Tracing the growth of the first black holes

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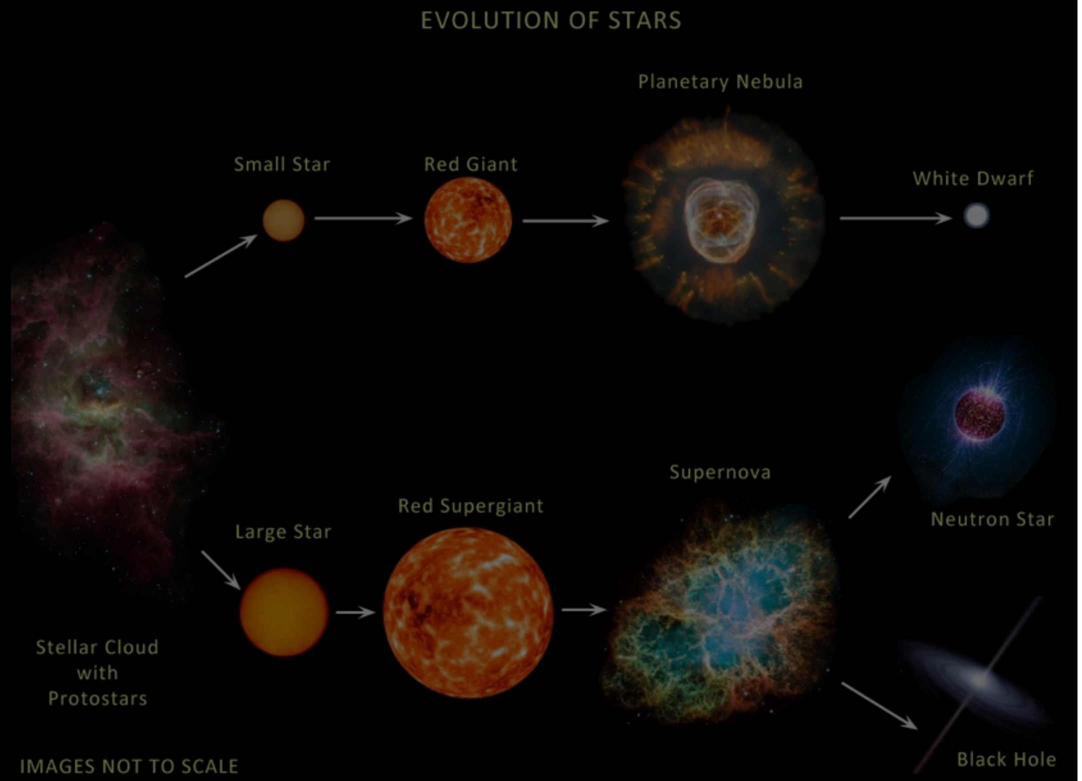
Stellar mass BHs

✔ formation through stellar evolution

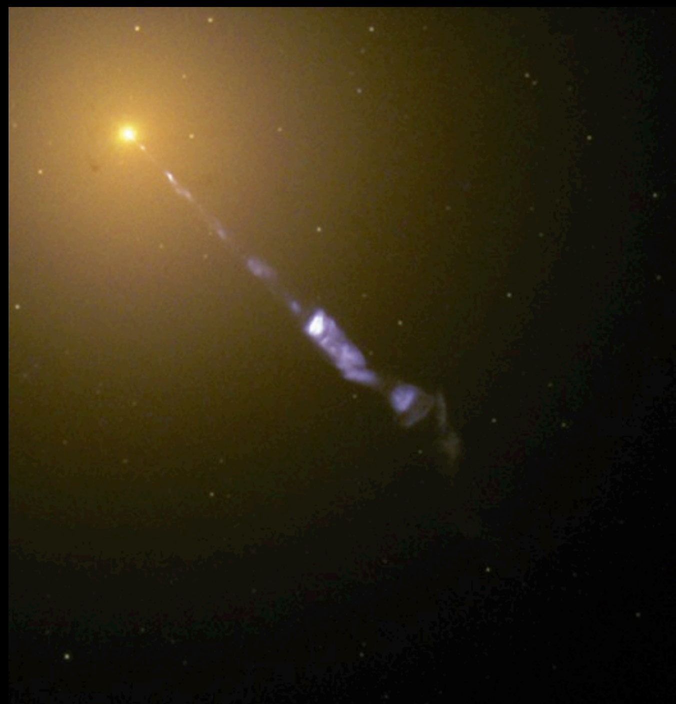
✔ mass < few tens Msun

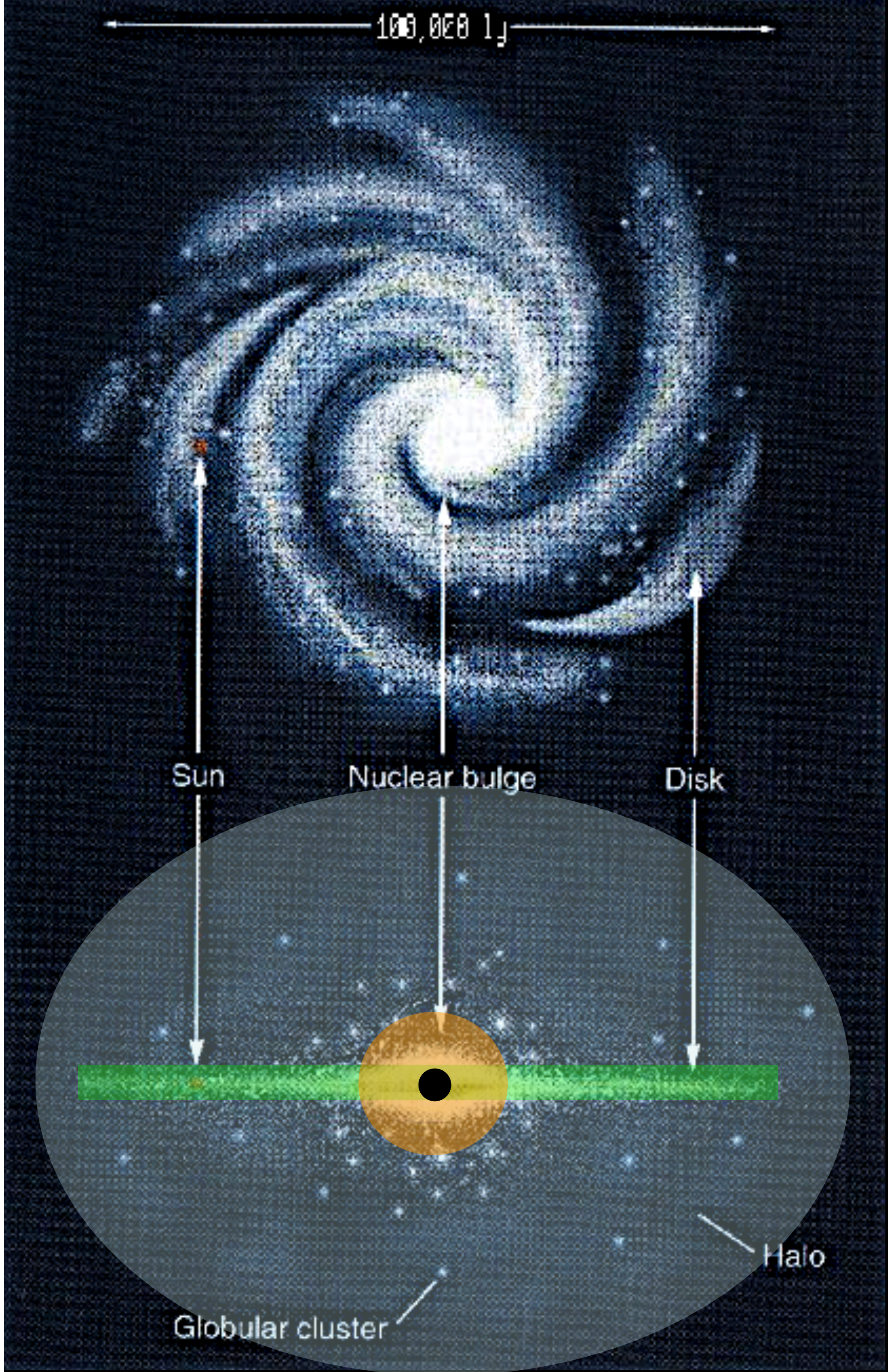


Massive BHs

✔ powering quasars

✔ mass > 10^5 Msun





Galaxies

mass: 10^9-10^{12} solar masses

$R_{halo} \sim GM_{halo}/\sigma^2$ MEGAPARSEC

$R_{bulge} \sim GM_{bulge}/\sigma^2$ KILOPARSEC

Massive Black Holes

mass: 10^5-10^9 solar masses

$R_{bondi} \sim GM_{BH}/c_s^2$ PARSEC

$R_{inf} \sim GM_{BH}/\sigma^2$ PARSEC

$R_{sch} = 2GM_{BH}/c^2$ MICROPARSEC

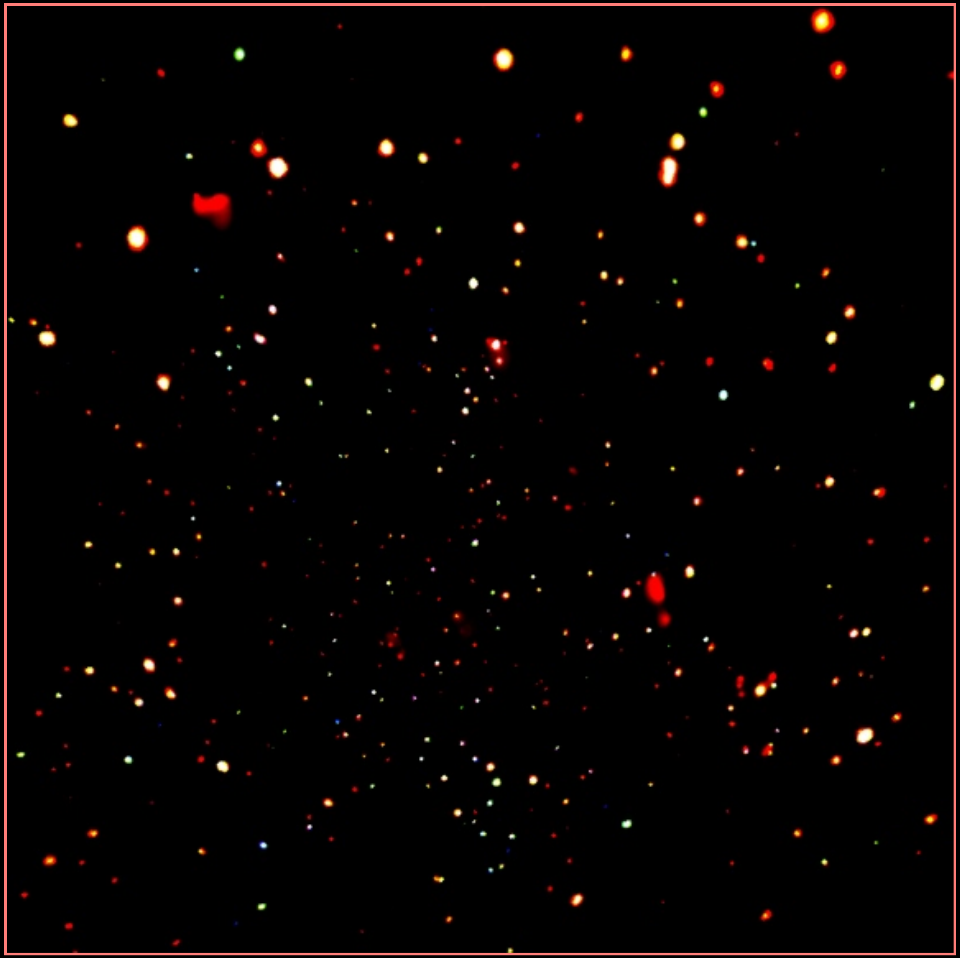
Shiny black holes out there....

Hubble Deep Field

visible light – starlight

all galaxies

“black” black holes?



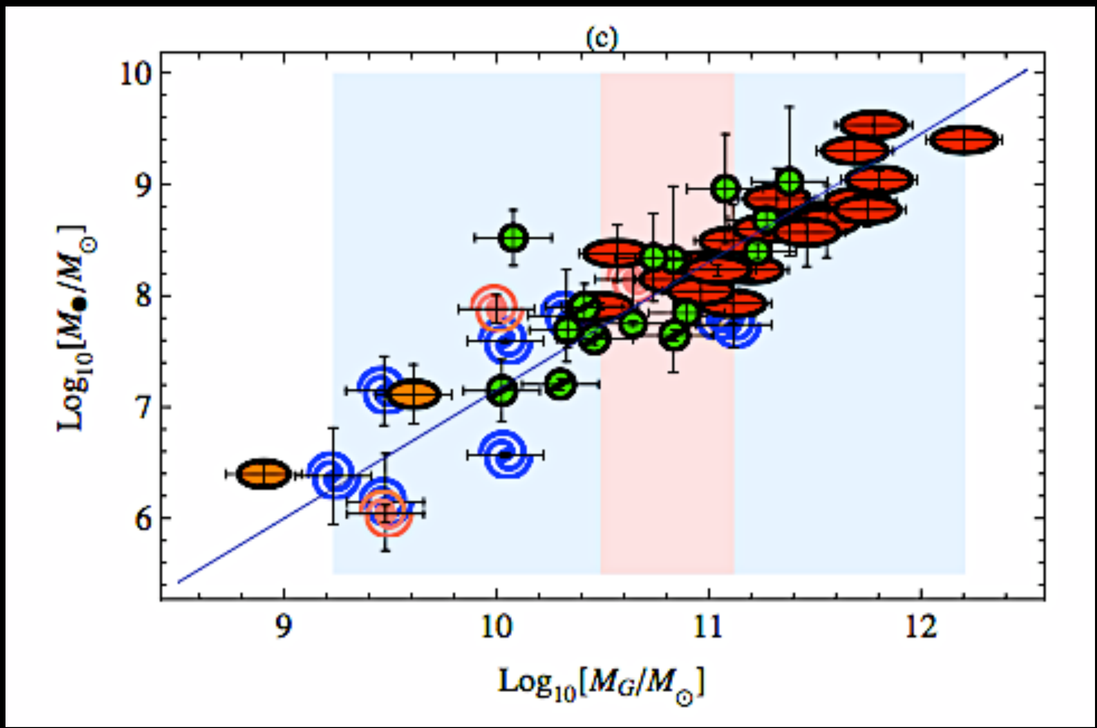
Chandra Deep Field

X-ray – high energy processes

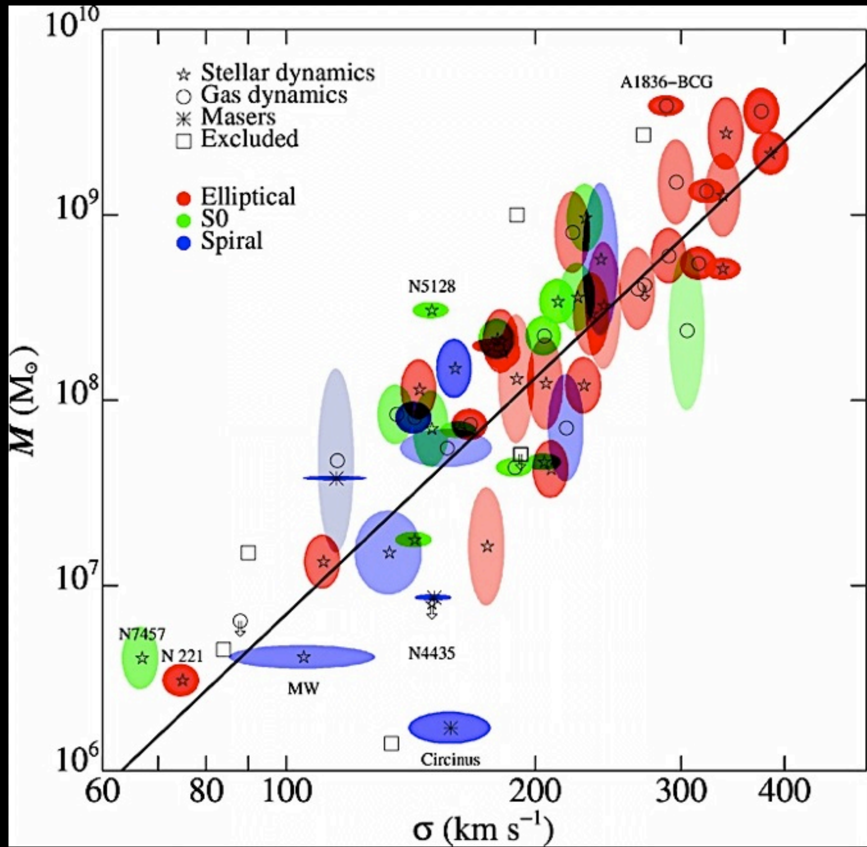
active galaxies

& black holes

MBH- host relations: co- evolution of MBHs and galaxies



Feoli & Mancini 2009



Gultekin et al. 2009

MBHs ⟷ stellar bulges ⟷ DM halos (???)

NUCLEI

Nuclear scales (sub-pc scale)

– Bridge from friction-driven to gravitational radiation-driven decay

– Spin evolution ⇔ Jet formation

GALAXIES

Galaxy scales (kpc-pc scale)

– Which galaxy mergers lead to MBH binaries?

– Merger-driven quasar/AGN activity

CONTEXT

Cosmic scales (Gpc-kpc scale)

– How and when MBHs form

– How many galaxies host MBHs

Semi-analytical models ➔
cosmic evolution ➔ statistical samples ➔observables

GW events

AGN/QSO binaries

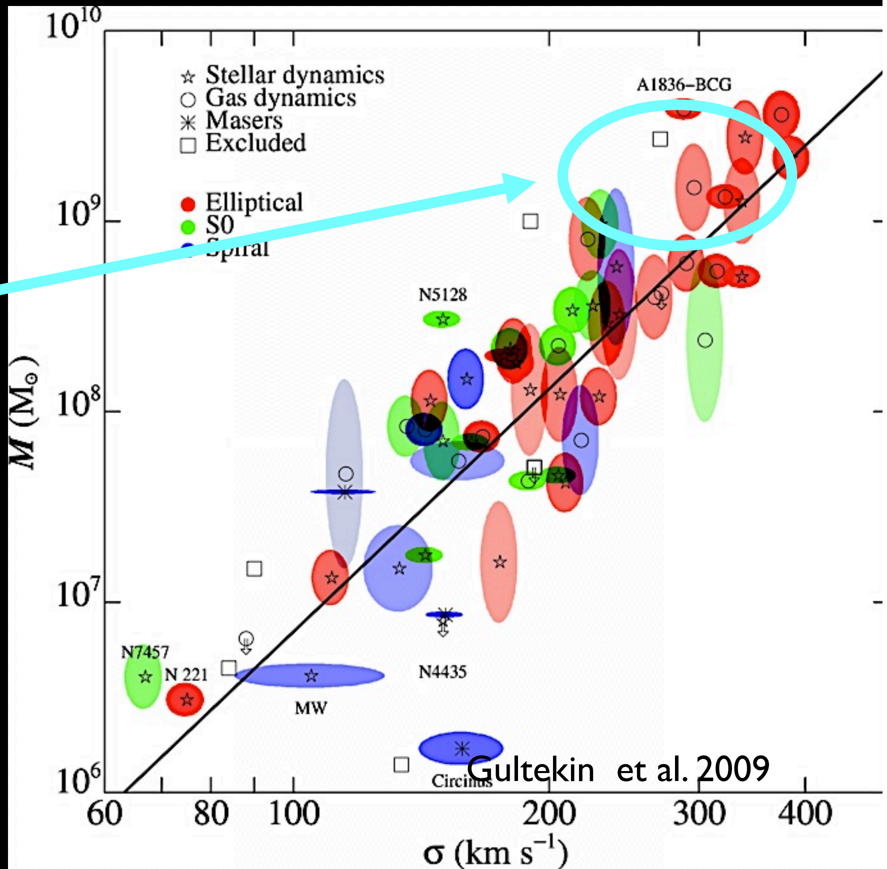
AGN/QSO pairs

MBH occupation fraction, LF of QSOs/AGN

WHEN do you make the first massive black holes?

The highest redshift quasar currently known, ULASJ112010641, at z=7.1 has estimates of the SMBH mass MBH~2 x10^9 Msun (Mortlock et al. 2011)

As massive as the largest SMBHs today, but when the Universe was 0.75 Gyr old!



Gultekin et al. 2009

For a BH accreting at a given fraction fEdd of the Eddington limit, the mass grows in time as:

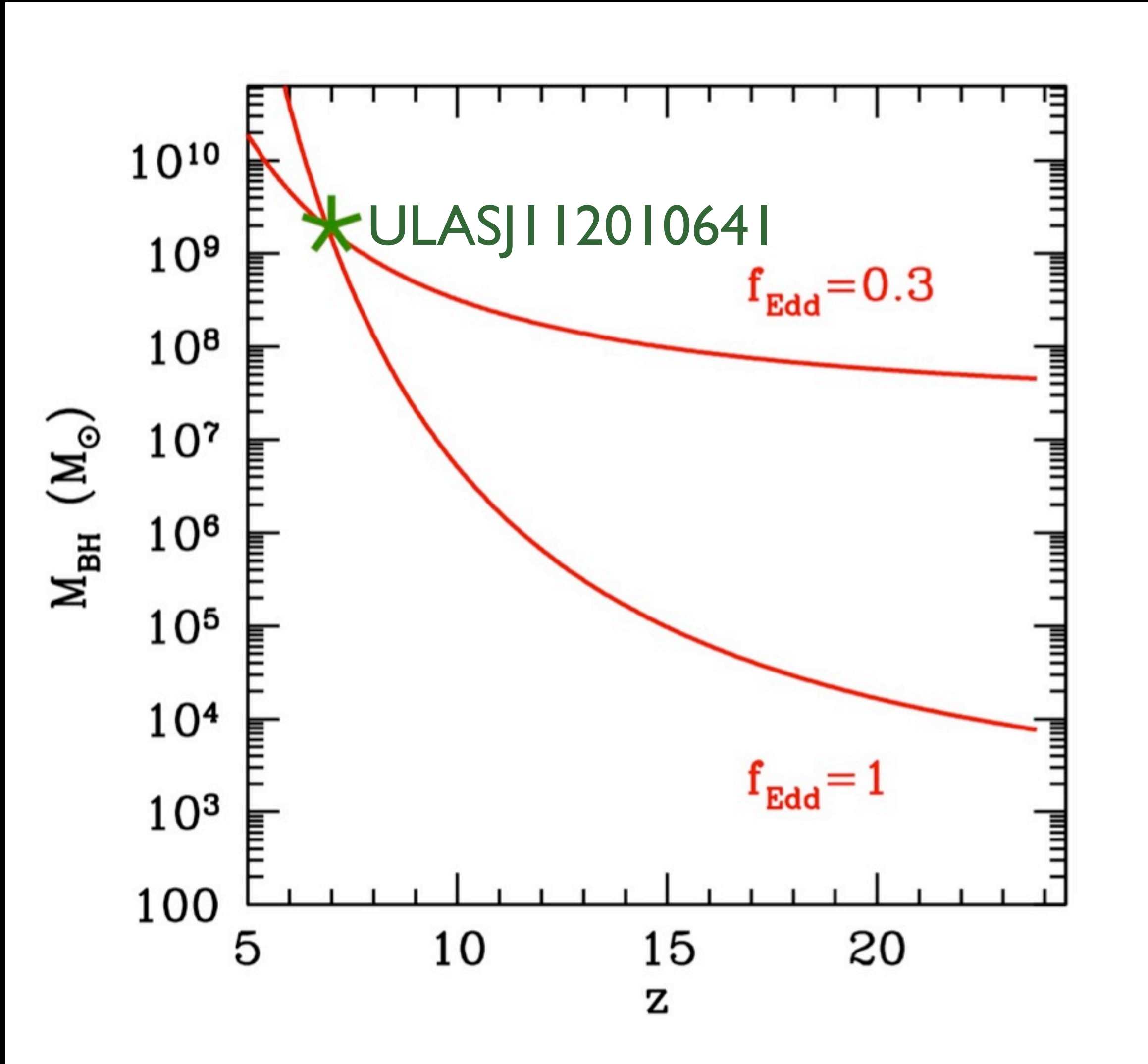
$$M(t) = M_{in}\, e^{\left(\frac{1-\varepsilon}{\varepsilon} f_{\rm Edd} \frac{t}{0.45\,{\rm Gyr}}\right)}$$

M_{fin}=2x10^9 Msun

t_H(z=7)~0.75 Gyr

f_{Edd}=0.3-1; ε~0.1

⇒ M_{in}>300-ish Msun

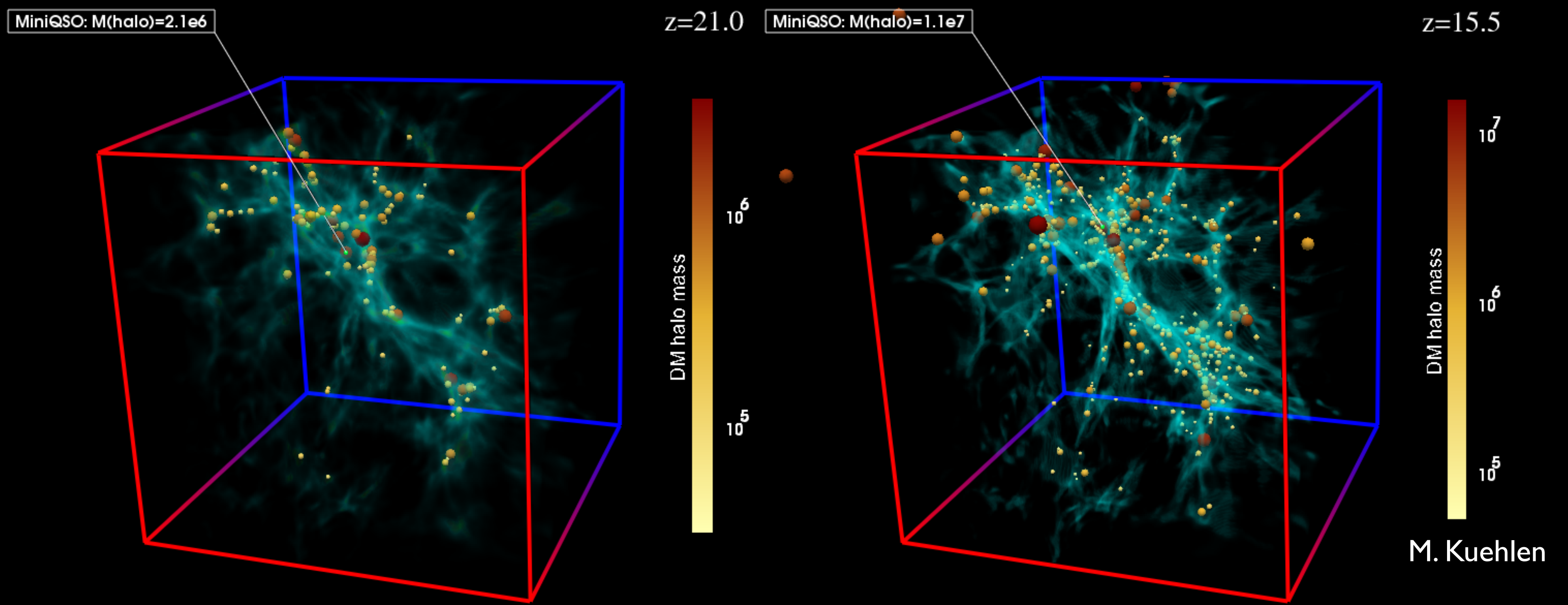


HOW

can you make a massive black hole 'seed'?

Hierarchical Galaxy Formation

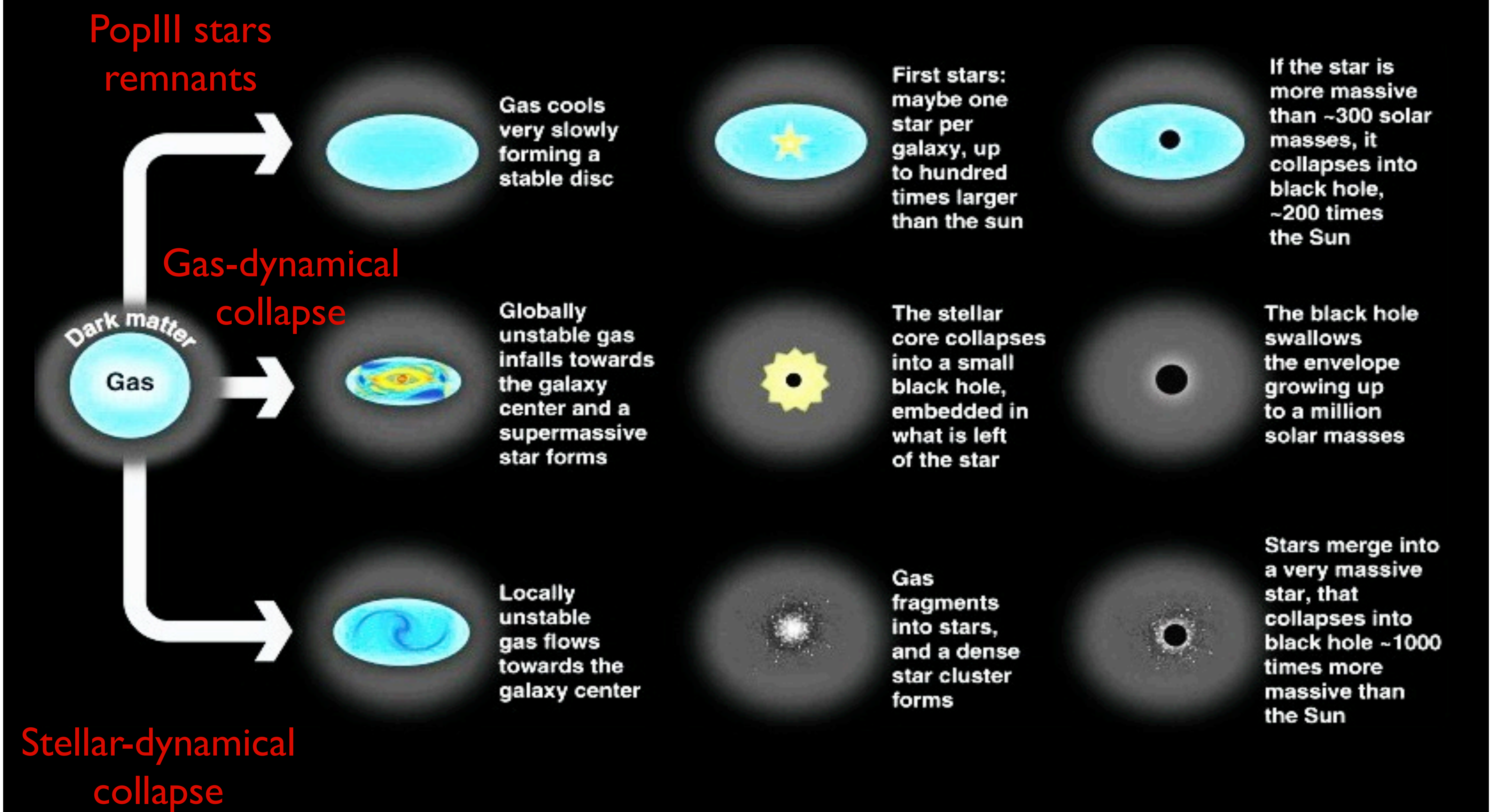
small scales collapse first



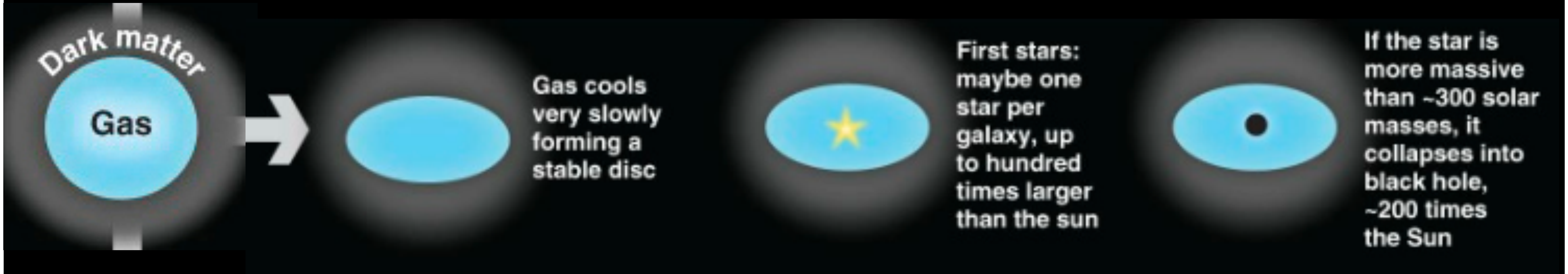
M. Kuehlen

Baryons: need to cool => possible only in the most massive halos $>10^6$-10^8 M_{sun}, i.e. the rarest at these highest redshifts

HOW can you make the first massive black holes?



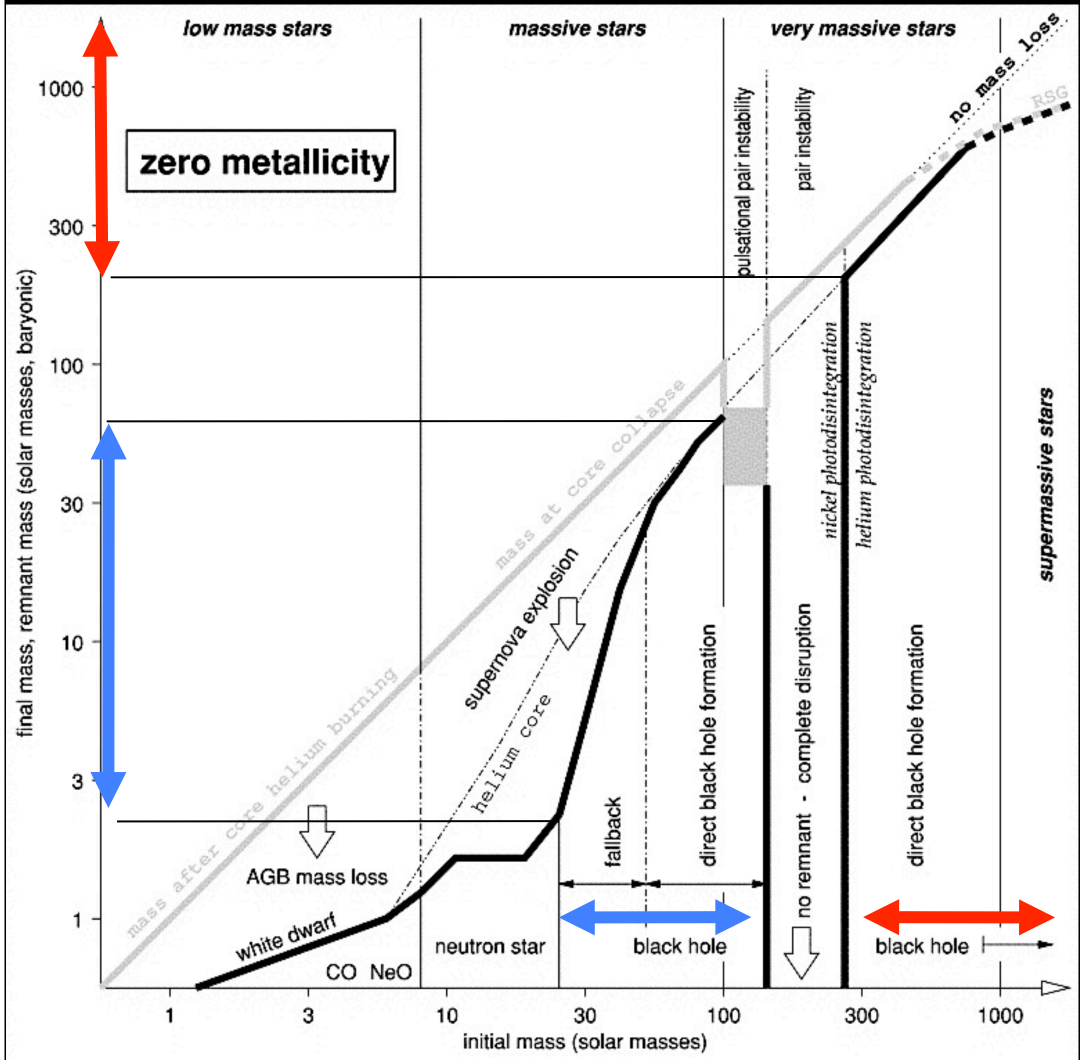
PopIII stars remnants



✔Some simulations suggest that the first stars are massive M~100-600 Msun (e.g., Abel et al. 2002; Bromm et al. 2003)

✔Metal free dying stars with M>260Msun leave remnant BHs with Mseed≥100Msun (Fryer, Woosley & Heger 2003)

Problem: are the first stars massive enough?



$M_{*} > 260\ M_{sun} \rightarrow M_{BH} > 150\ M_{sun}$

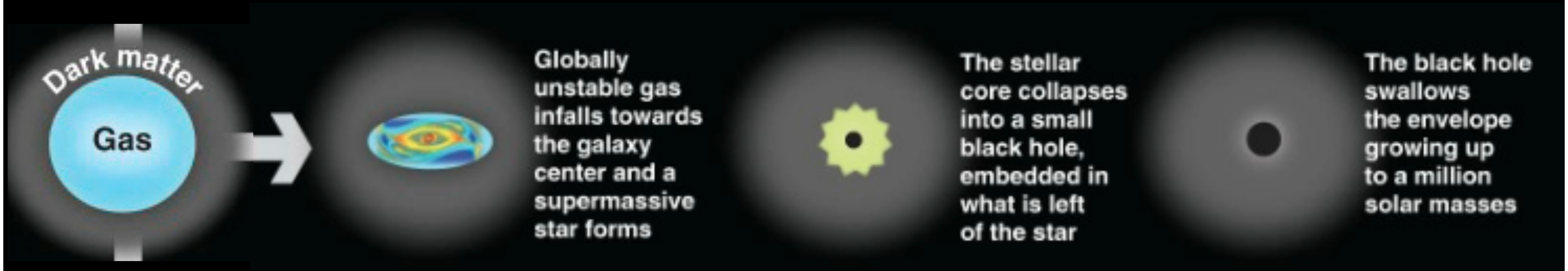
Recent simulations revise the initial estimates of the stellar masses to possibly much lower values, just a few tens Msun

$M_{*} \sim 30\text{-}150\ M_{sun} \rightarrow M_{BH} << 100\ M_{sun}$

If BH mass too small difficult to settle down into galaxy center => dynamics suppresses accretion/growth opportunities

Gas-dynamical collapse

(e.g. Bromm & Loeb 2003, Begelman, MV & Rees 2006)



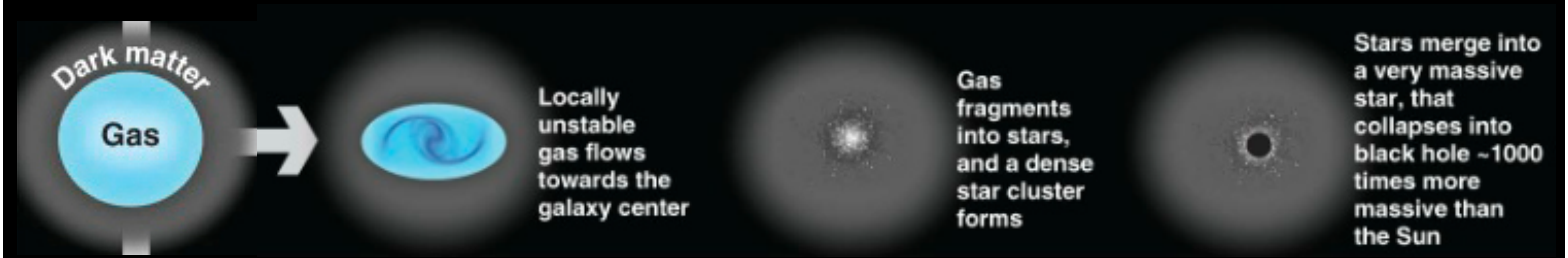
✔Deep potential well for gas infall and collapse

✔*Global dynamical instabilities* to trigger inflow and dissipate angular momentum

✔Zero or low-metallicity to avoid star formation - SNe can blow away the gas reservoir

Stellar-dynamical processes

Devecchi & MV 2009



Local dynamical instabilities can lead to mass infall instead of fragmentation and global star formation

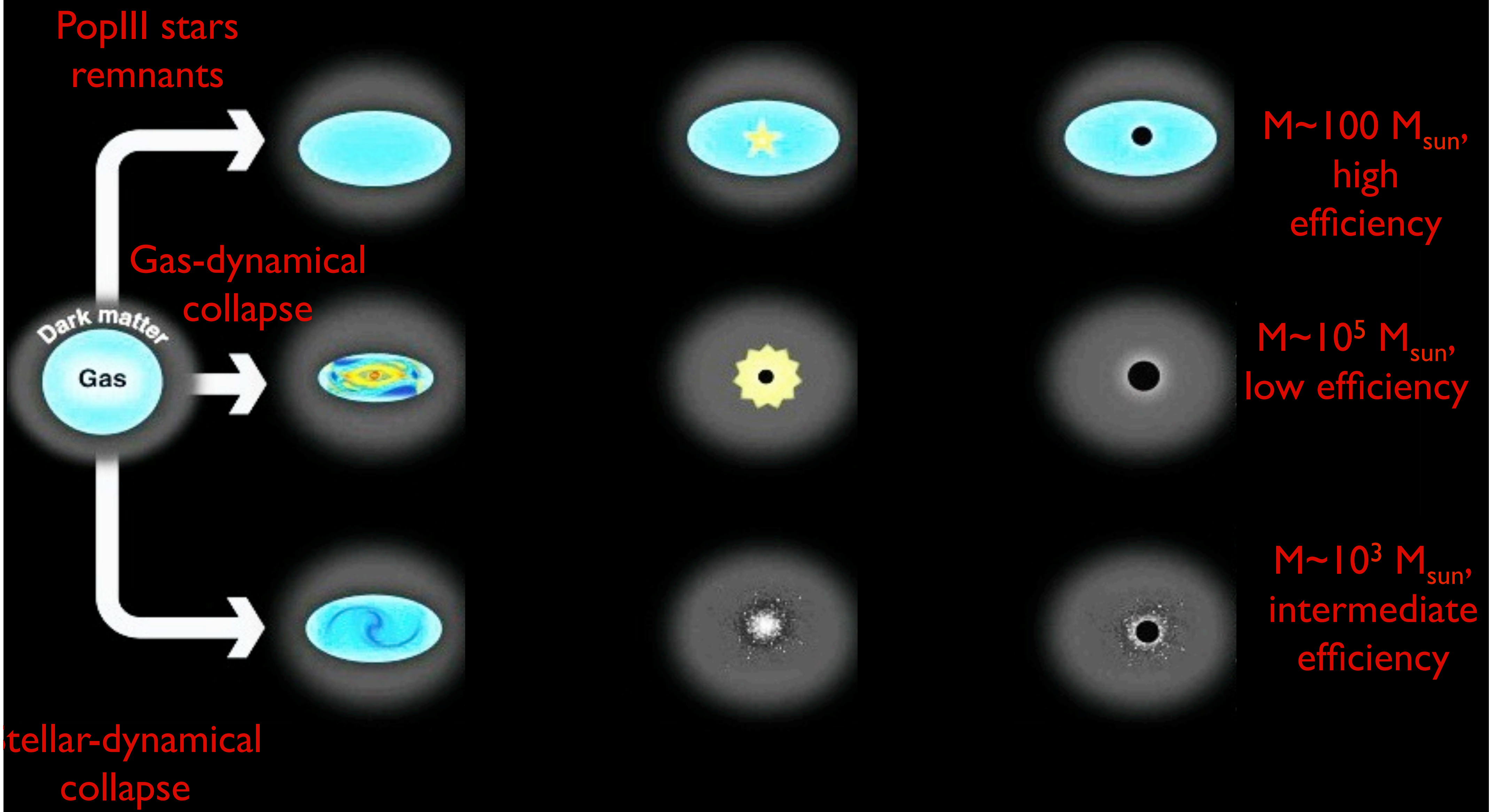
VERY LOW, but NON-ZERO METALLICITY:

✔ Inflow ⇒ within an inner, compact, region stars form abundantly ⇒ very dense cluster

✔mass segregation: massive stars sink to the center

✔ stellar collisions form a very massive star ⇒ massive black hole

HOW can you make the first massive black holes?



Testing MBH seed formation: two techniques

1. Semi-analytical modelling
   - Analytical "recipes" for MBH formation and growth
   - Monte-Carlo realizations of the merger history of dark matter halos in a LCDM cosmology
   - computationally inexpensive =>statistical samples

MV, Haardt & Madau 2003,MV & Natarajan 2009, MV & Begelman 2010

2. Cosmological simulations
   - No need to use global quantities or smooth functions
   - Gravity and hydrodynamics naturally included
   - Either high resolution or large volume due to computational costs

Galaxies

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HOW can you make the first massive black holes?

PopIII stars remnants

Gas-dynamical collapse

Stellar-dynamical collapse

✔High gas density

✔Zero or low-metallicity to avoid fragmentation

Bellovary, MV et al. 2011

Simulations of MBH seed formation

- GASOLINE SPH *N*-body code (Wadsley et al. 2004)
  - Star formation, supernova feedback, metal diffusion, metal line cooling
- New additions:
  - Seed BH formation
  - MBH mergers
  - MBH accretion
  - MBH feedback

Seed MBH Prescription

- Forming Seed MBHs
  - Form seed black holes out of cold, dense, zero-metallicity gas ($n>10^2$ cm^{-3}, $T<10^4$ K)
  - Probability of forming a black hole ("efficiency")
  - Seed mass same as gas particle (10^4 - 10^6 $M_\odot$)

Local prescription – driven by *gas physics*

Testing MBH seed formation

- High resolution “zoomed-in” cosmological simulations. We can accurately model the environment of BH formation and evolution

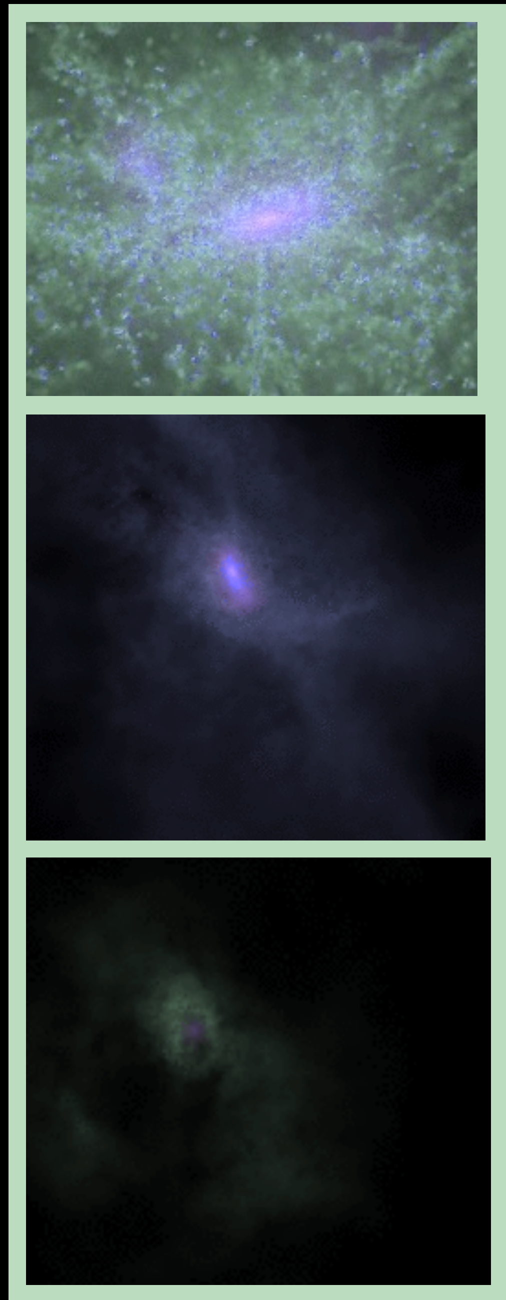
- Three galaxies to z=5

- Four values of BH formation efficiency (0.05, 0.1, 0.3, 0.5)

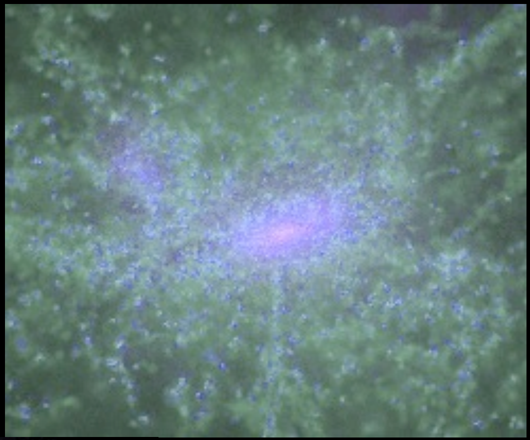
hz1

h258

h603



Testing MBH seed formation



hz1

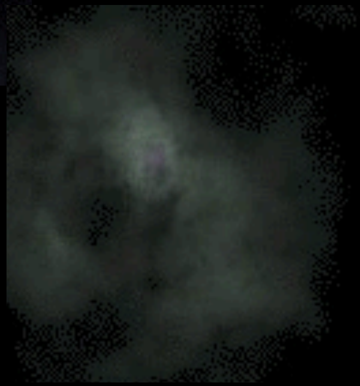
at z = 5: M = 6×10^{11} $M_\odot$

at z = 0: Massive elliptical

h258

at z = 5: M = 3×10^{10} $M_\odot$

at z = 0: Milky Way mass

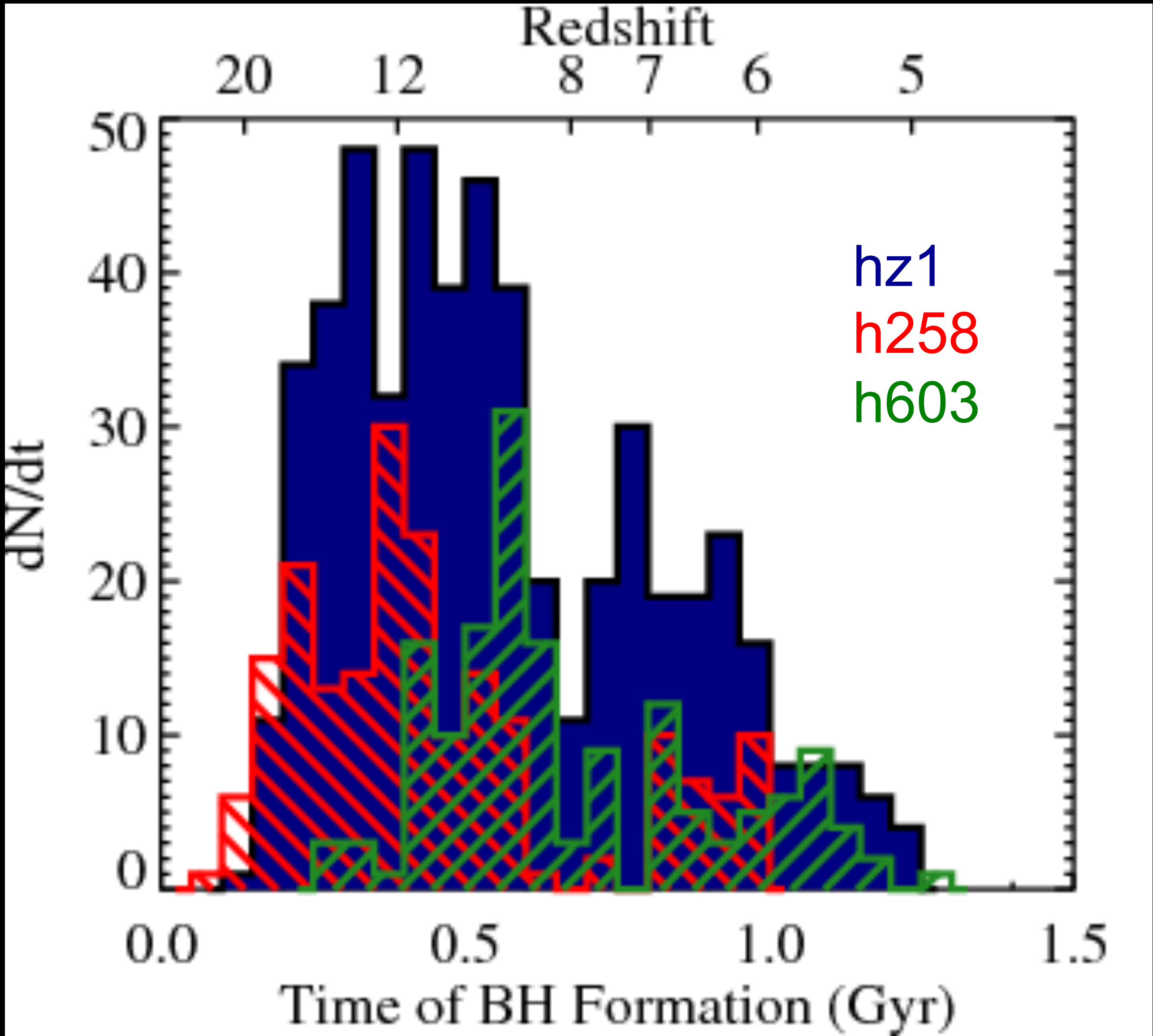


h603

At z = 5: M = 8×10^{9} $M_\odot$

at z = 0: Low-mass disk galaxy

MBH seeds form early



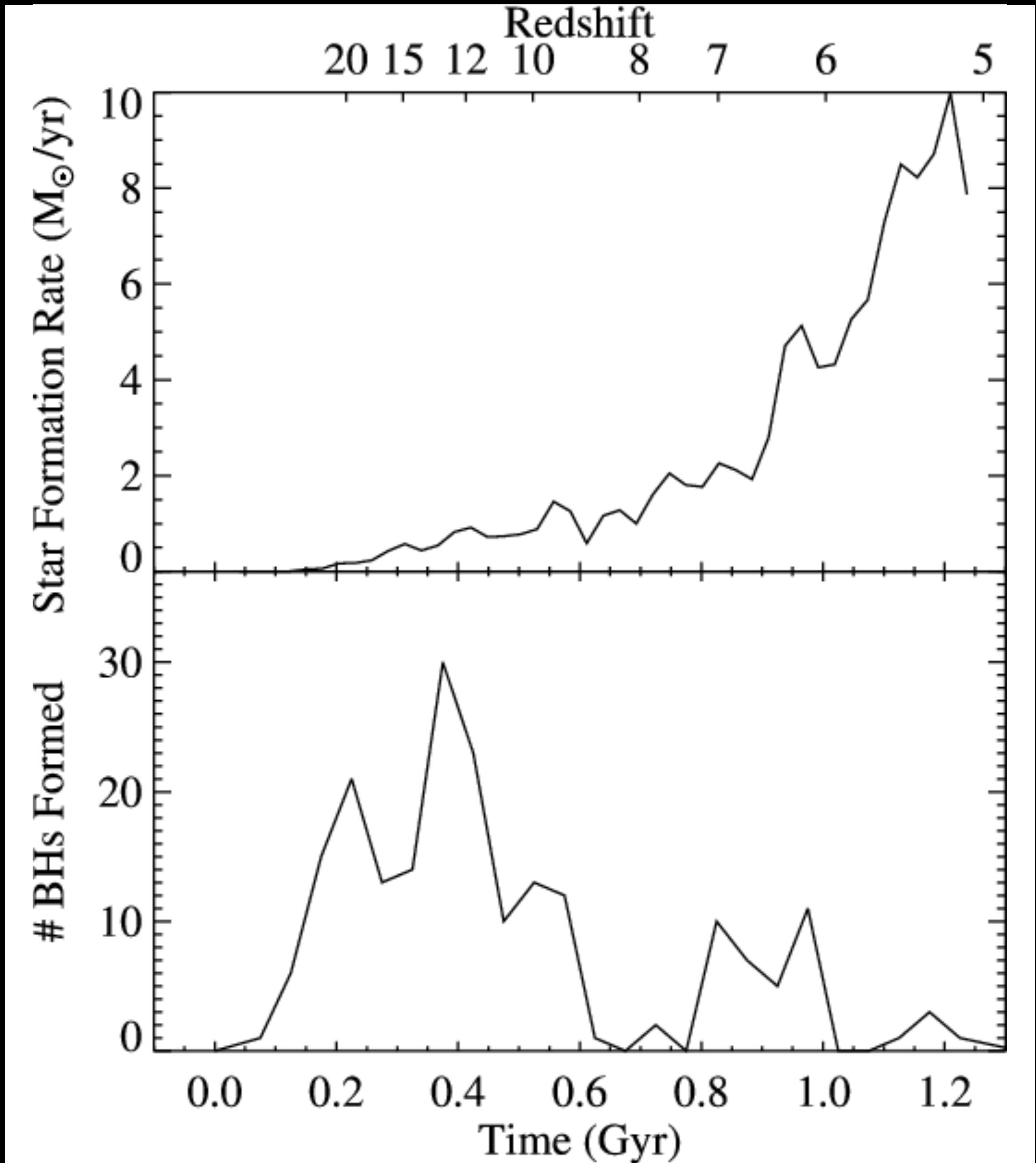
Black holes form earlier in more biased halos

Different efficiencies just change how many MBHs form

Efficiency = 0.1

Bellovary, MV et al. 2011

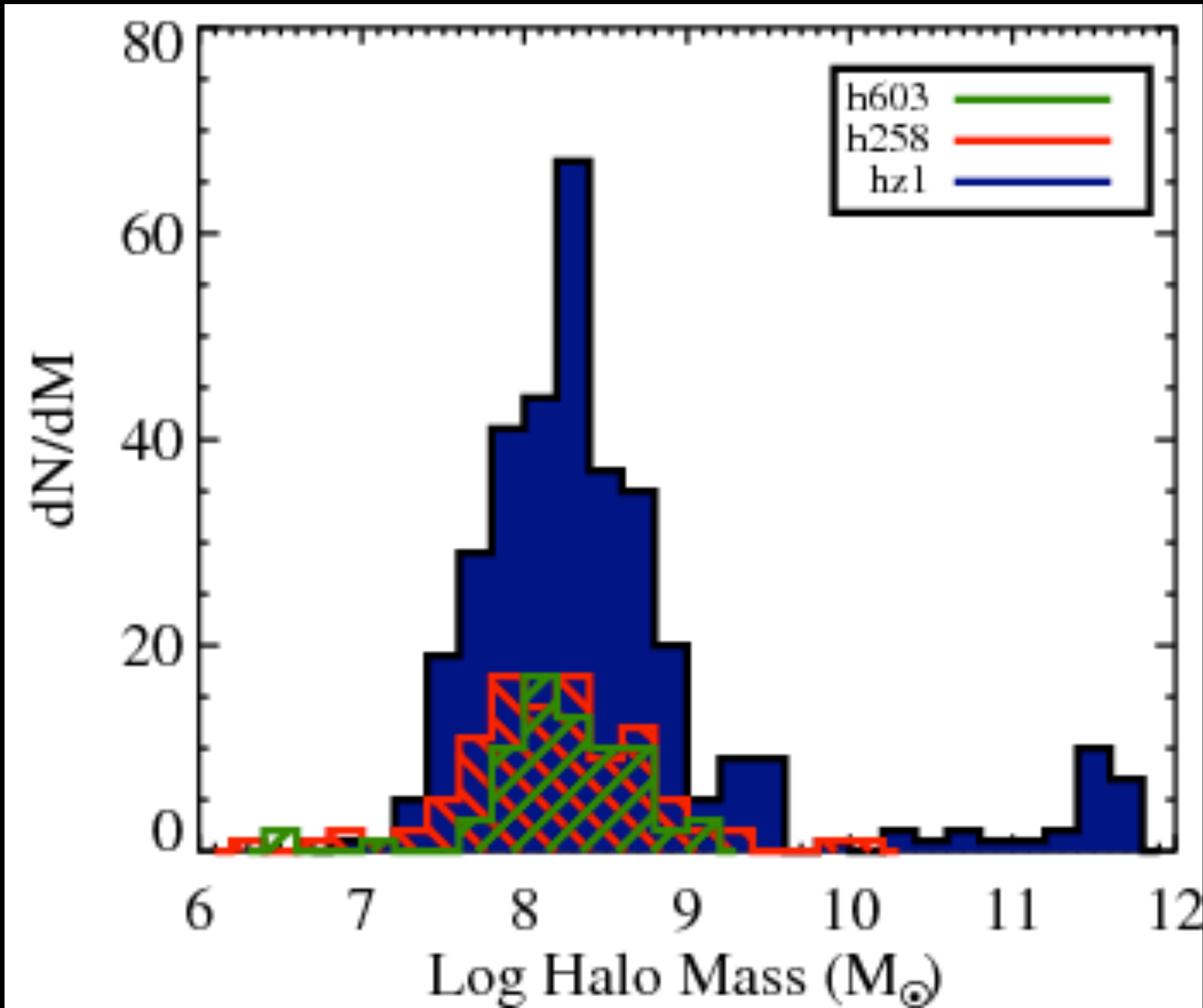
MBH seeds form early



MBH formation is truncated due to contamination by heavy elements, while stars continue forming

h258 eff = 0.1 z = 5

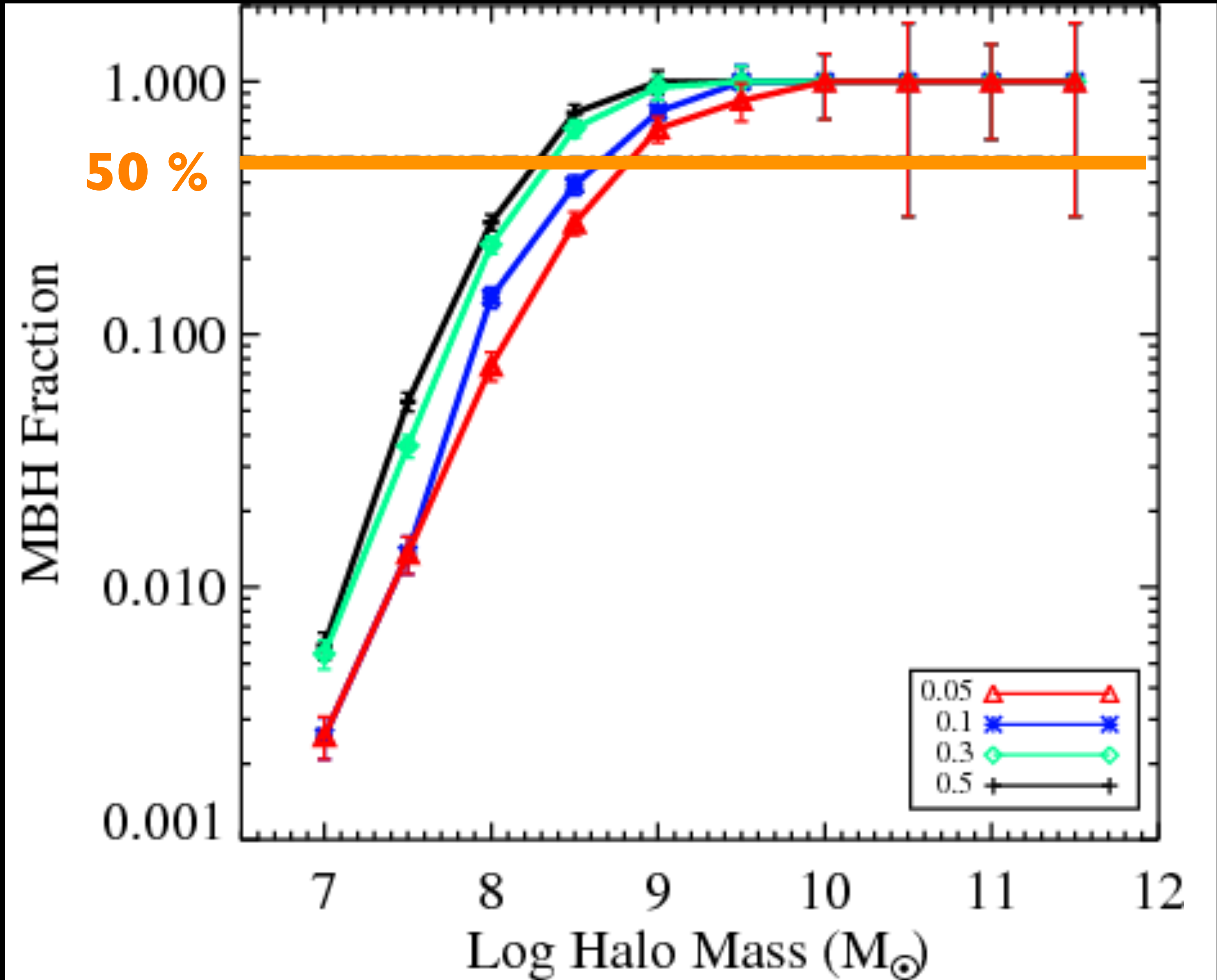
Halo Mass at time of MBH formation



Eff = 0.1

$M \sim 10^8$ Msun << than assumed in cosmological simulations (10^{10} Msun) => implications for AGN feedback on the first galaxies

What is the smallest halo hosting a MBH?



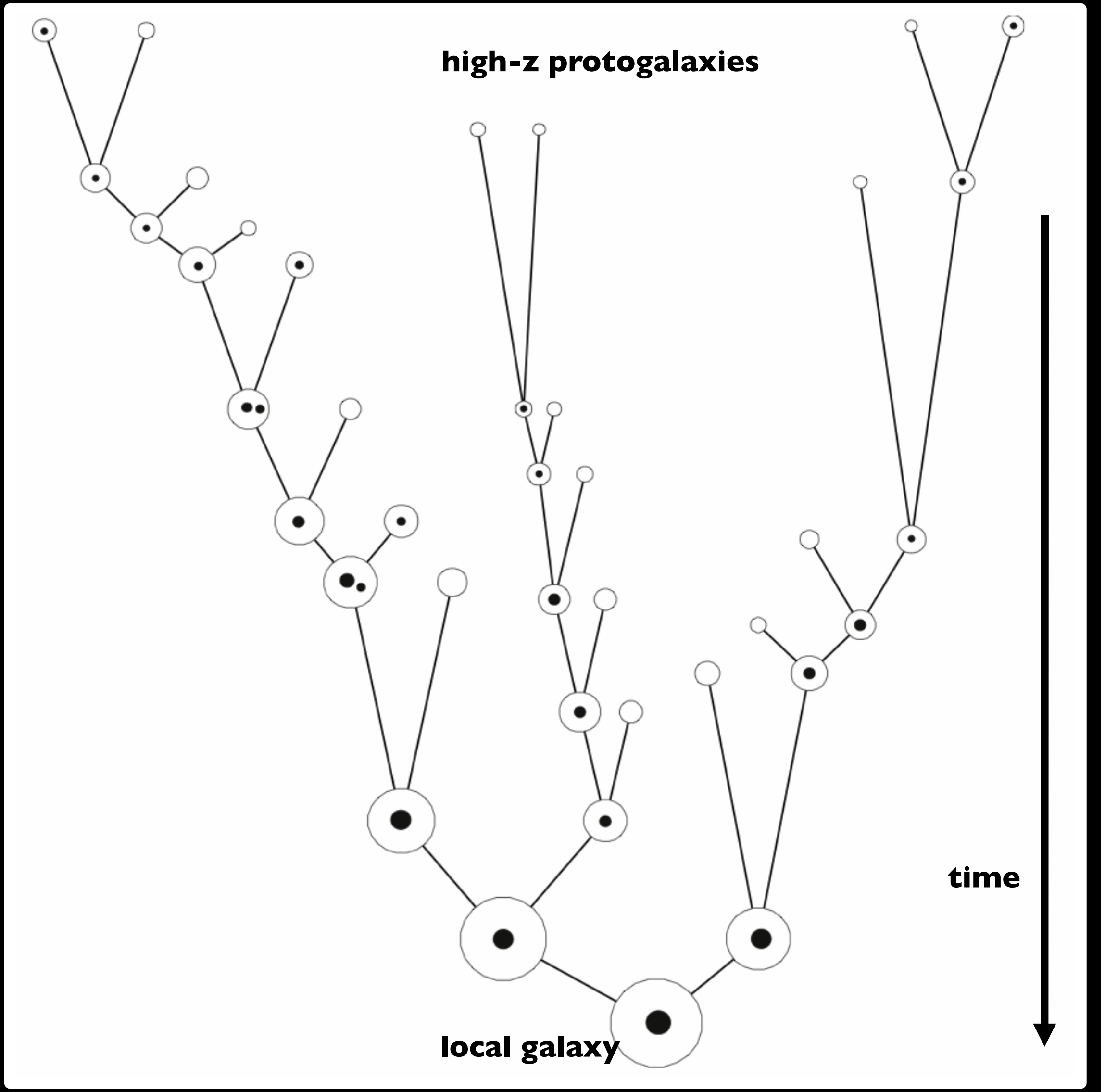
MBH fraction at the end of MBH formation epoch (z~5)

HOW

can we find signatures of

massive black hole ‘seeds’?

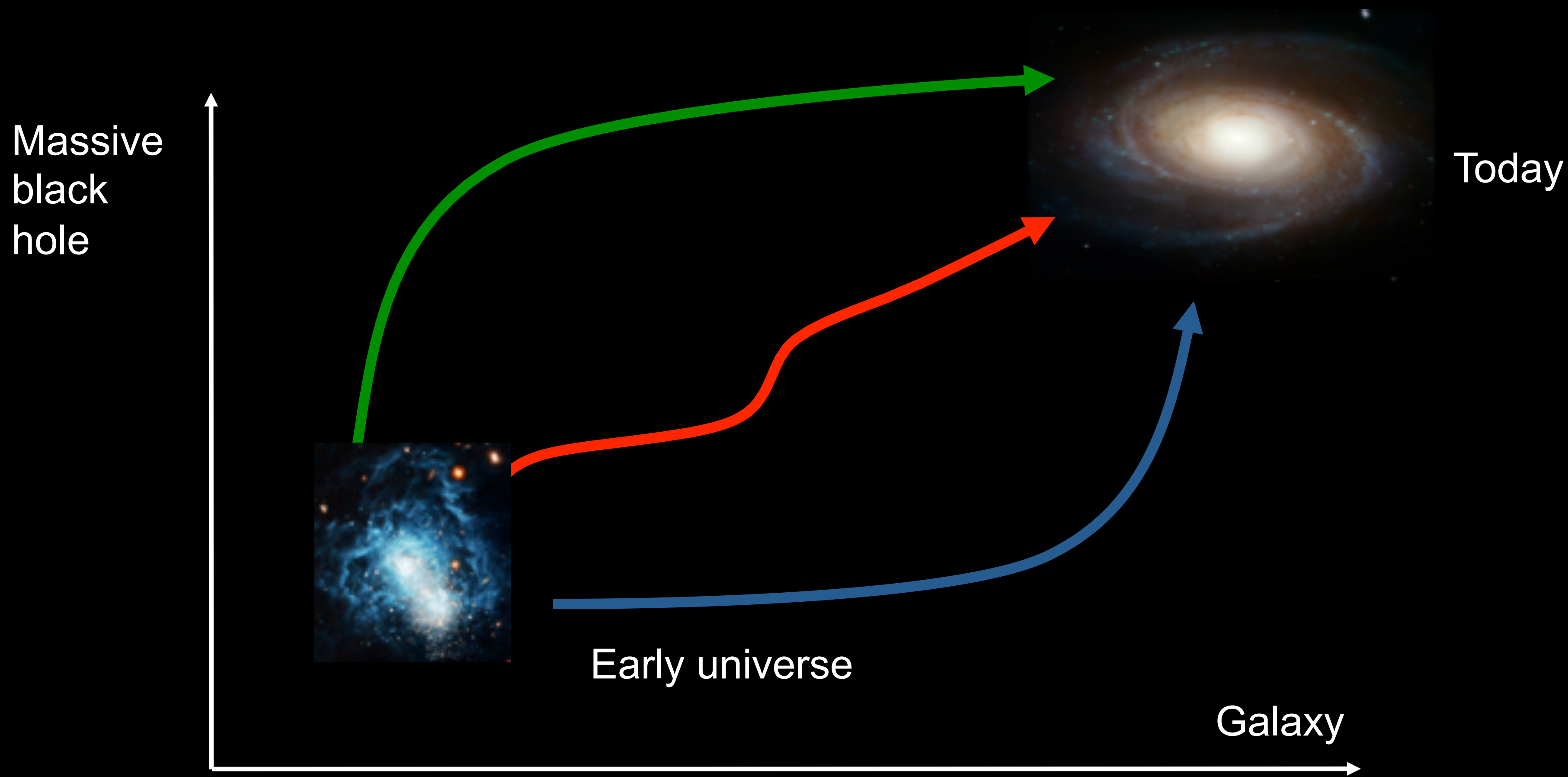
MBHS are grown from seed BHs at high-z. These seeds are incorporated into larger and larger halos, **accreting gas** and **dynamically interacting** after mergers.



MV, Haardt & Madau 2003

Since the "average" MBH grows by several orders of magnitude the initial conditions are washed out

"The night in which all cows are black" (Hegel)



Look for uncontaminated clues

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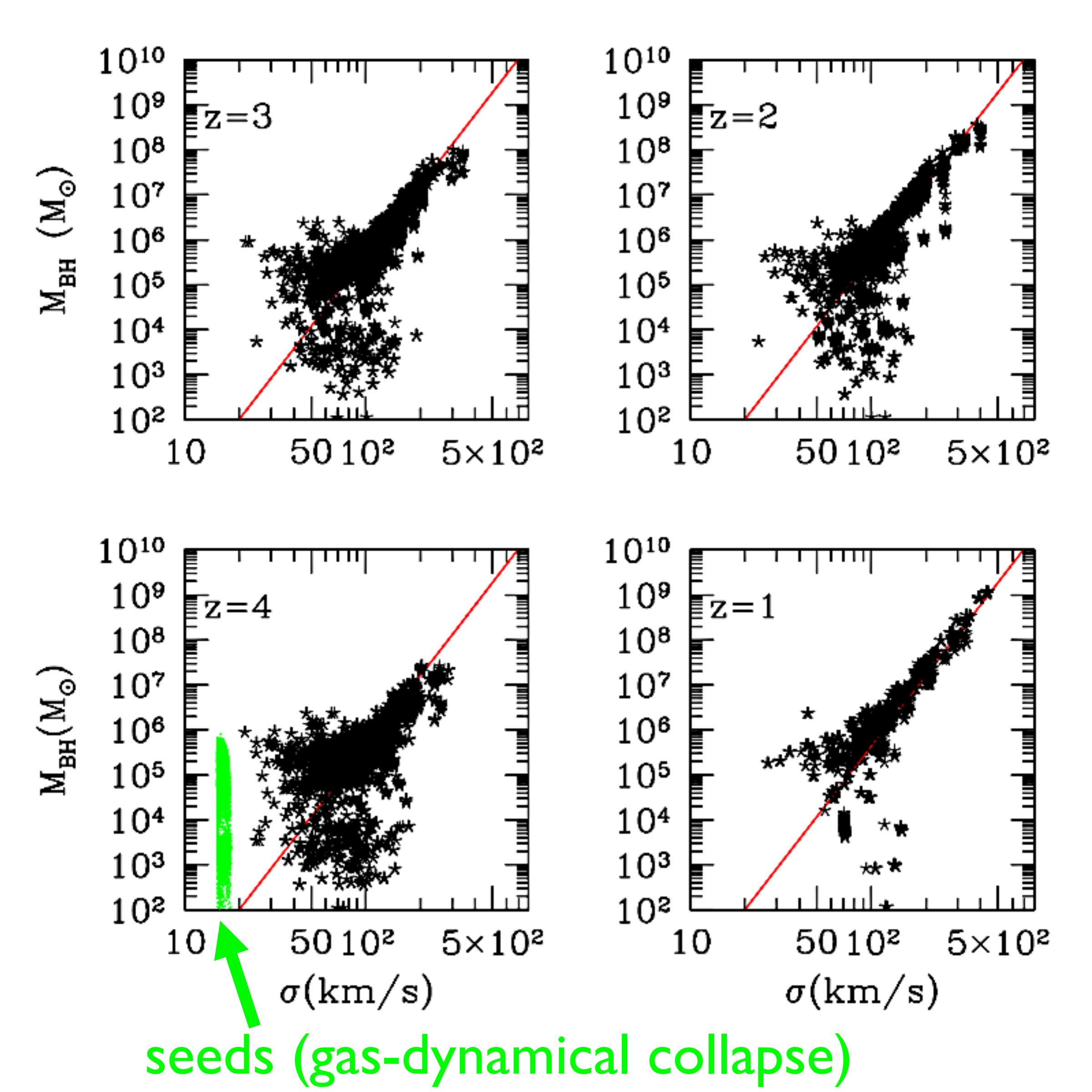
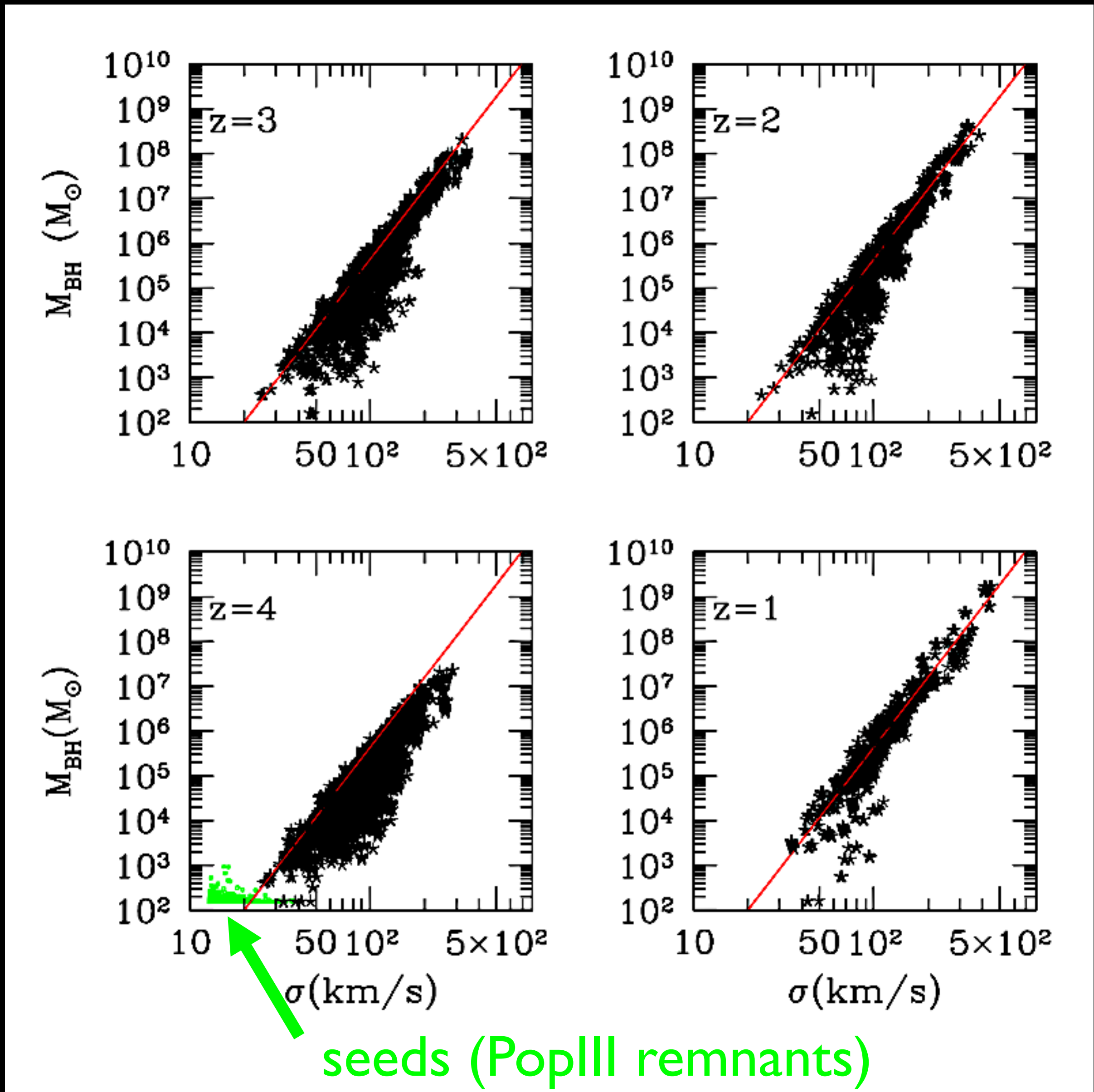
The MBH cosmic journey

(MV & Natarajan 2009)



Relationship between MBHs and their hosts establishes first in the most massive galaxies: high-bias => earliest growth

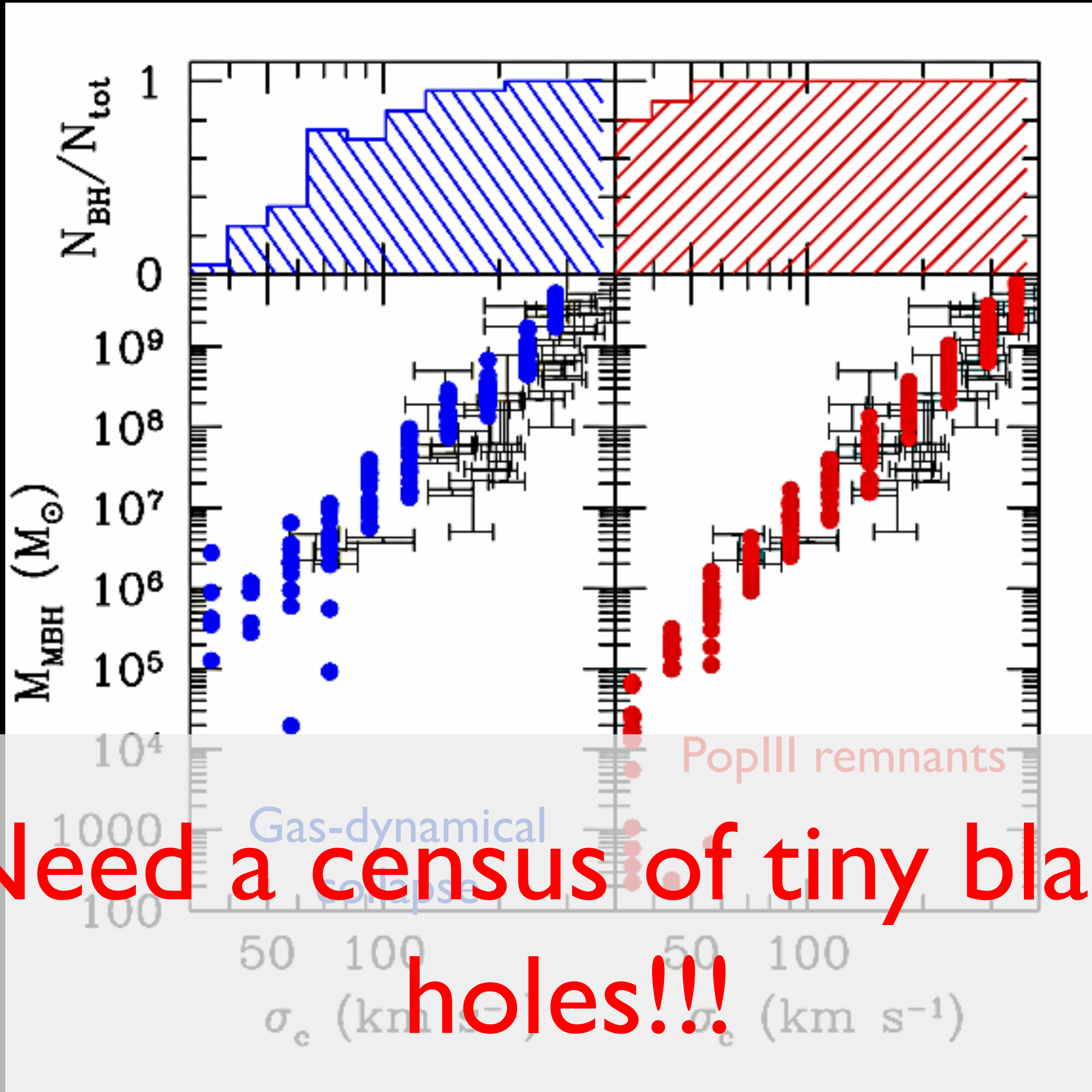
The MBH cosmic journey



MBHs hosted in low-mass galaxies provide the least contaminated clues

Occupation fraction and MBH- σ @ z=0

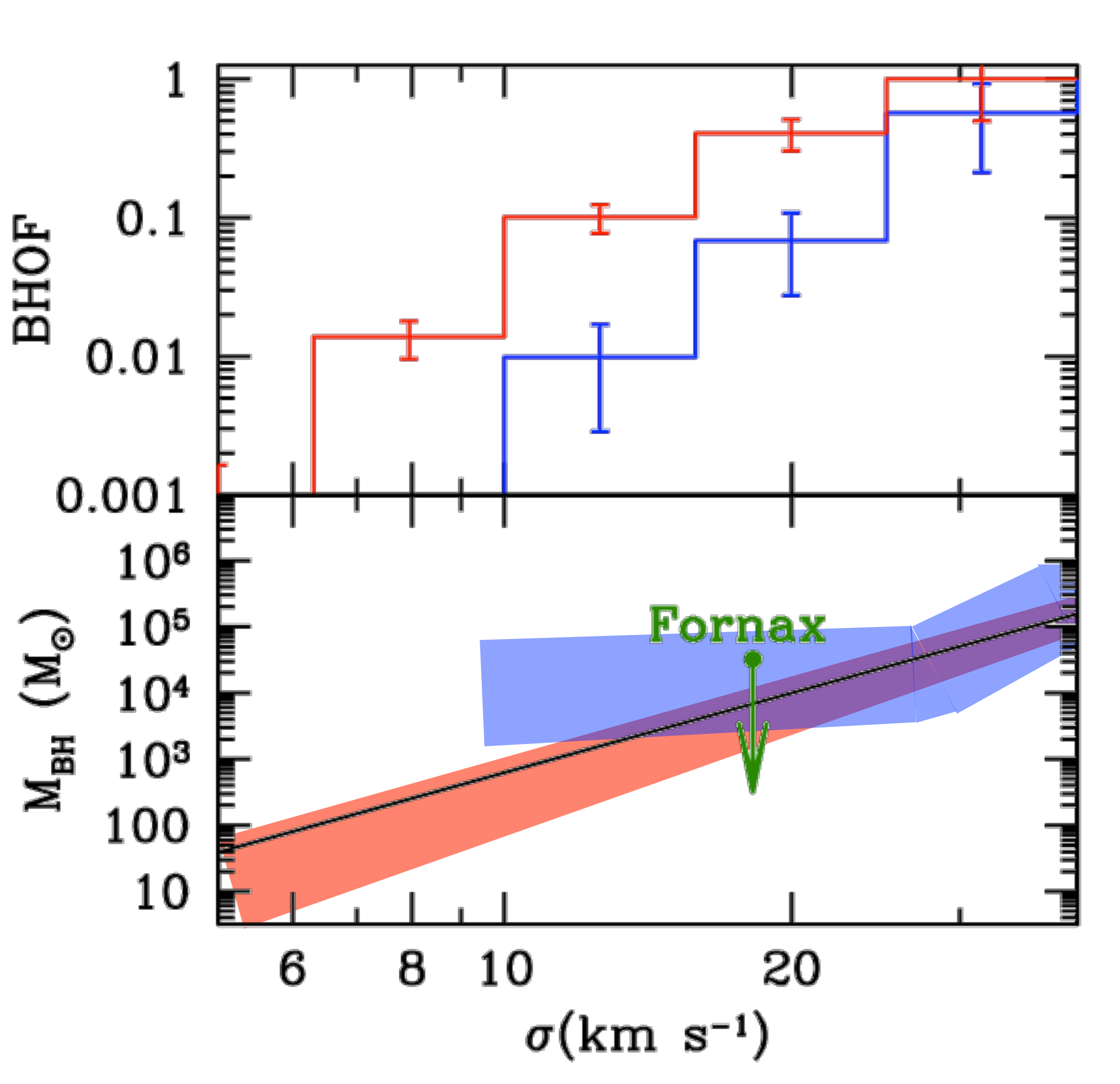
(MV, Lodato & Natarajan 2008)



Need a census of tiny black holes!!!

MBHs in Milky Way Satellites

(Van Wassenhove, MV et al. 2010)



Gas-dynamical collapse: less, more massive BHs & asymptotic behavior ~10^4-10^5 Msun

PopIII remnants: more, lower mass BHs &minimum mass ~100 Msun => steadier slope

Summary – forming MBHs

- Implement *physically motivated* MBH formation in cosmological simulation
- MBHs form abundantly at early times; star formation and metal pollution shut MBH formation at z~7
- The first MBHs form in ~10^8 Msun halos
- MBHs @ low masses tell the story