

astro PG course

lecture 2

# galaxy formation theory

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Sownak Bose

[sownak.bose@durham.ac.uk](mailto:sownak.bose@durham.ac.uk)

 @Swnk16



# outline of the course

- a brief review of the observational background
- assembly of dark matter haloes
- **gas cooling**
- **angular momentum**
- star formation
- feedback
- galaxy mergers & morphology
- evolution of supermassive black holes

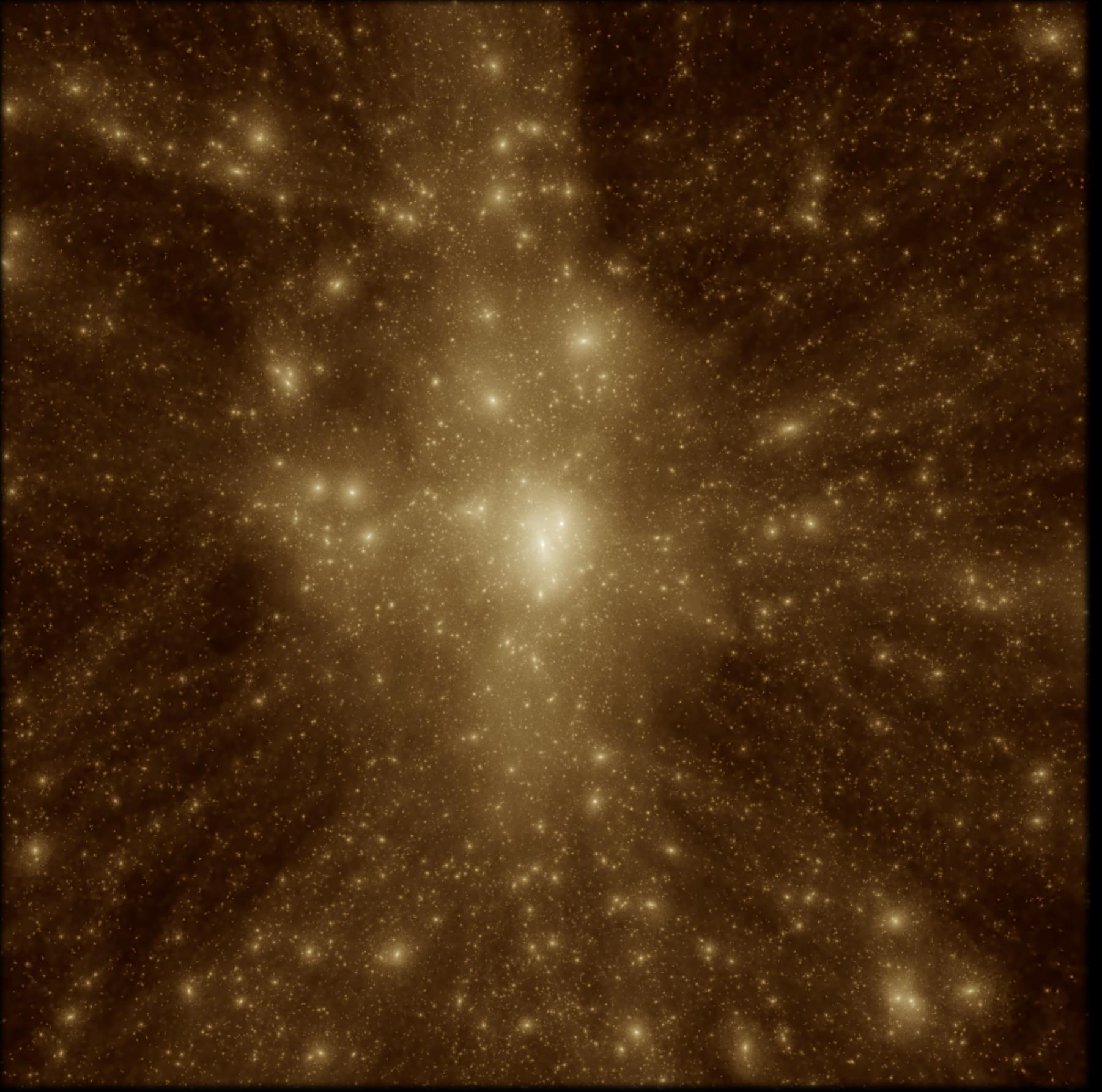
### **3. heating and cooling of gas in haloes**

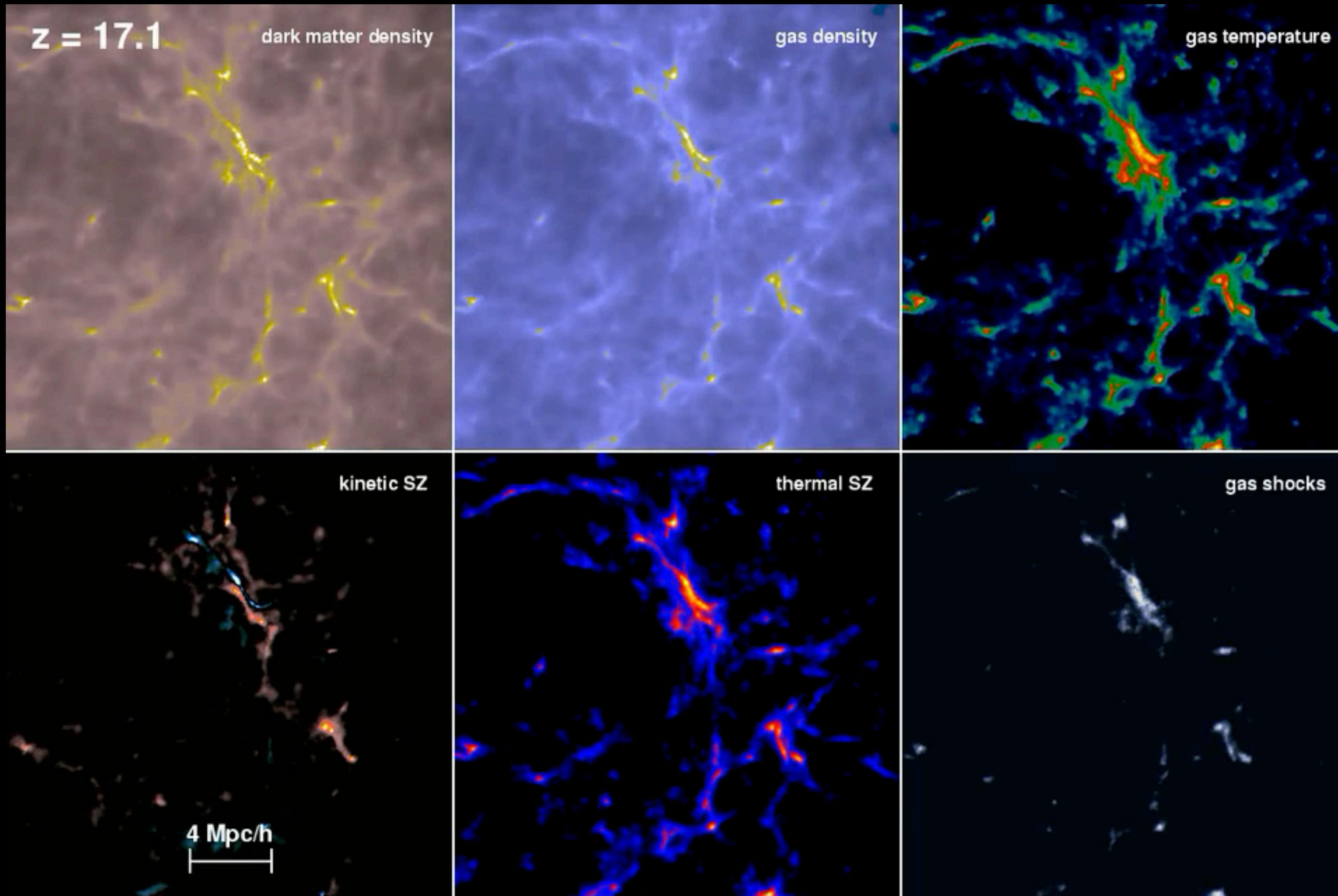
# characteristic quantities in DM haloes

- haloes in simulations are roughly in dynamical equilibrium at mean interior densities:

$$M \left( < r_{\text{vir}} \right) / \left( 4\pi/3 r_{\text{vir}}^3 \right) = \rho_{\text{vir}}(z)$$

- $\rho_{\text{vir}}$  is given by spherical collapse model:  
$$\rho_{\text{vir}}(z) = \Delta_{\text{vir}} \rho_m(z) \sim 200 \rho_m(z) \propto (1+z)^3$$
- which also defines a characteristic radius for each halo:  $r_{\text{vir}} \propto M^{1/3}/(1+z)$
- characteristic circular velocity for halo:  
$$V_{\text{vir}} = \left( GM \left( < r_{\text{vir}} \right) / r_{\text{vir}} \right)^{1/2} \propto M^{1/3} (1+z)^{1/2}$$





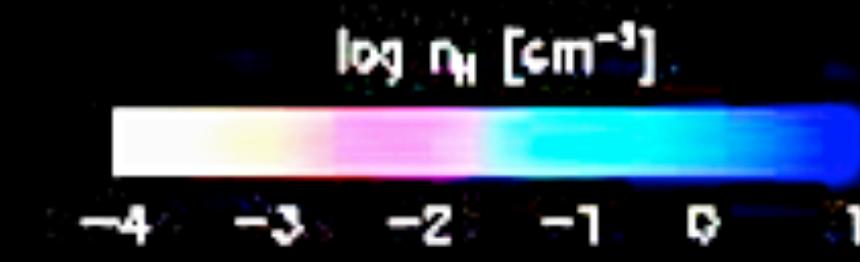
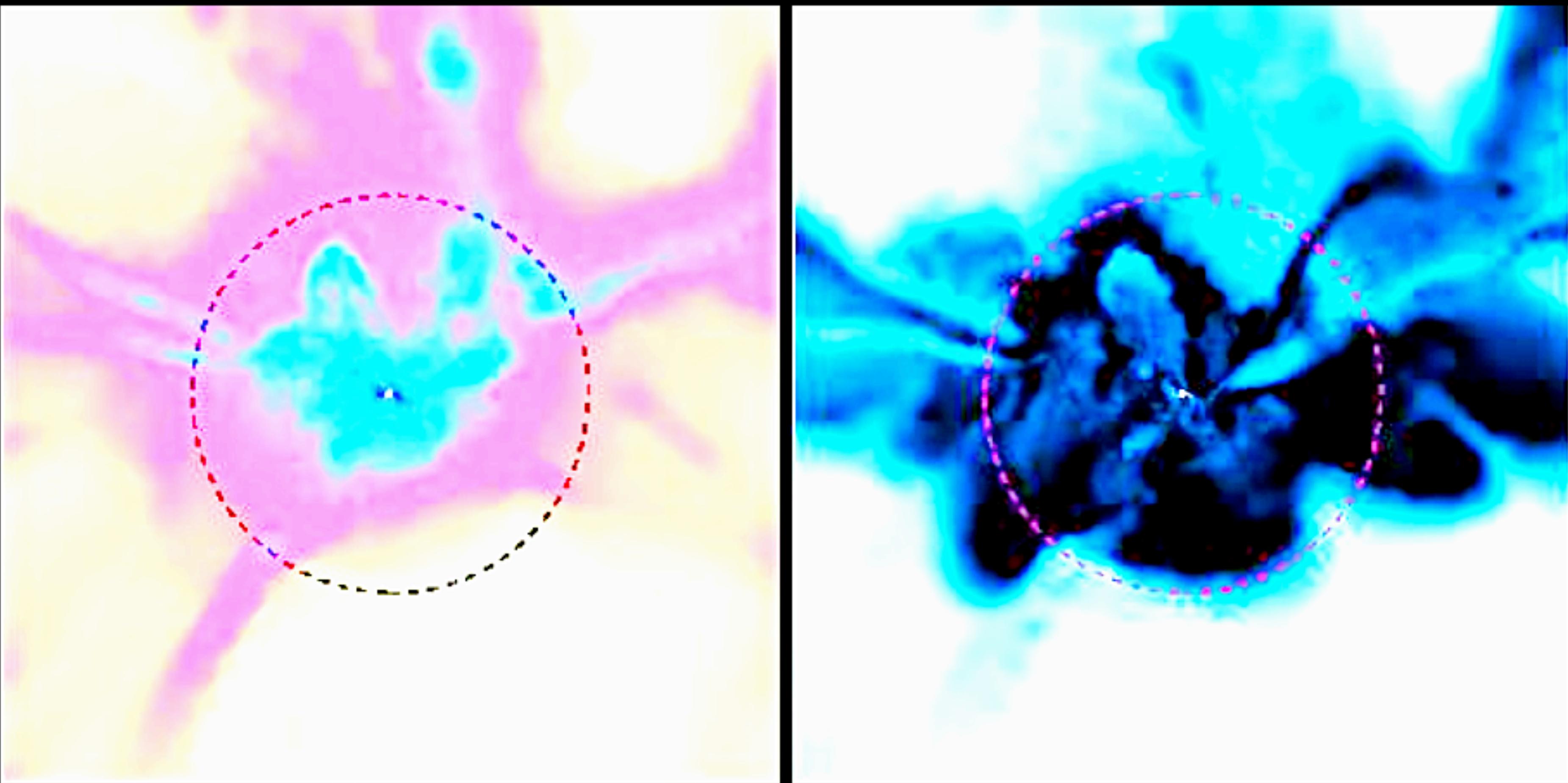
# characteristic temperature for shock-heating in haloes

- gas falling into halo releases gravitational potential energy per unit mass  $\sim GM_{\text{vir}}/r_{\text{vir}} = V_{\text{vir}}^2$
- in the absence of cooling, KE is thermalised in shock
- thermal energy per unit mass is  $\sim k_B T/\mu m_H$  ( $\mu$  = mean molecular weight =  $\rho/(nm_H)$ )
- so, if radiative cooling in the shock negligible, gas in haloes is shock-heated to temperature  $\sim T_{\text{vir}}$

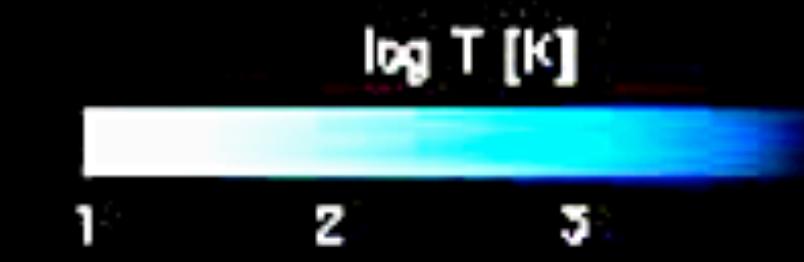
gas at this temperature is supported against further collapse in halo by its thermal pressure —  
**hydrostatic equilibrium**

$$T_{\text{vir}} = \frac{\mu m_p}{2k_B} V_{\text{vir}}^2 \approx 3.6 \times 10^5 K \left( \frac{V_{\text{vir}}}{100 \text{ kms}^{-1}} \right)$$

assuming  $\mu = 0.59$   
for primordial gas



Size: 40 kpc (comoving)  
x-y plane  
 $z = 10.62$   
 $t = 429.4 \text{ Myr}$



Greif+ (2008)

# the role of radiative cooling

- in galaxy cluster mass halo ( $M_{\text{halo}} \sim 10^{14} - 10^{15} M_{\odot}$ ), radiative cooling of gas NOT important,  $t_{\text{cool}} > t_{\text{Hub}}$ 
  - gas ends up in hydrostatic equilibrium with similar distribution to DM
- in galaxy size halos ( $M_{\text{halo}} < \sim 10^{12} M_{\odot}$ ), radiative cooling of gas IS important,  $t_{\text{cool}} < t_{\text{Hub}}$ 
  - dissipation of thermal energy (by radiative cooling) allows gas to sink towards centre of halo
  - gas ends up in disc of radius  $r_{\text{gal}} \sim 0.1 r_{\text{vir}} \sim 10 \text{ kpc}$
  - very different from DM in sphere of radius  $r_{\text{vir}} \sim 100 \text{ kpc}$  (for  $M_{\text{halo}} \sim 10^{12} M_{\odot}$ )

# The EAGLE simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

A project of the Virgo consortium

disc galaxy formation: **radiative cooling is important!**

$z = 0.9$   
 $L = 0.8 \text{ cMpc}$

Visible components:  
Gas

# radiative cooling in haloes

we define the radiative cooling rate per unit volume,  $\Lambda(\rho, T, Z)$

explicit dependence on density,  
temperature, and metallicity of  
the gas

the radiative cooling timescale,  $t_{\text{cool}}$ , quantifies the time it takes for the gas to radiate away its internal energy, and is given by:

$$t_{\text{cool}} = \frac{\frac{3}{2}nk_B T}{\Lambda(\rho, T, Z)}$$

depends on a variety of atomic and molecular processes: atomic + ionic cooling dominates for  $T > 10^4$  K

for an ideal, monoatomic gas:

$$t_{\text{cool}} = \frac{\frac{3}{2}nk_B T}{n_H^2 \Lambda(T)} \approx 3.3 \times 10^9 \text{ yr} \left( \frac{T}{10^6 \text{ K}} \right) \left( \frac{n}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{\Lambda(T)}{10^{23} \text{ ergs}^{-1} \text{ cm}^3} \right)^{-1}$$

number density of hydrogen molecules

$$t_{\text{cool}} \propto n^{-1} \propto \rho^{-1}$$

denser gas cools faster!

# some important timescales in gas cooling

- the age of the Universe, which is roughly the **Hubble time**, is given by:

$$t_H = \frac{1}{H(z)} \propto \frac{1}{\sqrt{G\rho_m}} \quad \rho_m = \Omega_m \rho_{\text{crit}}$$

- the **dynamical time** (or the so-called “free-fall” time) of the system is set by:

$$t_{\text{ff}} = \left( \frac{3\pi}{32G\bar{\rho}_{\text{tot}}} \right)^{1/2} \quad \bar{\rho}_{\text{tot}} = \bar{\rho}_{\text{DM}} + \bar{\rho}_{\text{gas}}$$

in the absence of pressure, sets the timescale on which a **gas cloud collapses under gravity** & the timescale on which the system is **restored to equilibrium after being disturbed**

$$t_{\text{cool}} > t_H$$

cooling is unimportant & gas is in hydrostatic equilibrium

$$t_{\text{ff}} < t_{\text{cool}} < t_H$$

system in quasi-hydrostatic equilibrium. gas contracts as system cools but it has enough time to restore hydrostatic equilibrium.

$$t_{\text{cool}} < t_{\text{ff}}$$

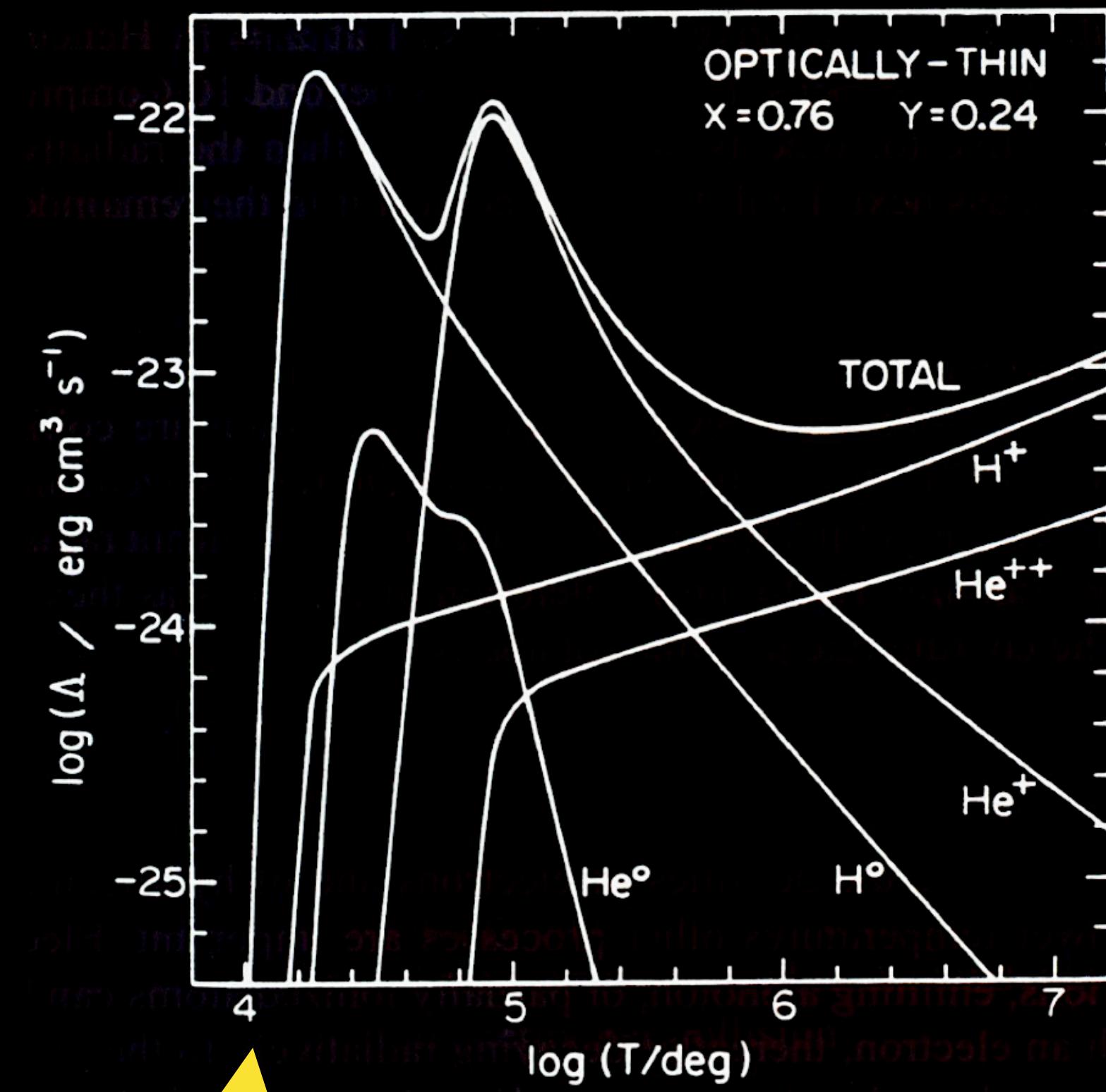
gas unable to respond in time to loss of pressure: as  $t_{\text{cool}} \propto \rho^{-1}$ , cooling proceeds faster and faster — it is a “**catastrophic**” process

# radiative cooling processes

in the galaxy formation process, the primary cooling process is through 2-body interactions in which gas loses energy through the emission of photons

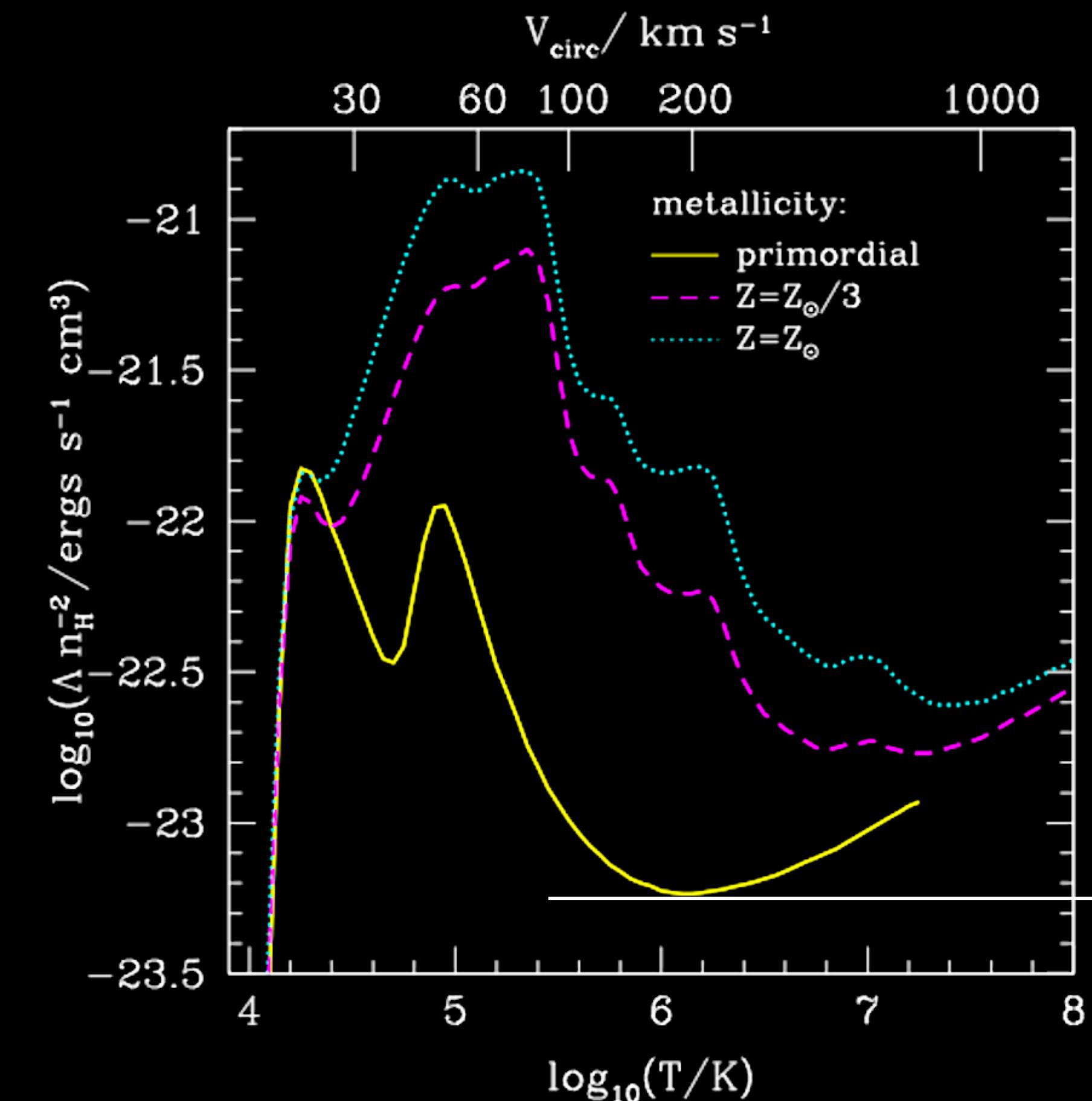
type	reaction	name	description
free-free	$e^- + X^+ \rightarrow e^- + X^+ + \gamma$	bremsstrahlung	free electron accelerated by an ion: accelerated charge emits a photon, resulting in cooling
free-bound	$e^- + X^+ \rightarrow X + \gamma$	recombination	free electron recombines with ion; binding energy + electron's KE radiated away
bound-free	$e^- + X \rightarrow X^+ + 2e^-$	collisional ionisation	impact of free electron ionises a formerly bound electron, taking KE from it
bound-bound	$e^- + X \rightarrow e^- + X' \rightarrow e^- + X + \gamma$	collisional excitation	impact of free electron knocks bound electron to excited state; as it decays, it emits a photon

## primordial gas (H + He)



atomic cooling cuts off for  $T < 10^4 \text{ K}$

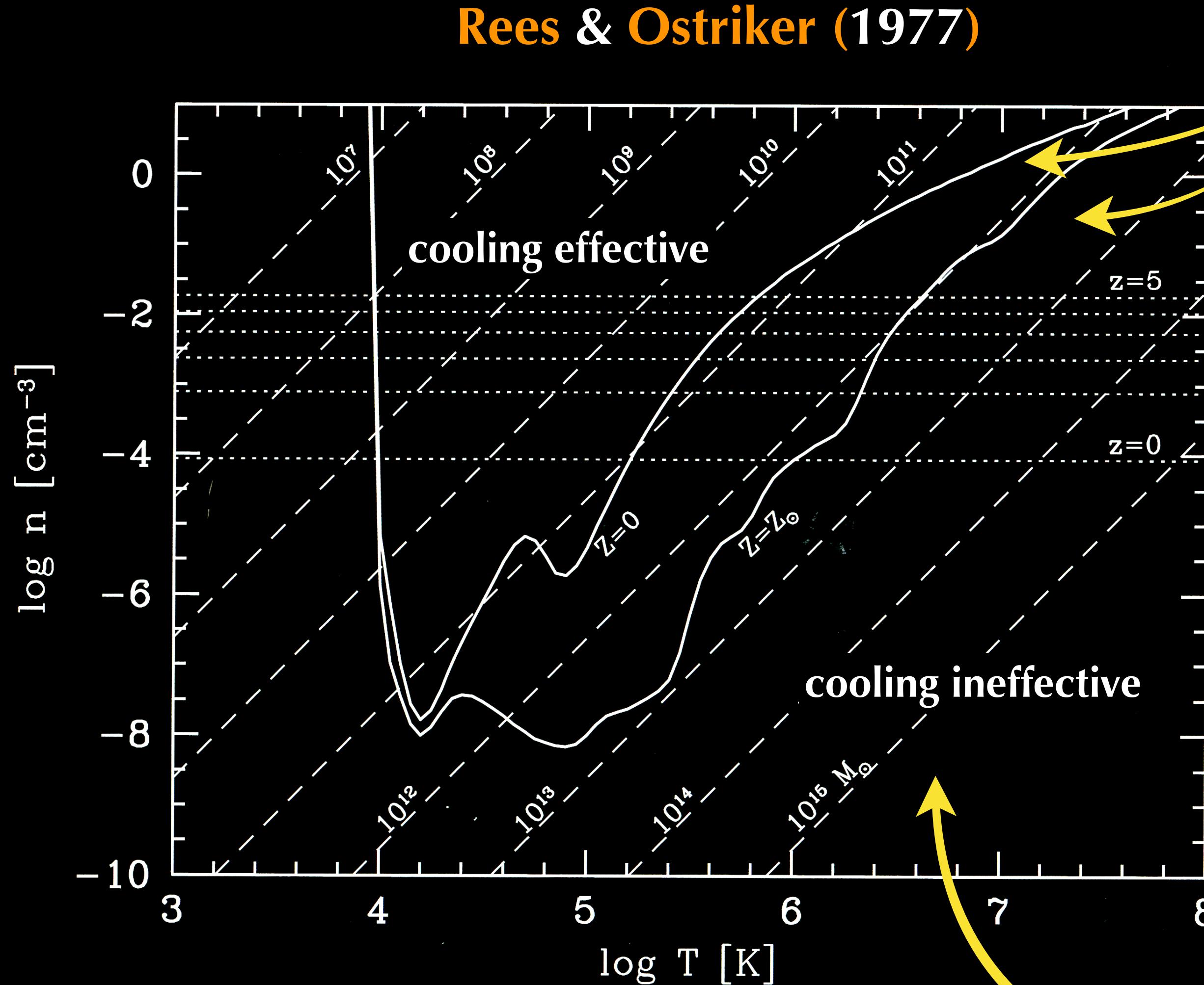
## metal-enriched gas



cooling most rapid here

bremsstrahlung dominates; cooling is inefficient

Rees & Ostriker (1977)



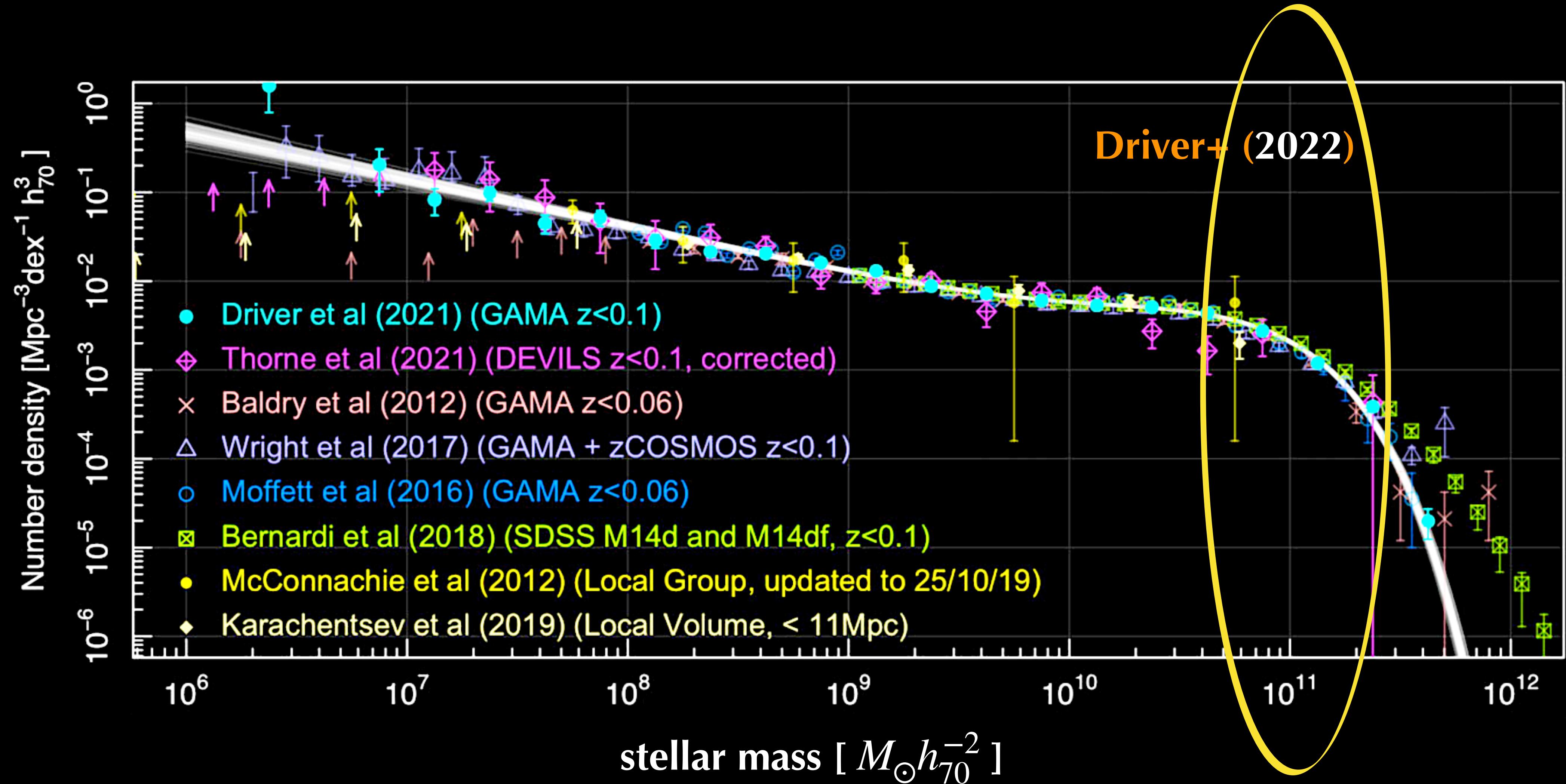
$$t_{\text{cool}} = t_{\text{ff}}$$

**“efficient” cooling for  $t_{\text{cool}} < t_{\text{ff}}$ , which corresponds to  $n$  being above the curve in the adjacent diagram**

haloes with  $M_{\text{vir}} < 10^9 M_{\odot}$  struggle to cool gas (through atomic cooling anyway)

this also defines a characteristic halo mass  
 $M_{\text{crit}} \sim 10^{11} - 10^{12} M_{\odot}$  above which cooling is inefficient

curves of constant  $M_{\text{gas}}$



at this scale,  $M_{\text{vir}} \sim 10^{12} M_\odot$

→ this suggests that cooling sets the characteristic mass of galaxies... but this can't be quite right as galaxies form **hierarchically**: the **progenitors** of massive galaxies must have gone through the cooling phase

# the cooling radius: hot vs cold accretion

in realistic haloes, there isn't just one (virial) temperature and density: these have their own **radial profiles**. we can then generalise the definition of cooling time to the following:

$$t_{\text{cool}}(r) = \frac{\frac{3}{2}n(r)k_B T(r)}{n_H^2(r)\Lambda(T)}$$

the **cooling radius**,  $r_{\text{cool}}$ , is at value of r at which this is equal to  $t_{\text{ff}}$  or  $t_H$ . this allows us to further define two regimes:

$$r_{\text{cool}} \gg r_{\text{vir}}$$

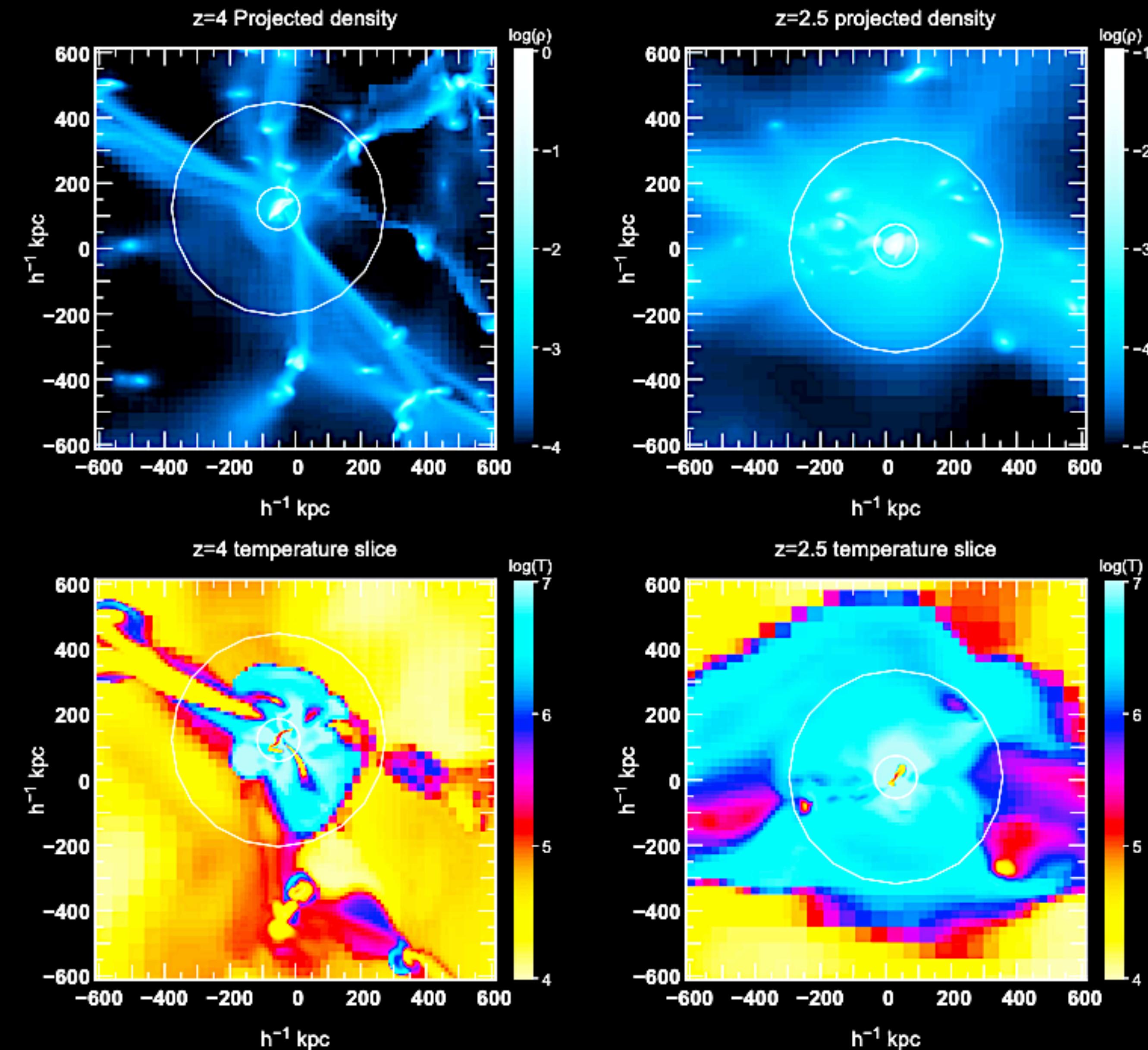
this is the “**catastrophic**” cooling regime, as all gas in the halo is assumed to have cooled. any new gas that is accreted does not get shock heated: cold gas accretes along filaments. → **cold mode accretion**

$$r_{\text{cool}} \ll r_{\text{vir}}$$

only the gas interior to  $r_{\text{cool}}$  can cool. halo has a hot atmosphere, and an accretion shock near the virial radius where gas is shock heated to  $T \sim 10^4$  K. this gas cools quasi-statically in the halo. → **hot mode accretion**

Ocvirk+ (2008)

cold accretion along  
filaments observed  
at high-z

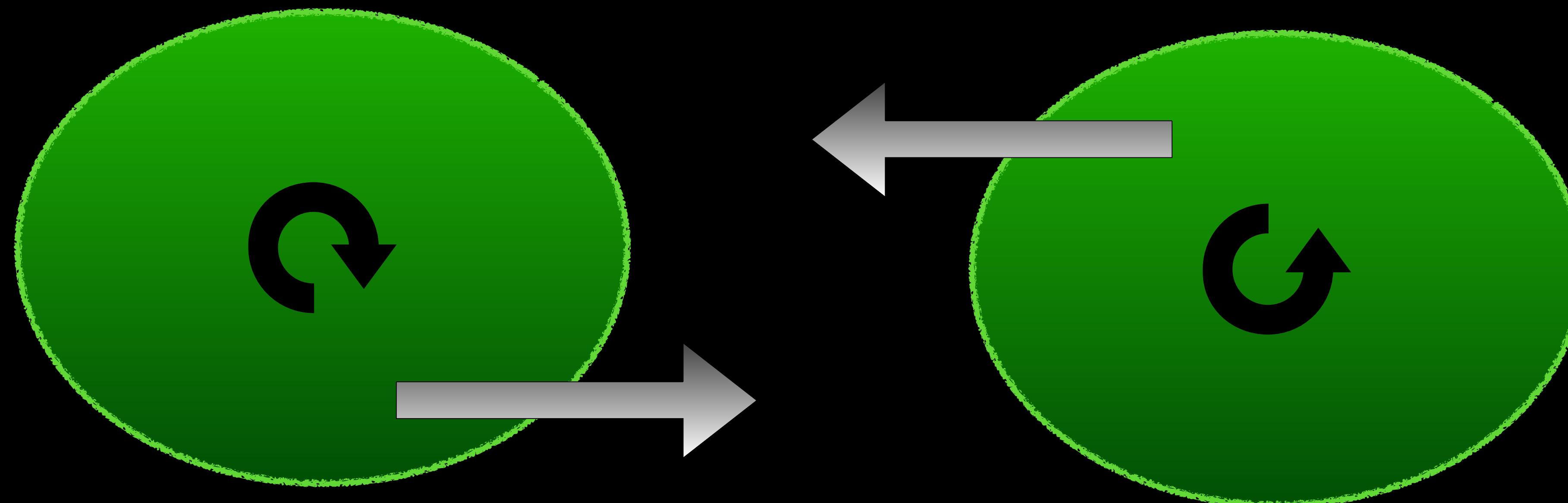


virial shock forms  
only for  
 $M_{\text{vir}} > M_{\text{crit}} \sim 10^{12} M_{\odot}$

# 4. angular momentum

object 1

object 2



gravitational tidal torques between neighbouring non-spherical structures cause objects to acquire angular momentum — **tidal torquing**

# generation of angular momentum by **tidal torques**

the angular momentum of an object changes due to external torques:

$$\dot{\mathbf{J}} = \int (\mathbf{r} - \mathbf{r}_{CM}) \wedge \nabla \Phi_{ext} \rho dV$$

if we now expand  $\Phi$  around the centre of mass (CM) of the object:

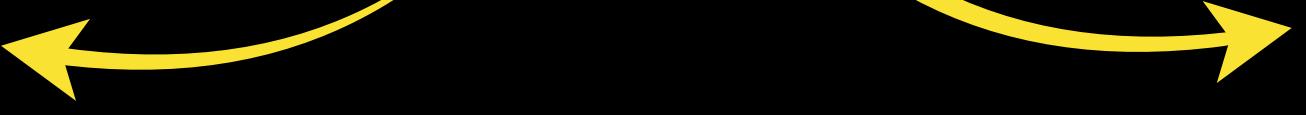
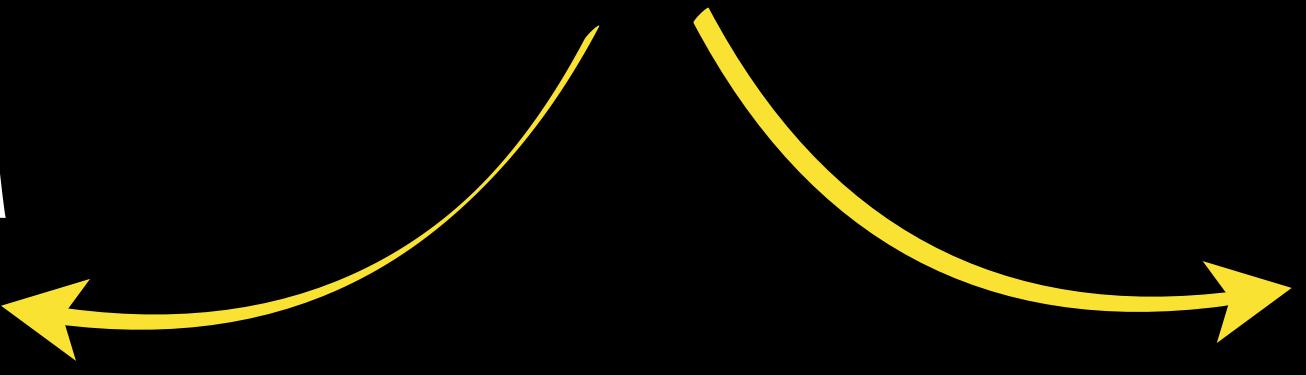
$$\dot{\mathbf{J}}_i = - \varepsilon_{ijk} \mathbf{T}_{kl} \mathbf{I}_{jl}$$

gravitational tidal field at CM

$$\mathbf{T}_{kl} = \partial^2 \Phi_{ext} / \partial x_k \partial x_l$$

moment of inertia tensor

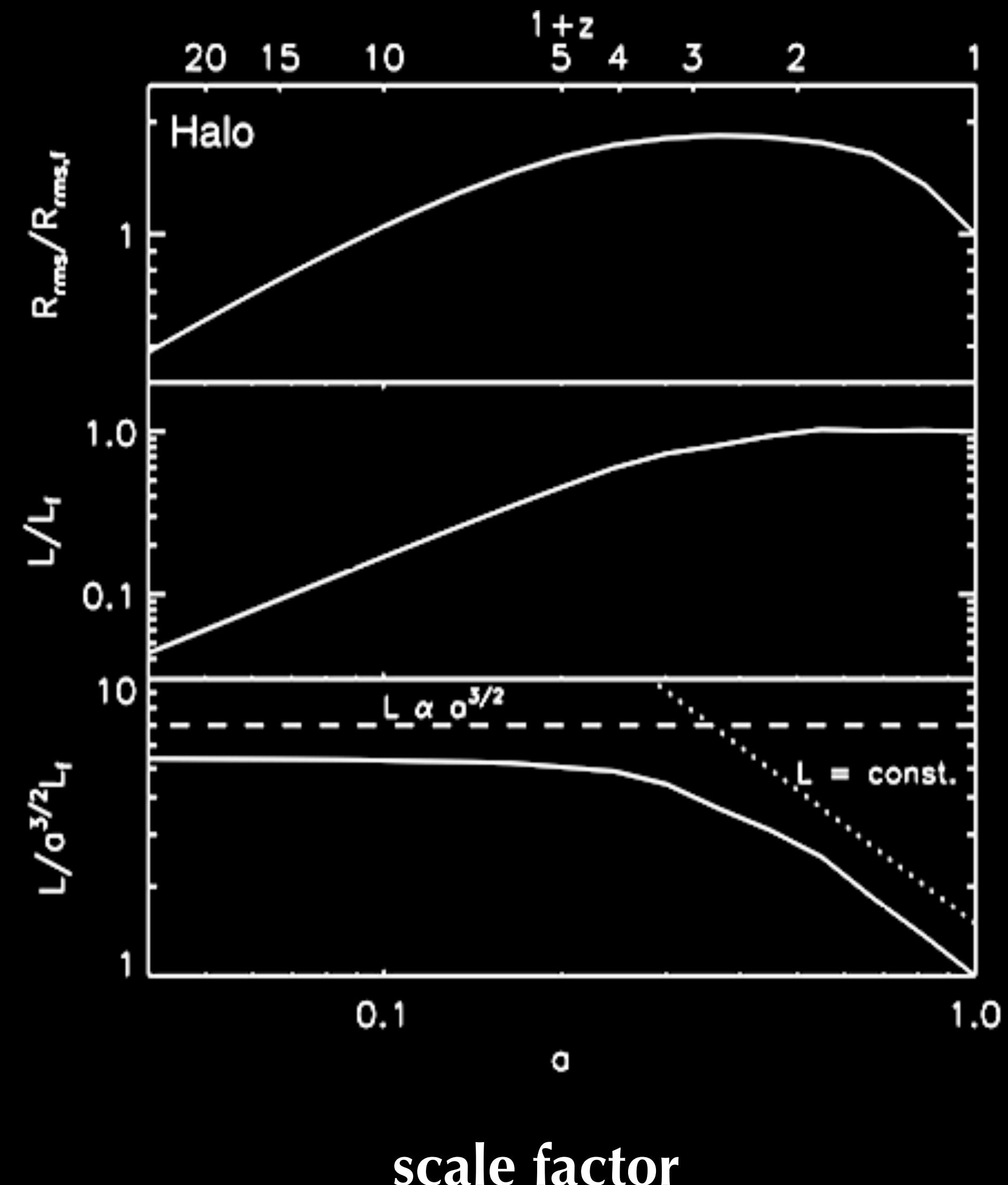
$$\mathbf{I}_{jl} = \int (x_j - x_j^{CM}) (x_l - x_l^{CM}) \rho dV$$



thus, angular momentum grows due to the **coupling of the external tidal field to the quadruple moment of the object**

Zavala+ (2007)

size  
angular  
momentum  
normalised  
to final  
value



- angular momentum grows due to gravitational tidal torques between non-spherical structures
- using perturbation theory, can show that in an Einstein-de Sitter ( $\Omega_m = 1$ ) universe:  $J \propto t \propto a^{3/2} \Rightarrow J/a^{3/2} = \text{constant}$
- N-body simulations show that  $J$  roughly follows this until structure turns around and collapses
- $J$  then freezes out to a constant value

# the halo **spin** parameter

a common way to represent the angular momentum of a halo is via the dimensionless spin parameter:

$$\lambda = \frac{J |E|^{1/2}}{GM^{5/2}}$$

(Peebles 1980)

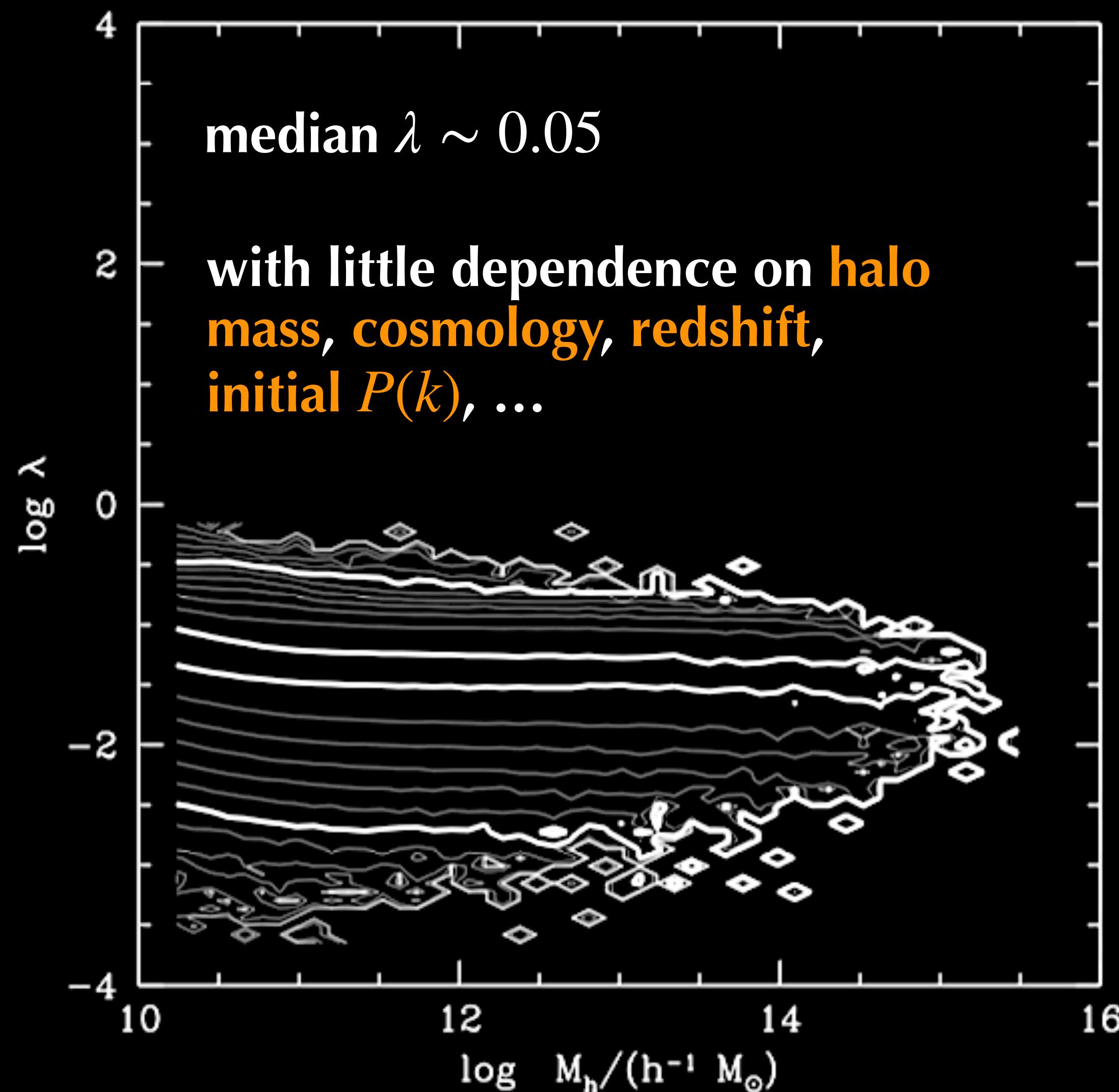
for an object in virial equilibrium with rotational velocity  $V_{\text{rot}} \ll \sigma$ , where  $\sigma$  is the velocity dispersion given by  $\sigma \sim (GM/r)^{1/2}$ , and assuming  $J = MV_{\text{rot}} r$ , we get

$$\lambda \approx \frac{1}{4} \frac{V_{\text{rot}}}{\sigma}$$

so, for  $\lambda \ll 1$ , the object is **weakly rotating** ( $V_{\text{rot}} \ll \sigma$ ) and is supported against gravity by random motions. conversely, for  $V_{\text{rot}} \gg \sigma$ ,  $\lambda \sim 1$ , the object is **strongly rotating** and is supported by rotational motions.

haloes formed in cosmological simulations are all found to have  $\lambda \ll 1$

Bett+ (2007)



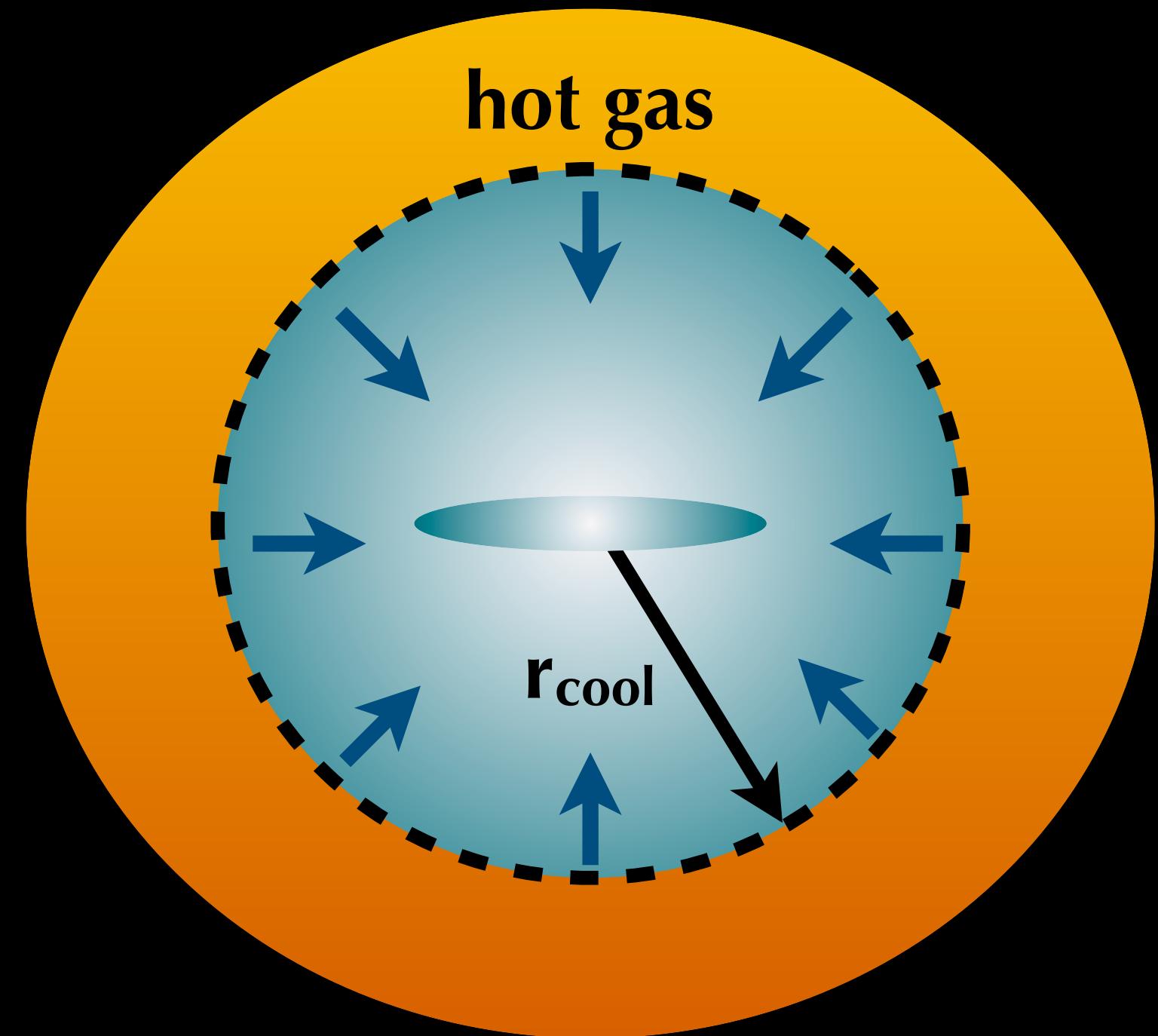
# the importance of angular momentum in galaxy formation

- if the gas contained in a halo can radiate away all of its energy, then what halts its gravitational collapse is angular momentum (assuming it cannot transfer all of this to the DM halo)

- stars & gas in galactic discs are on nearly circular orbits — centrifugally supported against gravity,

$$V_{\text{rot}} = (GM( < r)/r)^{1/2}$$

- so, the sizes of galaxy discs are controlled by how much angular momentum they have



(iii) gas conserves  $\mathbf{J}$  as it collapses

(iv) collapse eventually stops when the gas becomes rotationally supported

(i) assume that gas cools out to some radius,  $r_{\text{cool}}$

(ii) gas in halo initially has same specific angular momentum as the DM halo itself

# a simple model for the radii of galaxy discs

for simplicity, let's make the following assumptions:

- ignore the self-gravity of baryons
- the halo has a **singular isothermal density profile**:

$$\rho_H = V_c^2 / (4\pi G r^2) \quad \text{constant, } = V_{\text{rot}}$$

- the disc is assumed to have an **exponential surface density profile**:

$$\Sigma_D \propto \exp(-r/h_D)$$

(only gas within  $r_{\text{cool}}$  is relevant)

- then:  $J_H/M_H = 2\lambda_H V_c r_{\text{cool}}$  and  $J_D/M_D = 2h_D V_c$

if **angular momentum is conserved**, we can equate these two to get:

$$h_D = \lambda_H r_{\text{cool}}$$

- so, the gas has collapsed in radius by a factor:  $r_D/r_{\text{cool}} \sim h_D/r_{\text{cool}} \sim \lambda_H \sim 0.1$

(c.f. Fall & Efstathiou 1980)

# a simple model for the **radii** of galaxy discs

this model therefore predicts that:

$$r_{\text{disc}} \sim \lambda_H r_{\text{cool}}$$

if gas cools only within the radius  $r_{\text{cool}}$

$$r_{\text{disc}} \sim \lambda_H r_{\text{vir}}$$

if all the gas within the halo cools to form a disc

when combined with the predicted values of  $\lambda_H$  from cosmological simulations, it turns out that this is in ~rough~ agreement with the observed sizes of galaxy discs at  $z \sim 0$ . but there have been several updates to the model inc. **Mo, Mao & White (1998)**, **Dutton & van den Bosch (2012)** etc.

**what about the sizes of spheroids?** if the spheroid galaxies are formed by **merging galaxy discs**, then their sizes are determined by the sizes of their progenitor discs — and, therefore, also determined (**indirectly**) by disc angular momentum