Formation of Massive Black Hole Seeds in First Galaxies

Hide Yajima (Tohoku University)

Sadegh Khochfar (Edinburgh)

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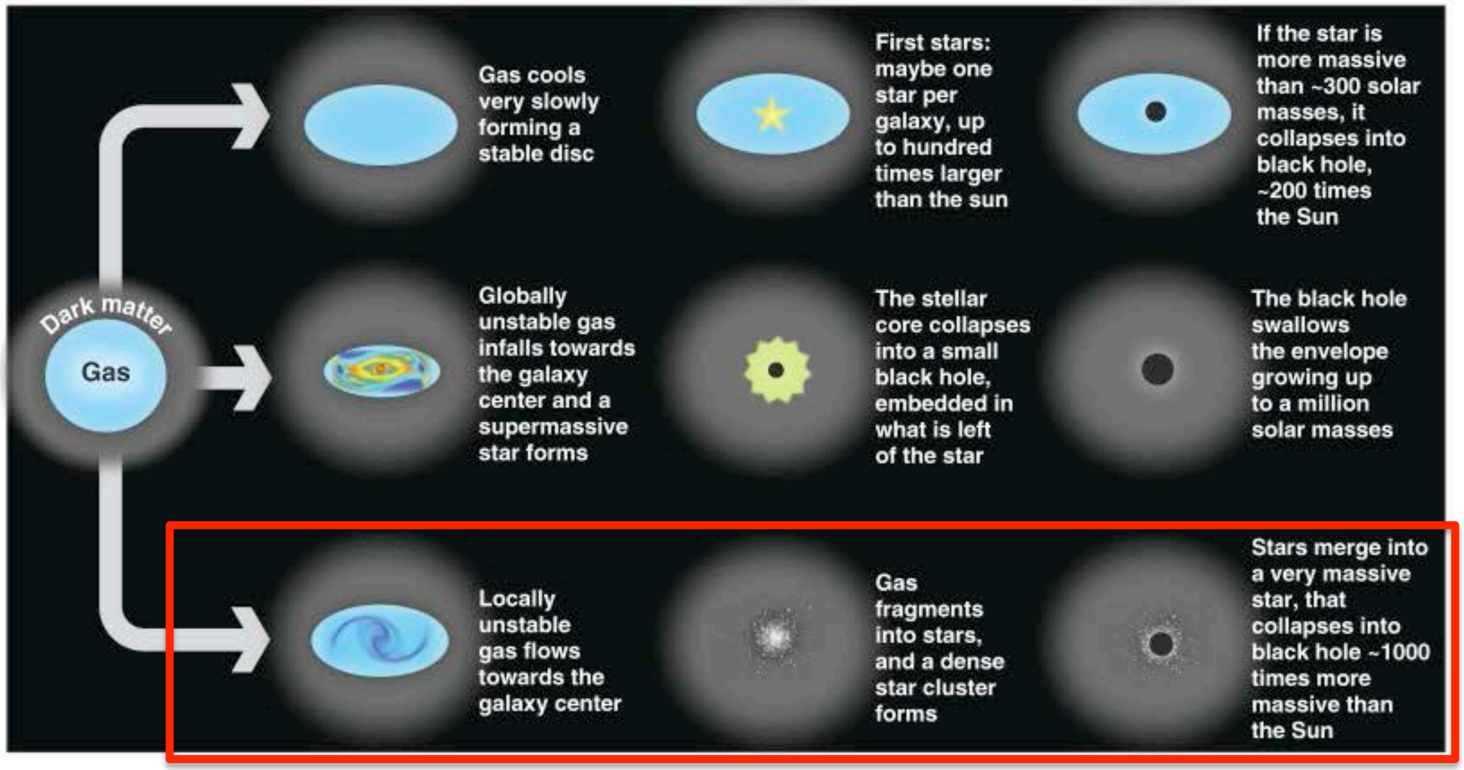
Models of formation of MBHs

Volonteri (2012)



Stellar mass BHs as Pop III star remnants

Direct collapse

Merging of stars

See also Rees (1984)

Star clusters

Galactic Bulge

M_{star}~10^{10-12} M_{sun}

R~5 kpc

Open clusters

M_{star}~10^{2-3} M_{sun}

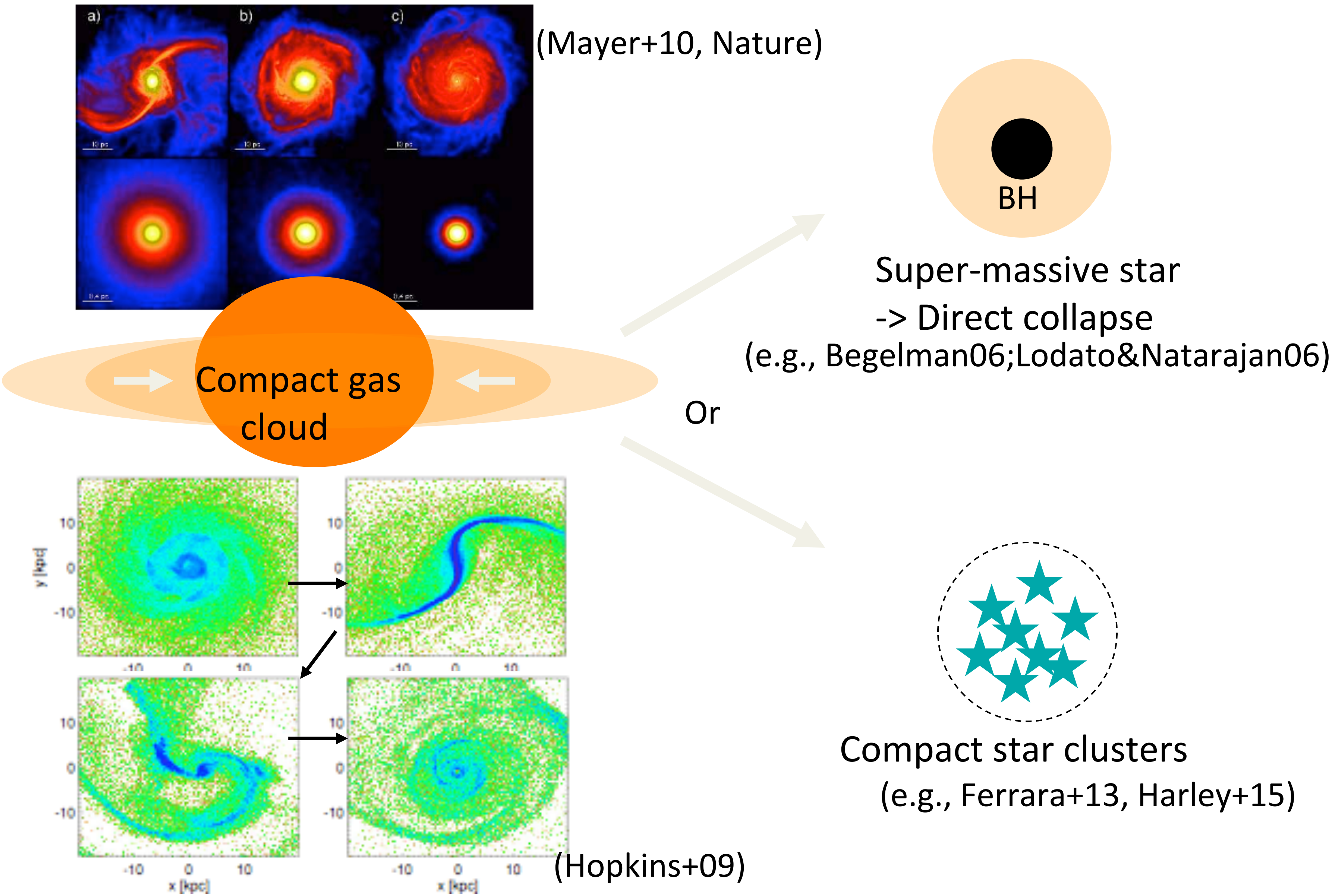
R~10 pc

Globular clusters

M_{star}~10^{4-7} M_{sun}

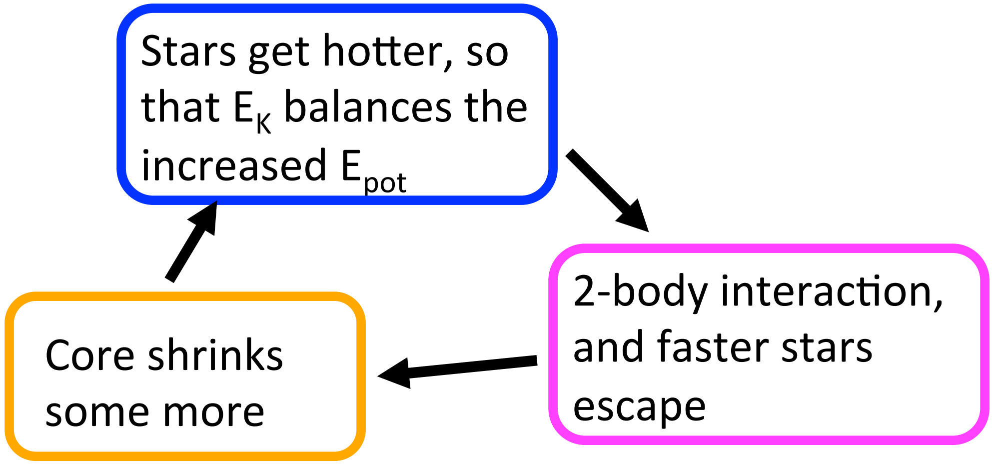
R~5 pc

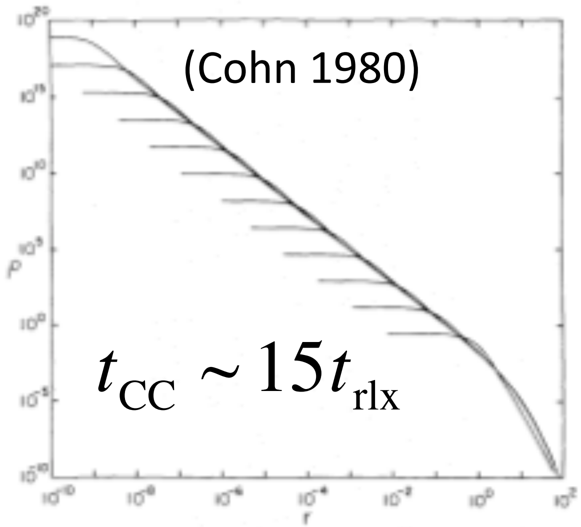
Formation of dens star clusters

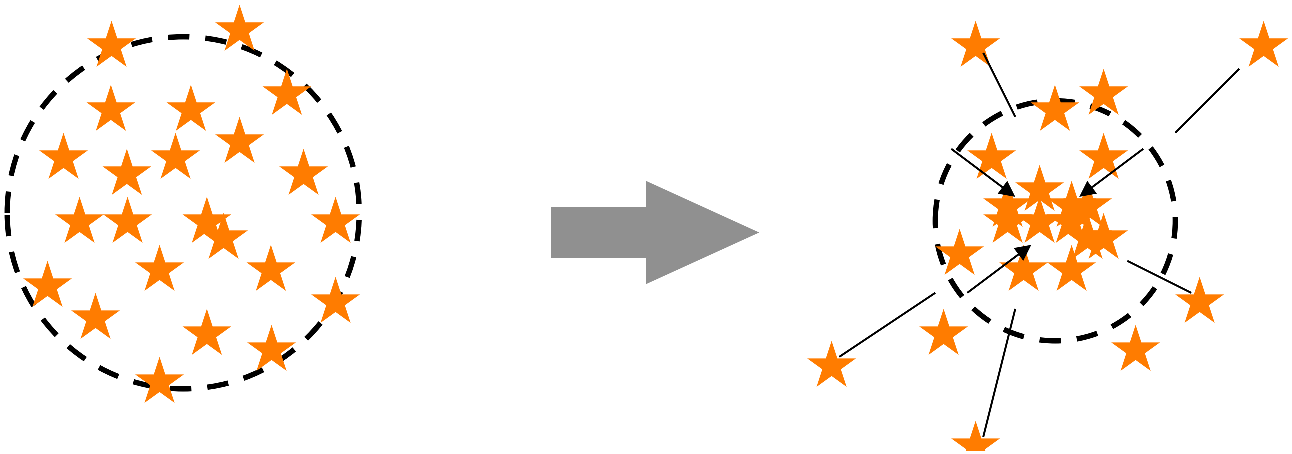


Core collapse

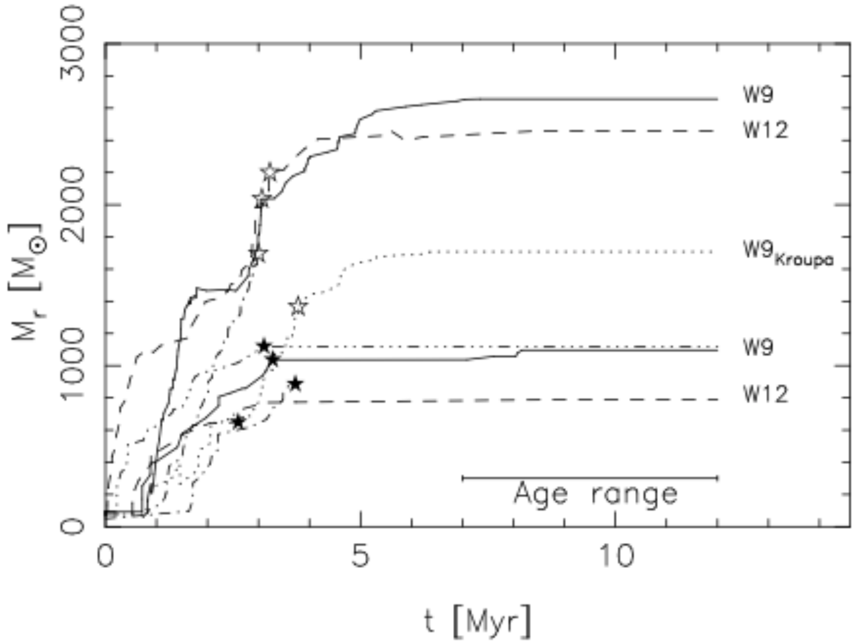
Star clusters cause core collapse by
2-body interaction







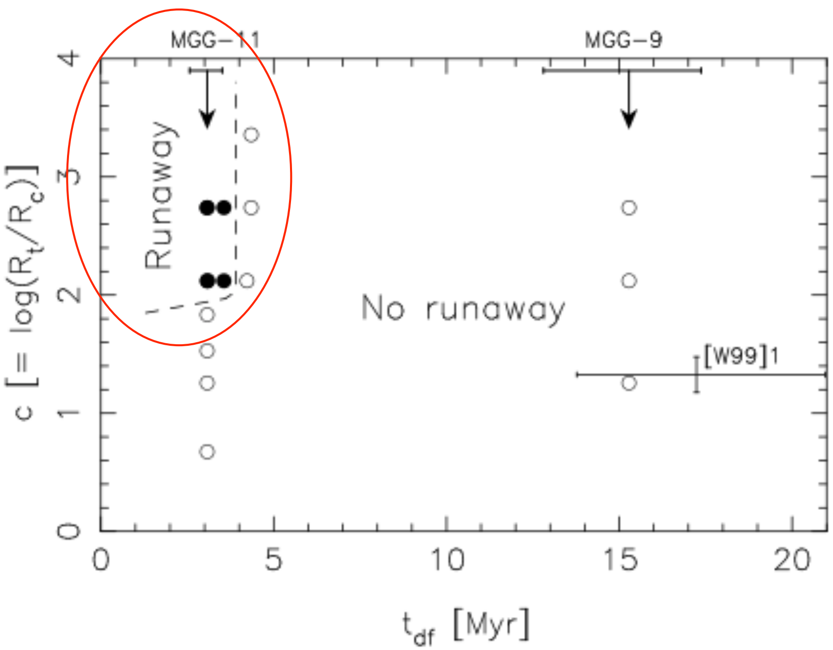
Very Massive Stars in compact star clusters



Portegies Zwart et al. (2004, Nature)

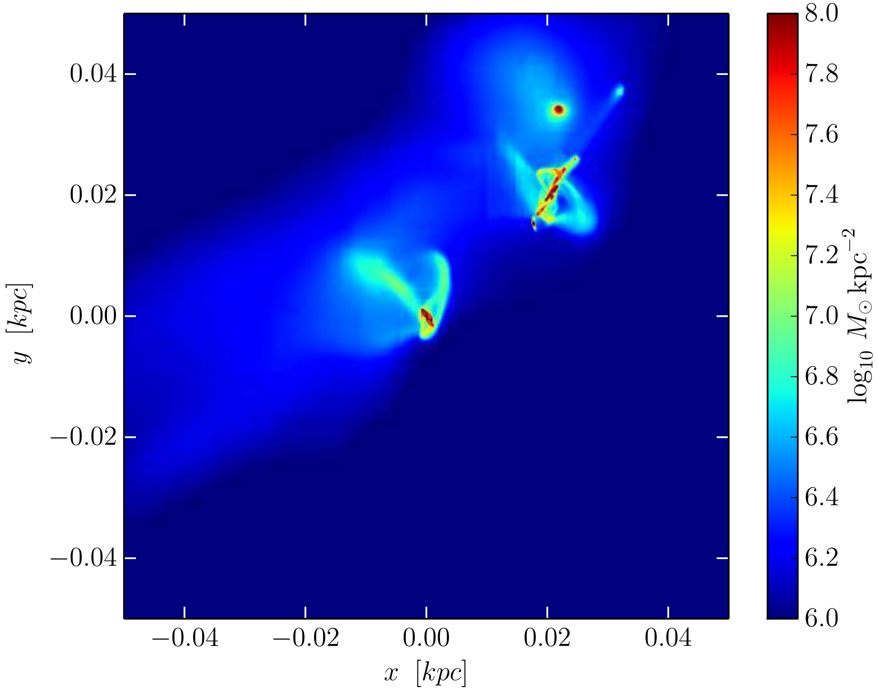
N-body simulations

Compact star clusters -> core-collapse -> merging of stars -> very massive stars



Recent cosmological simulation

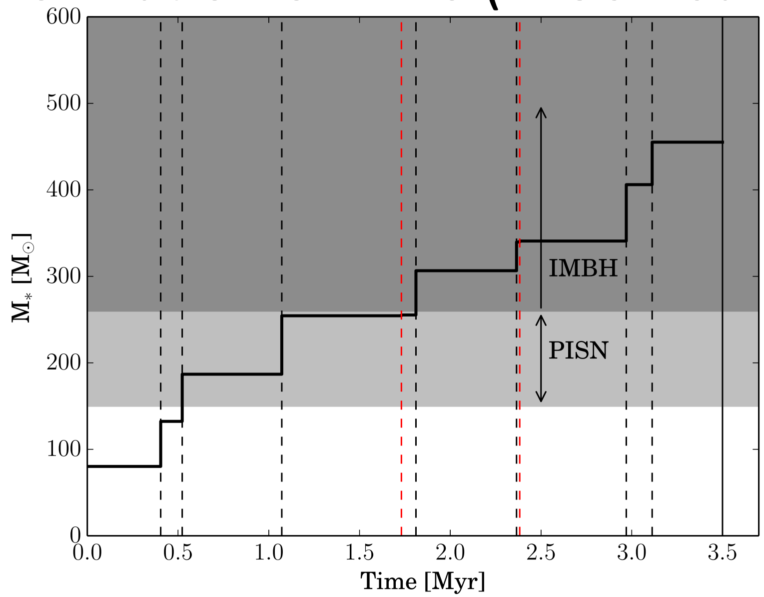
Katz+(2015)



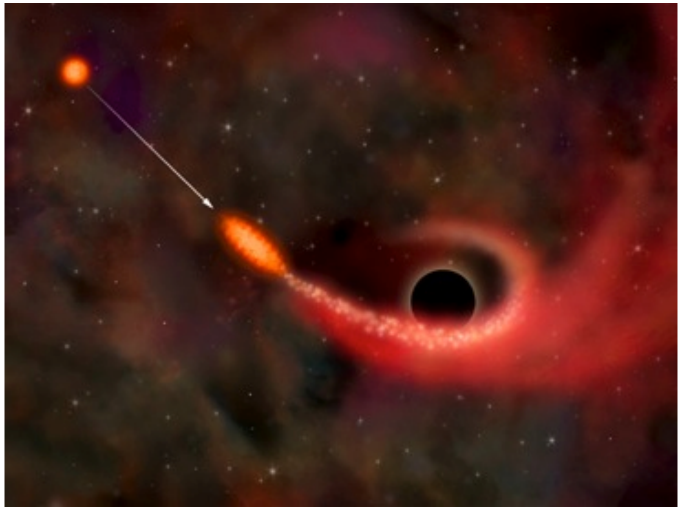
Mini-halos merger at z>~20

Cosmological AMR simulation (RAMSES)
+
N-body simulation

Formation of VMS (~450Msun)

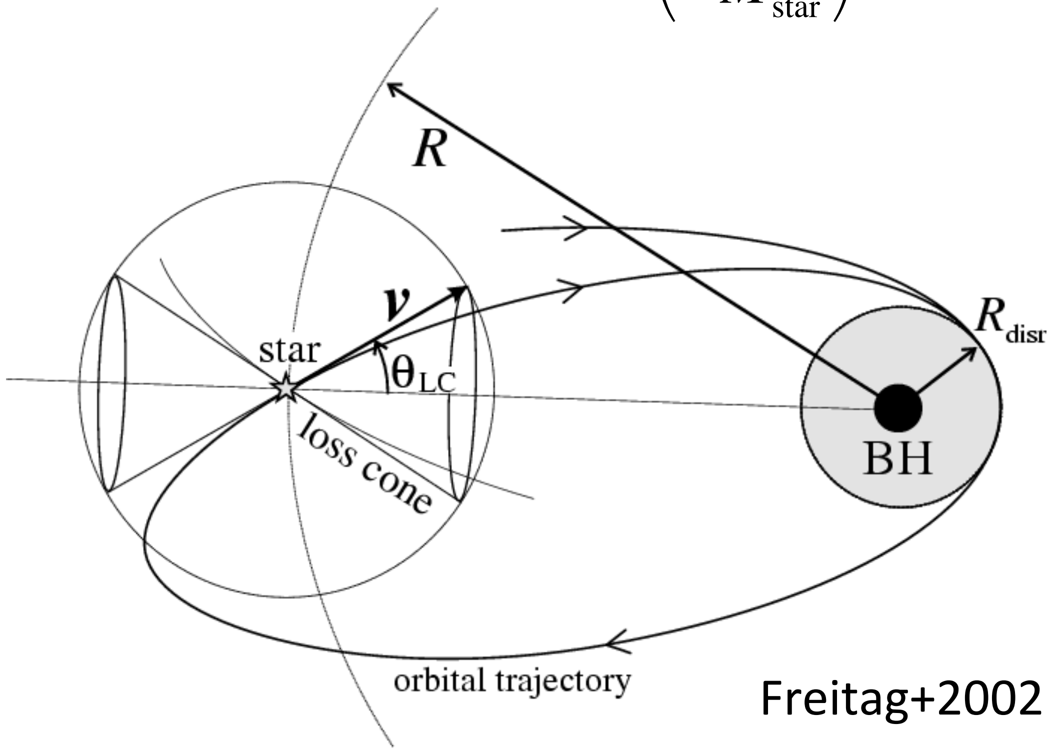


Tidal disruption & Loss cone depletion



Stars passing within tidal radius of BHs are destroyed and accreted onto the BHs

$$R_{\rm disr} \cong \left(2\frac{M_{\rm BH}}{M_{\rm star}}\right)^{1/3} R_{\rm star}$$

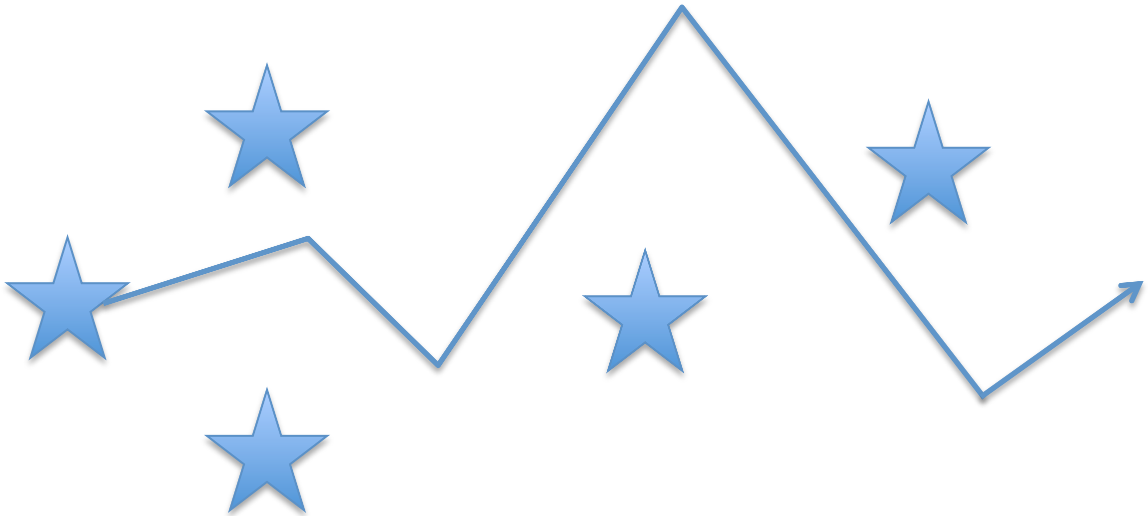


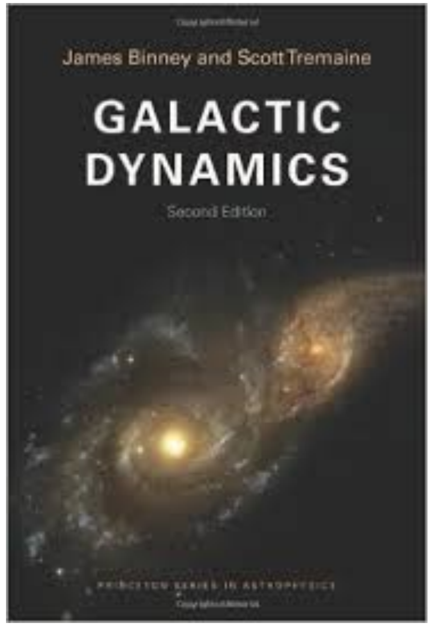
Freitag+2002

Consequently, loss cone is made

$$\theta_{\rm LC}^2 \cong 2\frac{GM_{\rm BH}R_{\rm disr}}{v^2R^2}$$

2-body relaxation



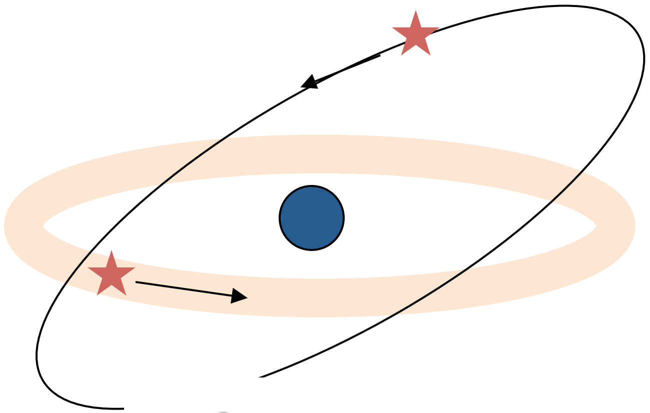


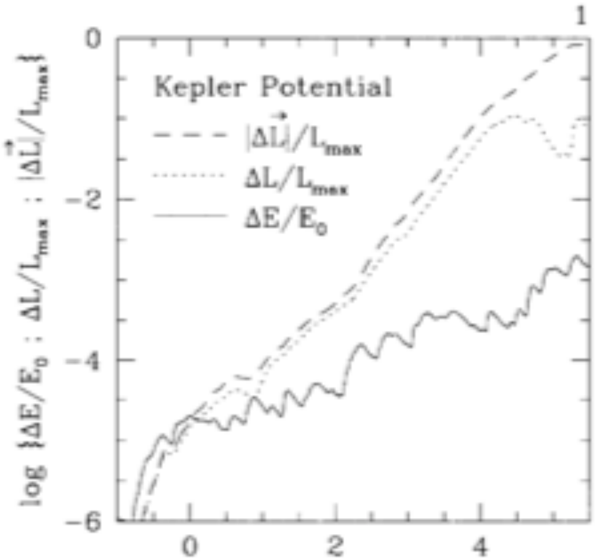
Time scale until stellar orbit is totally 90 degree changed by star-star collisions

$$\tau_{\rm NR}(r) = 0.34 \frac{\sigma^3}{G^2 \rho m_2 \ln(\Lambda)}$$

Resonant Relaxation (RR)

Rauch & Tremaine (1996)

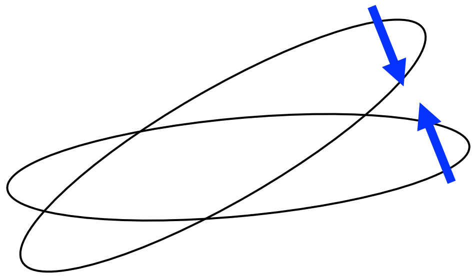


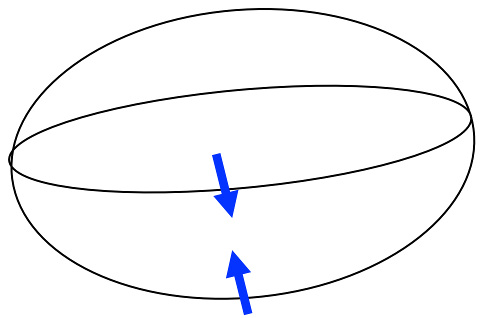


Star in Kepler motion can give a torque to other stars for a time t < t_{prec}

$$\dot{J} \sim \frac{\sqrt{N}Gm}{R^2} \times R$$

$$\frac{\Delta J}{J_c} = \frac{\dot{J}t}{J_c} \sim \sqrt{N}\left(\frac{M_{star}}{M_\bullet}\right)\frac{t}{2\pi\sqrt{R^3/GM_\bullet}}$$





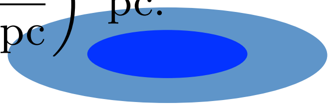
Model: Disk model & star cluster

1: Disk surface density
Isothermal Mestel disk

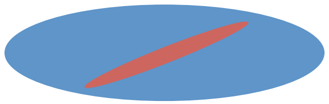
$$\Sigma(r) = \Sigma_0 \frac{R_{\rm d}}{r}$$ (Mestel 1963)

$$\Sigma_0 = 70 \left(\frac{V_{\rm h}}{15 \ {\rm km \ s^{-1}}} \right) \ {\rm M_\odot \ pc^{-2}},$$

$$R_{\rm d} = 100 \left(\frac{\lambda}{0.05} \right) \left(\frac{R_{\rm vir}}{700 \ {\rm pc}} \right) \ {\rm pc}.$$



2: Gas inflow by bar instability after Major merging



$$M_{\rm Inf} = 2\pi\Sigma_0 \frac{1}{v_\phi} \frac{GM_{\rm bar}}{R_0} \Delta\tau$$

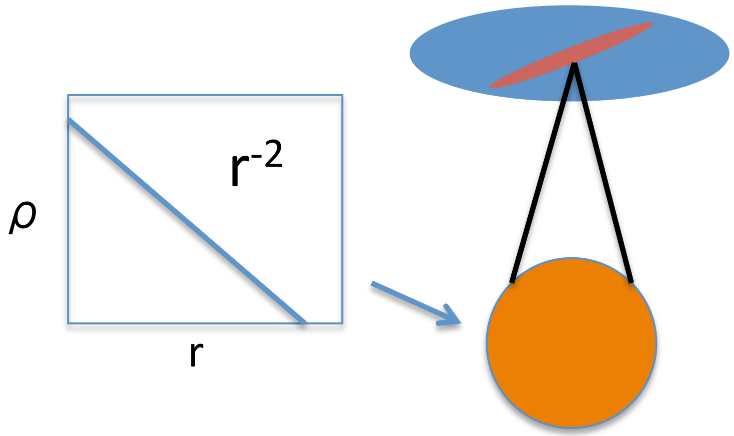
$$\Delta\tau \sim 3{\rm Myr}$$

(e.g., Hopkins et al. 2009)

3: Spherical density structure at galactic centers with a singular isothermal solution

$$\rho_{\rm gas} = \frac{c_{\rm s}^2}{2\pi {\rm G} r^2}$$

$$r_{\rm cl} = 0.22 \ {\rm pc} \ \left(\frac{\sigma_{\rm s}}{10 \ {\rm km \ s^{-1}}} \right)^{-2} \left(\frac{M_{\rm inf}}{10^5 \ {\rm M_\odot}} \right)$$

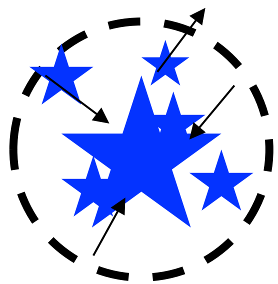


Model:Growth of BH

4: Core-collapse timescale

$$t_{\mathrm{CC}} \sim t_{\mathrm{df}} = \frac{1.91}{\ln \Lambda'} \frac{r^2 \sigma_{3\mathrm{D}}}{G m_{\max}}$$

(Fujii & Portegies Zwart 2014)

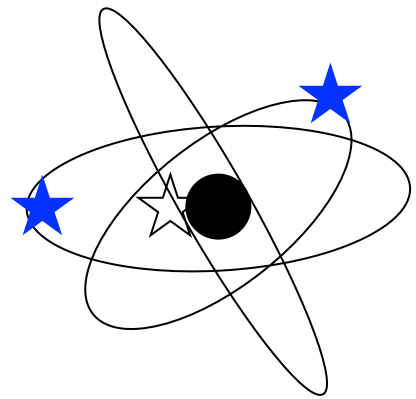


5: Growth of massive mass

$$M_{\mathrm{VMS}} = m_{\mathrm{init}} + 4 \times 10^{-3} M_{\mathrm{cluster}} f_{\mathrm{c}} \ln \lambda_{\mathrm{C}} \ln \left(\frac{3\ \mathrm{Myr}}{t_{\mathrm{CC}}} \right)$$

(Portegies Zwart & McMillan 2002)

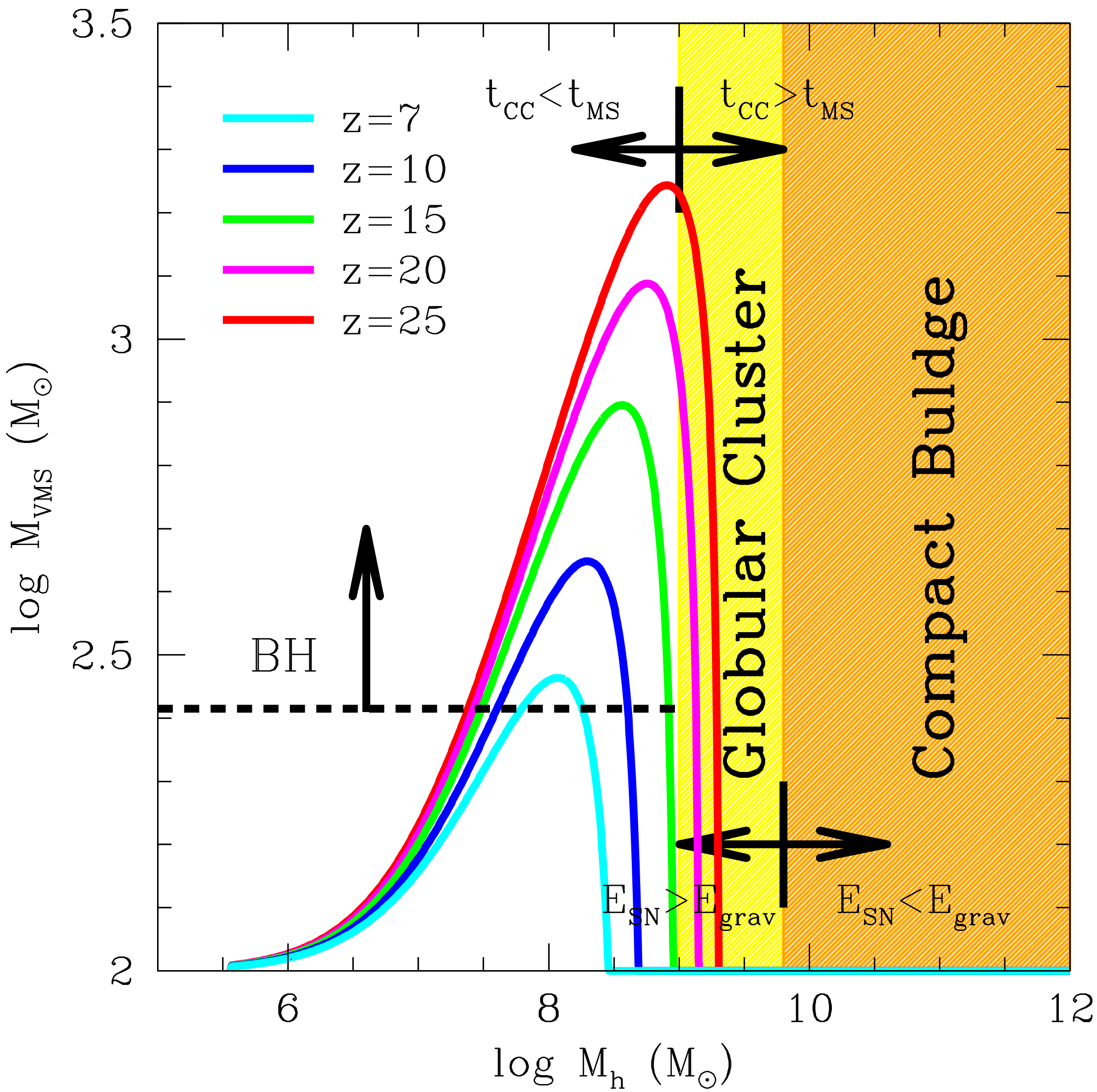
6: Initial Mass Function: Salpeter IMF with 0.1-100 M_{sun}



7: Growth of BH

$$M_{\mathrm{BH}}(t) = M_{\mathrm{BH}}^{\mathrm{init}} + \int_0^t dt \int_0^{R_{\mathrm{cl}}} \frac{4\pi r^2 \rho_{\mathrm{star}}(r,t)}{t_{\mathrm{relax}}(r,t)} dr.$$

Very Massive Stars

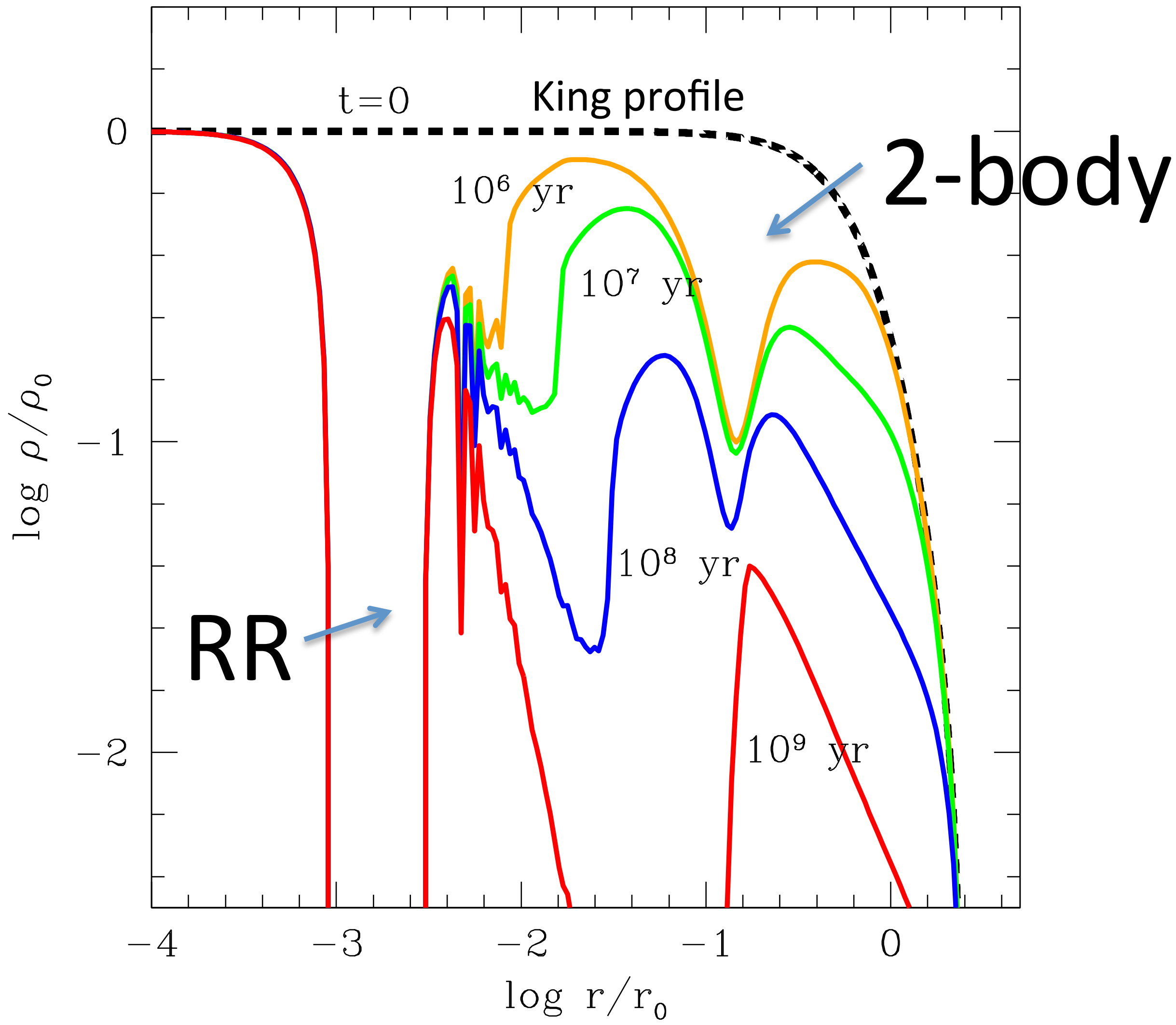


$$E_{\rm SN} \sim 0.007 \times M_{\rm cl} \times 10^{51} {\rm erg}$$

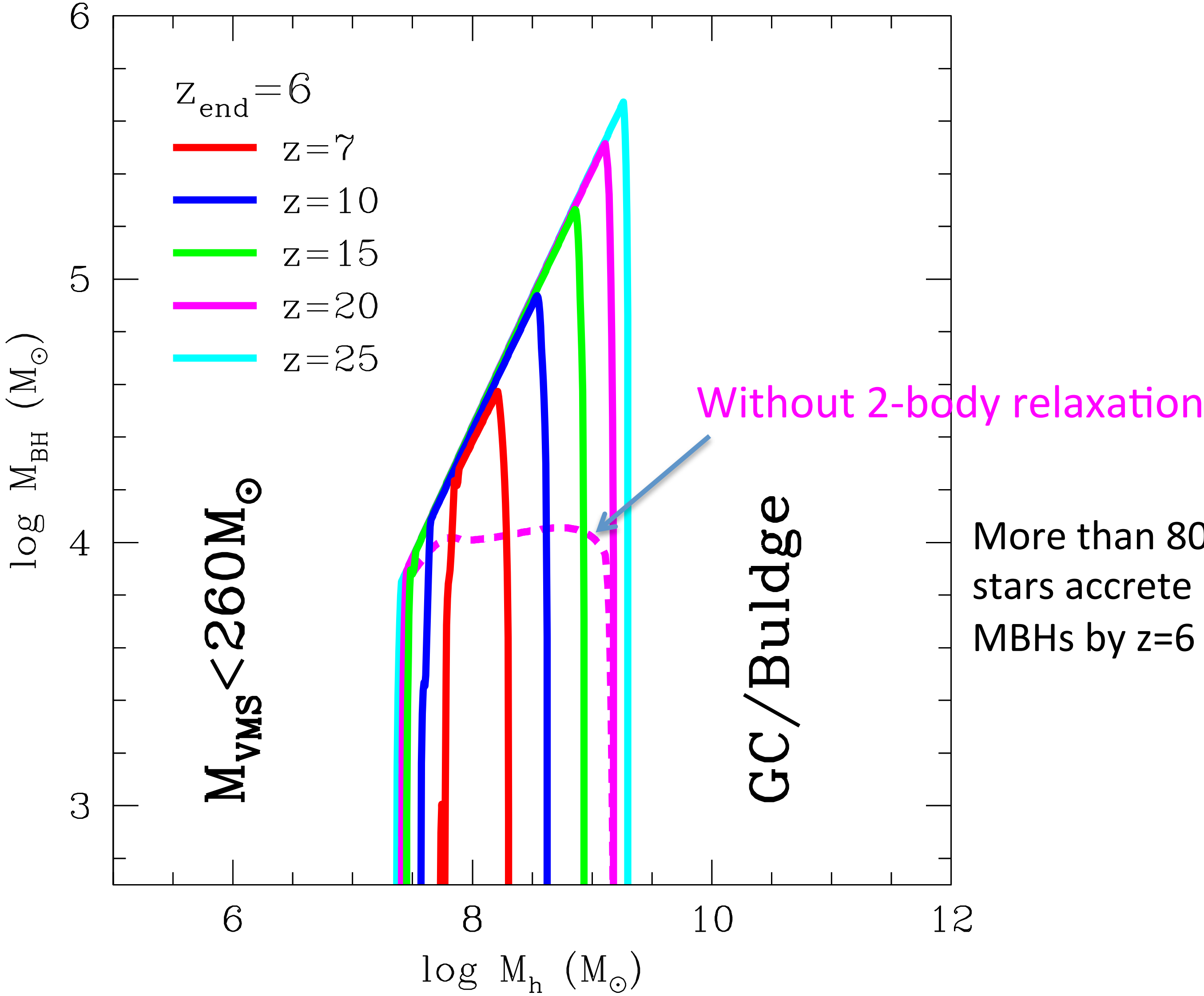
$$E_{\rm grav} \sim \lambda \frac{G M_h^2}{R_{\rm vir}}$$

Mass of VMSs decreases with redshift due to the bigger size of clusters

Stellar density distribution

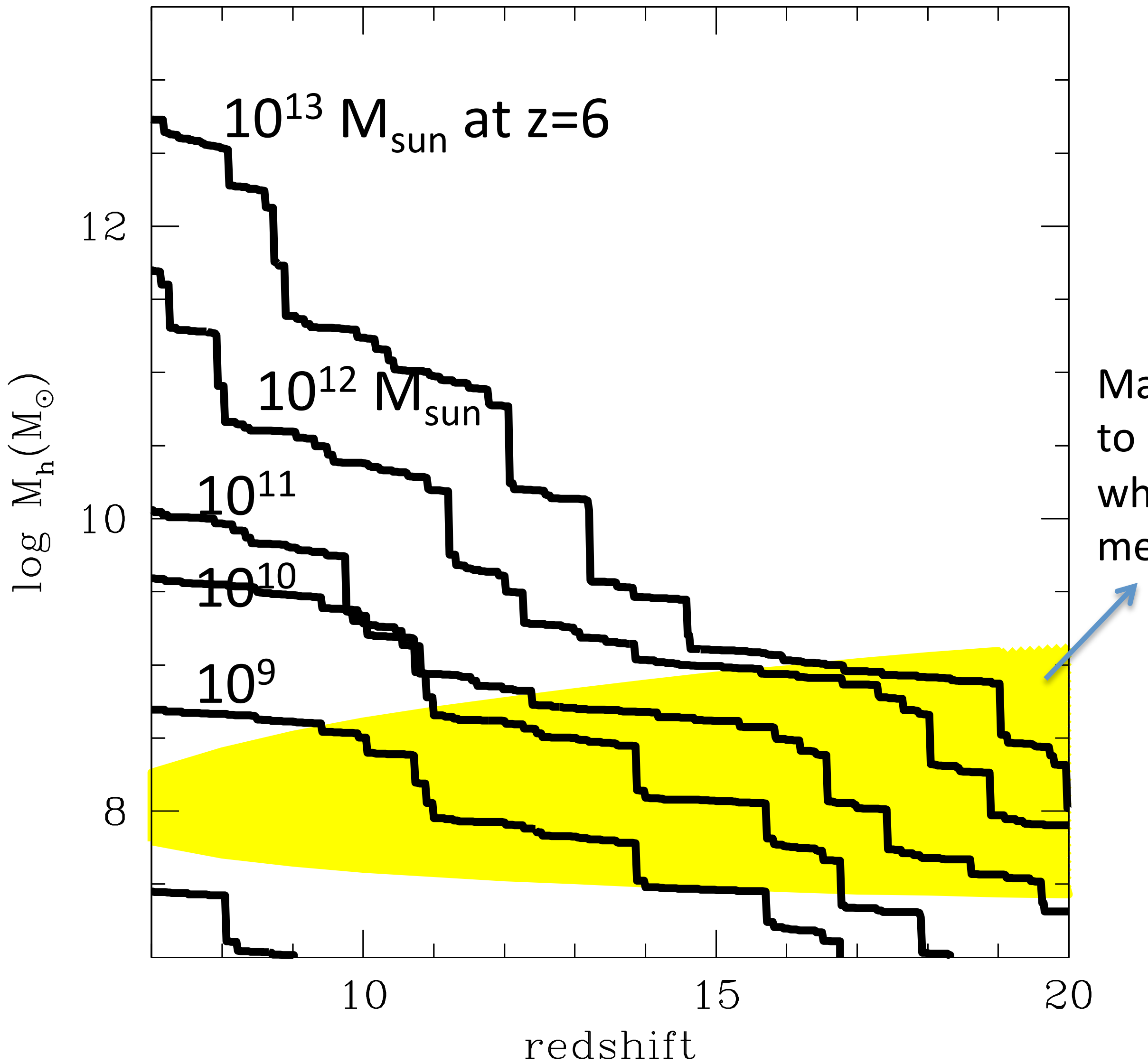


Black hole mass



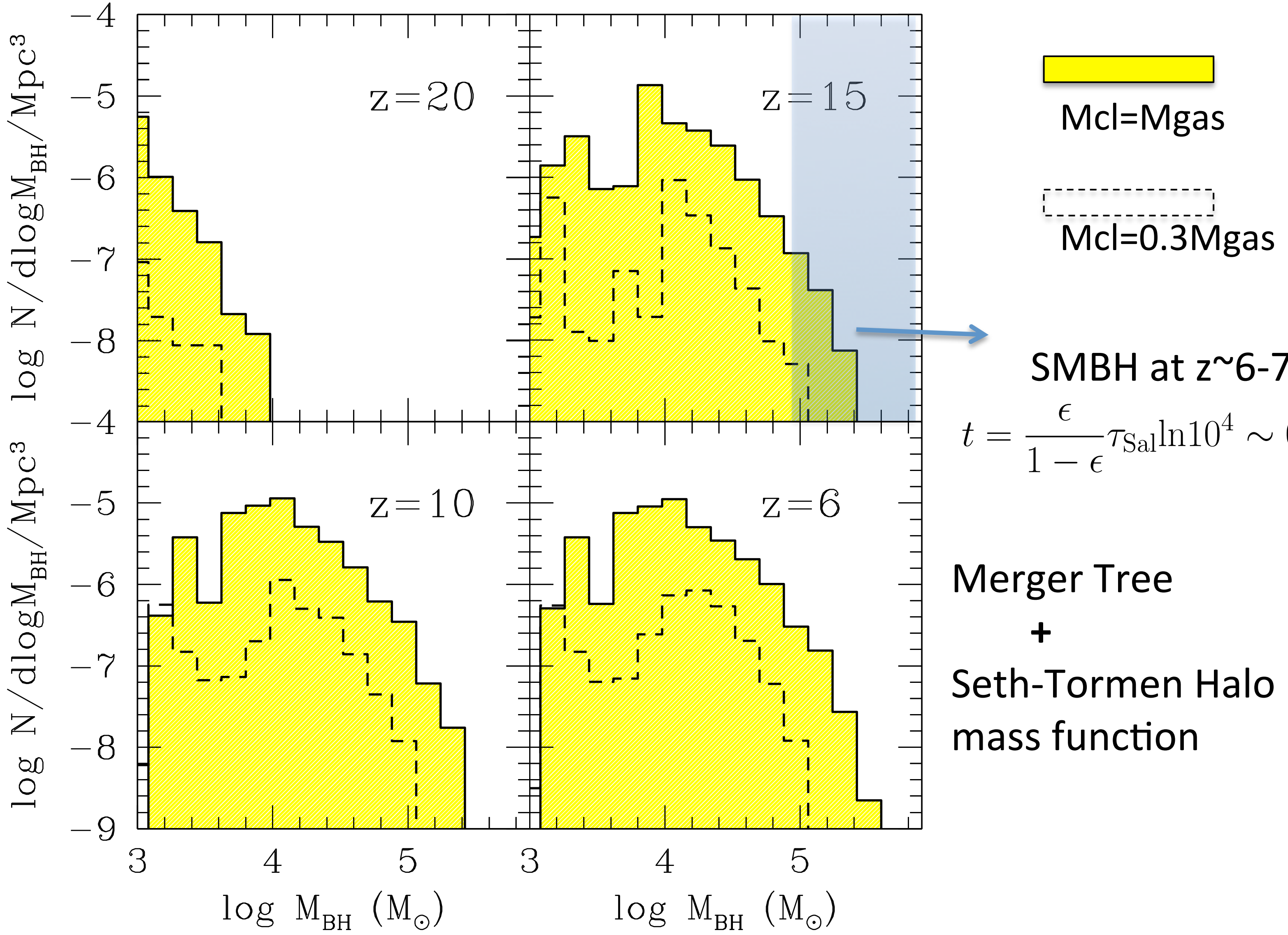
More than 80% of stars accrete onto MBHs by z=6

Halo Merger Tree



Mass range leading to core-collapse when major merger happens

BH mass function



SMBH at z~6-7?

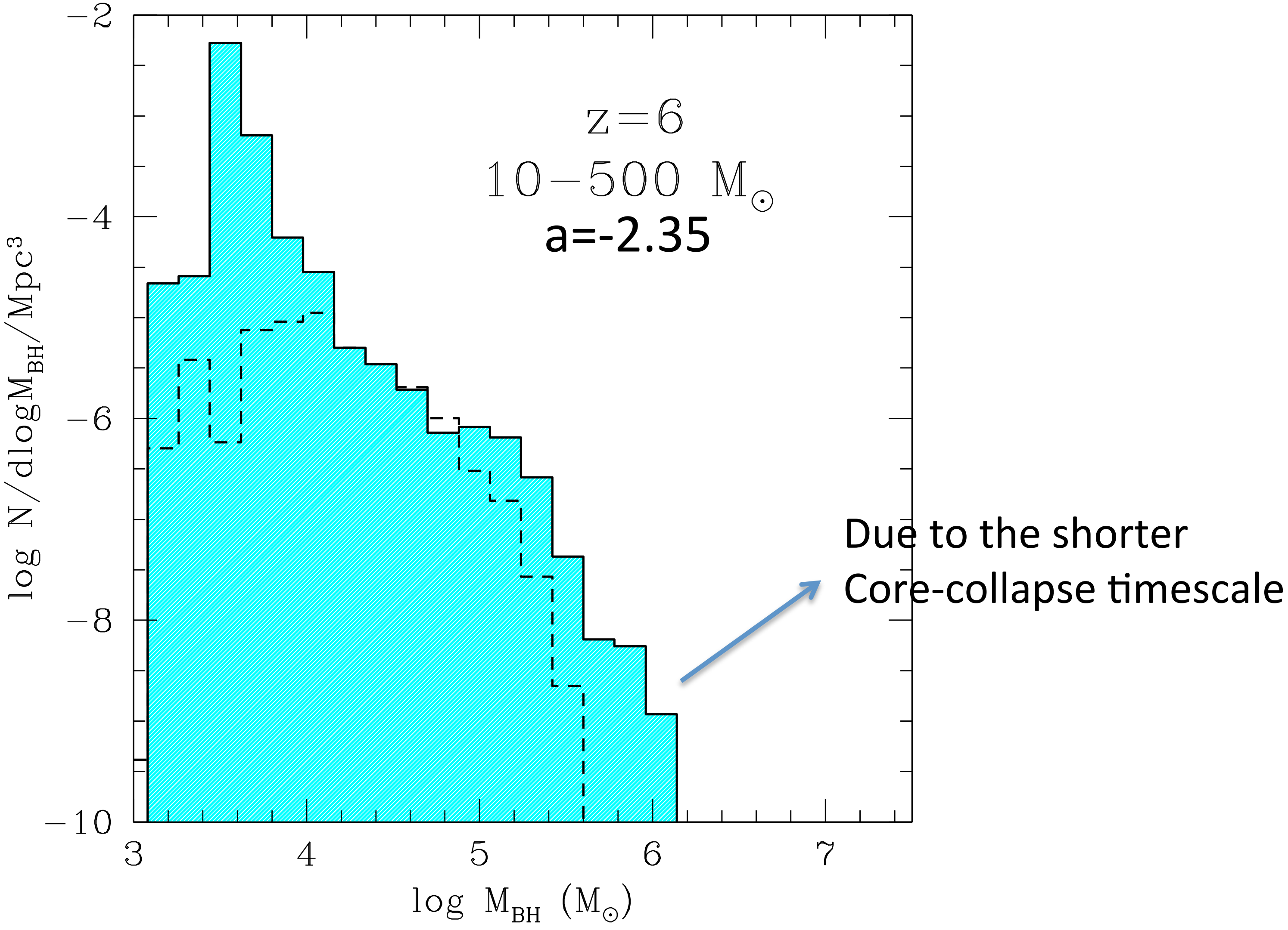
$$t = \frac{\epsilon}{1-\epsilon}\tau_{\rm Sal}\ln 10^4 \sim 0.46\ {\rm Gyr}$$

Merger Tree

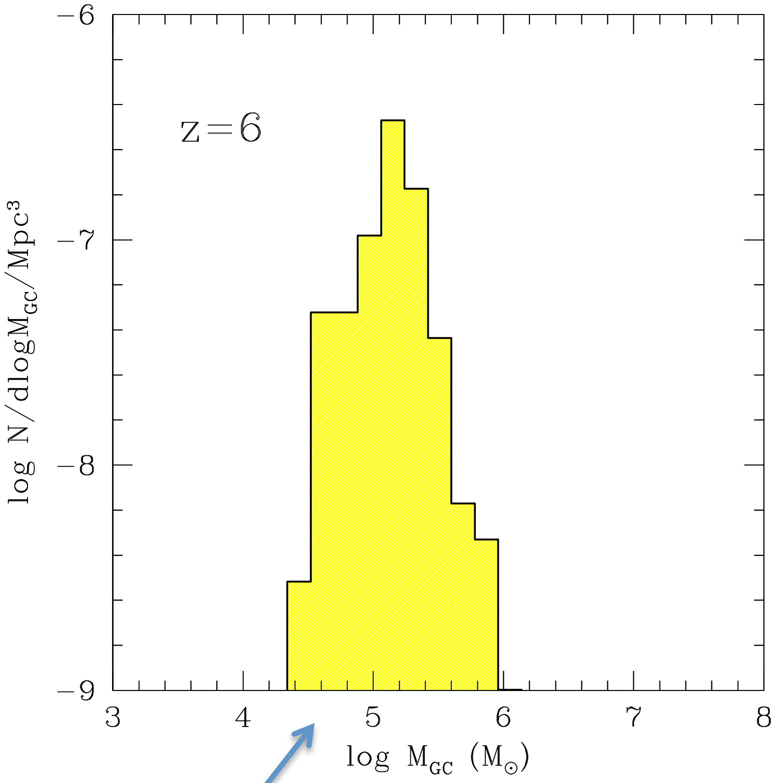
+

Seth-Tormen Halo mass function

If Pop III star clusters

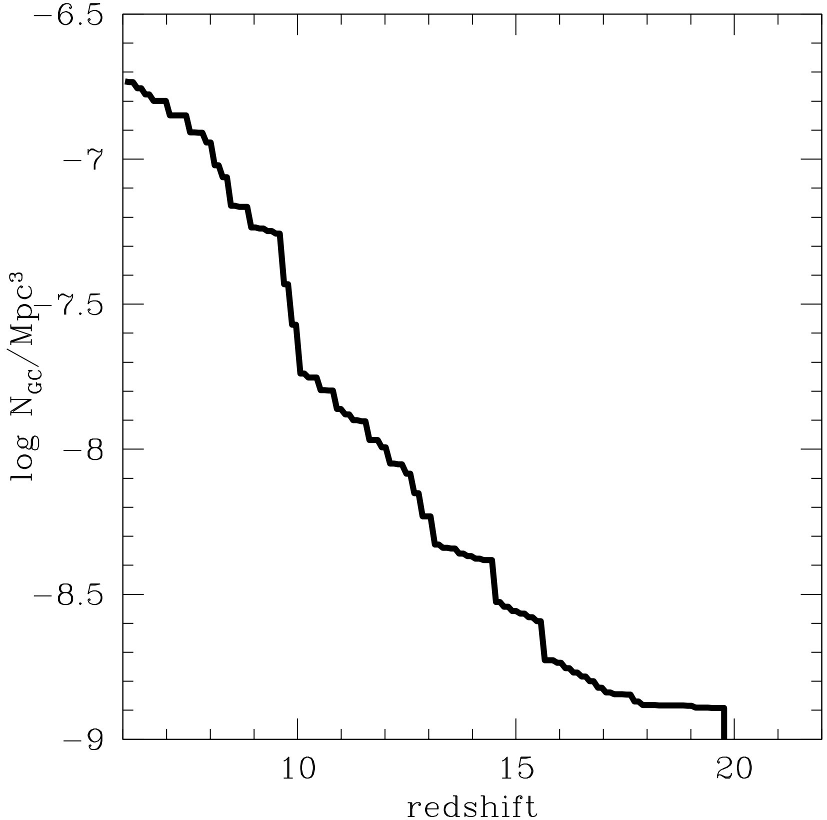


Globular Clusters



Mach the mass range of the observed local GCs

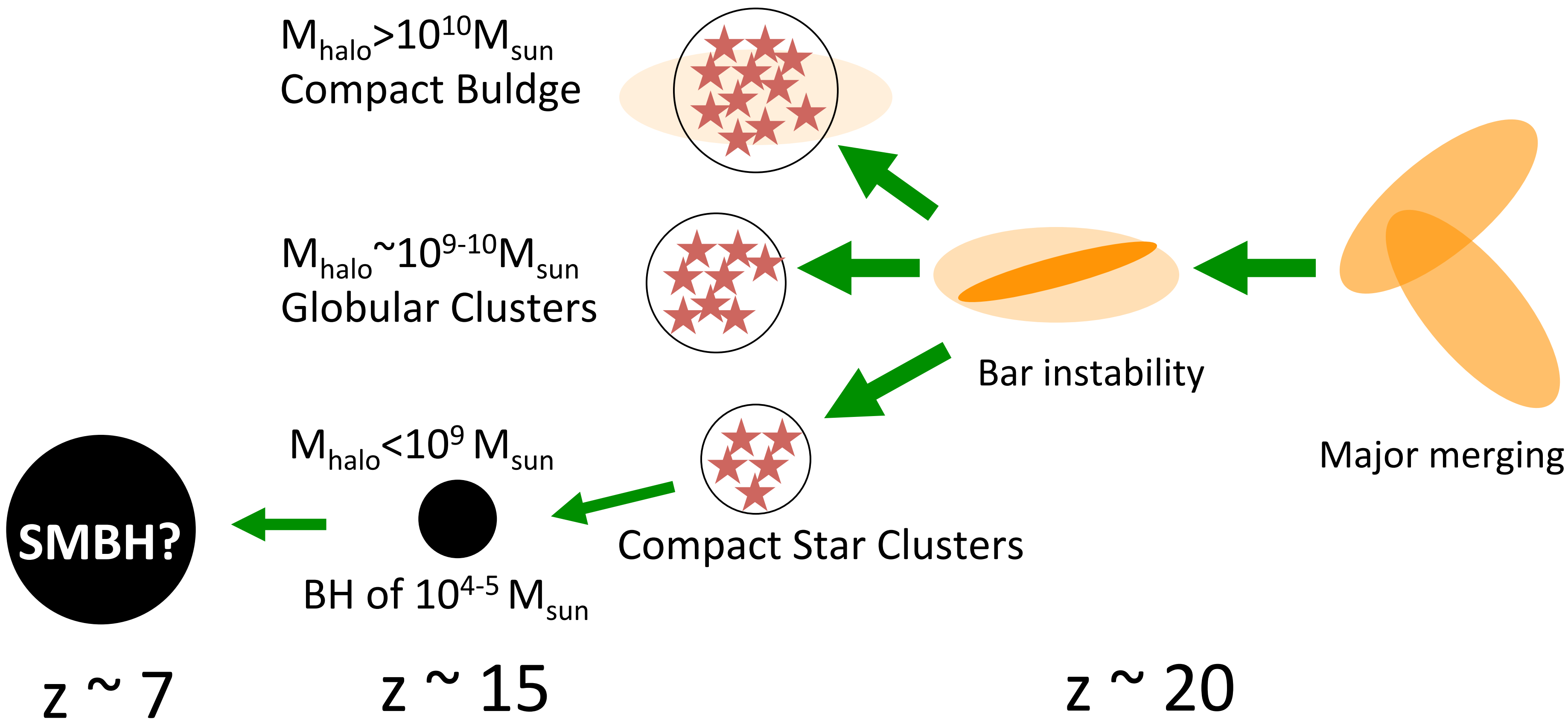
Number density of our modeled GCs Is much smaller than that of local observed GCs.



Summary

- We model the formation of SMBH seeds in merging first galaxies.
- Merging of galaxies with M_h~10^{8-9} M_{sun} leads to compact star clusters, resulting in very massive stars of ~1000 M_{sun} after the core-collapse
- Massive BHs can grow up to ~10^5 M_{sun} via stellar relaxation processes (2-body and resonant relaxation of stars)

Schematic view of our model



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