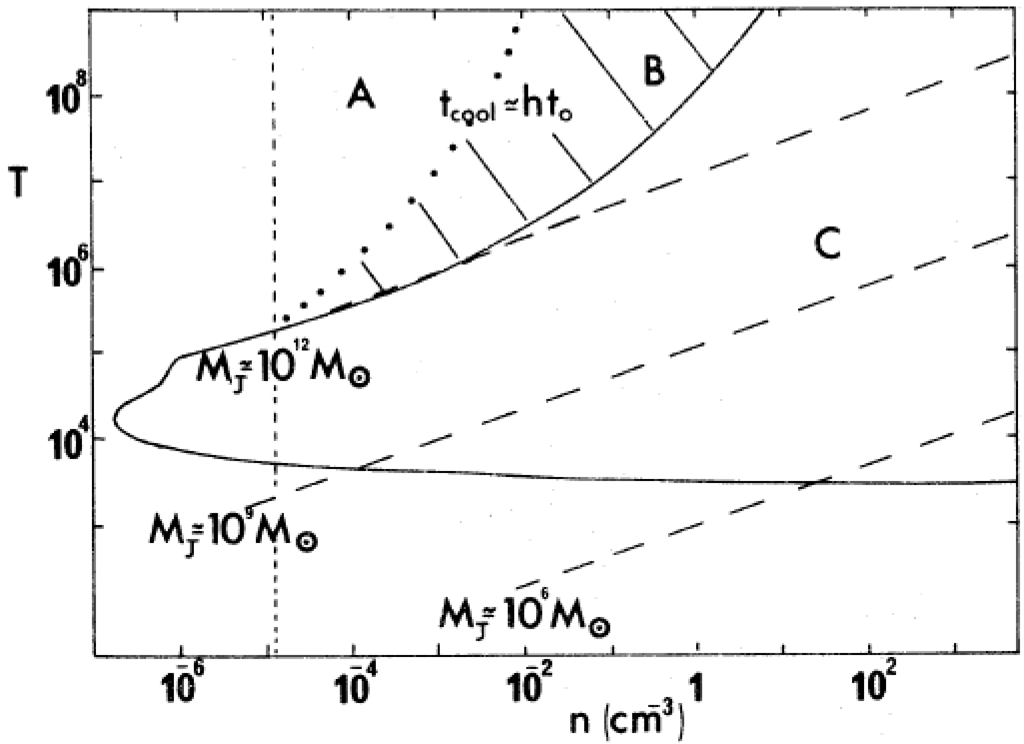
Gas Accretion during Galaxy Assembly

Simon D.M. White
Max Planck Institute for Astrophysics

Radiative processes in galaxy formation



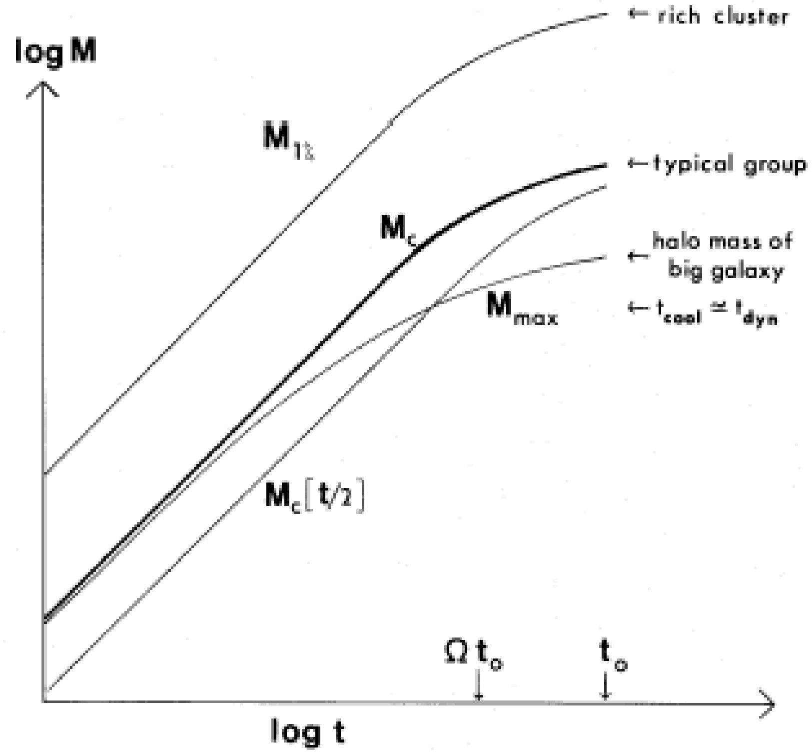
Rees & Ostriker 1977
Silk 1977
Binney 1977

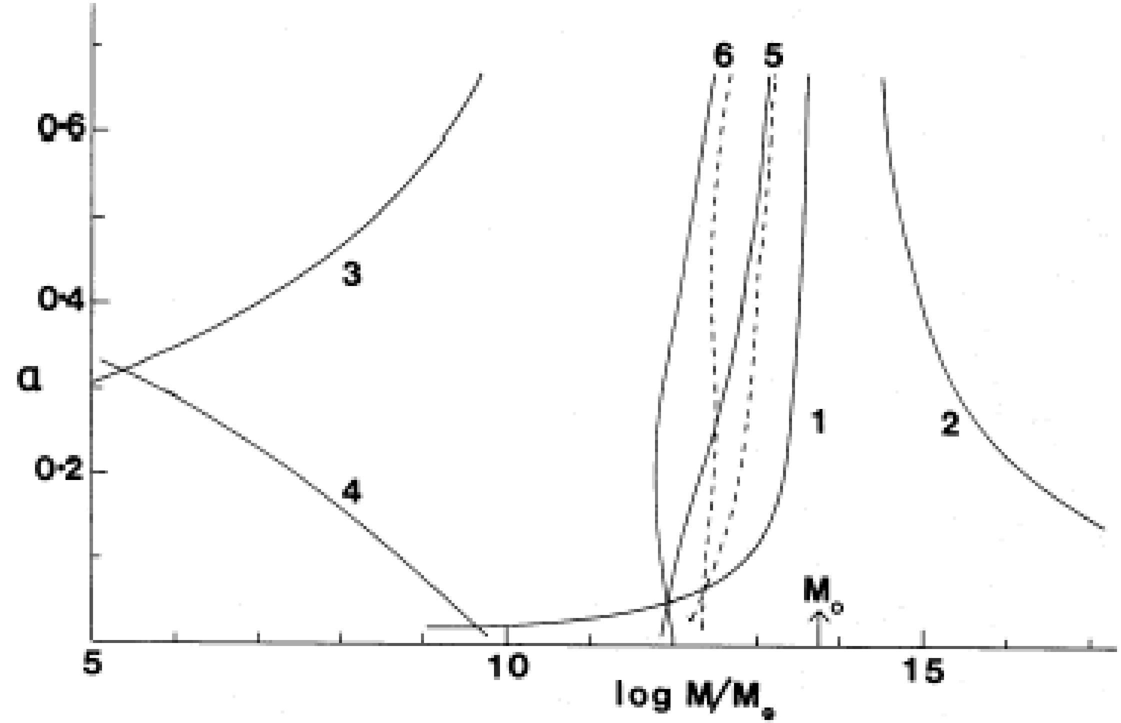
- When gas clouds of galactic mass collapse:
  - (i) shocks are radiative and collapse unimpeded, when $t_{cool} < t_{dyn}$
  - (ii) shocks are non-radiative and collapse arrested, when $t_{cool} > t_{dyn}$

  where quantities are estimated at virial equilibrium
- Galaxies form in case (ii) since fragmentation is possible
- Primordial cooling curve → characteristic mass $10^{12}\,M_\odot$

Towards a “modern” theory

White & Rees 1978

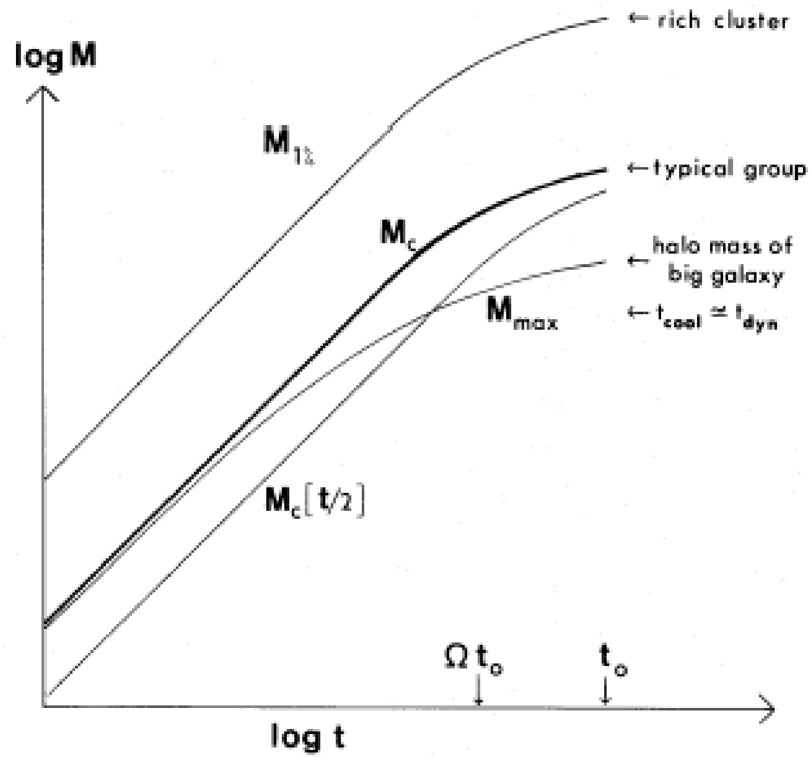


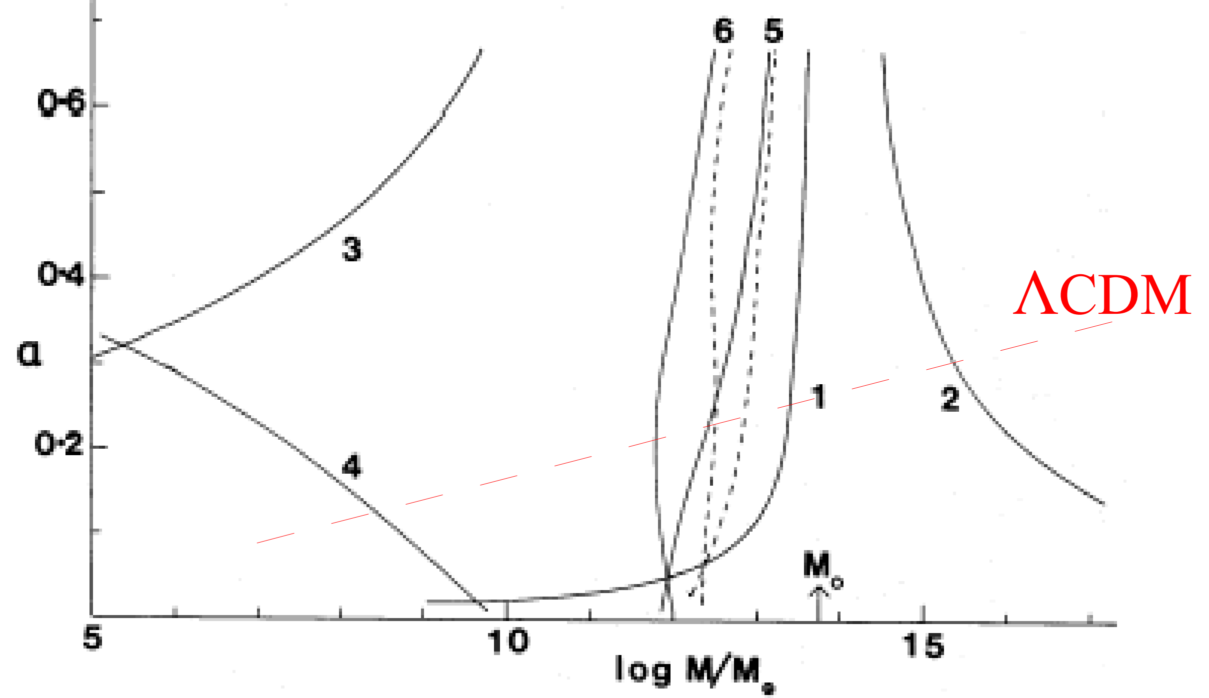


- Adding : (i) dark matter, (ii) hierarchical clustering, (iii) feedback
  - -- cooling always rapid for small masses and early times
  - -- only biggest galaxies sit in cooling flows
  - -- feedback *à la* Larson (1974) needed to suppress small galaxies

- A good model had: $\Omega_m = 0.20$, $\Omega_{gas} / \Omega_{DM} = 0.20$, $\alpha = 1/3$ $(n = -1)$

Towards a “modern” theory





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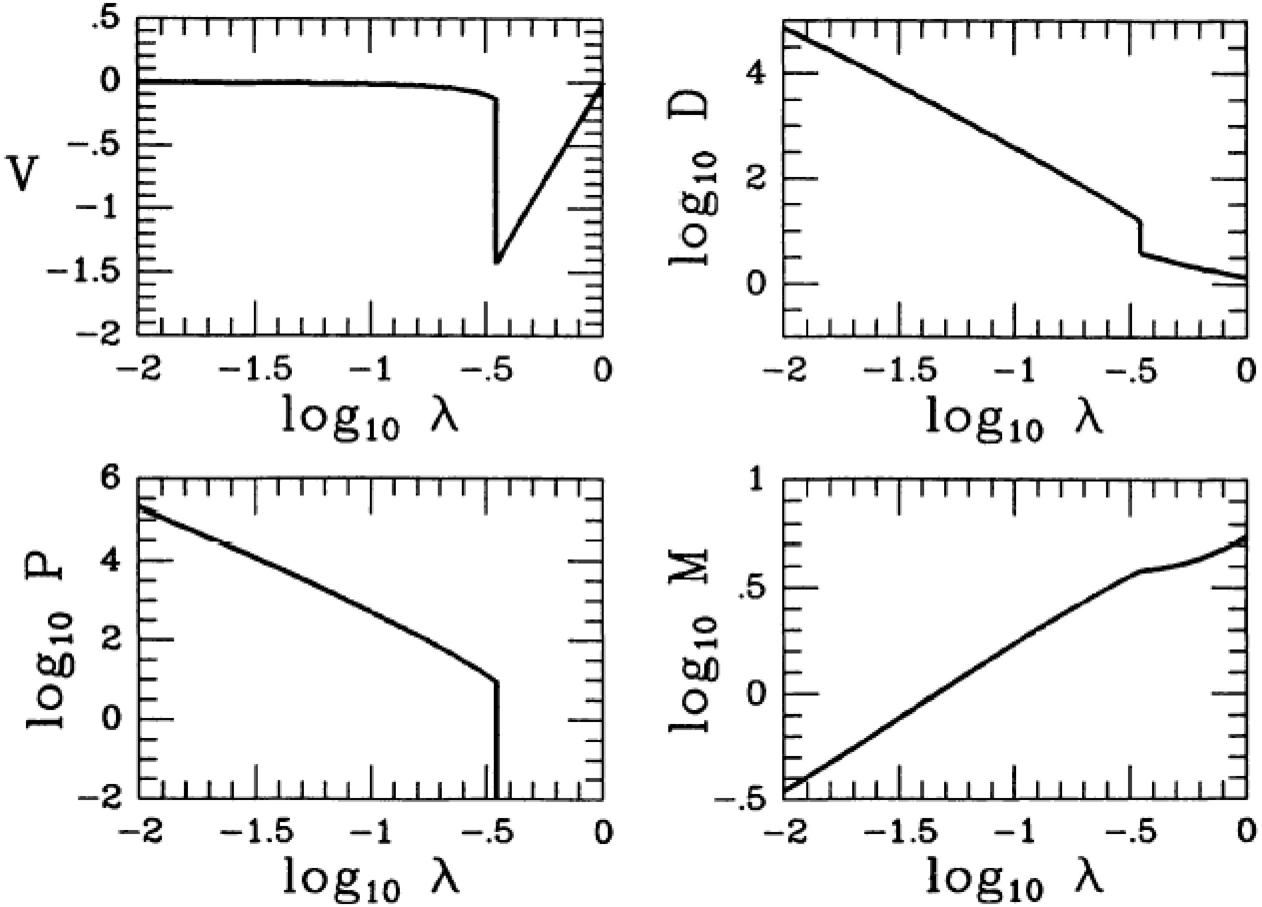
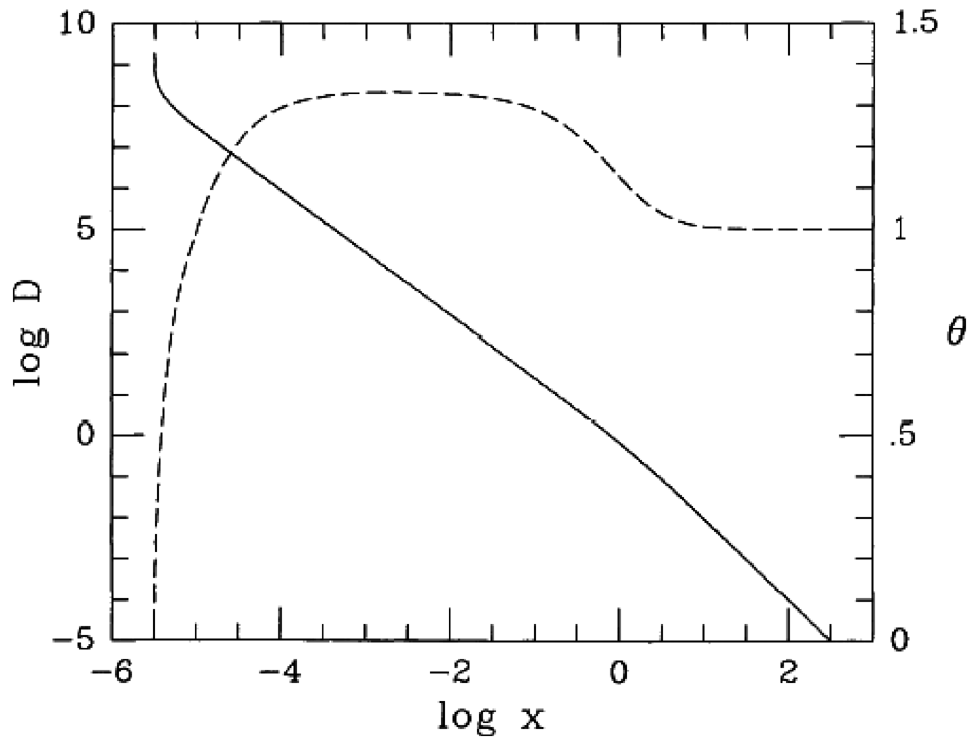
Spherical similarity solutions for infall



Bertschinger 1985

- Infall of DM + $\gamma = 5/3$ gas onto a point mass in an EdS universe
  - -- accretion shock at ~1/3 of turn-round radius
  - -- gas almost static inside shock
  - -- pre-shock gas has density about 4 times the cosmic mean
  - -- $kT(r) / \mu \sim GM(r) / r = V_c^2$; $R \sim V_c t$, $M \sim V_c^3 t / G$

Spherical similarity solutions for cooling

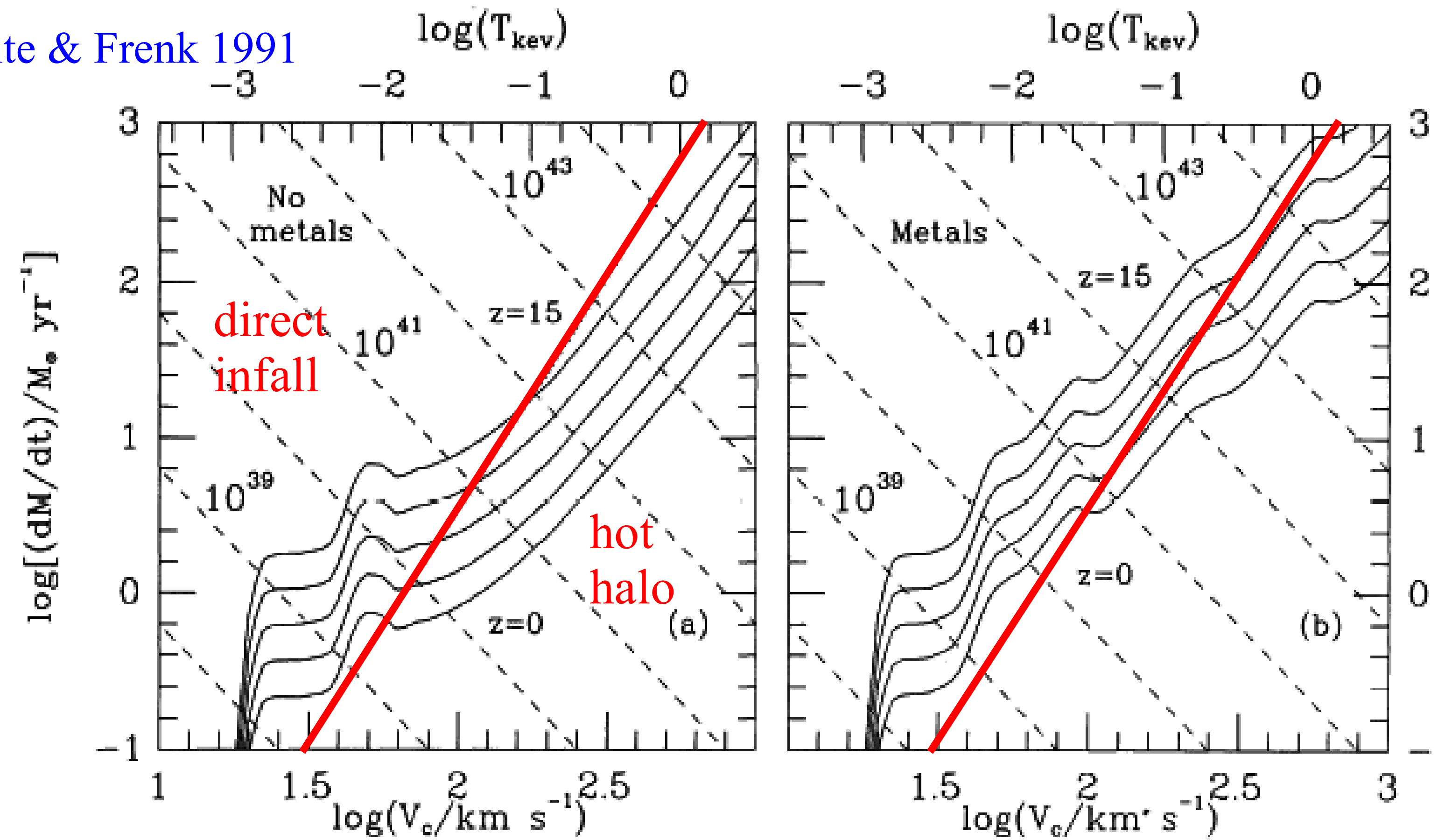


Bertschinger 1989

- Cooling wave in equilibrium gas in an isothermal DM potential
  - -- $\rho \propto r^{-2}$ at large radius $r > r_{cool}$ where $t_{cool}(r_{cool}) = t$
  - -- $\rho \propto r^{-1.5}$ and $T = 1.33\ T_{\infty}$ at $r_{sonic} < r < r_{cool}$
  - -- $\rho \propto r^{-1.5}$, flow is supersonic free-fall, and $T \rightarrow 0$ at $r < r_{sonic}$
- Inflow rate $\propto t^{-1/2}$, cooling radius and cold mass $\propto t^{+1/2}$
- $r_{sonic} \sim r_{cool} \sim r_{shock}$ in protogalaxies → no static atmosphere?

Putting it together in a sCDM universe

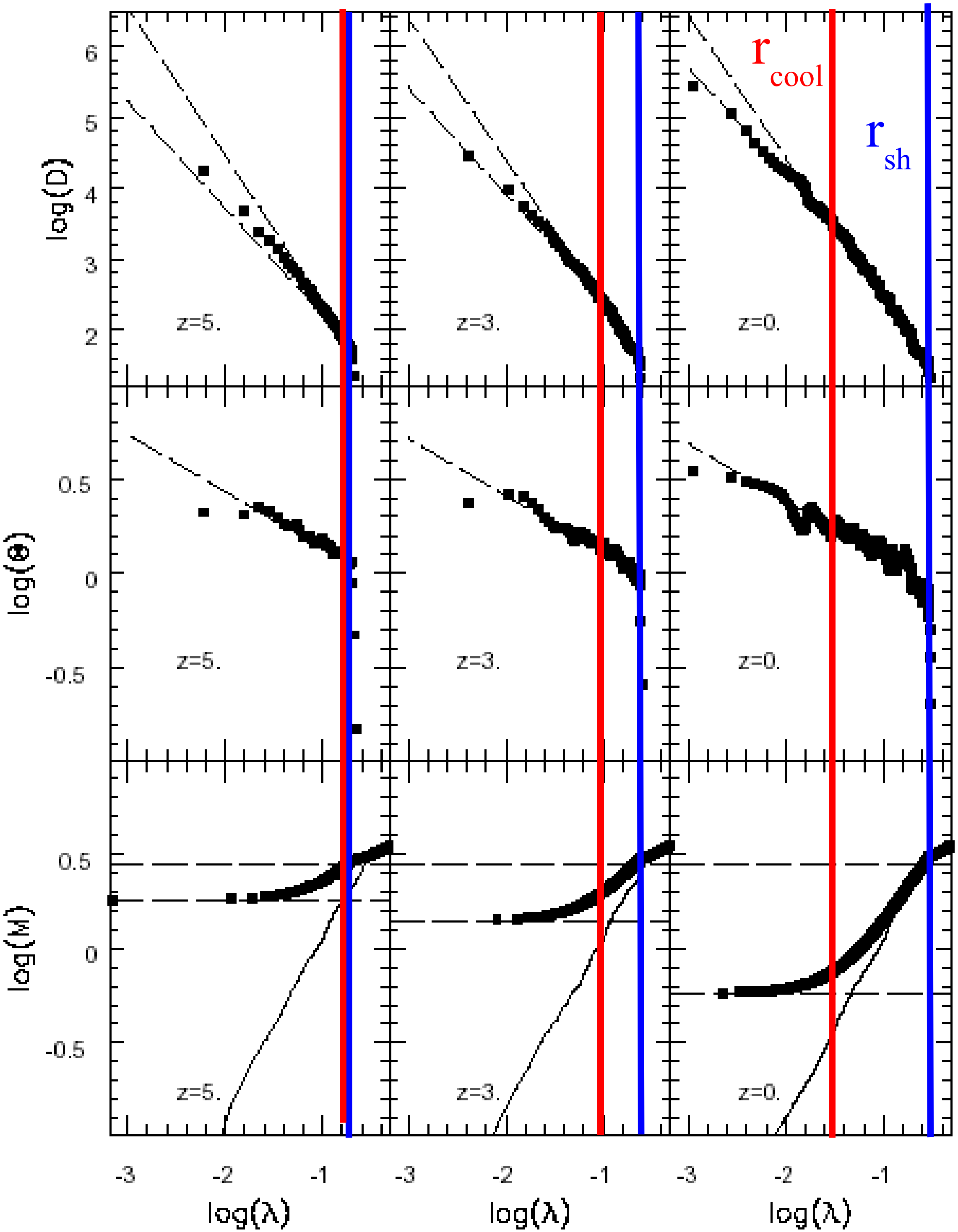
White & Frenk 1991



- *Assuming* $r_{cool} < r_{shock}$ for a hot atmosphere and taking $f_{baryon} = 0.1$ → direct infall (i.e. no hot atmosphere) for $V_{circ} < 80$ km/s at z=3 when there is no chemical mixing, and for $V_{circ} < 250$ km/s at z=3 when efficient mixing is assumed

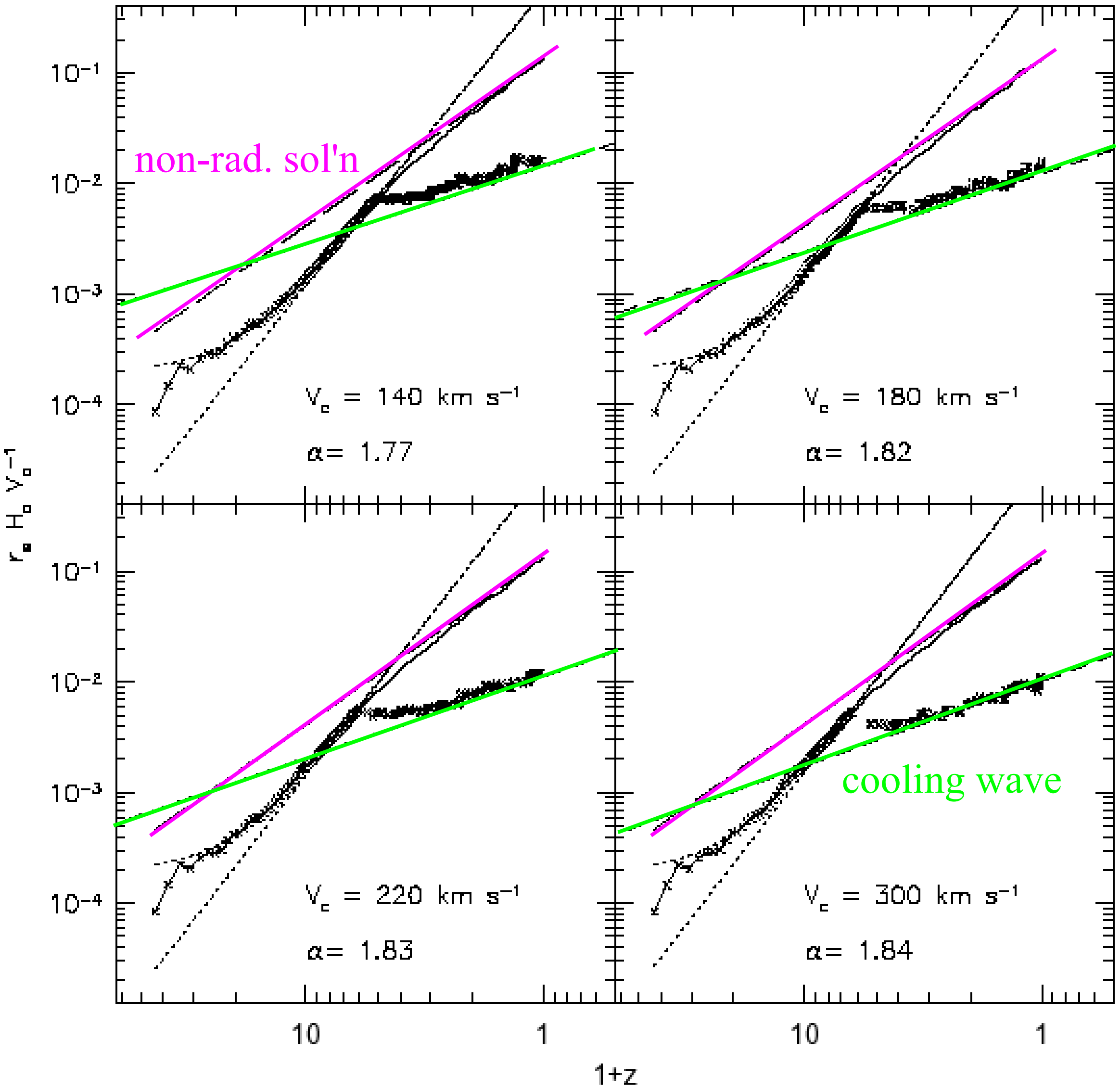
Radiative cooling in spherical infall models

Forcada-Miró & White 1997
astro-ph/9712204



- Spherical, isothermal infall model with V_{circ} = 220 km/s and f_{gas} = 0.05
- Non-equilibrium H and He ionization and radiation
- At early times r_{cool} and r_{shock} coincide; interior dynamic cooling flow has $\rho \propto r^{-1.5}$
- At later times r_{cool} and r_{shock} separate, enclosing a near static region: $\rho \propto r^{-2.0}$

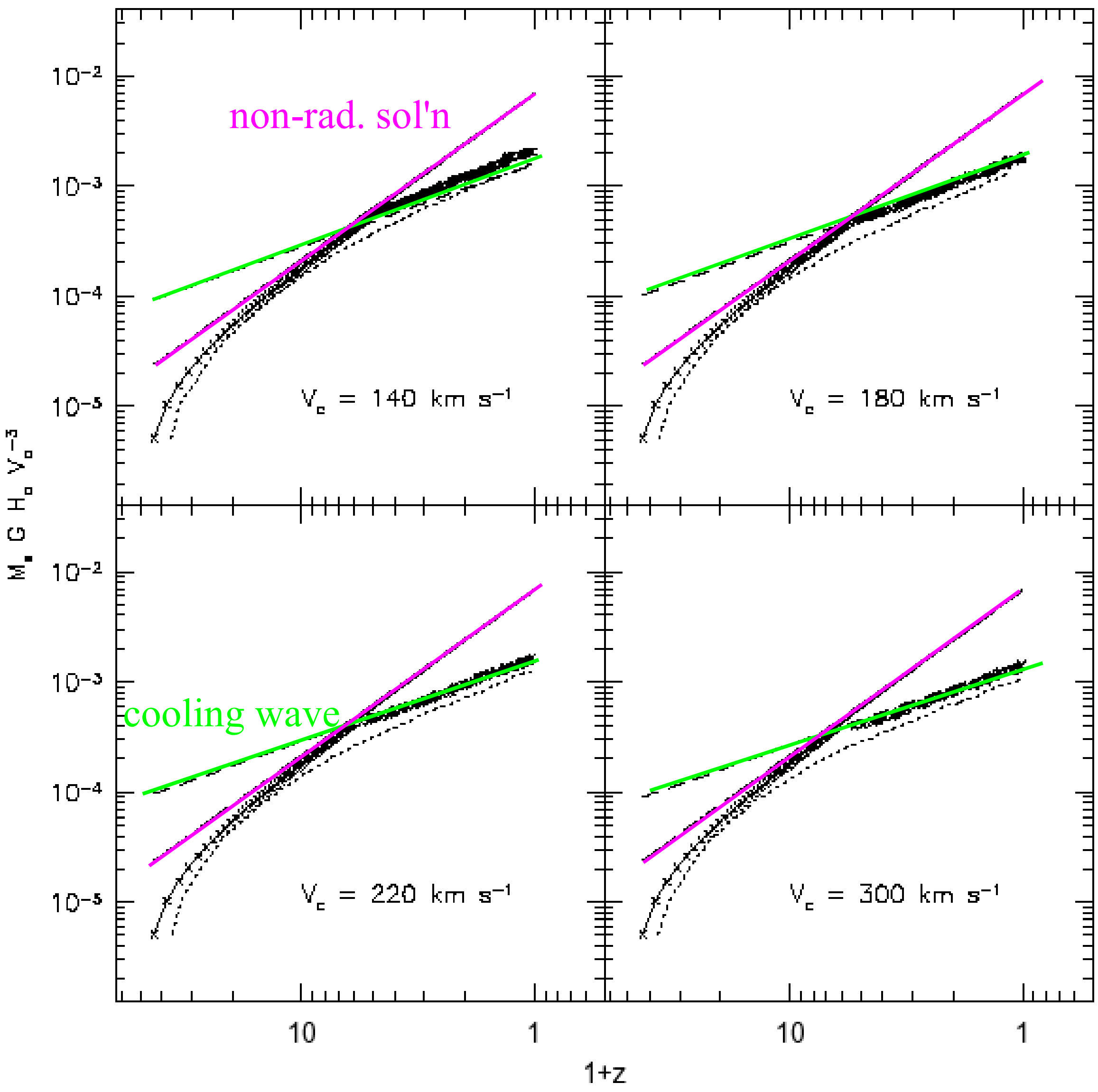
Shock and cooling radius evolution in isothermal models



Forcada-Miró & White 1997

- At early times shock and cooling radii are determined by $t_{cool} \approx t_{free\text{-}fall}$
  → $r_{cool} \approx r_{shock} \propto t^{1.8}$
- Cooling radius breaks away from shock as both near similarity shock radius
- Cooling radius then follows the Bertschinger solution
  $r_{cool} \propto t^{0.5}$
- Shock asymptotes to the non-radiative sim. solution
  $r_{shock} \propto t$

Cold and shocked mass evolution in isothermal models



Forcada-Miró & White 1997

- At early times cold mass and shocked mass grow as

  $$M_{cold} \approx M_{shock} \propto t$$

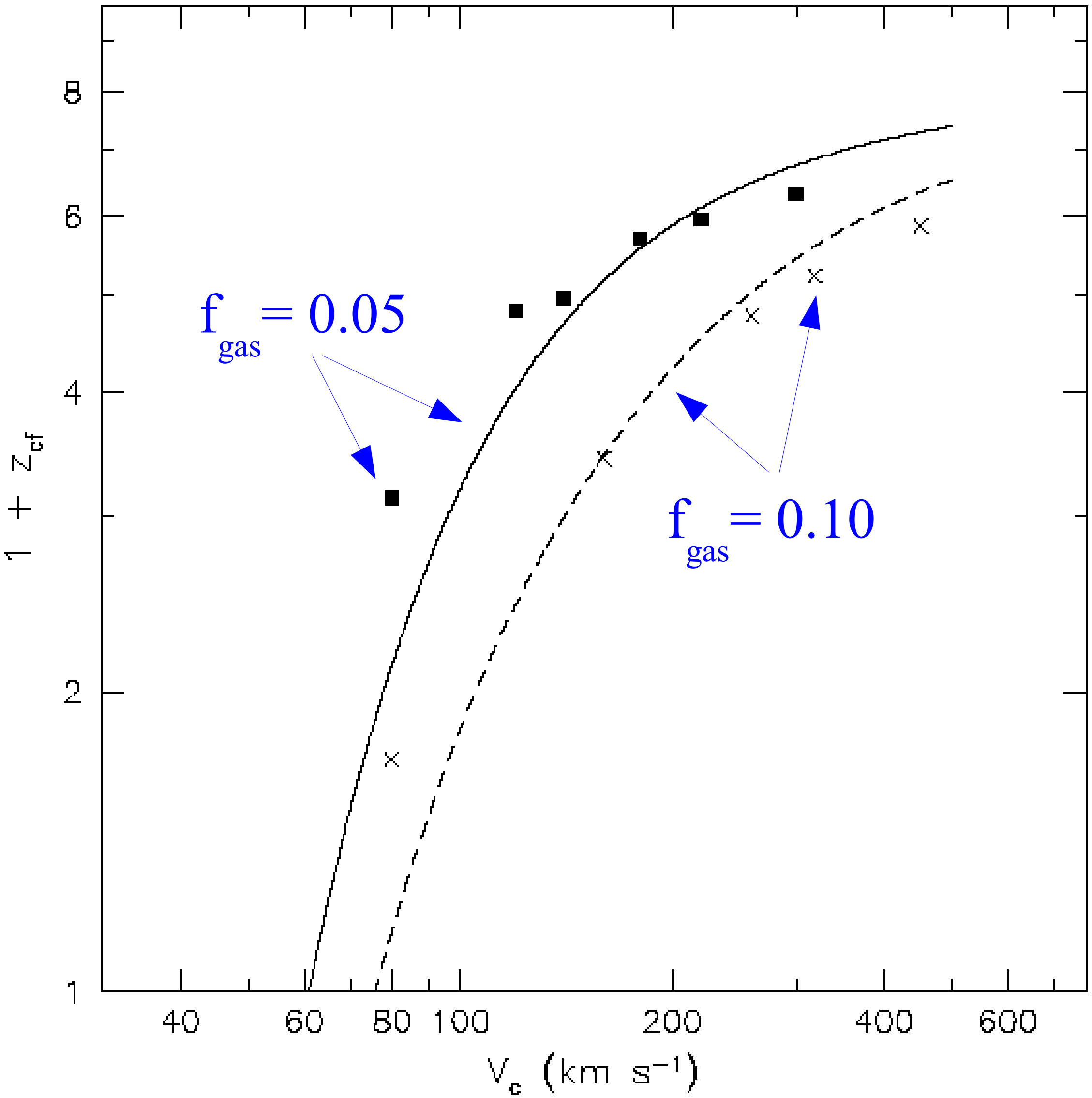
- At late times shocked mass continues this behaviour

  $$M_{shock} \propto t$$

- ..but cold mass follows the cooling wave solution

  $$M_{cool} \propto t^{0.5}$$

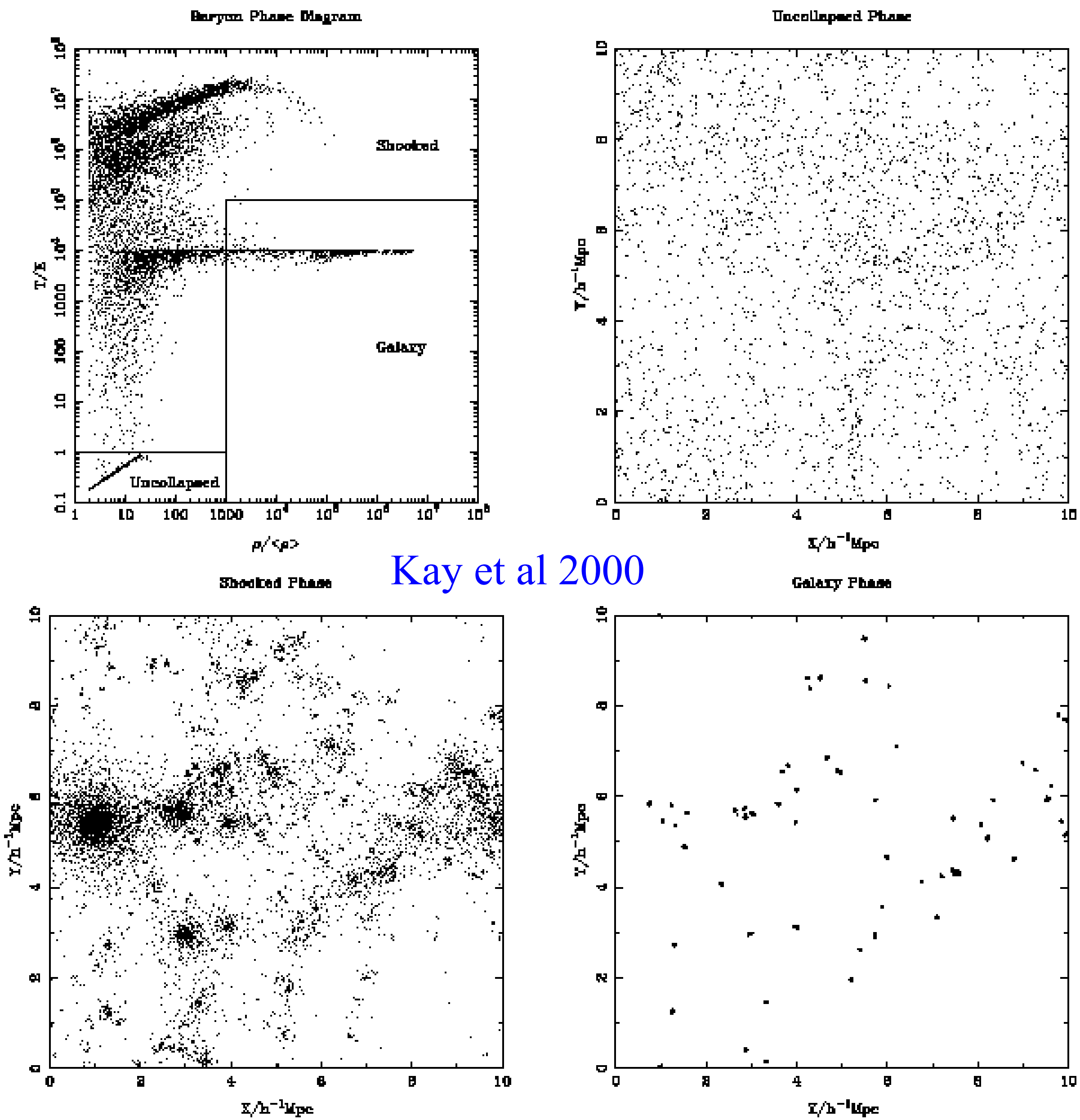
Transition from infall- to cooling-dominated flow



Forcada-Miró & White 1997

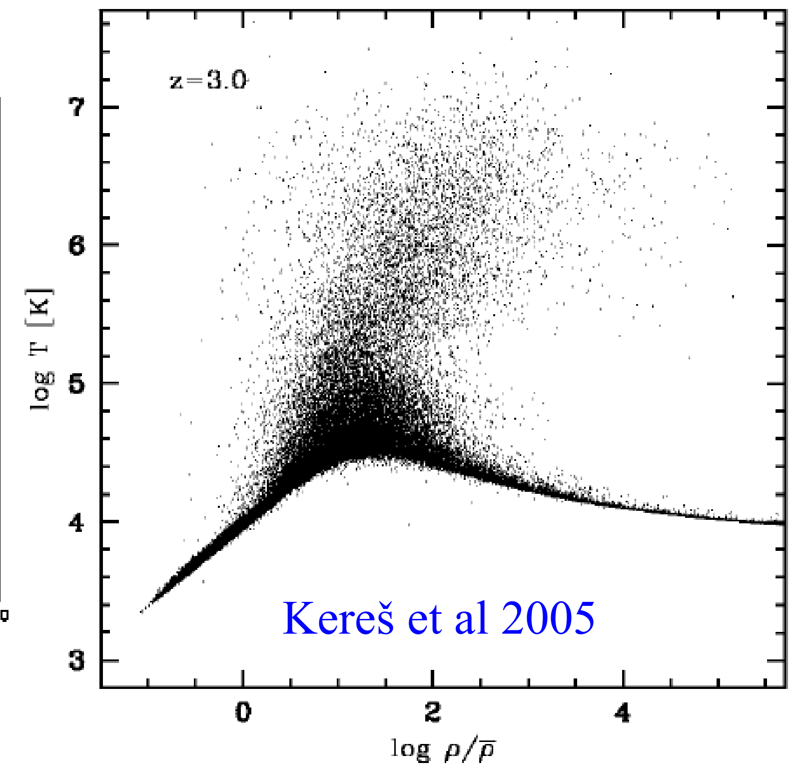
- Infall dominated flow switches to cooling from static atmosph.
  $r_{cool} \approx r_{shock} \longrightarrow r_{cool} < r_{shock}$
  when the cooling time for gas at the post-shock temperature and density in the *non-radiative* solution is equal to the age of the system
- This is the “semi-analytic” criterion suggested by White & Frenk (1991)

Gas cooling in cosmological simulations



Kay et al 2000

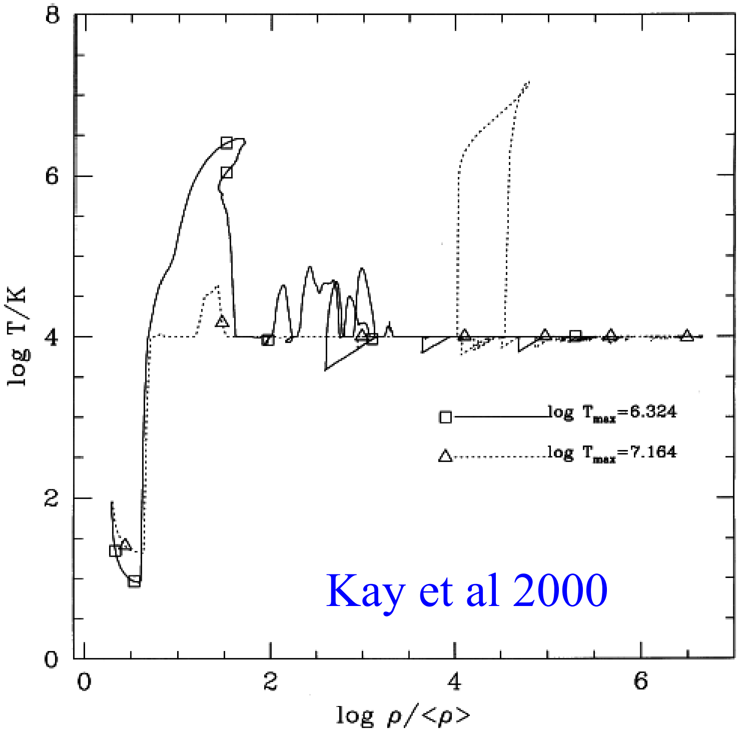
- Gas separates cleanly into three phases
  - --cool, diffuse IGM
  - --hot, shocked IGM
  - --cold, dense ISM

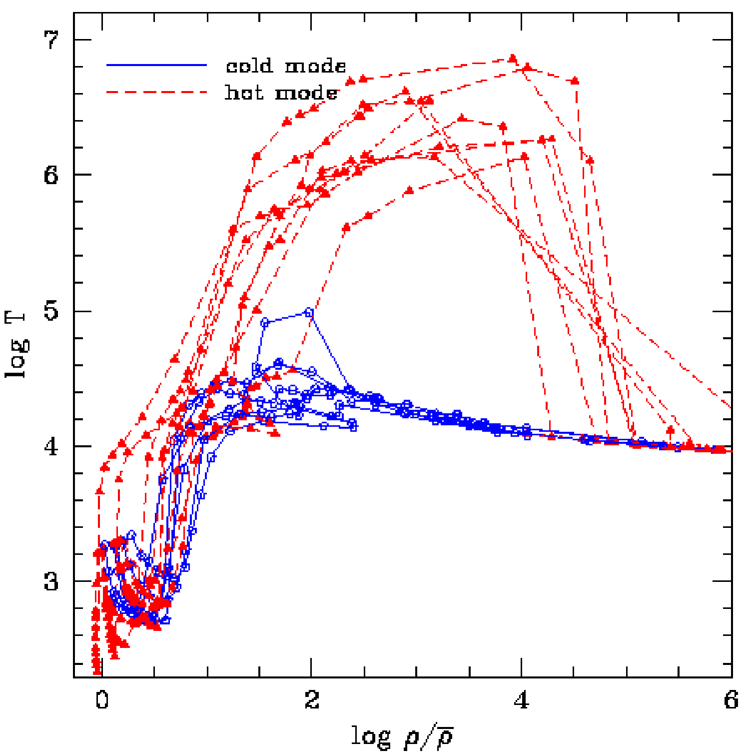


Kereš et al 2005

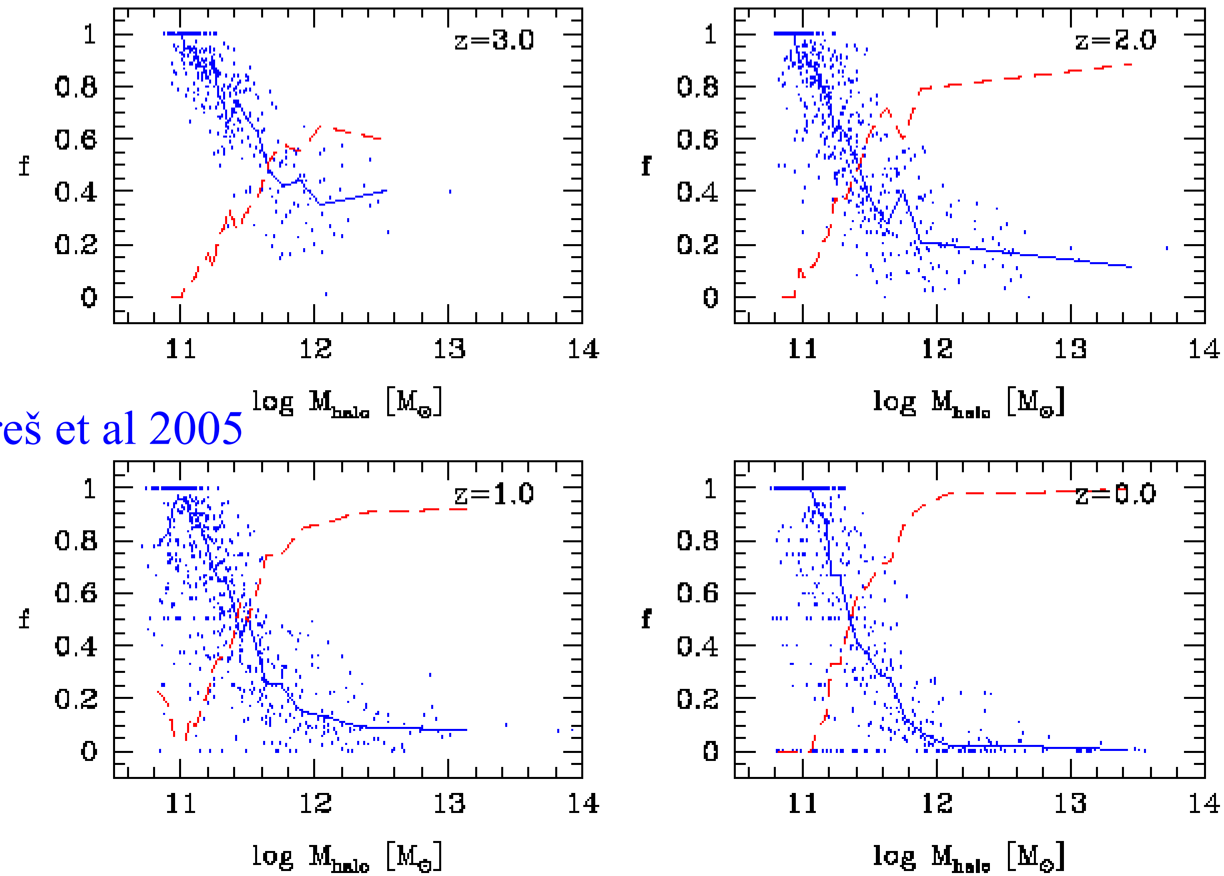
Cold and hot accretion modes

- ~0.5 of all SPH particles accreted onto galaxies never heat above a few 10^4 K
- "Cold" accretion dominates in halos with V_{circ} less than about 100 km/s
- Same point as transition from infall to cooling domination in spherical models?



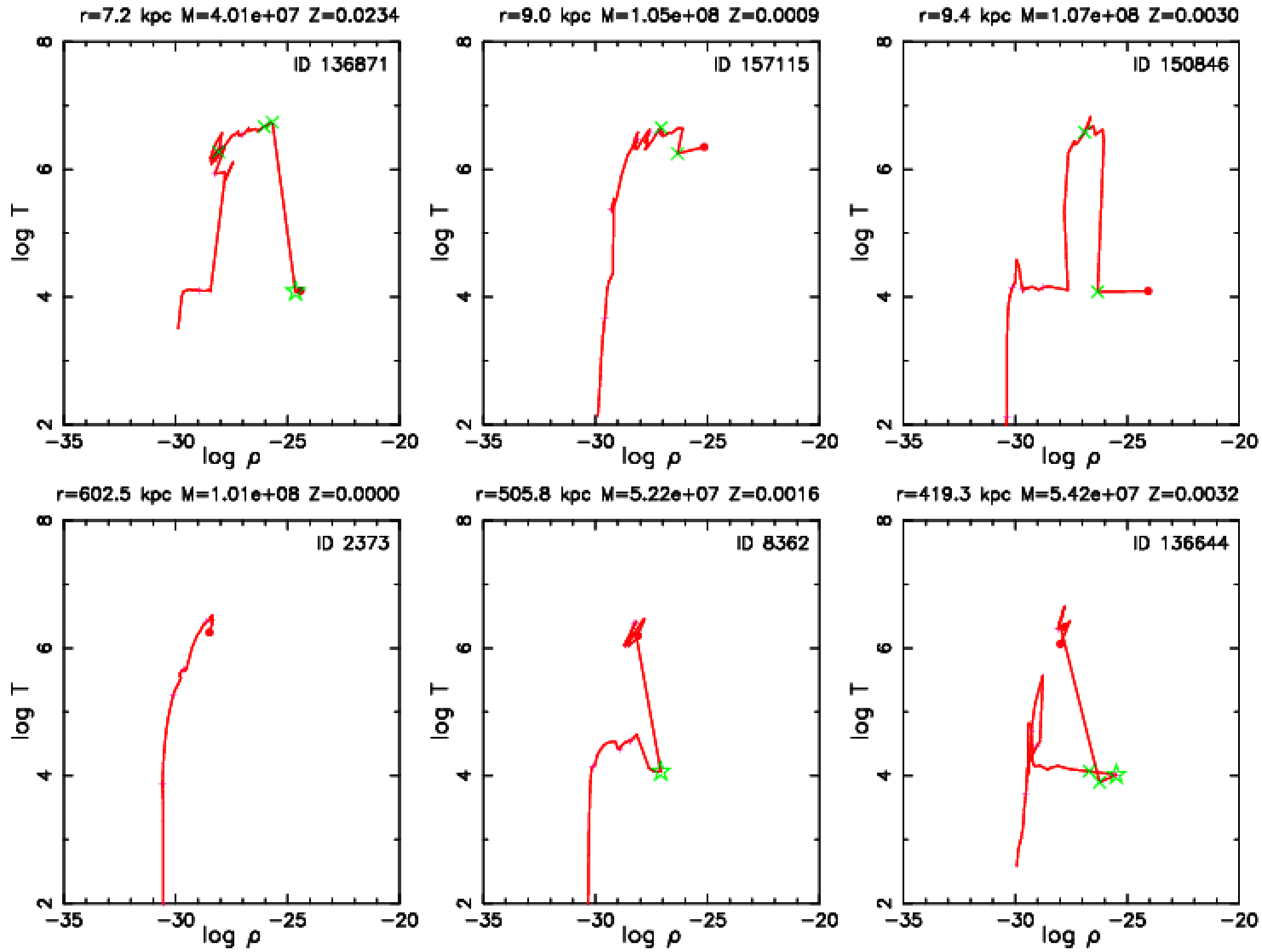


Kereš et al 2005



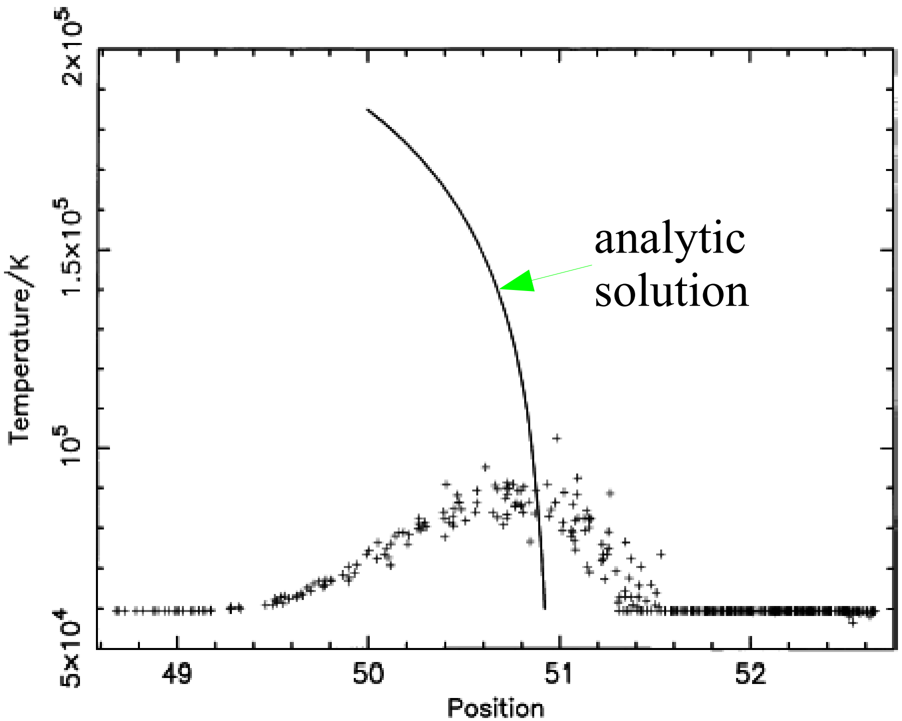
Gas particle tracks in a galaxy formation simulation

Kobayashi 2005



In-shock cooling

Hutchings & Thomas 2000



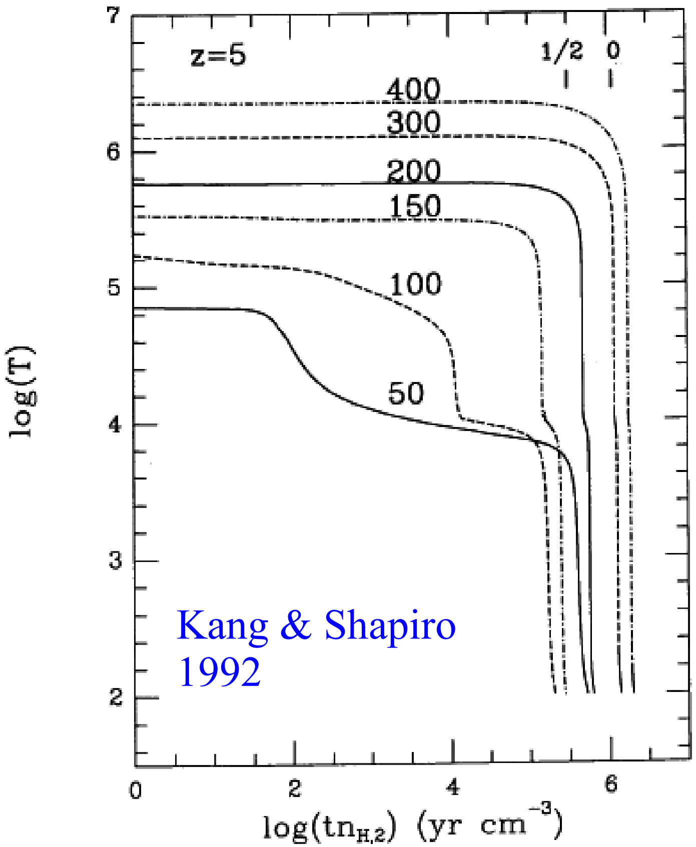
A radiative shock in a shock tube followed with SPH

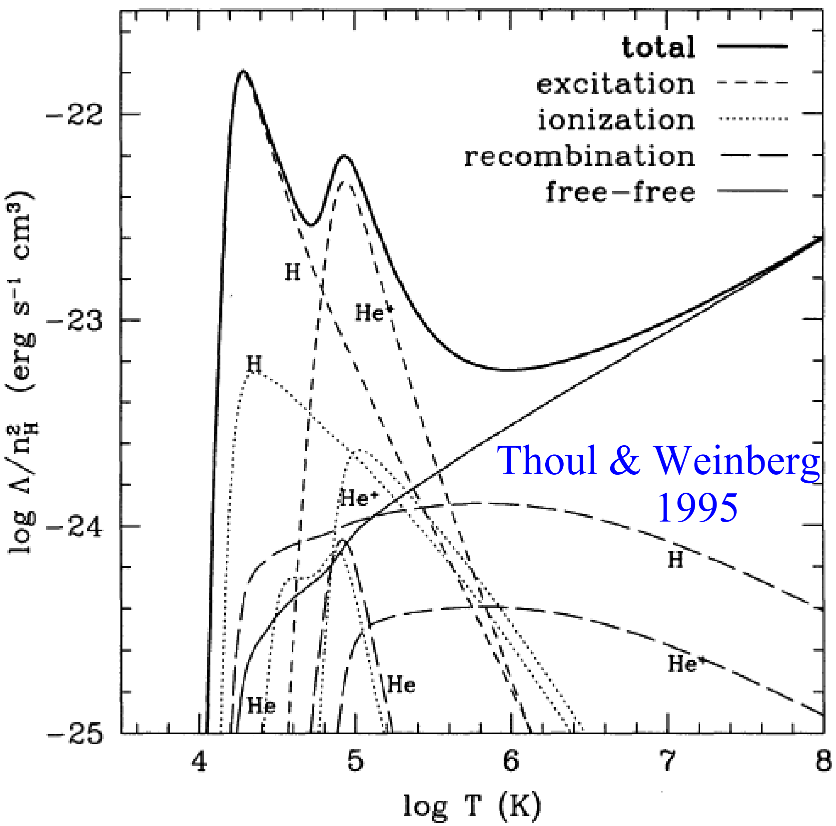
$$t_{cool} \sim h / V_{sh}$$

- Immediately behind a strong shock the gas heats to a temperature
  $$T = 3\mu V_{sh}^2 / 16\,k$$
  $$\sim 1.4 \times 10^5 (V_{sh} / 100\ \mathrm{km/s})^2$$
- Collisional thermalisation, ionisation and radiation processes then all occur simultaneously, often far from equilibrium
- Many numerical hydrodynamics schemes broaden the shock heating region over several zones (grid) or smoothing lengths (SPH)
- When post-shock cooling times are short this leads to spurious temperature evolution

Radiation from shocks

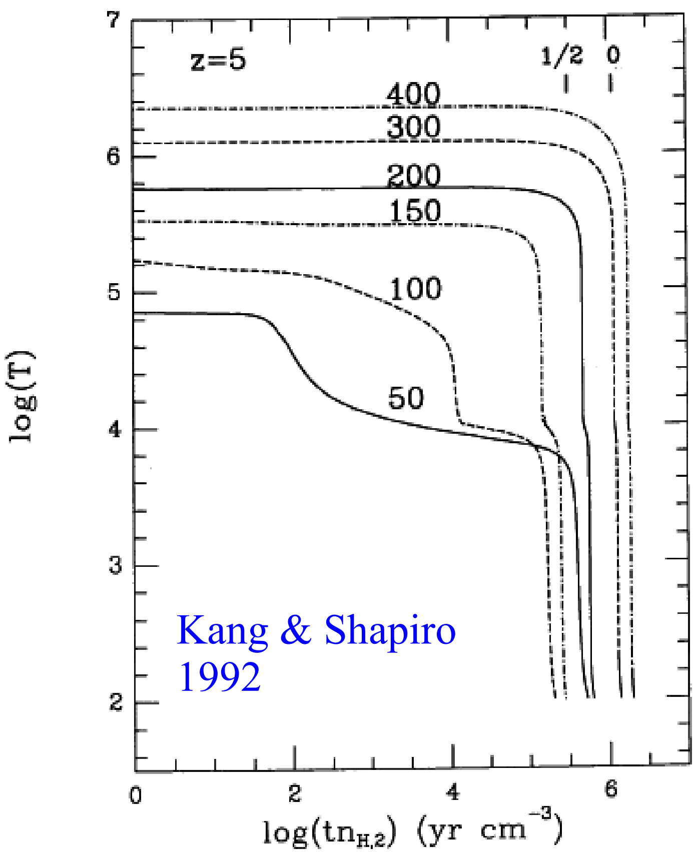
- For collisional ionisation equilibrium, the radiation from shocks would be dominated by He II 304 for 70 km/s < V_{sh} < 270 km/s

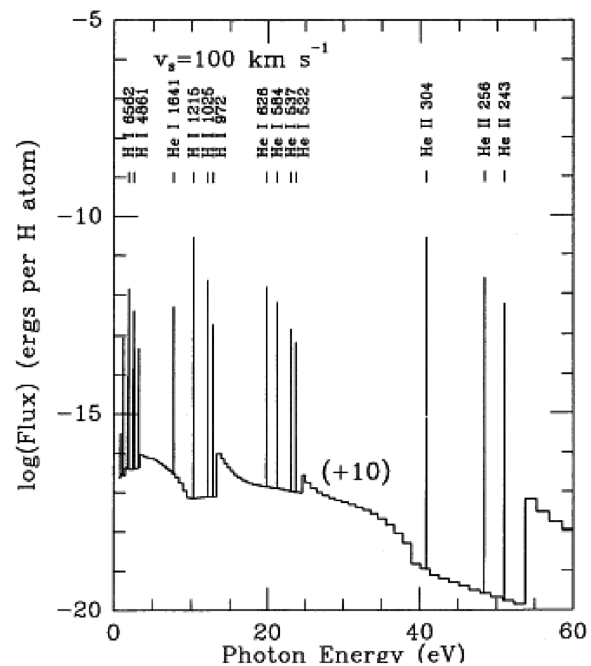


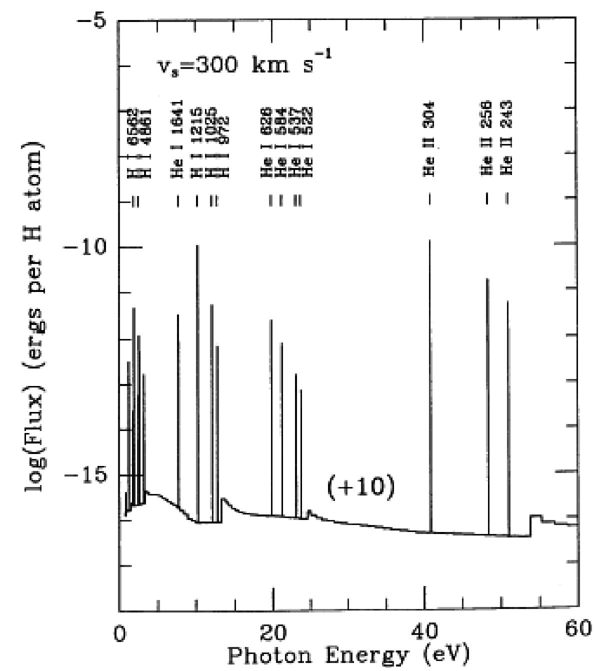


Radiation from shocks

- For collisional ionisation equilibrium, the radiation from shocks would be dominated by He II 304 for 70 km/s < V_{sh} < 270 km/s
- ...but, in fact, non-equilibrium processes affect line emission strongly, particularly enhancing H I 1216 (Ly α)

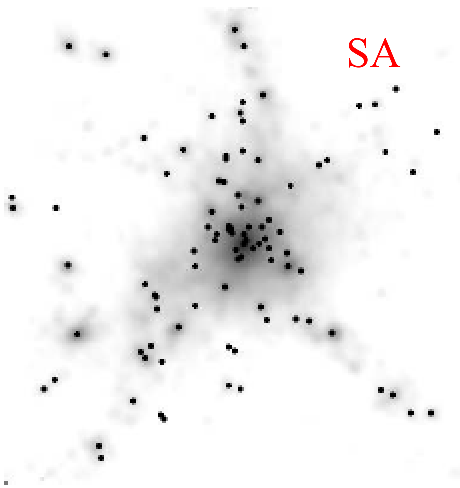




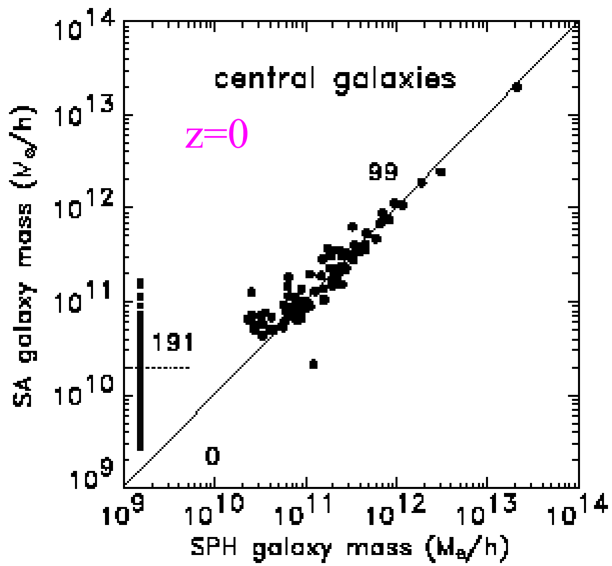


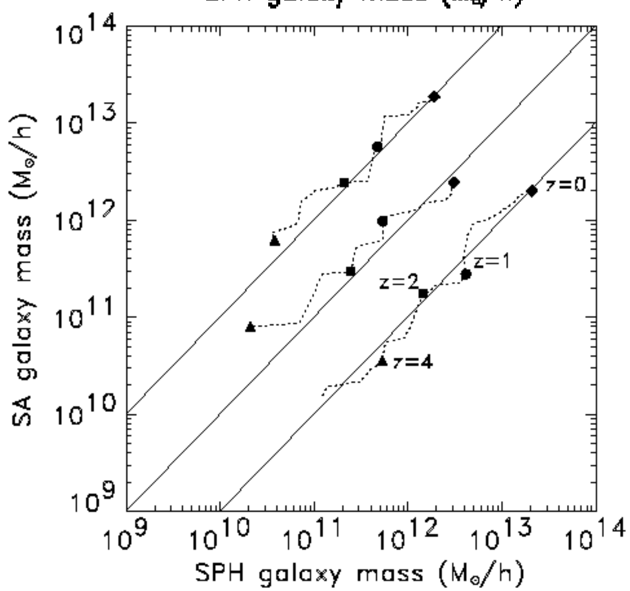
Cooling in SPH compared to a SA model

Yoshida et al 2002



$M_g > 6 \times 10^{10} h^{-1} M_\odot$

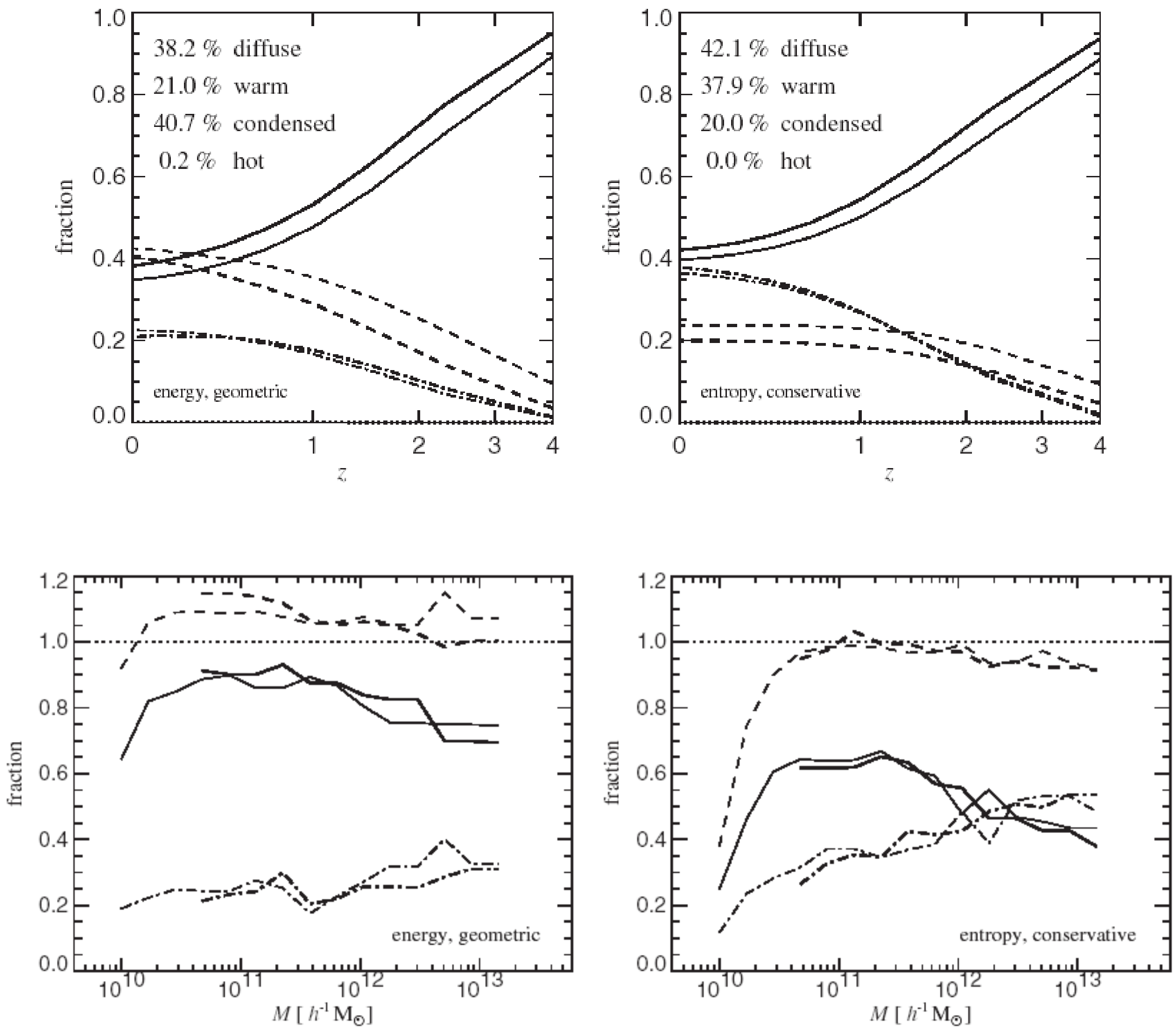




- Comparison of implementation in the *same* N-body ΛCDM cluster formation simulation of cooling
  - (a) with SPH (2 versions)
  - (b) with a standard SA model
- Masses of central objects in halos agree well once above the SPH resolution limit (~ 50 particles)
- Range checked includes transition from efficient to inefficient cooling
- Different SPH implementations give different results

Interface cooling in SPH

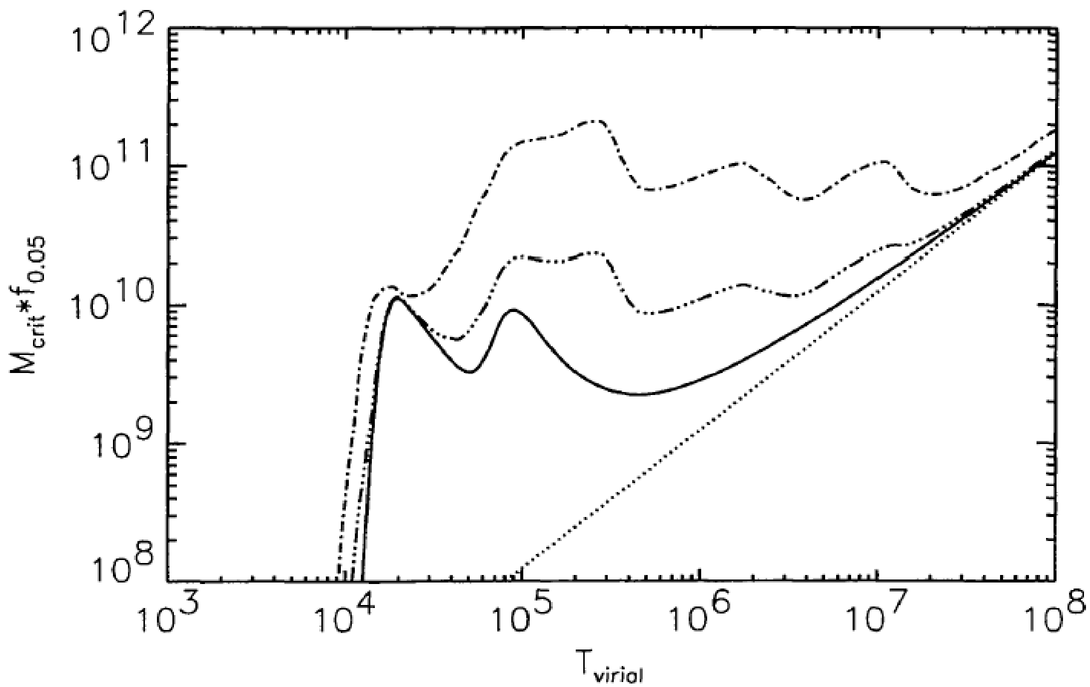
Springel & Hernquist 2002



- Hot SPH particles near an interface with cooler, denser gas have their kernel density estimates biased high → excessive cooling
- Different SPH versions suffer from the problem to different degrees
- S&H02 compare their own energy+entropy conserving scheme with the geometric averaging scheme used by Hernquist & Katz 1989; Katz, Weinberg & Hernquist 1996; Davé. Dubinski & Hernquist 1997; Carraro, Lia & Chiosi 1998; Springel et al 2001; Fardal et al 2001; Kereš et al 2005

Two-body heating in SPH simulations

Steinmetz & White 1997



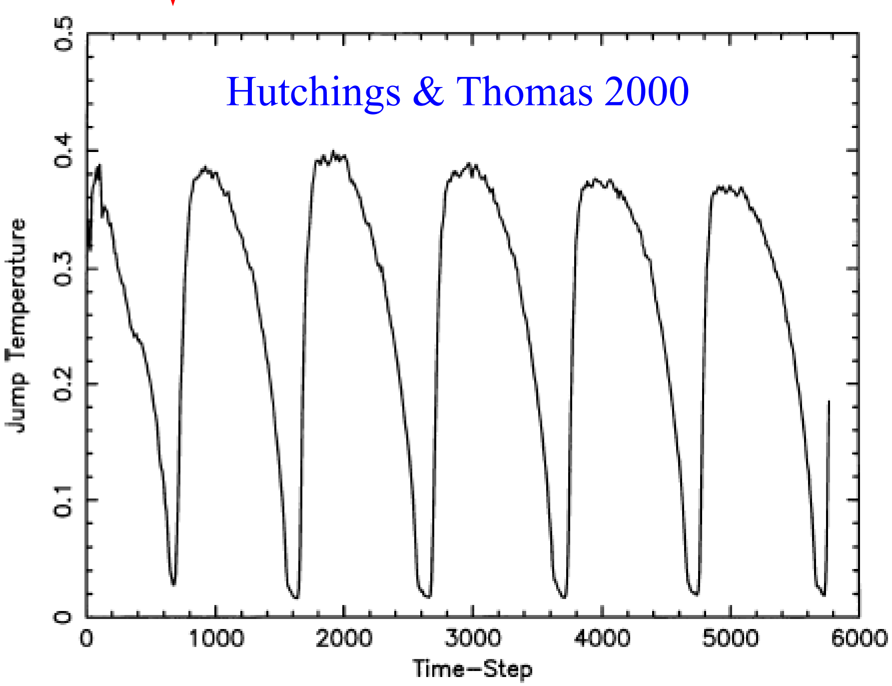
- Two-body encounters with DM particles generate spurious random motions of SPH particles which dissipate into heat
- This two-body heating overwhelms radiative cooling if the DM particle mass exceeds a critical value dependent on the local baryon fraction, gas temperature and metallicity

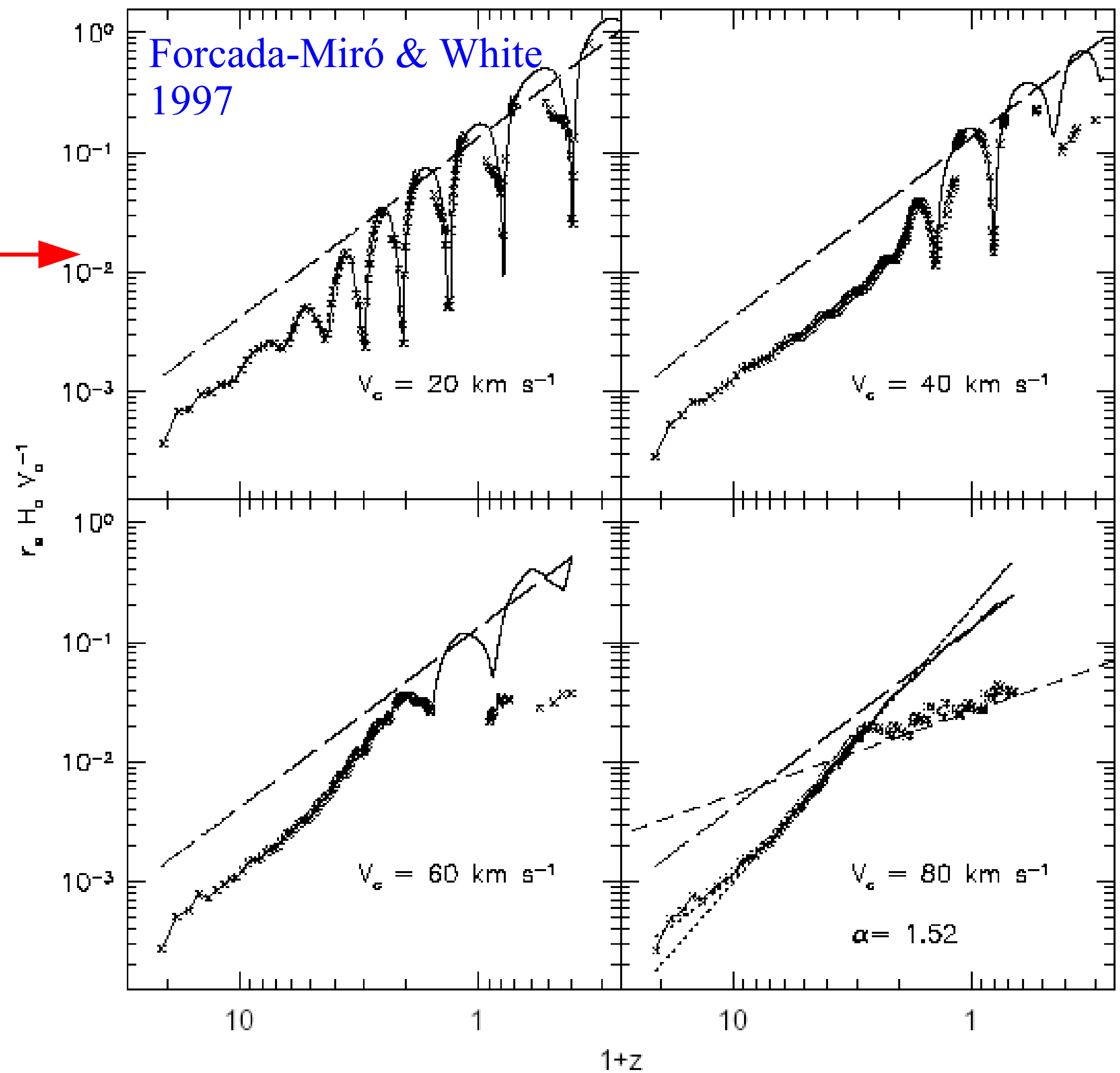
Instability of strongly radiative shocks

Strong, rapidly cooling shocks with $\Lambda(T) \propto T^{\alpha}$ are *unstable* to large amplitude oscillations in shock position, velocity and strength:

for $\alpha < 0.4$ (plane shocks)

for $\alpha < 0$ (sph. infall)





Other physical complications

- **Radiative mixing layers** (Begelman & Fabian 1990) on the interface between cold clouds and a hot phase may radiate much of the cooling energy at an intermediate temperature
- **Cosmic ray populations** (e.g. Miniati et al 2001) from large-scale shocks or radio galaxies may add pressure support and also provide additional heating and energy transport
- **Metal enhanced cooling instability** may occur in differentially enriched regions. The more metal-rich regions cool and condense faster, dropping preferentially out of the hot phase
- **Winds/outflows** from AGN and from star-forming regions interact with infalling gas
- **Radiative transfer** effects modify shock structure and emitted spectral energy distribution
- **Magnetic fields** as always...

Conclusions?

- Much of the gas which collapses to form most galaxies does so without ever being part of a hot, quasi-static, virialised atmosphere
- This was already postulated as part of the earliest "modern" theories in the late 1970's and has been explicit in most models since then
- Most gas *is* probably shocked to a temperature of order the virial temperature, but most of it cools without coming to equilibrium
- Cooling radiation typically comes from gas which is not in collisional ionisation equilibrium, leading typically to enhanced line emission
- Radiative shocks in forming galaxies can exhibit complex large amplitude oscillations
- Simple analytic arguments and numerical simulations agree roughly on the amount of gas which should condense in various halos in the ΛCDM cosmogony, but neither is more accurate than a factor of two
- Many physical processes may play a significant role which are not included in current models or simulations