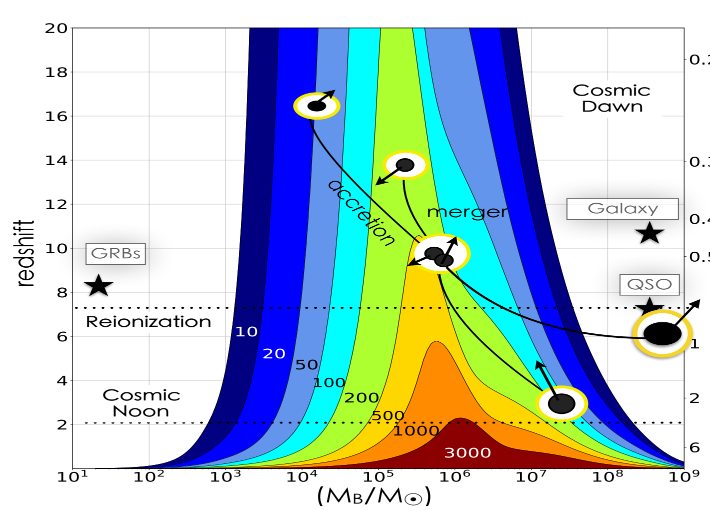
Any interesting applications?

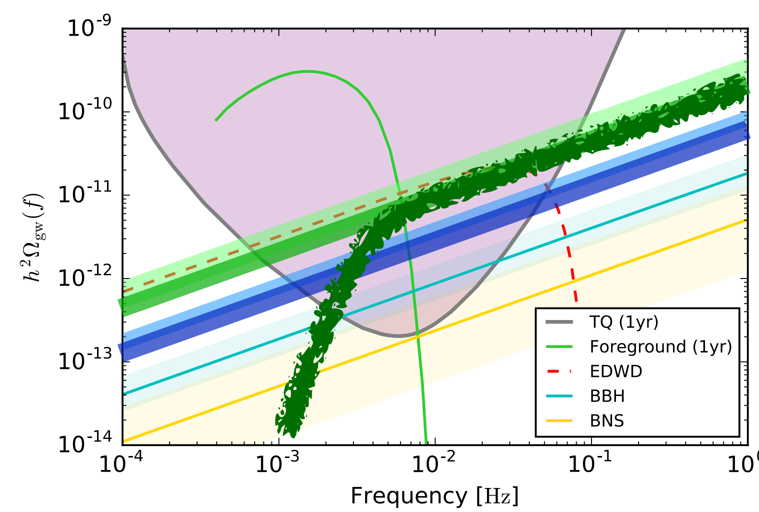
e.g., deviation of the $f^{2/3}$-law in the mHz bands due to eccentricities

Summary (+ discussion)

- The BH mass function for the earliest population has been constructed based on star-formation episodes at z>10
- Mergers of SMBHs/IMBHs with ~$10^{5\text{-}6}$ M_{sun} are great targets for Tianqin & LISA, but a reasonable event rate is achieved by hidden (non-quasar) populations (?)
- The stellar-mass BBH population at cosmic dawn would contribute to the production of a GW background, probed with multi-frequency GWs







Let us discuss :)