Effects of AGN feedback on structure formation

Yohan Dubois

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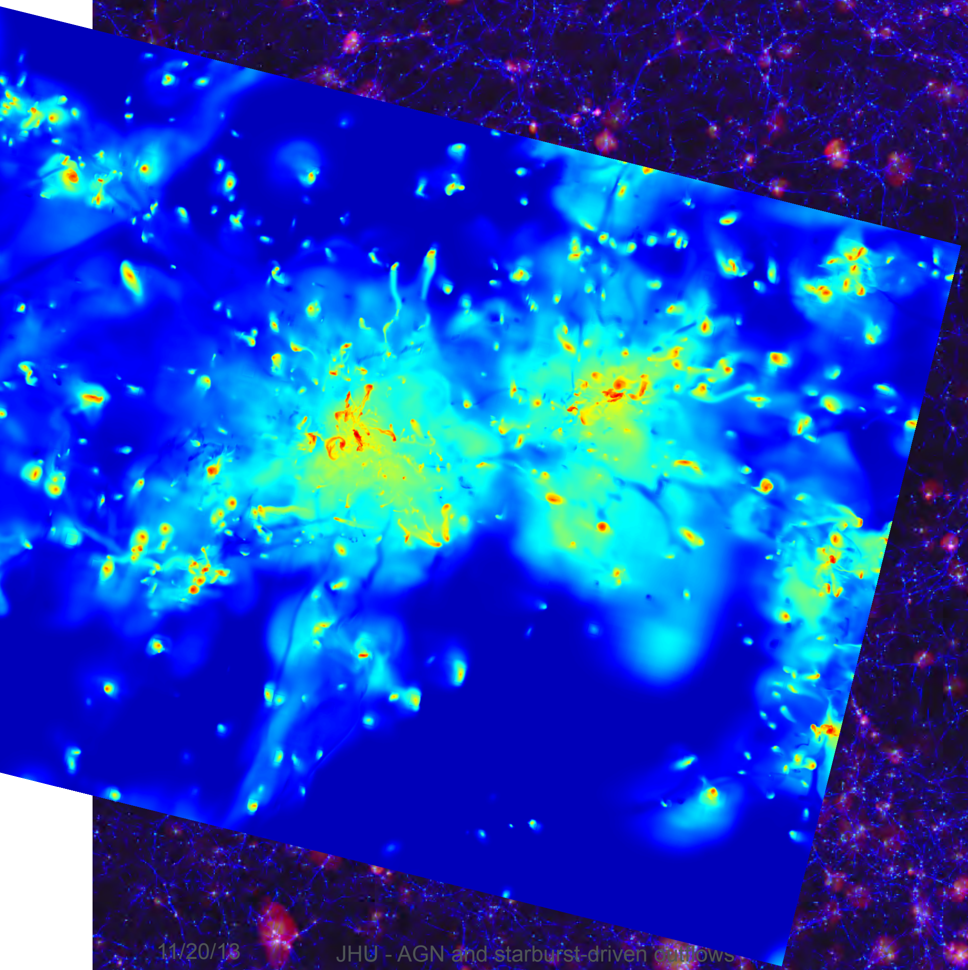
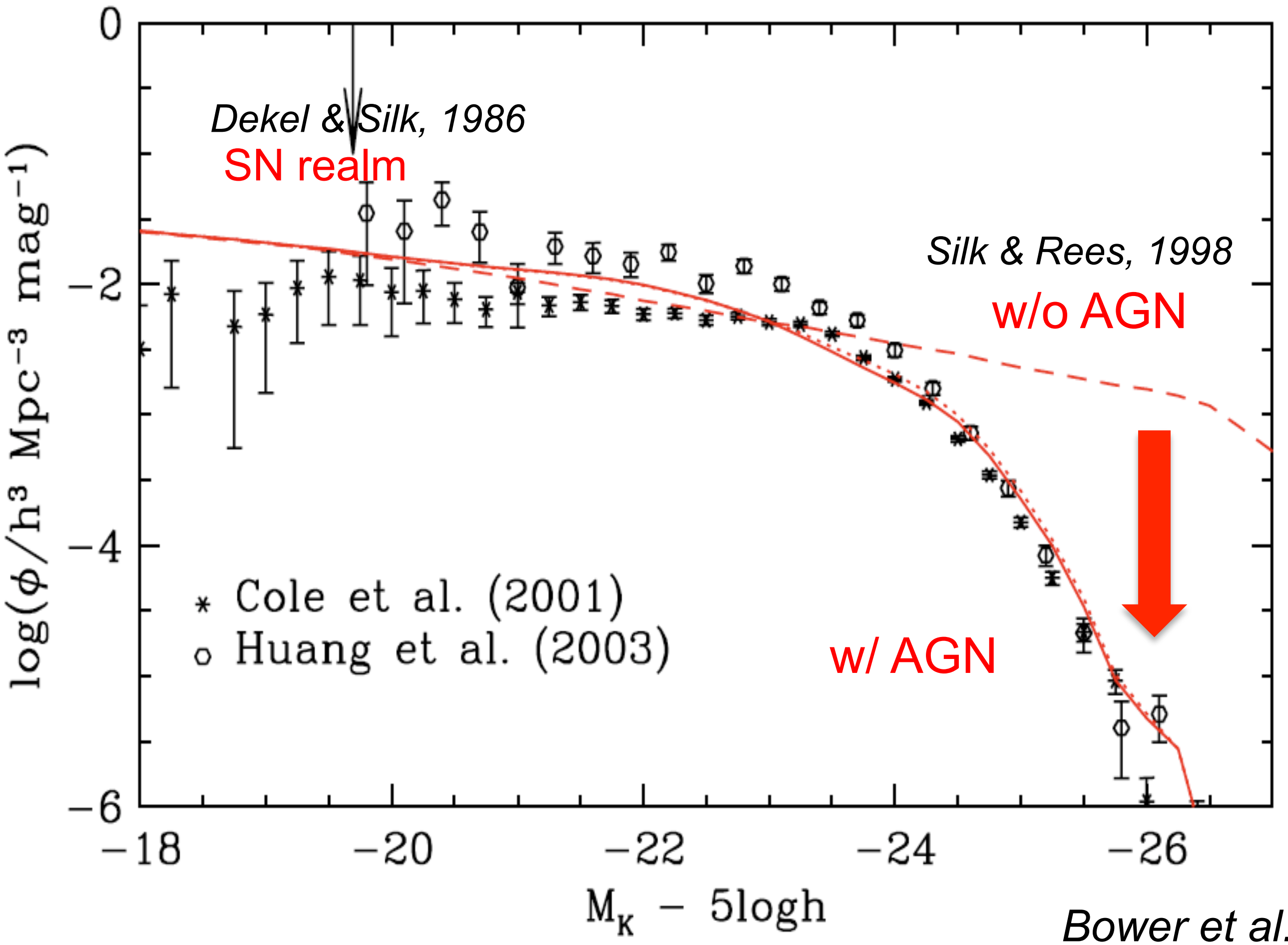


Raphael Gavazzi – IAP
Sébasten Peirani – IAP
Christophe Pichon – IAP
Joseph Silk – IAP
Marta Volonteri – IAP
Julien Devriendt – University of Oxford
Adrianne Slyz – University of Oxford
Romain Teyssier – UTH Zürich
Taysun Kimm – Princeton
Martin Haehnelt – University of Cambridge

Motivation for AGN feedback

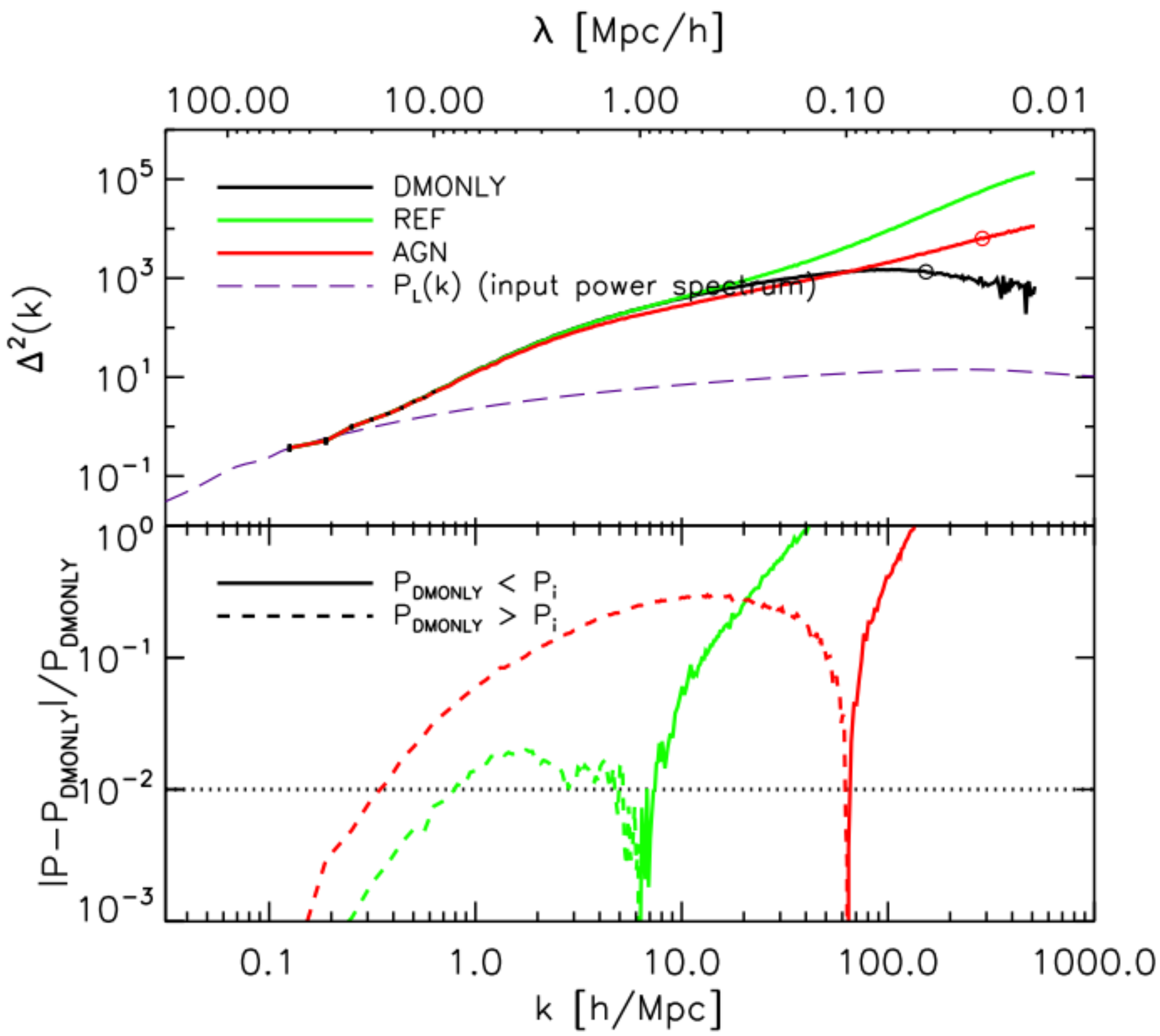
Galaxy luminosity (~mass) function

Semi-analytic models



Bower et al., 2006

Baryonic physics cannot be neglected (Euclid)

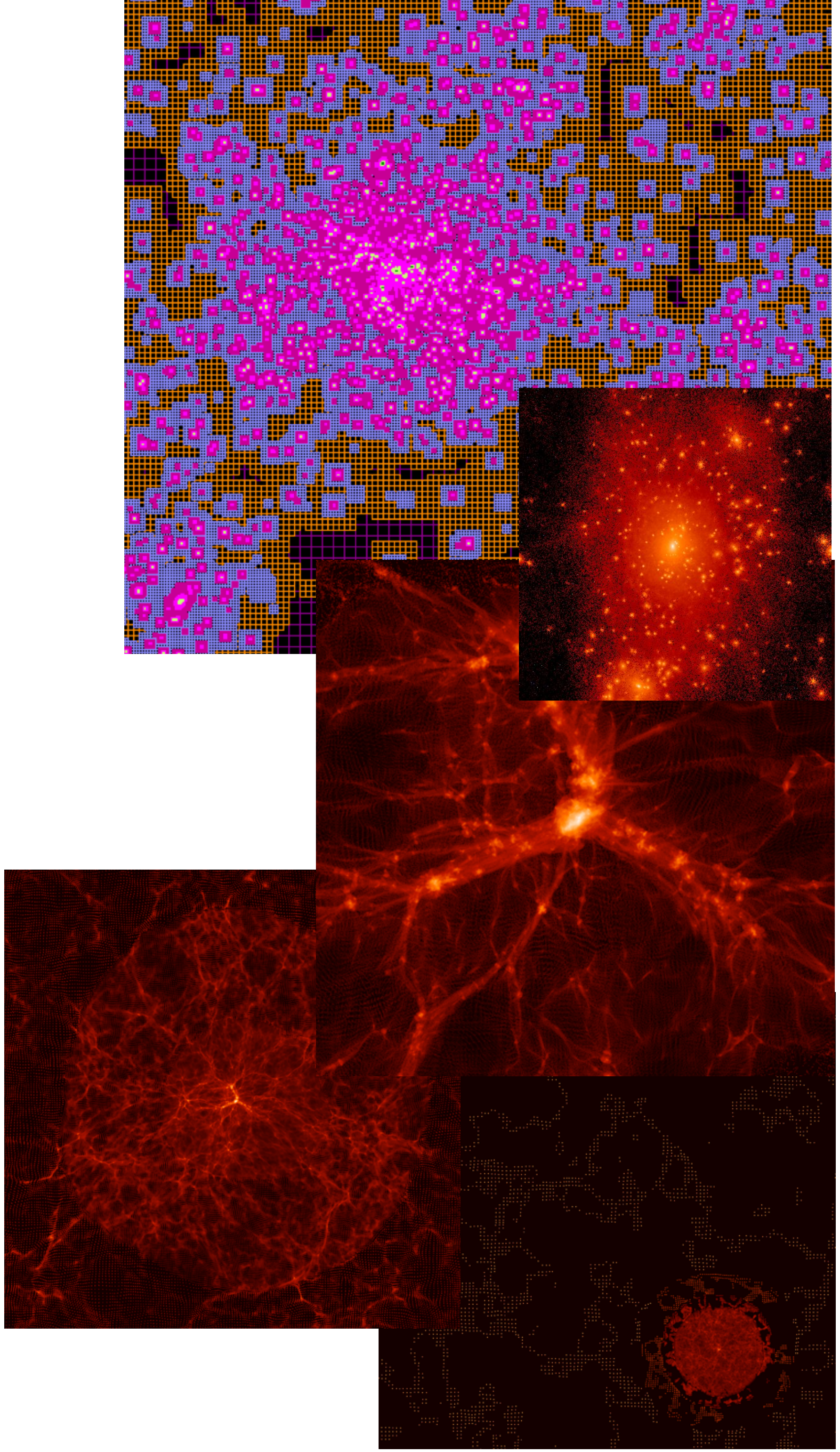


Van Daalen et al., 2011

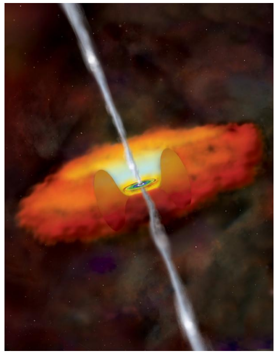
RAMSES : an Adaptive Mesh Refinement (AMR) code

- 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

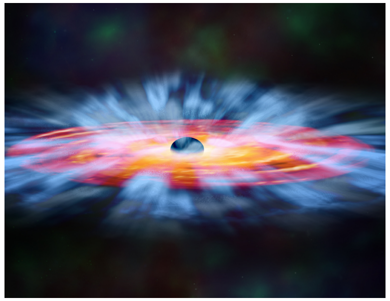
See Teyssier, 2002

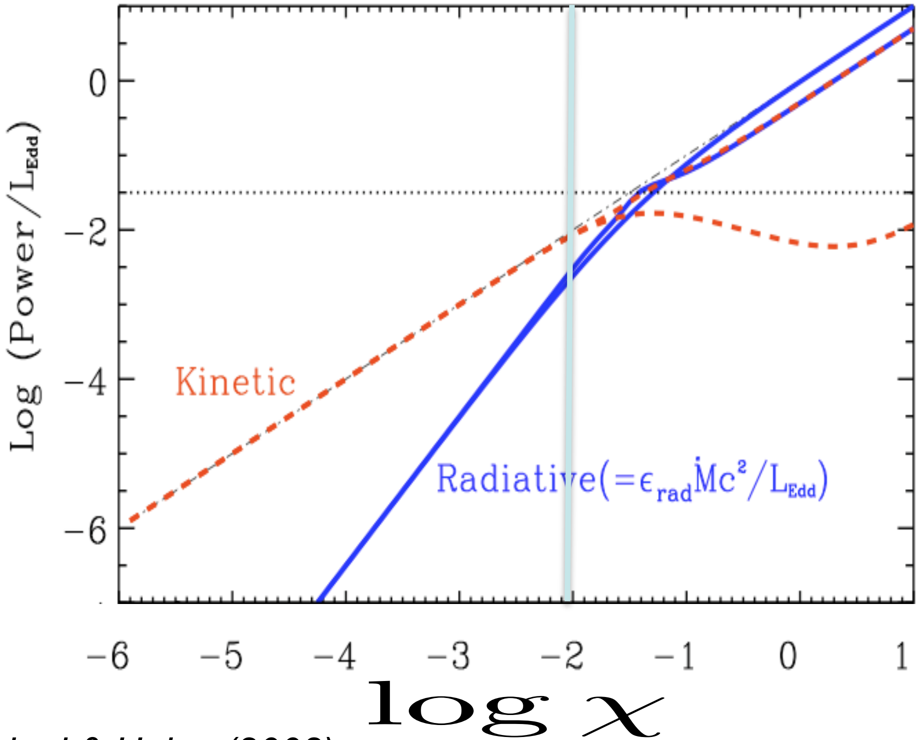


Two main modes of AGN feedback



or





Merloni & Heinz (2008)

Eddington ratio of the accretion rate

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

<u>Radio mode (kinetic jet) when</u>

$$\chi \leq 0.01$$

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

<u>Quasar mode (heating) when</u>

$$\chi > 0.01$$

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

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

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

AGN in cosmological simulations

<u>First</u> 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

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

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

Bondi accretion rate

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

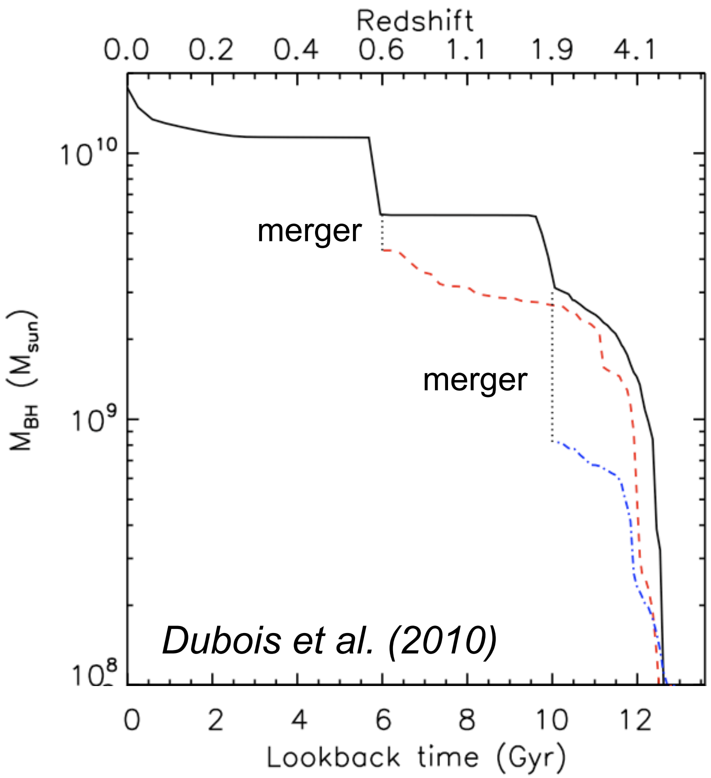
Fast accretion in dense and cold regions

AGN in cosmological simulations

<u>First</u> 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)



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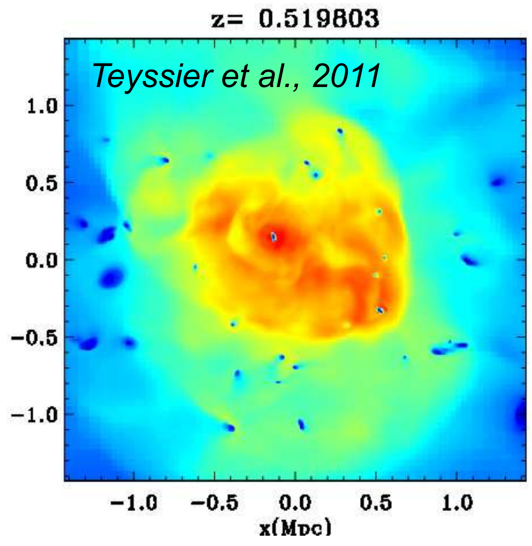
- Mimic the feedback from black holes (AGN)

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

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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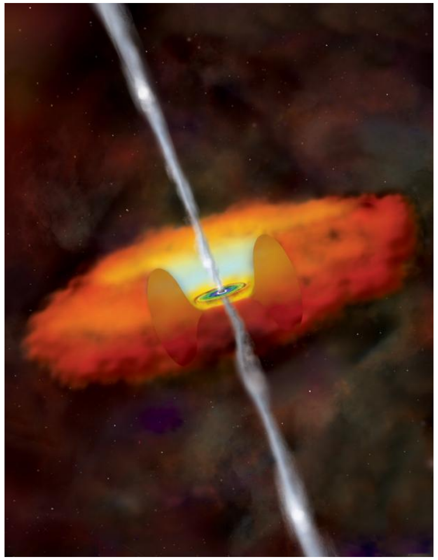
- Mimic the feedback from black holes (AGN)

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

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)

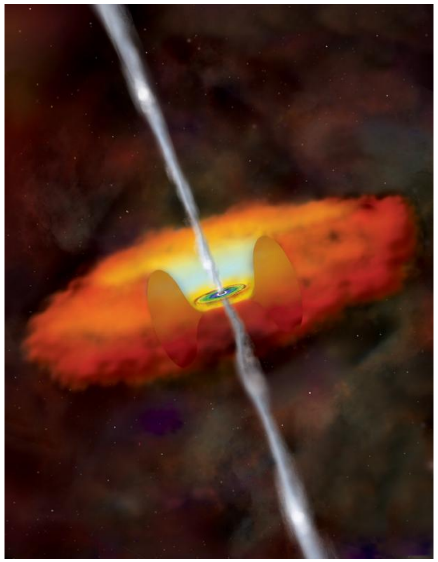
AGN in cosmological simulations

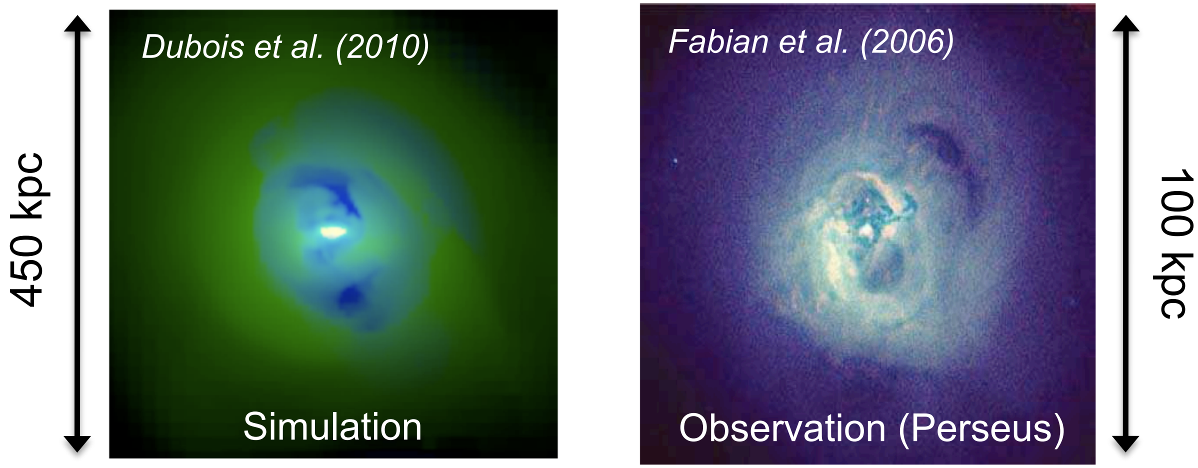
<u>First</u> AMR simulations of self-consistent AGN feedback in a cosmological context

- 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 — With thermal input (Teyssier et al., 2011)
Low accretion rates — or with jets (Dubois et al., 2010, 2011)





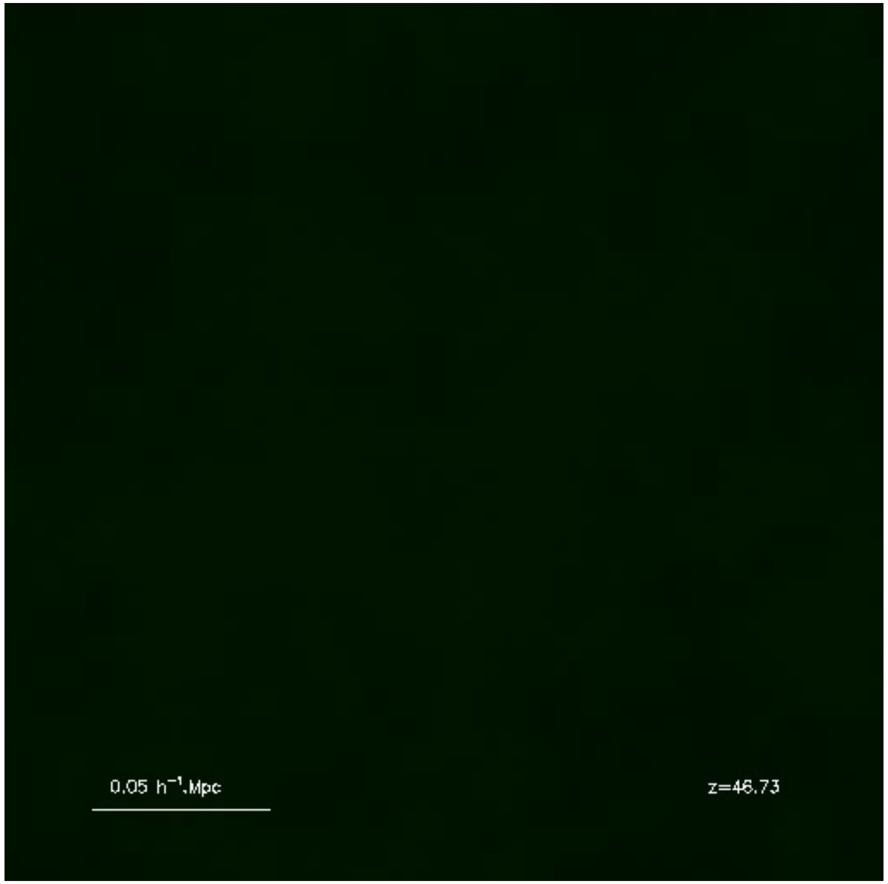
X-ray (3 bands)

$L_{\mathrm{box}} = 12.5\,\mathrm{Mpc/h}$
$\Delta x_{\mathrm{min}} = 0.38\,\mathrm{kpc/h}$

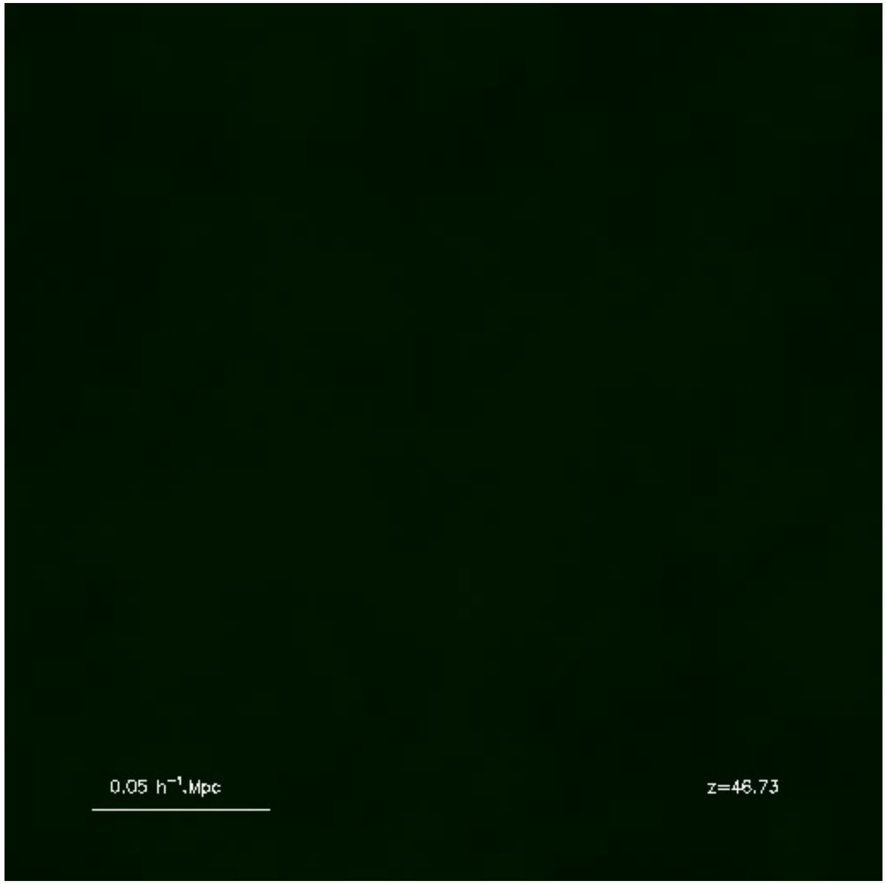
WMAP 5-year cosmology

17.10^6 DM particles
$M_{\mathrm{DM}} = 6.9\,10^6\,\mathrm{M_\odot/h}$

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

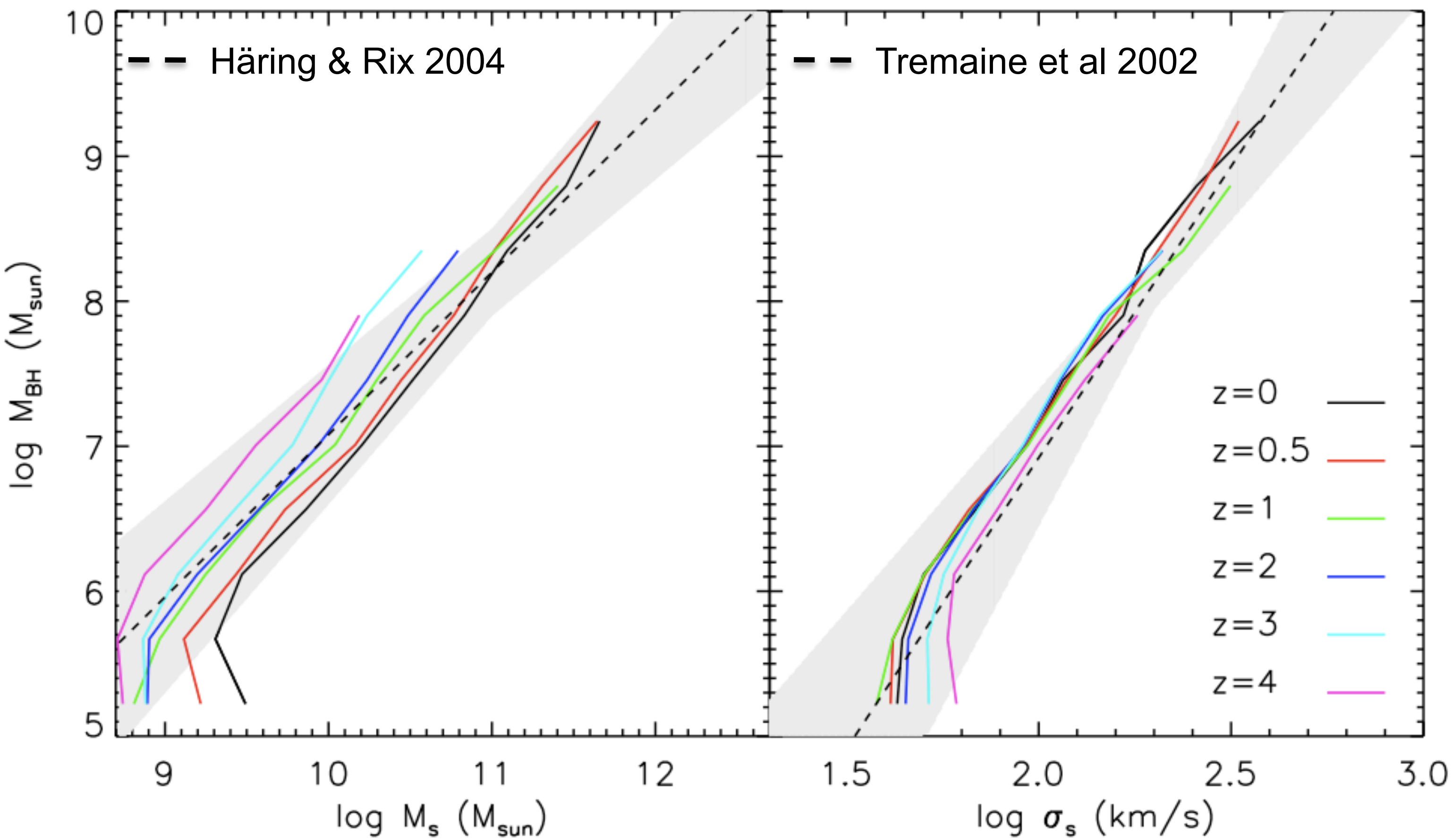


No AGN



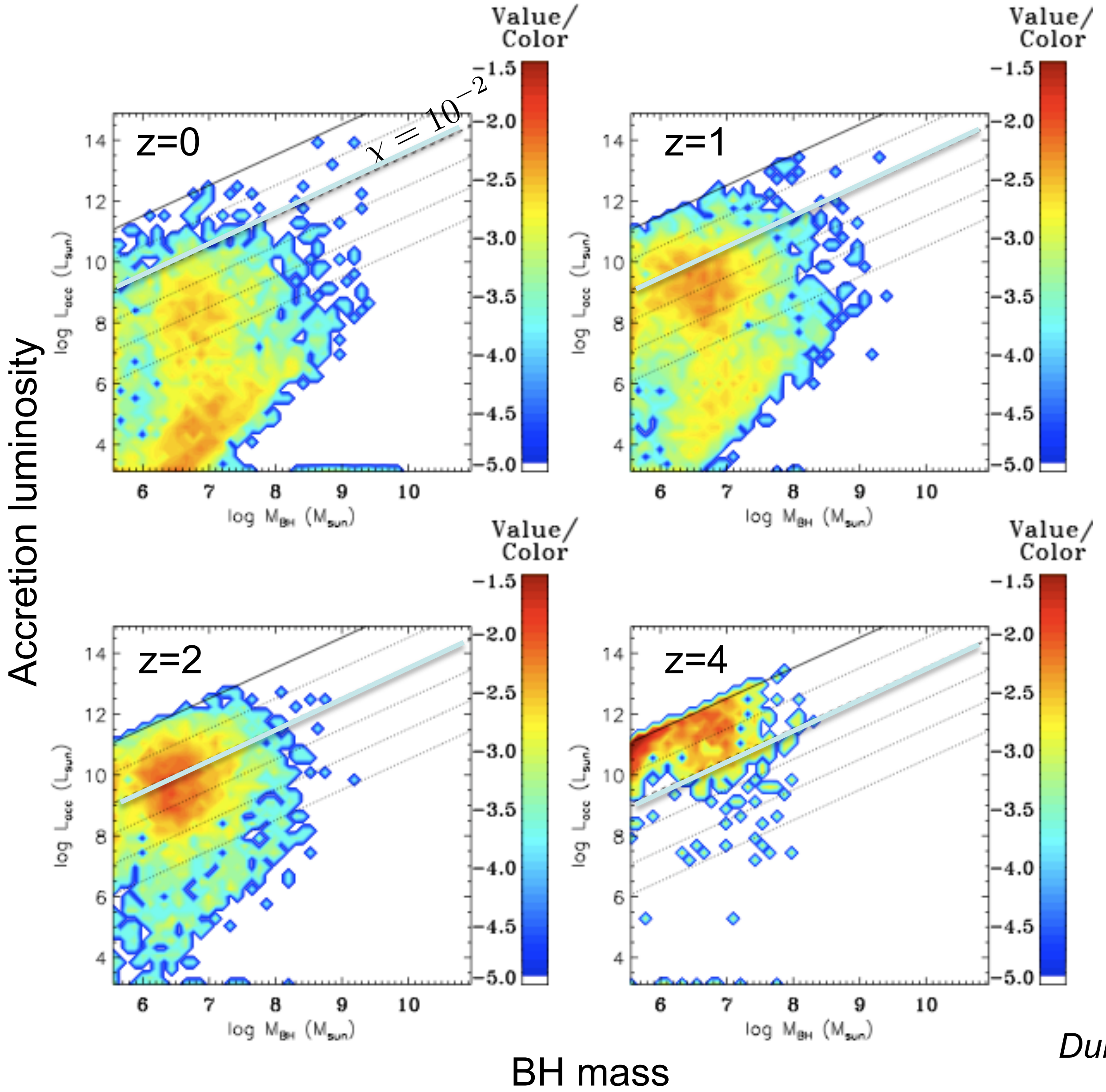
AGN

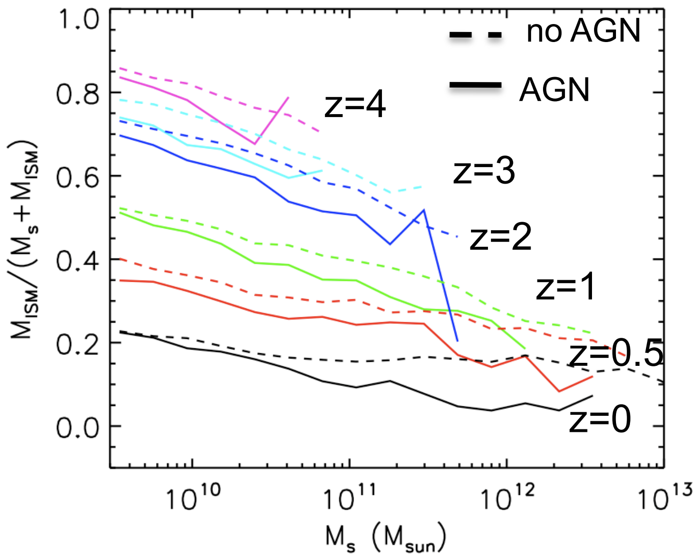
Fitting observationnal M_{BH}-M_* / M_{BH}-σ_* laws



Dubois, Devriendt, Slyz, Teyssier, 2012

Radio mode or quasar mode ?

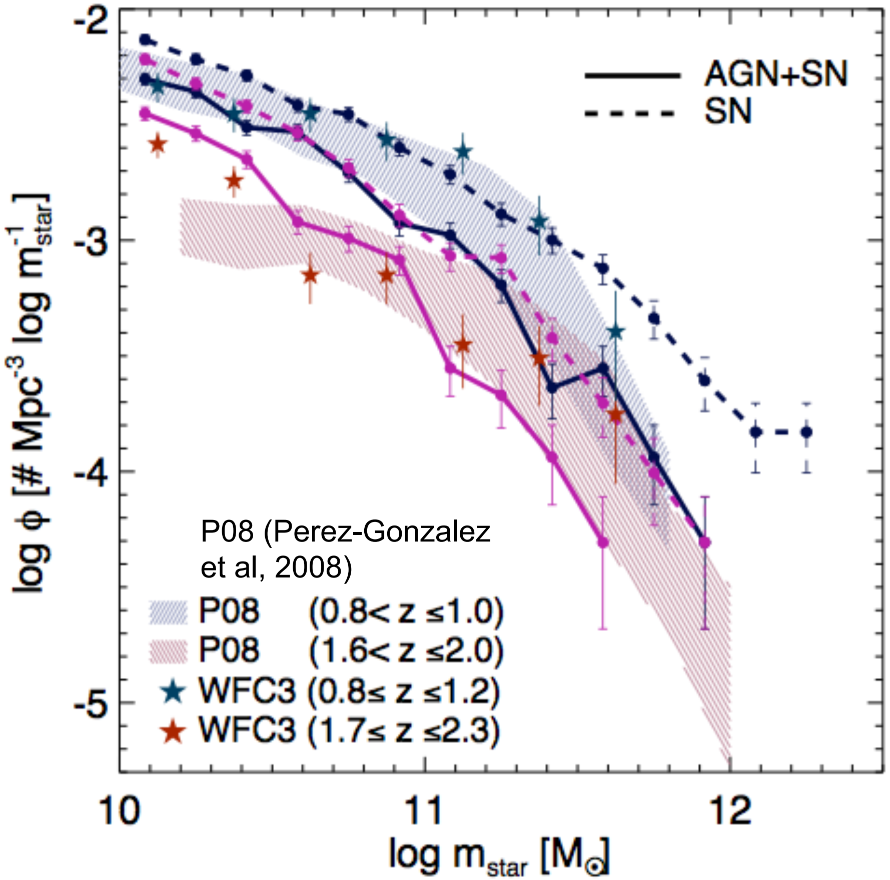




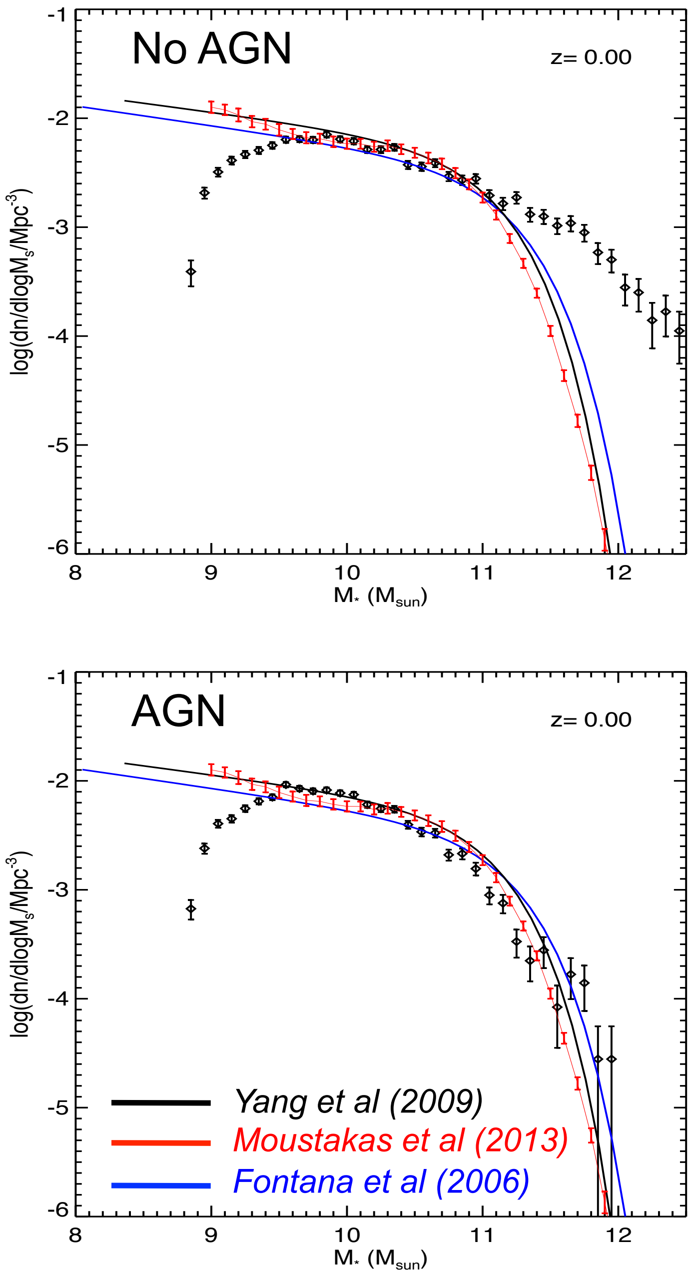
Galaxies are gas-rich at high-redshift
Star formation and feedback removes
cold gas efficiently

Dubois, Devriendt, Slyz, Teyssier, 2012

Stellar mass functions

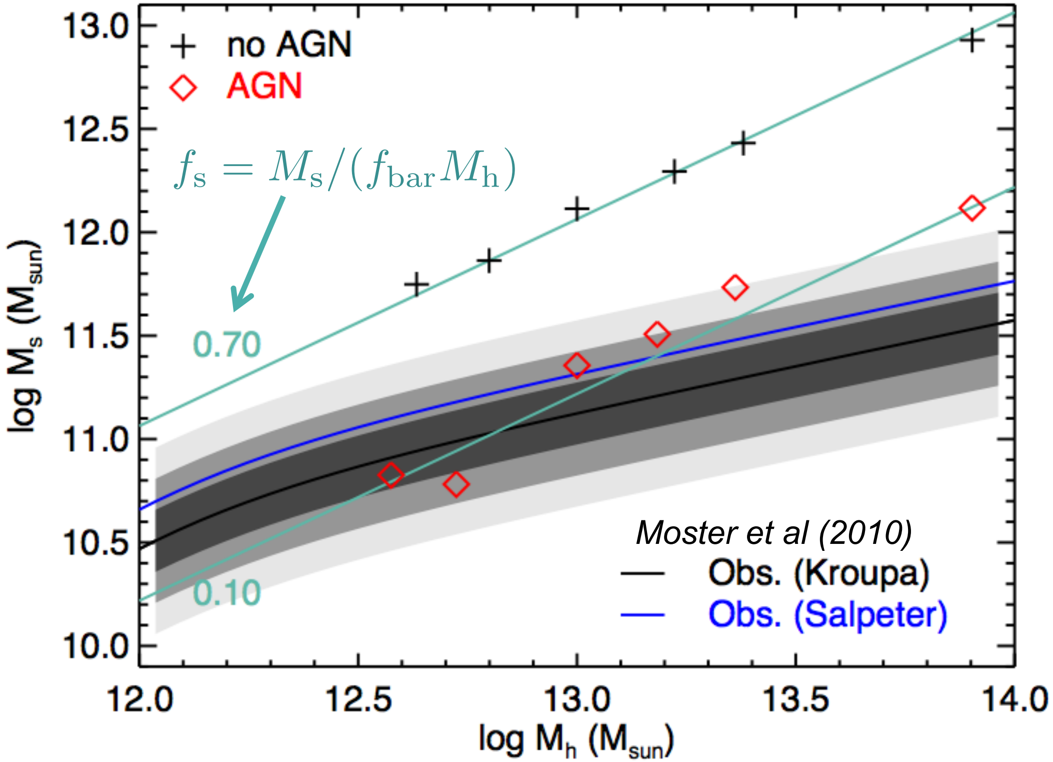


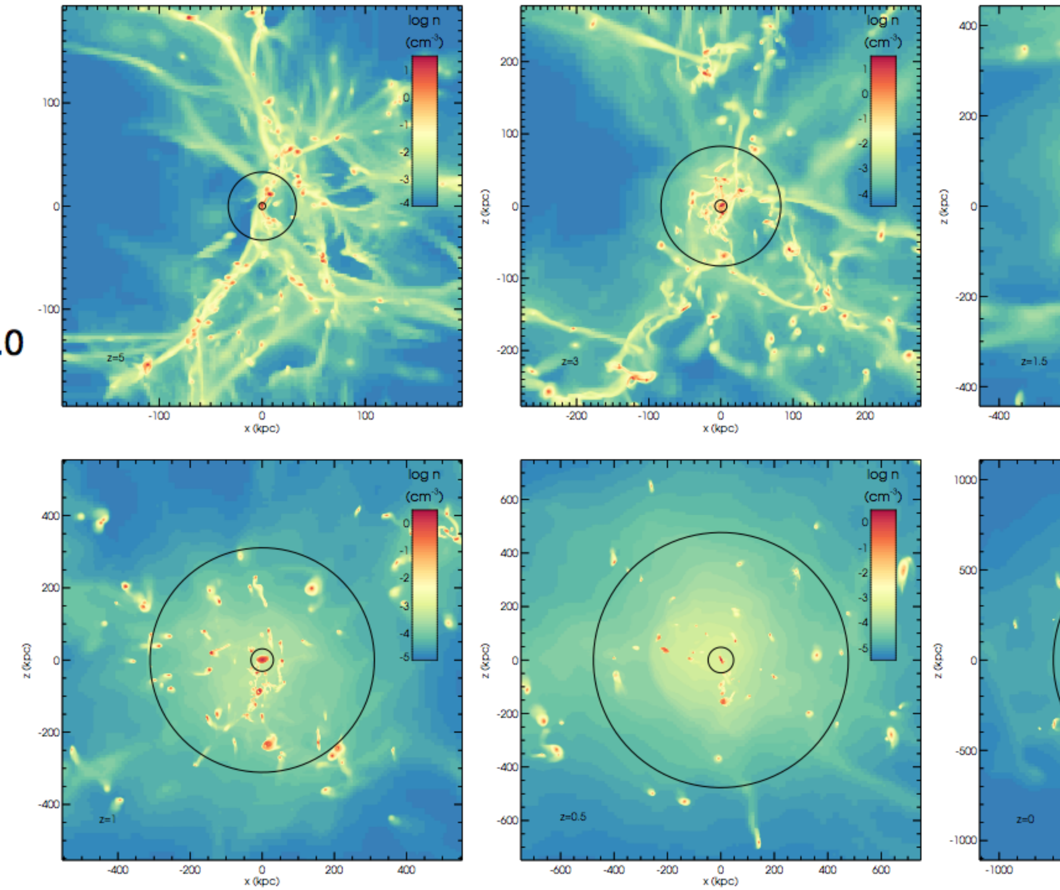
Kimm et al, 2012



Dubois et al, in prep.

Stellar mass in central massive galaxies

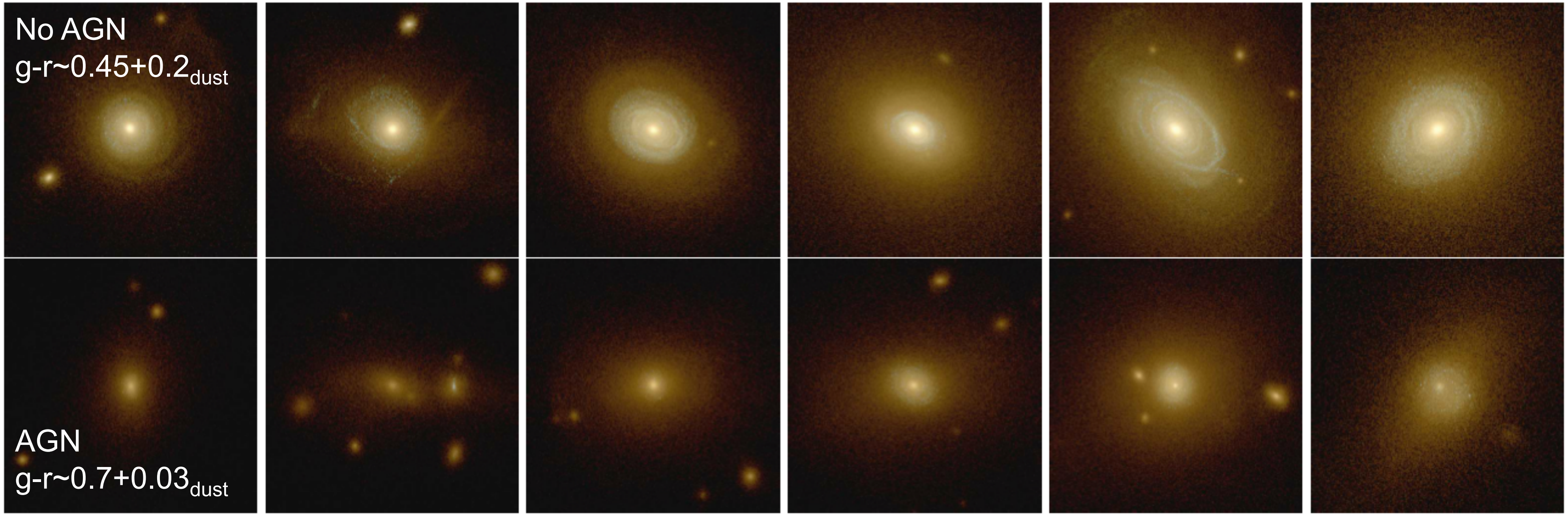




Dubois, Gavazzi, Peirani, Silk, 2013

Can we get massive galaxies that look like ellipticals ?

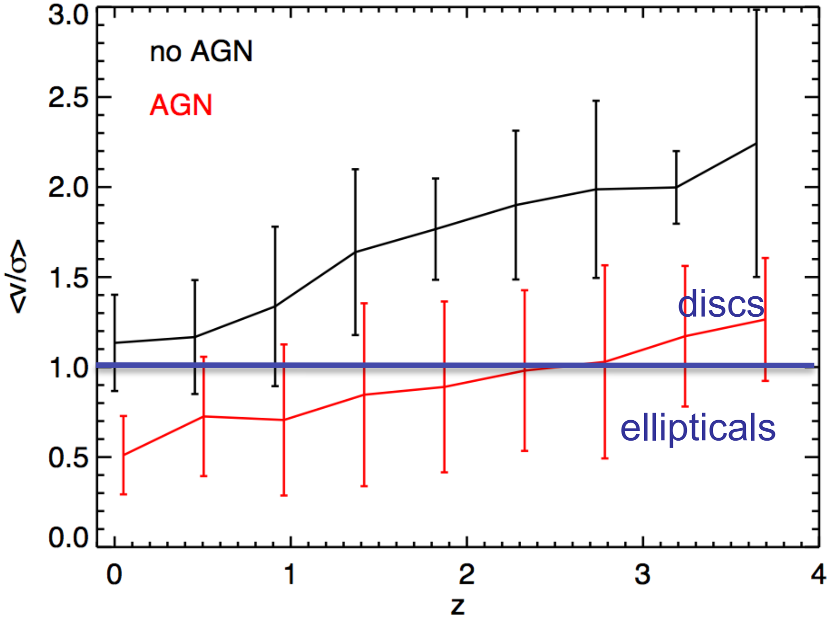
Increasing mass

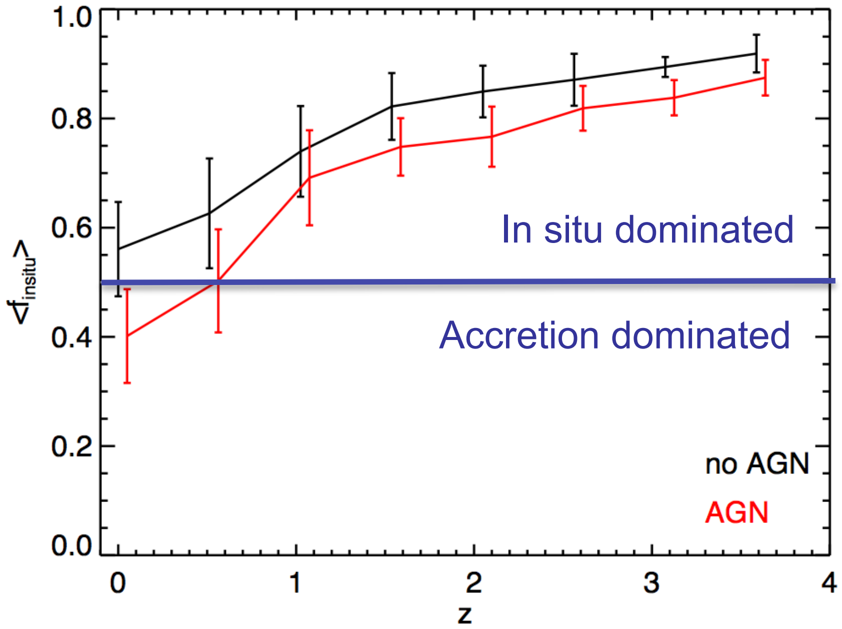


140 kpc

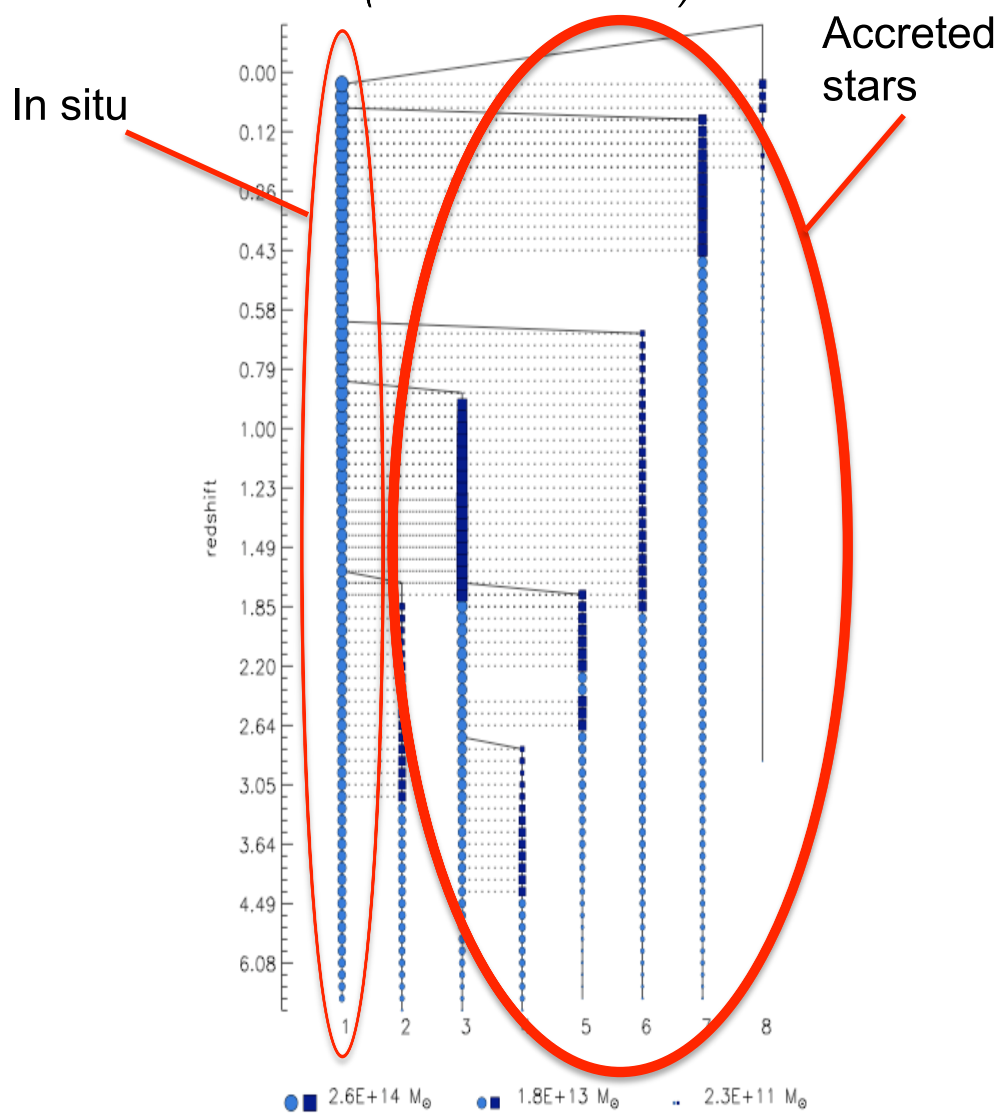
Dubois, Gavazzi, Peirani, Silk, 2013

Are they in rotation or supported by velocity dispersion ?



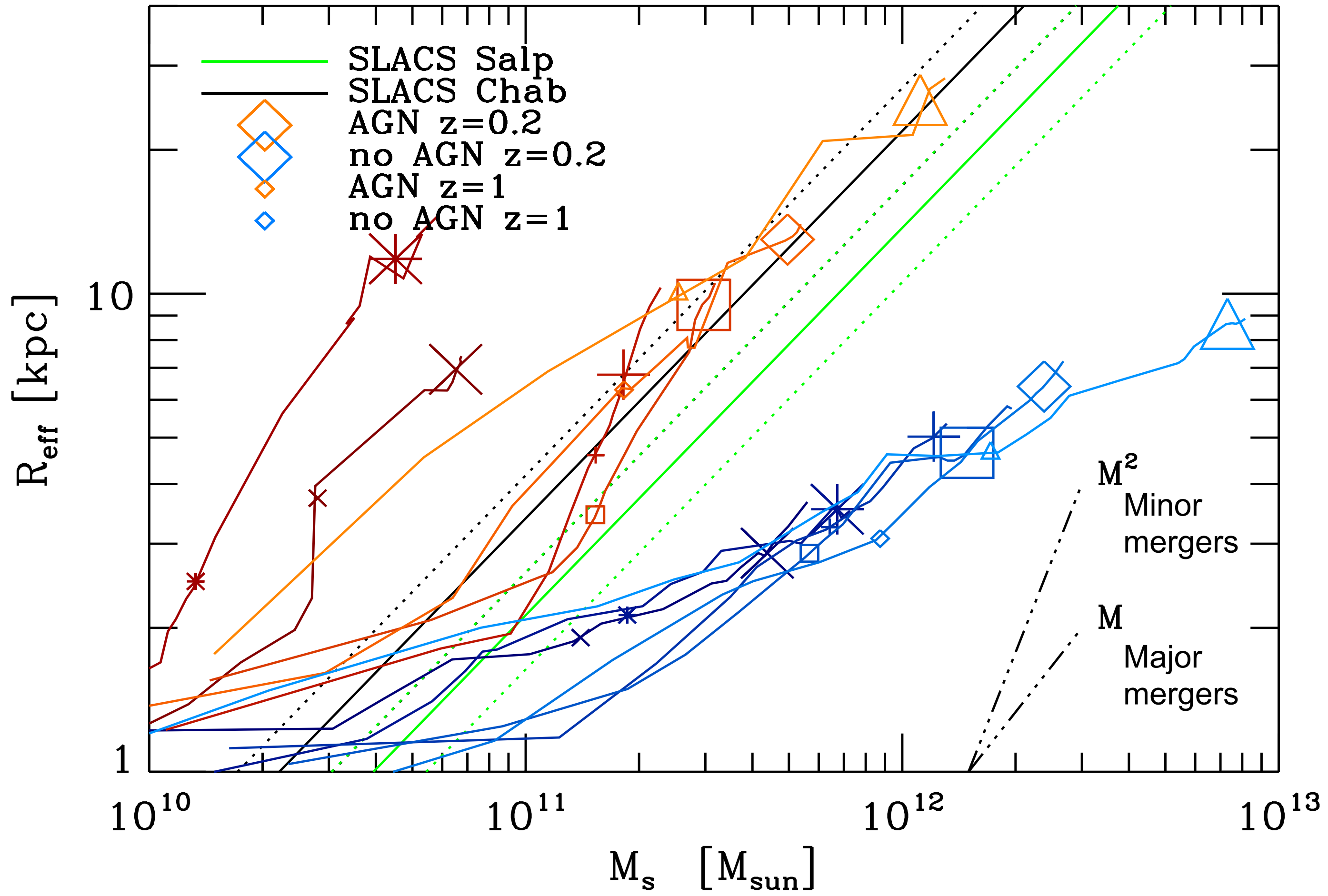


Merger tree
(Tweed et al. 2009)



Dubois, Gavazzi, Peirani, Silk, 2013

Changing the compactness of massive galaxies

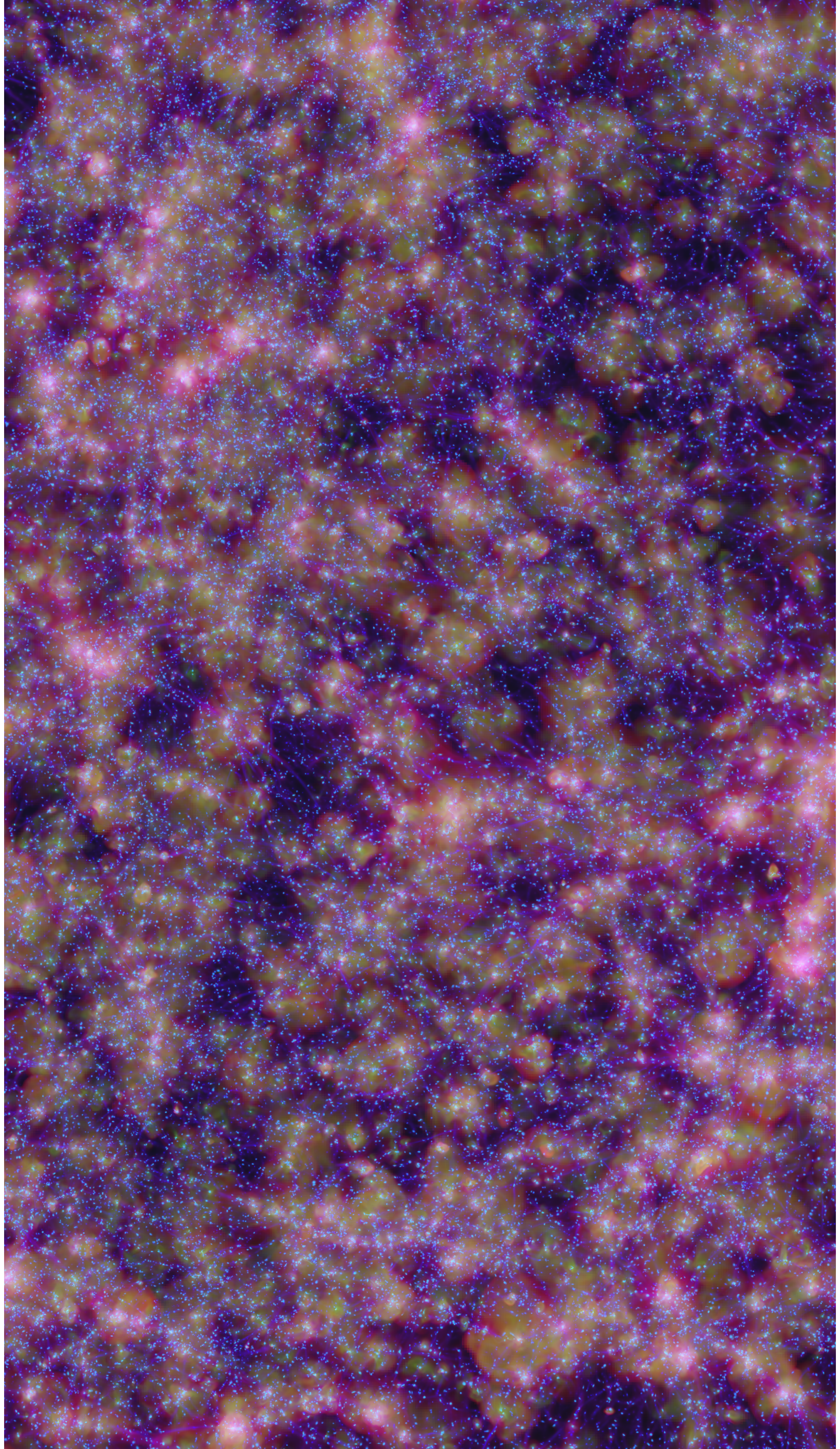


Dubois, Gavazzi, Peirani, Silk, 2013

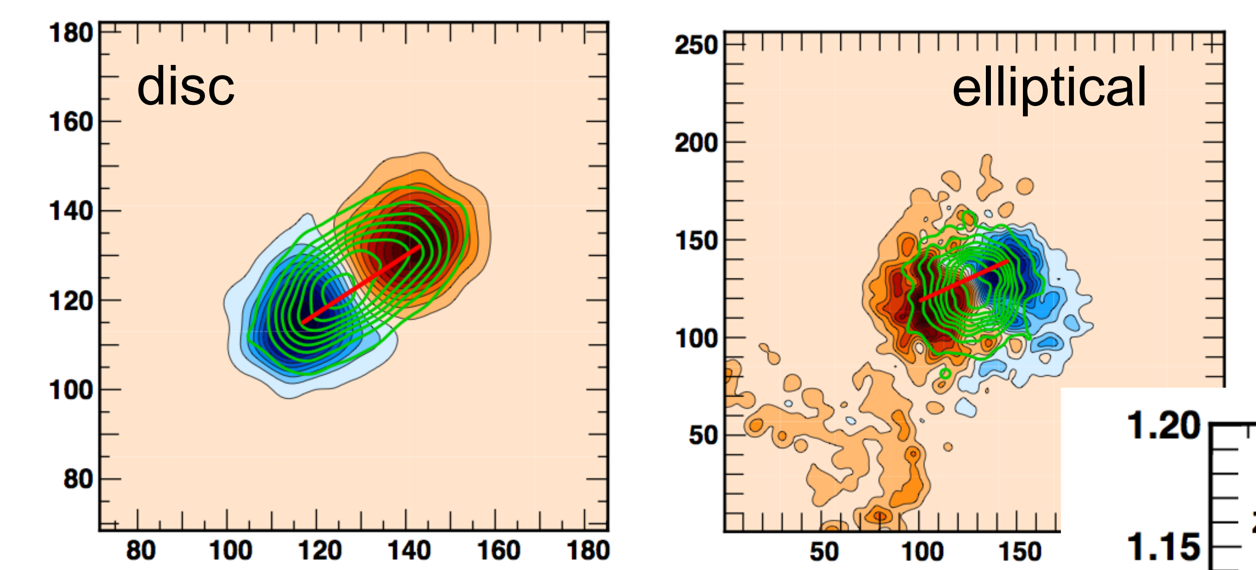
Get bigger

- Horizon-AGN simulation Jade (CINES)

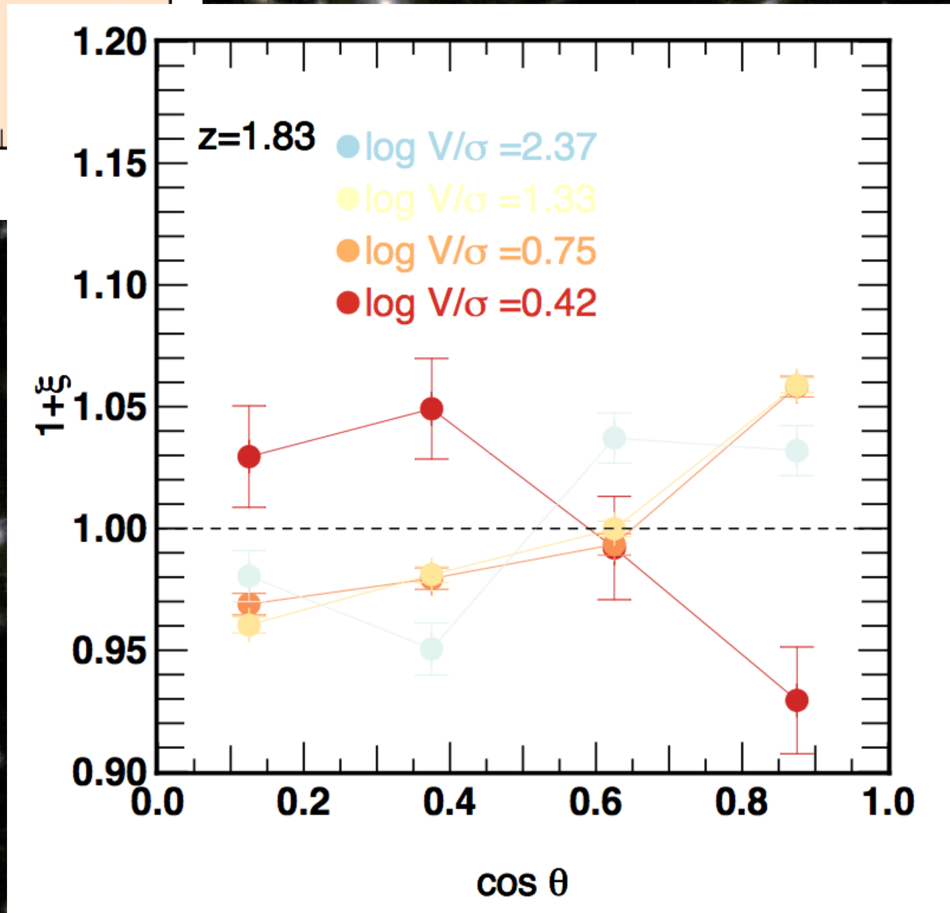
  (PI Y. Dubois, Co-I J. Devriendt & C. Pichon)
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8 \times 10^7\ M_{sun}$
  - Finest cell resolution dx=1 kpc
  - Gas cooling & UV background heating
  - Low efficiency star formation
  - Stellar winds + SNII + SNIa
  - O, Fe, C, N, Si, Mg, H
  - AGN feedback radio/quasar
- Outputs
  - Simulation outputs
  - Lightcones (1°x1°) performed on-the-fly
    - Dark Matter (position, velocity)
    - Gas (position, density, velocity, pressure, chemistry)
    - Stars (position, mass, velocity, age, chemistry)
    - Black holes (position, mass, velocity, accretion rate)
- z=1.5 using 3 Mhours on 4096 cores



Are the imprints of LSS noticeable on galaxy properties ?

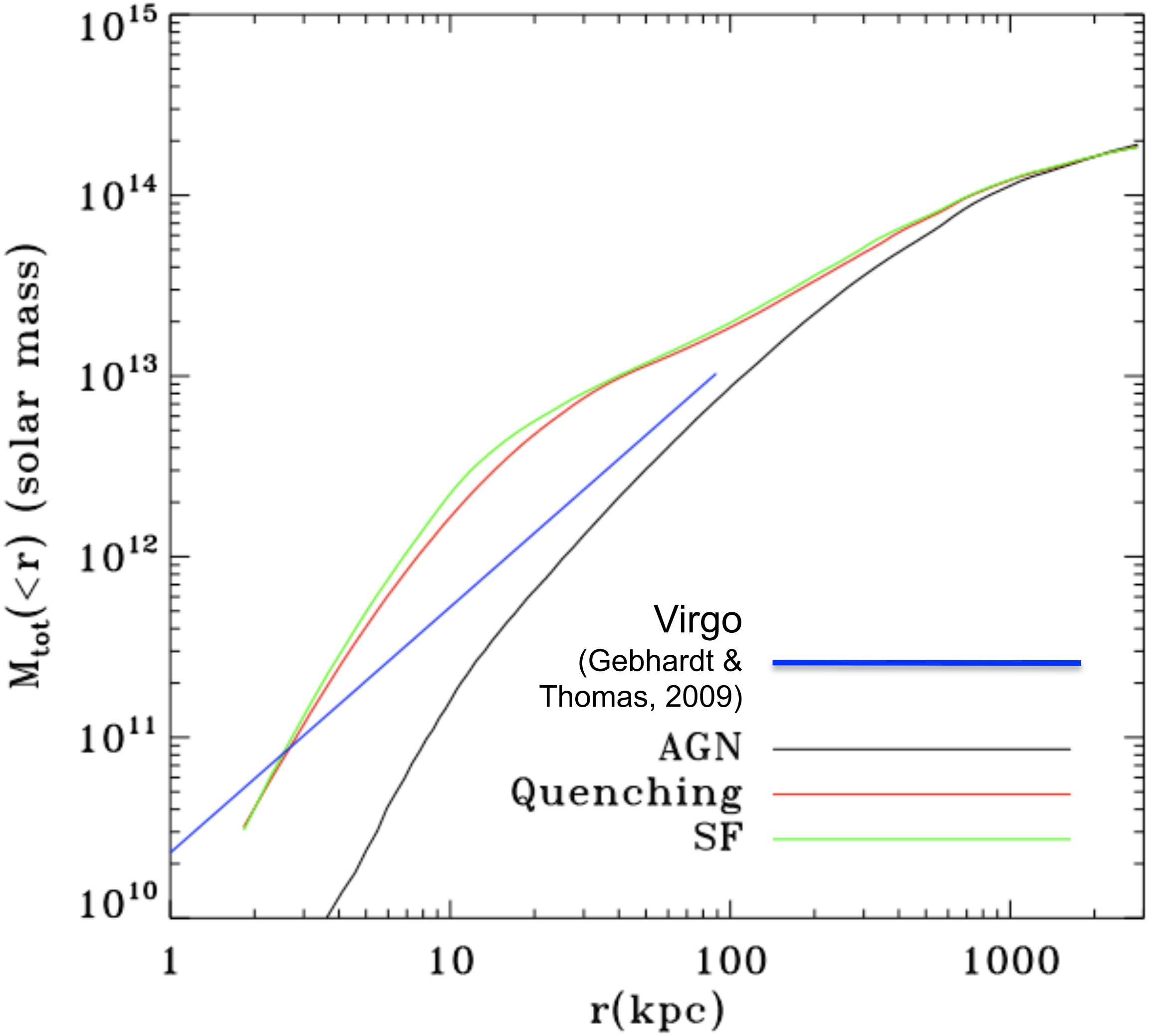


Horizon-AGN
>150 000 galaxies



Dubois et al, in prep.

Mass distribution in a Virgo-like cluster



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

Growing the first bright quasars

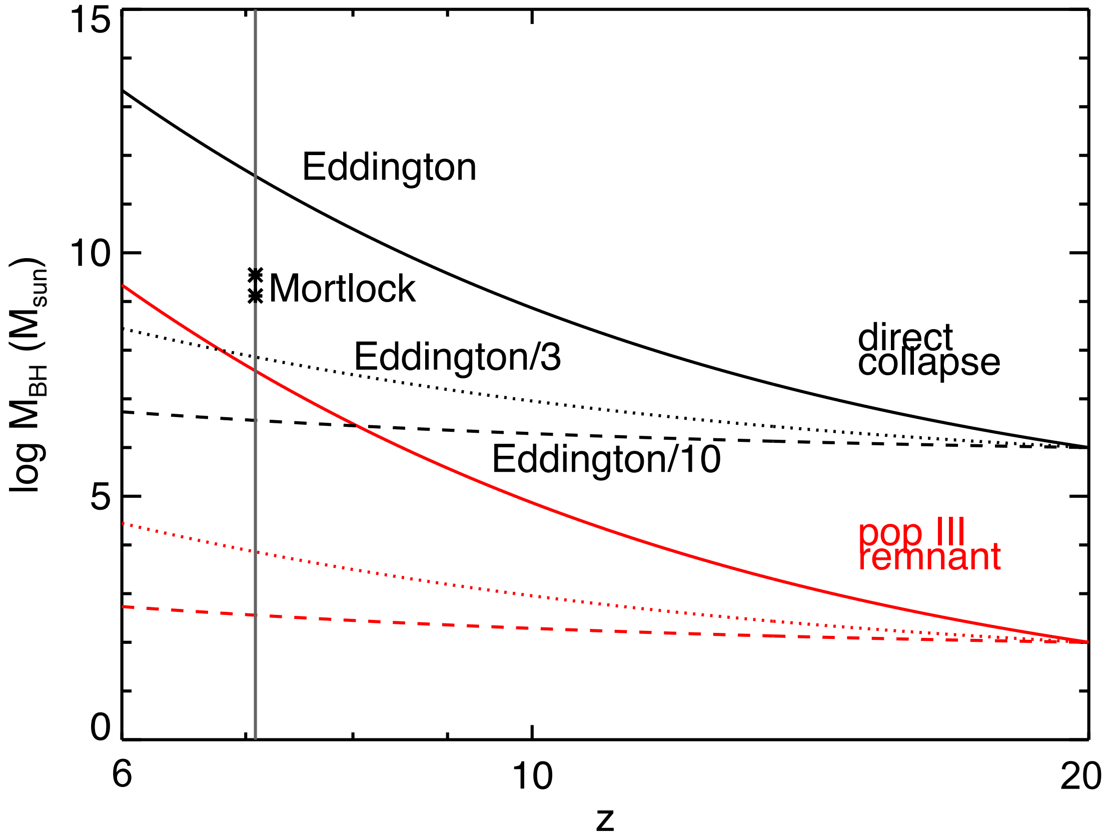
<u>Observationnal facts</u>:

- 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)

<u>Requirement</u>:

- 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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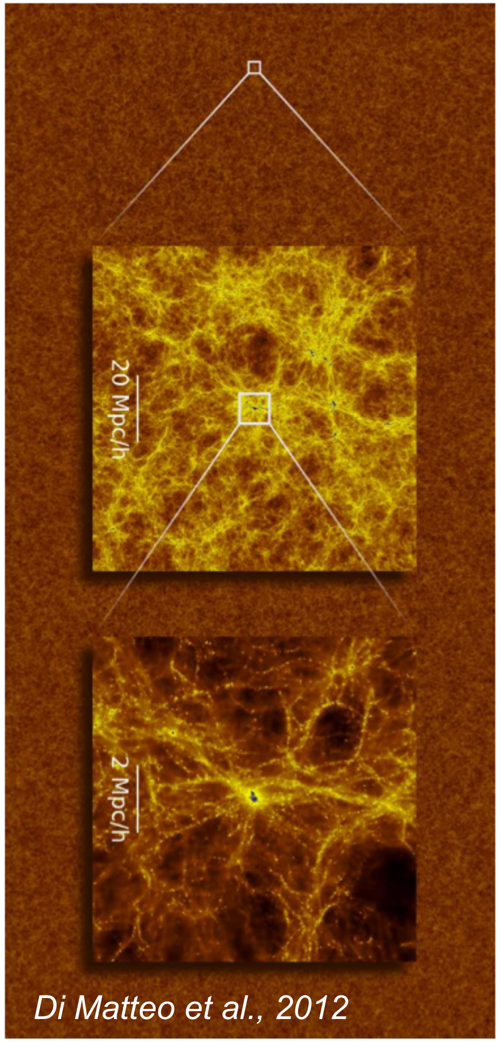

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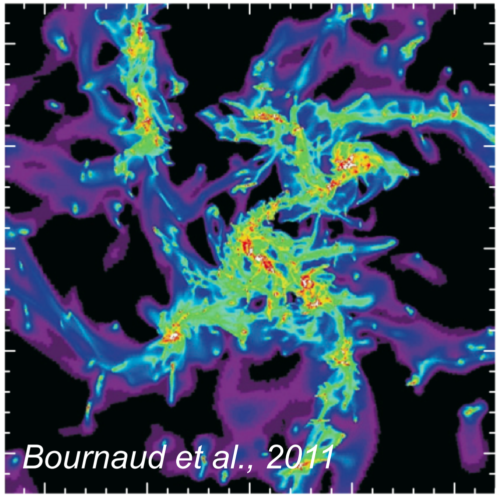
<u>Question</u>:
- How to bring gas sufficiently rapidly into the bulge of the galaxy ?



- 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

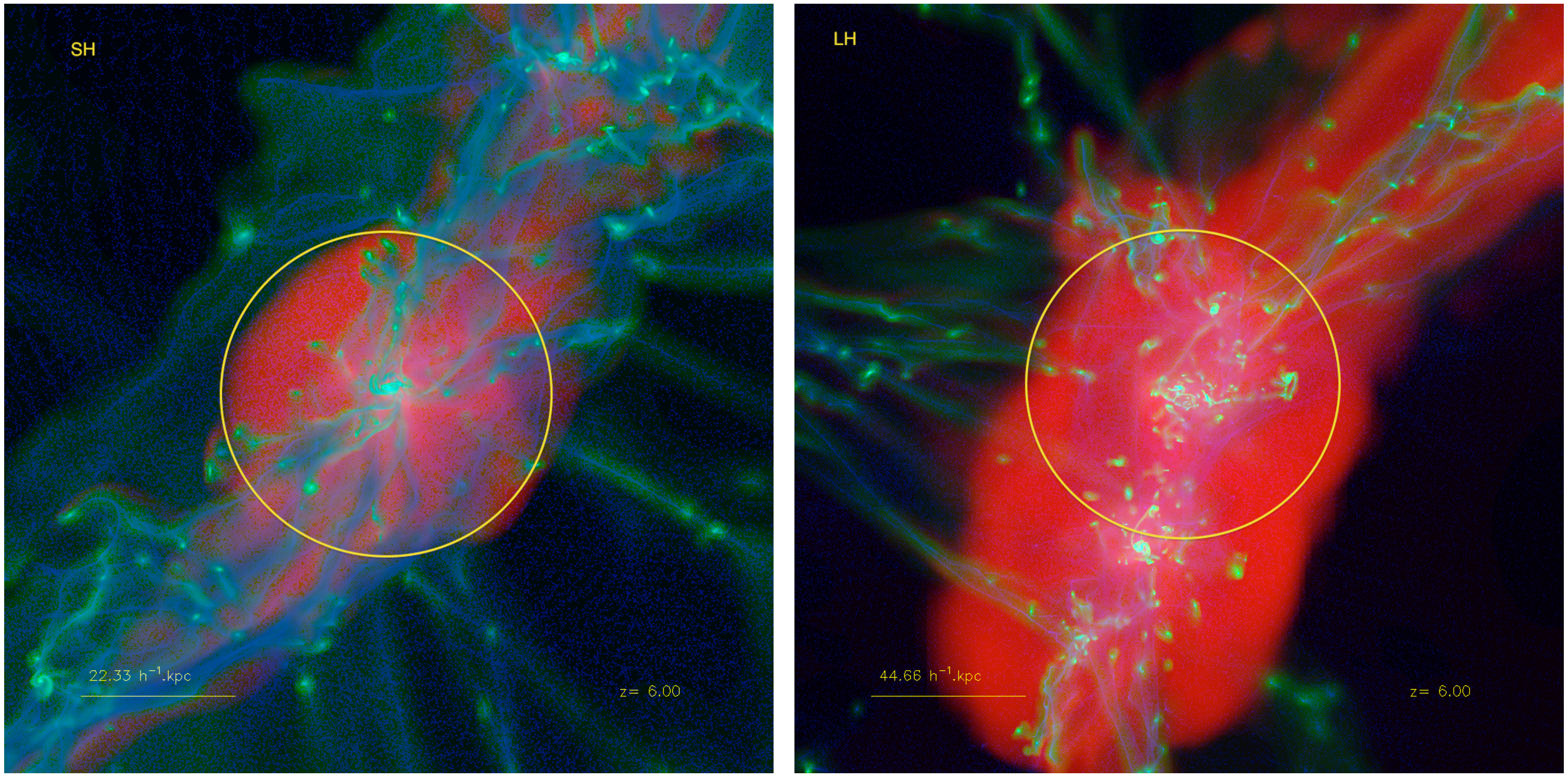
Very massive halos

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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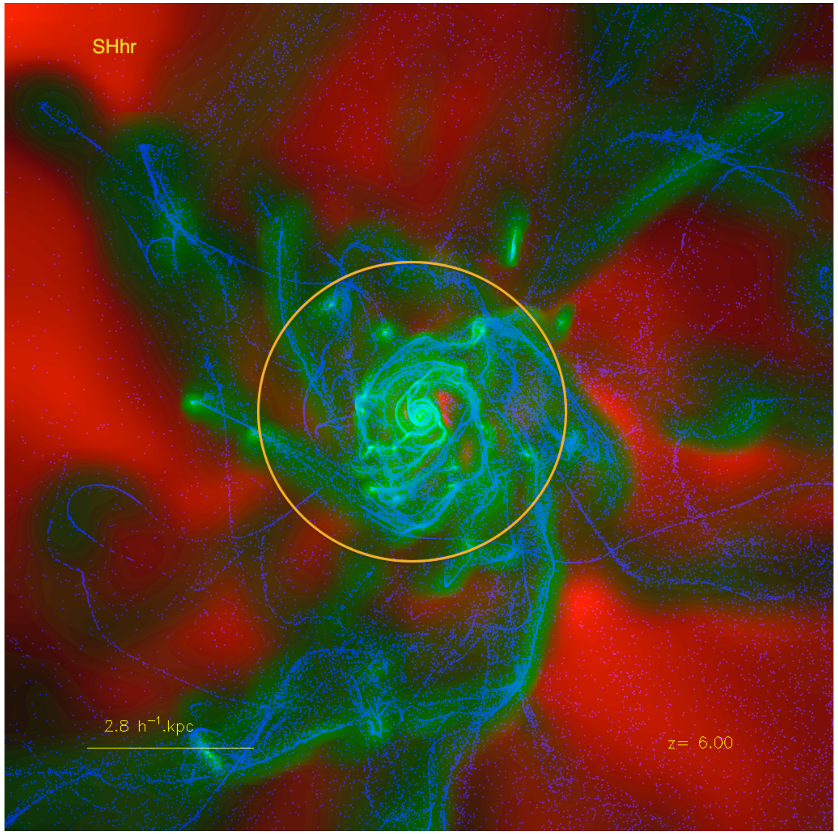
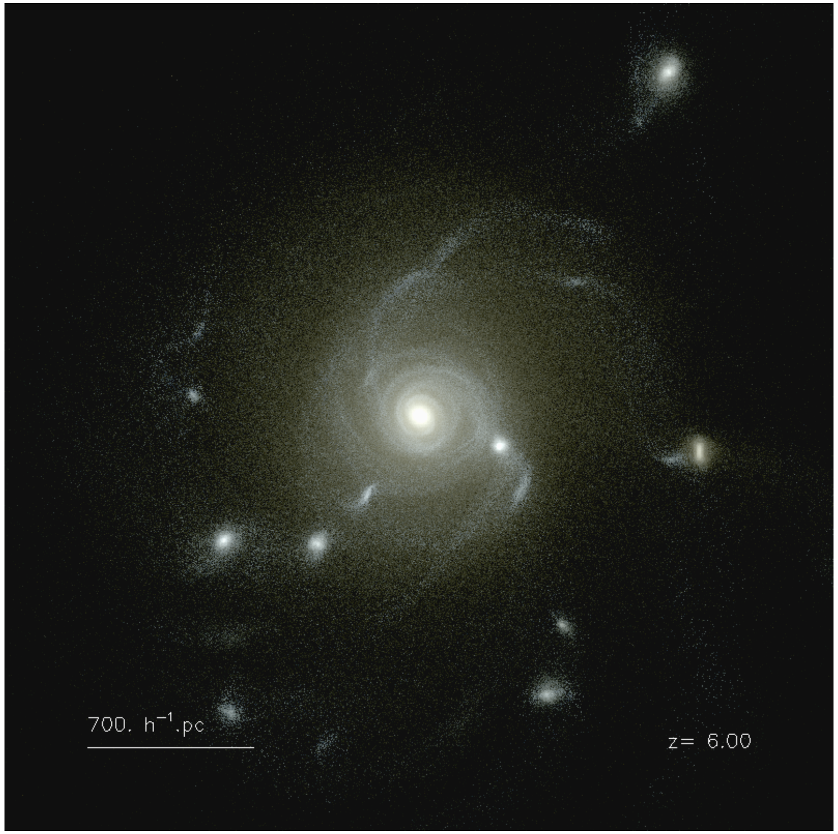
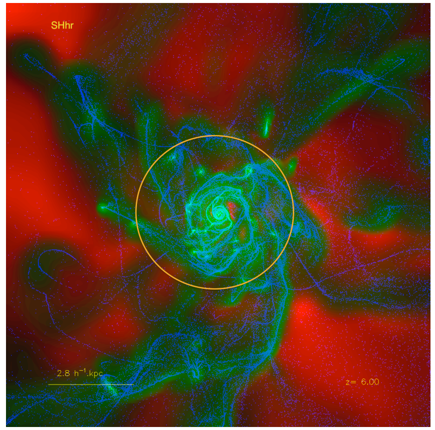
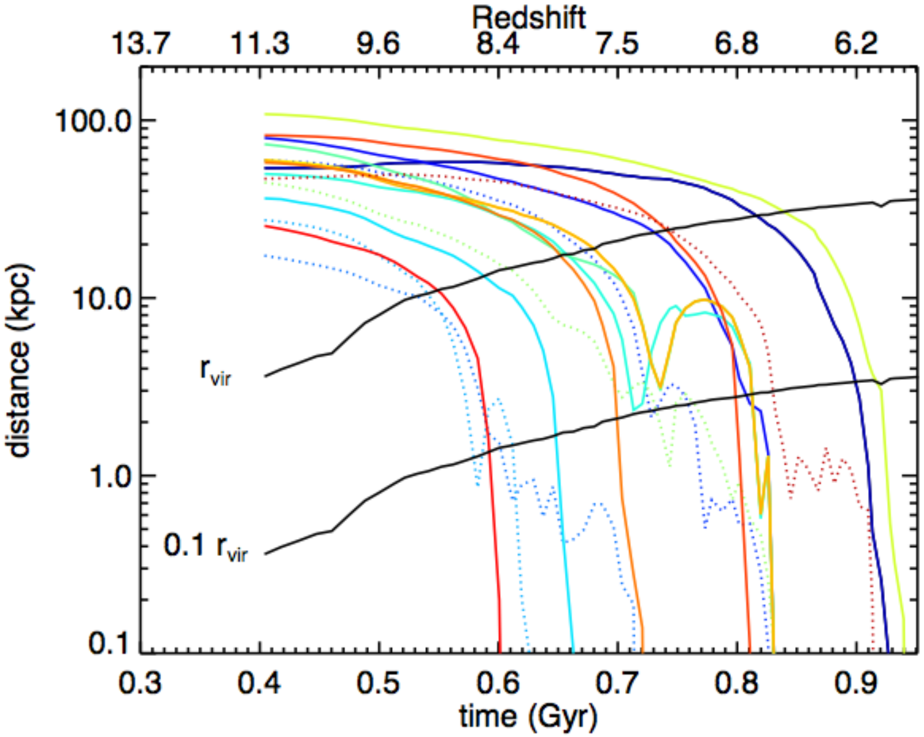


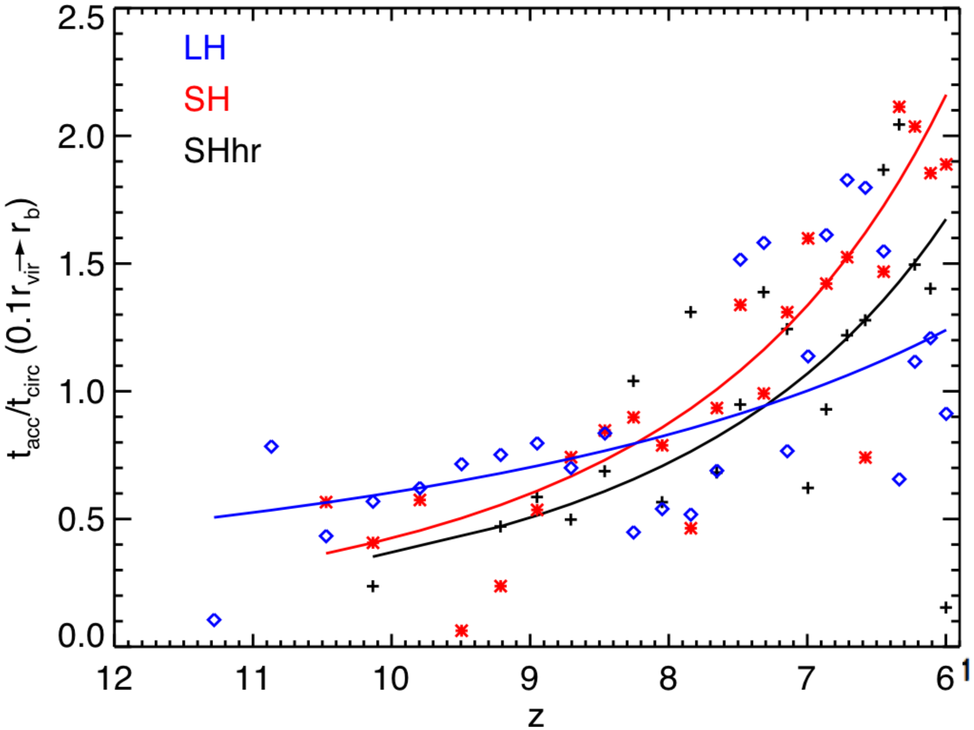


Follow the white rabbit…



Take the gas tracer particles that belong to the galactic bulge

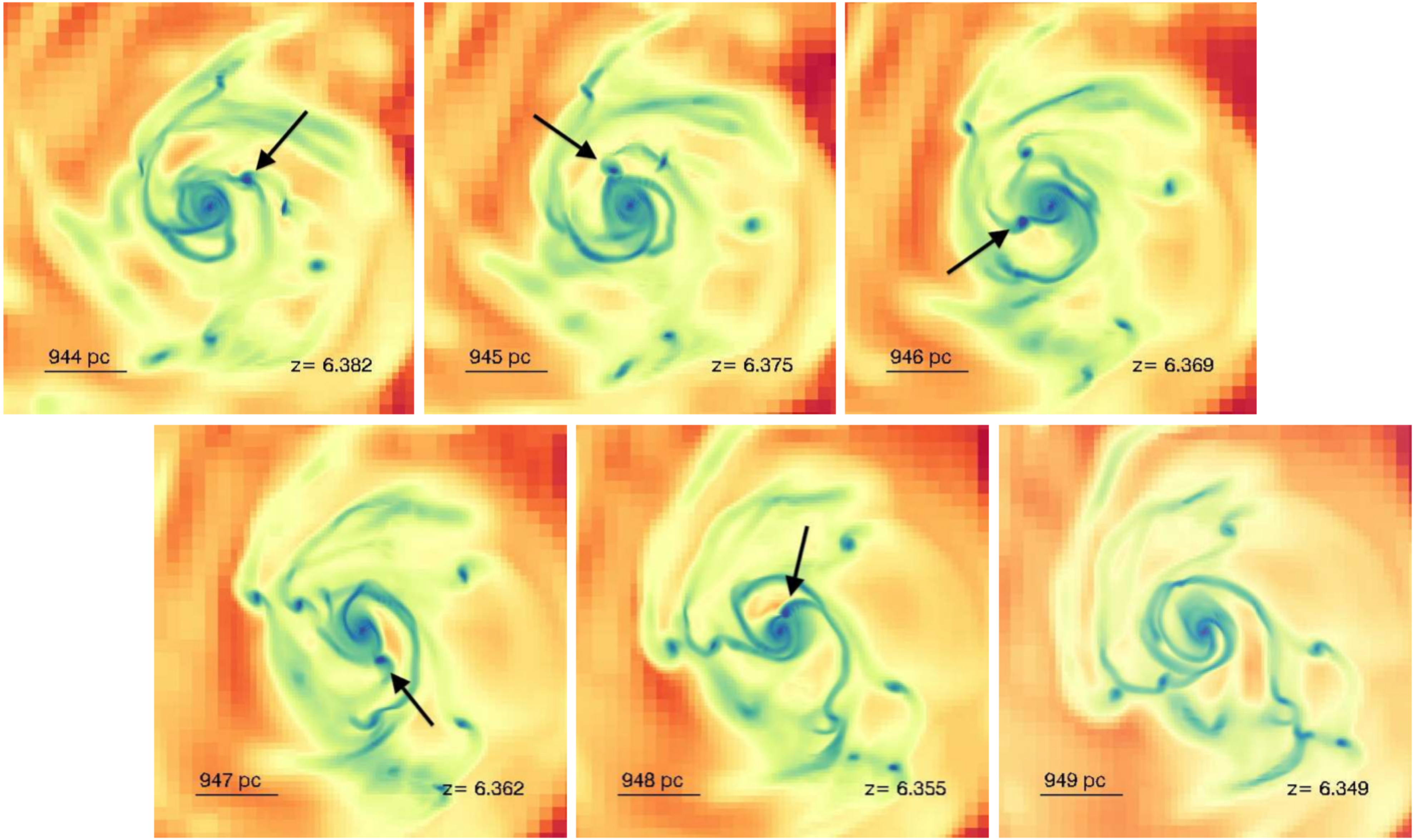




Dubois, Pichon, Haehnelt et al., 2012

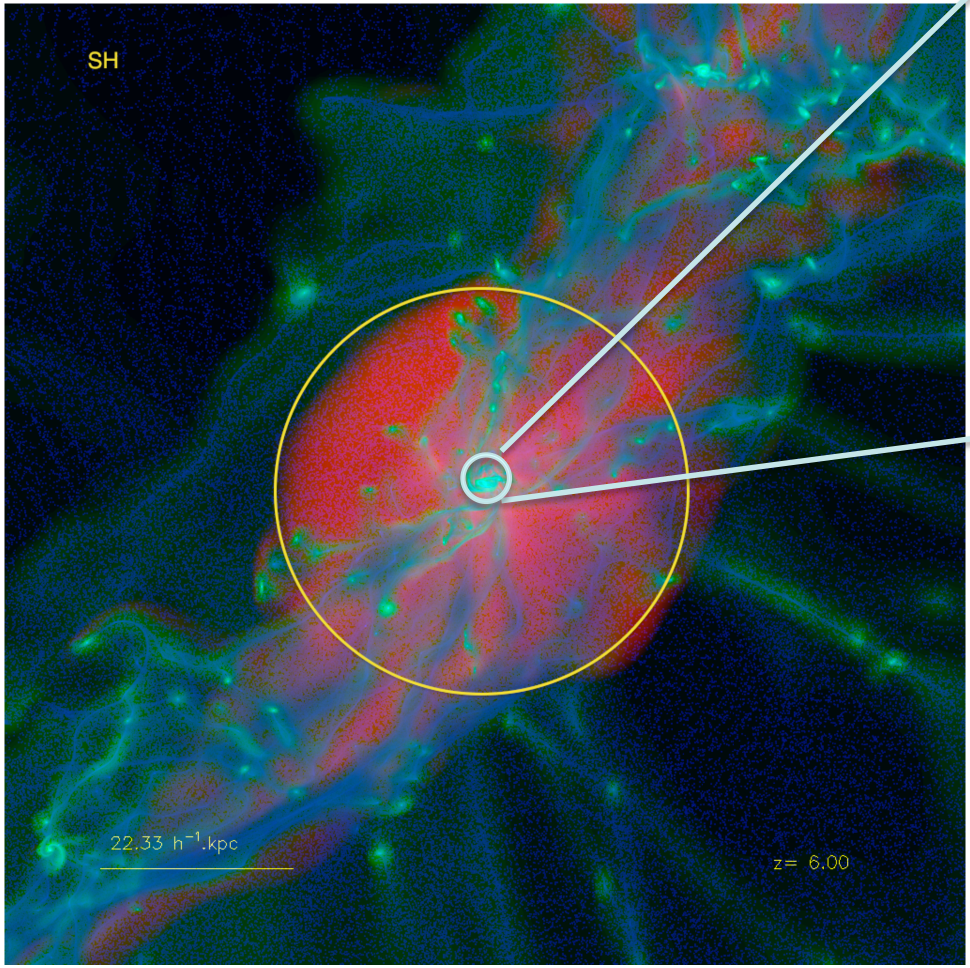
Late time gas infall do more rotations before being accreted.
Compatible with late-time cosmic filamentary infall having more angular momentum (Pichon et al., 2011, Kimm et al., arXiv:1106.0538, Codis et al., 2012)

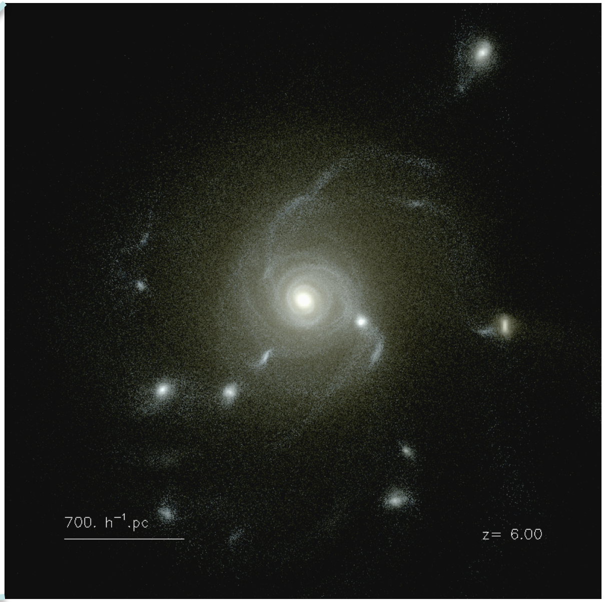
A rapid clump migration to trigger late-time AGN bursts



Dubois, Pichon et al., 2012

The good old picture





Dubois, Pichon et al, 2012, 2013

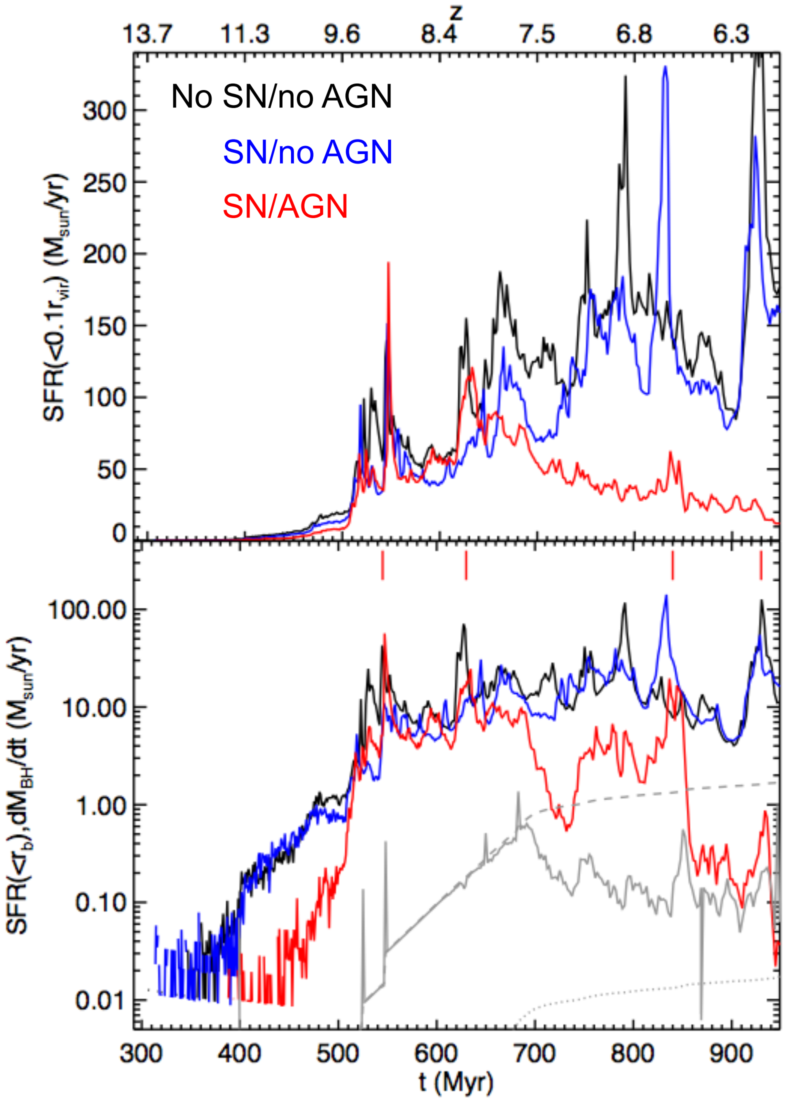
- Cold collimated streams of gas plunges into halos.
-They feed the central galaxy with large amounts of fresh material
- All of this neglects the role of (any) feedback

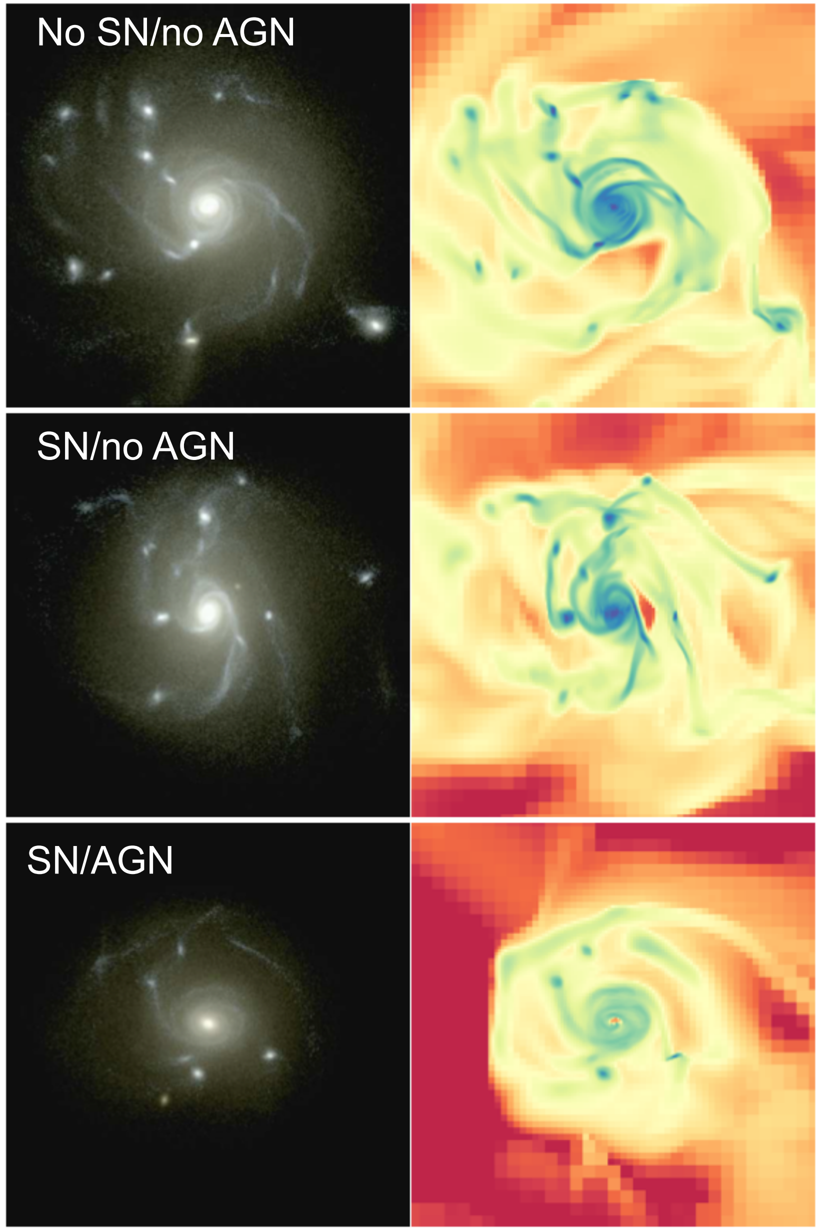
What about the impact of feedback on the gas accretion ?

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)

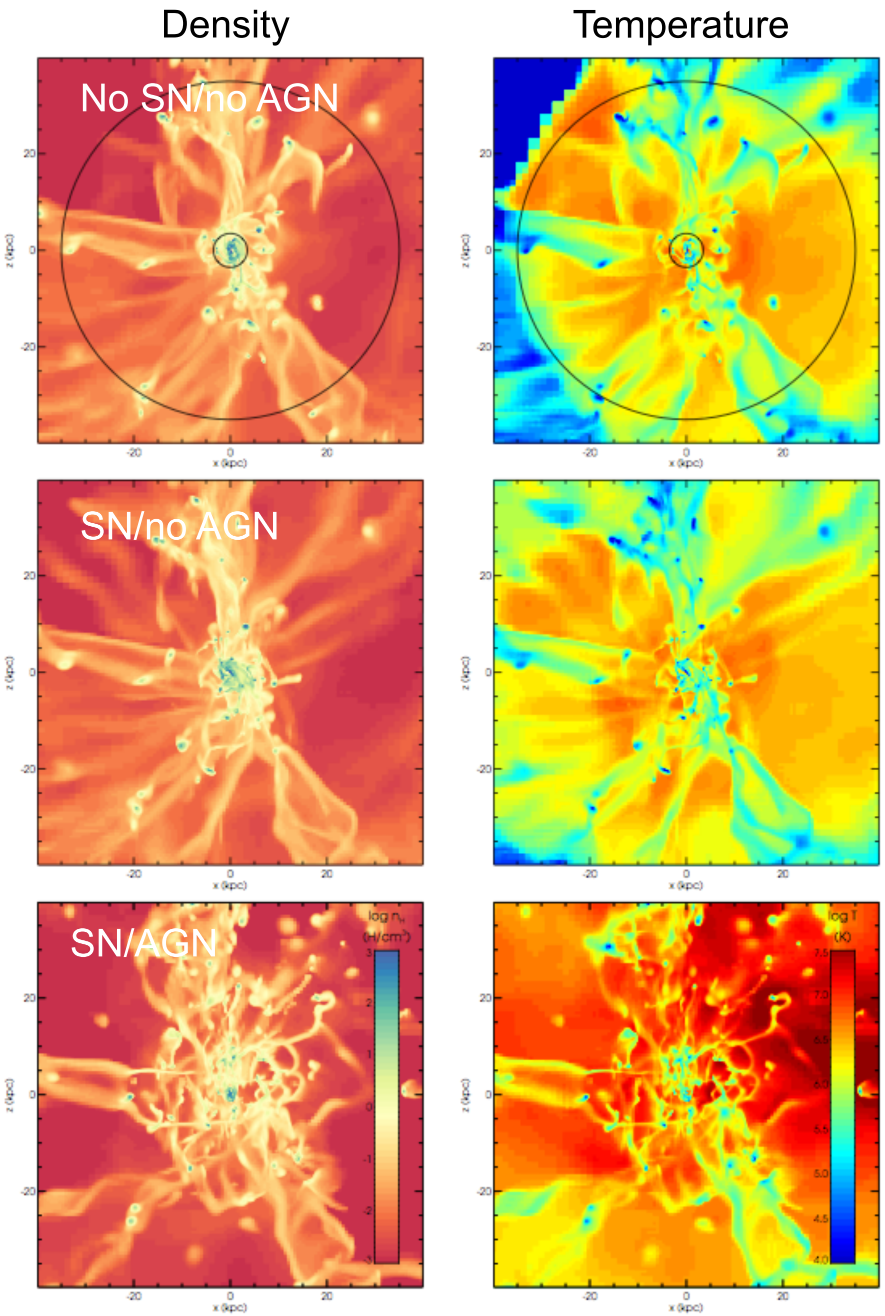
AGN quenches star formation efficiently early-on





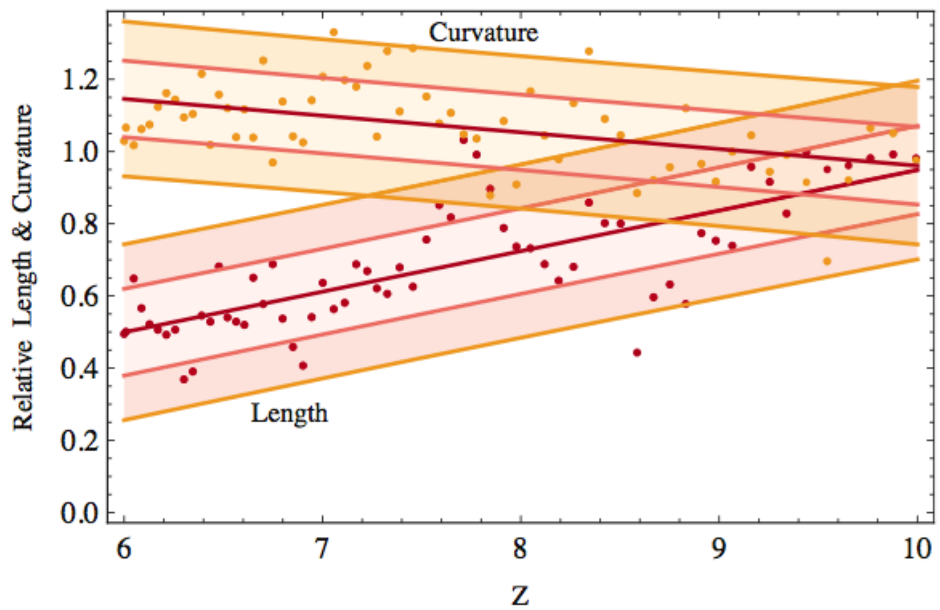
Dubois, Pichon et al., 2013

AGN blows cold flows away



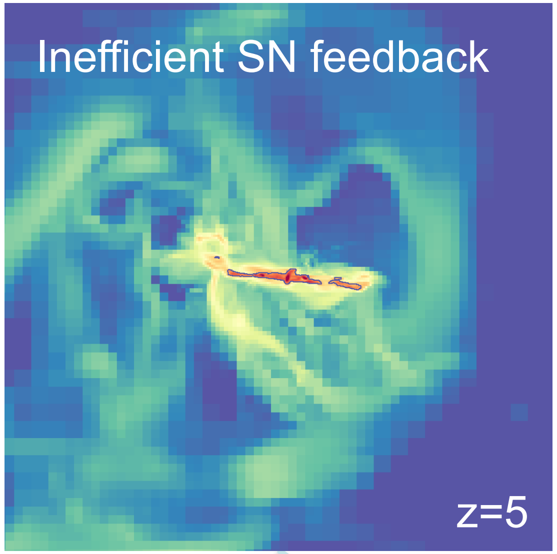
Gas is driven out hot from the central galaxy due to AGN.

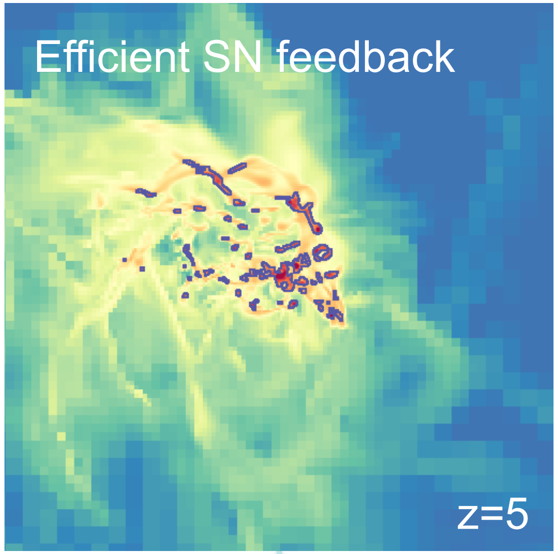
Cold filaments are repelled from the halo. Their structure is strongly perturbed (Skeleton, *Sousbie et al, 2009*)

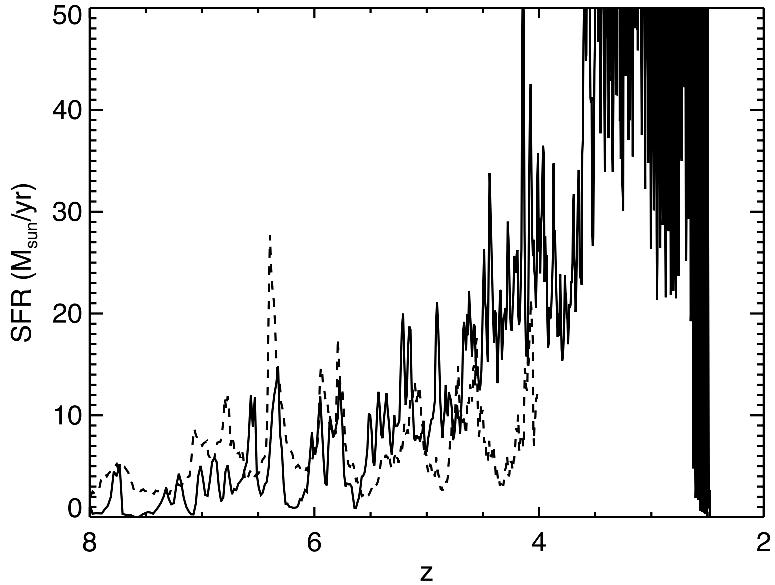


Dubois, Pichon et al., 2013

BH growth quenched by (too?) efficient SN feedback







"Inefficient": kinetic blast wave model (Dubois & Teyssier, 2008)

"Efficient": non-thermal component (CR, turbulence, magnetic fields) that delays gas cooling (Teyssier et al, 2013)