Are Early Extremely Supermassive Black Holes Consistent with ΛCDM?

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related work w/ Olga Mena, Aurora Ireland, Dan Hooper, Gordan Krnjaic

Primordial Non-Gaussianty and Beyond
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“community” view

SMBH challenging for ΛCDM

hard to grow BHs to $10^{9+} M_{\odot}$ by $z > 6$

- *… this* (QSO) *is only the latest and most extreme of a growing number of known giant BHs at early times whose rapid growth, within the (somewhat squishy) constraint of the Eddington limit, is difficult to understand. …*
- *The point worth making is this: Such objects are so rare that any attempt to find a “natural” explanation is probably wrong.* ***If the suggested process that makes these objects is not extremely unusual, it is probably the wrong process****.* **Kormendy 2013**
- rare-processes are a good way to probe models at their limits!

Modifications to a "base model" ΛCDM which might more easily produce early SMBHs?

- mechanism: early universe production of compact (black hole?) "seeds"
  - enhanced (super horizon) inhomogeneities on small scales
  - non-gaussianity enhancing rare small scale inhomogeneities

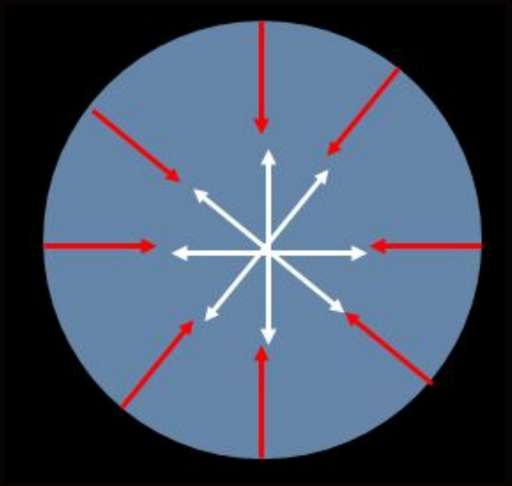
- mechanism: enhance growth rate of BHs with "new" physics
  - typically involves dark matter accretion enhanced by self-interactions

No modifications needed?

- baryonic "direct formation" of say, $10^4\,M_\odot$, BH seeds
- growth rate of BHs is short enough to produce observed BHs

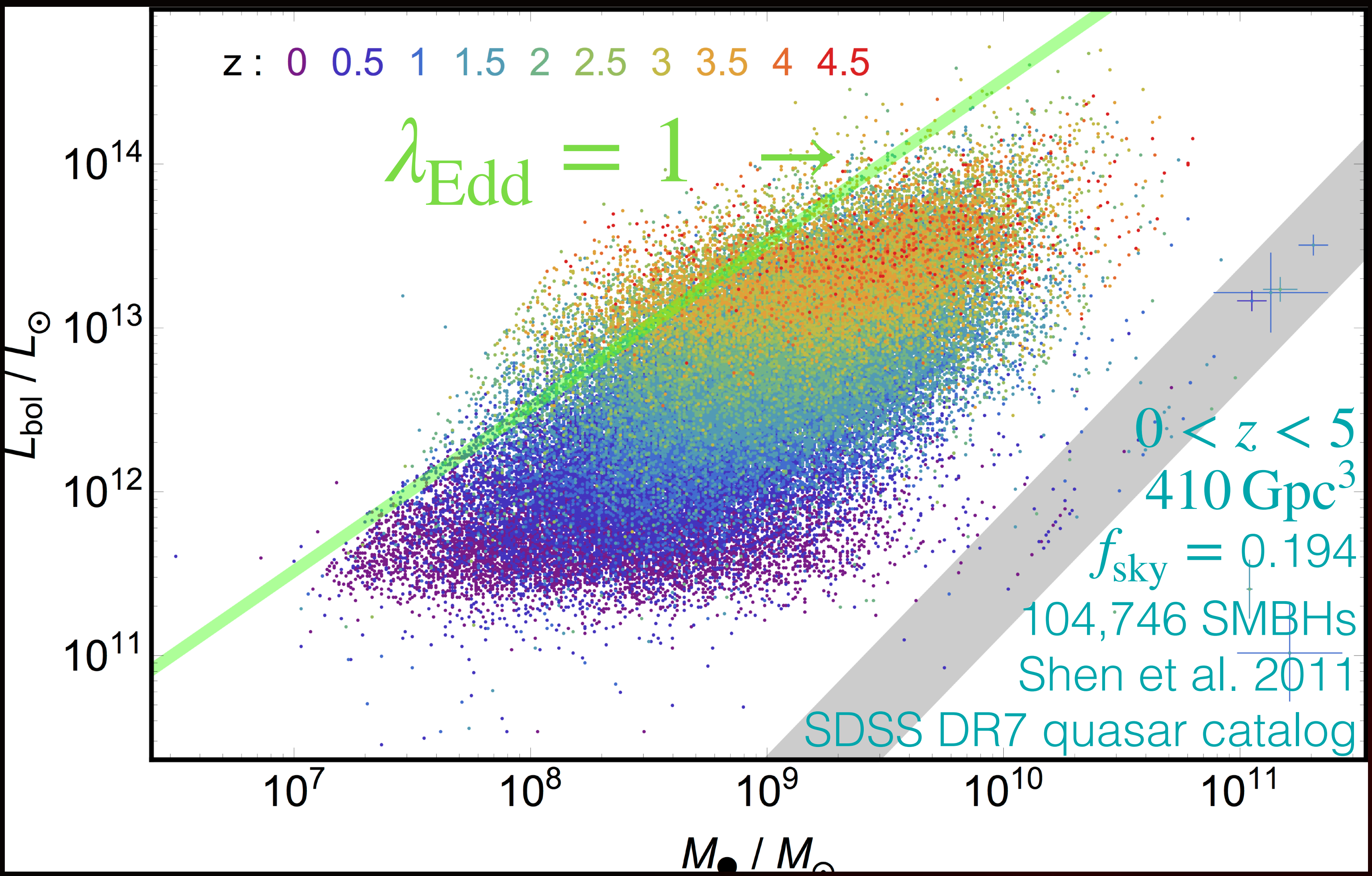
Black Hole Growth by Accretion

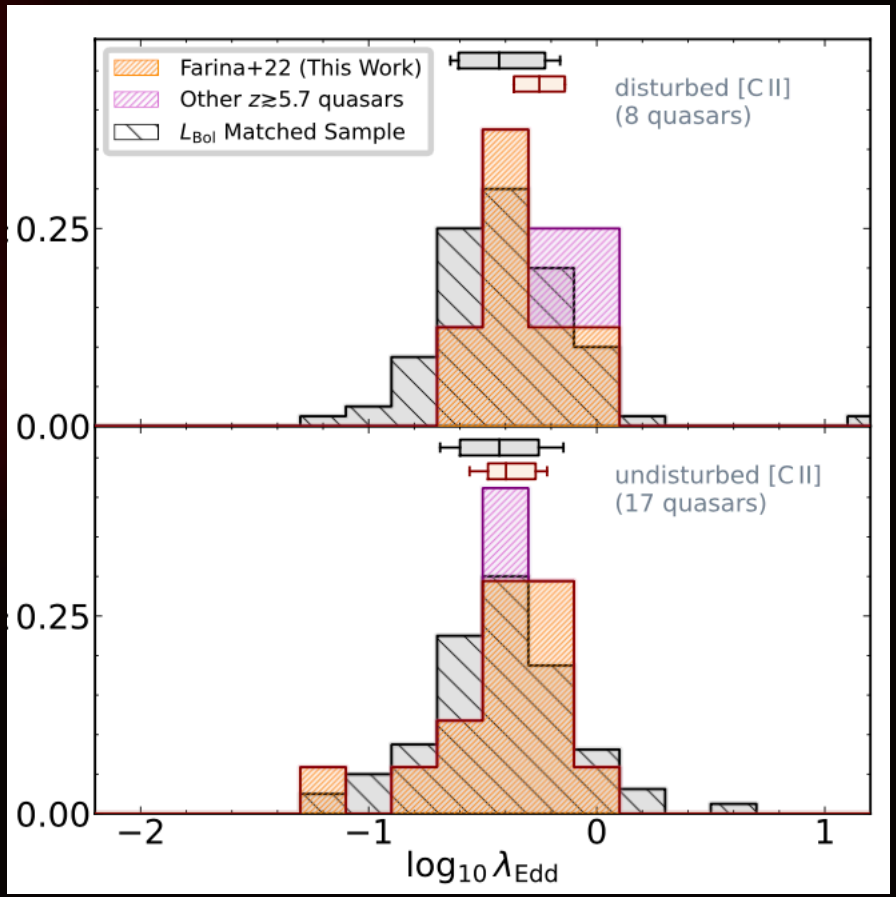
- Eddington Limit
  - for accretion radiation Thomson scattering repulsion < gravitational attraction
  - $$\frac{L_{\rm bol}}{M} < \frac{L_{\rm Edd}}{M} = \frac{4\pi\, G\, m_{\rm p}}{\sigma_{\rm T}\left(1 - \frac{1}{2}\, Y_{\rm He}\right)} = 3.72 \times 10^4\, \frac{L_\odot}{M_\odot}$$

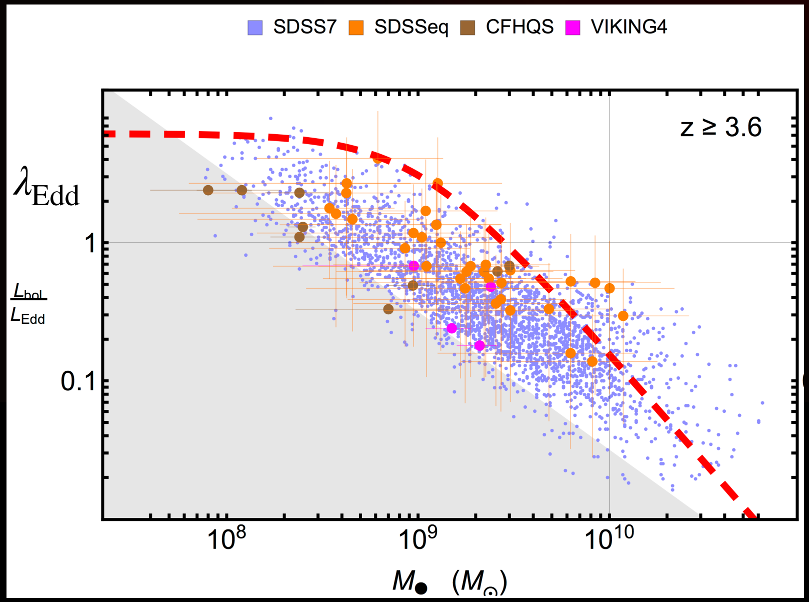


- PARAMETERS
  - Eddington ratio: $\lambda_{\rm Edd} = \dfrac{L_{\rm bol}}{L_{\rm Edd}}$
  - radiative efficiency: $\eta_{\rm rad} = \dfrac{L_{\rm bol}}{\dot{M}_{\rm gas}\, c^2}$ $\quad \epsilon_{\rm rad} = \dfrac{L_{\rm bol}}{\dot{M}_{\rm BH}\, c^2} = \dfrac{\eta_{\rm rad}}{1 - \eta_{\rm rad}}$
  - Salpeter growth timescale: $\tau_{\rm Salp} = \dfrac{M_{\rm BH}}{\dot{M}_{\rm BH}} = \dfrac{39.6\,{\rm Myr}}{\lambda_{\rm Edd}}\, \dfrac{\epsilon_{\rm rad}}{0.1}$
- N.B. one can measure $L_{\rm bol}$, $M_{\rm BH}$, $\lambda_{\rm Edd}$ directly in quasars - but not $\epsilon_{\rm rad}$

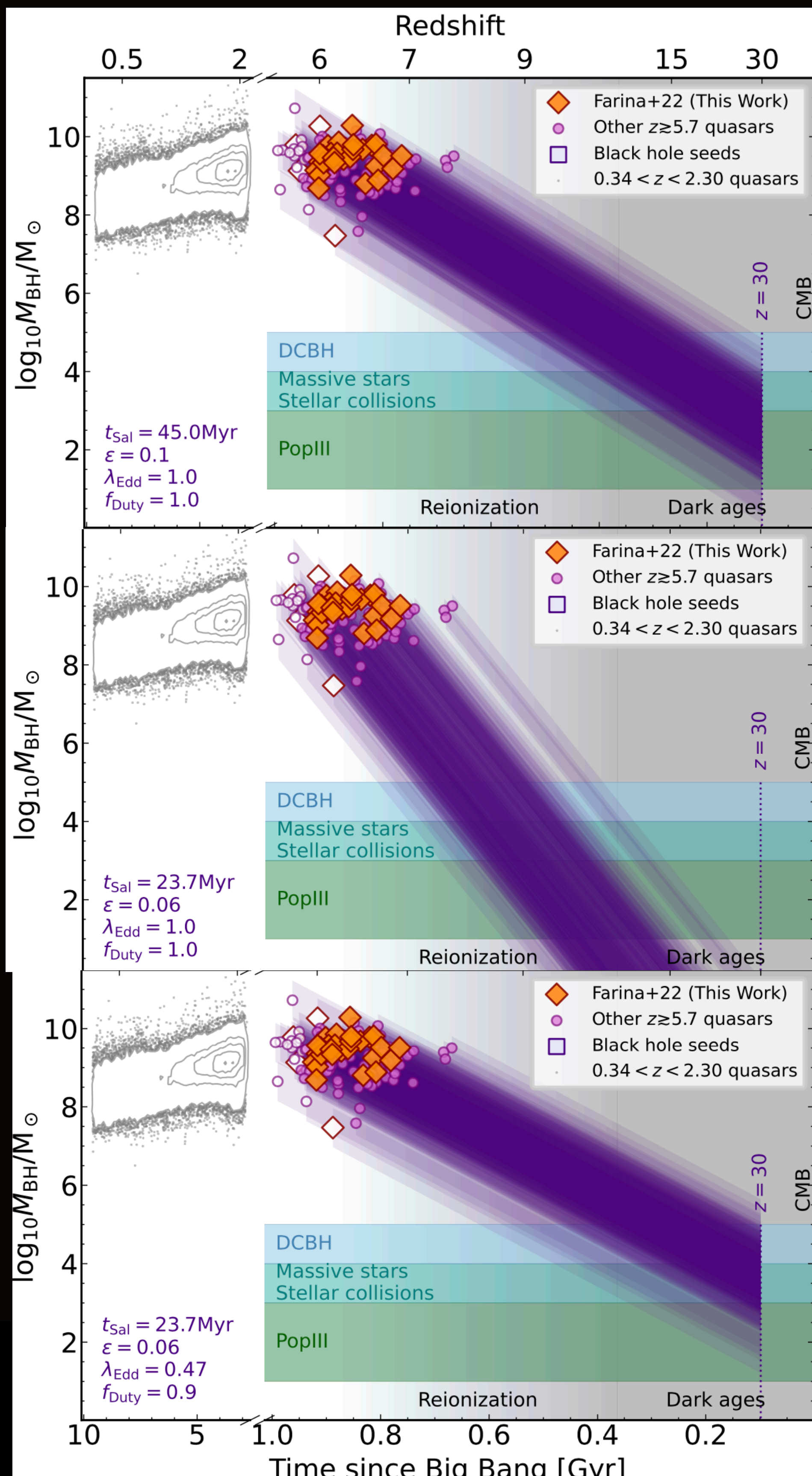
$\lambda_{\rm Edd} < 1$ is typical







Are Early SMBHs really problematic?



← canonical parameter

← decrease efficiency by 40%

← more “realistic” λ_{Edd} , duty cycle

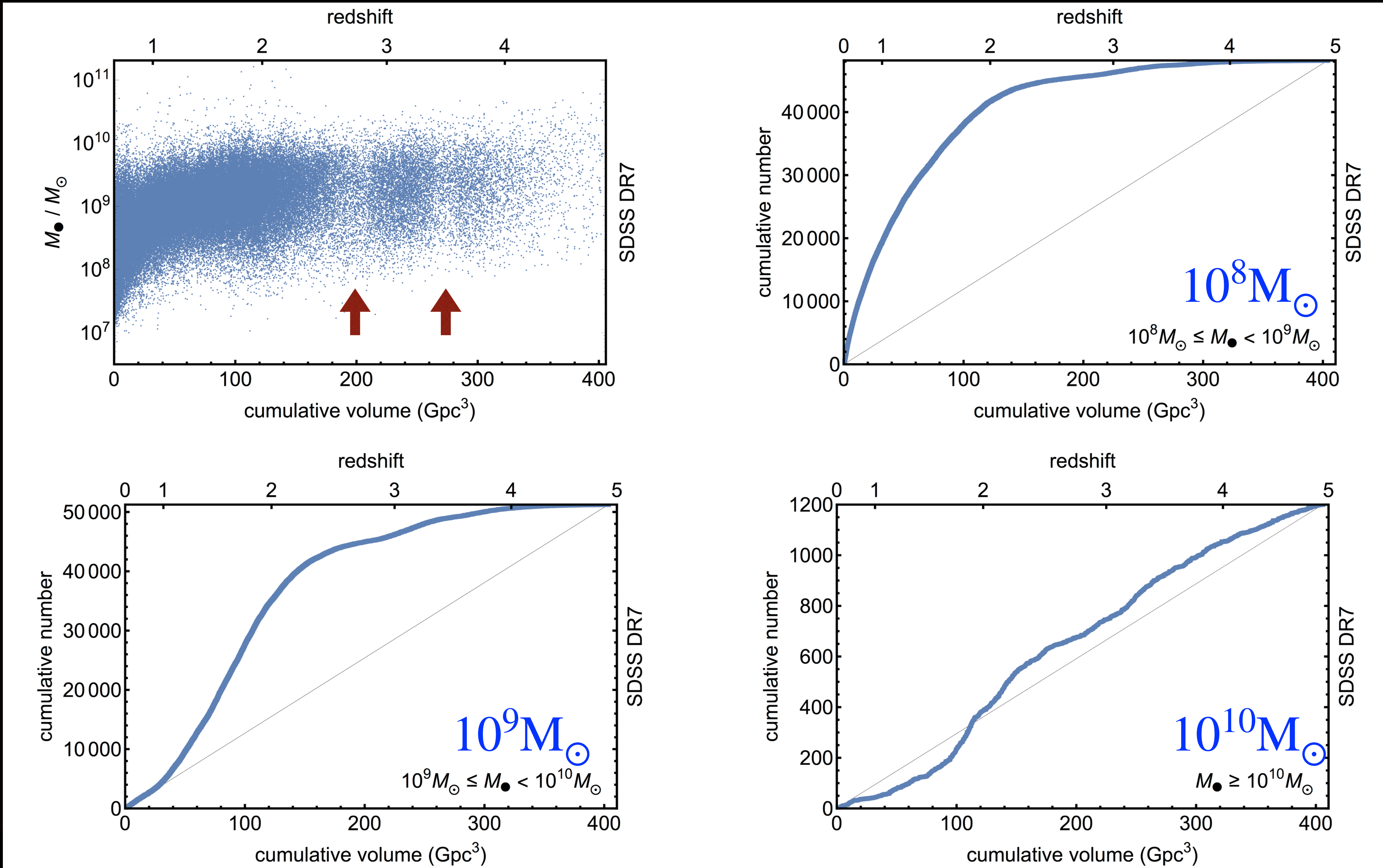
Farina et al. 2022

Individual QSO growth argument inconclusive as to whether this is a problem for the base ΛCDM model

due to uncertainty as to reasonable values for τ_{Salp}

can learn more about τ_{Salp} from QSO population dynamics

Slow evolution of most massive luminous BHs



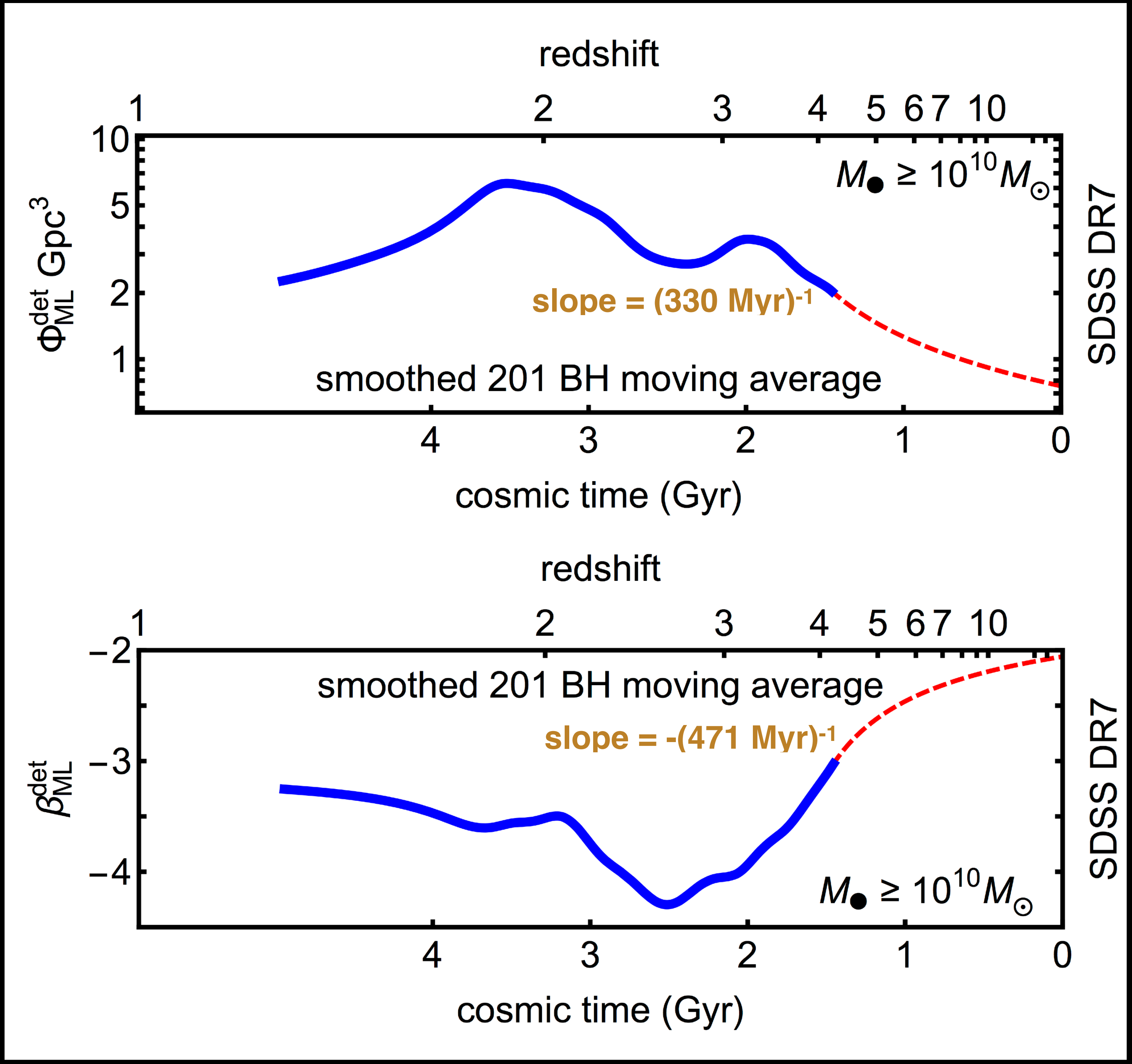
SDSS DR7

BH Population Dynamics

- Quasar distribution in luminosity redshift give clues for BH timescales
  - consider (toy) non-stochastic accretion only evolution: $\dot{M}[M]$
  - $\Psi[M,t] \equiv \dfrac{dn_{\rm co}}{d\ln M}$ cosmic time $\dfrac{dt}{dz} = \dfrac{1}{(1+z)\,H[z]}$
  - $\dfrac{\partial \Psi[M,t]}{\partial t} = -M\dfrac{\partial}{\partial M}\left(\dfrac{\dot{M}[M]}{M}\Psi[M,t]\right) = -M\dfrac{\partial}{\partial M}\left(\dfrac{\Psi[M,t]}{\tau[M]}\right)$
- closed form solution w/ initial condition $\Psi[M,t_0] = \Psi_0[M]$
  - $\Psi[M,t] = \dfrac{\tau[M]\,\Psi_0[\tilde{M}[M_1,\tilde{T}[M_1,M]-(t-t_0)]]}{\tau[\tilde{M}[M_1,\tilde{T}[M_1,M]-(t-t_0)]]}$, M_1 arbitrary
  - $\tilde{T}[M_1,M_2] \equiv \displaystyle\int_{M_1}^{M_2}\frac{dM}{M}\,\tau[M]$ with inverse $\tilde{M}[M_1,\tilde{T}[M_1,M_2]] = M_2$

*for compactness subscripts are dropped here

$t = 0$ extrapolation of $M_{BH} > 10^{10}\, M_\odot$ population



$$\beta \equiv \frac{\partial \ln \Psi}{\partial \ln M_{BH}} \to -2.05$$

$$\tau_{Salp} \to 805\,\mathrm{Myr}\left(\frac{M_{BH}}{10^{10}\,M_\odot}\right)^{1.6}$$

$$\int_{10^{10} M_\odot}^{\infty} \frac{dM}{M}\Psi \to \frac{0.76}{\mathrm{Gpc}^3}\left(\frac{M_{BH}}{10^{10}\,M_\odot}\right)^{-1.05}$$

- extrapolates to extremely massive extremely rare SMBHs in early universe!
- extending to smaller masses
- “point defect” type of non-Gausianity

QSO flickering

- SMBHs not always bright enough to be seen as QSOs or AGNs
  - sometimes $\lambda_{\rm Edd} \ll 1$ (for most SMBHs in late universe $z \lesssim 1$)
  - model: flicker on (duty cycle $f_{\rm on}$) and off (duty cycle $1 - f_{\rm on}$)
  - caused by interruptions in gas supply for accretion
- large fraction of unseen SMBHs modifies population dynamics
  - $\tau_{\rm Salp}^{\rm effective} \to \dfrac{\tau_{\rm Salp}}{f_{\rm duty}}$ $f_{\rm duty}$ time varying in uncontrolled way
  - contributes to slow evolution
  - hard to quantify

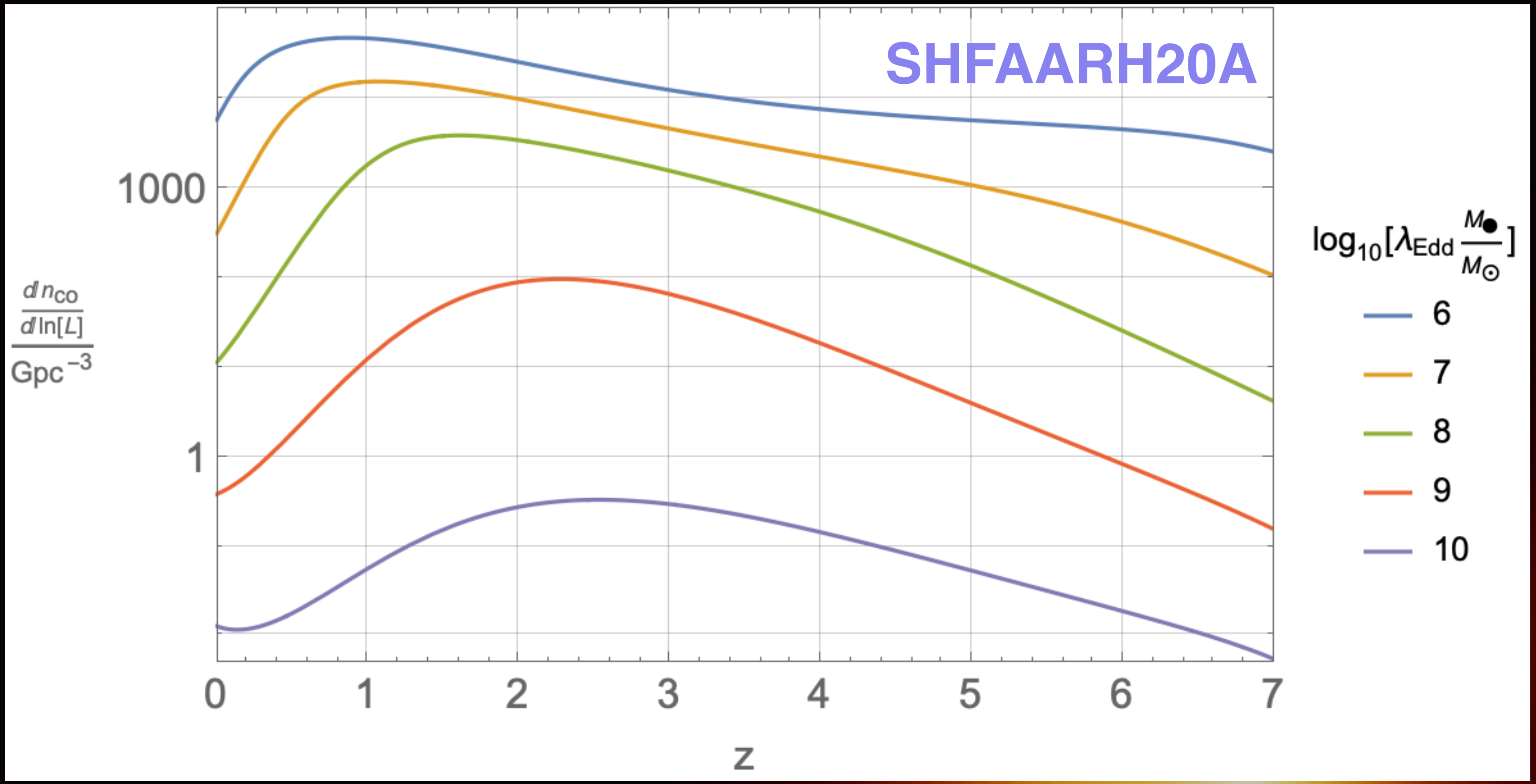
Nord Stream
Secure gas supply for Europe

QSO surveys now extend to higher z

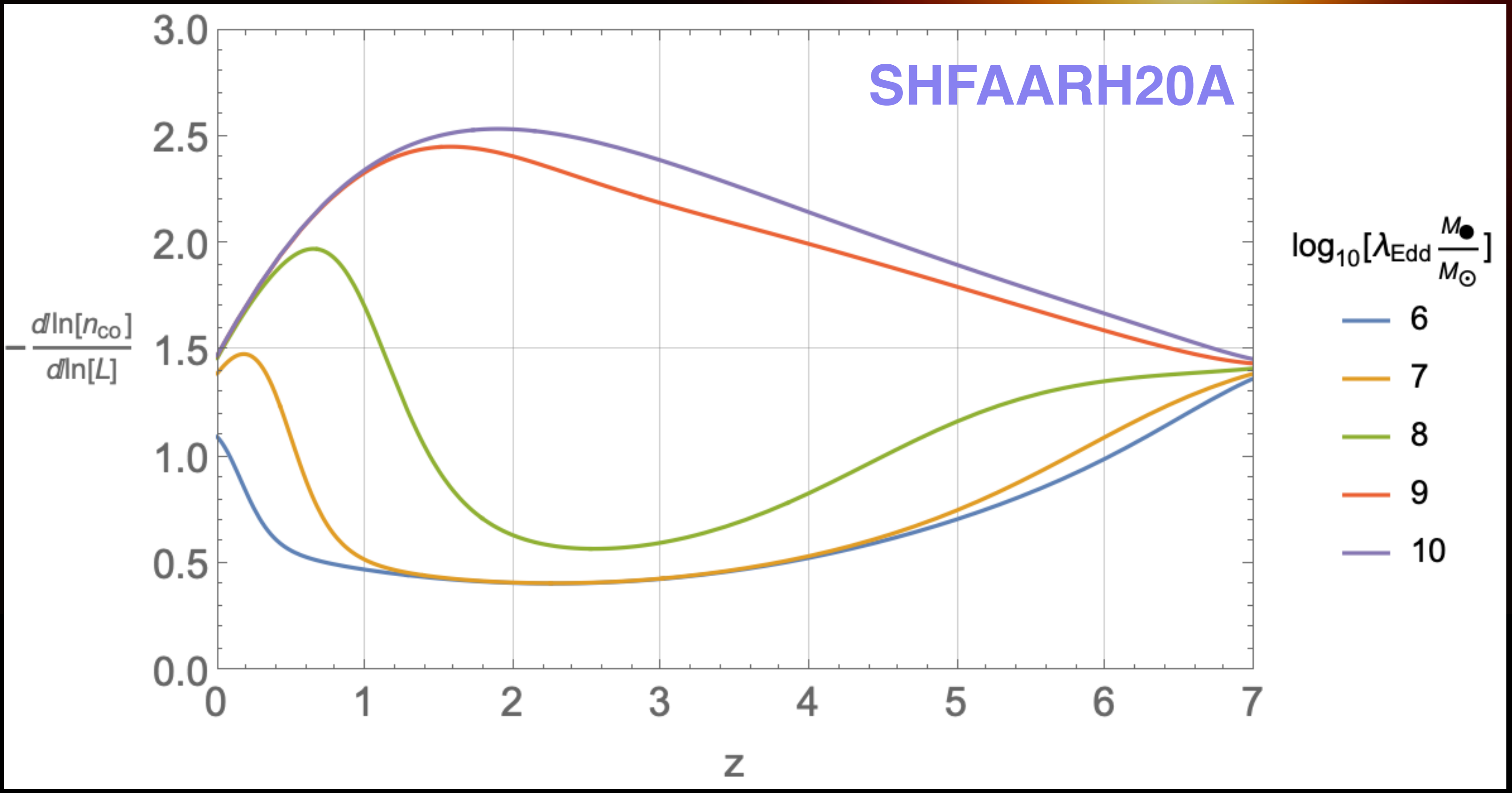
- **Shen et al. 2020 (SHFAARH20)**
- 10 or 11 parameter fit of QSO luminosity function $0 < z < 7$
- $$\Phi[L, z] = \frac{2\,\Phi_*[z]}{\left(\frac{L}{L_\star[z]}\right)^{\gamma_1[z]} + \left(\frac{L}{L_\star[z]}\right)^{\gamma_2[z]}}$$
- model A: $\gamma_1[z] = \tilde{a}_0 + \tilde{a}_1\, z + \tilde{a}_2\, z^2$ / model B: $\gamma_1[z] = a_0 \left(\frac{1+z}{3}\right)^{a_1}$
- $$\gamma_2[z] = \frac{2\, b_0}{\left(\frac{1+z}{3}\right)^{b_1} + \left(\frac{1+z}{3}\right)^{b_2}}$$
- $$\log_{10}\left[\frac{L_*[z]}{L_\odot}\right] = \frac{2\, c_0}{\left(\frac{1+z}{3}\right)^{c_1} + \left(\frac{1+z}{3}\right)^{c_2}}$$
- $\log_{10}\left[\mathrm{Mpc}^3\, \Phi_*[z]\right] = \tilde{d}_0 + \tilde{d}_1\, z$

- hi-z functional form “biased” by lo-z observations - much extrapolation

QSO evolution speeds up at hi-z



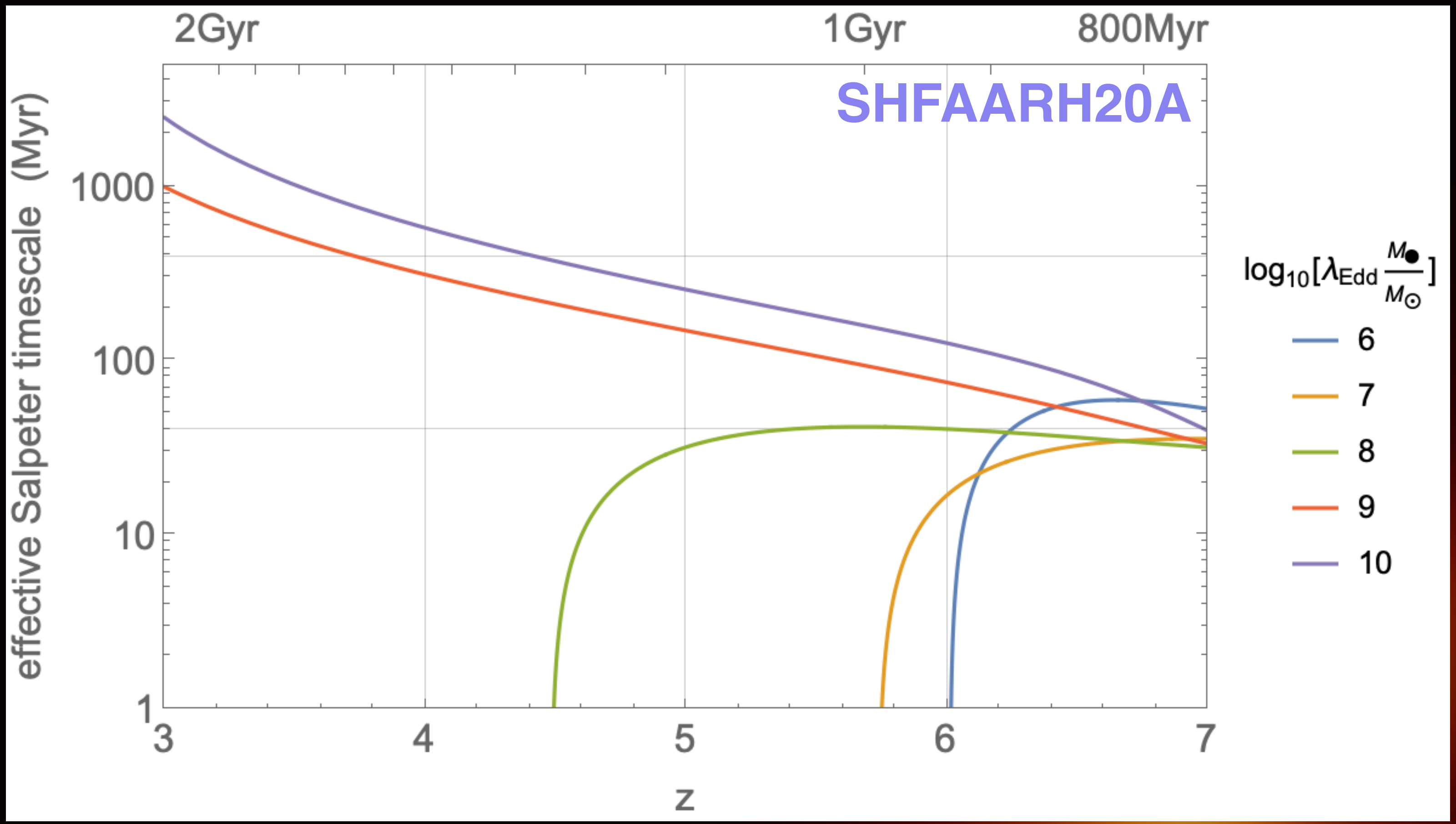
from $z = 5$ to 7 number of $M_{BH} \sim 10^{10}\,M_\odot$ falls by order of magnitude



luminosity function slope flattens to $\beta \approx -1.5$ for over entire mass range

not for small mass in model B

evolution timescale attains canonical value



$\tau_{\rm Salp}^{\rm effective} \approx 40 - 50\,{\rm Myr}$ (canonical value!) at $z = 7$ in this model fit for all $M_{\rm BH}$

gas supply secure for $z > 7$ - no flickering (?)

This evolution timescale is not fast enough to easily explain the most massive early SMBHs from population III stars!

Should we (PNG) declare victory and go home?
No!

- evolution timescale may continue to decrease
- SHFAARH20 fit suspect - data still too sparse

my take

- there is still room for very large black hole seeds from the early universe
- however, whether the existence of early high mass SMBHs is problematic in any sense has not been empirically established
  - quasar observations are only now getting into a redshift regime where we might or might not see fast exponential growth of SMBH populations
- while $\epsilon_{\rm rad} \approx 0.1$ is well motivated by accretion disk theory how certain are we that in very rare cases that it might, sustainably, be 30-40% smaller
  - in rare regions of very low angular momentum gas?
  - can PNG make this more common?