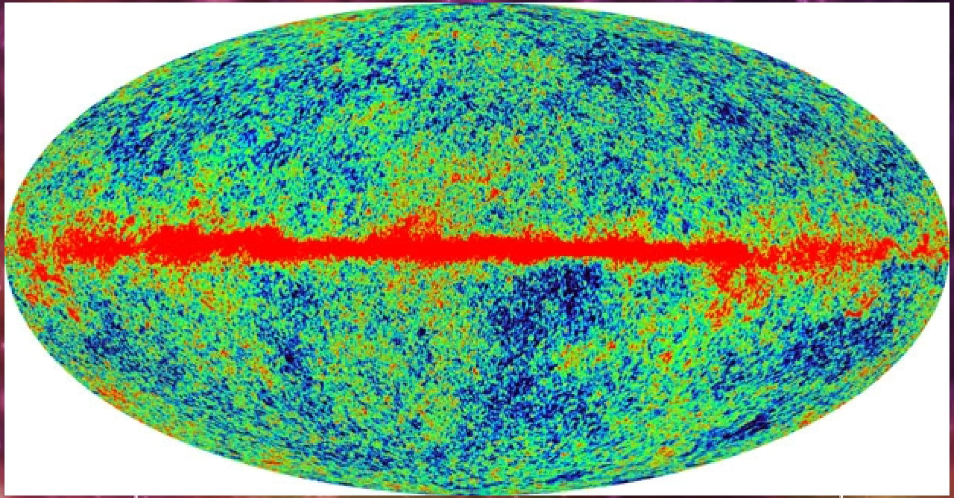
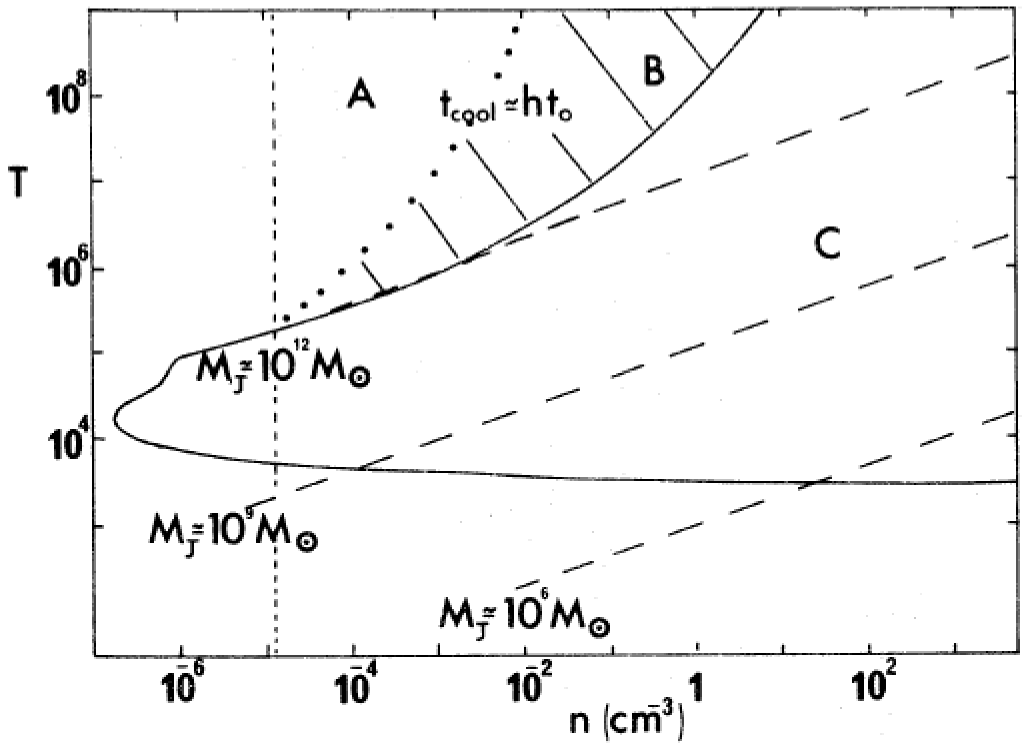


Gas Accretion and Star Formation in Galaxies
Garching, Sept. 2007

How do Galaxies get their Gas? (Theory)

Simon D.M. White
Max Planck Institute for Astrophysics

Radiative processes in galaxy formation



Rees & Ostriker 1977
Silk 1977
Binney 1977

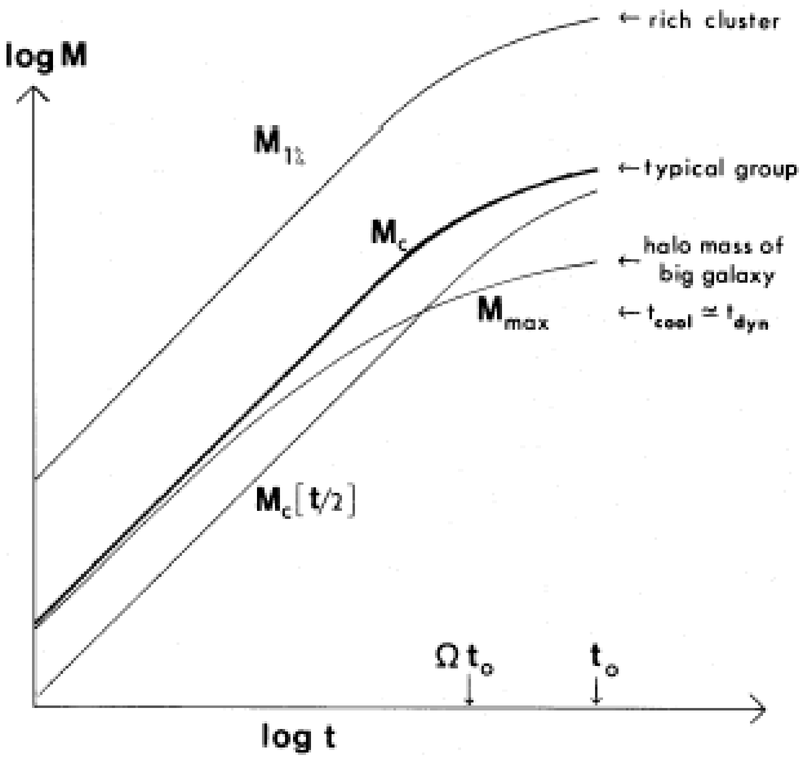
- When gas clouds of galactic mass collapse:
  - (i) shocks are radiative and collapse unimpeded, when $t_{cool} < t_{dyn}$
  - (ii) shocks are non-radiative and collapse arrested, when $t_{cool} > t_{dyn}$

  where quantities are estimated at virial equilibrium

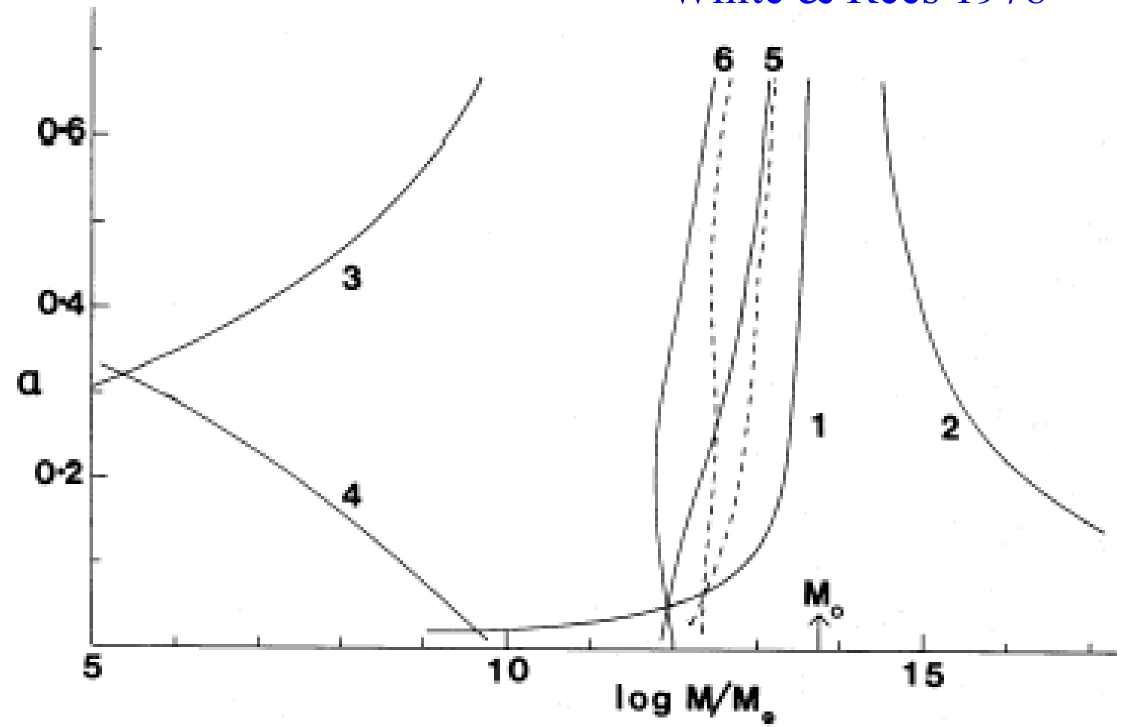
- Galaxies form in case (i) since fragmentation is possible

- Primordial cooling curve ⟶ characteristic mass $10^{12} M_\odot$

Towards a "modern" theory



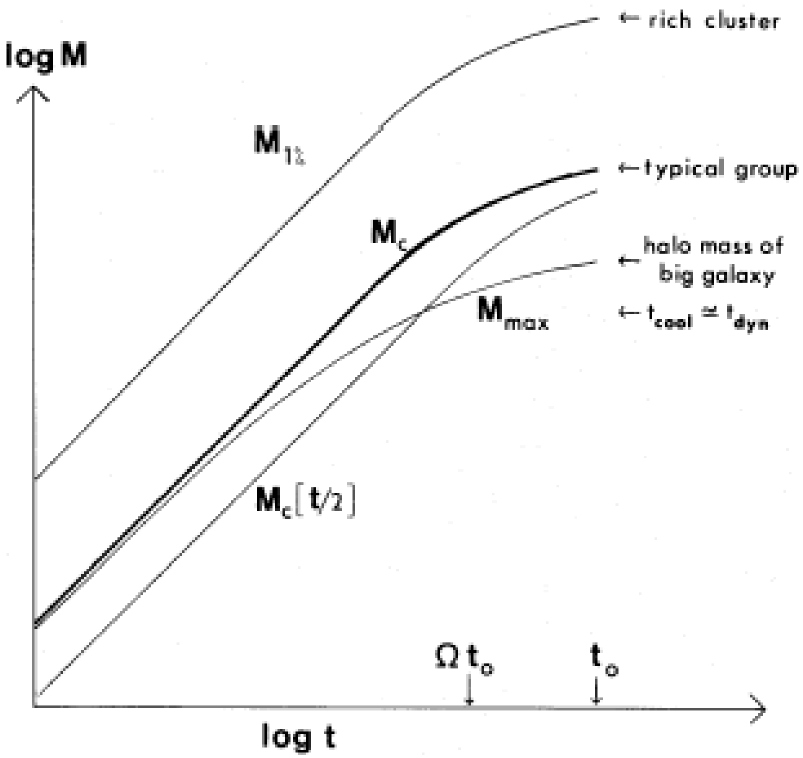
White & Rees 1978



- 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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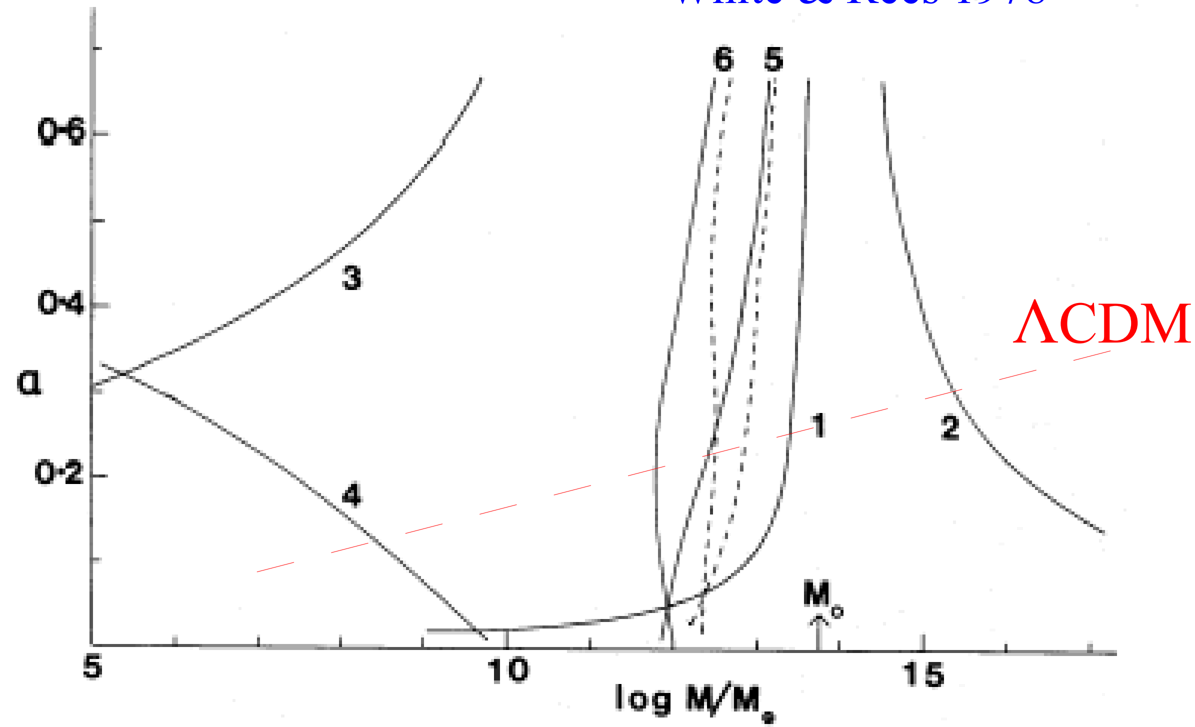

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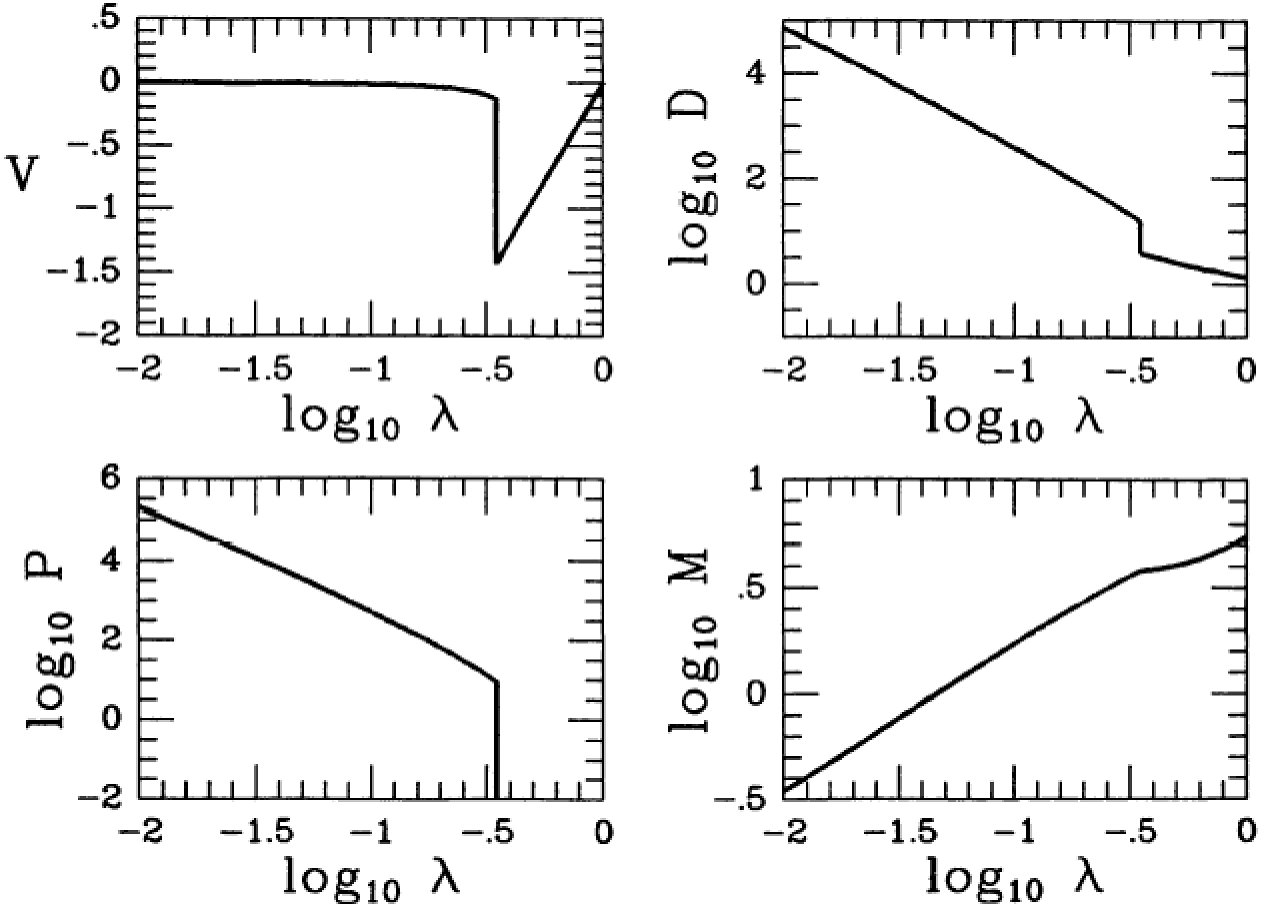
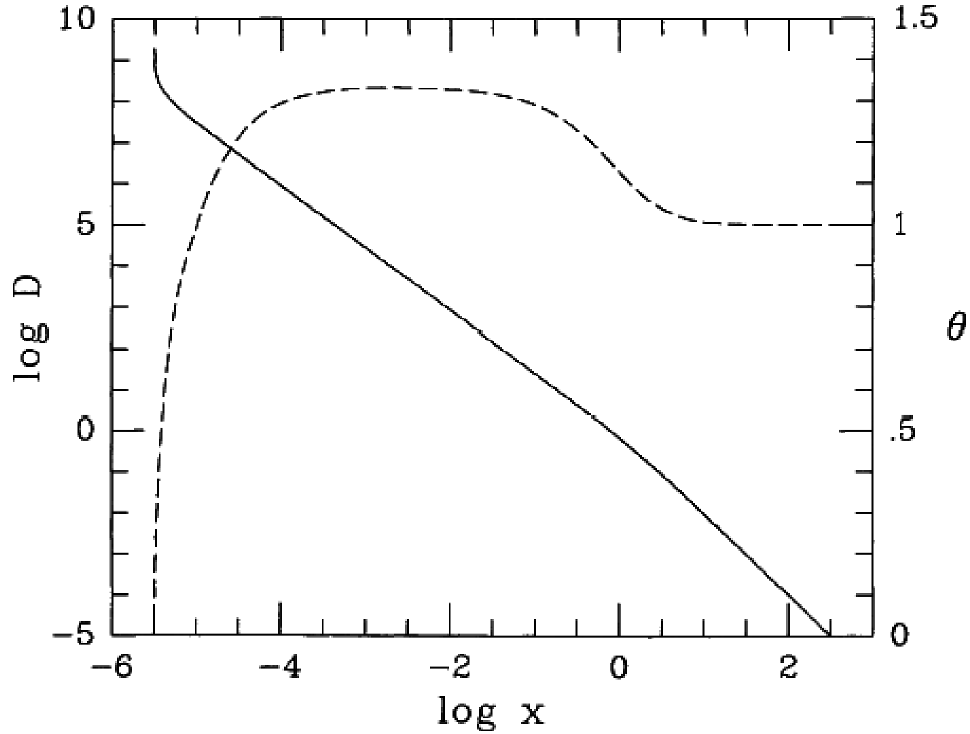
Spherical similarity solutions for infall



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

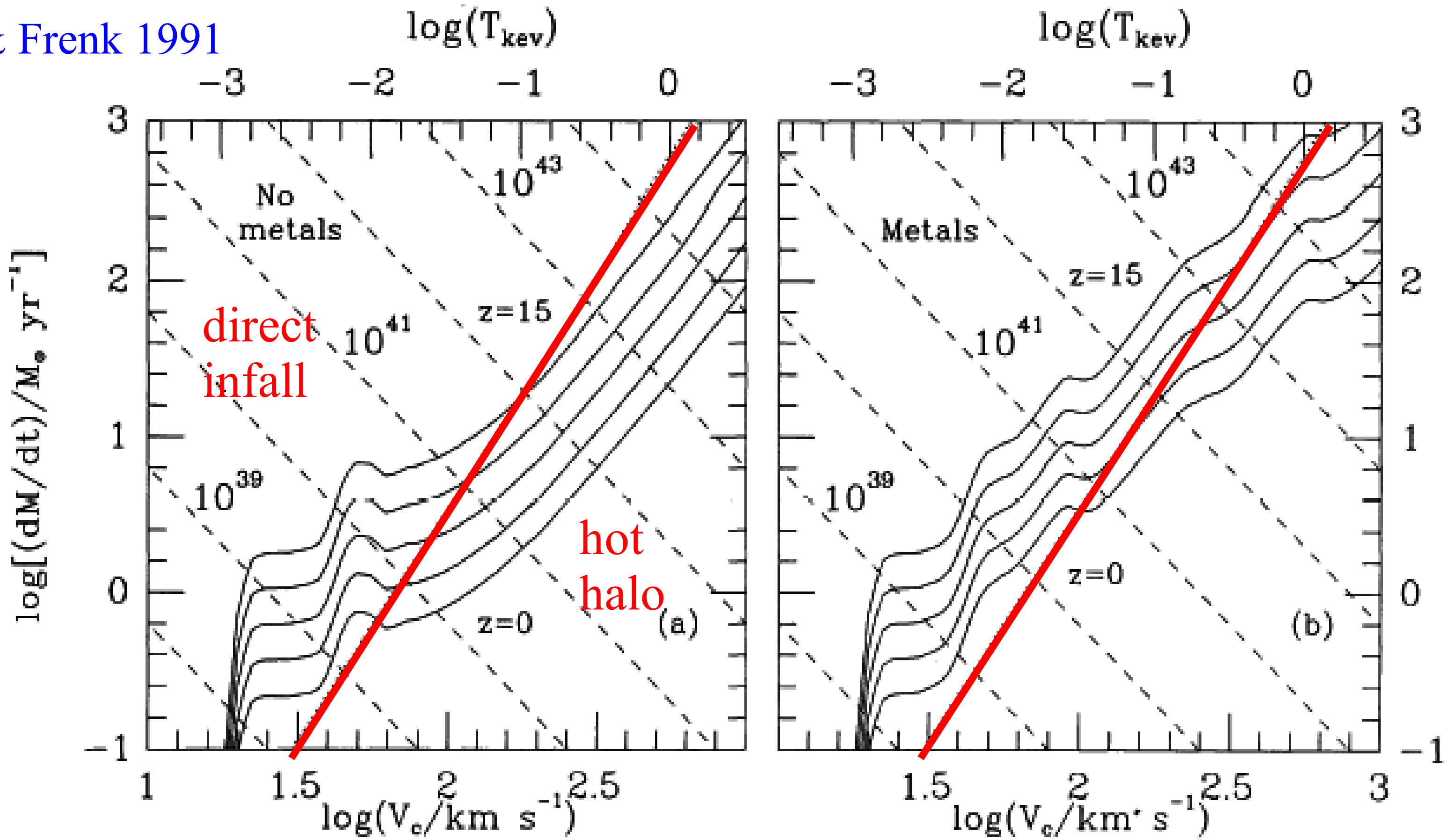


Bertschinger 1989

- 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 $\longrightarrow$ no static atmosphere?

Putting it together in a CDM universe

White & Frenk 1991



$\Omega = 1$

Assuming $r_{cool} < r_{shock}$ required for a hot atmosphere and taking $f_{baryon} = 0.1$

→ direct infall (i.e. *no* hot atmosphere) when

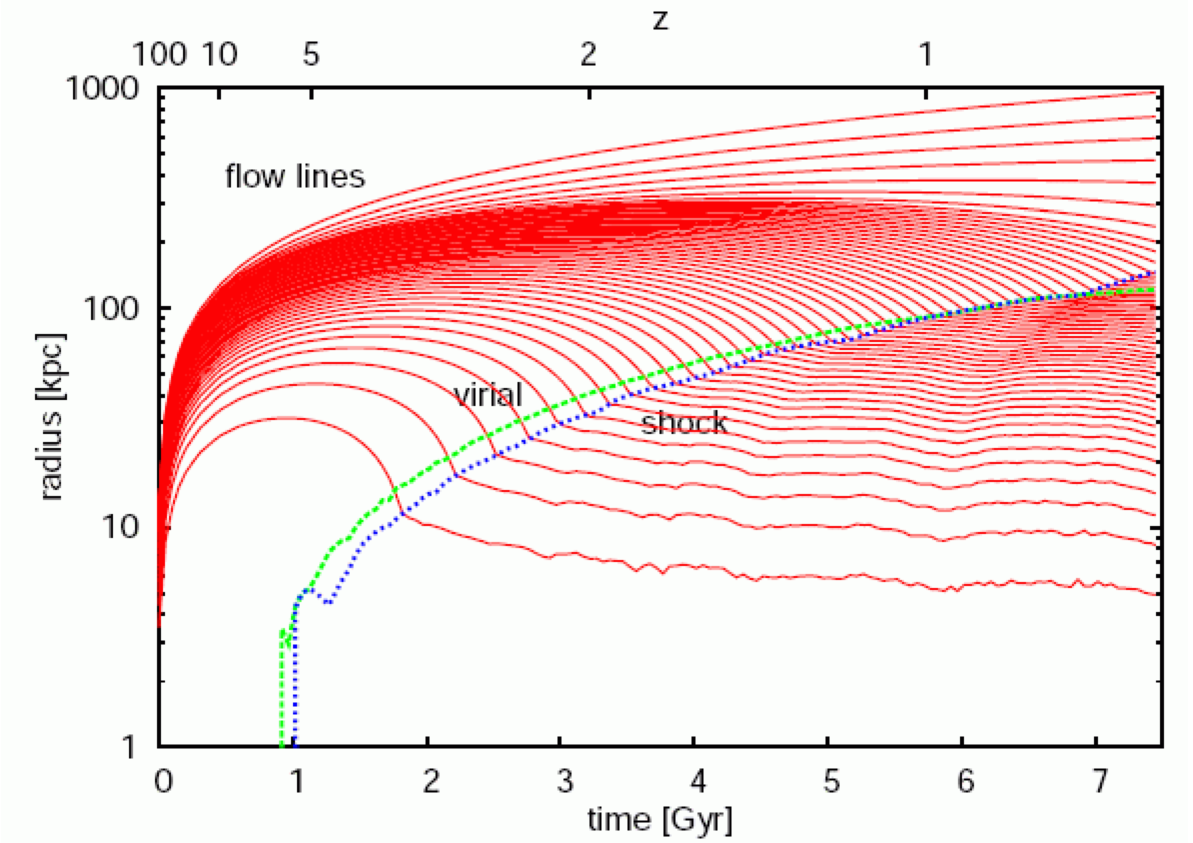
$V_{circ} <$ 80 km/s at z=3 when there is no chemical mixing, and for

$V_{circ} <$ 250 km/s at z=3 when efficient mixing is assumed

Growth of a spherical lump in a CDM universe

Birnboim & Dekel 2003

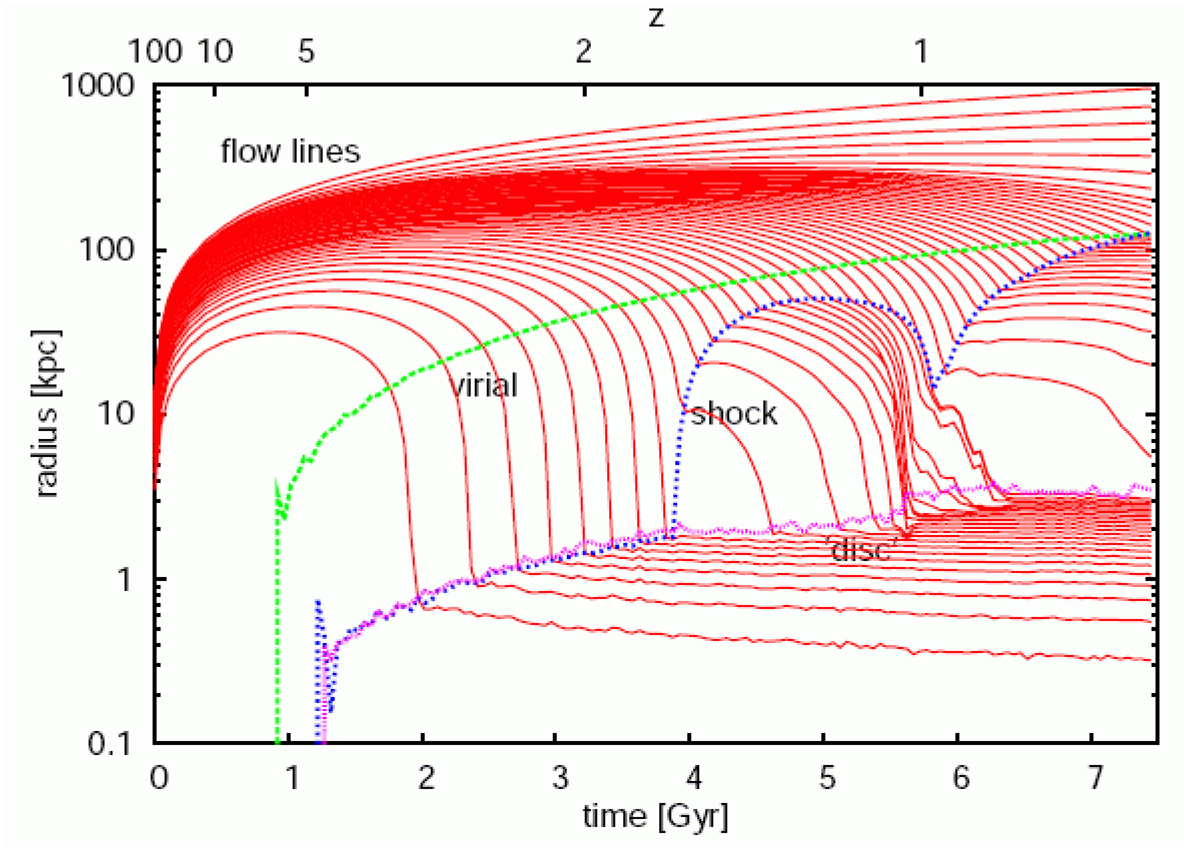
Non-radiative infall



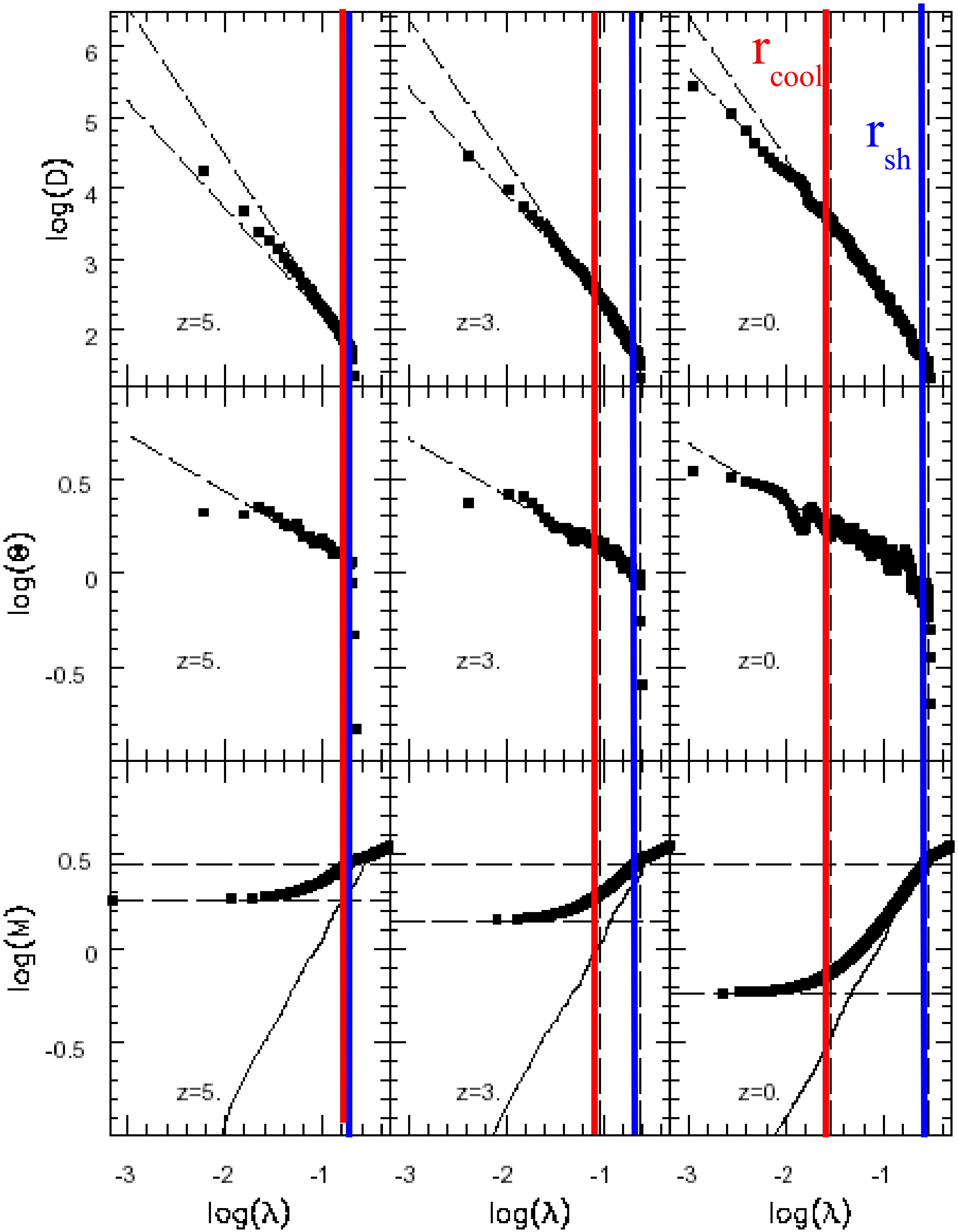
Growth of a spherical lump in a CDM universe

Birnboim & Dekel 2003

Infall with metal-free cooling



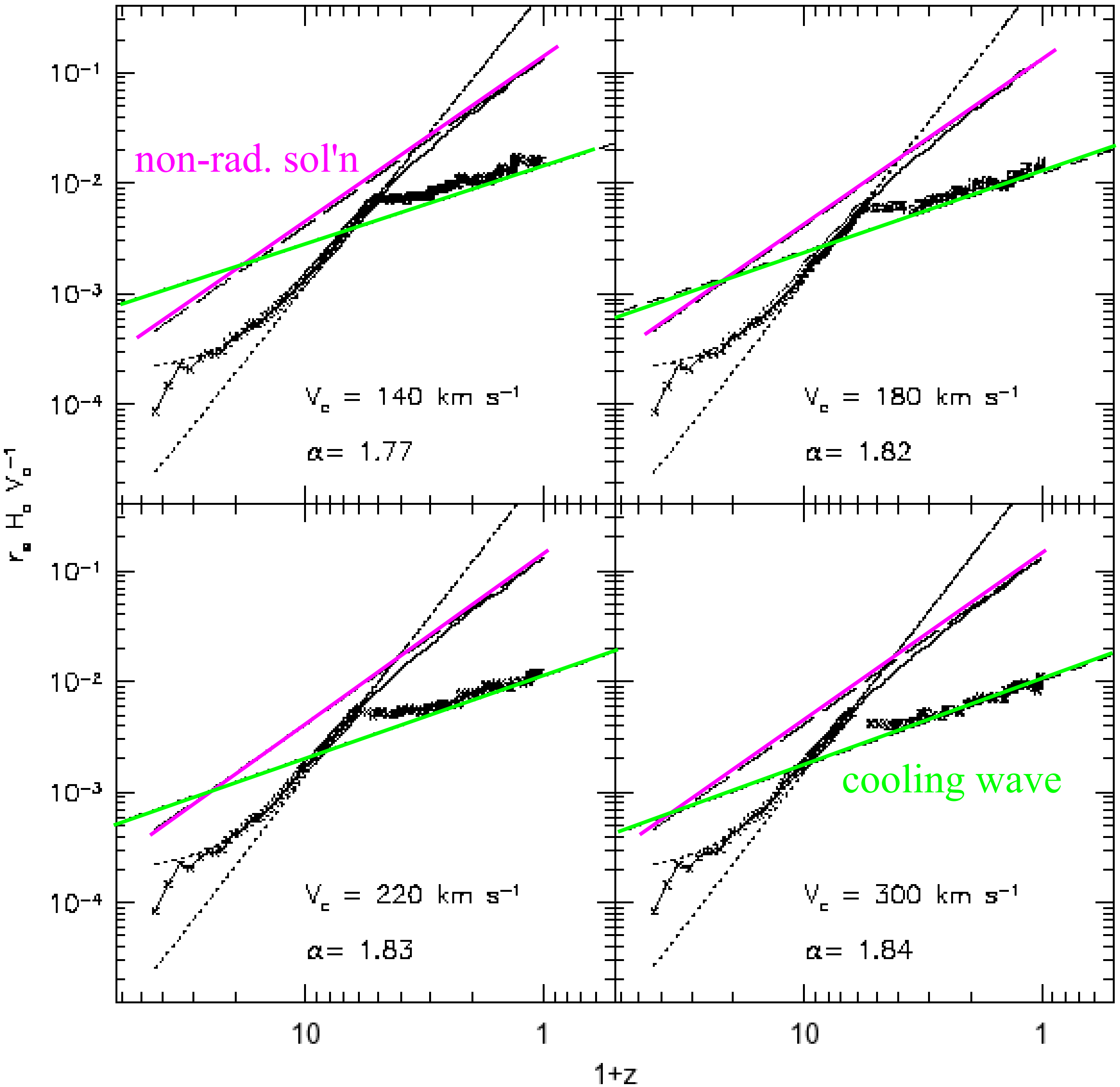
Radiative cooling in spherical infall models



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 $t_{cool} \approx t_{free\text{-}fall}$

  $\rightarrow$ $r_{cool} \approx r_{shock} \propto t^{1.8}$

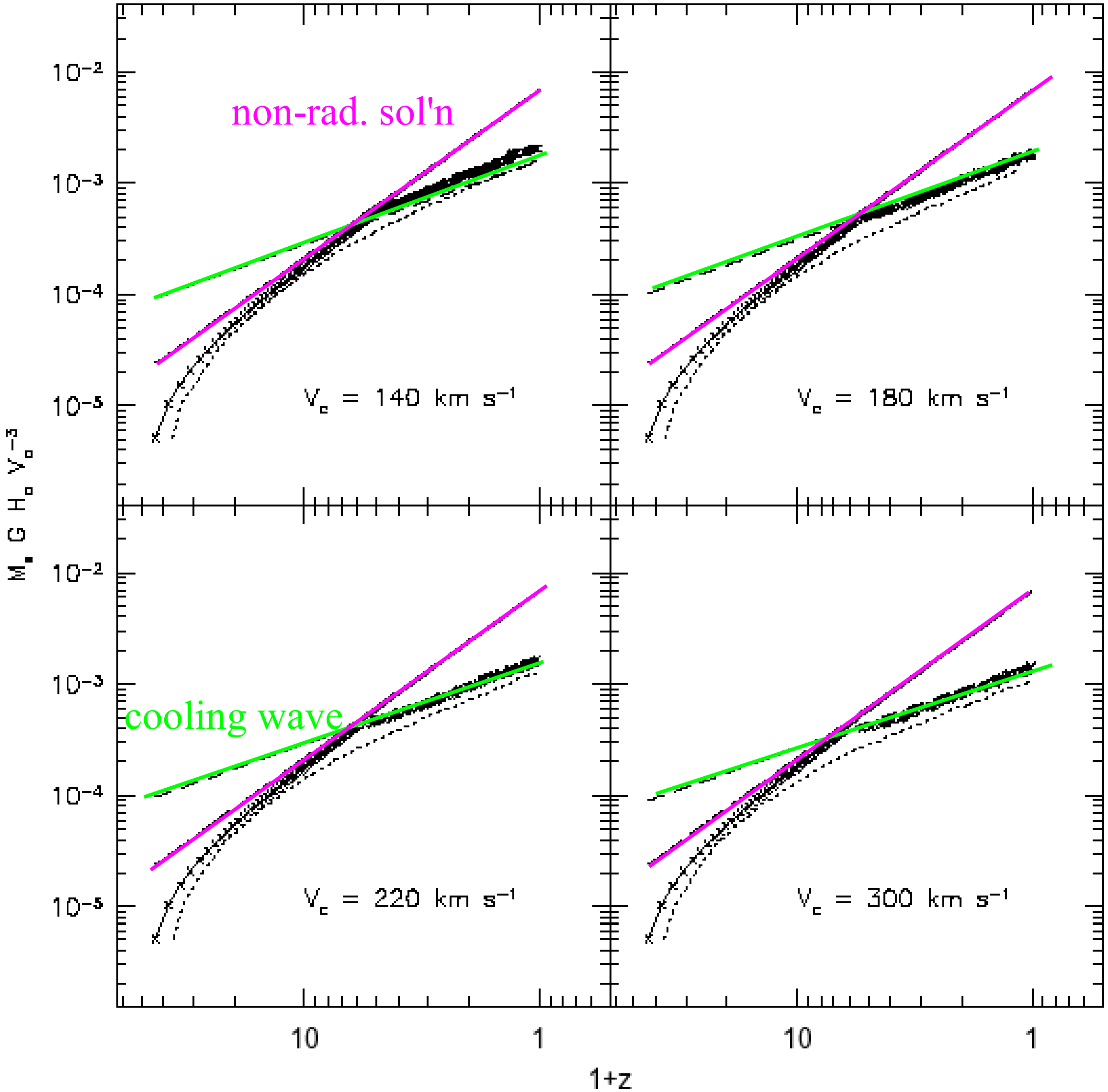
- Cooling radius breaks away from shock as both near similarity shock radius
- Cooling radius then follows the Bertschinger solution

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

- Shock asymptotes to the non-radiative sim. solution

  $r_{shock} \propto t$

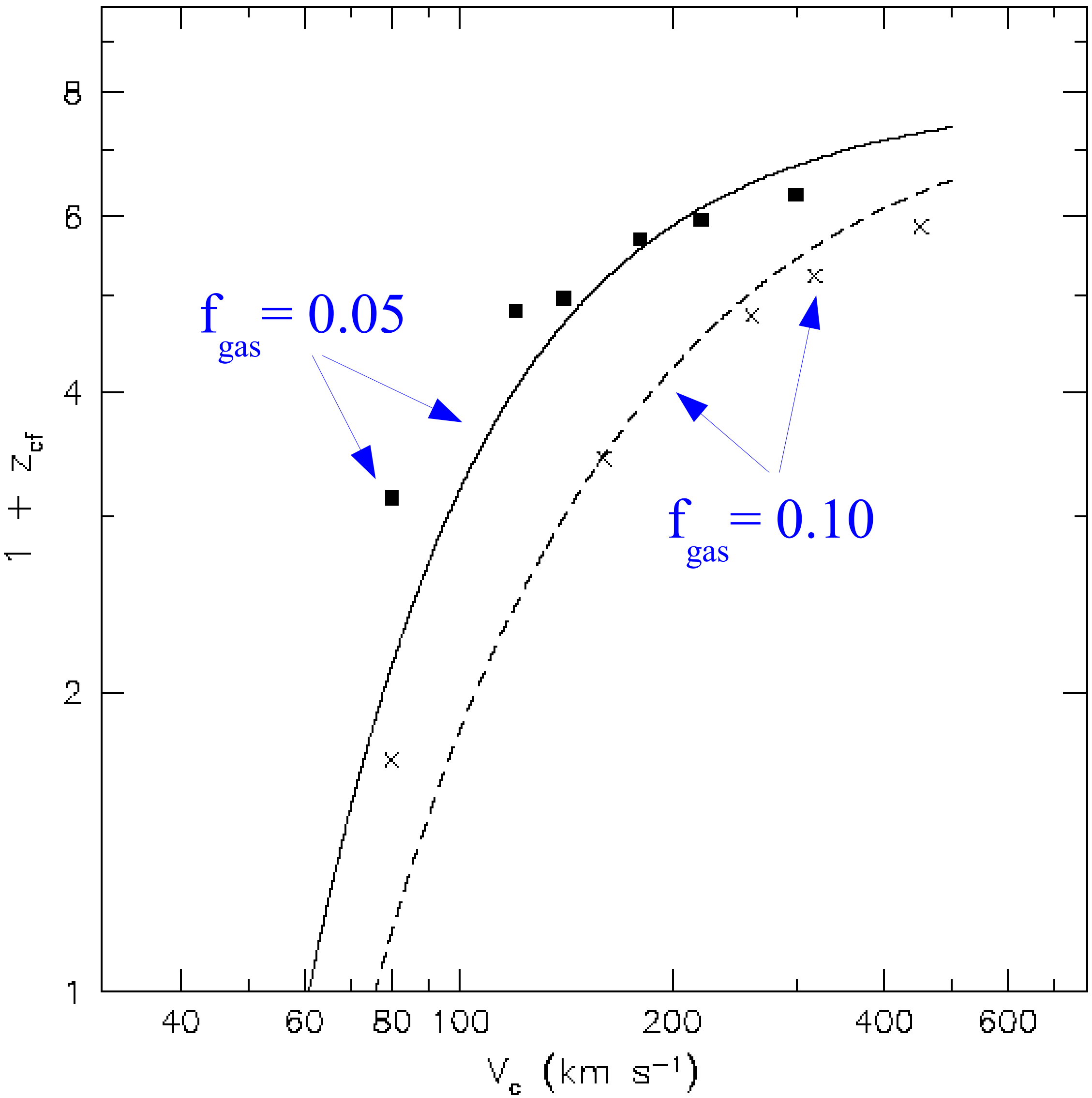
Cold and shocked mass evolution in isothermal models



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)

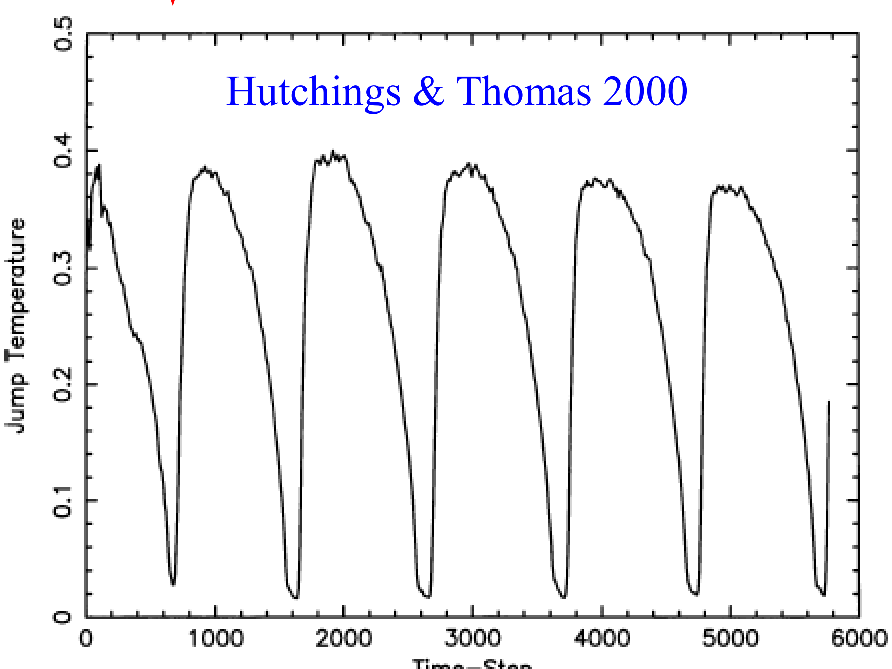
cf also Birnboim & Dekel (2003)

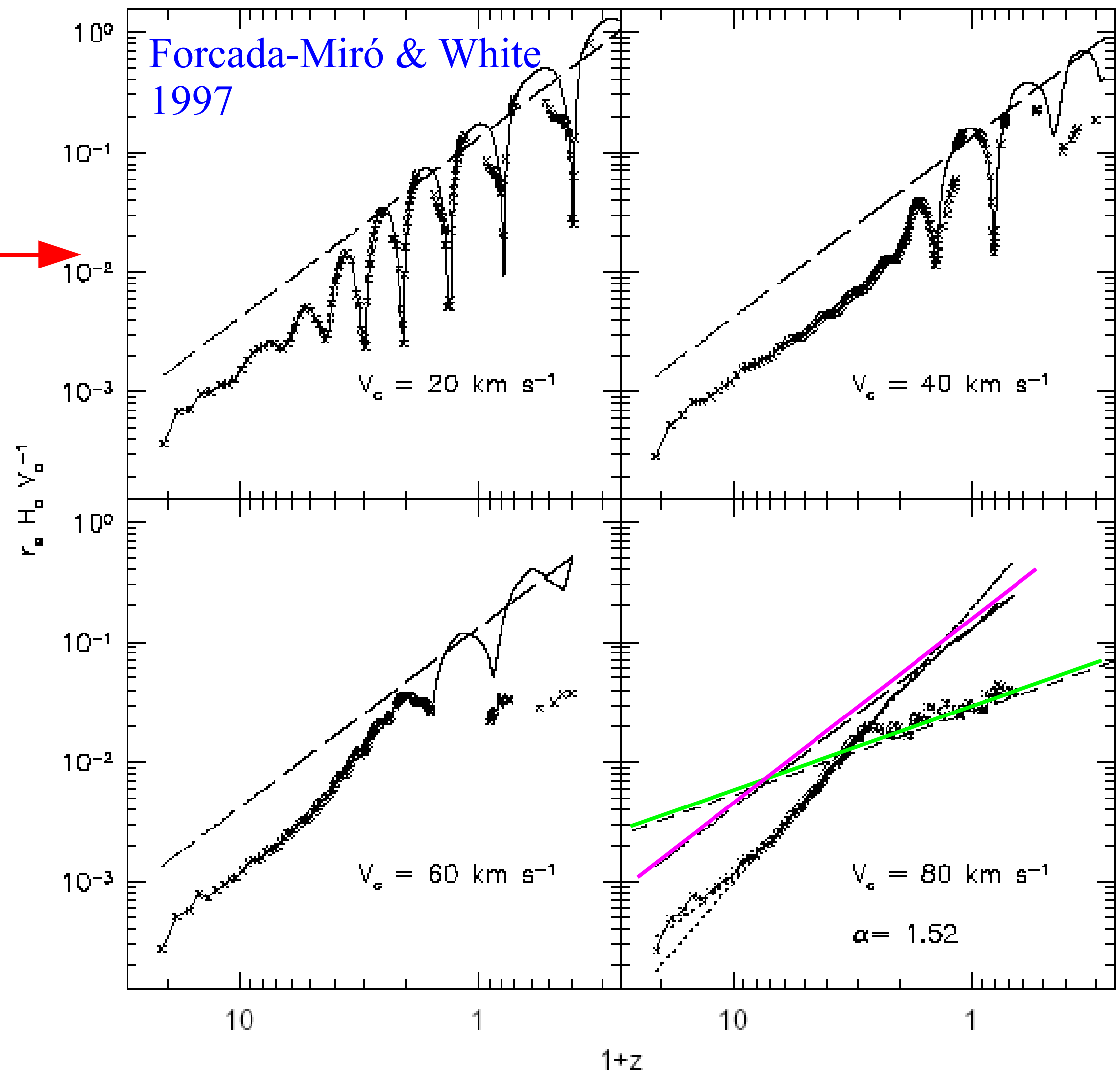
Instability of strongly radiative shocks

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

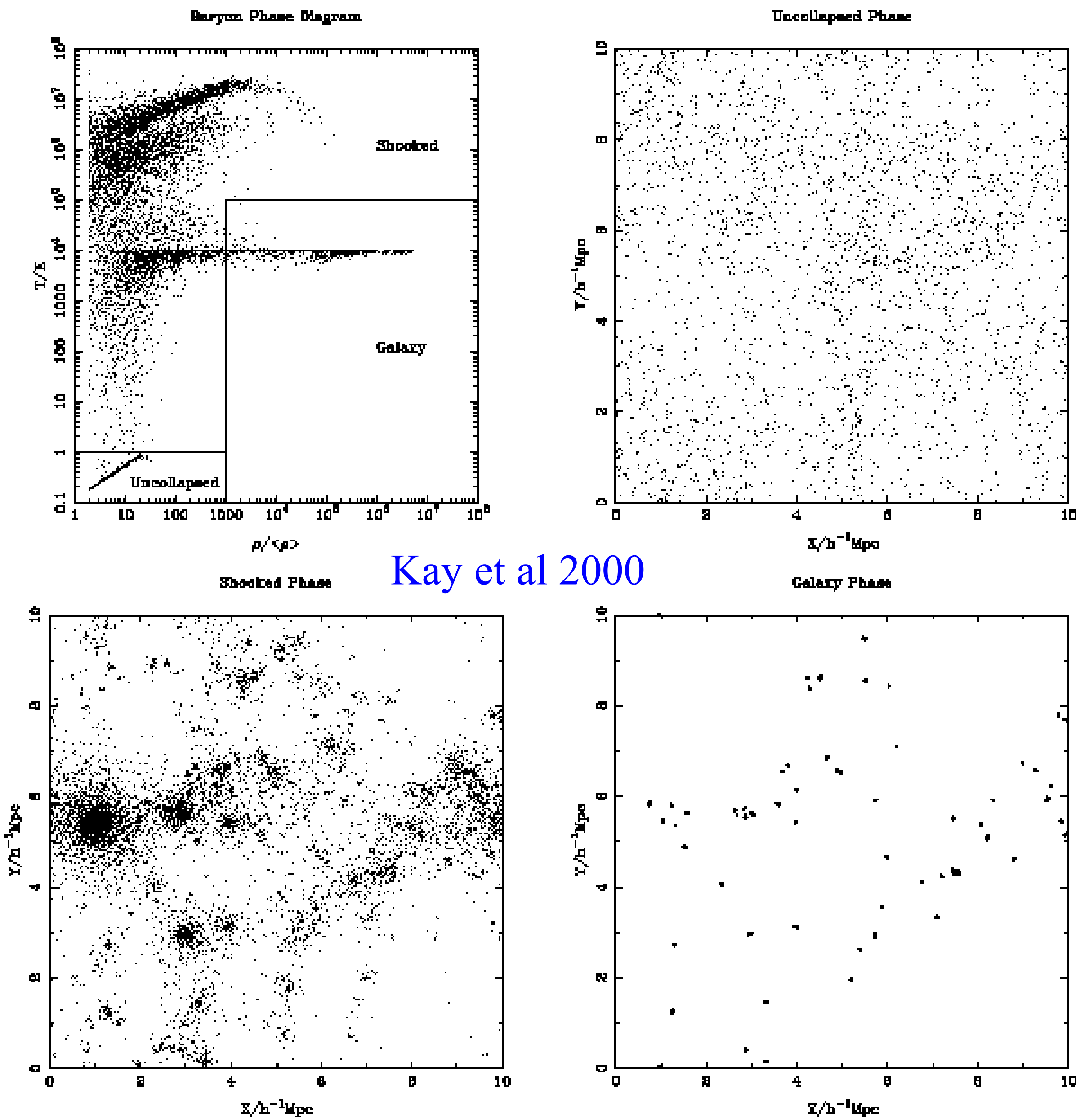
for $\alpha < 0.4$ (plane shocks)

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



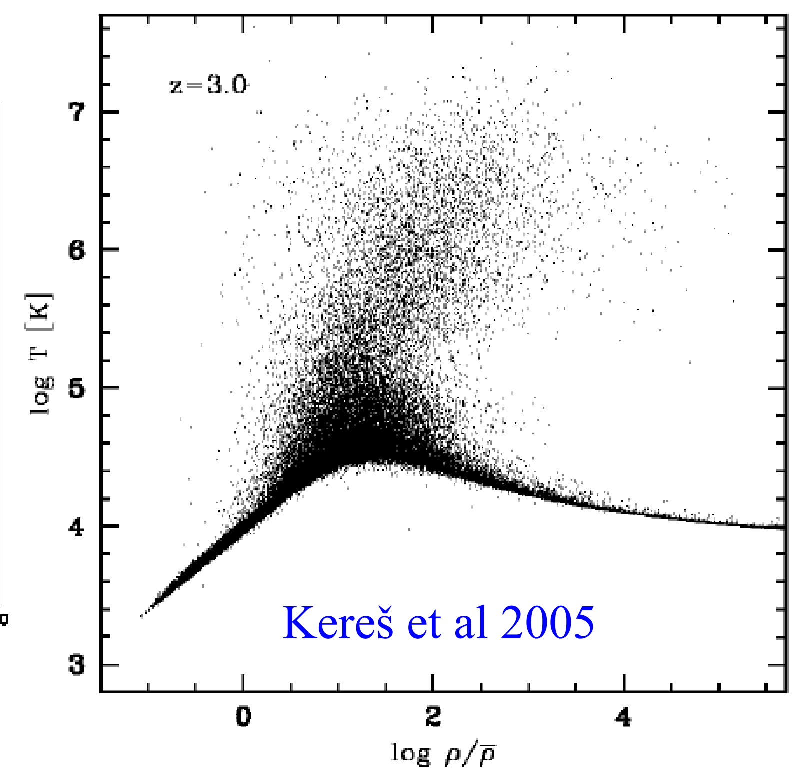


Gas cooling in cosmological simulations



Kay et al 2000

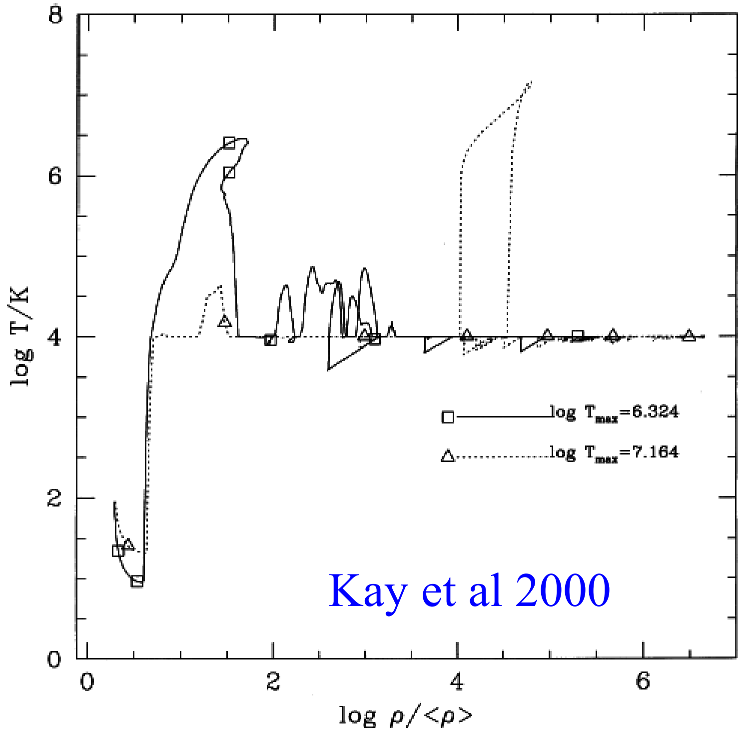
- Gas separates cleanly into three phases
  - --cool, diffuse IGM
  - --hot, shocked IGM
  - --cold, dense ISM

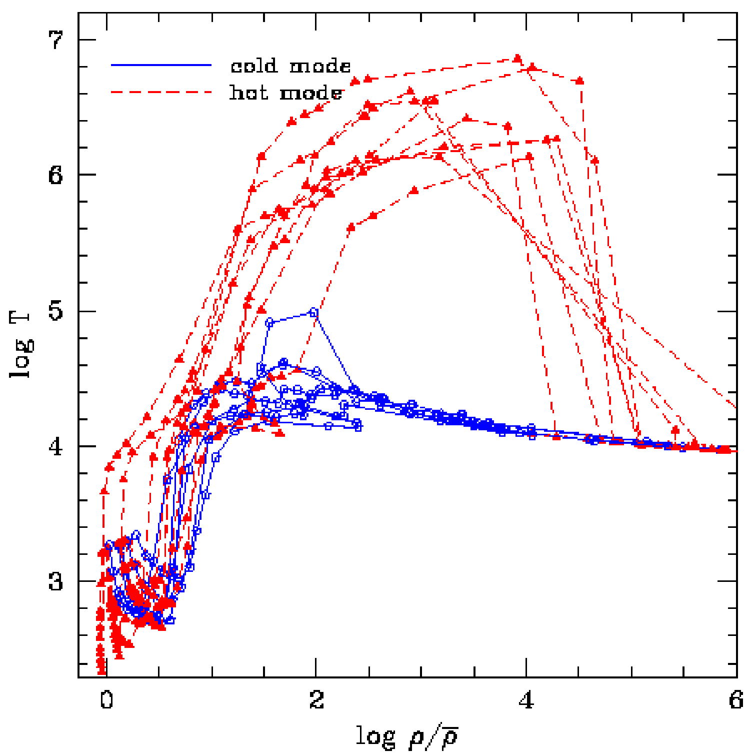


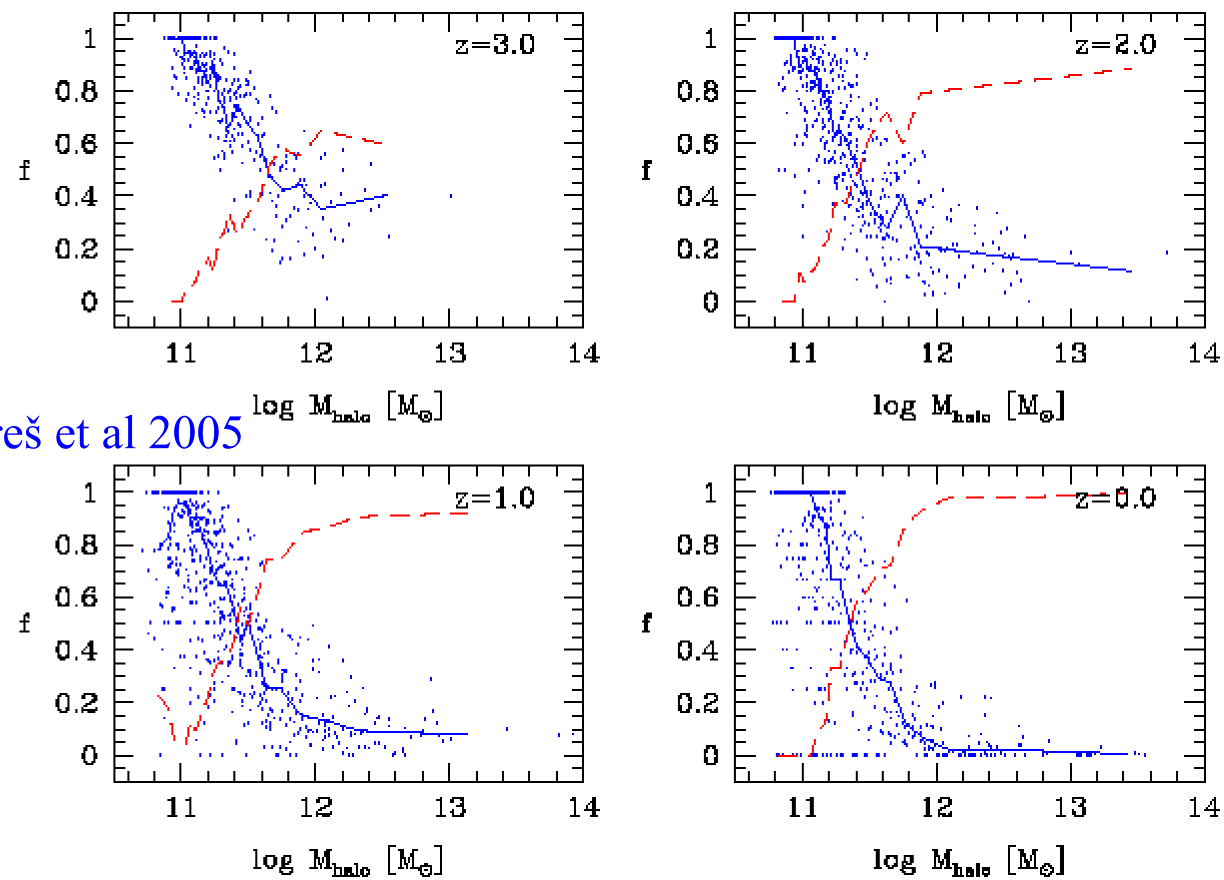
Kereš et al 2005

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?



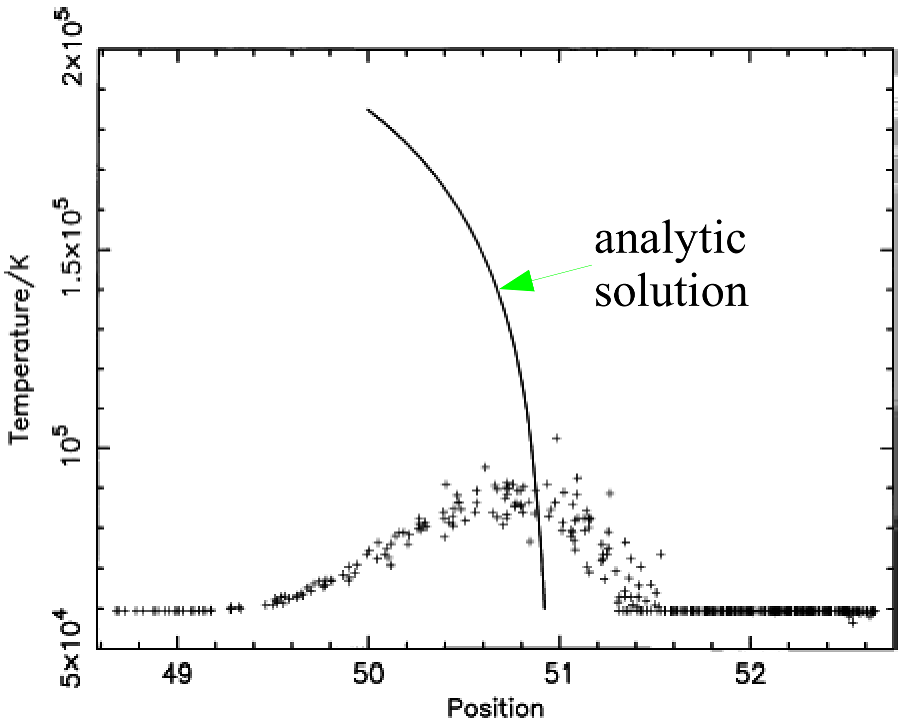




Kereš et al 2005

In-shock cooling

Hutchings & Thomas 2000



A radiative shock in a shock tube followed with SPH

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

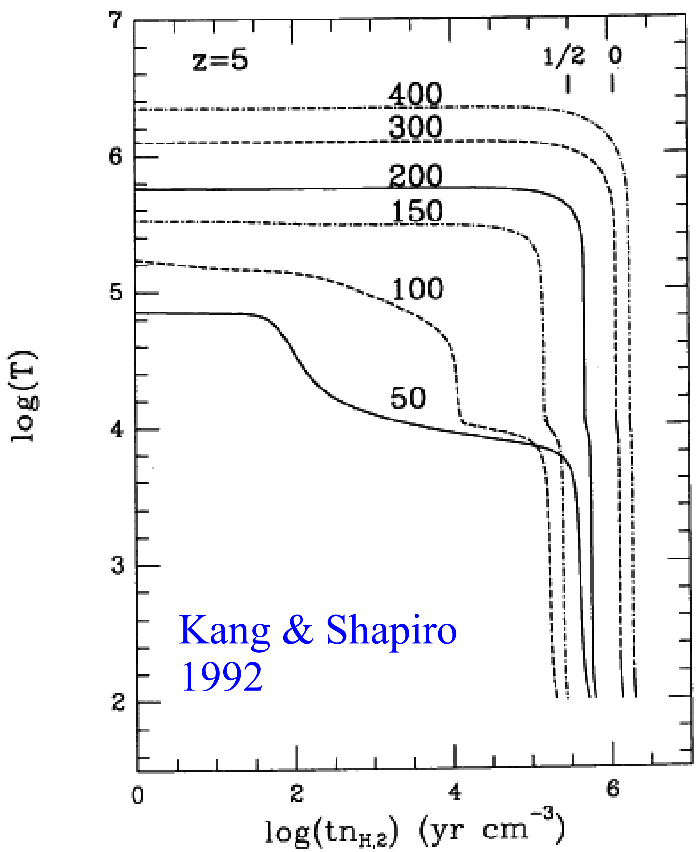
- Immediately behind a strong shock the gas heats to a temperature

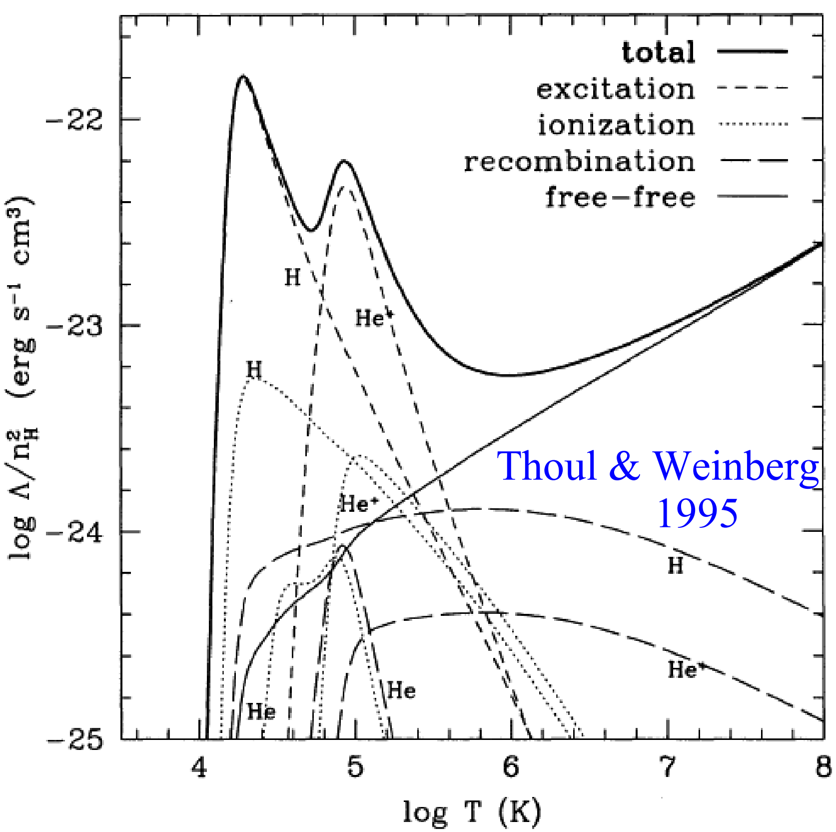
$$T = 3\mu V_{sh}^2 / 16\,k$$
$$\sim 1.4 \times 10^5 (V_{sh} / 100\ \mathrm{km/s})^2$$

- 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

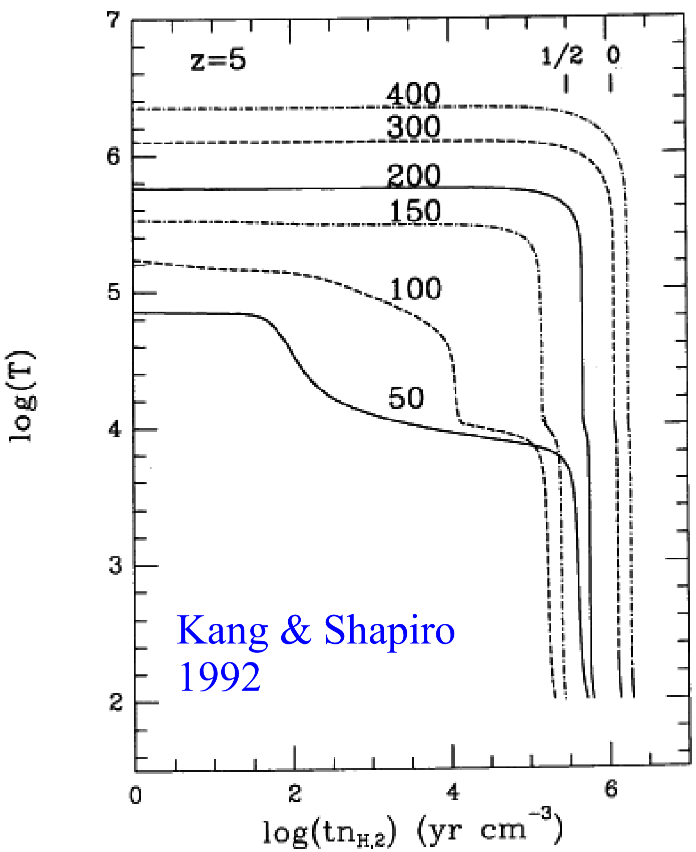
- For collisional ionisation equilibrium, the radiation from shocks would be dominated by He II 304 for 70 km/s < V_{sh} < 270 km/s

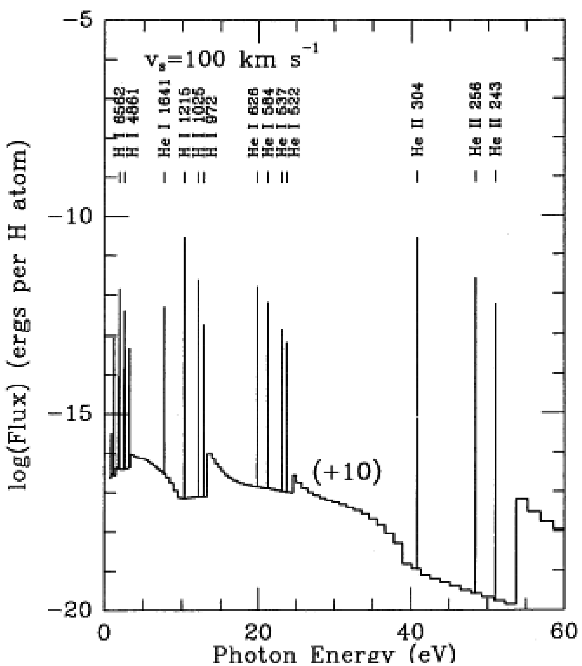


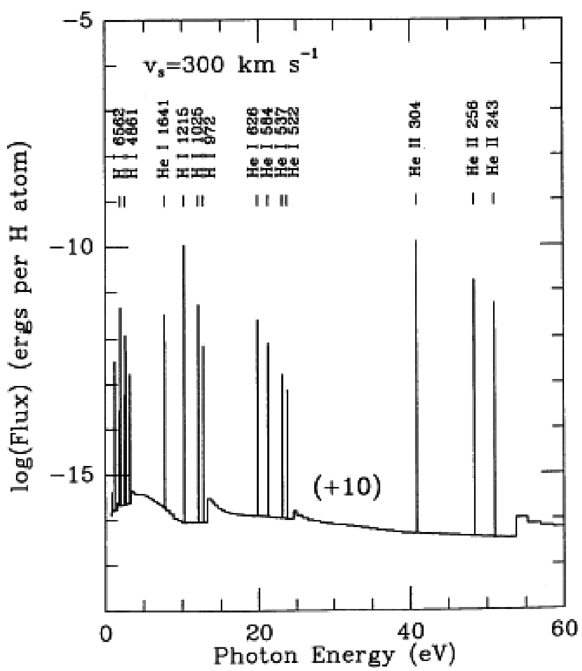


Radiation from shocks

- 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)

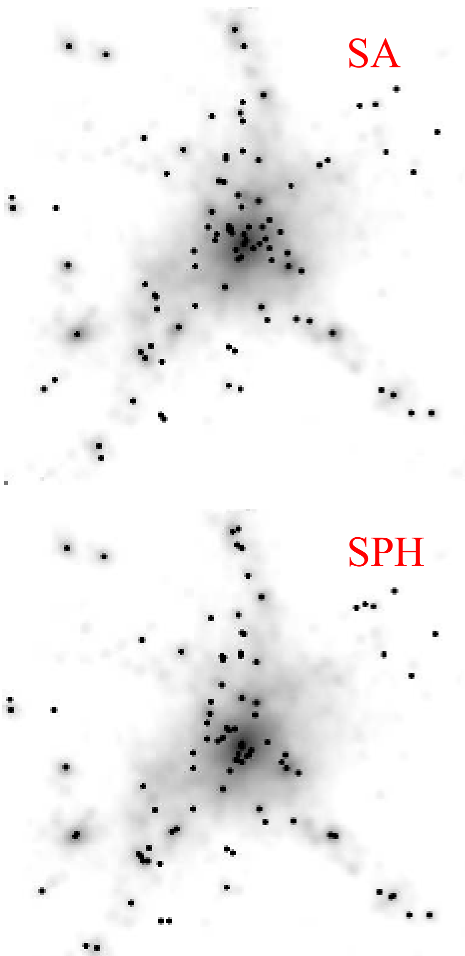




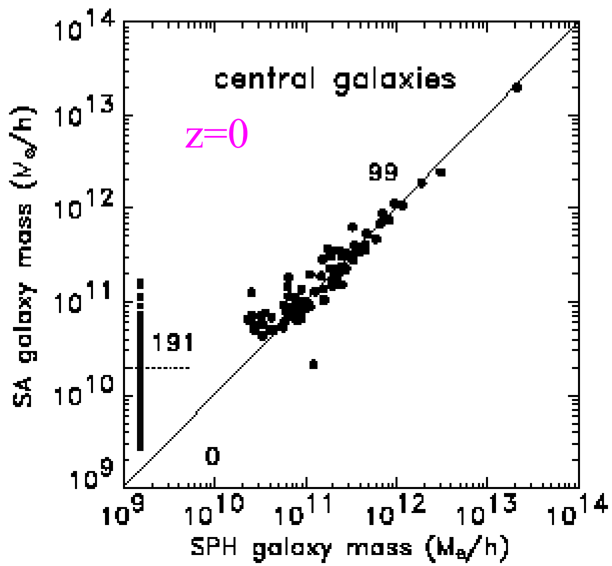


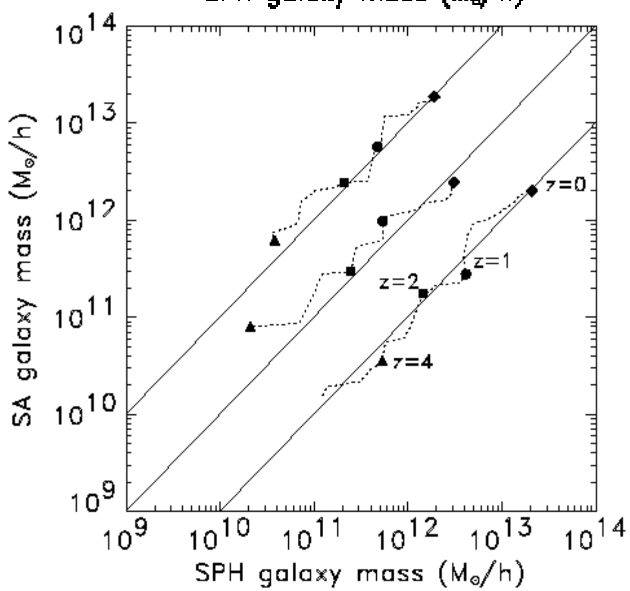
Cooling in SPH compared to a SA model

Yoshida et al 2002



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



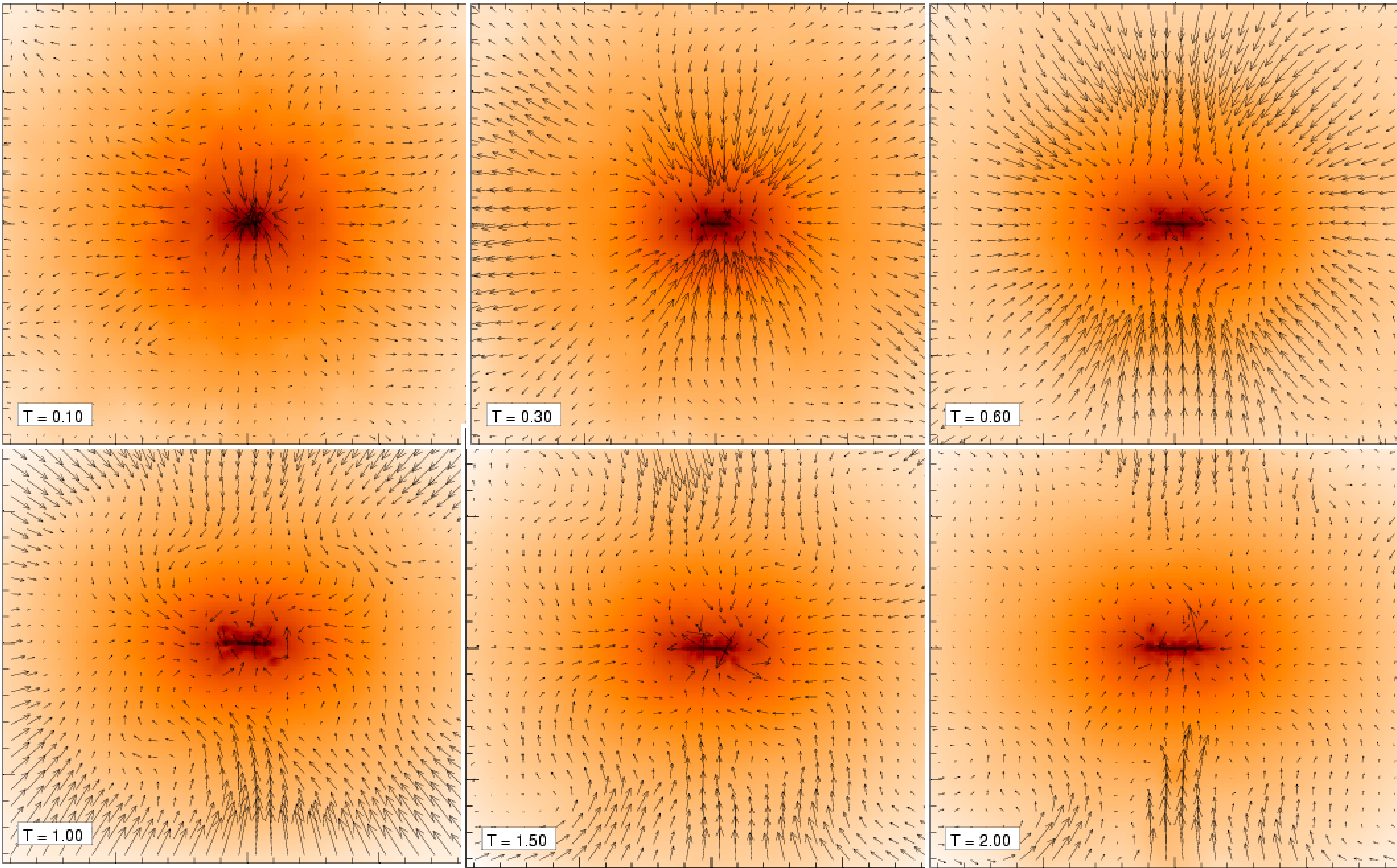


- Comparison of implementation in the *same* N-body ΛCDM cluster formation simulation of cooling
  - (a) with SPH (2 versions)
  - (b) with a standard SA model
- Masses of central objects in halos agree well once above the SPH resolution limit (~ 50 particles)
- Range checked includes transition from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

Disk Galaxy formation from simplified IC's but including star formation and feedback

Springel & Hernquist 2003

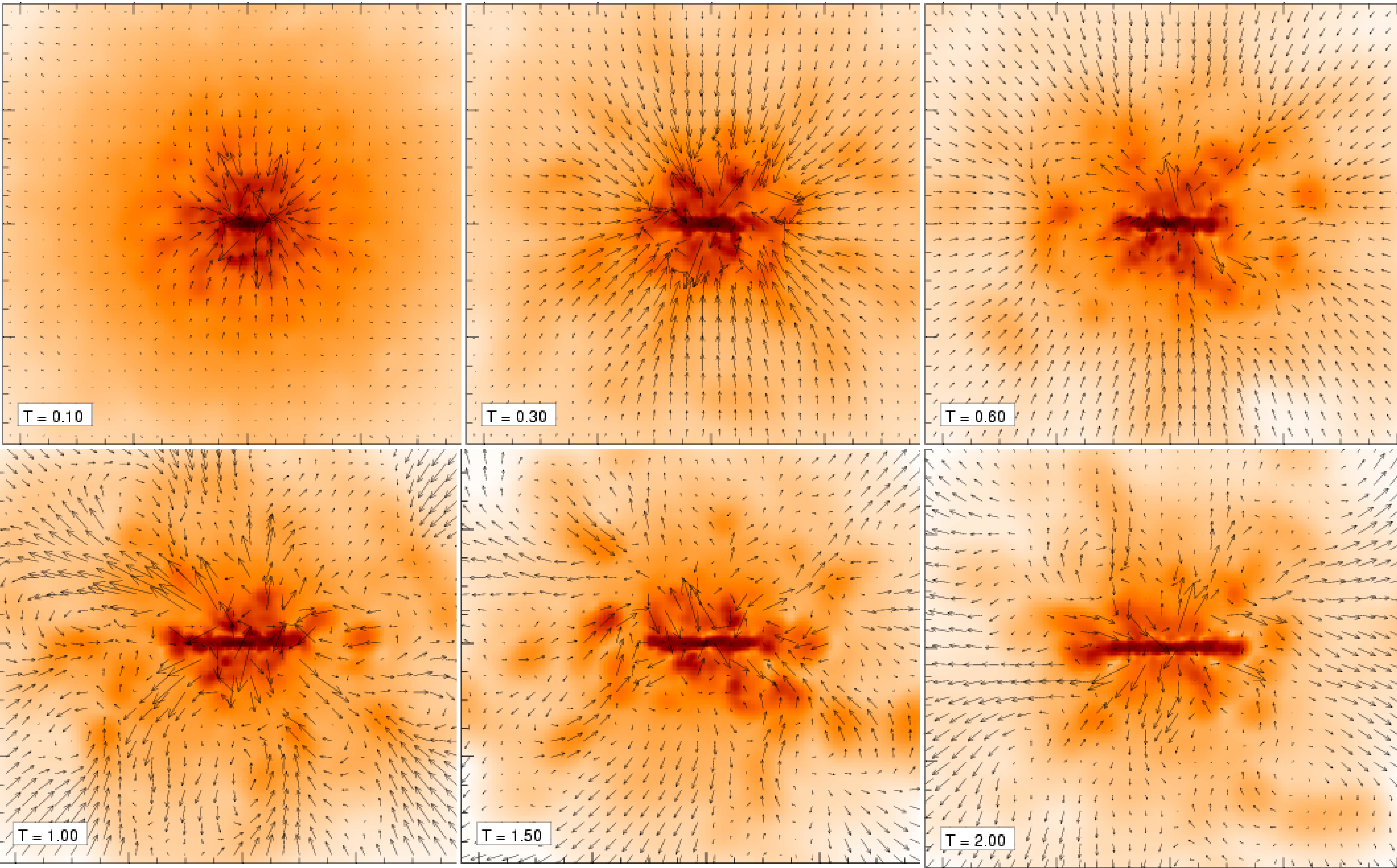
$M = 10^{12}\,h^{-1}\,M_\odot$



Disk Galaxy formation from simplified IC's but including star formation and feedback

Springel & Hernquist 2003

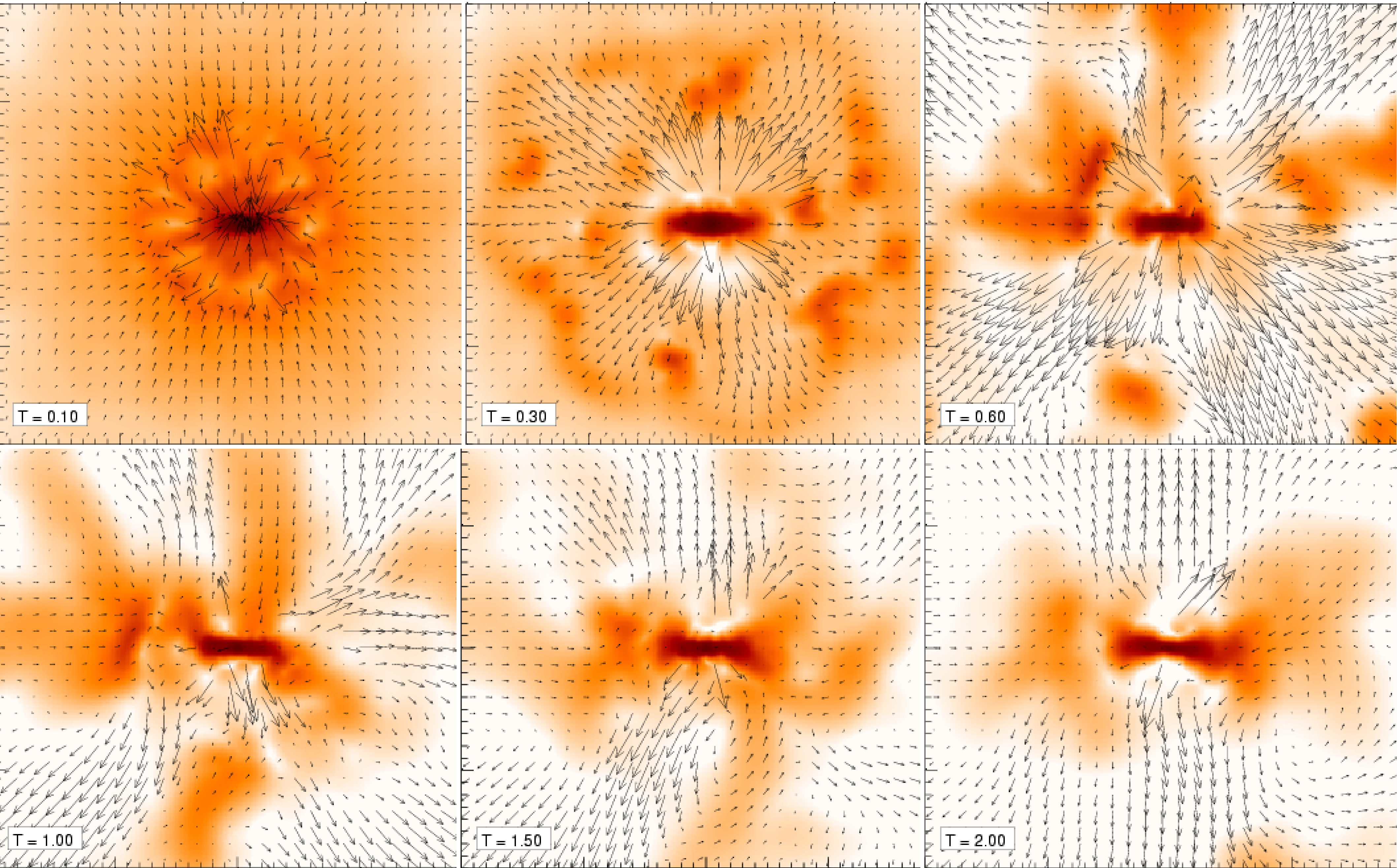
$M = 10^{11}\,h^{-1}\,M_\odot$

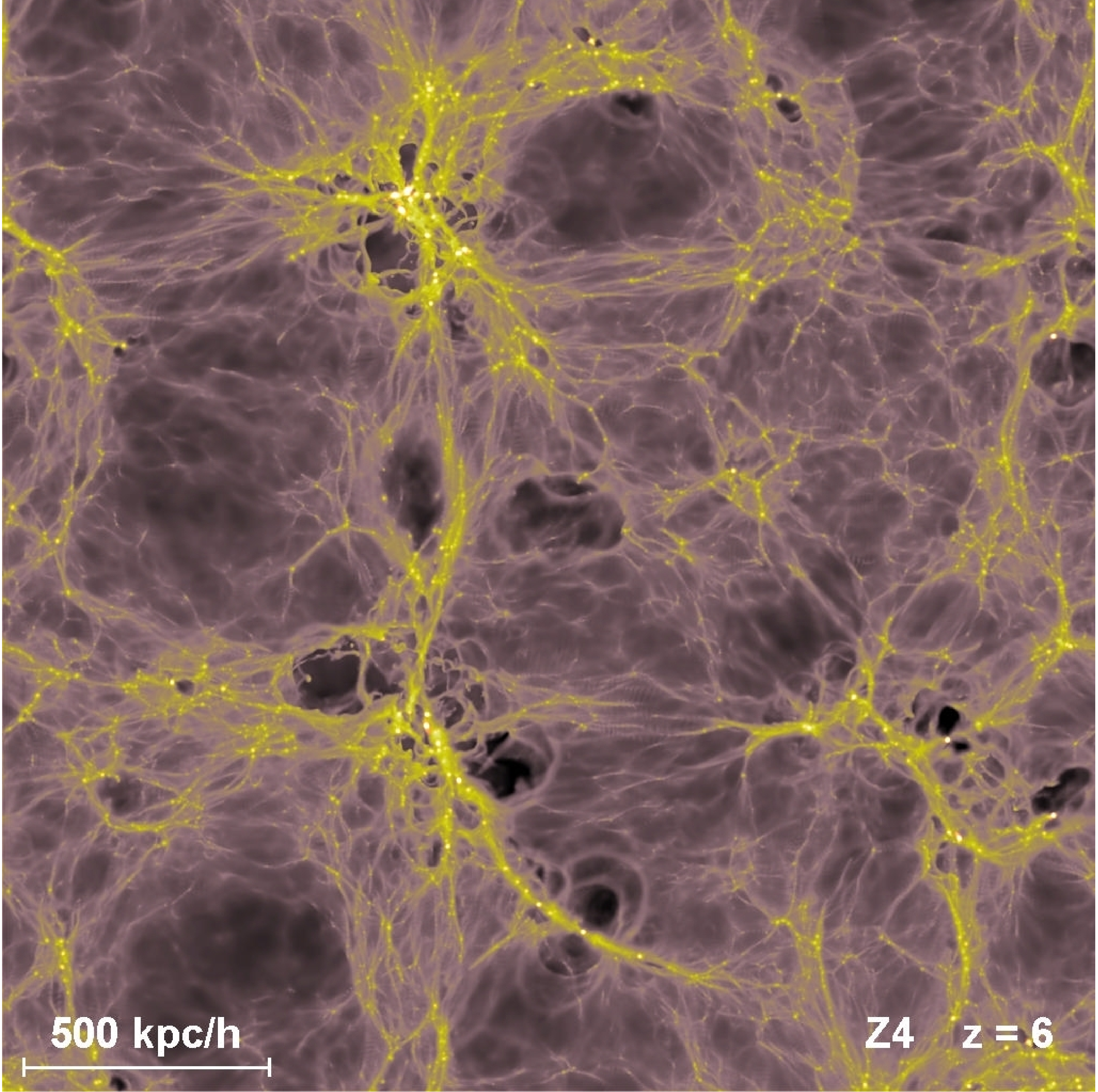


Disk Galaxy formation from simplified IC's but including star formation and feedback

Springel & Hernquist 2003

$M = 10^{10}\,h^{-1}\,M_\odot$



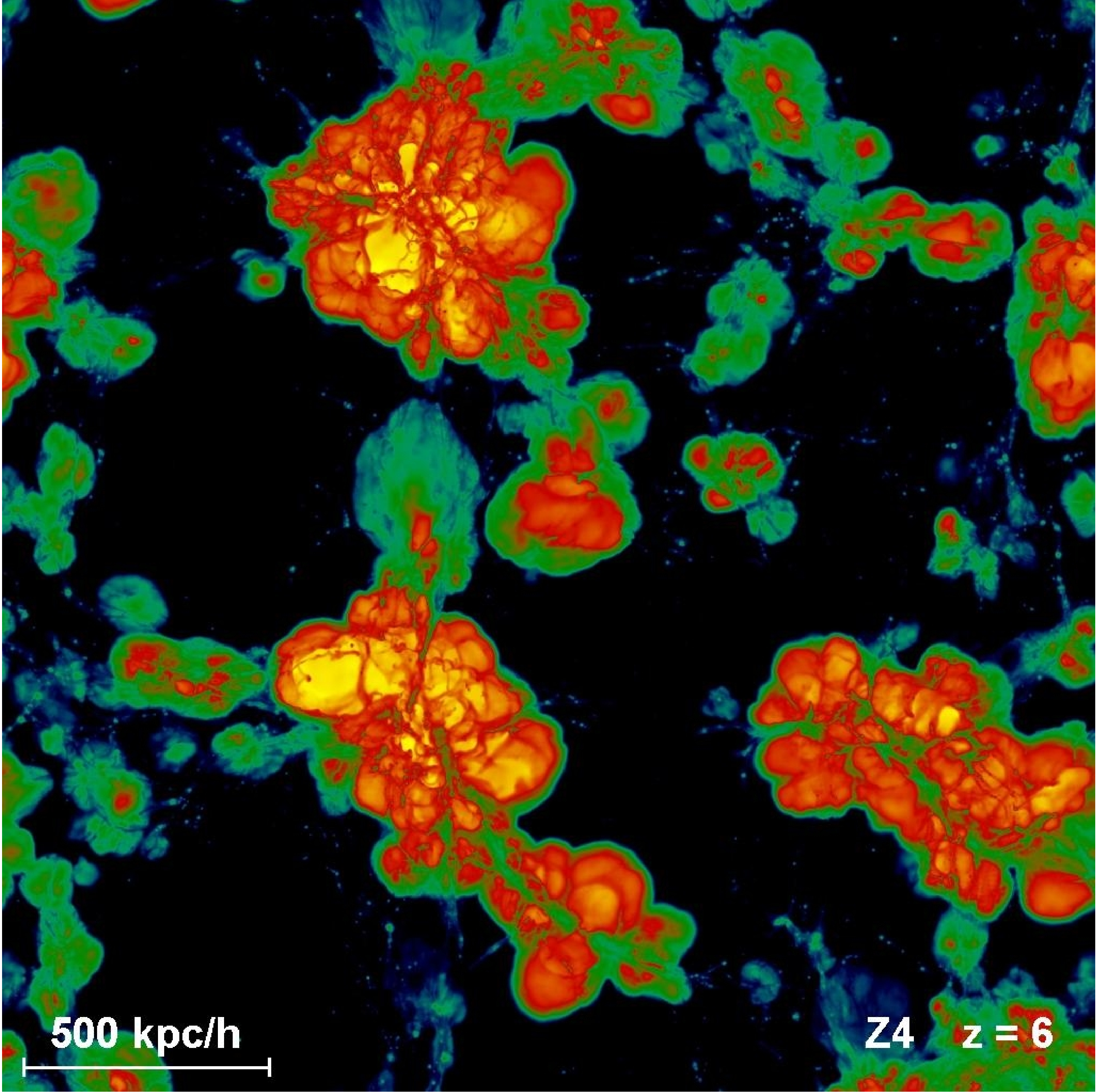


Springel & Hernquist 2003

Interaction of inhomogeneous inflows with galactic winds

In- and outflow coexist over large volumes

Interfaces will be important for mixing, cooling and radiation



Springel & Hernquist 2003

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In- and outflow coexist over large volumes

Interfaces will be important for mixing, cooling and radiation

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
- **Radiation** from central AGN and star-forming regions ionises and exerts pressure on infalling/outflowing gas and *dust*
- **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 it cools without coming to hydrostatic equilibrium
- Cooling radiation usually 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 yet included in current models or simulations

Critical points for further work

- Proper treatment of radiation from accretion shocks
- Proper treatment of interaction between in- and outflows
  -- interface/mixing layers, entrainment
  -- chemical/dust mixing
  -- conduction
- Verification that large-scale effects are independent of numerical resolution and "subgrid" model
- Inclusion of dust/cosmic ray/B-field effects
- Does significant gas cool from the hot phase now? ever?

It is unclear (to me) that current simulations are even approximately correct in their treatment of the physics. Their observational predictions may thus be qualitatively as well as quantitatively incorrect.