galaxy formation theory

lecture 2

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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

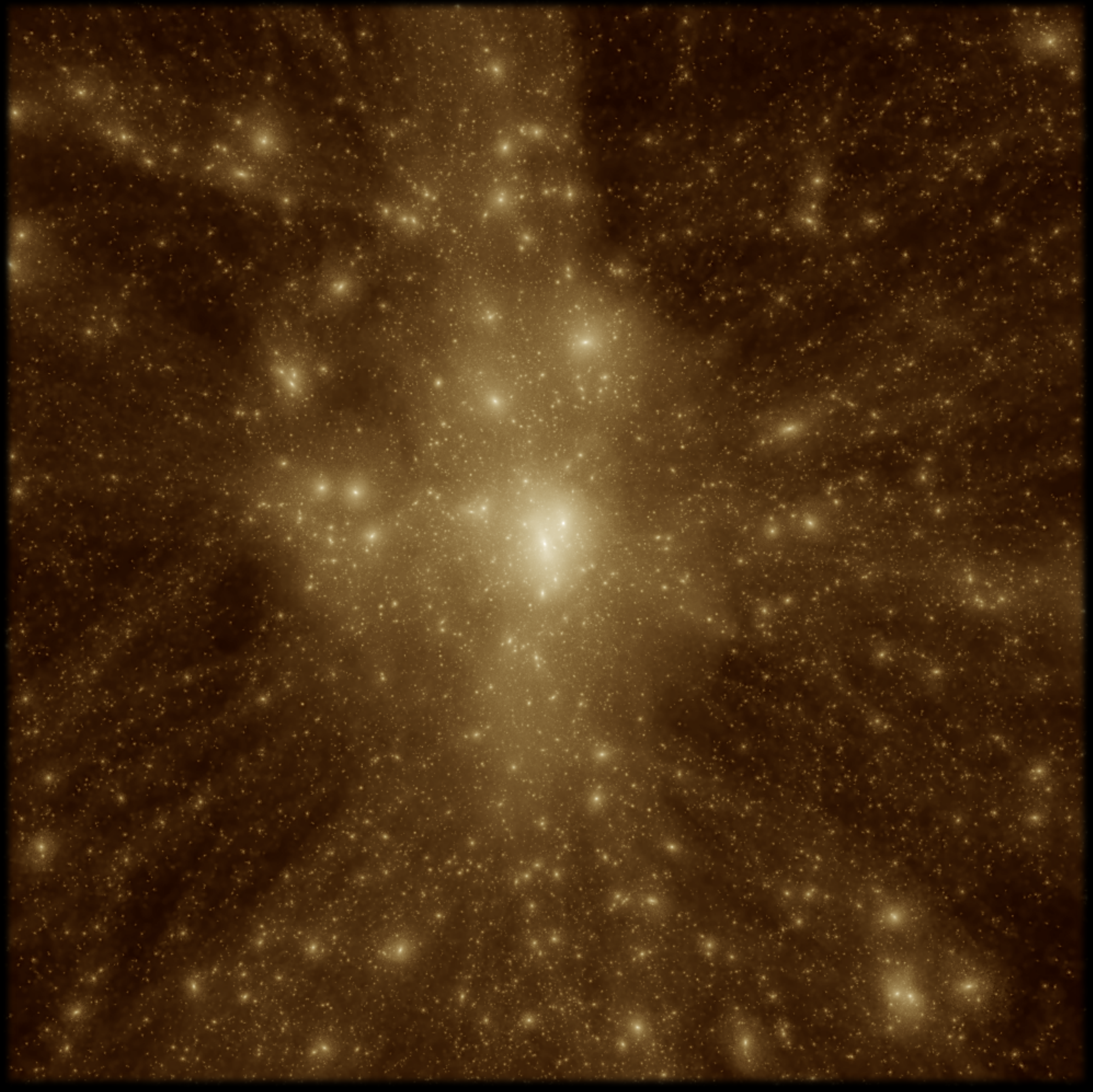
characteristic quantities in DM haloes

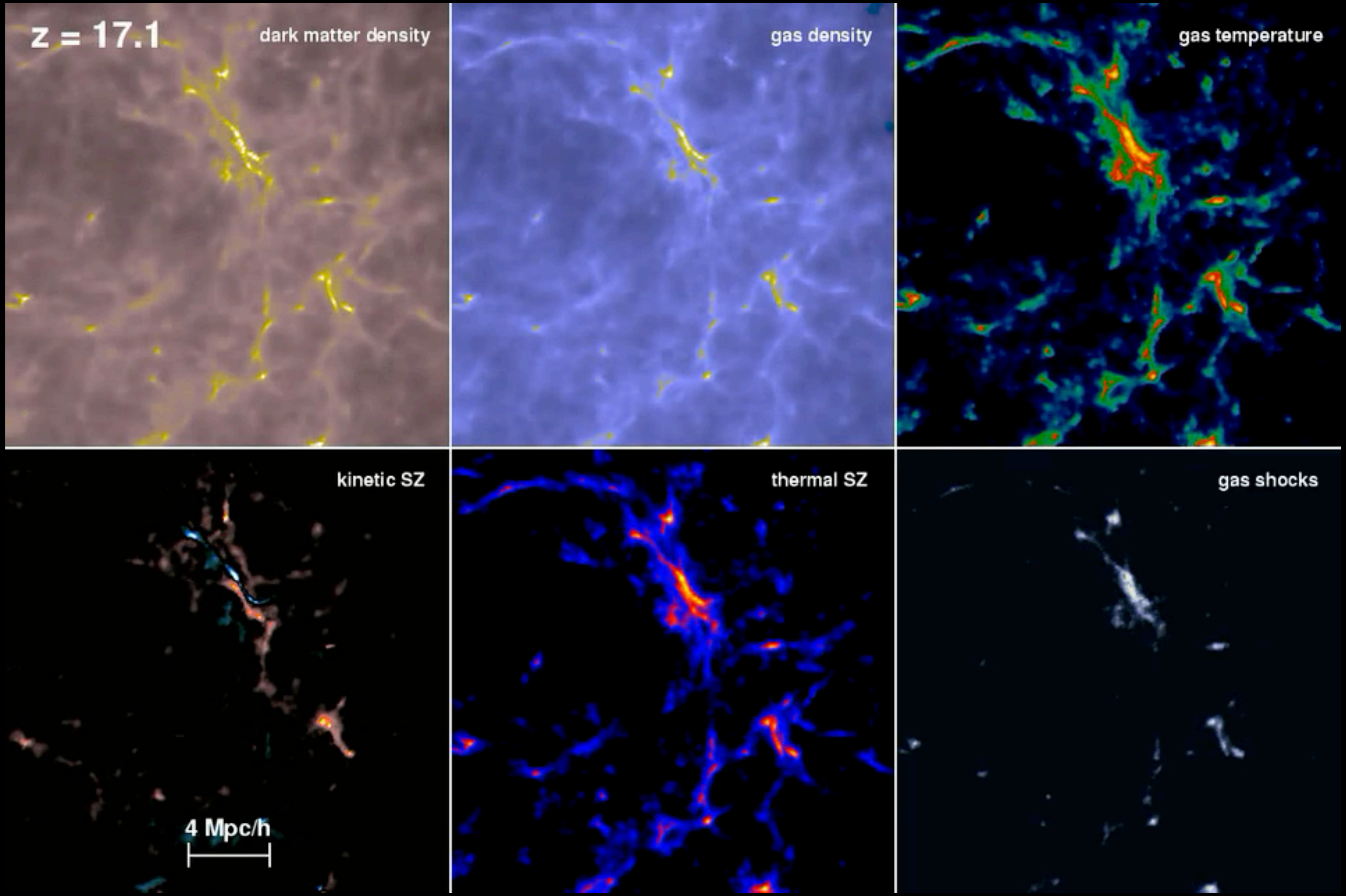
- haloes in simulations are roughly in dynamical equilibrium at mean interior densities:
  $M\left(<r_{\rm vir}\right)/\left(4\pi/3r_{\rm vir}^3\right)=\rho_{\rm vir}(z)$

- $\rho_{\rm vir}$ is given by spherical collapse model:
  $\rho_{\rm vir}(z)=\Delta_{\rm vir}\,\rho_m(z)\sim 200\,\rho_m(z)\propto(1+z)^3$

- which also defines a characteristic radius for each halo: $r_{\rm vir}\propto M^{1/3}/(1+z)$

- characteristic circular velocity for halo:
  $V_{\rm vir}=\left(GM\left(<r_{\rm vir}\right)/r_{\rm vir}\right)^{1/2}\propto M^{1/3}\,(1+z)^{1/2}$





www.mpa-garching.mpg.de/galform/data_vis

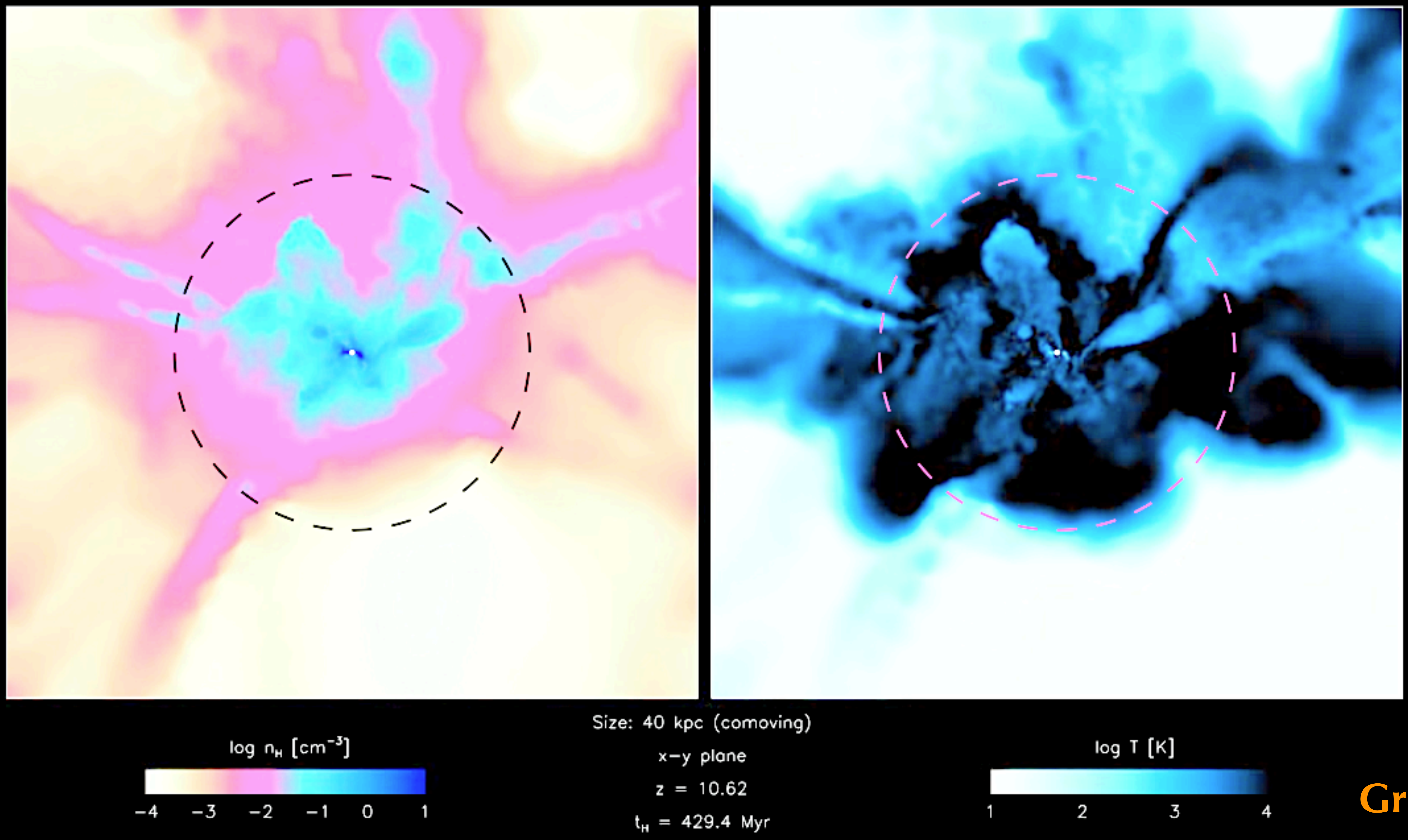
characteristic temperature for shock-heating in haloes

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

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

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

assuming $\mu = 0.59$ for primordial gas



Size: 40 kpc (comoving)
x–y plane
z = 10.62
t_H = 429.4 Myr
log n_H [cm^-3]
−4 −3 −2 −1 0 1
log T [K]
1 2 3 4

Greif+ (2008)

the role of radiative cooling

- in galaxy cluster mass halo ($M_{halo} \sim 10^{14} - 10^{15}\ M_{o}$), radiative cooling of gas NOT important, $t_{cool} > t_{Hub}$

  – gas ends up in hydrostatic equilibrium with similar distribution to DM

- in galaxy size halos ($M_{halo} <\sim 10^{12}\ M_{o}$), radiative cooling of gas IS important, $t_{cool} < t_{Hub}$

  – dissipation of thermal energy (by radiative cooling) allows gas to sink towards centre of halo
  – gas ends up in disc of radius $r_{gal} \sim 0.1\ r_{vir} \sim 10$ kpc
  – very different from DM in sphere of radius $r_{vir} \sim 100$ kpc (for $M_{halo} \sim 10^{12} M_{o}$)


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 cMpc
Visible components:
Gas

radiative cooling in haloes

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

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

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

$$\boxed{t_{\rm cool} = \frac{\frac{3}{2} n k_B T}{\Lambda\left(\rho, T, Z\right)}}$$

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

for an ideal, monoatomic gas: $$t_{\rm cool} = \frac{\frac{3}{2} n k_B T}{n_{\rm H}^2 \Lambda(T)} \approx 3.3 \times 10^9\,{\rm yr} \left(\frac{T}{10^6 K}\right)\left(\frac{n}{10^{-3}\,{\rm cm}^{-3}}\right)\left(\frac{\Lambda(T)}{10^{23}\,{\rm ergs}^{-1}{\rm cm}^3}\right)^{-1}$$

number density of hydrogen molecules

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

denser gas cools faster!

some important timescales in gas cooling

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

$$t_H = \frac{1}{H(z)} \propto \frac{1}{\sqrt{G\rho_m}}$$

$$\rho_m = \Omega_m \rho_{\rm crit}$$

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

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

$$\bar{\rho}_{\rm tot} = \bar{\rho}_{\rm DM} + \bar{\rho}_{\rm gas}$$

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

$t_{\rm cool} > t_H$	cooling is unimportant & gas is in hydrostatic equilibrium
$t_{\rm ff} < t_{\rm cool} < t_H$	system in quasi-hydrostatic equilibrium. gas contracts as system cools but it has enough time to restore hydrostatic equilibrium.
$t_{\rm cool} < t_{\rm ff}$	gas unable to respond in time to loss of pressure: as $t_{\rm cool} \propto \rho^{-1}$, cooling proceeds faster and faster — it is a "catastrophic" process

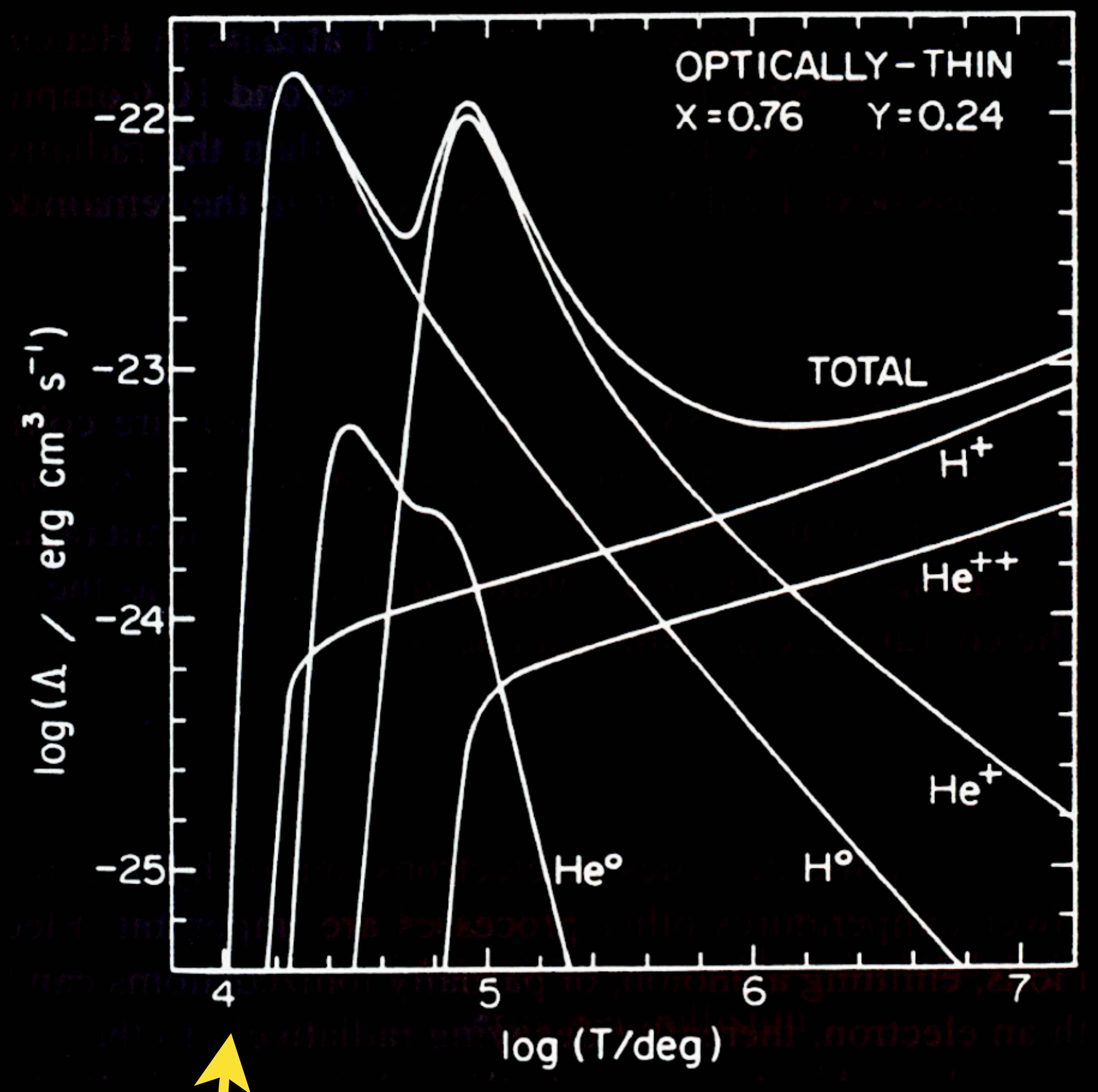
radiative cooling processes

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

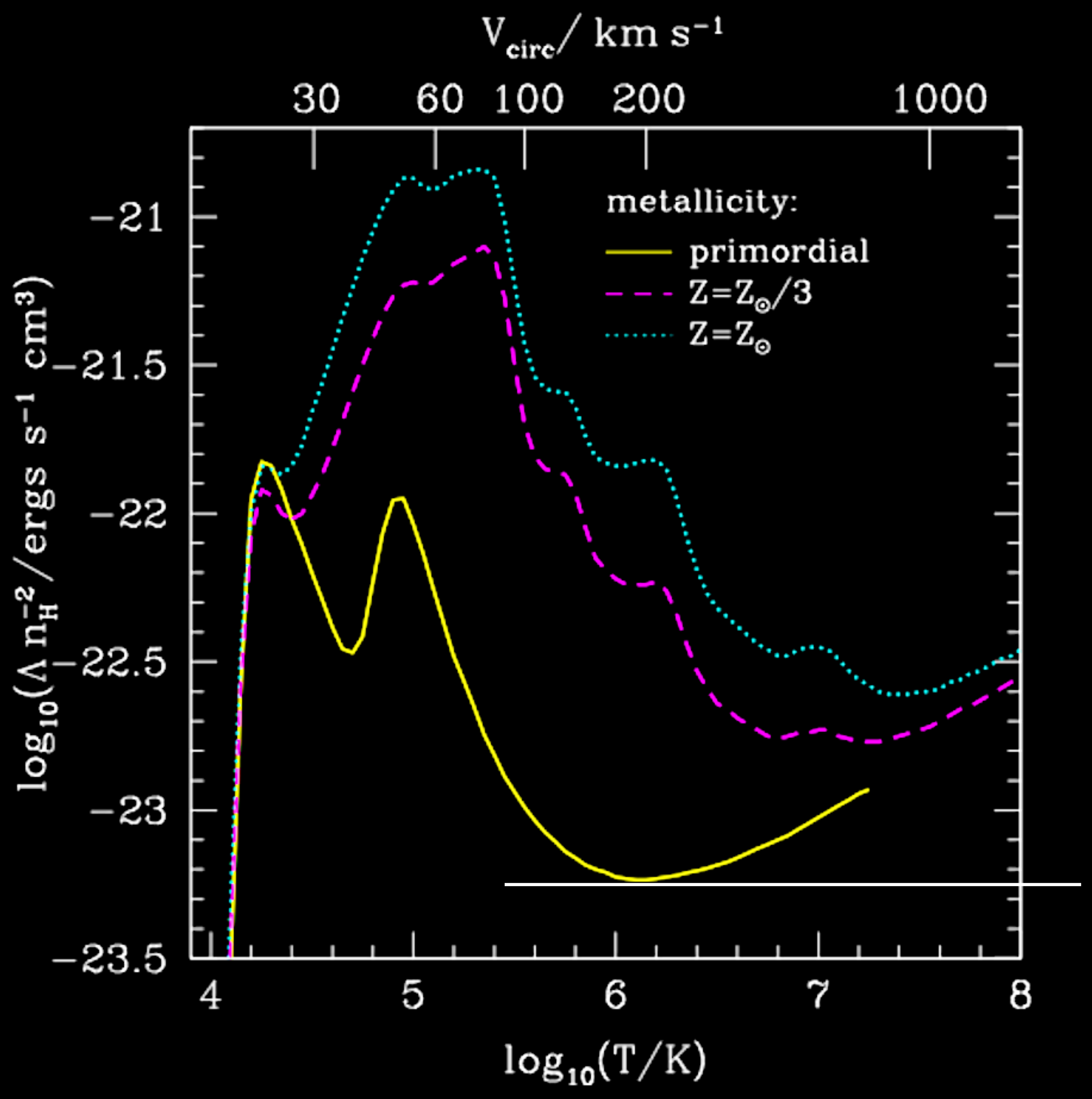
credit: Frank van den Bosch

primordial gas (H + He)



atomic cooling cuts off for T < 10^4K

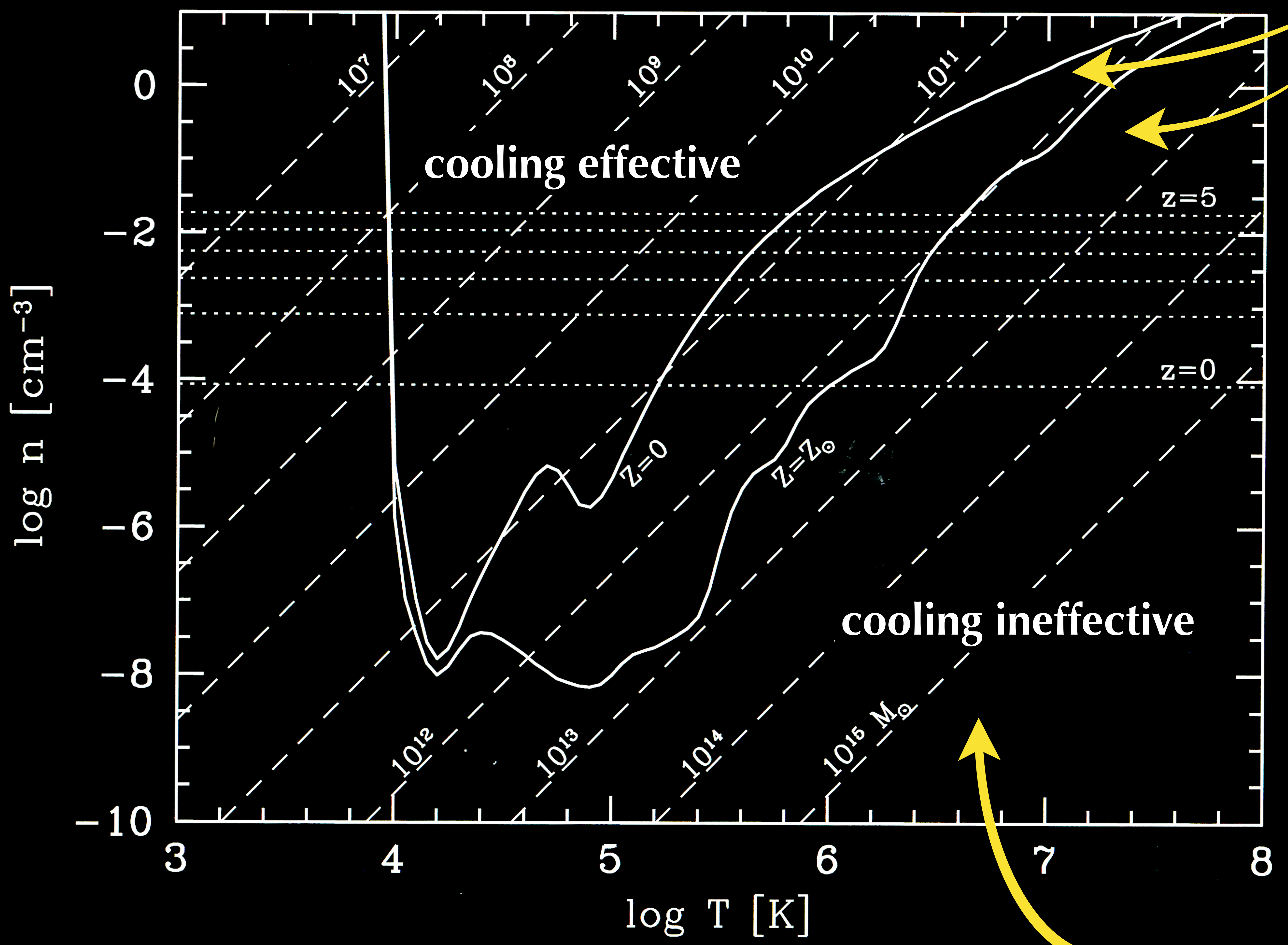
metal-enriched gas



cooling most rapid here

bremsstrahlung dominates; cooling is inefficient

Rees & Ostriker (1977)



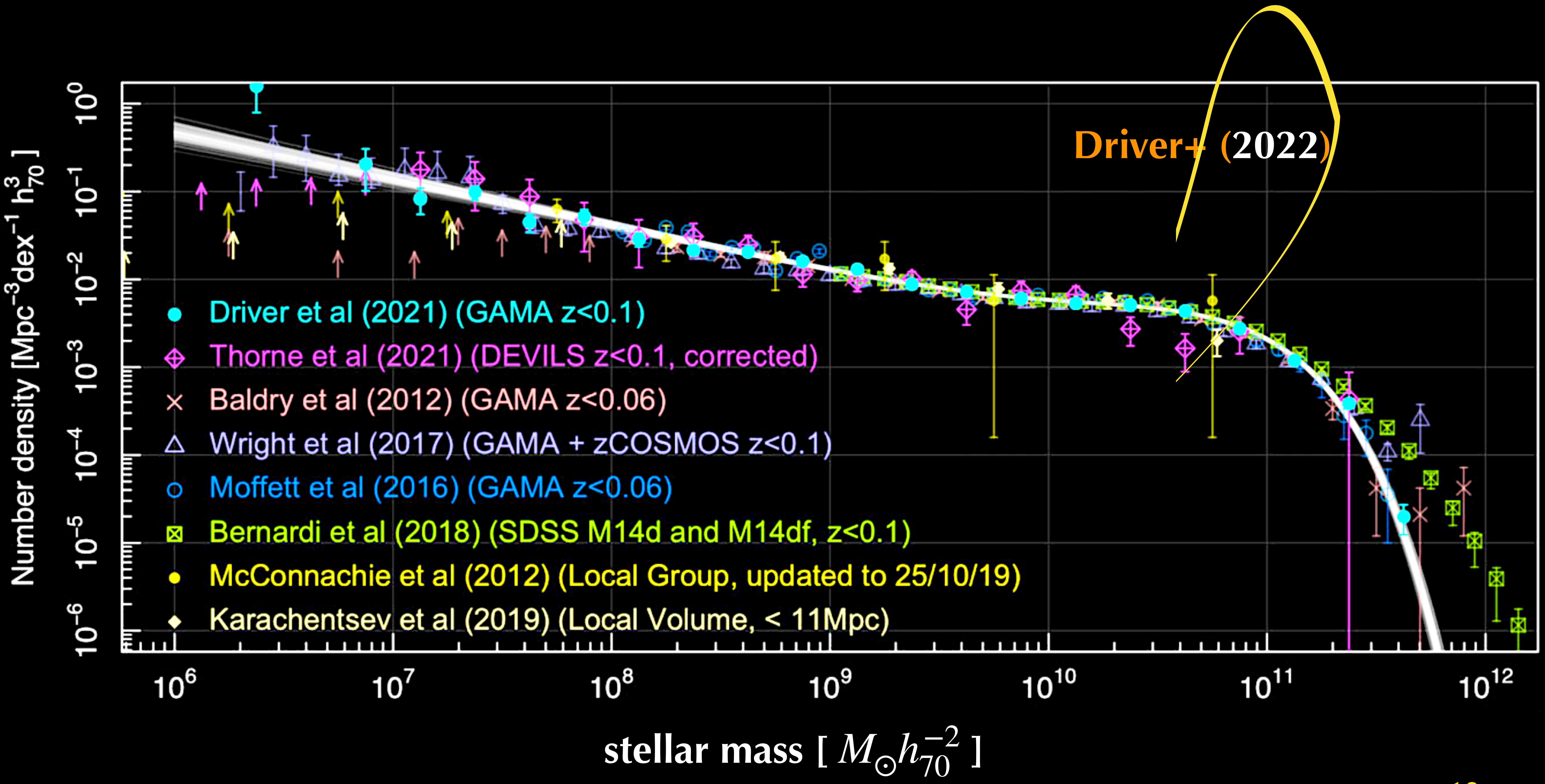
$t_{\rm cool} = t_{\rm ff}$

curves of constant $M_{\rm gas}$

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

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

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



at this scale, $M_{\rm vir} \sim 10^{12}{\rm M}_\odot$

$\longrightarrow$ 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:

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

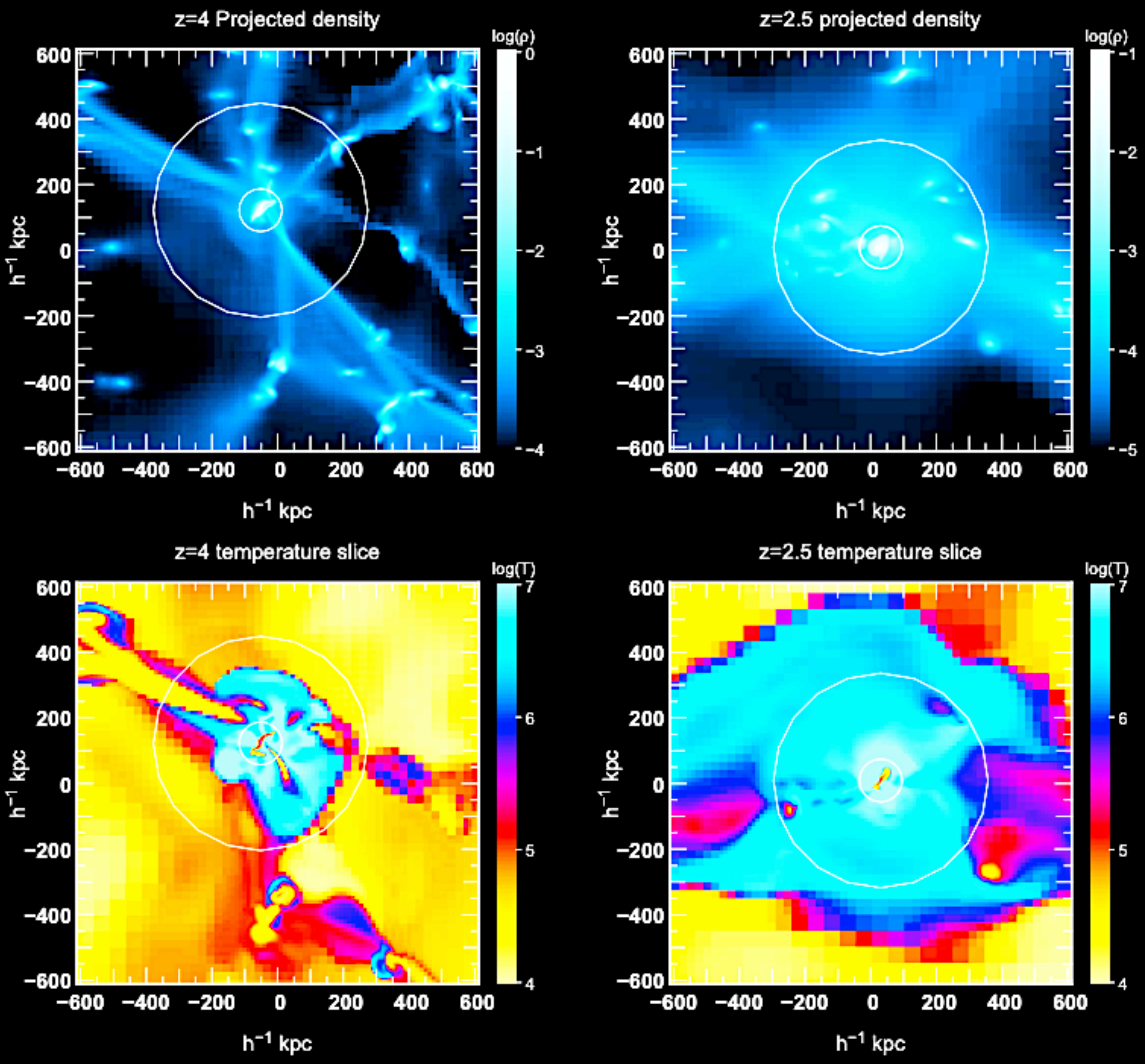
the cooling radius, r_{cool}, is at value of r at which this is equal to t_{ff} or t_H. this allows us to further define two regimes:

$r_{\mathrm{cool}} \gg r_{\mathrm{vir}}$ — 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. $\longrightarrow$ cold mode accretion

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

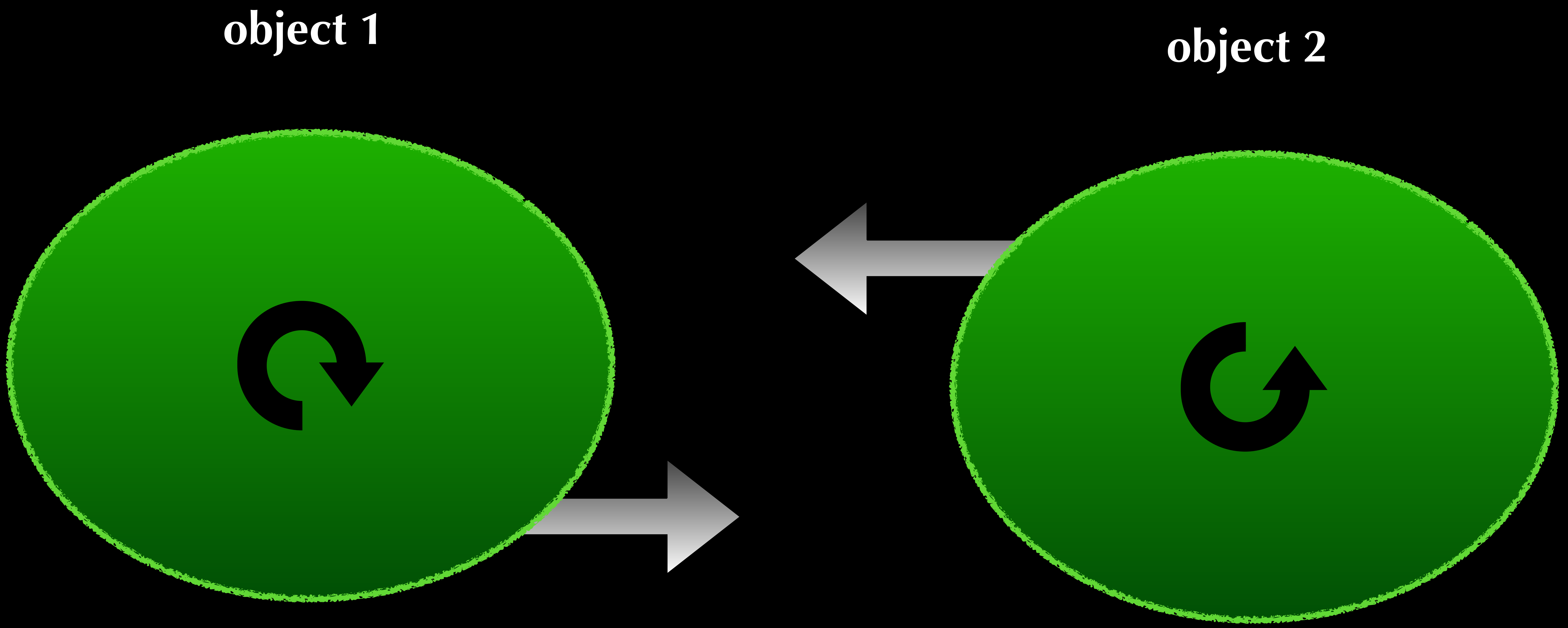
Ocvirk+ (2008)

cold accretion along filaments observed at high-z



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

4. angular momentum



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:

$$\dot{\mathbf{J}} = \int \left(\mathbf{r} - \mathbf{r}_{\mathrm{CM}}\right) \wedge \nabla \boldsymbol{\Phi}_{\mathrm{ext}}\, \rho \mathrm{d}V$$

if we now expand $\boldsymbol{\Phi}$ 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

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

moment of inertia tensor

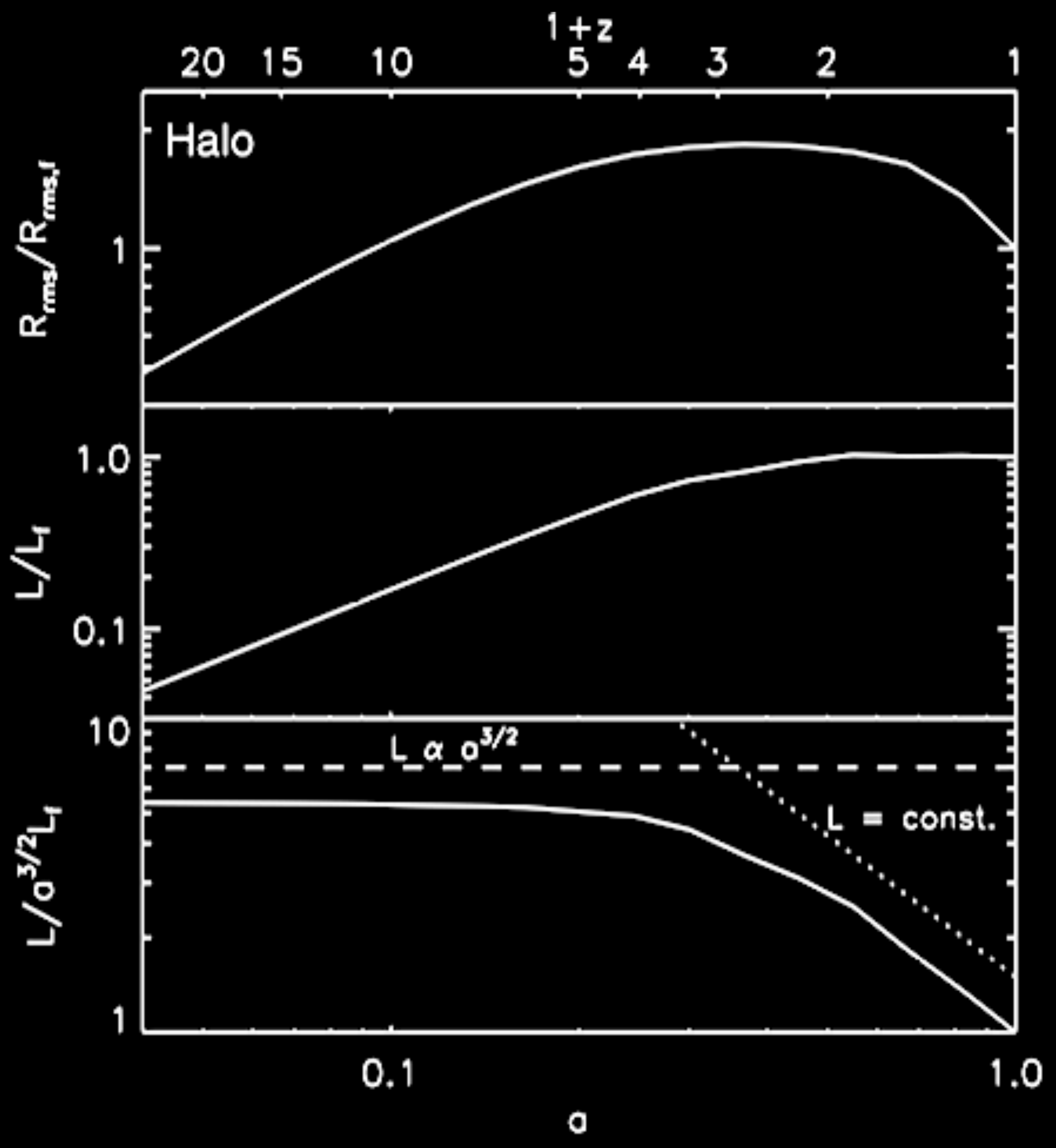
➤ $$\mathbf{I}_{jl} = \int \left(x_j - x_j^{\mathrm{CM}}\right) \left(x_l - x_l^{\mathrm{CM}}\right) \rho \mathrm{d}V$$

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



scale factor

- 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: $J \propto t \propto a^{3/2} \Rightarrow J/a^{3/2} =$ 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)

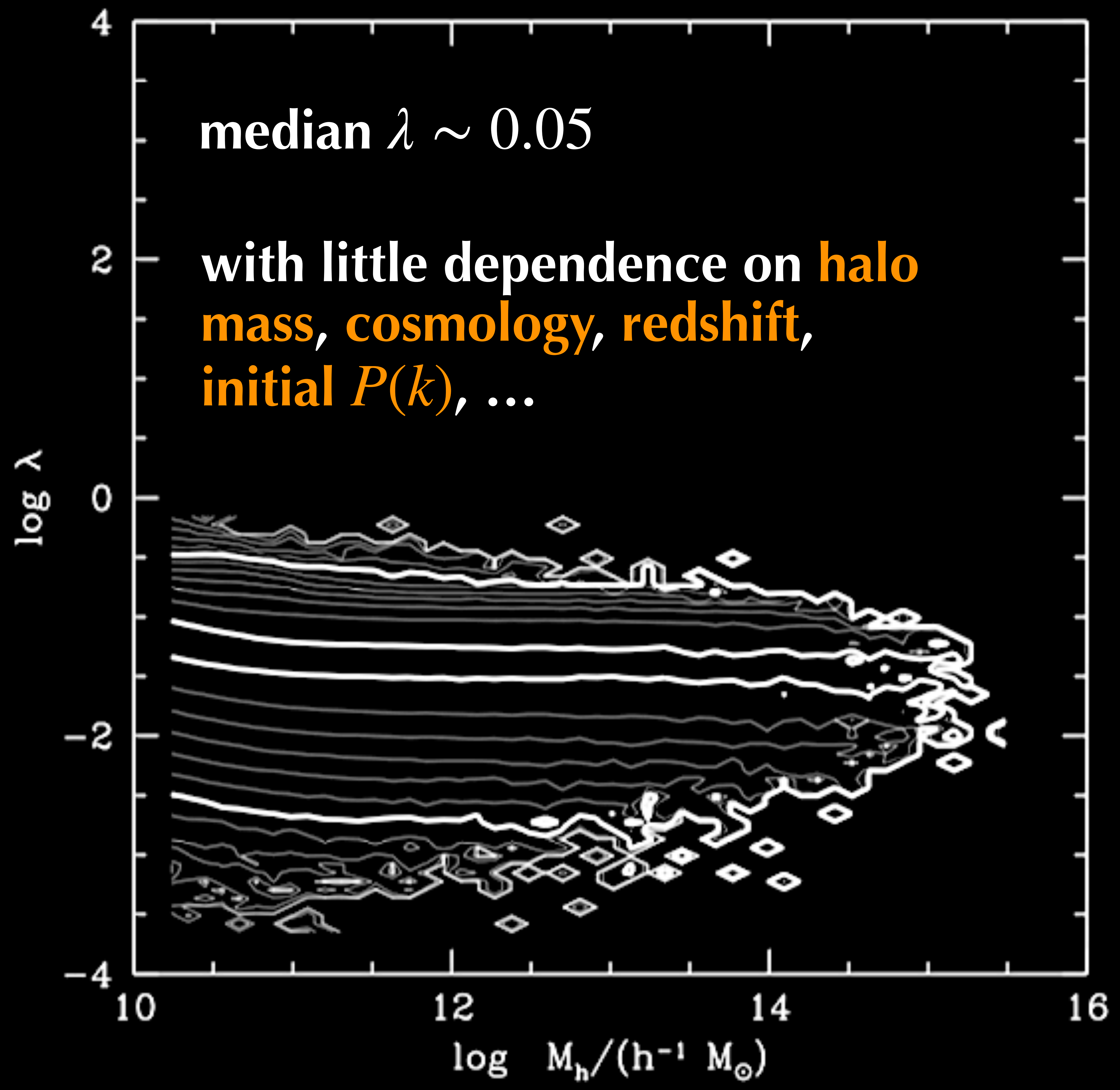
for an object in virial equilibrium with rotational velocity $V_{\rm rot} \ll \sigma$, where σ is the velocity dispersion given by $\sigma \sim (GM/r)^{1/2}$, and assuming $J = MV_{\rm rot}\, r$, we get

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

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

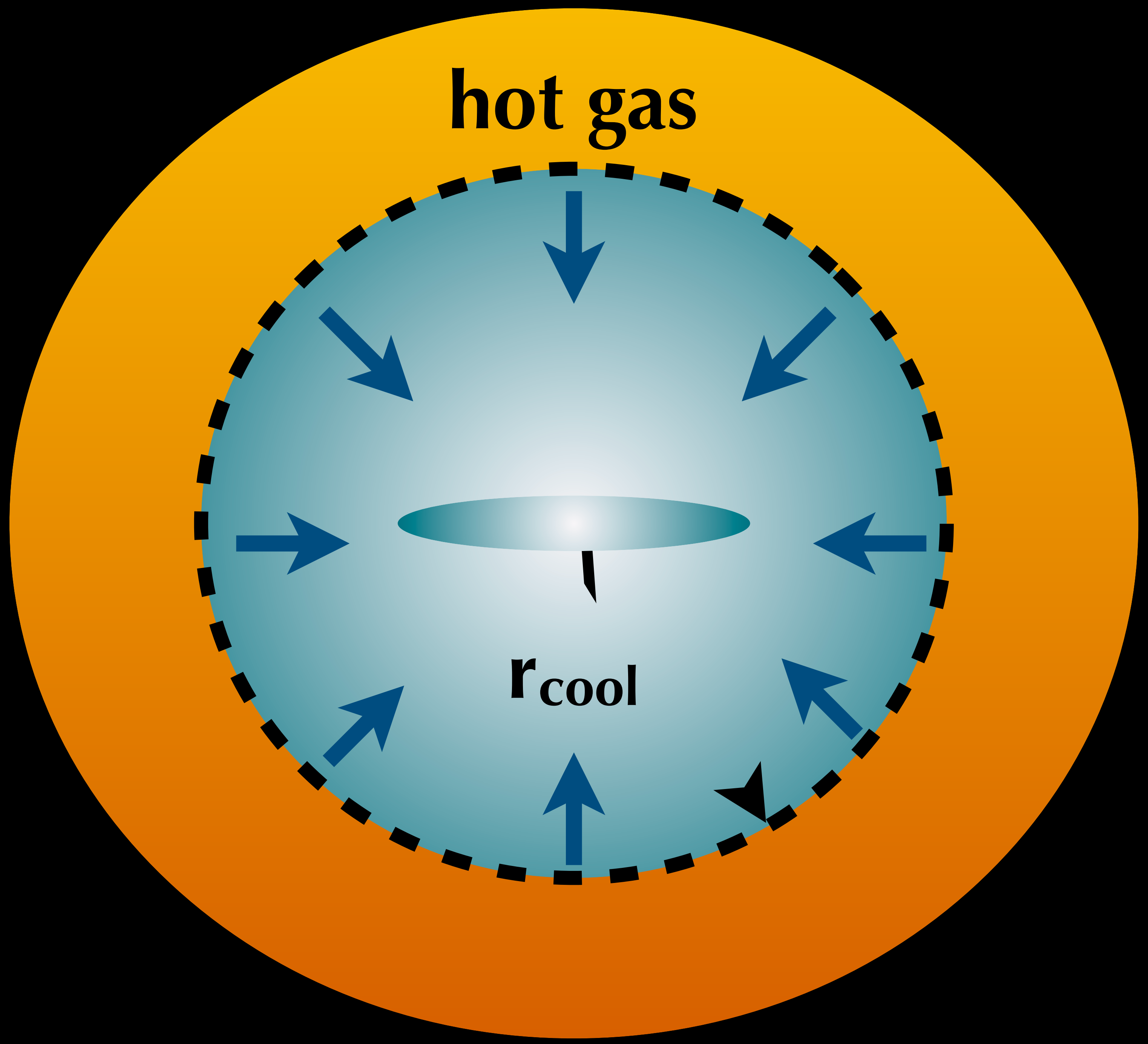
haloes formed in cosmological simulations are all found to have $\lambda \ll 1$

Bett+ (2007)


median $\lambda \sim 0.05$
with little dependence on halo mass, cosmology, redshift, initial $P(k)$, ...
log λ
4
2
0
−2
−4
10
12
14
16
log $M_h/(h^{-1}\,M_\odot)$

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, $V_{rot} = (GM(<r)/r)^{1/2}$
- so, the sizes of galaxy discs are controlled by how much angular momentum they have



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

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

(iii) gas conserves J as it collapses

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

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

(c.f. Fall & Efstathiou 1980)

for simplicity, let's make the following assumptions:

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

$$\rho_{\mathrm{H}} = V_c^2 / \left(4\pi G r^2\right)$$

constant, = V_{rot}

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

$$\Sigma_{\mathrm{D}} \propto \exp\left(-r/h_{\mathrm{D}}\right)$$

(only gas within r_{cool} is relevant)

- then: $J_{\mathrm{H}}/M_{\mathrm{H}} = 2\lambda_{\mathrm{H}} V_c r_{\mathrm{cool}}$ and $J_{\mathrm{D}}/M_{\mathrm{D}} = 2h_{\mathrm{D}} V_c$

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

$$h_{\mathrm{D}} = \lambda_{\mathrm{H}} r_{\mathrm{cool}}$$

- so, the gas has collapsed in radius by a factor: $r_{\mathrm{D}}/r_{\mathrm{cool}} \sim h_{\mathrm{D}}/r_{\mathrm{cool}} \sim \lambda_{\mathrm{H}} \sim 0.1$

a simple model for the radii of galaxy discs

this model therefore predicts that:

$r_{\mathrm{disc}} \sim \lambda_{\mathrm{H}} r_{\mathrm{cool}}$ if gas cools only within the radius r_{cool}

$r_{\mathrm{disc}} \sim \lambda_{\mathrm{H}} r_{\mathrm{vir}}$ if all the gas within the halo cools to form a disc

when combined with the predicted values of λ_{H} from cosmological simulations, it turns out that this is in ~rough~ agreement with the observed sizes of galaxy discs at z~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