Unravelling the growth of the first black holes using SKA PTA

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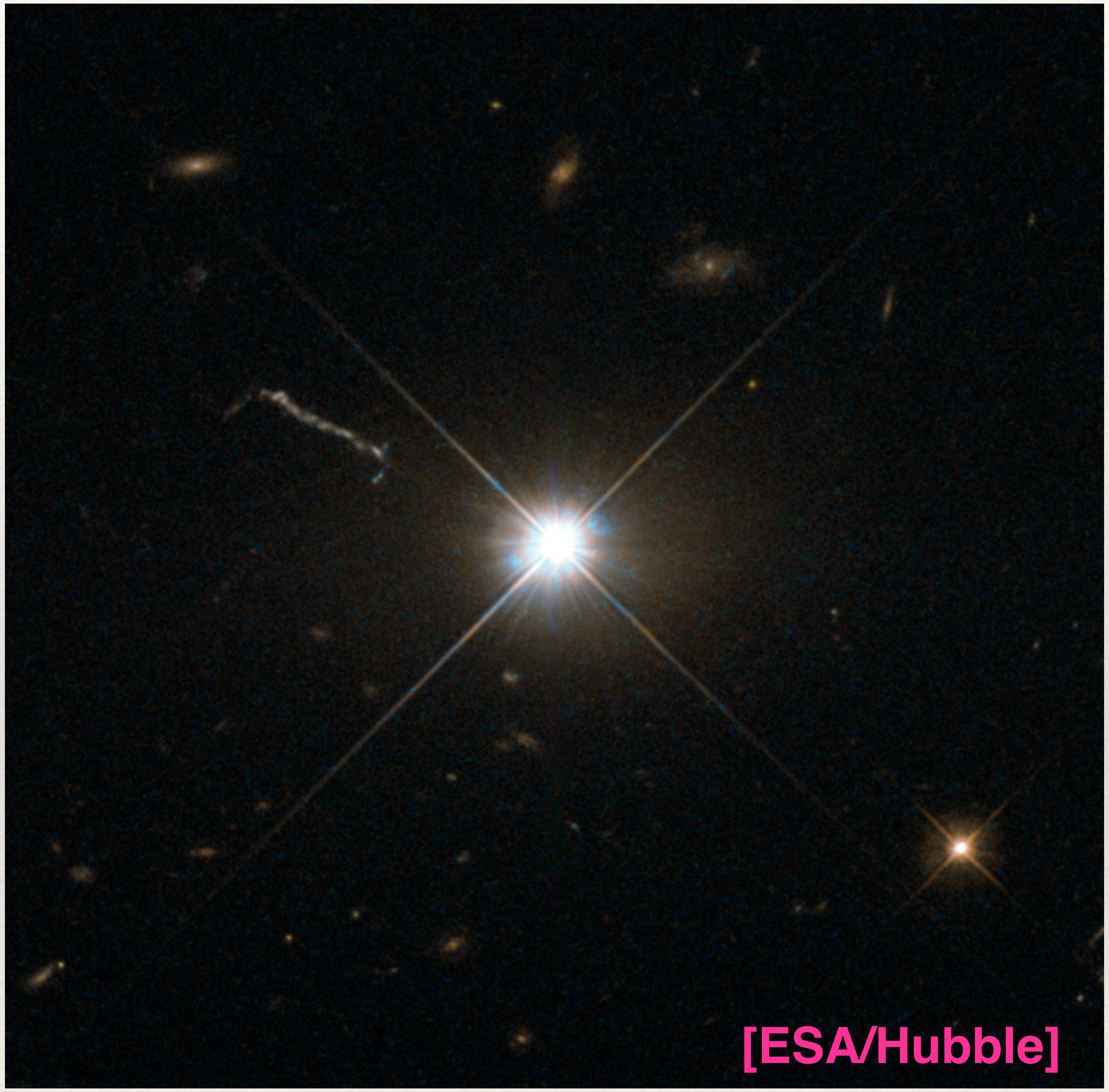
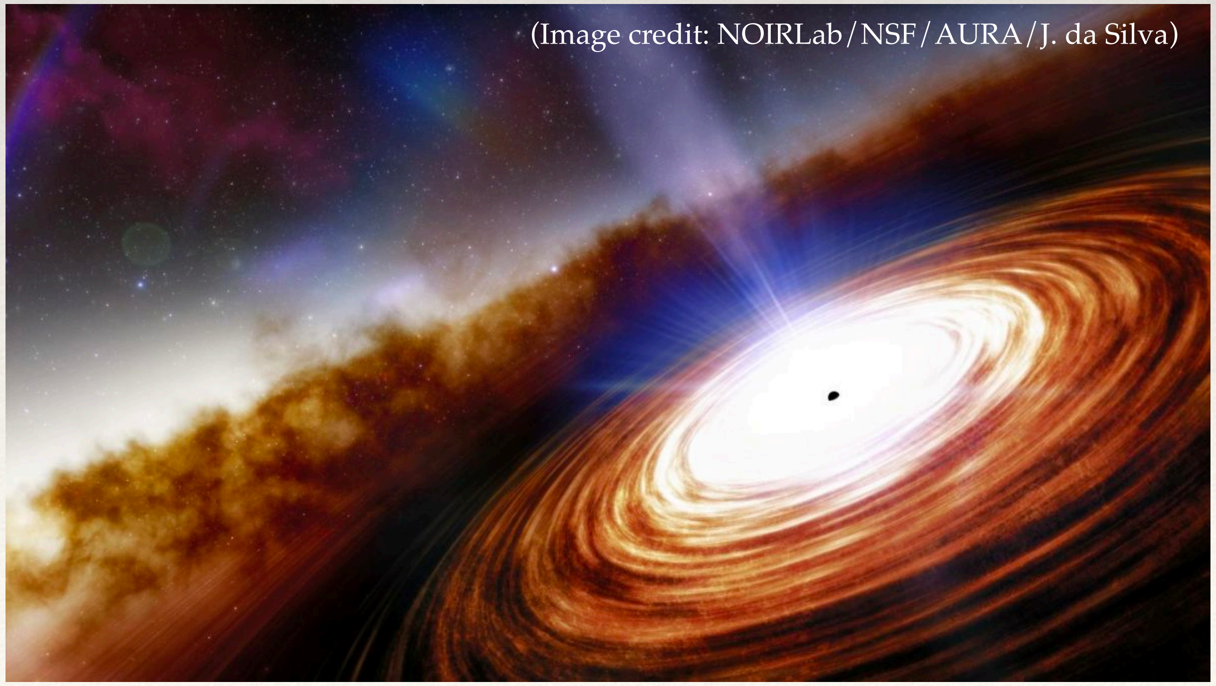
(Super)massive black holes are at the hearts of nearly all galaxies



This paradigm has a long history …

The first black holes

- Observations of QSOs at z ~ 6 indicate supermassive BH of masses $10^9 - 10^{10} M_\odot$ at $z \gtrsim 6$ [Fan+ (2006), Banados+ (2018)]
- Highest mass predicted to be ~ $10^{10} M_\odot$, also observed … [Haiman & Loeb (2001), Wu+ (2015)]
- … just a few Myr after the first stars [e.g. Barkana & Loeb (2001)]
- Growing a ~ $10^9 M_\odot$ BH from an initial seed of 100 $M_\odot$ needs ~ 1 Gyr of continuous Eddington accretion … [Volonteri+ (2010, 2012)]
- … which is difficult to reconcile with the short lifetimes of formation [e.g. Inayoshi+ (2020)]



Quasar J0313–1806, most distant, z ~ 7.64

Fuelling and growth of black holes

Two main parameters

Eddington ratio
($\eta_{\rm Edd}$)

Radiative efficiency
(ϵ)

$$L_{\rm Bol} = 1.38 \times 10^{38} \eta_{\rm Edd} \left(\frac{M_{\rm BH}}{M_\odot} \right) \ {\rm erg\ s^{-1}}$$

$$M_{\rm BH} = M_{\rm seed} \exp(t_{\rm QSO}/t_S)$$

$$t_{\rm S} = 0.45 \, (\epsilon/1-\epsilon) \, (L_{\rm bol}/L_{\rm Edd})^{-1} \ \ {\rm Gyr}$$

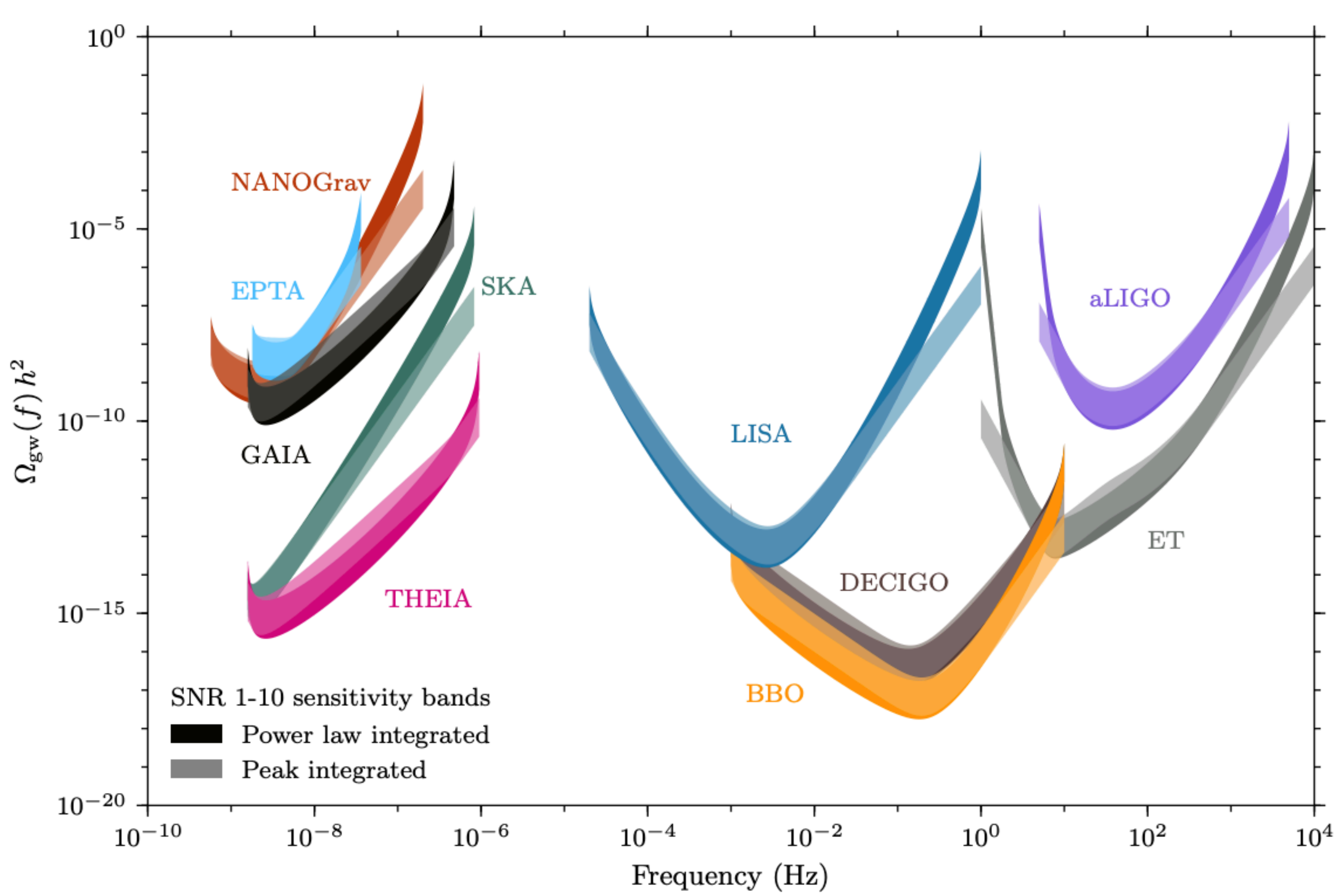
Most high-redshift SMBHs rapidly accreting, $\eta_{\rm Edd} \sim 1$ and $t_{\rm QSO} \sim 10^4 - 10^6$ yrs

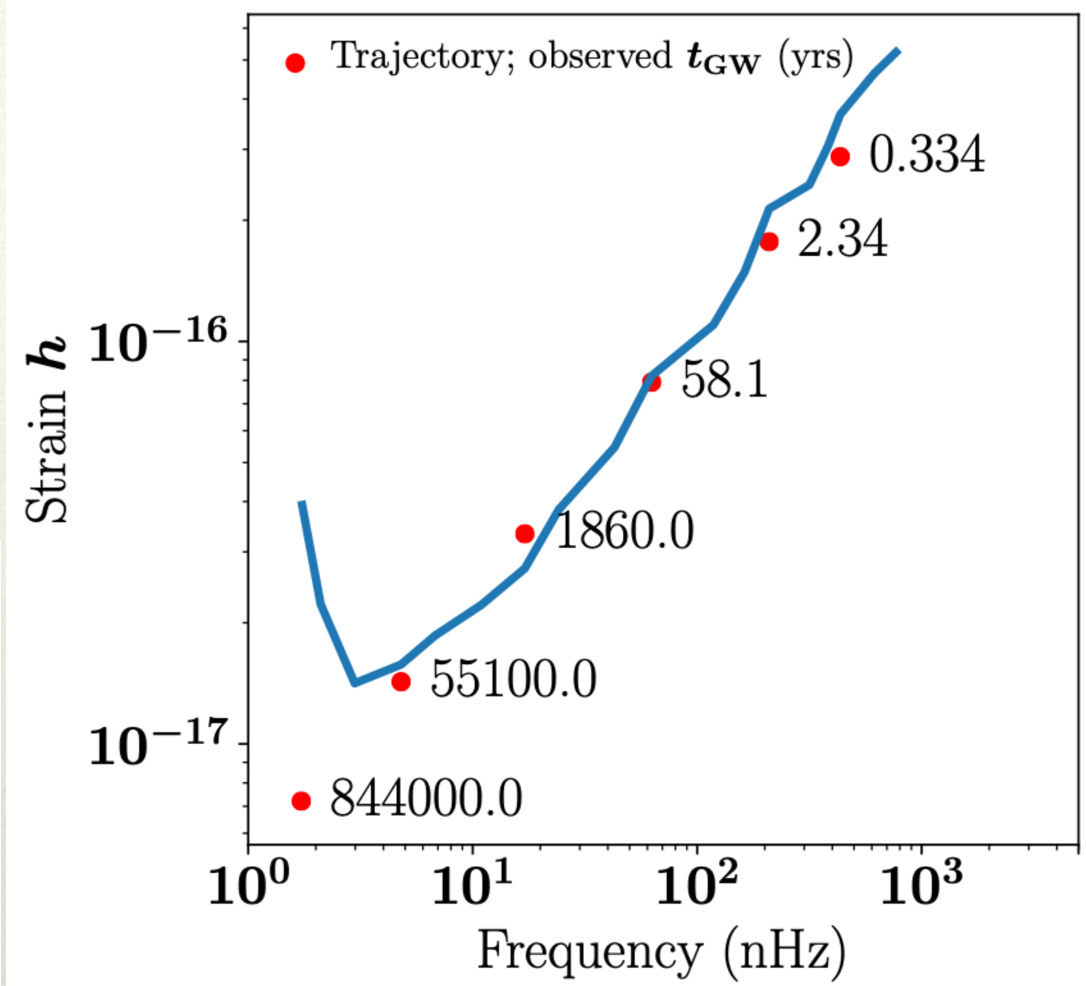
[e.g., Willott+ (2015), Trakhtenbrot+ (2017), Khrykin+ (2021), Eilers+ (2020)]

GW emission detectable with PTAs

SKA pulsar timing residuals are affected by a stochastic GW background in the nHz regime; sourced e.g. by SMBH coalescence

[Kramer+ (2004), Janessen+ (2015)]





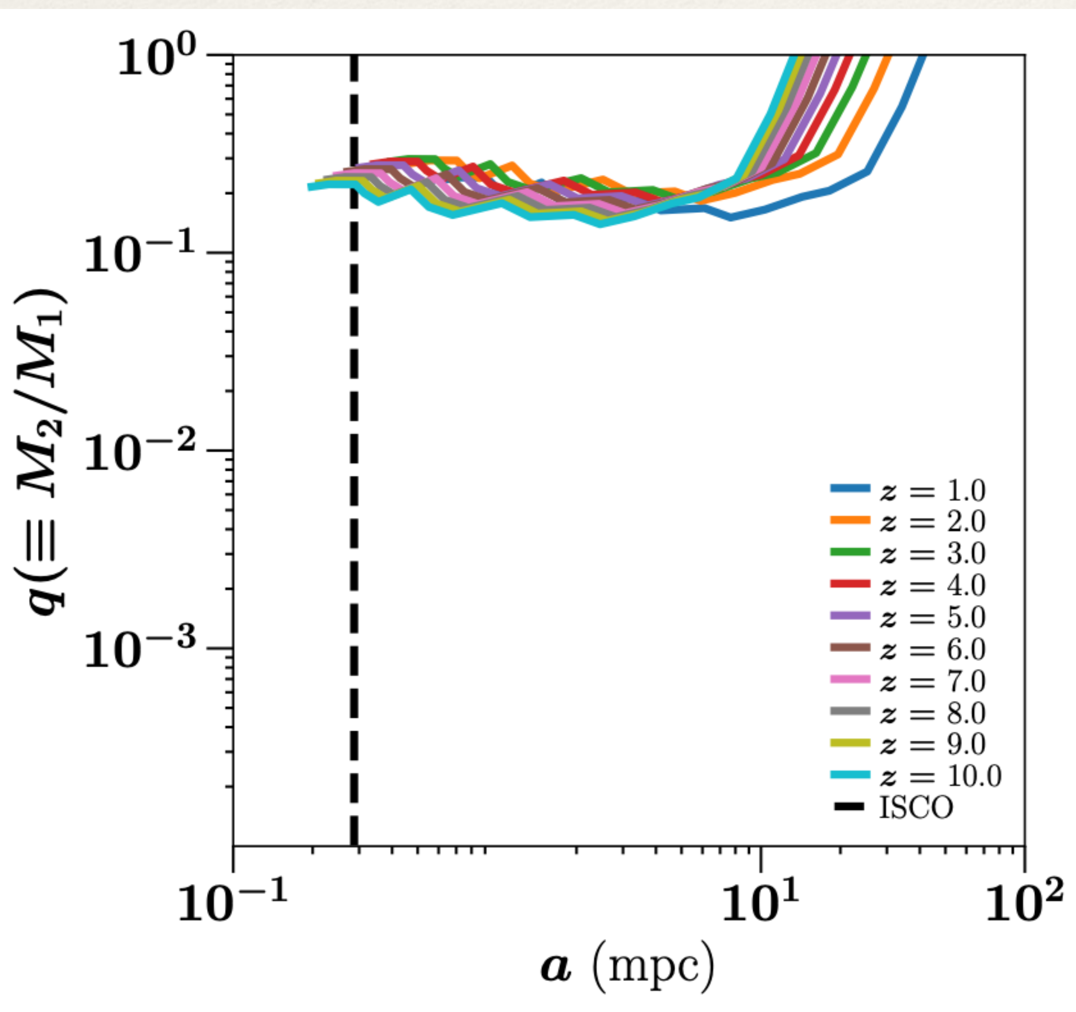
$$t_{\mathrm{gw,obs}} = \frac{5}{256} \frac{c^5 a^4 (1+z)}{G^3 M_1 M_2 (M_1 + M_2)}$$

[Garcia-Bellido+ (2021)]

$$h = \frac{2(G\mathcal{M}_{\rm obs})^{5/3}(\pi f_{\rm obs})^{2/3}}{c^4 d_L}$$

$$f_{\rm obs} = \frac{1}{\pi}\sqrt{\frac{G}{a^3}}\frac{(M_1+M_2)^{1/2}}{(1+z)}$$

$M_1 = 10^9 M_\odot$



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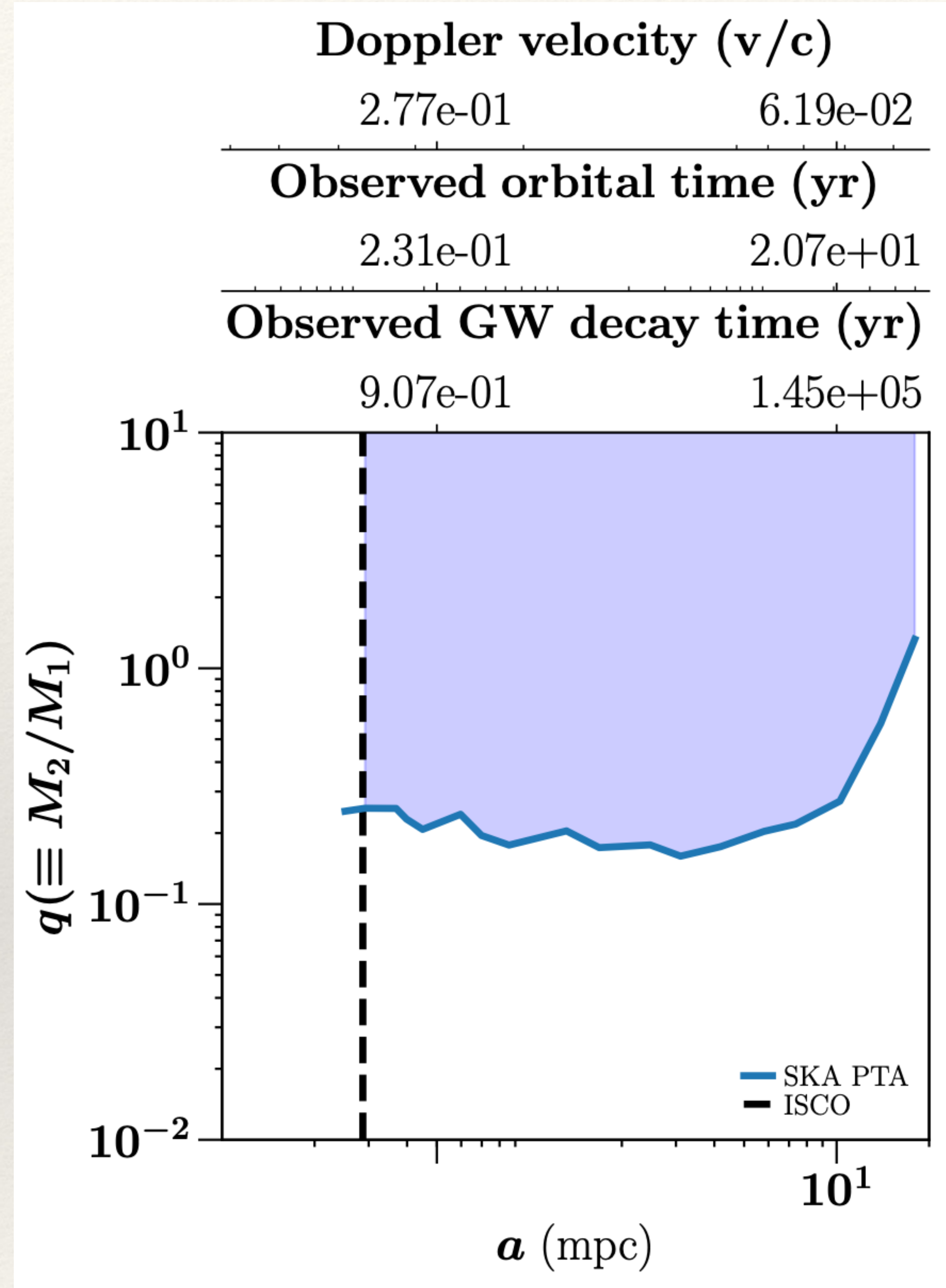


SKA is sensitive to $M_{\rm BH} \gtrsim 10^9 M_\odot$, separations ~ 1 - 50 mpc, $q_{\rm min} = 0.005 - 0.25$

Merger rates: analytical formulation

Black hole mass - halo mass relation: **[e.g., Wyithe & Loeb 2002]**

$$M_{\rm BH} = M_{\rm h}\epsilon_0 \left(\frac{M}{10^{12}M_\odot}\right)^{\gamma/3-1} \left(\frac{\Delta_v \Omega_m h^2}{18\pi^2}\right)^{\gamma/6} (1+z)^{\gamma/2}$$

Combine with merger rates of DM haloes: **[Fakhouri+ 2013]**

$$\frac{dn_{\rm BHB}}{dz dq d\log_{10} M_{\rm BH}} = A_1 f_{\rm bh} \frac{3}{\gamma} \left(\frac{M_{\rm h}(M_{\rm BH})}{10^{12}M_\odot}\right)^{\alpha} q^{3/\gamma-1+3\beta/\gamma}(1+z)^{\eta} \exp\left[\left(\frac{q}{\bar{q}}\right)^{3\gamma_1/\gamma}\right] \frac{dn_{\rm h}}{d\log_{10} M_{\rm h}}$$

$$\phi_{\rm BHB}(M_{\rm BH}) \equiv \frac{dn_{\rm BHB}}{d\log_{10} M_{\rm BH}} = \int_{q_{\rm min}}^{1} dq \frac{dn_{\rm BHB}}{dt\; dq\; d\log_{10} M_{\rm BH}} t_{\rm gw}(a_{\rm gw})$$

Radius at which GW emission takes over

Total number of BHBs in a given redshift interval:

$$\frac{dN_{\rm BHB,gw}(M_{\rm BH}, q_{\rm min})}{d\log_{10} M_{\rm BH}} = dV(z_1, z_2)\; \phi_{\rm BHB,gw}(M_{\rm BH}, q_{\rm min})$$

Quasars as electromagnetic counterparts

Use QSO luminosity function, convert to mass: **[e.g., Shen et al. 2020]**

$$\phi(L) \equiv \frac{dn_{\rm QSO}}{d\log_{10}L} = \frac{\phi_*}{2(L/L_*)^{\gamma_1}}, \phi(M_{\rm BH}\,|\,{\rm QSO}, \eta_{\rm Edd}) = \frac{dn_{\rm QSO}}{d\log_{10}M_{\rm BH|QSO}}$$

BH mass function of all (i.e. not just active) black holes:

$$\phi_{\rm BH}(M_{\rm BH}) = f_{\rm BH}\frac{dn_{\rm h}}{d\log_{10}M_{\rm h}}\left|\frac{d\log_{10}M_{\rm h}}{d\log_{10}M_{\rm BH}}\right|$$

Active fraction of BH:

$$f_{\rm active}(M_{\rm BH}\,|\,\eta_{\rm Edd}) = \phi(M_{\rm BH}\,|\,{\rm QSO}, \eta_{\rm Edd})/\phi_{\rm BH}(M_{\rm BH});$$

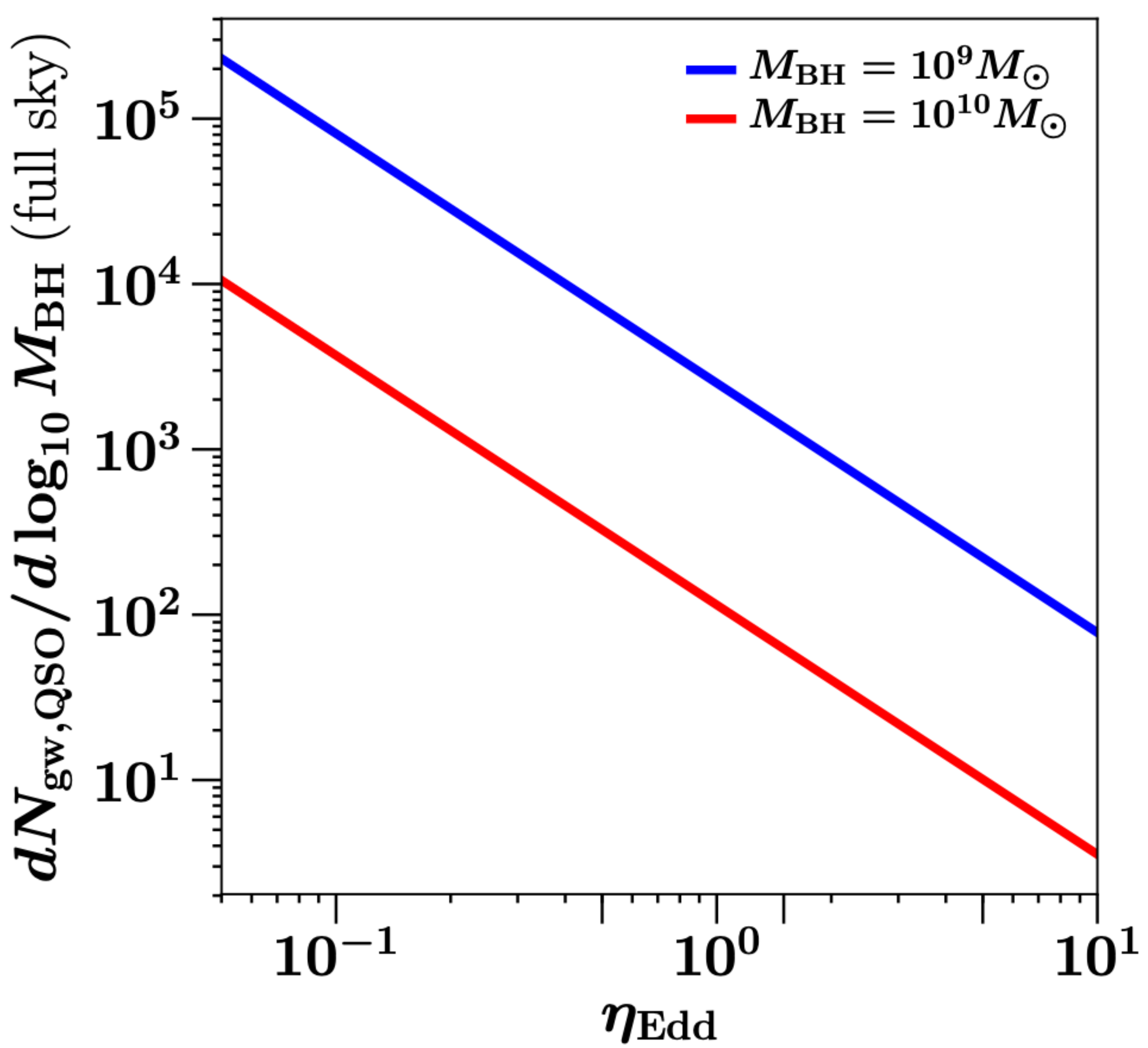
Number of active quasar counterparts to SKA PTA:

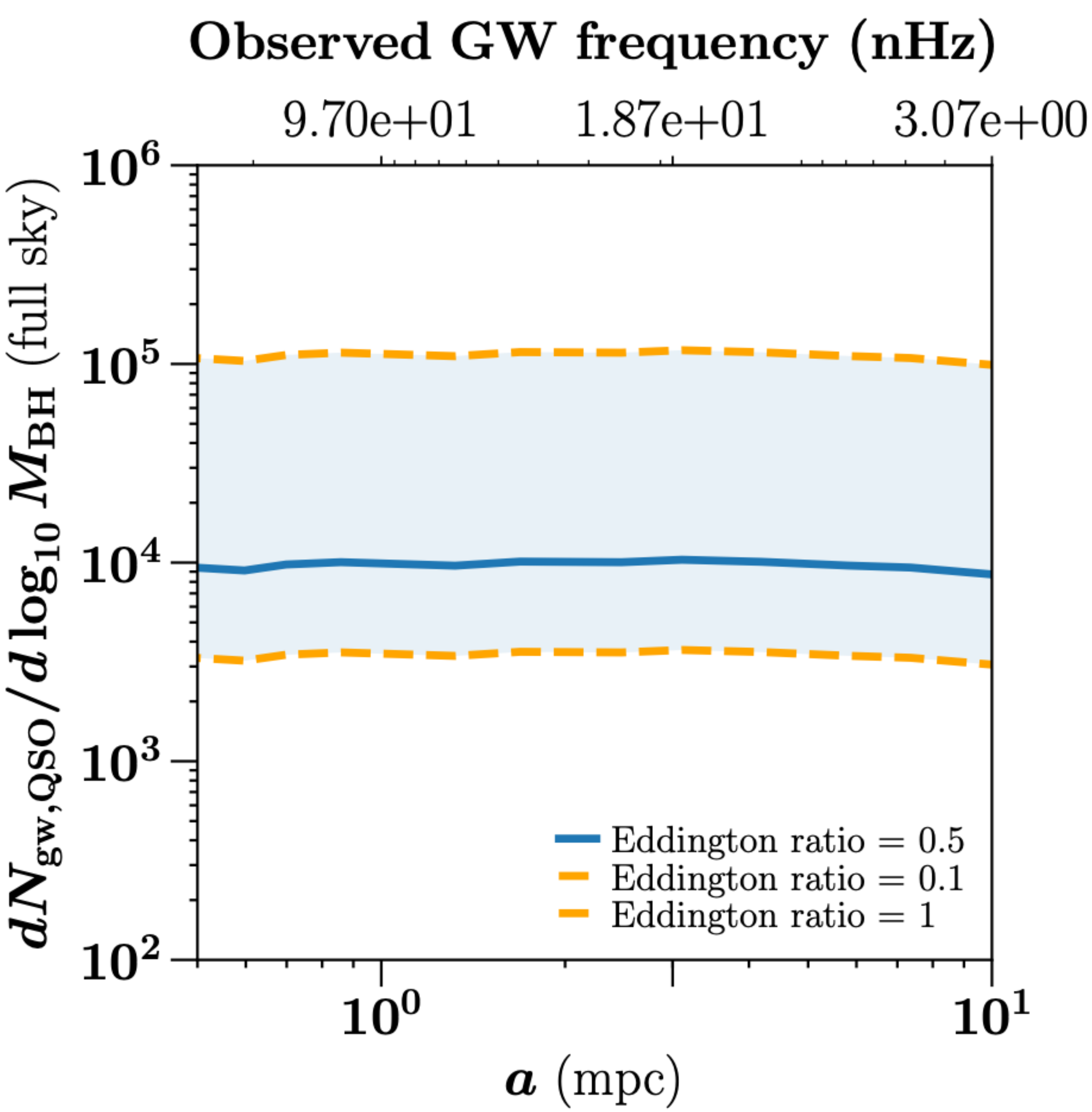
$$\frac{dN_{\rm gw,QSO}(M_{\rm BH}, q_{\rm min}\,|\,\eta_{\rm Edd})}{d\log_{10}M_{\rm BH}} = f_{\rm active}(M_{\rm BH}\,|\,\eta_{\rm Edd}) \times \frac{dN_{\rm BHB,gw}(M_{\rm BH}, q_{\rm min})}{d\log_{10}M_{\rm BH}}$$

Quasars as electromagnetic counterparts

M_{BH}	$\phi_{BHB,gw}$ (cMpc^{-3})	$dN_{BHB,gw}/d\log_{10} M_{BH}$	$N_{gw,QSO}$ (in 70 deg^{-2})
$10^9 M_\odot$	4.2×10^{-4}	1.0×10^8	$\sim 7 - 45$
$10^{10} M_\odot$	1.54×10^{-5}	2.4×10^6	$\lesssim 1$

QSO counterpart is *uniquely localised*





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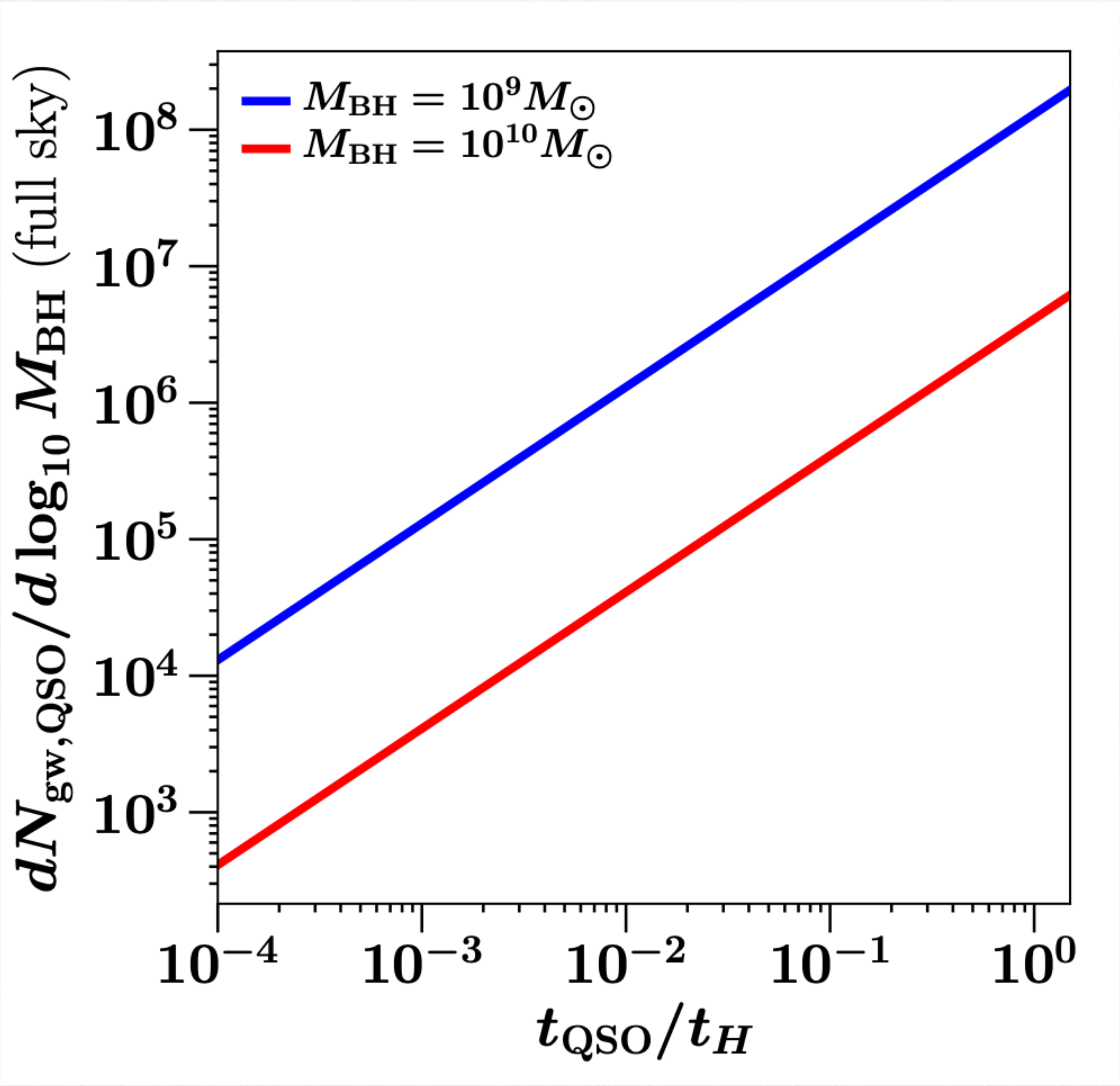
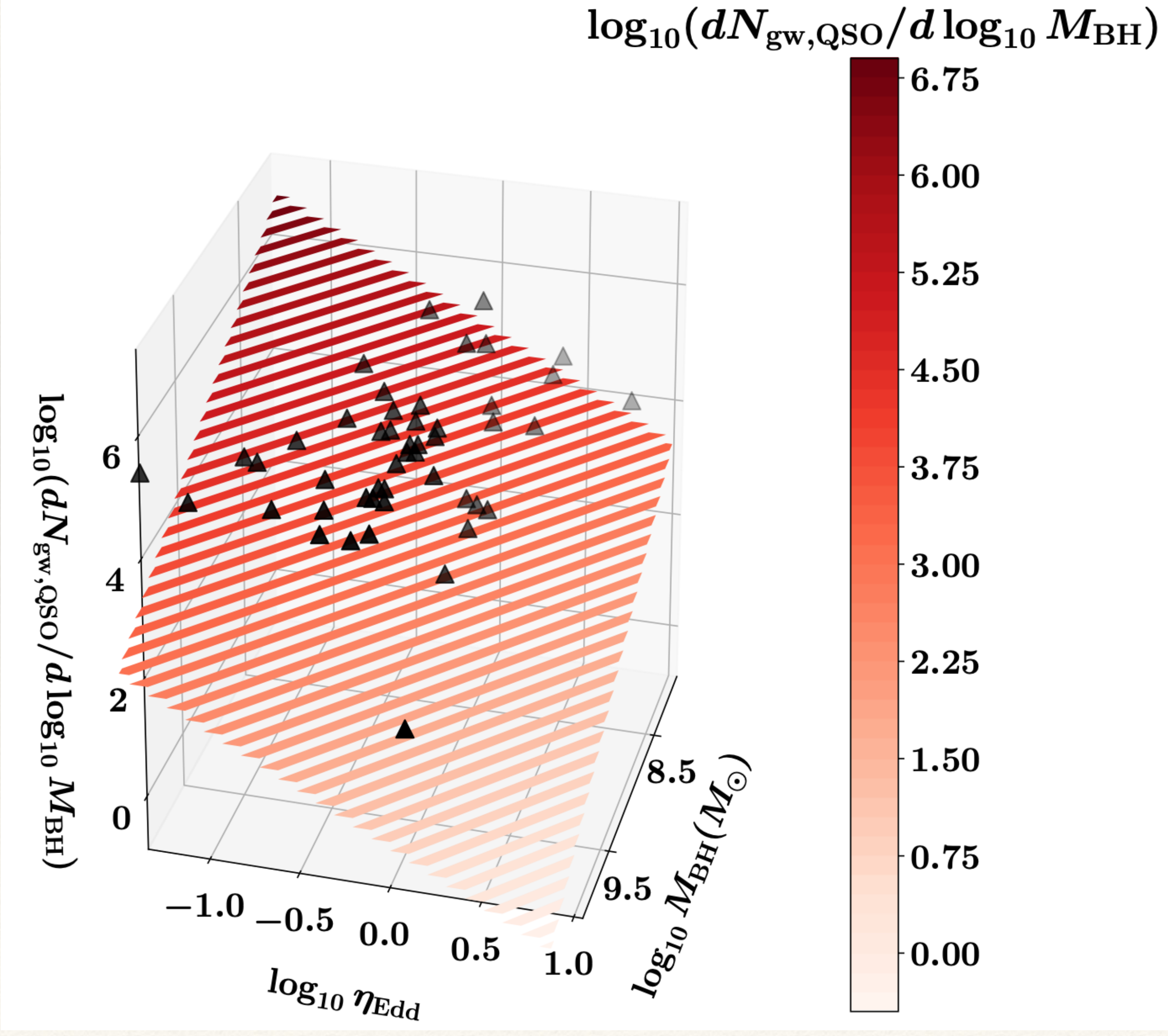


$f_{\rm BH} \sim 1$ **[e.g., Ricarte & Natarajan (2018)]**



BH with known masses and $\eta_{\rm Edd}$

[Kim & Im (2019)]

To summarize …

- We still don’t know the mechanism by which the first SMBHs were assembled — GWs offer a promising view towards their properties
- SKA PTA is sensitive to SMBHs with primary black hole masses $M_{\rm BH} \gtrsim 10^9 M_\odot$, separations of $a \sim 0.5 - 50$ mpc, and $q > q_{\rm min} = 0.005 - 0.25$, *fairly independently of redshift*
- SKA PTA will detect $10^7 - 10^8$ SMBHBs over the full sky at $z \gtrsim 6$ …
- … with prompt electromagnetic follow-ups (e.g., Doppler boosting, periodic variability) on orbital periods of ~ weeks to years, velocities ~ 0.2c
- EM counterpart of the most massive SMBH binaries is *uniquely localizable* within SKA error ellipse at $z \gtrsim 6$
- Data-driven forecasts for the number of active quasar counterparts to PTA events, as a function of the quasar's Eddington luminosity ($\eta_{\rm Edd}$) and active lifetime ($t_{\rm QSO}$)
- Number of active SKA PTA counterparts place direct constraints on seeding and growth scenarios of the first SMBHs

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Thank you!