Virial shocks in galaxy and cluster halos

Yuval Birnboim

Harvard-Smithsonian Center for Astrophysics

Gas & Galaxies: Common wisdom

Hubble expansion

Gravitational instability

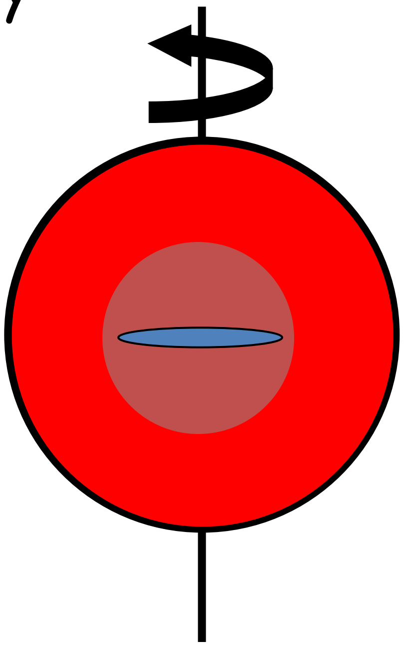
Shock heating

Cooling

Angular momentum

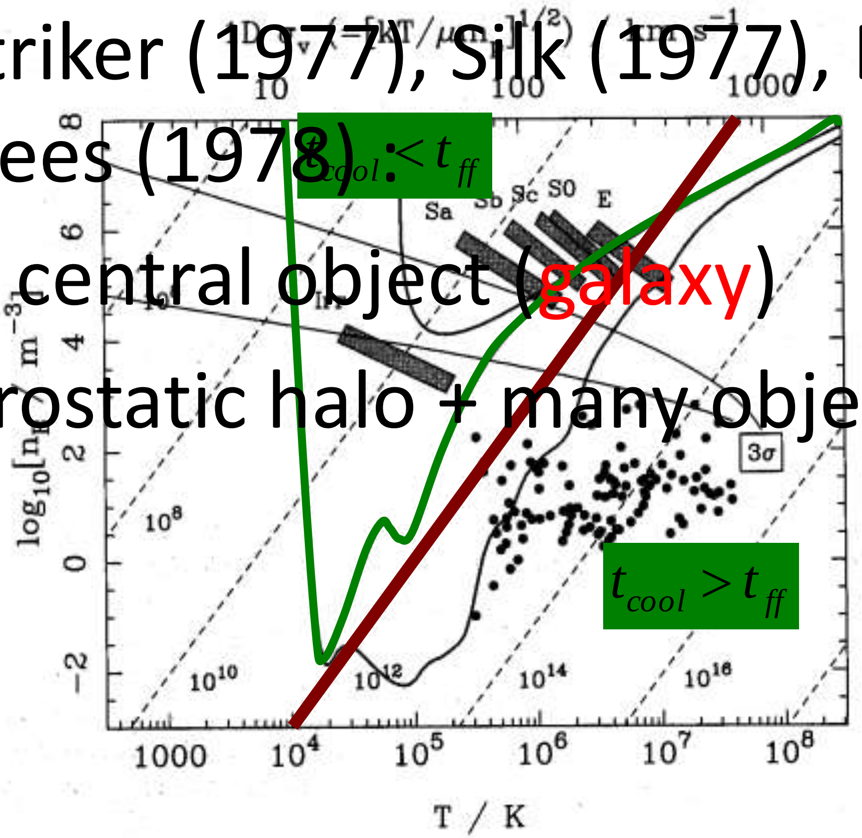
Accretion to galactic spiral disk

Stars, SN, feedback



Galaxy/Cluster segregation

Rees & Ostriker (1977), Silk (1977), Binney(1977), White & Rees (1978) :

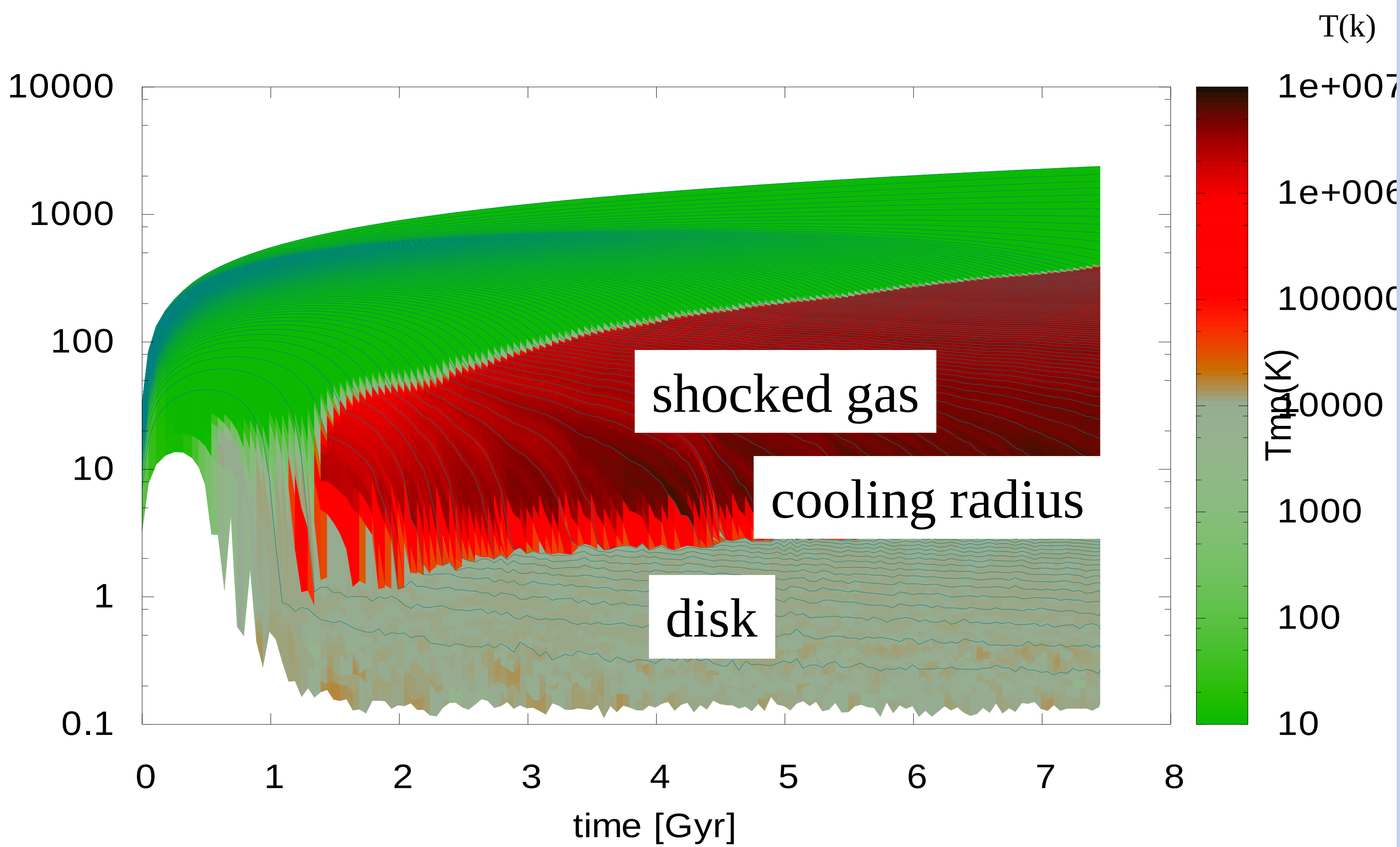


$t_{cool}<t_{ff}$ – one central object (galaxy)

$t_{cool}>t_{ff}$ – hydrostatic halo + many objects (cluster)

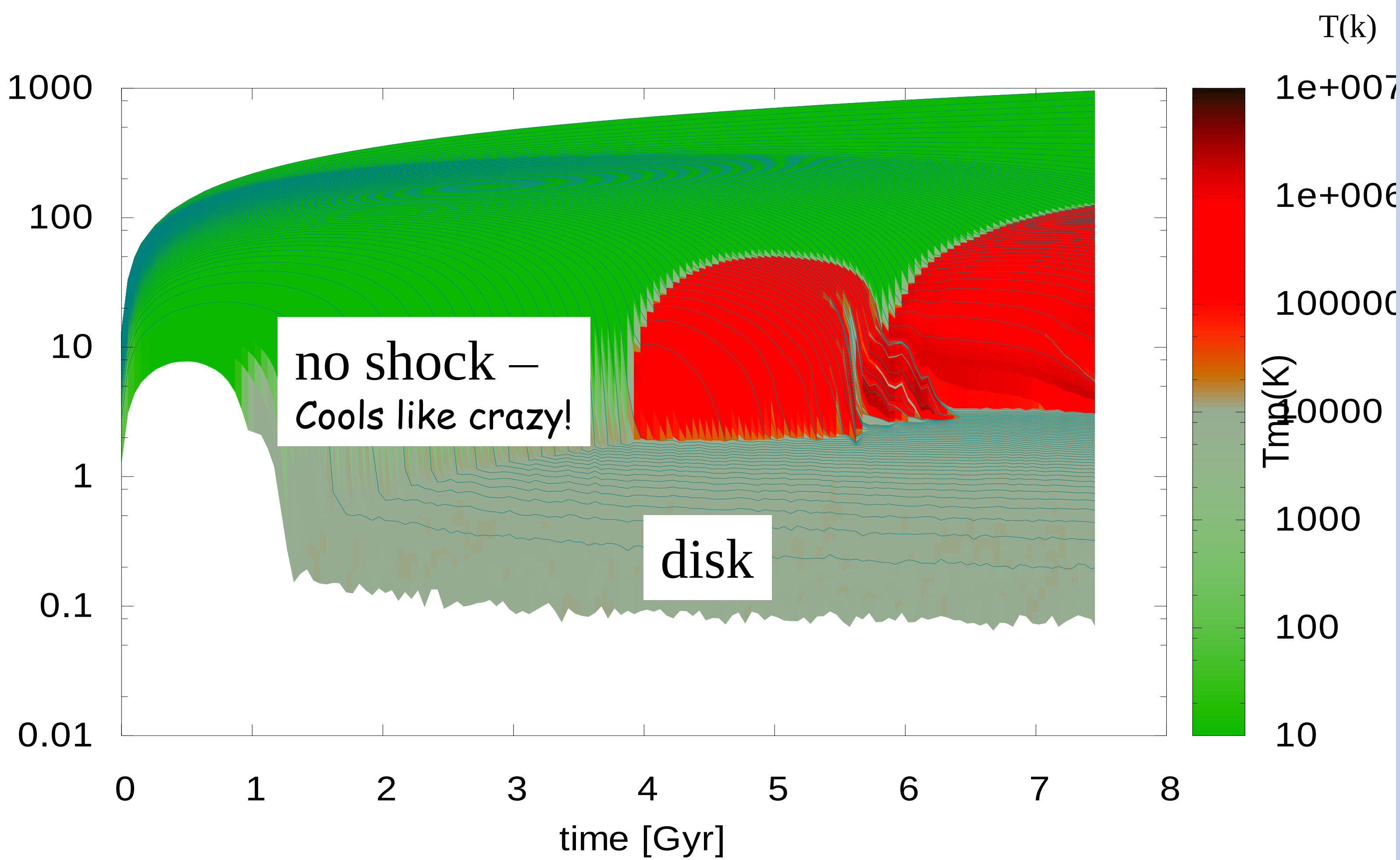
Blumenthal, Faber, Primack & Rees 86

Evolution of radii of gas shells - big halo



Birnboim & Dekel 2003

Same stuff for a smaller halo



When can gas be hydrostatic?

(the adiabatic case)

- Ideal gas: $P(\rho, e) = (\gamma - 1)\rho e$

$$\gamma = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s \quad \left(\gamma = \frac{5}{3} \quad \text{for monoatomic gas}\right)$$

- Gas in the halo

Isentropic: $P \propto \rho^{\gamma}$

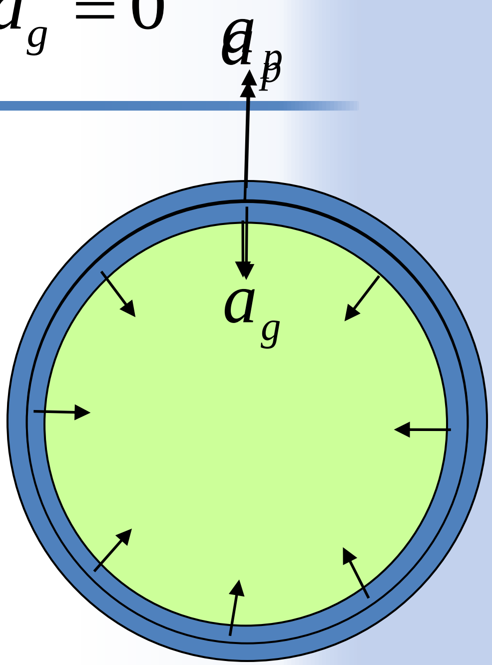
Power law profile: $\rho \propto r^{\alpha}$

Homologeous collapse $M \propto \rho r^3$

(for every fixed M)

- Start with hydrostatic equilibrium: $\ddot{r} = a_p + a_g = 0$

$$a_p = -\frac{1}{\rho}\nabla P \propto \frac{1}{\rho}\frac{P}{r} \propto \frac{1}{\rho}\frac{\rho^{\gamma}}{r} \propto \rho^{\gamma-2/3}$$



- The gravitational acceleration is:

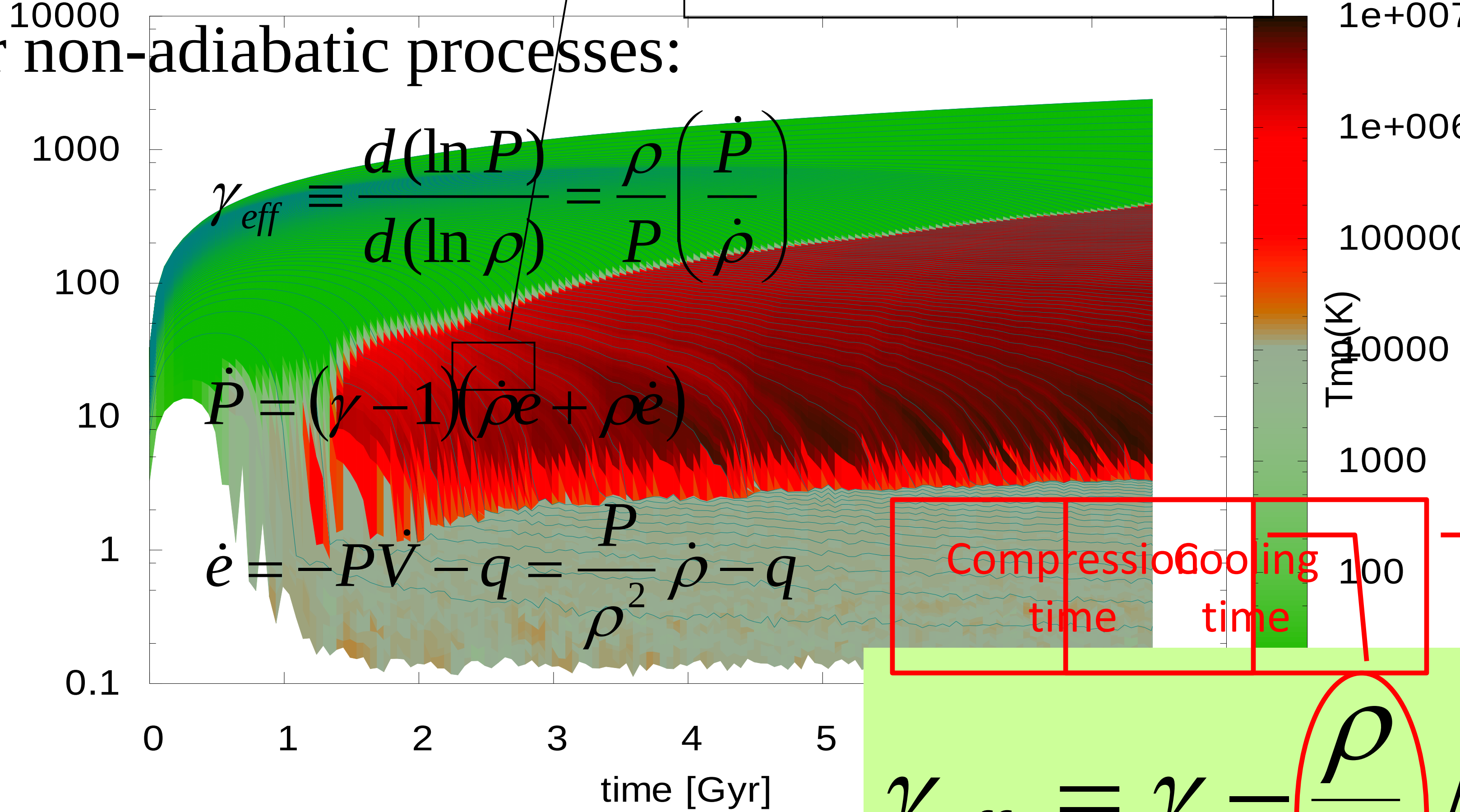
$$a_g \propto \frac{M}{r^2} \propto \frac{\rho r^3}{r^2} \propto \rho^{2/3}$$

$$\frac{a_p}{a_g} \propto \rho^{\gamma-4/3} \quad \Longrightarrow \quad \gamma_{crit} = 4/3$$

Stable: small perturbation inwards increases the ratio of pressure to gravity the ideal EOS: $P = (\gamma - 1)\rho e$

Let's check the stability behind the shock

for non-adiabatic processes:



$$\gamma_{eff} \equiv \frac{d(\ln P)}{d(\ln \rho)} = \frac{\rho}{P}\left(\frac{\dot{P}}{\dot{\rho}}\right)$$

$$\dot{P} = (\gamma - 1)(\dot{\rho}e + \rho\dot{e})$$

$$\dot{e} = -P\dot{V} - q = \frac{P}{\rho^2}\dot{\rho} - q$$

Compression time

Cooling time

$$\gamma_{eff} = \gamma - \frac{\rho}{\dot{\rho}} \Big/ \frac{e}{q}$$

Perturbation analysis of the force equation

$$\ddot{r} = -\frac{1}{\rho}\nabla P - \frac{GM}{r^2} = -4\pi r^2 P' - \frac{GM}{r^2} = 0$$ (sub-sonic)

$$\delta r = u\delta t = \frac{u_1}{r_s} r\delta t$$ (homology)

$$r \Rightarrow r + \delta r \quad ; \quad P \Rightarrow P + \delta P$$

… and after some algebra:

$$\delta\ddot{r} = \underbrace{\frac{12\pi r^2 u_1 \delta t P'}{r_s}}_{>0} \left[\gamma - \frac{2}{\gamma_{eff}} (\gamma - \gamma_{eff}) - \frac{4}{3} \right]$$

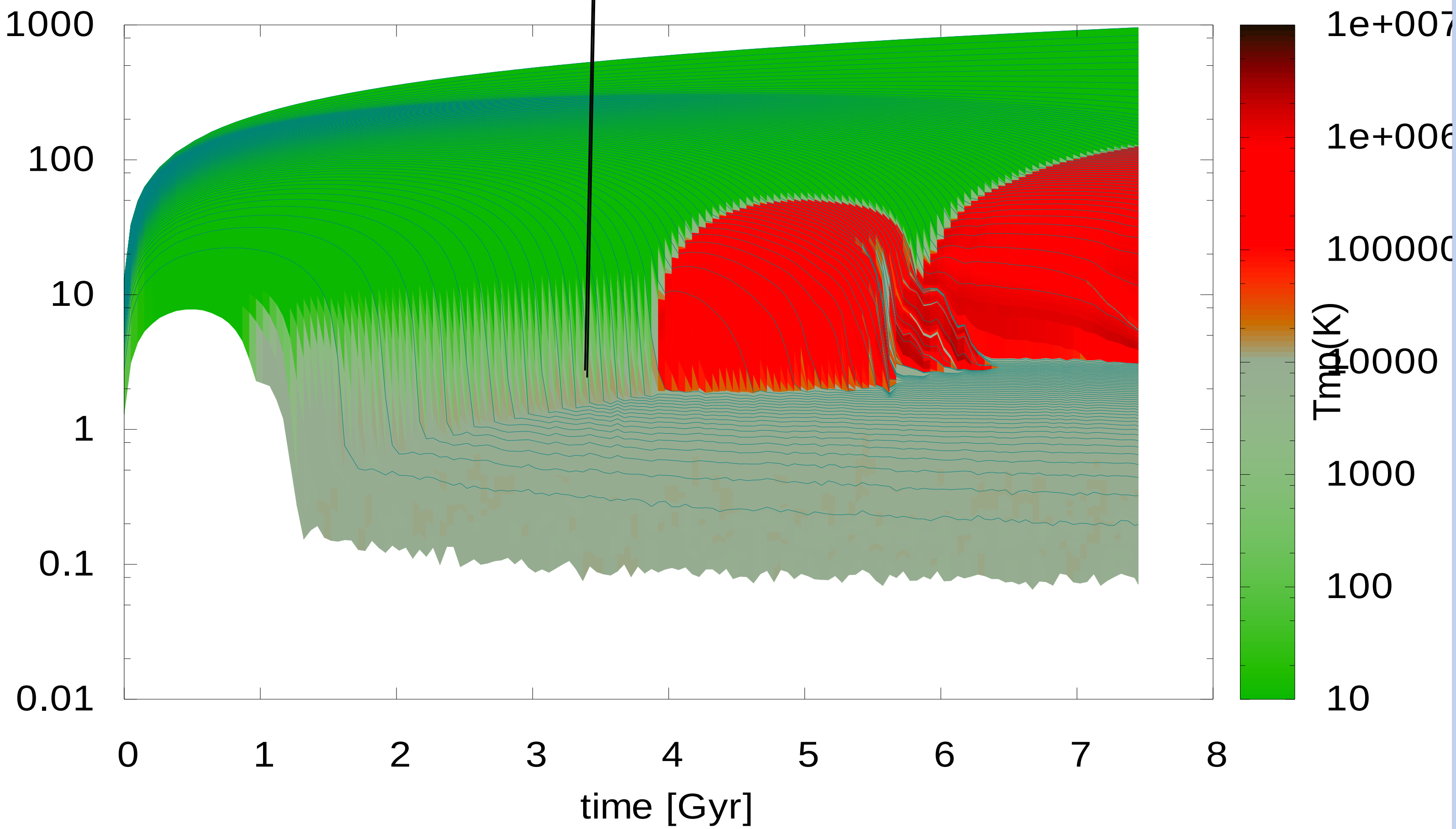
So,

$$\gamma_{crit} = \frac{2\gamma}{\gamma + 2/3} \quad = 1.43 \quad \text{for } \gamma = 5/3 \text{ gas}$$

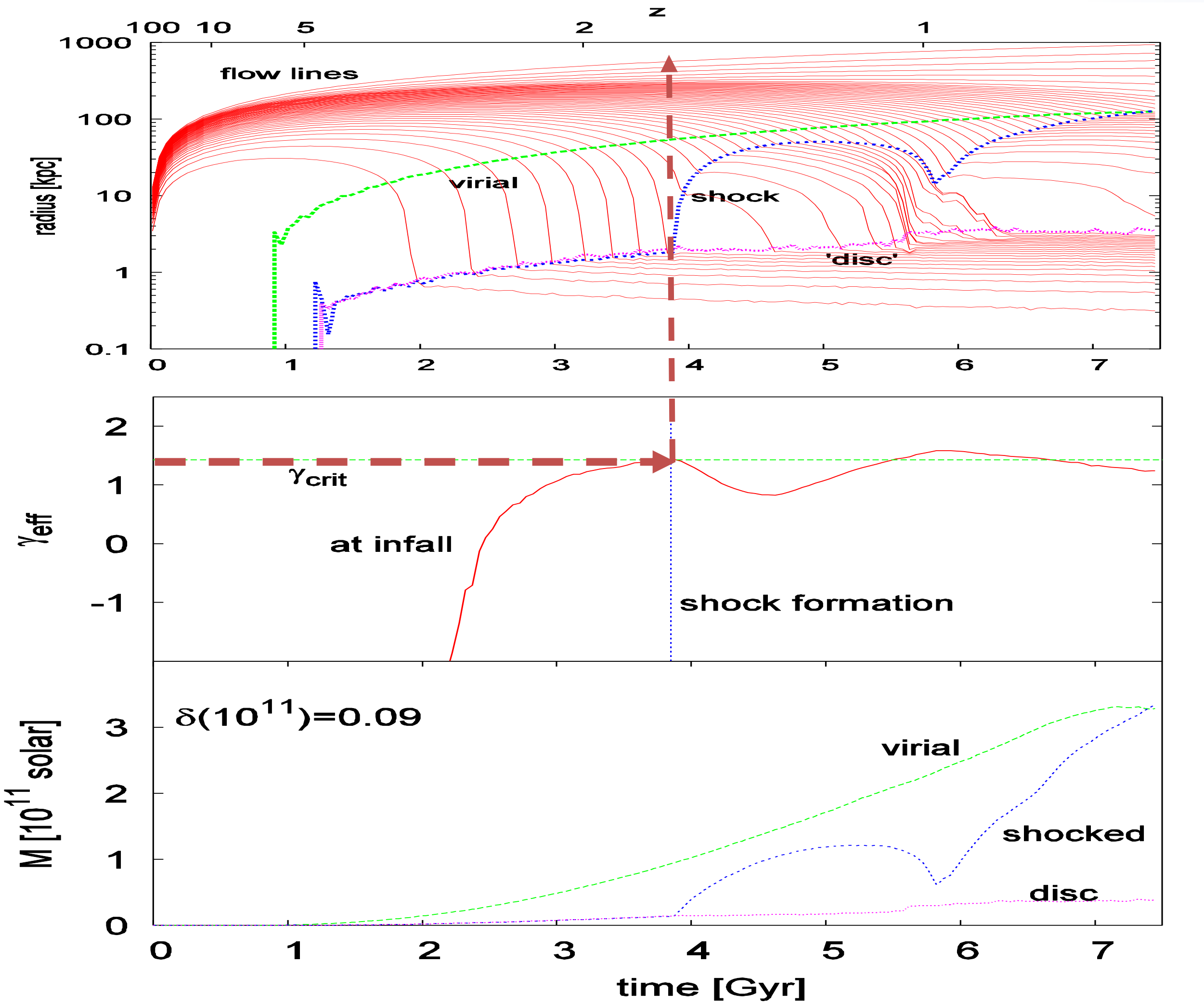
$\gamma_{eff} < \gamma_{crit}$ unstable

$\gamma_{eff} > \gamma_{crit}$ stable

Assume hypothetic shock there and find out.

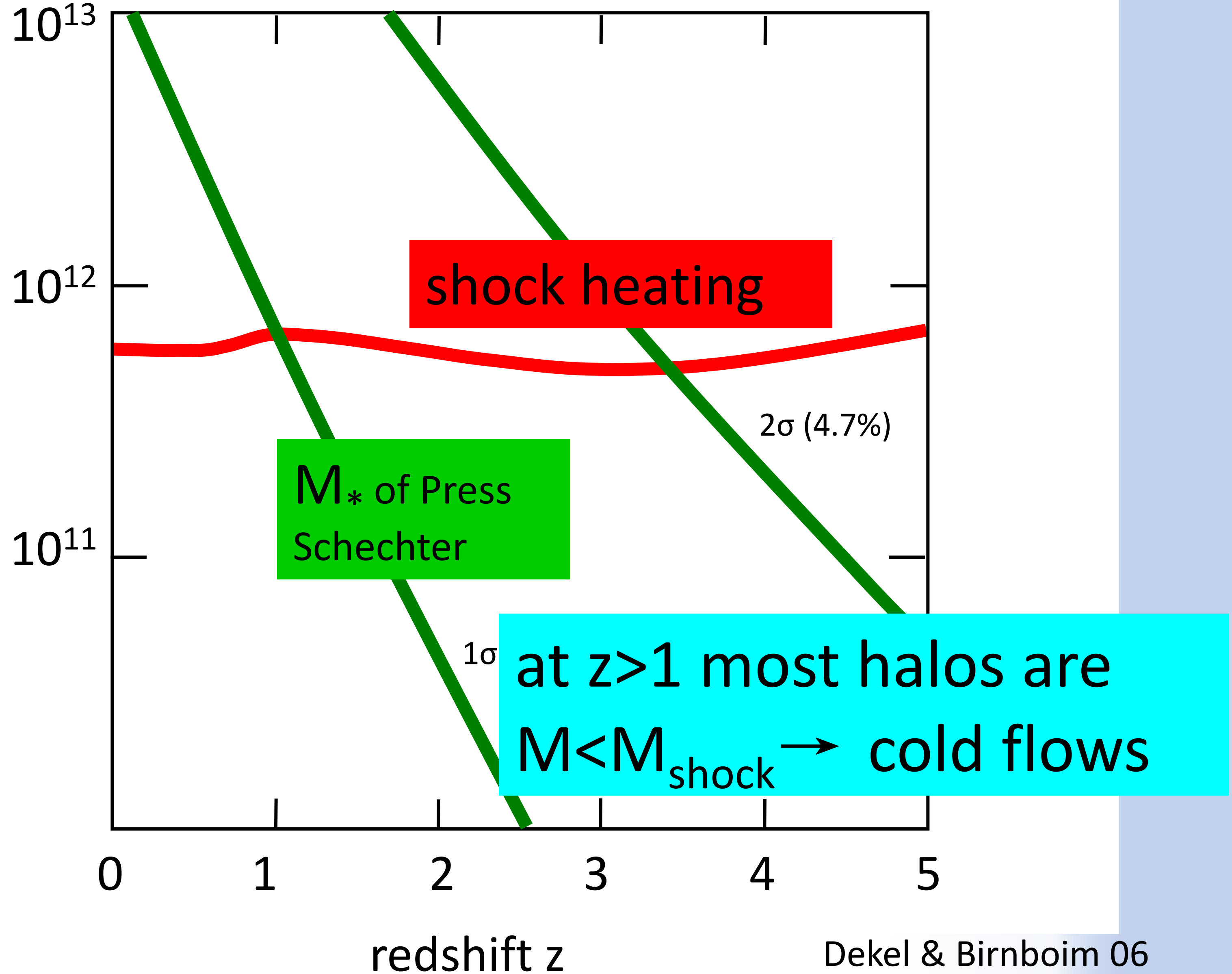


Simulation confirms analytic model: shock when $\gamma_{eff} > \gamma_{crit}$=1.43



No free parameters, no fudge factors

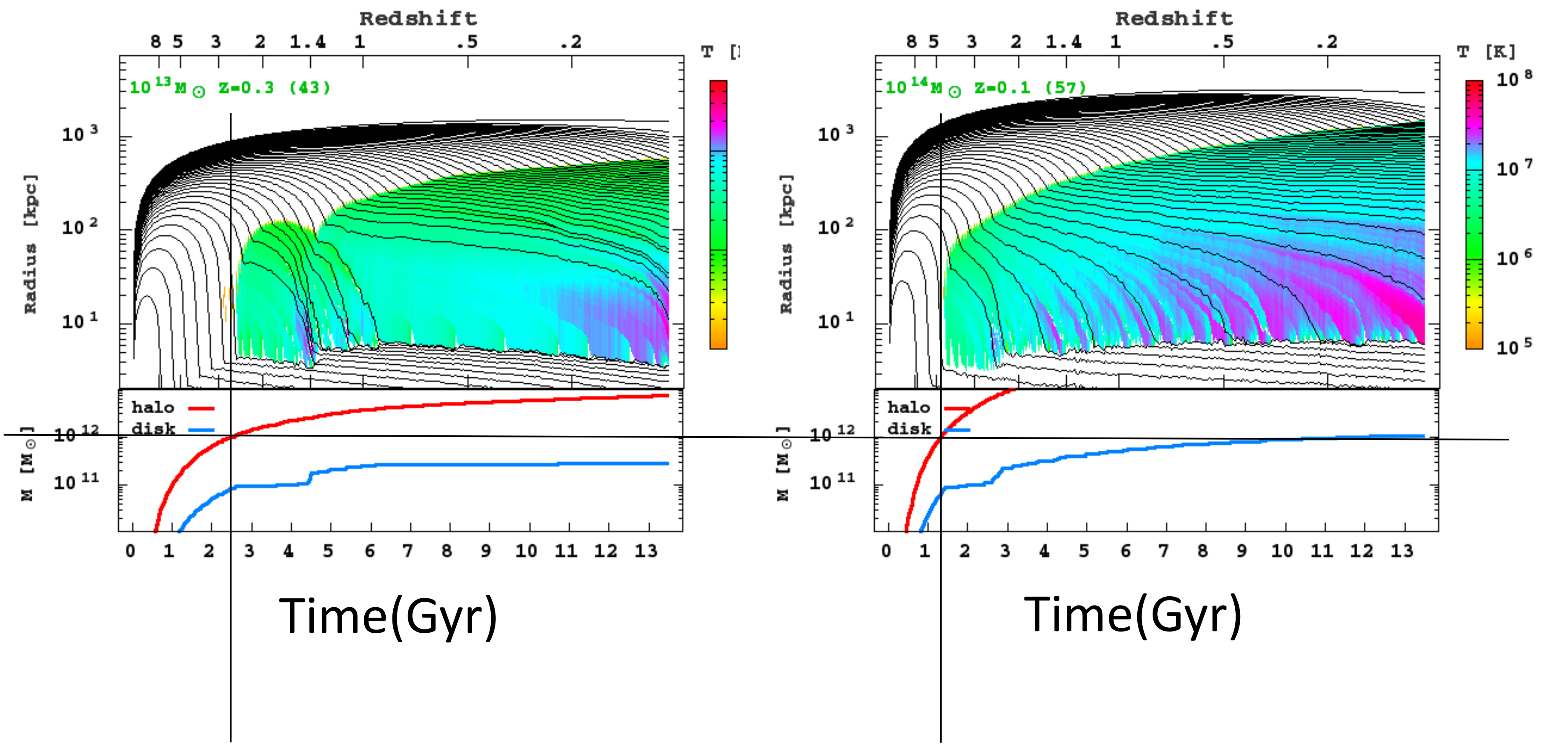
Cold Flows in Halos



Assuming:
- Overdensity evolution
- Metalicity evolution

Dekel & Birnboim 06

Shock always forms at same mass



Applications - Cold flows and:

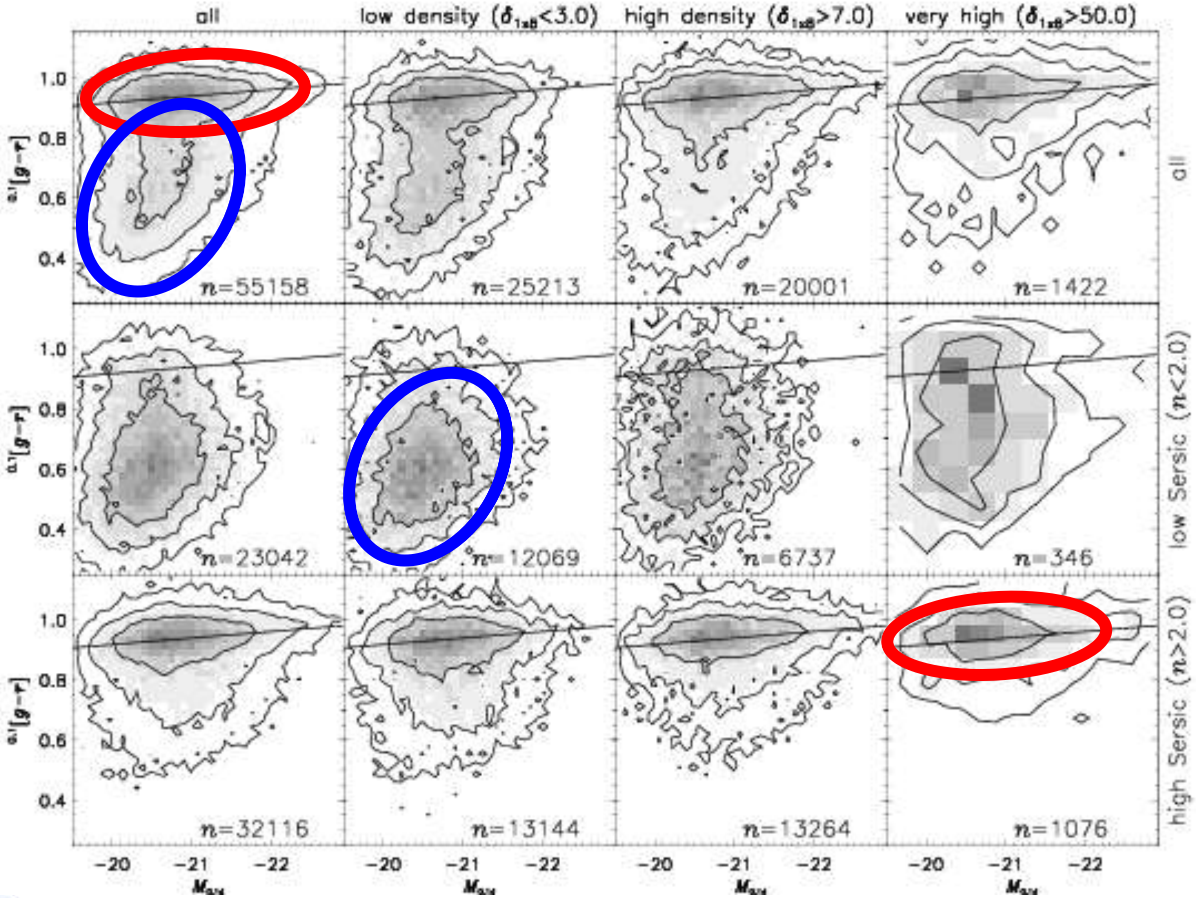
1. The galaxy bi-modality
2. High-z star forming galaxies
3. Groups and clusters

Applications - Cold flows and:

1. The galaxy bi-modality
2. High-z star forming galaxies
3. Groups and clusters

Color-Magnitude bimodality & B/D depend on environment ~ halo mass

environment density: low high very high



disks

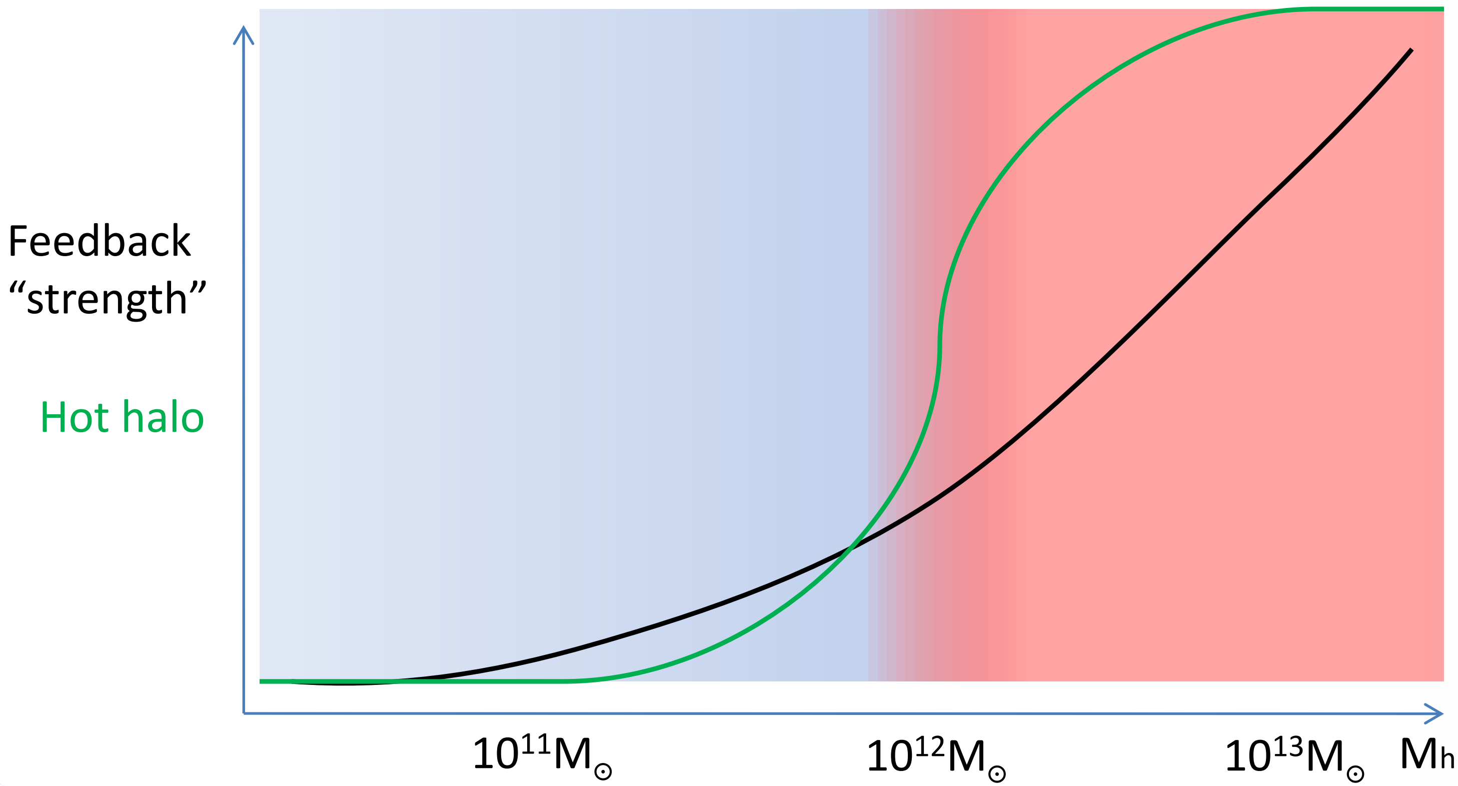
spheroids

$M_{halo}<6x10^{11}$
"field"

$M_{halo}>6x10^{11}$
"cluster"

SDSS: Hogg et al. 03

Halo gas and AGN feedback



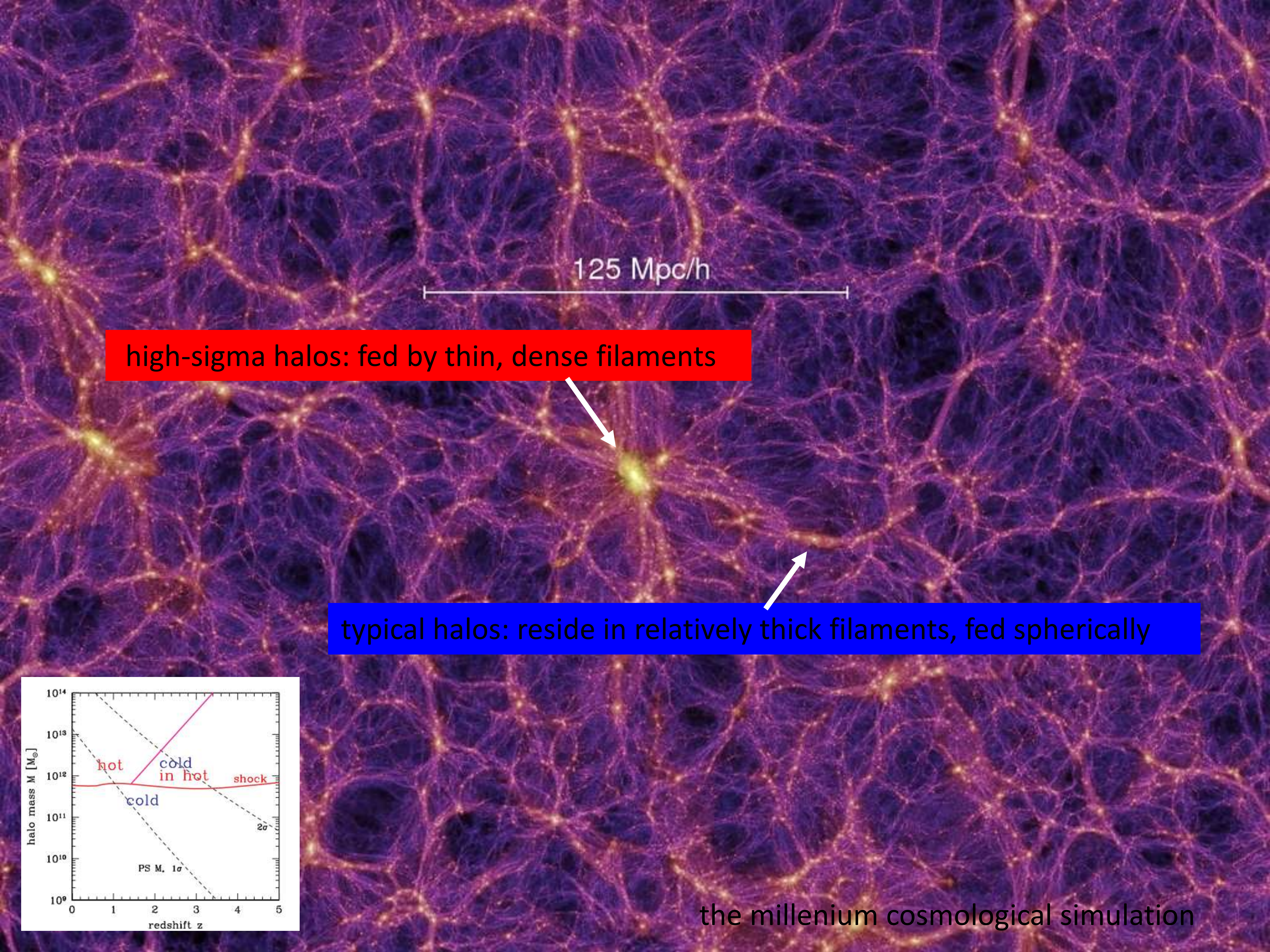
Hot halos and Bi-modality

- Green valley - a sharp cutoff in gas accretion to galaxies
- Feedback processes are “too smooth”
- Formation of hot halos makes feedback effective

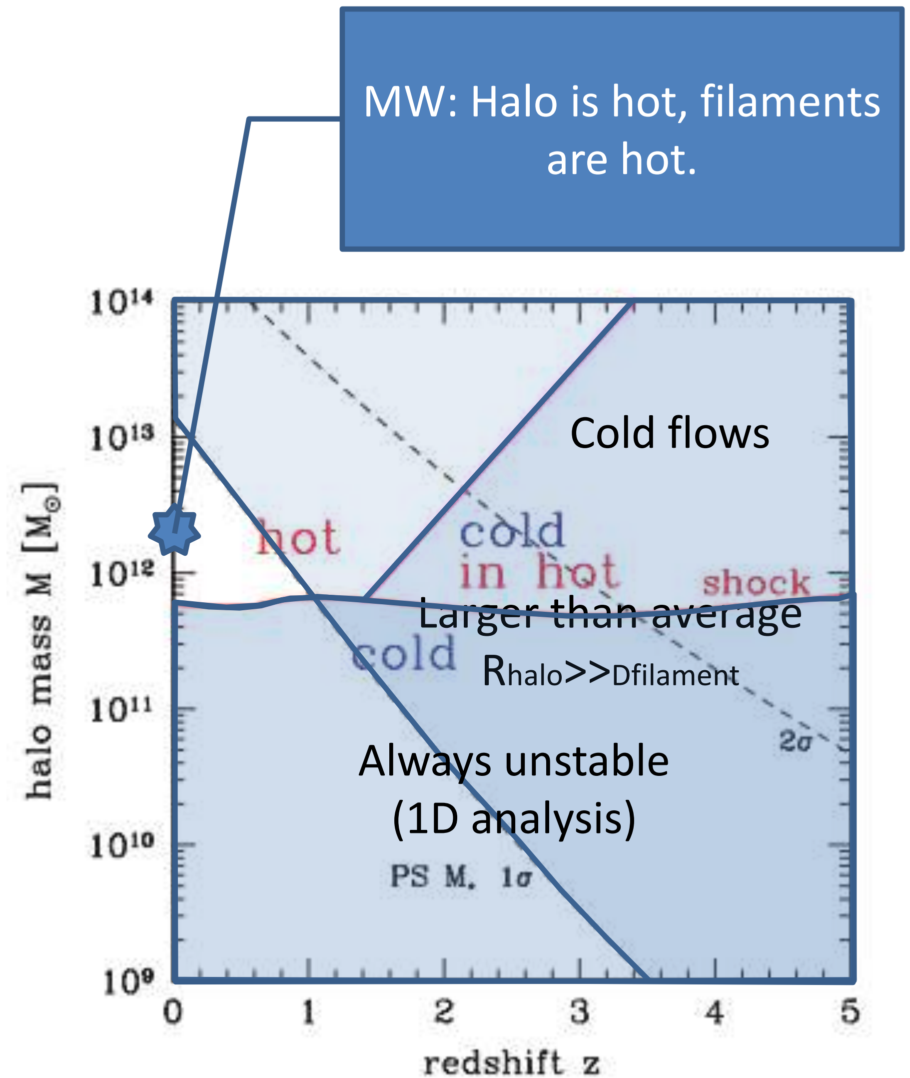
Applications

1. The galaxy bi-modality
2. High-z star forming galaxies
3. Groups and clusters

Deviations from the spherical cow approximation

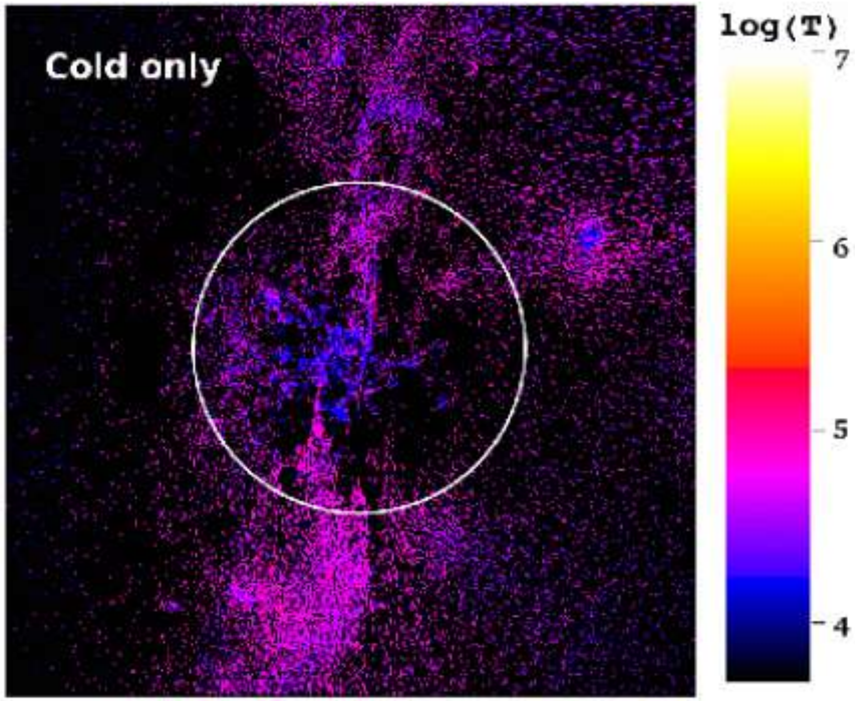

125 Mpc/h
high-sigma halos: fed by thin, dense filaments
typical halos: reside in relatively thick filaments, fed spherically
halo mass M [M$_\odot$]
redshift z
hot
cold
cold
in hot
shock
2σ
PS M, 1σ
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
0
1
2
3
4
5
the millenium cosmological simulation

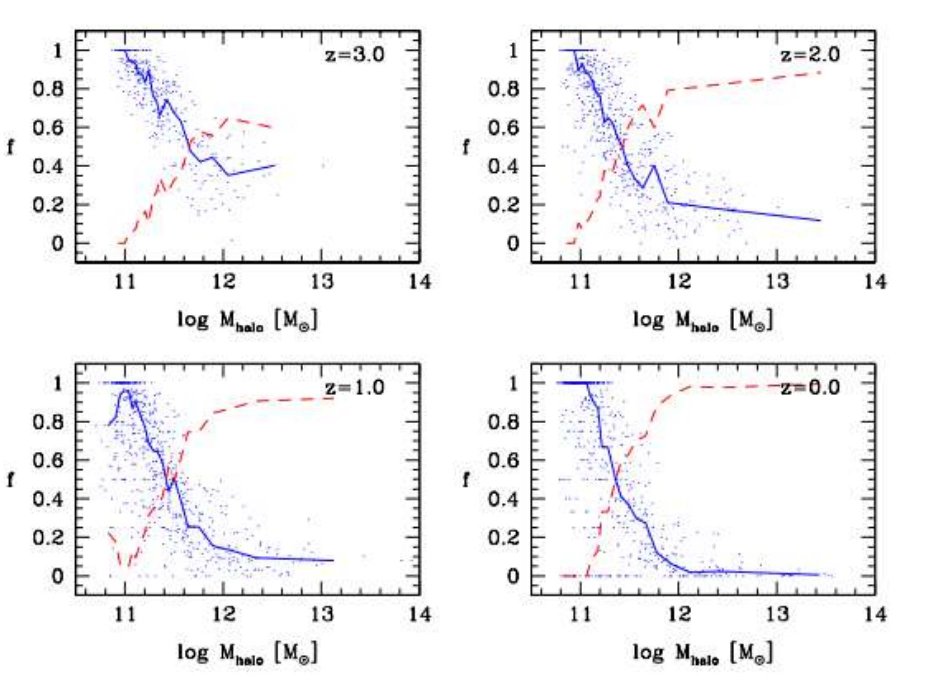
Cosmological Context



Dekel & Birnboim 2006

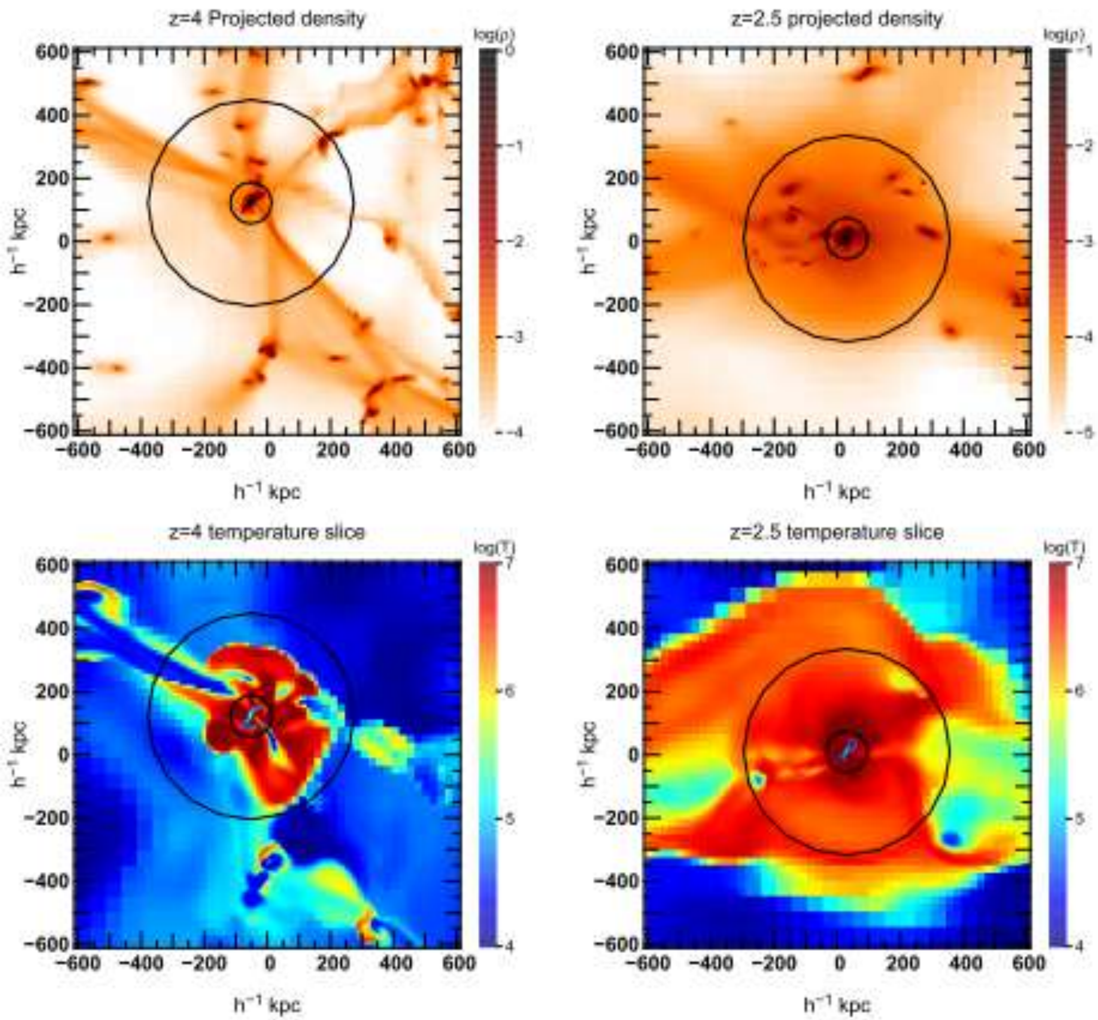
3D SPH hydro-simulations

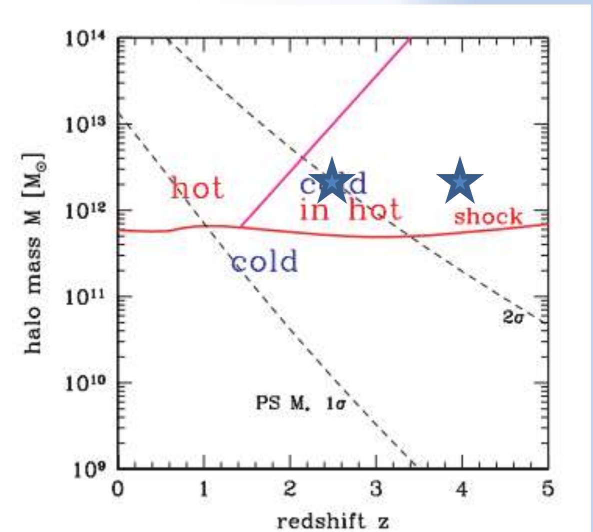


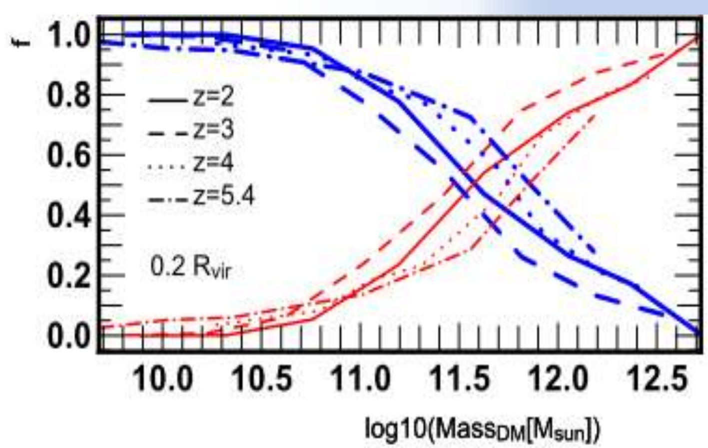


Kereš et al. 2005
Kereš et al. 2009

3D Eulerian hydro-simulations





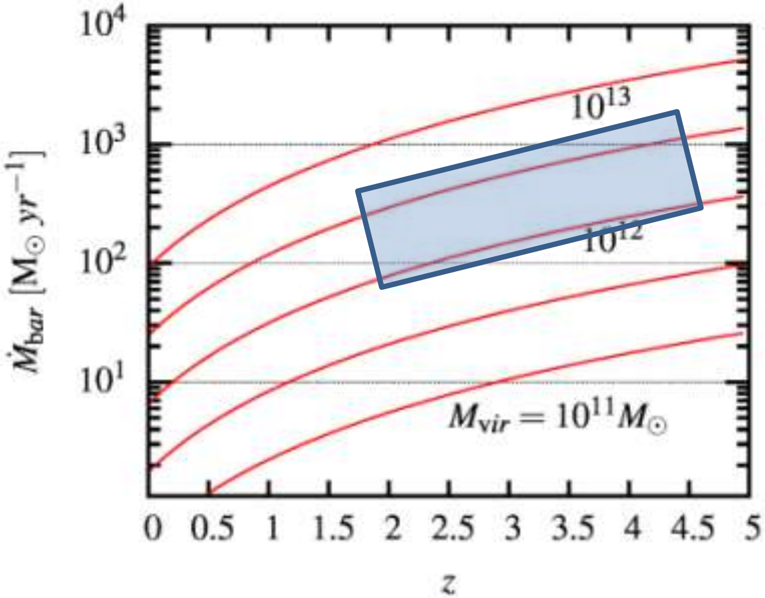


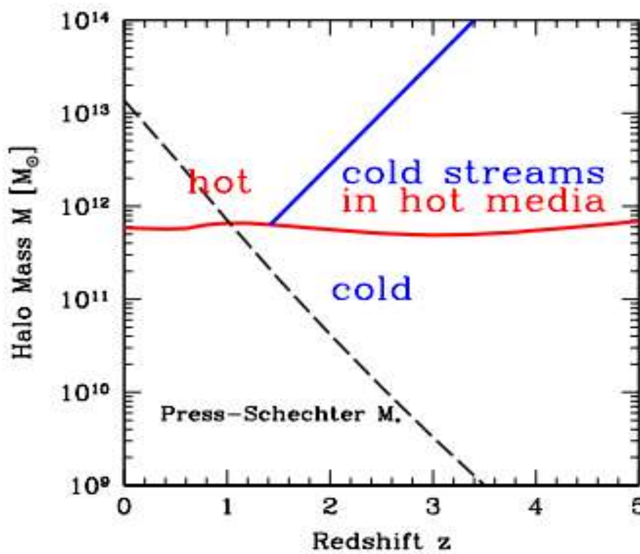
Ocvirk et al. 2008

2e12 halo, z=4

2e12 halo, z=2.5

Accretion at high-z

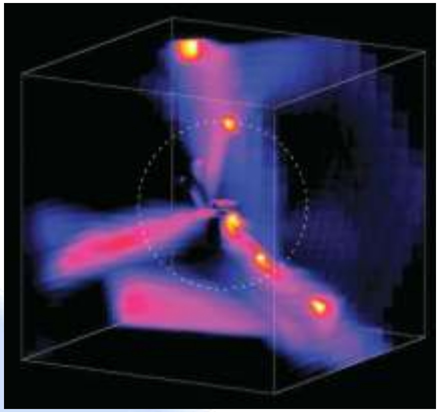




Dekel & Birnboim 2006
Keres et al. 05-09

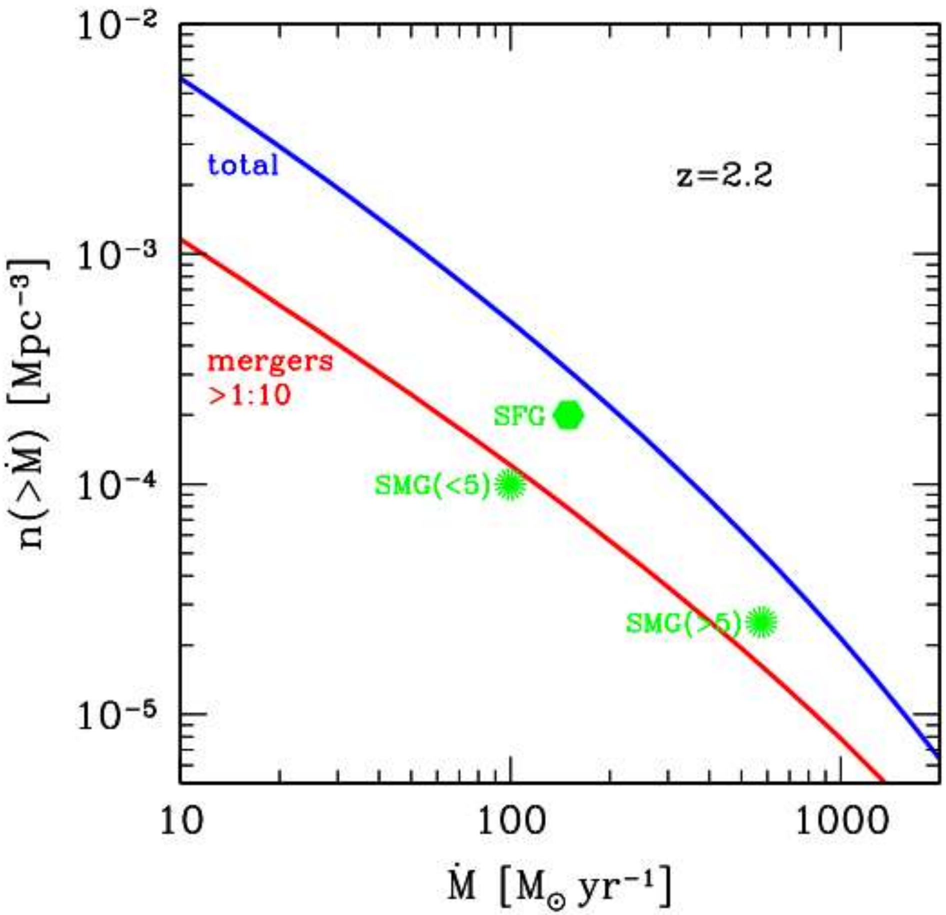
Wechsler et al 2002, Dekel et al. 2009, Fakhouri & Ma 2008

Agertz et al. 2009



Star forming galaxies

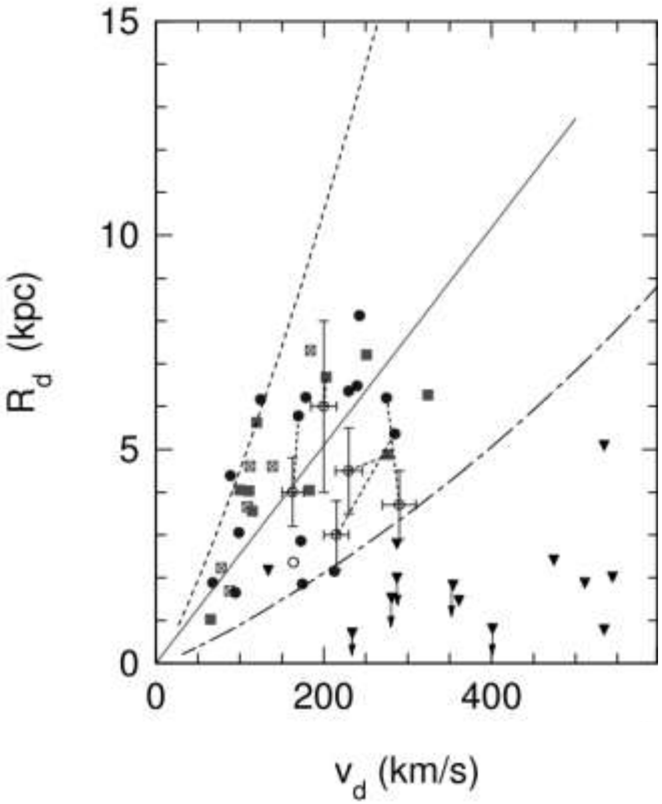
Cold accretion vs. Merger induced star bursts

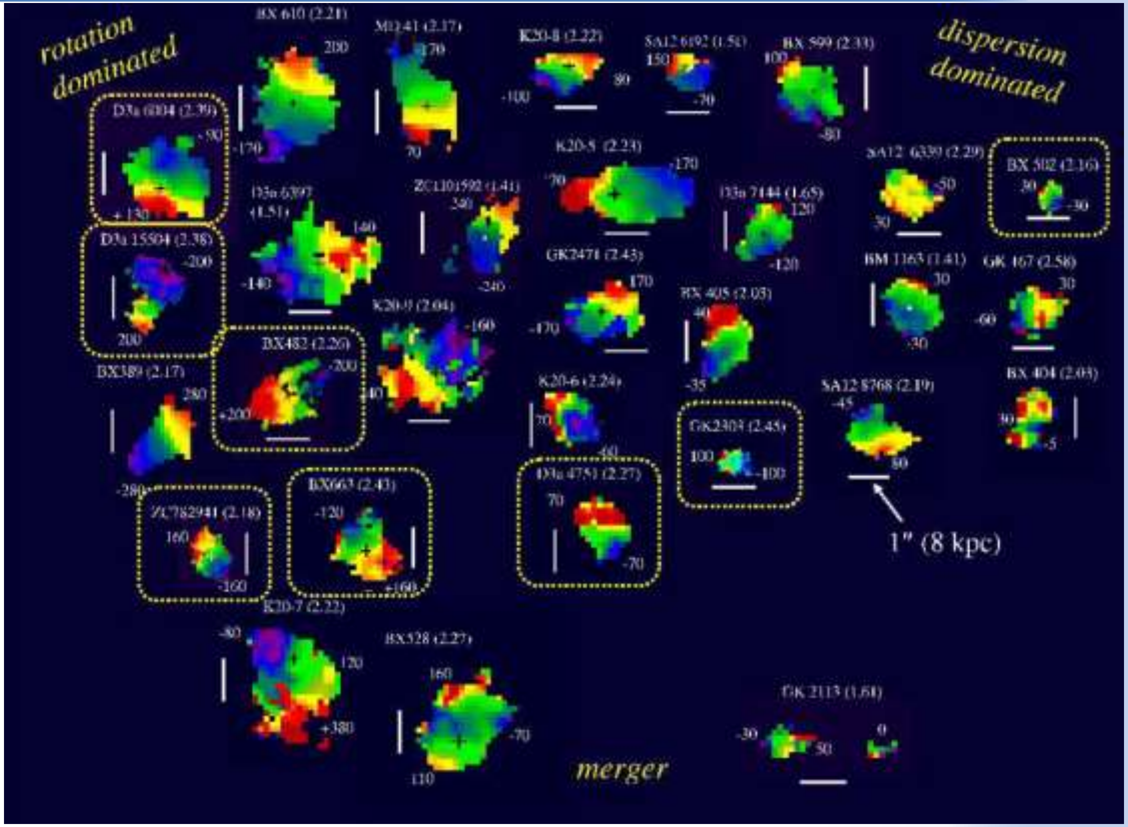


Cold accretion dominates the star formation history at all times

Dekel, Birnboim et al. 2009, Nature

z=2 disks
SINS Hα survey





Bouché et al. 2007

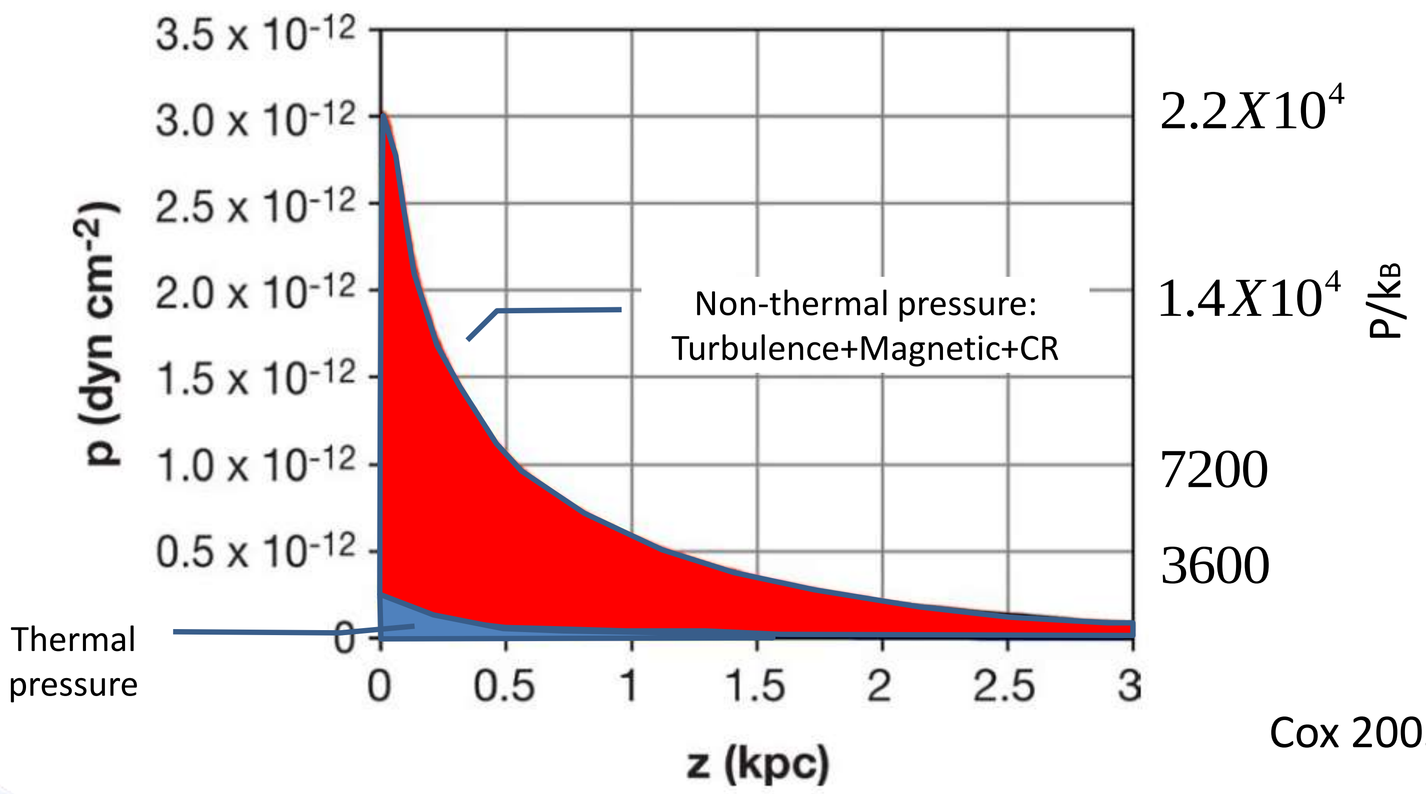
Förster Schreiber et al. 2006
Daddi et al. 2004

A short note on galaxy formation and magnetic fields…

Magnetic fields are important in high-z, high sfr galaxies: Need cosmologic MHD simulations

Vertical hydrostatic equilibrium

- Most of the pressure (9/10) comes from non-thermal components

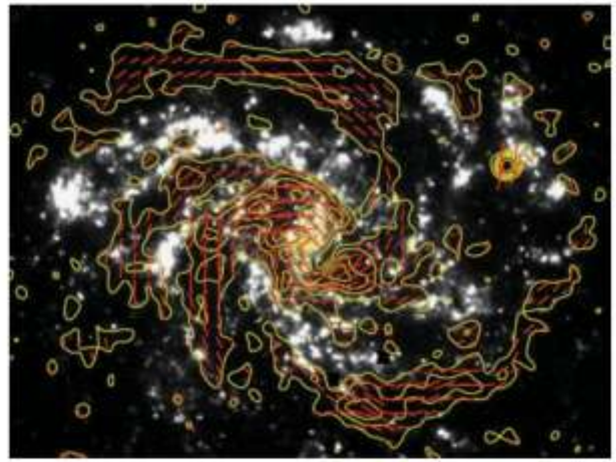


Cox 2005

Magnetic fields in nearby galaxies

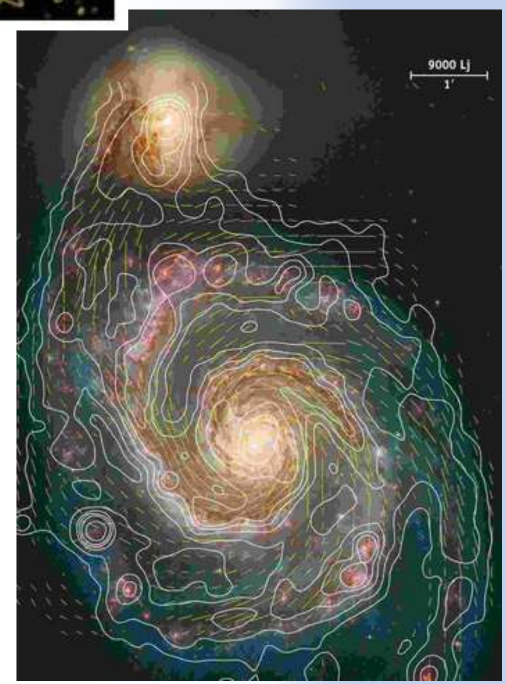
$$\text{"Starbursting"}:$$
$$B \approx 50\text{-}100\mu G$$

M82, 50μG
(Klein et al. 1988)



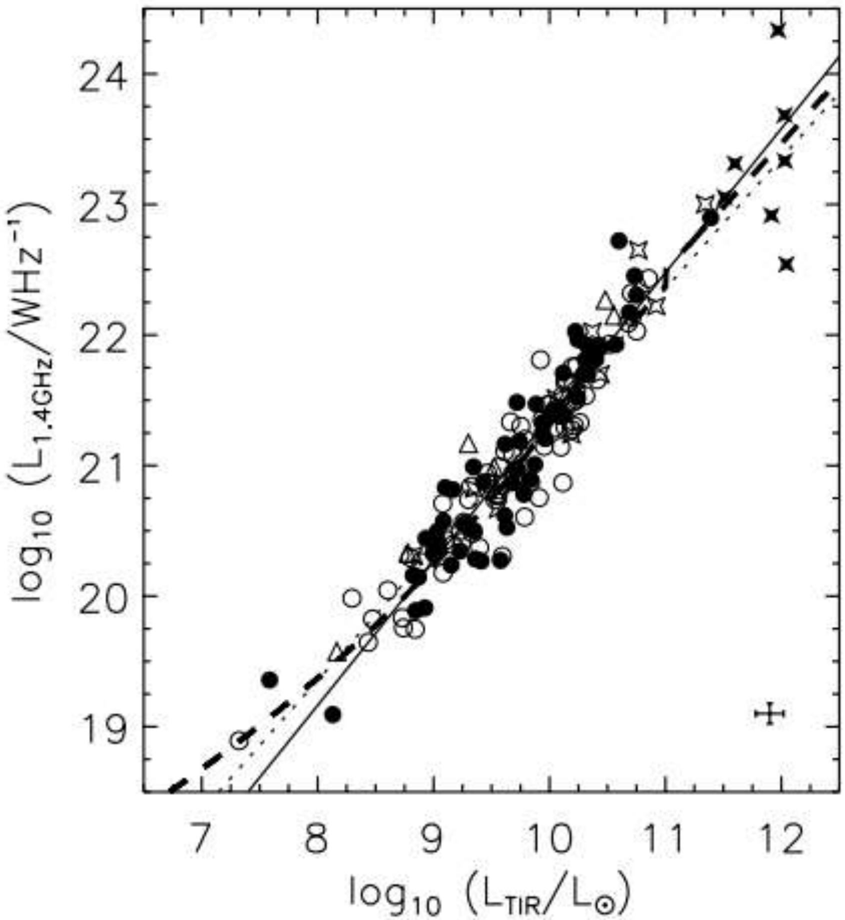
NGC 6946

$$\text{"Star forming"}:$$
$$B \approx 20\text{-}30\mu G$$



M51, HST,
MPIfR Bonn

SFR and magnetic fields



Bell 2003

$B^2 \propto SFR$ (Lisenfeld et al. 2003)

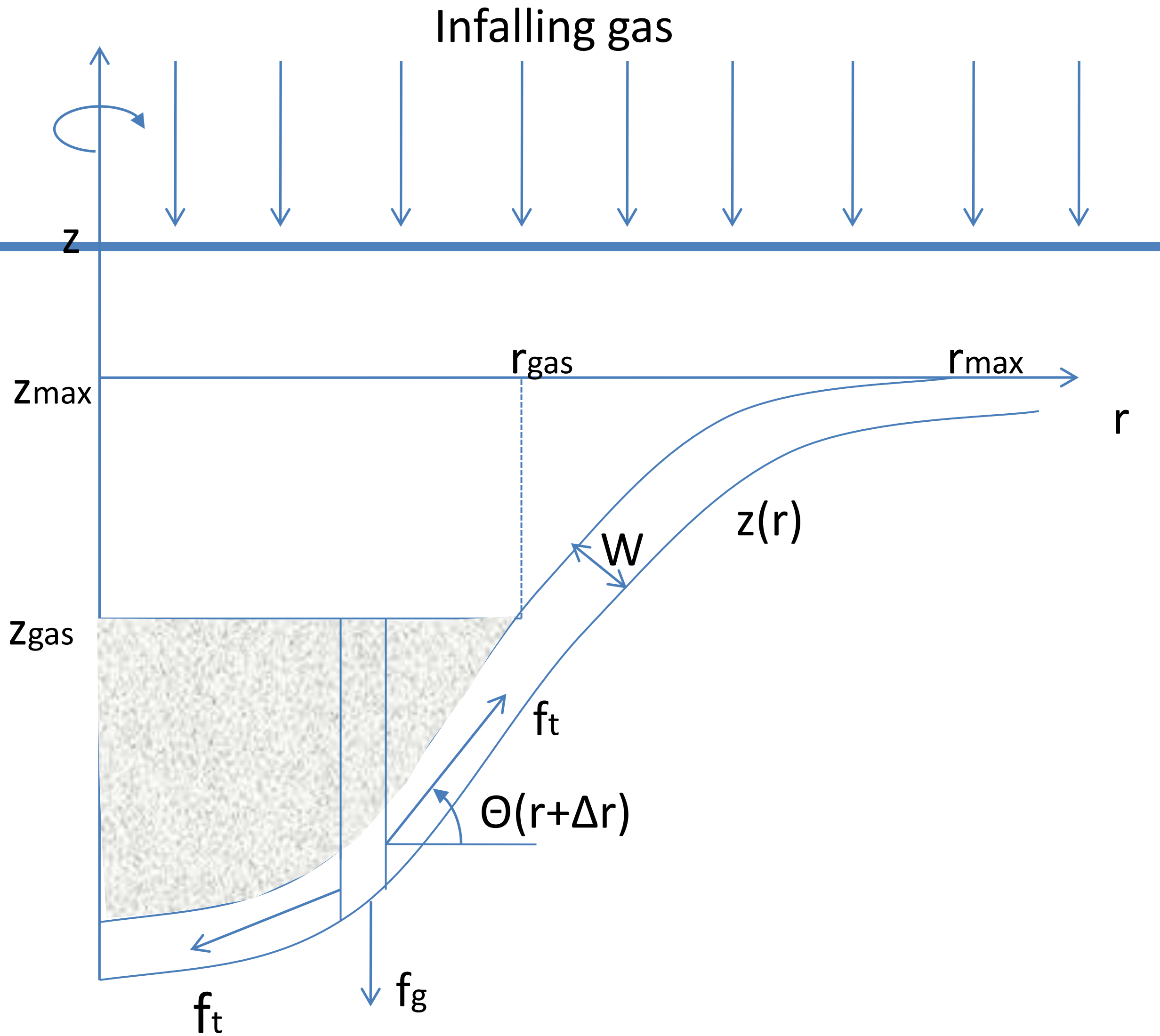
Magnetic fields of starburst galaxies

Ballpark value for magnetic fields of high-z SFG: ~100μG.

Object Name	z [a]	D [b] (Mpc)	$\log(\Sigma_g)$ [c] (g cm^{-2})	$\log(\dot{\Sigma}_\star)$ [d] ($M_\odot$ yr^{-1})	[illegible] (mJy)	[illegible]	[illegible]	[illegible]us (pc)	$B_{\rm min}$ [g] (mG)	$B_{\rm eq}$ [h] (mG)	Radio References
IC 883 (Arp 193)...........	0.0233	98.5	0.25	2.68	34.9	22.61	[illegible]	0.16	0.33	4.06	1
Mrk 273	0.0378	159.6	0.66	3.36	43.5	23.13	0.35	0.14	0.51	10.45	1
Arp 220 (west)................	0.0181	76.6	0.94	3.55	72.2	22.71	0.40	0.07	0.55	19.91	1
Arp 220 (east)................	0.0181	76.6	0.78	2.96	60.7	22.63	0.66	0.12	0.39	13.77	1

Thompson et al. 2006

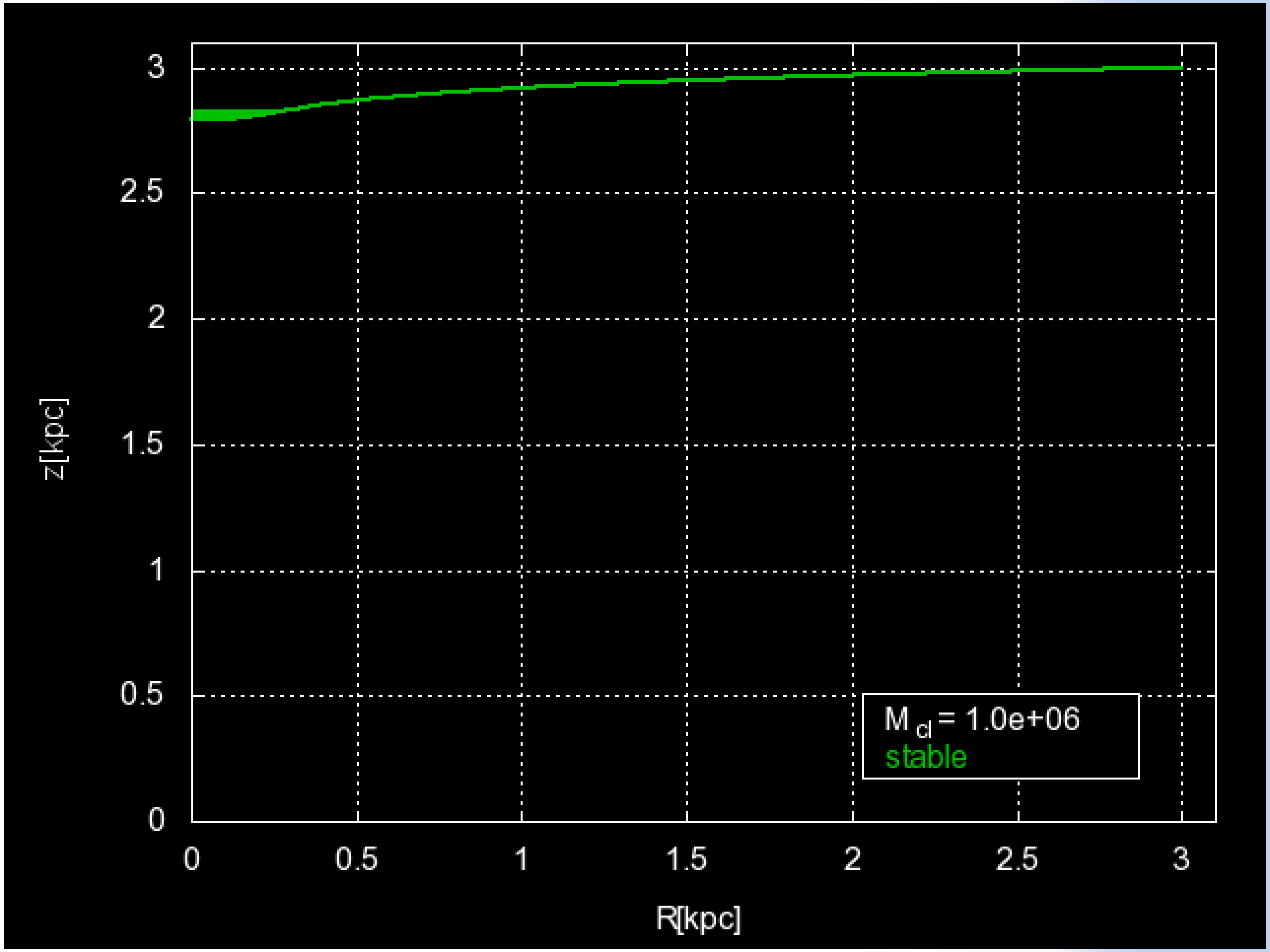
Elastic Magnetic Fields



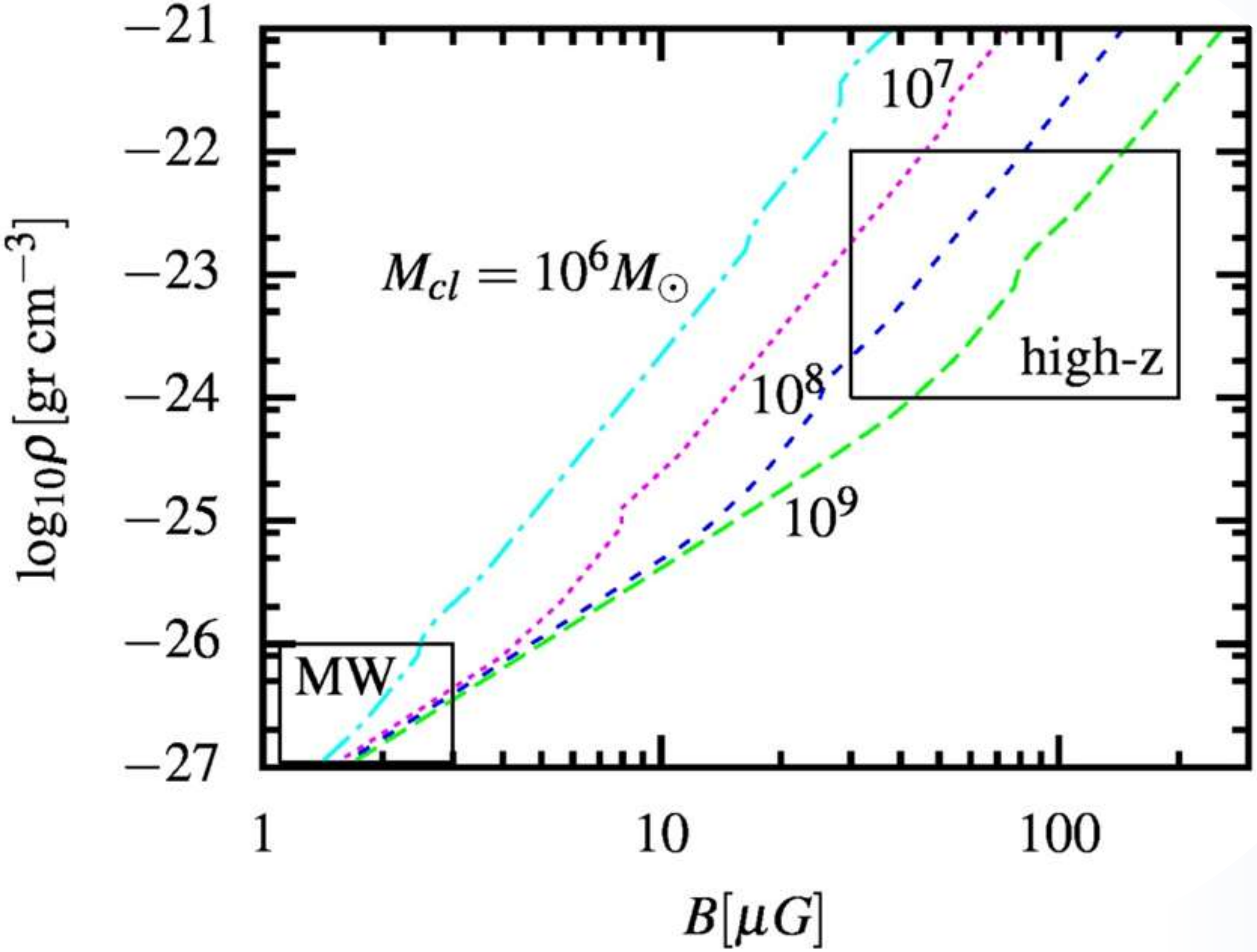
$$2\pi r(z_{\rm gas} - z(r))\rho_{\rm gas} g(z)\ dr = 2\pi(r+\Delta r)W\sigma \sin[\theta(r+\Delta r)] - 2\pi r W \sigma \sin[\theta(r)]$$

Accretion on magnetic fields

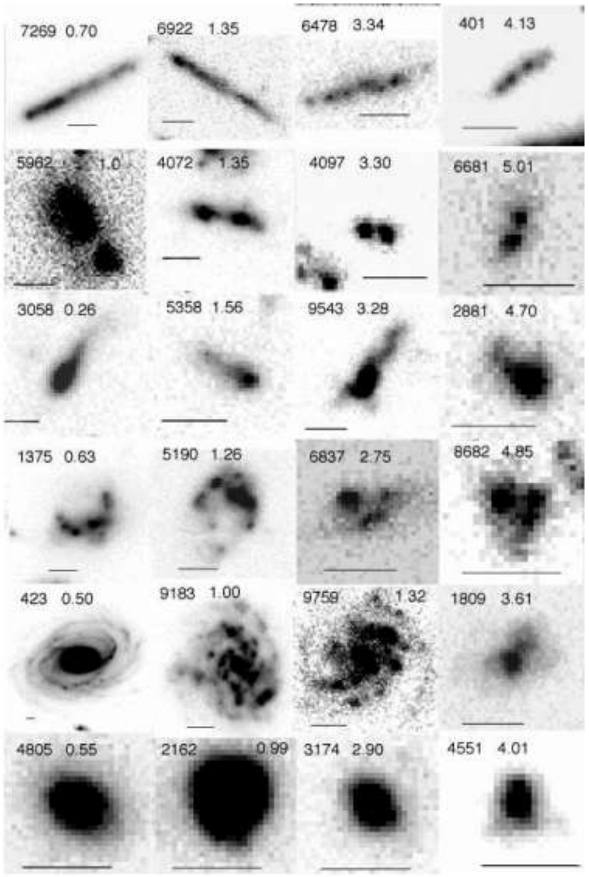
$$n_{H,gas} = 6\,[\mathrm{cm}^{-3}]$$
$$B = 50\mu G$$
$$g_{\mathrm{model}} = MW$$
$$l_W = 0.3$$



Puncture mass



Clump clusters



Clumps in clump clusters: $M=10^7$-$10^9 M_\odot$,
D=~1kpc (Elmegreen et al. 07,09, SINS)

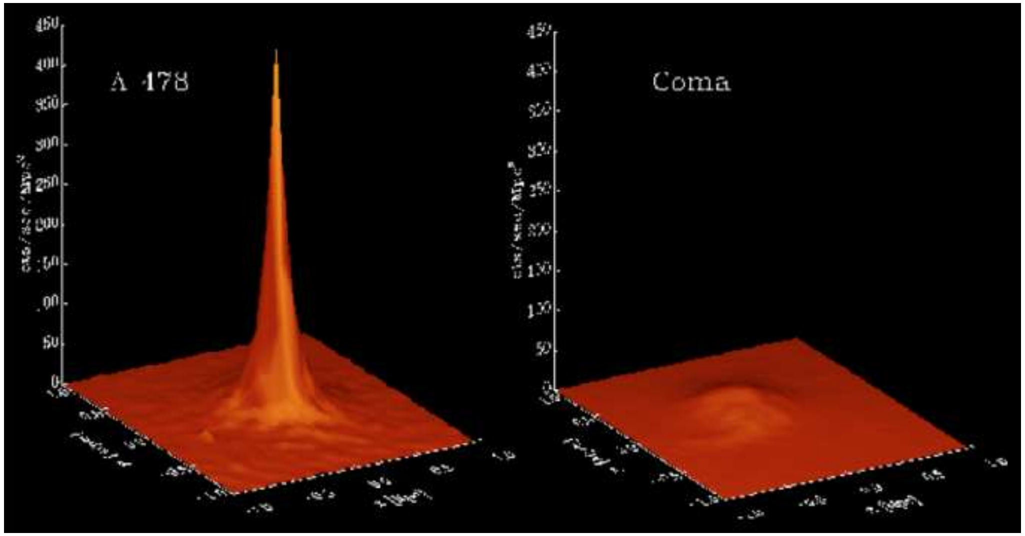
Elmegreen et al. 2007

Applications

1. The galaxy bi-modality
2. High-z star forming galaxies
3. Groups and clusters

Towards a solution of the overcooling problem of clusters (the "high-risk—high-gain" part of the talk)

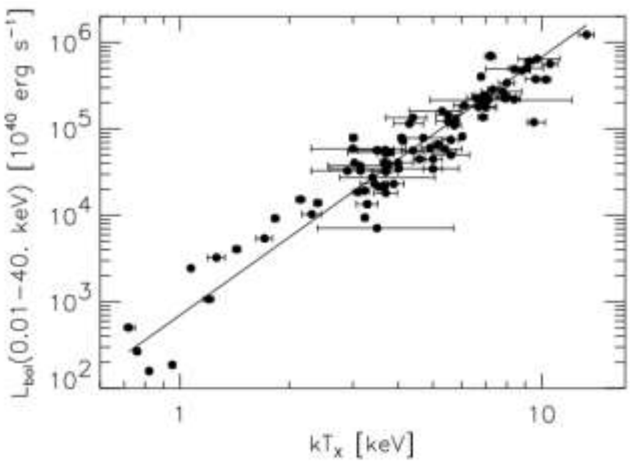
The cooling flow Problem in Cool Core Clusters



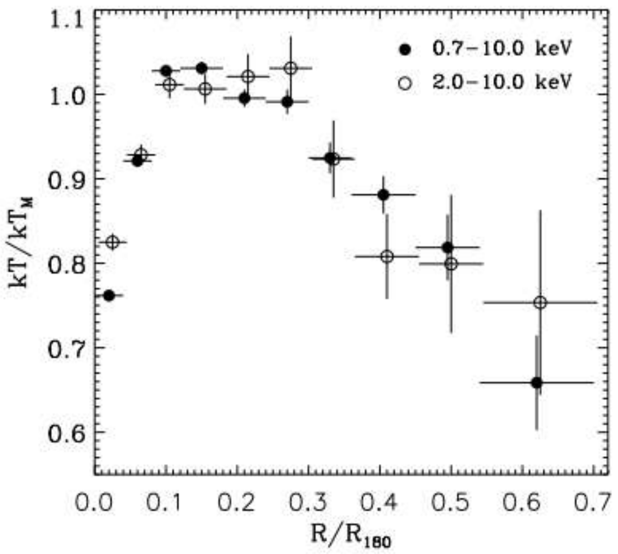
Allen & Ebeling

1. No cool (<1keV) gas
2. Star formation in brightest central galaxy lower by 10-100 than expected from cooling
3. BCG smaller by a factor or a few than expected

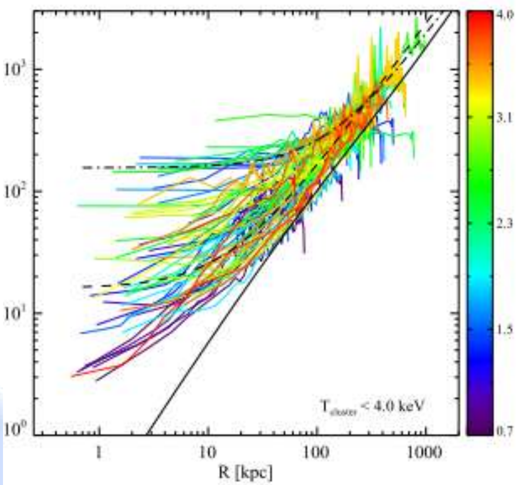
Cool Core Cluster properties

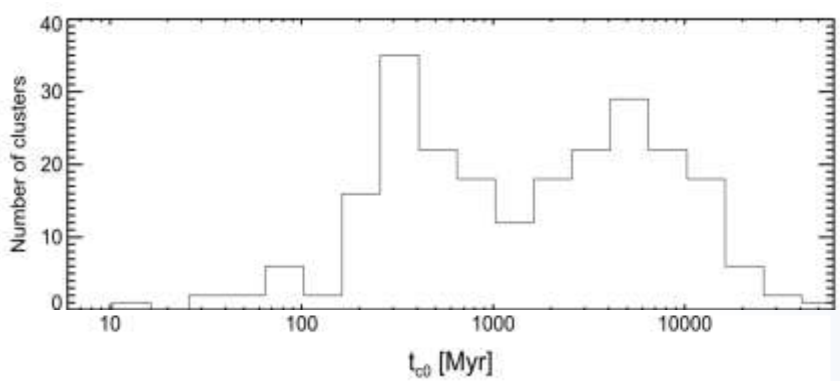


Reiprich 2003



Leccardi & Molendi 2008



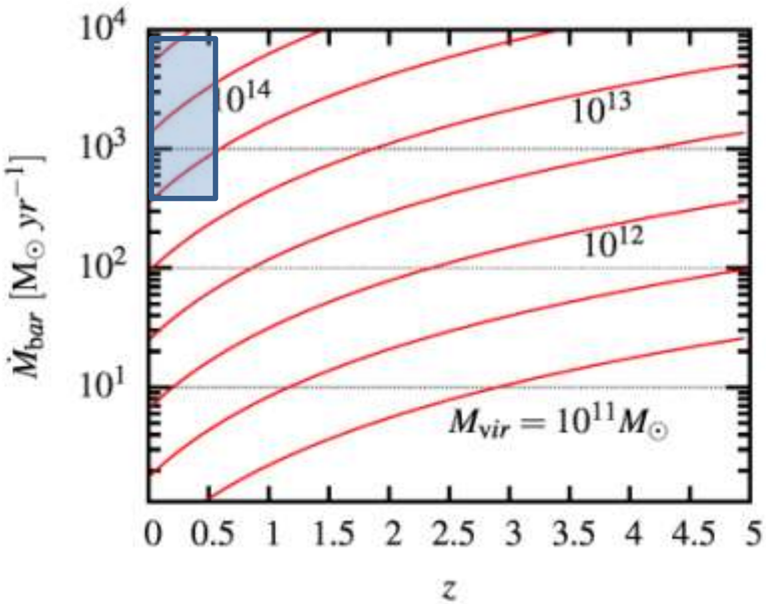


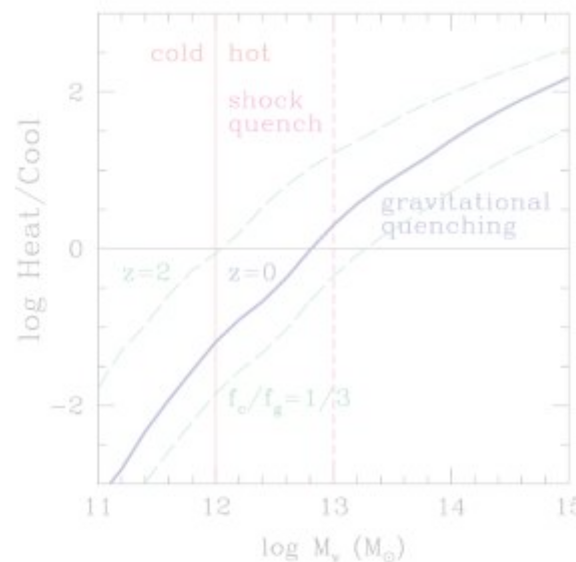
Cavagnolo et al. 2009

Criteria for cluster heat source

1) Enough energy
2) Smooth in time ($t_{off}<t_{cool}$)
3) Smooth in space (<10kpc)
4) No explosions, please

Accretion and Gravitational heating in Clusters





$f_{gas} = 0.05$ $\qquad Z = 0.3 Z_\odot$

$f_{clump} = 0.05$ $\qquad z = 0$

$f_{bar} = f_{gas} + f_{clump}$ $\qquad R_{penetration} = 0.1 R_{vir}$

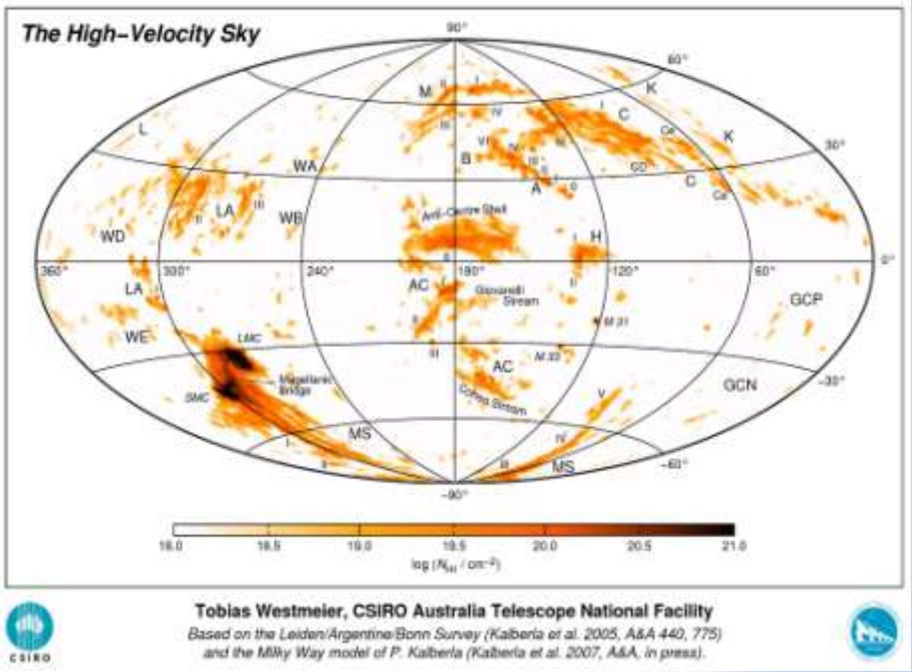
Dekel & Birnboim 2008

Is clumpy accretion so crazy?

Cold gas in Perseus

Conselice et al. 2001

HVCs in MW



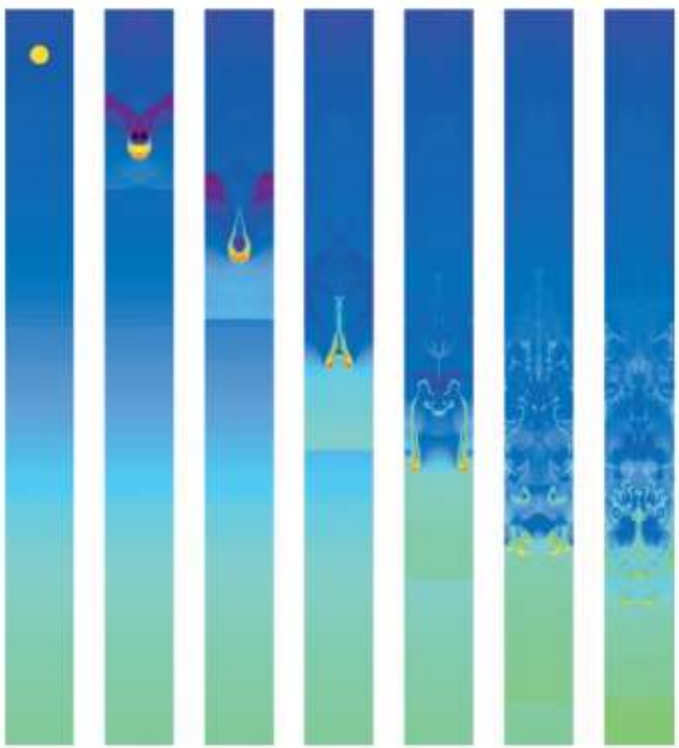
Mass of structures: 10^6-$10^8 M_\odot$ (Fabian et al. 2008)

Clump physics

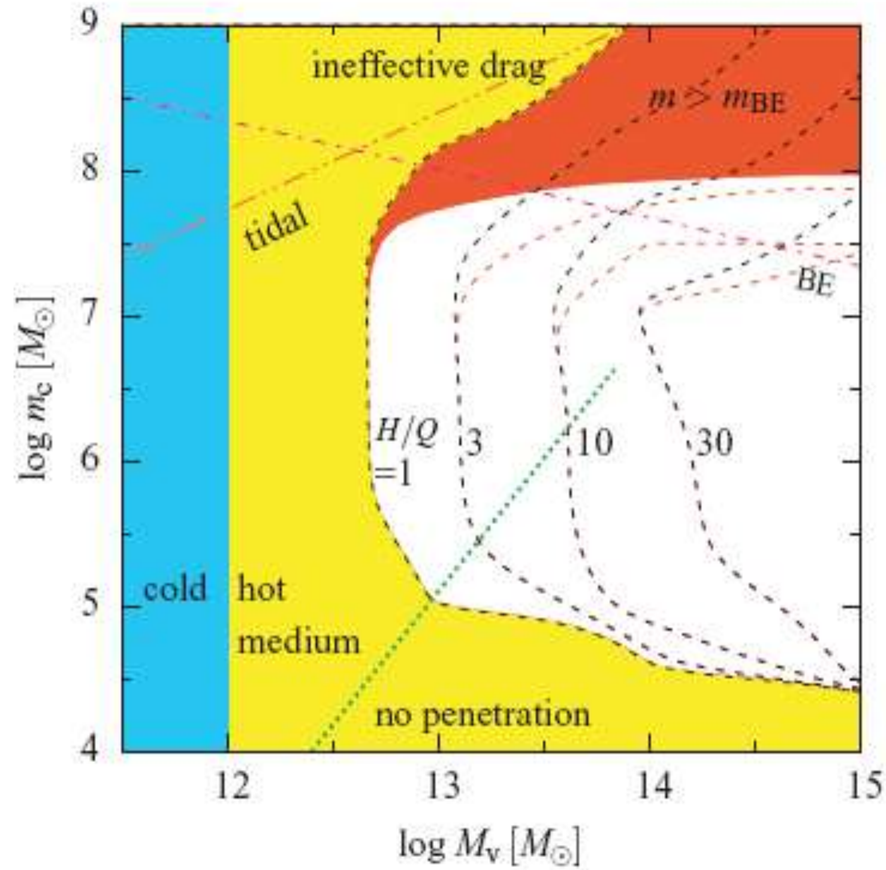
Heating by baryonic cold clumps

1. Hydrodynamic drag
2. Jeans mass (Bonnor-Ebert)
3. K-H/R-T instabilities and clump fragmentation
4. DF
5. Conduction/evaporation (Gnat et al. 2010)

Gravitational heating by clumps



Murray & Lin 2004



Dekel & Birnboim 2008

Dynamic response

Problems with static calculations:

- Cold mass is brought to center
- Energy injection is not self regulated
- Timescale of clumps: many Gyrs

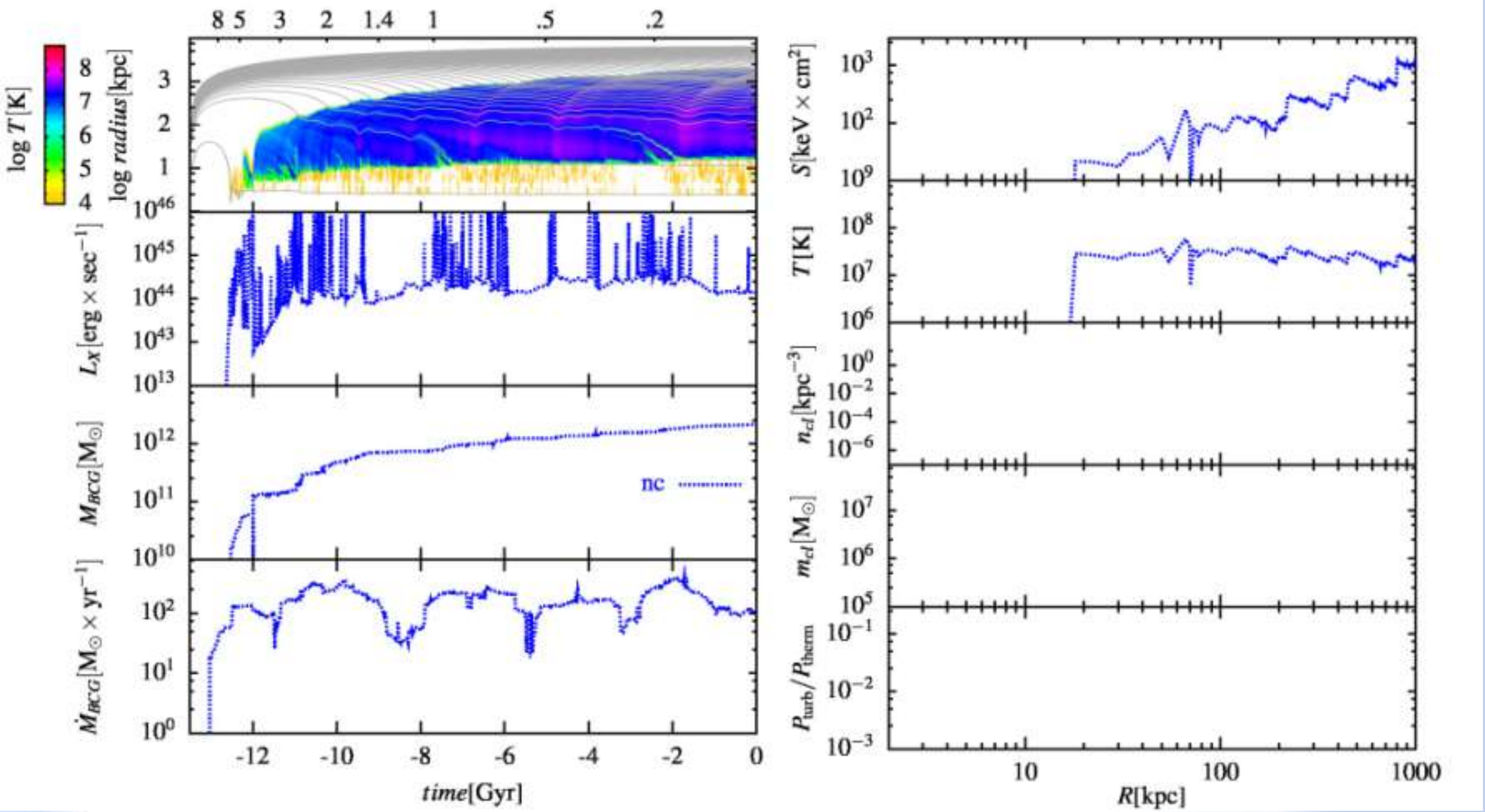
Problems with full 3D hydro:

- Resolution

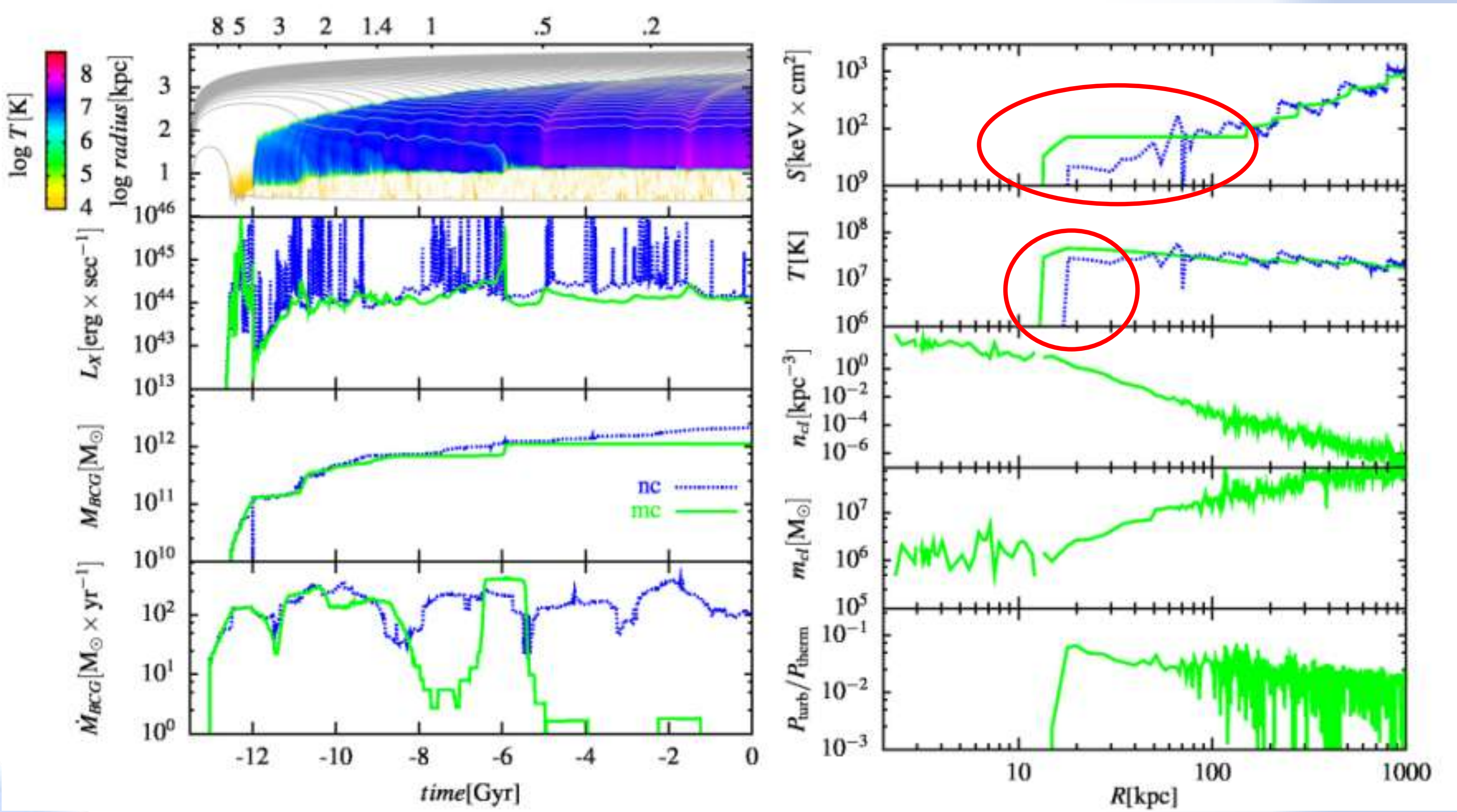
Subgrid 1D model:

- clump shells interact with gas
- At clump destruction – cold mass added in situ

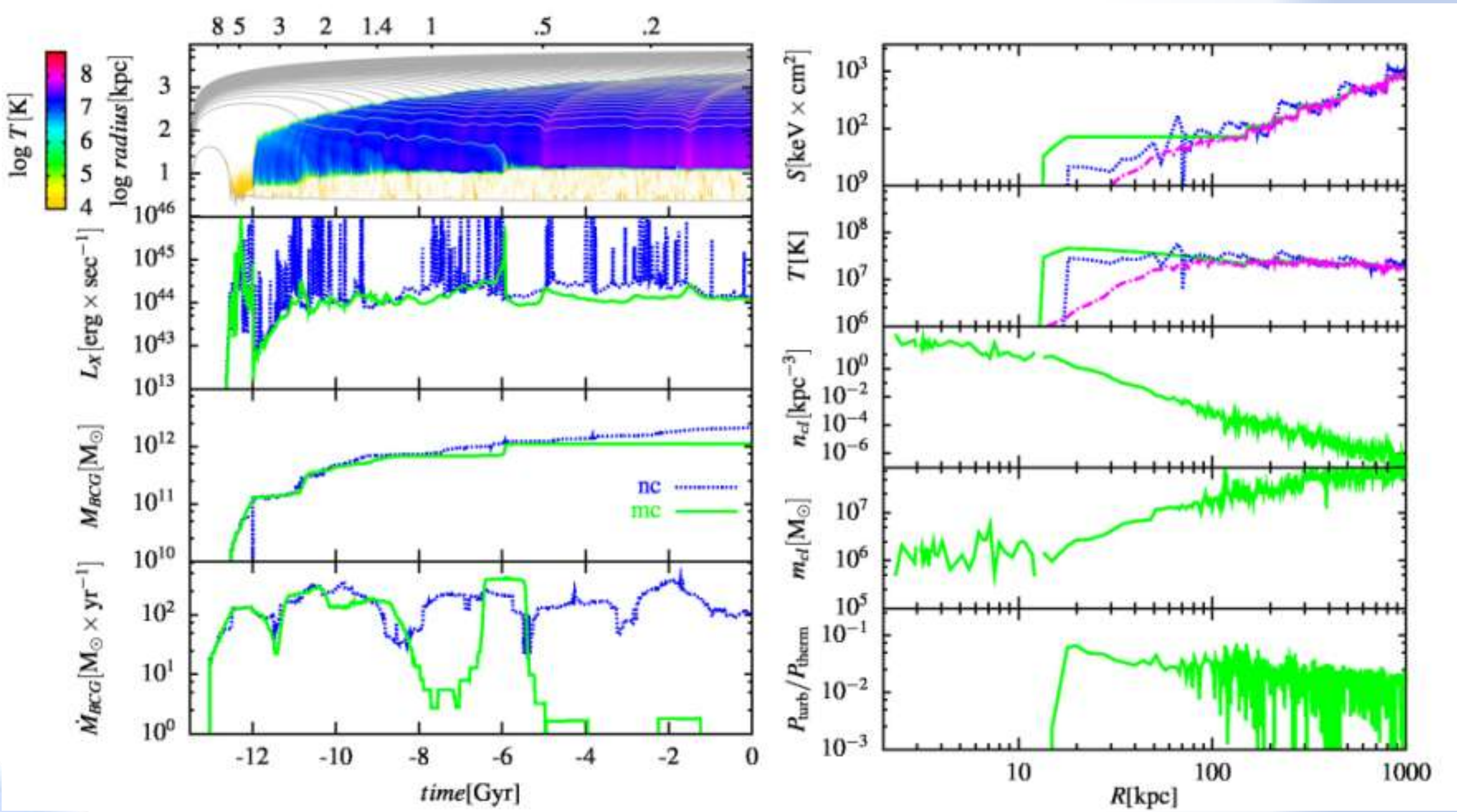
No clump simulation – Overcooling
$M_{vir}=3X10^{14}M_{\odot}$



5% of baryons in clumps of $10^8 M_\odot$
Clumps + Convection



Clumps + Convection. Effective S, T



Summary

- Critical mass for hot halo formation ~ $10^{12}M_{\odot}$
- Important for the color magnitude bi-modality
- Most stars formed through cold flows
- For High-z galaxies magnetic fields affect accretion
- For clusters, cold accretion in clumps actually heats!

Thank you