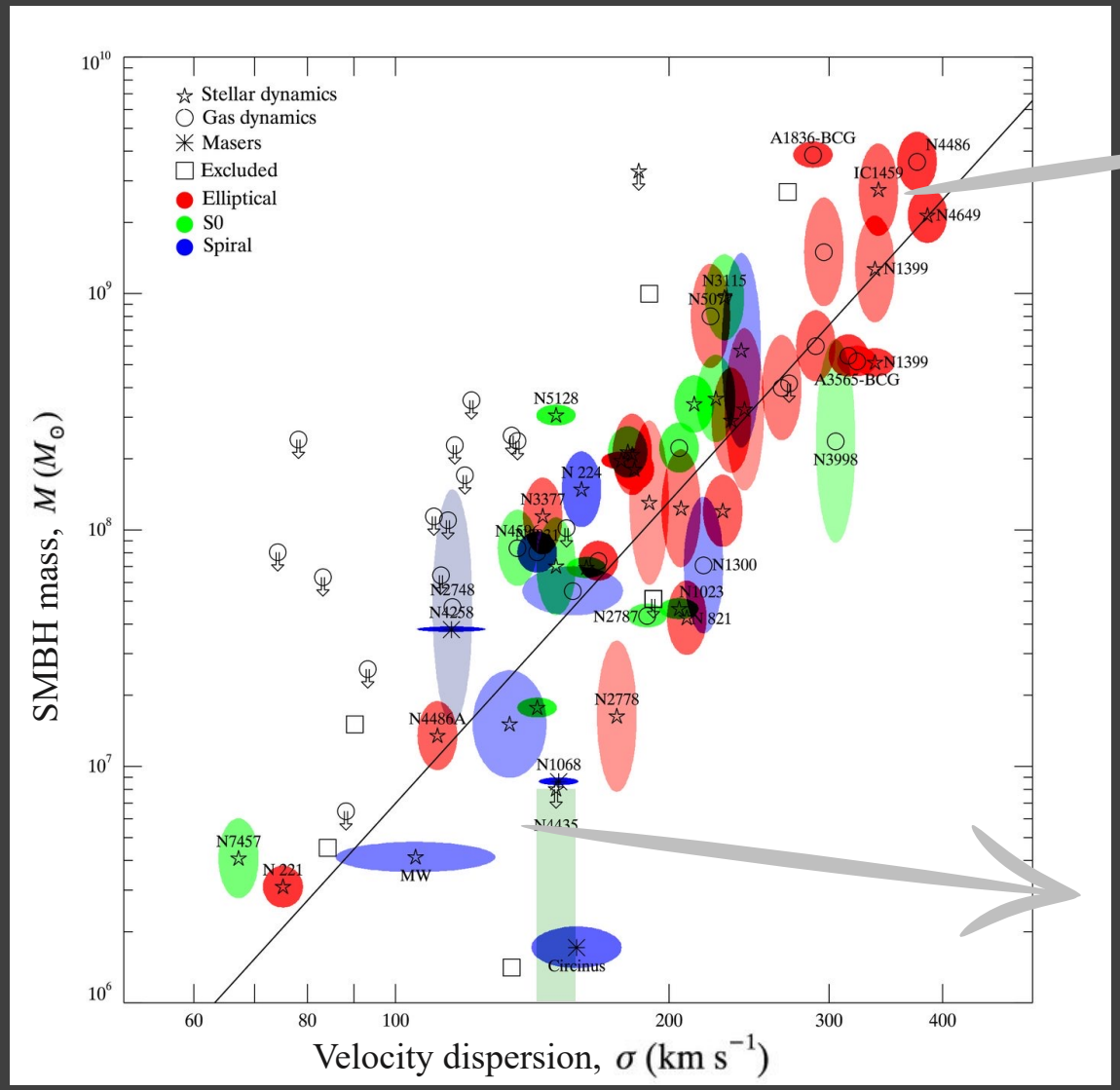
Universiteit Leiden
Leiden Observatory

Elia Pizzati
with Joe Hennawi, Joop Schaye
Matthieu Schaller, Christina Eilers
Feige Wang, Jiamu Huang, and JT Schindler

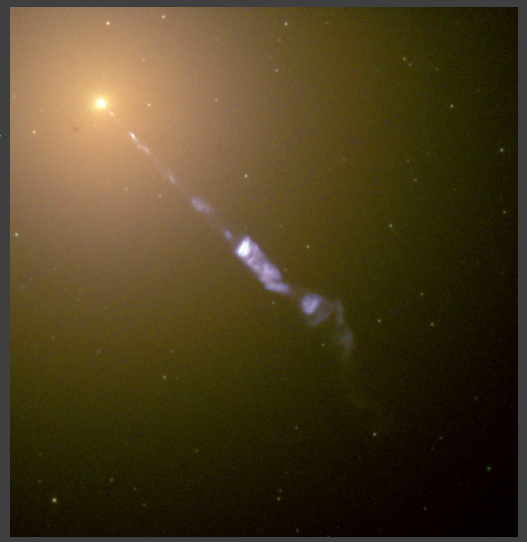
Tracing the Growth and Evolution of Supermassive Black Holes with High-z Quasar Clustering Measurements

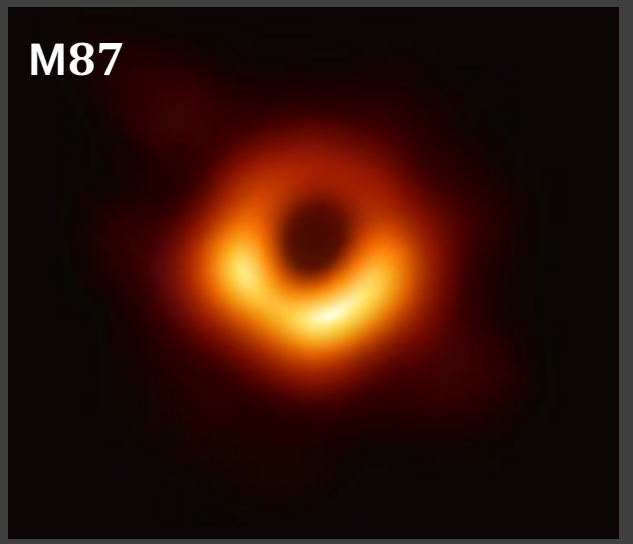
Image credits:
FLAMINGO simulation (Schaye+23)

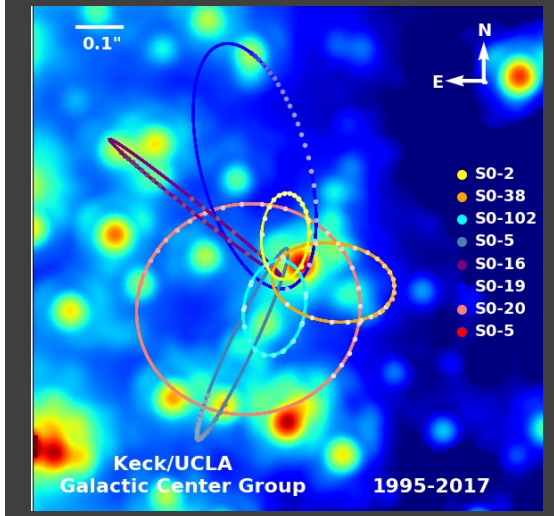
Supermassive black holes in the local universe...



Gultekin+09







Credits: EHT Collaboration

…quasars/AGN at cosmological scales

Galactic Nuclei as Collapsed Old Quasars

by

D. LYNDEN-BELL
Royal Greenwich Observatory,
Herstmonceux Castle, Sussex

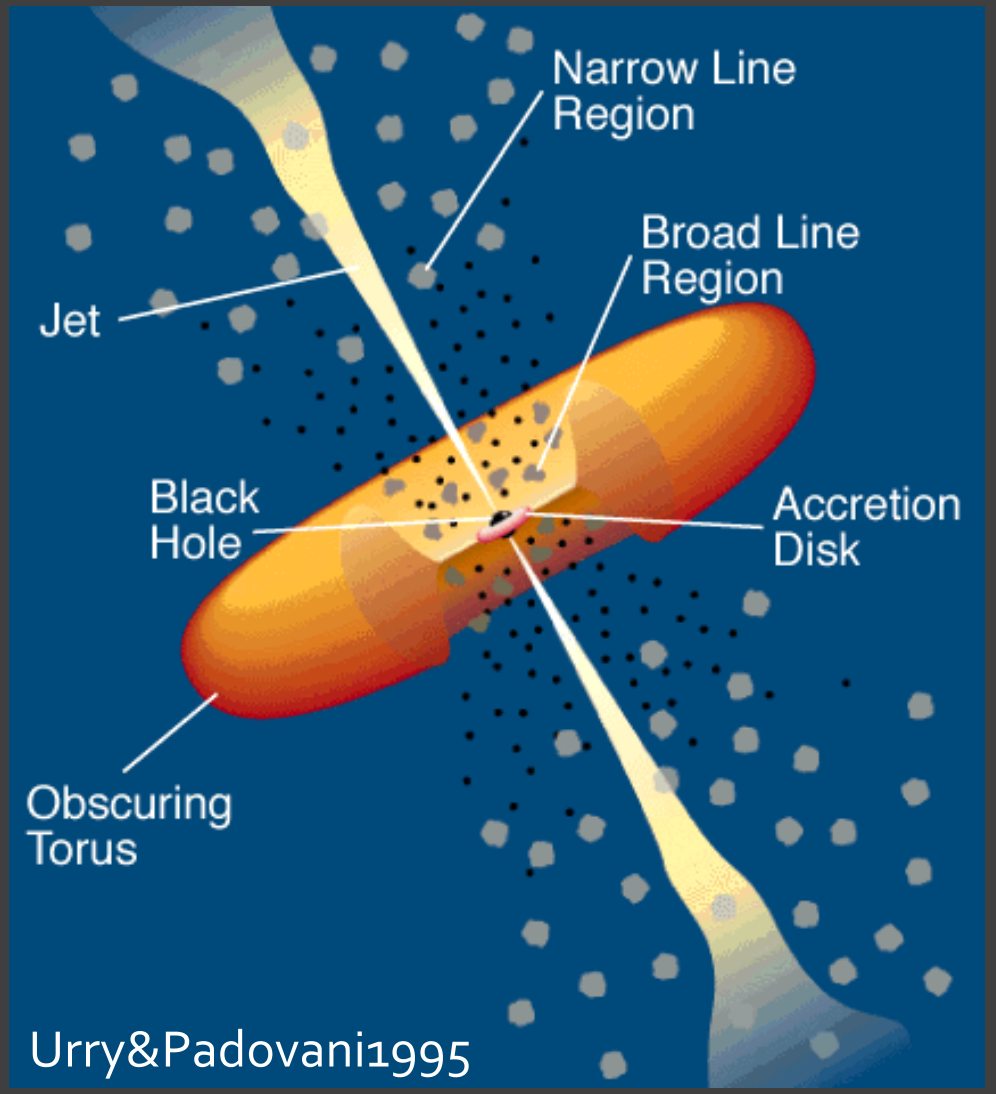
Powerful emissions from the centres of nearby galaxies may represent dead quasars.

Gas accreting on a SMBH ***radiates away*** a ***fraction*** of its rest-frame energy:

$$L = \varepsilon \dot{M} c^2 \qquad \varepsilon \sim 0.1 - 0.3$$

The remaining fraction ***grow*** the SMBH:

$$\dot{M}_{BH} = \frac{1-\varepsilon}{\varepsilon c^2} L$$



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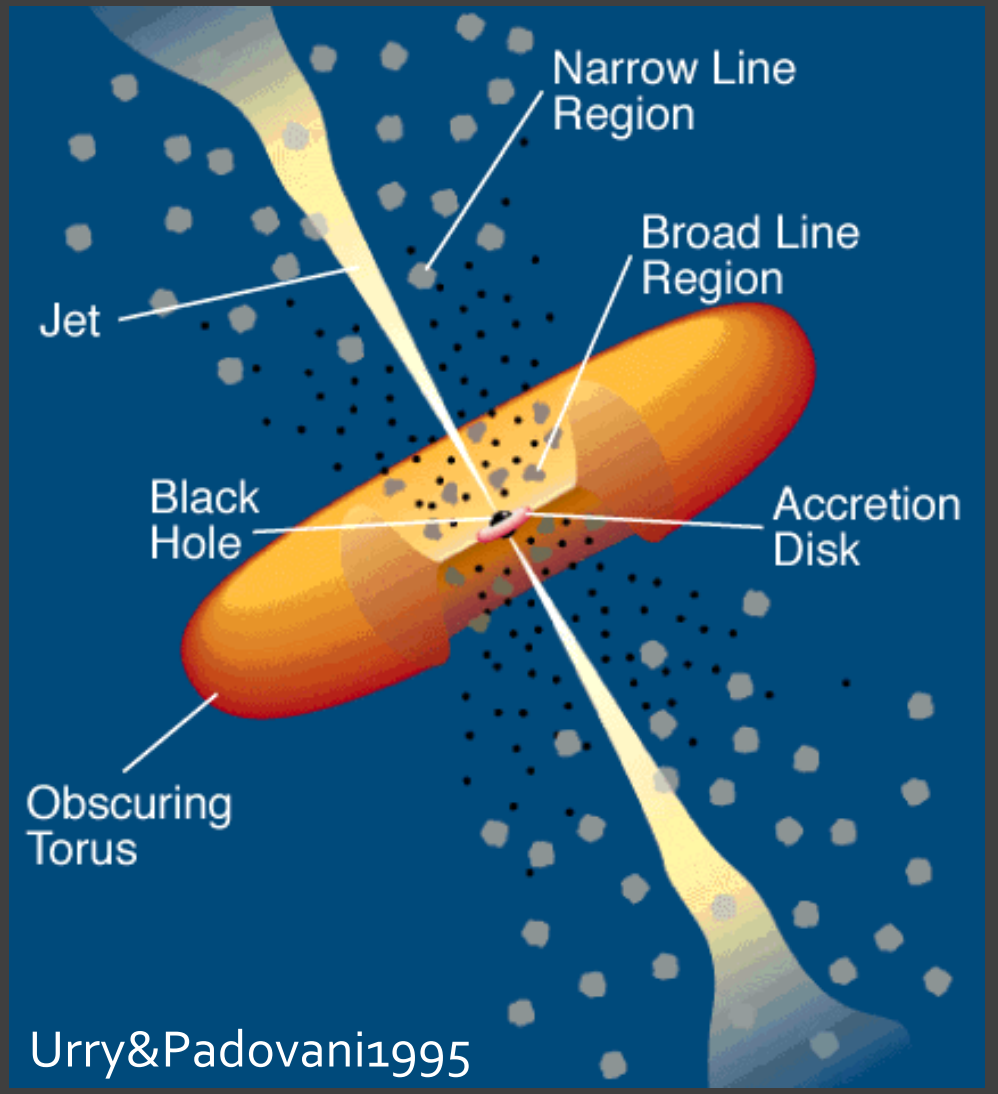
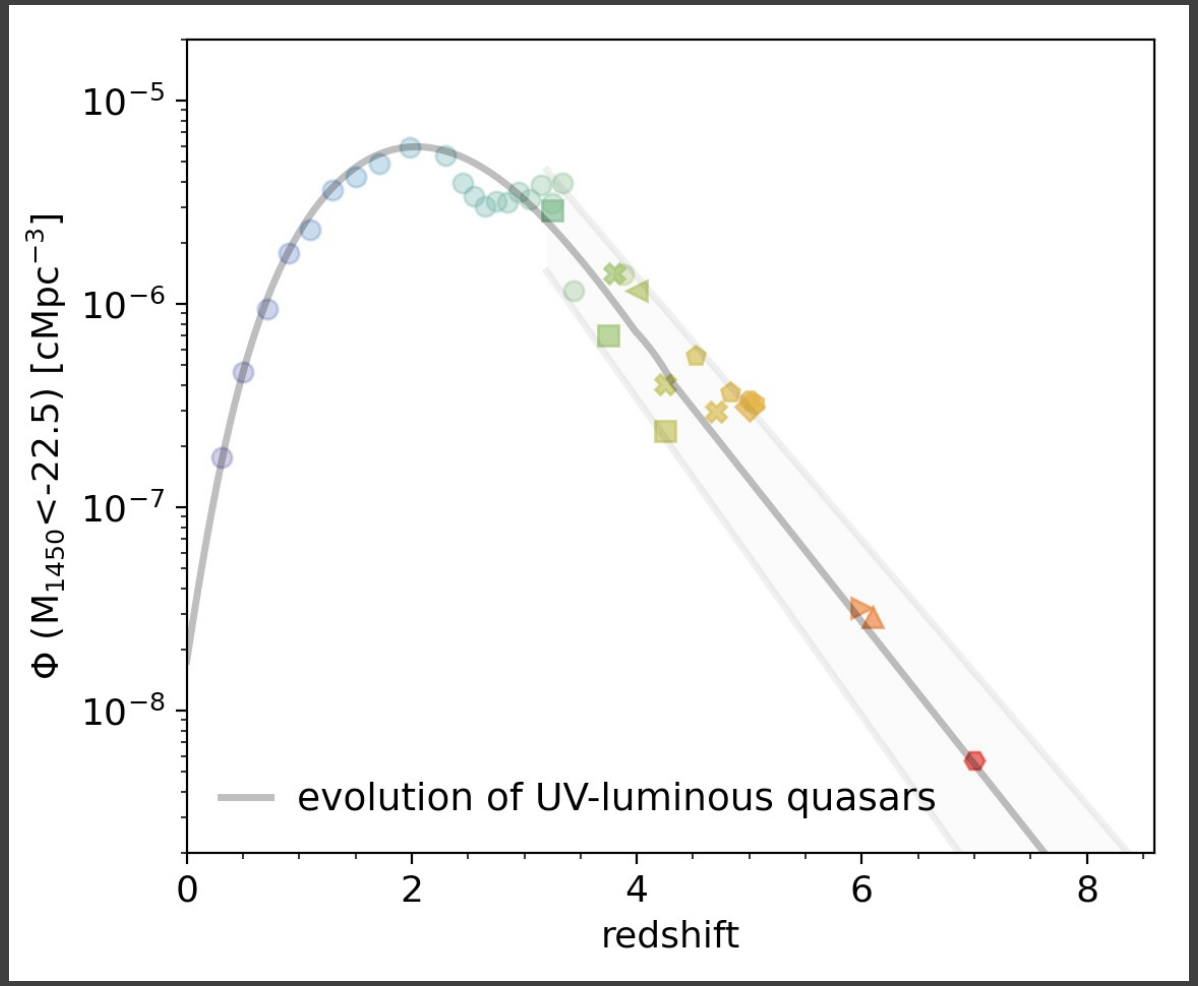
SMBH GROWTH ⟷ **QUASAR ACTIVITY**



Connecting quasar activity to SMBH evolution



Adapted from *Pizzati+24c*

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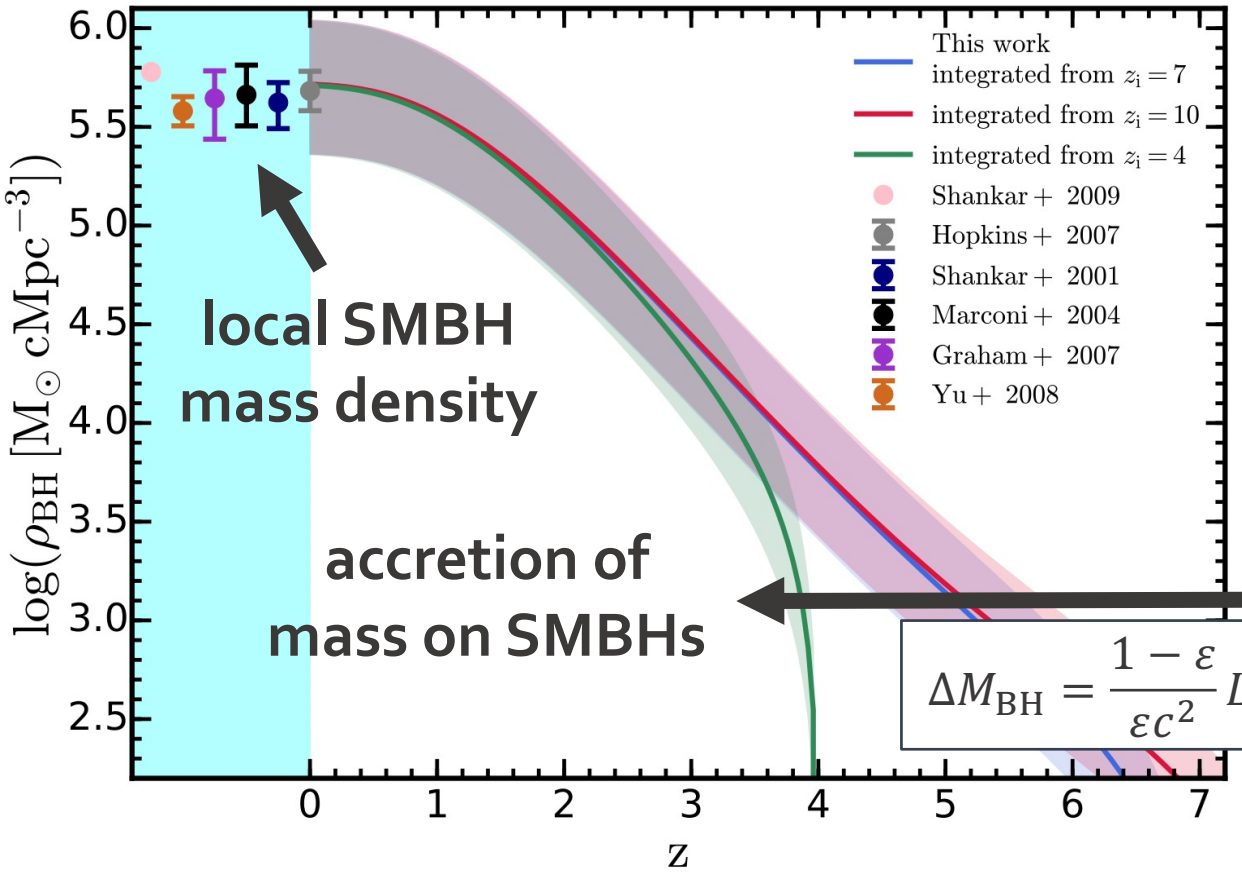
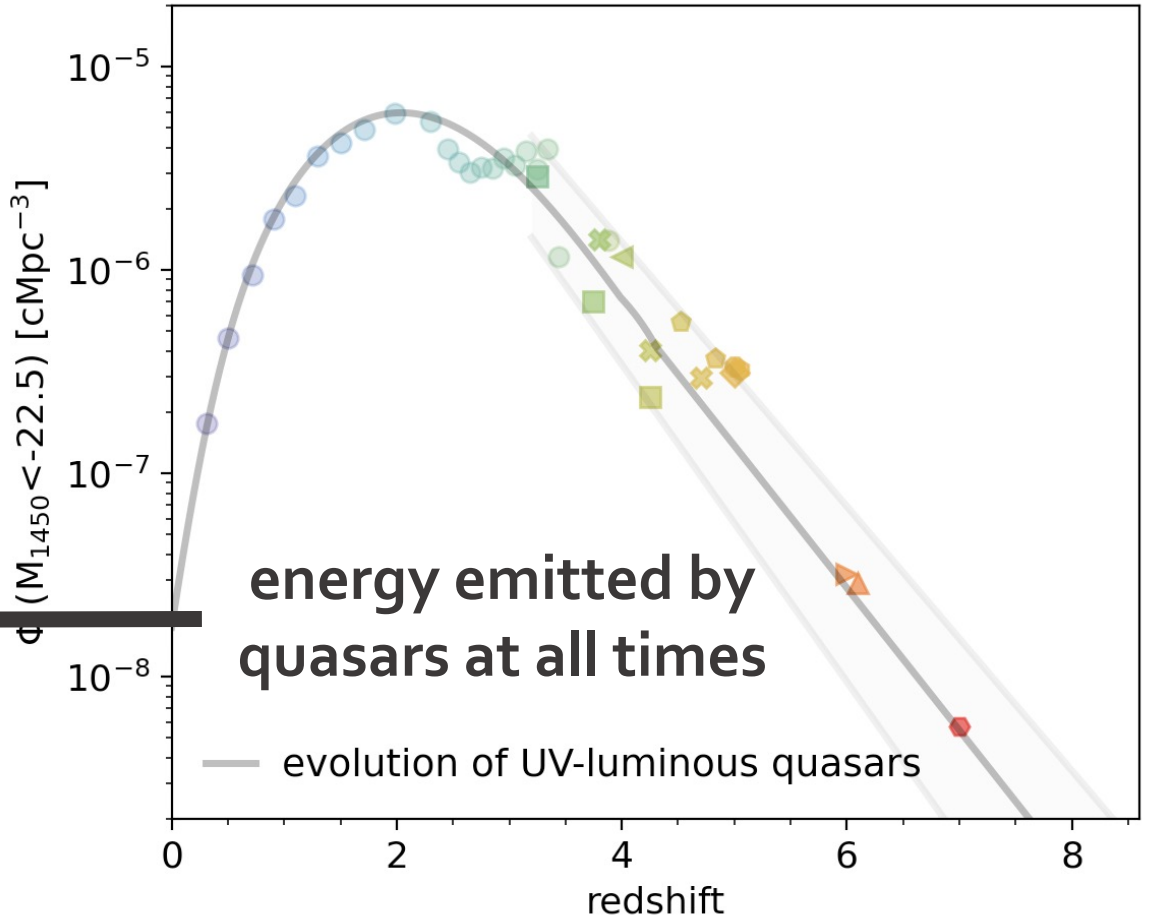


$$\Delta M_{BH} = \frac{1-\varepsilon}{\varepsilon c^2} L \Delta t$$



Shen+20

Adapted from *Pizzati*+24c

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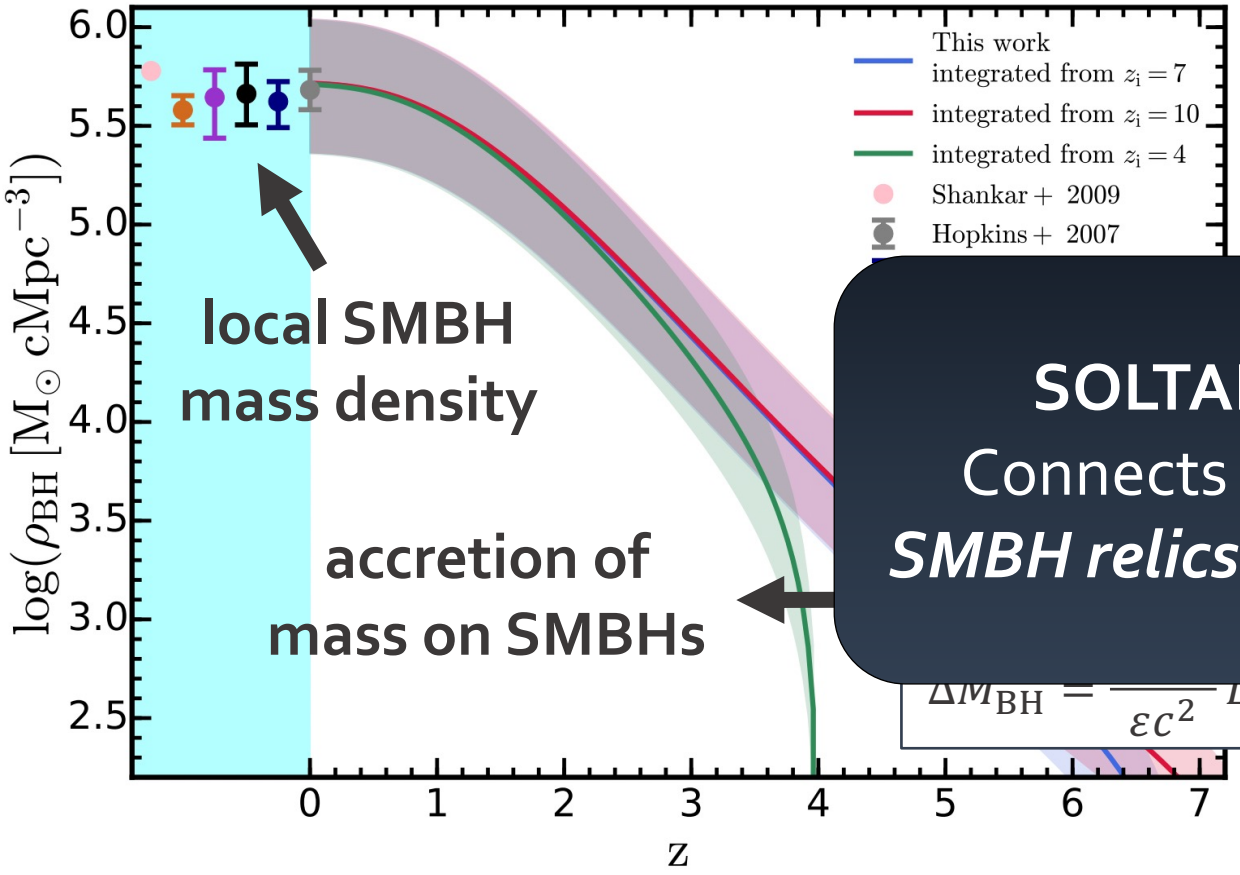
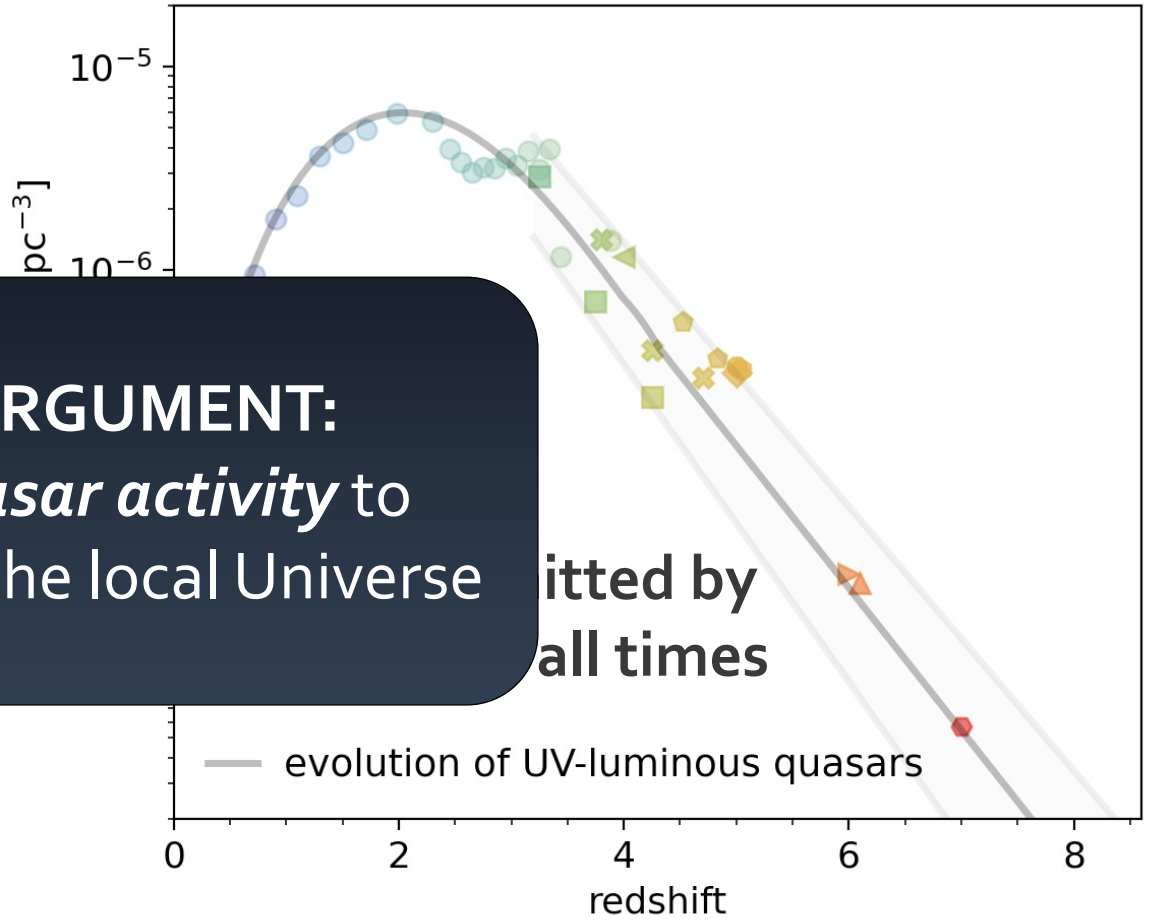


SOLTAN ARGUMENT:
Connects ***quasar activity*** to ***SMBH relics*** in the local Universe

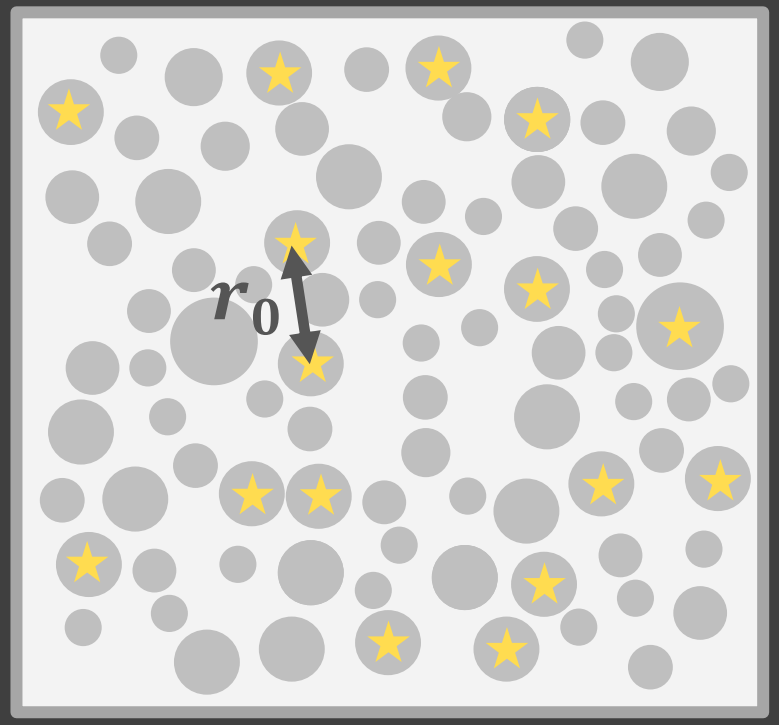
$$\Delta M_{BH} = \frac{}{\varepsilon c^2} L \Delta t$$



Shen+20

Adapted from *Pizzati*+24c

Embedding quasars in a cosmological context: *clustering measurements* across cosmic time…



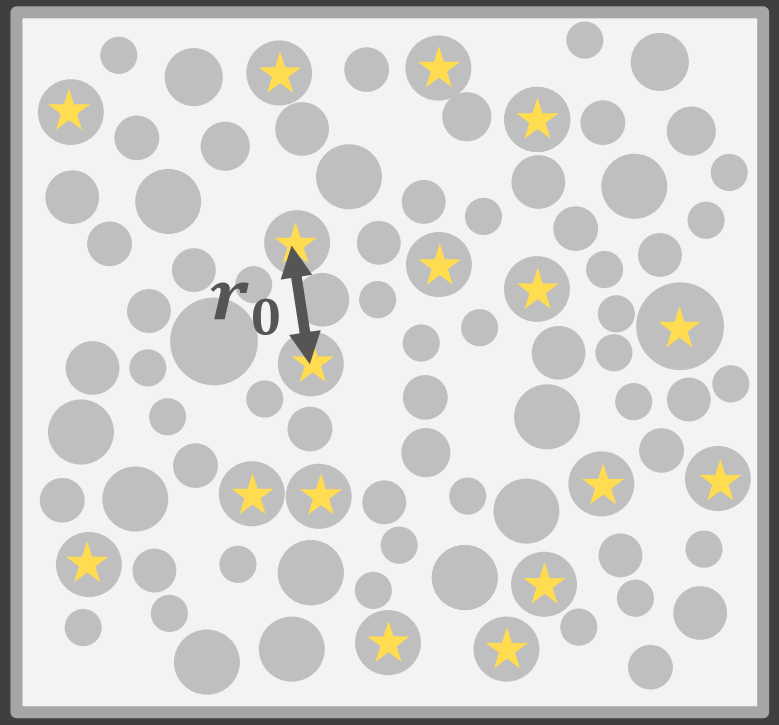
All DM Halos

★ Quasars that we observe with JWST

- Quasar clustering traces SMBH-hosting halos:

$$r_0 \rightarrow b(M) \rightarrow M_{\mathrm{hosts}} \rightarrow n_{\mathrm{hosts}}$$

Not just environments… clustering and the constraints on the *duty cycle* of quasar activity



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- Quasars *subsample* the SMBH population
- ***Quasar duty cycle*** → active SMBHs vs total population of SMBHs in $n_{\rm hosts}$

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number of quasars (from "counting") / number of host halos (from clustering)

$$\frac{n_{\rm quasar}}{n_{\rm hosts}} \sim f_{\rm duty} \sim \frac{t_{\rm Q}}{t_{\rm H}}$$

Quasar duty cycle

Quasar lifetime

Hubble time (~host lifetime)

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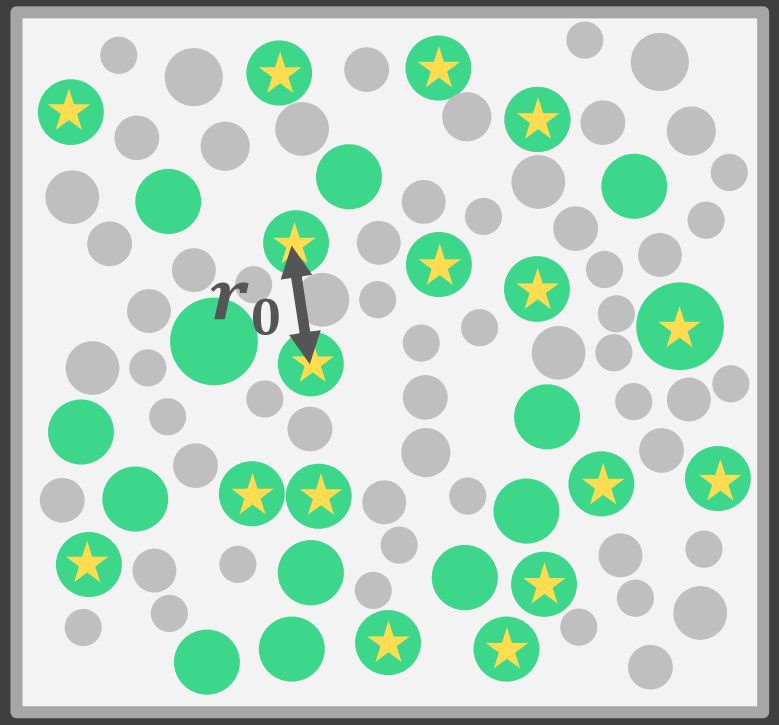

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SMBH Host Halos

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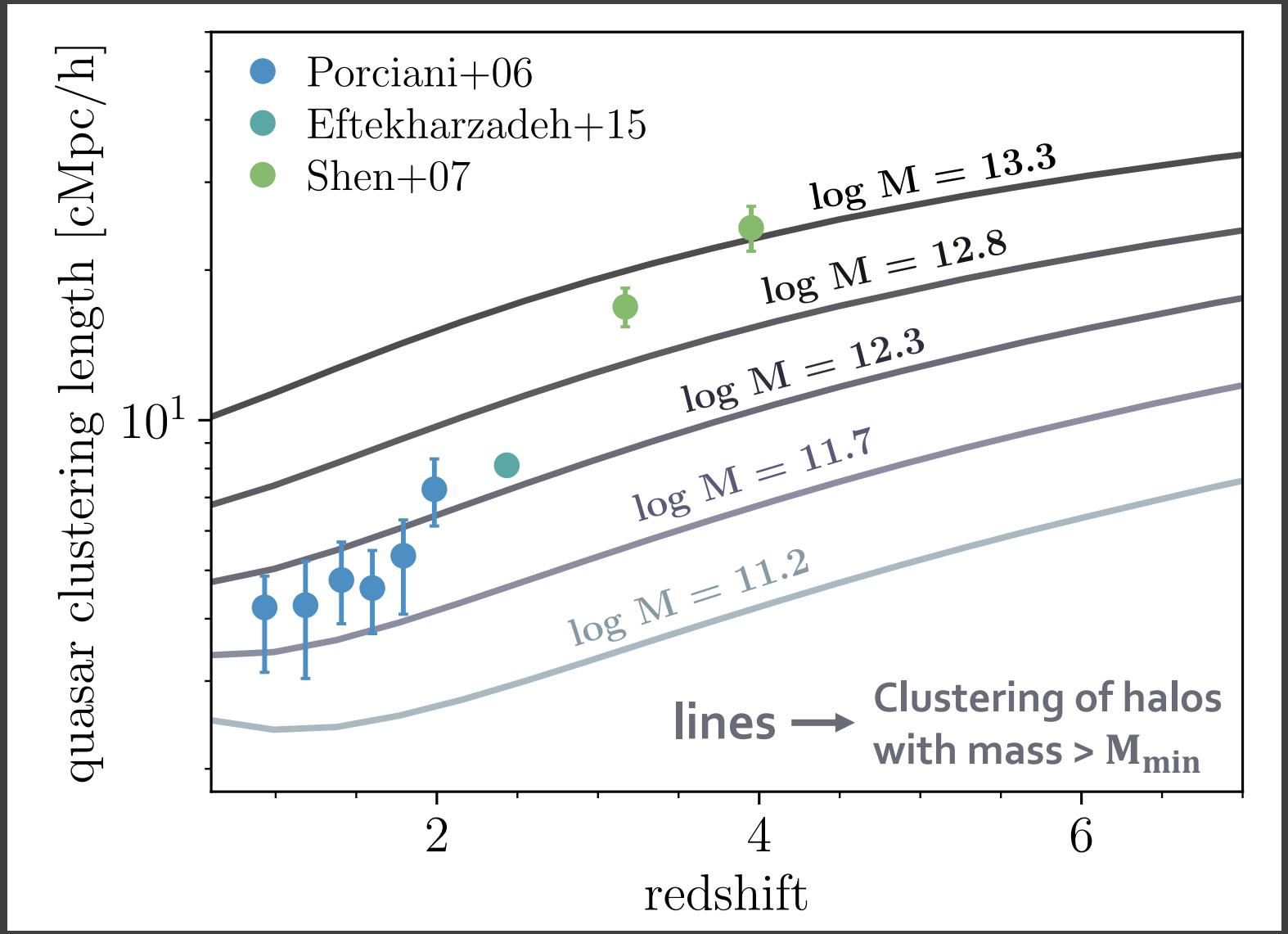
Quasar lifetime

Hubble time (~halo lifetime)

Two decades of quasar clustering measurement

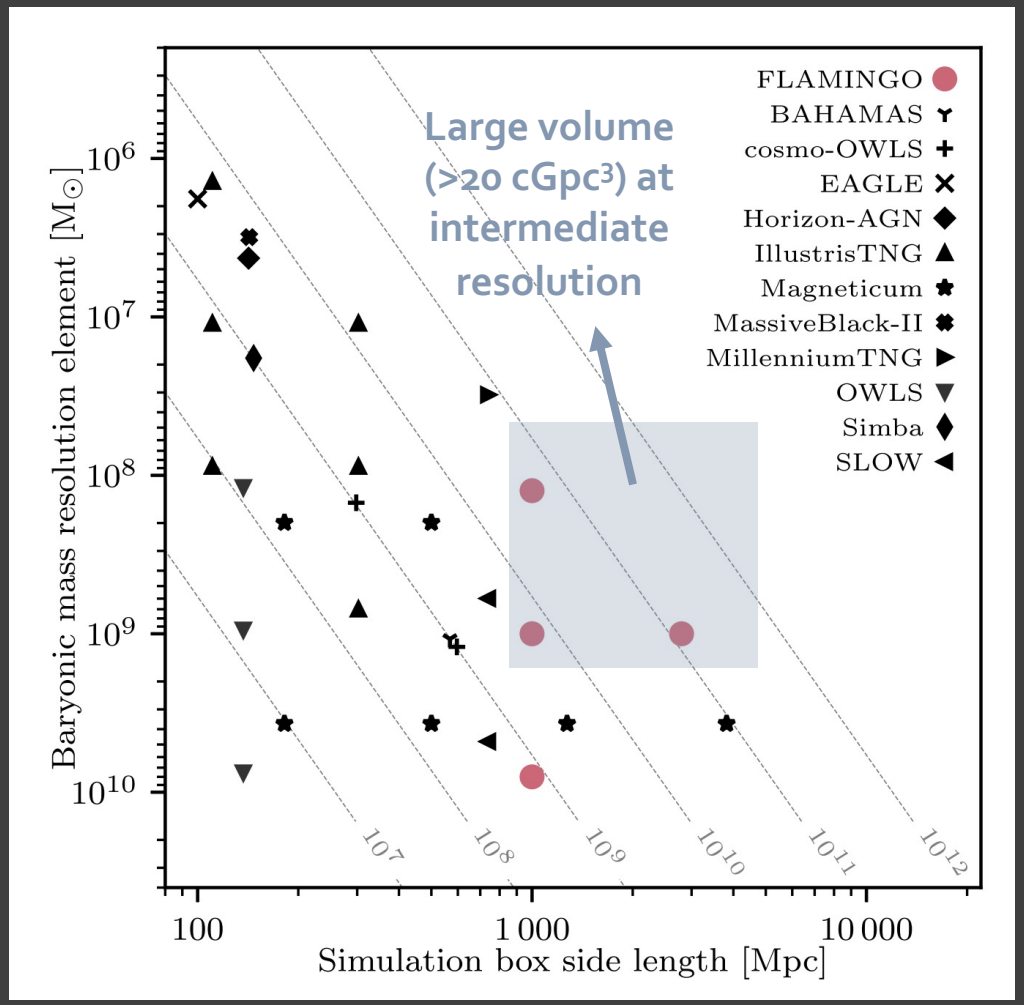


Low-z quasars → ***common*** phenomena, living in ~10^{12} solar-mass halos

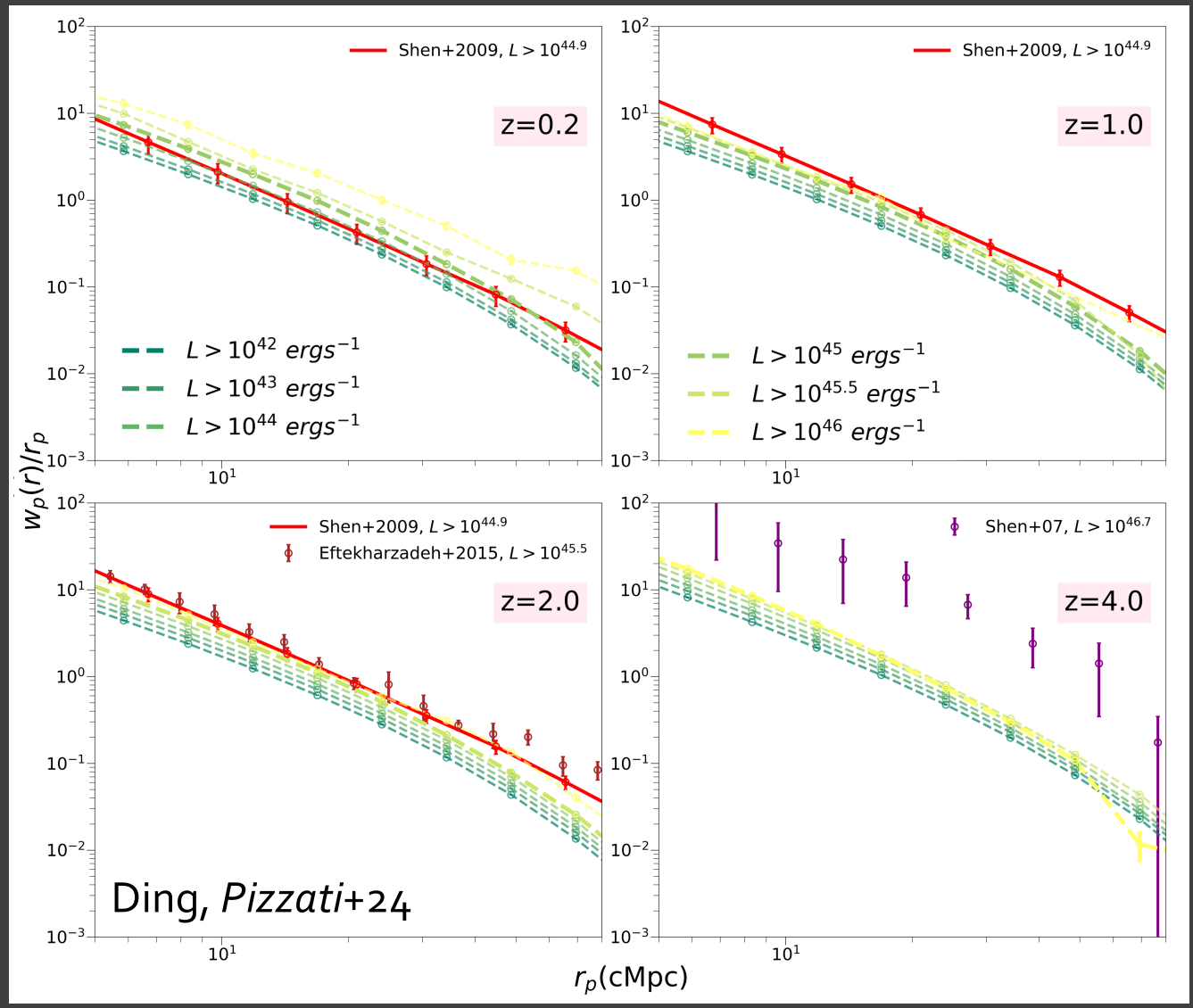
Models using clustering to connect SMBH to halos/gal.:

- (semi)***empirical*** models:
  Shankar+09; White+12; Hopkins+07; Croton+09; Shankar+10; Conroy+13; Aversa+15; *Pizzati*+24a
- ***semianalytic*** models:
  Bonoli+09; Fanidakis+13; Oogi+16

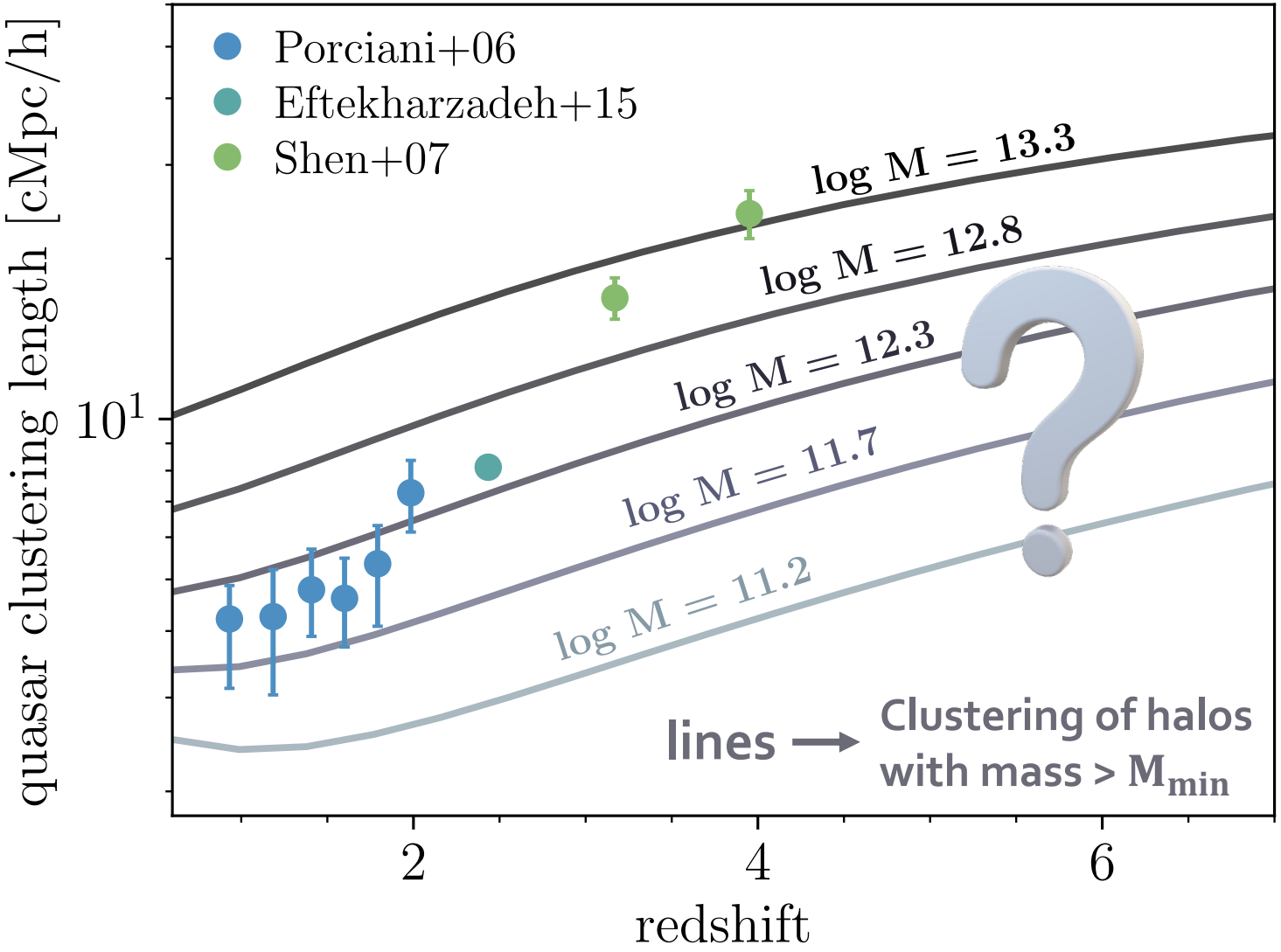
Clustering measurements in large-volume hydro cosmological simulations



Schaye+23



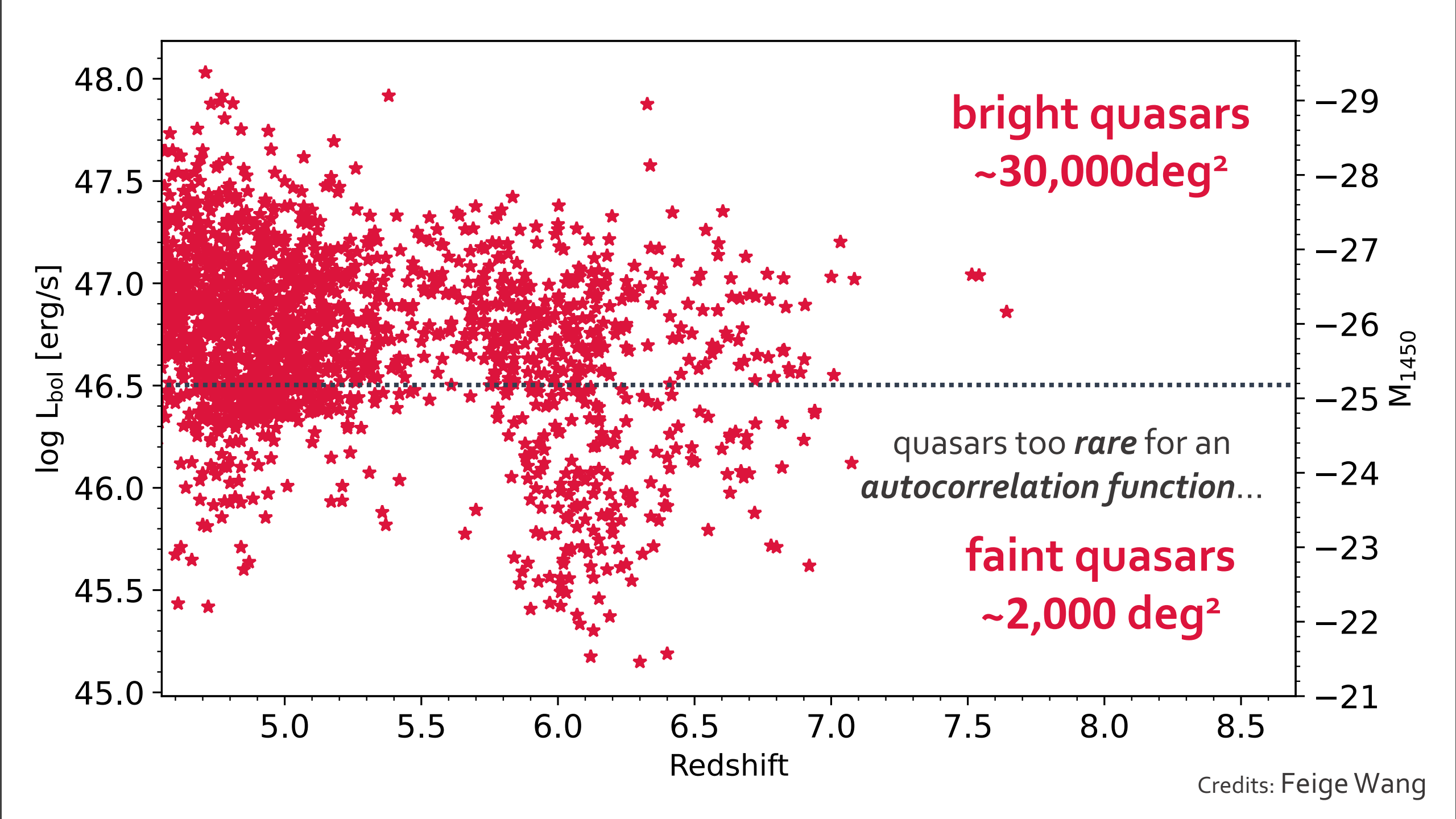
At high redshift clustering increases steeply…



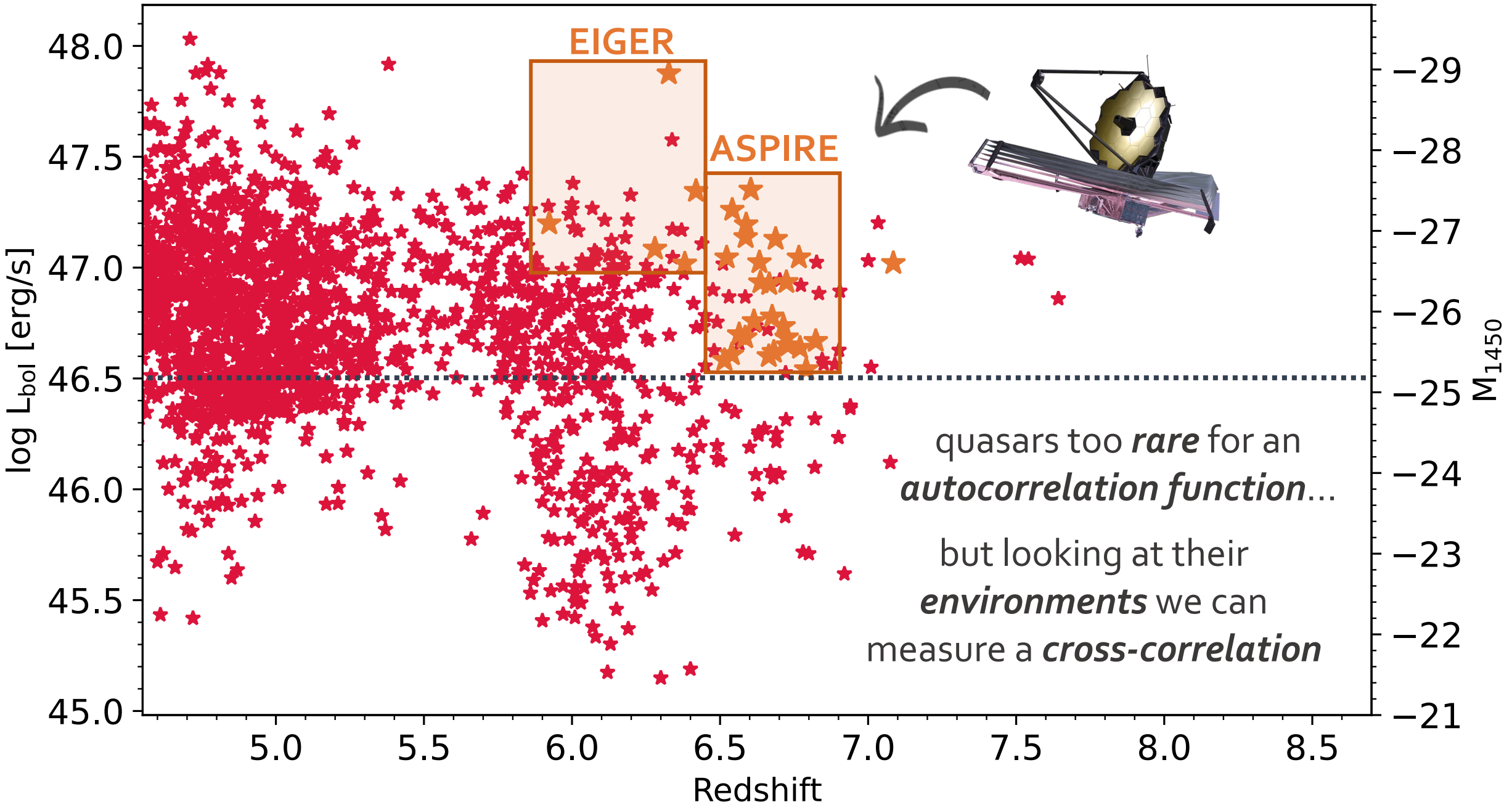
Low-z quasars → ***common*** phenomena, living in ~10^{12} solar-mass halos

High-z quasars → very ***rare*** phenomena, living only in the ***most massive*** systems (>4-σ ***peaks***)

Highest redshifts? Can we constrain the sites where the ***first quasars*** formed?

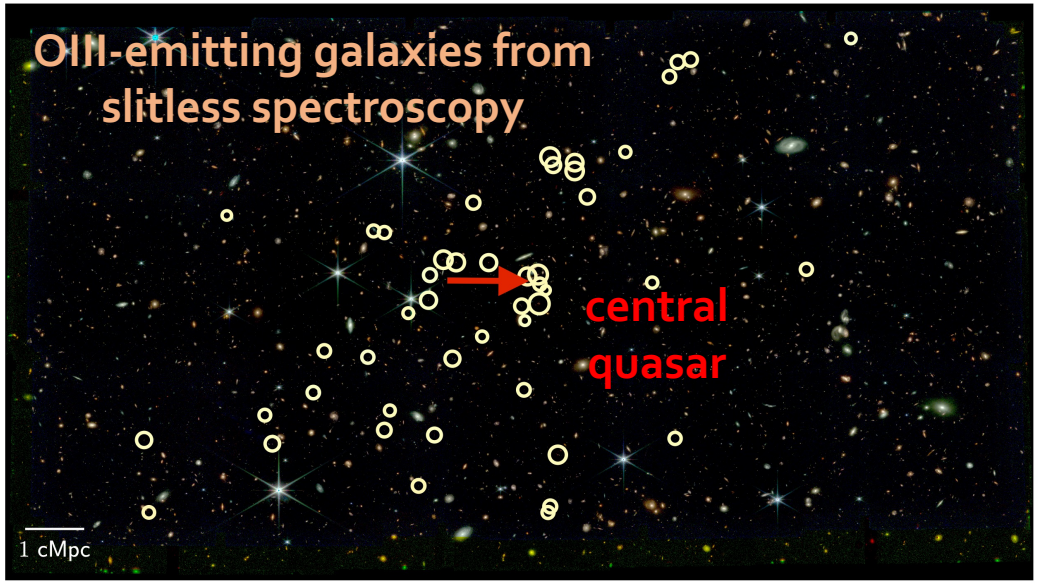


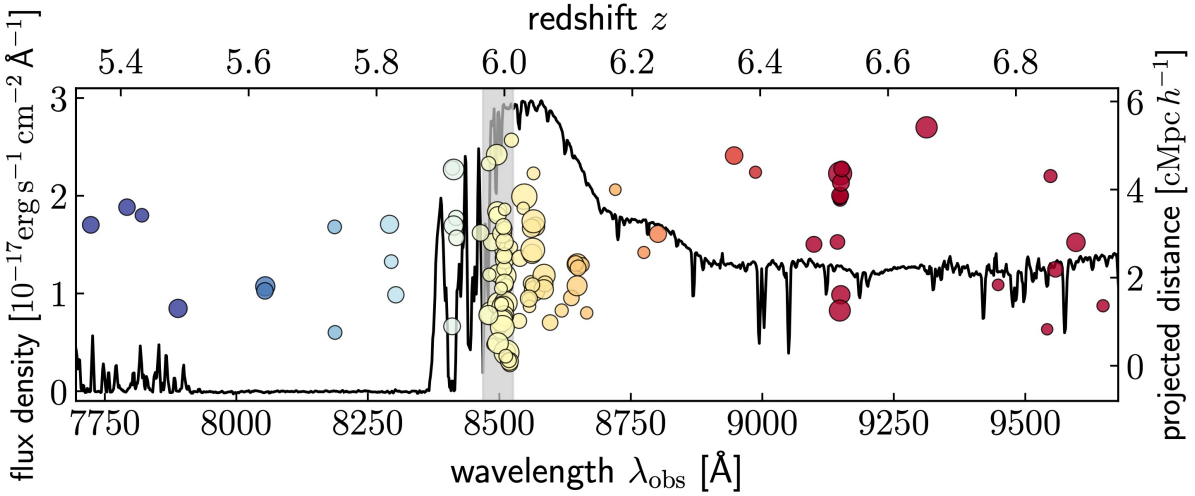
Credits: Feige Wang

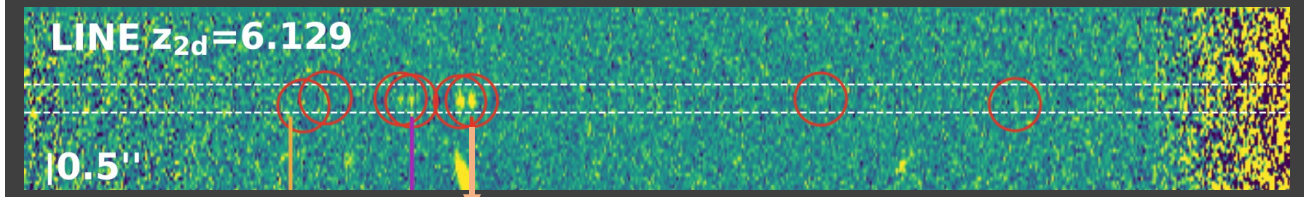

EIGER
ASPIRE
quasars too *rare* for an *autocorrelation function*...
but looking at their *environments* we can measure a *cross-correlation*
log L_{bol} [erg/s]
48.0
47.5
47.0
46.5
46.0
45.5
45.0
M_{1450}
−29
−28
−27
−26
−25
−24
−23
−22
−21
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
Redshift

JWST slitless observations of z~6 quasar fields

Eilers,Mackenzie,*Pizzati*+24







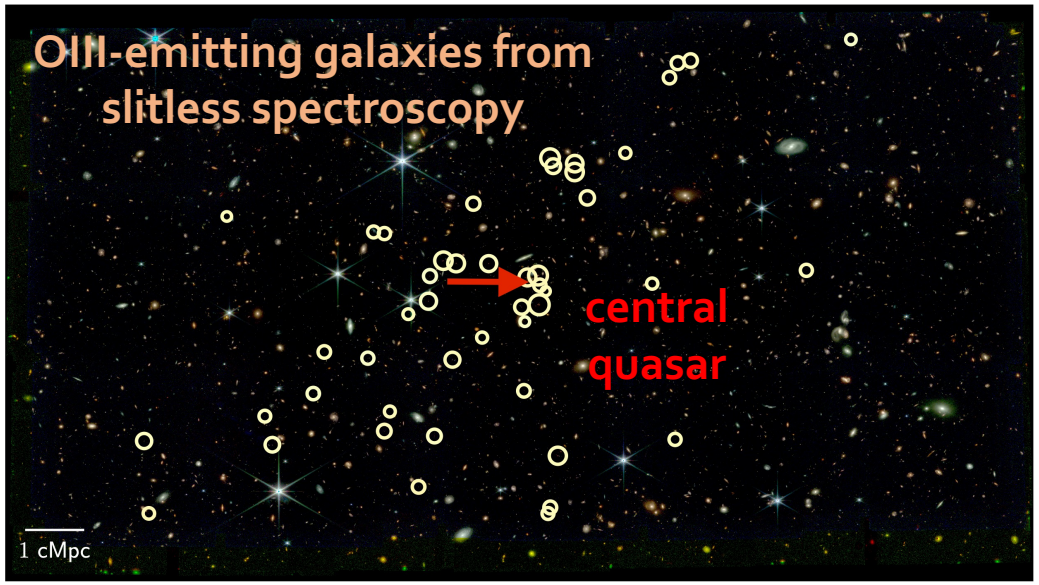
[OIII] doublet from slitless spectra

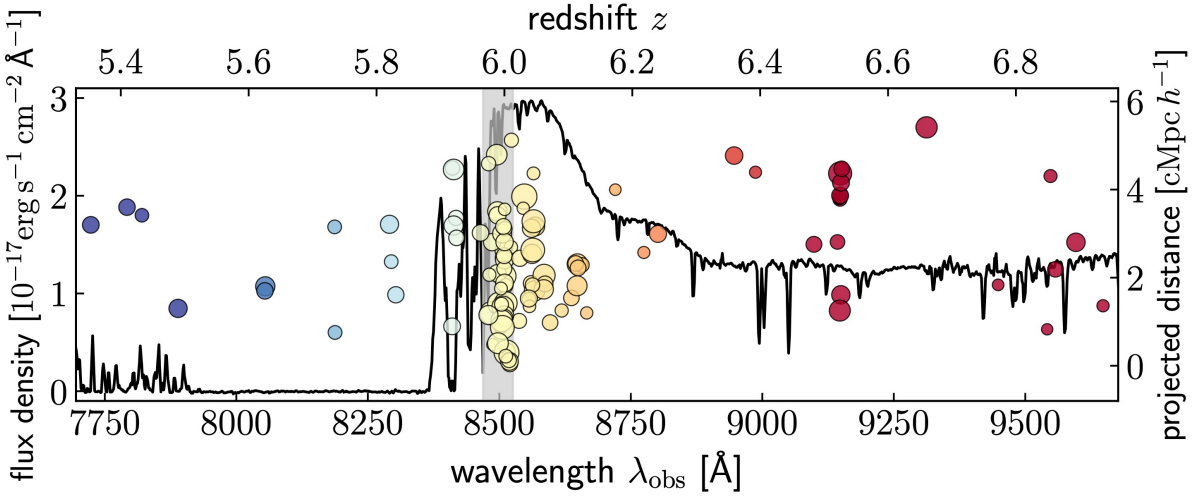
Why NIRCam slitless spectroscopy?

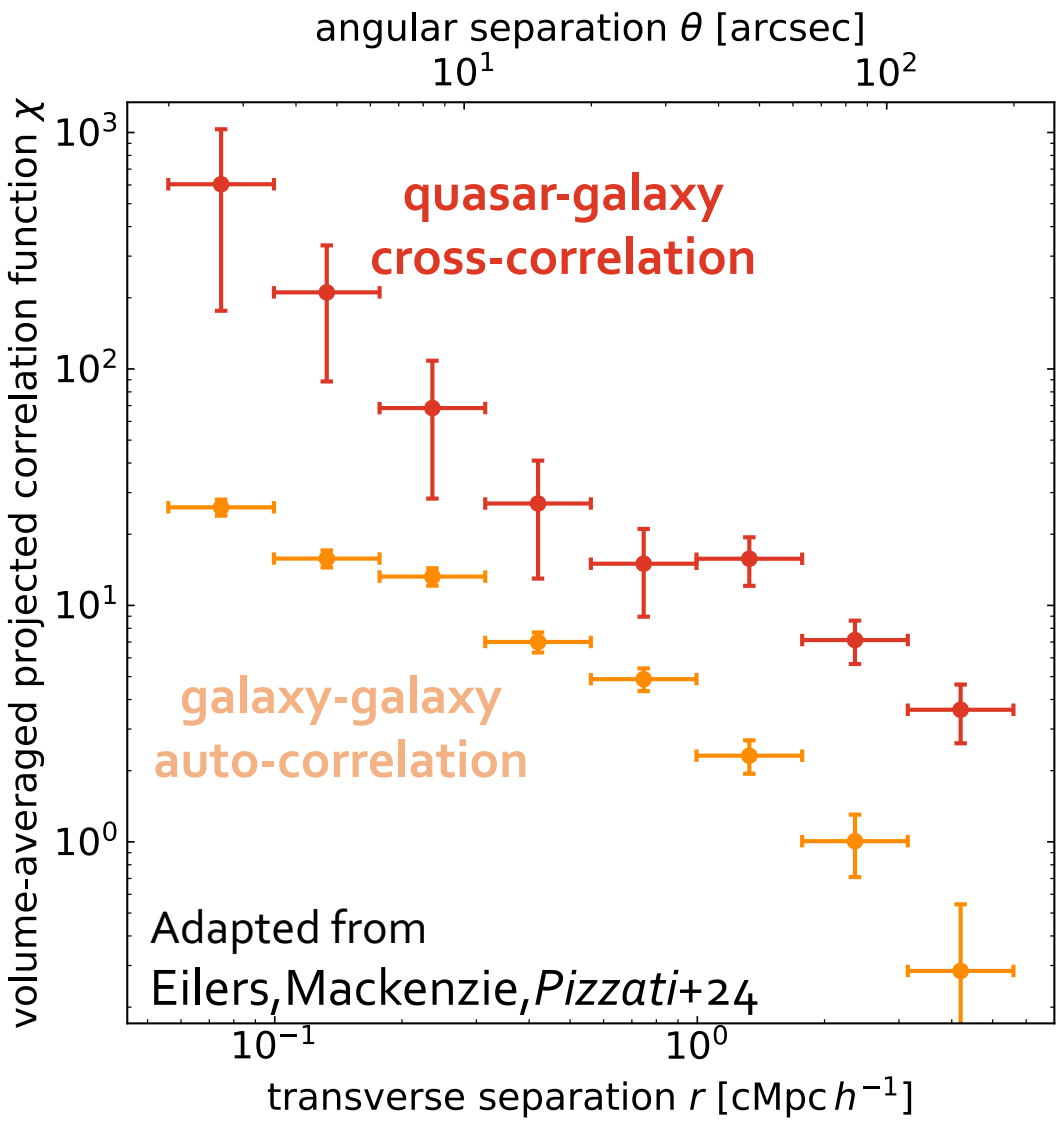
- Accurate ***3-d positions*** of [OIII] emitters from imaging+redshift
- Straightforward selection function
- Homogeneous measurement of the ***galaxy autocorrelation function*** by masking out the quasar redshift

Quasar-galaxy cross-correlation from EIGER

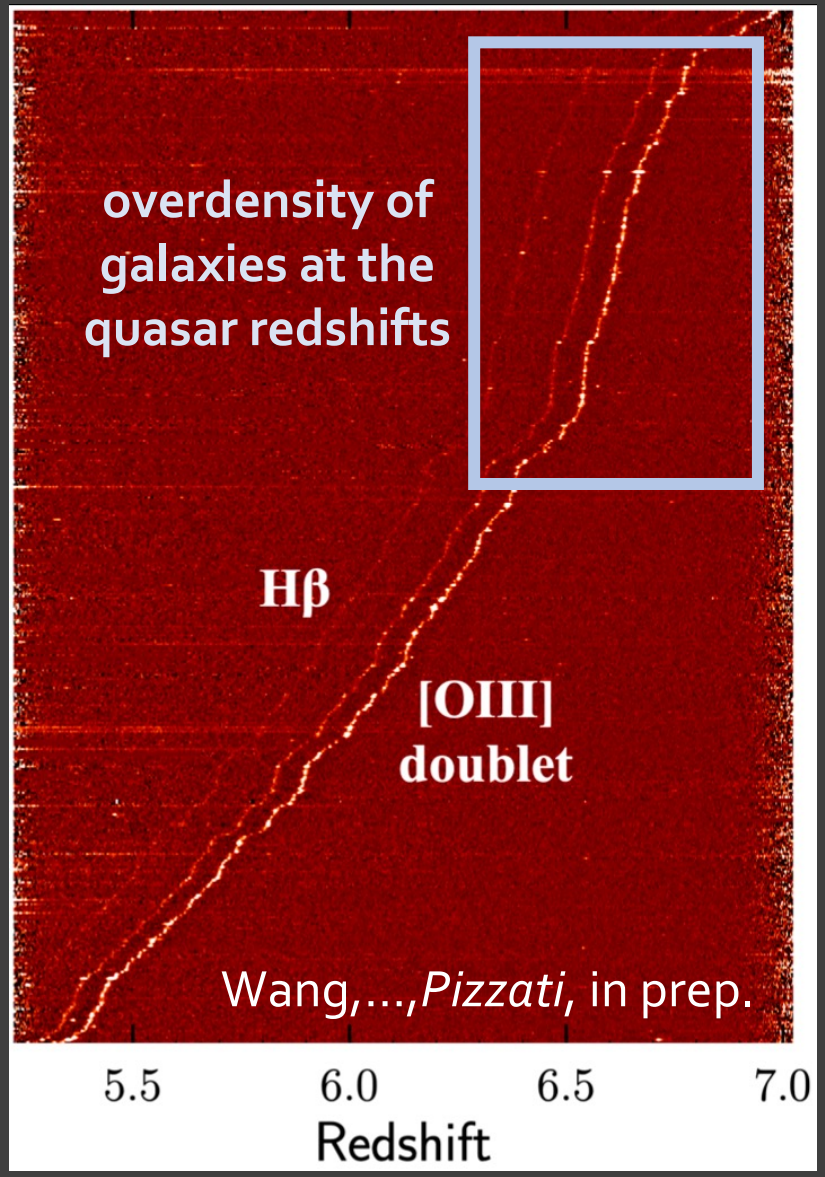
Eilers,Mackenzie,*Pizzati*+24

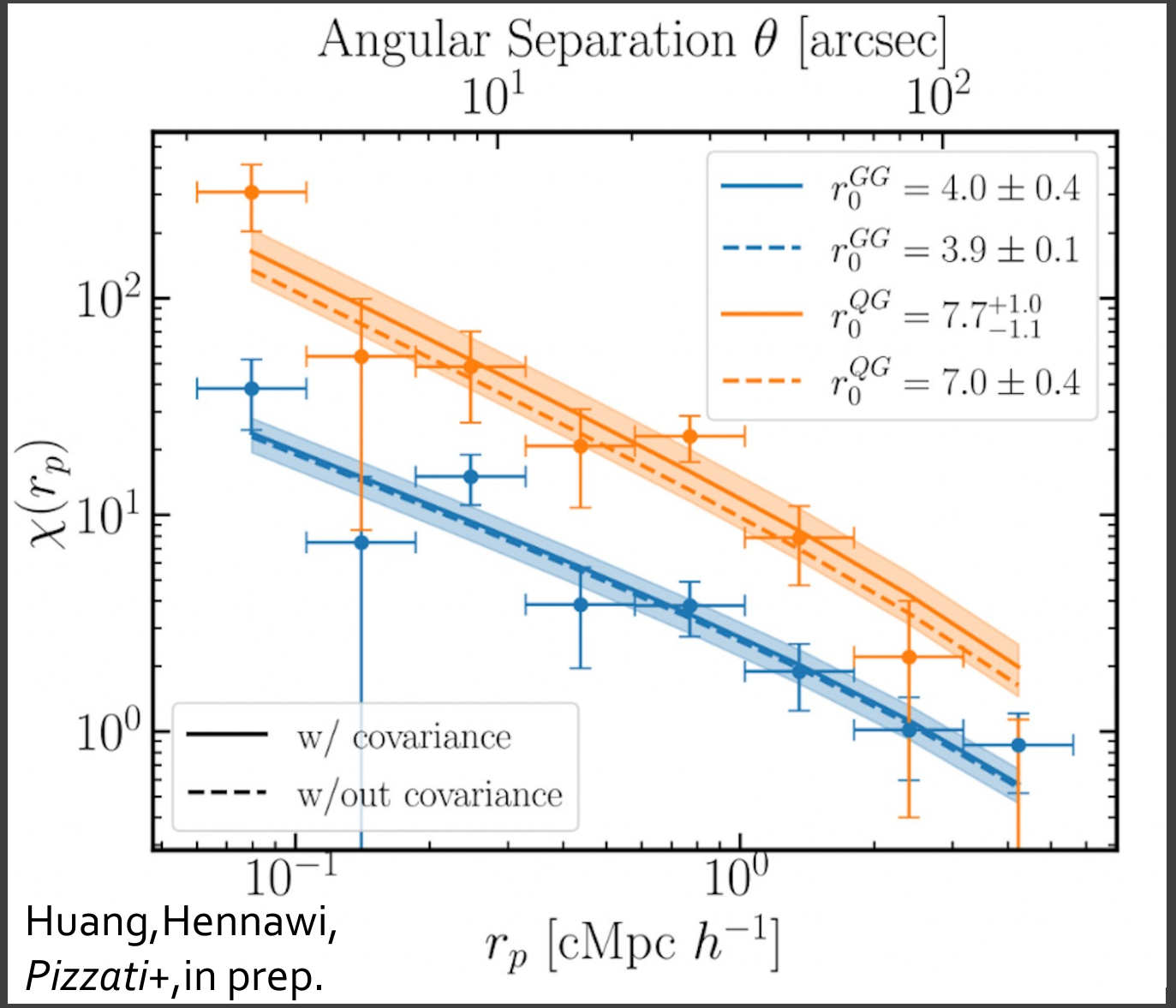






ASPIRE extends the quasar sample (*preliminary*)





Huang,Hennawi, *Pizzati*+,in prep.

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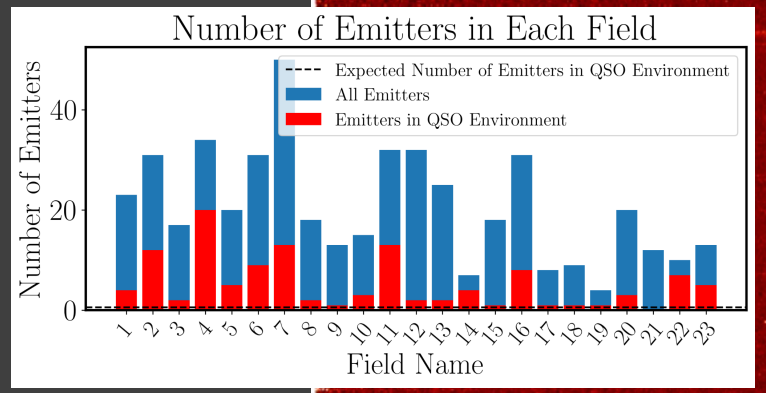
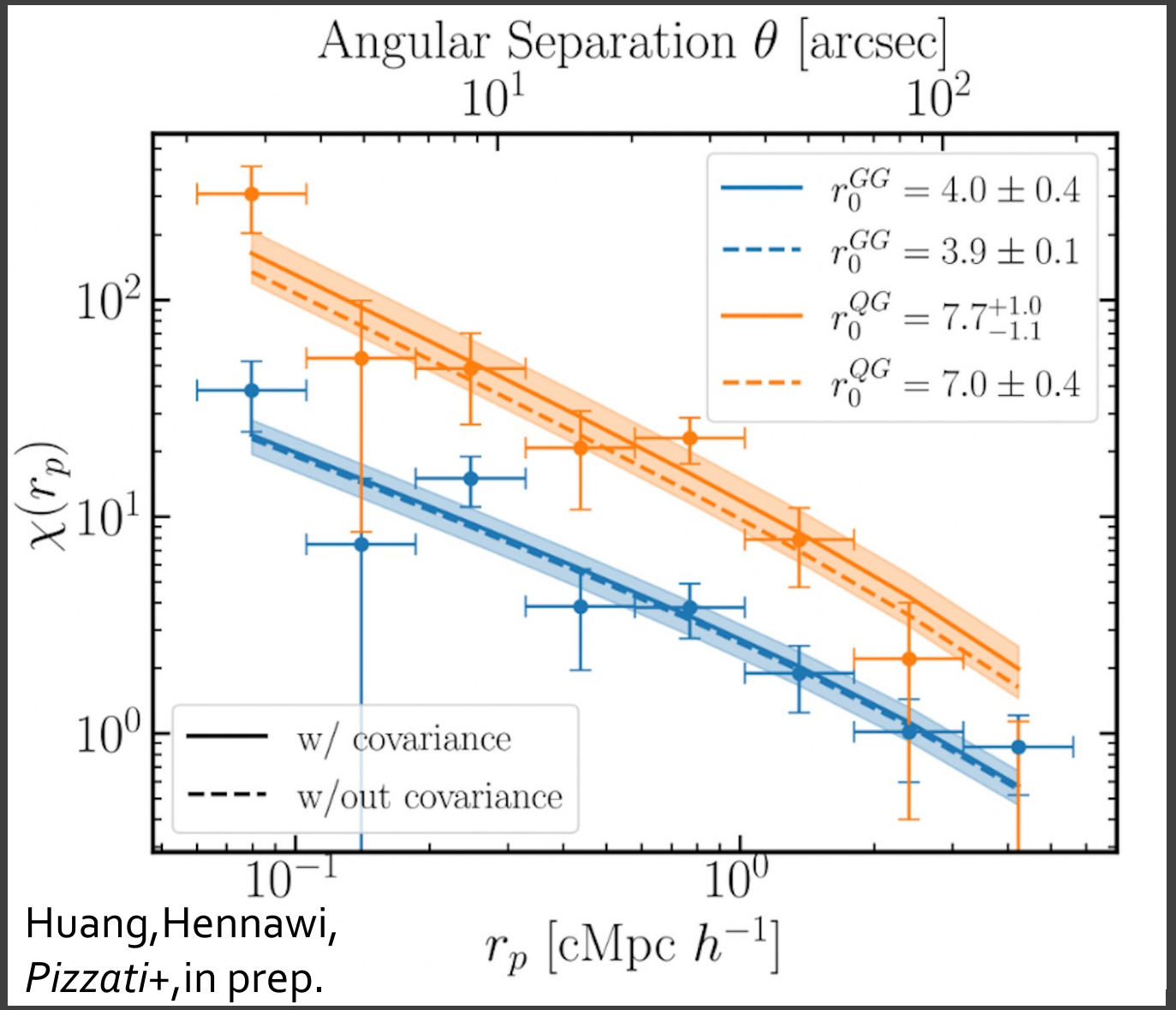


Credits:
Jiamu Huang



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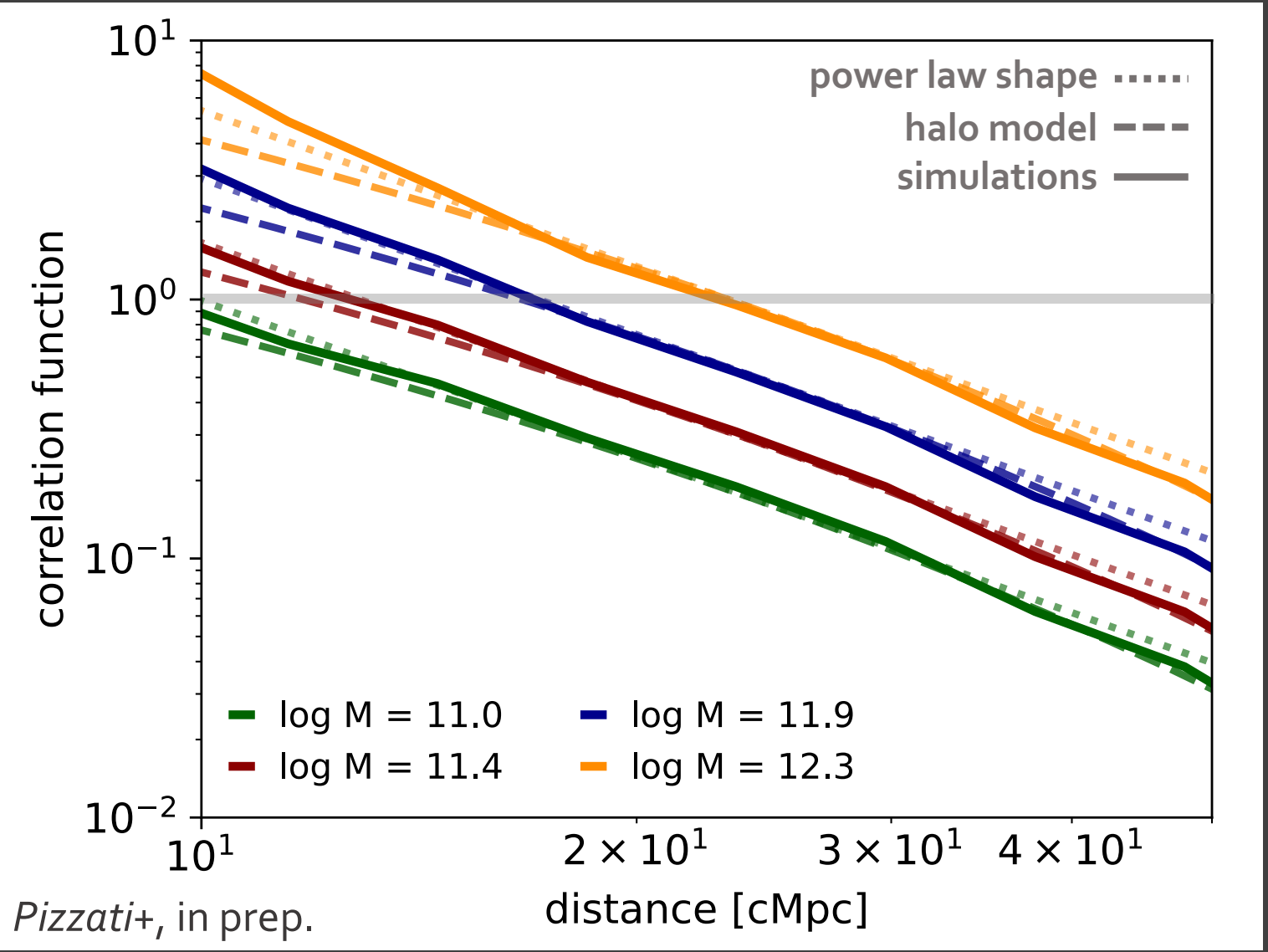

Pizzati+, in prep.

Many ways to model correlation functions…

Power-law?

Halo model/linear theory?

N-body simulations?

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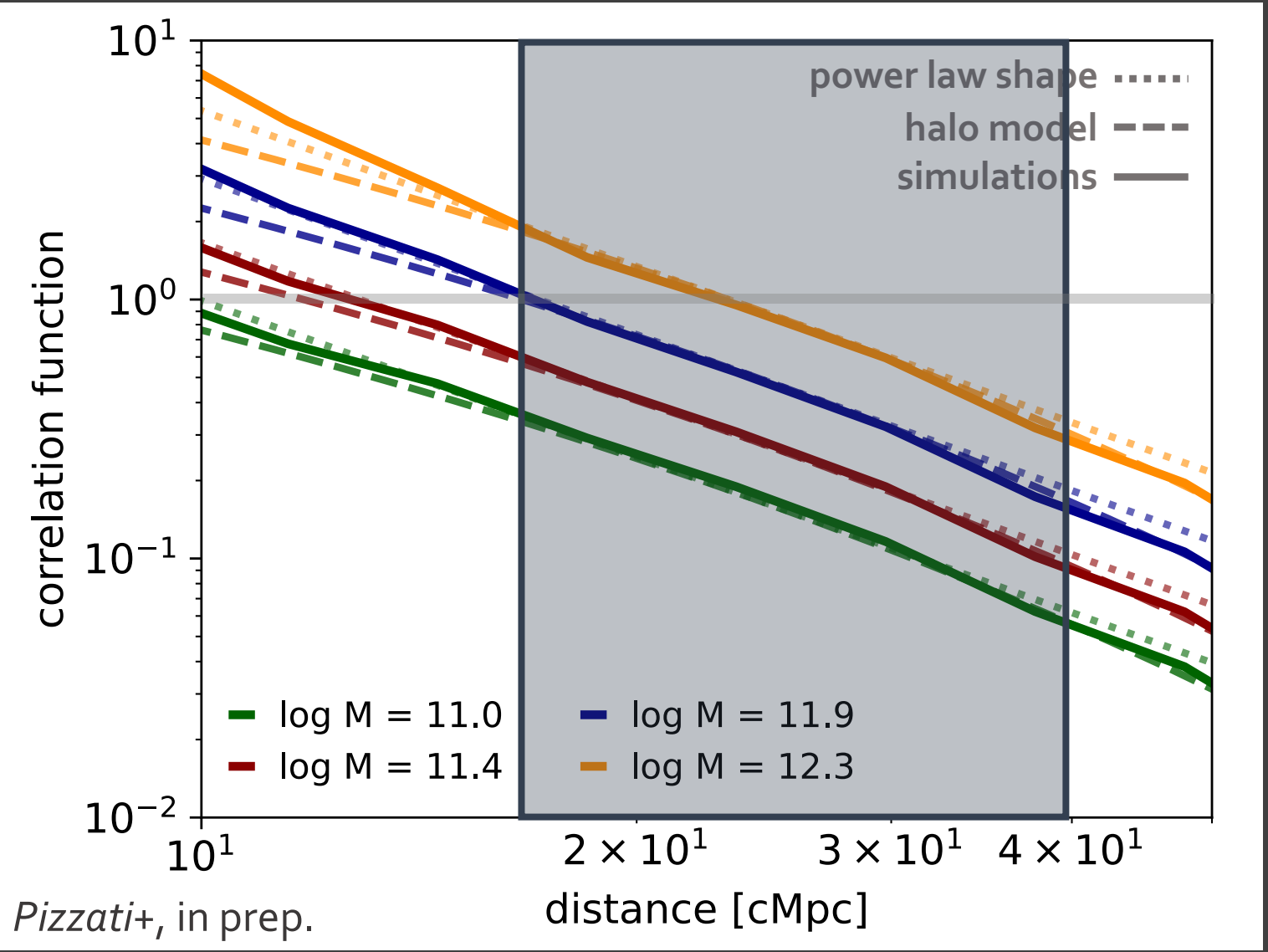

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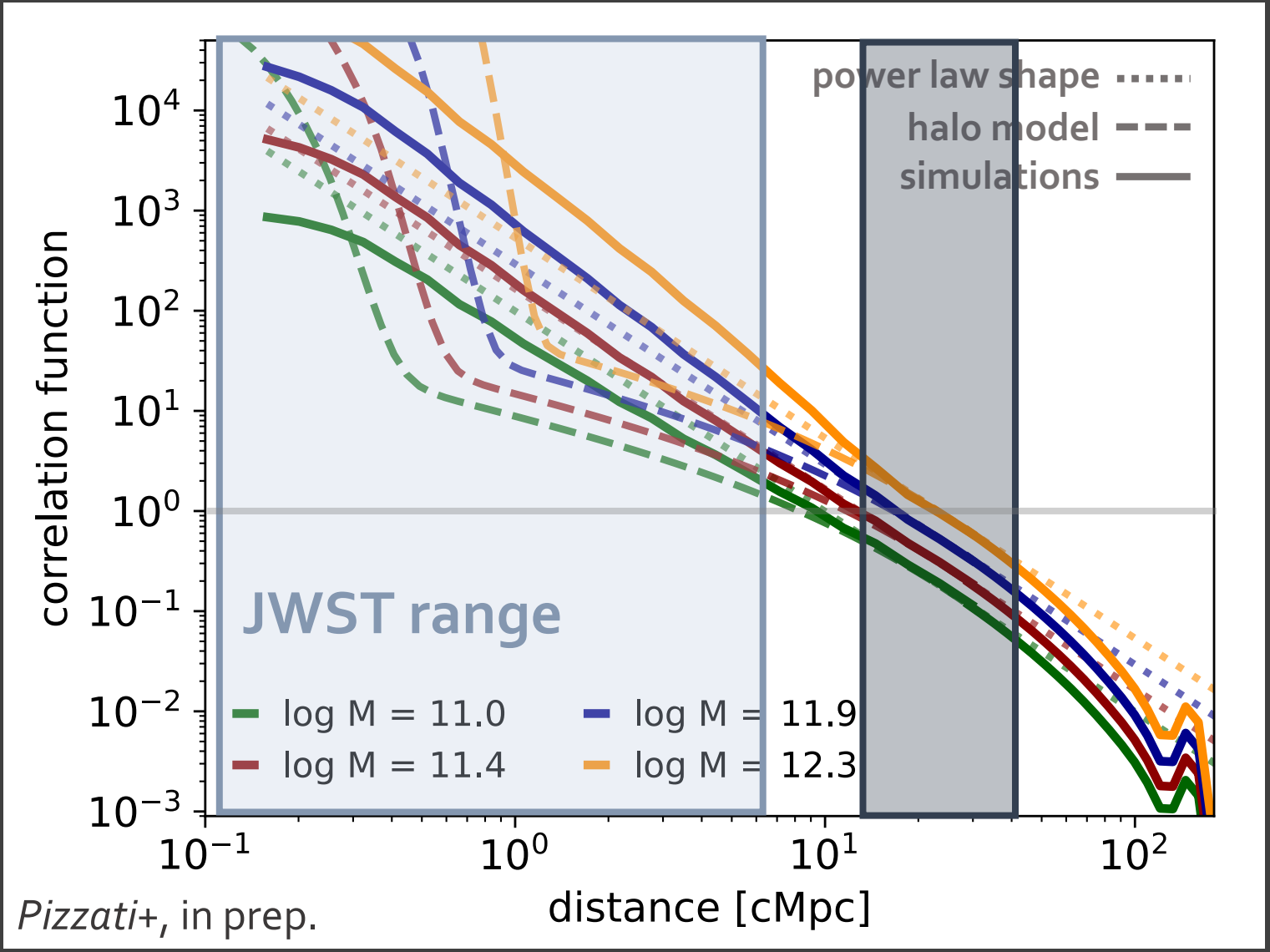

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Many ways to model correlation functions…

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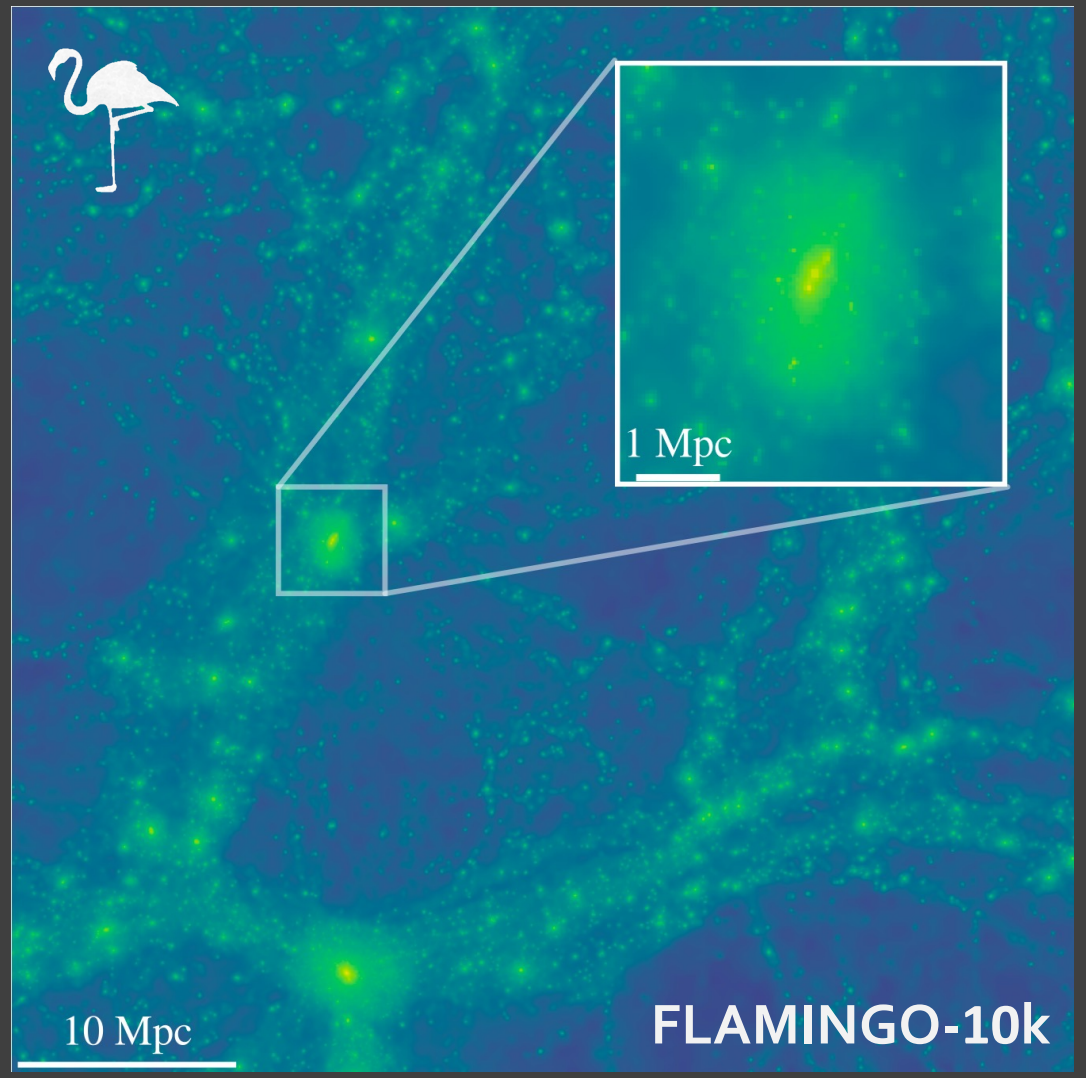
Non-linear (*small*) scales give very different answers → JWST data challenging!

A flexible model for quasars + galaxies in halos

Pizzati+24ab

Dark-matter-only ***simulation*** +
Conditional Luminosity Functions



A flexible model for quasars + galaxies in halos

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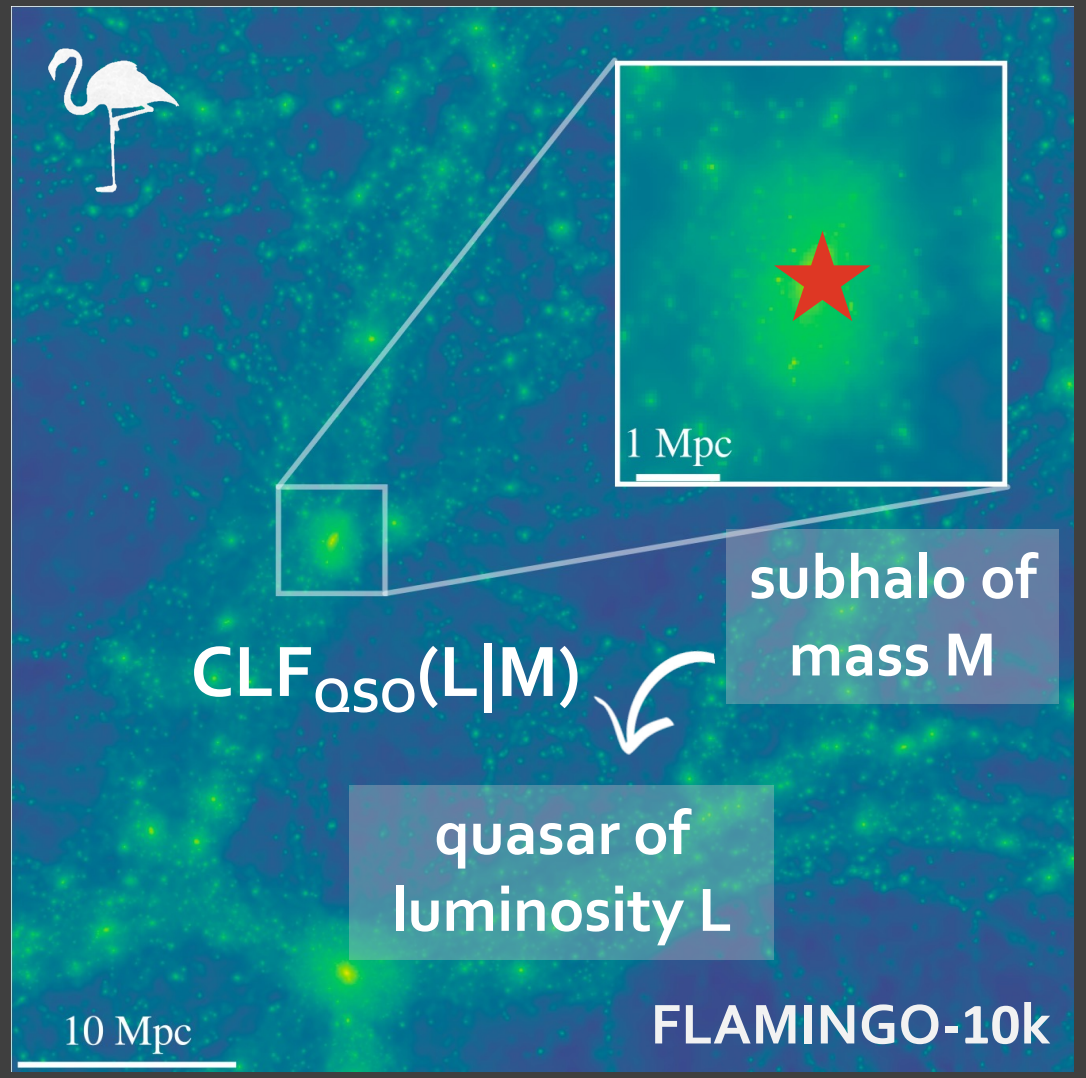
1. assign quasars and galaxies to (sub)halos based on their CLFs



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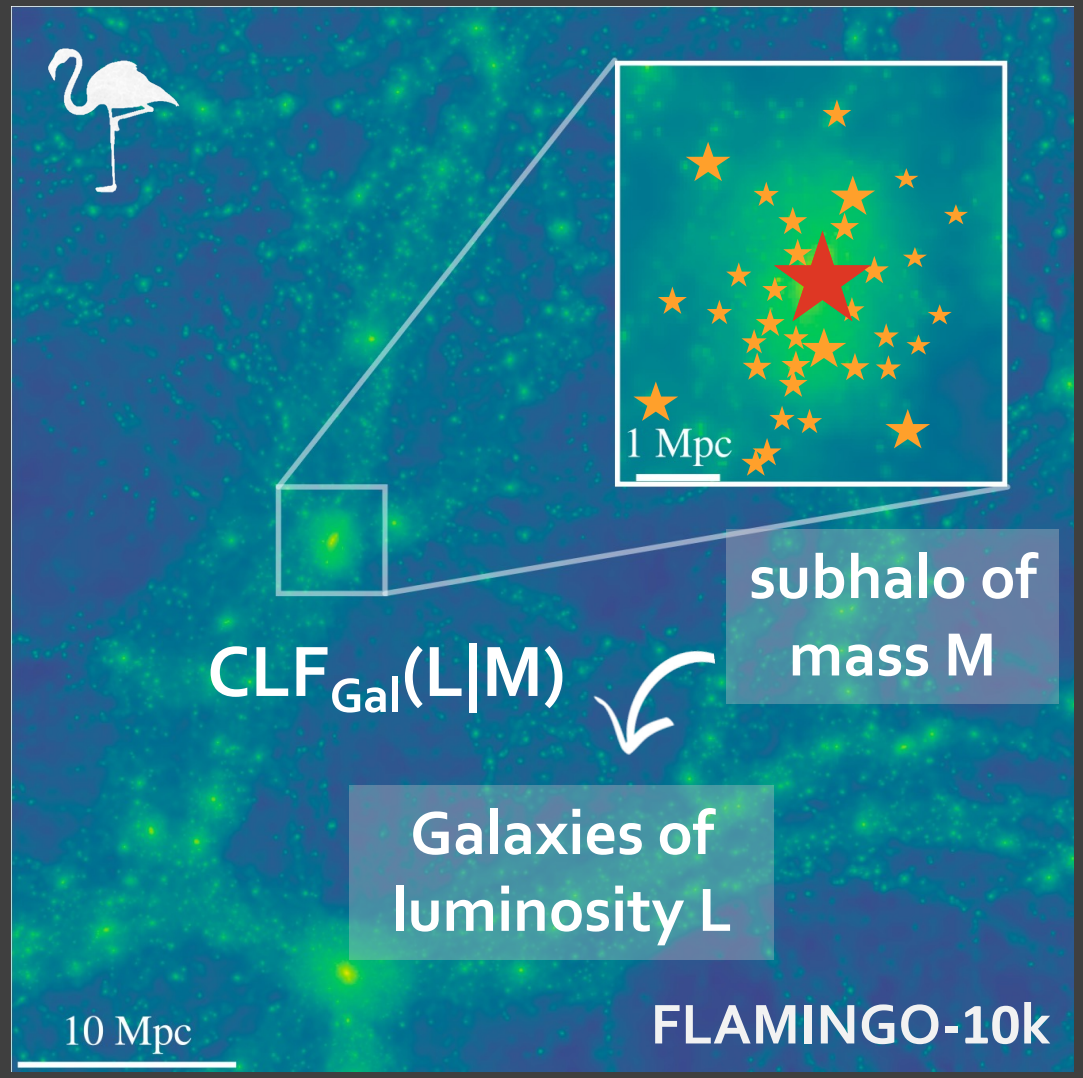


A flexible model for quasars + galaxies in halos

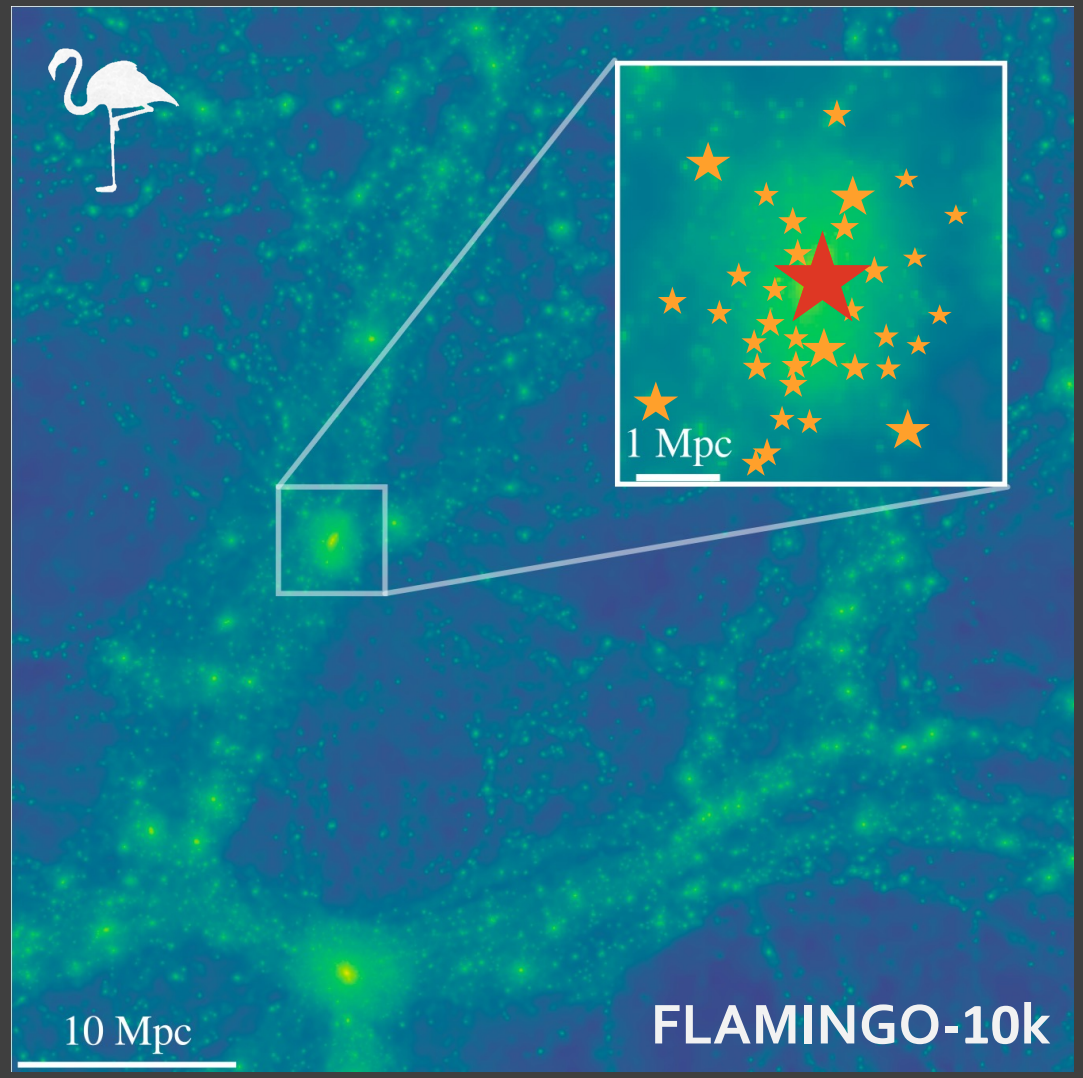
Pizzati+24ab

Dark-matter-only ***simulation*** + ***Conditional Luminosity Functions***

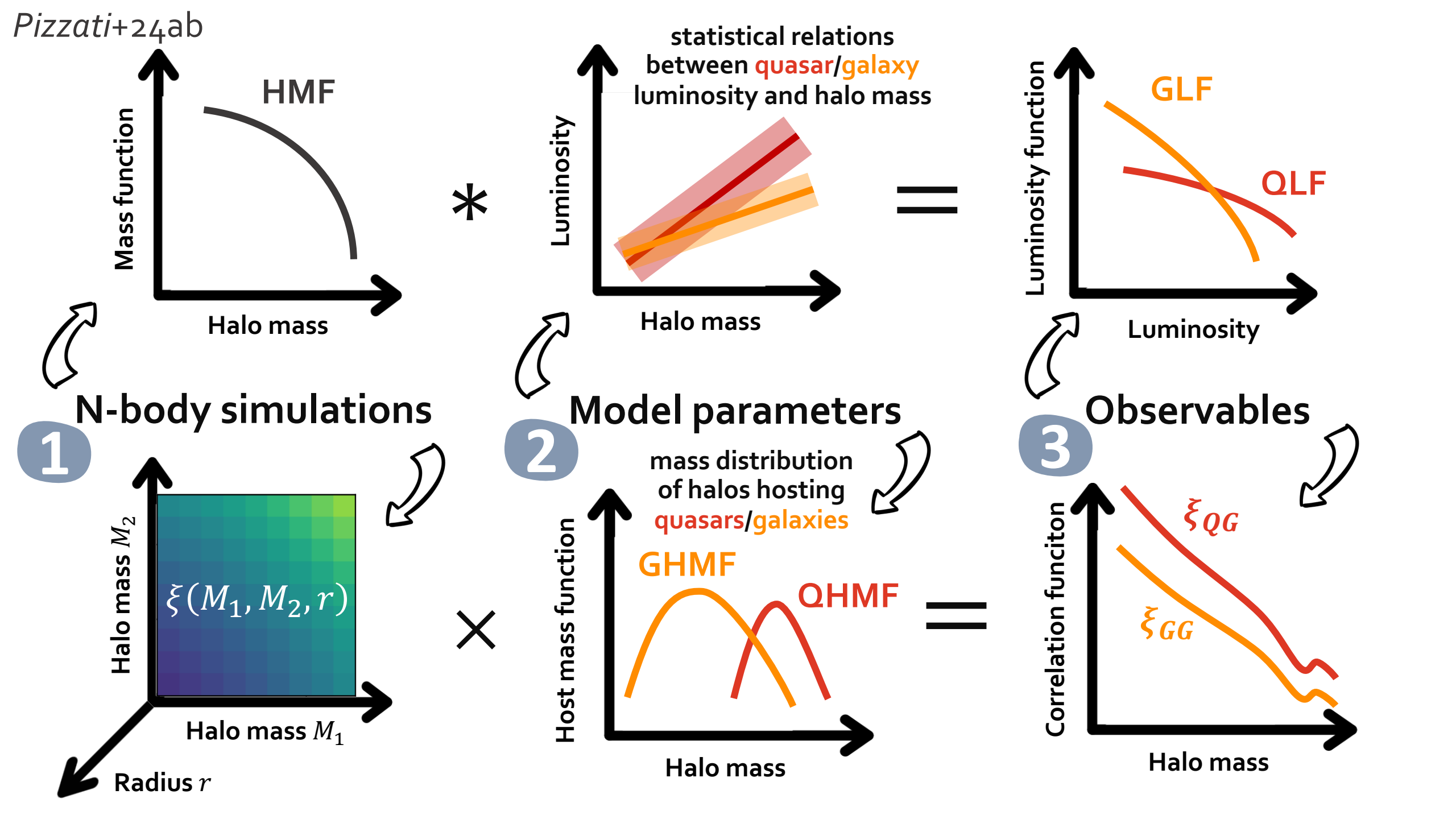
1. assign quasars and galaxies to (sub)halos based on their CLFs

2. predict the ***clustering*** of quasars and galaxies and their ***luminosity functions***

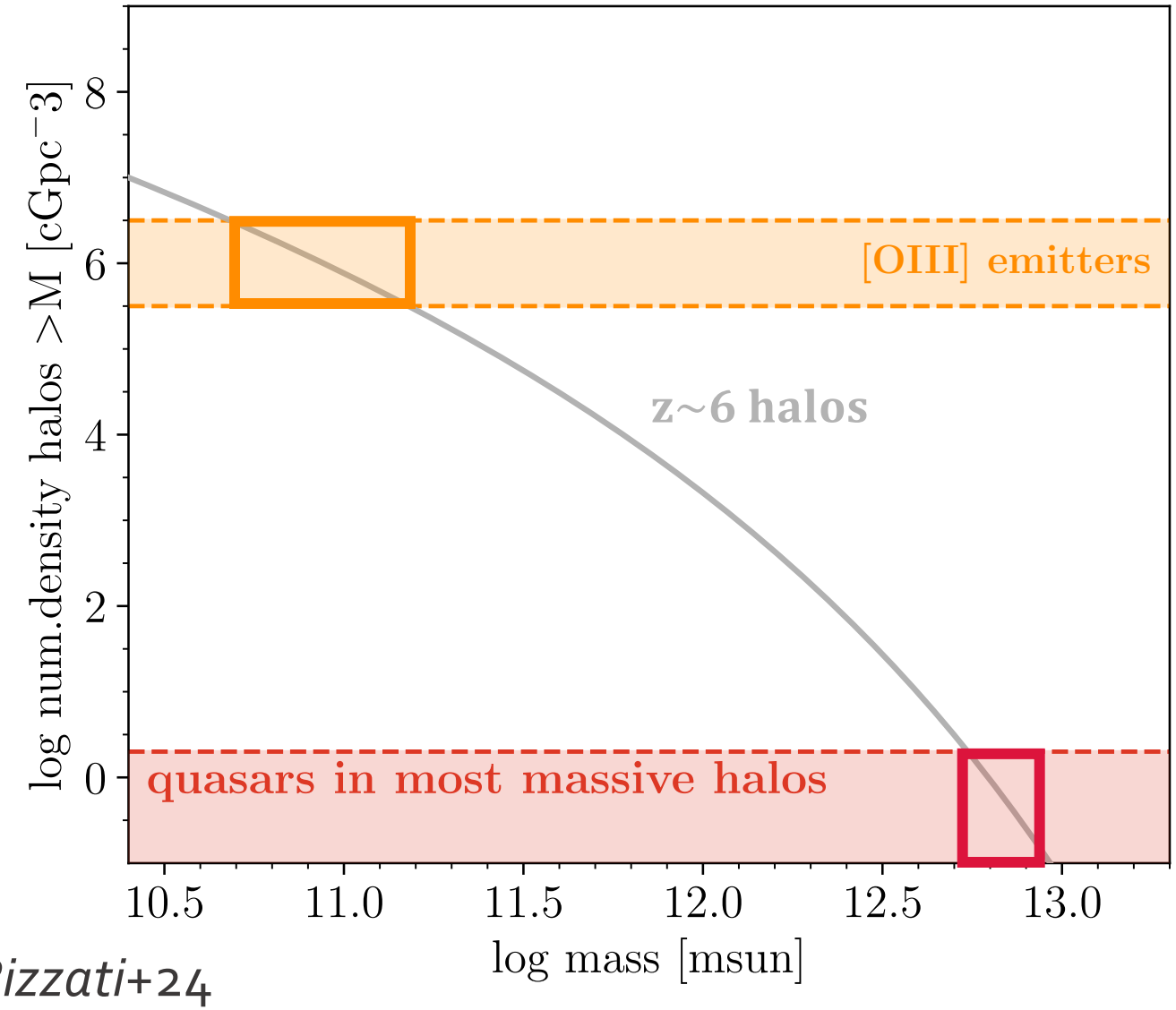
3. ***infer*** the luminosity-halo mass relation, ***host masses*** and ***duty cycle*** of quasars and galaxies



Pizzati+24ab



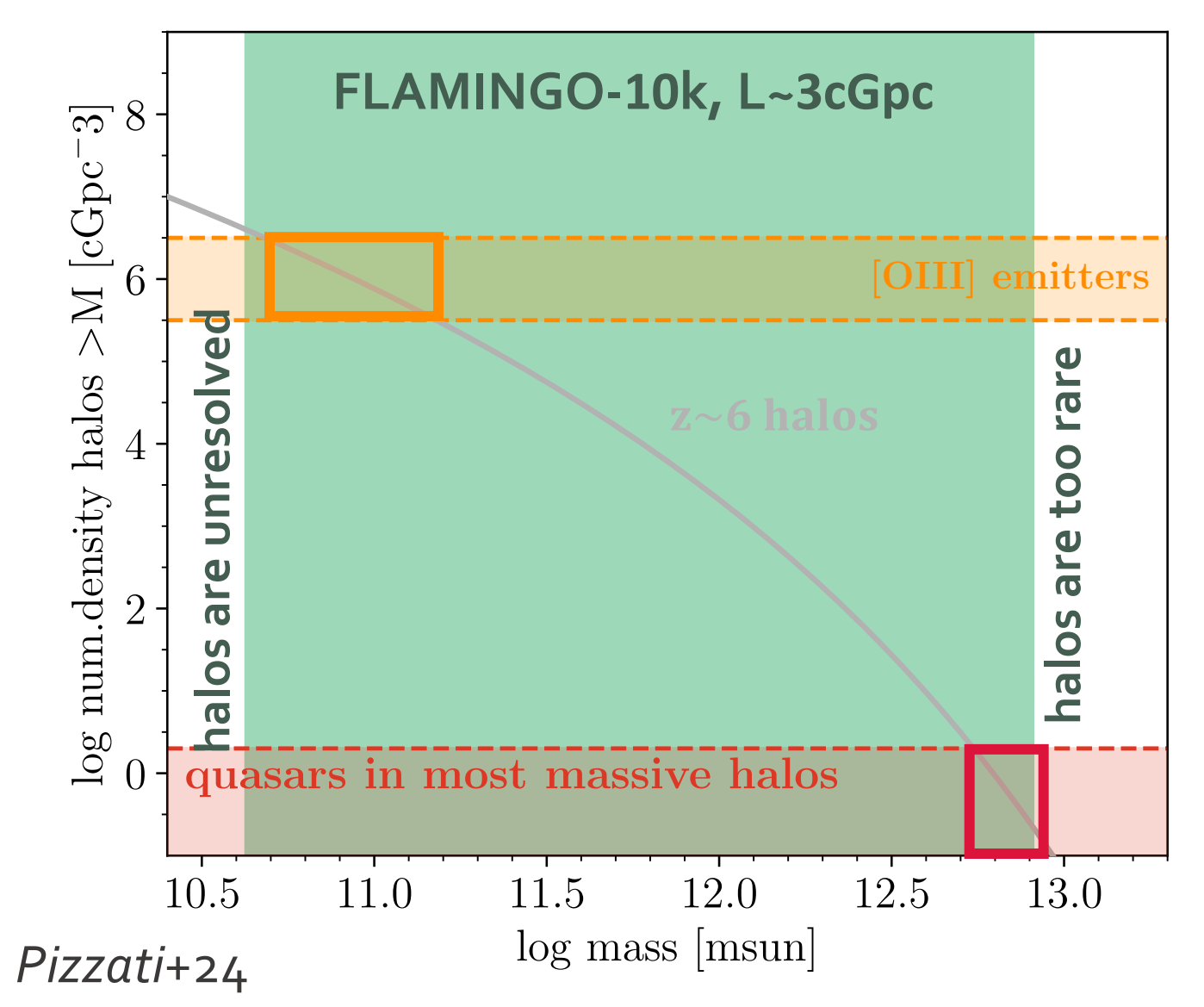
The challenge of dynamic range in simulations



Pizzati+24

OIII emitters are ~10^7 more *abundant* than high-z quasars!
→ different *host halo masses*

The challenge of dynamic range in simulations



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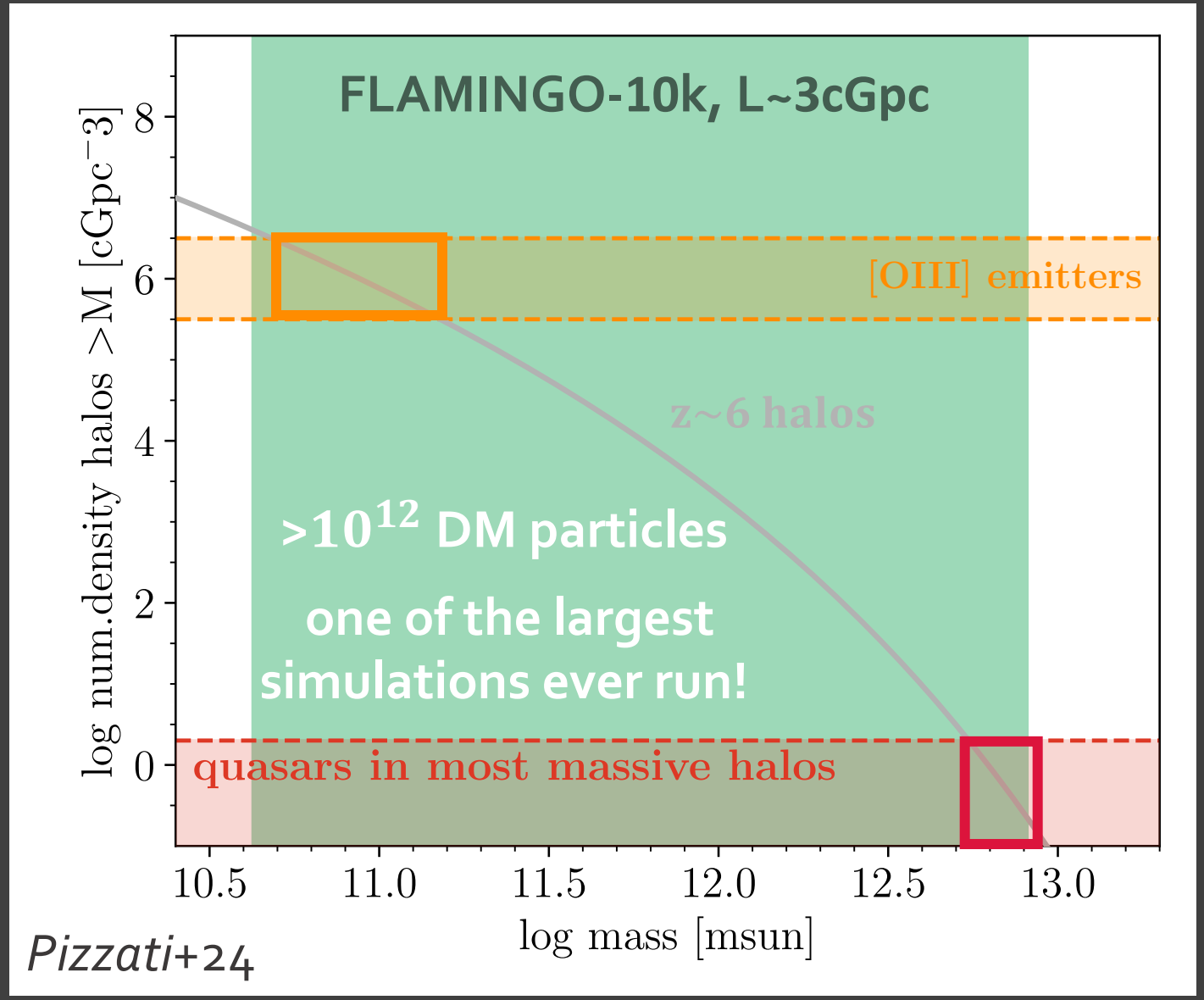
FLAMINGO: very ***large volume***, but ***low resolution***

FLAMINGO-10k: same volume, 8x ***higher resolution***
→ can resolve quasars and galaxies ***at the same time***

The challenge of dynamic range in simulations



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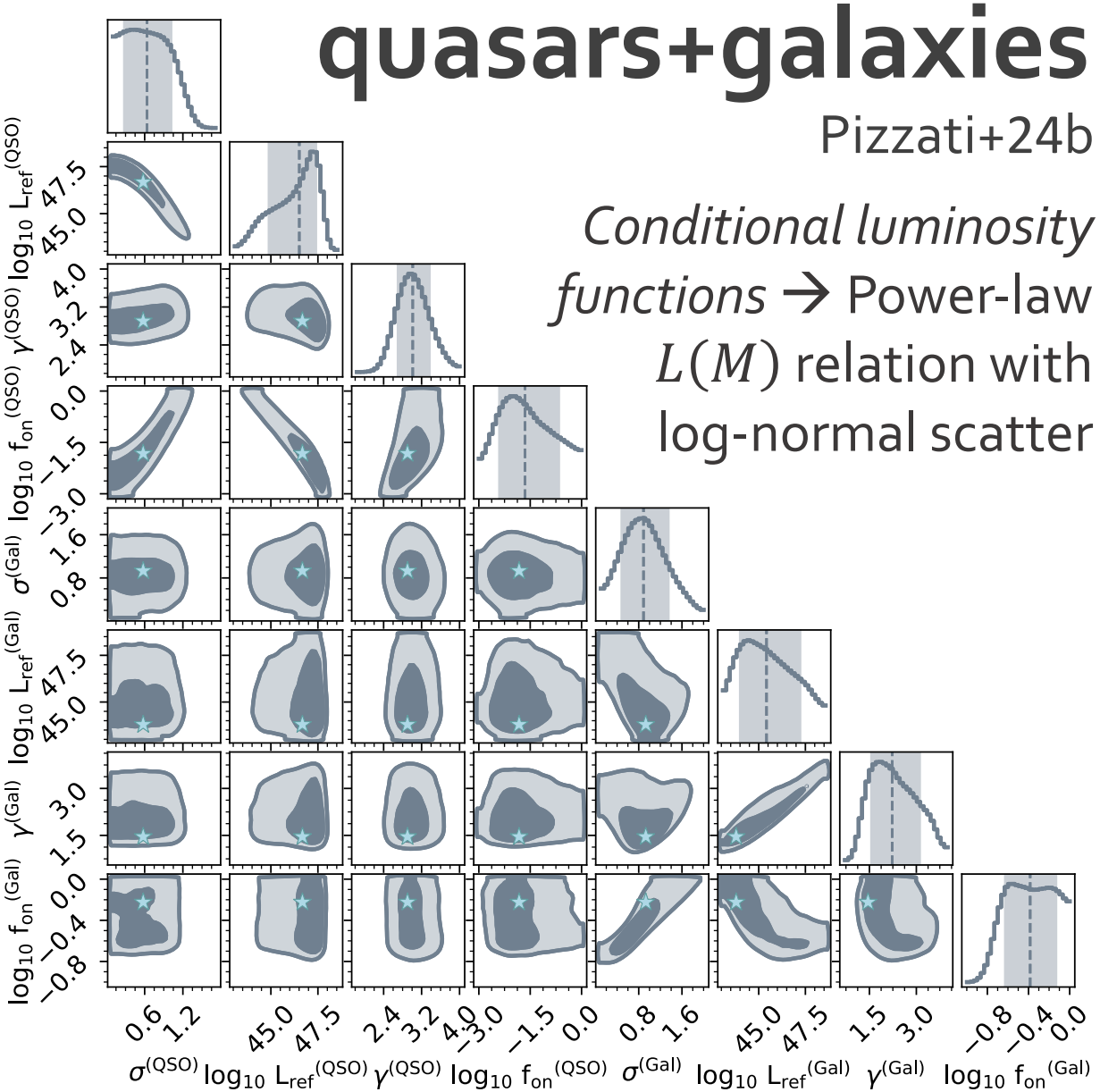
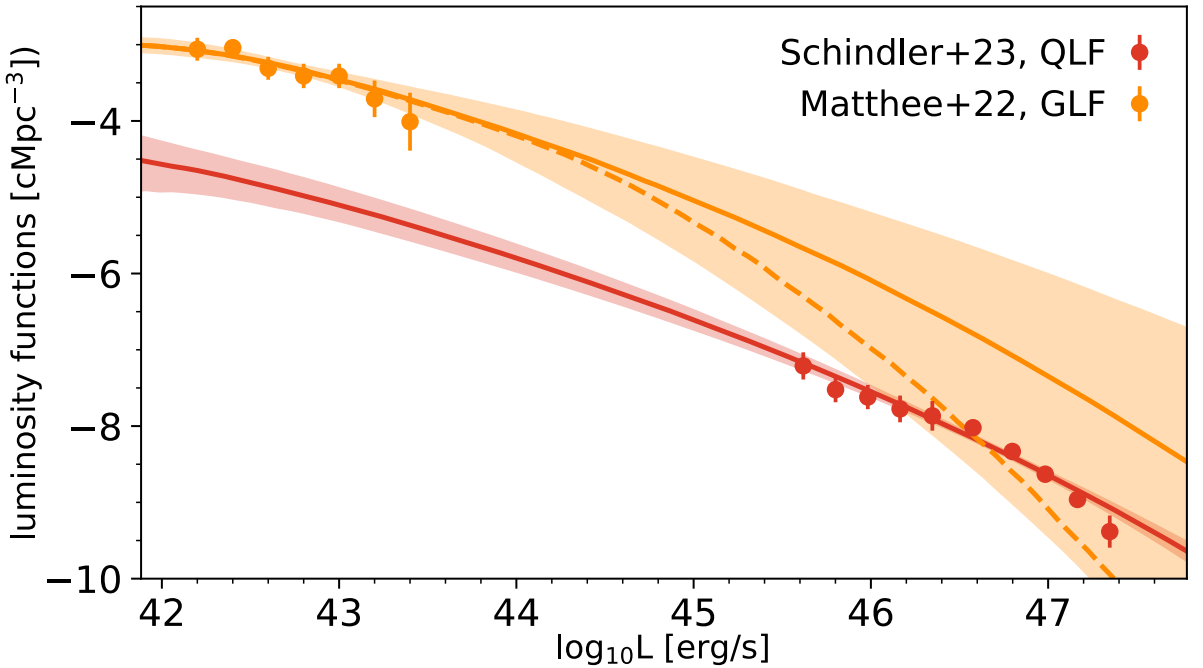
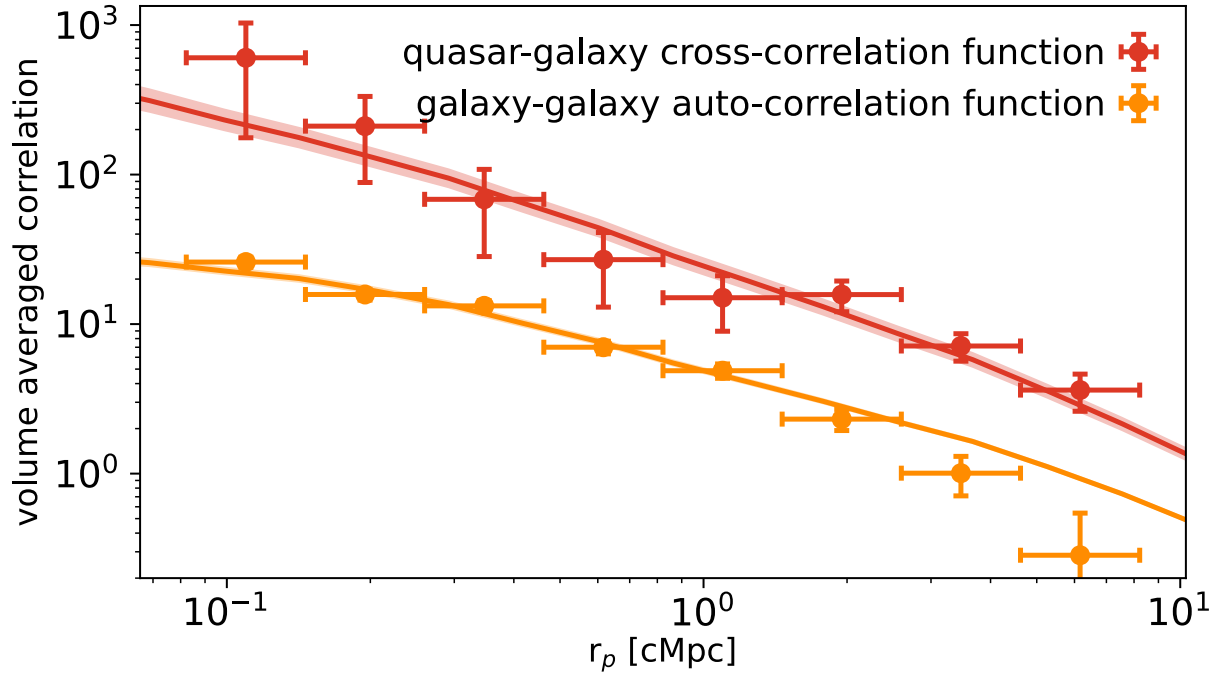
Joint inference of quasars+galaxies

Pizzati+24b

Conditional luminosity functions → Power-law $L(M)$ relation with log-normal scatter







Results for JWST quasar-galaxy clustering

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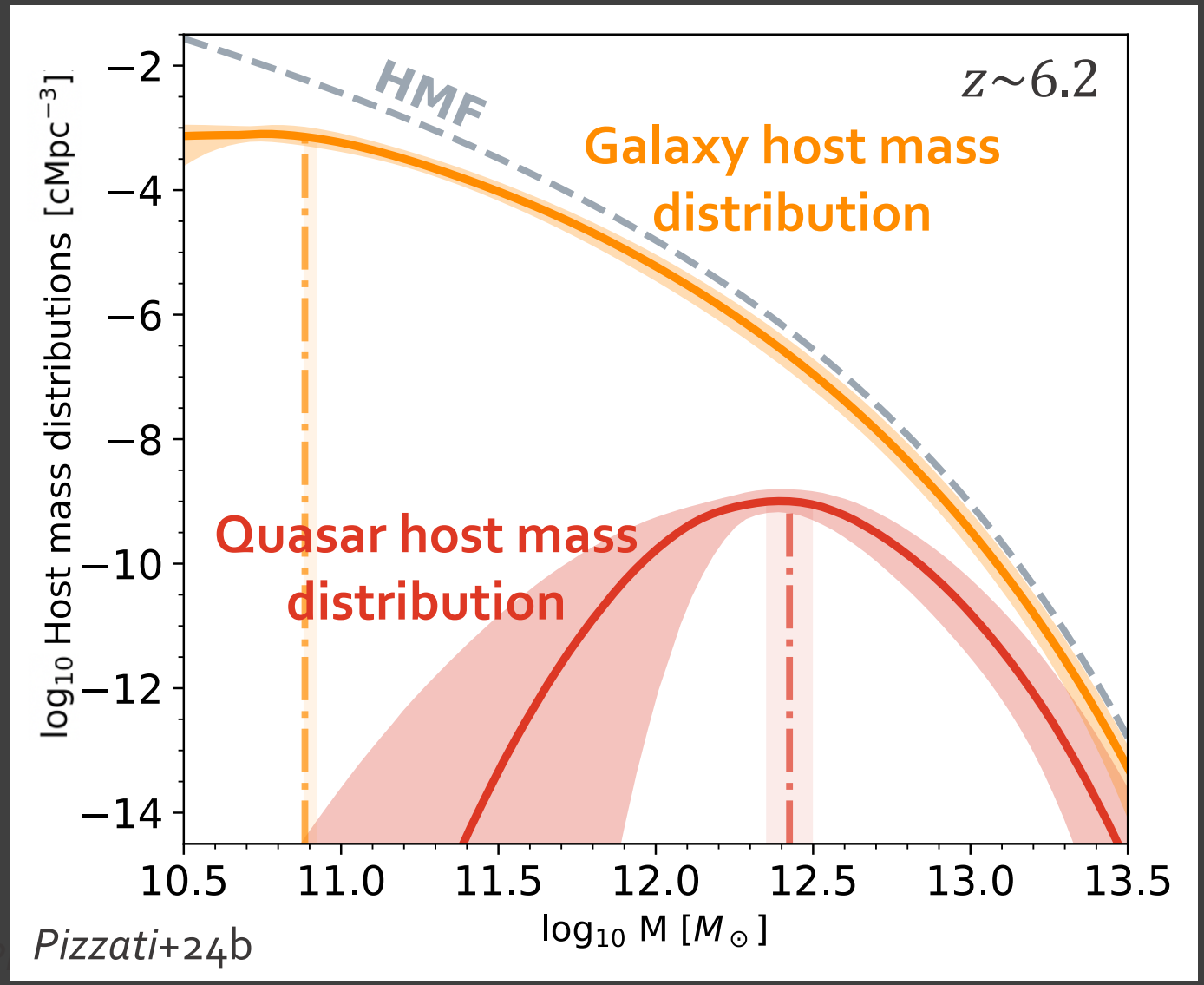
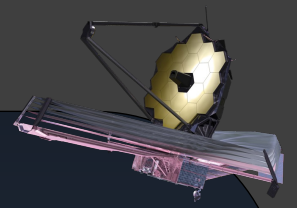
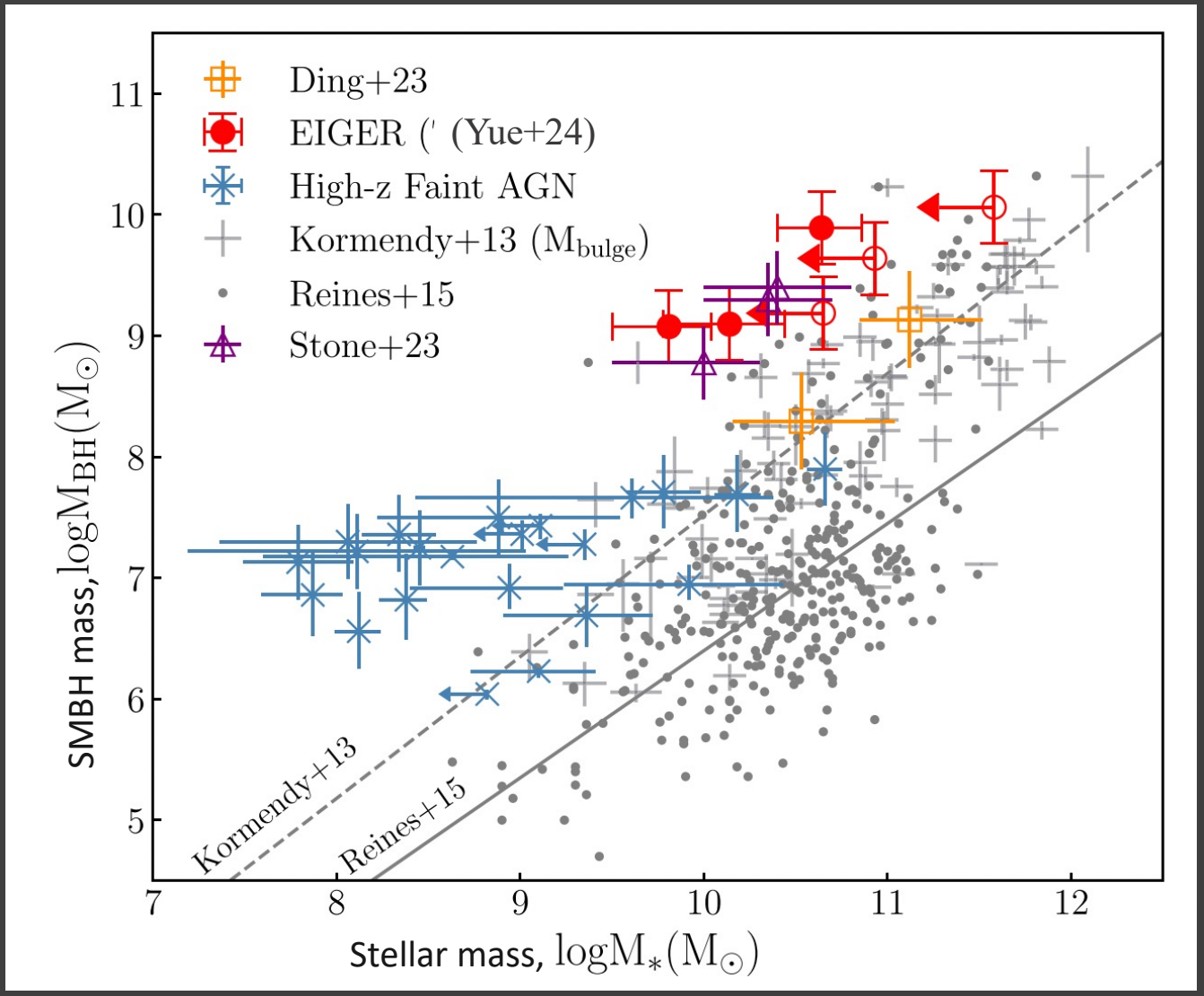


SMBH, stellar, halo masses in the JWST era

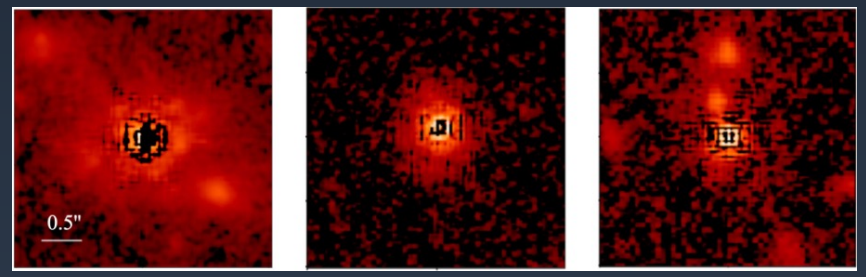




Yue+24

SMBH masses (M_{BH}) → from broad lines in quasar spectra

Stellar masses (M_*) → from direct detection of the host galaxy light



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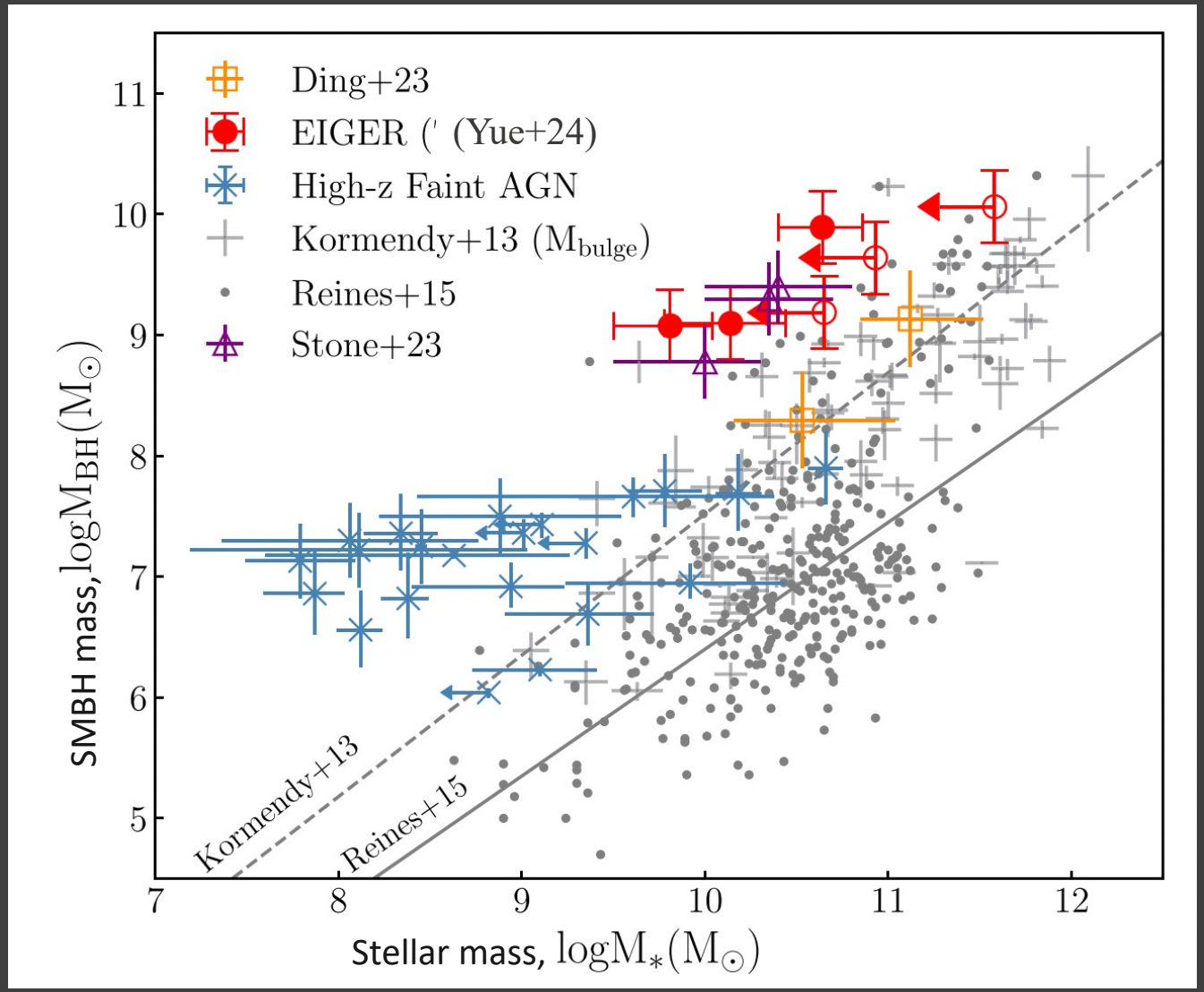

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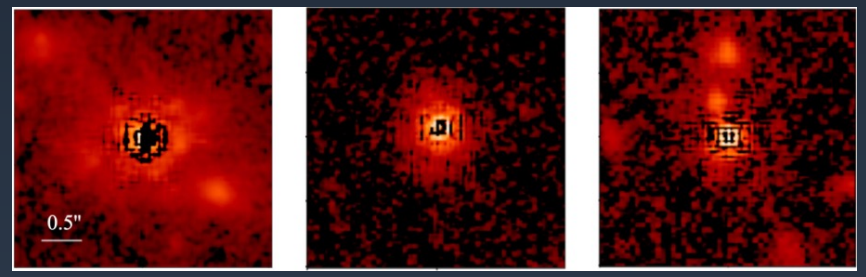
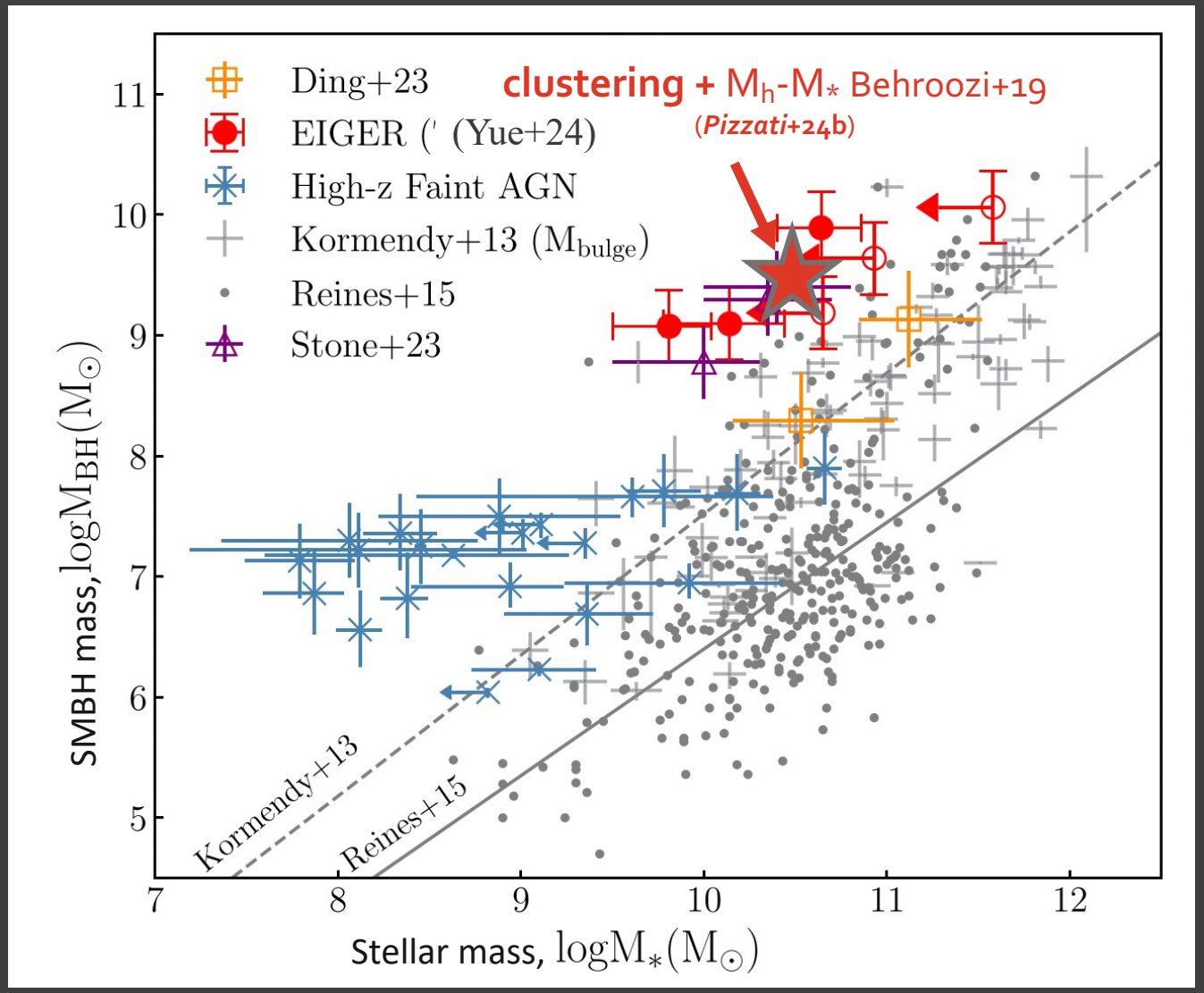


Yue+24

(average) ***halo masses*** (M_h) → from ***clustering*** measurements

SMBH, stellar, halo masses in the JWST era



Yue+24

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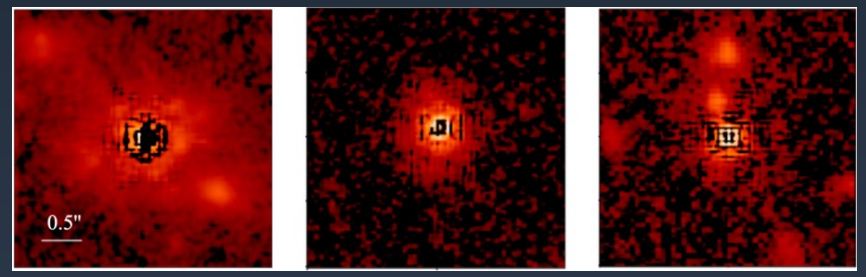

Yue+24

(average) ***halo masses*** (M_h) → from ***clustering*** measurements → consistent with stellar masses assuming a M_h-M_* relation

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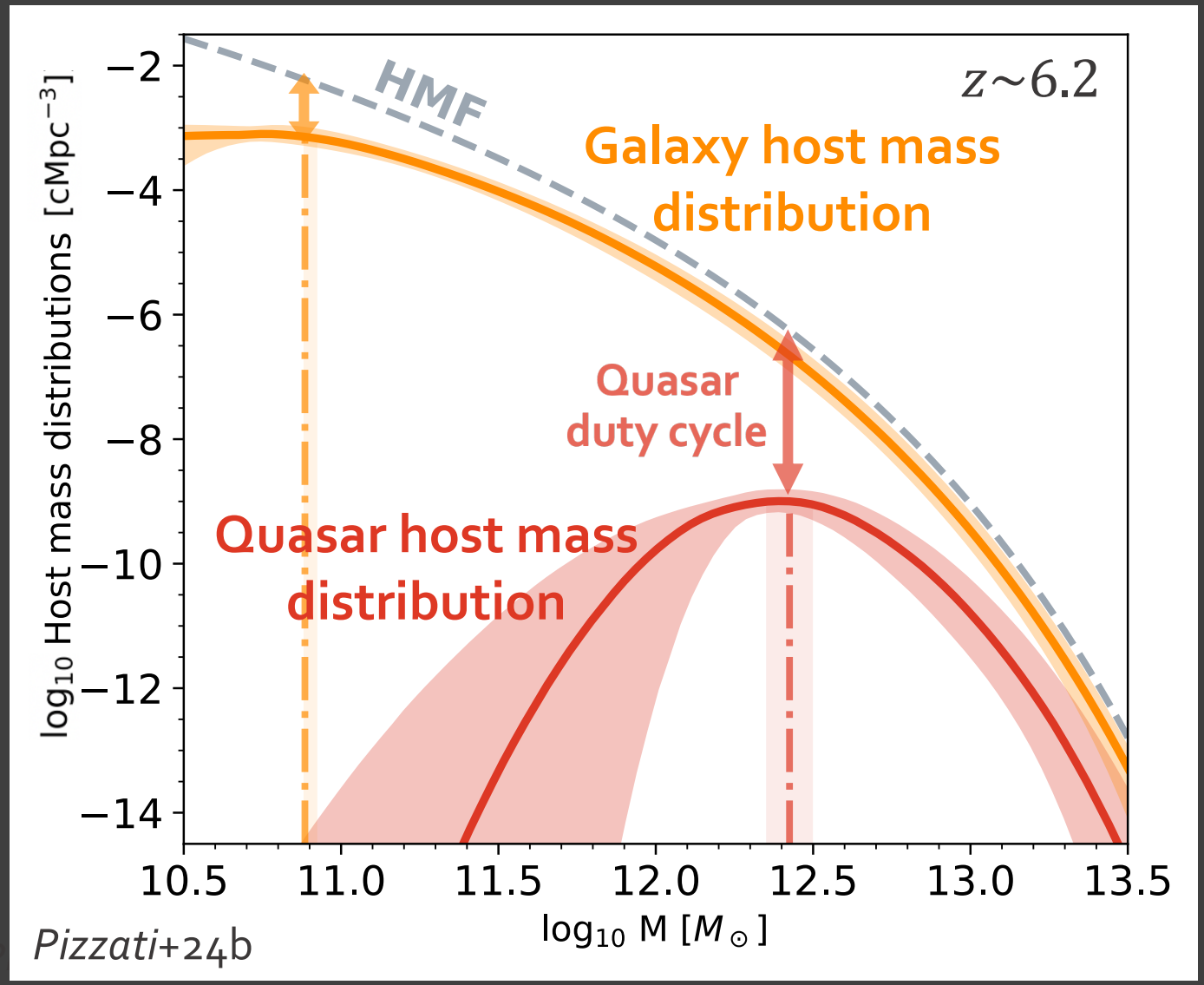


Challenges to BH growth at the highest redshifts

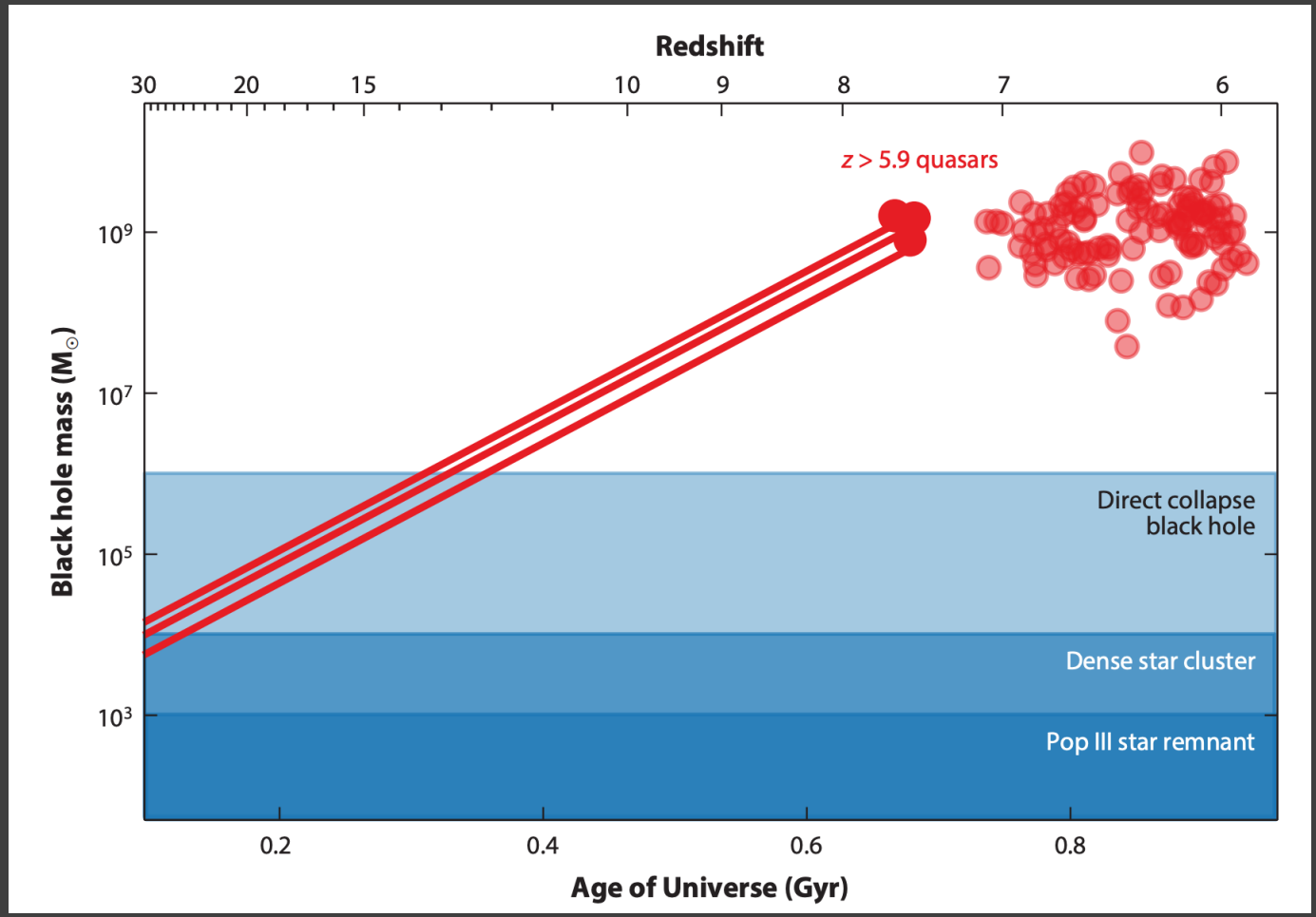
Steady accretion with constant ***Eddington ratio*** → **exponential growth**:

$$M_{BH} = M_{seed}\, e^{t/t_S}$$

with a ***Salpeter timescale***:

$$t_{\rm Salp} \sim 45\ {\rm Myr} \left(\frac{\varepsilon}{0.1}\right)\left(\frac{L}{L_{\rm E}}\right)^{-1}$$

At z>6-7, SMBH need to be growing ***continously***



Fan+23

A *bursty* star formation/BH accretion history?

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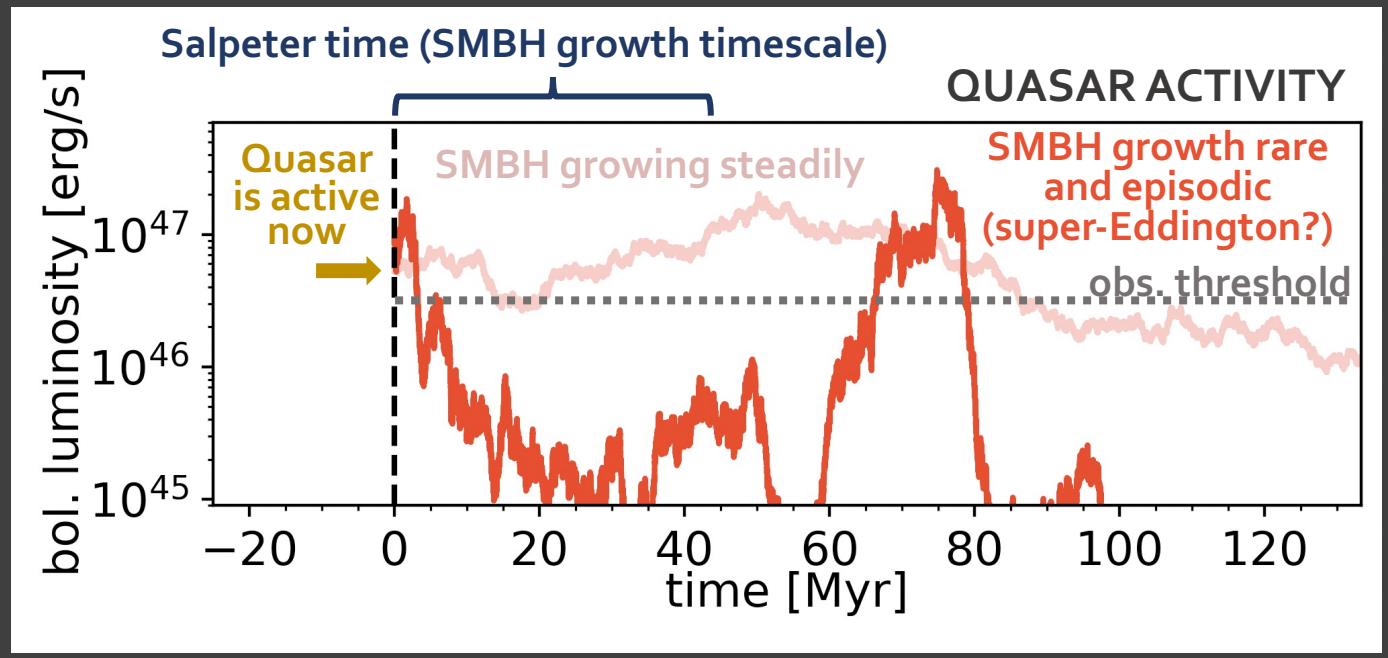

Pizzati+24b

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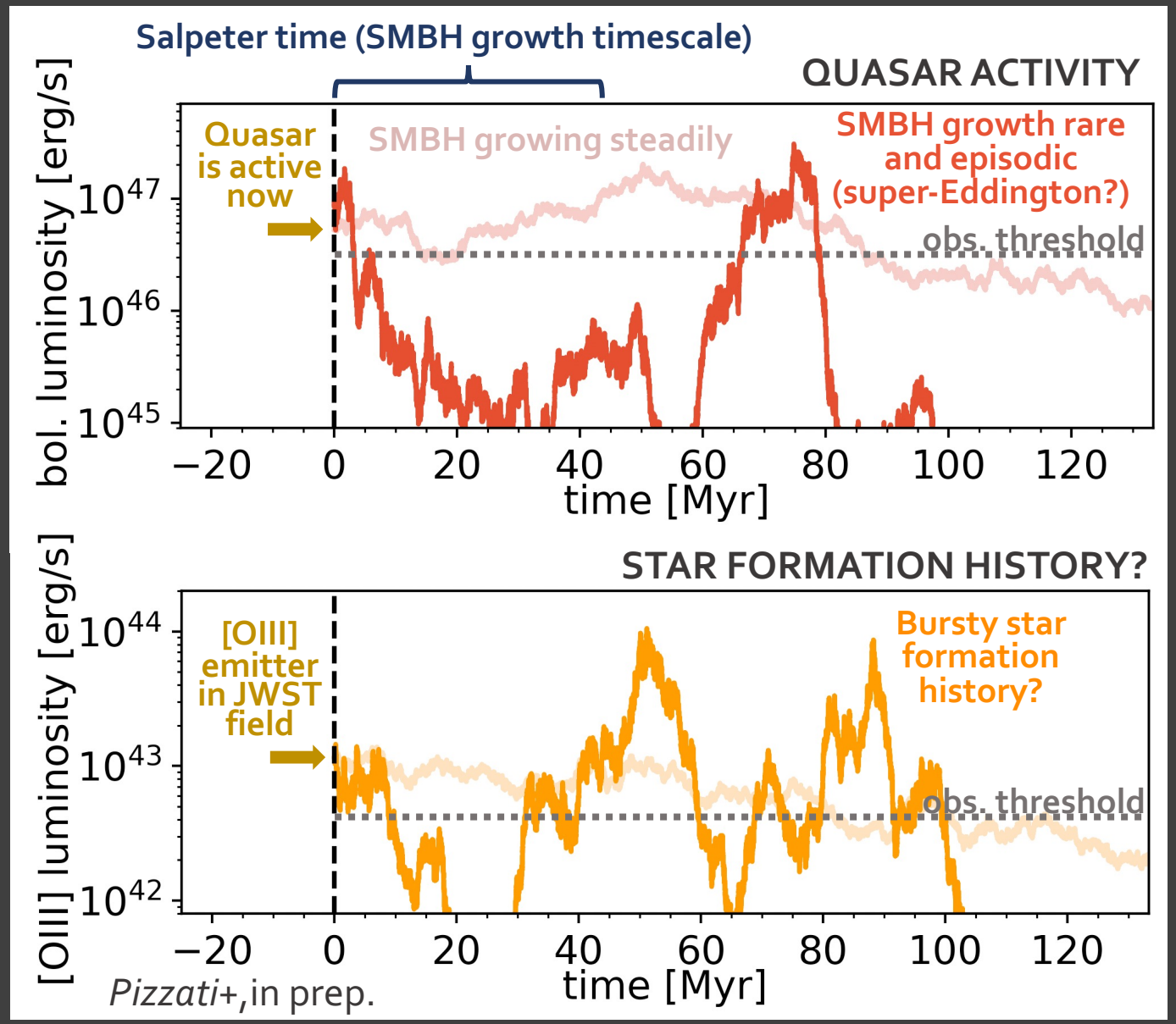
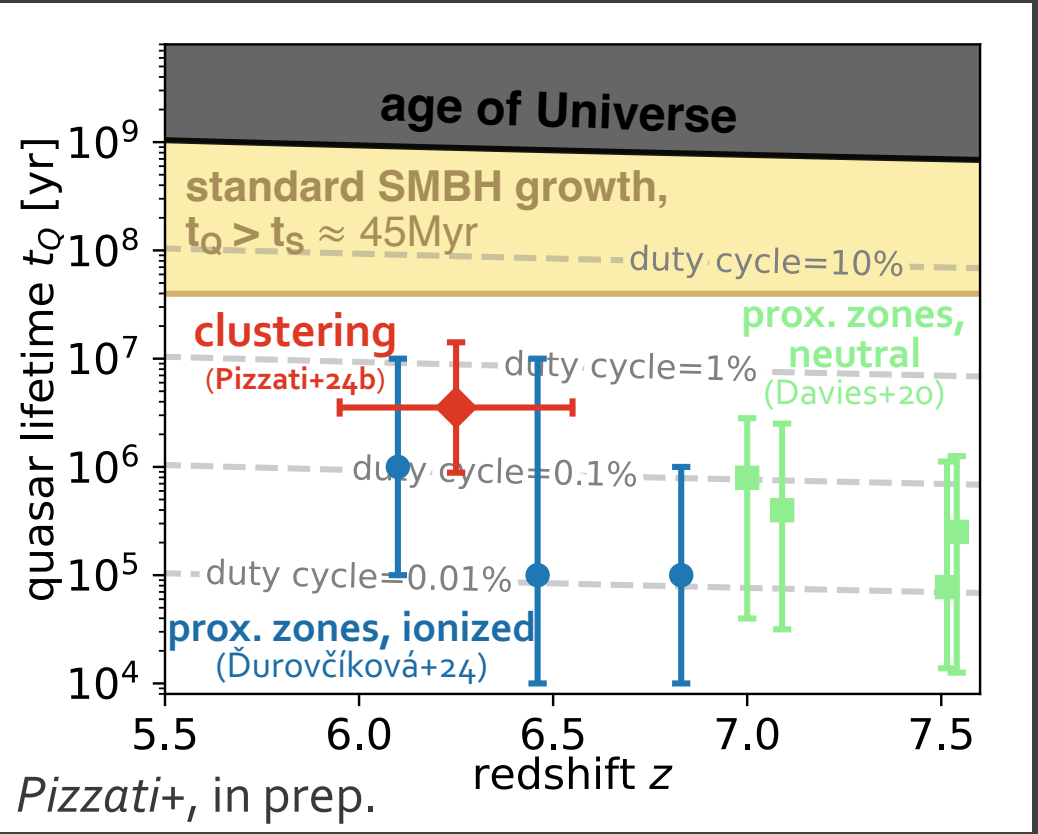


Constraints on the *lifetime* of high-z quasars



SMBHs grow rapidly but we do not see this in quasar light

$$\dot{M}_{BH} \neq \frac{1-\varepsilon}{\varepsilon c^2} L \quad ???$$

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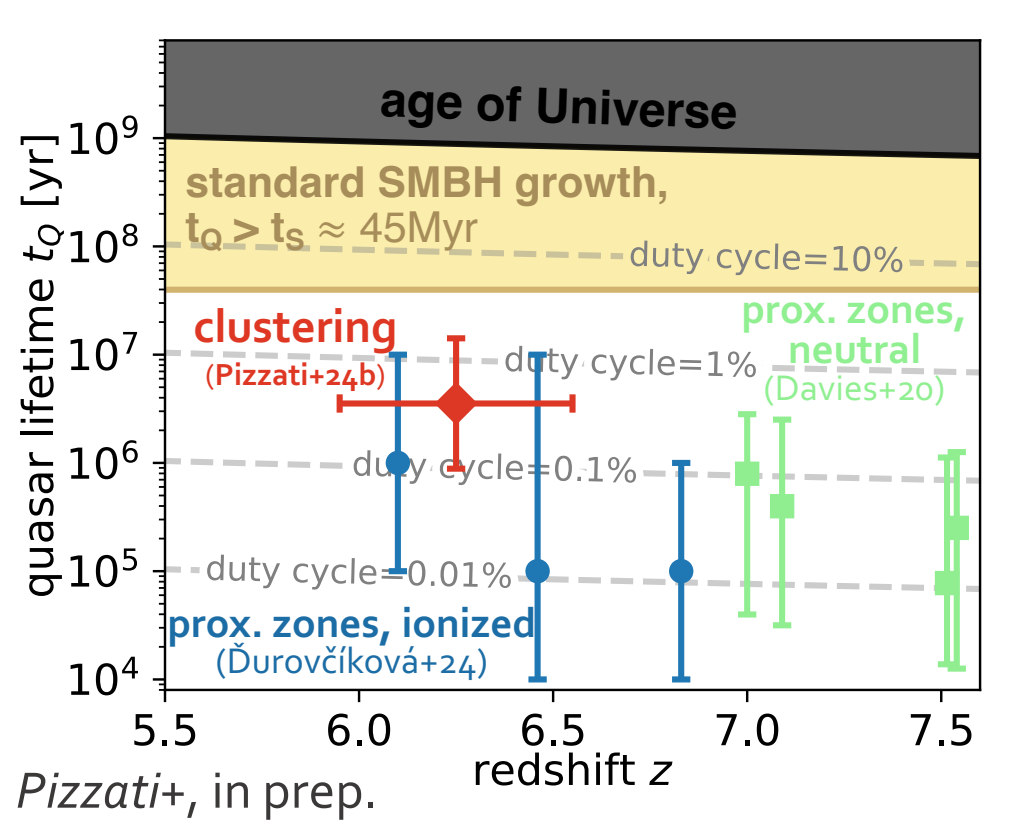


Pizzati+, in prep.

SMBHs grow rapidly but we do not see this in quasar light

$$\dot{M}_{BH} \not< \frac{1-\varepsilon}{\varepsilon c^2} L \quad ???$$

1

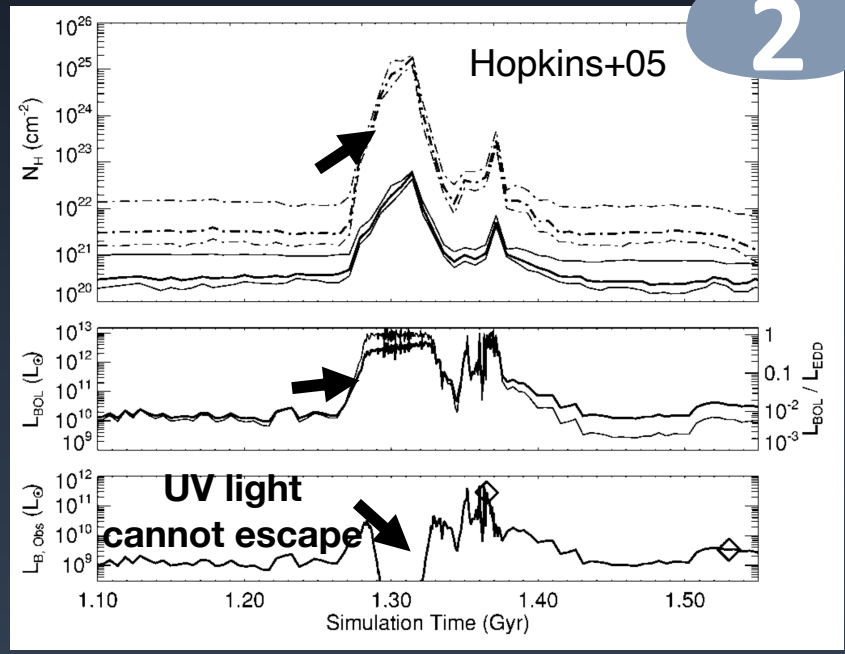
Is t_Q intrinsically short? rapid ***radiatively inefficient*** ($\varepsilon \sim 0.002$) accretion?

$$t_{\rm Salp} \sim 45\ {\rm Myr} \left(\frac{\varepsilon}{0.1}\right)\left(\frac{L}{L_{\rm E}}\right)^{-1}$$

2

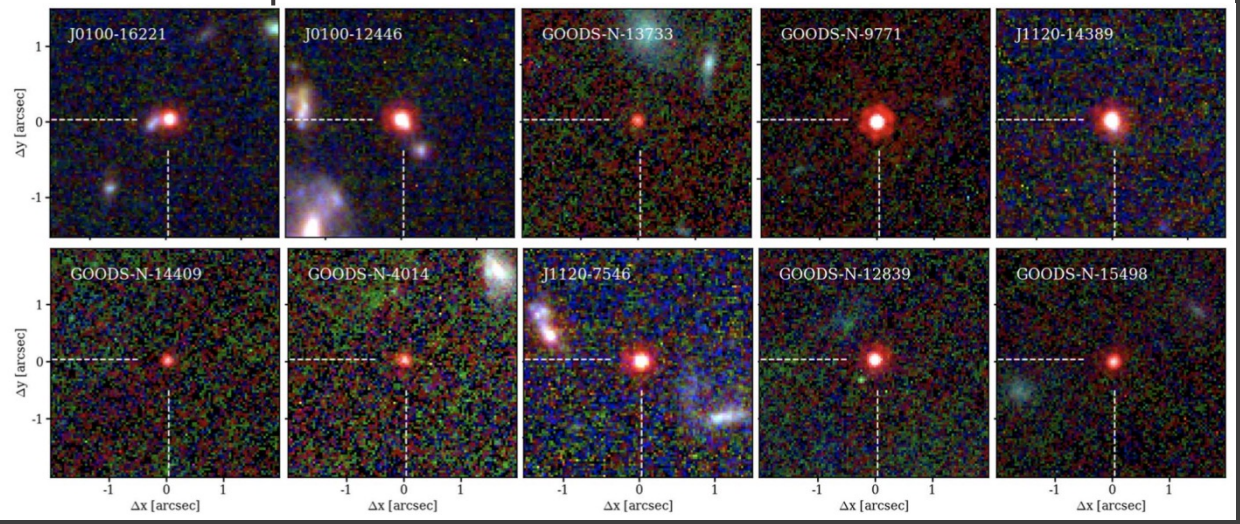
Is most of SMBH growth ***UV-obscured***?

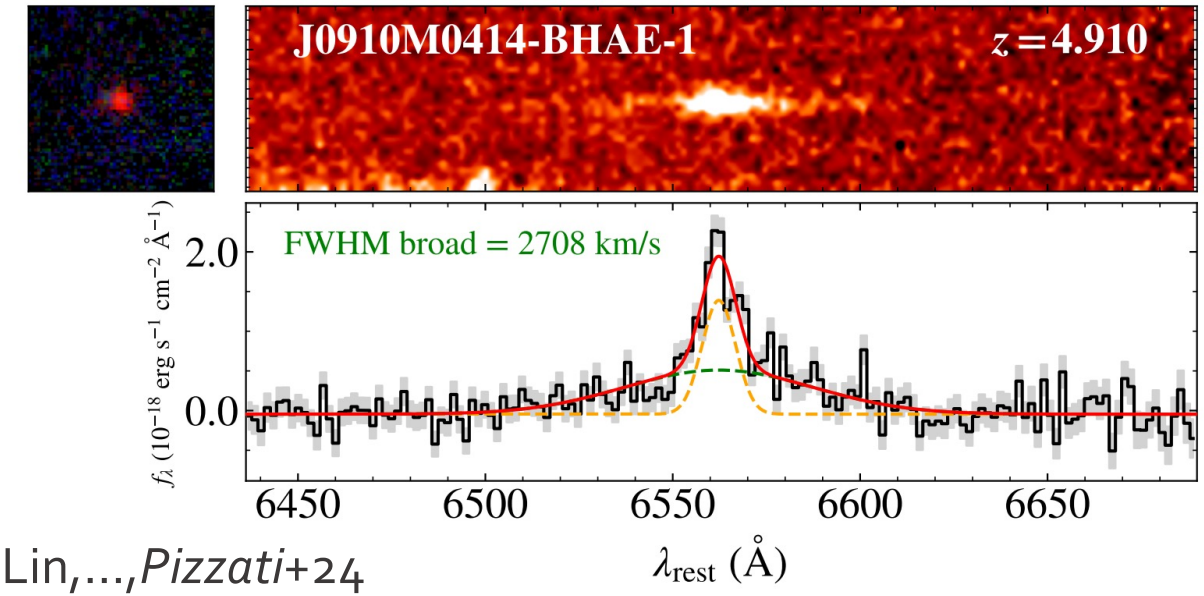
obscured: unobscured ratio ~ 50:1



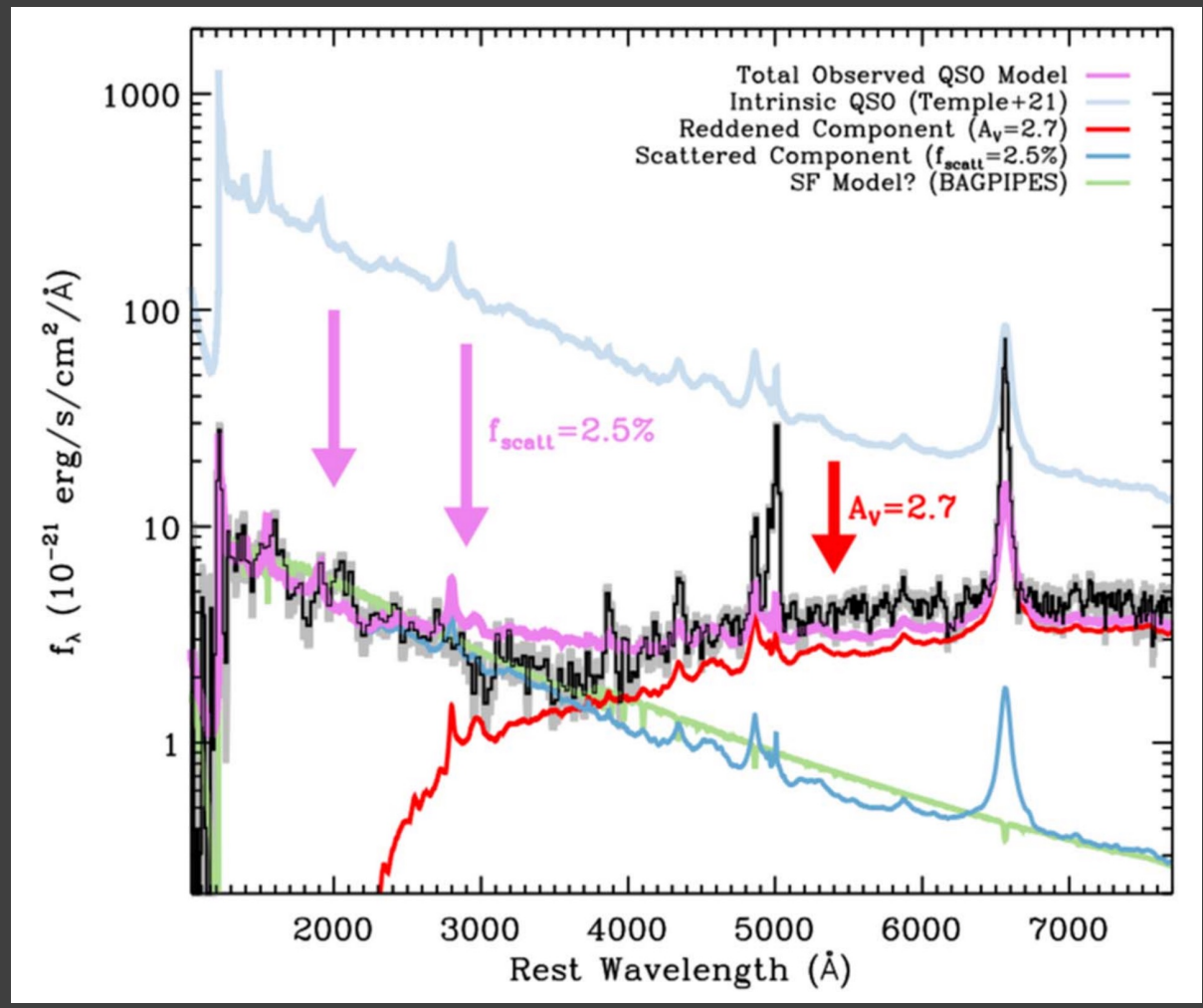
Reddened broad line AGN? the "Little Red Dots"

Matthee+24



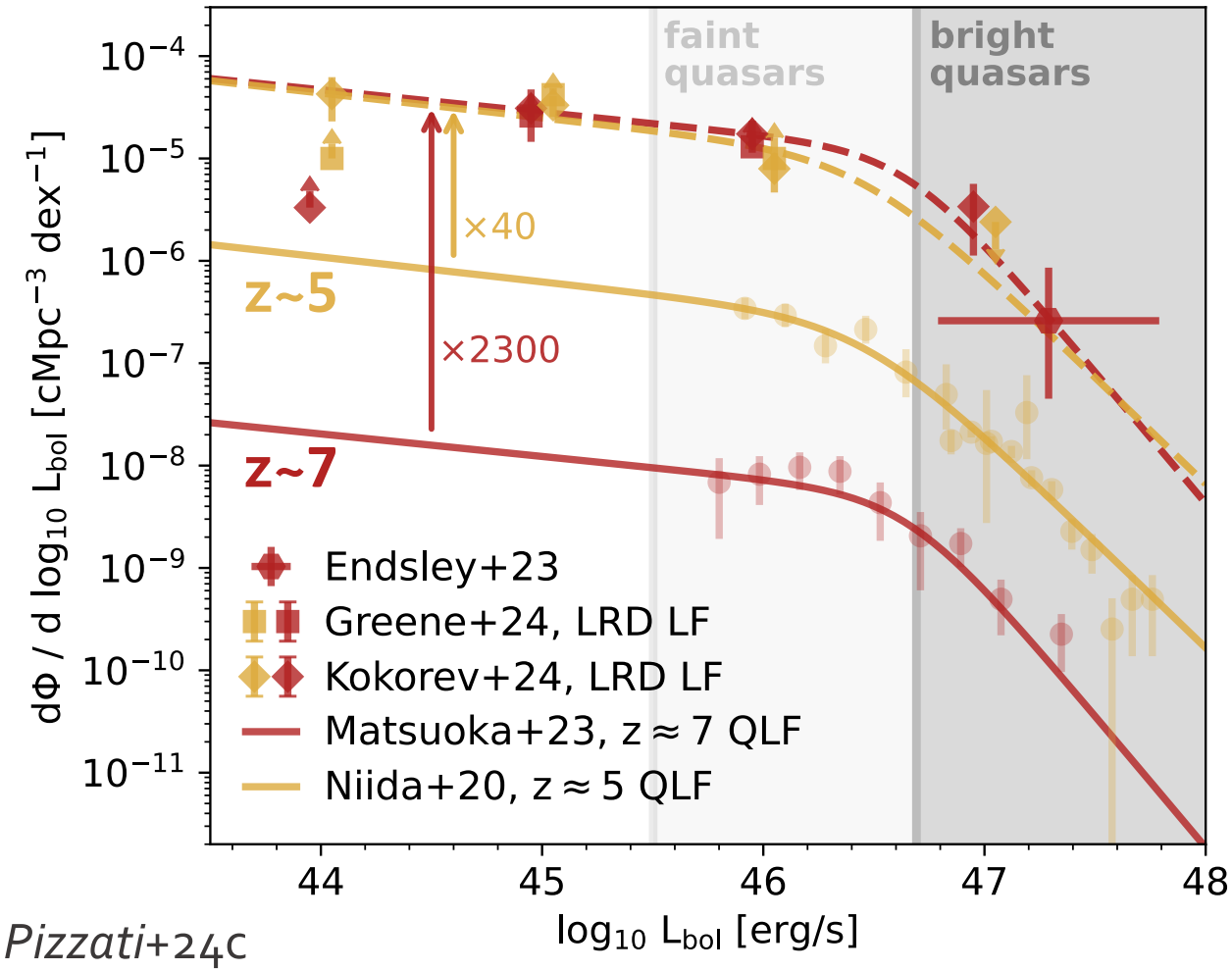


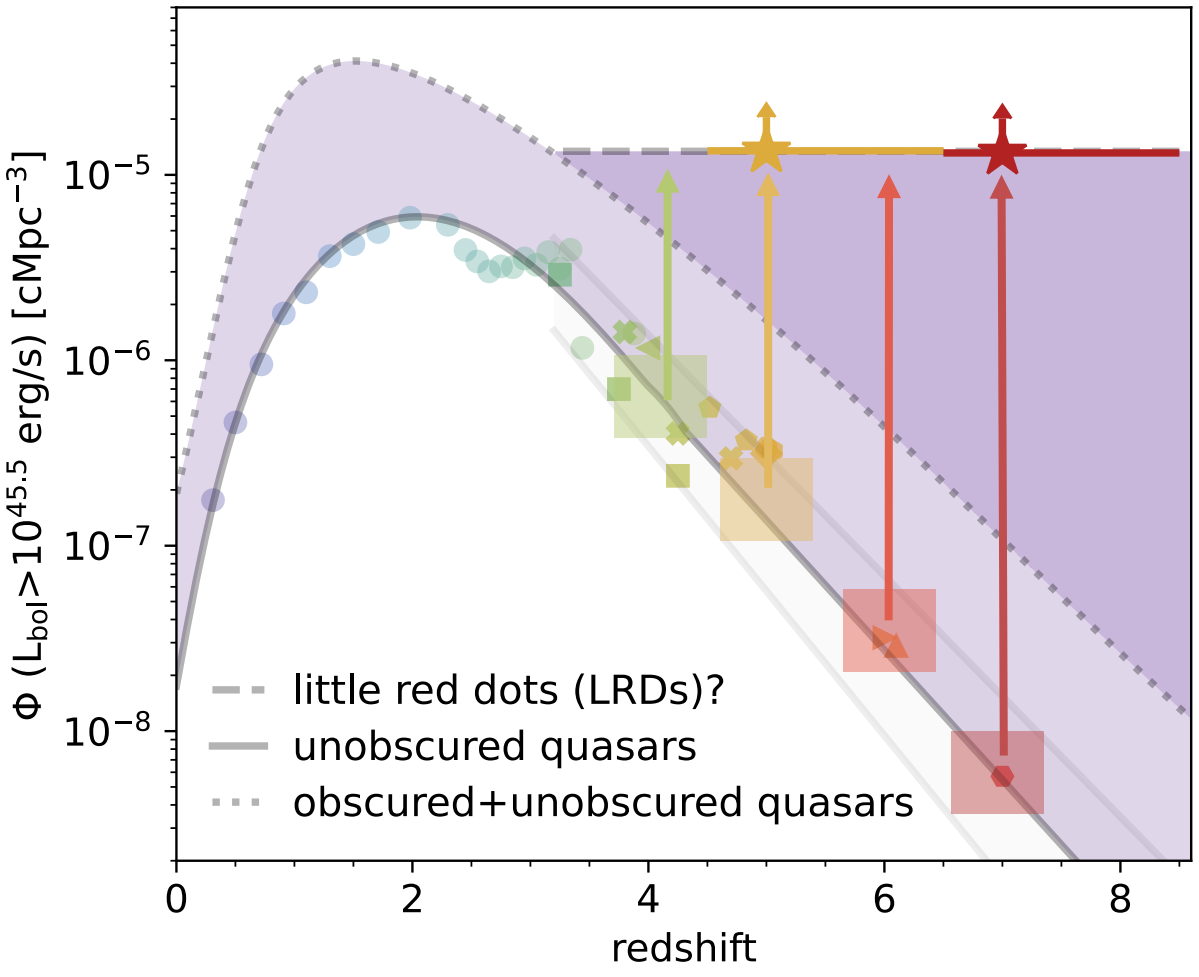
Lin,…,*Pizzati*+24



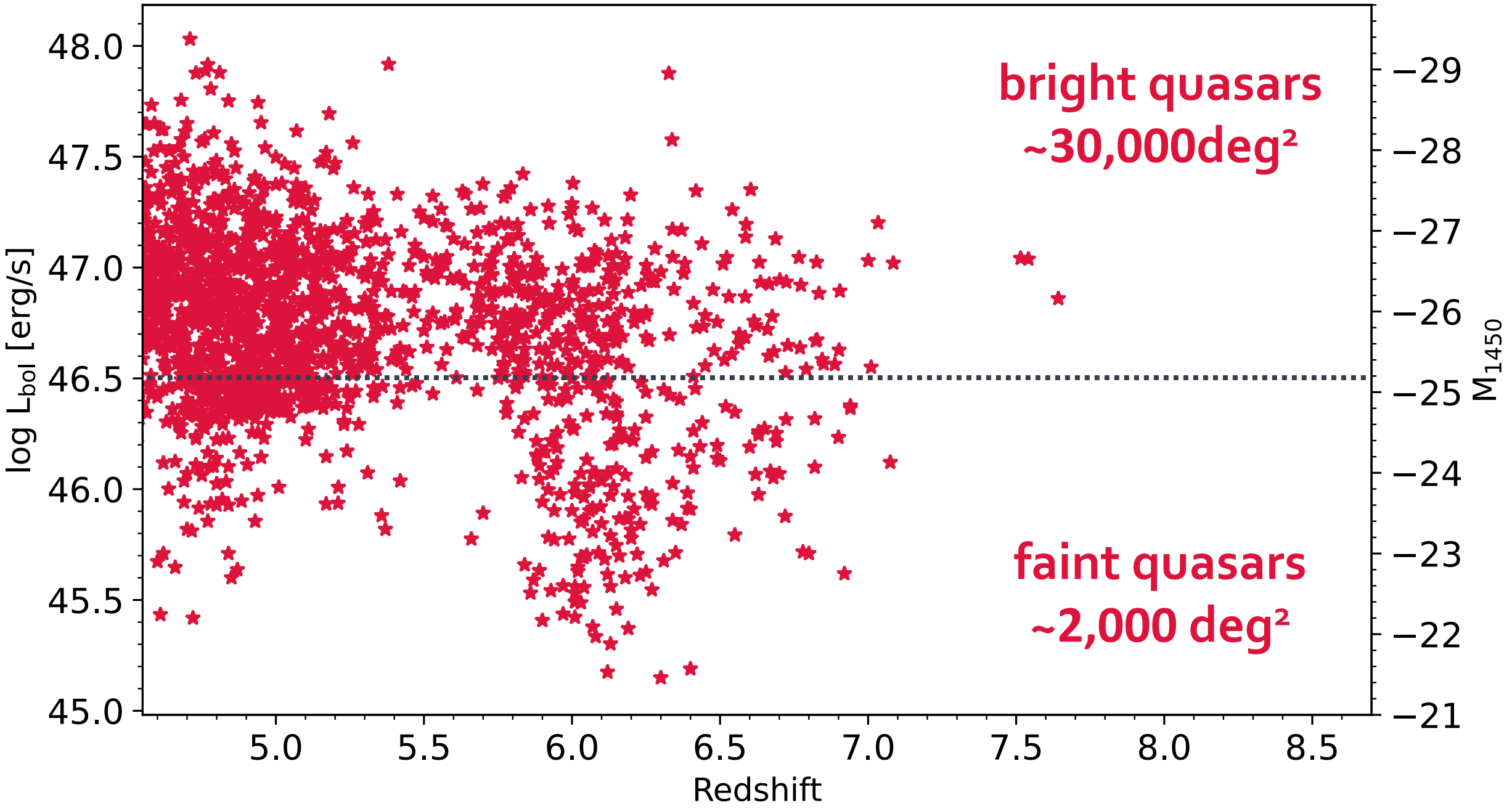
Greene+24

A huge UV-obscured AGN population at high z?





Pizzati+24c


bright quasars
~30,000deg²
faint quasars
~2,000 deg²
log L_bol [erg/s]
M_1450
Redshift
48.0
47.5
47.0
46.5
46.0
45.5
45.0
−29
−28
−27
−26
−25
−24
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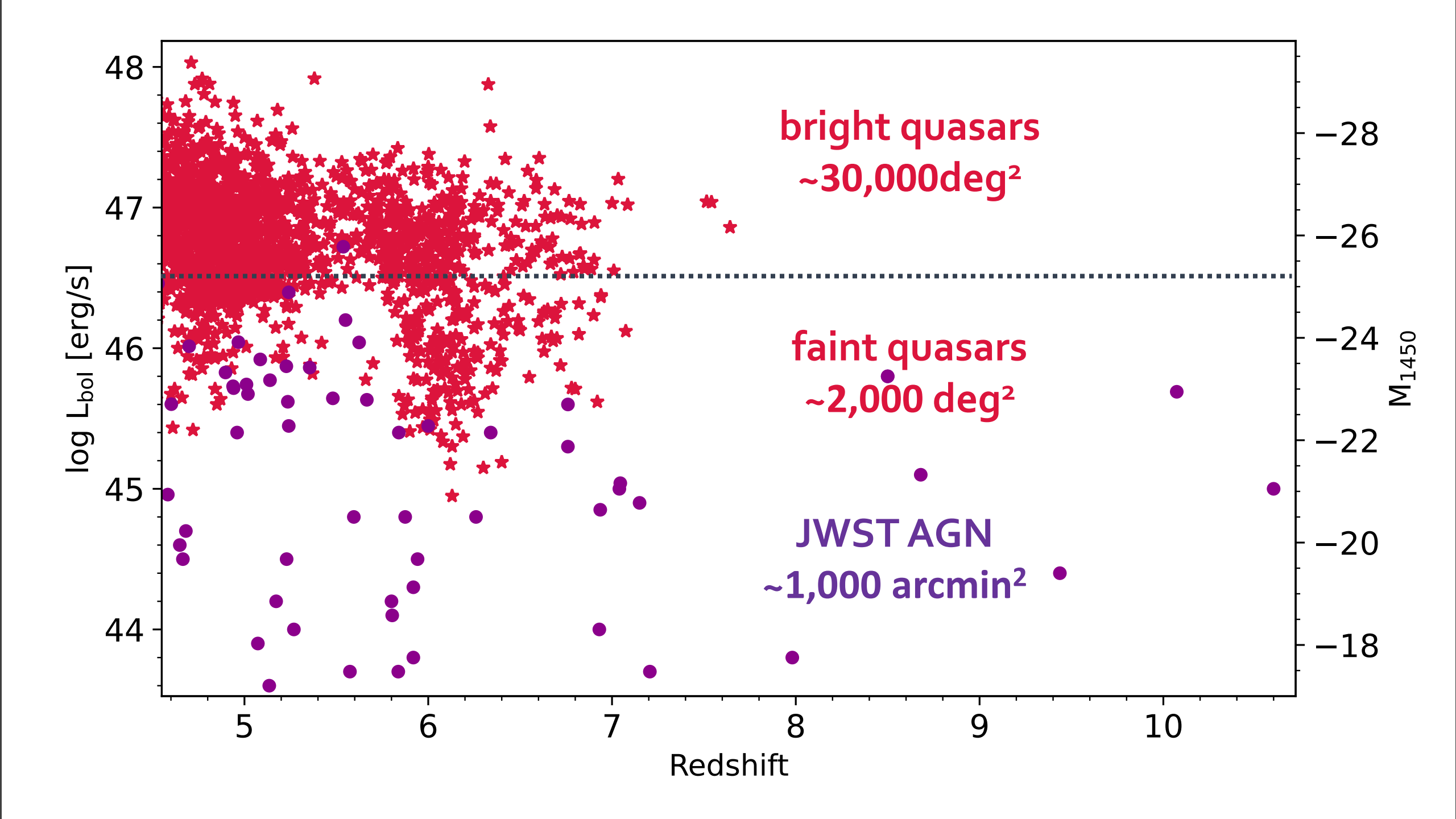
6.0
6.5
7.0
7.5
8.0
8.5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JWST AGN
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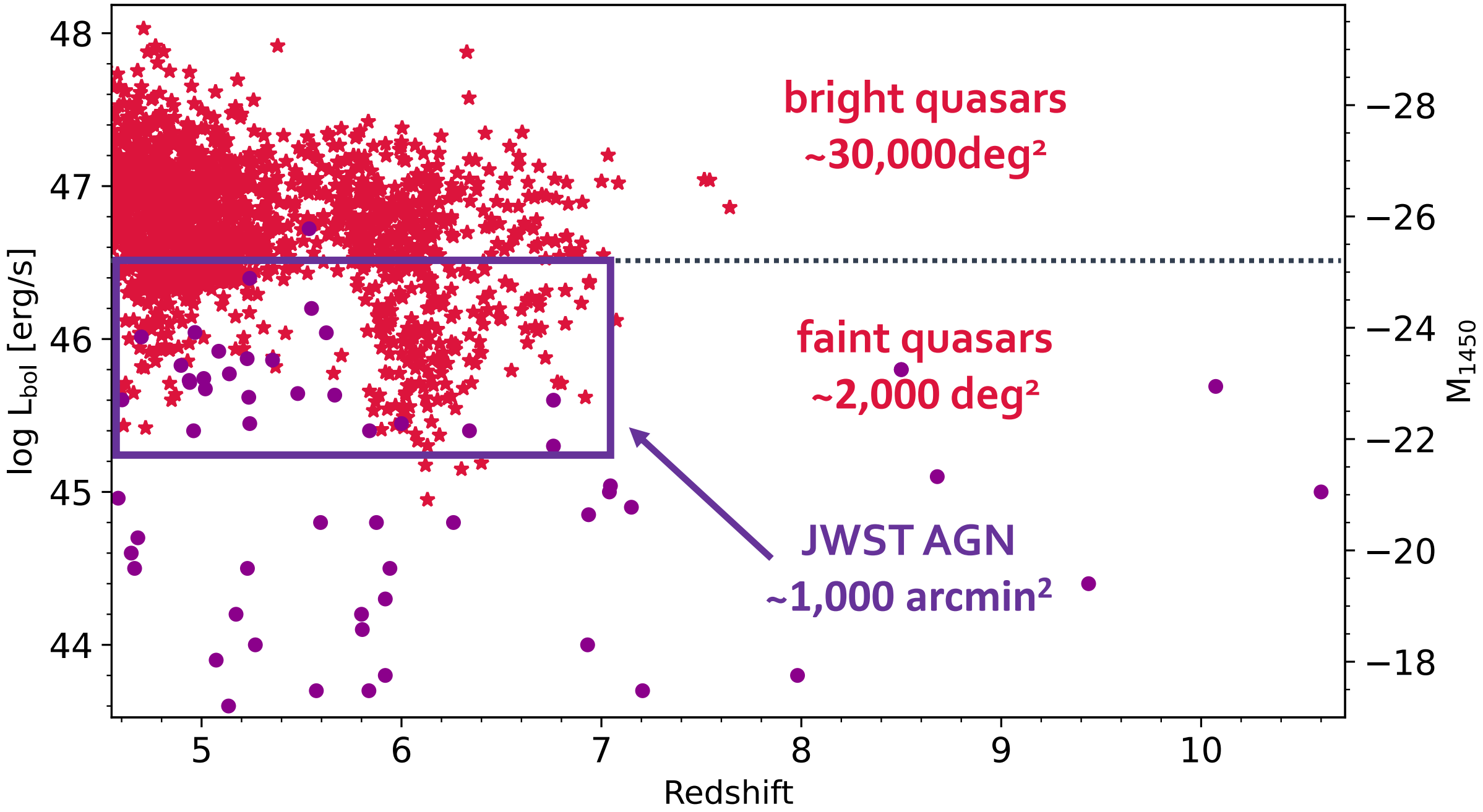
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48
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−26
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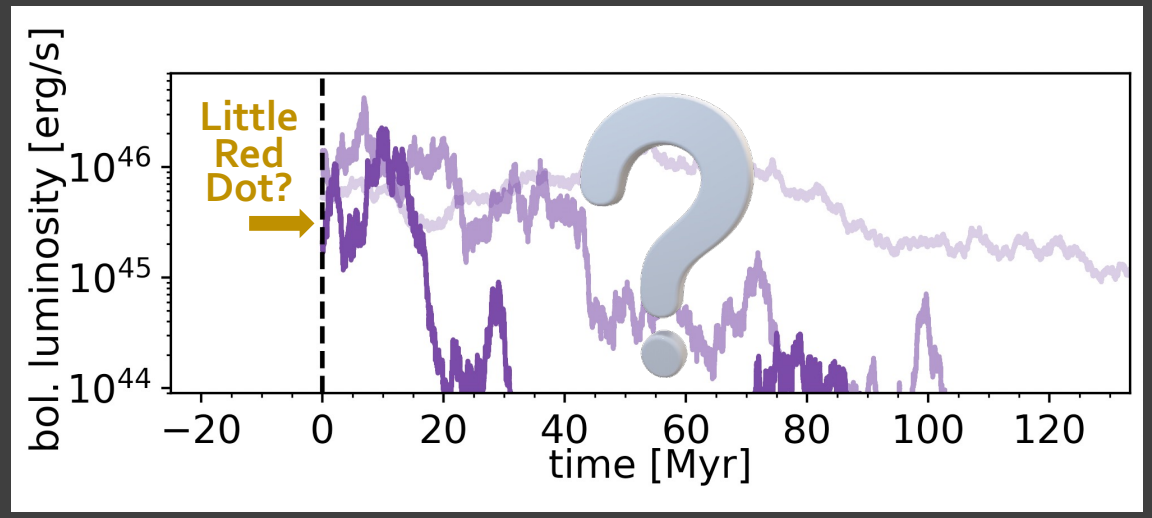
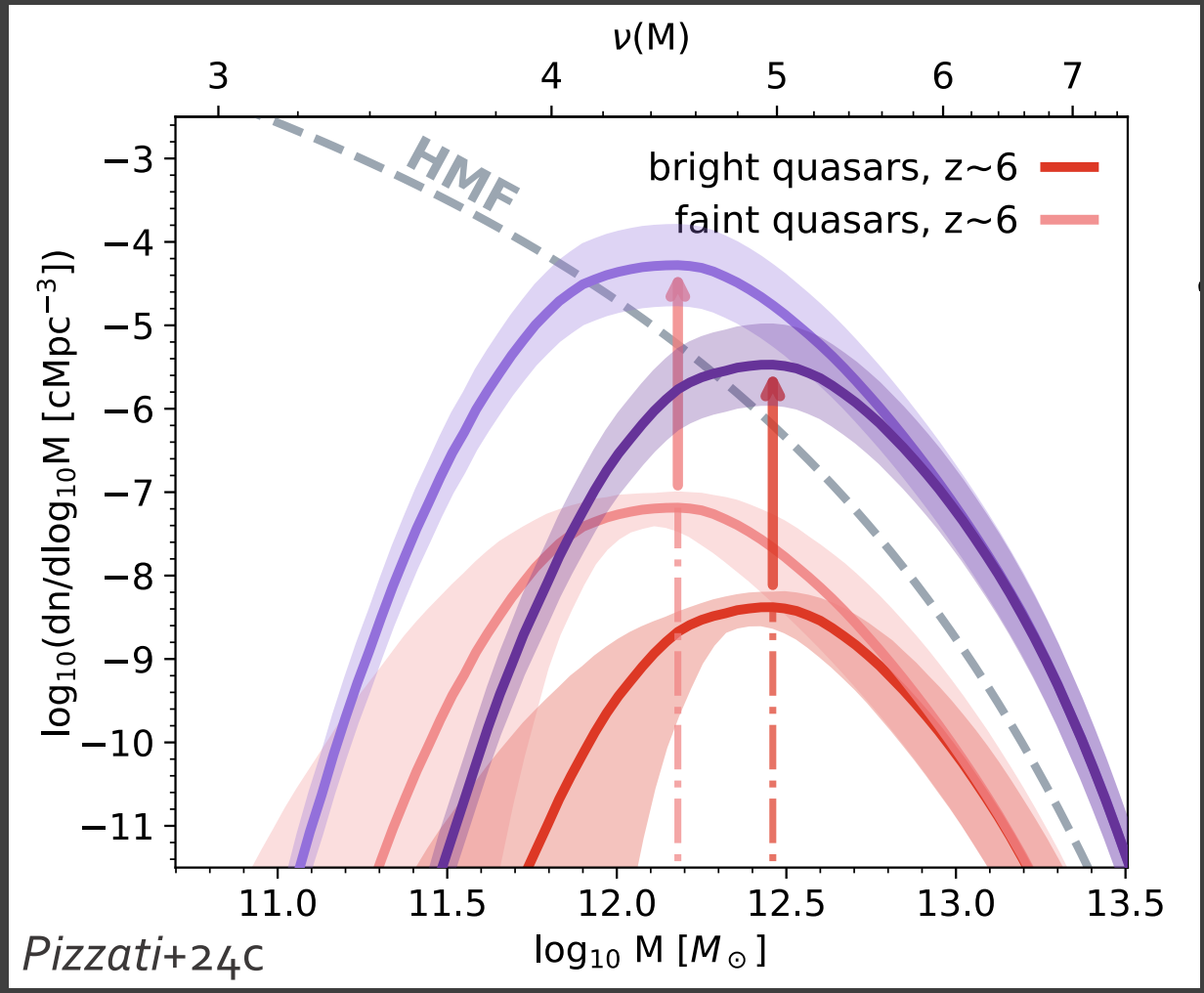
5
6
7
8
9
10

LCDM+quasar clustering can give us insight…

Little Red Dots?

- They are too abundant to live in the same halos as quasars → *LCDM* tells us they obey ***different scaling relations!***
- Duty cycle? SMBH growth?

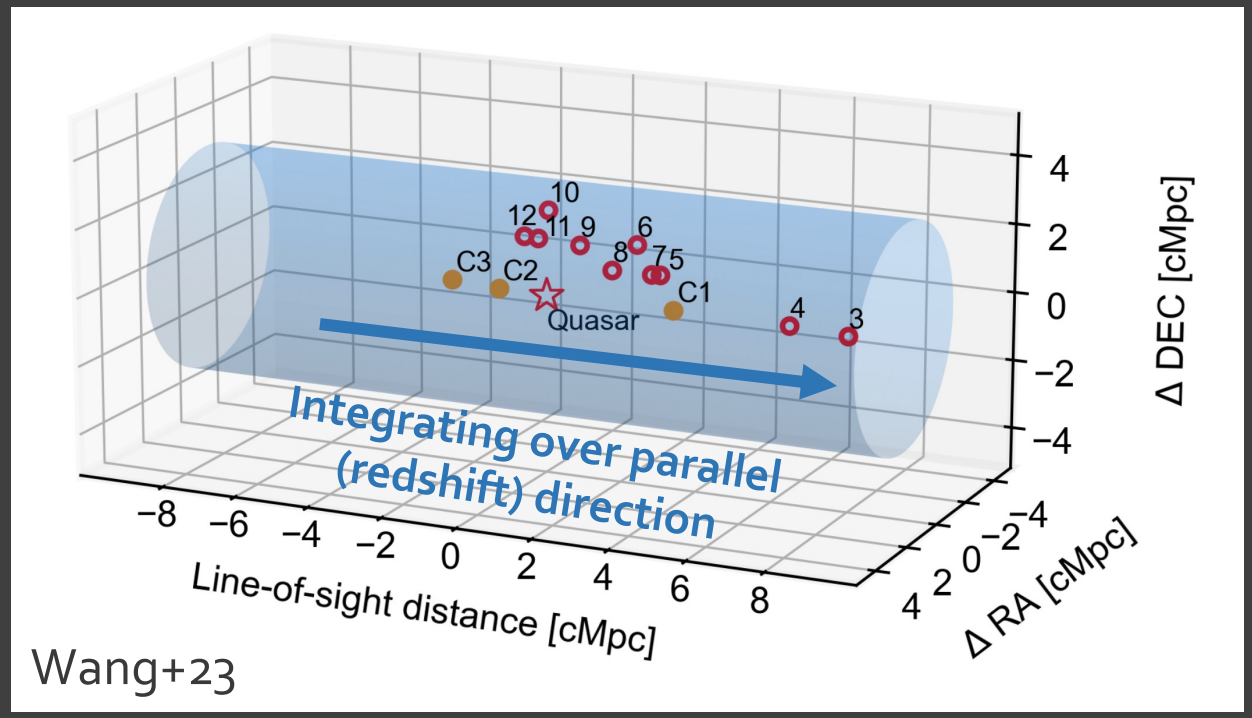




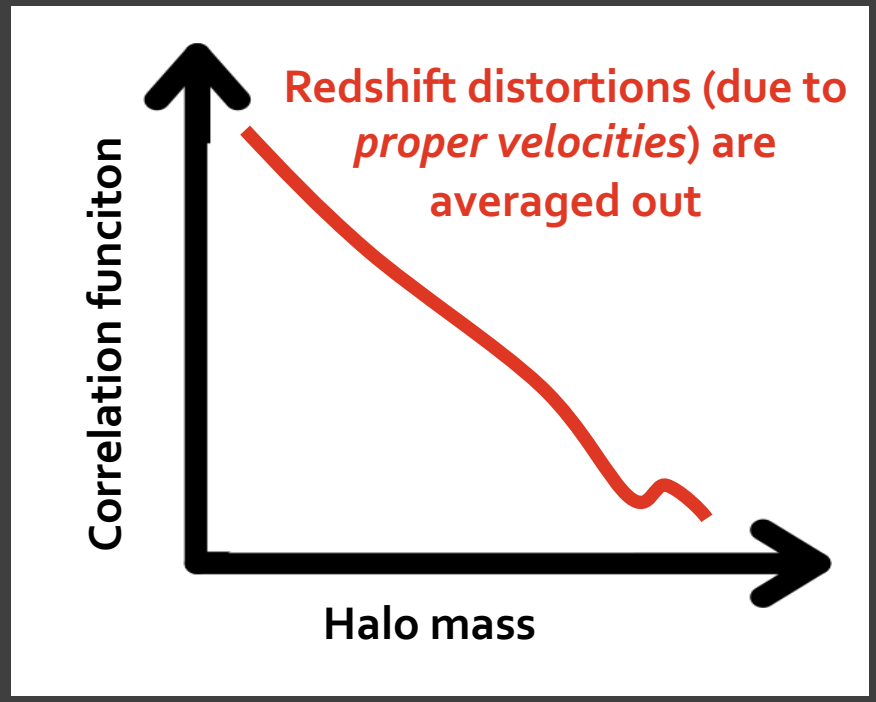
What's next? Connecting the pieces of this story

1. Make use of the velocity information of [OIII] emitters in JWST slitless clustering measurements
2. Quantify the role of field-to-field variance and assess its constraing power
3. Connect quasar obervables at different redshifts and study the implications for SMBH growth

Exploiting the velocity information for clustering



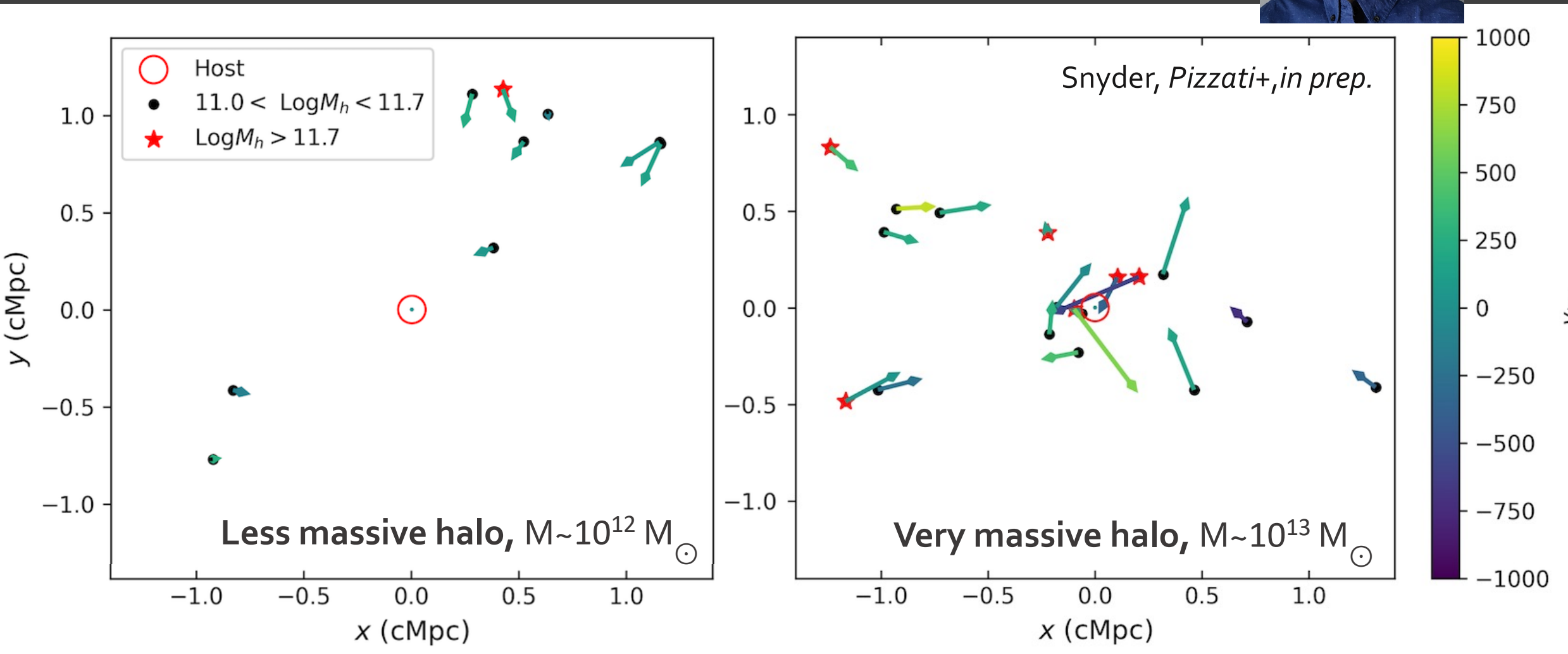
Wang+23



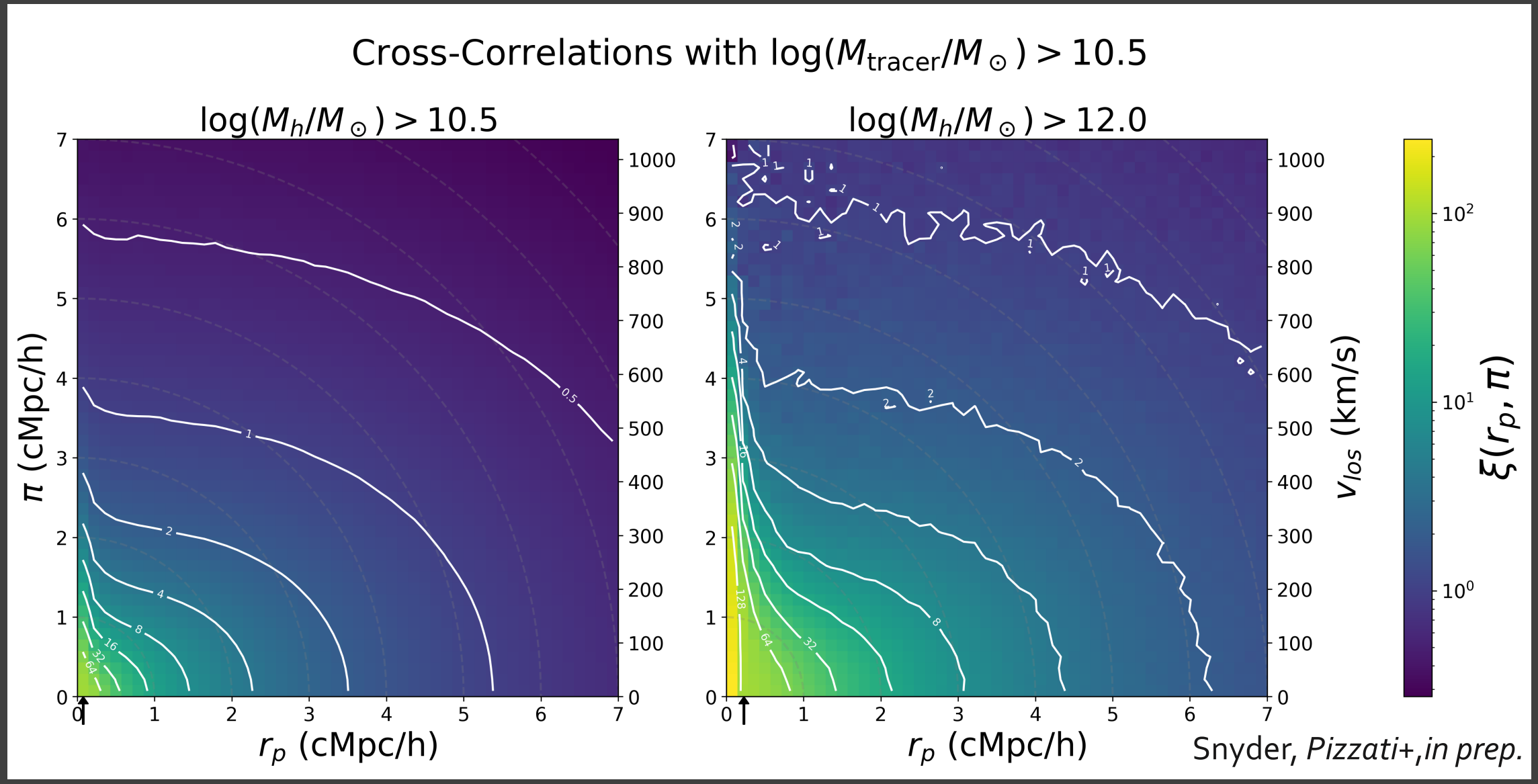
By integrating over the line of sight we are throwing away most of the information in JWST surveys…

Pizzati+24b

Not just pair counts… velocities also scale with halo mass: FLAMINGO-10k

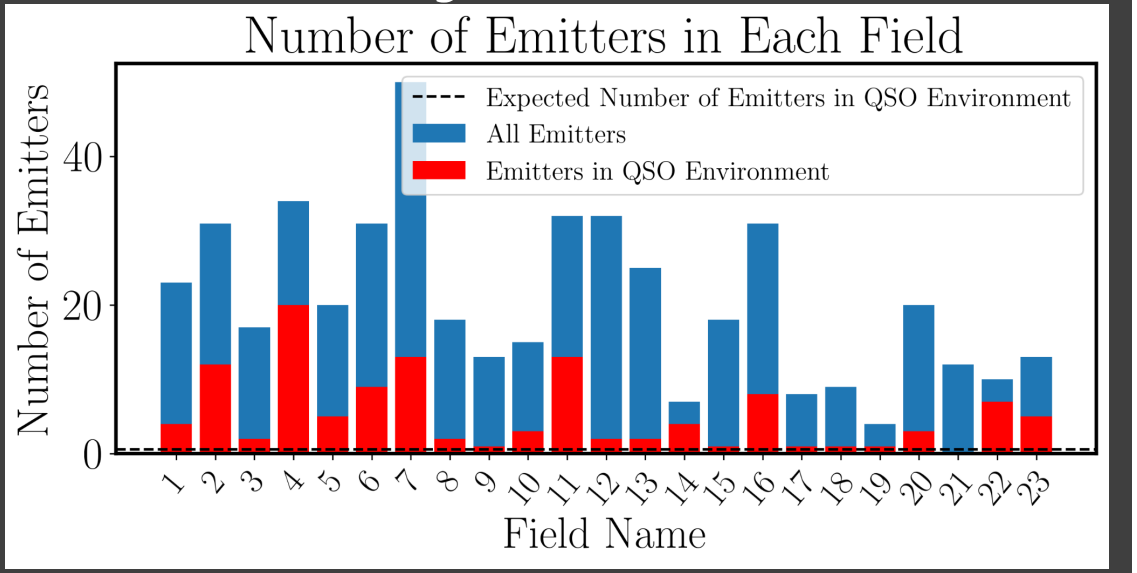


2-d cross-correlations preserve the velocity info

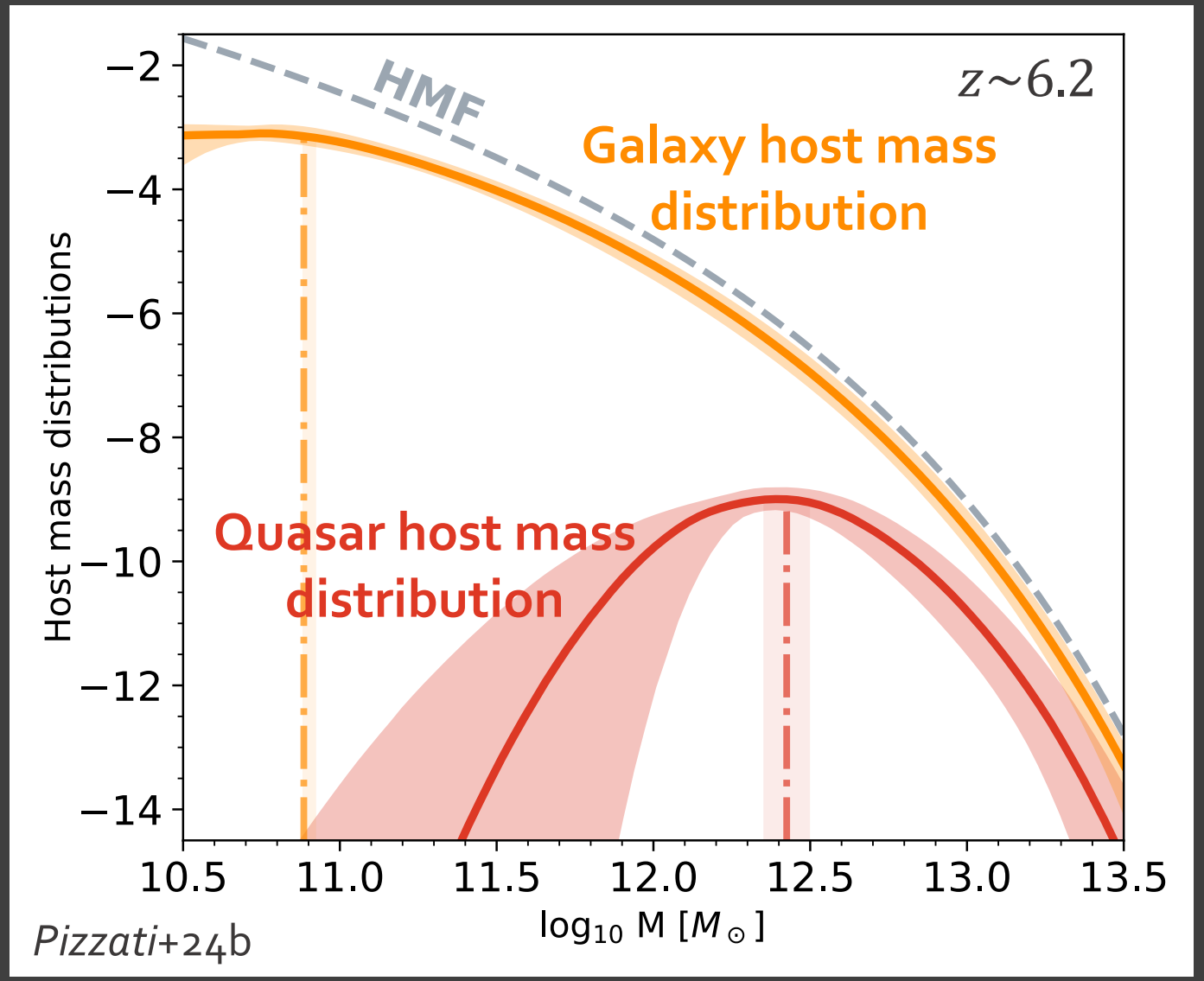


Characterizing field-to-field variance for quasars

Credits: Jiamu Huang



scatter in quasar host halo mass +
scatter in OIII emitter luminosity +
cosmic variance



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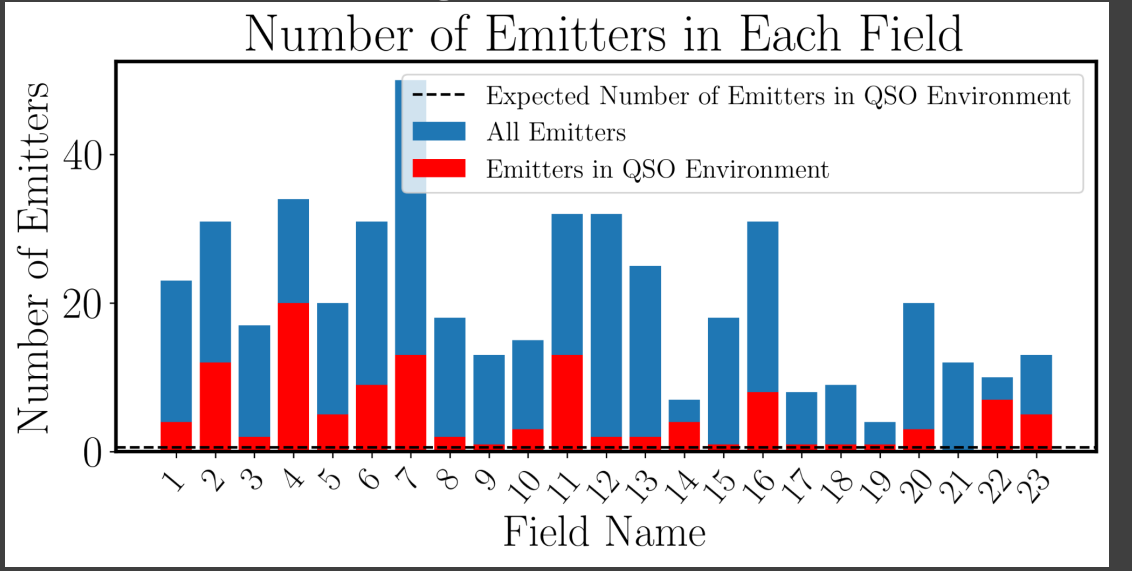

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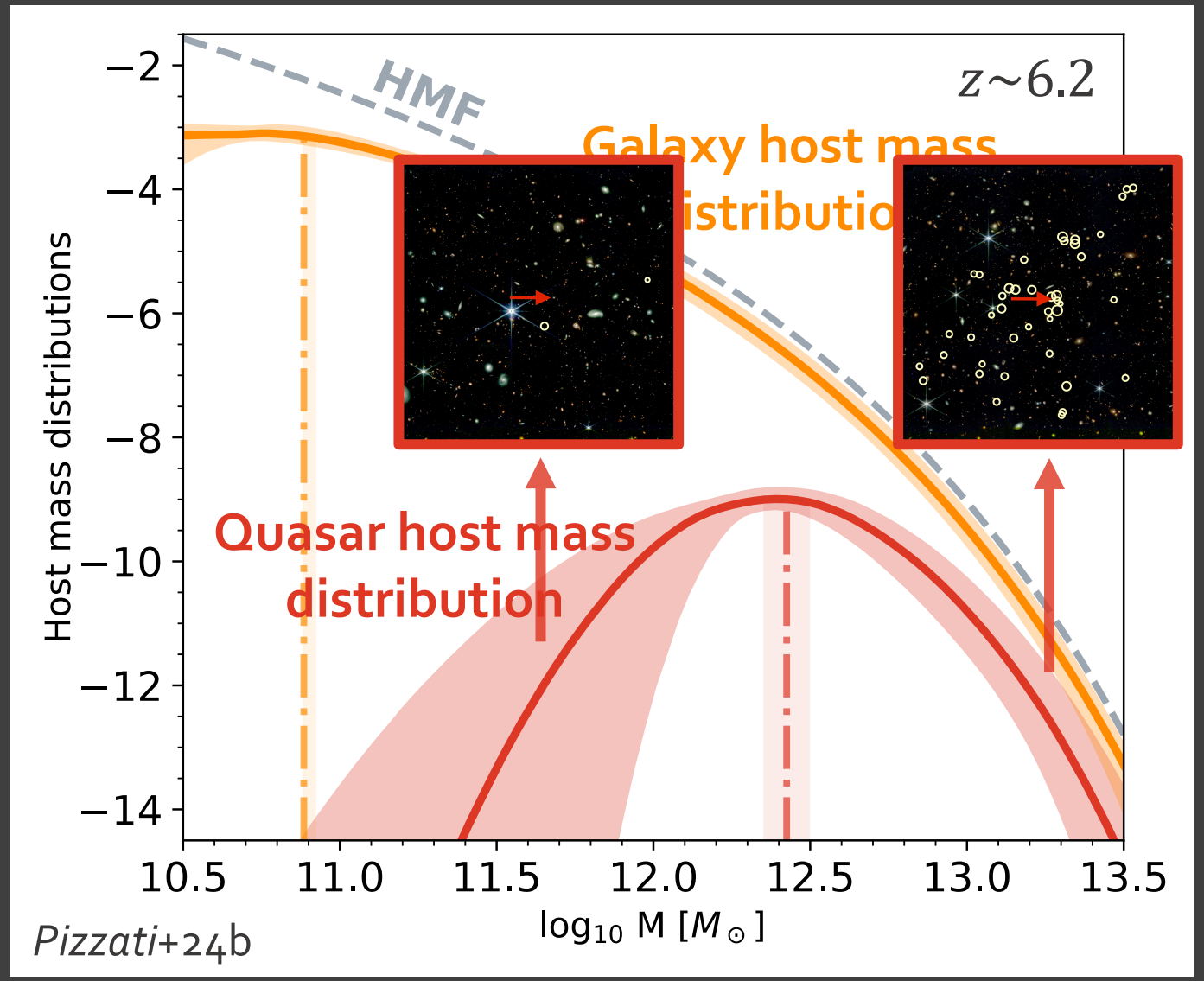
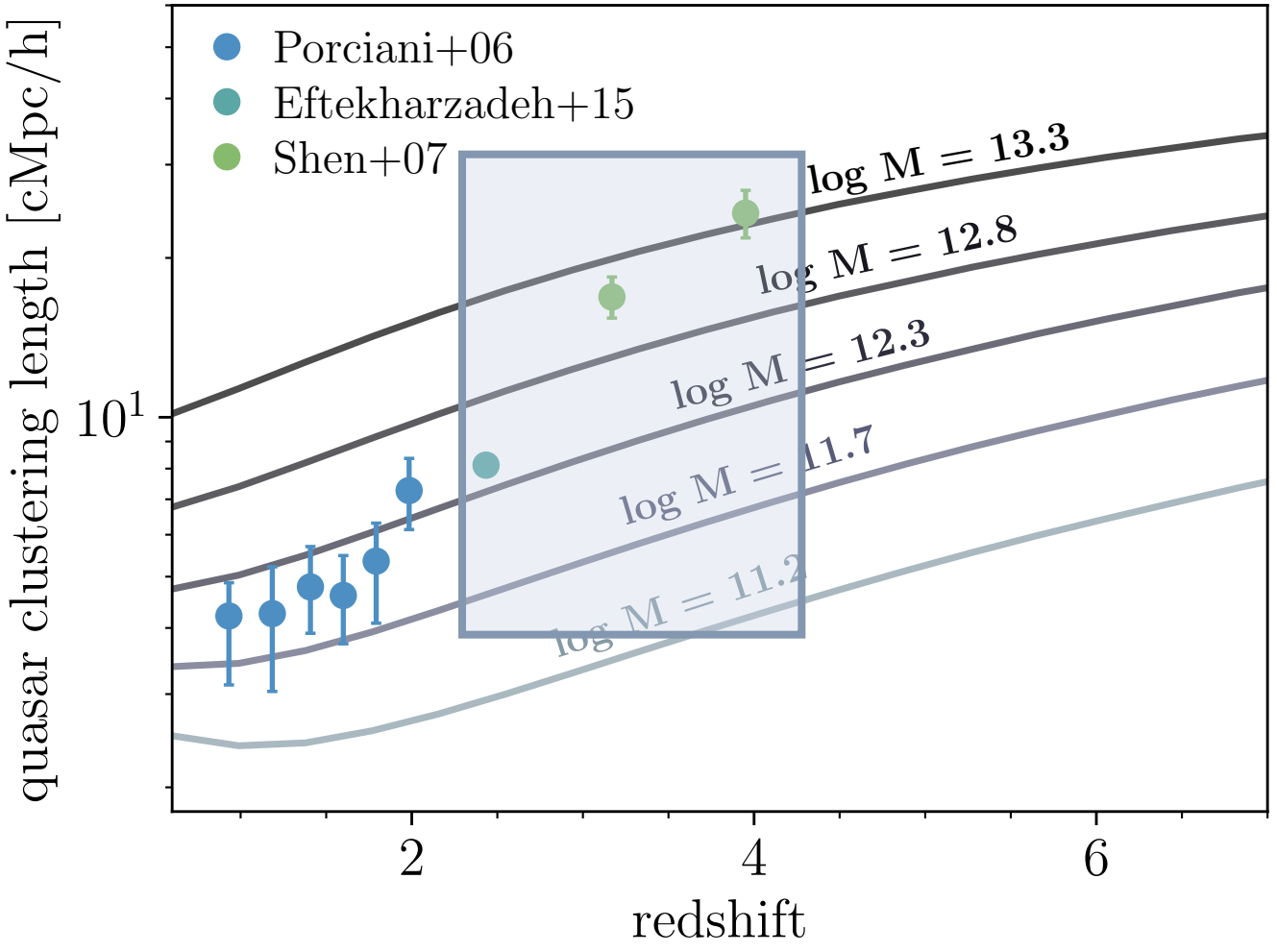
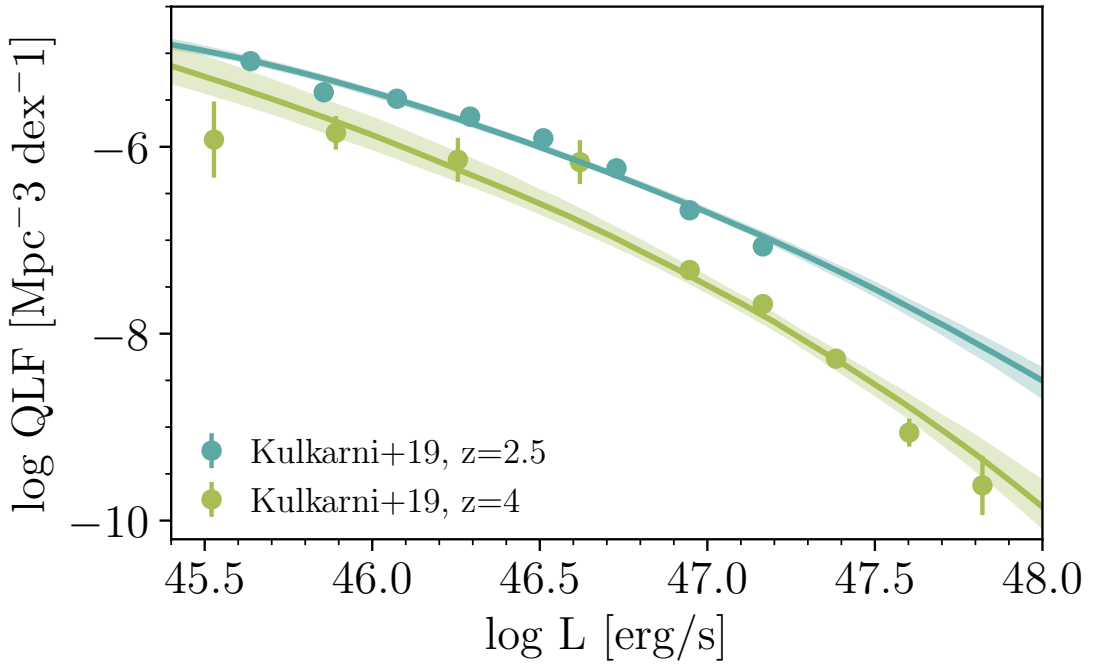
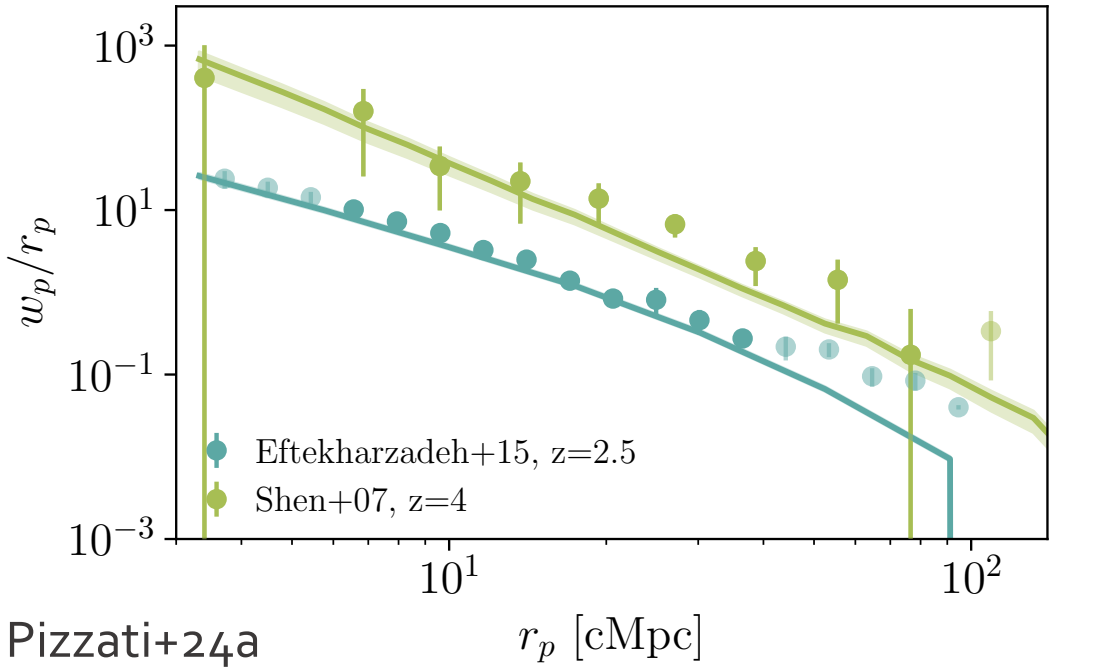


Modeling the increase of quasar clustering with z

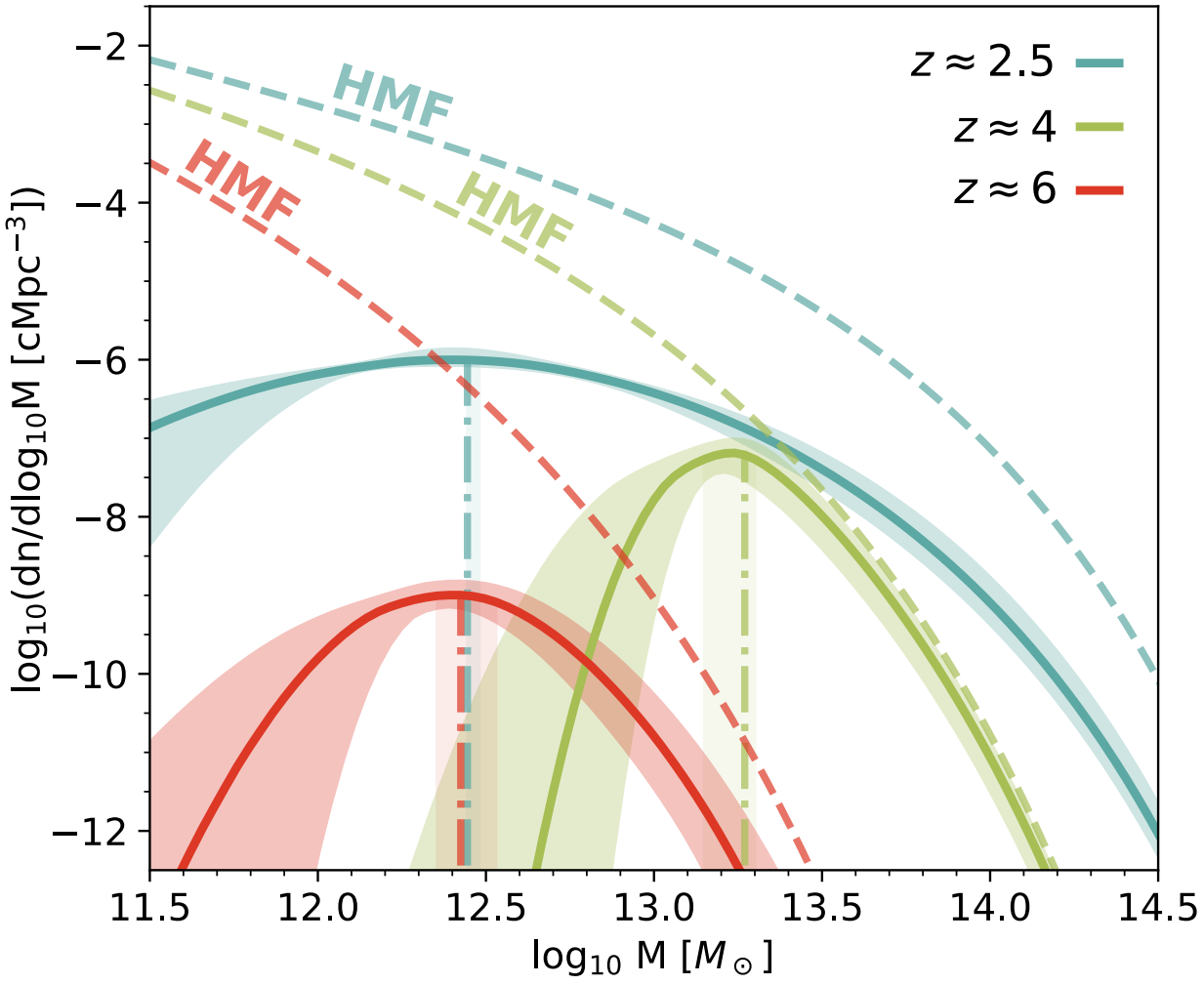


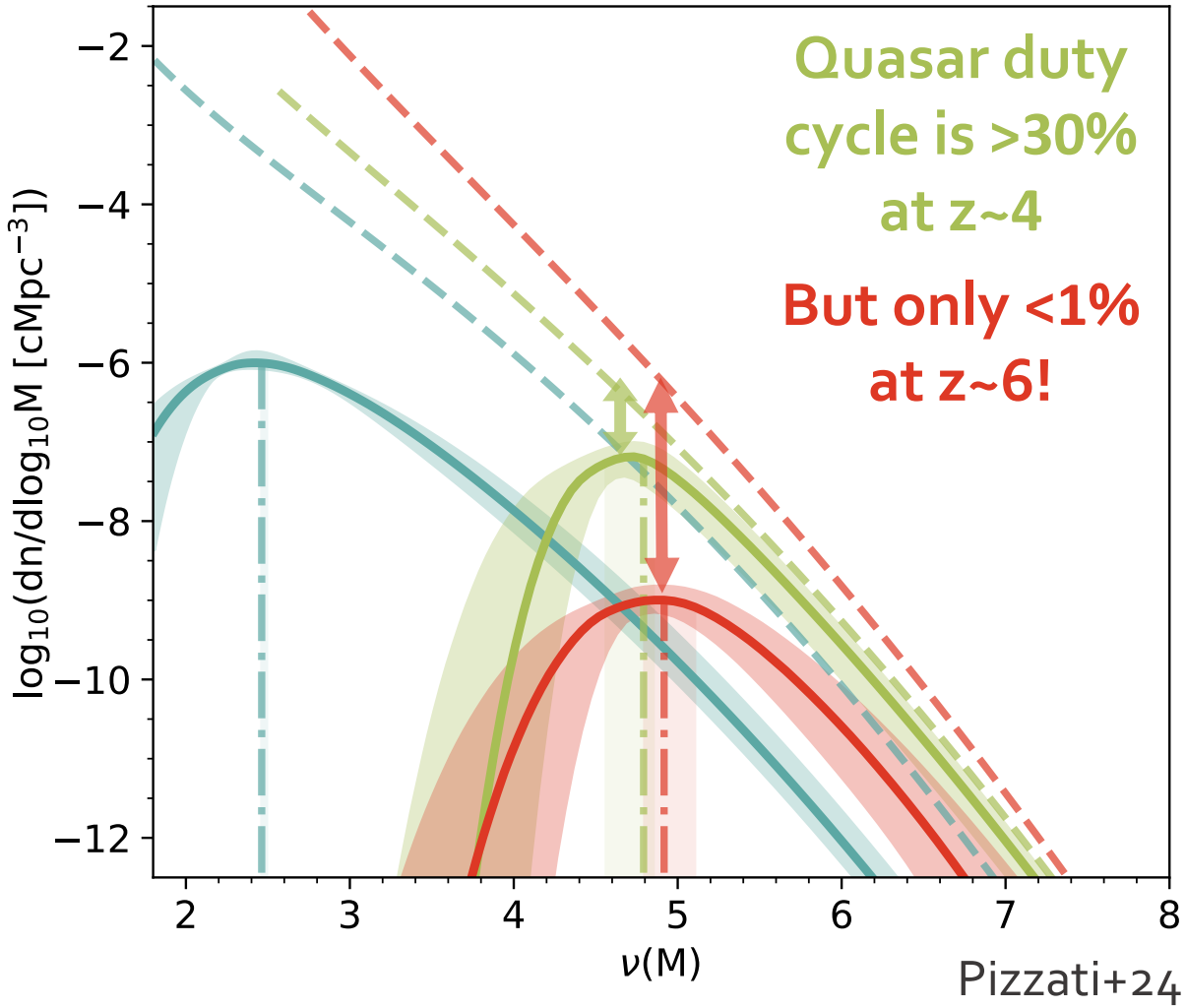




Pizzati+24a

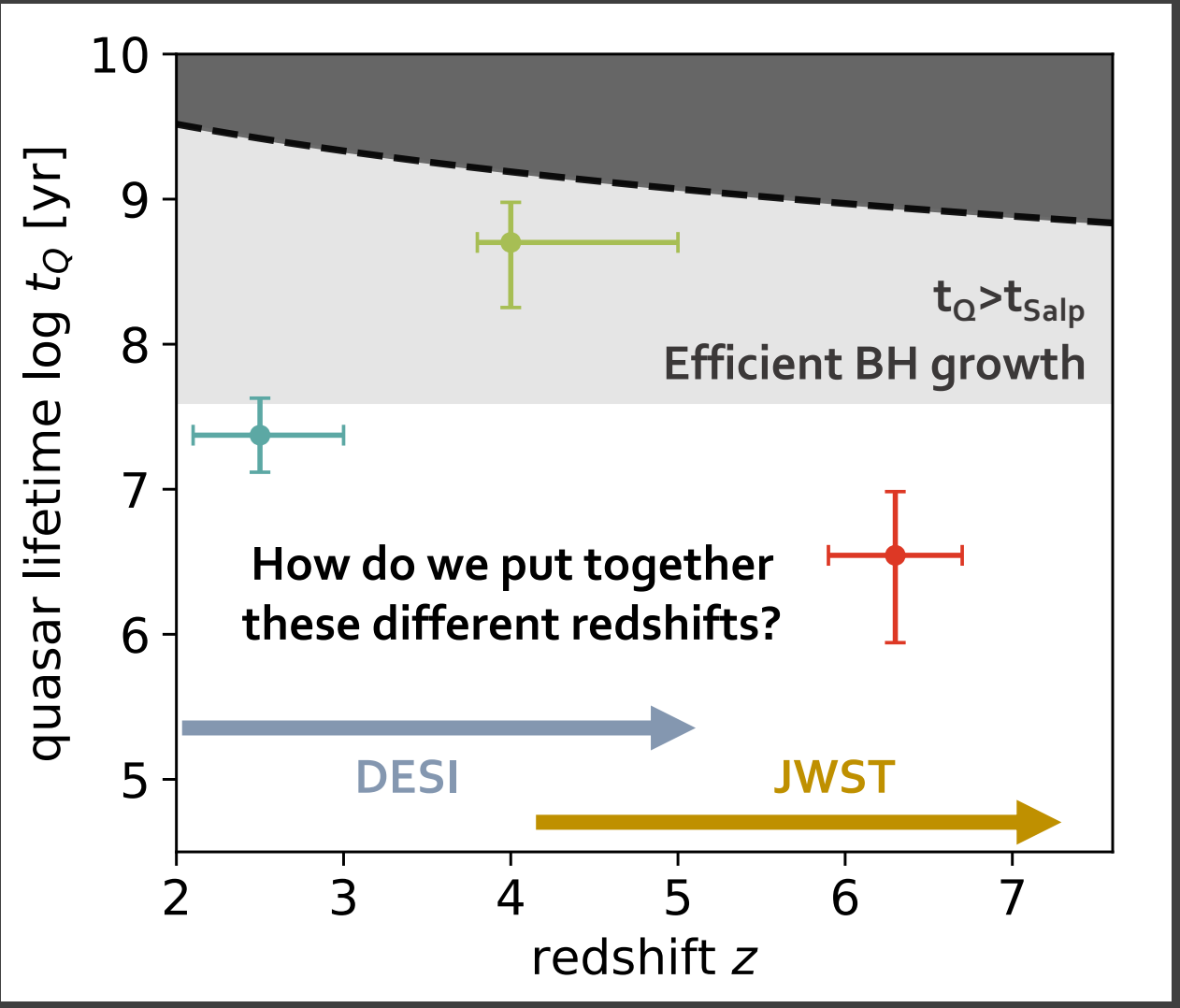
A uniform model for the evolution of quasar properties and environments across cosmic time

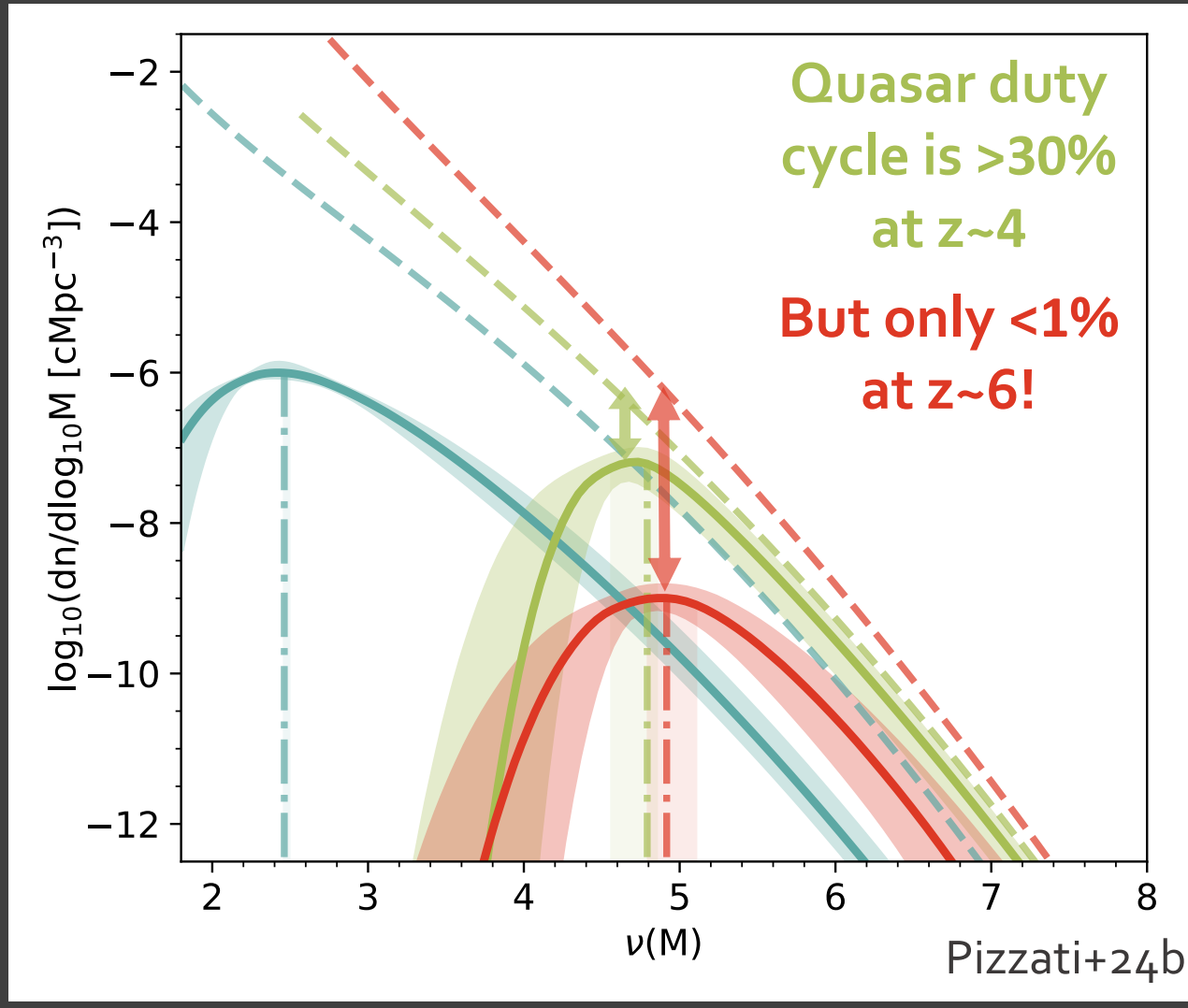




Pizzati+24b

Connecting quasar activity to SMBH growth at different redshifts and different timescales





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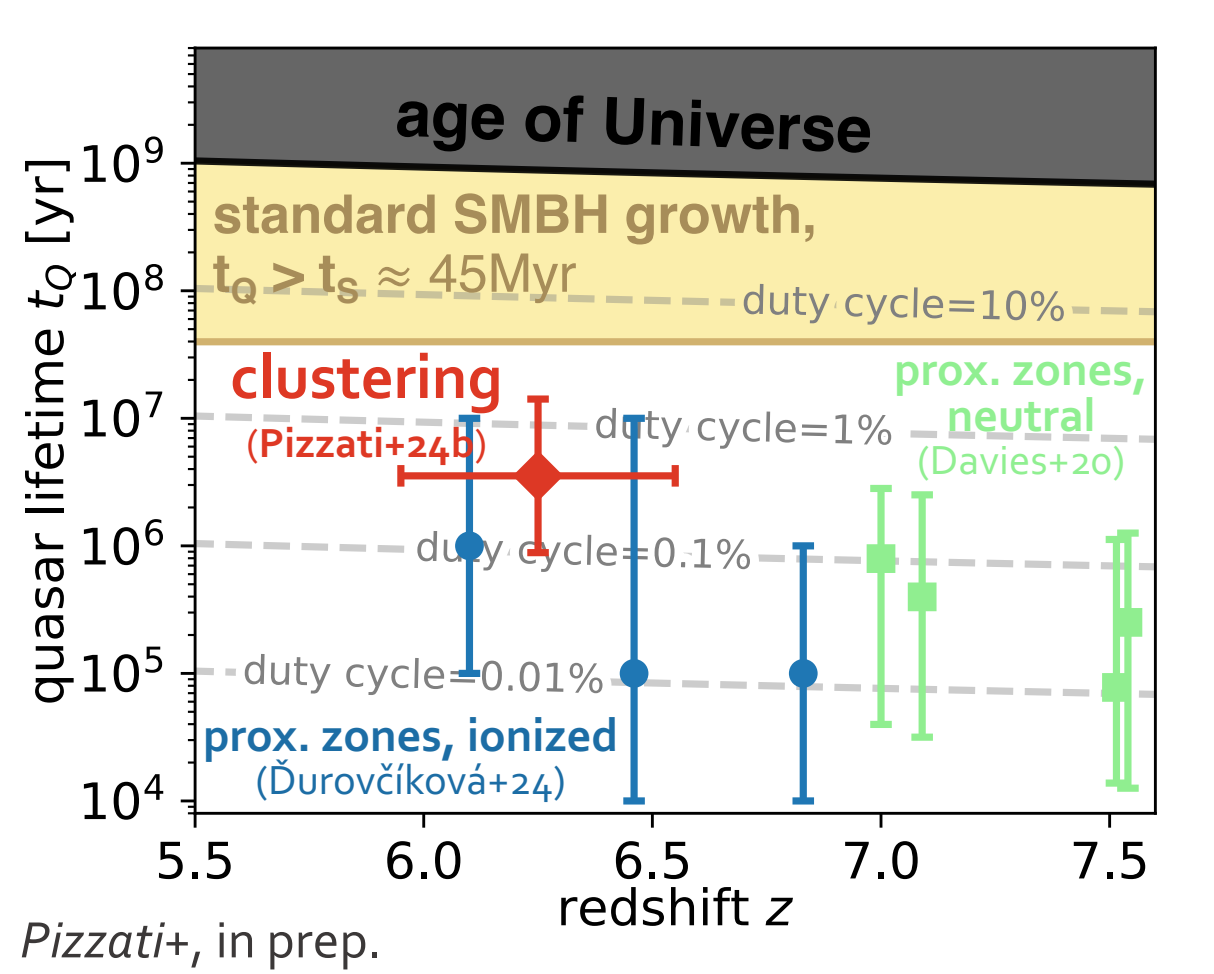
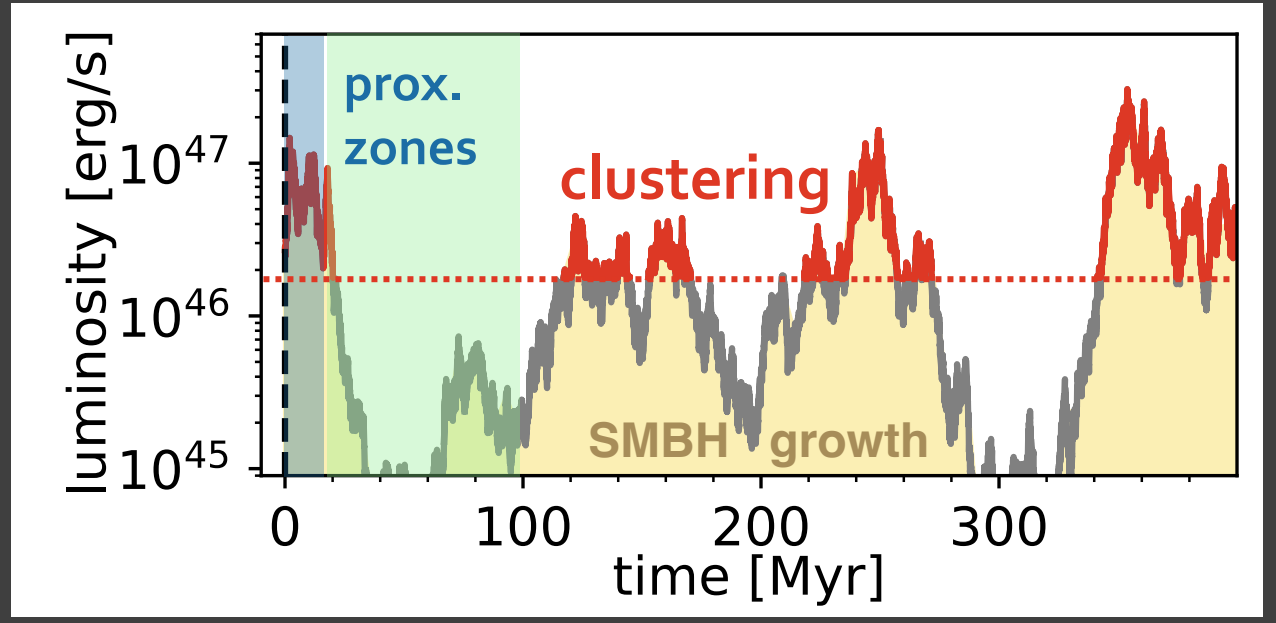


Pizzati+, in prep.



Can we interpret these different observables with a ***consistent model*** of ***quasar activity*** across cosmic time?

Thank you!

- Clustering constraints give key information on quasar ***environment*** and ***duty cycle***, but measurements and ***numerical modeling*** at high z are challenging
- JWST slitless spectroscopy → promising for ***quasar and galaxy clustering*** at high z
- z>6 quasars live in ***moderately massive halos***, but the duty cycle is ***only ~1%***
- Low high-z quasar activity but ***rapid SMBH growth***→ super-Eddington? obscuration?
- Unobscured quasars vs ***obscured JWST AGN***→ clustering can give key insight
- Next→ linking of quasar observables and SMBH growth across cosmic time