Lecture

On the Origin of Galaxy Bi-modality: Cold Flows, Clustering and Feedback

- Observed bi-modality
- Shock heating vs cold flows
- Cold filaments in hot halos -- clustering scale
- Feedback Processes
- Origin of the bi-modality

1. Observed Bimodality

Observed Scale

- bi-modality/transition at

$M_* \sim 3\times10^{10} M_\_ \sim L_*$ $\quad M_{halo} \sim 6\times10^{11} M_\_$

below: disks, blue, star forming, low Z, LSB, M/L decreasing with M along a "fundamental line", in field (small halos), …

above: spheroids, red, old-pop, high Z, HSB, M/L increasing with M, "fundamental plane", clustered (massive halos), AGNs, …

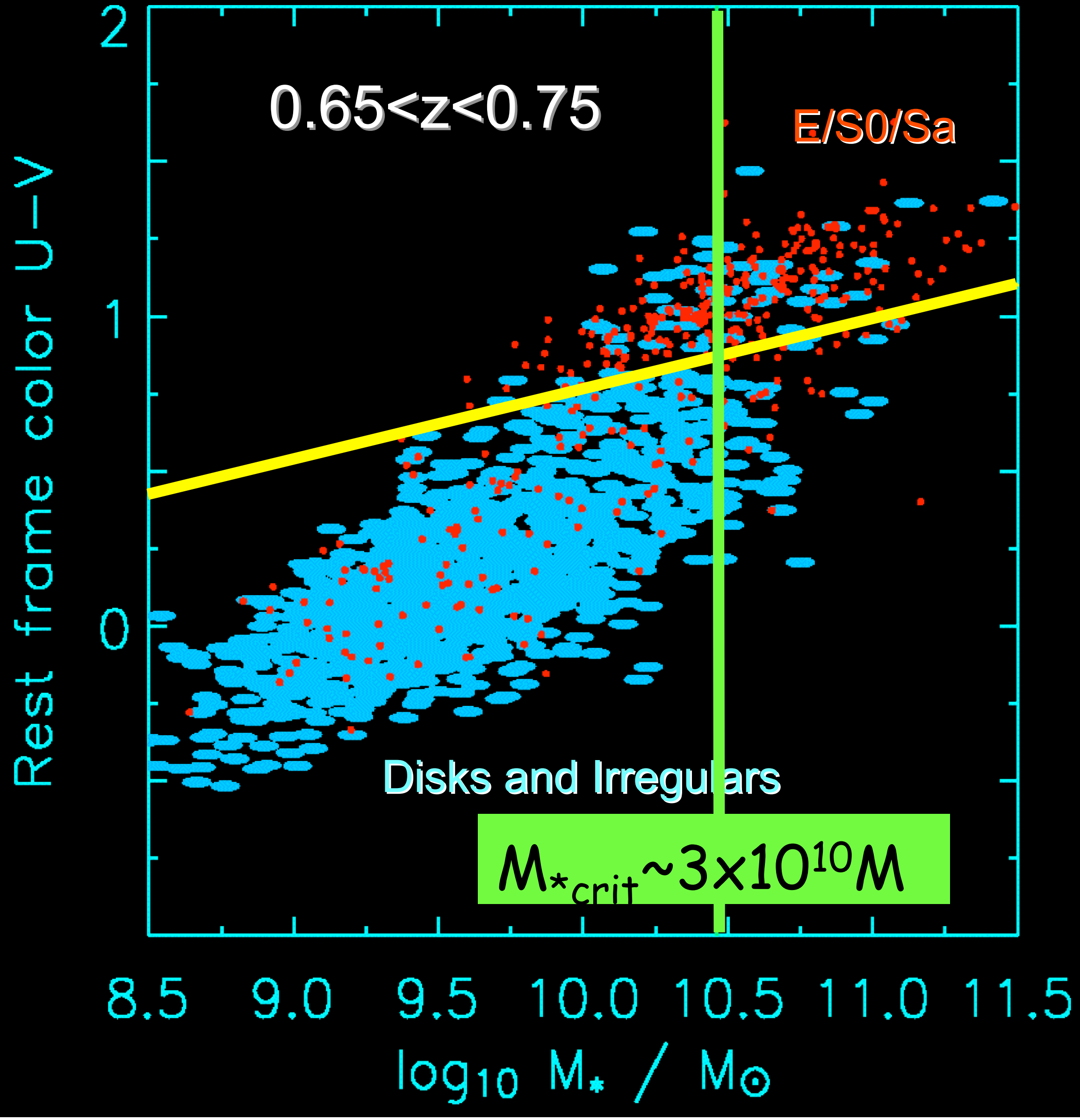
- very blue galaxies _ bursty star formation
- big blue galaxies at z~2-3 (e.g. SCUBA)

_ early star formation in big objects

- luminous red galaxies at z~0-1 (e.g. EROs)

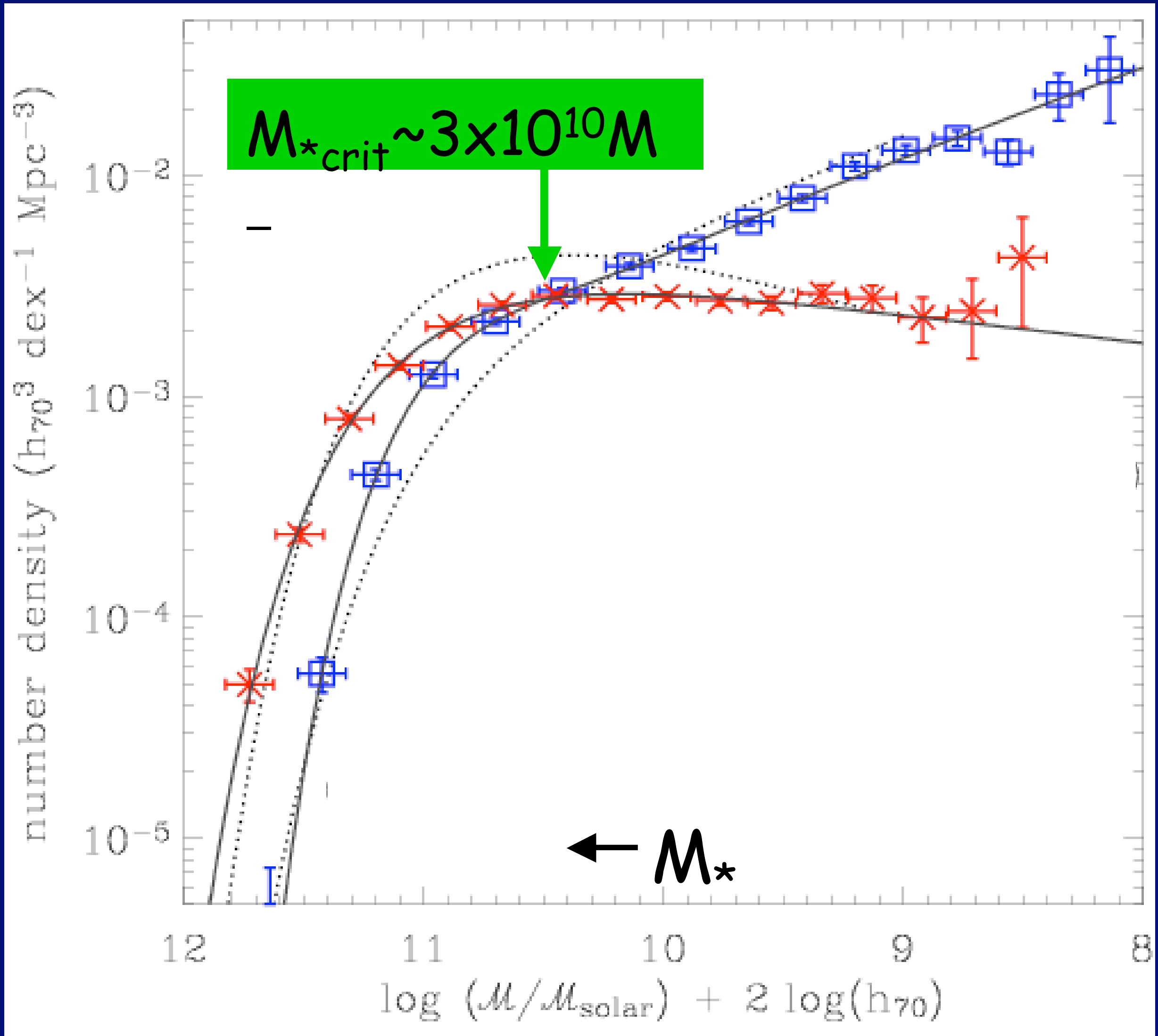
_ early star formation, then shut off

Bi-modality in color, SFR, bulge/disk



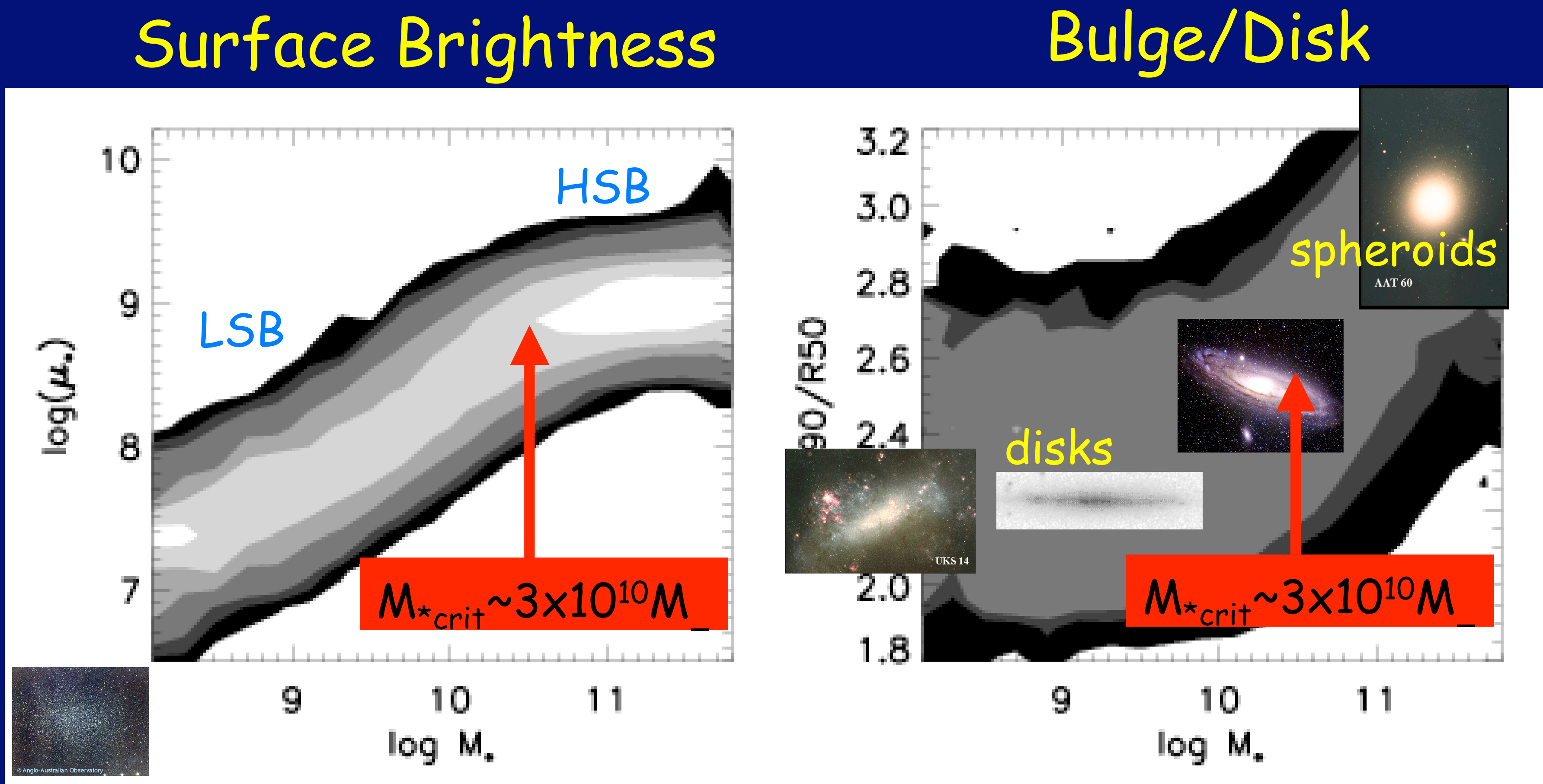
Bell

Luminosity function: Red vs Blue



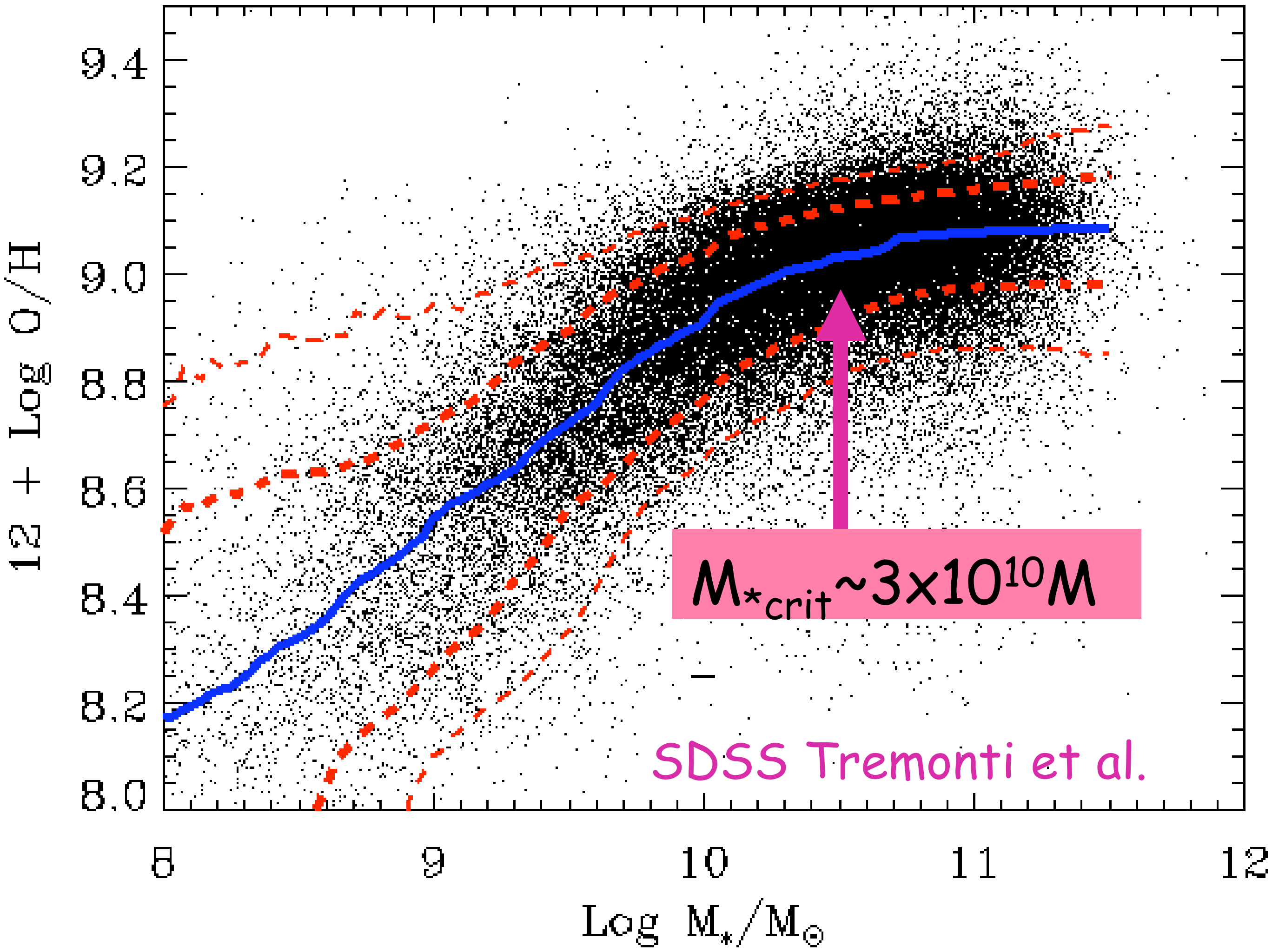
SDSS
Baldry et al. 04

Transition Scale

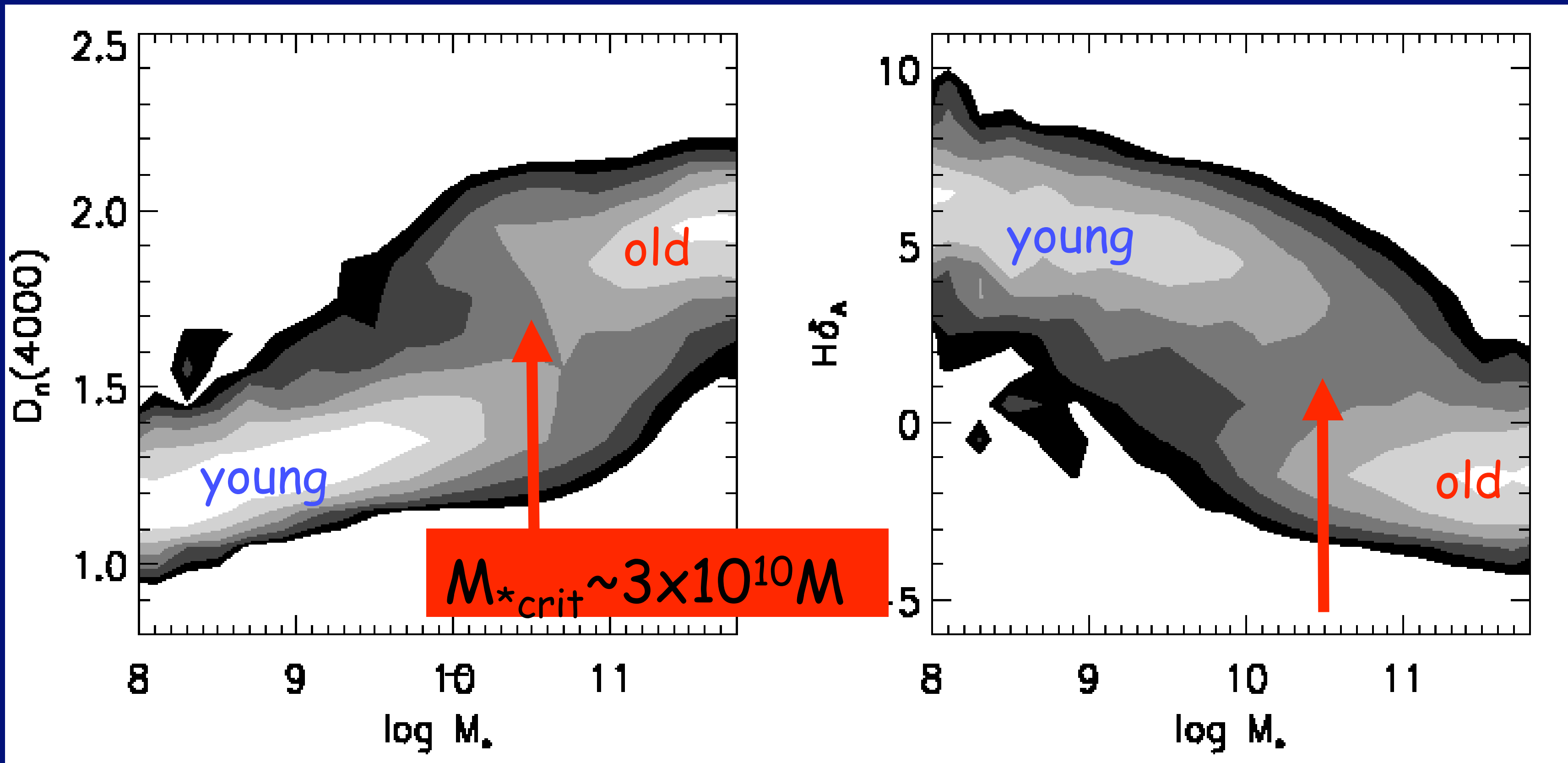


SDSS Kauffmann et al. 03

Transition in Metallicity

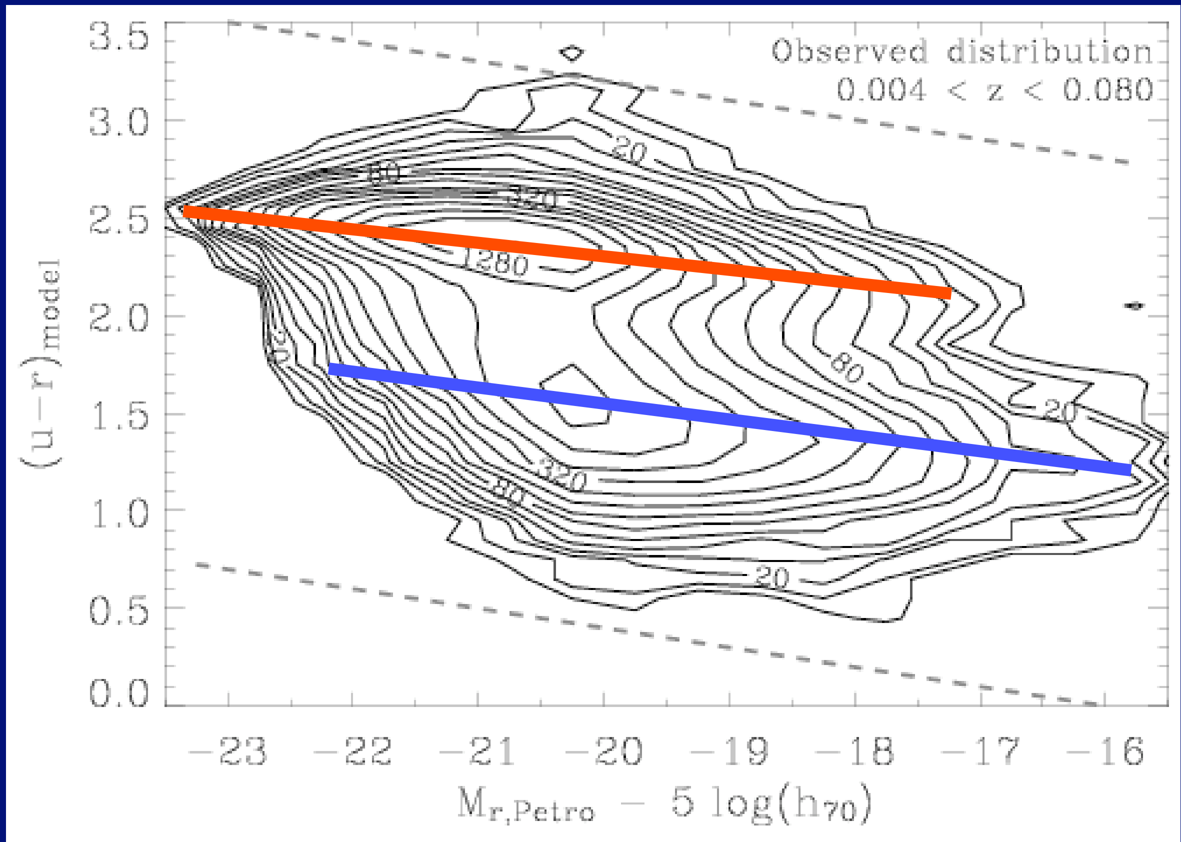


Bi-modality: Age vs Stellar Mass



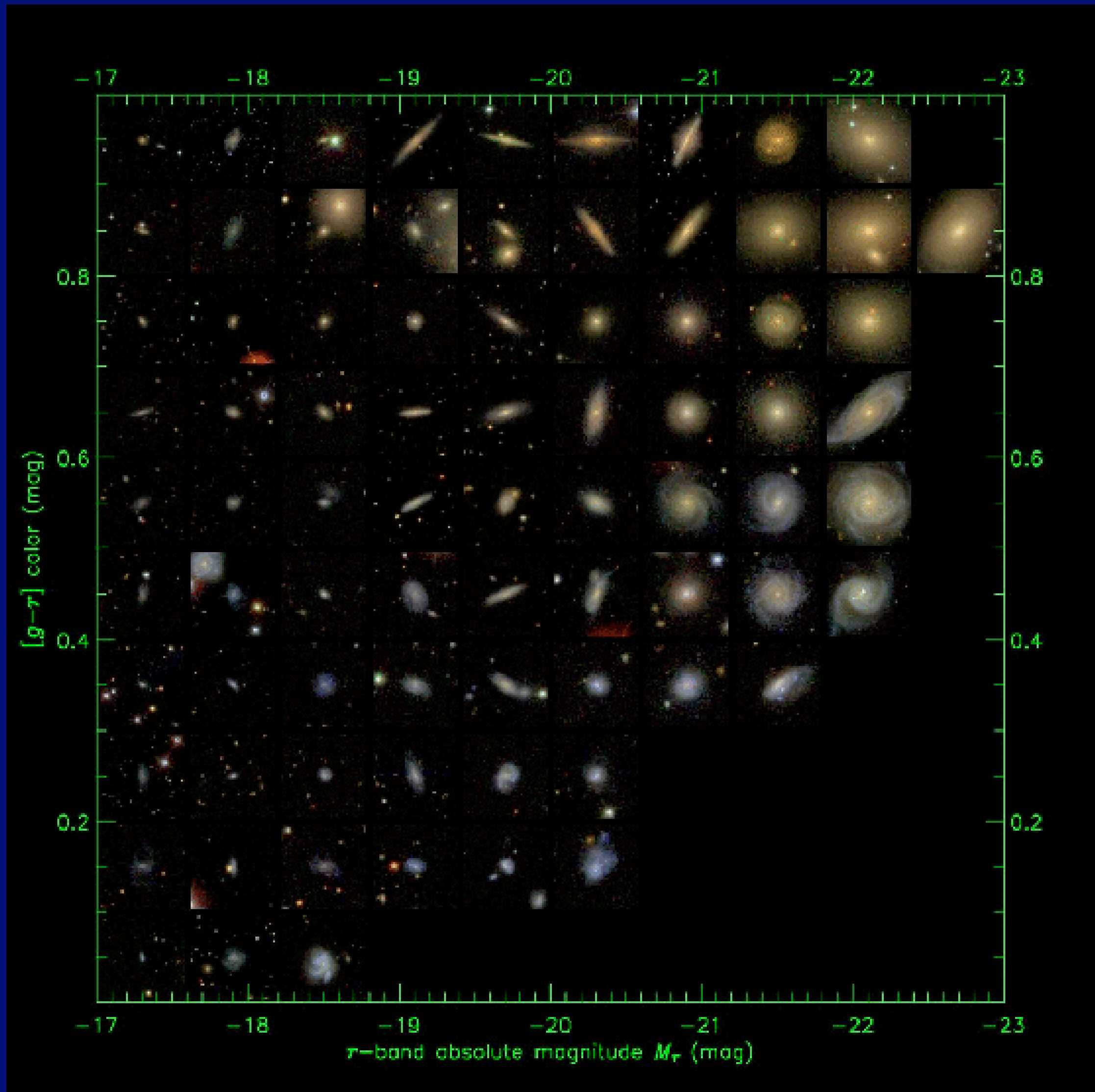
SDSS Kauffmann et al. 03

Bi-modality in Color-Magnitude



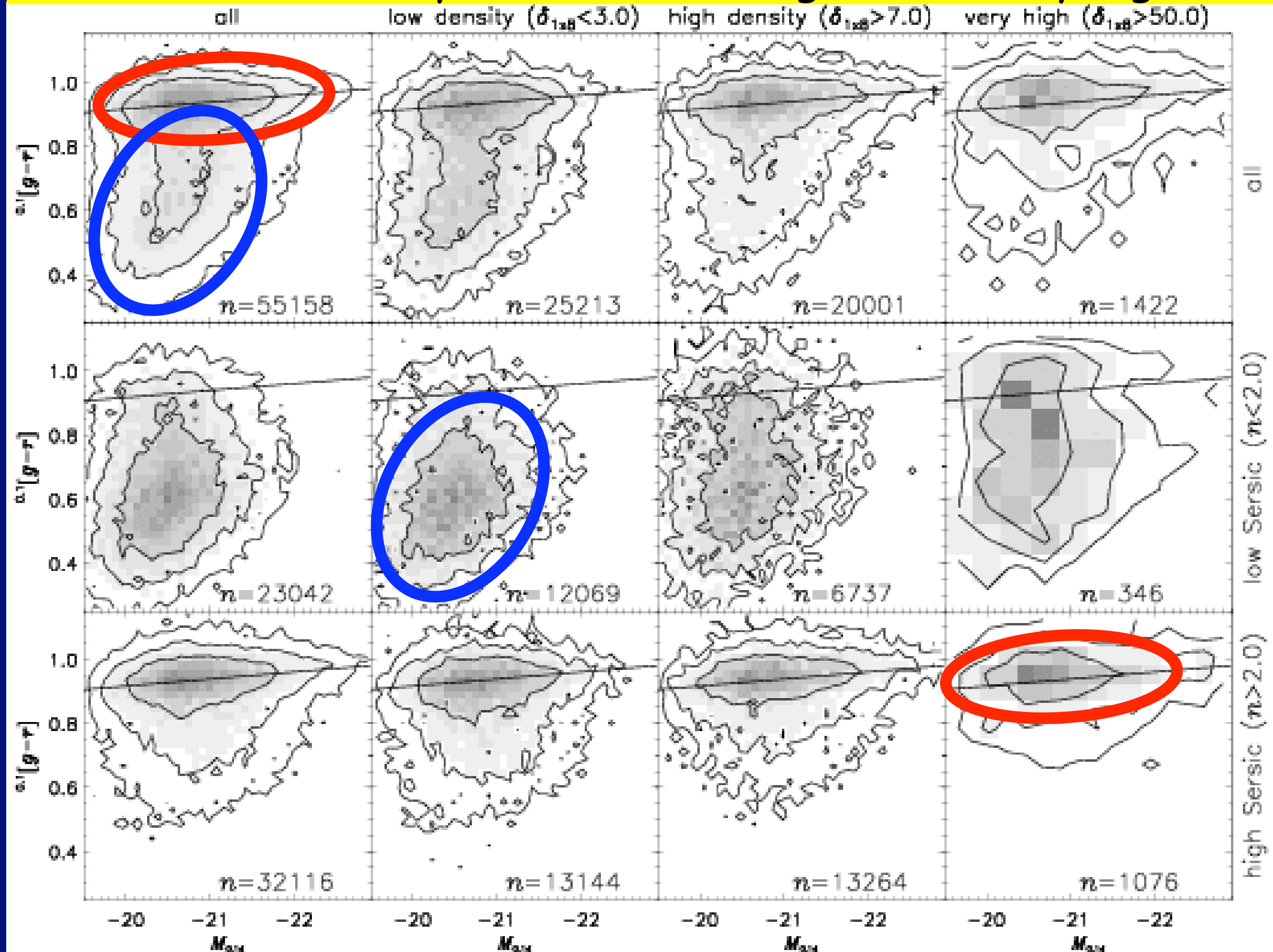
SDSS Baldry et al. 04

Color-Magnitude-Morphology in SDSS



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

environment density: low high very high



disks

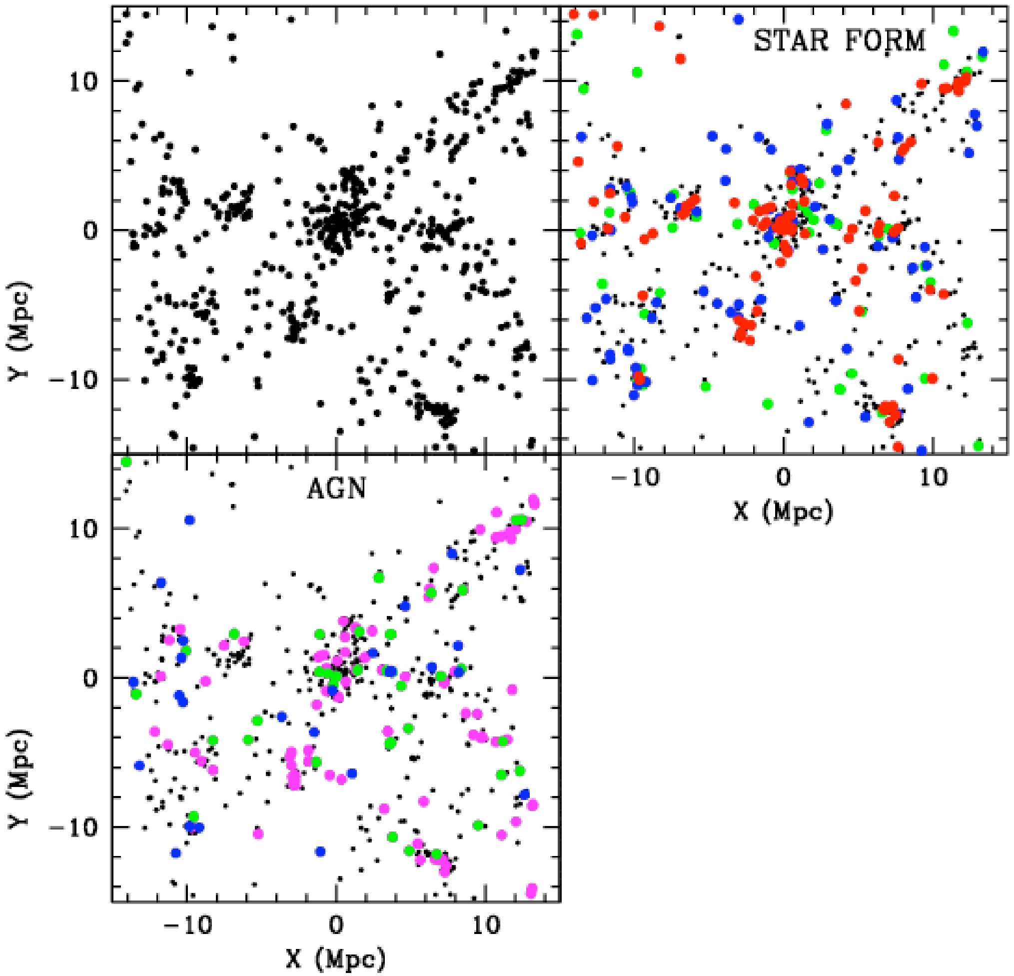
spheroids

M_{halo}<6×10^{11} "field"

M_{halo}>6×10^{11} "cluster"

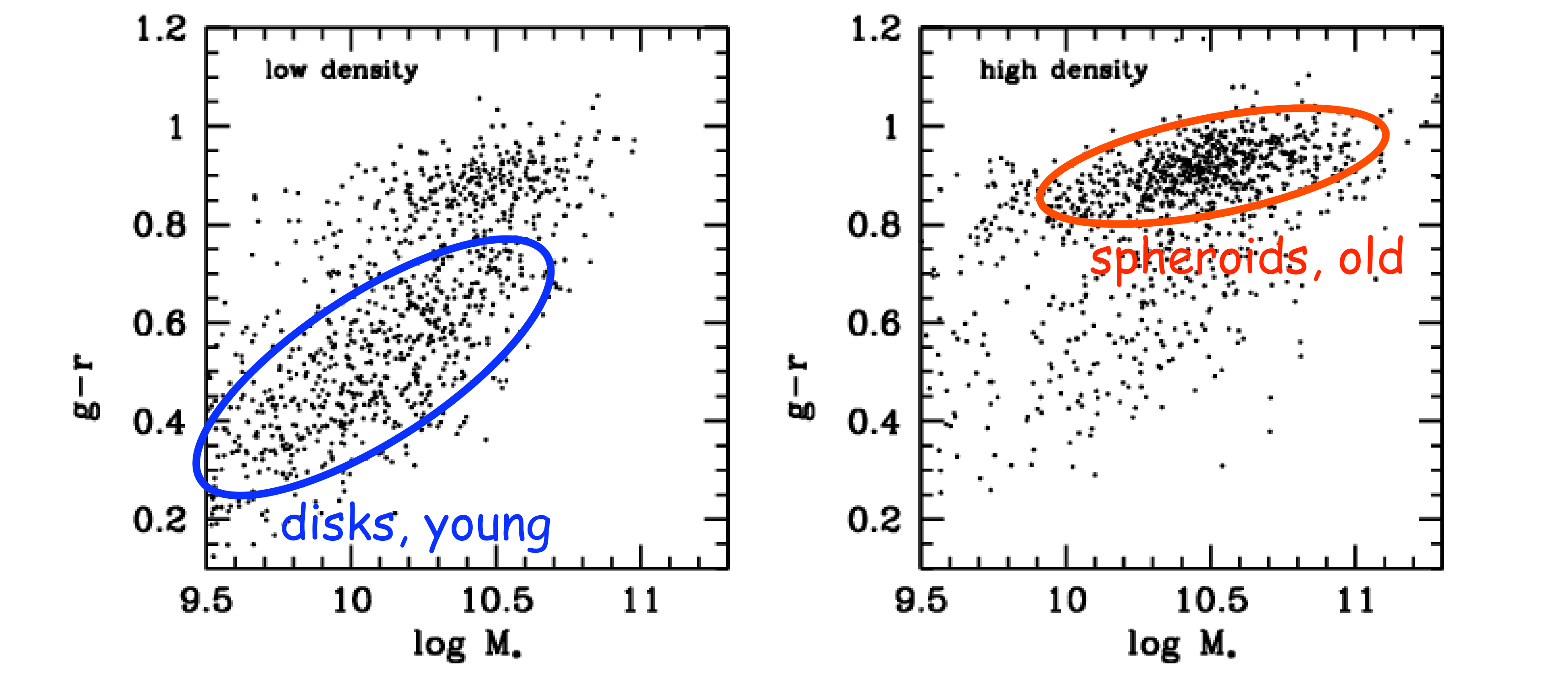
SDSS: Hogg et al. 03

Color - Environment



Age & Color bi-modalily correlated with environment density, or halo mass

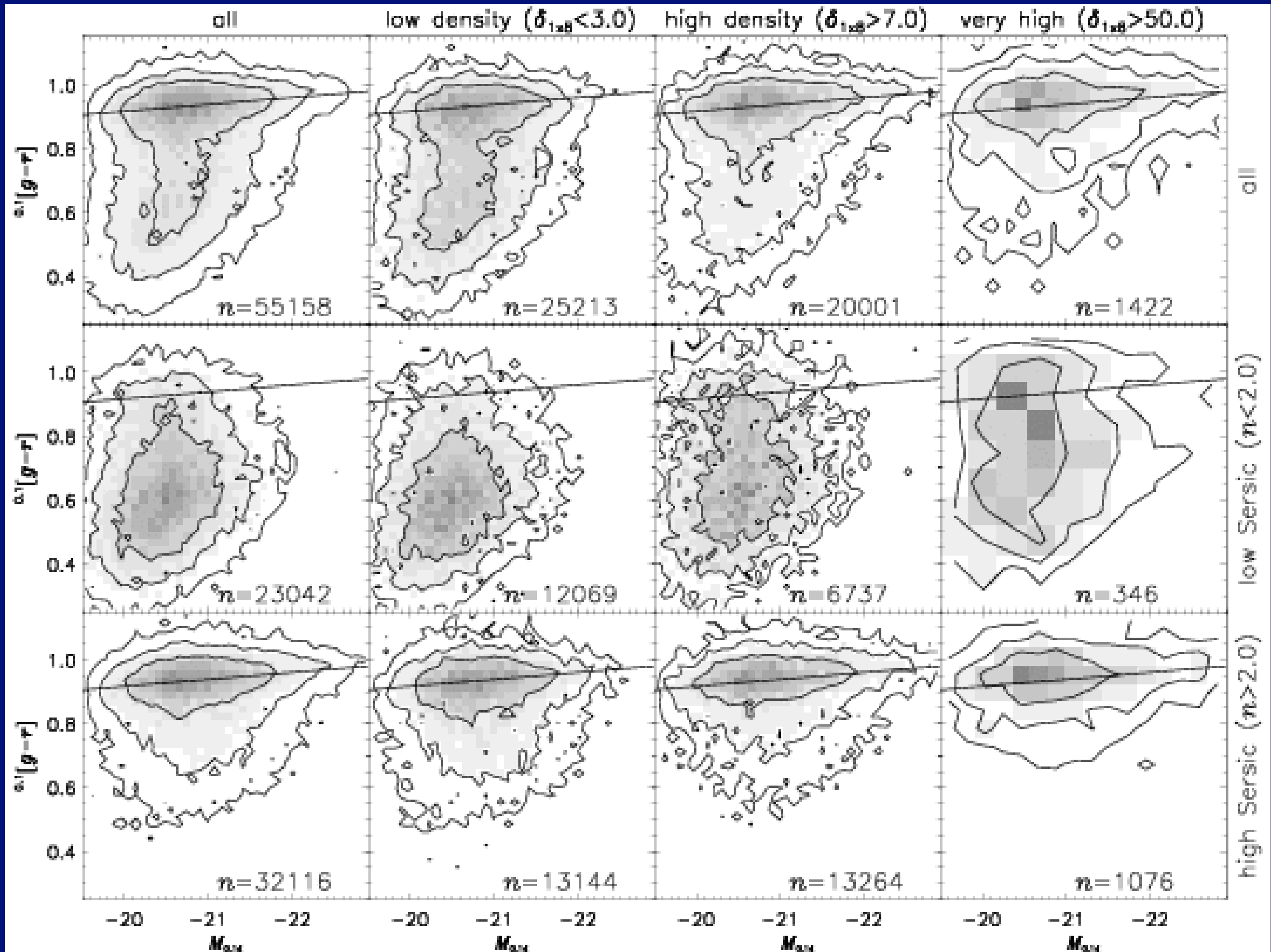
$M_{halo}<6\times10^{11}$ "field" $M_{halo}>6\times10^{11}$ "cluster"



Kauffmann et al. 2004

Color-Magnitude Bimodality depends on B/D and Environment

density: low high very high

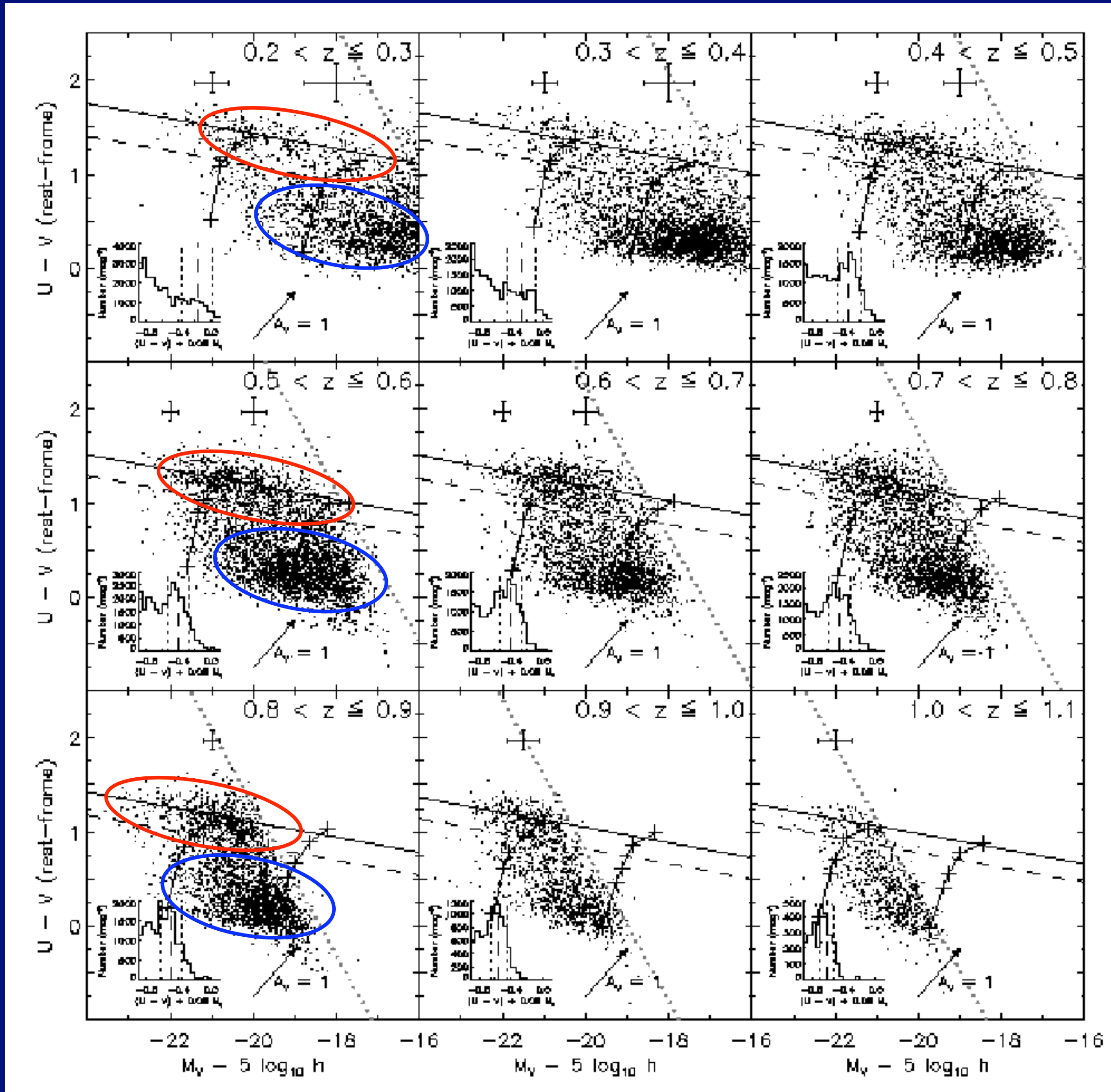


disks

spheroids

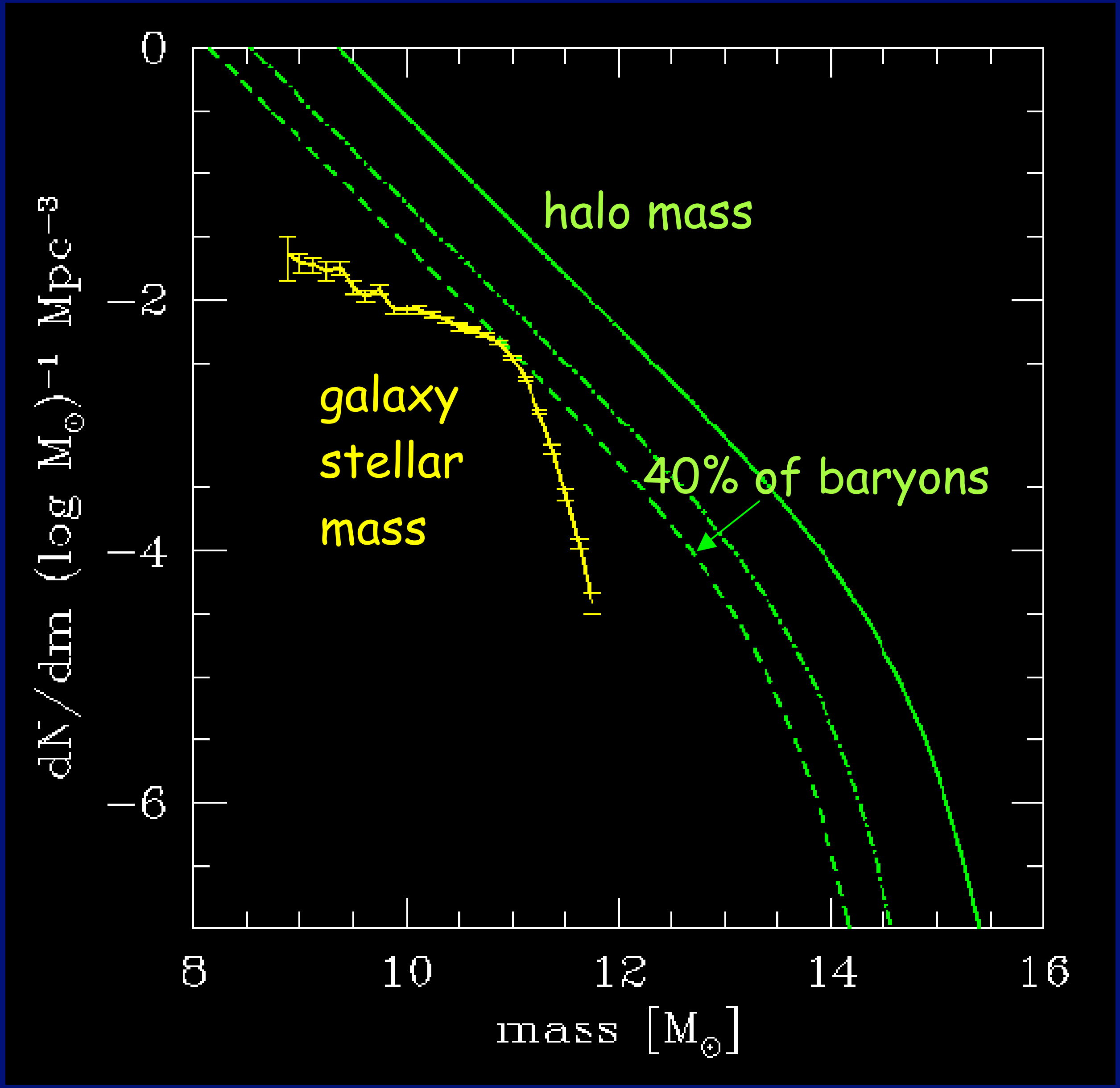
SDSS: Hogg et al. 03

Bi-modality at high z

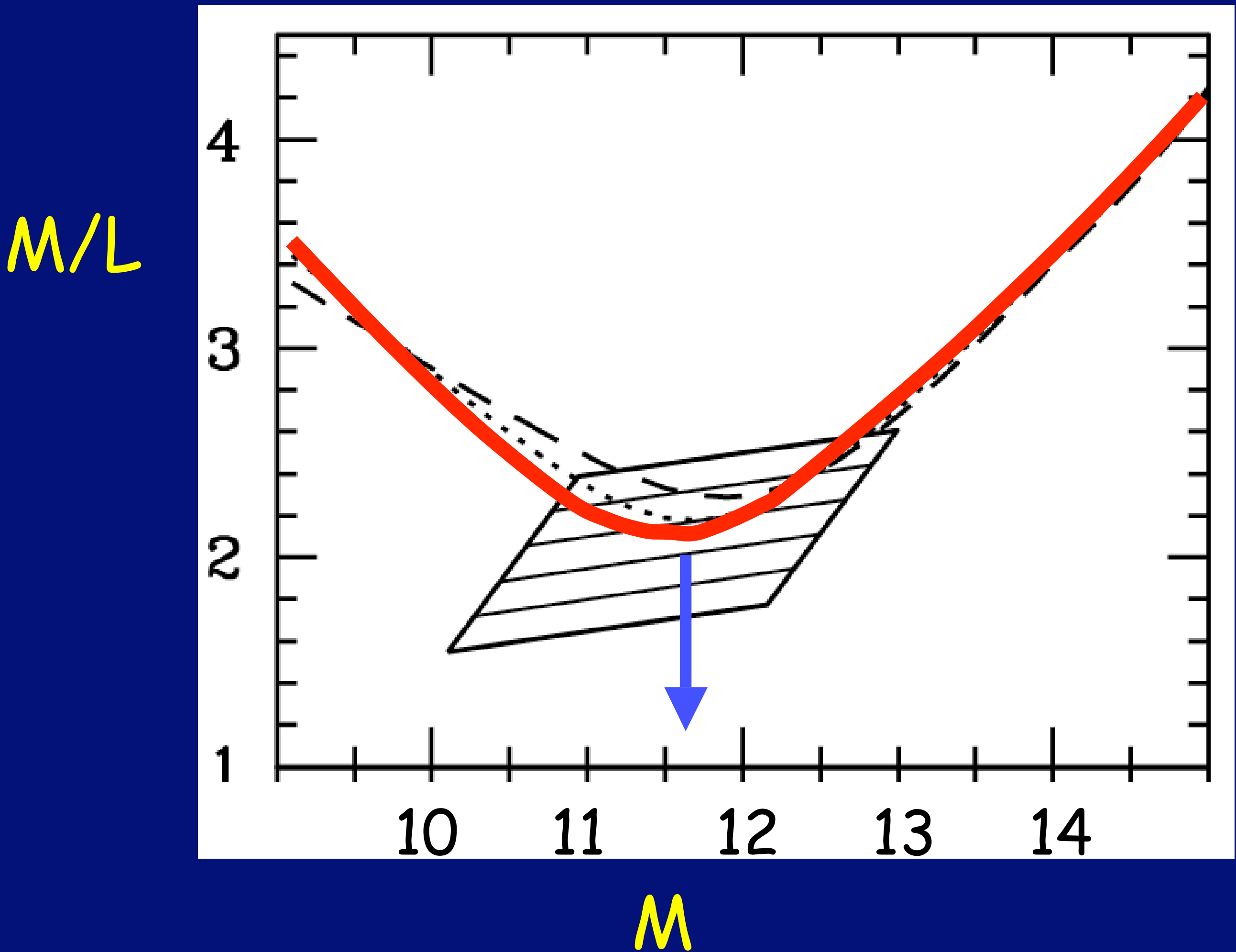


Combo-17

Mass versus Light Distribution

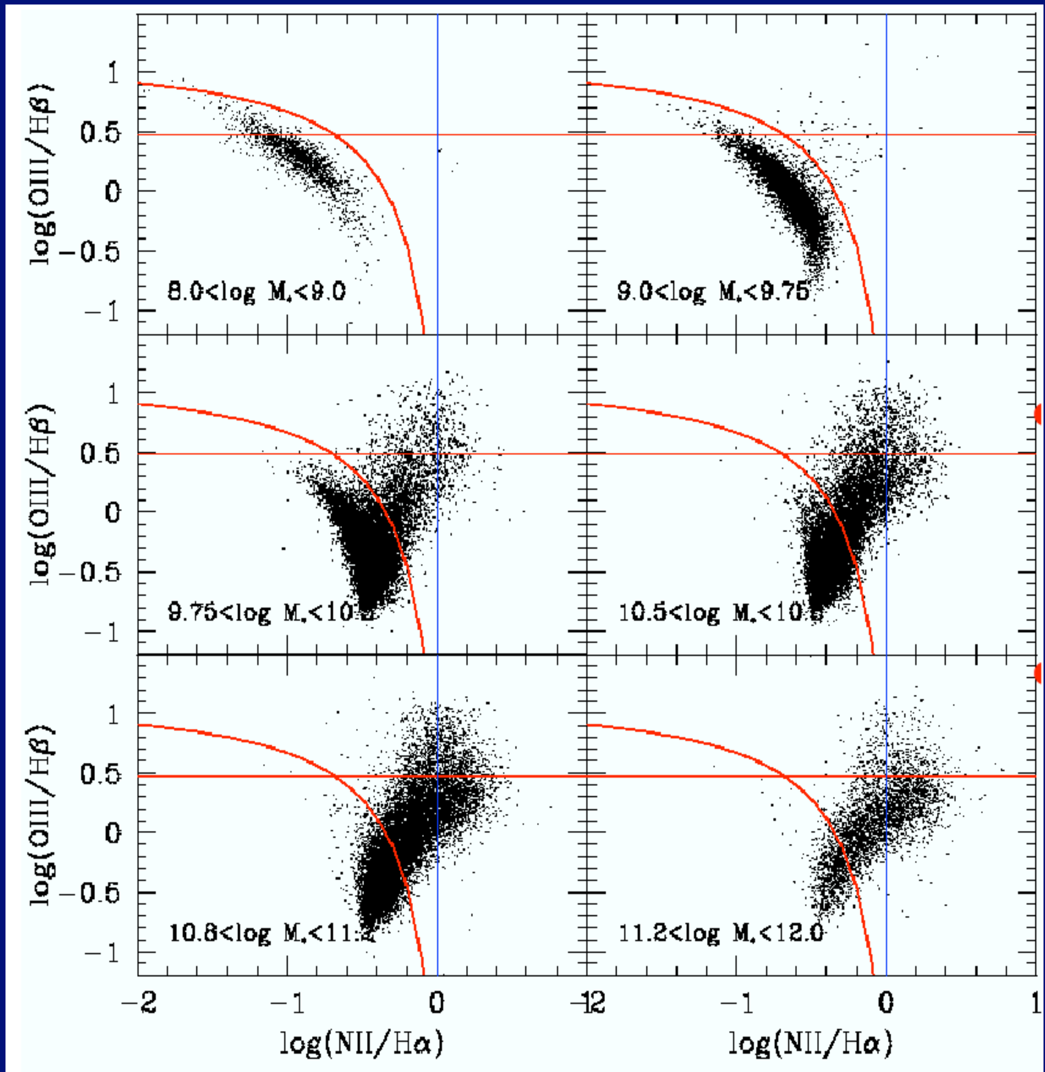


<M/L> vs M for halos in 2dF assuming _CDM



Using conditional luminosity function: Van den Bosch, Mo, Yang 03

Emission Properties vs. Stellar Mass



low-mass emission galaxies are almost all star formers

high-mass emission galaxies are almost all AGN

Kauffmann et al. 2004

Observed Characteristic Scale

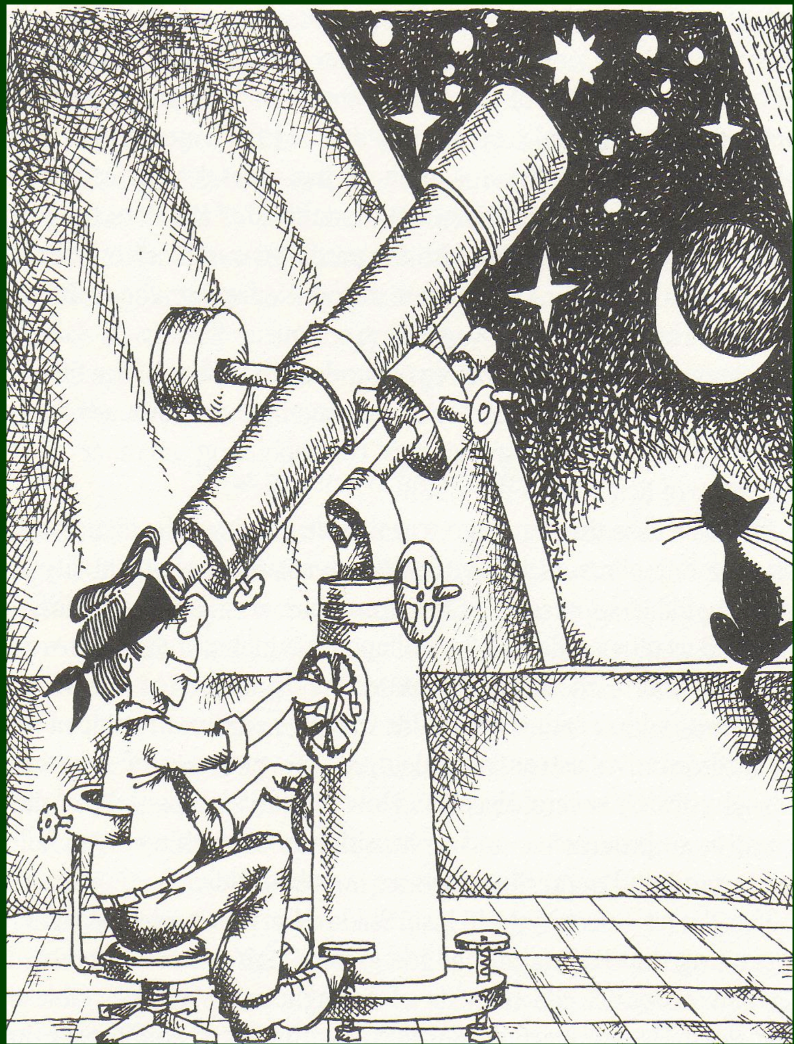
bi-modality / transition

$M_{*} \sim 3x10^{10} M\_$ $M_{vir} \sim 6x10^{11} M\_$ $V_{vir} \sim 120$ km/s

discs, blue star-forming, low Z, LSB $M/L \propto M^{-1}$,
fundamental line, small halos (field)

spheroids, red old-pop, high Z, HSB $M/L \propto M$,
fundamental plane, massive halos (clustered), AGNs

Theory



Standard Picture of Infall to a Disc

Rees & Ostriker 77, Silk 77, White & Rees 78, …

Perturbed expansion

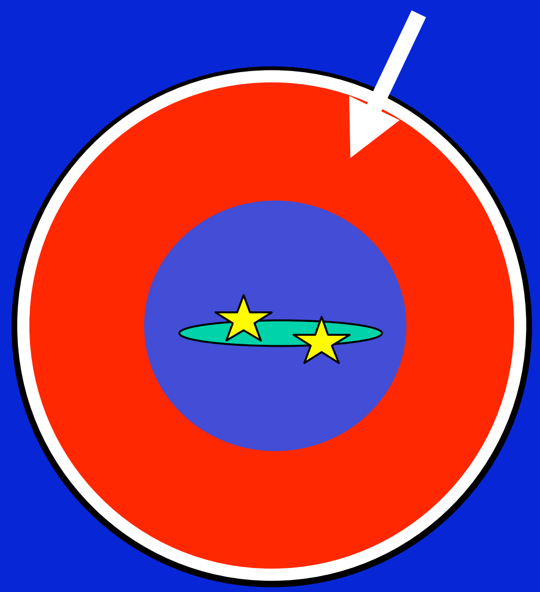
Halo virialization

Gas infall, shock heating at the virial radius

Radiative cooling

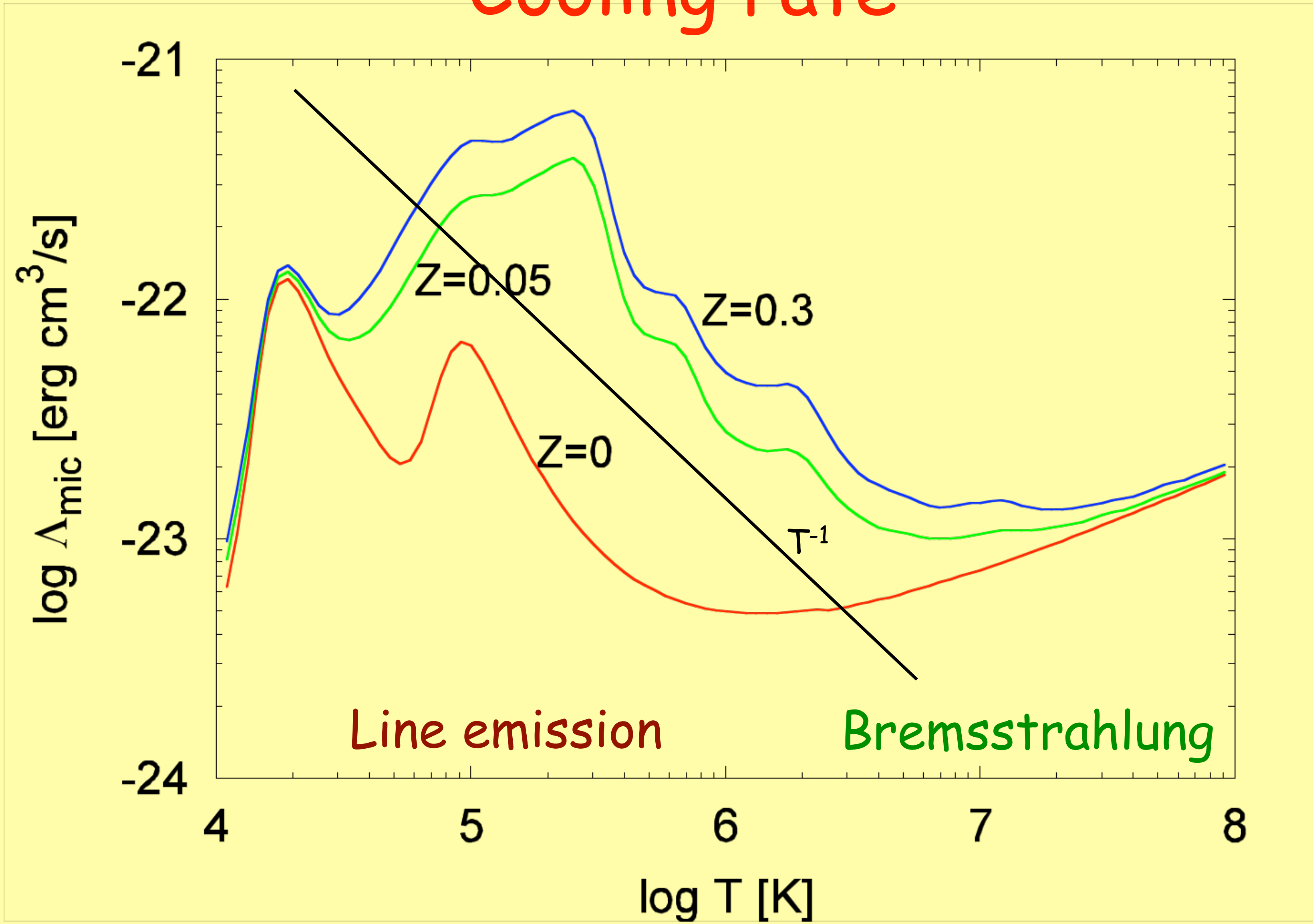
Accretion to disc if $t_{cool} < t_{ff}$

Stars & feedback



$M < M_{cool} \sim 10^{12-13} M_{\odot}$

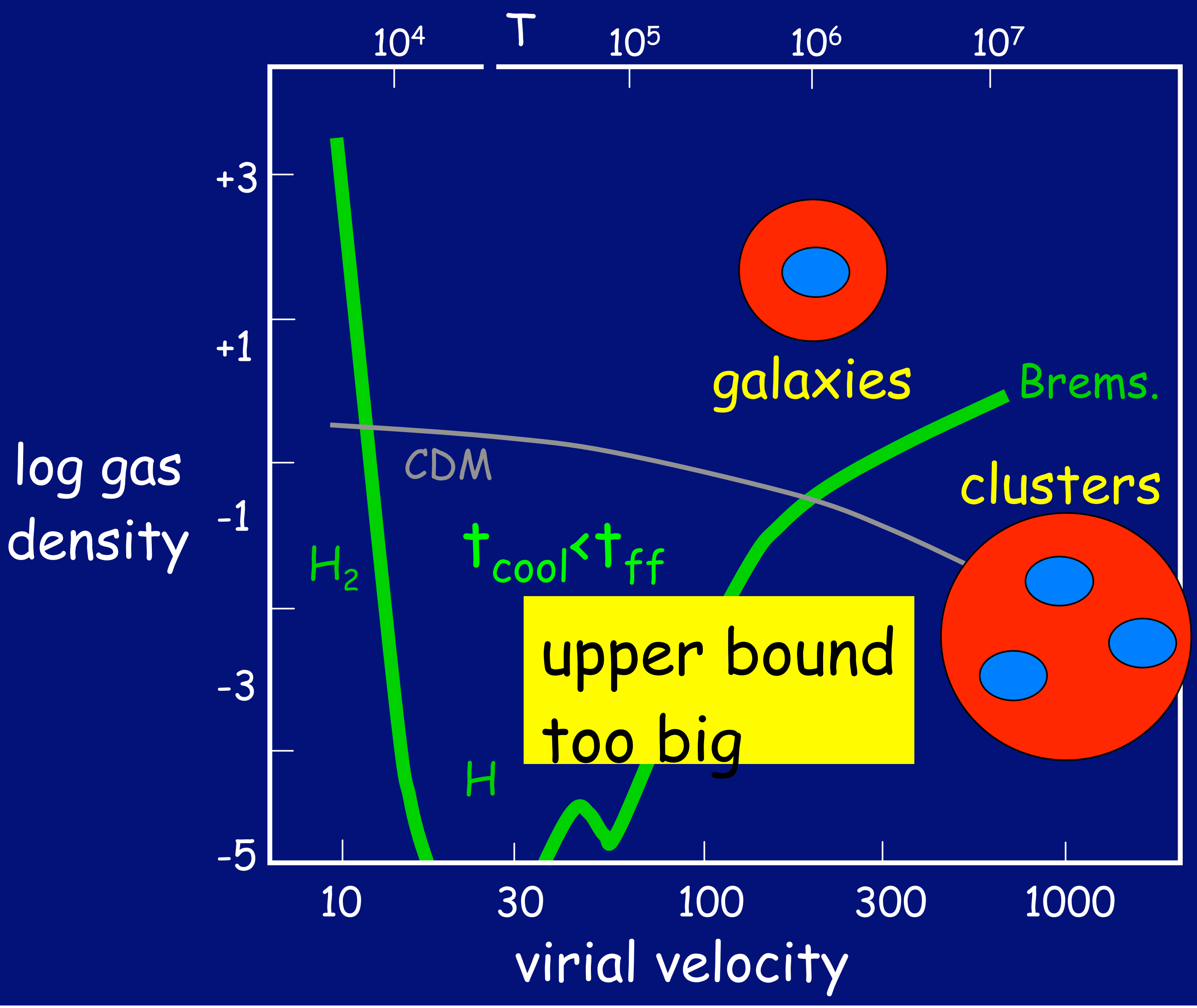
Cooling rate



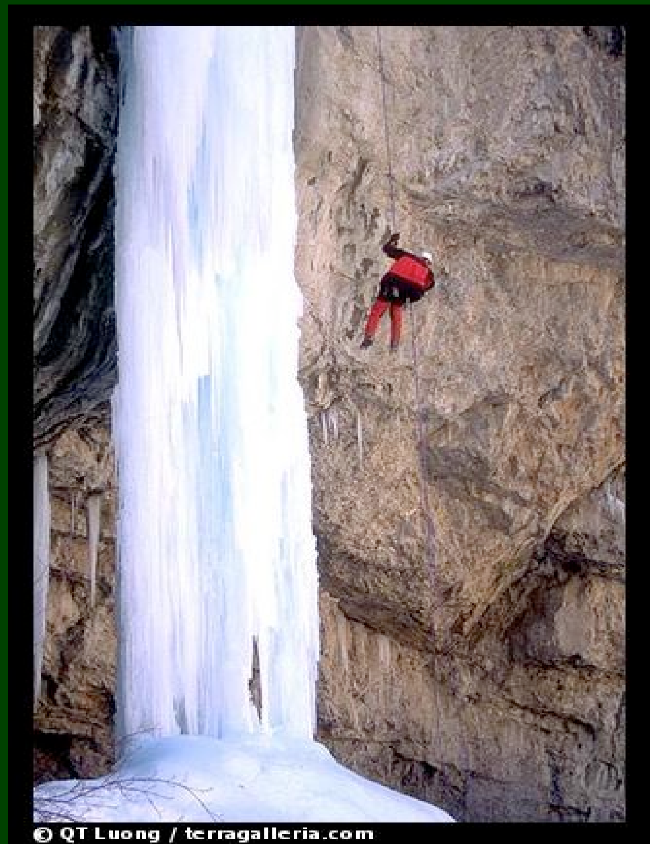
$q = \frac{N_A{}^2 \chi^2}{\mu^2} \Lambda(T) \rho$ [erg g^{-1} s^{-1}] $\quad N_A / \mu$ molecules per g $\quad \chi$ e$^-$ per particle

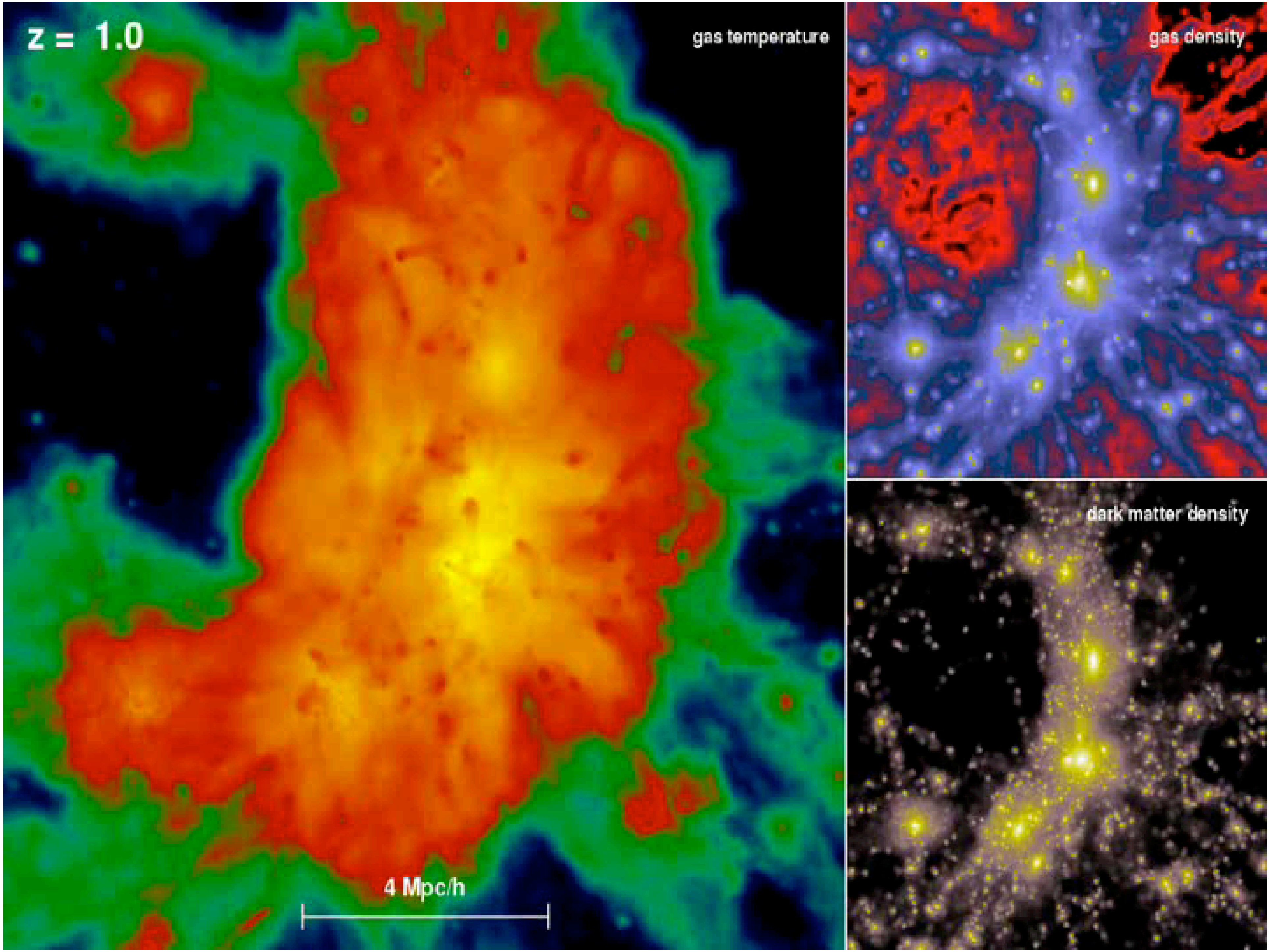
Cooling vs Free Fall

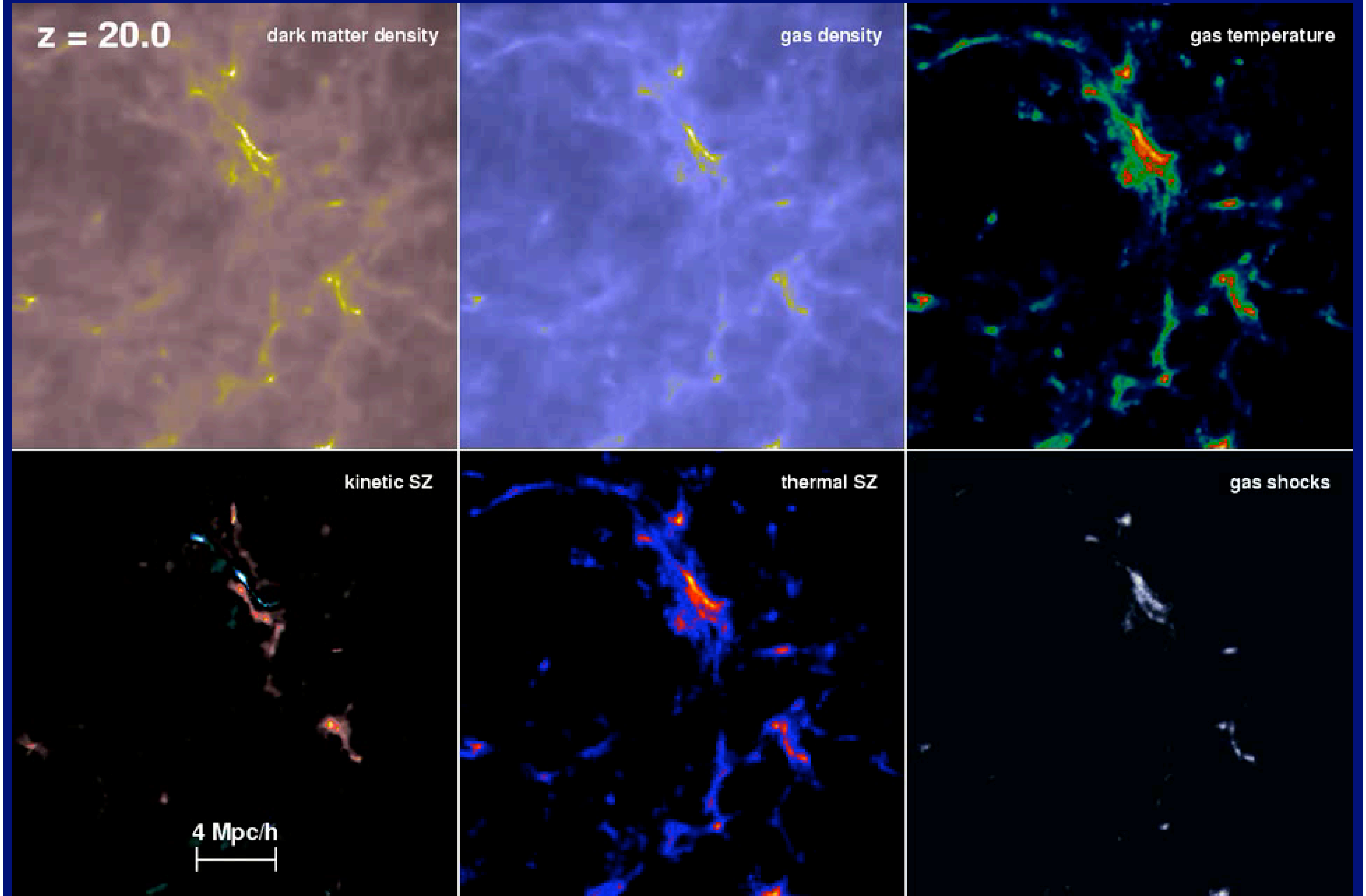
Rees & Ostriker 77, Silk 77, White & Rees 78   Blumenthal, Faber, Primack & Rees 86



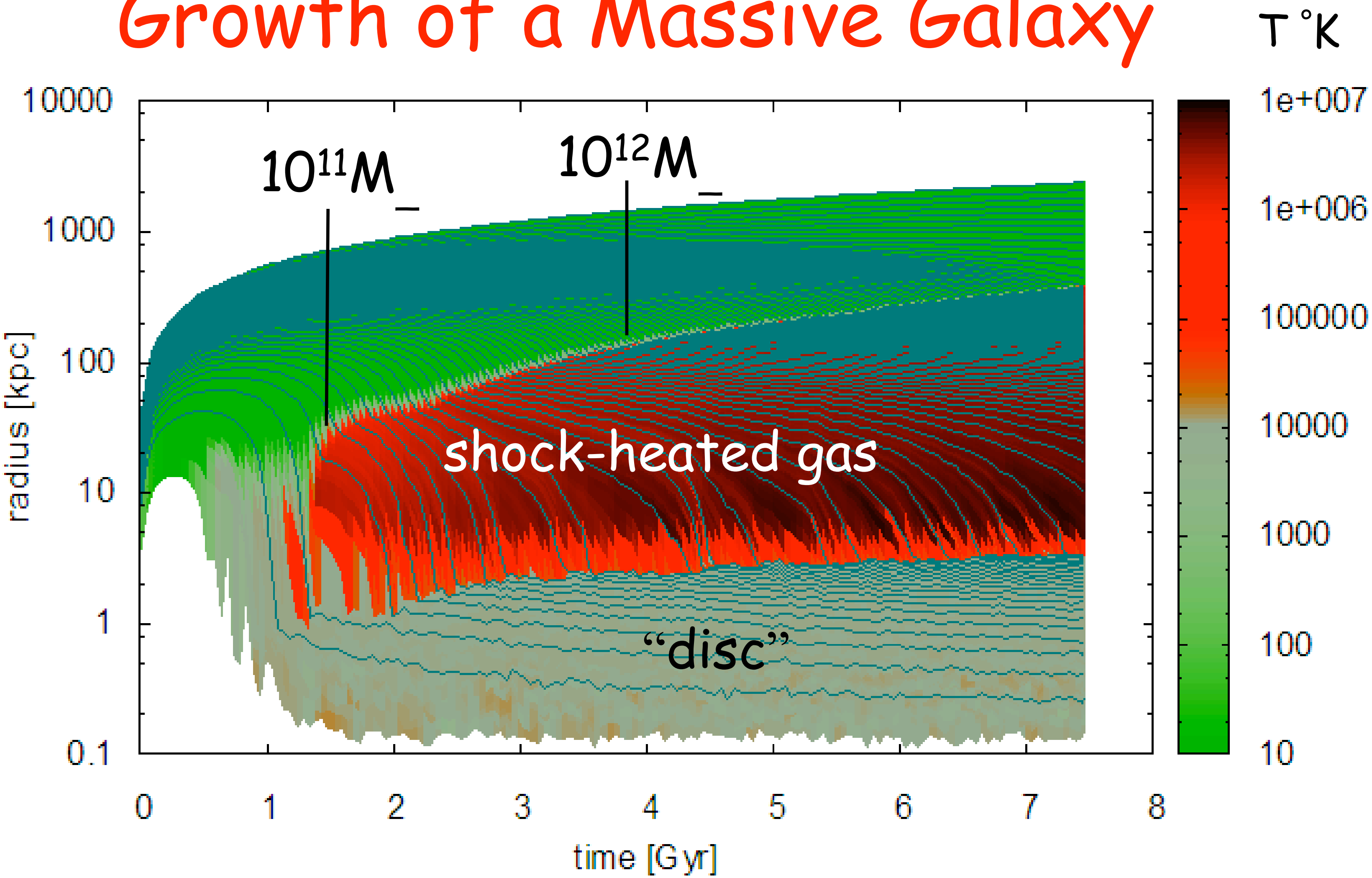
2. Shock-Heating vs Cold Flows




z = 1.0
gas temperature
4 Mpc/h
gas density
dark matter density


z = 20.0
dark matter density
gas density
gas temperature
kinetic SZ
thermal SZ
gas shocks
4 Mpc/h

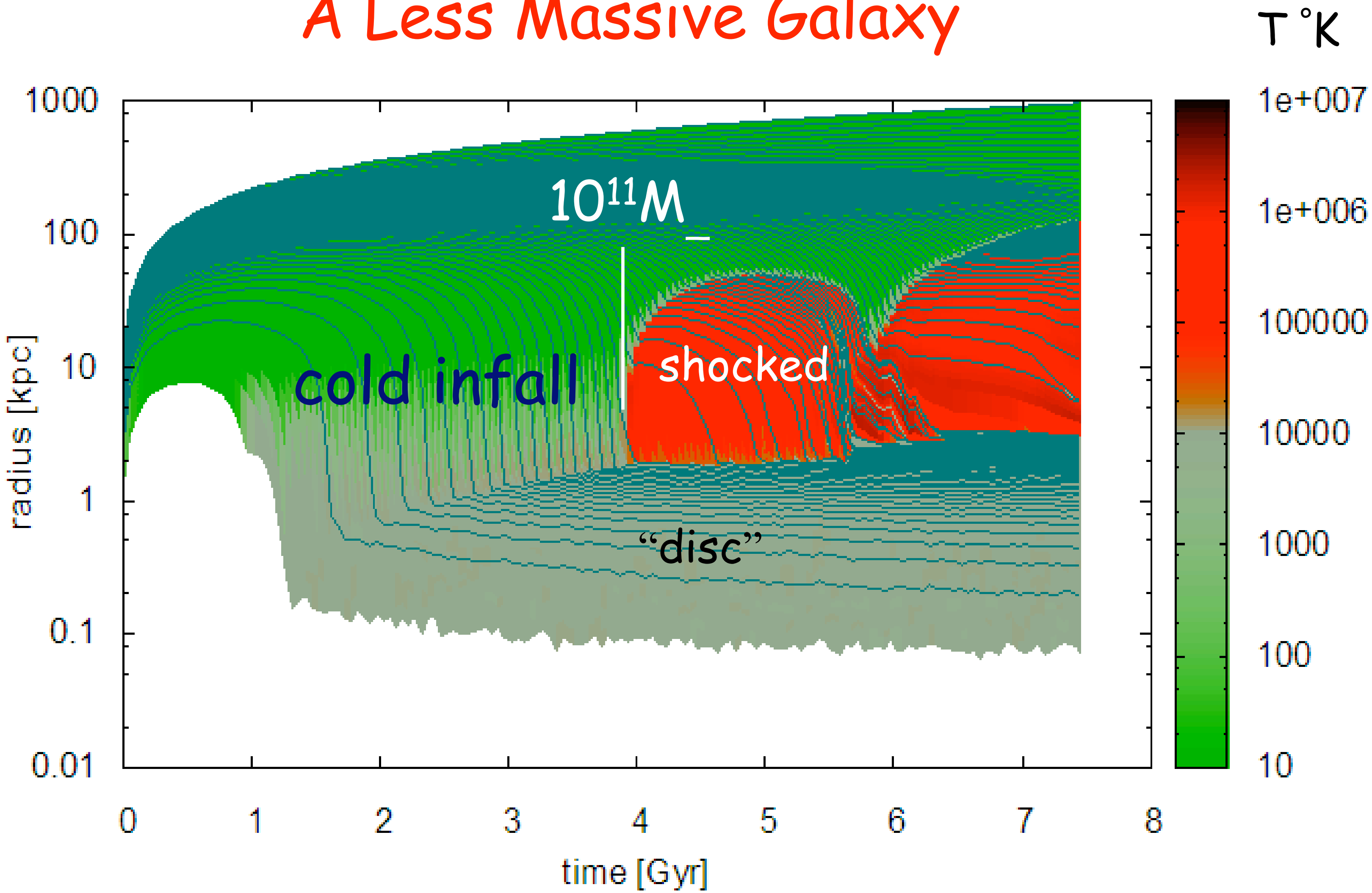
Growth of a Massive Galaxy



Spherical hydro simulation

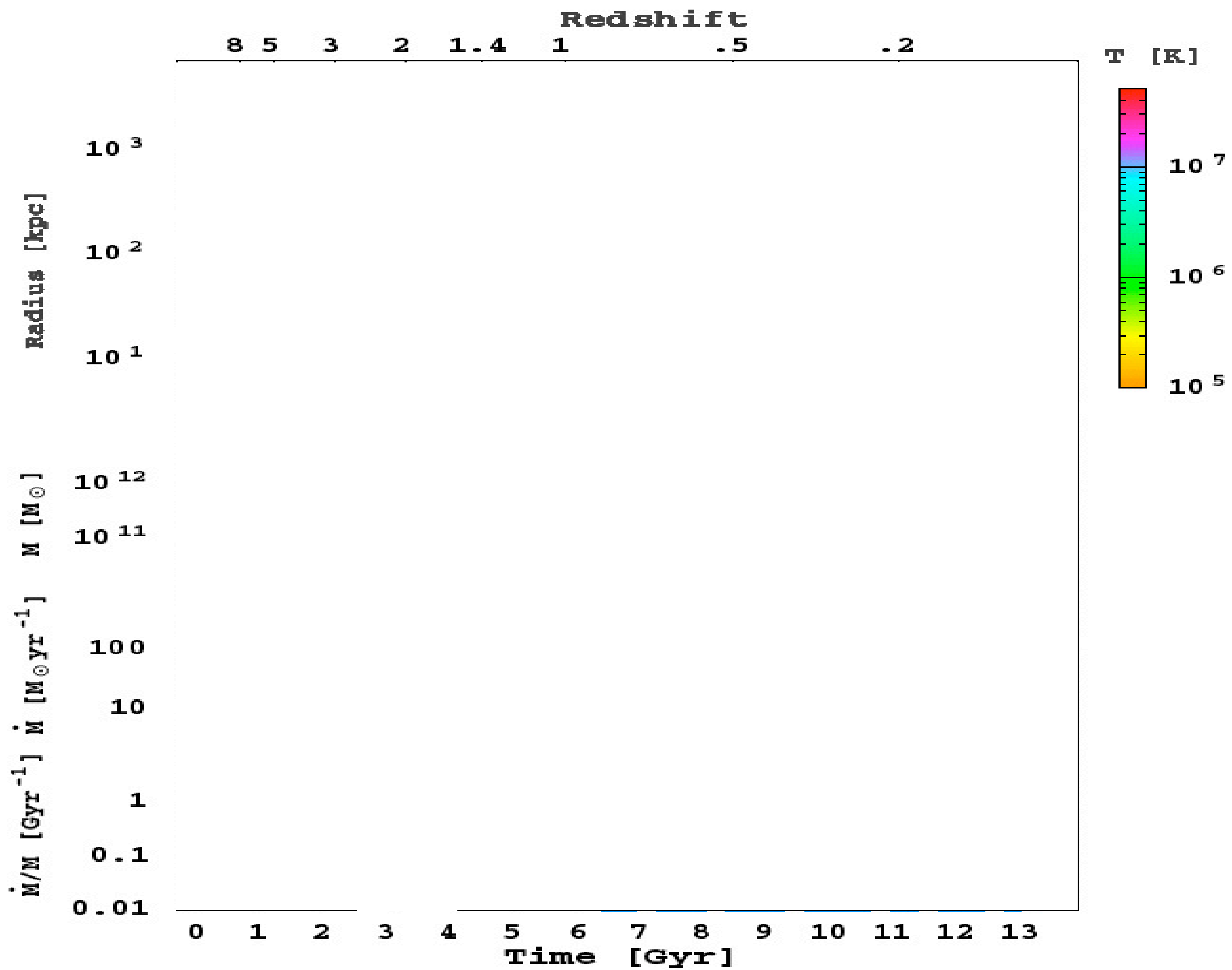
Birnboim & Dekel 03

A Less Massive Galaxy



Spherical hydro simulation

Birnboim & Dekel 03



Redshift
8
5
3
2
1.4
1
.5
.2
T [K]
10 7
10 6
10 5
Radius [kpc]
10 3
10 2
10 1
M [M⊙]
10 12
10 11
Ṁ [M⊙ yr -1]
100
10
Ṁ/M [Gyr -1]
1
0.1
0.01
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Time [Gyr]

Hydro Simulation: ~Massive $M=3\times10^{11}$

Kravtsov et al.

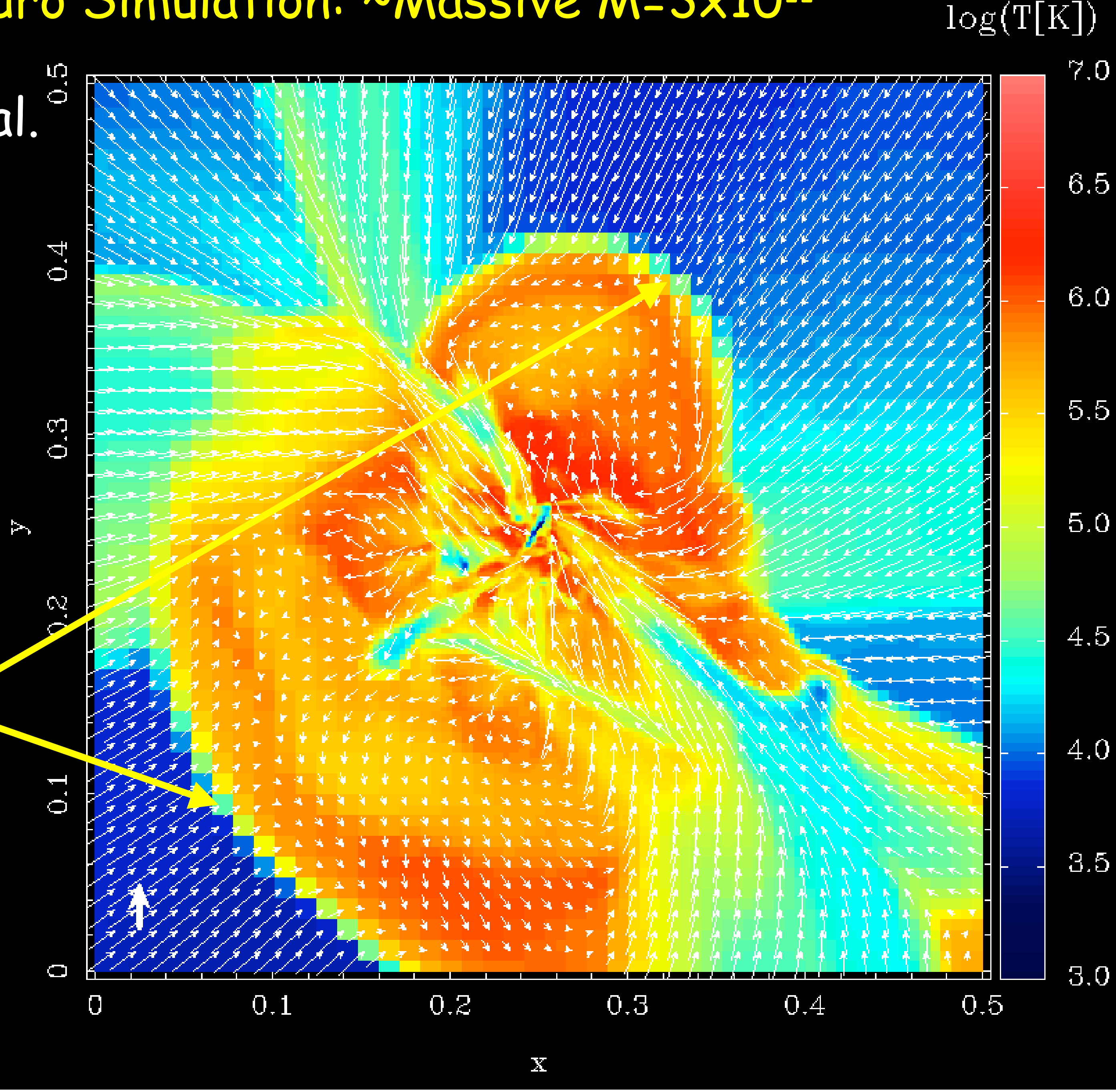
$z=4$

$M=3\times10^{11}$

$T_{vir}=1.2\times10^{6}$

$R_{vir}=34$ kpc

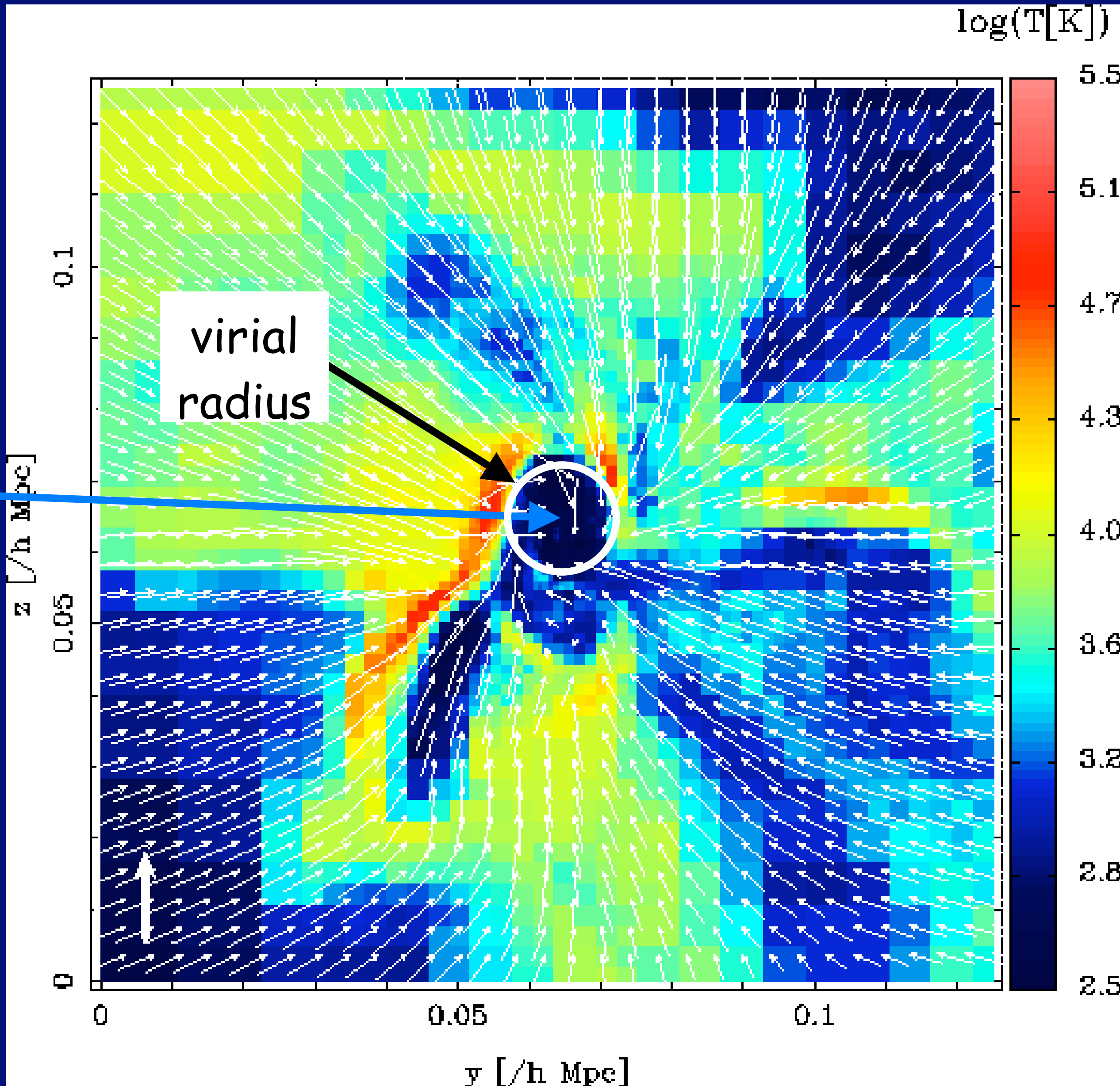
virial shock



Less Massive $M=1.8\times10^{10}$

Kravtsov et al.

cold infall



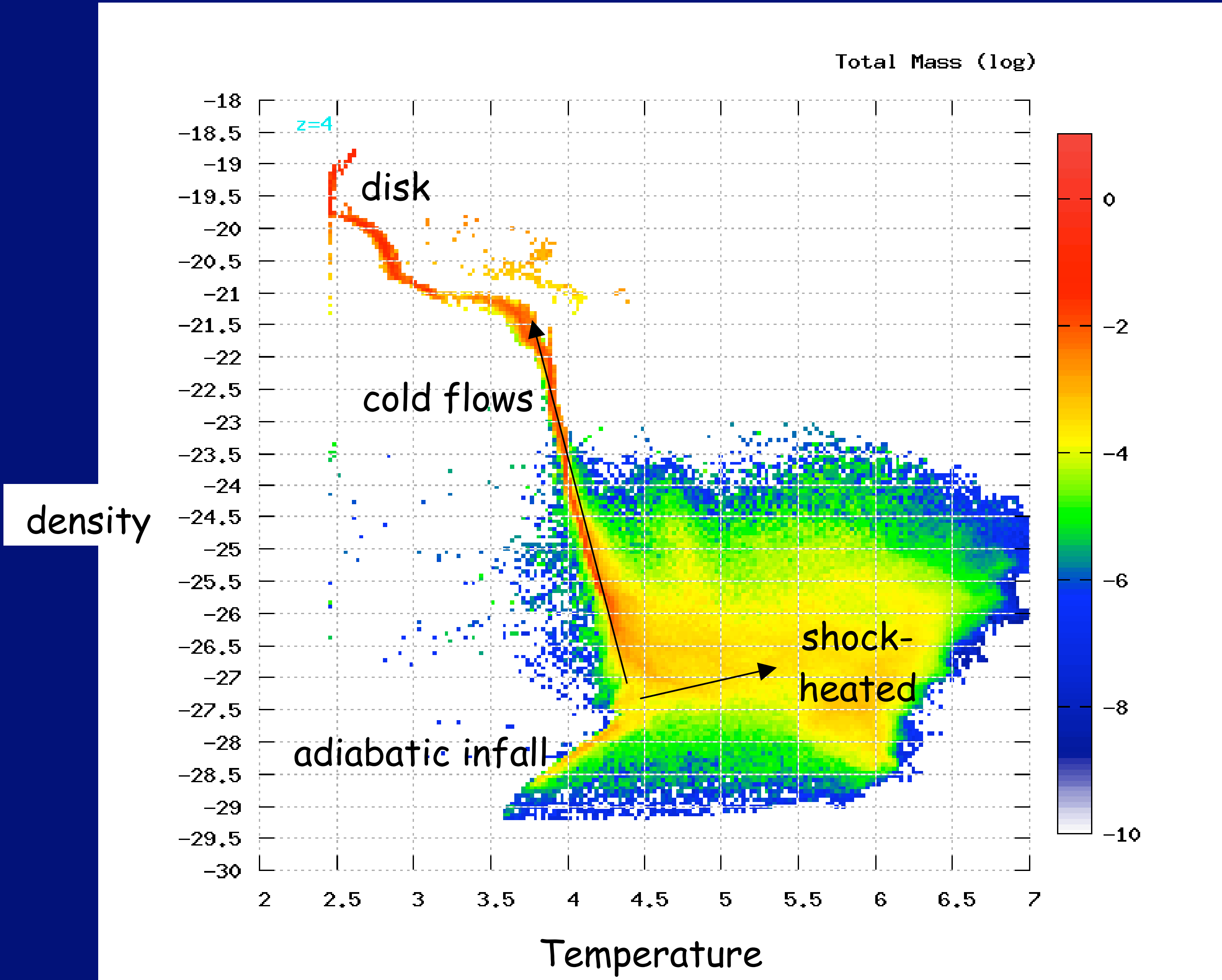
$z=9$

$M=1.8\times10^{10}$

$T_{vir}=3.5\times10^{5}$

$R_{vir}=7$ kpc

Mass Distribution of Halo Gas



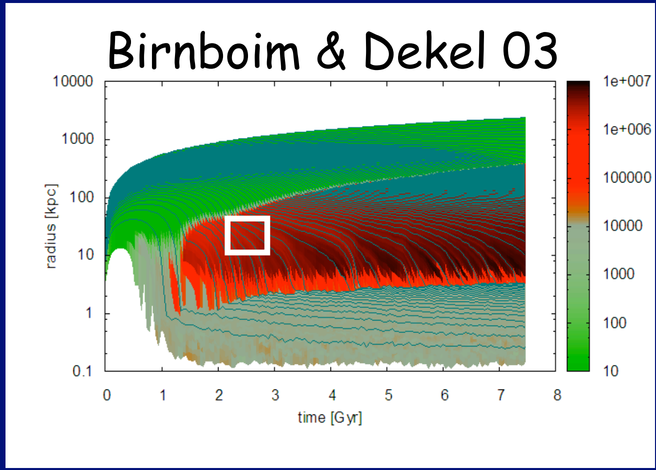
Analysis of Eulerian hydro simulations by Birnboim, Zinger, Dekel, Kravtsov

Shock Stability (Birnboim & Dekel 03) :

post-shock pressure vs. gravitational collapse

adiabatic: $\gamma = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$

stable: $\gamma > 4/3$



with cooling rate q (internal energy e):

$$\gamma_{eff} \equiv \frac{d(\ln P)}{d(\ln \rho)} = \gamma - \frac{\rho}{\dot\rho}\frac{q}{e} = \frac{5}{3} - \frac{5}{21}\frac{t_{comp}}{t_{cool}}$$

$$\dot e = -P\dot V - q$$

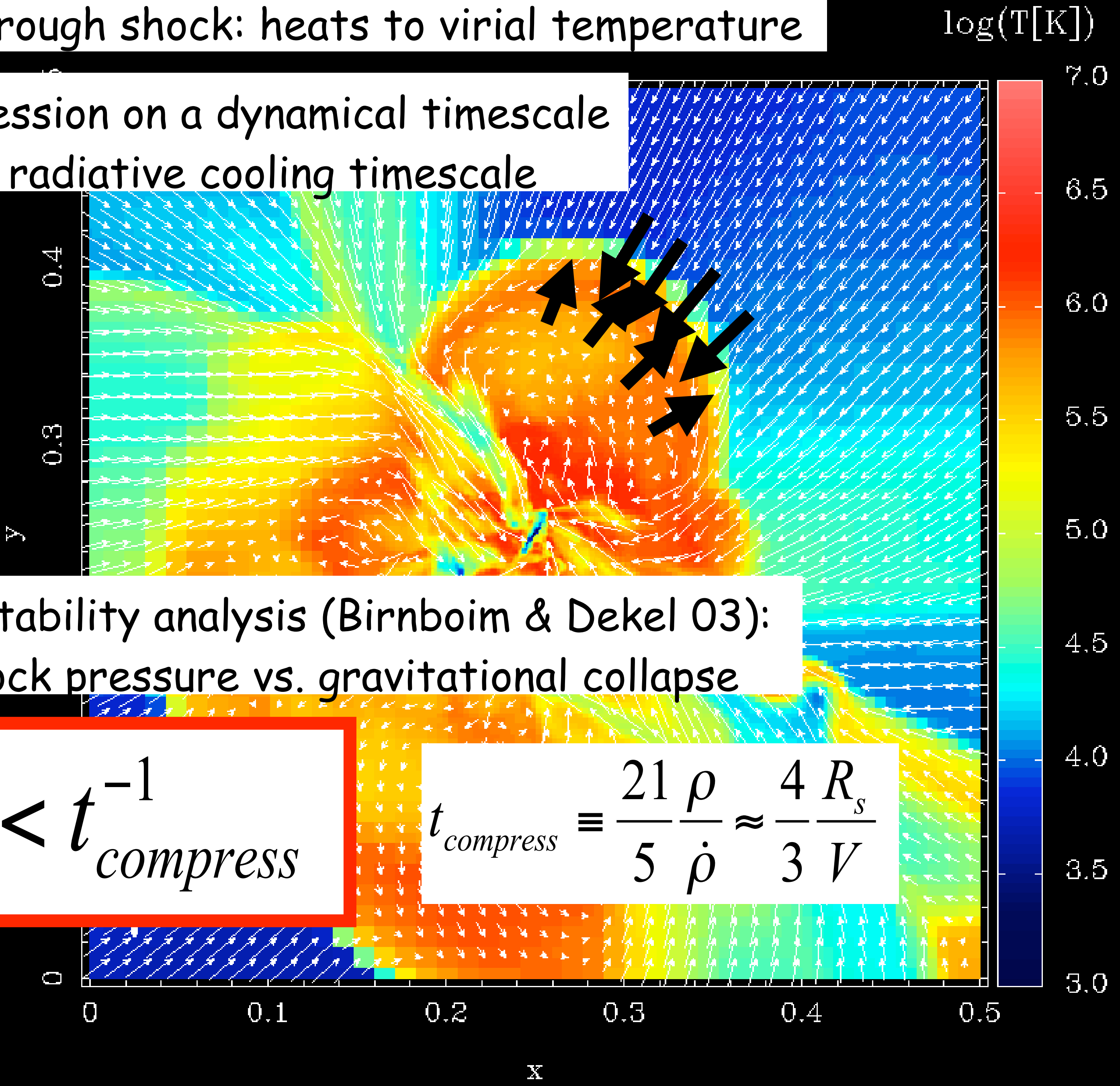
$$t_{comp} \equiv \frac{21}{5}\frac{\rho}{\dot\rho} \approx \frac{4}{3}\frac{R_s}{V}$$

$$t_{cool} \equiv \frac{e}{q} \propto \frac{T}{\rho\Lambda(T,Z)} \qquad T \approx \frac{3}{16}V^2 \qquad \rho_{post} \approx 4\rho_{pre}$$

Stability criterion: $\gamma_{eff} > \frac{10}{7} \longrightarrow \boxed{t_{cool}^{-1} < t_{compress}^{-1}}$

Gas through shock: heats to virial temperature

compression on a dynamical timescale
versus radiative cooling timescale

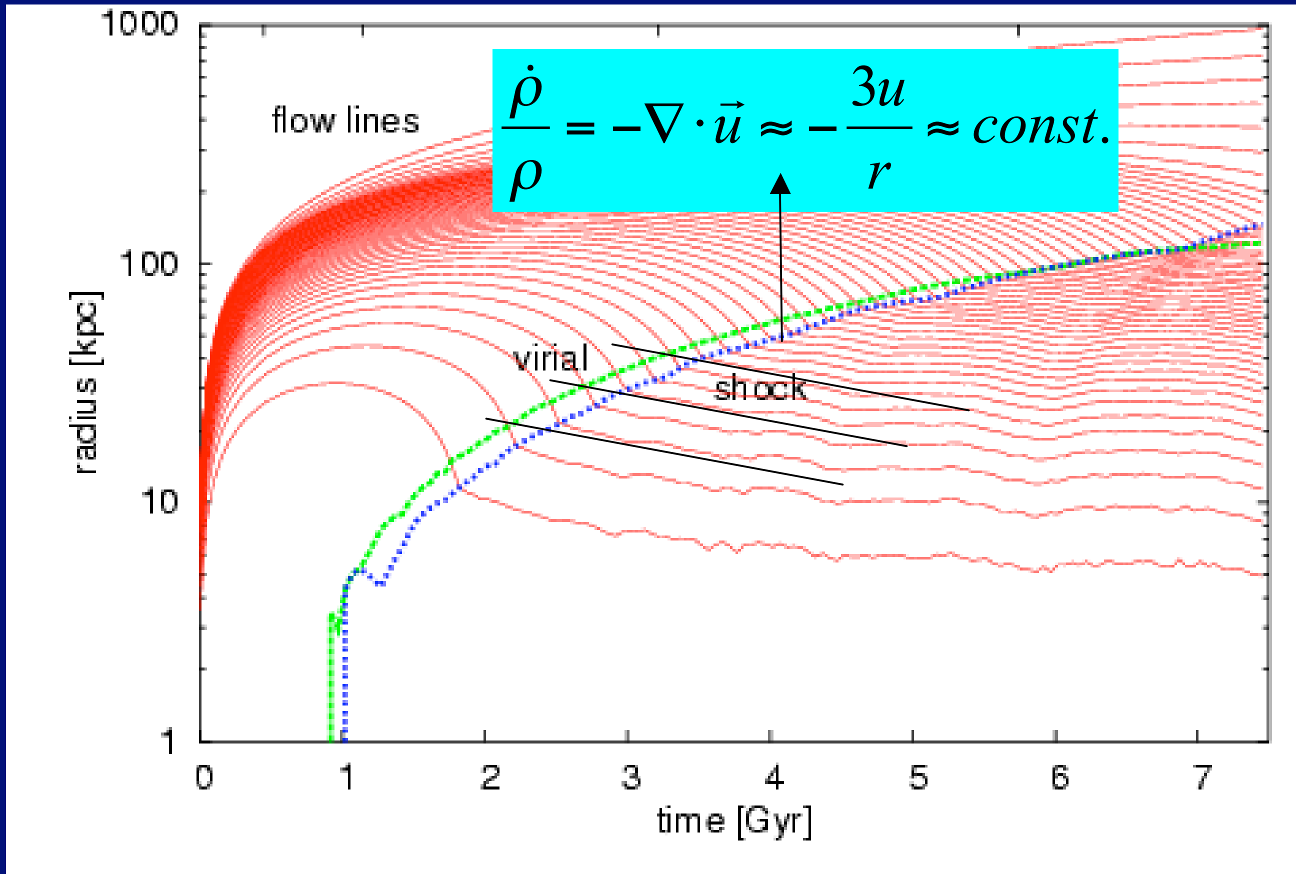


Shock-stability analysis (Birnboim & Dekel 03):
post-shock pressure vs. gravitational collapse

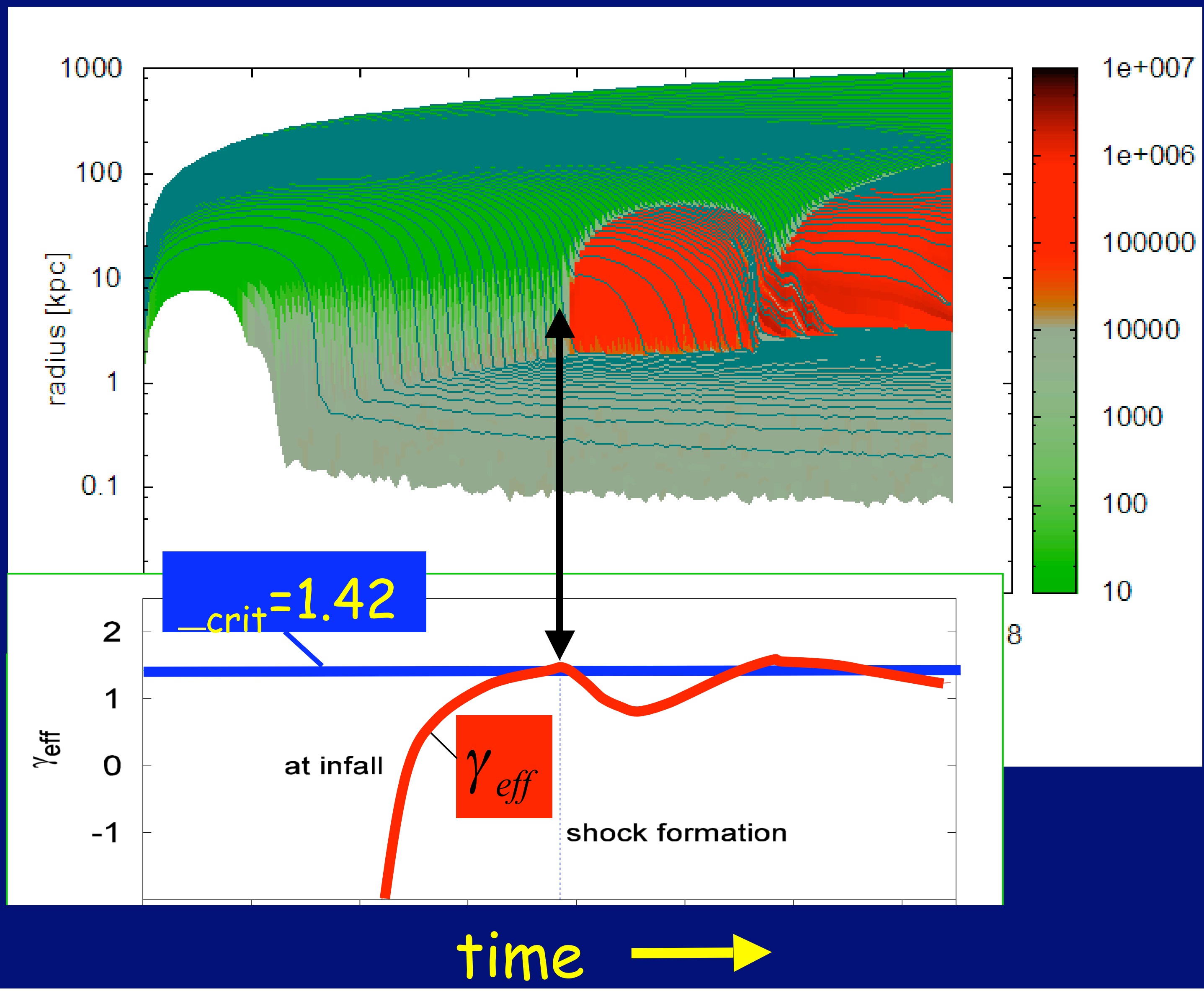
$$\boxed{t_{cool}^{-1} < t_{compress}^{-1}}$$

$$t_{compress} \equiv \frac{21}{5}\frac{\rho}{\dot{\rho}} \approx \frac{4}{3}\frac{R_s}{V}$$

Compression



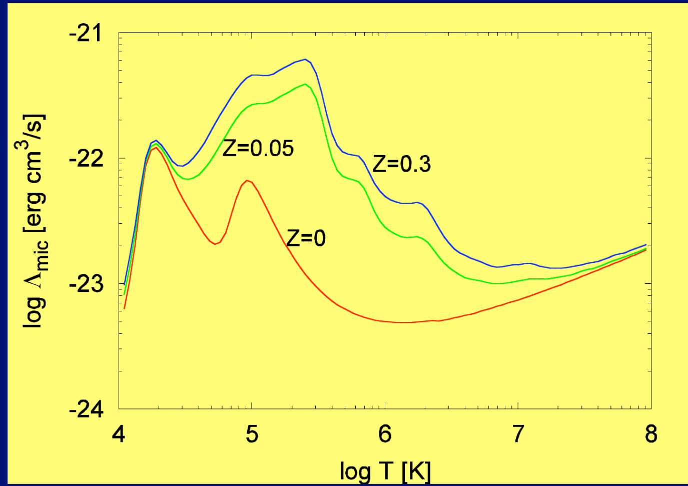
Spherical Simulation vs Model



Critical mass for shock heating:

Apply $t_{cool} \sim t_{compress}$ with _, V, R at the virial radius for ΛCDM halos

Approximate cooling: $\Lambda \propto Z^{0.7} T^{-1}$



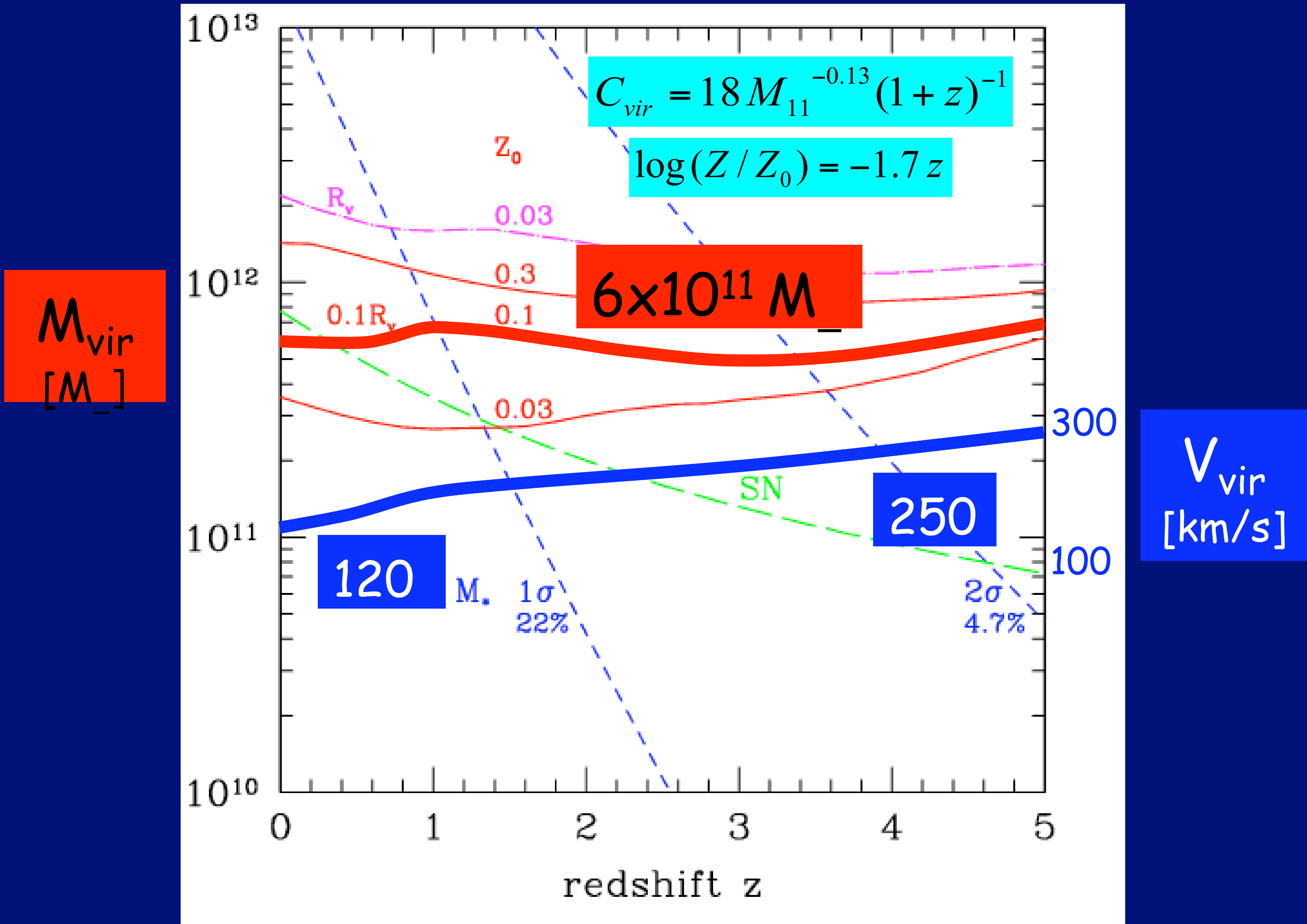
$T \sim 1.6\times10^6$ K [$(Z/0.1)^{0.7}$ $(f_b/0.05)$ $(\_r/v)_{0.1Rv}$ $(1+z)^{3/2}]^{1/2}$

$V_{vir} \sim 140$ km/s [$(Z/0.1)^{0.7}$ $(f_b/0.05)$ $(\_r/v)_{0.1Rv}$ $(1+z)^{3/2}$ $]^{1/4}$

$M_{halo} \sim 7\times10^{11}$ $M_{\_}$ [$(Z/0.1)^{0.7}$ $(f_b/0.05)$ $(\_r/v)_{0.1Rv}$ $(1+z)^{-1/2}$ $]^{3/4}$

~coincides with the bi-modality scale

Shock-Heating Scale



Fraction of cold/hot accretion

SPH simulation

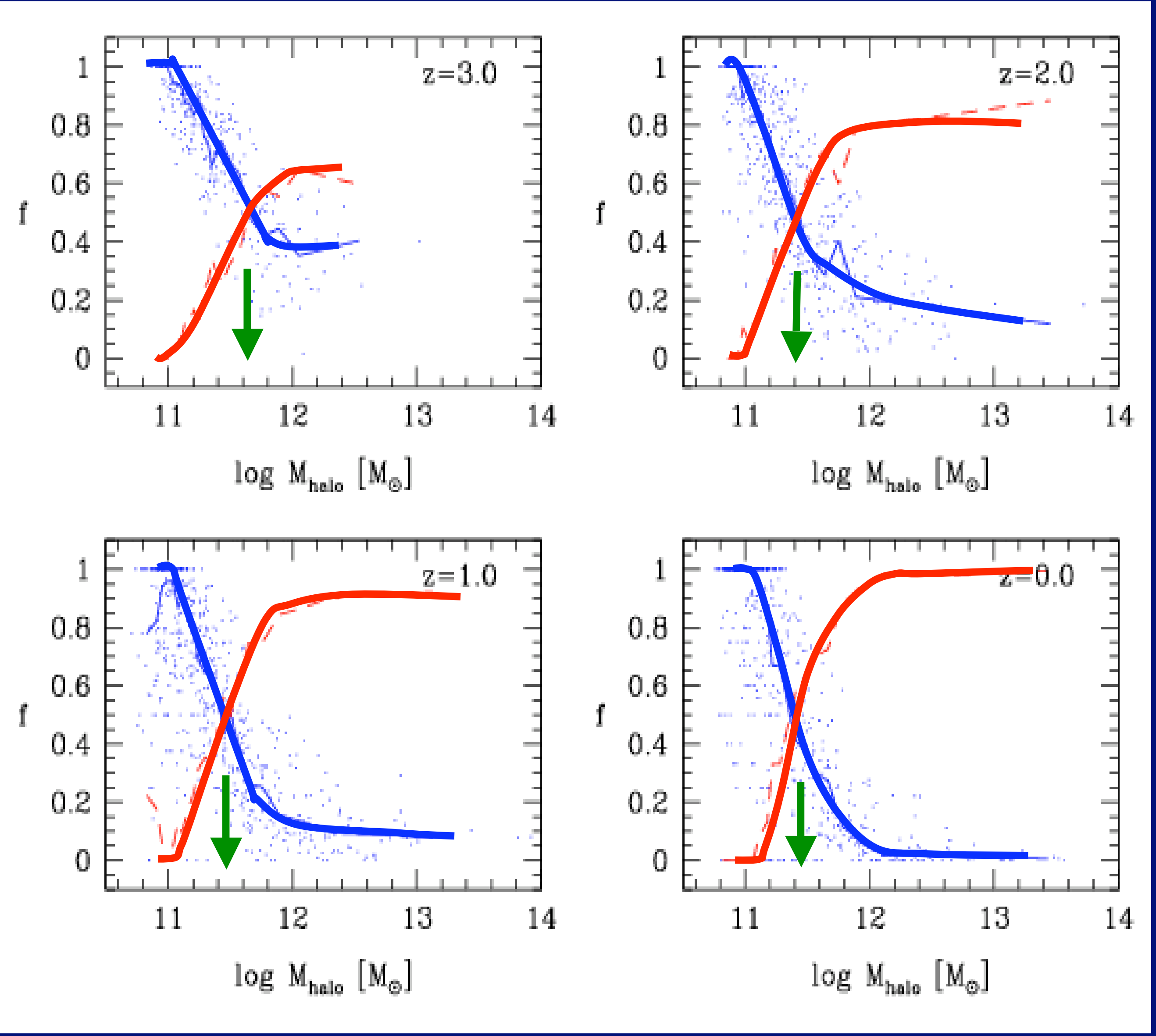
Keres, Katz, Weinberg, Dav'e 2004

Z=0, under-estimating M_{shock}

sharp transition

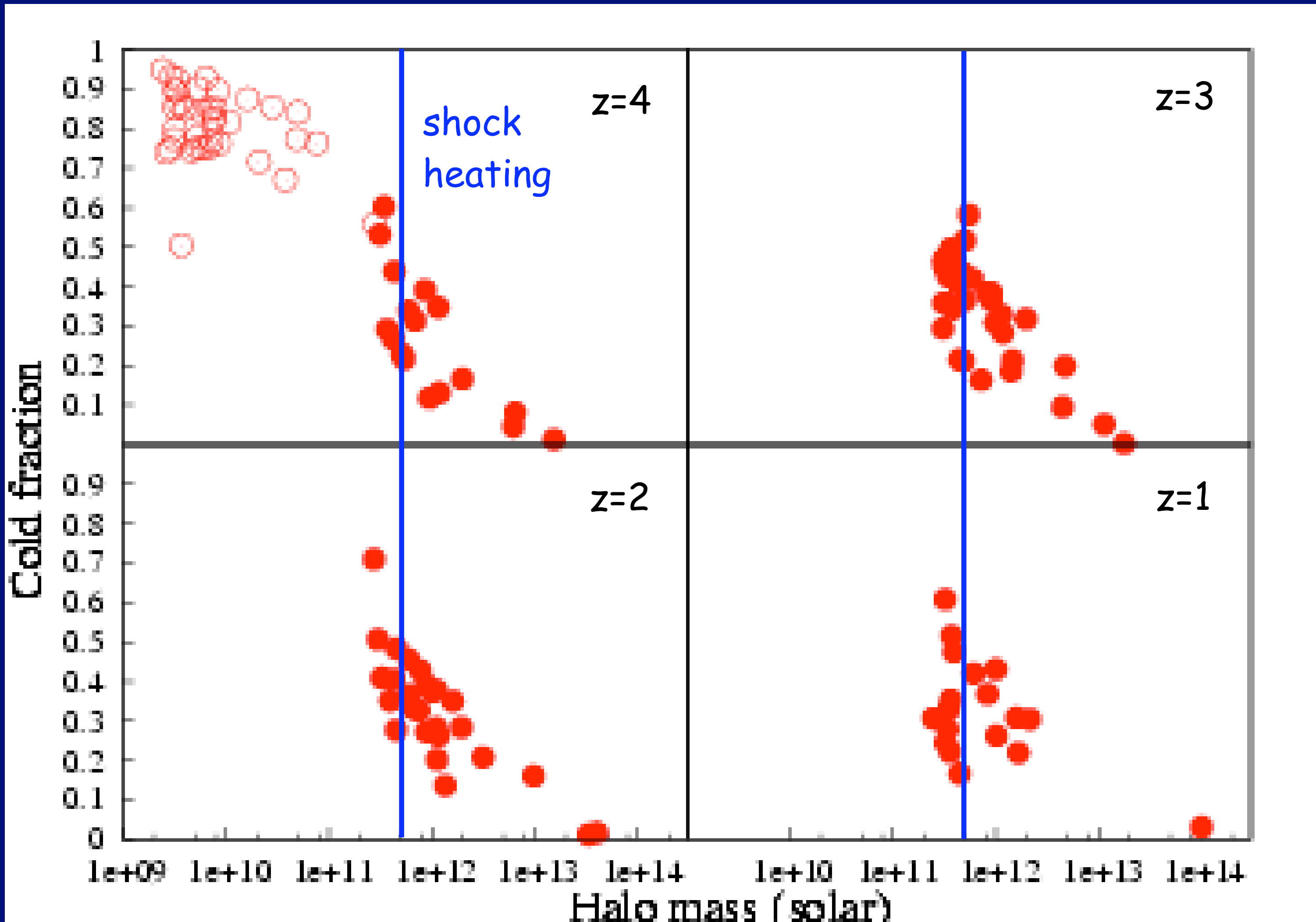
$$\frac{M_{cold}}{M_{tot}} \propto M^{-2/3}$$

$$\rightarrow \frac{M}{L} \propto M^{2/3}$$

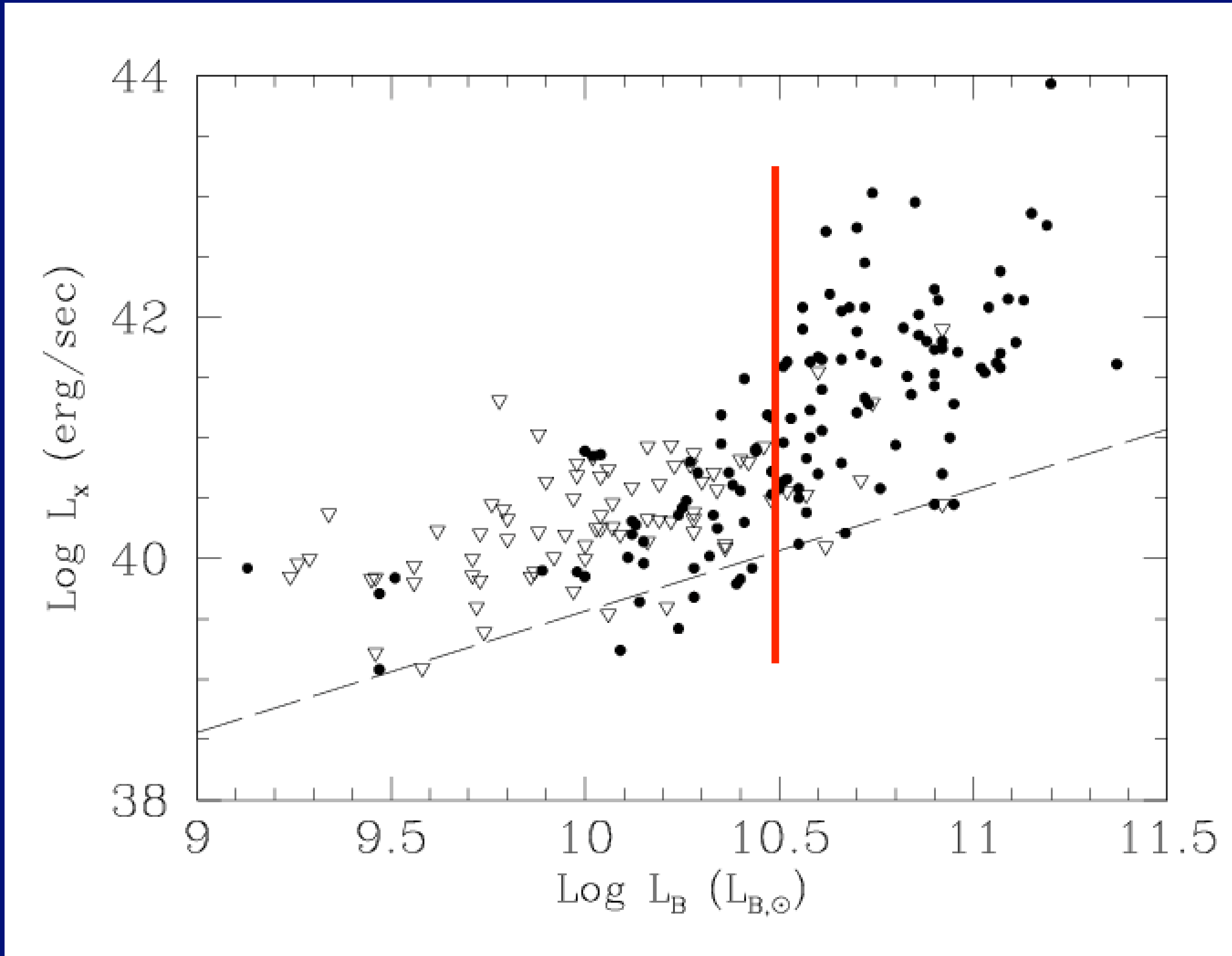


Fraction of cold gas in halos: Eulerian simulations

Birnboim, Dekel, Kravtsov, Zinger 2007

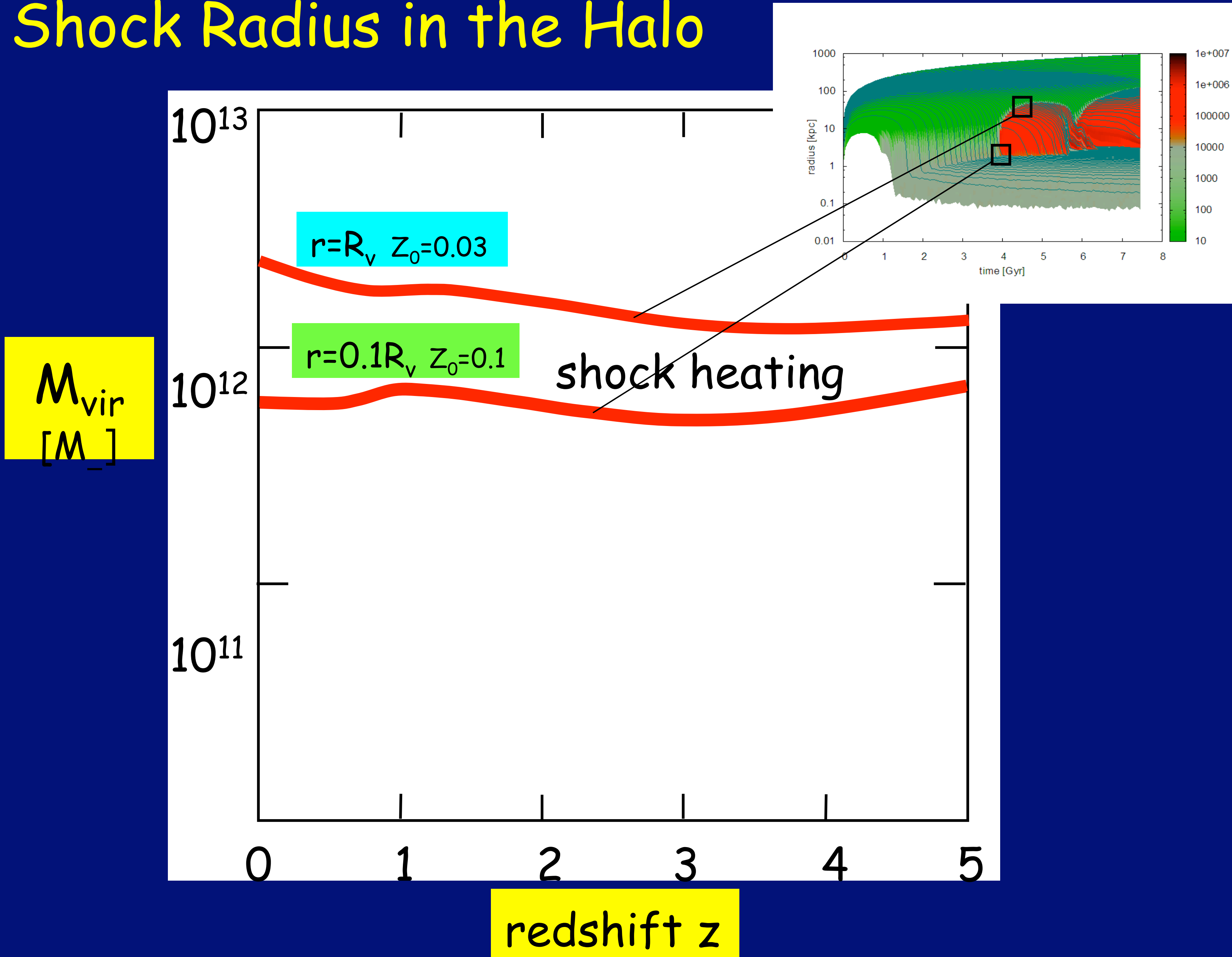


Hot Gas in Elliptical Galaxies

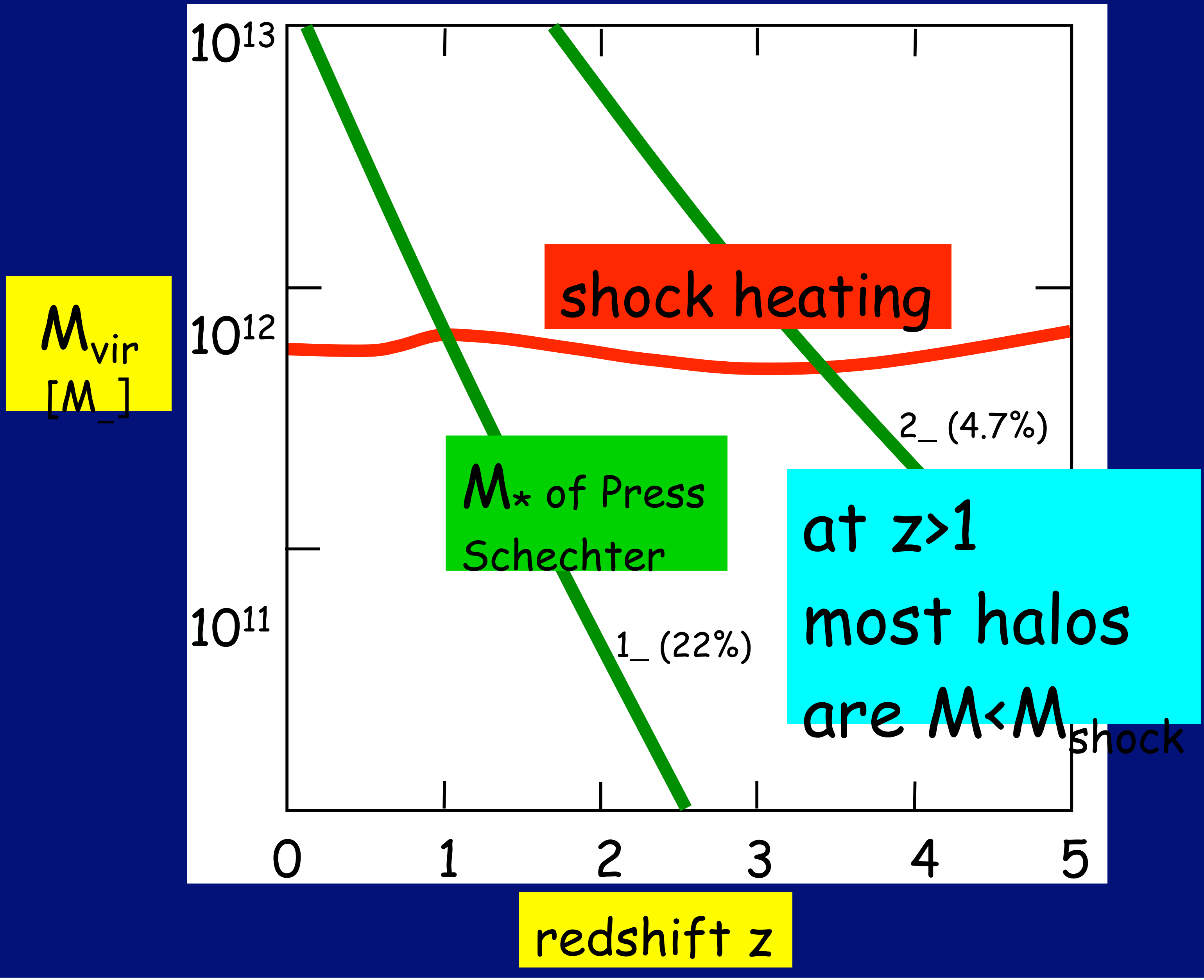


Mathews & Brighenti 04; O'Sullivan et al. 01

Shock Radius in the Halo

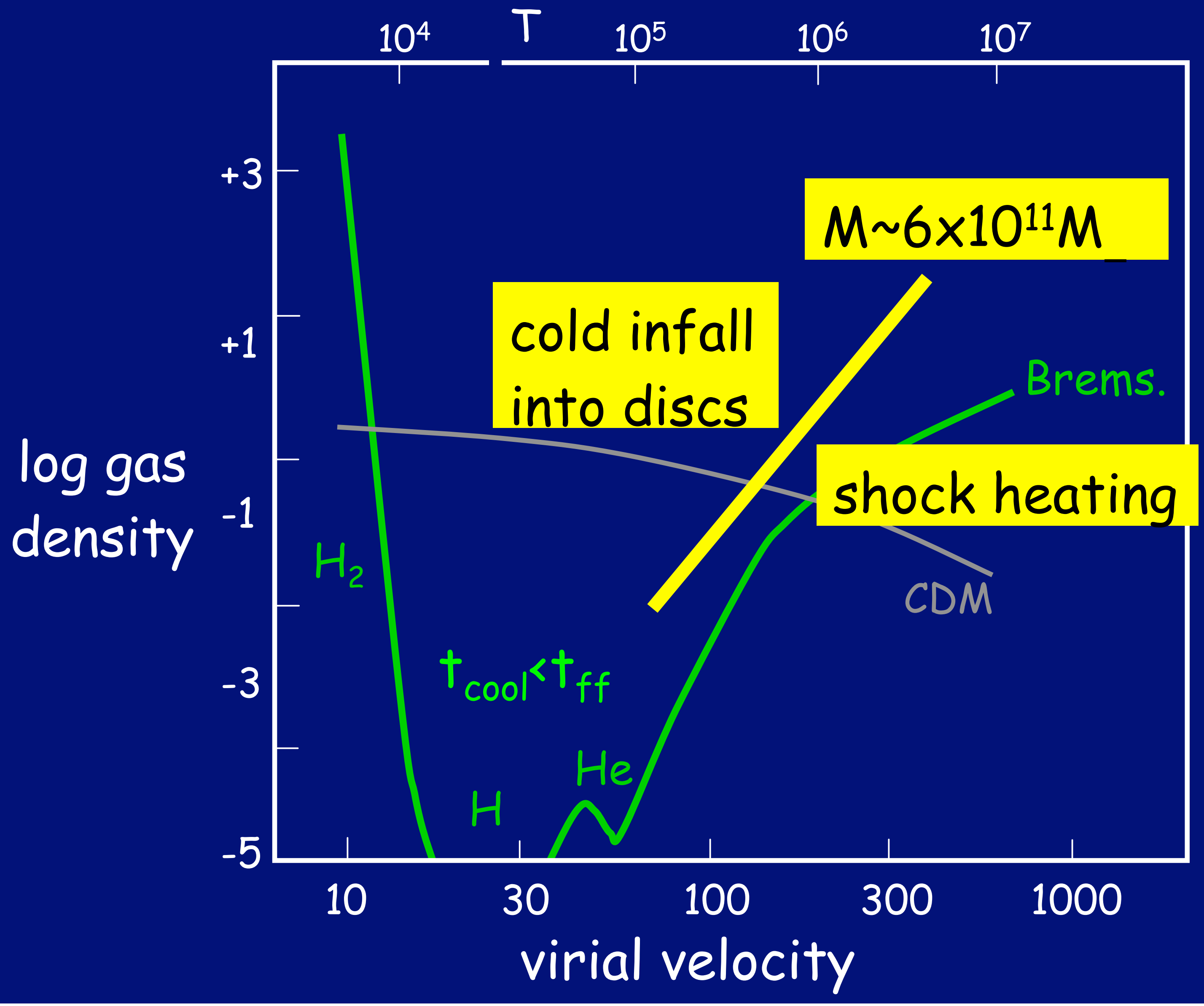


Cold Flows in Typical Halos



Shock-heating Scale

Birnboim & Dekel 03



3. Filaments in Hot Medium

At high redshift, in relatively isolated galaxies

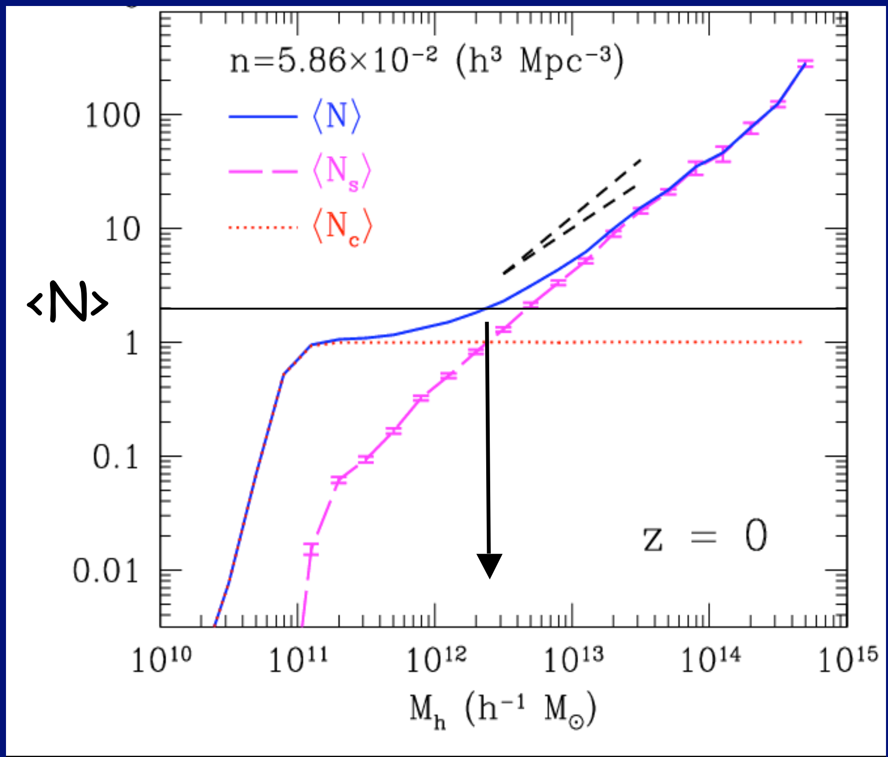
Relation to the universal clustering scale

Clustering Scale

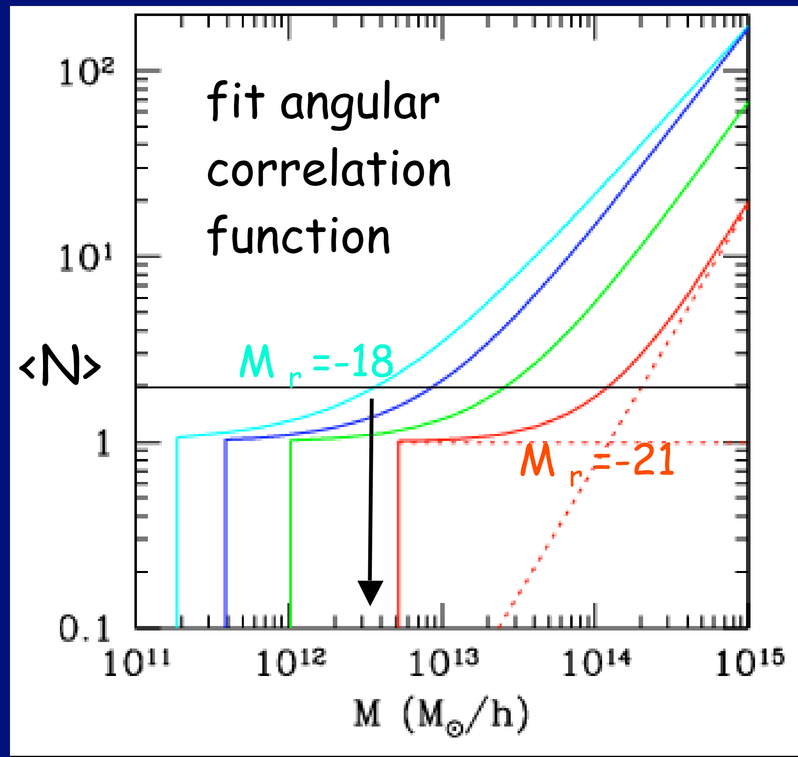
Cooling vs dynamical time scales?

or/and gravity + fluctuation amplitude?

Dark-Matter Halo Occupation Distribution



Kravtsov et al. 04, N-body simulations



Zehavi et al. 04, SDSS

$M \sim M_*(t) \rightarrow$ group at z=0 ~$10^{13}M$_ at z=1 ~$10^{12}M$_

$M \ll M_*(t)$ °˙early formation, satellites decay by dynamical friction

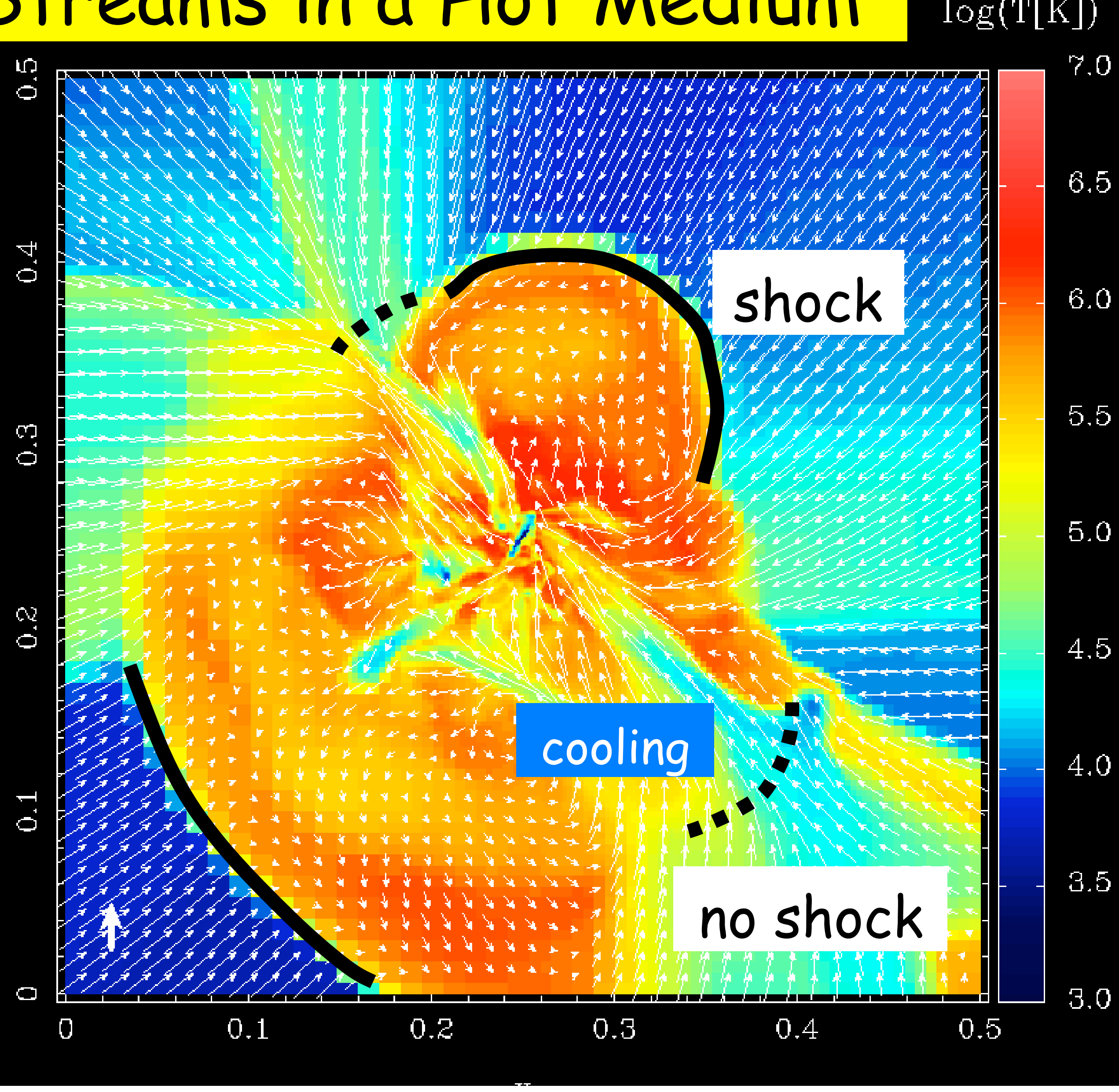
$$\frac{m_{sat}}{M_{halo}} < (0.01 - 0.1)\left(\frac{M_{halo}}{M_{*0}}\right)^{0.3}$$

At High z, in Massive Halos: Cold Streams in a Hot Medium

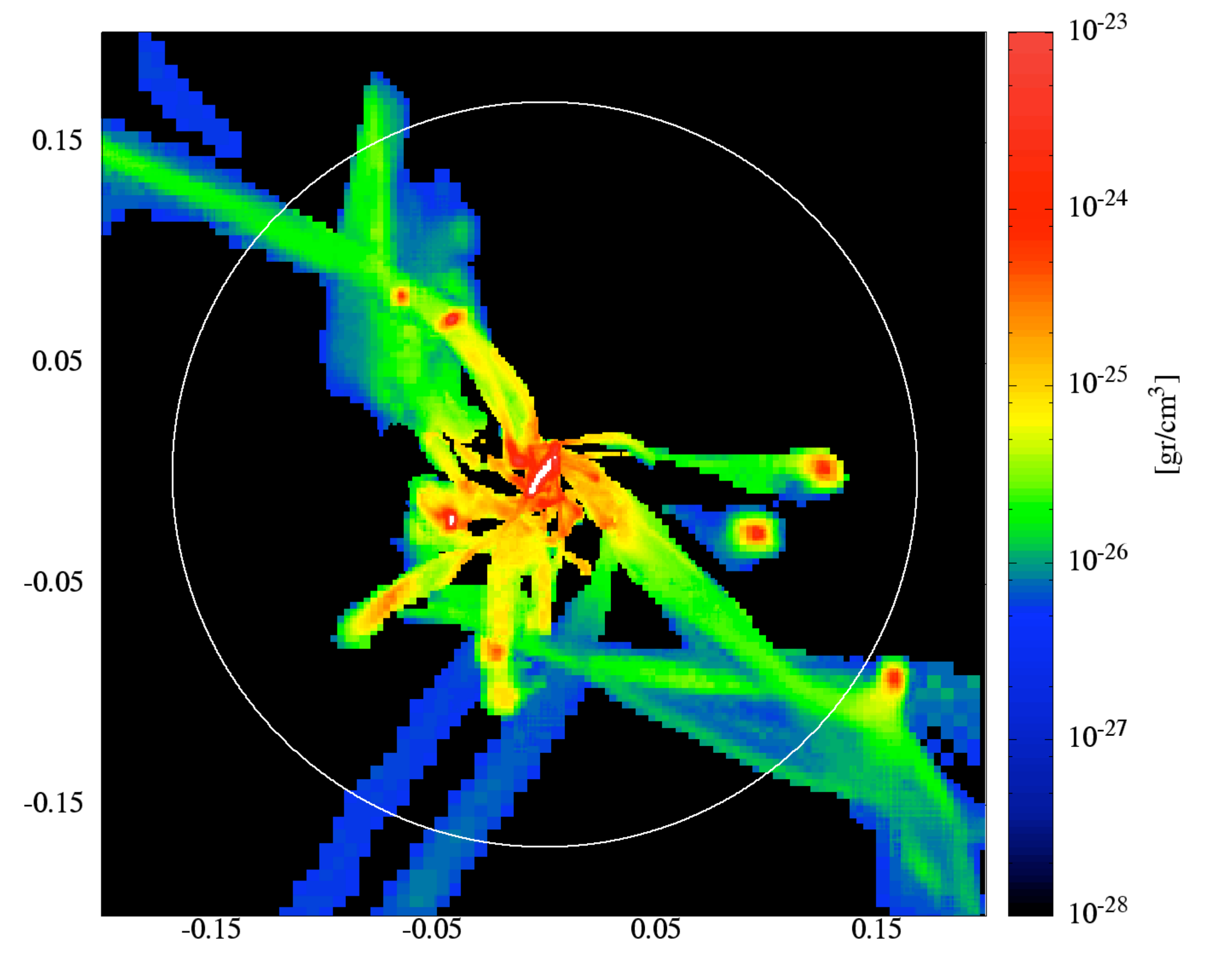
in $M>M_{shock}$

Totally hot at z<1

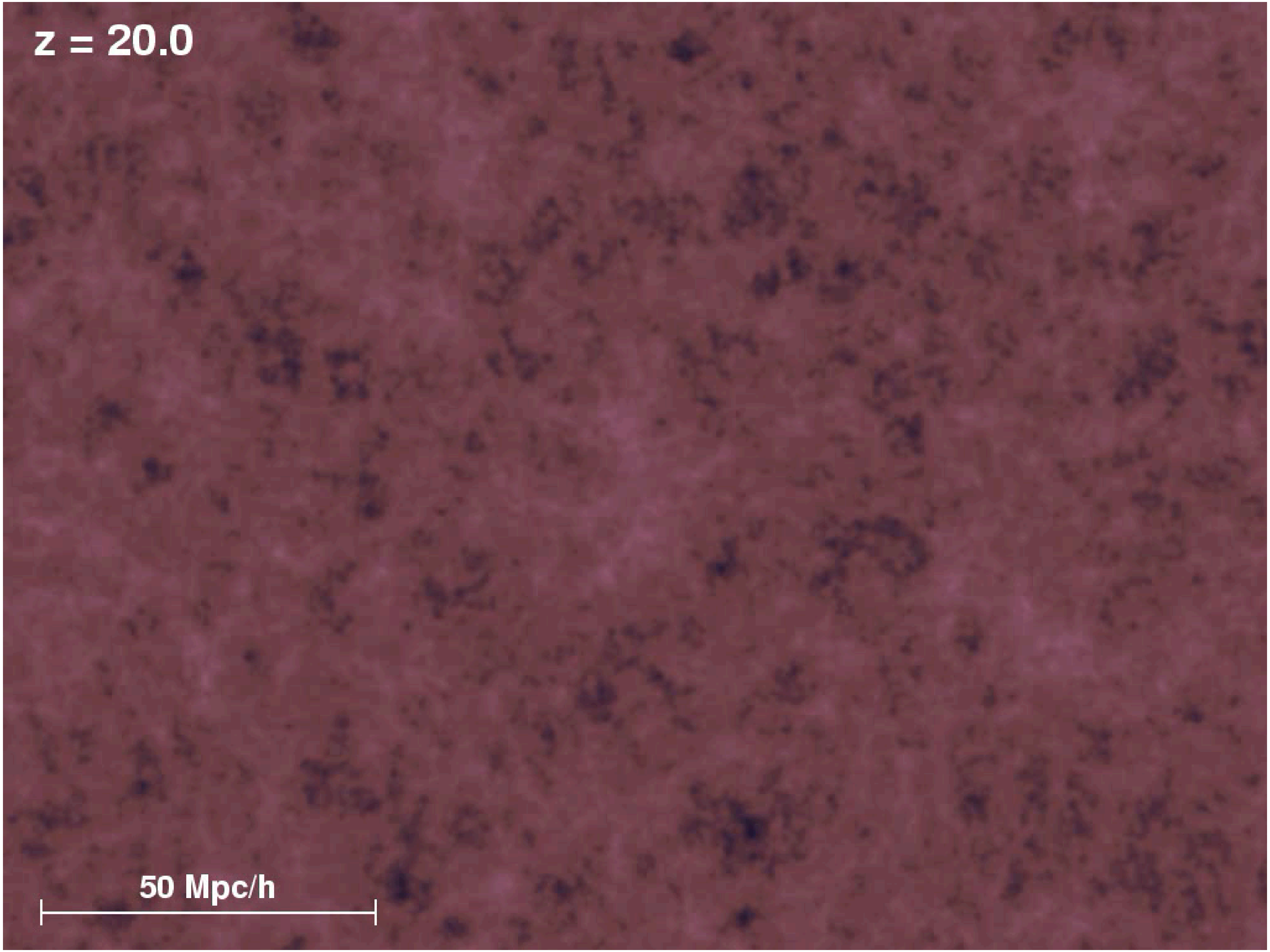
Cold streams at z>2



Cold, dense filaments and clumps (50%) riding on dark-matter filaments and sub-halos



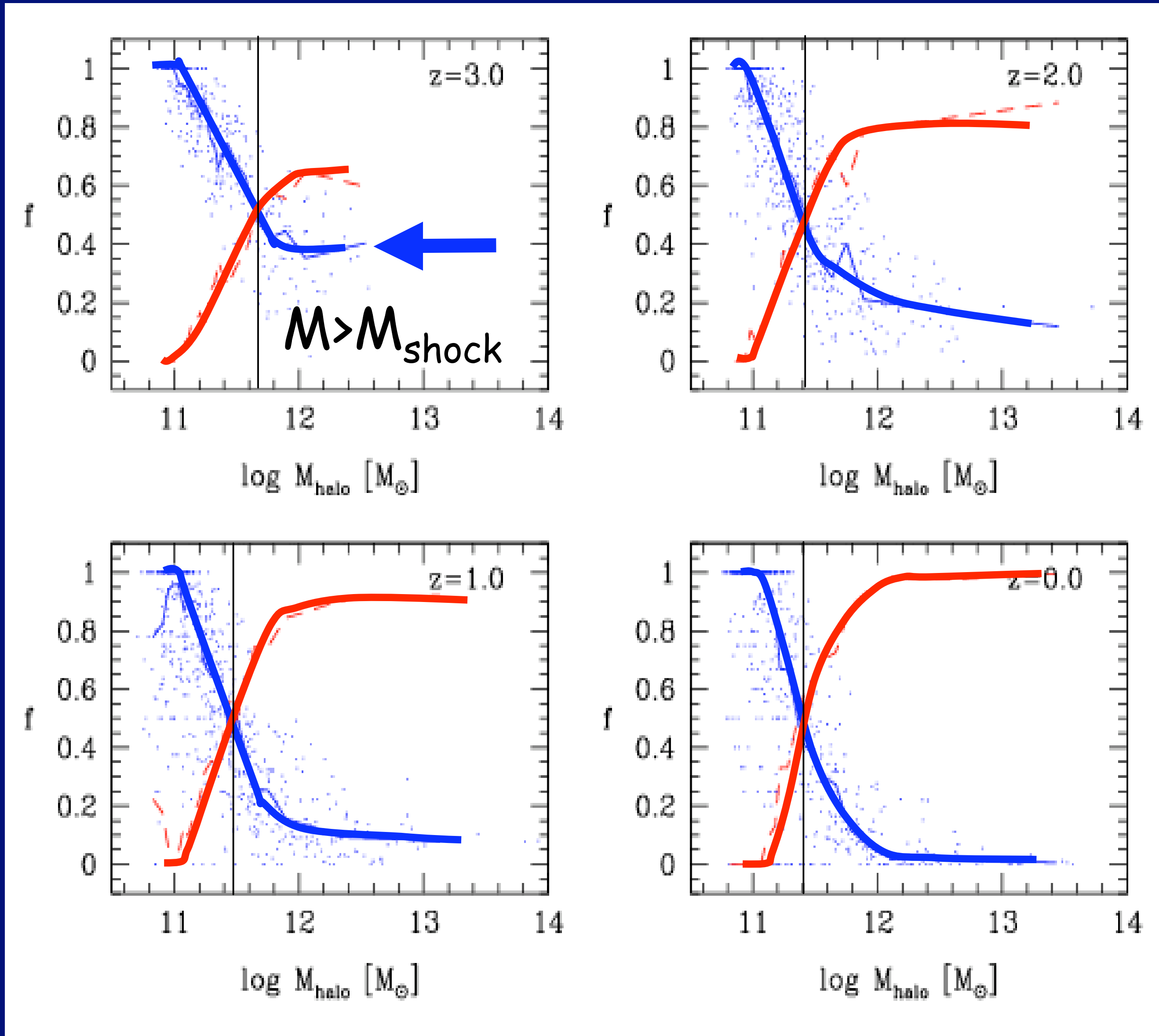
Birnboim, Zinger, Dekel, Kravtsov


z = 20.0
50 Mpc/h

Formation of Large-Scale Structure: comoving

Fraction of cold/hot accretion

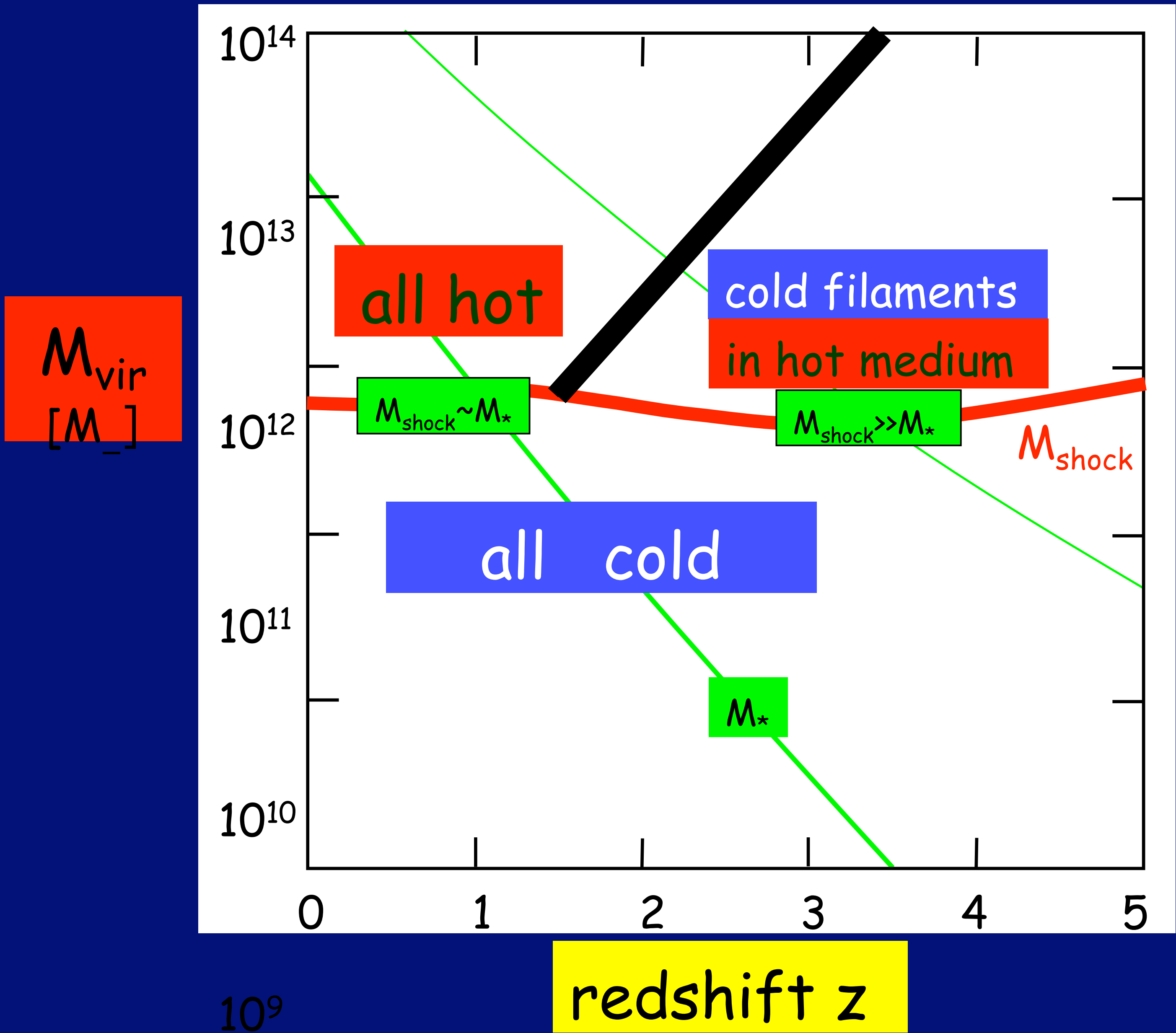
cold streams in a hot medium

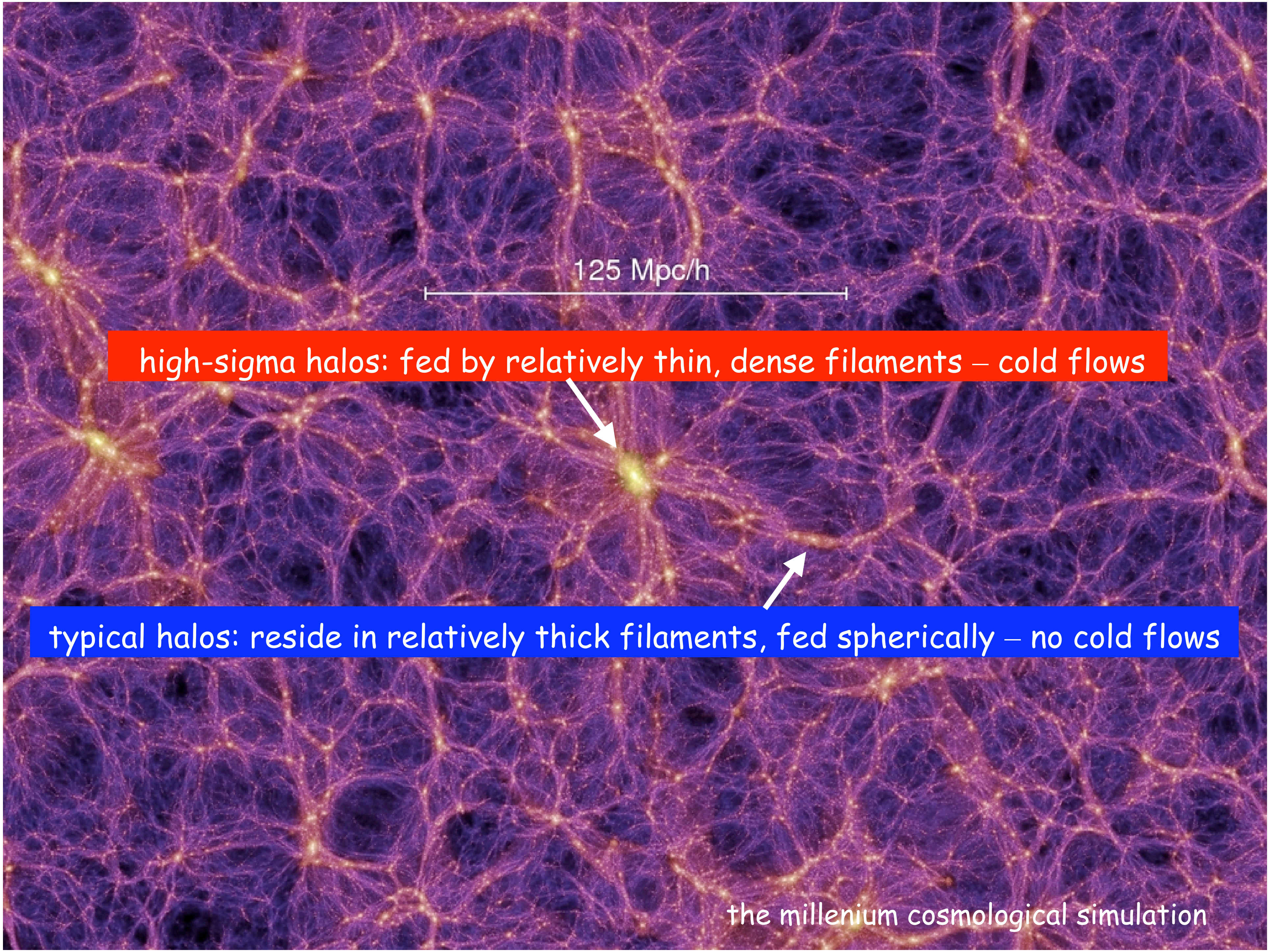


SPH simulation

Keres, Katz, Weinberg, Dav'e 2004

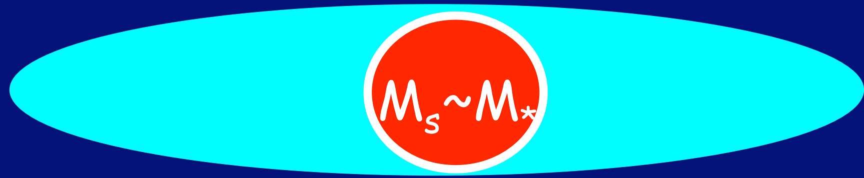
Cold Streams in Big Galaxies at High z



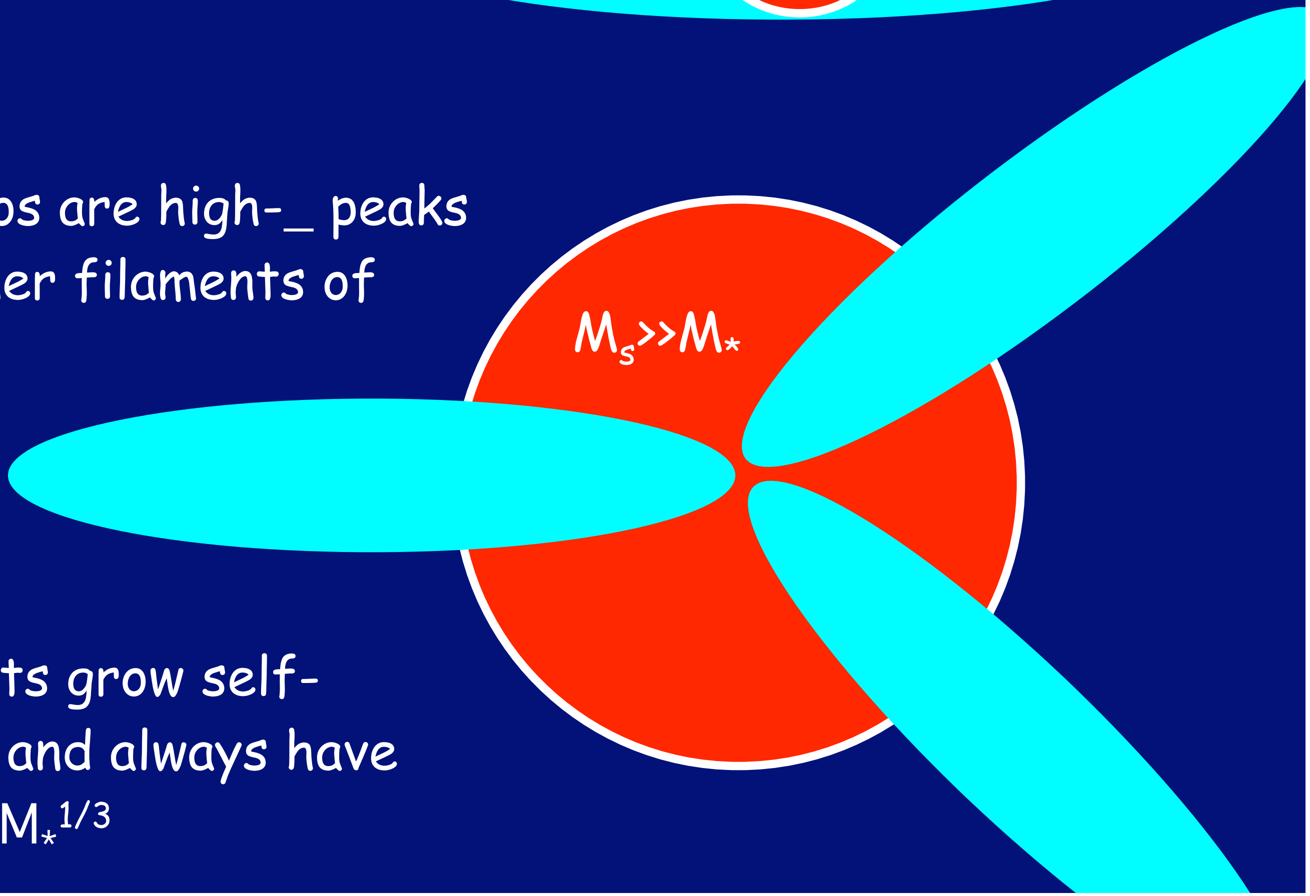

125 Mpc/h
high-sigma halos: fed by relatively thin, dense filaments – cold flows
typical halos: reside in relatively thick filaments, fed spherically – no cold flows
the millenium cosmological simulation

Origin of dense filaments in hot halos (M_M_{shock}) at high z

At low z, M_{shock} halos are typical - residiing in thicker filaments of comparable density



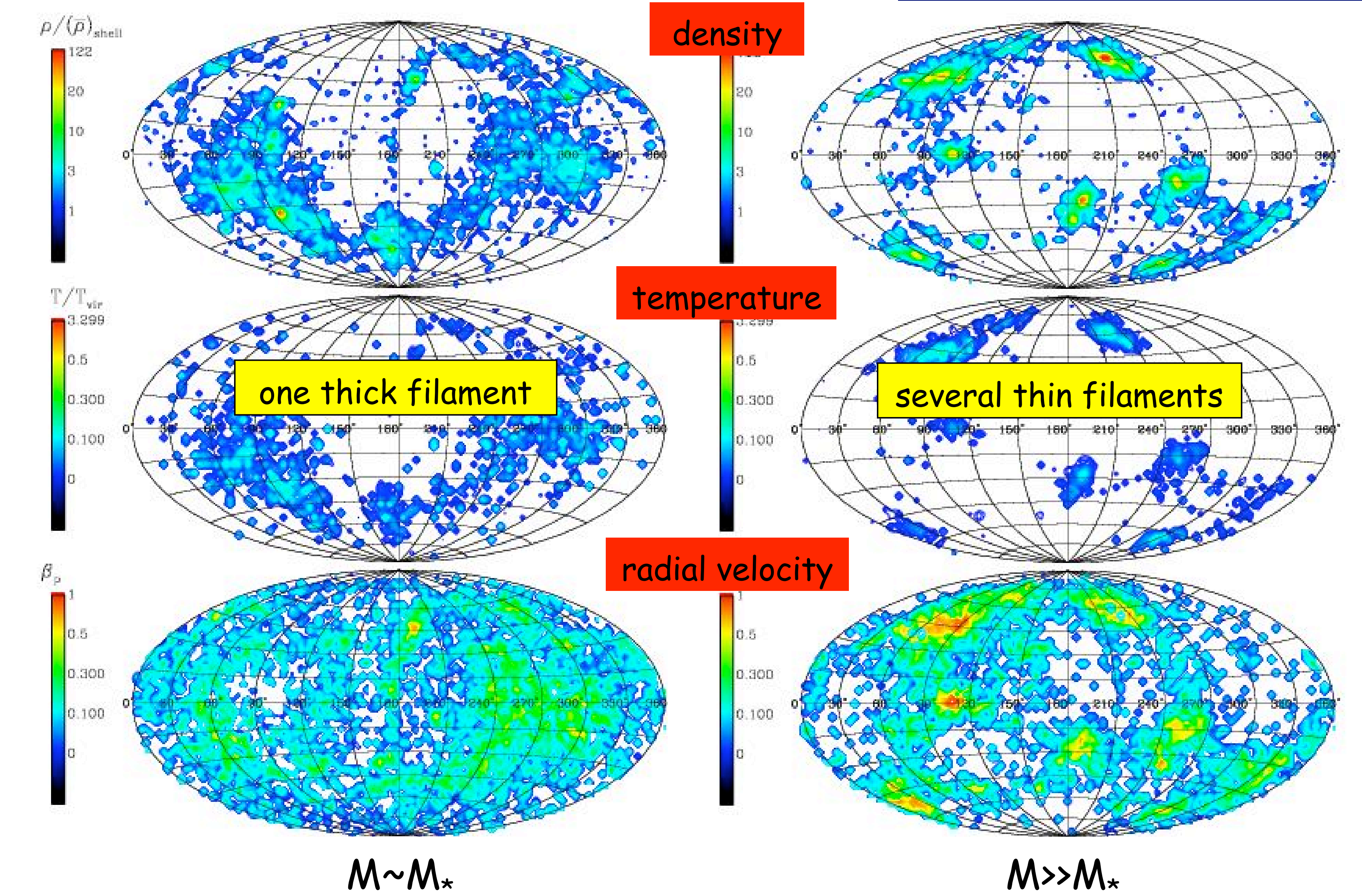
At high z, M_{shock} halos are high-_ peaks - fed by a few thinner filaments of higher density



Large-scale filaments grow self-similarly with $M_*(t)$ and always have typical width $\sim R_* \propto M_*^{1/3}$

Dark-matter inflow in a shell 1-3R_{vir}

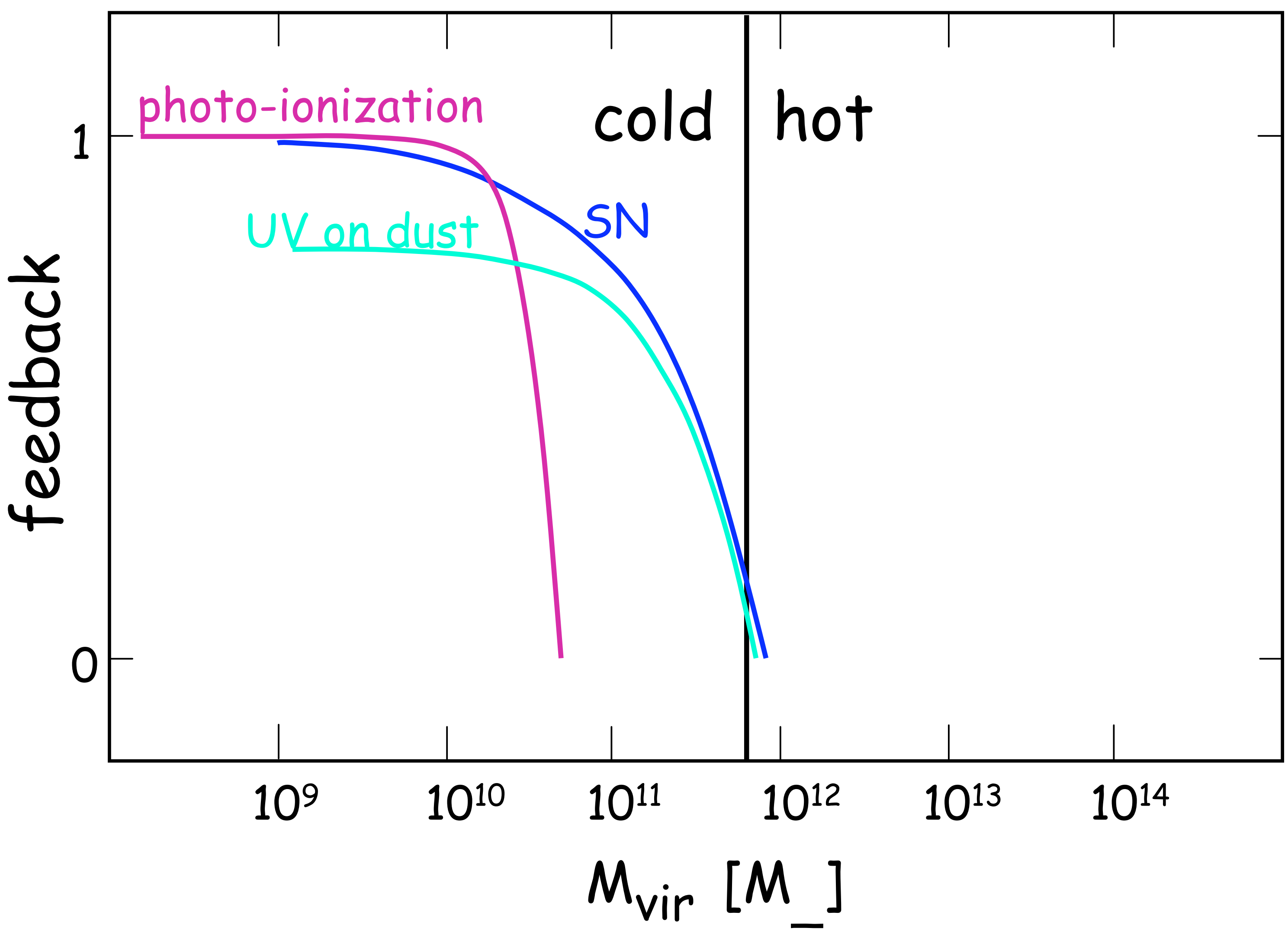
Seleson & Dekel



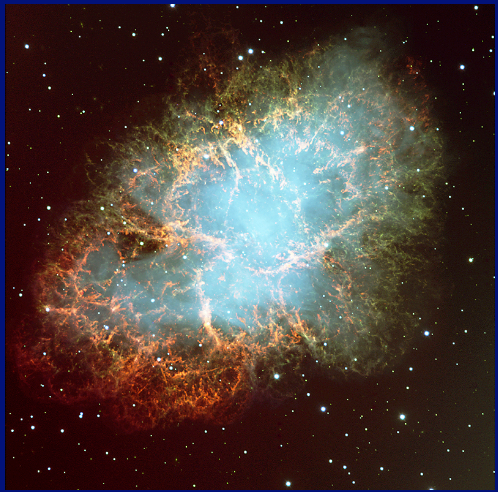
4. Feedback Processes

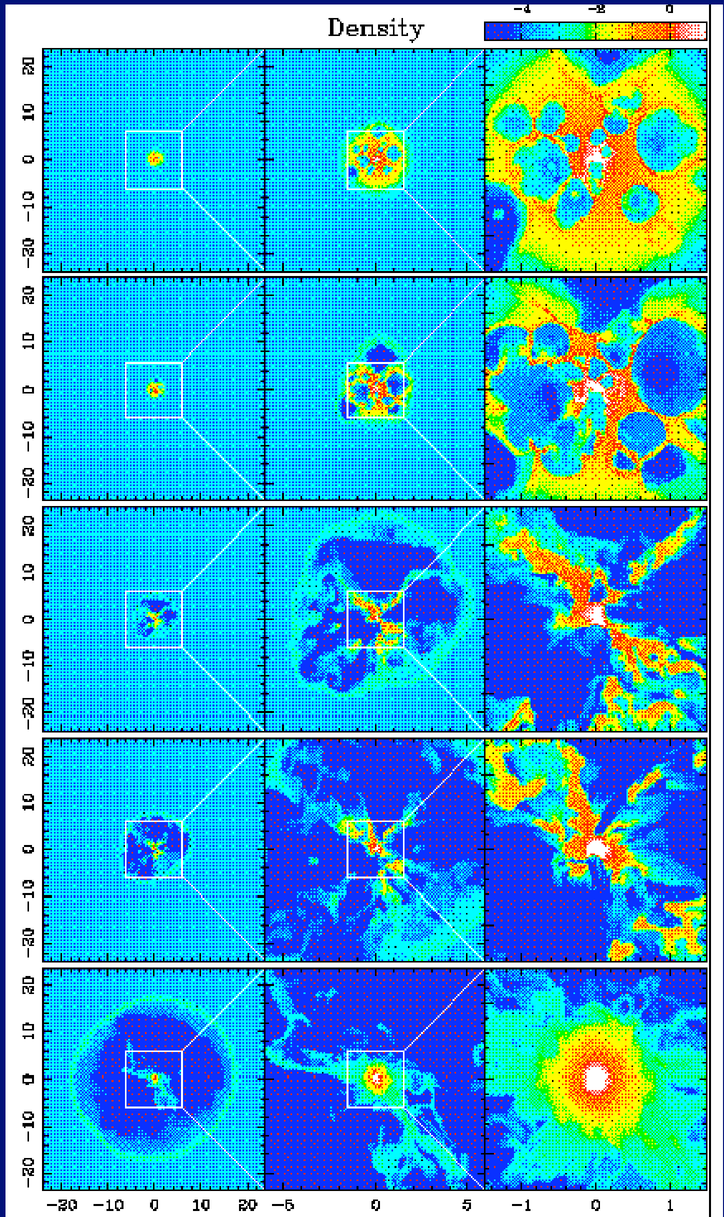
and the shock-heating scale

Below the Shock-Heating Mass

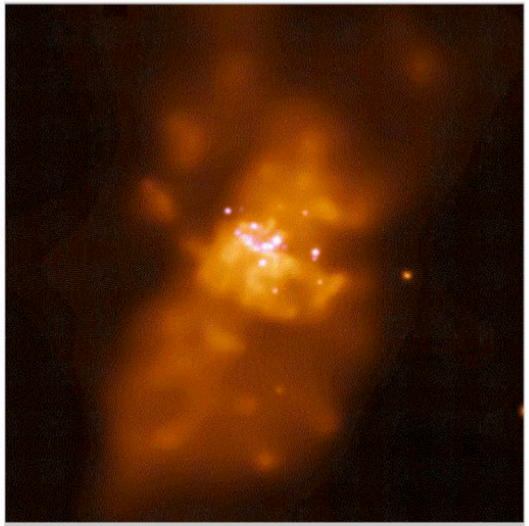


Supernova Feedback



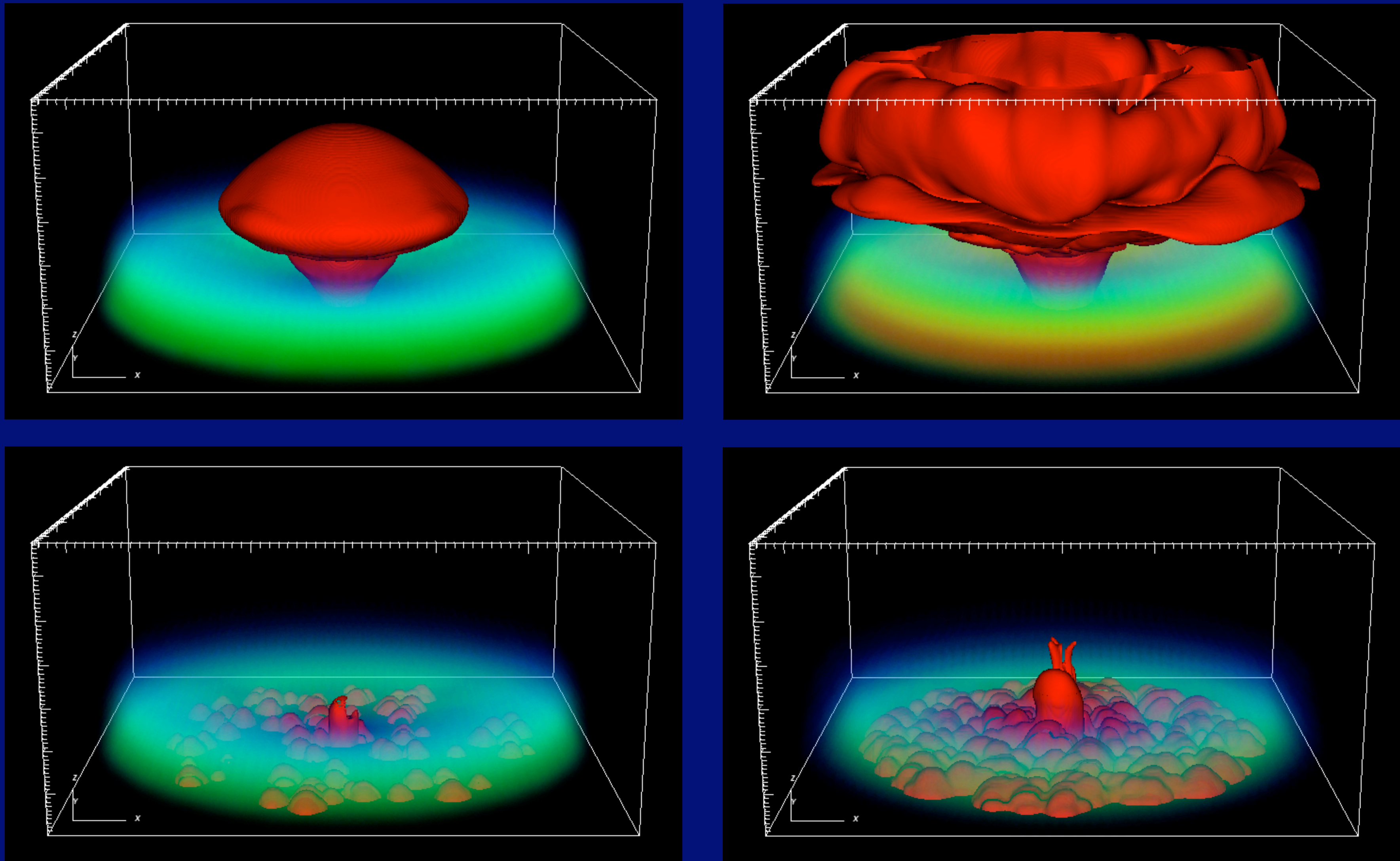


Mori et al.



Chandra X-Ray Observatory image of M82

Supernova Feedback



Fragile, Murray, Lin 04

Supernova Feedback Scale (Dekel & Silk 86, Dekel & Woo 03)

Energy fed to the ISM during the "adiabatic" phase:

$$E_{\rm SN} \approx \nu\varepsilon\, \dot{M}_*\, t_{\rm rad} \quad \propto M_* (t_{\rm rad}/t_{\rm ff})$$

$$\dot{M}_* \approx M_*/t_{\rm ff}$$

$$\approx 0.01$$

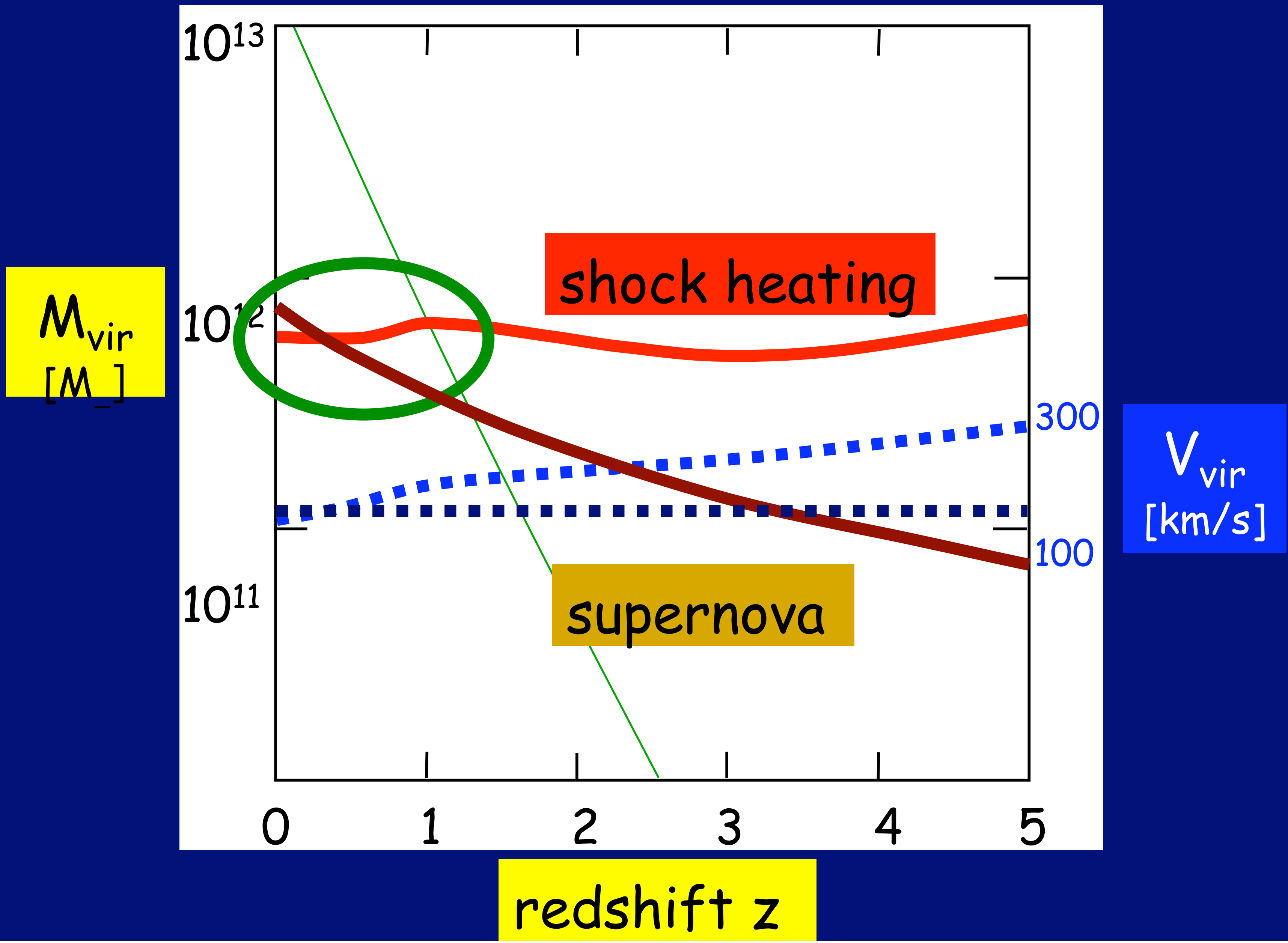
for $\Lambda \propto T^{-1}$ at $T \sim 10^5 K$

Energy required for blowout:

$$E_{\rm SN} \approx M_{\rm gas} V^2$$

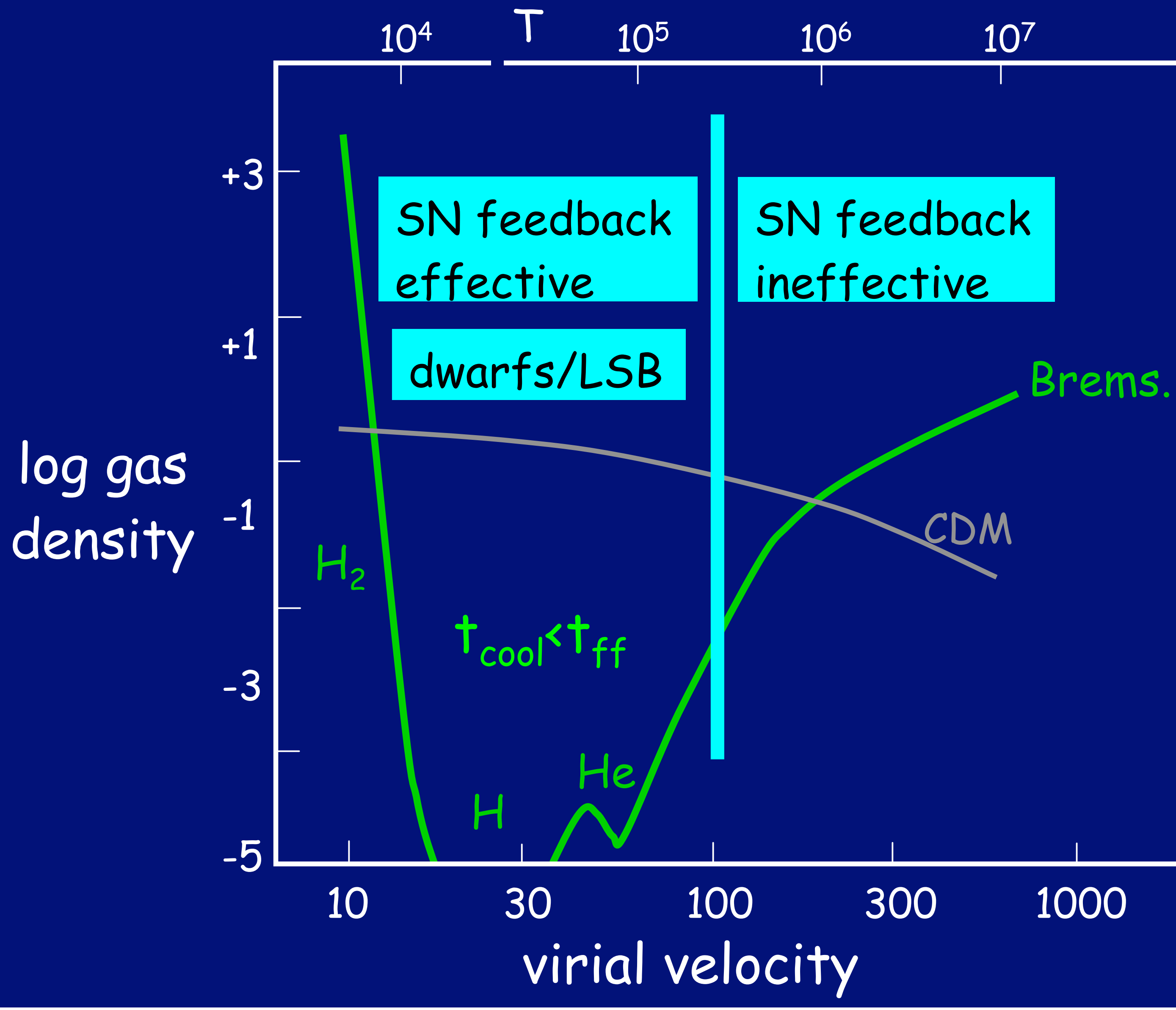
$$\boxed{\rightarrow \quad V_{\rm crit} \approx 120 \ \text{ km/s} \quad \rightarrow \quad M_{\rm crit} \approx 7\times 10^{11} M_\circ}$$

Shock-Heating vs Supernova Scale



Supernova Feedback Scale

Dekel & Silk 86



Model: fundamental line of LSB/Dwarfs

(Dekel & Woo 03)

- Energy: $E_{\mathrm{SN}} \propto M_* \propto M_{\mathrm{gas}} V^2$ → $\boxed{M_* / M_{gas} \propto V^2}$

  <<1

- Virial halo: $V^3 \propto M \propto R^3$

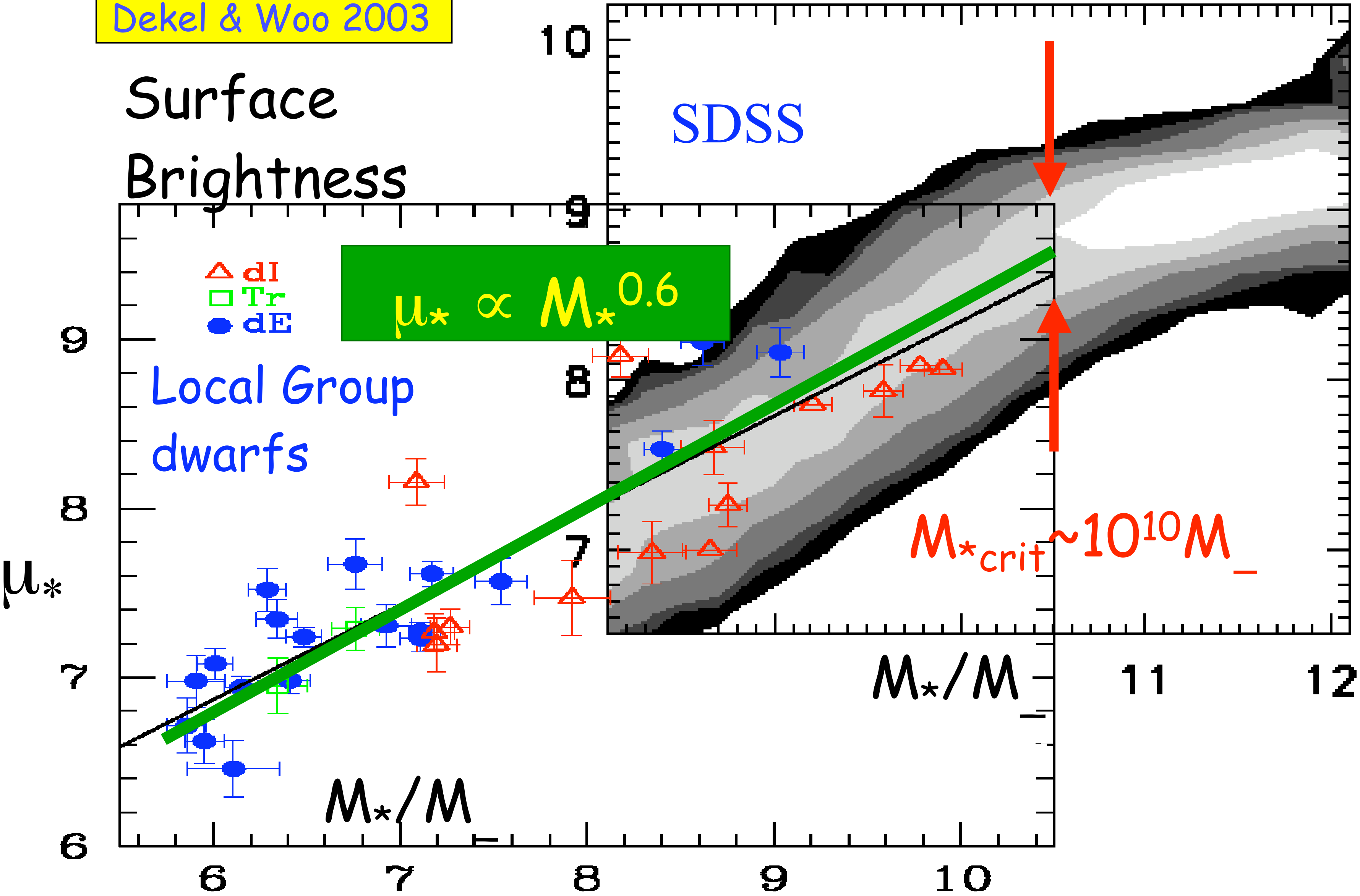
→ $V \propto M_*^{1/5}$ "Tully Fisher"

$Z \propto M_* / M_{gas}$ → $Z \propto M_*^{2/5}$ metallicity

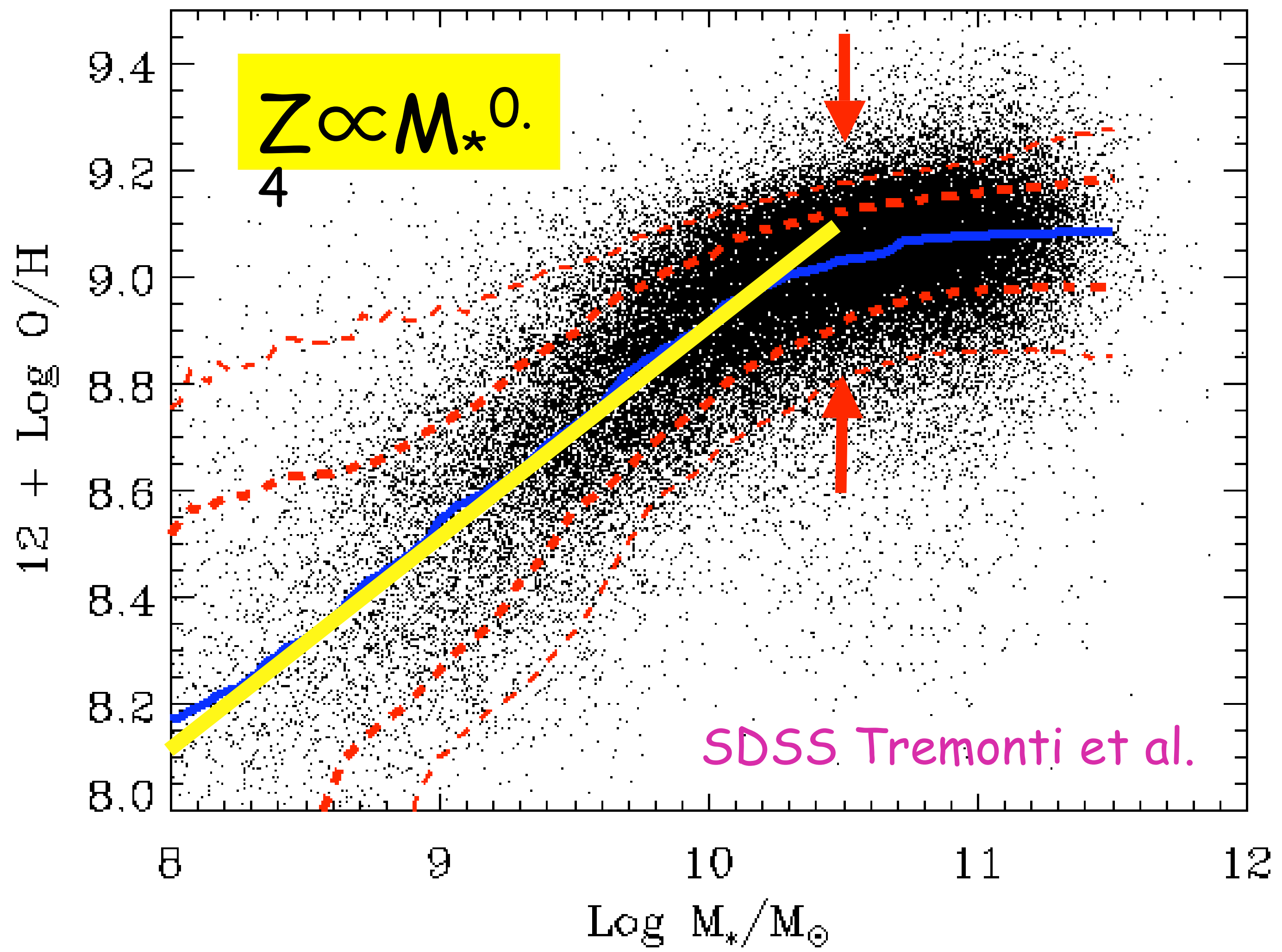
$R_* \approx \lambda R$ → $\mu \propto \lambda^{-2} M_*^{3/5}$ surface brightness

"Fundamental Line" of LSB/Dwarfs

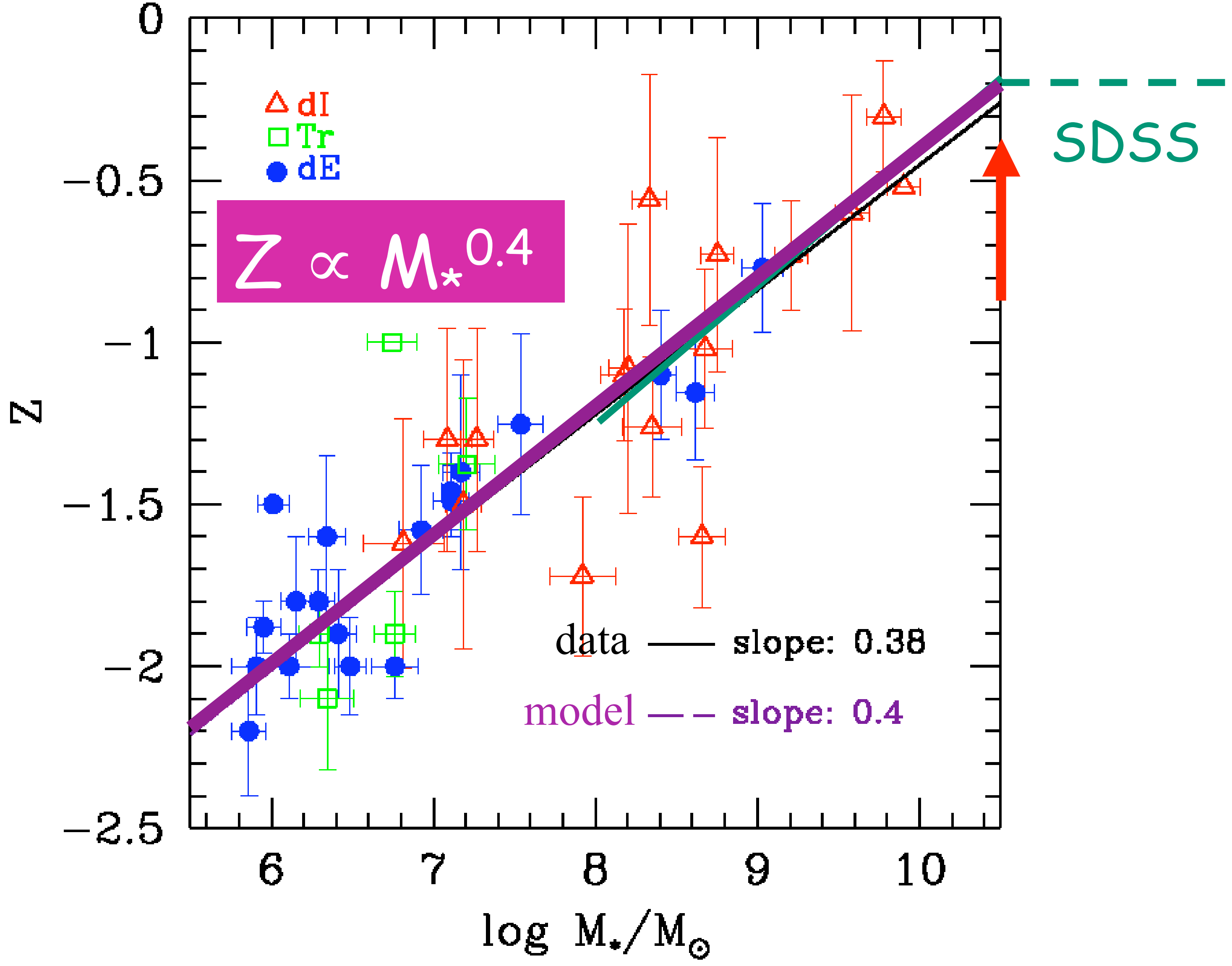
Dekel & Woo 2003



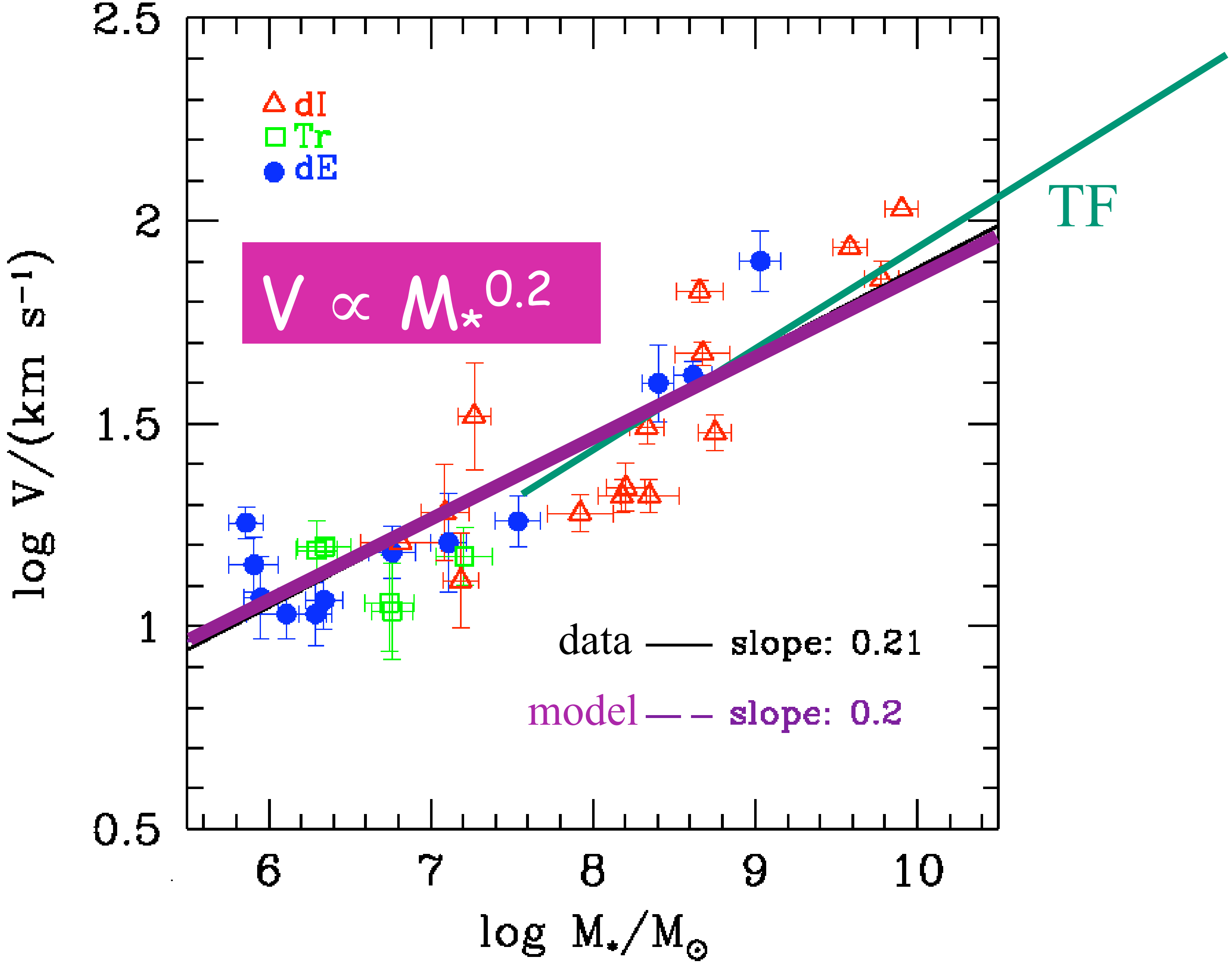
Metallicity



Local Group Dwarfs: Metallicity



LG Dwarfs: Velocity



Summary: SN feedback

Could be partly responsible for the transition scale at $M_*=3\times10^{10}$, and the "fundamental line" of LSB/dwarf galaxies, $M^*/M \propto V^2$.

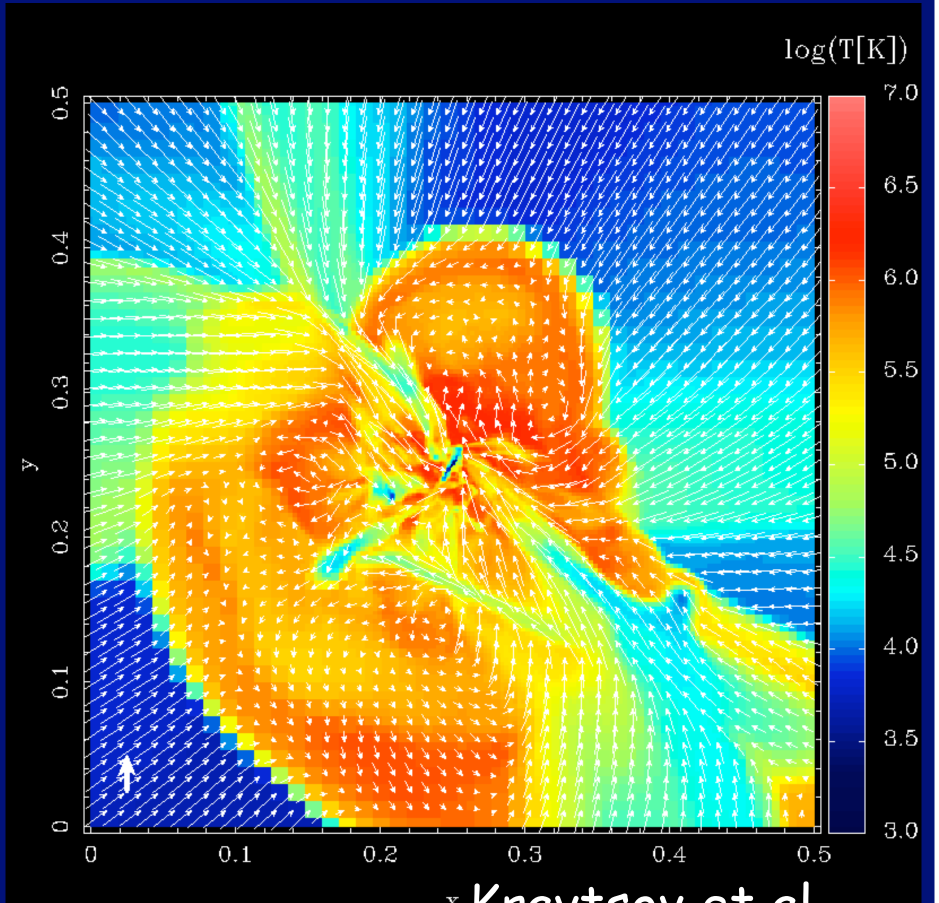
Shock Heating Triggers AGN Feedback

$M > M_{shock}$

More than enough energy is available in AGNs

Hot gas is vulnerable to AGN feedback, while cold streams are shielded

°Shock heating is the trigger for AGN feedback in massive halos



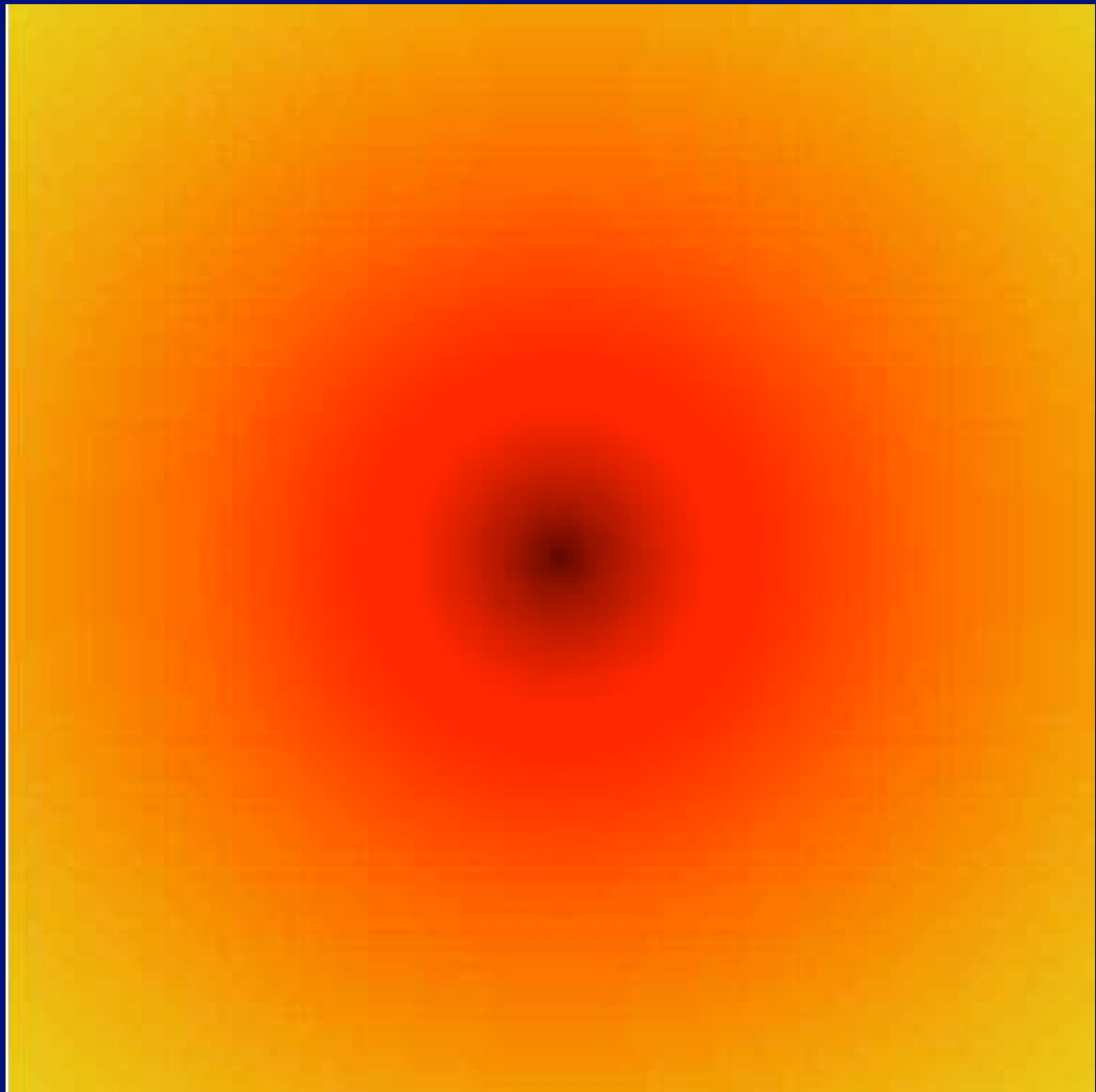
Kravtsov et al.

AGN Feedback in Perseus

Fabian et al.

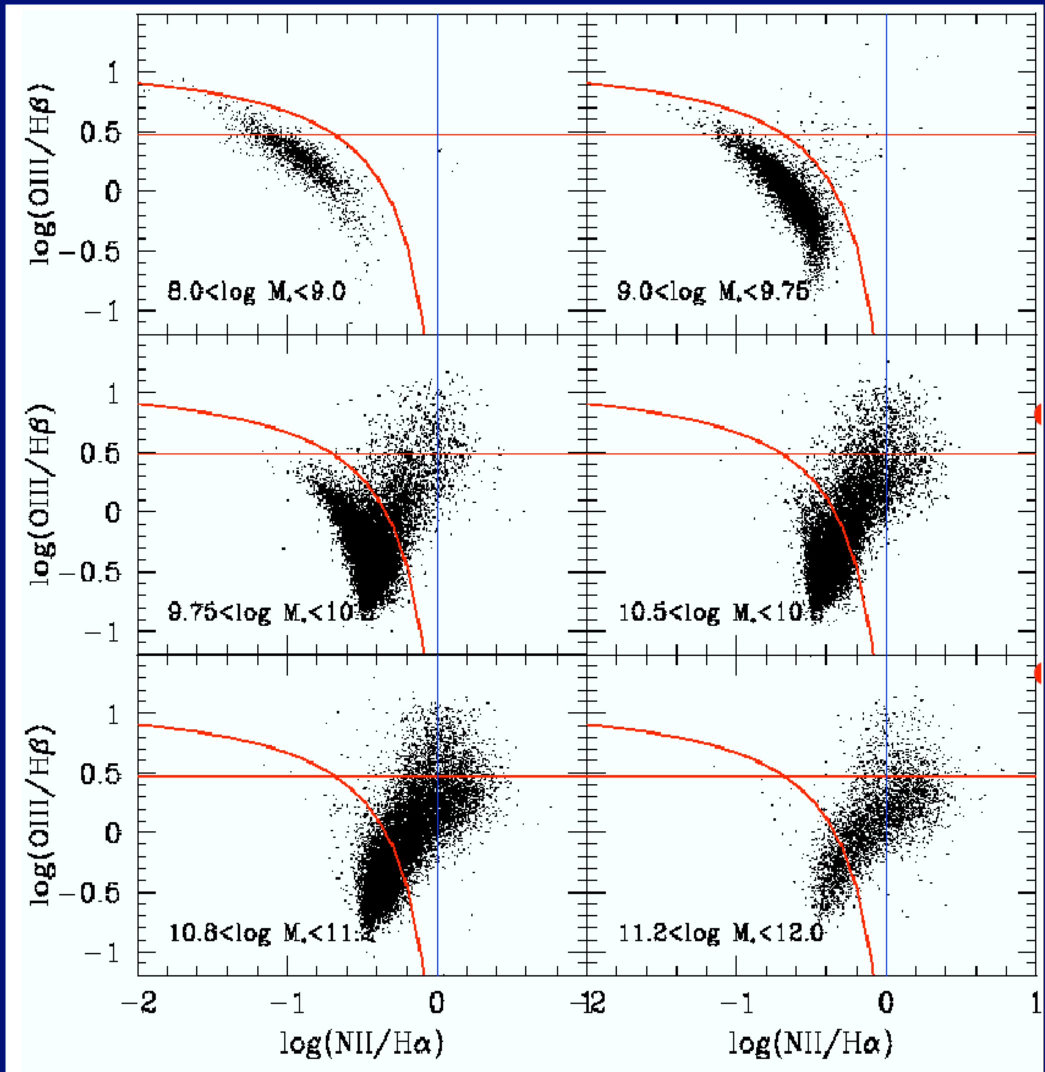
AGN Feedback

Ruszkowski, Bruggen, Begelman 03



jets – very hot bubbles – buoyancy – horizontal spread

Emission Properties vs. Stellar Mass

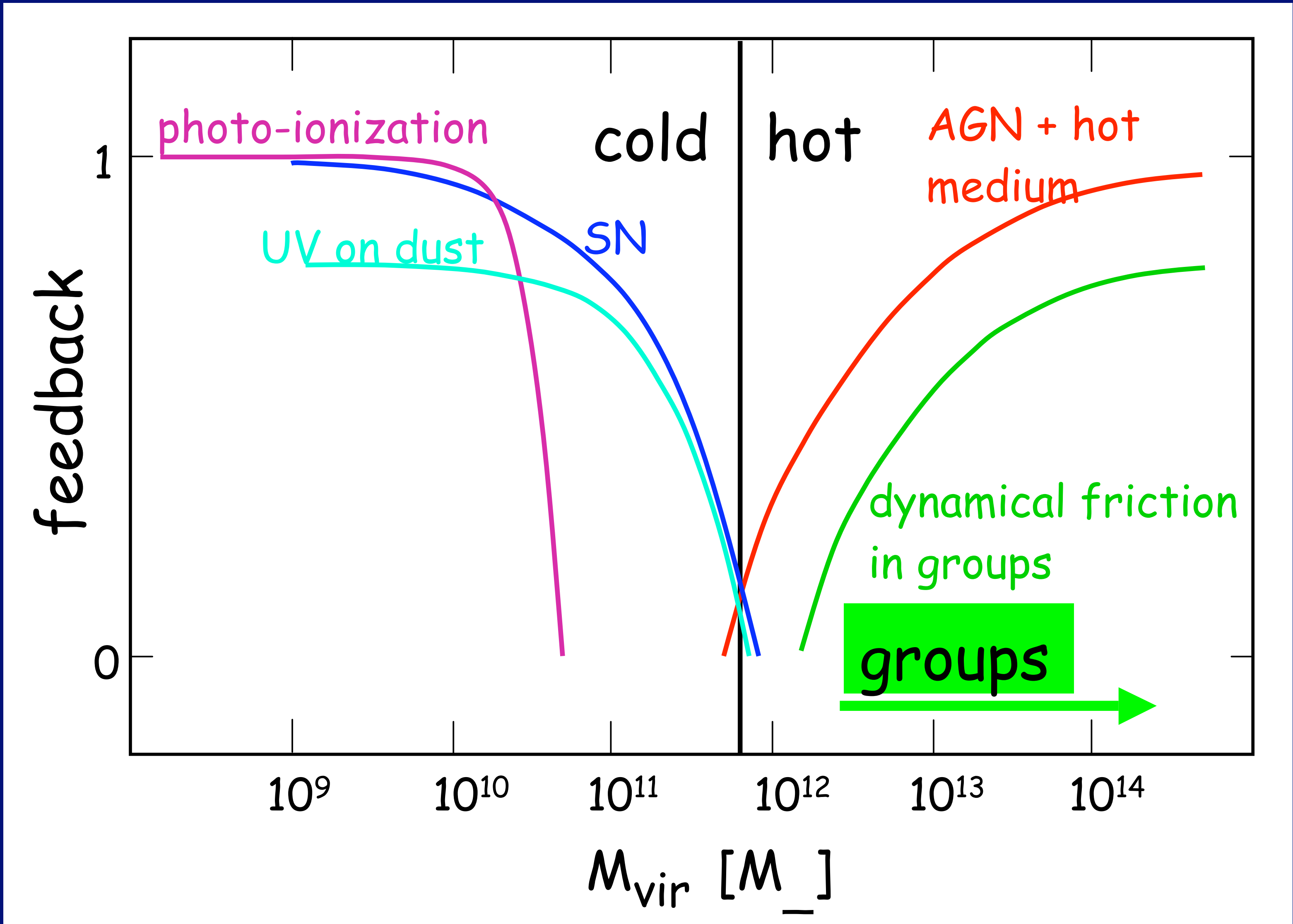


low-mass emission galaxies are almost all star formers

high-mass emission galaxies are almost all AGN

Kauffmann et al. 2004

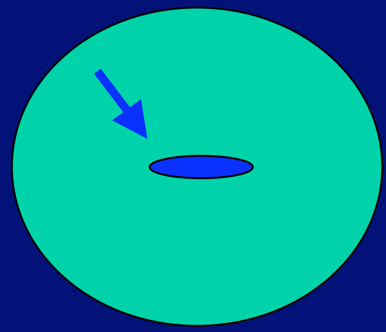
Above the Shock-Heating Mass



Dynamical-Friction Heating

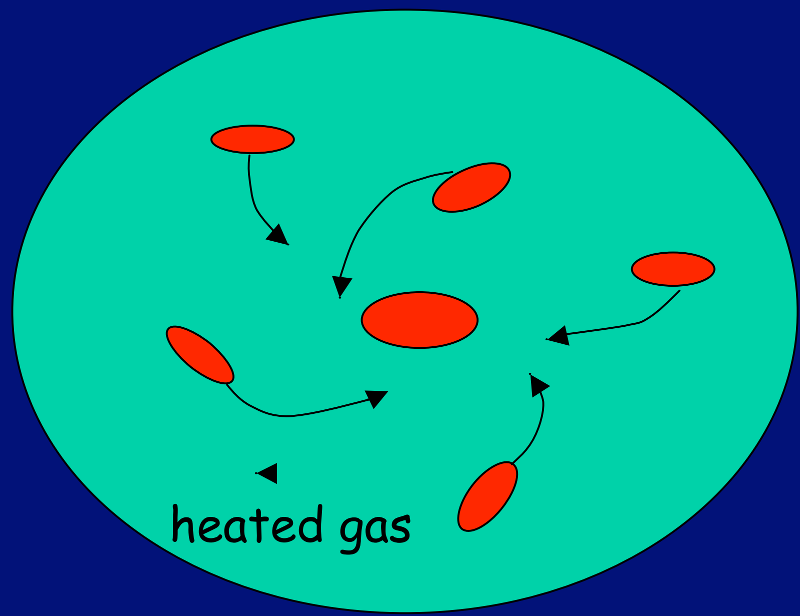
- $M<M_{crit}$ °˙cold flows
- a single-galaxy halo

°˙no effect



- $M>M_{crit}$ °˙hot gas
- a multi-galaxy halo

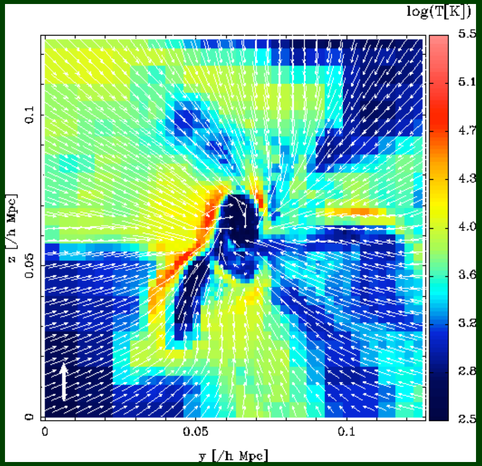
°˙dynamical-friction
heating of hot gas

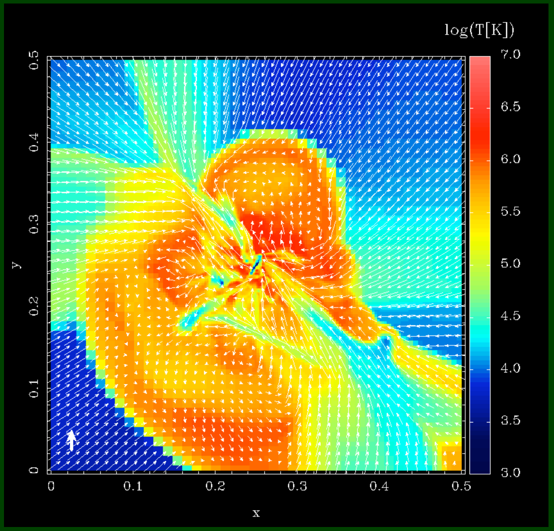


El-Zant, Kim, Kamionkowski 04

5. Origin of the Bi-modality

Dekel & Birnboim 04



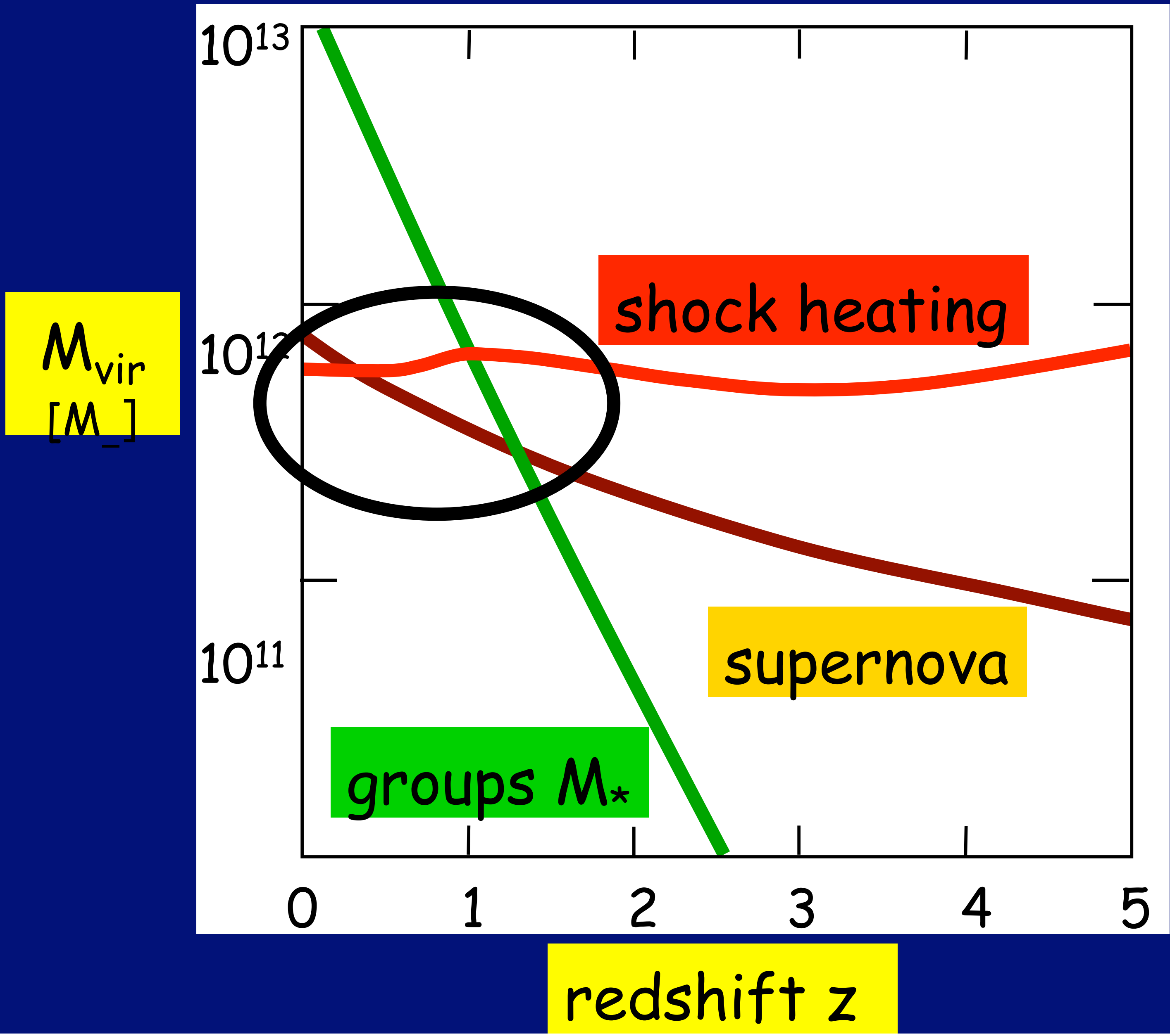


cold vs hot

ungrouped vs grouped

SN feedback vs AGN feedback

Scales Roughly Coincide



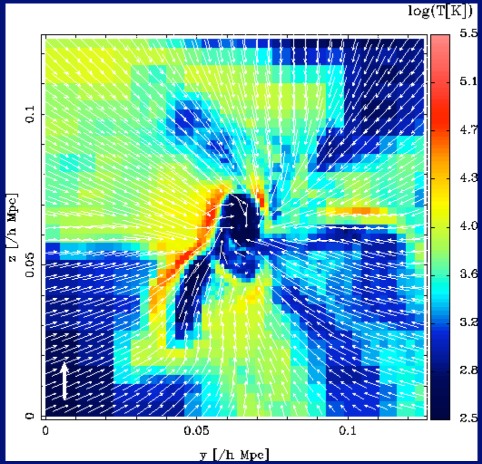
Key Ideas:

Cold flows _ star burst

supersonic stream collides with disk

efficient cooling behind isothermal shock

°˙dense, cold slab °˙star burst



Hot medium °˙halt star formation

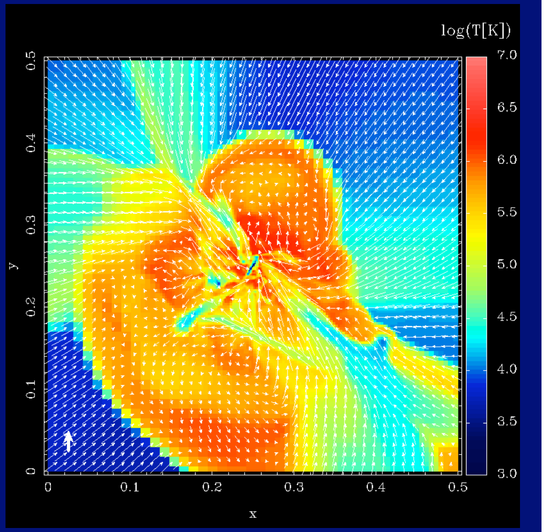
dilute medium vulnerable to AGN fdbk

+ slow cooling because of two-phase medium

+ dynamical-friction in hot groups

°˙shock-heated gas never cools

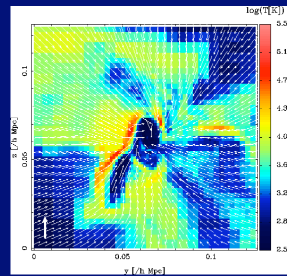
°˙shut down disk and star formation



Origin of bi-modality

While halos grow by mergers and accretion

$M<M_{crit}$: The Blue Sequence



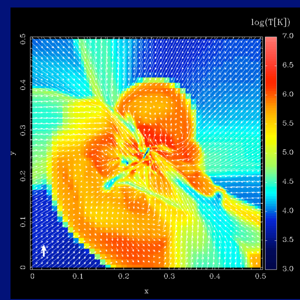
cold gas supply °˙disk growth & star formation

SN-**fdbk** regulates star formation °long duration

bursts °˙very blue

mergers & bar instability °˙bulges

$M>M_{crit}$: The Red Sequence



shock-heated gas +AGN fdbk °˙no new gas supply

+gas exhausted + AGNs especially in bulges

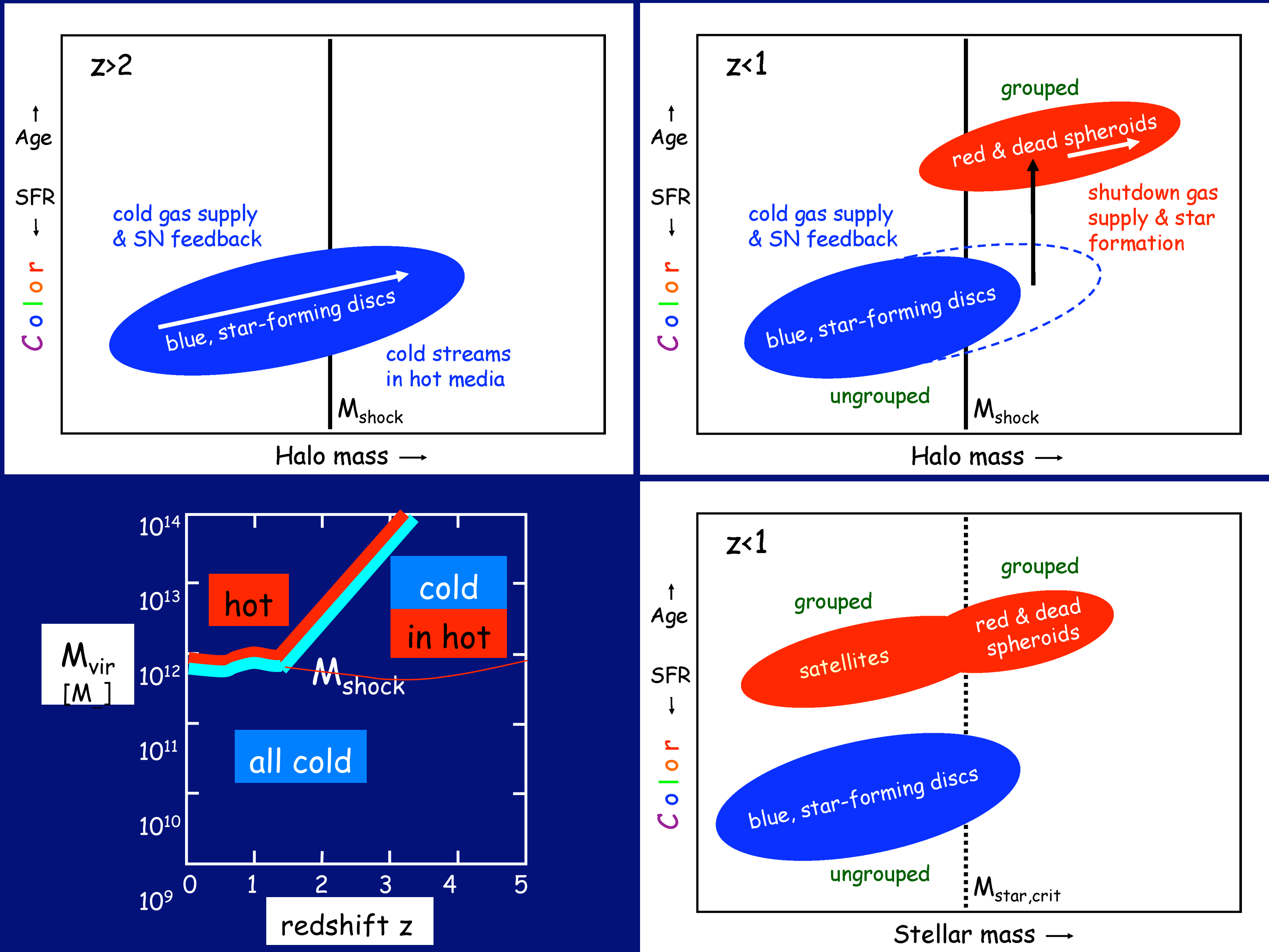
°˙no disk growth, star formation shuts off

passive stellar evolution °˙red & dead

further growth of spheroids by gas-poor mergers

Shutdown above a critical halo mass does wonders

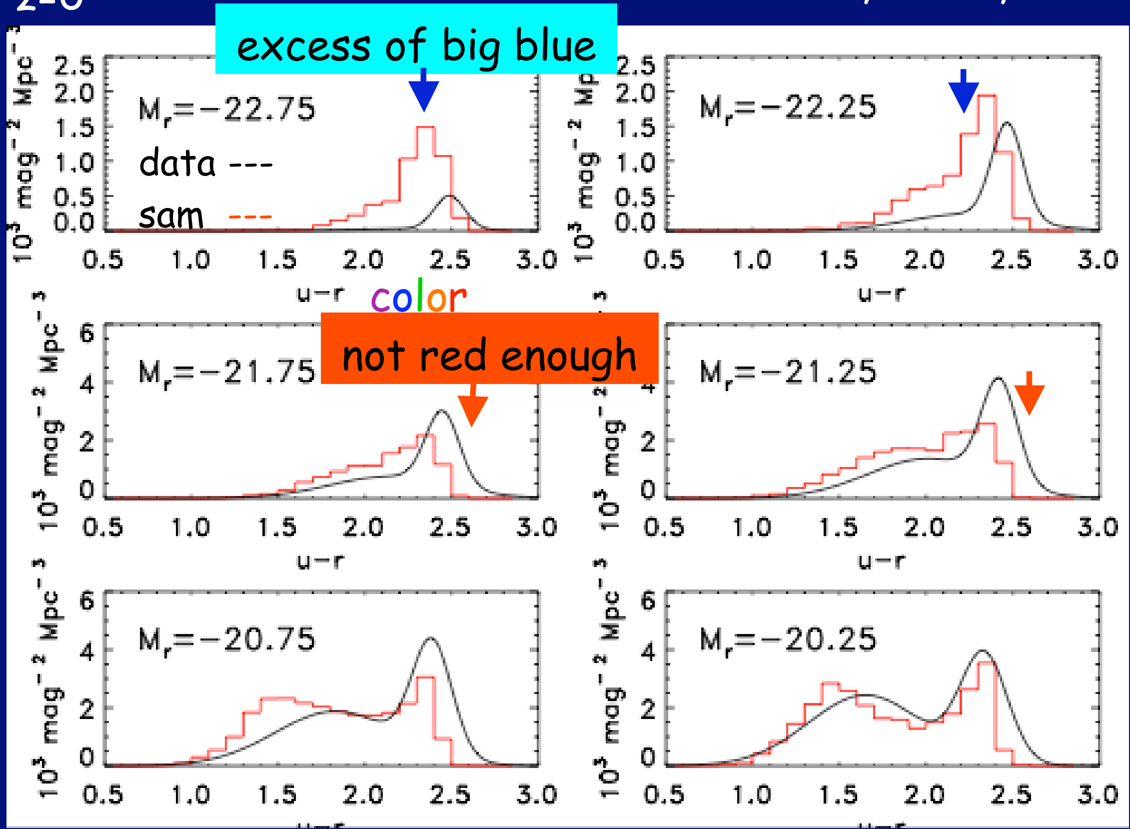
From blue to red sequence by shutdown Dekel & Birnboim 06

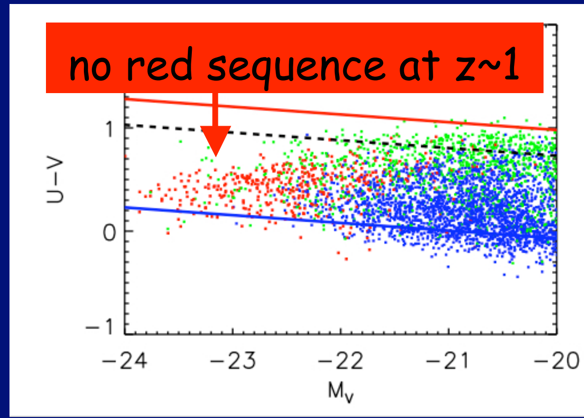


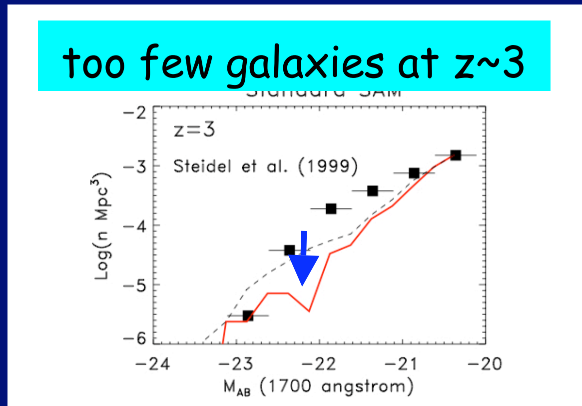
In a standard Semi Analytic Simulation (GalICS)

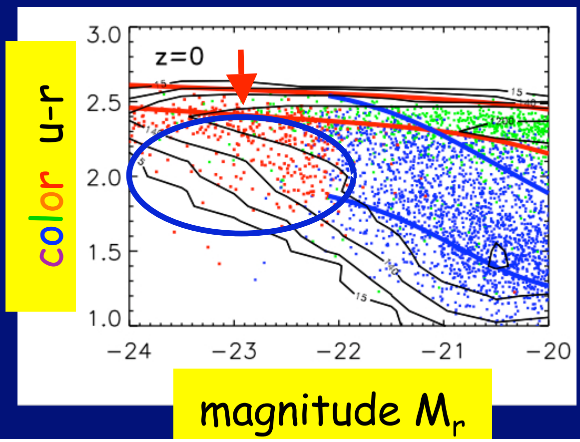
Cattaneo, Dekel, Devriendt, Guiderdoni, Blaizot 06

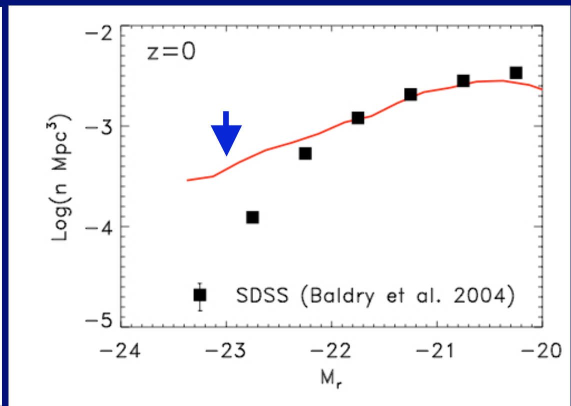
z=0

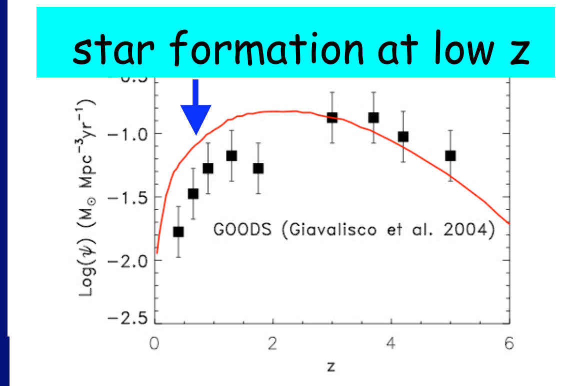




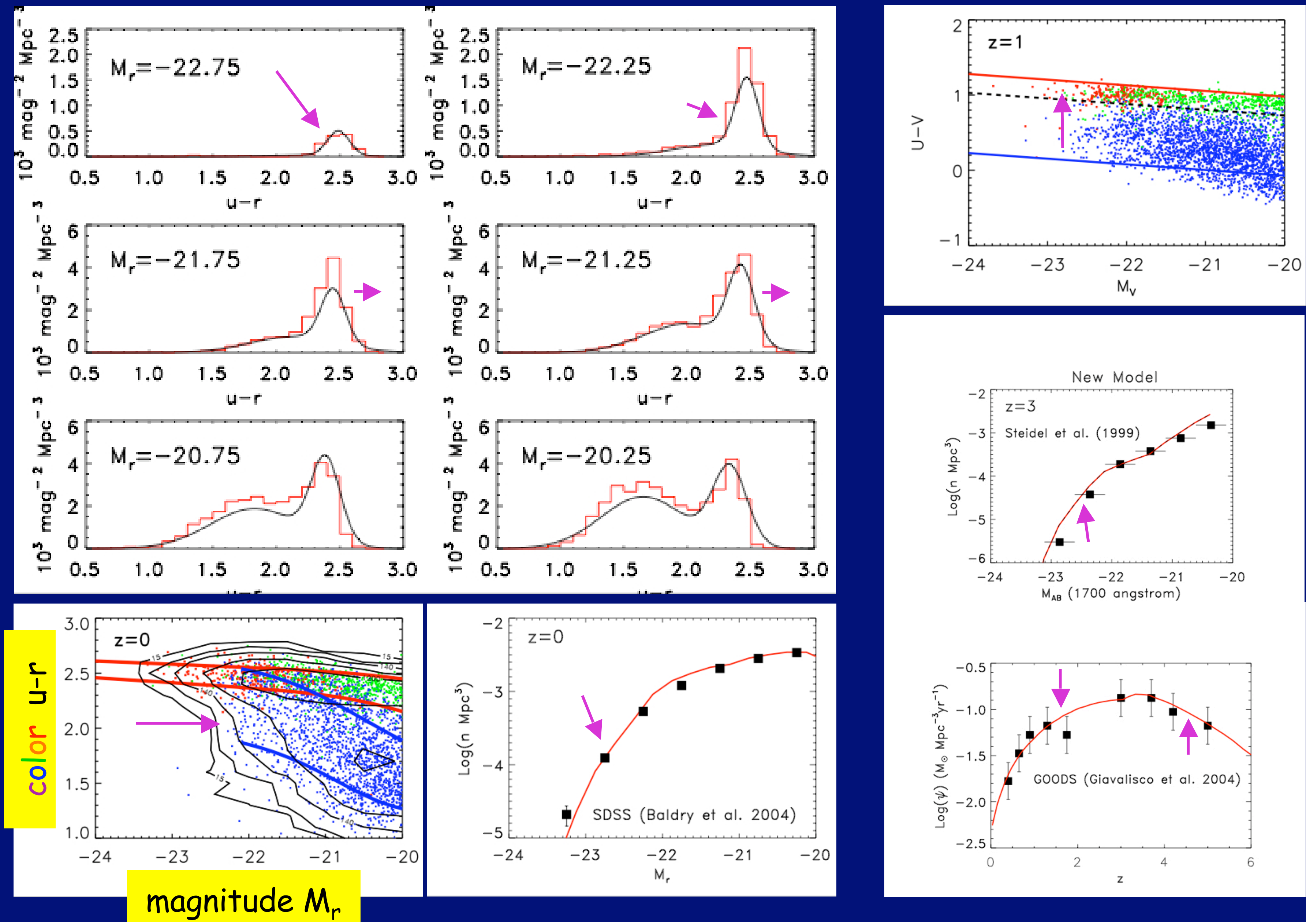




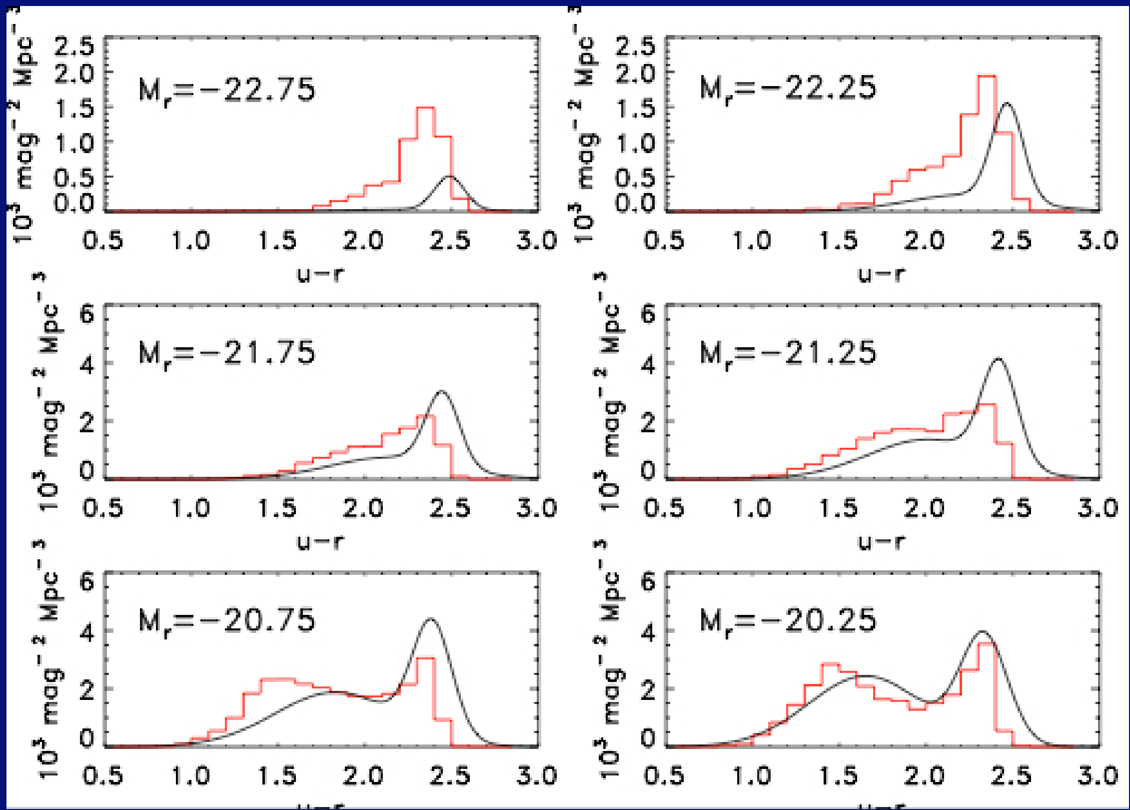




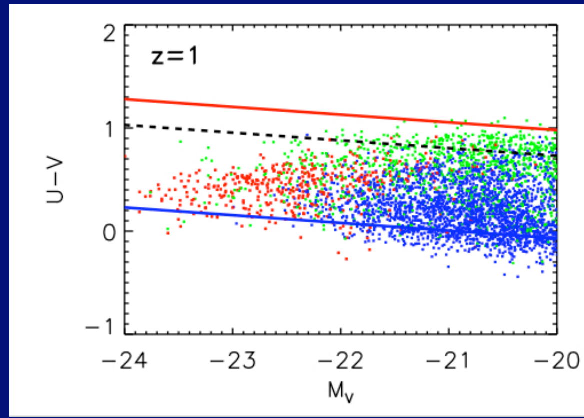
With Shutdown Above 10^{12} M_



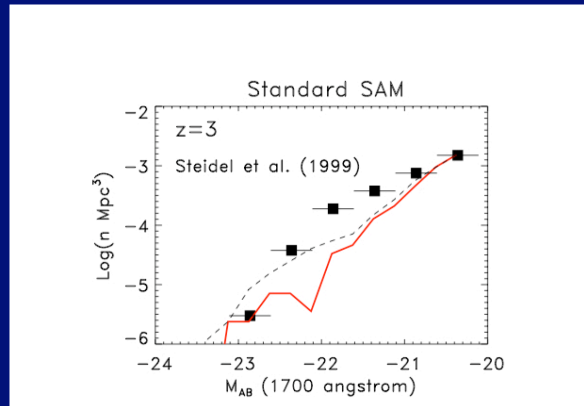
Standard



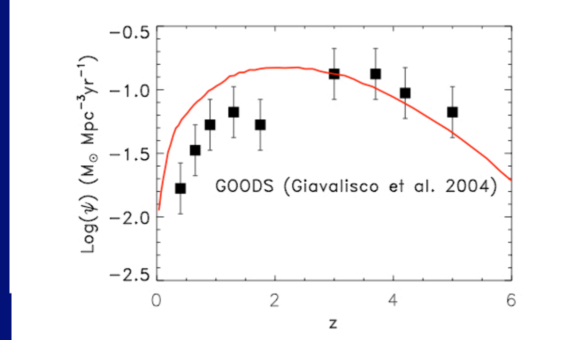
M_r=−22.75
M_r=−22.25
M_r=−21.75
M_r=−21.25
M_r=−20.75
M_r=−20.25
u−r
10^3 mag^{-2} Mpc^{-3}



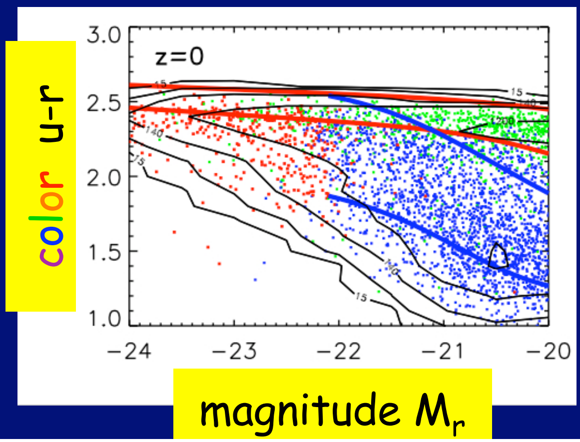
z=1
U−V
M_V



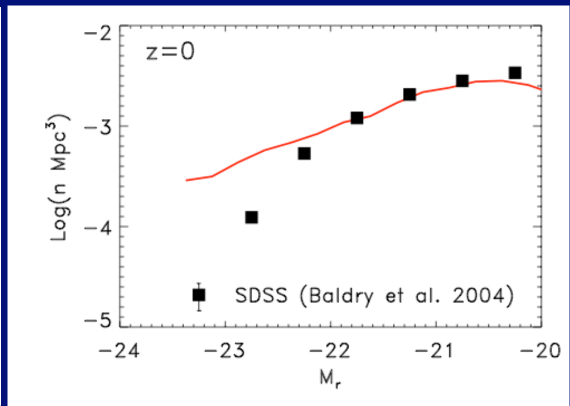
Standard SAM
z=3
Steidel et al. (1999)
Log(n Mpc^3)
M_{AB} (1700 angstrom)



GOODS (Giavalisco et al. 2004)
Log(ψ) ($M_\odot$ Mpc^{-3}yr^{-1})
z

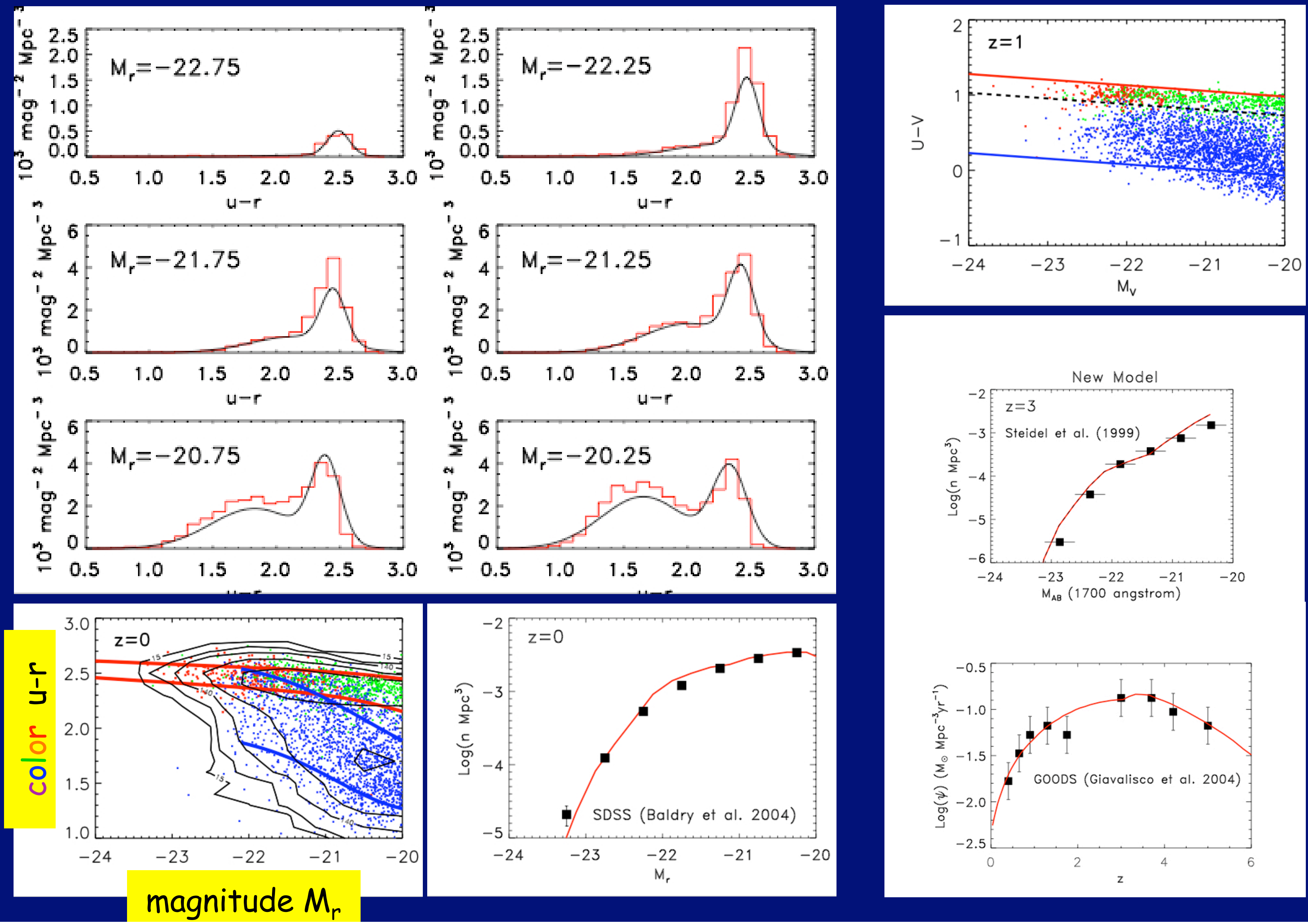


z=0
color u-r
magnitude M_r

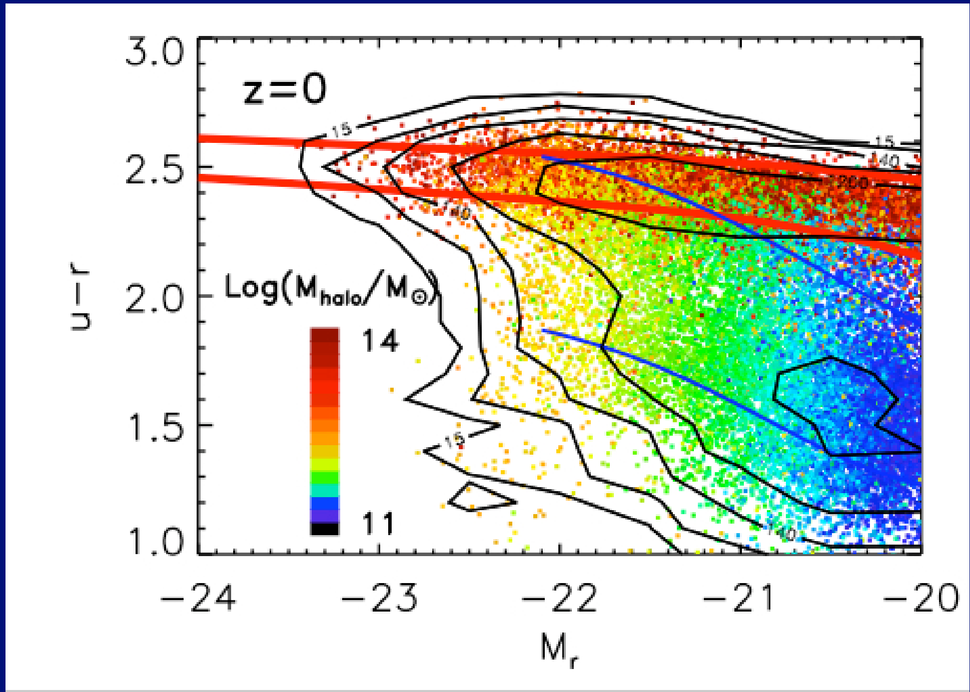


z=0
SDSS (Baldry et al. 2004)
Log(n Mpc^3)
M_r

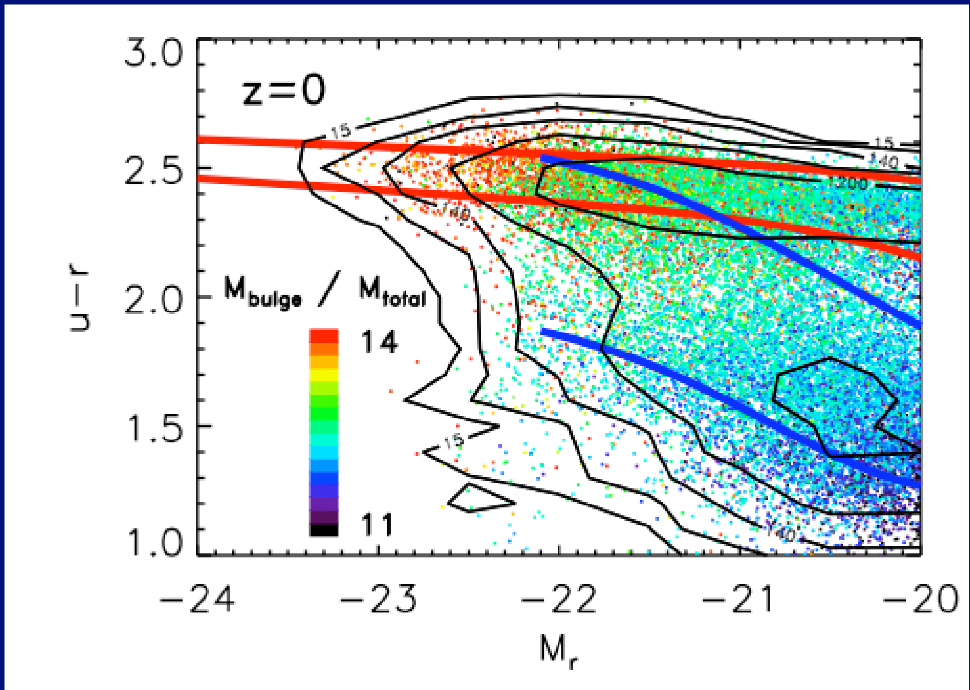
With Shutdown Above 10^{12} M_



Environment dependence via halo mass



Bulge to disk ratio



Environment Dependence

$M > M_{shock}$ °high HOD groups (at low z)

°red sequence in dense environment

cold streams harassed in groups

but survive in isolated galaxies

even for $M > M_{shock}$

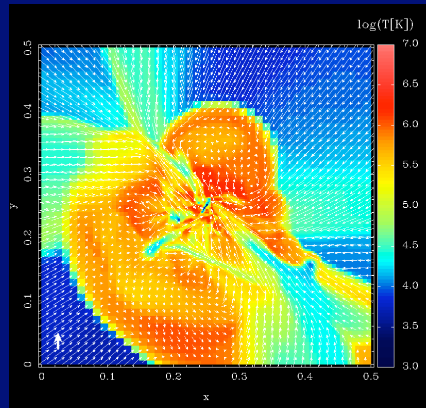
$M_{group} \sim M_*(t)$ ↗

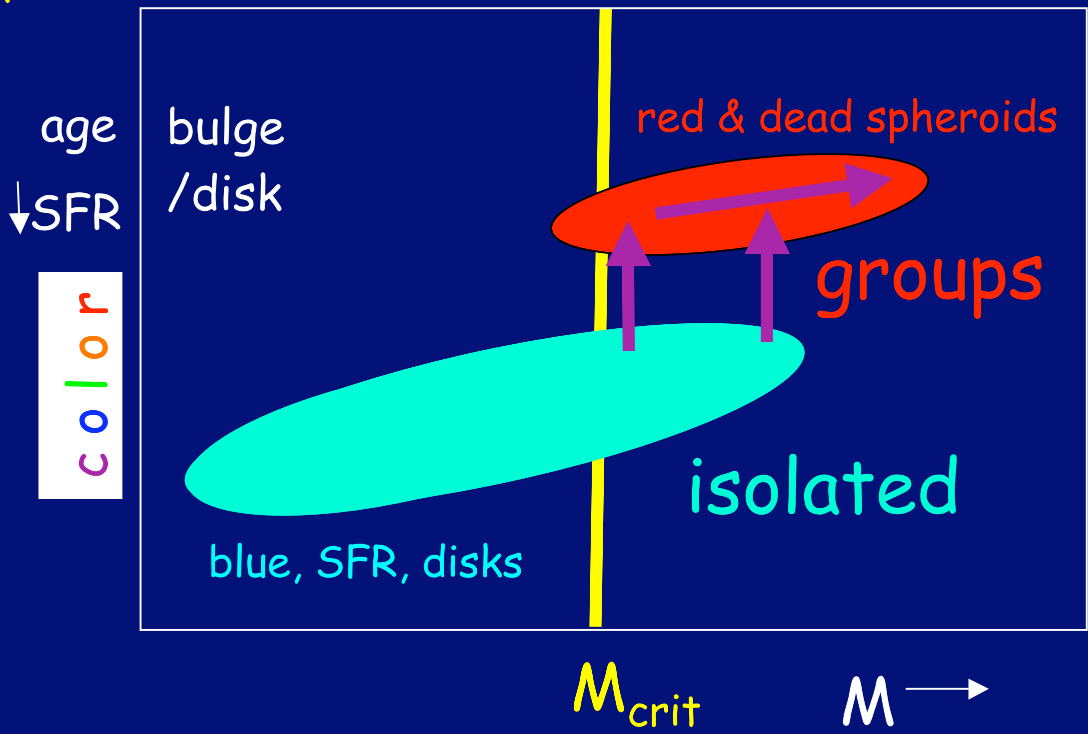
°big blue disks

form at high z

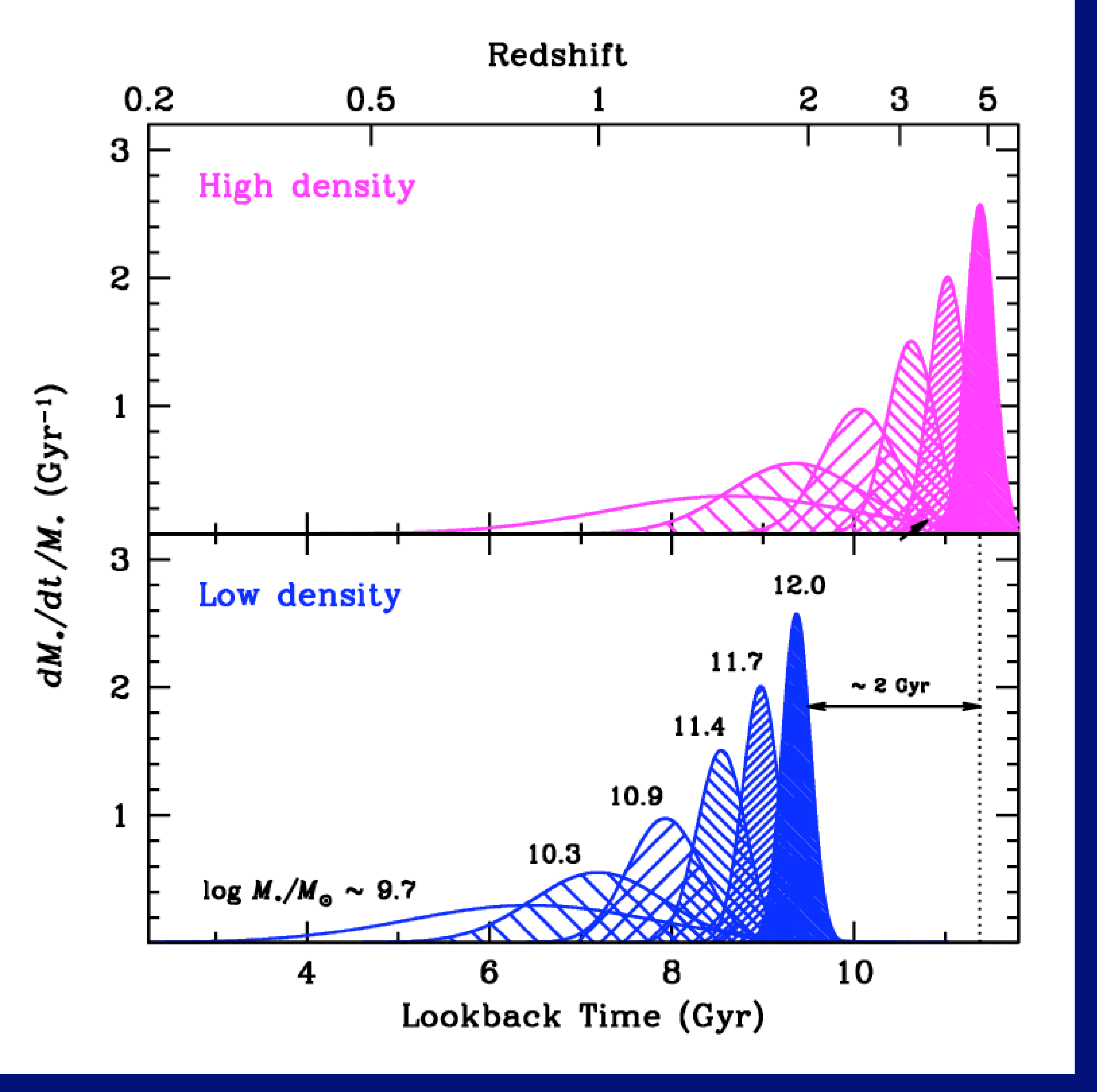
become big red

spheroids later





Downsizing: epoch of star formation in E's

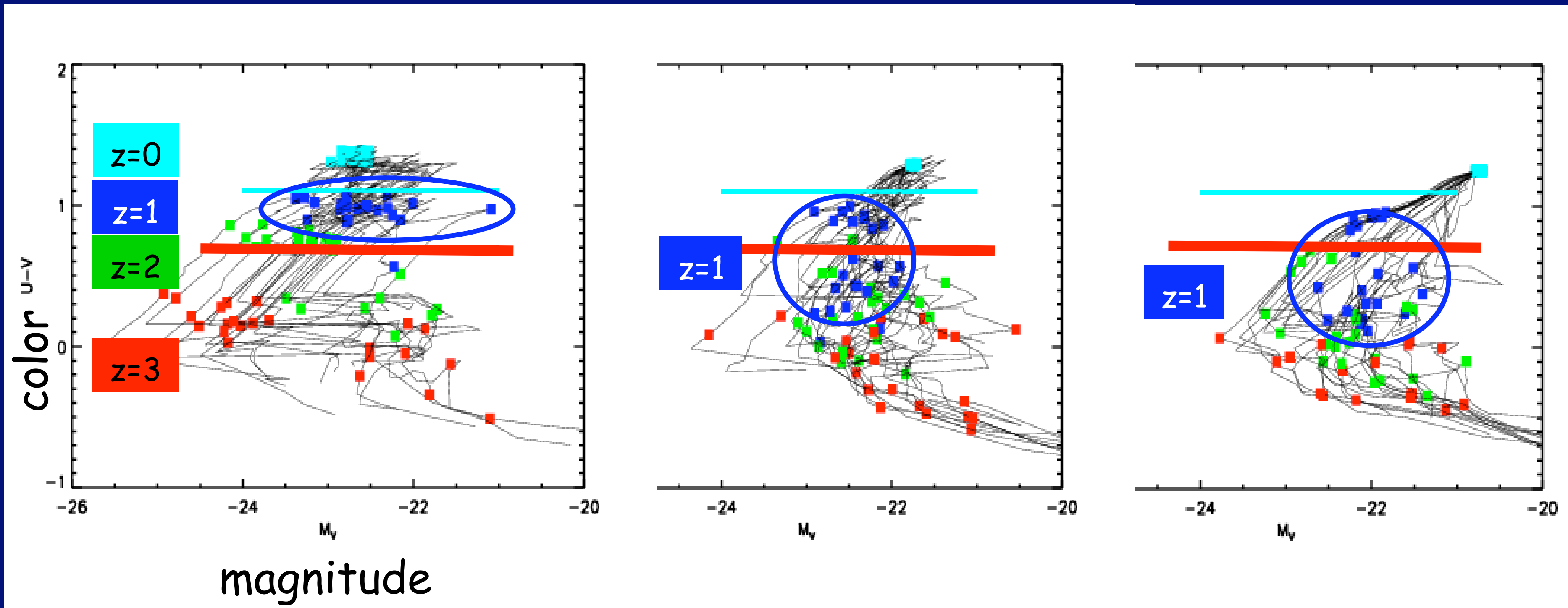


Thomas et al. 2005

Downsizing due to Shutdown

Cattaneo, Dekel, Faber 2006

bright	intermediate	faint
central	central/satellites	satellites

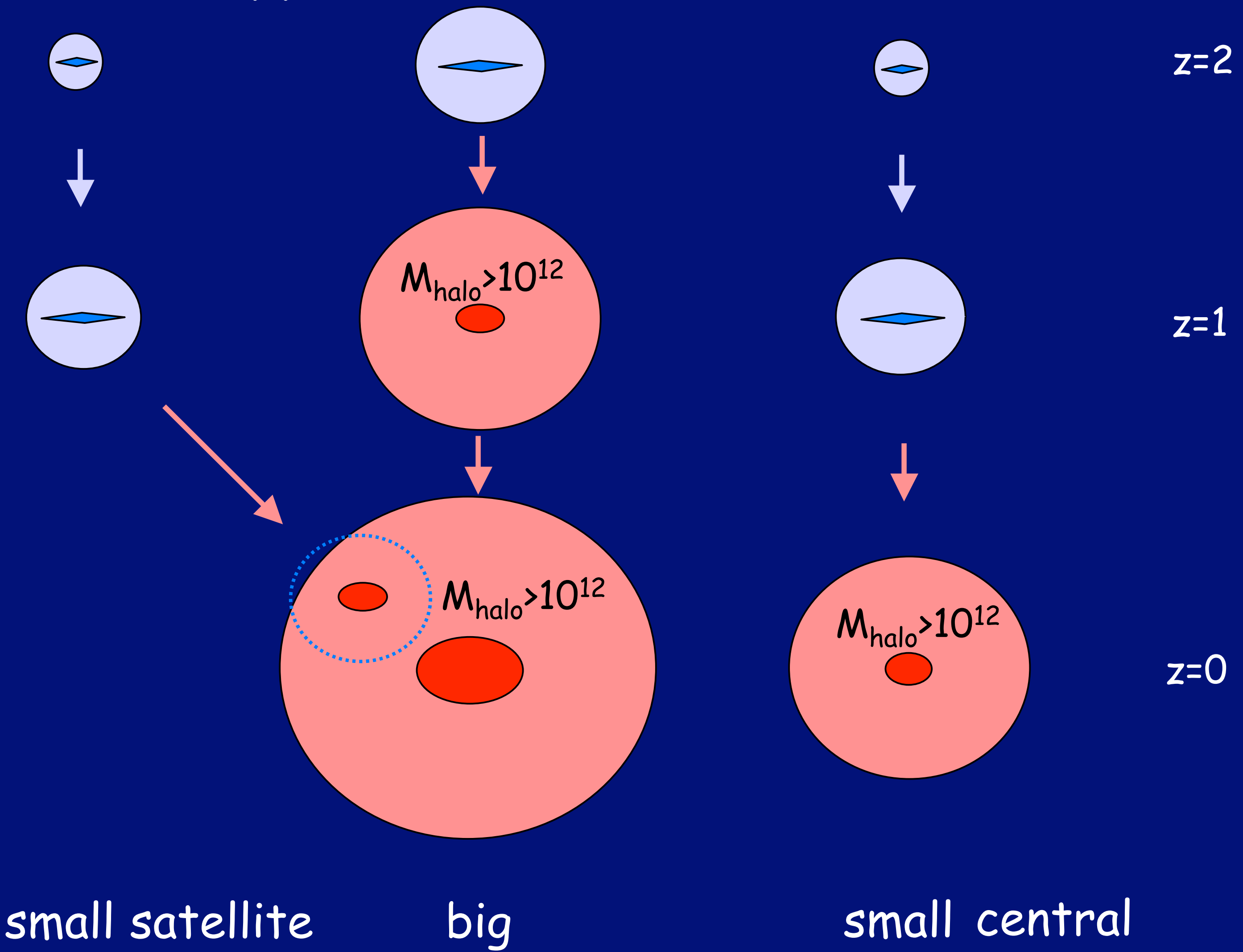


in place by z~1

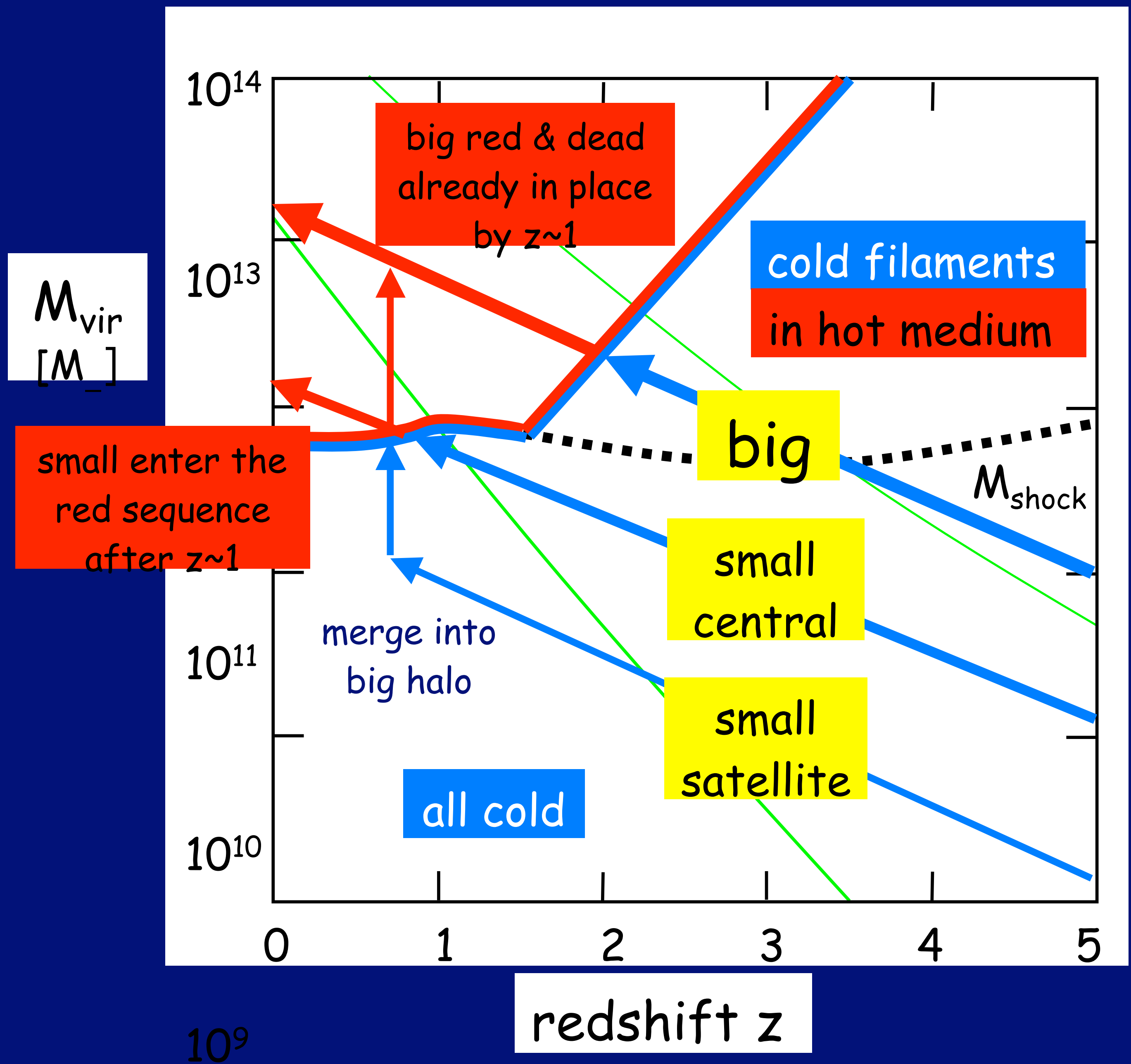
turn red after z~1

Downsizing by Shutdown at $M_{halo}>10^{12}$

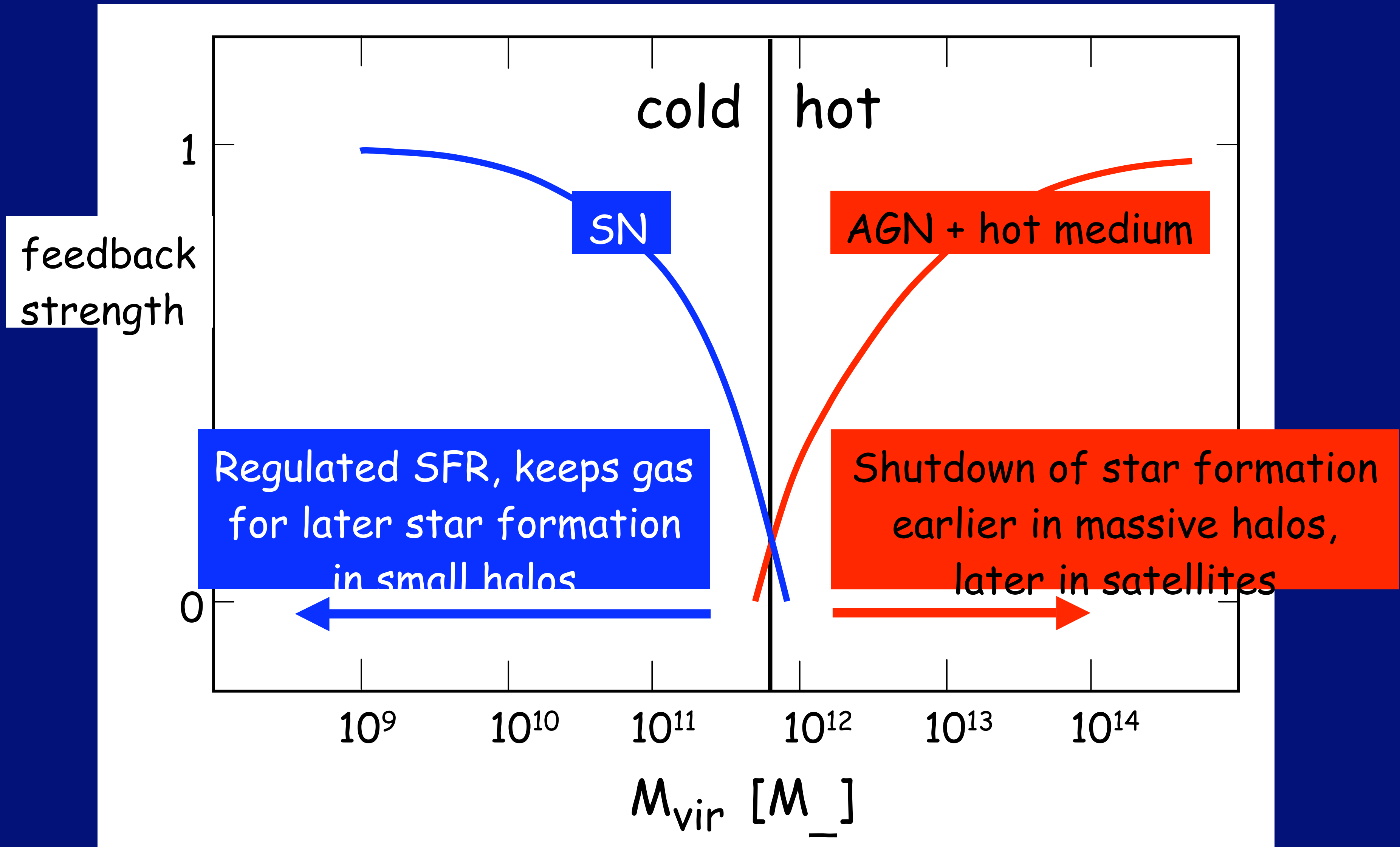
The bright red & dead E's are in place by z~1
while smaller E's appear on the red sequence after z~1



Downsizing by Shutdown at $M_{halo}>10^{12}$



Downsizing by Feedback and Shutdown

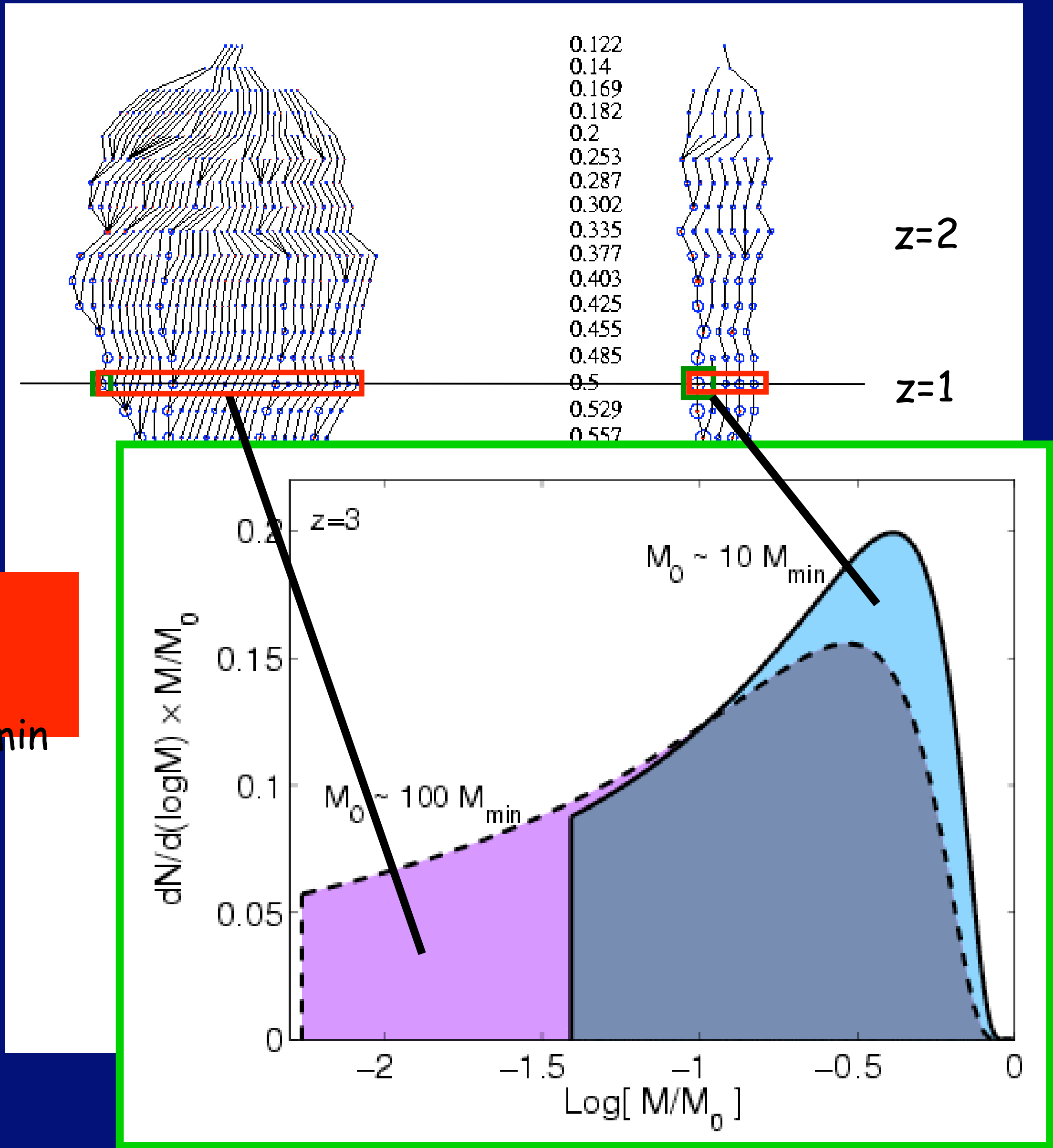


Is Downsizing Anti-hierarchical?

Merger trees
of dark-matter
halos $M>M_{min}$

Upsizing of mass
in **main** progenitor

Downsizing of mass
in **all** progenitors $>M_{min}$

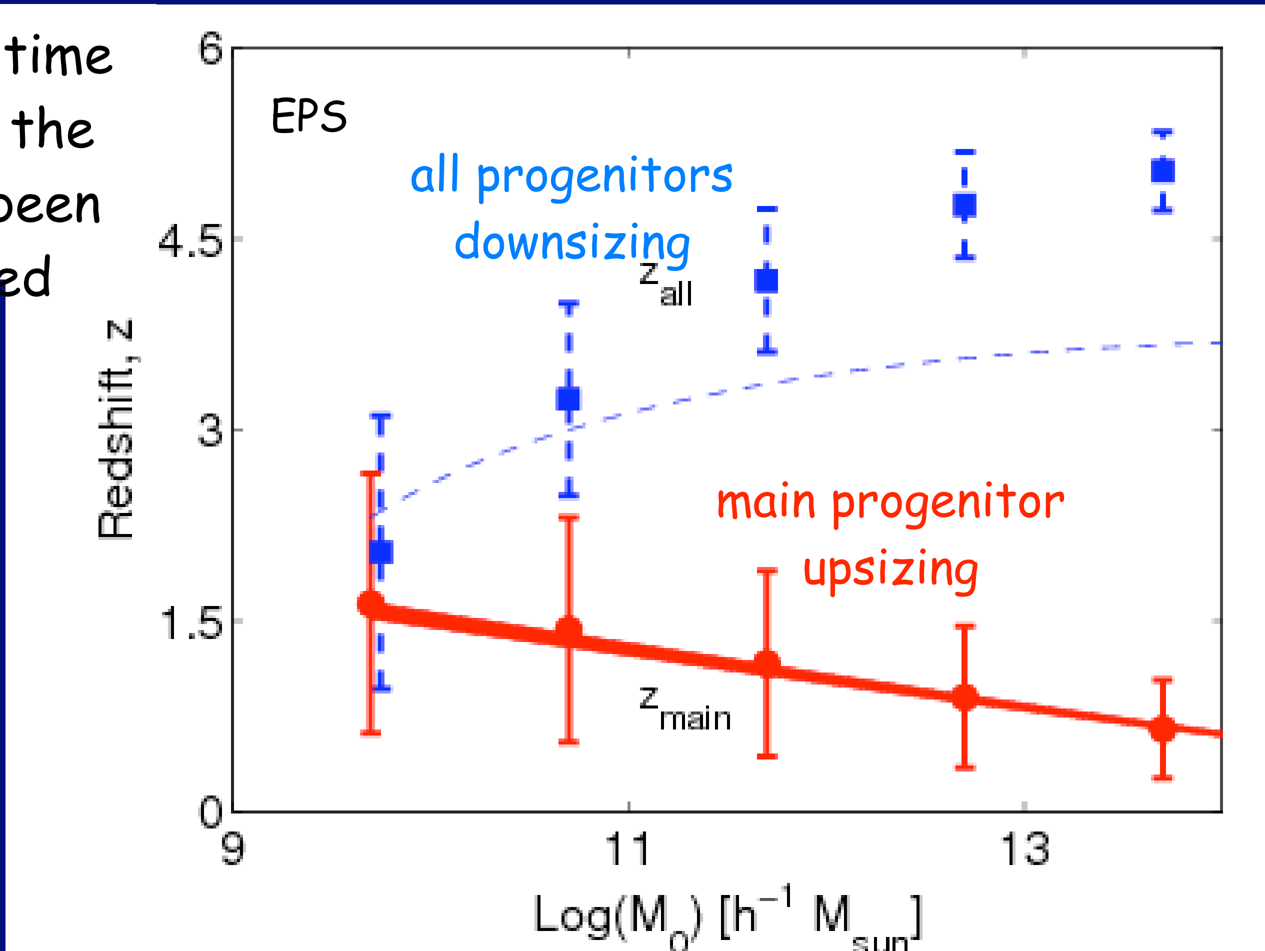


Neistein, van den
Bosch, Dekel 2006

Natural Downsizing in Hierarchical Clustering

Neistein, van den Bosch, Dekel 2006

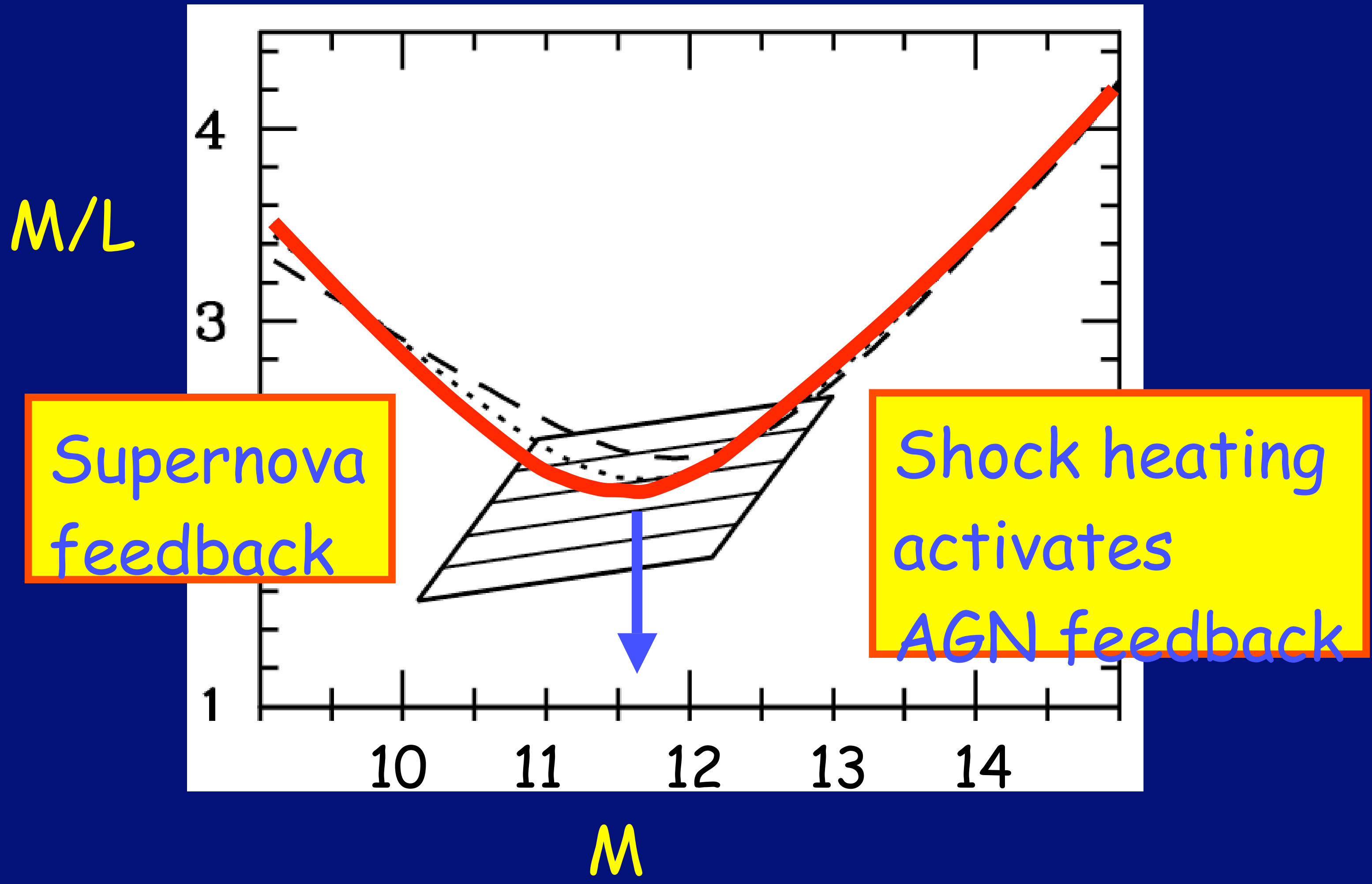
Formation time when half the mass has been assembled



Conclusions

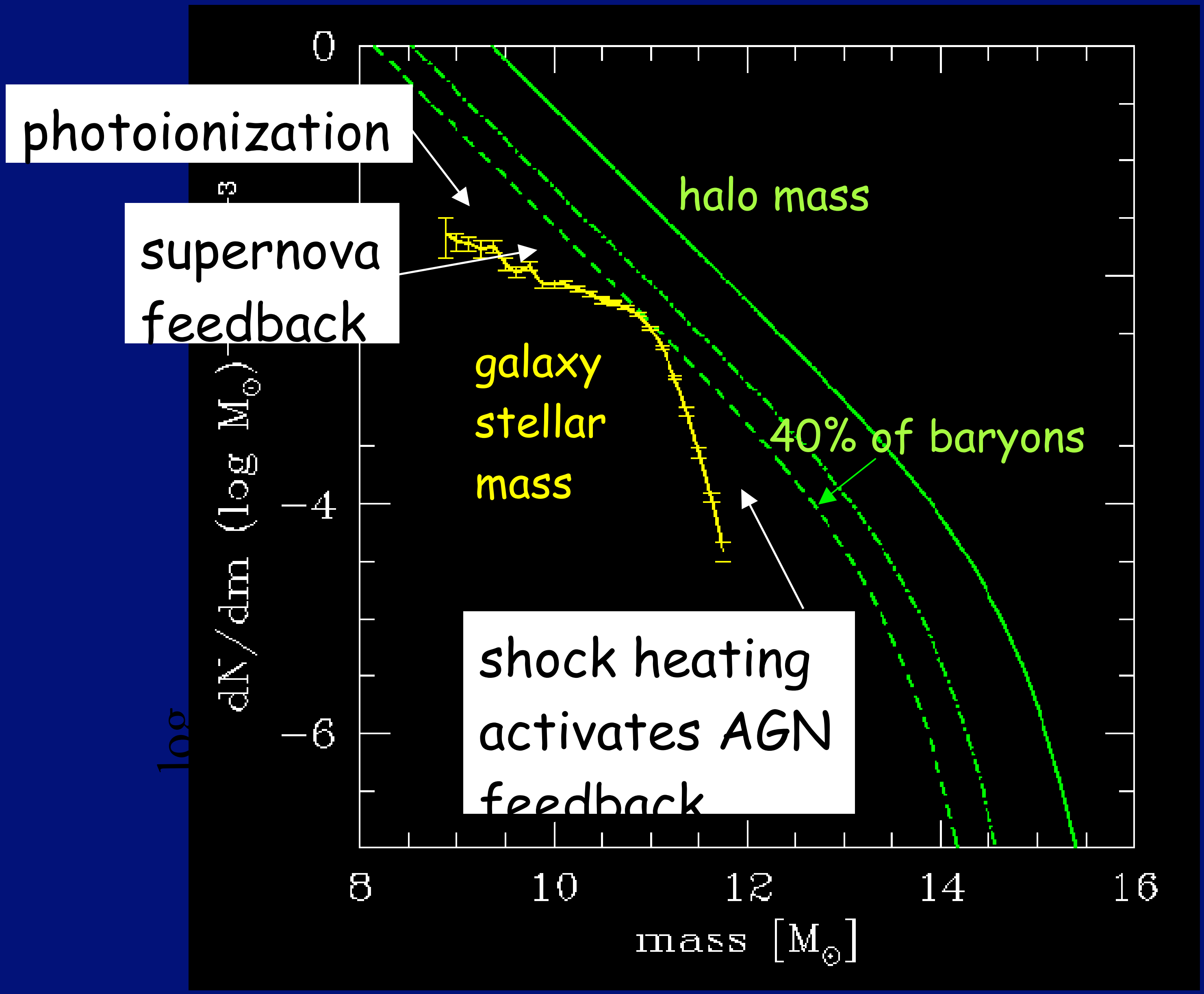
1. Galaxy type is driven by dark-halo mass:
   M_{crit}~$10^{12}M$_ by shock heating (+feedback & clustering)
2. Disk & star formation by cold flows riding DM filaments
3. Early (z>2) big halos (M~10^{12})
   big high-SFR galaxies by cold flows in hot media
4. Late (z<2) big halos M>10^{12} (groups):
   virial shock heating triggers "AGN feedback"
   _ shutdown of star formation _ red sequence
5. Late (z<2) small halos M<10^{12} (field): blue disks M_*<$10^{10.5}$
6. Downsizing is seeded in the DM hierarchical clustering
7. Downsizing is shaped up by feedback & shutdown M>10^{12}
8. Two different tracks from blue to red sequence

<M/L> has a minimum at M_{crit}

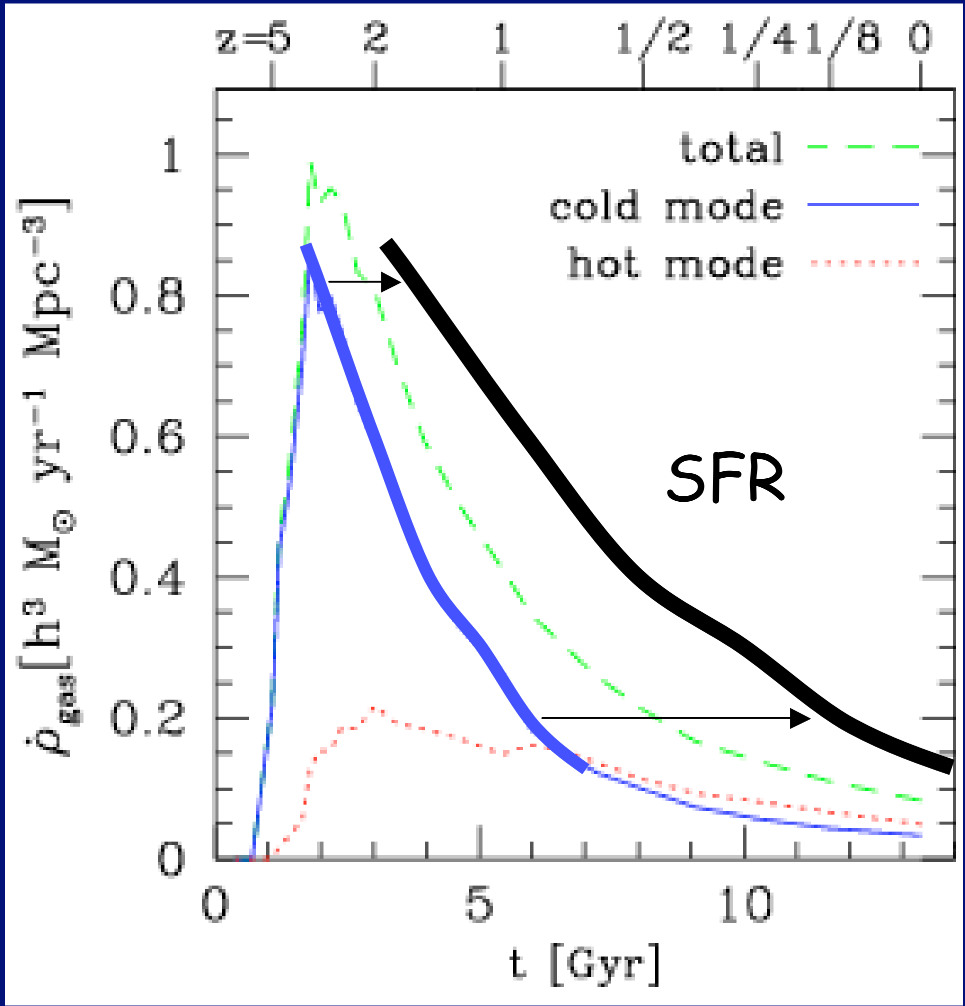


Using conditional luminosity function: Van den Bosch, Mo, Yang 03

A Sharp knee in the luminosity function



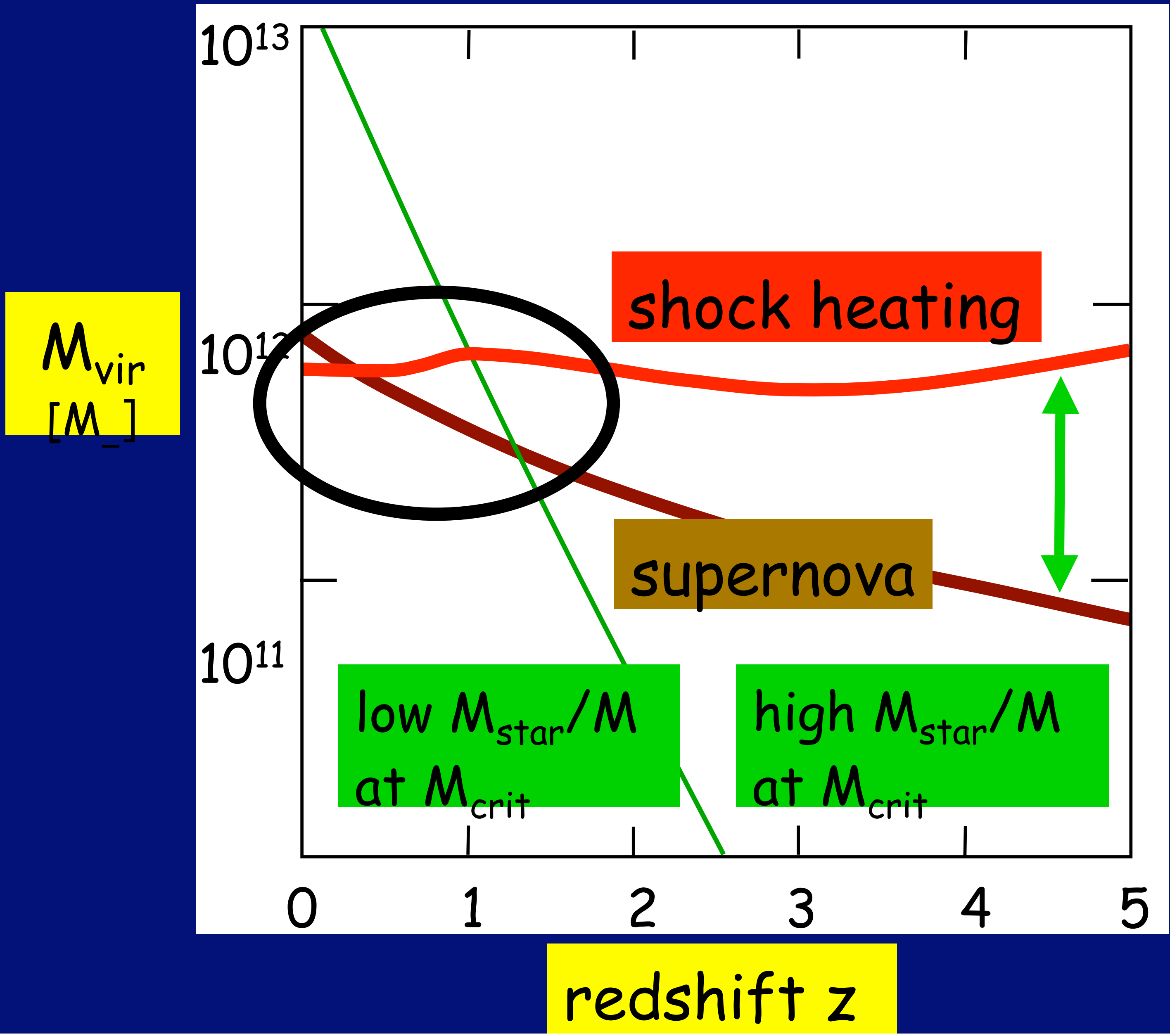
Cold infall history °˙
Star formation history



SPH simulation

Keres, Katz, Weinberg, Dav'e 2004

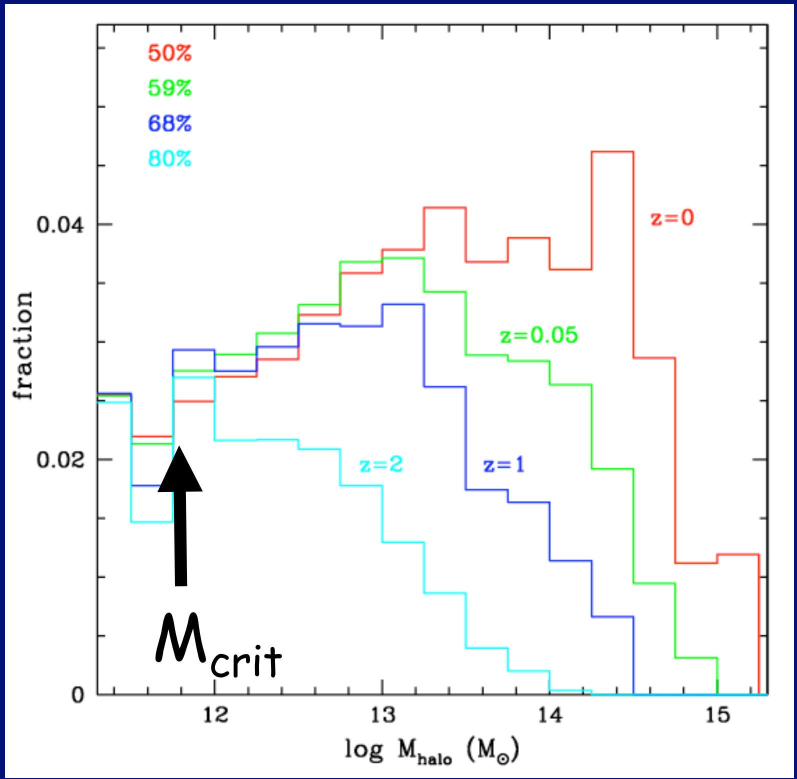
Shock-Heating vs SN Feedback at high z



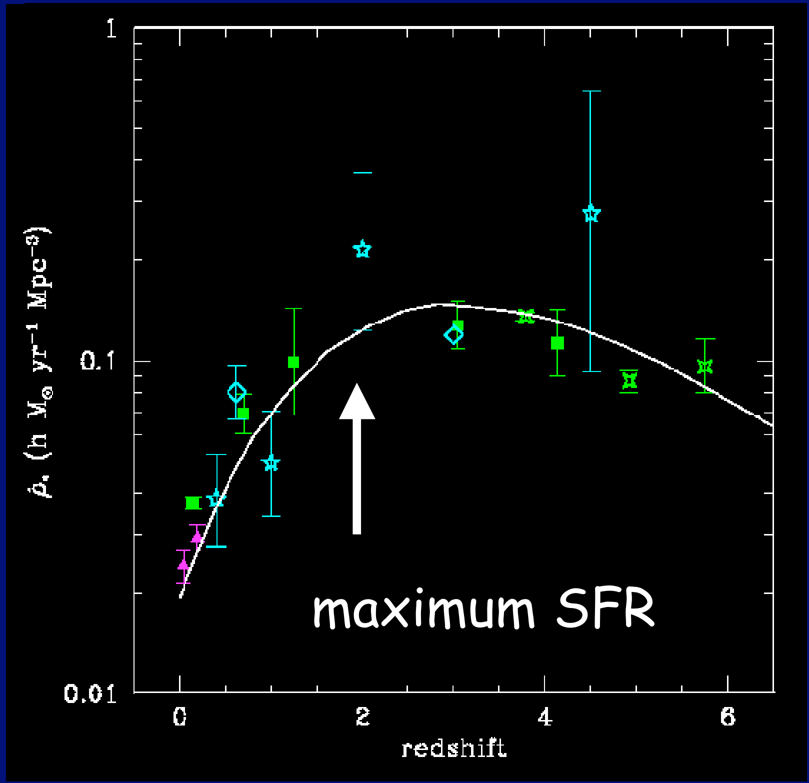
History of Star Formation

Most-efficient star formation near M_{crit}

evolution of
halo mass function



evolution of
star formation rate



The Angular Momentum problem

hydro simulations fail to produce large disks, over-produce bulges (Navarro, Steinmetz, …)

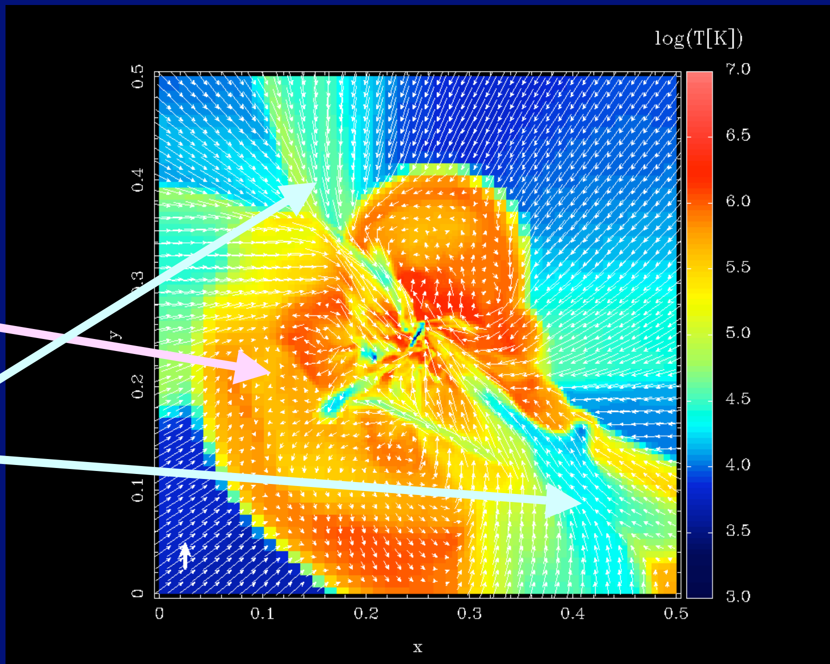
$\therefore$ should get rid of low j tail

$M<M_{crit}$ SN blowout from dwarf halos, which enter as minor mergers (Maller & Dekel 02)

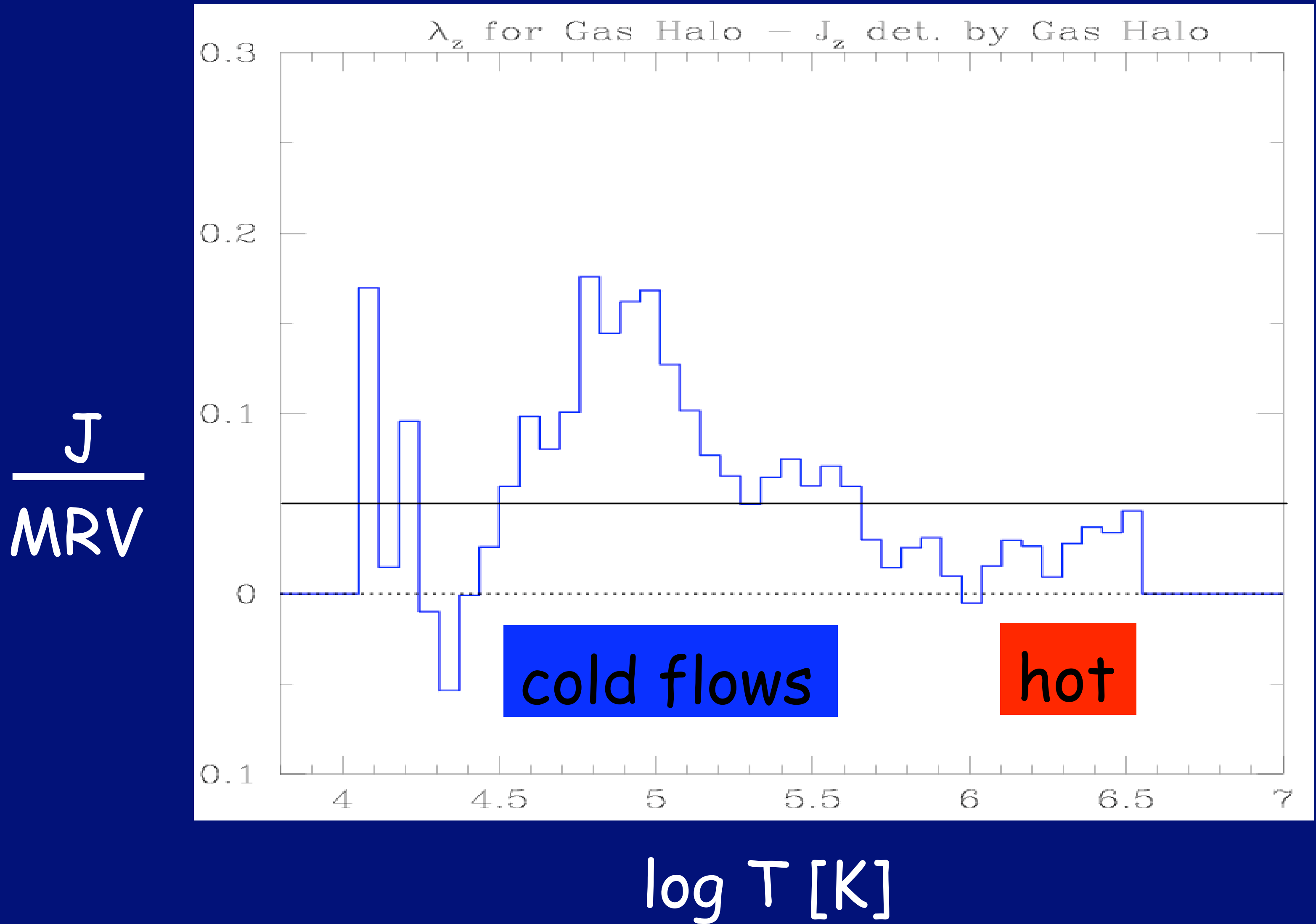
$M>M_{crit}$

AGN blowout of the low j hot medium

high j comes with cold streams



Angular Momentum: Cold vs Hot Gas



Zinger, Birnboim, Dekel, Kravtsov

Conclusions

Summary: Magic Scale

$M_* \sim 3\times10^{10} M\_$, $M_{vir} \sim 6\times10^{11} M\_$

$M < M_{crit}$

cold infall °˙disks

star bursts, field

SN feedback regulates SFR

°˙blue, young pop

$M_*/M \propto V^2 \rightarrow$ LSB fundamental line

starves AGNs

Ly-_ emitters

$M > M_{crit}$

hi-z progenitors < M_{crit} °˙disks

SF stops when $> M_{crit}$ °˙red, old,

spheroids in groups

hot gas (+ cold flows at z>2)

AGN feedback prevents cooling

of shock-heated gas

X-ray

Origin of the Observed Features

Blue sequence & FL: Cold flows in $M<M_{shock}$ halos (+mergers); SFR regulated by SN fdbk

Big reds & no big blues at $z<1$: Shutdown SFR in $M>M_{shock}\sim10^{12}$ due to coupling of hot gas with AGN fdbk; Mergers in groups --> spheroids help shutdown

Big blues at $z>2$: Cold streams in hot $M>M_{shock}$ before $z_{crit}\sim2$

Color bimodality gap: Abrupt shutdown of SFR; Spheroids get red; Satellites
Environment dependence: HOD -- halo mass, $M_{group}\sim M_{shock}$

Bulge/Disk bimodality: Disks by cold flows in $M<M_{shock}\sim M_{group}$;
Merger rate in groups --> spheroids + BH --> AGN fdbk

Minimum in M/L M_{shock}: Minimum in feedback efficiency

SFR peaks near $z\sim1$: Maximum cold flow, minimum feedback

Angular momentum: By cold flows

To do (partial list) :

Cold flows: fate? star formation, SN feedback

Hot medium: two phases, AGN feedback

X-ray, L_ emission , external ionizing flux

Angular momentum

Star formation history

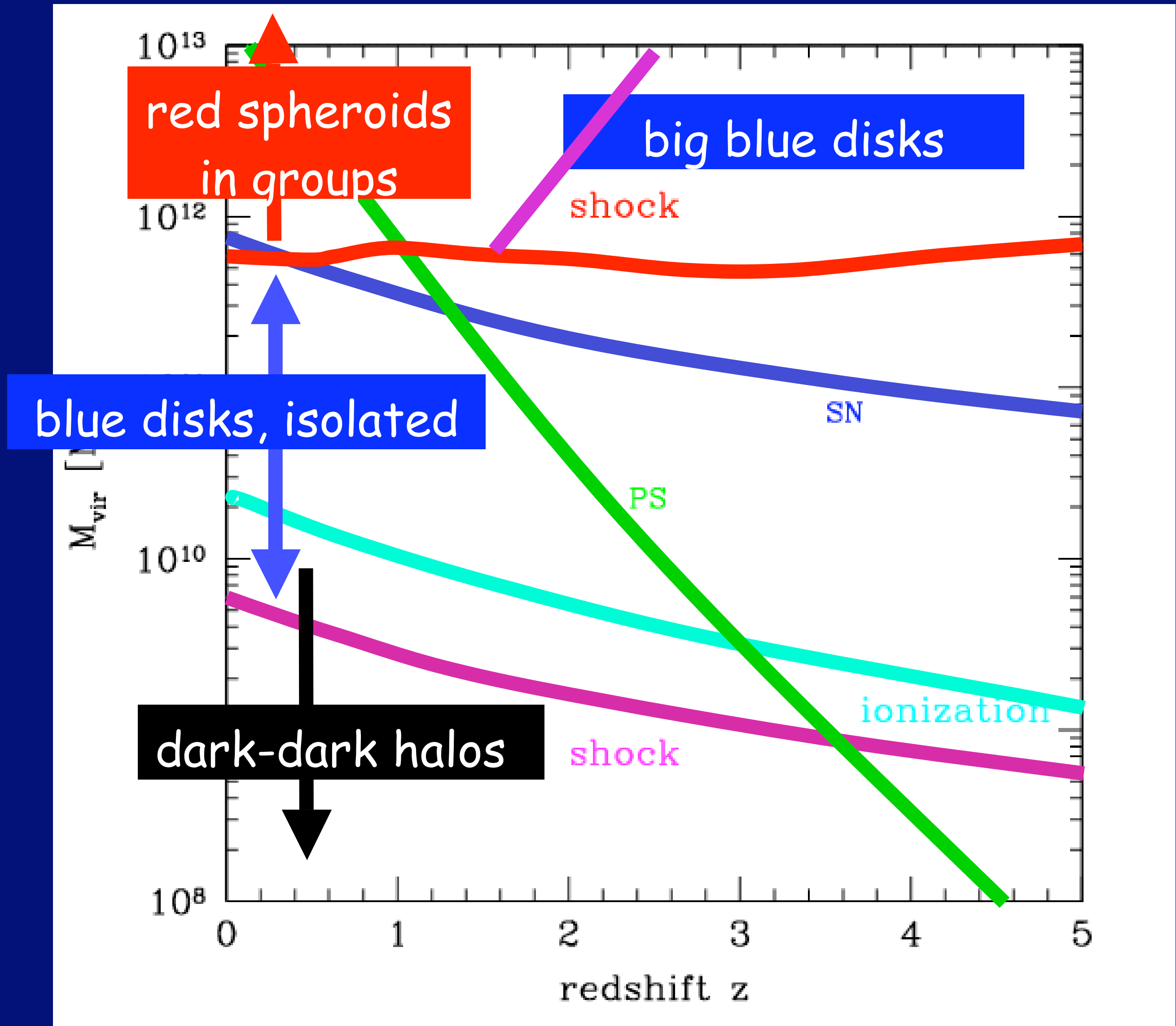
Implement in semi-analytic models

Theory vs. simulations

Re-engineering SAMs

- $M<M_{shockt}$: efficient early star formation by cold streams hitting disks
- $M>M_{shock}$ but $z>1.5$ (low HOD?): further star formation by cold streams
- $M>M_{shock}$ at $z<1.5$ in groups: shut off disk growth and star formation due to shock-heating + AGN feedback, preferably if big bulge
- no "cooling radius"; heating (not cooling) from the inside out

Characteristic Scales



Thank you

Talks

Jan 2005, Lyon

Oct 03 Venice 30 min
Dec 03 IAP EARA workshop 30
Dec 03 Meudon 45
Dec 03 IAP 45
Dec 03 ETH Zurich 45

Jan 04 Oxford ddh+vf 30 and bimodality 45
Feb 04 DM Marina del Rey bimodality30
Apr 04 Texas A&M bimodality30 (45)
Apr 04 Berkeley colloq bimodality
Apr 04 LNLL
May 04 U of Arizona
May 04 CfA colloq
May 04 UCSB physics colloq
May 04 Caltech colloq
May 04 UCSC astronomy colloq
June 04 KIPAC Stanford colloq
July 04 Plumian 300 IoA bi30 (30)
August 04 UCSC workshop bi30 (30)
August 04 UVic bi50
Oct 04 KITP bi50