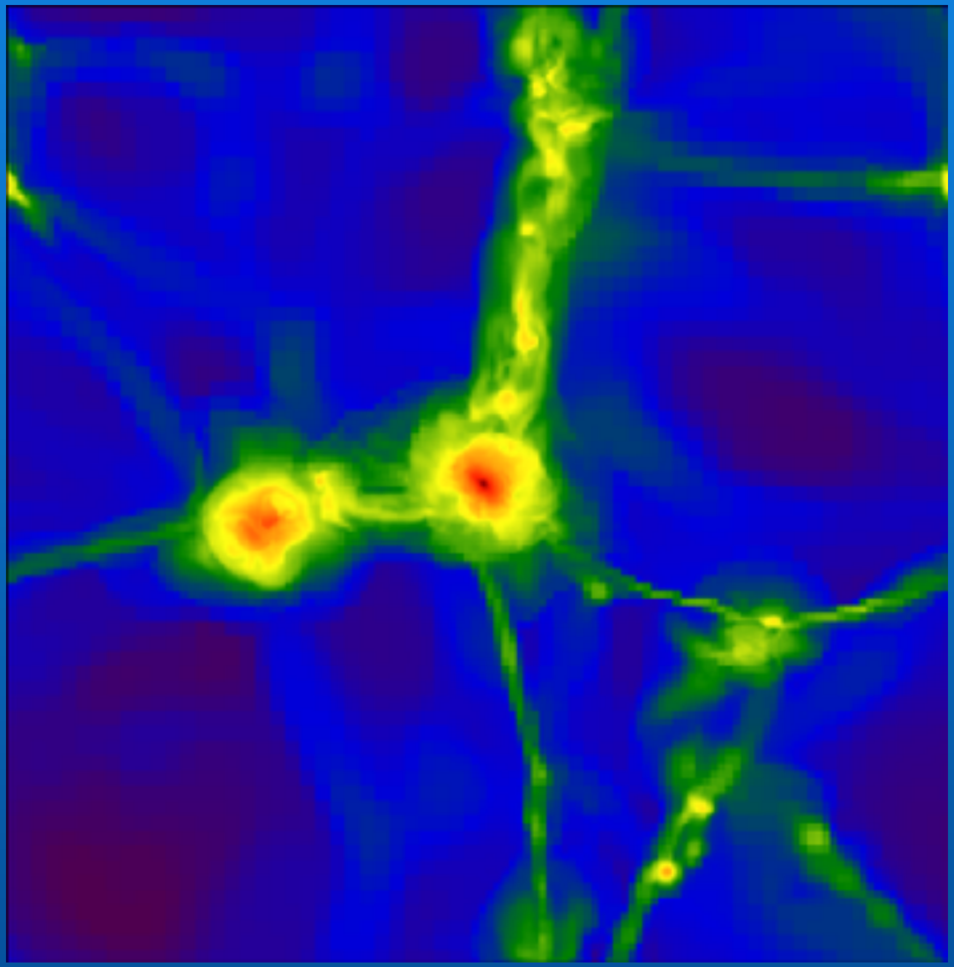
Unveiling the first black holes

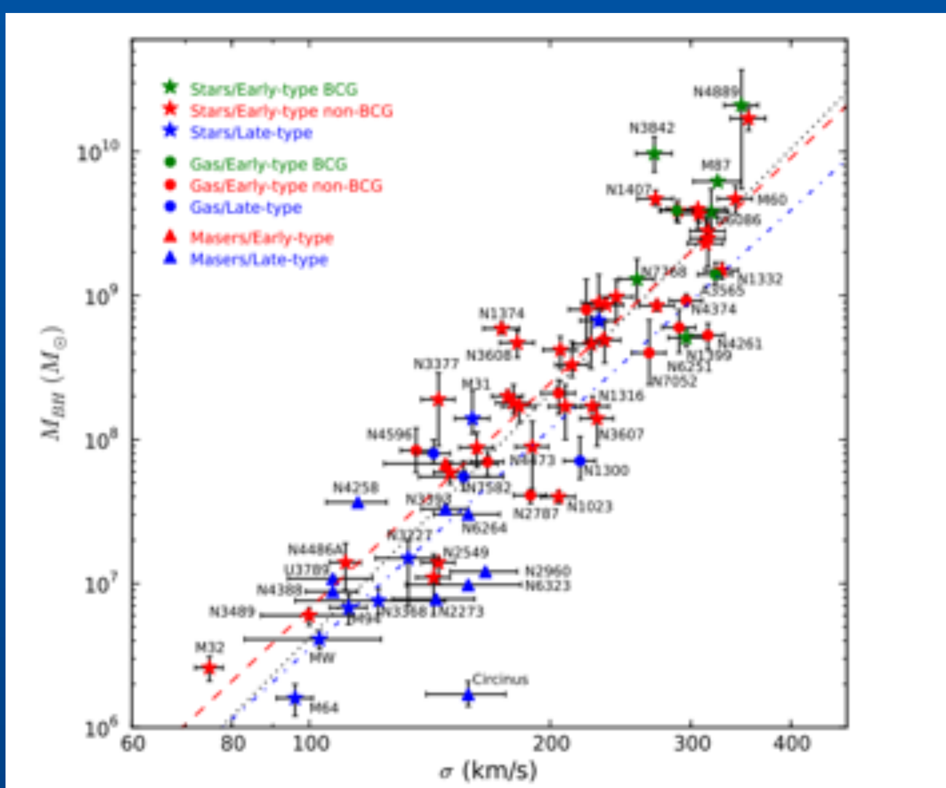


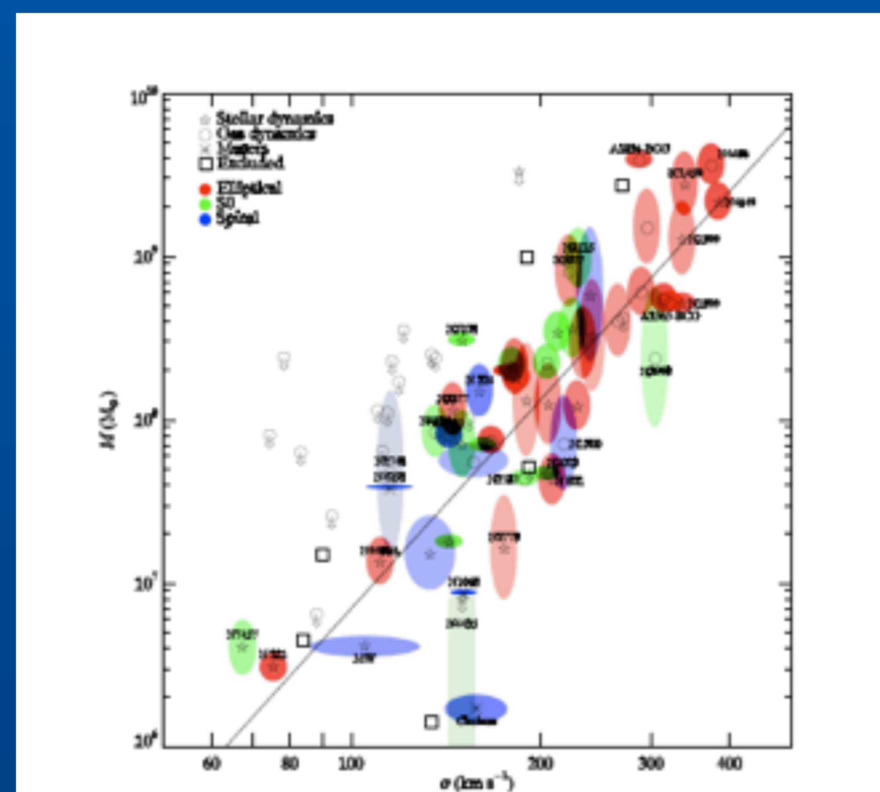
Agarwal+; Haiman+; Tanaka+; Johnson+; Park+; Ricotti+; Khochfar+; Di Matteo+; Yoshida+ Schneider+Dubois+; Bournoud+; Ferrara+; Pacucci+; Bromm+; Milosavljevic+; Ricotti+; Norman+; Omukai+; Inayoshi+; Regan+; Sijacki+; Habuzit+; Smith+; Abel+; Wise+; Latif+; Whalen+

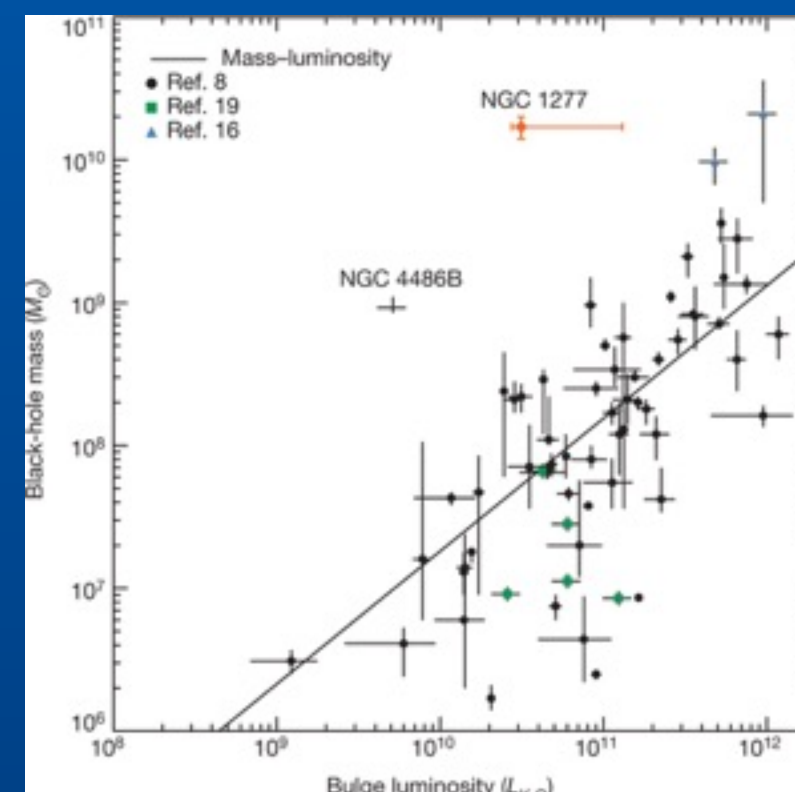
Priyamvada Natarajan
Yale University

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



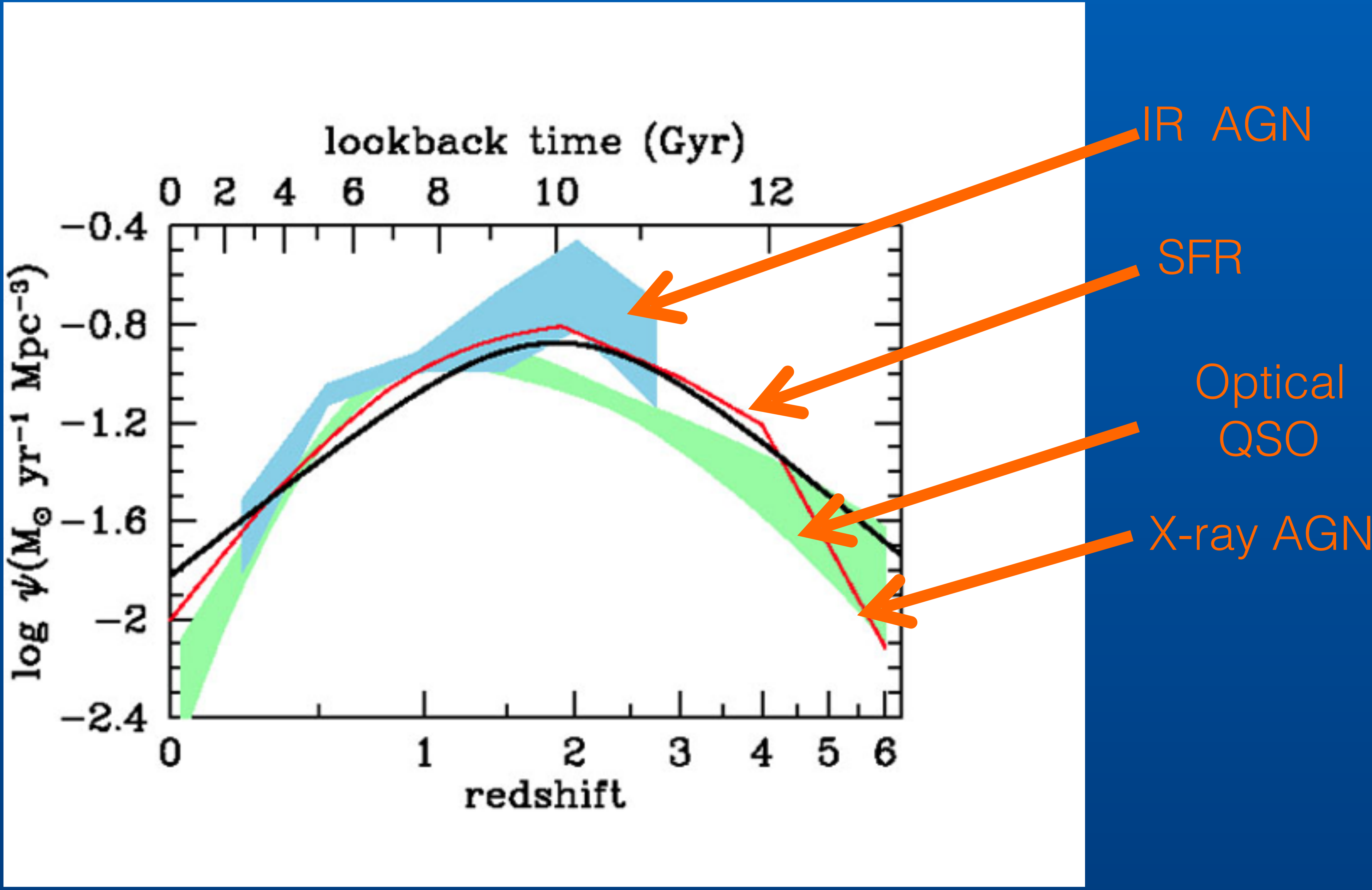




McConnell & Ma+13

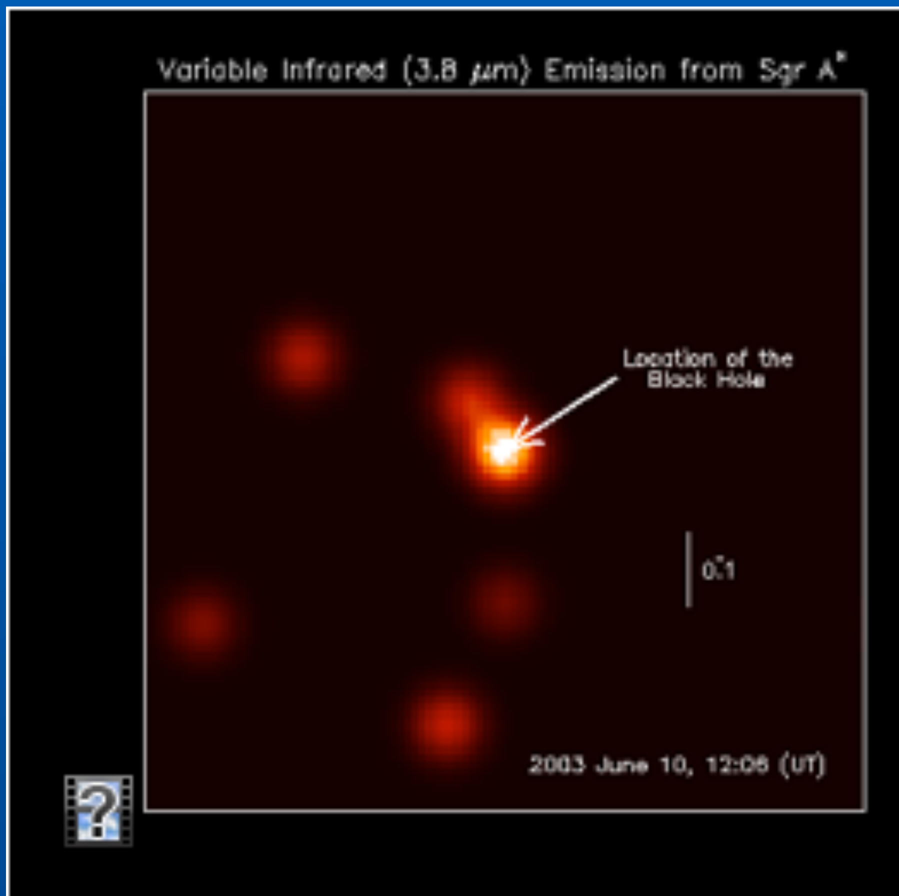
van den Bosch et al.+12

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



Delvecchio+ 14; Aird+ 10; Shankar+ 09

MULTI-WAVELENGTH DATA FOR ACTIVE & QUIESCENT BHs



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

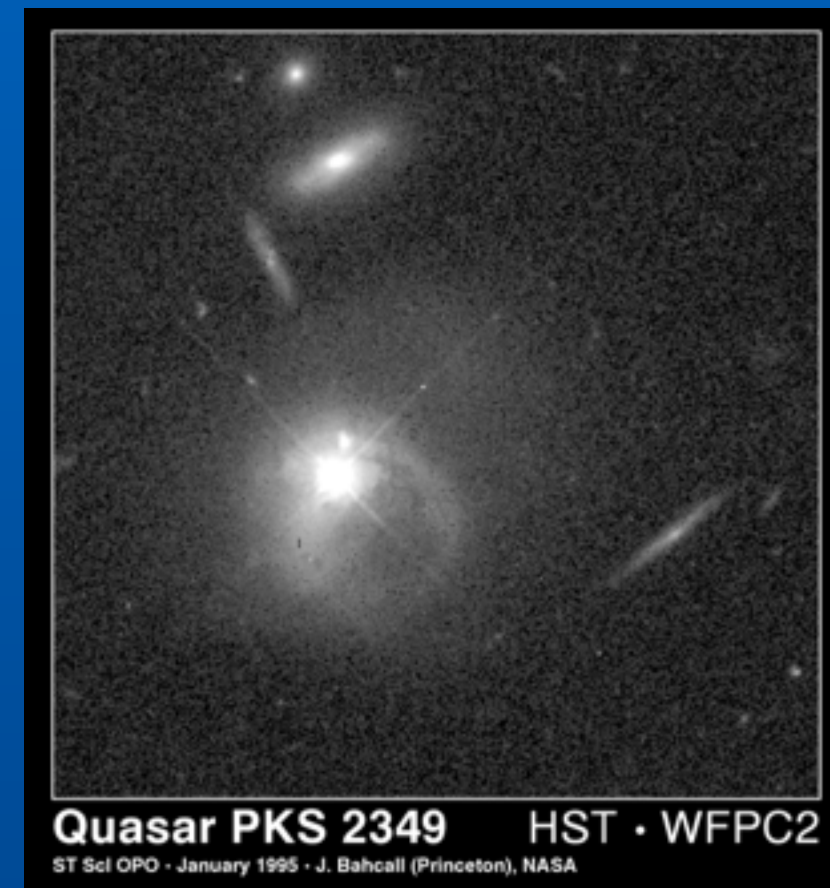
even 10^{10} M_{sun}

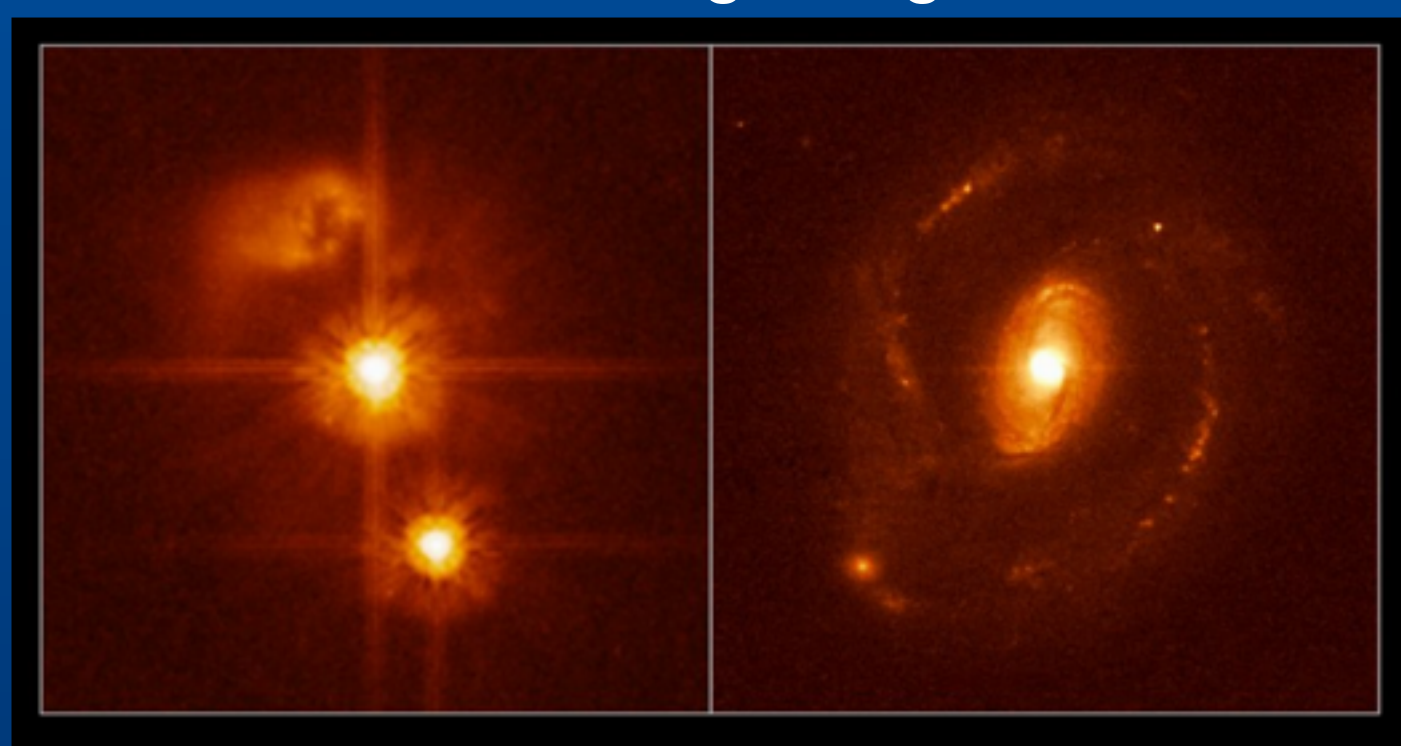
z ~ 0 – 7

z=7

756 Myr after

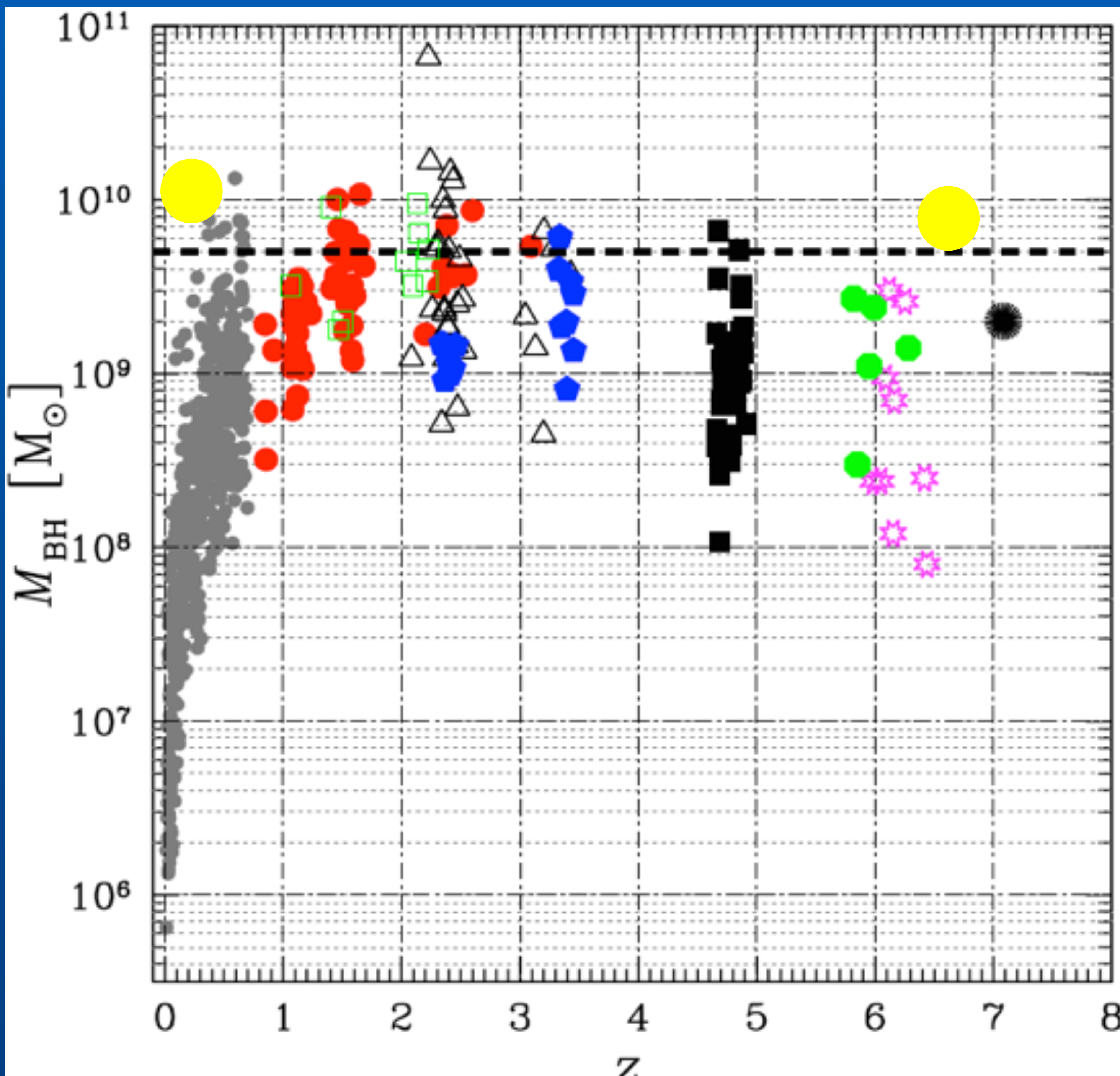
the Big Bang

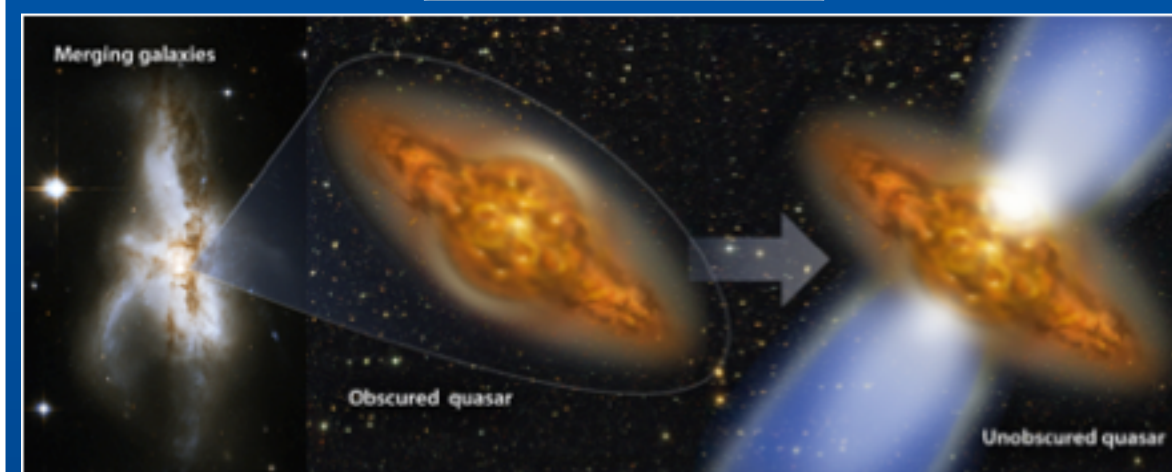




Urry+; Treister+; Scoville+; Sanders; Faber +;Wu+; Fan+; Ferguson+; Harrison+; Hasinger+; Comastri+; Gilli+

The Most Massive Black Holes in the Universe





Lauer+ 05, 06; Bernardi+ 06; PN & Treister 09; McConnell+ 11,12; PN & Volonteri 13

Marziani & Sulentic 12; Mortlock+ 14; Wu+ 2015; Kulier+15; Thomas+ 16

HIGH-z QUASARS & THE TIMING CRUNCH TO ASSEMBLE SMBHs

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

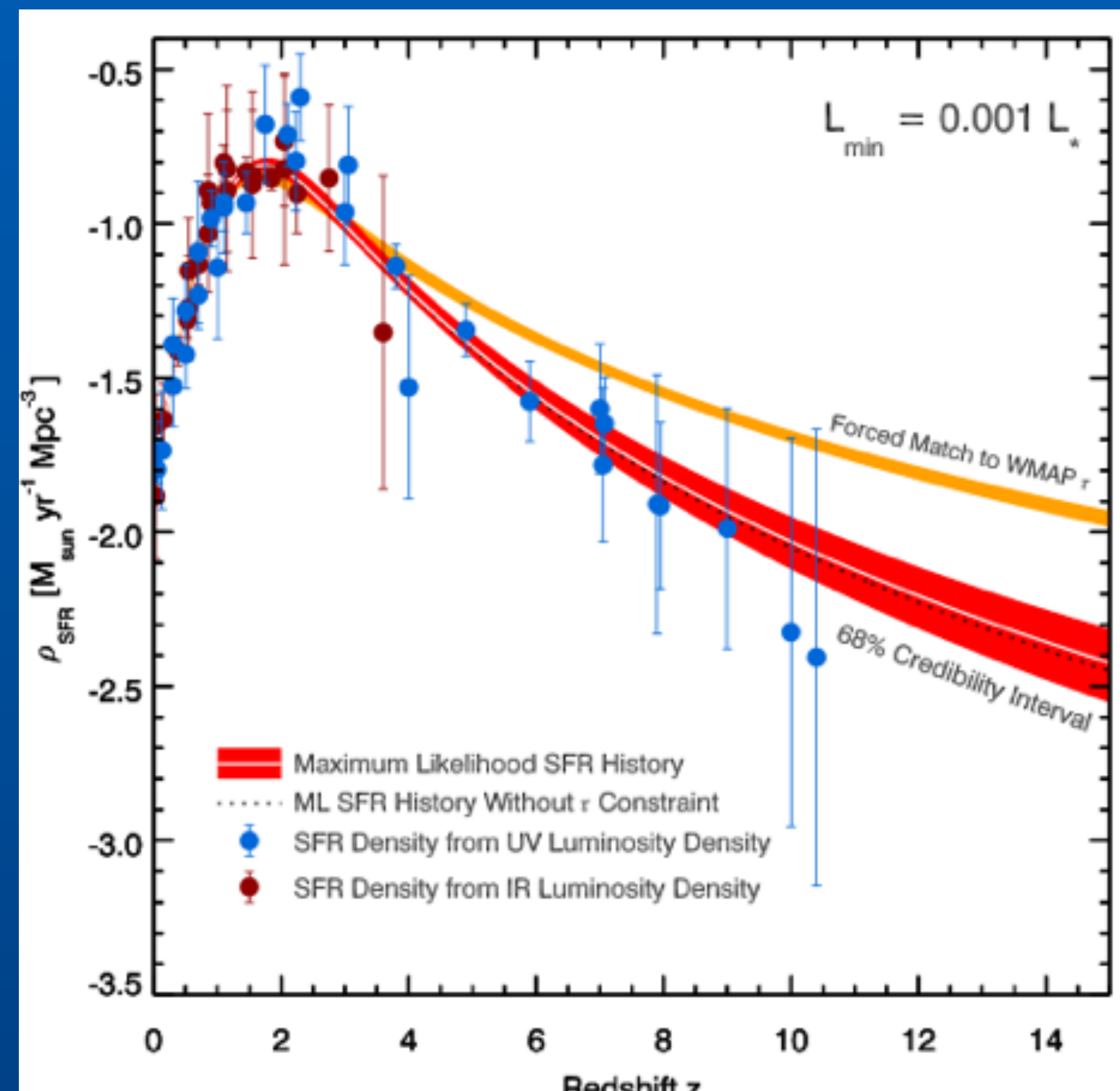
Age of the universe 1 Gyr

Eddington limit growth rate of mass

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

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

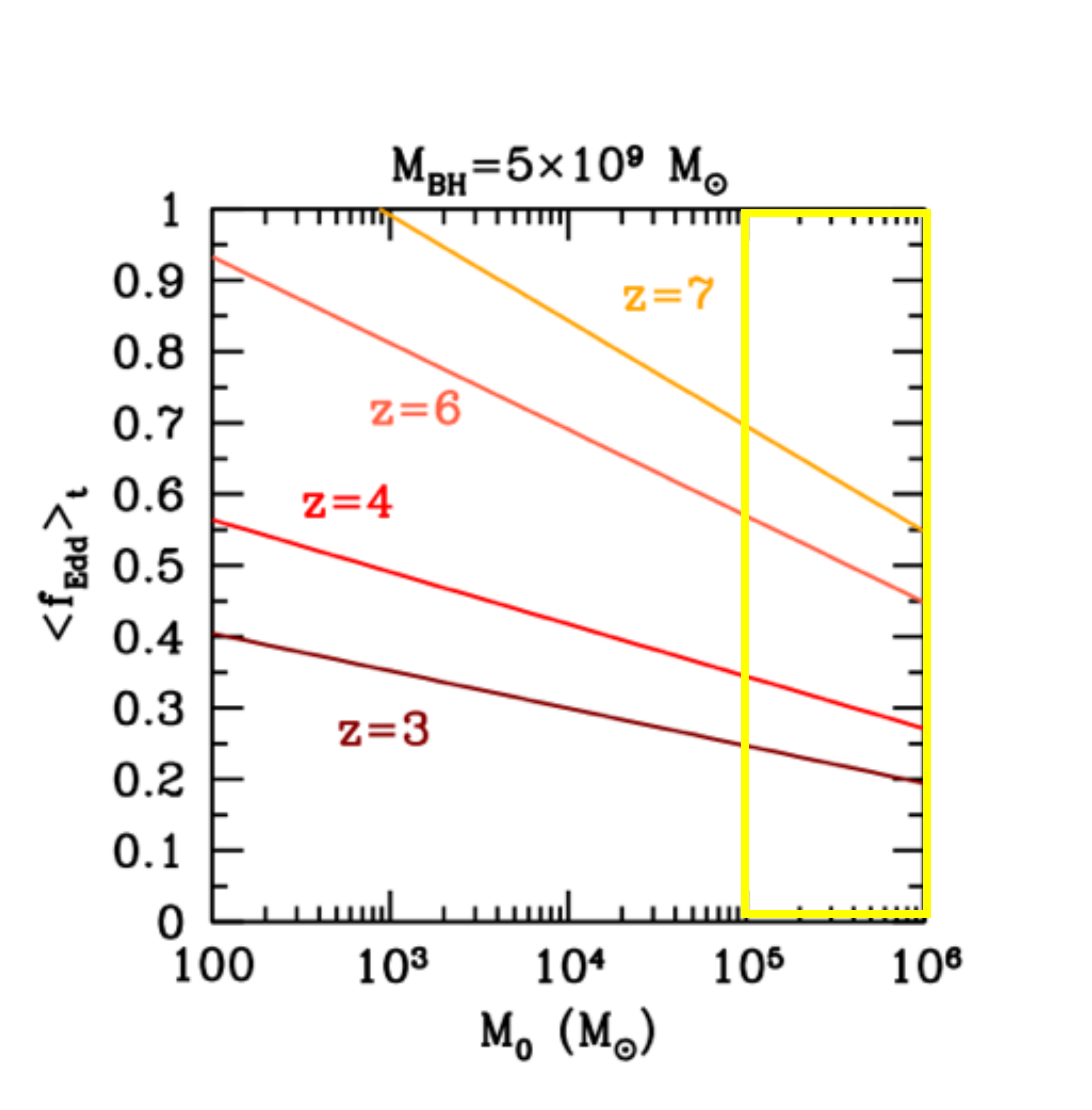
$$\tau = \frac{\eta c \sigma_T}{4\pi G m_p} \approx 5 \times 10^7 \, yr$$



LATEST PLANCK RESULTS: first stars form even later!

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

MASS GROWTH OF BH SEEDS: TIME CRUNCH



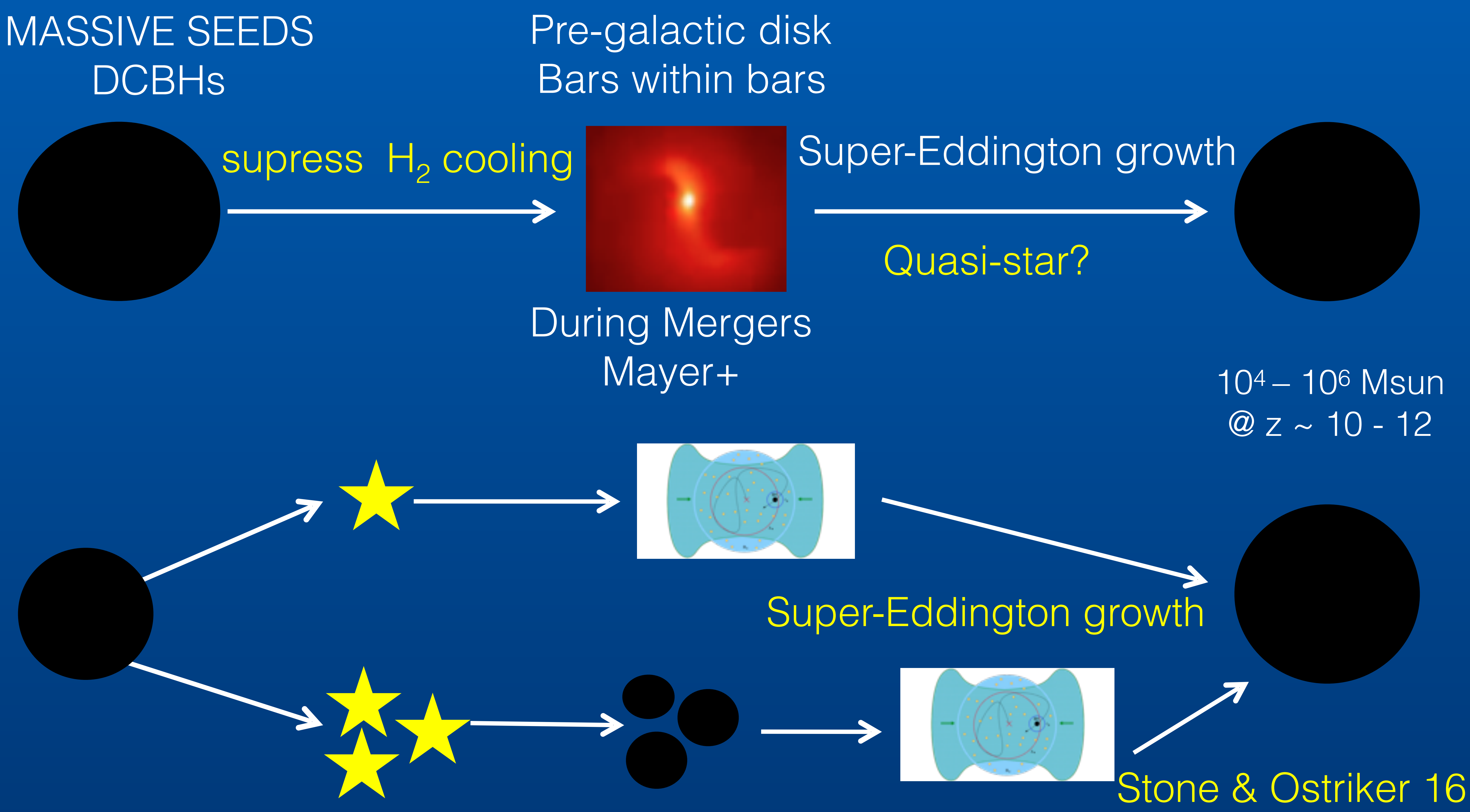
$$\langle f_{\rm Edd}\rangle_t = \frac{t_{\rm Edd}}{t_{\rm Hubble}(z)}\frac{\epsilon}{1-\epsilon}\ln\left(\frac{M_{\rm BH}}{M_0}\right).$$

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

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 HIGH-x BHs



LIGHT SEEDS

PopIII

~10^{1-2} M_{sun}

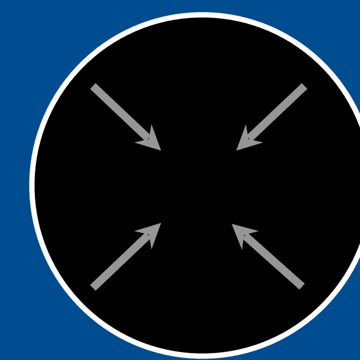
MASSIVE SEEDS

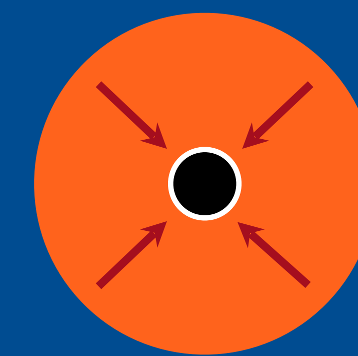
Direct collapse

Nuclear star cluster

~10^{3} M_{sun}

Supermassive Star





Quasi star

~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)

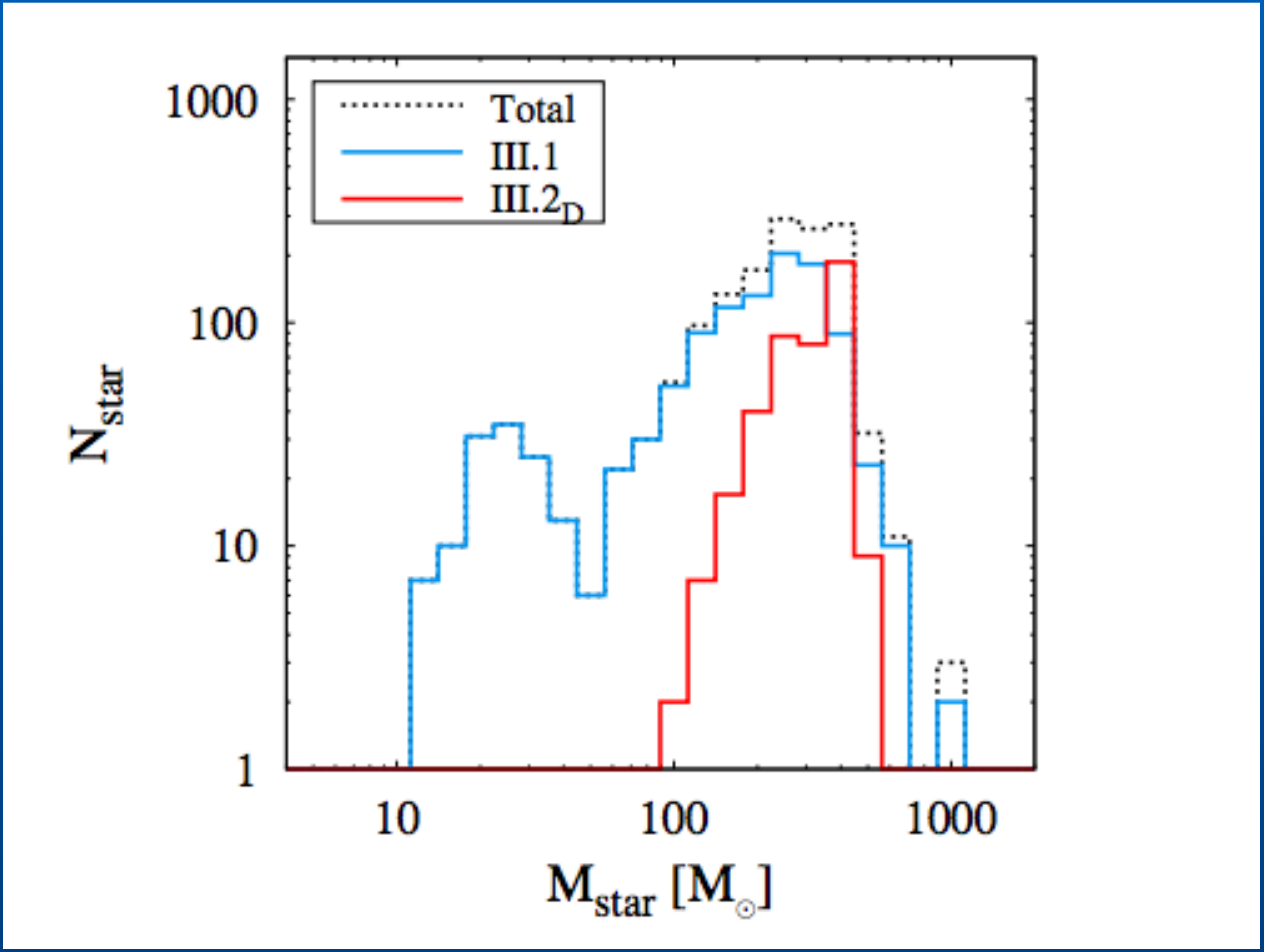
Supermassive star (Haehnelt & Rees 93)

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

PRIMORDIAL BLACK HOLES

Post-Inflation formation of black holes during the phase transition that ends expansion (Khlopov+ 07; 09)
Unresolved CIRB, XRB Excess? CMBR distortions, no stringent constraints

HOW MASSIVE ARE POP III STARS?

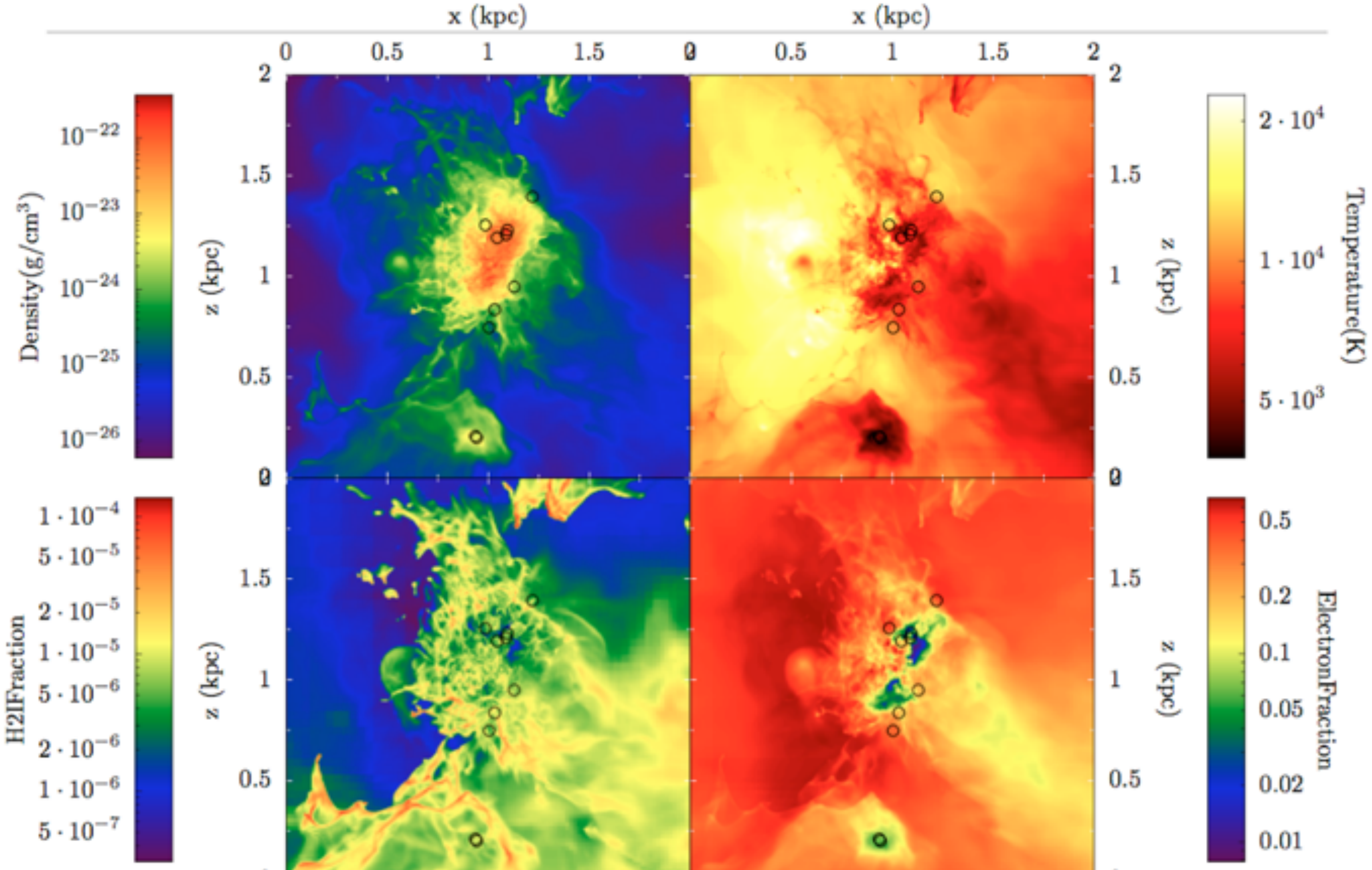


~ Mass distribution of Pop III stars formed at z = 30 -> 10

Hirano+ 15

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

z=8.2 still no further growth. Halo: 2x10^8 solar mass
3 solar masses total on 25 black holes

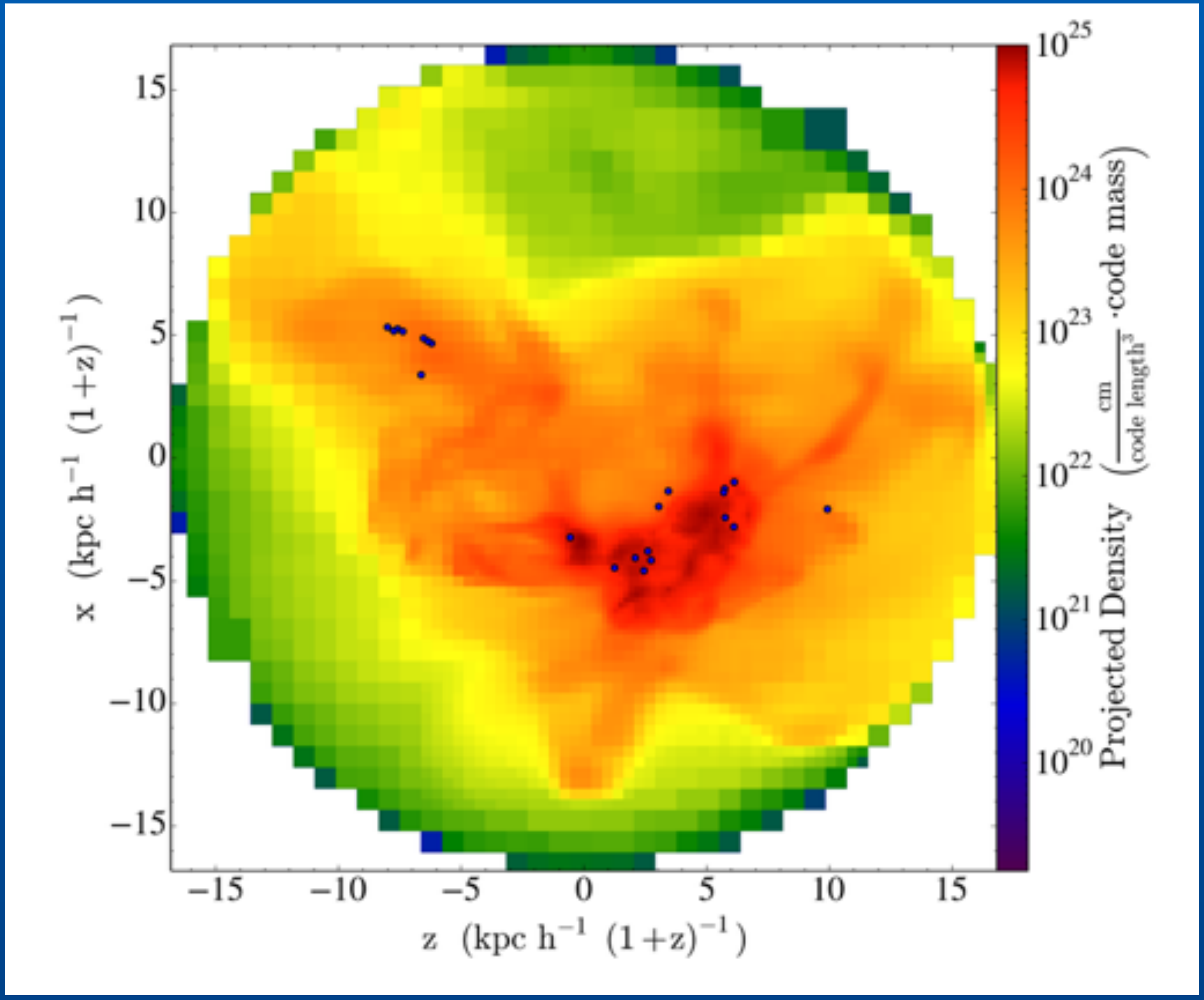


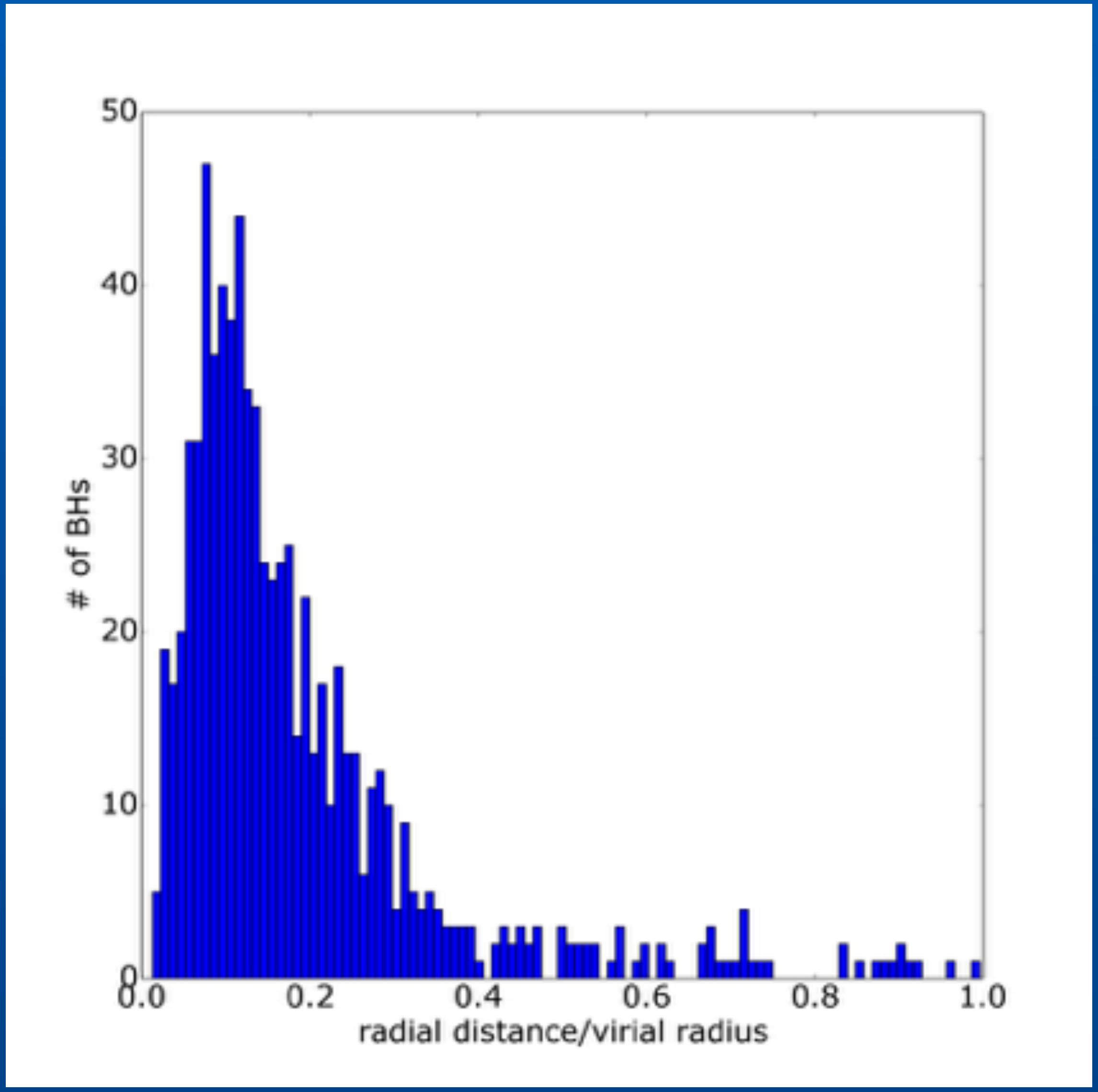
BHs simply not growing much down to z = 8
even when PopIII formation has ceased
BHs spend almost all their time in the wrong place
in 10^8 M_{sun} DM halos

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



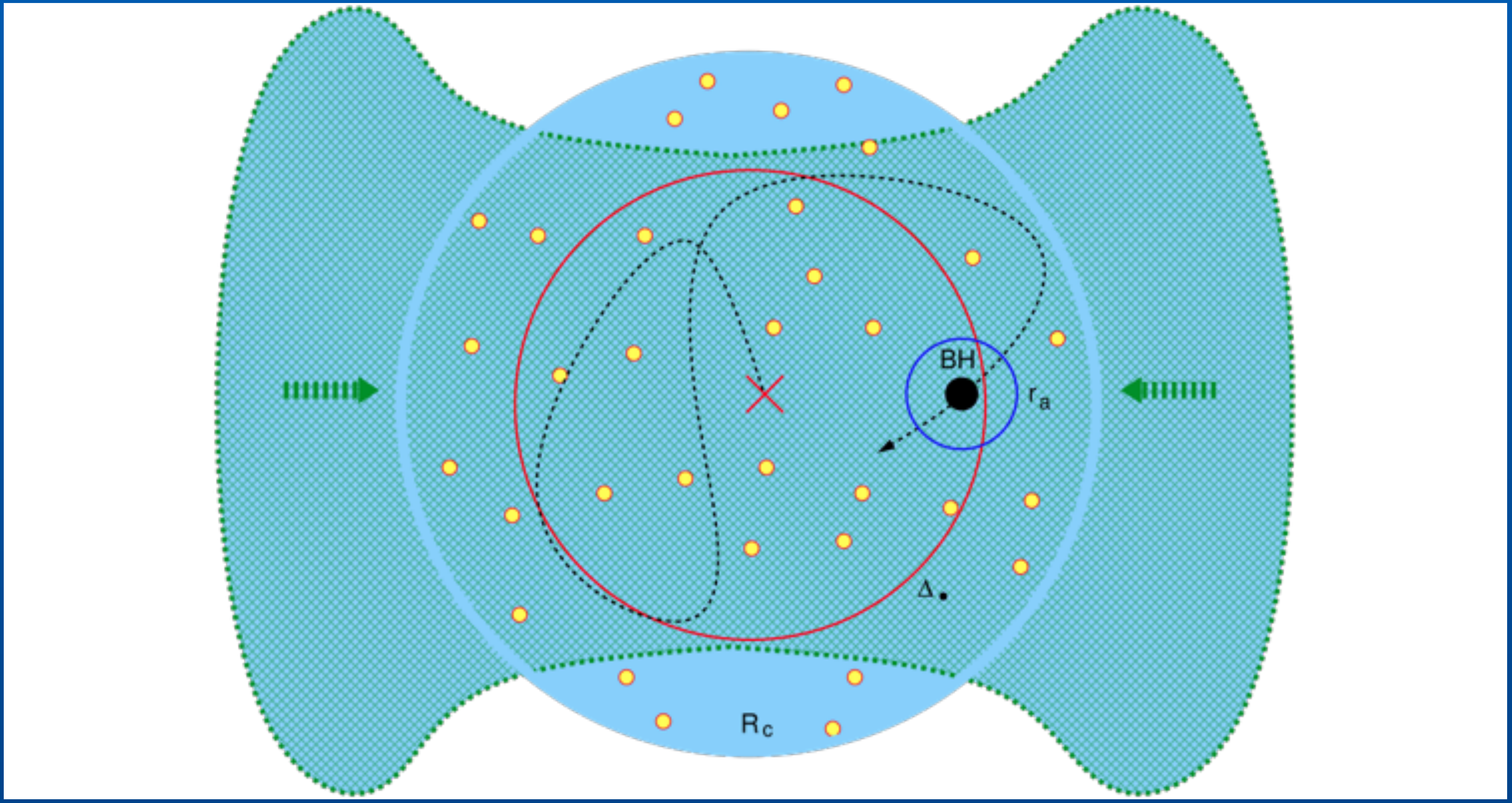


snapshot with 20 BH seeds, 300 Mpc^3 box, ENZO AMR 12 level refinements ~ 19 comoving pc, DM resolution ~ 3 X 10^4 M_{sun}

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

Shi+ 15

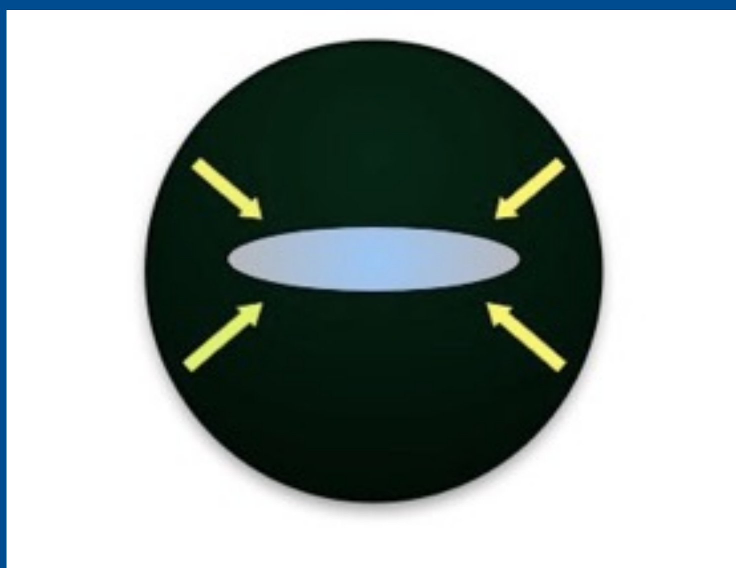
SUPER BOOSTING EARLY BH GROWTH



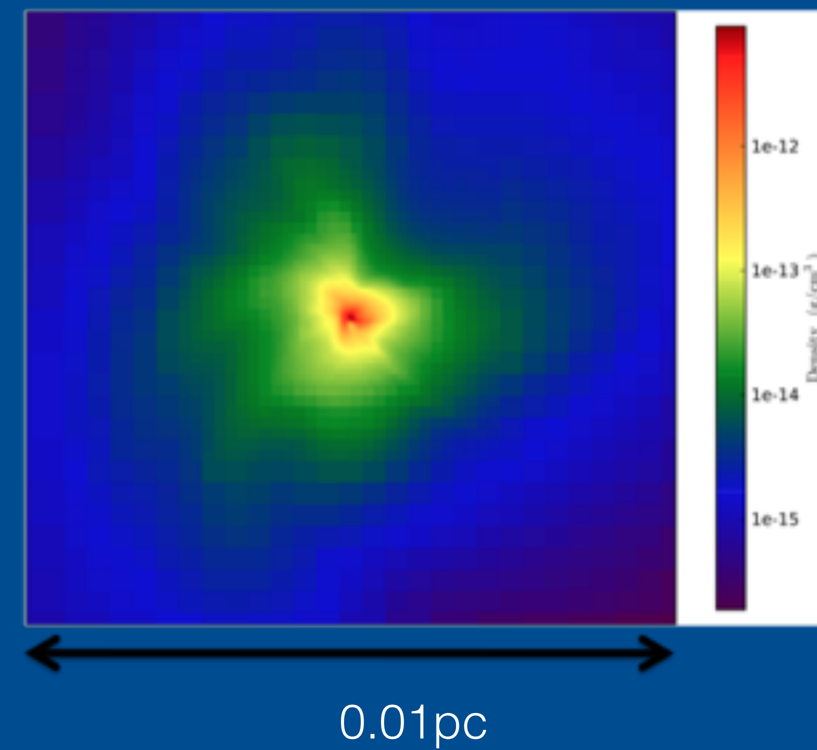
Circumventing the Eddington limit

Alexander & Natarajan 14

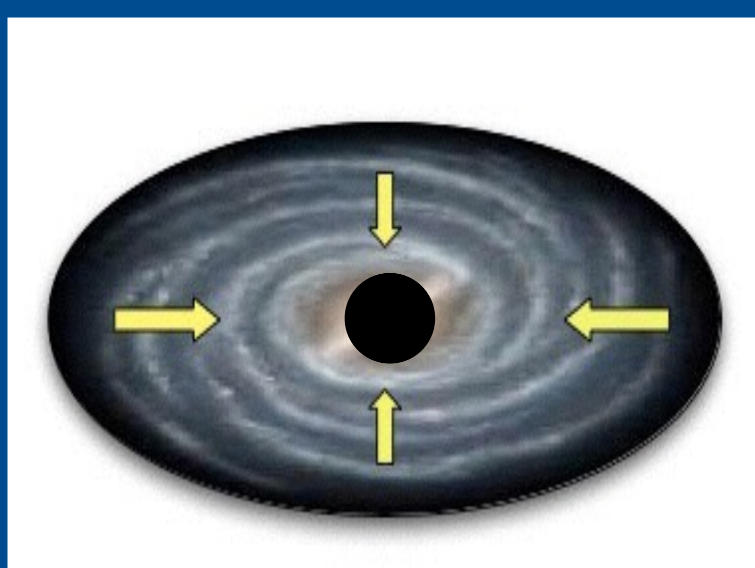
BH seed formation at high z



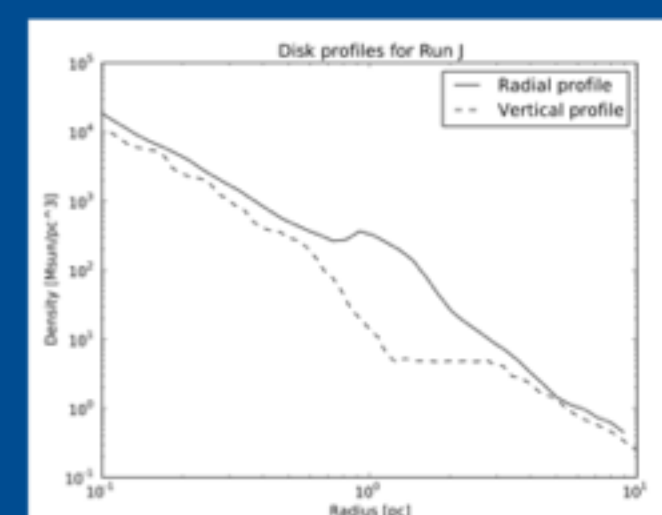
Baryons inside DM halo collapse and form a rotating pre-galactic disc



Disc becomes gravitationally unstable and accretes to the center



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

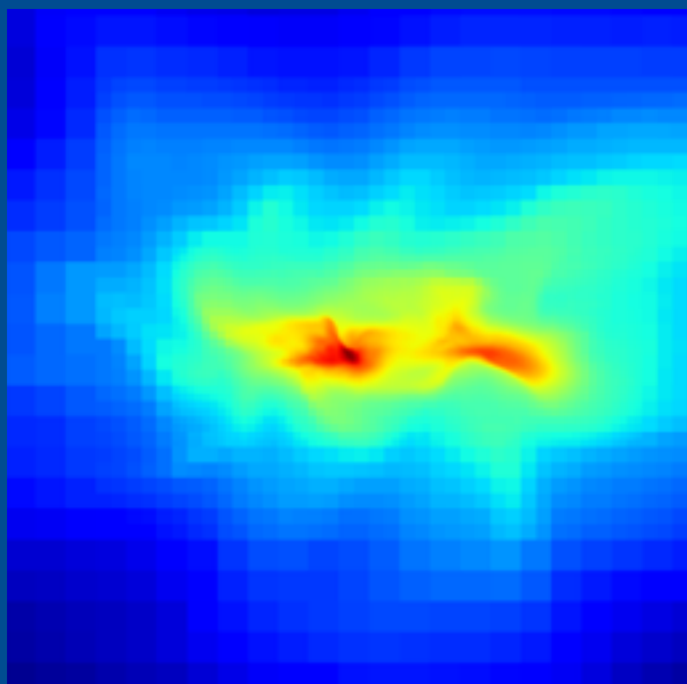


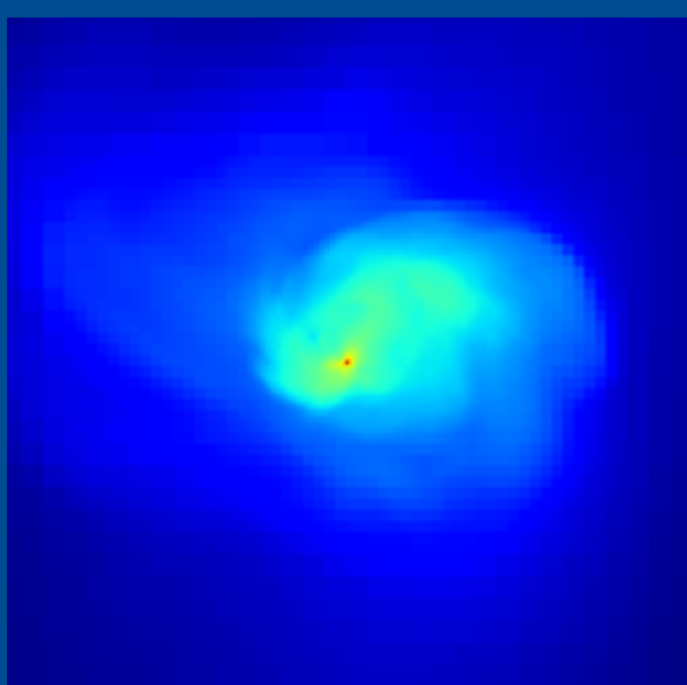
↓

FINAL DCBH MASS

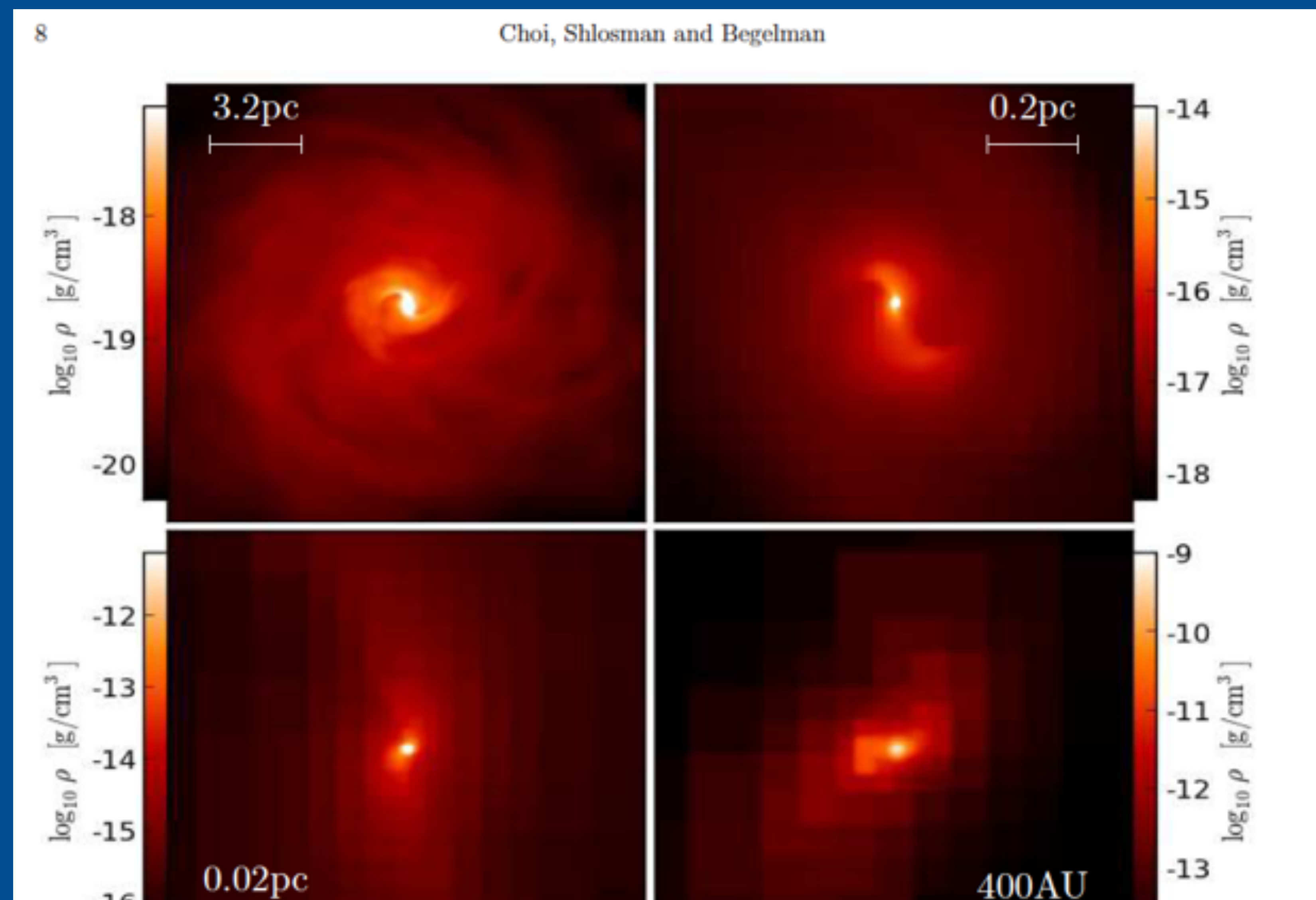
Lodato & PN 06; 07; PN 11; Regan+ 12; 14; Latif & Ferrara 16

Massive BH seed formation simulations





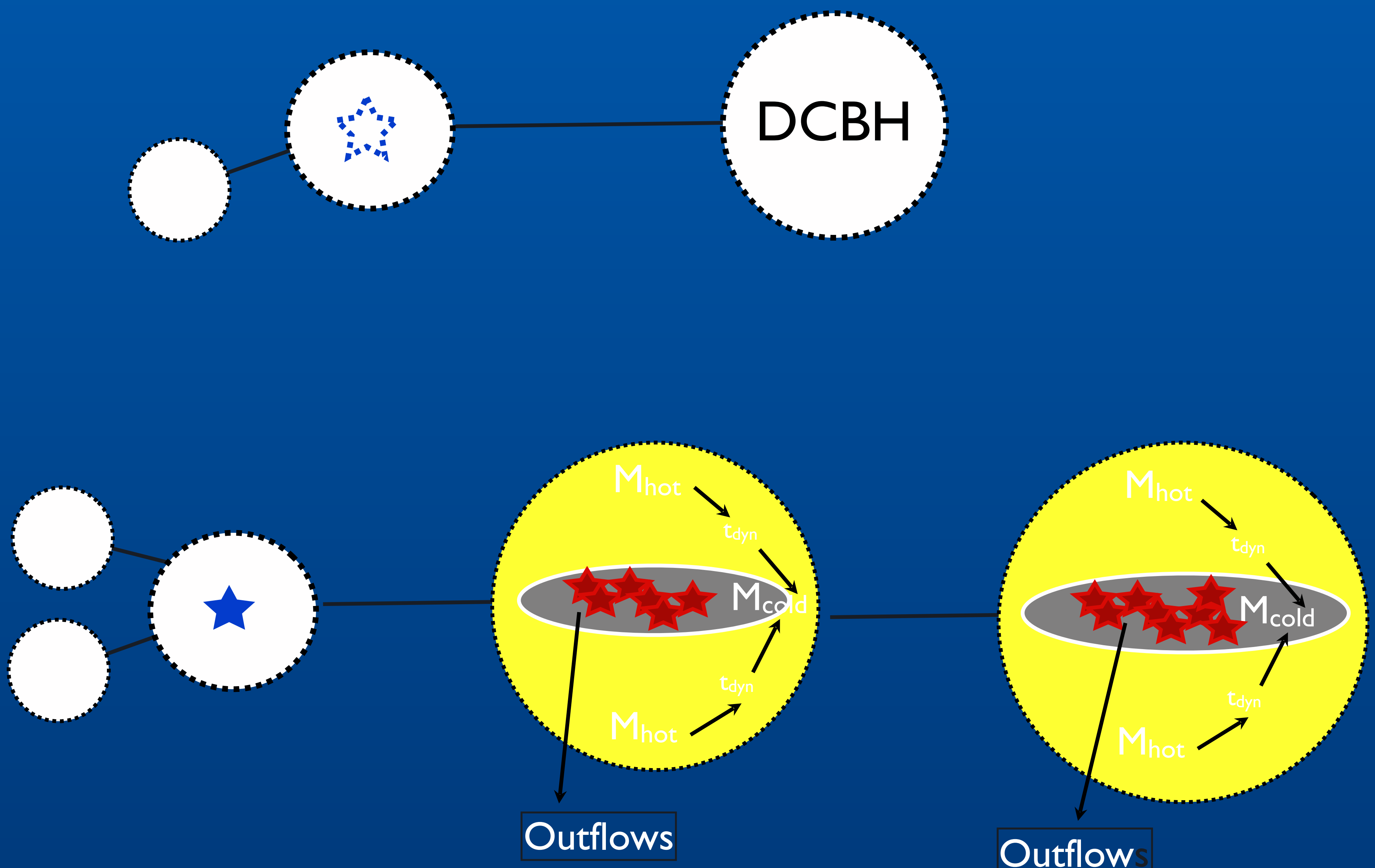
Regan+ 08; 13; Hirano+ 14; Davis & PN 12; Bournaud +; Habuzit+ 14, 15; 13; Hirano+ 14



Choi, Shlosman & Begelman 13

OPTIMAL SITES FOR DCBH FORMATION

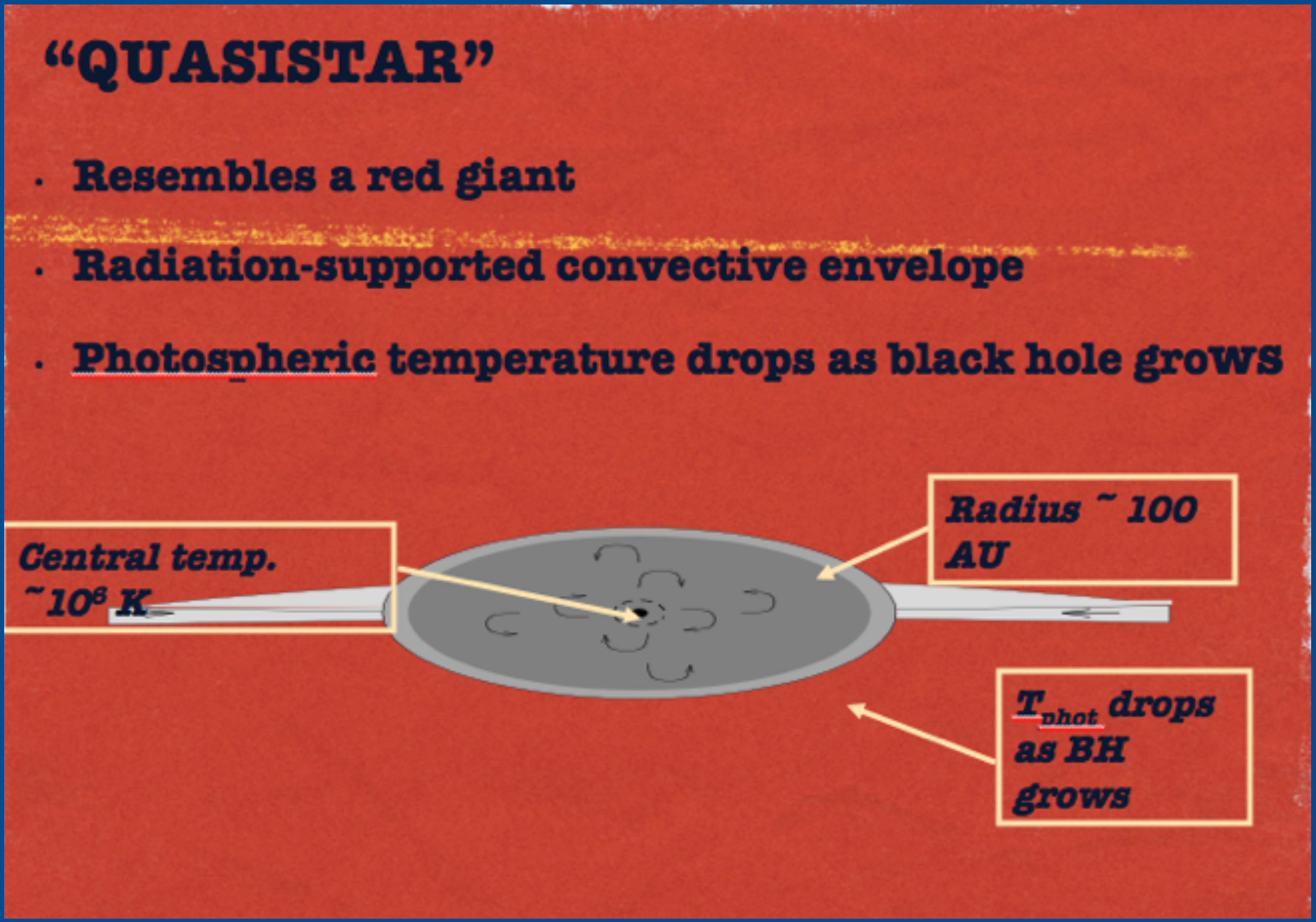
Low spin DM halos; satellite halos; Lyman-Werner radiation from nearby halos with star formation to dissociate mol H and prevent fragmentation



Agarwal+ 15

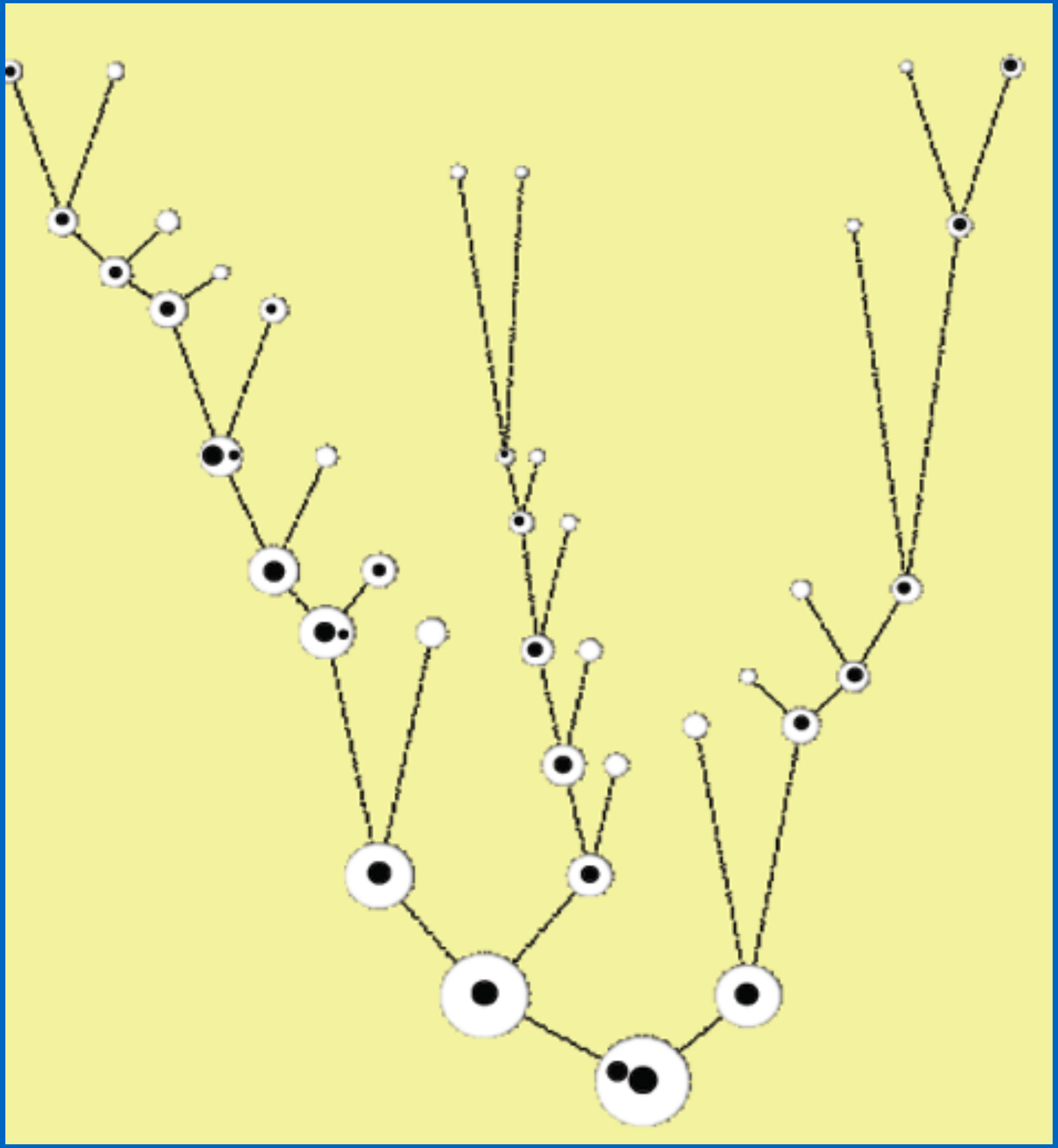
Direct Collapse Black Holes

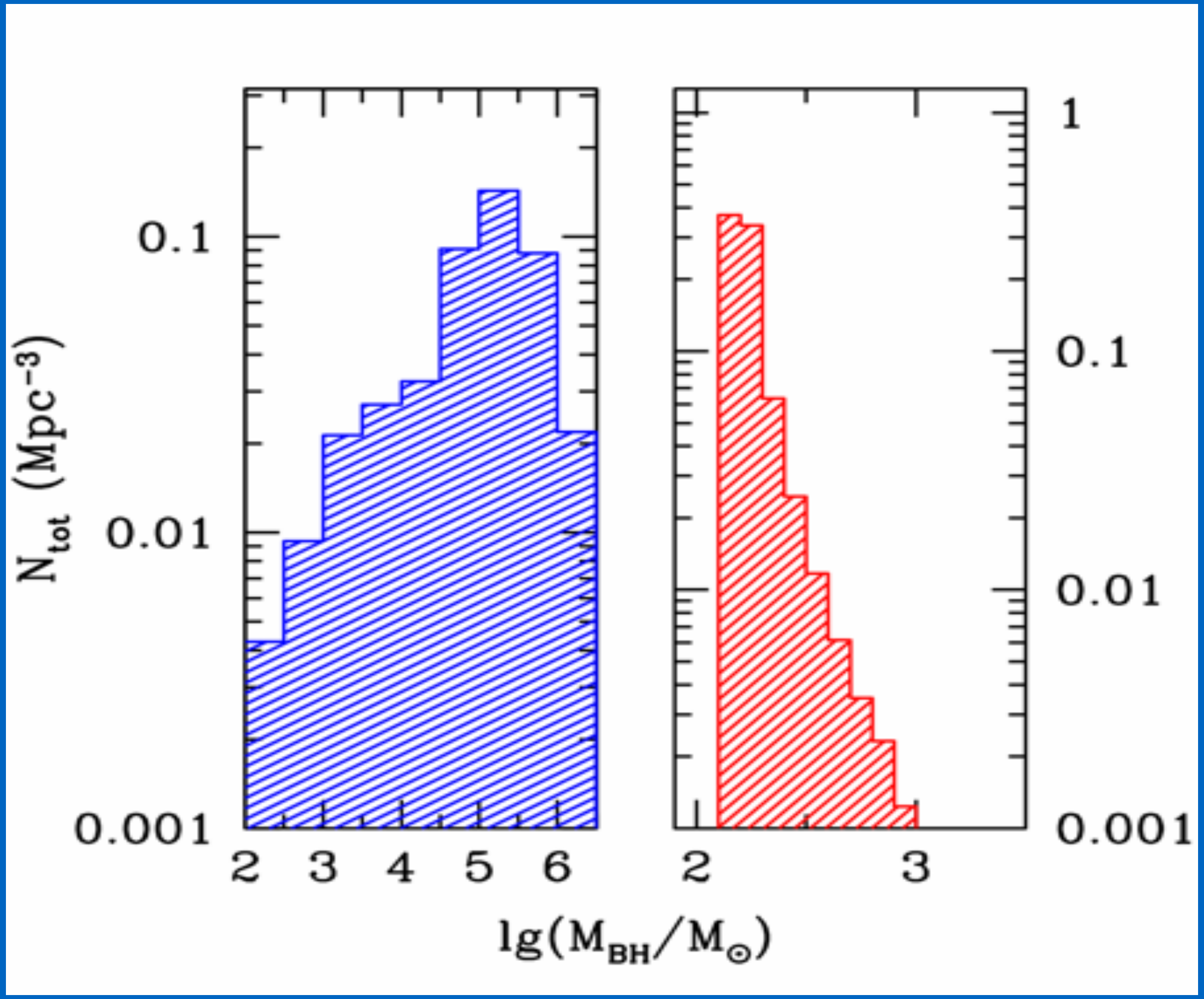
- Metal Free gas in atomic cooling halos ($T_{vir}>10^4$ K): predominantly atomic H Avoid fragmentation into stars: high densities Prevent H_2 formation (molecular hydrogen) in central region of halo; High level of LW radiation to dissociate H_2; SMS/Quasi-star followed by black hole of mass ~ 10^4 $M_{solar;}$ N ~1% of ~ 10^7-10^8 M_{sun} DM halos at z=15 form such seeds



Oh & Haiman 2002; Bromm & Loeb 2003; Begelman et al. 2006; Lodato & PN 2006; 2007, Spaans & Silk 2006; Latif+; Johnson+

Merger induced accretion + CDM merger trees + BH seeds





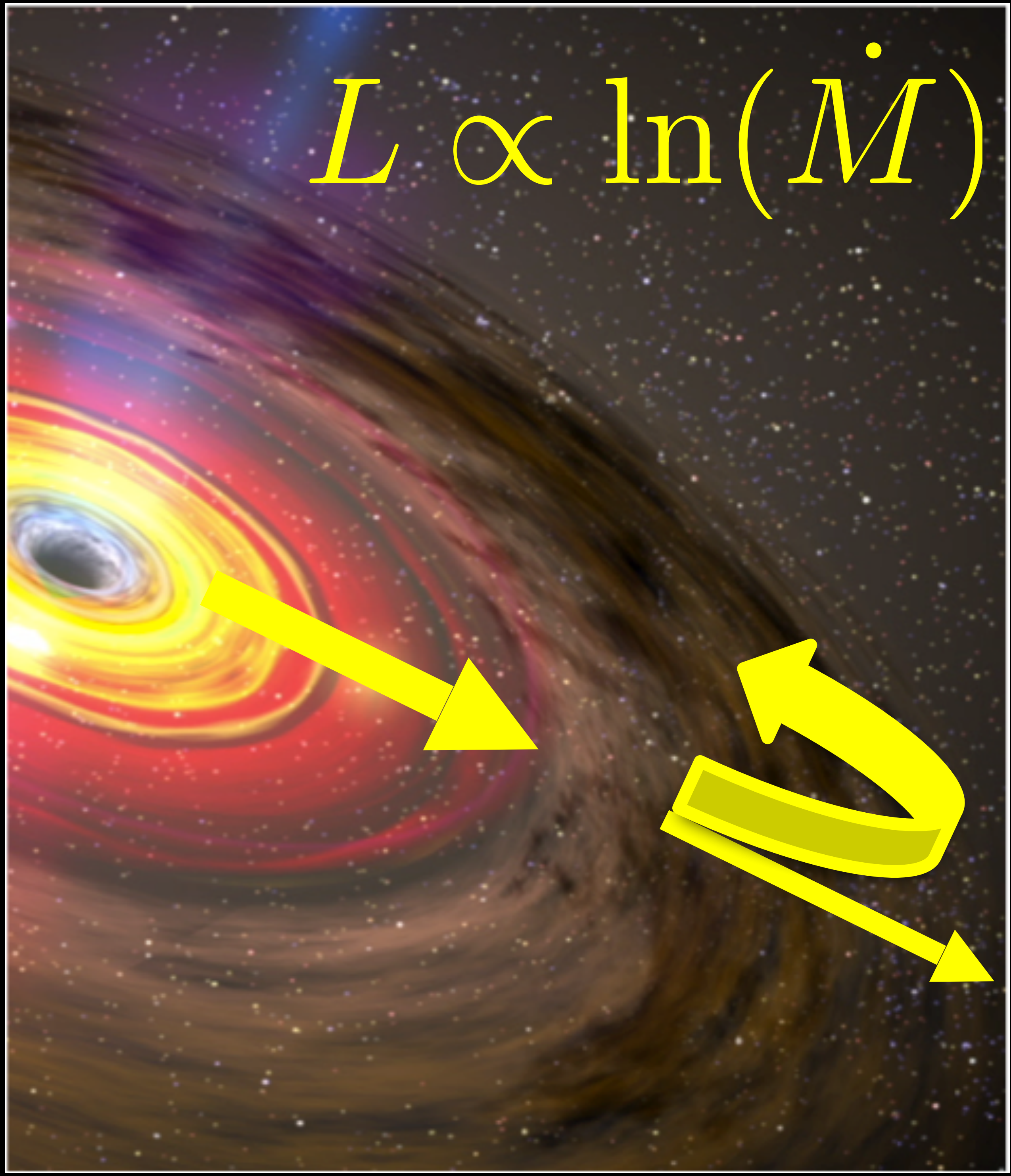
DCBH SEED PEAK MASS

Volonteri, Lodato & PN 08

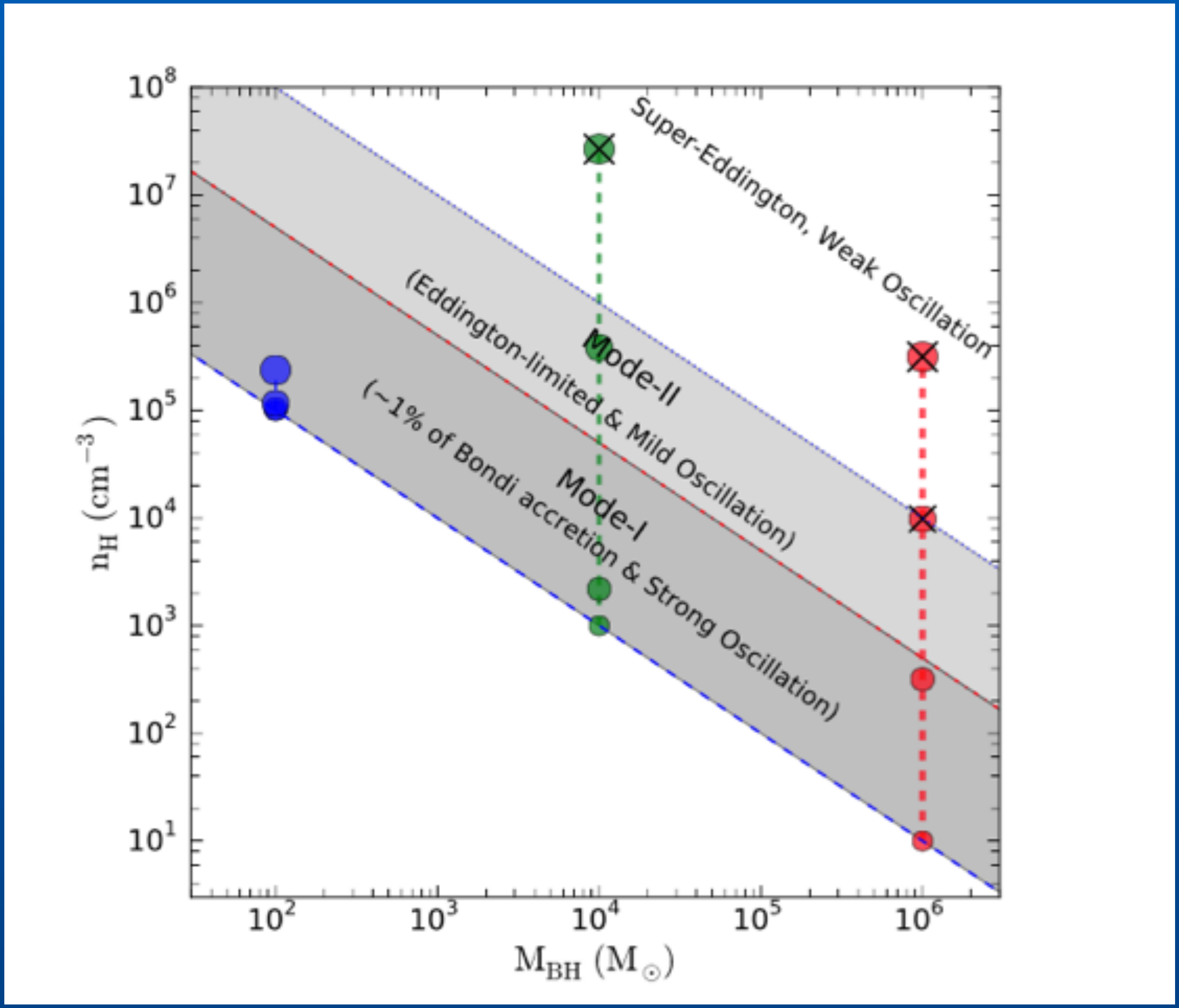
Standard Accretion

Slim Disk Accretion

Steady trickle throughout cosmic time



Understanding what limits growth rates by accretion



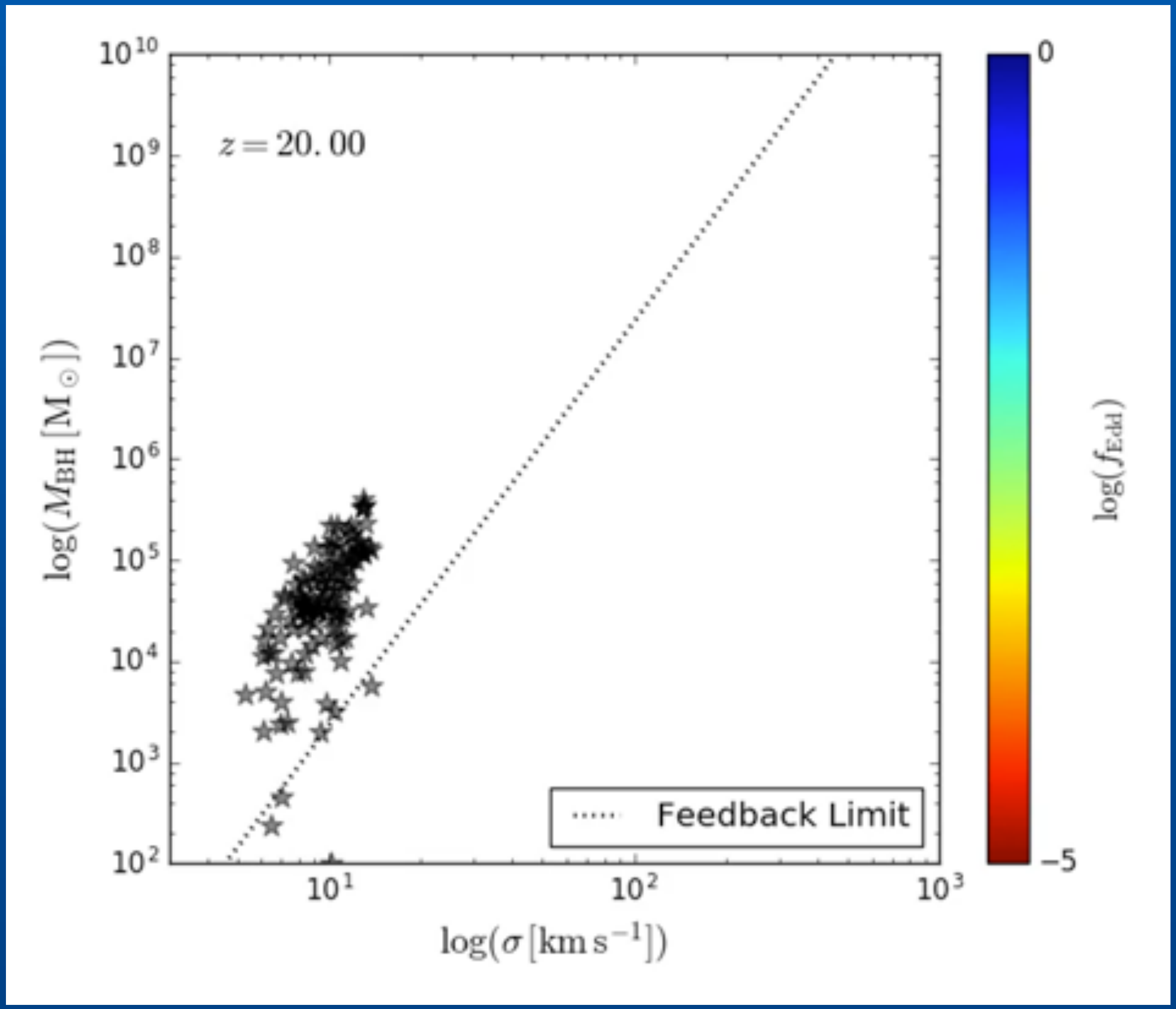
Growth is faster
for larger
black hole masses

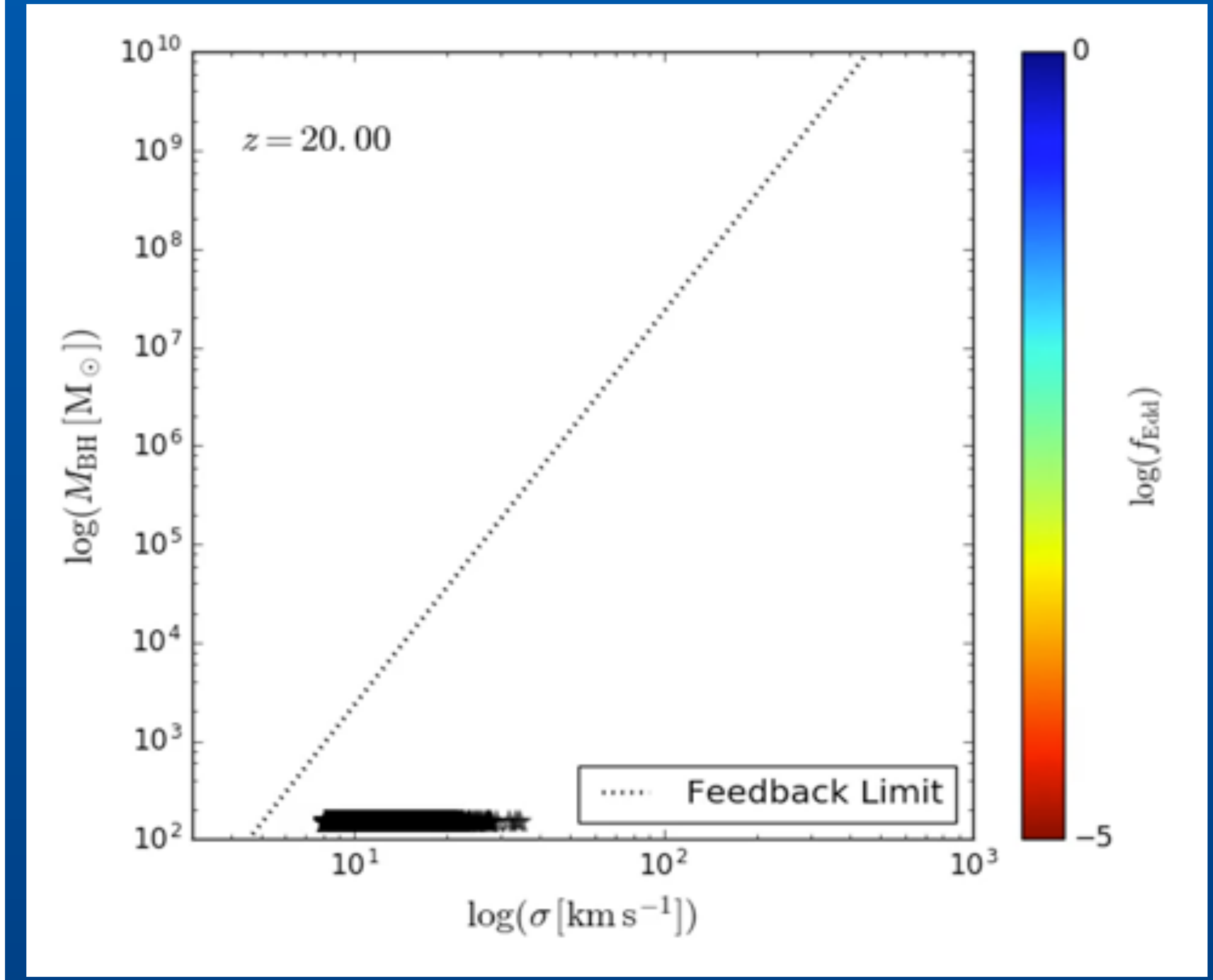
FEEDBACK LIMITED MODE
Inefficient growth, outflows,
~ 15% of gas accreted
LOW MASS SEEDS

GAS SUPPLY LIMITED MODE
Super-Eddington growth, outflows
unimportant, low radiative efficiency
~ 80% of gas accreted
MASSIVE SEEDS

Alexander & PN 14; Park+15; Pacucci+15

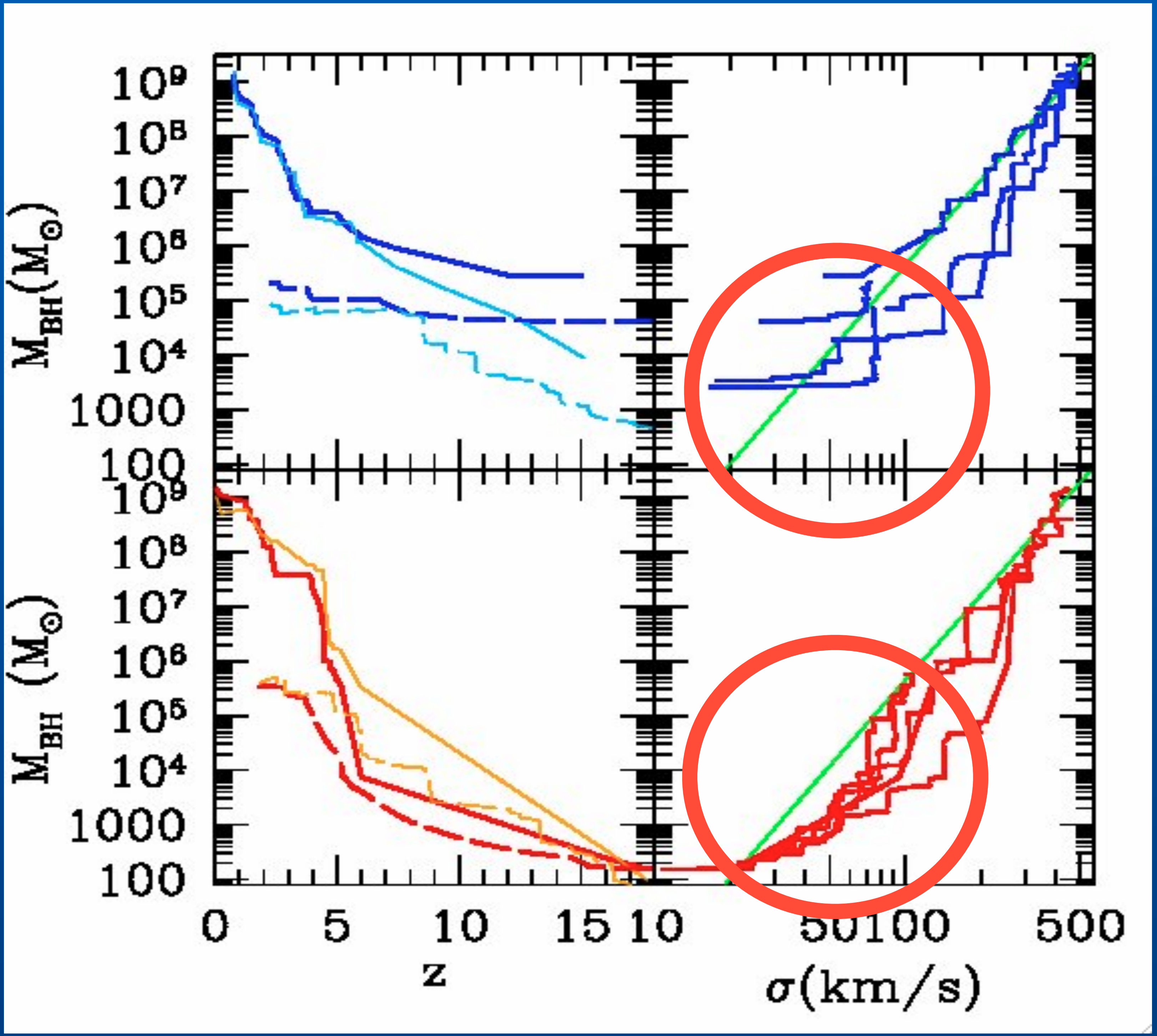
Assembly History of Black Holes over cosmic time





Ricarte, PN+ 16; Volonteri & PN 09

MODEL GROWTH HISTORIES OF BHs OVER COSMIC TIME



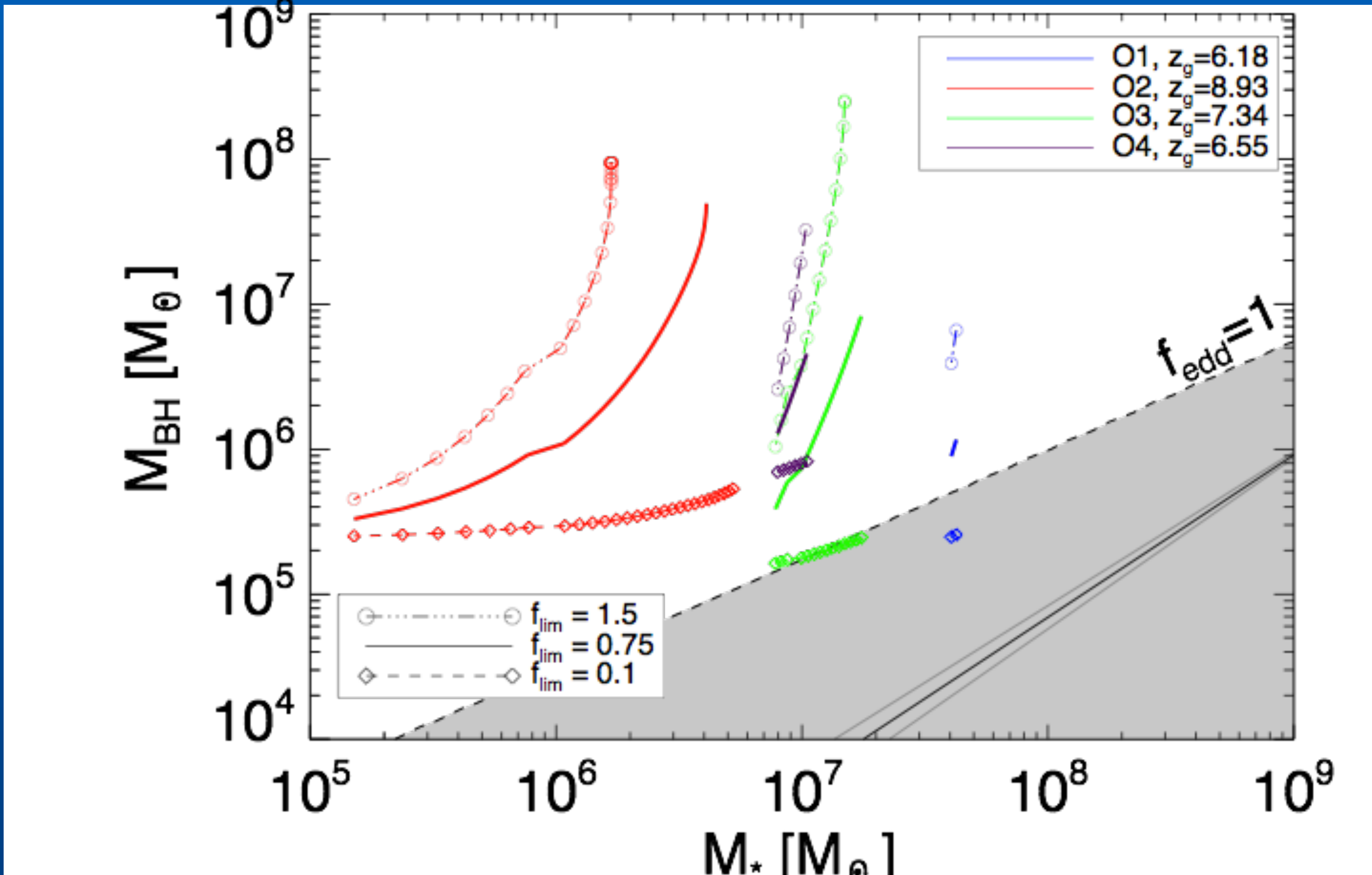
MASSIVE

LIGHT

10^{13} M_{sun} halo
standard
accretion

Volonteri & PN 09; 11, 13

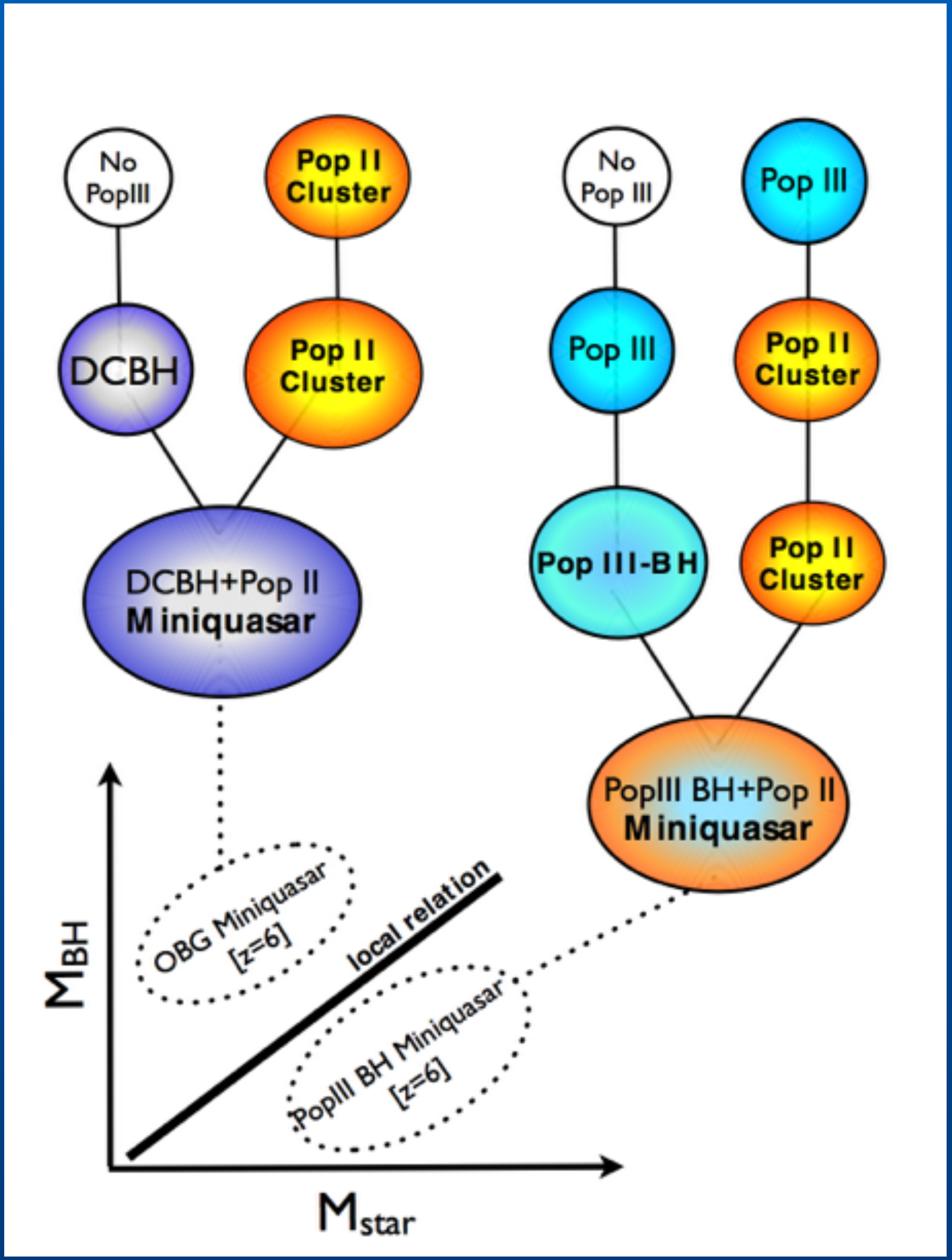
HIGH REDSHIFT SIGNATURE OF MASSIVE BH SEEDING MODELS



PREDICT NEW TRANSIENT STAGE FOR GALAXIES
OBESE BH GALAXIES (OBGs)

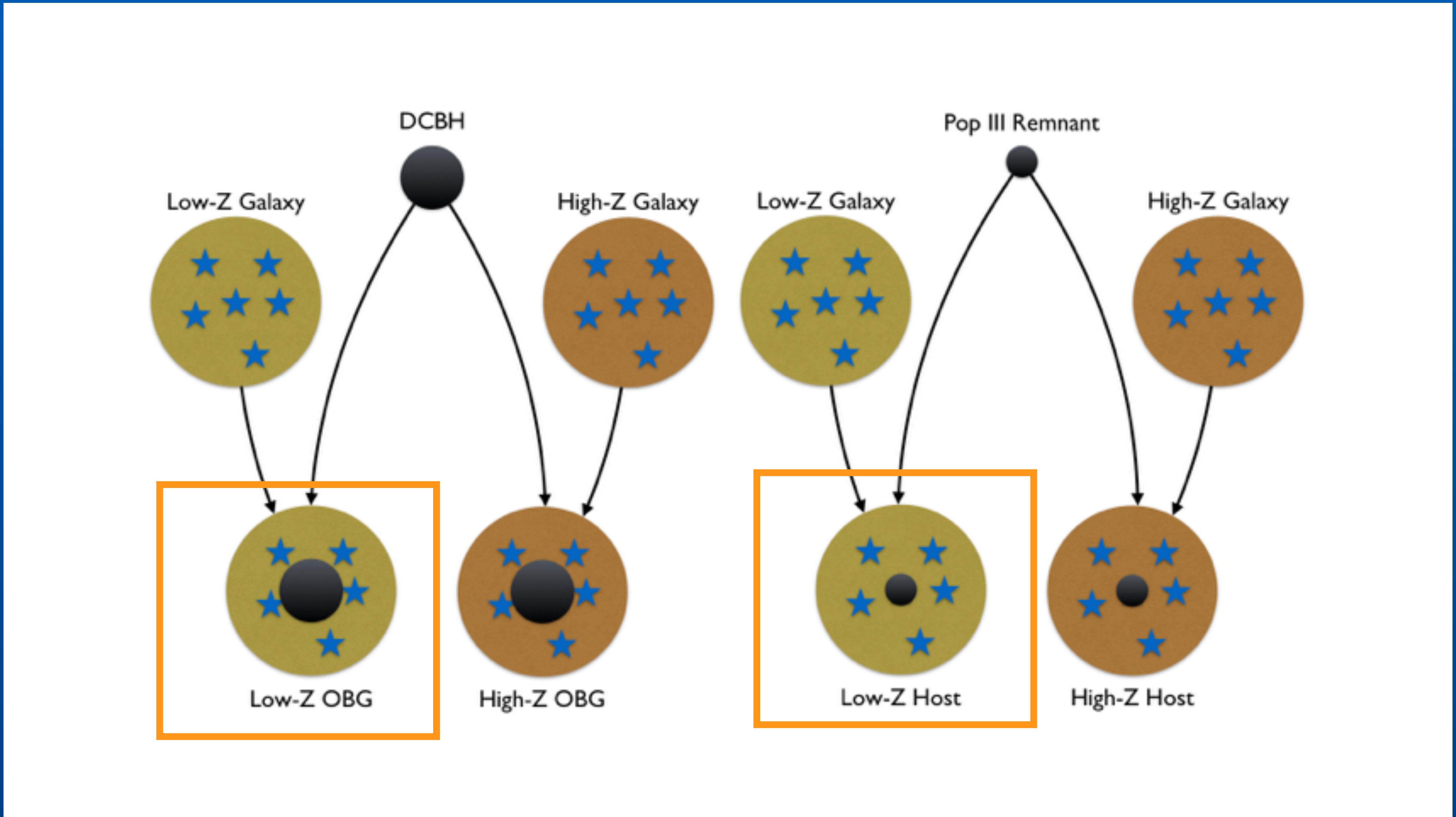
Agarwal+ 12; 14

DIRECT COLLAPSE BHs AND THEIR OBESE BH HOST GALAXIES



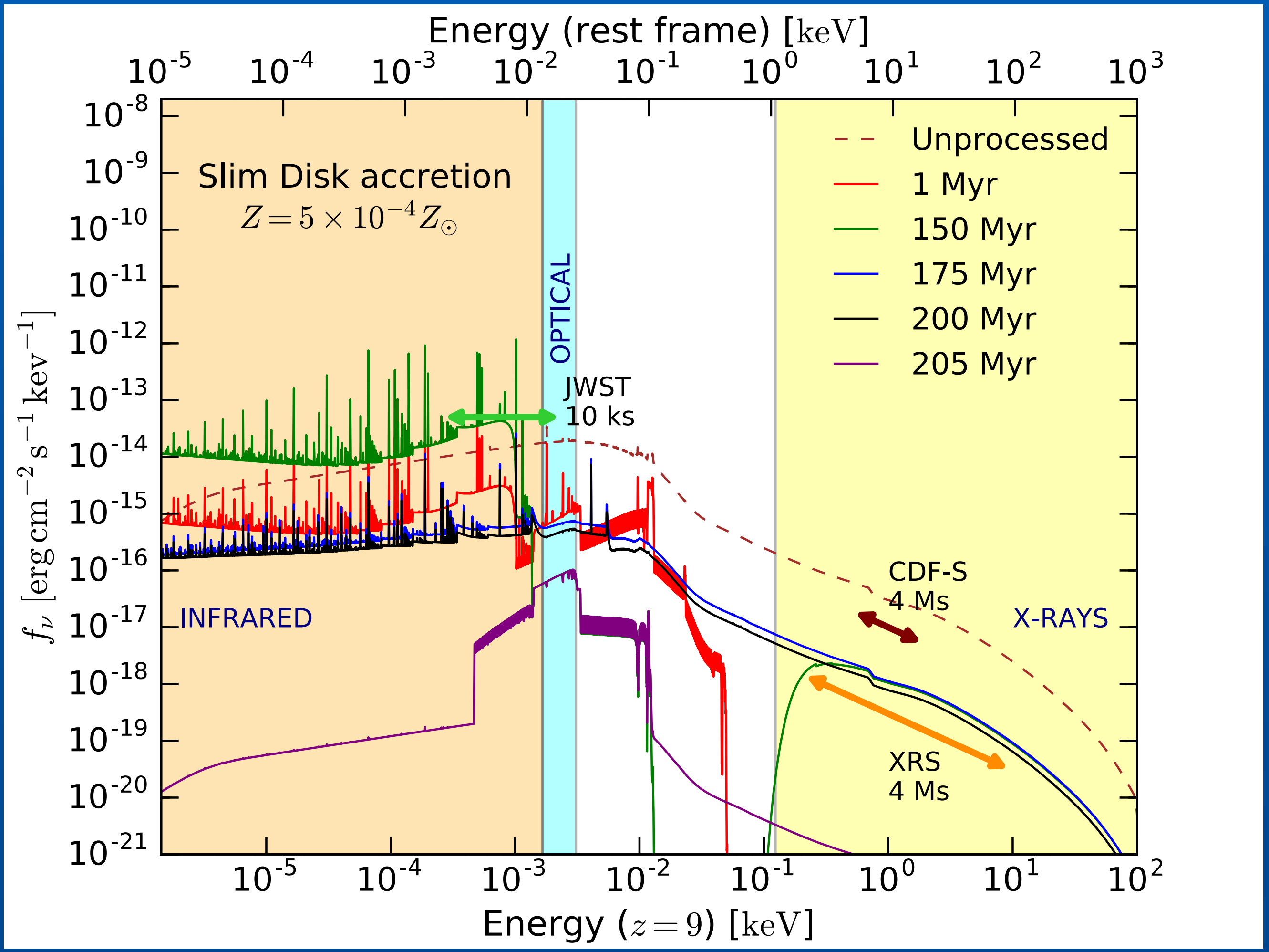
Agarwal+ 12; 14

SCHEMATIC OF HIGH-Z JWST SOURCES



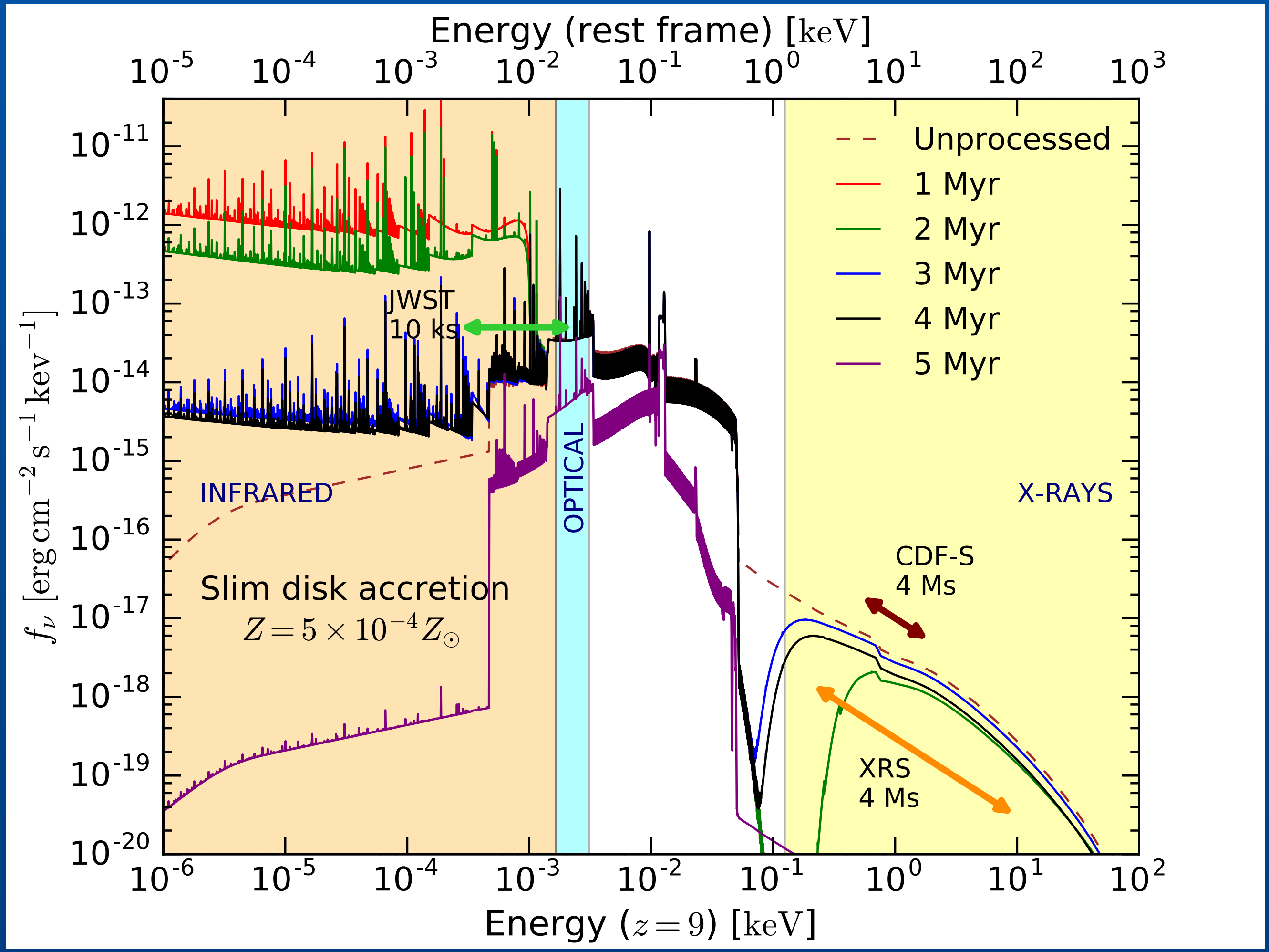
PN, Pacucci, Ferrara, Agarwal+ 16

MULTI-WAVELENGTH SPECTRAL PREDICTIONS



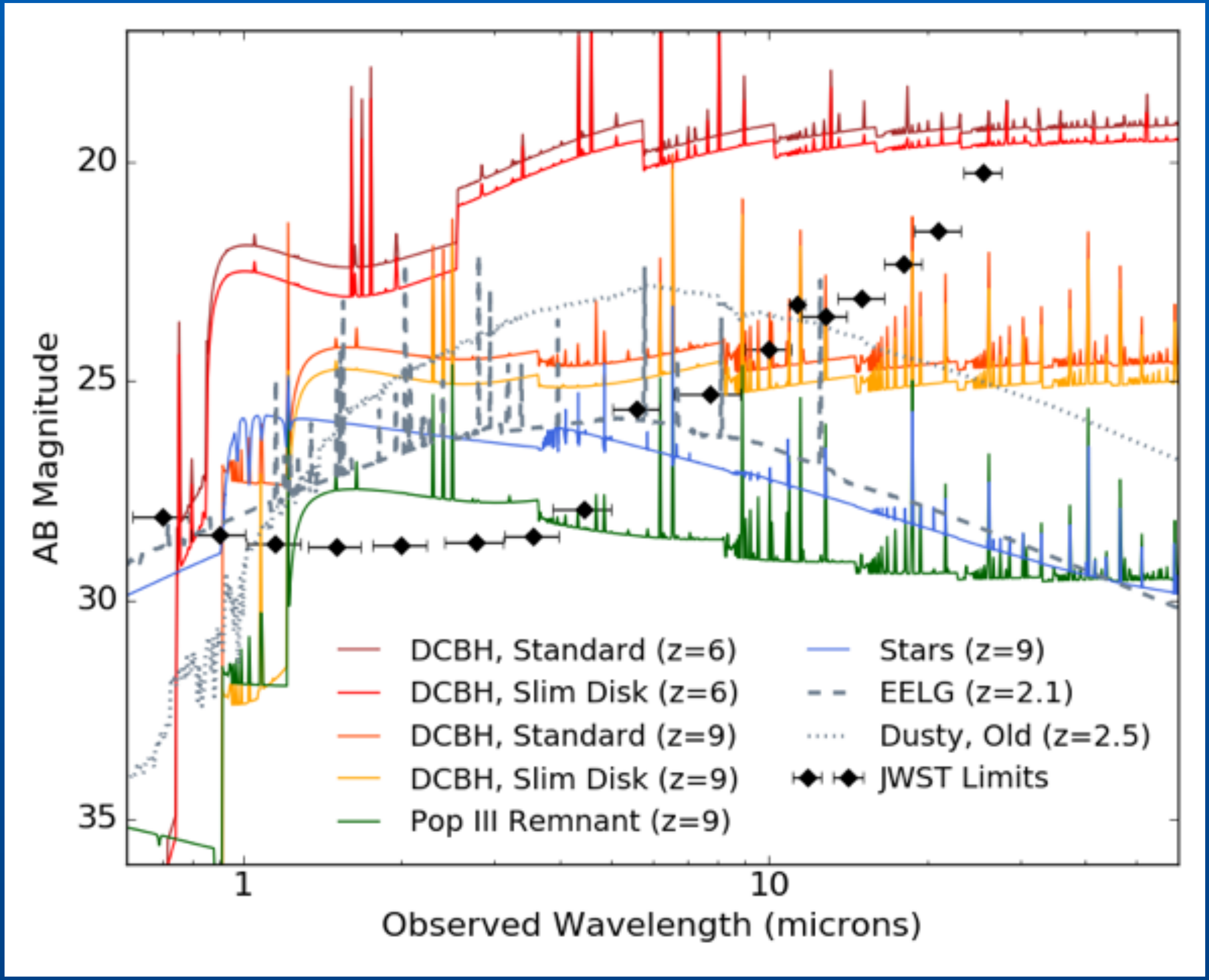
Pop III SEED + STELLAR COMPONENT SLIM DISK

DCBH SEED + STELLAR COMPONENT (OBG) SLIM DISK



Pacucci+ 15; 16; PN 16; PN, Pacucci, Ferrara, Agarwal+ 16

OBSERVATIONAL SIGNATURES OF DCBHs

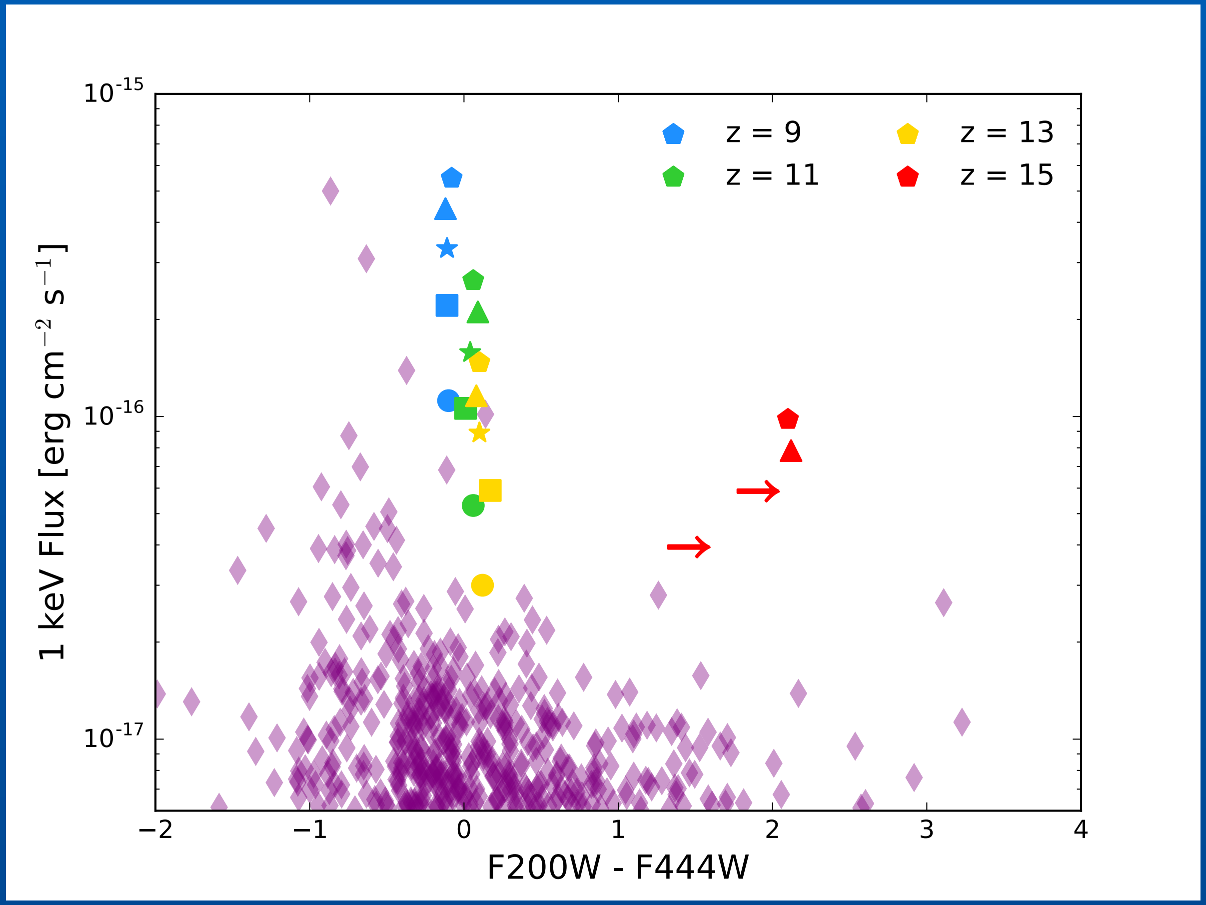


~ JWST spectra for growing DCBHs

Discriminant slope and amplitude between 1 - 10 microns

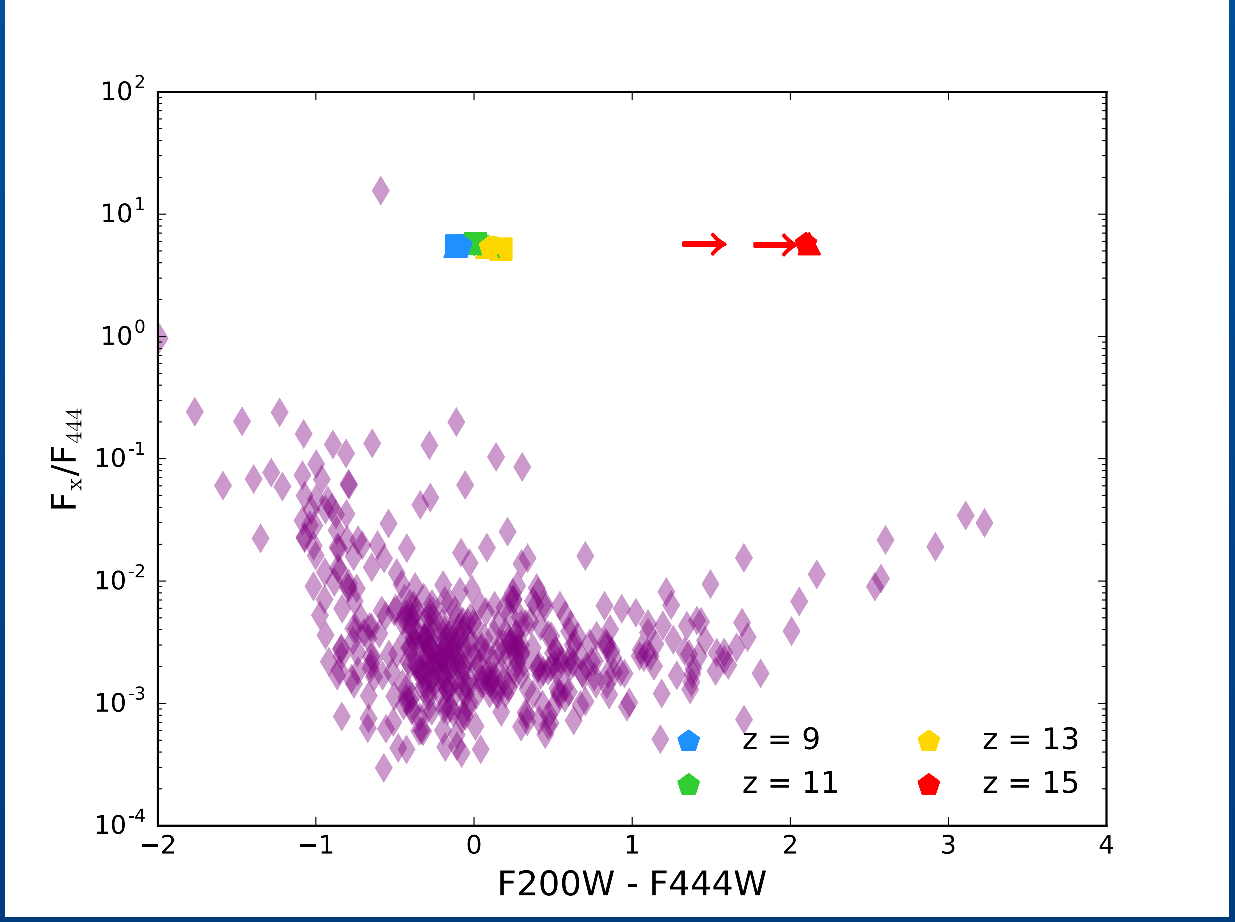
PN, Pacucci, Ferrara, Agarwal+ 16

SELECTION CRITERIA FOR CANDIDATES

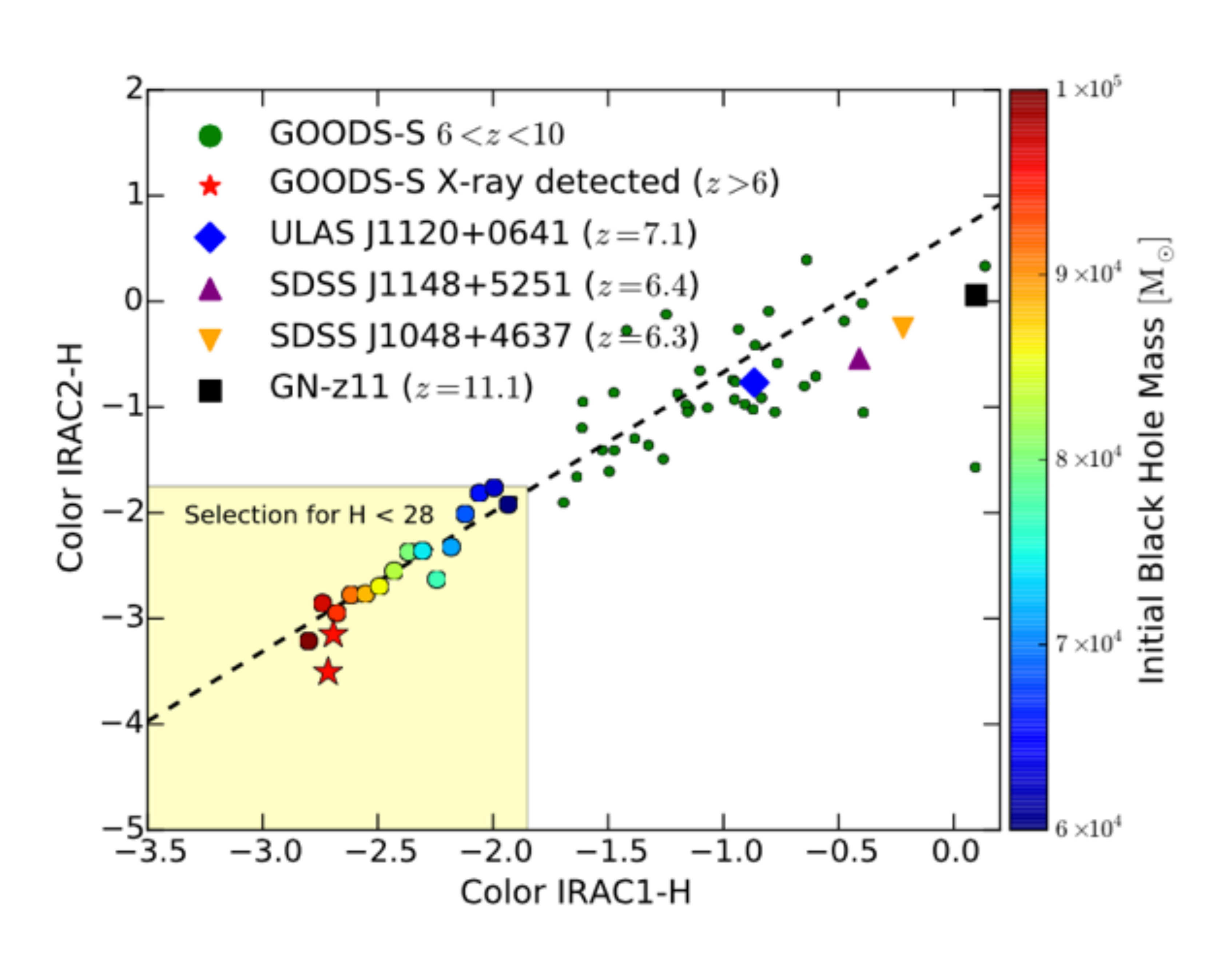


Drop-outs in F070W that are detected in both F200W and F444W (selecting for high z)

X-ray Flux/IR Flux > 1



HAVE WE FOUND EVIDENCE FOR MASSIVE SEEDS/DCBHs?

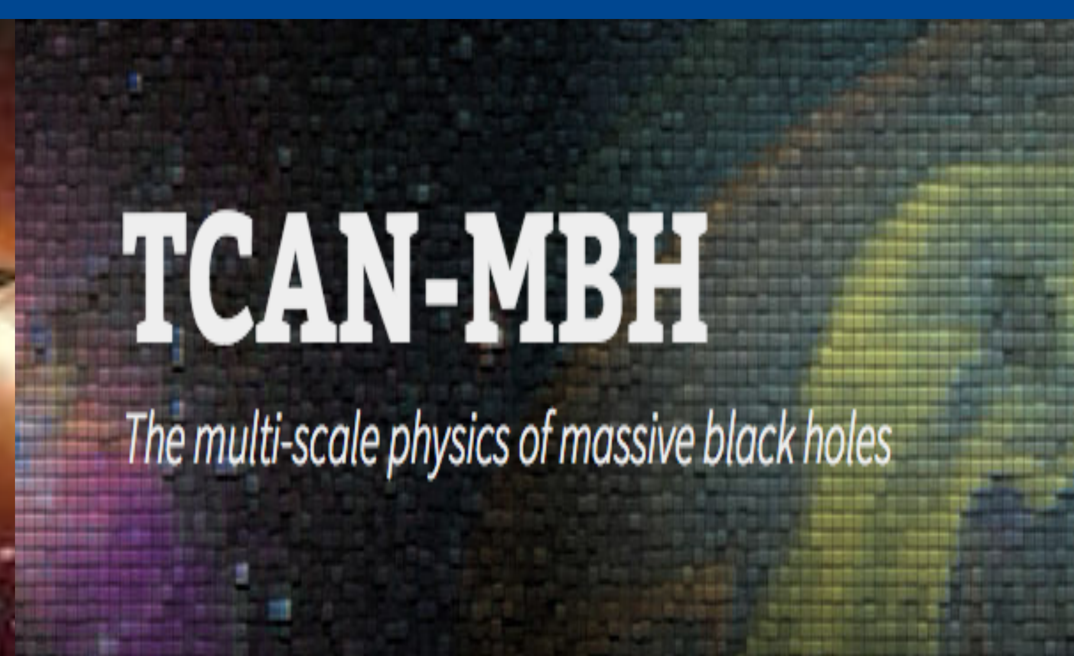


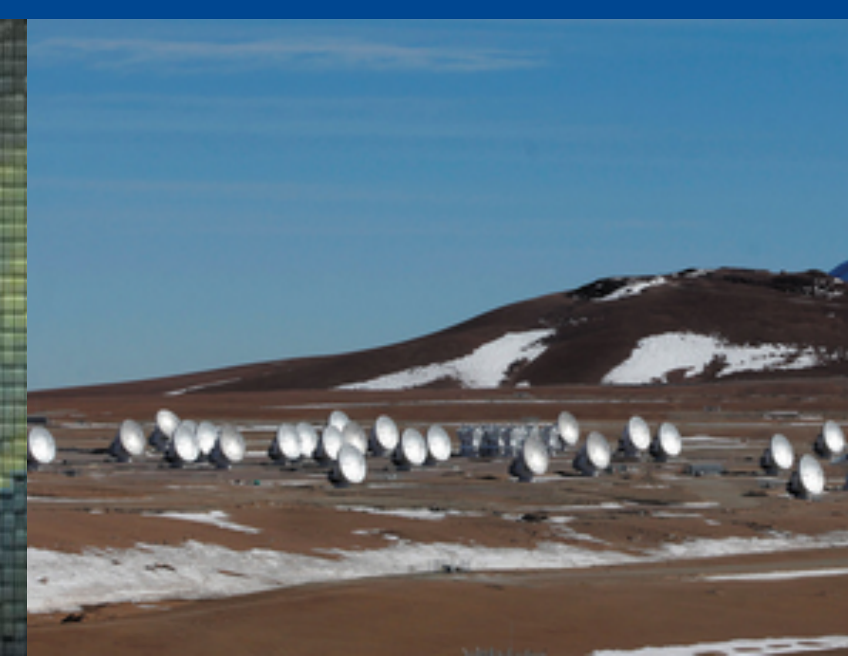
COLOR-COLOR SELECTION AND CANDIDATES
CANDELS/GOODS FIELDS

Pacucci+ 15; 16

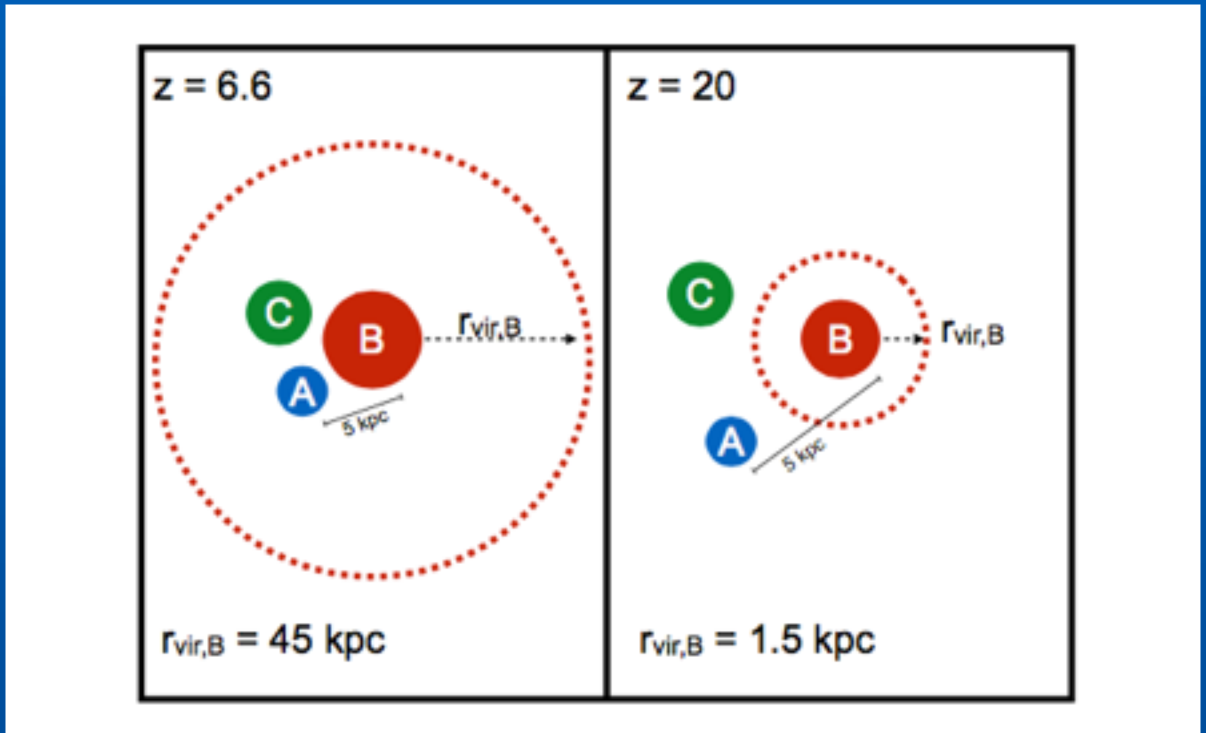
STATUS REPORT OF WHERE WE ARE & OPEN QUESTIONS

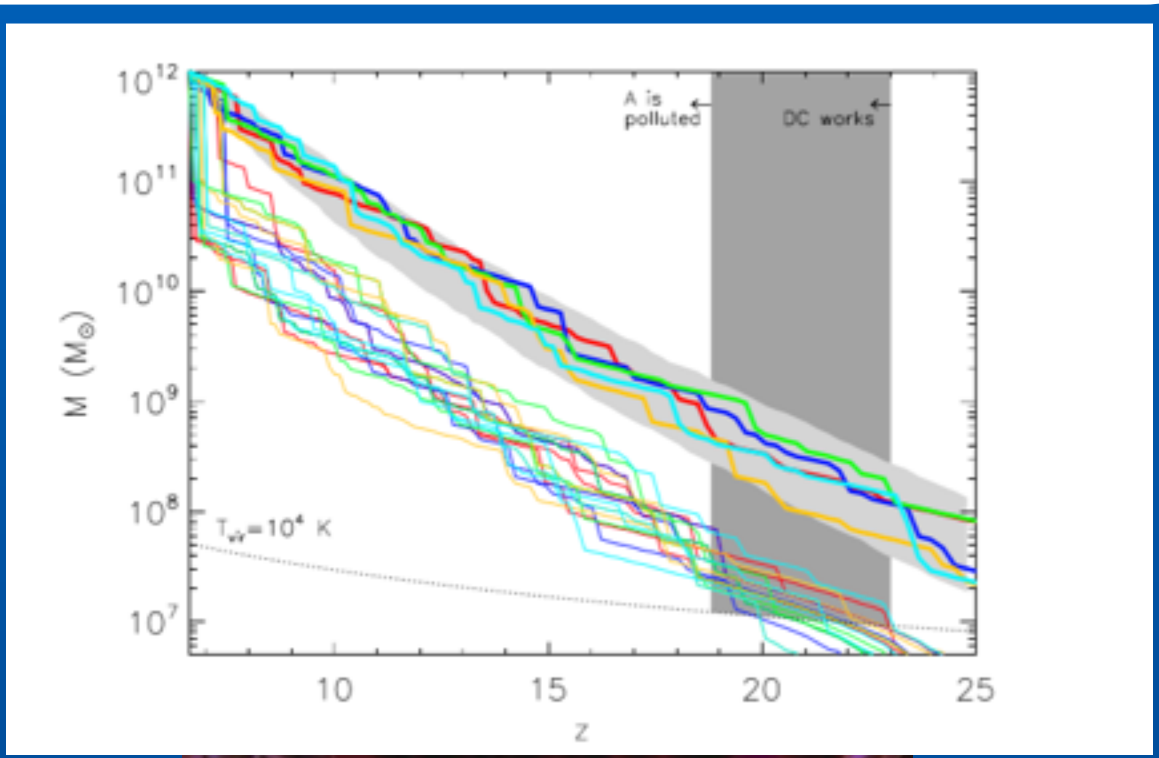
Masses of initial BH seeds
Early accretion history of seed BHs
Contribution to Re-ionization
Observational signatures of Super-Eddington flows
Importance of mergers
Detection of signature of mergers – gravitational waves
When do the correlations between BHs and their hosts get set-up

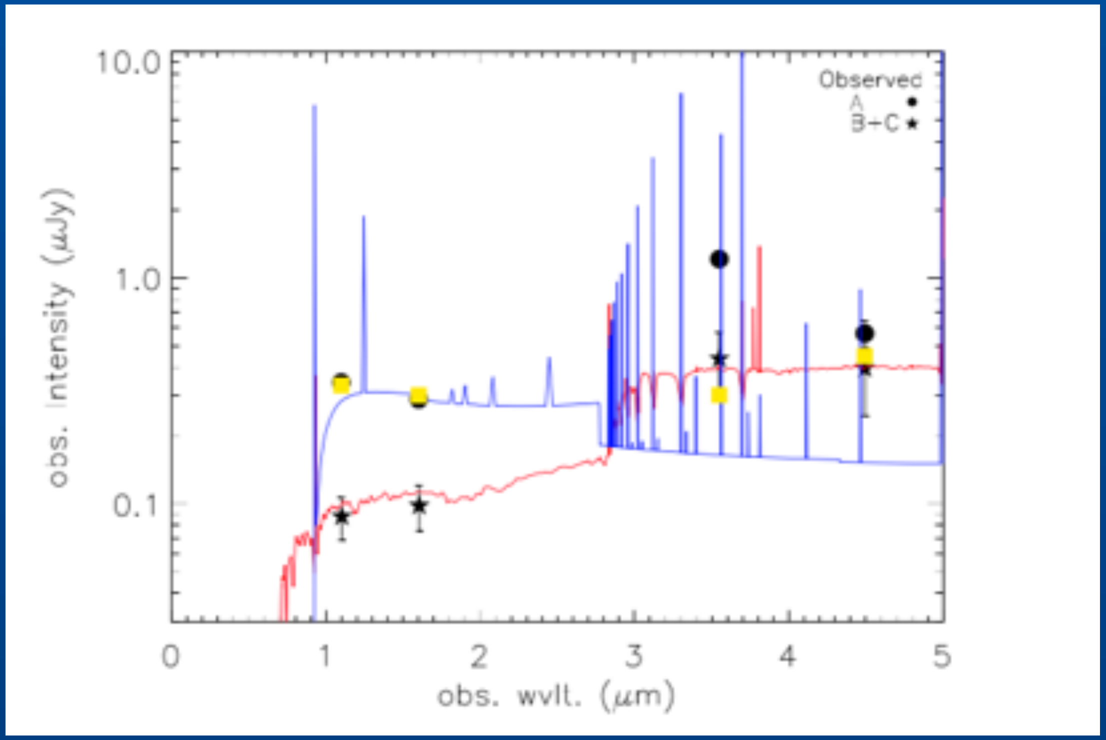


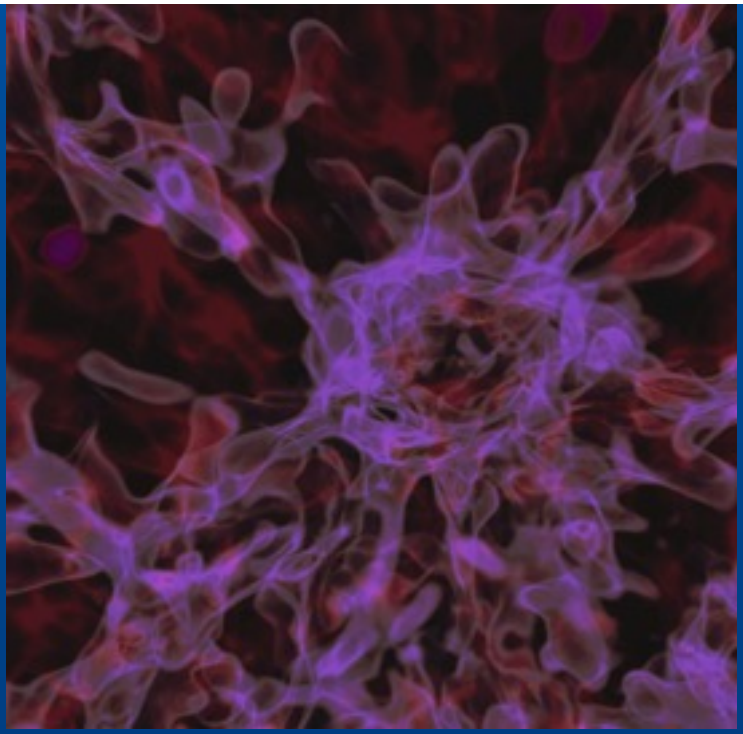


HAVE WE FOUND EVIDENCE FOR MASSIVE SEEDS/DCBHs?





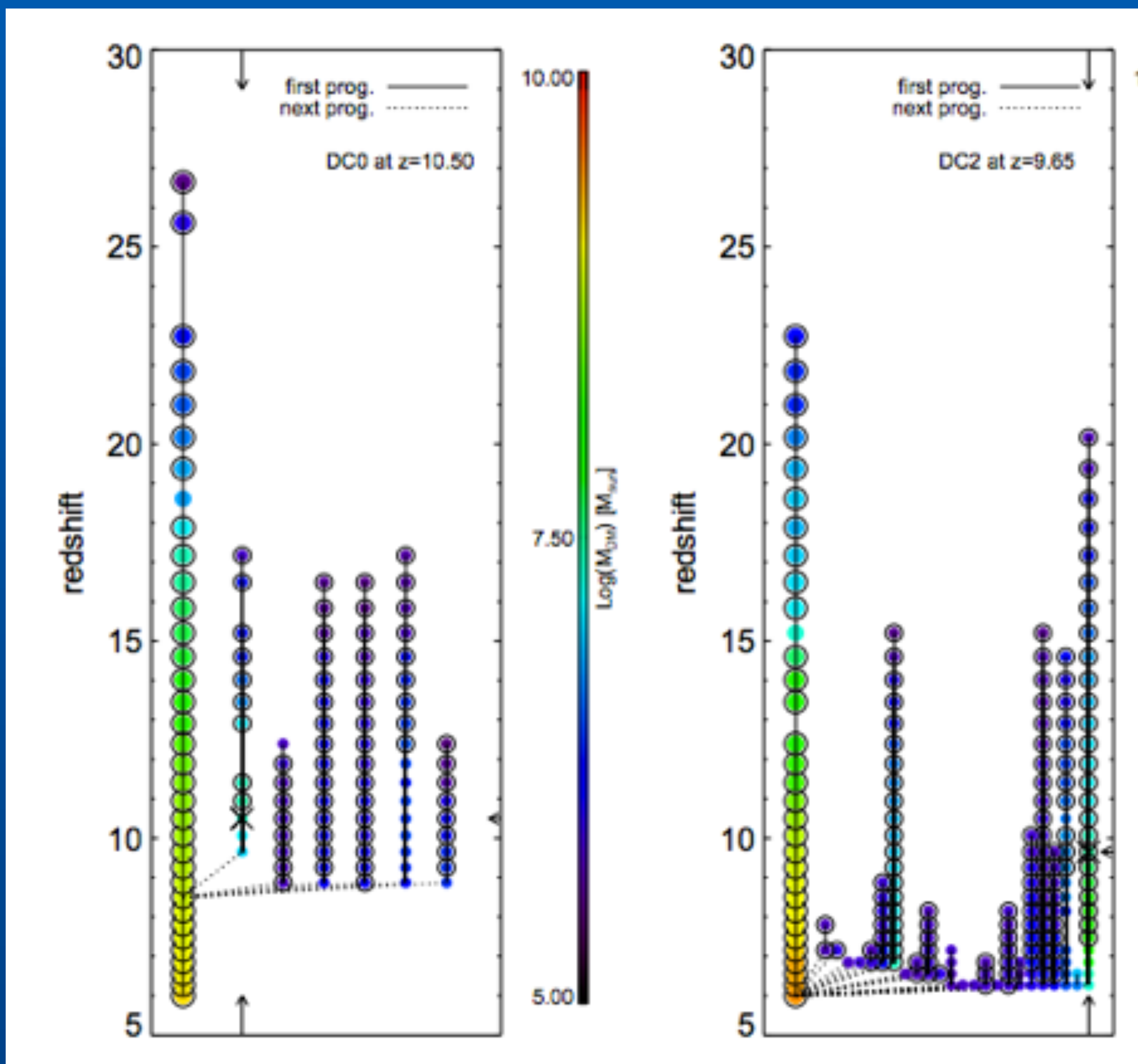




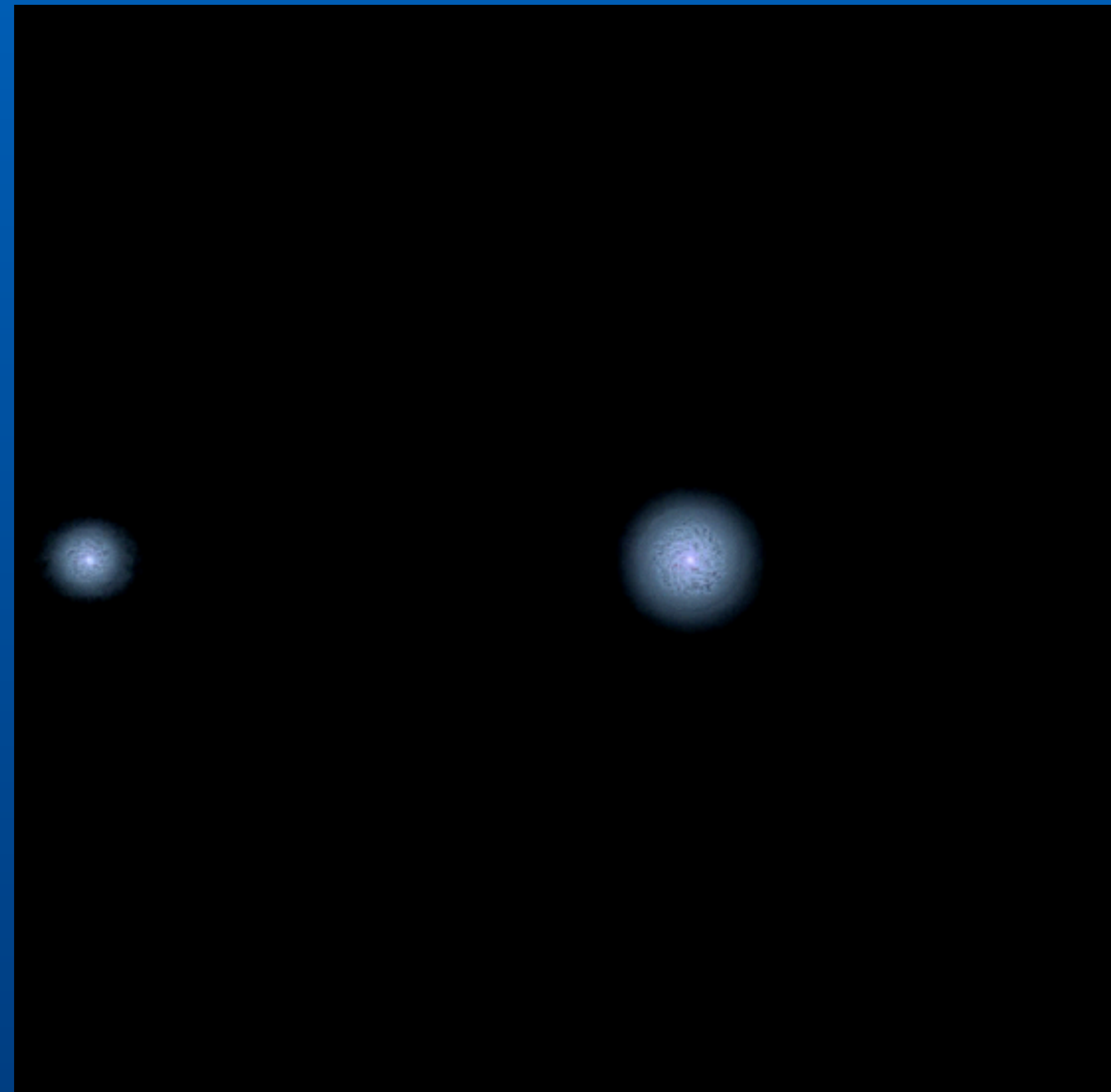
THE LYMAN-ALPHA EMITTER CR7?

Agarwal+ 16; Smith+ 16; Hartwig+ 15; Pallotini+ 15; Sobral+15

How significant are black hole mergers and merger triggered accretion at high redshifts and low redshifts?

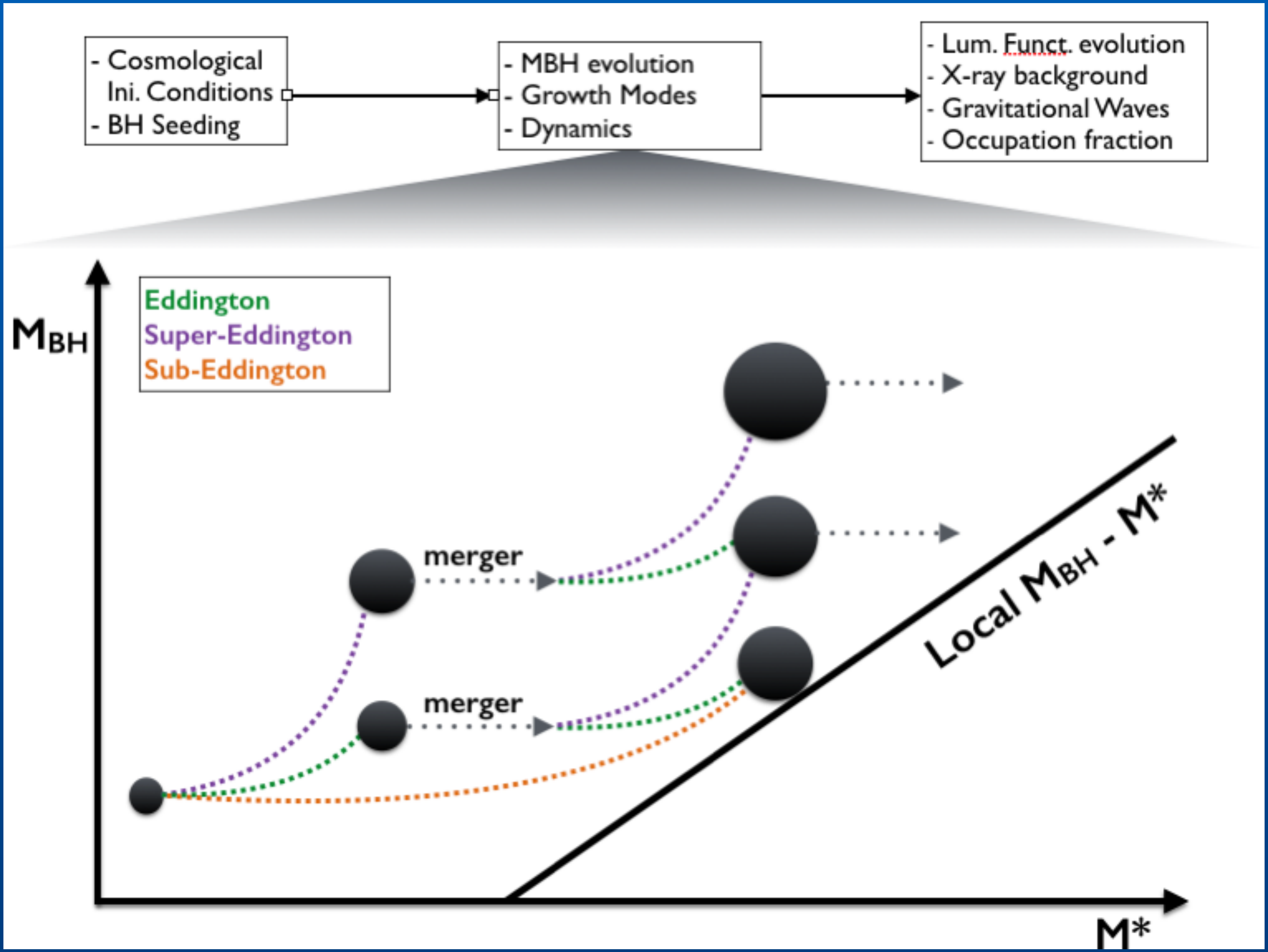


Example from the FiBY simulation
Khochfar; Agarwal



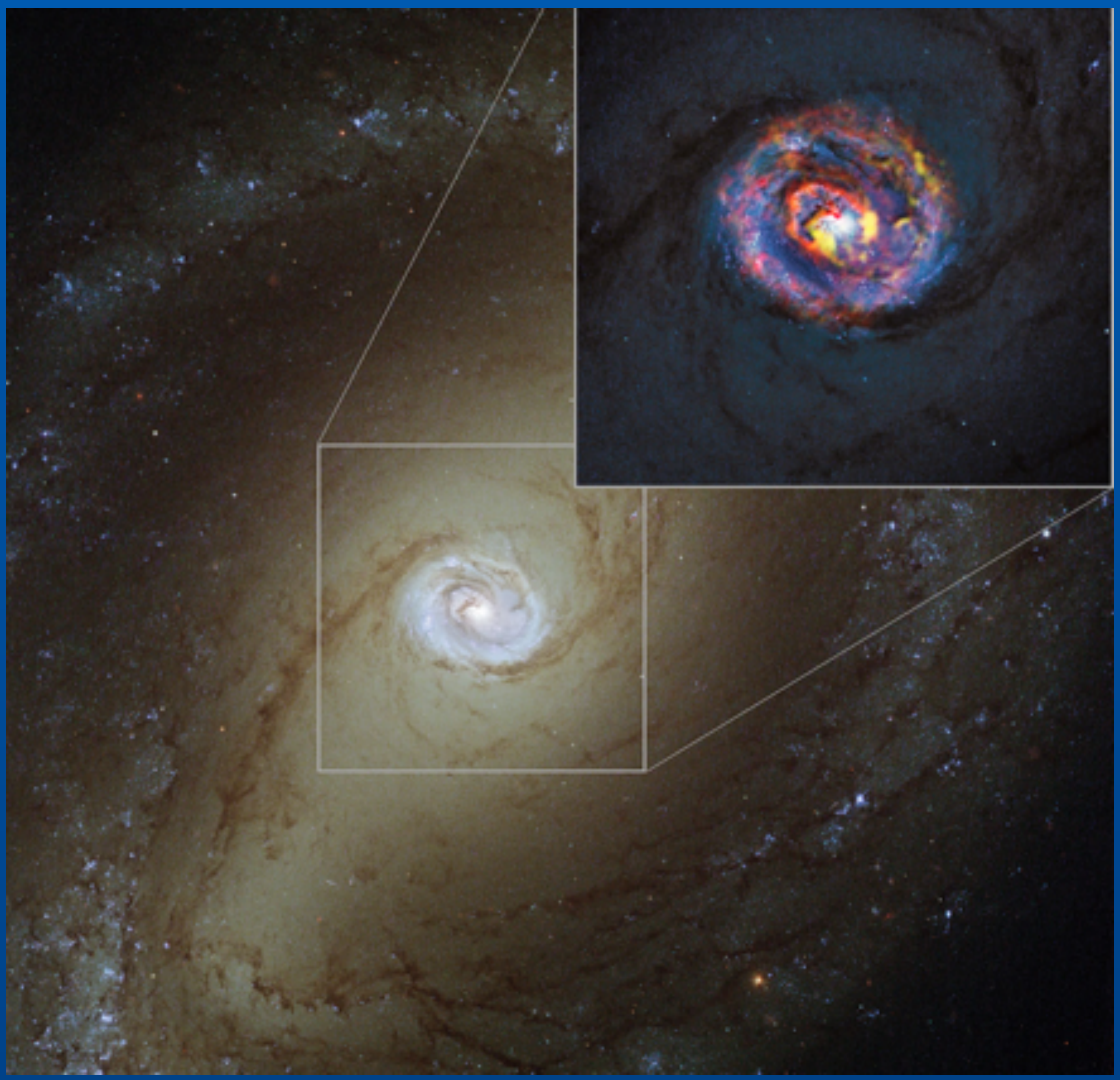
Hopkins+ Hernquist+ Capelo+ 15

Tracing the growth history of black holes in the universe

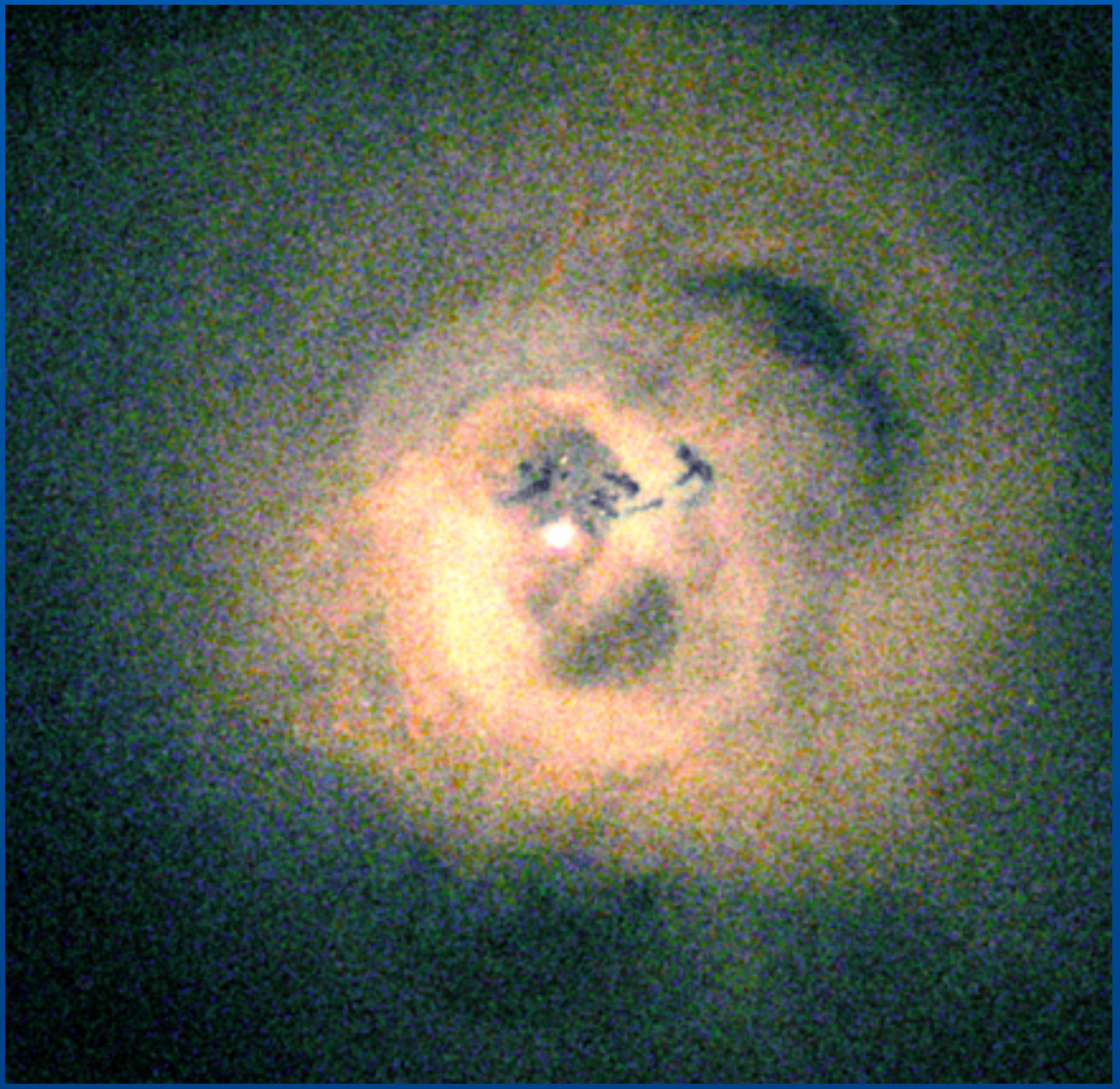


Ricarte, PN+ 16

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

BHMF FOR BLQSOs FROM SDSS 1 < z < 4.5

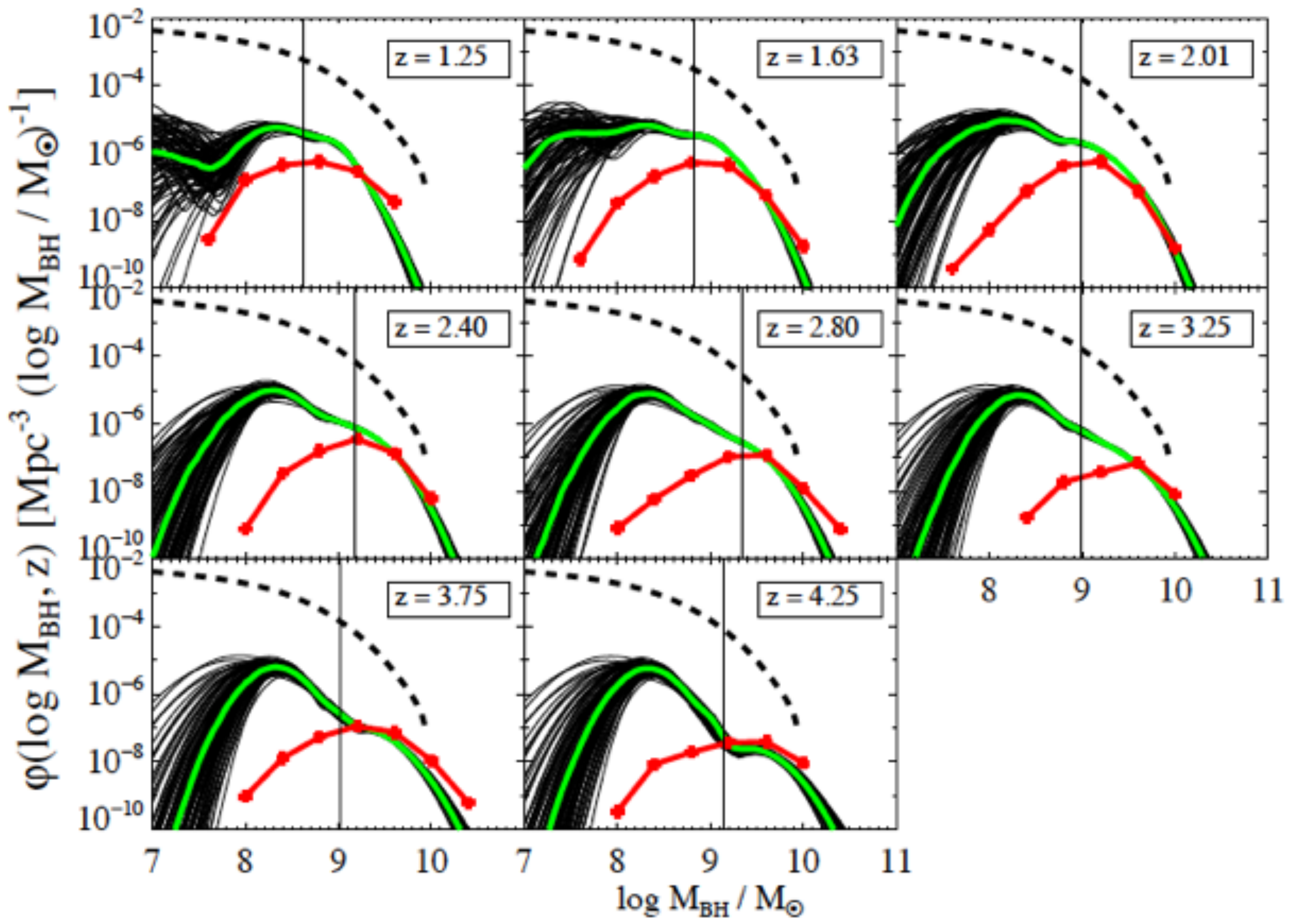


FIG. 3.— BLQSO BHMF (thin solid lines) obtained using our Bayesian approach, compared with the local BHMF fo all SMBHs (dashed line), and the BHMF from Vestergaard et al. (2008, solid red line with points); as in Figure 1, each thin solid line denotes a random draw of the BHMF from its probability distribution. 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

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

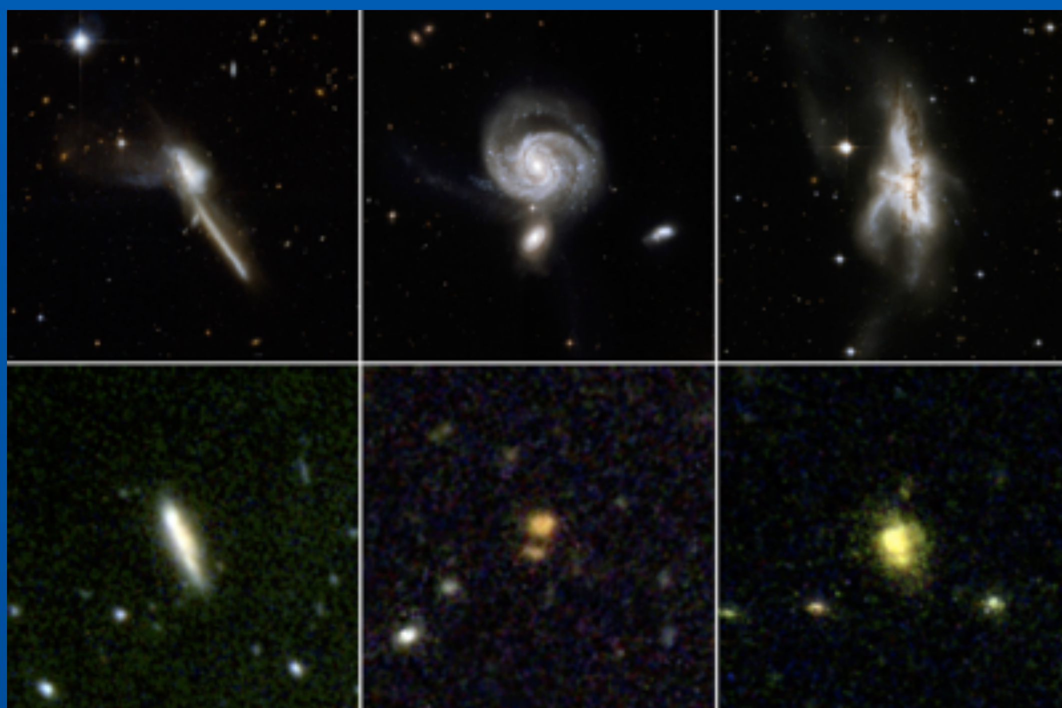
When are these correlations set up

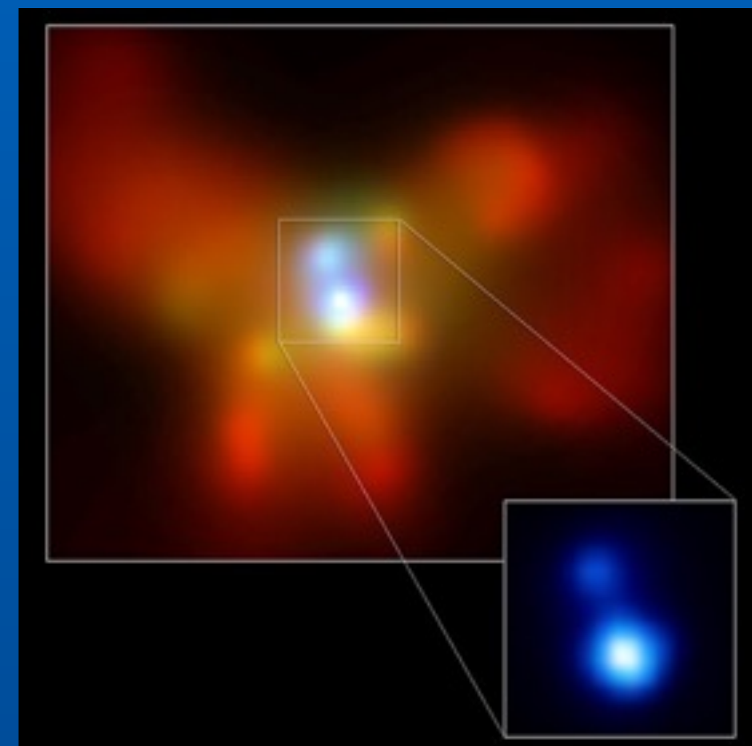
Initial conditions? accretion physics? merger dynamics? self-regulated feedback?

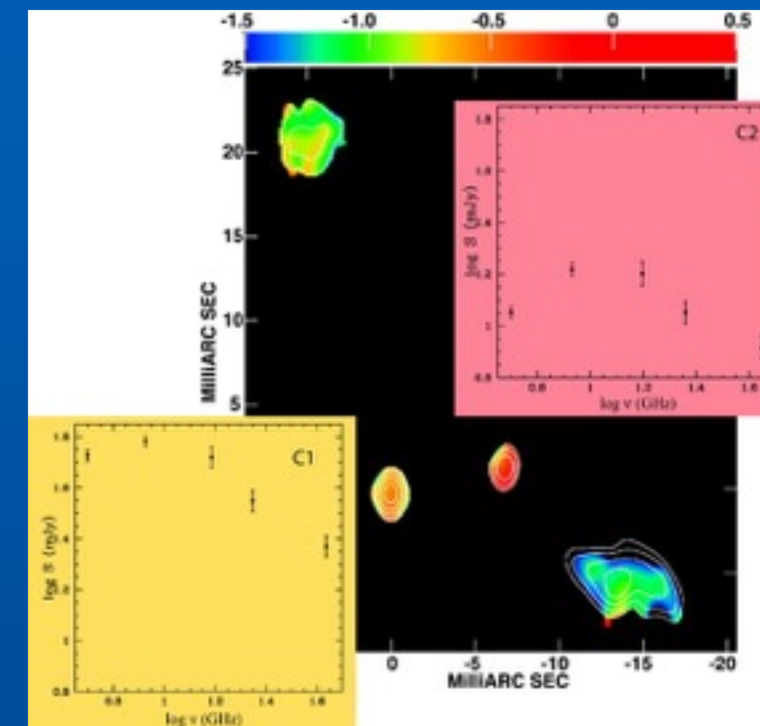
How do seed BHs grow

How do seed BHs form

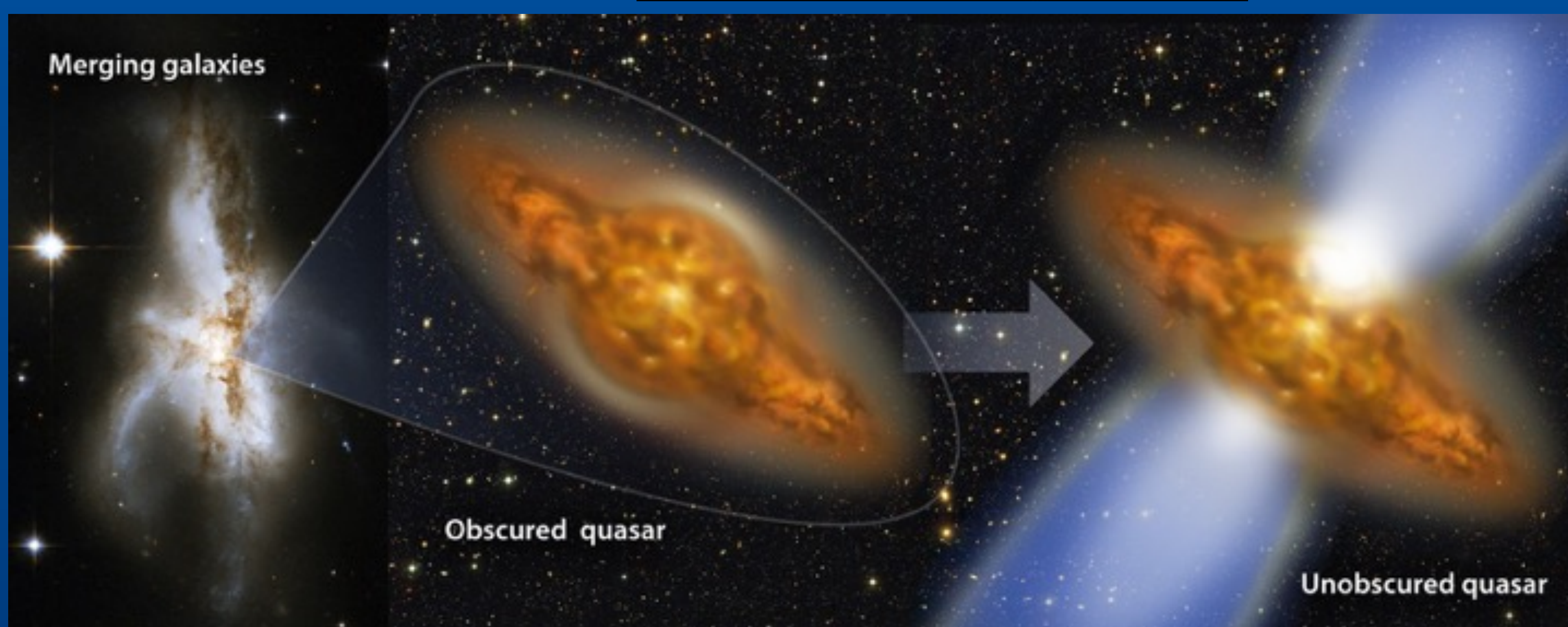
Dramatic BH growth spurts triggered by major mergers but not all BH growth







LOW z CANDELS steady growth



HIGH z HIGH L merger triggered

Treister+ 11; Hopkins & Quateart+ 11; Ballantyne+ 12; Hirschmann+12; Villforth+14