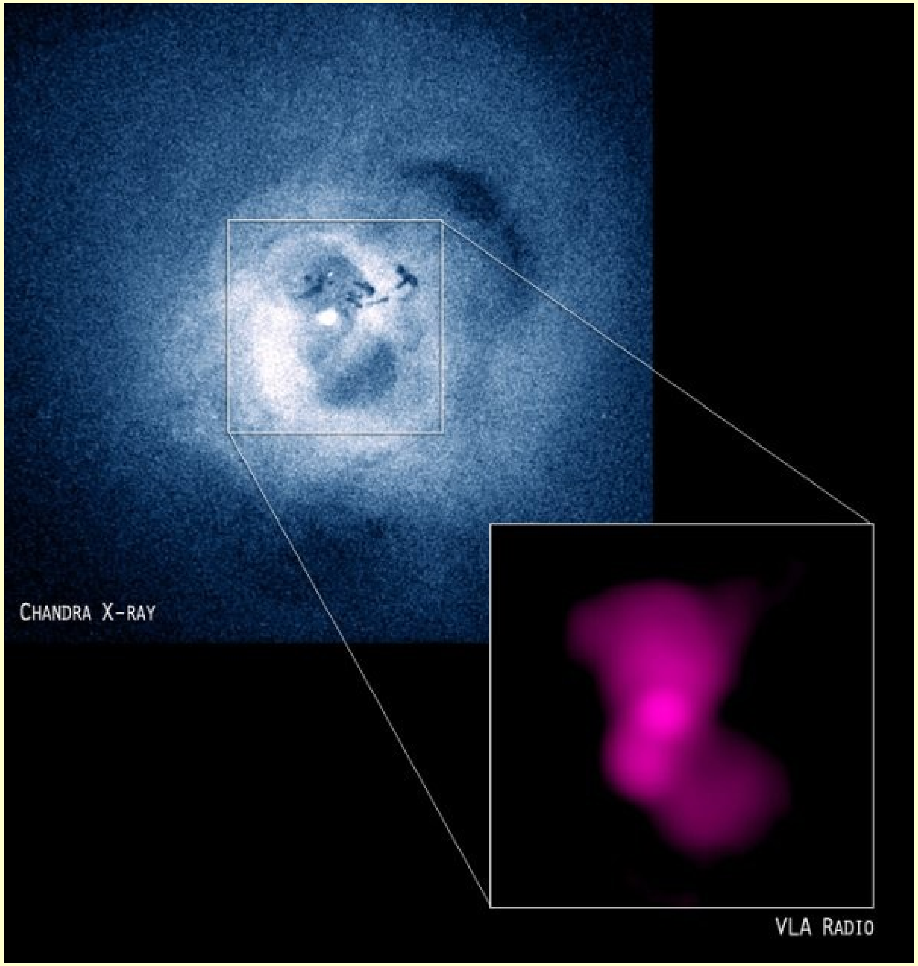
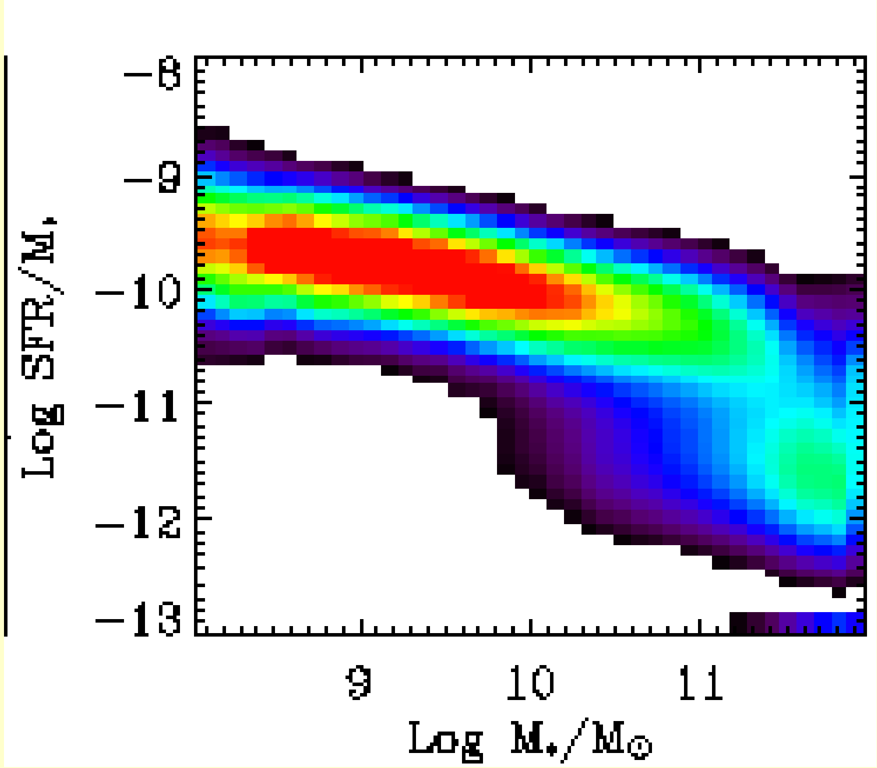
The importance of cooling flows for galaxy formation

Pierluigi Monaco, Astronomy Department, University of Trieste



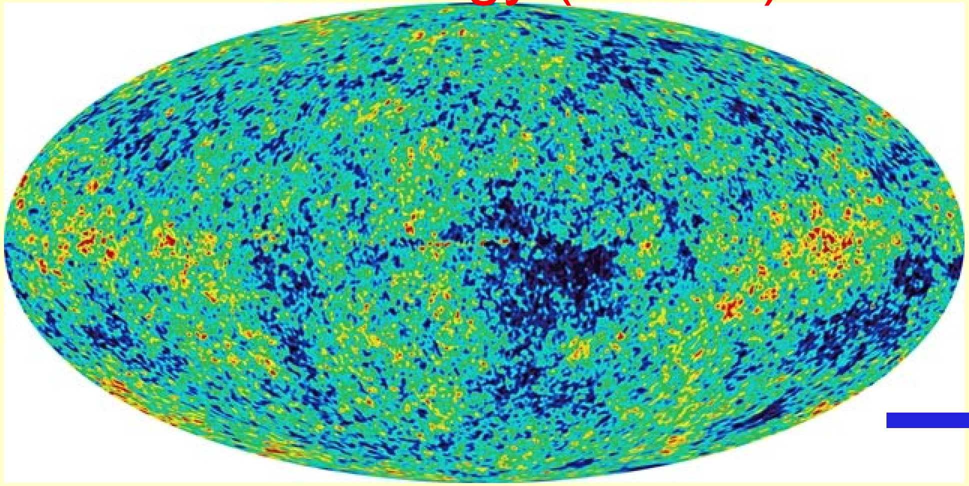


Cosmological Flows, ICTP,
Trieste, October 2007

Part I

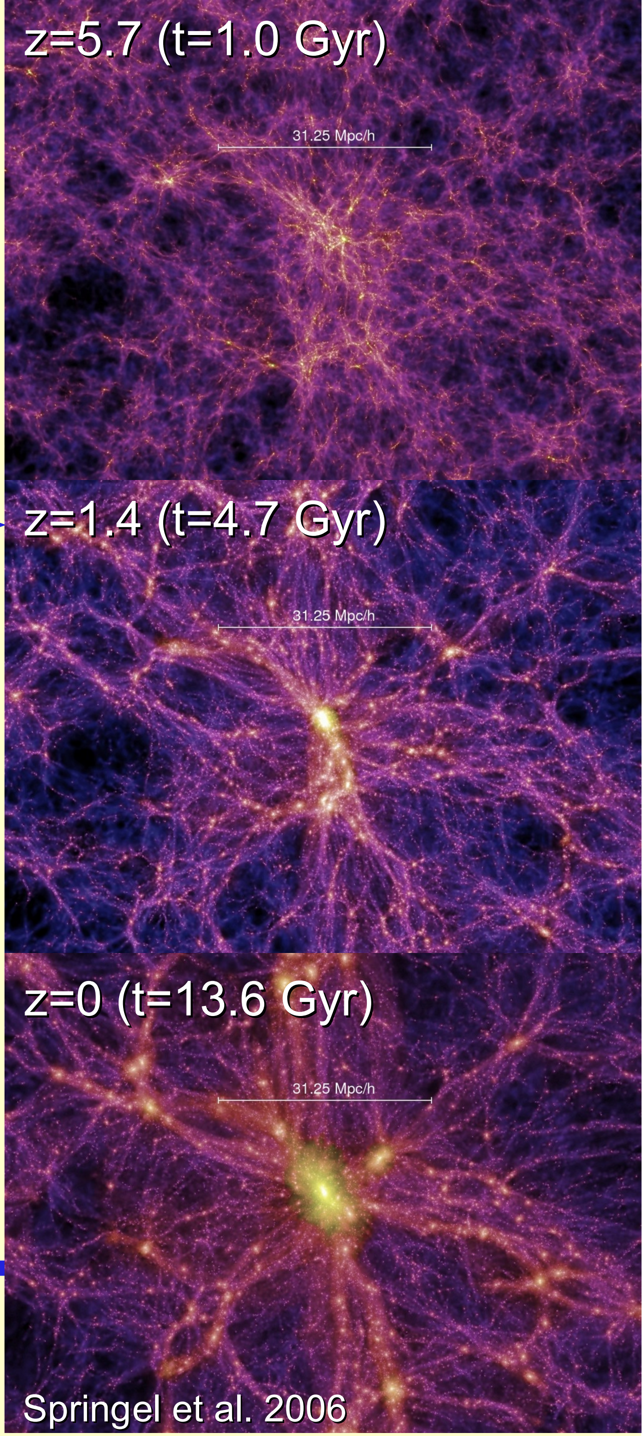
A brief introduction to cooling flows

Cosmology (ΛCDM)



gravitational

collapse



Springel et al. 2006

Dark matter

“gastrophysics”

Galaxies

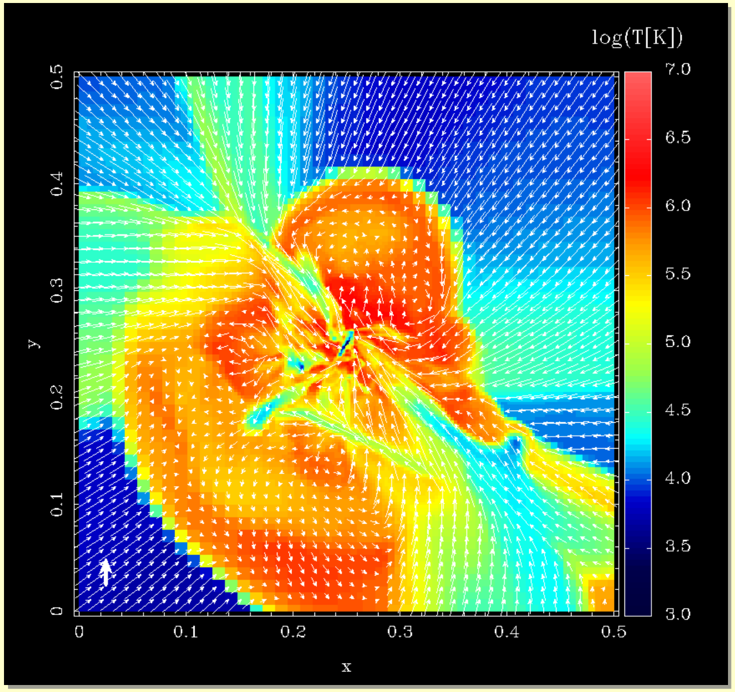
The first steps of "gastrophysics": infall and shock-heating

Massive halos (>10^{12} M_{sun}):

cooling is slower than infall

gas is shock- heated at T_{vir}

and is in roughly hydrostatic equilibrium

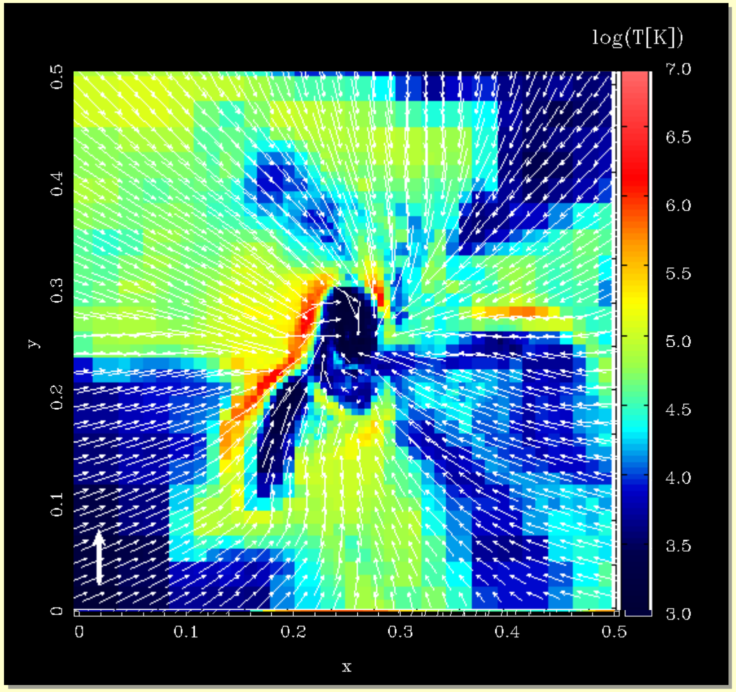


Small halos (<10^{11} M_{sun}):

cooling is faster than infall

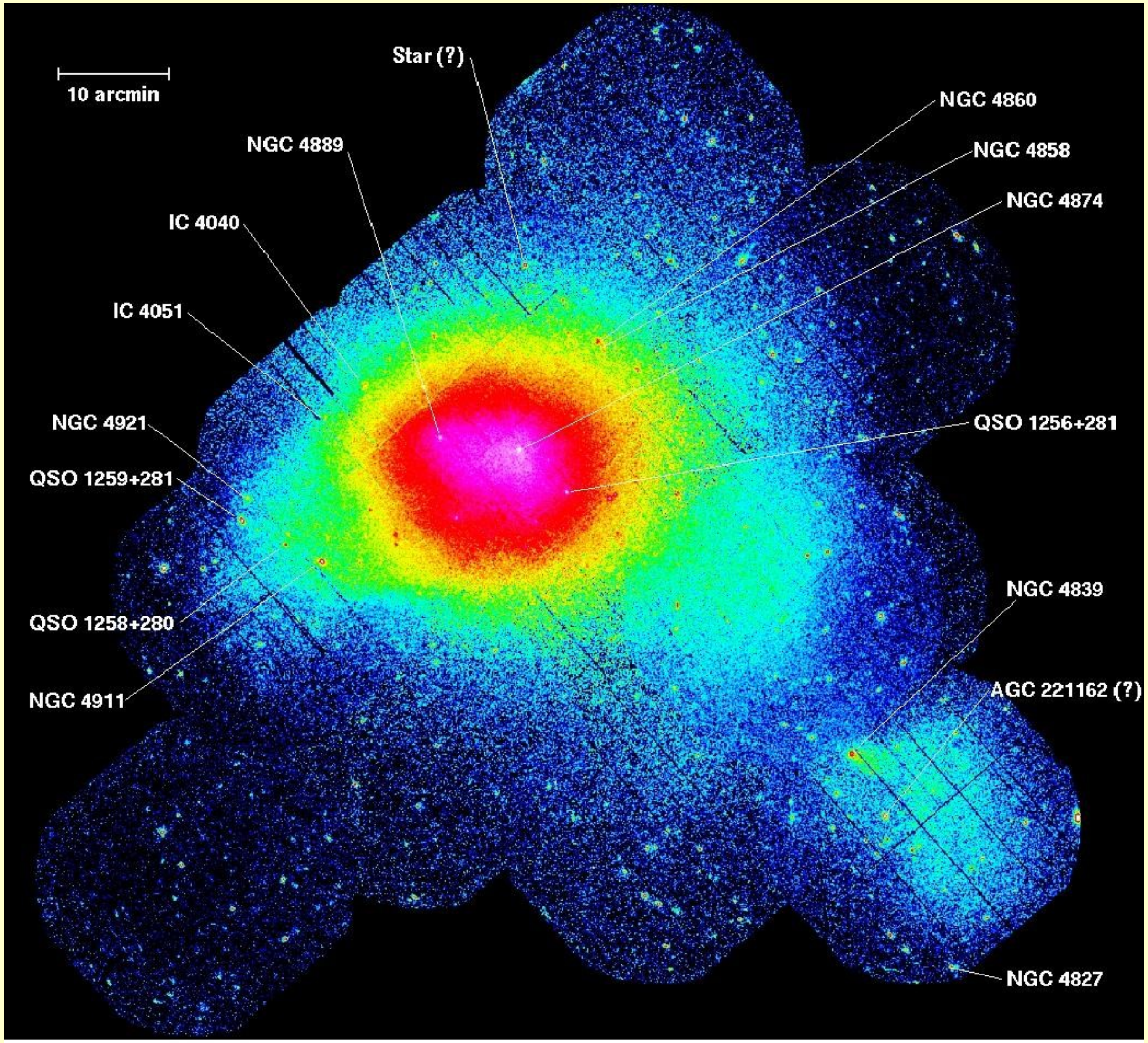
cold gas falls directly to the centre

the shock energy is quickly dissipated



Kravtzov et al. 2004

Galaxy clusters show such hot gas



Coma Cluster of galaxies

Image courtesy of U. Briel, MPE Garching, Germany

European Space Agency

Radiative cooling of an optically thin plasma: primordial composition

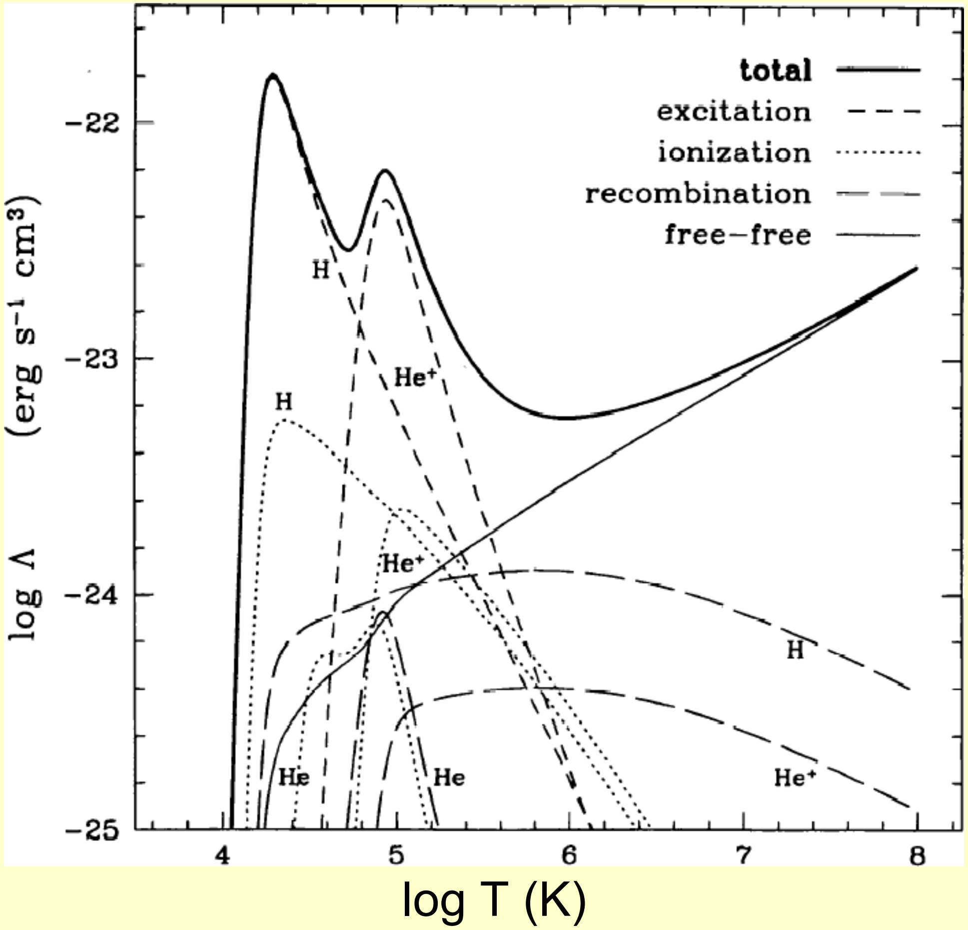
$$L = n_i n_e \Lambda(\rho, T)$$

$$t_{cool} = \left| \frac{d \ln T}{dt} \right|^{-1} = \frac{E_{th}}{L} = \frac{3nkT}{2 n_e n_i \Lambda}$$

Assumptions:

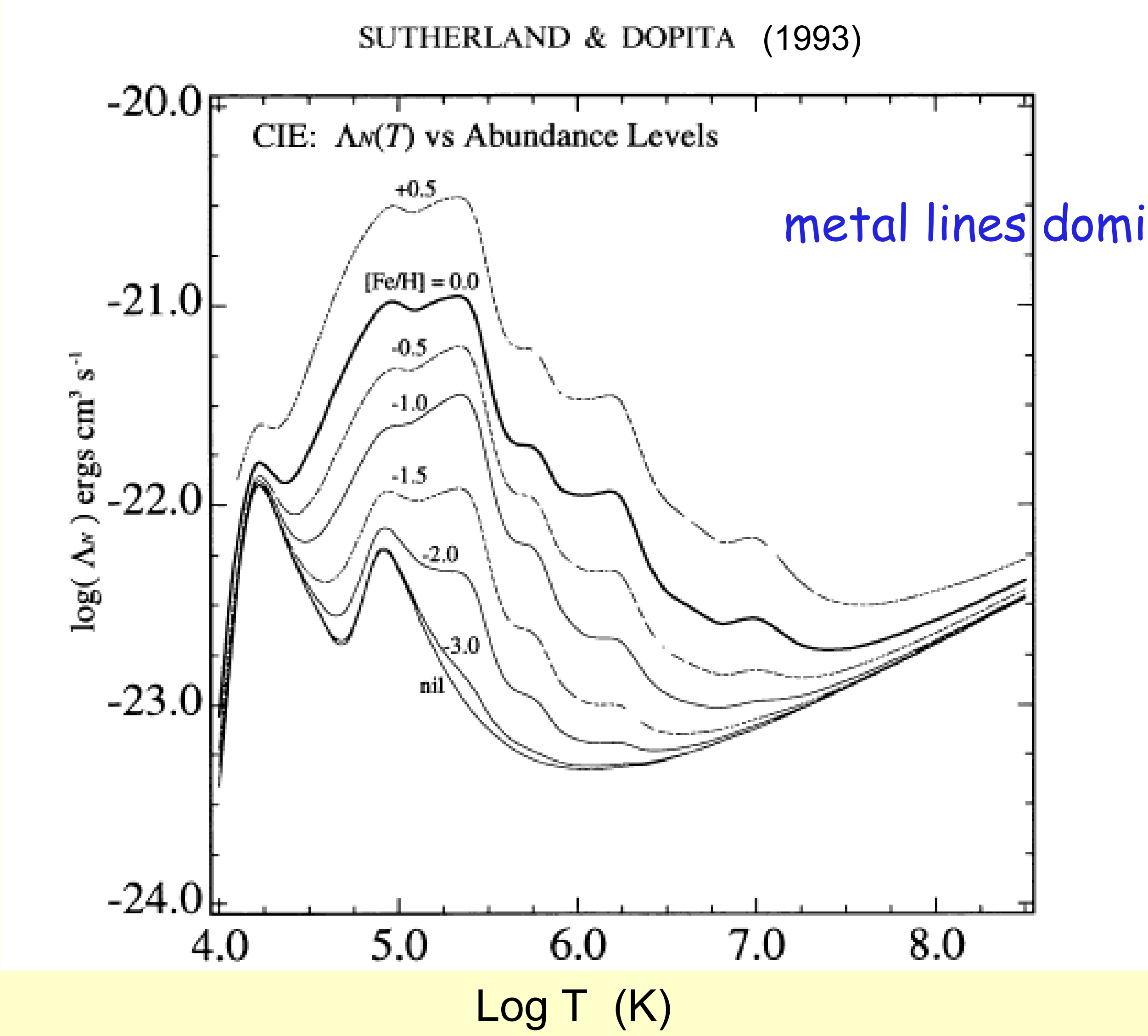
- collisional ionisation equilibrium
- thermal distribution of e^- and ions
- no external ionising radiation

(Katz, Weinberg & Hernquist 1996)



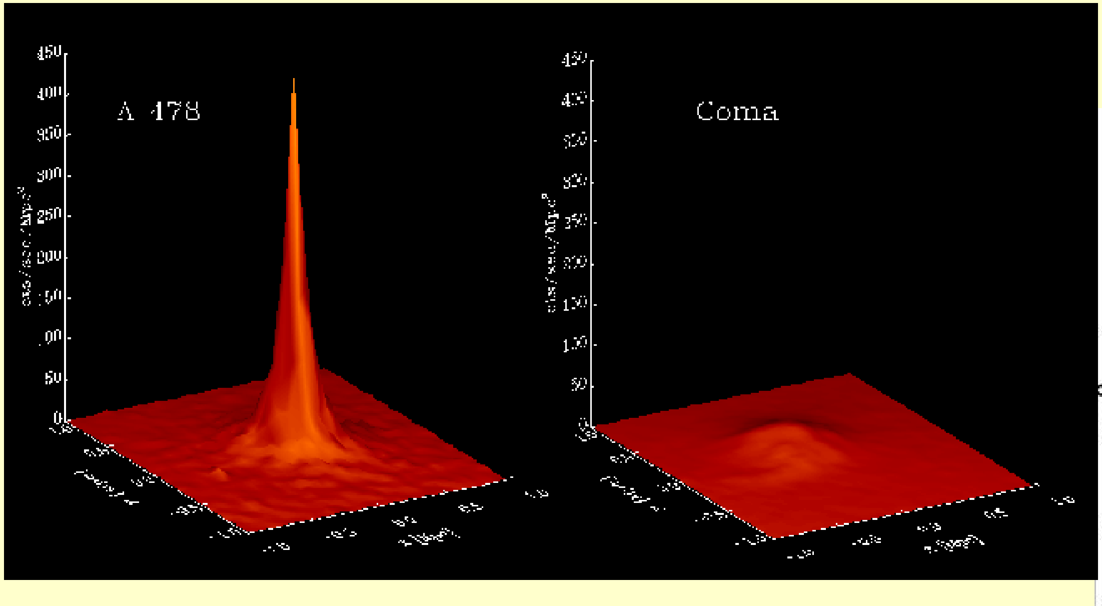
Radiative cooling of an optically thin plasma: solar composition

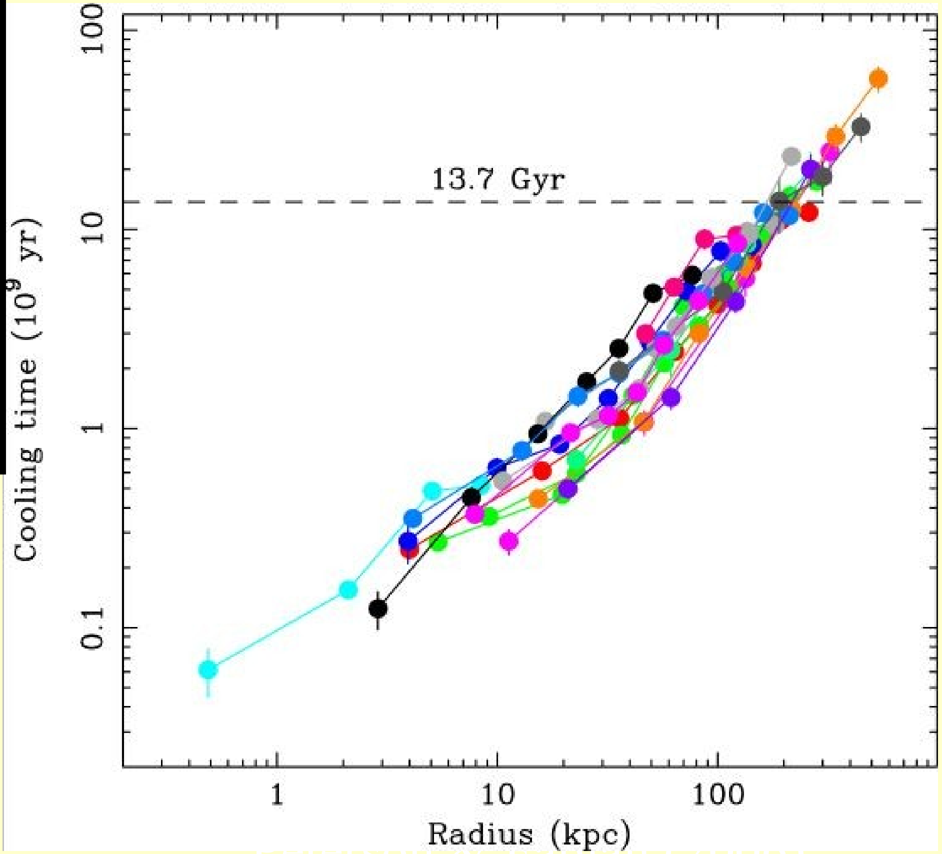
SUTHERLAND & DOPITA (1993)



metal lines dominate cooling

A problem with cooling flows in Galaxy Clusters



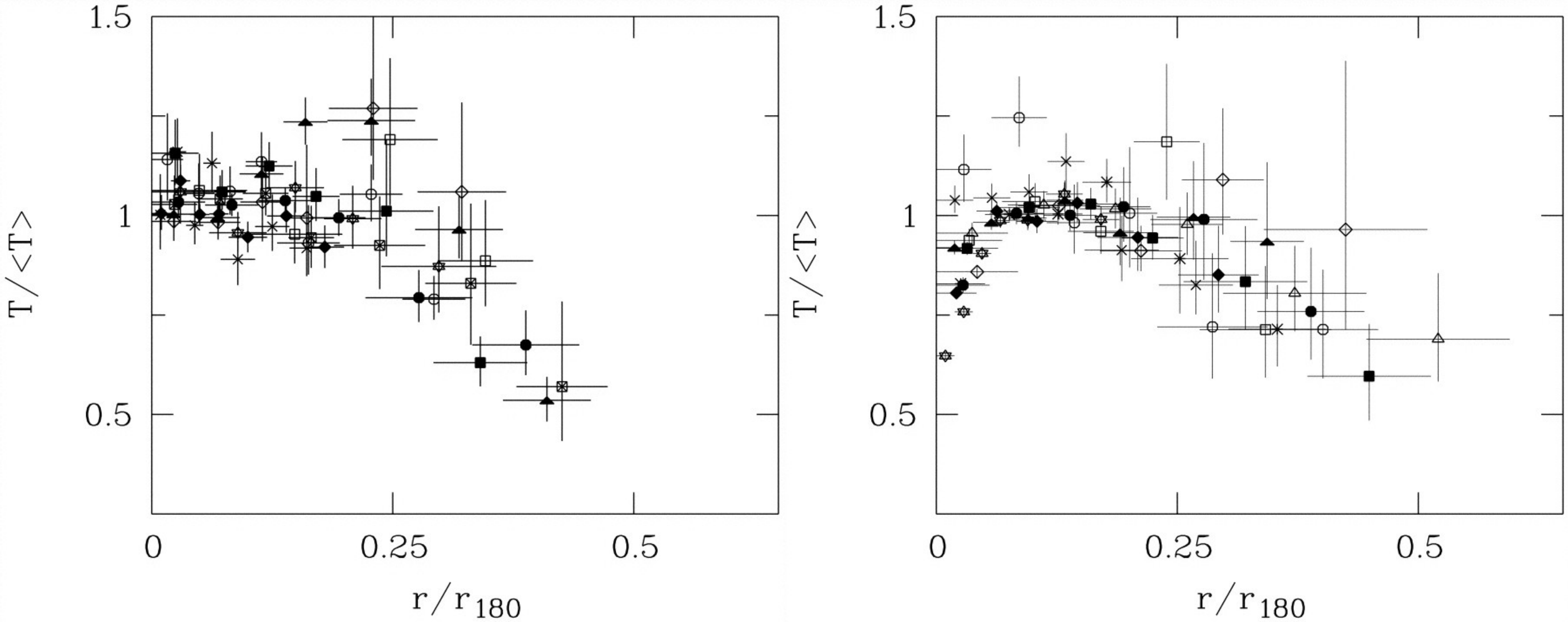


Peterson & Fabian (2006)

X-ray observations of galaxy clusters allow us to estimate density and temperature, and then cooling time, of the hot gas.

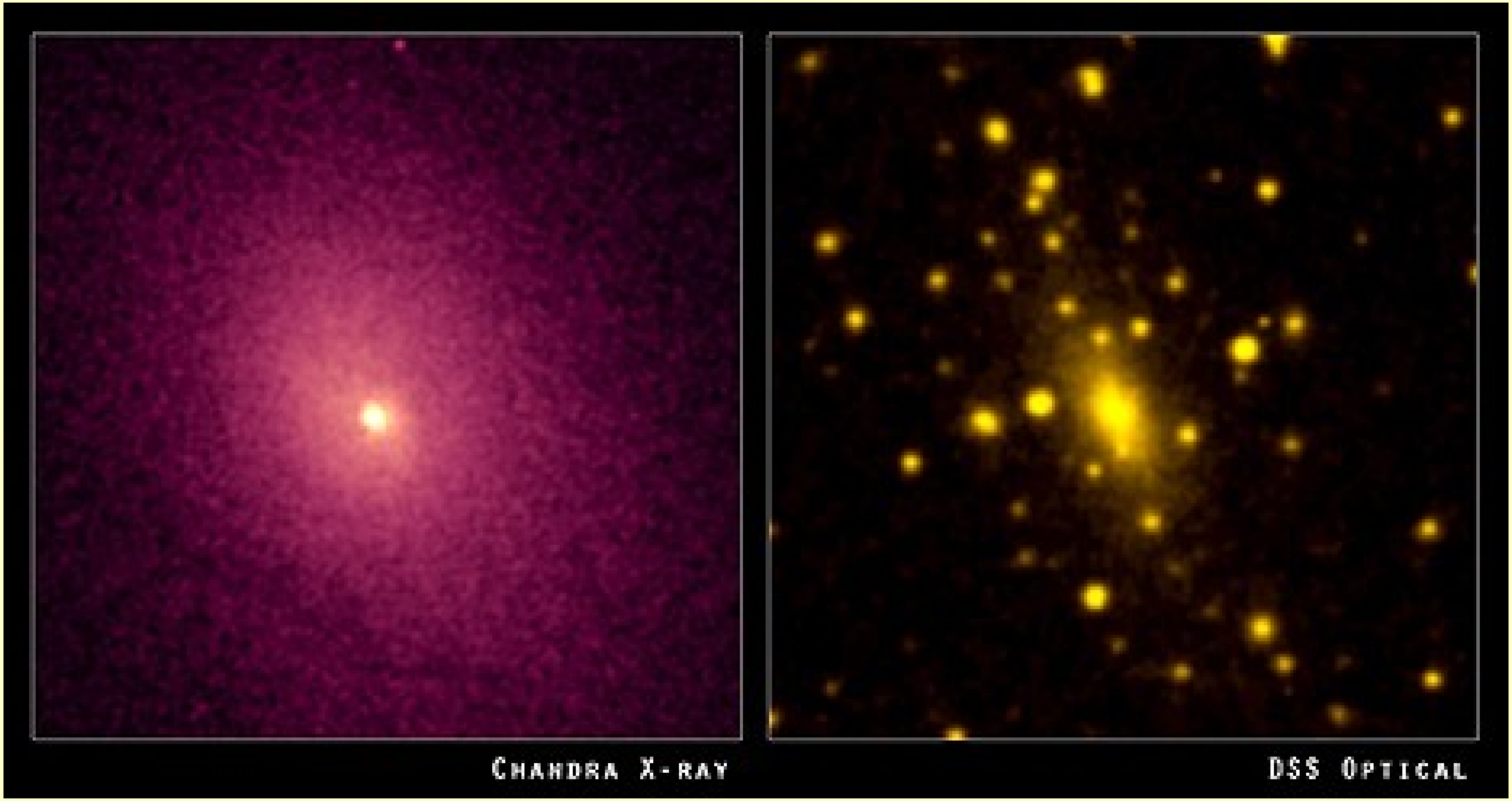
Some clusters should be sites of strong cooling flows

...from cooling flow clusters to cool core clusters...

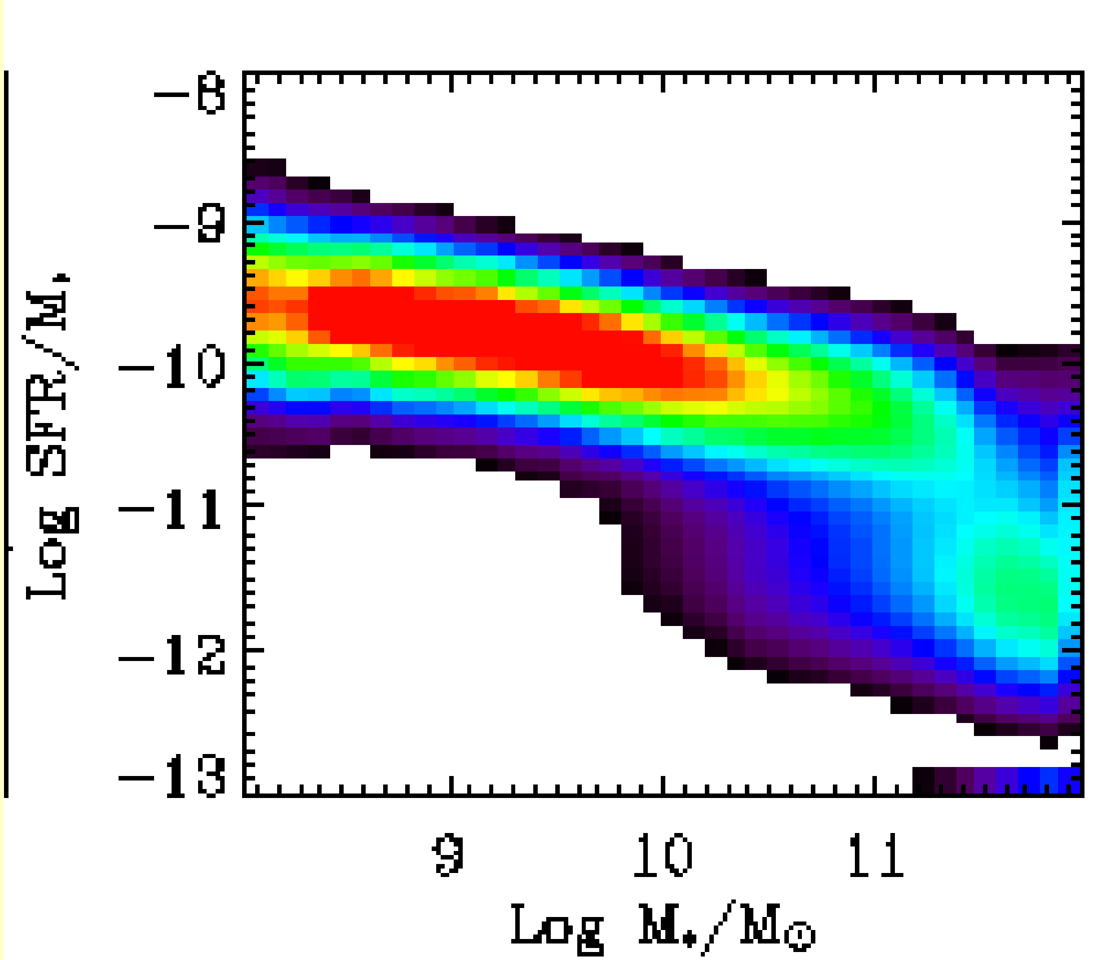


(De grandi & Molendi 2002)

Massive (cD) elliptical galaxies reside at the centre of galaxy clusters



Why are massive galaxies red & dead?



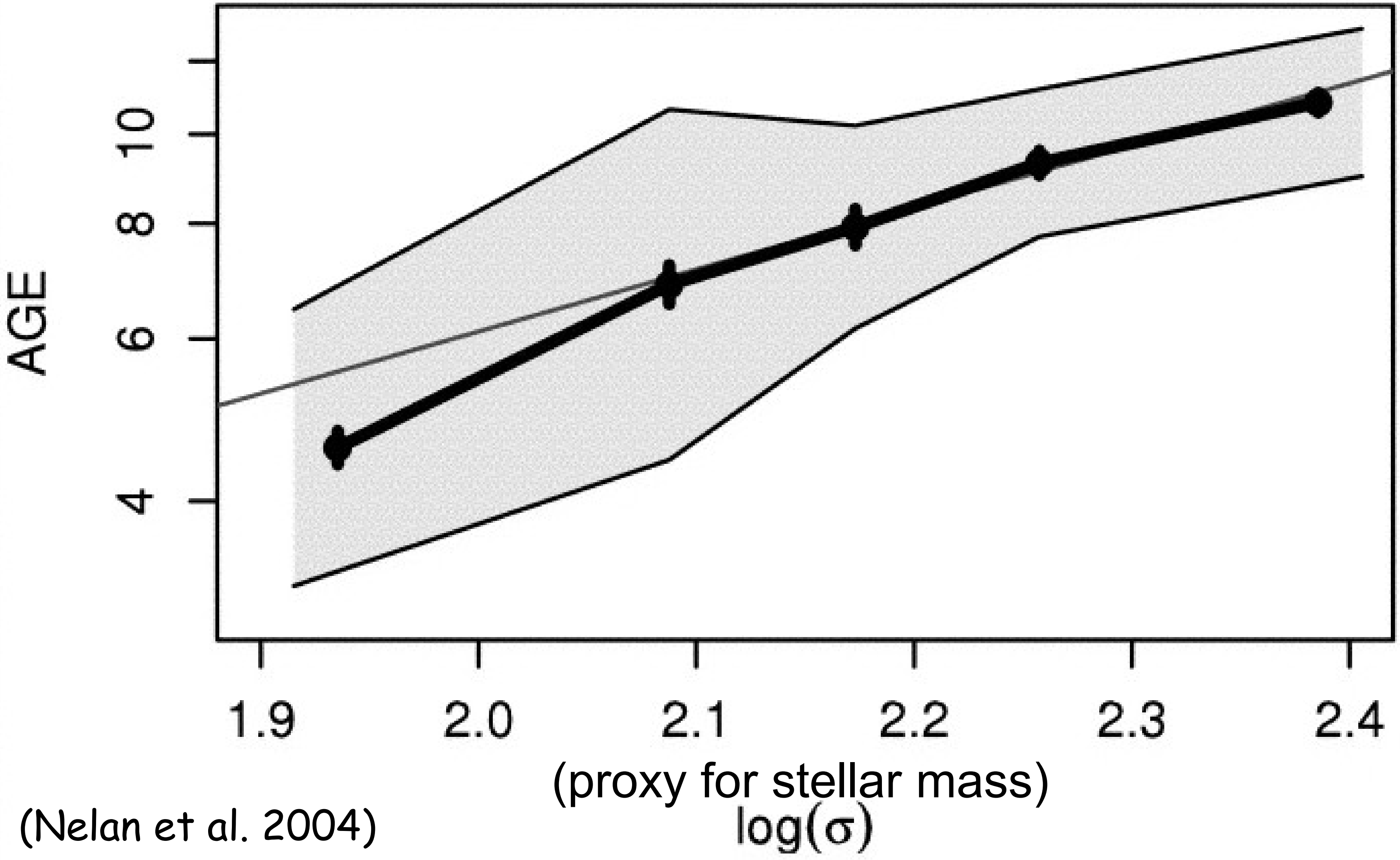
specific star formation rate

stellar mass

The mass deposited into the galaxy is 10^{-1} or 10^{-2} times that suggested by the cooling flow

(Brinchmann et al. 2003)

Why are massive ellipticals so old?

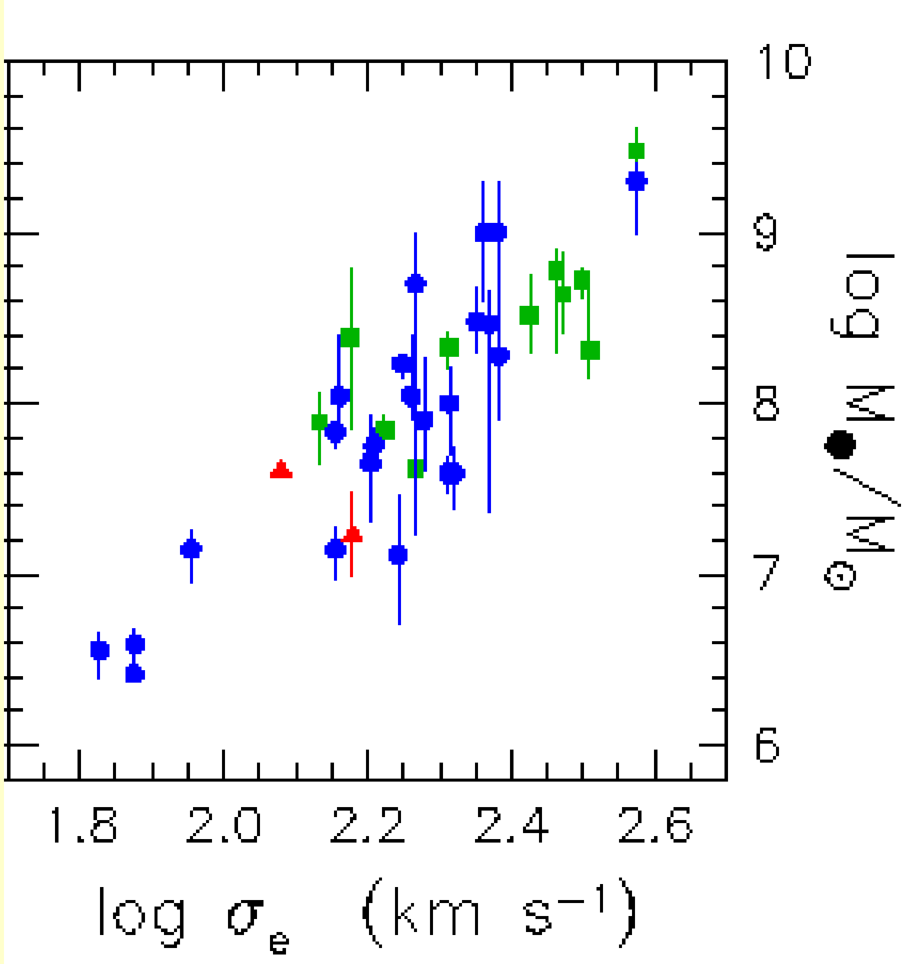


(Nelan et al. 2004)

A possible answer: AGN feedback

Every elliptical galaxy hosts a super-massive black hole at its centre

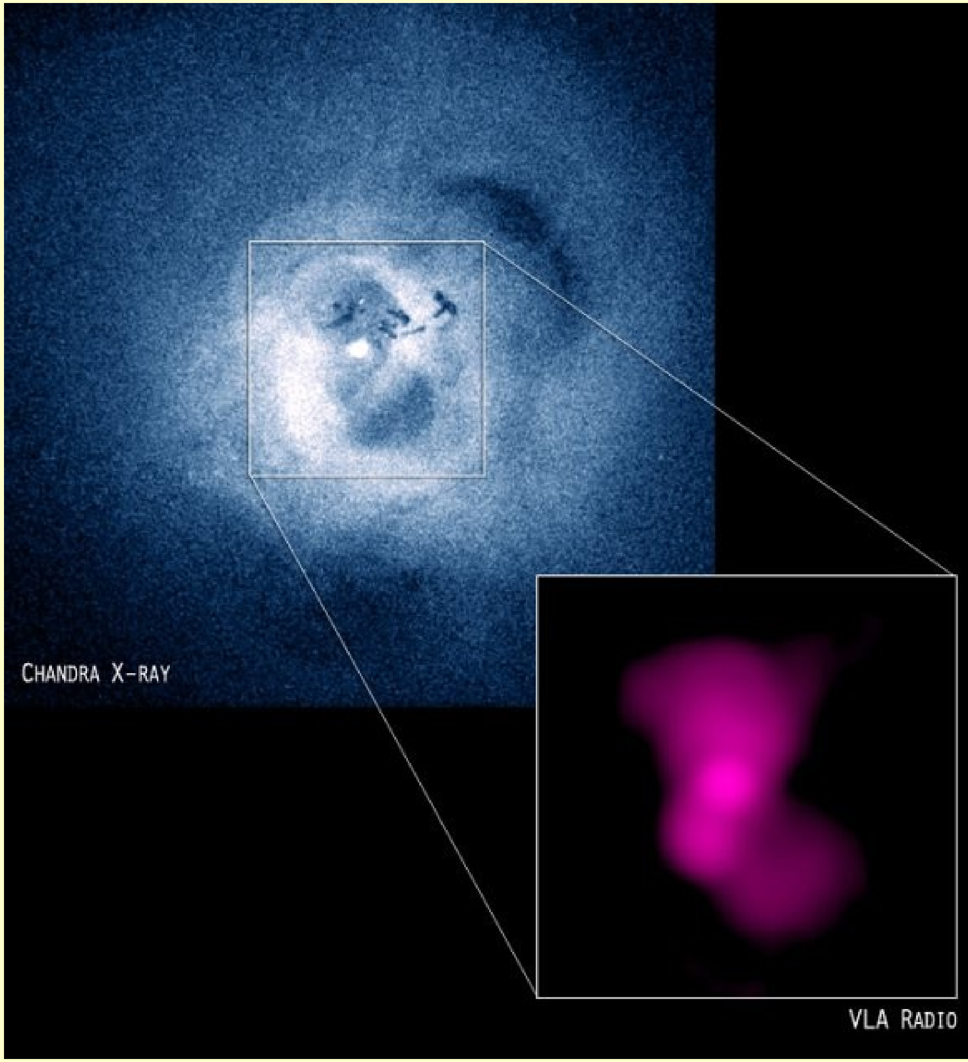
These black holes may be reactivated by the cooling gas

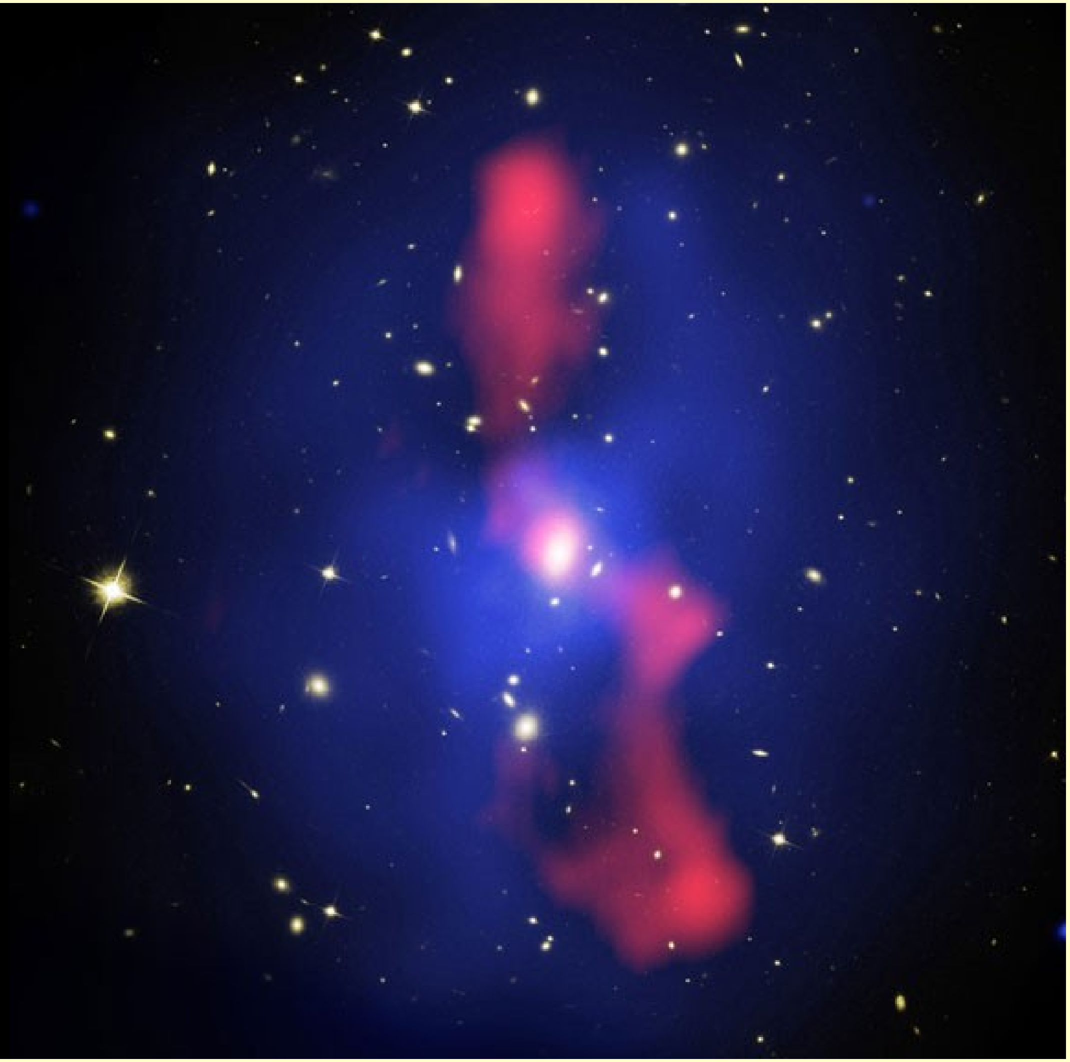


(proxy for stellar mass)

Ferrarese & Merritt 2000
Gebhardt et al. 2000

AGN feedback in action?

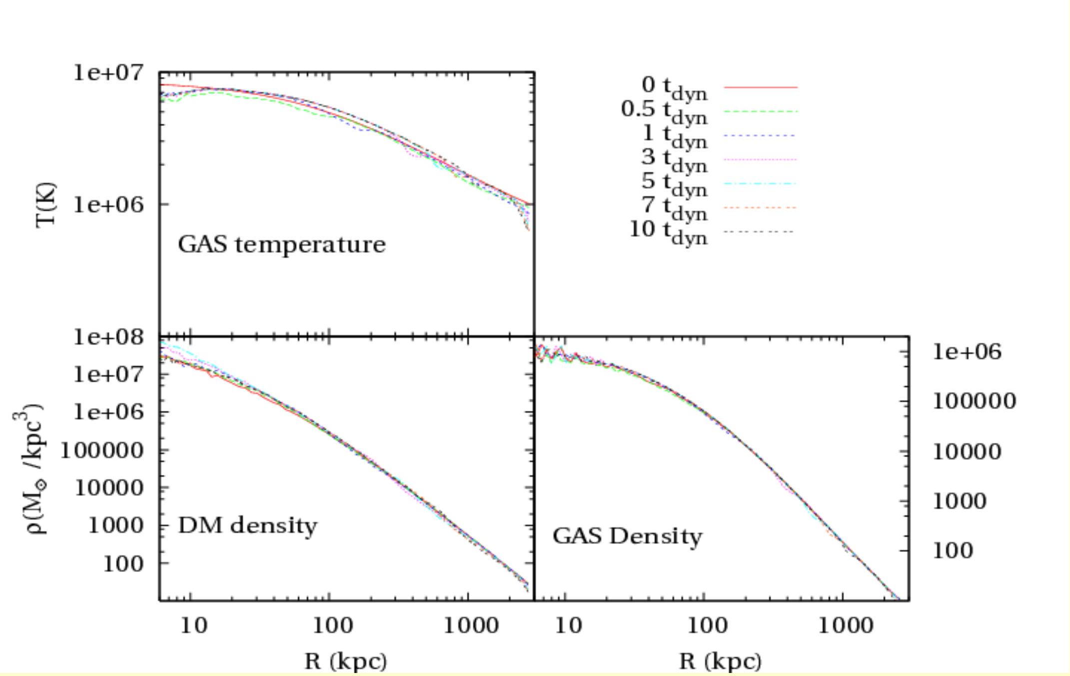




Part II

Simulating cooling flows (with some surprises…)

Hot baryons in DM halos



$\rho = \rho_{crit} \dfrac{\delta_c}{(r/r_s)(1+r/r_s)^2}$	NFW profile for the total mass
$c = r_{vir}/r_s$	halo concentration
$\dfrac{dP_g}{dr} = -G \dfrac{\rho_g M(r)}{r^2}$	hydrostatic equilibrium
$P_g \propto \rho_g^{\gamma_p}$	polytropic equation of state (γ_p~1.2)
$\rho_g(r) = \rho_{g0} \left[1 - a \left(1 - \dfrac{\ln(1+r/rs)}{r/r_s} \right) \right]^{1/(\gamma_p - 1)}$	solution for the density

$$a = a(T_{g0}/T_{vir}, \gamma_p, c)$$

The "classical" cooling model

The cooling radius:

$$r_{cool}(t): \quad t_{cool}(r) = t$$

Bertschinger's (1989) self-similar solutions:

$$\dot{M}_{cool} \propto 4\pi \rho_g(r_{cool}) r_{cool}^2 \frac{dr_{cool}}{dt}$$

The "classical" cooling model (White & Frenk 1991):

$$\dot{M}_{cool} = 4\pi \rho_g(r_{cool}) r_{cool}^2 \frac{dr_{cool}}{dt}$$

Total cooling time of a mass element:

$$t_{total} : T(t_{total}) \ll T(t=0)$$

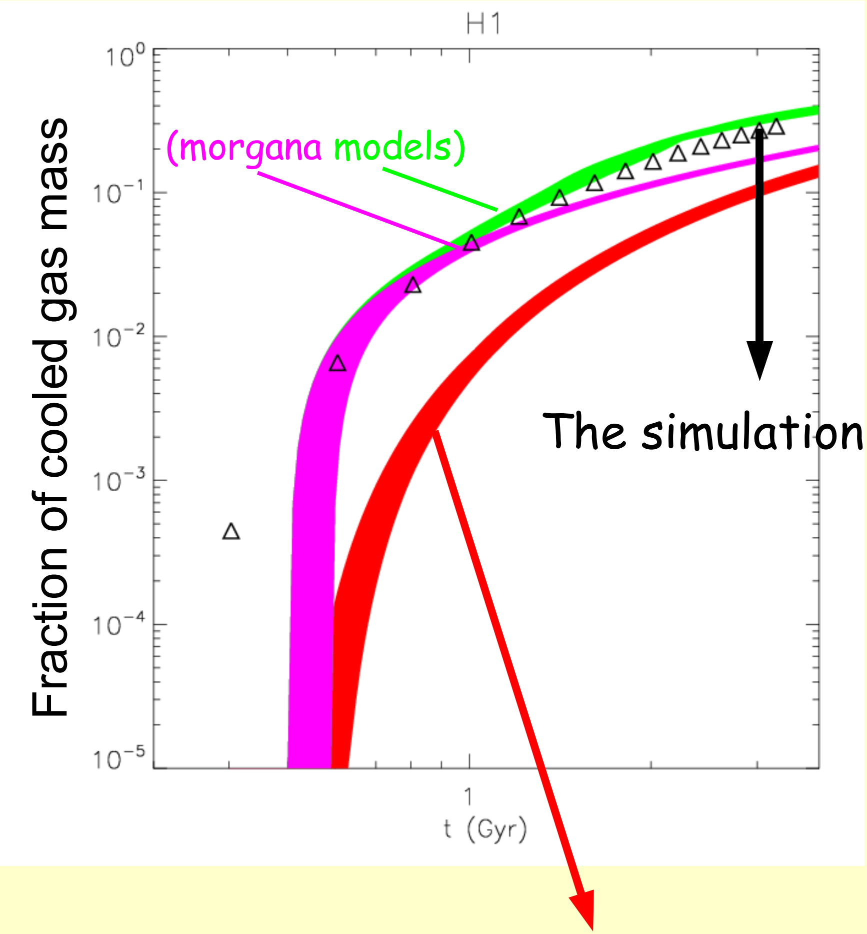
The classical model implies that:

$$t_{cool}(r) = t_{total}(r)$$

Controlled numerical experiments of cooling in a DM halo

- Gadget2 SPH code with entropy-conserving integration
- 60000 DM particles and 60000 gas particles inside the virial radius
- Static DM halo with NFW profile
- Gas profile in hydrostatic equilibrium
- Run for two dynamical times without cooling to ensure relaxation
- Radiative cooling switched on
- Checked stability of results with respect to number of particles, softening, "star formation", number of SPH neighbours

$M_H = 10^{13}\ M_{sun}$ @ $z=0$, $c=6.3$



(morgana models)

The simulation

The classical model

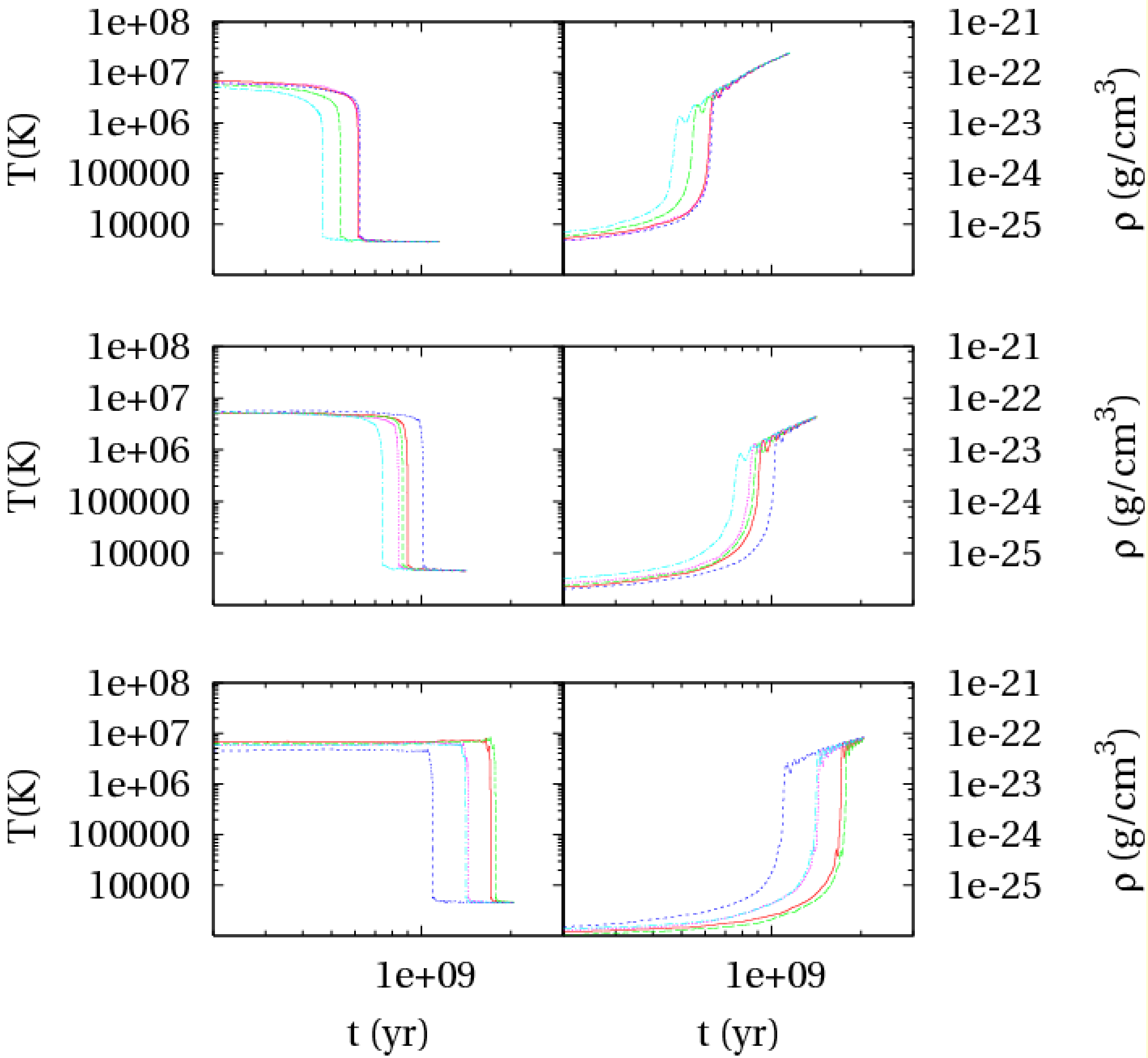
(Viola, PM, Borgani, Murante, Tornatore, MNRAS, in press)

What happens to mass elements?

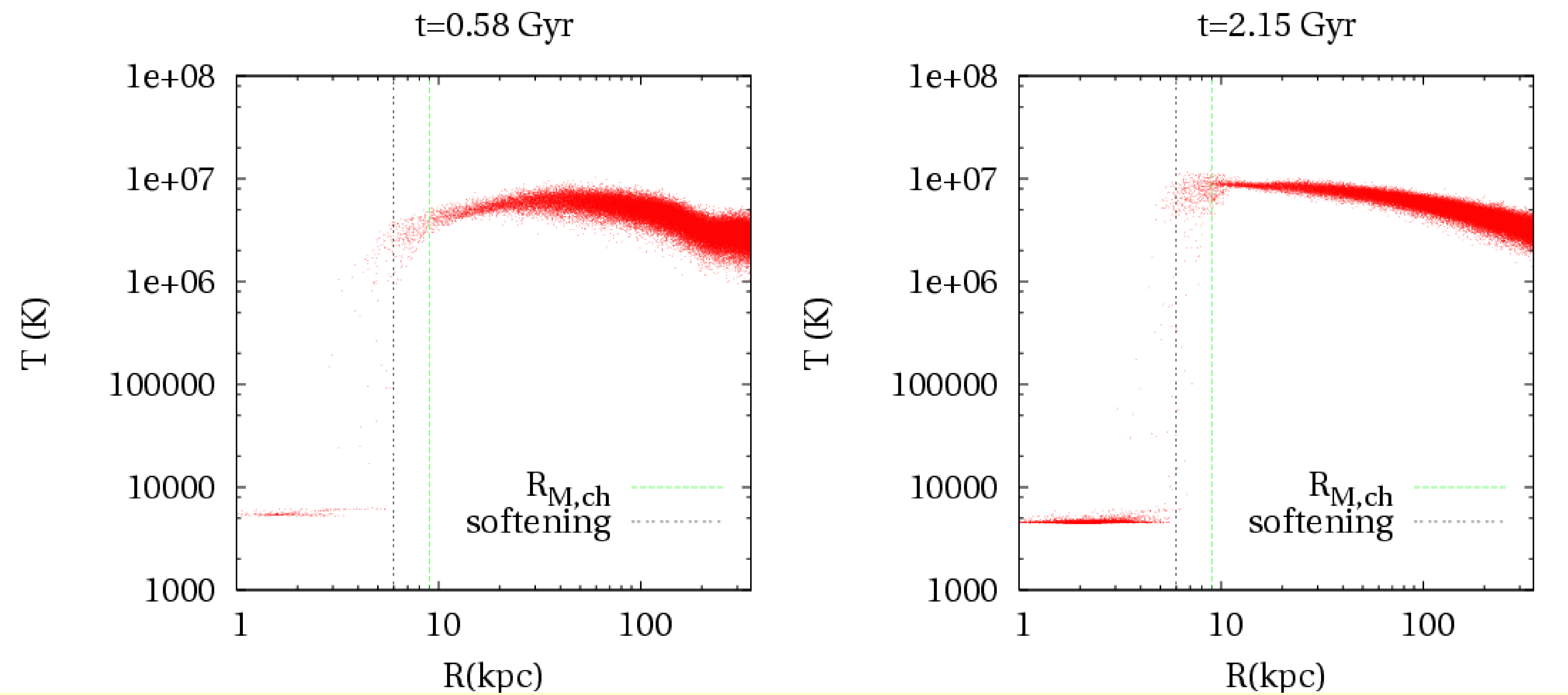
They travel inwards at roughly constant temperature and increasing density

-> cooling is counteracted by PdV compression.

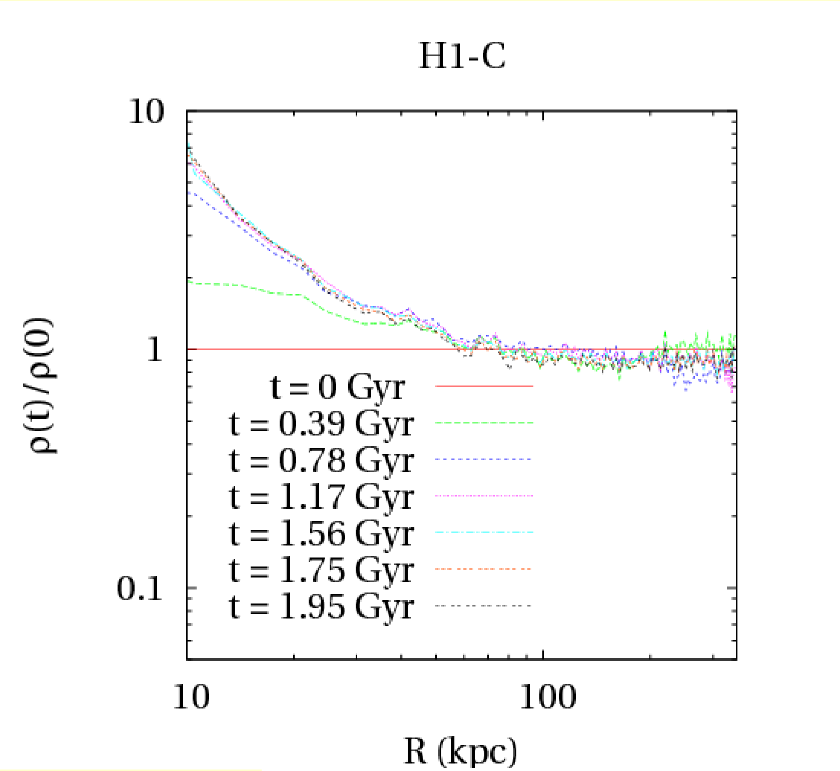
This stops when the mass element gets to the halo centre.

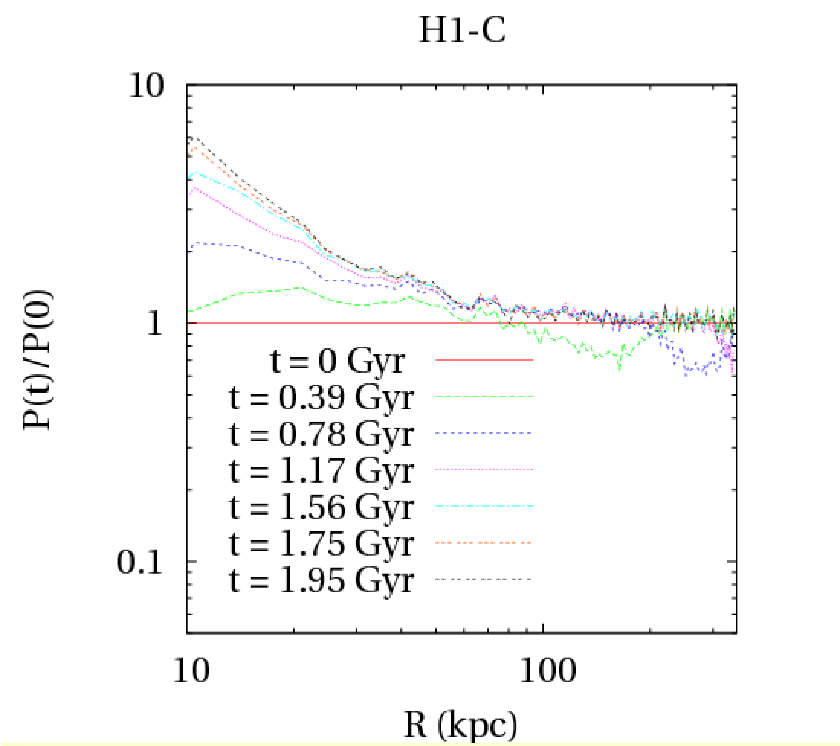


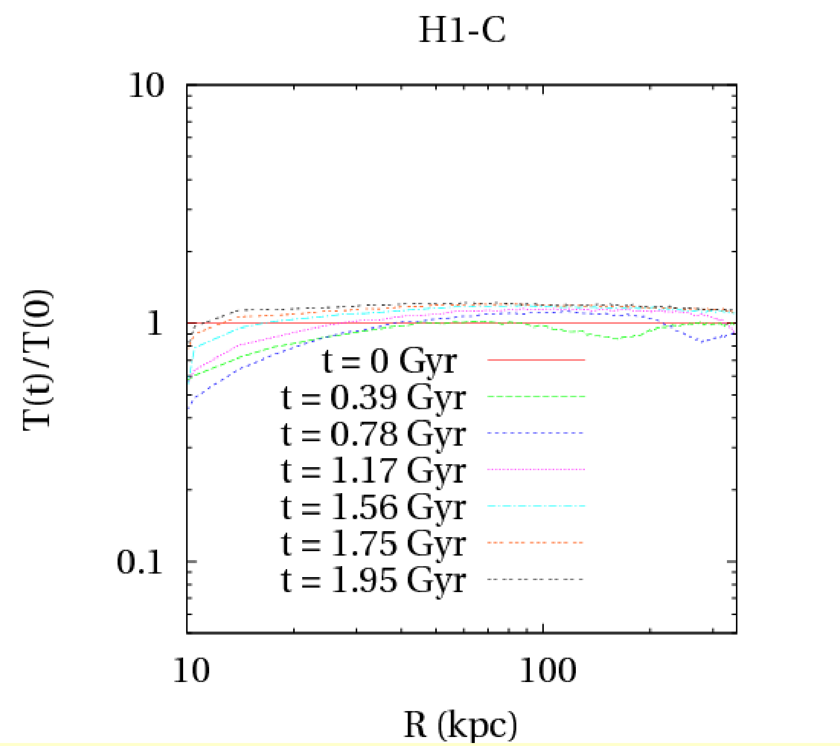
Cold and hot phases are well separated, but the cooling region is not resolved



Evolution of density, temperature and pressure profiles







The evolution is **not** self-similar

and

$$t_{\text{total}} \neq t_{\text{cool}}$$

The MORGANA cooling model

(PM, Fontanot & Taffoni, MNRAS, 375, 1189)

Each shell cools at a rate:

$$\Delta \dot{M}_{cool}(r) = \frac{4\pi r^2 \rho_g(r)\Delta r}{t_{cool}(r)}$$

The total cooling rate assumes that a sharp border is present:

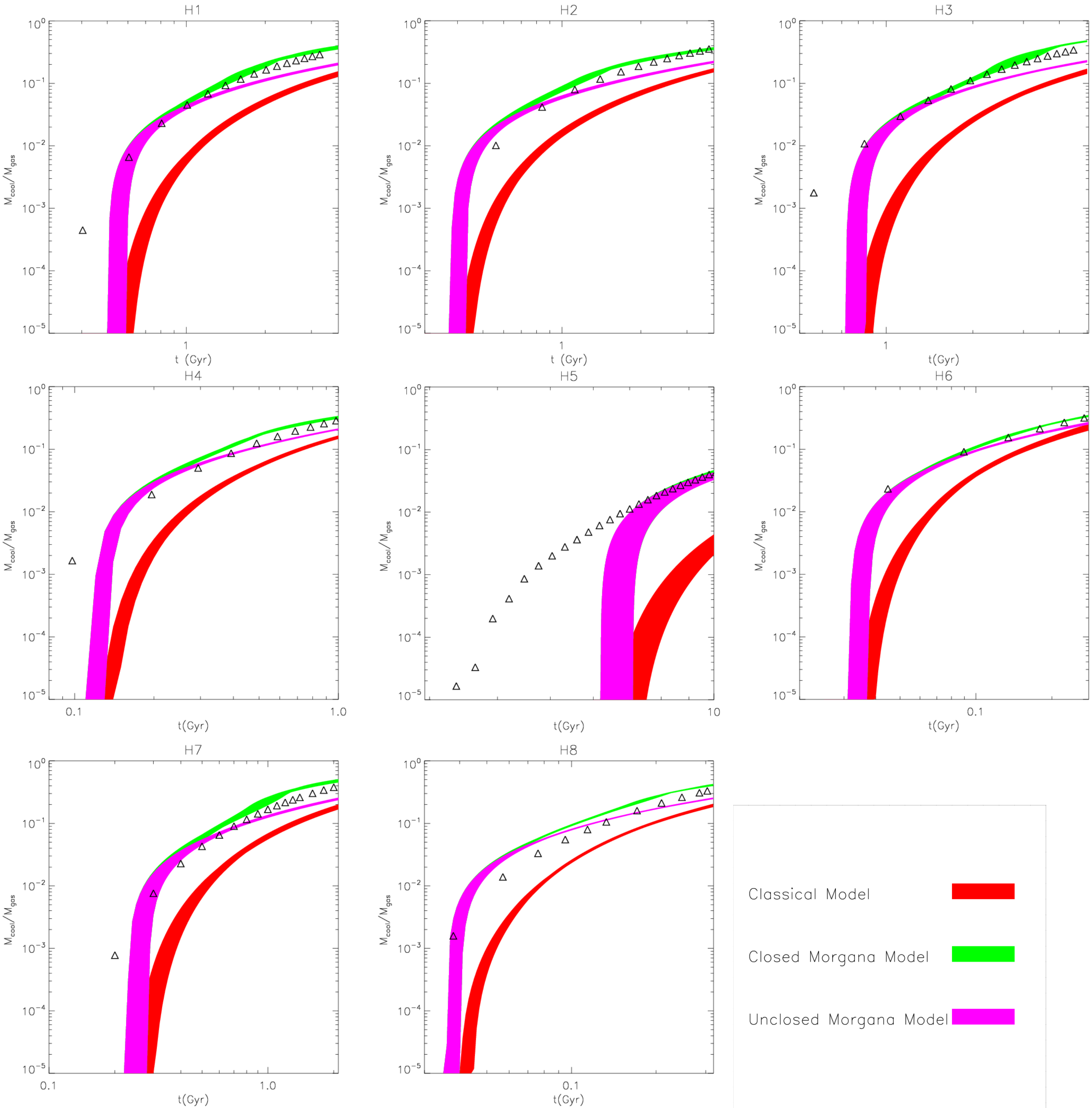
$$\dot{M}_{cool} = \int_{r_{cool}}^{r_{vir}} \Delta \dot{M}_{cool}(r)$$

The cooling radius is computed after the cooling rate:

$$\dot{r}_{cool} = \frac{\dot{M}_{cool}}{4\pi \rho_g(r_{cool}) r_{cool}^2}$$

Alternatively, the cooling radius is closed at the sound speed:

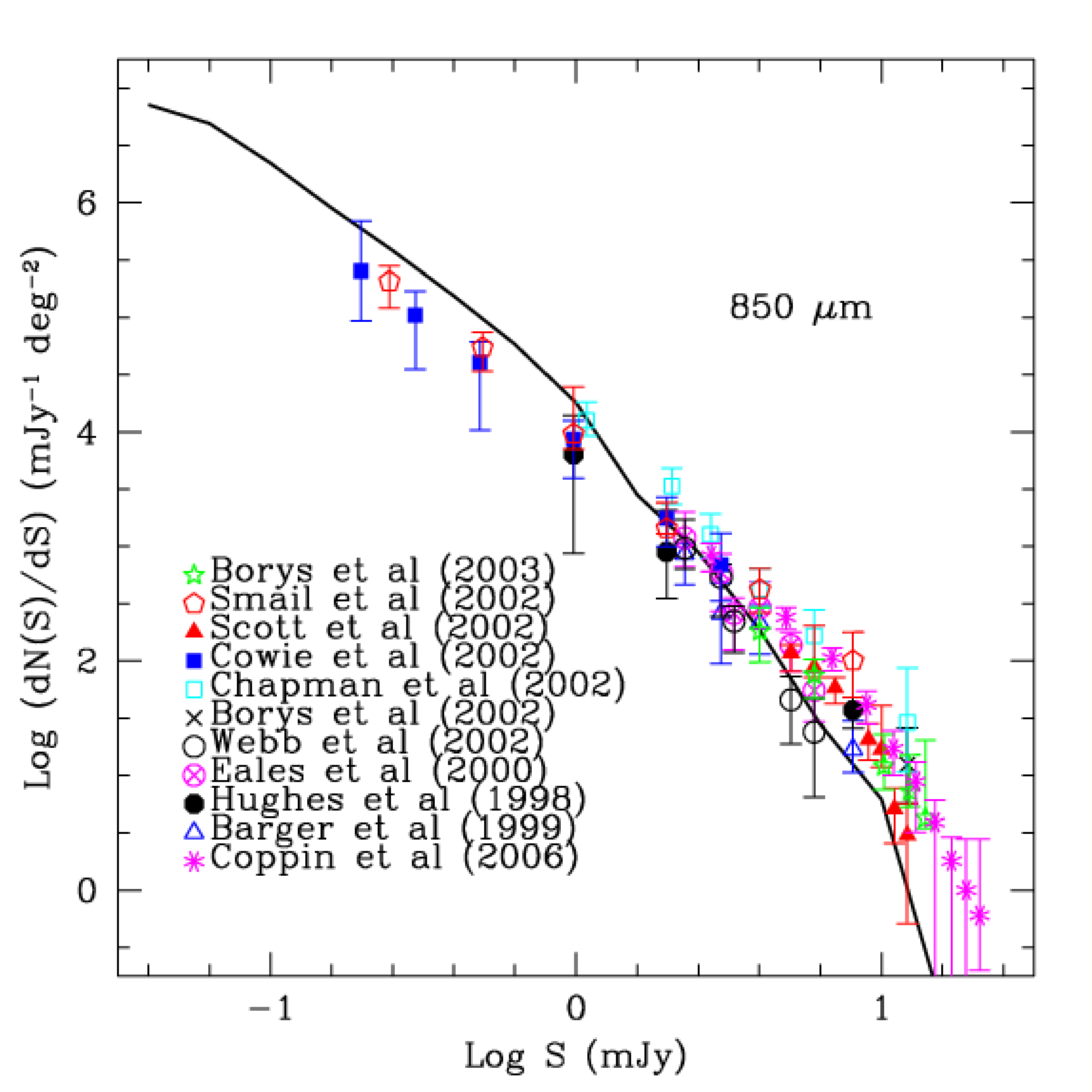
$$\dot{r}_{cool} = \frac{\dot{M}_{cool}}{4\pi \rho_g(r_{cool}) r_{cool}^2} - c_s$$


H1
H2
H3
H4
H5
H6
H7
H8
M_{cool}/M_{gas}
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
t (Gyr)
t(Gyr)
0.1
1
1.0
10
Classical Model
Closed Morgana Model
Unclosed Morgana Model

Observational consequences

All semi-analytic galaxy formation models, but one, use the classical cooling model.

The stronger cooling flows allow to reproduce the elusive sub-mm counts of high-redshift star-forming galaxies.



(Fontanot, PM, Silva & Grazian, 2007, MNRAS, in press)