Galaxy formation: lecture 2
The physics of galaxy formation

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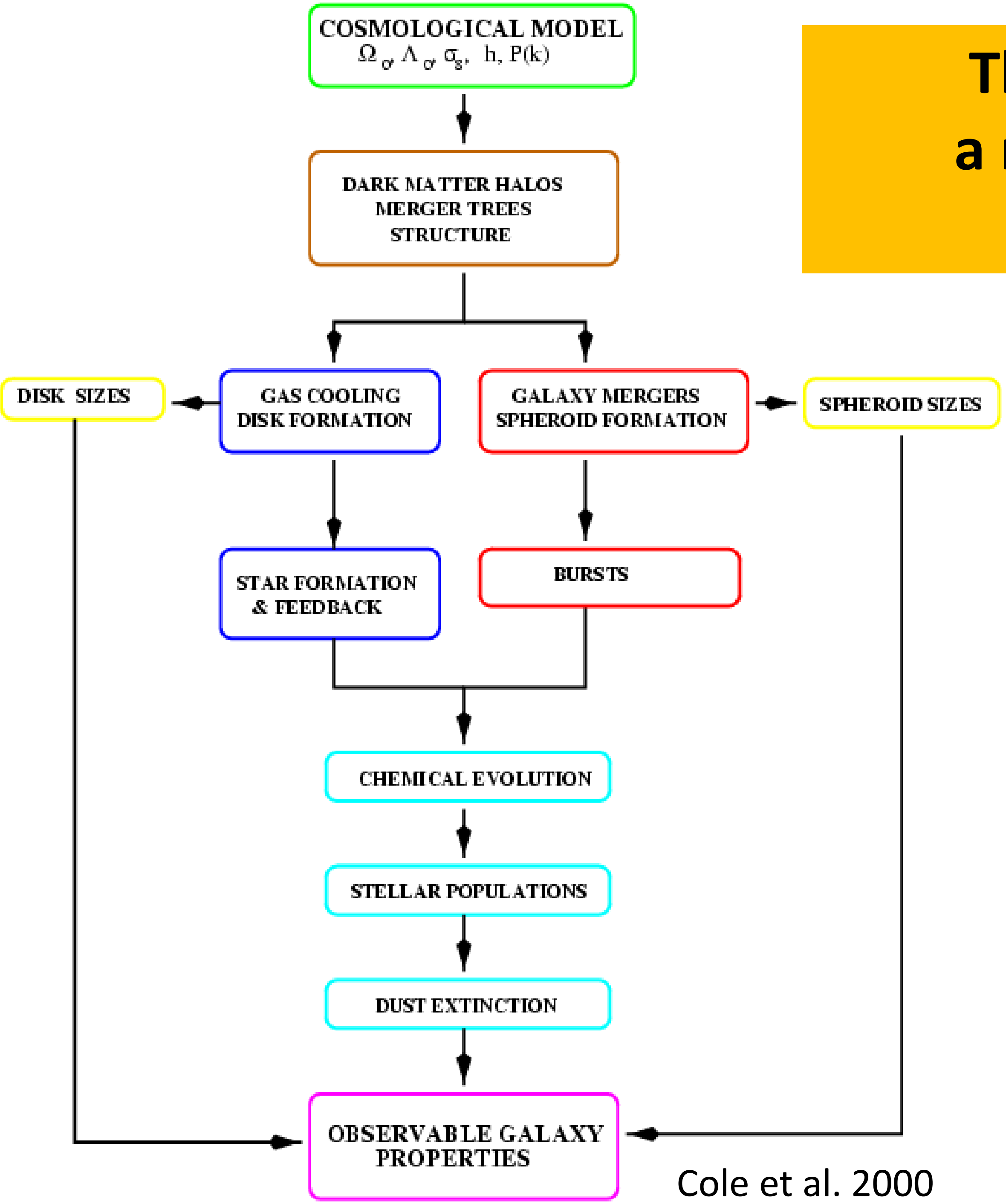
Trieste 2012

Lecture 2

"…. a disheartening number of ingredients must be assembled to produce a plausibly complete recipe for galaxy formation"

- White & Frenk 1991

The processes in a model of galaxy formation



COSMOLOGICAL MODEL
$\Omega_0, \Lambda_0, \sigma_8$, h, P(k)

DARK MATTER HALOS
MERGER TREES
STRUCTURE

DISK SIZES

GAS COOLING
DISK FORMATION

GALAXY MERGERS
SPHEROID FORMATION

SPHEROID SIZES

STAR FORMATION
& FEEDBACK

BURSTS

CHEMICAL EVOLUTION

STELLAR POPULATIONS

DUST EXTINCTION

OBSERVABLE GALAXY
PROPERTIES

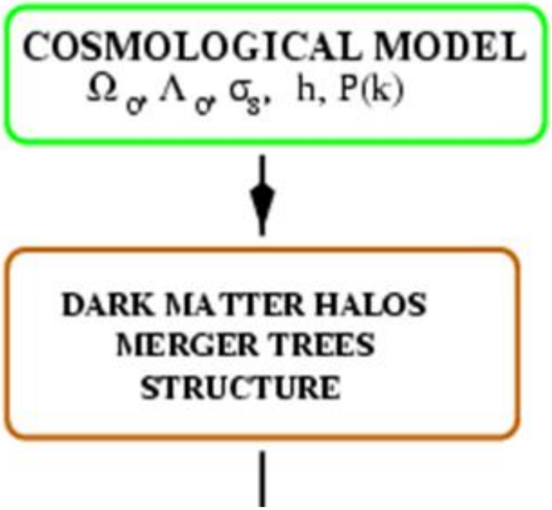
Cole et al. 2000

This lecture:
the physics behind
these processes

Next lecture:
Implementation in models

Baugh 2006 Rep. Prog. Phys.

Structure formation in the DM



COSMOLOGICAL MODEL

$\Omega_0, \Lambda_0, \sigma_8$, h, P(k)

DARK MATTER HALOS

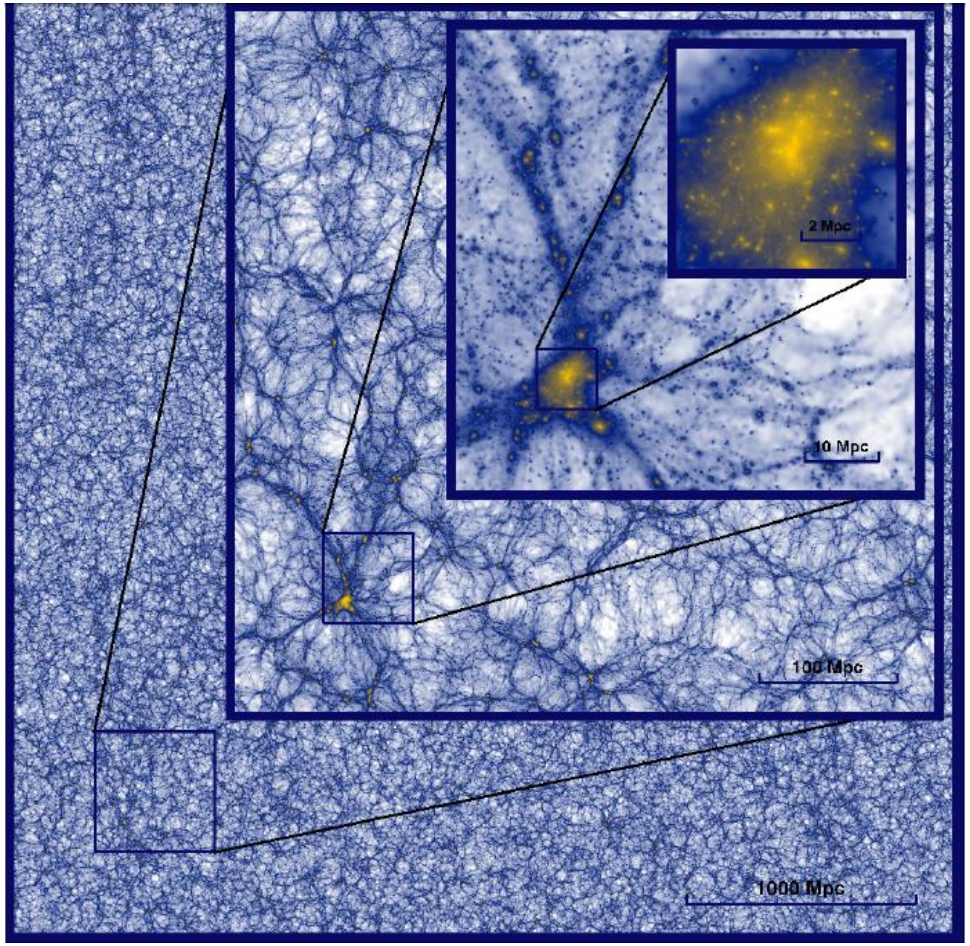
MERGER TREES

STRUCTURE

N-body simulation

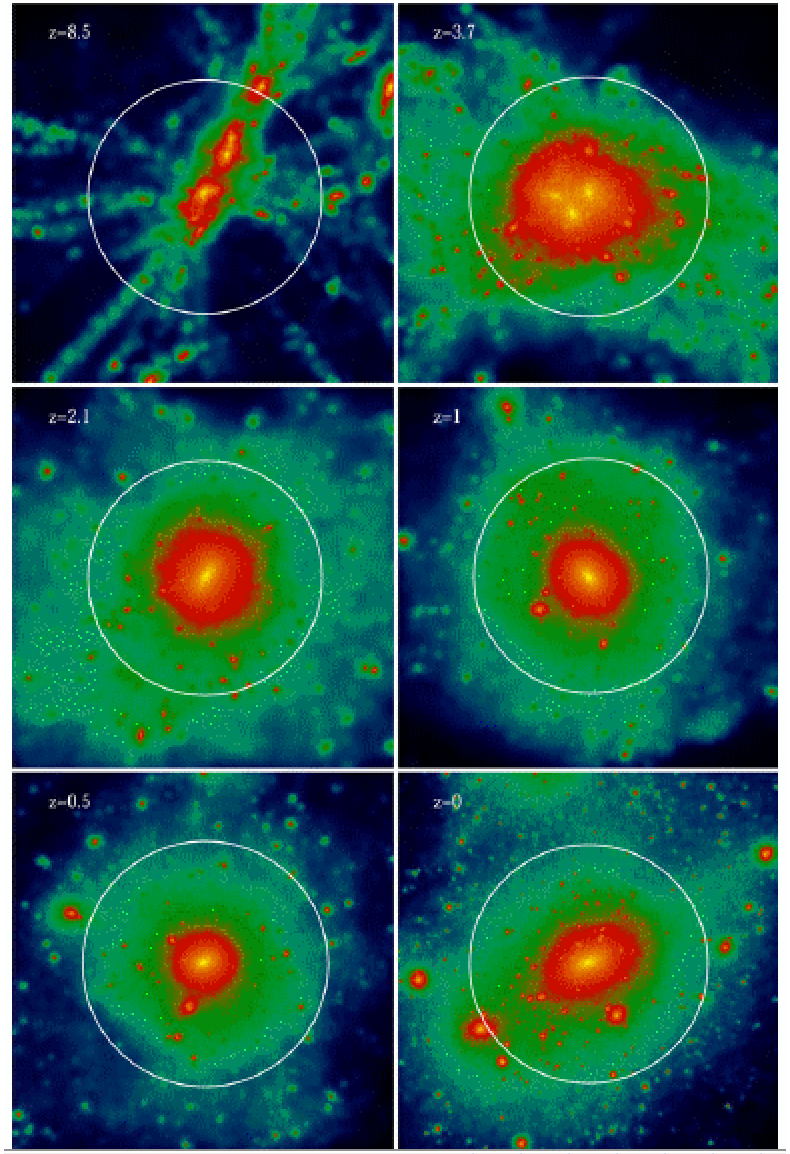
Monte Carlo

Analytic fits to growth history

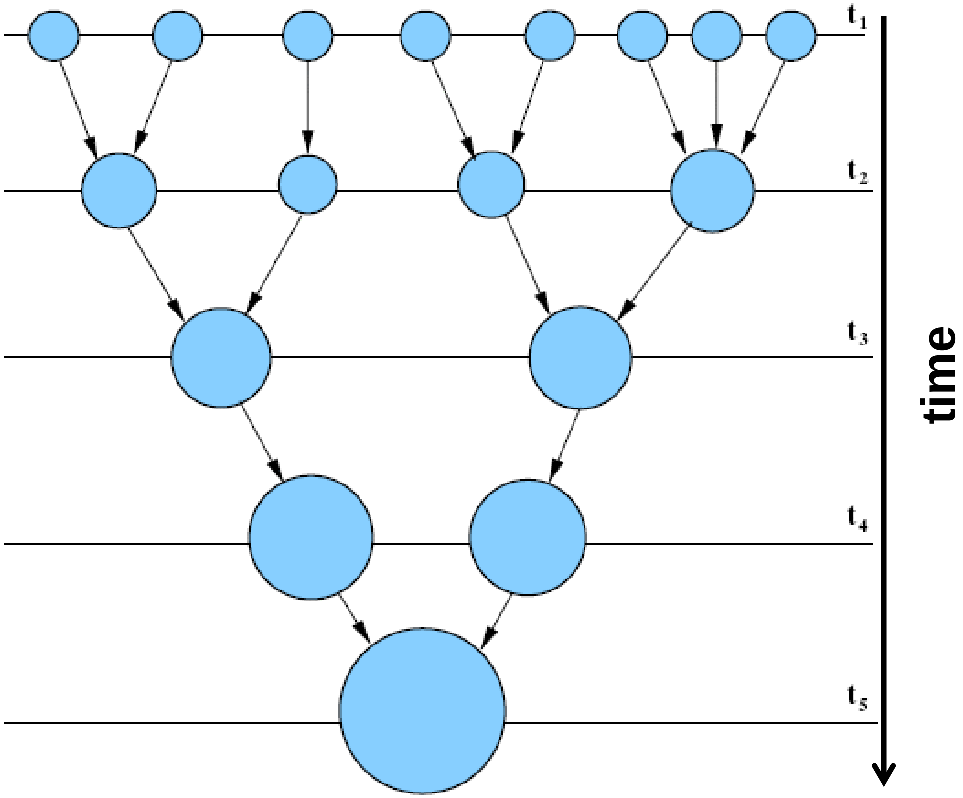


MXXL run Angulo et al. 2012

Starting point: halo merger tree



Images by Chris Power



Bathtub model of galaxy formation

$$\dot{M}_{\rm gas} = \dot{M}_{\rm gas,in} - (1 - R)\dot{M}_{\star} - \dot{M}_{\rm gas,out}$$

$$\begin{aligned}\dot{M}_{\rm gas,in} &= \epsilon_{\rm in}\, f_{\rm b}\, \dot{M}_{\rm h} \\ &\simeq 90\, \epsilon_{\rm in}\, f_{\rm b,0.18}\, M_{\rm h,12}^{1.1}\, (1+z)_{3.2}^{2.2}\, M_{\odot}\ {\rm yr}^{-1}\end{aligned}$$

$$\dot{M}_{\rm gas,out} = a \times {\rm SFR},$$

More than one equation needed!

$$\dot{M}_* = (1 - R)\psi \tag{4.6}$$

$$\dot{M}_{\rm hot} = -\dot{M}_{\rm cool} + \beta\psi \tag{4.7}$$

$$\boxed{\dot{M}_{\rm cold} = \dot{M}_{\rm cool} - (1 - R + \beta)\psi} \tag{4.8}$$

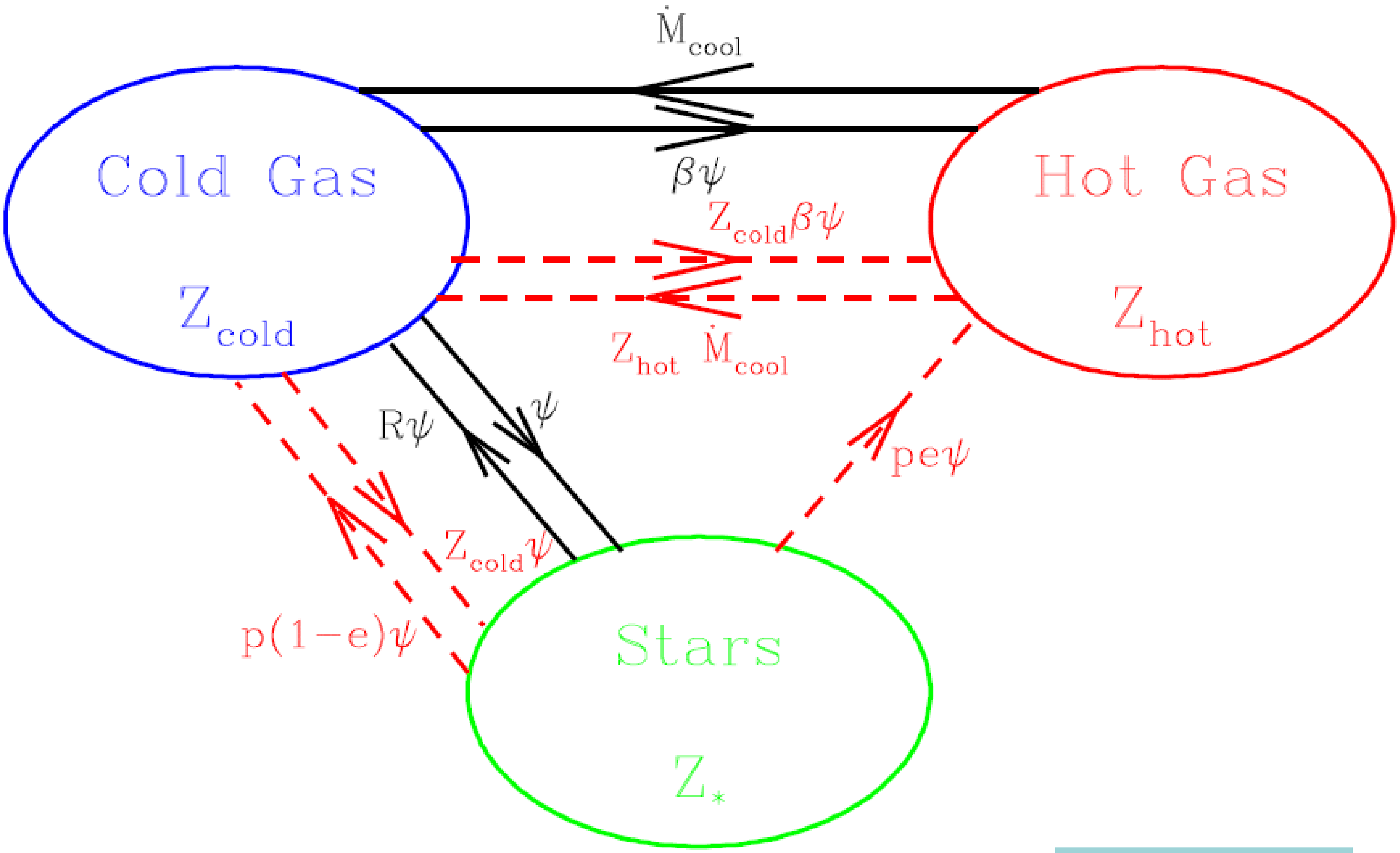
$$\dot{M}_*^Z = (1 - R)Z_{\rm cold}\psi \tag{4.9}$$

$$\dot{M}_{\rm hot}^Z = -\dot{M}_{\rm cool}Z_{\rm hot} + (pe + \beta Z_{\rm cold})\psi \tag{4.10}$$

$$\dot{M}_{\rm cold}^Z = \dot{M}_{\rm cool}Z_{\rm hot} + [p(1 - e) - (1 + \beta - R)Z_{\rm cold}]\psi, \tag{4.11}$$

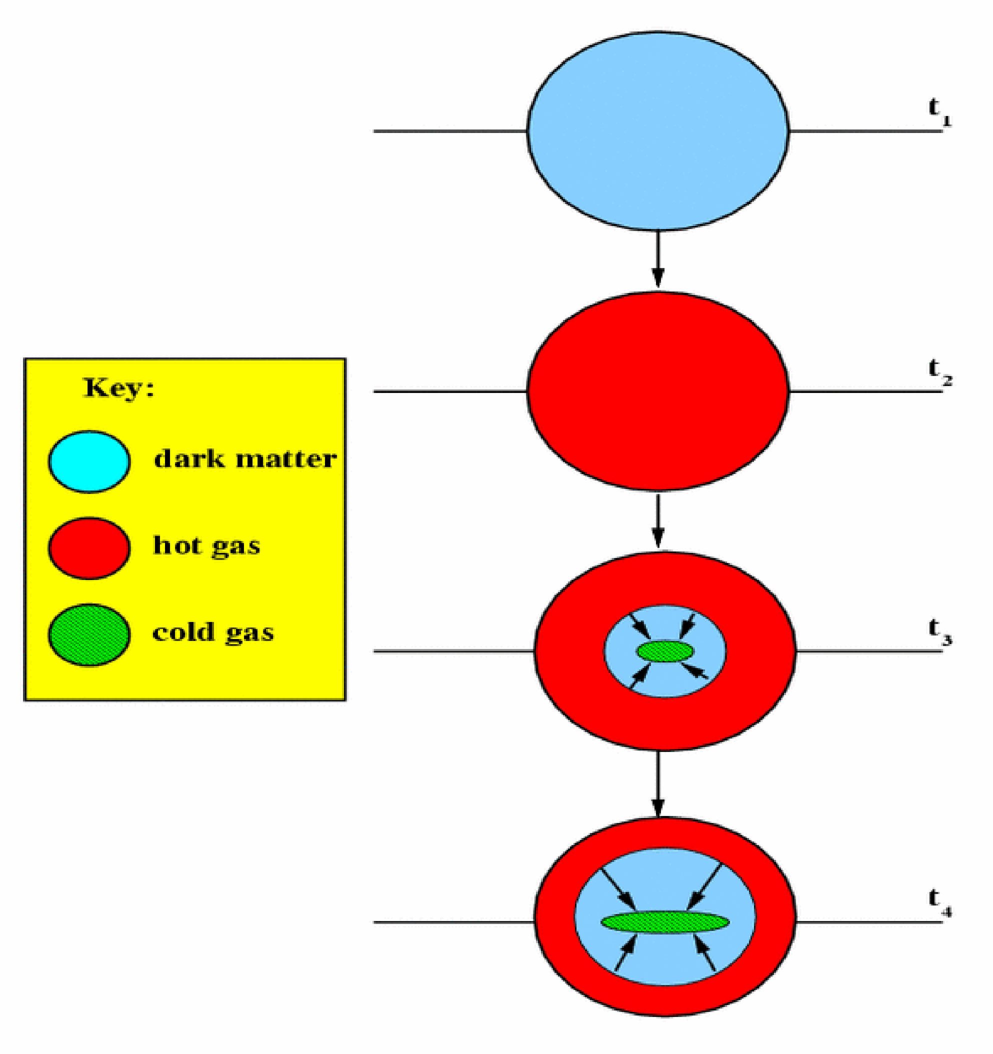
Cole et al. 2000

Exchange of mass and metals between reservoirs



Cole et al. 2000

Add in baryonic physics:
Gas cooling inside a dark halo



Baryons shock heated in
gravitational potential
well of the halo.

Gas is ionised and cools
mainly by radiative transitions

Simple model:
spherical symmetry
propagate cooling radius

Balance between cooling time
and infall time

Gas cooling mechanisms

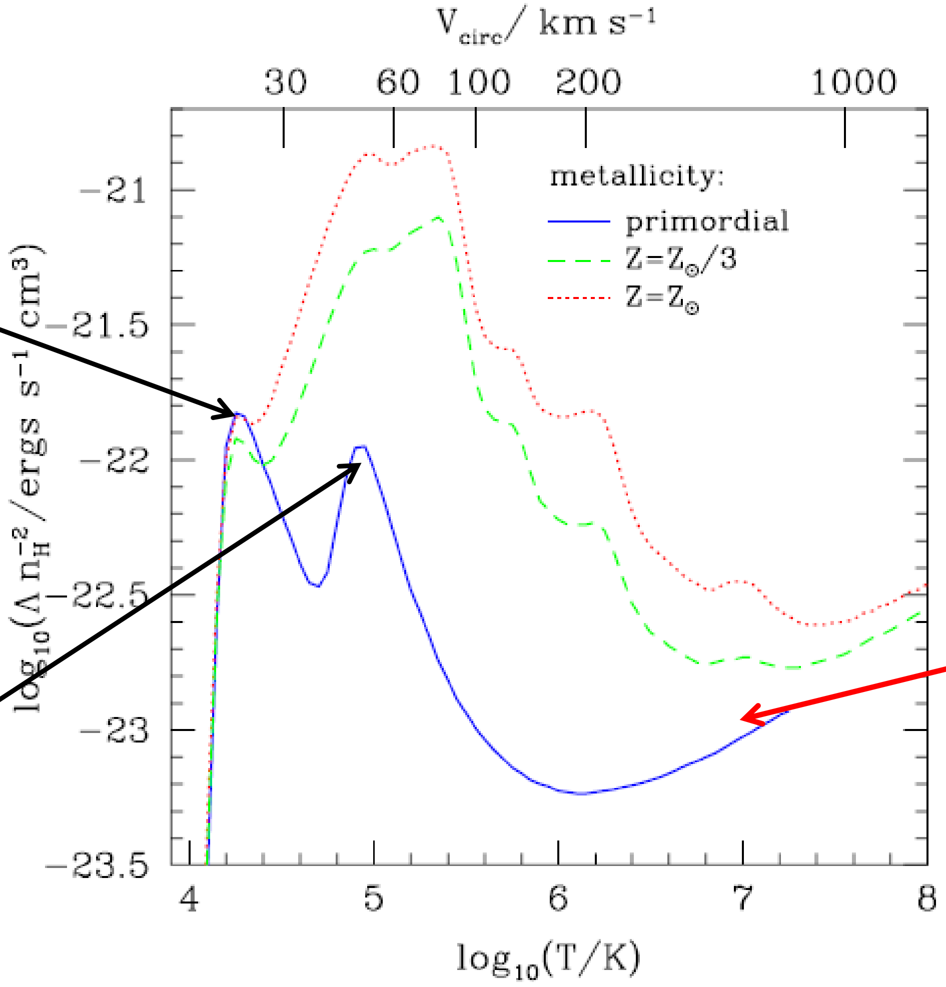
- High redshift: inverse Compton scattering of CMB photons
- Galactic mass haloes: radiation of photons following collisional excitation
- Cluster mass haloes: Bremsstrahlung radiation in fully ionised plasma
- 10,000K to 100K: molecular hydrogen transitions (rotational, vibrational)

Two-body

Gas cooling

$$t_{\rm cool}(r) = \left(\frac{3}{2}\frac{\rho_{\rm gas} k T_{\rm vir}}{\mu m_{\rm H}}\right) / \left(\rho_{\rm gas}^2 \Lambda(T_{\rm vir}, Z_{\rm gas})\right)$$

Cooling function



H

He+

bremsstrahlung

$\propto T^{1/2}$

How much gas cools?

Compute time for gas to cool within radius r:

$$t_{\rm cool}(r) = \left(\frac{3}{2}\frac{\rho_{\rm gas} k T_{\rm vir}}{\mu m_{\rm H}}\right) / \left(\rho_{\rm gas}^2 \Lambda(T_{\rm vir}, Z_{\rm gas})\right)$$

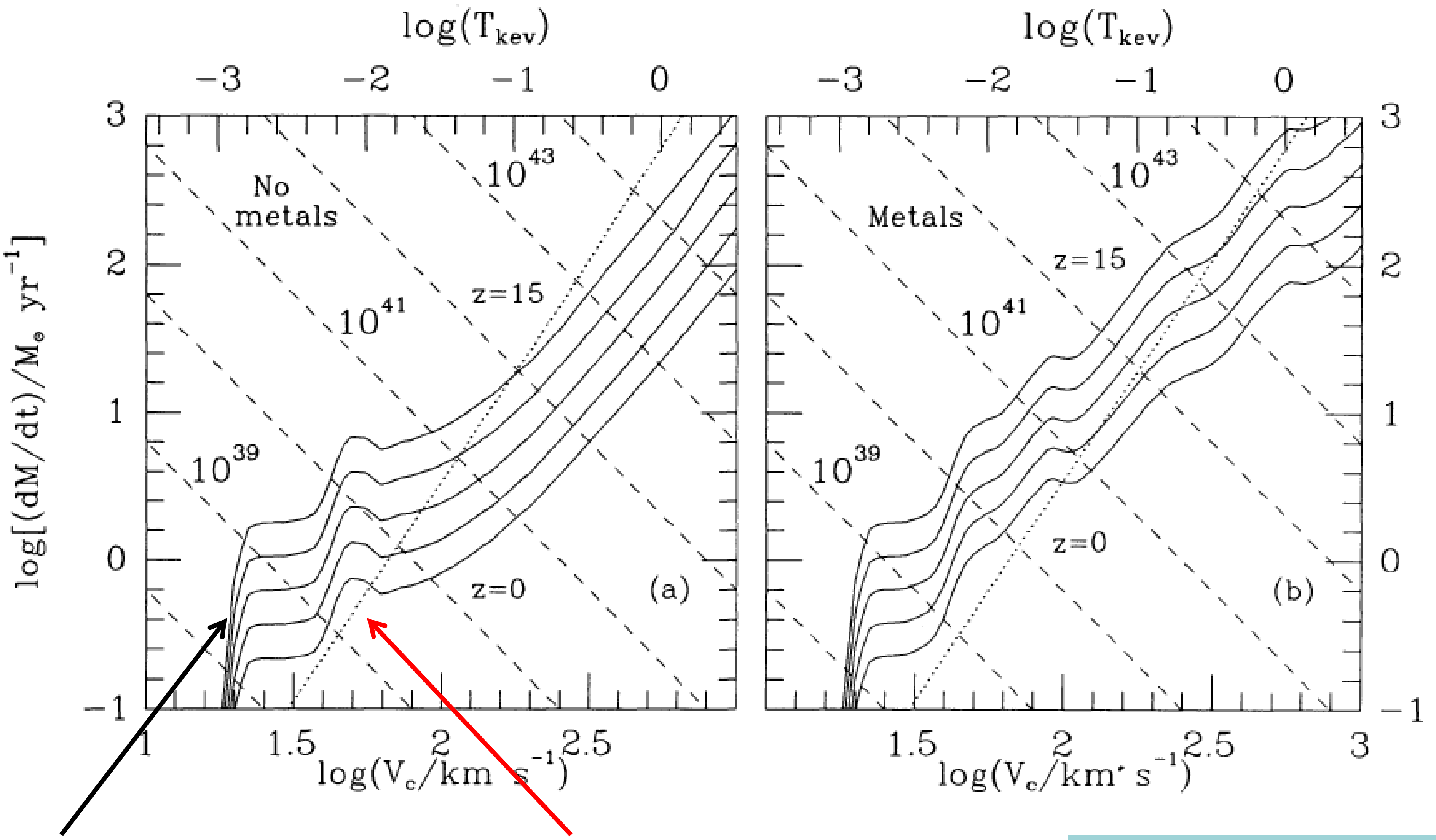
Time for gas to fall into centre of halo once pressure support removed:

$$t_{ff} = \frac{1}{4}\sqrt{\frac{3\pi}{2G\rho}}$$

Gas within rmin is assumed to cool over timestep dt

$$r_{\rm min}(t) = {\rm min}[r_{\rm cool}, r_{\rm ff}]$$

Gas cooling and infall



Cooling rates

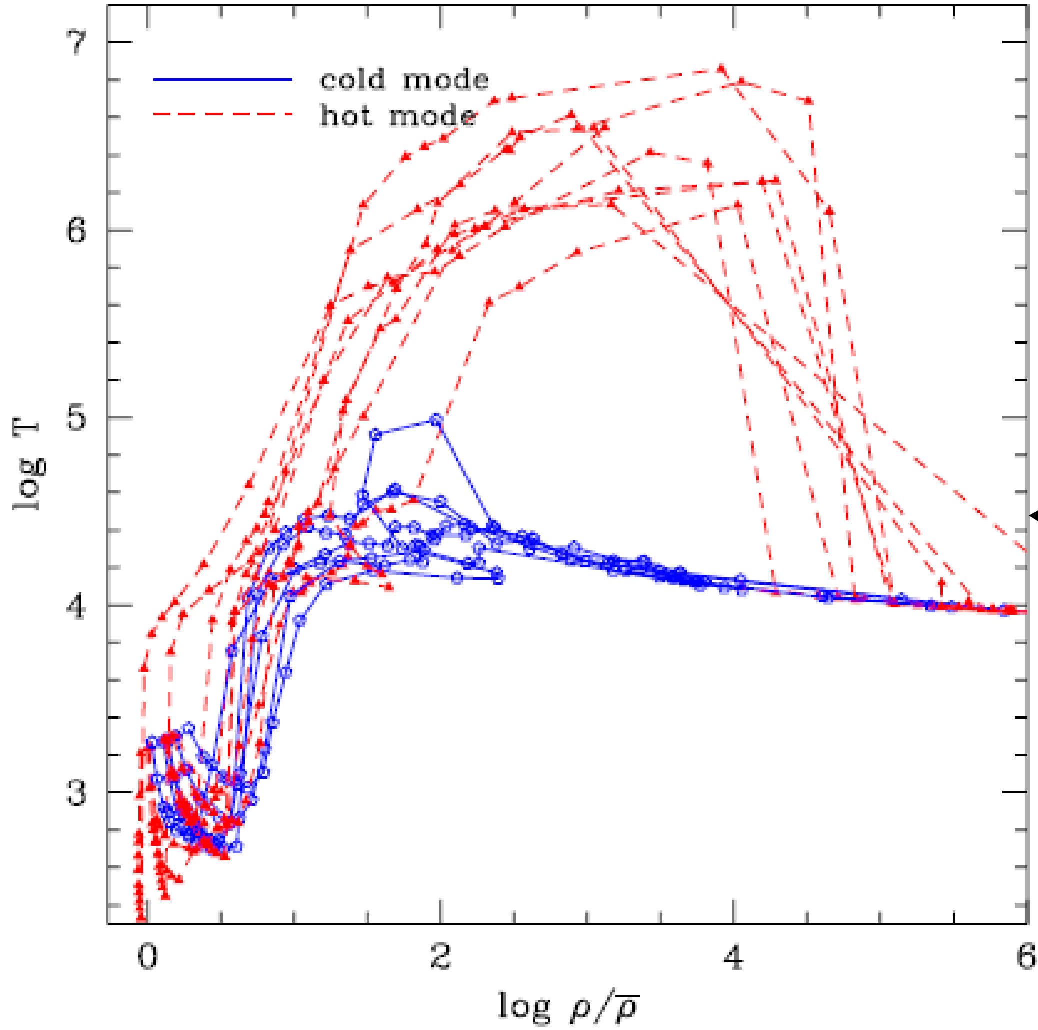
Infall rate

White & Frenk 1991

How good is this model?

- Does an accretion shock form?
- Spherical symmetry of halo?

Thermal history of gas in a simulation



Track the temperature and density of gas in SPH

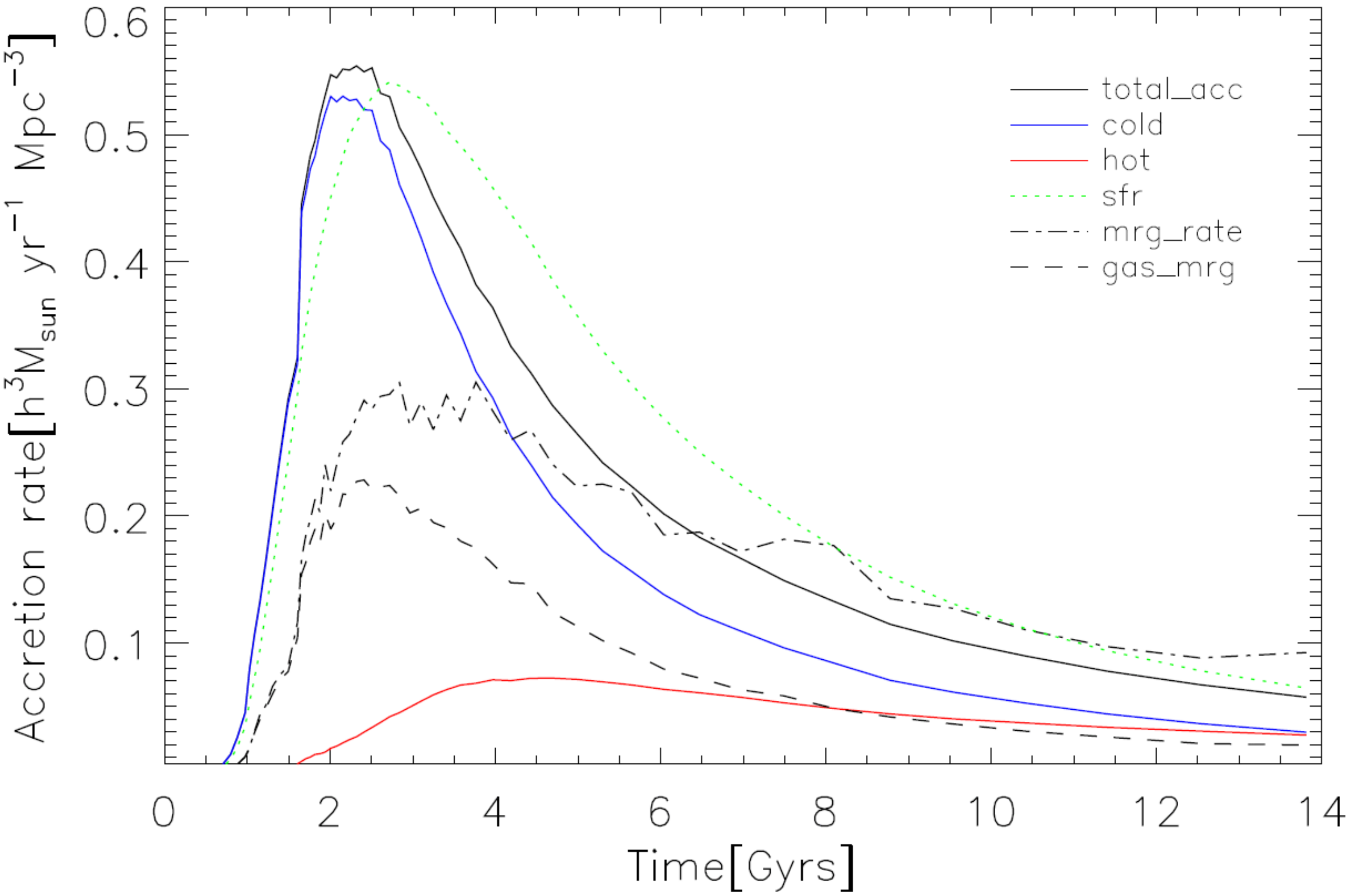
Some gas never reaches the virial temperature of the associated halo

30 km/s

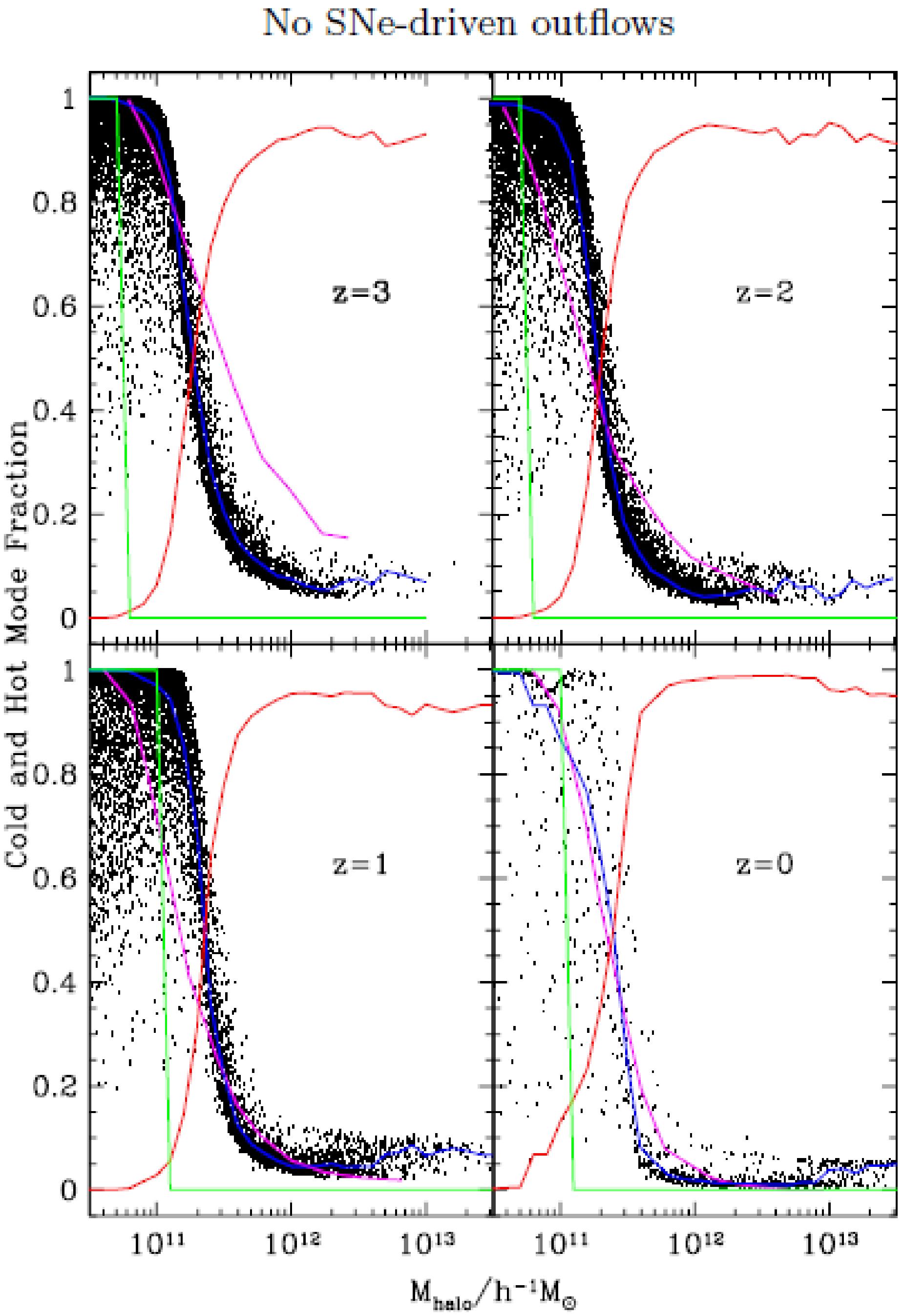
$$T_{\rm vir} = \frac{1}{2}\frac{\mu m_{\rm H}}{k} V_{\rm H}^2$$

Kay et al. 2000
Keres et al 2005

Cold vs hot accretion



SPH simulations of Keres et al 0809.1430

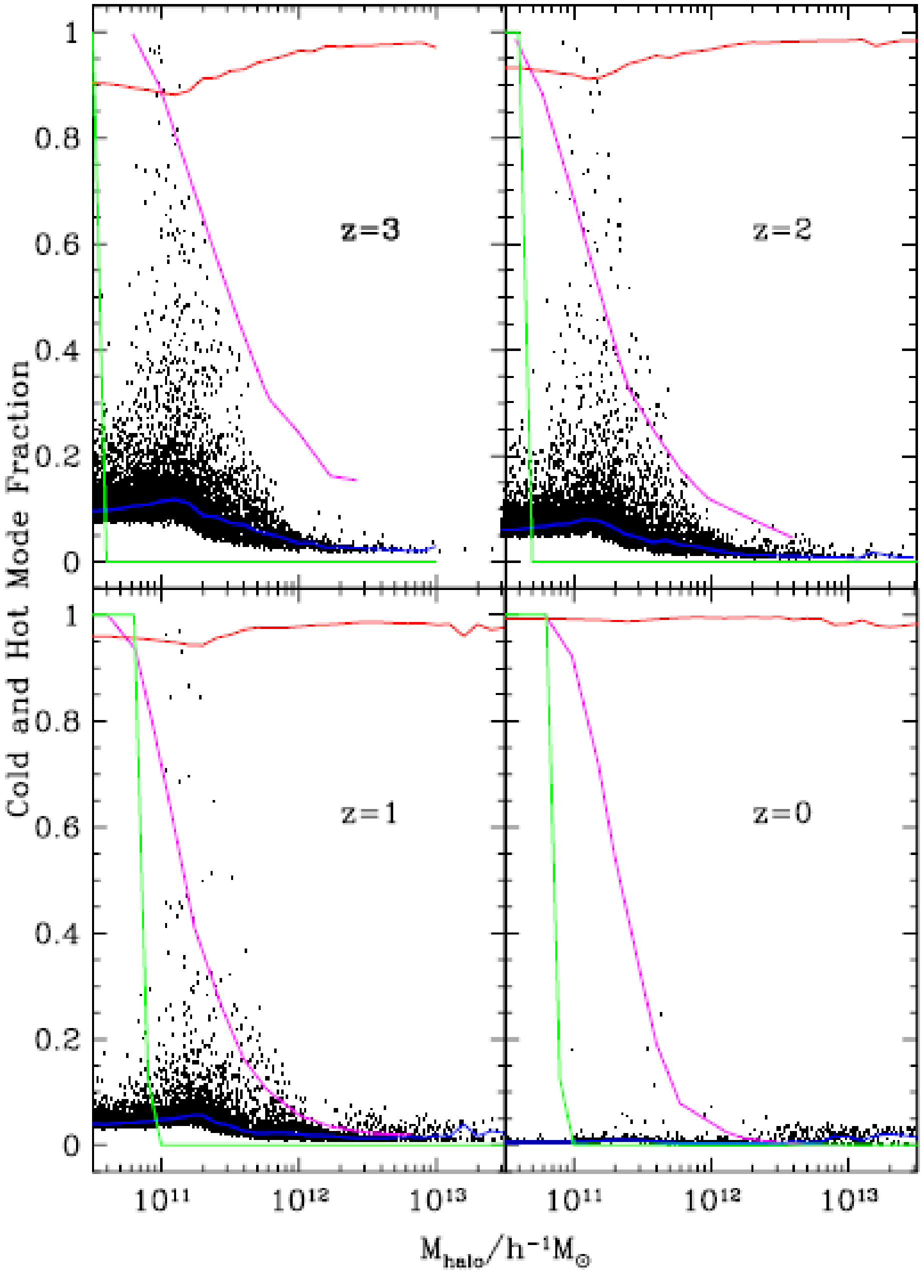


How do galaxies get their gas?

- Modified cooling calculation to ignore shock heating in cold mode
- Without SNe heating find most of gas is accreted in cold mode

Benson & Bower 2011

Including SNe-driven outflows



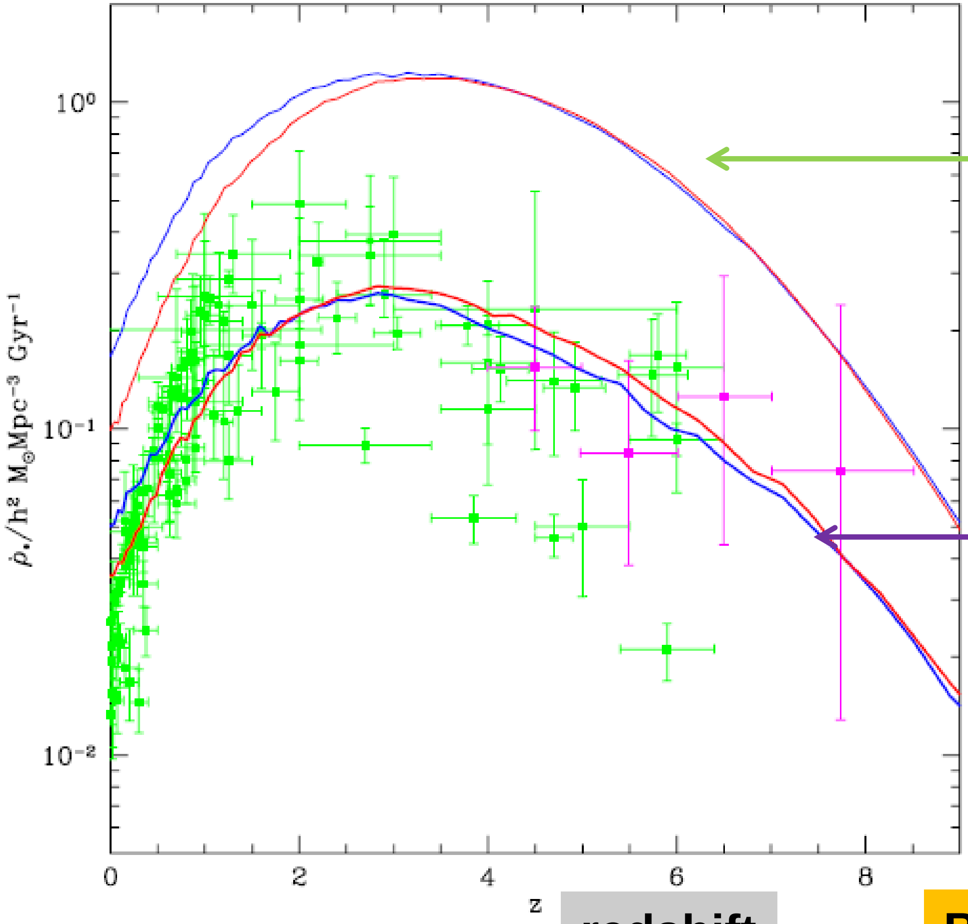
How do galaxies get their gas?

- Modified cooling calculation to ignore shock heating in cold mode
- With SNe heating find much less gas accreted in cold mode

Benson & Bower 2011

What impact does cold mode have?

Global star formation density per unit volume over history of Universe



SFR/V

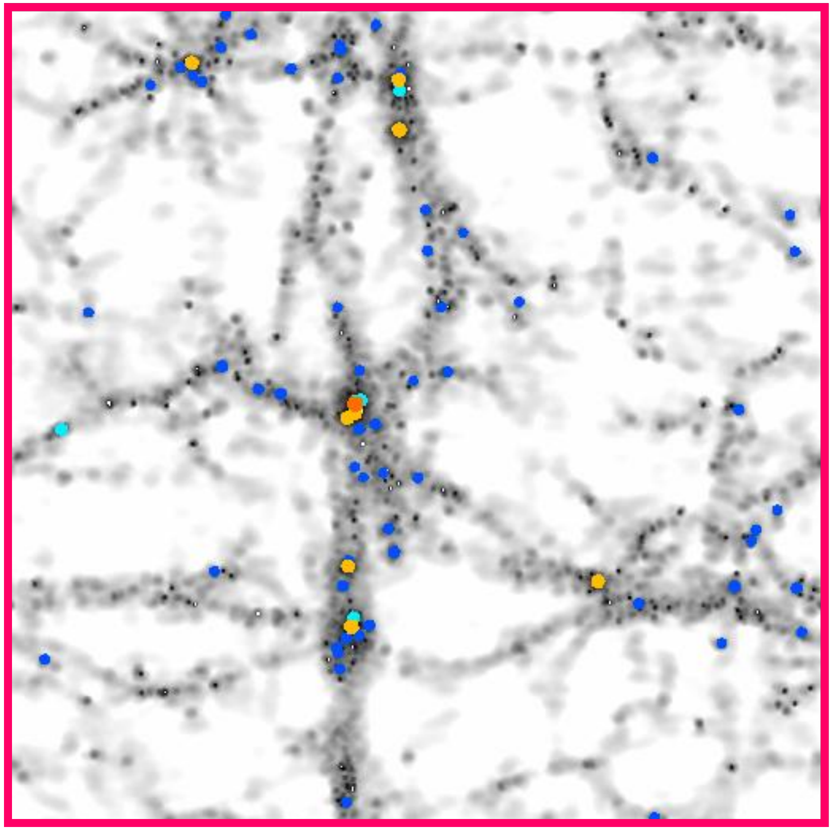
redshift

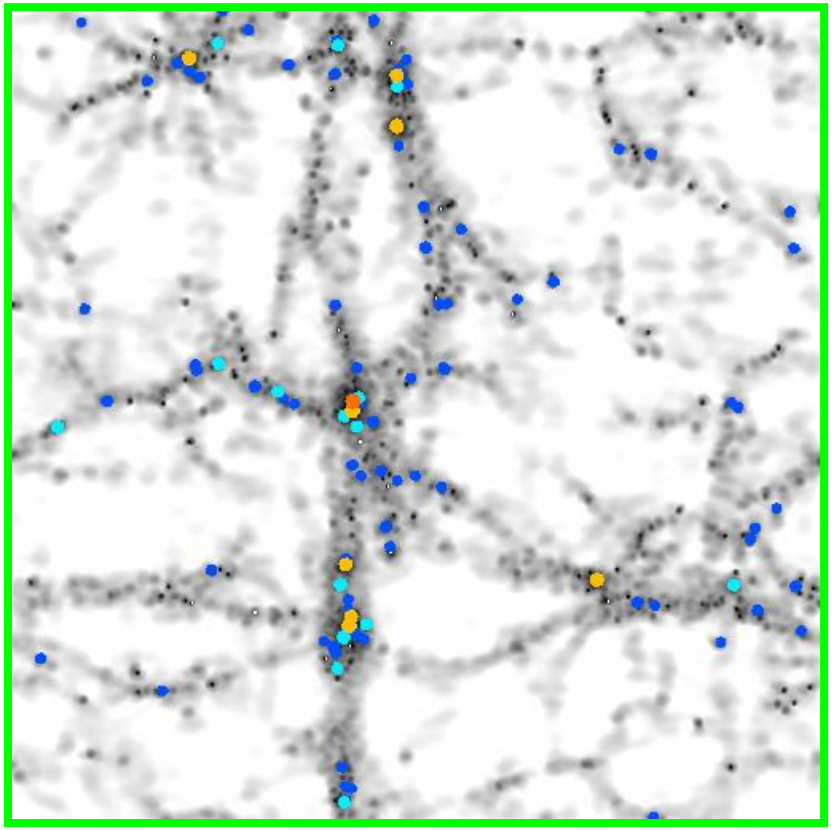
No Sne feedback

With SNe

Benson & Bower 2011

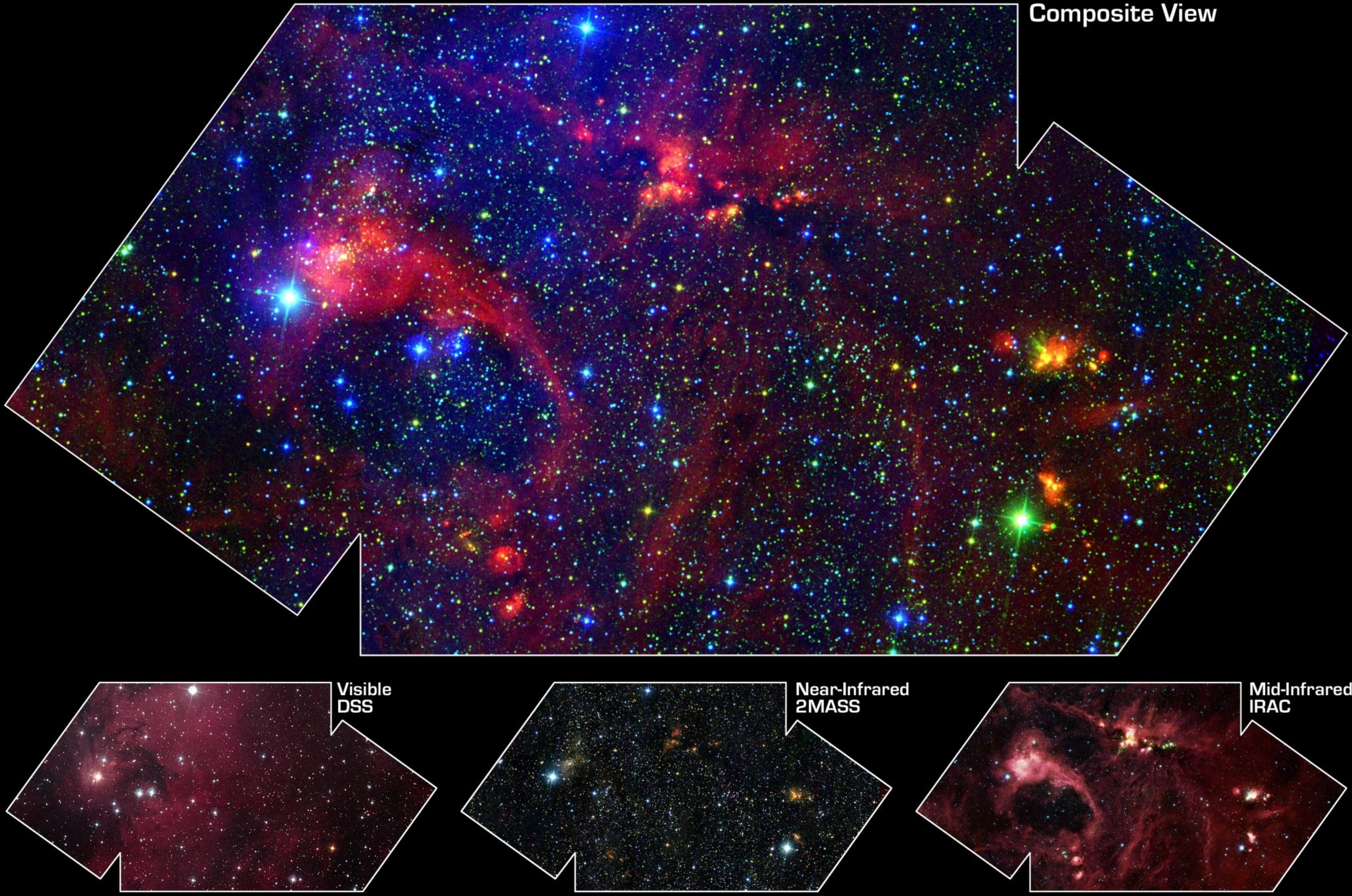
Assumption of spherical symmetry: Gas simulations vs analytic calculation





Compare gas cooling in ``stripped down" SPH and semi-analytic codes

Helly et al 2003; Yoshida et al 2002



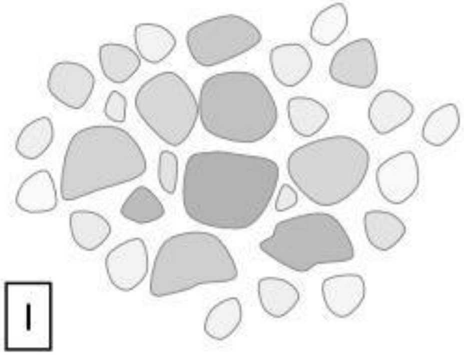
Star Formation in the DR21 Region

Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / A. Marston (ESTEC/ESA)

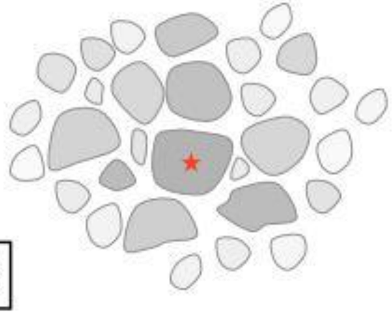
ssc2004-06b

STAR FORMATION – Klessen 2011



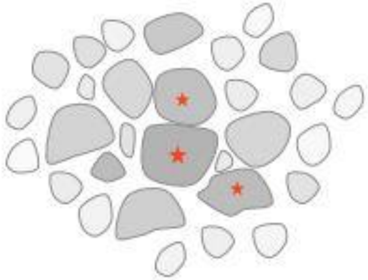
1

turbulence creates a hierarchy of clumps



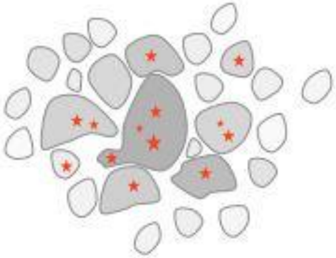
2

while the whole region contracts, individual clumps collapse to form stars



3

individual clumps collapse to form stars

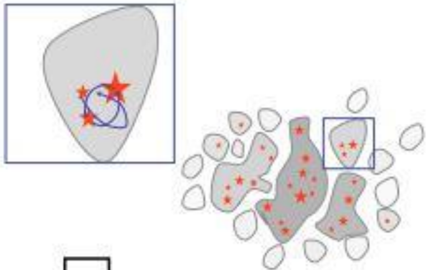


4

in *dense clusters* clumps may merge while collapsing → contain multiple protostars

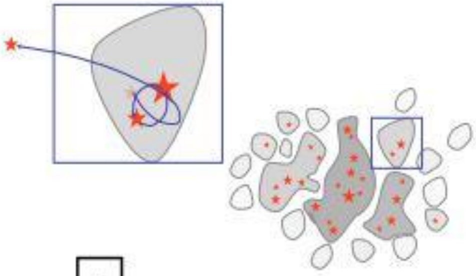
5

in *dense clusters* competitive mass growth becomes important



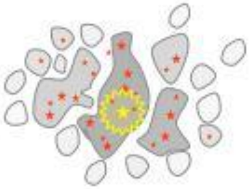
6

in *dense clusters* N-body effects influence mass growth



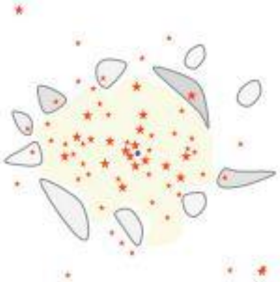
5

low-mass objects may become ejected → accretion stops



8

feedback terminates star formation



9

result: star cluster, possibly with HII region

Star formation

Star formation takes place in dense molecular clouds:

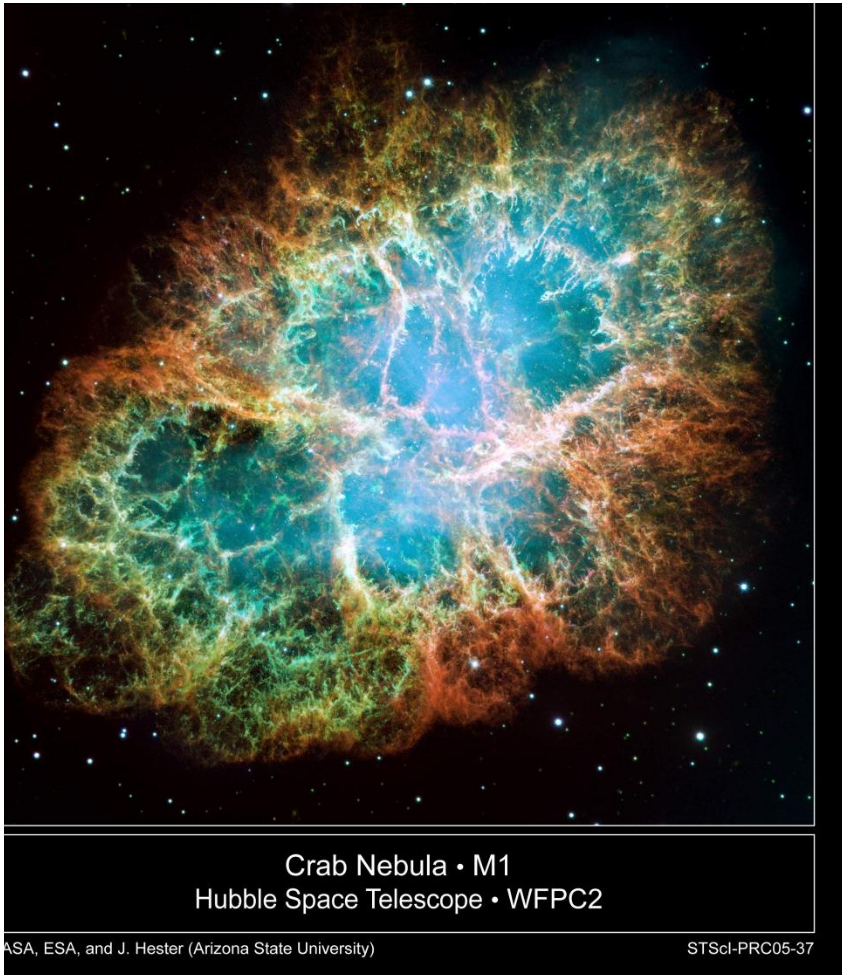
Formation of molecular hydrogen opens new cooling channels to allow gas to reach 100K

Collisions excite rotational/vibrational levels which decay radiating energy

Simple dimensional argument for global SFR in a galaxy:

$$\dot{M}_* \propto \frac{M_{\rm cold}}{\tau}$$

SNe heating

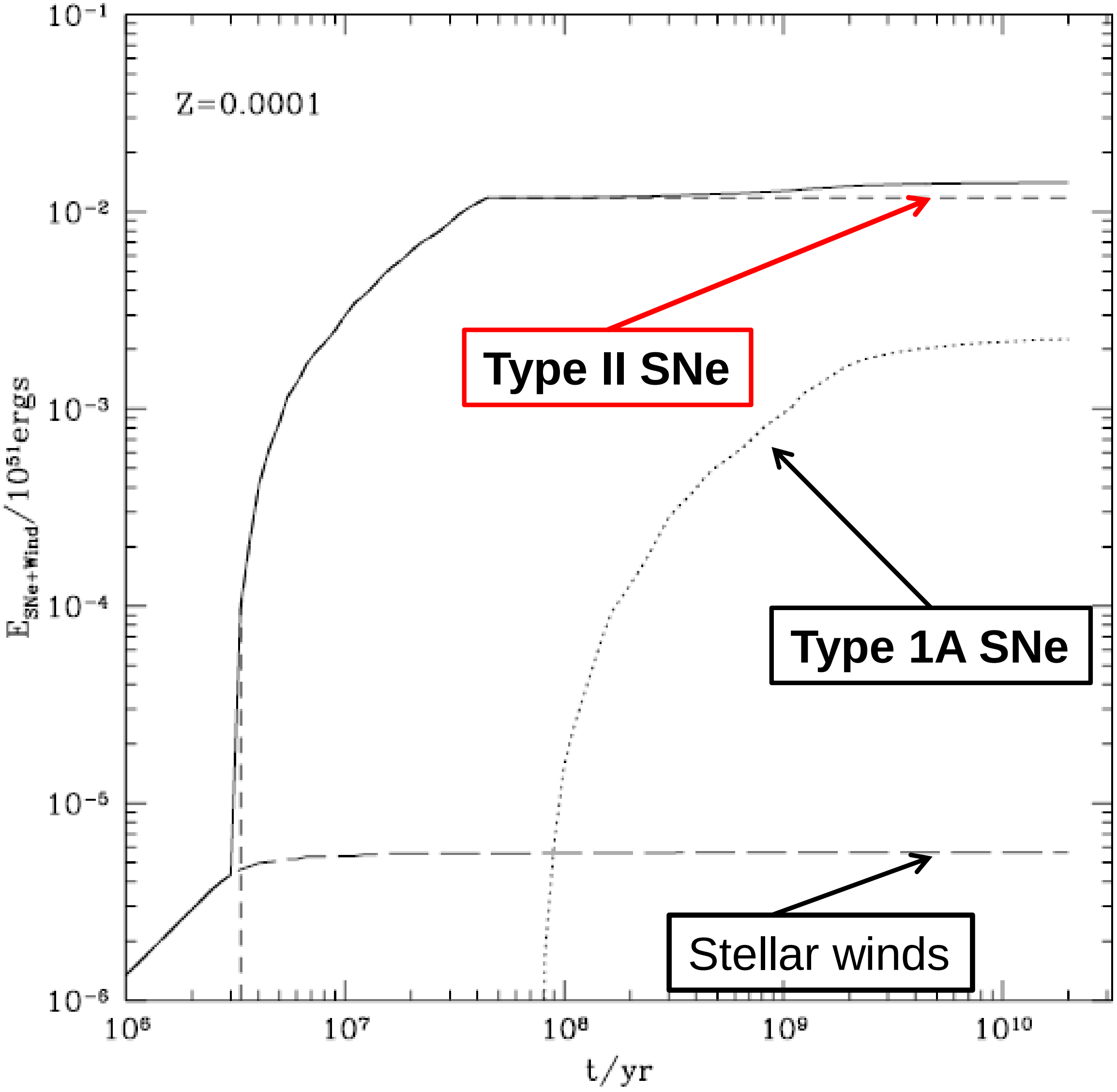


Crab Nebula • M1
Hubble Space Telescope • WFPC2

ASA, ESA, and J. Hester (Arizona State University)
STScI-PRC05-37

Energy input into ISM from stars

Total energy released



Type II SNe

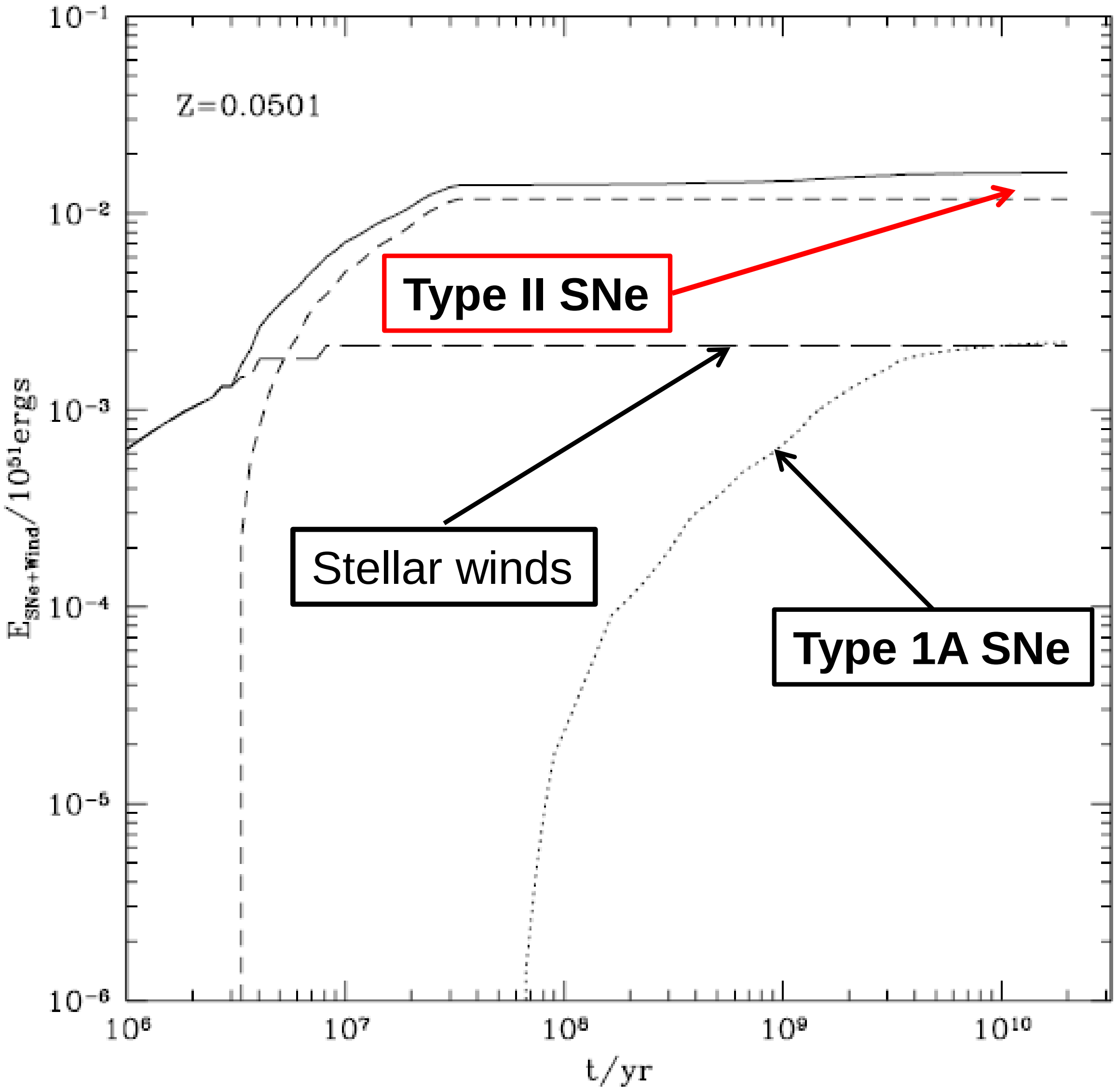
Type 1A SNe

Stellar winds

Very low metallicity star

Benson 2010

Energy input into ISM from stars



Total energy released

Type II SNe

Stellar winds

Type 1A SNe

High metallicity star

Benson 2010

What impact does this energy have?

Assume fraction of energy injected drives outflow with escape velocity:

$$\begin{aligned}\frac{1}{2}\dot{M}_{\rm out}V^2_{\rm esc} &= \epsilon\int_0^t \dot{M}_\star(t')\dot{E}_{\rm SNe+winds}(t-t')\,{\rm d}t' \\ &\approx \epsilon\,\dot{M}_\star(t)E_{\rm SN+winds},\end{aligned}$$

Derive outflow rate:

$$\dot{M}_{\rm out} = \dot{M}_\star(t)\frac{2\epsilon E_{\rm SN+winds}}{V^2_{\rm esc}}.$$

Benson 2010

What impact does this energy have?

Consider another scenario in which the SNe remnant radiates and so Momentum is conserved rather than energy:

$$\dot{P}_{\mathrm{W}} = \dot{M}_{\mathrm{out}} V_{\infty};$$

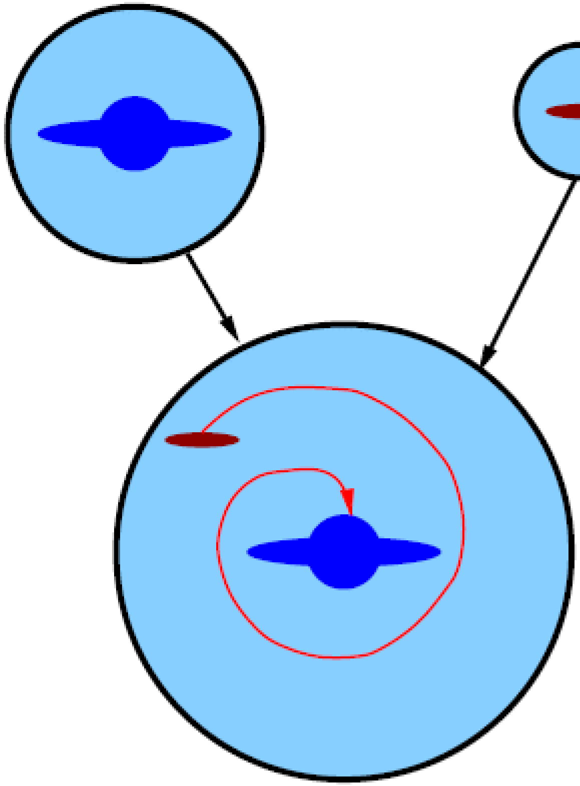
Derive outflow rate conserving momentum:

$$\dot{M}_{\mathrm{out}} \approx \frac{\dot{P}_{\mathrm{SN}}}{V_{\mathrm{esc}}}$$

assuming $V_{\infty} \approx V_{\mathrm{esc}}$

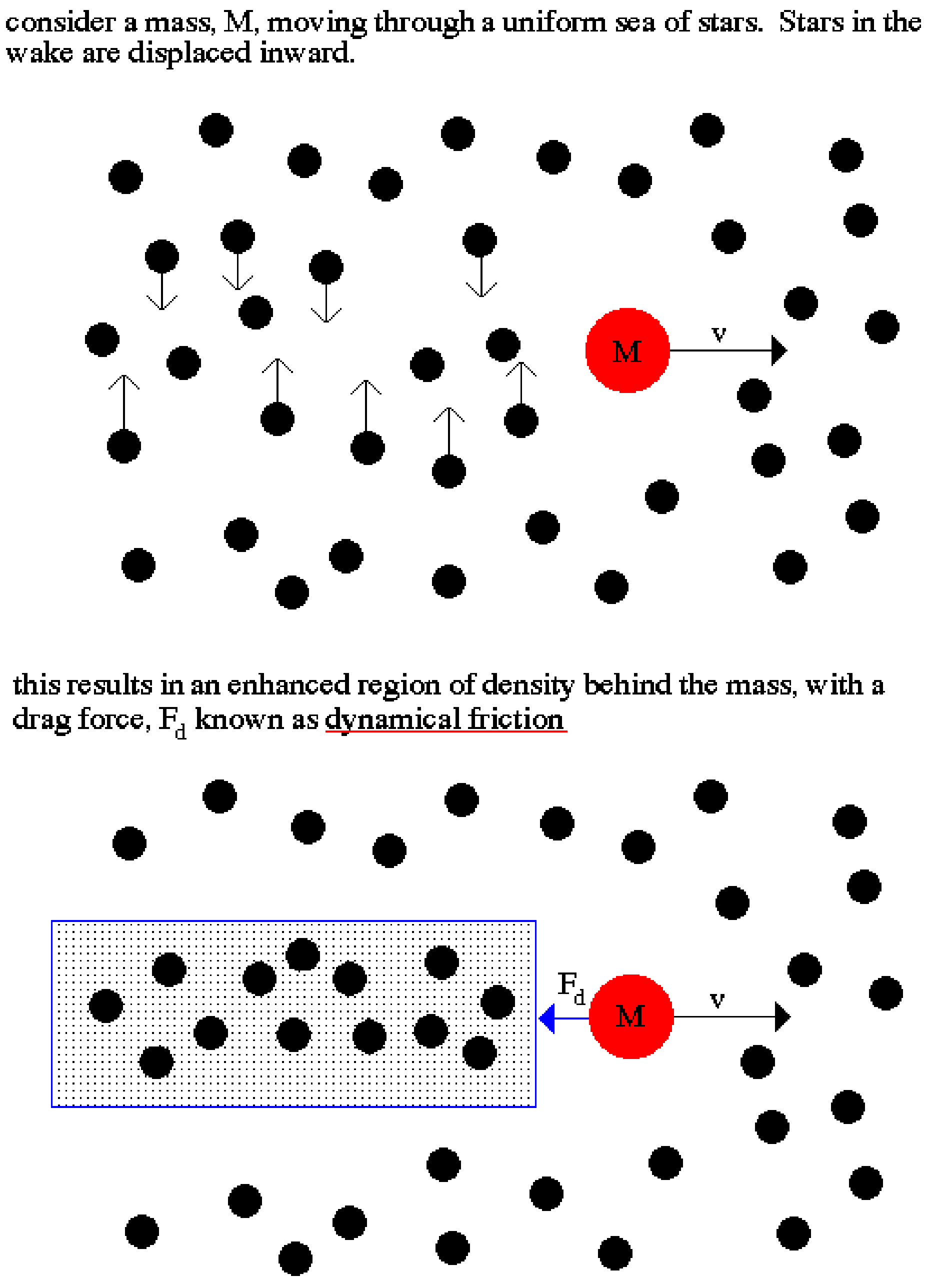
Benson 2010

Halo and galaxy mergers



- Haloes merge
- Diffuse outer parts stripped rapidly
- Typically hot gas of satellite stripped: strangulation (see Font et al 2008 for another model)
- Denser cores survive longer
- Galaxies merge through dynamical friction
- Merger could be accompanied by star bursts
- Galaxy morphology may change

How does dynamical friction work?



consider a mass, M, moving through a uniform sea of stars. Stars in the wake are displaced inward.

this results in an enhanced region of density behind the mass, with a drag force, F_d known as dynamical friction

Deceleration of orbiting galaxy results in decay of orbital radius and movement to centre of halo, as satellite loses energy

Image: James Schombert

Calculation of merger timescale

Derivation of dynamical friction timescale due to motion of heavy mass through
Distribution of lighter masses original applied to globular clusters by Chandrasekar

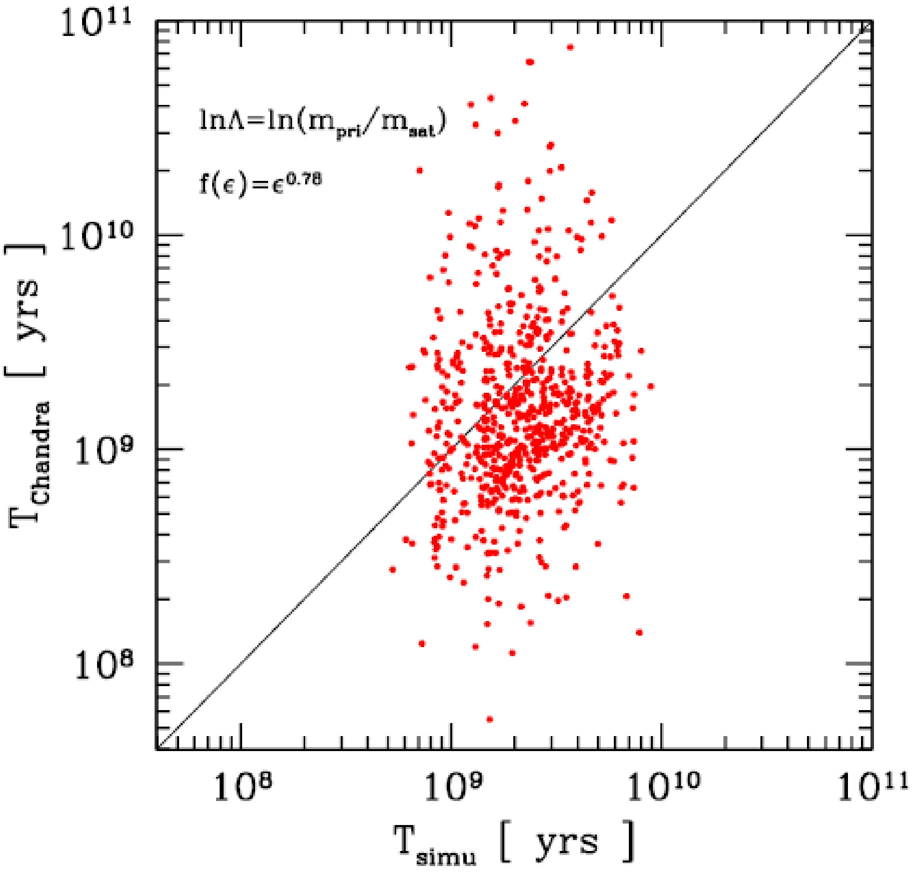
$$T_{\mathrm{df}} = \frac{f(\epsilon)\tau_{\mathrm{dyn}}}{2B(1)\ln\Lambda}\left(\frac{r_c}{R_{\mathrm{v}}}\right)^2\left(\frac{M_{\mathrm{v}}}{m_{\mathrm{v}}}\right) \qquad \tau_{\mathrm{dyn}} = R_{\mathrm{v}}/V_{\mathrm{v}}$$

Coulomb logarithm gives ratio of impact parameters which contribute to dynamical friction

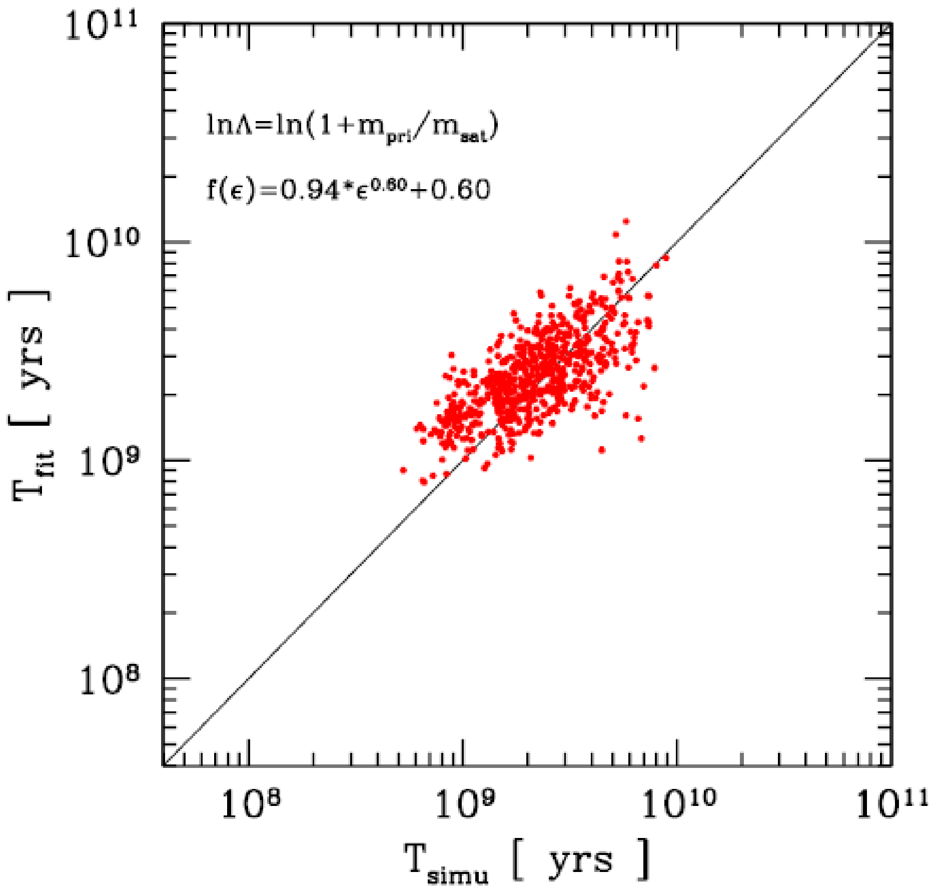
$$\ln\Lambda \approx \ln(r_{\mathrm{v}}V_{\mathrm{v}}^2/\mathrm{G}m_{\mathrm{v}}) \equiv \ln(M_{\mathrm{v}}/m_{\mathrm{v}})$$

Recalibrated using simulations

Jiang et al. 2008



$$T_{\rm df} = \frac{f(\epsilon)\tau_{\rm dyn}}{2B(1)\ln\Lambda}\left(\frac{r_c}{R_{\rm v}}\right)^2\left(\frac{M_{\rm v}}{m_{\rm v}}\right)$$



$$T_{\rm df} = \tau_{\rm dyn}\frac{0.94\epsilon^{0.60}+0.60}{2C}\frac{M_{\rm V}}{m_{\rm V}}\frac{1}{\ln(1+M_{\rm V}/m_{\rm V})}$$

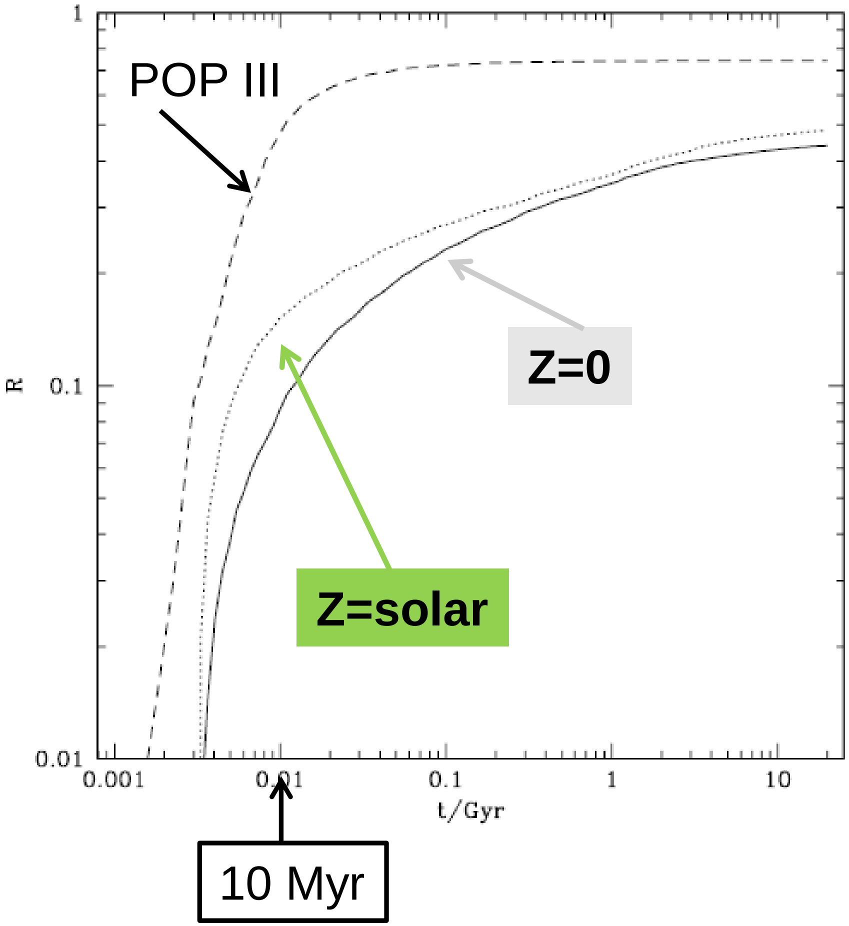
Chemical evolution

- Sne and winds release metals (>He)
- Metals change cooling timescale
- Metals change stellar luminosity
- Metals lead to dust extinction

Mass of stars formed in interval Δt ΔM

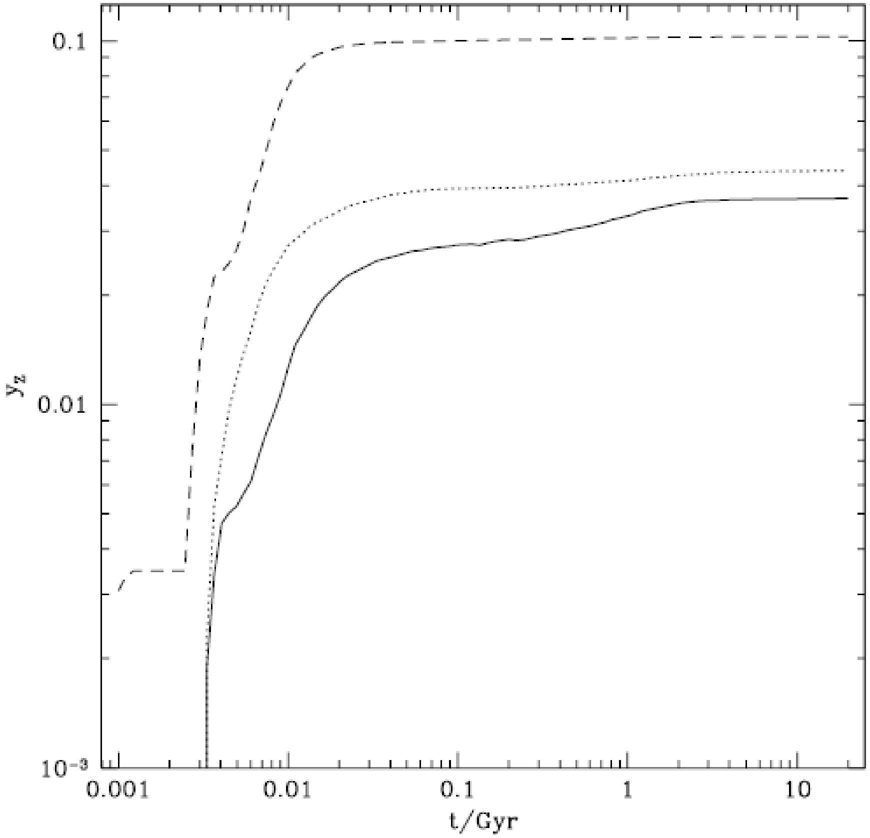
$R\Delta M$

Mass returned to ISM



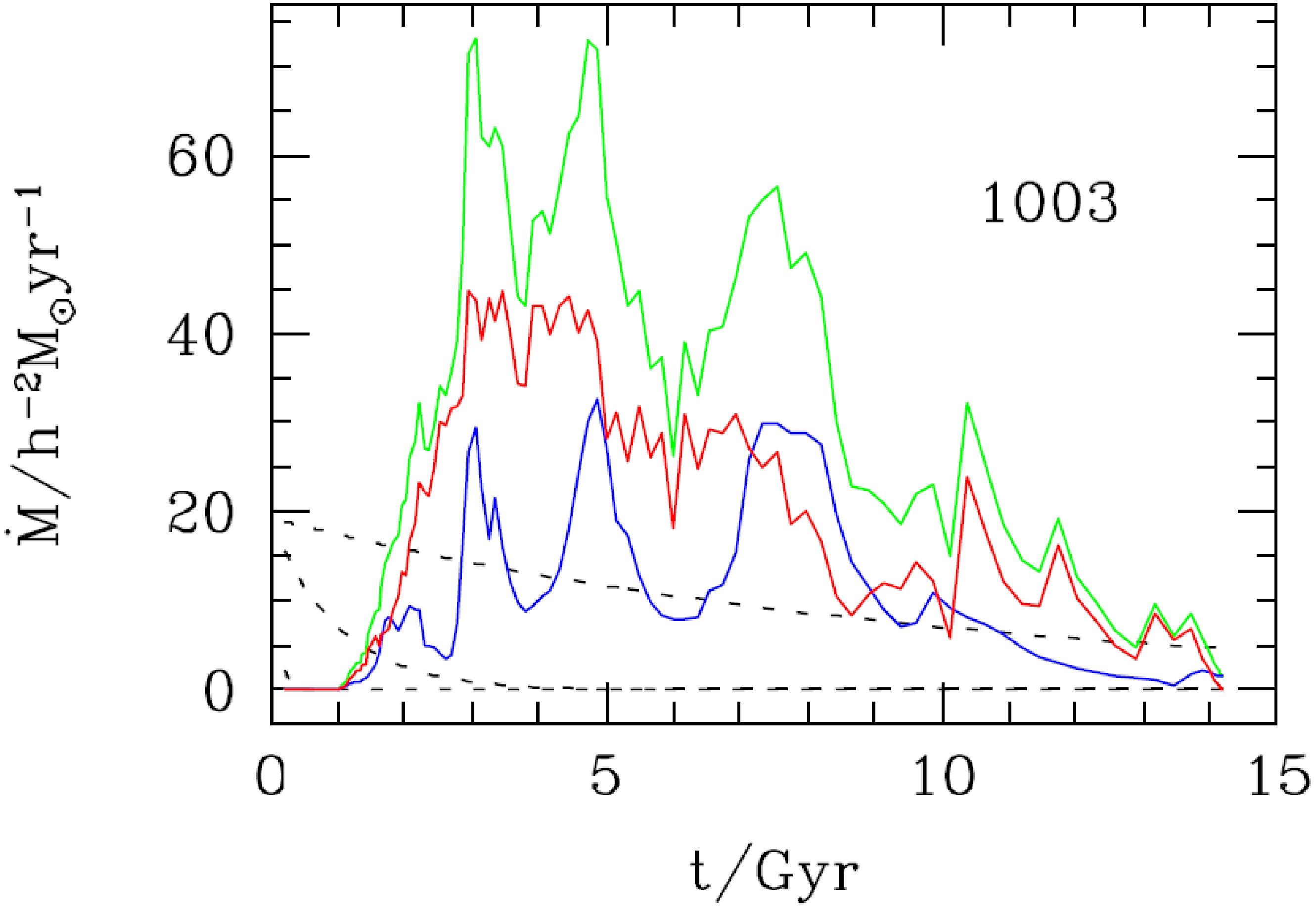
$p\Delta M$

Yield of metals

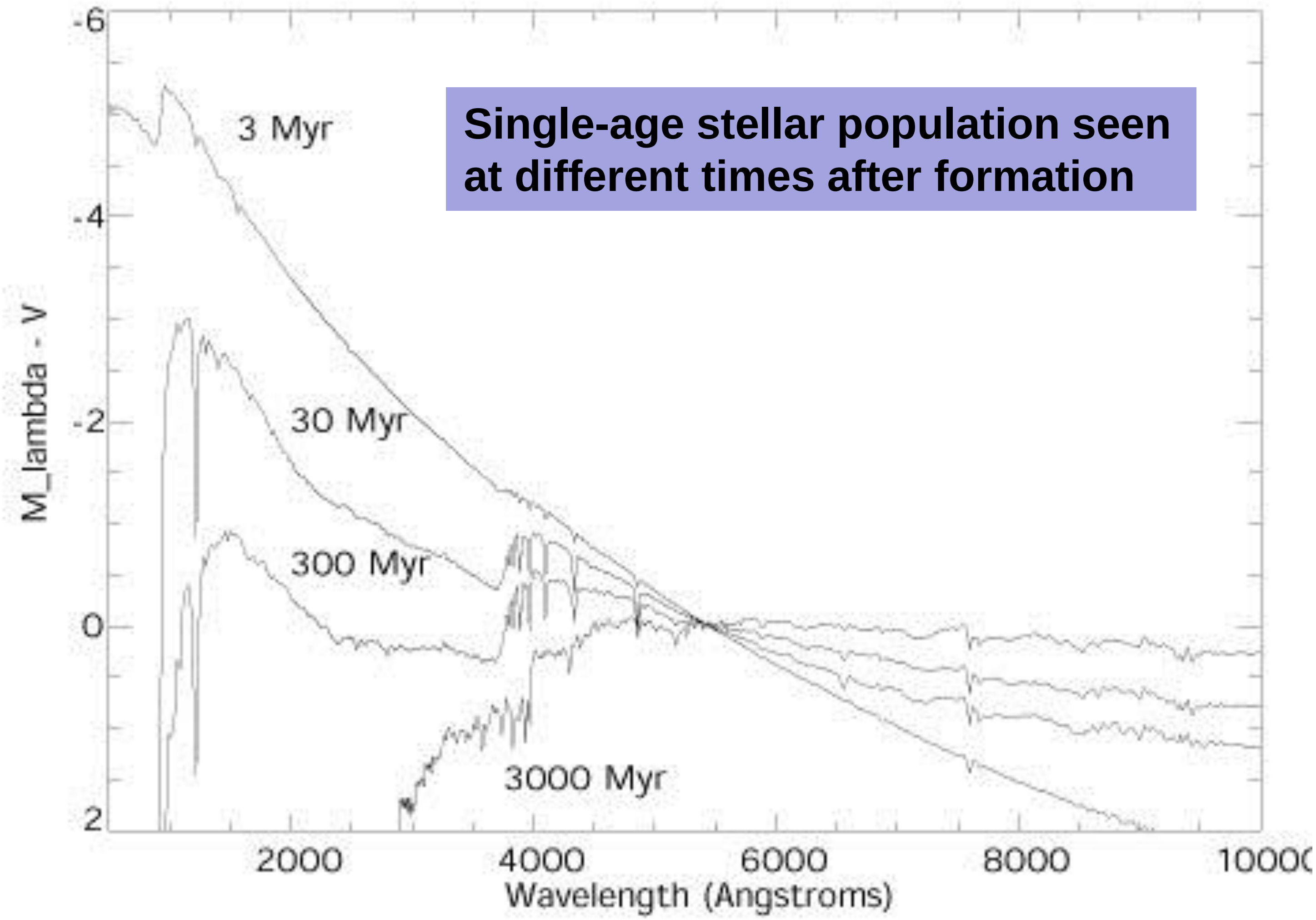


Benson 2010

Star formation history of galaxy

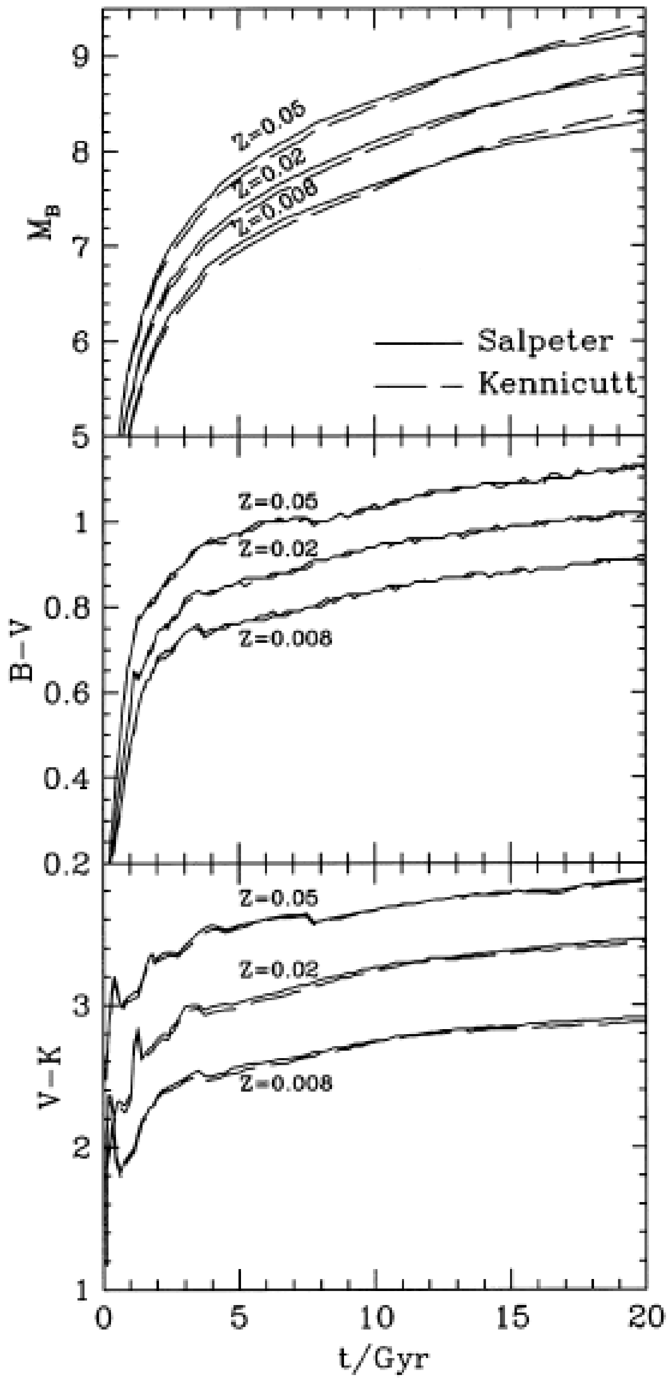


stellar population synthesis



Single-age stellar population seen at different times after formation

Let there be light: stellar population synthesis



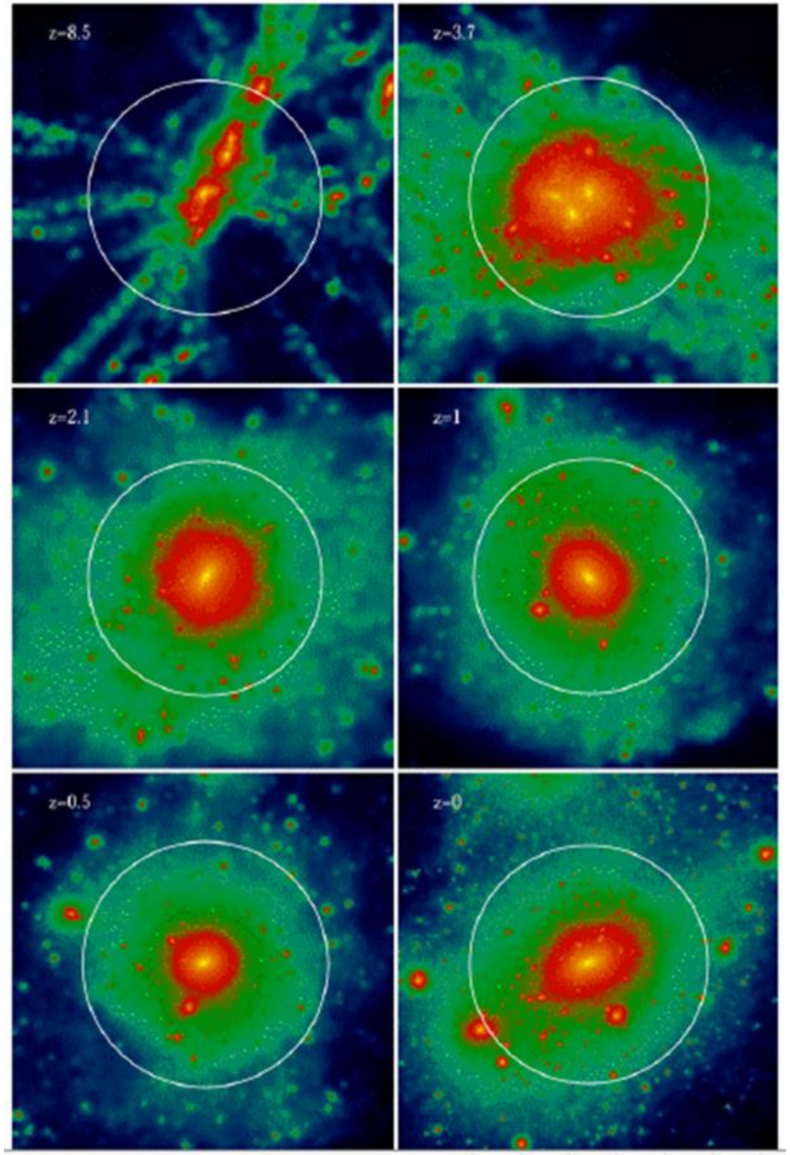
$$L_\lambda(t) = \int_0^t l_\lambda[t-t', Z(t')]\,\psi(t')\,\mathrm{d}t',$$

Luminosity of population of stars, t-t’ after formation

SFR

Cole et al . 2000

Galaxy sizes



- Inhomogeneous gravitational field exerts tidal torque
- Causes DM halo to spin
- Maximum effect at turn-round radius
- Assume gas acquires same angular momentum as DM

Disk galaxy formation

- If gas retains angular momentum as it cools, forms rotationally supported disk
- Collapse in DM halo gives right sizes if angular momentum conserved
- Apply conservation of angular momentum and centrifugal equilibrium

$$j_{\mathrm{D}}^2 = k_{\mathrm{D}}^2 r_{\mathrm{D}}^2 V_{\mathrm{cD}}^2(r_{\mathrm{D}}) = k_{\mathrm{D}}^2 G r_{\mathrm{D}} \left[f_{\mathrm{H}} M_{\mathrm{H0}}(r_{\mathrm{D0}}) + \tfrac{1}{2} k_{\mathrm{h}} M_{\mathrm{D}} + M_B(r_{\mathrm{D}}) \right]$$

- Fall & Efstathiou (1980), Mo et al, Mao et al 1998, Cole et al. 2000

Bulge formation

- Secular: strongly self-gravitating disks unstable to formation of a bar which channels gas to centre

$$\epsilon_{\rm m} \equiv \frac{V_{\rm max}}{(GM_{\rm disc}/r_{\rm disc})^{1/2}}$$

Stable disk if $\epsilon_{\rm m} \gtrsim 1.1$

- Mergers: apply virial theorem and conservation of energy (internal and orbital)

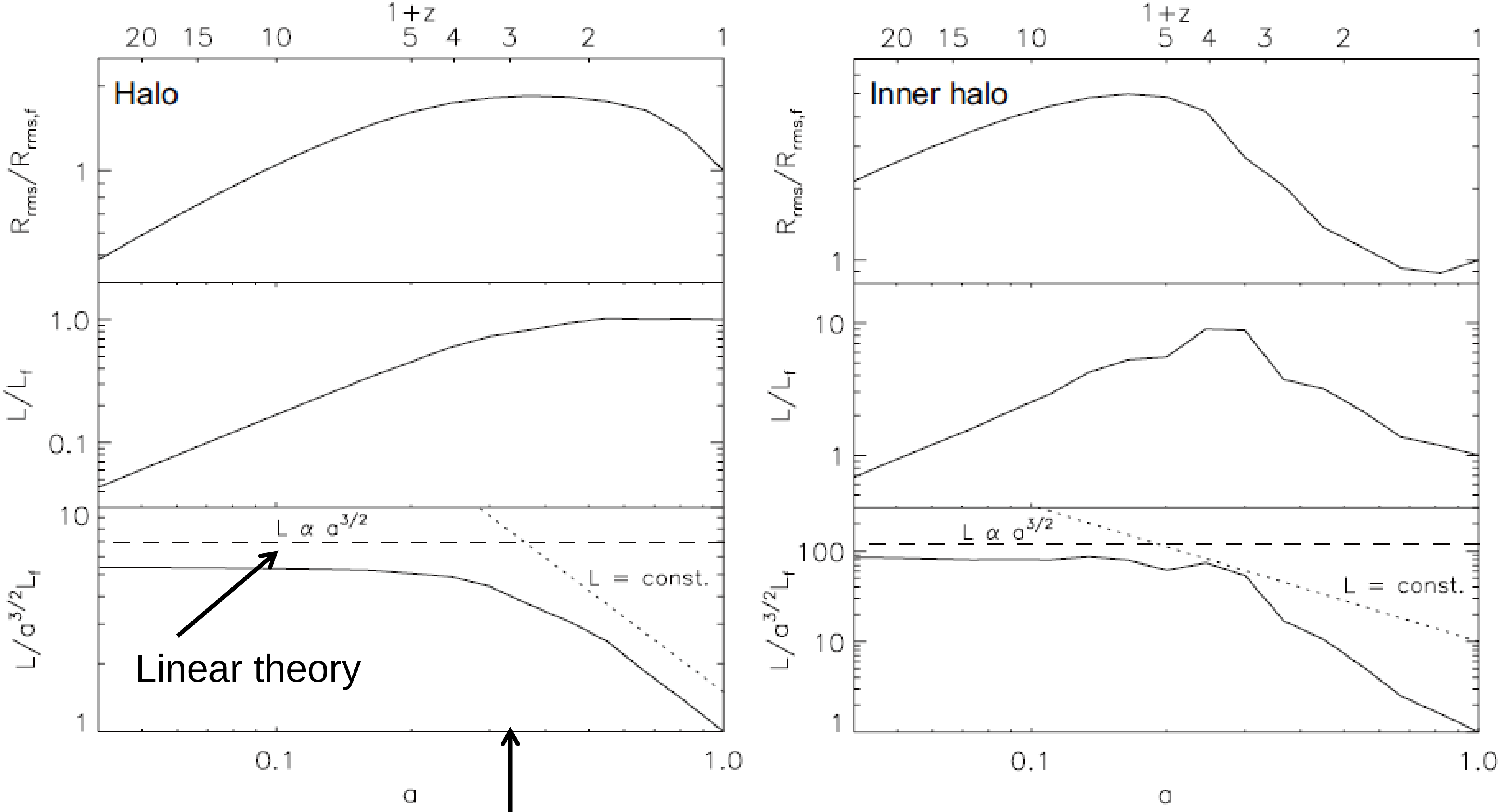
$$E_{\rm int} = -\frac{\bar{c}}{2}\frac{GM^2}{r}$$

$$E_{\rm orbit} = -\frac{f_{\rm orbit}}{2}\frac{GM_1M_2}{r_1+r_2}$$

Solve to find merger remnant size:

$$\frac{(M_1+M_2)^2}{r_{\rm new}} = \frac{M_1^2}{r_1} + \frac{M_2^2}{r_2} + \frac{f_{\rm orbit}}{\bar{c}}\frac{M_1M_2}{r_1+r_2}$$

Evolution of AM inside a DM halo



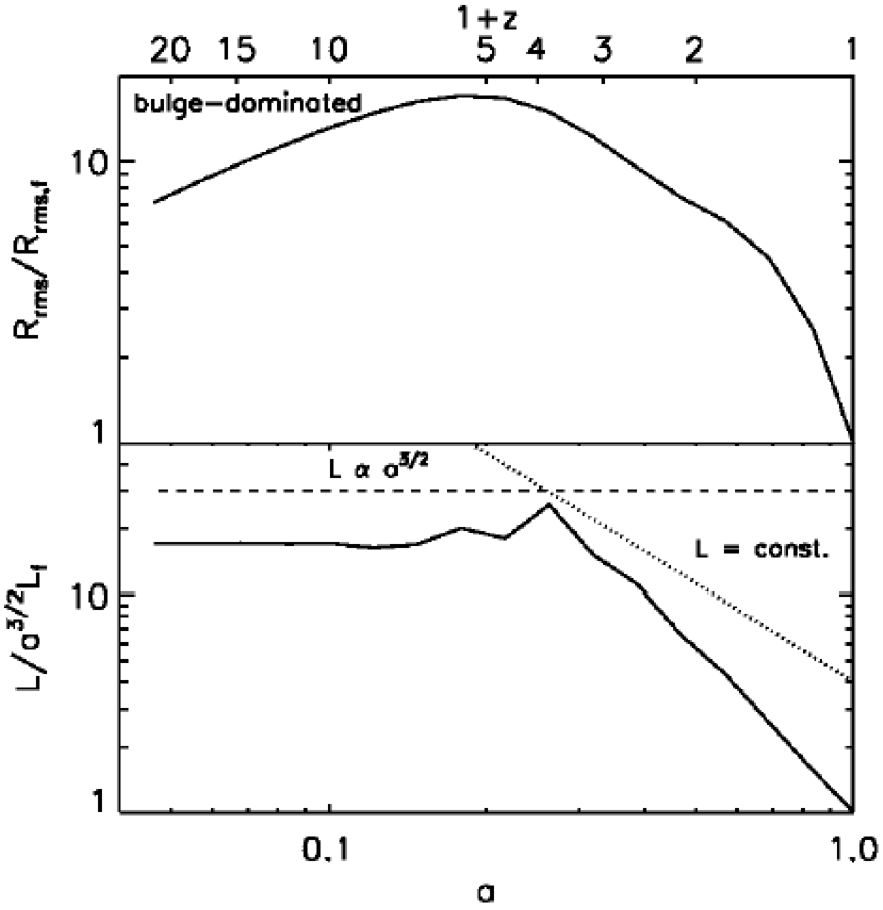
Linear theory

Turn-around radius

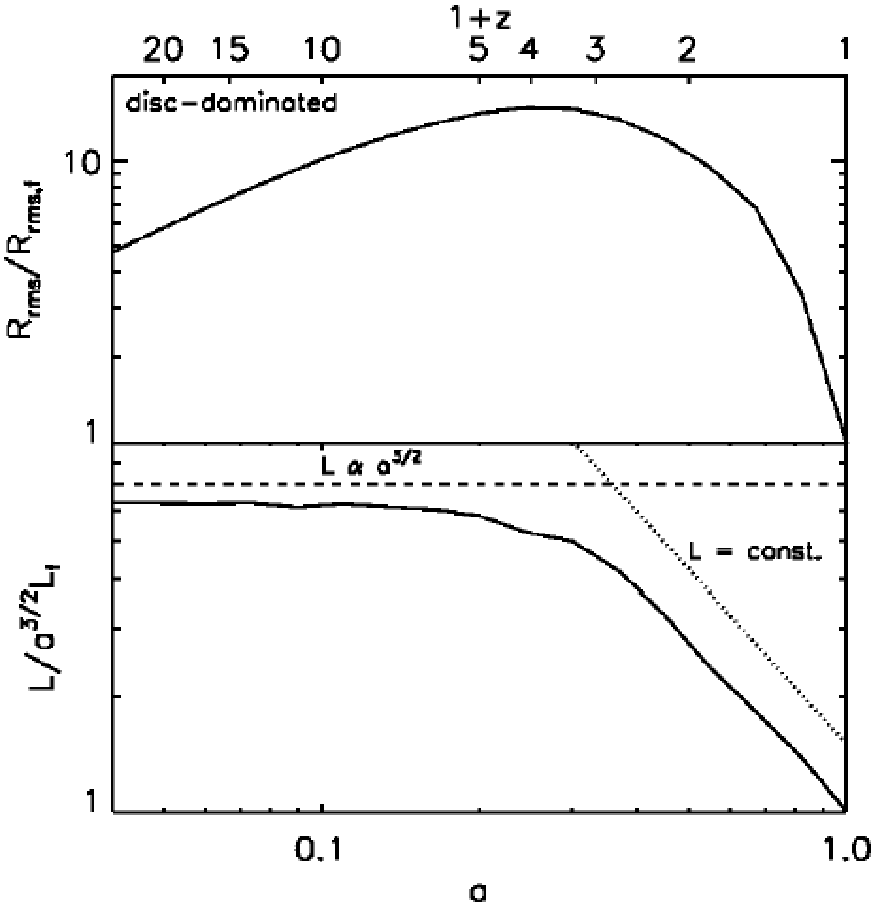
Zavala et al. 2008

DM plus baryons

Weak feedback

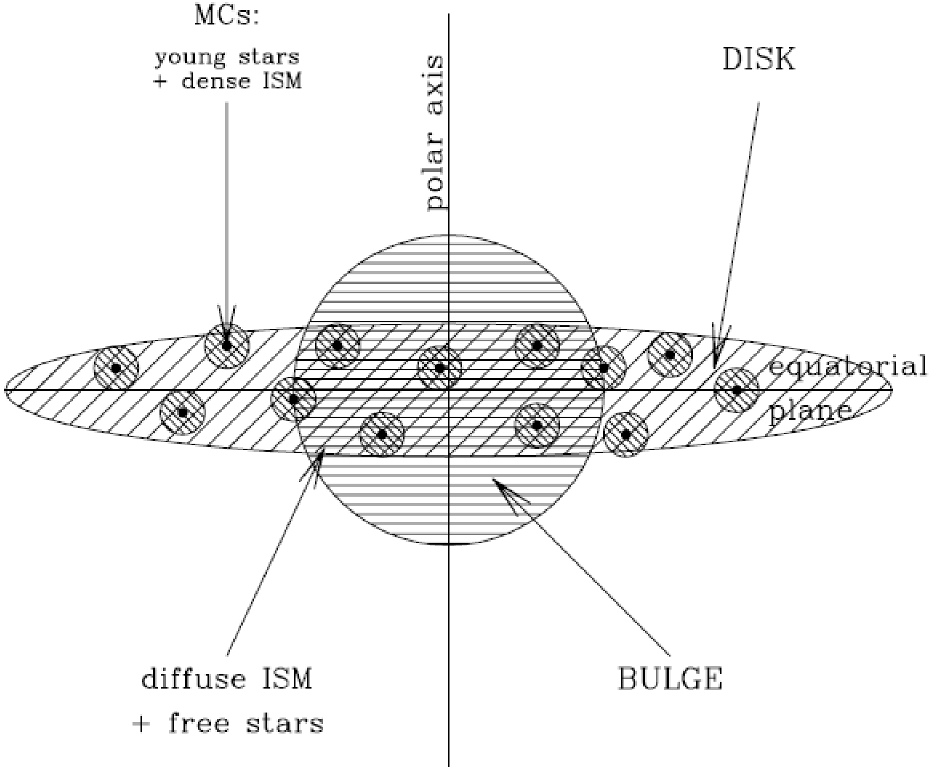


Strong feedback



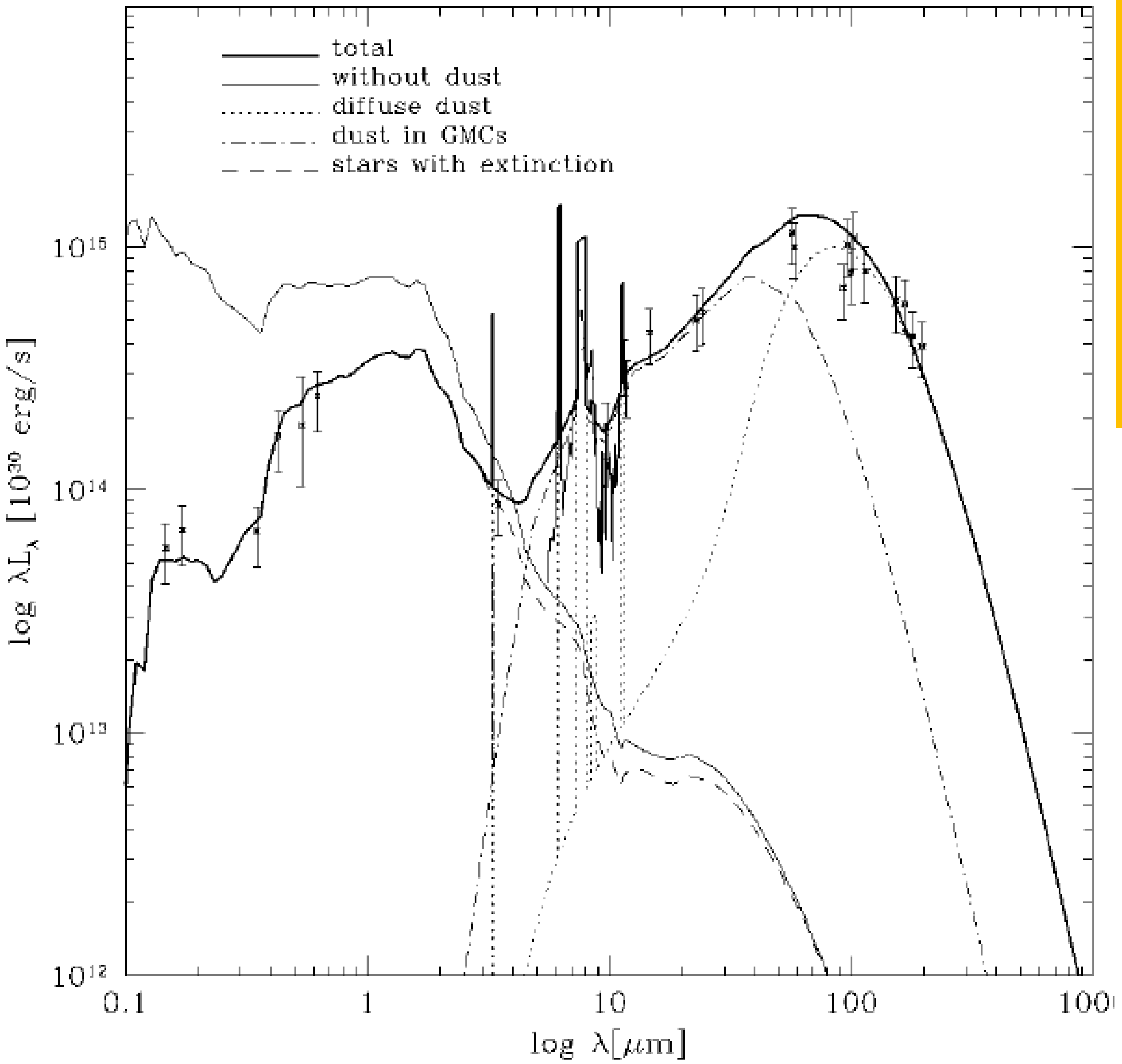
Zavala et al. 2008

Dust extinction



- Stars and gas and dust should be mixed together
- However sometimes still see foreground slab models

Silva et al. 1998



Dust extinction and emission

Silva et al. 1998

Summary

- Have covered all of the core ingredients of a galaxy formation model (except for one!)
- Gas cooling
- Star formation
- SNe feedback
- Chemical enrichment
- Galaxy mergers
- Galaxy sizes
- Dust extinction

Next: implementation