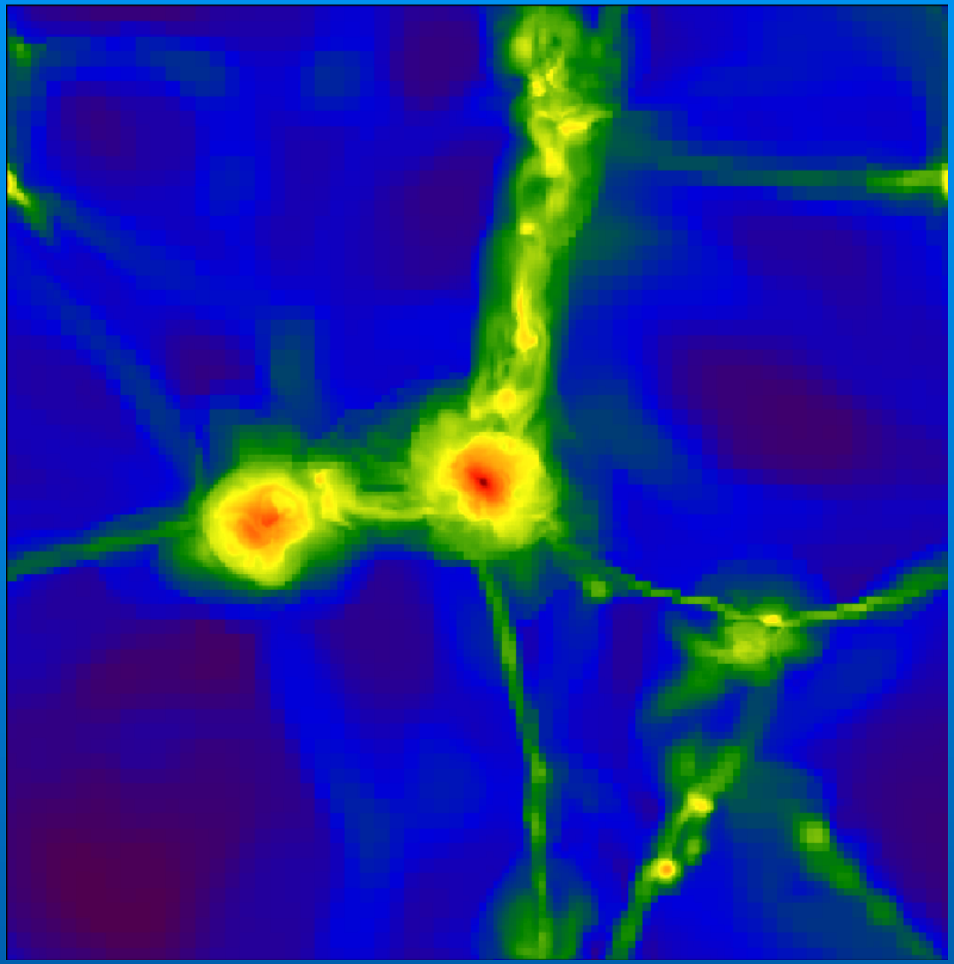
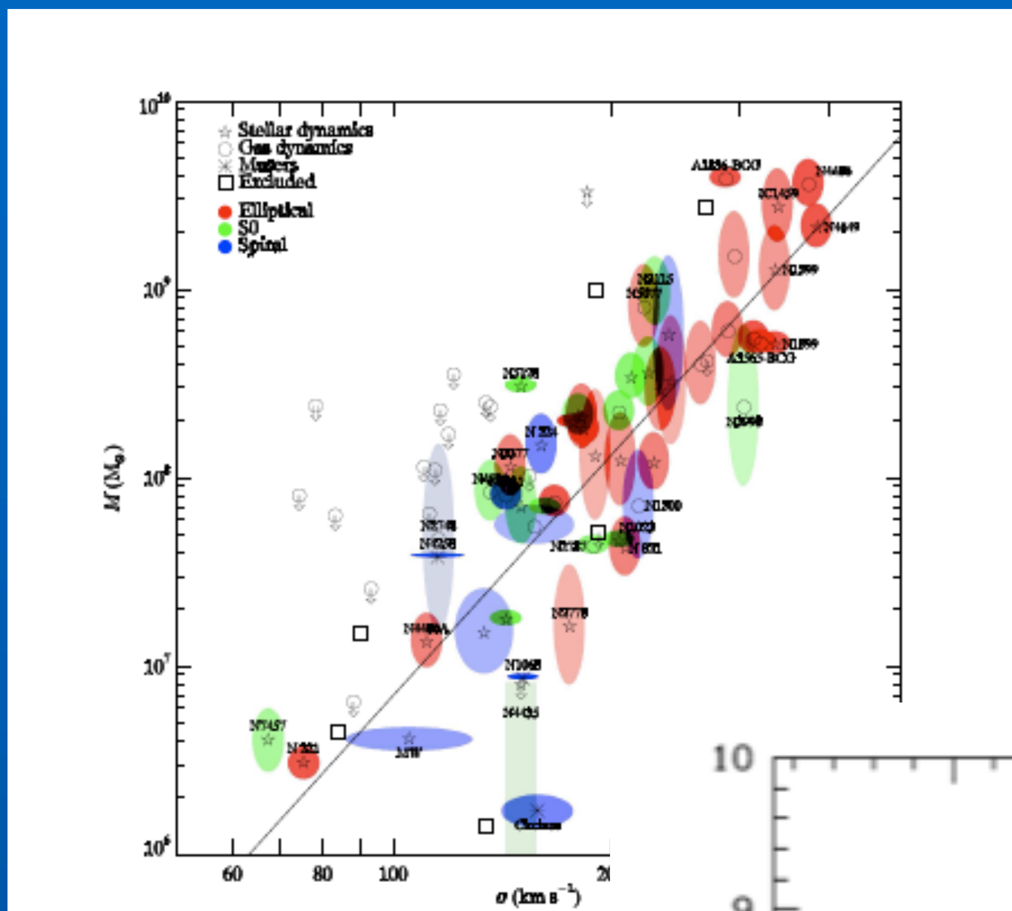
Formation and detection of supermassive black holes at high redshift

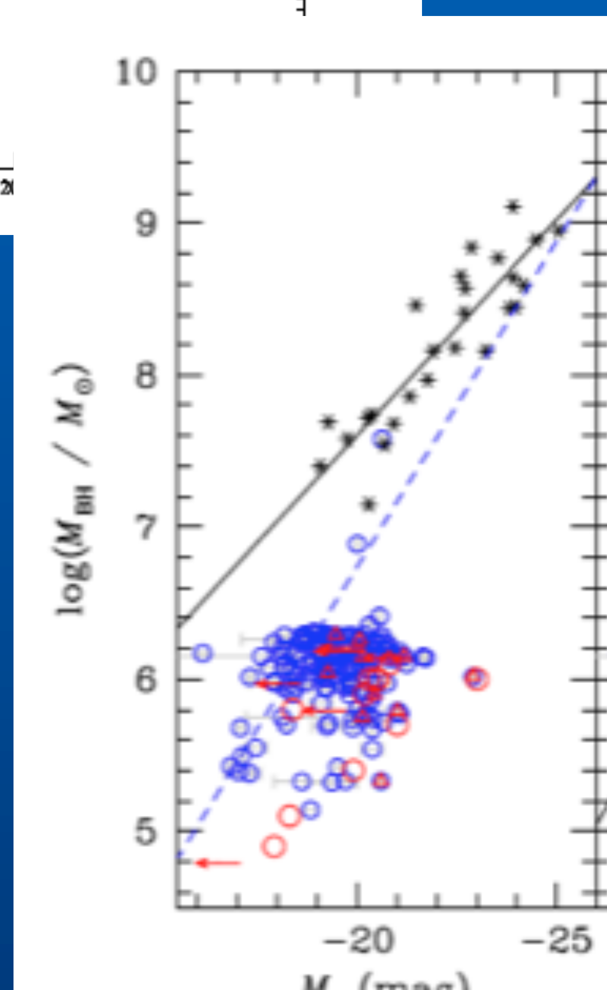


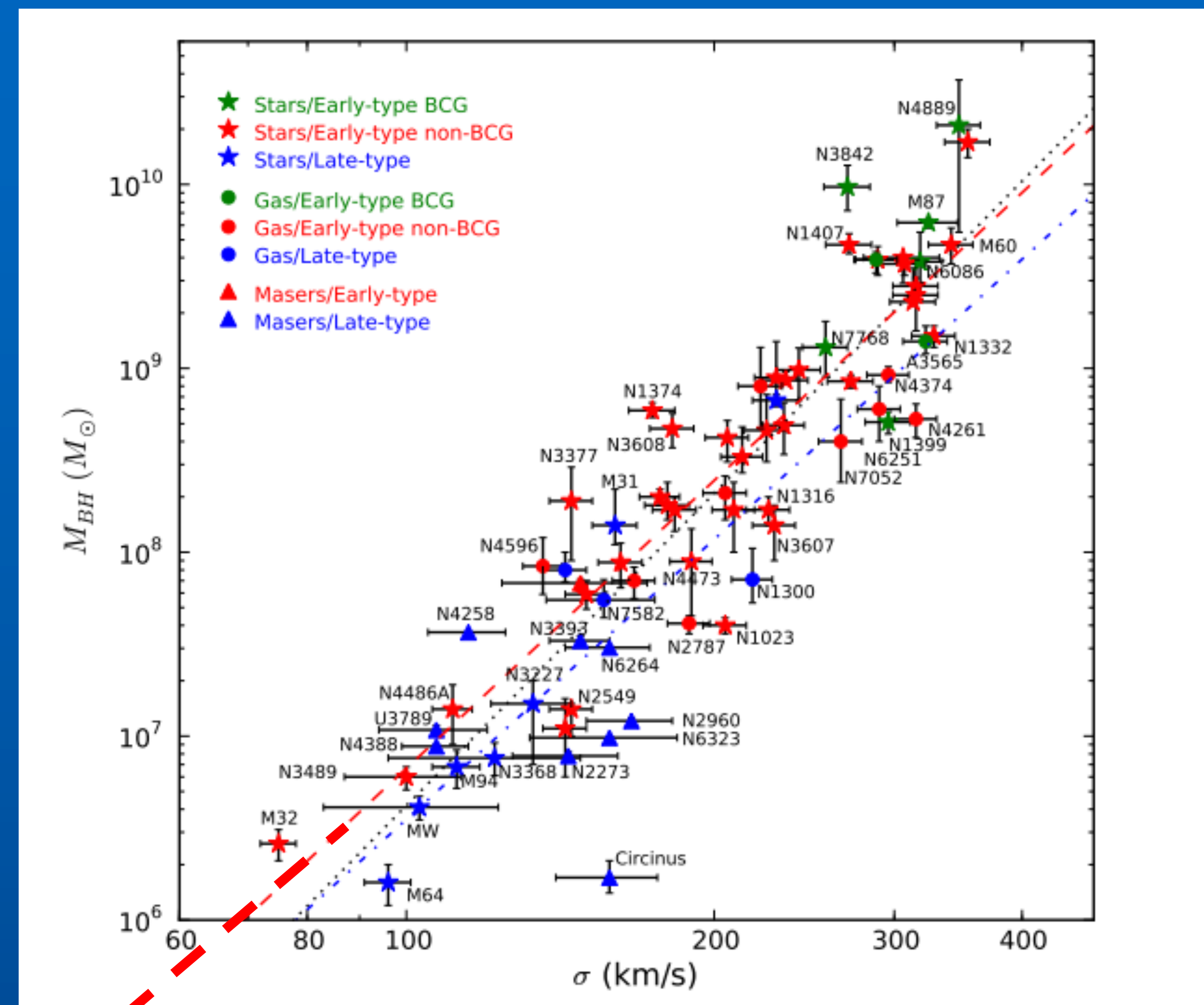
Haiman+; Tanaka+; Johnson+; Park+; Ricotti+; Khochfar+; Di Matteo+; Yoshida+ Schneider+ Dubois+; Bournoud+; Ferrara+; Milosavljevic+; Ricotti+; Abel+; Bromm+; Latif+; Whalen+

Priyamvada Natarajan
Yale University

LOCAL RELATION BETWEEN BH MASS & STELLAR BULGE VELOCITY DISPERSION



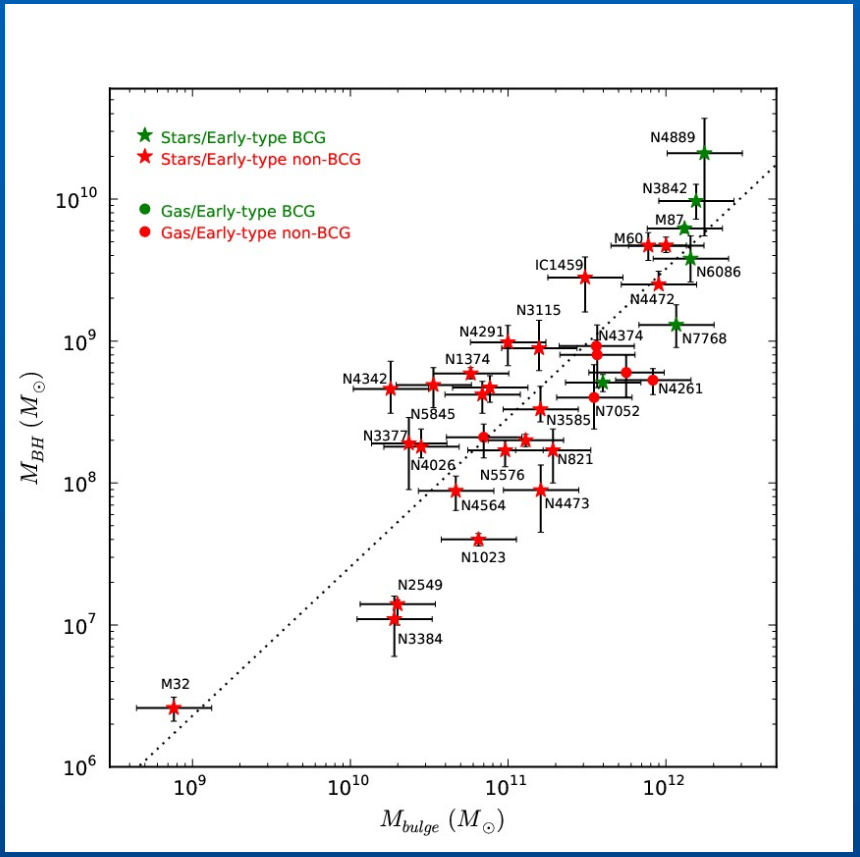




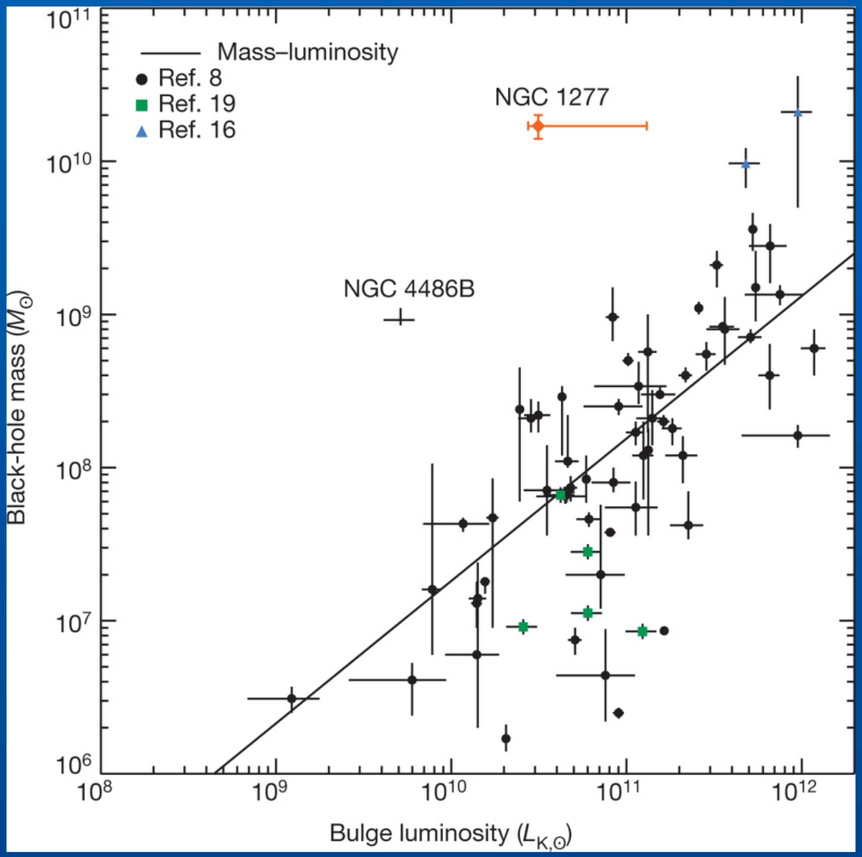
Reines+ 14; McConnell+ 13; Jiang, Greene & Ho 11; Gultekin+09

Correlations Between M_{BH}-Host Galaxy Properties

- ✦ **Galaxy bulge mass** [$M_{BH} \sim 10^{-3}\ M_{bulge}$] Dressler 89; Magorrian+ 98
- ✦ Galaxy bulge luminosity [M_{BH}-$L^{1.0\pm0.1}$] Kormendy 93; Kormendy & Richstone 95
- ✦ Stellar velocity dispersion [$M_{BH} \sim \sigma^4$] Tremaine+ 99; Ferrarese & Merritt 00



McConnell & Ma+13



van den Bosch et al.+12

HOW IS THIS OCCUR IN INVIDIVIDUAL GALACTIC NUCLEI & THE POPULATION

How do BHs and the host galaxy know about each other

Do these scaling relations evolve through cosmic time

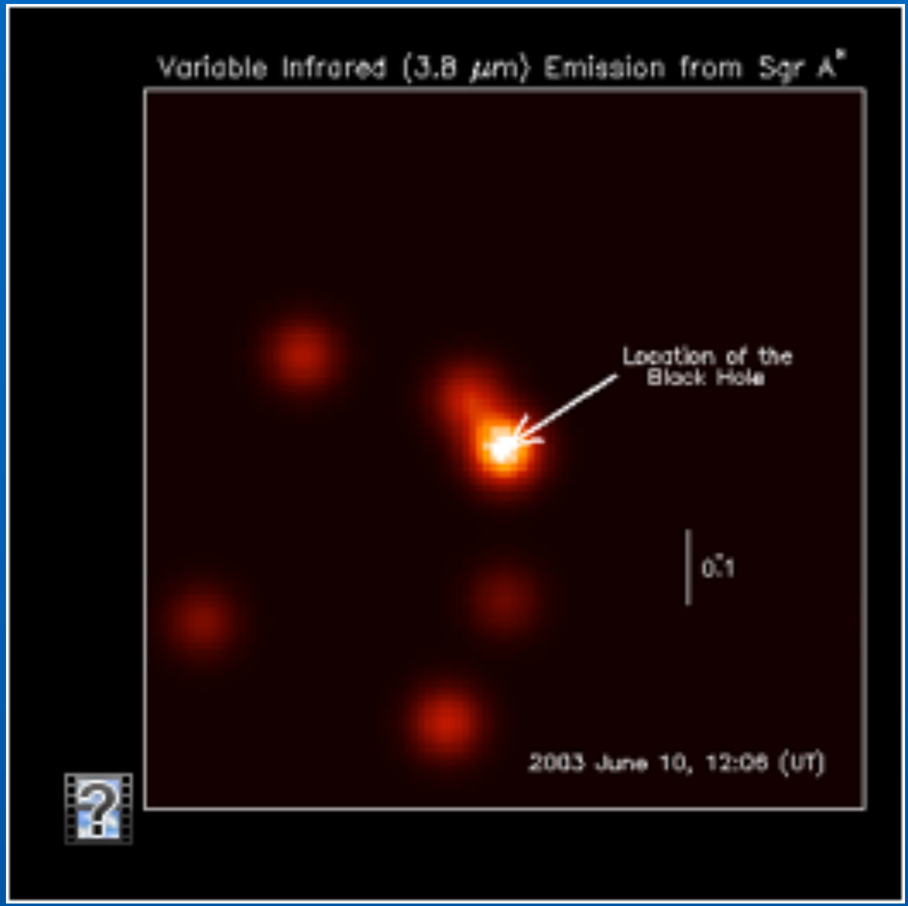
When are these correlations set up

Initial conditions? accretion physics? merger dynamics? self-regulated feedback?

How do seed BHs grow? can we see this?

How do seed BHs form? can we constrain this?

MULTI-WAVELENGTH DATA FOR ACTIVE & QUIESCENT BHs



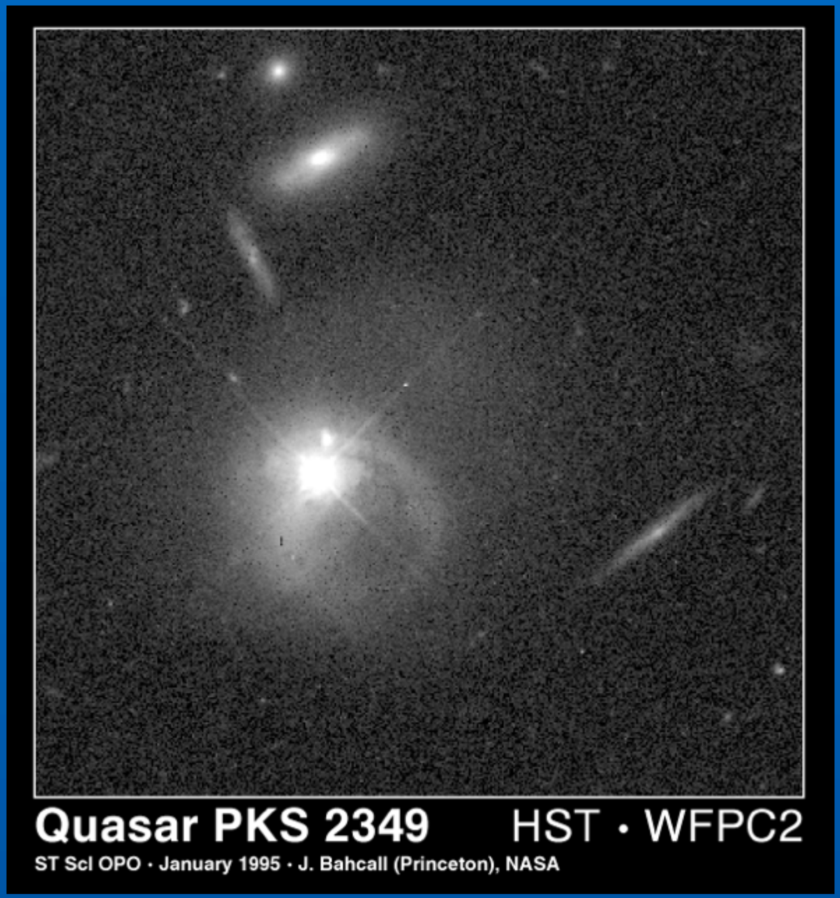
$M_{BH} \sim 10^{6\text{ -}9}\, M_{sun}$

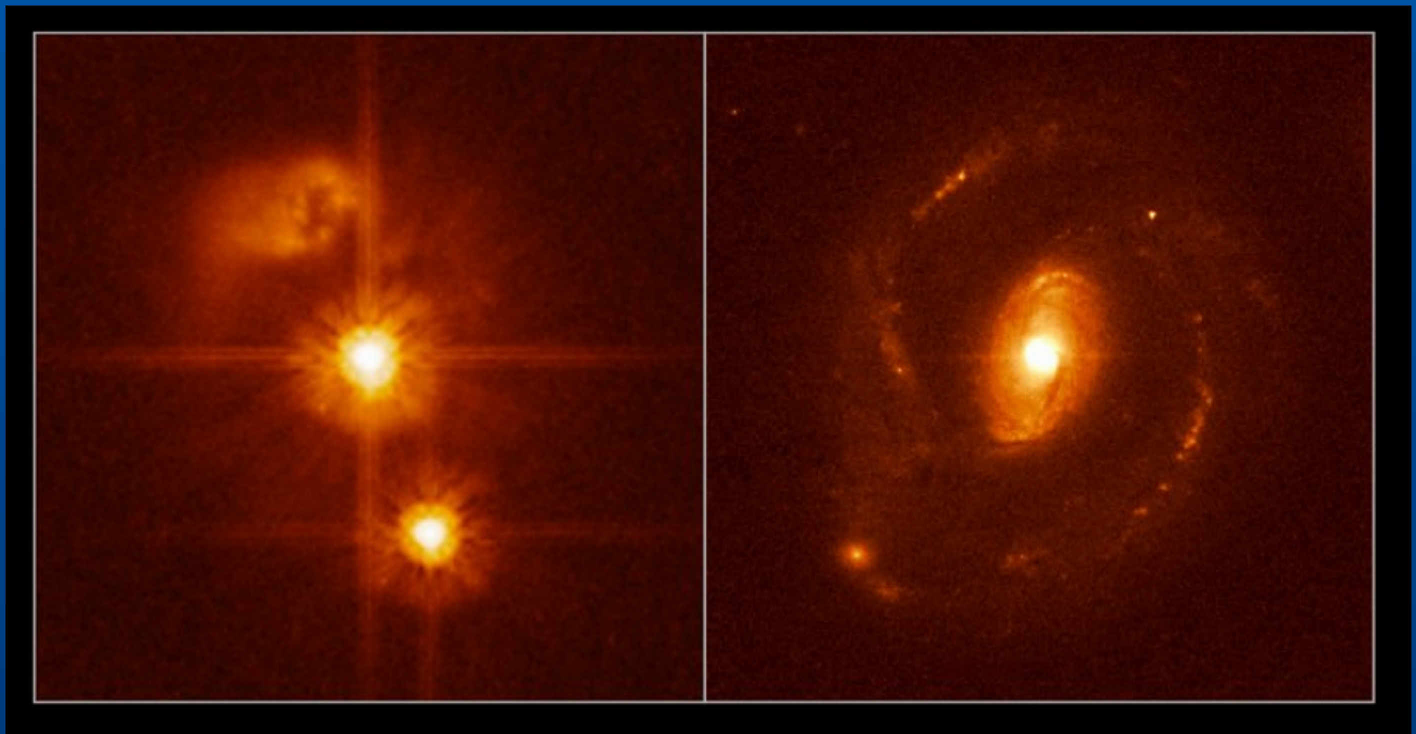
even $10^{10}\, M_{sun}$

$z \sim 0 – 7$

z=7 660 Myr
550 Myr after

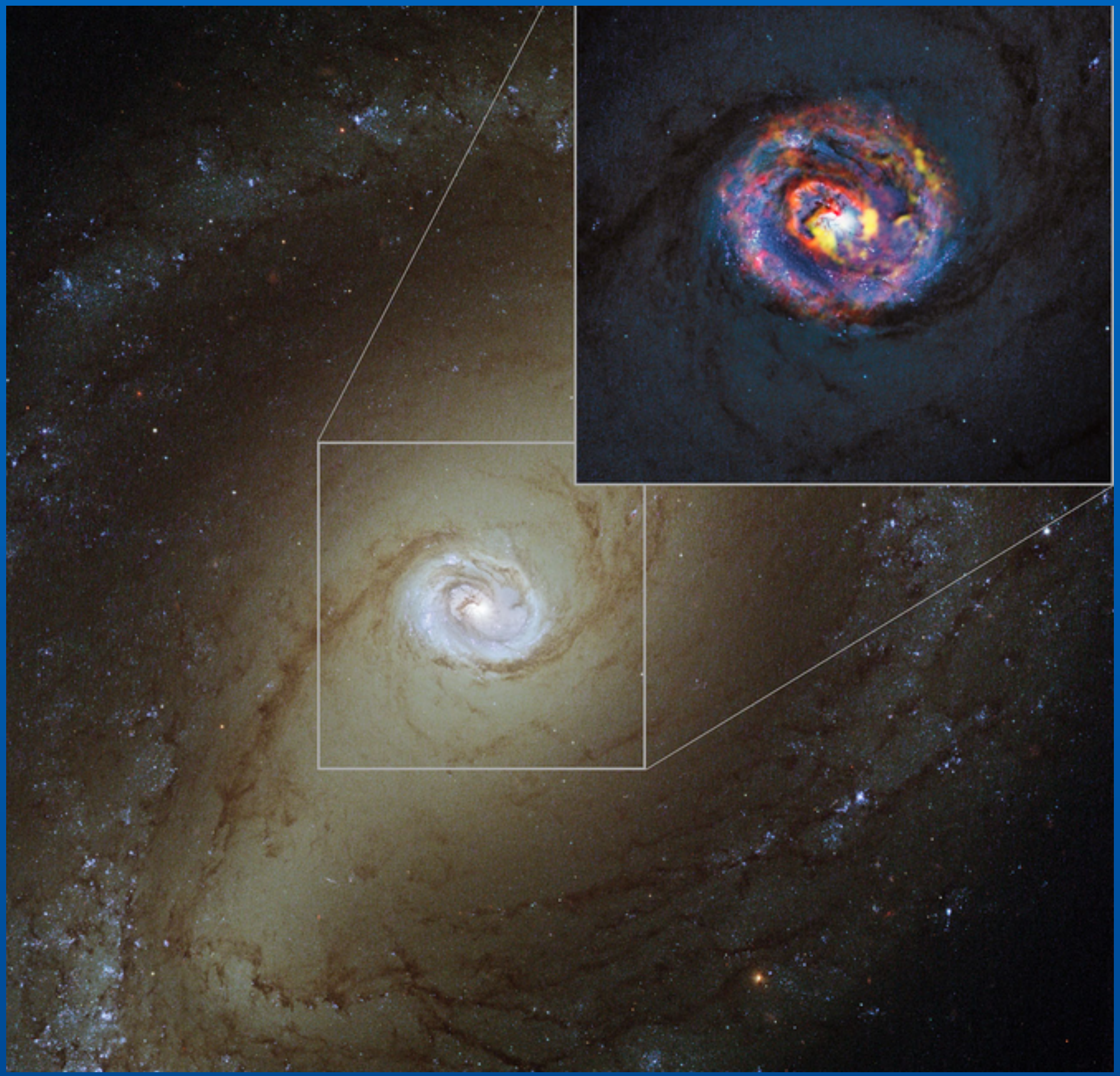
the Big Bang



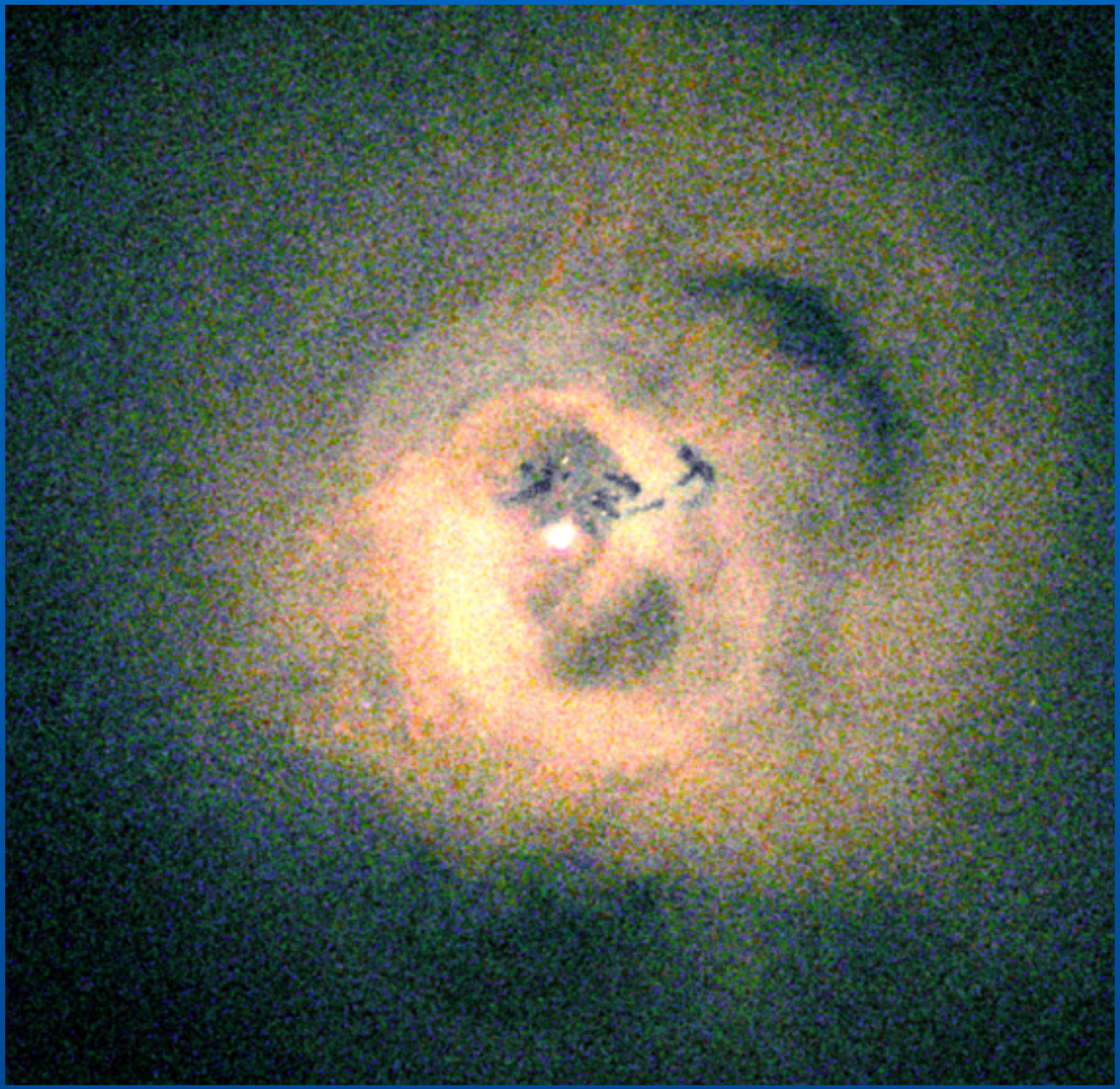


Urry+; Treister+; Scoville+; Sanders; Faber+; Wu+; Ferguson+; Harrison+; Hasinger+; Comastri+; Gilli+

EVIDENCE FOR IMPACT OF BHs ON THEIR ENVIRONMENT

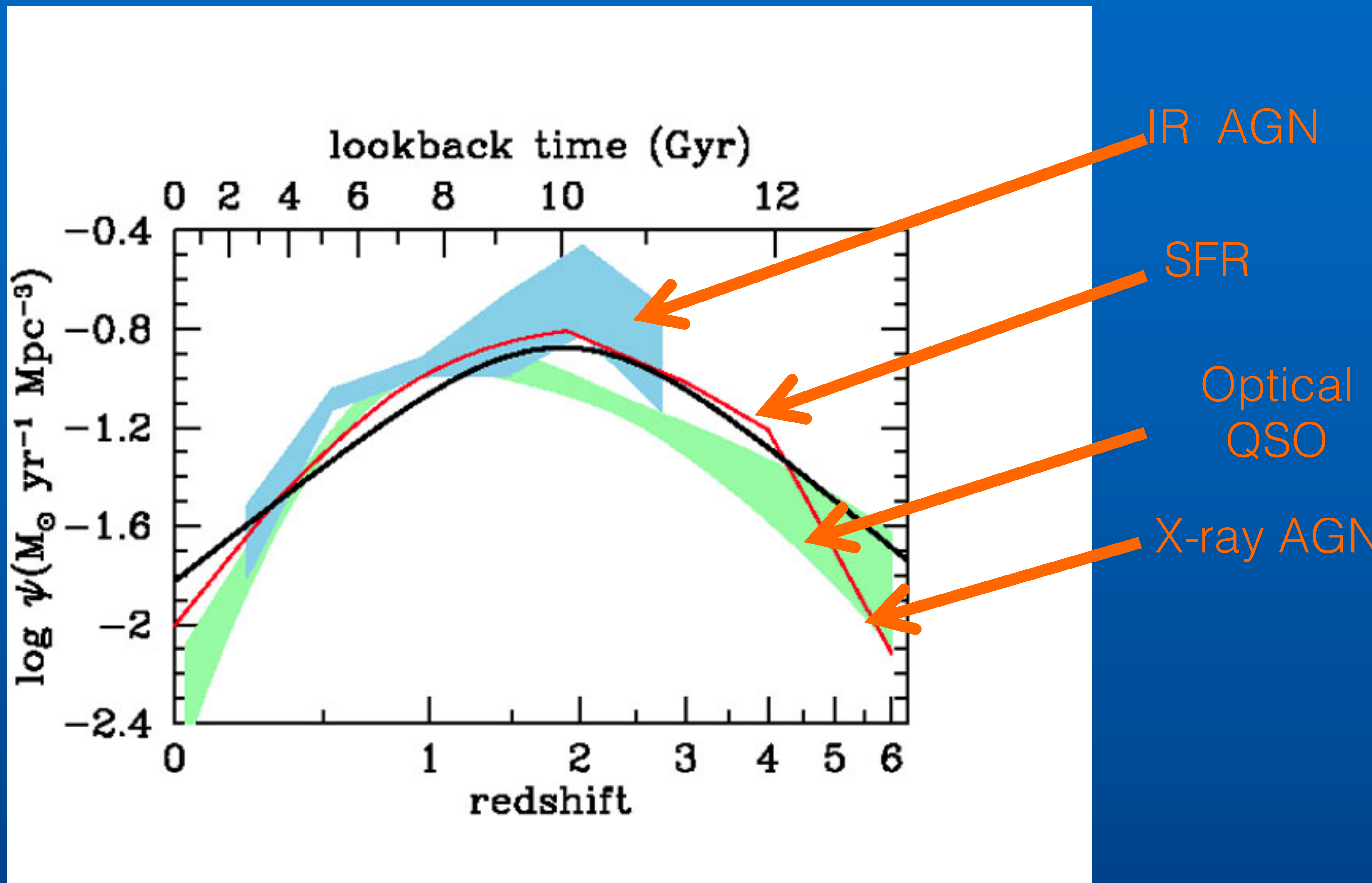


On the smallest scales
ALMA data of NGC 1433
outflows & molecular disk



On the largest scales CHANDRA data of the Perseus cluster outflows & shells

BH ACCRETION RATE & STAR FORMATION RATE AS A FUNCTION OF COSMIC TIME



Delvecchio+ 14; Aird+ 10; Shankar+ 09

BHMF FOR BLQSOs FROM SDSS 1 < z < 4.5

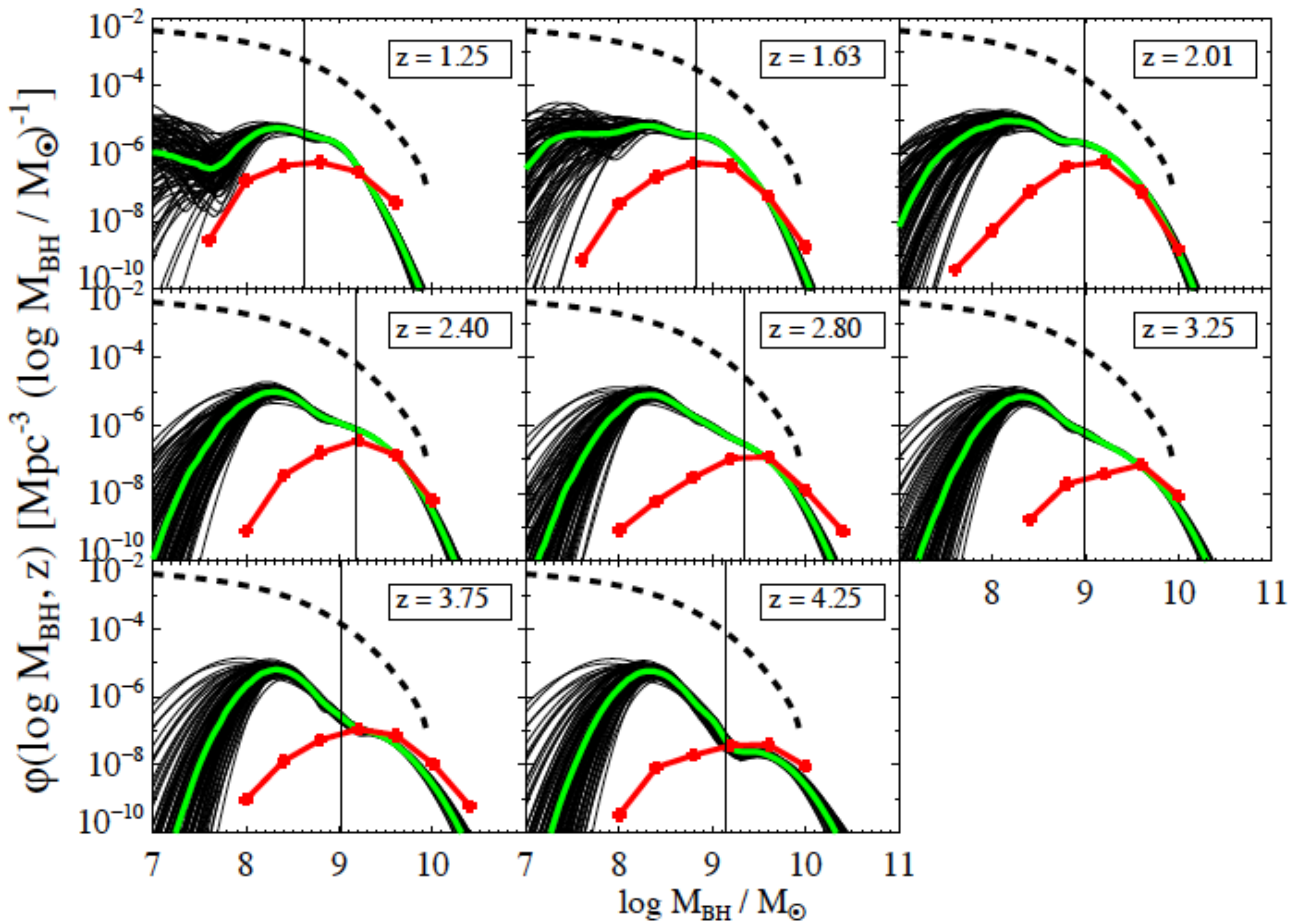
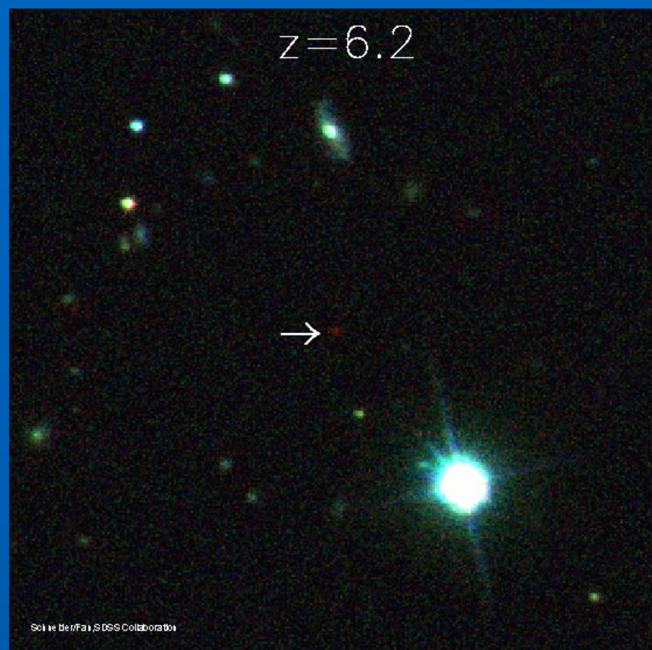


Fig. 3.— BLQSO BHMF (thin solid lines) obtained using our Bayesian approach, compared with the local BHMF fo all SMBHs (dashed line), and the BHMF from Vestergaard et al. (2008, solid red line with points); as in Figure 1, each thin solid line denotes a random draw of the BHMF from its probability distribution. The thick green line is the median of the BHMF random draws, and may be considered our 'best-fit' estimate. The vertical line marks the mass at which the SDSS DR3 sample becomes 10% complete.

Kelly, Shen+ 10; 11

HIGH-z QUASARS & THE TIMING PROBLEM TO ASSEMBLE SMBHs

Bright quasars host 10^9 - 10^{10} M_{sun} BHs



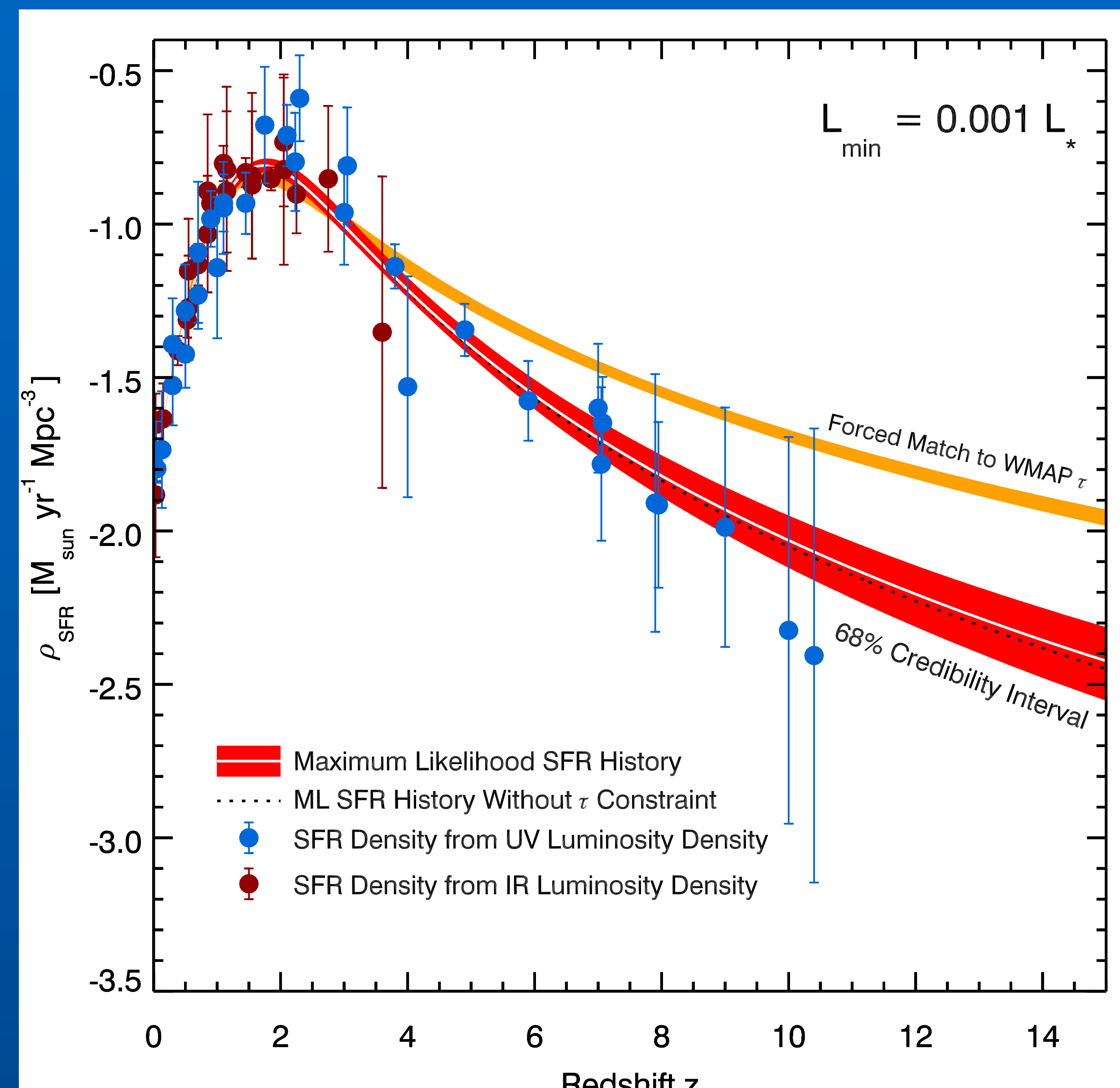
Age of the universe 1 Gyr

Eddington limit growth rate of mass

$$\frac{dM}{dt} = \frac{L_{acc}}{\eta c^2} < \frac{4\pi G M m_p}{\eta c \sigma_T}$$

$$M \leq M_0 e^{\frac{t}{\tau}}$$

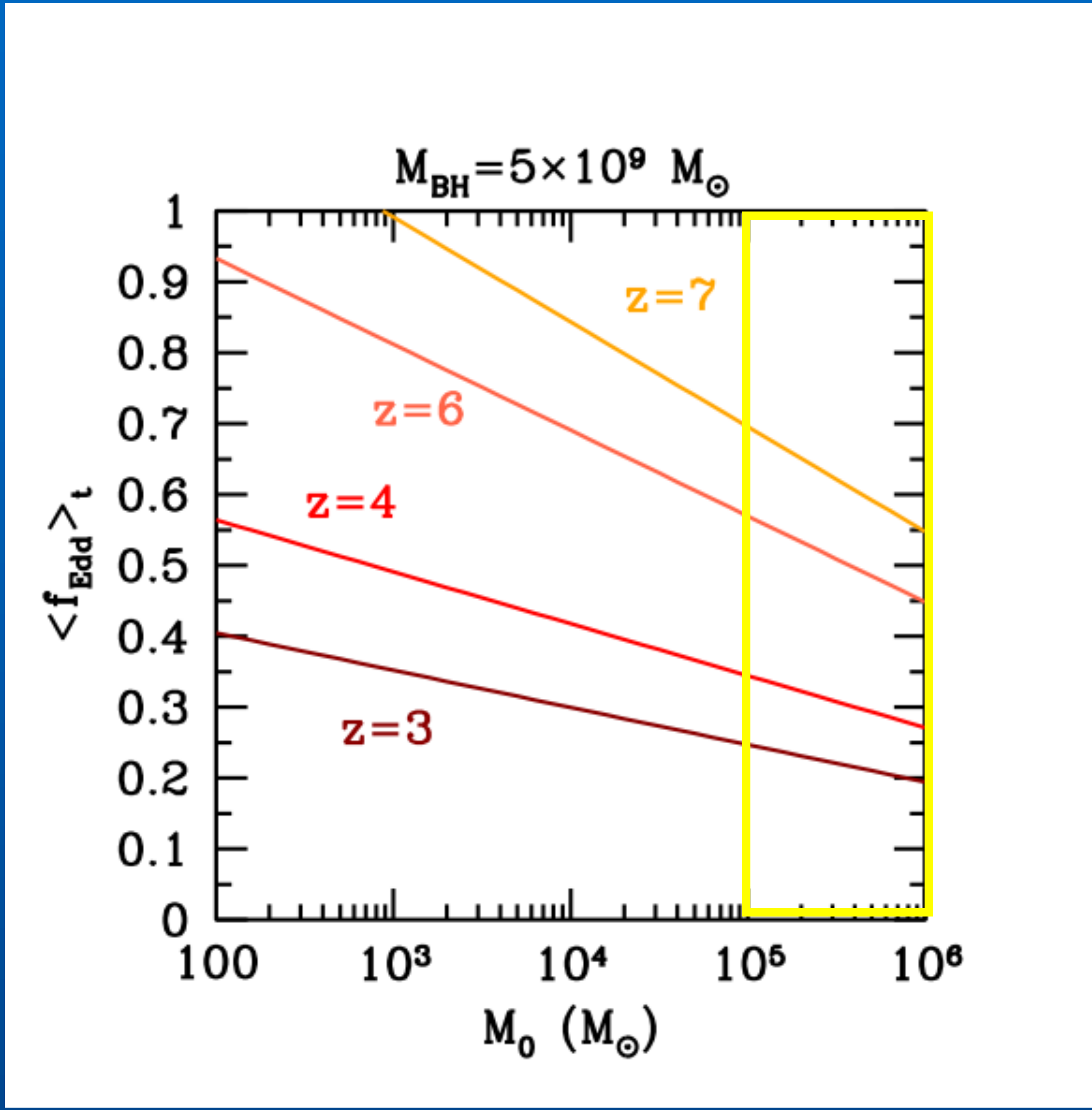
$$\tau = \frac{\eta c \sigma_T}{4\pi G m_p} \approx 5\times 10^7\, yr$$



LATEST PLANCK RESULTS: first stars form even later!

Wu+ 15; Robertson+ 15; Planck+ XIII 15

MASS GROWTH OF BH SEEDS: TIMING CHALLENGE



$$\langle f_{\rm Edd}\rangle_t = \frac{t_{\rm Edd}}{t_{\rm Hubble}(z)}\frac{\epsilon}{1-\epsilon}\ln\left(\frac{M_{\rm BH}}{M_0}\right).$$

$$L = \epsilon\,\dot{M}_{in}c^2 = f_{\rm Edd}L_{\rm Edd}c^2,$$

AGE OF THE UNIVERSE AT z = 7 [771 Myr]; z= 4[1.57 Gyr]; z= 3 [2.9 Gyr]

PN+ 15; Alexander & PN 14;Treister+ 13

LIGHT SEEDS

PopIII

$\sim 10^{1-2}\ M_{sun}$

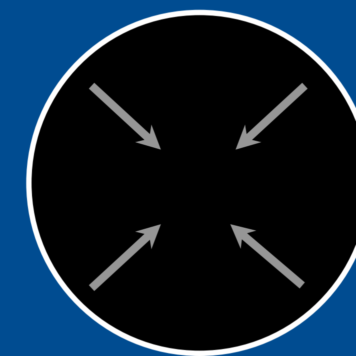
MASSIVE SEEDS

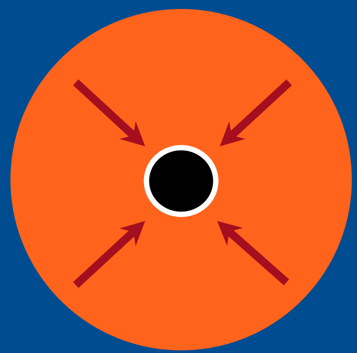
Direct collapse

Nuclear star cluster

$\sim 10^{3}\ M_{sun}$

Supermassive Star





Quasi star

$\sim 10^{4-6}\ M_{sun}$

Uncertainity in the masses of the first stars

A challenge to grow monster BHs seen by t < 2 Gyrs

New Planck results push first stars to later even ~550 Myrs after the Big Bang

In protogalaxies: need to avoid fragmentation and star formation, need to centrally concentrate mass

- Metal-free gas
- Prevent molecular H-cooling

First black holes in pre-galactic halos z = 20-30

$M_{BH} \sim 1 - 100\ M_{sun}$ **LIGHT SEEDS**

Pop III remnants : Simulations suggest that the first stars have a range of masses (Bromm+ 02 ; Abel+ 02; Abel+ 00; Alvarez+ 08; Hirano+ 14) Metal free Pop III stars leave remnant BHs

Supra-exponential early growth boost: Super-Eddington growth in nuclear star clusters at high-z (Alexander & PN 14)

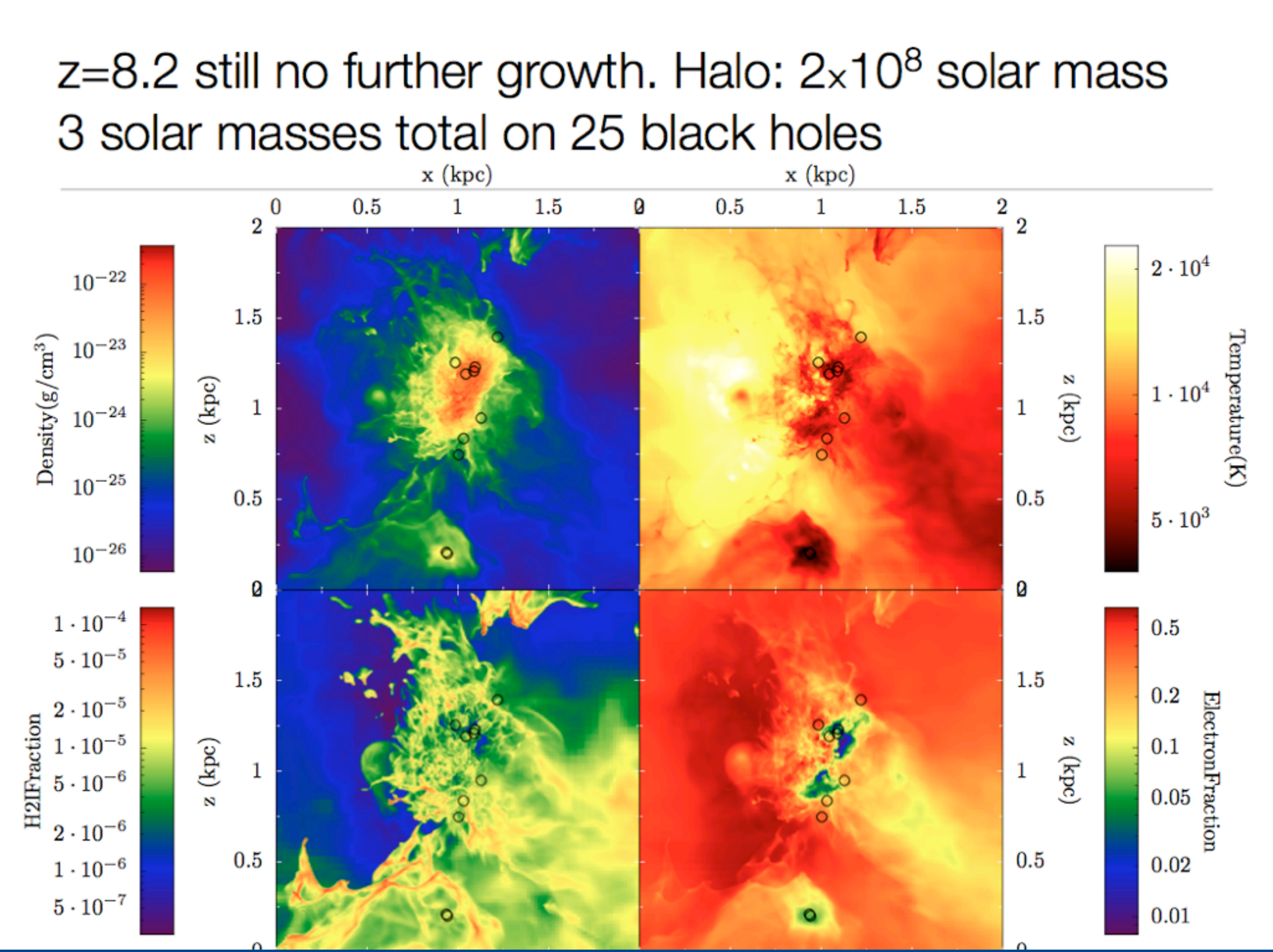
$M_{BH} \sim 10^3 - 10^6\ M_{sun}$ **MASSIVE SEEDS**

Direct Collapse – efficient viscous transport, H2 cooling suppressed, Lyman-Werner radiation, formation of central concentration (Eisenstein & Loeb 95; Koushiappas+ 04)+ proper dynamical treatment of disk stability (Lodato & PN 06, 07)

Supermassive star (Haehnelt & Rees 93)

Quasi-star - Bar unstable self-gravitating gas + large quasi-star (Begelman 08; 10; 12)

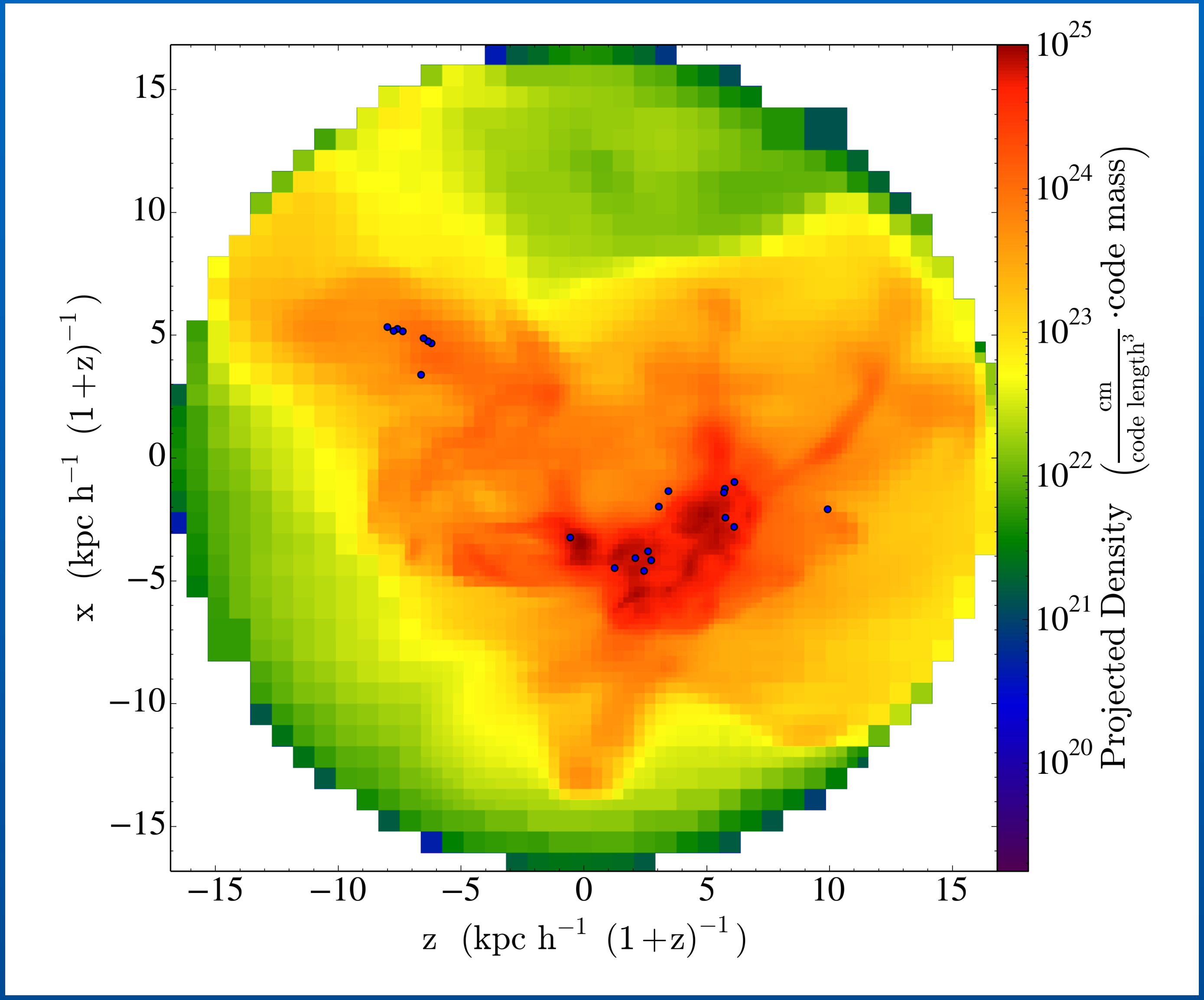
DO WE NEED MASSIVE BH SEEDS?
Tracking the fate of PopIII seeds in 2.5-3 sigma peaks

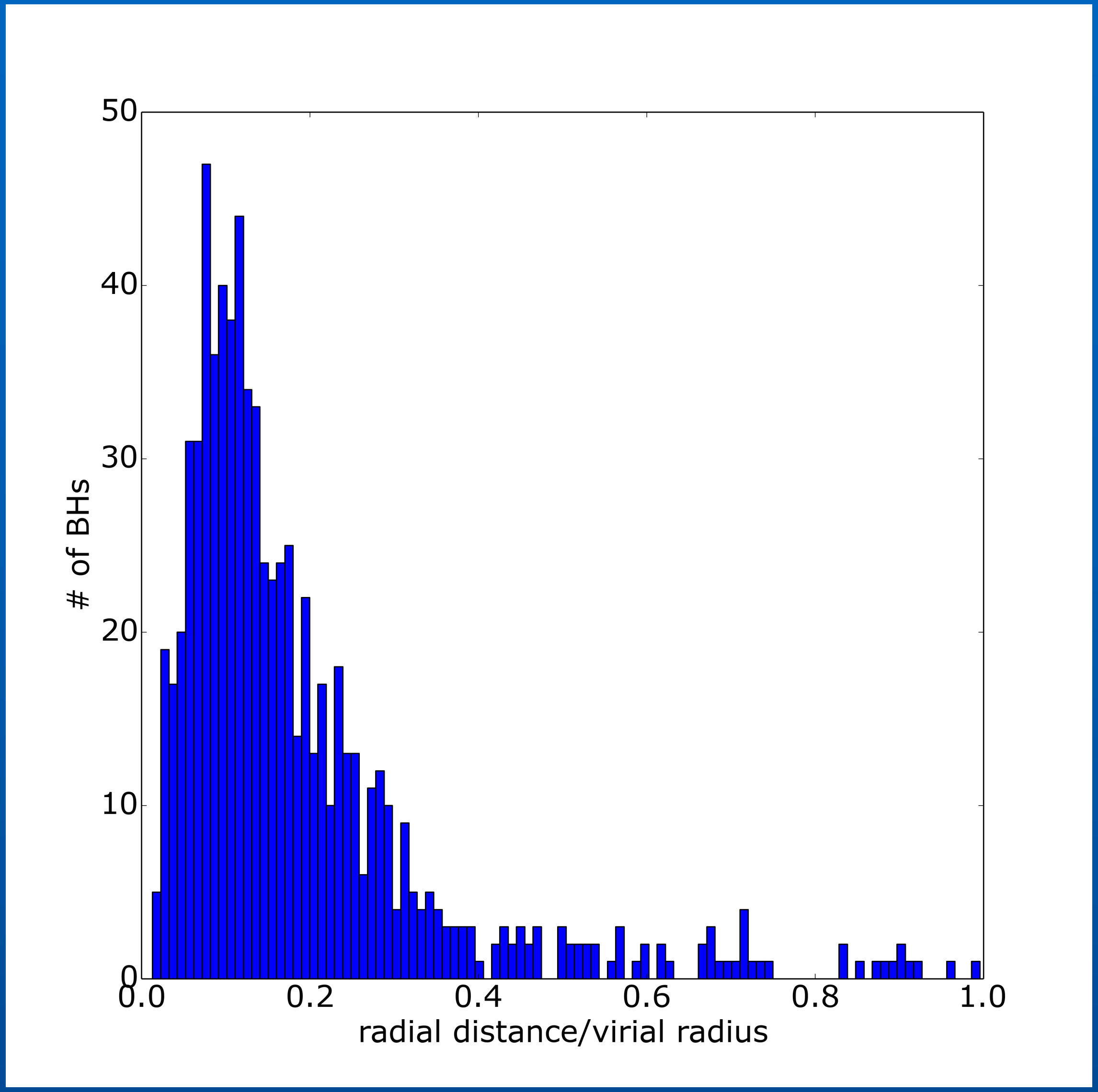


BHs simply not growing much down to z = 8
even when PopIII formation has ceased
BHs spend almost all their time in the wrong place
in 10^8 M_{sun} DM halos

Abel, Wise, Turk, Alvarez+; Stacy+

WHAT ABOUT Pop III REMNANTS IN 10^9 M_{sun} HALOS AT z=15
Tracking the fate of Pop III remnant BHs in 3-sigma peaks



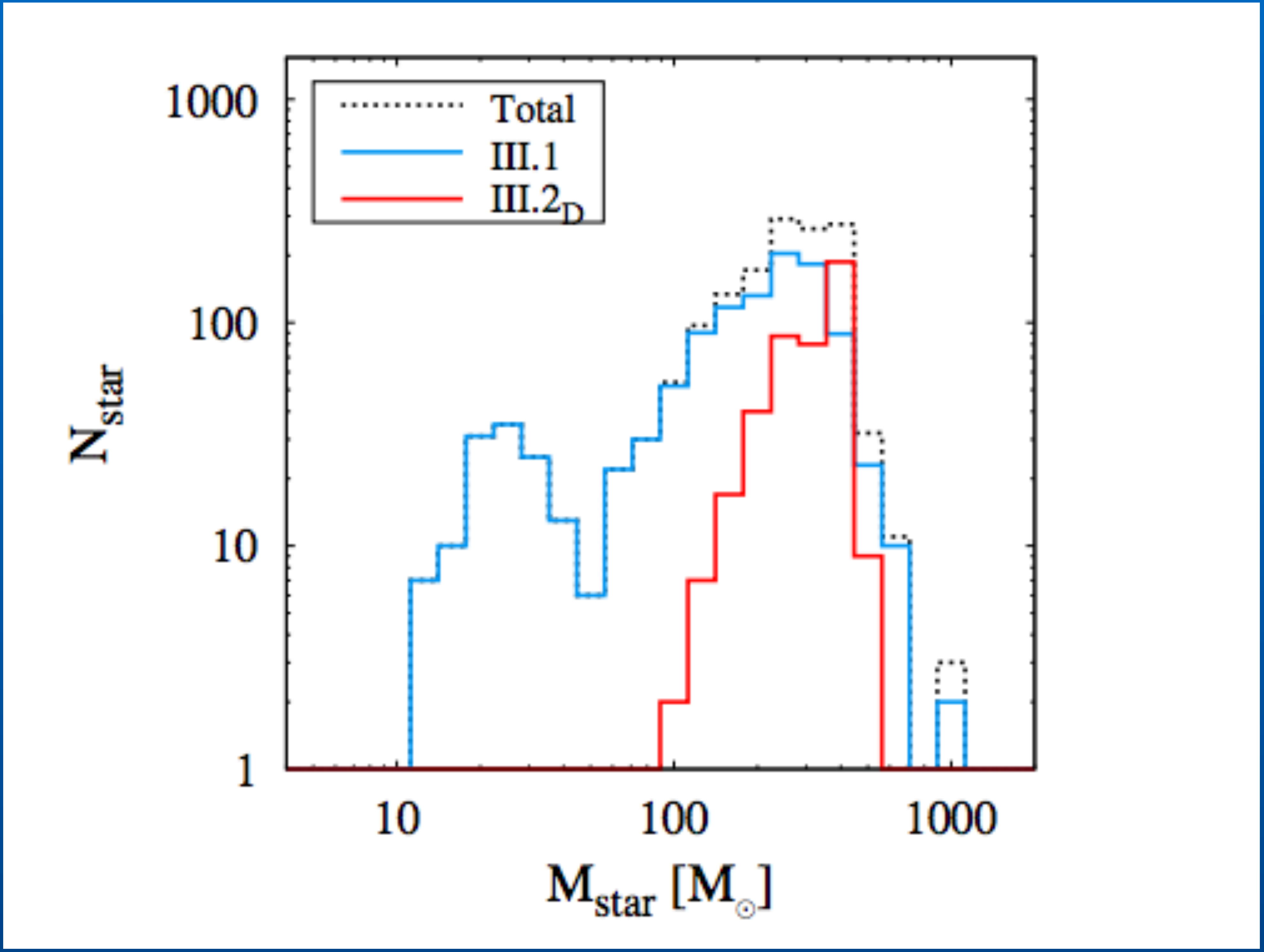


snapshot with 20 BH seeds, 300 Mpc^3 box, ENZO AMR 12 level refinements ~ 19 comoving pc, DM resolution ~ 3 X 10^4 M_{sun}

~ DM halos where Pop III star clusters formed at z = 15

Shi+ 15

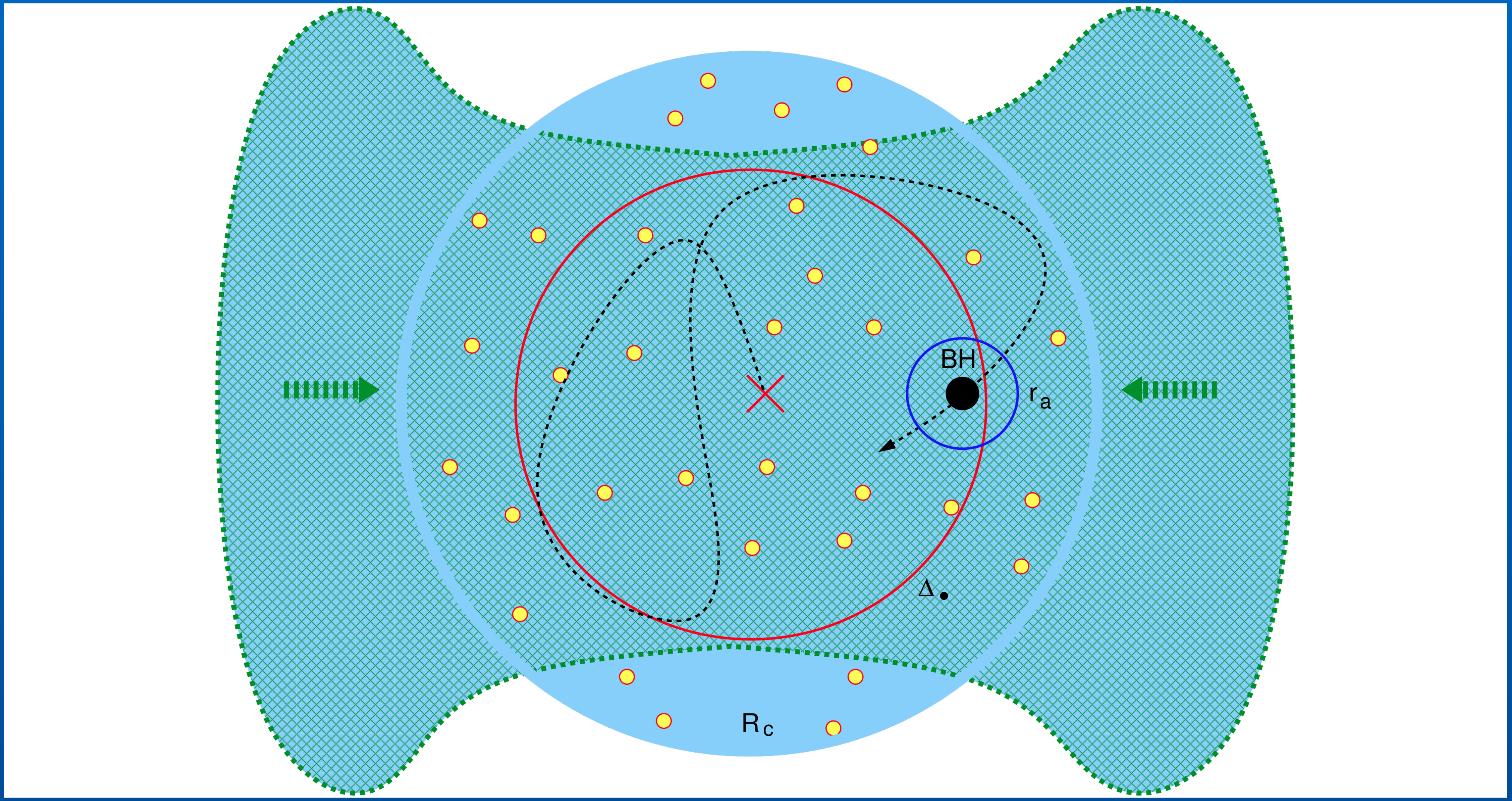
HOW MASSIVE ARE POP III STARS?



~ Mass distribution of Pop III stars formed at z = 30 -> 10

Hirano+ 14

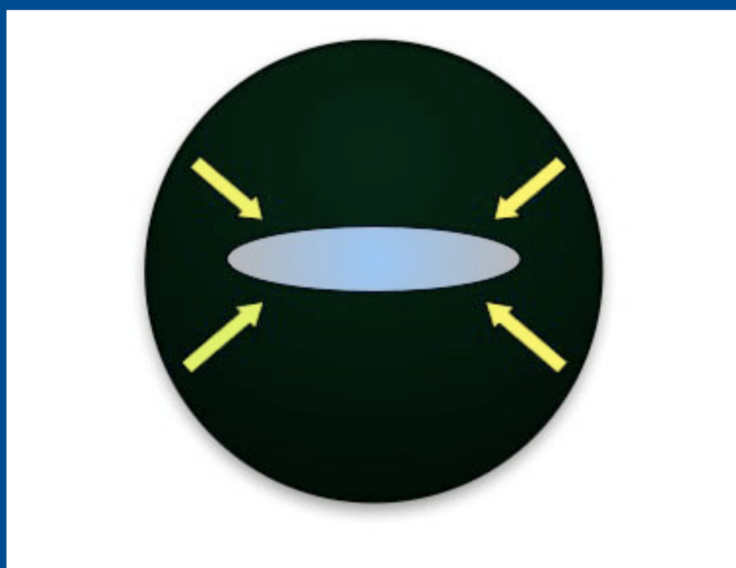
SUPER BOOSTING EARLY BH GROWTH



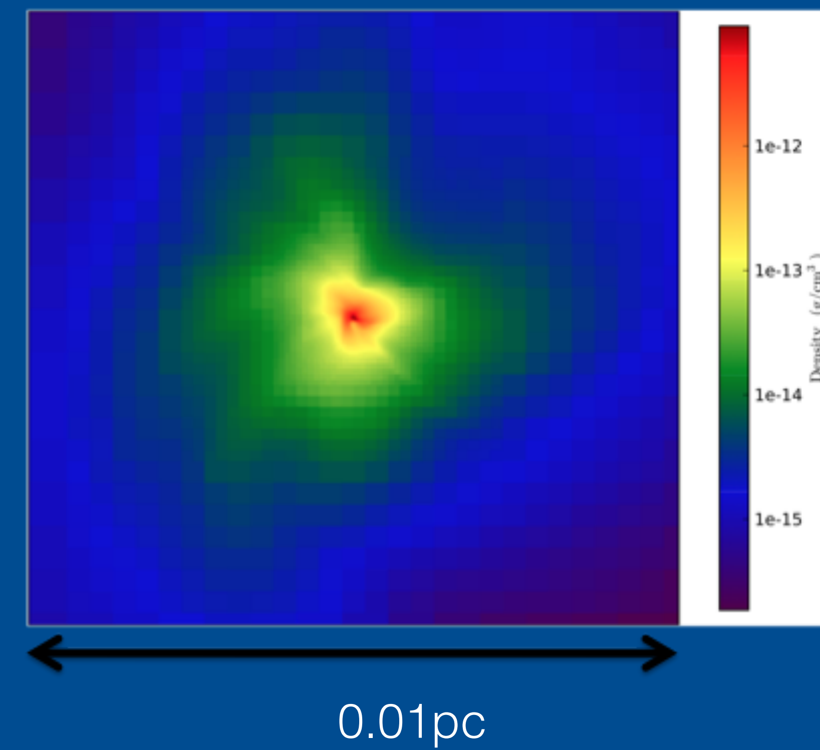
Circumventing the Eddington limit

Alexander & Natarajan 14

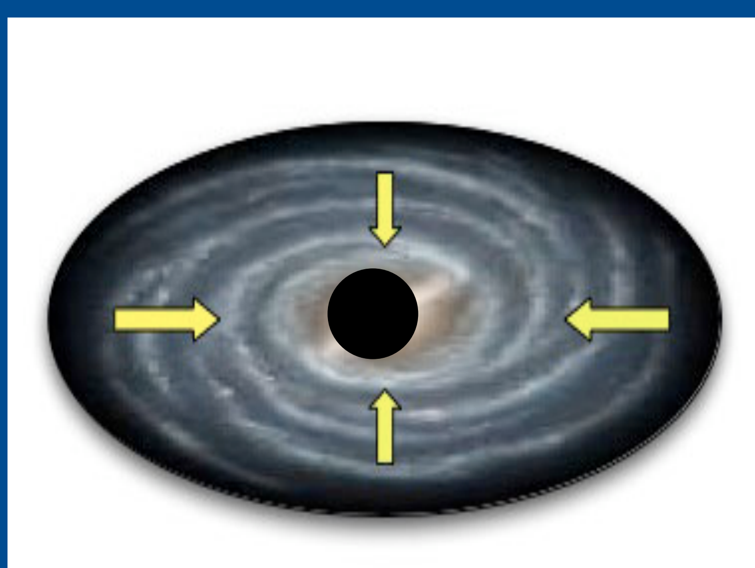
BH seed formation at high z



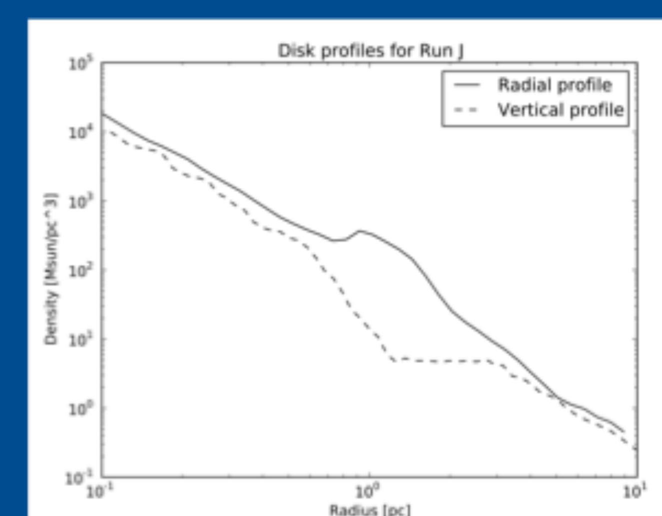
Baryons inside DM halo collapse and form a rotating pre-galactic disc



Disc becomes gravitationally unstable and accretes to the center



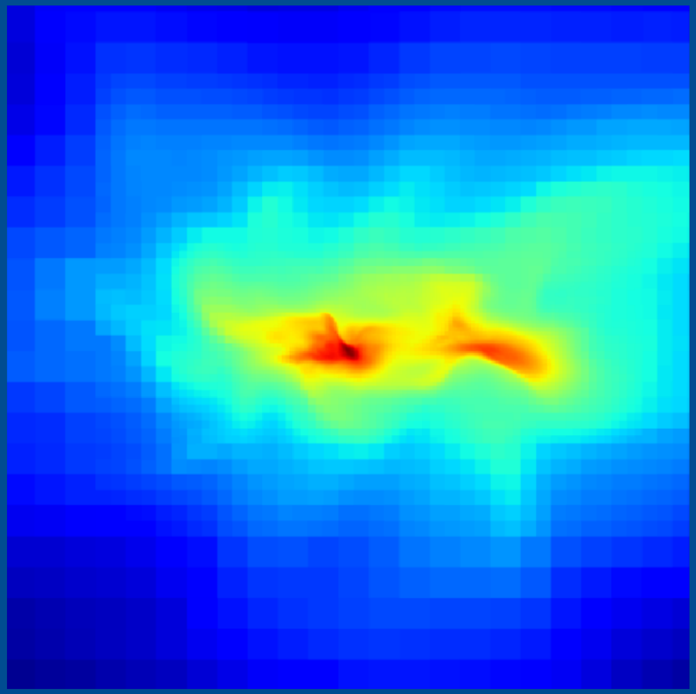
Angular mom of DM halo + Gas reservoir + dynamics (disc stability) + cooling

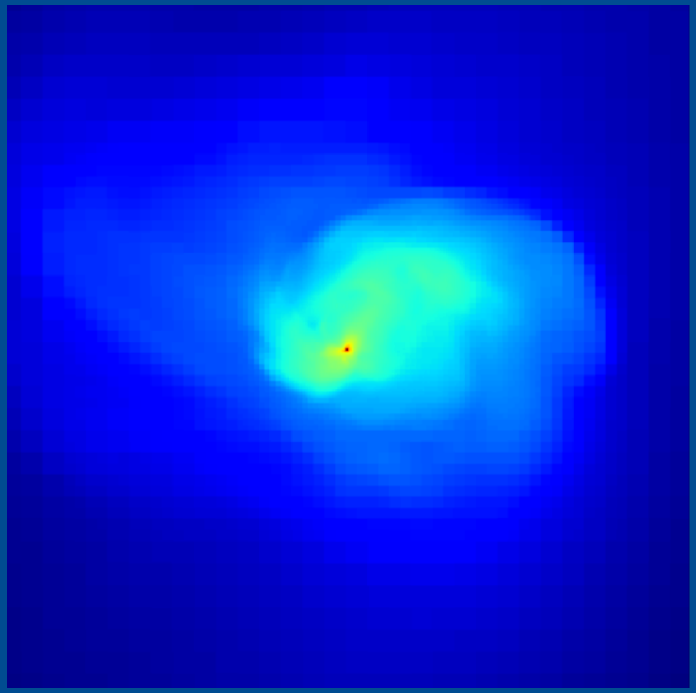


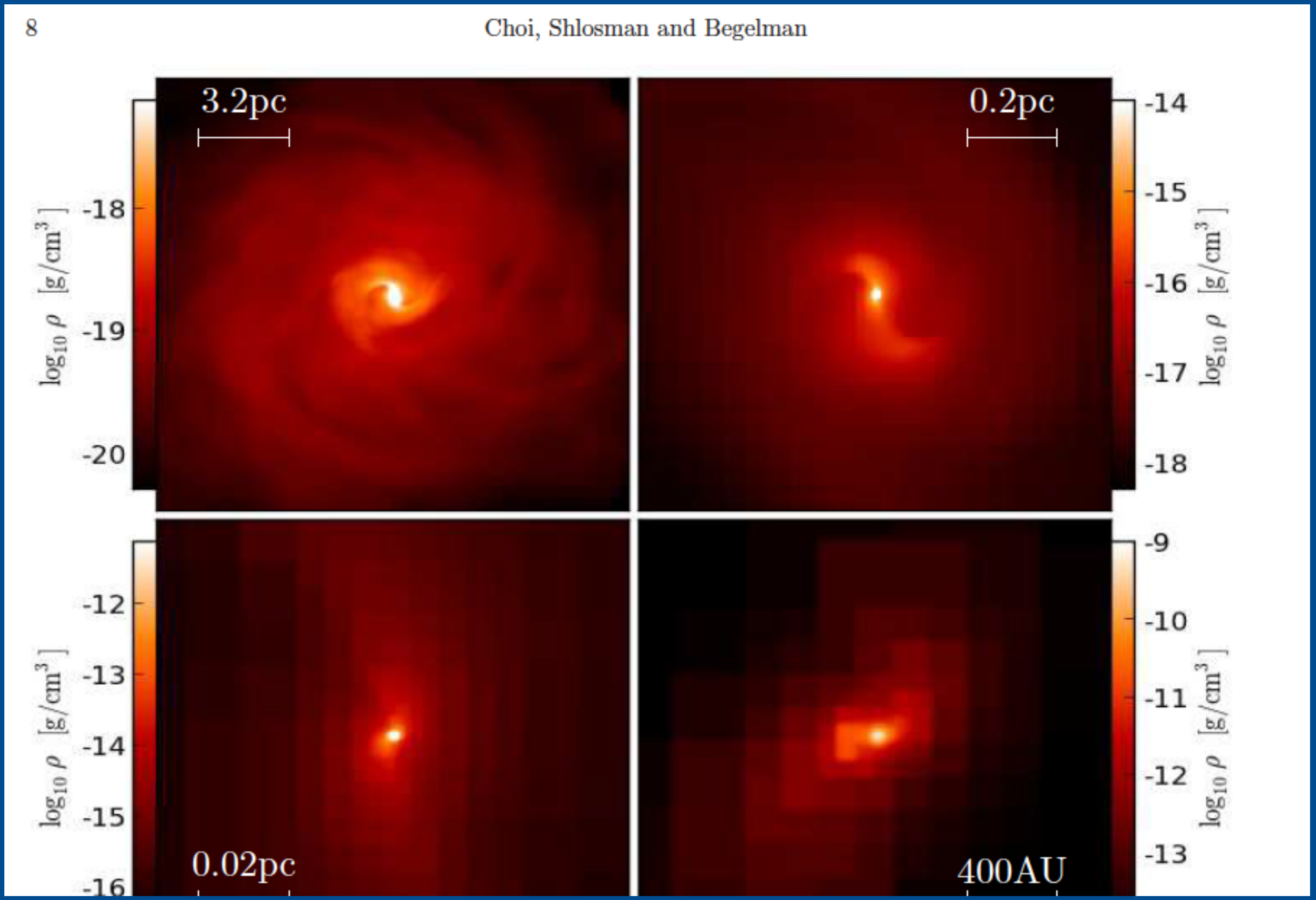
FINAL DCBH MASS

Regan+ 12; 14; Latif+ 15; Hirano+ 14

Massive BH seed formation simulations







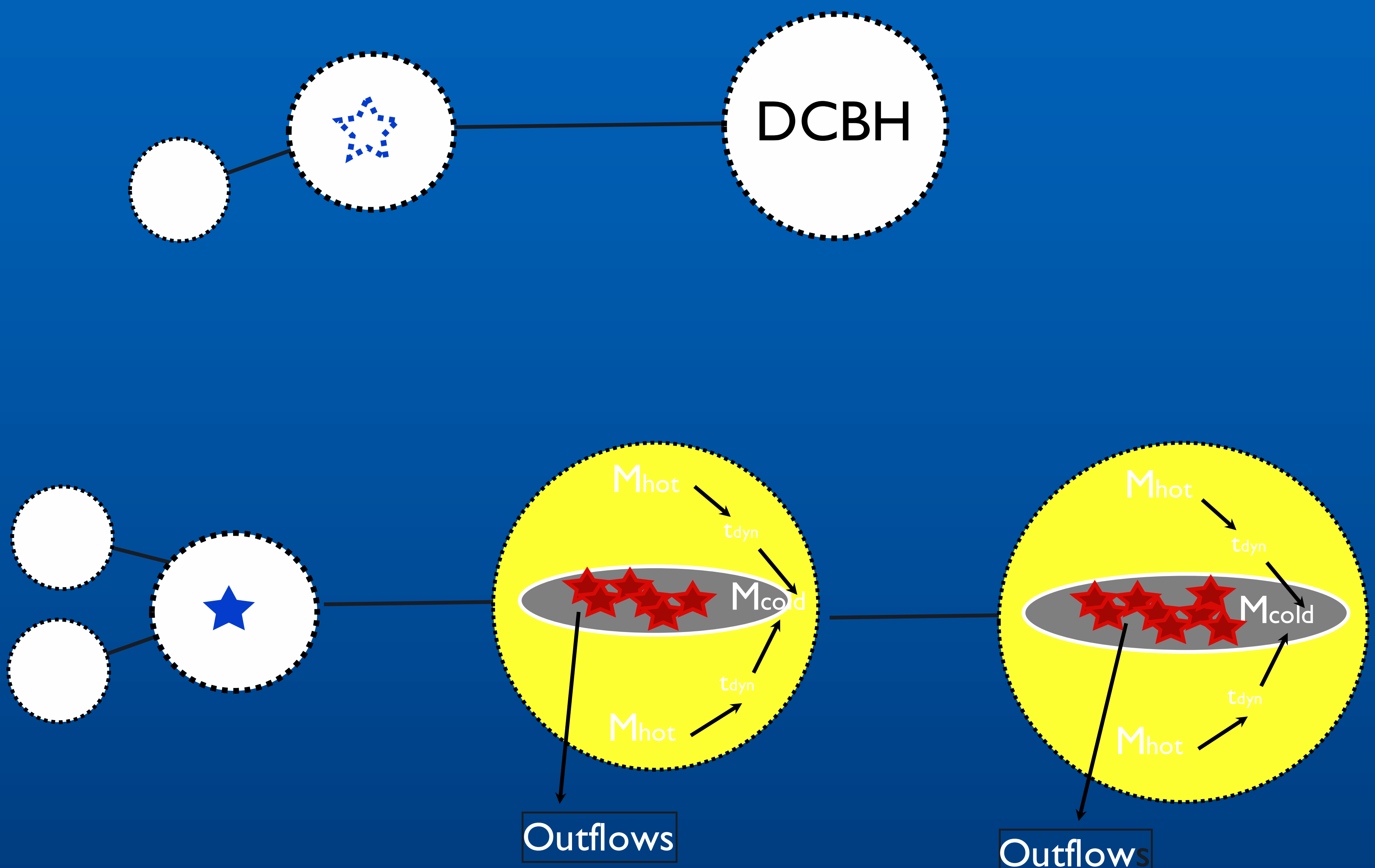
Smith, Davis & PN 15; Regan+ 08; 13; Hirano+ 14

Choi, Shlosman & Begelman 13

STRUCTURE FORMATION IN THE EARLY UNIVERSE
First Billion Years

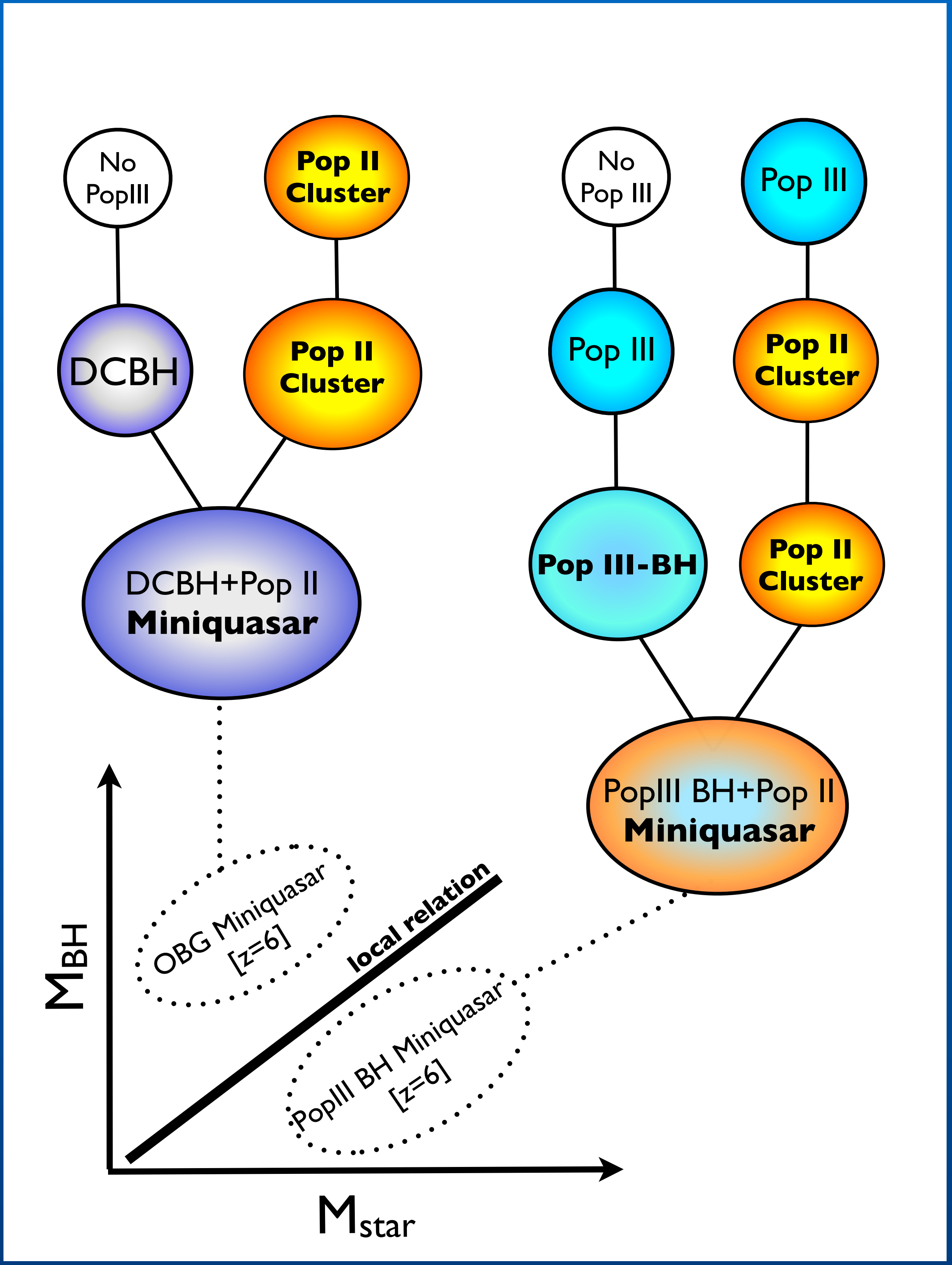
OPTIMAL SITES FOR DCBH FORMATION

Low spin DM halos; satellite halos; Lyman-Werner radiation from nearby halos with star formation to dissociate mol H and prevent fragmentation



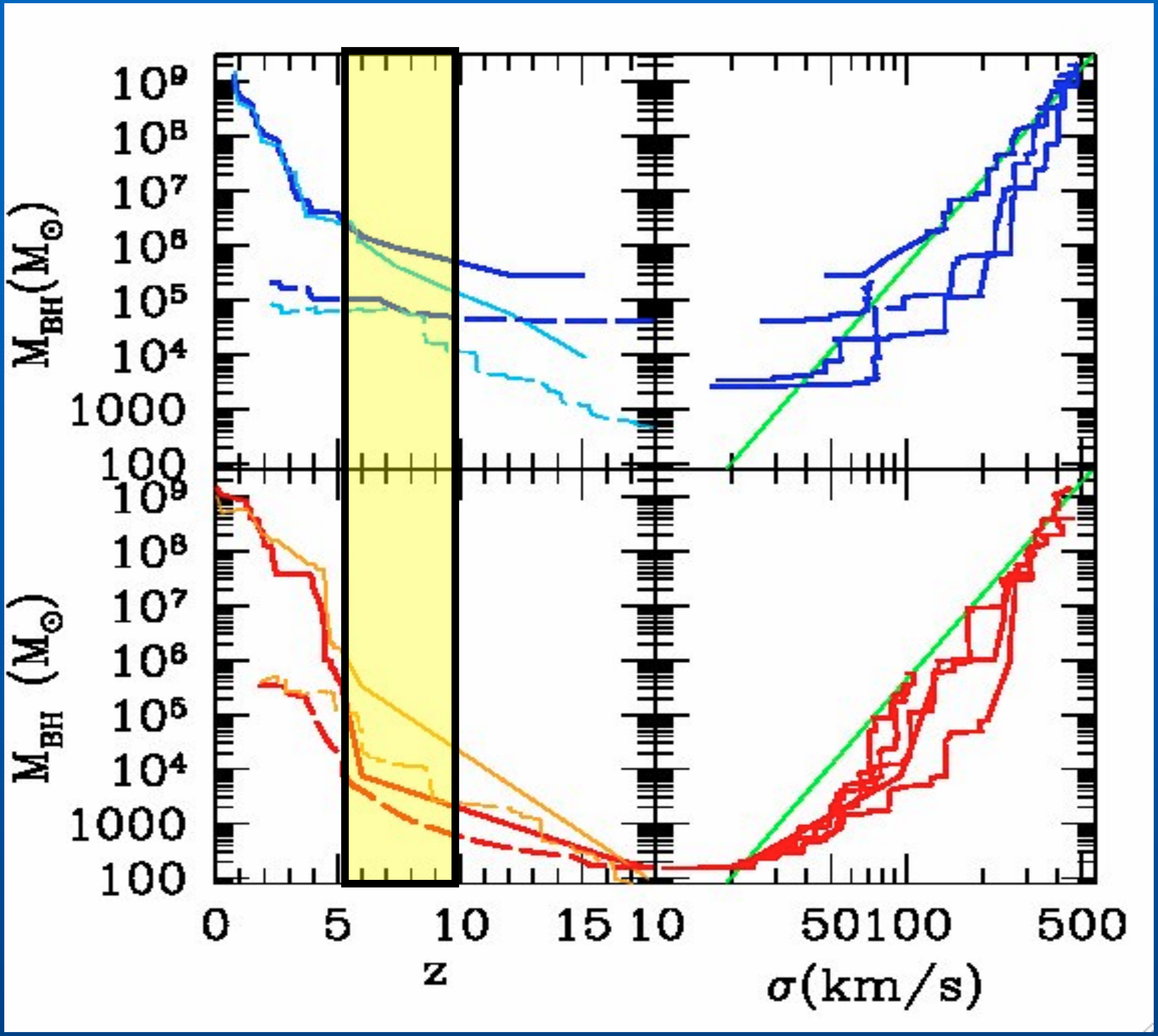
Agarwal+ 15

DIRECT COLLAPSE BHs AND THEIR OBESE BH HOST GALAXIES



Agarwal+ 12; 14

MODEL GROWTH HISTORIES OF BHs OVER COSMIC TIME



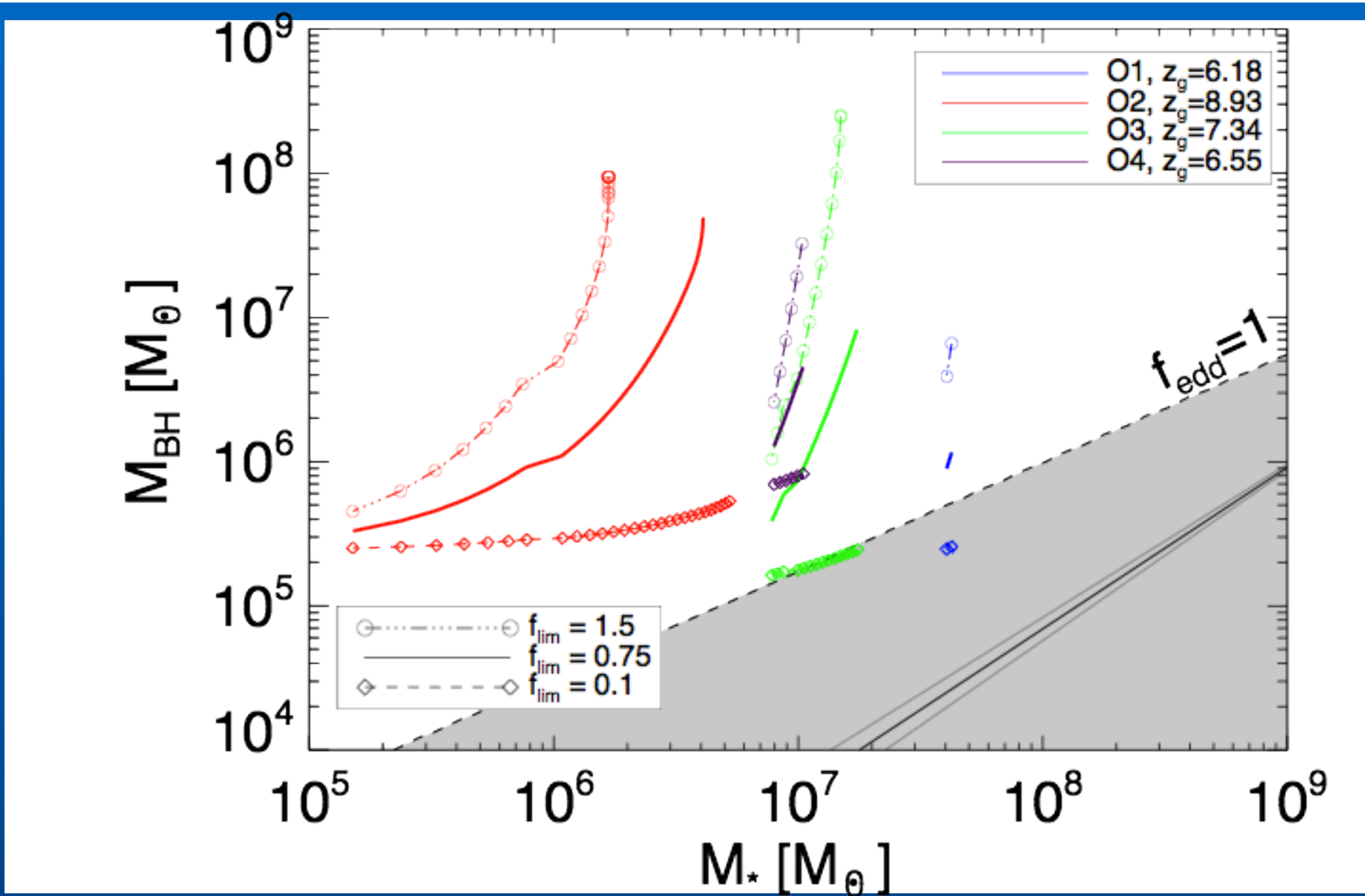
10^{13} M_{sun} halo

MASSIVE

LIGHT

Volonteri & PN 09; 11, 13

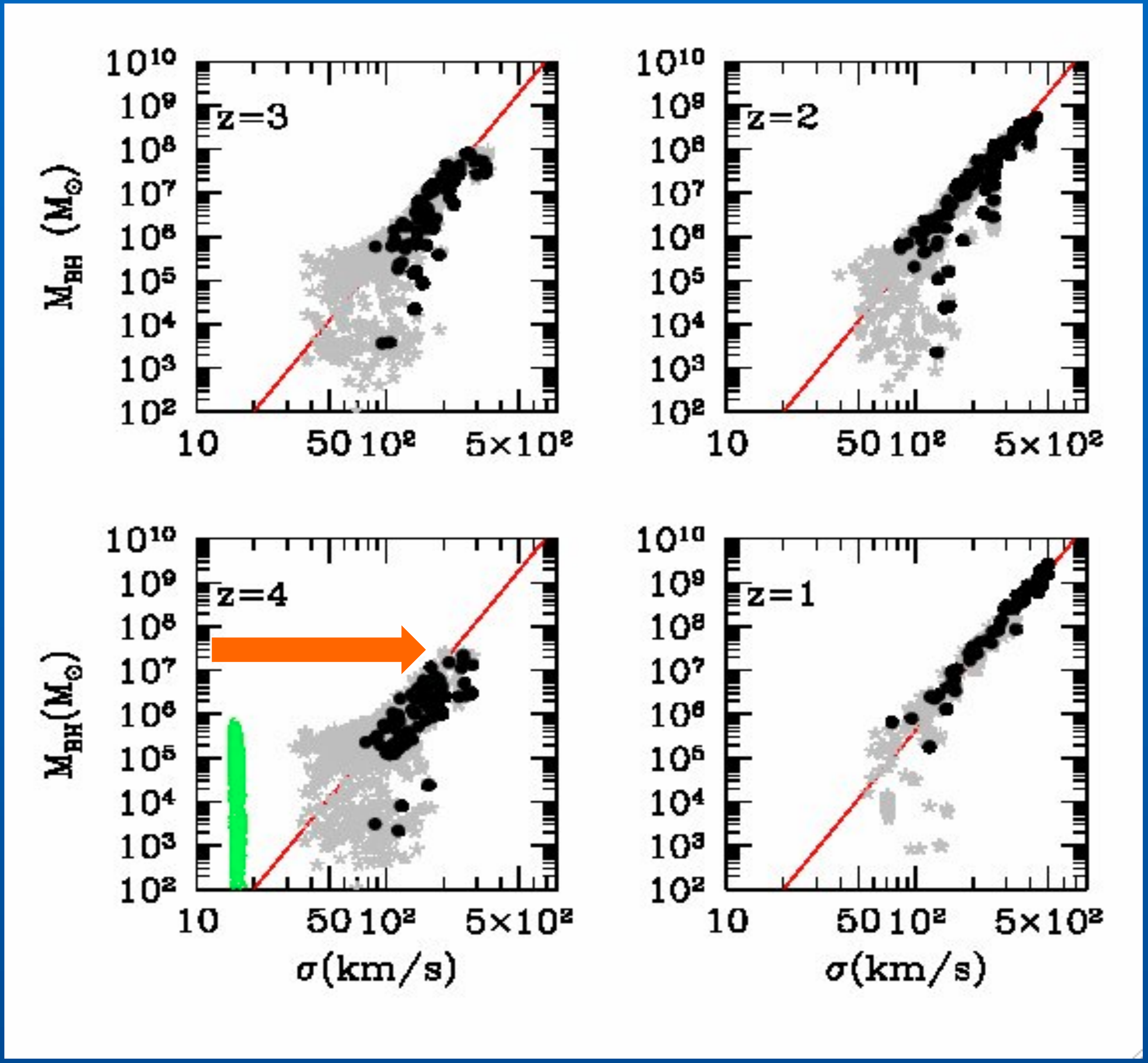
HIGH REDSHIFT SIGNATURE OF MASSIVE BH SEEDING MODELS

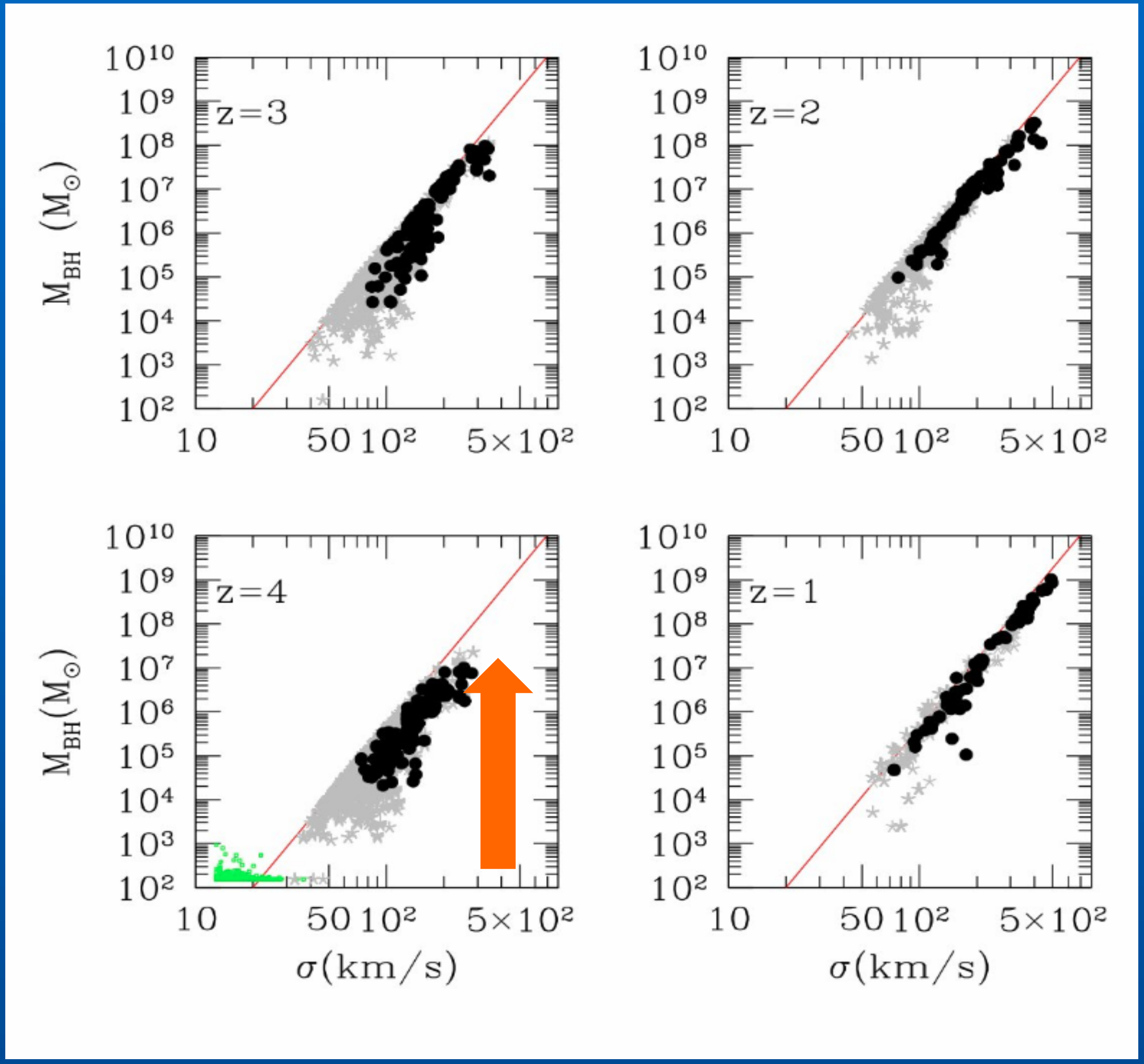


PREDICT NEW CLASS OF GALAXIES
OBESE BH GALAXIES (OBGs)

Agarwal+ 12; 14

Inter-mediate z signature: journey to the M_{BH}- sigma relation; overmassive BHs outliers

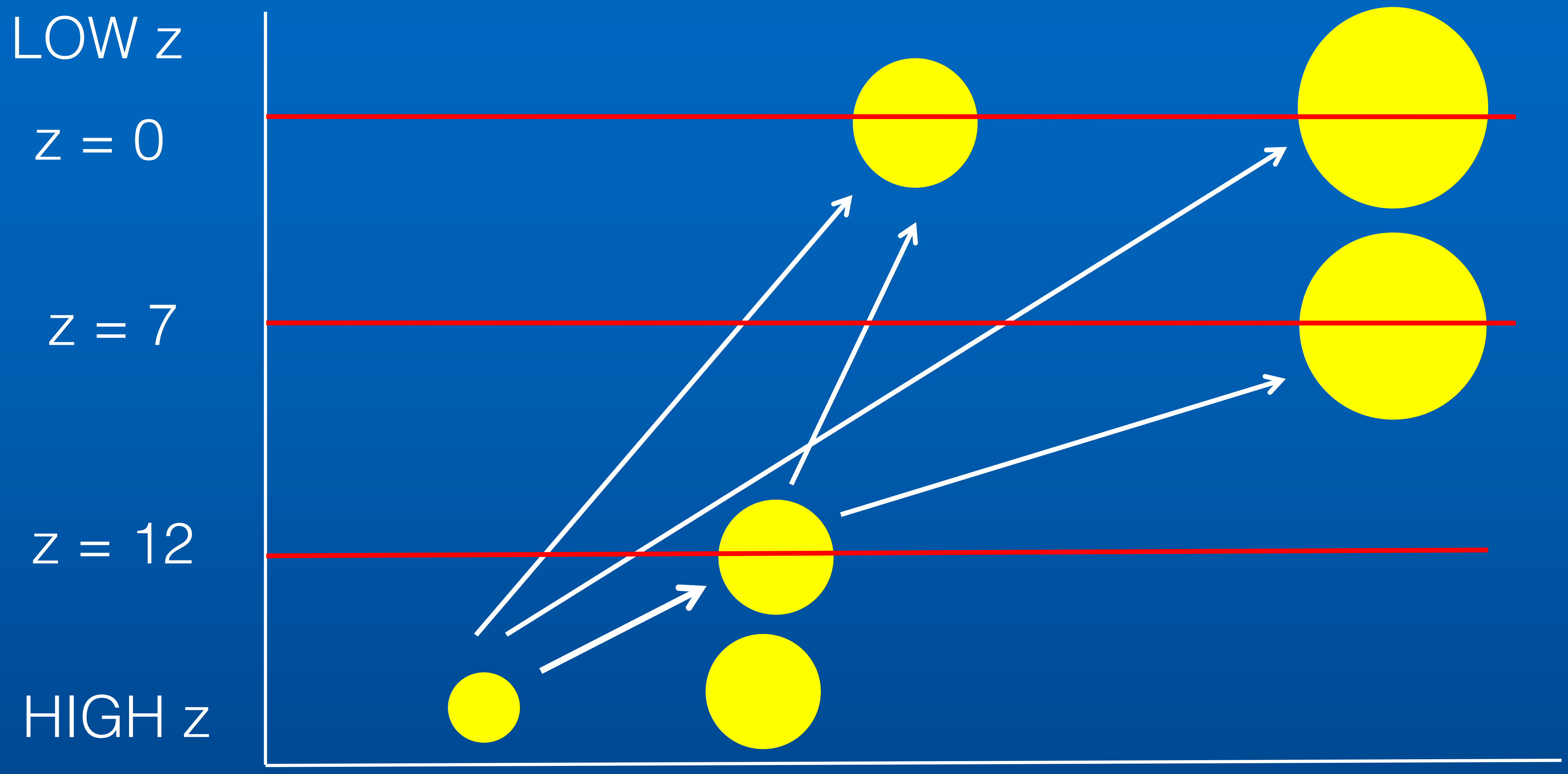




Sequence of BH growth versus stellar assembly
scatter in z = 1 to z = 4 correlations
overmassive BHs for their host galaxies

Volonteri & PN 09; PN 13

Exploring growth histories

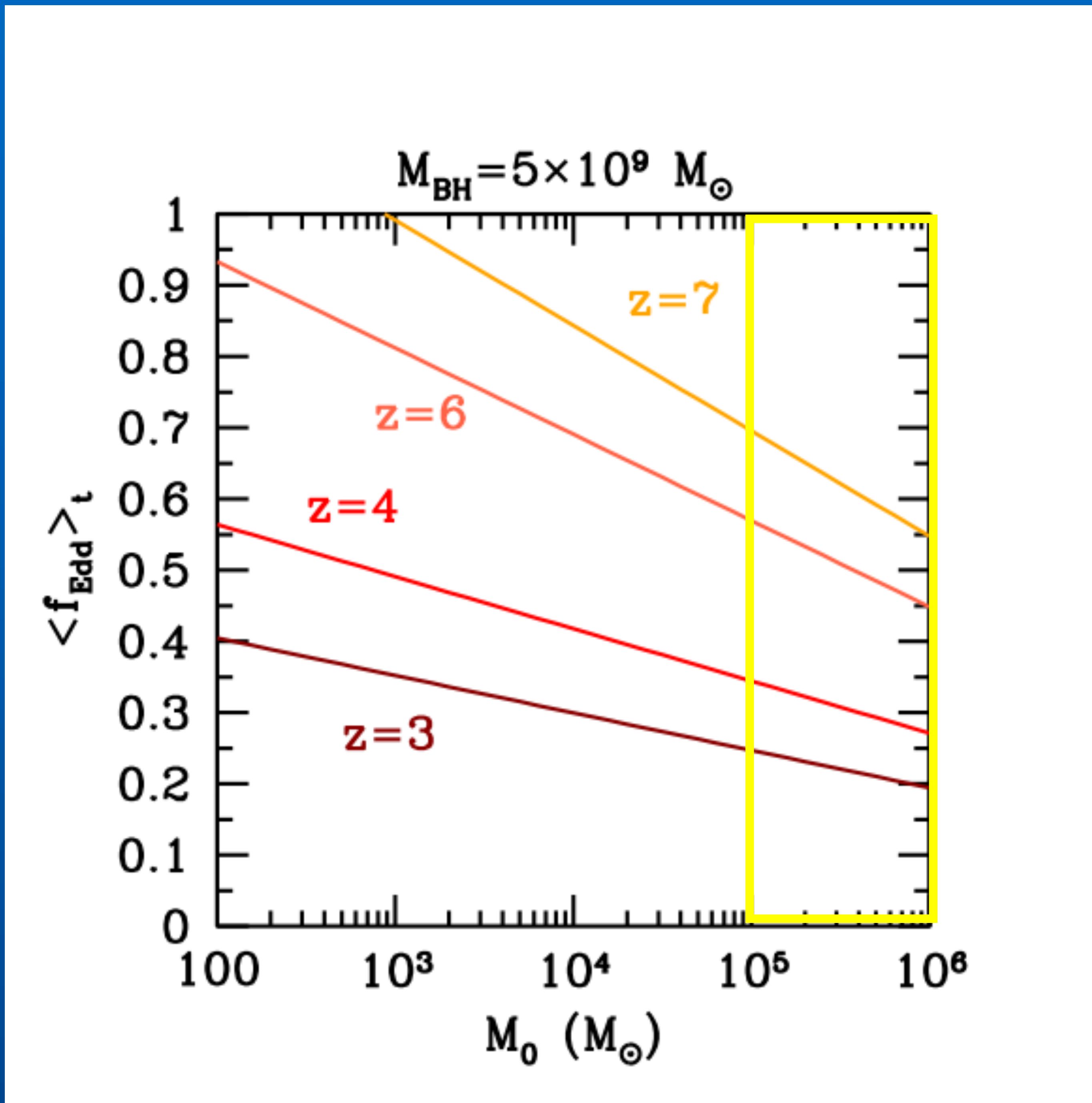


BH MASS ASSEMBLY

Outliers encode information on seed formation channels

CDM halo merging, environment

MASS GROWTH OF BH SEEDS: TIMING CHALLENGE



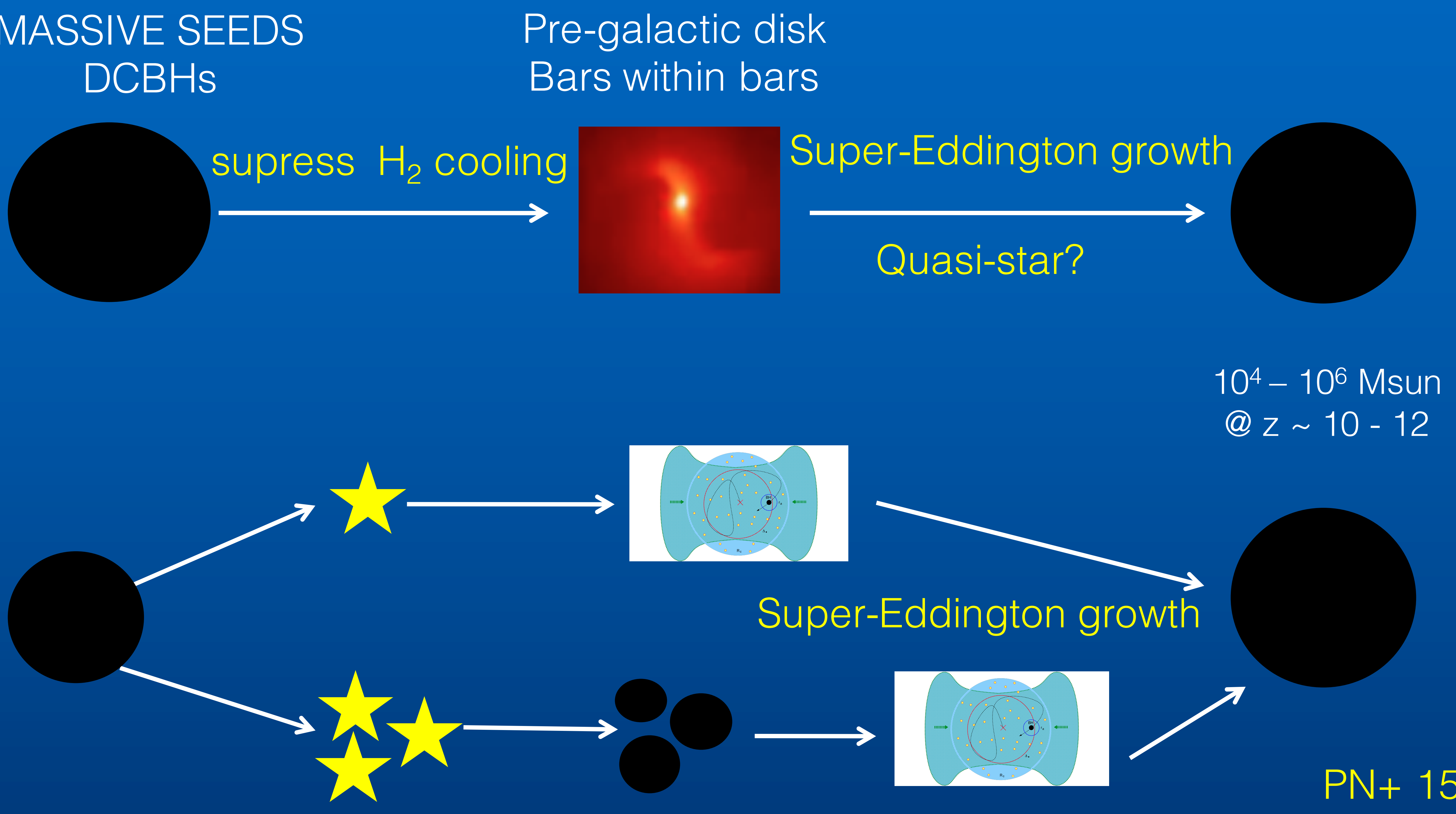
$$\langle f_{\rm Edd}\rangle_t = \frac{t_{\rm Edd}}{t_{\rm Hubble}(z)}\frac{\epsilon}{1-\epsilon}\ln\left(\frac{M_{\rm BH}}{M_0}\right).$$

$$L = \epsilon\,\dot{M}_{in}c^2 = f_{\rm Edd}L_{\rm Edd}c^2,$$

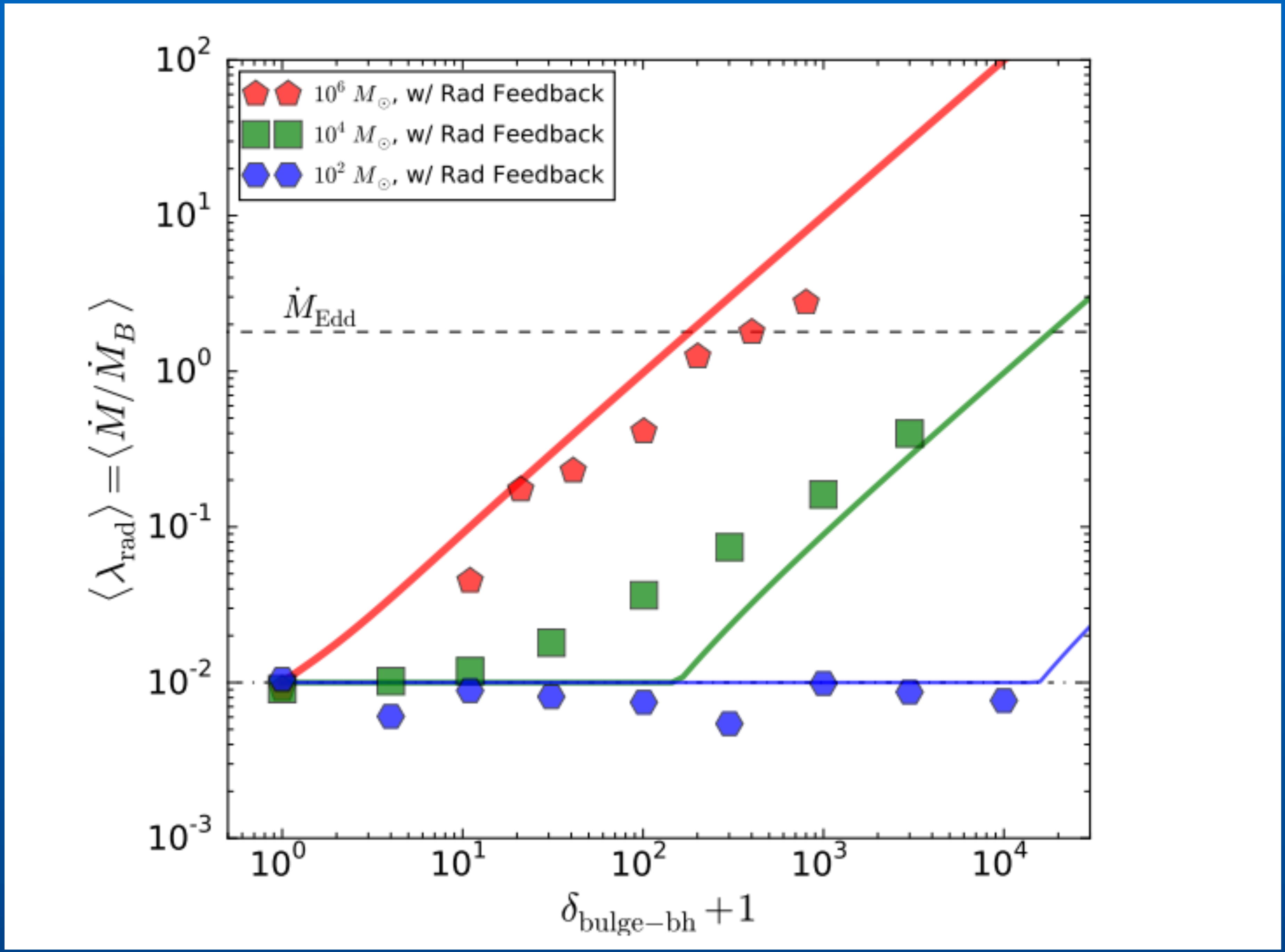
AGE OF THE UNIVERSE AT z = 7 [771 Myr]; z= 4[1.57 Gyr]; z= 3 [2.9 Gyr]

PN+ 15; Treister+ 13

SYNOPSIS OF CURRENT VIEW ON BH SEEDS TO MAKE THE MOST MASSIVE BHs AT ALL EPOCHS

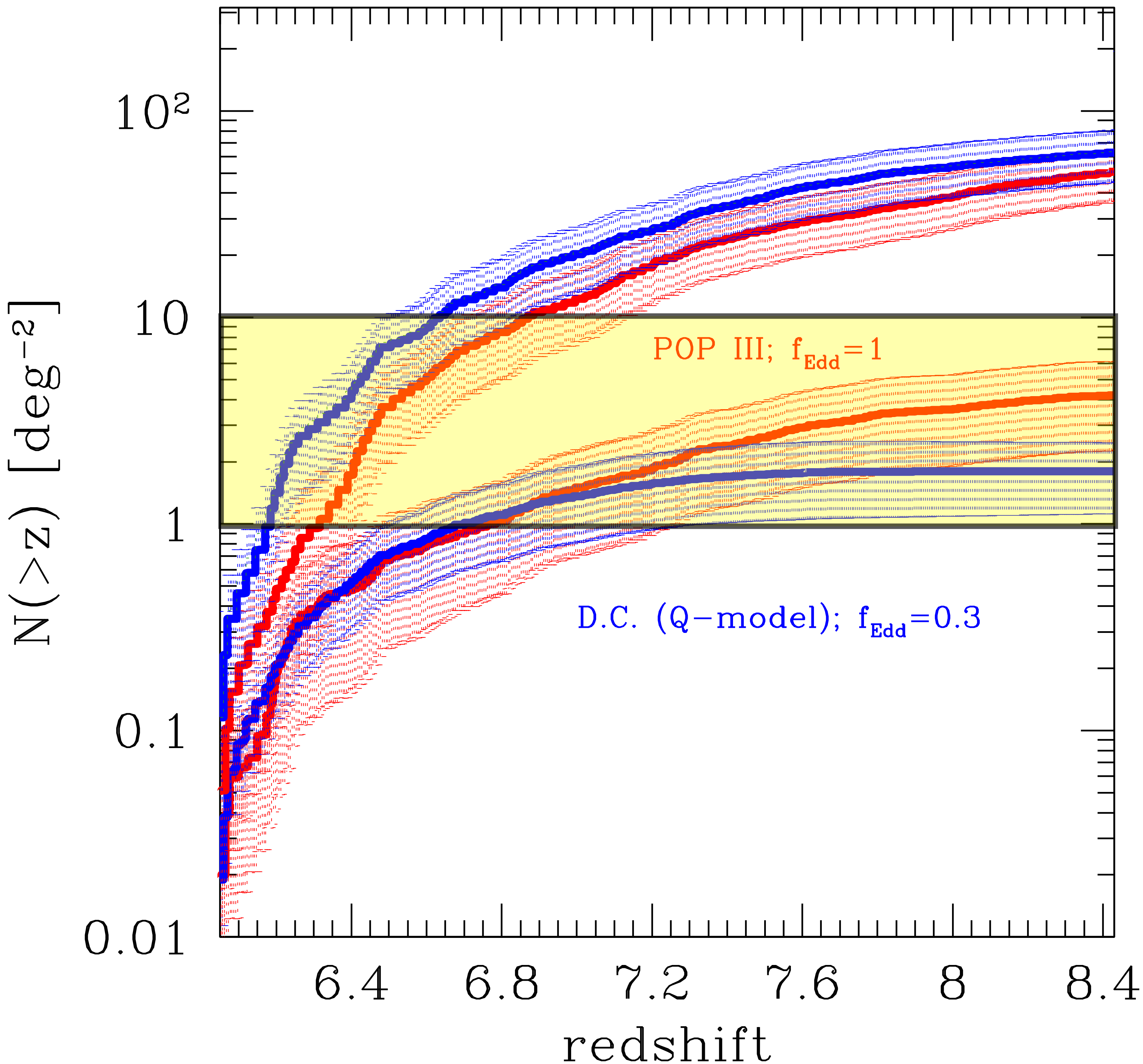


Detecting the first black holes: Pop III seeds & DCBHs



Park, Ricotti, PN+ 15

What can we do with X-ray Surveyor



OPEN QUESTIONS

Masses of initial BH seeds
Early accretion history of seed BHs
Contribution to Re-ionization
Observational signatures of Super-Eddington flows
Importance of mergers
When do the correlations between BHs and their hosts get set-up