Galaxy Formation

par Avishai Dekel

The Hebrew University of Jerusalem
& Chaire Internationale de Recherche Blaise Pascal, Paris

Une série de cours (en anglais) pour les étudiants en thèse (et M2) et les chercheurs

les mercredis, de 17h00 à 19h00 à l'amphithéâtre de l'IAP

98bis Bd Arago - Paris 14ème - M° St Jacques ou Denfert-Rochereau

20 octobre

1. The standard cosmology
2. Linear growth of fluctuations by gravitational instability

A special lecture series on Galaxy Formation

by Avishai Dekel (Chaire Internationale Blaise Pascal)

for graduate students and researchers; IAP/OP Wednesdays 17:00-19:00

Octobre 20	1. the standard cosmology
	2. linear growth of fluctuations by gravitational instability
Novembre 17	3. statistics of density fluctuations: the CDM scenario
	4. nonlinear growth: spherical model, filamentary structure
Decembre 8	5. numerical simulations of structure formation
	6. hierarchical clustering: Press-Schechter formalism, biasing
Decembre 15	7. dark-matter halos: density profile, cusp/core problem
	8. halo substructure: dynamical friction, tidal effects, HOD
Janvier 5	9. angular momentum problem: tidal torques, disk formation
	10. the origin of galaxy scaling relations and their scatter
Janvier 12	11. semi-analytic modeling: cooling, star formartion, mergers
	12. feedback processes: supernova, AGN and black holes
Fevrier 9	13. cold flows versus shock heating
	14. origin of bi-modality in galaxies
Fevrier 16	15. dwarf galaxies and the "fundamental line"
	16. dark-dark halos: effect of cosmological photoionization

Lectures 13-14 (some 11-12)

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

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

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, ...

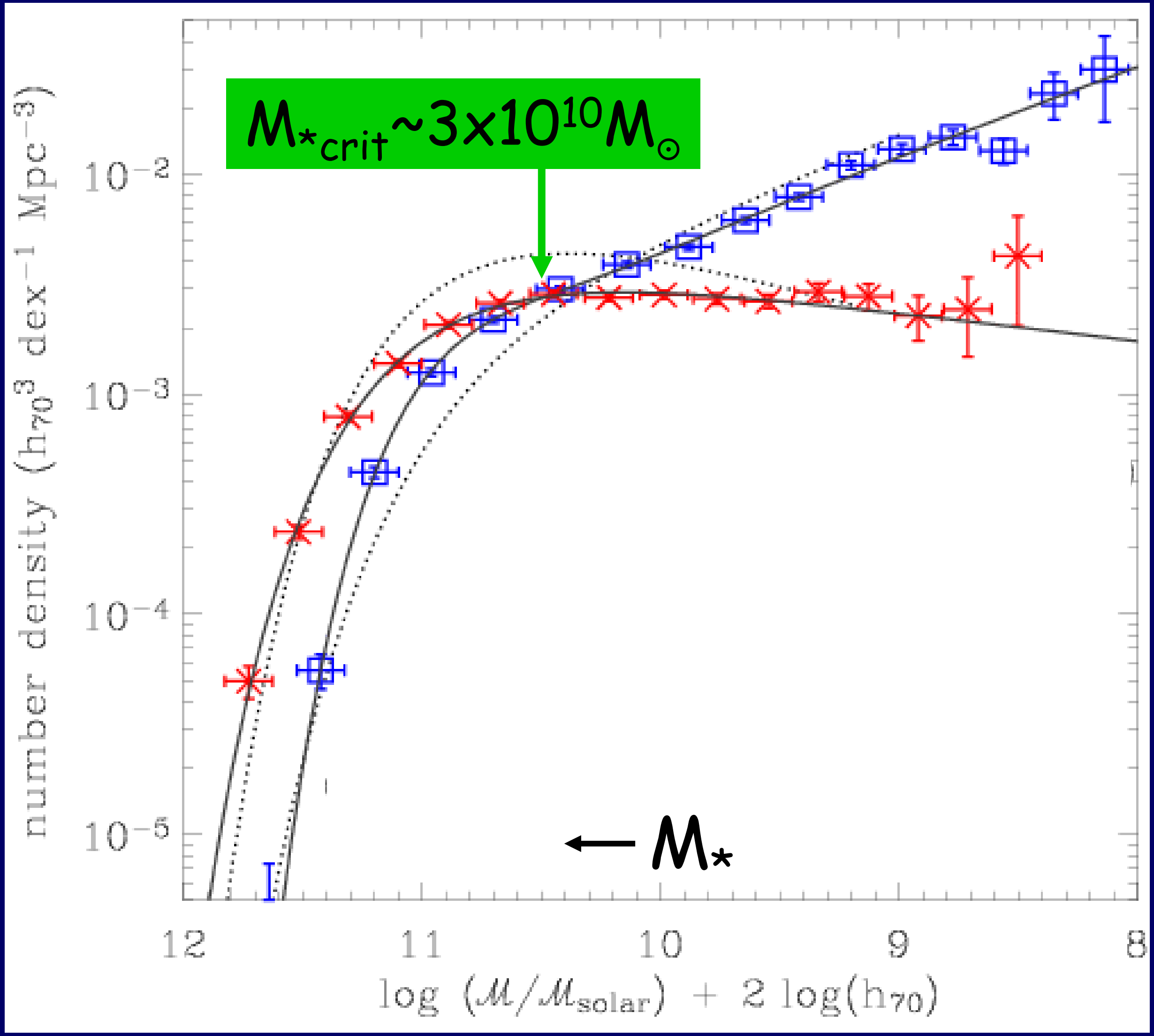
- very blue galaxies → bursty star formation
- big blue galaxies at z~2-3 (e.g. SCUBA)

→ early star formation in big objects

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

→ early star formation, then shut off

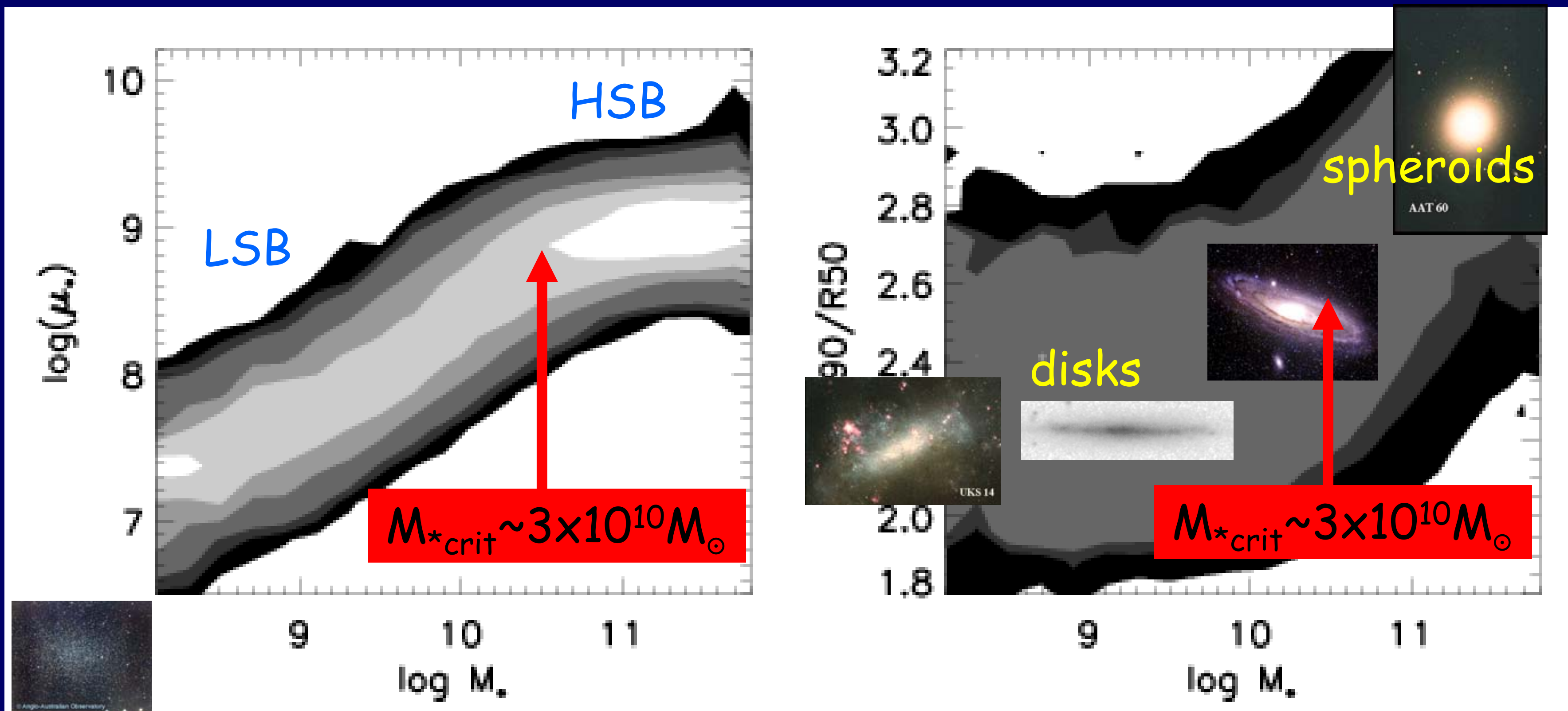
Luminosity function: Red vs Blue



SDSS
Baldry et al. 04

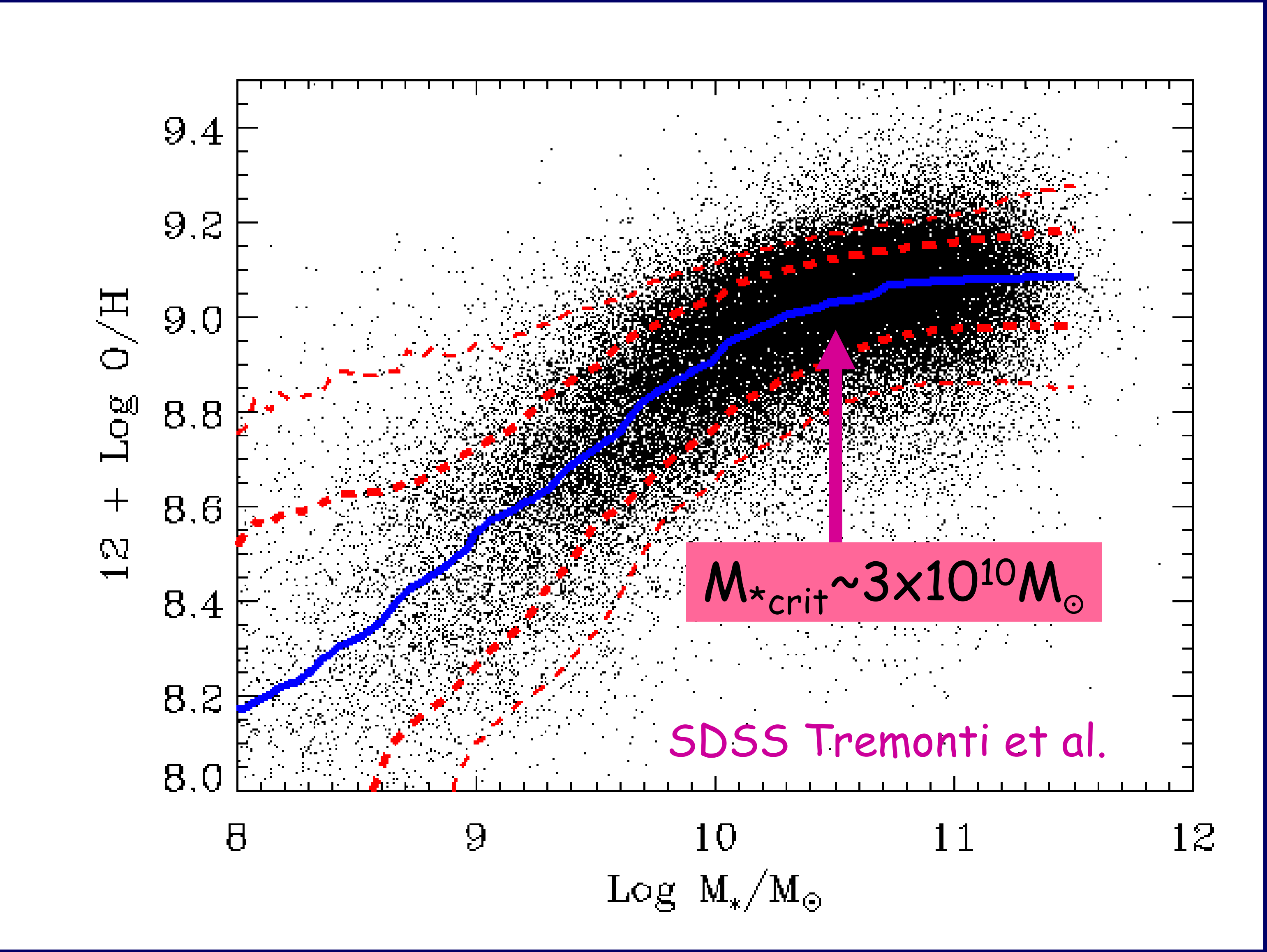
Transition Scale

Surface Brightness | Bulge/Disk

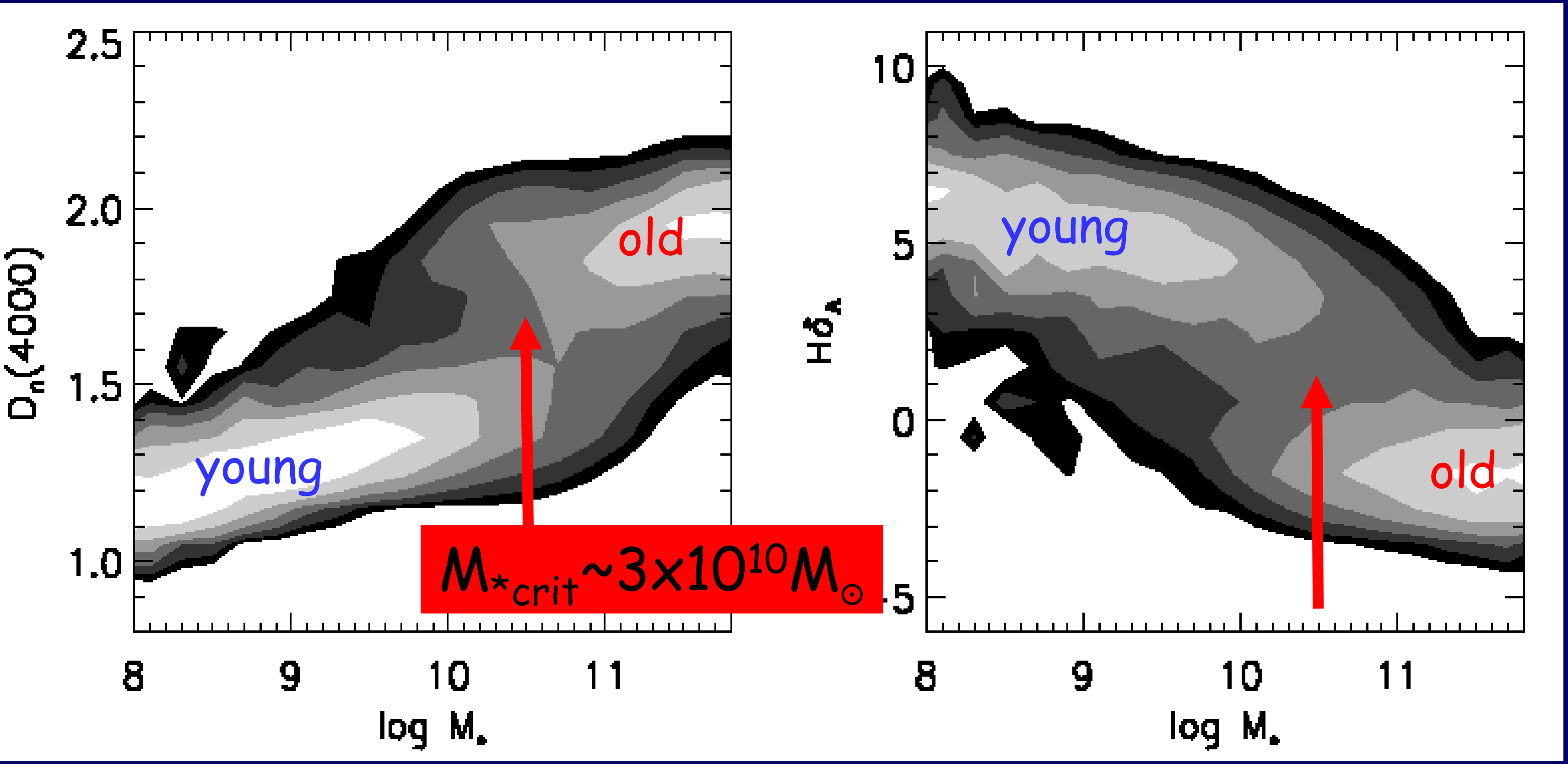


SDSS Kauffmann et al. 03

Transition in Metallicity

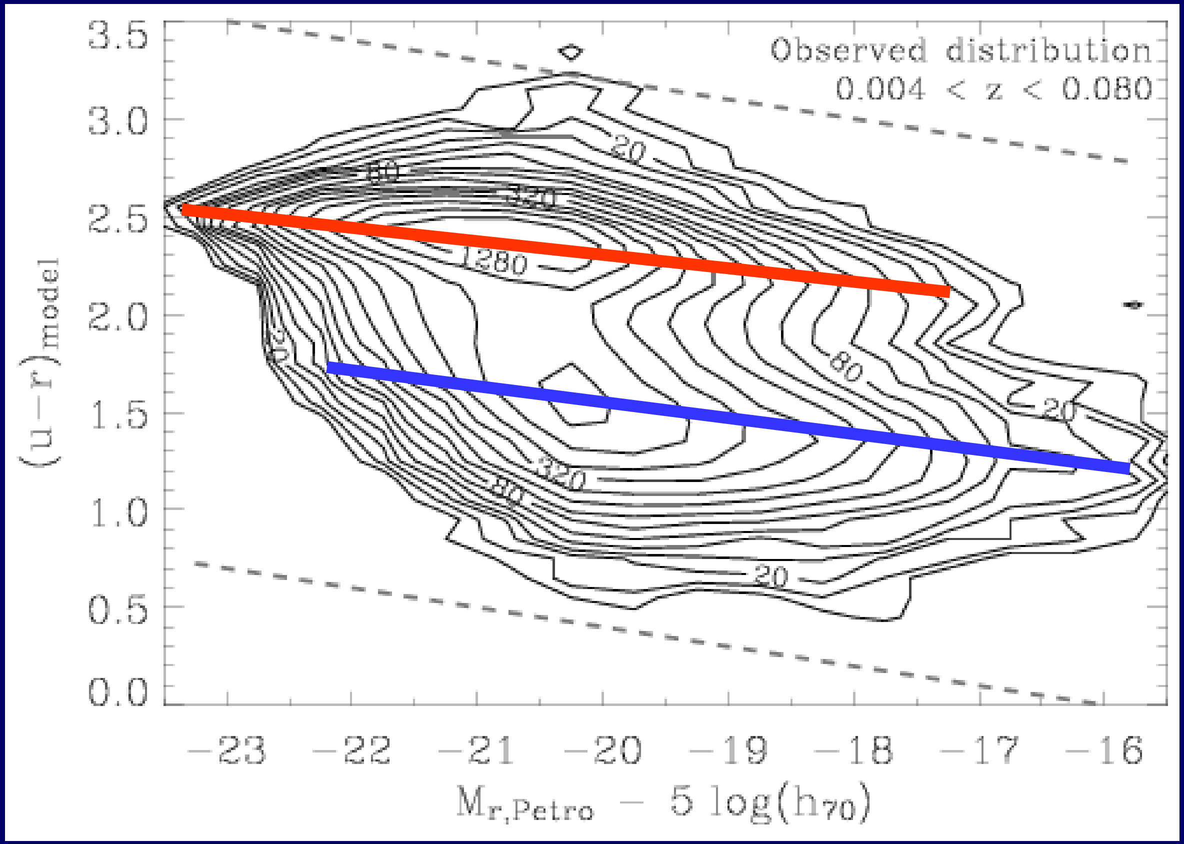


Bi-modality: Age vs Stellar Mass



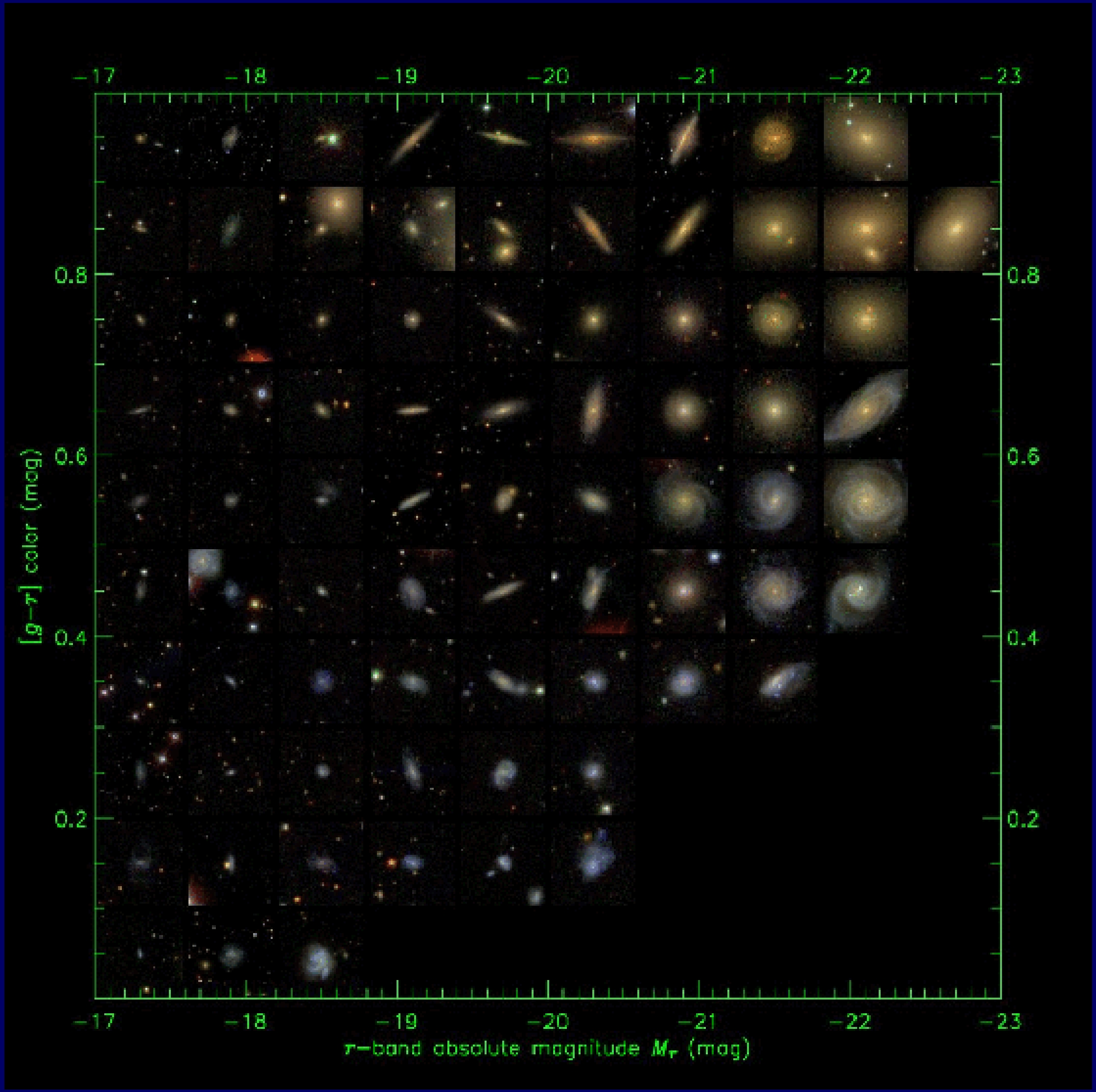
SDSS Kauffmann et al. 03

Bi-modality in Color-Magnitude

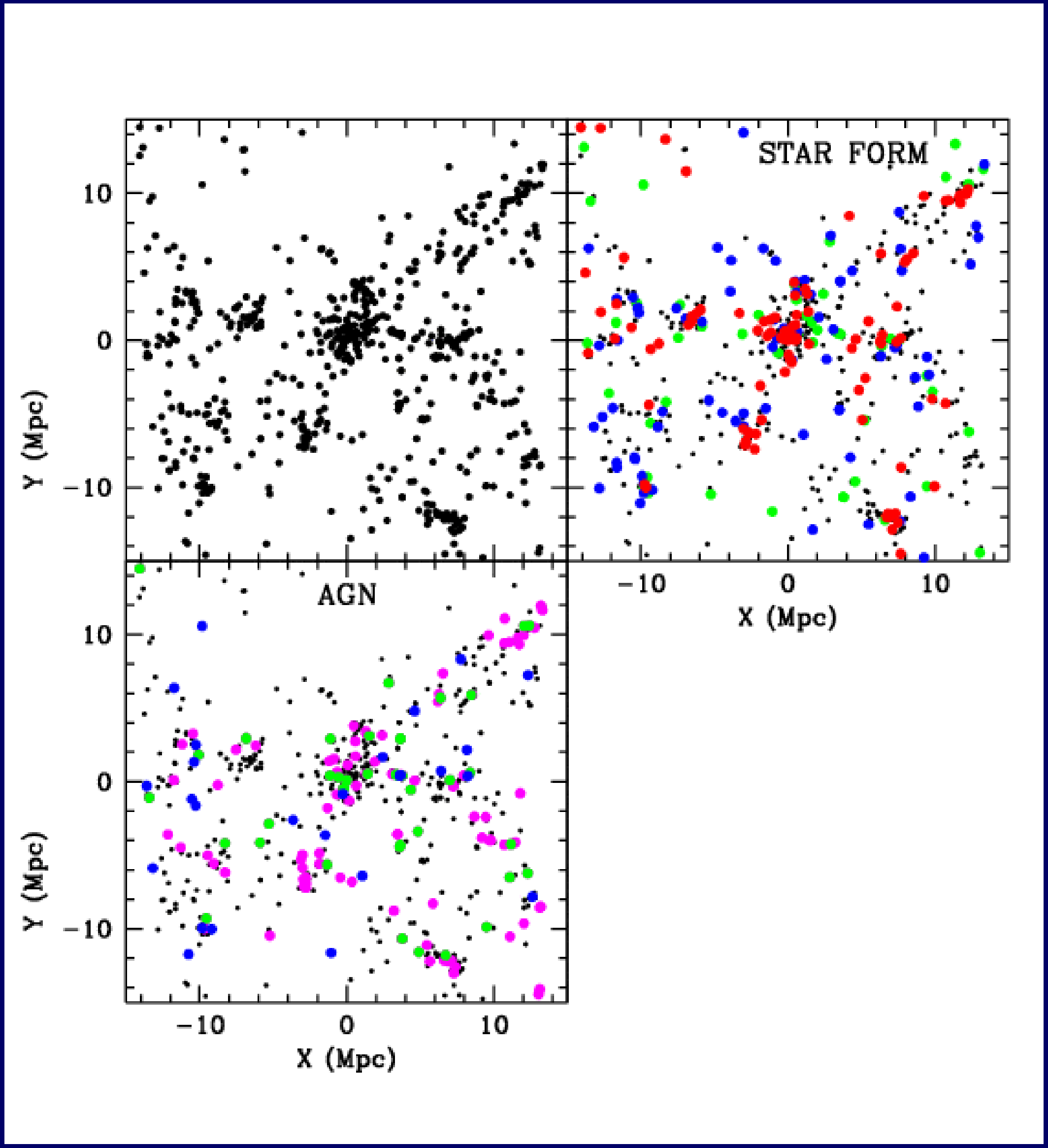


SDSS Baldry et al. 04

Color-Magnitude-Morphology in SDSS

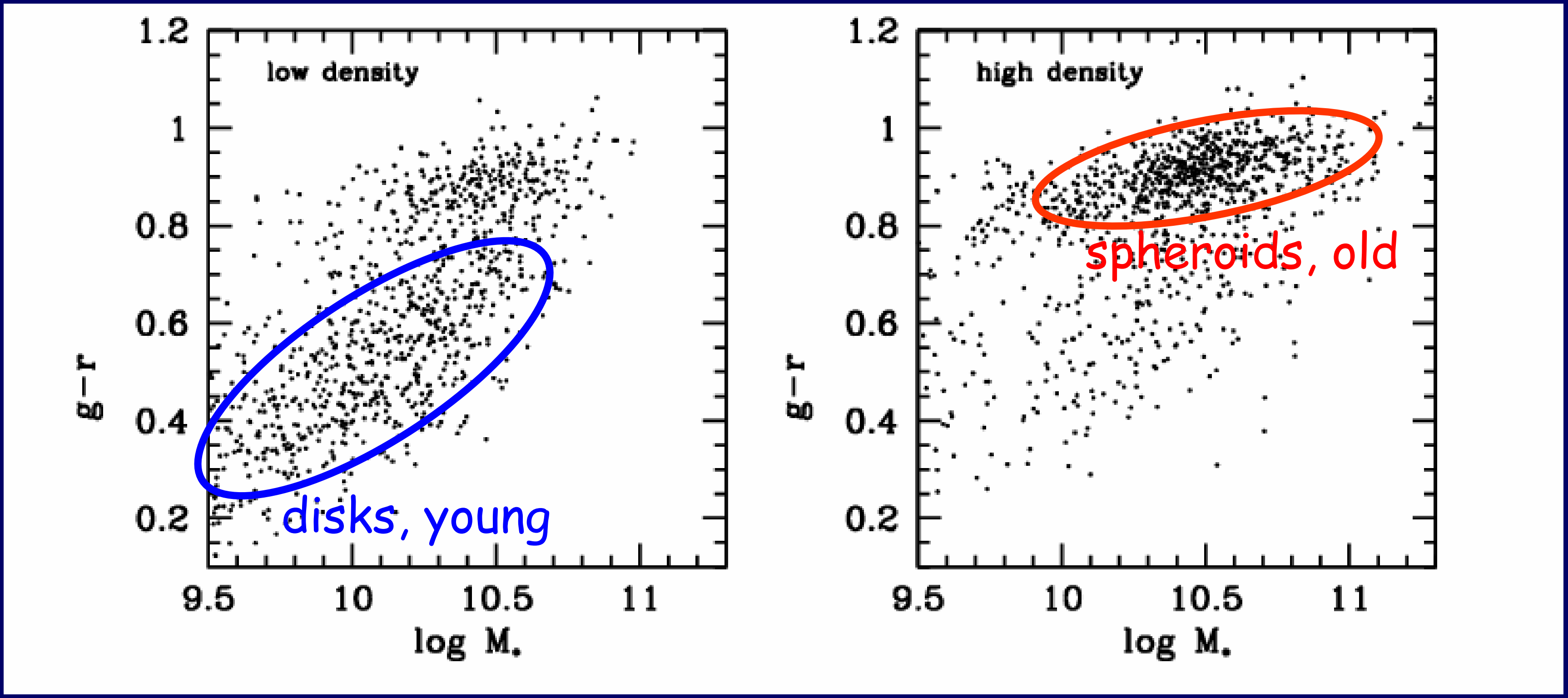


Color - Environment



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

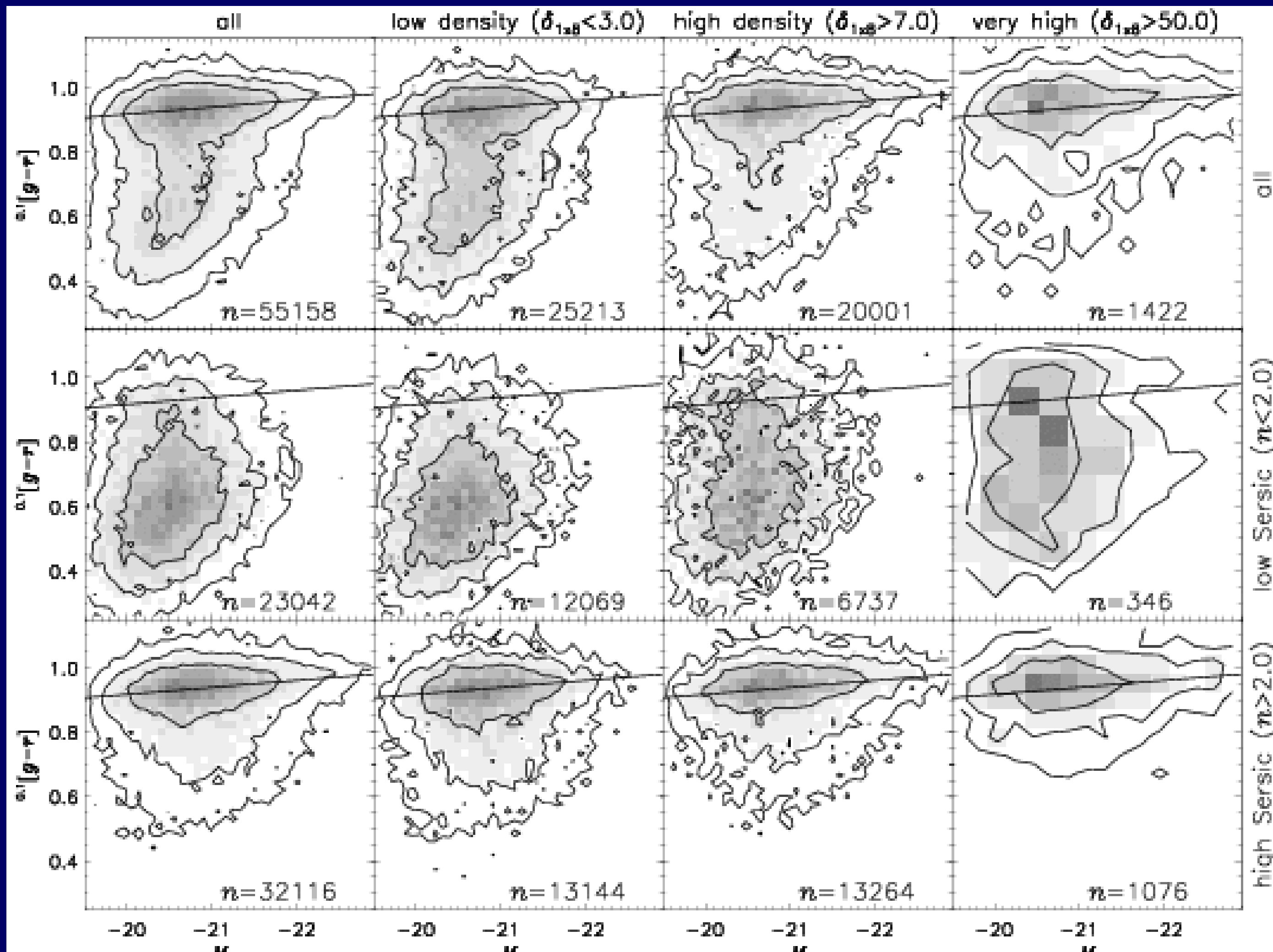
M_{halo}<6x10^{11} "field" M_{halo}>6x10^{11} "cluster"



Kauffmann et al. 2004

Color-Magnitude Bimodality depends on B/D and Environment

density: low high very high

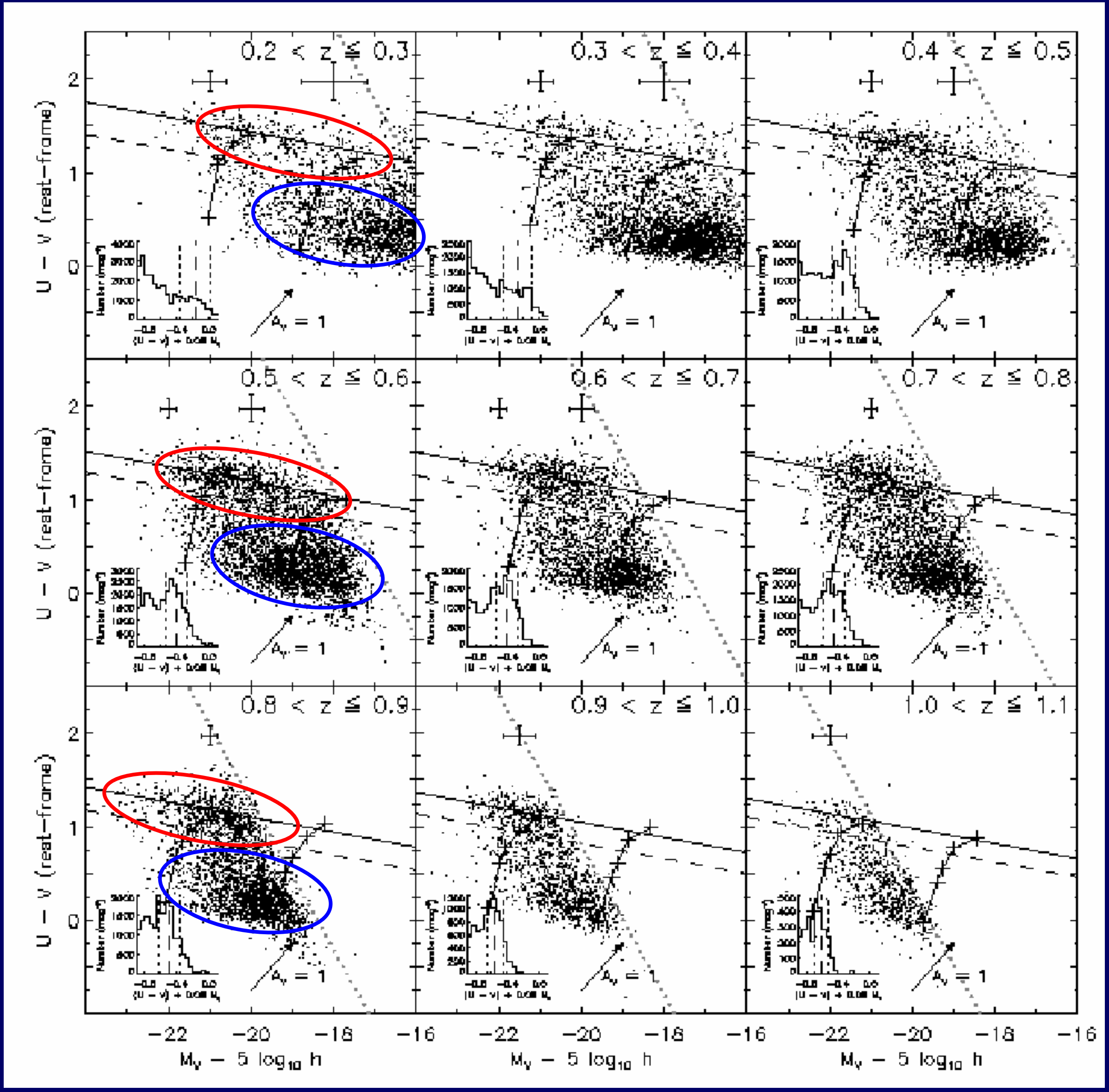


disks

spheroids

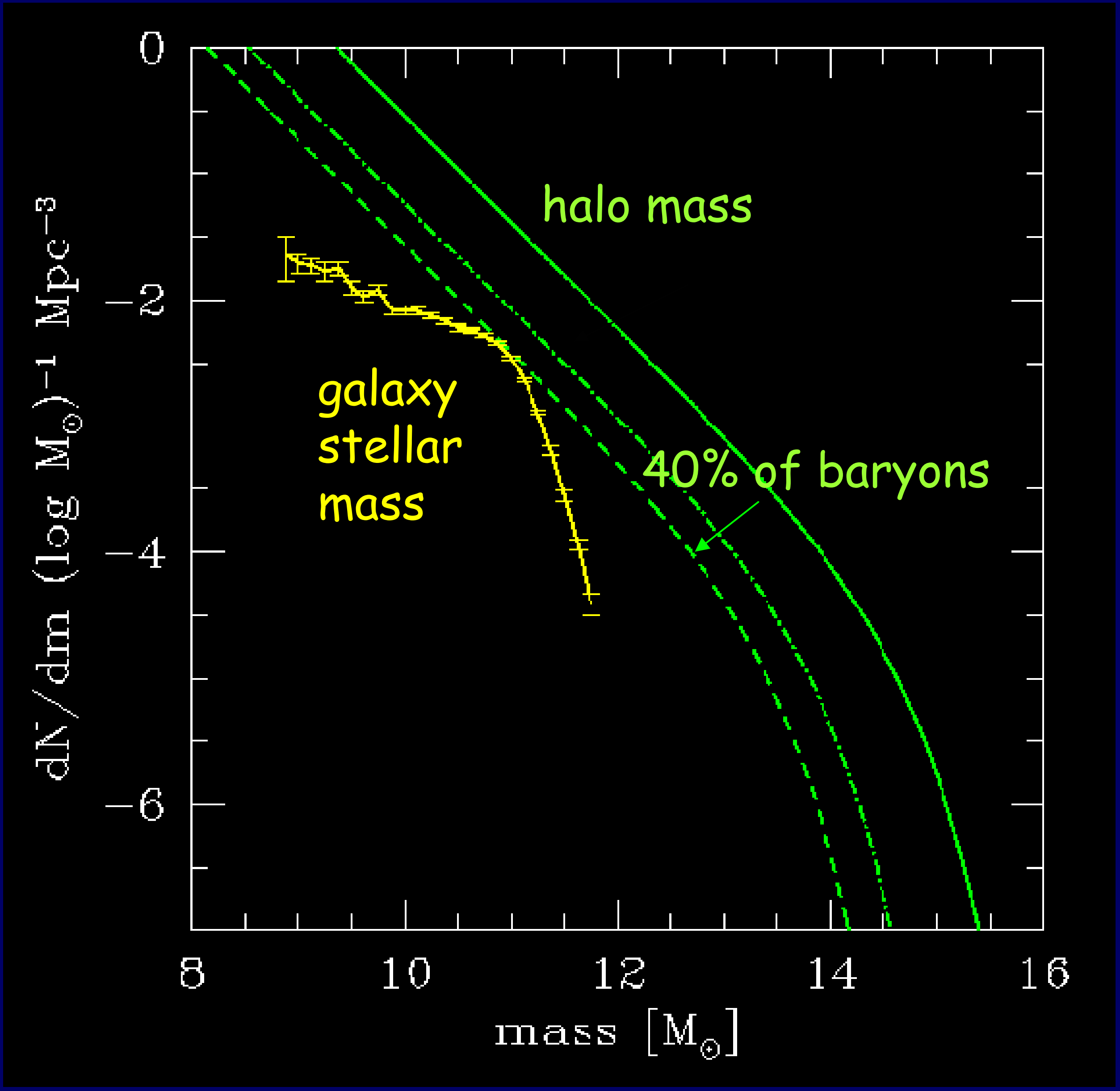
SDSS: Hogg et al. 03

Bi-modality at high z

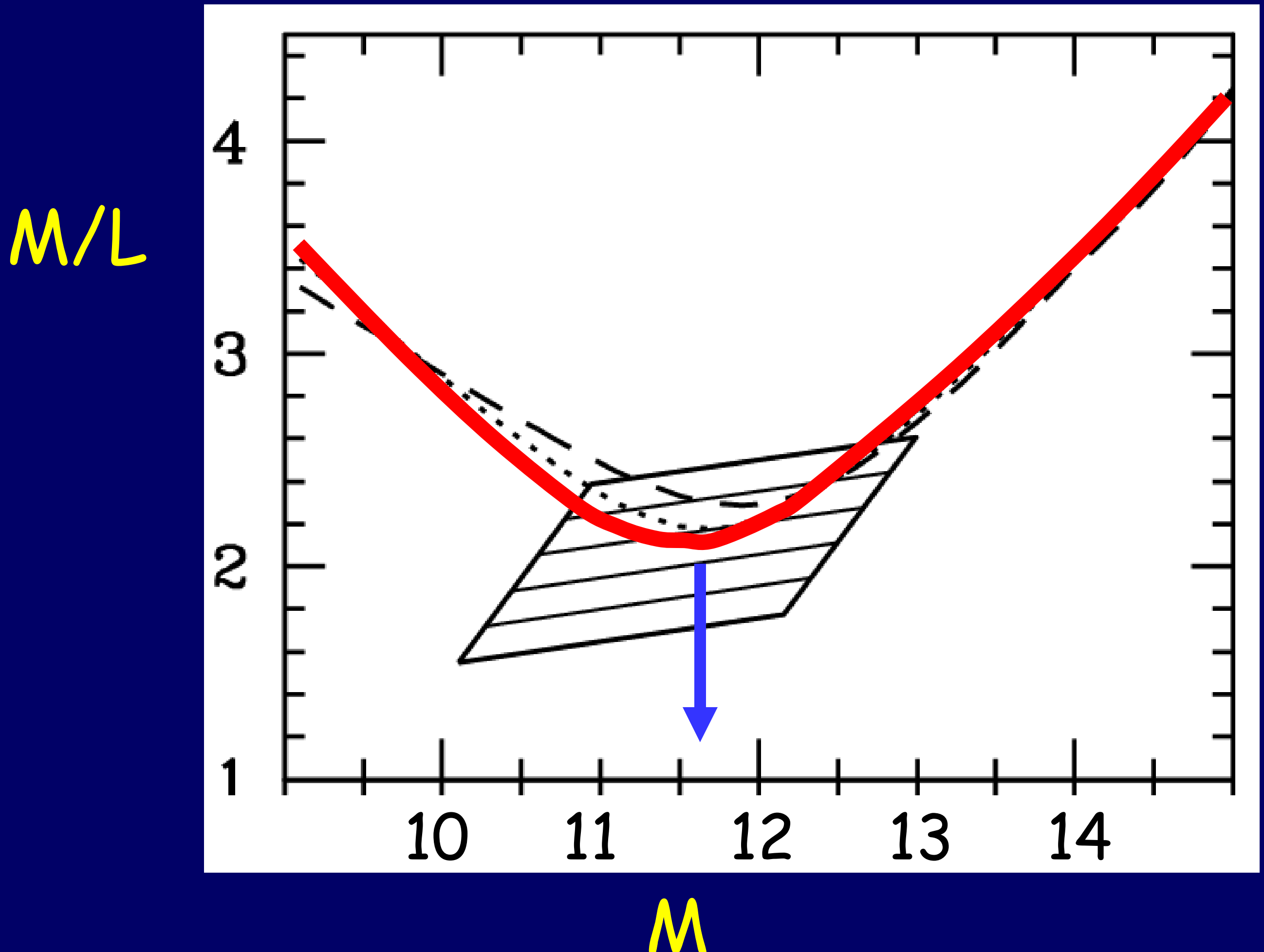


Combo-17

Mass versus Light Distribution

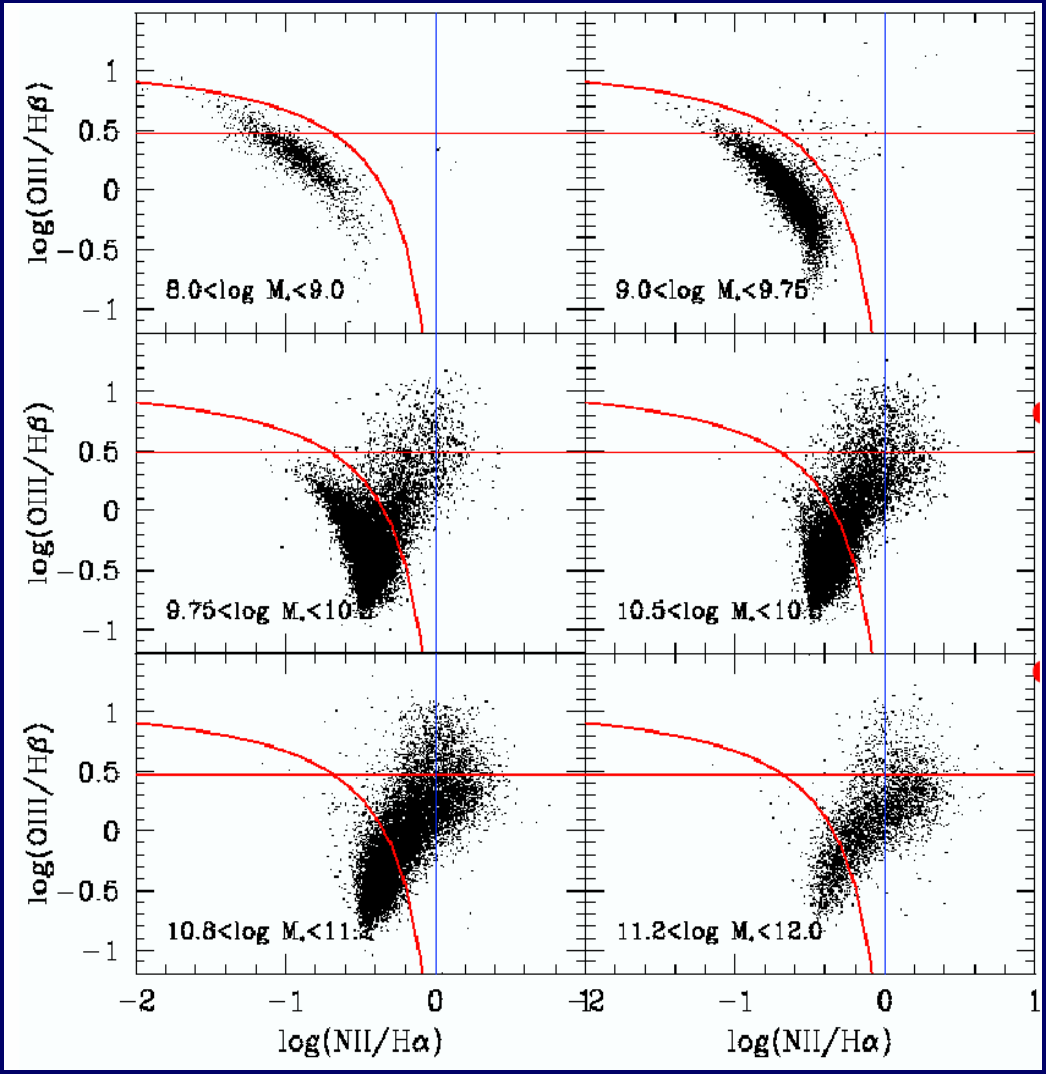


<M/L> vs M for halos in 2dF assuming ΛCDM



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

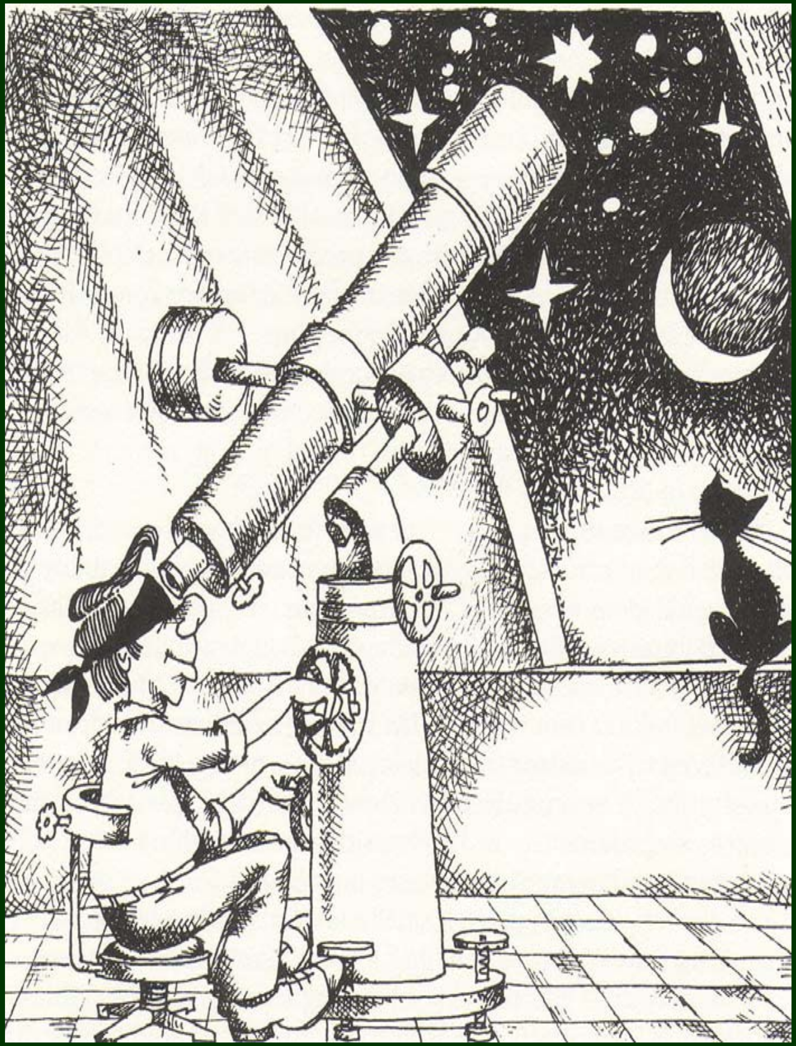
bi-modality / transition

$M_* \sim 3 \times 10^{10} M_\odot$ $M_{vir} \sim 6 \times 10^{11} M_\odot$ $V_{vir} \sim 120$ 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

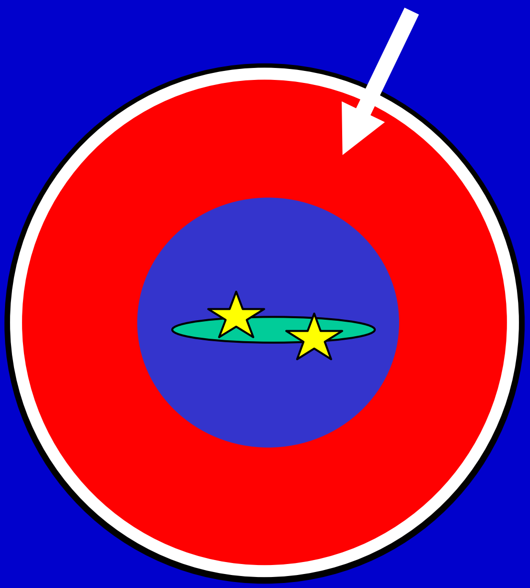
Halo virialization

Gas infall, shock heating at the virial radius

Radiative cooling

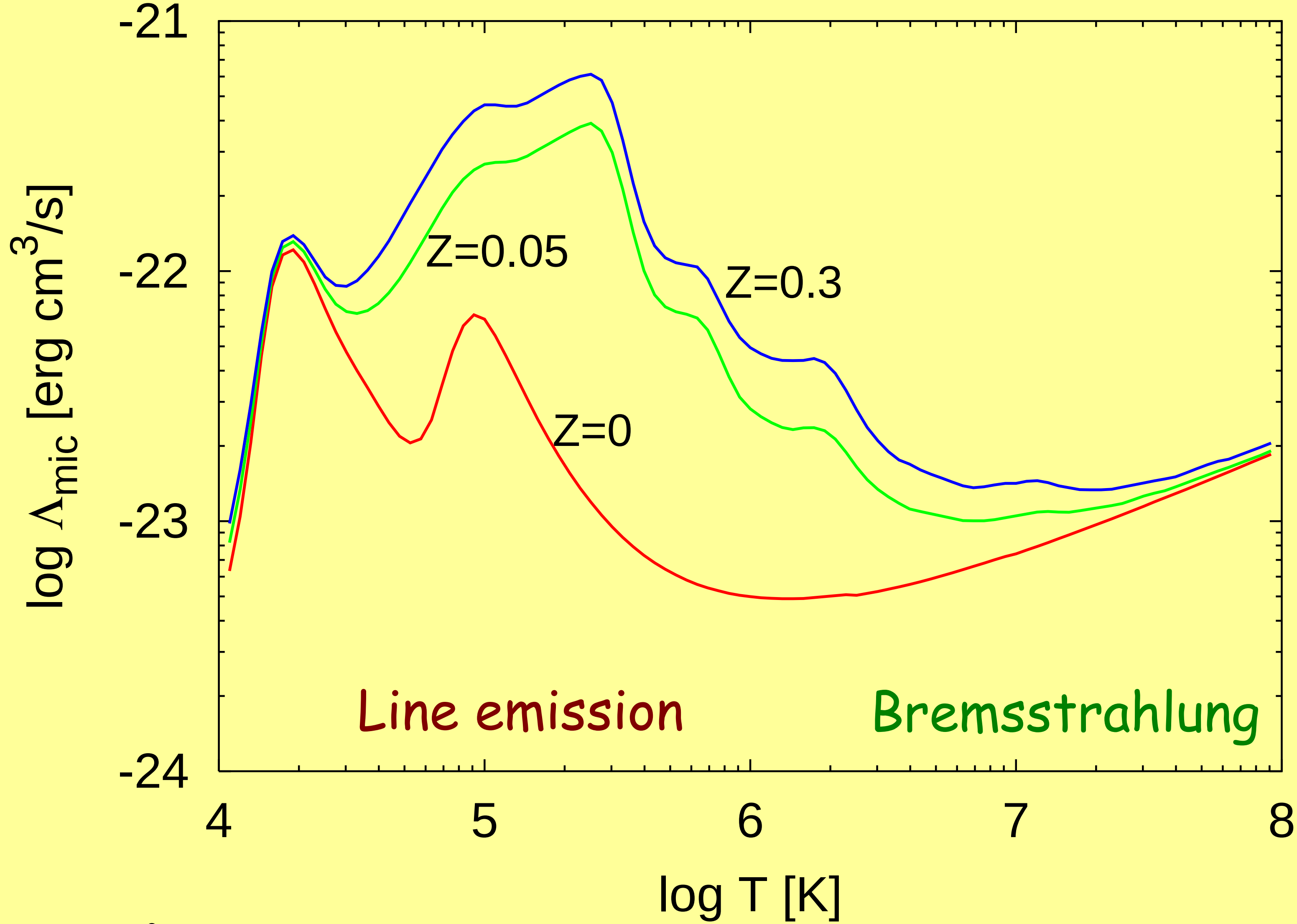
Accretion to disc if $t_{cool} < t_{ff}$

Stars & feedback



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

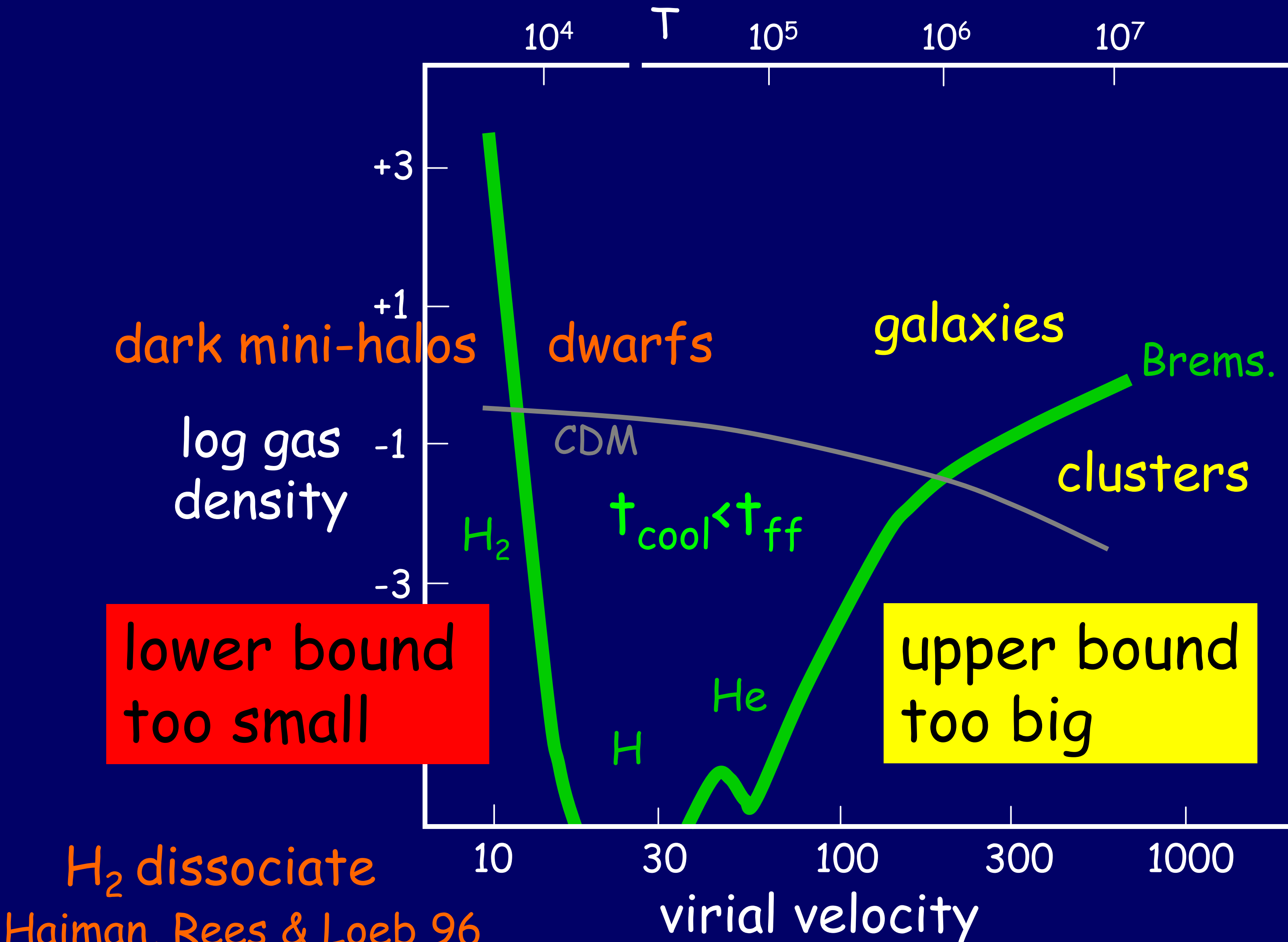
Cooling rate



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

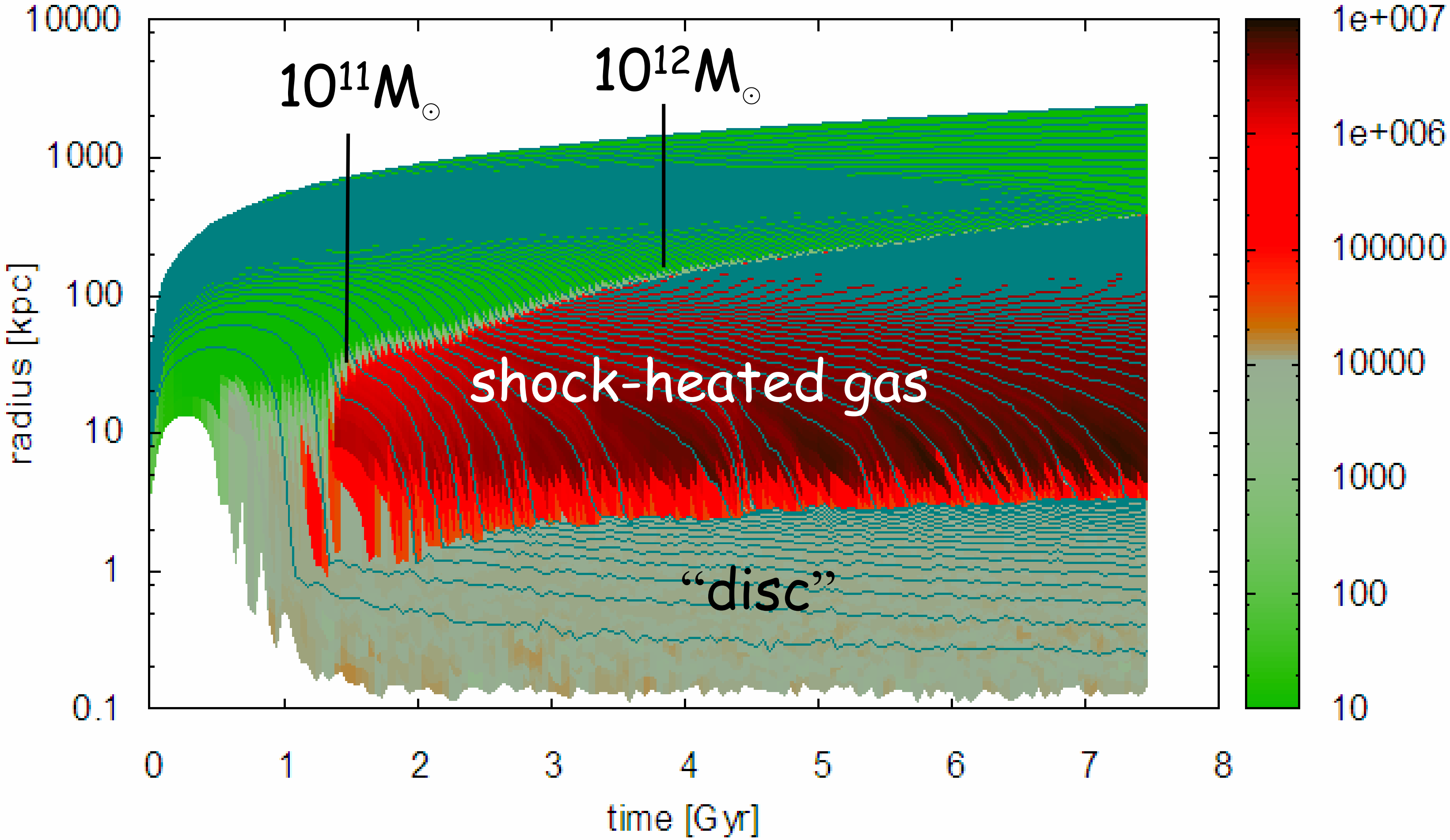
Cooling vs Free Fall

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



2. Shock-Heating vs Cold Flows

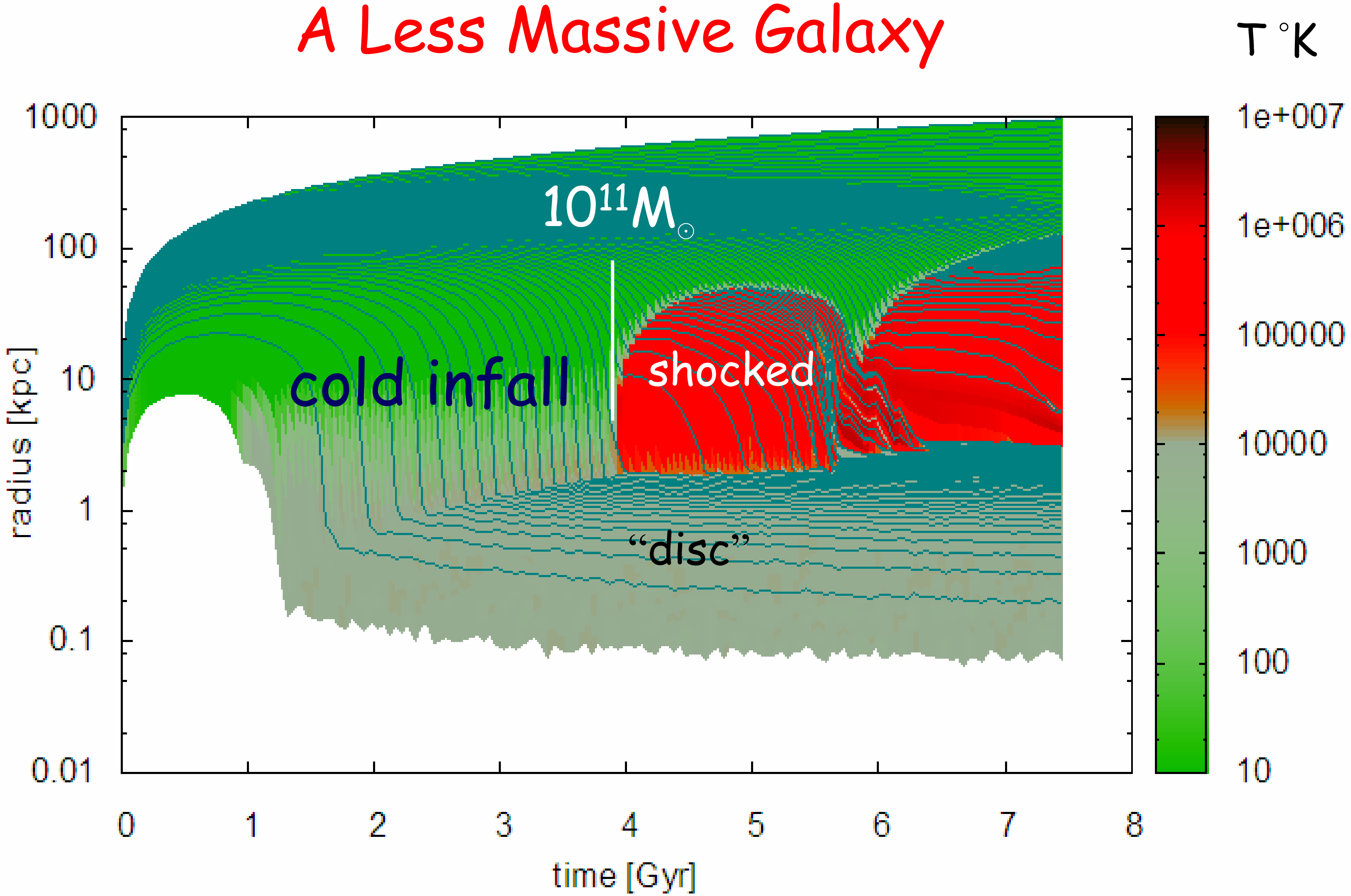
Growth of a Massive Galaxy



Spherical hydro simulation

Birnboim & Dekel 03

A Less Massive Galaxy



Spherical hydro simulation

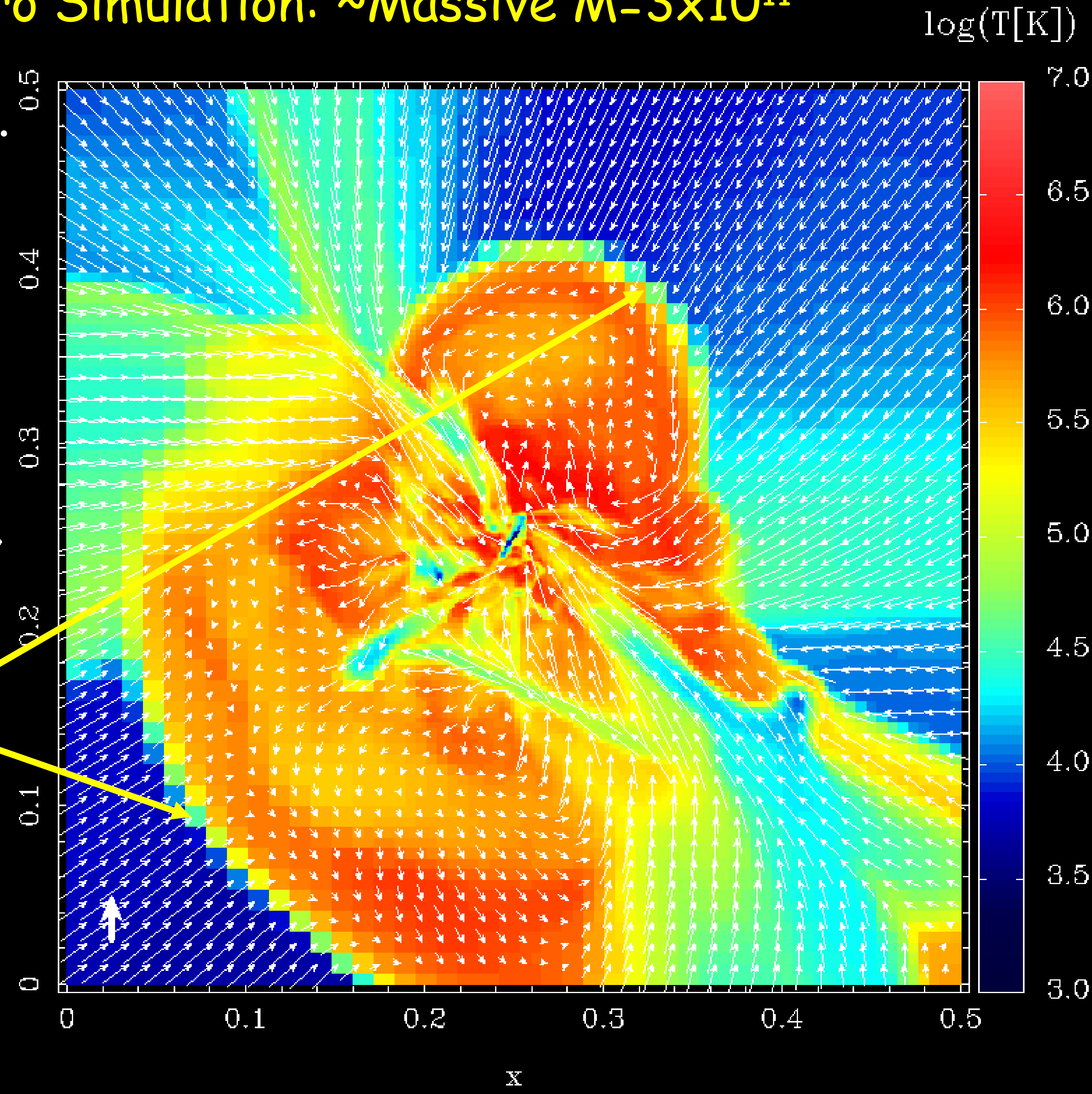
Birnboim & Dekel 03

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

Kravtsov et al.

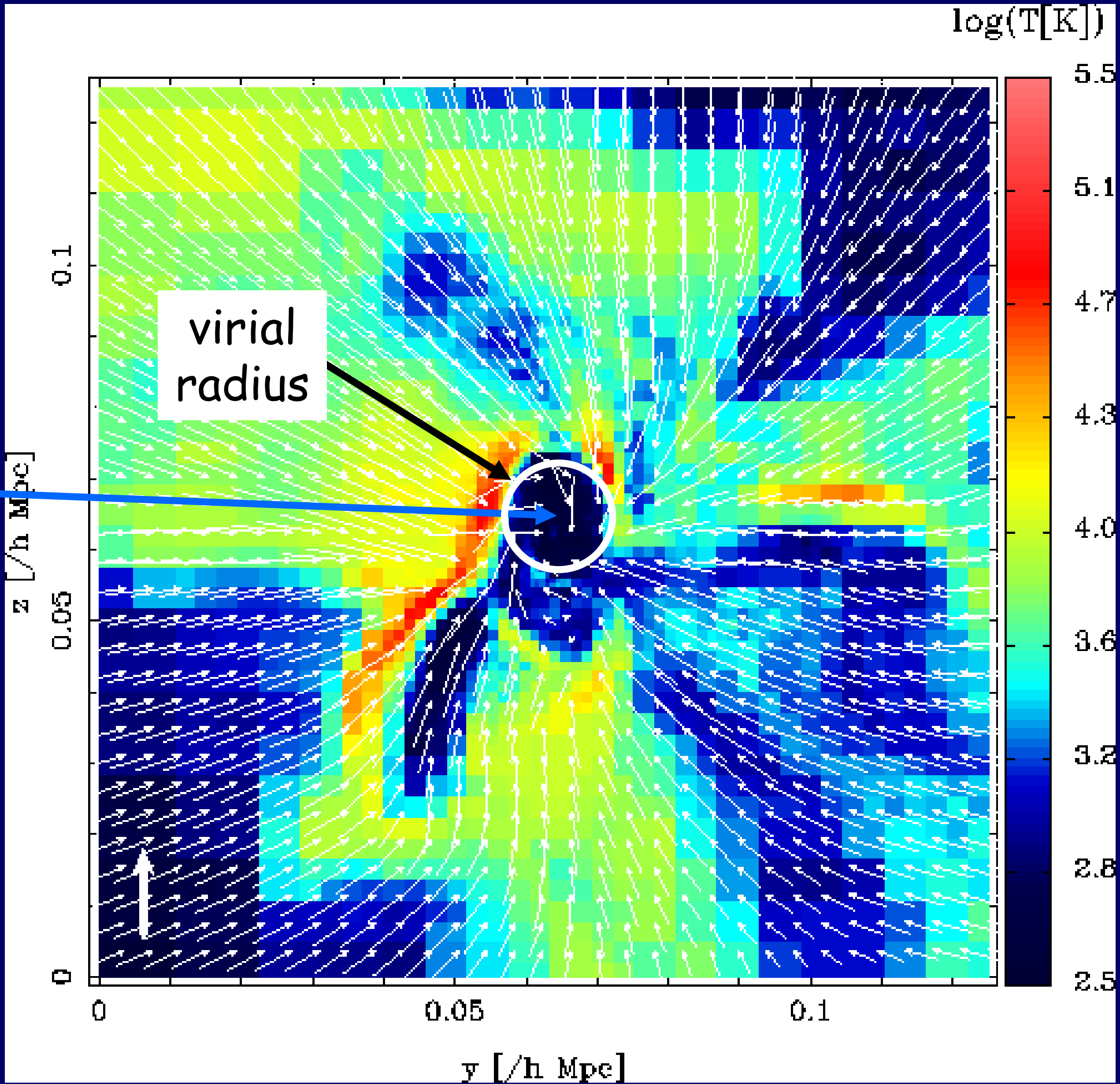
$z=4$
$M=3\times10^{11}$
$T_{vir}=1.2\times10^{6}$
$R_{vir}=34$ kpc

virial shock



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

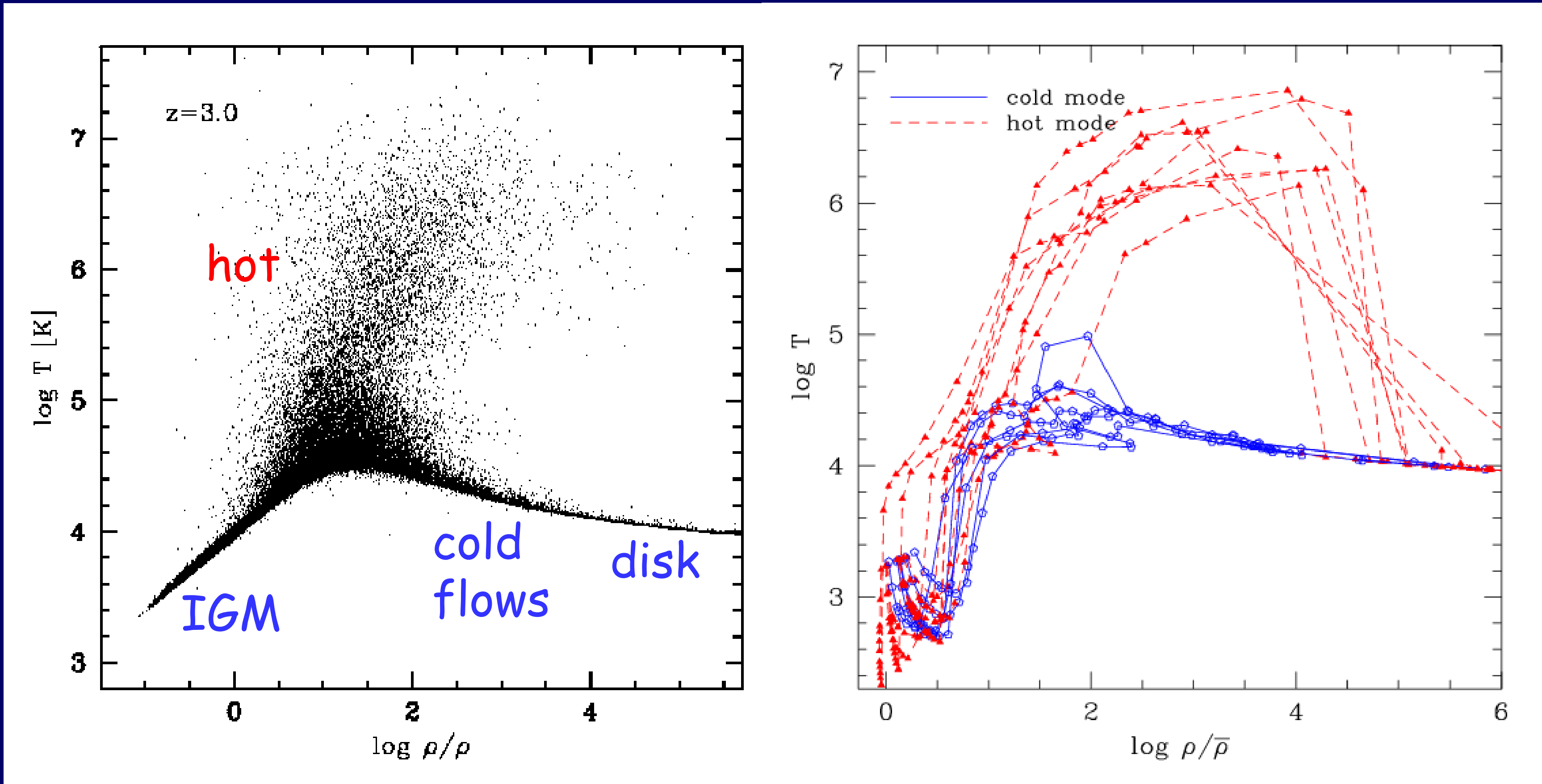
Kravtsov et al.



cold infall

$z=9$
$M=1.8\times10^{10}$
$T_{vir}=3.5\times10^5$
$R_{vir}=7$ kpc

Cold and Hot Modes in SPH Simulations

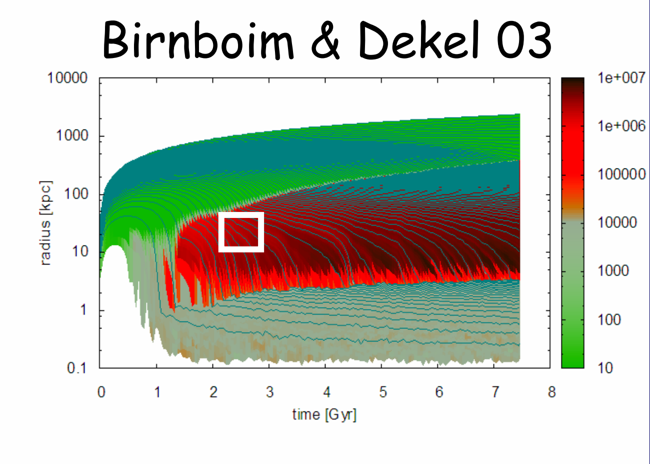


Keres, Katz, Weinberg, Dav'e 2004

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):

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

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

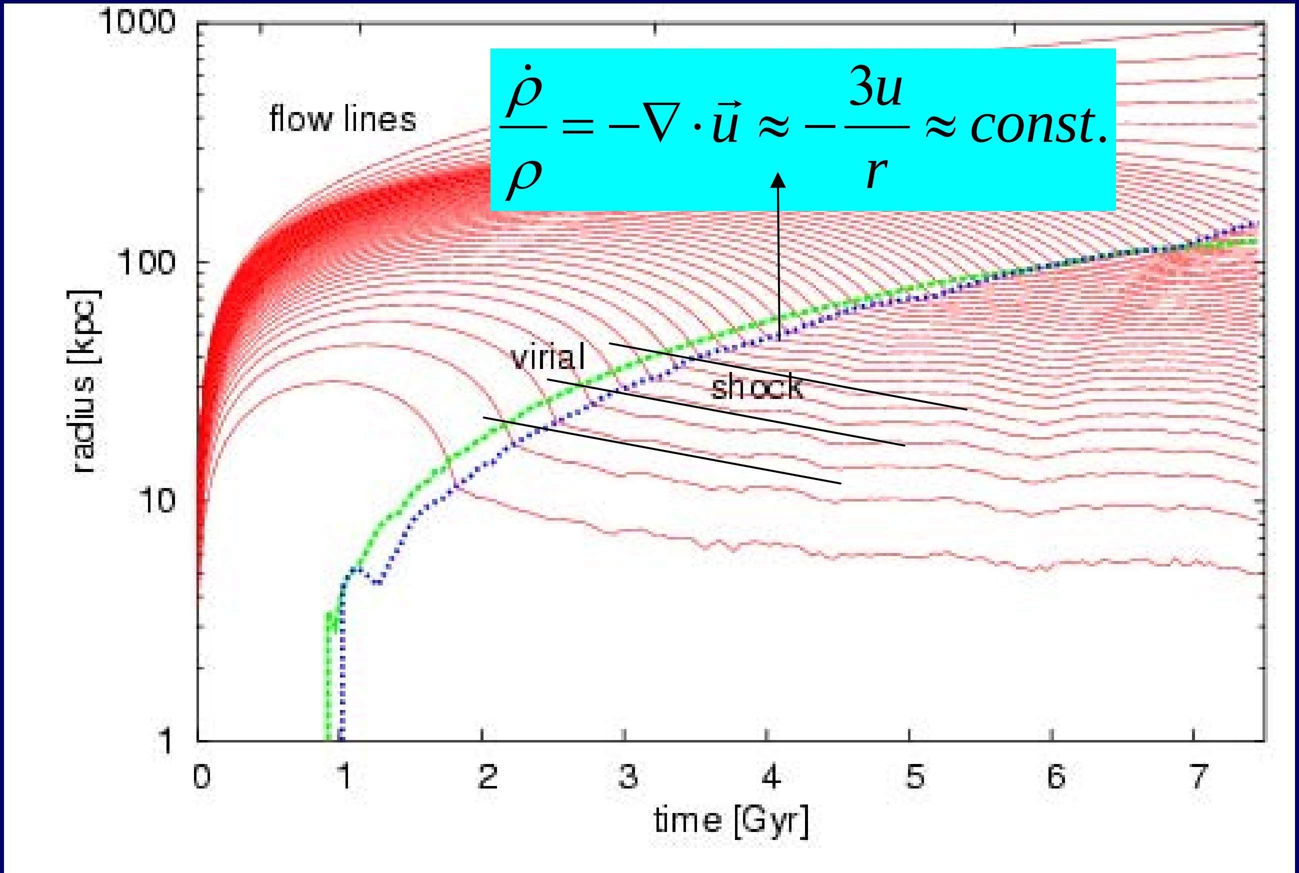
$$t_{comp} \equiv \frac{21}{5}\frac{\rho}{\dot\rho} \approx \frac{4}{3}\frac{R_s}{V}$$

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

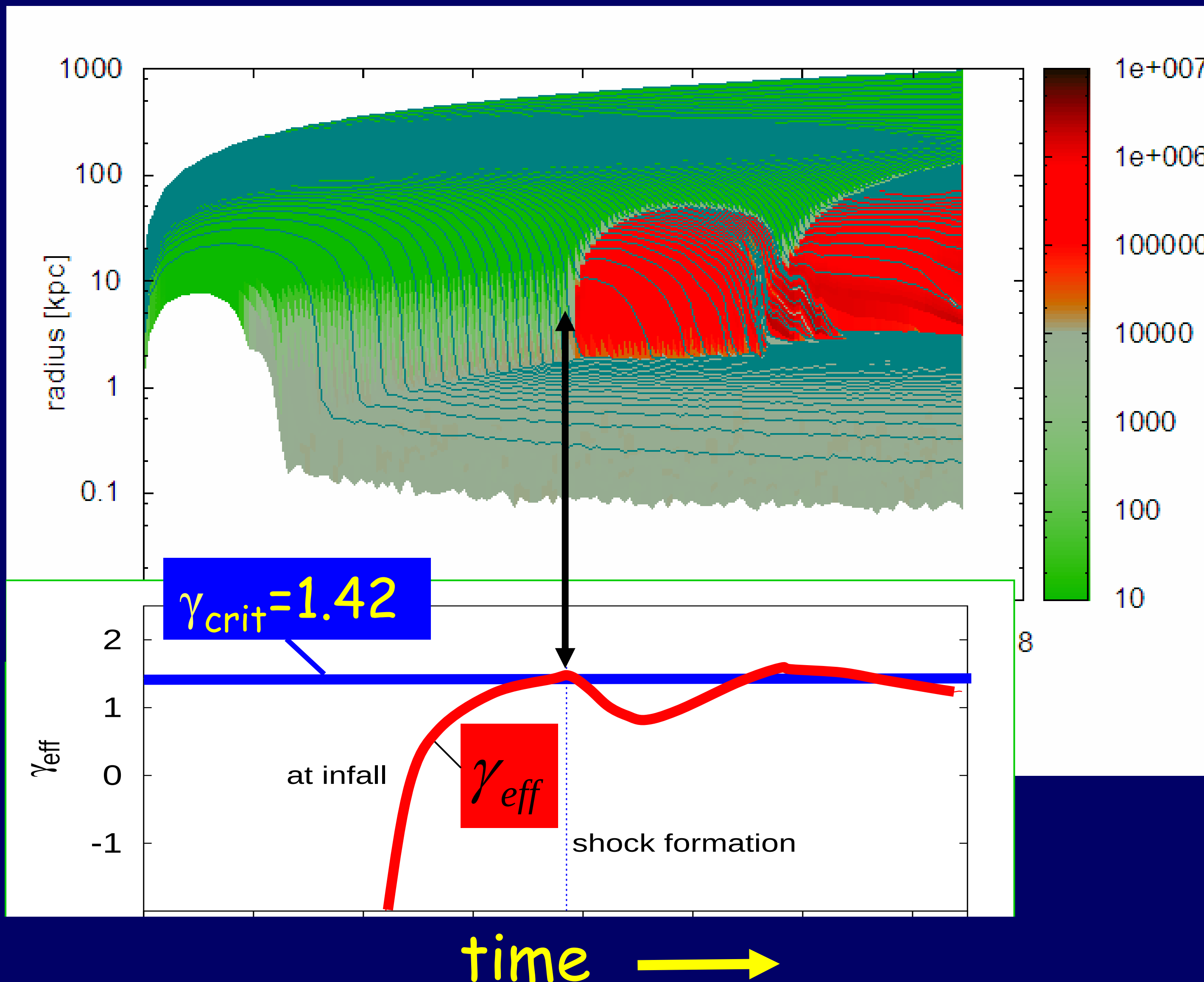
Stability criterion: $\gamma_{eff} > \frac{10}{7}$ $\longrightarrow$

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

Compression



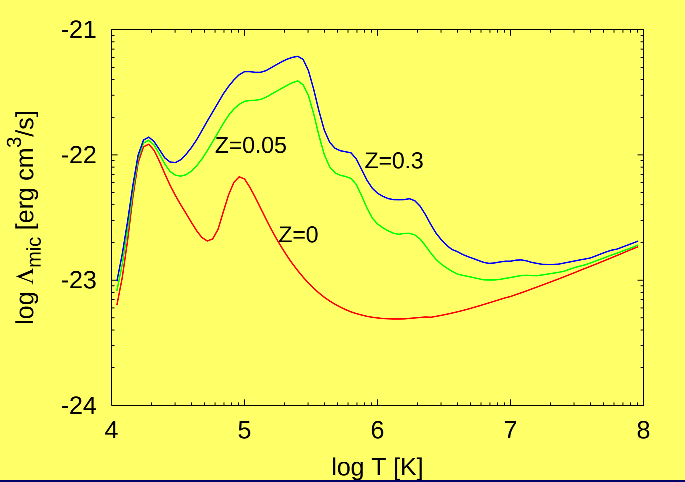
Spherical Simulation vs Model



Critical mass for shock heating:

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

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



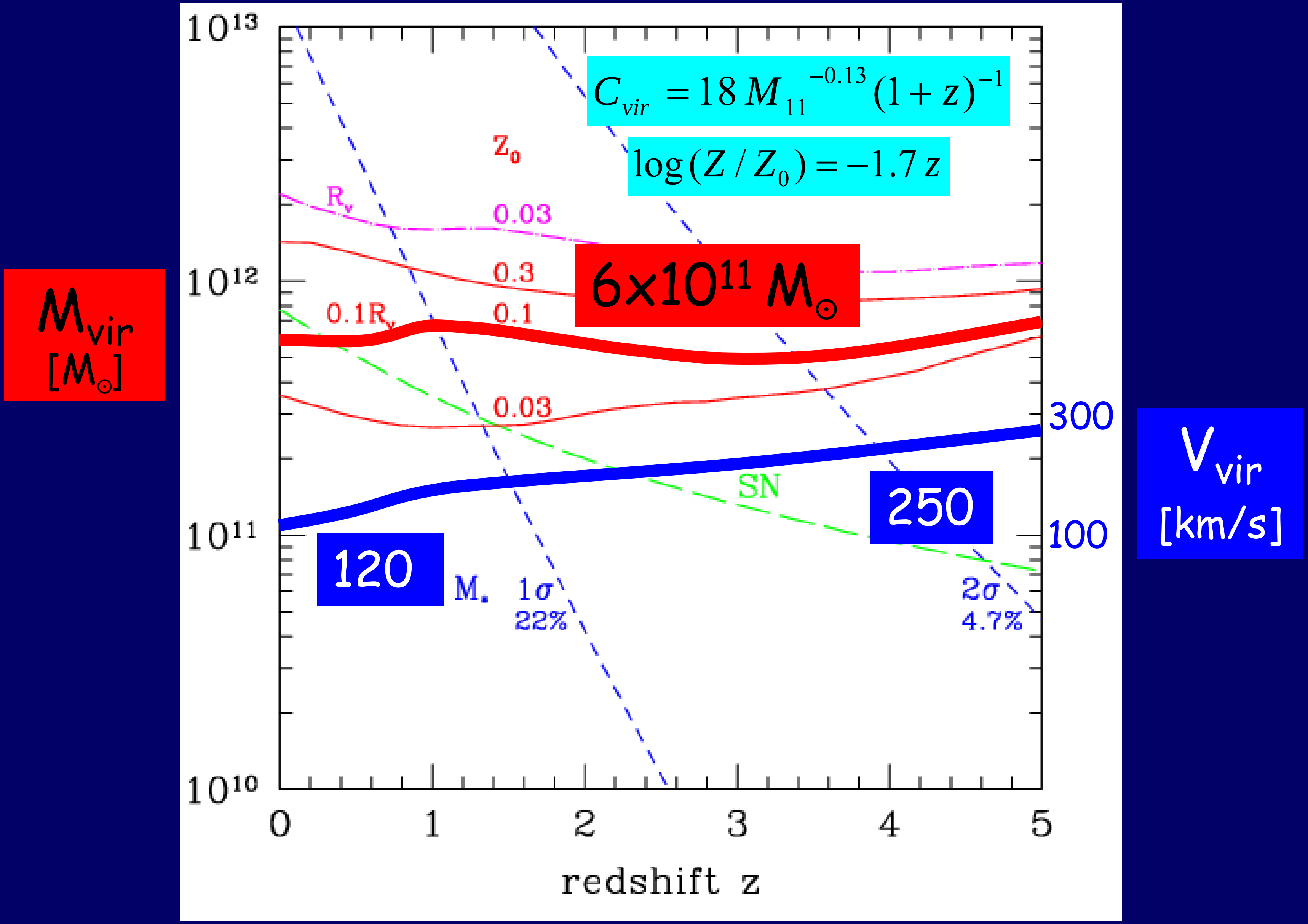
$T \sim 1.6\times10^{6}$ K $[\,(Z/0.1)^{0.7}\,(f_b/0.05)\,(\rho r/v)_{0.1Rv}\,(1+z)^{3/2}]^{1/2}$

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

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

~coincides with the bi-modality scale

Shock-Heating Scale



Fraction of cold/hot accretion

SPH simulation

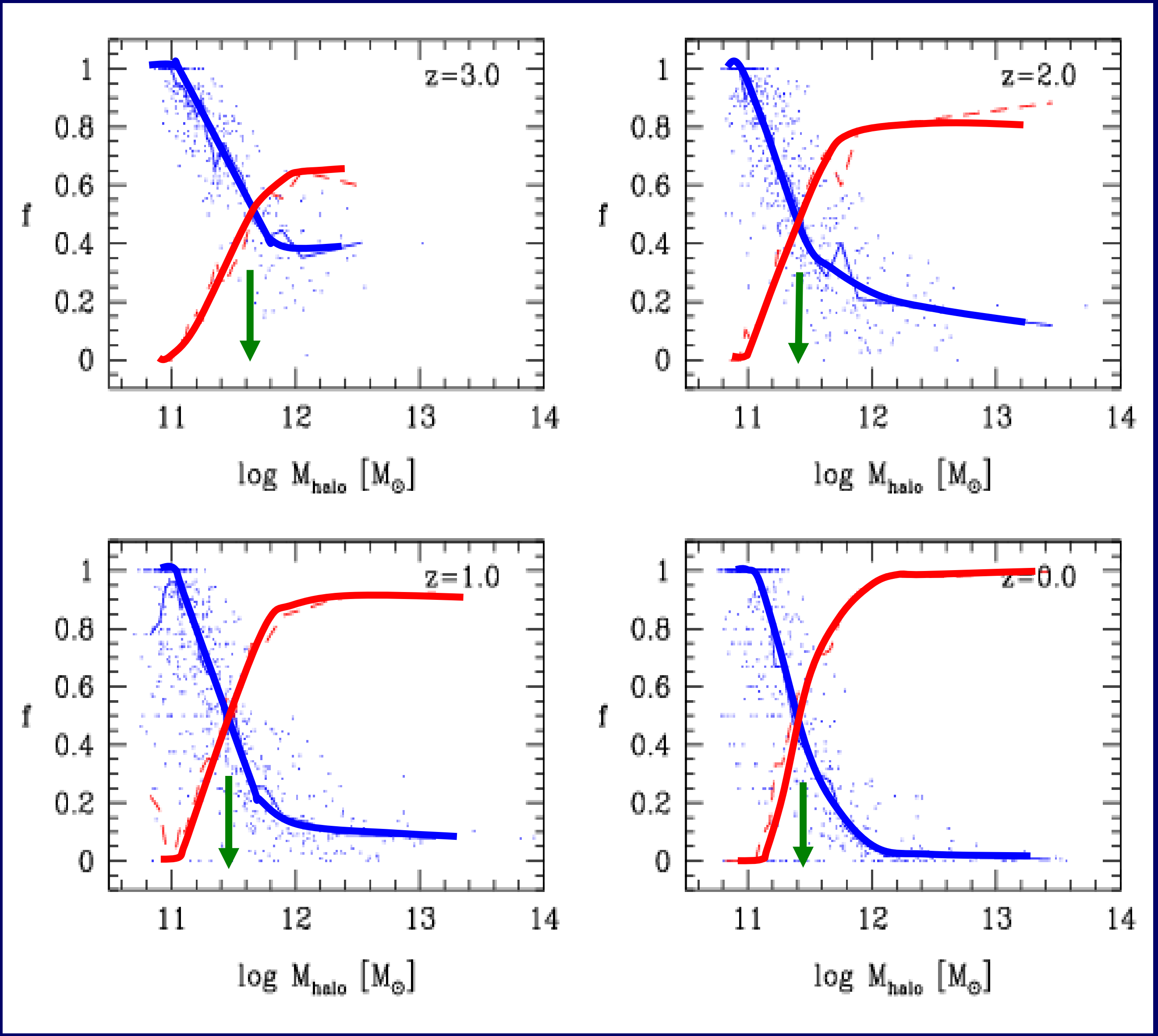
Keres, Katz, Weinberg, Dav'e 2004

Z=0, under-estimating M_{shock}

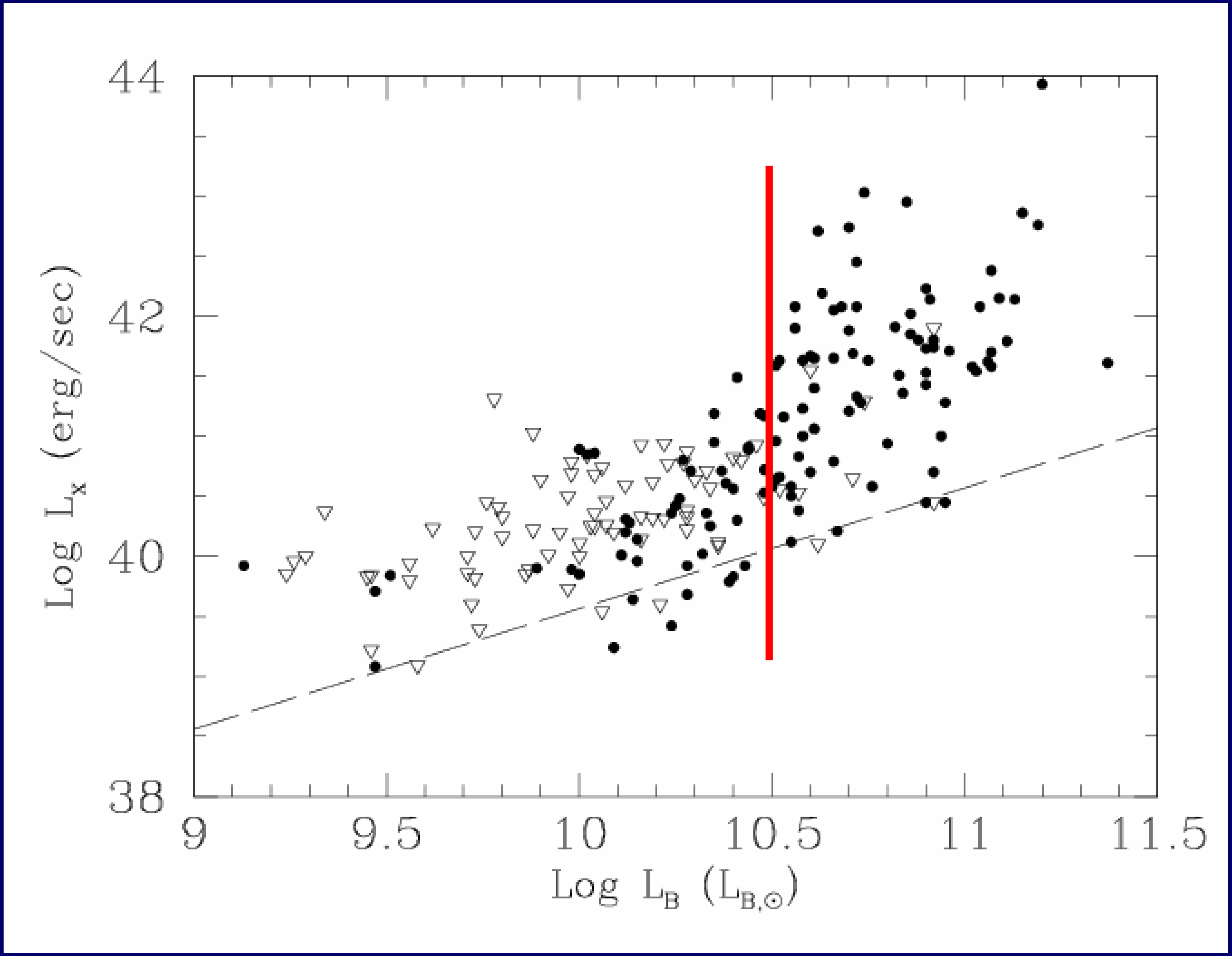
sharp transition

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

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

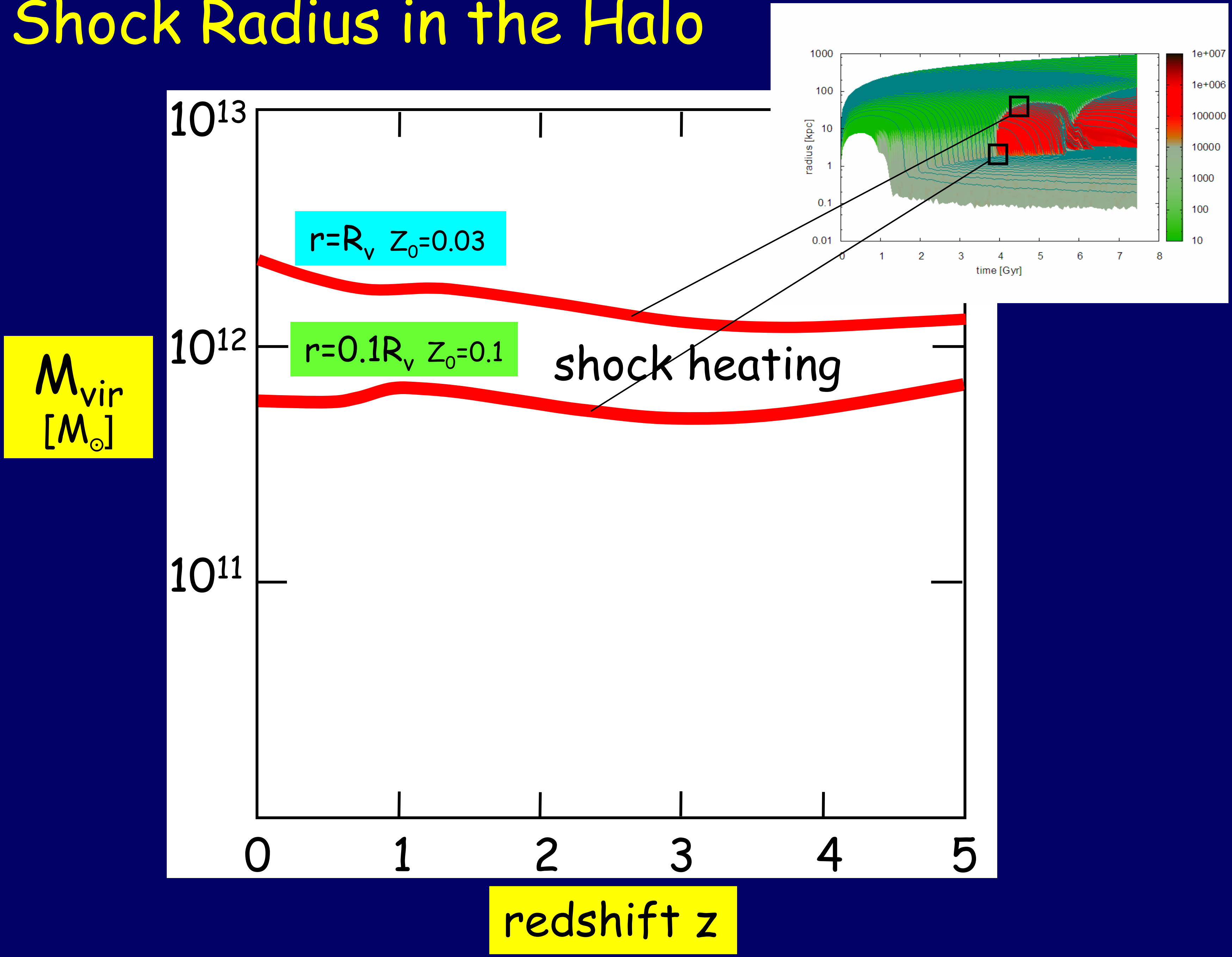


Hot Gas in Elliptical Galaxies

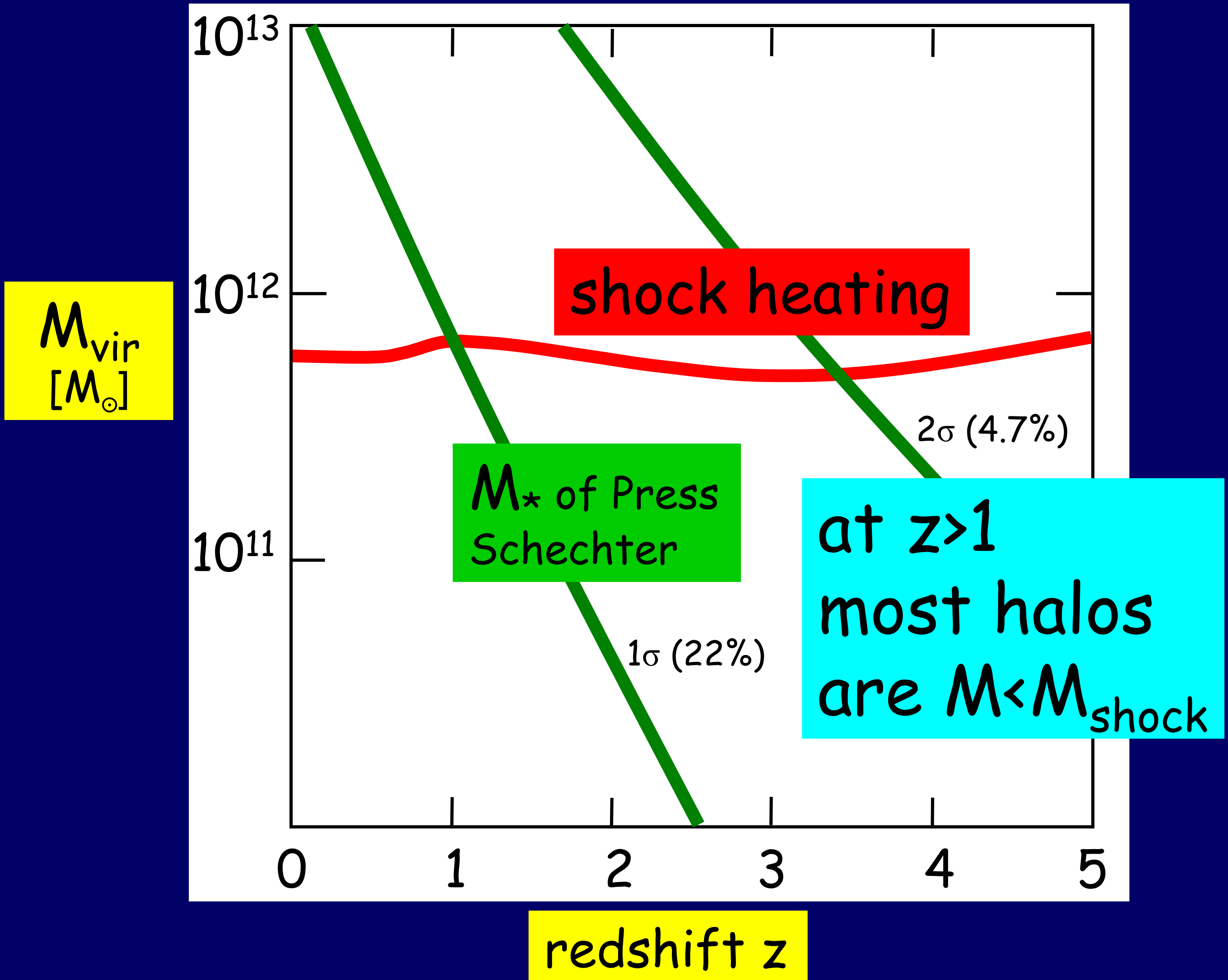


Mathews & Brighenti 04; O'Sullivan et al. 01

Shock Radius in the Halo

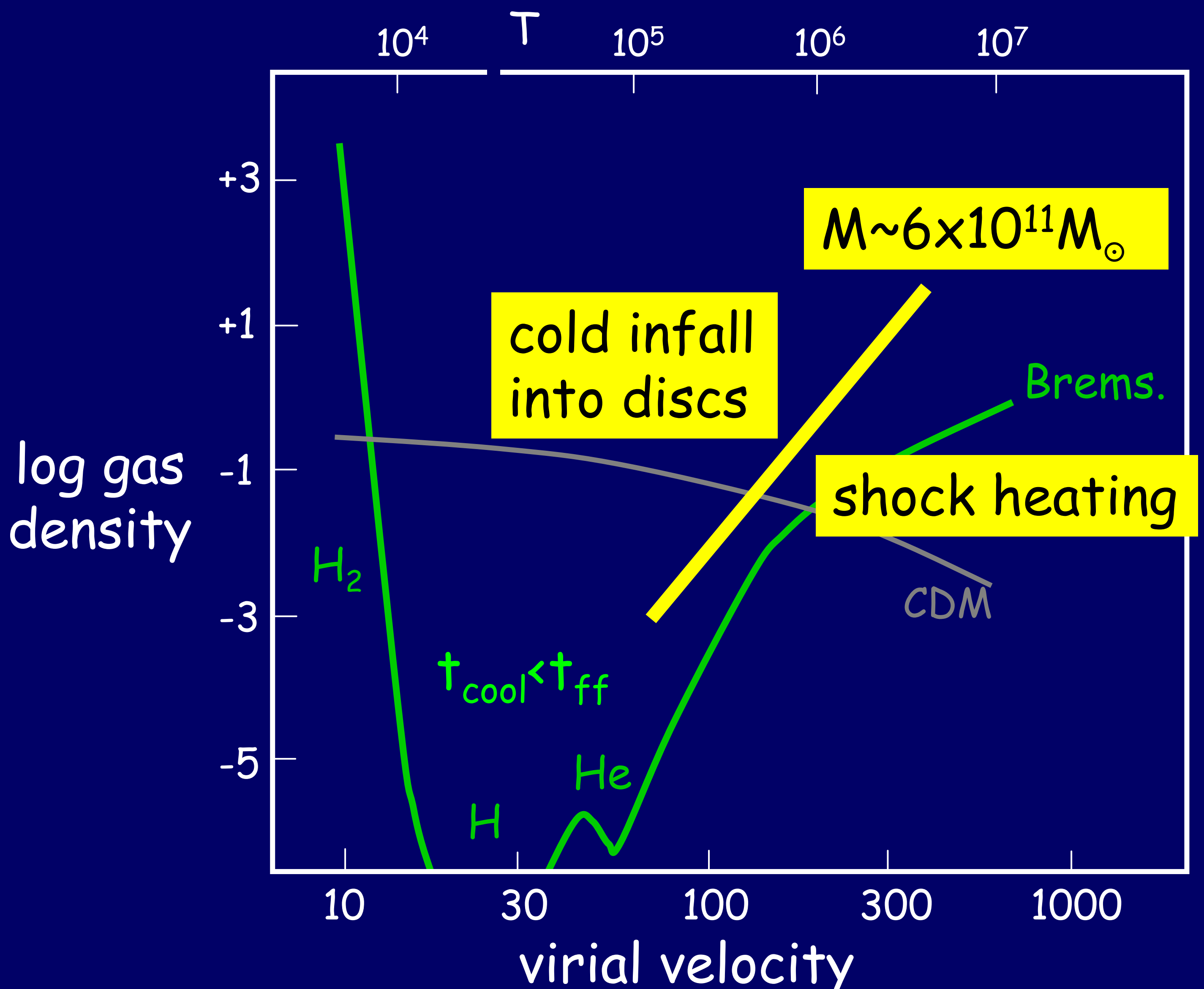


Cold Flows in Typical Halos



Shock-heating Scale

Birnboim & Dekel 03



3. Filaments in Hot Medium

At high redshift, in relatively isolated galaxies

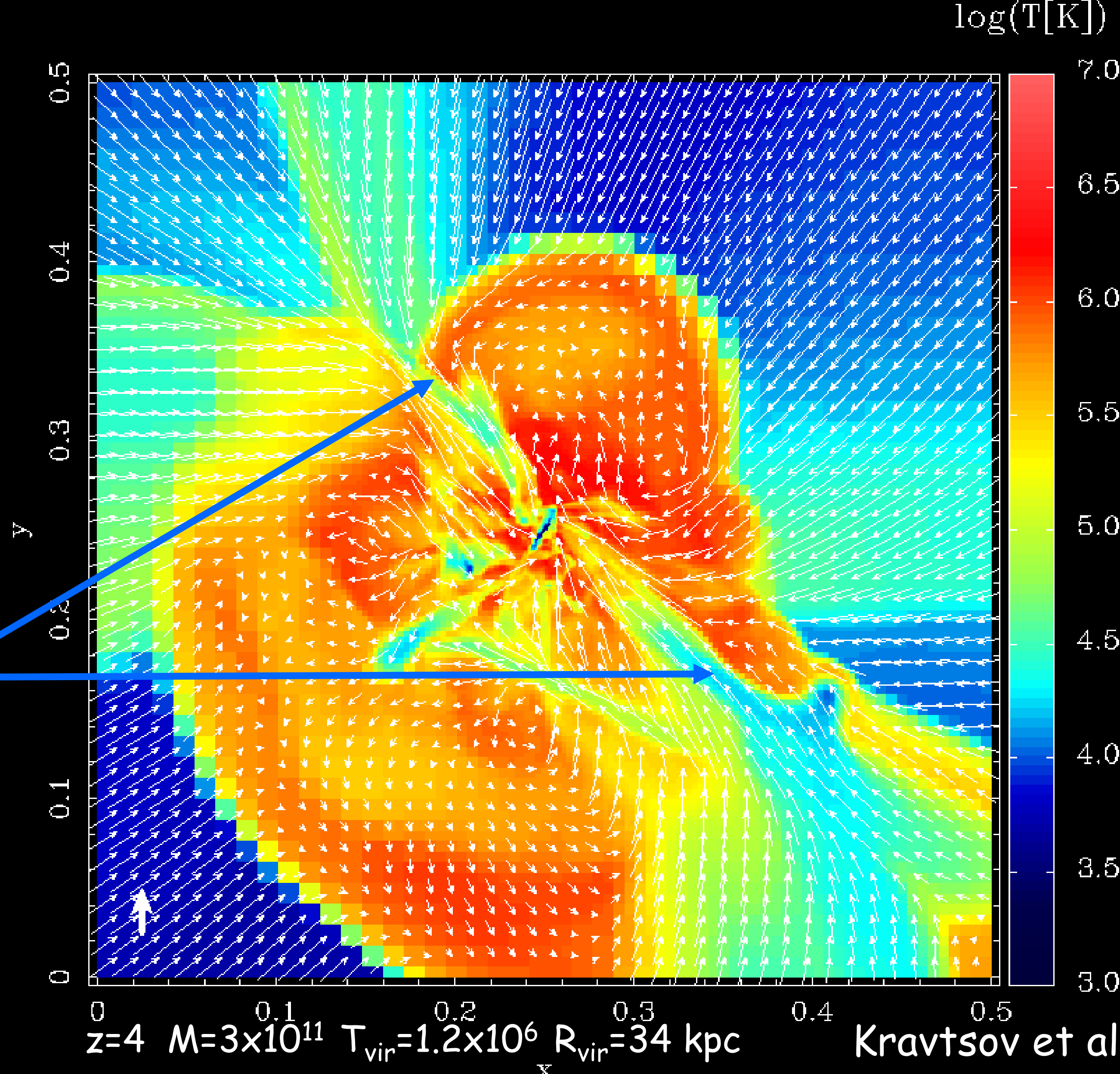
Relation to the universal clustering scale

Cold Streams in a Hot Medium

$M>M_{shock}$

Cold streams at z>2

Totally hot at z<1

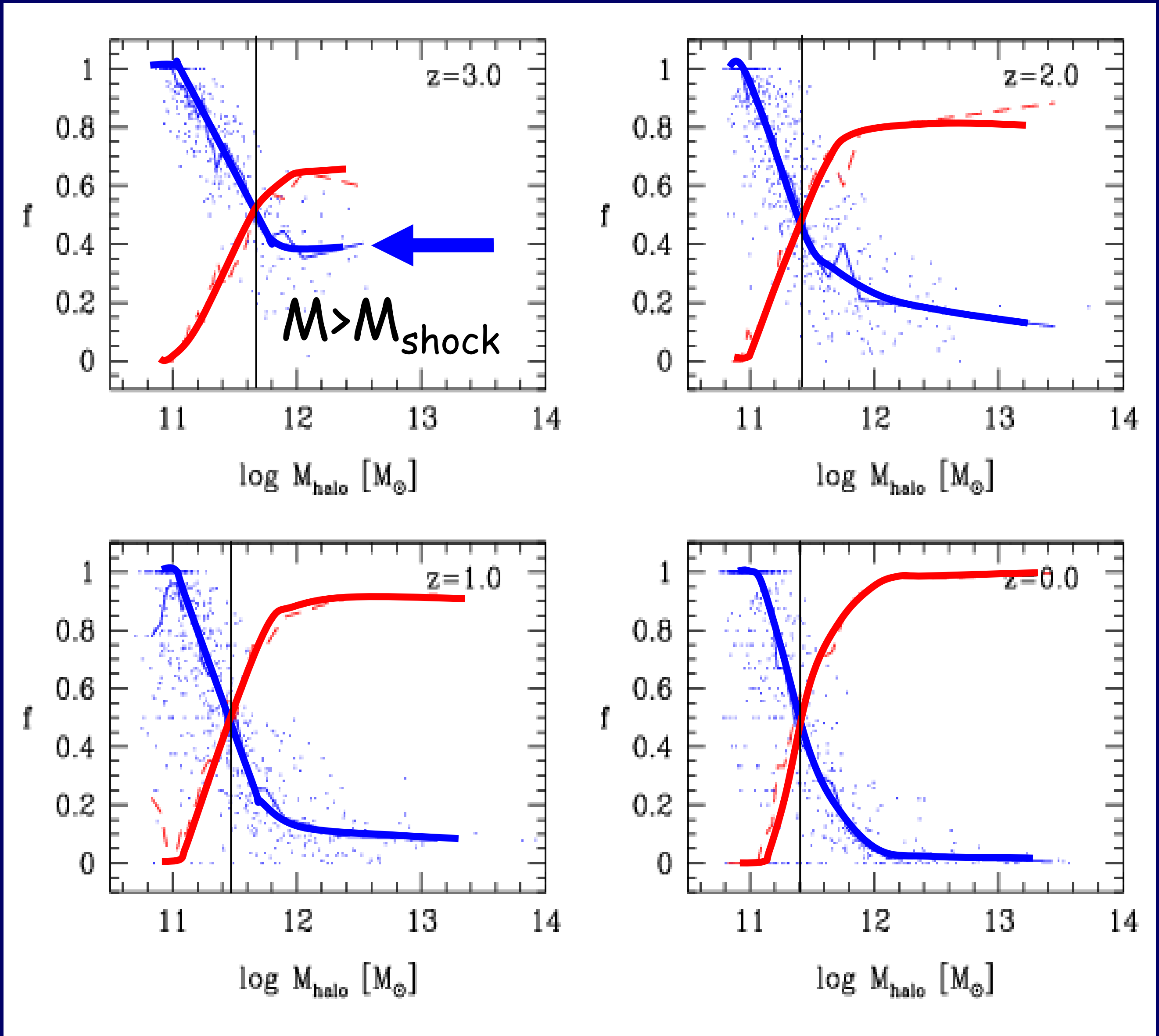


z=4 $M=3\times10^{11}$ $T_{vir}=1.2\times10^{6}$ $R_{vir}=34$ kpc

Kravtsov et al.

Fraction of cold/hot accretion

cold streams in a hot medium

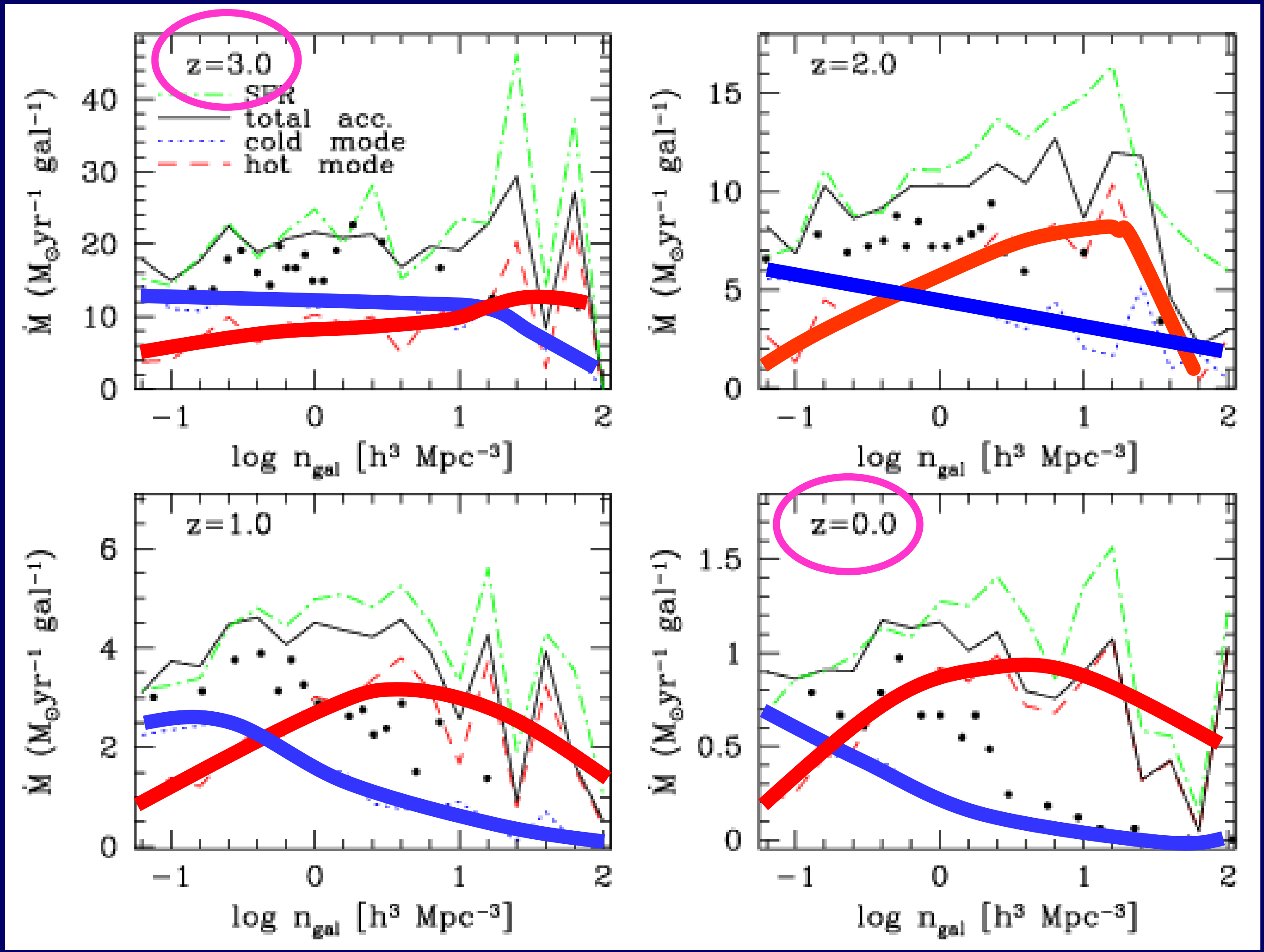


SPH simulation

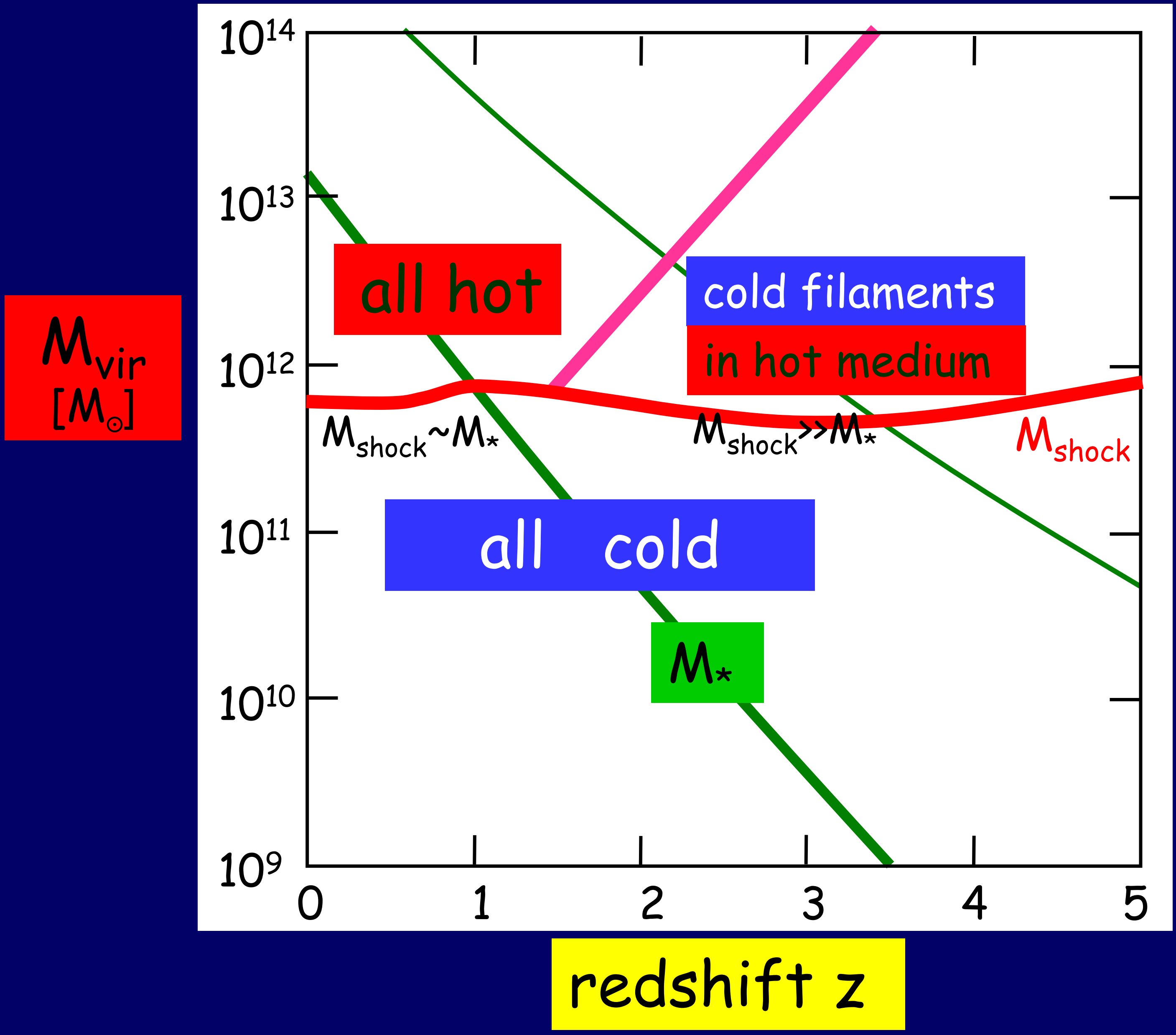
Keres, Katz, Weinberg, Dav'e 2004

Environment Dependence of Cold vs Hot Infall Rate

Hydro Simulations by Keres et al. 04



Shock-Heating vs Clustering Scale

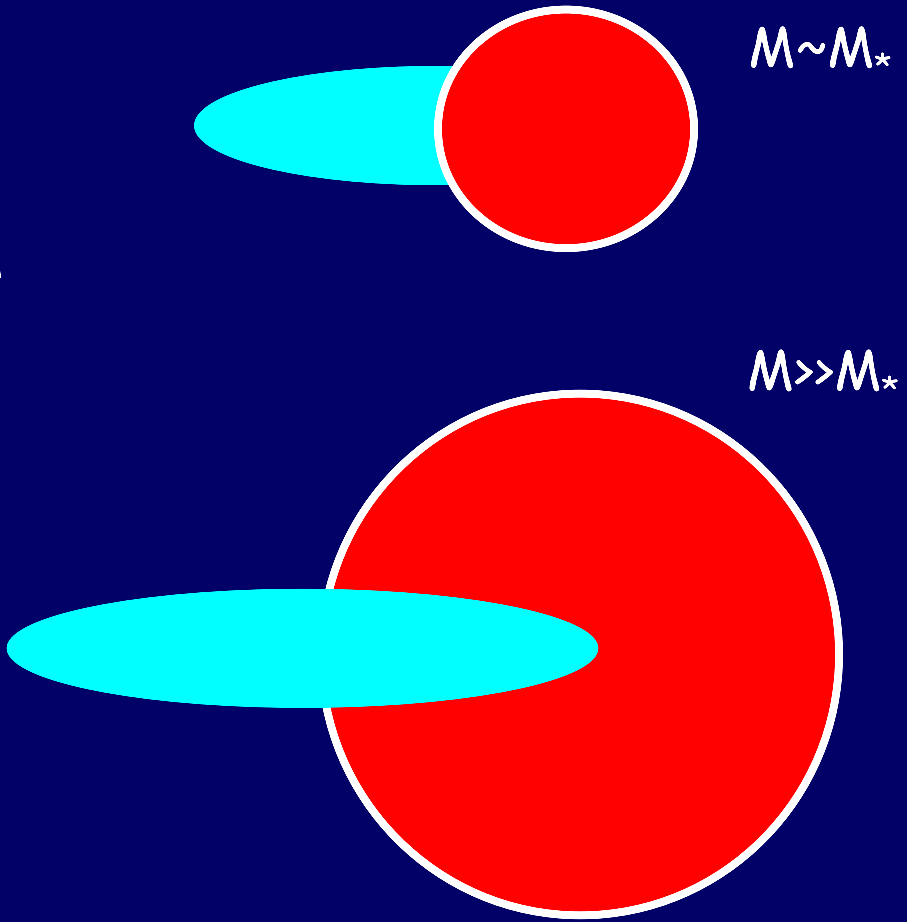


Dense Filaments in $M \geq M_{shock}$ Halos when $M_{shock} >> M_*$ Halos

Large-scale filaments grow

self-similarly with $M_*(t)$

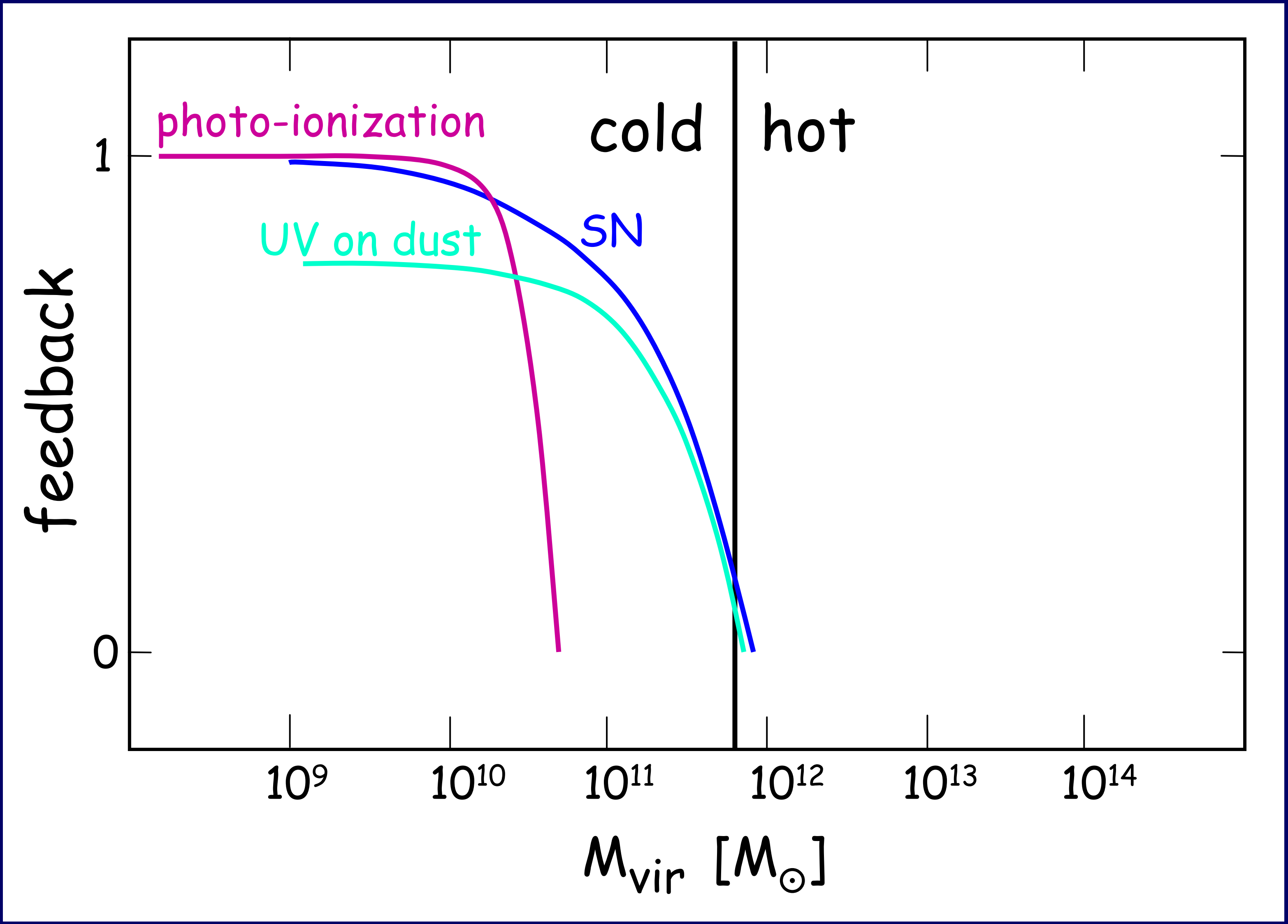
and always have typical width $\sim R_* \propto M_*^{1/3}$



4. Feedback Processes

and the shock-heating scale

Below the Shock-Heating Mass



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

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

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

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

$$\approx 0.01$$

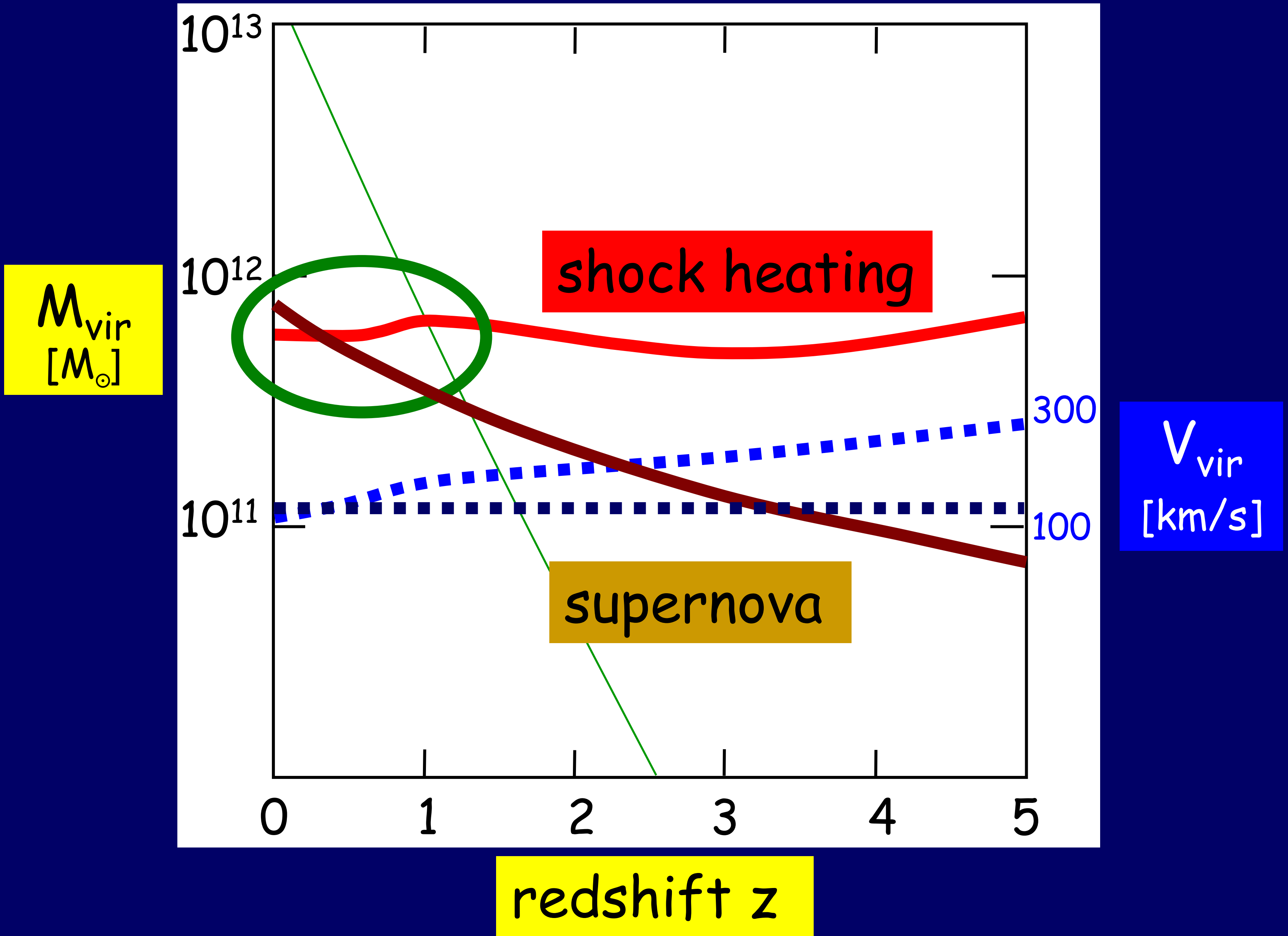
for $\Lambda \propto T^{-1}$ at $T \sim 10^5 K$

Energy required for blowout:

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

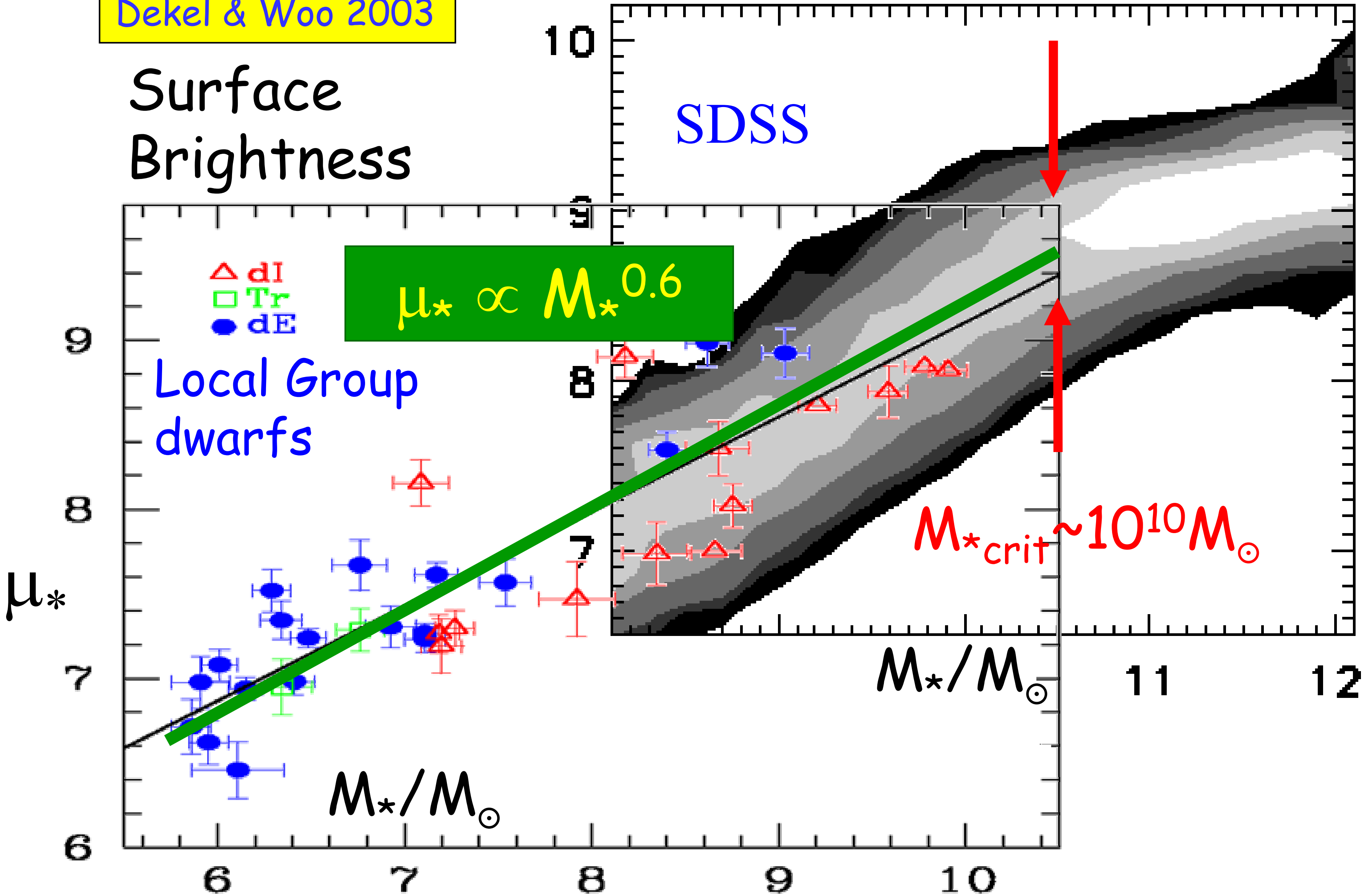
$$\rightarrow \quad V_{\rm crit} \approx 120 \text{ km/s} \quad \rightarrow \quad M_{\rm crit} \approx 7\times10^{11} M_\odot$$

Shock-Heating vs Supernova Scale



"Fundamental Line" of LSB/Dwarfs

Dekel & Woo 2003



Summary: SN feedback

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

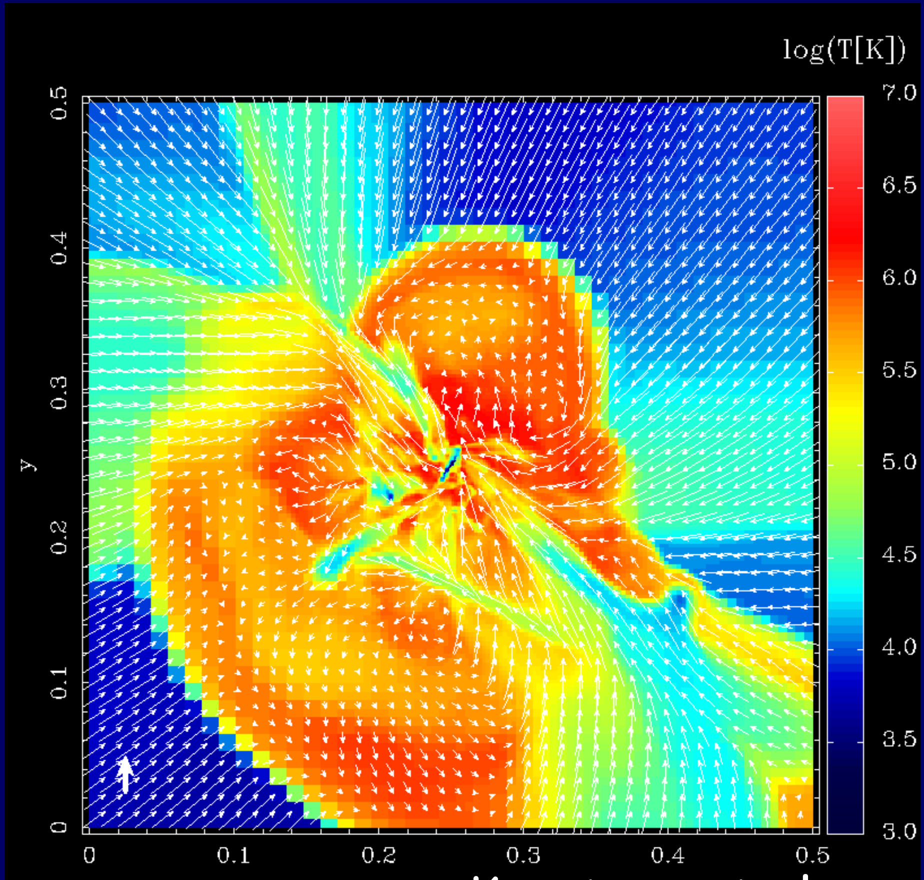
Shock Heating Triggers AGN Feedback

$M > M_{shock}$

More than enough energy is available in AGNs

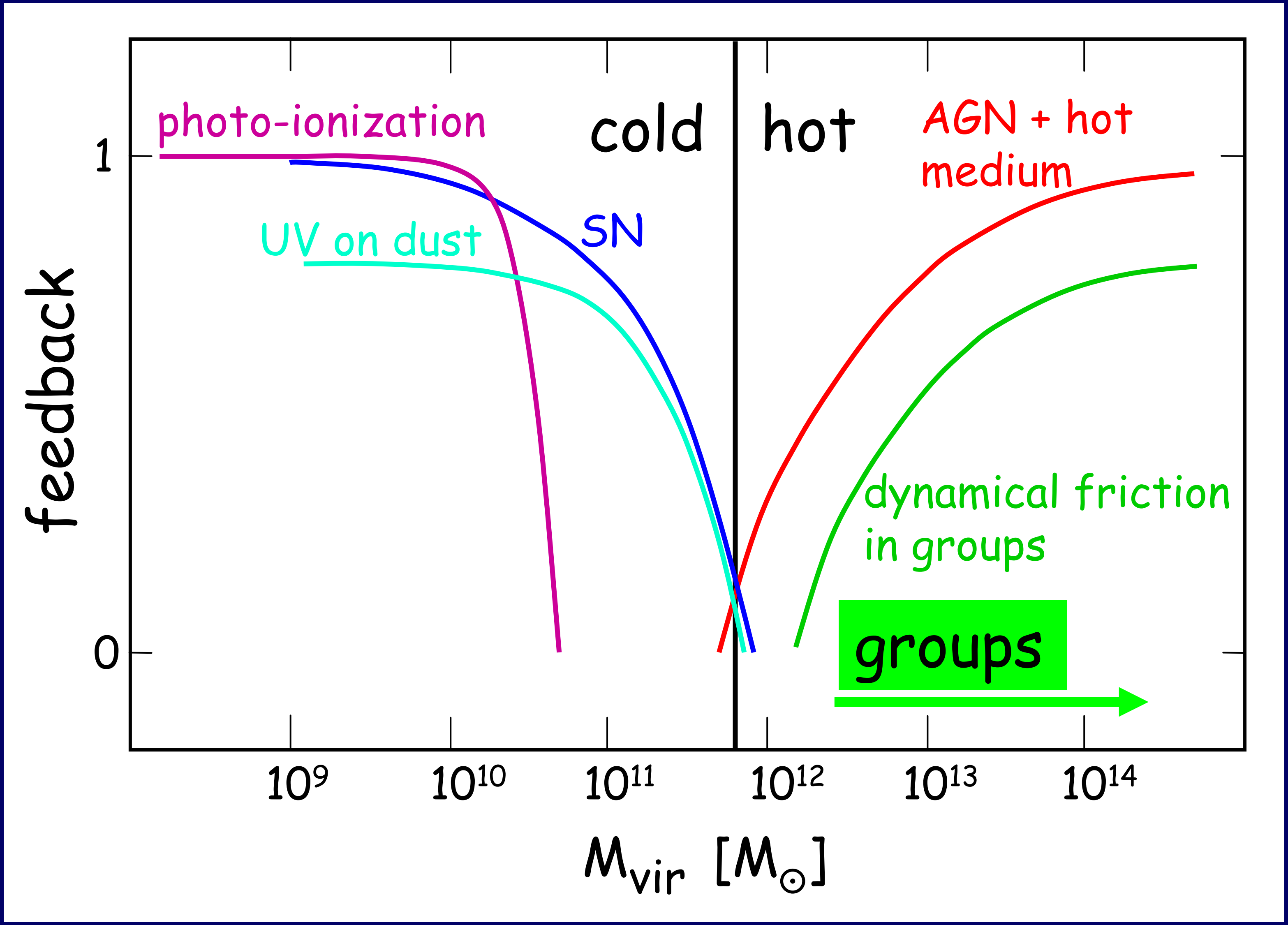
Hot gas is vulnerable to AGN feedback, while cold streams are shielded

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



Kravtsov et al.

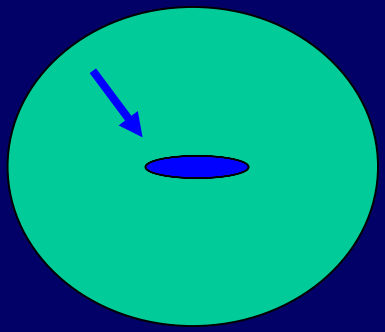
Above the Shock-Heating Mass



Dynamical-Friction Heating

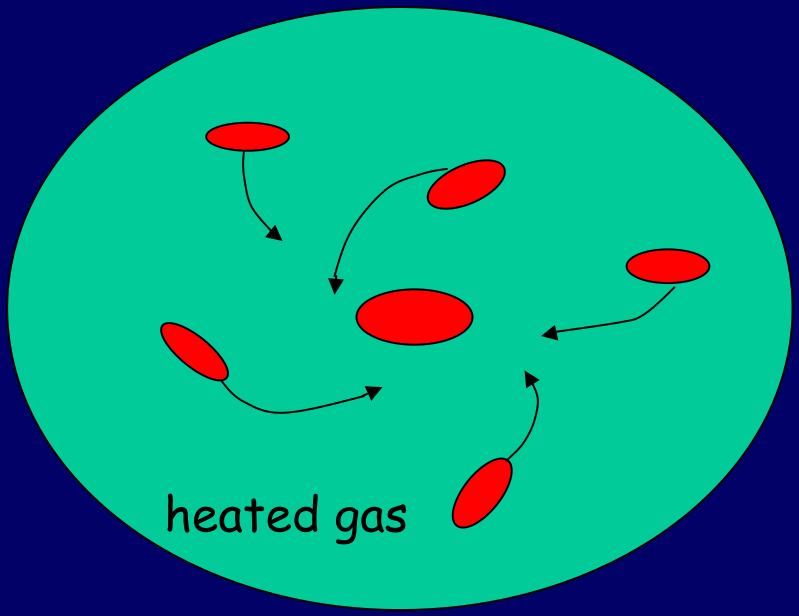
- $M < M_{crit}$ → cold flows
- a single-galaxy halo

→ no effect



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

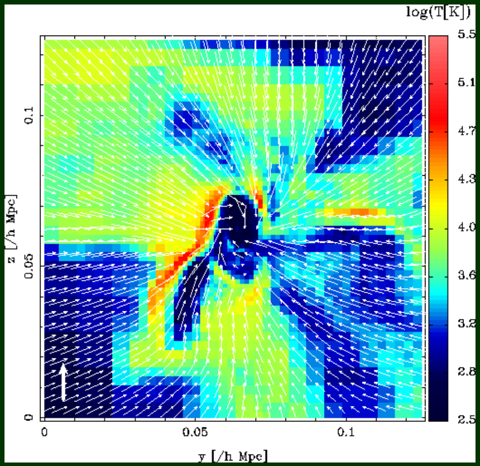
→ dynamical-friction heating of hot gas

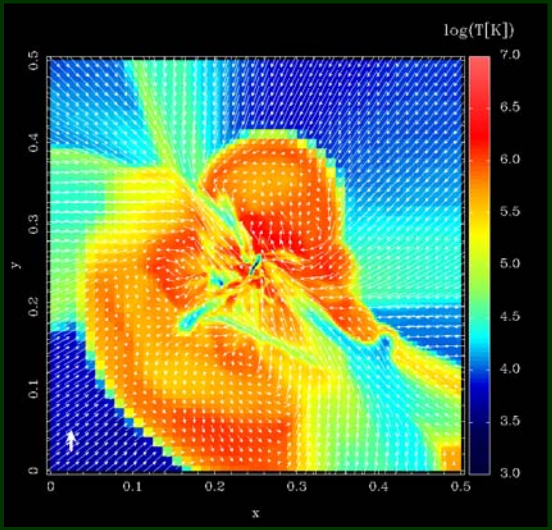


El-Zant, Kim, Kamionkowski 04

5. Origin of the Bi-modality

Dekel & Birnboim 04



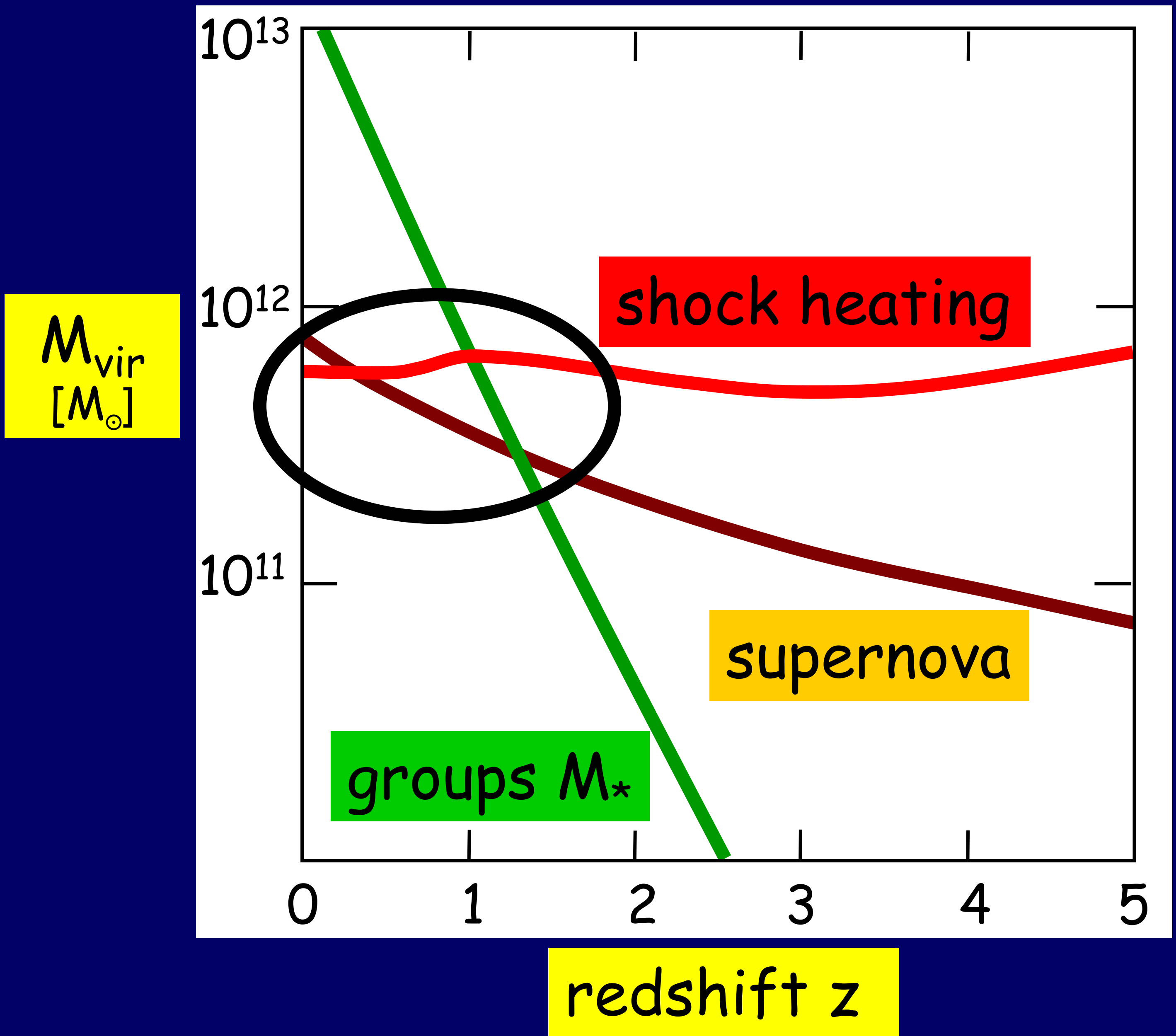


cold vs hot

ungrouped vs grouped

SN feedback vs AGN feedback

Scales Roughly Coincide



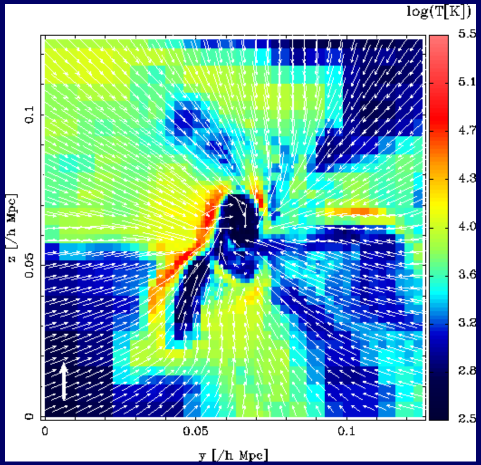
Key Ideas:

Cold flows → star burst

supersonic stream collides with disk

efficient cooling behind isothermal shock

→ dense, cold slab → star burst



Hot medium → halt star formation

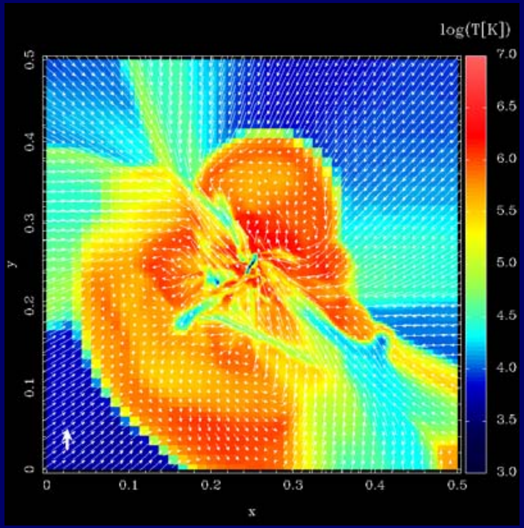
dilute medium vulnerable to AGN fdbk

+ slow cooling because of two-phase medium

+ dynamical-friction in hot groups

→ shock-heated gas never cools

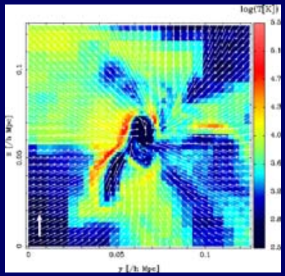
→ shut down disk and star formation



Origin of bi-modality

While halos grow by mergers and accretion

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



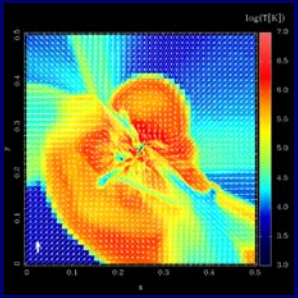
cold gas supply → disk growth & star formation

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

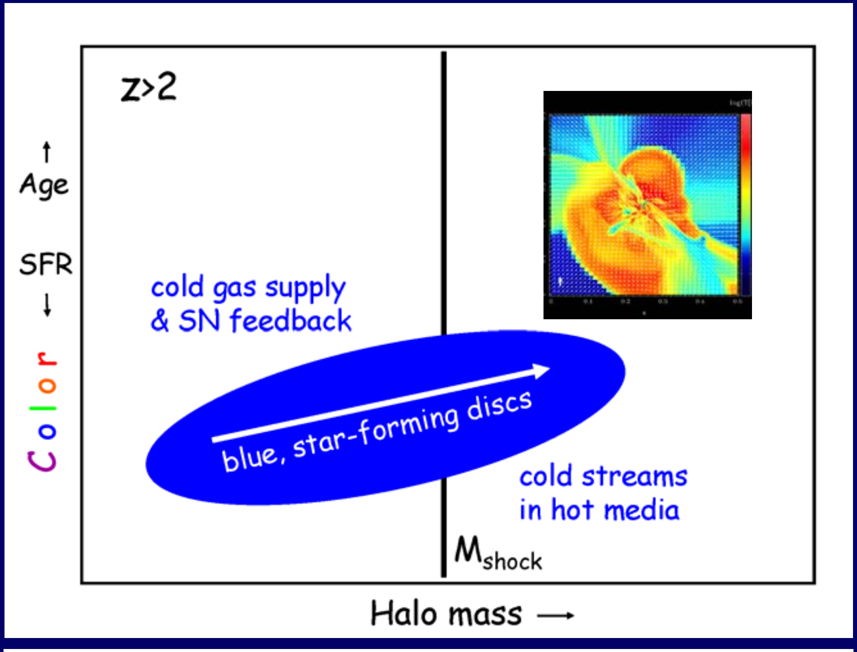
+gas exhausted + AGNs especially in bulges

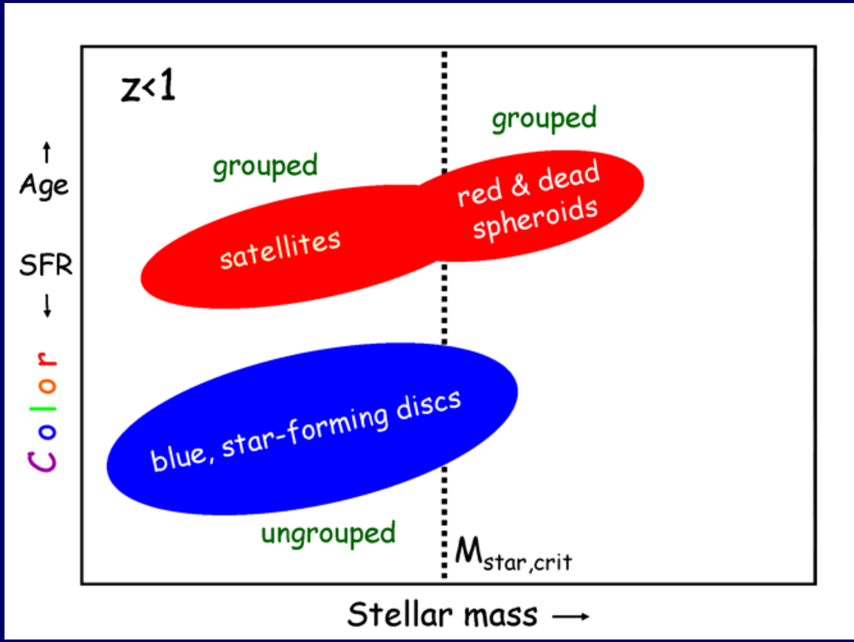
→ no disk growth, star formation shuts off

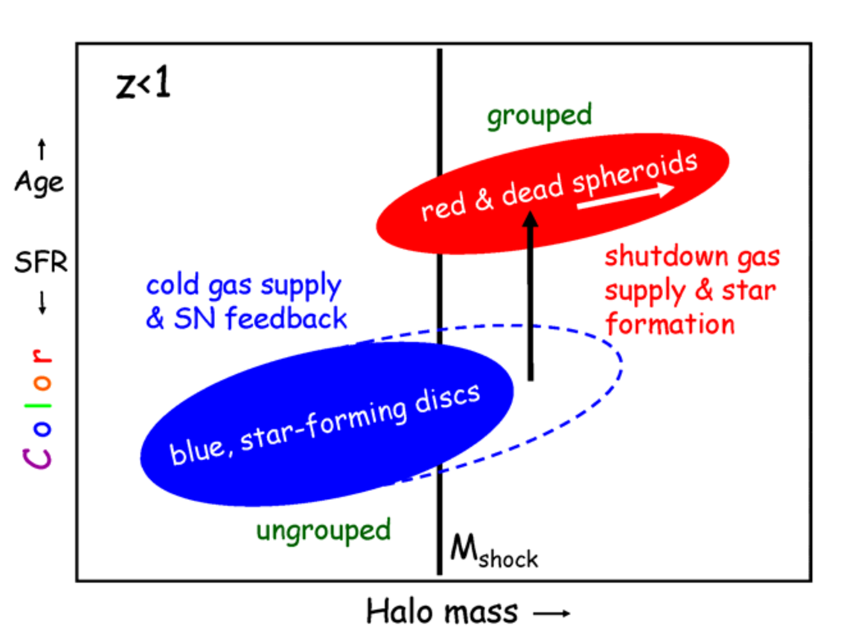
passive stellar evolution → red & dead

further growth of spheroids by gas-poor mergers

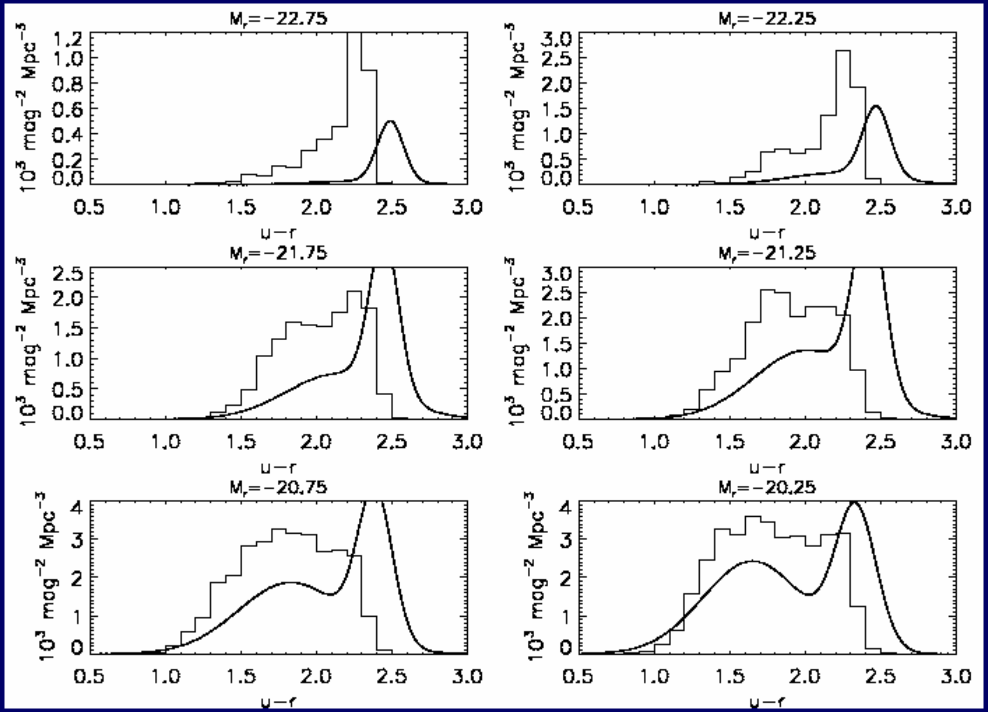
From blue sequence to red sequence

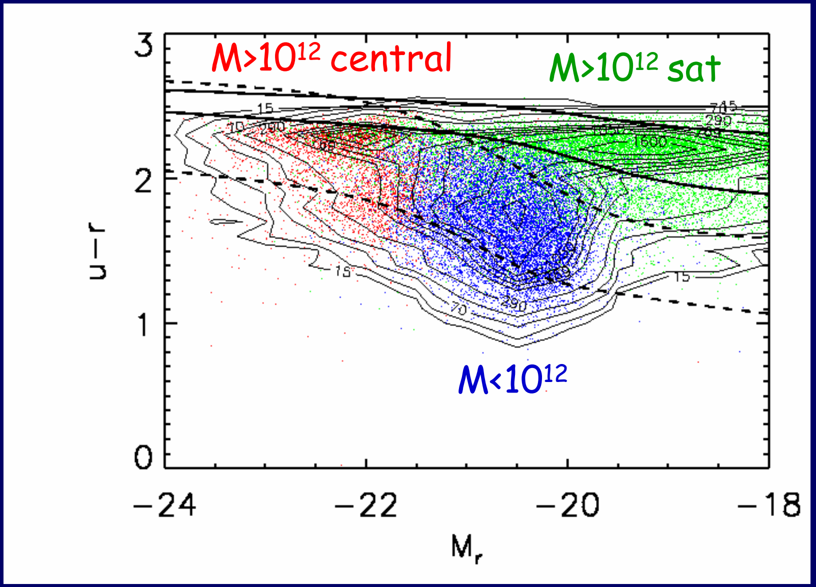


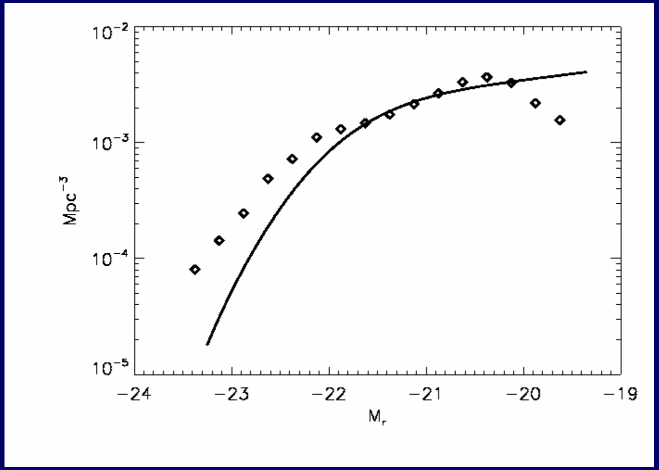


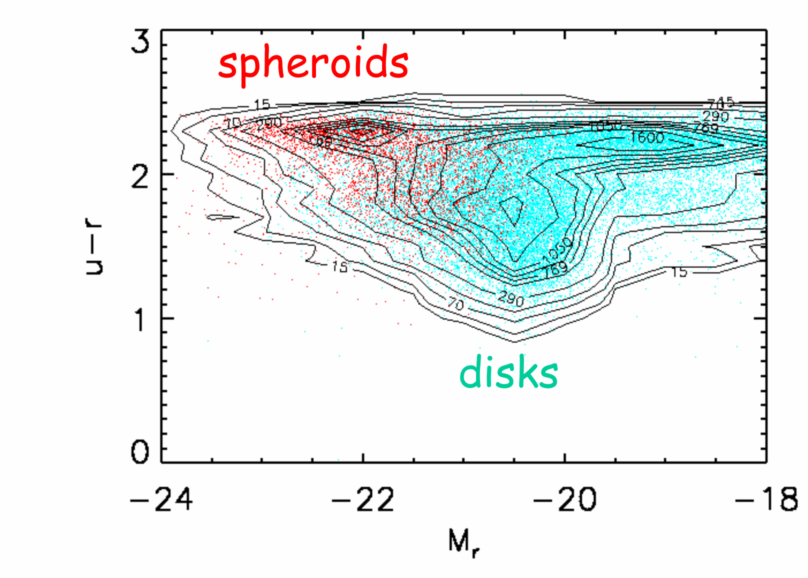


In a Semi Analytic Model (Standard GalICS)



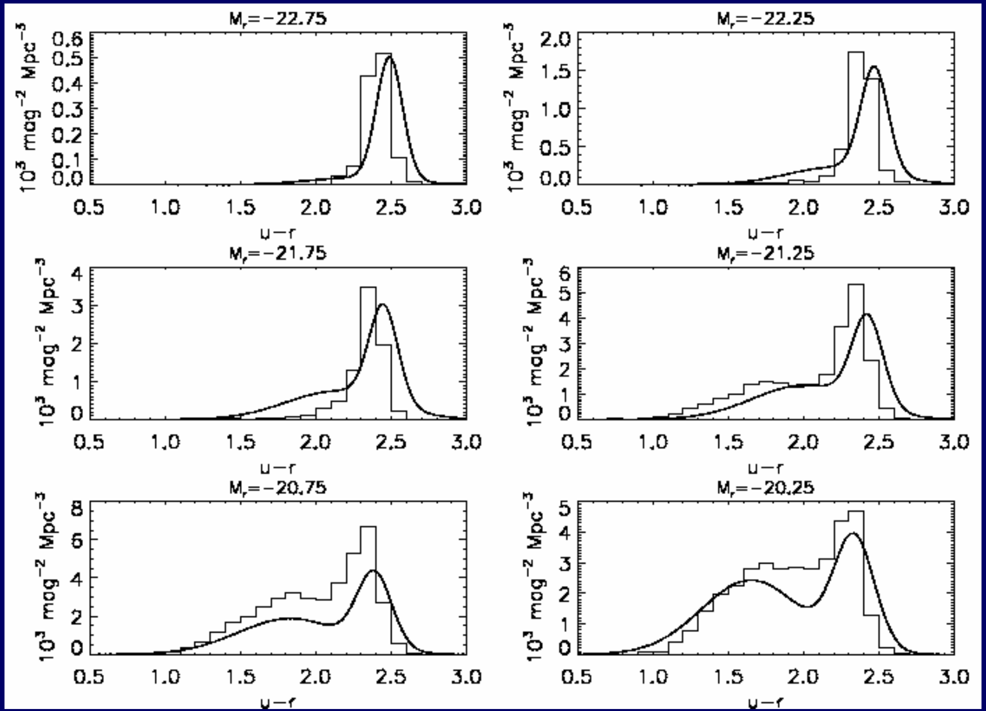


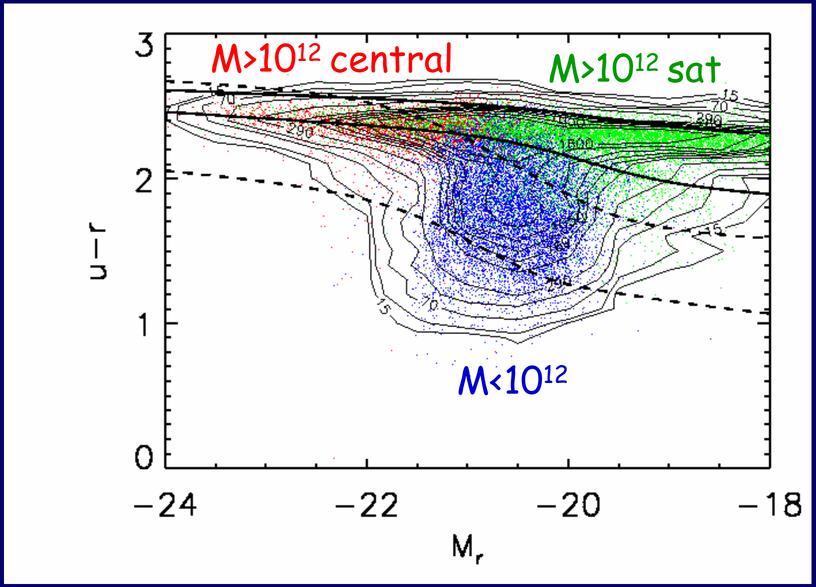


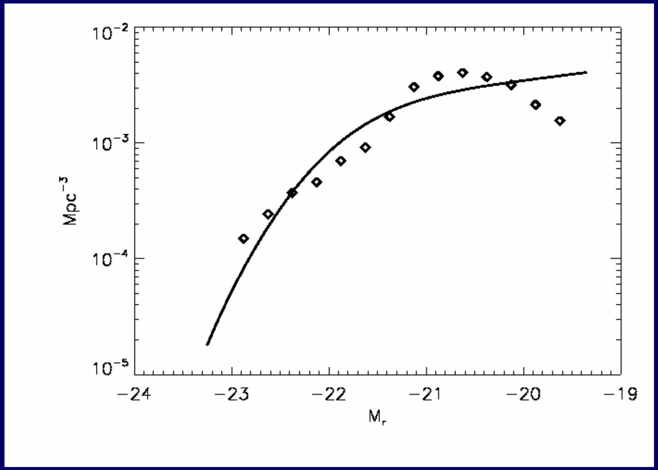


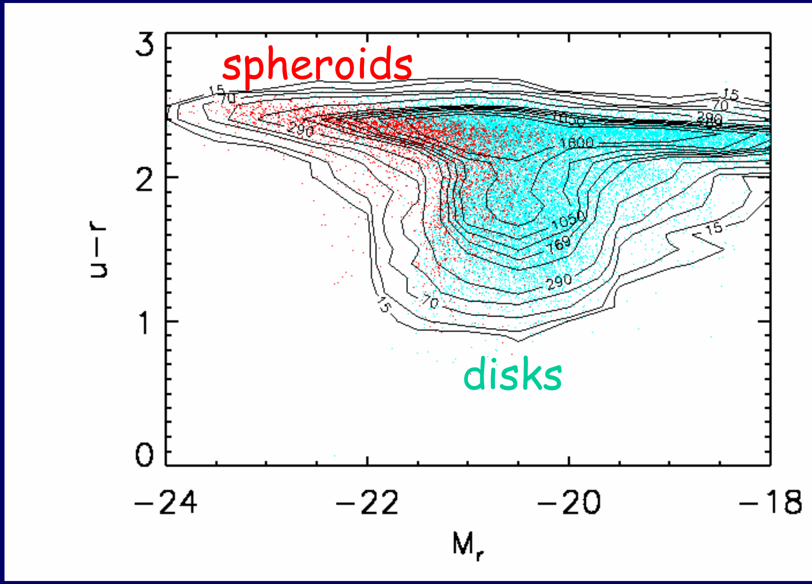
Revised SAM with M_{shock} =7.5x10[11], z_c=2.2,

weaker fdbk (ε=0.15), slower DF (at V>300)





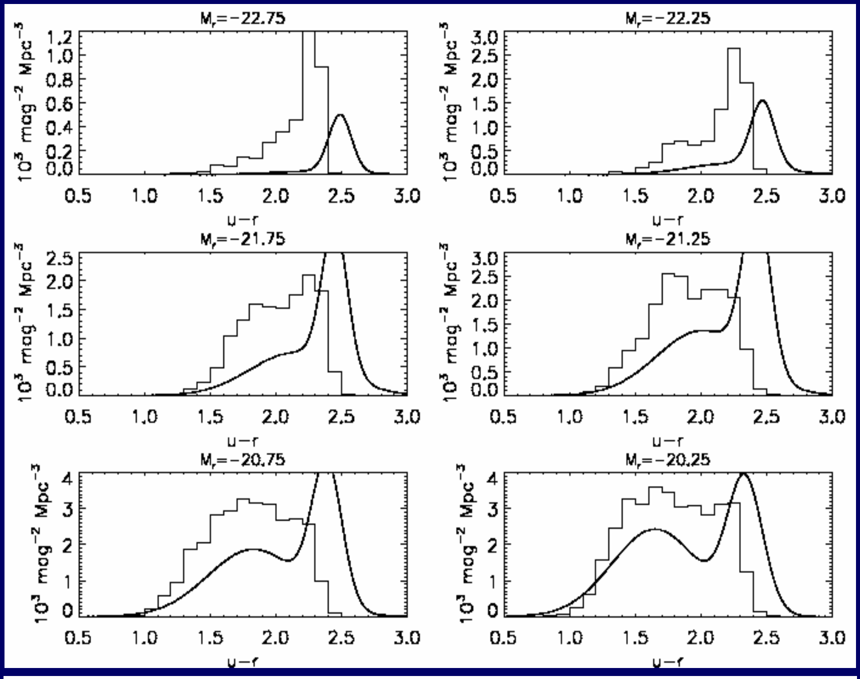


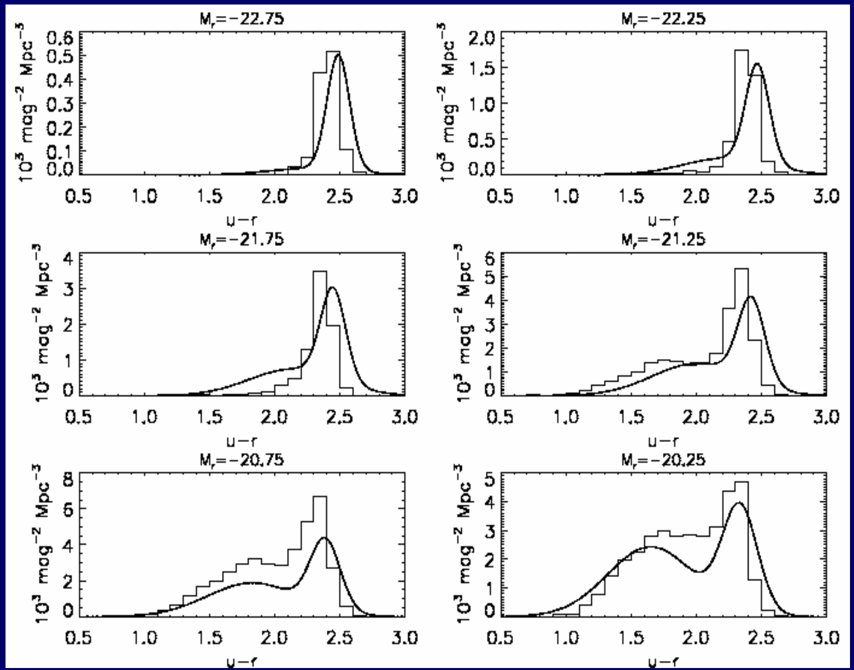


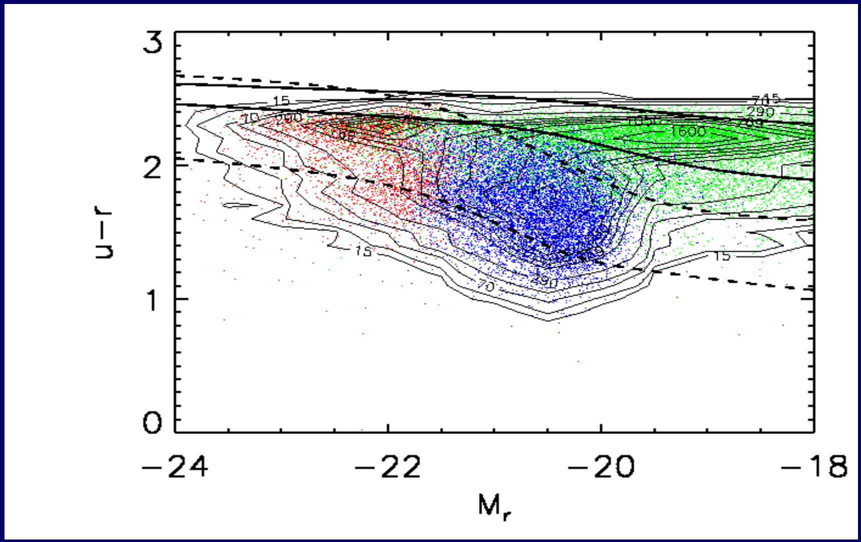
The effect of M_{shock} (z=0)

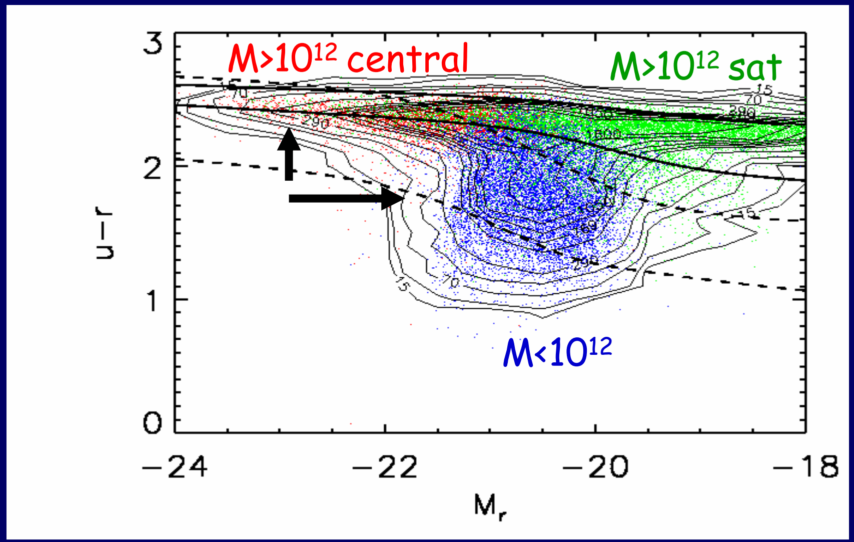
standard

revised

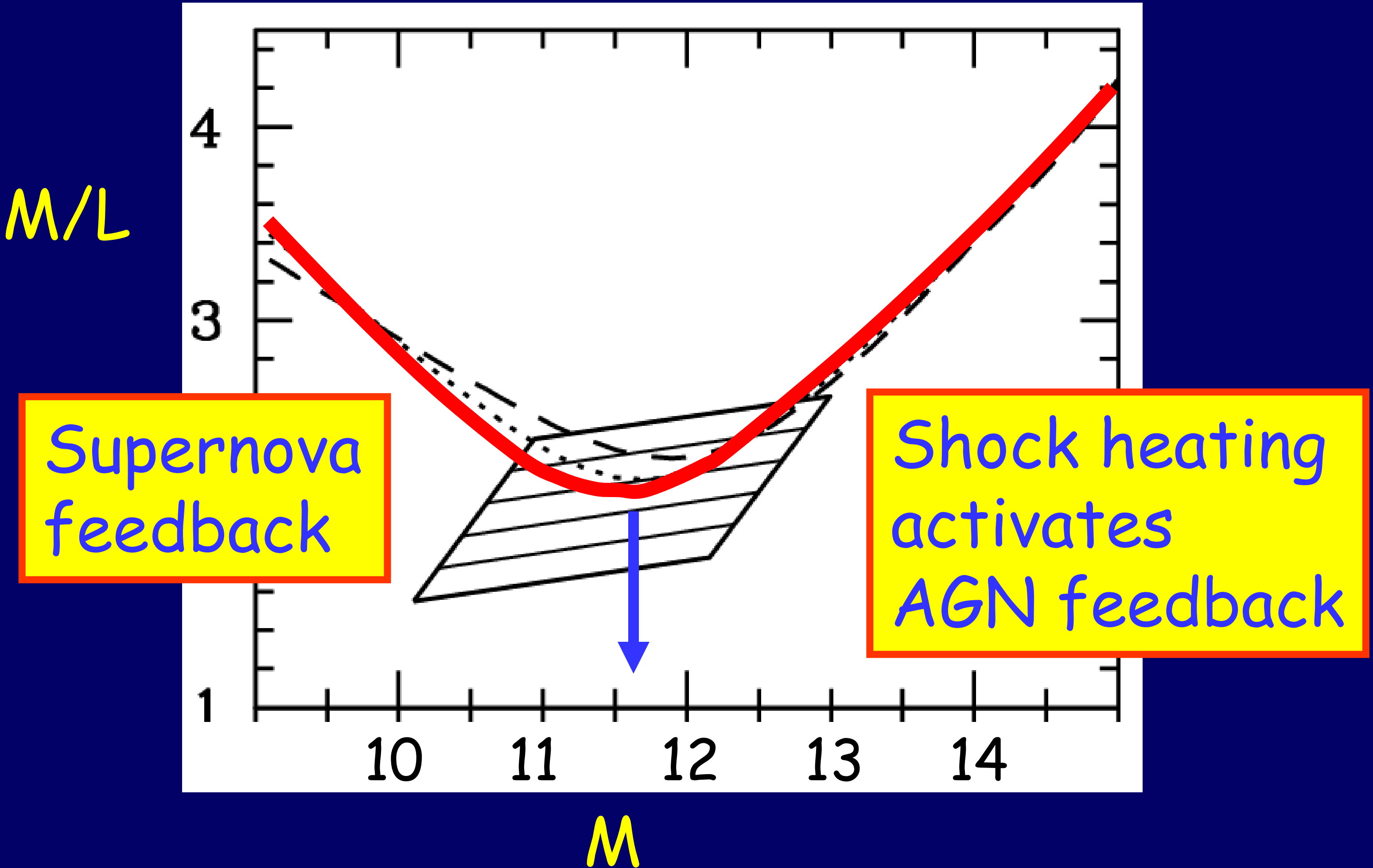






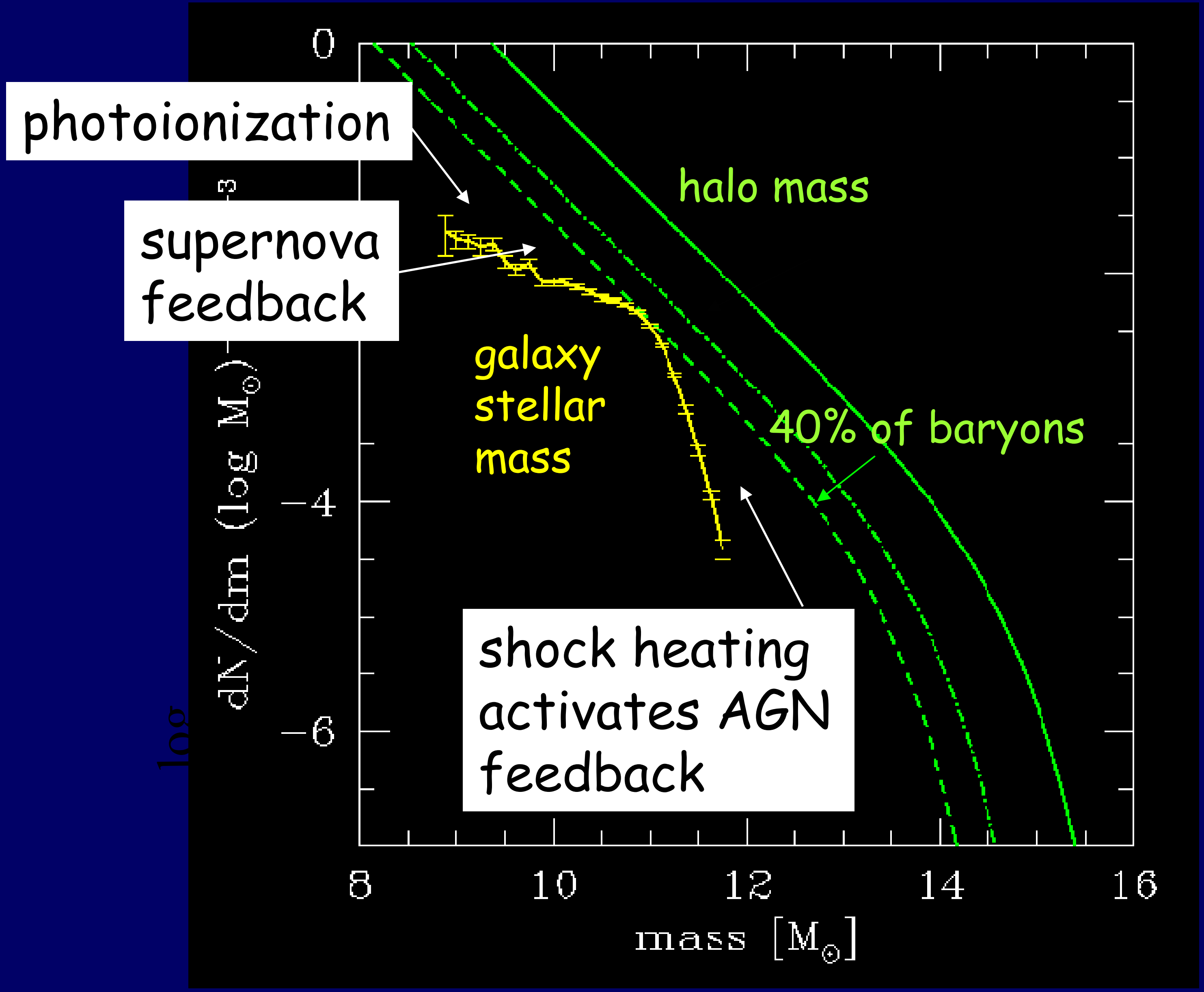


$\langle M/L \rangle$ has a minimum at M_{crit}



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

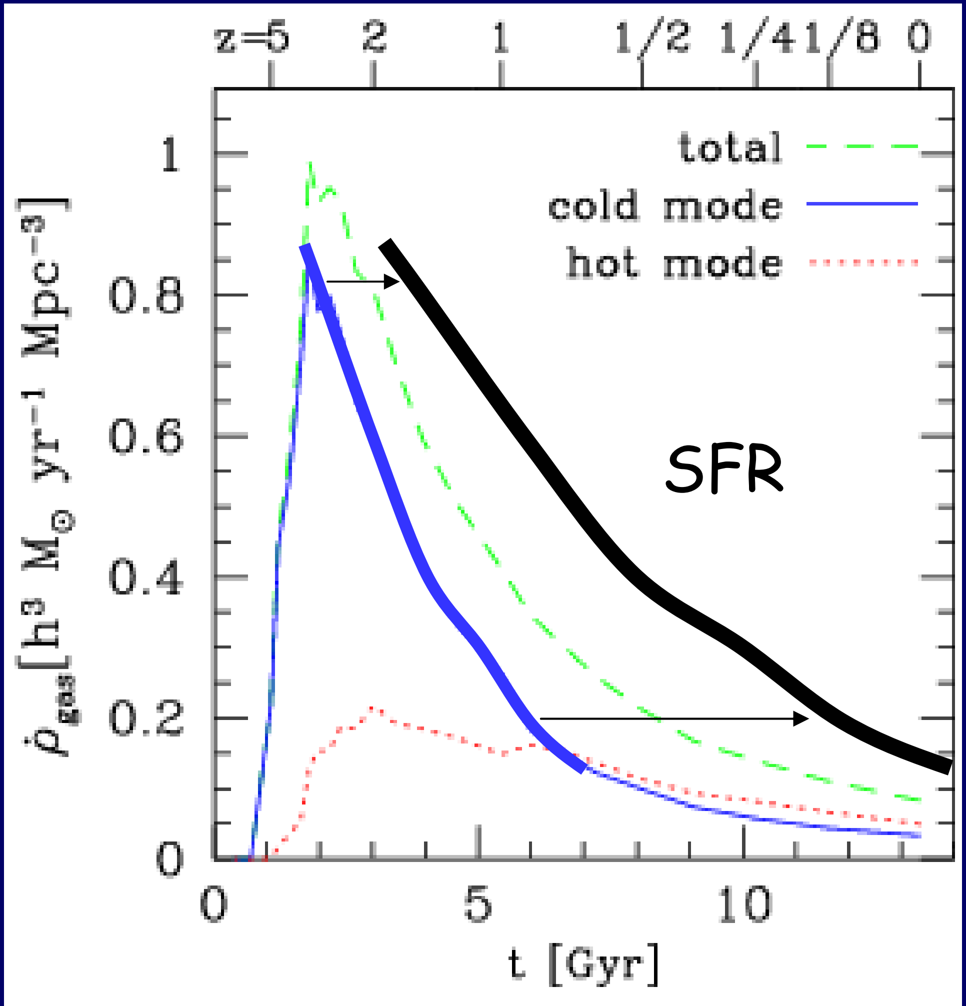
A Sharp knee in the luminosity function



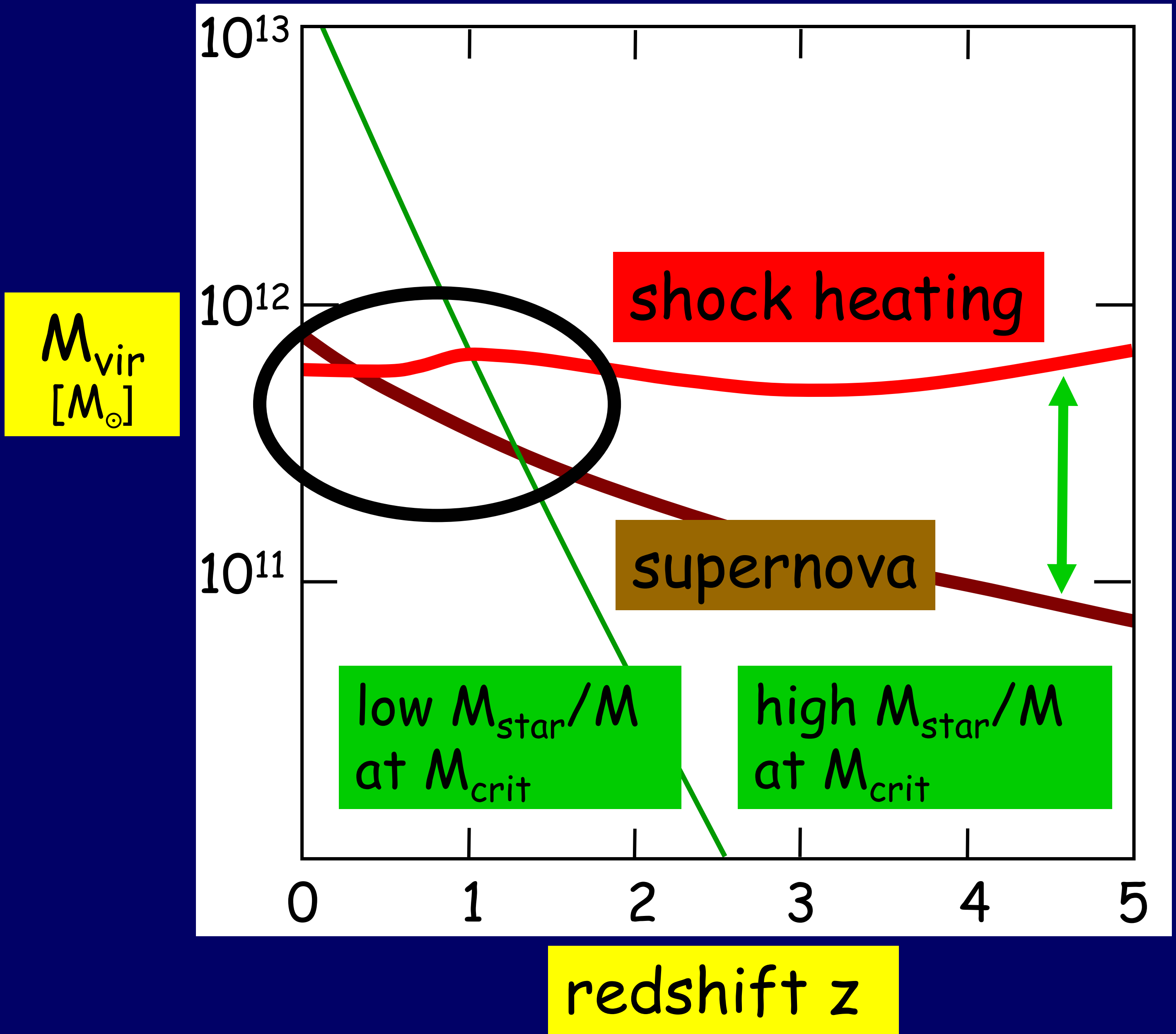
Cold infall history →
Star formation history

SPH
simulation

Keres, Katz,
Weinberg,
Dav'e 2004



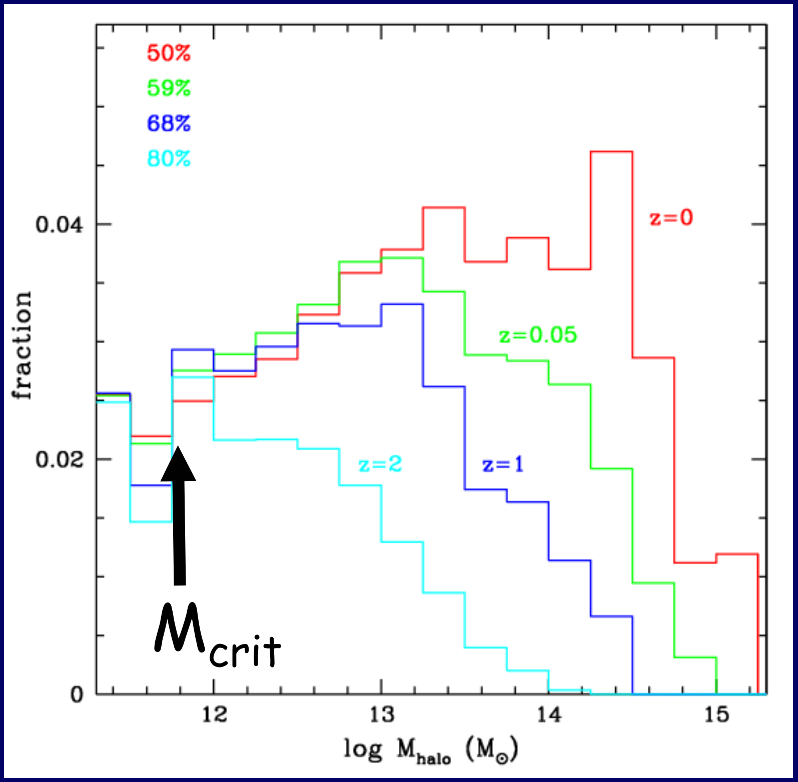
Shock-Heating vs SN Feedback at high z



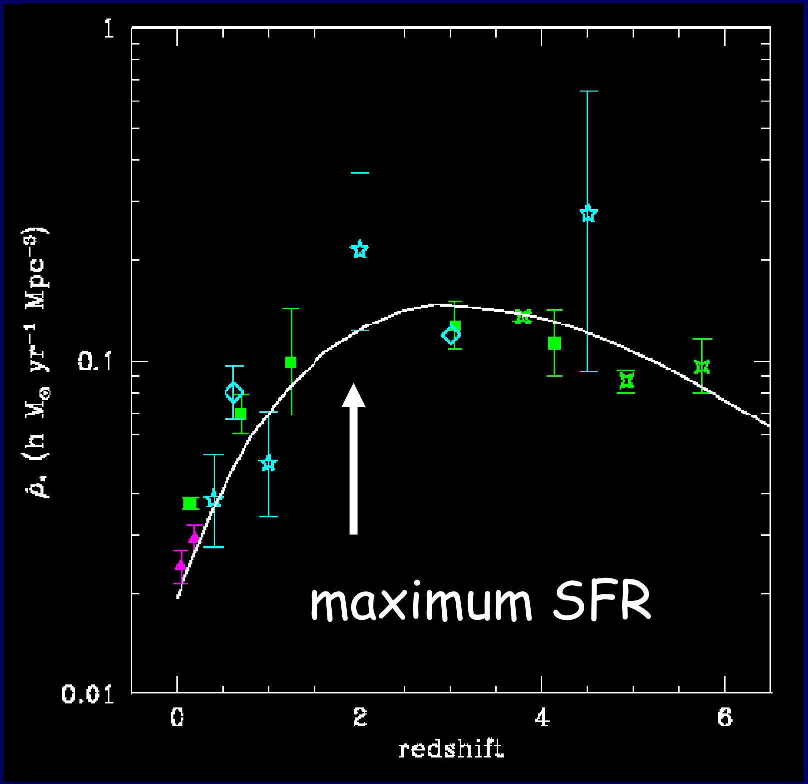
History of Star Formation

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, …)

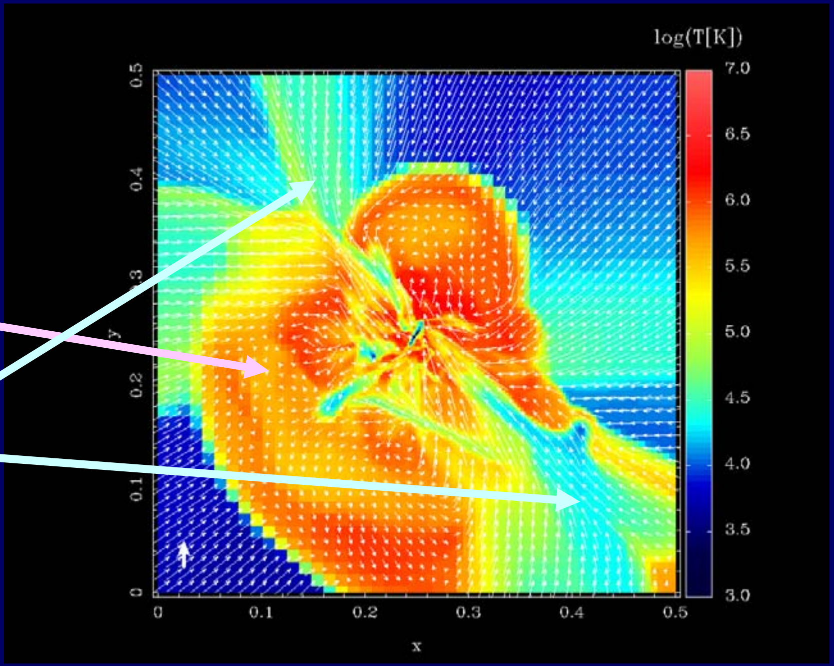
→ should get rid of low j tail

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

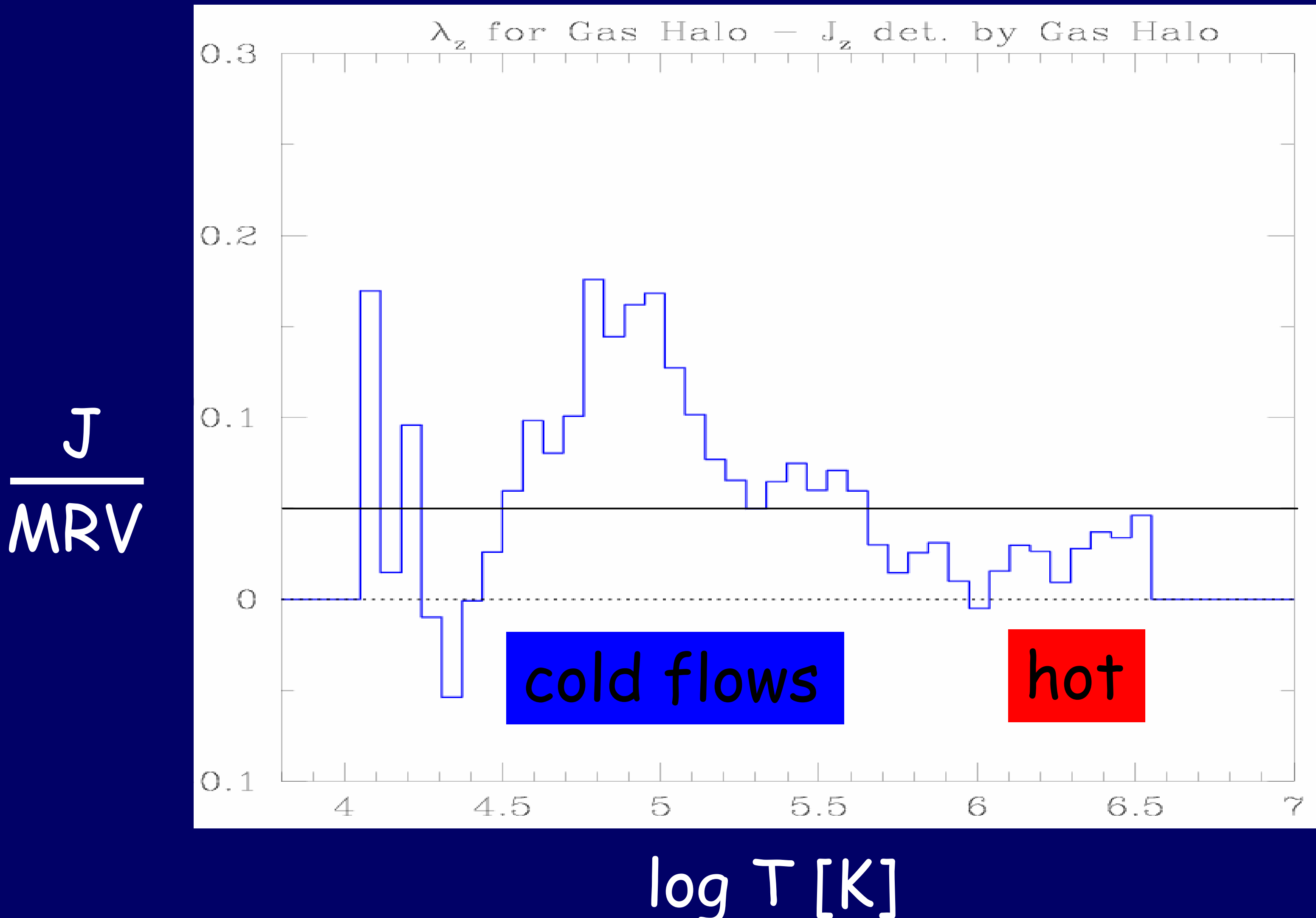
$M>M_{crit}$

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

$M < M_{crit}$

cold infall → disks

star bursts, field

SN feedback regulates SFR

→ blue, young pop

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

starves AGNs

Ly-α 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, Lα 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