AGN feedback in adaptive mesh refinement cosmological simulations

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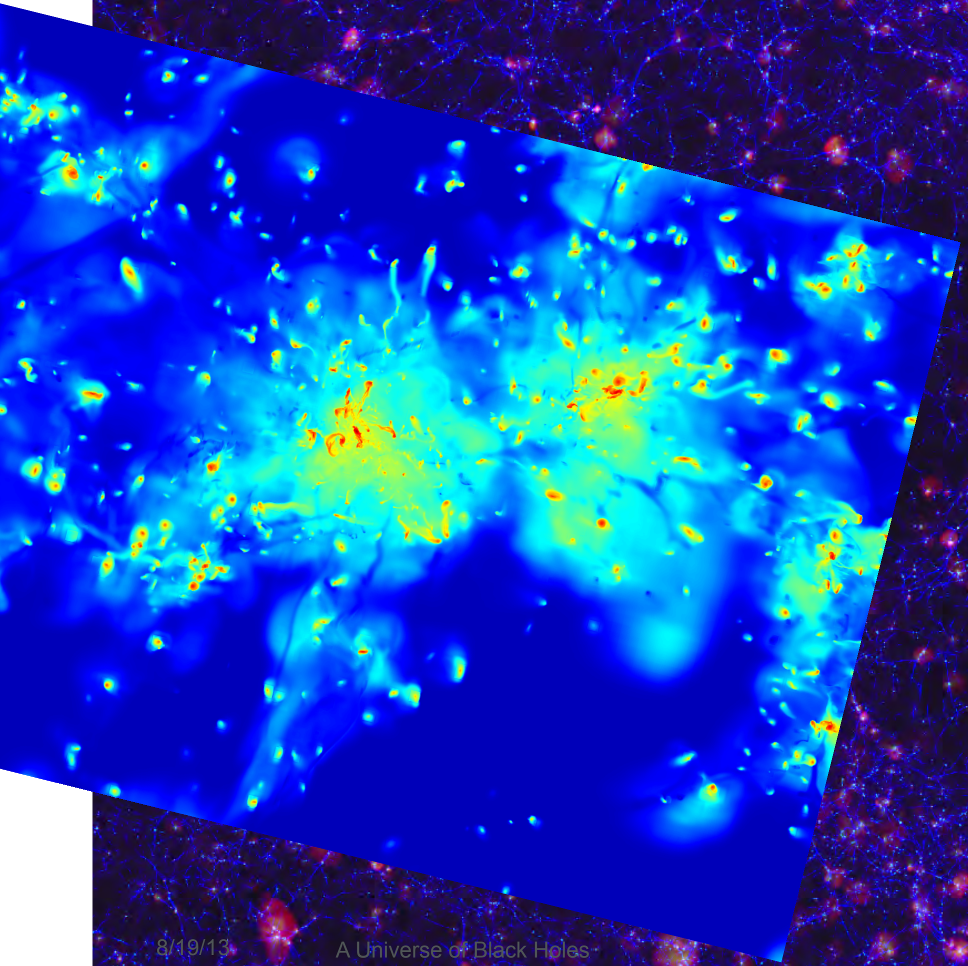
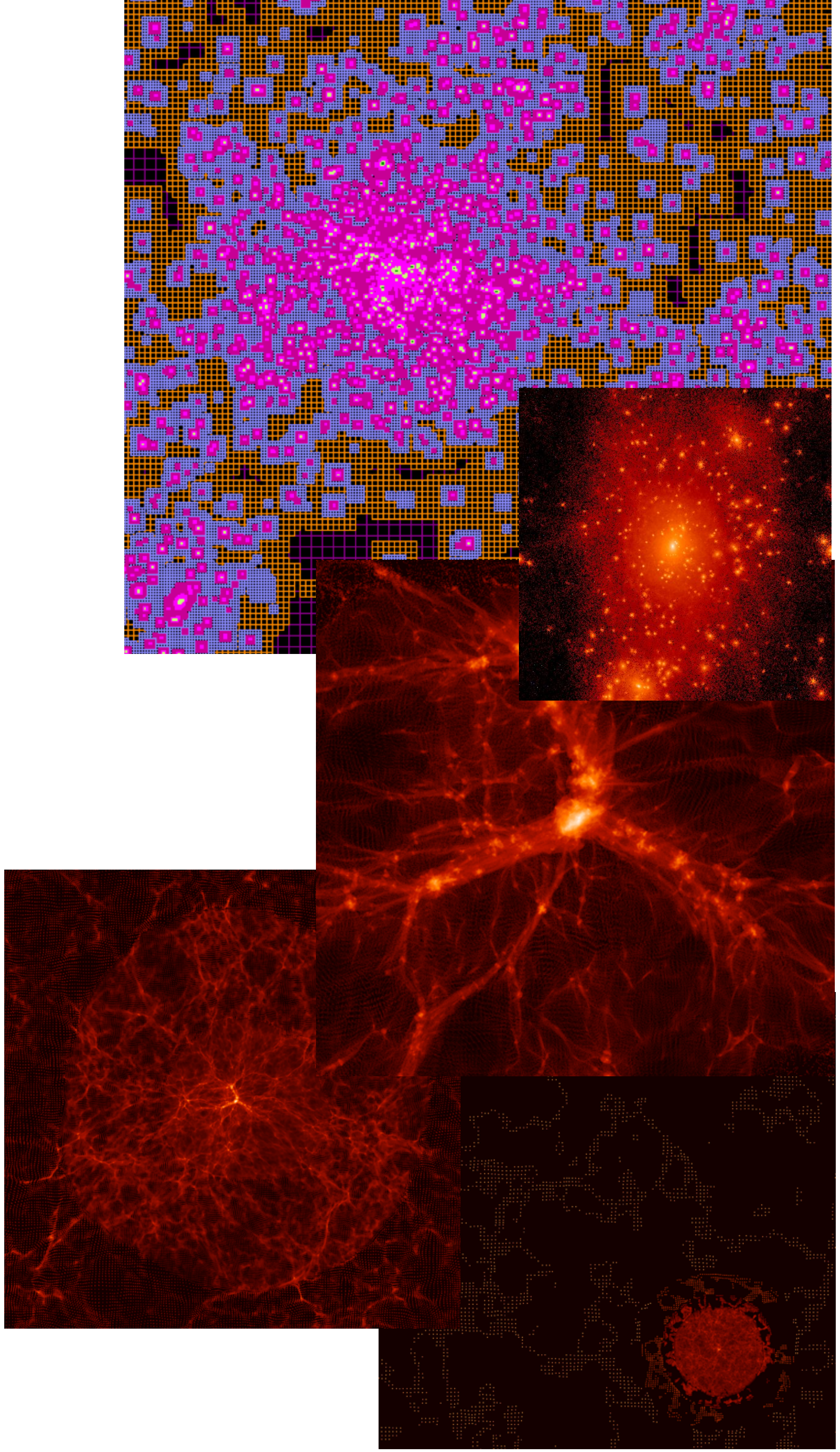


Raphael Gavazzi – IAP
Sébasten Peirani – IAP
Christophe Pichon – IAP
Joseph Silk – IAP
Marta Volonteri – IAP
Julien Devriendt – University of Oxford
Adrianne Slyz – University of Oxford
Romain Teyssier – UTH Zürich
Taysun Kimm – Princeton
Martin Haehnelt – University of Cambridge
Sugata Kaviraj – Imperial College London

RAMSES : an Adaptive Mesh Refinement (AMR) code

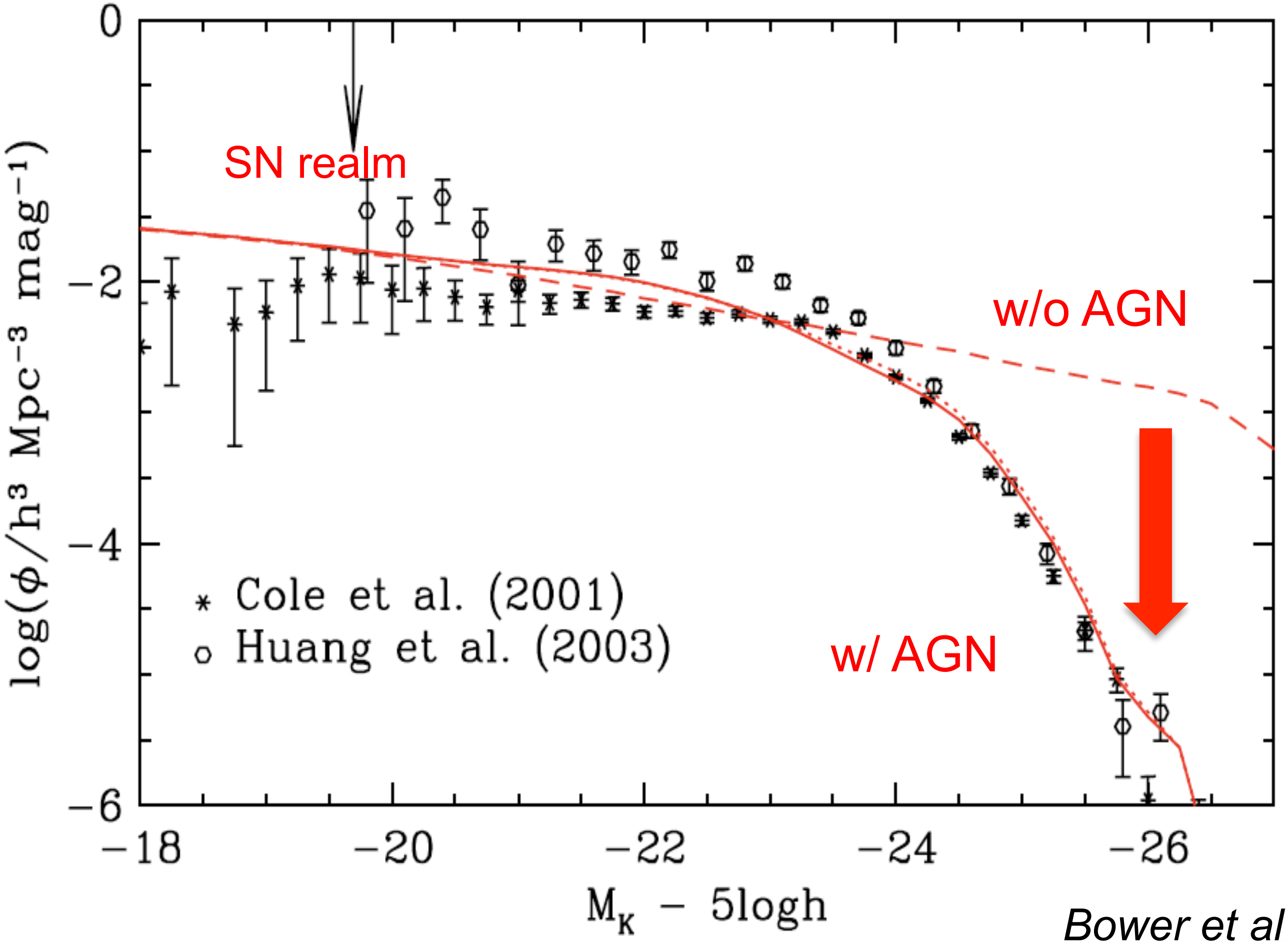
- Language :
  - Fortran 90
  - MPI parallel
- Method : adaptive grid refinement
- Equations :
  - Hydrodynamics
  - Gravity
  - Atomic/Metal cooling + UV-heating
  - (Magneto-hydrodynamics)
  - (Radiative transfer)
- Sub-grid physics :
  - Star formation
  - Supernovae & Stellar Winds
  - Active Galactic Nuclei (AGN)
- Cosmology

See Teyssier, 2002



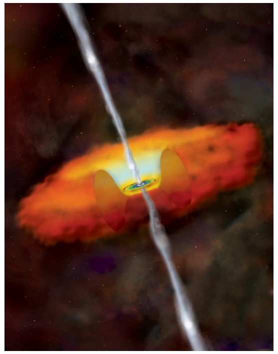
Motivation for AGN feedback

Galaxy luminosity (~mass) function
<u>Semi-analytic</u> models

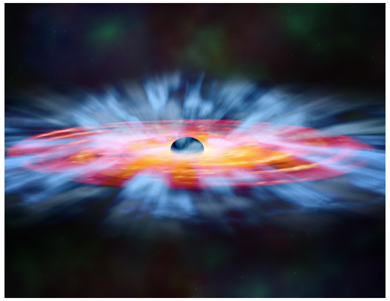


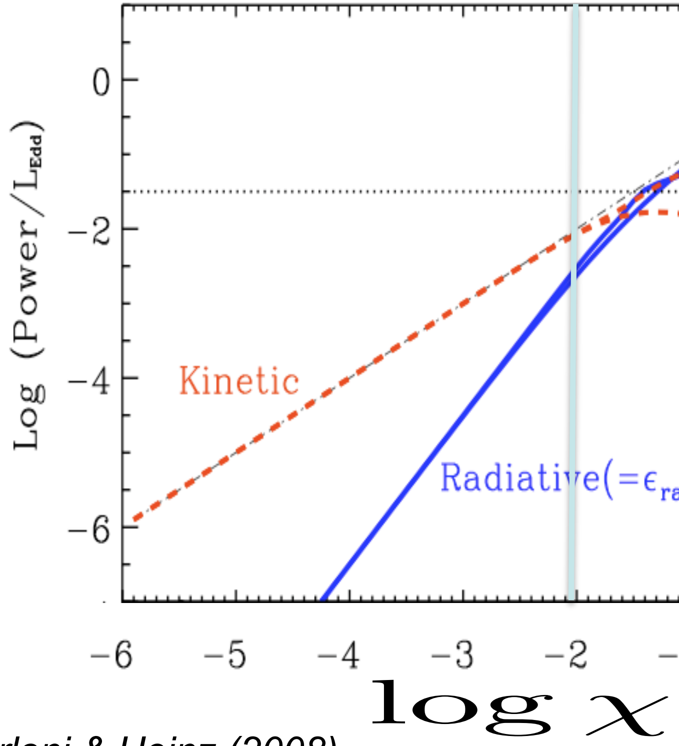
Bower et al., 2006

Two main modes of AGN feedback



or





Merloni & Heinz (2008)

Eddington ratio of the accretion rate

$$\chi = \frac{\dot{M}_{\rm BH}}{\dot{M}_{\rm Edd}}$$

Radio mode (kinetic jet) when

$$\chi \leq 0.01$$

$$\boxed{L_{\rm radio} = 0.1\dot{M}_{\rm BH}c^2}$$

Quasar mode (heating) when

$$\chi > 0.01$$

$$\boxed{L_{\rm quasar} = 0.015\dot{M}_{\rm BH}c^2}$$

Heuristic efficiencies calibrated from cosmological simulations

AGN in cosmological simulations

First AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)

In the centre of galaxies in high gas and stellar-density regions

$$M_{\rm seed} = 10^5\, \mathrm{M}_\odot$$

AGN in cosmological simulations

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- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes

In the centre of galaxies in high gas and stellar-density regions

$$M_{\rm seed} = 10^5\,{\rm M}_\odot$$

Bondi accretion rate

$$\dot{M}_{\rm BH} \propto \rho \frac{M_{\rm BH}^2}{c_{\rm s}^3}$$

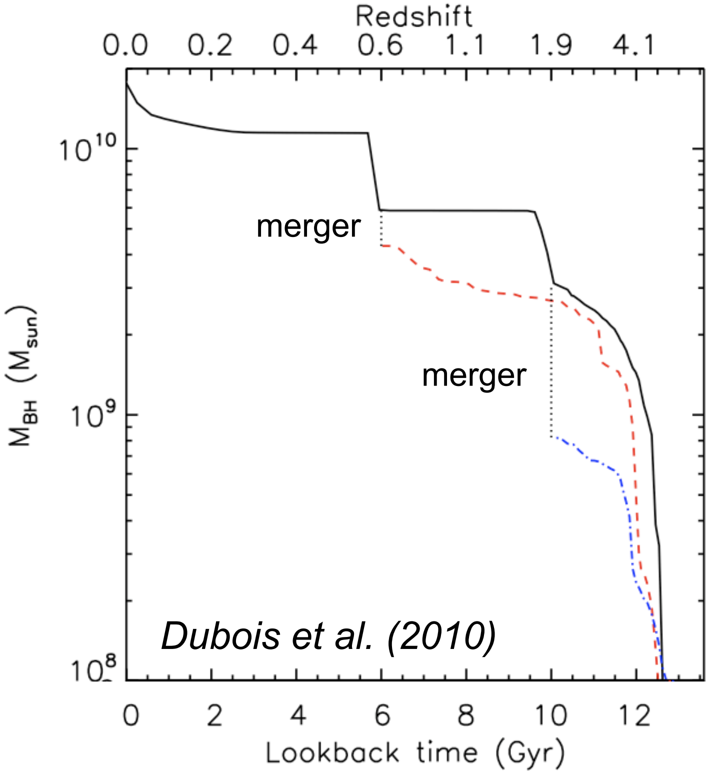
Fast accretion in dense and cold regions

AGN in cosmological simulations

First AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes
- Mimic the mergers between black holes (Friend-of-friend algorithm)

sink particles (Bate et al., 1995, Krumholz et al., 2004)



Dubois et al. (2010)

AGN in cosmological simulations

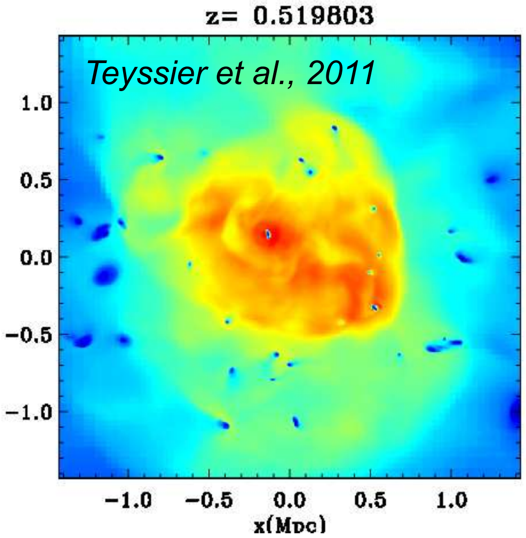
First AMR simulations of self-consistent AGN feedback in a cosmological context

- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes
- Mimic the mergers between black holes (Friend-of-friend algorithm)
- Mimic the feedback from black holes (AGN)

$$L_{\rm AGN} = \epsilon_f \epsilon_r \dot{M}_{\rm BH} c^2$$

High accretion rates
Quasar mode

With thermal input (Teyssier et al., 2011)
(see Di Matteo/Springel/Sijacki et al. papers, and Booth & Schaye papers)



Modification of the internal energy

-> increase the gas temperature

AGN in cosmological simulations

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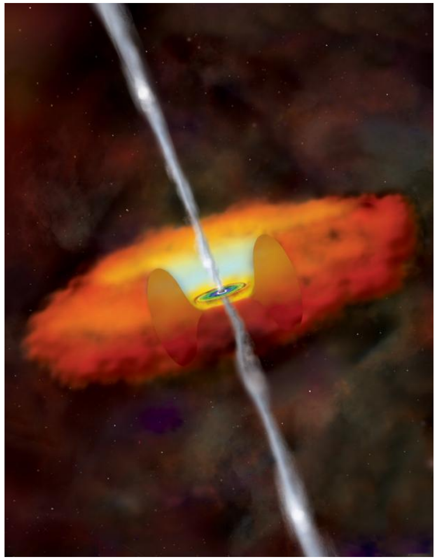
$$L_{\mathrm{AGN}} = \epsilon_f \epsilon_r \dot{M}_{\mathrm{BH}} c^2$$

Low accretion rates
Radio mode

or with jets (Dubois et al., 2010, 2011)



Compute gas angular momentum around the black hole
-> jet axis

Kinetic energy with bipolar outflow

Mass ejected with velocity 10 000 km/s

(jet-model based on Omma et al. 2004)

AGN in cosmological simulations

First AMR simulations of self-consistent AGN feedback in a cosmological context

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High accretion rates	With thermal input (Teyssier et al., 2011)
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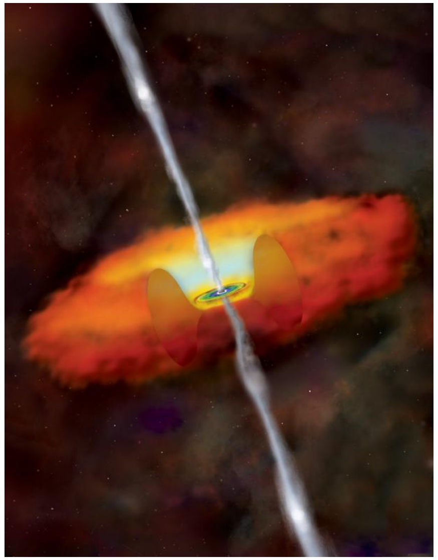
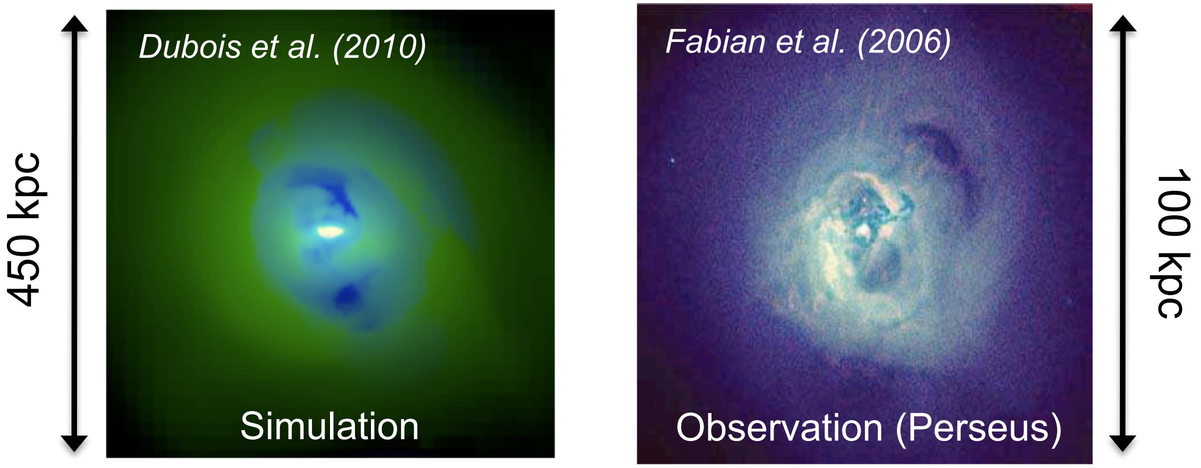




X-ray (3 bands)

$L_{\rm box} = 12.5\,{\rm Mpc/h}$

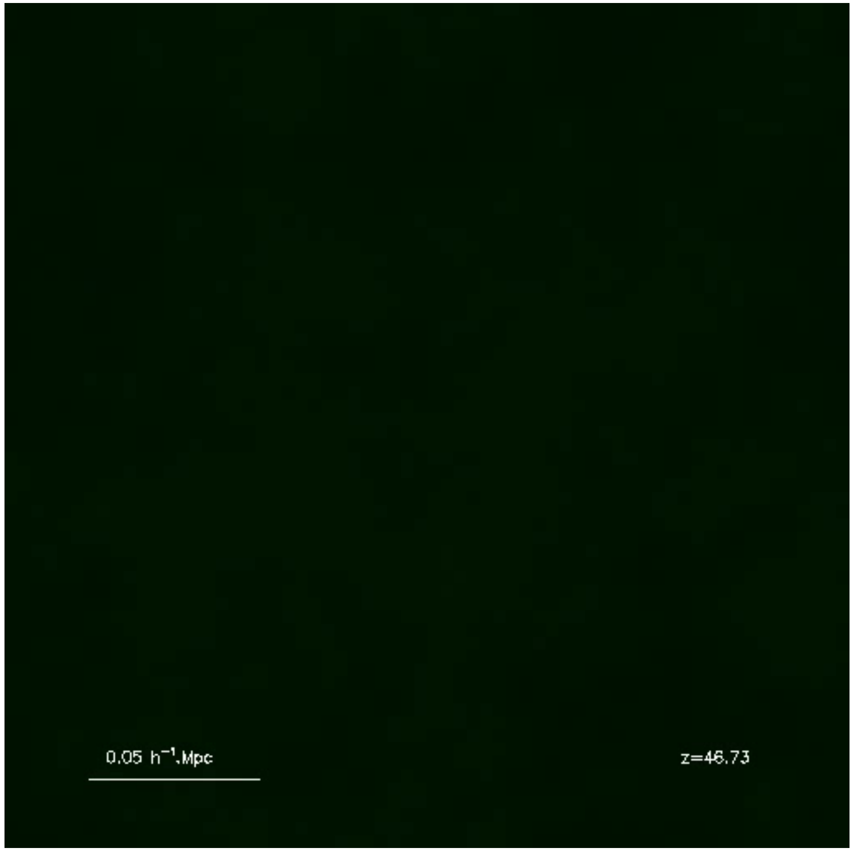
$\Delta x_{\rm min} = 0.38\,{\rm kpc/h}$

WMAP 5-year cosmology

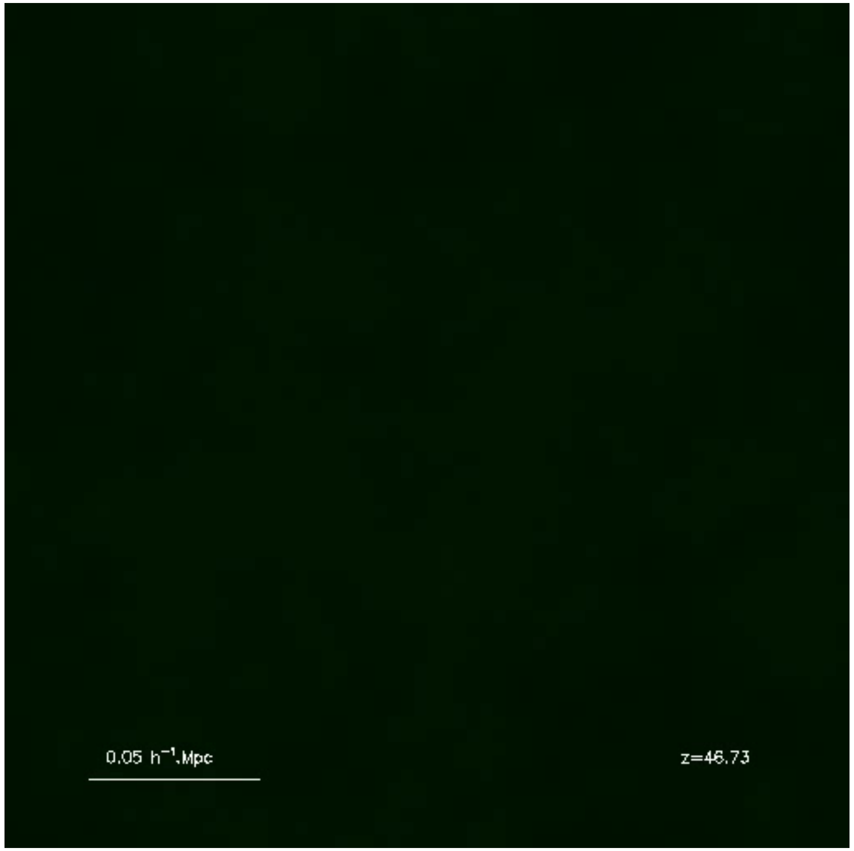
17.10^6 DM particles

$M_{\rm DM} = 6.9\,10^6\,{\rm M_\odot/h}$

Red = gas temperature / Green = gas density / Blue = gas metallicity



No AGN



AGN

Testing the model: parameters and resolution

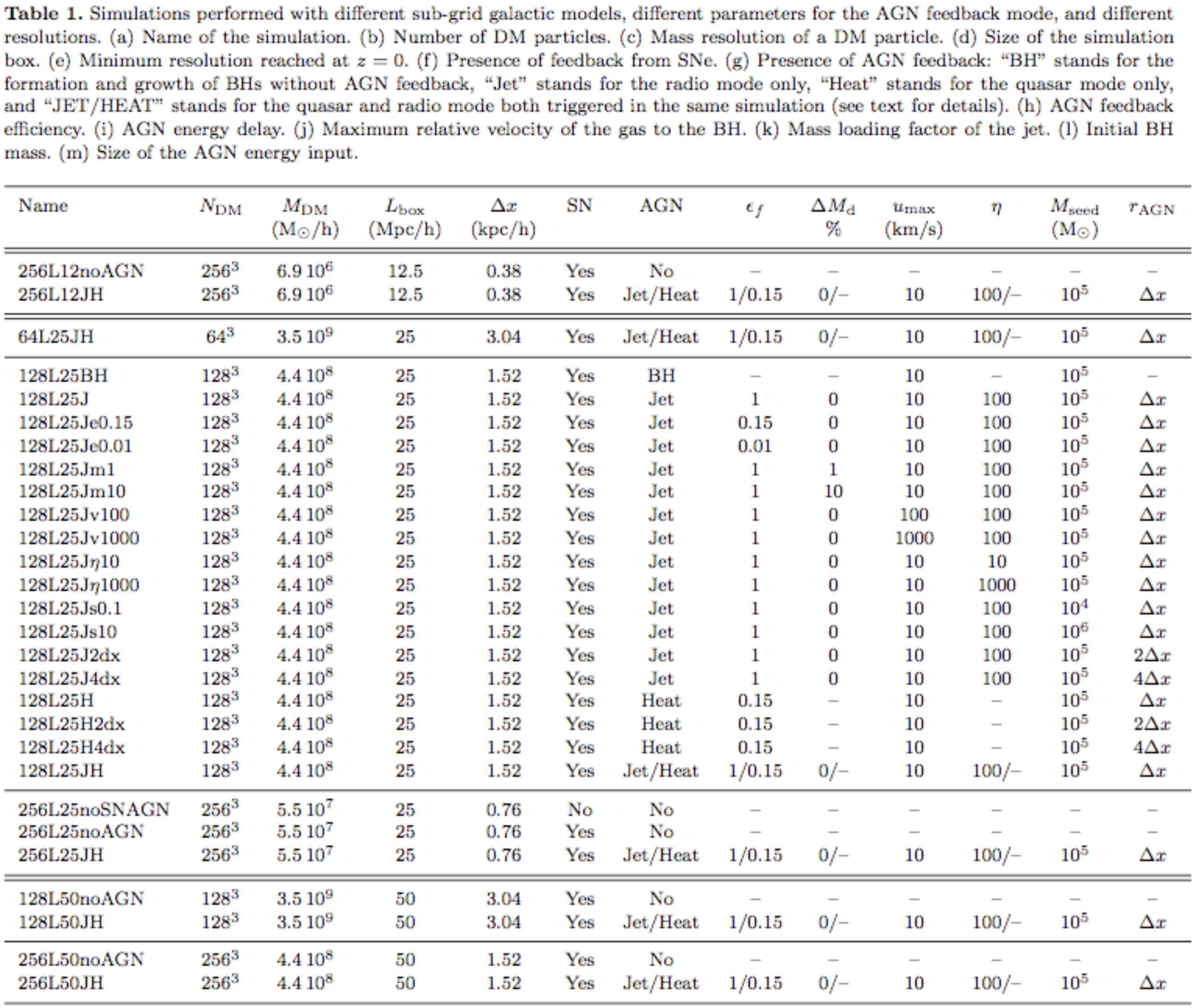
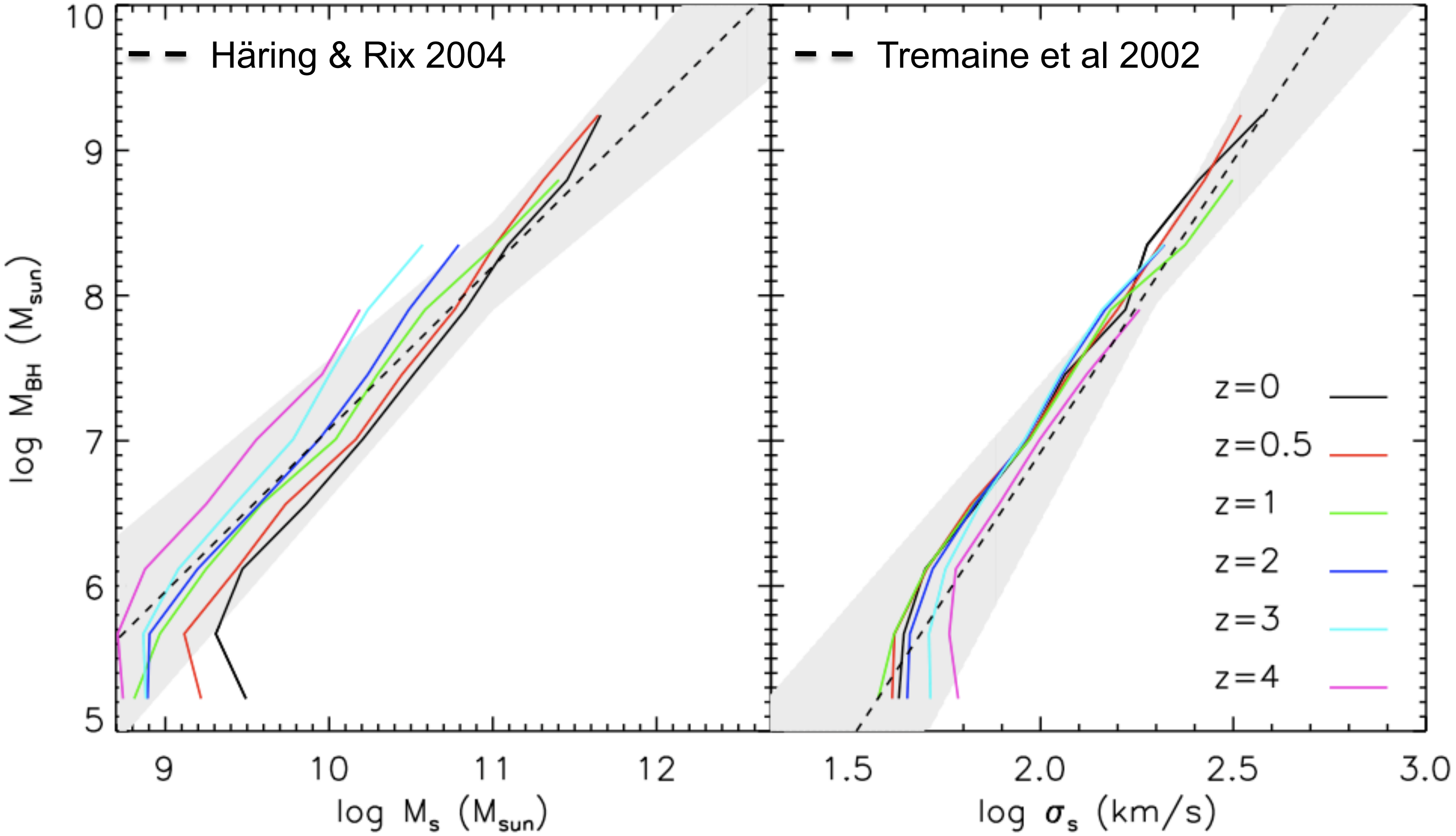


Table 1. Simulations performed with different sub-grid galactic models, different parameters for the AGN feedback mode, and different resolutions. (a) Name of the simulation. (b) Number of DM particles. (c) Mass resolution of a DM particle. (d) Size of the simulation box. (e) Minimum resolution reached at $z = 0$. (f) Presence of feedback from SNe. (g) Presence of AGN feedback: "BH" stands for the formation and growth of BHs without AGN feedback, "Jet" stands for the radio mode only, "Heat" stands for the quasar mode only, and "JET/HEAT" stands for the quasar and radio mode both triggered in the same simulation (see text for details). (h) AGN feedback efficiency. (i) AGN energy delay. (j) Maximum relative velocity of the gas to the BH. (k) Mass loading factor of the jet. (l) Initial BH mass. (m) Size of the AGN energy input.

Name	$N_{\rm DM}$	$M_{\rm DM}$ (M$_\odot$/h)	$L_{\rm box}$ (Mpc/h)	Δx (kpc/h)	SN	AGN	ϵ_f	$\Delta M_{\rm d}$ %	$u_{\rm max}$ (km/s)	η	$M_{\rm seed}$ (M$_\odot$)	$r_{\rm AGN}$
256L12noAGN	256^3	$6.9\,10^6$	12.5	0.38	Yes	No	–	–	–	–	–	–
256L12JH	256^3	$6.9\,10^6$	12.5	0.38	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
64L25JH	64^3	$3.5\,10^9$	25	3.04	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
128L25BH	128^3	$4.4\,10^8$	25	1.52	Yes	BH	–	–	10	–	10^5	–
128L25J	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^5	Δx
128L25Je0.15	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	0.15	0	10	100	10^5	Δx
128L25Je0.01	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	0.01	0	10	100	10^5	Δx
128L25Jm1	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	1	10	100	10^5	Δx
128L25Jm10	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	10	10	100	10^5	Δx
128L25Jv100	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	100	100	10^5	Δx
128L25Jv1000	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	1000	100	10^5	Δx
128L25Jη10	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	10	10^5	Δx
128L25Jη1000	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	1000	10^5	Δx
128L25Js0.1	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^4	Δx
128L25Js10	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^6	Δx
128L25J2dx	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^5	$2\Delta x$
128L25J4dx	128^3	$4.4\,10^8$	25	1.52	Yes	Jet	1	0	10	100	10^5	$4\Delta x$
128L25H	128^3	$4.4\,10^8$	25	1.52	Yes	Heat	0.15	–	10	–	10^5	Δx
128L25H2dx	128^3	$4.4\,10^8$	25	1.52	Yes	Heat	0.15	–	10	–	10^5	$2\Delta x$
128L25H4dx	128^3	$4.4\,10^8$	25	1.52	Yes	Heat	0.15	–	10	–	10^5	$4\Delta x$
128L25JH	128^3	$4.4\,10^8$	25	1.52	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
256L25noSNAGN	256^3	$5.5\,10^7$	25	0.76	No	No	–	–	–	–	–	–
256L25noAGN	256^3	$5.5\,10^7$	25	0.76	Yes	No	–	–	–	–	–	–
256L25JH	256^3	$5.5\,10^7$	25	0.76	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
128L50noAGN	128^3	$3.5\,10^9$	50	3.04	Yes	No	–	–	–	–	–	–
128L50JH	128^3	$3.5\,10^9$	50	3.04	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx
256L50noAGN	256^3	$4.4\,10^8$	50	1.52	Yes	No	–	–	–	–	–	–
256L50JH	256^3	$4.4\,10^8$	50	1.52	Yes	Jet/Heat	1/0.15	0/–	10	100/–	10^5	Δx

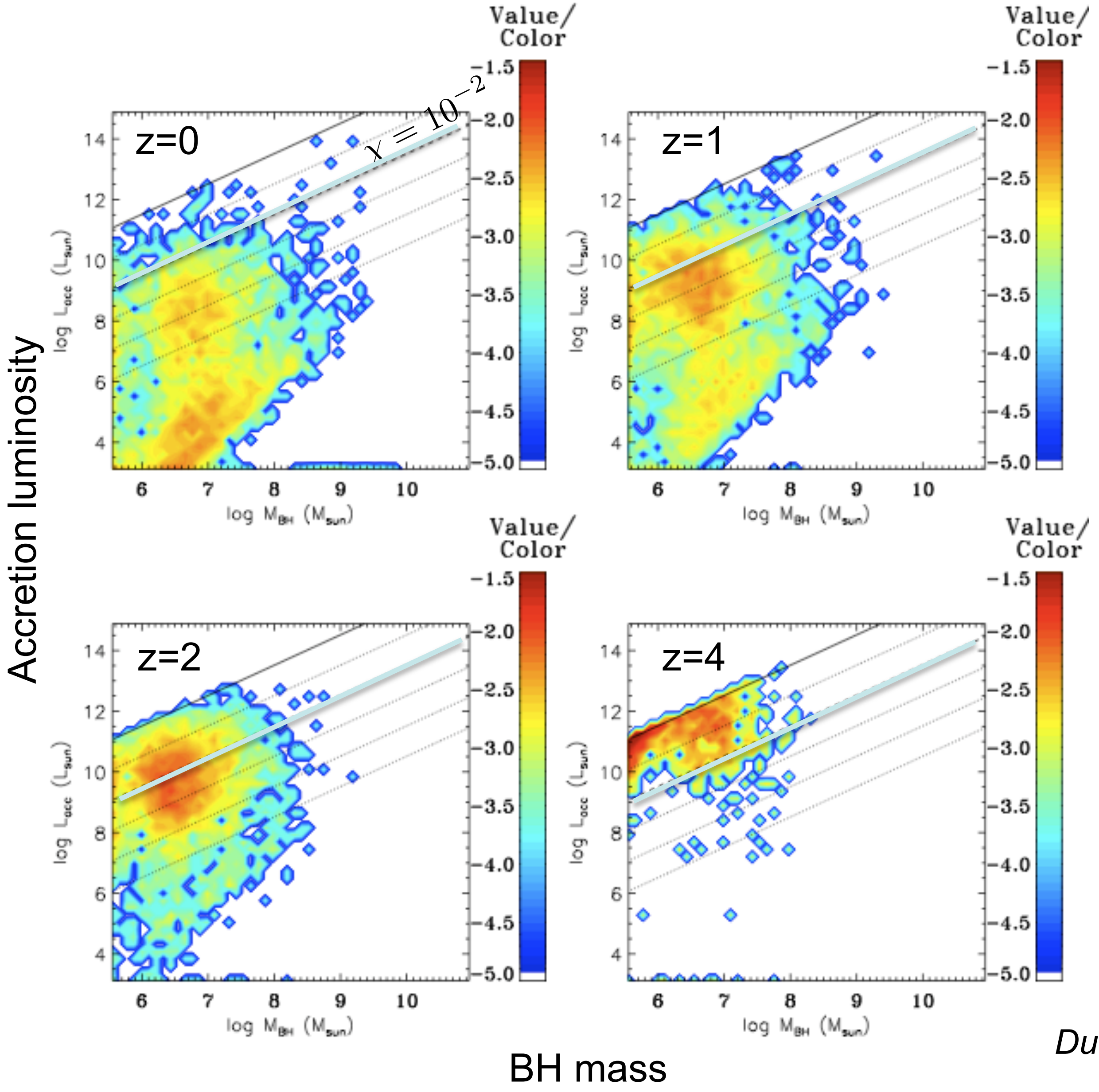
Dubois, Devriendt, Slyz, Teyssier, 2012

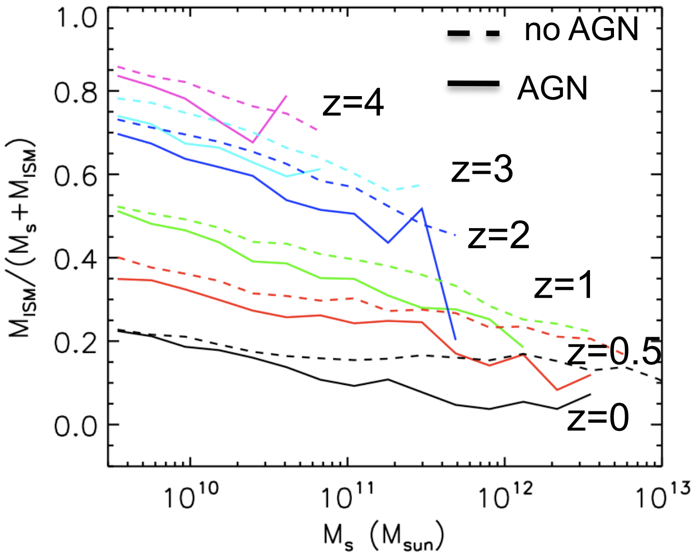
Fitting observationnal M_{BH}-M_* / M_{BH}-σ_* laws



Dubois, Devriendt, Slyz, Teyssier, 2012

Radio mode or quasar mode ?

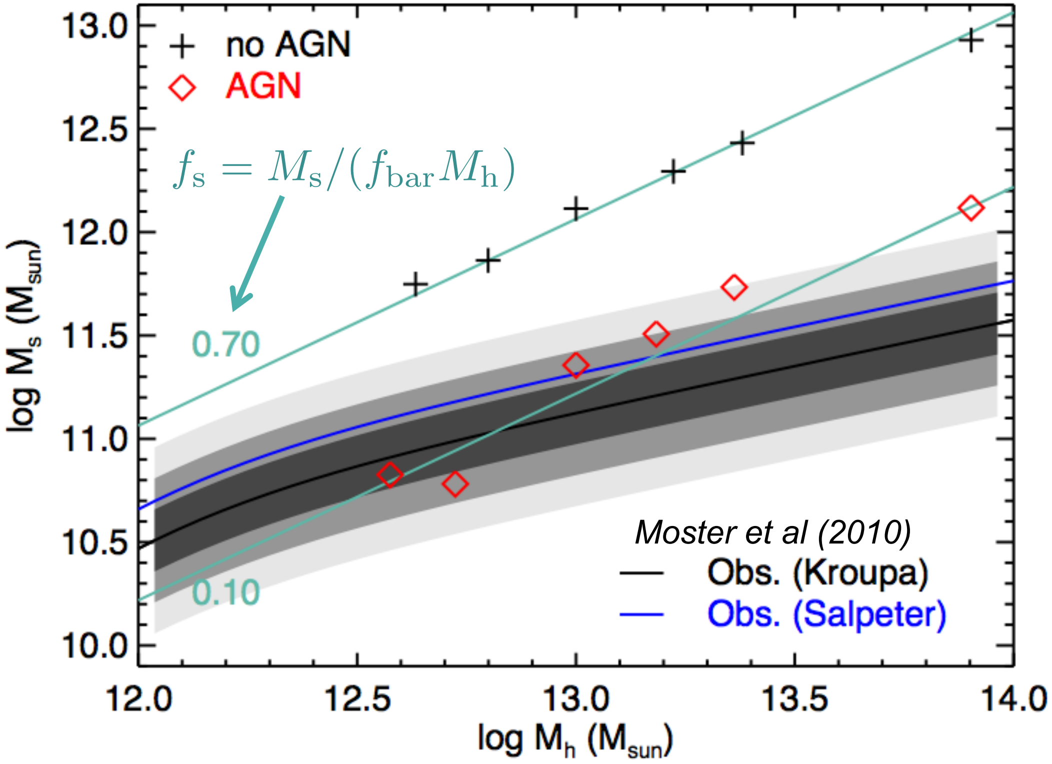


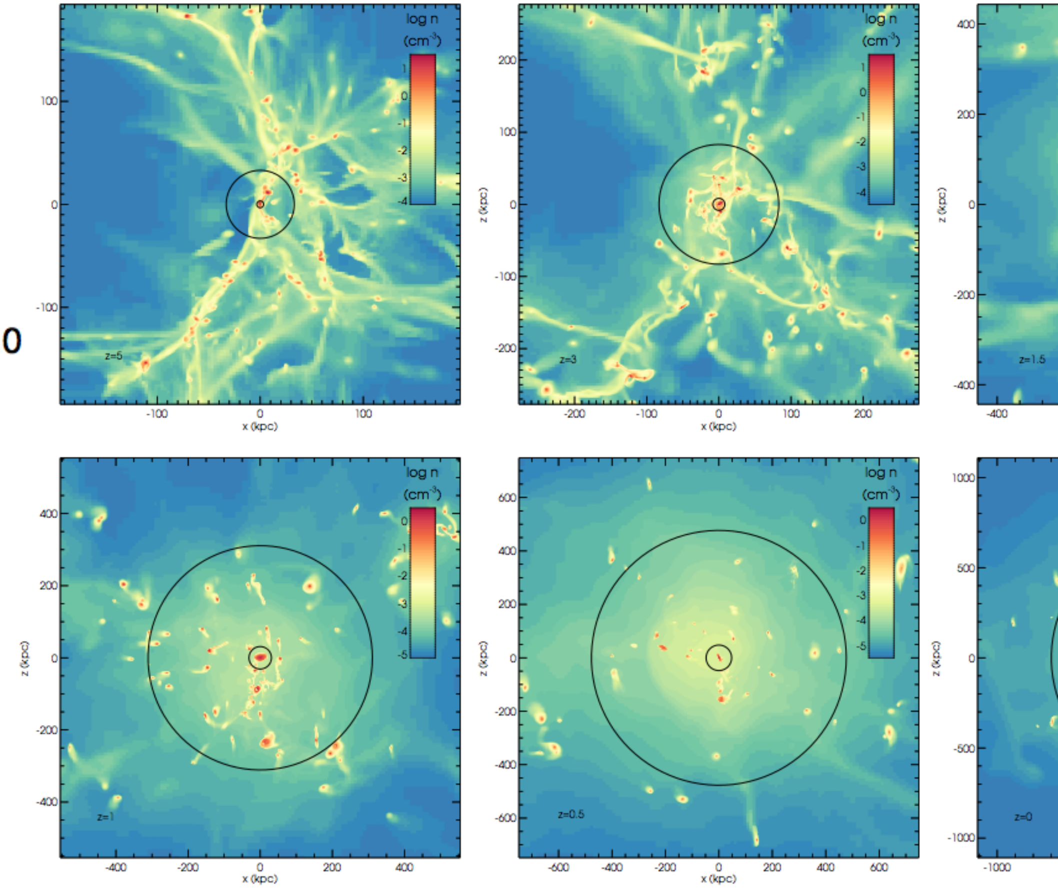


Galaxies are gas-rich at high-redshift
Star formation and feedback removes
cold gas efficiently

Dubois, Devriendt, Slyz, Teyssier, 2012

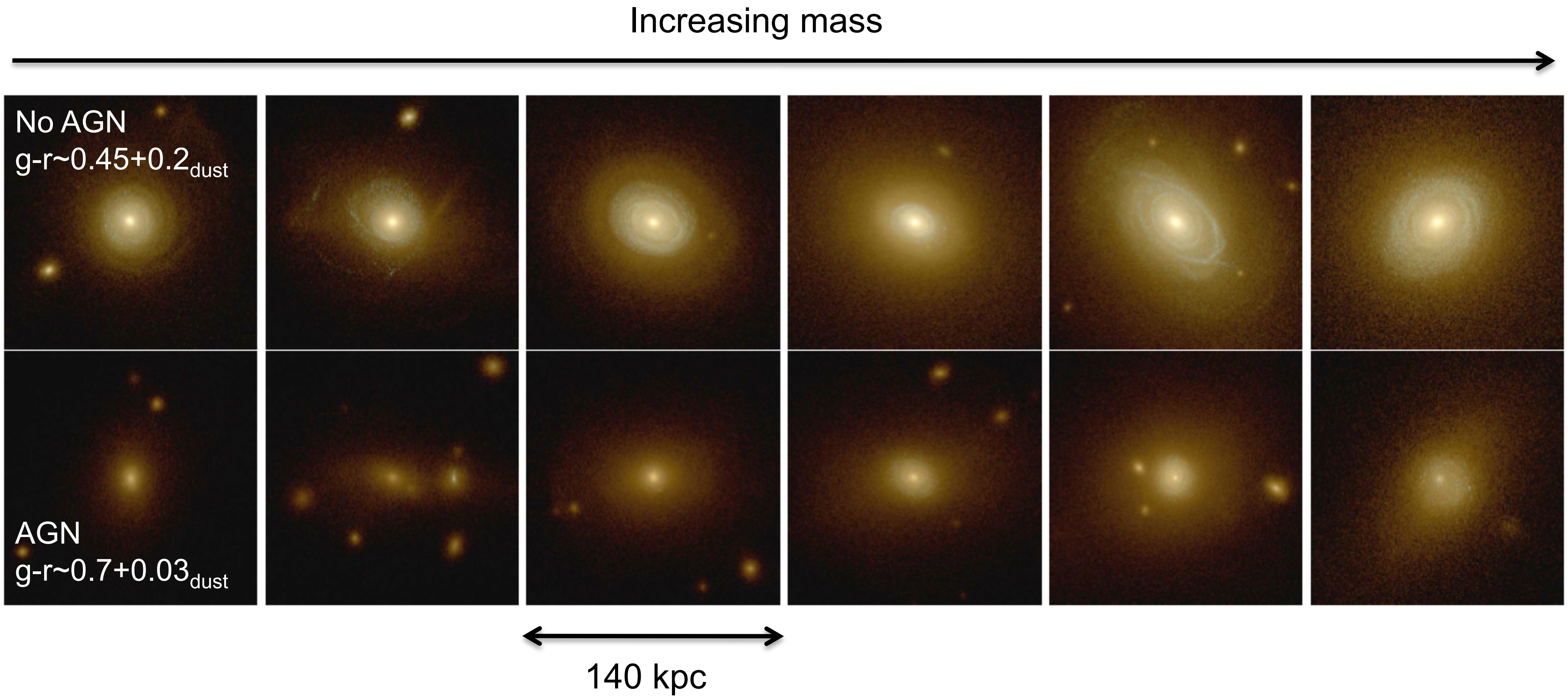
Stellar mass in central massive galaxies





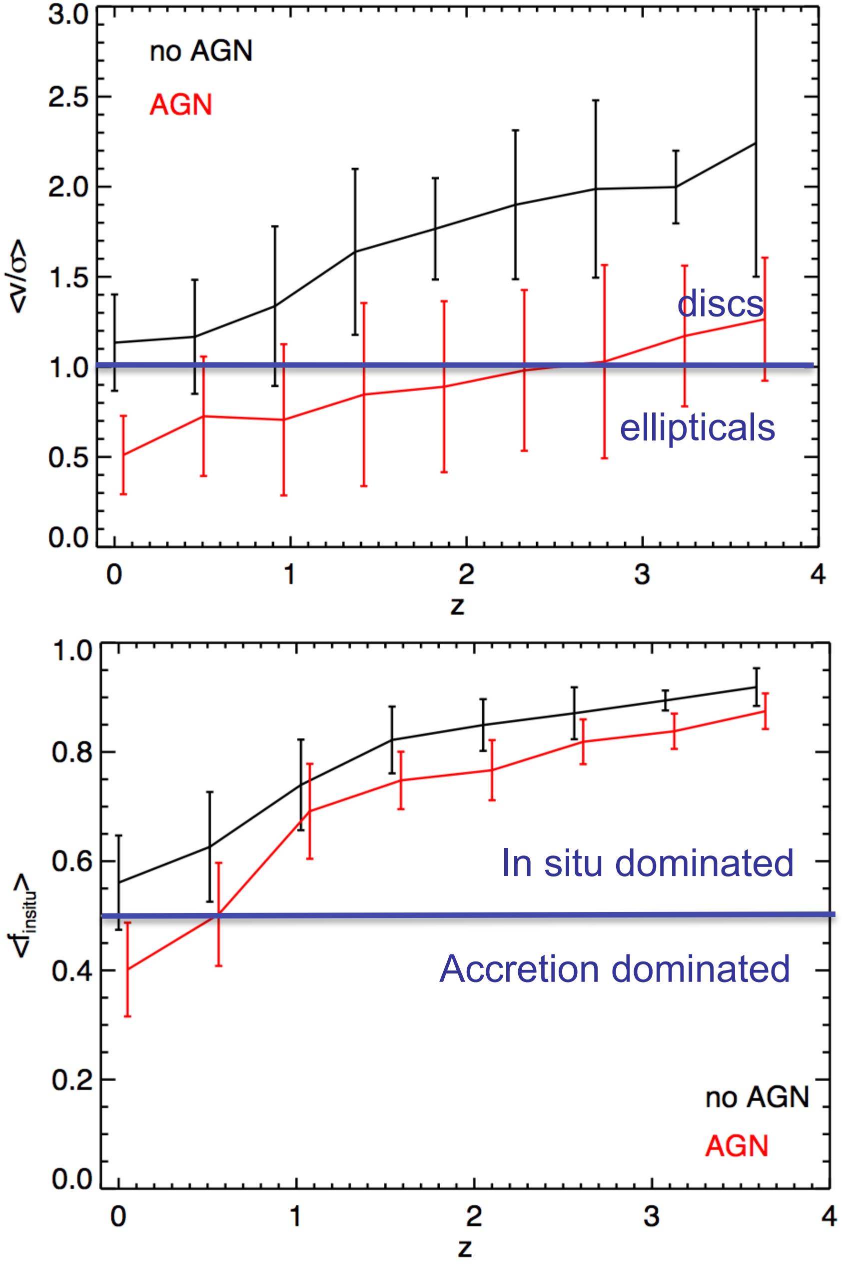
Dubois, Gavazzi, Peirani, Silk, 2013

Can we get massive galaxies that look like ellipticals ?

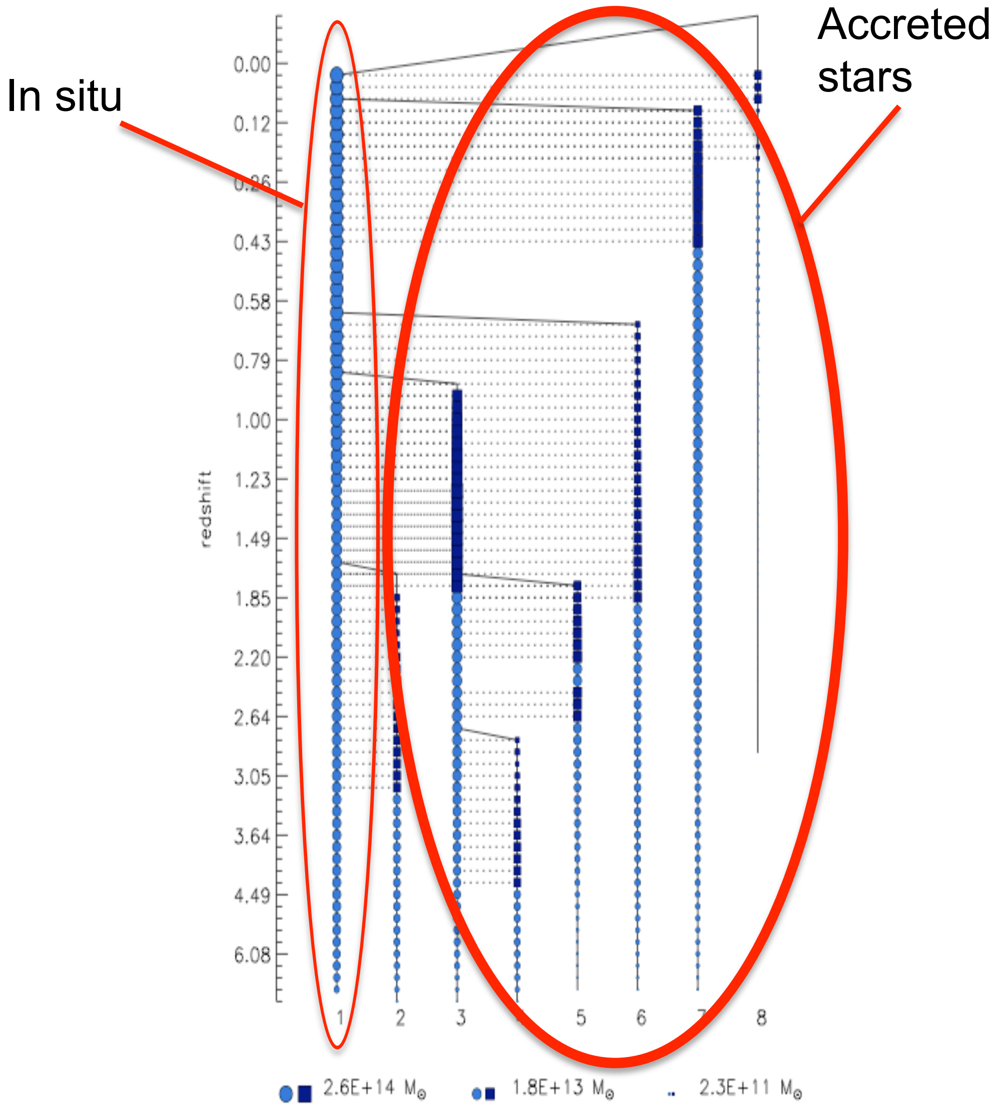


Dubois, Gavazzi, Peirani, Silk, 2013

Are they in rotation or supported by velocity dispersion ?

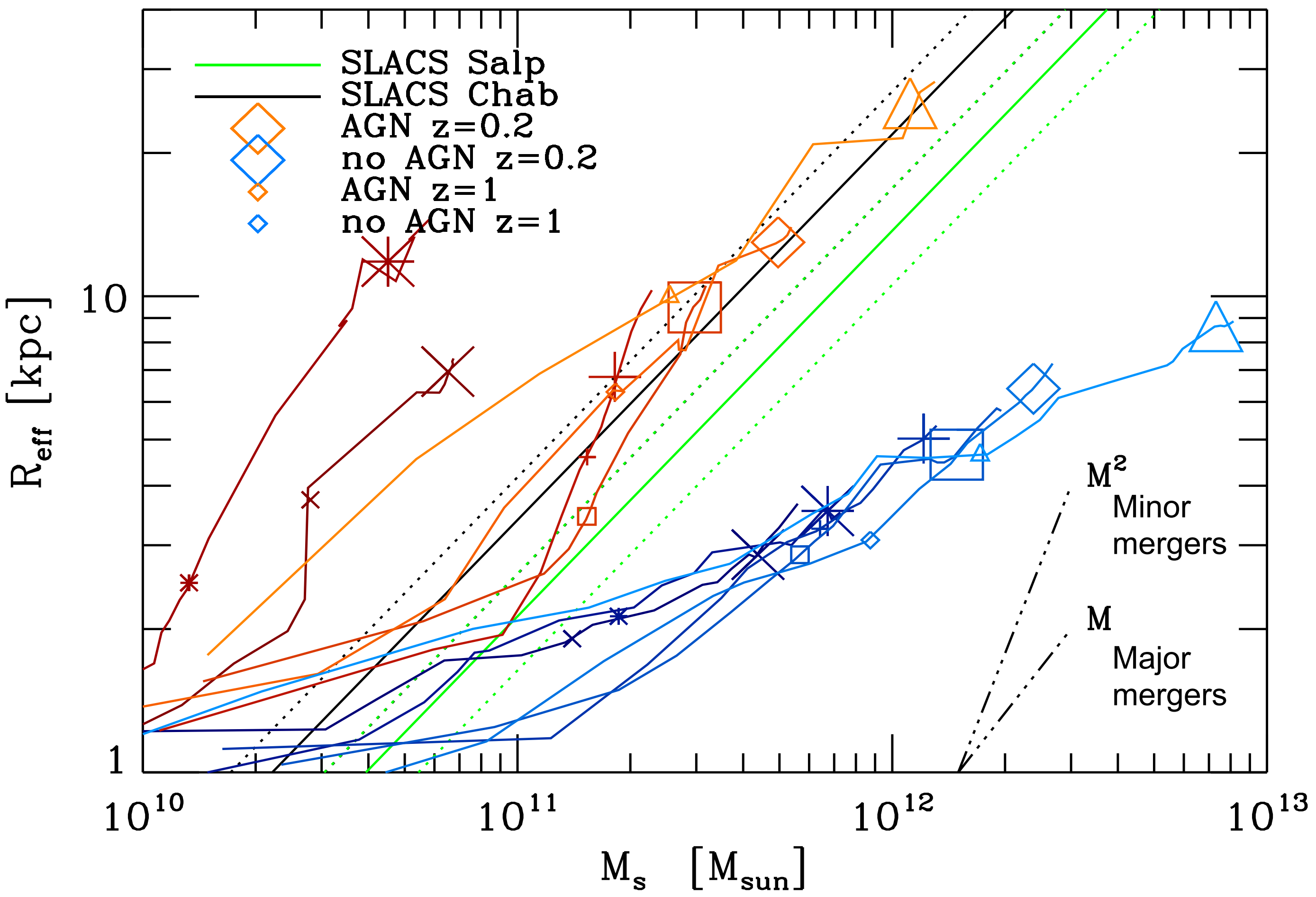


Merger tree
(Tweed et al. 2009)



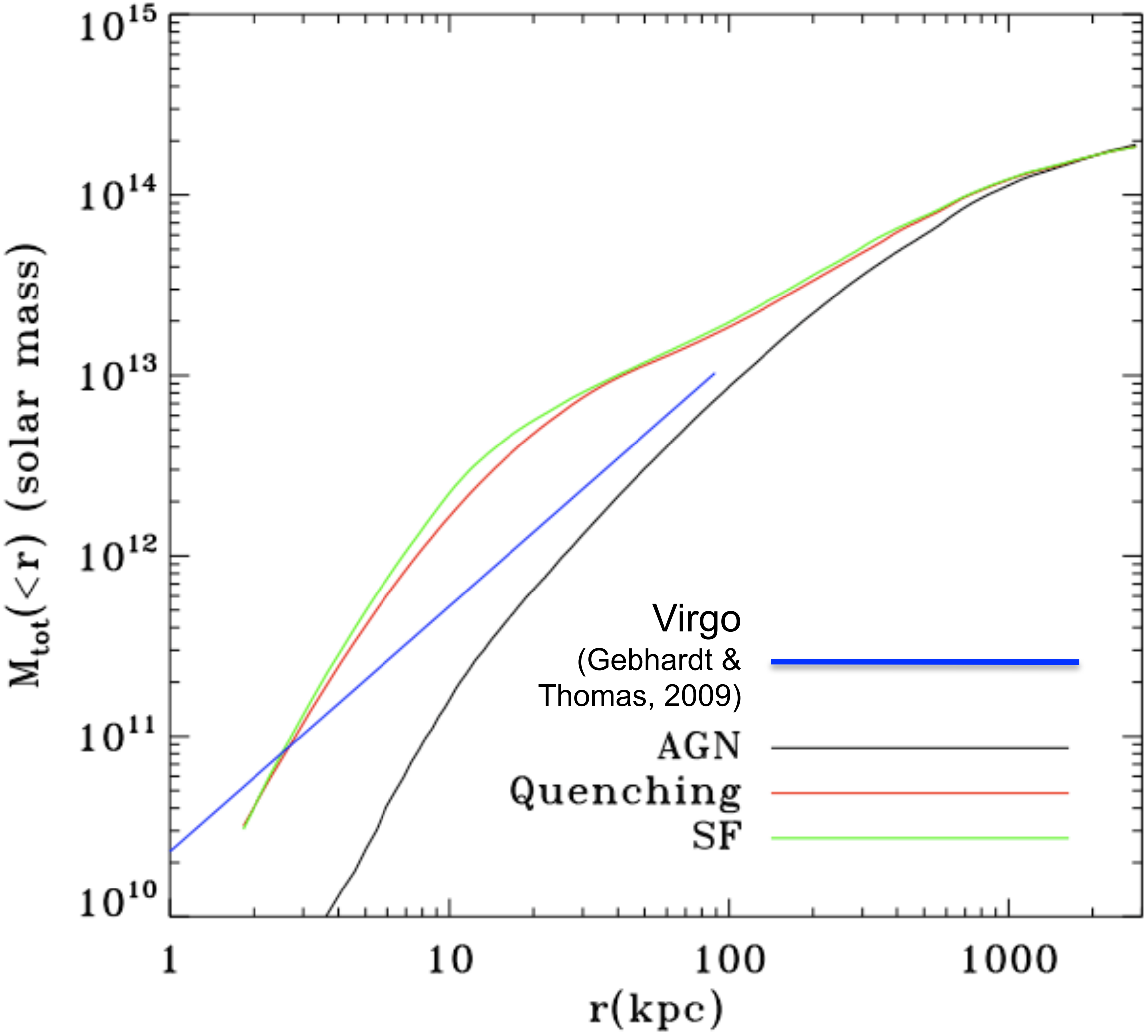
Dubois, Gavazzi, Peirani, Silk, 2013

Changing the compactness of massive galaxies



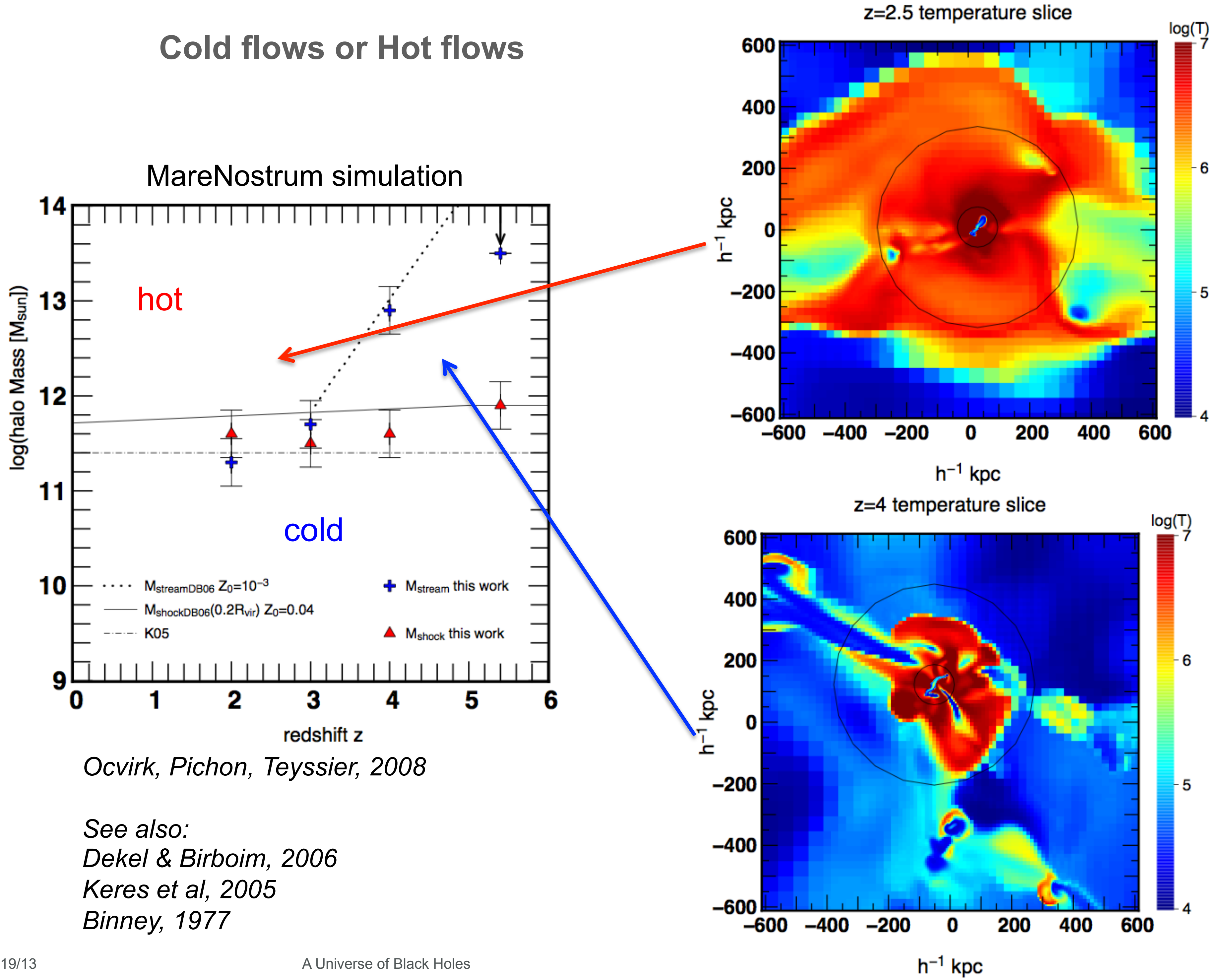
Dubois, Gavazzi, Peirani, Silk, 2013

Mass distribution in a Virgo-like cluster



Teyssier et al., 2011
(see also Dubois et al, 2010, Martizzi et al, 2012)

Cold flows or Hot flows



Ocvirk, Pichon, Teyssier, 2008

See also:
Dekel & Birboim, 2006
Keres et al, 2005
Binney, 1977

Growing the first bright quasars

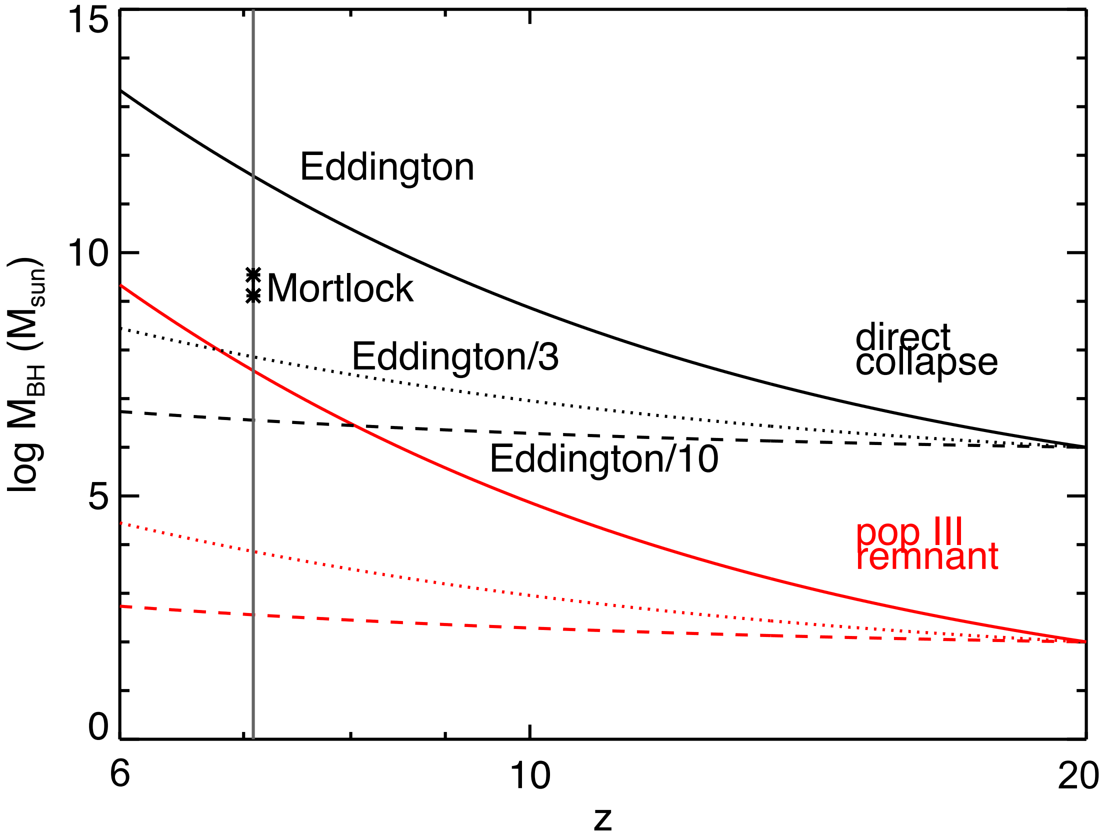
Observationnal facts:

- Very bright quasars in the SDSS with z>6 (Willott et al., 2003; Fan et al., 2006; Jiang et al., 2009)
- Detection of a 2.10^9 M$_{sun}$ BH at z=7 (Mortlock et al., 2011)

Requirement:

- Need to grow from 10^5-10^6 M$_{sun}$ up to 10^9 M$_{sun}$ in less than 700 Myrs !

Eddington limit provides an e-folding time = 45 Myr



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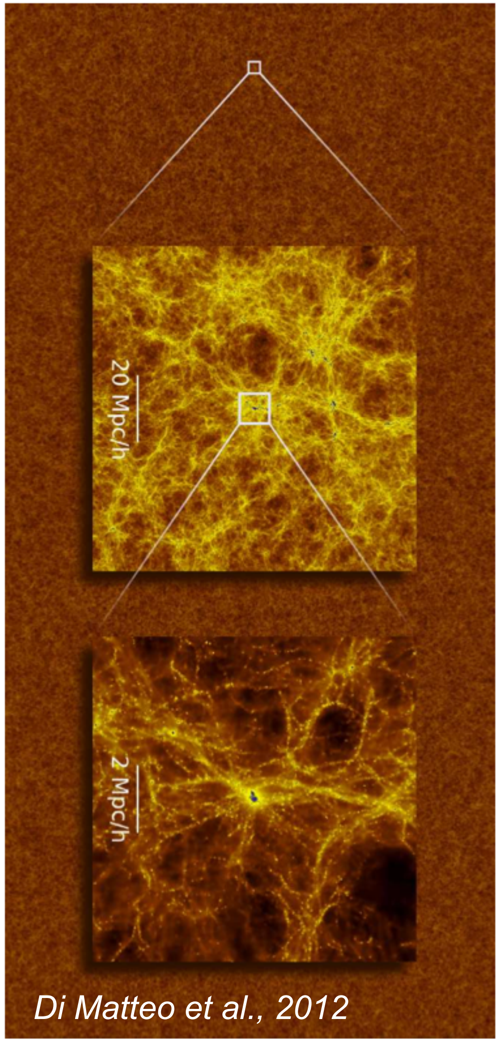

Di Matteo et al., 2012

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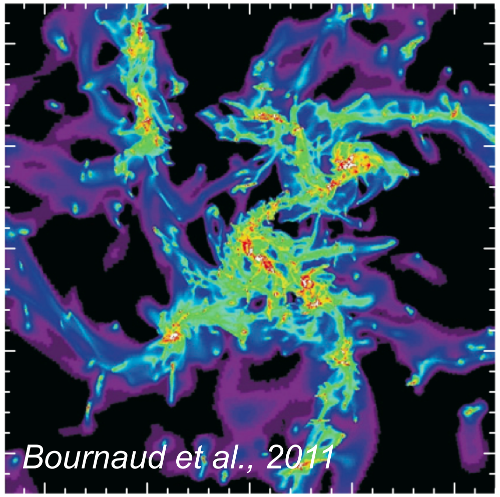
Question:

- How to bring gas sufficiently rapidly into the bulge of the galaxy ?



Bournaud et al., 2011

- Direct accretion from the cosmic cold flows (Di Matteo et al., 2012)

Cosmological context with large statistics but low resolution (~1kpc)

Versus

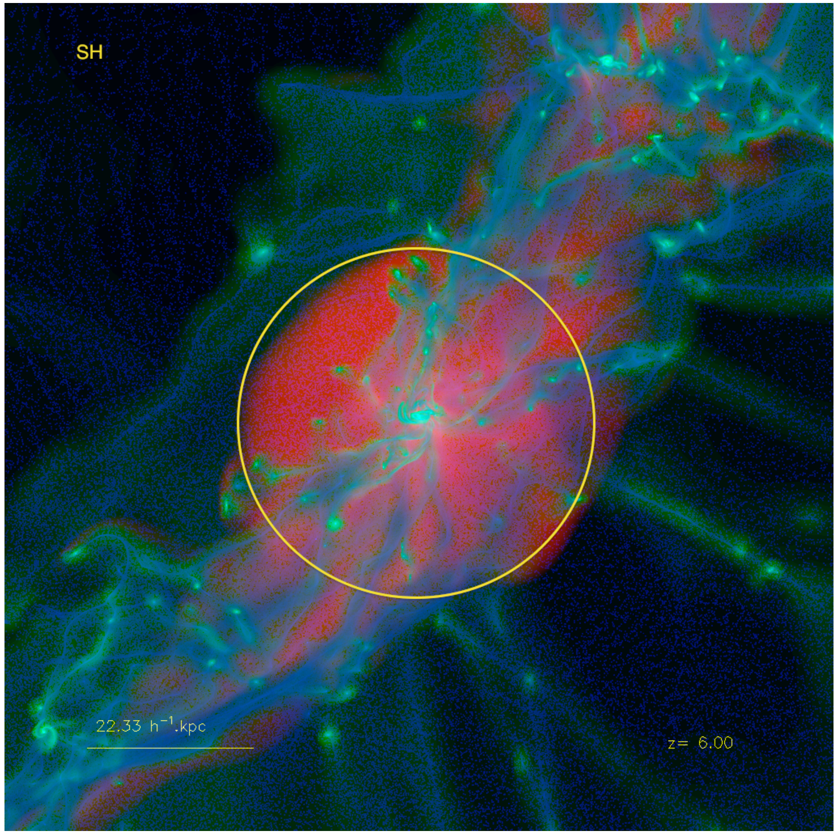
- Violent disc instabilities (Bournaud et al., 2011)

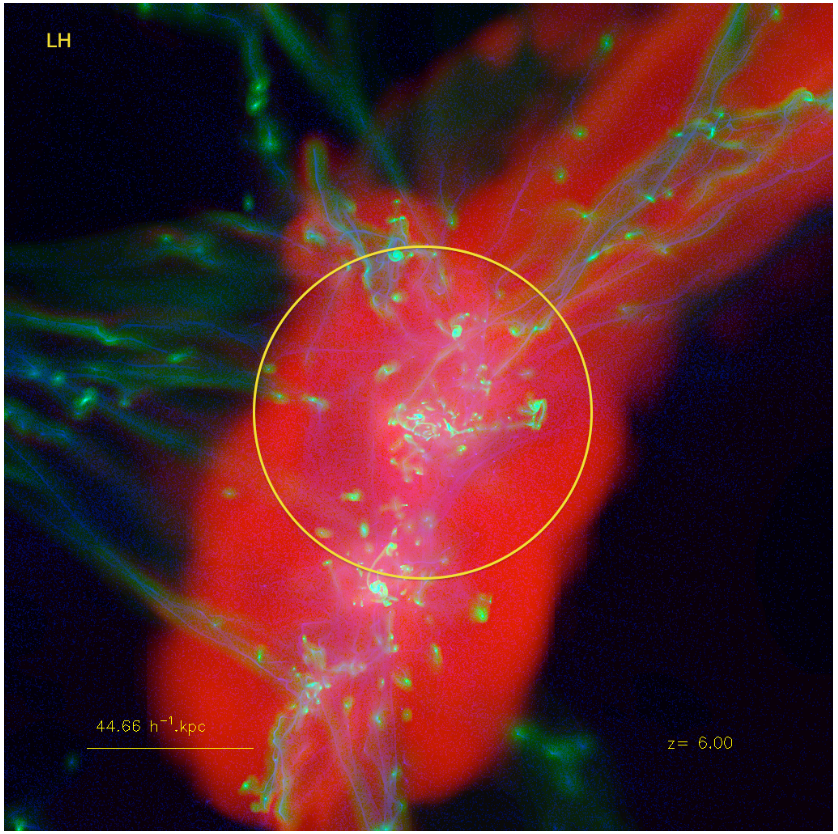
High resolution (1pc) but isolated disc

Very massive halos

Simulate a rare density peak: very massive halo that could host a very massive BH

Set of simulations:
-A low mass halo SH with 5.10^{11} M_{sun} at z=6, and 100 pc resolution
-A high mass halo LH with 2.10^{12} M_{sun} at z=6, and 100 pc resolution





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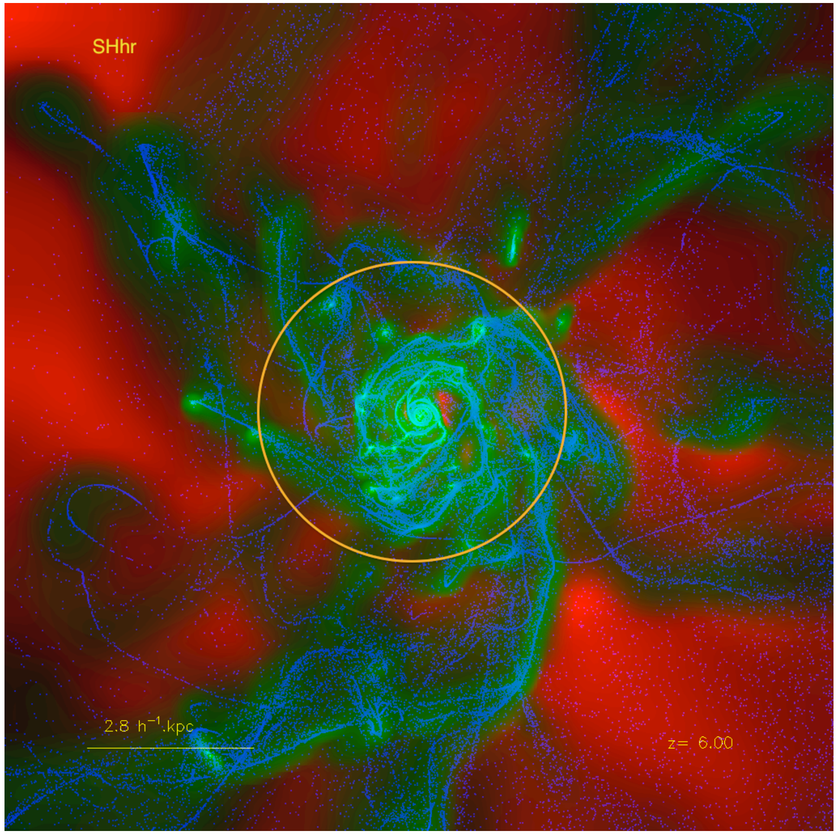
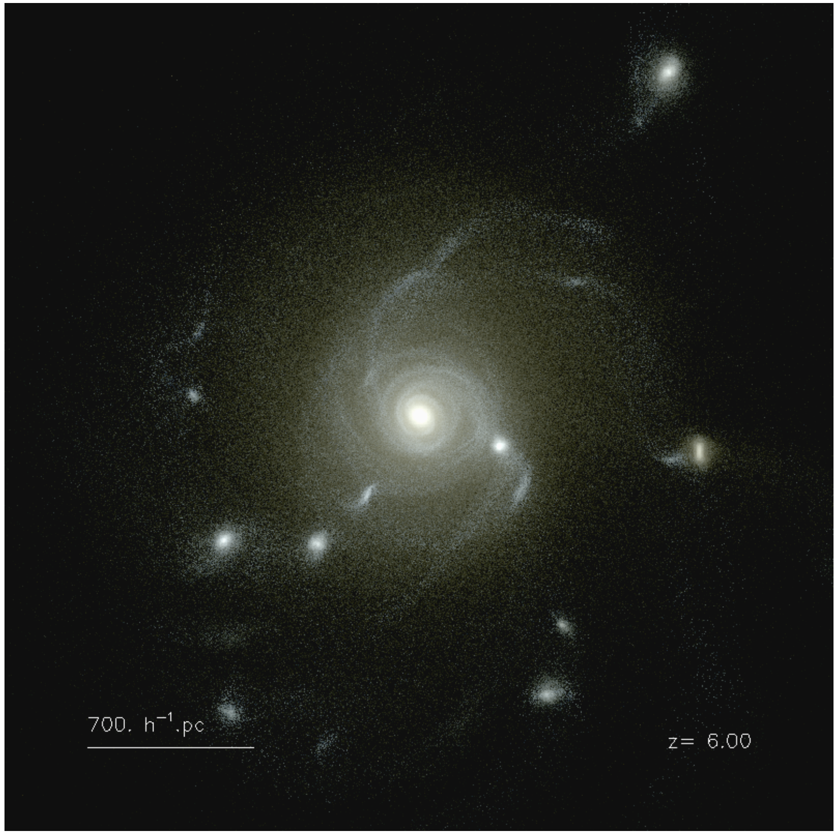
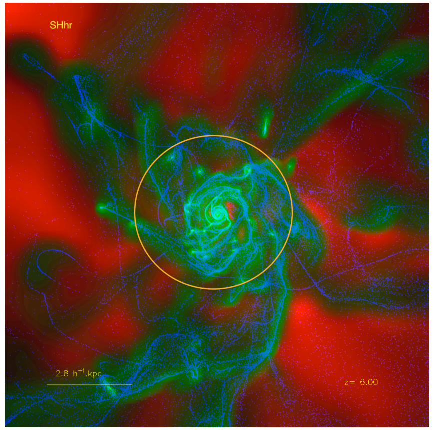
- -A low mass halo SH with 5.10^{11} M_{sun} at z=6, and 15 pc resolution

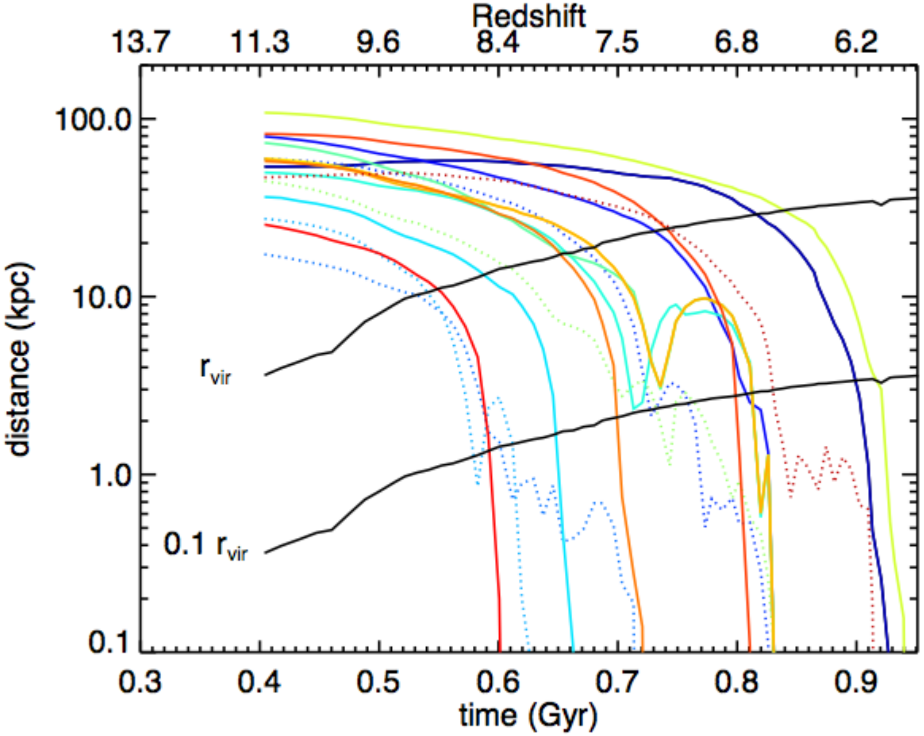


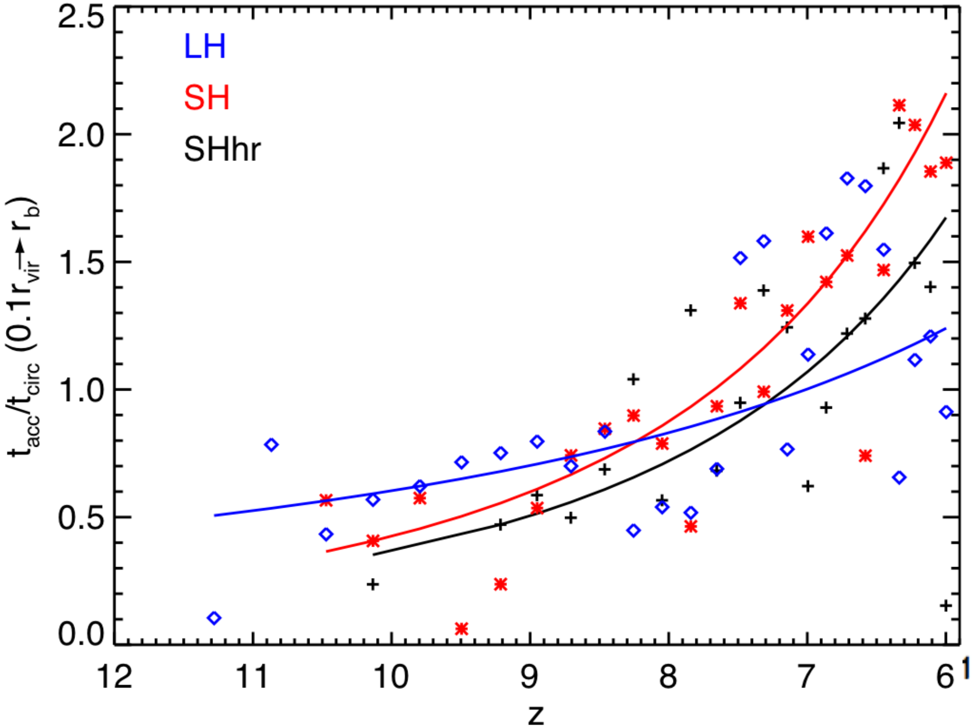


Follow the white rabbit…



Take the gas tracer particles that belong to the galactic bulge

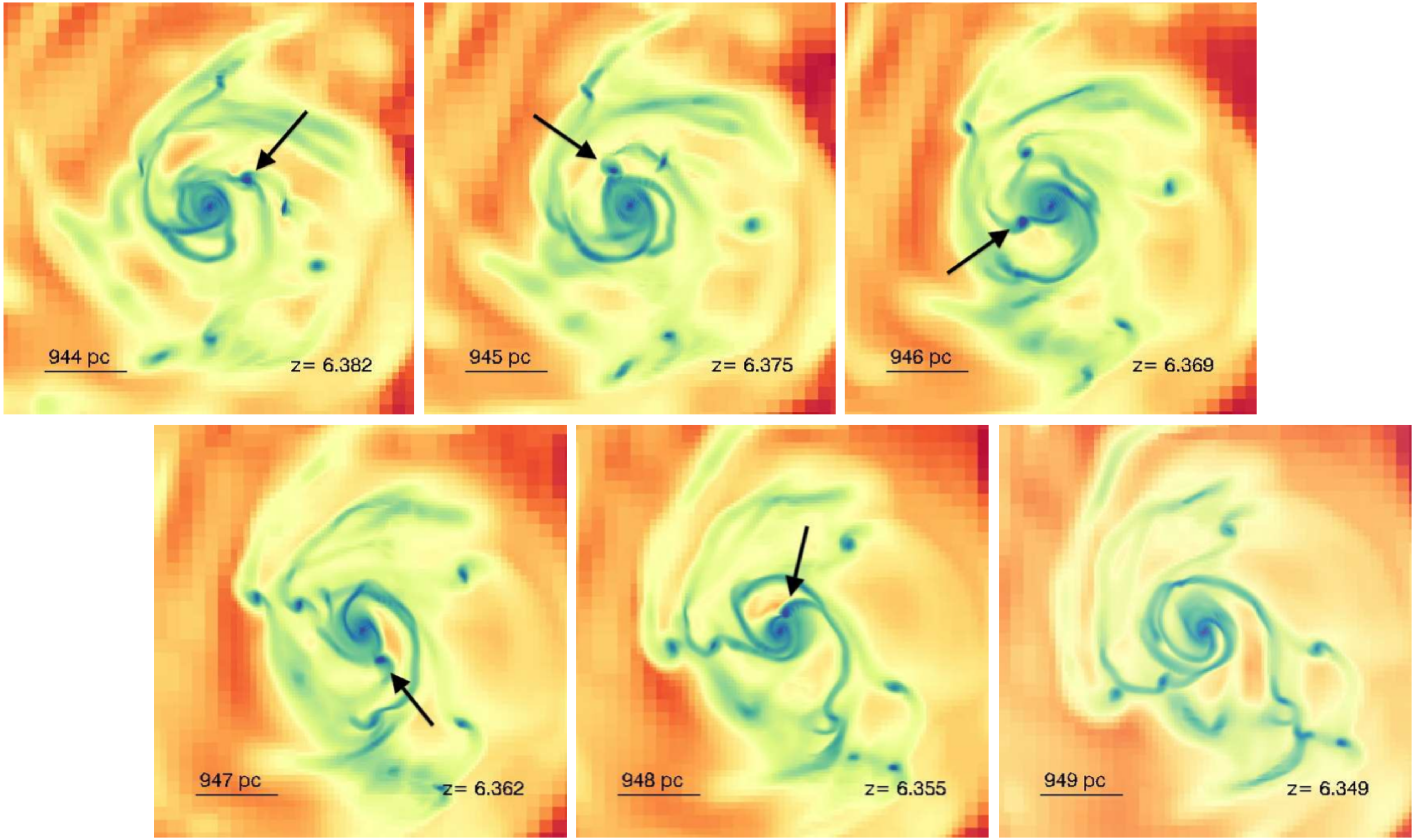




Dubois, Pichon, Haehnelt et al., 2012

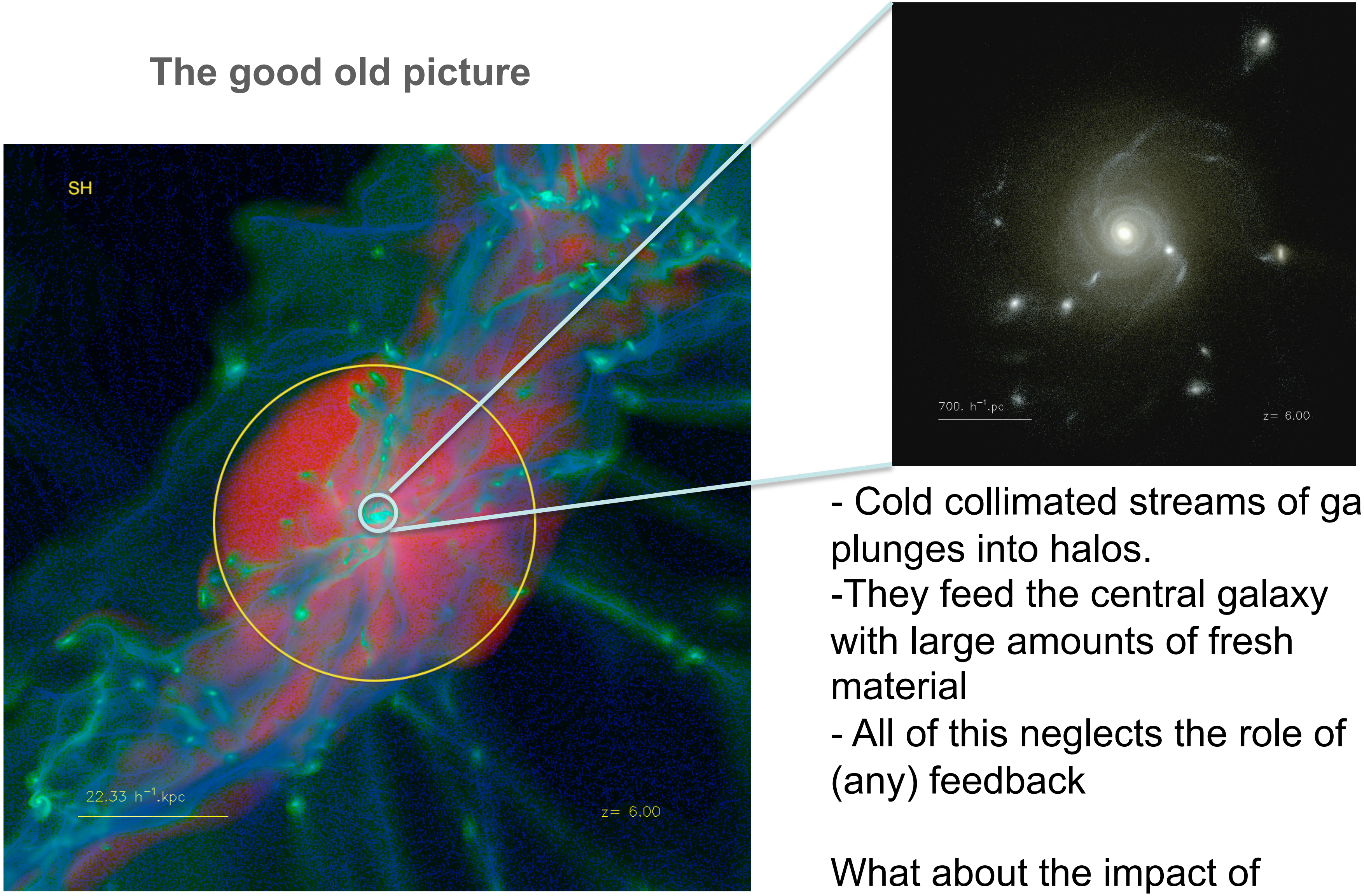
Late time gas infall do more rotations before being accreted.
Compatible with late-time cosmic filamentary infall having more angular momentum (Pichon et al., 2011, Kimm et al., arXiv:1106.0538, Codis et al., 2012)

A rapid clump migration to trigger late-time AGN bursts



Dubois, Pichon et al., 2012

The good old picture



Dubois, Pichon et al, 2012, 2013

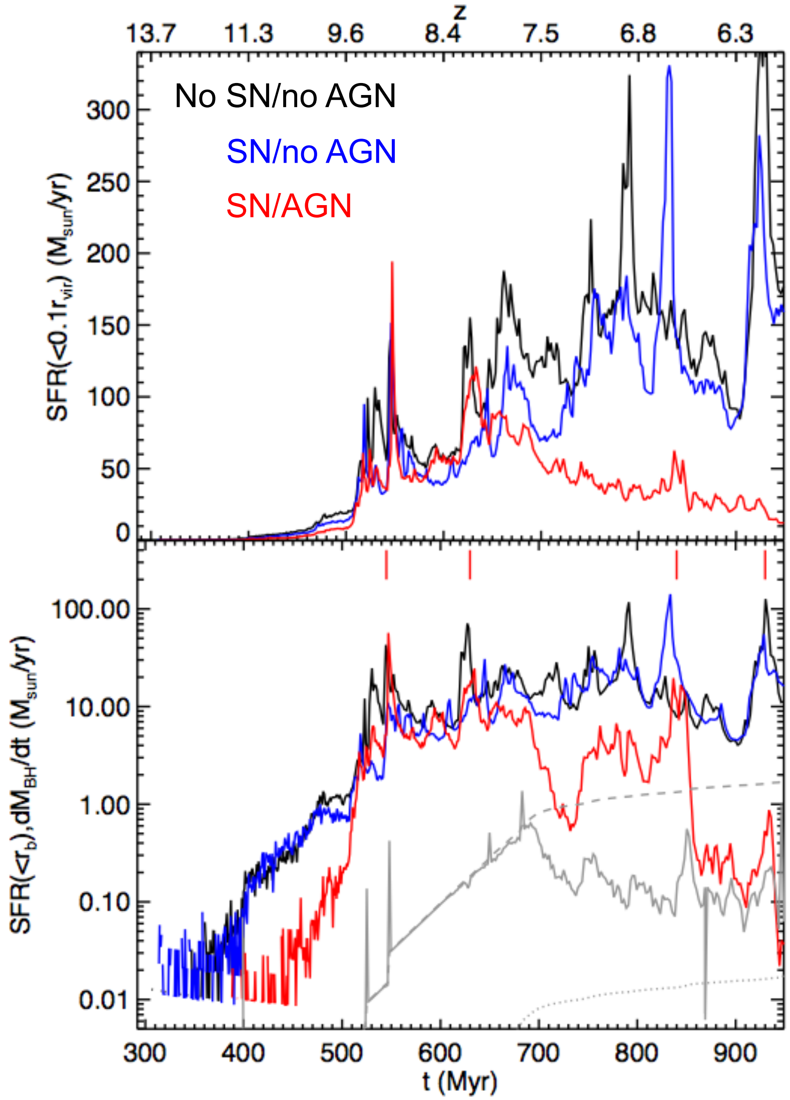
- Cold collimated streams of gas plunges into halos.
-They feed the central galaxy with large amounts of fresh material
- All of this neglects the role of (any) feedback

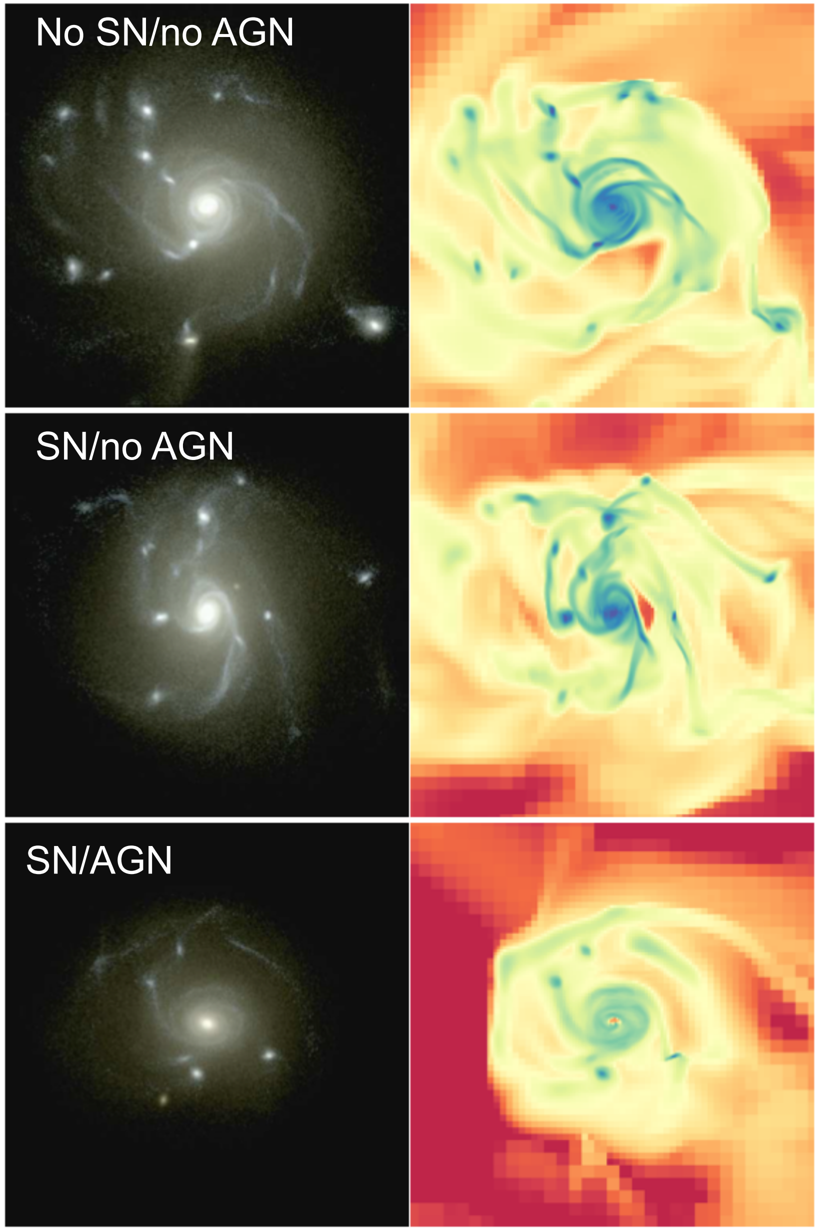
What about the impact of feedback on the gas accretion ?

Let’s do the full monty: star formation + SN feedback + AGN

Halo mass is 5.10^{11} M$_{sun}$ at z=6 (10 pc resolution)

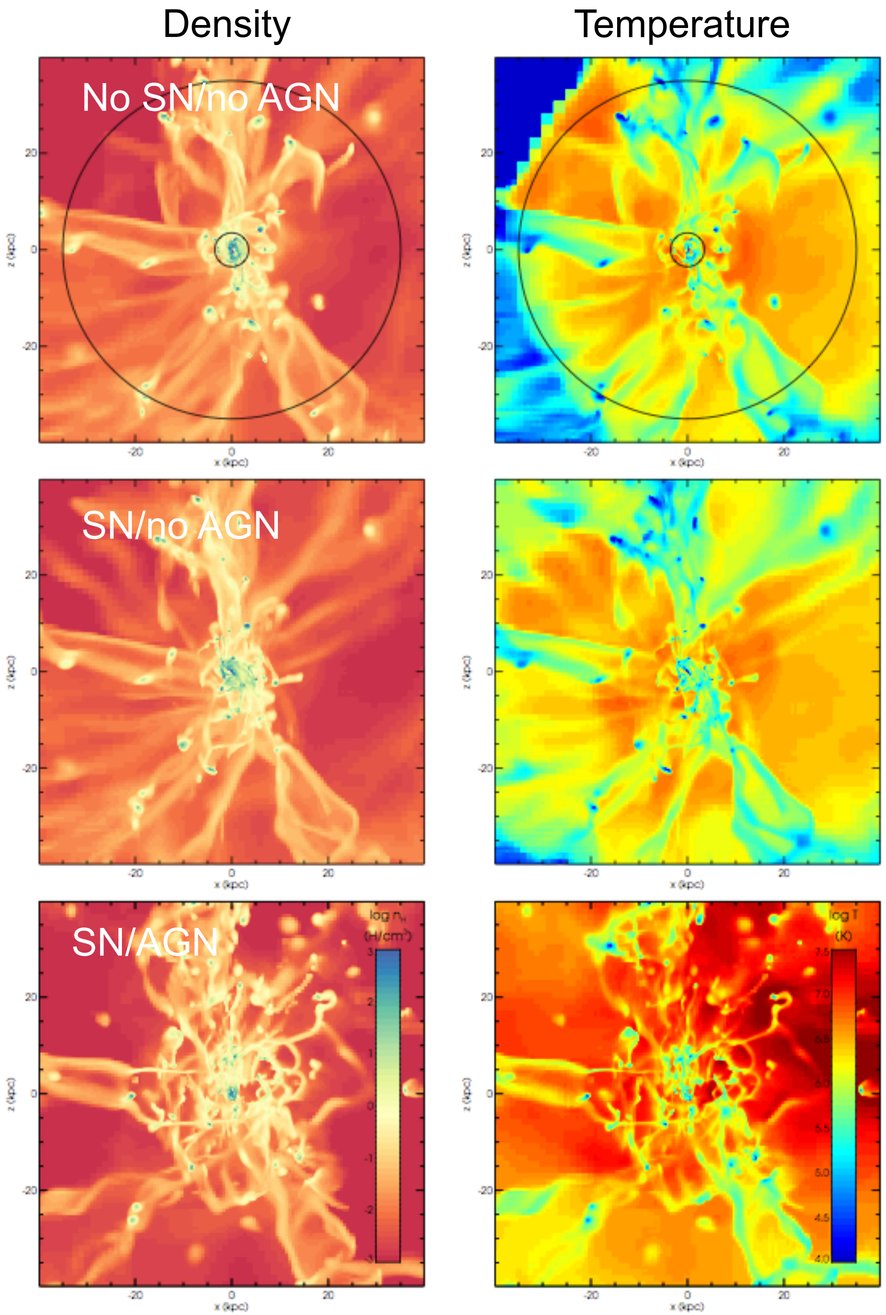
AGN quenches star formation efficiently early-on





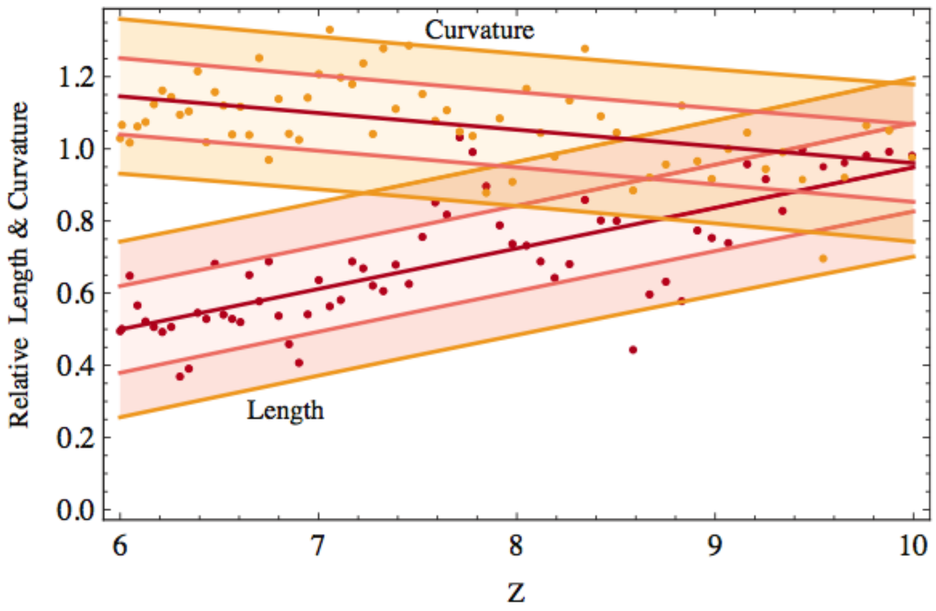
Dubois, Pichon et al., 2013

AGN blows cold flows away



Gas is driven out hot from the central galaxy due to AGN.

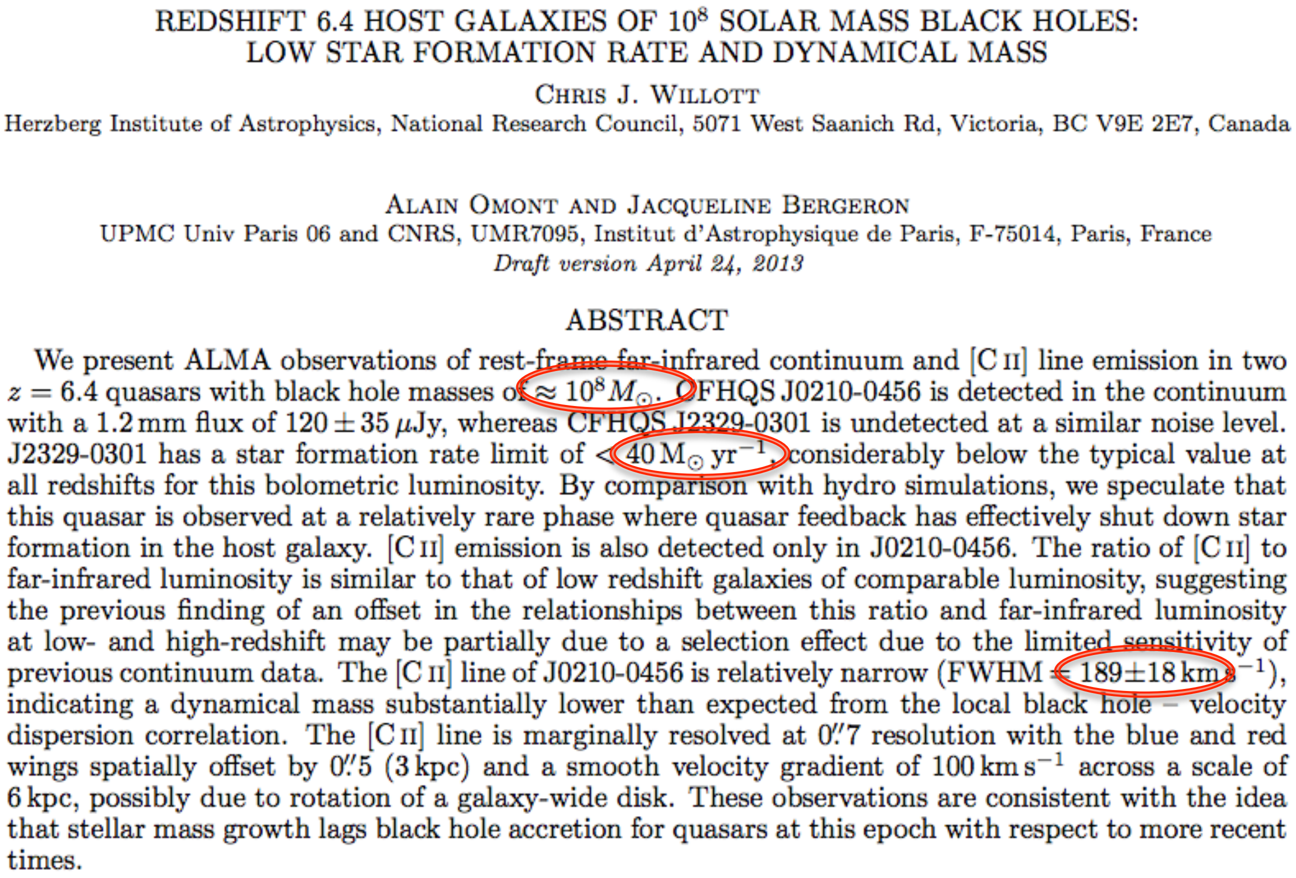
Cold filaments are repelled from the halo. Their structure is strongly perturbed (Skeleton, *Sousbie et al, 2009*)



Dubois, Pichon et al., 2013

Properties of the simulated galaxy at z=6

SFR~30 M_{sun}/yr $M_{BH}=8.10^7\,M_{sun}$ A gaz velocity dispersion of 300 km/s in the wind



REDSHIFT 6.4 HOST GALAXIES OF 10^8 SOLAR MASS BLACK HOLES:
LOW STAR FORMATION RATE AND DYNAMICAL MASS

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ABSTRACT

We present ALMA observations of rest-frame far-infrared continuum and [C II] line emission in two $z = 6.4$ quasars with black hole masses of $\approx 10^8 M_\odot$. CFHQS J0210-0456 is detected in the continuum with a 1.2 mm flux of $120 \pm 35\,\mu$Jy, whereas CFHQS J2329-0301 is undetected at a similar noise level. J2329-0301 has a star formation rate limit of $< 40\,M_\odot\,yr^{-1}$, considerably below the typical value at all redshifts for this bolometric luminosity. By comparison with hydro simulations, we speculate that this quasar is observed at a relatively rare phase where quasar feedback has effectively shut down star formation in the host galaxy. [C II] emission is also detected only in J0210-0456. The ratio of [C II] to far-infrared luminosity is similar to that of low redshift galaxies of comparable luminosity, suggesting the previous finding of an offset in the relationships between this ratio and far-infrared luminosity at low- and high-redshift may be partially due to a selection effect due to the limited sensitivity of previous continuum data. The [C II] line of J0210-0456 is relatively narrow (FWHM $= 189\pm18\,km\,s^{-1}$), indicating a dynamical mass substantially lower than expected from the local black hole – velocity dispersion correlation. The [C II] line is marginally resolved at $0''.7$ resolution with the blue and red wings spatially offset by $0''.5$ (3 kpc) and a smooth velocity gradient of $100\,km\,s^{-1}$ across a scale of 6 kpc, possibly due to rotation of a galaxy-wide disk. These observations are consistent with the idea that stellar mass growth lags black hole accretion for quasars at this epoch with respect to more recent times.

Such systems do exist!
Are they representative? Need more simulations…

BH spin and its consequence on BH growth

- Radiative efficiency depends on the BH spin parameter

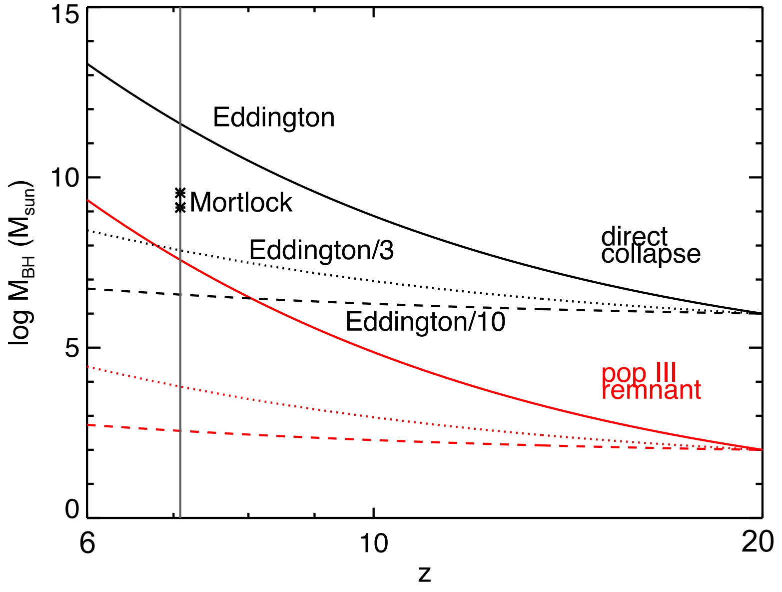
- A non-spinning BH has a low radiative efficiency e_r=0.057. For a maximally spinning BH with a=0.998 e_r=0.321 (e_r=0.038 if a=-0.998)

- The spin of BH is inherited from the history of gas accretion and successive mergers.

- Potential issue here: if BHs are maximally spinning then t_{Edd}(a=0.998)=144 Myr. Only possible to grow a 10^5 M_{sun} seed BH up to 10^8 M_{sun} in a Gyr (z=6)

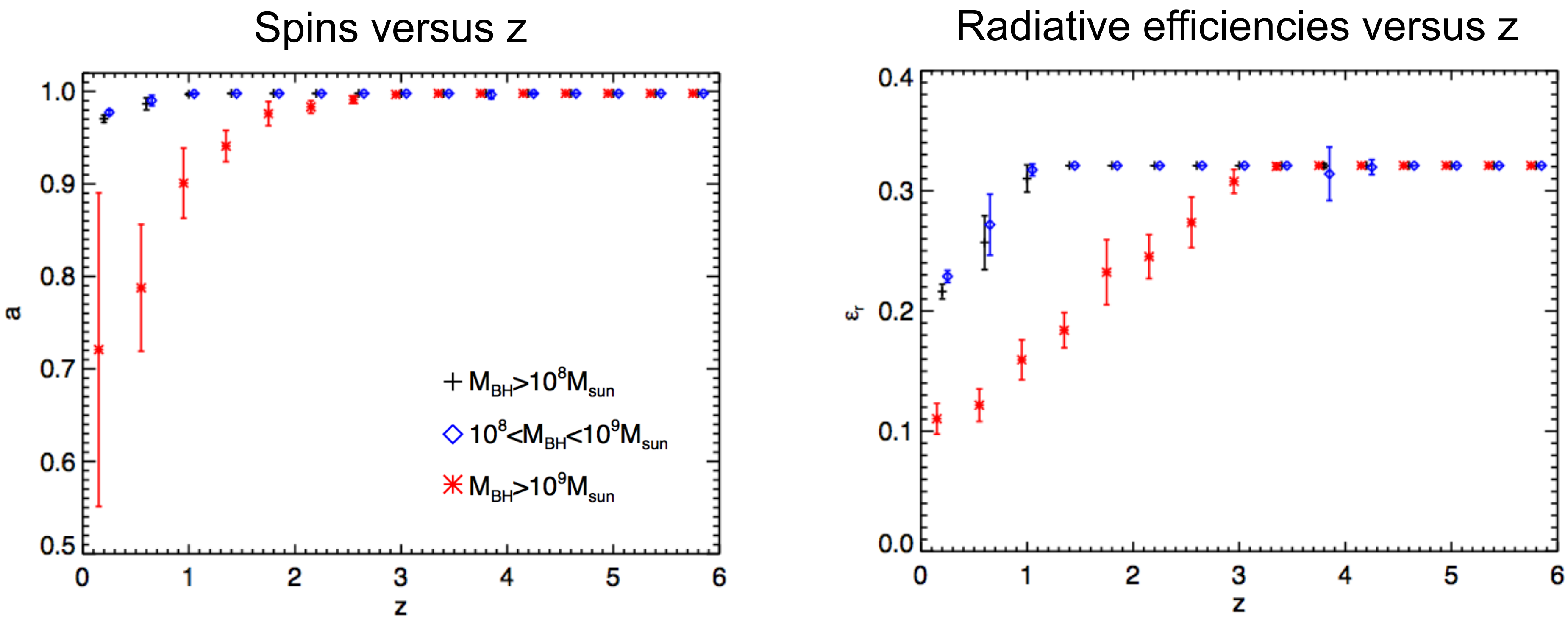
$$t_{\rm Edd} = \frac{M_{\rm BH}}{\dot{M}_{\rm Edd}} = \frac{\epsilon_{\rm r}\sigma_{\rm T}c}{4\pi G m_{\rm p}}$$

Let's inspect that…



BH spin evolution for cosmological runs with kpc resolution

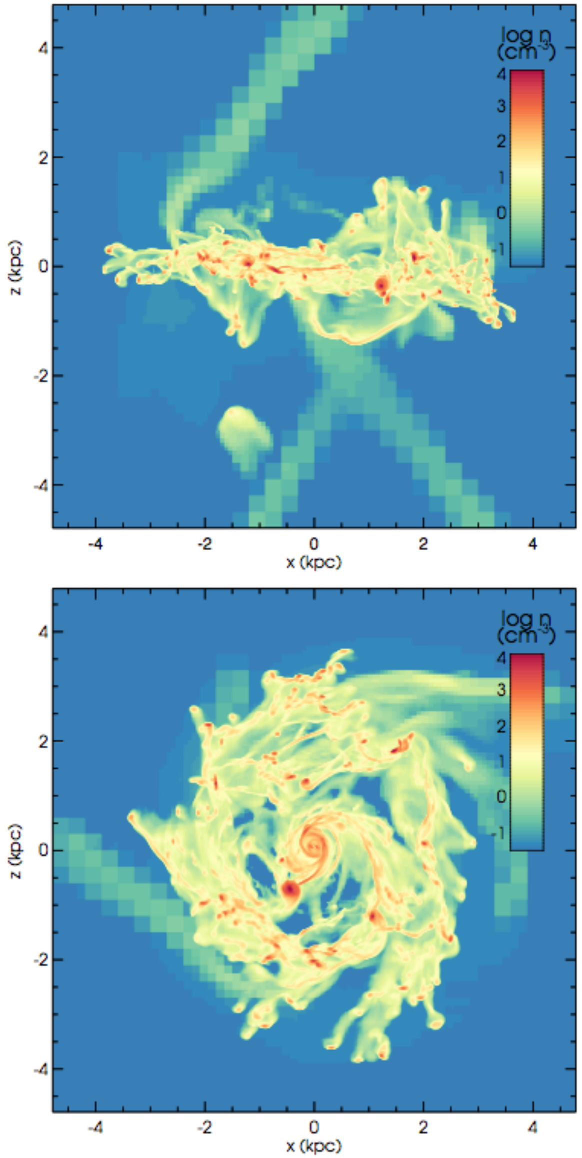
Recipes are: Spins grow through gas accretion and change with BH coalescence

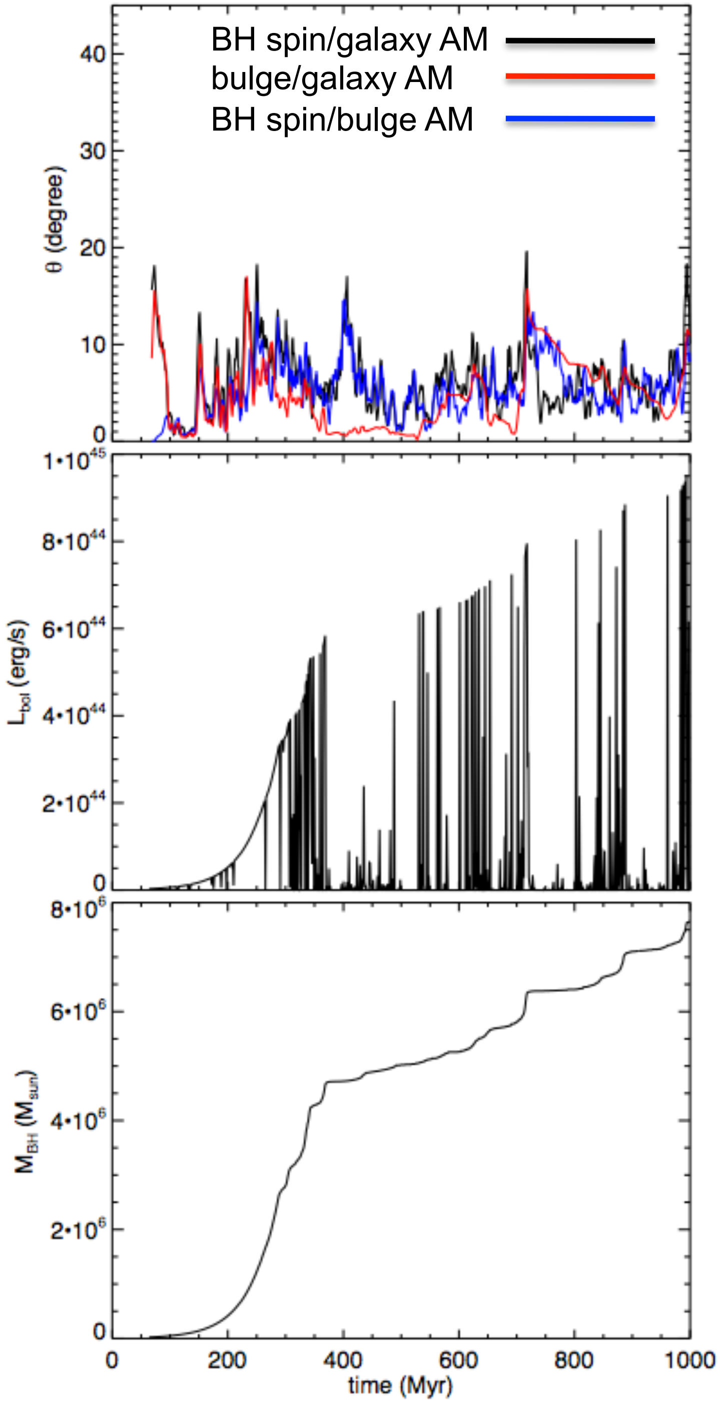


Possibly an effect of resolution ?
Small-scale turbulence is not resolved

Dubois, Volonteri, Silk, sub. , arXiv:1304.4583

Strong coherence of gas accretion





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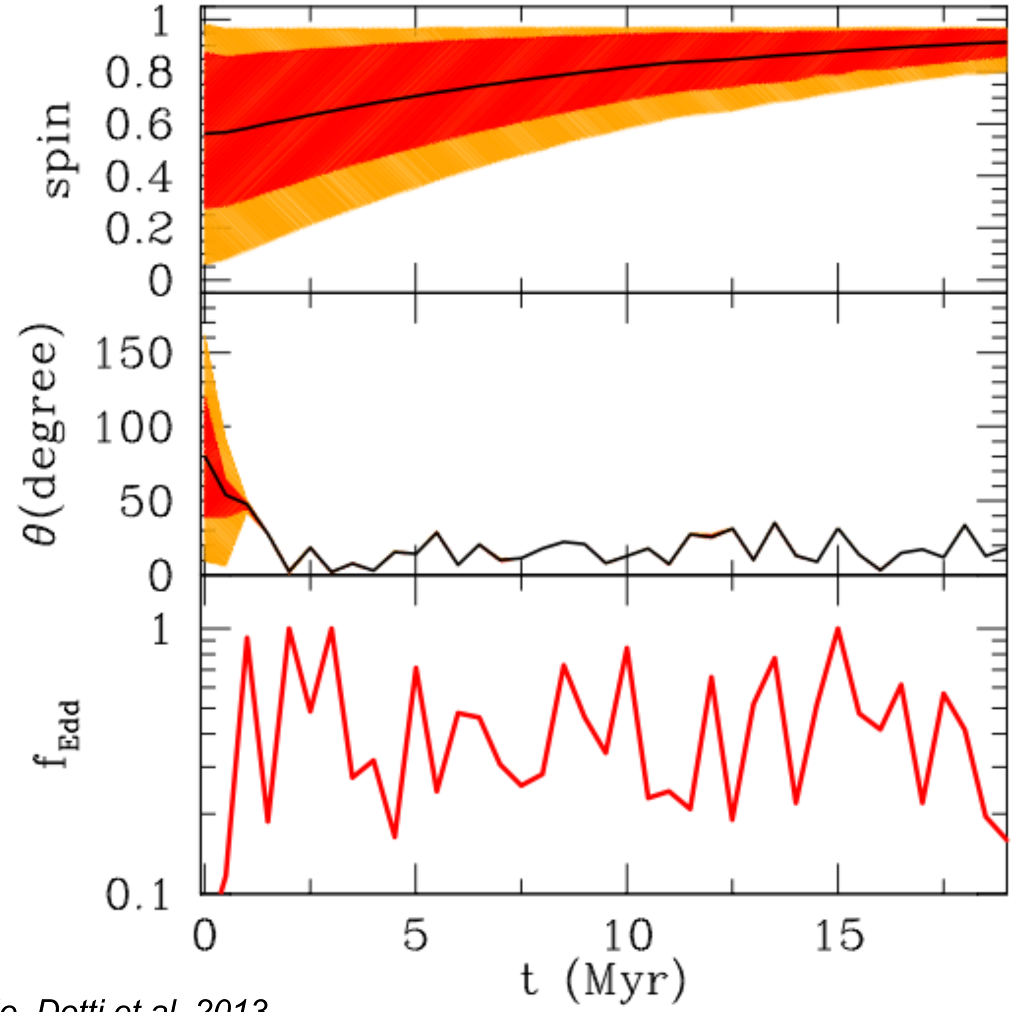
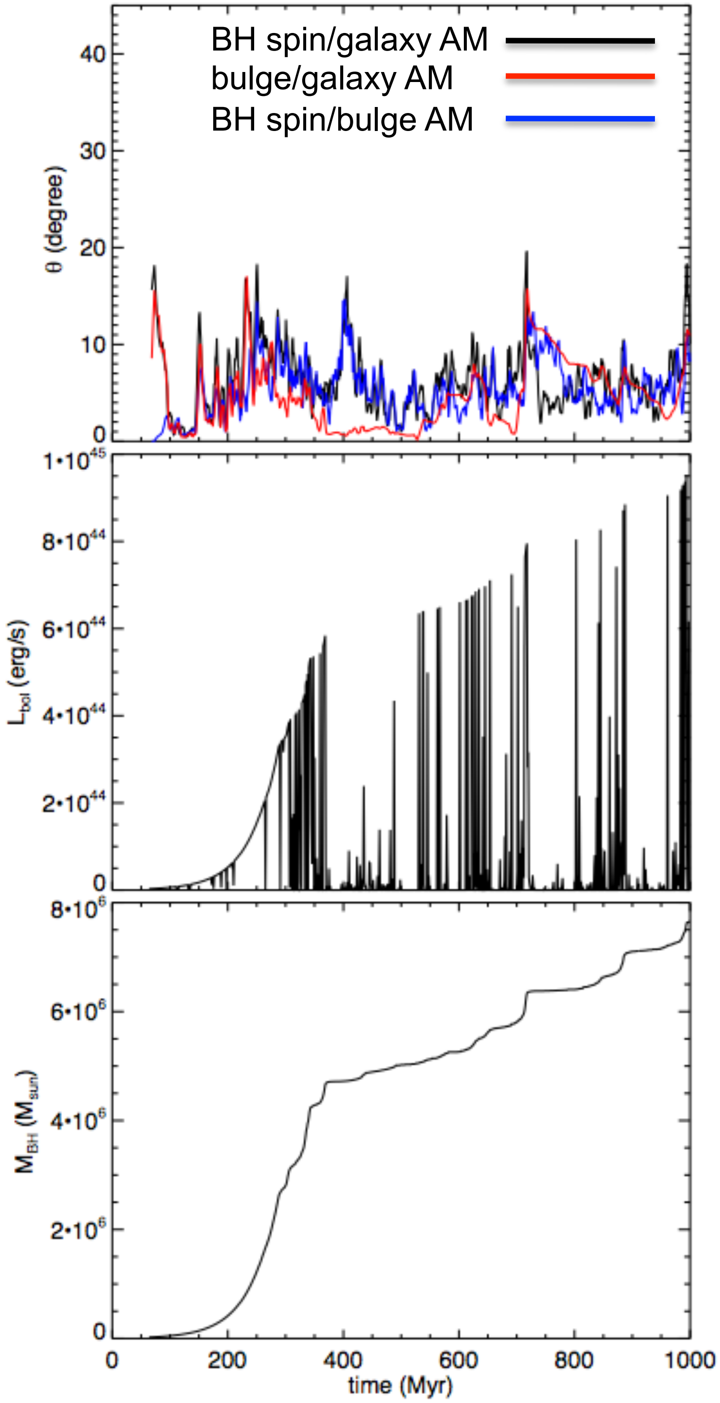
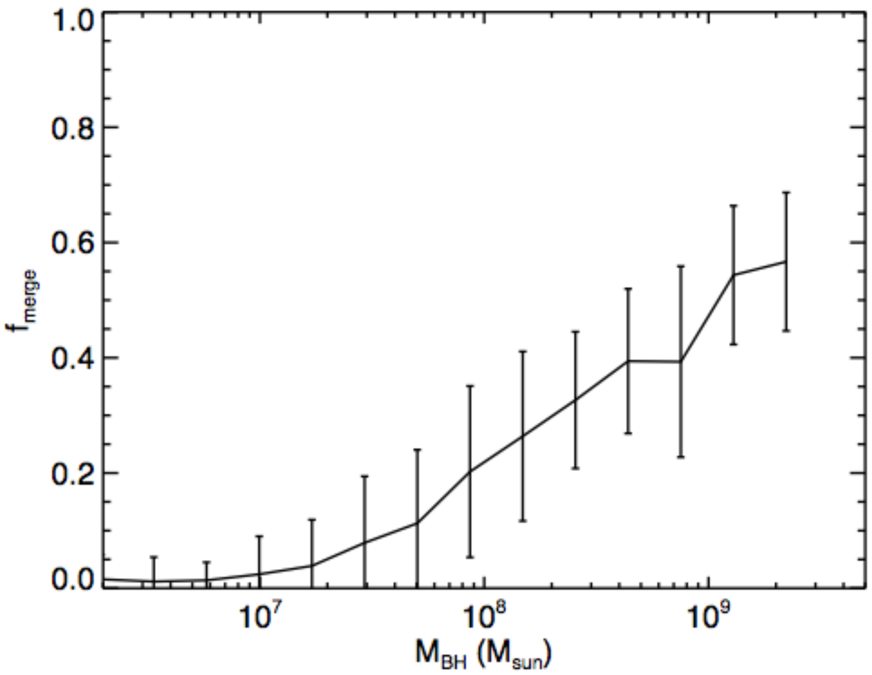
Strong coherence of gas accretion



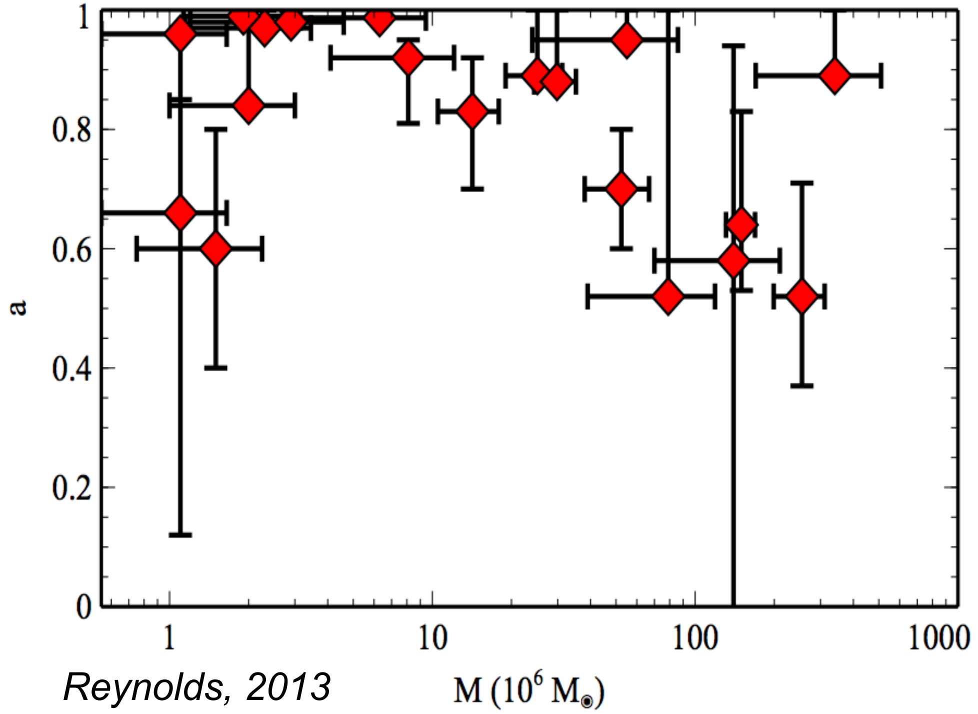
Maio, Dotti et al, 2013



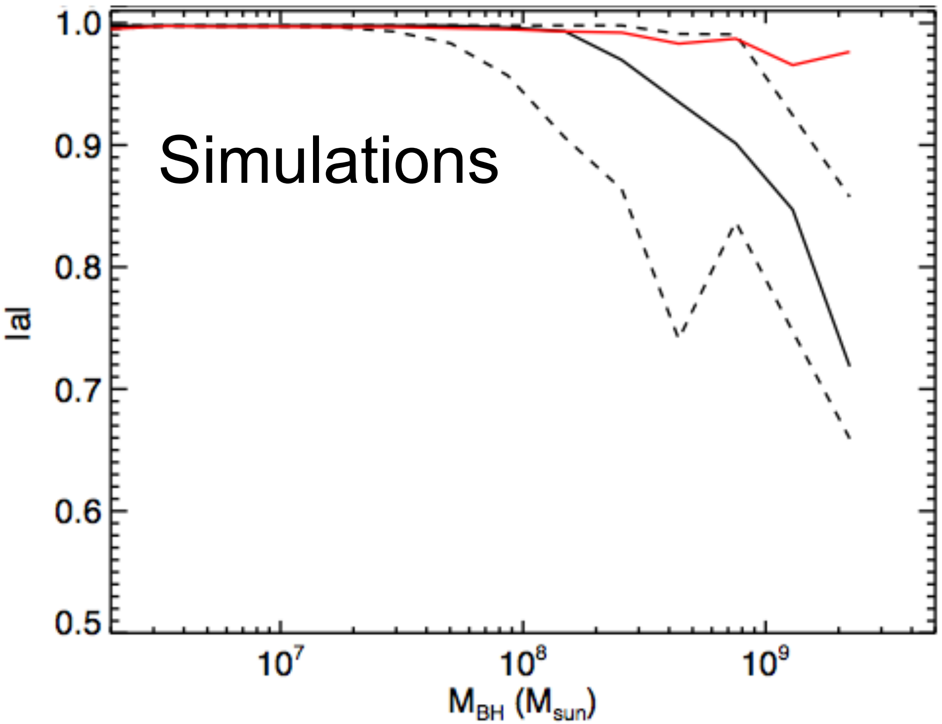
Spins versus Masses



Observations



Reynolds, 2013



Simulations

Summary on AGN feedback

- Powerful quasar modes are preferentially triggered at high redshift in gas rich systems
- Quiescent radio modes are predominant at low redshift in massive structures (little cold material)

- <u>AGN feedback in low-redshift galaxies</u>
  - In situ star formation quenched in massive galaxies
  - Transform discs into elliptical by increasing the fraction of dry mergers
  - Galaxies get more extended
  - Massive halos are less cuspy

- <u>AGN feedback in high redshift galaxies</u>
  - The gas accretion onto BHs is driven first by cold streams, and, then, by galactic disc feeding through disc instabilities (clump migration): confirmed by Bellovary, Brooks, Volonteri et al, 2013, Kulier, Ostriker et al, 2013, and Costa, Sijacki et al, 2013
  - Quasars at high redshift obliterates the gas content in massive bulges and strongly perturb the cold accretion of gas
  - Enough gas coming close to the BH but…

    difficult to grow BHs up to 10^9 M_{sun} due to large Eddington e-folding times (large spins?) and AGN feedback.
    - Super-Eddington accretion?
    - More turbulence for the ISM to reduce BH spins and efficiencies? More feedback?
    - Need to treat quasar feedback with radiative transfer properly?
    - More massive halos? (Tiziana’s talk)