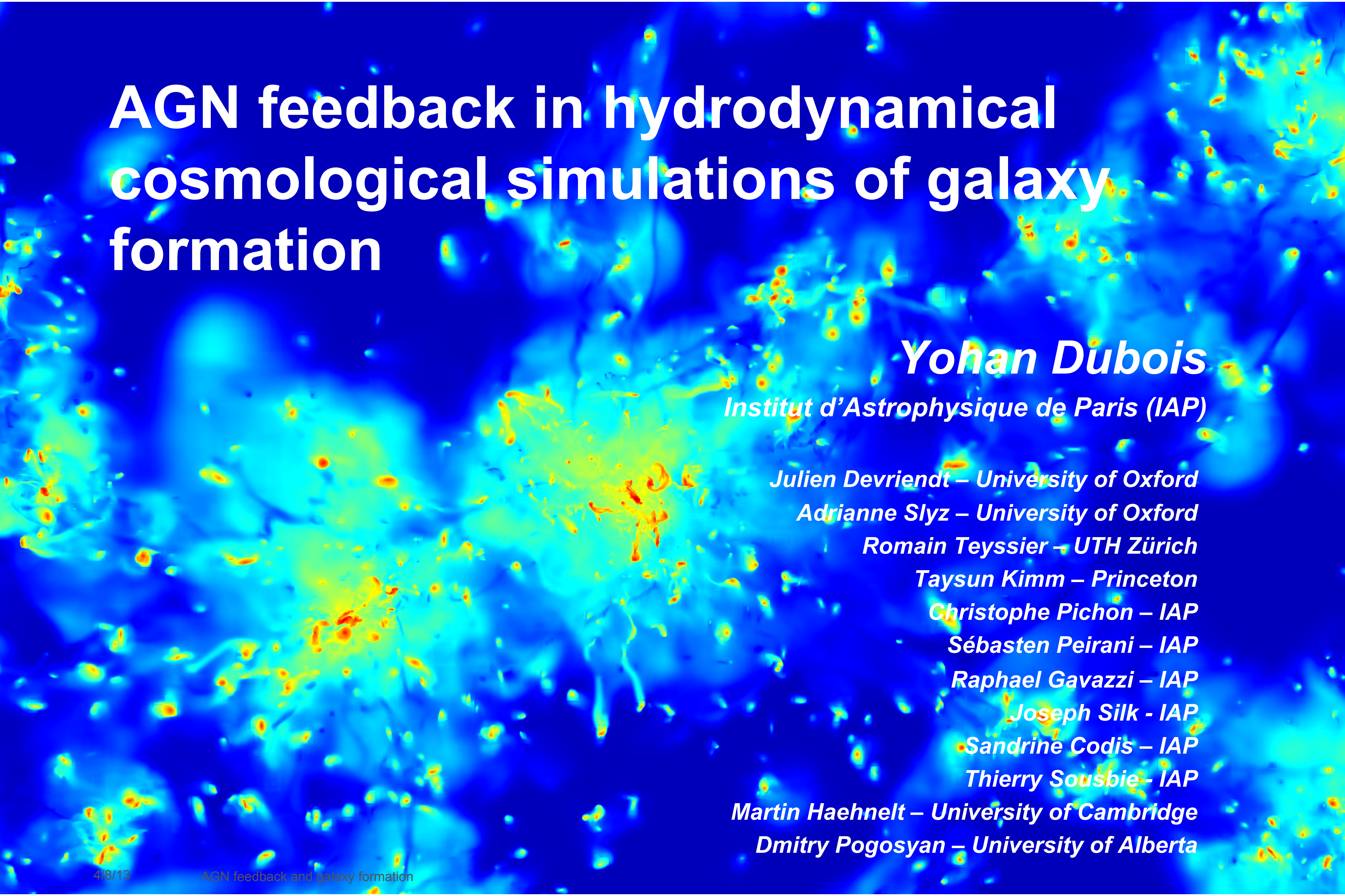

AGN feedback in hydrodynamical cosmological simulations of galaxy formation

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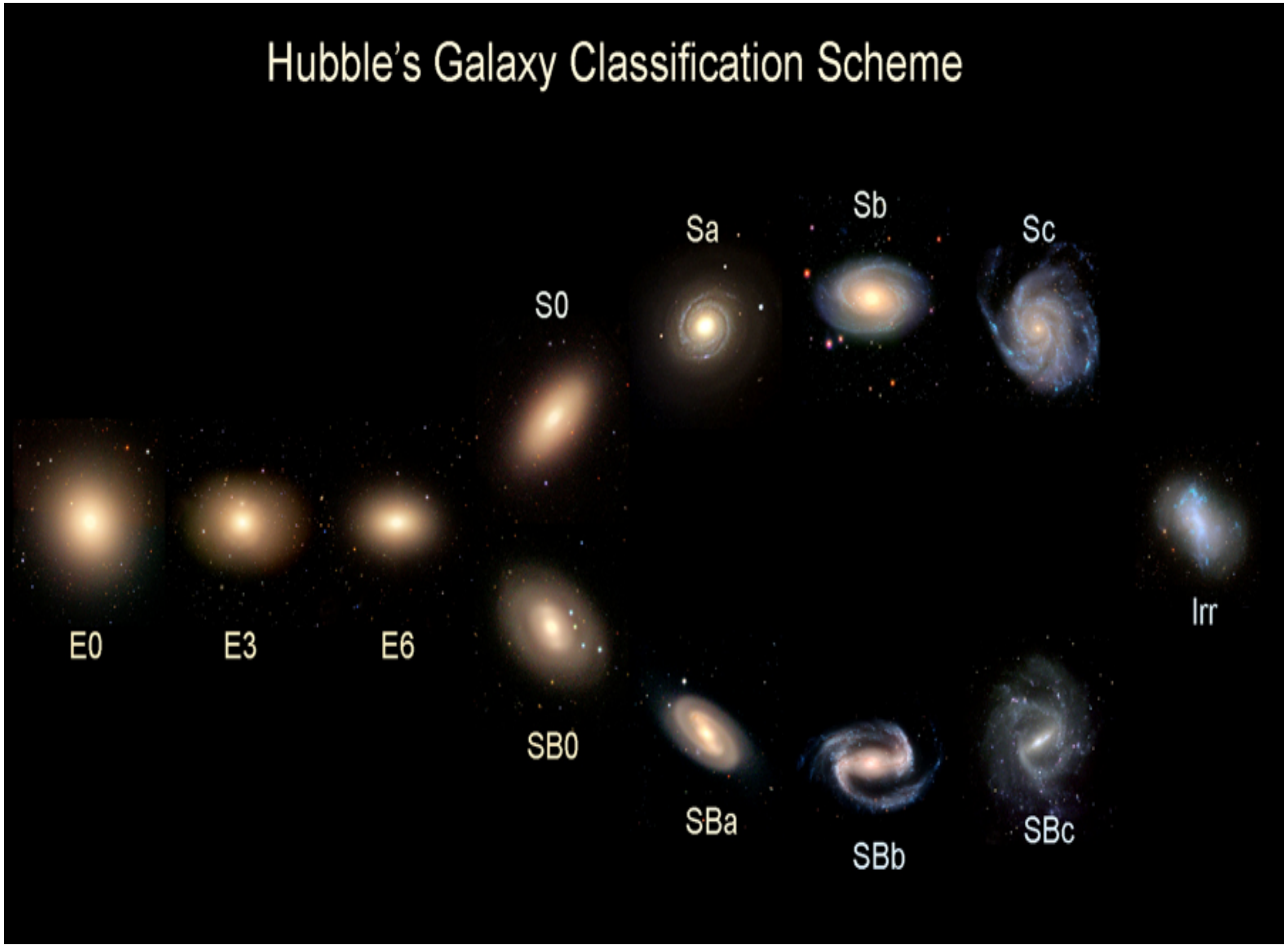
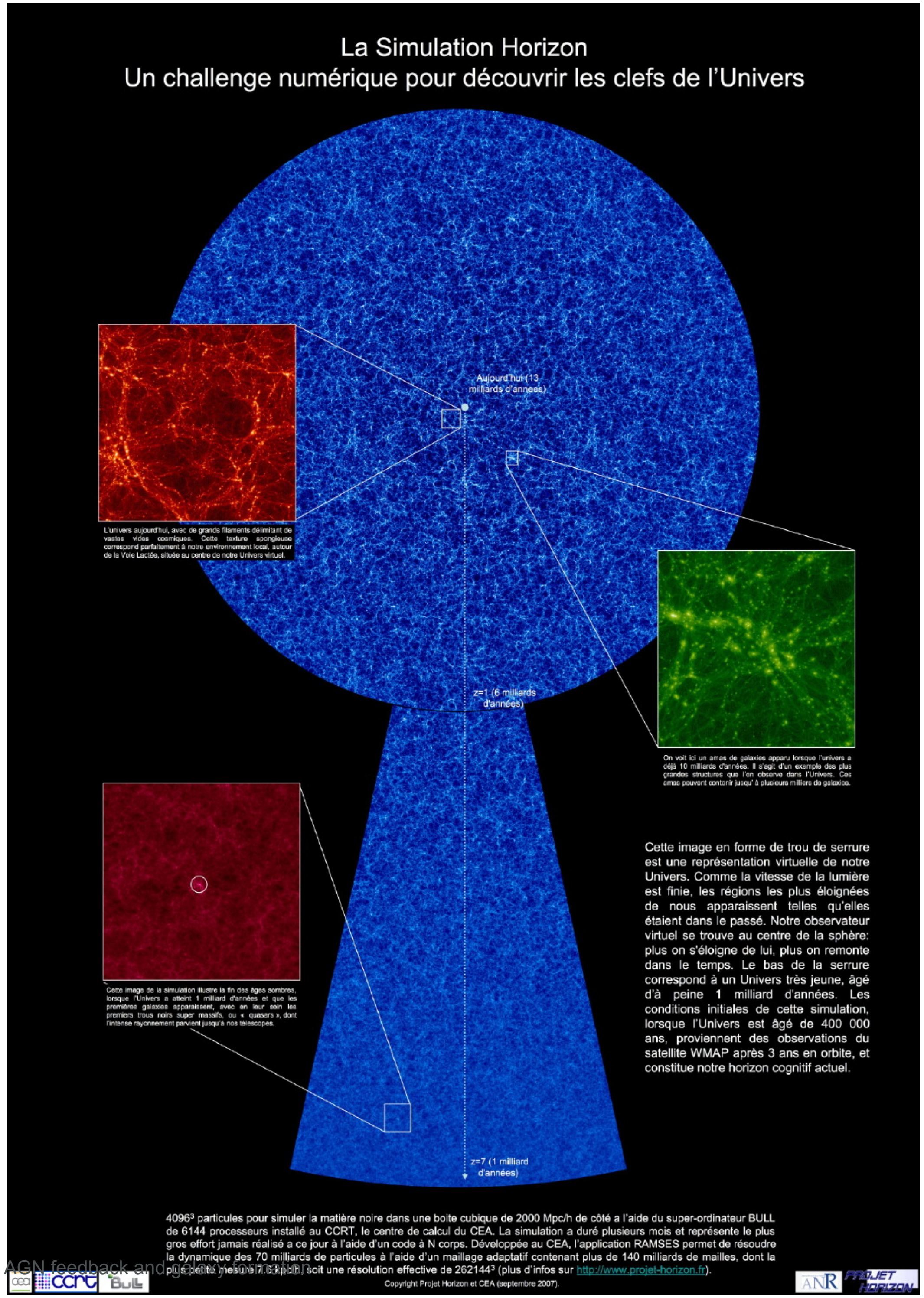
Romain Teyssier – UTH Zürich
Taysun Kimm – Princeton
Christophe Pichon – IAP
Sébasten Peirani – IAP
Raphael Gavazzi – IAP
Joseph Silk - IAP
Sandrine Codis – IAP
Thierry Sousbie - IAP
Martin Haehnelt – University of Cambridge
Dmitry Pogosyan – University of Alberta

A large variety of galaxies





La Simulation Horizon
Un challenge numérique pour découvrir les clefs de l'Univers

L'univers aujourd'hui, avec de grands filaments délimitant de vastes vides cosmiques. Cette texture spongieuse correspond parfaitement à notre environnement local, autour de la Voie Lactée, située au centre de notre Univers virtuel.

On voit ici un amas de galaxies apparu lorsque l'univers a déjà 10 milliards d'années. Il s'agit d'un exemple des plus grandes structures que l'on observe dans l'Univers. Ces amas peuvent contenir jusqu' à plusieurs milliers de galaxies.

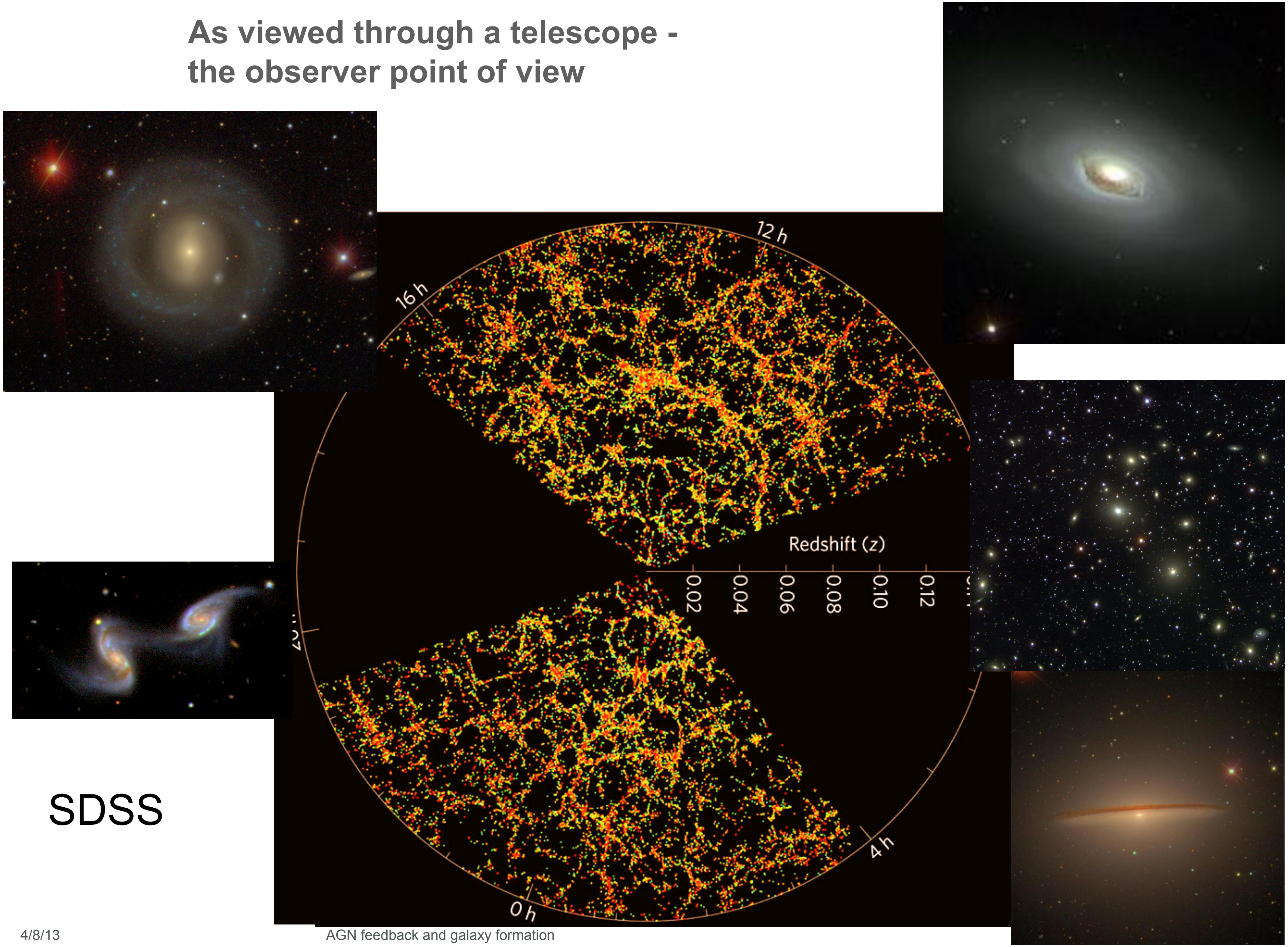
Cette image de la simulation illustre la fin des âges sombres, lorsque l'Univers a atteint 1 milliard d'années et que les premières galaxies apparaissent, avec en leur sein les premiers trous noirs super massifs, ou « quasars », dont l'intense rayonnement parvient jusqu'à nos télescopes.

Cette image en forme de trou de serrure est une représentation virtuelle de notre Univers. Comme la vitesse de la lumière est finie, les régions les plus éloignées de nous apparaissent telles qu'elles étaient dans le passé. Notre observateur virtuel se trouve au centre de la sphère: plus on s'éloigne de lui, plus on remonte dans le temps. Le bas de la serrure correspond à un Univers très jeune, âgé d'à peine 1 milliard d'années. Les conditions initiales de cette simulation, lorsque l'Univers est âgé de 400 000 ans, proviennent des observations du satellite WMAP après 3 ans en orbite, et constitue notre horizon cognitif actuel.

4096^3 particules pour simuler la matière noire dans une boite cubique de 2000 Mpc/h de côté a l'aide du super-ordinateur BULL de 6144 processeurs installé au CCRT, le centre de calcul du CEA. La simulation a duré plusieurs mois et représente le plus gros effort jamais réalisé a ce jour à l'aide d'un code à N corps. Développée au CEA, l'application RAMSES permet de résoudre la dynamique des 70 milliards de particules à l'aide d'un maillage adaptatif contenant plus de 140 milliards de mailles, dont la plus petite mesure 7.6 kpc/h, soit une résolution effective de 262144^3 (plus d'infos sur http://www.projet-horizon.fr).

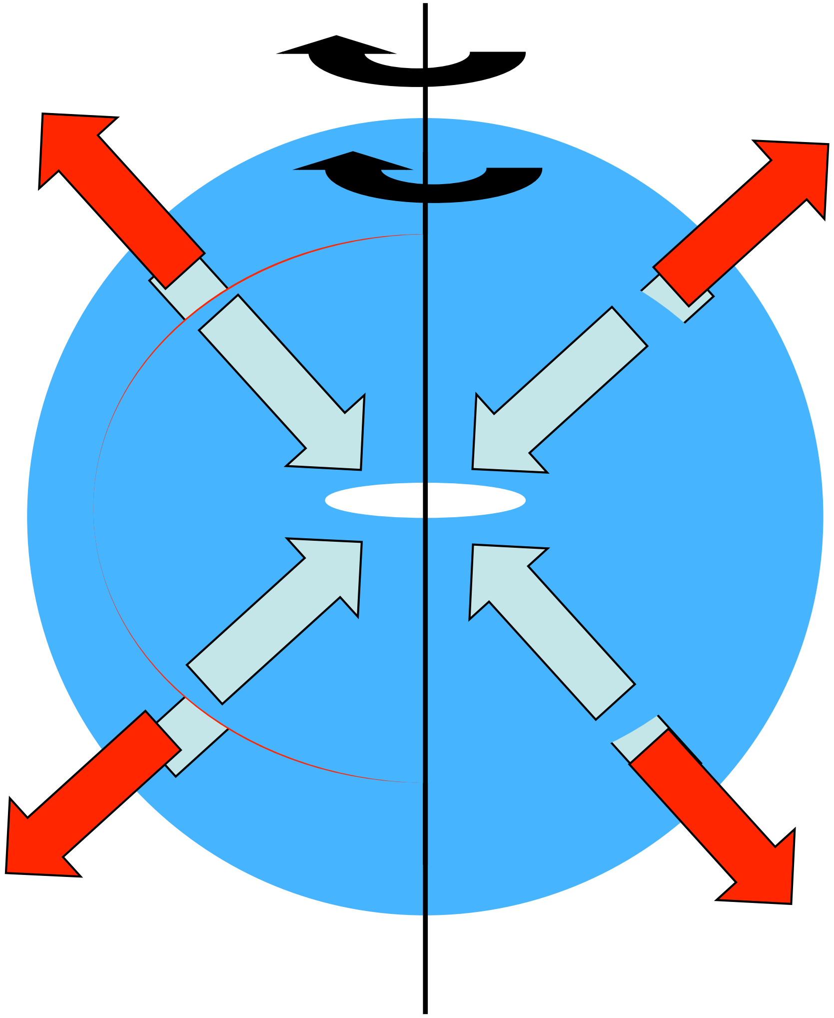
Teyssier, et al., 2009

As viewed through a telescope - the observer point of view



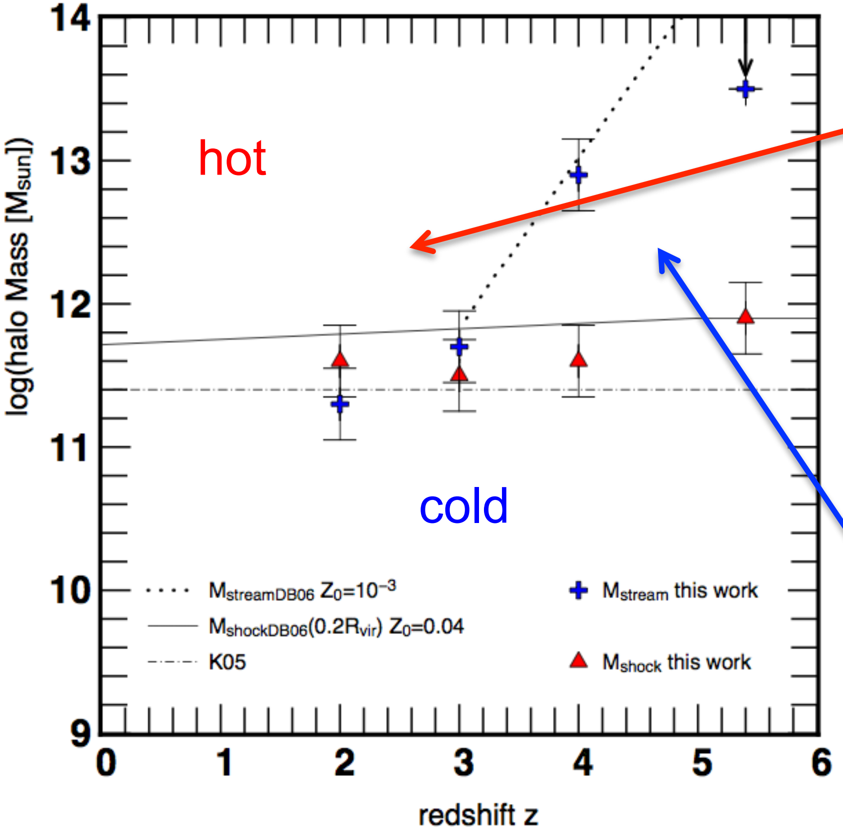
SDSS

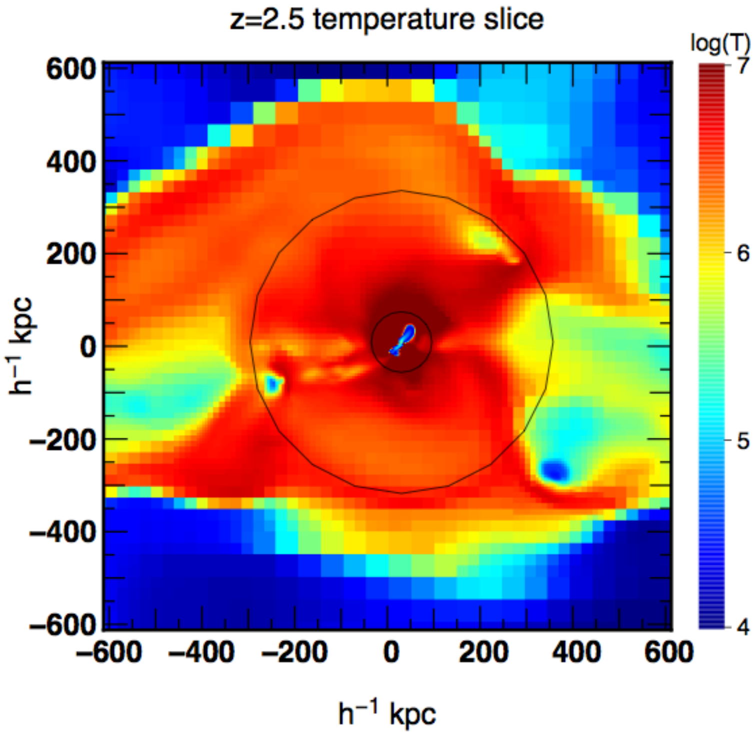
How do galaxies form ? (crude picture)

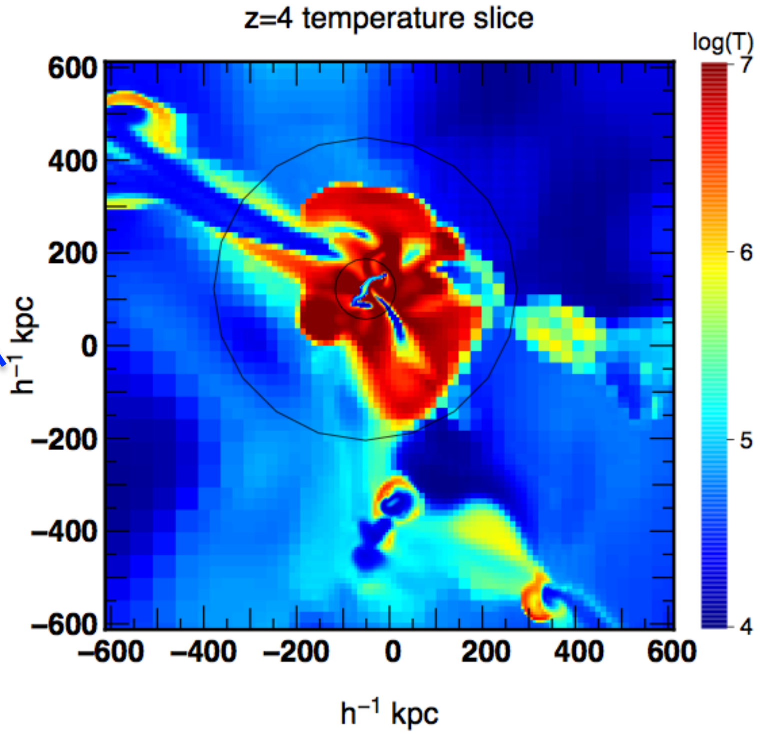


A bit more complicated…

Cold flows or Hot flows

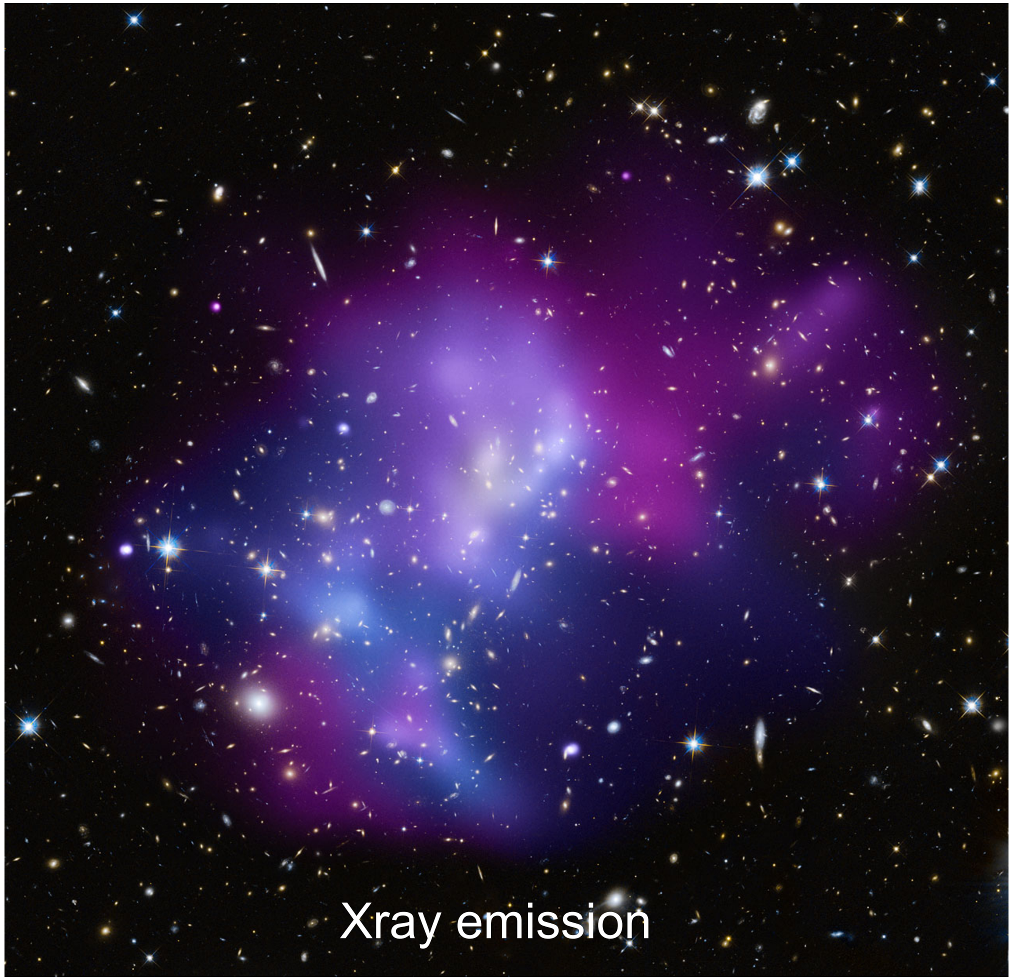


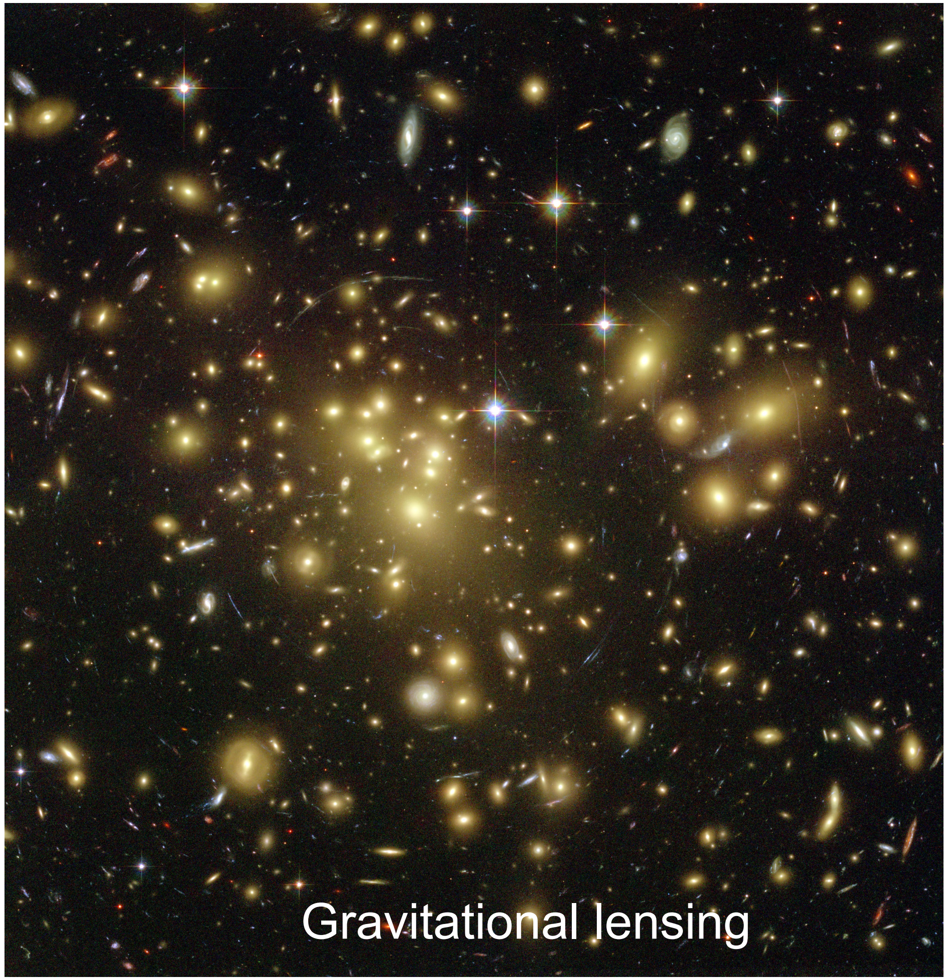




Ocvirk et al., 2008

Observations support the hot halo picture

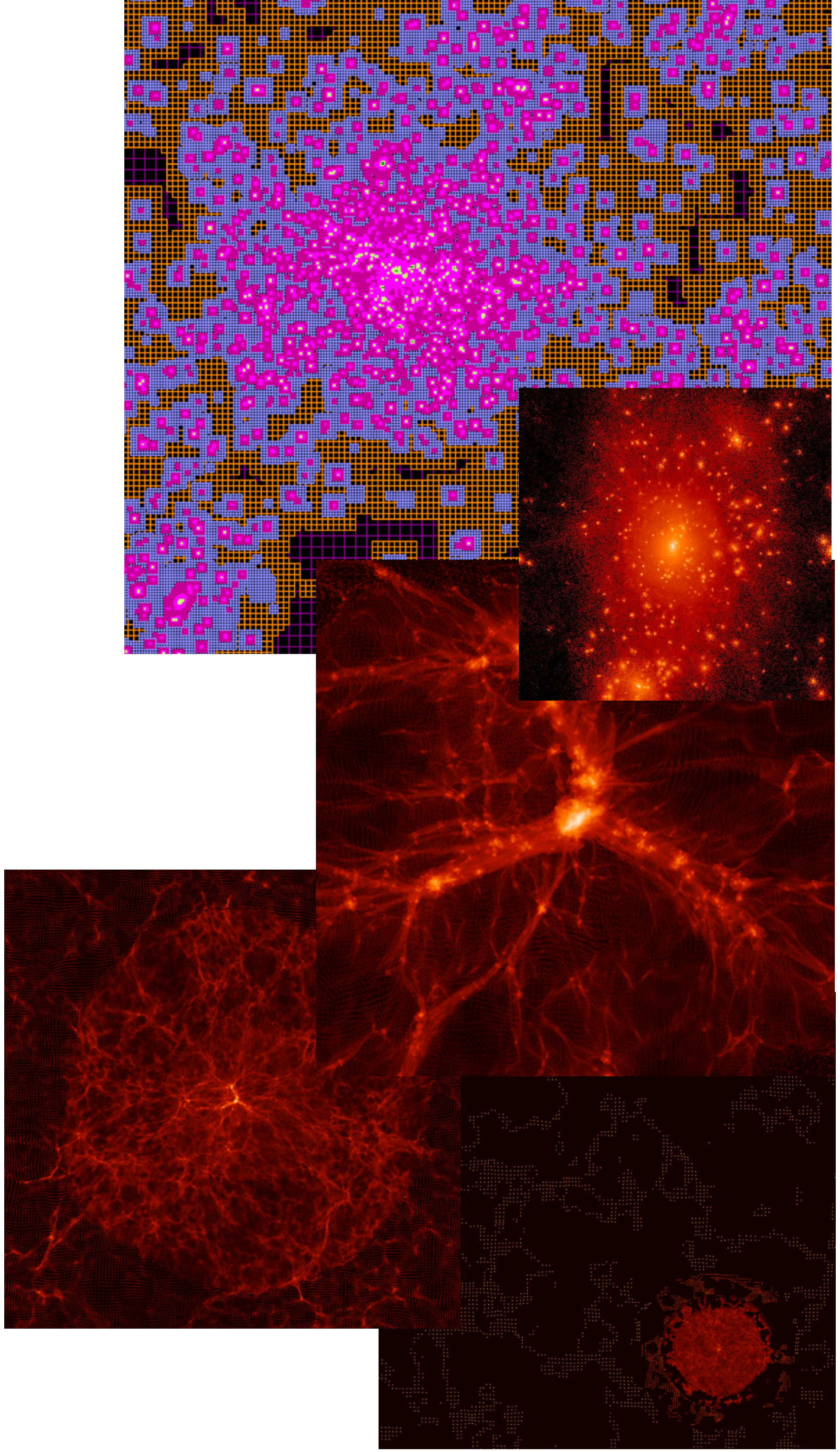




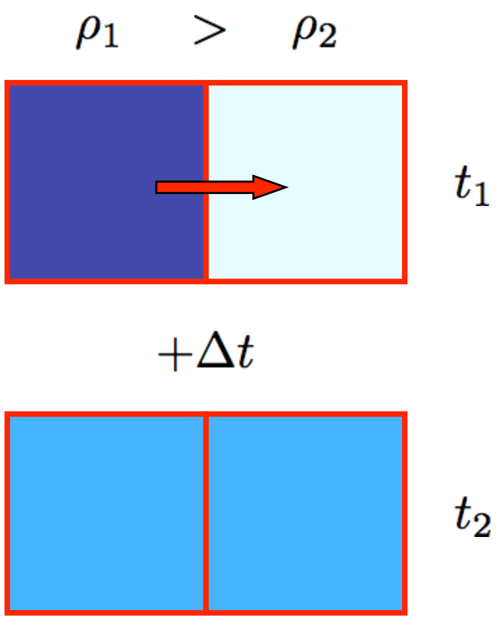
RAMSES : an Adaptive Mesh Refinement (AMR) code

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

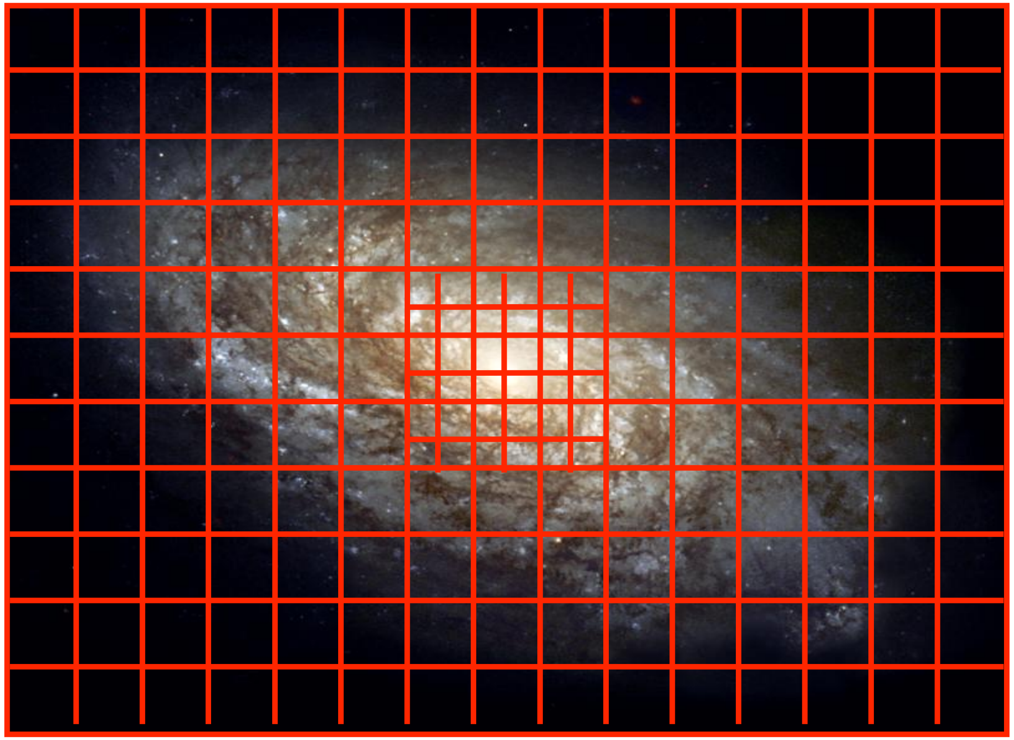
See Teyssier, 2002



AMR: idea



Adaptive Mesh Refinement

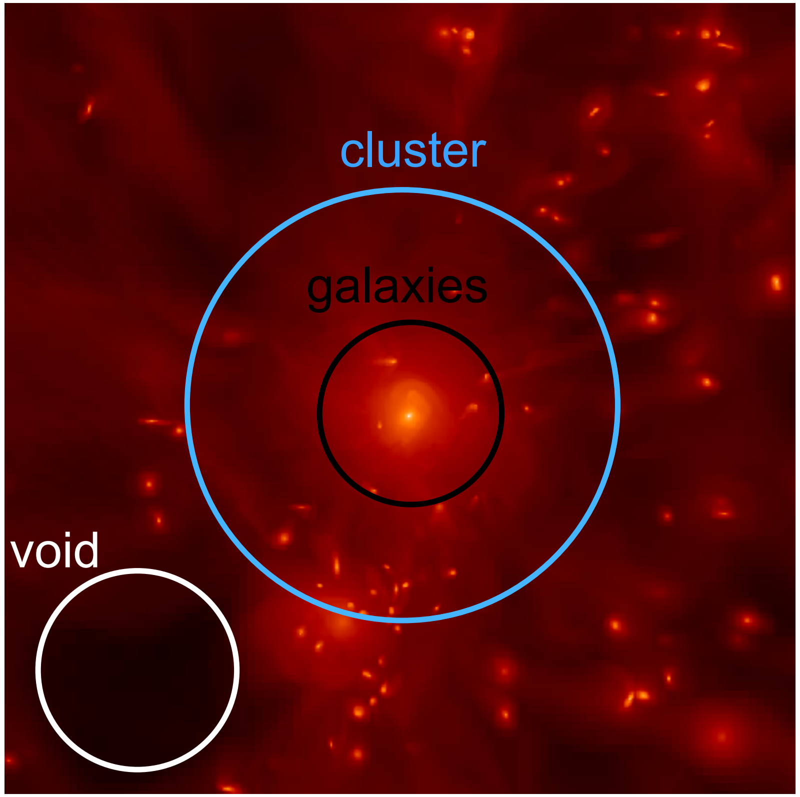


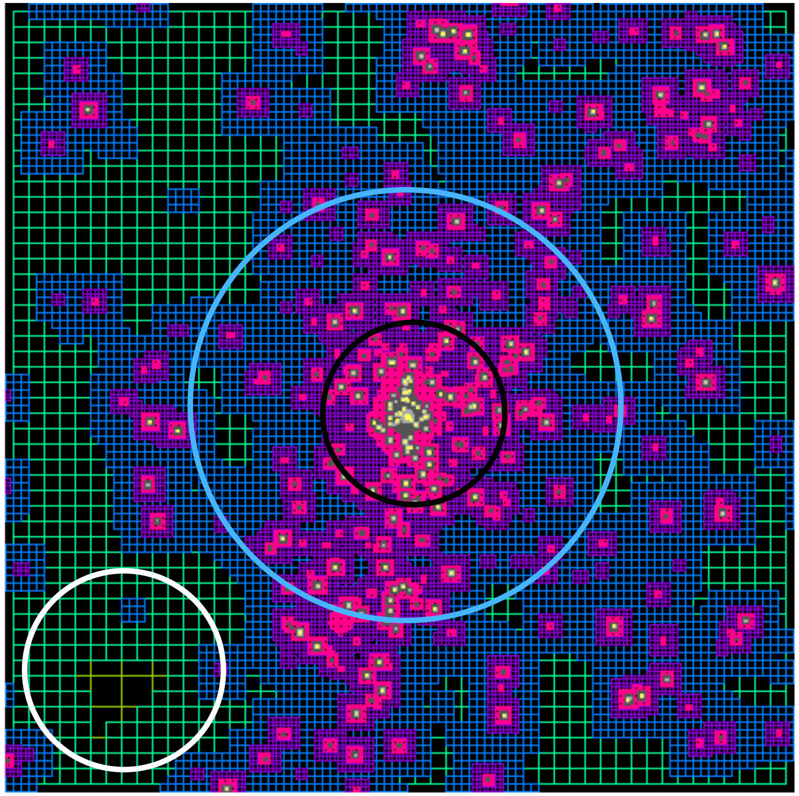
Compute the flux
at the cell interface

→

Gas evolution for
surrounding cells

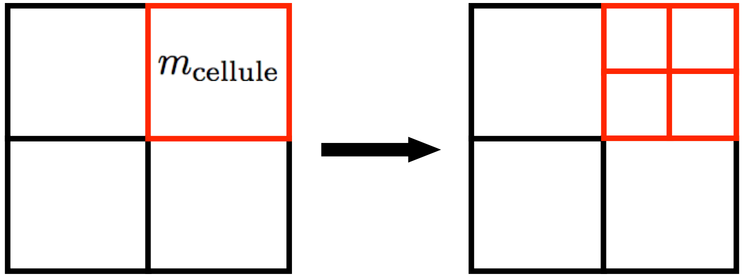
Refining the mesh





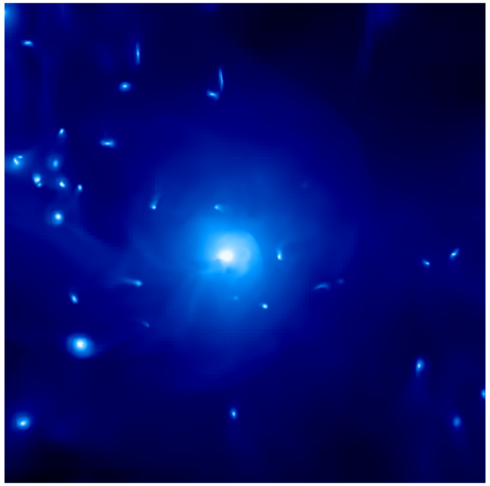
Local mass criterion

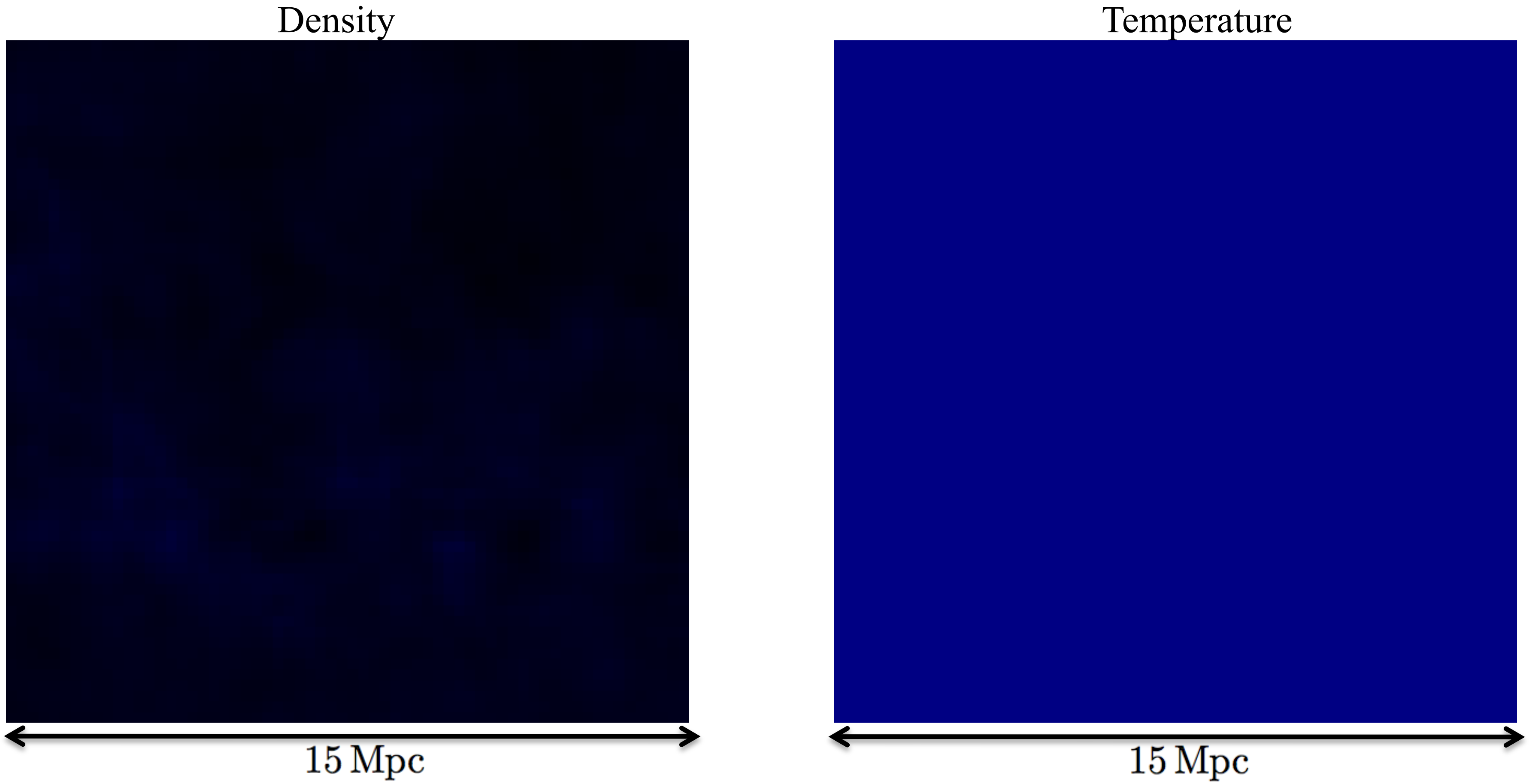
if $m_{\mathrm{cellule}} > m_0$ then



Let’s do a simple test…

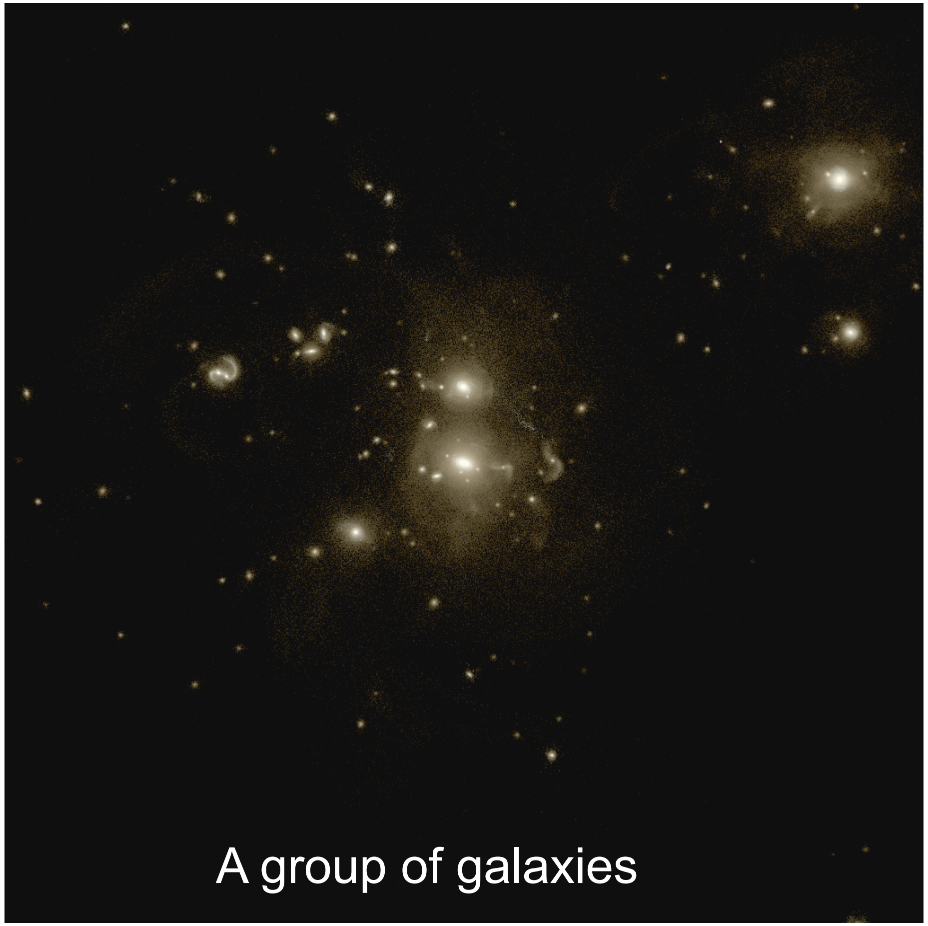
- Put DM particles together with a gas distribution consistent with the CMB power spectrum
- Allow for gas cooling and star formation



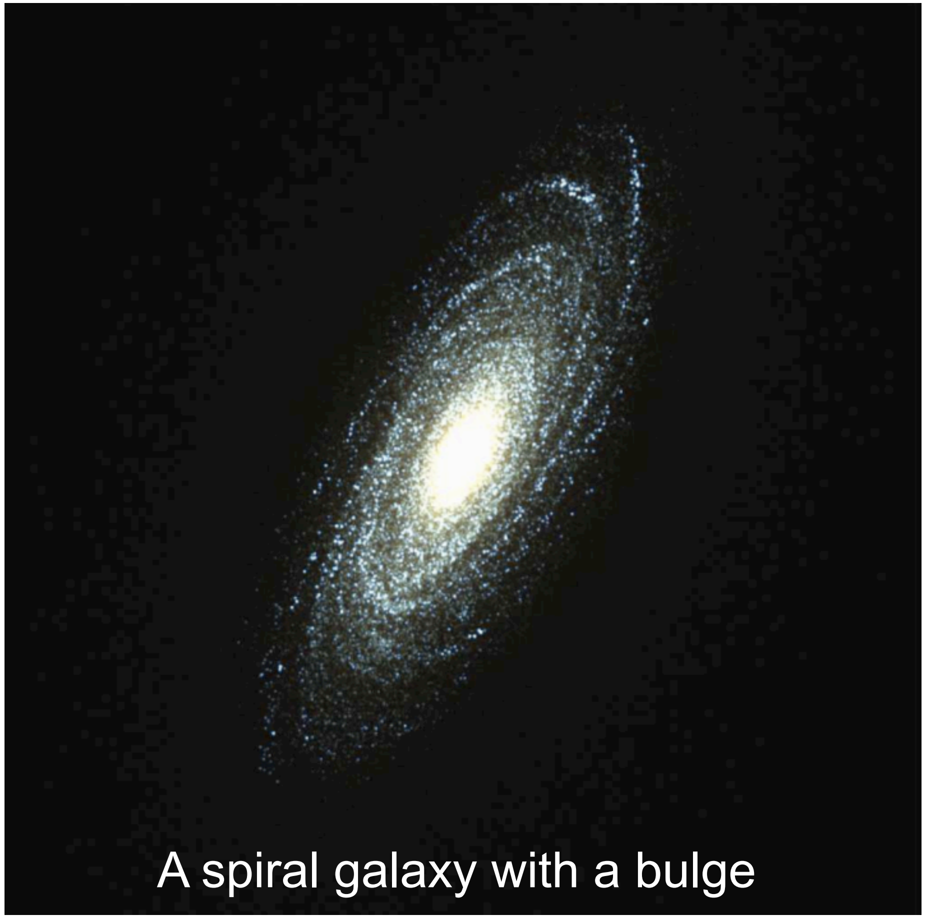


Dubois & Teyssier, 2008, 2010, 2011

Does a simulated galaxy look like a real galaxy?



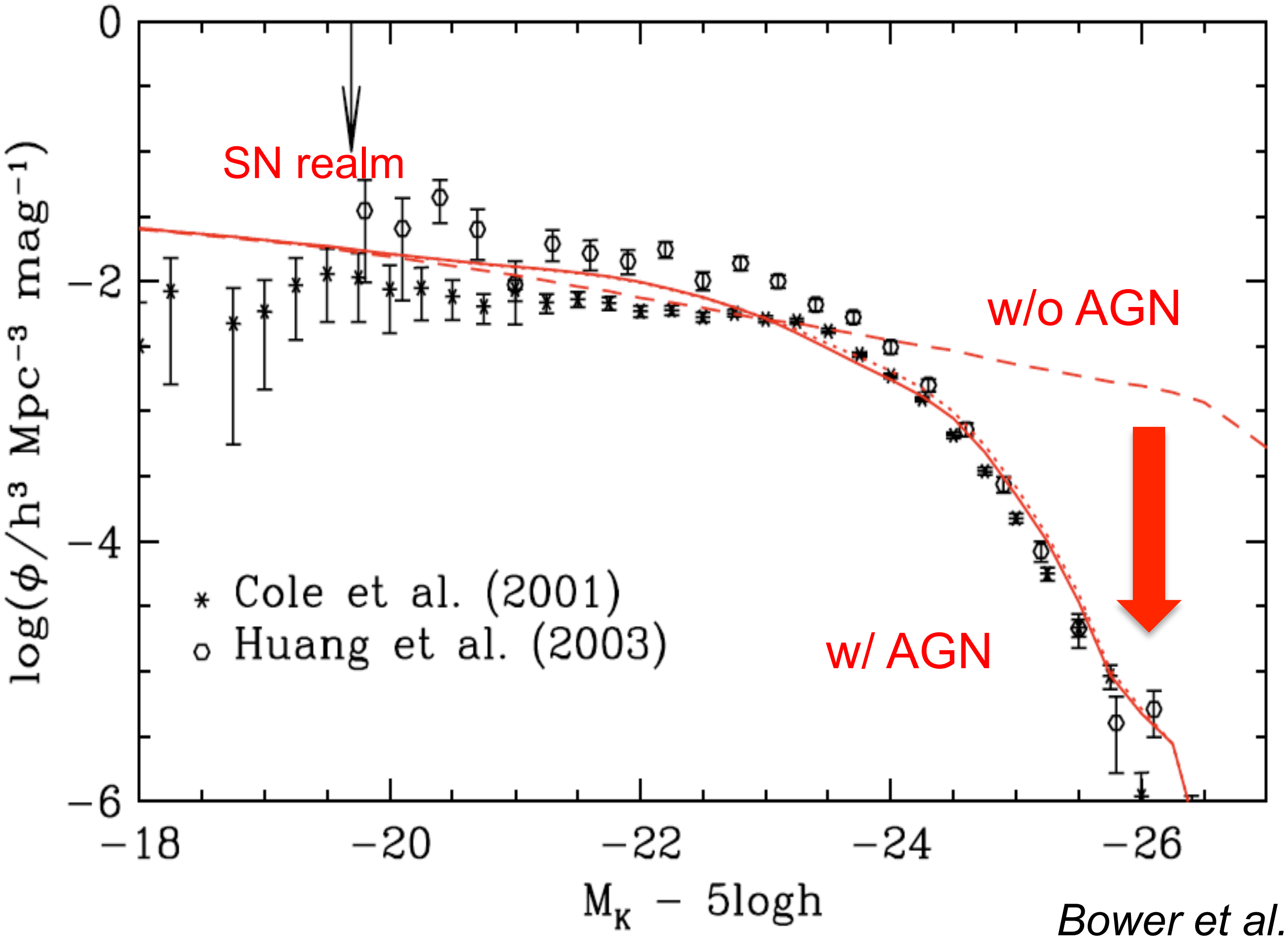
Dubois, Gavazzi, Peirani, Silk, 2013



Kimm, et al., 2013

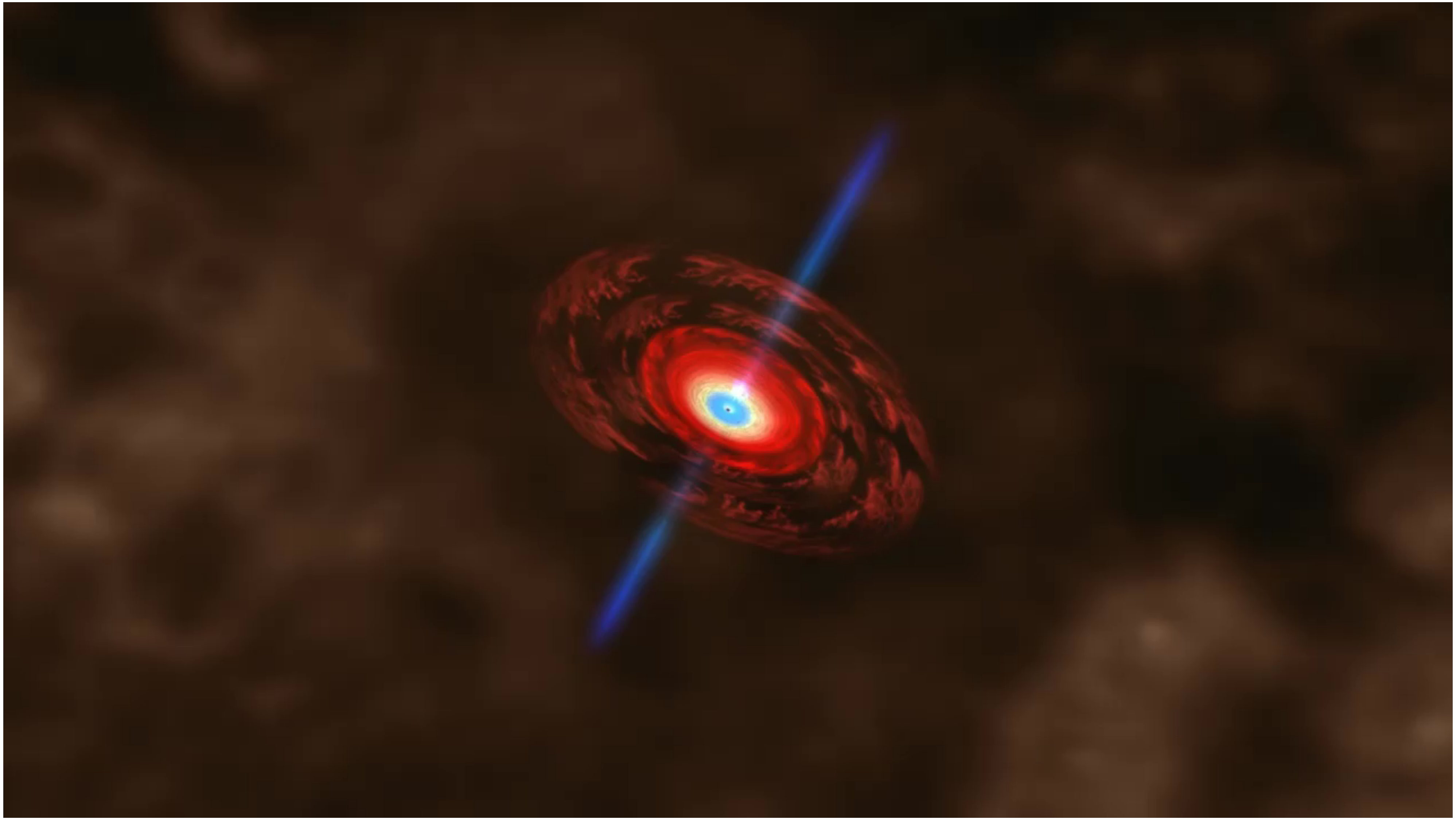
Motivation for AGN feedback

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



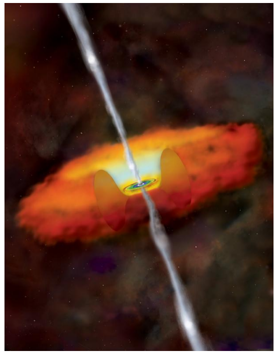
Bower et al., 2006

What’s an Active Galactic Nuclei (AGN)

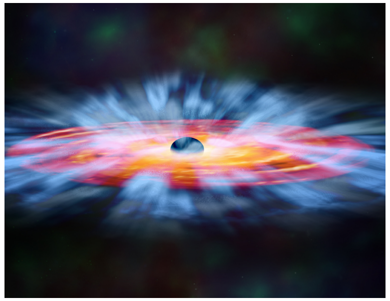


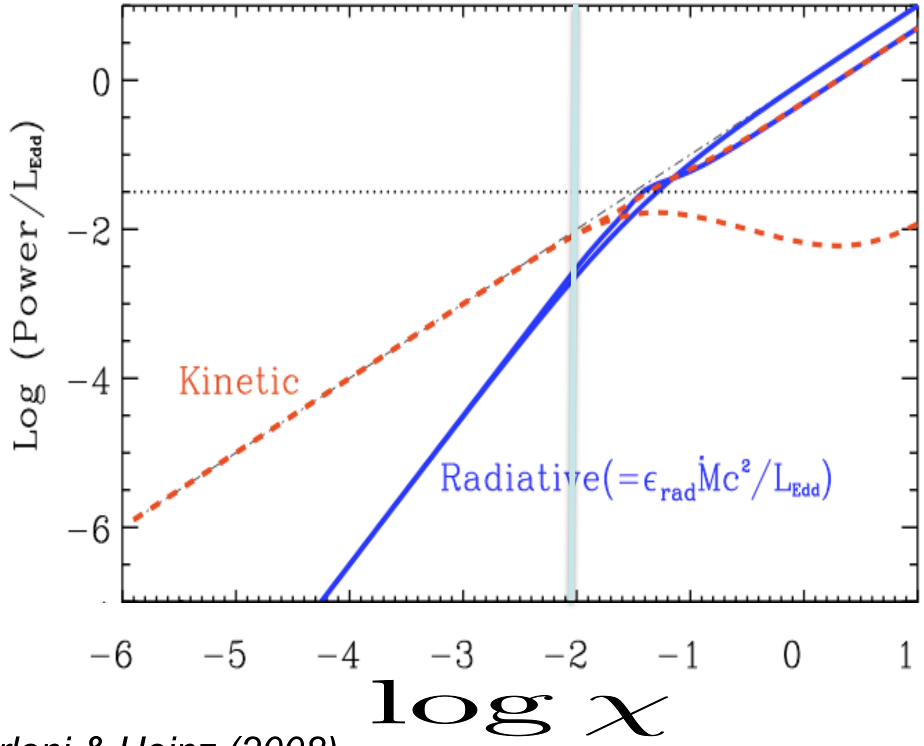
Credits: NASA

Two modes for AGN feedback



or





Merloni & Heinz (2008)

Eddington ratio of the accretion rate

$$\chi = \frac{\dot{M}_{\rm BH} c^2}{L_{\rm Edd}}$$

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 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

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

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

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

Bondi accretion rate

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

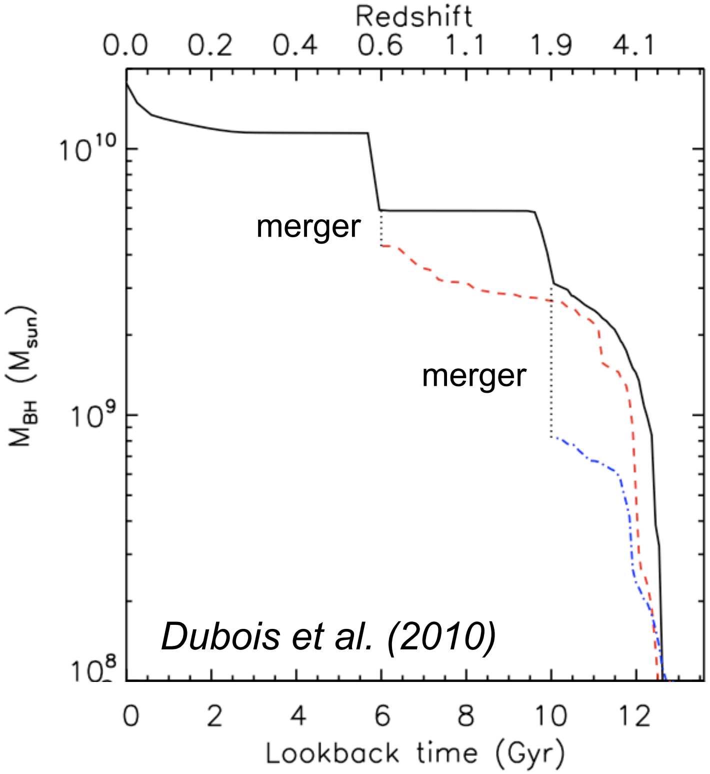
Fast accretion in dense and cold regions

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)



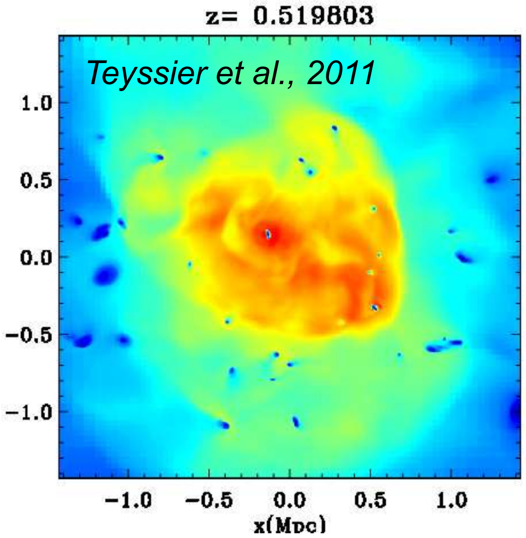
Dubois et al. (2010)

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)

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

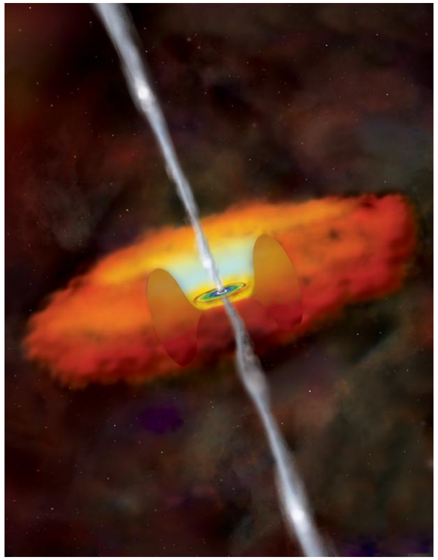
AGN in cosmological simulations

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)

With thermal input (Teyssier et al., 2011)
or with jets (Dubois et al., 2010, 2011)

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



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)

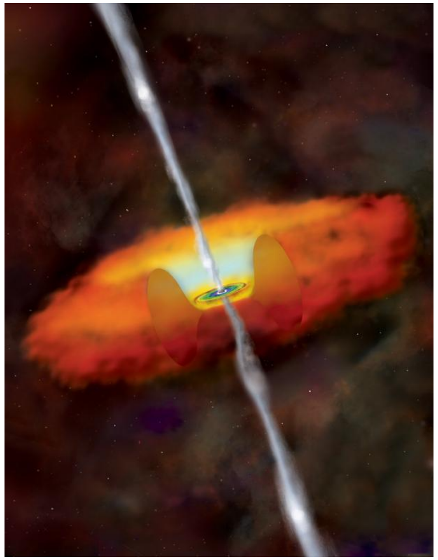
AGN in cosmological simulations

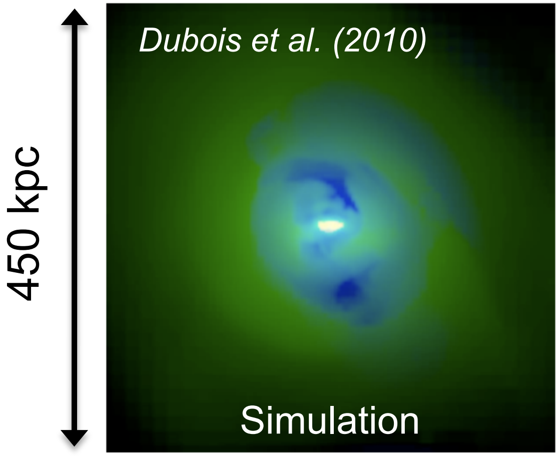
First AMR simulations of self-consistent AGN feedback in a cosmological context

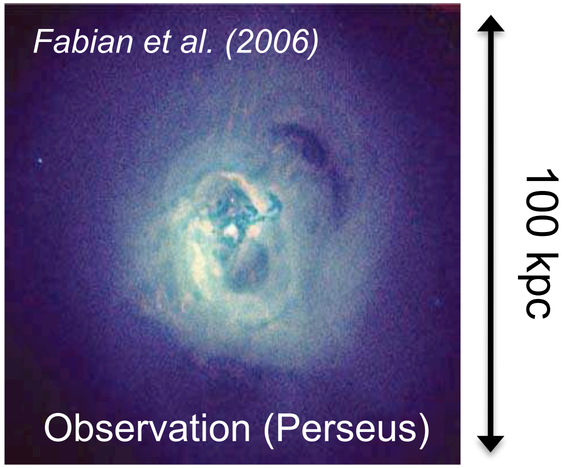
- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes
- Mimic the mergers between black holes (Friend-of-friend algorithm)
- Mimic the feedback from black holes (AGN)

With thermal input (Teyssier et al., 2011)
or with jets (Dubois et al., 2010, 2011)

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







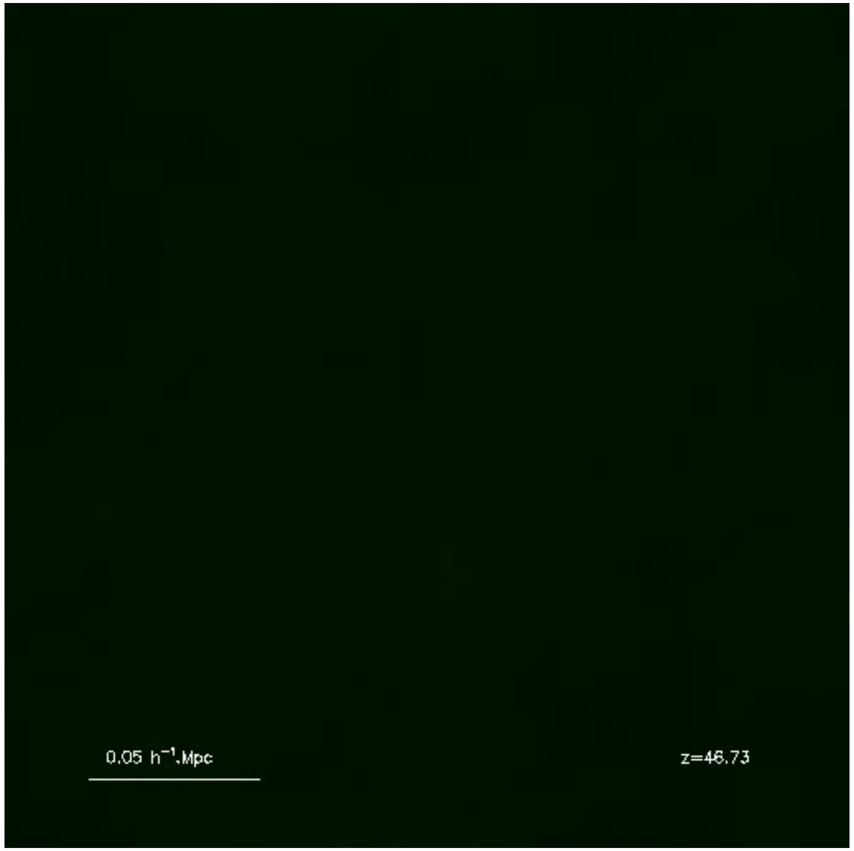
X-ray (3 bands)

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

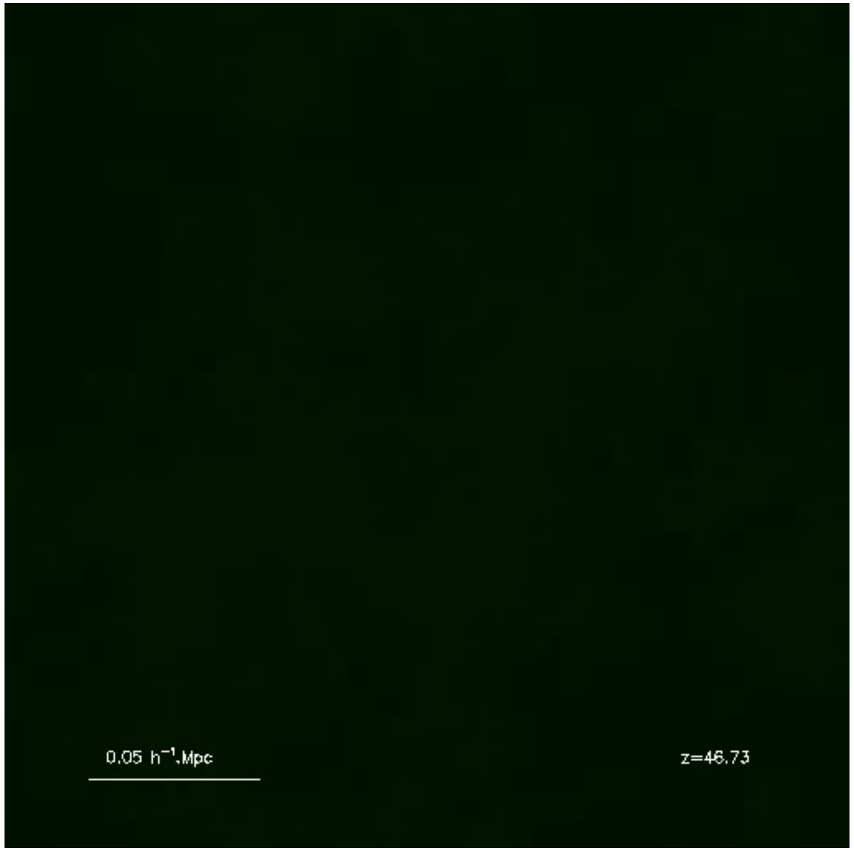
WMAP 5-year cosmology

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

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



No AGN



AGN

Testing the model: parameters and resolution

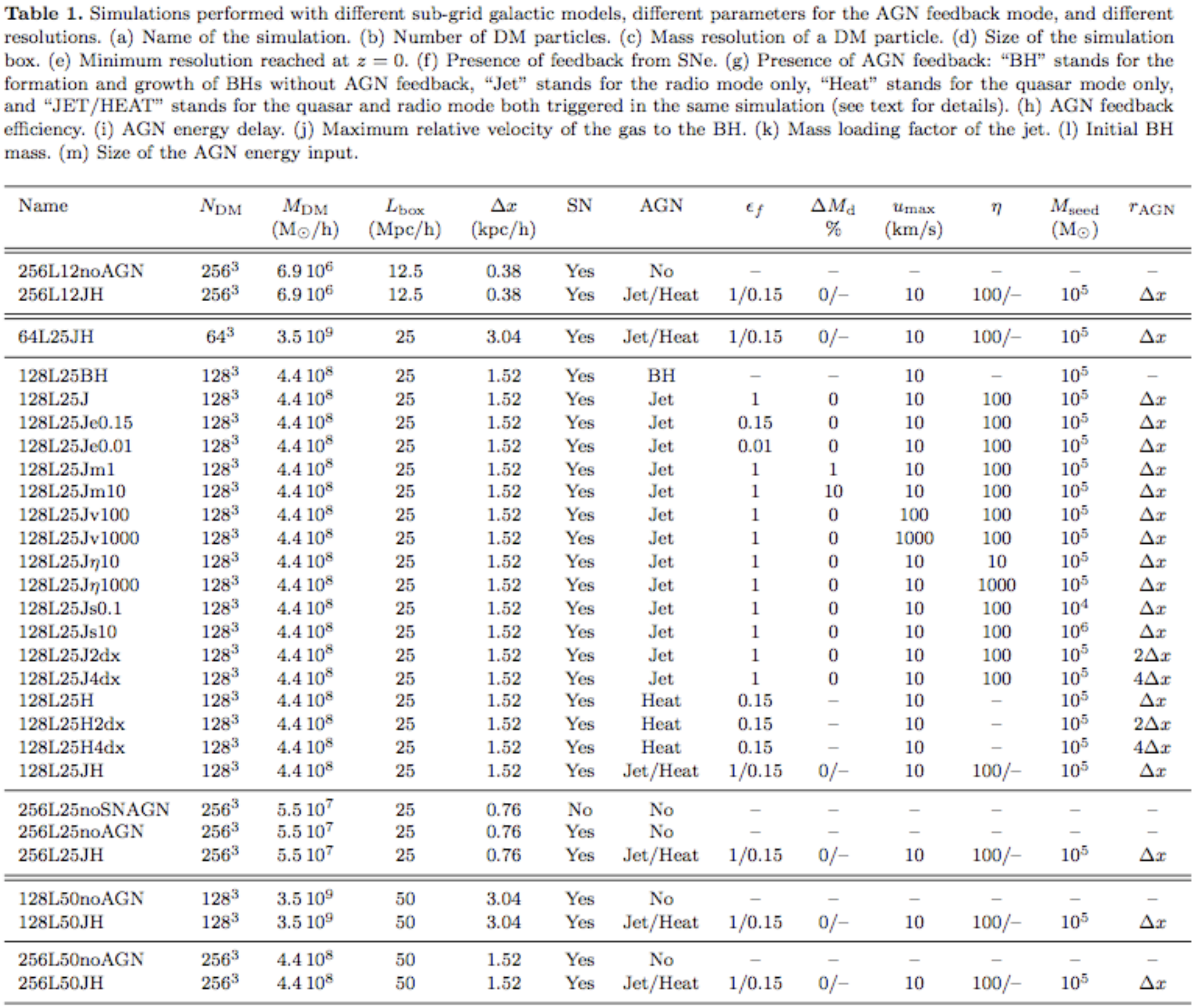


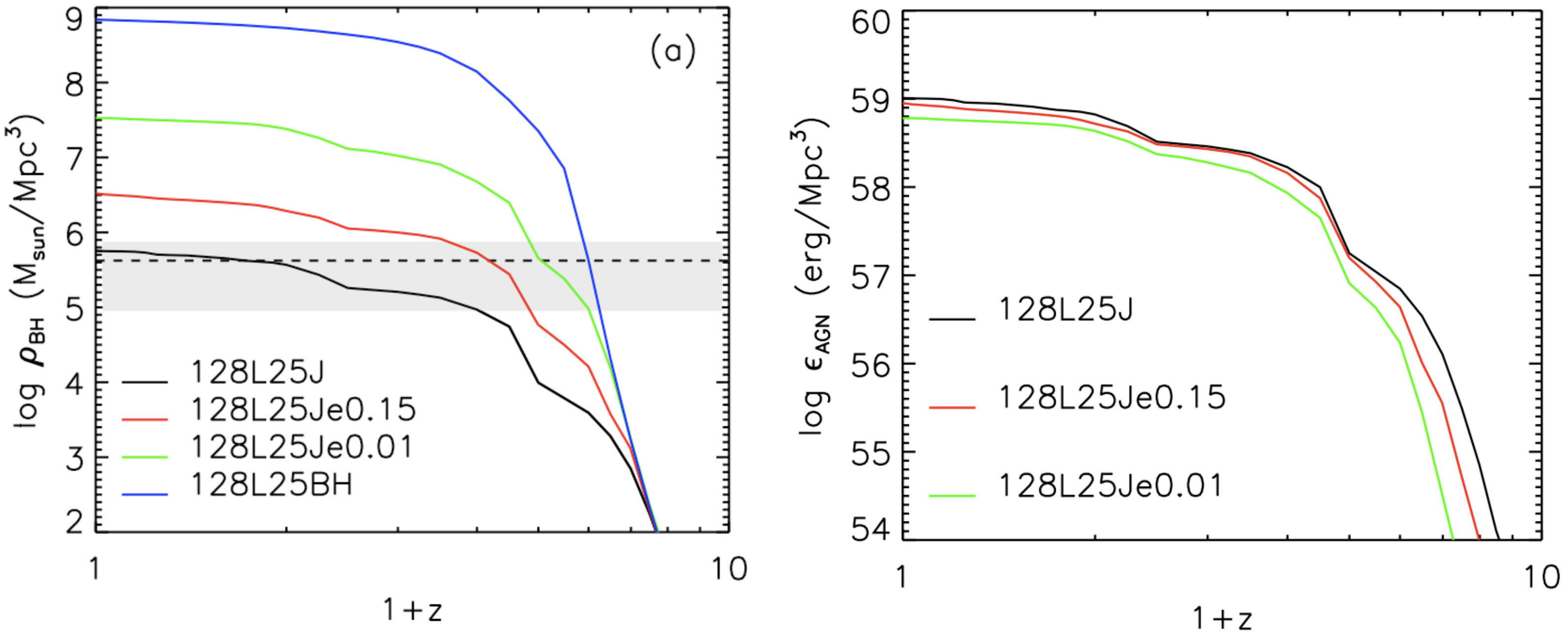
Table 1. Simulations performed with different sub-grid galactic models, different parameters for the AGN feedback mode, and different resolutions. (a) Name of the simulation. (b) Number of DM particles. (c) Mass resolution of a DM particle. (d) Size of the simulation box. (e) Minimum resolution reached 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 et al., 2012

Parameter test: the efficiency

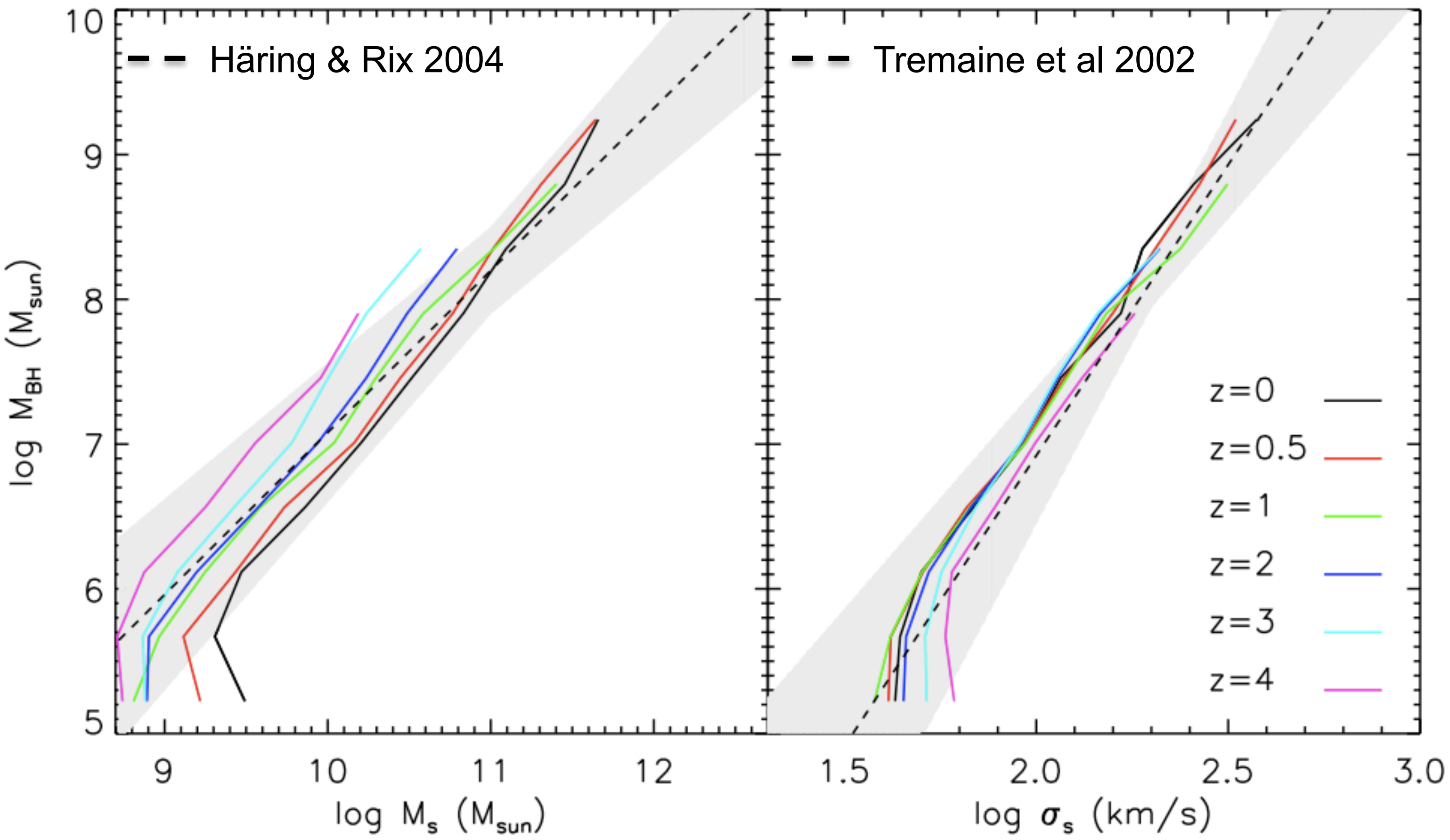
$$L_{\rm AGN} = \epsilon_f \epsilon_r \dot{M}_{\rm BH} c^2$$



BHs deposit the same energy / independant of the AGN efficiency

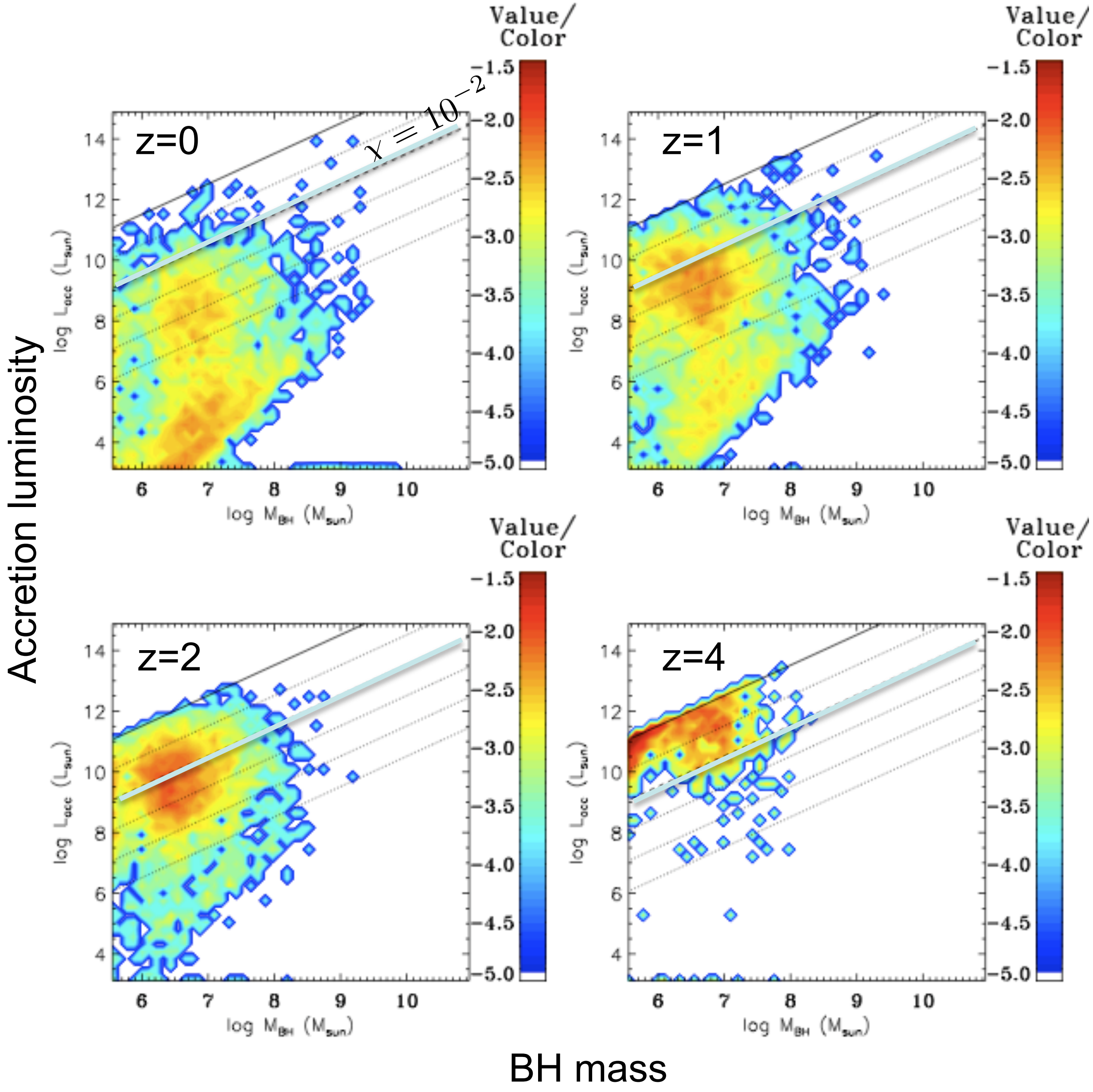
Dubois et al., 2012

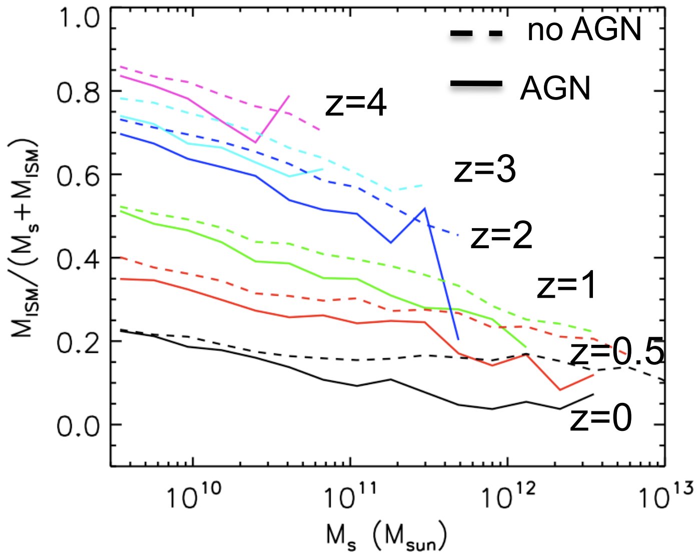
Fitting observationnal M_{BH}-M_* / M_{BH}-σ_* laws



Dubois et al., 2012

Radio mode or quasar mode ?



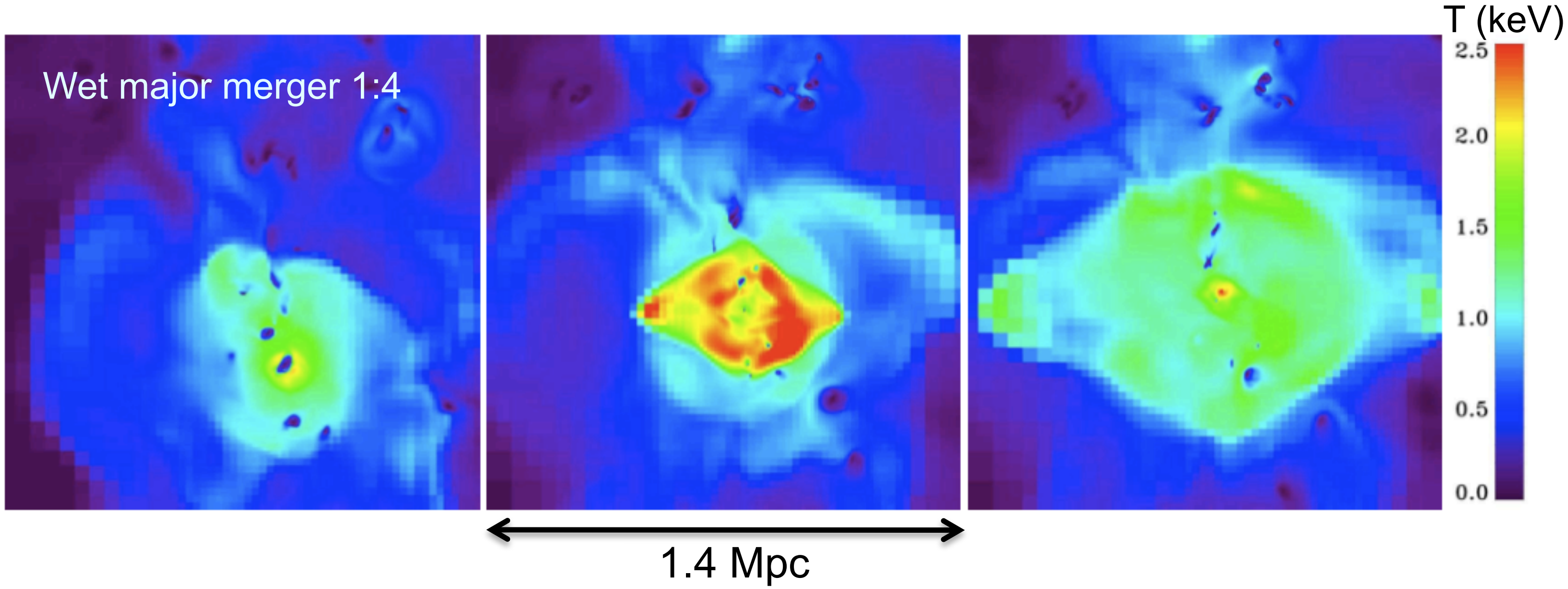


Galaxies are gas-rich at high-redshift
Star formation and feedback removes
cold gas efficiently

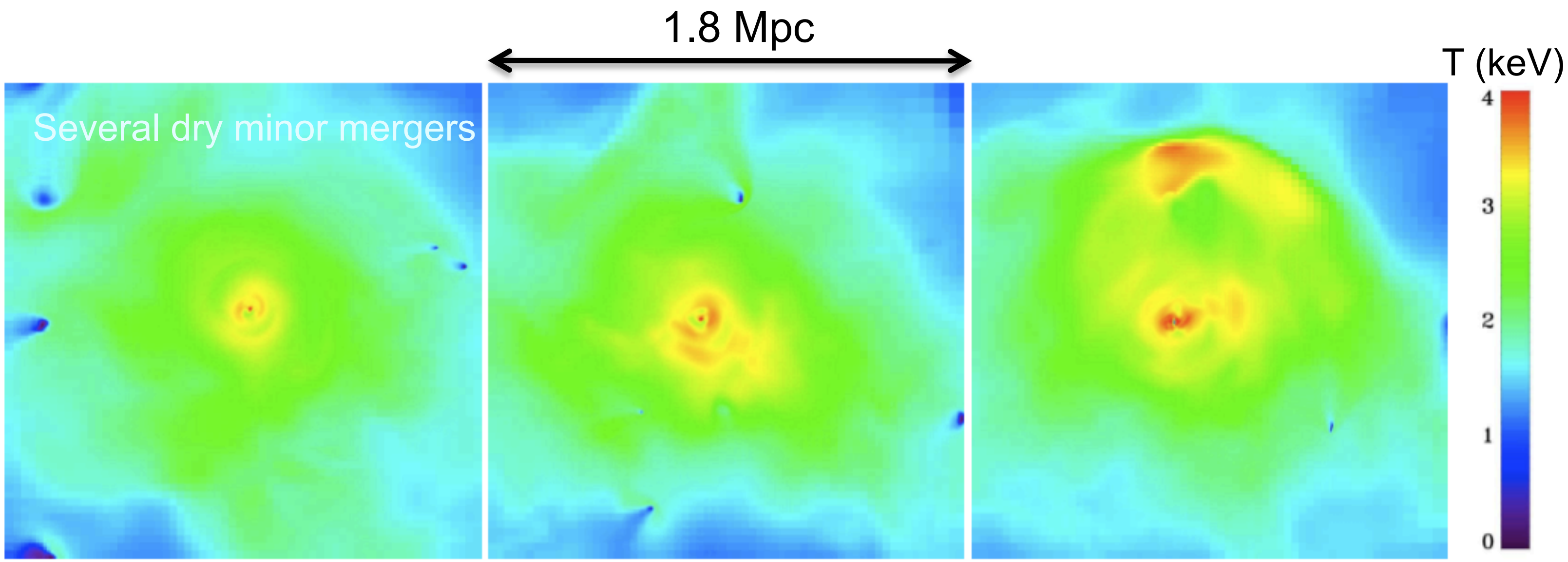
Dubois et al., 2012

Quasar mode versus radio mode

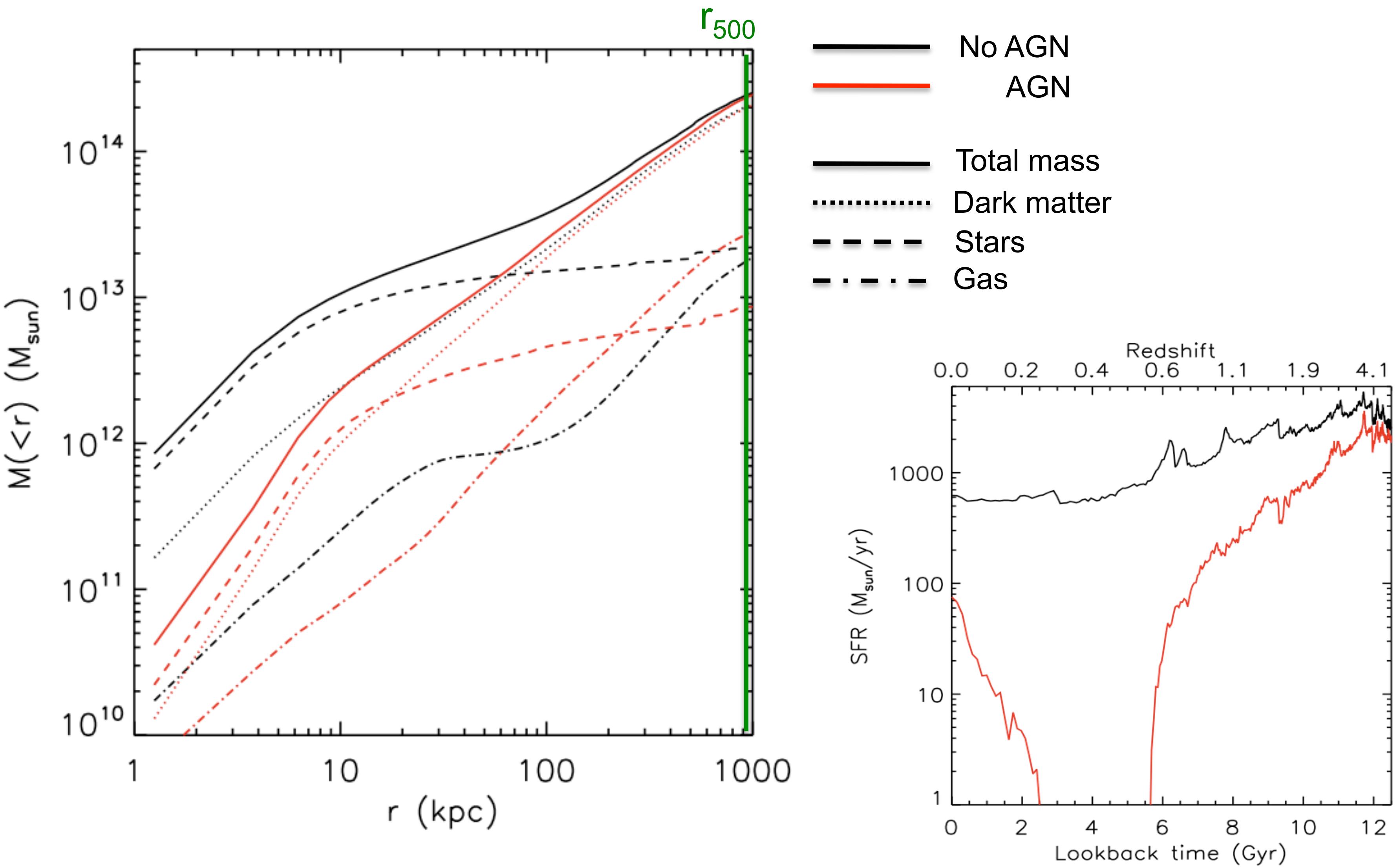
z=1.5
Quasar mode



z=0
Radio mode



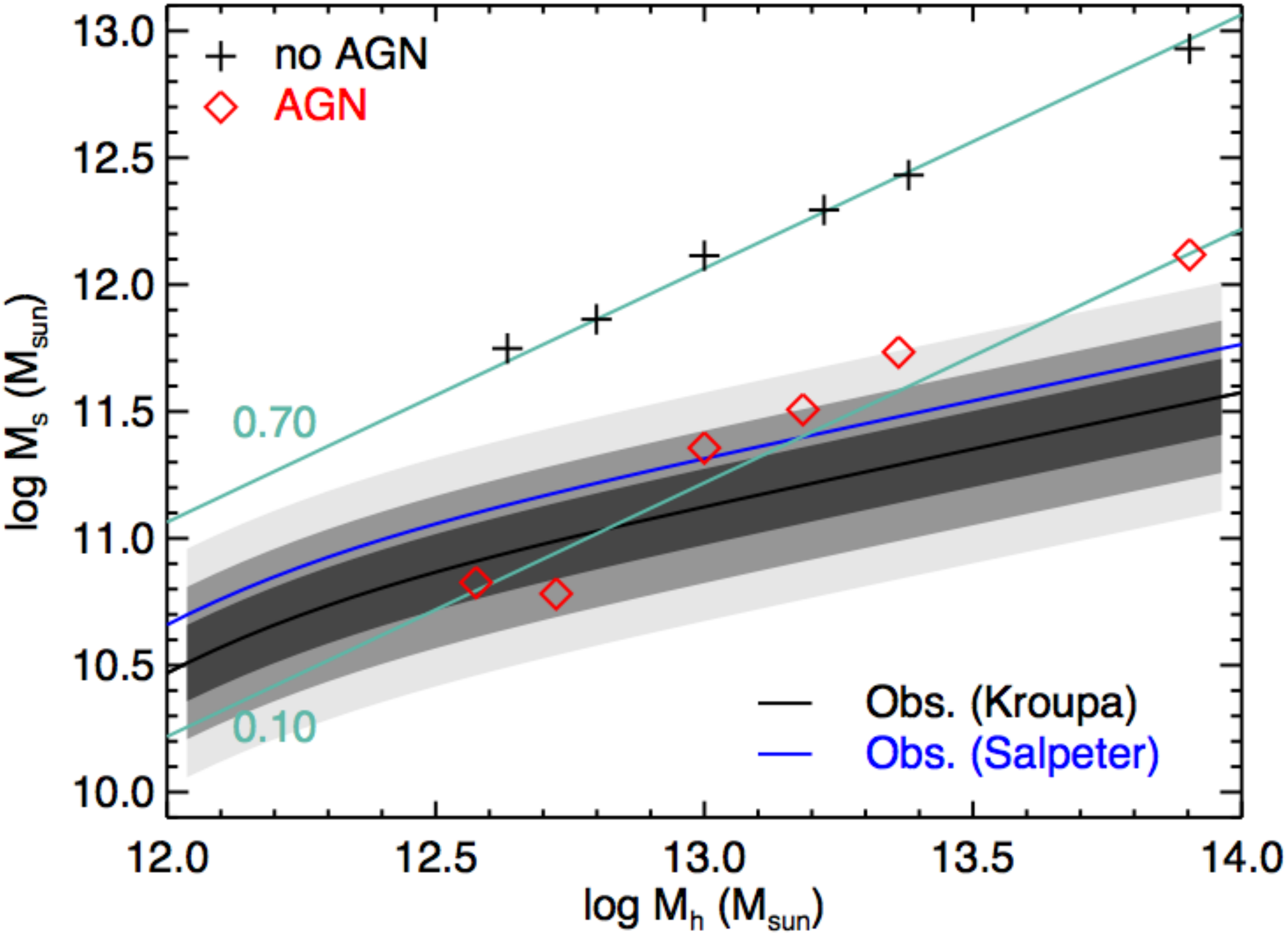
Mass distribution in a cluster of galaxies



Dubois et al., 2010

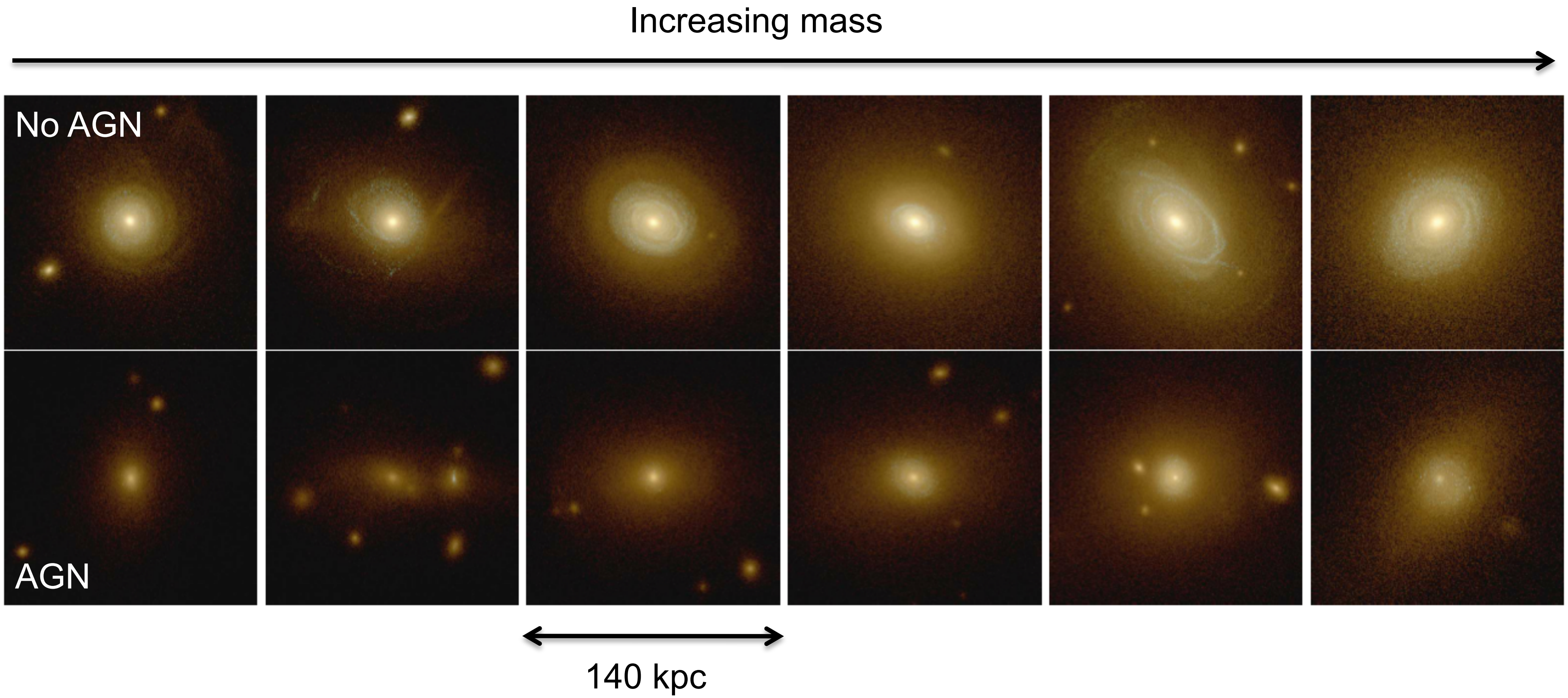
See also Teyssier, et al., 2011; Martizzi et al., 2012

Stellar mass in the central galaxy



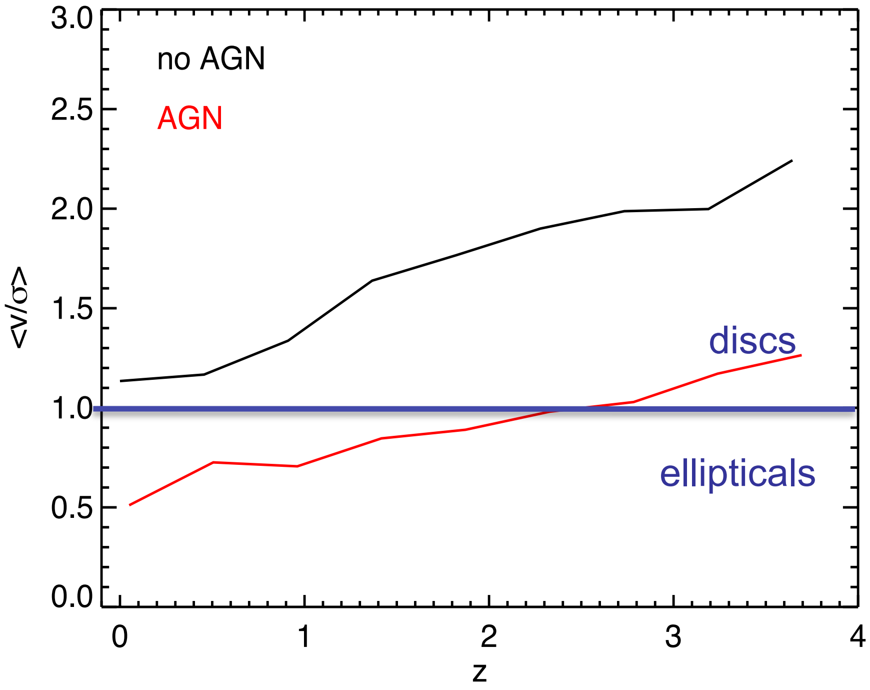
Dubois, Gavazzi, Peirani, Silk, arXiv:1301.3092

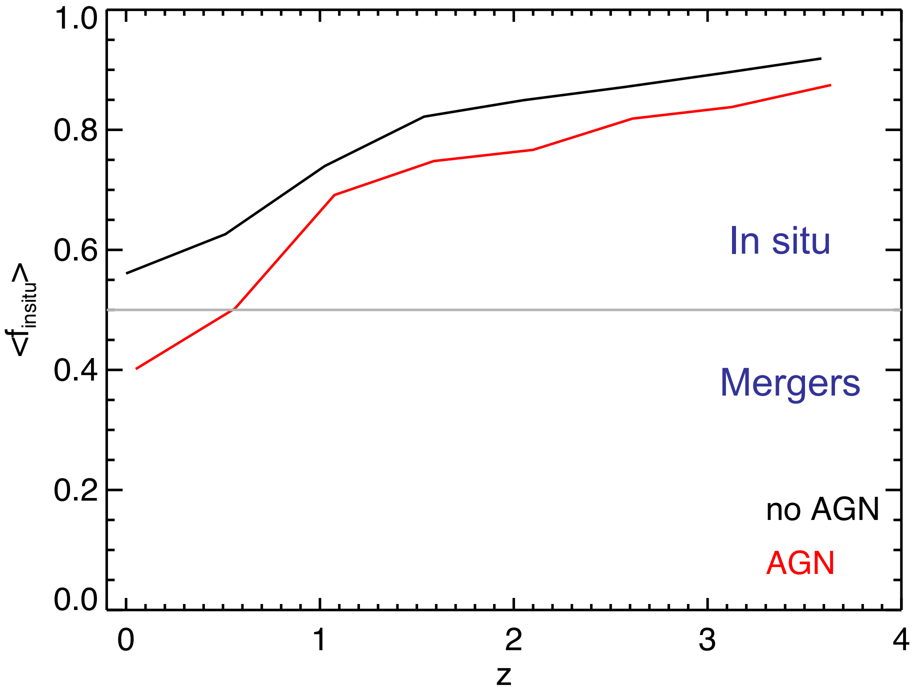
Can we get massive galaxies that look like ellipticals ?



Dubois, Gavazzi, Peirani, Silk, arXiv:1301.3092

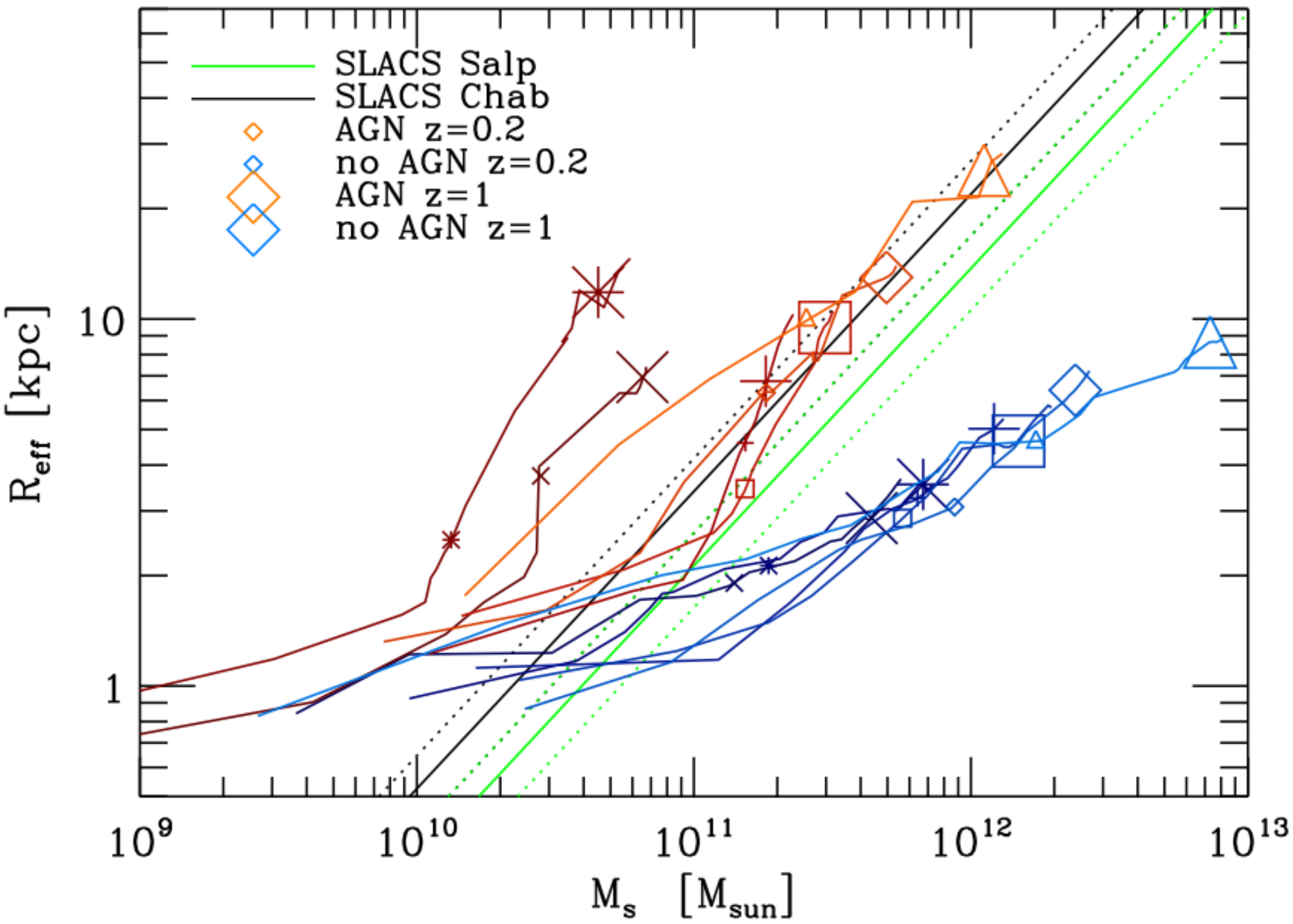
Are they in rotation or dominated by velocity dispersion ?





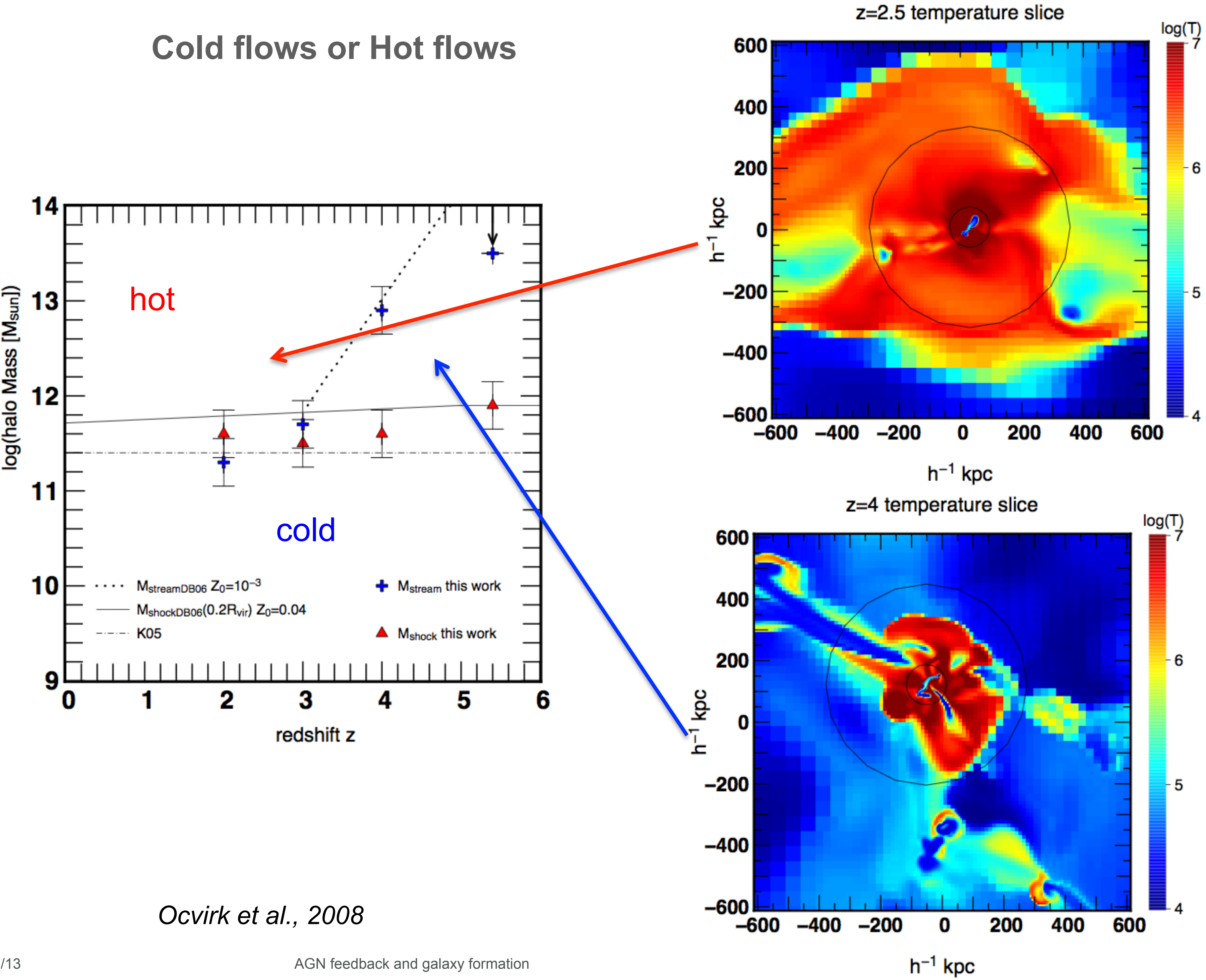
Dubois, Gavazzi, Peirani, Silk, arXiv:1301.3092

Changing the compactness of massive galaxies



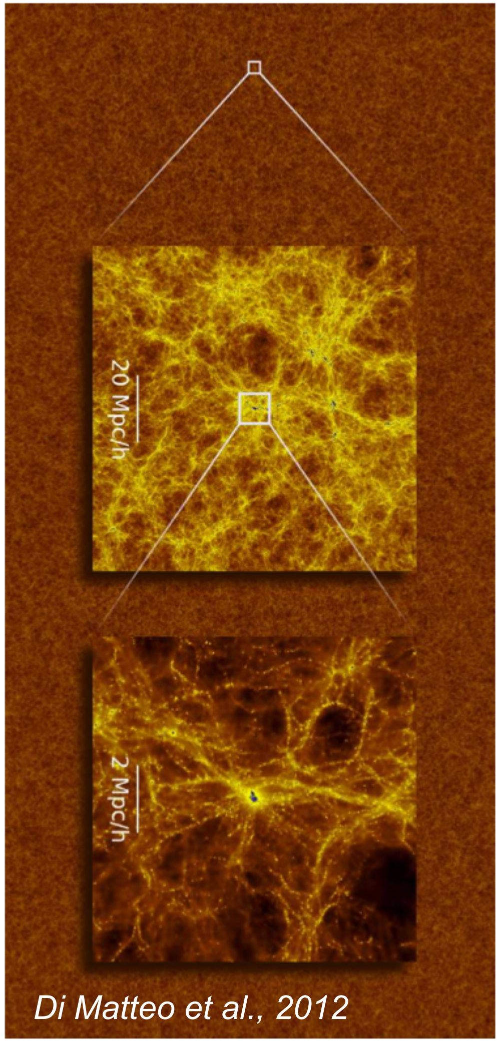
Dubois, Gavazzi, Peirani, Silk, arXiv:1301.3092

Cold flows or Hot flows



Ocvirk et al., 2008

Growing the first bright quasars



Di Matteo et al., 2012

Observationnal facts:

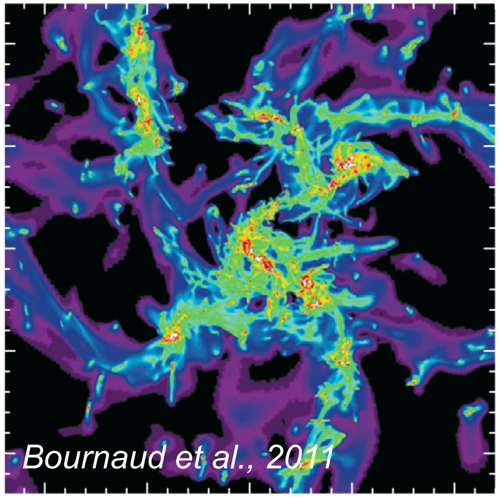
- Very bright quasars in the SDSS with z>6 (Willott et al., 2003; Fan et al., 2006; Jiang et al., 2009)
- Detection of a 2.10^9 M_{sun} BH at z=7 (Mortlock et al., 2011)

Requirement:

- Need to grow from 10^2-10^3 M_{sun} up to 10^9 M_{sun} in less than 700 Myrs ! Eddington limit provides an e-folding time = 45 Myr

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

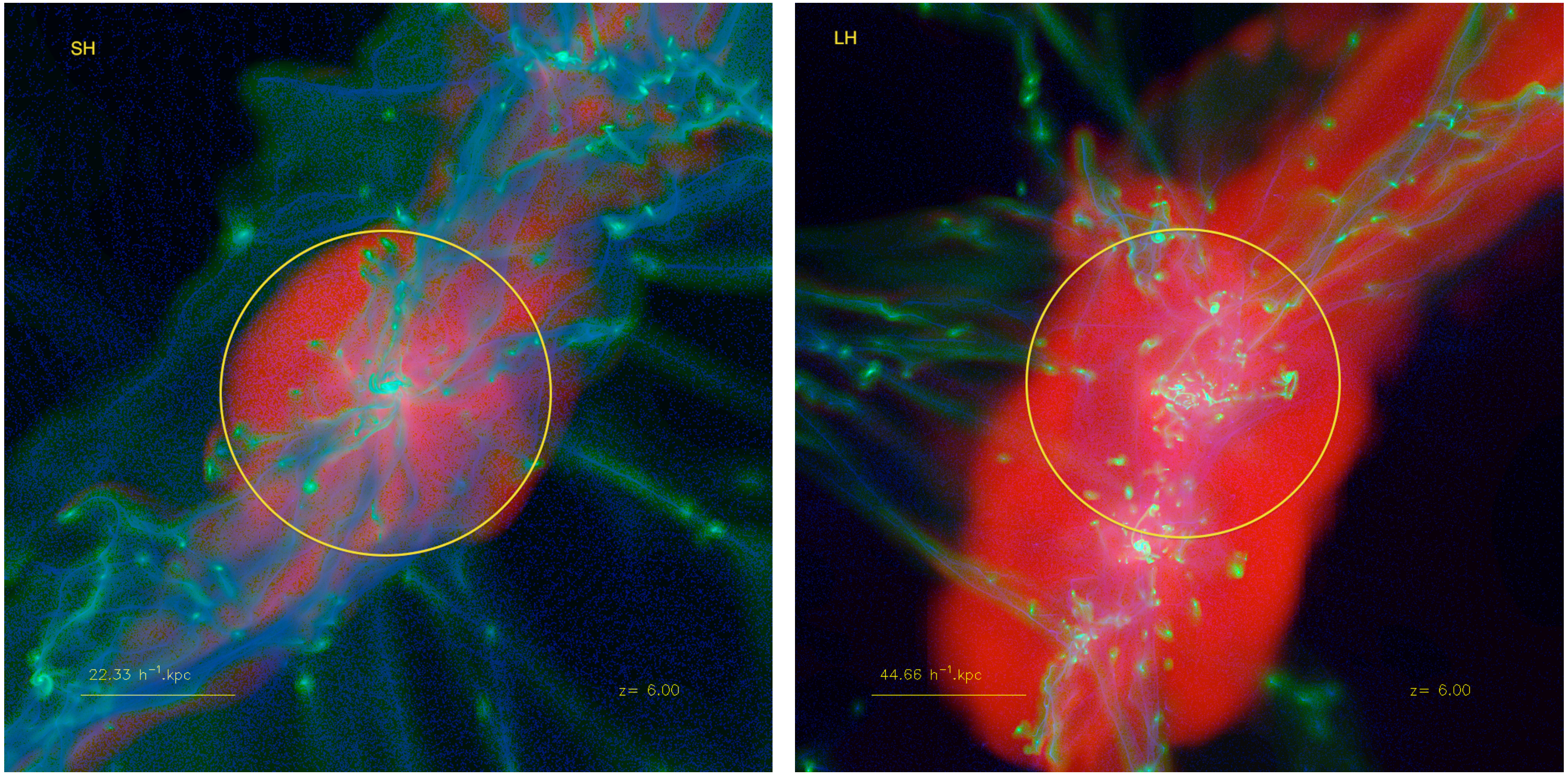
Very massive halos

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



Very massive halos

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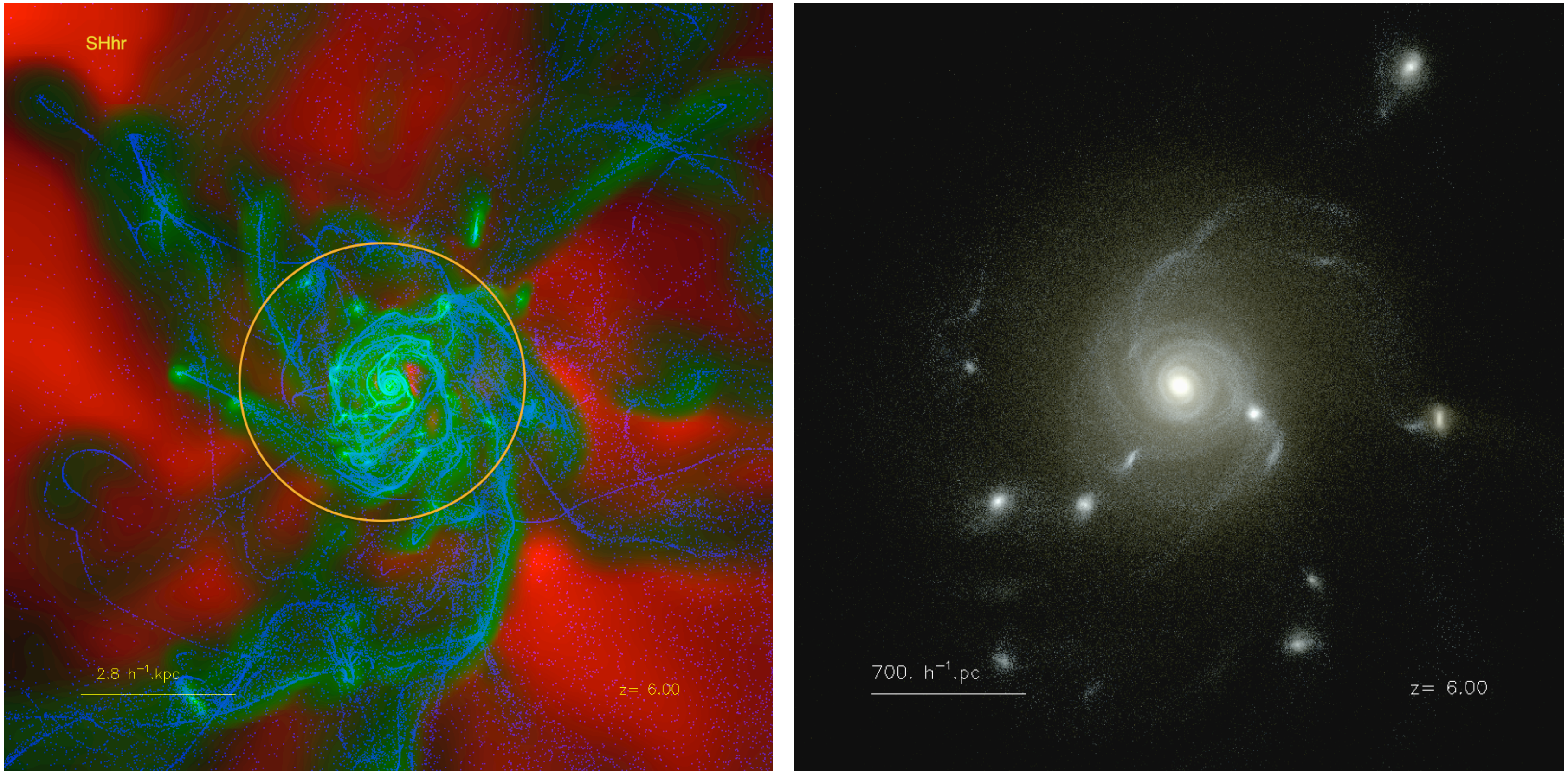
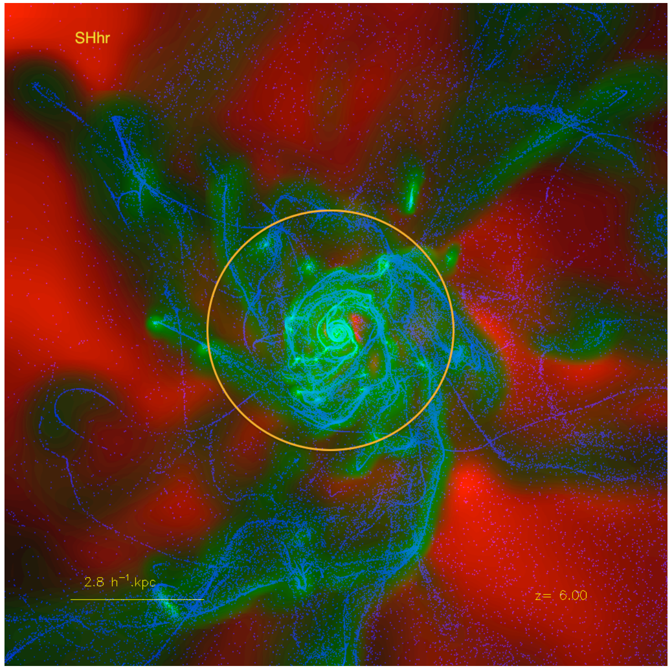
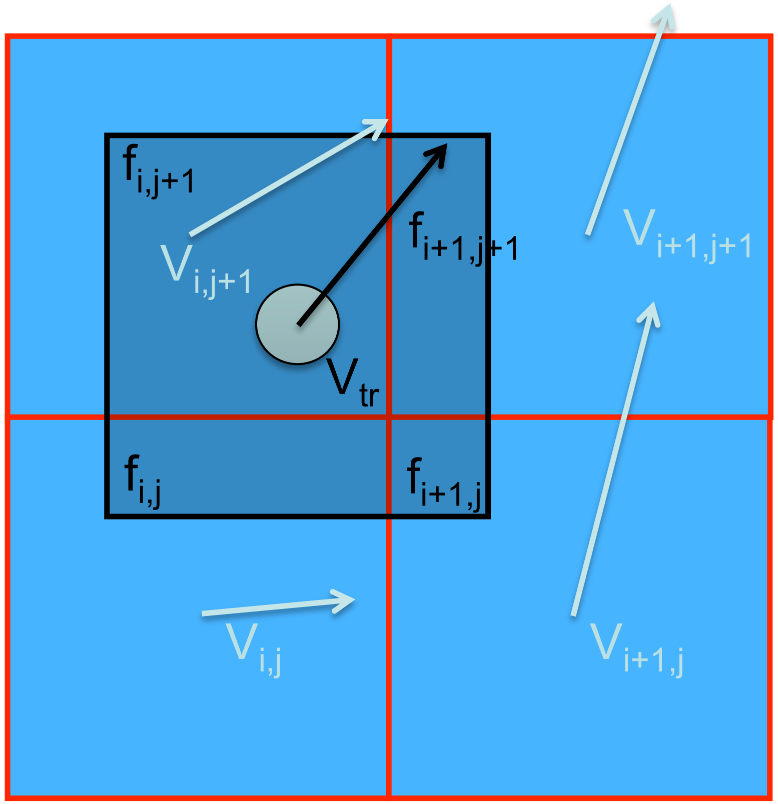
-A low mass halo SH with 5.10^{11} M$_{sun}$ at z=6, and 100 pc resolution
-A high mass halo LH with 2.10^{12} M$_{sun}$ at z=6, and 100 pc resolution
-A low mass halo SH with 5.10^{11} M$_{sun}$ at z=6, and 15 pc resolution



Tracer particles: the Lagrangian history of the gas flow

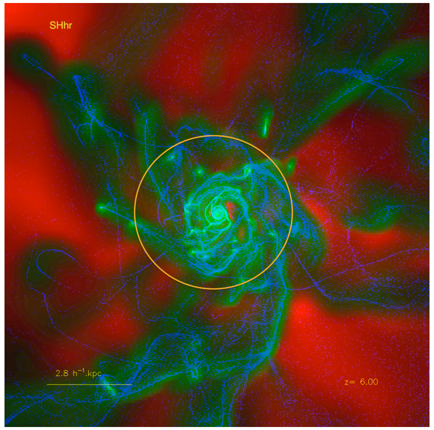




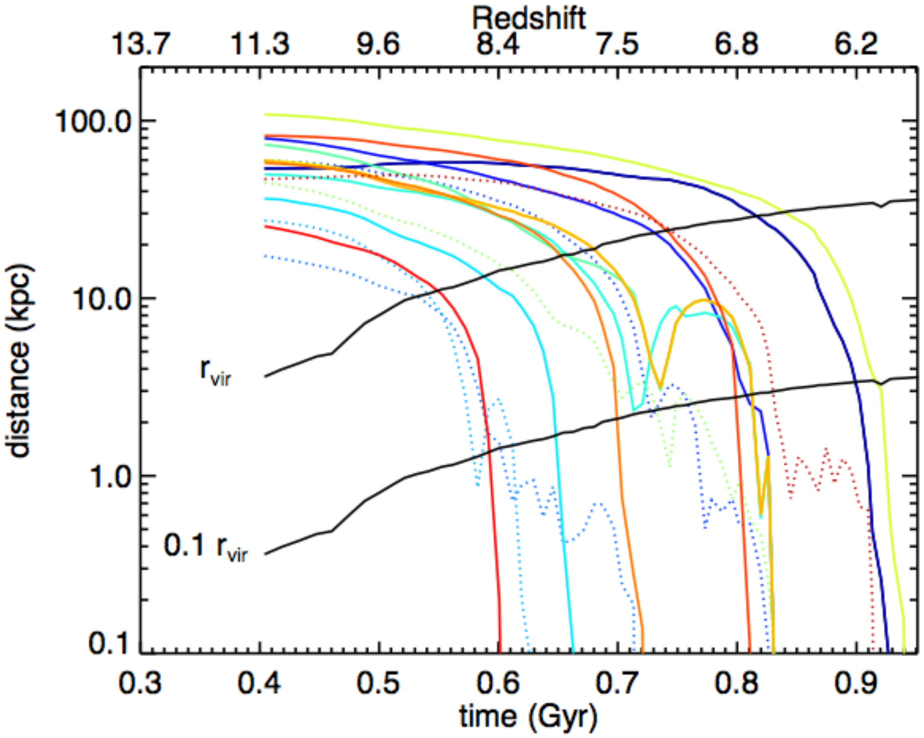
$$v_{tr} = f_{i,j}.v_{i,j} + f_{i+1,j}.v_{i+1,j} + f_{i,j+1}.v_{i,j+1} + f_{i+1,j+1}.v_{i+1,j+1}$$

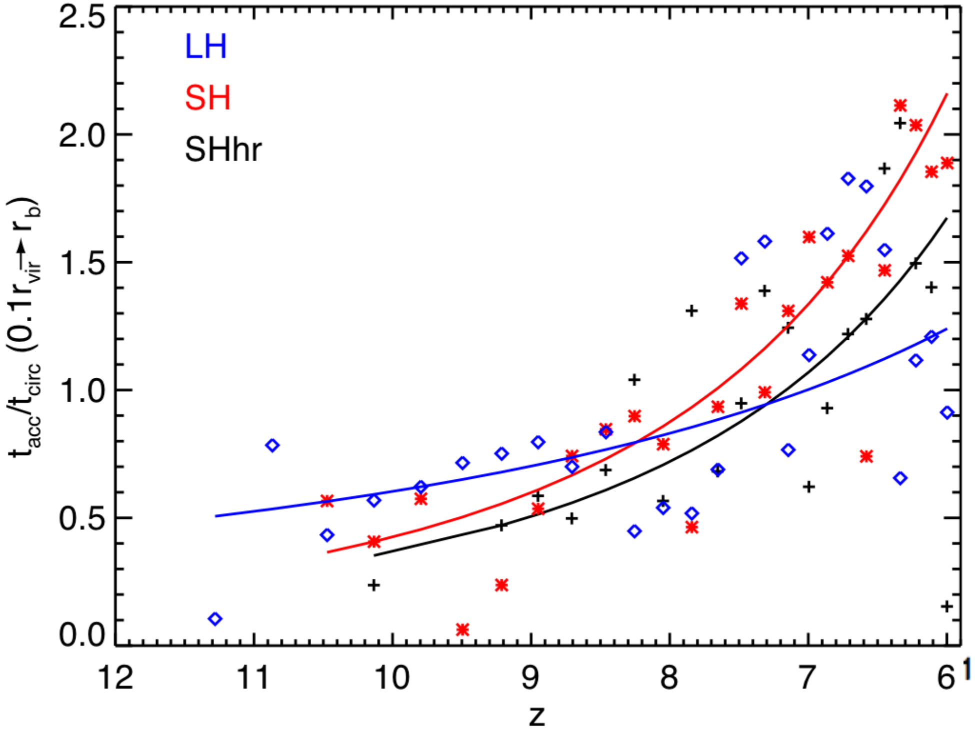
$$x_{tr}^{n+1} = x_{tr}^{n} + v_{tr}^{n}.(t^{n+1} - t^{n})$$

Follow the white rabbit…



Take the tracer particles that belong to the galactic bulge





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)

Direct infall or disc feeding?

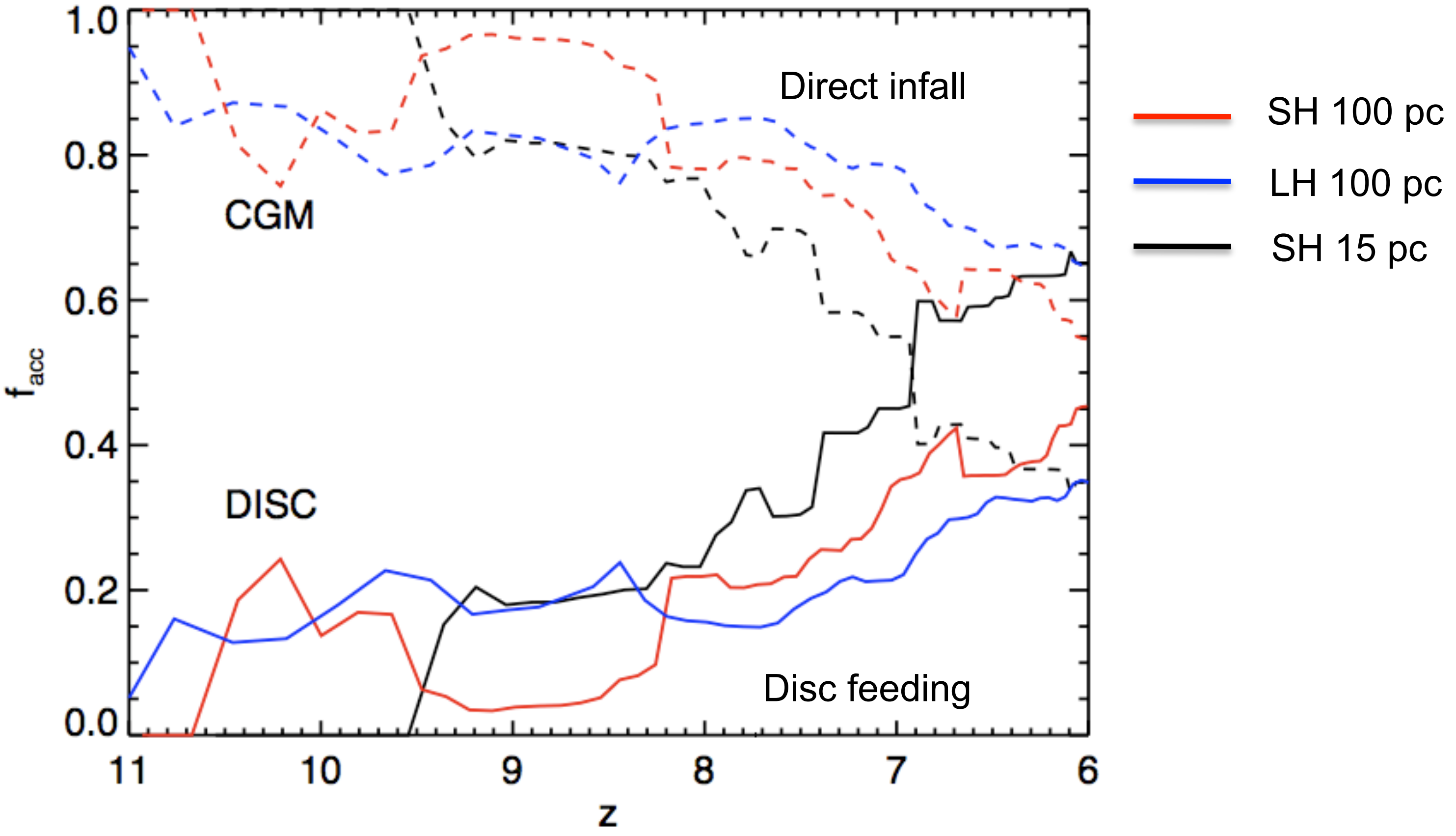
How to bring gas sufficiently rapidely into the bulge of the galaxy ?

- direct accretion from the cosmic cold filaments (Di Matteo et al., 2012)

versus

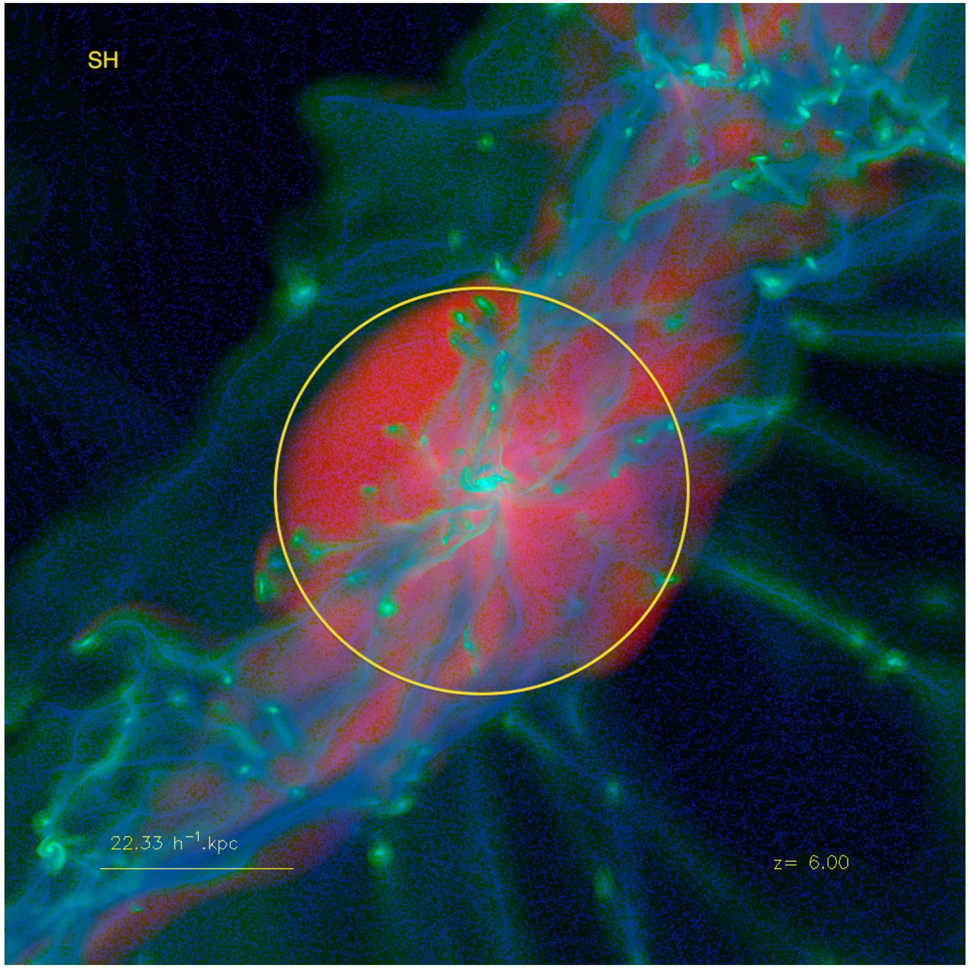
- violent disc instabilities (Bournaud et al., 2011)

It's in between !



Dubois, Pichon, Haehnelt et al., 2012, arXiv:1112.2479

The good old picture

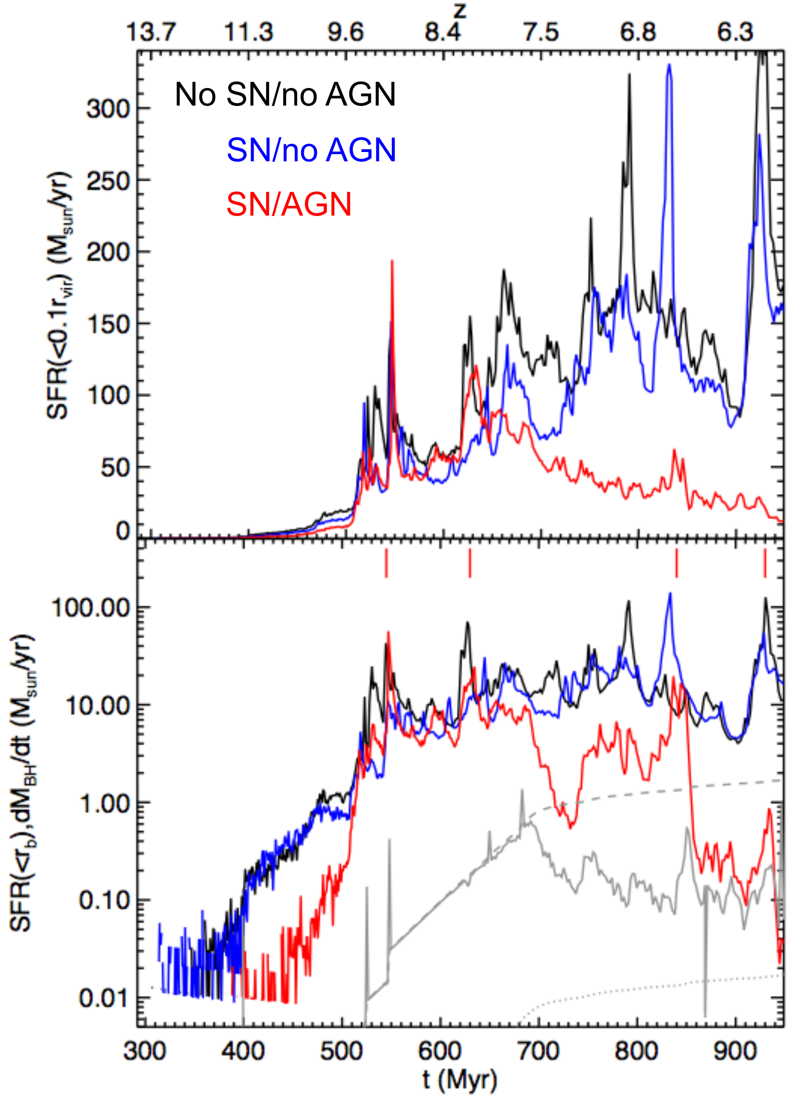


- Cold collimated streams of gas plunges into halos.
-They feed the central galaxy with large amounts of fresh material
- All of this neglects the role of (any) feedback

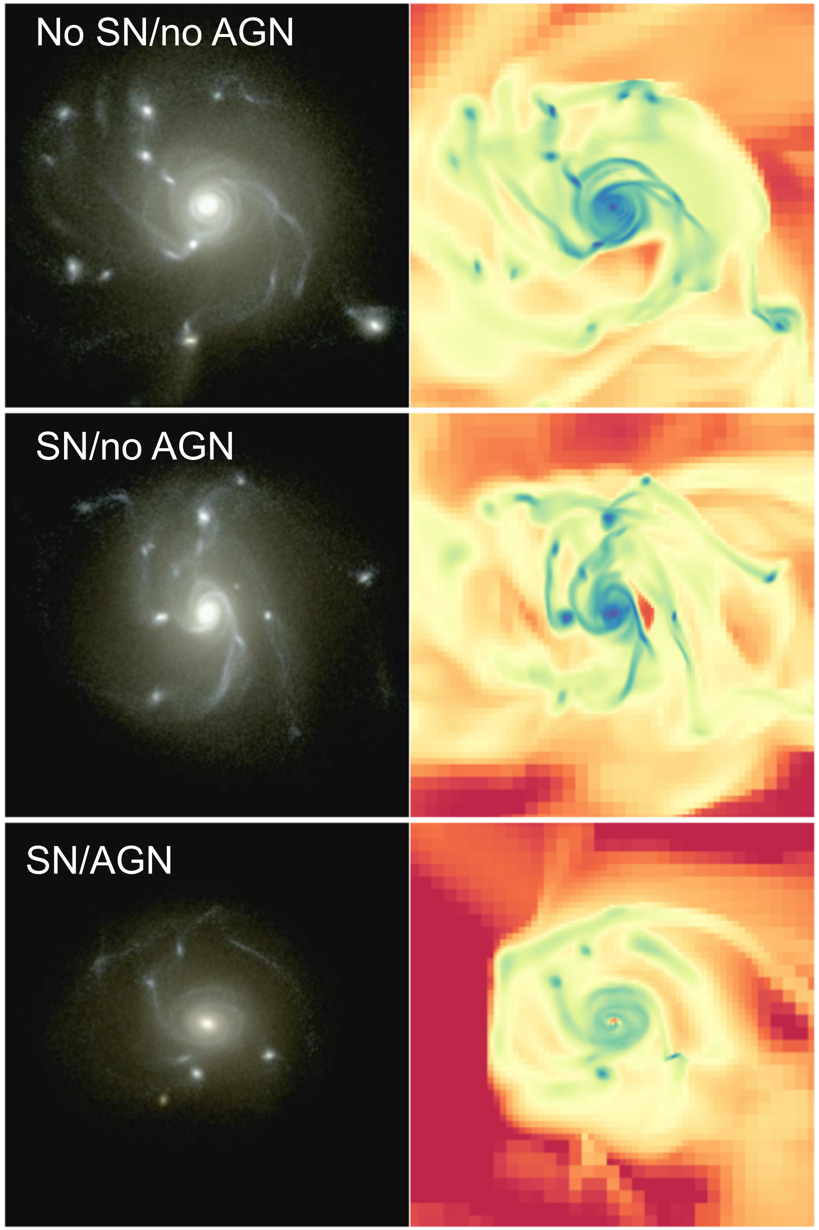
What about the impact of feedback on the gas accretion ?

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

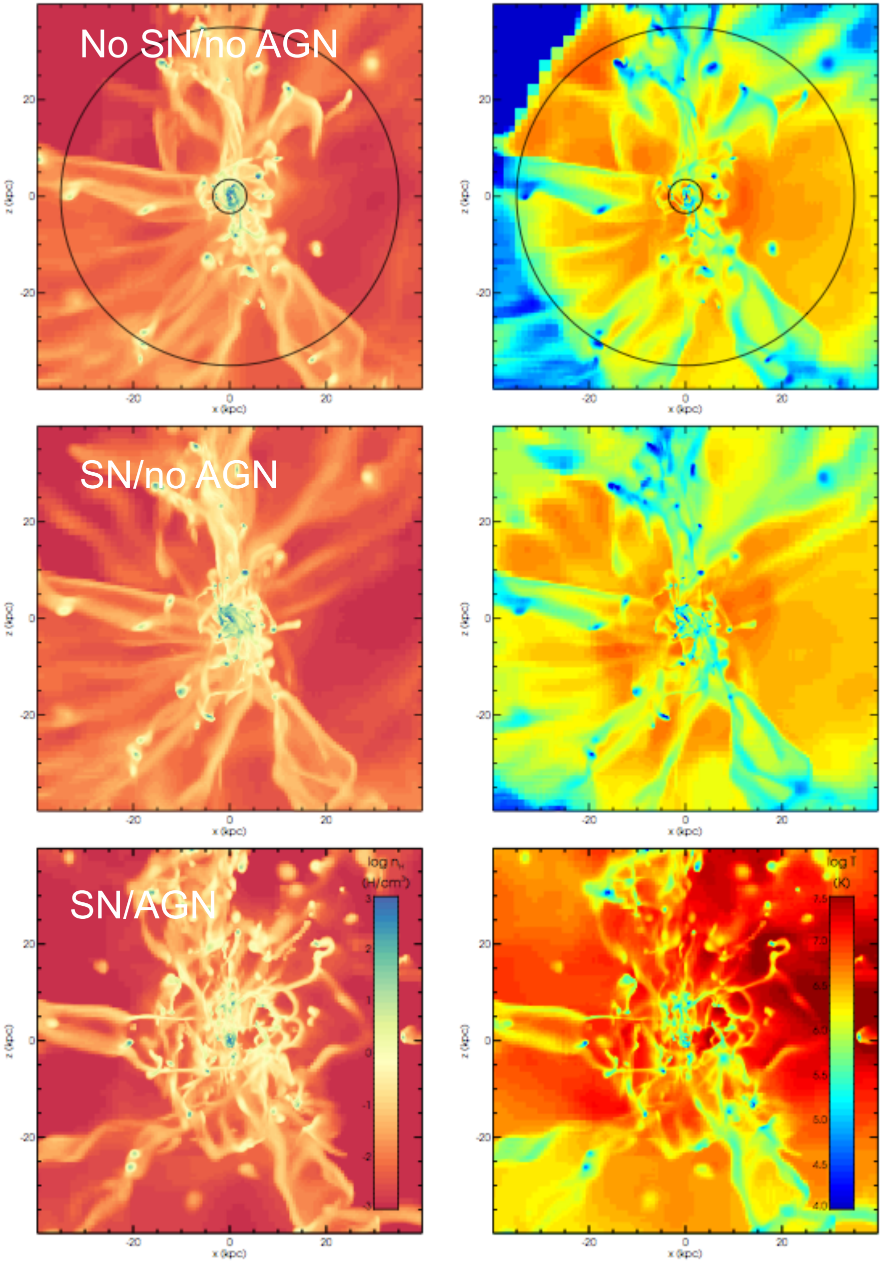
AGN quenches star formation efficiently early-on



Dubois, Pichon et al., 2013

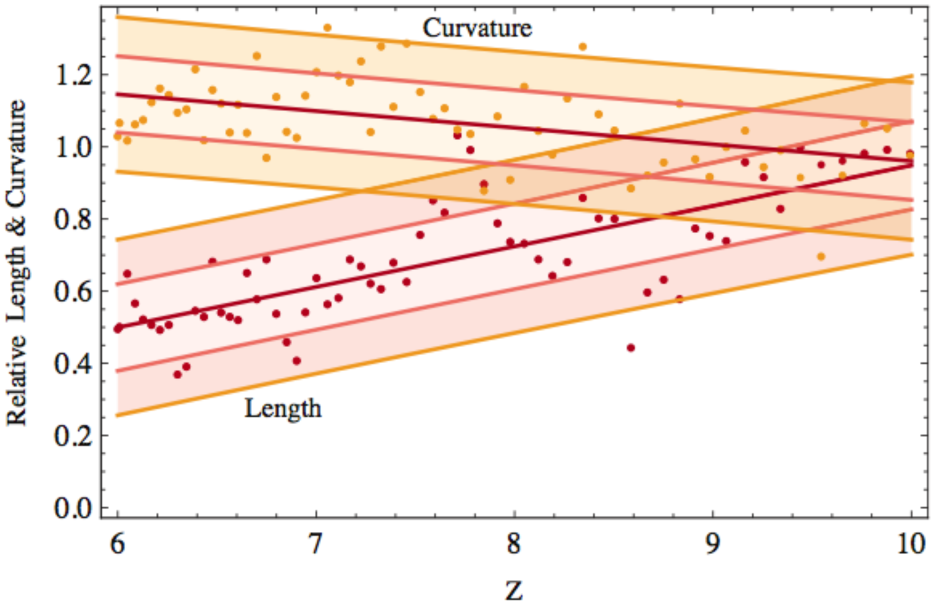


AGN blows cold flows away



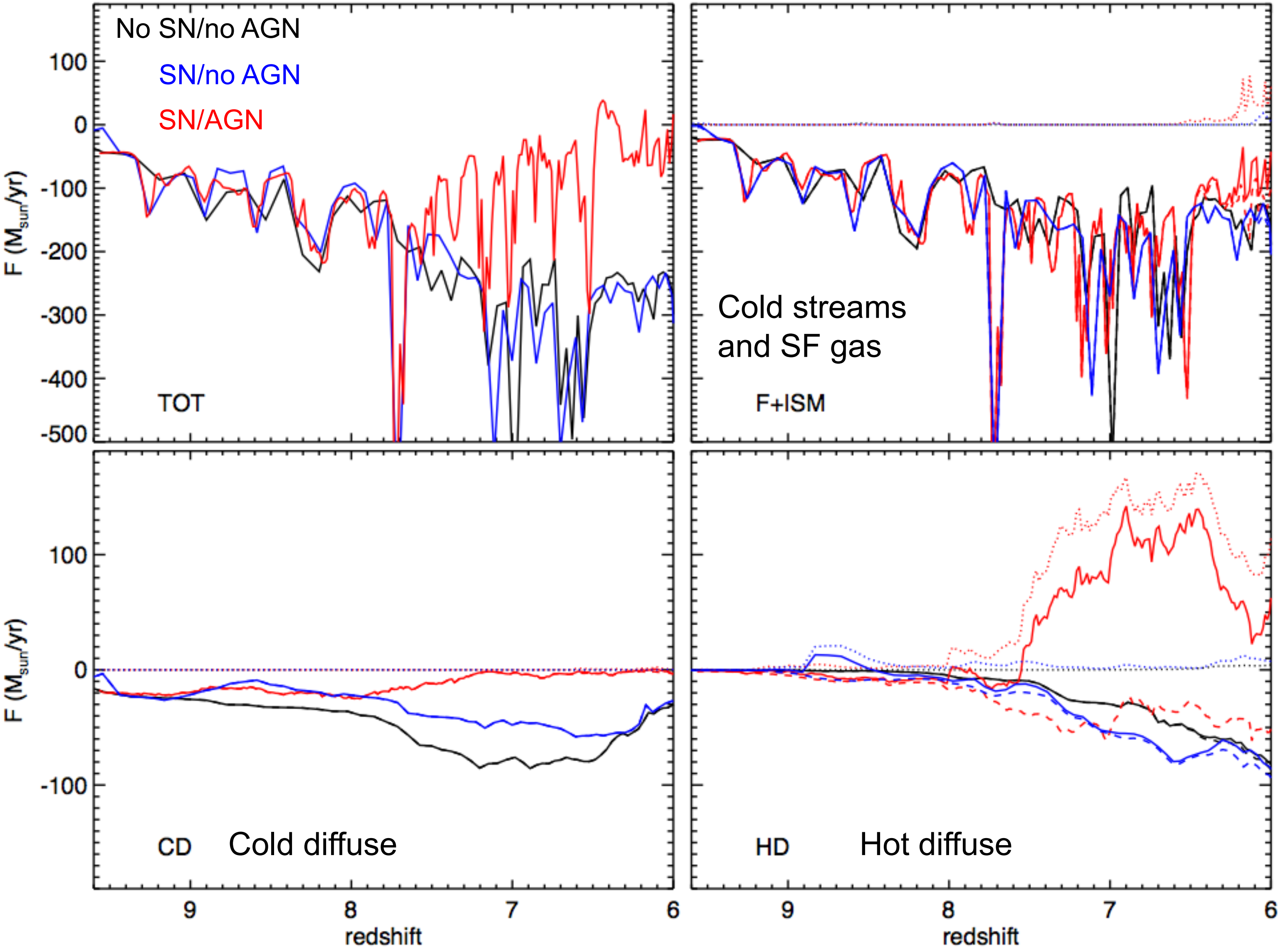
Gas is driven out hot from the central galaxy due to AGN.

Cold filaments are repelled from the halo. Their structure is strongly perturbed

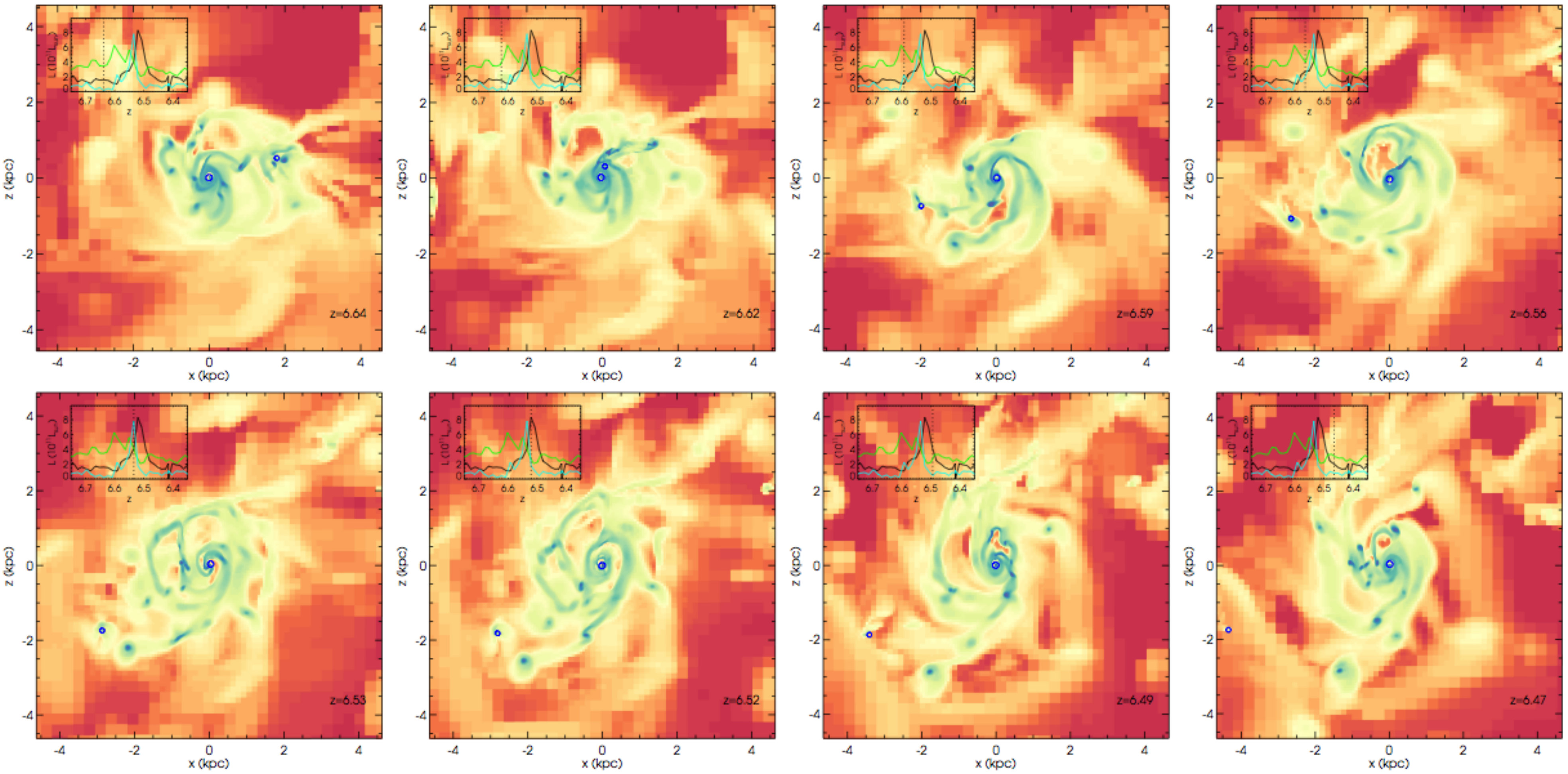


Dubois, Pichon et al., 2013.

Control over the accretion of gas



The essential role of mergers for a rapid clump migration to trigger AGN bursts



Dubois, Pichon et al., 2013

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)

- AGN can reheat the core of massive halos and prevent cooling catastrophe
  - Efficiently suppresses star formation
  - Prevents high concentration of material
  - Control the level of entropy in cluster cores
  - Transform disc galaxies into ellipticals

- AGN quasars in high redshift galaxies
  - The gas accretion onto BHs is driven first by cold streams, and, then, by galactic disc feeding through disc instabilities (clump migration)
  - Quasars at high redshift obliterates the gas content in massive bulges and strongly perturb the cold accretion of gas
  - Prevent large gas concentration in halos

Thank you for your attention