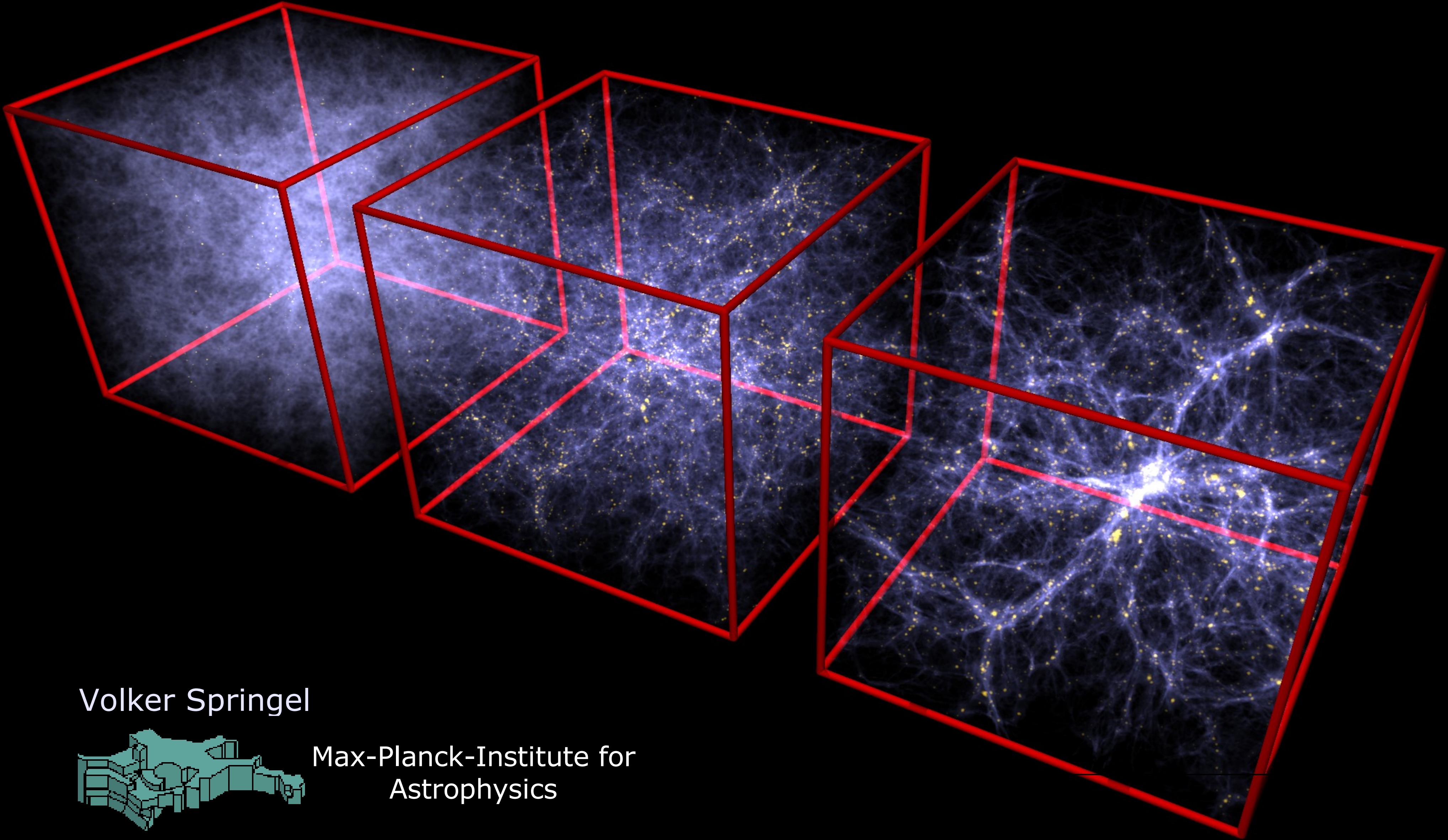
# Summer school on cosmological numerical simulations
## 3rd week – THURSDAY

Helmholtz School of Astrophysics
Potsdam, July/August 2006



Volker Springel

Max-Planck-Institute for
Astrophysics

# Galaxy mergers and the role of feedback in galaxy formation

***THURSDAY-Lecture of 3rd week***

Volker Springel

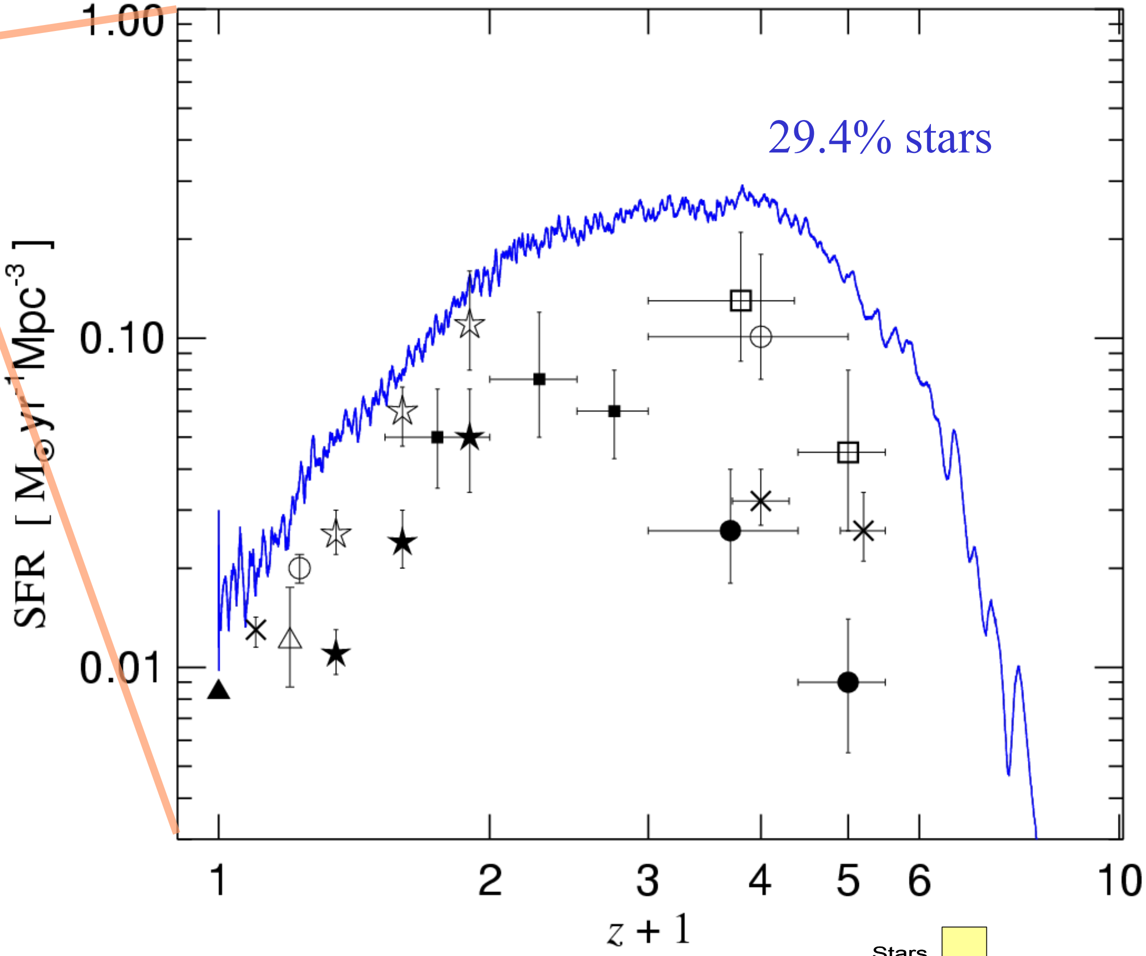
- The importance of feedback
- Compound galaxies and galaxy mergers
- Black hole growth in merging galaxies
- AGN in clusters of galaxies and results from semi-analytic models

# Motivation for feedback

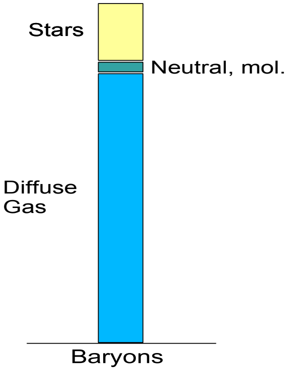
# Simulations with no or week feedback tend to overpredict the cosmic star formation history substantially

KEY AREAS WHERE FEEDBACK IS ESSENTIAL

Feedback can cure the **overcooling problem** and regulate star formation



**But: K-band results suggest values for $\Omega_*/\Omega_b$ below 10% !**



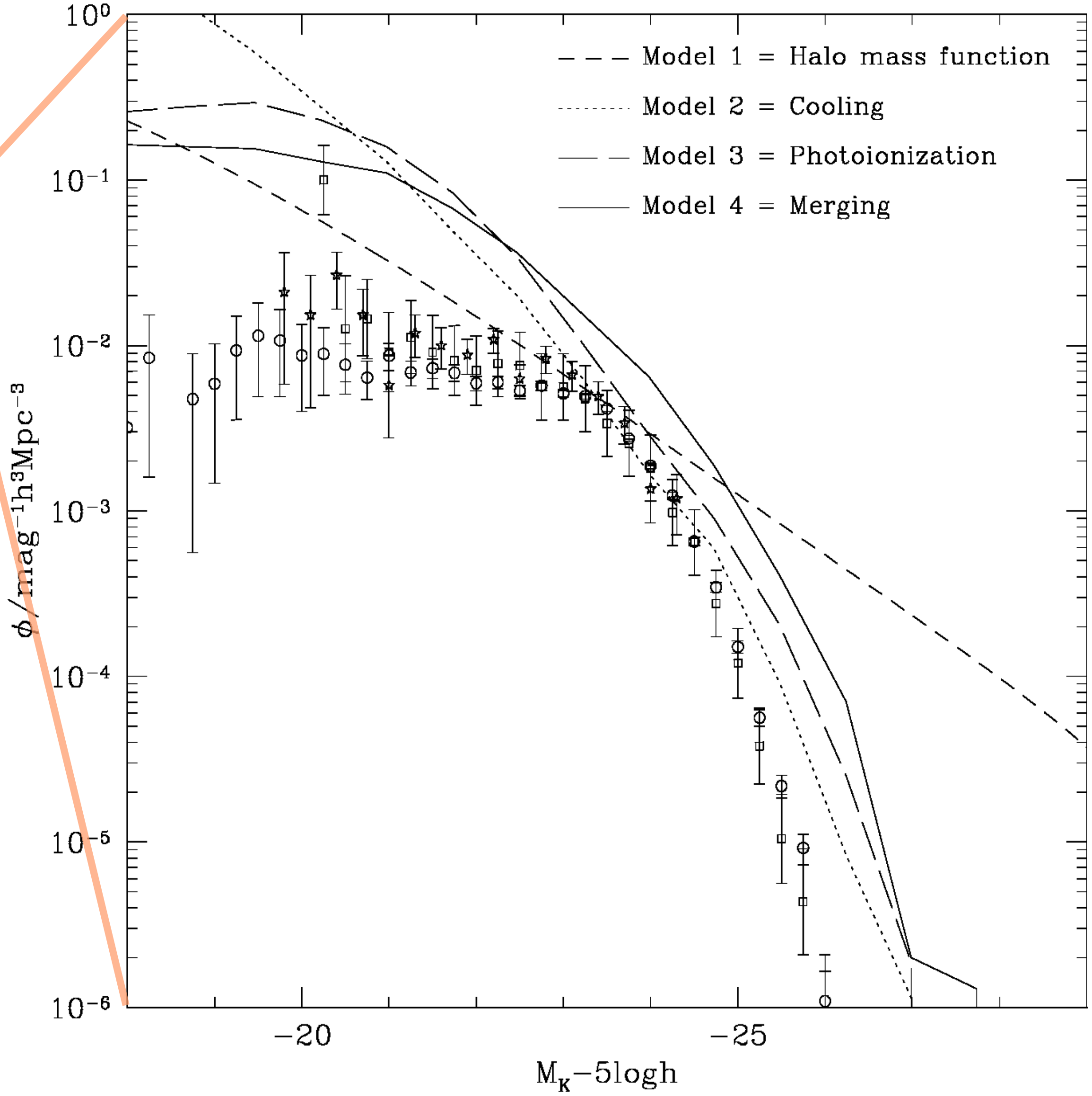
# The shapes of the CDM halo mass function and the K-band luminosity function are very different

KEY AREAS WHERE FEEDBACK IS ESSENTIAL

Benson et al. (2003)

Feedback can cure the **overcooling problem** and regulate star formation

Feedback is needed to **shape the luminosity function** of galaxies



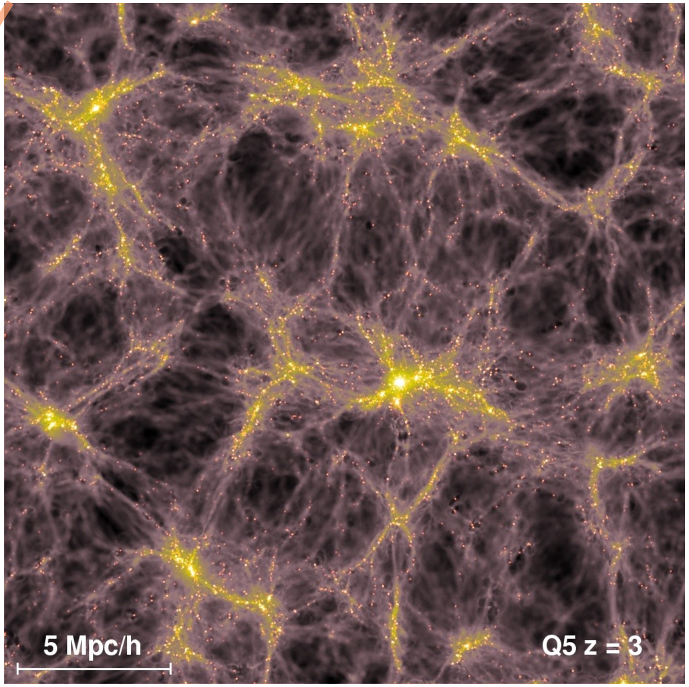
# Feedback appears required to polute low density gas in hierarchical models of galaxy formation in CDM universes

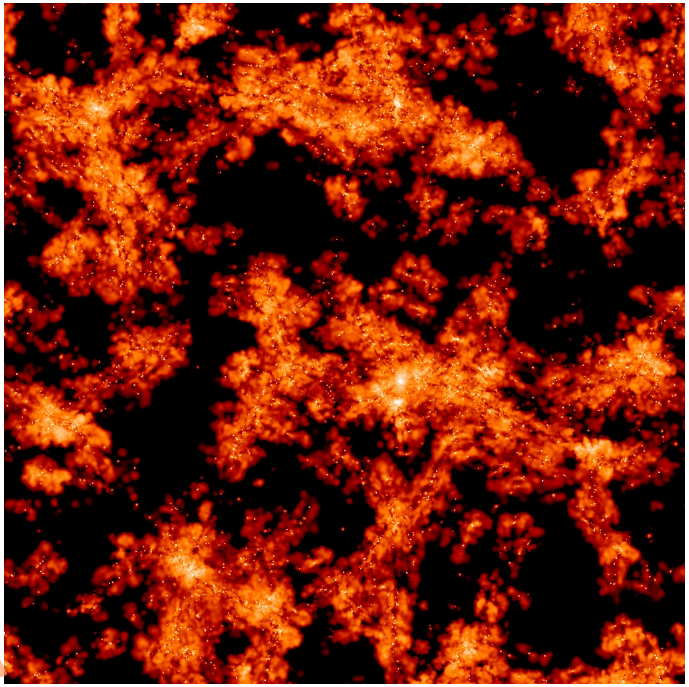
KEY AREAS WHERE FEEDBACK IS ESSENTIAL

Feedback can cure the **overcooling problem** and regulate star formation

Feedback is needed to **shape the luminosity function** of galaxies

Feedback is required to explain **intergalactic metals**





# Feedback appears required in hierarchical modes of galaxy formation in CDM universes

## KEY AREAS WHERE FEEDBACK IS ESSENTIAL

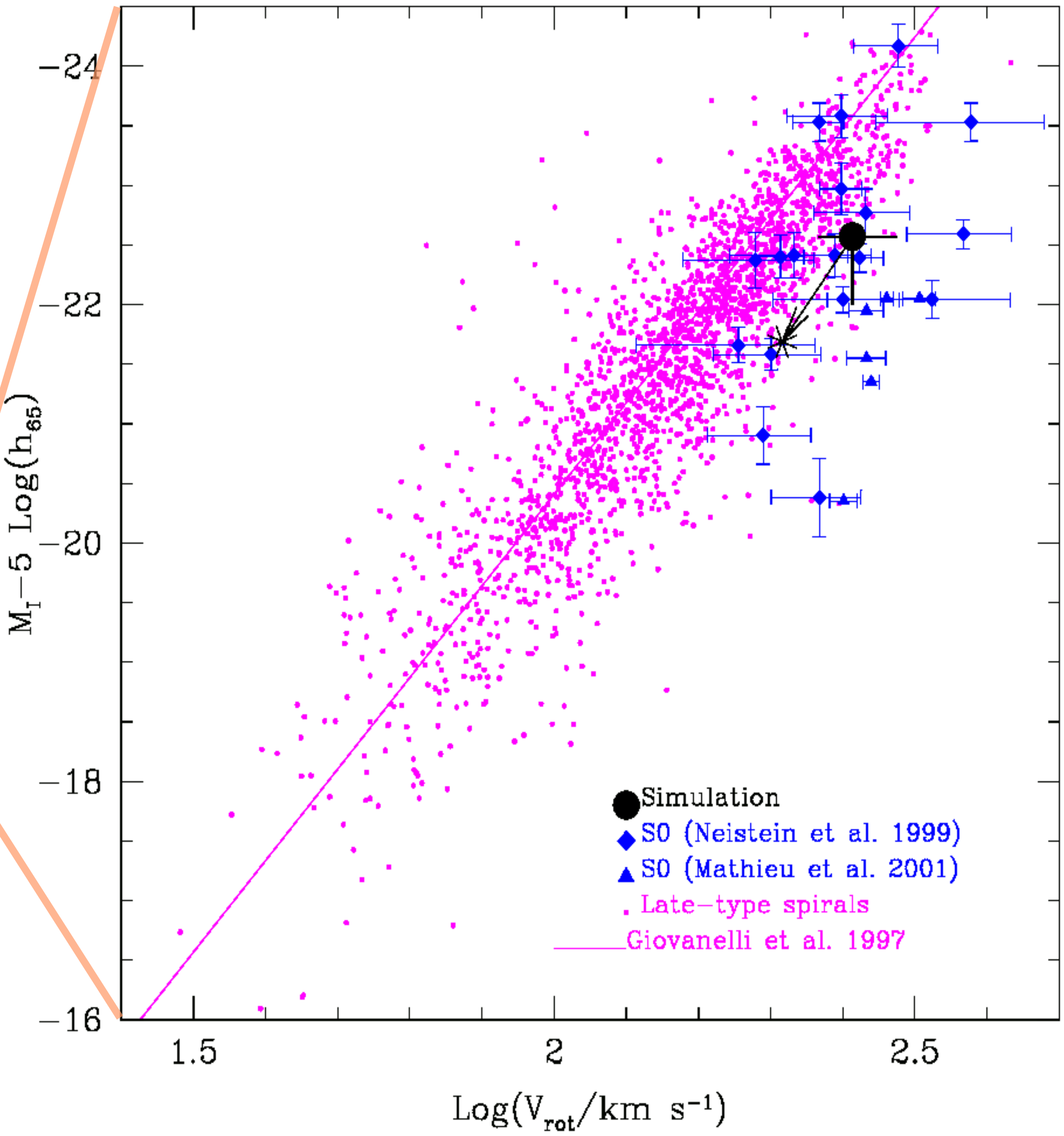
Feedback can cure the **overcooling problem** and regulate star formation

Feedback is needed to **shape the luminosity function** of galaxies

Feedback is required to explain **intergalactic metals**

Feedback may solve the **angular momentum problem**

Abadi, Navarro, Steinmetz & Eke (2003)



# On group scales, simulated clusters are too luminous in X-rays

## KEY AREAS WHERE FEEDBACK IS ESSENTIAL

Feedback can cure the **overcooling problem** and regulate star formation

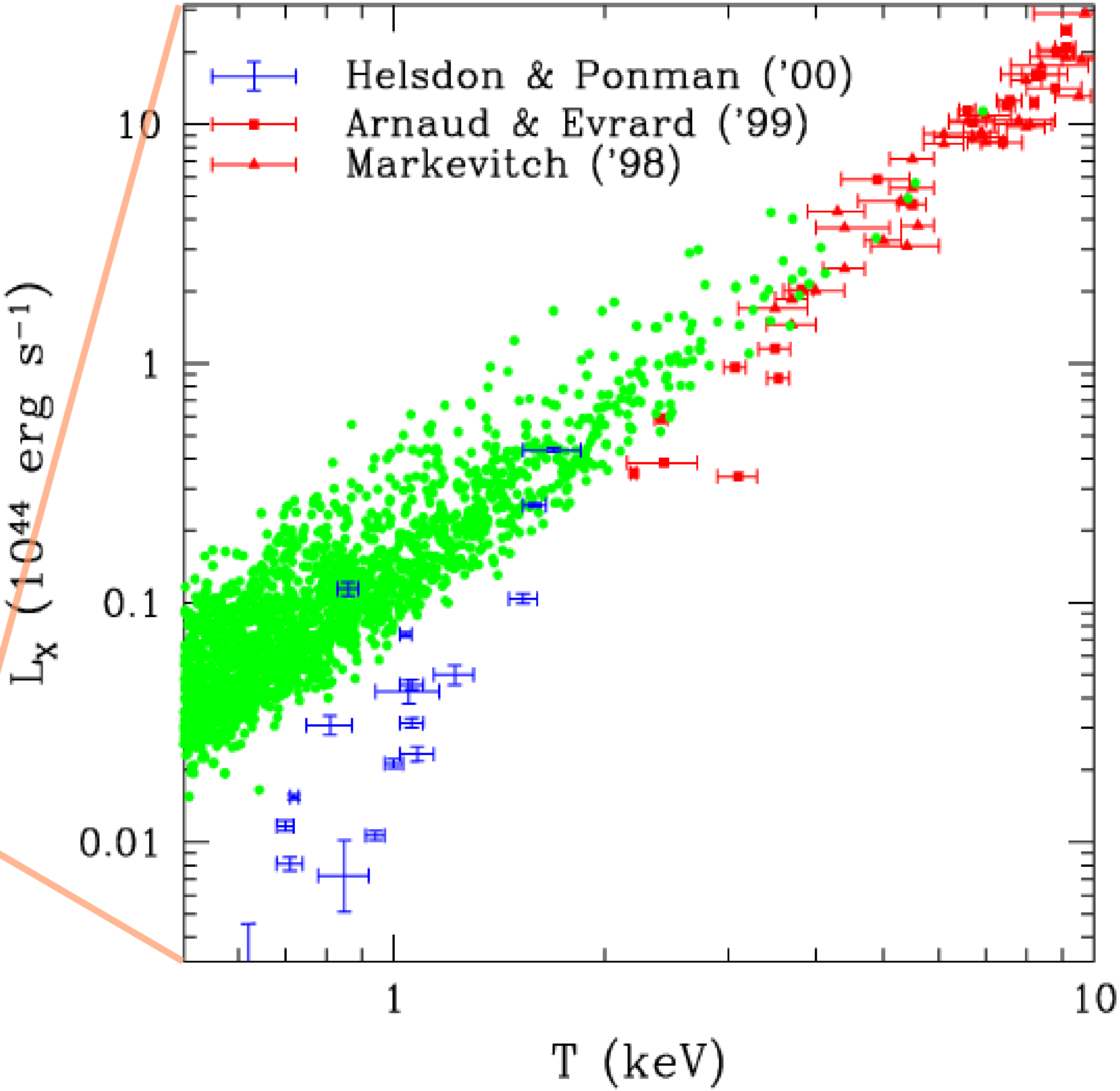
Feedback is needed to **shape the luminosity function** of galaxies

Feedback is required to explain **intergalactic metals**

Feedback may solve the **angular momentum problem**

Feedback may explain the **cluster scaling relations**

Borgani et al. (2003)



# Feedback appears required in hierarchical modes of galaxy formation in CDM universes

## KEY AREAS WHERE FEEDBACK IS ESSENTIAL

Feedback can cure the **overcooling problem** and regulate star formation

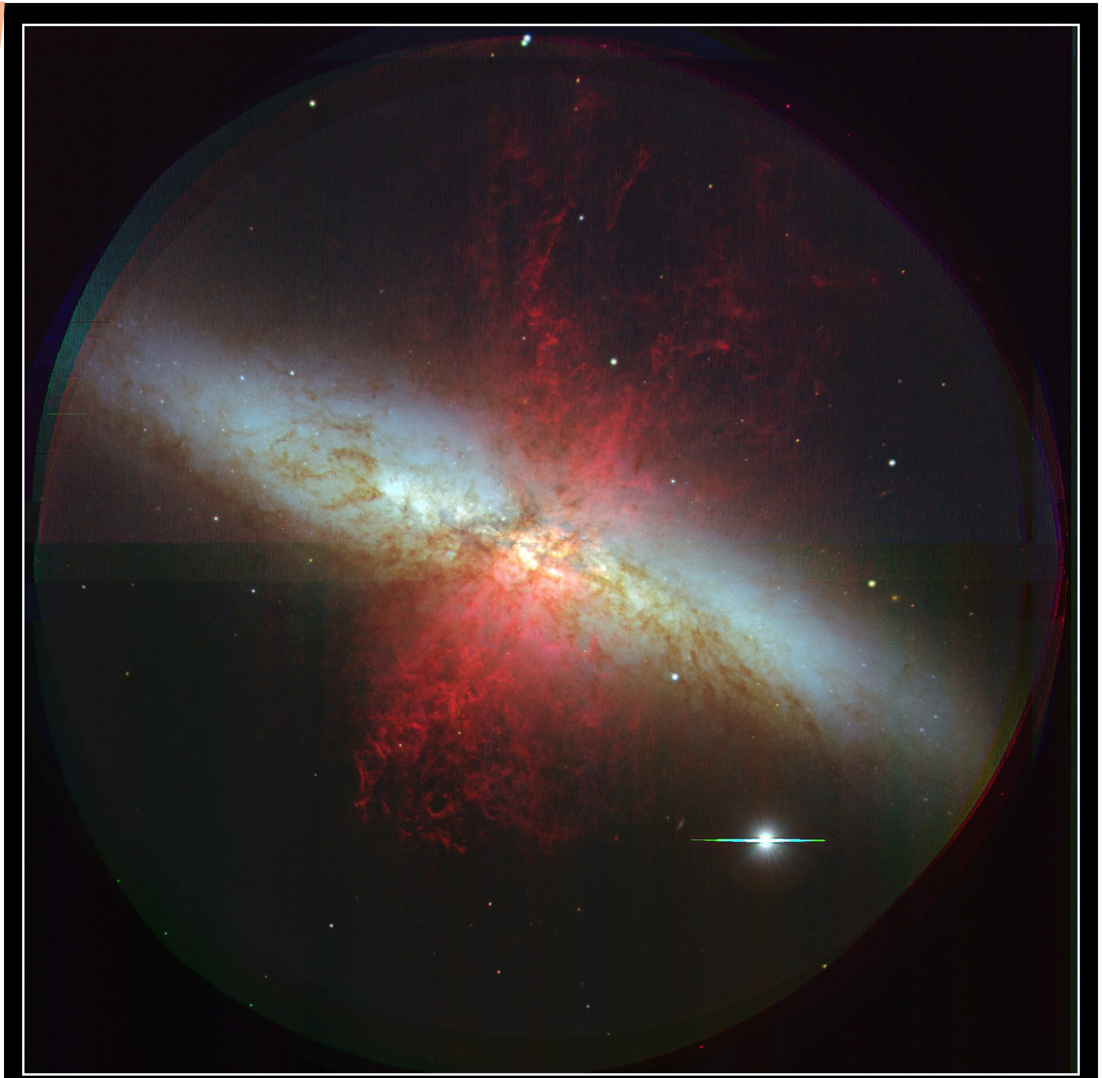
Feedback is needed to **shape the luminosity function** of galaxies

Feedback is required to explain **intergalactic metals**

Feedback may solve the **angular momentum problem**

Feedback may explain the **entropy floor** in the **intraclustermedium**

**Feedback is oberved !**



**M 82 (NGC 3034)**

FOCAS (B, V, Hα )

Subaru Telescope, National Astronomical Observatory of Japan

March 24, 2000

# A subresolution modelling for supernova feedback

# Modeling true multi-phase ISM in cosmological volumes is currently not feasible

## THE COMPUTATIONAL CHALLENGE

Giant molecular clouds

$$\begin{aligned} M_{\rm cl} &\sim 5\times 10^5\ {\rm M}_\odot \\ R_{\rm cl} &\sim 30\ {\rm pc} \\ \overline{n} &\sim 200\ {\rm cm}^{-3} \\ \delta &\sim 10^9 \\ t_{\rm cl} &\sim 4\times 10^6\ {\rm yr} \end{aligned}$$

Currently achievable resolution

$$\text{for } L \geq 50\, h^{-1}{\rm Mpc}:$$

$$\begin{aligned} M_{\rm sph} &\sim 10^7\ {\rm M}_\odot \\ \epsilon &\sim 1\ {\rm kpc} \\ \delta &\sim 10^7 \end{aligned}$$

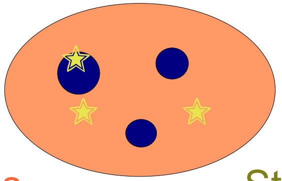
huge dynamic range + difficult/unclear physics !

→ *Need to develop effective subgrid-models that are motivated by physical models of the ISM*

# A multi-phase model for cosmological simulations

## MODEL EQUATIONS

Subresolution phases
of the ISM:



Yepes, Kates, Khokhlov & Klypin (1997)
Hultman & Pharasyn (1999)

<u>Star formation:</u>

supernova mass fraction

$$\frac{\mathrm{d}\rho_\star}{\mathrm{d}t} = (1-\beta)\frac{\rho_c}{t_\star}$$

star formation timescale

<u>Cloud evaporation:</u>

$$\left.\frac{\mathrm{d}\rho_h}{\mathrm{d}t}\right|_{\mathrm{evap}} = A\beta\frac{\rho_c}{t_\star}$$

cloud evaporation paramater

<u>Growth of clouds:</u>

$$\left.\frac{\mathrm{d}\rho_c}{\mathrm{d}t}\right|_{\mathrm{TI}} = -\left.\frac{\mathrm{d}\rho_h}{\mathrm{d}t}\right|_{\mathrm{TI}} = \frac{\Lambda_{\mathrm{net}}(\rho_h, u_h)}{u_h - u_c}$$

→ radiative losses cool material from the hot phase to the cold clouds

## Thermal energy budget:

supernova `temperature' ~ $10^8$ K

$$\frac{\mathrm{d}}{\mathrm{d}t}(\rho_h u_h + \rho_c u_c) = -\Lambda_{\mathrm{net}}(\rho_h, u_h) + \beta \frac{\rho_c}{t_\star} u_{\mathrm{SN}} - (1-\beta)\frac{\rho_c}{t_\star} u_c,$$

Total energy

Cooling

Feedback

Loss to stars

cold clouds:

$$\frac{\mathrm{d}}{\mathrm{d}t}(\rho_c u_c) = -\frac{\rho_c}{t_\star} u_c - A\beta \frac{\rho_c}{t_\star} u_c + \frac{(1-f)u_c}{u_h - u_c}\Lambda_{\mathrm{net}}$$

$$f = \begin{cases} 1 & \text{normal cooling} \\ 0 & \text{thermal instability} \end{cases}$$

hot phase:

$$\frac{\mathrm{d}}{\mathrm{d}t}(\rho_h u_h) = \beta \frac{\rho_c}{t_\star}(u_{\mathrm{SN}} + u_c) + A\beta \frac{\rho_c}{t_\star} u_c - \frac{u_h - f u_c}{u_h - u_c}\Lambda_{\mathrm{net}}$$

## Mass transfer budget:

Star formation

cold clouds:

$$\frac{\mathrm{d}\rho_c}{\mathrm{d}t} = -\frac{\rho_c}{t_\star} - A\beta \frac{\rho_c}{t_\star} + \frac{(1-f)}{u_h - u_c}\Lambda_{\mathrm{net}}$$

Evaporation

Cloud Growth

hot phase:

$$\frac{\mathrm{d}\rho_h}{\mathrm{d}t} = \beta \frac{\rho_c}{t_\star} + A\beta \frac{\rho_c}{t_\star} - \frac{(1-f)}{u_h - u_c}\Lambda_{\mathrm{net}}$$

Supernovas

## Temperature evolution:

hot phase:

$$\rho_h \frac{\mathrm{d}u_h}{\mathrm{d}t} = \left[u_{\mathrm{SN}} - (A+1)(u_h - u_c)\right] \beta \frac{\rho_c}{t_\star} - f\Lambda_{\mathrm{net}}$$

cold clouds: temperature assumed to be constant at ~ $10^4$ K

equilibirum temperature for star formation
+ thermal instability →

$$u_h = \frac{u_{\mathrm{SN}}}{A+1} + u_c$$

## Evaporation efficiency:

$$A(\rho) = A_0 \left(\frac{\rho}{\rho_{\mathrm{th}}}\right)^{-4/5}$$

McKee & Ostriker (1977)

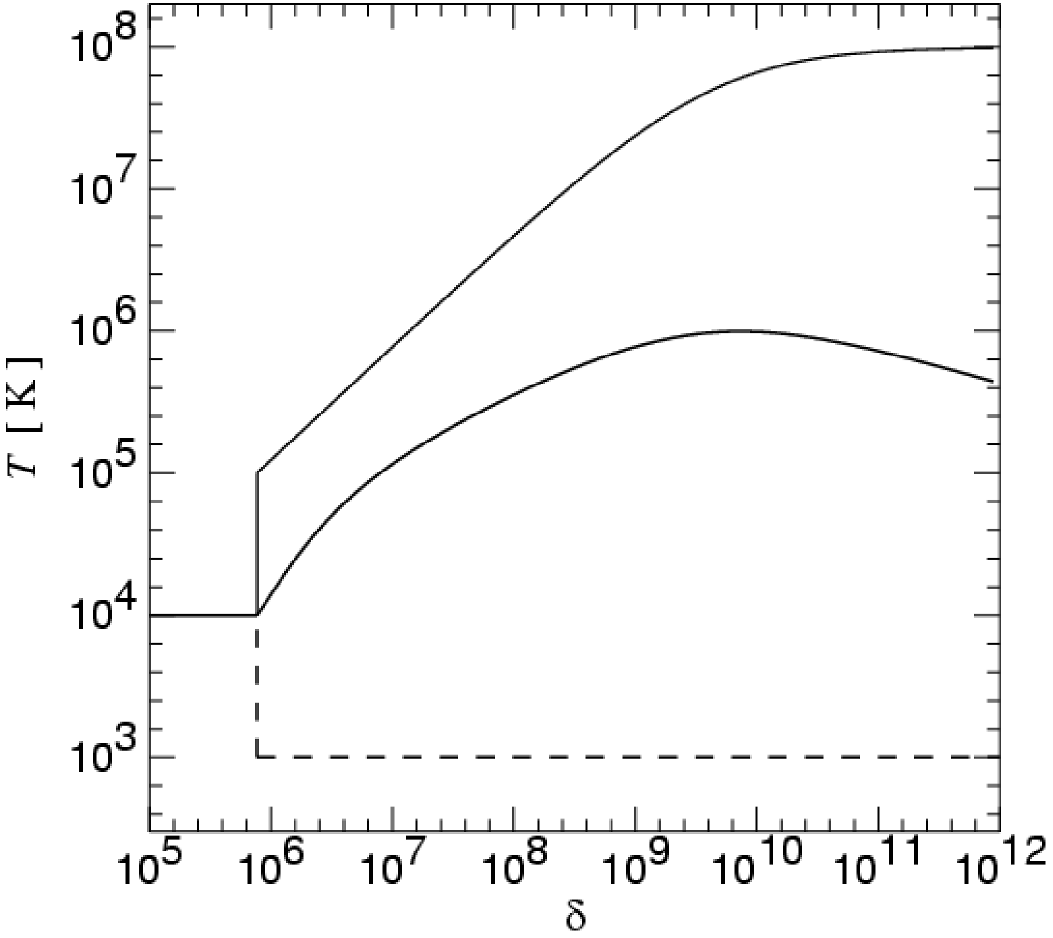
## Star formation timescale:

$$t_\star(\rho) = t_\star^0 \left(\frac{\rho}{\rho_{\mathrm{th}}}\right)^{-1/2}$$

$\rho_{\mathrm{th}}$ and $A_0$ are constraint by
plausible temperature range of the ISM → star formation timescale $t_\star^0$
is adjustable parameter of model

# The ISM is pressurized by star formation in the region of coexistence between a hot medium and embedded cold clouds

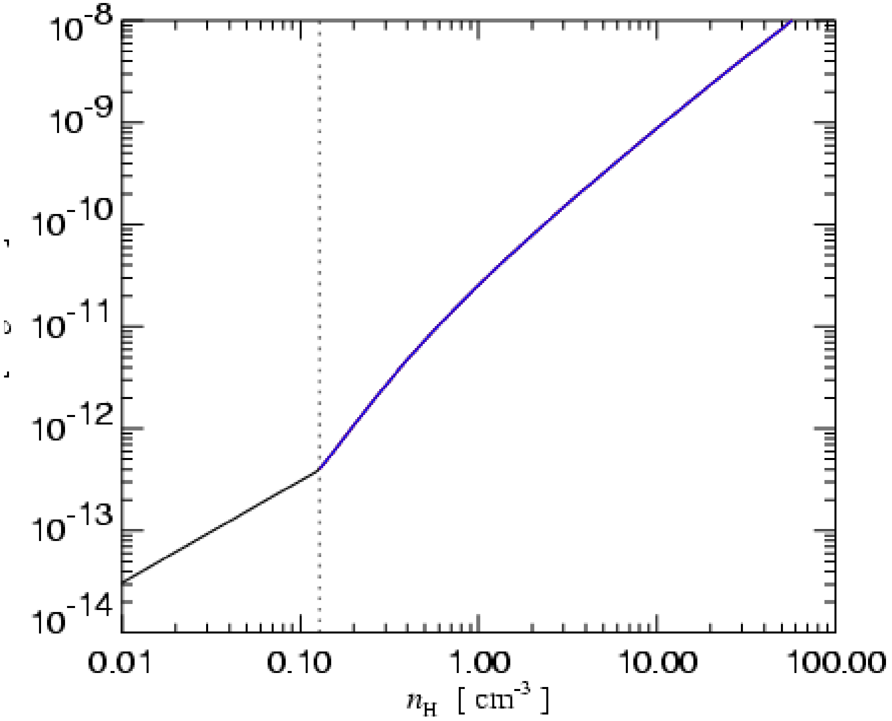
## EFFECTIVE EQUATION OF STATE



**Effective Pressure:**

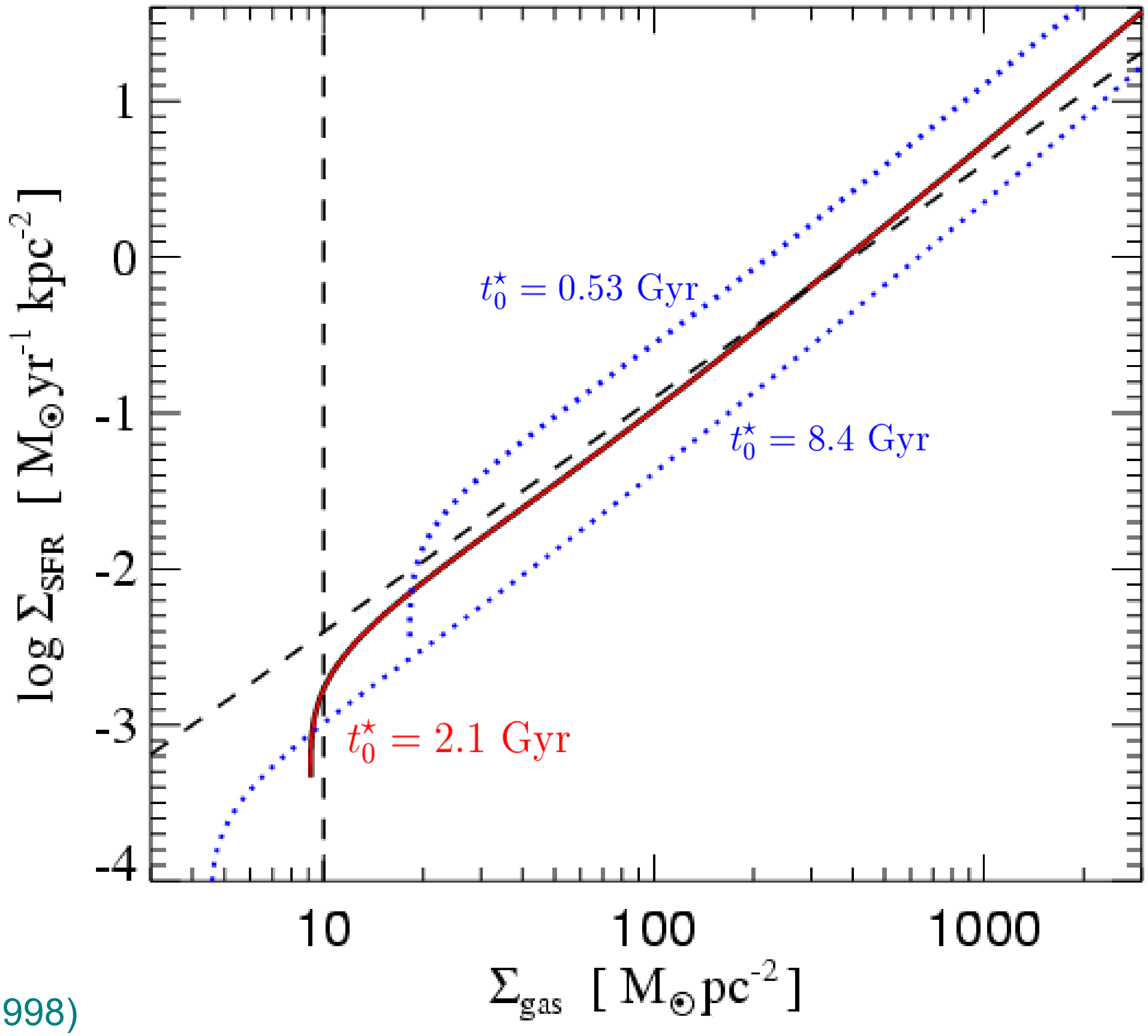
$$P_{\text{eff}} \equiv (\gamma - 1)(\rho_h u_h + \rho_c u_c)$$

$$T_{\text{eff}} \equiv \frac{\mu}{k}\frac{P_{\text{eff}}}{\rho}$$



# Self-gravitating sheets of gas are used to normalize the multi-phase model

## KENNICUTT LAW

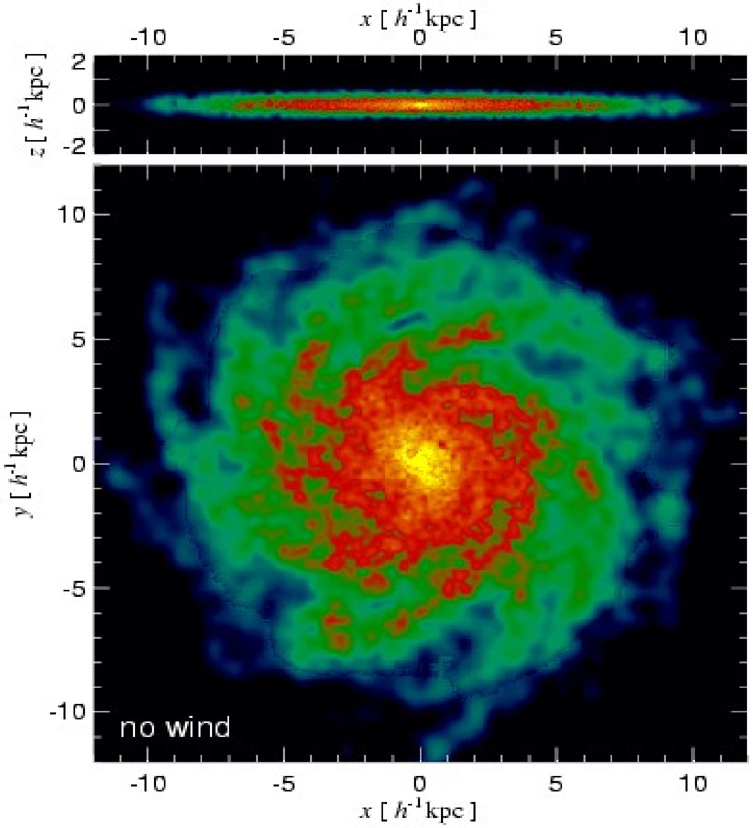


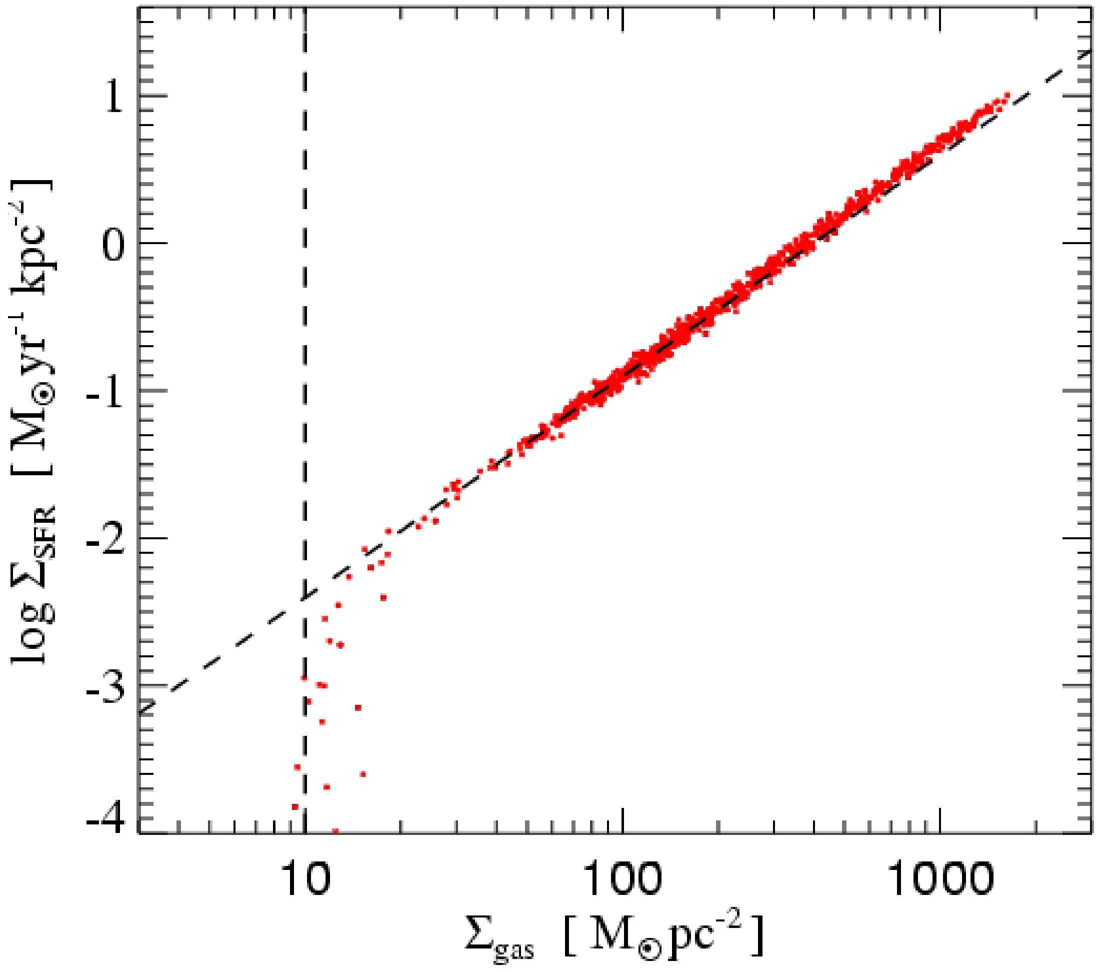
Global "Kennicutt-law" (Kennicutt 1998)

$$\Sigma_{\rm SFR} = (2.5 \pm 0.7) \times 10^{-4} \left( \frac{\Sigma_{\rm gas}}{\rm M_\odot pc^{-2}} \right)^{1.4\pm0.15} \frac{\rm M_\odot}{\rm yr\,kpc^2}$$

# Simulations of isolated disk galaxies are used to check the normalization of the multi-phase model

## MEASURED KENNICUTT LAW

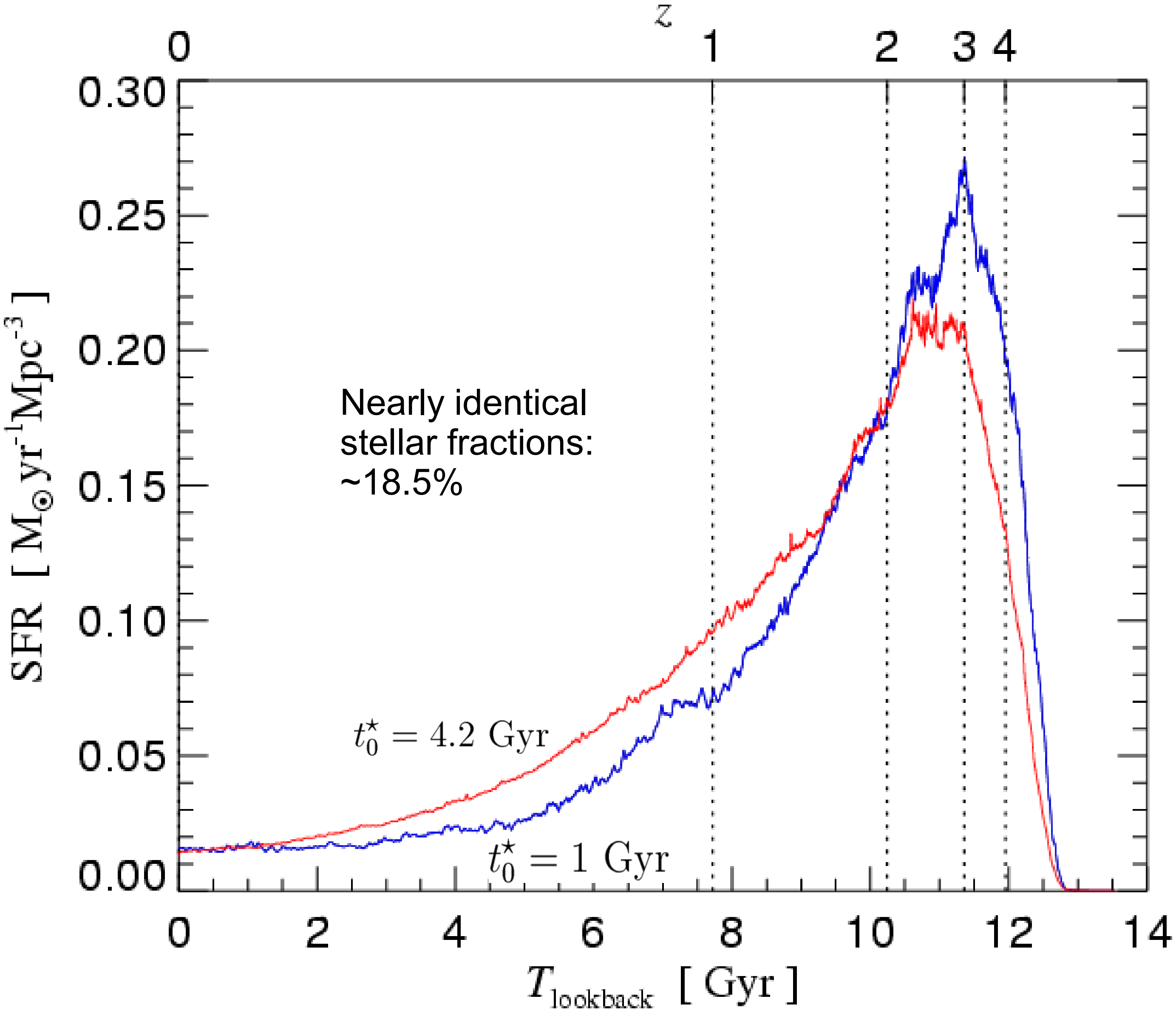




# Galactic winds

# The quiescent model of star formation does hardly affect the total amount of baryons locked up in stars

## COSMIC STAR FORMATION HISTORY



Nearly identical stellar fractions: ~18.5%

# Galactic winds associated with star formation transport metals and provide stong feedback

## A PHENOMENOLOGICAL WIND MODEL

- Observations suggest disk-mass loss rates of order the star-formation rate or higher

(e.g. Martin 1998,1999)

$$\dot{M}_{\rm w} = \eta \dot{M}_{\star}$$

- Parameterize the energy in the wind as a fraction $\chi$ of the supernova energy

$$\frac{1}{2}\dot{M}_{\rm w} v_{\rm w}^2 = \chi \epsilon_{\rm SN} \dot{M}_{\star}$$

$$\text{for}: \quad \eta = 2, \; \chi = 0.25$$

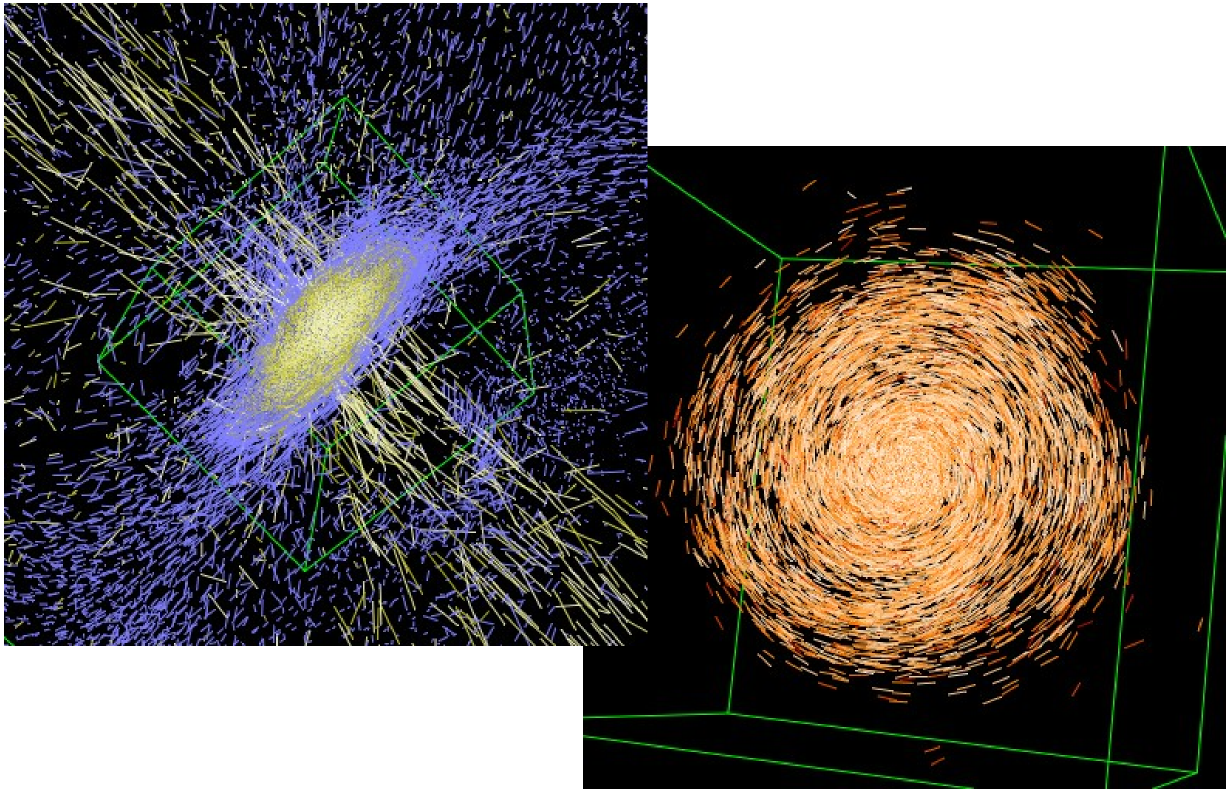
$$v_{\rm w} = 242 \;\; {\rm km\,s^{-1}}$$

# Galactic winds provide strong feedback in halos of small mass, leading to metal enrichment of the halo and the IGM

A WIND IN A **$10^{10}$ $M_{\odot}$/h** HALO

$$
\begin{aligned}
M_{\rm tot} &= 10^{10}\ h^{-1}\,{\rm M}_{\odot} \\
R_{\rm vir} &= 35\ h^{-1}\,{\rm kpc} \\
c &= 15 \\
\lambda &= 0.1 \\
f_{\rm gas} &= 10\% \\
v_{\rm esc} &\simeq 130\ {\rm km\,s^{-1}}
\end{aligned}
$$

$$v_{\rm w} = 242\ {\rm km\,s^{-1}}$$



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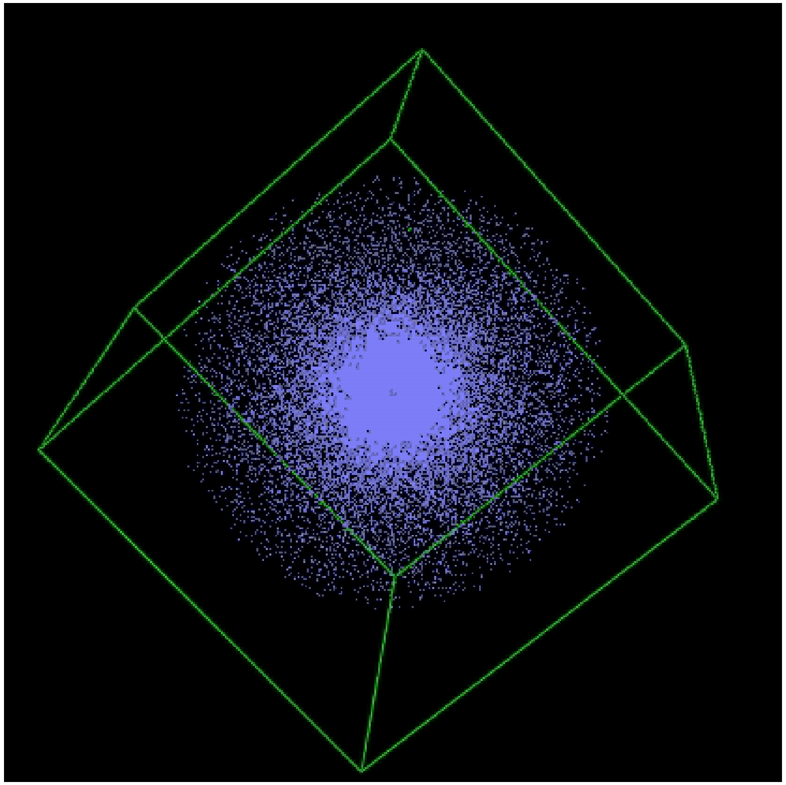
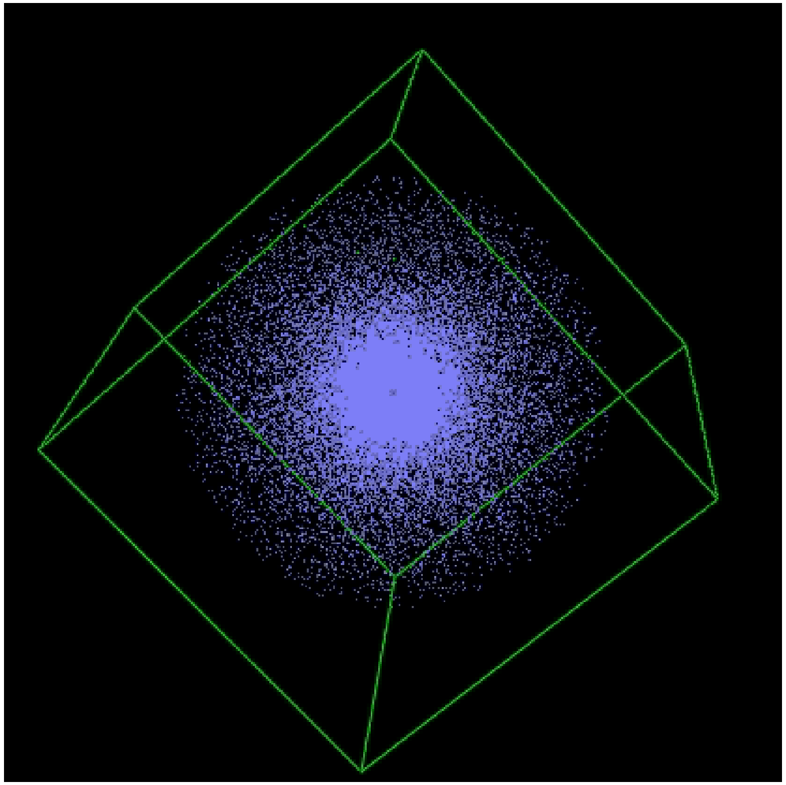


# Galactic winds provide strong feedback in halos of small mass, leading to metal enrichment of the halo and the IGM

A WIND IN A **$10^{11}$ $M_\odot$/h** HALO

$$
\begin{aligned}
M_{\rm tot} &= 10^{11}\ h^{-1}\,{\rm M}_\odot \\
R_{\rm vir} &= 75.3\ h^{-1}\,{\rm kpc} \\
c &= 15 \\
\lambda &= 0.1 \\
f_{\rm gas} &= 10\% \\
v_{\rm esc} &\simeq 280\ {\rm km\,s^{-1}}
\end{aligned}
$$

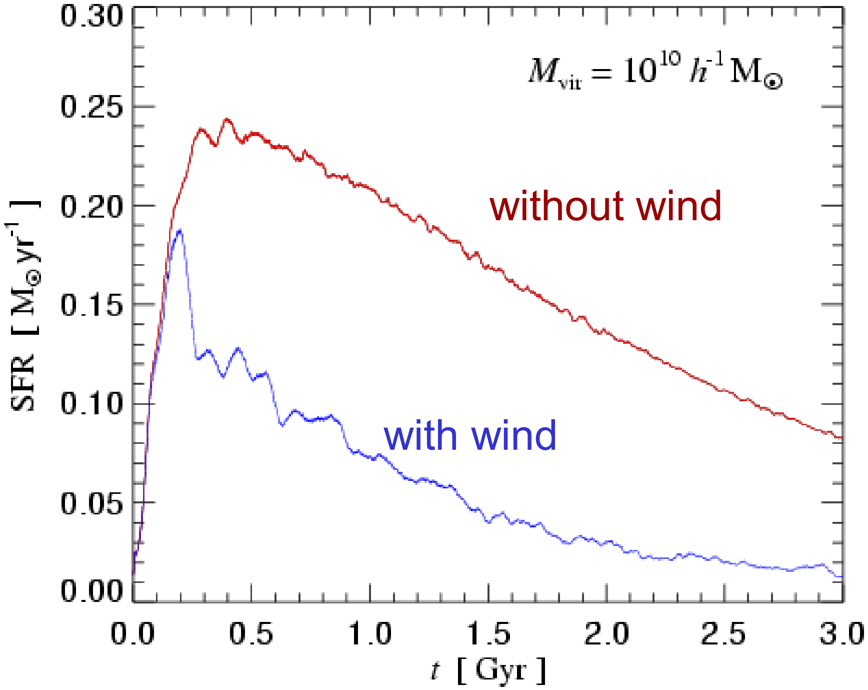
$$v_{\rm w} = 242\ {\rm km\,s^{-1}}$$



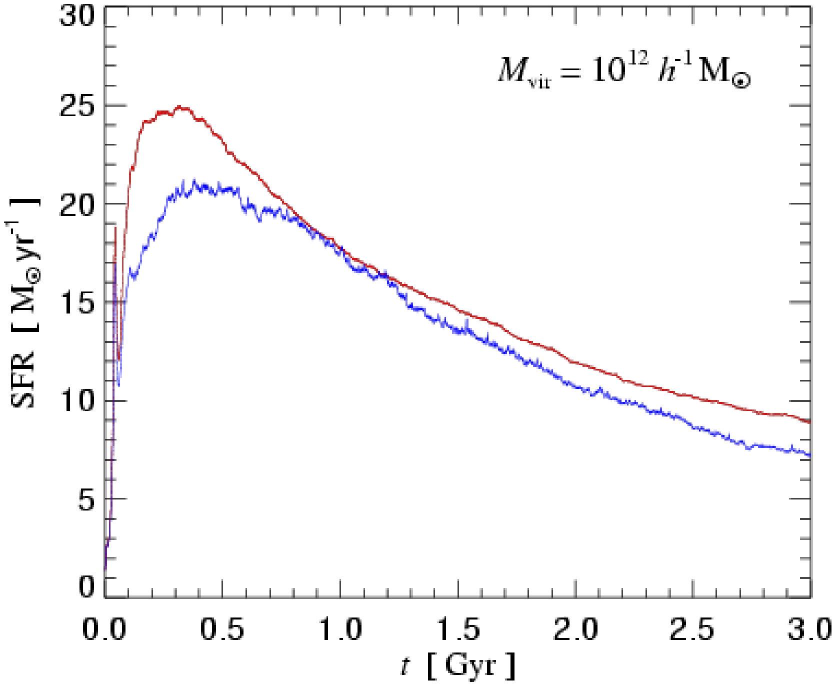
# A galactic wind can strongly reduce the star formation rate in a halo if the wind can (nearly) escape from the halo

## STAR FORMATION RATES IN HALOS

$10^{10}$ M$_\odot$/*h*

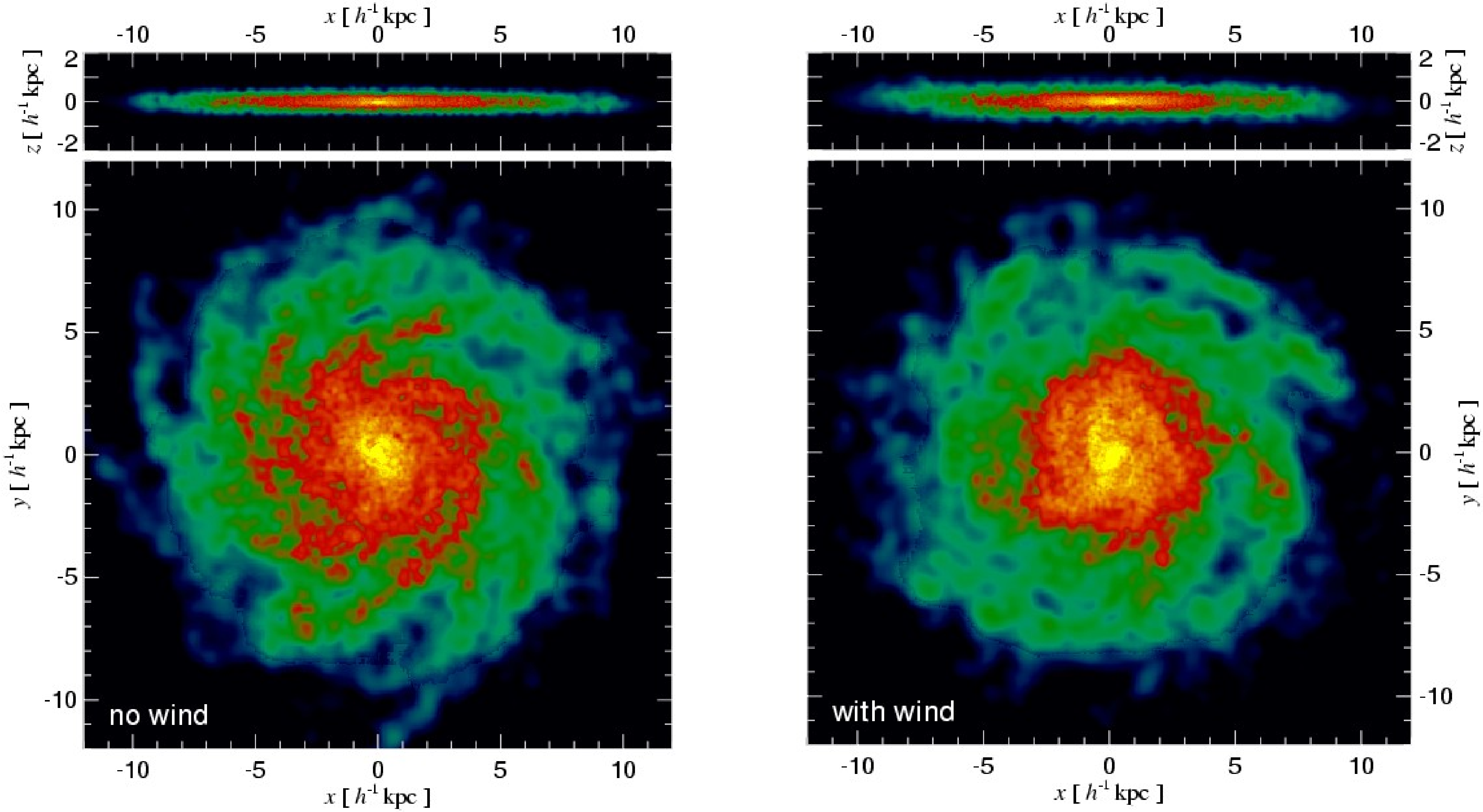


$10^{12}$ M$_\odot$/*h*



# The winds hardly affect the morphology of the forming stellar disks

STELLAR DISK IN A **$10^{12}$ M$_\odot$/*h*** HALO



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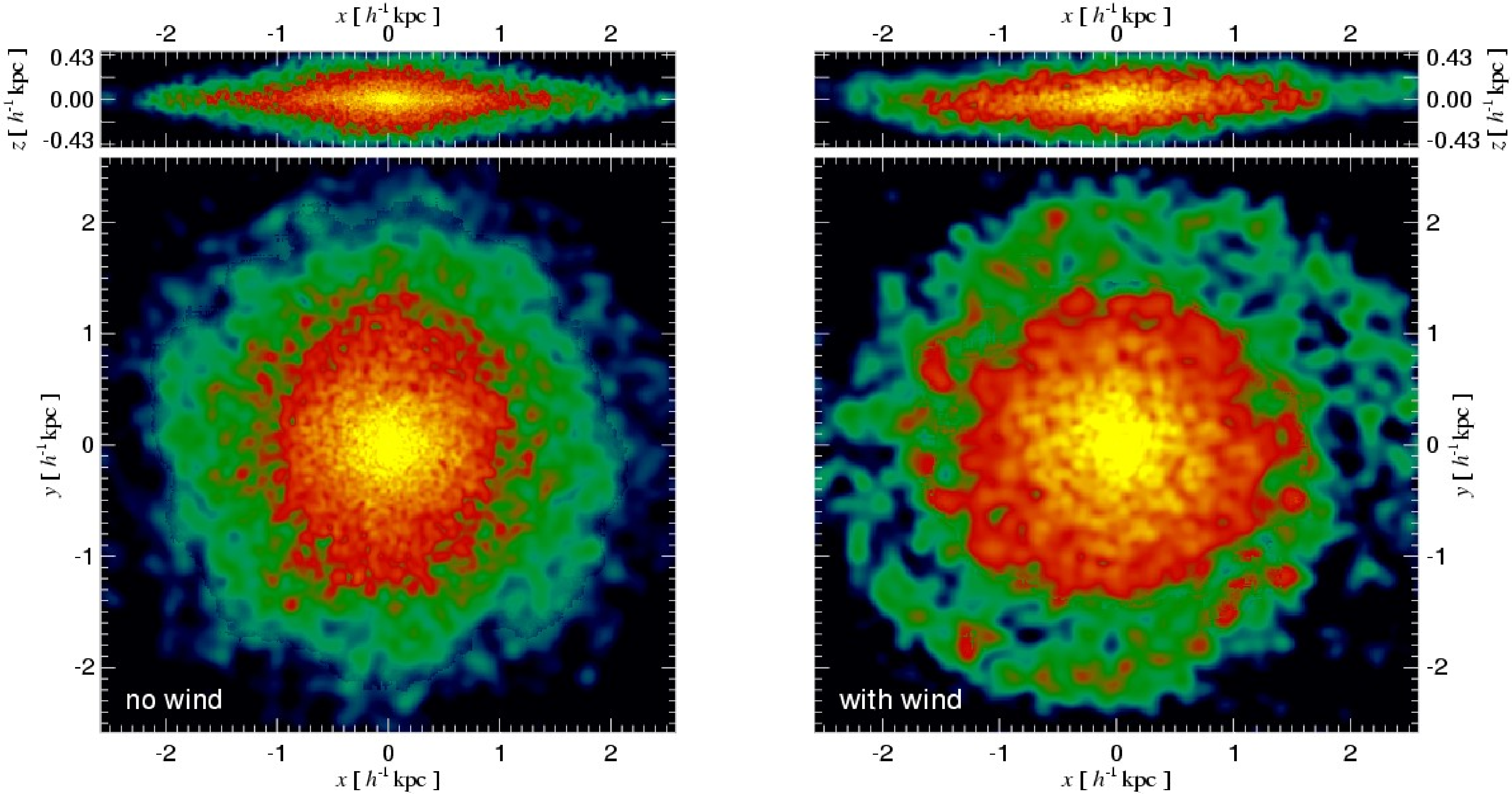
STELLAR DISK IN A $\mathbf{10^{10}\,M_\odot}/h$ HALO



# Direct simulations of star formation in cosmological volumes have proven to be very difficult

## COMMON HEADACHES OF SIMULATORS OF GALAXY FORMATION

- Cooling catastrophe & overproduction of stars
- Thermal supernova-feedback fails to regulate star formation, and fails to explain metal enrichment of the IGM
- Collapse of gas halted by numerical resolution not by physics
- The real structure of the ISM is known to be multi-phase

*- Hybrid multi-phase model for the ISM*
*- Inclusion of galactic winds*

**And the simulations are very expensive:**

- **Required dynamic range is huge**

To resolve ***all*** the star formation, one needs:

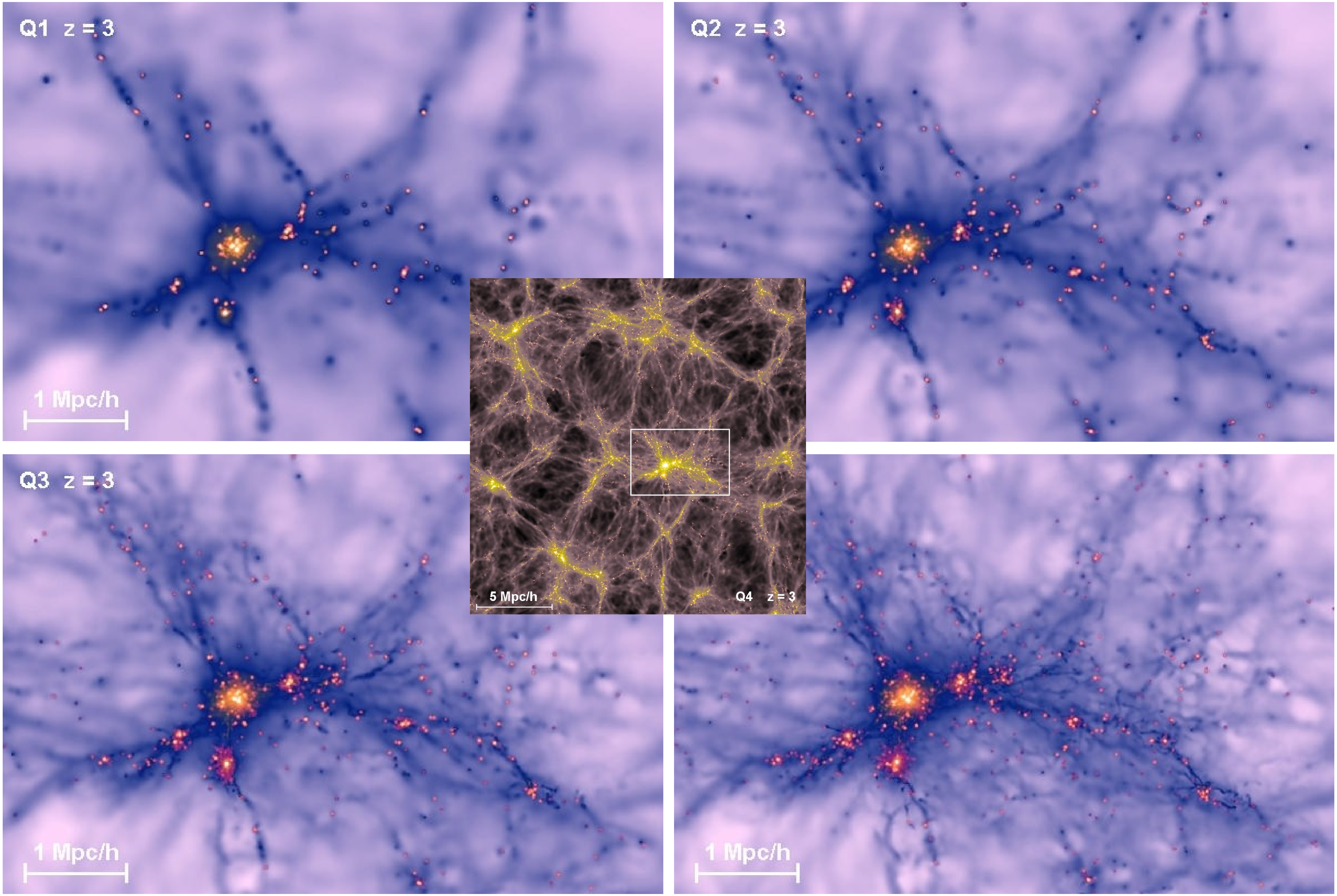
$L \sim 100$ Mpc/h

$m_{gas} \sim 10^6 M_\odot/h$

$\sim 10^{11}$ simulation particles

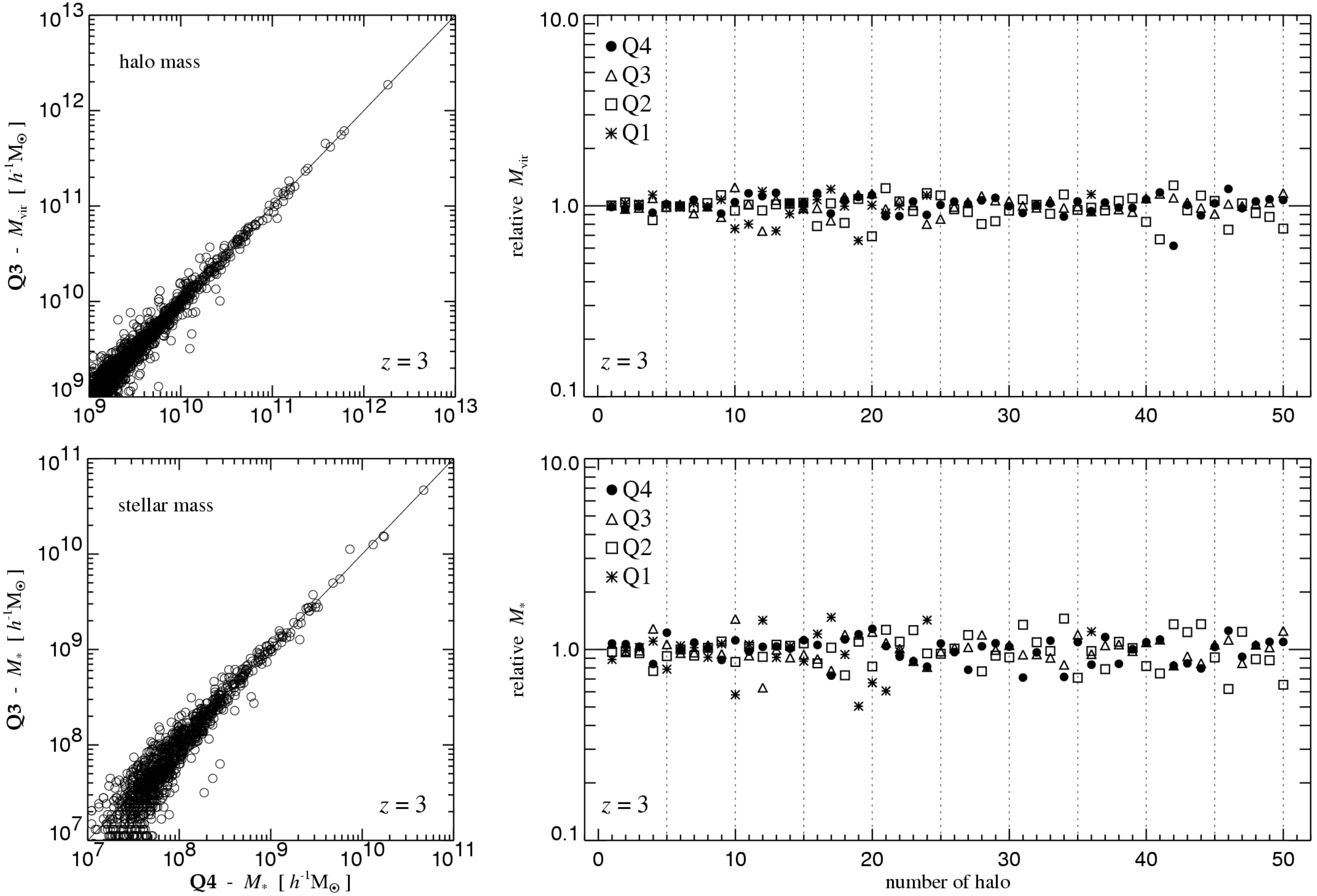
*Comprehensive set of simulations on interlocking scales*

# Higher mass resolution can resolve smaller galaxies



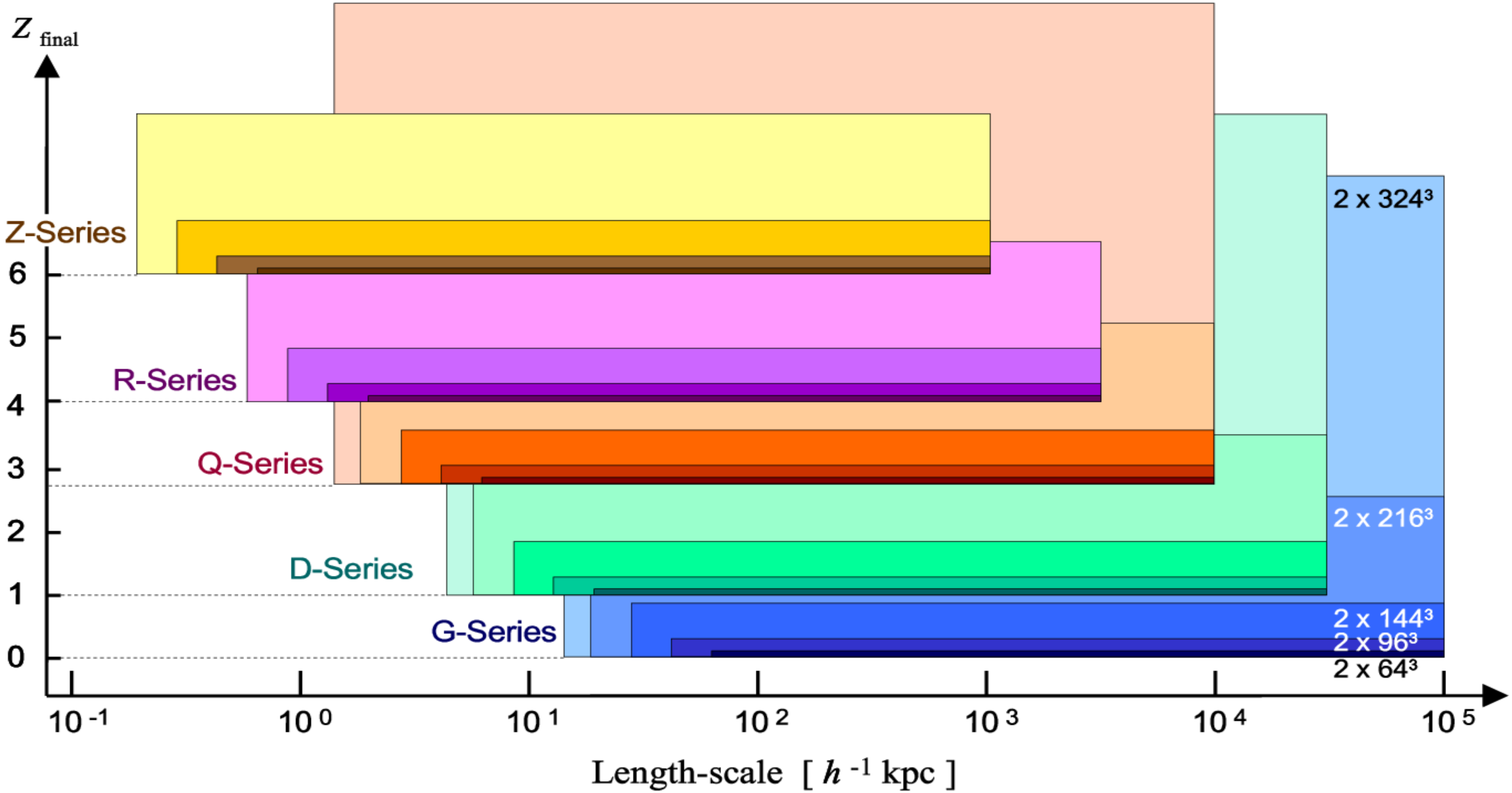
# The star formation rate of individual galaxies converges well for sufficient mass resolution

## OBJECT-BY-OBJECT RESOLUTION STUDY



# To study the star formation history, we have run a program of simulations on a set of interlocking scales and resolutions

SIMULATION PROGRAM



**Beowulf-class computer**

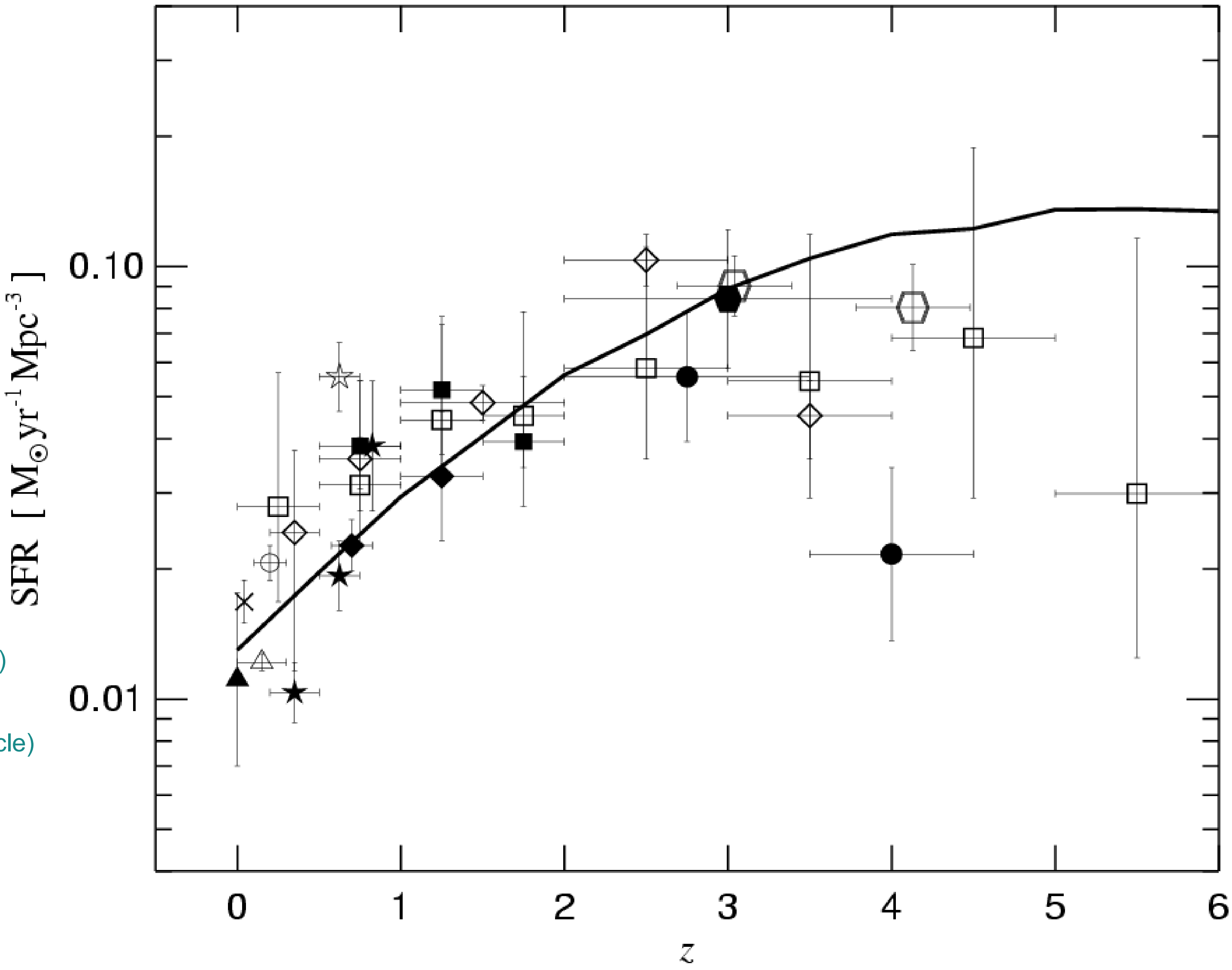
Configuration:

256 Athlon MP (1.6 GHz) arranged in 128 double-processor SMP nodes with 1 GB RAM each, 100 Base-T switched Ethernet, Linux

Separate frontend and 2 big fileservers

# Comparison of the predicted star formation history with observational results

## THE EVOLUTION OF THE COSMIC STAR FORMATION DENSITY



Data points by:
Gallego et al. (1996, filled triangles)
Gronwall (1999, diagonal crosses)
Tryer et al. (1998, open triangle)
Tresse & Maddox (1998, empty circle)
Lilly et al. (1996, filled stars)
Conolly et al. (1997, filled squares)
Madau el al. (1996, filled circles)
Pettini et al. (1998 empty squares)
Flores et al. (1999, empty stars)

# Construction of compound galaxies

# Galaxy collisions are common in the universe, and the collision of two spirals should lead to the formation of an elliptical galaxy

THE "MICE" NGC 4676

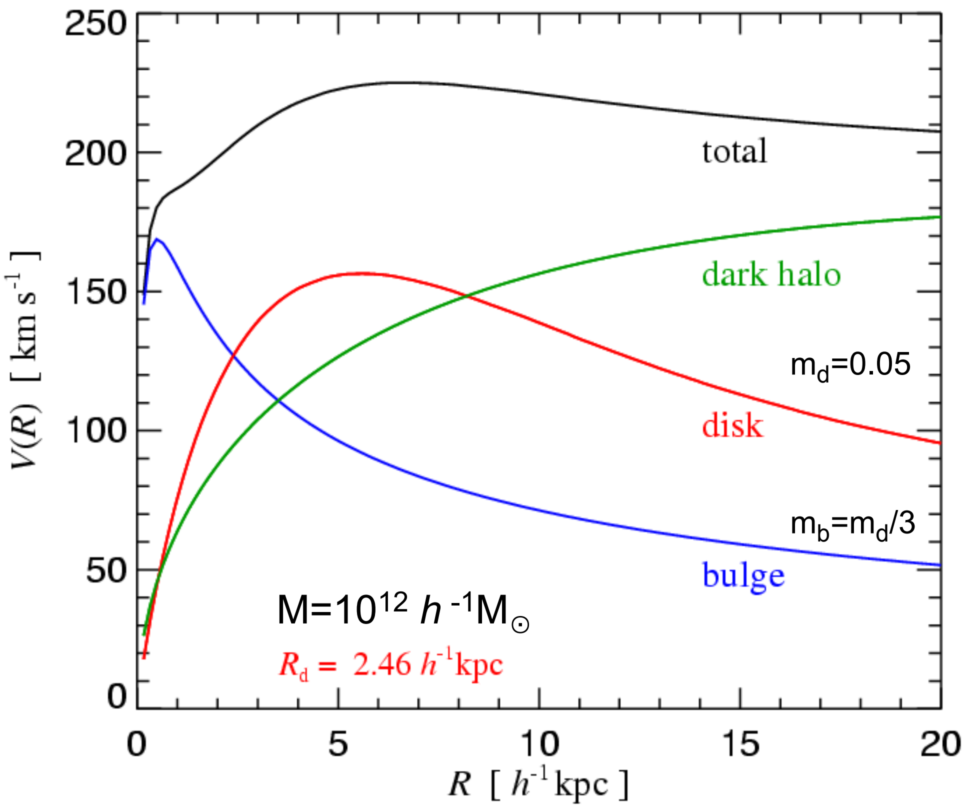
# We construct compound disk galaxies that are in dynamical equilibrium

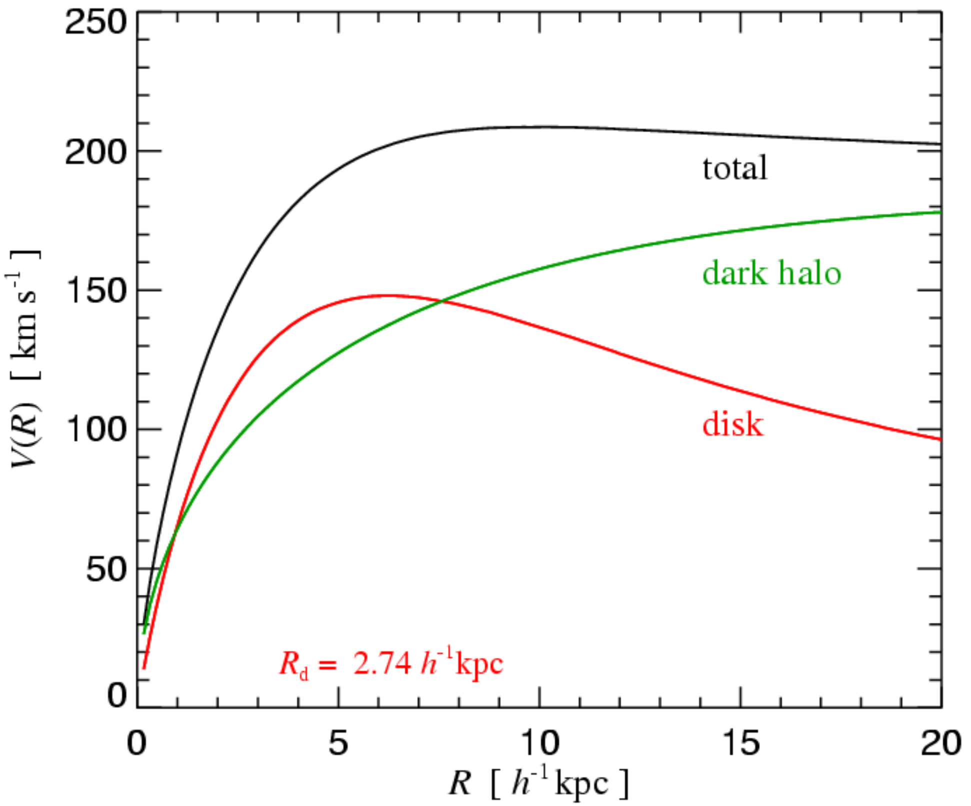
## STRUCTURAL PROPERTIES OF MODEL GALAXIES

**Components:**

- Dark halo (Hernquist profile matched to NFW halo)
- Stellar disk (expontial)
- Stellar bulge
- Gaseous disk (expontial)
- Central supermassive black hole (small seed mass)

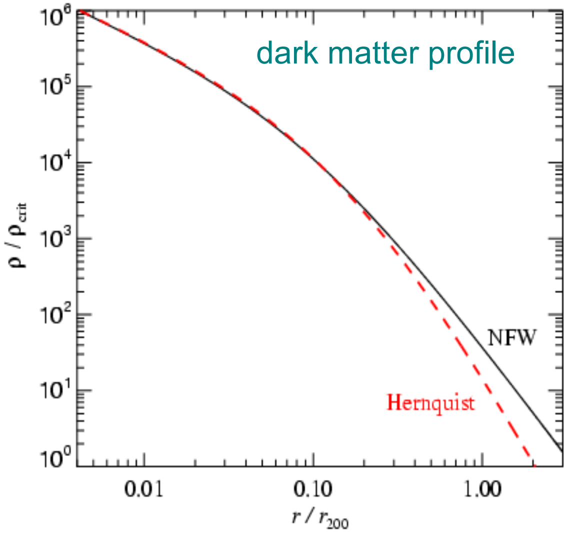
- We compute the exact gravitational potential for the axisymmetric mass distribution and solve the Jeans equations
- Gas pressure effects are included
- The gaseous scale-height is allowed to vary with radius





# The first step in constructing an isolated galaxy model is the specification of the density structure of all mass components

## DENSITY DISTRIBUTIONS OF DARK MATTER AND STARS IN BULGE AND DISK



**Dark matter:**

$$\rho_{\rm dm}(r) = \frac{M_{\rm dm}}{2\pi} \frac{a}{r(r+a)^3}$$

Hernquist or NFW profile

**Stars in the disk:**

$$\Sigma_\star(r) = \frac{M_\star}{2\pi h^2} \exp(-r/h)$$

“Isothermal sheet” with exponential profile

$$\rho_\star(R,z) = \frac{M_\star}{4\pi z_0\, h^2} \,\mathrm{sech}^2\left(\frac{z}{2\, z_0}\right) \exp\left(-\frac{R}{h}\right)$$

Disk scale length ***h*** determined by spin parameter of halo.

**Stars in the bulge:**

$$\rho_{\rm b}(r) = \frac{M_{\rm b}}{2\pi} \frac{b}{r(r+b)^3}$$

Bulge scale length ***b*** can be set to a fraction of the disk scale-length ***h*.**

**Gas in the disk:**

$$\Sigma_{\rm gas}(r) = \frac{M_{\rm gas}}{2\pi h^2} \exp(-r/h)$$

Vertical structure given by hydrostatic equlibrium.
Depends on the equation of state of the gas.

$$-\frac{1}{\rho_{\rm g}} \frac{\partial P}{\partial z} - \frac{\partial \Phi}{\partial z} = 0$$

# Solving the Jeans equations allows the construction of dynamically stable disk galaxy models

## MOMENT EQUATIONS FOR THE VELOCITY STRUCTURE

We assume that the **velocity distribution function** of dark matter and stars can be approximated everywhere by a **triaxial Gaussian.**

Further, we assume axisymmetry, and that the distribution function depends only on $E$ and $L_z$

Then cross-moments vanish:

$$\langle v_R v_z \rangle = \langle v_z v_\phi \rangle = \langle v_R v_\phi \rangle = 0$$

$$\langle v_R \rangle = \langle v_z \rangle = 0$$

The radial and vertical moments are given by:

$$\left\langle v_z^2 \right\rangle = \left\langle v_R^2 \right\rangle = \frac{1}{\rho} \int_z^\infty \rho(z', R) \frac{\partial \Phi}{\partial z'} \, \mathrm{d}z'$$

The azimuthal dispersion fulfills a separate equation:

$$\left\langle v_\phi^2 \right\rangle = \left\langle v_R^2 \right\rangle + \frac{R}{\rho} \frac{\partial \left( \rho \left\langle v_R^2 \right\rangle \right)}{\partial R} + v_c^2$$

Circular velocity: $v_c^2 \equiv R \dfrac{\partial \Phi}{\partial R}$

A remaining freedom lies in the azimuthal streaming $\langle v_\phi \rangle$ , which is not determined by the above assumptions. For the dark matter, it can be set to zero, or to a value corresponding to a prescribed spin.

$$\sigma_\phi^2 = \left\langle v_\phi^2 \right\rangle - \langle v_\phi \rangle^2$$

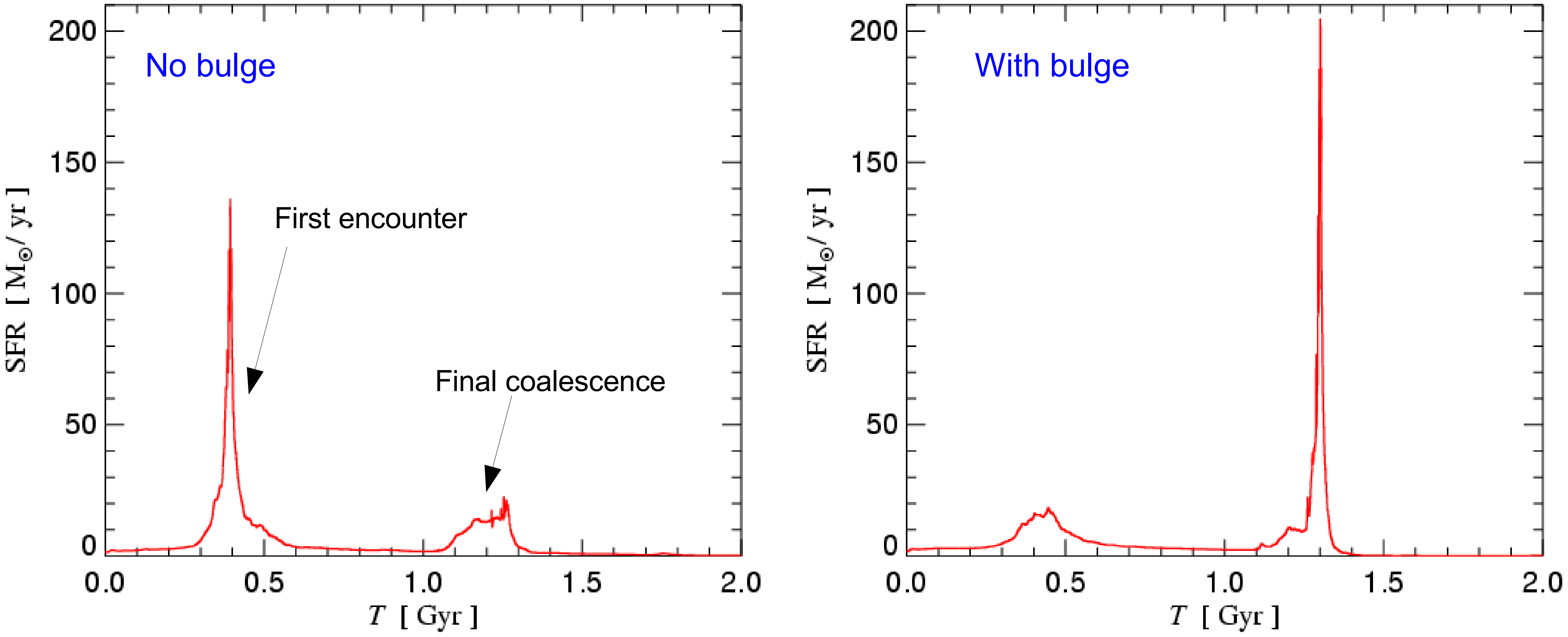
**Note:** For the stellar disk, we instead use the epicycle theory to relate radial and vertical dispersions.

# Galaxy mergers

# Phases of a galaxy merger with an active quasar

# The strength and morphology of the starburts depends on the structural stability of the disks, and on the collision orbit

## STARBURSTS IN MODELS WITH ISOTHERMAL EQUATION OF STATE



Same behaviour as in: Mihos & Hernquist (1995)
Springel (2000)

# Strong nuclear starbusts may leave behind a central luminosity spike in the merger remants

## STELLAR PROFILES OF MERGER REMNANTS WITH ISOTHERMAL ISM

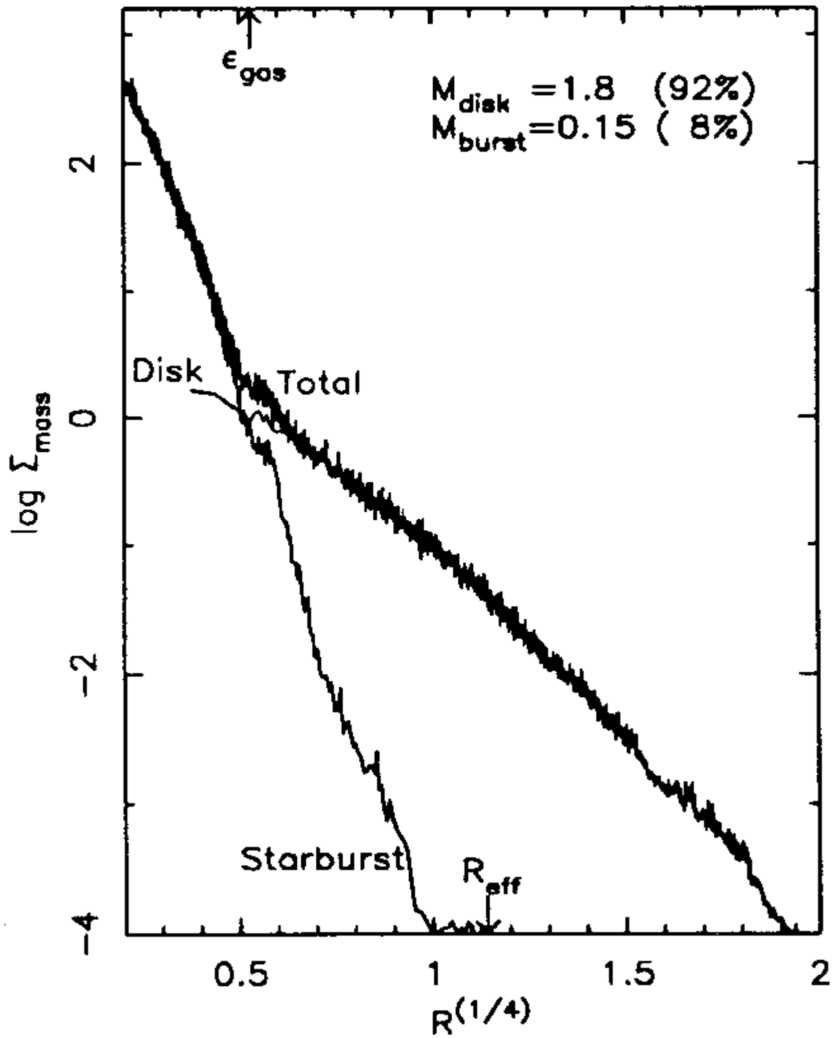


FIG. 1*a*

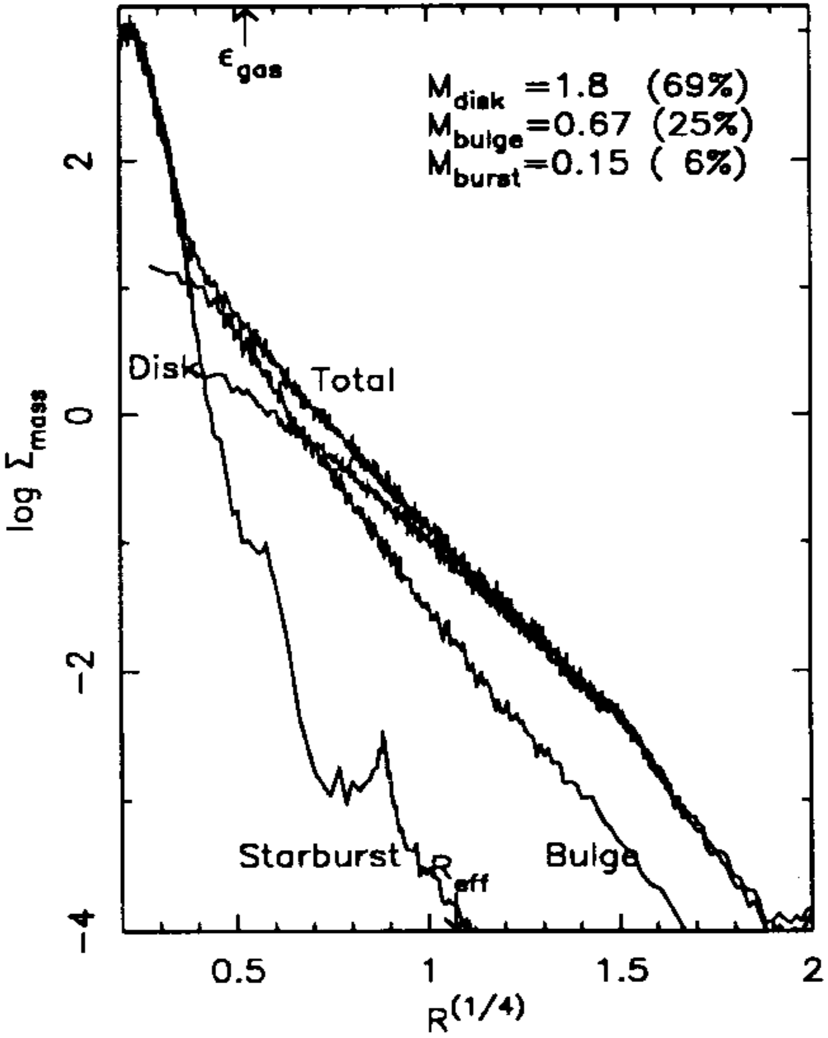


FIG. 1*b*

Mihos & Hernquist (1994)

# The role of AGN in galaxy formation

# There are different **simulation** methodologies to model **quasar feedback** and its effect on structure formation

## OVERVIEW ABOUT SIMULATION APPROACHES

Semi-analytic simulations models of the galaxy population

Hydrodynamical simulations of AGN bubbles in clusters

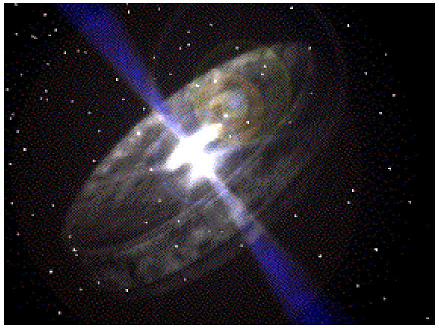
Hydrodynamical simulations of individual galaxies and their BHs

Cosmologial hydro-simulations of galaxy formation with BHs

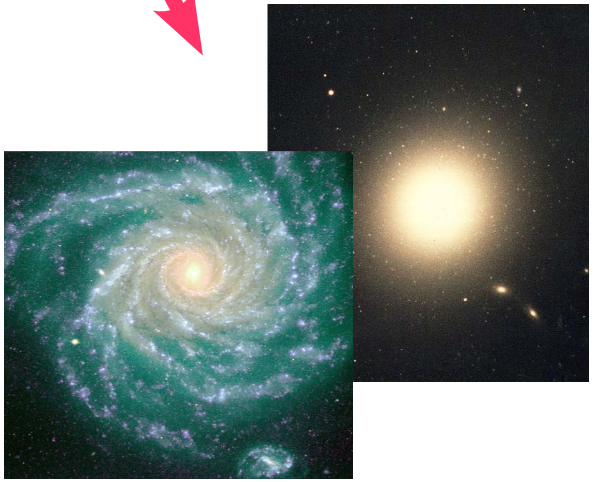
Hydro-simulations of accretion flows onto BHs and/or their jets

Ab initio treatment of the physics

**quasars**



**What's the connection?**



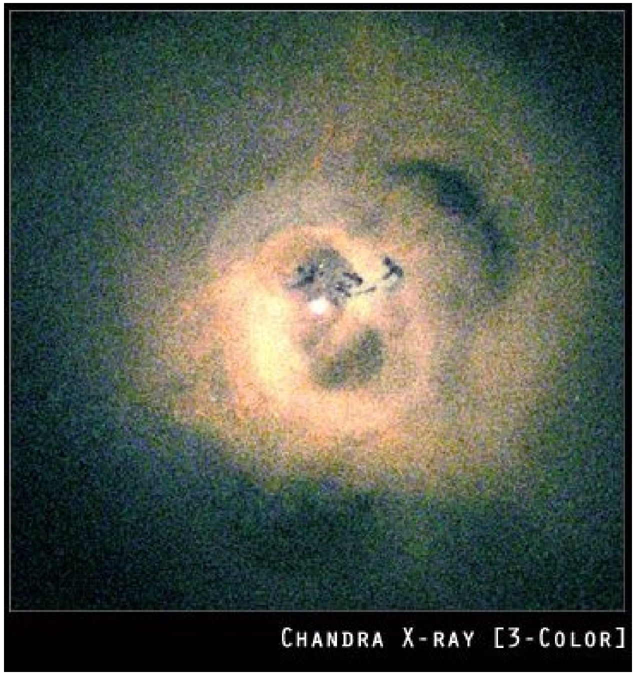
**galaxies**

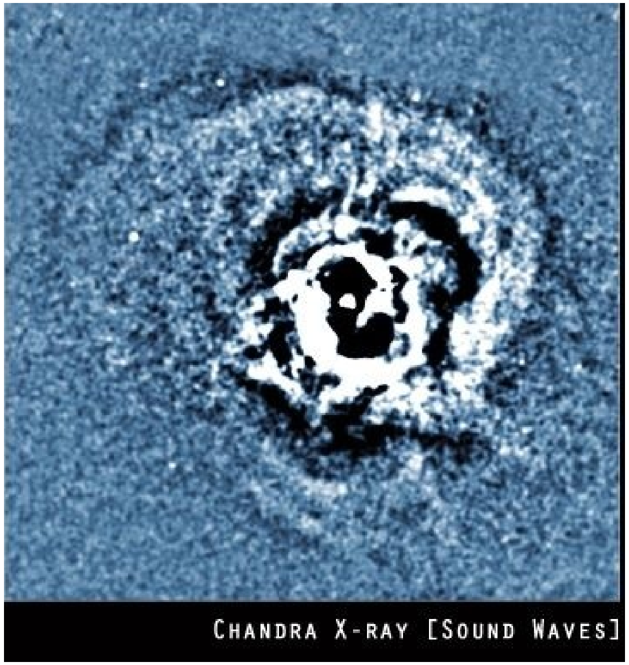
# Bubbles and radio feedback

# The ICM of clusters of galaxies represents a substantial challenge for hydrodynamic simulations

## UNSOLVED ISSUES

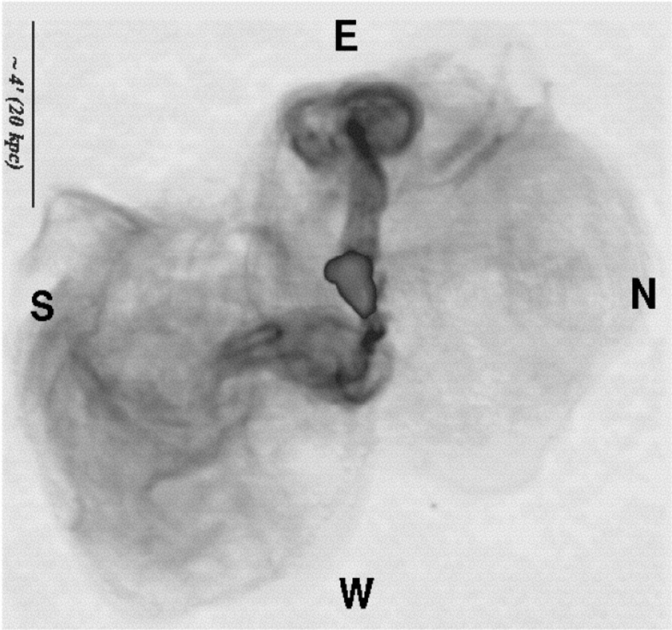
- Why are there (almost) no cooling flows in observed clusters? What's the heat source?
- What is responsible for the deviations of cluster scaling relations from self-similar predictions?
- What is the origin of the high metallicities of the ICM?
- How do the shapes of the observed temperature profiles in clusters arise?

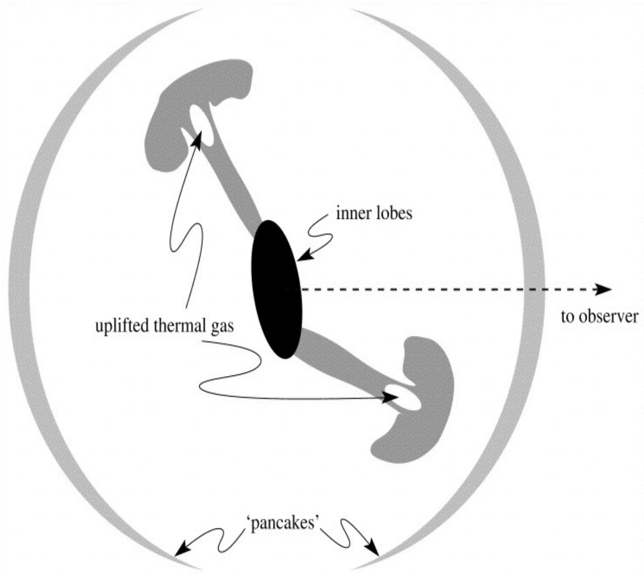




# Buoyant radio bubbles may be inflated by AGN and uplift cool gas

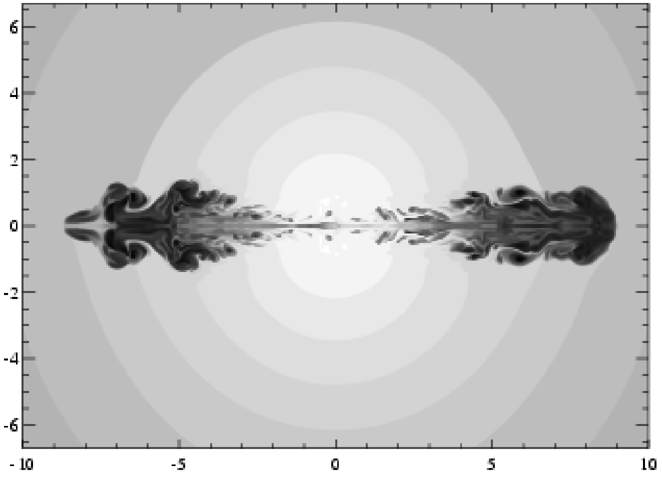
BUBBLES IN M87

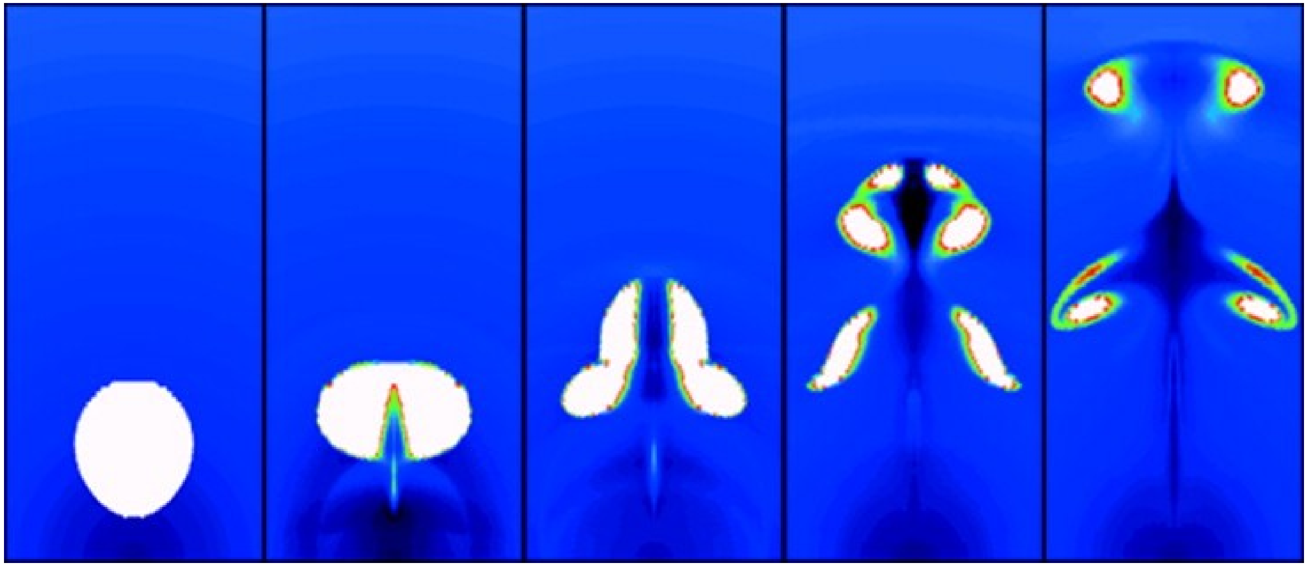




**Churazov et al. (2001)**

**Reynolds, Heinz & Begelman (2002)**



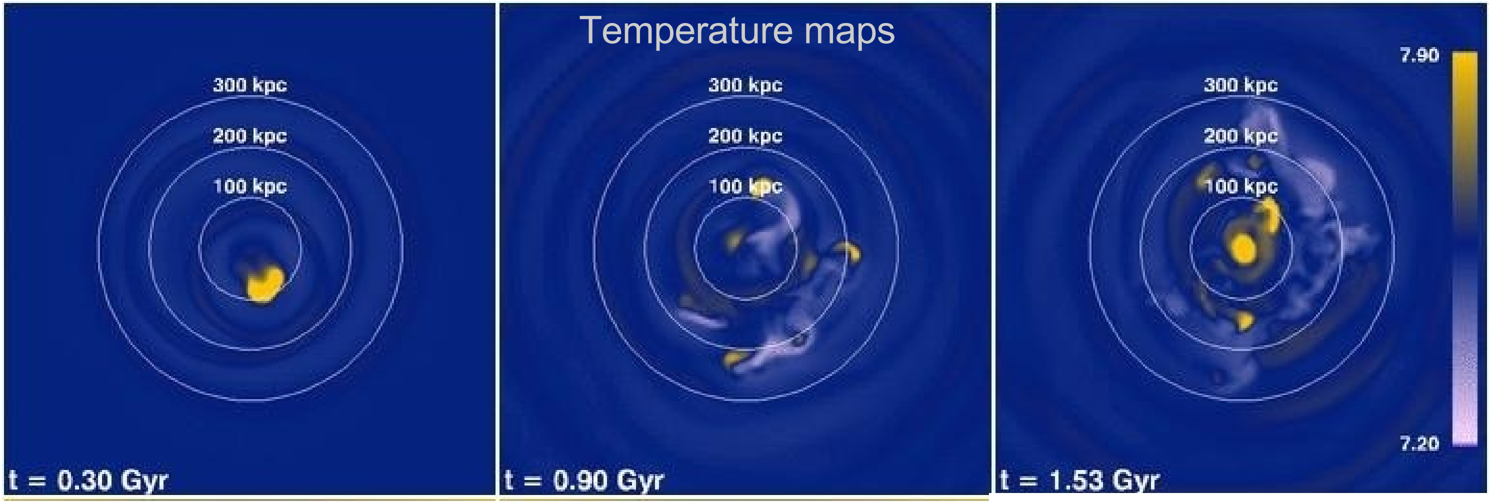


# Three dimensional simulations begin to suggest that AGN with the right duty cycle may indeed quench cooling flows

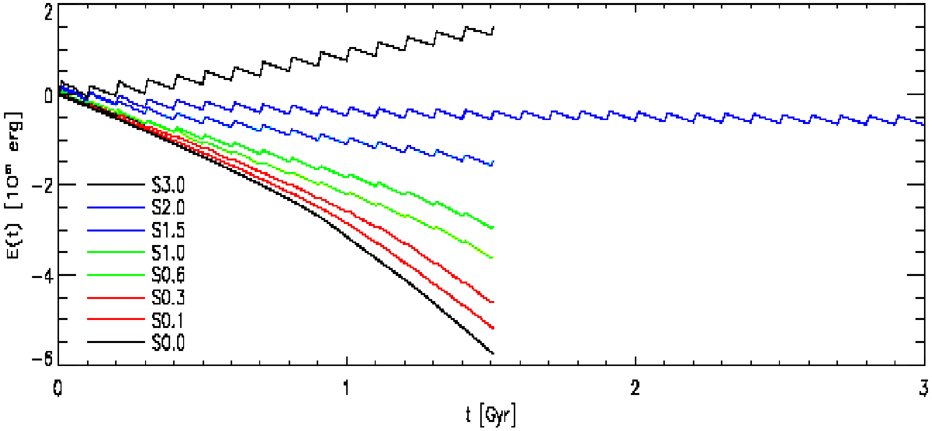
## 3D MODELS OF AGN HEATING

Quilis, Bower, Balogh (2001)
Basson & Alexander (2003)

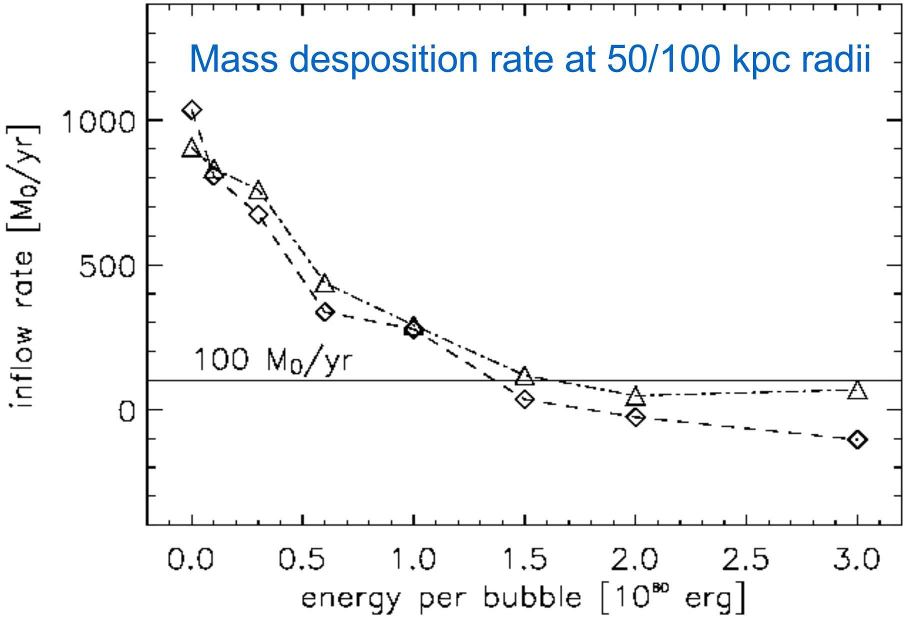
**Dalla Vecchia et al. (2004)**



Evolution of total energy for different bubble energies



Bubble every $10^8$ yrs within 50 kpc of center
(in a 3.1 keV cluster)


Mass desposition rate at 50/100 kpc radii

# Bubble heating works in SPH as well

## AGN HEATING MODEL BY RECURRENT AGN ACTIVITY

**Sijacki & Springel (2006)**

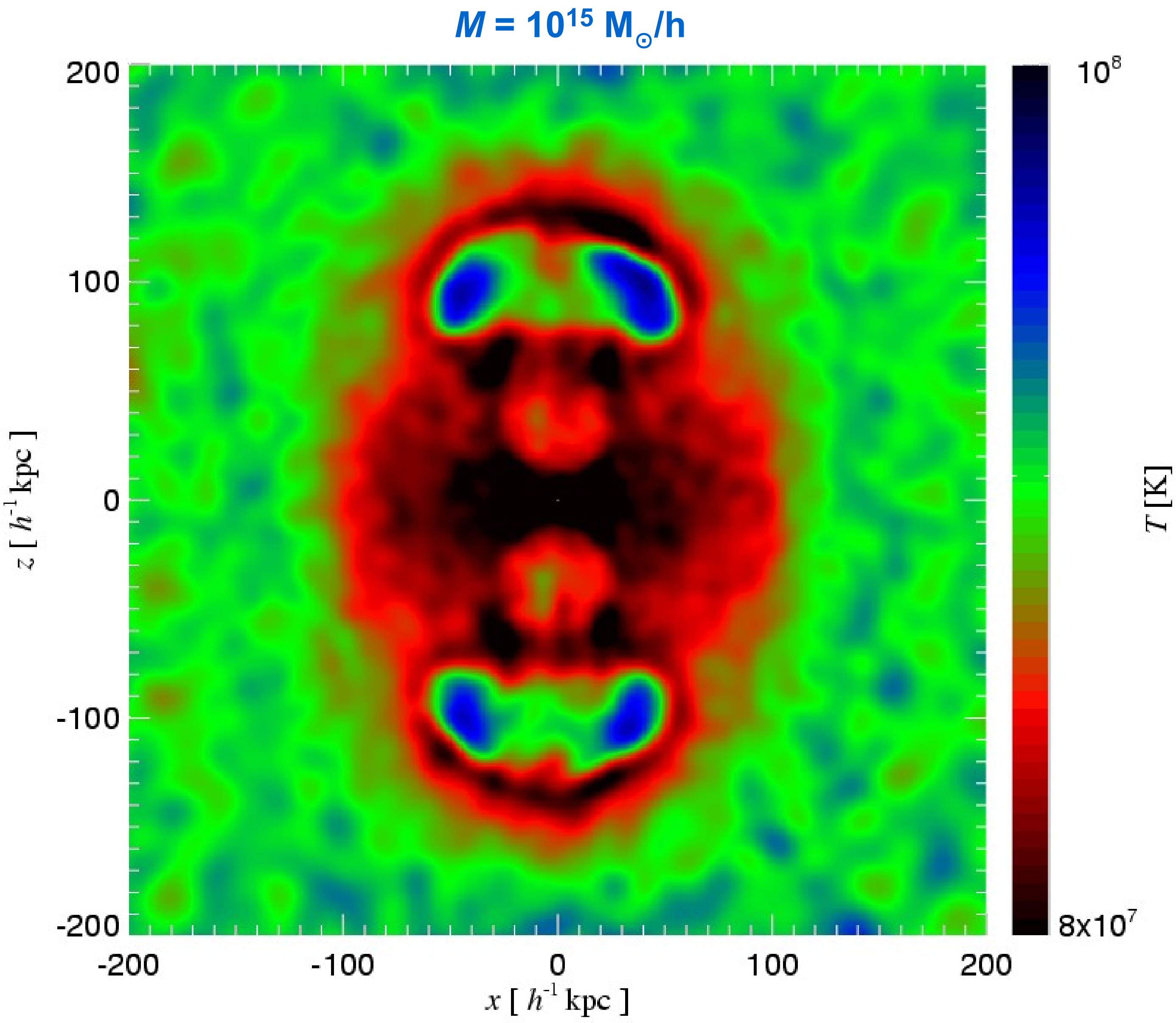
Recurrent bubble heating events:

$$t_{\rm duty} = 10^8\,{\rm yr}$$

$$E_{\rm bub} = 5 \times 10^{60}\,{\rm erg}$$

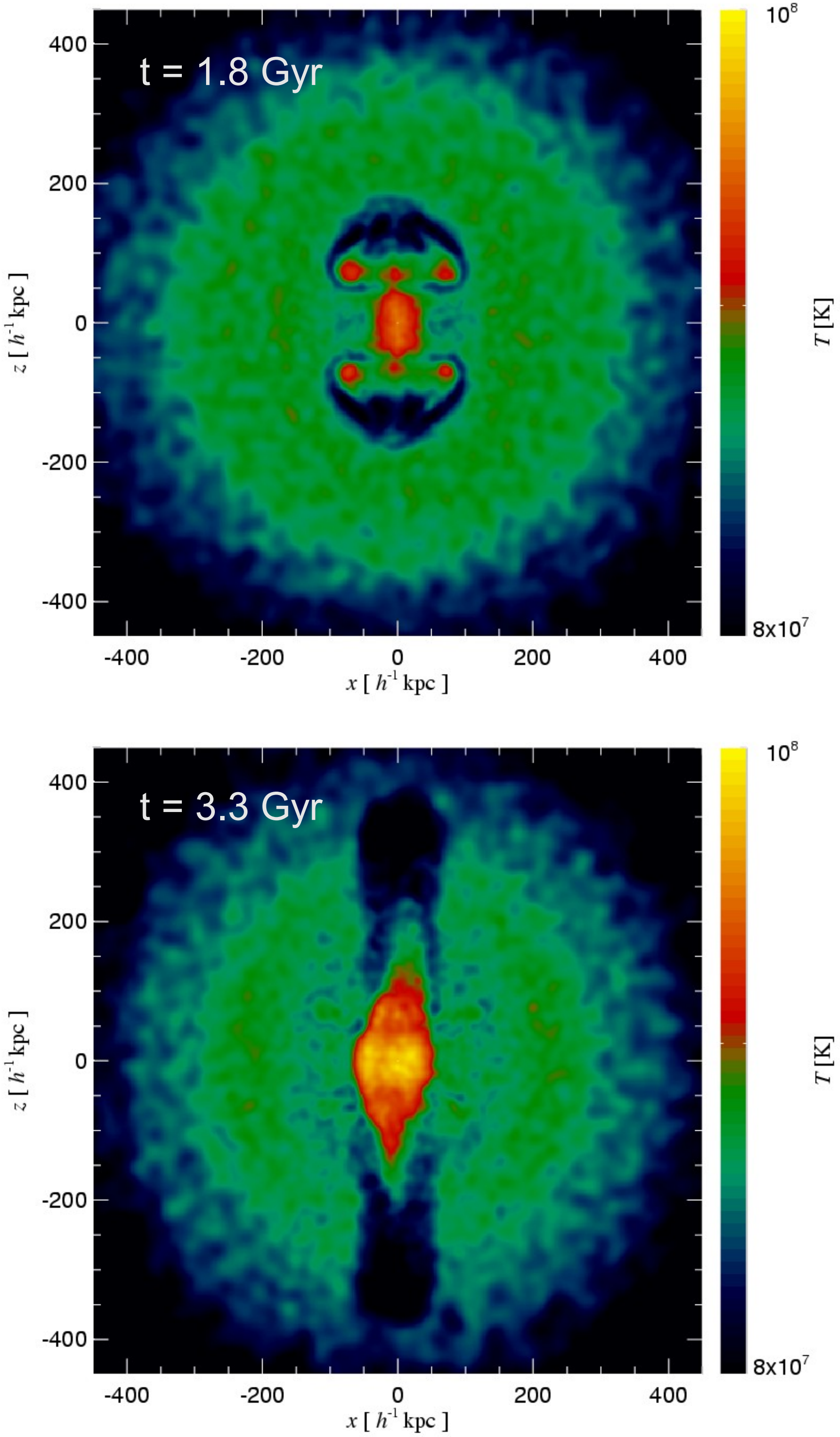
$$R_{\rm bub} = 30\,h^{-1}{\rm kpc}$$

$$d_{\rm bub} = 50\,h^{-1}{\rm kpc}$$

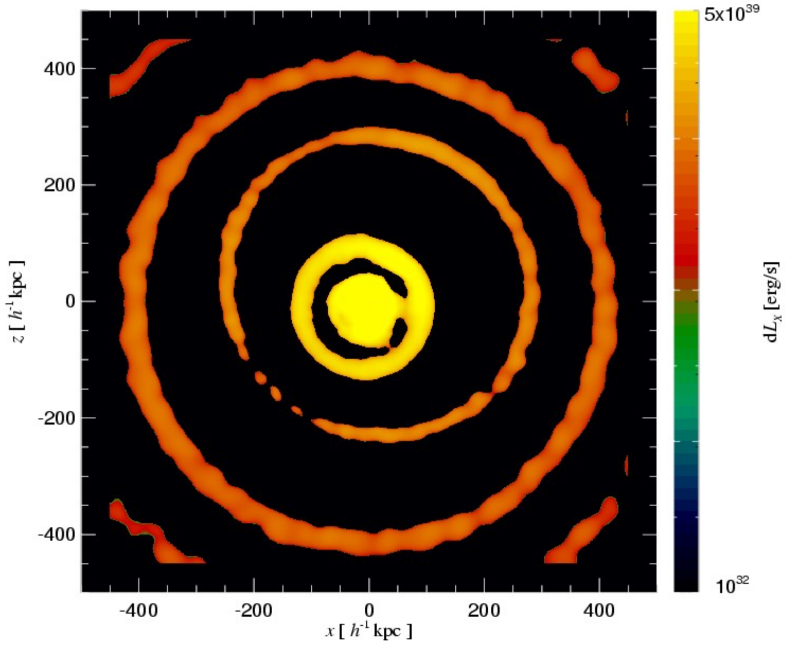


# AGN feedback heats the cluster centre and sends sound waves into the IGM

## BUBBLE EVOLUTION OVER TIME



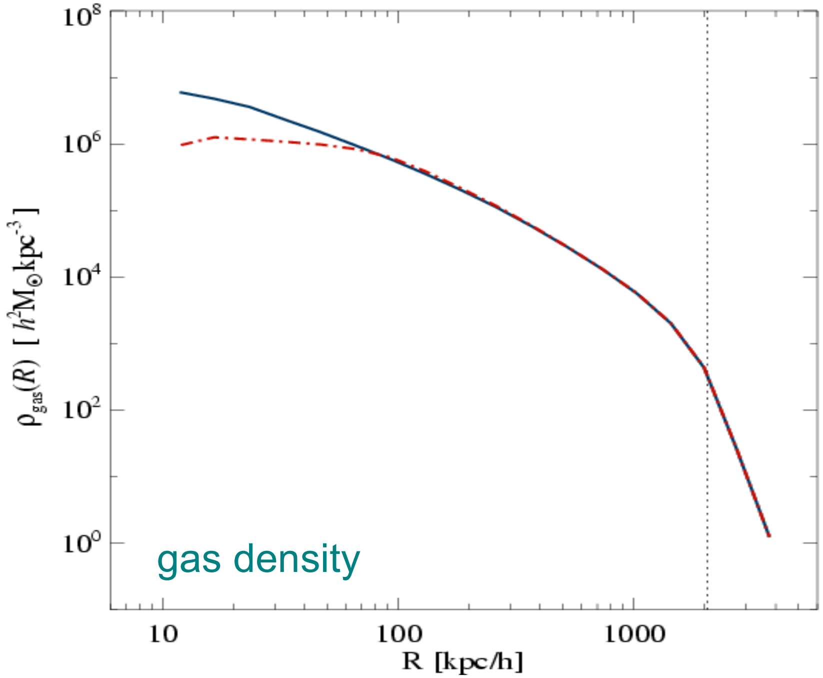
Unsharp masked image of the X-ray emissivity

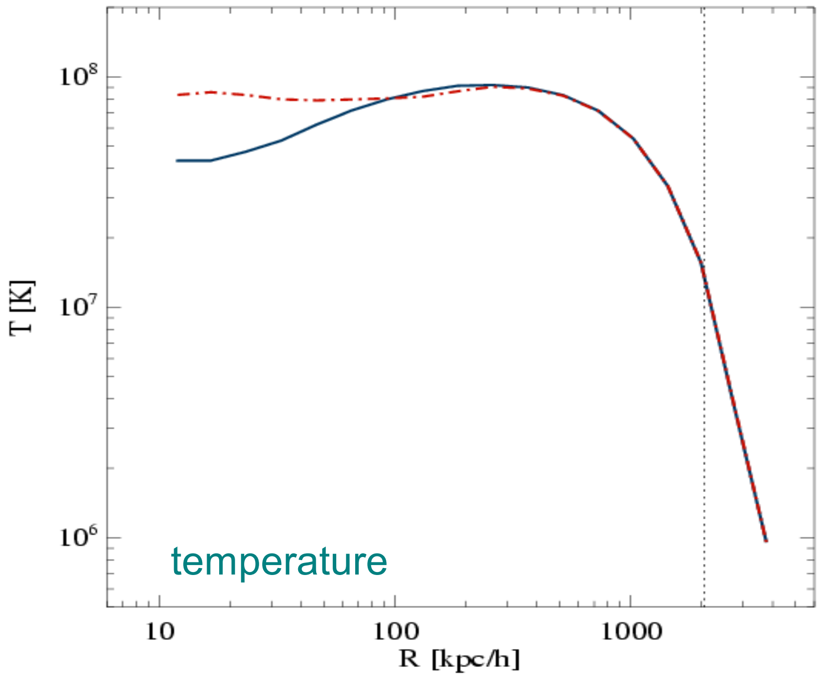


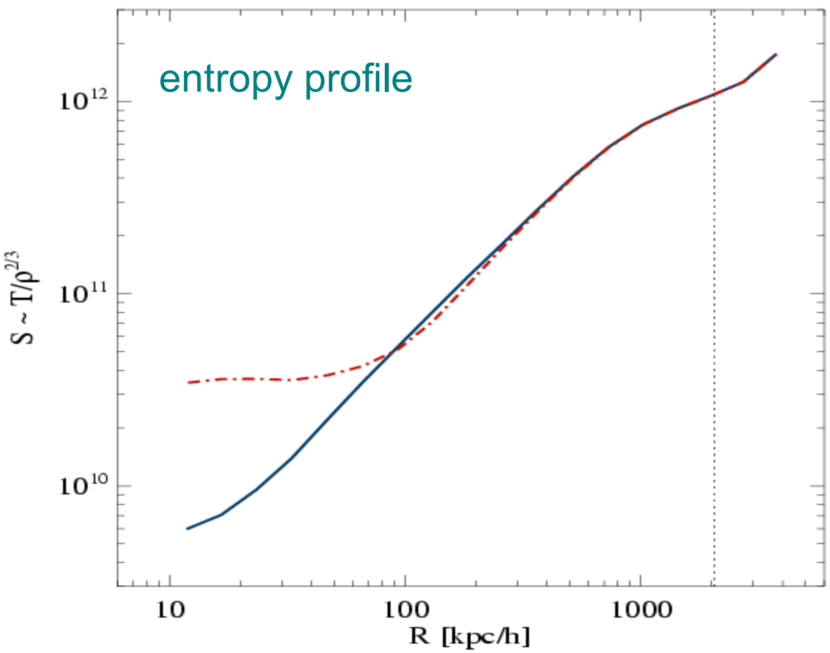
**Sijacki & Springel (2006)**

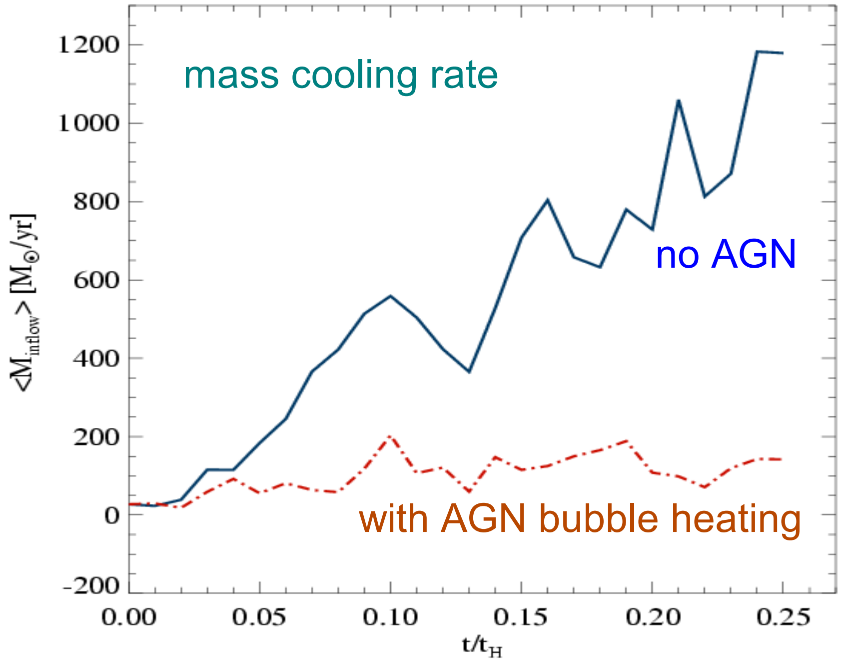
# Bubble heating in an isolated cluster can readily suppress a cooling flow

## RADIAL PROFILES OF AN ISOLATED CLUSTER MODEL





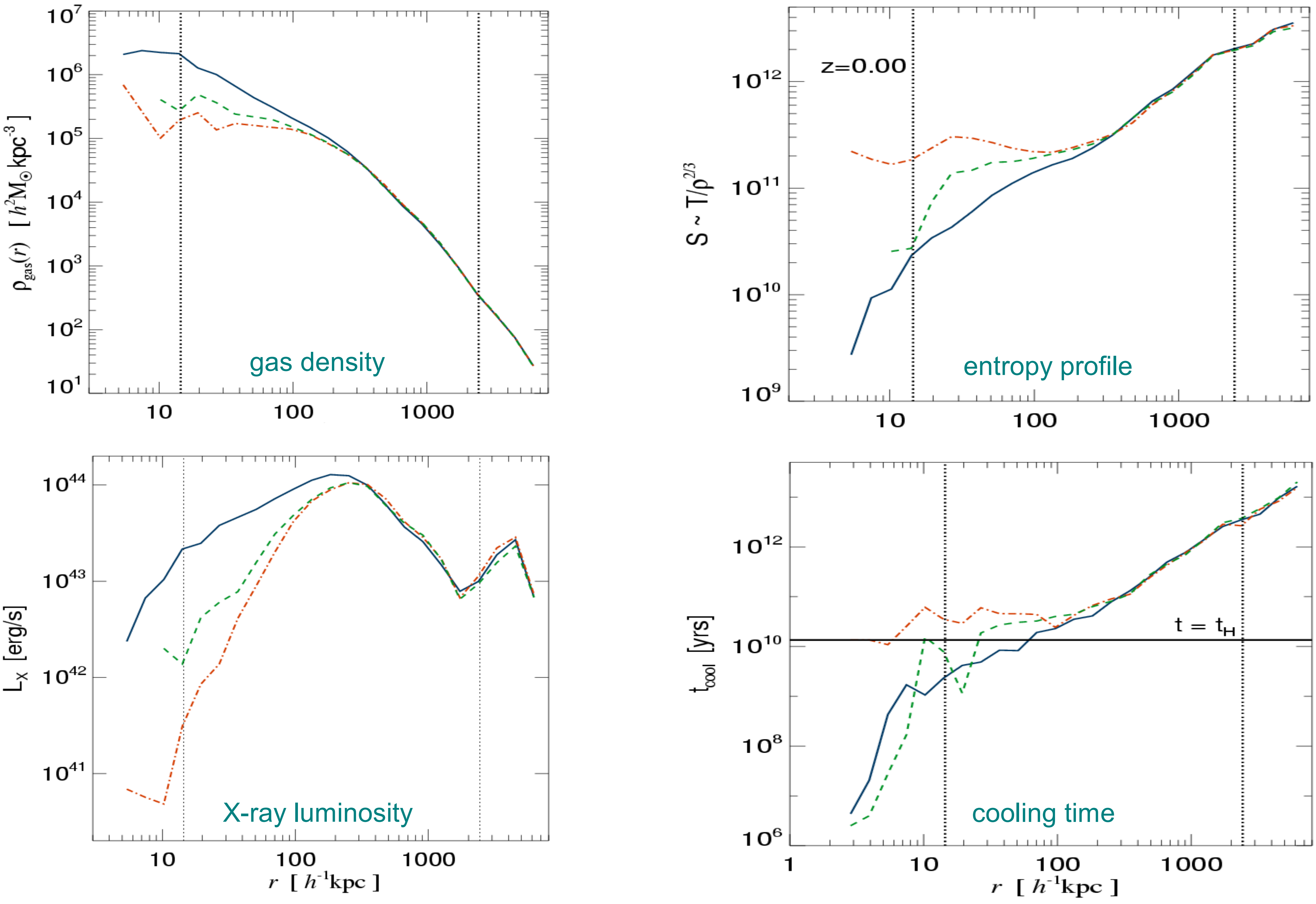




# AGN heating modifies the thermodynamic structure of massive clusters

RADIAL PROFILES OF A RICH CLUSTER AT Z=0

**Sijacki & Springel (2006)**

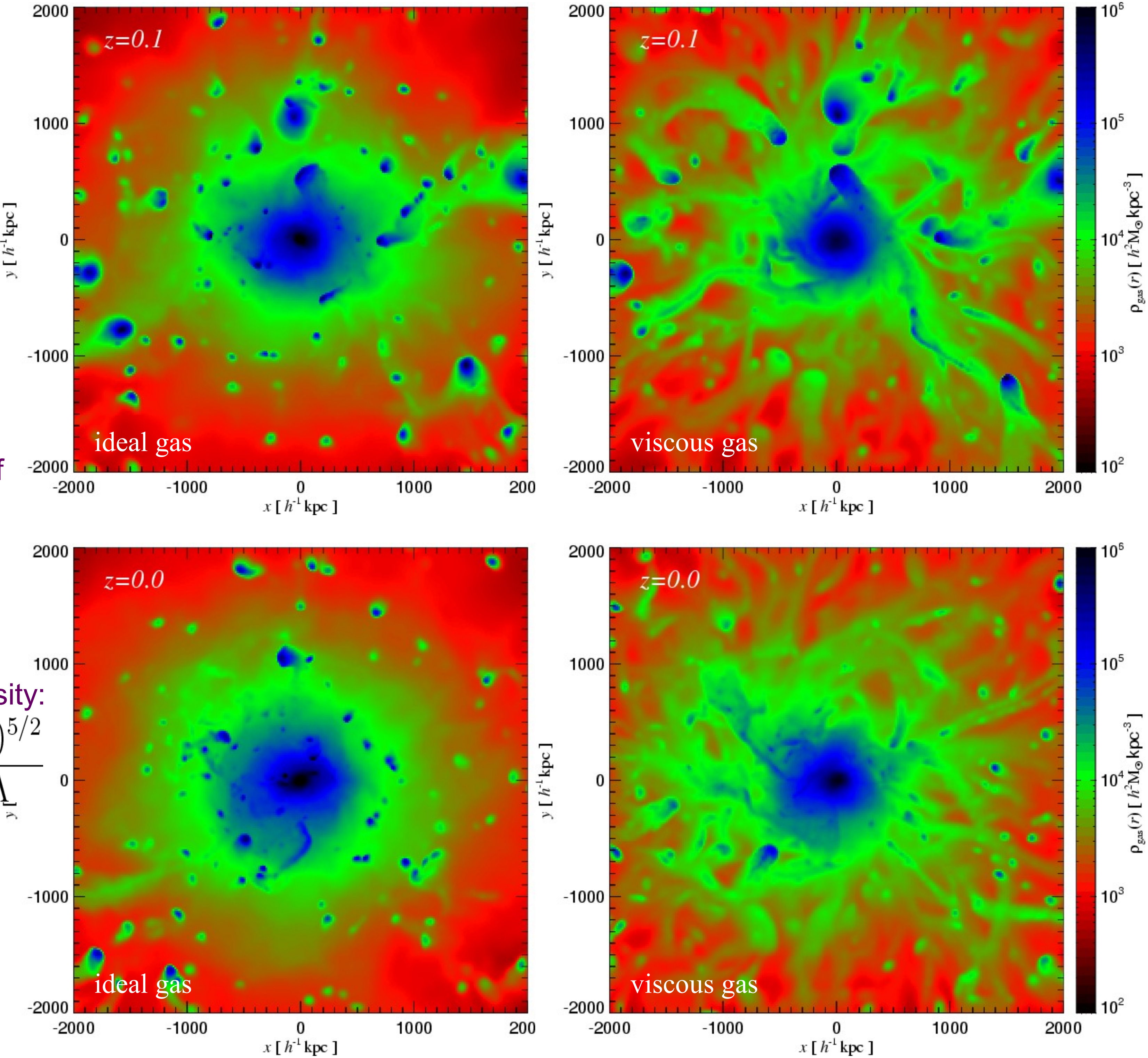


# Changes when viscosity is included

# Viscous shear changes gas stripping during cluster assembly

COMPARISON OF PROJECTED GAS DENSITY MAPS

**Sijacki & Springel (2006)**



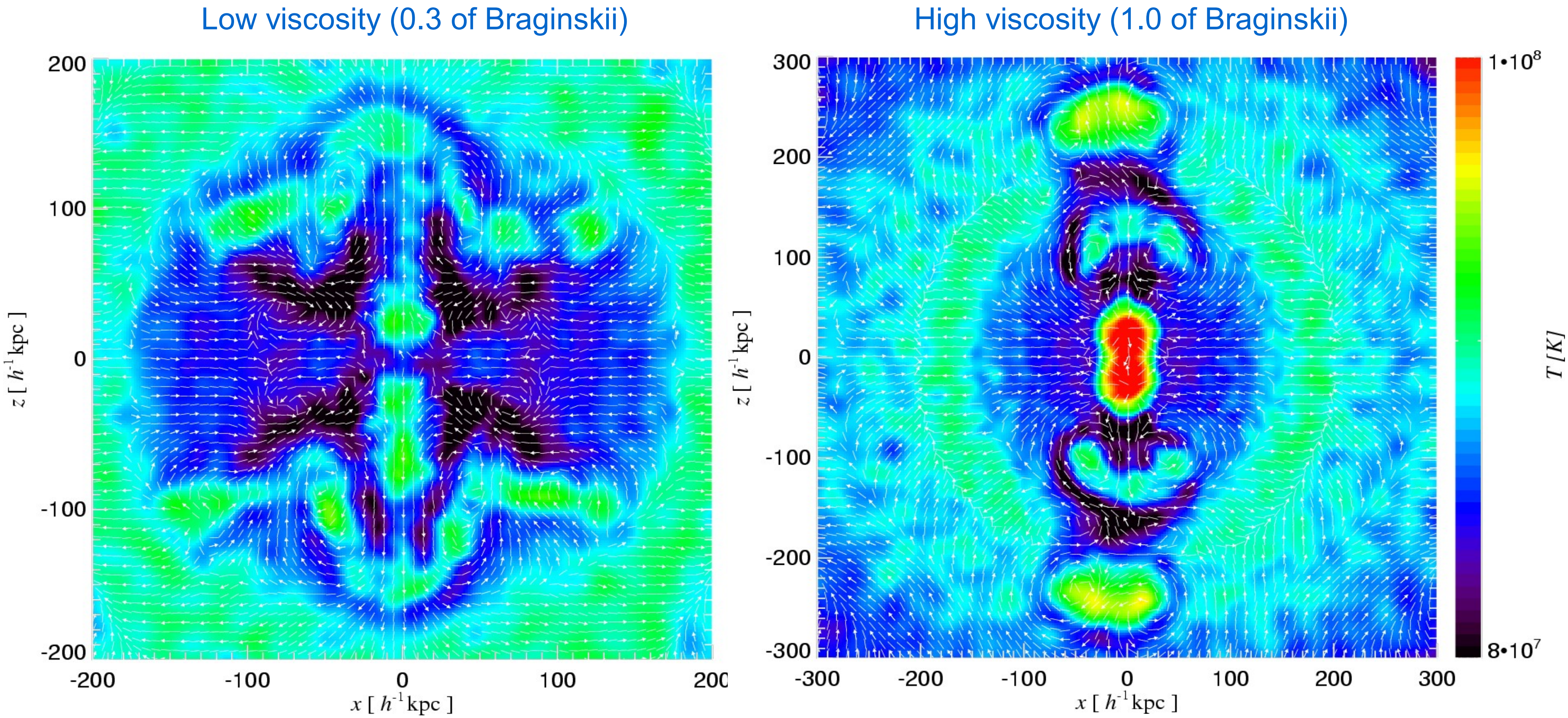
Novel discretization of the Navier-Stokes equations in SPH

Braginskii shear viscosity:

$$\eta = 0.406 \frac{m_i^{1/2} (k_B T_i)^{5/2}}{Z^4 e^4 \ln \Lambda}$$

# Viscous shear in a hot cluster prevents the early shredding of AGN inflated bubbles

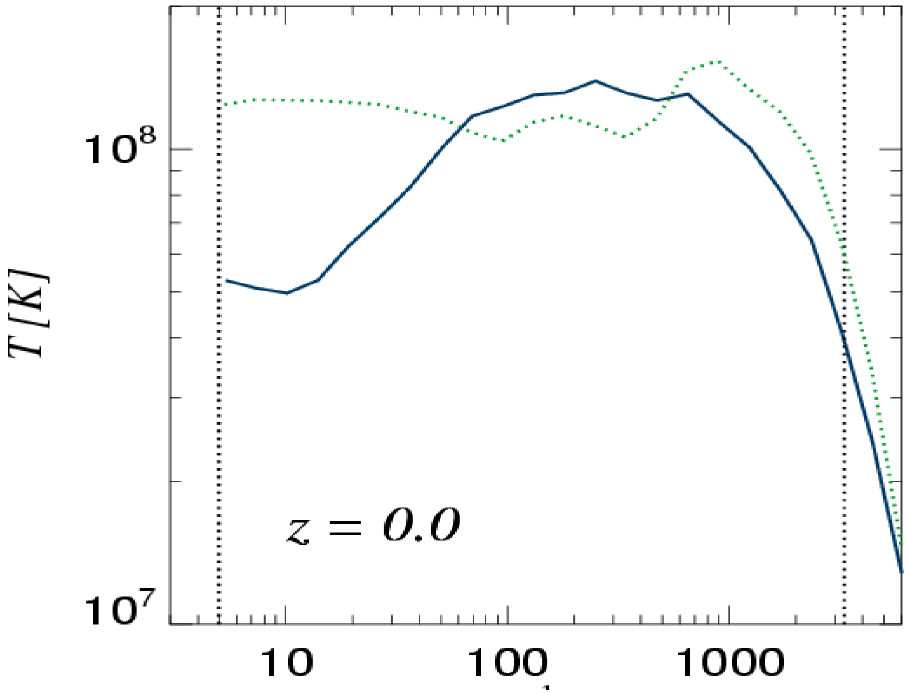
## PROJECTED TEMPERATURE AND VELCOCITY FIELDS IN AGN-HEATED CLUSTERS

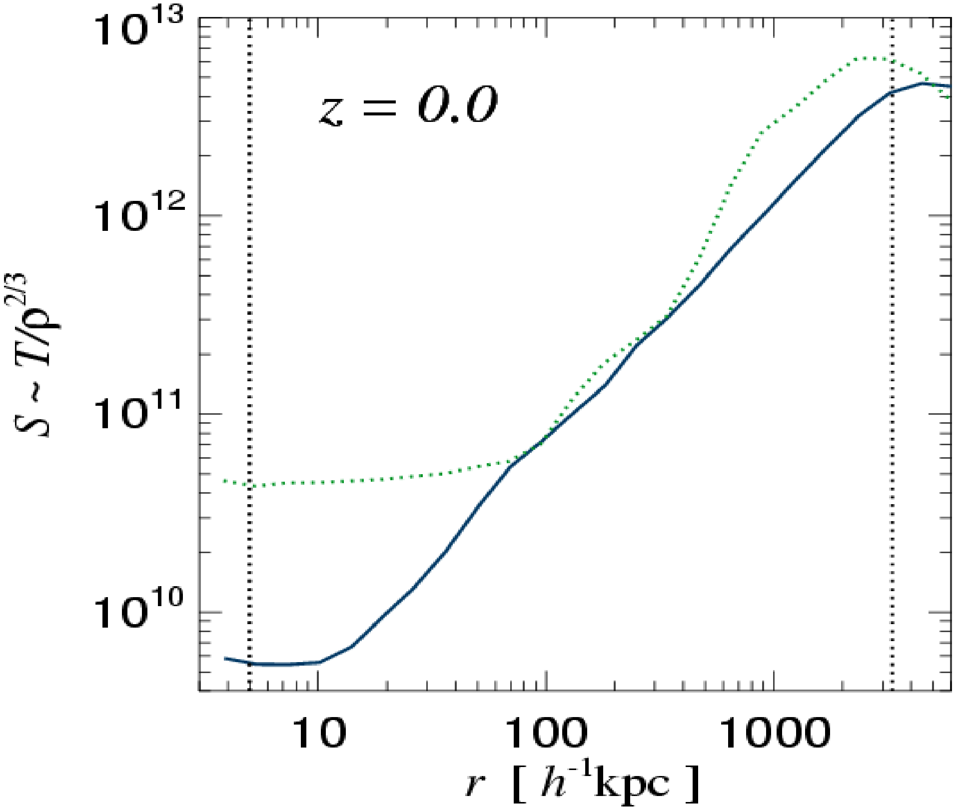


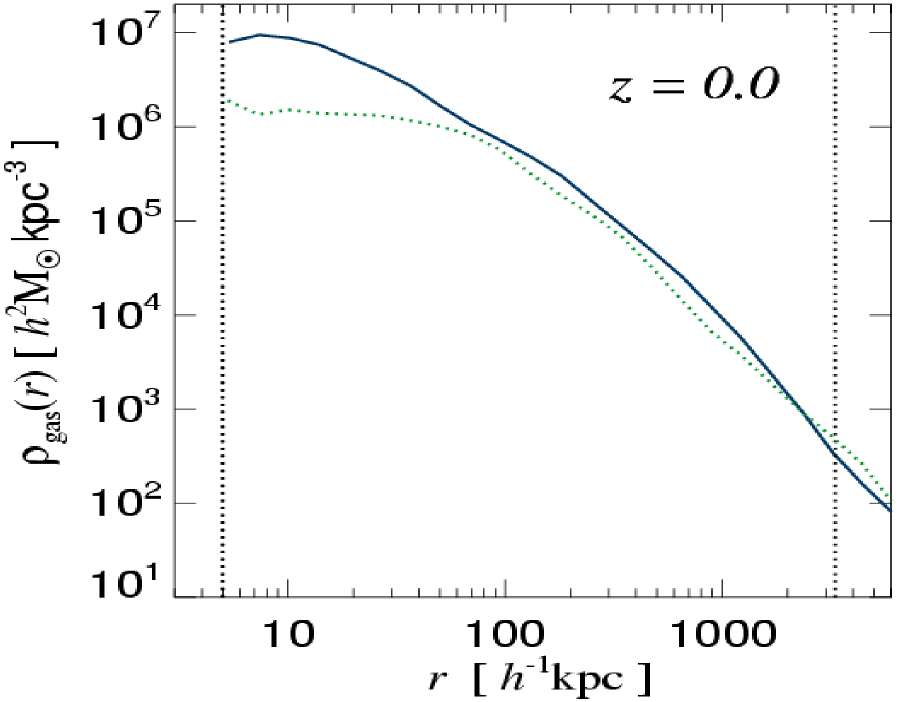
**Sijacki & Springel (2006)**

# Viscous shear changes the thermodynamic profiles of forming clusters of galaxies

## RADIAL PROFILES IN NONRADIATIVE SIMULATIONS WITH/WITHOUT SHEAR VISCOSITY







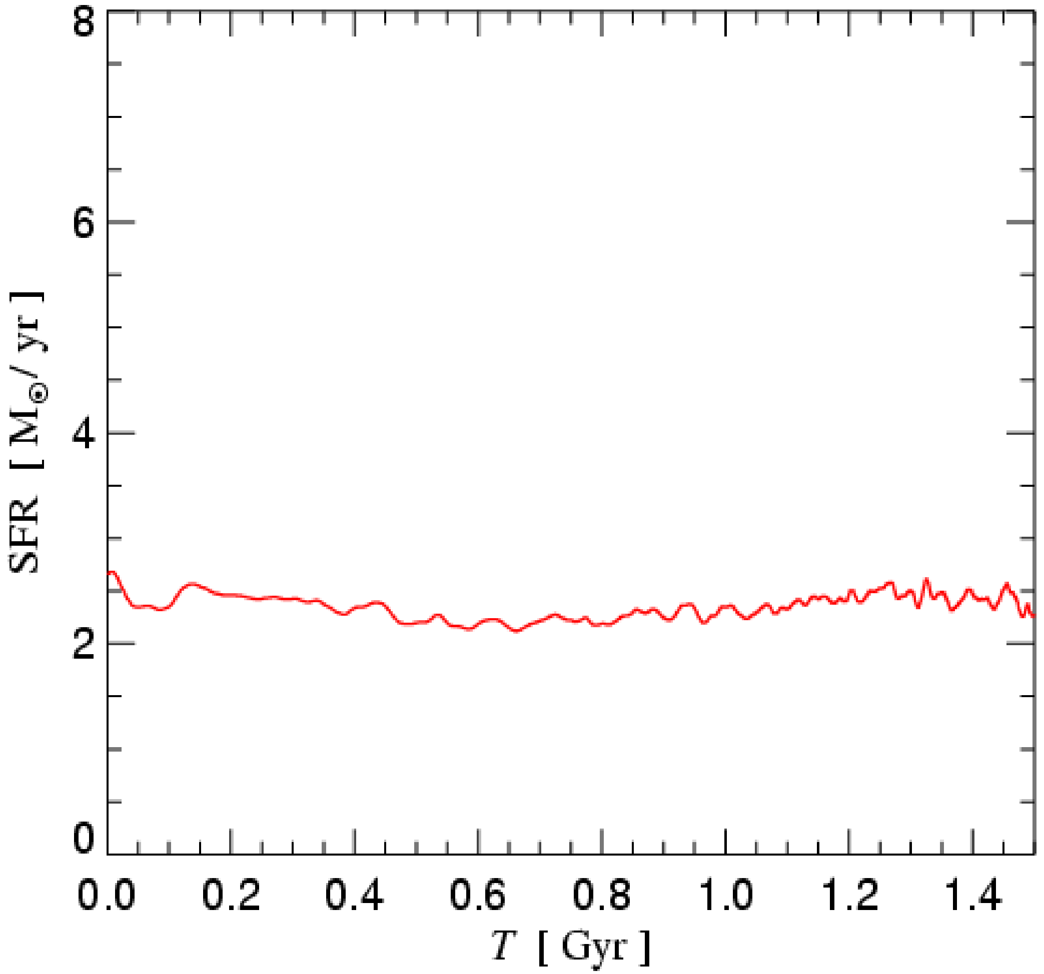
**Sijacki & Springel (2006)**

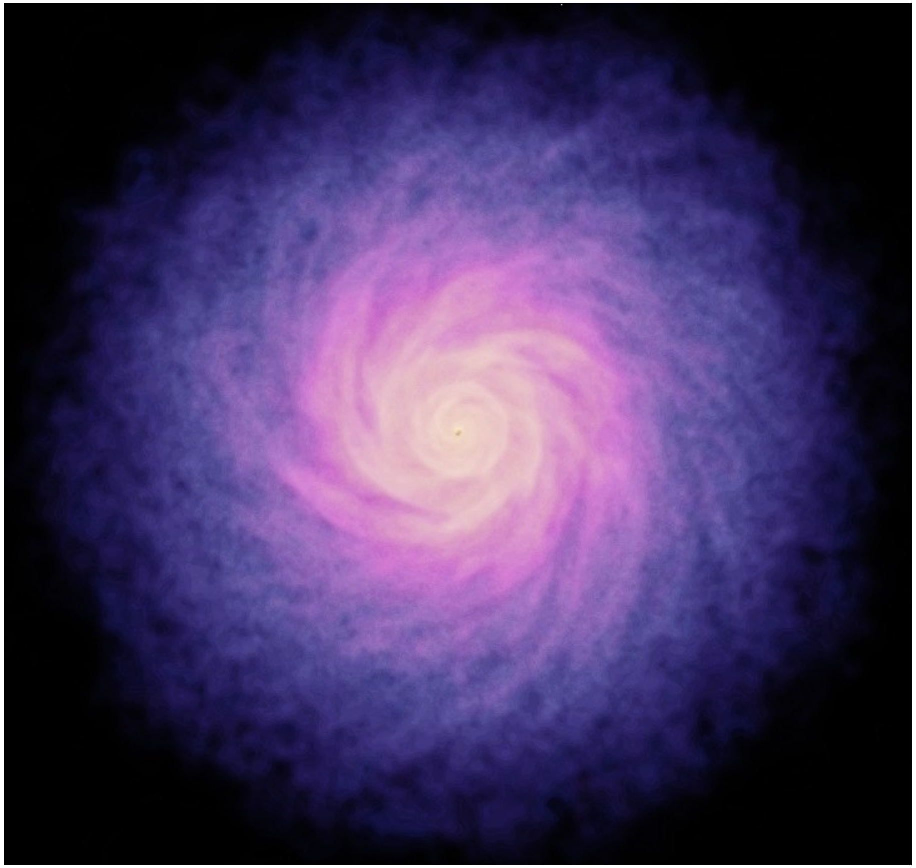
# BHs in individual galaxies

# The constructed compound galaxies are stable when evolved in isolation

## TIME EVOLUTION OF AN ISOLATED GALAXY WITH A CENTRAL BLACK HOLE

star formation rate





# Galaxy formation and accretion on supermassive black holes appear to be closely related

## BLACK HOLES MAY PLAY AN IMPORTANT ROLE IN THEORETICAL GALAXY FORMATION MODELS

Observational evidence suggests a link between BH growth and galaxy formation:

- $M_B$-$\sigma$ relation
- Similarity between cosmic SFR history and quasar evolution

Theoretical models often assume that BH growth is self-regulated by **strong** feedback:

- Blow out of gas in the halo once a crtitical $M_B$ is reached
  Silk & Rees (1998), Wyithe & Loeb (2003)

**Feedback by AGN may:**

- Solve the cooling flow riddle in clusters of galaxies
- Explain the cluster-scaling relations, e.g. the tilt of the $L_x$-T relation
- Explain why ellipticals are so gas-poor
- Drive metals into the IGM by quasar-driven winds
- Help to reionize the universe and surpress star formation in small galaxies

***Galaxy formation models need to include the growth and feedback of black holes !***

***This also applies to simulations !***

# Sink-particles and a simple parameterization of the accretion rate are used to model the growth of black holes

THE IMPLEMENTED BLACK HOLE ACCRETION MODEL

## Growth of Black Holes

Bondi-Hoyle-Lyttleton type accretion rate parameterization:

$$\dot{M}_{\rm B} = \alpha \times 4\pi R_{\rm B}^2 \, \rho \, c_s \simeq \frac{4\pi \alpha G^2 M_\bullet^2 \, \rho}{(c_s^2 + v^2)^{3/2}}$$

Limitation by the Eddington rate:

$$\dot{M}_\bullet = \min(\dot{M}_{\rm B}, \dot{M}_{\rm Edd})$$

## Feedback by Black Holes

Standard radiative efficiency:

$$L_{\rm bol} = 0.1 \times \dot{M}_\bullet \, c^2$$

Thermal coupling of some fraction of the energy output to the ambient gas:

$$\dot{E}_{\rm feedback} = f \times L_{\rm bol} \qquad f \simeq 5\%$$

## Implementation in SPH simulation code

Additions in the parallel GADGET-2 code:

- BH sink particles swallow gas stochastically from their local neighbourhoods, in accordance with the estimated BH accretion rate
- Feedback energy is injected locally into the thermal reservoir of gas
- On-the-fly FOF halo finder detects emerging galaxies and provides them with a seed black hole
- BHs are merged if they reach small separations and low enough relative speeds

# Growth rate of black holes in isolated galaxies

## THREE PHASES OF BLACK HOLE GROWTH

**Bondi-growth:**

$$\dot{M}(t) = \frac{M_0}{1 - 4\pi\alpha\rho G^2 M_0 t / c^3}$$

**Eddington-growth:**

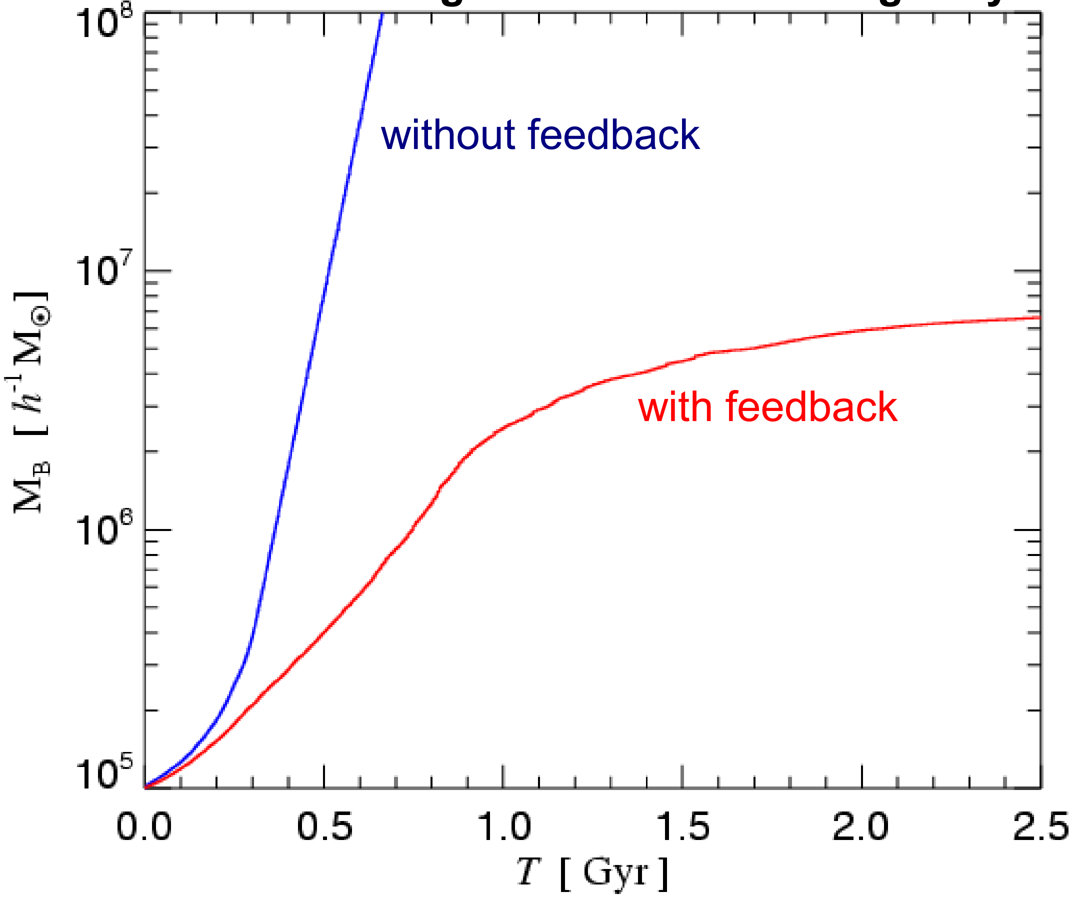
$$\dot{M}(t) = M_0 \exp\left(\frac{t}{t_S}\right)$$

**Slow, feedback regulated growth:**

$$\frac{\mathrm{d}E_{\mathrm{cool}}}{\mathrm{d}t} = \Lambda(T)\,\rho\,M_{\mathrm{gas}}$$

$$\frac{\mathrm{d}E_{\mathrm{heat}}}{\mathrm{d}t} = 0.1 f\,\dot{M}c^2 \propto \frac{\rho M_{\mathrm{B}}^2}{T^{3/2}}$$

Black hole growth in an isolated galaxy



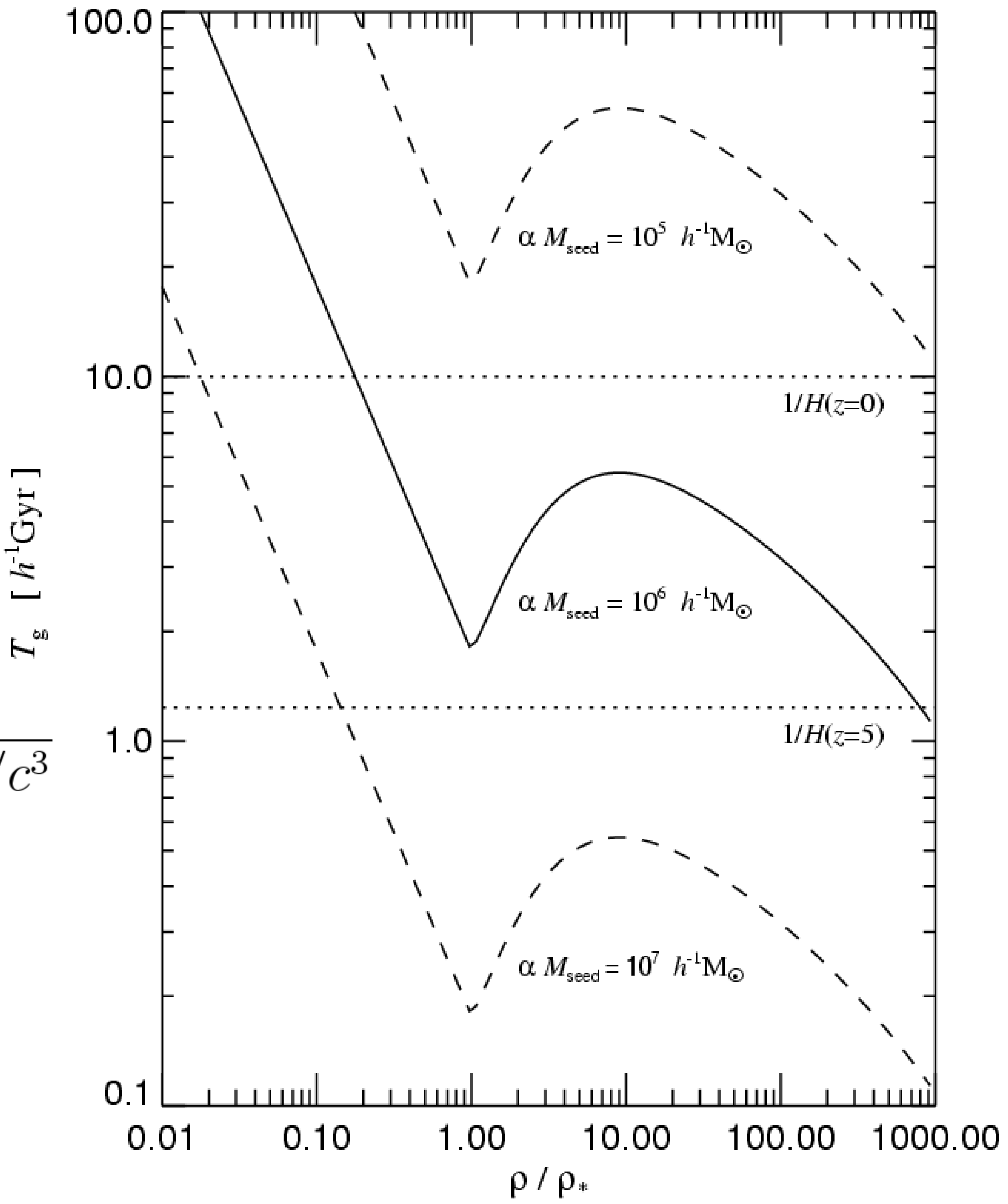
- $\mathbf{T_{equal}}$ independent of density
- for: $T_{\mathrm{equal}} \simeq T_{\mathrm{vir}},\ M_{\mathrm{gas}} \propto M_{\mathrm{halo}}$

$$M_{\mathrm{B}} \propto V_{\mathrm{vir}}^{7/2}$$

- If $\mathbf{T_{equal}}$ **>>** $\mathbf{T_{vir}}$, the hole is too big for the halo. It can blow gas out of the halo until there is none left.

## Since the black hole particles are embedded in star-forming gas, the Bondi growth-phase depends on the sub-resolution model for the ISM

RELATION OF BH ACCRETION TO THE STAR FORMATION MODEL



**Bondi-growth:**

$$\dot{M}(t) = \frac{M_0}{1 - 4\pi\alpha\rho\, G^2 M_0 t / c^3}$$

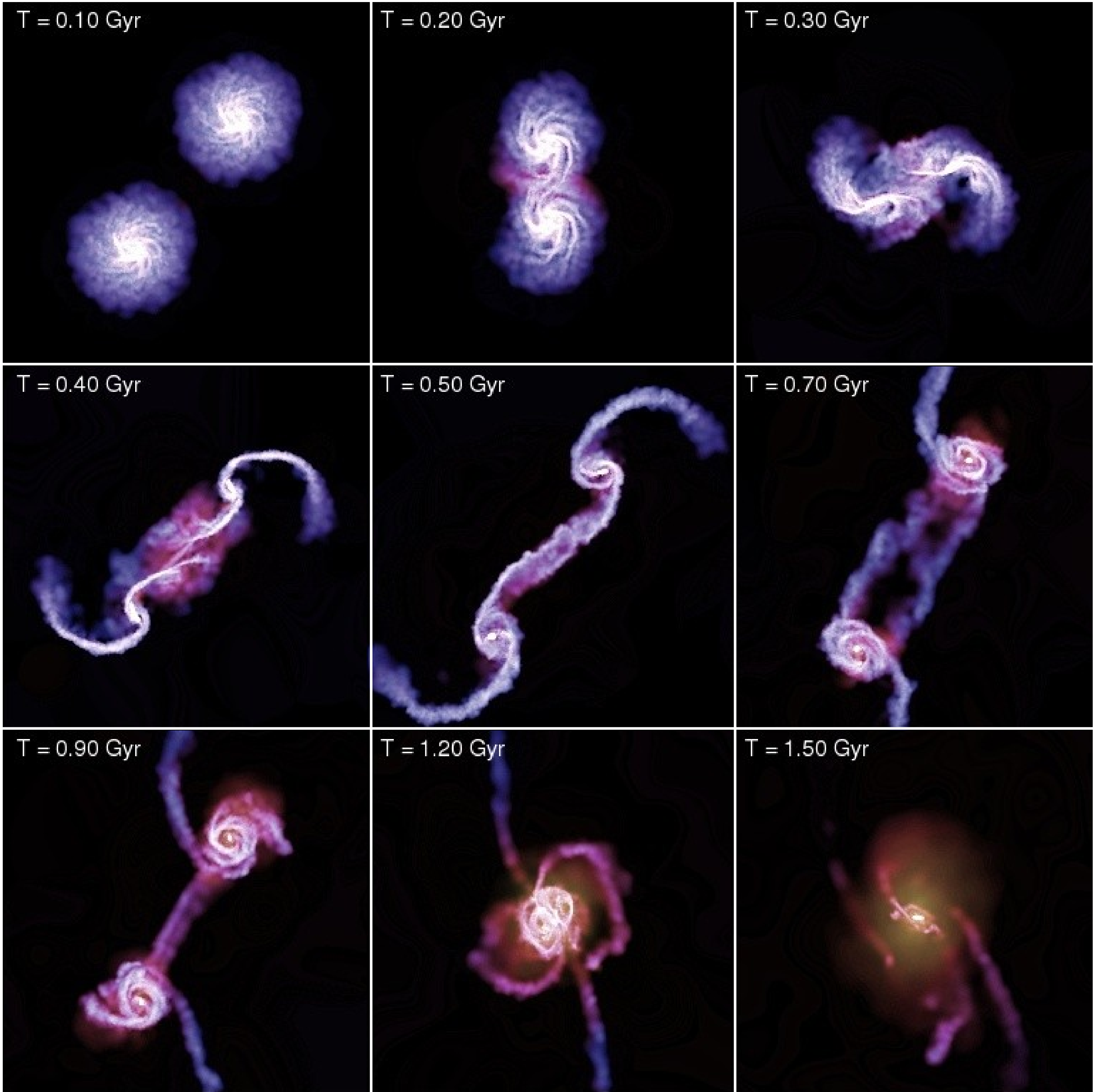
$$t_g = \frac{c^3}{4\pi\alpha\rho\, G^2 M_0}$$

→ If the seed black holes are too small, they will never grow.

# Galaxy collisions with BHs

In major-mergers between two disk galaxies, tidal torques extract angular momentum from cold gas, providing fuel for nuclear starbursts

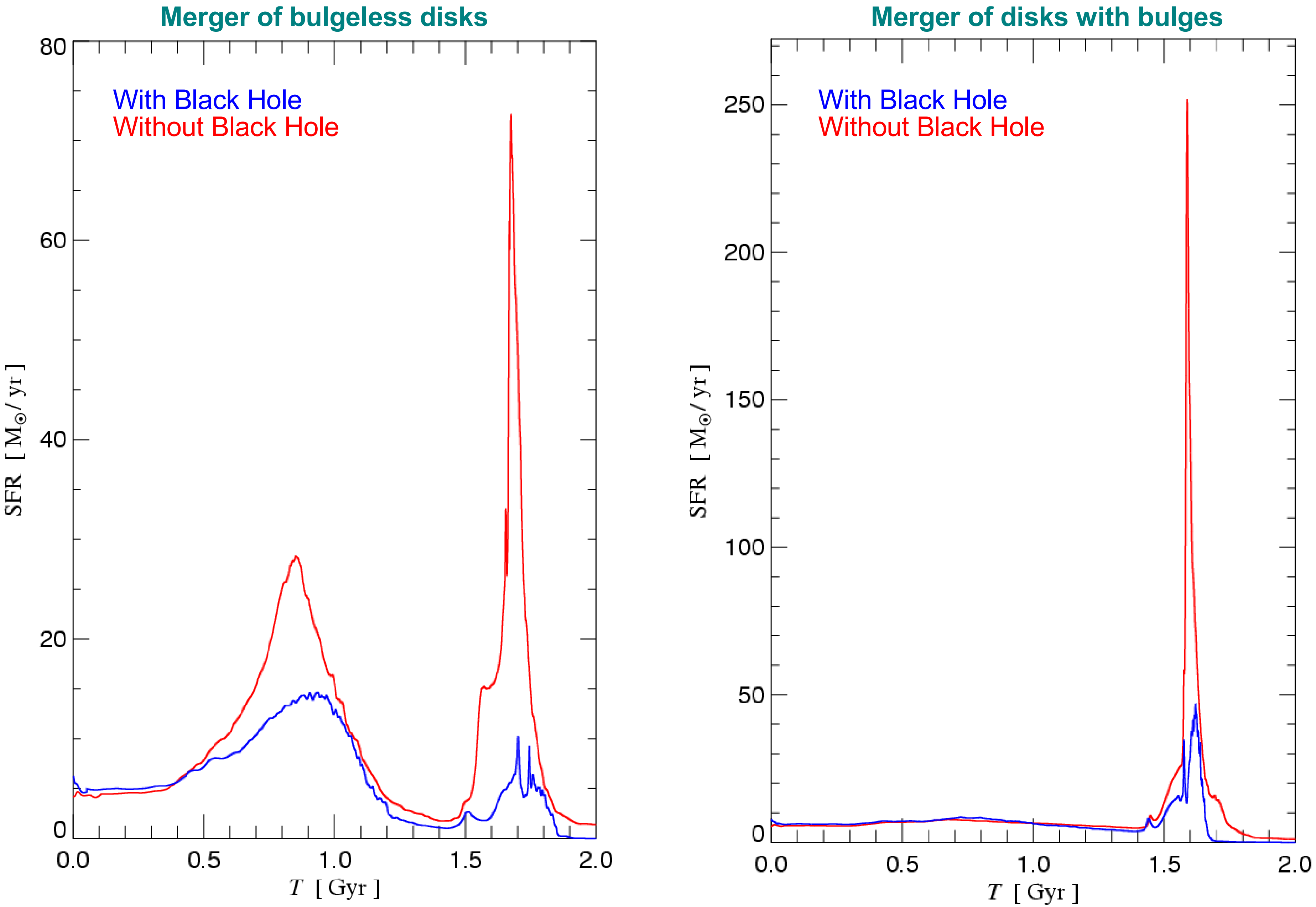
TIME EVOLUTION OF A PROGRADE MAJOR MERGER



**This may also fuel a central AGN !**

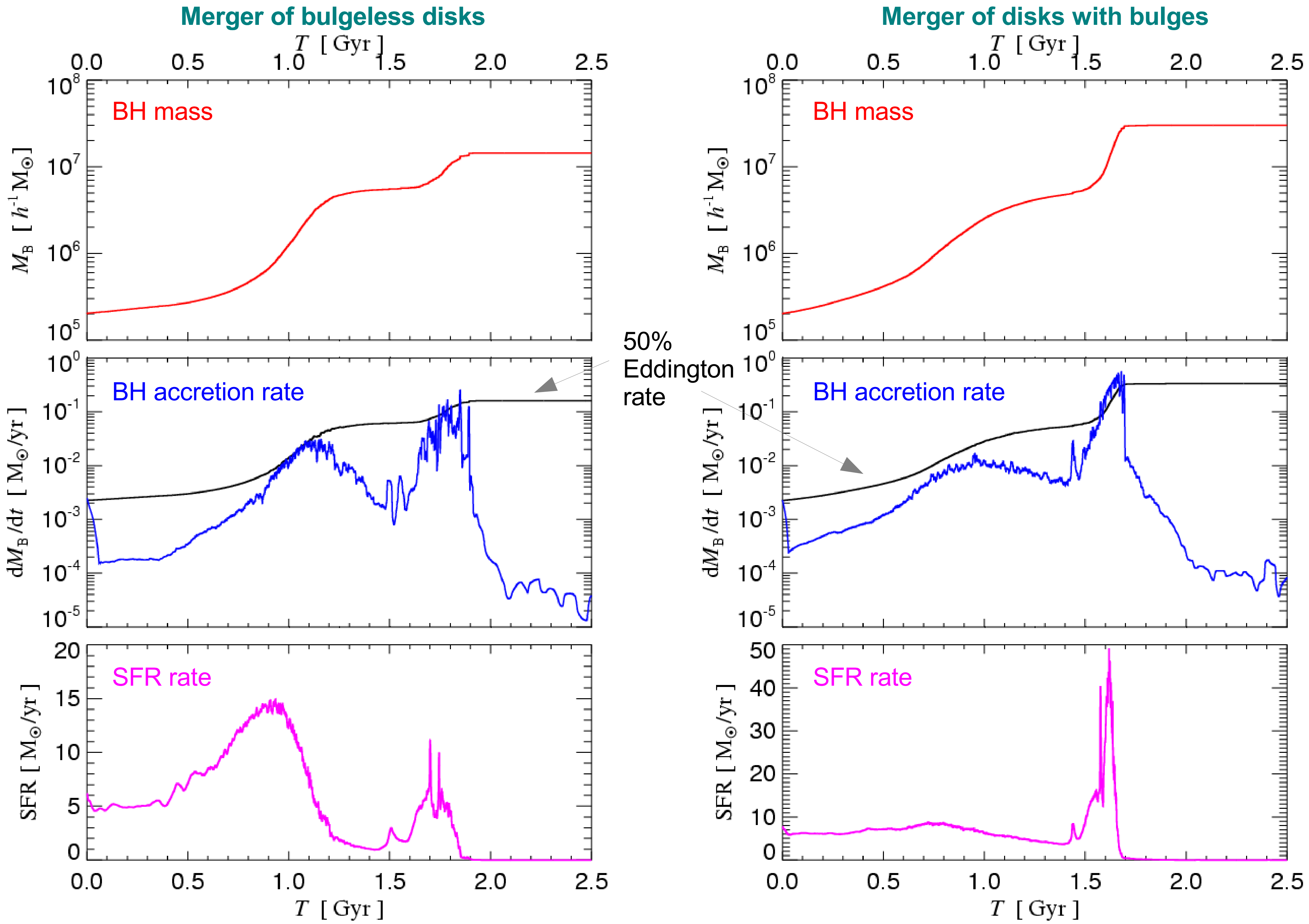
# The feedback by the AGN can reduce the strength of the starburst

## COMPARISON OF STAR FORMATION IN MERGERS WITH AND WITHOUT BLACK HOLE



# Mergers of disk galaxies trigger starburts and ignite central AGN activity

## TIME EVOLUTION OF STAR FORMATION RATE AND BLACK HOLE GROWTH IN A MERGER



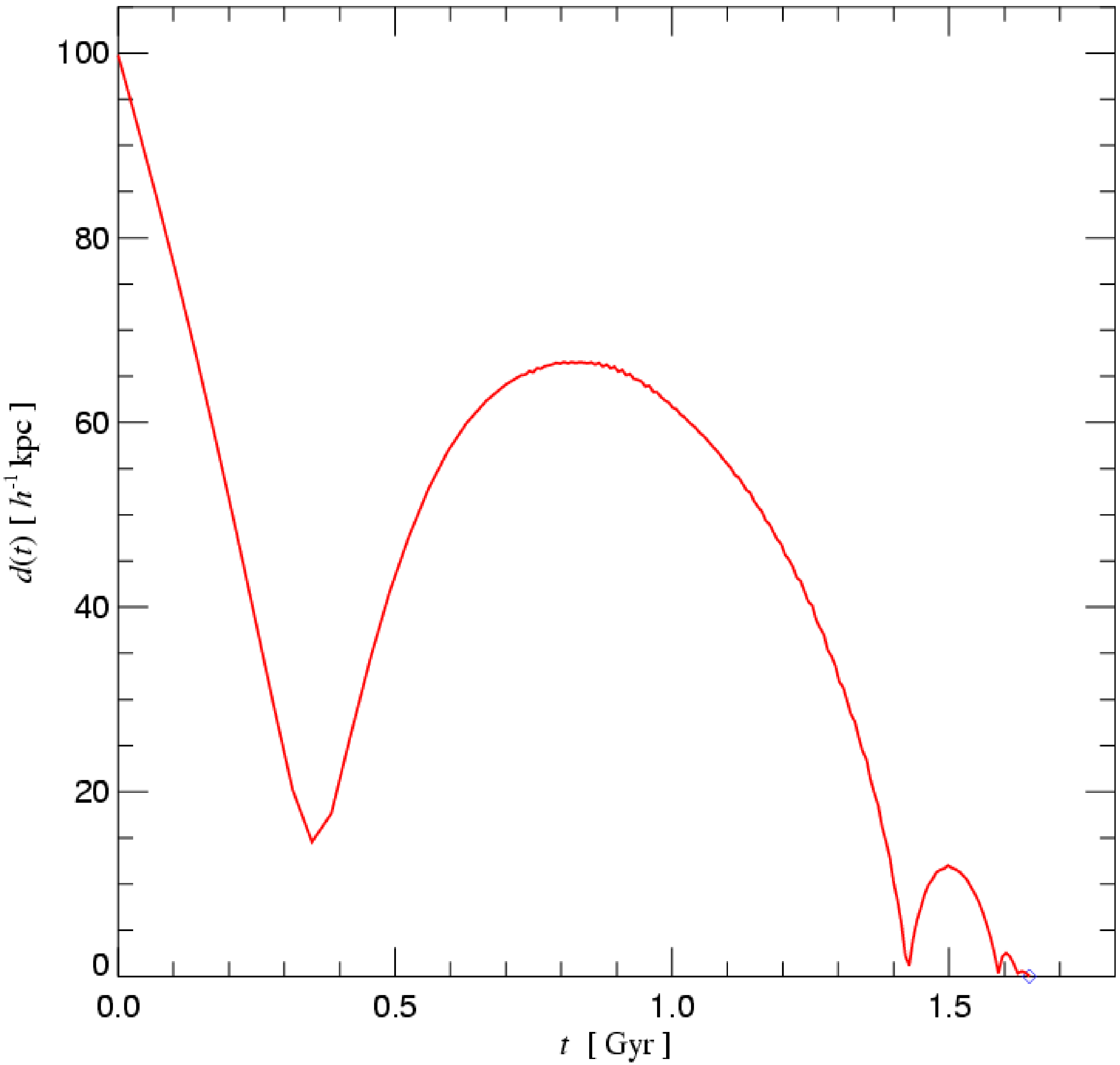
**Merger of bulgeless disks**

**Merger of disks with bulges**

50%
Eddington
rate

# Galaxy mergers bring their central supermassive black holes quickly to separations less than ~100 pc

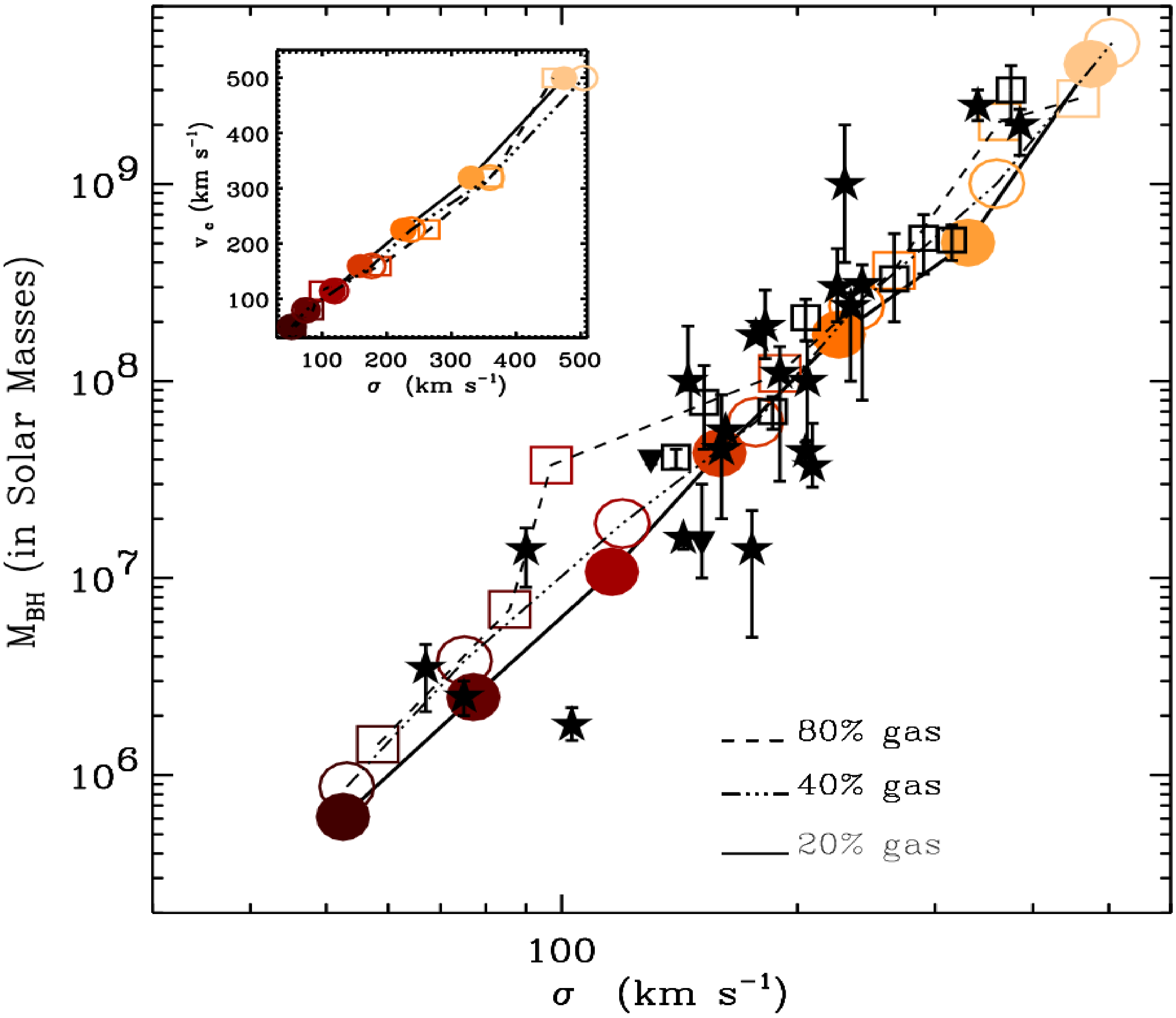
## APPROACH OF THE BLACK HOLES IN MERGER SIMULATIONS



Note: The actual formation of a black hole binary, and the hardening of it, cannot presently be addressed by our simulations in an adequate way, due to lack of spatial dynamic range.

# The relation between final black hole mass and stellar velocity dispersion follows a Magorrian-type relationship

BLACK HOLE MASSES IN MERGER REMNANTS



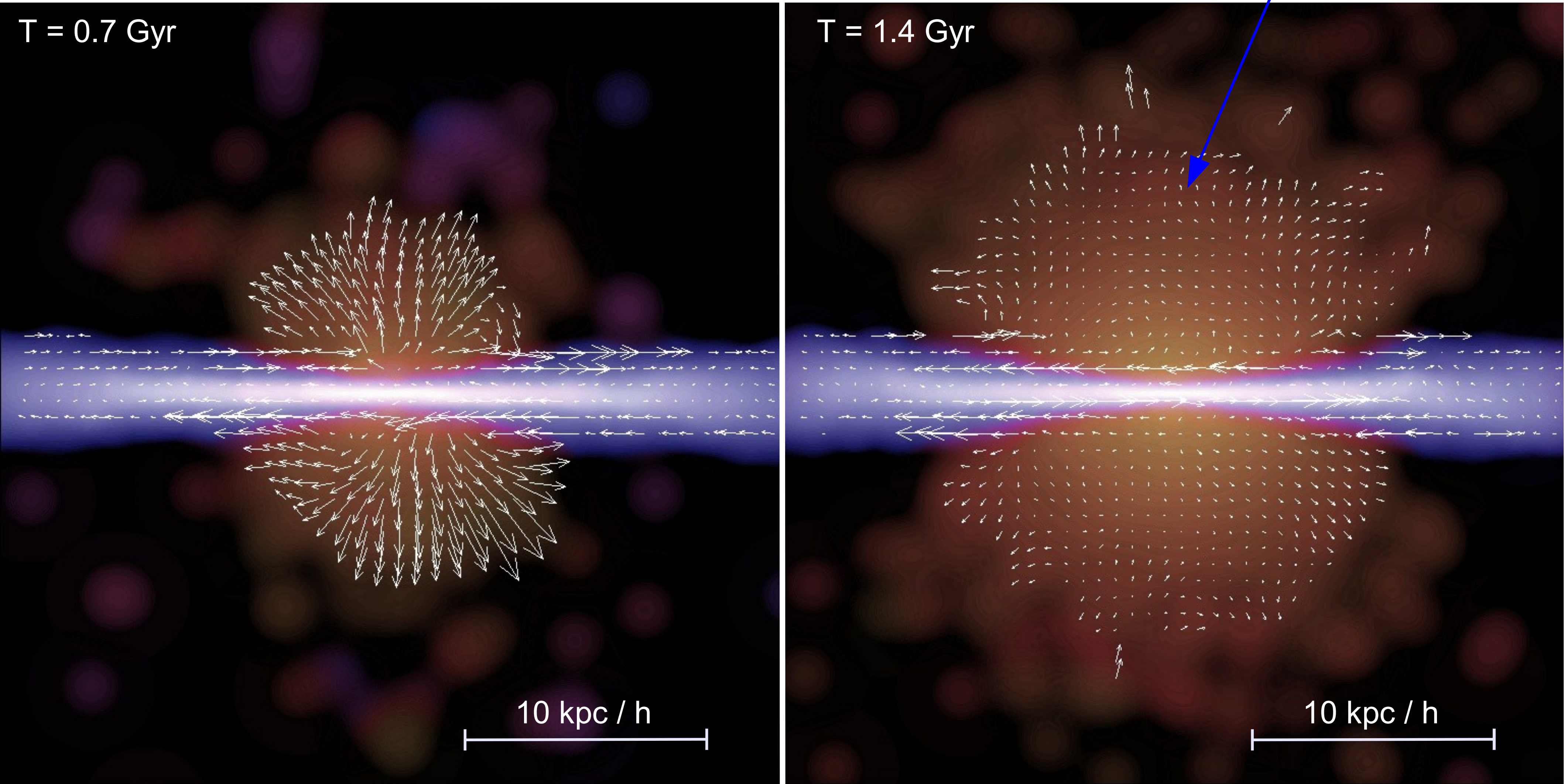
# At low accretion rates, feedback by the central black hole activity may blow a weak wind into the halo

GAS FLOW INTO THE HALO

**Isolated disk galaxy with bulge**

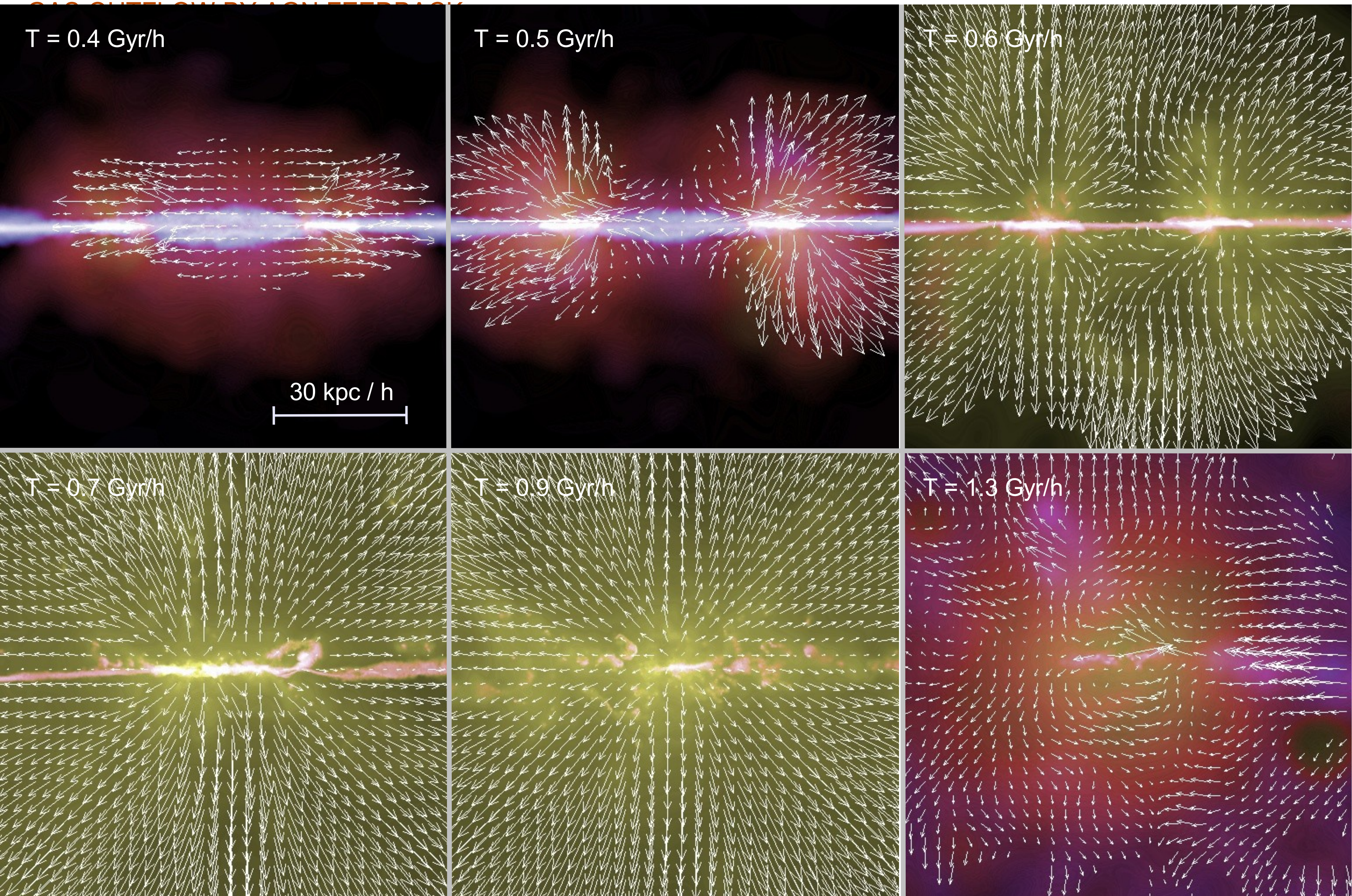
**Generated hot halos holds 1-2% of the gas**

(dynamic range in gas surface density ~$10^6$ )



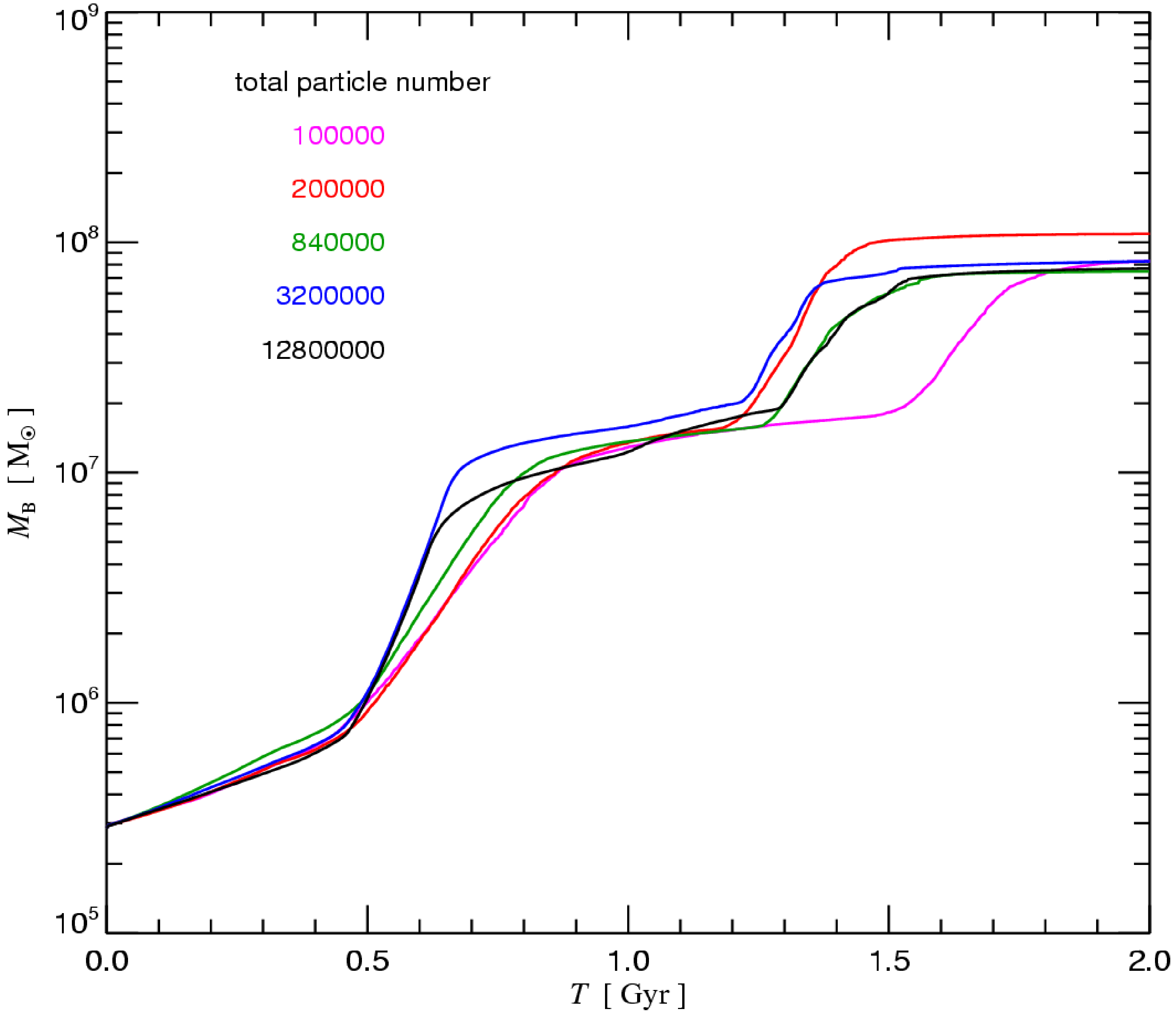
# The feedback by the central black activity may drive a strong quasar wind

(outflow reaches speeds of up to ~1800 km/sec)



# Robust numerical behaviour for the final black hole mass as a function of resolution is achieved

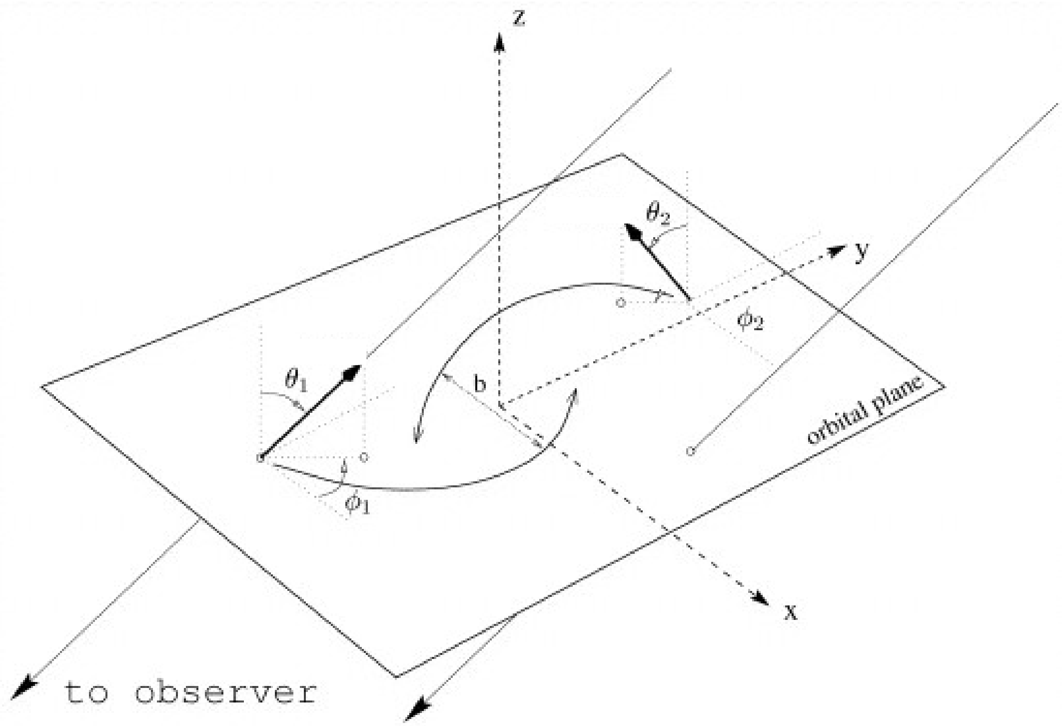
BLACK HOLE MASS EVOLUTION IN A MERGER CARRIED OUT WITH  DIFFERENT RESOLUTION

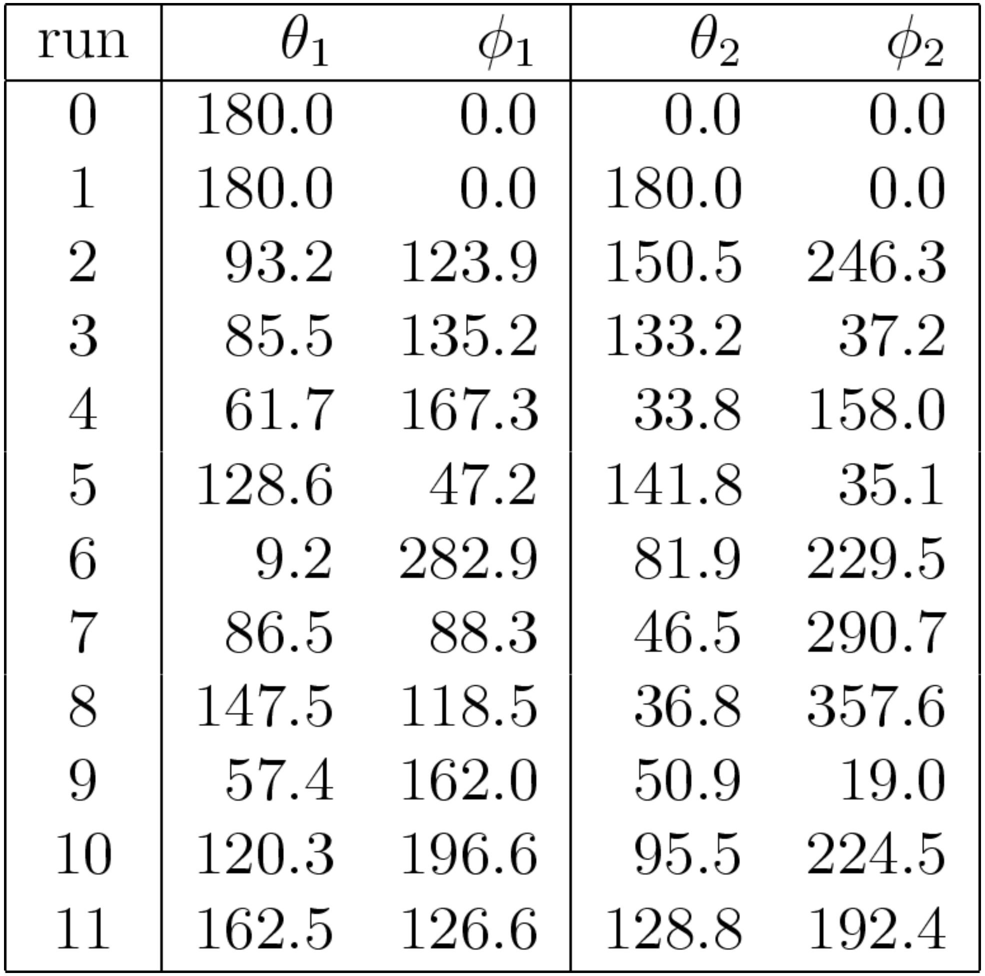


# Remnant properties

# A series of merger simulations is used to test how sensitive the black hole feeding is to the orbital geometry

## ENCOUNTER GEOMETRIES

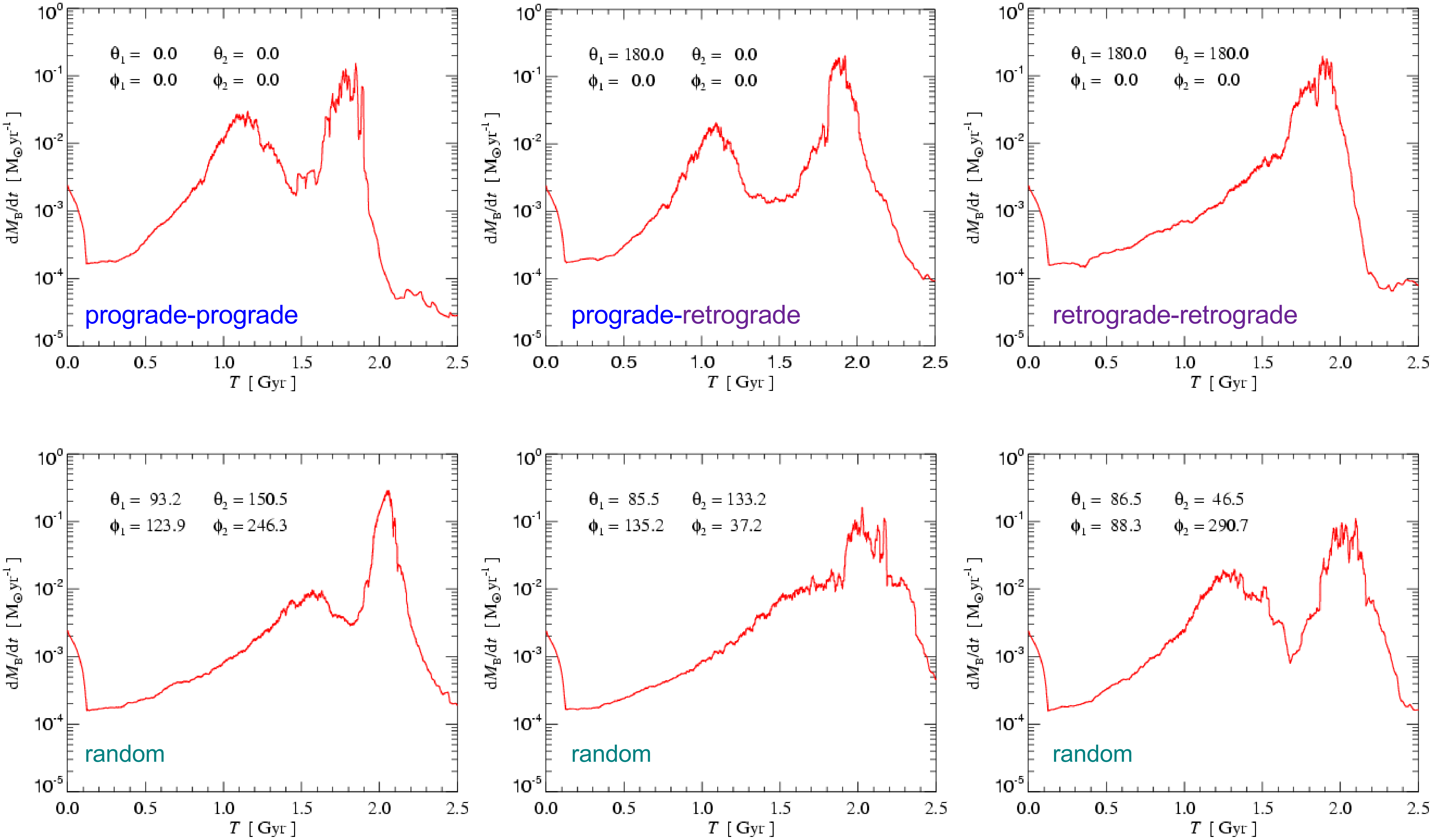




| run | $\theta_1$ | $\phi_1$ | $\theta_2$ | $\phi_2$ |
|---|---|---|---|---|
| 0 | 180.0 | 0.0 | 0.0 | 0.0 |
| 1 | 180.0 | 0.0 | 180.0 | 0.0 |
| 2 | 93.2 | 123.9 | 150.5 | 246.3 |
| 3 | 85.5 | 135.2 | 133.2 | 37.2 |
| 4 | 61.7 | 167.3 | 33.8 | 158.0 |
| 5 | 128.6 | 47.2 | 141.8 | 35.1 |
| 6 | 9.2 | 282.9 | 81.9 | 229.5 |
| 7 | 86.5 | 88.3 | 46.5 | 290.7 |
| 8 | 147.5 | 118.5 | 36.8 | 357.6 |
| 9 | 57.4 | 162.0 | 50.9 | 19.0 |
| 10 | 120.3 | 196.6 | 95.5 | 224.5 |
| 11 | 162.5 | 126.6 | 128.8 | 192.4 |

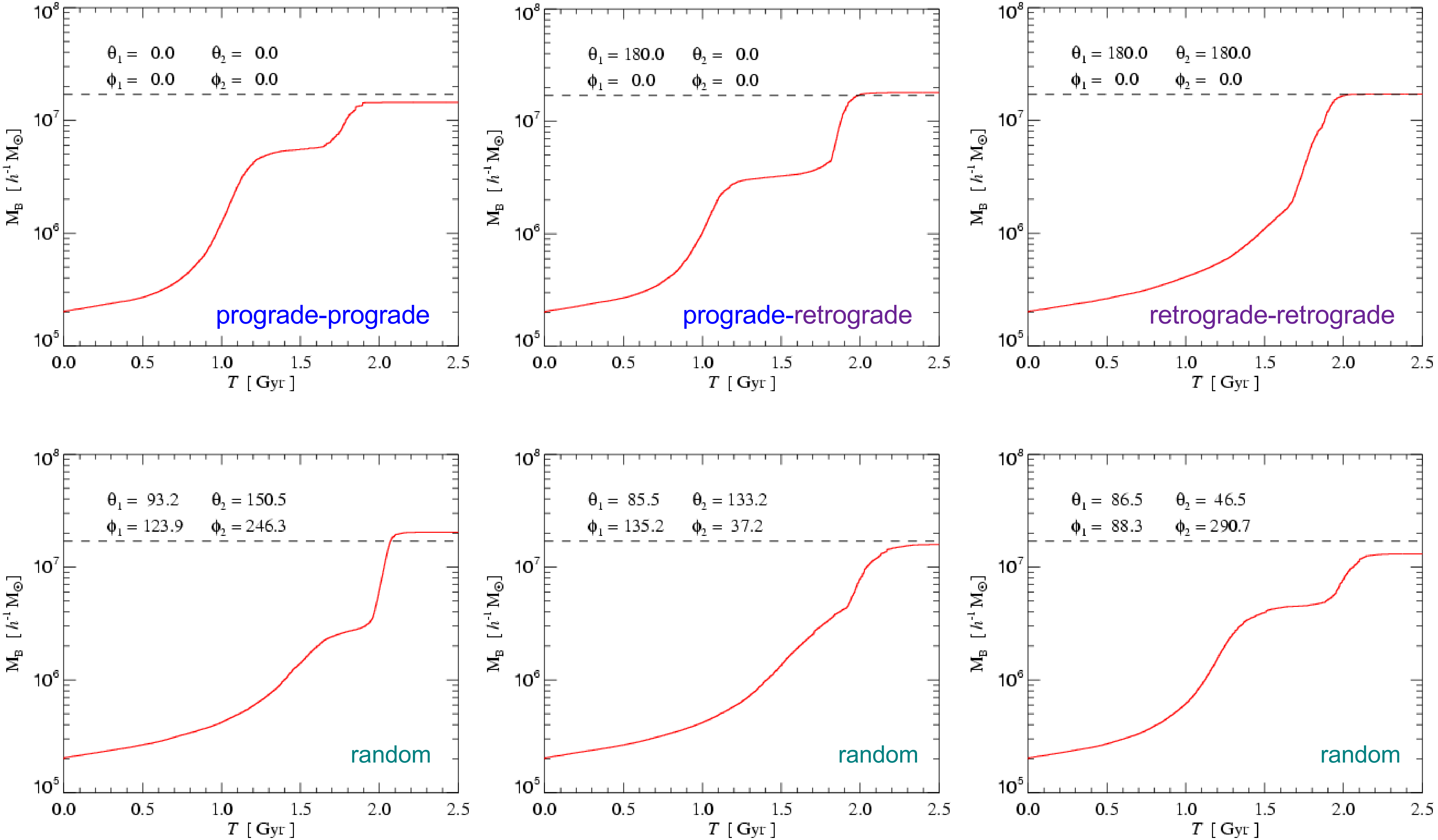
# The orientation of the galaxies in the merger affects the accretion pattern

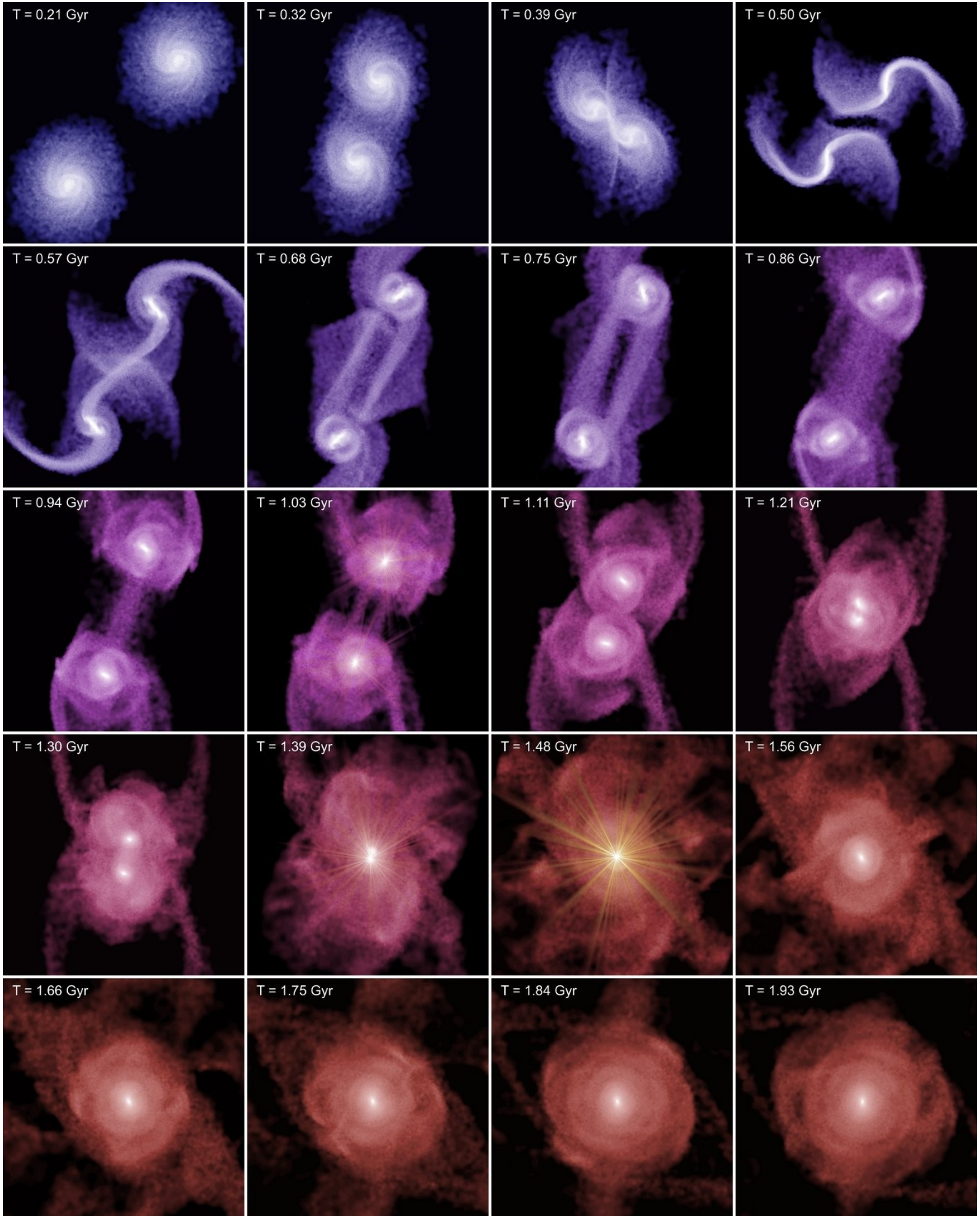
## BLACK HOLE ACCRETION RATE FOR DIFFERENT GALAXY ORIENTATIONS



# The final black hole mass in the merger remnant is not very sensitive to details of the orbit of the collision

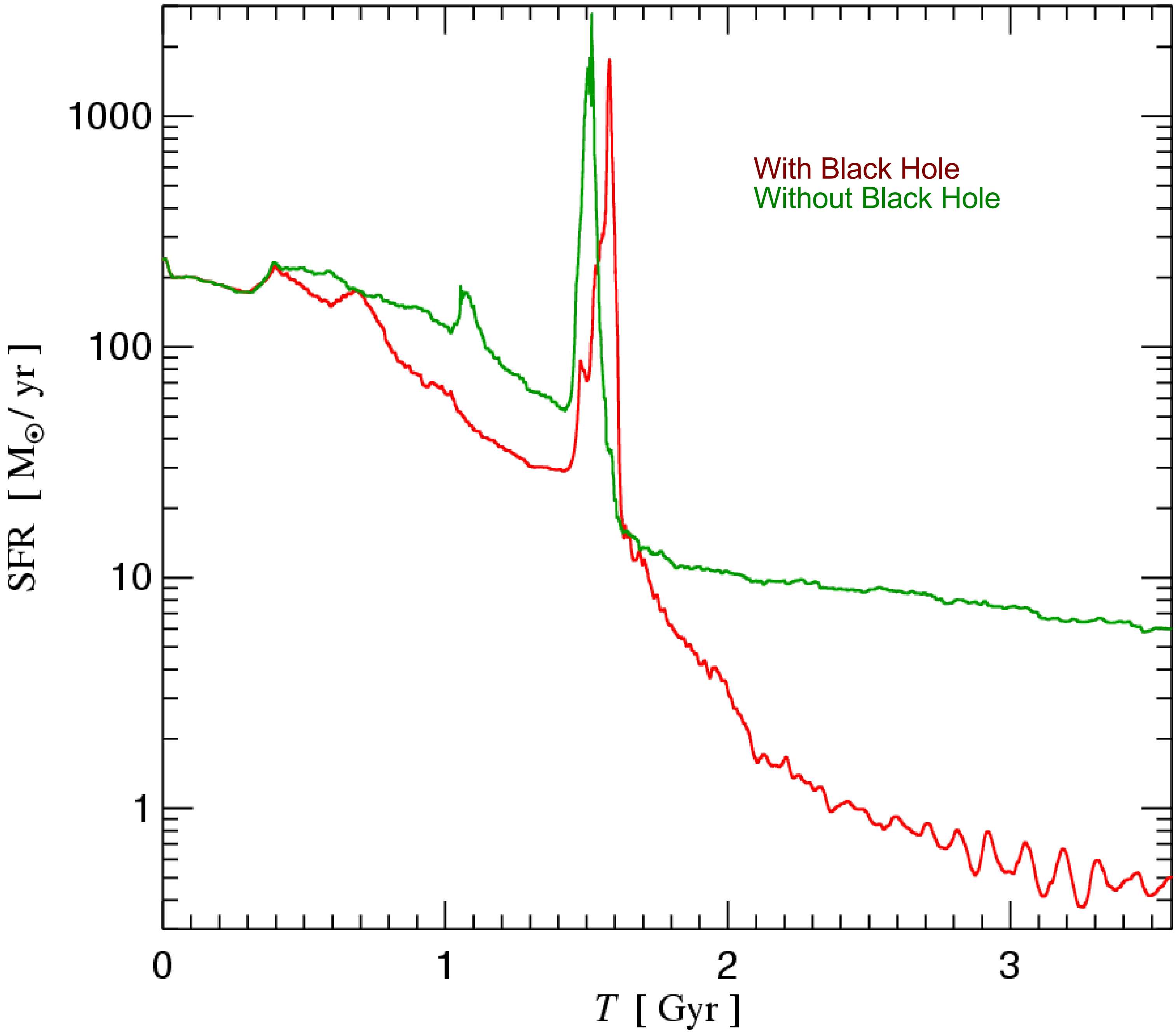
BLACK HOLE MASS FOR DIFFERENT GALAXY ORIENTATIONS




T = 0.21 Gyr
T = 0.32 Gyr
T = 0.39 Gyr
T = 0.50 Gyr
T = 0.57 Gyr
T = 0.68 Gyr
T = 0.75 Gyr
T = 0.86 Gyr
T = 0.94 Gyr
T = 1.03 Gyr
T = 1.11 Gyr
T = 1.21 Gyr
T = 1.30 Gyr
T = 1.39 Gyr
T = 1.48 Gyr
T = 1.56 Gyr
T = 1.66 Gyr
T = 1.75 Gyr
T = 1.84 Gyr
T = 1.93 Gyr

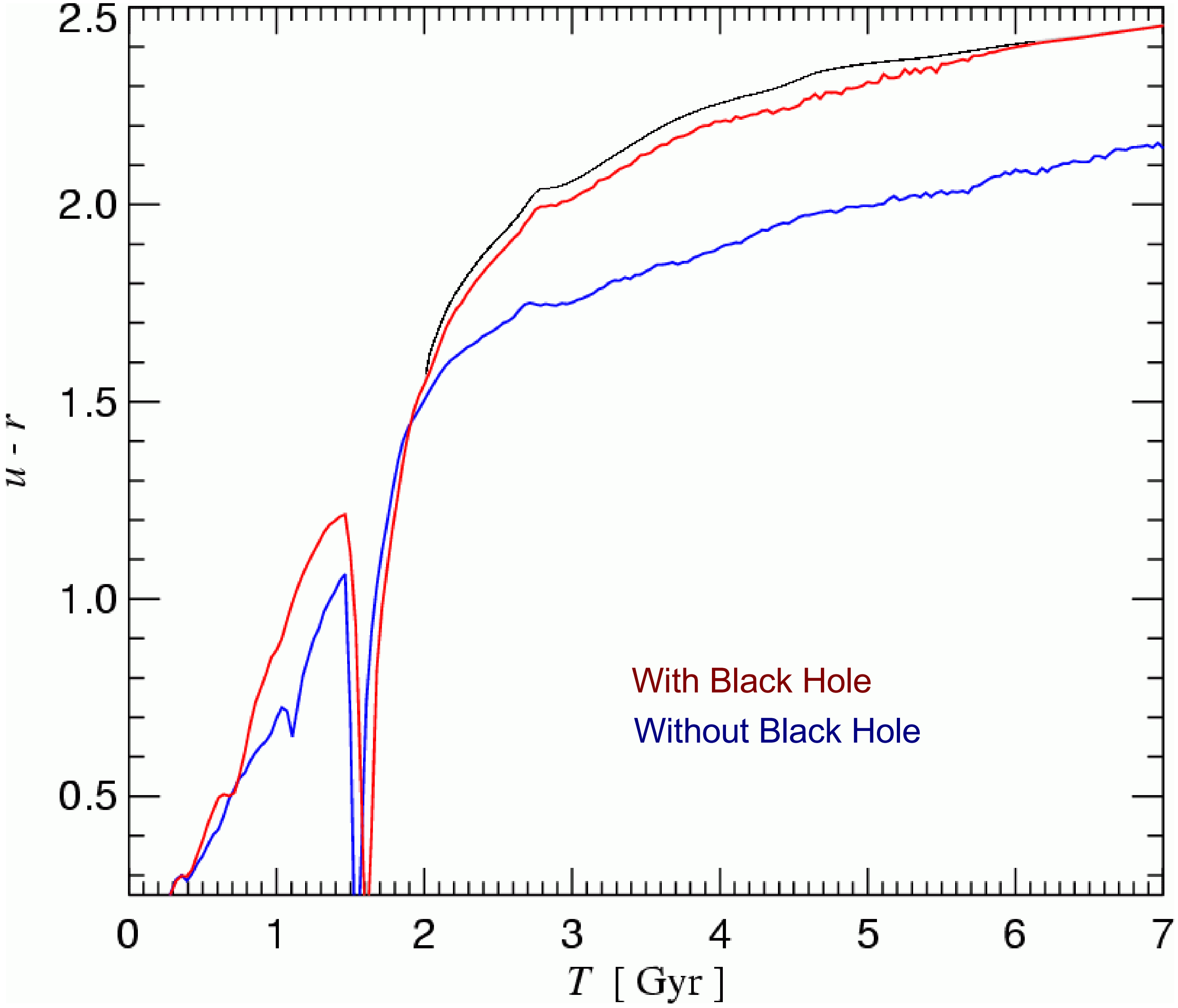
# The feedback by the AGN can reduce the strength of the starburst

## COMPARISON OF STAR FORMATION IN MERGERS WITH AND WITHOUT BLACK HOLE



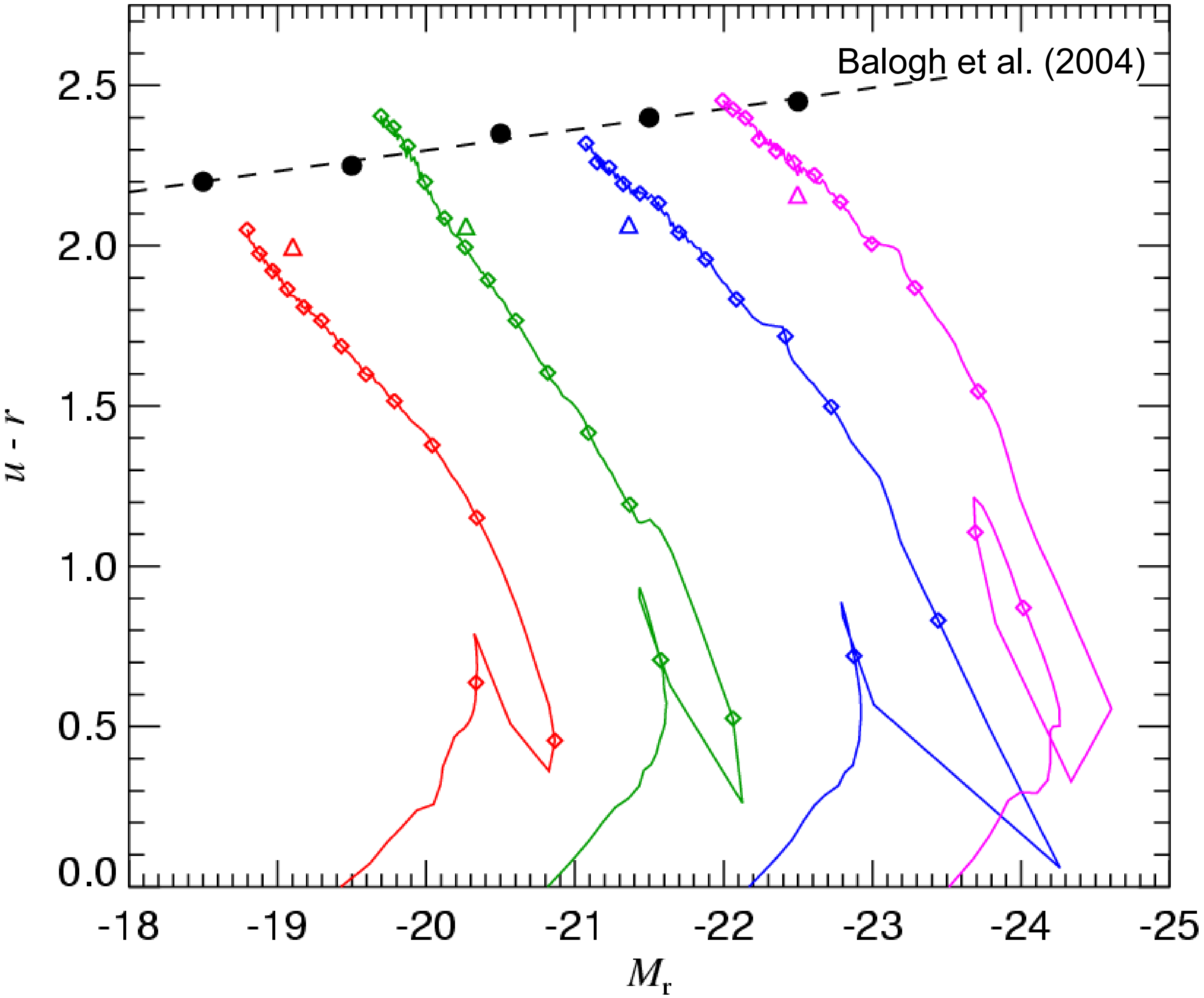
# Remnants in mergers with black holes redden more quickly due to efficient truncation of star formation

## COLOR EVOLUTION IN MERGER SIMULATIONS



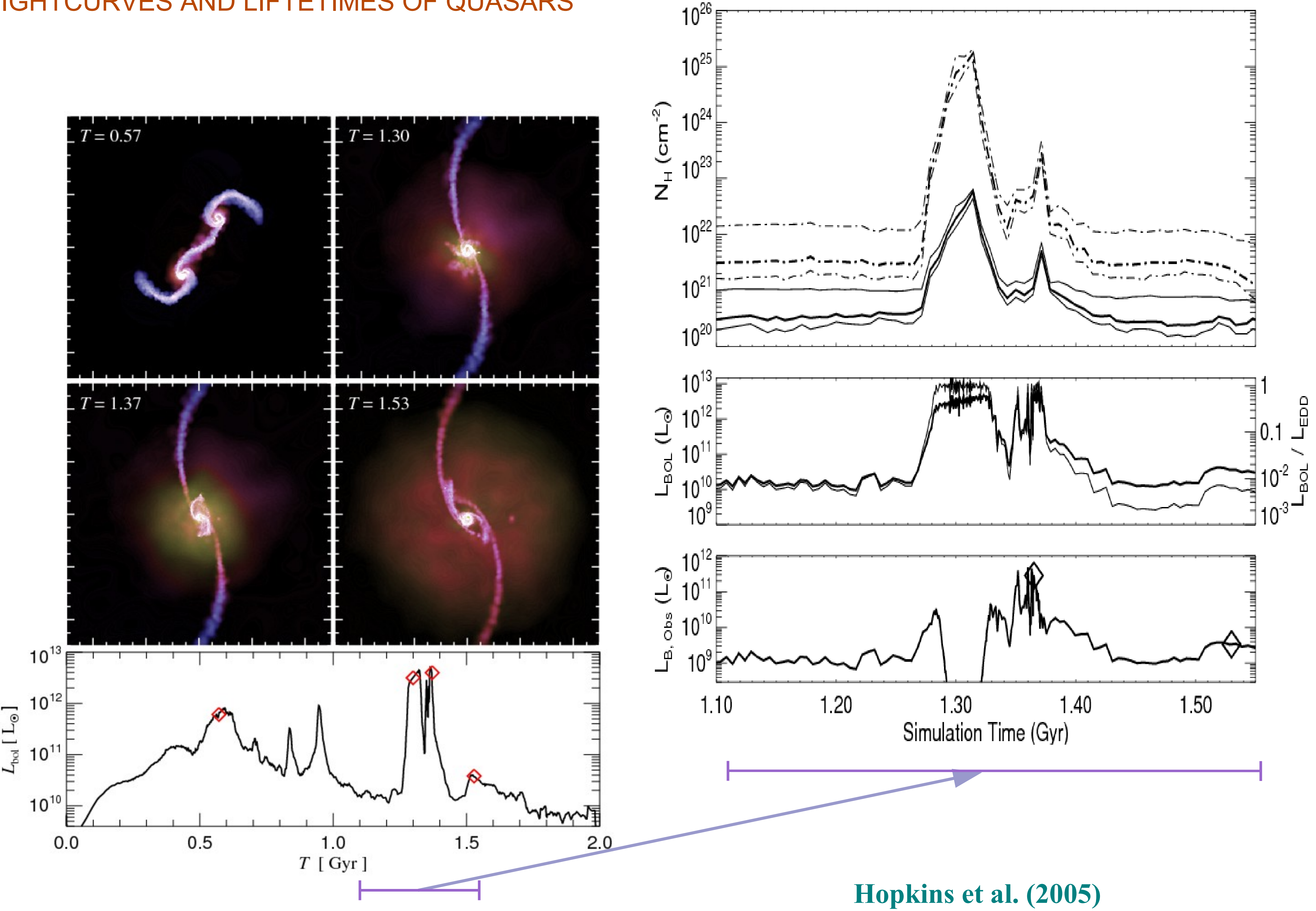
# AGN feedback may help in shaping the observed bimodal color distribution of galaxies

COLOR-MAGNITUDE TRACKS OF MERGERS OF DIFFERENT MASS



# The lifecylce of quasars: **Buried**, **Active**, and then **Dead**

## LIGHTCURVES AND LIFTETIMES OF QUASARS



**Hopkins et al. (2005)**

# Strong nuclear starbusts may leave behind a central luminosity spike in the merger remants

STELLAR PROFILES OF MERGER REMNANTS WITH ISOTHERMAL ISM

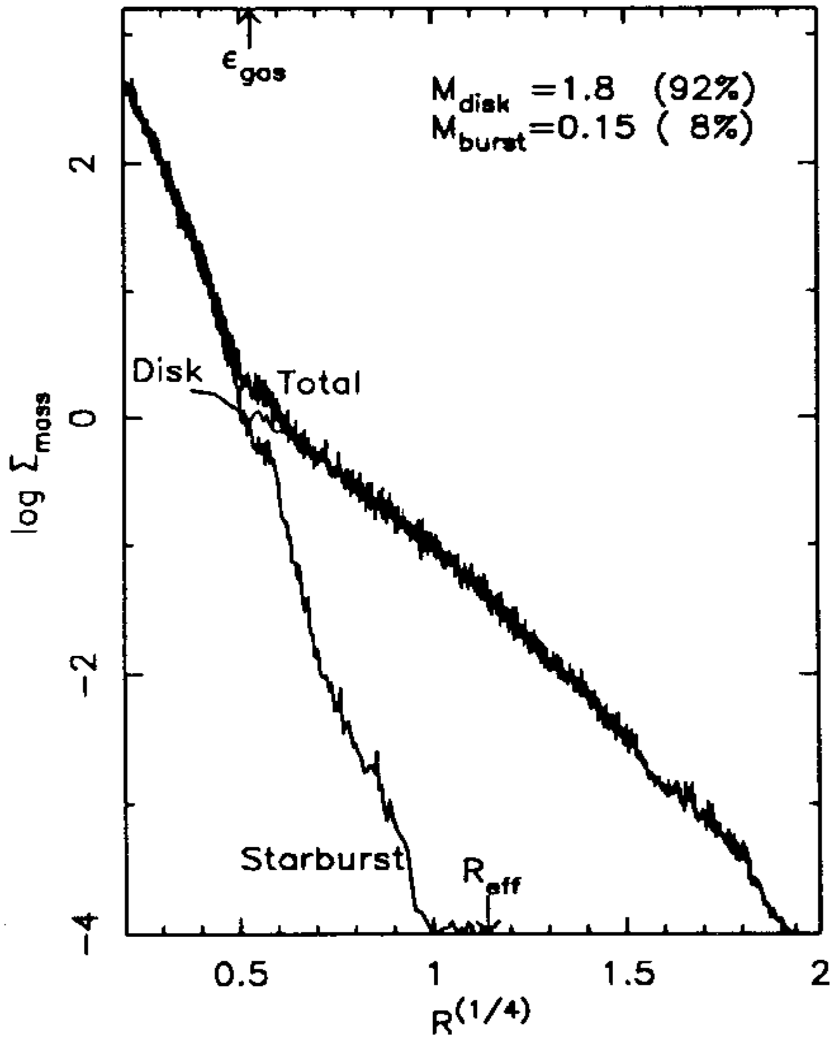


FIG. 1*a*

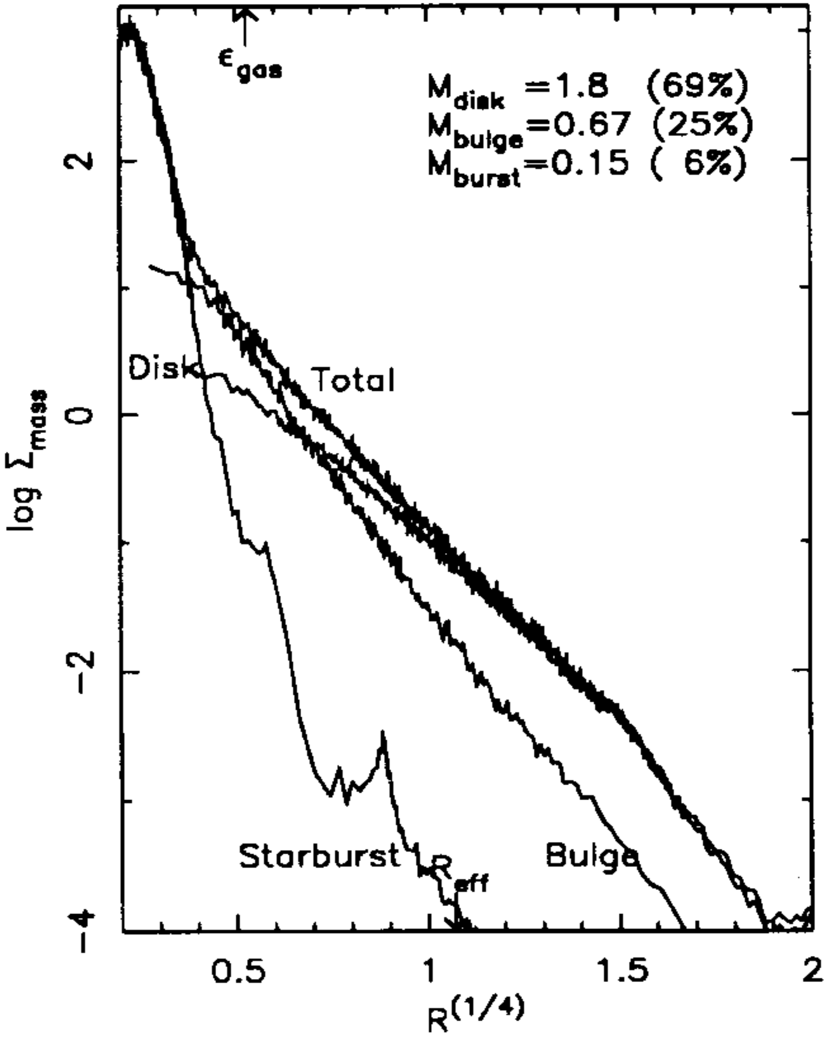
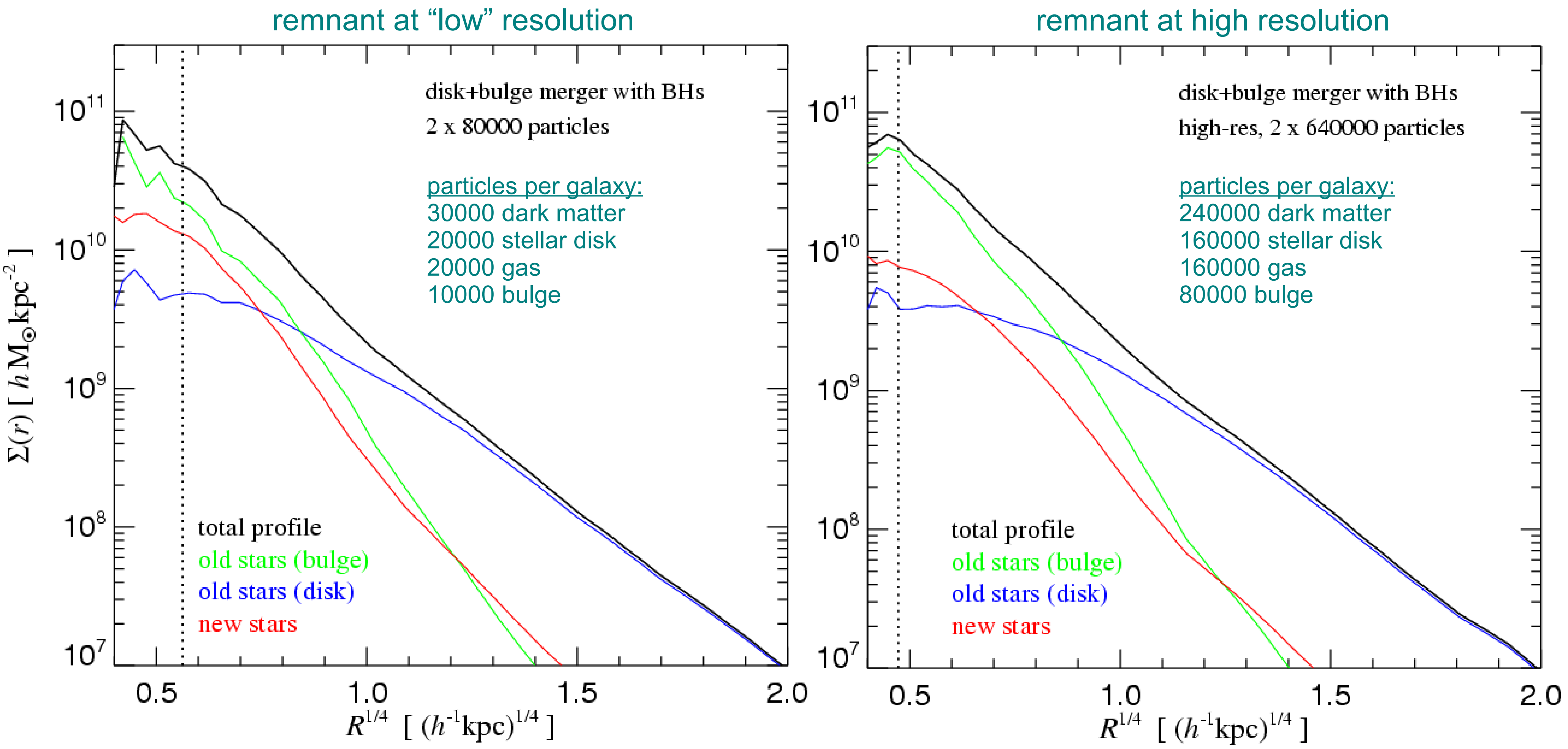


FIG. 1*b*

Mihos & Hernquist (1994)

# The stellar surface brightness profiles of merger remnants with black holes follow $r^{1/4}$ profiles

STELLAR SURFACE DENSITY PROFILES OF MERGER REMNANTS



remnant at “low” resolution

remnant at high resolution

→ quite reasonable convergence