# Pathways to massive black holes seed formation

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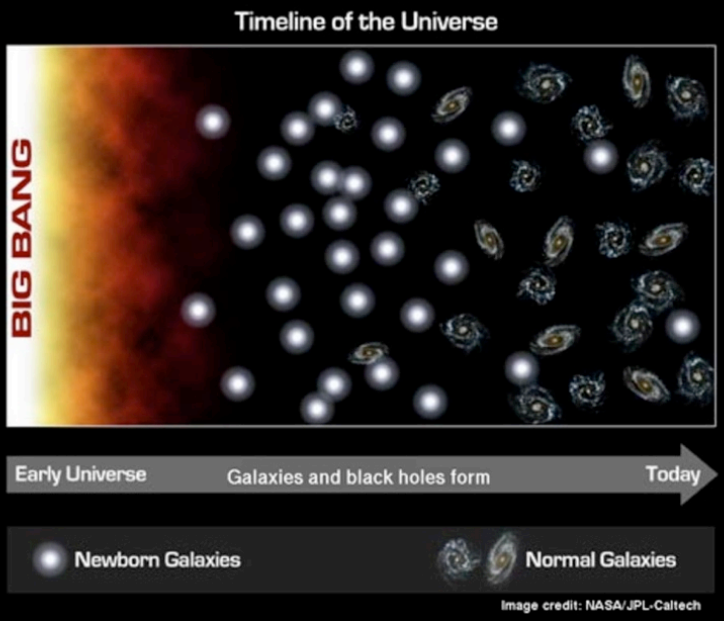
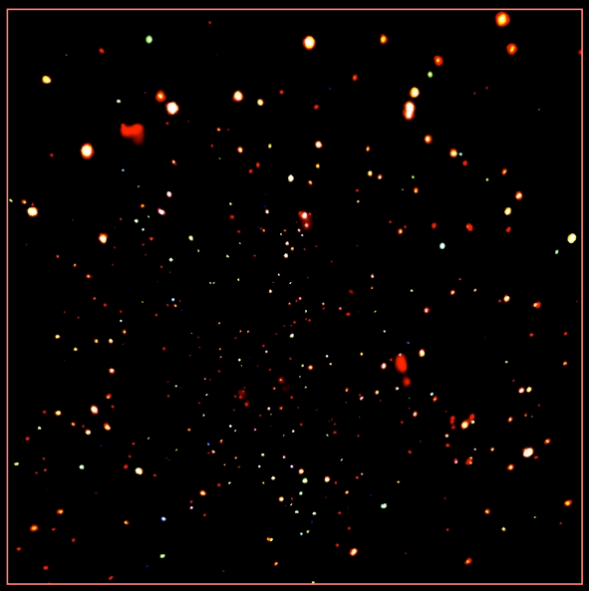



## Shiny black holes out there....

Hubble Deep Field

all galaxies



Chandra Deep Field

active galaxies

black holes

# Outline

✔MBHs in the local Universe: where from?

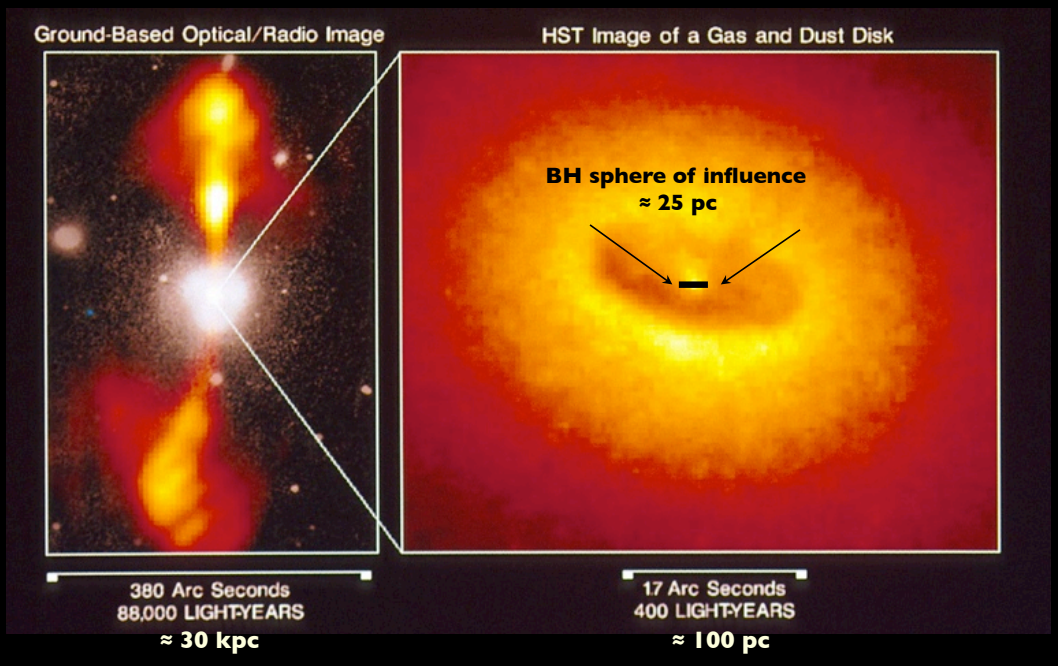
✔MBH evolution along cosmic time

✔Observational signatures

# SMBHs in local galaxies

A BH dominates the motions of stars and gas in a tiny volume

Sphere of influence: $$r_{inf} = 0.45\mathrm{pc}\left(\frac{M_{BH}}{10^6 M_\odot}\right)\left(\frac{\sigma}{100\mathrm{km/s}}\right)^{-2}$$

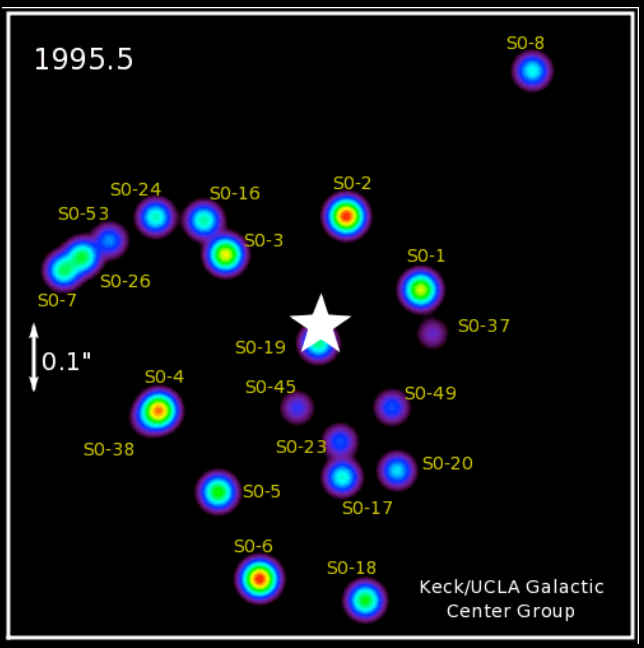


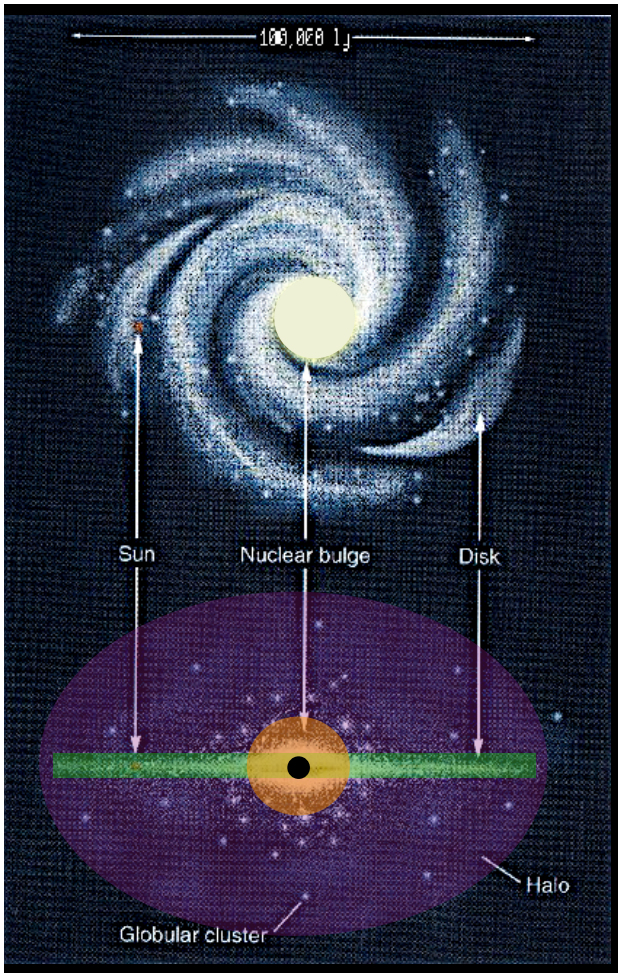
# SMBHs in local galaxies

Sphere of influence: $$r_{inf} = 0.45\mathrm{pc}\left(\frac{M_{BH}}{10^6 M_\odot}\right)\left(\frac{\sigma}{100\mathrm{km/s}}\right)^{-2}$$

The best example of search for a SMBH is the MILKY WAY: individual stars can be resolved

Beyond the MW: velocity dispersion profile + orbital modeling




What is a galaxy made of?

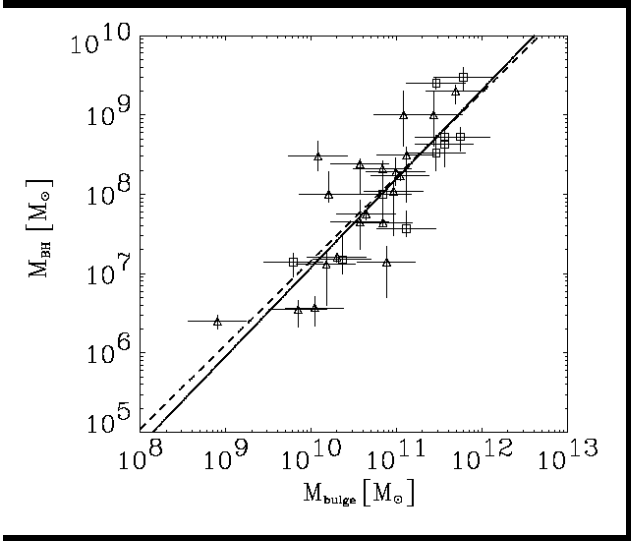
Halo: dark matter

Disc: gas+stars

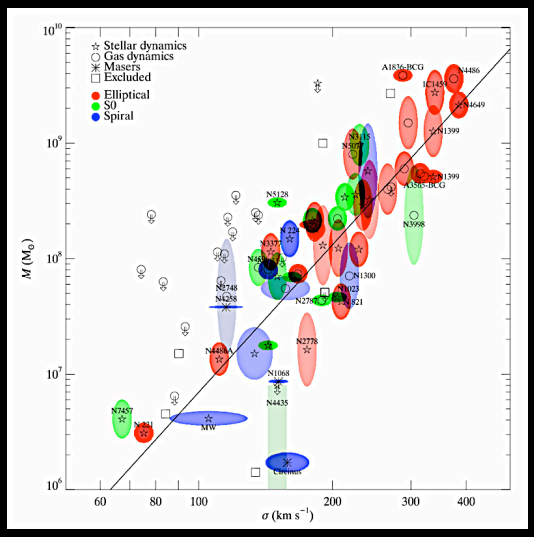
Bulge: stars

Black hole!

# $M_{BH}$- host relations: co- evolution of MBHs and galaxies




from Marconi & Hunt 2004



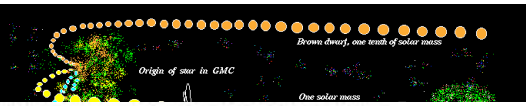

from Gultekin et al. 2009

tiny BHs know about big bulges!

## Stellar mass BHs

✔formation through stellar evolution

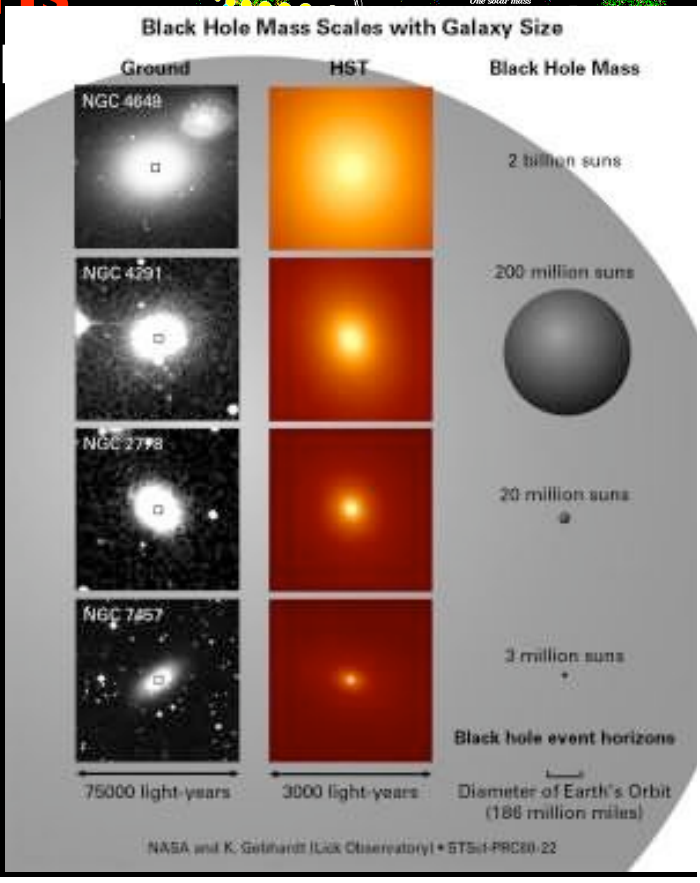
✔mass < few tens M




## Massive BHs

✔ powering quasars

✔ mass > $10^6$ $M_{sun}$



# 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*

$M_{BH}$=2-6 x$10^9$ $M_{sun}$

*(Willott et al 2003, Barth et al 2003)*

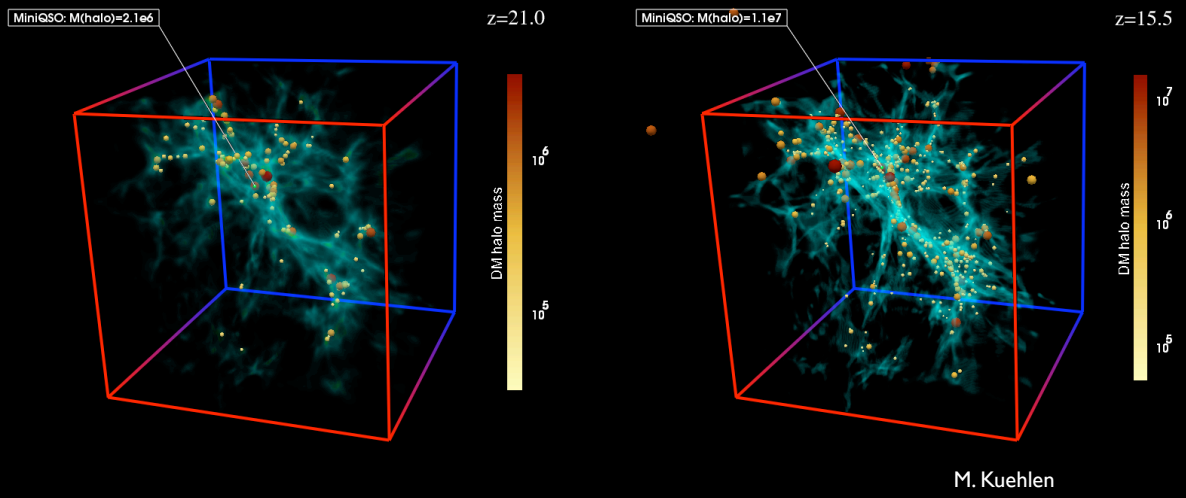
*AS LARGE AS THE LARGEST SMBHs SEEN TODAY, BUT*

*WHEN THE UNIVERSE WAS 1 Gyr OLD!*

Hey guys, we have to deal with cosmology...

# Hierarchical Galaxy Formation

small scales collapse first




M. Kuehlen

# First black holes

$M_{BH} \sim 100\ M_{sun}$

## PopIII stars/Dark stars remnants

✔Simulations suggest that the first stars are massive $M \sim 100\text{-}600\ M_{sun}$
(e.g., Abel et al. Bromm et al.)

✔Dark stars powered by DM annhilation massive $M \sim 500\text{-}1000\ M_{sun}$
(e.g. Spolyar et al 2008, Freese et al 2008)

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

$M_{BH} \sim 10^3\text{-}10^5\ M_{sun}$

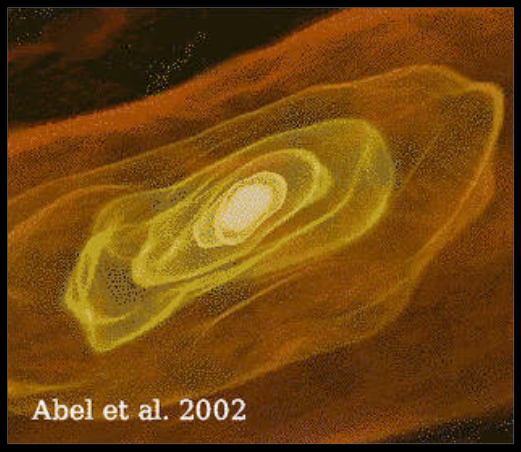
## Dynamical instabilities:

### I. 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)

### II. stellar dynamical processes
(Omukai et al. 2009, Devecchi & MV 2009)

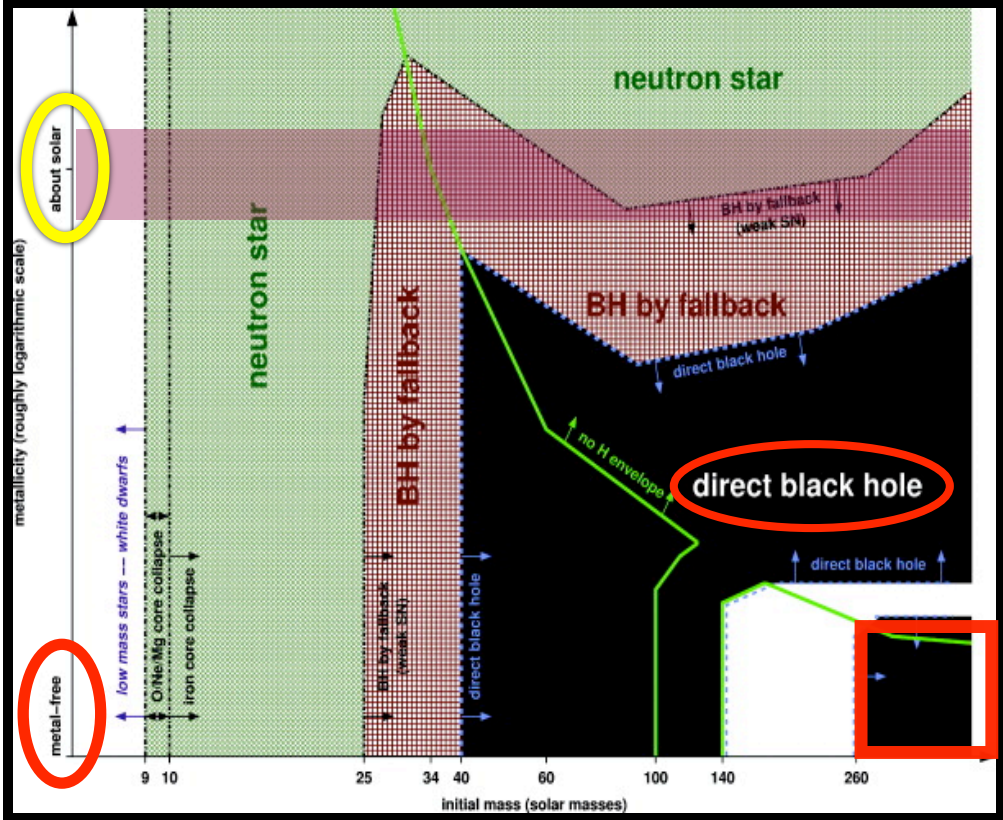
# Black holes from the firs (dark?) stars

***Metal free gas has to rely on inefficient $H_2$ cooling: slow, quasi-hydrostatic contraction***

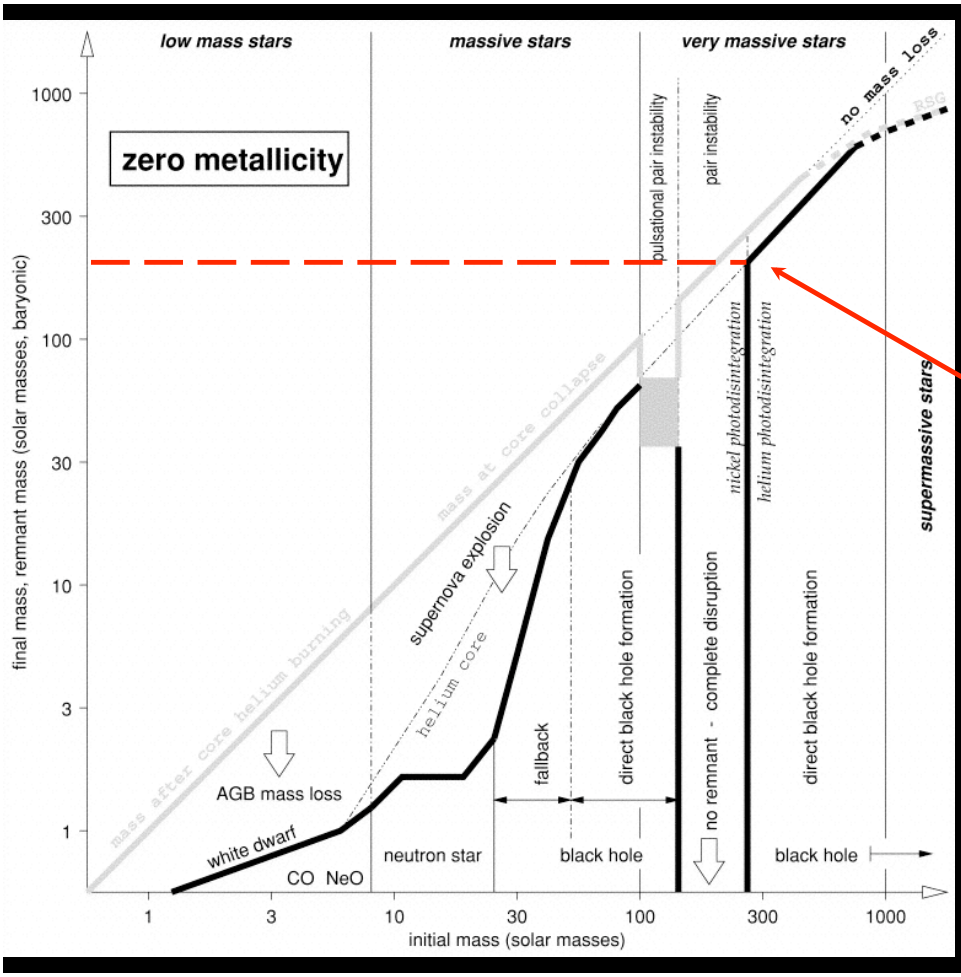



***Simulations suggest that the first stars are massive***
***$M \sim 100\text{-}600\ M_{\odot}$***
*(Abel et al., Bromm et al.)*

***and come in small batches (1 to ~a few per halo)***




*Heger et al.*




Metal free dying stars with $M>260M_{sun}$ leave remnant BHs with $M_{seed}\approx100M_{sun}$ (Fryer, Woosley & Heger)

# Gas-dynamical processes

## ANGULAR MOMENTUM TRANSPORT

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

## STAR FORMATION

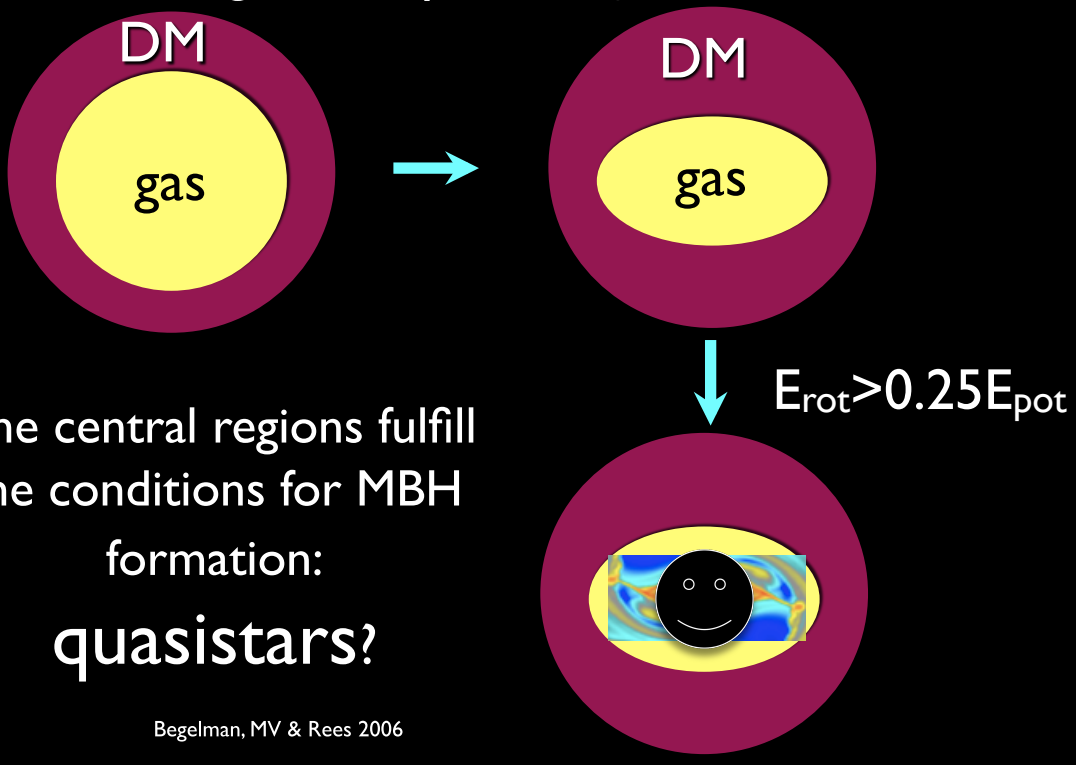
✔ competition in gas consumption

✔ collisionless stars do not dissipate angular momentum efficiently

✔ SNe can blow away the gas reservoir

## NO $H_2$/LOW METALLICITY/TURBULENCE HELP AVOID FRAGMENTATION

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




The central regions fulfill the conditions for MBH formation:

quasistars?

Begelman, MV & Rees 2006

# Stellar-dynamical processes

Devecchi & MV 2008

if a forming disk is Toomre-unstable @ Z>0, instabilities can lead to mass infall instead of fragmentation and global star formation

VERY LOW, but NON-ZERO METALLICITY

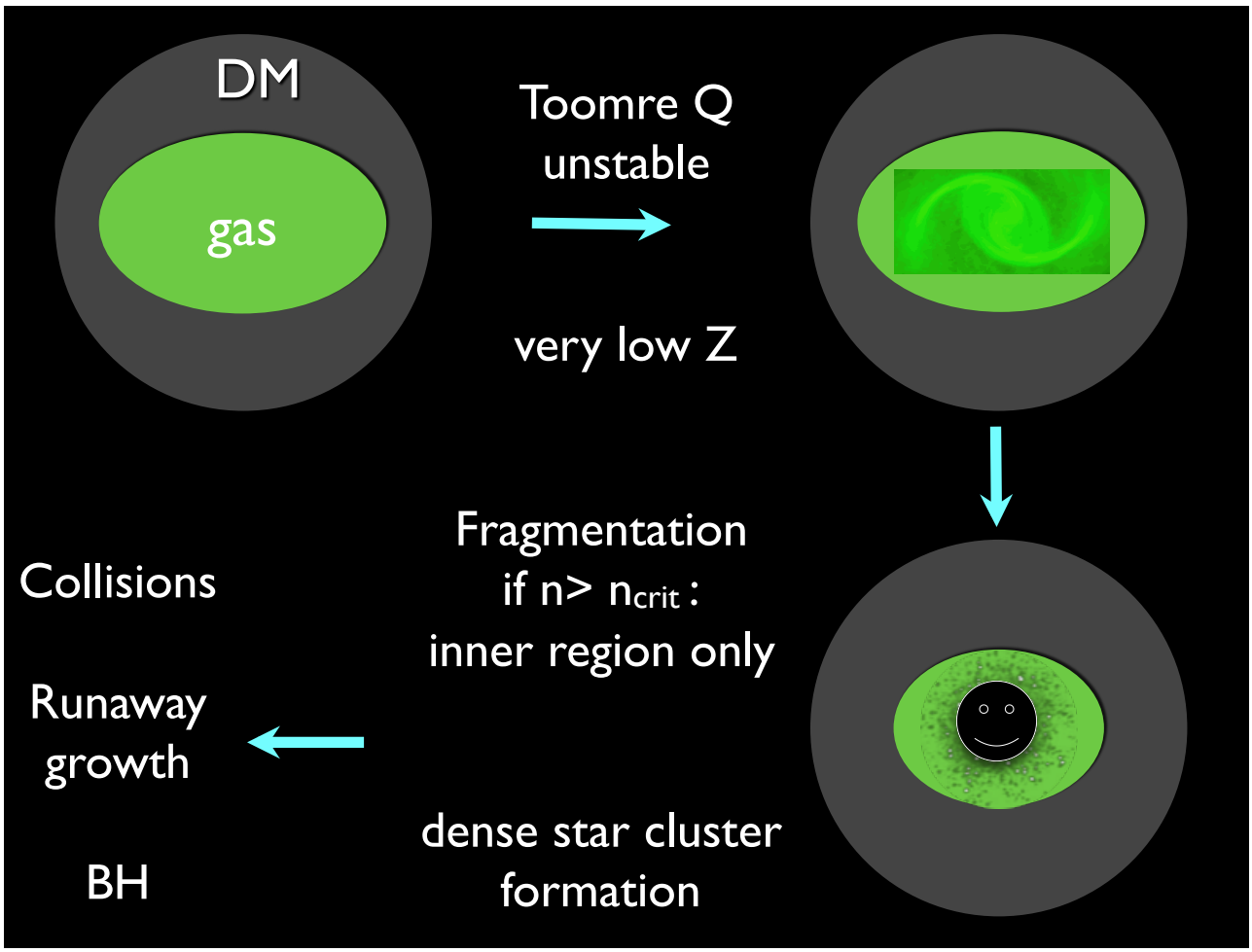
✔ Inefficient fragmentation unless very high density: n > ncrit,Z

STAR CLUSTER FORMATION

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

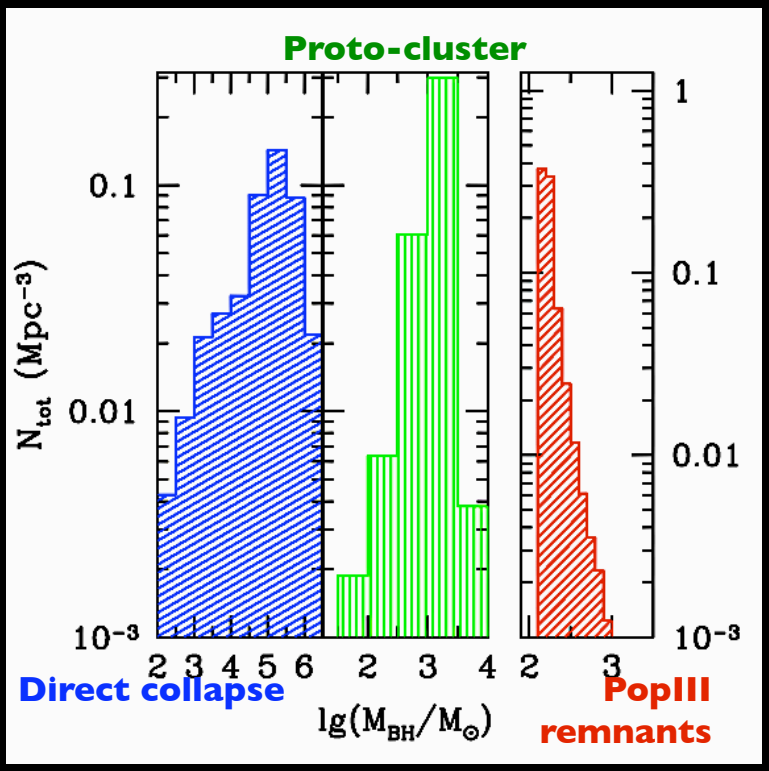
✔mass segregation: massive stars sink to the center

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



# Mass function of seed MBHs

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




# Outline

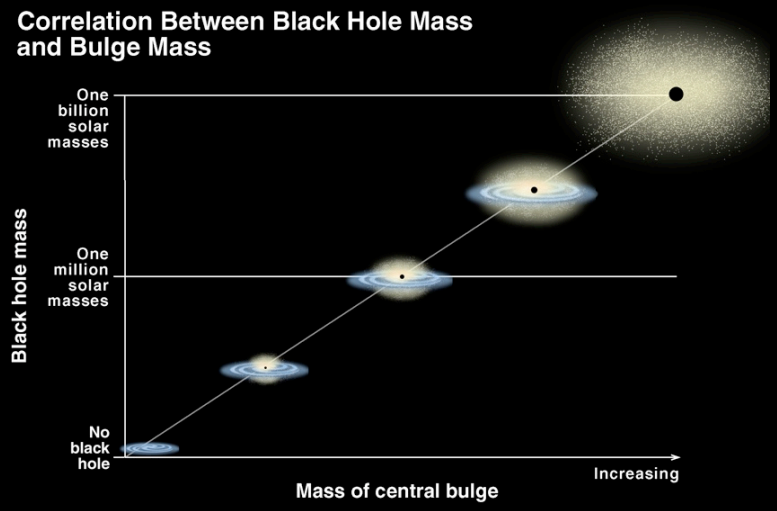
✔MBHs in the local Universe: where from?

✔MBH evolution along cosmic time

✔Observational signatures

The seeds at z>20 are small, ~100-$10^4$ $M_{sun}$

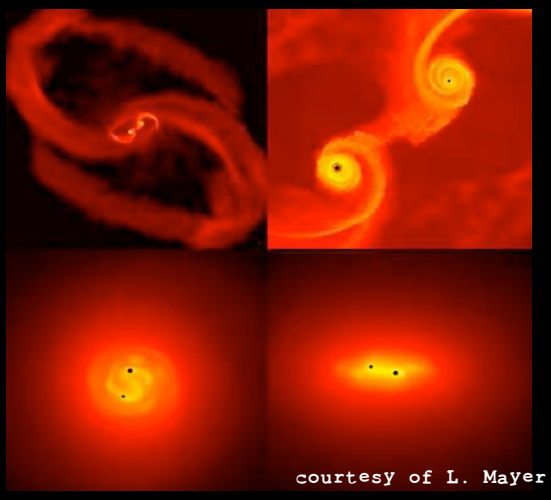
How do MBH seeds grow with their hosts?



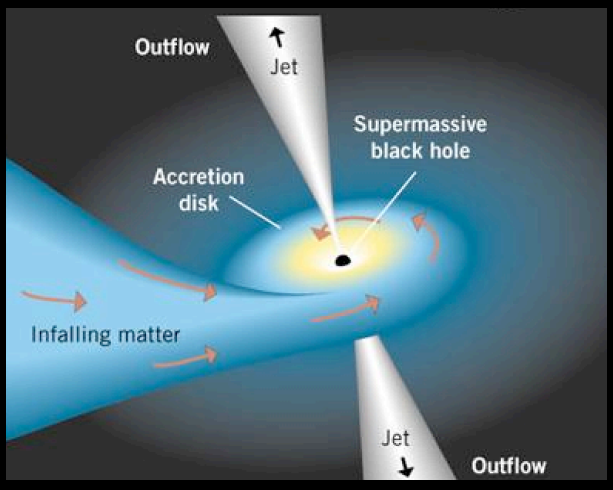

The seeds at z>20 are small, ~100-$10^5$ $M_{sun}$

How do MBH seeds grow to become supermassive?

BH-BH mergers vs gas accretion




**Total mass density in MBHs is almost constant in time: just reshuffle the mass function**



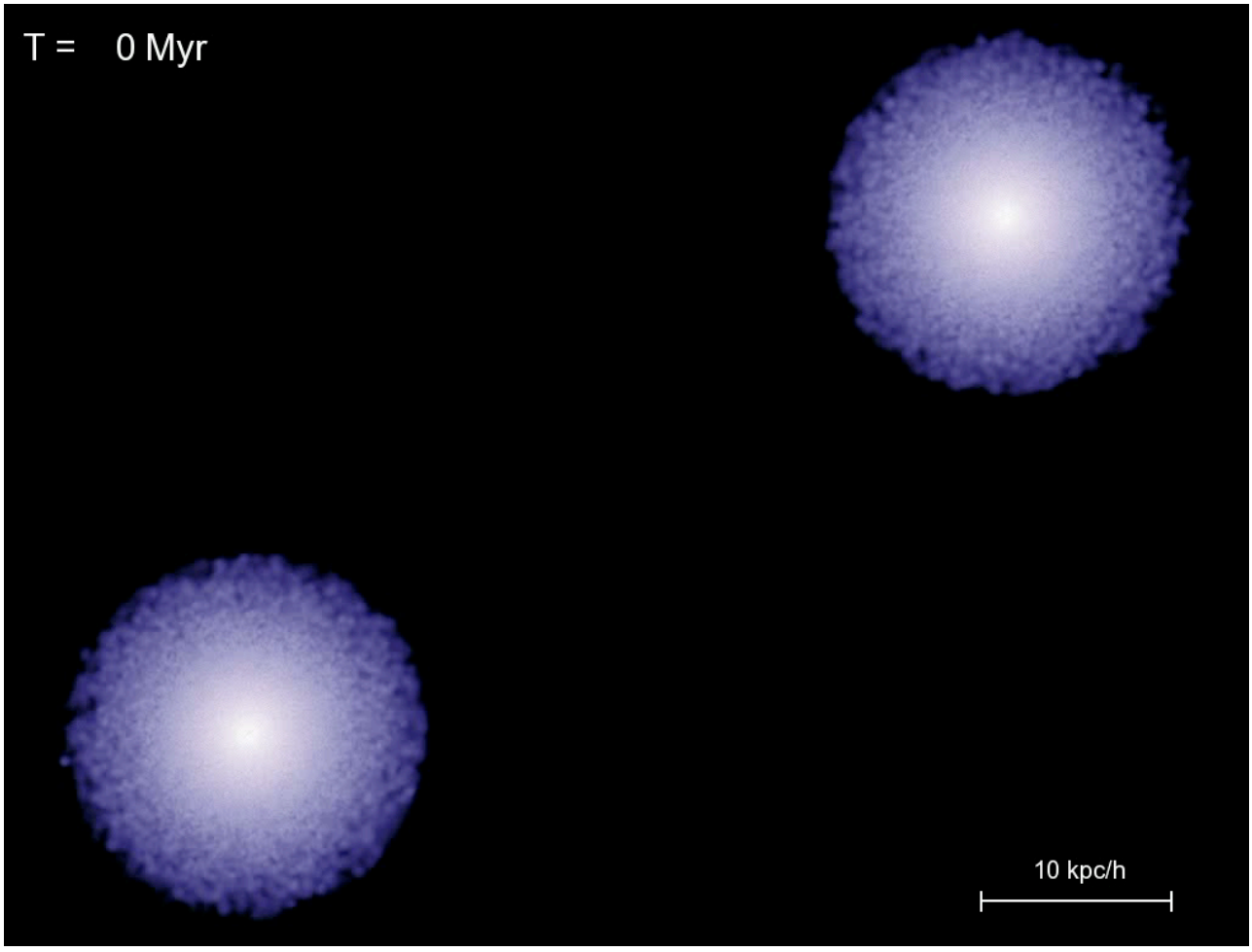

Total mass density in MBHs grows with time

To recover the local $M_{BH}$- σ & the quasar LF:

✓during major mergers { space density of quasars; SMBHs-bulges connection

✓ the accreted mass brings the MBHs onto the $M_{BH}$- σ relation { BH growth limited by feedback

cfr. Di Matteo et al.



## How does the SMBHs mass grow along the cosmic history?

➡ Mergers

➡ Accretion

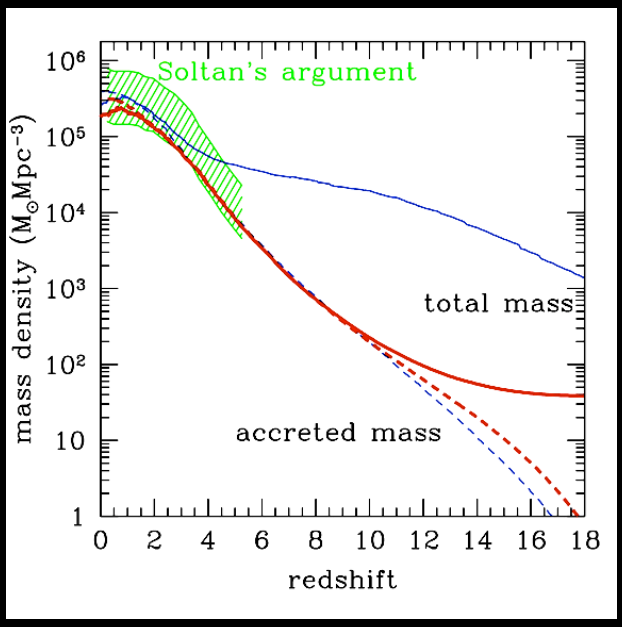
- @ z<3-5 Soltan's argument ➜ **accretion** leads

Yu & Tremaine 2002, Elvis et al 2002, Merloni et al 2004

$$\rho_{\rm BH} = \frac{1-\epsilon}{\epsilon c^2} \int_0^{z_s} dz \frac{dt}{dz} \int_{L_1}^{L_2} L\phi(L,z)\, d\log L$$

$\rho_{qso(z0)}$=integral over the LF of quasars at $z>z_0$

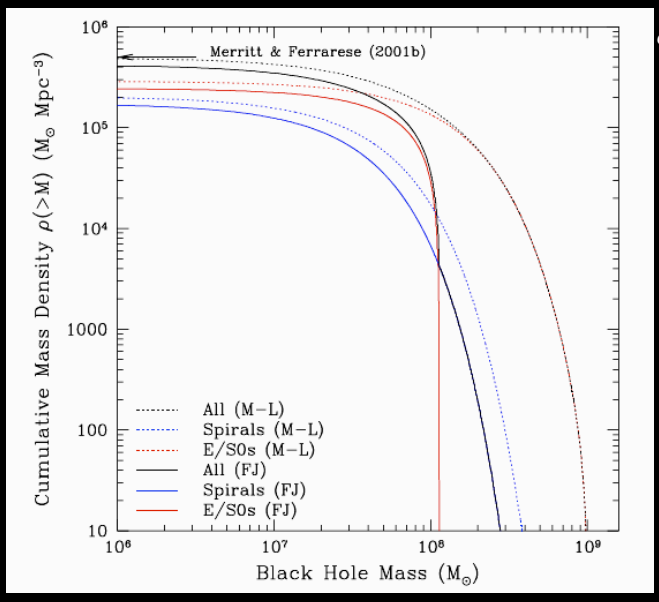
$$\rho_{\rm BH} = \frac{1-\epsilon}{\epsilon c^2} \int_0^{z_s} dz \frac{dt}{dz} \int_{L_1}^{L_2} L\phi(L,z)\, d\log L$$




$\rho_{qso(z0)}$=integral over the LF of quasars at $z>z_0$

$\rho_{qso(0)}=2\div4\times10^5[0.1(1-\varepsilon)/\varepsilon]M_{sun}\ Mpc^{-3}$

$\rho_{SMBH}=2.5\div4.5\times10^5 M_{sun}\ Mpc^{-3}$




*al 2004*

@ z<3-5 *the final mass of the SMBHs is dominated by accretion, with mergers playing a secondary role*

$M_{BH,acc} >> M_{BH,merg}$

# Outline

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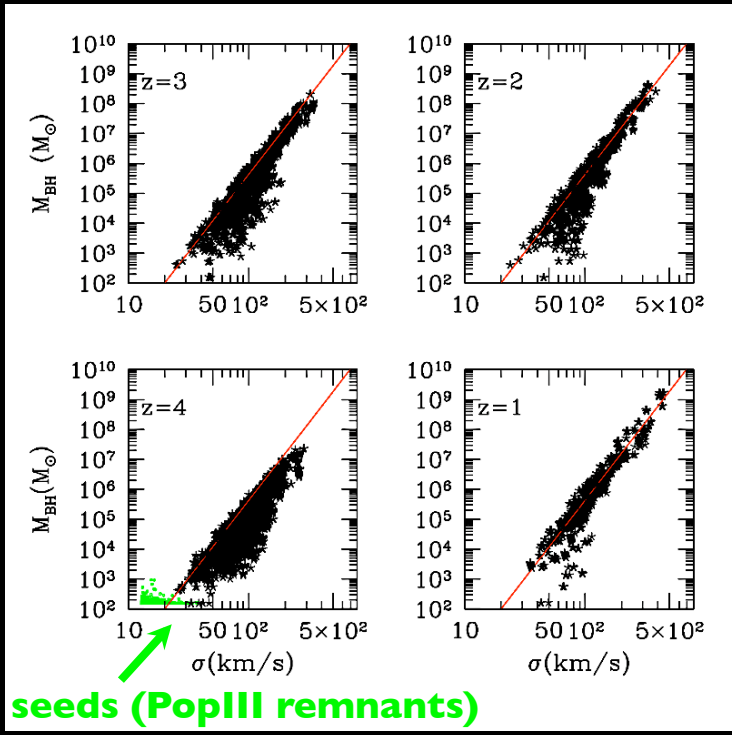
# Journey to the M-sigma relation

(MV & Natarajan 2009)

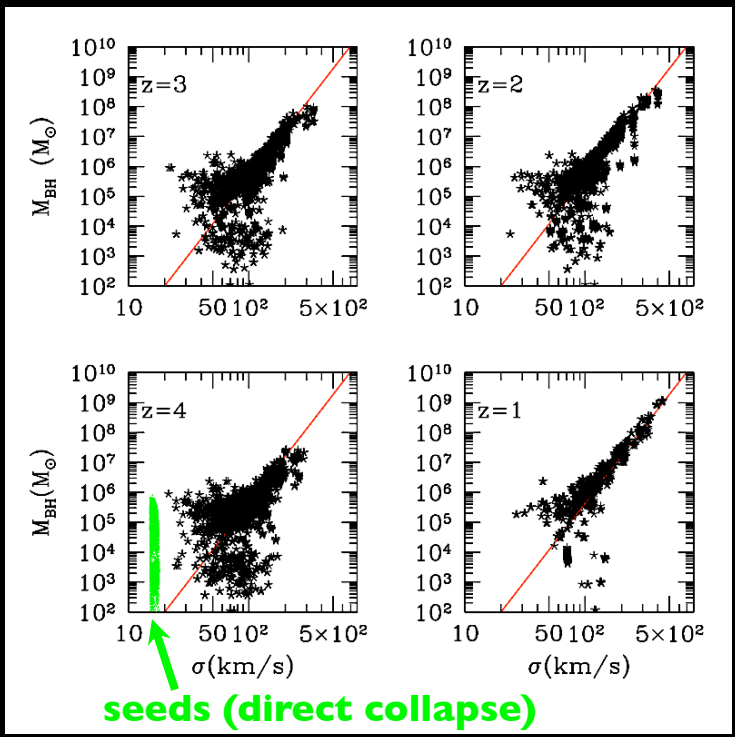



MBHs along the hierarchical build-up of a massive elliptical galaxy

PopIII remnants: MBHs move onto the M-sigma from below

# Journey to the M-sigma relation

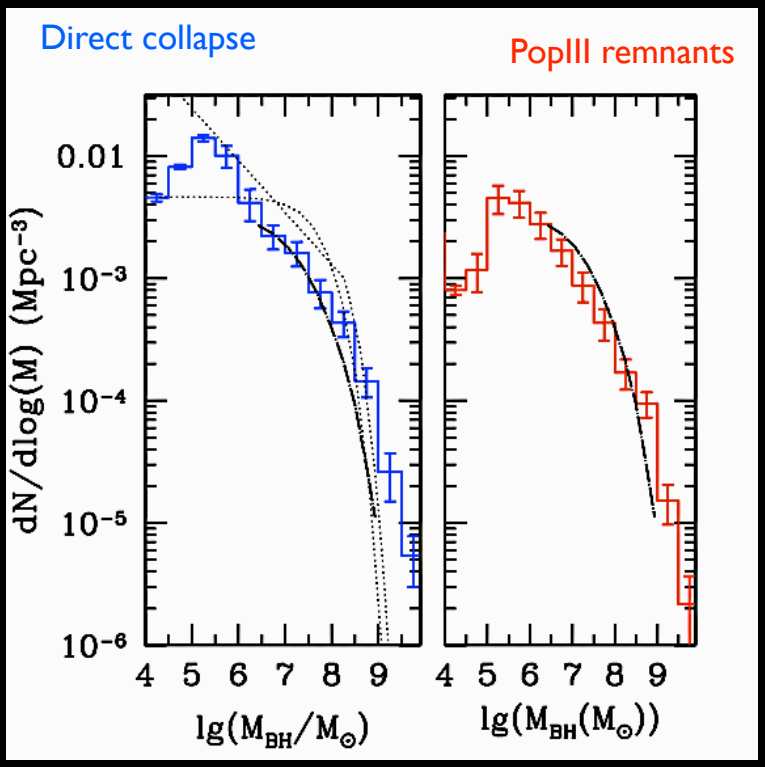
(MV & Natarajan 2009)




The smallest galaxies retain memory of the initial conditions: quiet life.... no major mergers, no accretion

# Mass function of MBHs @ z=0

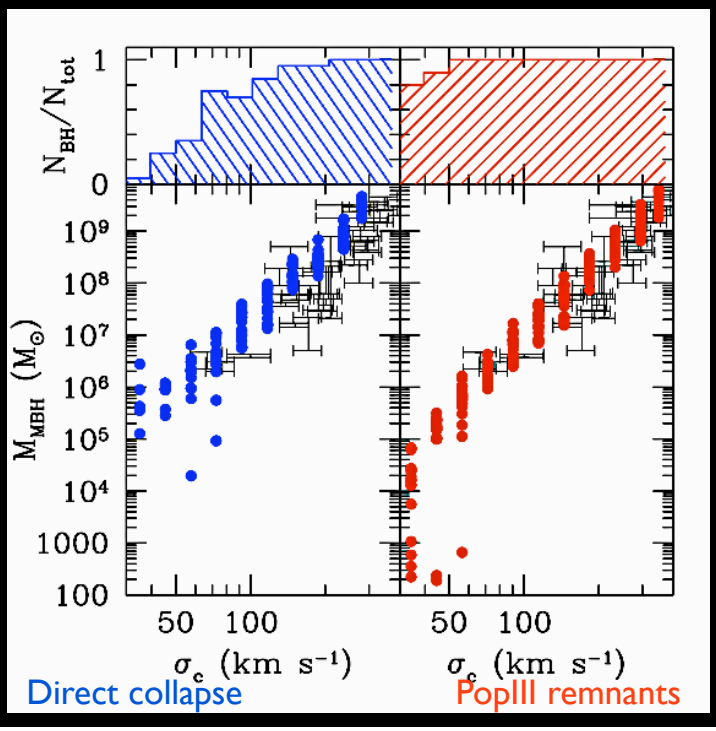
(MV, Lodato & Natarajan 2008)




Black curve:
Greene & Ho 2007

# Occupation fraction and $M_{BH}$-$\sigma$ @ z=0

(MV, Lodato & Natarajan 2008)



# Summary

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

✔seed MBHs form in high-z proto-galaxies

✔MBHs evolve through mergers and accretion

✔M-sigma & BHOF @ low masses tells the story