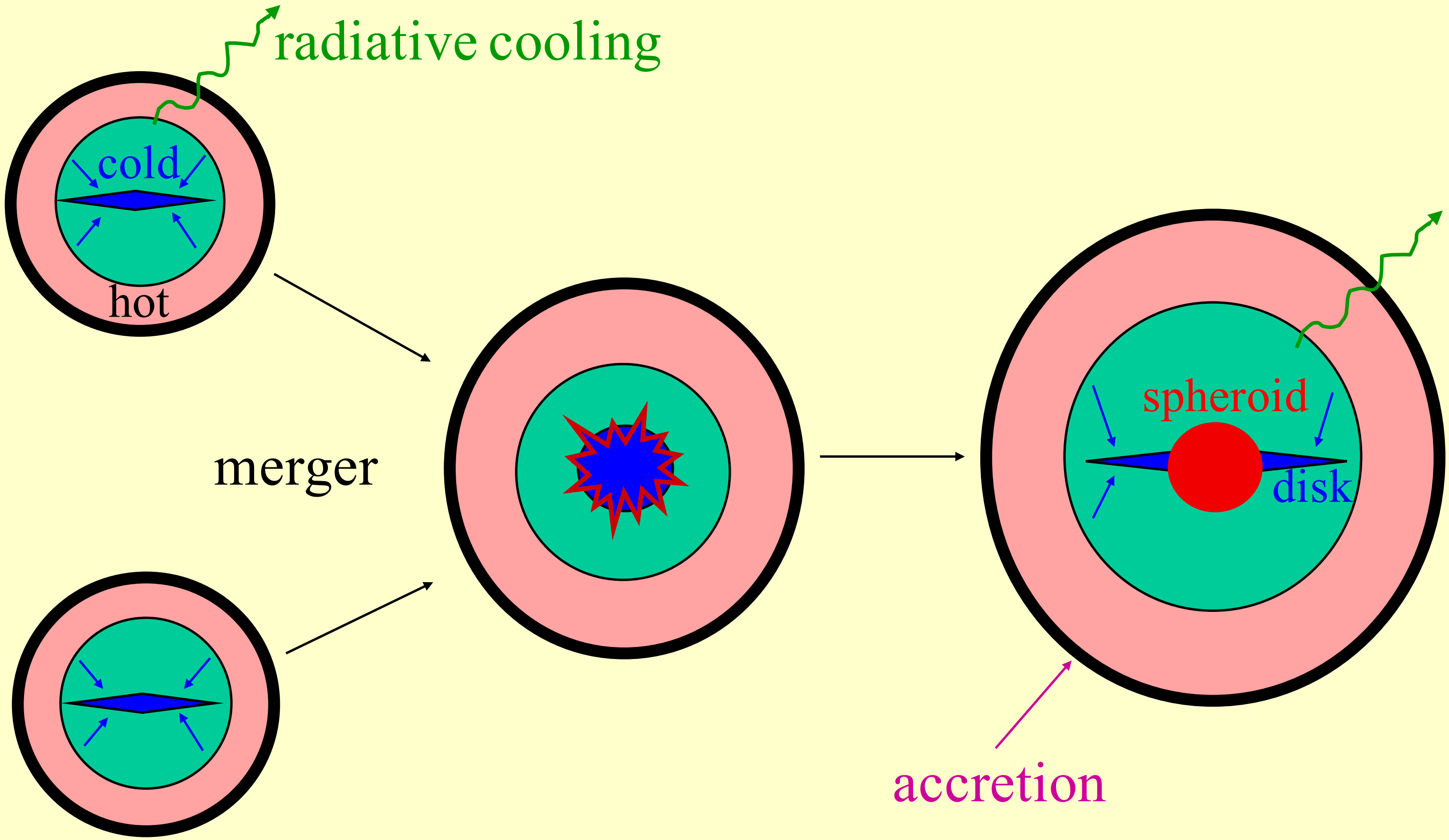
Semi-Analytic Modeling of Galaxy Formation

Standard Paradigm: Mergers



halos cold gas young stars old stars

Gas removal by QSOs leads to red-and-dead Ellipticals

Standard Picture of Infall to a Disc

Rees & Ostriker 77, Silk 77, White & Rees 78, ...

Perturbed expansion

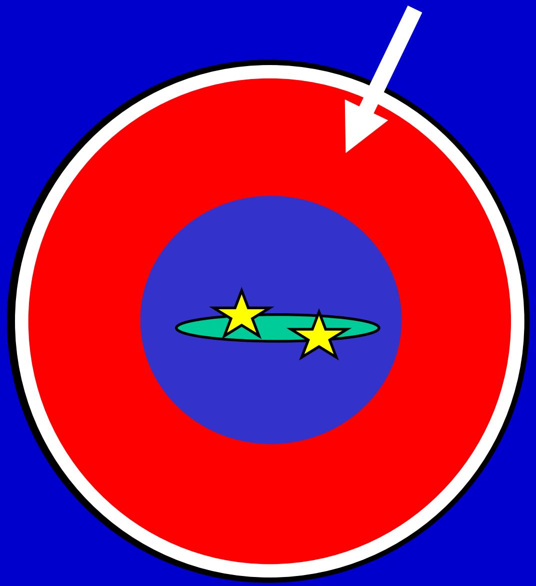
Halo virialization

Gas infall, shock heating at the virial radius

Radiative cooling

Accretion to disc if $t_{cool} < t_{ff}$

Stars & feedback



$M < M_{cool} \sim 10^{12-13} M_{\odot}$

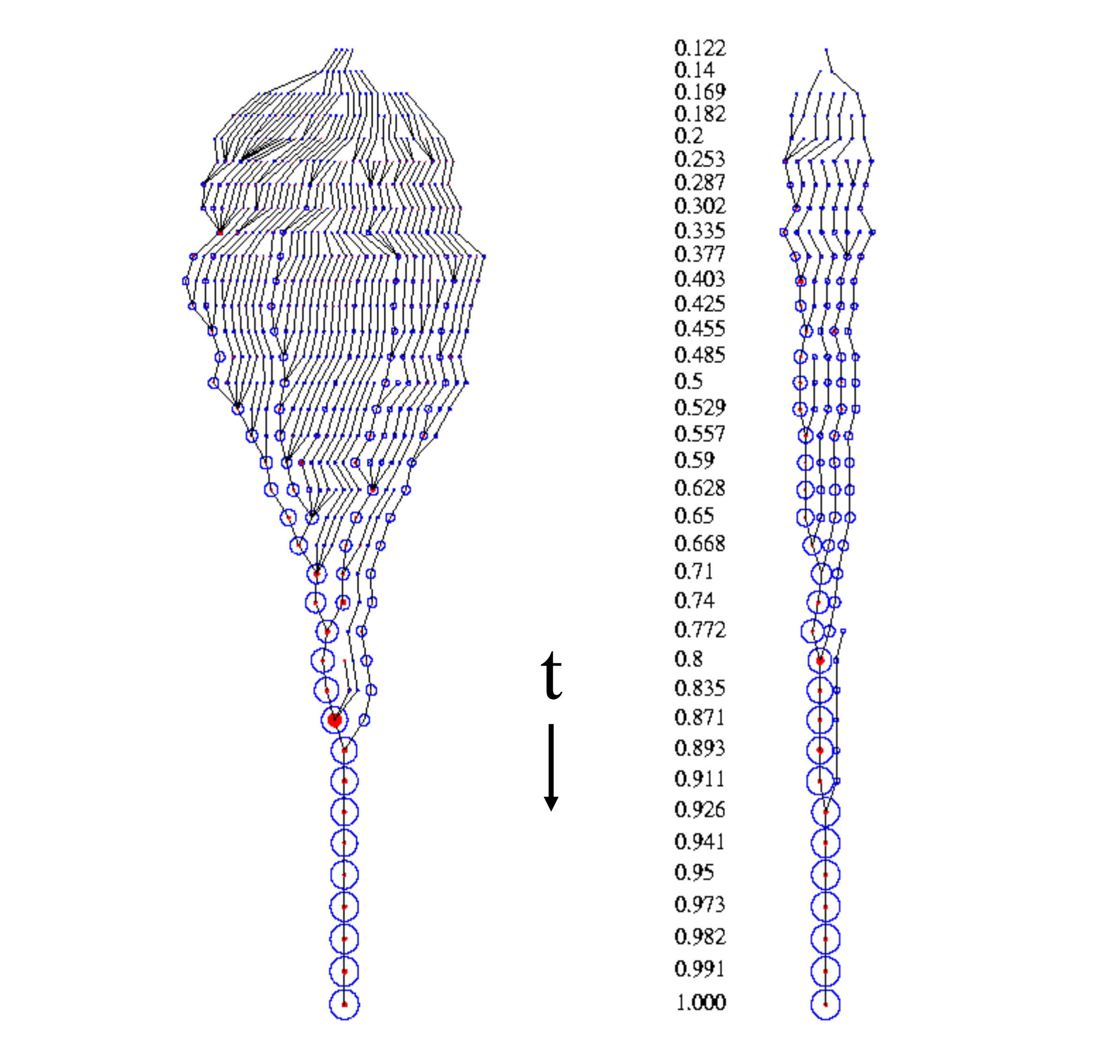
Semi-Analytic Modeling

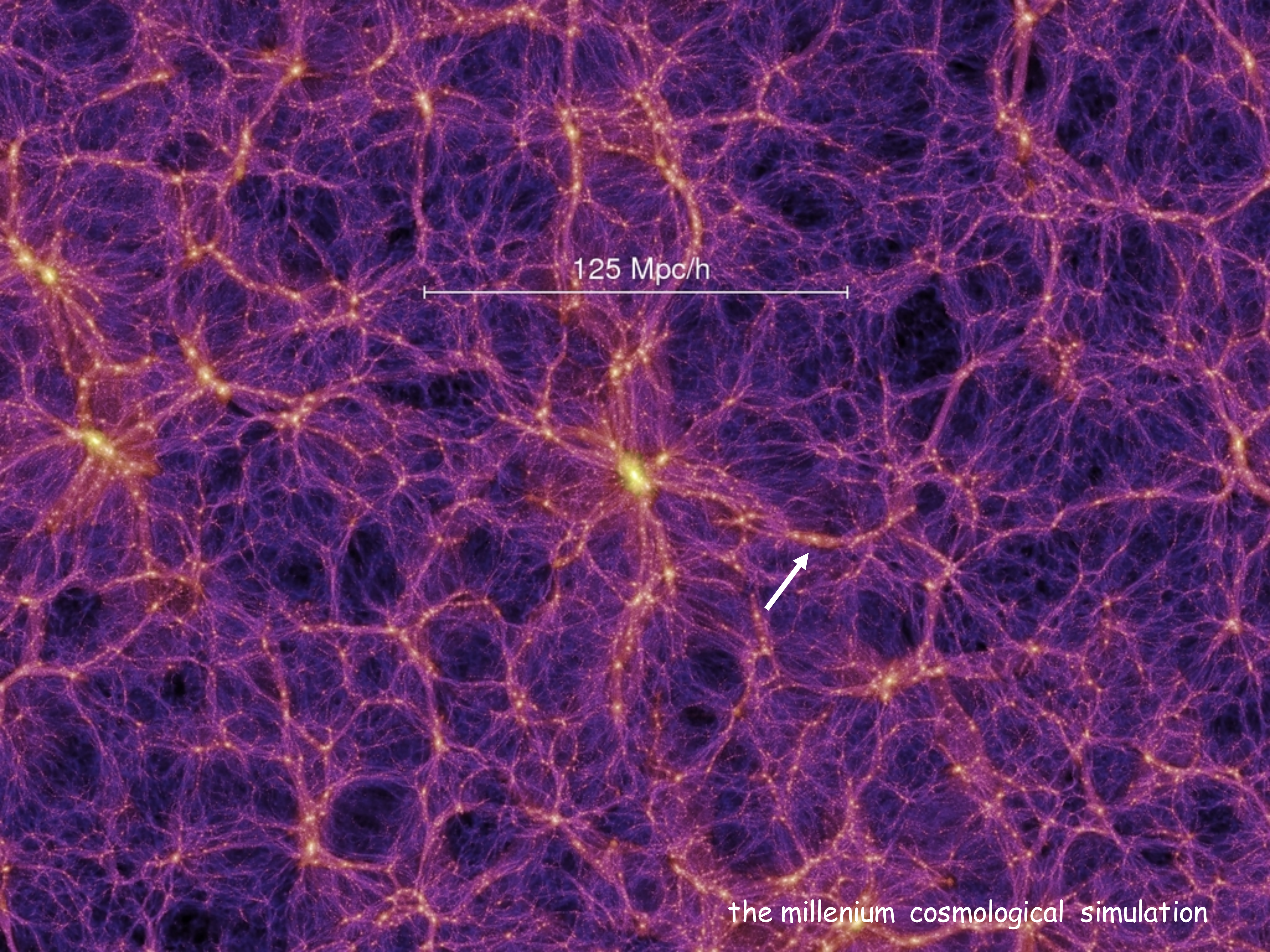
- Dark-matter halo merger tree (from EPS or N-body simulation)
  - Sub-halos by semi-analytic dynamical friction or high-res simulation

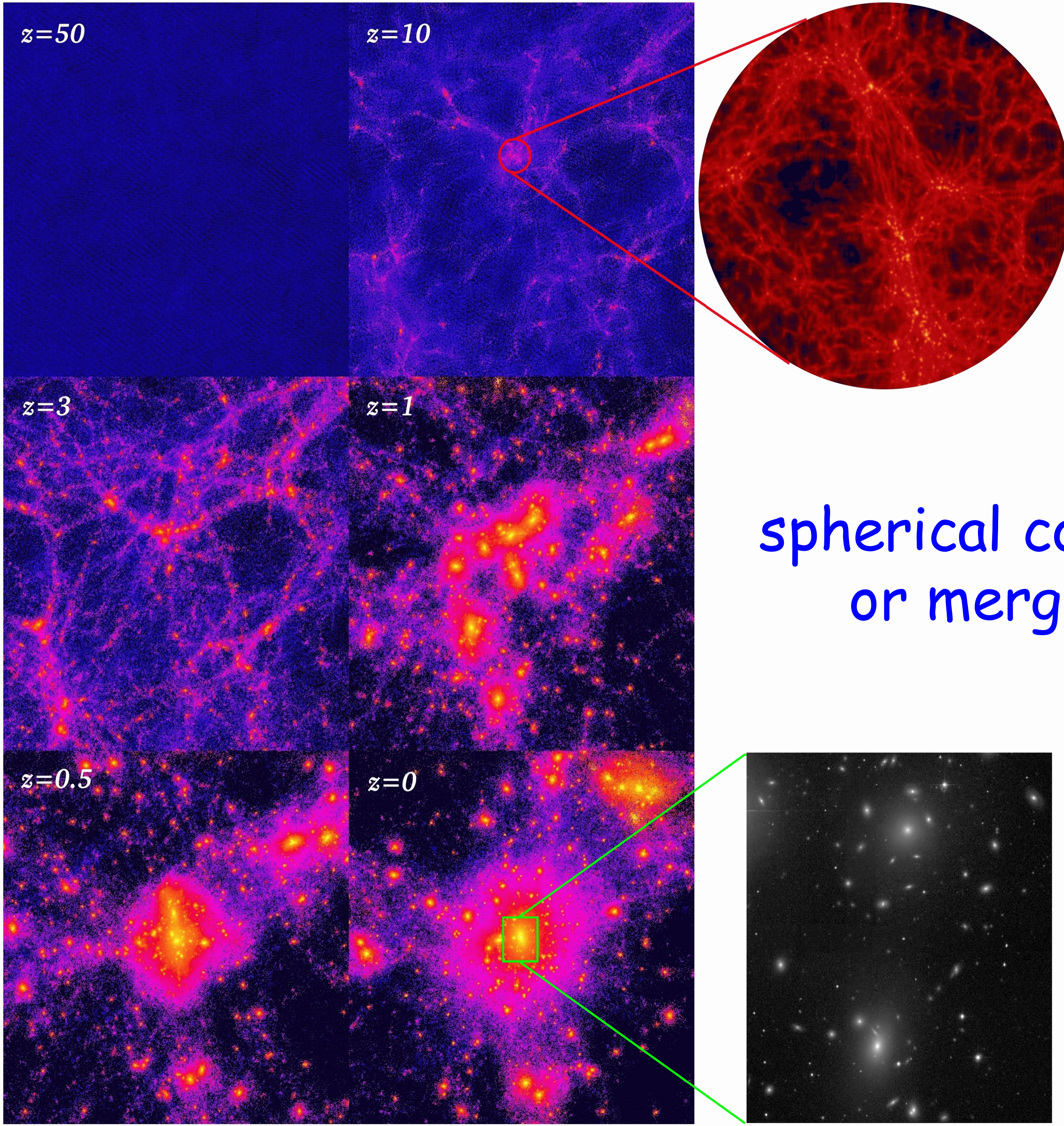
- Gas physics via recipes with free parameters – subgrid physics
  - Gas cooling and infall (M,z) – streams, virial shock heating
  - Star formation (ρ_{gas},T)
  - Feedback from stars and supernovae
  - Black-holes, AGN feedback

- Observables

Merger Tree: conditional probability



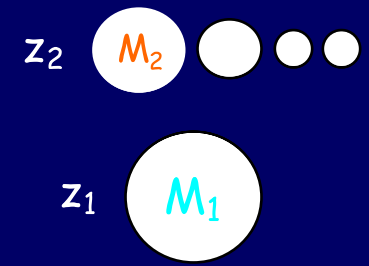

125 Mpc/h
the millenium cosmological simulation



spherical collapse
or mergers

Extended Press-Schechter (EPS): Merger Tree

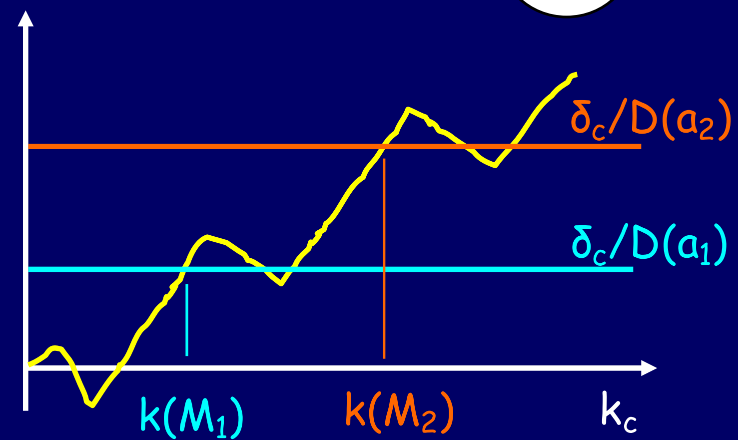
Given that a mass element belongs to halo M_1 at z_1,
what is the probability that it belonged to halo M_2 ($<M_1$) at z_2 ($>z_1$)?



Equivalent:

Given that $\delta_s(x;k_c)$ first crossed $\delta_c/D(a_1)$ at $k_c=k(M_1)$,

what is the probability that it first crossed $\delta_c/D(a_2)$ at $k_c=k(M_2)$.

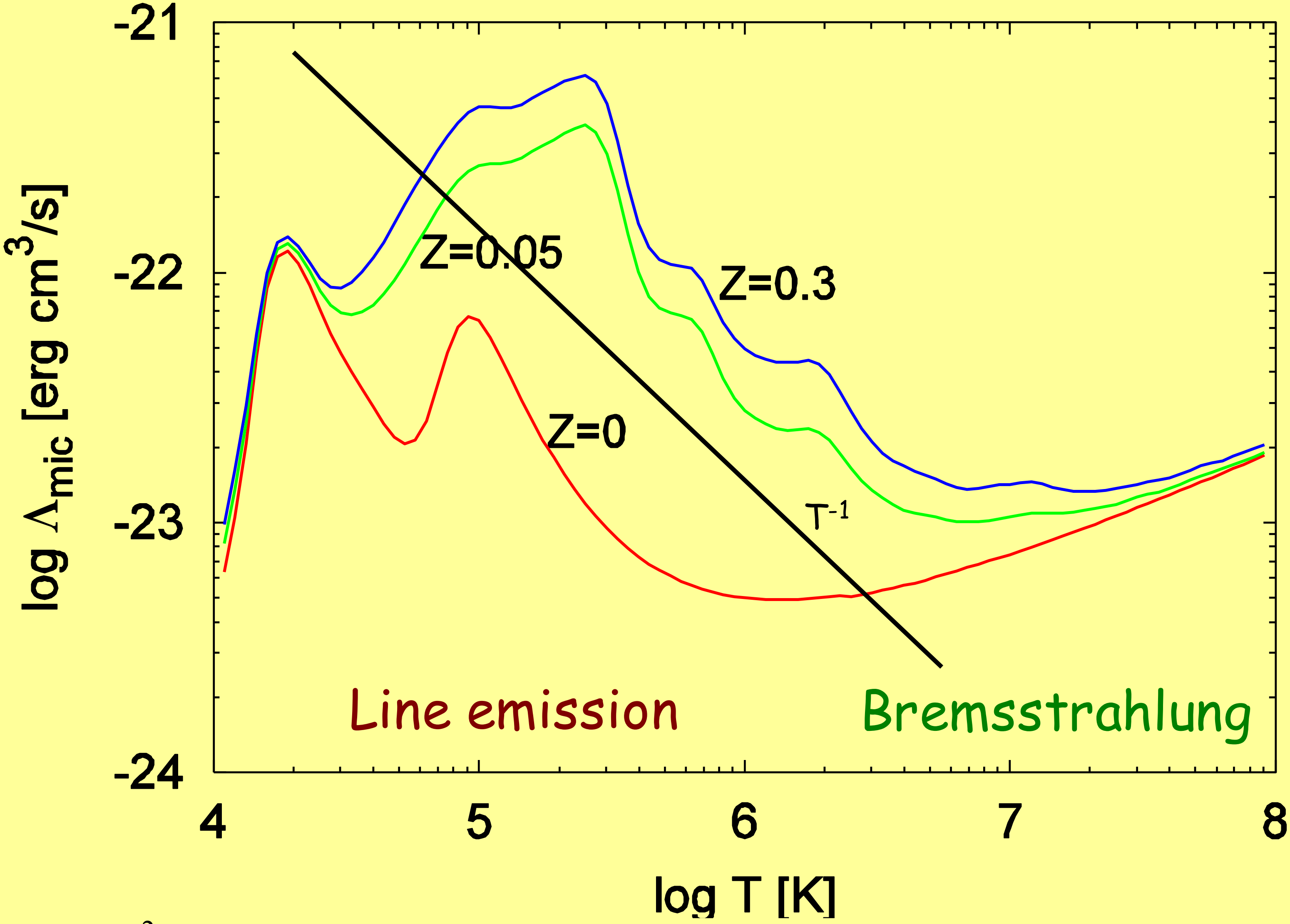


The same problem as before
but with the origin shifted:

$$n(M_2,z_2\,|\,M_1,z_1)\,dM_2 = -\left(\frac{2}{\pi}\right)^{1/2}\frac{M_1}{M_2}\,\frac{\delta_c(D_2^{-1}-D_1^{-1})}{(\sigma_2^{\,2}-\sigma_1^{\,2})^{1/2}}\,\frac{d\ln(\sigma_2^{\,2}-\sigma_1^{\,2})^{1/2}}{d\ln M_2}\,\exp\left(\frac{\delta_c^{\,2}(D_2^{-1}-D_1^{-1})^2}{2(\sigma_2^{\,2}-\sigma_1^{\,2})}\right)\frac{dM_2}{M_2}$$

- # of bright E galaxies in a cluster: $M=10^{15}$ today, how many 10^{12} progenitors at $z=2$?
- descendents of LGBs: massive halos at $z=3$ have $n=10^{-2}\,Mpc^{-1}$, what mass halos do they inhibit today?
- When did the most massive progenitor include half its current mass?
- How often do two 10^{12} halos merge?
- Infall rate of spirals into clusters: How often does a 10^{15} halo accrete a 10^{12} halo?

Cooling rate



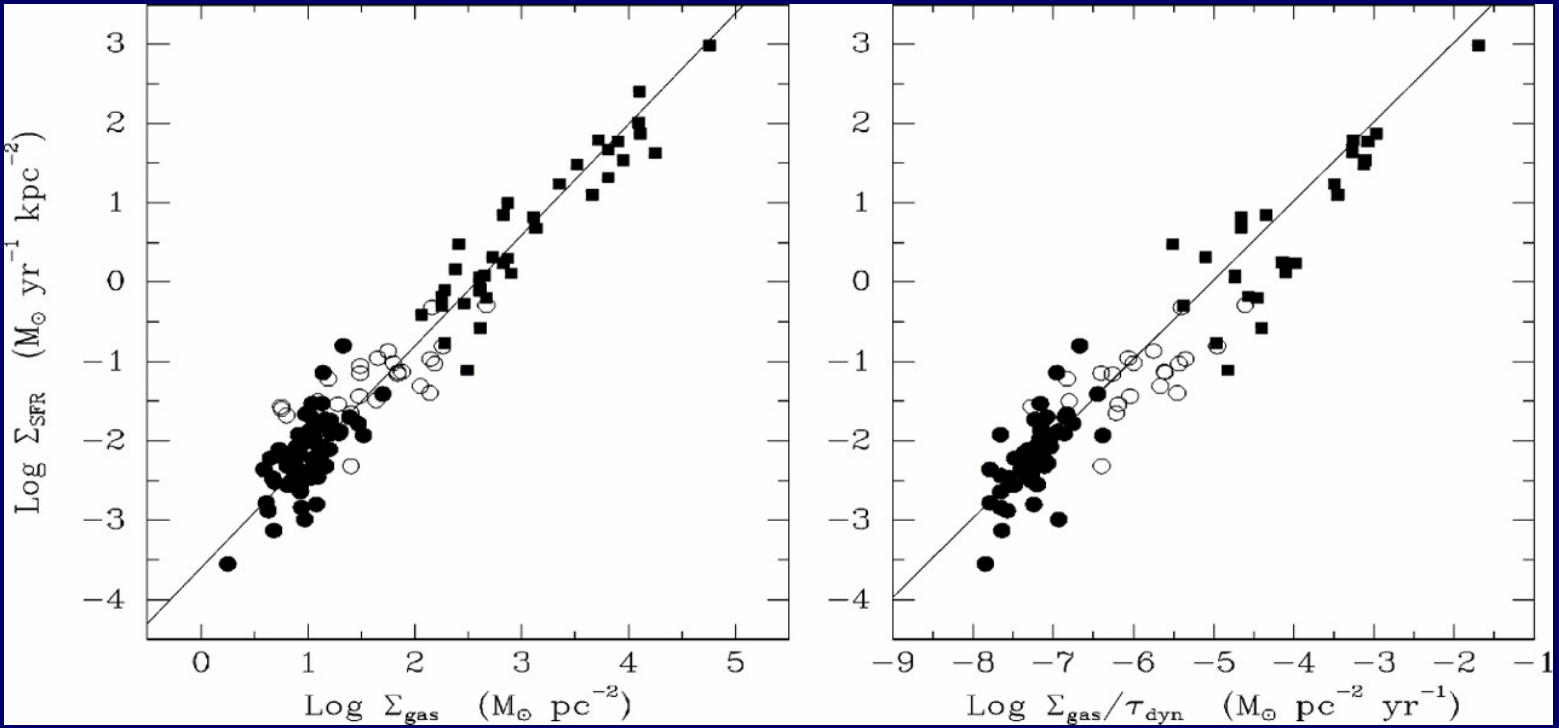
$$q = \frac{N_A{}^2 \chi^2}{\mu^2} \Lambda(T) \rho \quad [\mathrm{erg\,g^{-1}\,s^{-1}}] \qquad N_A / \mu \text{ molecules per g} \qquad \chi\ e^- \text{ per particle}$$

Star Formation Rate

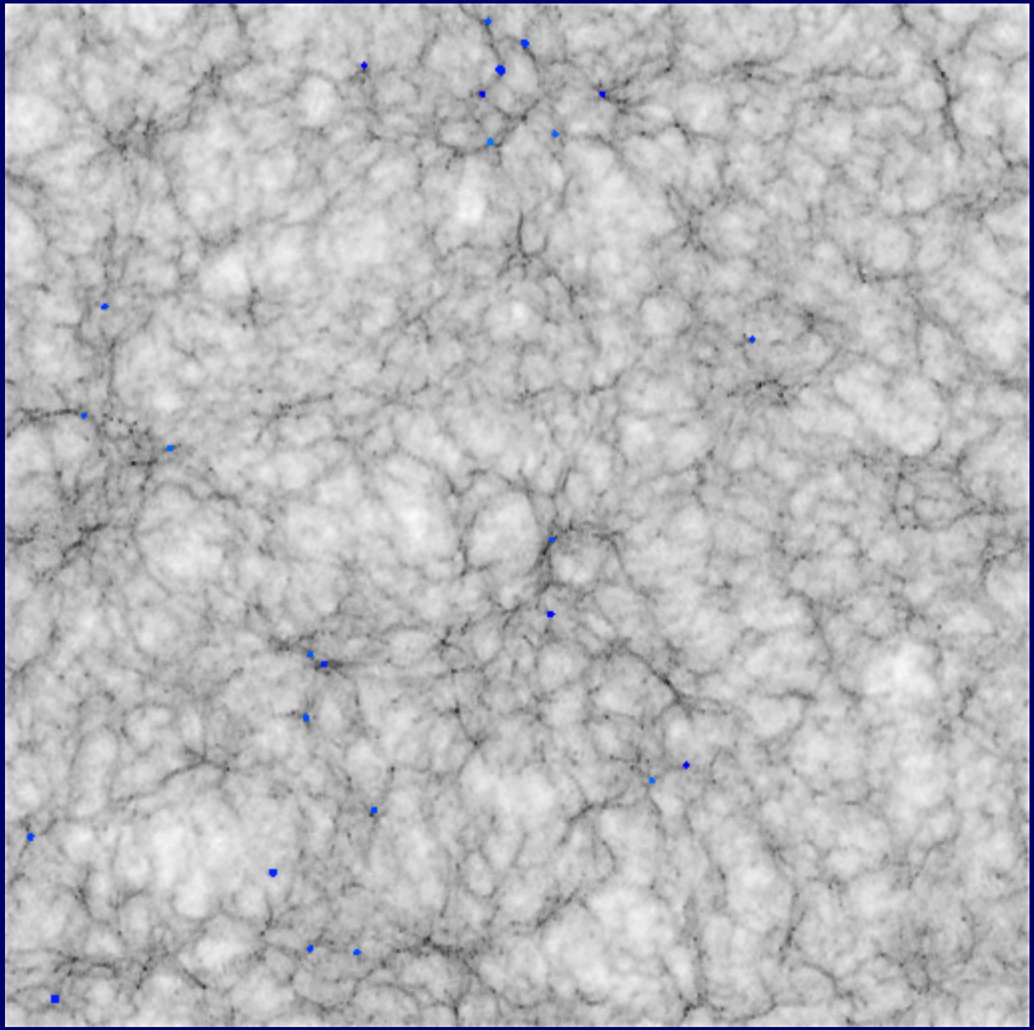
$$\text{Jeans mass} \quad M_J \equiv \frac{4\pi}{3}\rho_m\left(\frac{\pi c_s^{\,2}}{G\rho}\right)^{3/2} \propto \frac{T^{3/2}}{\rho^{1/2}}$$

$$\dot{\rho}_* = \eta\frac{\rho_{gas}}{t_{dyn}} \propto \rho_{gas}^{3/2} \qquad \eta \approx 0.01$$

Kennicutt-Schmidt law of SFR

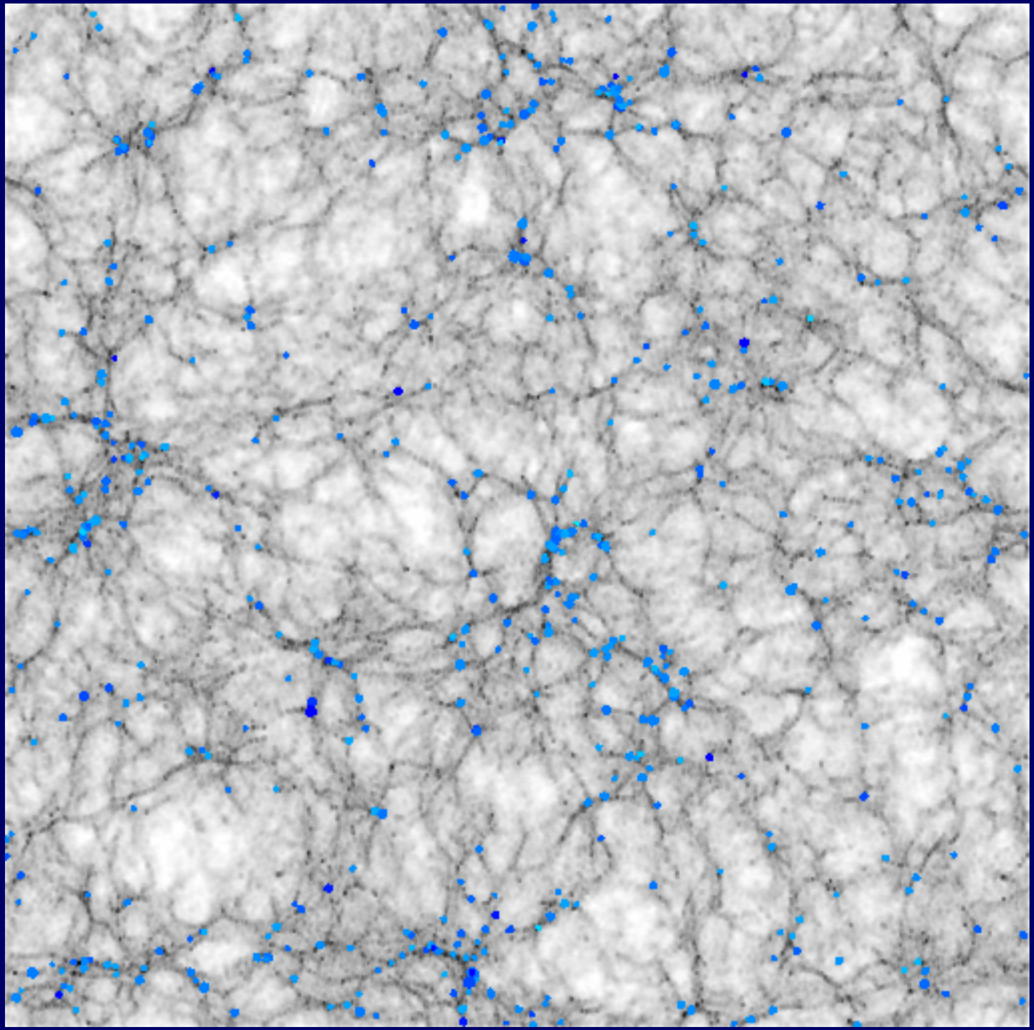


z=5

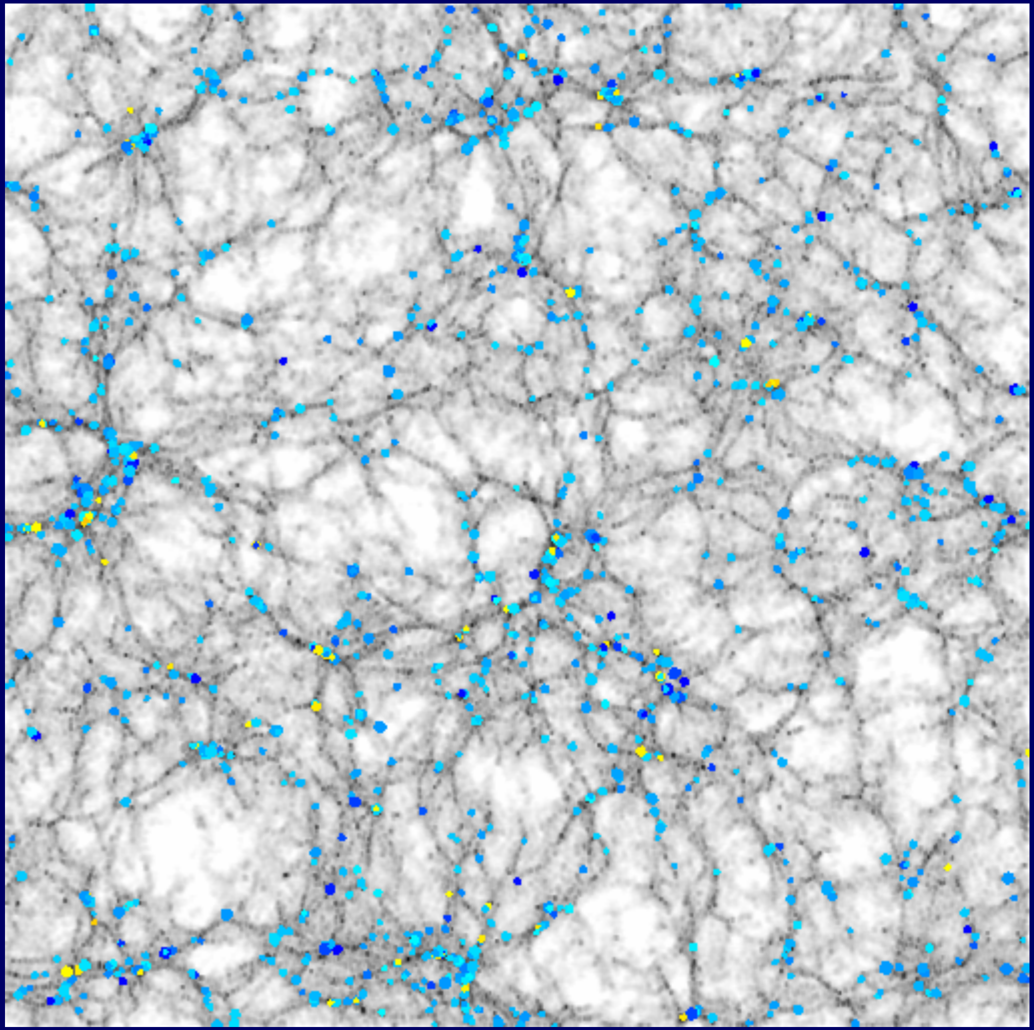


Durham SAM – Benson: Full simulation

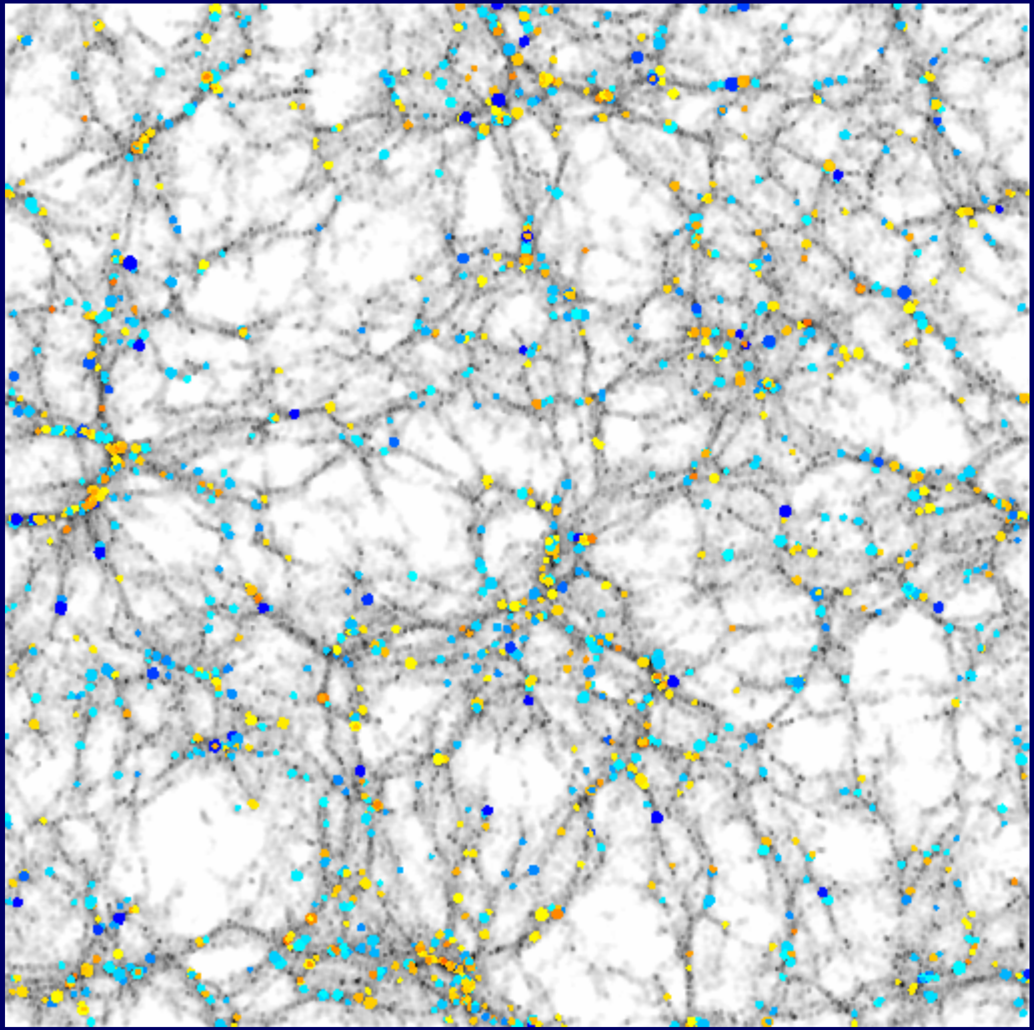
z=3



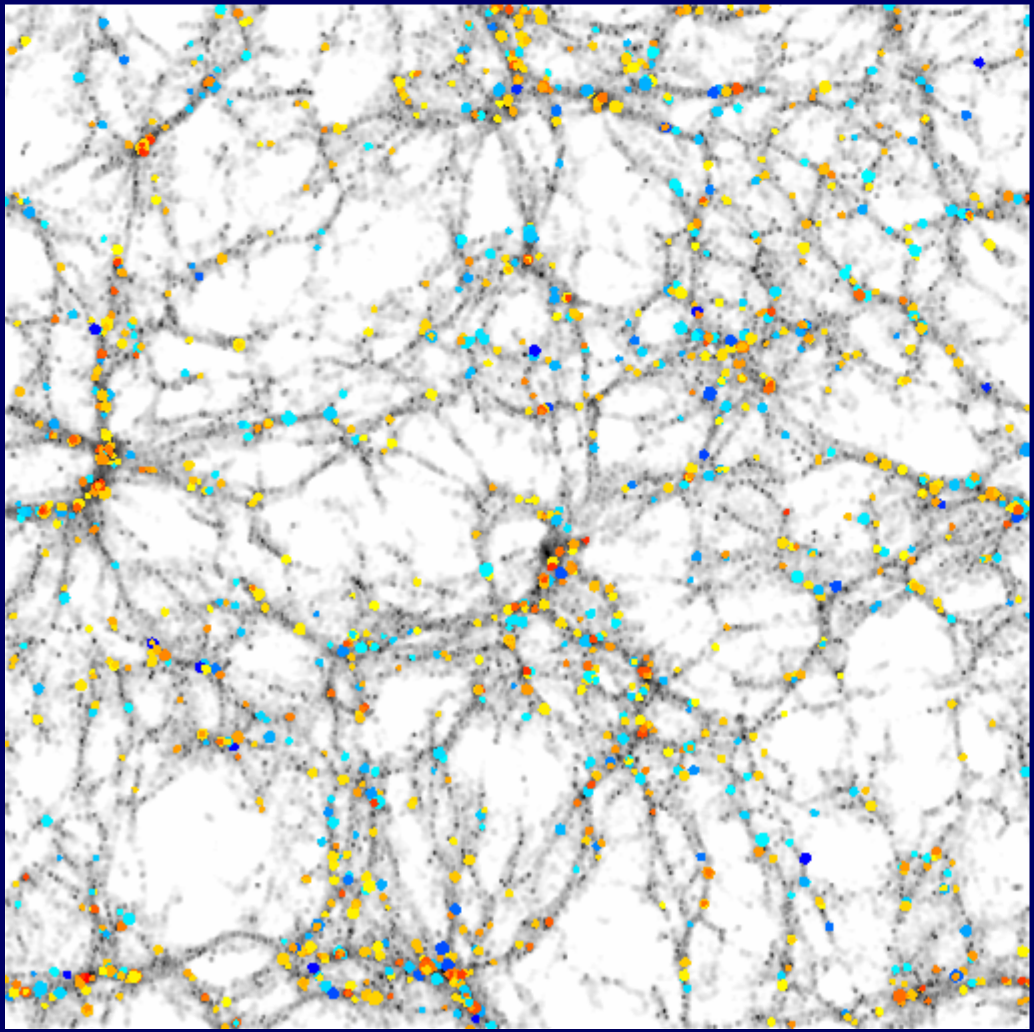
z=2



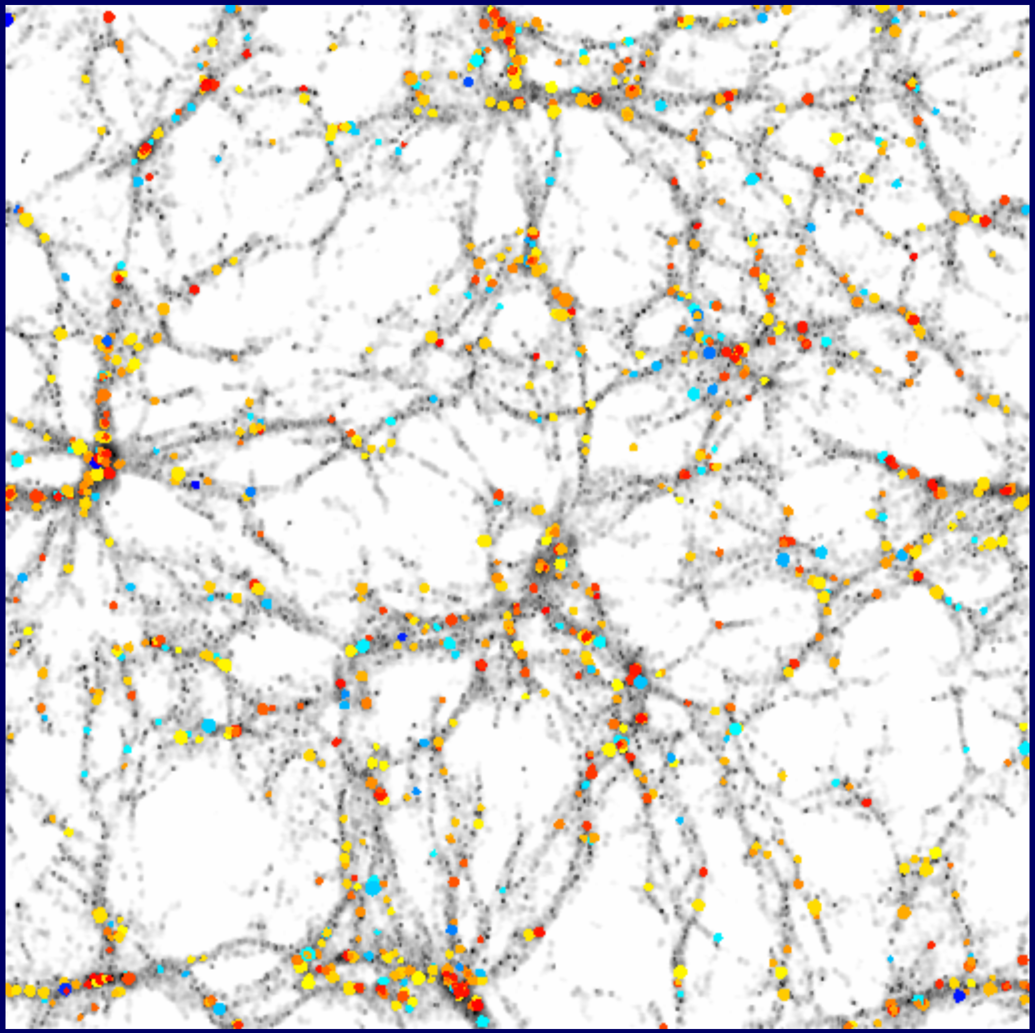
z=1



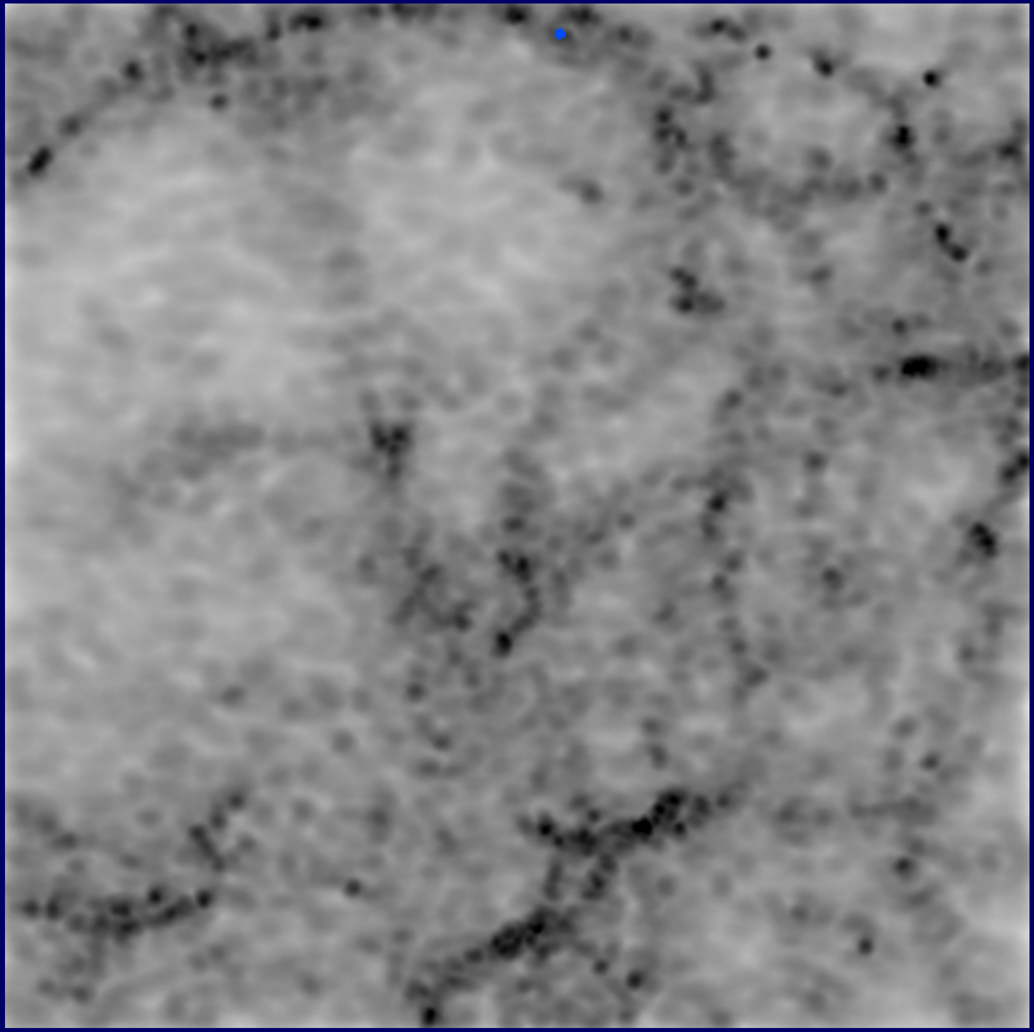
z=0.5



z=0

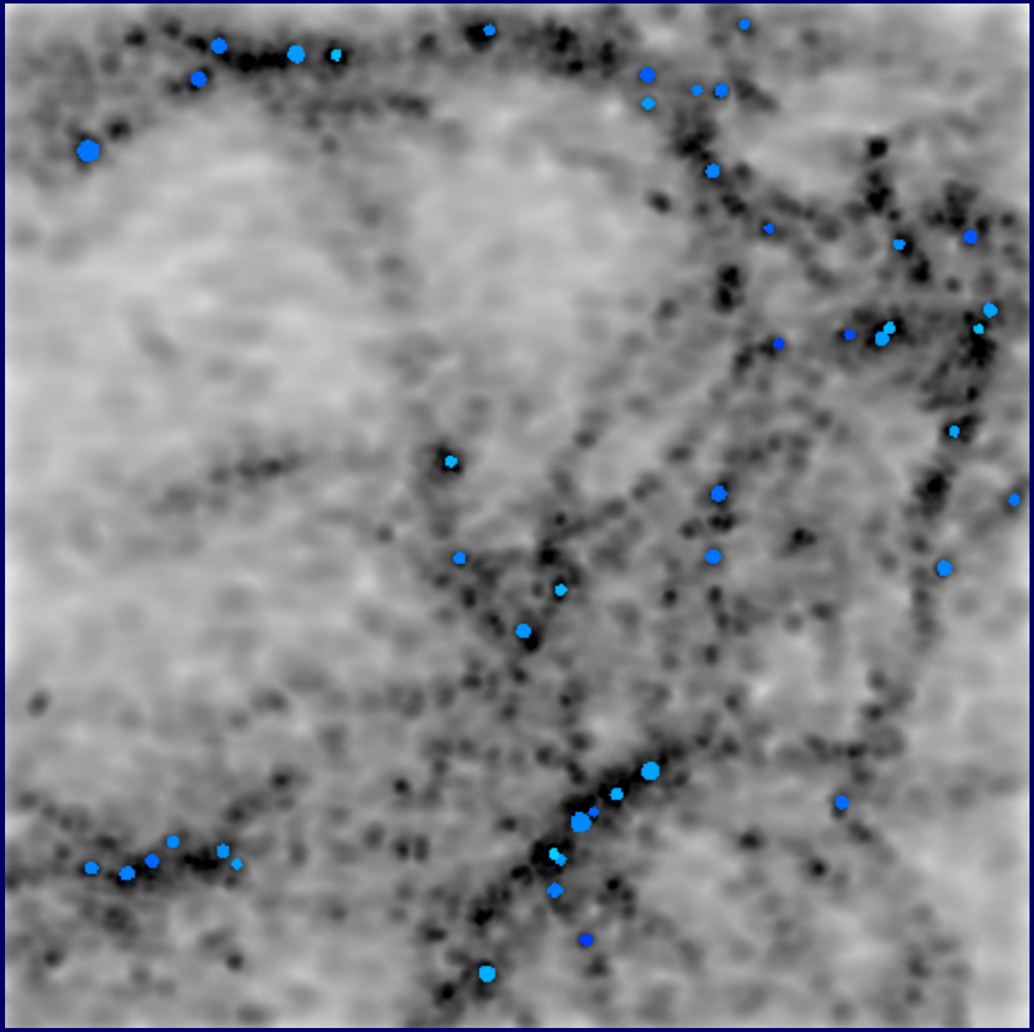


z=5

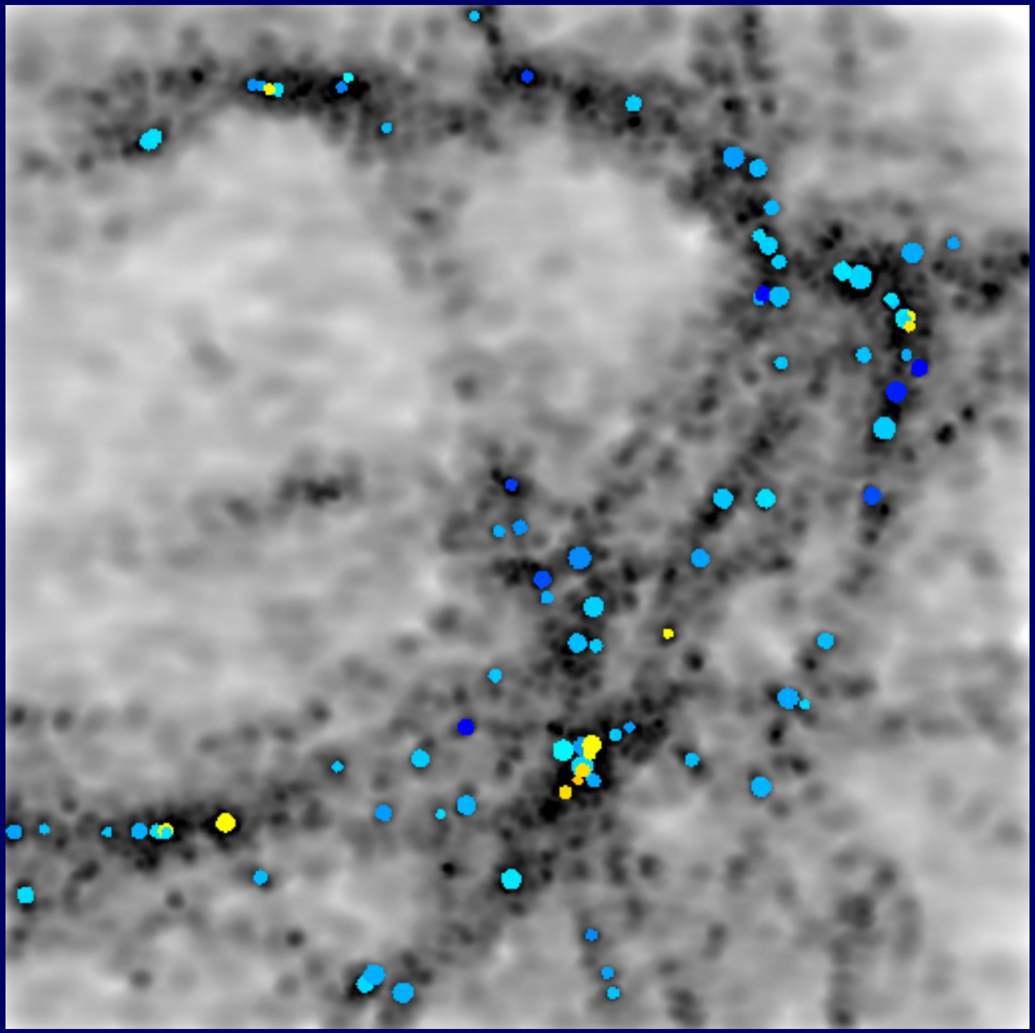


Durham SAM – Benson: Cluster region

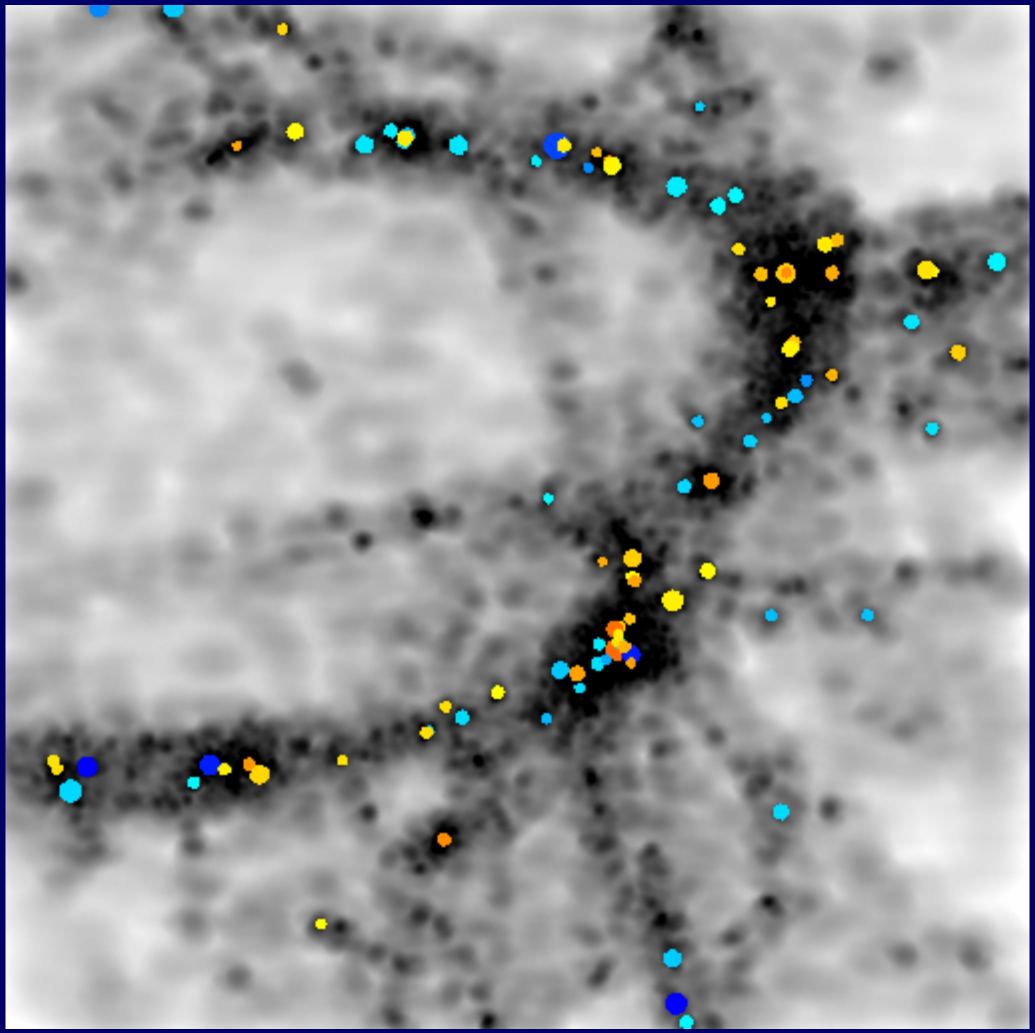
z=3



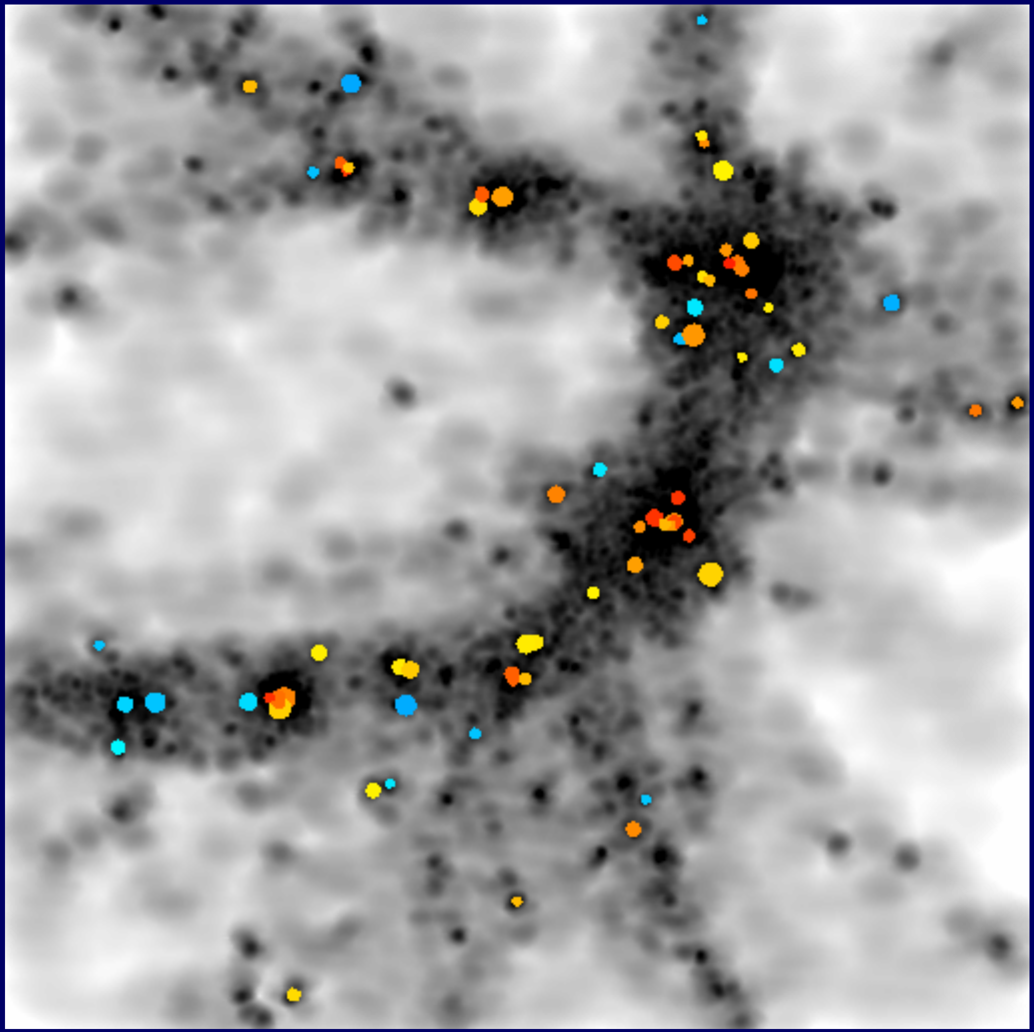
z=2



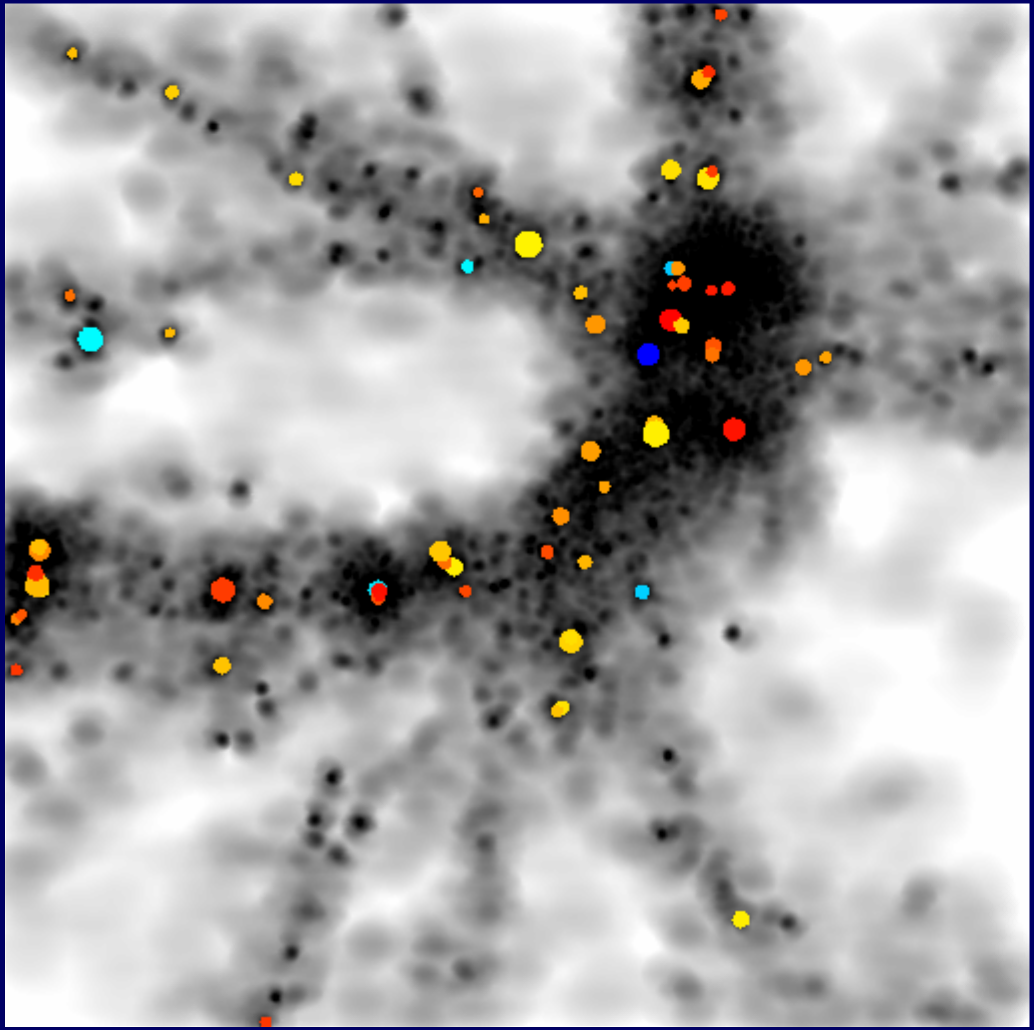
z=1

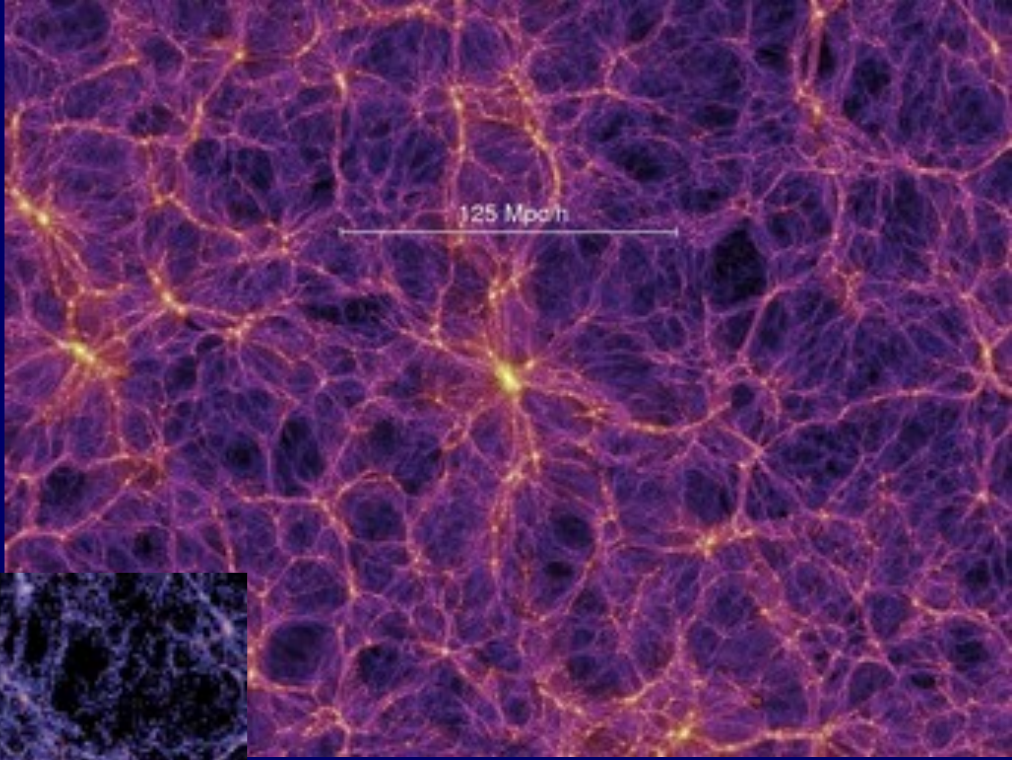


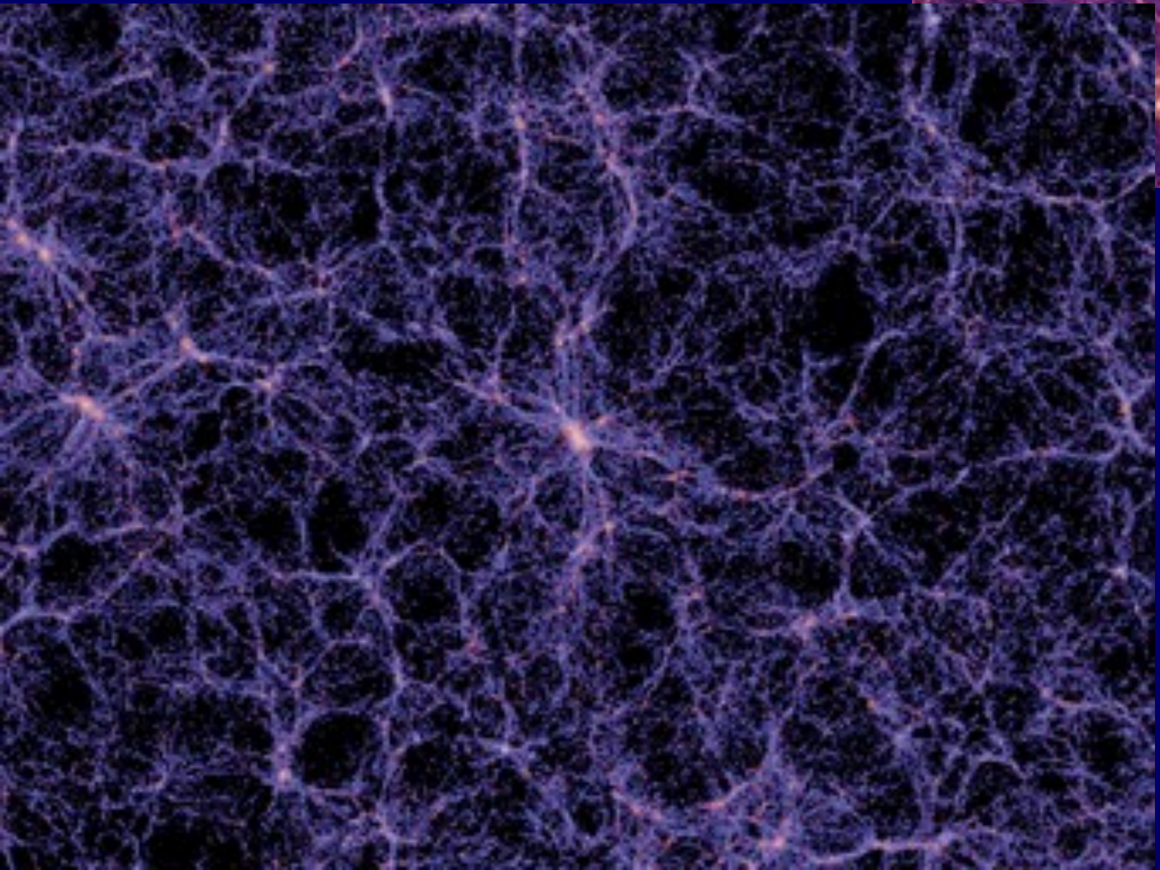
z=0.5

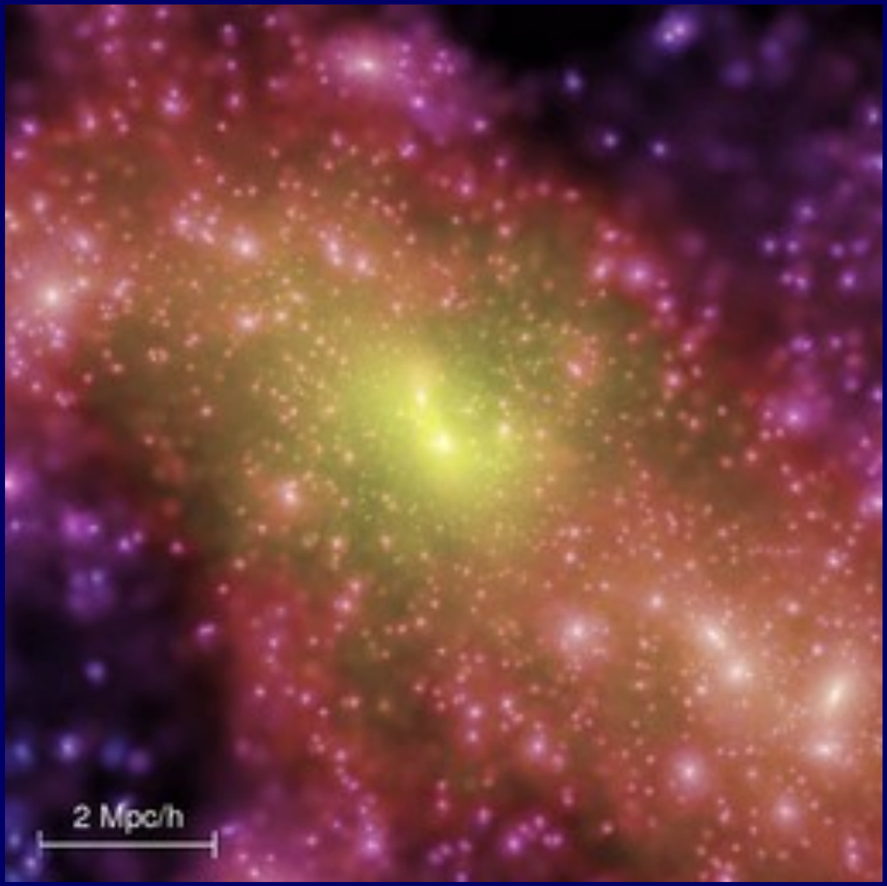


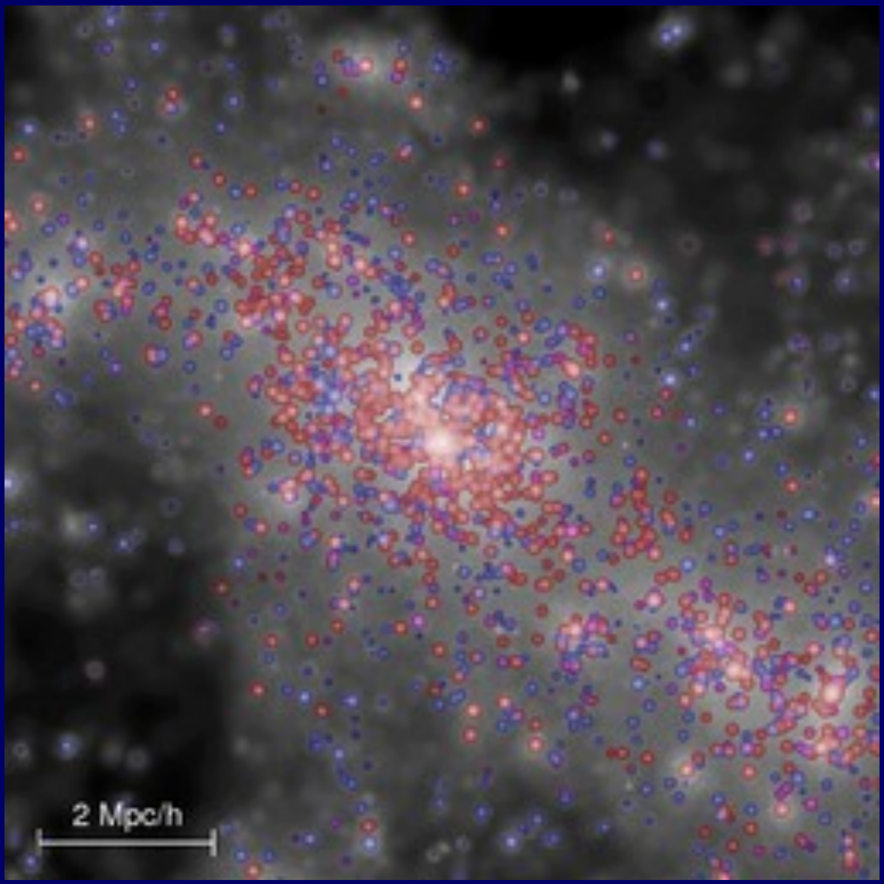
z=0



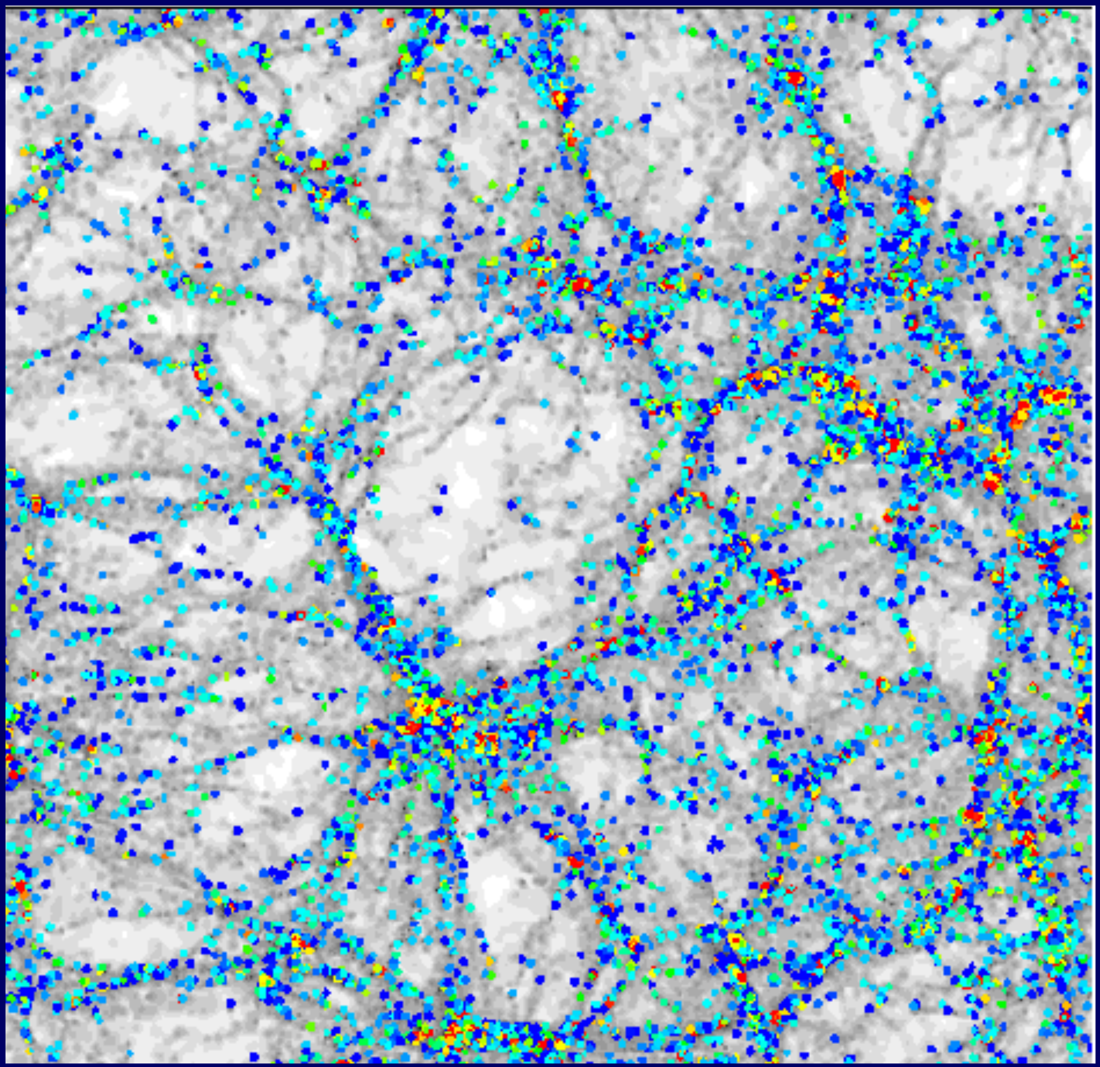

125 Mpc/h




2 Mpc/h


2 Mpc/h

Galaxy type correlated with large-scale structure



elliptical

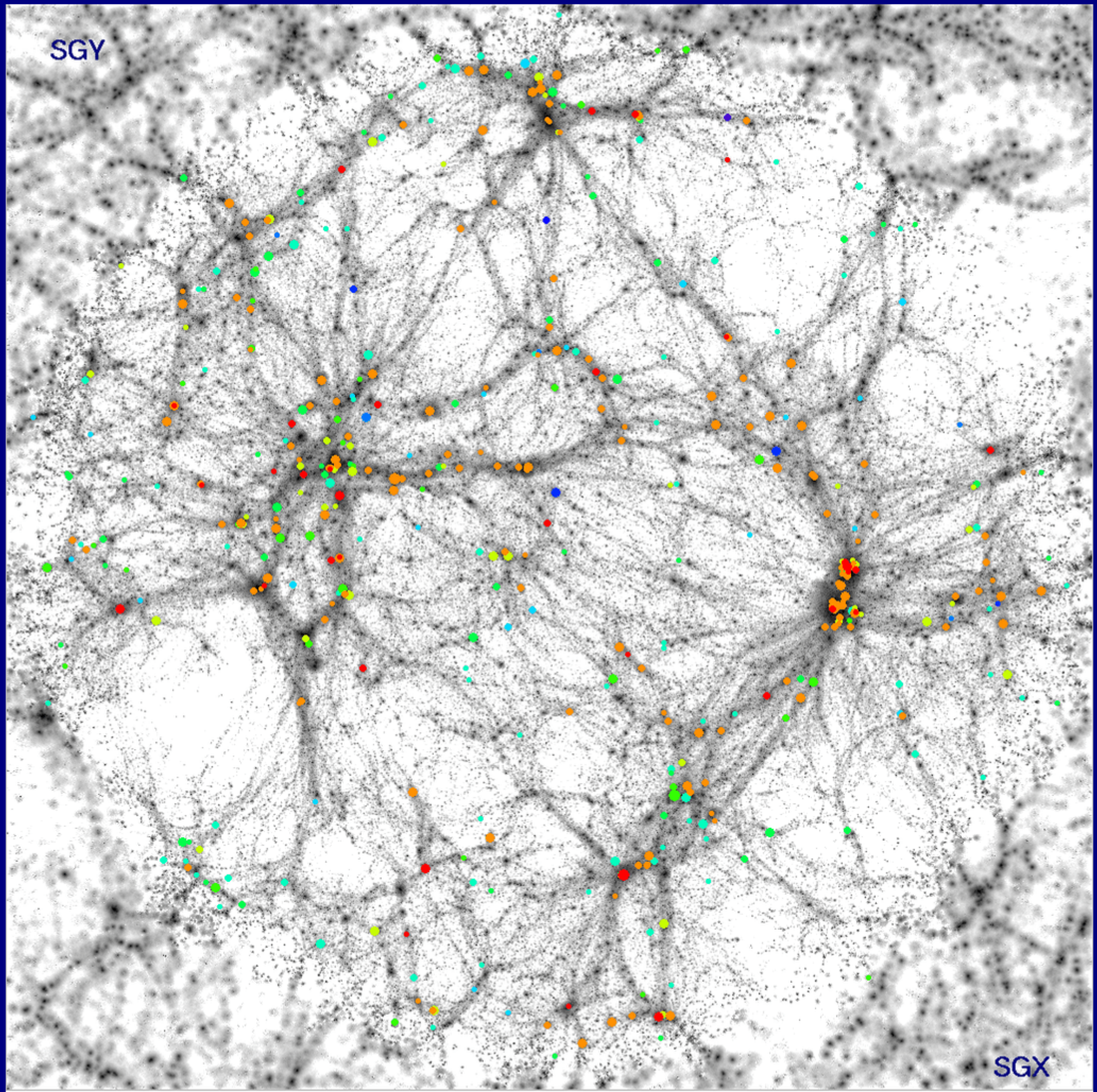
elliptical

bulge+disk

disk

Semi-Analytic Modeling

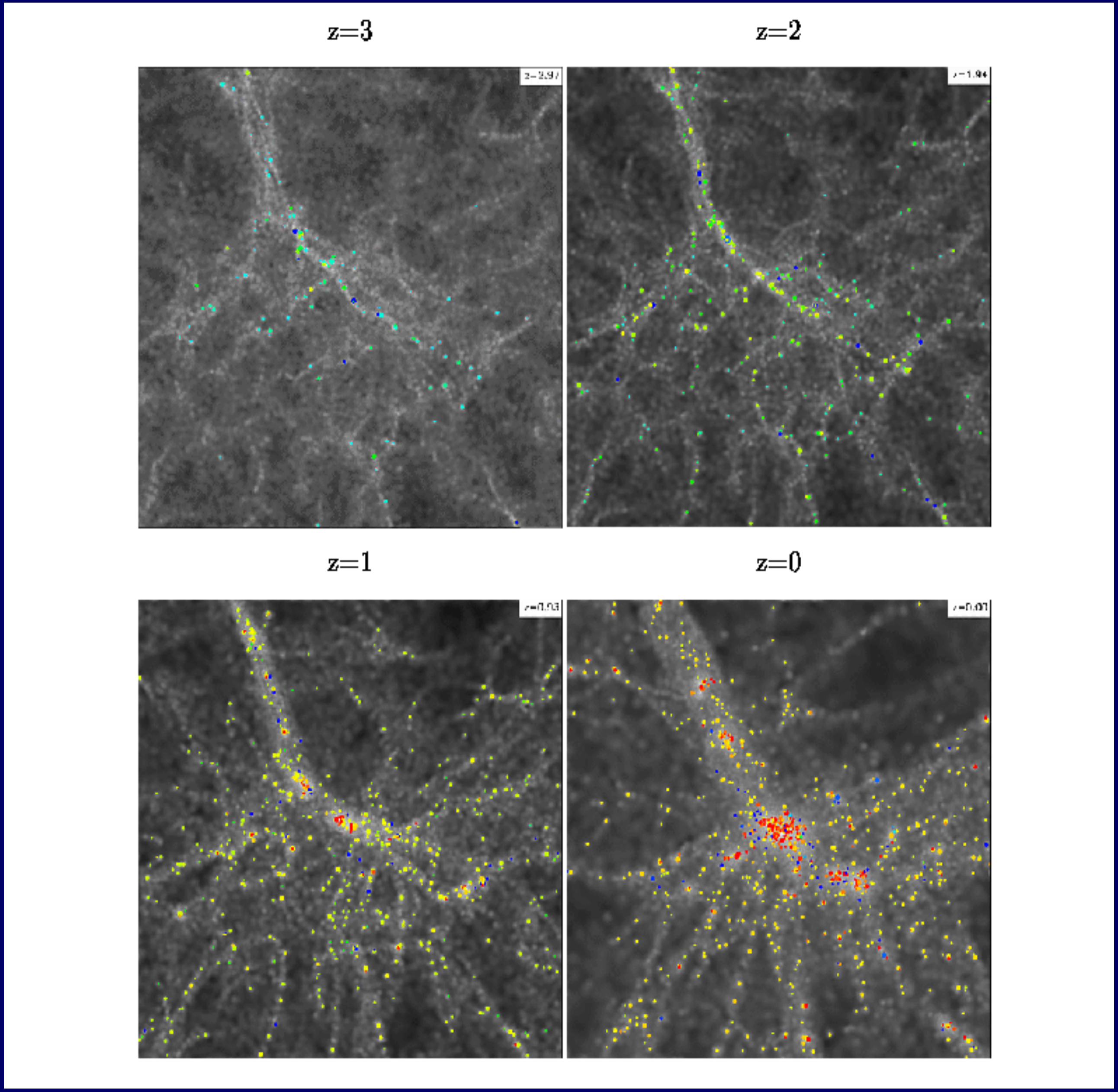
Elliptical galaxies in the local universe: biased with respect to the dark matter



ΛCDM CR : E and S0 galaxies
Credits : Mathis, Lemson, Springel, Kauffmann, White and Dekel.

GIF simulation

Formation of galaxies in a cluster

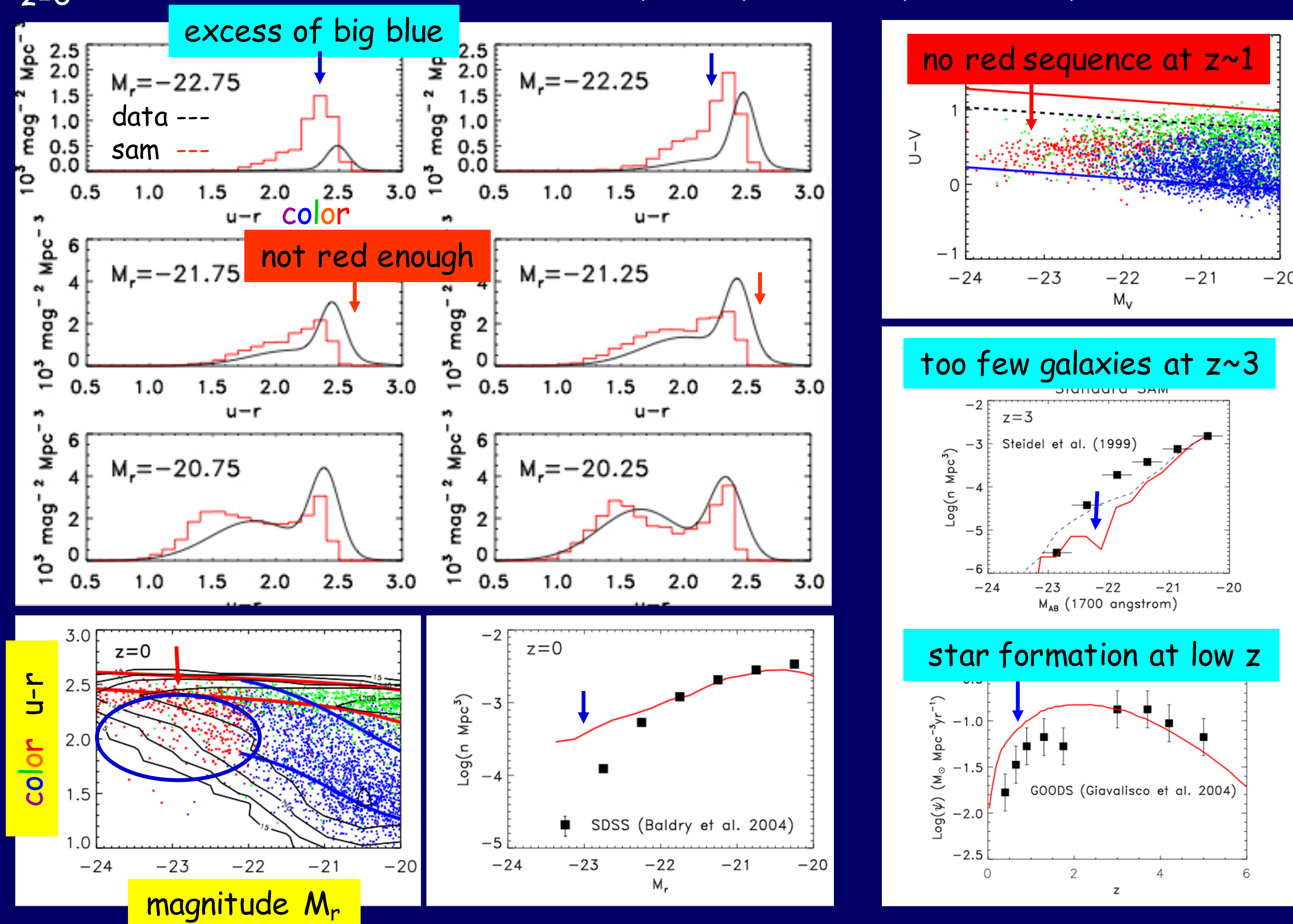


GIF

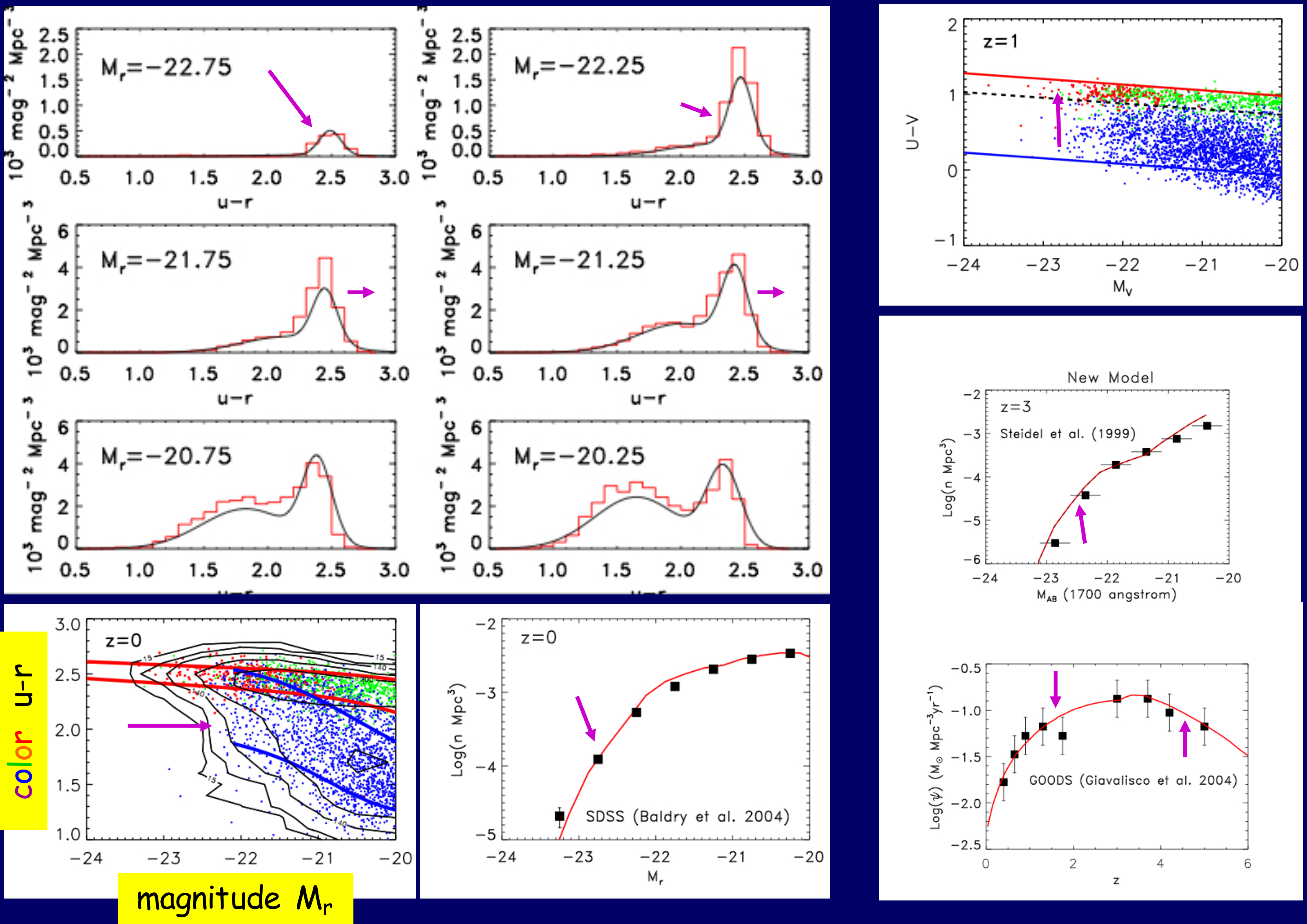
In a standard Semi Analytic Simulation (GalICS)

Cattaneo, Dekel, Devriendt, Guiderdoni, Blaizot 06

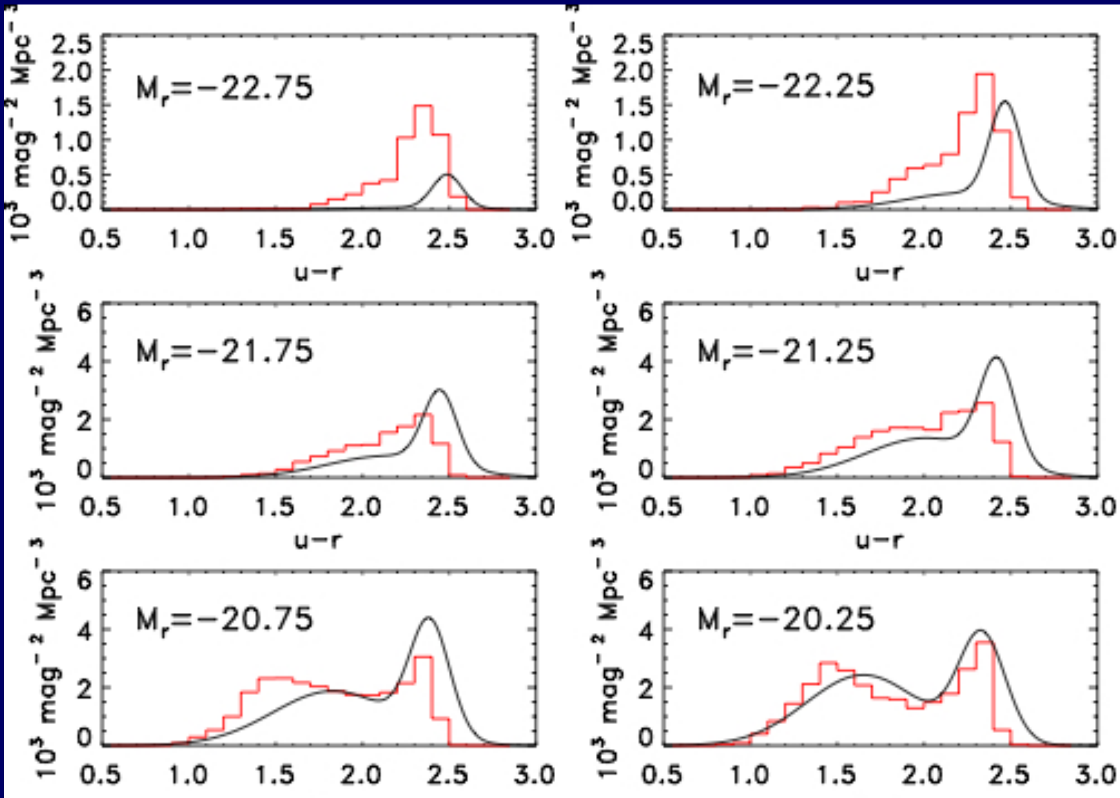
z=0



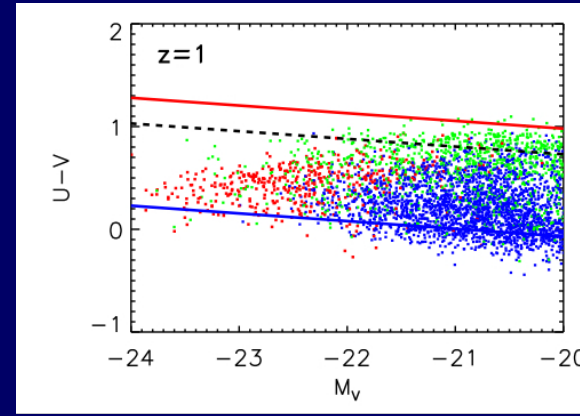
With Shutdown Above 10^{12} $M_\odot$



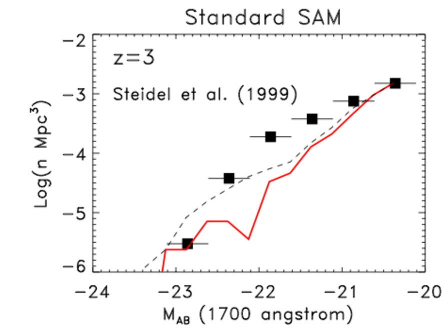
Standard



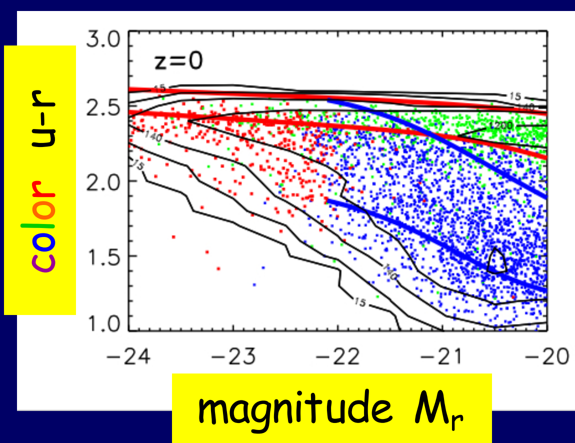
M_r=−22.75
M_r=−22.25
M_r=−21.75
M_r=−21.25
M_r=−20.75
M_r=−20.25
u−r
10^3 mag^{-2} Mpc^{-3}



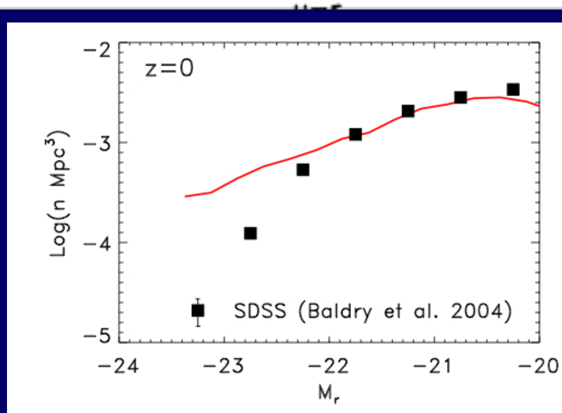
z=1
U−V
M_V



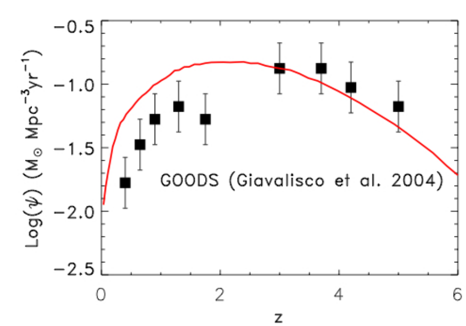
Standard SAM
z=3
Steidel et al. (1999)
Log(n Mpc^3)
M_{AB} (1700 angstrom)



z=0
color u-r
magnitude M_r

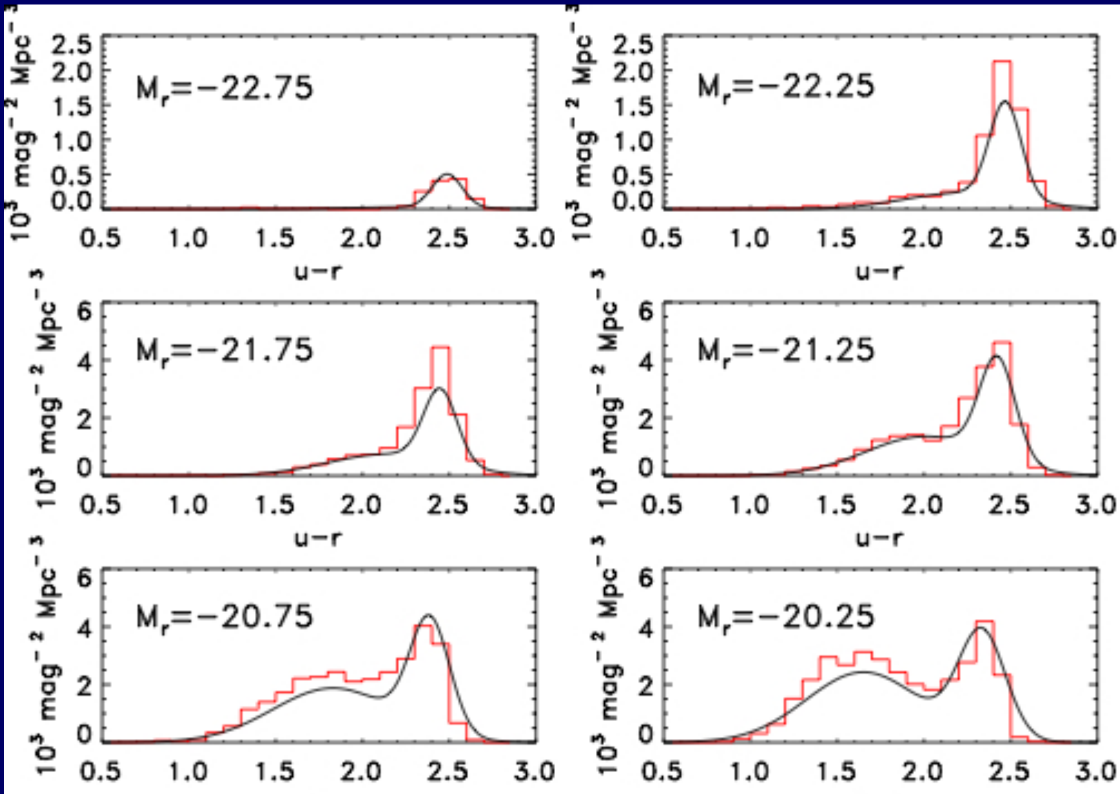


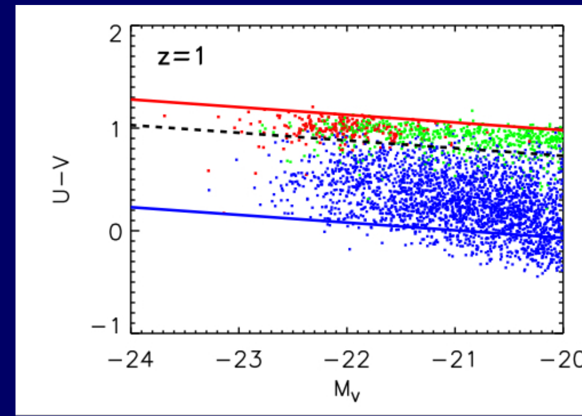
z=0
Log(n Mpc^3)
SDSS (Baldry et al. 2004)
M_r

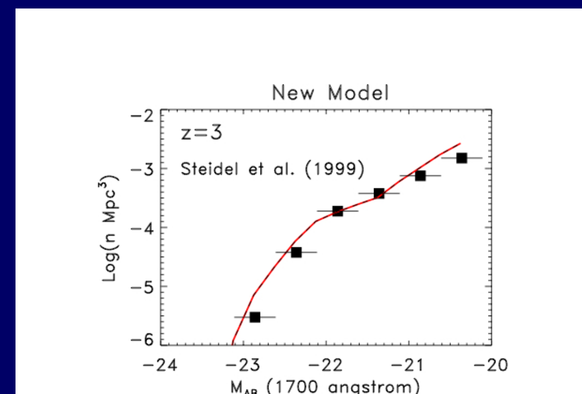


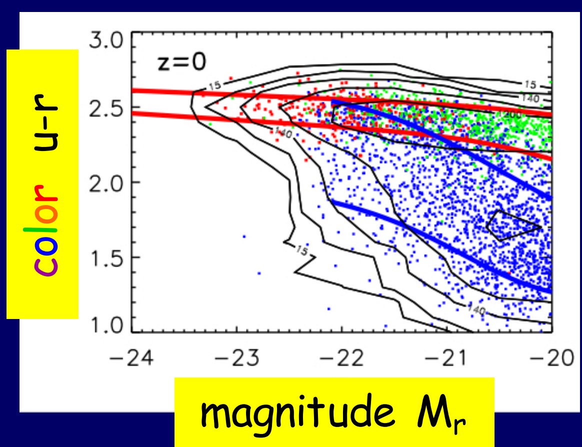
Log(ψ) ($M_\odot$ Mpc^{-3}yr^{-1})
GOODS (Giavalisco et al. 2004)
z

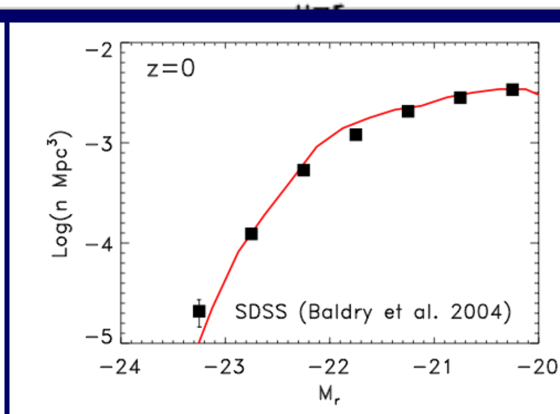
With Shutdown Above $10^{12}\ M_\odot$

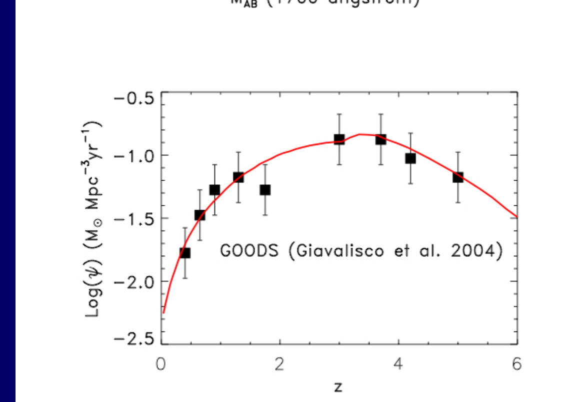




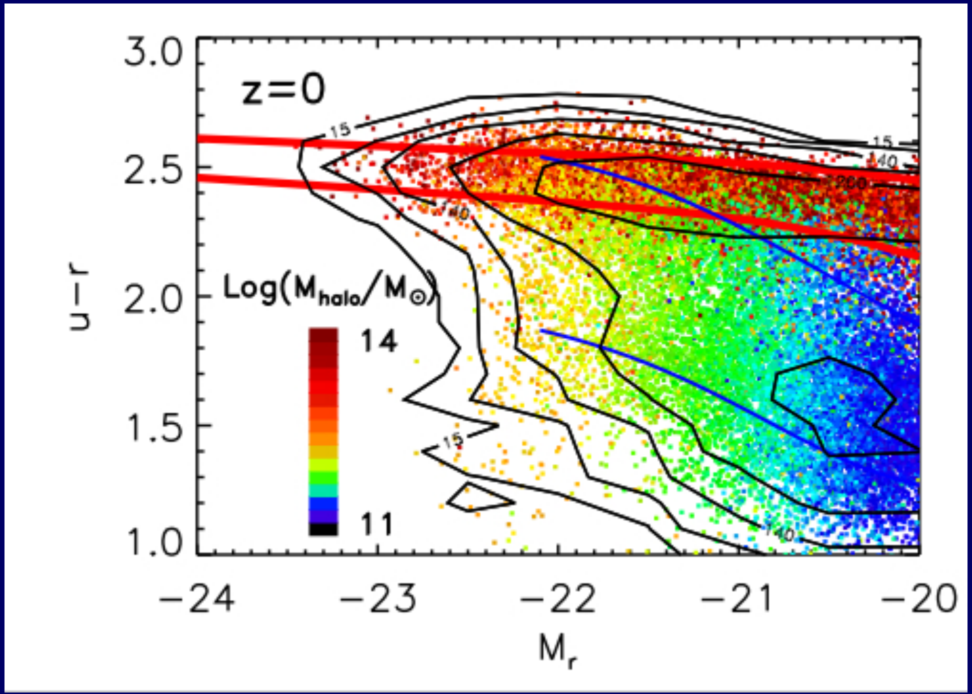




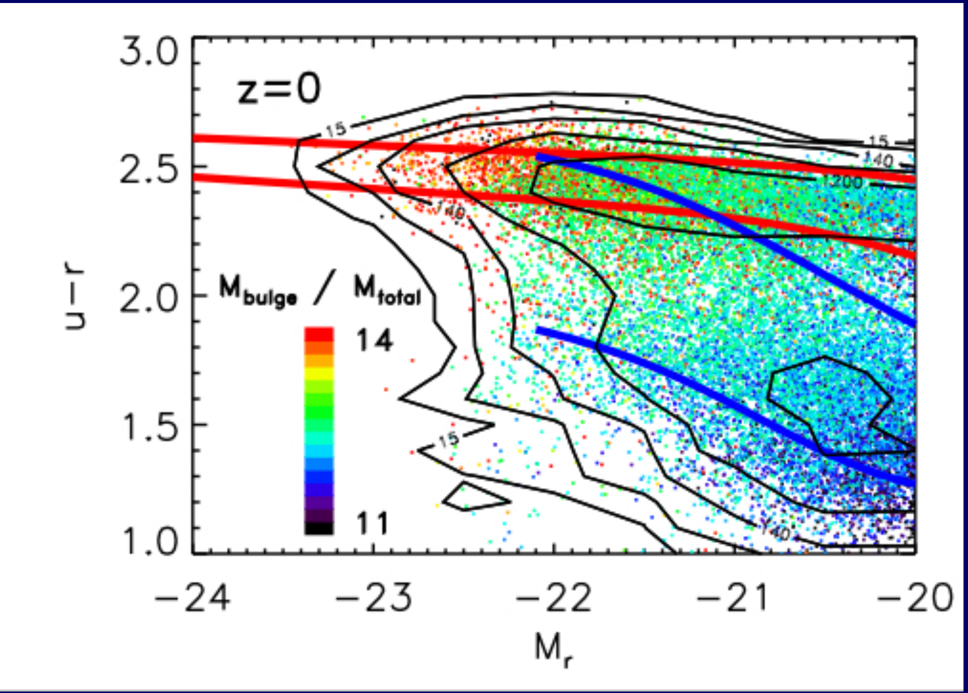




Environment dependence via halo mass



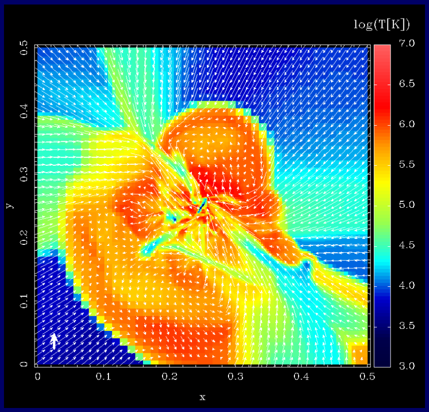
Bulge to disk ratio



Environment Dependence

$M > M_{shock}$ →high HOD groups (at low z)
→red sequence in dense environment

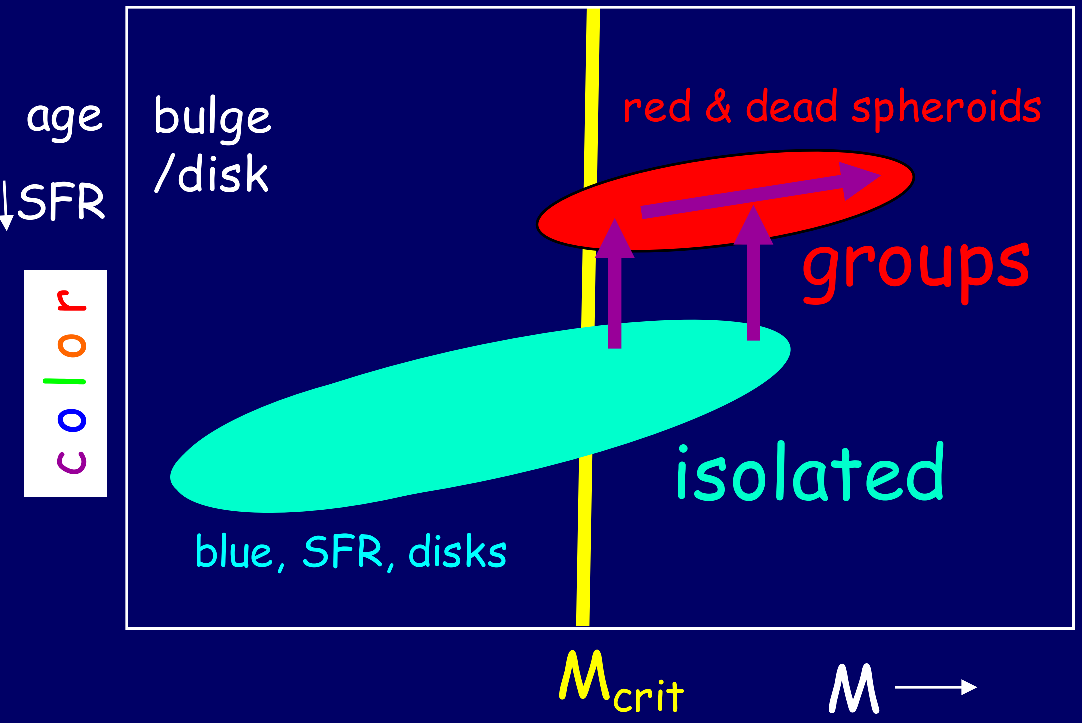
cold streams harassed in groups
but survive in isolated galaxies
even for $M > M_{shock}$



$M_{group} \sim M_*(t)$ ↗

→big blue disks
form at high z

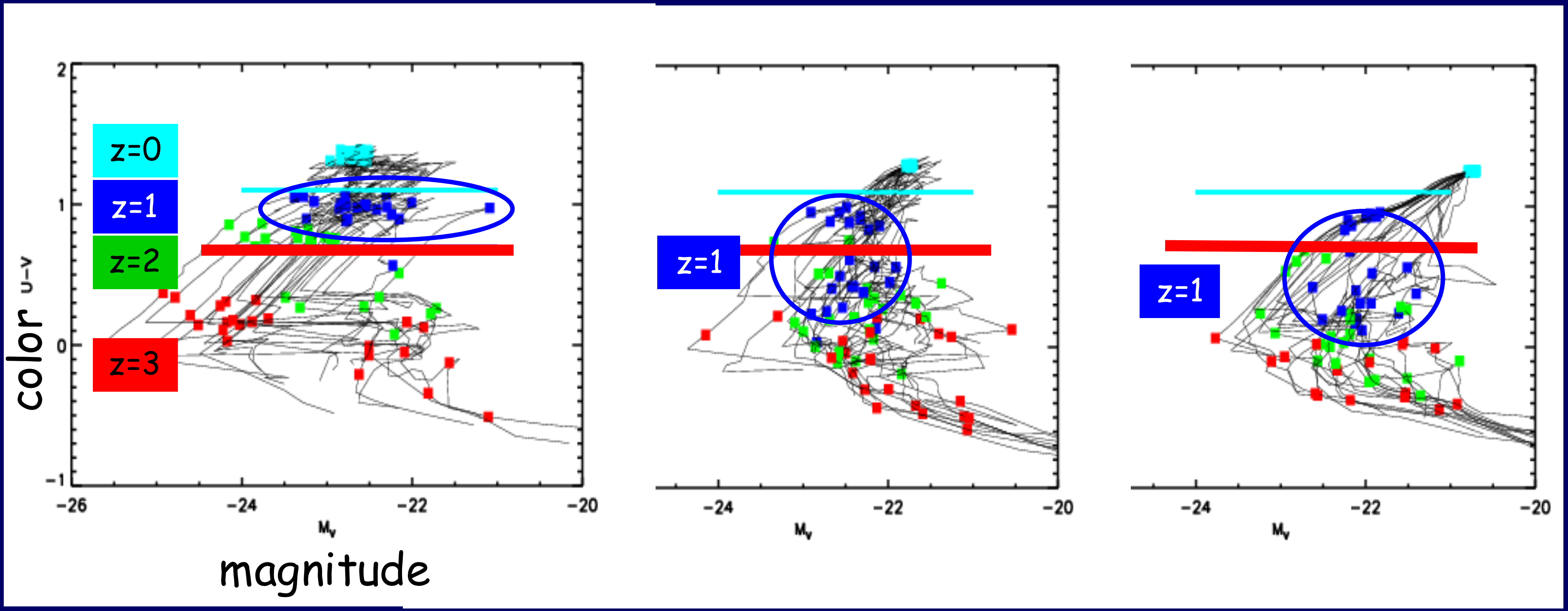
become big red
spheroids later



Downsizing due to Shutdown

Cattaneo, Dekel, Faber 2006

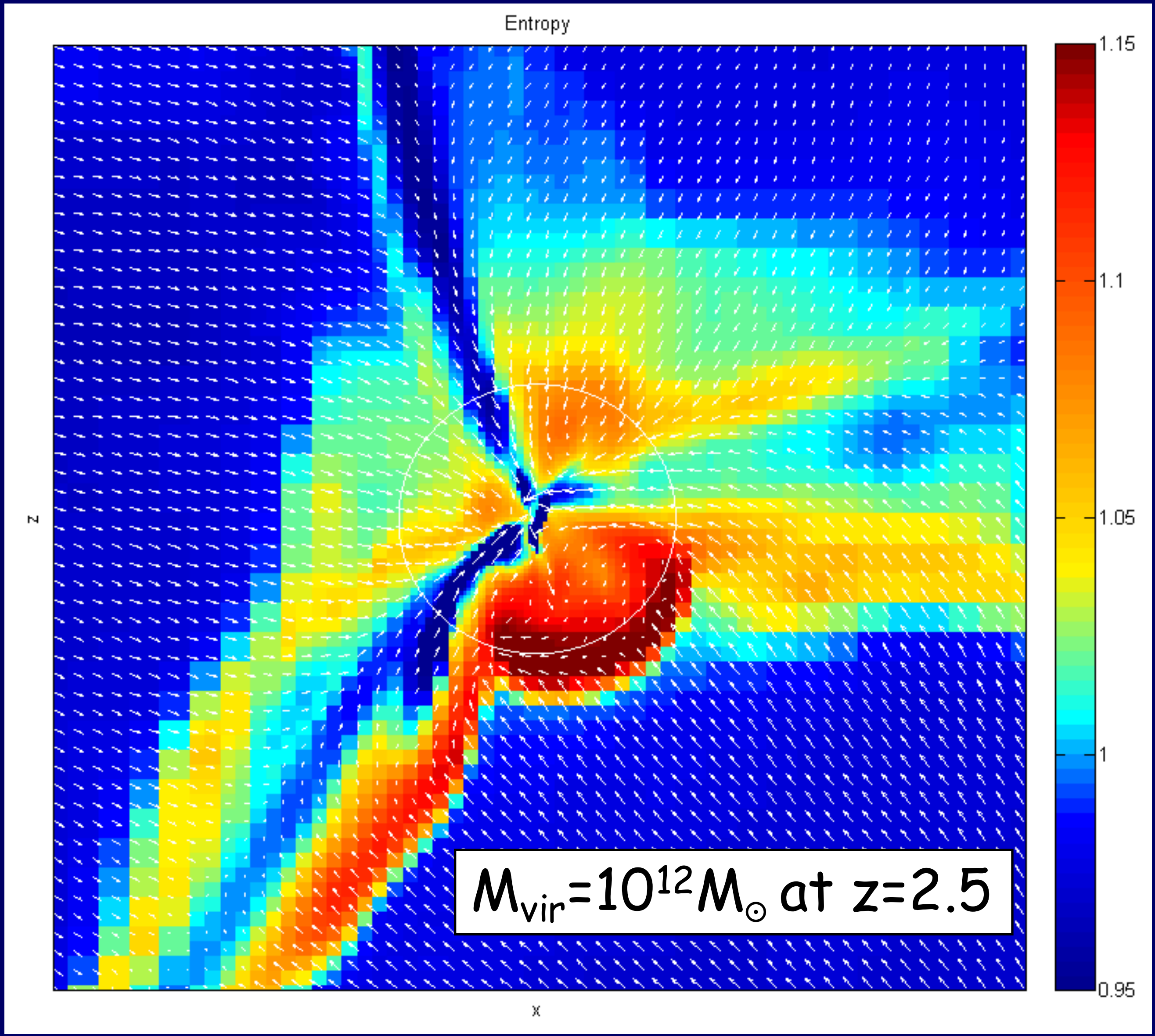
bright	intermediate	faint
central	central/satellites	satellites



in place by z~1

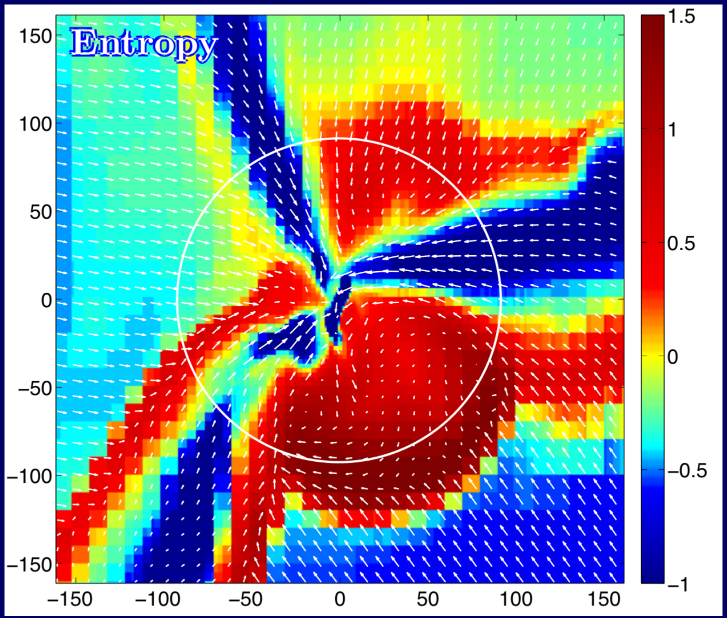
turn red after z~1

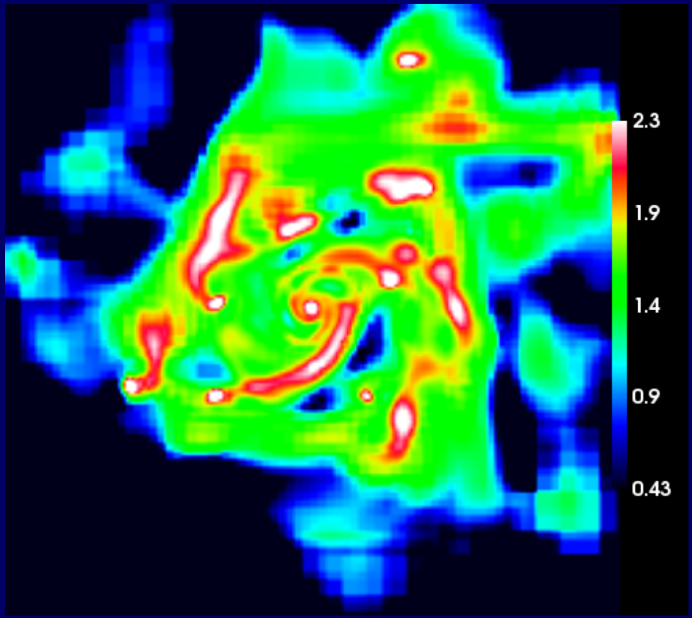
Massive high-z disks by cold narrow streams



Galaxy Formation at High Redshift:

Cold Streams, Clumpy Disks & Compact Spheroids

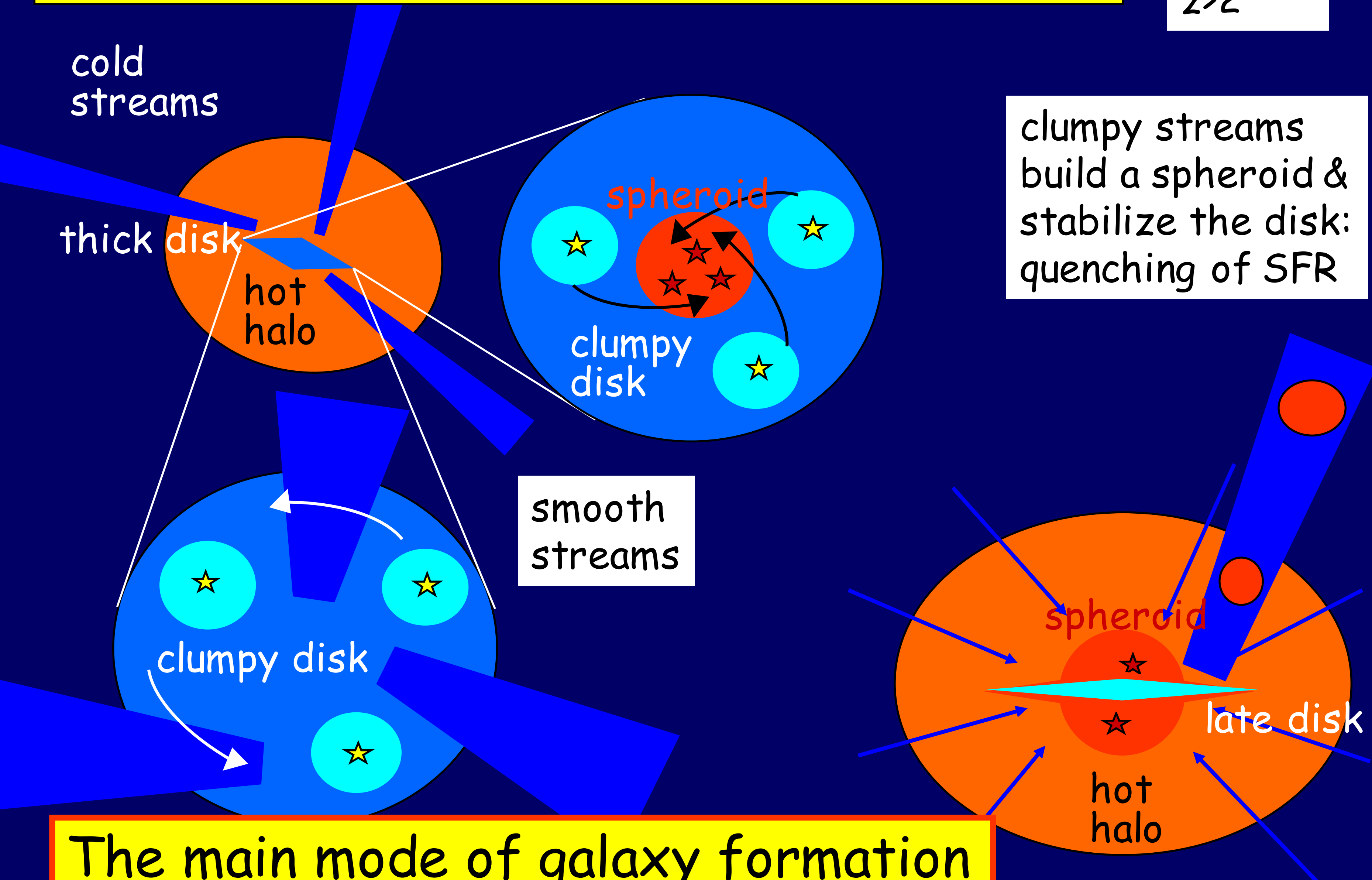




Bimodality of Stream-Fed Galaxies

$M_v > 10^{12}$

$z > 2$



The main mode of galaxy formation