Modeling the BH-Galaxy Connection over Cosmic Time

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Are AGN Special?

Semi-Analytic Models (SAMs) can self-consistently and rapidly produce a suite of different observables (e.g., Cole+1994, Volonteri+2003, Somerville+2008, Makiya+2016, Croton+2016, **Ricarte & Natarajan 2018**).

One realization of the universe going to 5 x 10^6 solar mass halos at z=20 takes ~20/number of cores hours.

What makes an AGN "special" is explicitly coded in.

Accretion: Ricarte & Natarajan (2018)

Seeding: Ricarte & Natarajan (in review)

How did SMBHs Assemble Their Masses?

Local relations set a boundary condition.

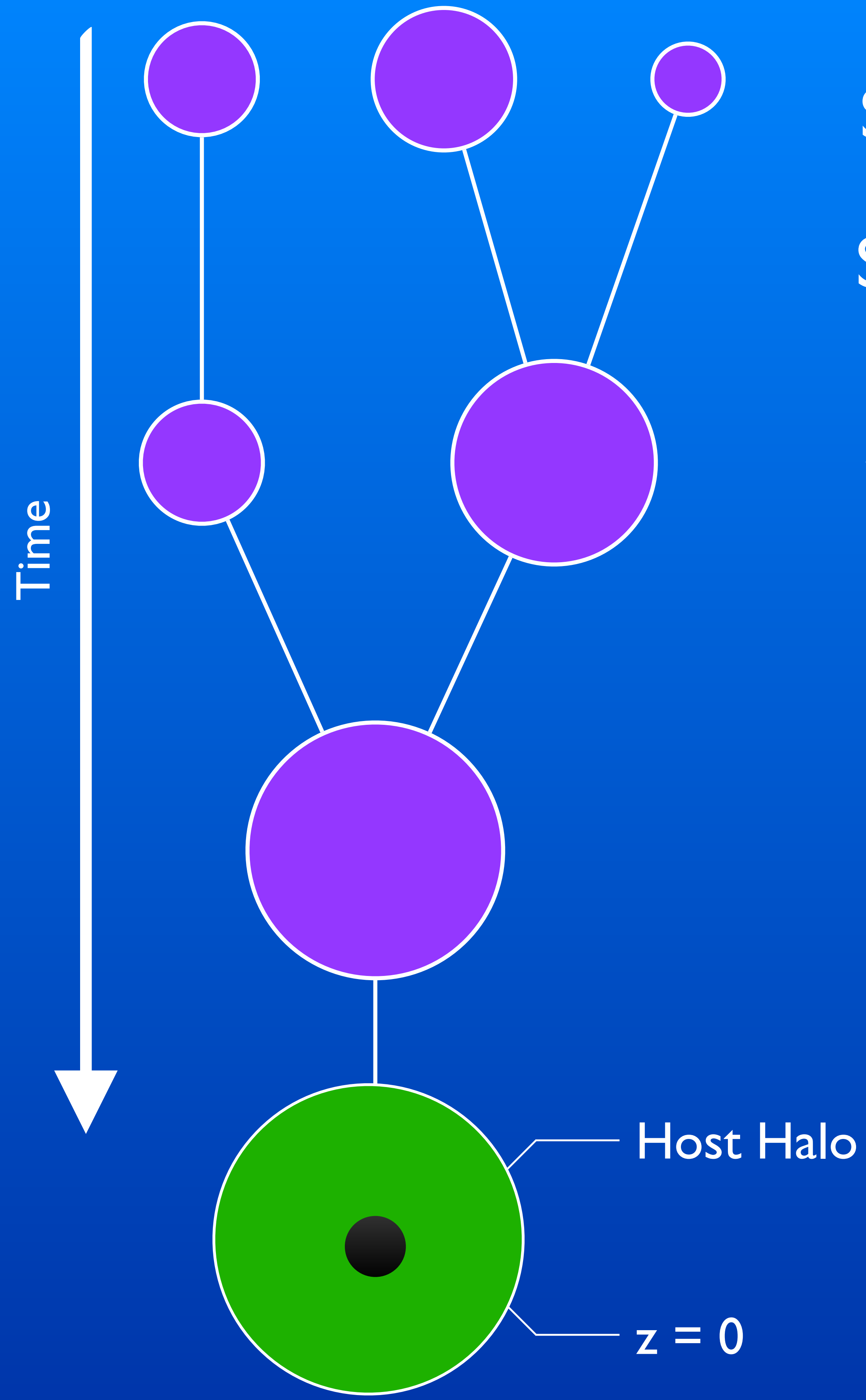
$$\log(M_\bullet/M_\odot) = \alpha + \beta \log(\sigma/200 \text{ km s}^{-1})$$

For example, 8.32 5.35 (van den Bosch 2016)

Luminosity functions tell you about the rate of change.

$$\Phi(L_\bullet, z) = \frac{d^2 N}{dV\, d\log L_\bullet} \qquad L_\bullet \approx 0.1 \dot{M}_\bullet c^2$$

LCDM gives us the framework.



Step 1: Generate a Merger Tree

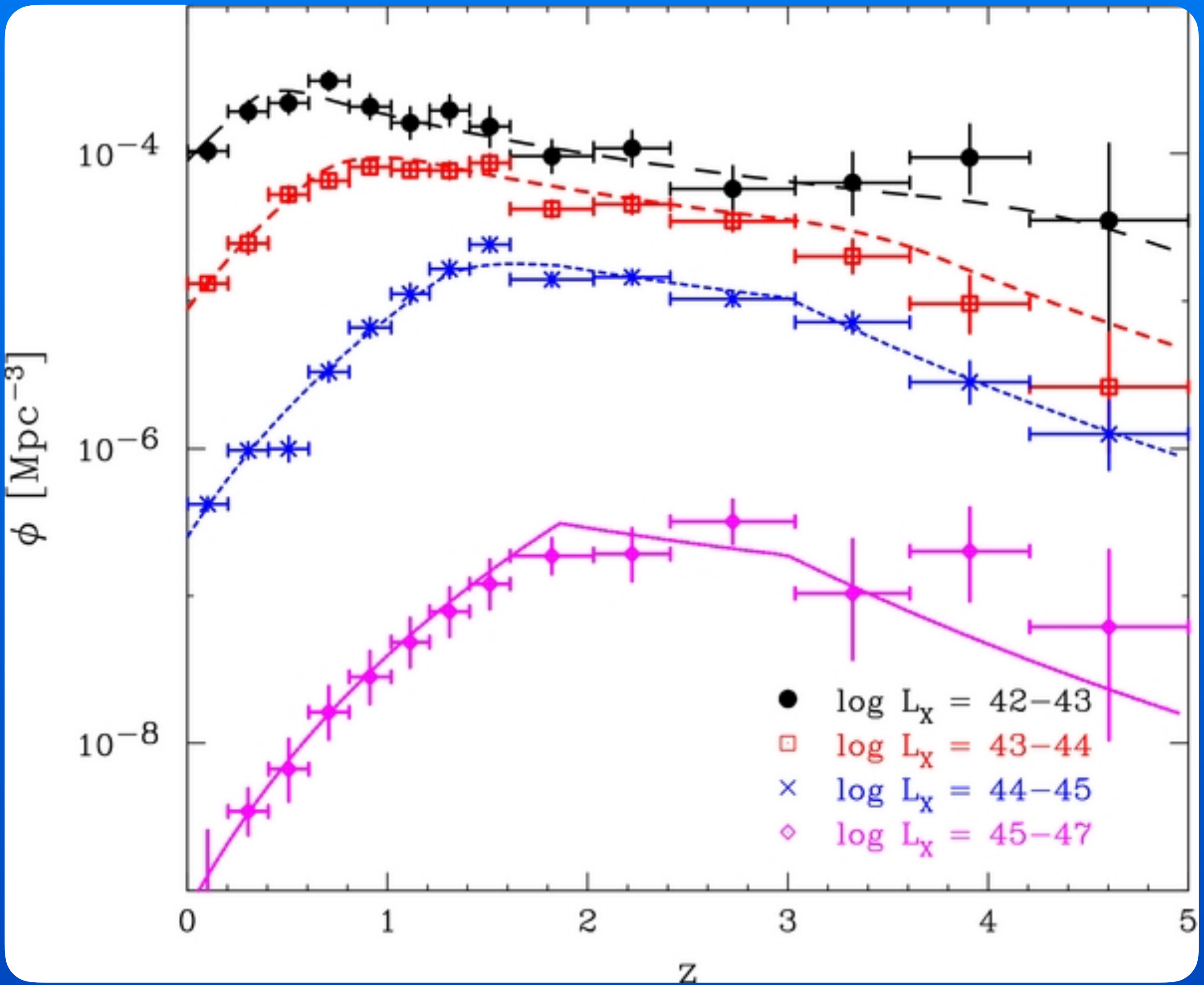
Step 2: Seeding: Heavy or Light?

At each time step, if a major merger occurs,

- A quasar turns on until the SMBH blows away its gas supply (M-sigma).
- Halos merge after a dynamical friction timescale, and their SMBHs may also merge.

Repeat for **20** halo masses, **15** times each

AGN Cannot Be *Completely* Random



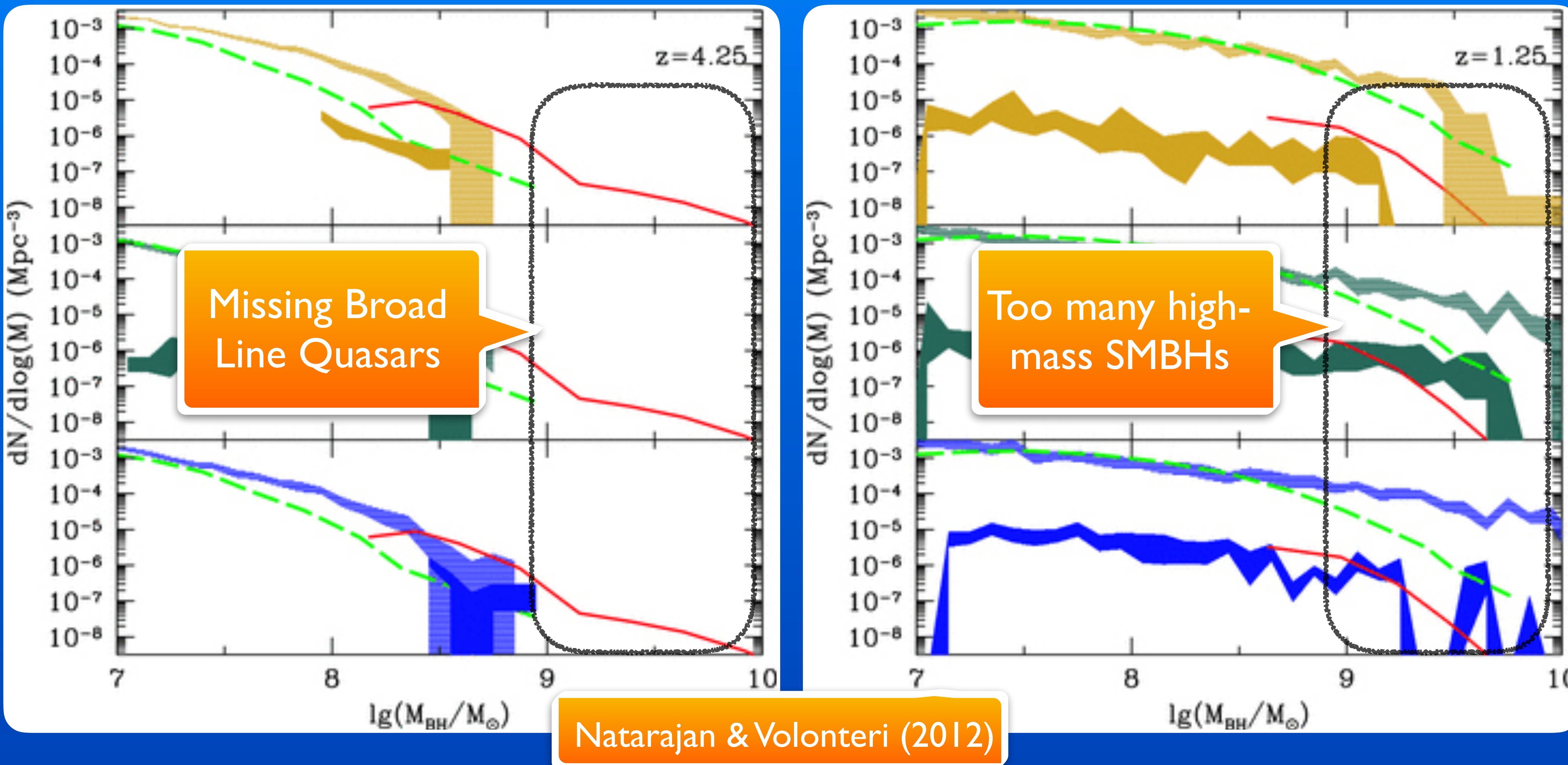
Ueda et al., (2014)

Downsizing: More luminous AGN peak at earlier epochs.

The maximum SMBH mass is ~10^{10} solar masses from $0<z<6$ (e.g., Wu+2015).

If Eddington ratios were *always* drawn randomly from a universal distribution, this could not happen.

SAMs have Struggled at High Mass

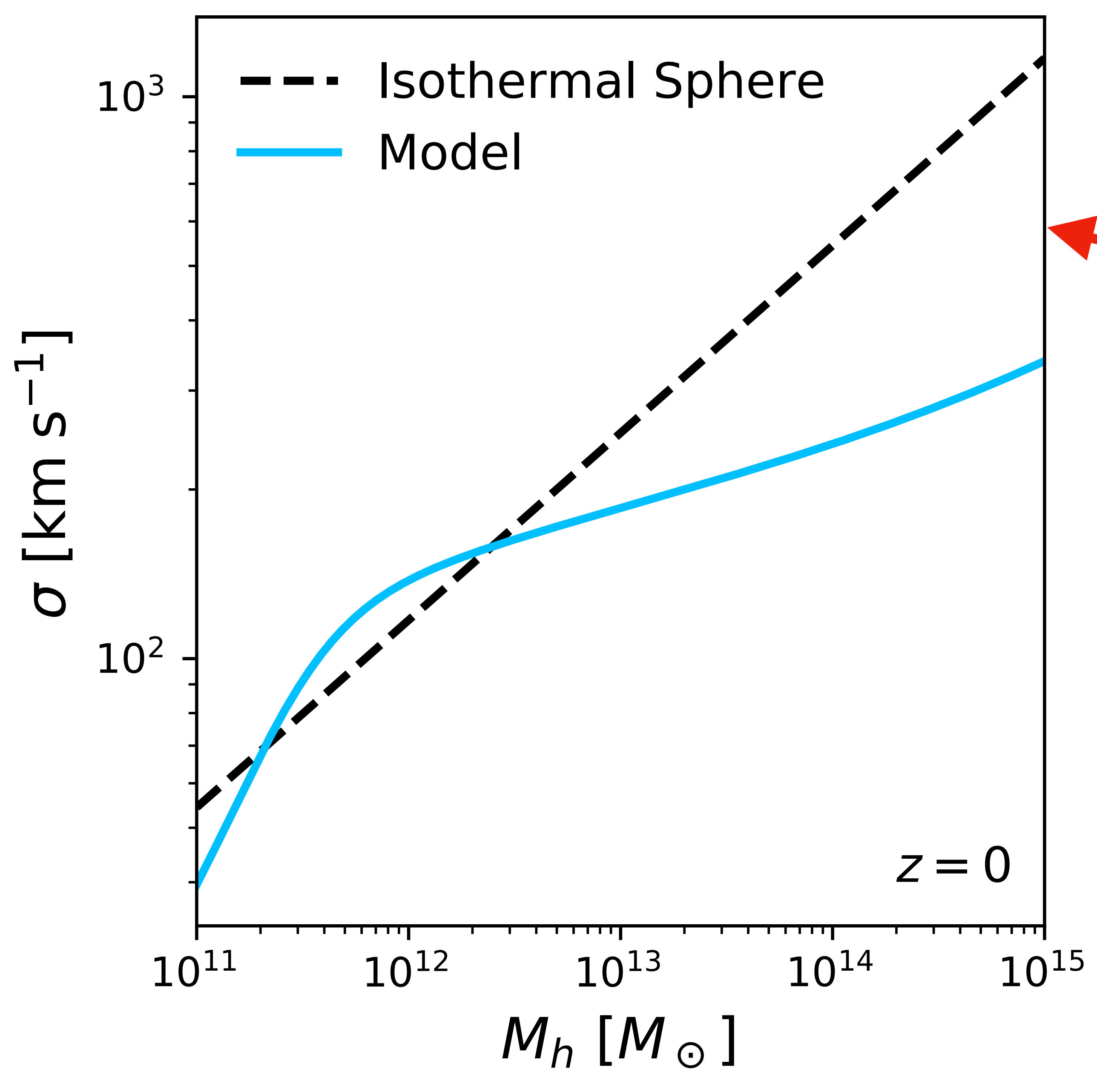


— Straight Lines: Observations

■ Filled Regions: SAM

Each row uses different recipes for seeding and accretion.

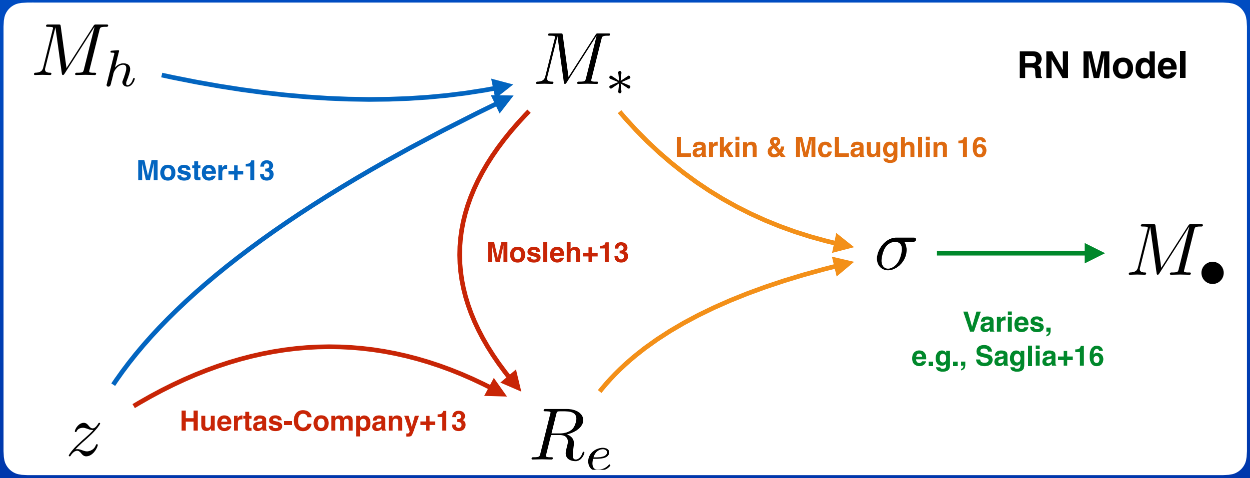
Improving the SMBH-Galaxy Connection



A discrepancy here gets raised to the 4th or 5th power!

$$\log M_{\bullet,\mathrm{cap}} = \alpha + \beta \log\left(\frac{\sigma}{200\ \mathrm{km\ s^{-1}}}\right)$$

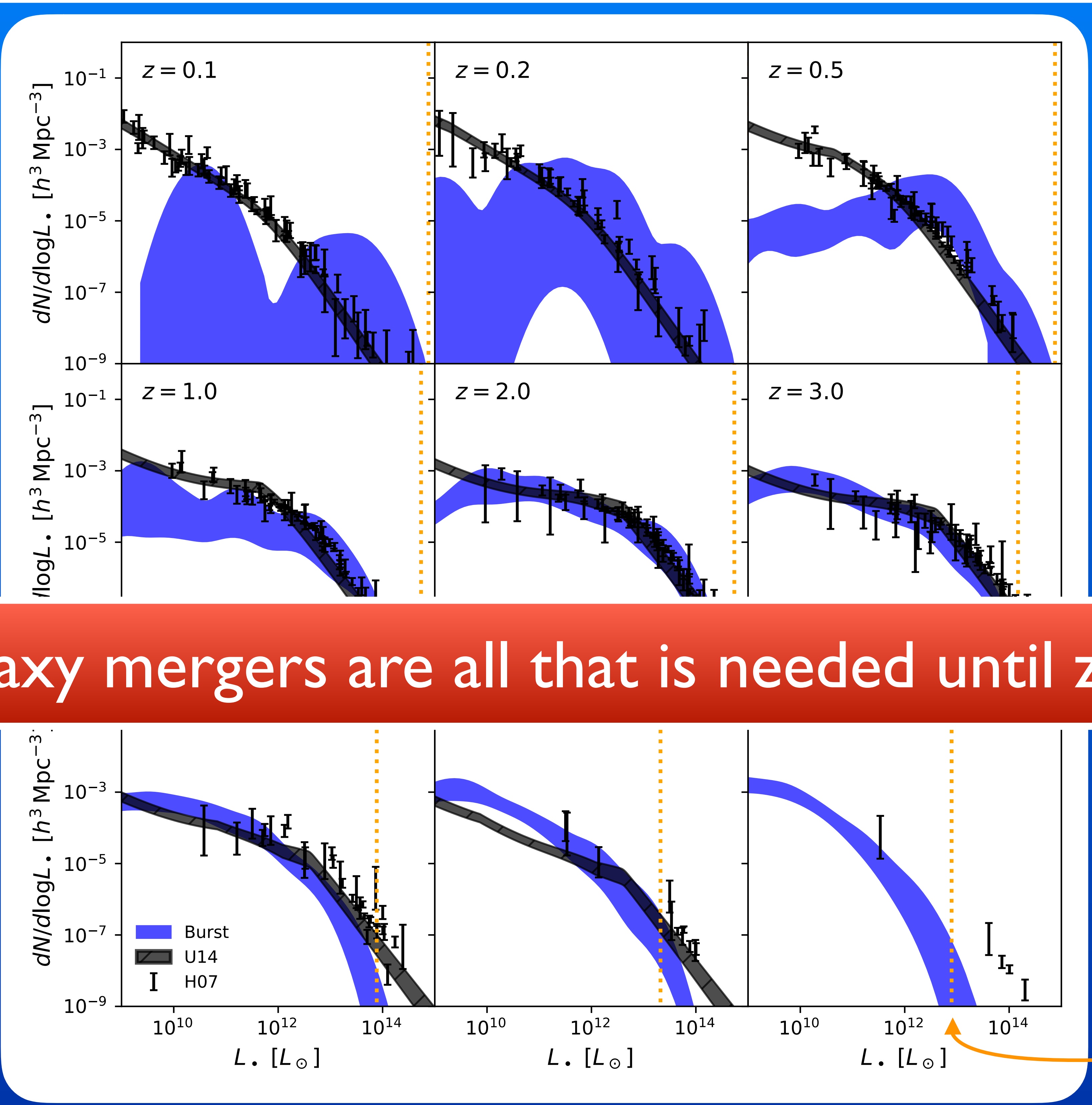
Tuned: 8.45 5



Ricarte & Natarajan (2018)

Luminosity Functions: Bursts Only

2 free parameters:
burst mode
normalization and slope



Galaxy mergers are all that is needed until z<2.

Not enough high-mass halos past here.

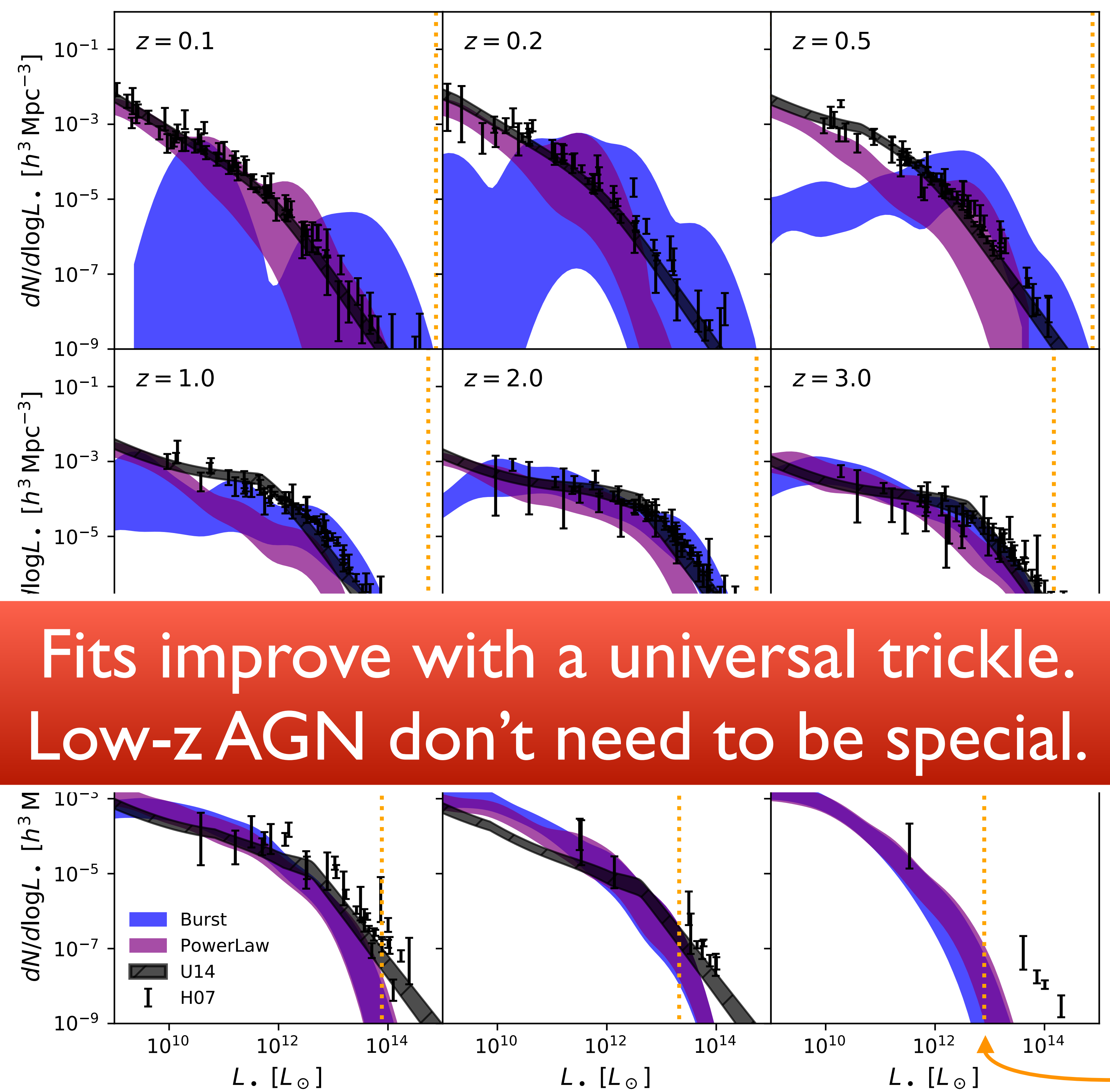
Data

Ueda et al., (2014)

Hopkins et al., (2007)

Luminosity Functions: Add Steady Mode

4 free parameters: burst mode normalization and slope, universal ERDF cutoff and slope



Fits improve with a universal trickle.
Low-z AGN don't need to be special.

Not enough high-mass halos past here.

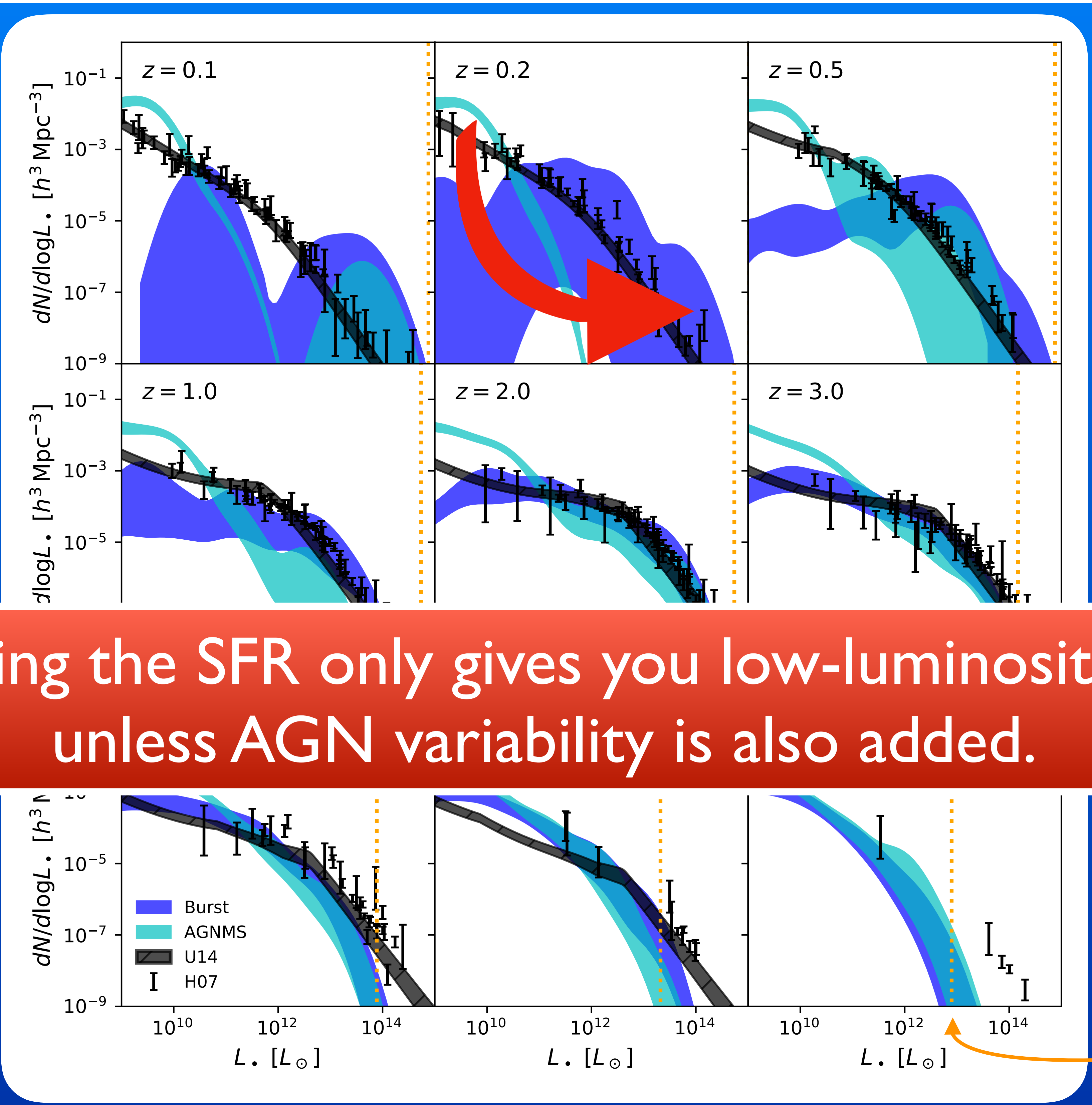
Data

Ueda et al., (2014)

Hopkins et al., (2007)

Luminosity Functions: Burst + AGNMS

3 free parameters: burst mode normalization and slope, BHAR/SFR



Following the SFR only gives you low-luminosity AGN unless AGN variability is also added.

Not enough high-mass halos past here.

Data

Ueda et al., (2014)

Hopkins et al., (2007)

Light Seeds (Pop III Remnants)

- Higher Abundance
- Lower Mass (~100 solar masses)

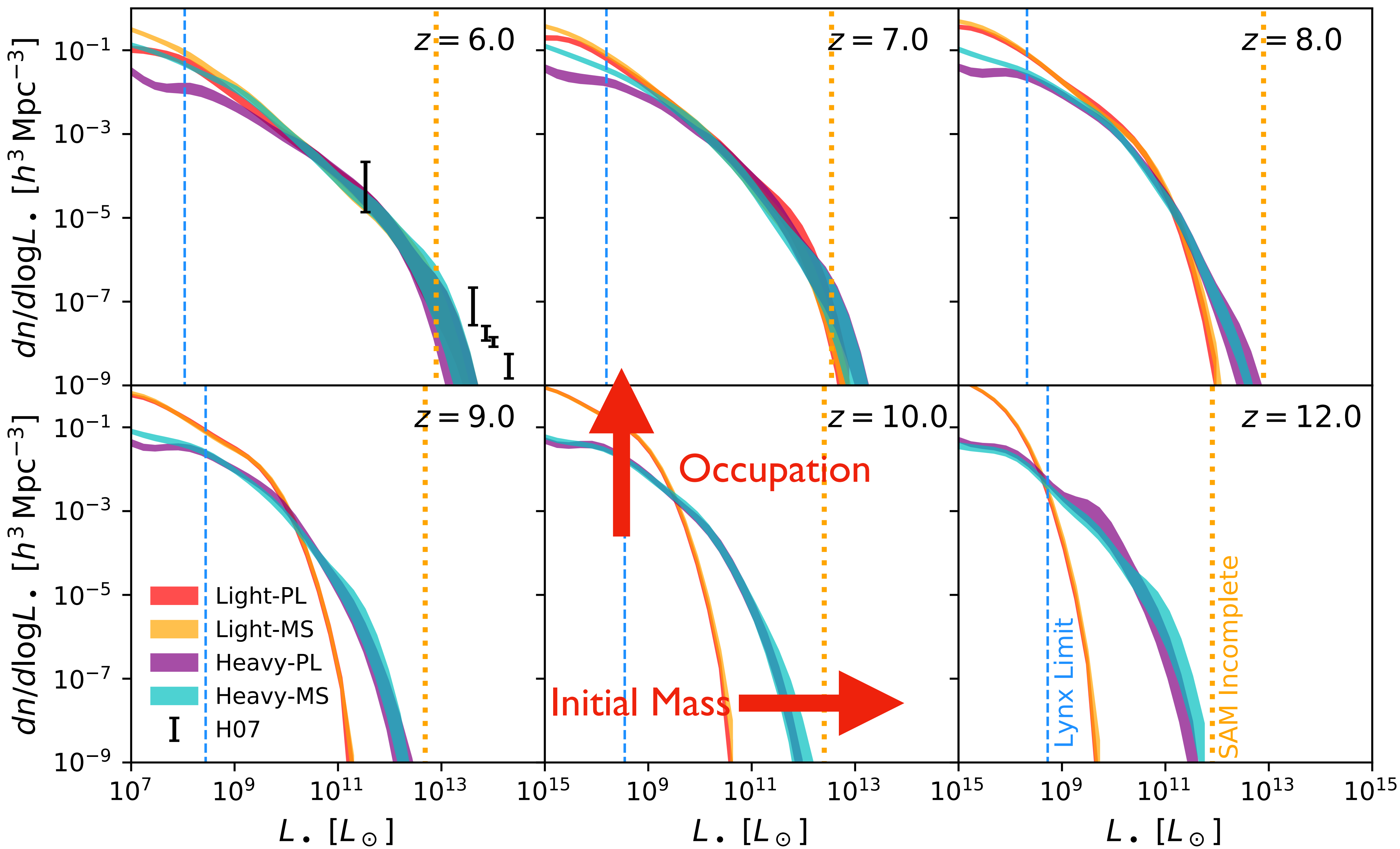
Draw from an IMF; (Stacy+2016)

Heavy Seeds (Direct Collapse)

- Lower Abundance
- Higher Mass (~10^5 solar masses)

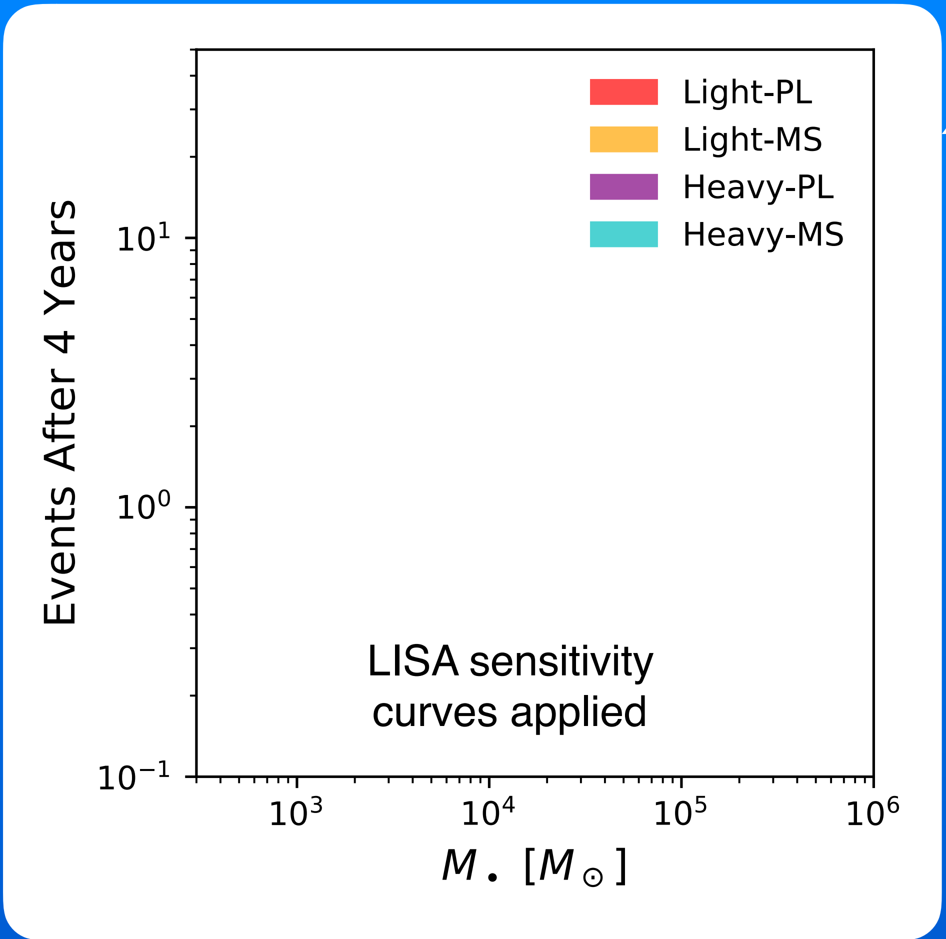
Mass depends on virial temperature and spin (Lodato & Natarajan 2006,2007).

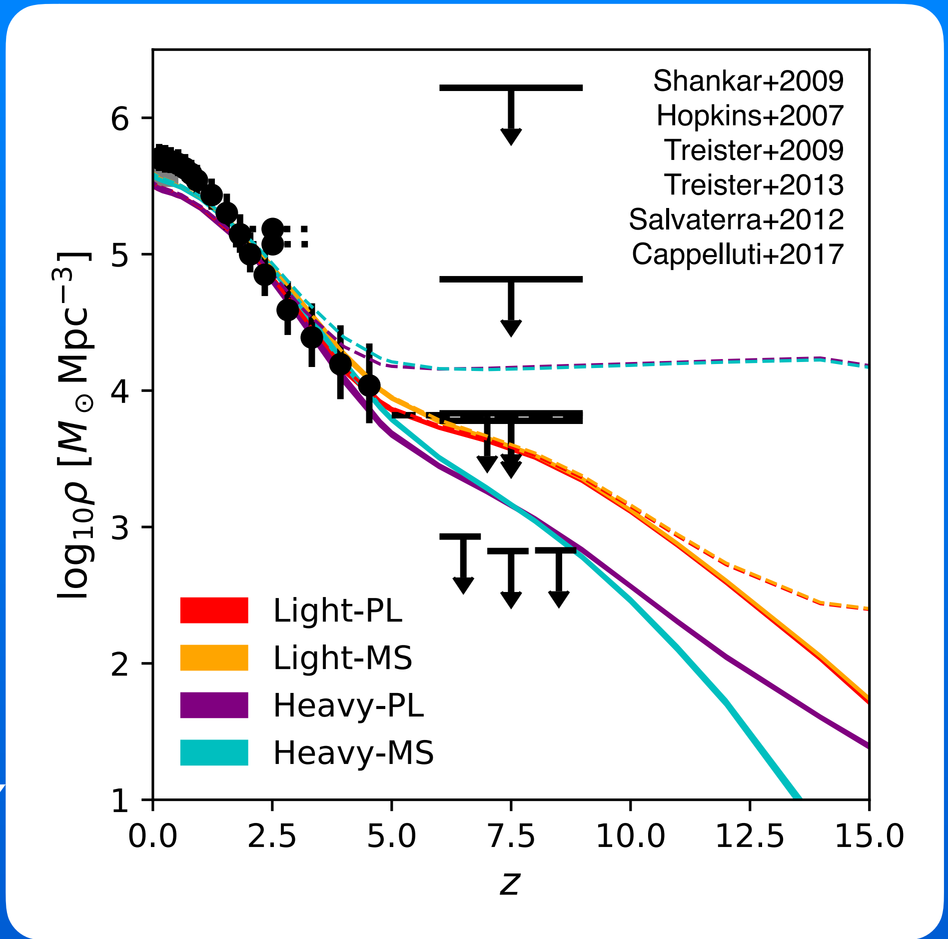
Next-generation Luminosity Functions



A Lynx deep field would tell us about seeding + accretion.

Ricarte & Natarajan (in review)





<u>Gravitational Wave Masses</u>

Seeding, Dynamics, (accretion)

<u>Cosmic Backgrounds</u>

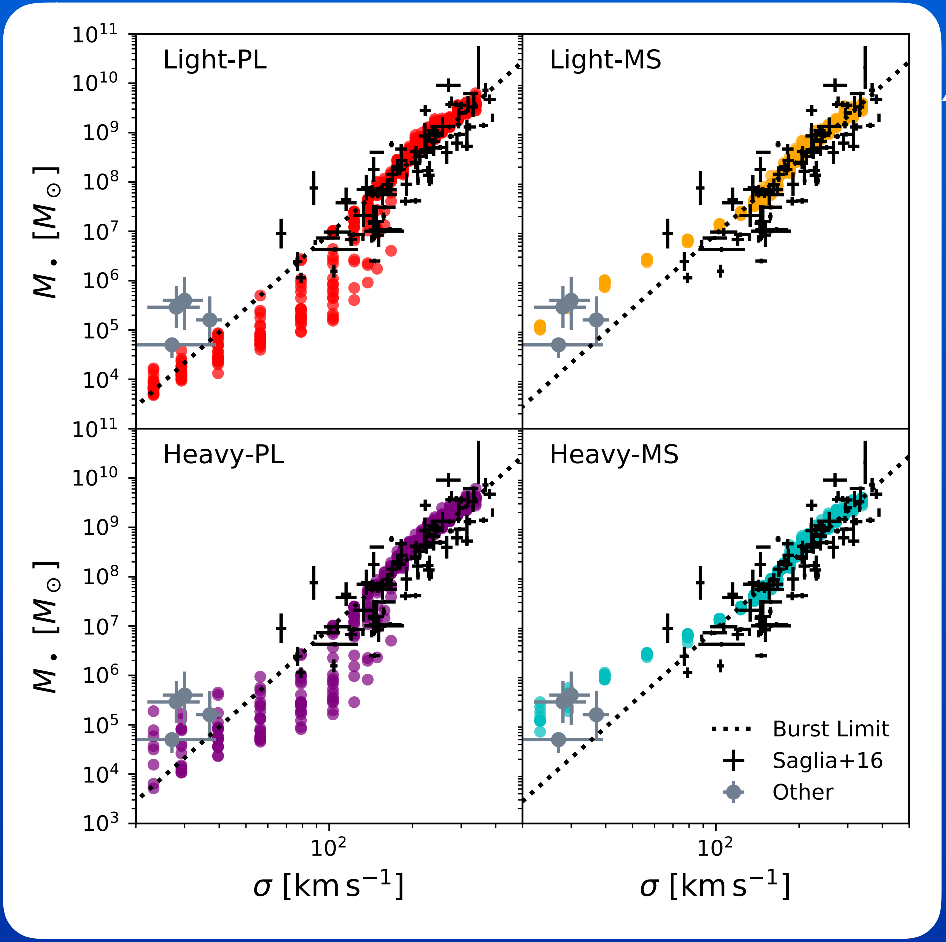
Accretion, Seeding

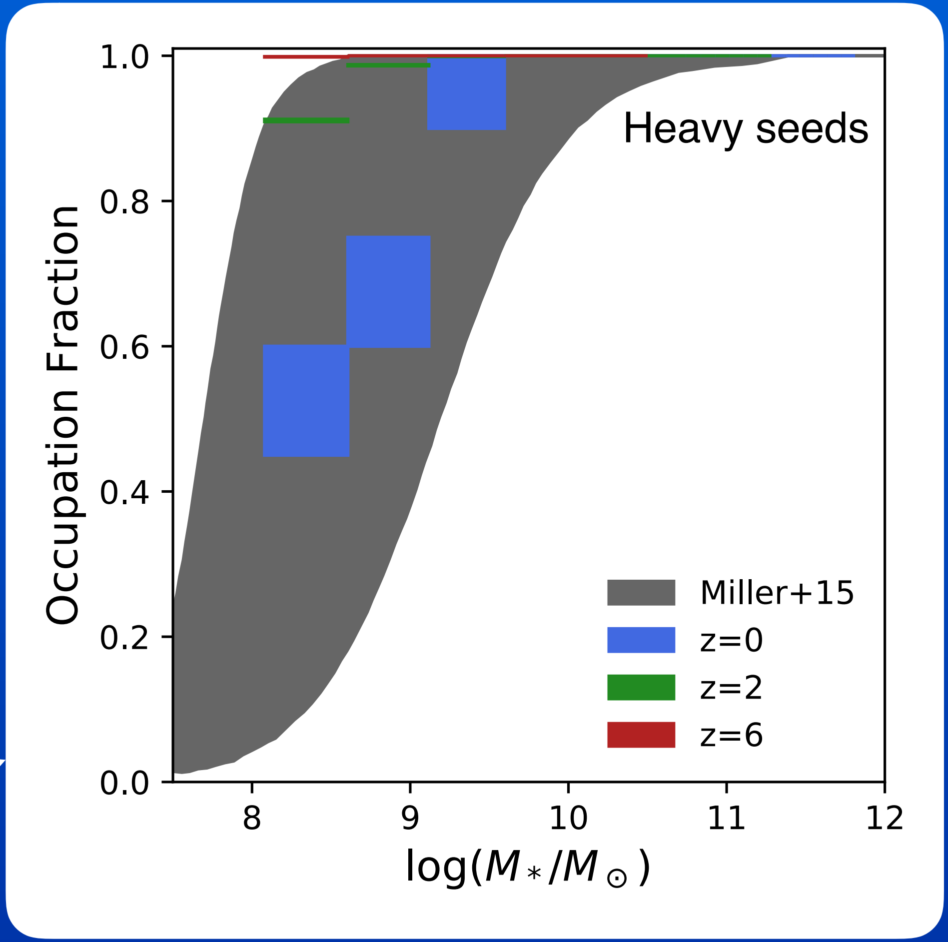
<u>Local M-sigma</u>

Accretion, (dynamics, seeding)

<u>Local Occupation Fraction</u>

Seeding, (dynamics)





Conclusions

Semi-analytic models allow us to rapidly make predictions for many different observables while testing different prescriptions for black hole assembly.

- Galaxy mergers + Eddington limited accretion can explain SMBH growth for $z>2$.
- If SMBH accretion is tied to the star formation rate, AGN variability must be invoked to explain high-L AGN.
- Signatures of SMBH seeding may become noticeable soon past our current redshift frontier. SAMs can break degeneracies.

Think AGN are special? Let me know what to test!