# Models of BH formation – how to make a middle weight black hole

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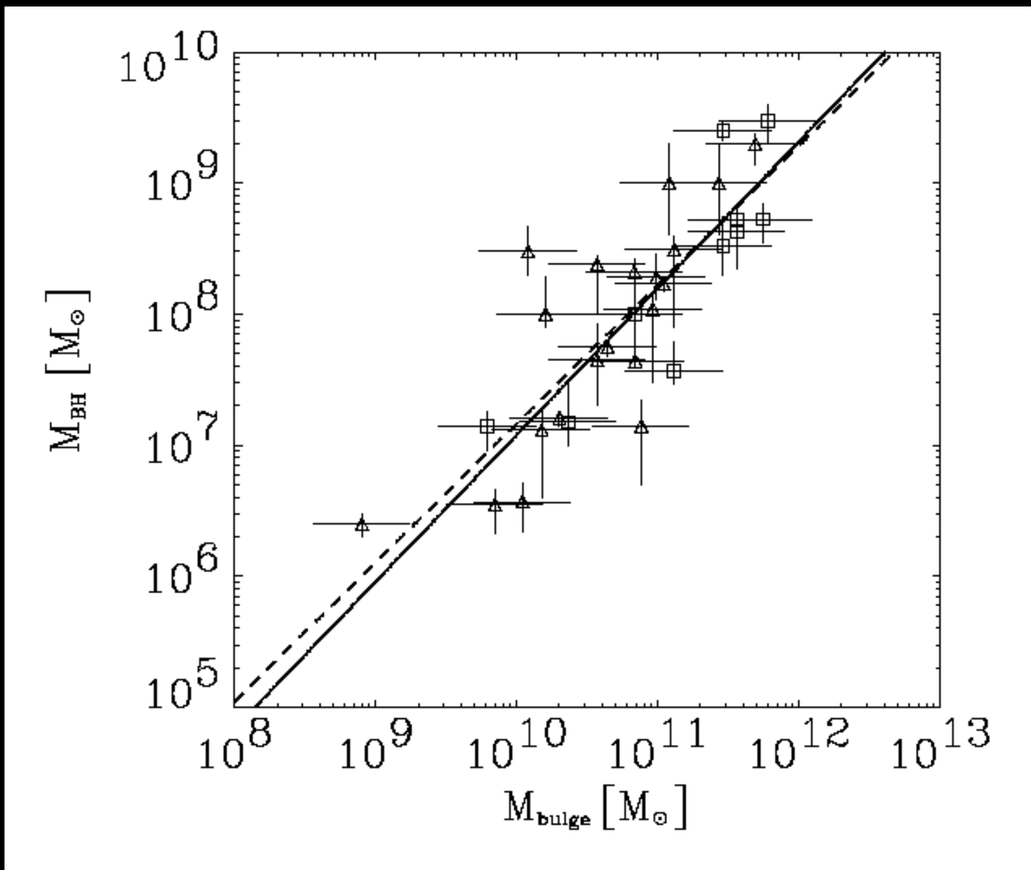
# Outline

- ✔MBHs in the local Universe: where from?

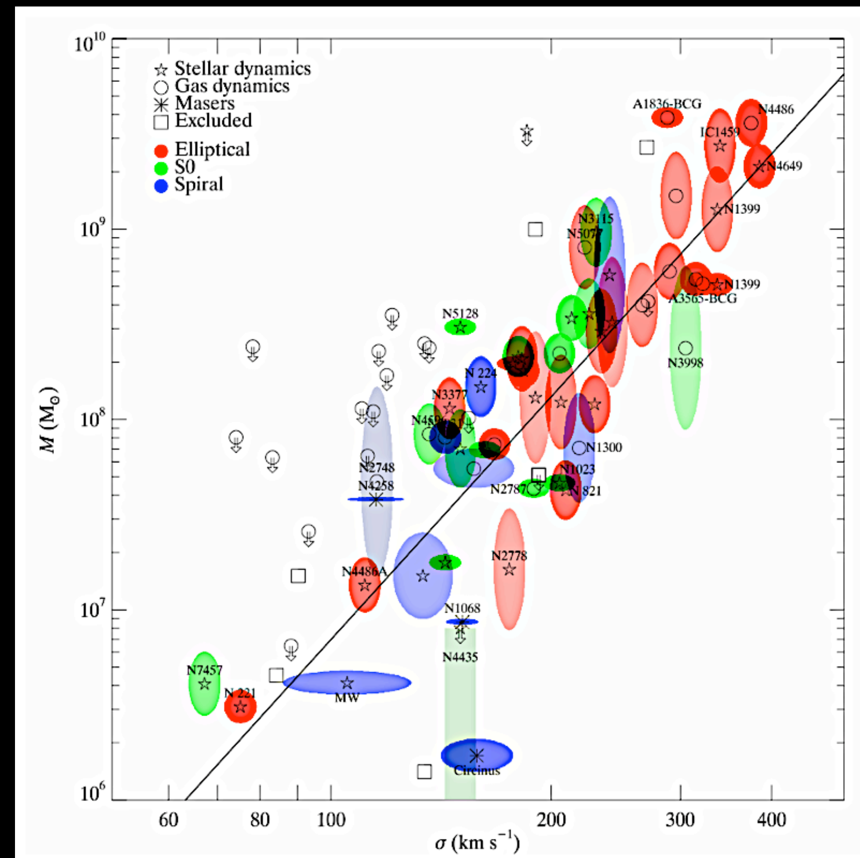
- ✔MBH formation

- ✔Looking for observational signatures

# $M_{BH}$- host relationships : co- evolution of SMBHs and galaxies




from Marconi & Hunt 2004




from Gultekin et al. 2009

SMBHs ⟷ stellar bulges ⟷ host DM halos (???)

# WHEN do you make a (super) massive black hole?

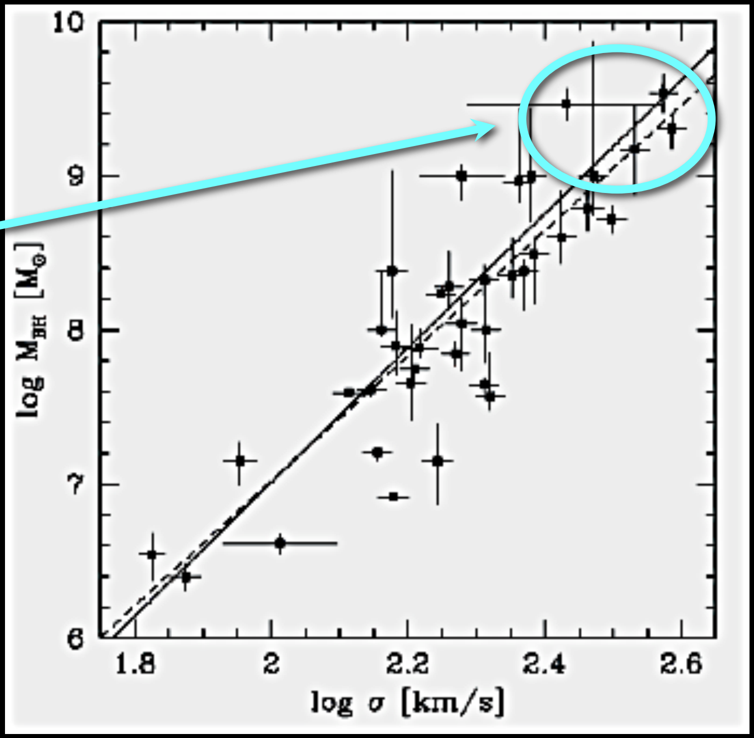
The highest redshift quasar currently known

SDSS 1148+3251 at $z=6.4$

has estimates of the SMBH mass

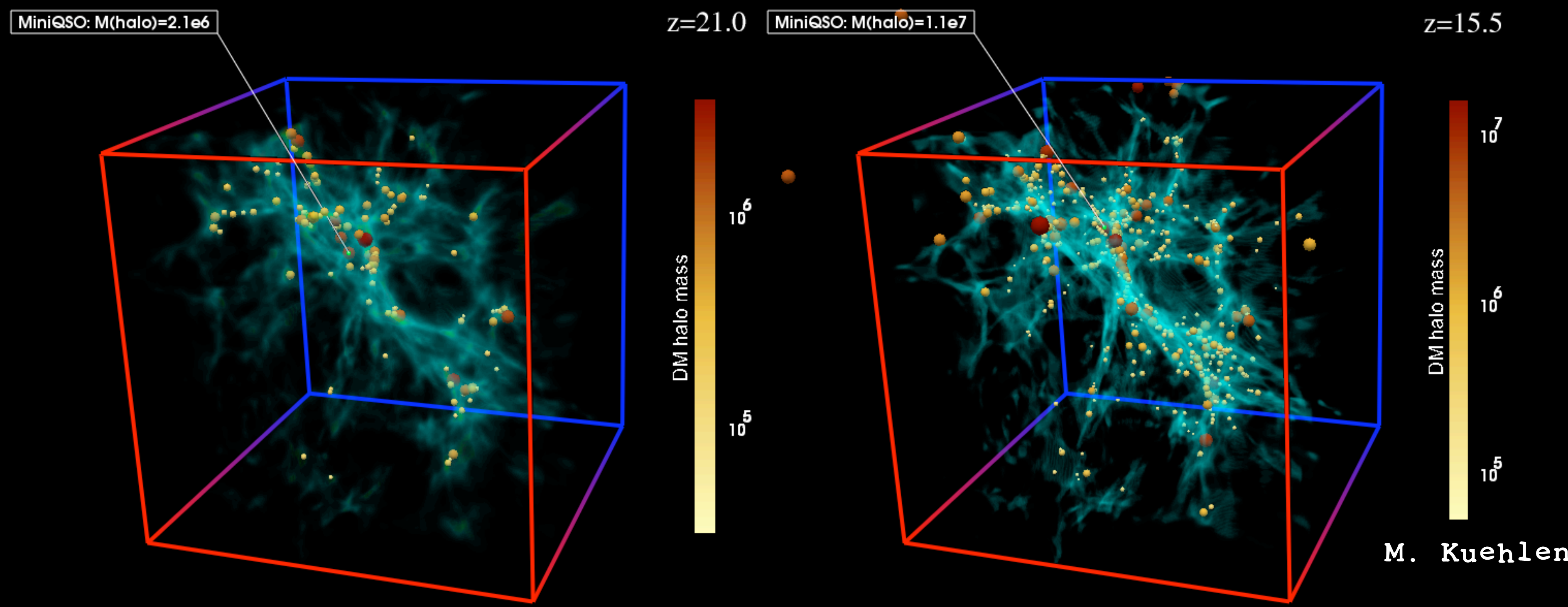
$M_{BH}=2\text{-}6 \times 10^9\ M_{sun}$ (Willott et al 2003, Barth et al 2003)

As massive as the largest SMBHs today, but when the Universe was 1 Gyr old!



# Hierarchical Galaxy Formation

small scales collapse first




BARYONS: need to COOL
only in the MOST MASSIVE HALOS, i.e.
the HIGHEST DENSITY
FLUCTUATIONS at z~20-30

# HOW can you make the first massive black holes?

$M_{BH}$~100 $M_{sun}$

## PopIII stars remnants

(Madau & Rees 2001, MV, Haardt & Madau 2003)

✔Simulations suggest that the first stars are massive M~100-600 $M_{sun}$

(e.g., Abel et al. Bromm et al.)

✔Metal free dying stars with $M>260M_{sun}$ leave remnant BHs with $M_{seed}\gtrsim 100M_{sun}$ (Fryer, Woosley & Heger)

$M_{BH}$ ~$10^3$-$10^5$ $M_{sun}$

## Gas-dynamical processes

(e.g. Haehnelt & Rees 1993, Eisenstein & Loeb 1995, Bromm & Loeb 2003, Koushiappas et al. 2004, Begelman, MV & Rees 2006, Lodato & Natarajan 2006)

## Stellar dynamical processes

(Devecchi & MV 2009, Omukai et al. 2009)

# Gas-dynamical processes

## ANGULAR MOMENTUM TRANSPORT

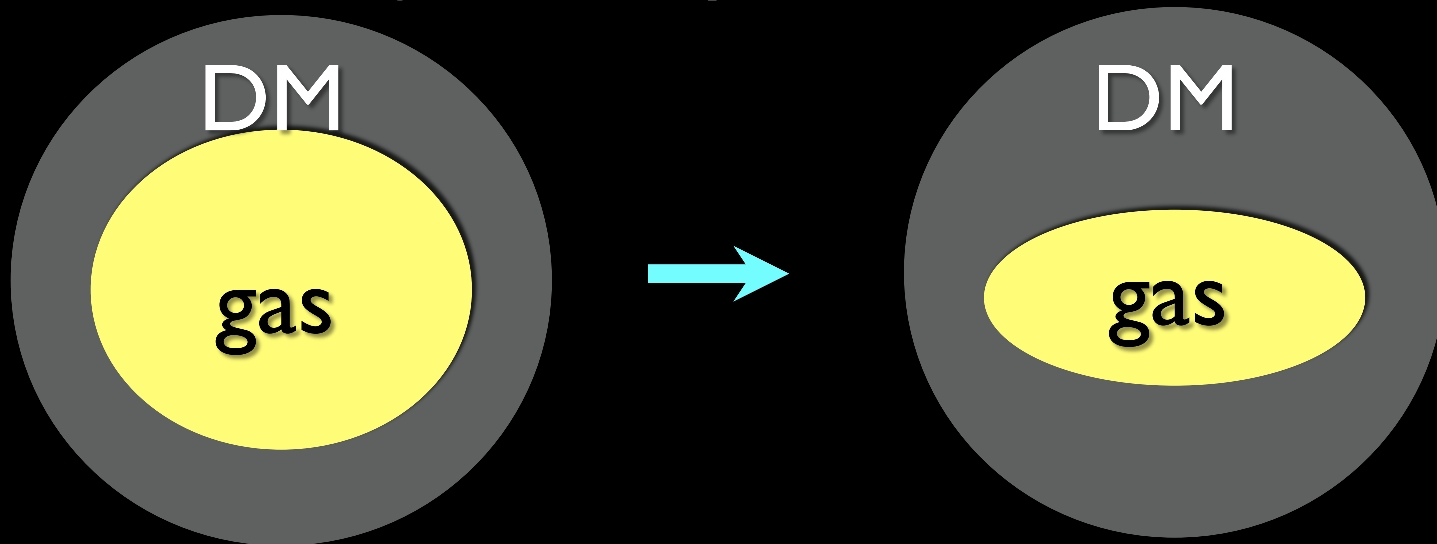
Collapsing gas clouds become rotationally supported at $10^{6\text{-}8}$ Schwarzschild radii.

## STAR FORMATION

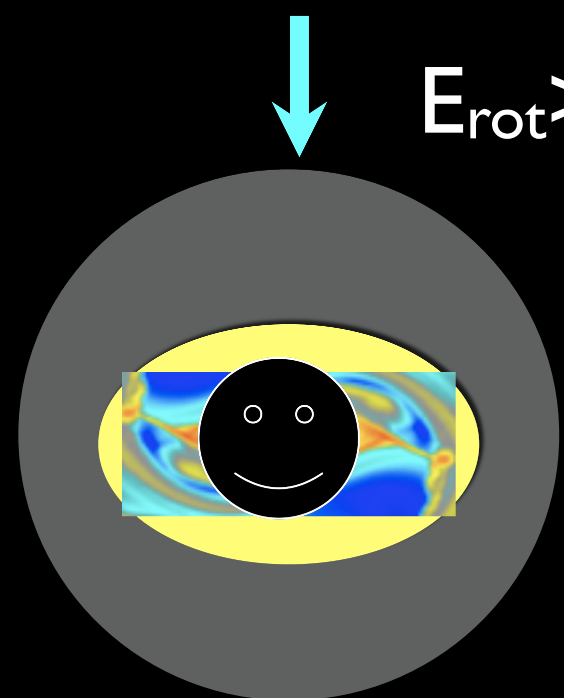
- ✔ competition in gas consumption
- ✔ collisionless stars do not dissipate angular momentum efficiently
- ✔ SNe can blow away the gas reservoir

NO H2/ZERO METALLICITY/TURBULENCE HELP AVOID FRAGMENTATION

# gas collapses if $T_{gas} < T_{vir}$

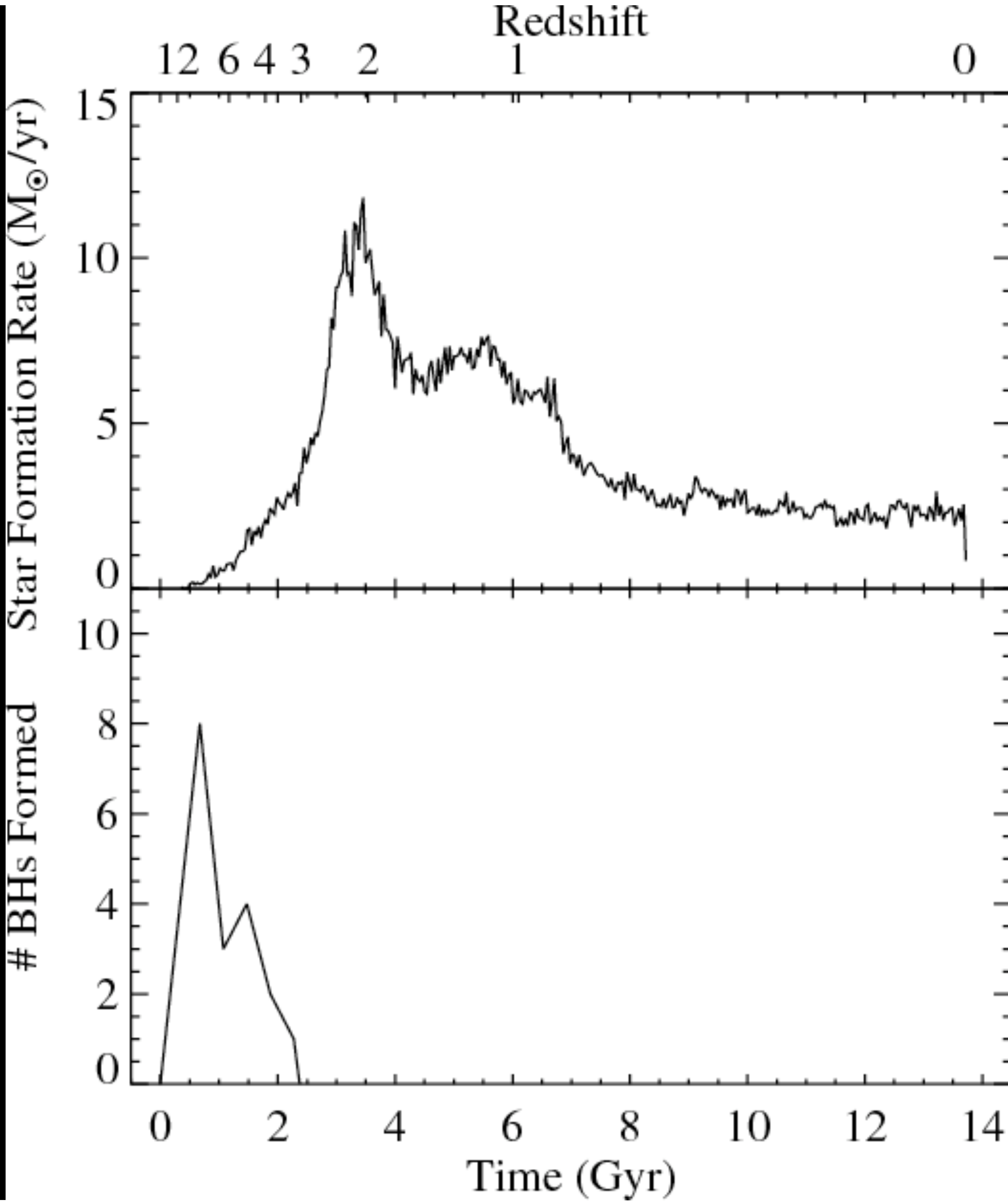



$E_{rot} > 0.25 E_{pot}$



The central regions fulfill the conditions for MBH formation: quasistars?

Begelman, MV & Rees 2006




Seeds are allowed to form if:
- zero metallicity
- n> 1 $cm^{-3}$

Truncation of seed BH formation at a redshift ~3.5 due to metal enrichment

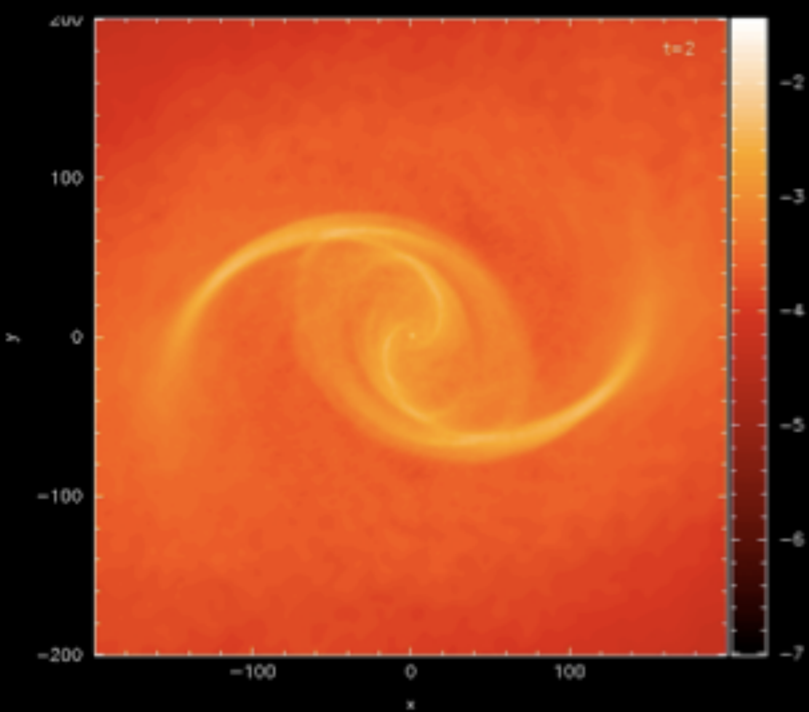
Bellovary et al. 2010

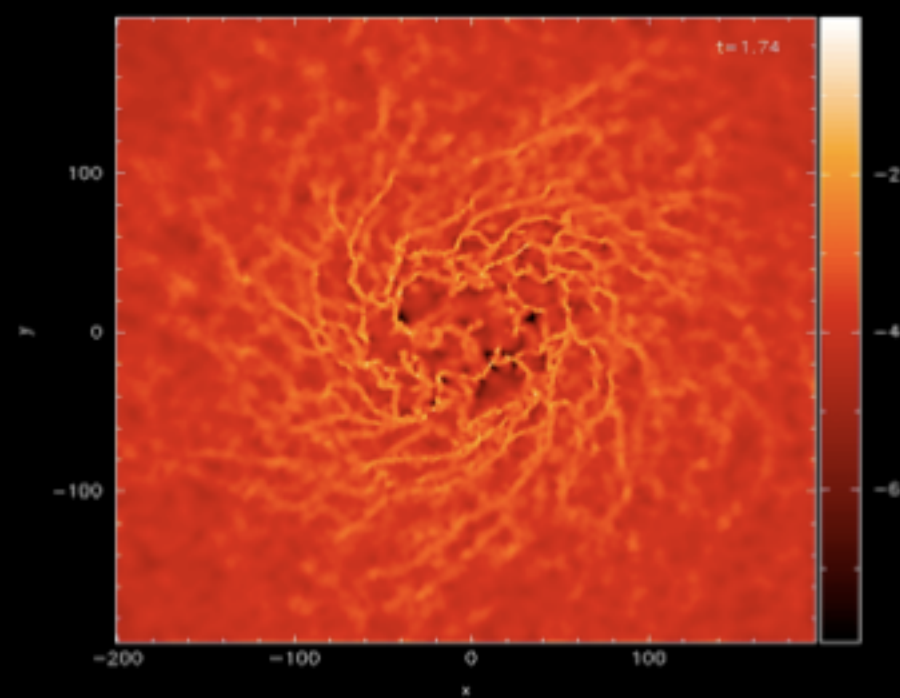
# Stellar-dynamical processes

Devecchi & MV 2008

Instabilities can lead to mass infall instead of fragmentation and global star formation

Inflow versus fragmentation



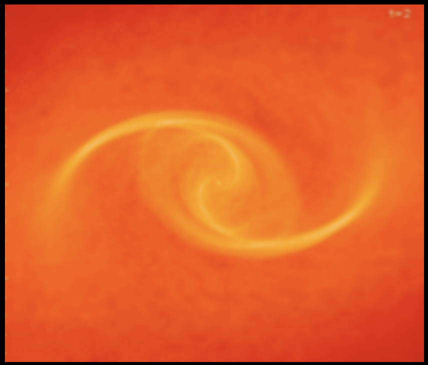
✔ Accumulation of infalling gas until outer disc ($R>R_{tr}$) is stable: Q=Qcrit in the outer disc

✔ Density increases in the very inner region

$$\Sigma(R) \sim \begin{cases} \Sigma_{in}\left(\frac{R}{R_0}\right)^{-5/3}\left(\frac{t}{t_0}\right)^{2/3} & R < R_{tr} \\ \Sigma_0\left(\frac{R}{R_0}\right)^{-1} & R > R_{tr} \end{cases}$$

✔ VERY LOW, but NON-ZERO METALLICITY: inefficient fragmentation unless very high density: $n > n_{crit,Z}$ (Santoro & Shull 2006)

$$R_{SF} = R_{tr}\left[\frac{\Sigma_0}{c_s}\frac{R_0}{R_{tr}}\sqrt{\frac{\pi G}{2\mu m_u n_{crit,Z}}}\right]^{1/\gamma}$$



✔ gas inflow increases central density, and within an inner, compact, region where $n > n_{crit,Z}$, stars can form ⇒ VERY DENSE CLUSTER

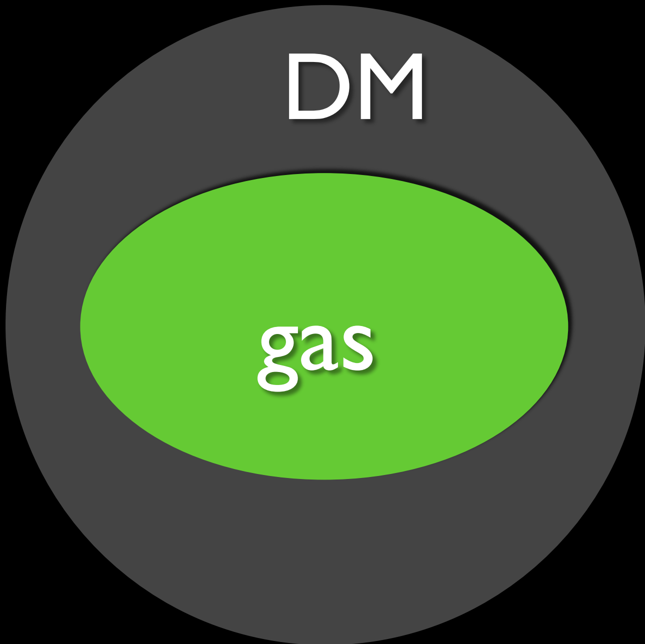
✔ mass segregation: massive stars sink to the center

✔ stellar collisions form a very massive star if $t_{merge} << t_{MS}$ : to avoid mass loss in SNae

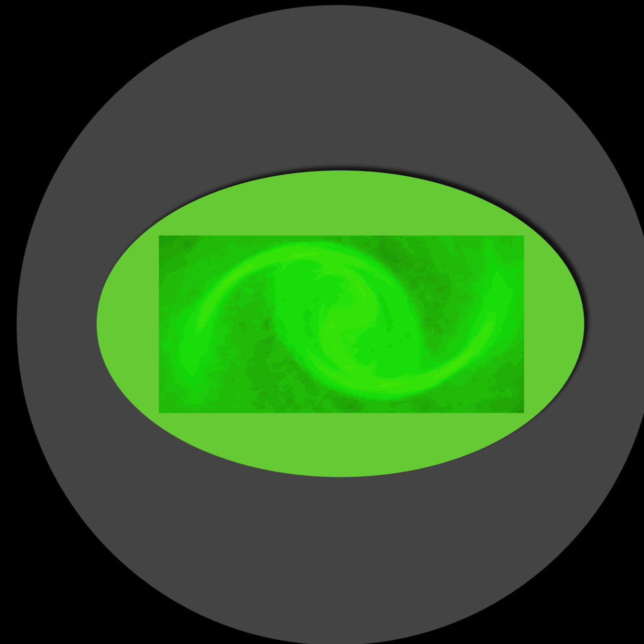
✔ at large metallicity stellar winds cause mass-loss. The supermassive star collapses into a low-mass BH

✔ at low metallicity mass loss is negligible: MBH seed!

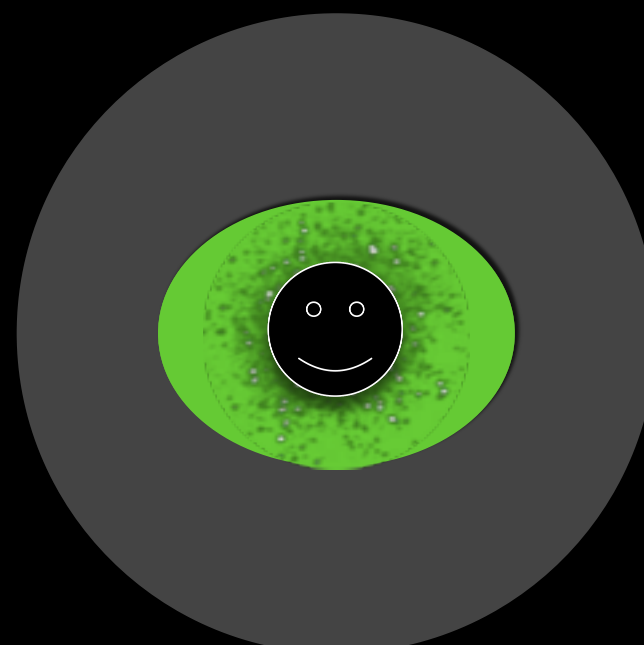
- ✔ metallicity increases with cosmic time
- ✔ critical density for SF decreases
- ✔ as time goes on clusters form more massive and less concentrated!
- ✔ mass segregation and core collapse are slower
- ✔ stellar collisions unable to build up a very massive star before SNae explode




Mildly unstable



very low Z



Fragmentation
if $n > n_{crit}$ :
inner region only

dense star cluster formation

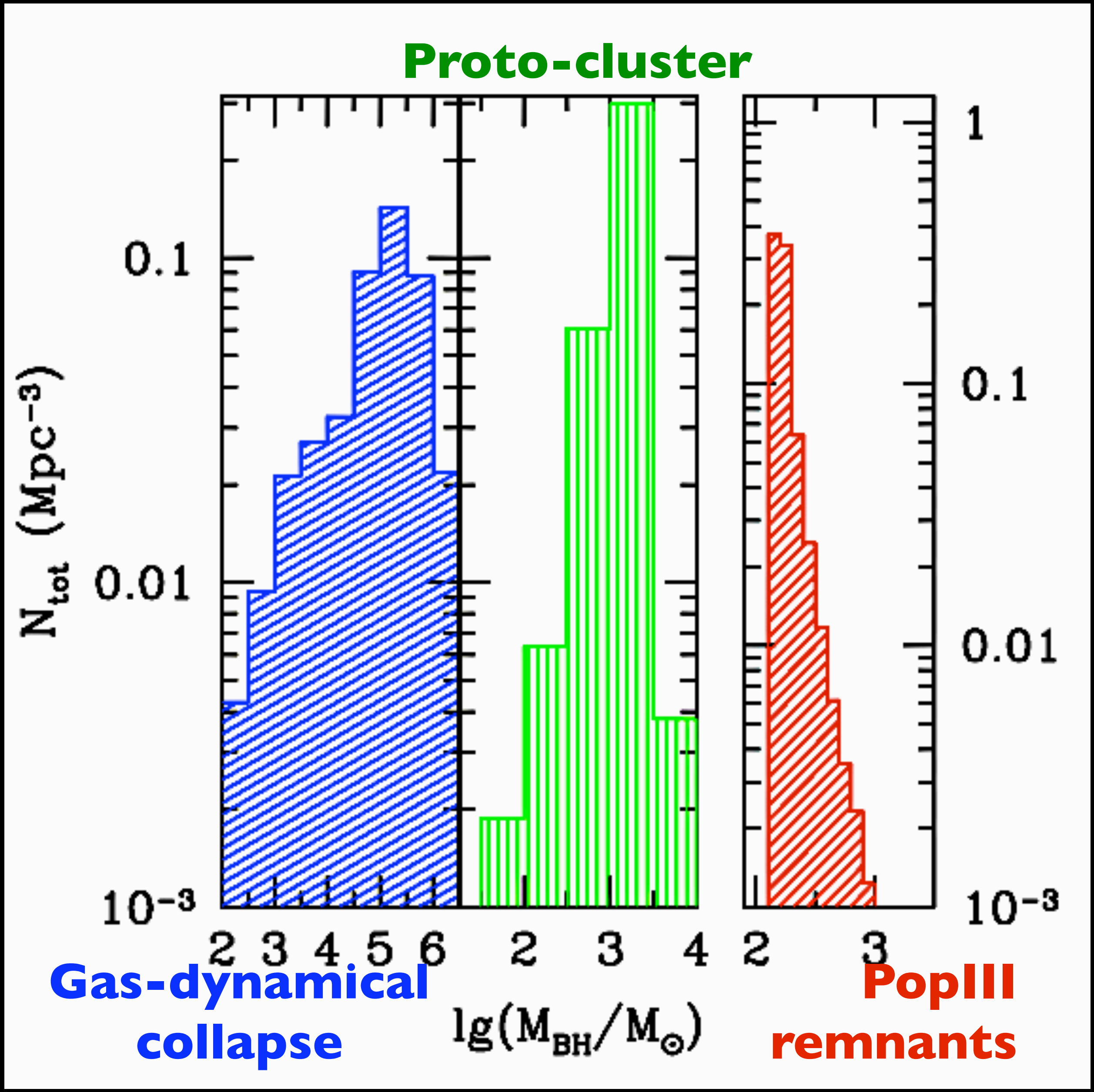
Collisions

Runaway growth

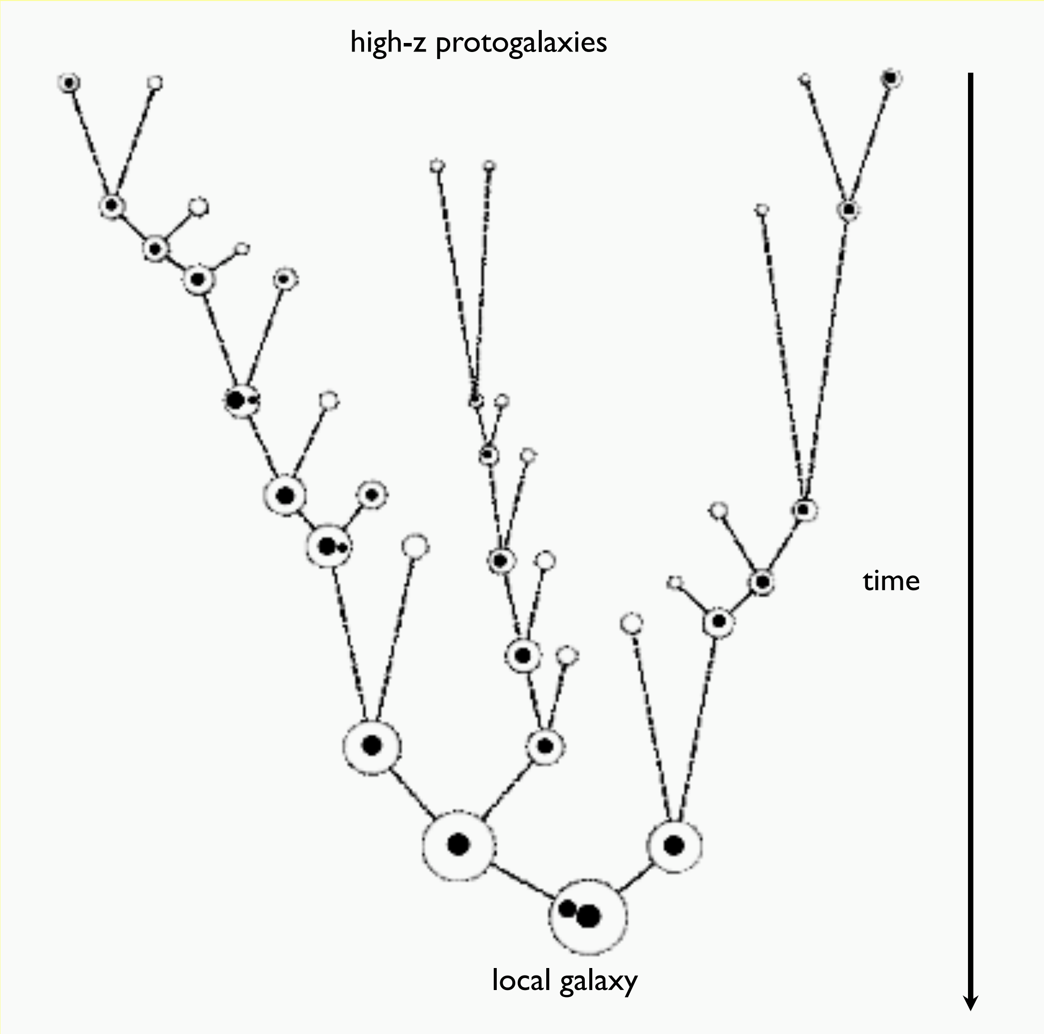
BH

# Mass function of seed MBHs

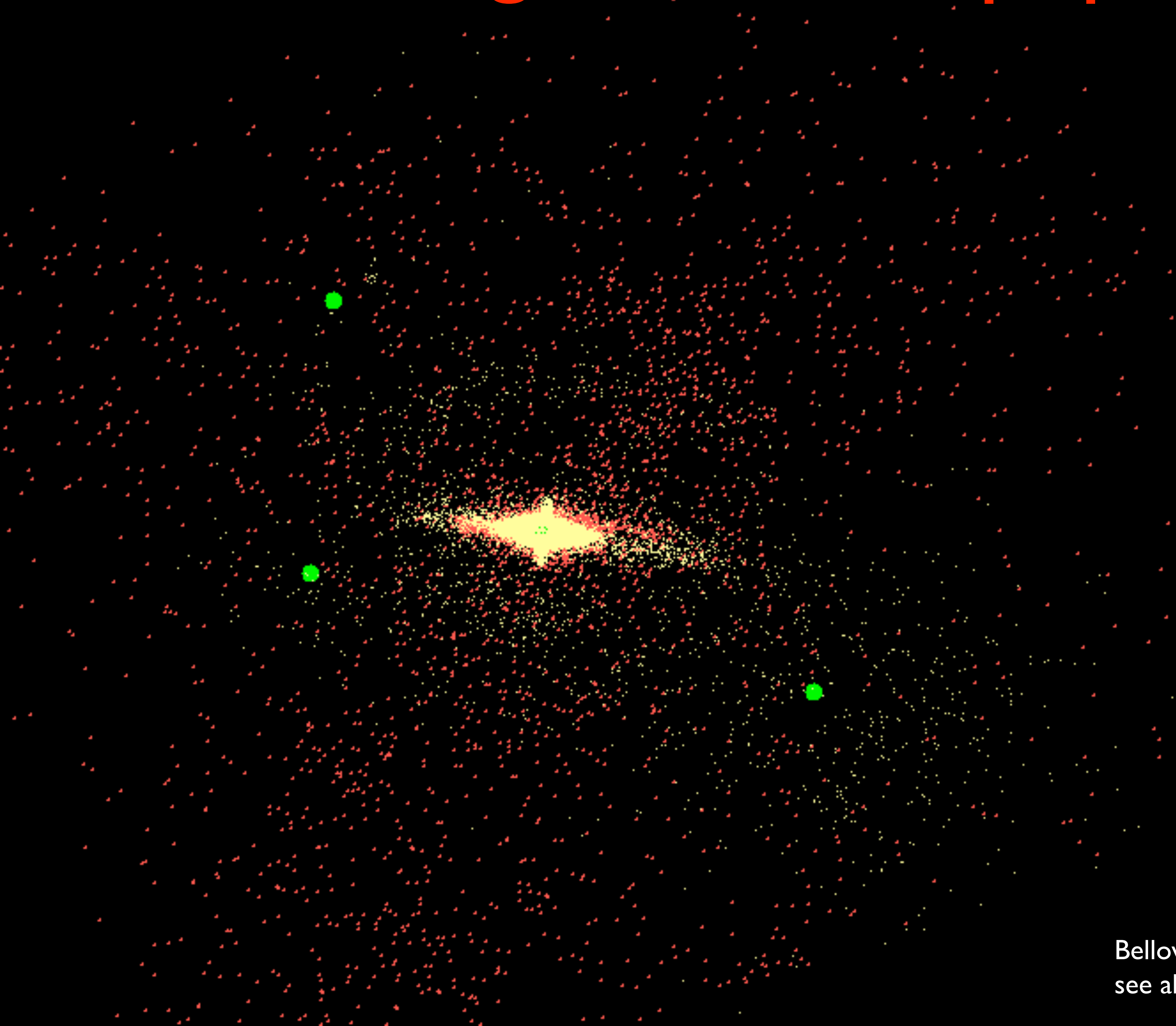
(MV, Lodato & Natarajan 2008;
Devecchi & MV 2009)



SMBHS are grown from seed pregalactic BHs. These seeds are incorporated in larger and larger halos, accreting gas and dynamically interacting after mergers.




# Wandering black hole populations...

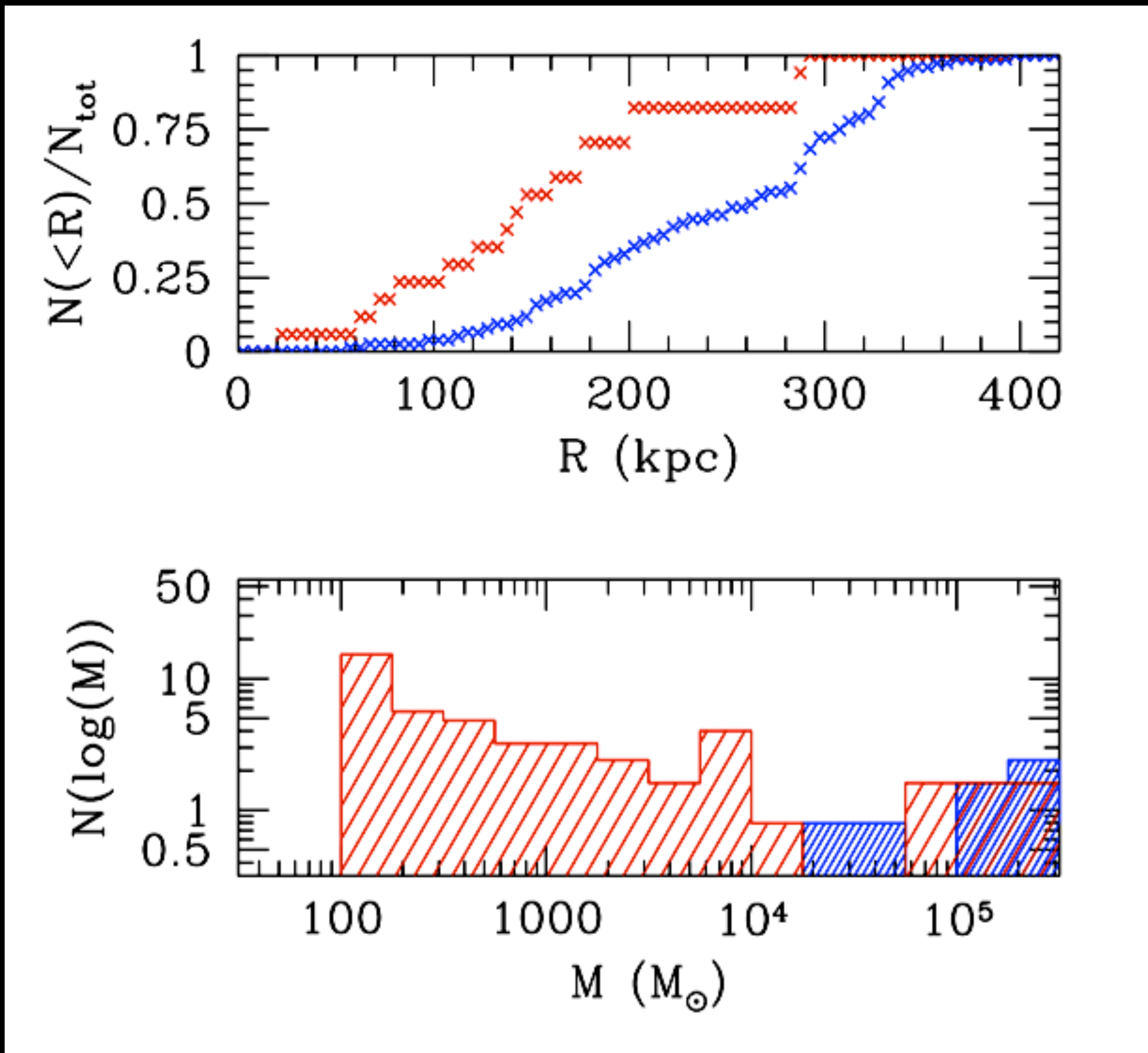


1. Ungrown seeds, accreted during the galaxy's hierarchical evolution

Bellovary et al. 2010,
see also Mapelli et al. 2006, 2007, 2008,

# MBHs in Milky Way

(Van Wassenhove,MV in prep)




Gas-dynamical collapse

PopIII remnants

* IF BH HOST COMPLETELY STRIPPED

- accretion when passage within the region of the disk
- $$\dot{M}_{BH} = \frac{4\pi G^2 M_{BH}^2 \rho}{\left(c_s^2 + v_{rel}^2\right)^{3/2}}$$
- fraction of time that a galaxy will harbor a ULX due to a wandering black hole: 0.2% --$10^{-2}$%

⇒between one in 500 and one in 15,000 MW-like galaxies will exhibit one such object

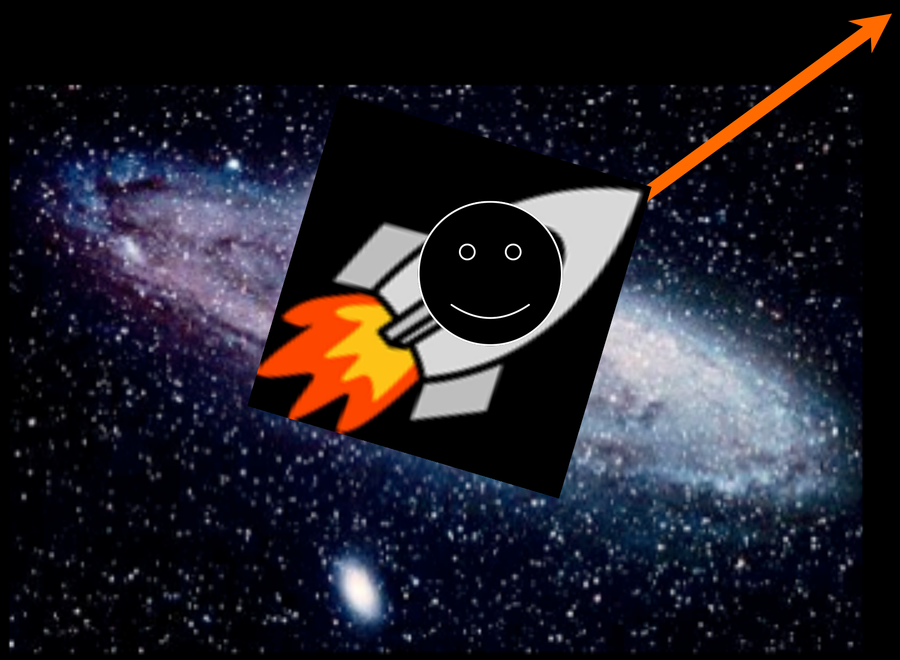
* IF BH HOST RETAINED ITS CORE

- BHs would not be active unless gas perturbed in some way (e.g., passage near center if on eccentric orbit)

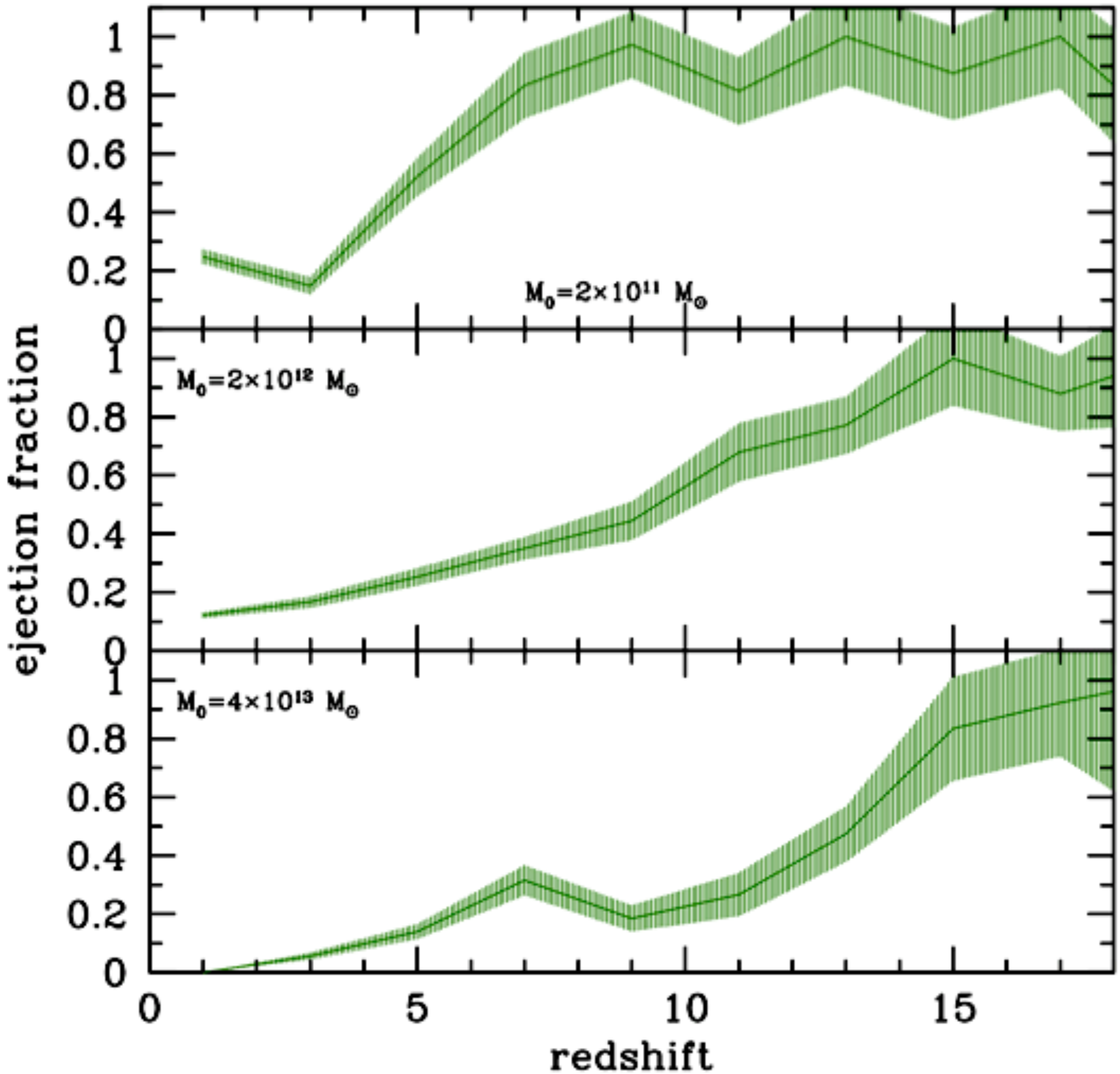
Bellovary et al. 2010,
see also Mapelli et al. 2006, 2007, 2008,

# Gravitational rocket

binary center of mass recoil during coalescence due to asymmetric emission of gravitational waves



2. massive black holes ejected from galaxies at merger

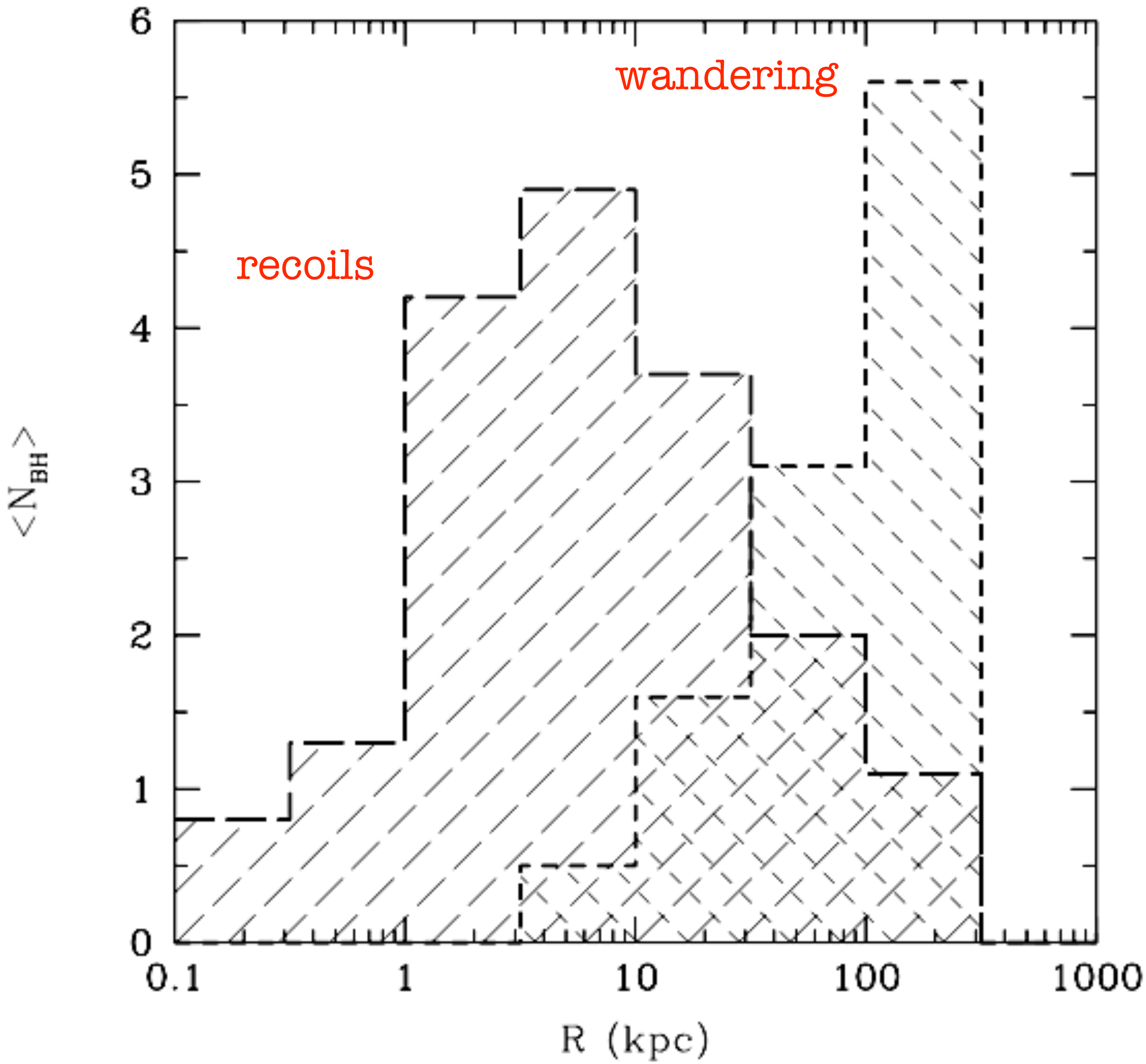



Dwarf-size galaxy

Milky Way-size galaxy

Elliptical-size galaxy

MV, Gultekin & Dotti 2010




MV & Perna 2005

# Summary

SMBHs can be built up from seeds dating back to the end of the cosmological dark ages

✔seed MBHs in proto-galaxies

✔MBHs evolve through mergers and accretion

✔recoils can displace/eject BHs

✔leftover population in today's galaxies