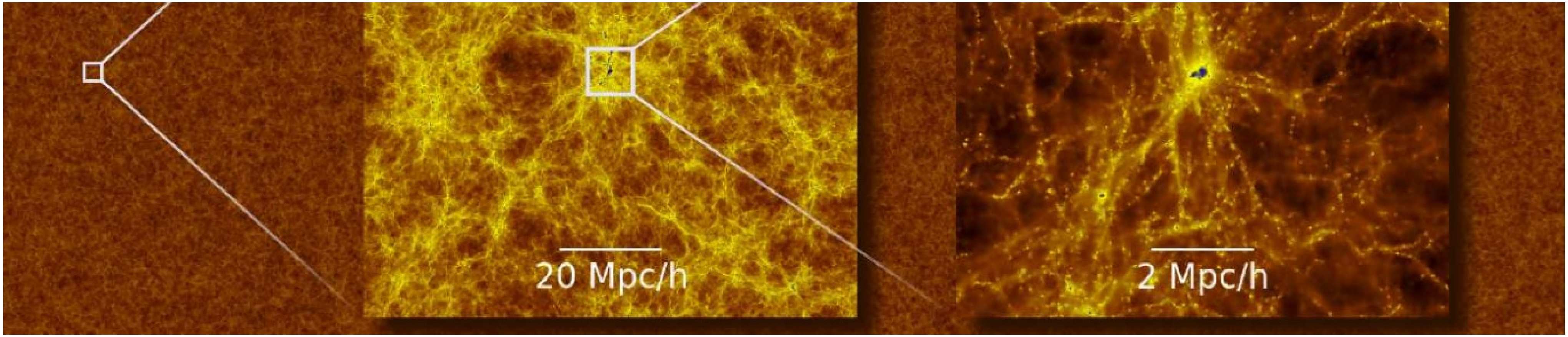
Hydrodynamical simulations of AGN and their clustering

Volker Springel



- Different types of AGN simulations and regimes of feedback
- Modelling quasar growth in numerical simulations
- Clustering predictions of quasar and radio-mode feedback scenarios
- Evidence for AGN feedback: Fact or Fiction?

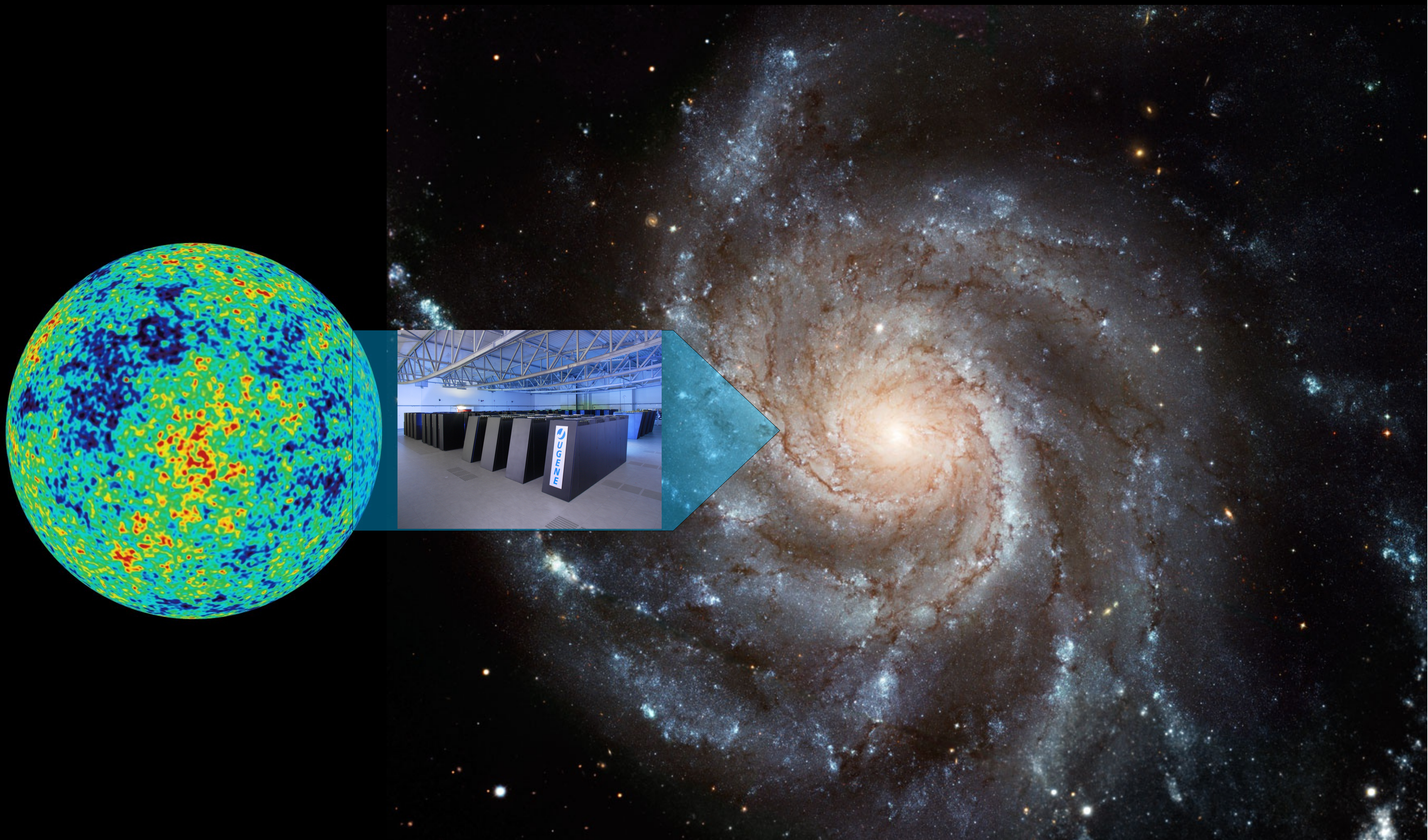
Heidelberg Institute for Theoretical Studies

HITS

Universität Heidelberg

Clustering Measurements of AGN
ESO Garching
July 2014

Cosmological simulations aim to bridge 13.6 billion years of evolution

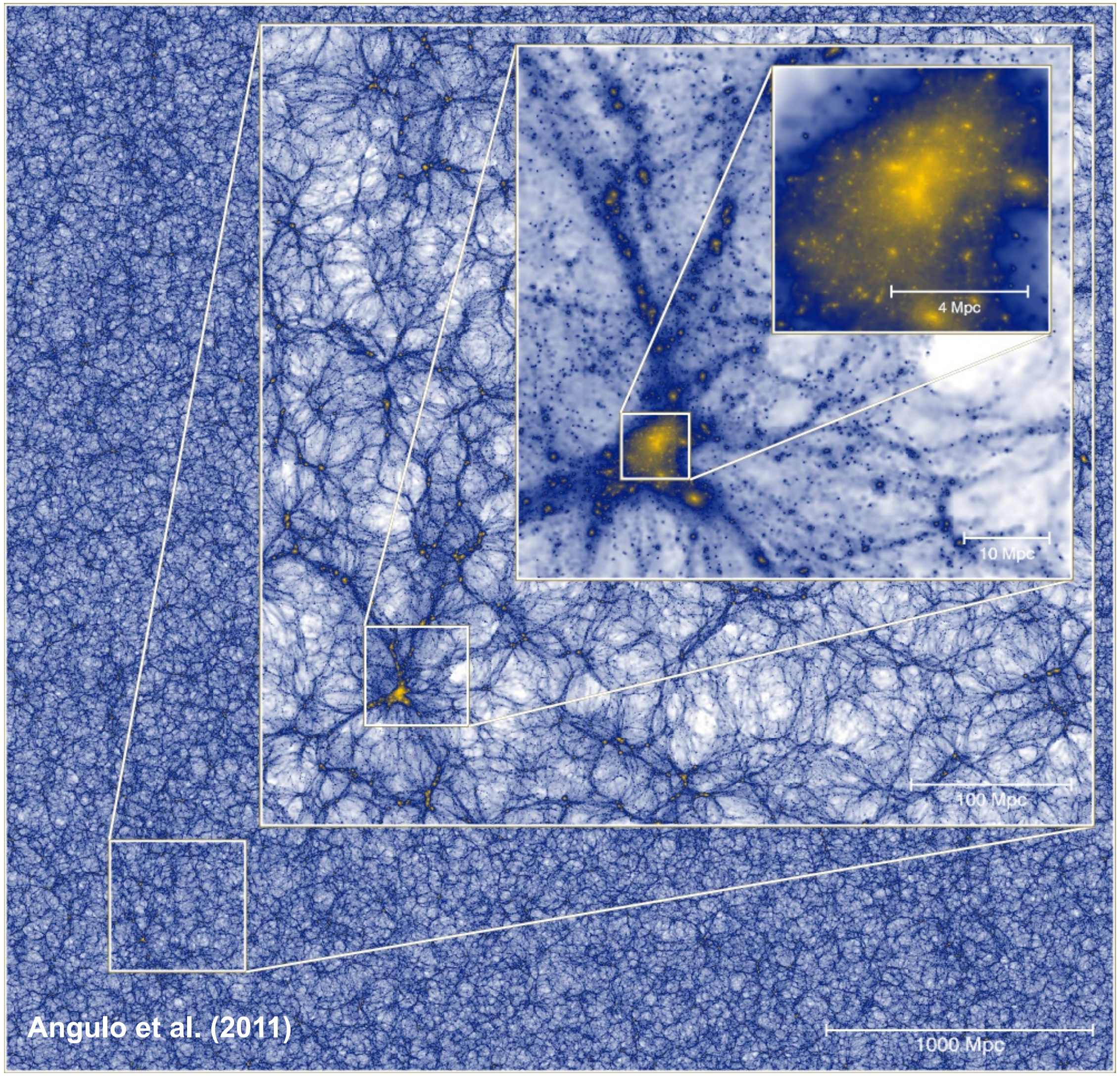


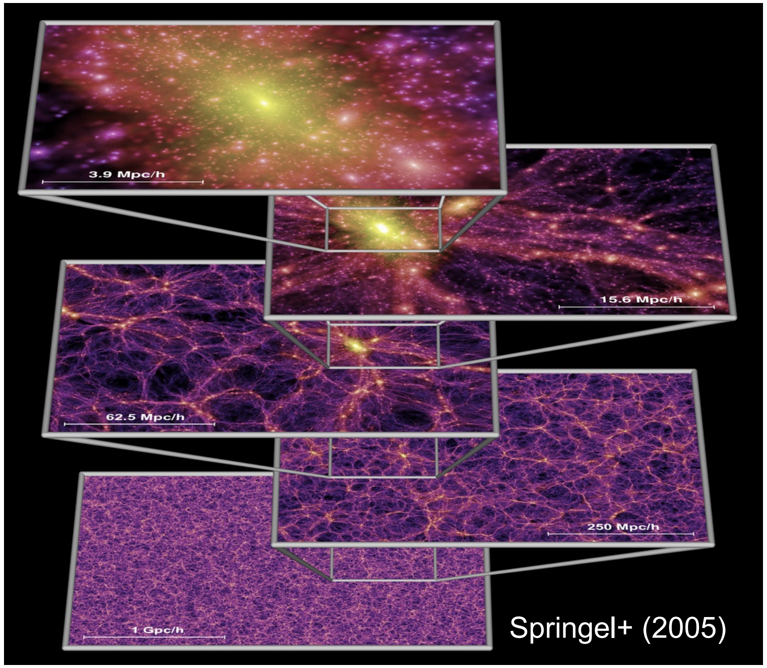
The *Millennium Simulations* help to understand the dark side of the Universe

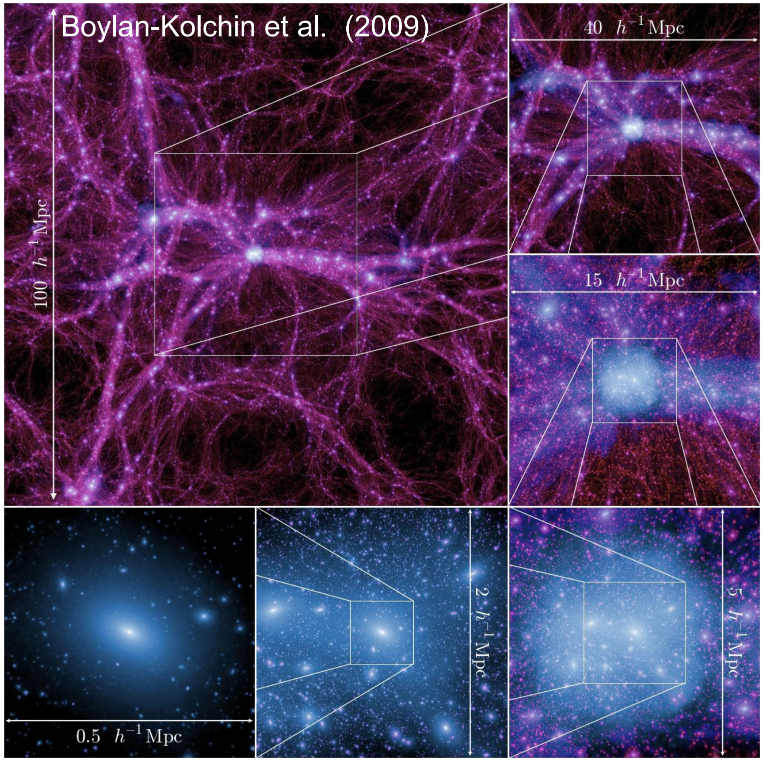
TRACKING COSMIC STRUCTURE FORMATION FAR INTO THE NON-LINEAR REGIME

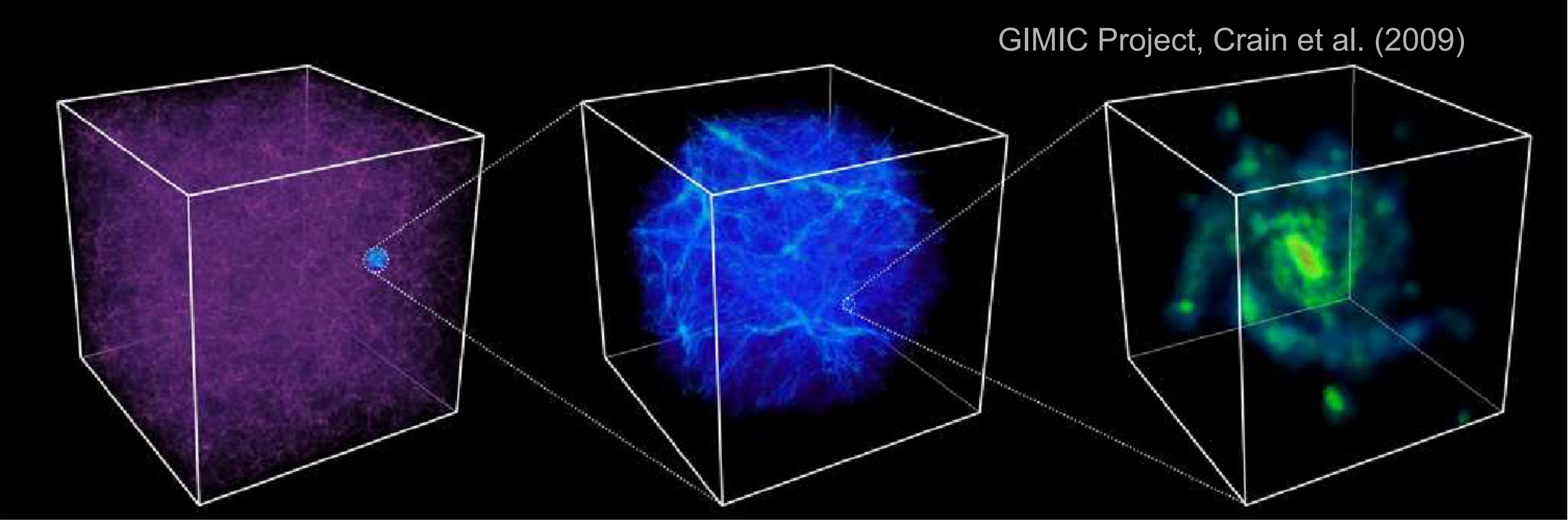
- 6720^3 ~ 303 billion particles
- 3000 Mpc/h box
- **12288 cores on JuRoPa**
- L-GADGET3 code

Millennium-XXL







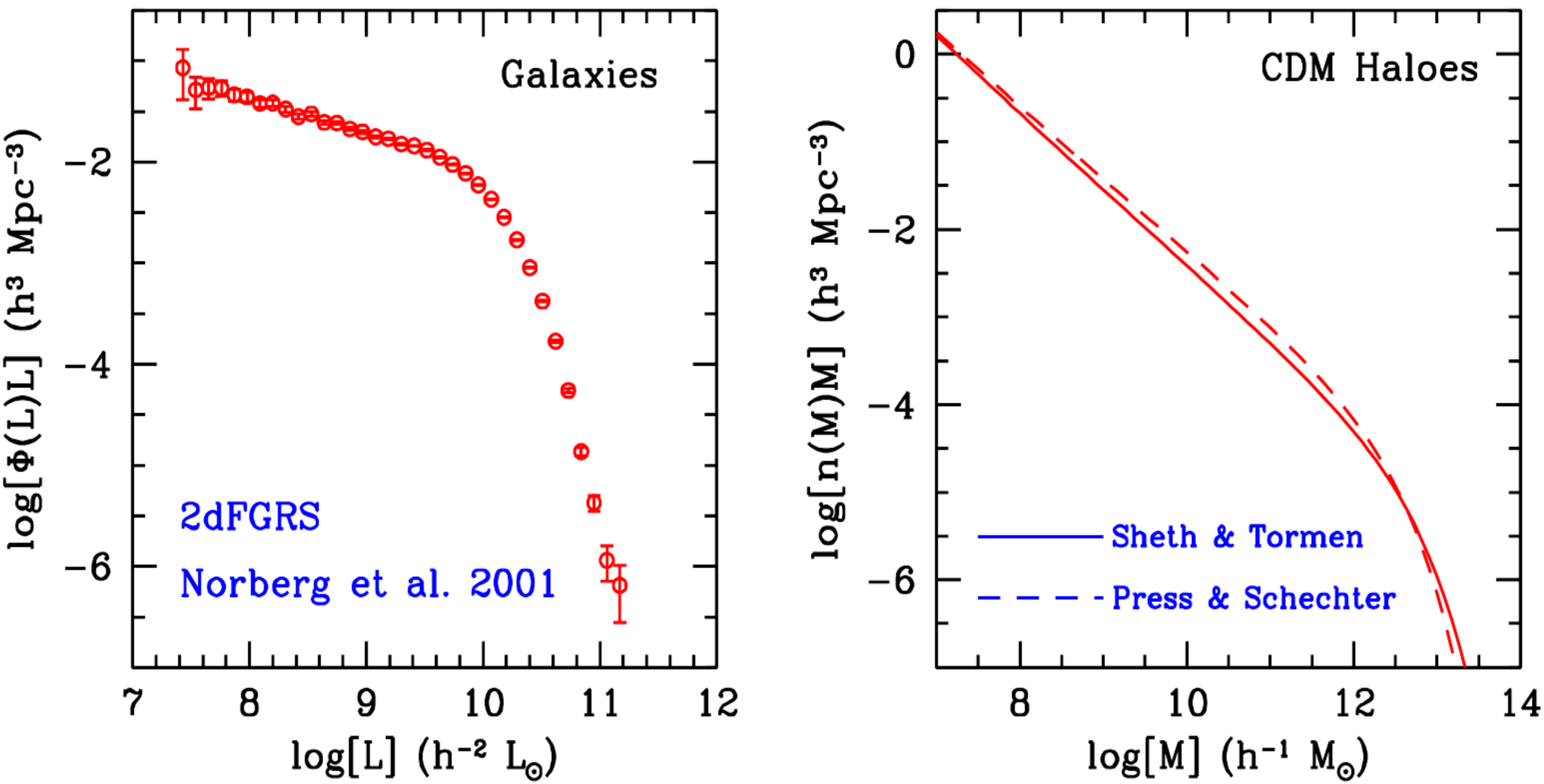


Hydrodynamical simulations aim to predict:

- Morphology of galaxies
- Fate of the diffuse gas, WHIM, metal enrichment
- X-ray atmospheres in halos
- Turbulence in halos and accretion shocks
- Large-scale regulation of star formation in galaxies through feedback processes from stars and black holes
- Transport processes (e.g. conduction)
- Stellar ages and galaxy kinematics
- Dynamical transformations (e.g. ram-pressure stripping)
- Magnetic fields in galaxies
- AGN activity!

A long standing issue in galaxy formation theory: The shapes of the CDM halo mass function and the galaxy luminosity function are very different

THE OBSERVED LF COMPARED TO THE SHAPE OF THE CDM HALO MASS FUNCTION

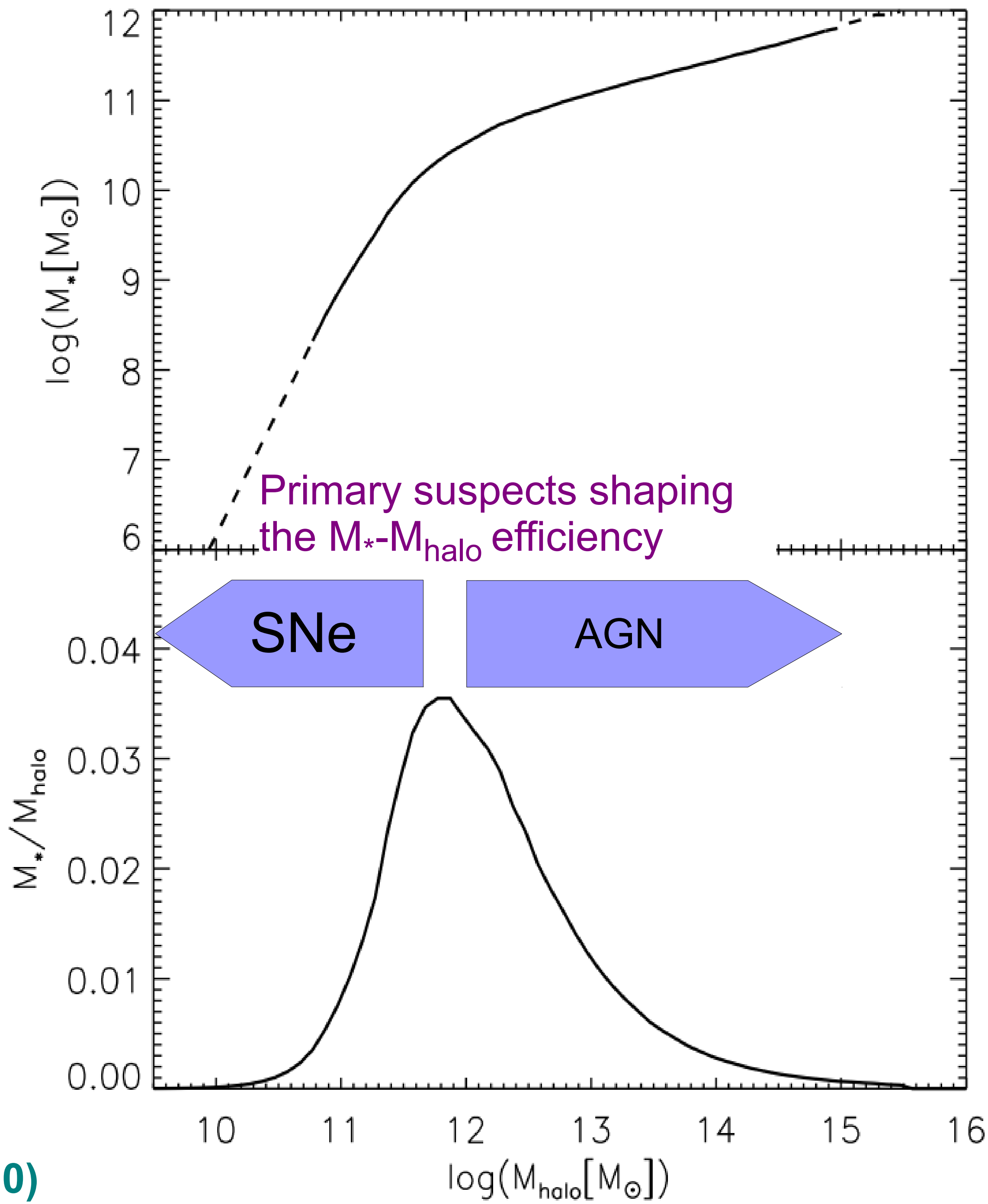


van den Bosch et al. (2004)

Abundance matching gives the expected halo mass – stellar mass relation in ΛCDM

STELLAR MASSES FROM SDSS/DR7 MATCHED TO ΛCDM SIMULATION EXPECTATIONS

Assumption:
Stellar mass is monotonically increasing with halo mass



Guo, White & Boylan-Kolchin (2010)

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

BLACK HOLES MAY PLAY AN IMPORTANT ROLE IN GALAXY FORMATION

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

- M_B-σ relation
- Similarity between cosmic SFR history and quasar evolution
- Local BH density matches integrated quasar light
- Downsizing observed for BH growth, just like for galaxies

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

- Removal of gas around the hole once a crtitical M_B is reached

Silk & Rees (1998), Wyithe & Loeb (2003)

Quasars release plenty of energy

$$L_Q \sim 10^{12}\, L_\odot \qquad t_Q \sim 10^7 - 10^8\,\mathrm{yr} \qquad E_Q \sim 10^{60} - 10^{61}\,\mathrm{erg}$$

a billion supernovae !

Total available feedback energy from BHs is comparable to that of supernovae

$$\rho_{\rm BH} \simeq 0.001\, \rho_\star$$

$$E_{\rm BH}/V \simeq 0.1\, \rho_{\rm BH}\, c^2$$

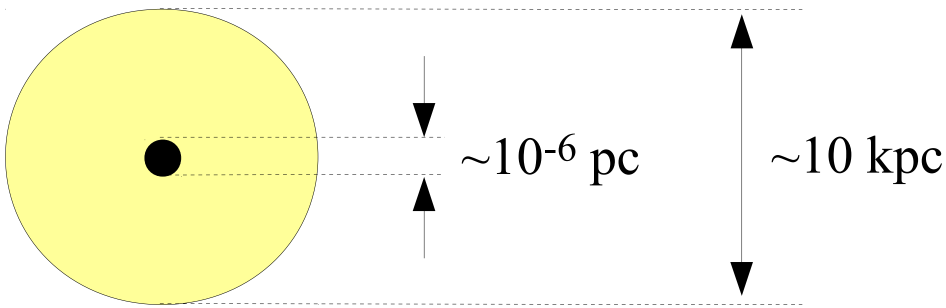
$$E_{\rm SN}/V \simeq \frac{10^{51}\,\mathrm{erg}}{100\,\mathrm{M}_\odot}\, \rho_\star$$

$$\frac{E_{\rm BH}}{E_{\rm SN}} \simeq 1.8$$

"Ab initio" modeling of AGN activity and star formation in cosmological simulations is extremely difficult – to put it mildly

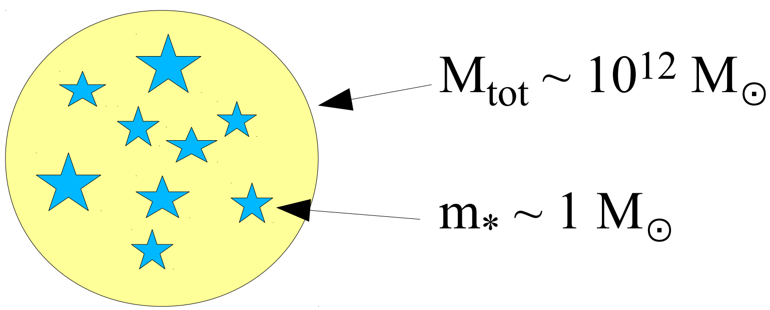
THE COMPUTATIONAL CHALLENGE

A supermassive BH in a galaxy



dynamic range of 10^{10}

Star formation in a normal galaxy



mass dynamic range of 10^{12}

→ **Dynamic range prohibitively large for ab-initio calculations**

→ **In addition: physics of star formation and AGN accretion only partially understood**

The **thin accretion disk** model is related to **radiativey efficient accretion**

PROPERTIES OF THE THIN ACCRETION DISK

Shakura & Sunyaev (1973)

Quasar mode

- Geometrically thin, cool gas disk
- Radiatively efficient accretion: L ~ (0.05-0.4) Mdot c^2
- Optically thick, black body radiation (systems show 'big blue bump')
- Most of the viscous heat energy is radiated away
- Quasars and very luminous, radio-quiet AGN are believed to be associated with this mode of accretion
- Probably associated with a wind, and **no/weak** jet
- Most BH mass must be assembled in this mode (Soltan argument)

Advection dominated flows are related to **radiatively inefficient accretion**

PROPERTIES OF ADAFs

Narayan & Yi (1994)

Radio mode

- Geometrically thick, very hot gas disk in sub-Keplerian rotation
- Radiatively inefficient accretion, but high mechanical luminosity
- Optically thin, no blue bump
- Viscous heat is advected with the flow
- Strong outflows and relativistic **jets** are produced, coupling of mechanical feedback to surrounding gas can be 100%
- SMBHs probably spend most of their lifetime in this state

The outflow and radiation efficiences seem to depend on the accretion rate

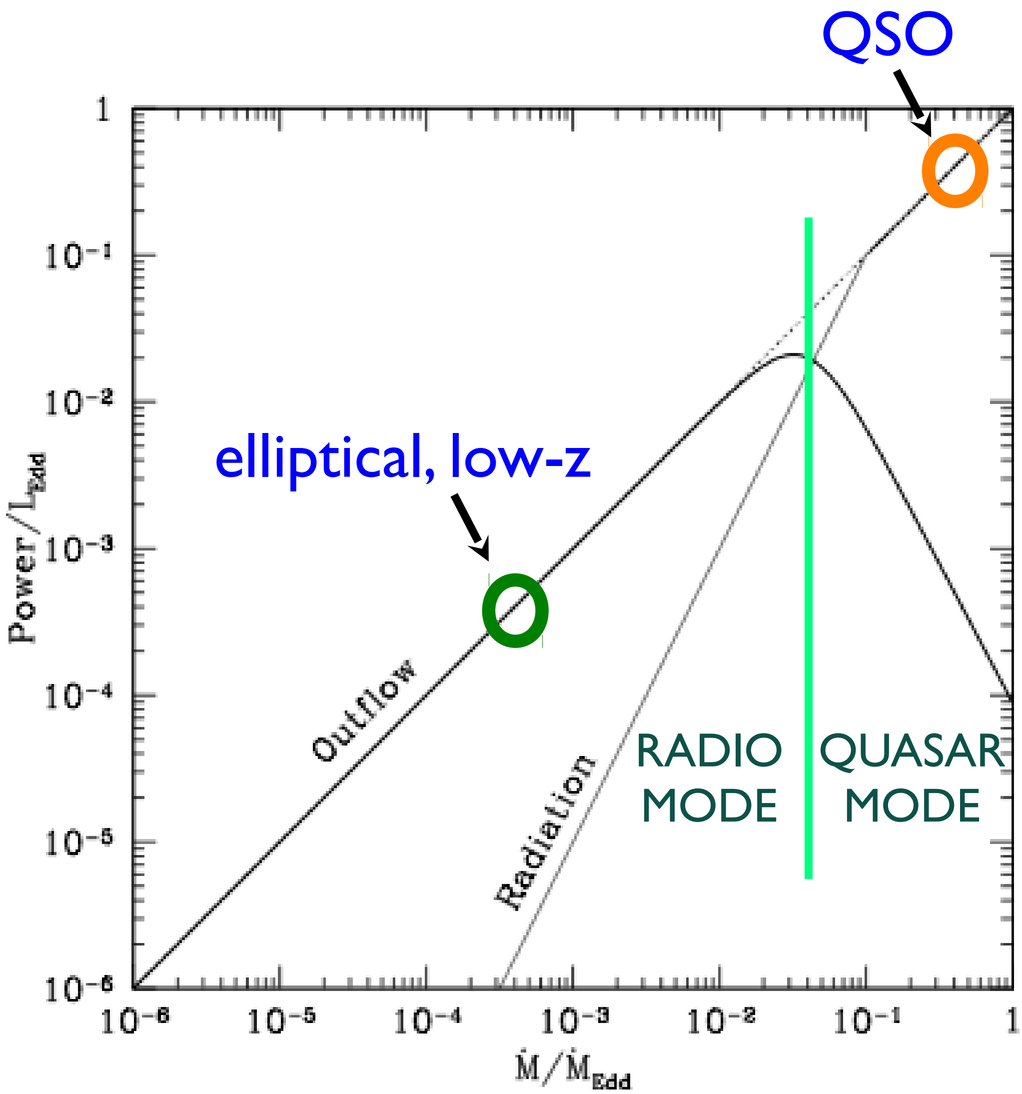
DIFFERENT REGIMES OF AGN FEEDBACK

observations of X-ray binaries (with stellar mass BHs) show:

- ➡ strong outflows exist for low accretion rates
- ➡ outflows are less important or cease at high accretion rates

this picture also seems to hold for the SMBHs in AGN

(Maccarone et al. 2003)



Churazov et al. (2005)

Black holes in galaxy mergers

A simple model for the quasar mode accretes gas with a Bondi-rate and exerts thermal feedback

THE FIRST COSMOLOGICAL BLACK HOLE FEEDBACK MODEL

Springel, Di Matteo & Hernquist (2005)

Black hole growth:

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:

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

Black hole feedback:

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:

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

Very similar implementations, among others, by:

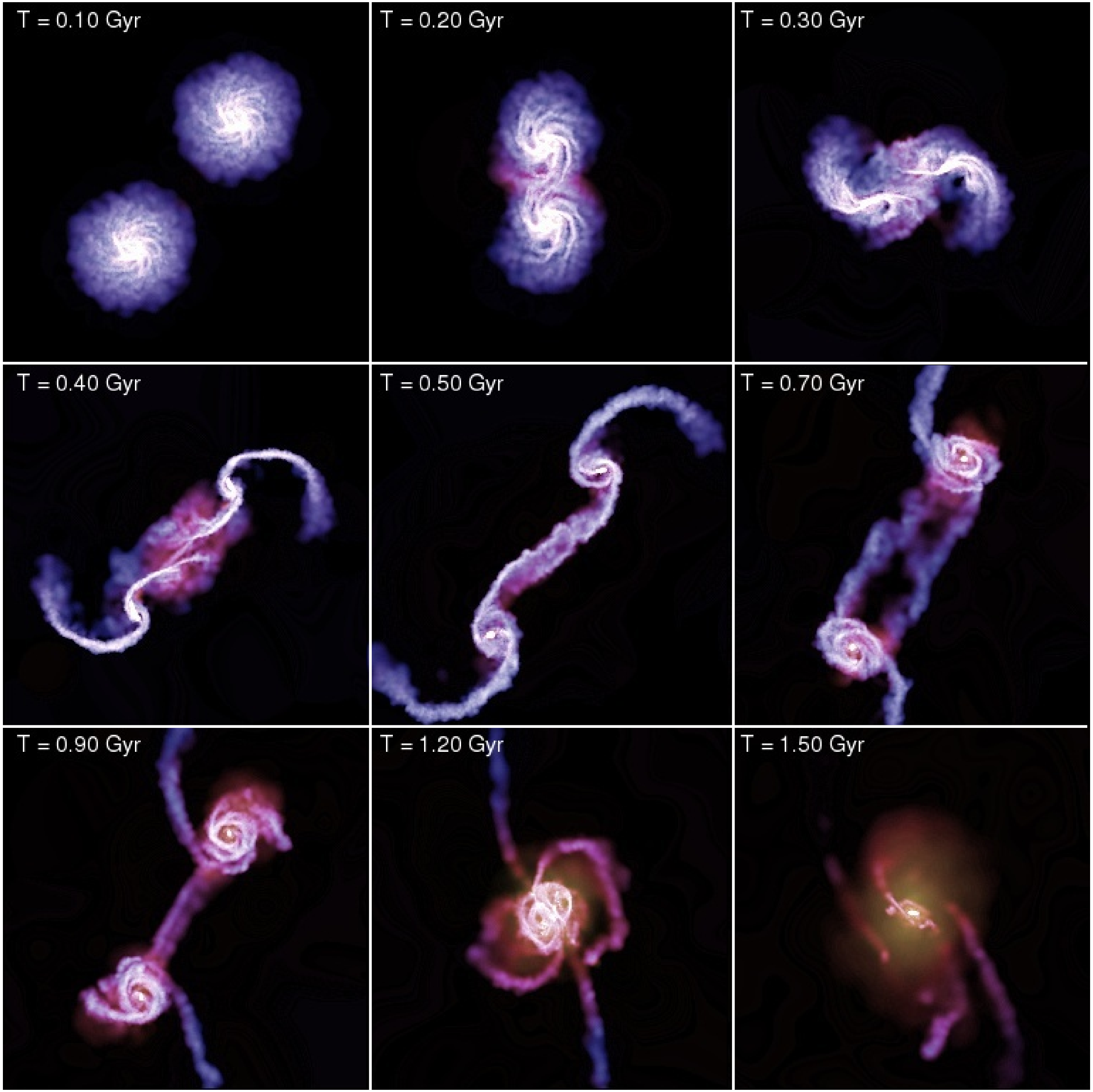
Khalatyan et al. (2008)

Johansson et al. (2009)

Booth & Schaye (2009)

In major mergers, tidal torques extract angular momentum from cold gas, providing fuel for nuclear starbursts and black hole growth

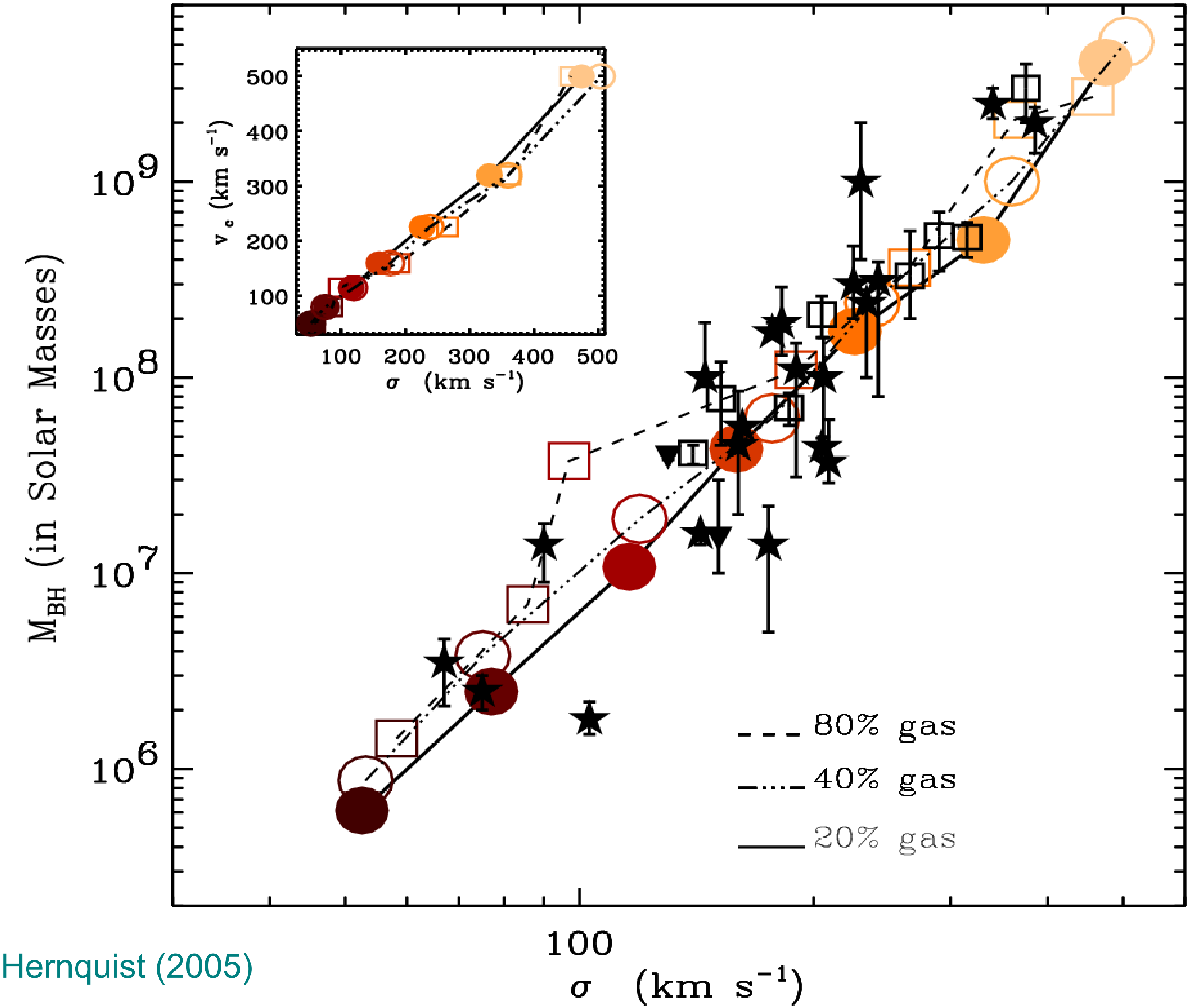
TIME EVOLUTION OF A PROGRADE MAJOR MERGER INCLUDING BLACK HOLES



Di Matteo, Springel & Hernquist (2005)

The relation between final black hole mass and stellar velocity dispersion follows the observed $M_{BH} - \sigma$ relationship

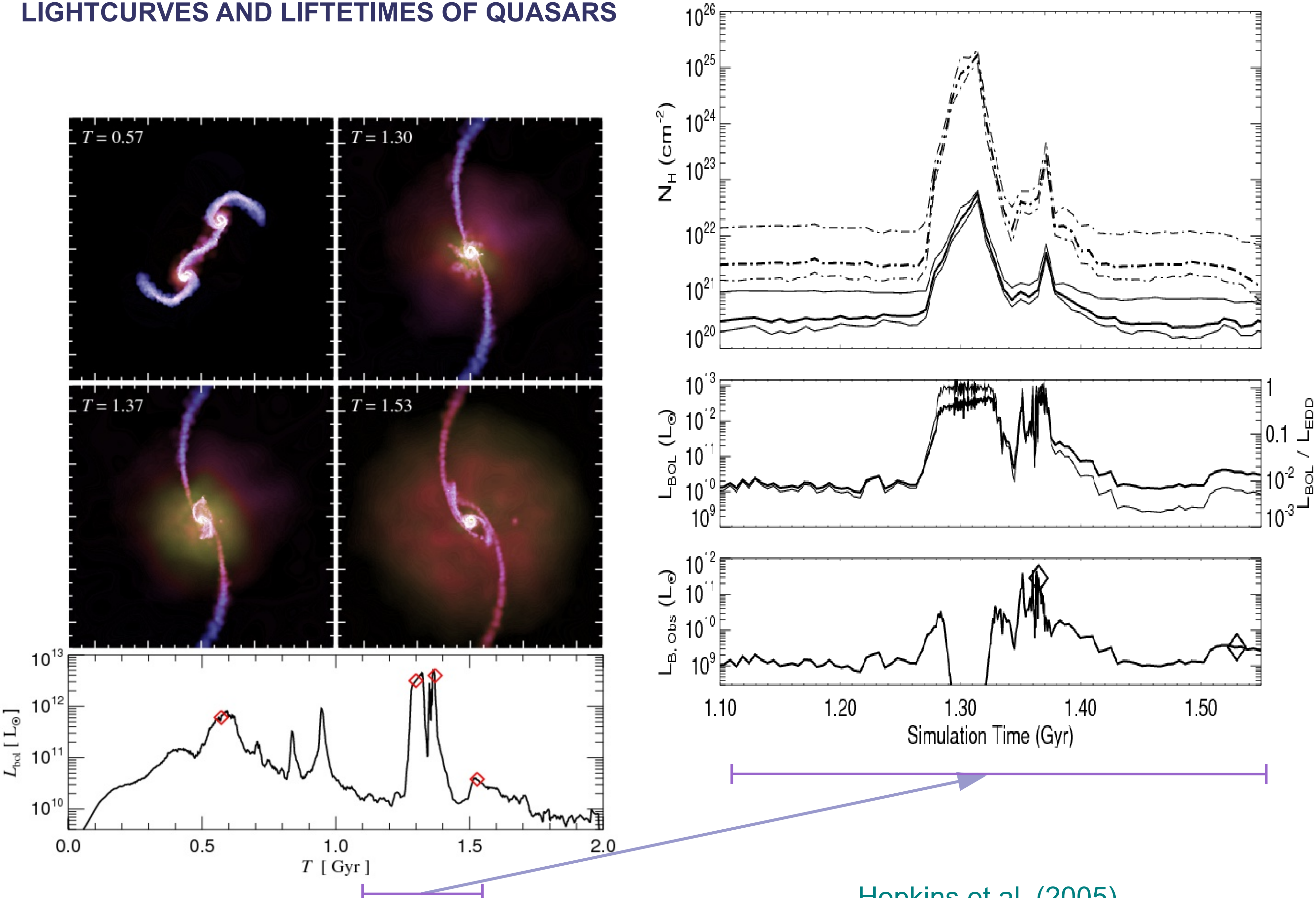
BLACK HOLE MASSES IN MERGER REMNANTS



Di Matteo, Springel & Hernquist (2005)

The lifecycle of quasars: **Buried, Active**, and then **Dead**

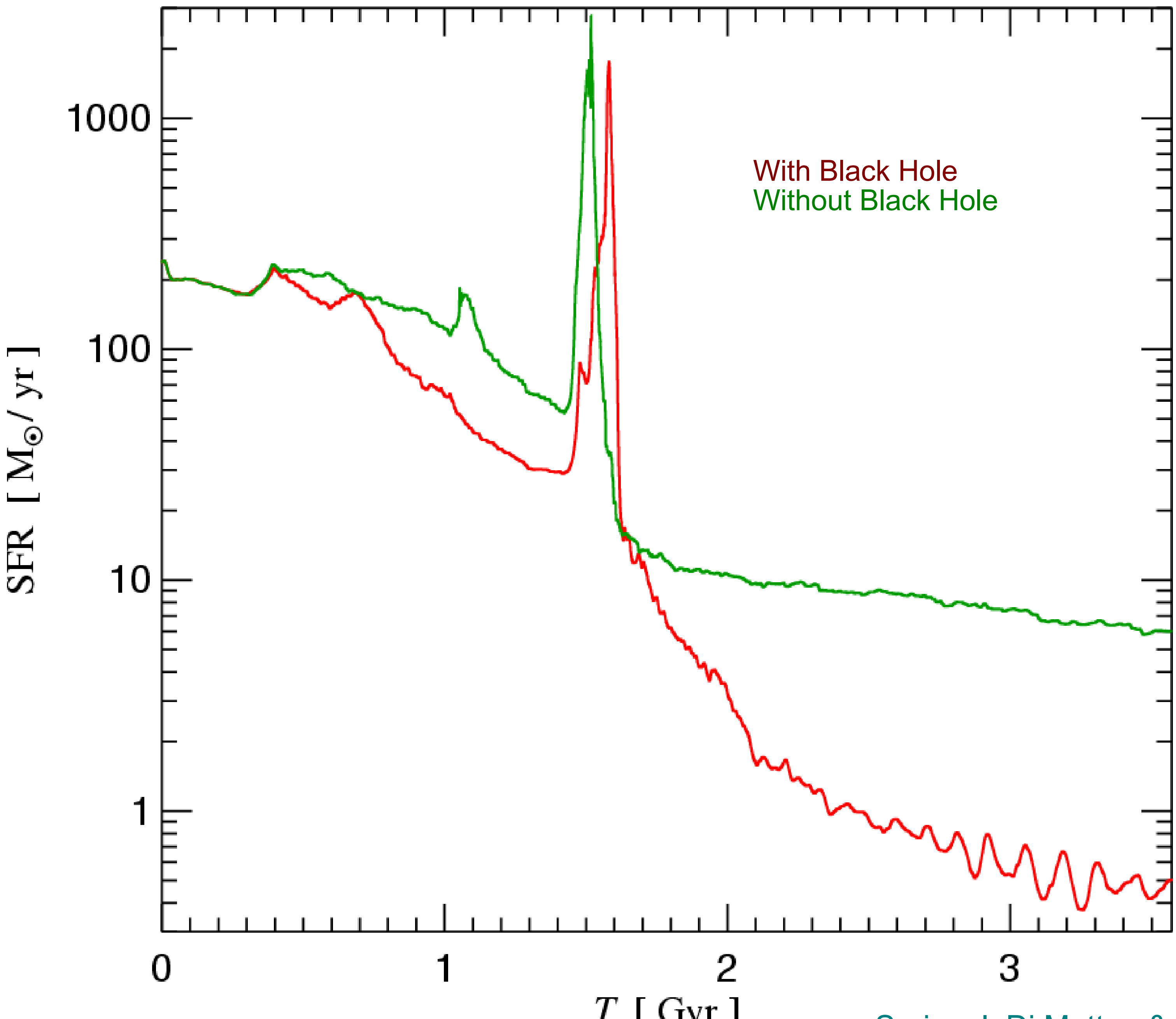
LIGHTCURVES AND LIFTETIMES OF QUASARS



Hopkins et al. (2005)

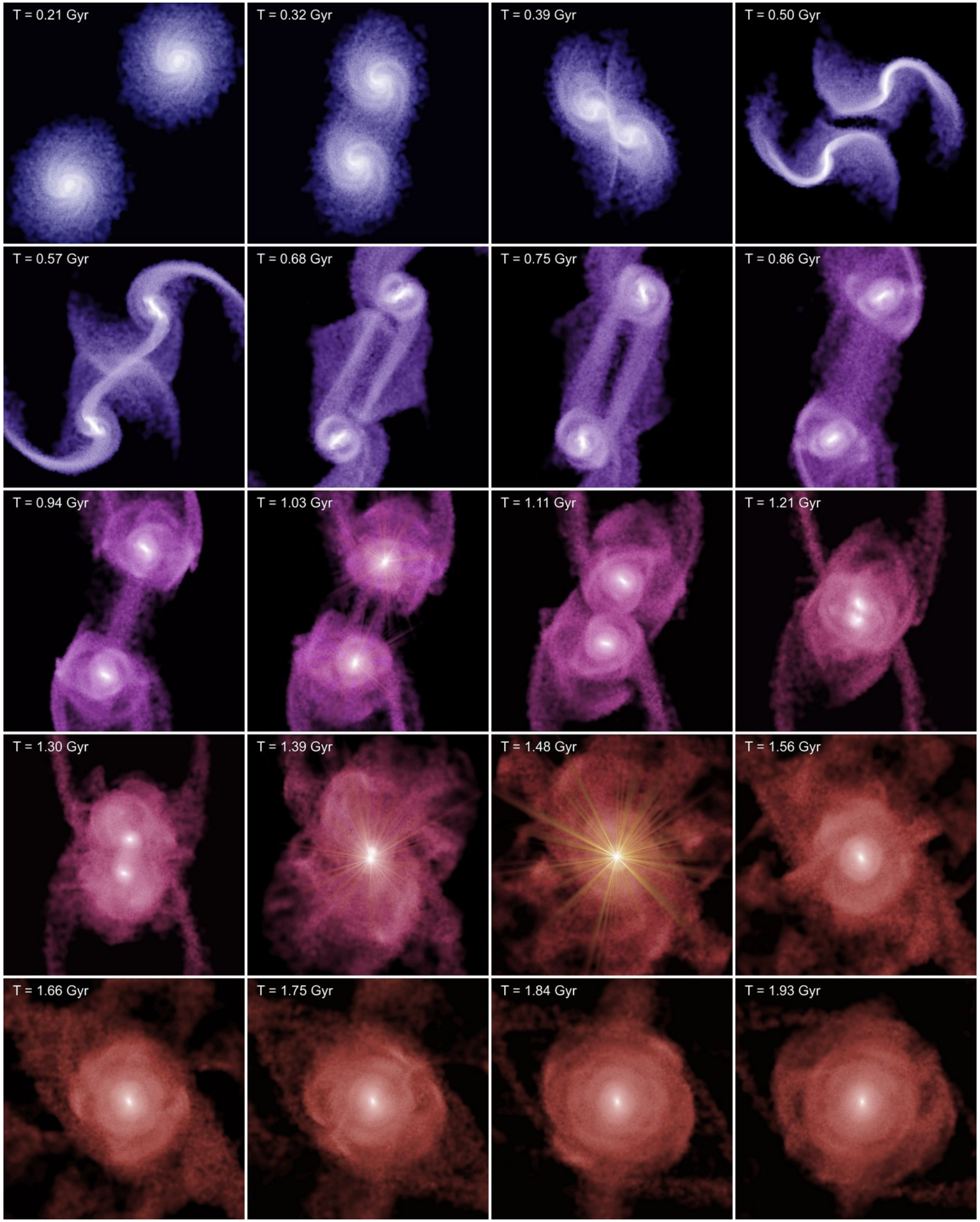
The feedback by the AGN can reduce the strength of the starburst

COMPARISON OF STAR FORMATION IN MERGERS WITH AND WITHOUT BLACK HOLE

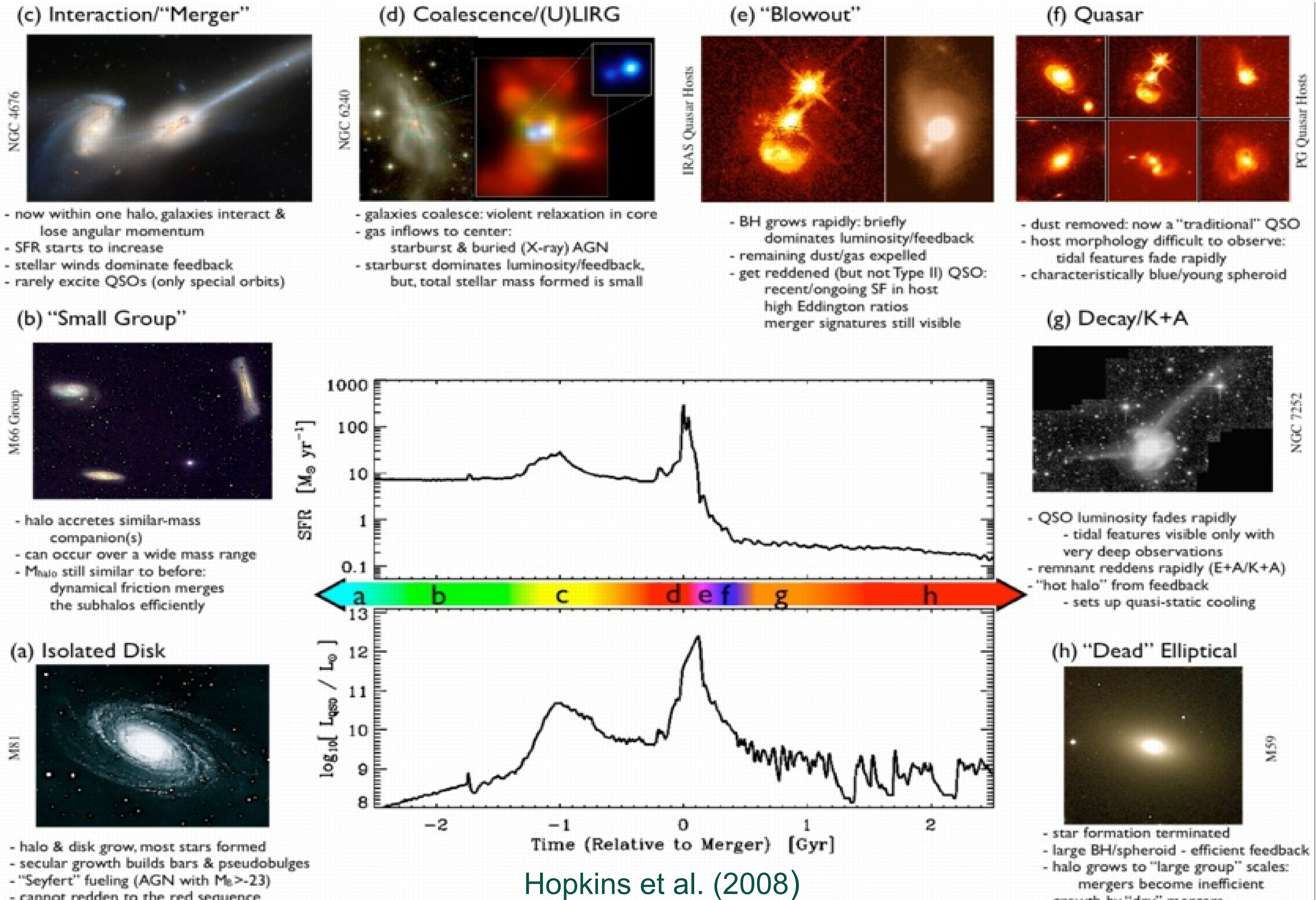


Springel, Di Matteo & Hernquist (2005)

- ***Starburst*-Phase**
  - Infalling gas causes a strong nuclear starburst
- **Quasar-Phase**
  - The Black Hole is burried in gas and dust → obscured growth
  - Released energy eventually uncovers the Black Hole → becomes briefly visible as a quasar
  - The quasar dies when the gas is consumed
- **Relaxation Phase**
  - The remnant system relaxes → Elliptical galaxy is formed
  - Low residual star formation → the system turns red
- **Signatures of dissipation in the remnant system**
  - Correlation between black hole and the host galaxy
  - Starburst component in the surface brightness profile



A unified picture for galaxy evolution based on mergers

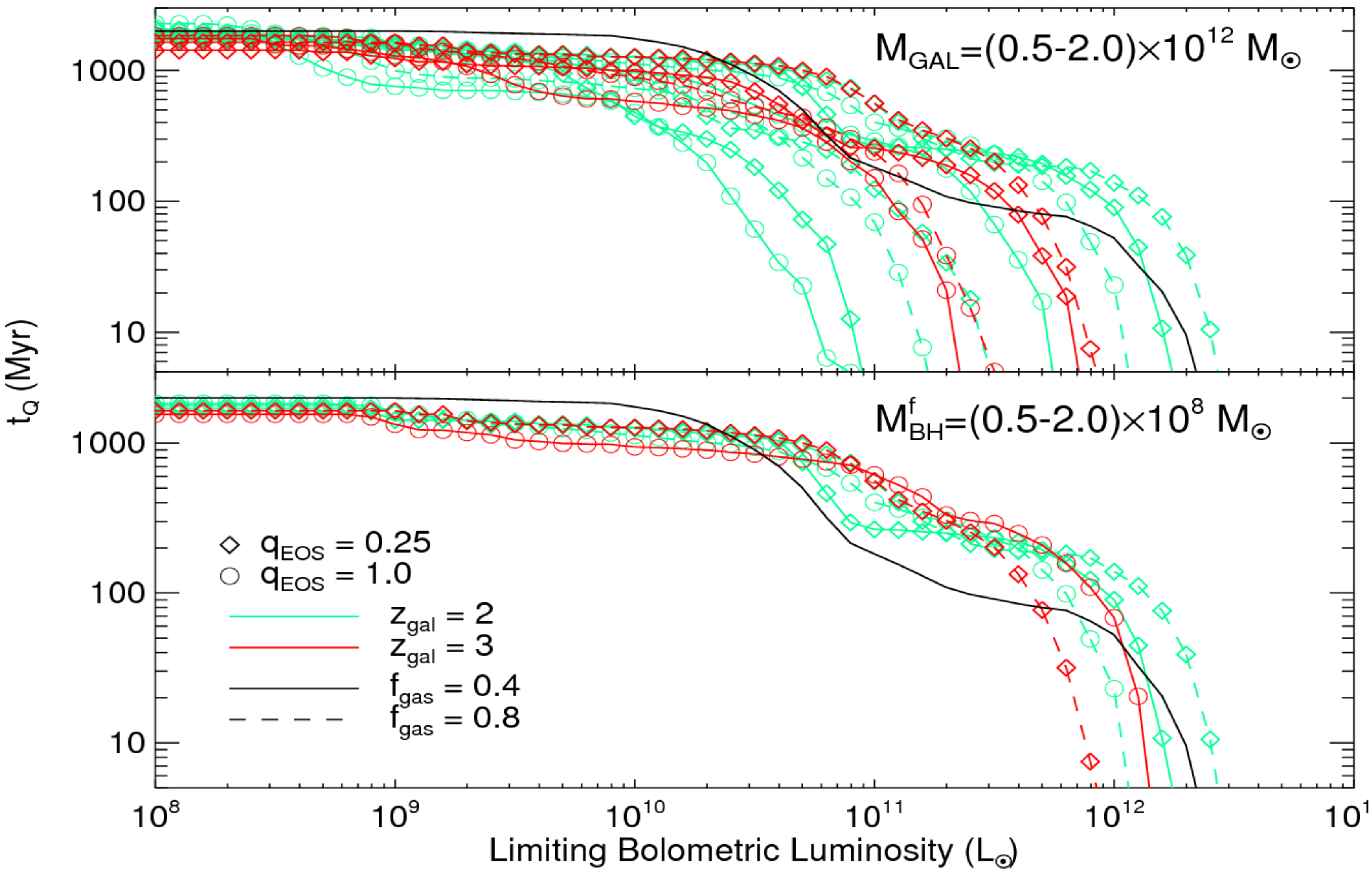


Hopkins et al. (2008)

Light curve predictions

The quasar lifetime in the simulations has a universal form as a function of final black hole mass

TIME SPENT ABOVE A LIMITING LUMINOSITY

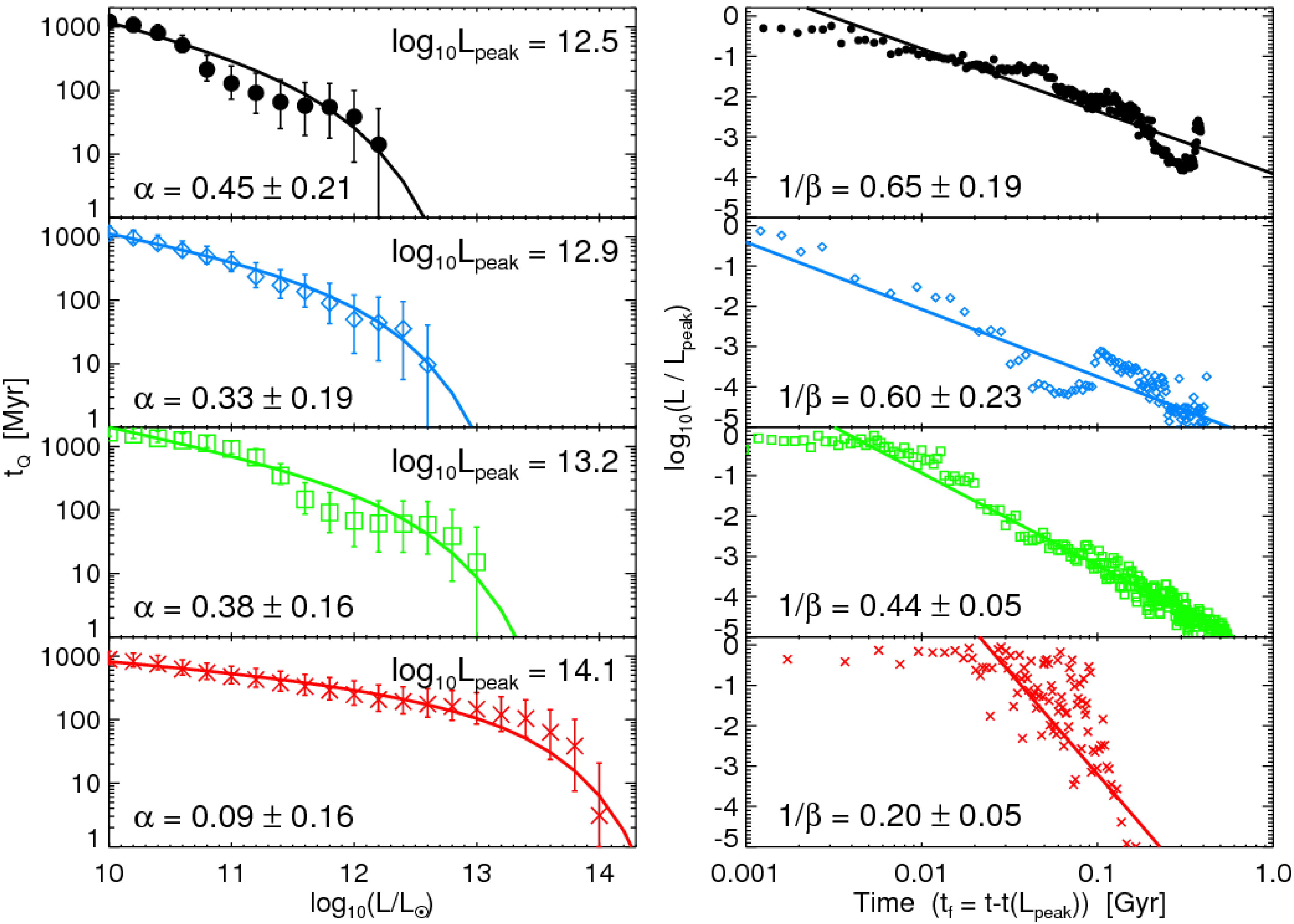


This is very different from the "light-bulb" or exponential decay models for the lifetime

Hopkins et al. (2006)

Quasar lifetimes are both a function of instantaneous and peak luminosity

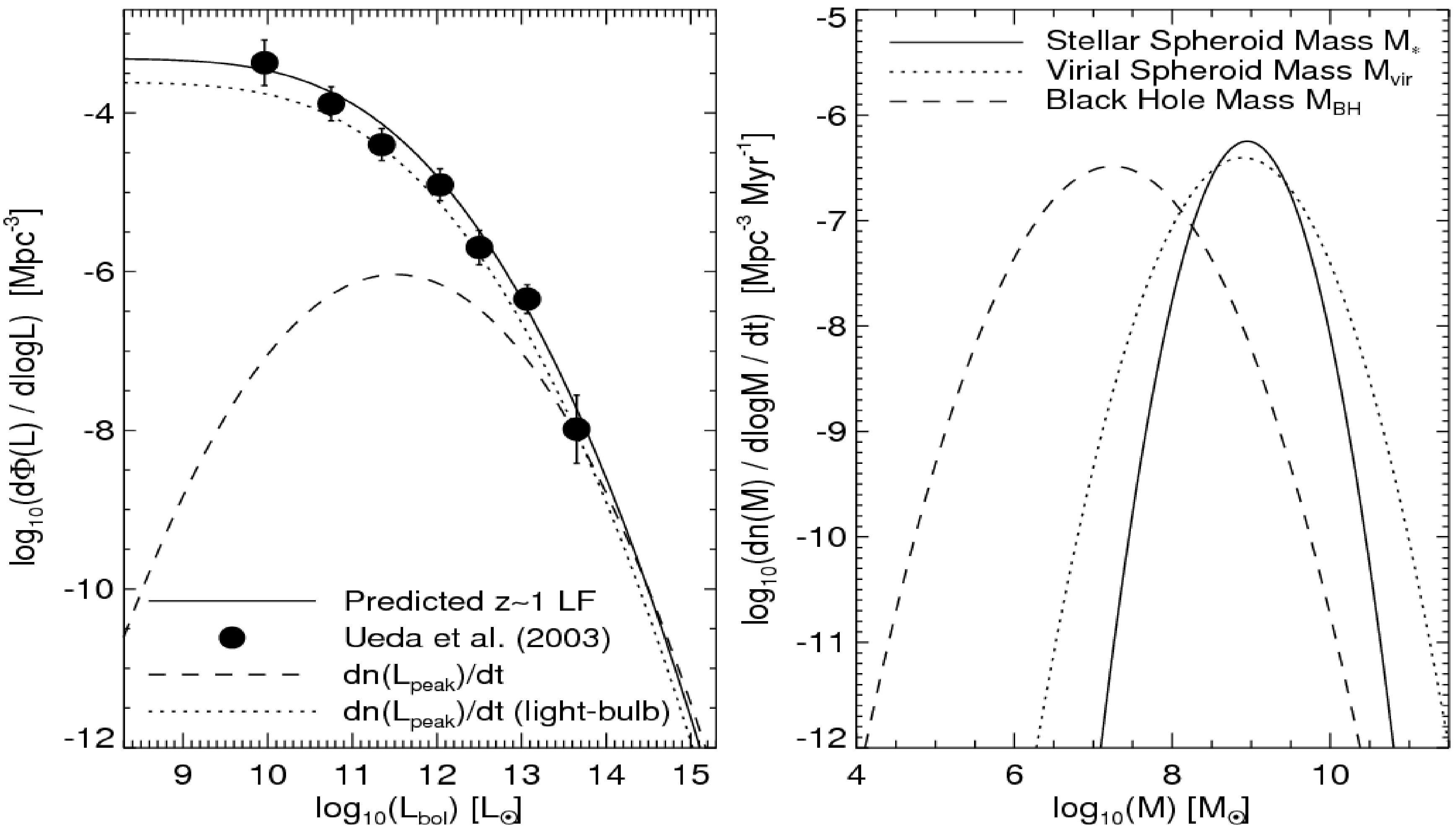
COMPARISON OF MODEL PARAMETERIZATION WITH SIMULATIONS



The quasar luminosity function is a convolution of the lifetime distribution and the rate at which black holes of a given mass are produced

QUASAR LUMINOSITY FUNCTION CONSTRUCTION

$$\phi(L) \equiv \int \frac{\mathrm{d}t(L, L_{\rm peak})}{\mathrm{d}\log(L)}\, \dot{n}(L_{\rm peak})\, \mathrm{d}\log(L_{\rm peak})$$



Hopkins et al. (2006)

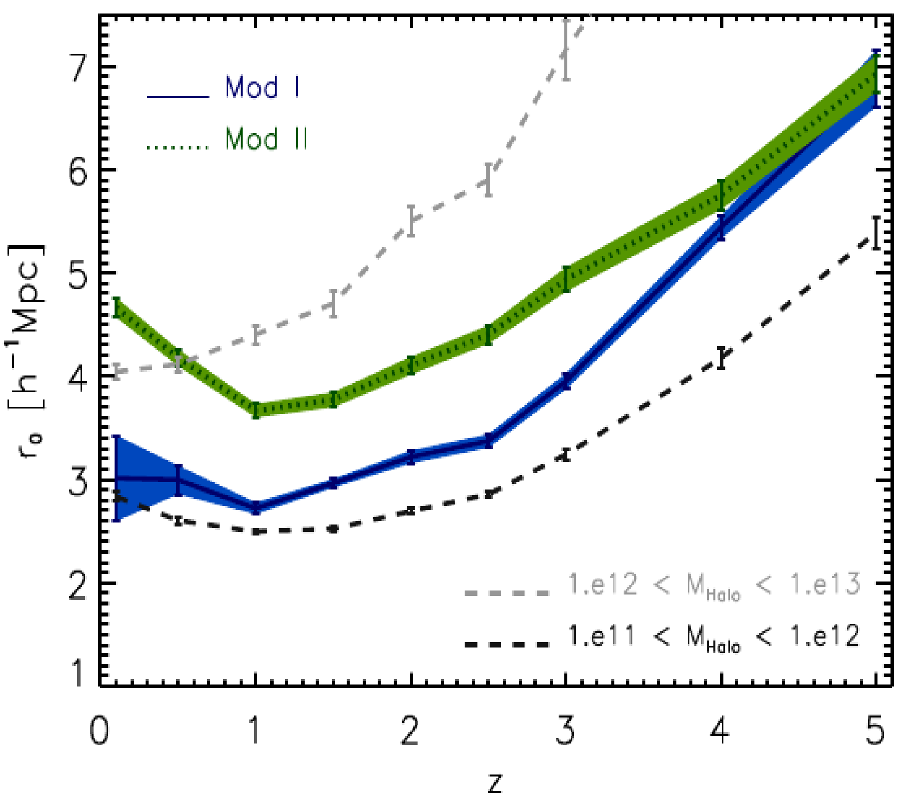
Quasar clustering predictions

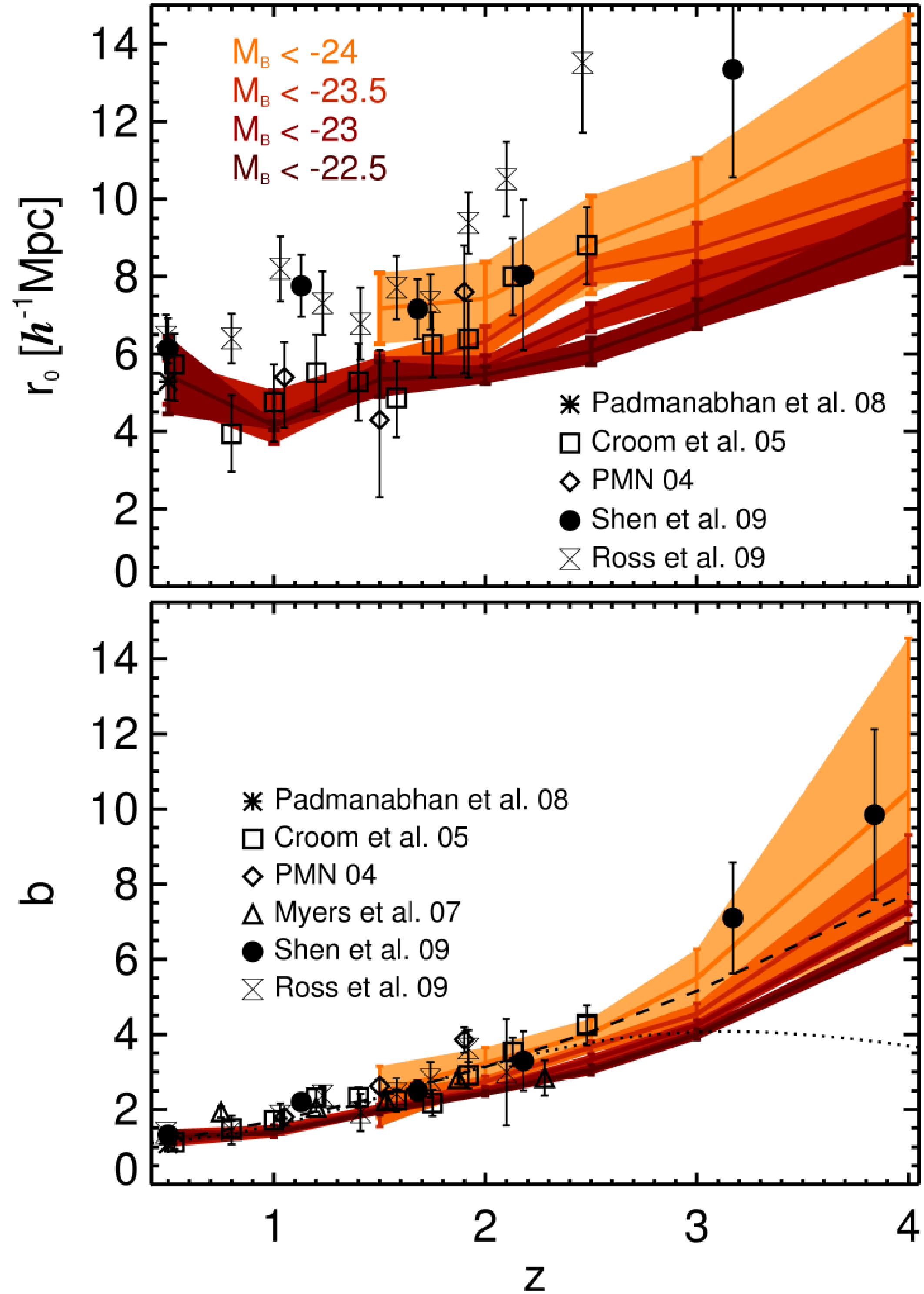
Bright quasars are hosted by halos of a narrow mass range, so their clustering is predicted to be only a weak function of luminosity

QUASAR CLUSTERING AS A TEST OF LIGHTCURVE MODELS

Bonoli et al. (2009)

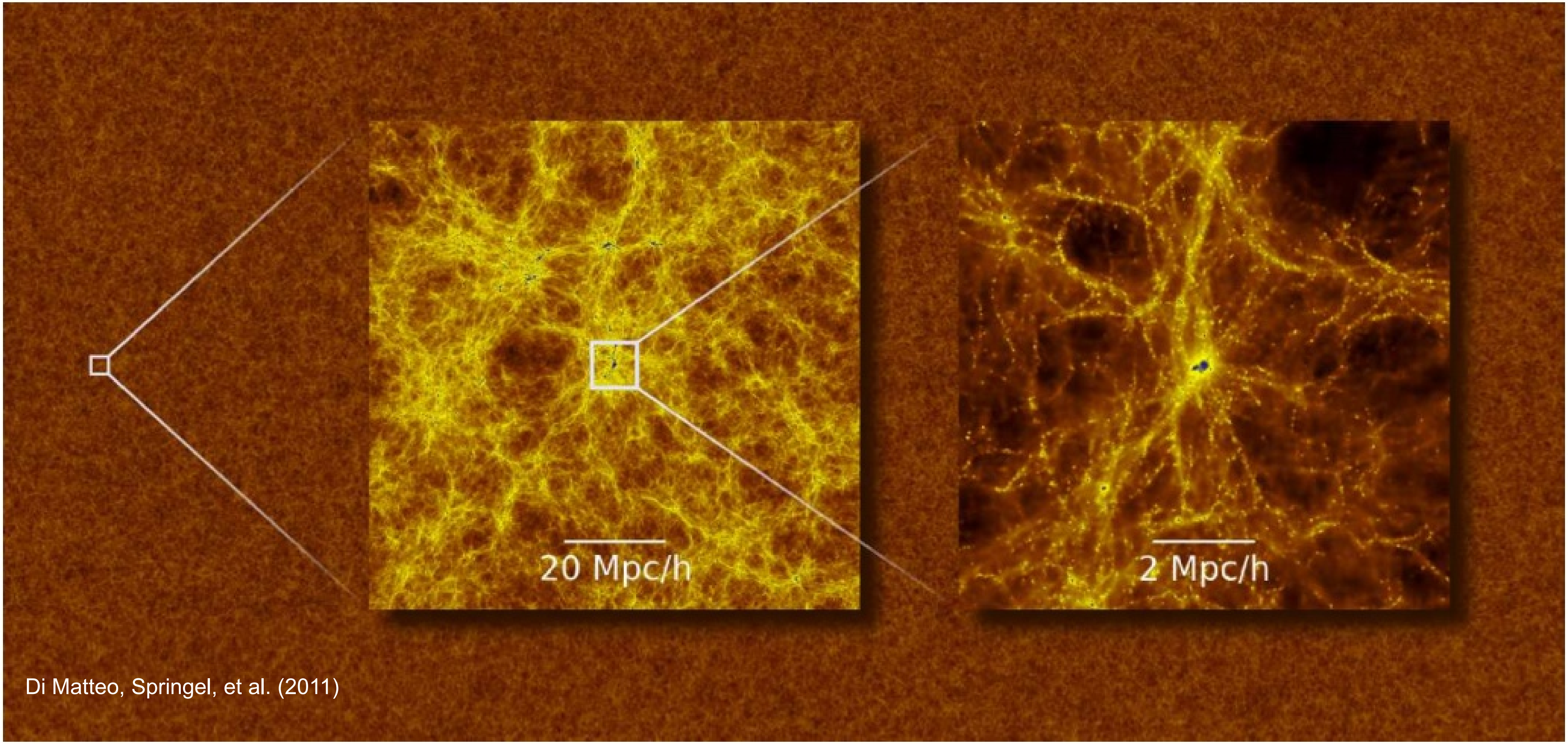
Lidz et al. (2006)



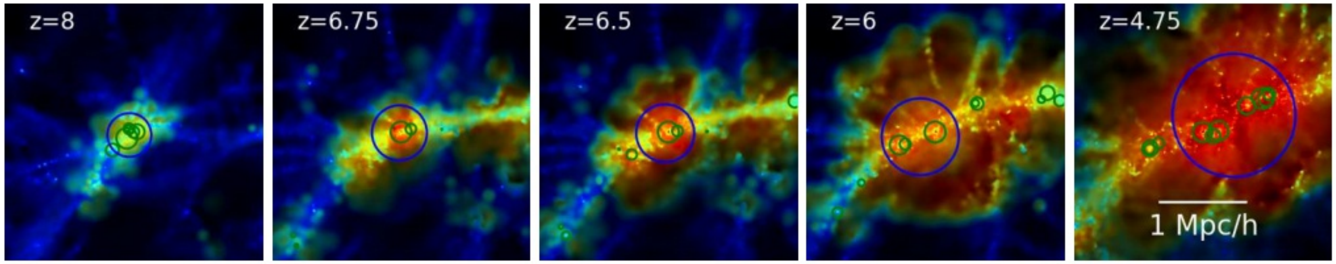


The *MassiveBlack* simulation is the largest astrophysical SPH simulation to date

TRACKING THE FORMATION OF THE FIRST QUSARS ON A PETAFLOP MACHINE

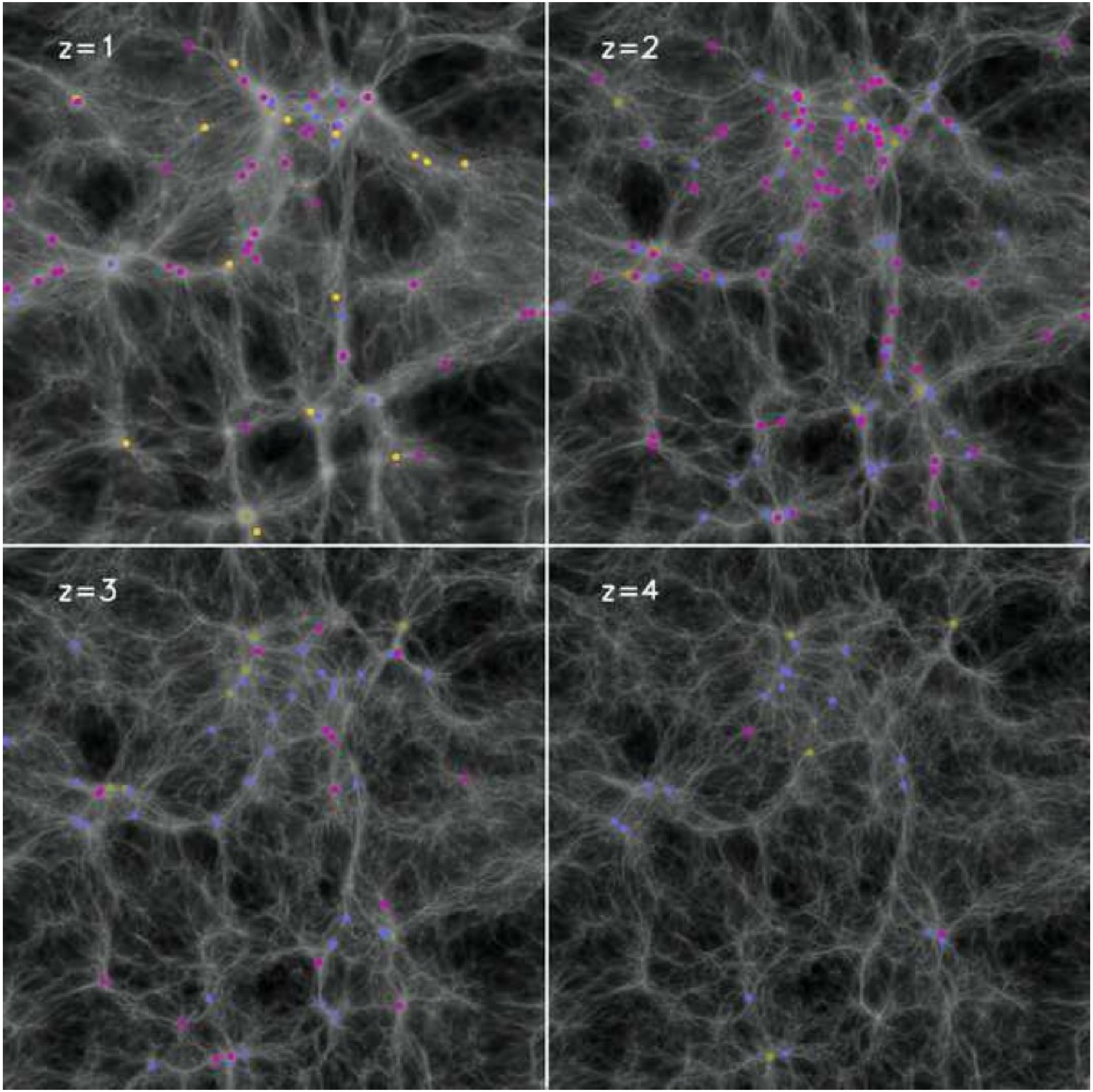


- 2 x 3200^3 ~ 65.5 billion particles
- 533 Mpc/h box
- **10^5 cores on Kraken** (Cray XT-5)
- Multi-threaded P-GADGET3 code



Hydrodynamical simulation predict the evolving spatial distribution of quasars of different luminosity

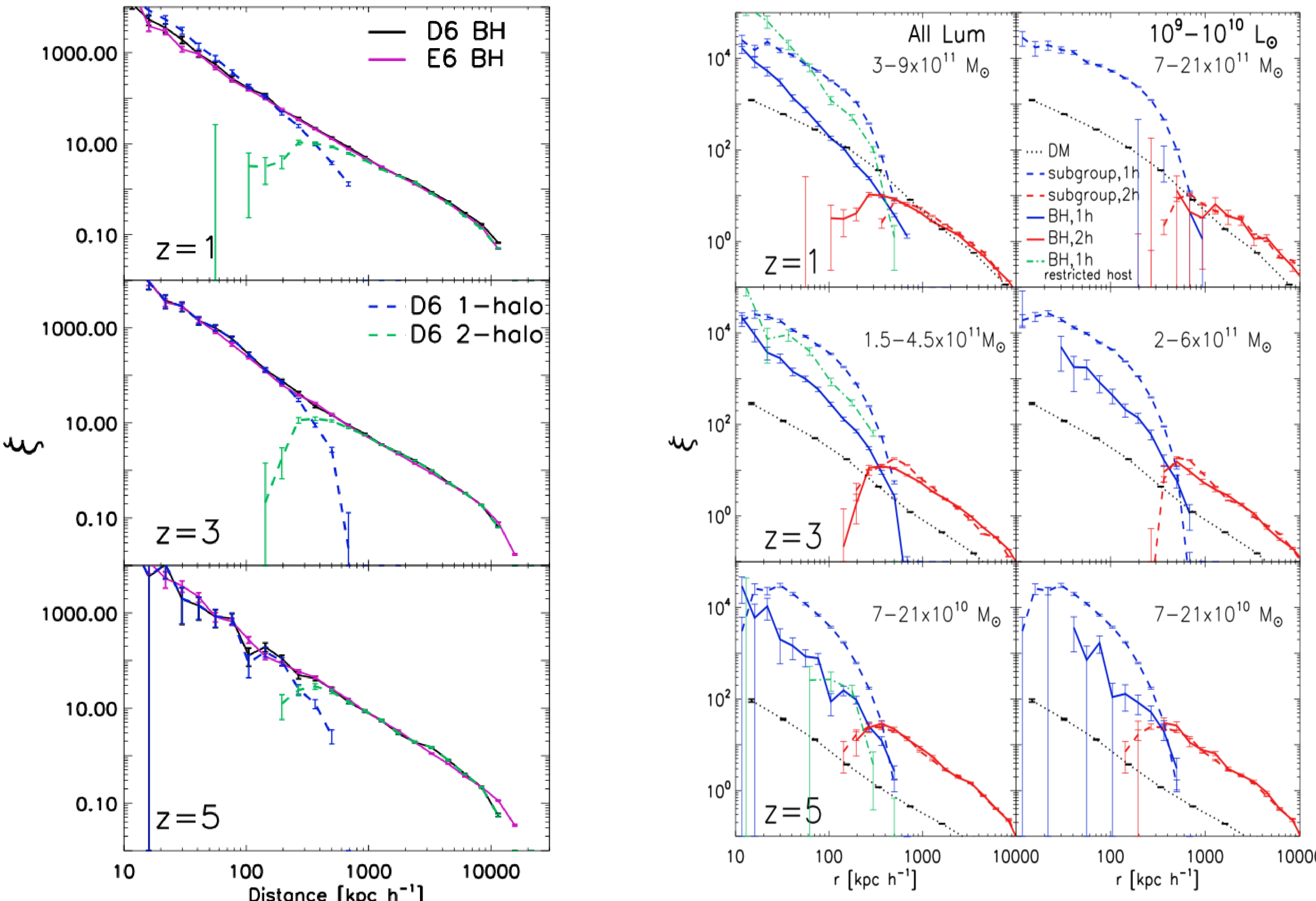
QUASARS OVERLAID OVER THE GAS DISTRIBUTION



Degraf, Di Matteo & Springel (2010)

The black halo clustering can be described through a halo model

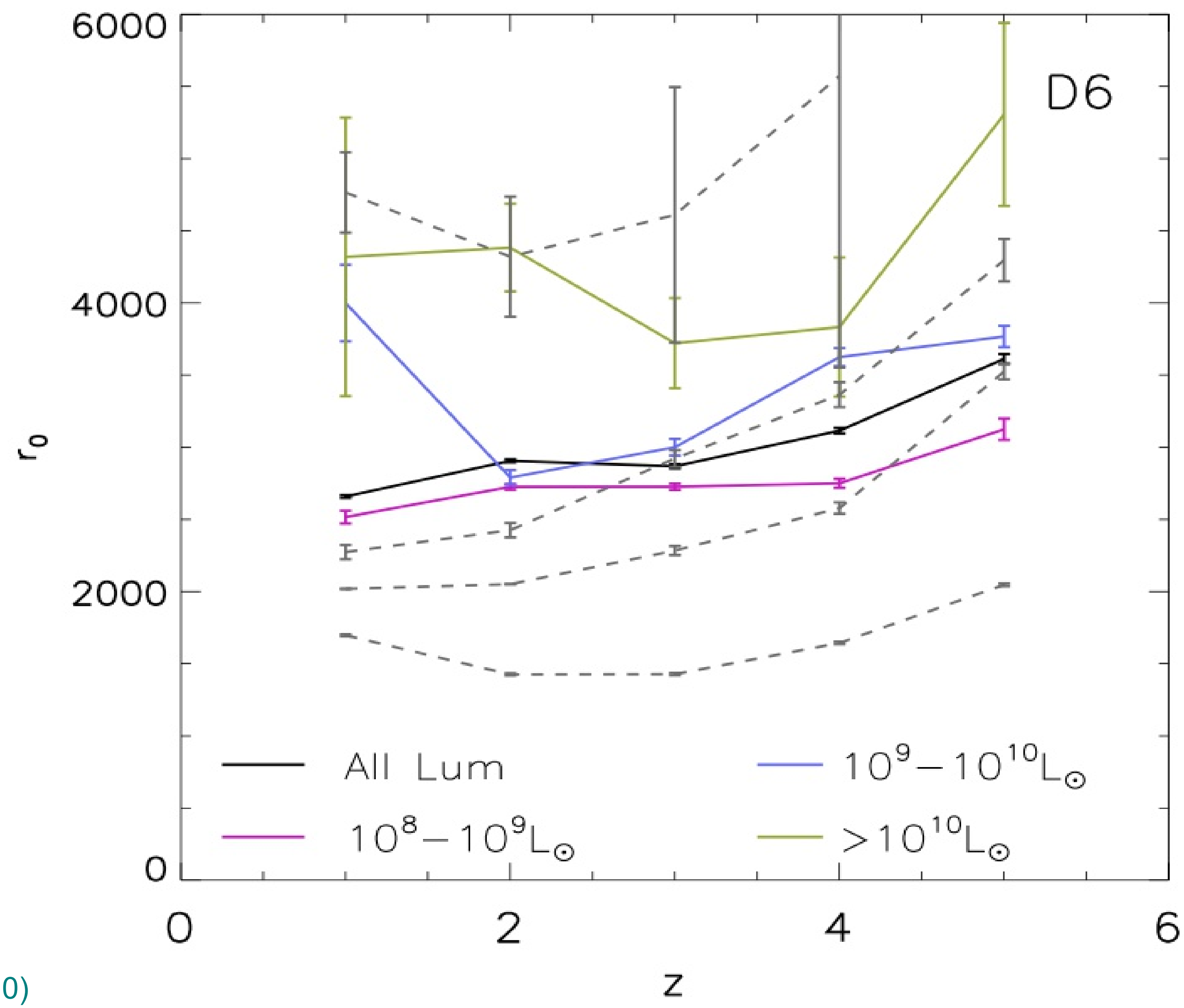
TWO-POINT FUNCTIONS WITH 1-HALO AND 2-HALO TERMS



Degraf, Di Matteo & Springel (2010)

The simulations predict a slight luminosity and redshift dependence of the AGN clustering

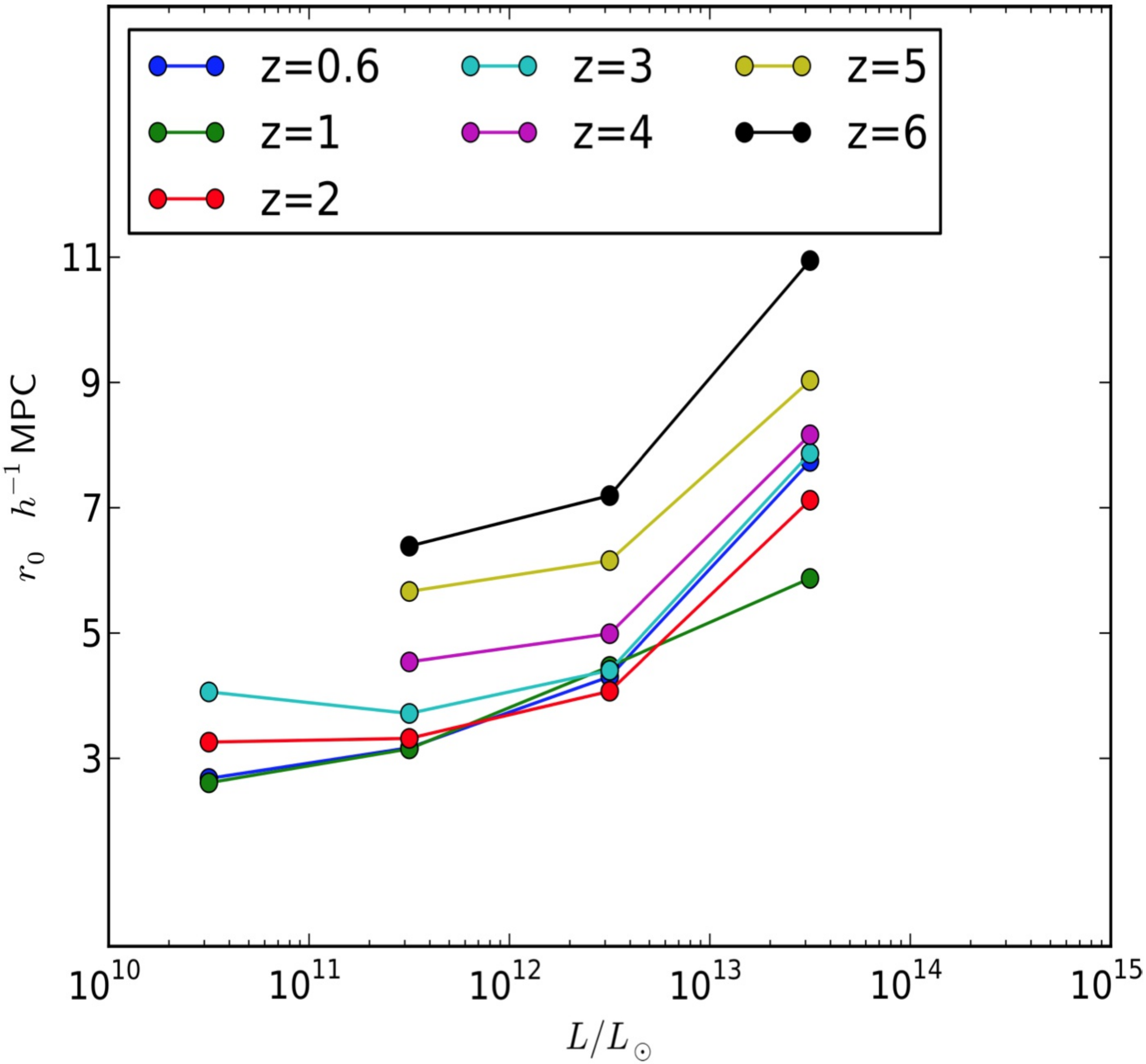
BLACK HOLE CORRELATION LENGTHS AS A FUNCTION OF REDSHIFT



Degraf, Di Matteo & Springel (2010)

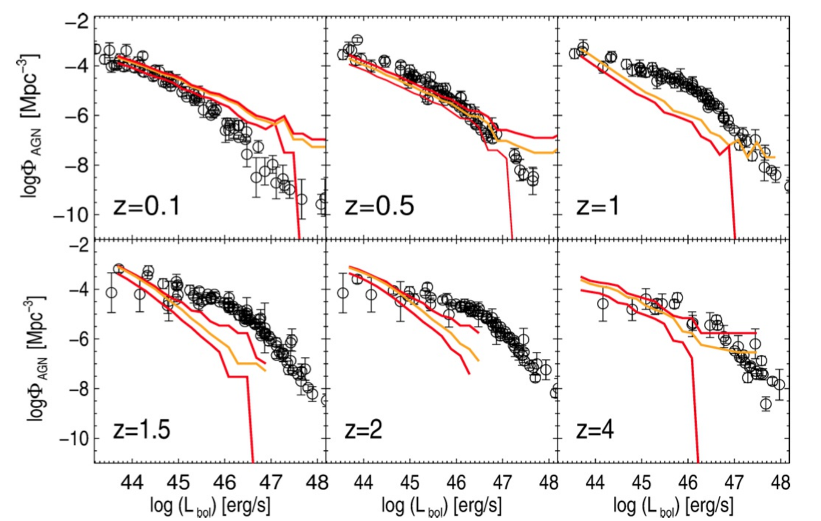
The recent *MassiveBlack-II* simulation reaffirms the prediction of luminosity-dependent clustering

CORRELATION LENGTH AS A FUNCTION OF QUASAR LUMINOSITY



Khandai et al. (2014)

Quasar luminosity functions:

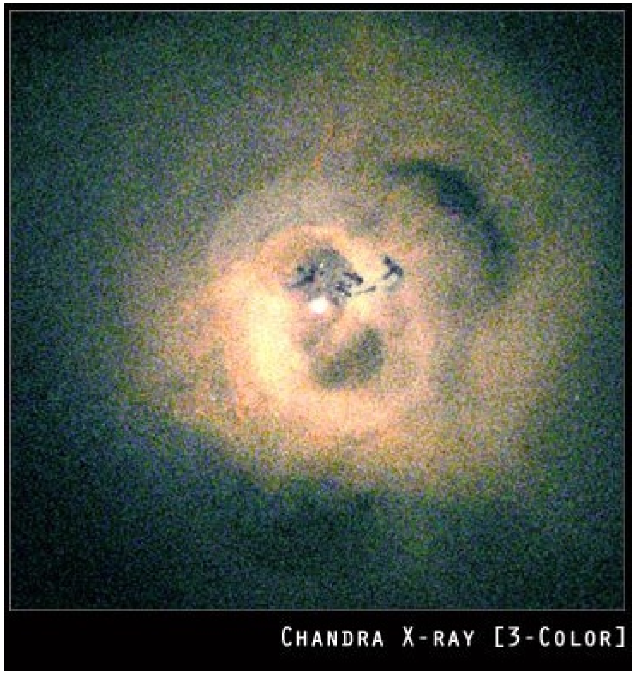


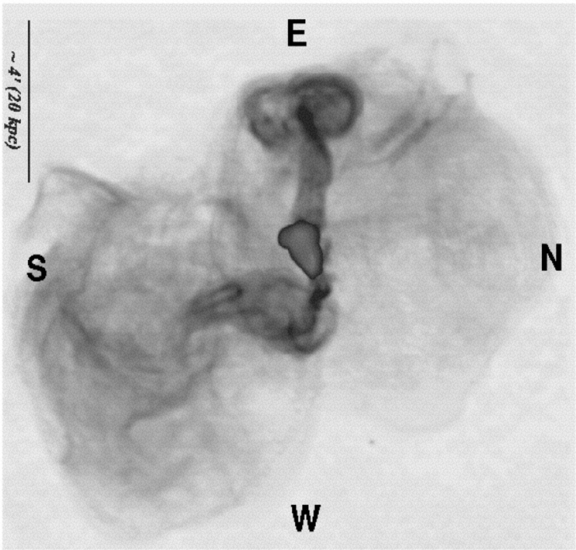
Bubbles and radio feedback

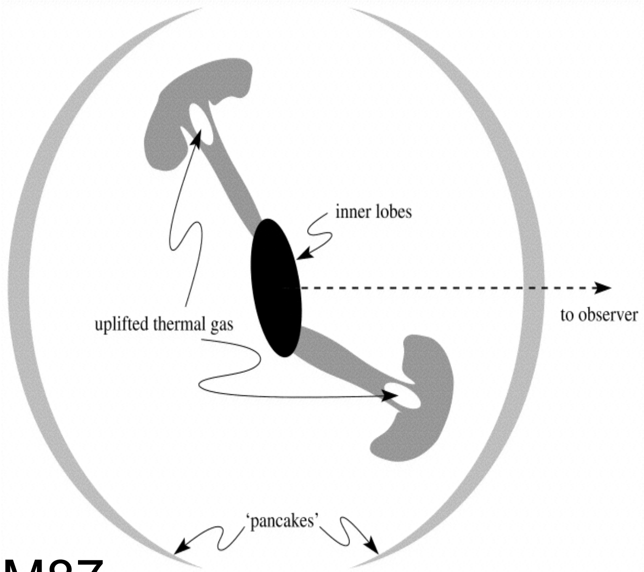
The ICM of clusters of galaxies is a substantial challenge for hydrodynamic simulations

UNSOLVED ISSUES

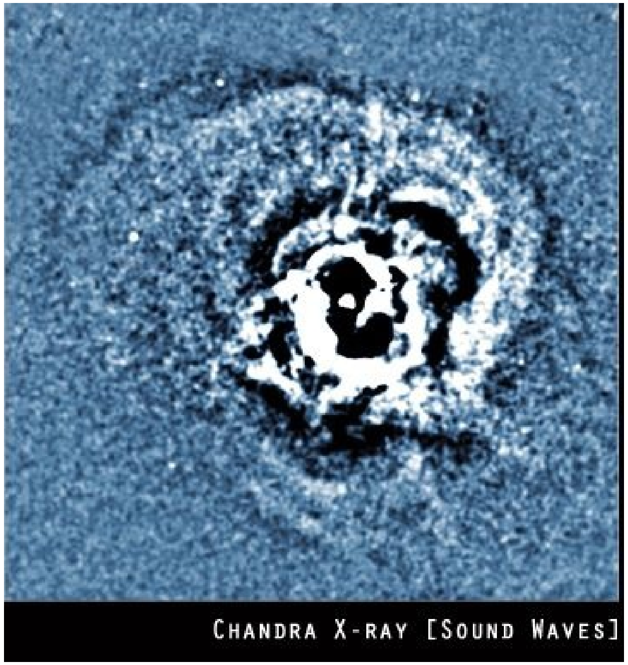
- Why are there (almost) no cooling flows in observed clusters? What's the heat source?
- What is responsible for the deviations of cluster scaling relations from self-similar predictions?
- What is the origin of the high metallicities of the ICM?
- How do the shapes of the observed temperature profiles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







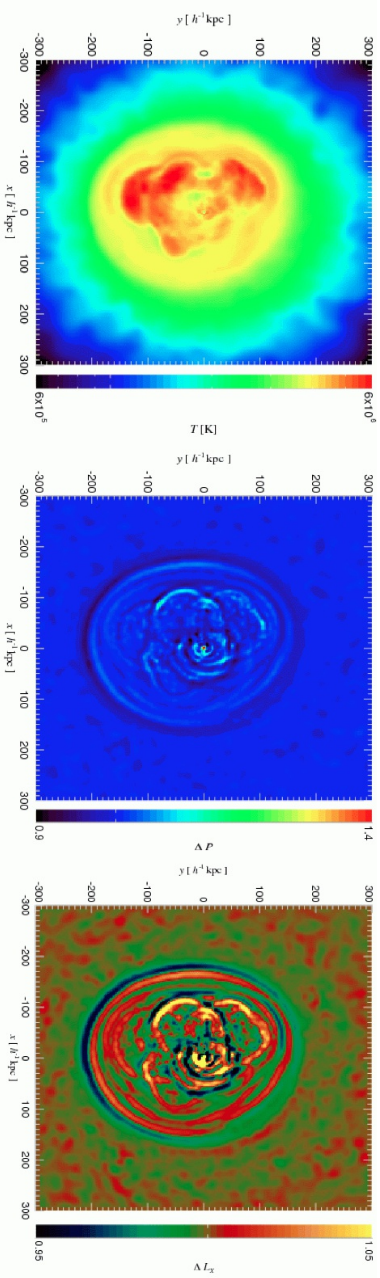
M87



Radio mode feedback can be implemented as a periodic heating process for BHs that are in a low accretion state

RADIO MODE PARAMETERIZATION

Sijacki & Springel (2007)



If the accretion rate is less than 1% of the Eddington rate: → ***Radio mode:*** Recurrent injection of hot bubbles into ICM

Injection is triggered when BH's mass increases by a certain fraction.

$$\delta M_{BH}/M_{BH}$$

Energy of

$$E_{\rm bub} = \epsilon_{\rm m}\epsilon_{\rm r} c^2 \delta M_{\rm BH}$$

with

$$\epsilon_r = 0.1 \qquad \epsilon_m = 0.2$$

Thermally injected into bubble of radius:

$$R_{\rm bub} = R_{\rm bub,0}\left(\frac{E_{\rm bub}/E_{\rm bub,0}}{\rho_{\rm ICM}/\rho_{\rm ICM,0}}\right)^{1/5}$$

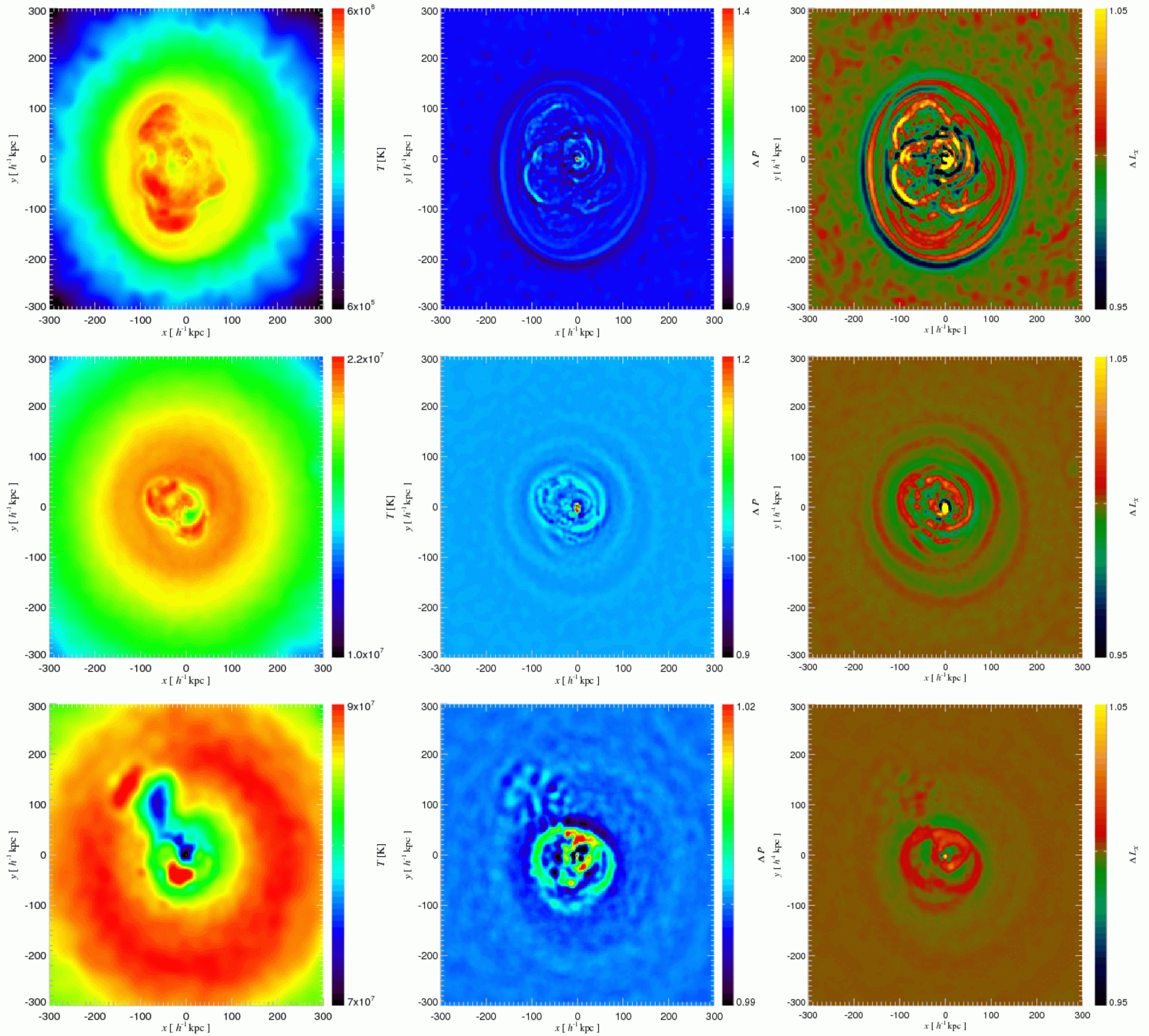
AGN feedback heats the cluster center and sends sound waves into the IGM

UNSHARP MASKED MAPS

$M = 10^{13}\ M_\odot/h$

$M = 10^{14}\ M_\odot/h$

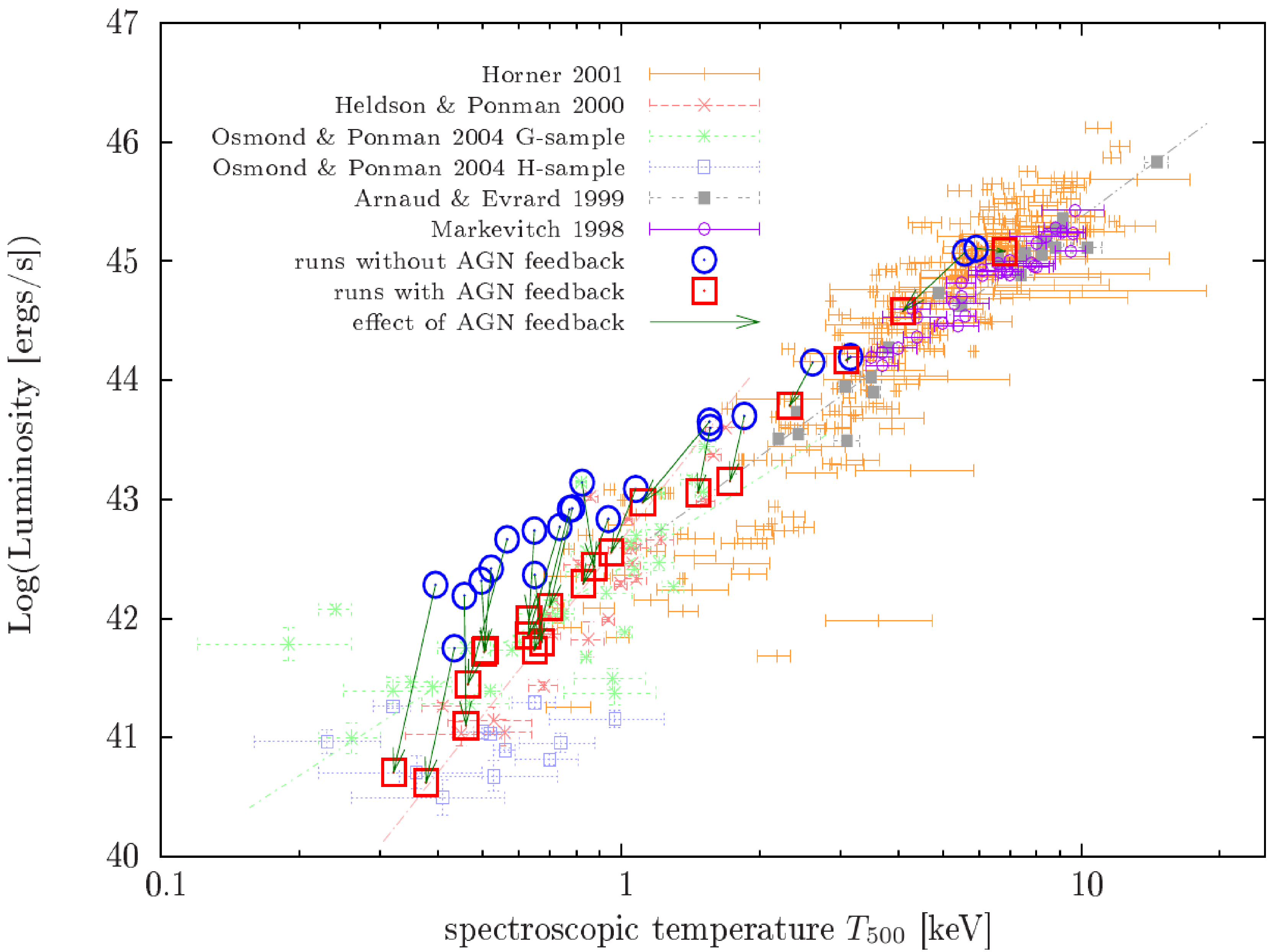
$M = 10^{15}\ M_\odot/h$



Sijacki & Springel (2007)

AGN Feedback reduces the luminosities of poor clusters and groups

THE Lx-T RELATION OF SIMULATIONS AND OBSERVATIONS



Puchwein, Sijacki & Springel (2008)

The Illustris Simulation

$3 \times 1820^3 = 18.1 \times 10^9$
cells / particles / tracers

106.5 Mpc boxsize

$M_{baryon} = 1.26 \times 10^6 M_{\odot}$
$M_{dm} = 6.26 \times 10^6 M_{\odot}$

~50 pc smallest cell size

16 (+3) million CPU hours

www.illustris-project.org

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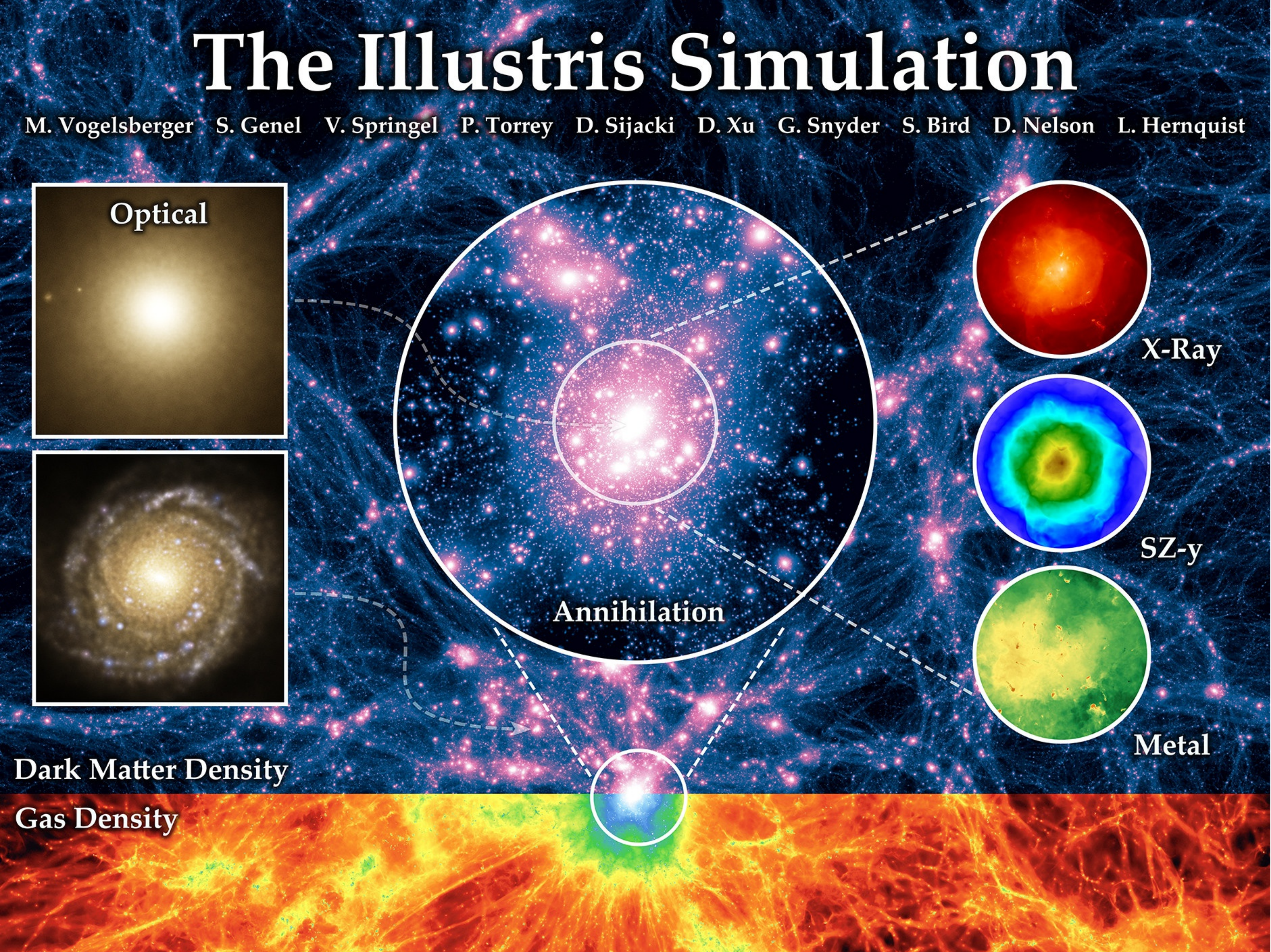
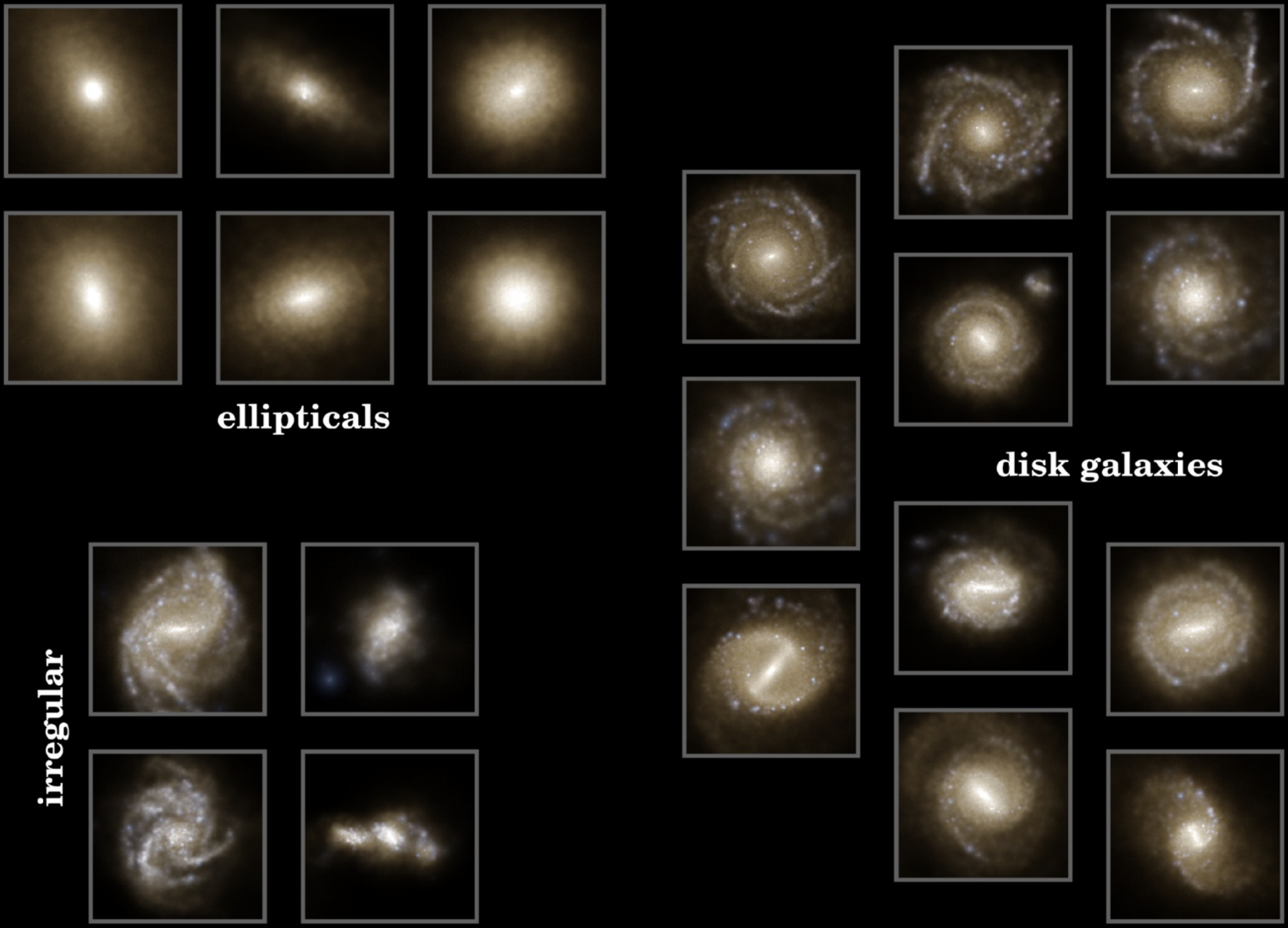
- ***Properties of galaxies reproduced by a hydrodynamic simulation***
  Vogelsberger et al., 2014, Nature, 509, 177
- ***Introducing the Illustris Project: Simulating the coevolution of dark and visible matter in the Universe***
  Vogelsberger et al., 2014, submitted to MNRAS, arXiv:1405.2921
- ***The Illustris Simulation: the evolution of galaxy populations across cosmic time***
  Genel et al., 2014, submitted to MNRAS, arXiv:1405.3749)
- ***Damped Lyman-alpha absorbers as a probe of stellar feedback***
  Bird et al., 2014, submitted to MNRAS, arXiv:1405.3994


The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
Annihilation
X-Ray
SZ-y
Metal
Dark Matter Density
Gas Density

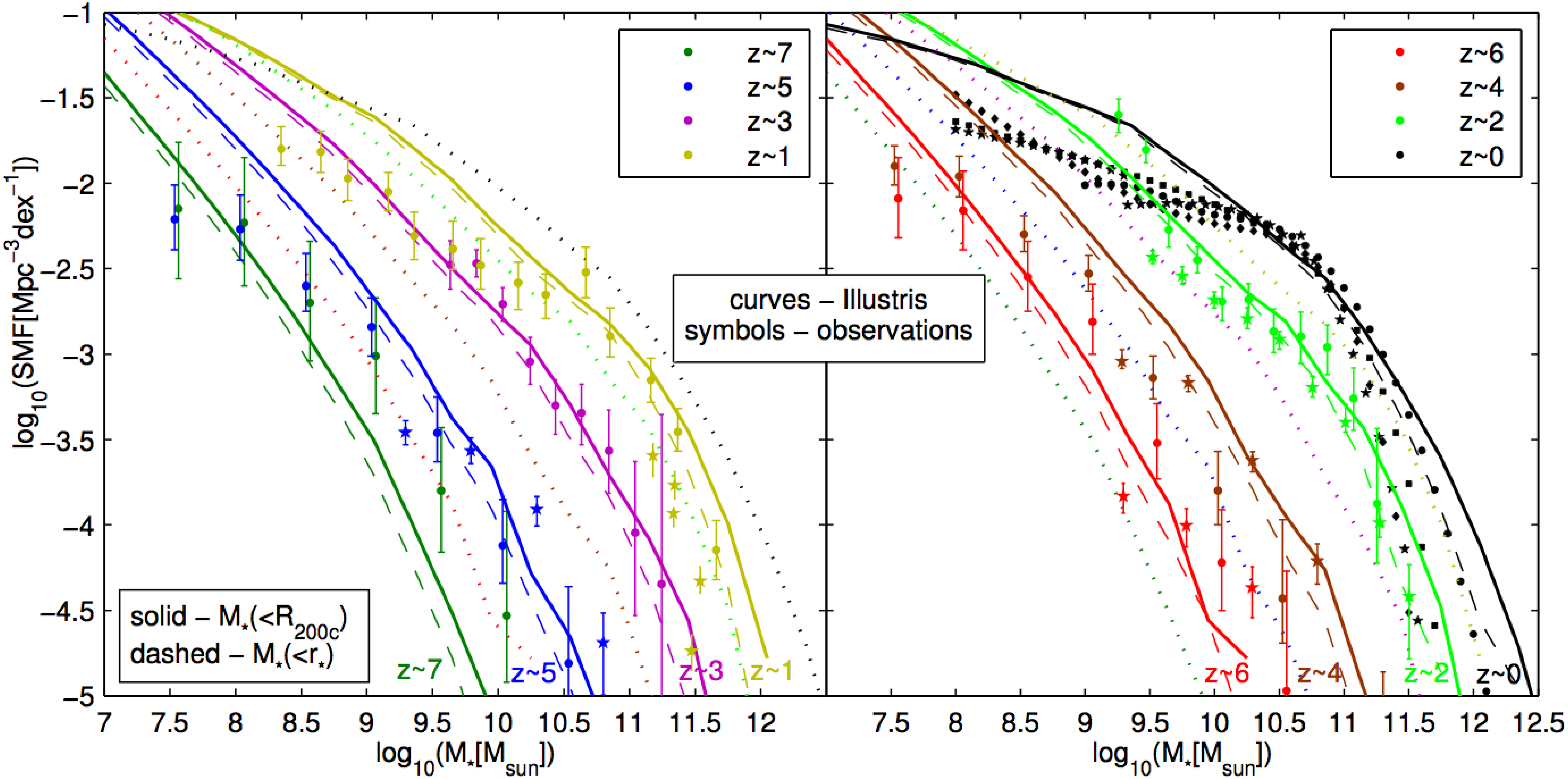
The Illustris simulation reproduces the morphological mix of galaxies

SIMULATED HUBBLE TUNING FORK DIAGRAM



The stellar mass functions match observations at different redshift well

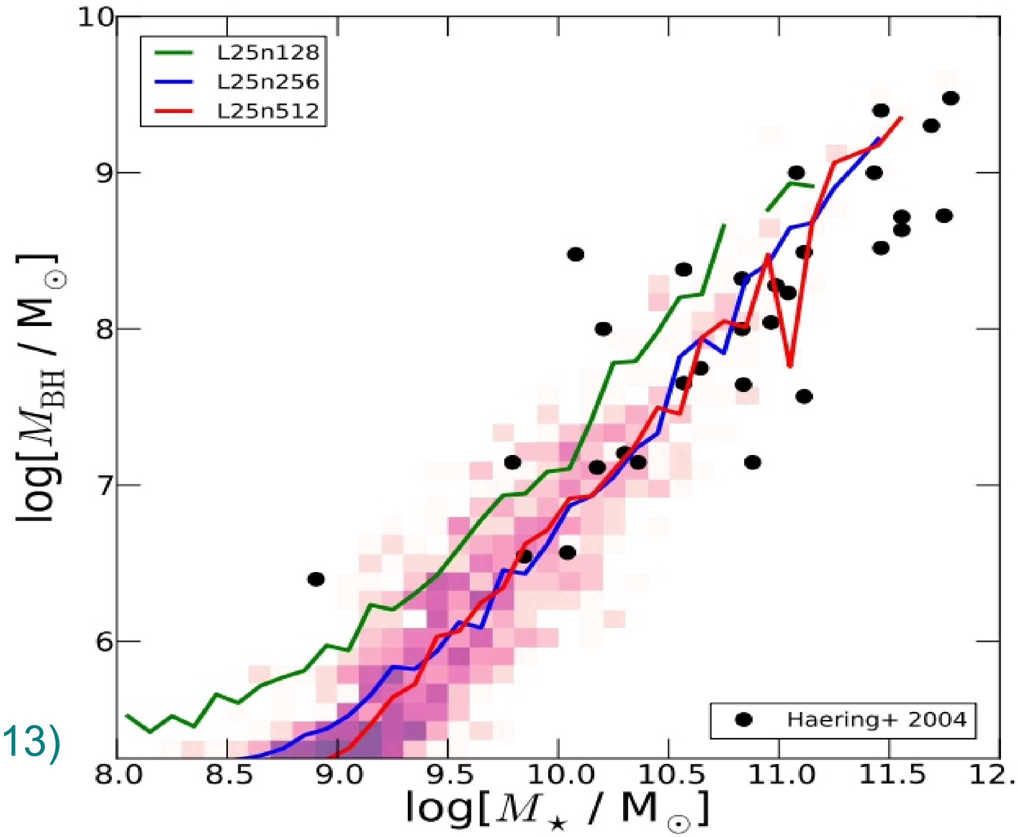
STELLAR MASS FUNCTIONS OF ILLUSTRIS COMPARED TO HIGH-Z OBSERVATIONS



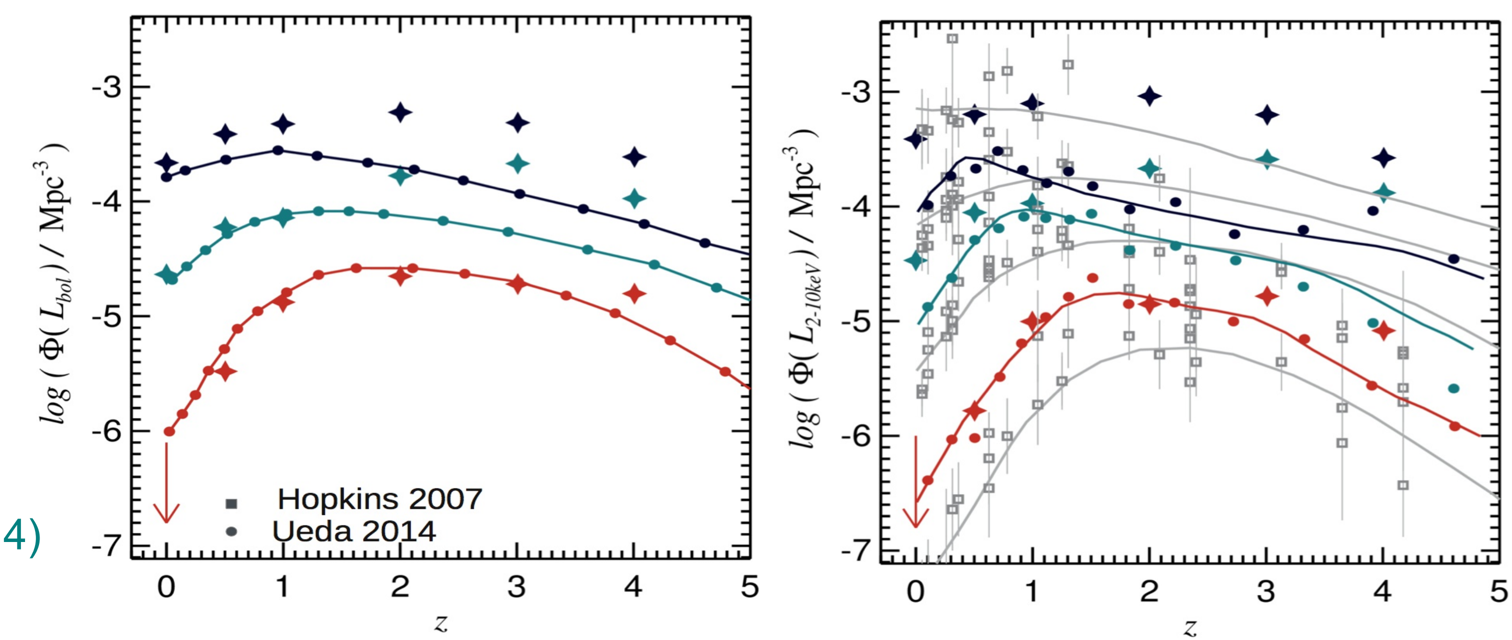
Genel et al. (2014)

Basic black hole properties in Illustris broadly agree with observations

BLACK HOLE MASS SCALING RELATIONS AND QUASAR LUMINOSITY FUNCTIONS



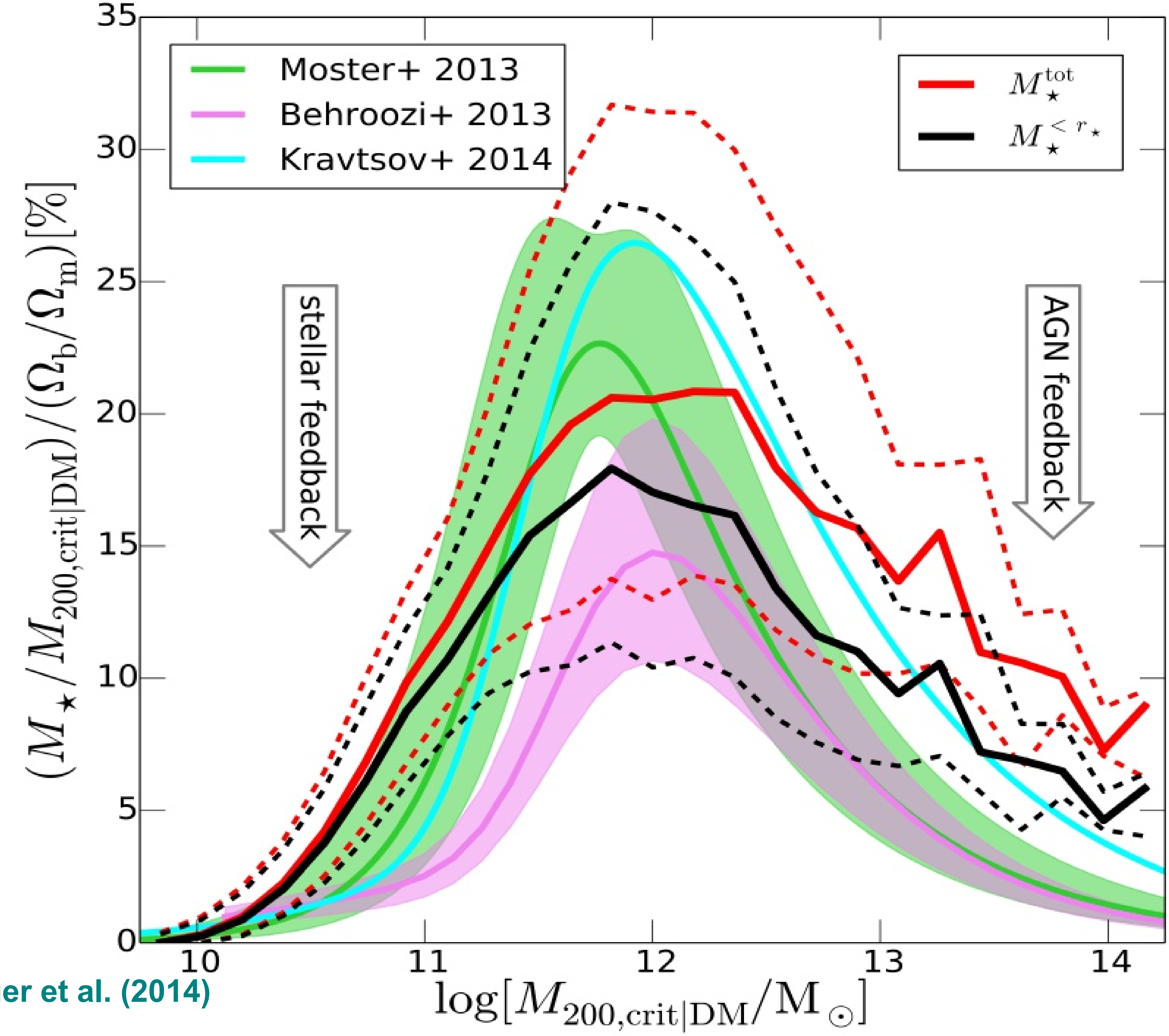
Vogelsberger et al. (2013)



Sijacki et al. (2014)

The efficiency of star formation is a strong function of halo mass in Illustris

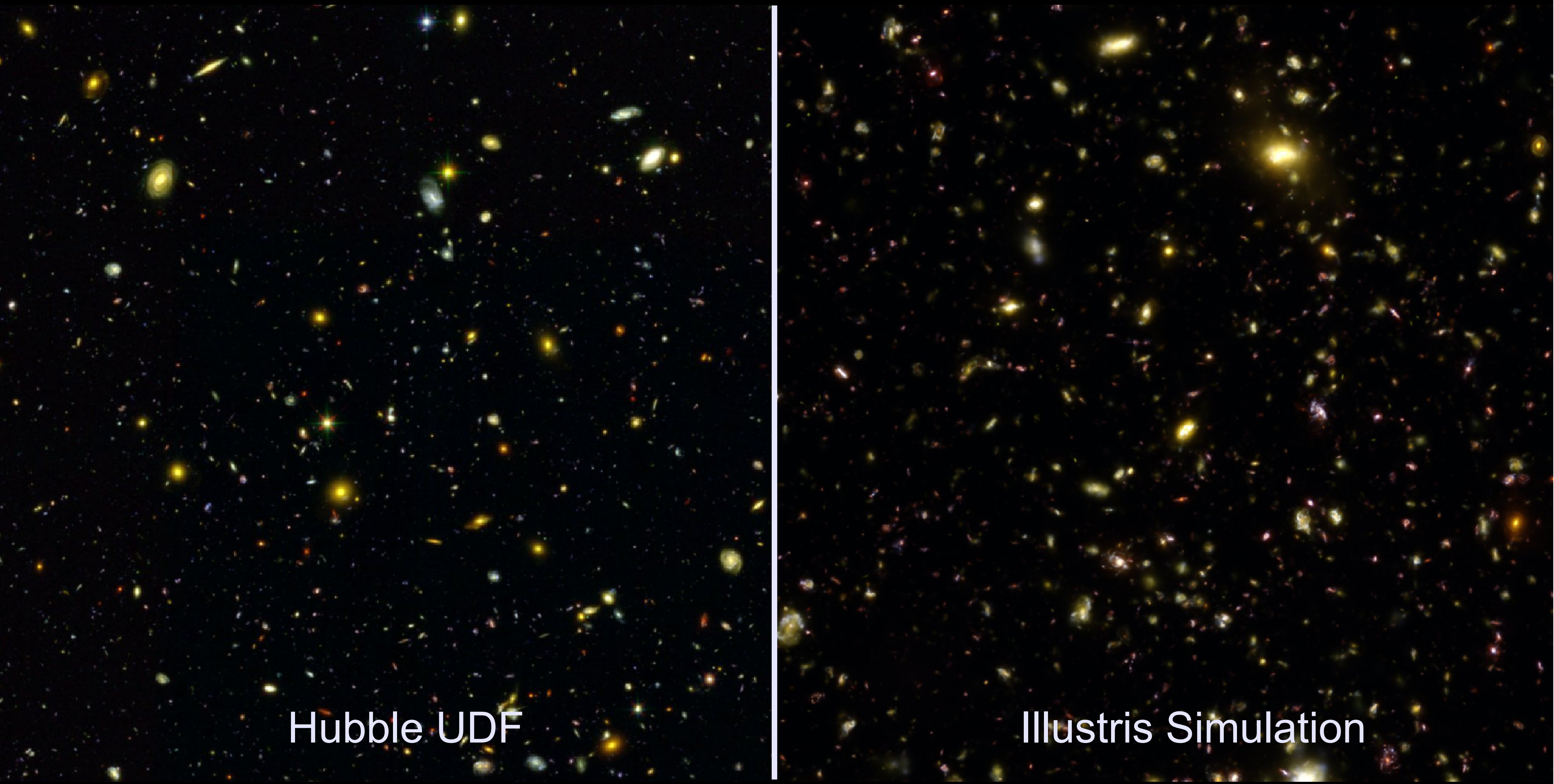
STELLAR MASS FRACTION COMPARED TO ABUNDANCE MATCHING PREDICTIONS



Vogelsberger et al. (2014)

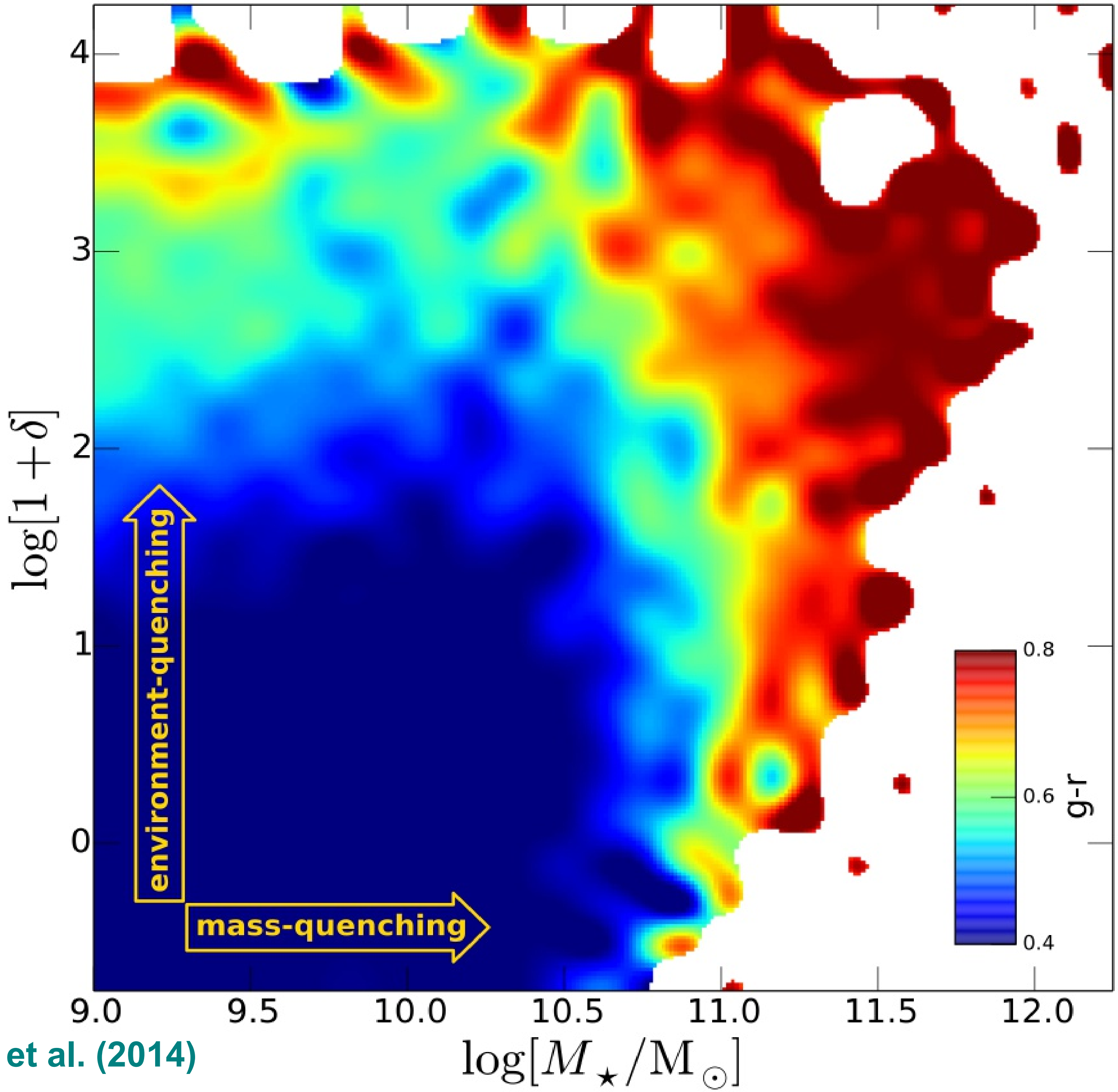
Artificial light cone observations look rather similar to the real **Hubble Ultra Deep Field**

MOCK VS REAL UDF



Hydrodynamical effects such as ram pressure establish environmental quenching in addition to mass-dependent effects

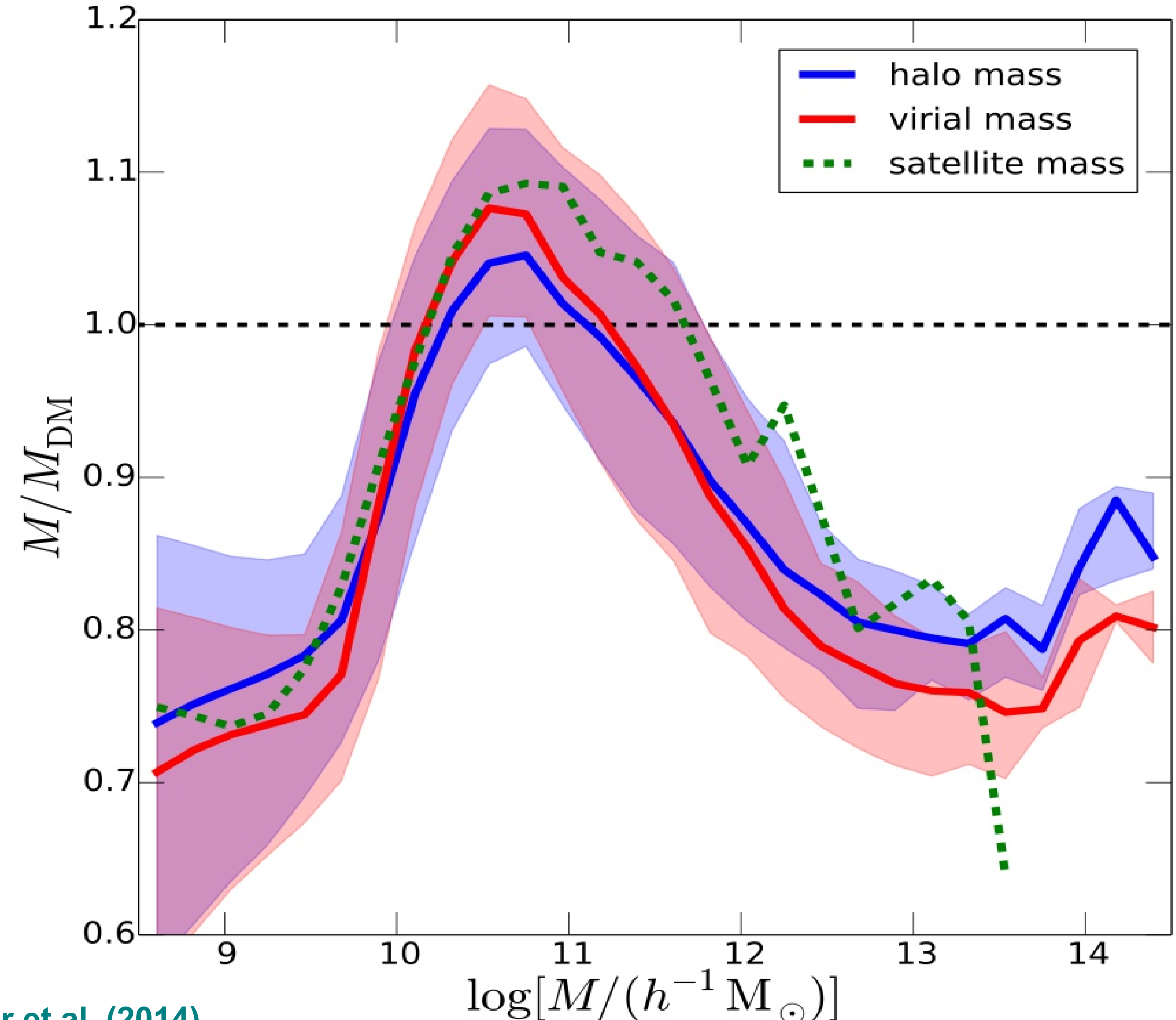
AVERAGE G - R COLOR AS A FUNCTION OF MASS AND OVERDENSITY



Vogelsberger et al. (2014)

Baryonic effects impact the dark matter distribution

AVERAGE MODIFICATION OF HALO MASSES AS A FUNCTION OF MASS SCALE



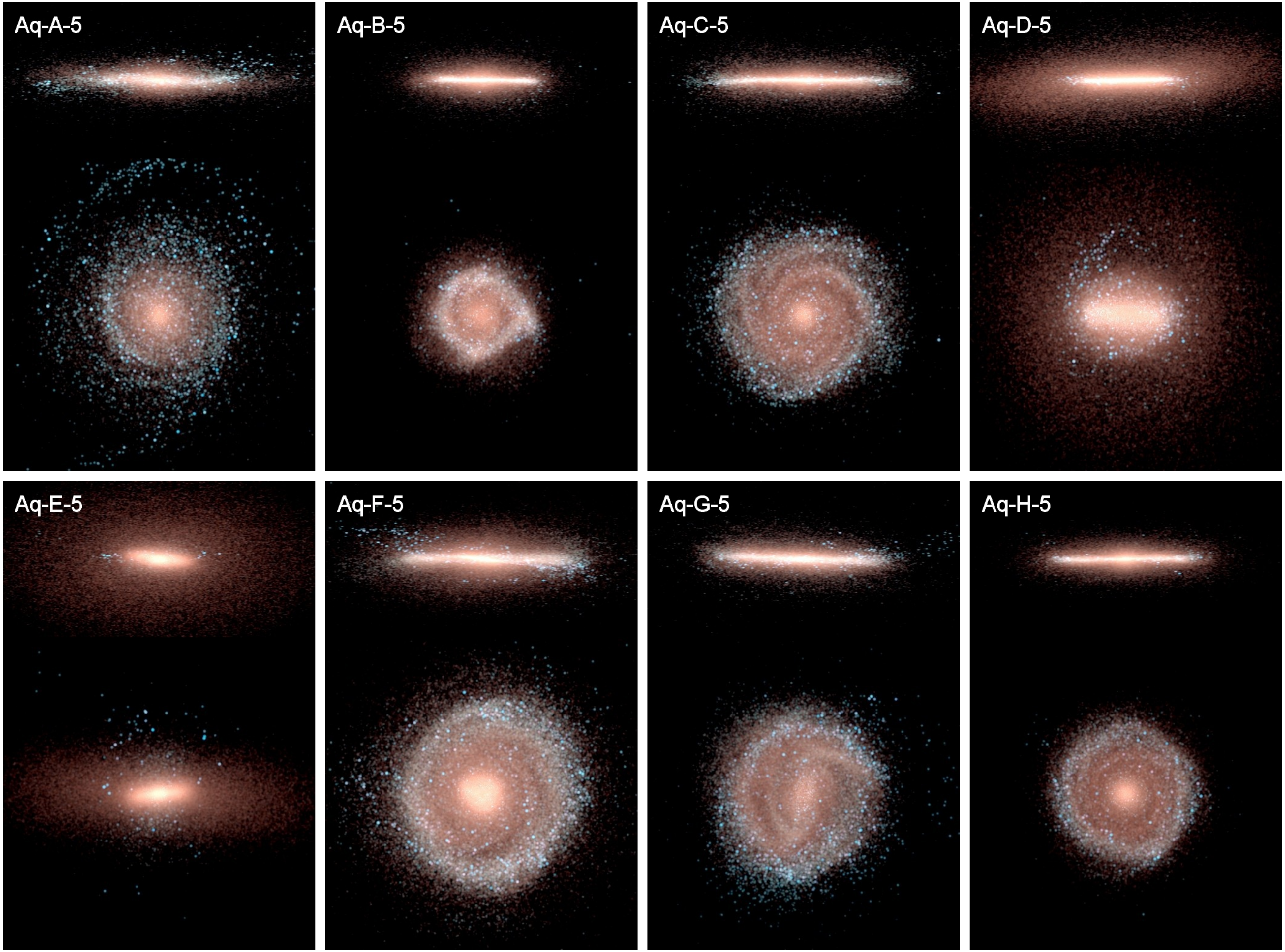
Vogelsberger et al. (2014)

Quasars in individual galaxies

Visualizing the formation of a galaxy over time highlights the complexity of its dynamics over many dynamical times

AQ-C-5 SIMULATION (WITH TOO FEW OUTPUTS TIMES...)

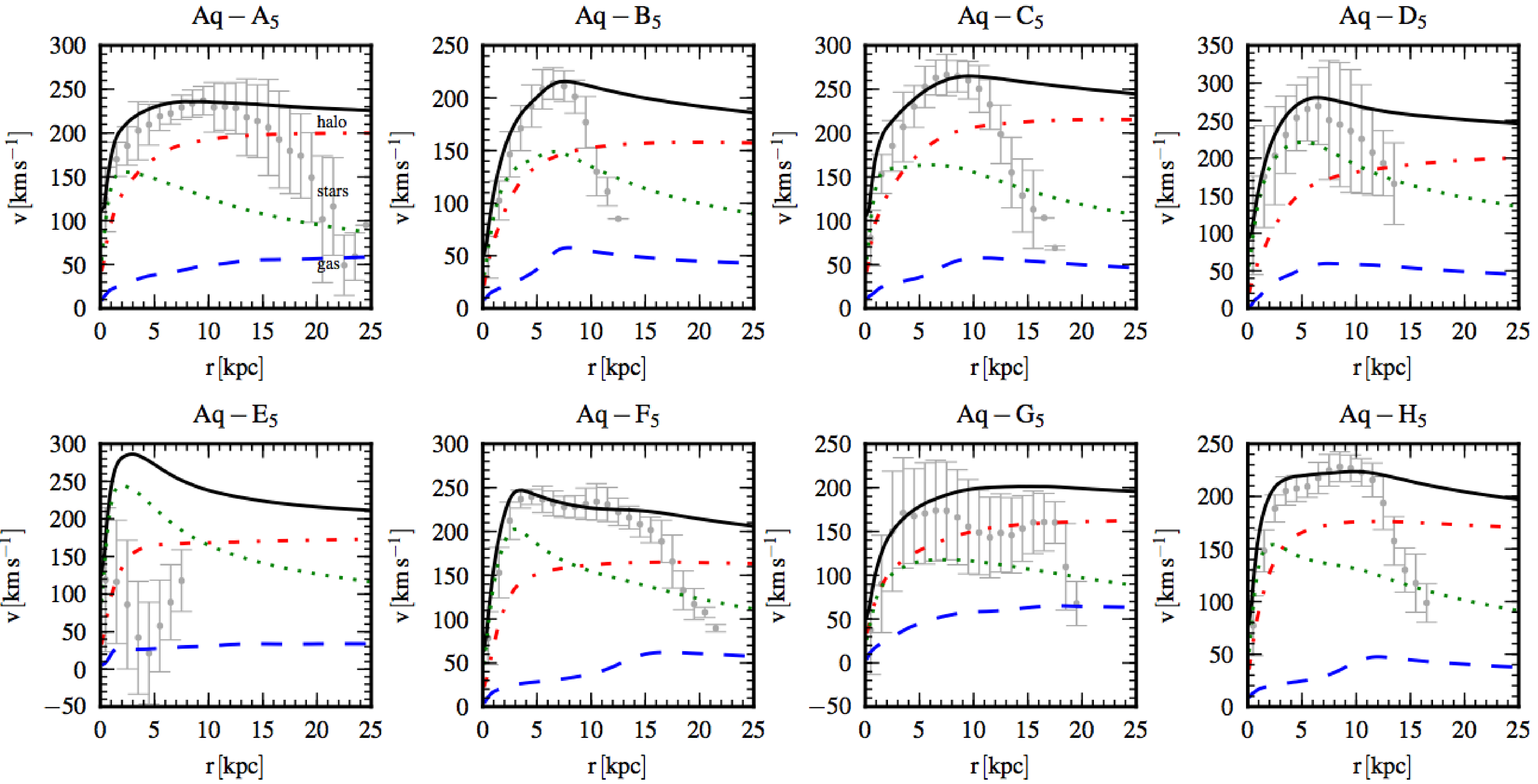
Our set of 8 galaxies formed in Milky Way sized dark matter halos



Marinacci, Pakmor & Springel (2013)

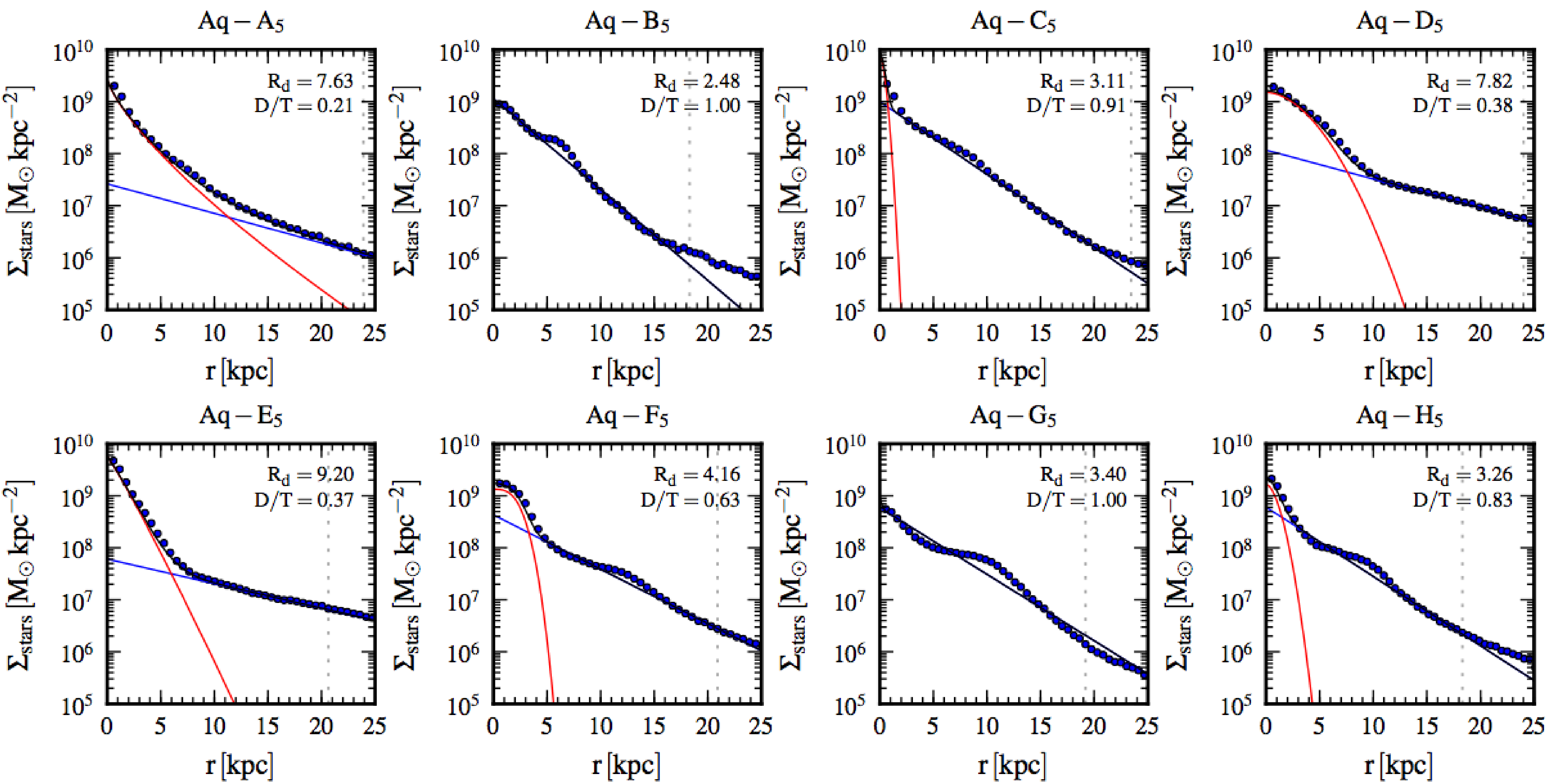
The rotation curves have reasonable shapes, most of them are (almost) flat

ROTATION CURVES OF OUR SIMULATED MILKY WAY-SIZED GALAXIES



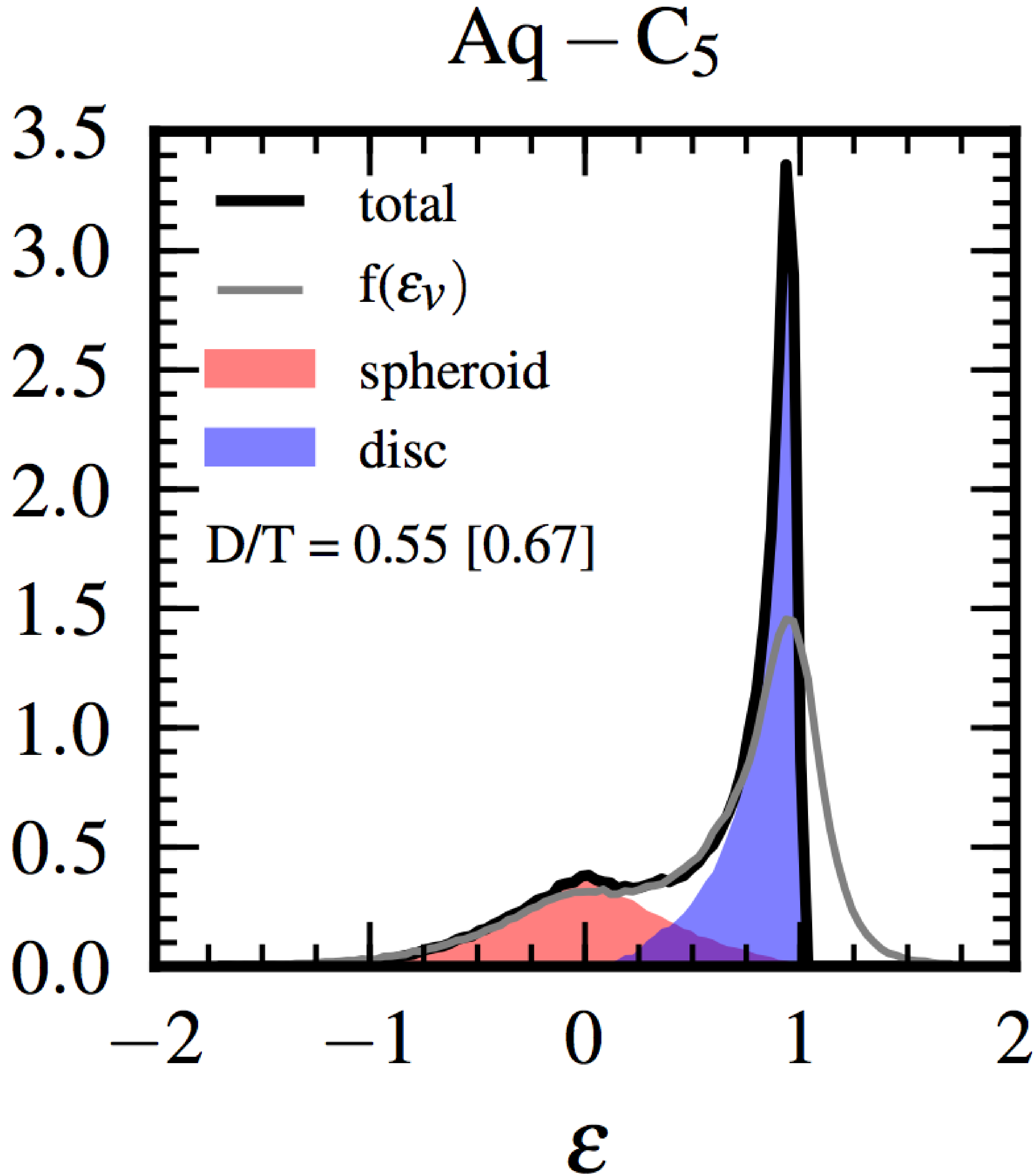
The stellar surface density profiles are close to exponential, with (sometimes) an obvious bulge component

STELLAR SURFACE DENSITY PROFILES WITH EXPONENTAL AND SERSIC FITS



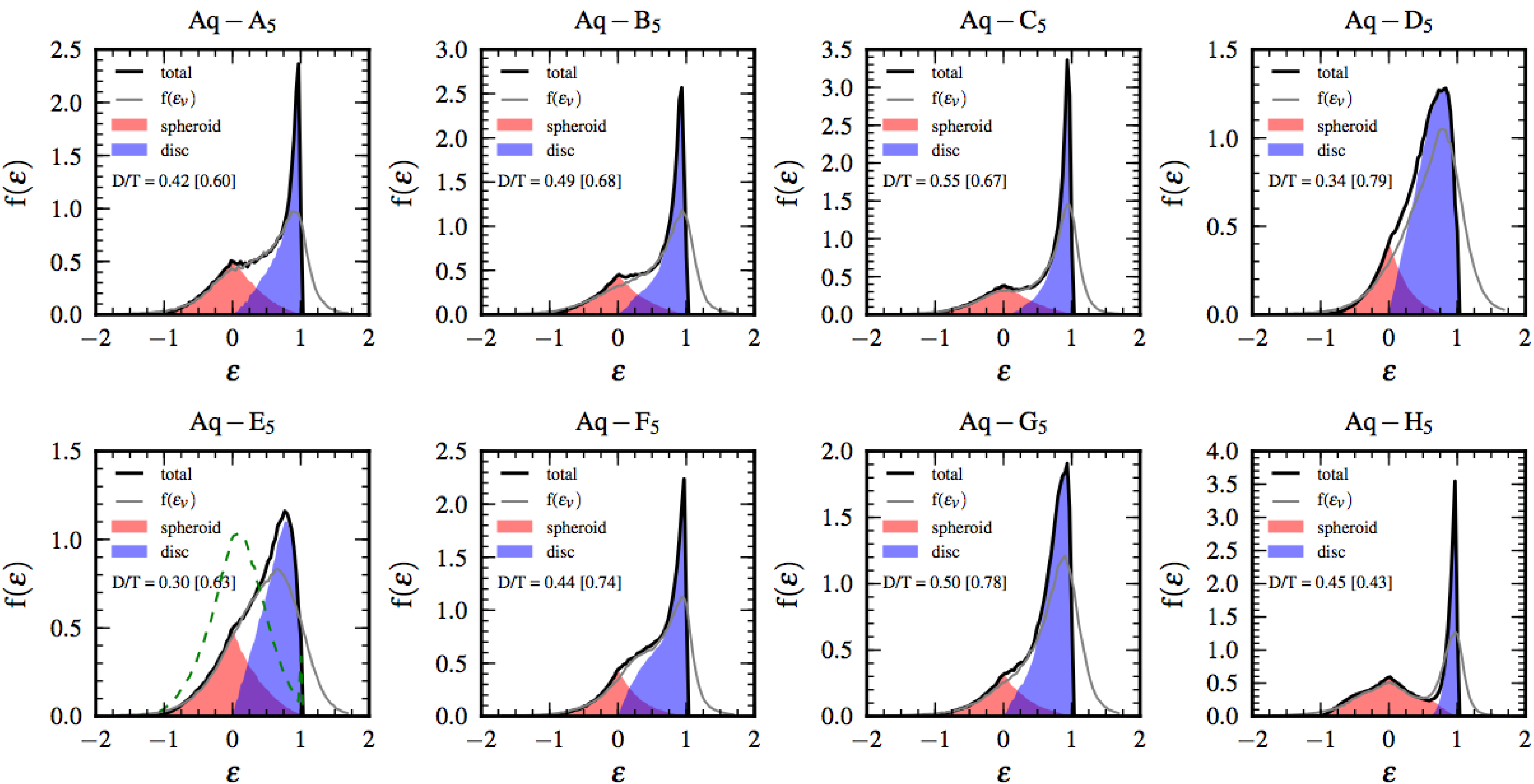
A kinematic analysis can be used to reliably quantify the relative amount of disk and bulge stars

ECCENTRICTY DISTRIBUTION FOR ALL STARS IN THE AQ-C SYSTEM



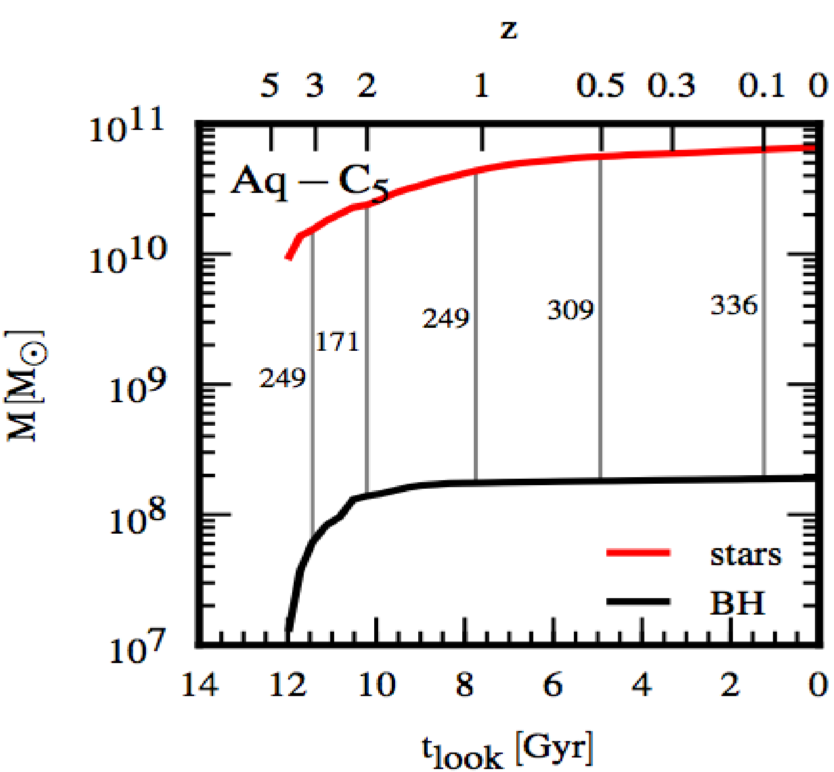
All our galaxies show a significant disc component with a subdominant bulge

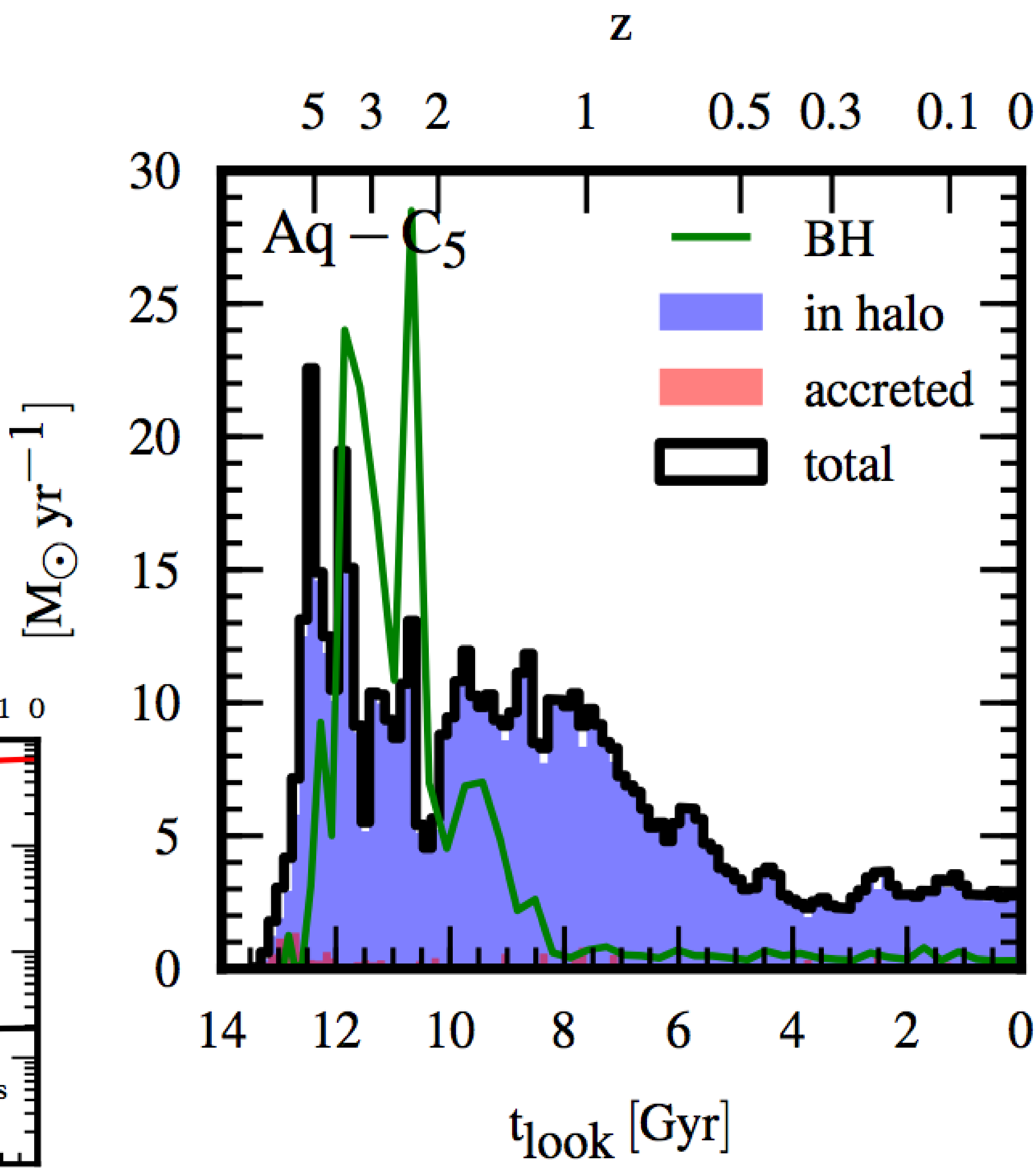
ECCENTRICTY DISTRIBUTIONS STARS IN THE AQUARIUS SYSTEMS



Starbursts at high redshift correlate with episodic black hole growth

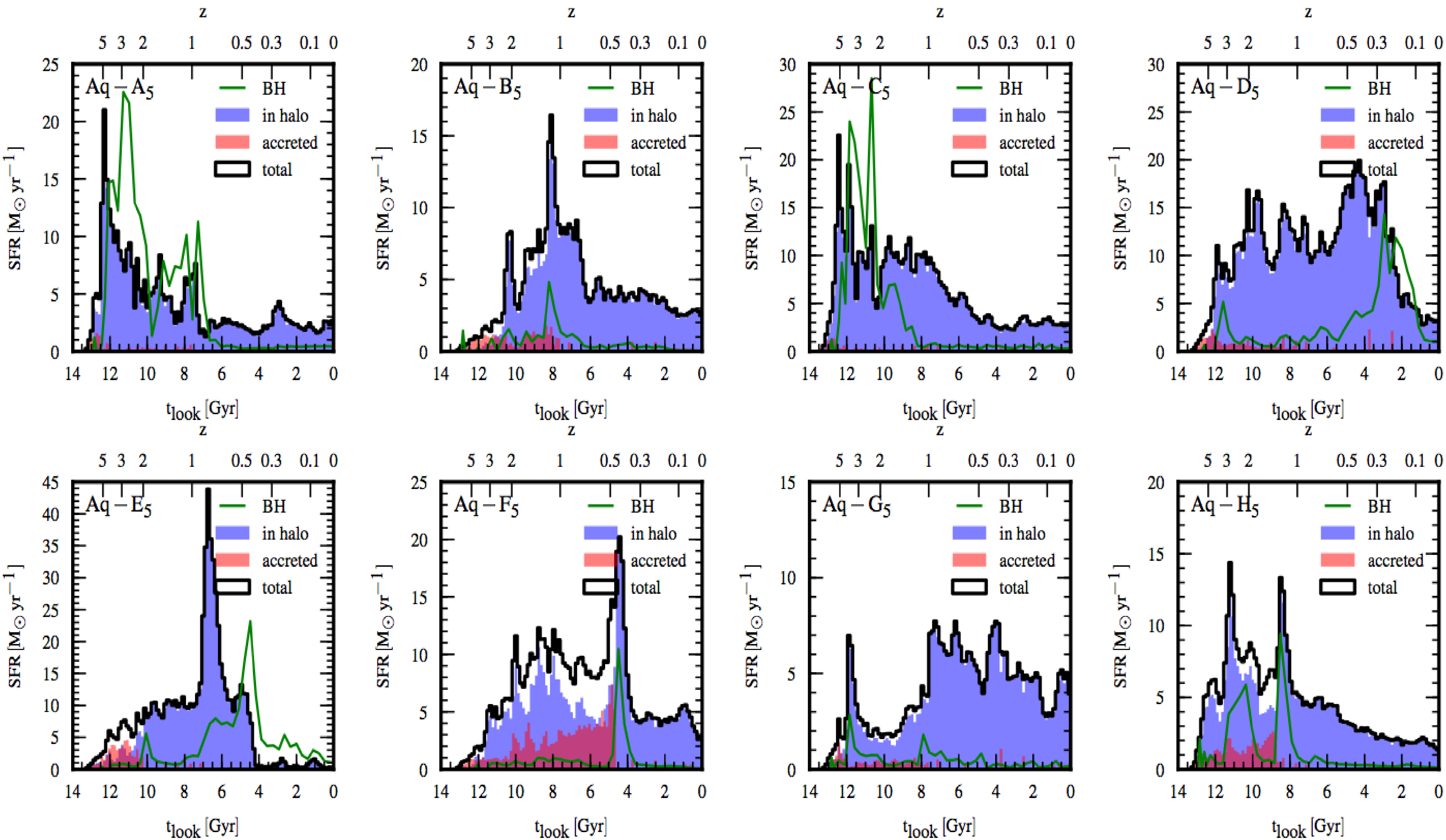
STAR FORMATION HISTORY OF THE AQ-C SYSTEM





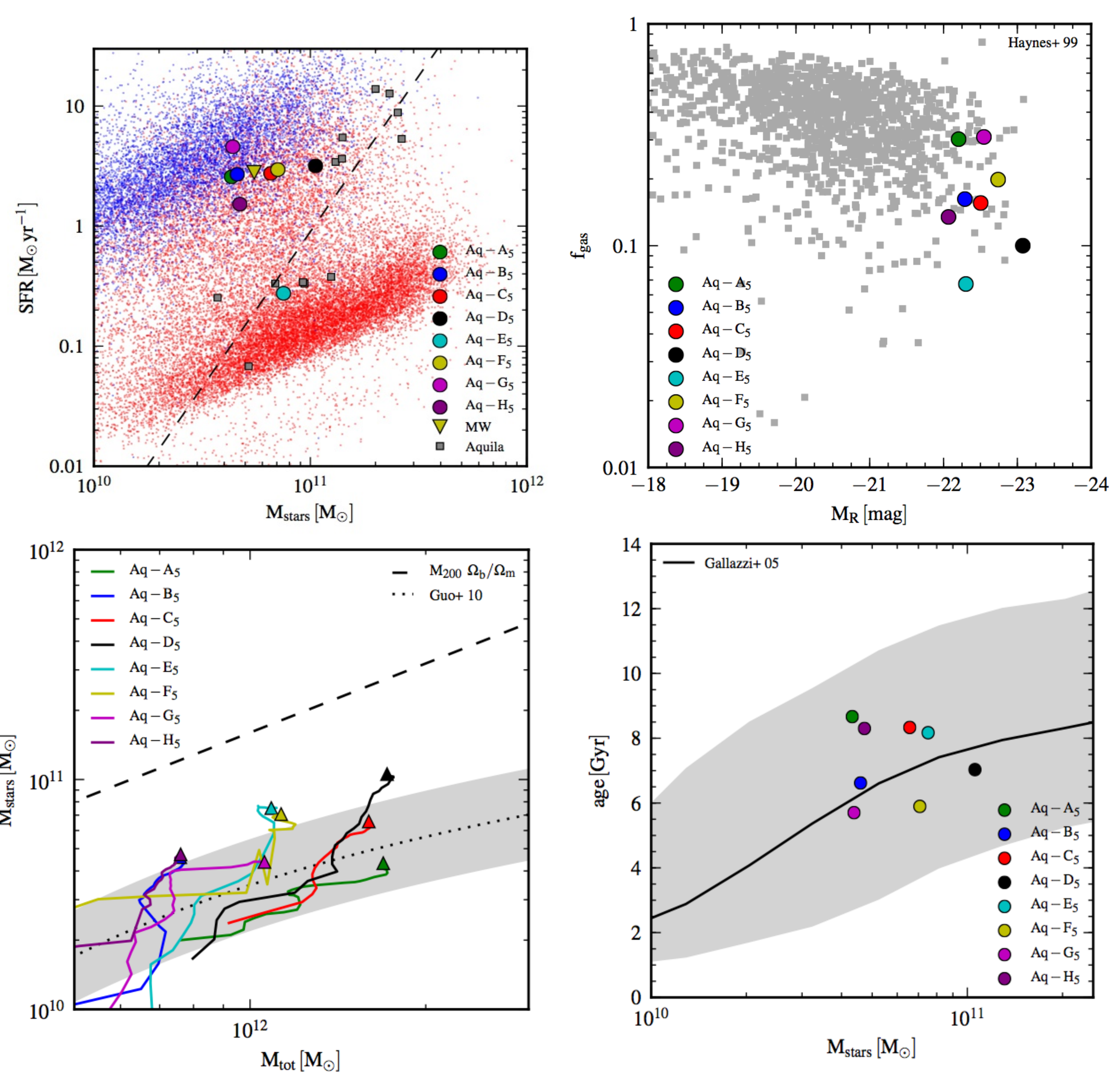
Most stars form “in-situ”, and the black hole growth is largely over by z~1

STAR FORMATION RATE AND BLACK HOLE ACCRETION RATE AS A FUNCTION OF LOOKBACK TIME



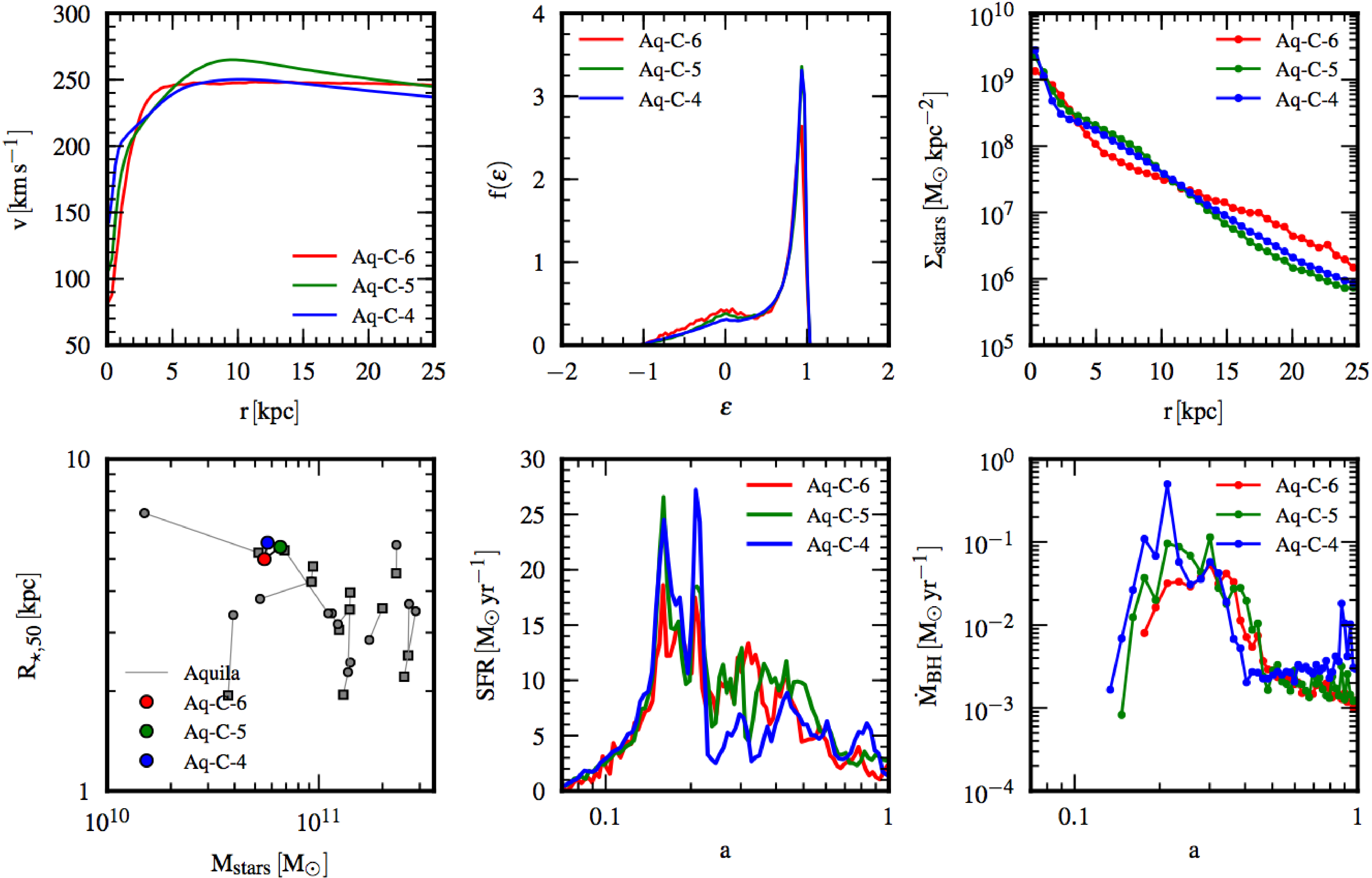
For the first time, simulated disc galaxies match the properties of the Milky Way

VARIOUS PROPERTIES OF THE AQ-C GALAXY



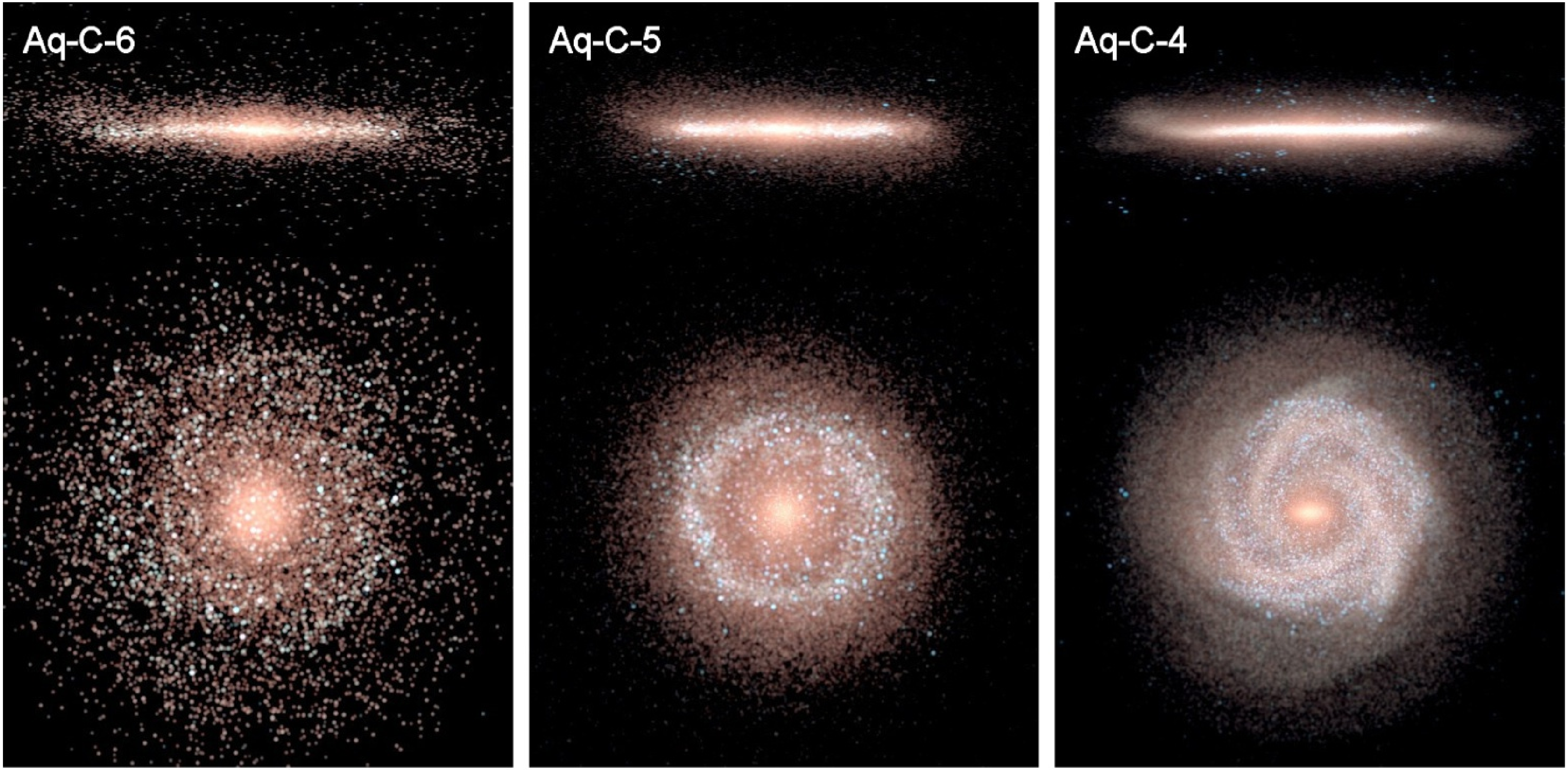
Our modelling of sub-grid physics is numerically well posed and leads to converged results

RESOLUTION COMPARISON OF KEY QUANTITIES FOR RESOLUTION LEVELS AQ-C-4, AQ-5 AND AQ-C-6



The visual galaxy morphology agrees well even for drastic resolution changes

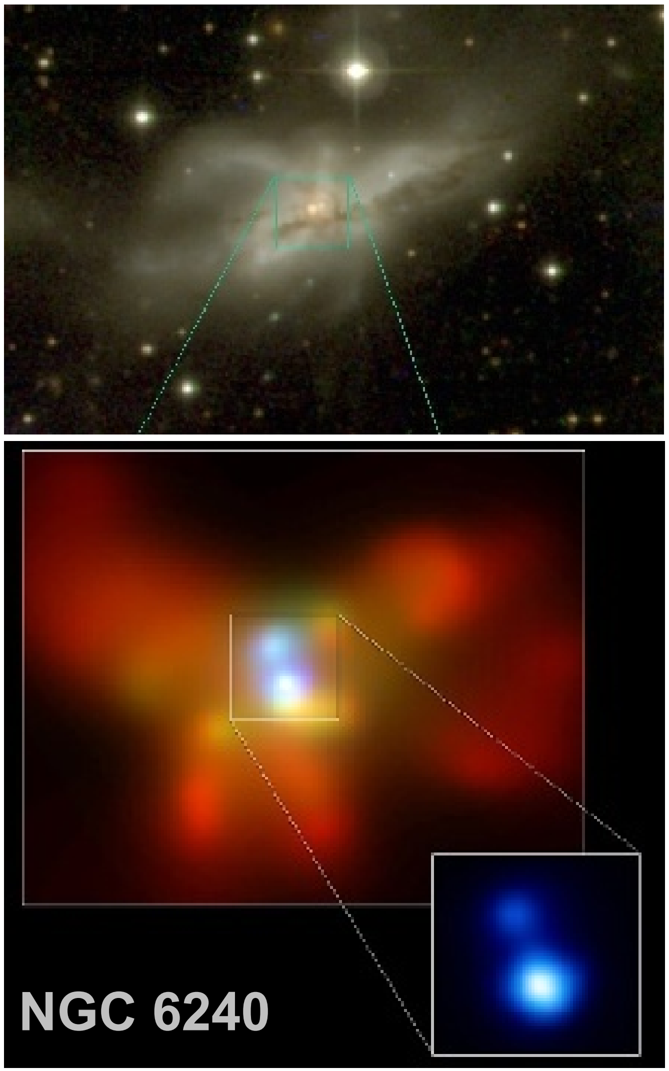
STELLAR DENSITY DISTRIBUTION FOR AQ-C, OVER A RANGE OF 64 IN MASS RESOLUTION



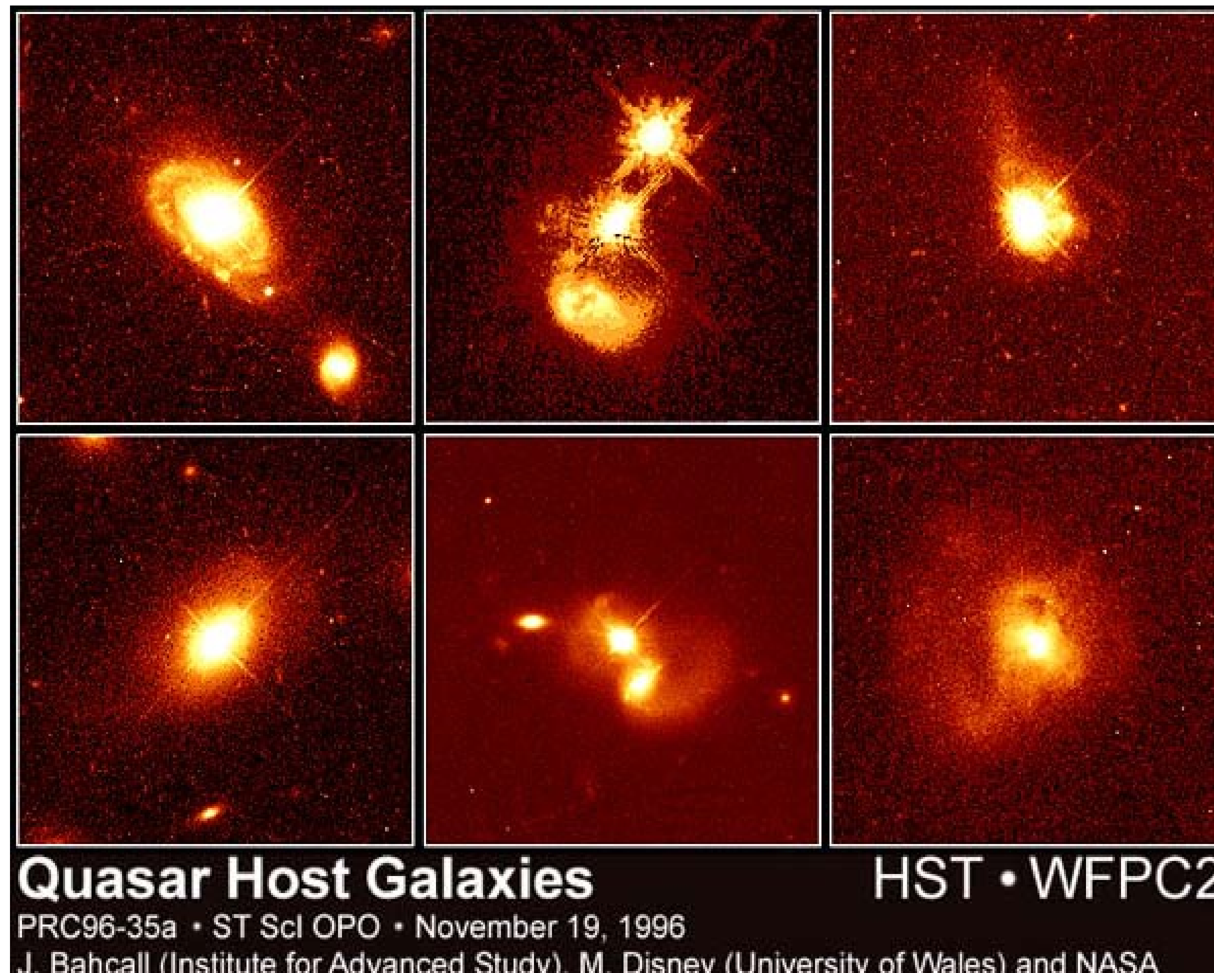
Evidence for quasar feedback?

In certain cases, quasar activity can be clearly linked to interactions and mergers

QUASAR HOSTS WITH MERGER SIGNATURES



Komossa et al. (2003)

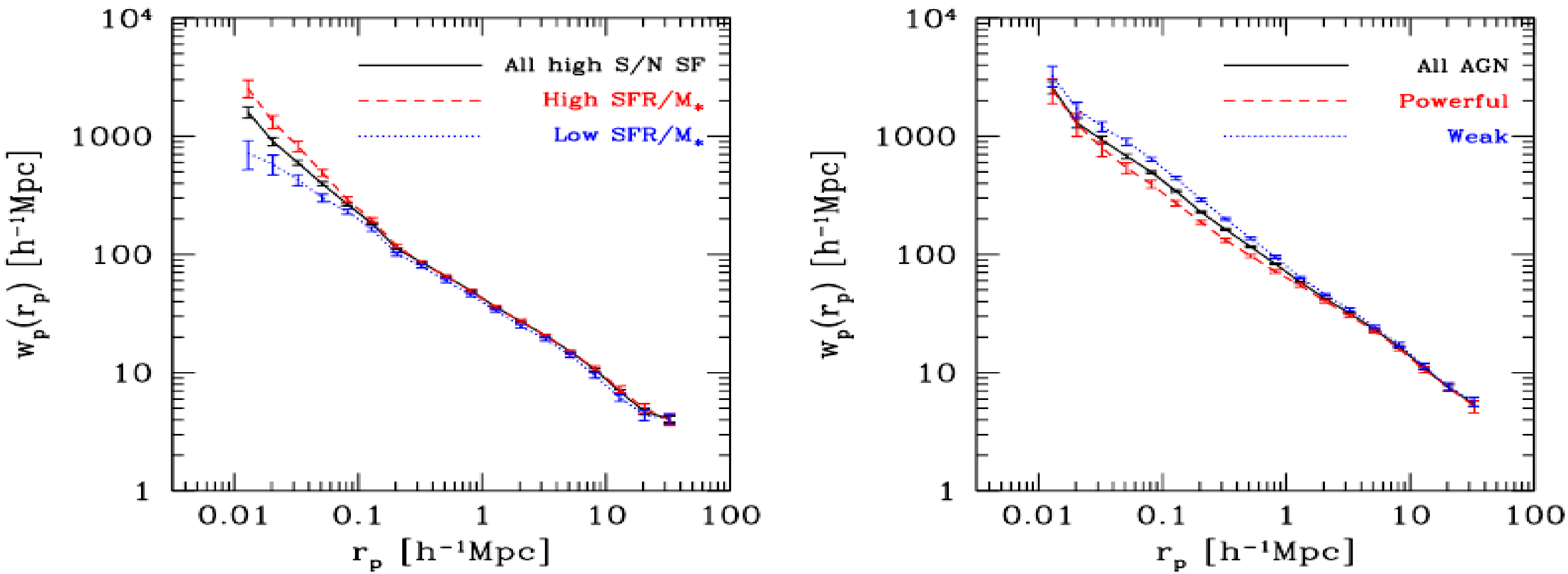


Quasar feedback: Fact or Fiction ?

IT IS NOT REALLY CLEAR WHETHER PRIMARILY MERGERS TRIGGER QUASARS

Li, Kauffmann, Heckman et al. (2008):

Find that close pairs of galaxies have enhanced SFR, but no evidence for increased AGN activity.



But some evidence for enhanced small scale-clustering of optical quasars has been found, e.g. by:

Serber et al. (2006)
Hennawi et al. (2006)

Quasar feedback: Fact or Fiction?

Are quasar outflows observed?

Yes, but unclear how much gas they can take with them.

Ganguly & Brotherton (2007)

- 60% of AGN show evidence for outflows, fairly independent of luminosity

Nesvadba (2009)
Nesvadba et al. (2006, 2007, 2008)

- They identify spatially extended, kpc-scale outflows of ionized gas at solar metallicity corresponding to a significant fraction of the ISM of gas-rich galaxies at z~2 (based on integral-field spectroscopy at the VLT)

Simoes Lopes et al. (2009)
Storchi-Bergmann et al. (2009)

- Conical outflows with ~600 km/s detected in the NLR, e.g. in NGC 4151 and in other Seyferts

Reeves et al. (2009)

- High velocity, clumpy outflow discovered in the high-luminosity quasar PDS 456 (z=0.184) with kinetic luminosity comparable to the bolometric luminosity.

Di Rijcke et al. (2009)

- Large amounts of gas observed outside interacting poststarburst systems

- Would like to have more smoking guns !

Conclusions

Simulations of galaxy formation can self-consistently address the history of nuclear BHs in galaxies.

The case for **AGN radio feedback** looks strong. It is well motivated observationally and theoretically, and provides the only working solution thus far for the bright end of the galaxy LF.

The case for **AGN quasar-mode feedback** is open. It is still primarily a theoretical concept, but one that makes a number of powerful predictions – including clustering predictions.

Self-regulated BH growth models where most of the mass growth happens in major mergers can reproduce a number of important observational facts. They give a quite compelling unified scenario for the joint growth of spheroids and BHs.

Caveat: While some form of quasar feedback is necessary to regulate the BH growth, it is unclear to what extent the quasar can really affect the whole galaxy. As the AGN activity is co-eval with a nuclear starburst, there is a degeneracy between AGN and supernova feedback.