Simulations of quasar feedback

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Main collaborators:

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Phil Hopkins
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- Modelling the galaxy/BH population with semi-analytic simulation models
- Simulations of clusters of galaxies with central AGN
- BH growth and quasar activity in galaxy mergers
- Cosmological hydrodynamical simulations of the joint formation of galaxies and BHs

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Max-Planck-Institut
für Astrophysik

Conference: *The history of nuclear black holes in galaxies*
Harvard-CfA, May, 2006

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

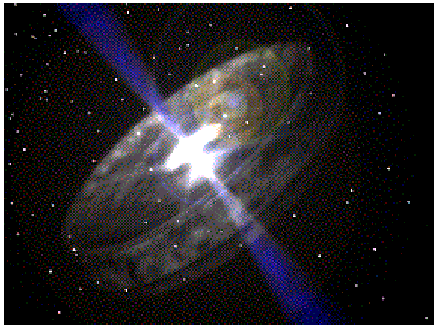
Hydrodynamical simulations of individual galaxies and their BHs

Cosmologial hydro-simulations of galaxy formation with BHs

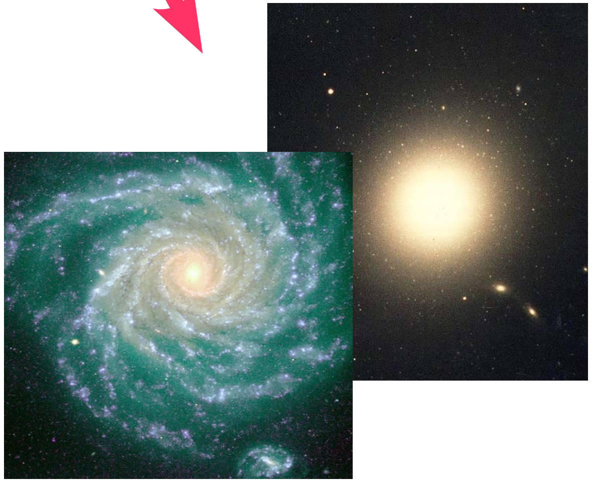
Hydro-simulations of accretion flows onto BHs and/or their jets

Ab initio treatment of the physics

quasars



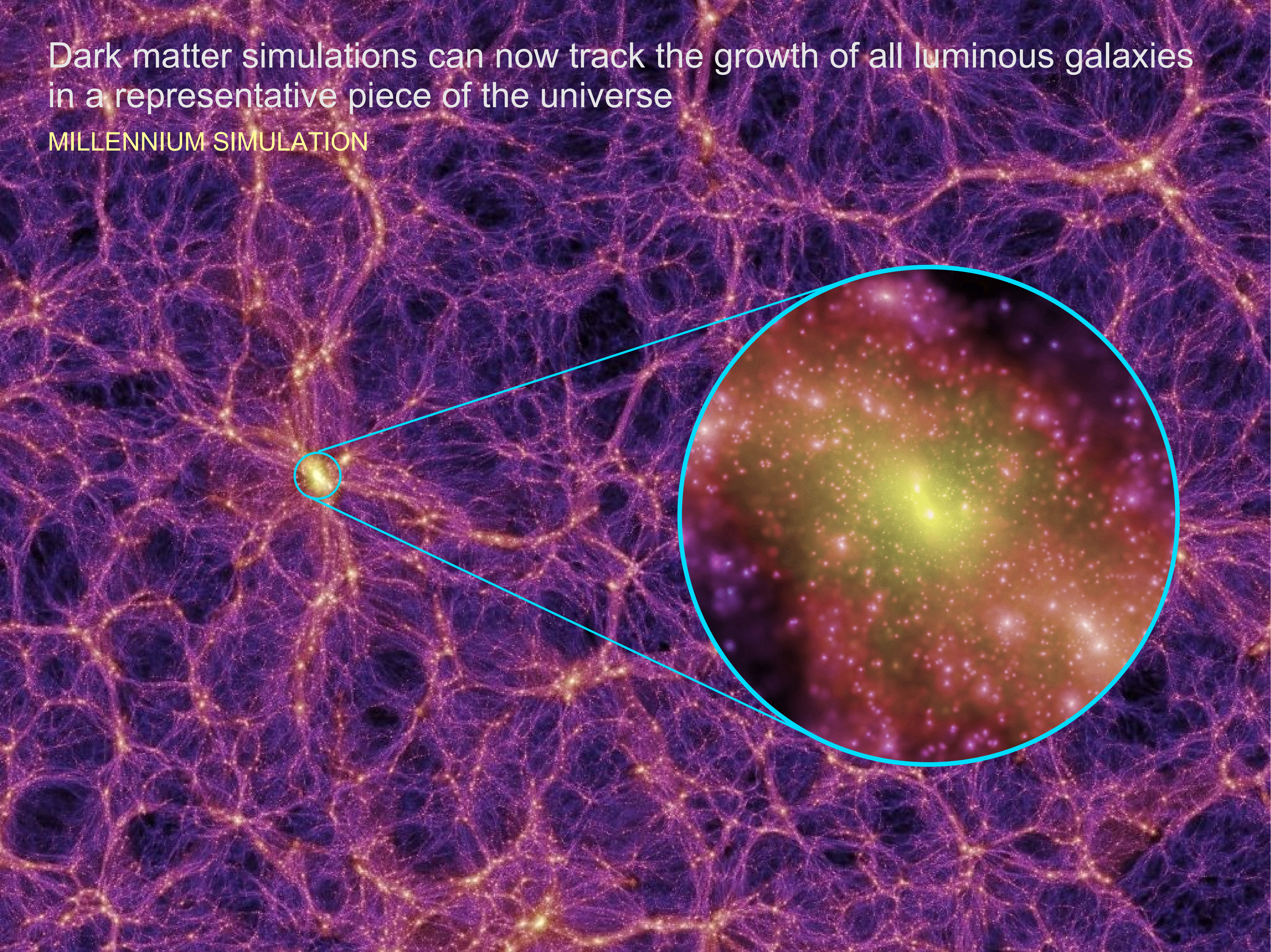
What's the connection?



galaxies

Dark matter simulations can now track the growth of all luminous galaxies in a representative piece of the universe

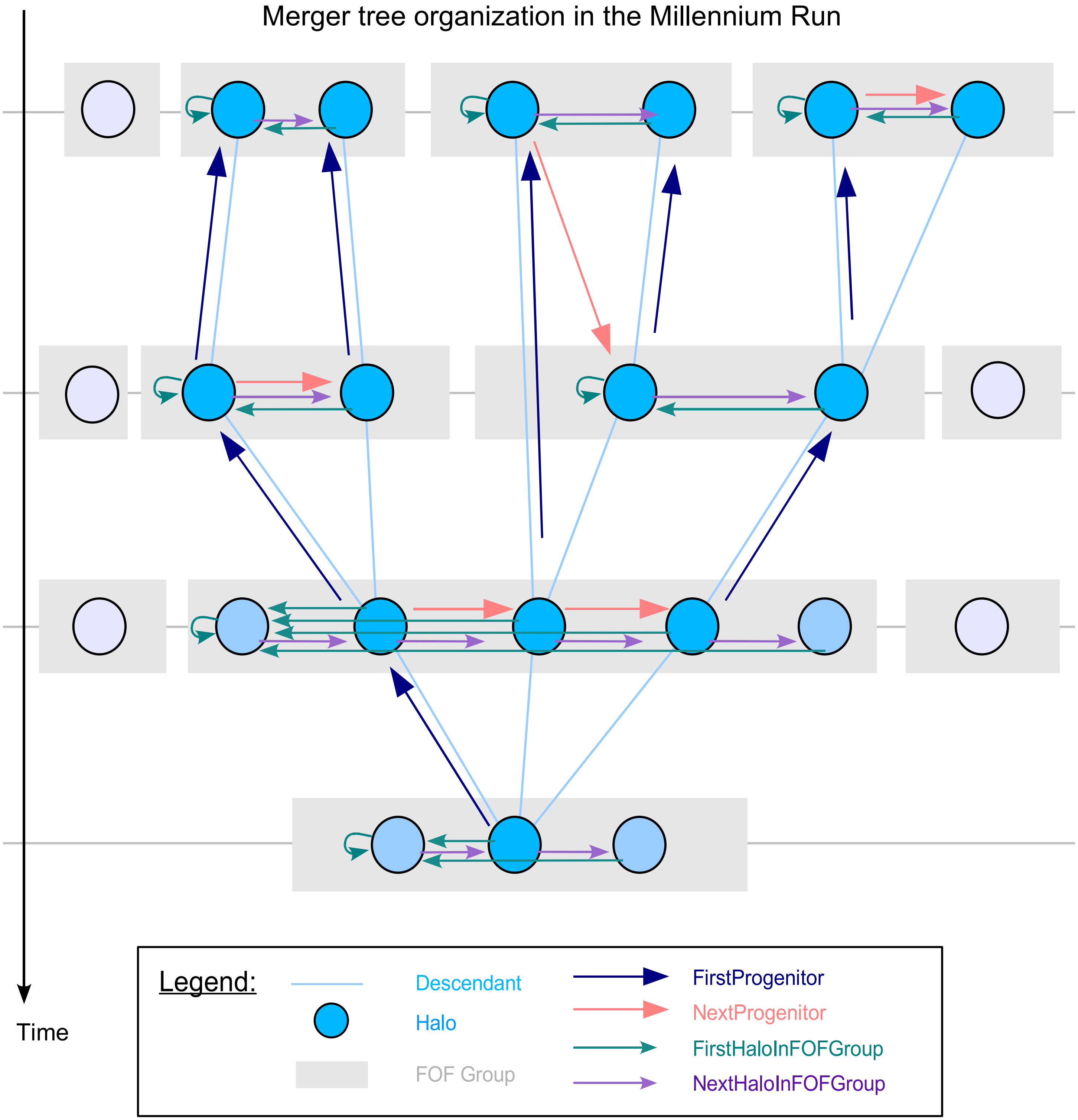
MILLENNIUM SIMULATION



The merger-tree of the Millennium Run connects about 800 million subhalos

SCHEMATIC MERGER TREE

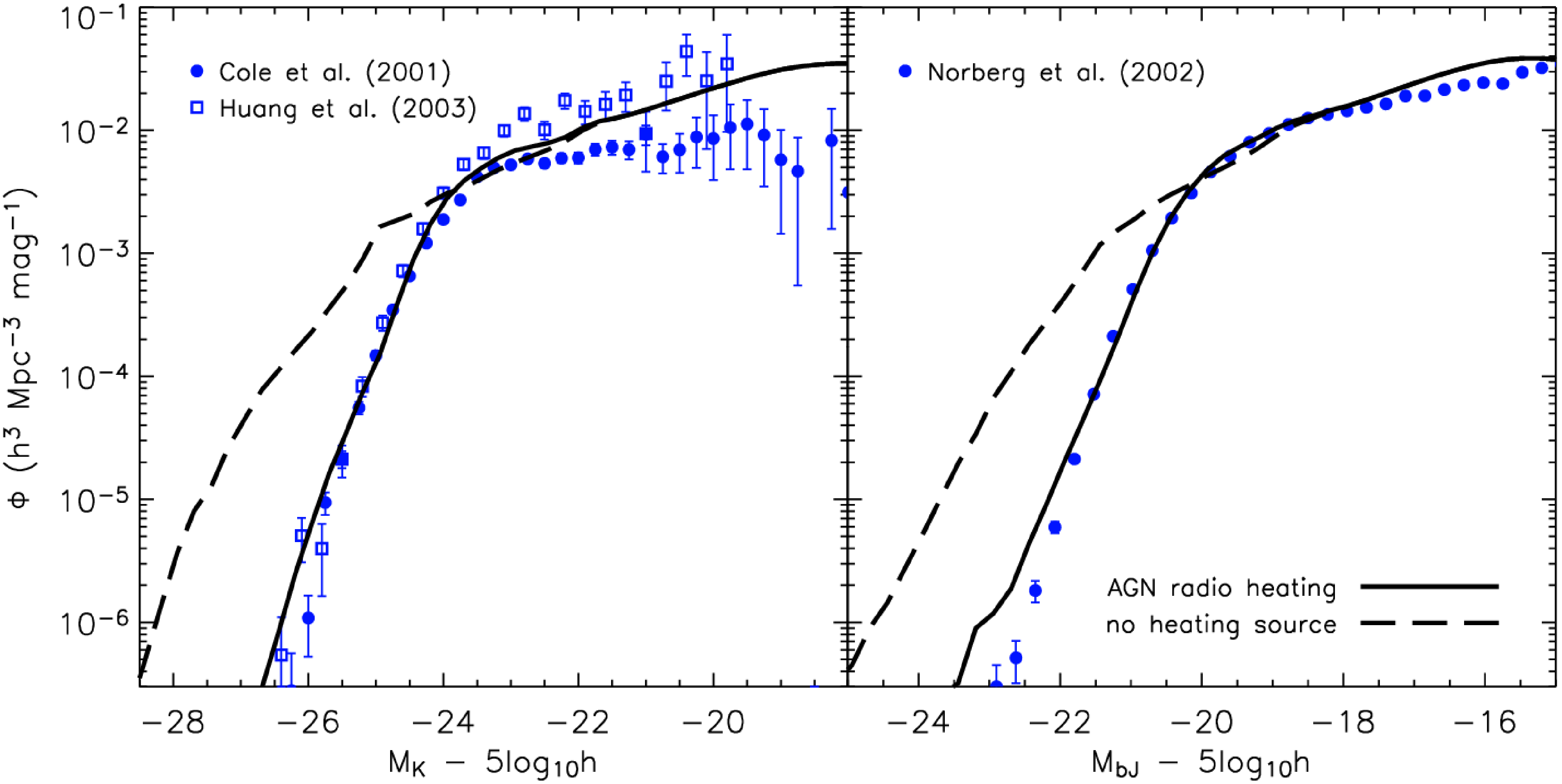
- The trees are stored as self-contained objects, which are the input to the semi-analytic code
- Each tree corresponds to a FOF halo at z=0 (not always exactly)
- The collection of all trees (a whole forest of them) describes all the structures/galaxies in the simulated universe



The inclusion of AGN feedback allows semi-analytic models to reproduce a multitude of observational data

K-BAND AND Bj-BAND LUMINOSITY FUNCTIONS

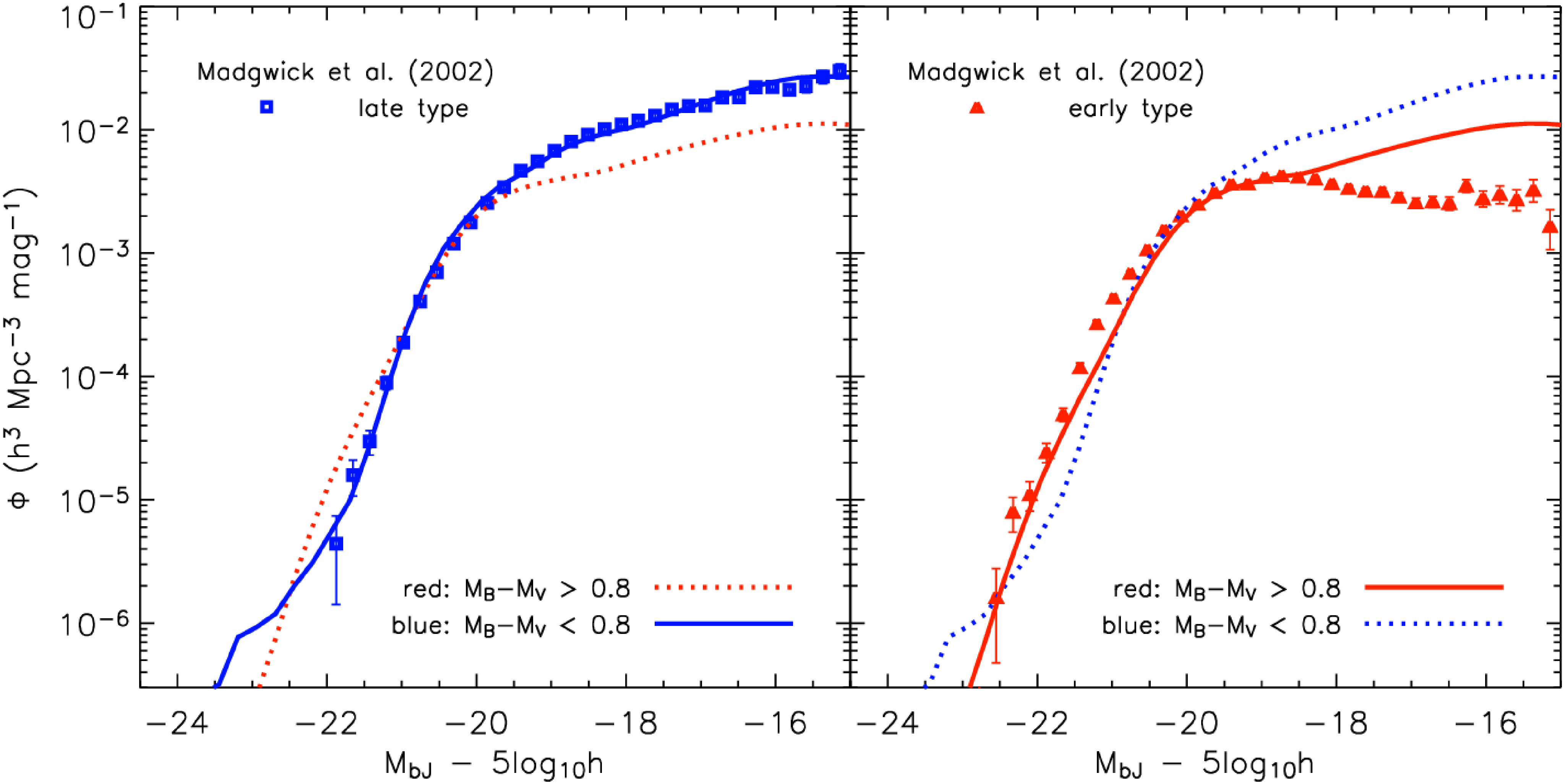
Croton et al. (2006)



The luminosity functions split by color are well reproduced, except for faint red galaxies

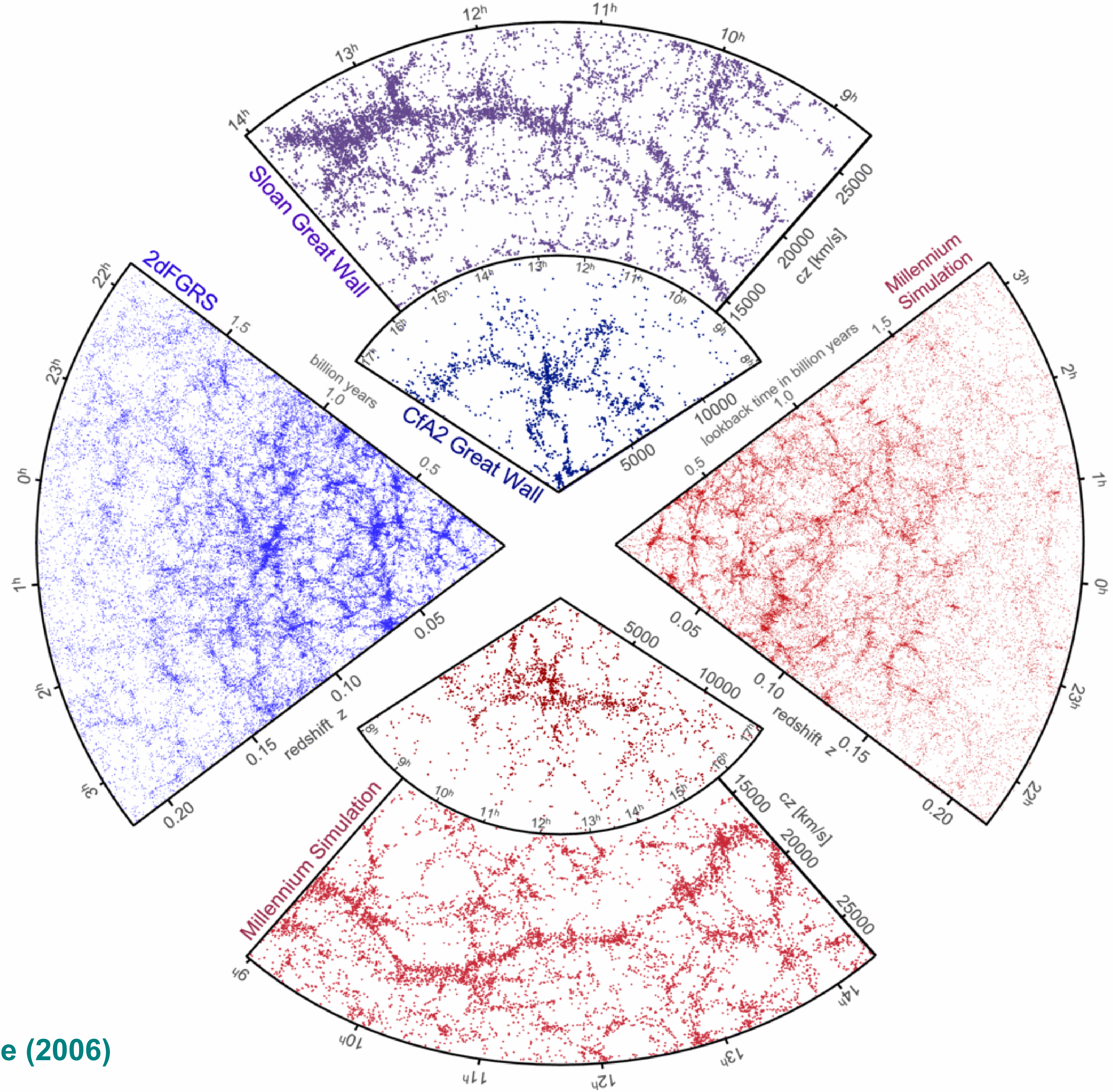
LUMINOSITY FUNCTIONS SPLIT BY B-V COLOR COMPARED TO 2DFGRS

Croton et al. (2006)



The galaxies of the Millennium Simulation reproduce the observed large-scale clustering very well

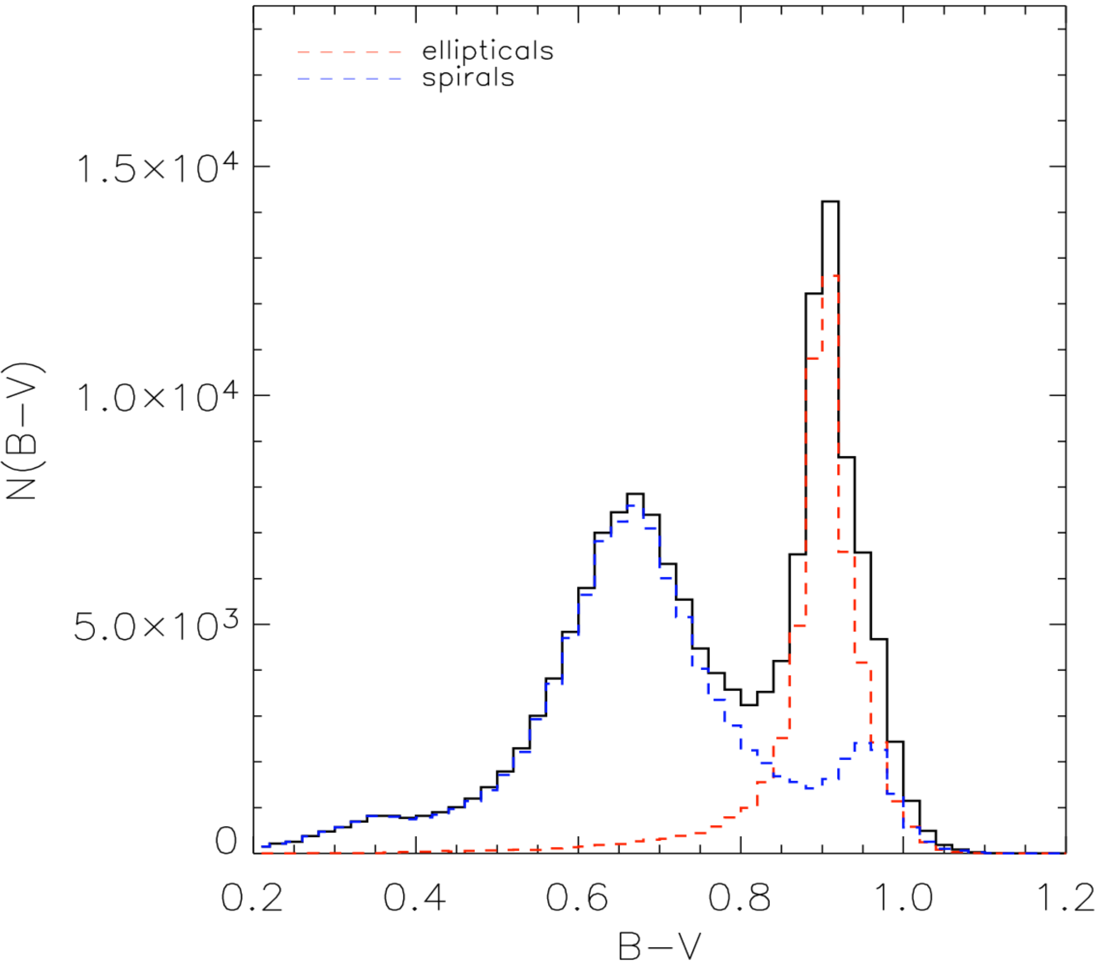
PIE DIAGRAMS OF REDSHIFT SURVEYS AND THE MILLENNIUM SIMULATION

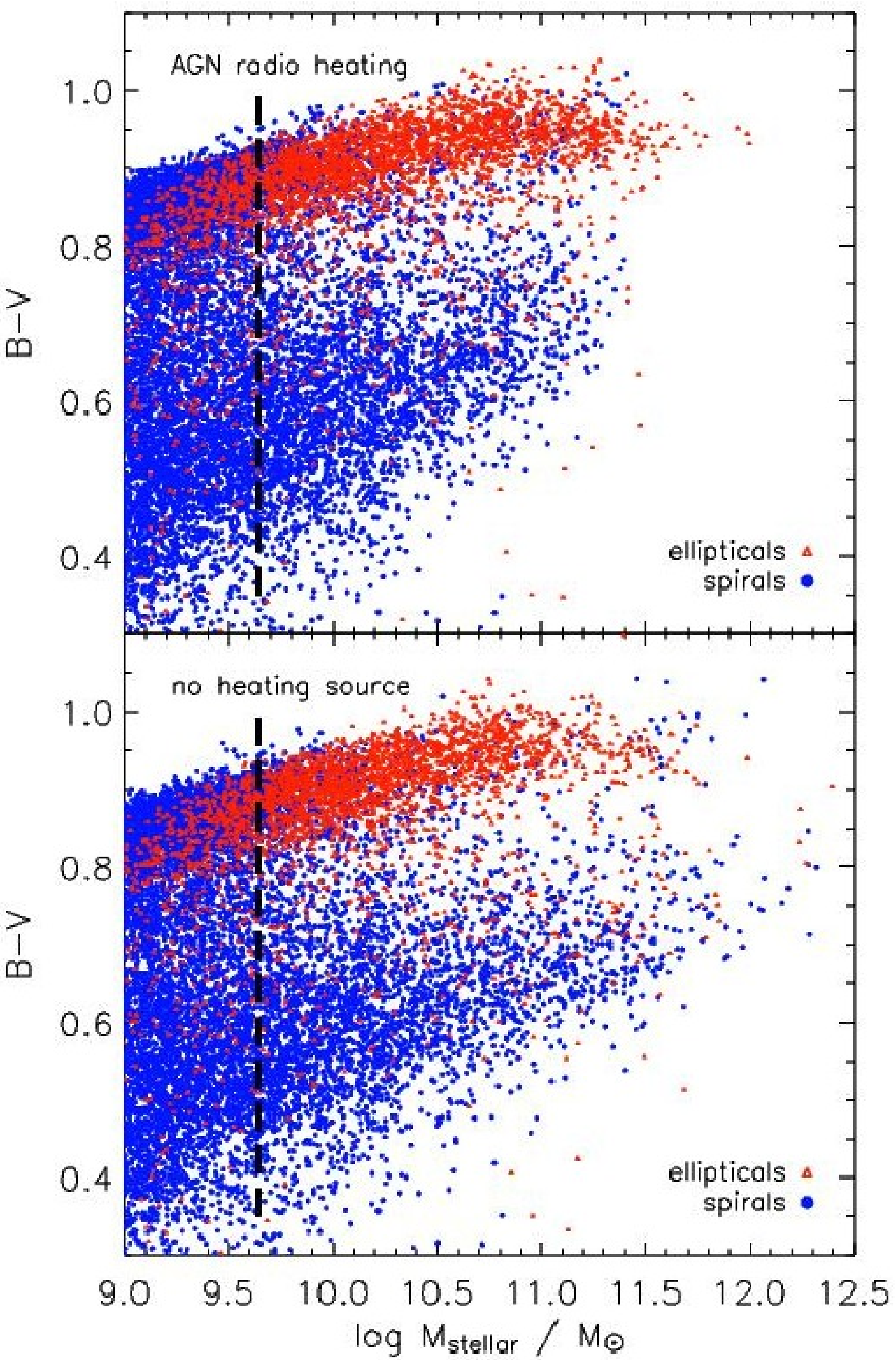


Springel, Frenk & White (2006)

For the first time, semi-analytic models reproduce the red colours of the most luminous ellipticals

B-V COLOUR DISTRIBUTION





Croton et al. (2006)

Only a "radio mode" of feedback is presently included in the semi-analytic models

MODEL ASSUMPTIONS

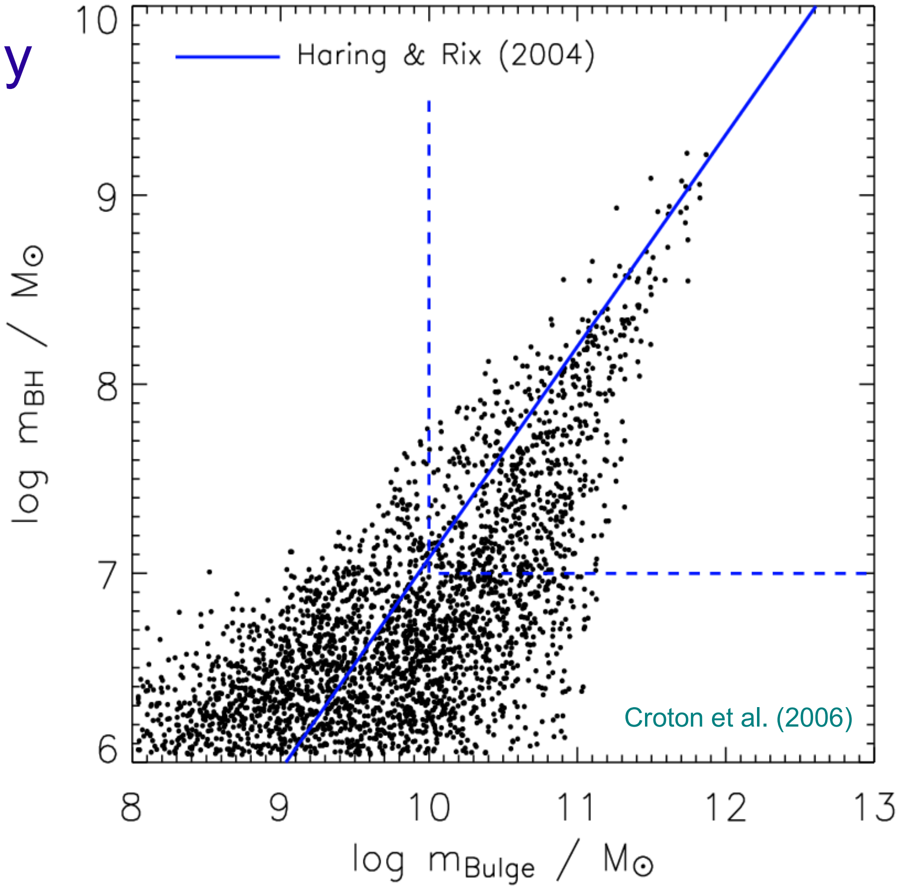
Croton et al. (2006):

- Quasars are triggered in mergers or by disk instability (Haehnelt & Kauffmann model)
- Radio mode heating should become more efficient in large halos

$$\dot{m}'_{\rm cool} = \dot{m}_{\rm cool} - \frac{L_{\rm BH}}{\frac{1}{2}V_{\rm vir}^2}$$

$$L_{\rm BH} = 0.1\,\dot{m}_{\rm BH}c^2$$

$$\dot{m}_{\rm BH} = \kappa_{\rm AGN}\, f_{\rm hot}\, V_{\rm vir}^3\, m_{\rm BH}$$

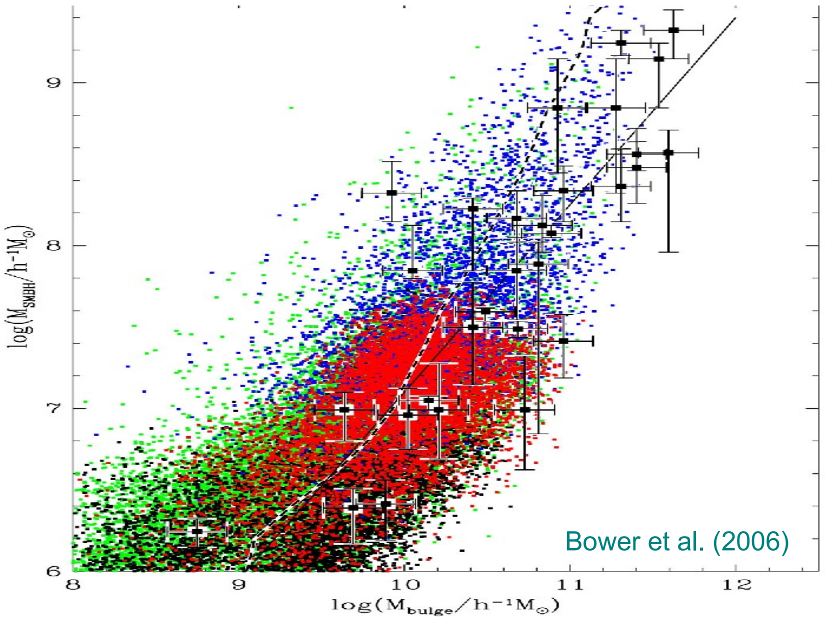


Croton et al. (2006)

Bower et al. (2006):

- Alternative model for radio mode: Assume that the flow will adjust itself such that heating balances cooling, whenever the Eddington luminosity of the BH of a quasistatically cooling halo is sufficiently large, i.e. when

$$L_{\rm cool} < \epsilon L_{\rm Edd}$$

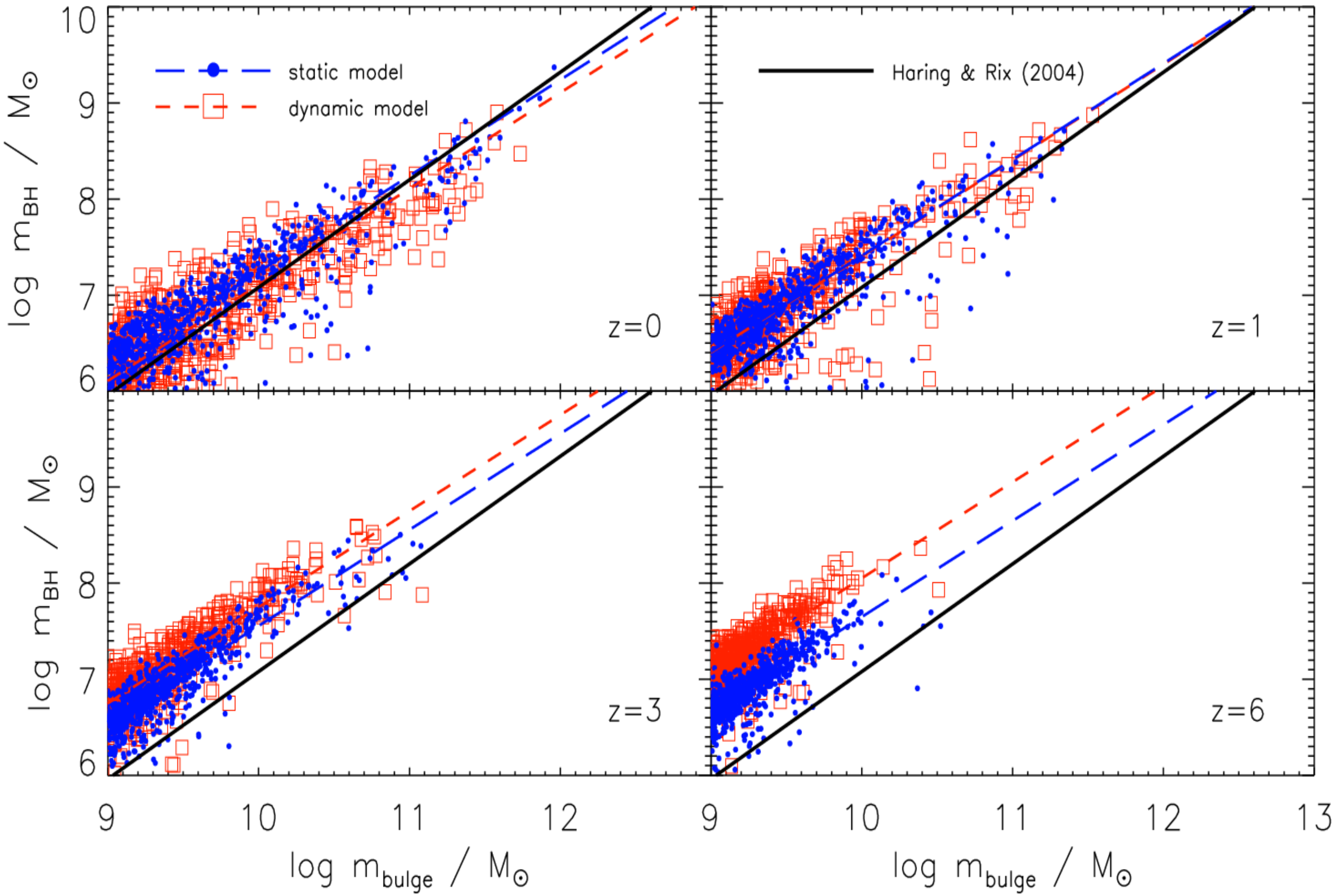


Bower et al. (2006)

The particular assumptions made in this semi-analytic model predict an evolution in the BH-mass bulge-mass relationship

THE M_{BH} - M_{Bulge} RELATIONSHIP AT DIFFERENT TIMES

Croton (2006)



In this model, the bulge grows both from the merger-induced starburst and the associated disk disruption.

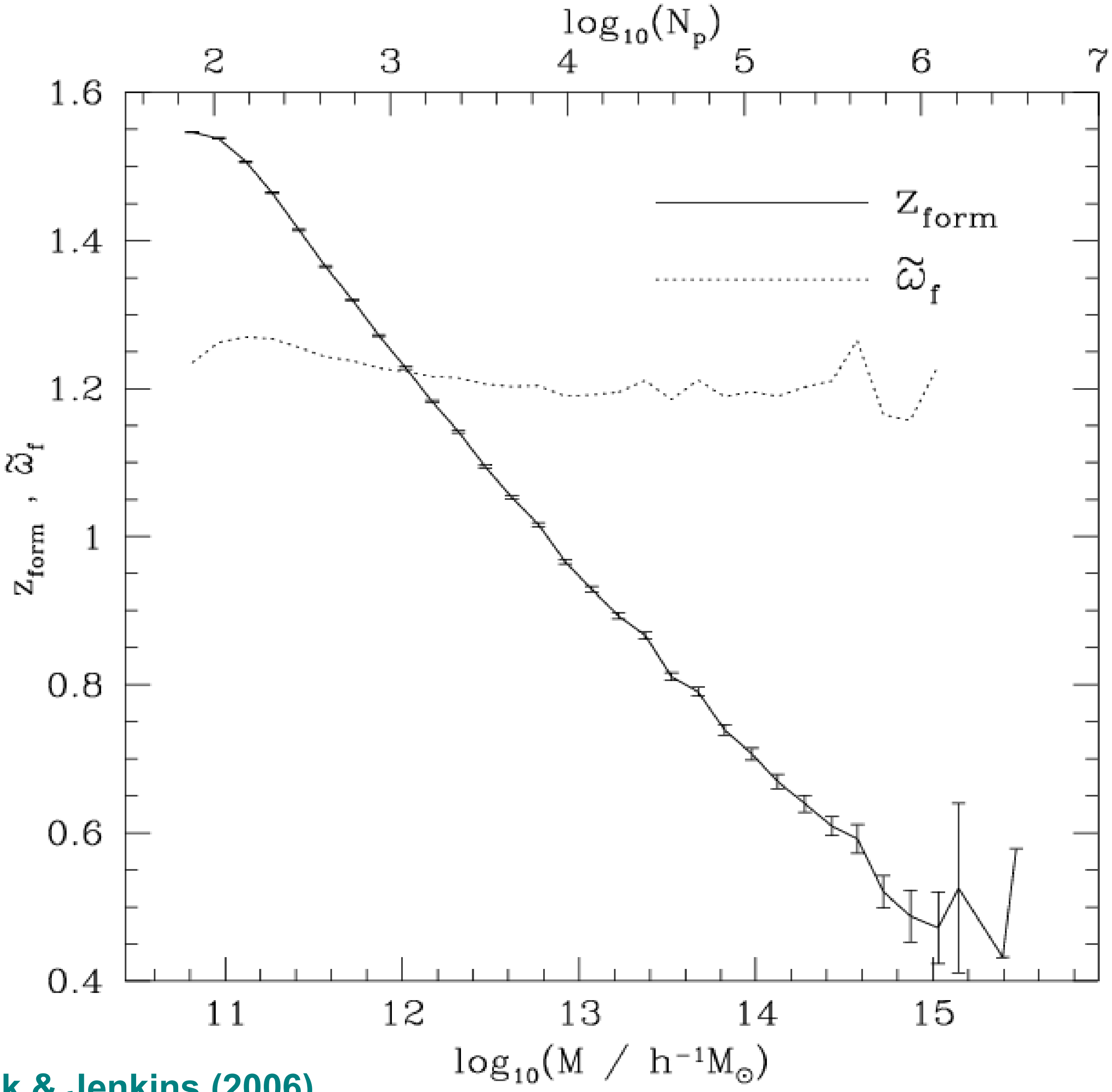
The latter channel becomes more important at low redshift, leading to evolution in the M_{BH}-M_{bulge} relation.

→ Allows interesting comparisons to the results of **Robertson et al. (2006)** based on hydro simulations, who find only a very weak evolution in this relation.

The formation time of halos depends strongly on mass and implies a hierarchical formation of objects

AVERAGE FORMATION TIME OF HALOS AS A FUNTION OF HALO MASS

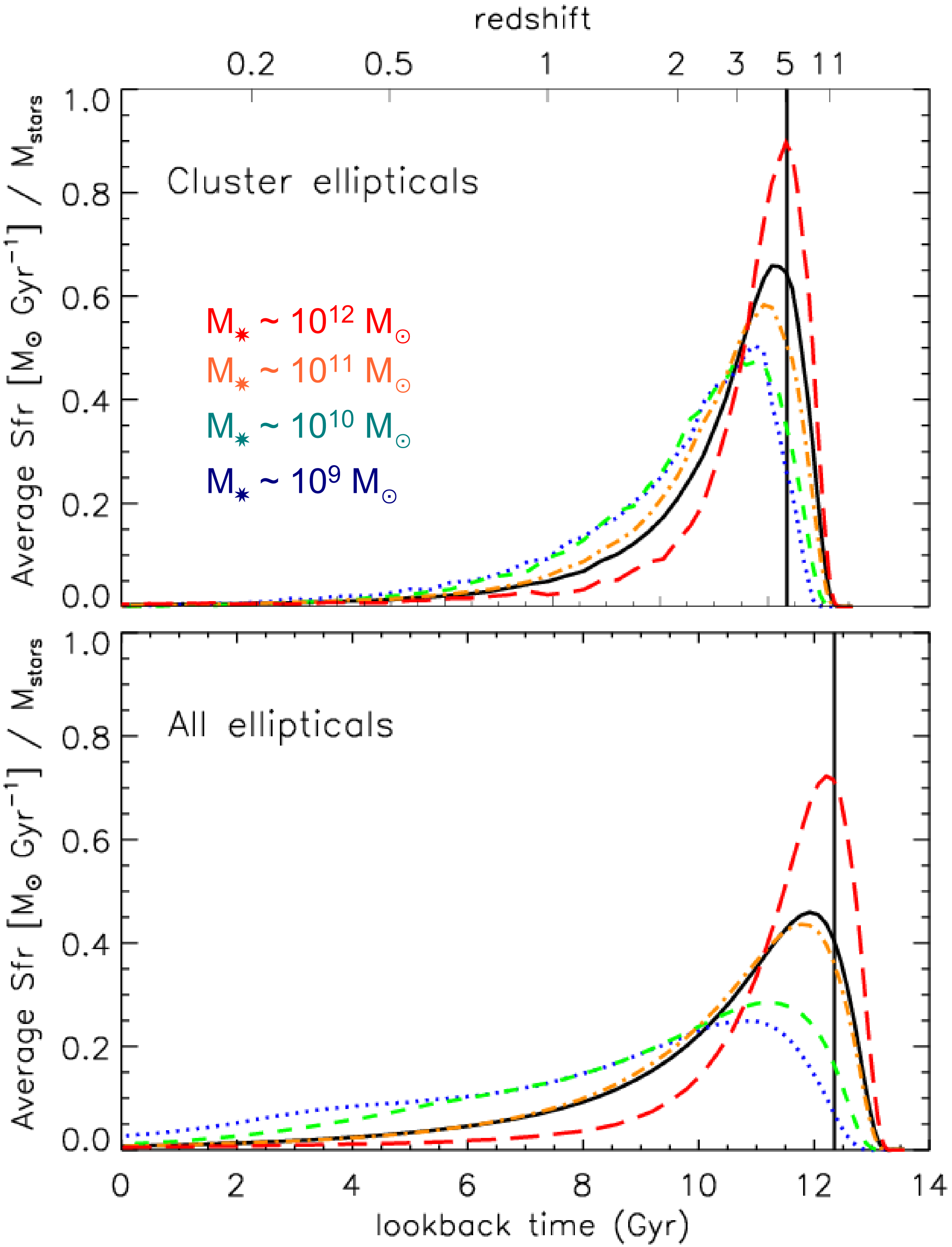
How can it be that the most massive ellipticals are also the oldest and reddest?



Harker, Cole, Helly, Frenk & Jenkins (2006)

More massive elliptical galaxies form their stars on average earlier

STAR FORMATION HISTORIES OF ELLIPTICALS

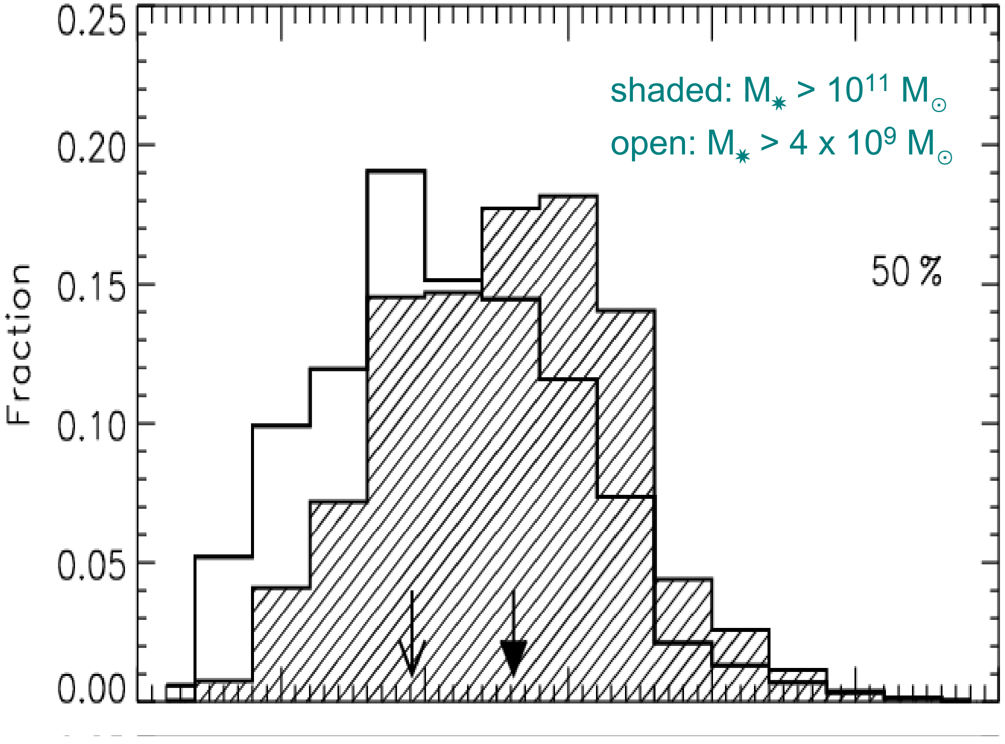


de Lucia, Springel, White, Croton & Kauffmann (2006)

The formation and assembly times differ substantially for elliptical galaxies, and show opposite trends with stellar mass

HISTOGRAMS OF FORMATION TIMES

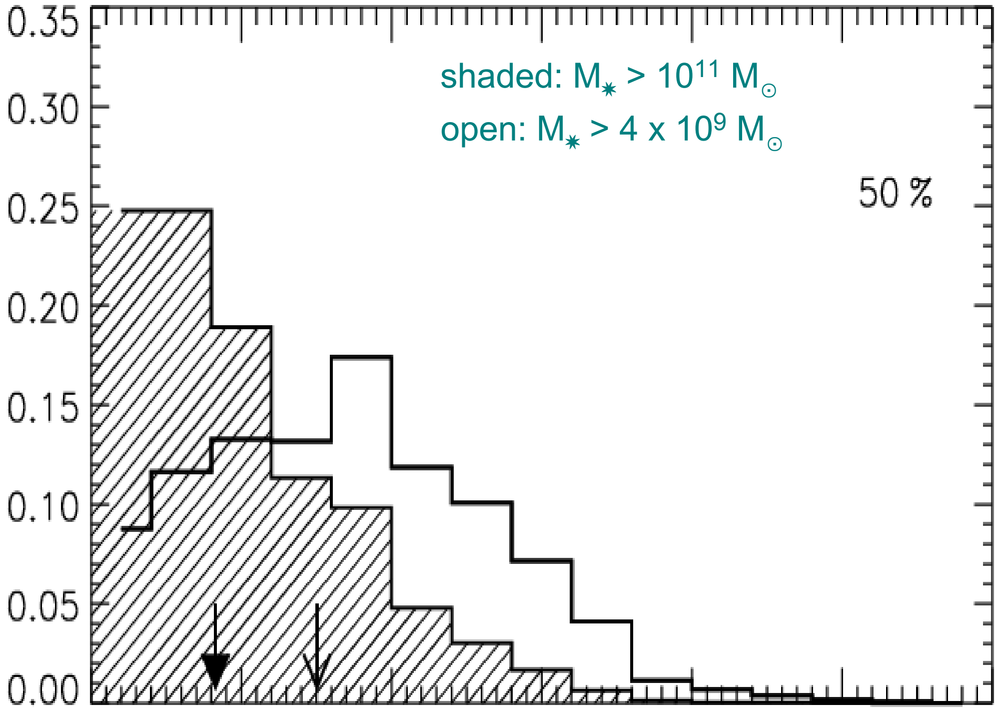
formation time of stars



shaded: $M_* > 10^{11}\ M_\odot$

open: $M_* > 4 \times 10^9\ M_\odot$

assembly time of ellipticals



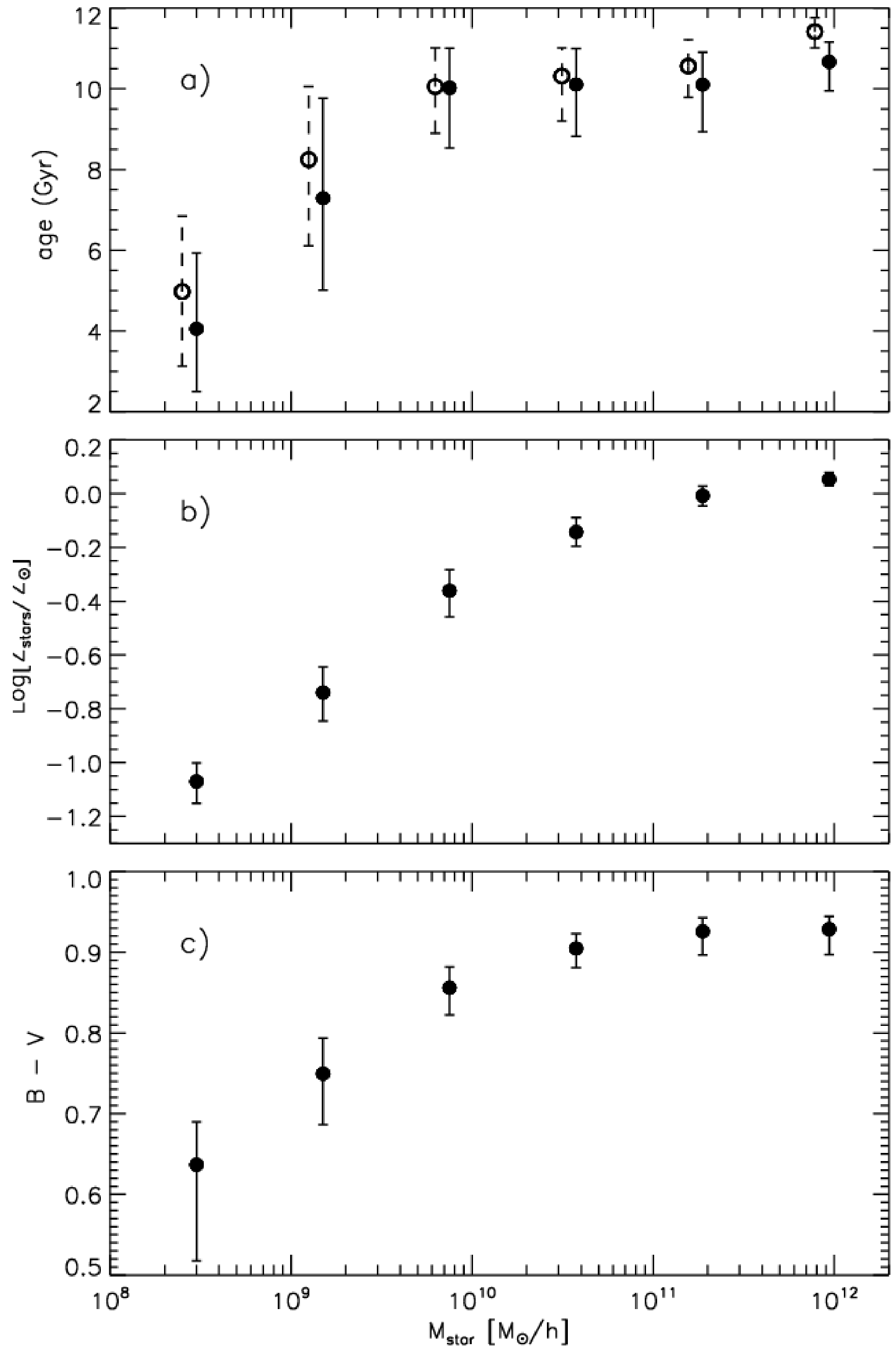
shaded: $M_* > 10^{11}\ M_\odot$

open: $M_* > 4 \times 10^9\ M_\odot$

de Lucia et al. (2006)

The most massive ellipticals have the oldest, reddest and most metal rich stellar populations

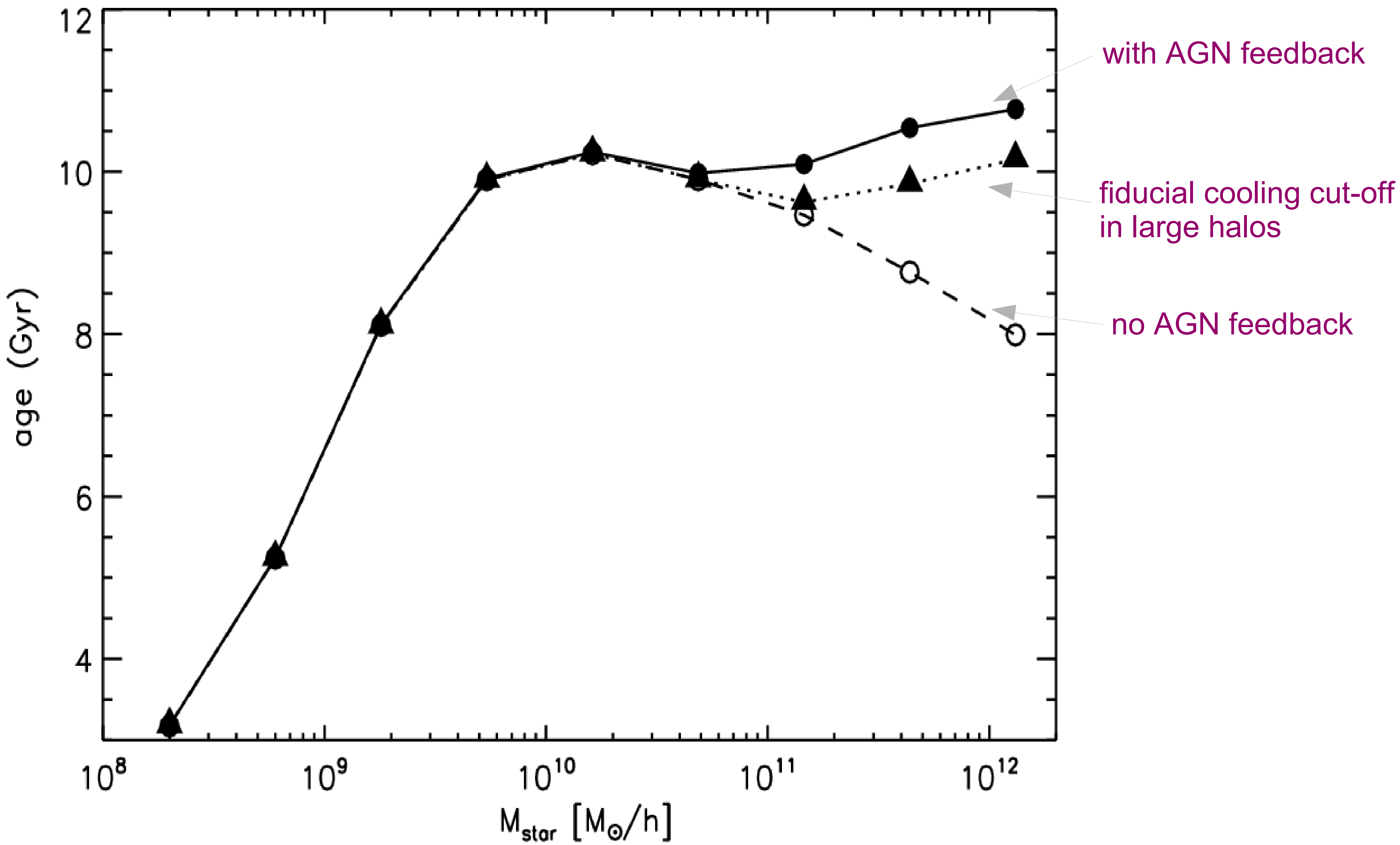
THE **ANTI-HIERARCHICAL** FORMATION OF ELLIPTICALS



de Lucia et al. (2006)

The success of the semi-analytic model has its origin in the inclusion of AGN feedback

AGE VS STELLAR-MASS RELATIONSHIP FOR DIFFERENT FEEDBACK MODELS



with AGN feedback

fiducial cooling cut-off in large halos

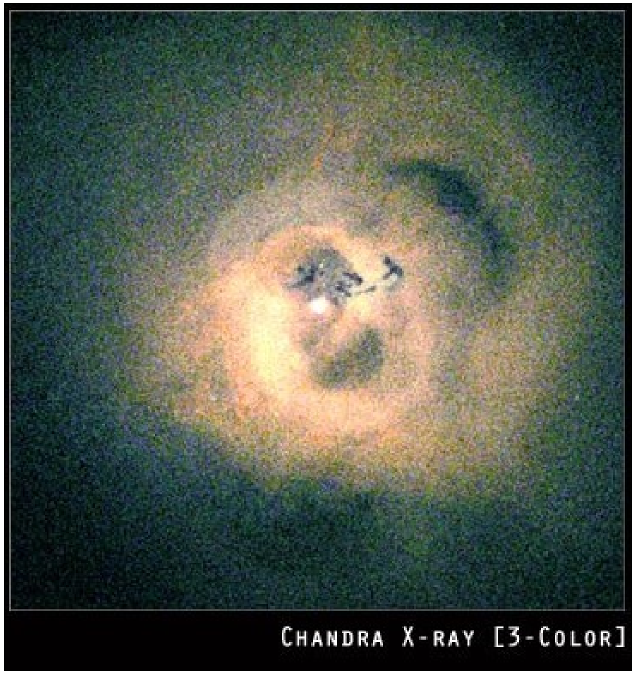
no AGN feedback

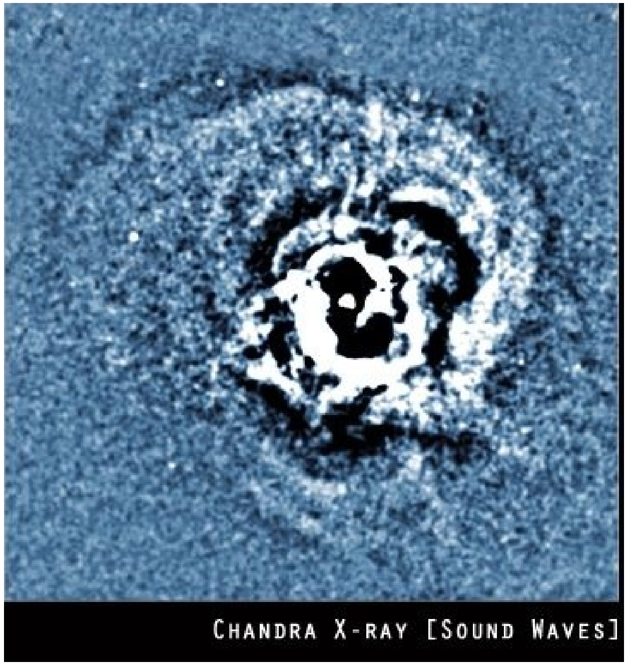
de Lucia et al. (2006)

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

UNSOLVED ISSUES

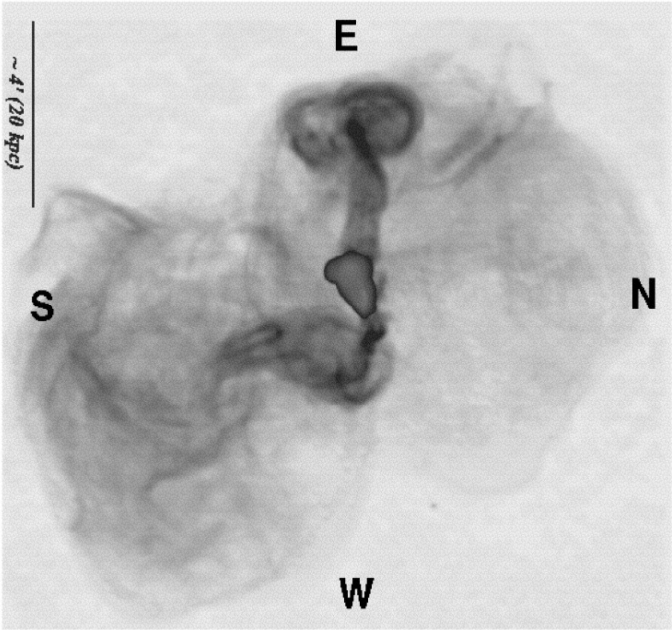
- Why are there (almost) no cooling flows in observed clusters? What's the heat source?
- What is responsible for the deviations of cluster scaling relations from self-similar predictions?
- What is the origin of the high metallicities of the ICM?
- How do the shapes of the observed temperature profiles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

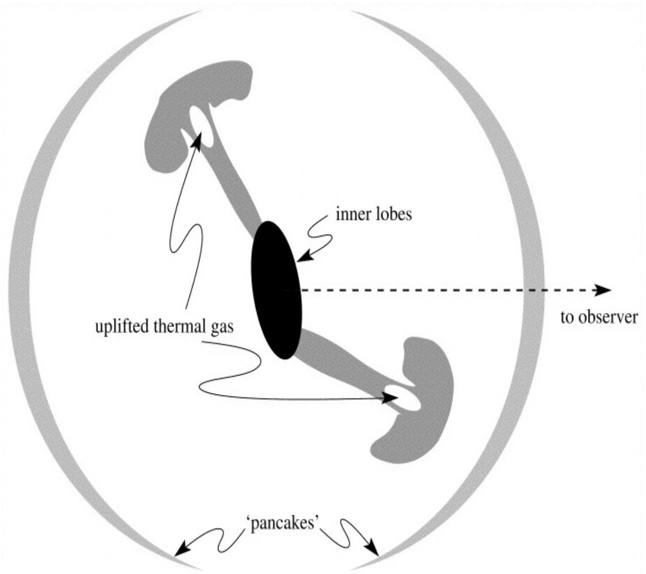




Buoyant radio bubbles may be inflated by AGN and uplift cool gas

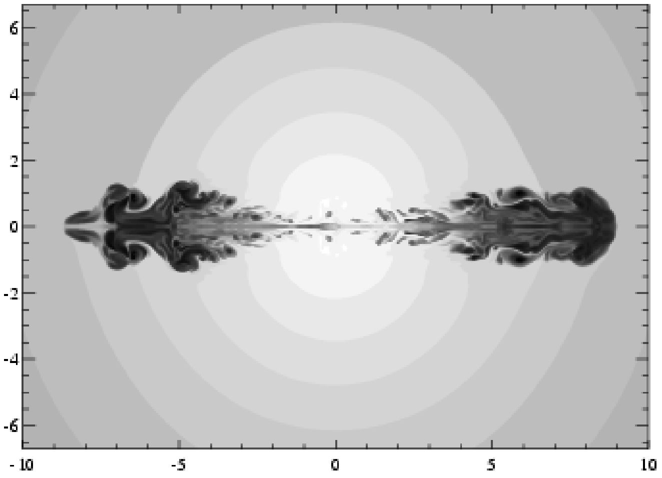
BUBBLES IN M87

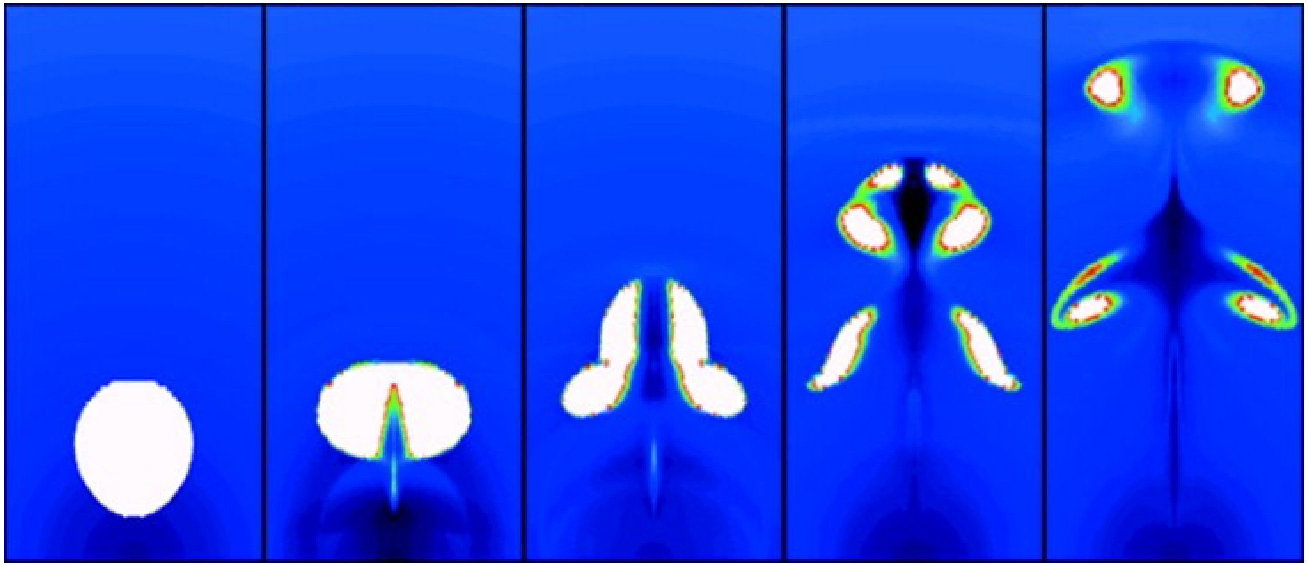




Churazov et al. (2001)

Reynolds, Heinz & Begelman (2002)



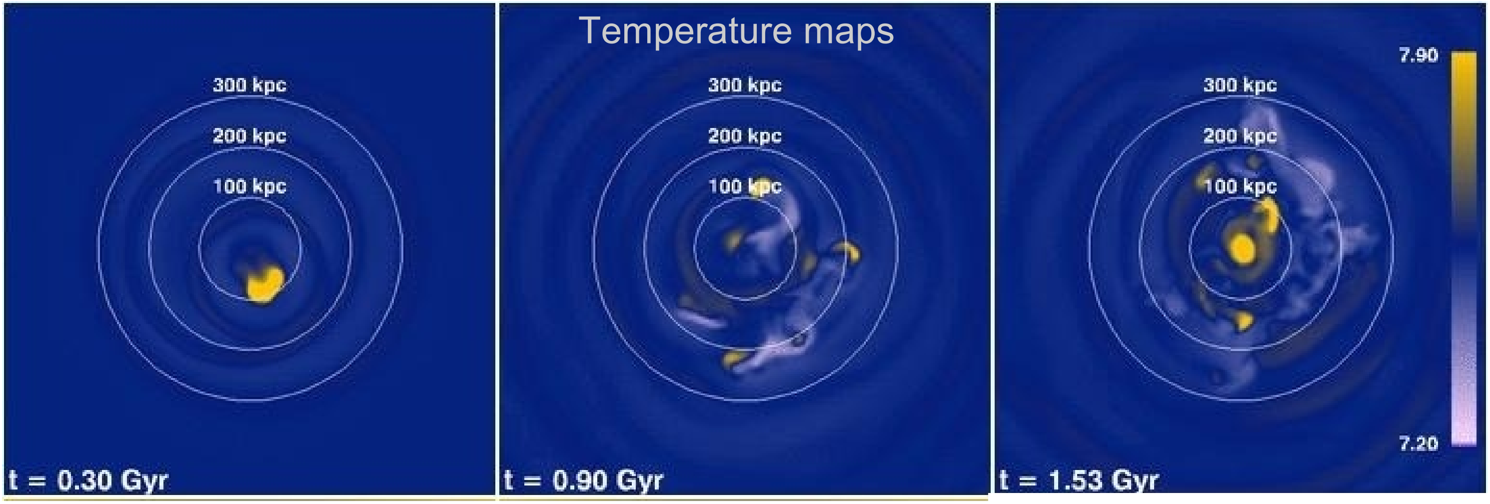


Three dimensional simulations begin to suggest that AGN with the right duty cycle may indeed quench cooling flows

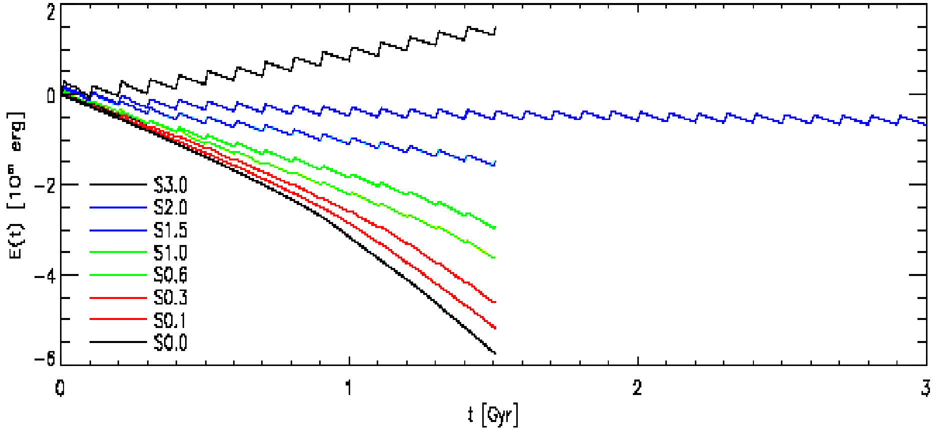
3D MODELS OF AGN HEATING

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

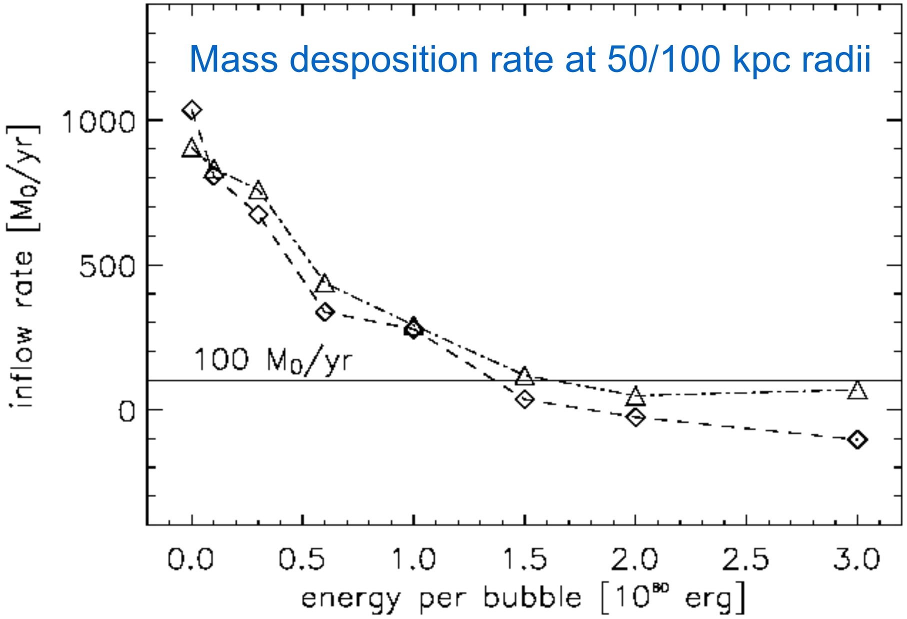
Dalla Vecchia et al. (2004)


Temperature maps

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:

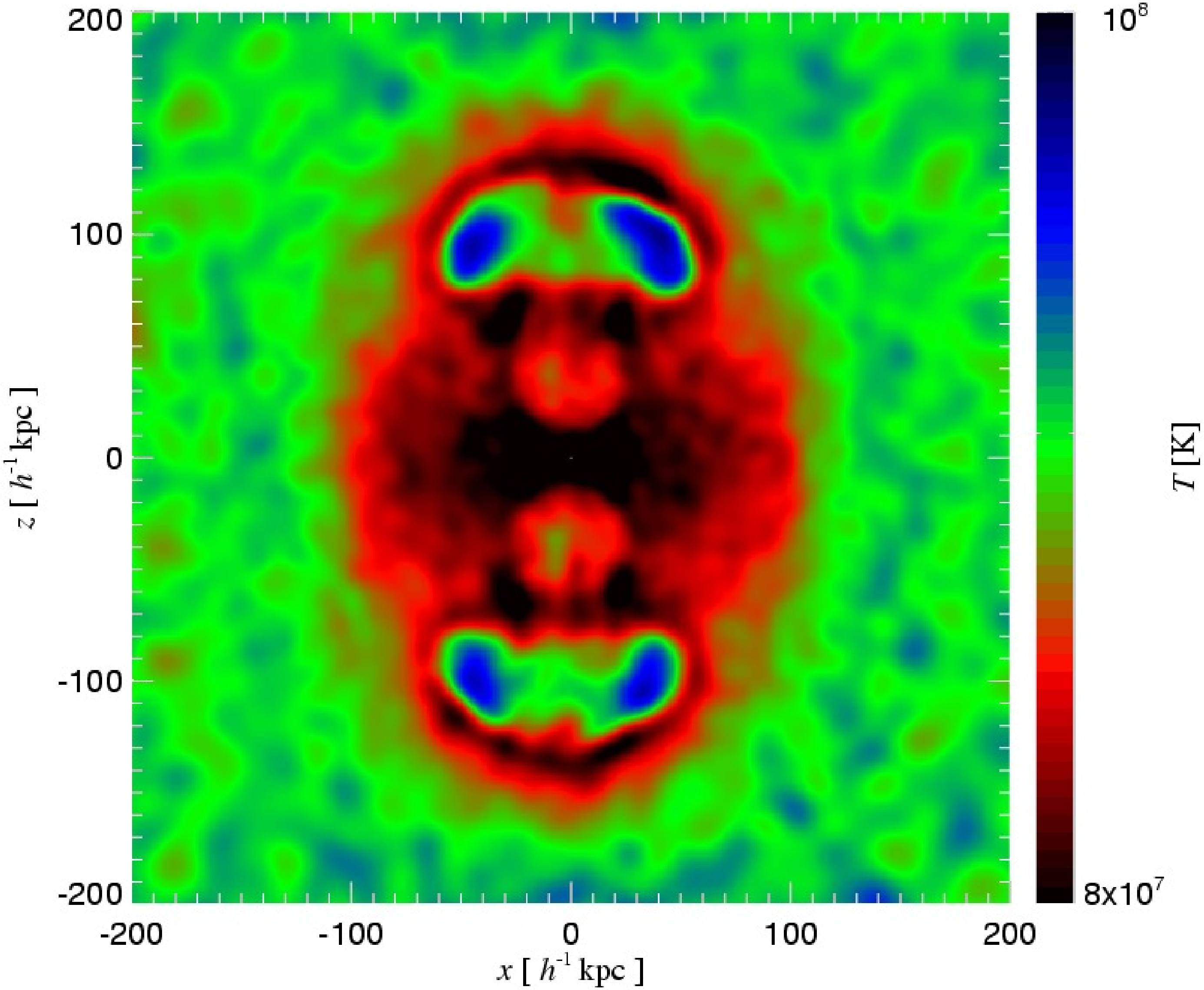
$$t_{\rm duty} = 10^8\,{\rm yr}$$

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

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

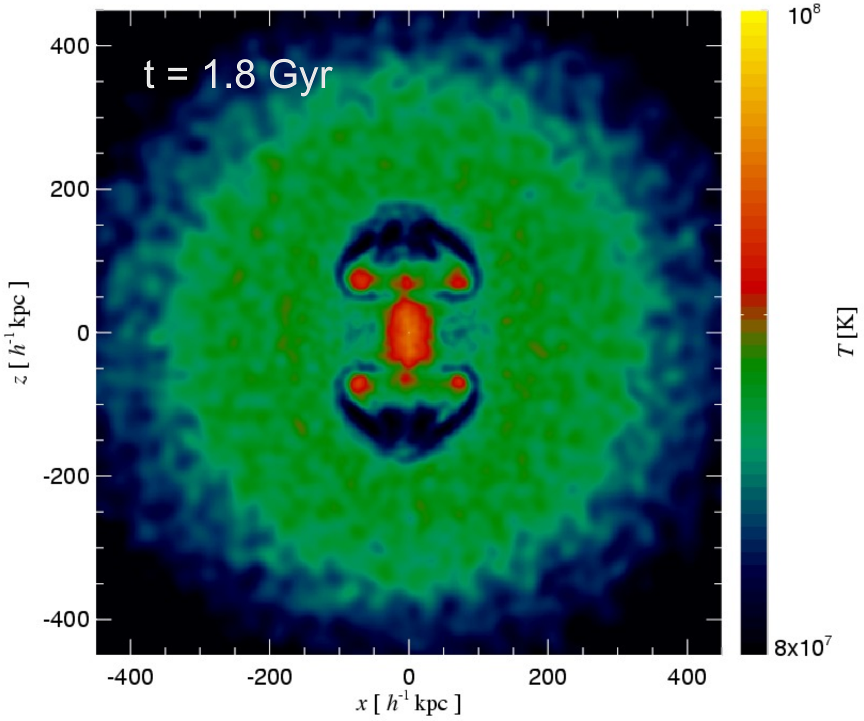
$$d_{\rm bub} = 50\,h^{-1}{\rm kpc}$$

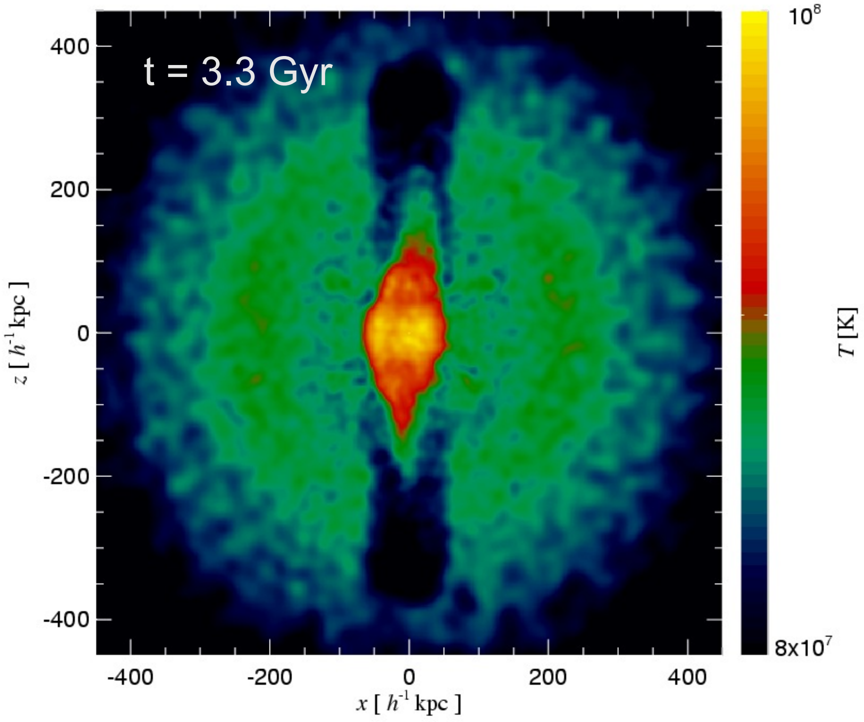
$M = 10^{15}\,M_\odot/h$



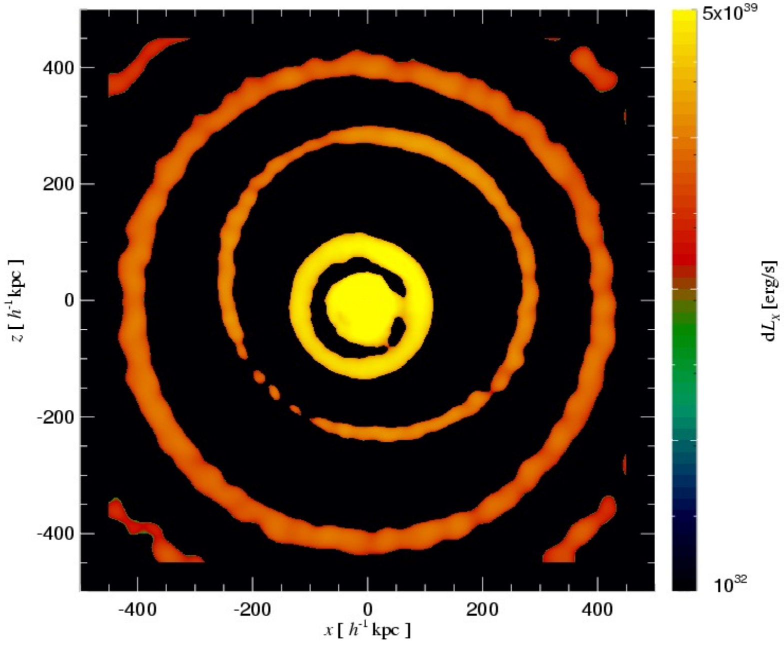
AGN feedback heats the cluster centre and sends sound waves into the IGM

BUBBLE EVOLUTION OVER TIME





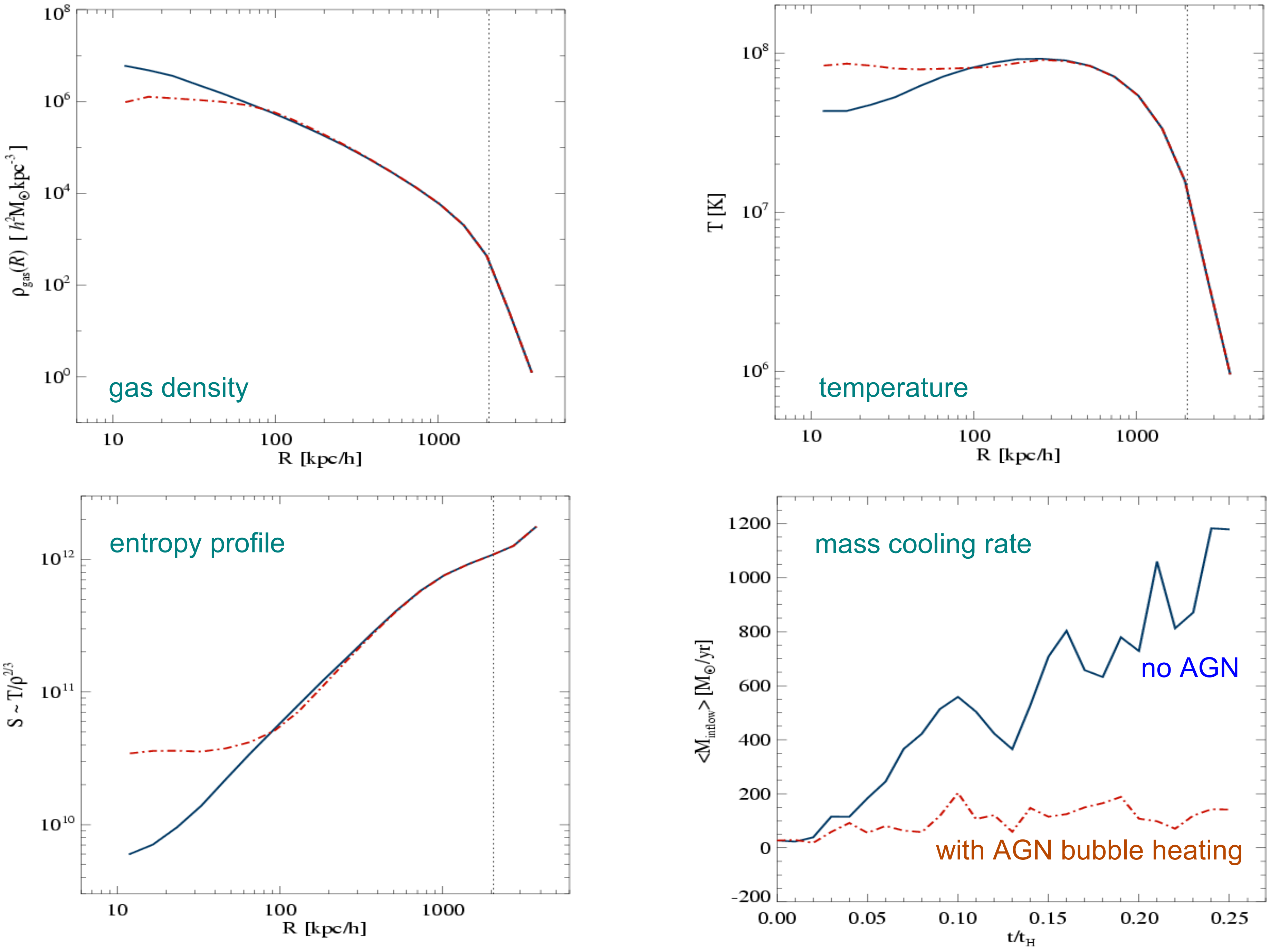
Unsharp masked image of the X-ray emissivity



Sijacki & Springel (2006)

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

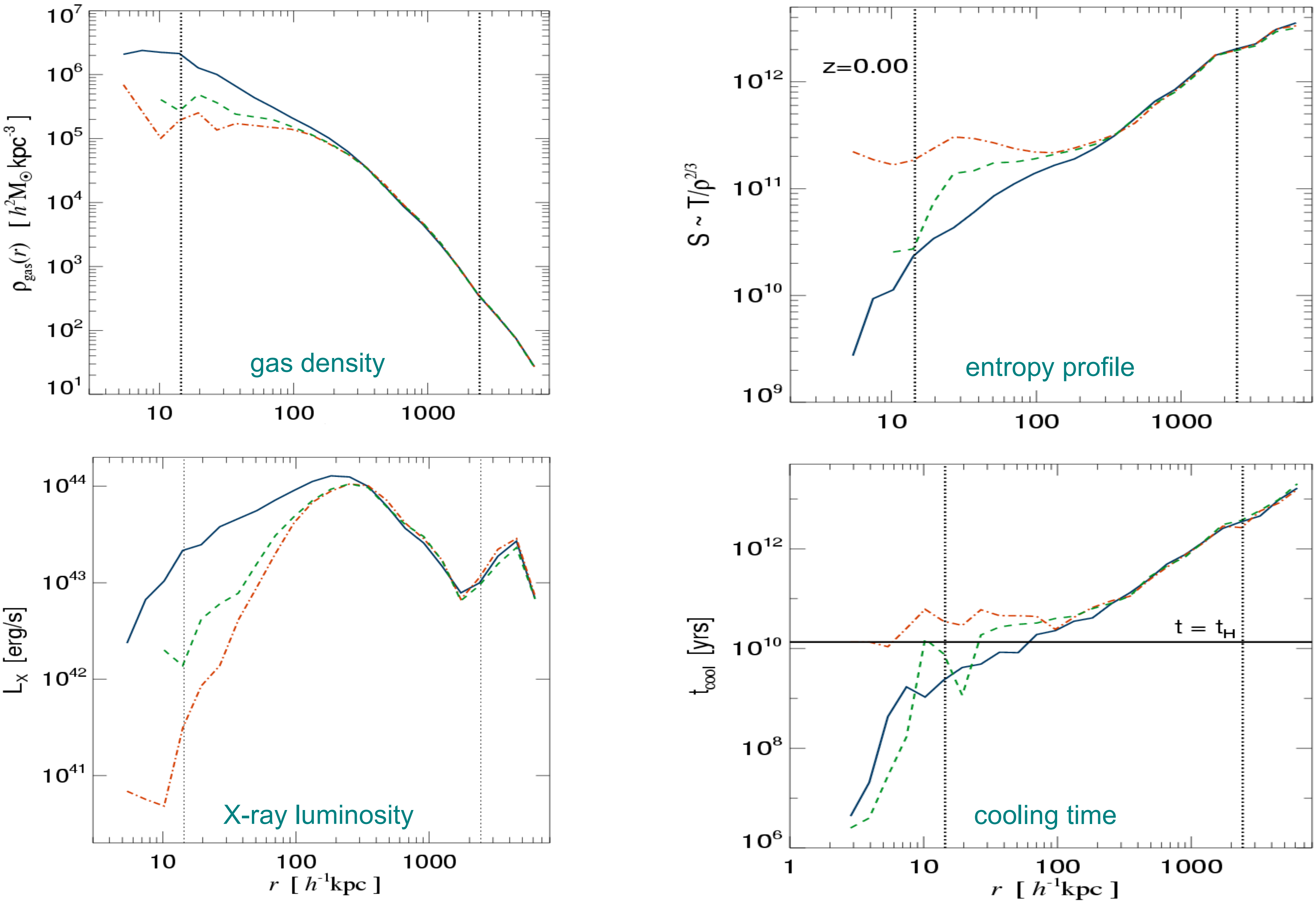
RADIAL PROFILES OF AN ISOLATED CLUSTER MODEL



AGN heating modifies the thermodynamic structure of massive clusters

RADIAL PROFILES OF A RICH CLUSTER AT Z=0

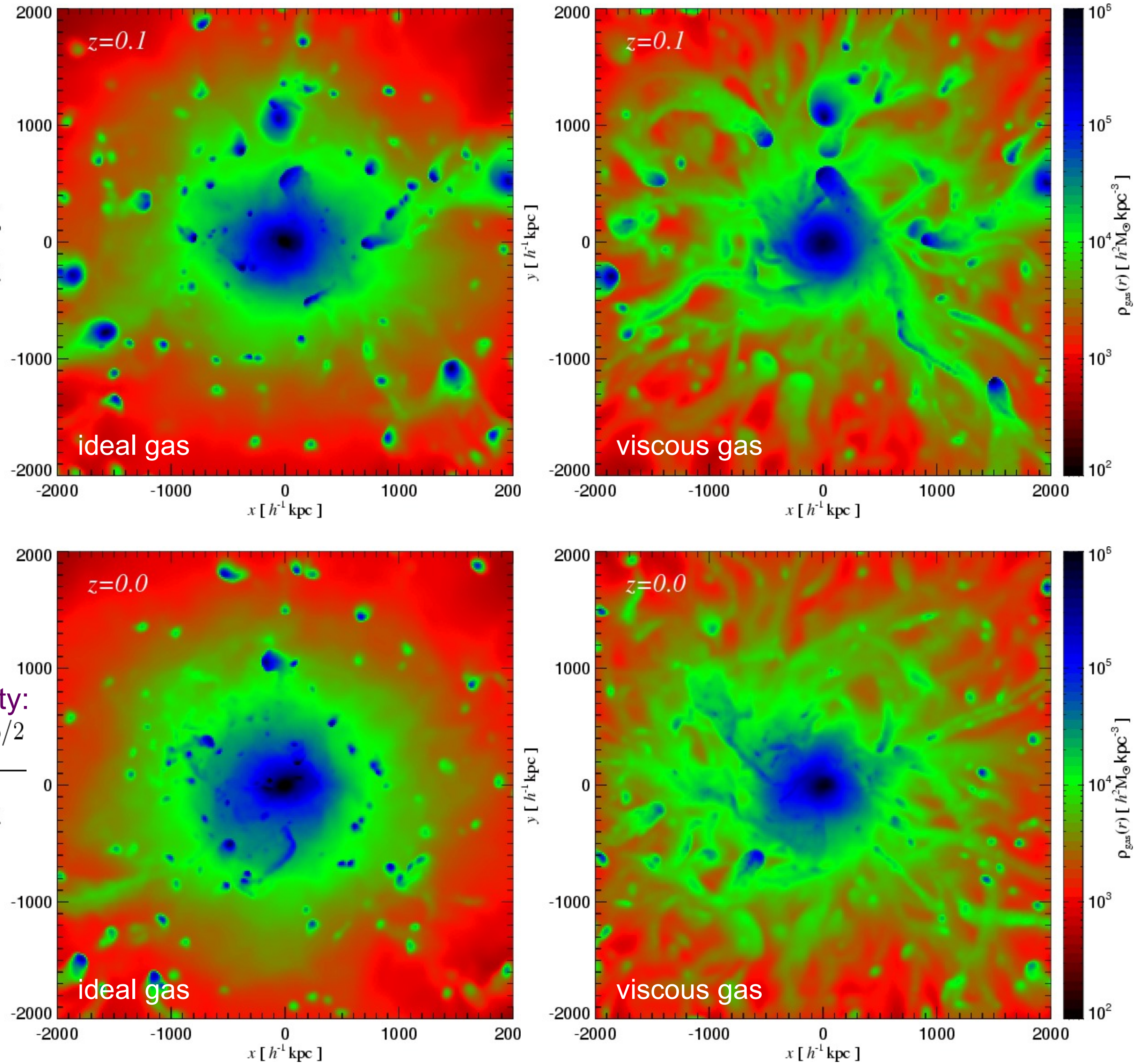
Sijacki & Springel (2006)



Viscous shear changes gas stripping during cluster assembly

COMPARISON OF PROJECTED GAS DENSITY MAPS

Sijacki & Springel (2006)



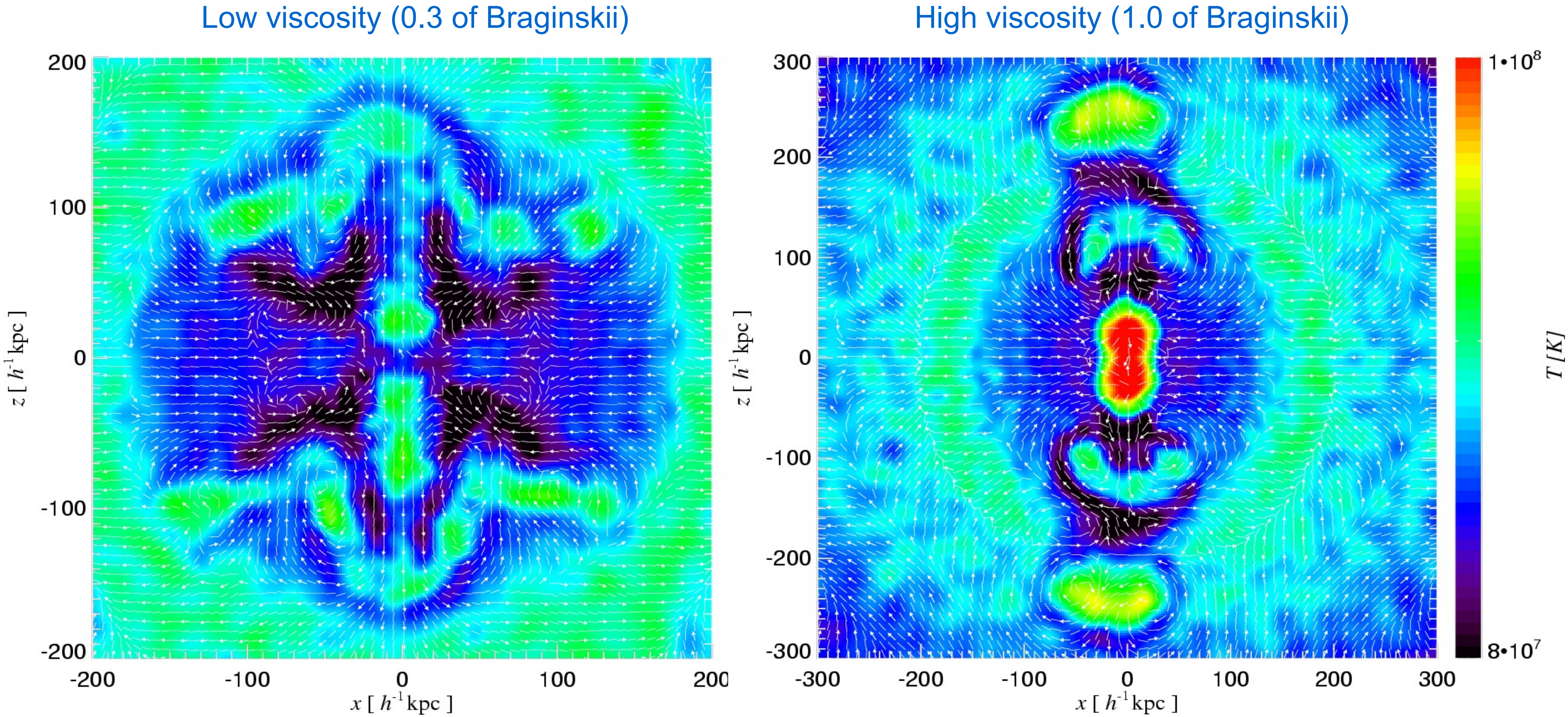
Novel discretization of the Navier-Stokes equations in SPH

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

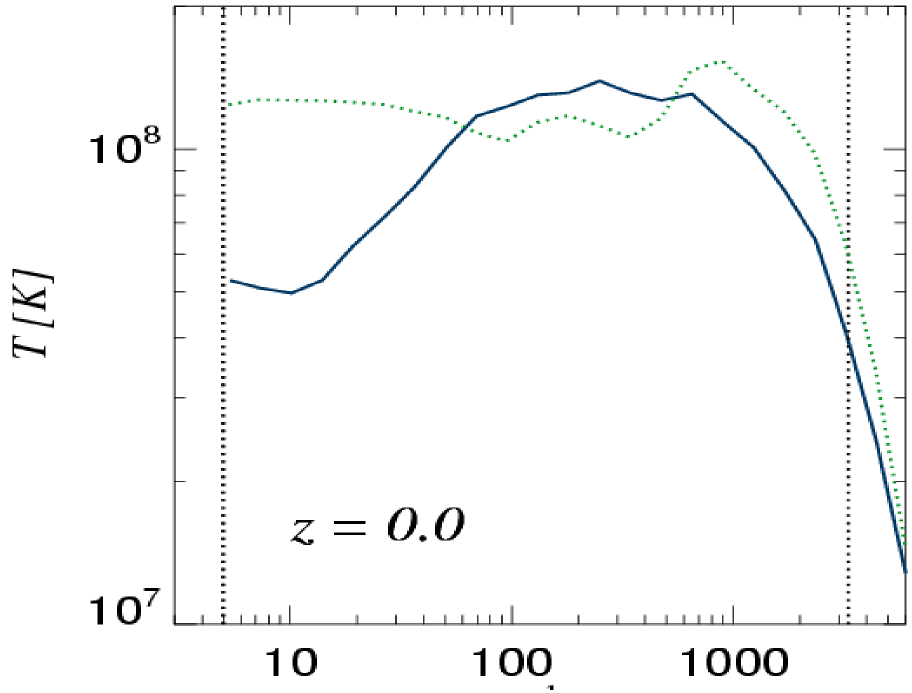
PROJECTED TEMPERATURE AND VELCOCITY FIELDS IN AGN-HEATED CLUSTERS

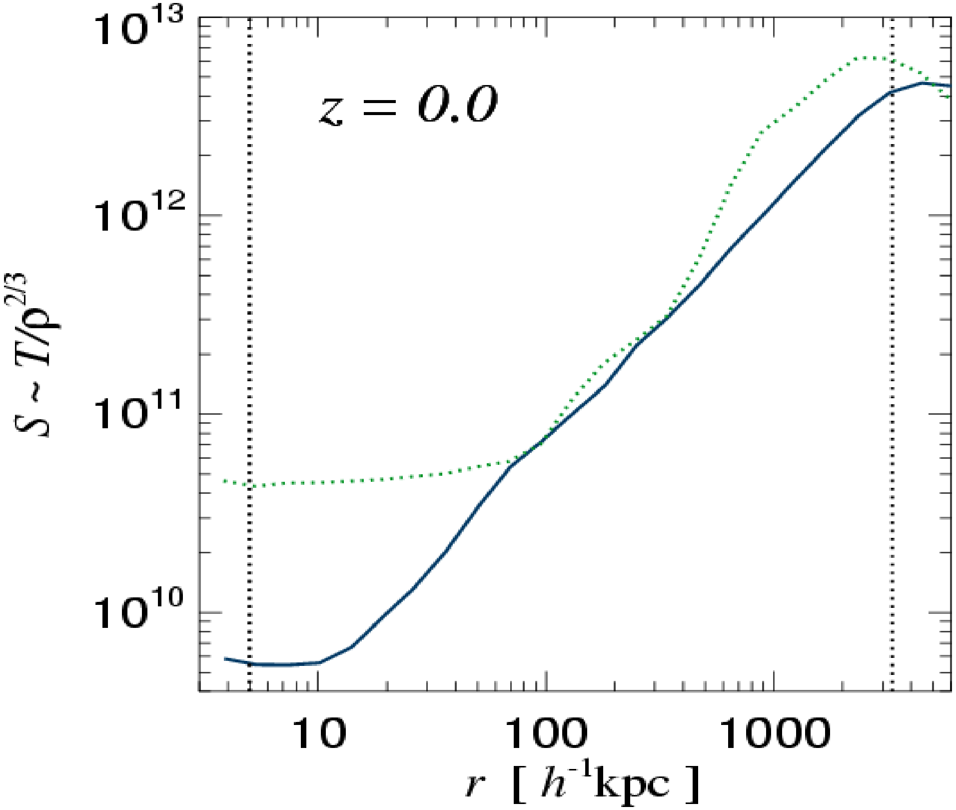


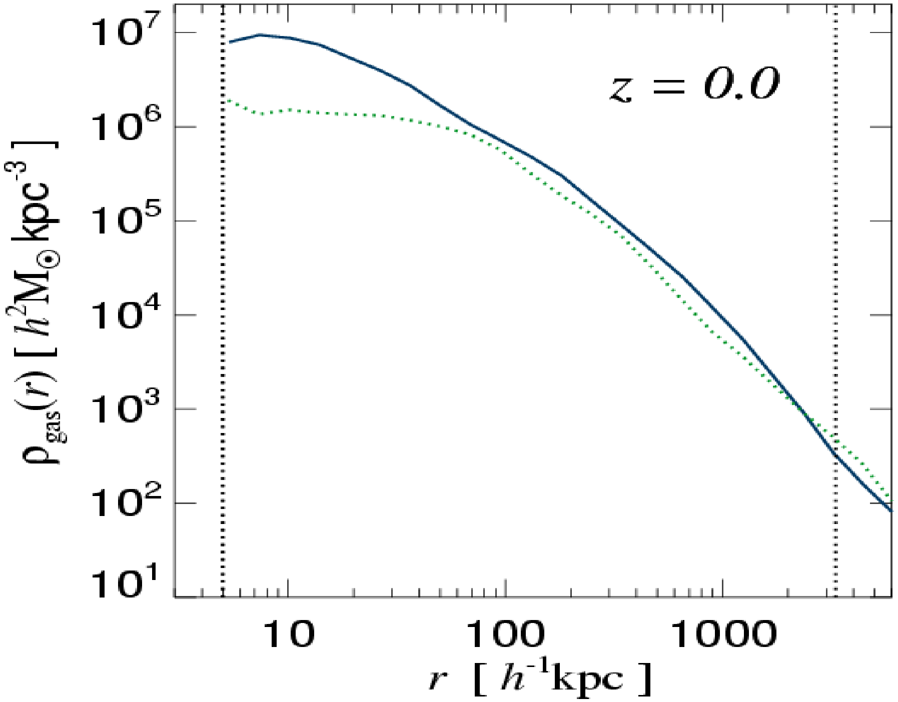
Sijacki & Springel (2006)

Viscous shear changes the thermodynamic profiles of forming clusters of galaxies

RADIAL PROFILES IN NONRADIATIVE SIMULATIONS WITH/WITHOUT SHEAR VISCOSITY







Sijacki & Springel (2006)

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-σ 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 !

Direct simulations of star formation in cosmological volumes are 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
- **Required dynamic range is huge**

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

- *Comprehensive set of simulations on interlocking scales*

Multi-phase subresolution model for the ISM (Springel & Hernquist 2003)

Describes cloud formation, star formation out of clouds, and evaporation of clouds by supernova explosions.

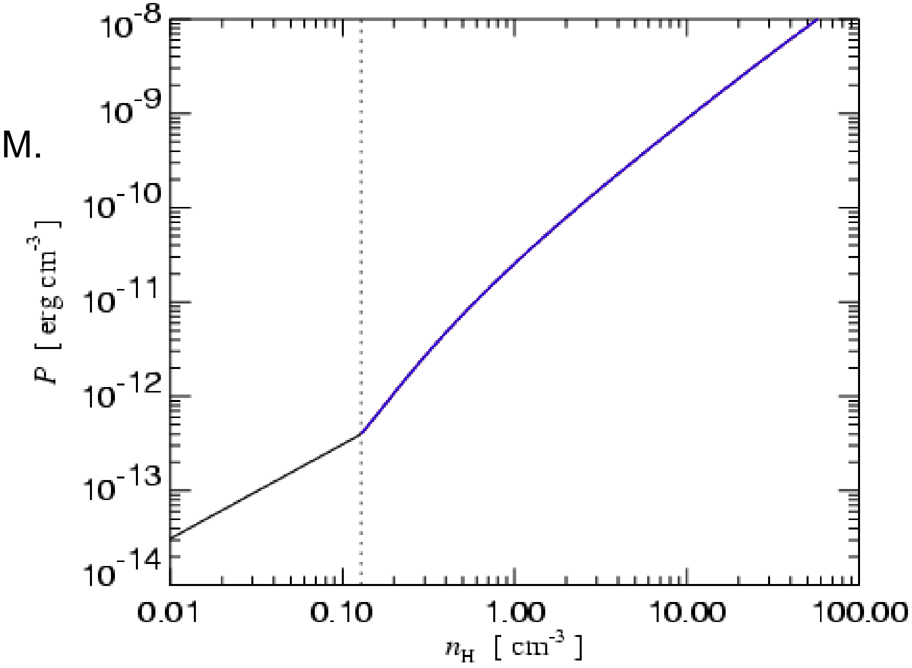
Works with an **effective equation of state** for the star-forming ISM.

Successes:

- Numerically converged prediction for the cosmic star formation history
- Moderation of the cooling catastrophy, ~10% of baryons end up in stars
- Metal enrichment of the IGM can be accounted for

But:

- Luminosity functions has steep faint-end
- Clusters have strong cooling flows



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

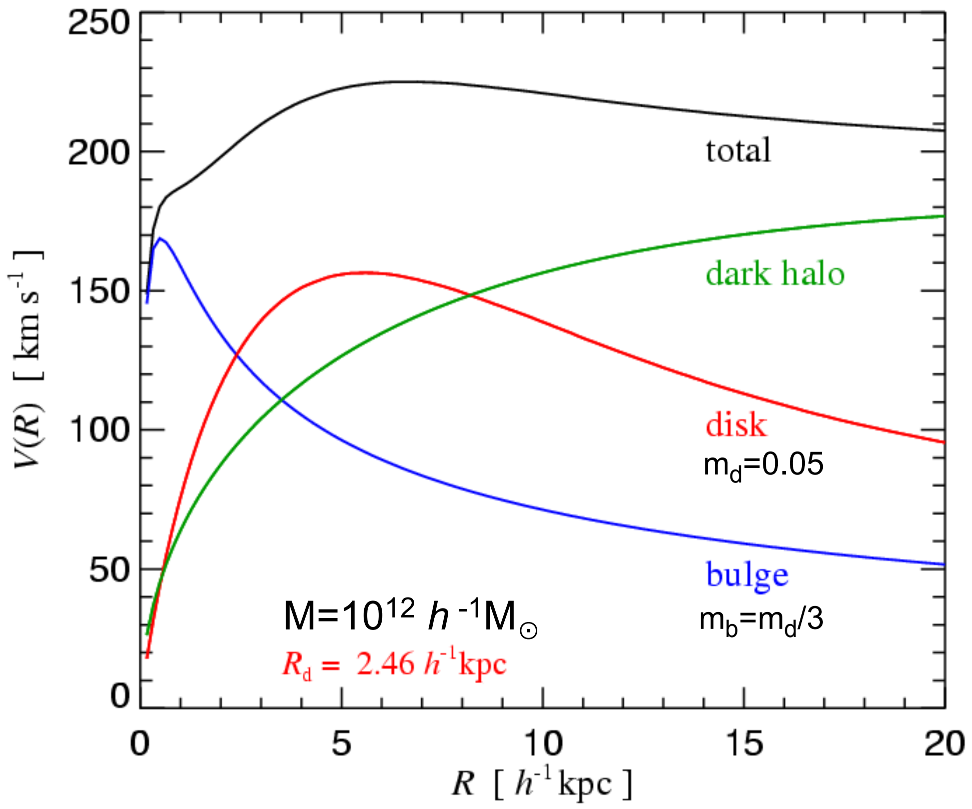
We construct compound disk galaxies that are in dynamical equilibrium

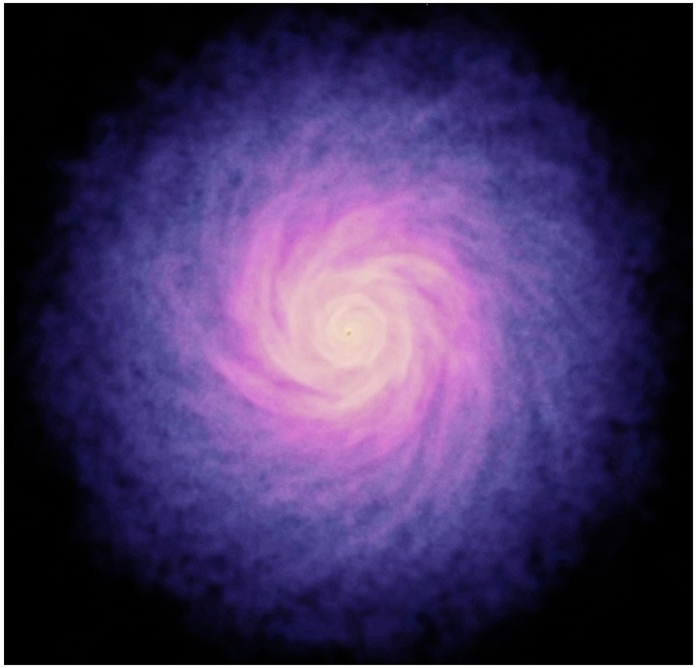
STRUCTURAL PROPERTIES OF MODEL GALAXIES

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





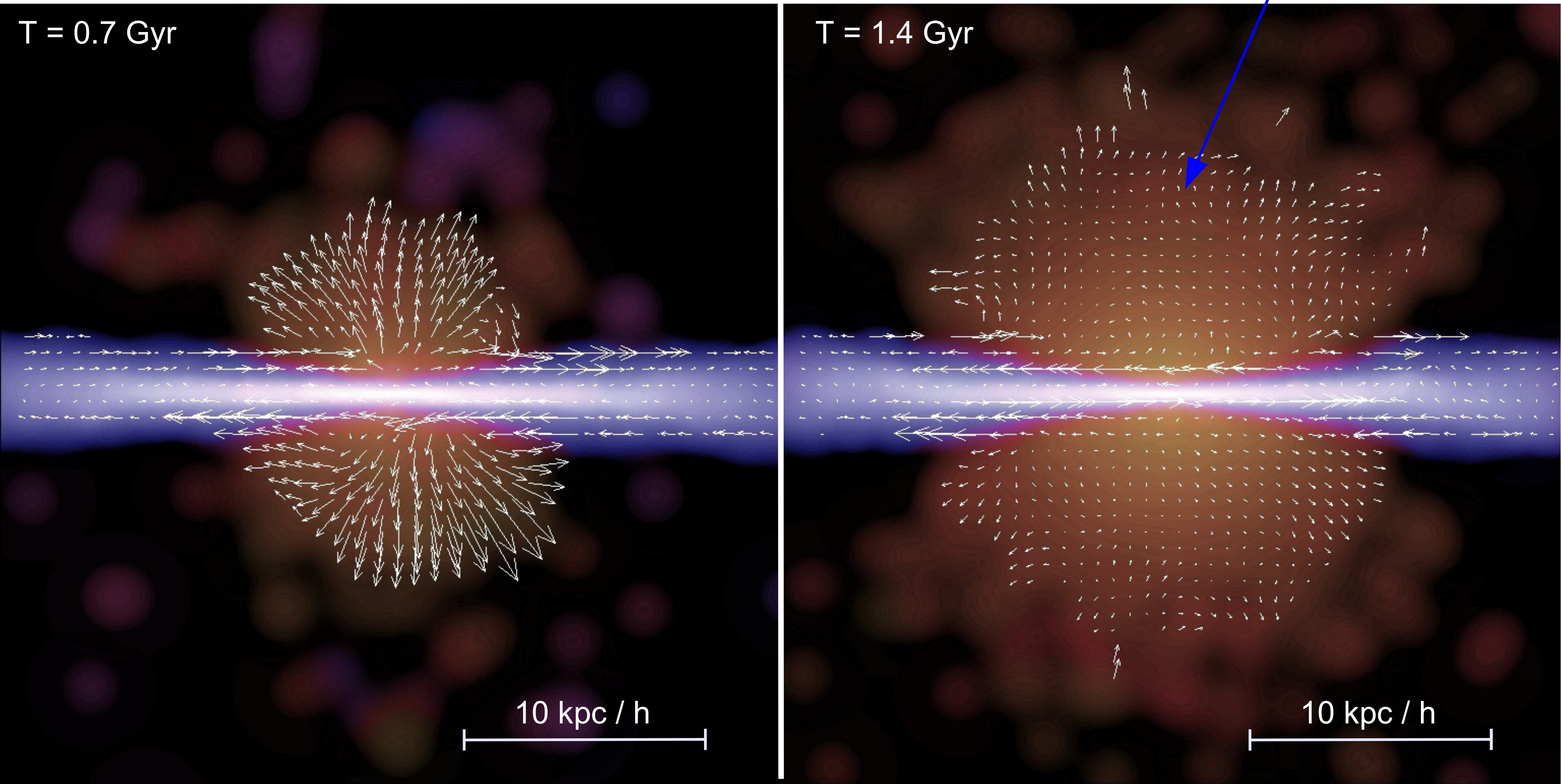
At low accretion rates, feedback by the central black hole activity may blow a weak wind into the halo

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)



Growth rate of black holes in isolated galaxies

THREE PHASES OF BLACK HOLE GROWTH

Bondi-growth:

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

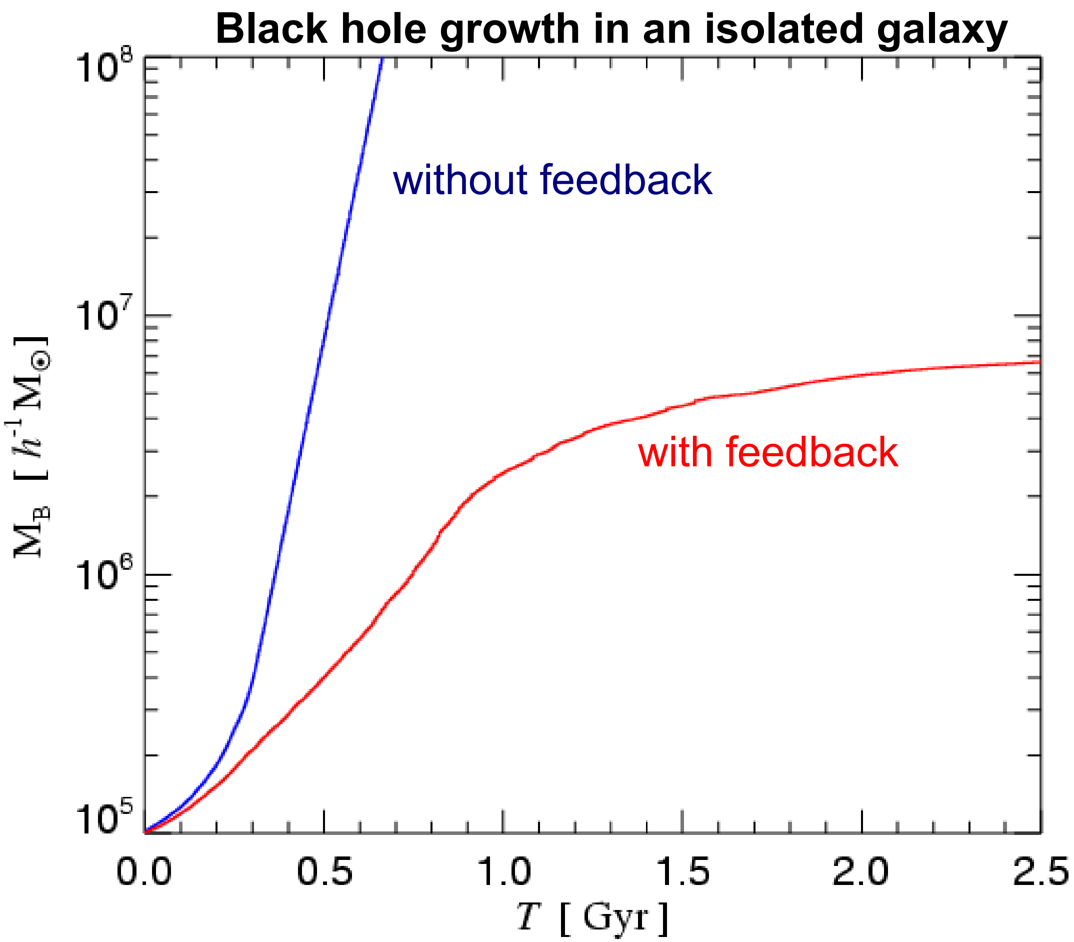
Eddington-growth:

$$\dot{M}(t) = M_0 \exp\left(\frac{t}{t_{\rm S}}\right)$$

Slow, feedback regulated growth:

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

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



Black hole growth in an isolated galaxy

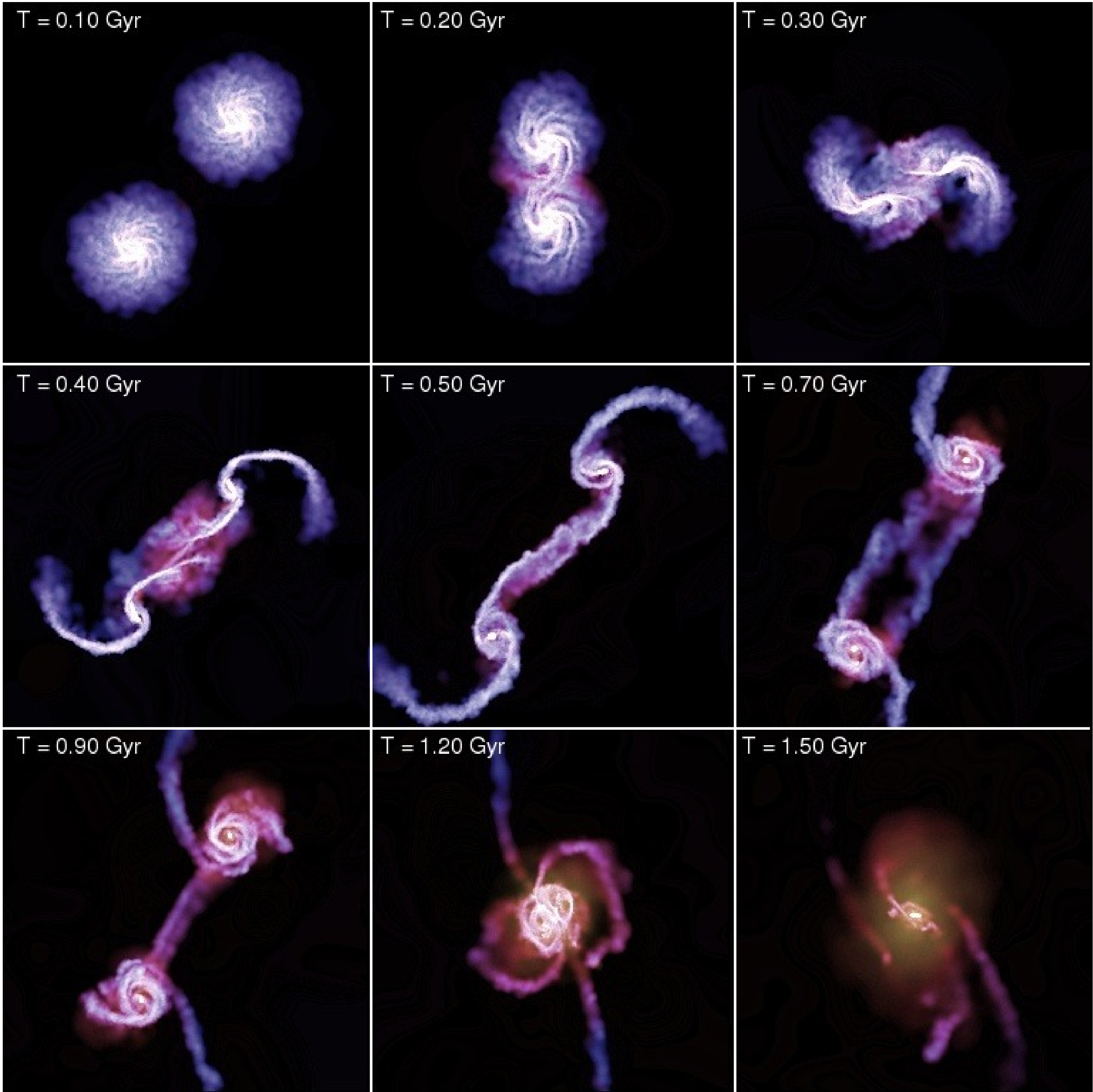
- $\mathbf{T_{equal}}$ independent of density
- for: $T_{\rm equal} \simeq T_{\rm vir},\;\; M_{\rm gas} \propto M_{\rm halo}$

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

- 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.

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

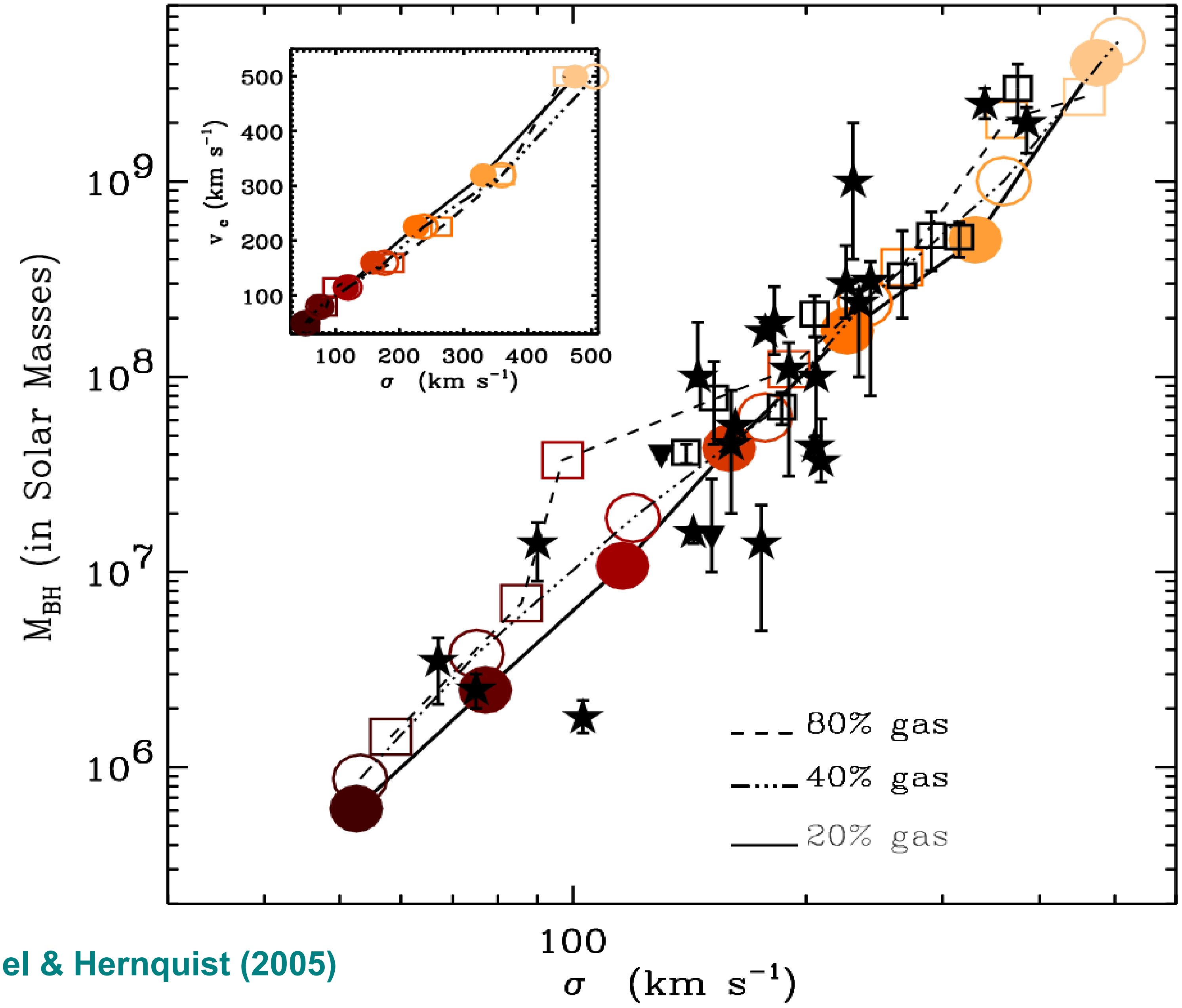
TIME EVOLUTION OF A PROGRADE MAJOR MERGER



This may also fuel a central AGN !

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

BLACK HOLE MASSES IN MERGER REMNANTS

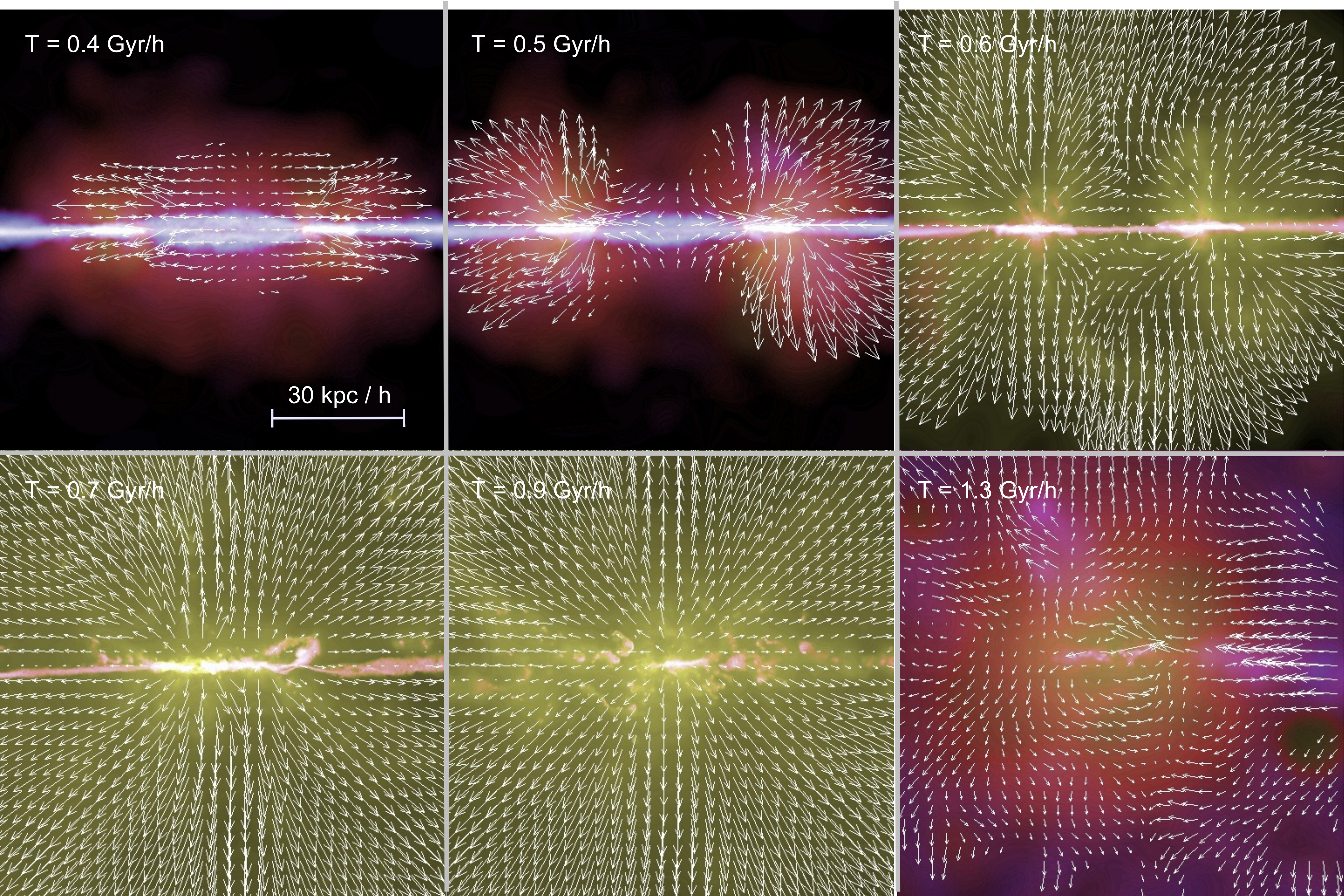


Di Matteo, Springel & Hernquist (2005)

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

GAS OUTFLOW BY AGN FEEDBACK

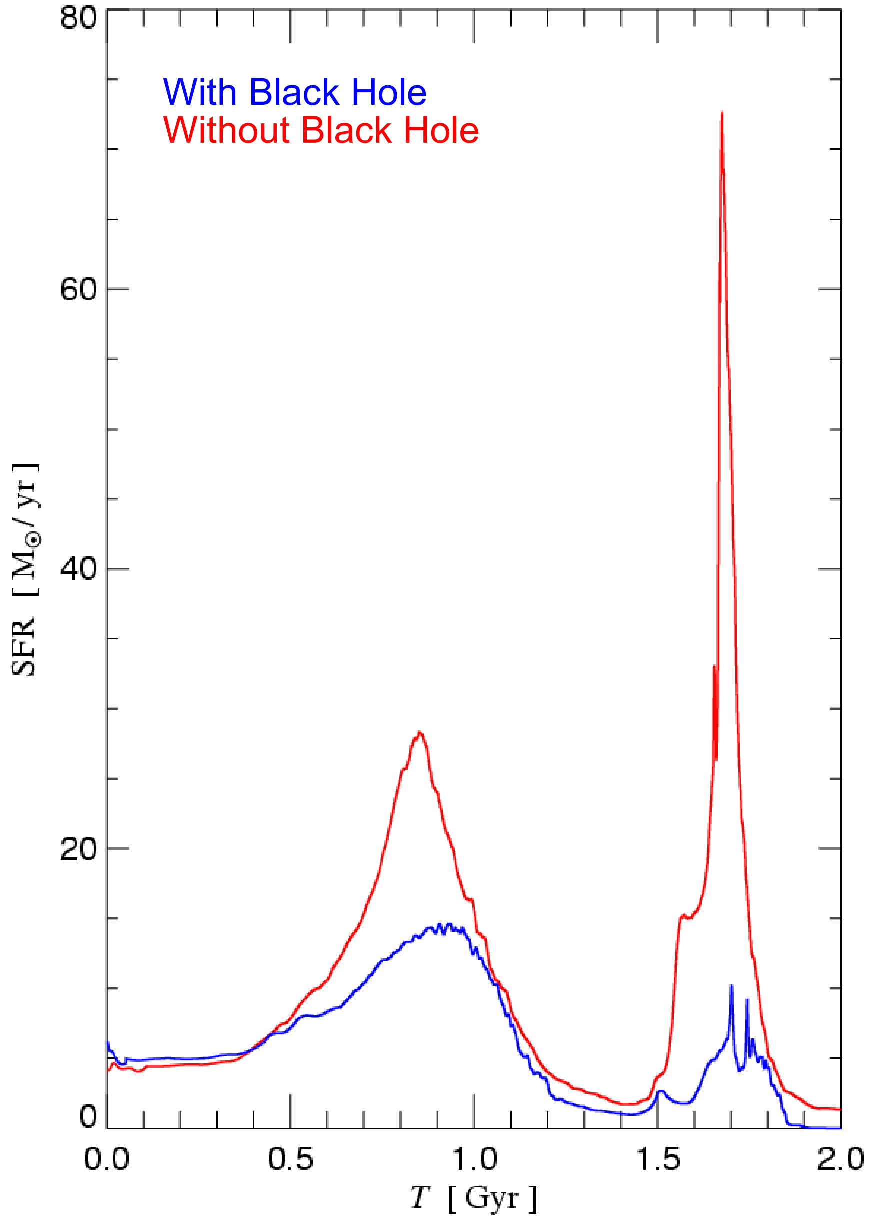
(outflow reaches speeds of up to ~1800 km/sec)



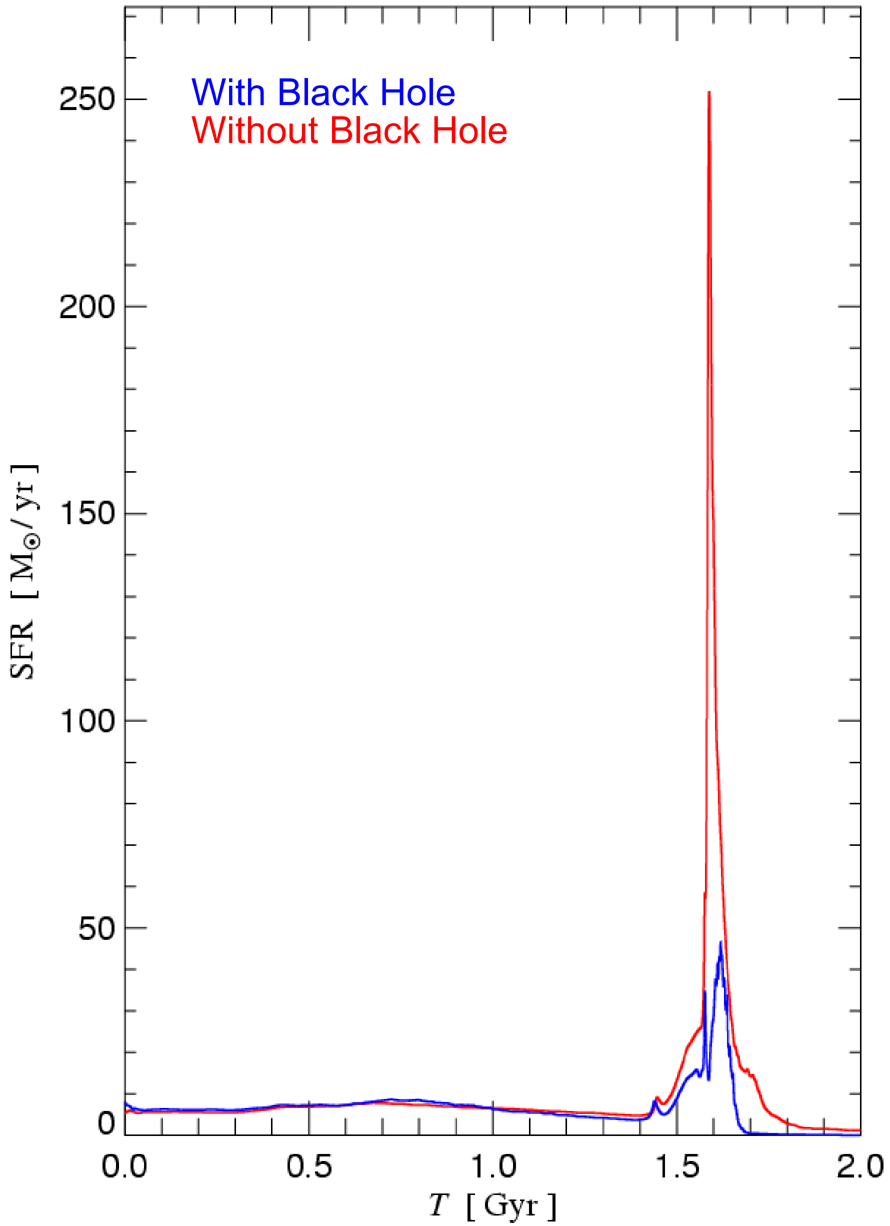
Starburst and AGN activity are coupled and depend on the structural properties of the progenitor systems

COMPARISON OF STAR FORMATION IN MERGERS WITH AND WITHOUT BLACK HOLE

Merger of bulgeless disks

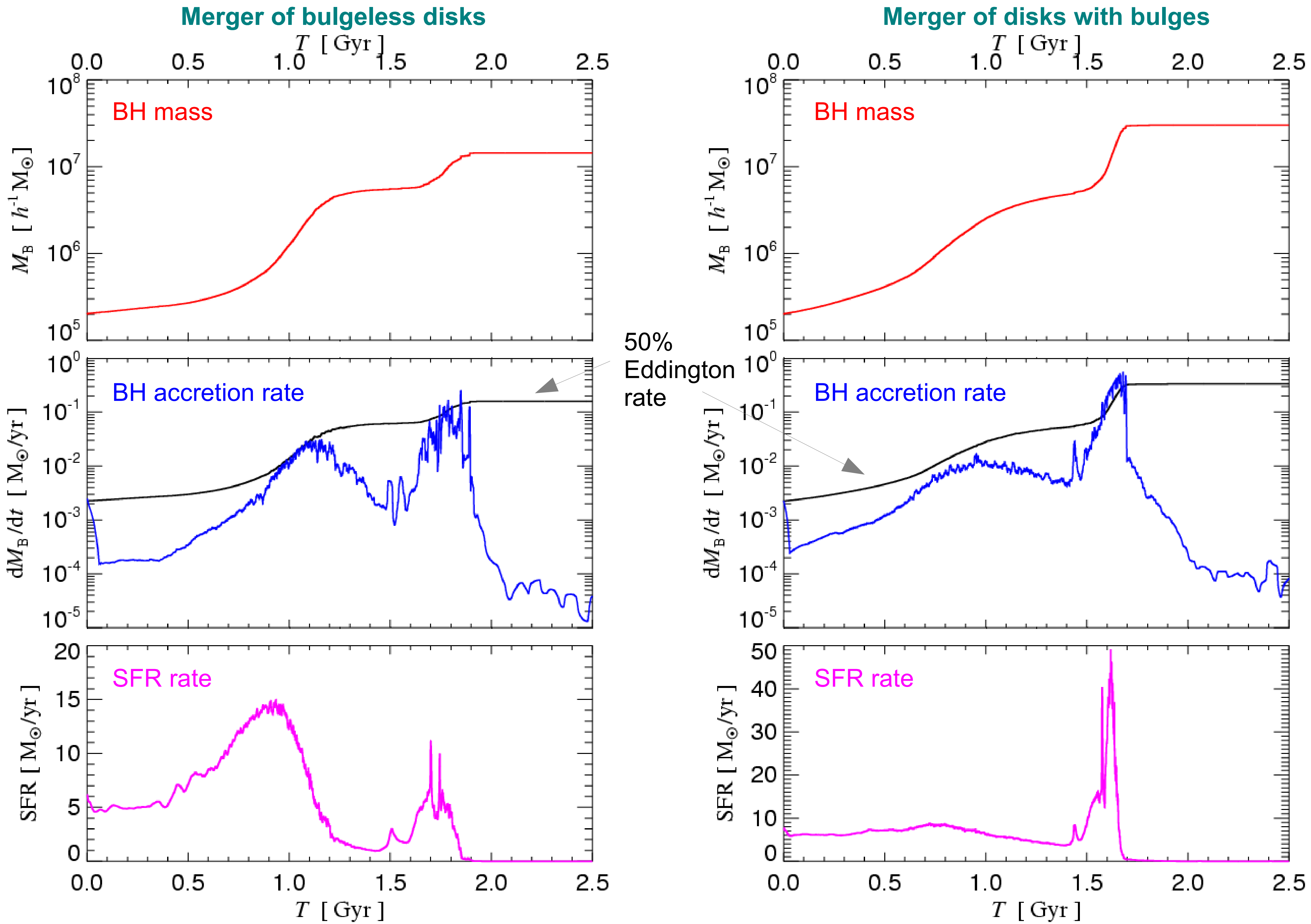


Merger of disks with bulges



Mergers of disk galaxies trigger starburts and ignite central AGN activity

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



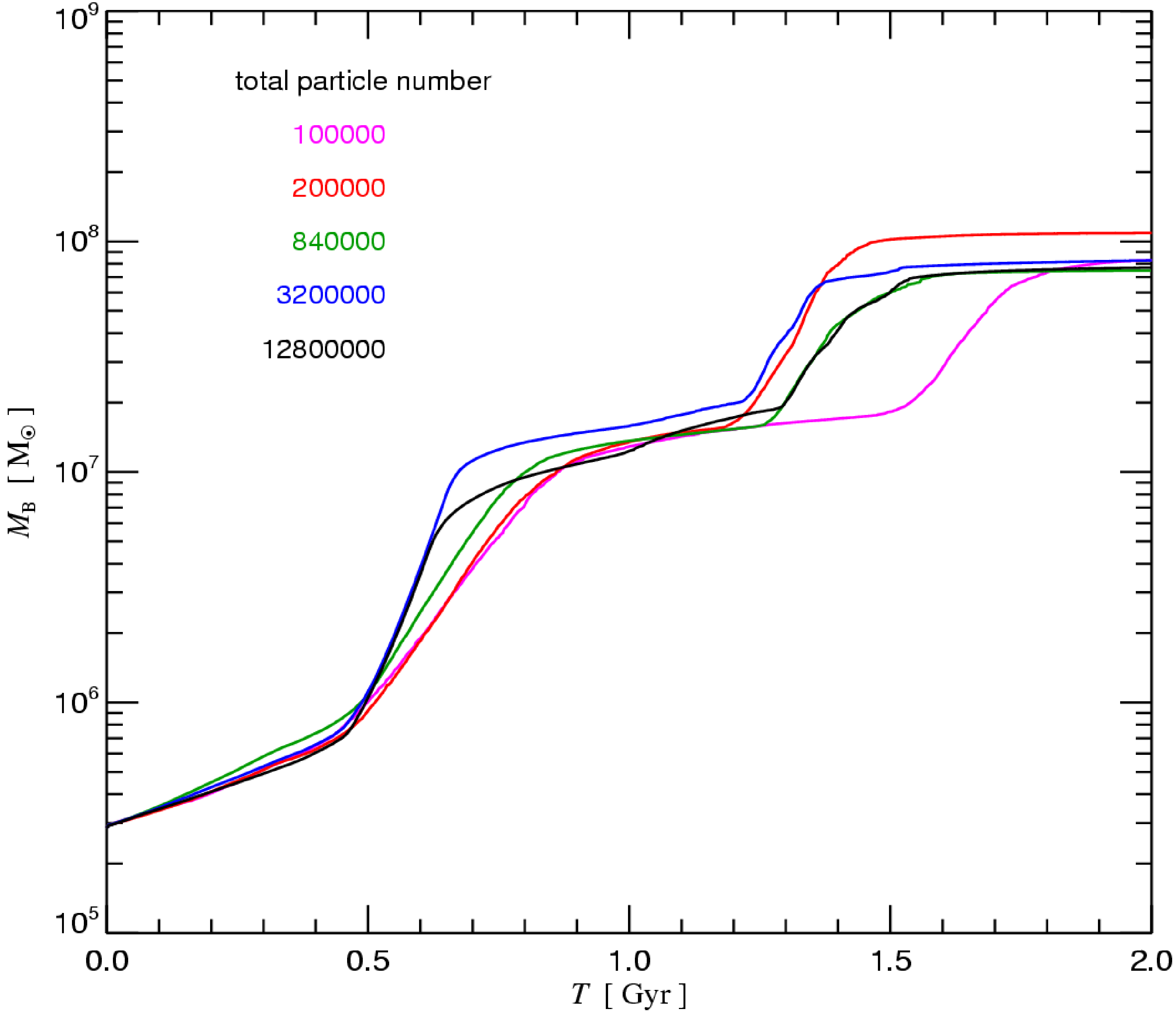
Merger of bulgeless disks

Merger of disks with bulges

50% Eddington rate

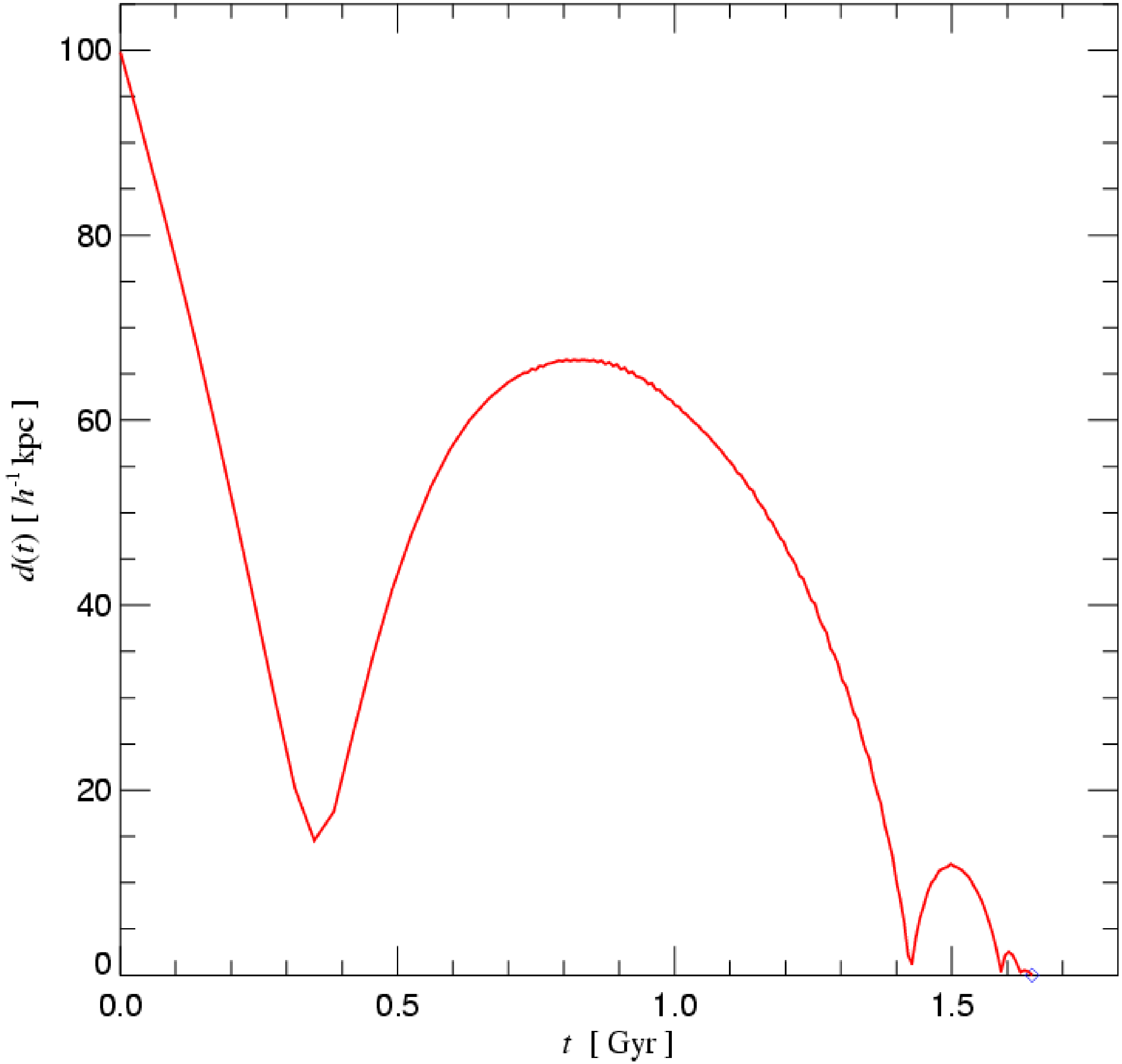
Robust numerical behaviour for the final black hole mass as a function of resolution is achieved

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



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

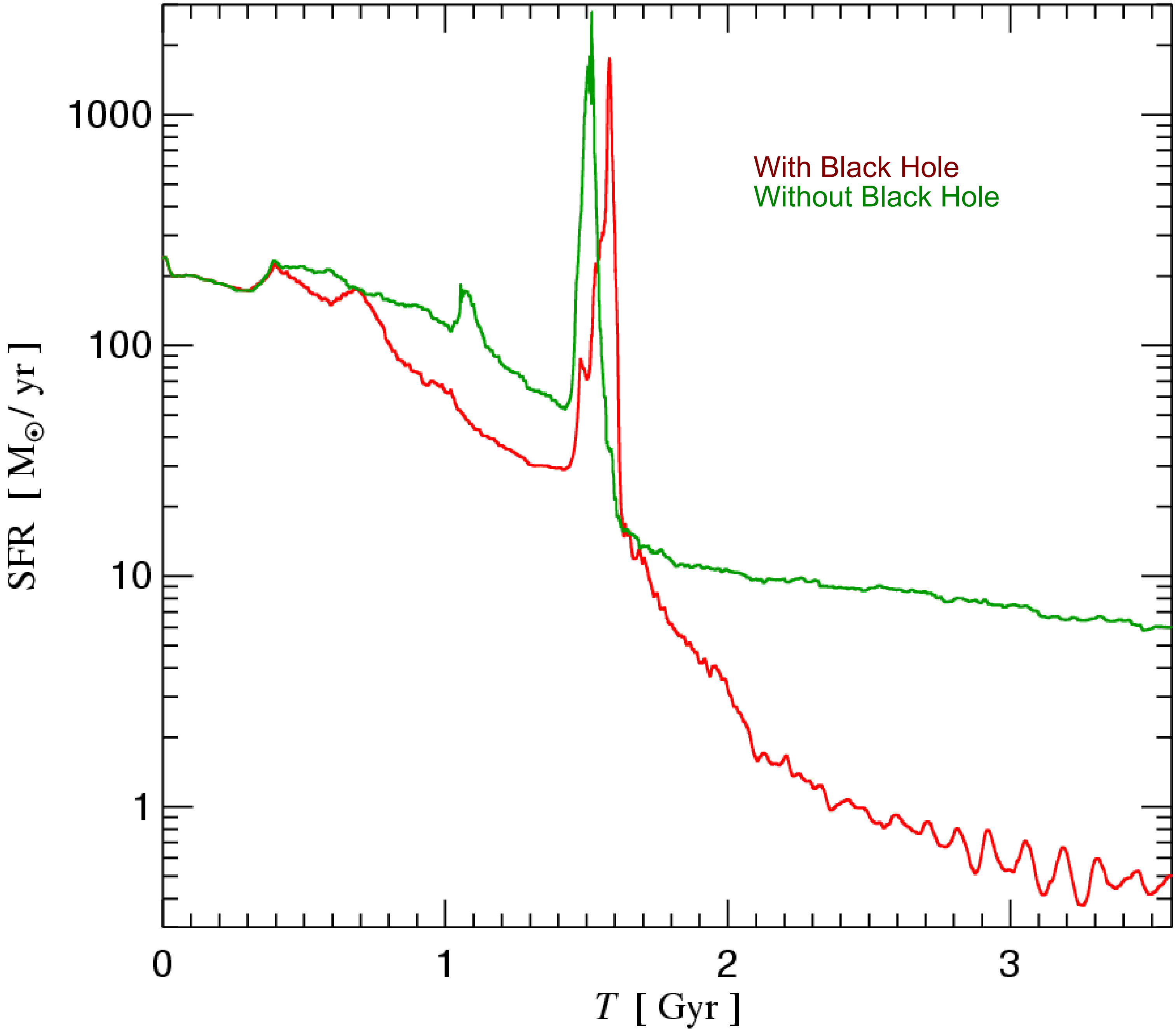
APPROACH OF THE BLACK HOLES IN MERGER SIMULATIONS



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.

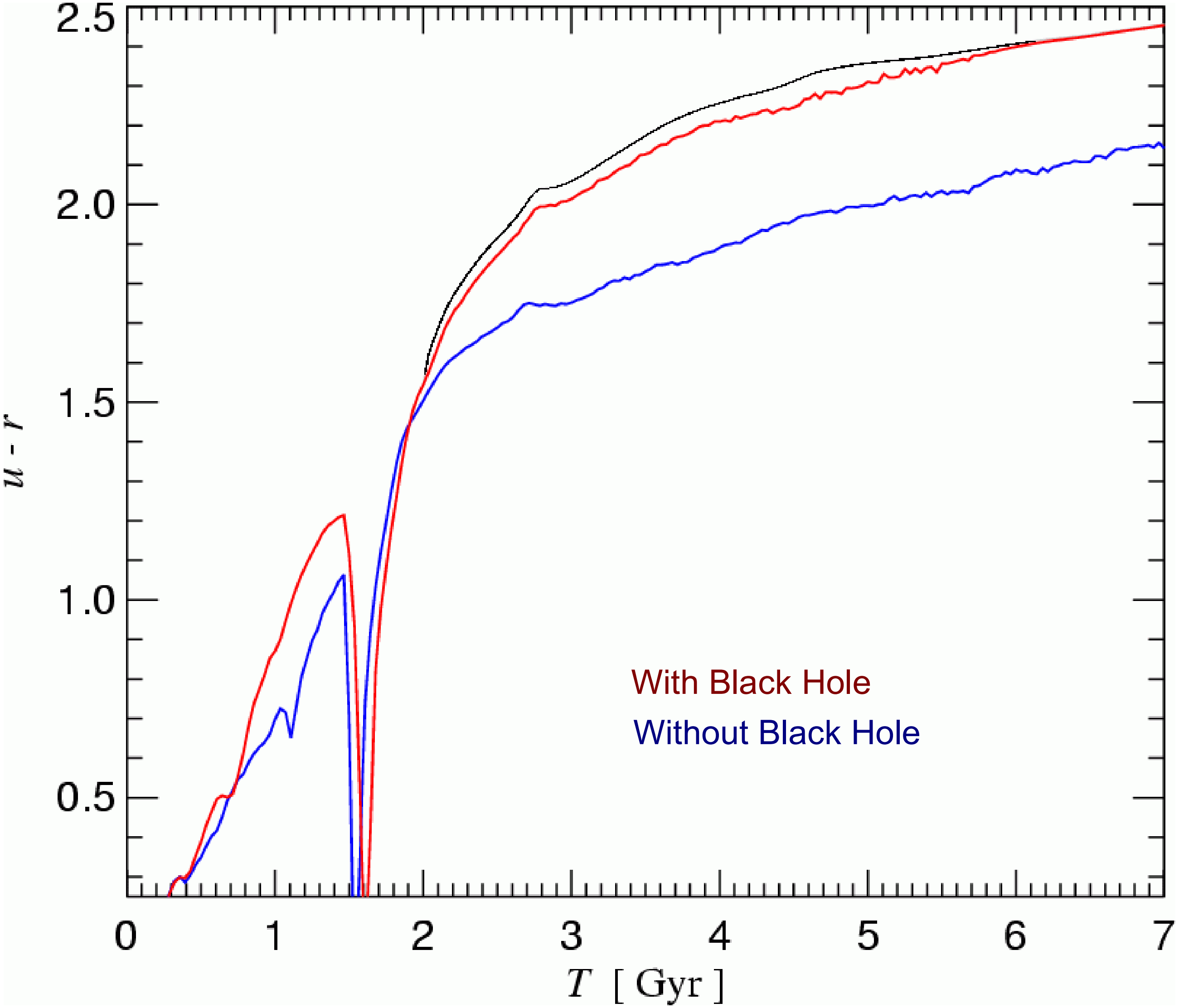
The feedback by the AGN can reduce the strength of the starburst

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

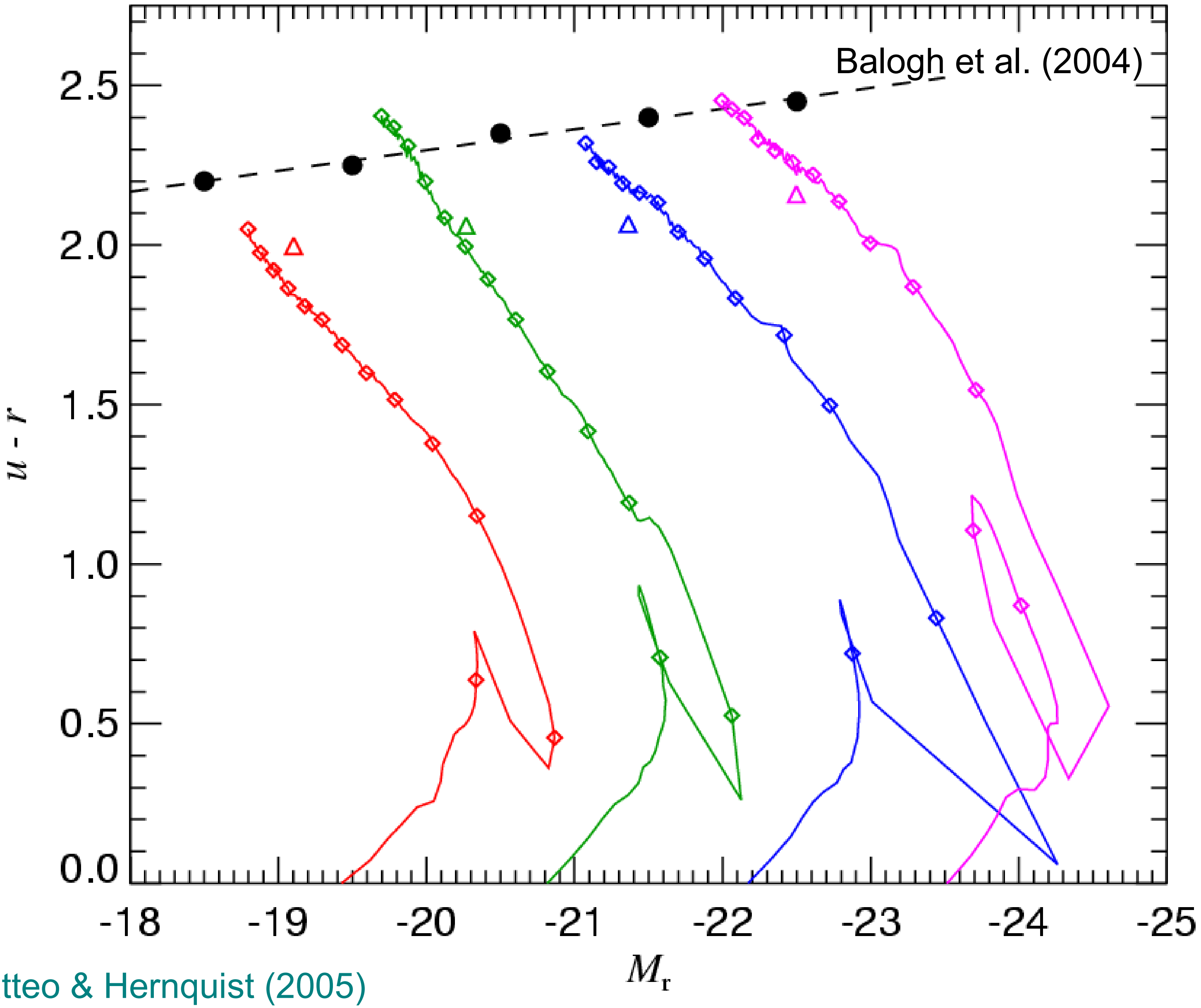
COLOR EVOLUTION IN MERGER SIMULATIONS



Springel, Di Matteo & Hernquist (2005)

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

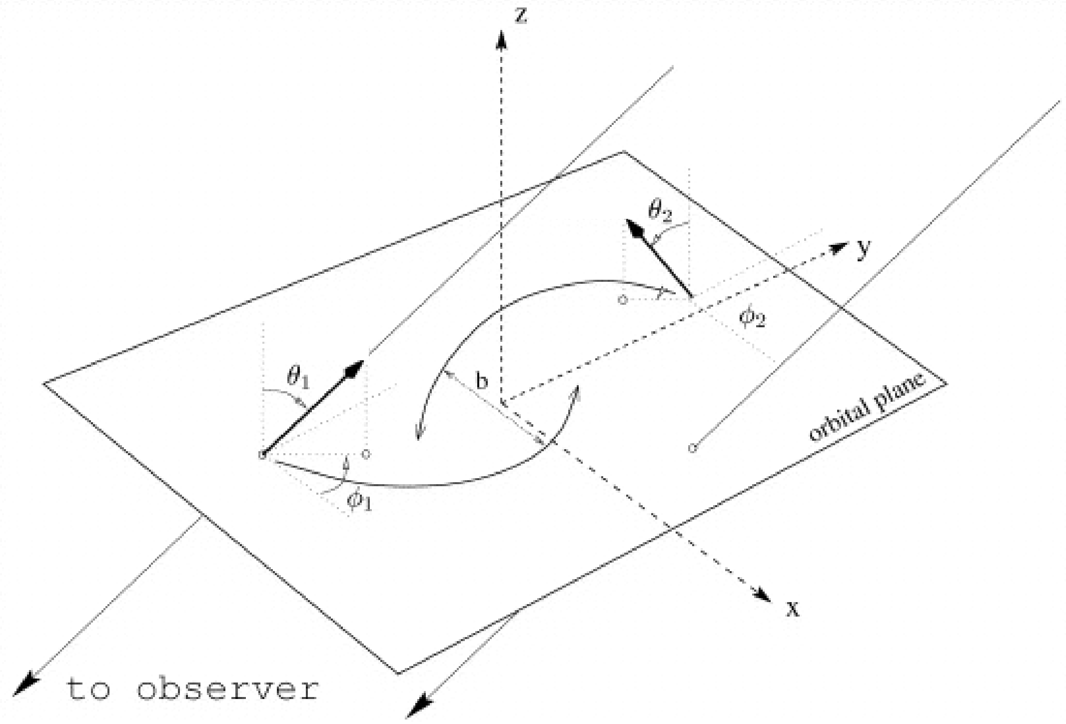
COLOR-MAGNITUDE TRACKS OF MERGERS OF DIFFERENT MASS

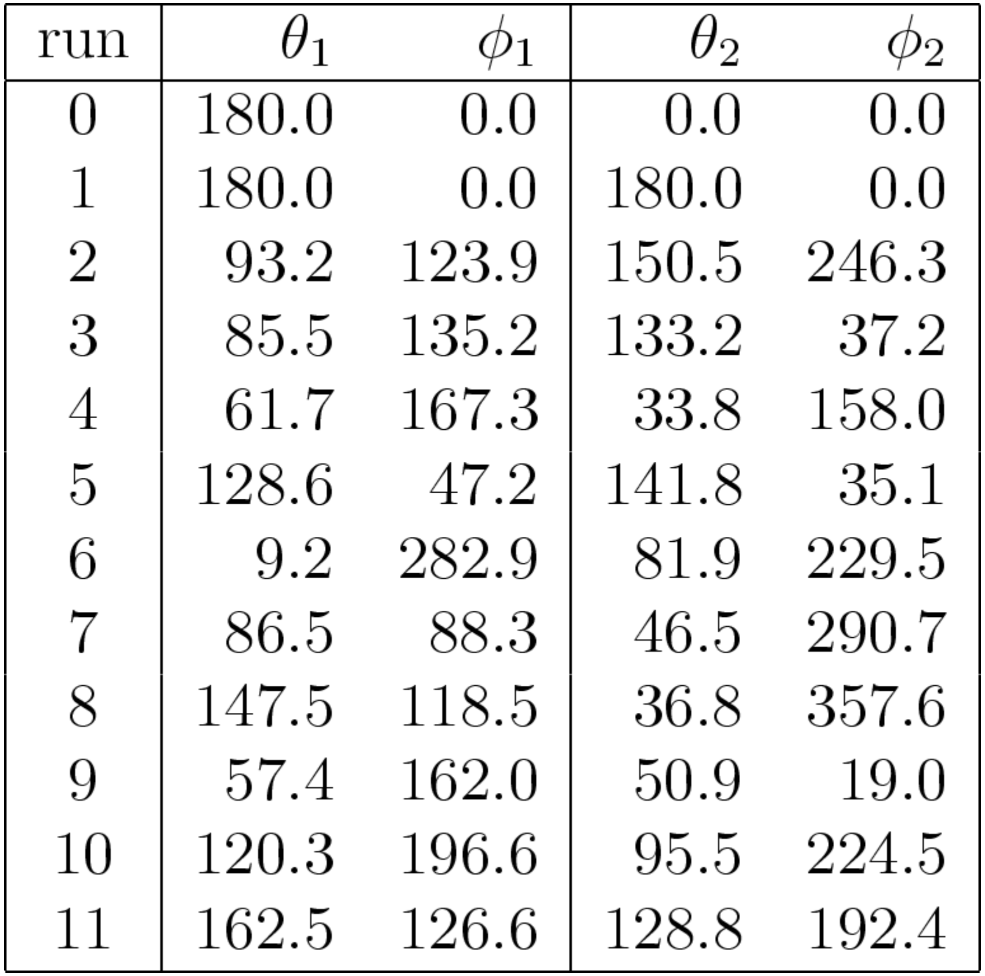


Springel, Di Matteo & Hernquist (2005)

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

ENCOUNTER GEOMETRIES

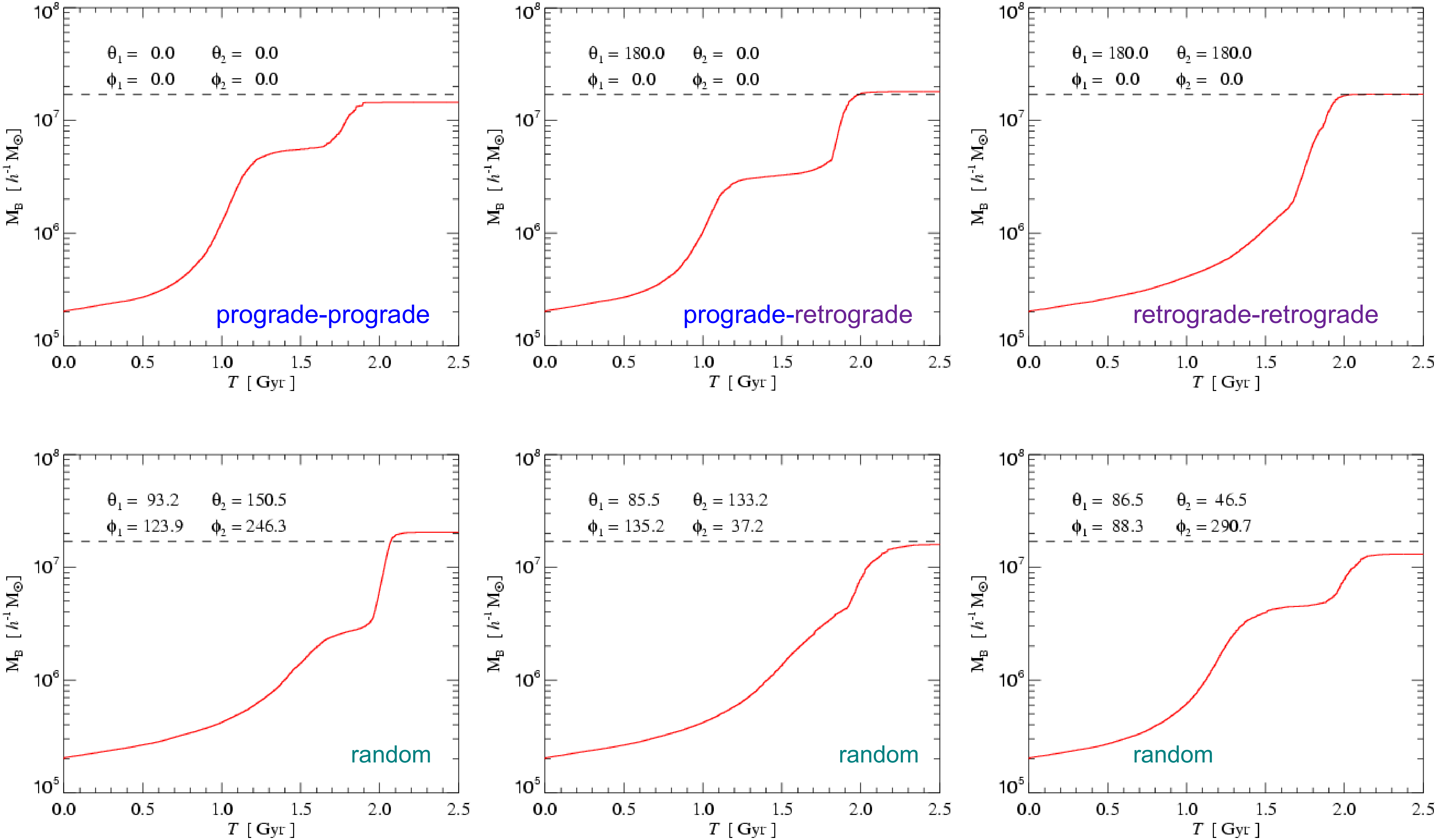




run	θ_1	ϕ_1	θ_2	ϕ_2
0	180.0	0.0	0.0	0.0
1	180.0	0.0	180.0	0.0
2	93.2	123.9	150.5	246.3
3	85.5	135.2	133.2	37.2
4	61.7	167.3	33.8	158.0
5	128.6	47.2	141.8	35.1
6	9.2	282.9	81.9	229.5
7	86.5	88.3	46.5	290.7
8	147.5	118.5	36.8	357.6
9	57.4	162.0	50.9	19.0
10	120.3	196.6	95.5	224.5
11	162.5	126.6	128.8	192.4

The 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

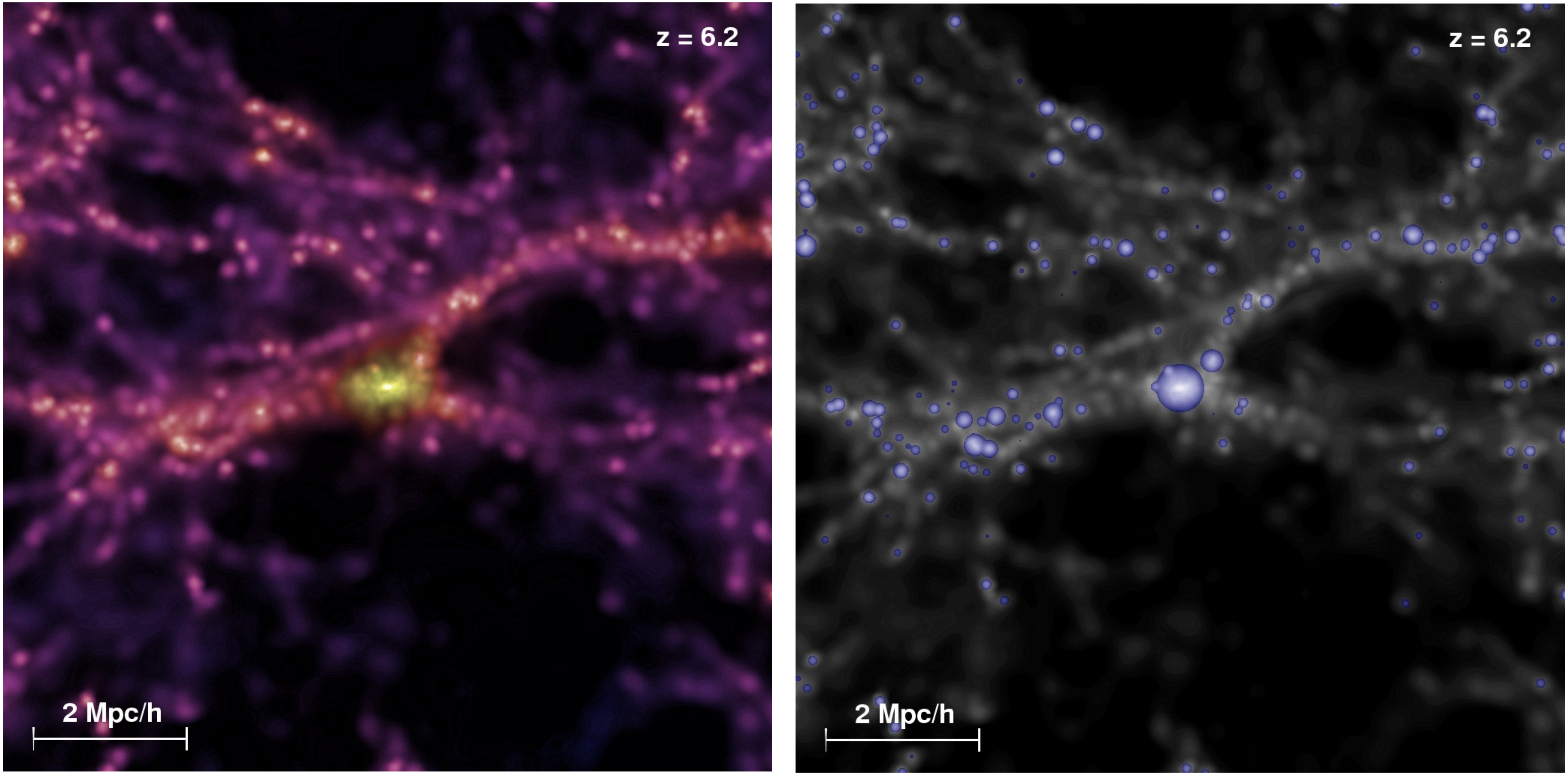


In the Millennium Simulation, we can identify most massive halos/galaxies at z~6.2 as plausible Sloan quasar candidates

DARK MATTER AND GALAXY DISTRIBUTION AROUND THE GALAXY WITH THE LARGEST STELLAR MASS AT Z=6.2

$M_h = 5.3 \times 10^{12}\ h^{-1}M_\odot$

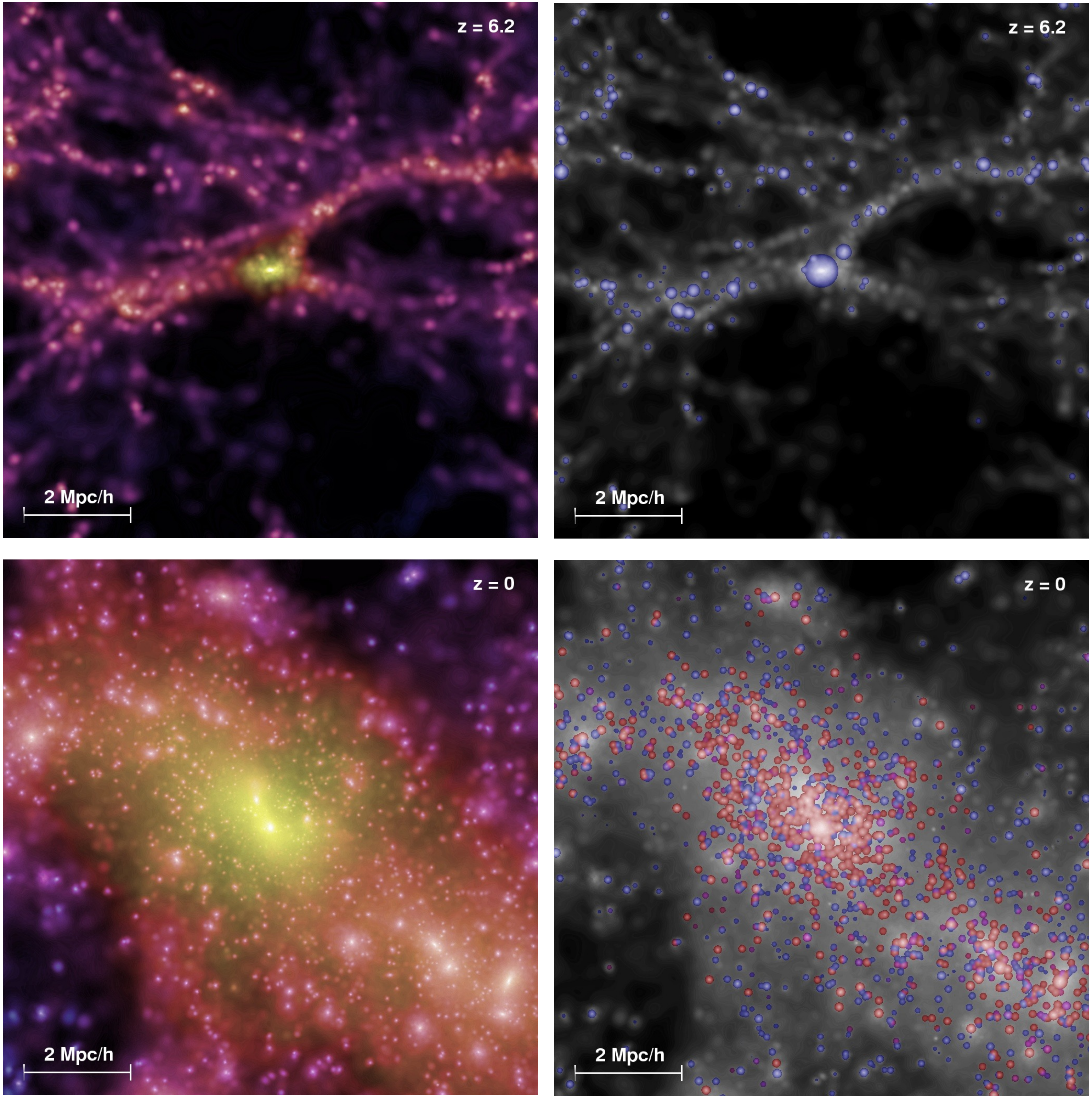
$M_* = 8.2 \times 10^{10}\ h^{-1}M_\odot$ SFR = 235 $M_\odot$ / yr



Springel et al. (2005)

The quasars end up as cD galaxies in rich galaxy clusters today

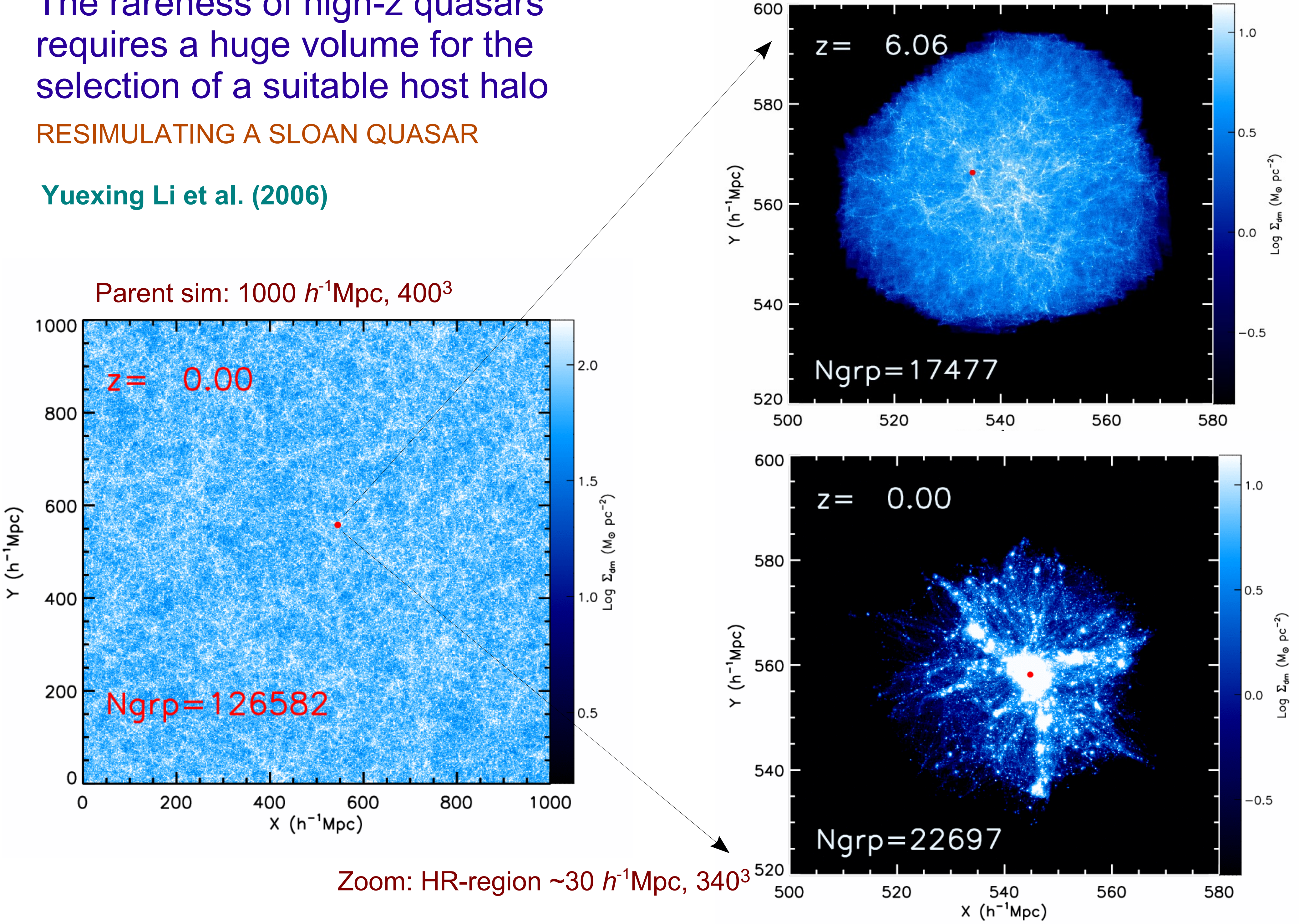
TRACING GALAXIES OVER COSMIC TIME



The rareness of high-z quasars requires a huge volume for the selection of a suitable host halo

RESIMULATING A SLOAN QUASAR

Yuexing Li et al. (2006)



Parent sim: 1000 h^{-1}Mpc, 400^3

Zoom: HR-region ~30 h^{-1}Mpc, 340^3

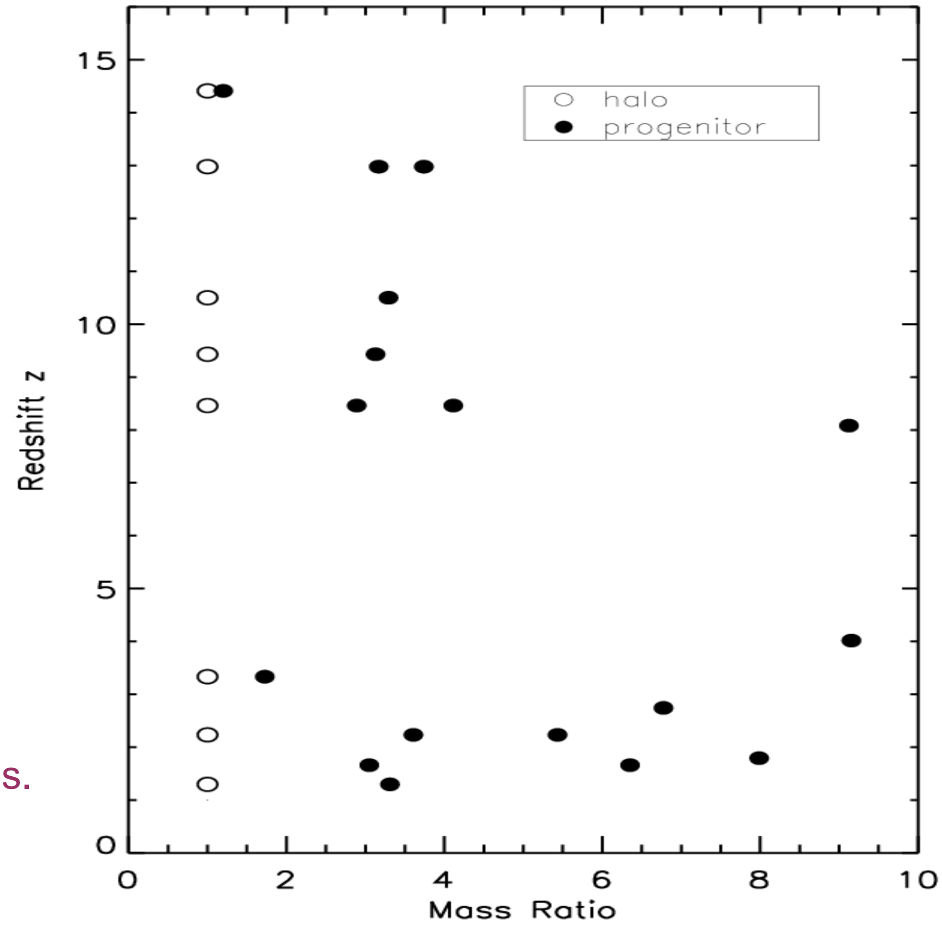
A measurement of the merger tree in the dark matter simulation is used to set-up a hydrodynamical multi-merger reconstruction of the formation history of the halo

DETAILS OF THE PROGENTOR SET-UP

Li et al. (2006)

BH seeds are assumed to have grown at Eddington from 200 $M_\odot$ at z=30 to the time they enter the calculation.

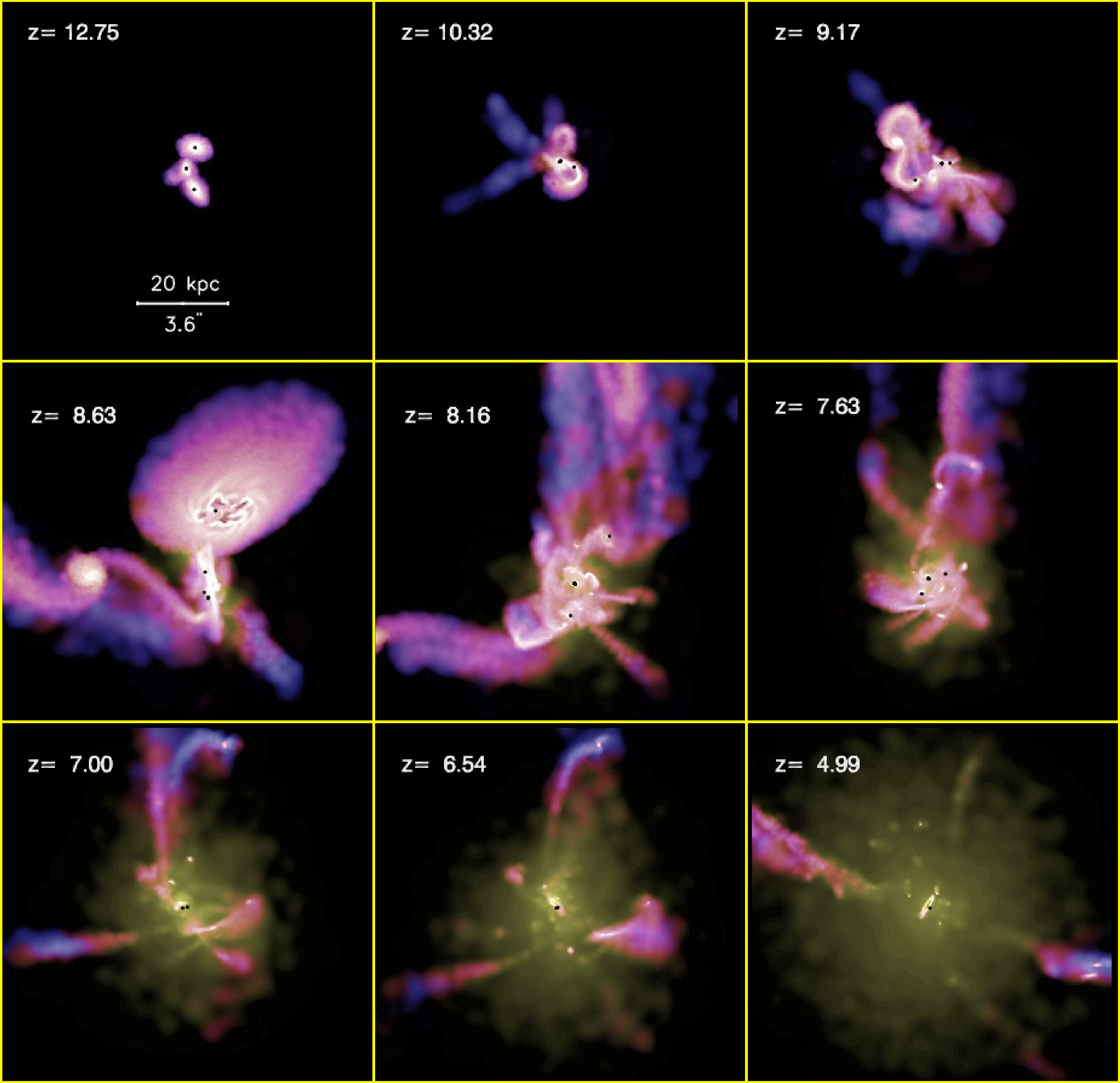
The total seed BH mass is less than 1% of the final BH mass.



Galaxy[1]	z[2]	$M_{\rm vir}$[3] $[10^{10} M_\odot]$	$V_{\rm vir}$[4] [km/s]	$f_{\rm gas}$[5]	$M_{\rm BH}$[6] $[10^5 M_\odot]$	θ_1[7]	ϕ_1[8]	θ_2[9]	ϕ_2[10]	$R_{\rm p}$[11] [kpc]	R_0[12] [kpc]
G1	14.4	9.0	234.1	1.0	0.21	–	–	–	–	–	–
G2	14.4	7.5	220.3	1.0	0.21	128.7	34.6	144.9	24.0	0.2	7.1
G3	13.9	21.4	297.8	1.0	0.51	38.3	93.9	94.2	119.6	0.2	8.5
G4	13.9	25.3	314.6	1.0	0.51	68.3	319.5	115.2	99.0	0.3	10.7
G5	10.5	70.1	401.0	1.0	3.56	81.7	230.2	87.8	198.9	0.4	11.3
G6	9.4	113.7	448.6	0.9	16.4	61.4	49.9	41.2	80.4	0.5	18.2
G7	8.5	228.5	540.4	0.9	88.2	86.6	93.4	21.6	43.3	0.7	25.2
G8	8.5	296.7	589.5	0.9	88.2	113.3	259.1	80.0	343.3	1.0	34.5

Hydro-simulation of the hierarchical build-up of an early Sloan quasar

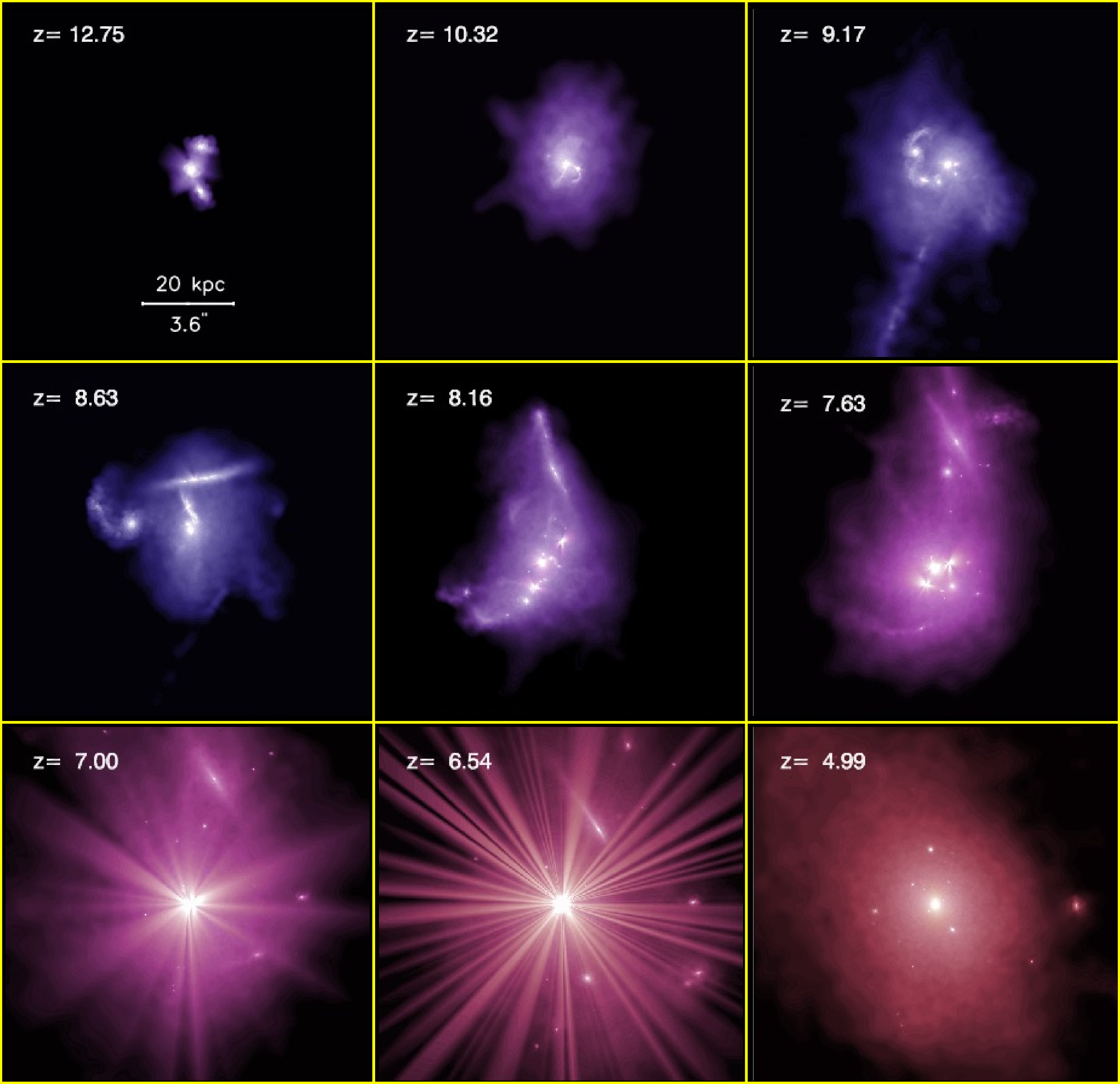
TIME EVOLUTION OF THE PROJECTED GAS DISTRIBUTION



Li et al. (2006)

Hydro-simulation of the hierarchical build-up of an early Sloan quasar

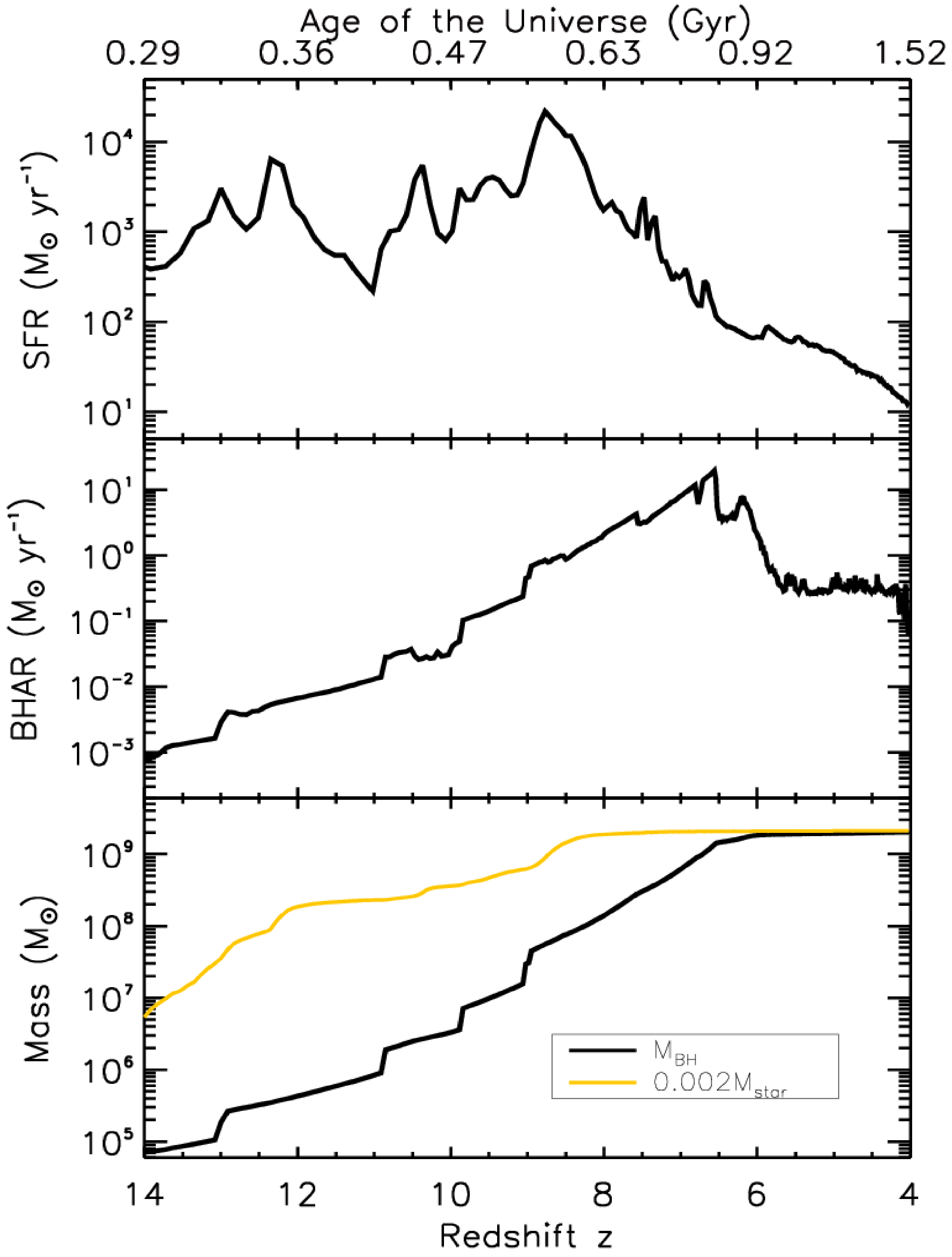
TIME EVOLUTION OF THE PROJECTED STELLAR MASS



Li et al. (2006)

The black holes of the quasar progenitors have grown at ~50% of their liftetime at the Eddington luminosity, and show a high variability of their SFR

TIME EVOLUTION OF THE BH GROWTH AND THE HOST'S SFR

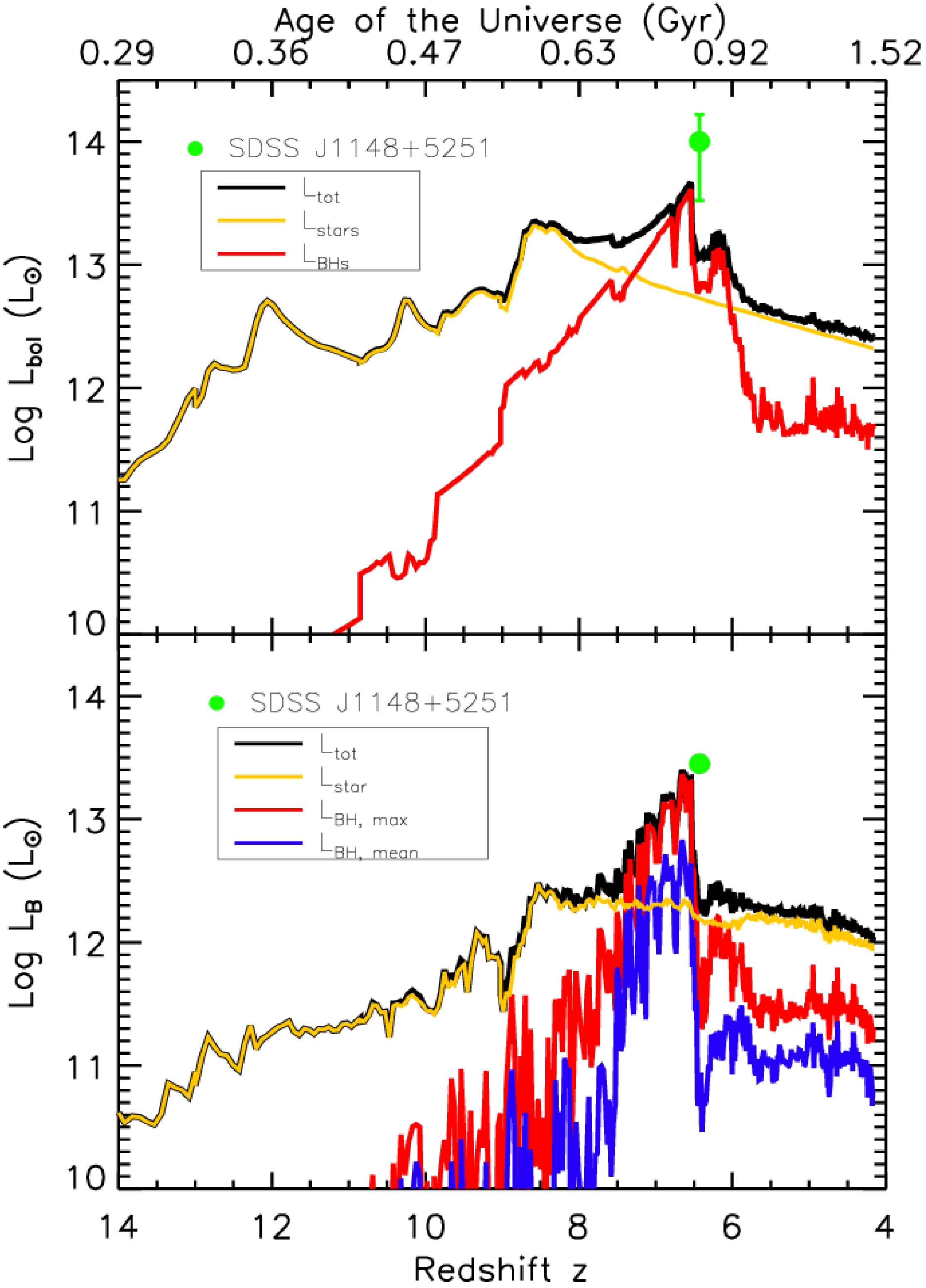


SFR peaks at >1000 $M_\odot$/yr at z~9, but drops to ~100 $M_\odot$/yr when the quasar is most luminous. Stellar mass at that time is 10^{12} $M_\odot$

Li et al. (2006)

The luminosity of the BH shows large variability and substantial line-of-sight dependence due to the obscuring gas distribution

LUMINOSITY EVOLUTION OF THE QUASAR AND THE HOST GALAXY



System is intrinsically bright can can power a ULRIG with $L > 10^{12} L_\odot$ for most of the simulation.

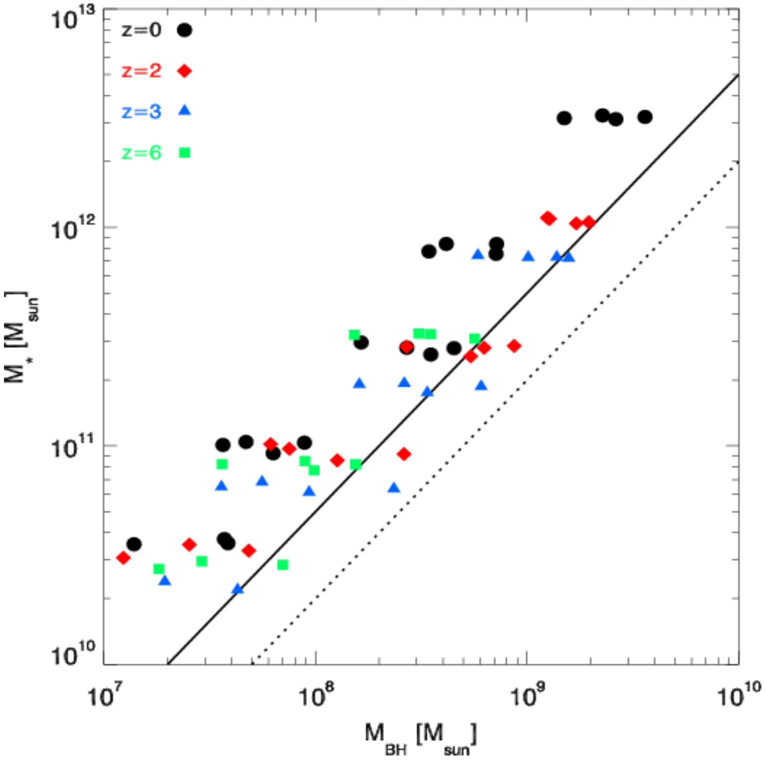
For the B-band luminosity, the obscuring gas column has been taken into account. The quasar would be visible as optically bright for ~160 million years between z=7.5 and z=6.4.

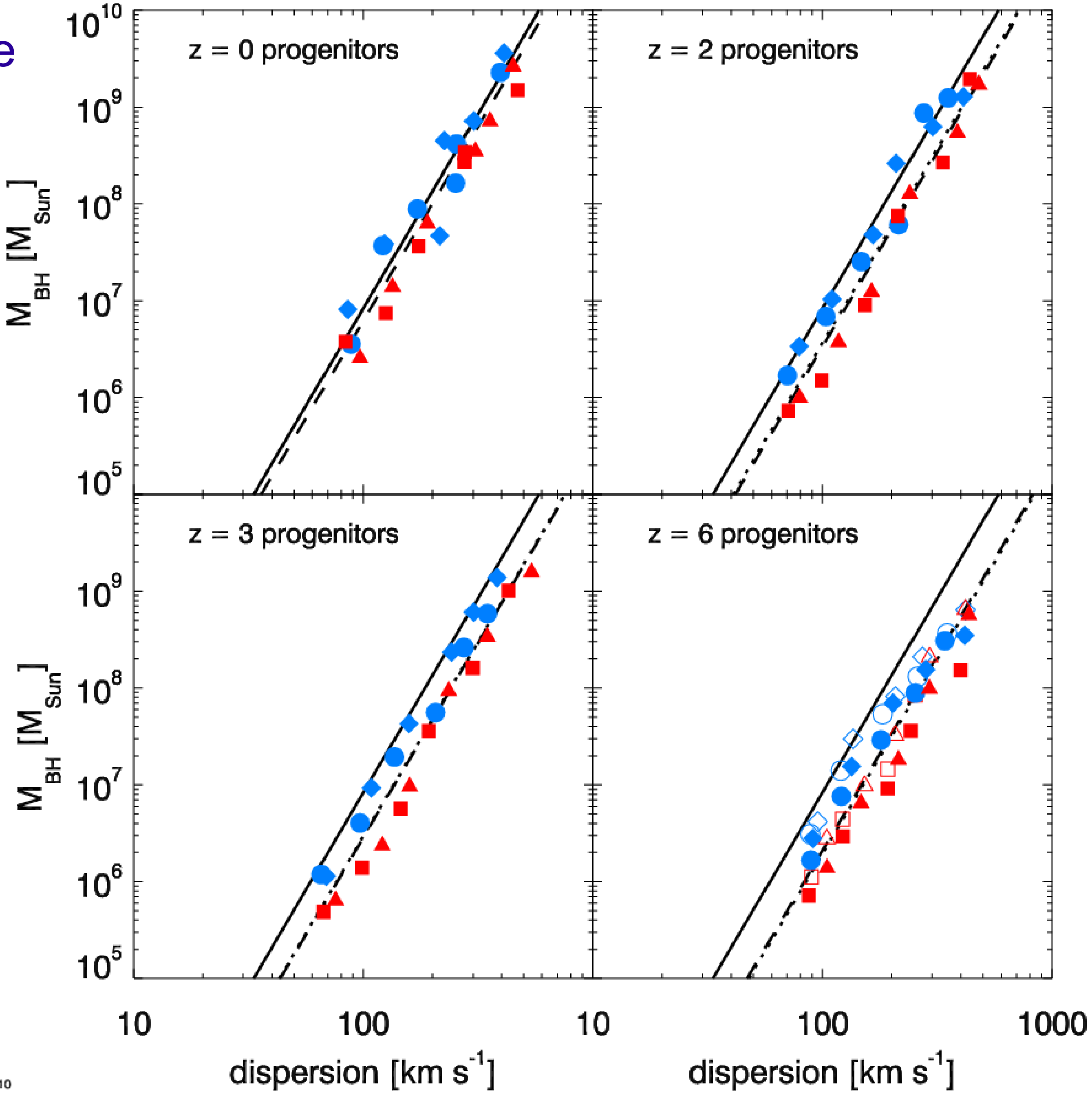
Li et al. (2006)

Using mergers of high-z galaxies, one can predict the evolution of the M_{BH} dispersion relationship

BH MASS – VELOCITY DISPERSION RELATIONSHIP AT DIFFERENT EPOCHS

Robertson et al. (2006)

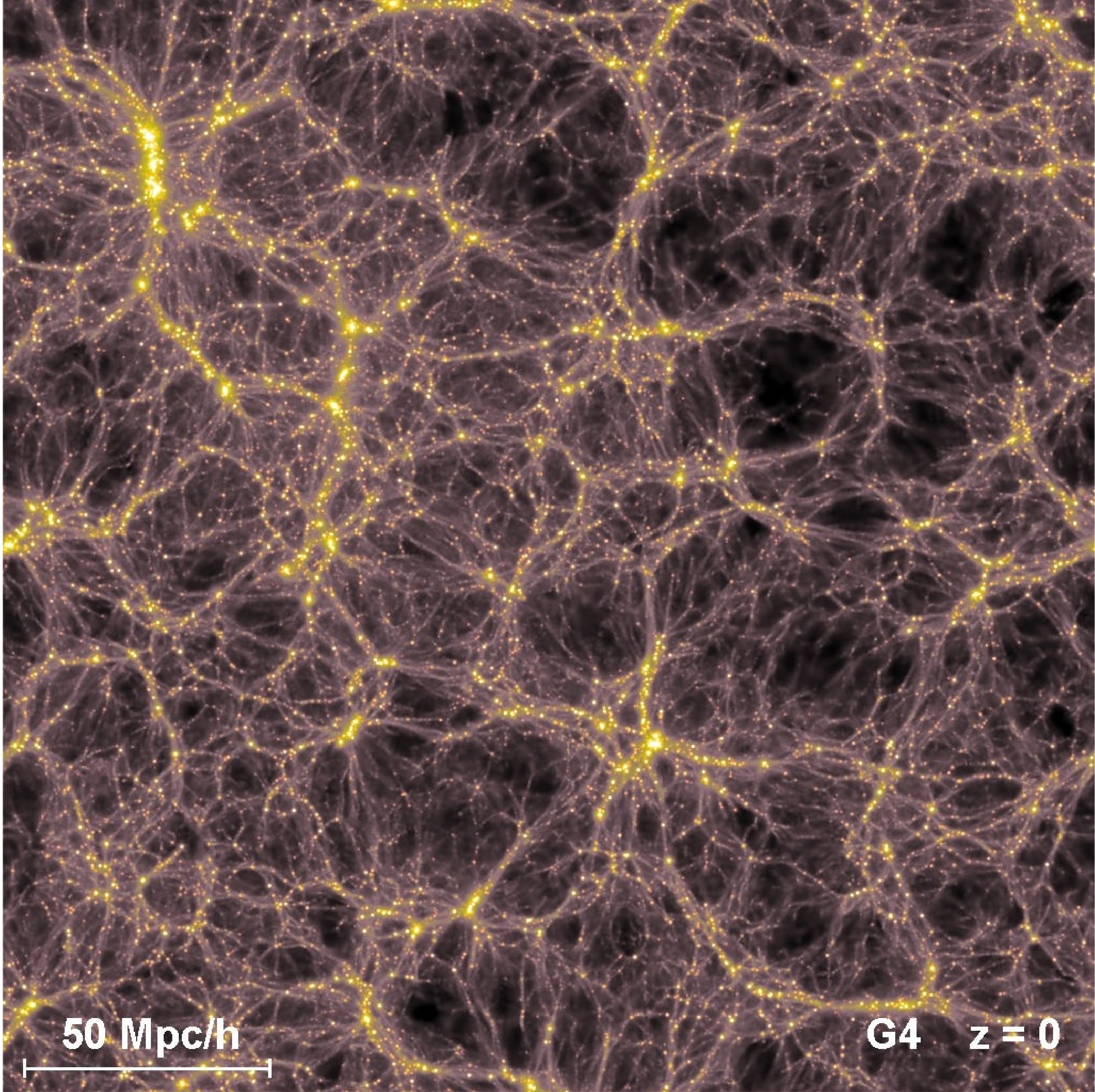




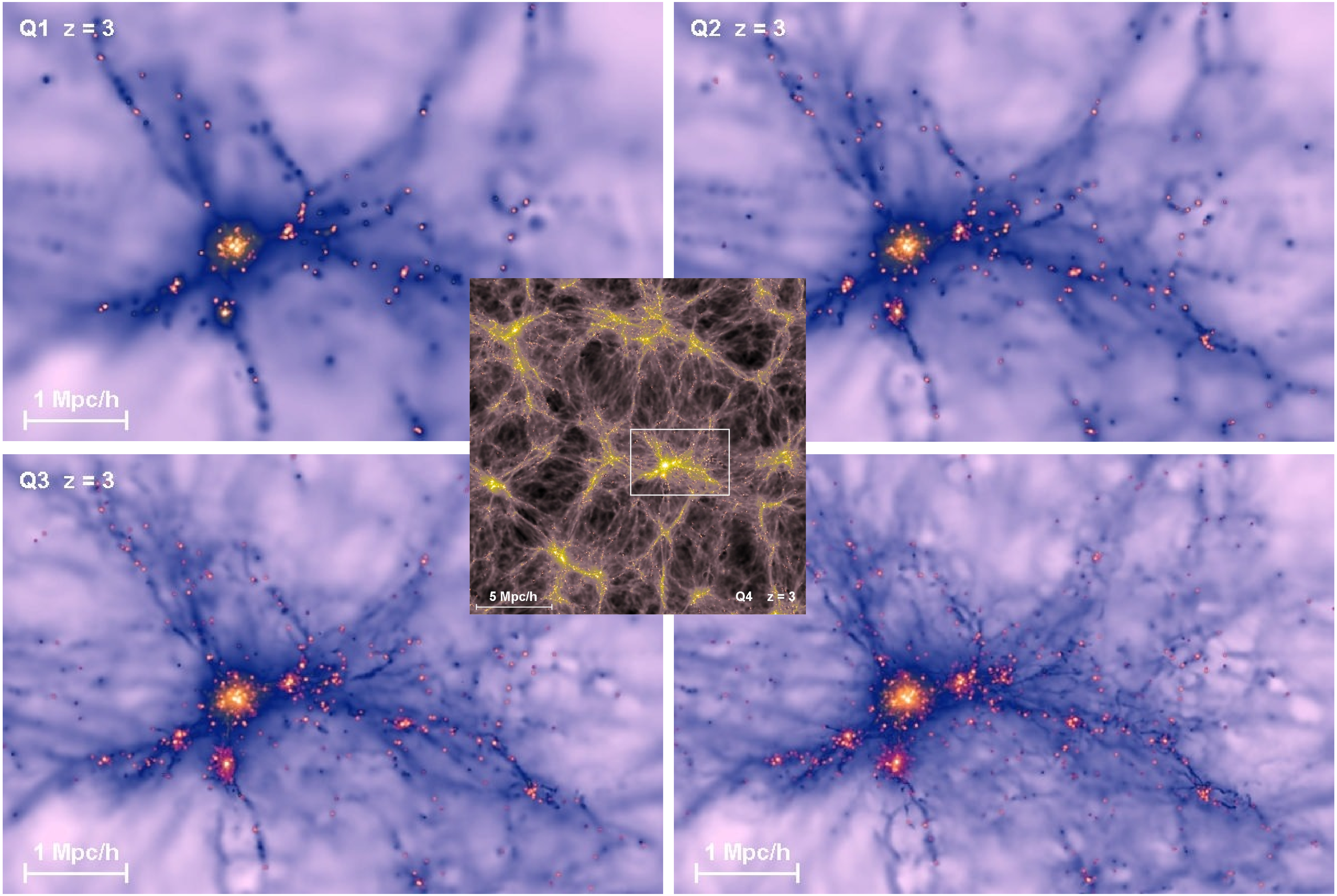
Hydrodynamical cosmological simulations of galaxy formation have so far generally not included black hole growth

BARYONIC DENSITY IN SIMULATIONS WITH RADIATIVE COOLING, STAR FORMATION AND FEEDBACK

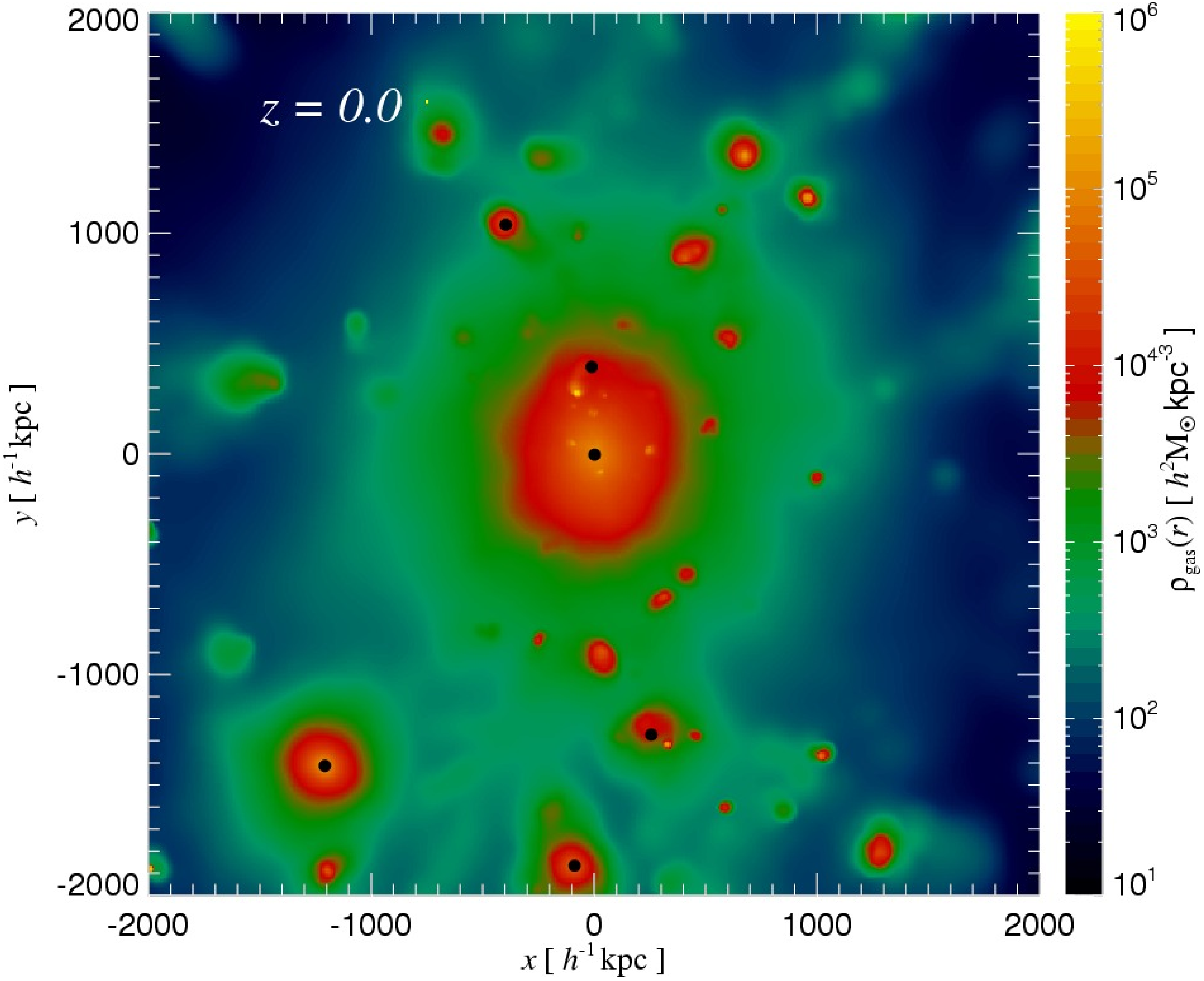
Springel & Hernquist (2003)



Higher mass resolution can resolve smaller galaxies

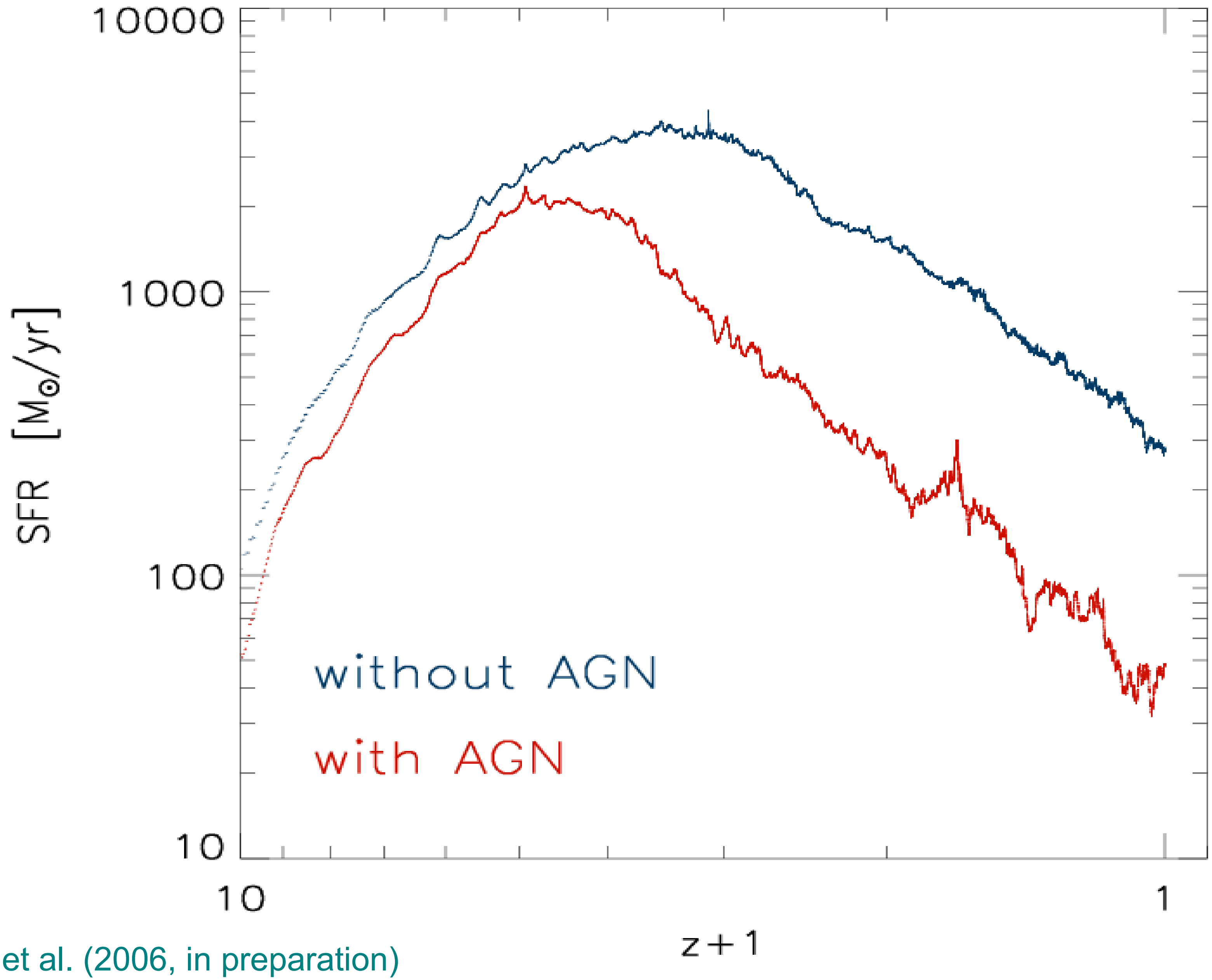


Due to their locally better resolution, cosmological simulations of galaxy clusters are particularly interesting for tracking BH growth and feedback



Quasar feedback substantially alters the star formation history of a cluster and suppresses late time cooling flows

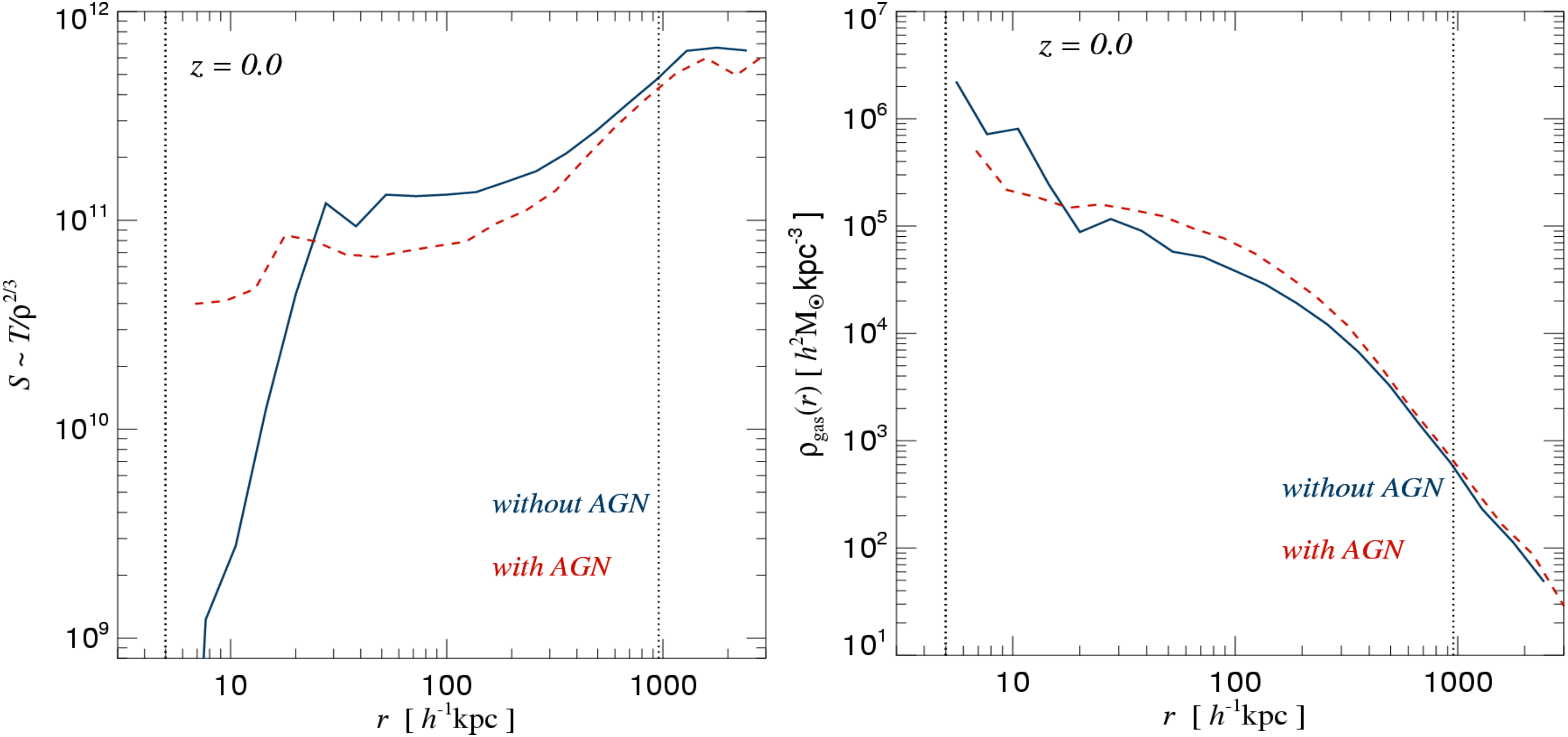
STAR FORMATION HISTORY OF A CLUSTER RE-SIMULATION



Sijacki et al. (2006, in preparation)

The cumulative impact of quasar feedback changes the thermodynamic cluster profiles

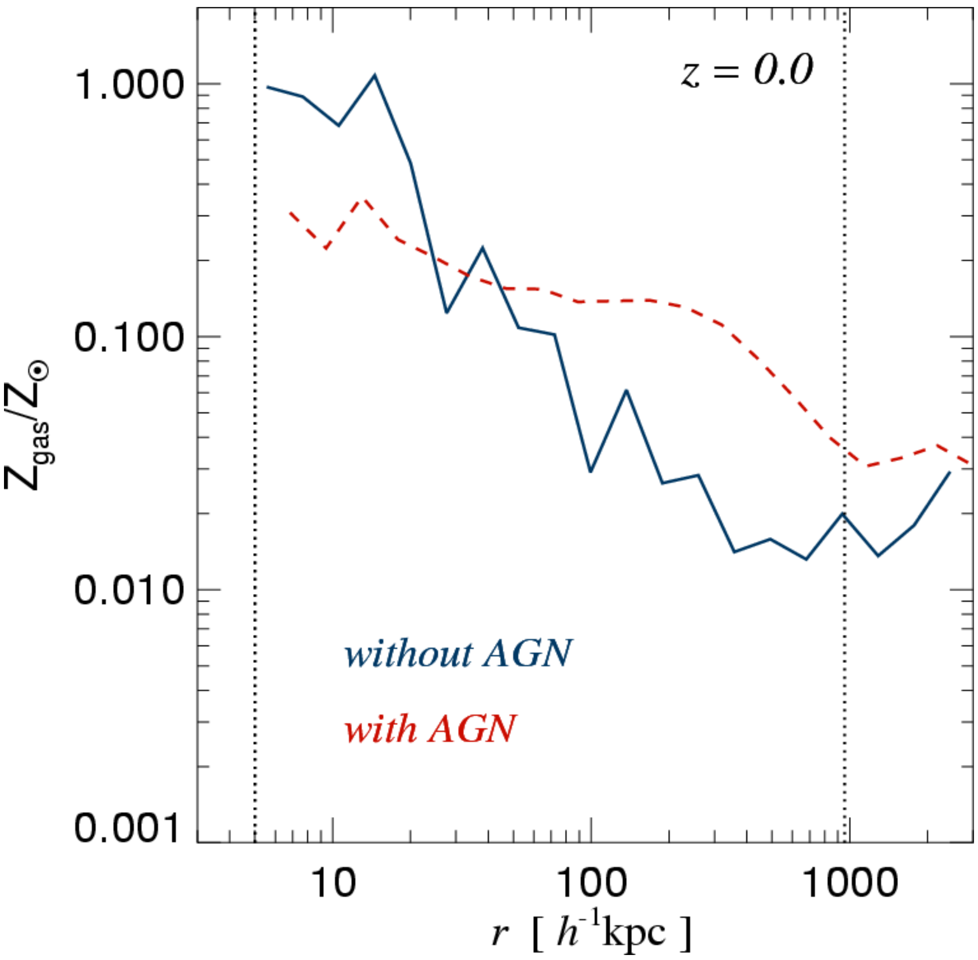
RADIAL CLUSTER PROFILES

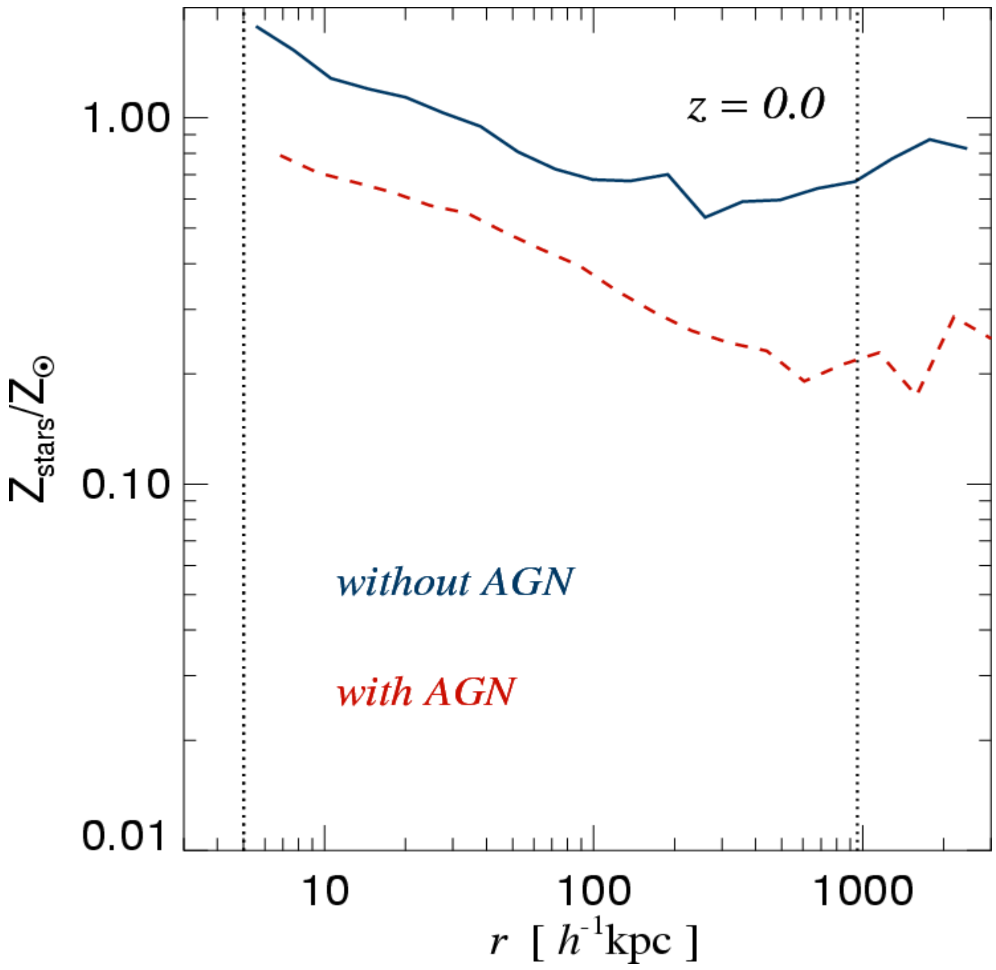


Sijacki et al. (2006, in preparation)

The cumulative impact of quasar feedback flattens the metallicity distribution in clusters of galaxies

METALLICITY PROFILES OF GAS AND STARS





Sijacki et al. (in preparation)

Conclusions

Any theory of galaxy formation must address the history of nuclear BHs in galaxies.

- Simulations of the galaxy population as a whole are extremely successful, provided BH growth is tracked and quasar feedback in large halos is included.

- Simulations of AGN bubble feedback allow a direct study of how cluster cooling flows are heated and prevented, and how this modifies the thermodynamics of the ICM.

- We have developed numerical methods that allow us to simulate high-resolution mergers of galaxies that track the growth of supermassive black holes and their energy feedback.

- The growth of black holes is self-regulated by AGN feedback. The relation between final black hole mass and halo size follows the Magorrian relation.

- Mergers of galaxies exhibit a complex interplay between starbursts and nuclear AGN activity. In a major merger, star formation and accretion can be terminated on very short timescales, with the black hole driving a strong quasar outflow. Remnants in galaxy mergers with black holes are relatively gas-poor, show low star formation activity, and redden quickly.

- The first cosmological simulations with this model show encouraging results for the black hole sector. The cumulative BH mass density is roughly consistent with observational estimates. Cluster metallicity profiles become shallower, and central cooling flows can be stopped. A unified simulation description with a self-consistent triggering of radio-mode feedback is still missing though.