BH growth and the impact of AGN feedback on galaxy evolution

Yohan Dubois

Collaborators:
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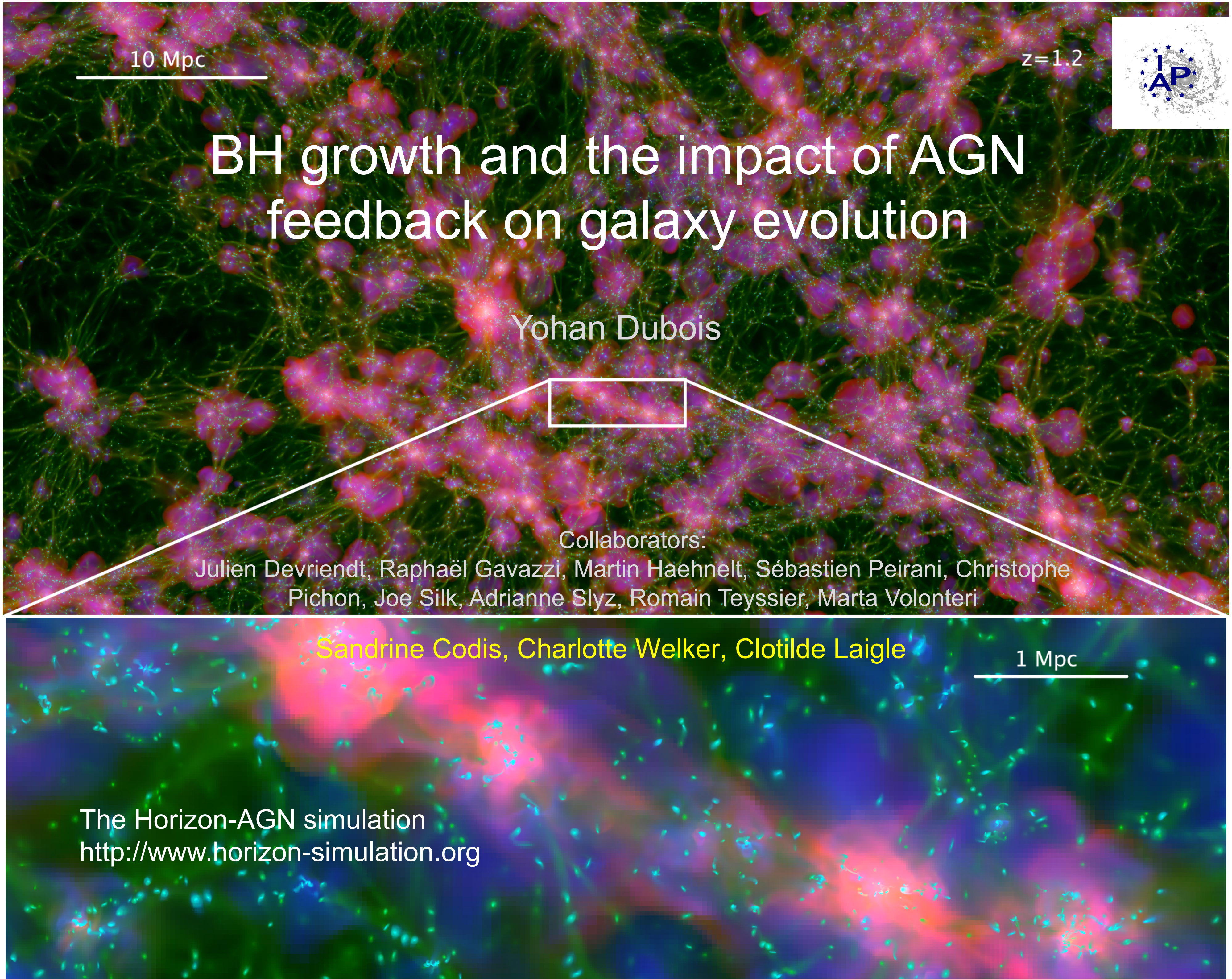
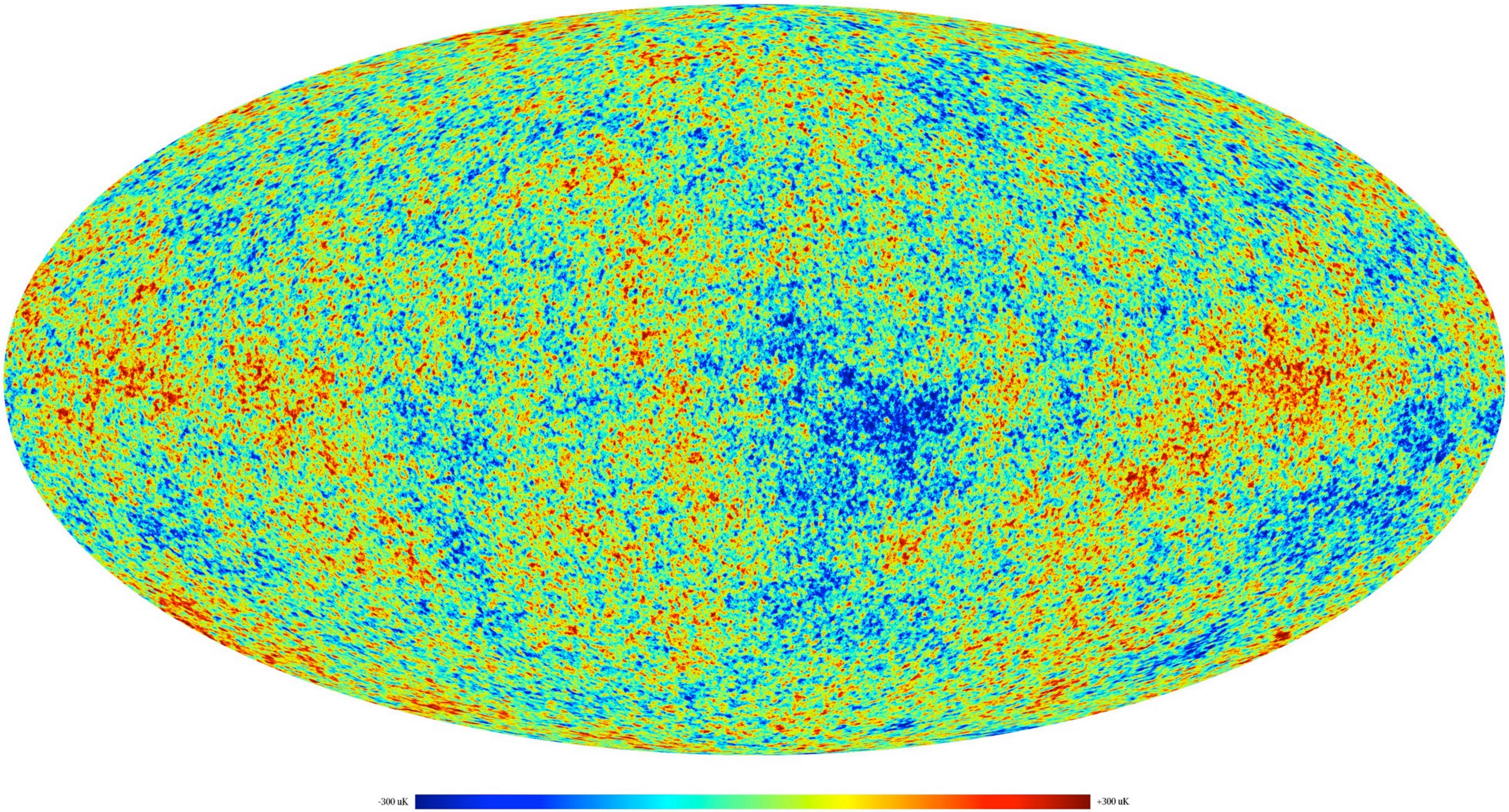
Sandrine Codis, Charlotte Welker, Clotilde Laigle

The Horizon-AGN simulation
http://www.horizon-simulation.org

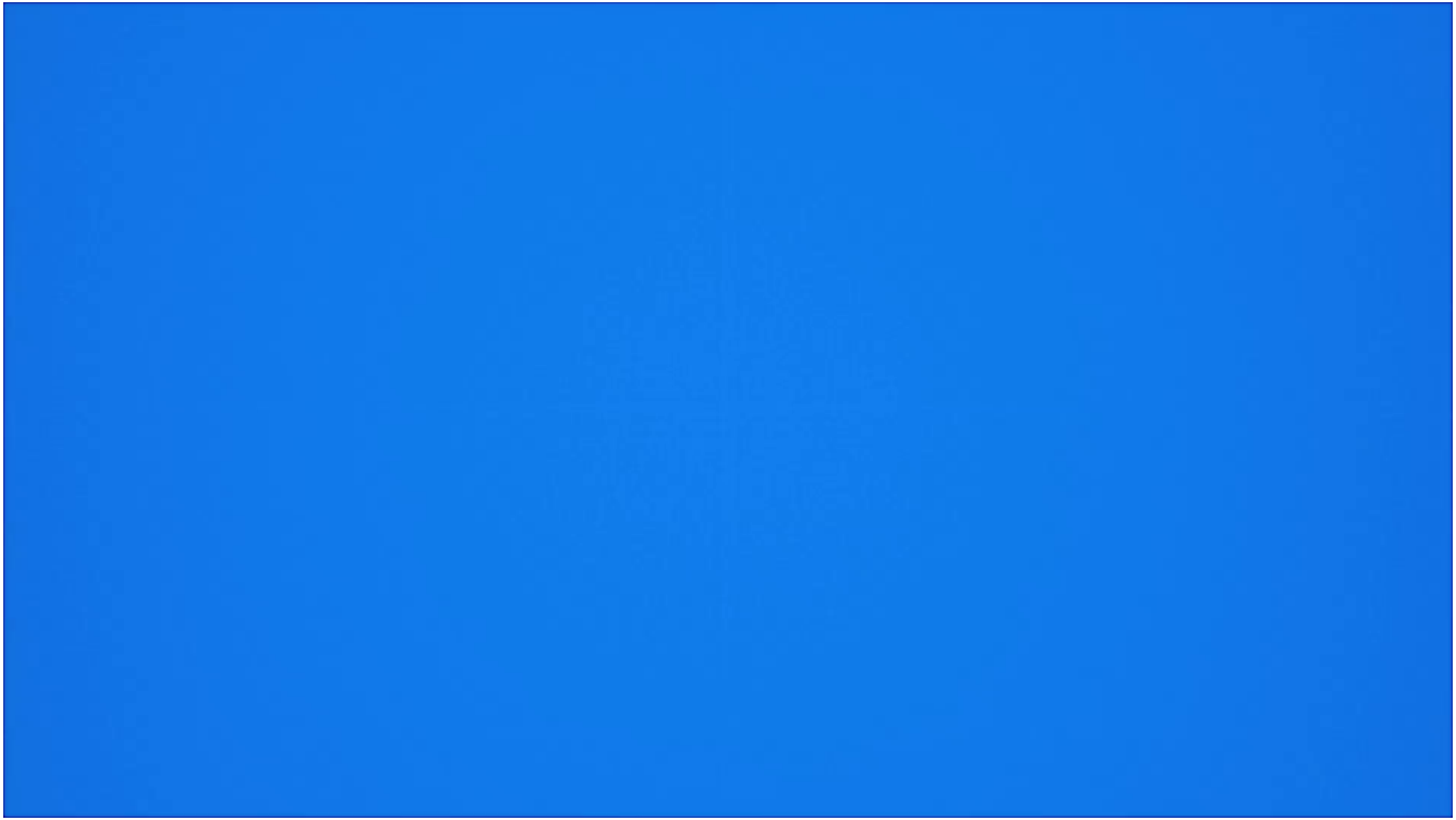


First observable light of the Universe

Small density variations in the cosmic microwave background.
Of the order of 10^{-5} in relative variation

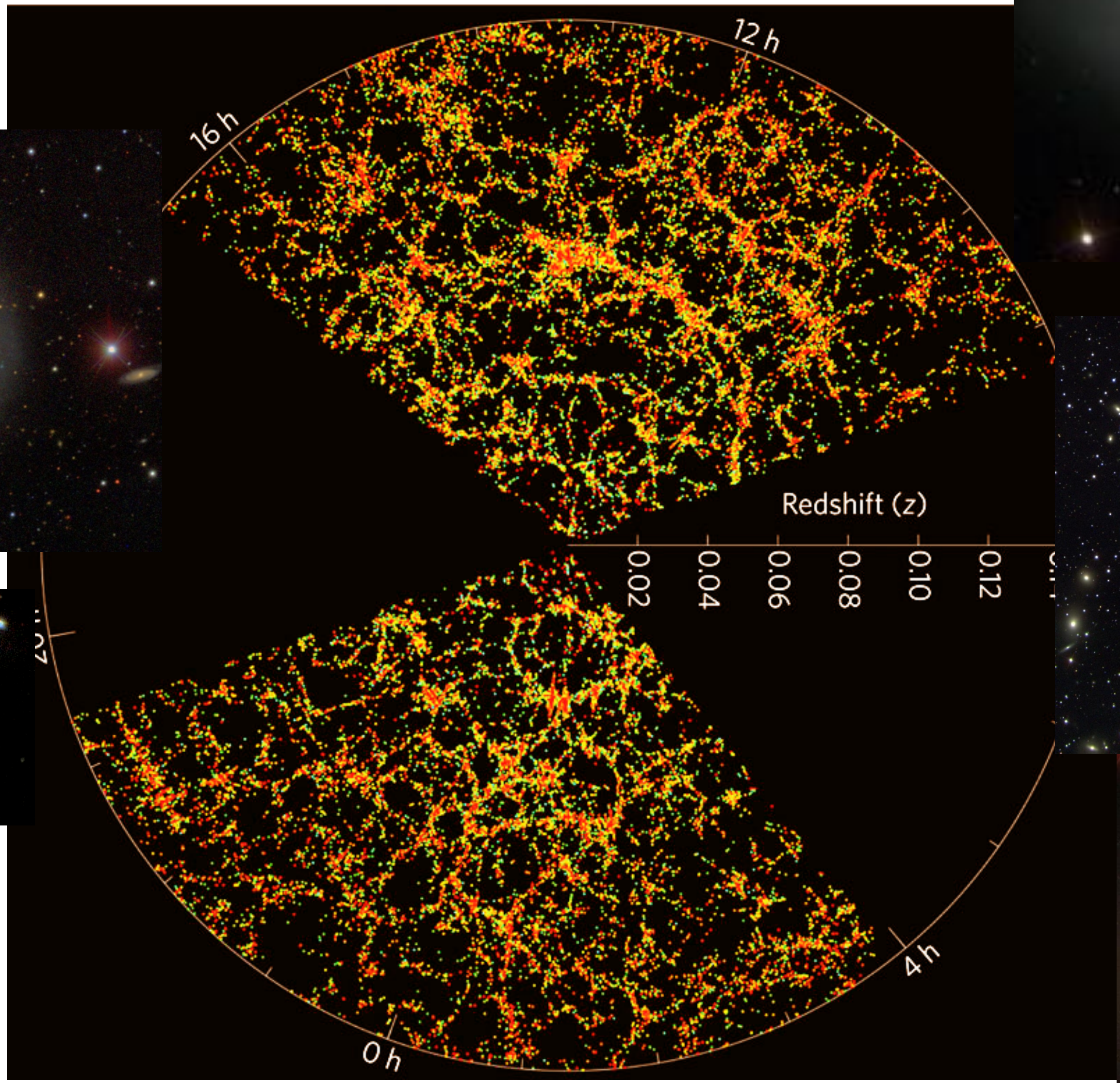


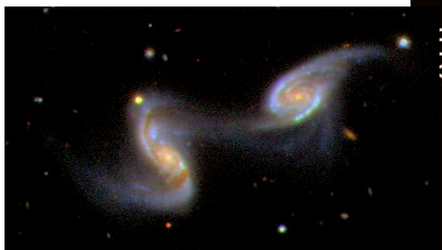
Planck



Colombi & Dubois

As seen with through observations of galaxies

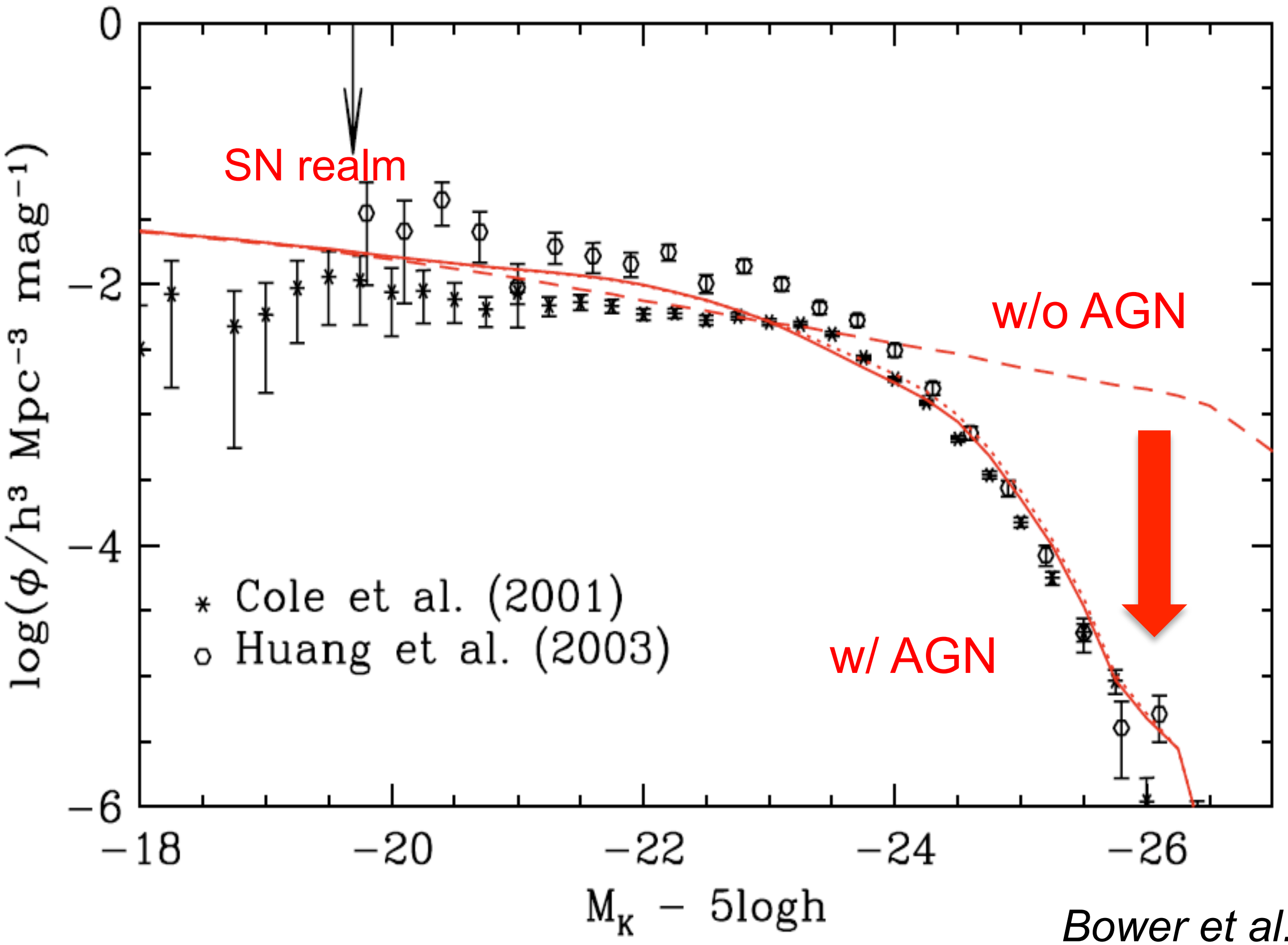




SDSS

Motivation for AGN feedback

Galaxy luminosity (~mass) function
Semi-analytic models

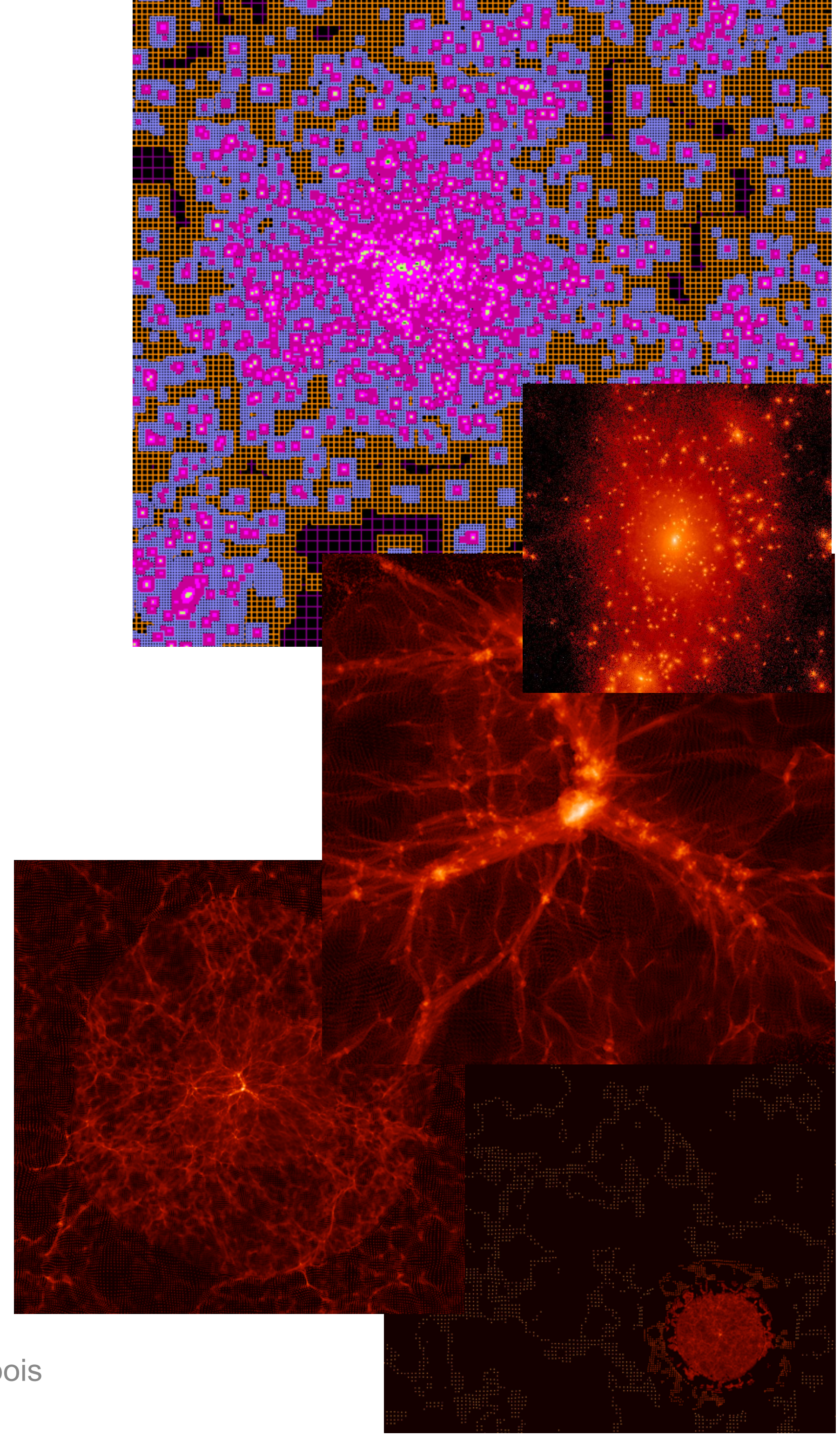


Bower et al., 2006

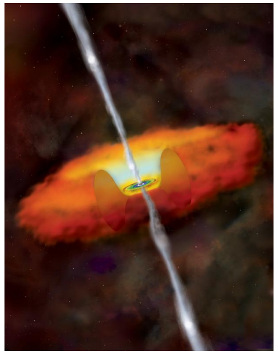
RAMSES : an Adaptive Mesh Refinement (AMR) code

- 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

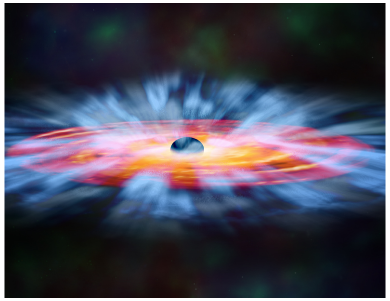
See Teyssier (2002)

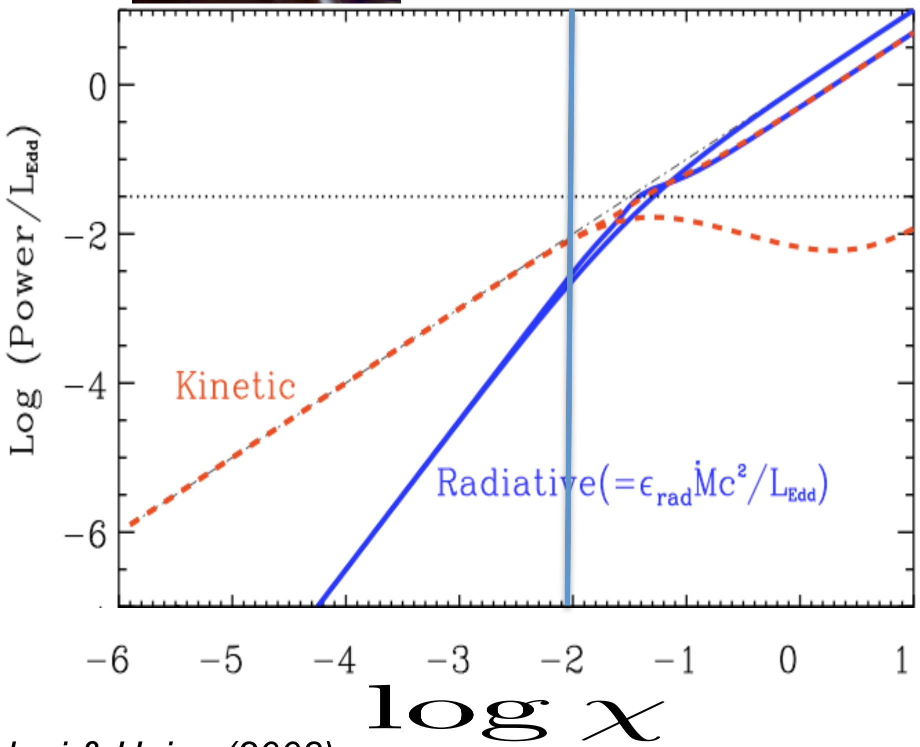


Two main modes of AGN feedback



or





Merloni & Heinz (2008)

Eddington ratio of the accretion rate

Bondi accretion

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

<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

- Mimic the formation of black holes

<u>Where</u> ?
In the centre of galaxies in high gas and stellar-density regions →

- Gas and stellar number densities are larger than 0.1 cm^{-3}
- Stellar velocity dispersion is larger than 100 $km.s^{-1}$
- Exclusion radius: BHs cannot for at a smaller distance r_{gal}~ a few 10 kpc from any other BH

With what initial seed BH mass ?

Quite arbitrary choice → $M_{\rm seed} = 10^5\,{\rm M}_\odot$

AGN in cosmological simulations

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

Bondi accretion rate capped at Eddington

$$\dot{M}_{\rm BH} = \alpha 4\pi G \rho \frac{M_{\rm BH}^2}{(c_{\rm s}^2 + v_{\rm rel}^2)^{3/2}}$$

Fudge factor

Gas density

Sound speed

Relative BH-gas velocity

$$\alpha = 1 \,\mathrm{if}\, \rho < \rho_{0,\rm SF}$$

$$\alpha = \left(\frac{\rho}{\rho_{0,\rm SF}}\right)^2 \,\mathrm{if}\, \rho \geq \rho_{0,\rm SF}$$

Required to capture the fast accretion rates due to unresolved large density contrasts Booth & Schaye (2009)

How to compute the averaged gas quantities?

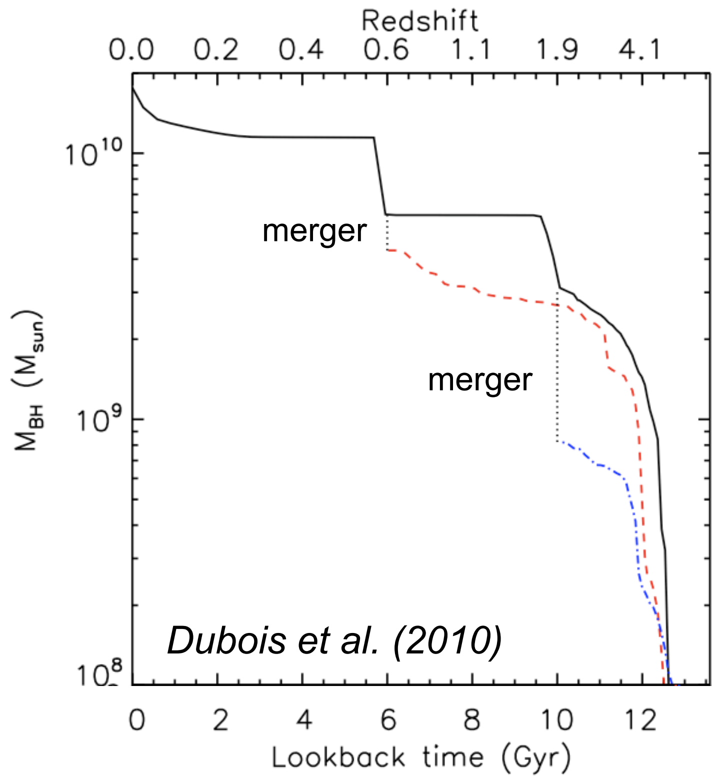
Use cloud particles to interpolate quantities from neighbouring cells

AGN in cosmological simulations

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

Proximity criterion: two BHs must be closer than $4\Delta x$

Escape velocity criterion: two BHs must have a relative velocity smaller than the escape velocity of the binary

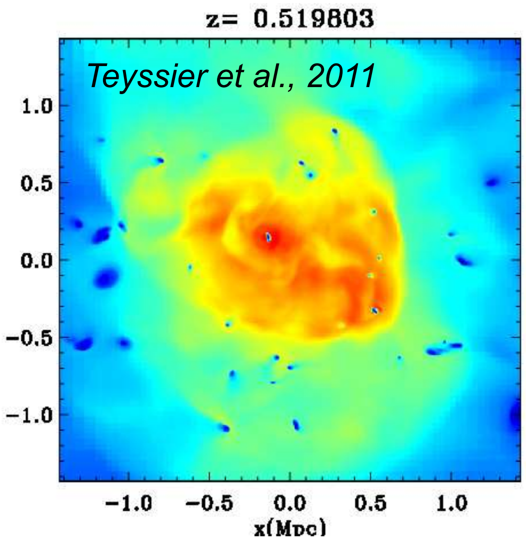


AGN in cosmological simulations

- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes
- Mimic the mergers between black holes
- (Mimic the drag force exerted from the gas onto BHs)
- Mimic the feedback from black holes (AGN)

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

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 by uniformly distributing the specific energy (uniform temperature variation) in a sphere of radius $r_{\rm AGN}=\Delta x, 2\Delta x, 4\Delta x$

AGN in cosmological simulations

- Mimic the formation of black holes (where and when)
- Mimic the gas accretion onto black holes
- Mimic the mergers between black holes
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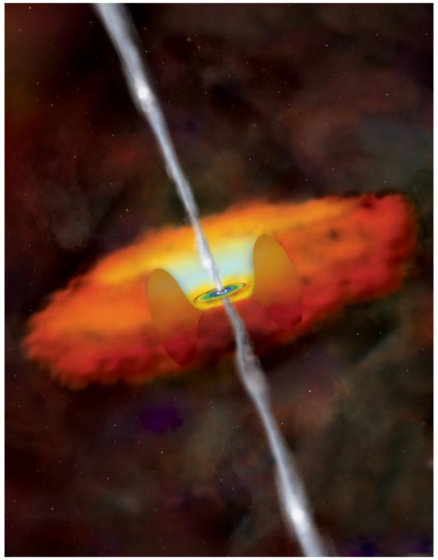
$$L_{\rm AGN} = \epsilon_f \epsilon_r \dot{M}_{\rm BH} c^2$$

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



Compute gas angular momentum around the black hole
-> jet axis (should actually be spin axis)

Kinetic energy with bipolar outflow in a cylinder of radius and semi-height Δx, $2\Delta x$, $4\Delta x$

Mass ejected with velocity 10 000 km/s = mass loading of the jet (arbitrary value)

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

AGN in cosmological simulations

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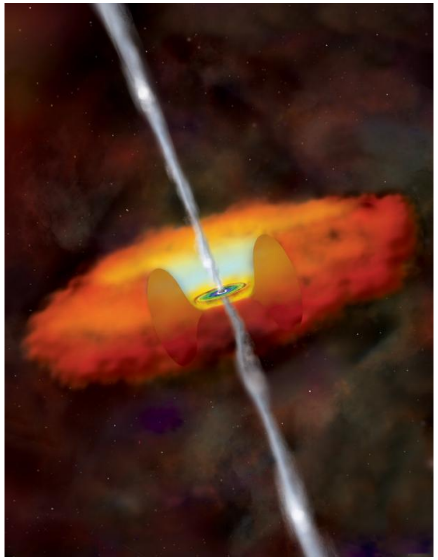
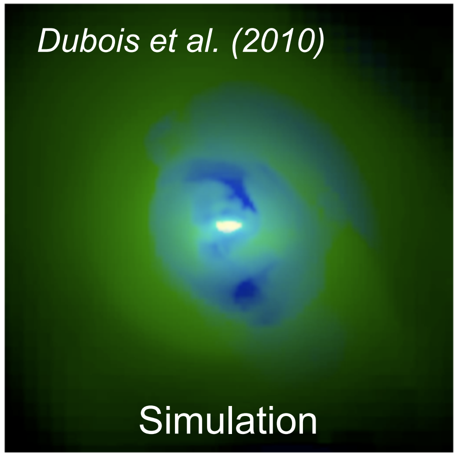
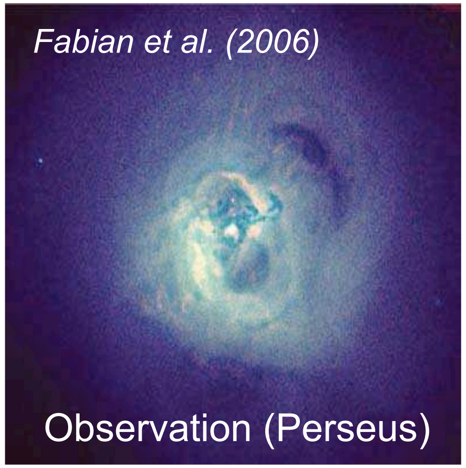


450 kpc





100 kpc

X-ray (3 bands)

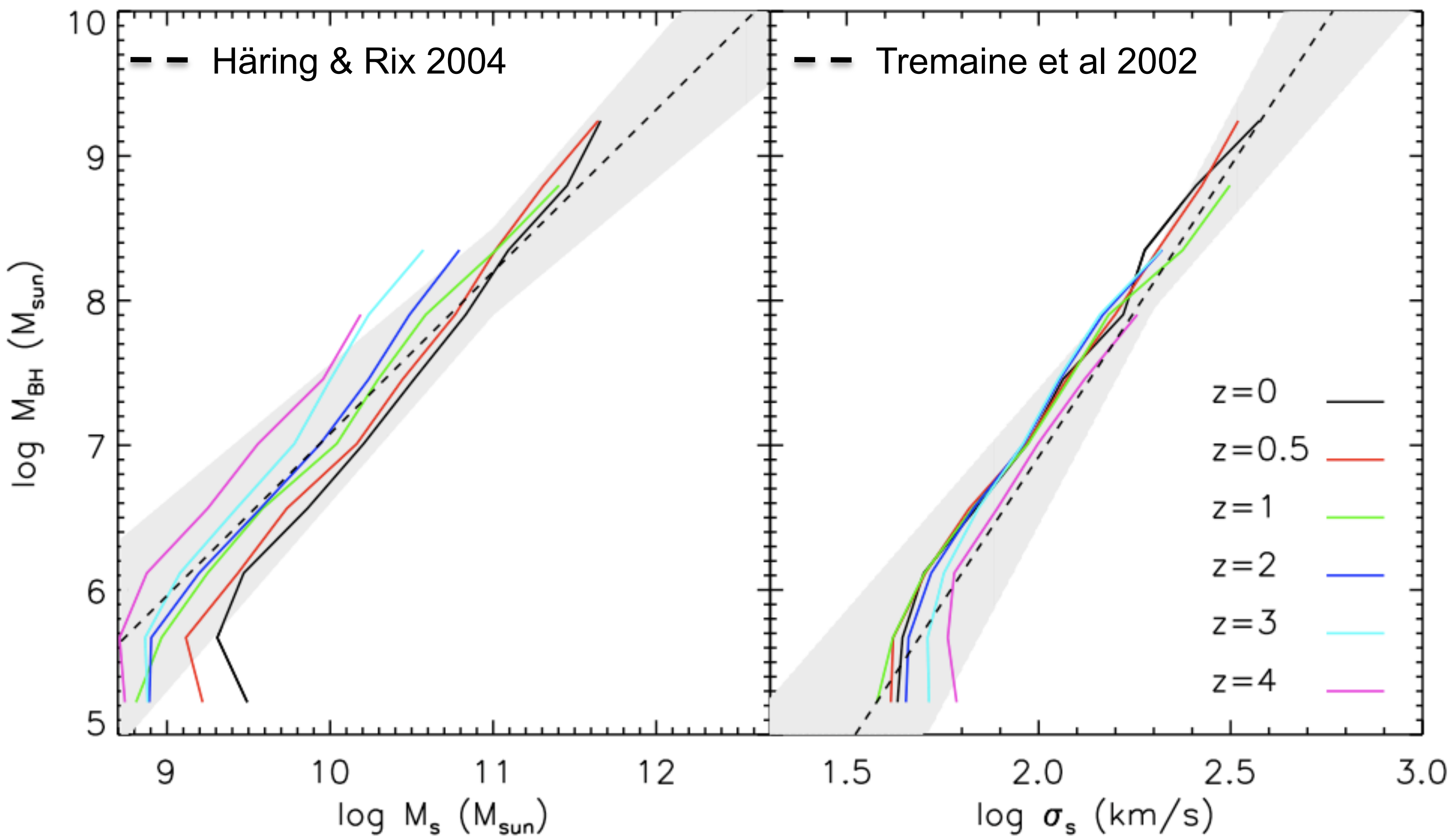
Testing the model: parameters and resolution

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

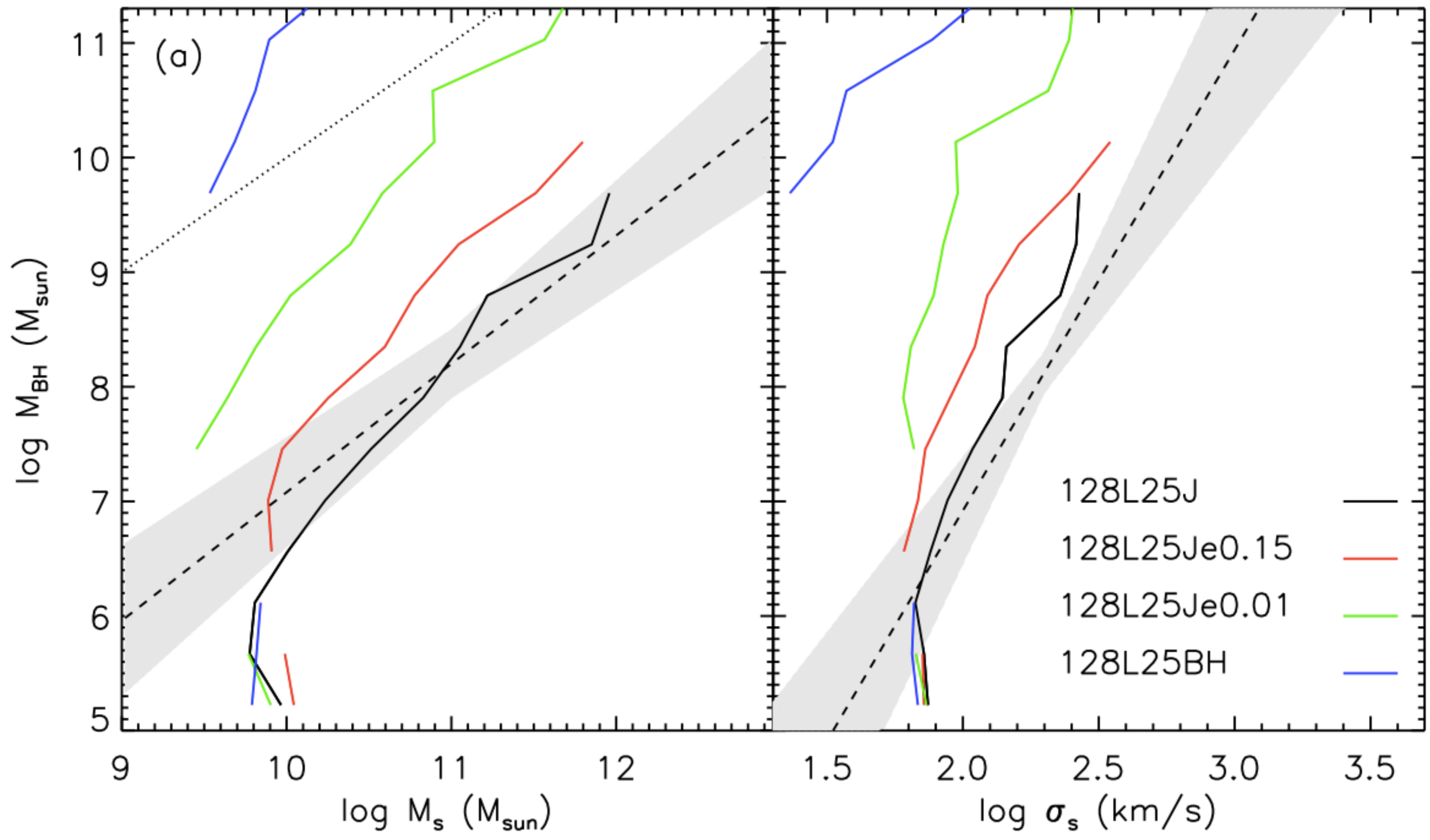
Dubois et al, 2012

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



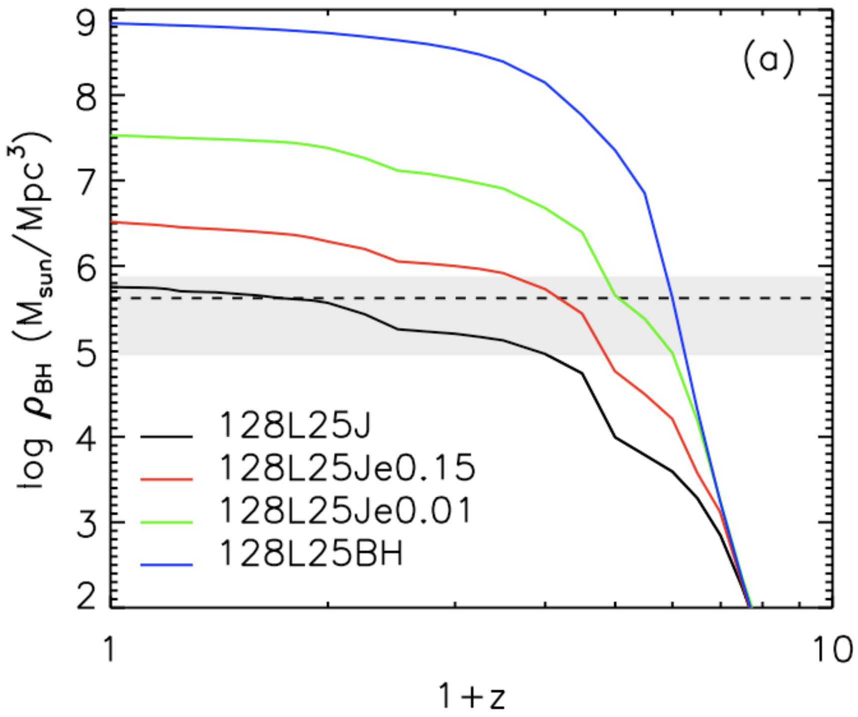
Testing the efficiency

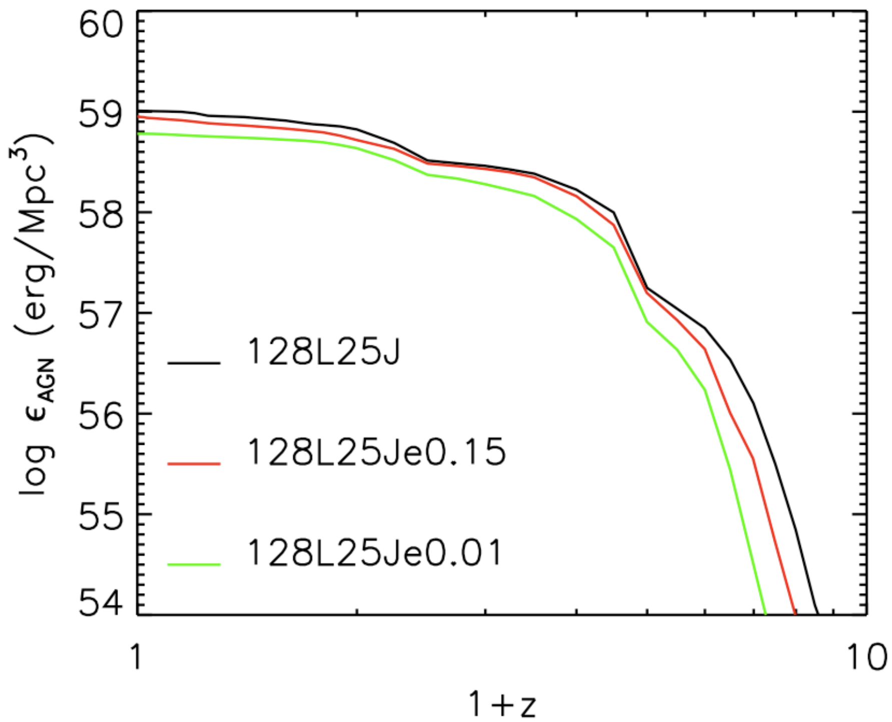
The observational relations put strong constraints on the feedback efficiency ε_f=1 in the jet mode and ε_f=0.15 in the quasar mode



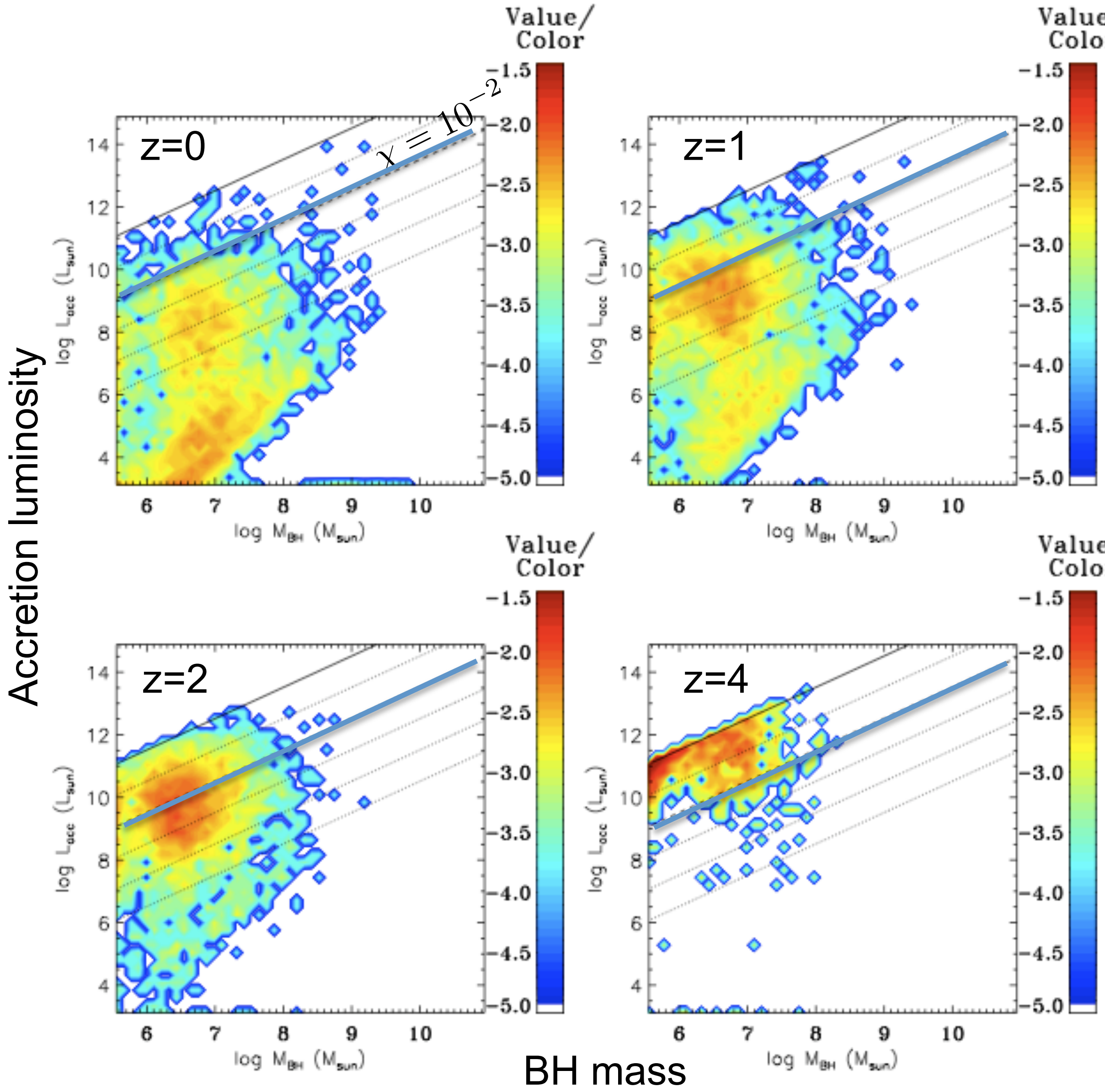
Testing the efficiency

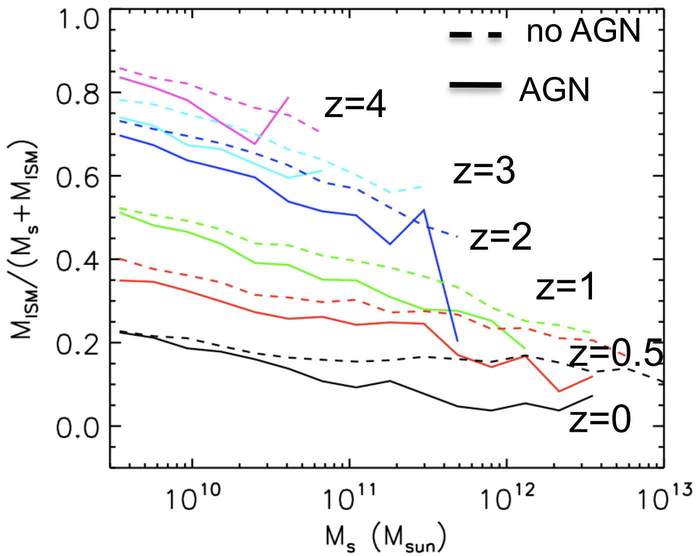
BHs deposit the same energy / independant of the AGN efficiency





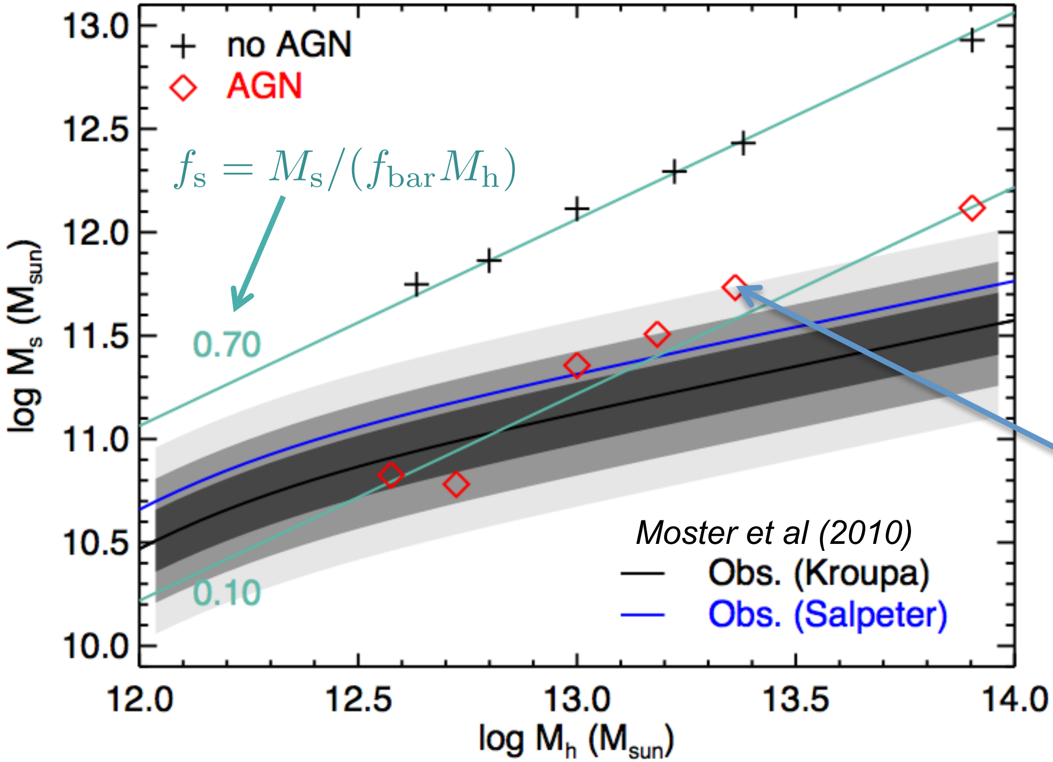
Radio mode or quasar mode ?

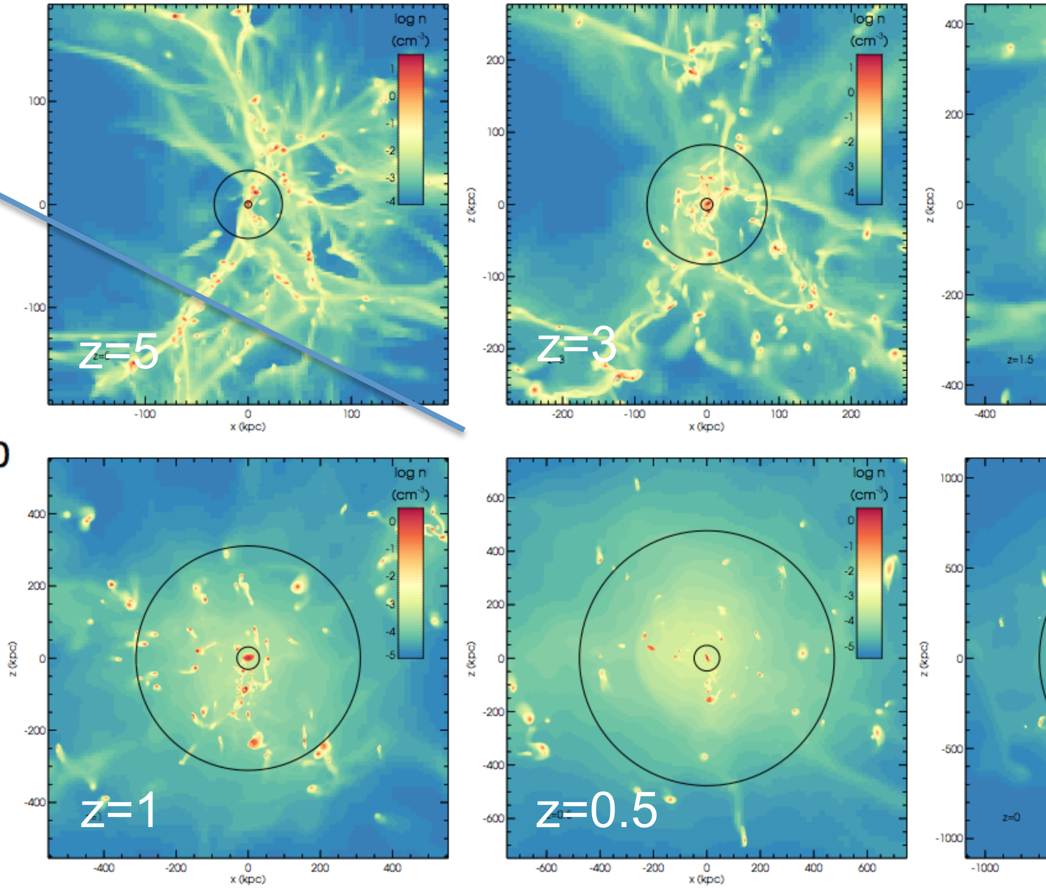




Galaxies are gas-rich at high-redshift
Star formation and feedback removes cold gas efficiently

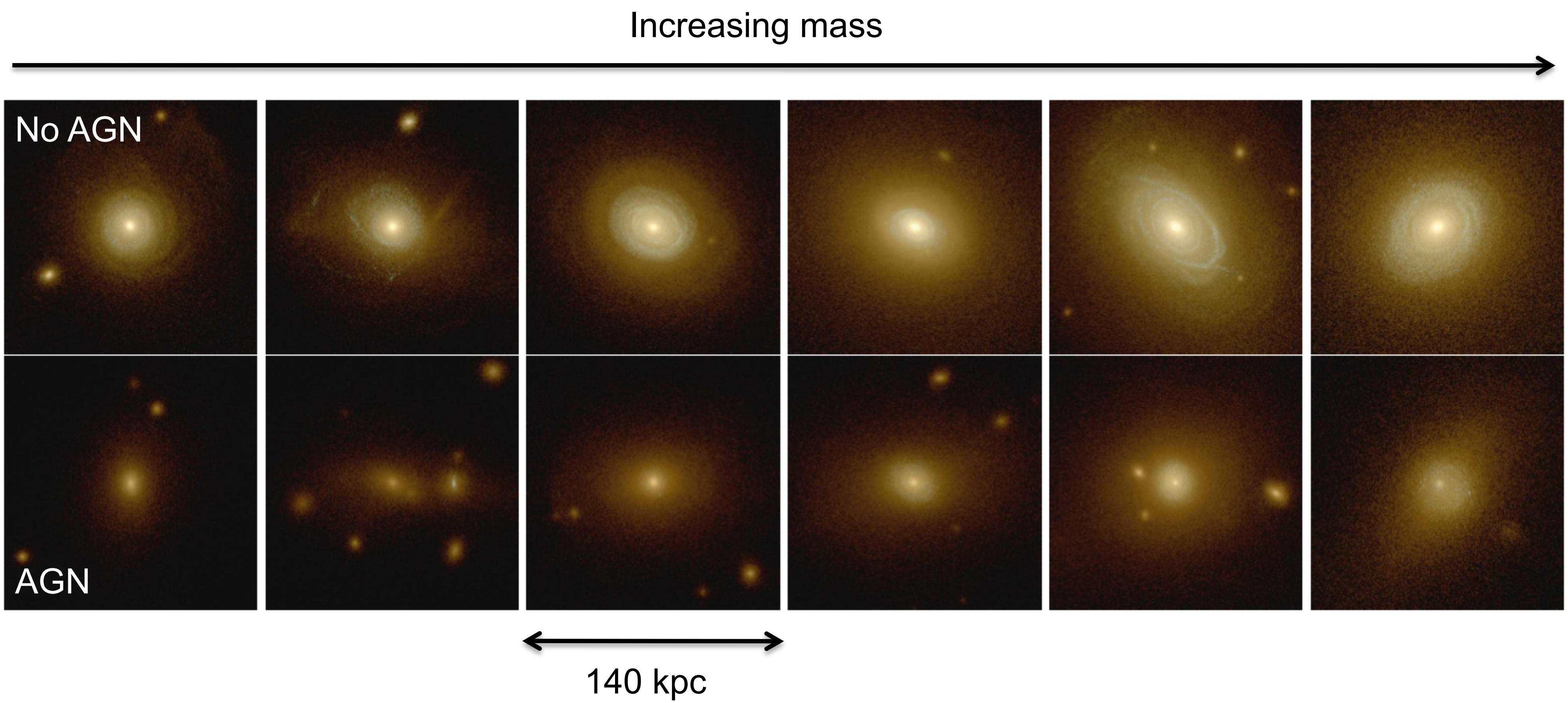
Stellar mass in central massive galaxies



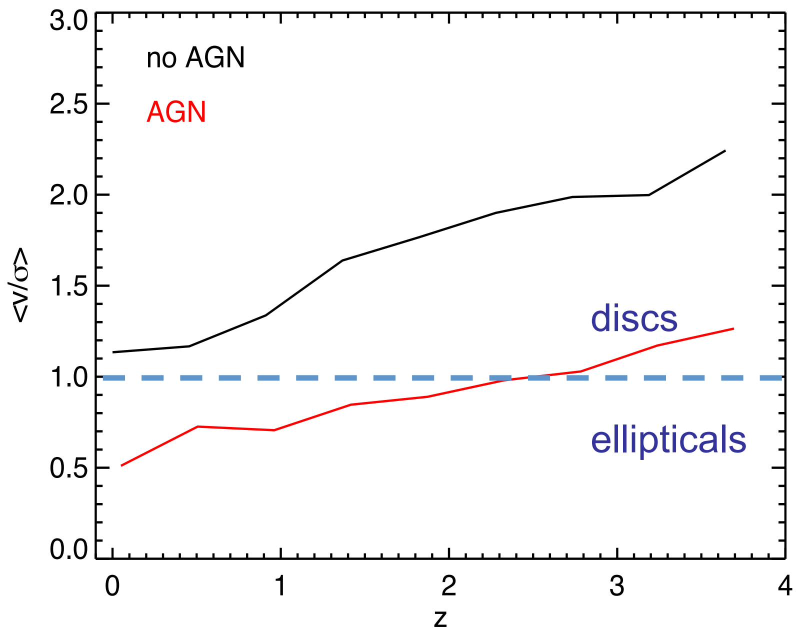


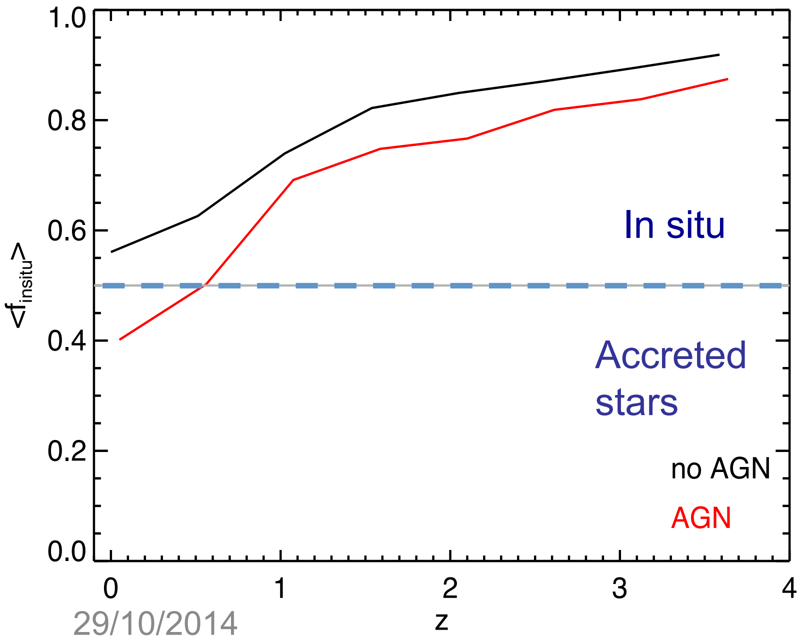
Dubois, Gavazzi, Peirani, Silk, 2013

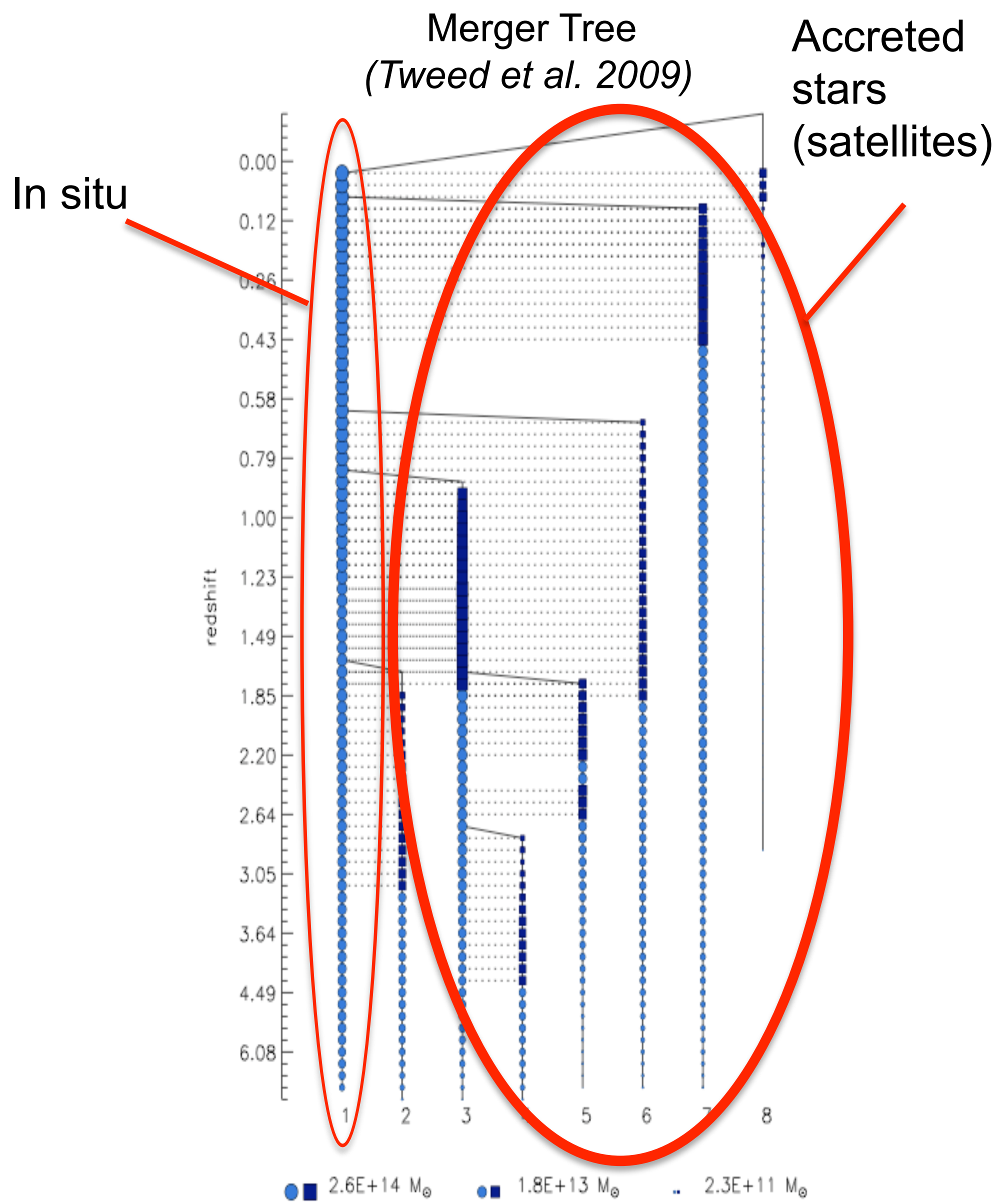
Can we get massive galaxies that look like ellipticals ?



Rotation or dispersion-dominated galaxies?

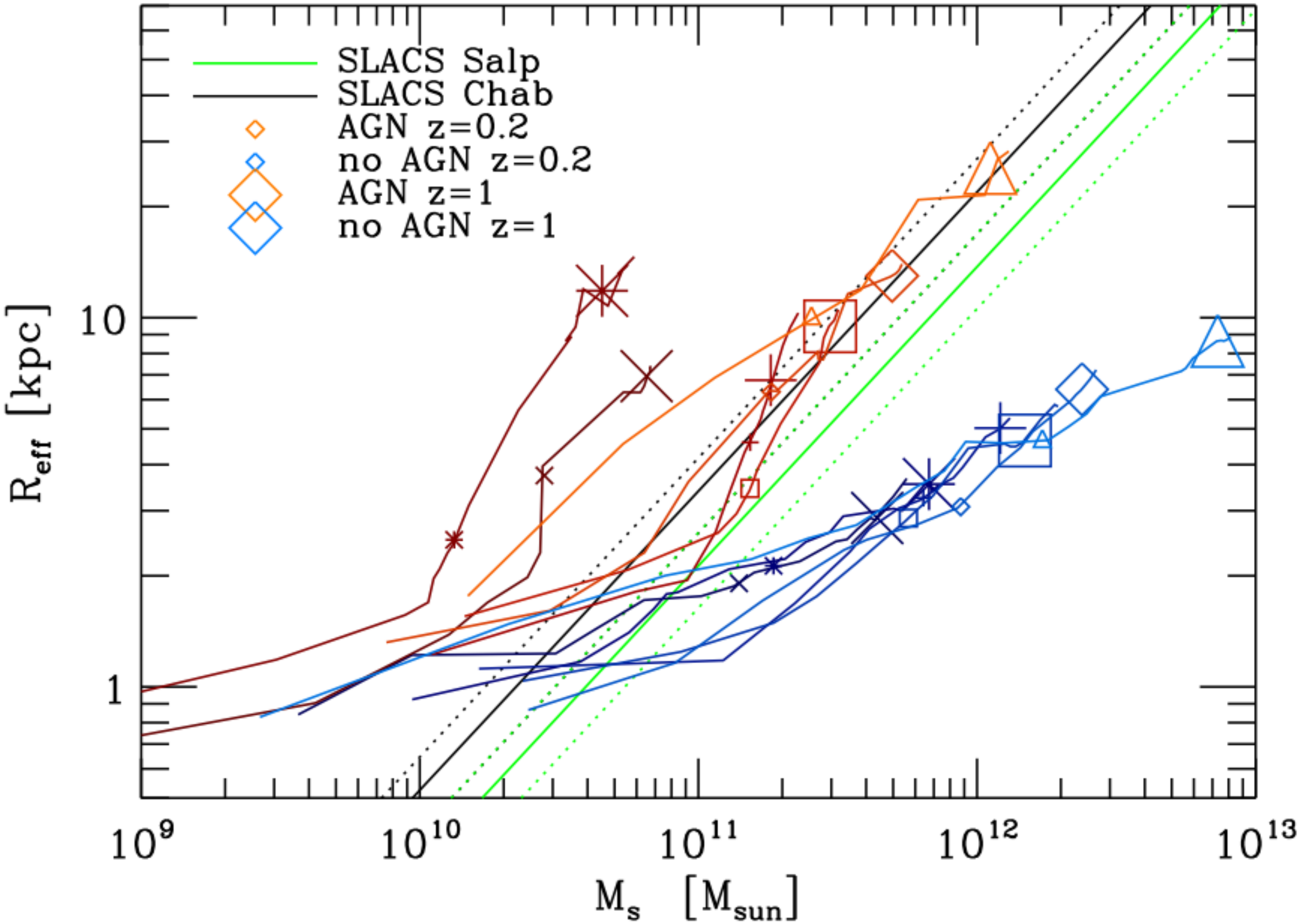






Dubois, Gavazzi, Peirani, Silk, 2013

AGN change galaxy sizes

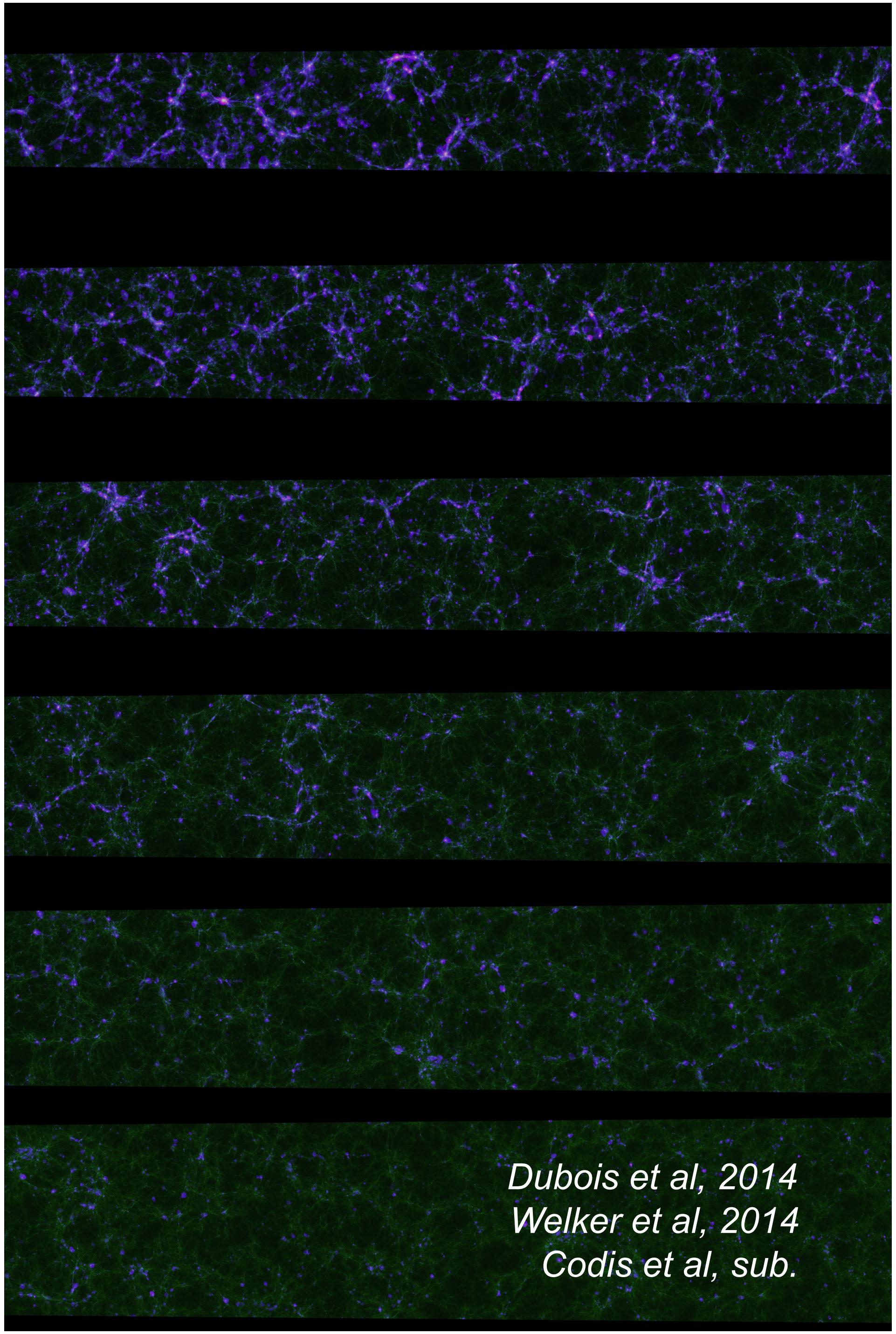


Dubois, Gavazzi, Peirani, Silk, 2013

The Horizon-AGN simulation

- Simulation content
  - Run with Ramses (AMR) *Teyssier (2002)*
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8\mathrm{x}10^7\ M_{sun}$
  - 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
  - Standard outputs ~200 Myrs
  - Star particles are backed up every 10-20 Myr
  - 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=0.6 using 6.7 Mhours on 4096 cores
- 150 000 galaxies per snapshot (> 50 part.)
- 7.10^9 leaf cells (more than Illustris or EAGLE)

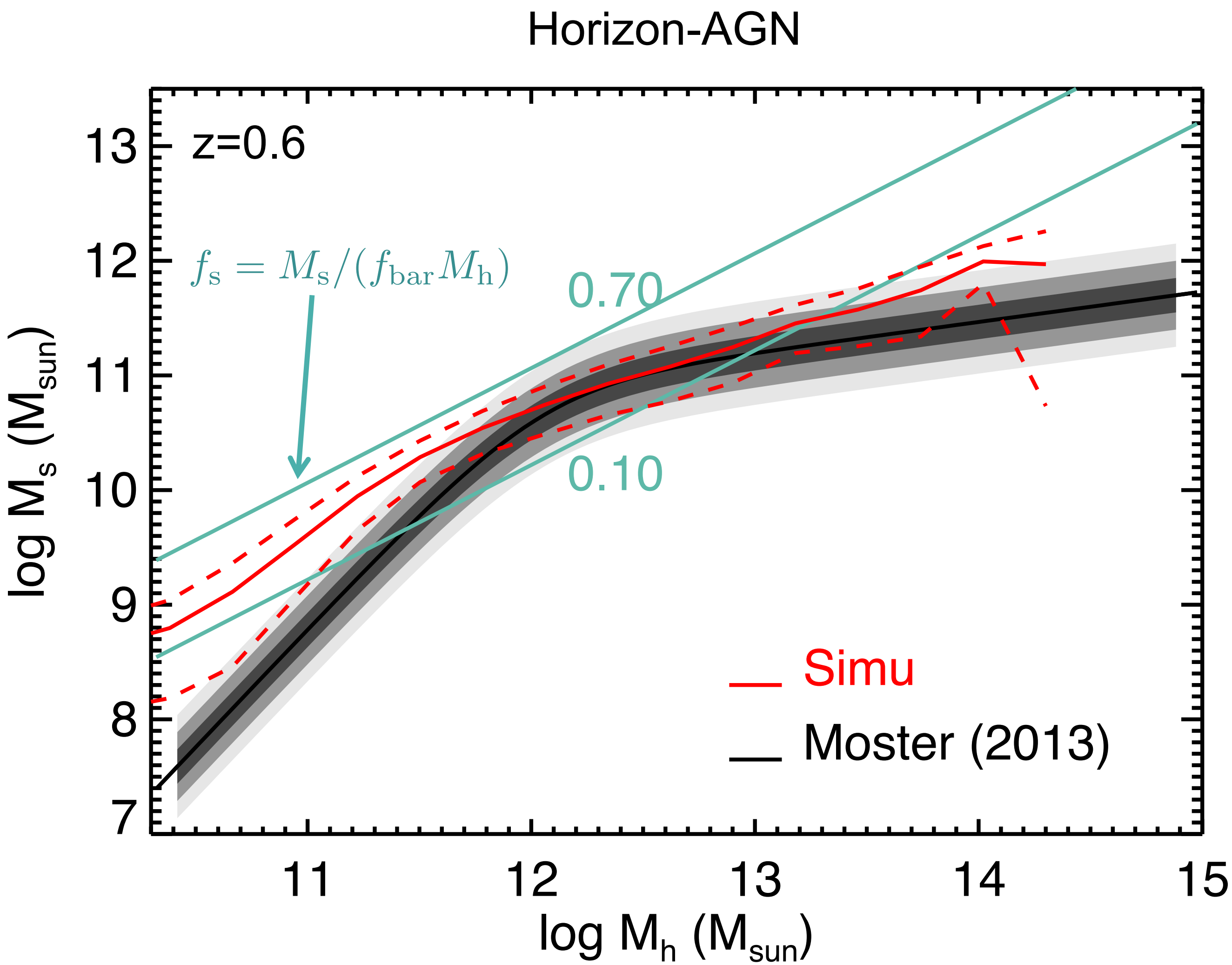
http://www.horizon-simulation.org/



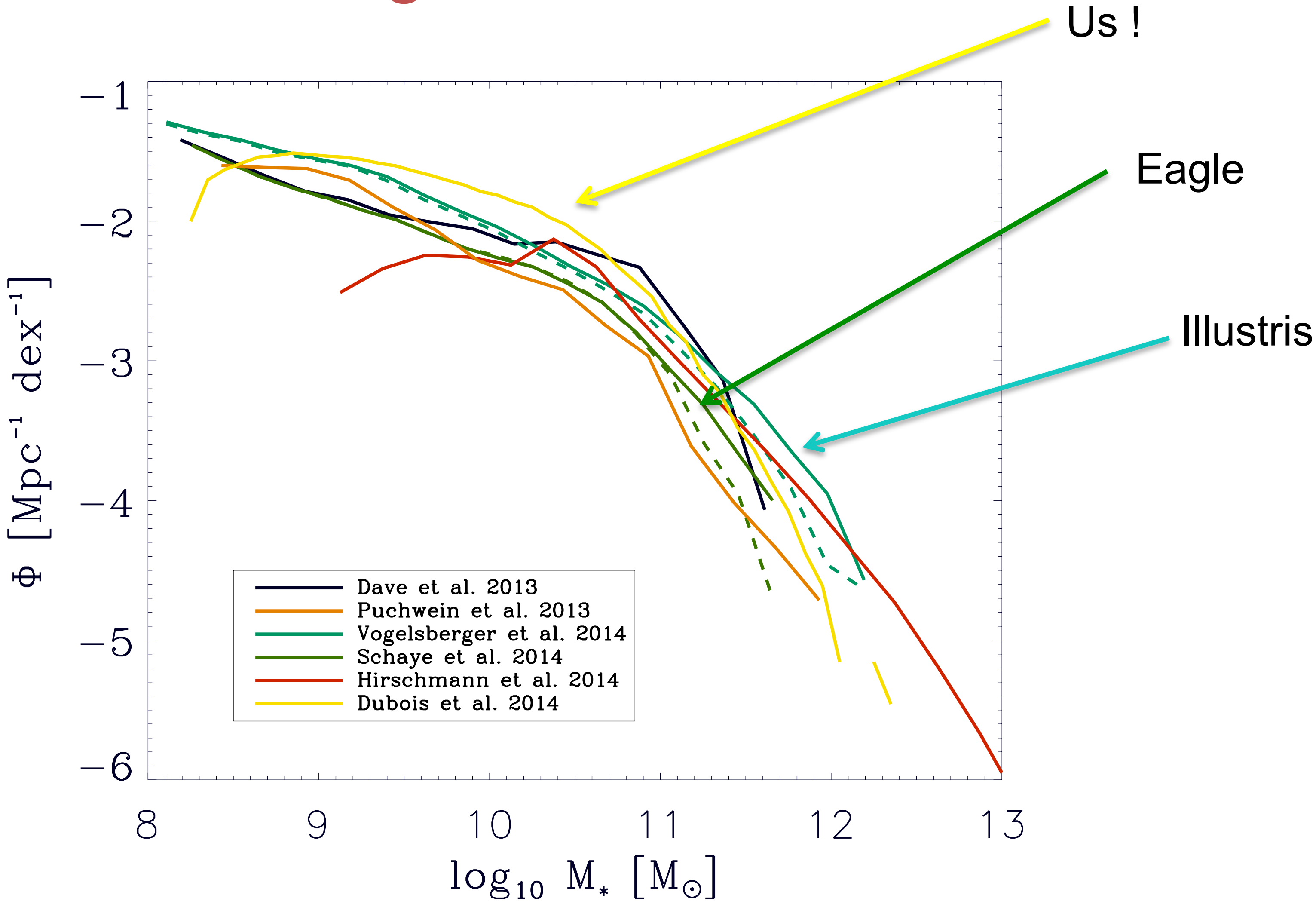
Green: gas density / Red: temperature / Blue: metallicity

Zoomed in

Stellar mass in central galaxies versus halo mass

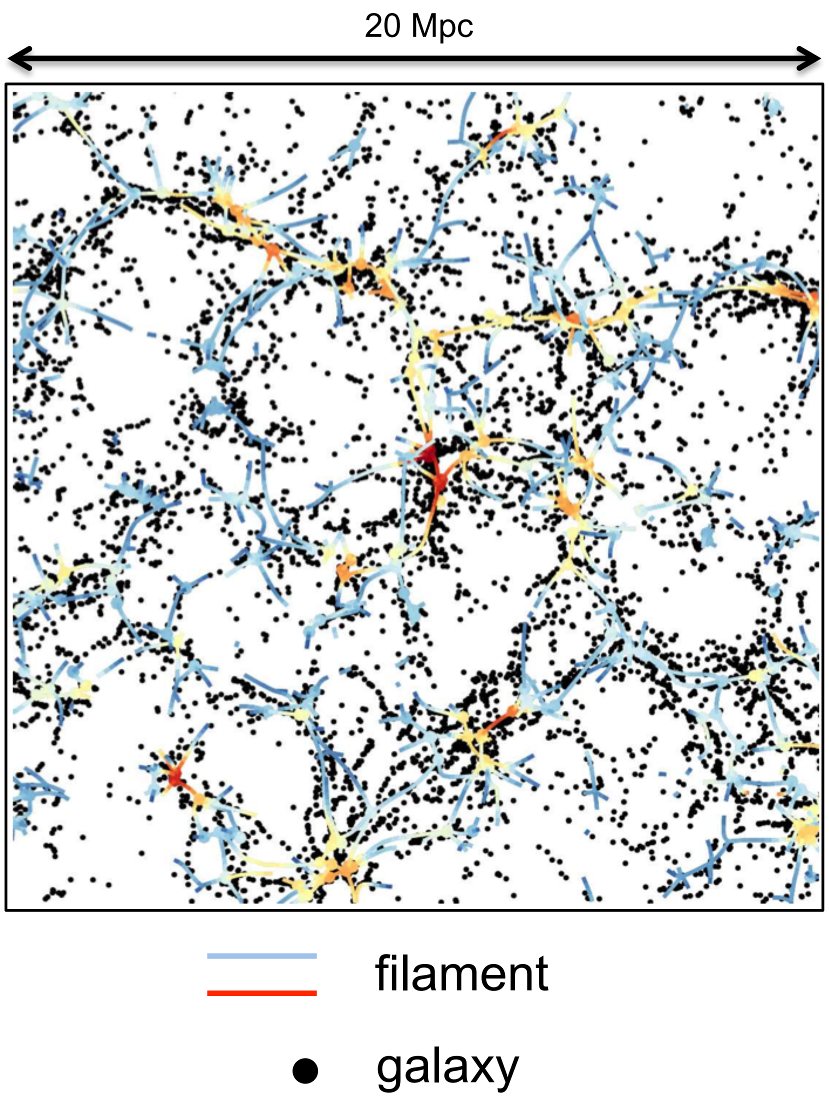


How it compares to state-of-the-art hydro cosmological simulations

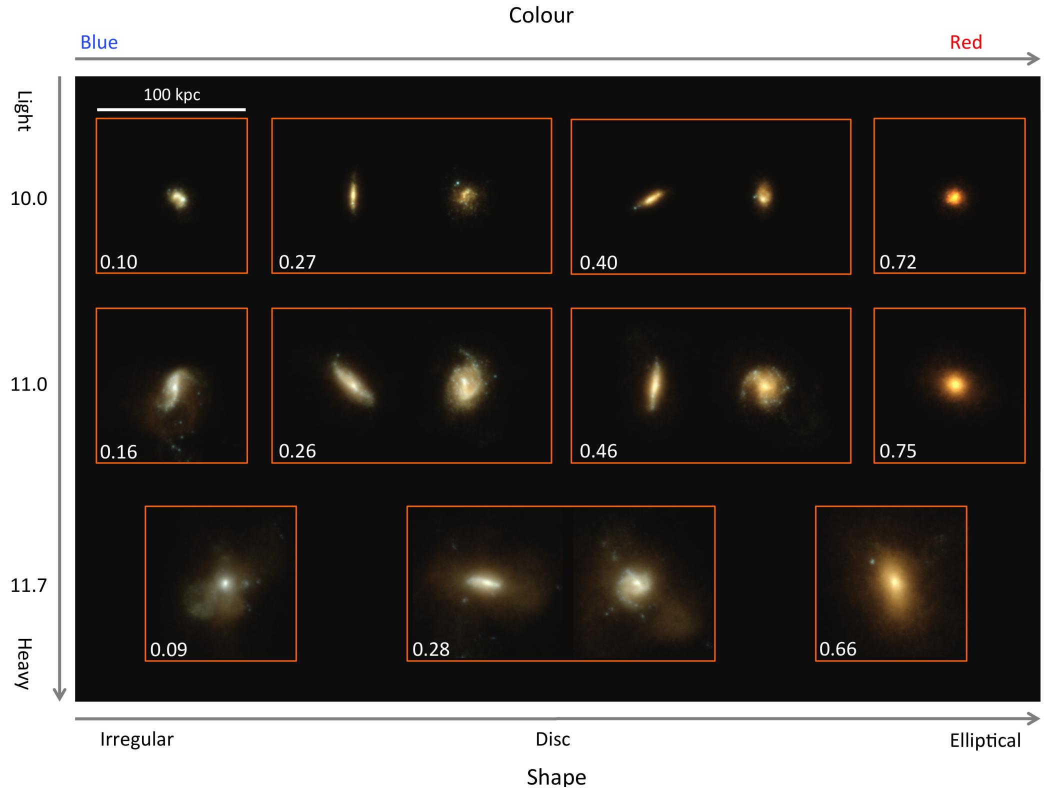


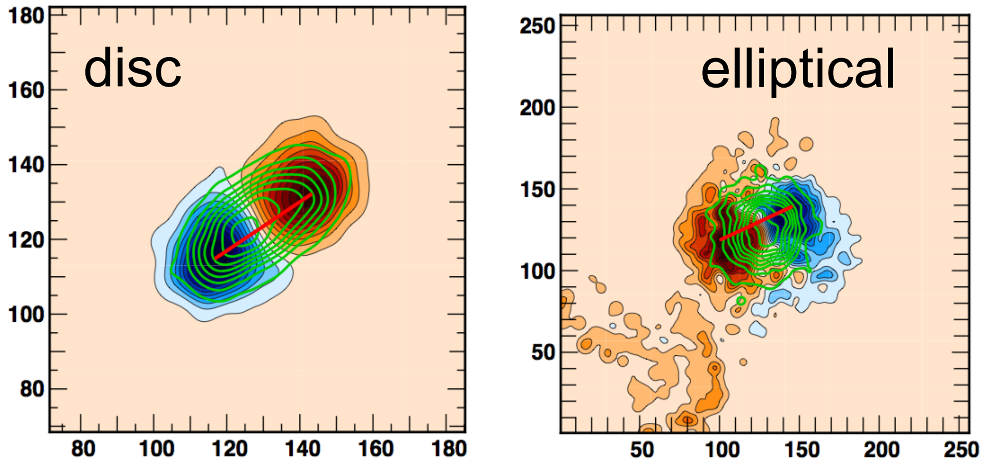
Naab & Ostriker, review in prep.

Galaxies and filaments



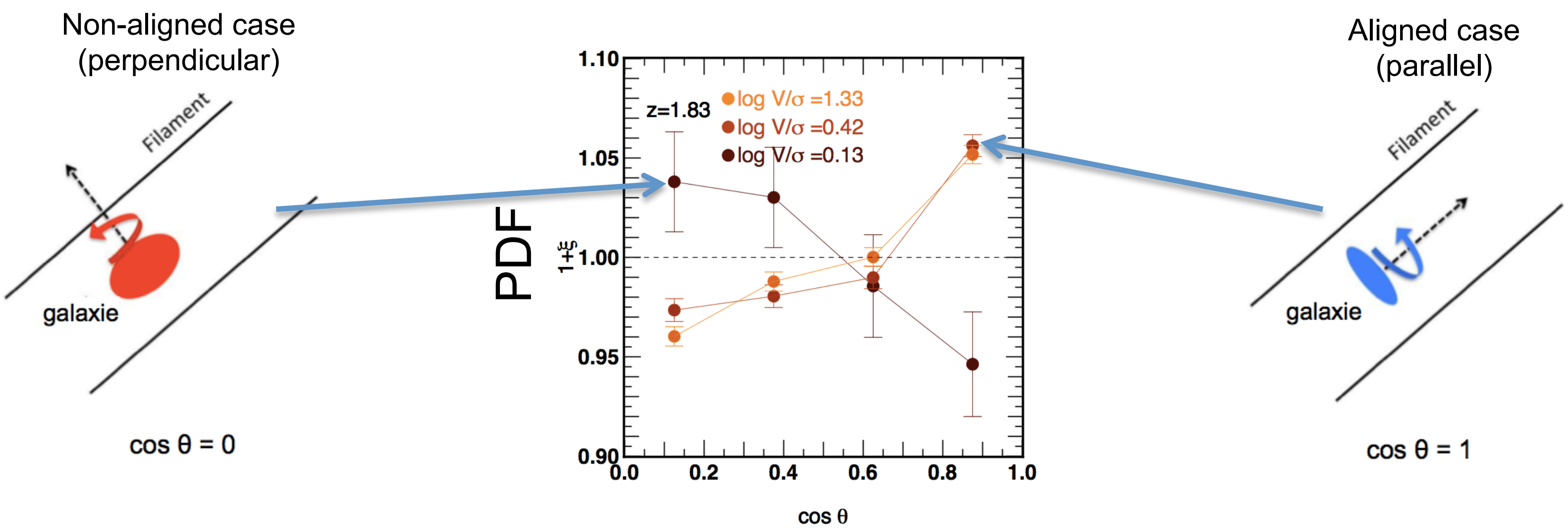
Skeleton, *Soubie et al (2009)*





Cosmic web and galaxies alignment

Discs : spin aligned with cosmic filaments
Ellipticals : spin perpendicular with cosmic filaments

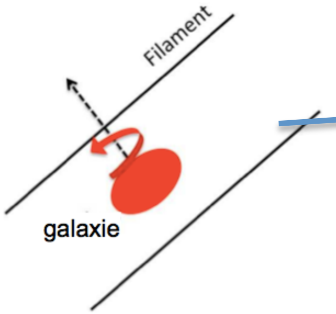


Horizon-AGN simulation / *Dubois et al., 2014*

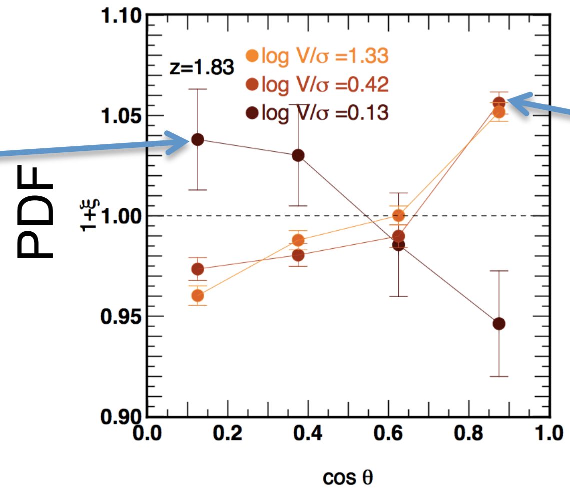
Cosmic web and galaxies alignment

Discs : spin aligned with cosmic filaments
Ellipticals : spin perpendicular with cosmic filaments

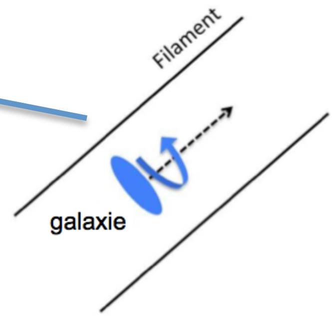
Non-aligned case
(perpendicular)



cos θ = 0



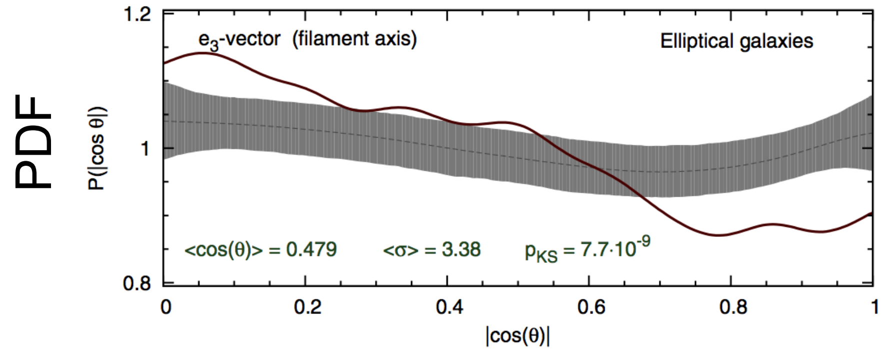
Aligned case
(parallel)

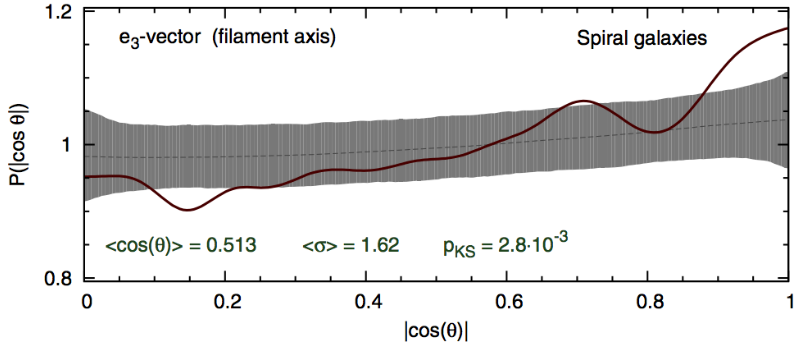


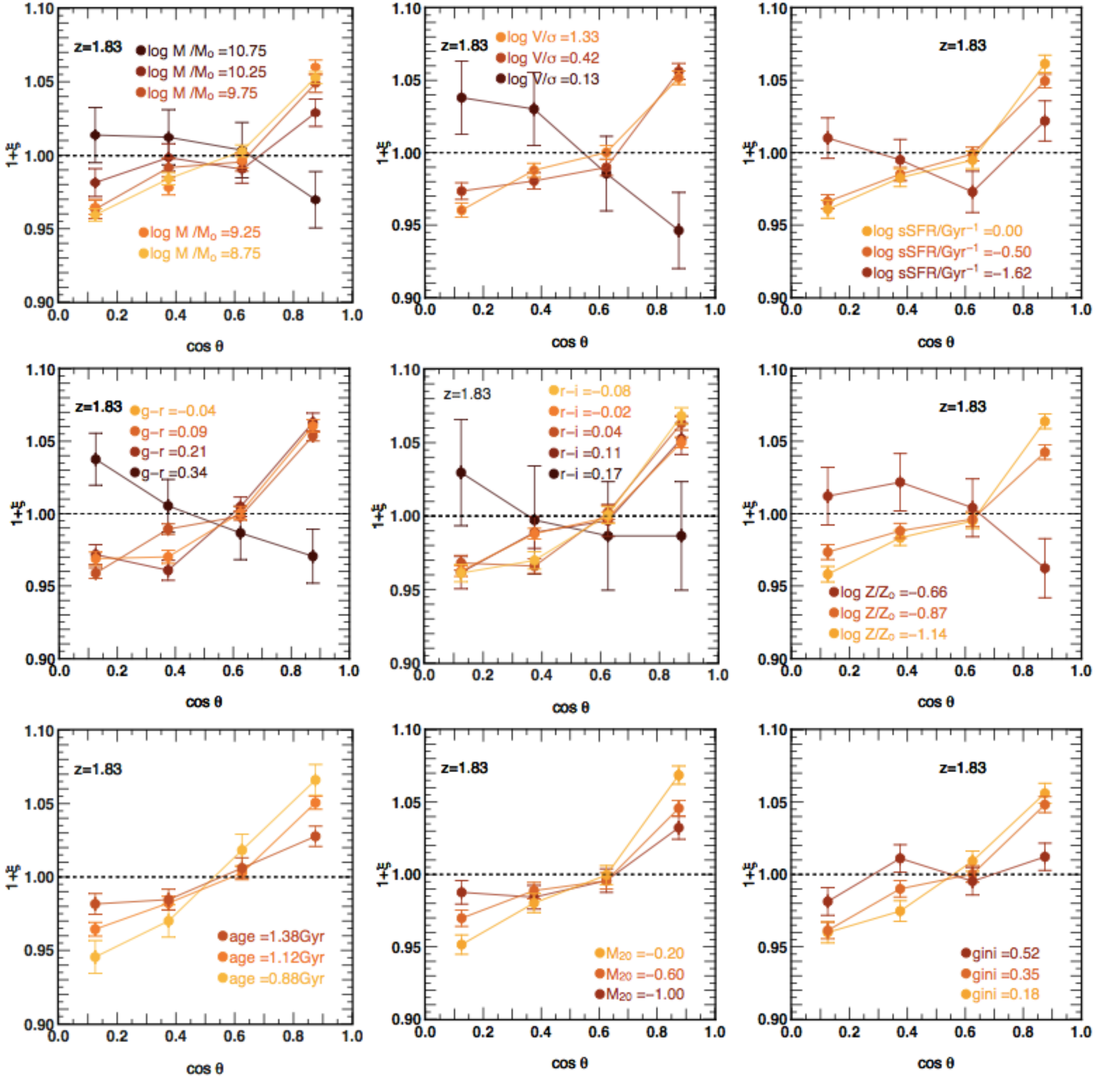
cos θ = 1

Horizon-AGN simulation / *Dubois et al., 2014*

Observations (SDSS) / *Tempel & Libeskind, 2013*



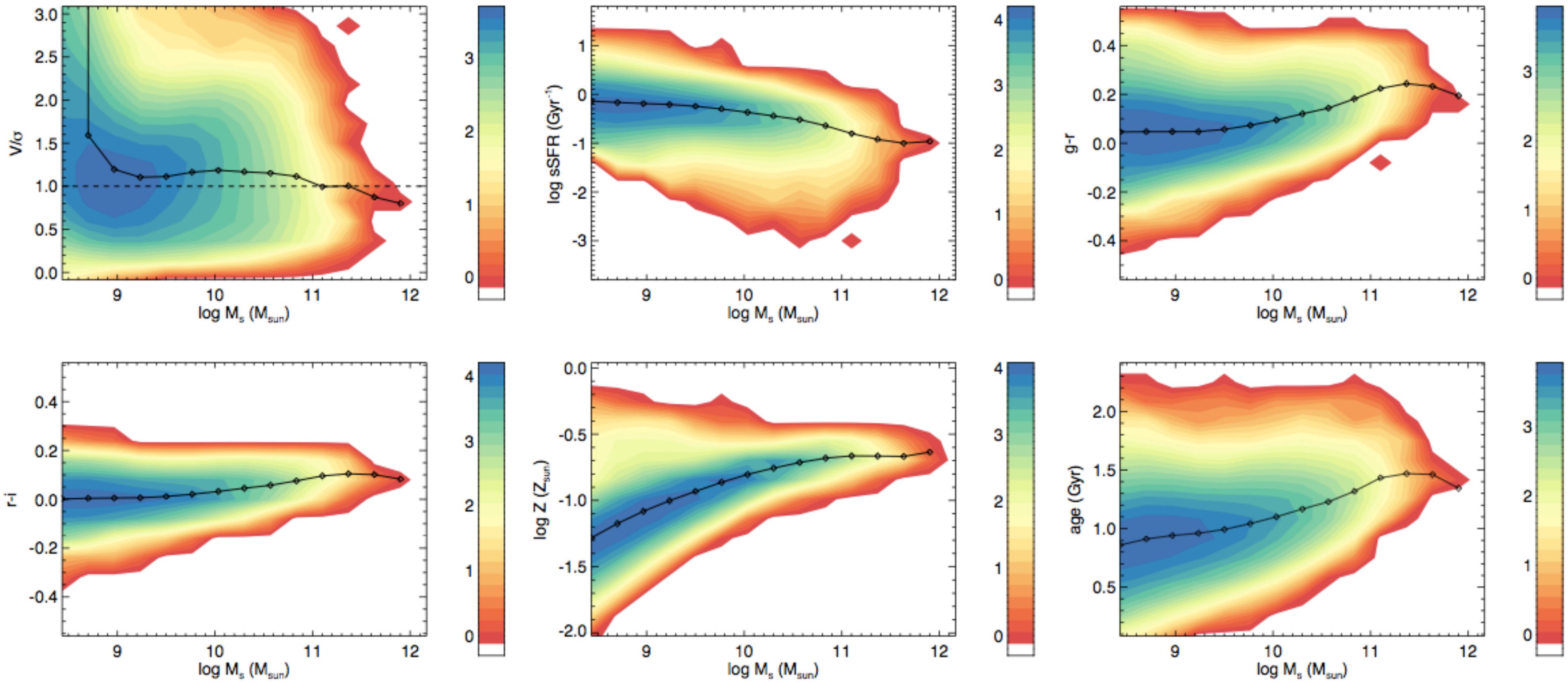




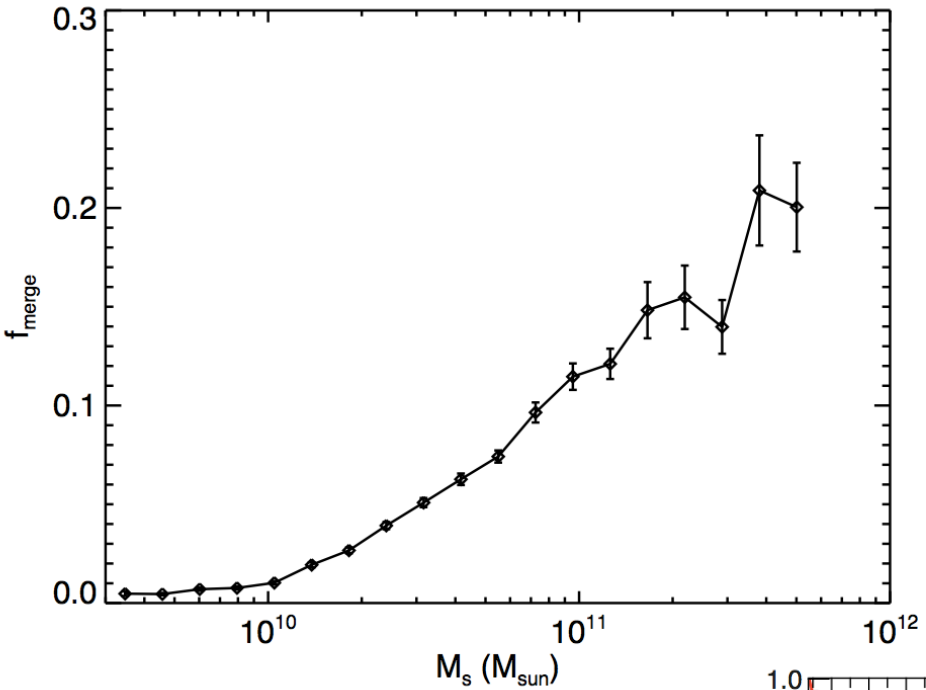
Dubois et al., arXiv:1402.1165

Galaxy properties correlate with their mass

z=1.8



How comes some galaxies are aligned and other misaligned?

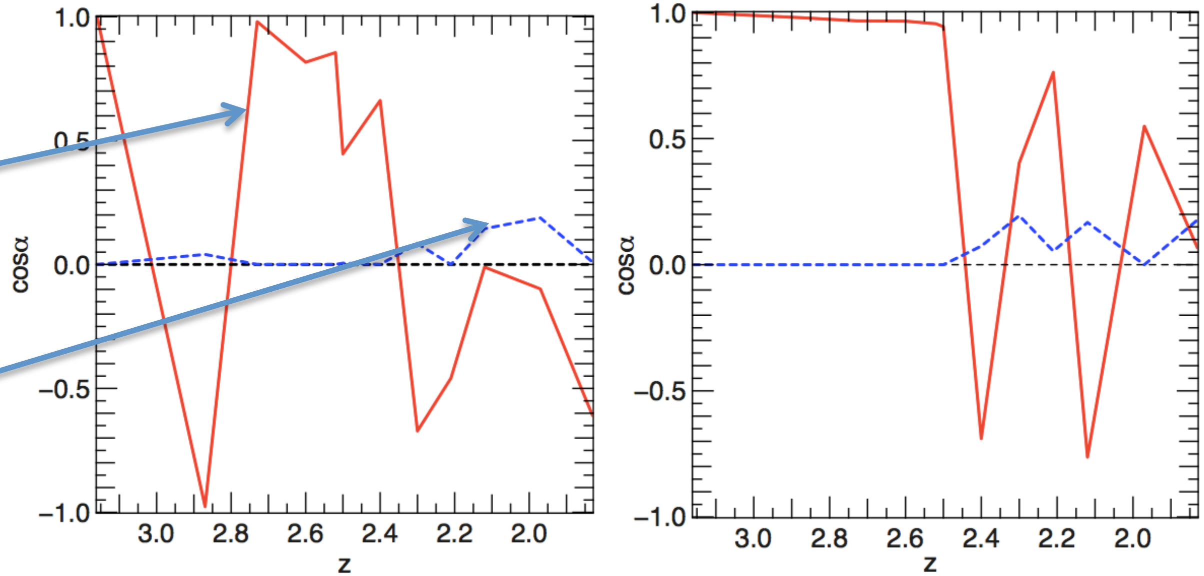


Mergers drive spin reorientation

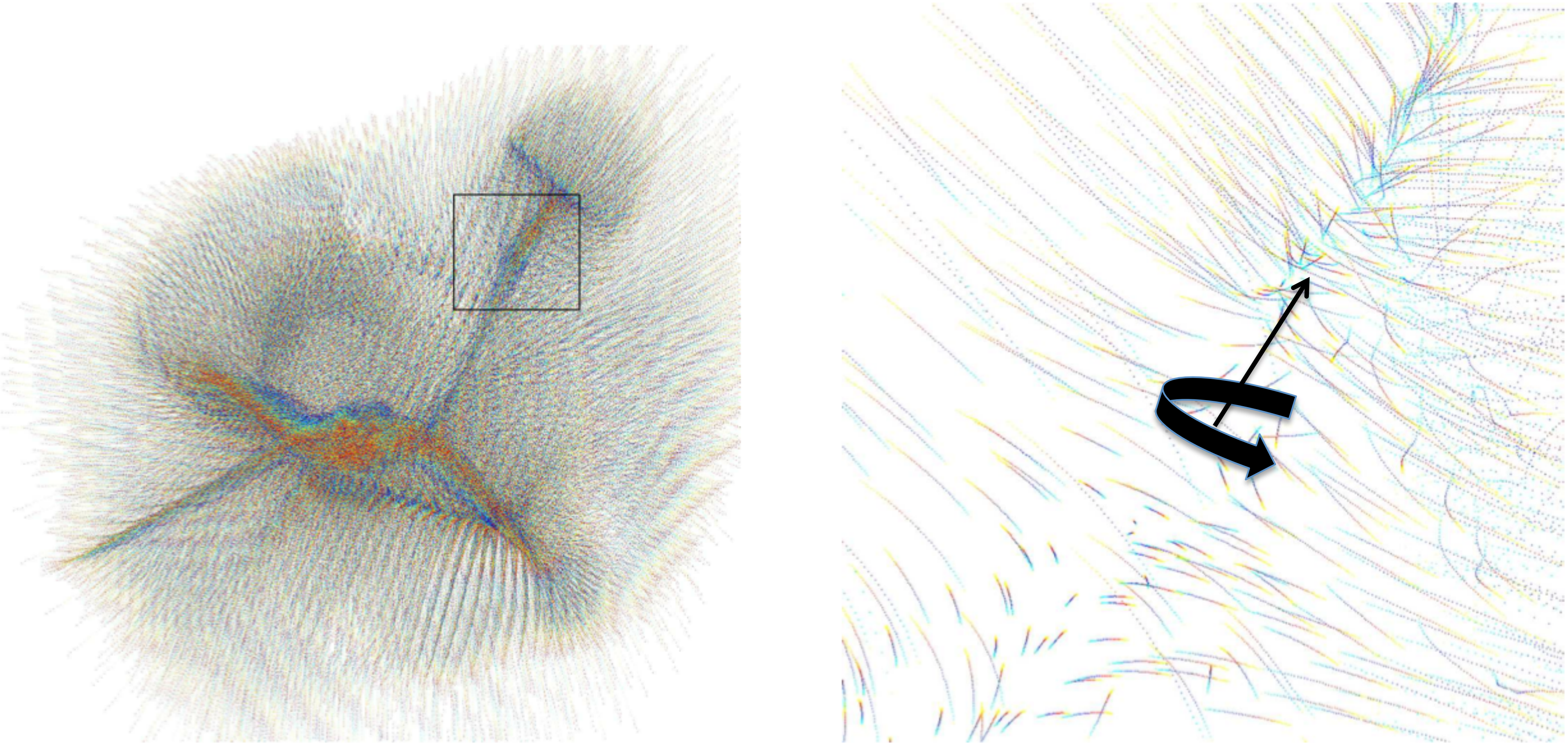
Two exemples of galaxies with mergers

Angle between the galaxy spin and its initial orientation

Merger mass ratio

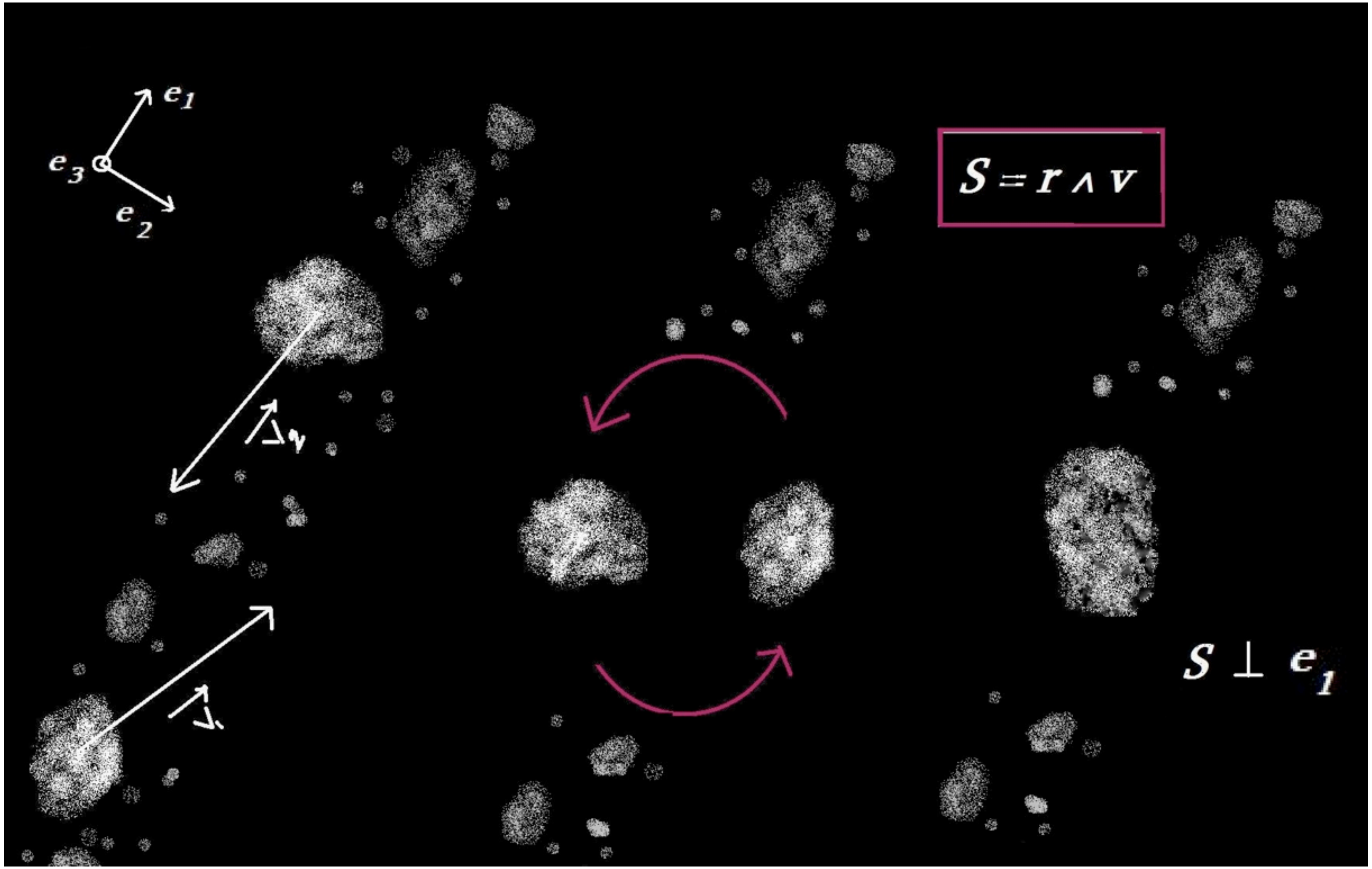


Why do low-mass halos align with filaments?



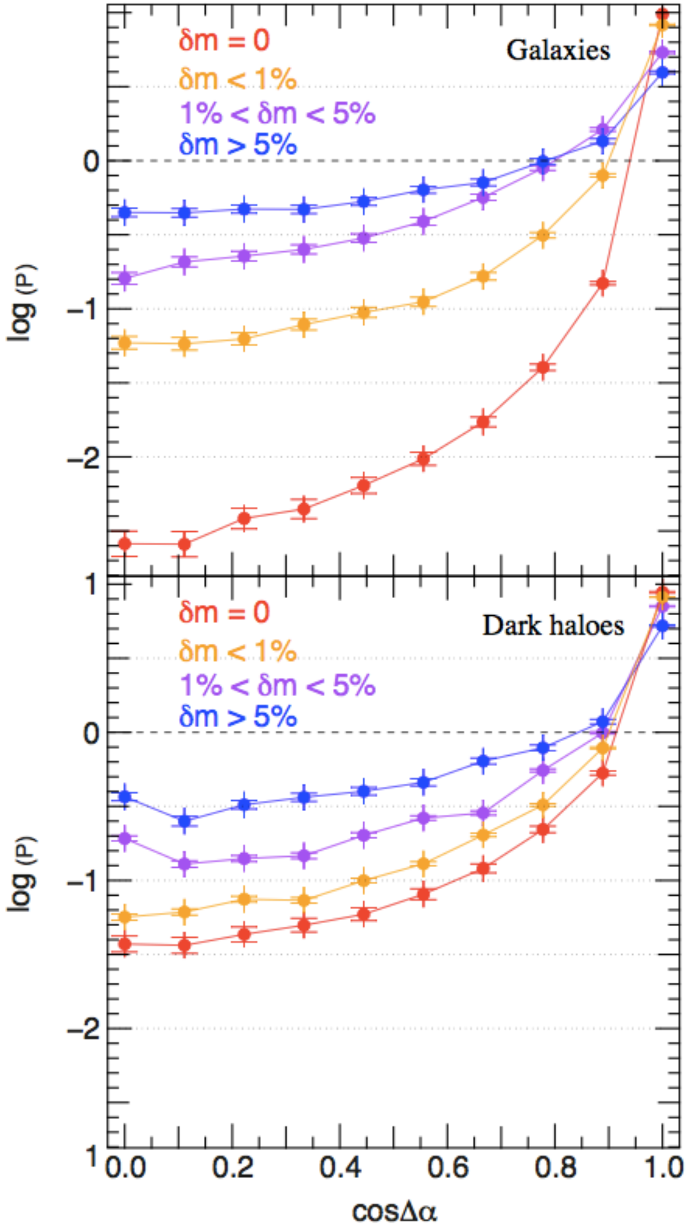
Pichon et al (2011)
See also Pichon & Bernardeau (1999)
Laigle et al (2014)

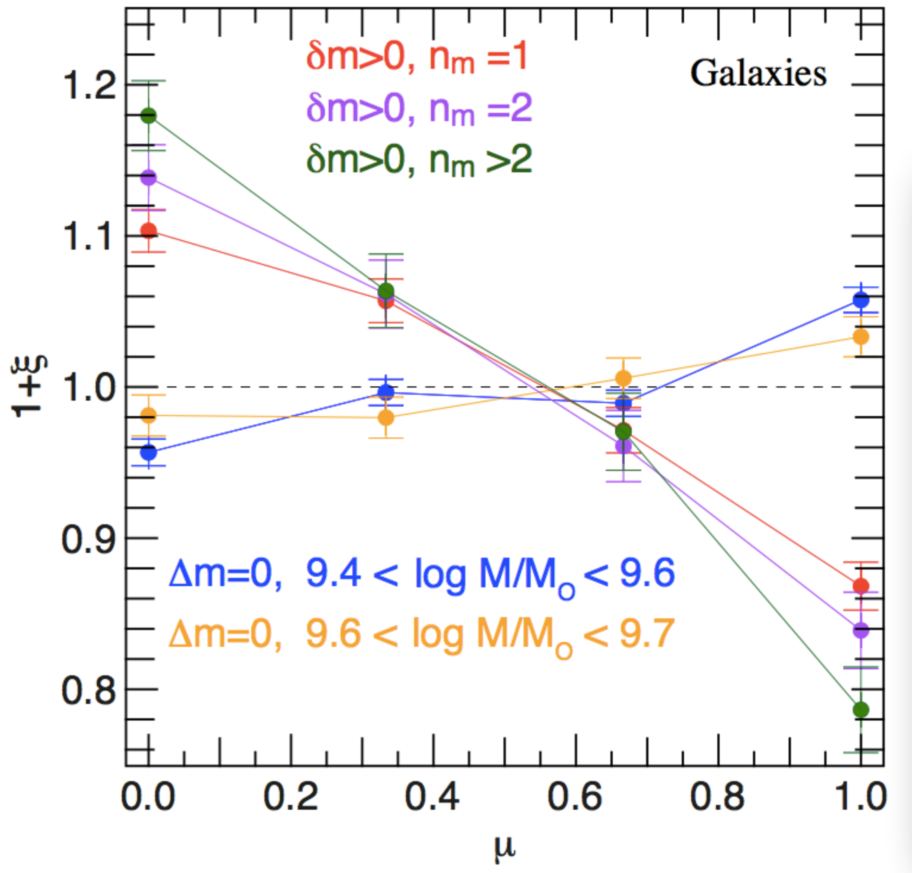
Why do high-mass halos are perpendicular to filaments?



Courtesy of S. Codis

Mergers are responsible for spin swings

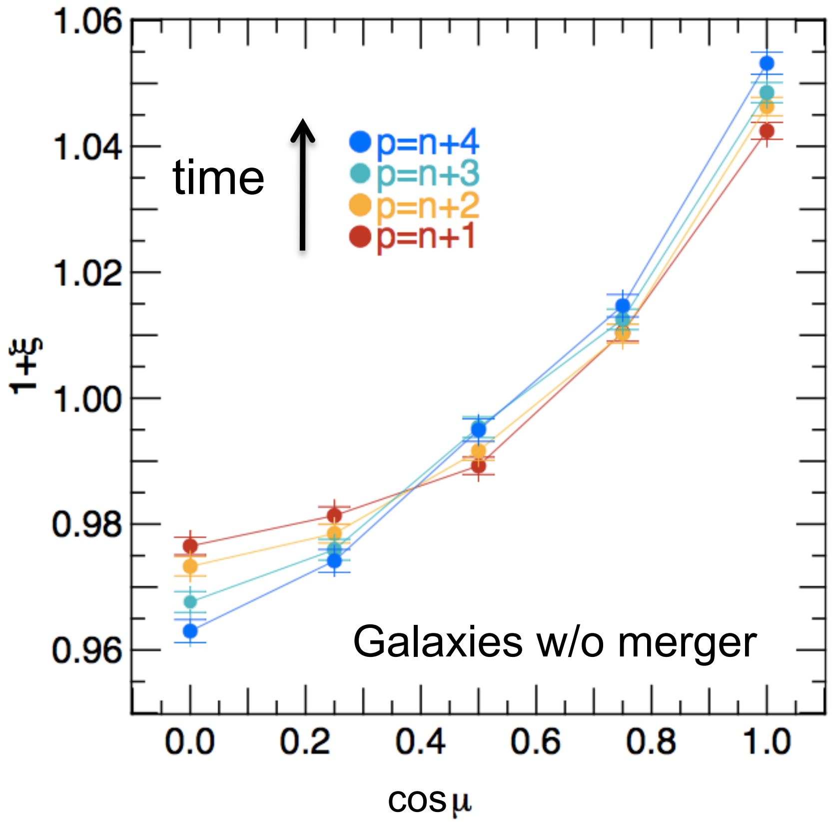




Welker et al, 2014

Re-alignment of galaxies

In absence of mergers, galaxies tend to realign with the cosmic web because of gas accretion



As AGN feedback prevents gas accretion in massive galaxies, it also prevents massive galaxies to realign with the cosmic filaments after a merger.

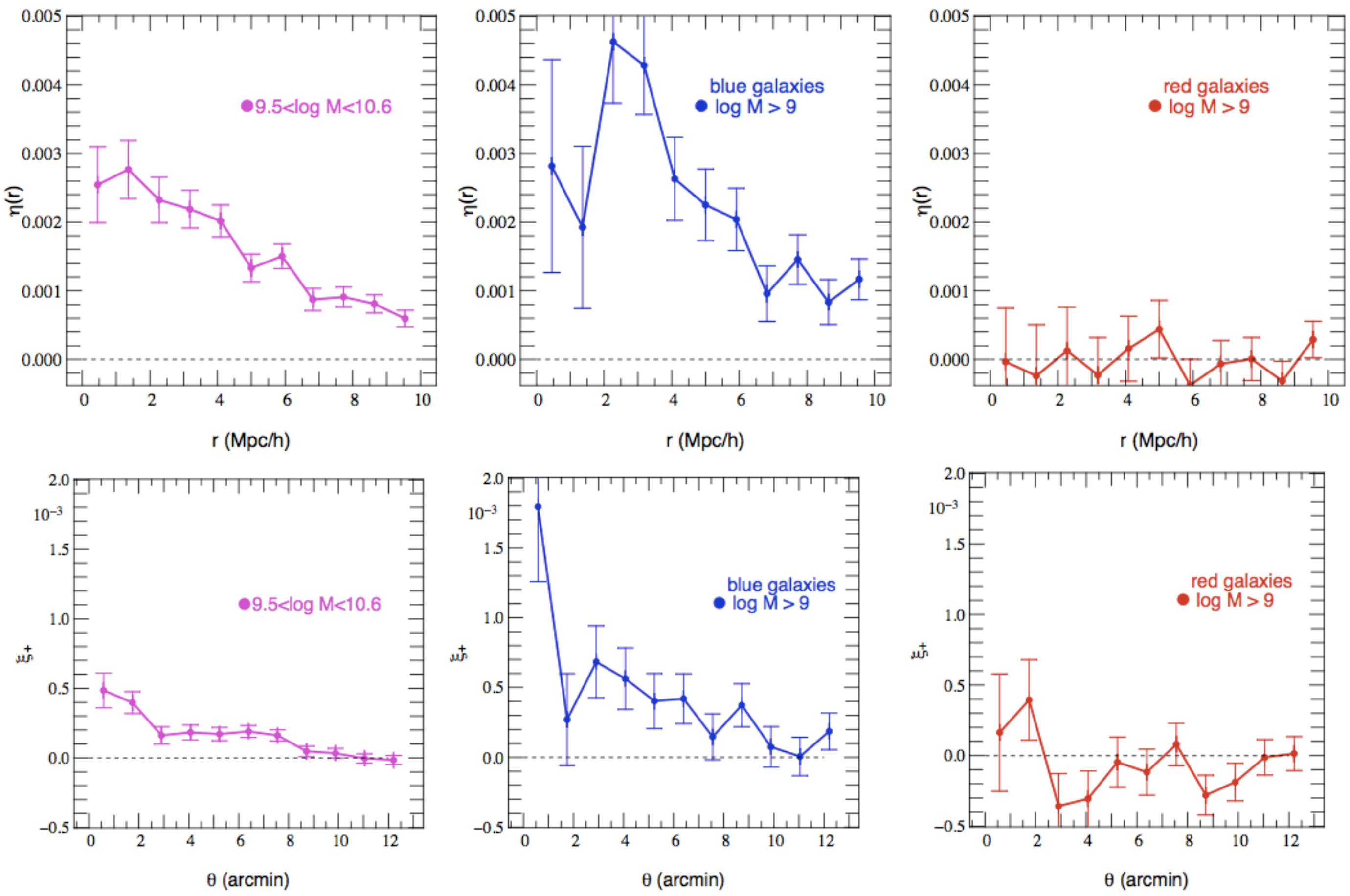
Therefore, AGN feedback is mandatory to get galaxies perpendicular with cosmic filaments.

Welker et al, 2014

Thank you for your attention

Extra slides

Intrinsic alignement (II) signal



Codis et al, arXiv:1406.4668C

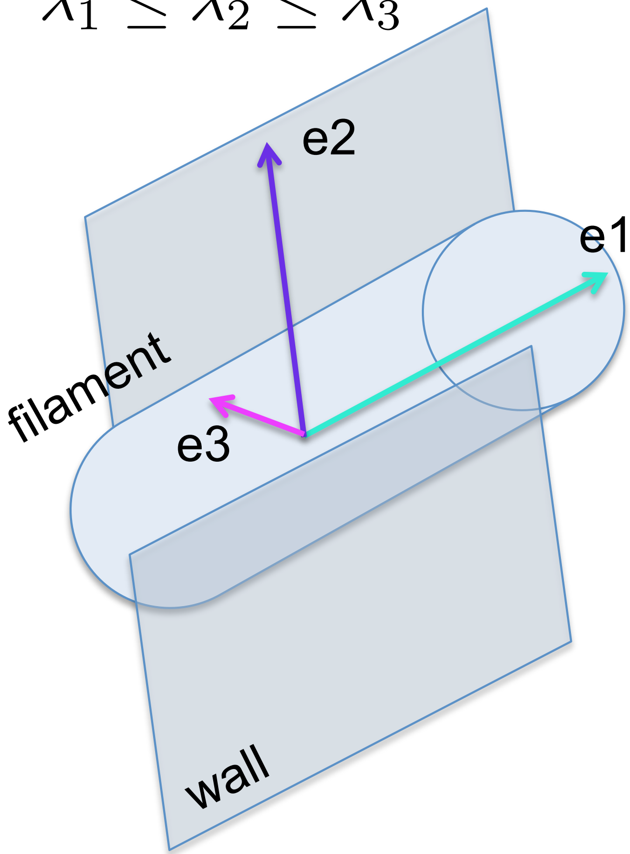
Spin-shear alignement (IG) signal (1-point)

Tidal shear tensor:

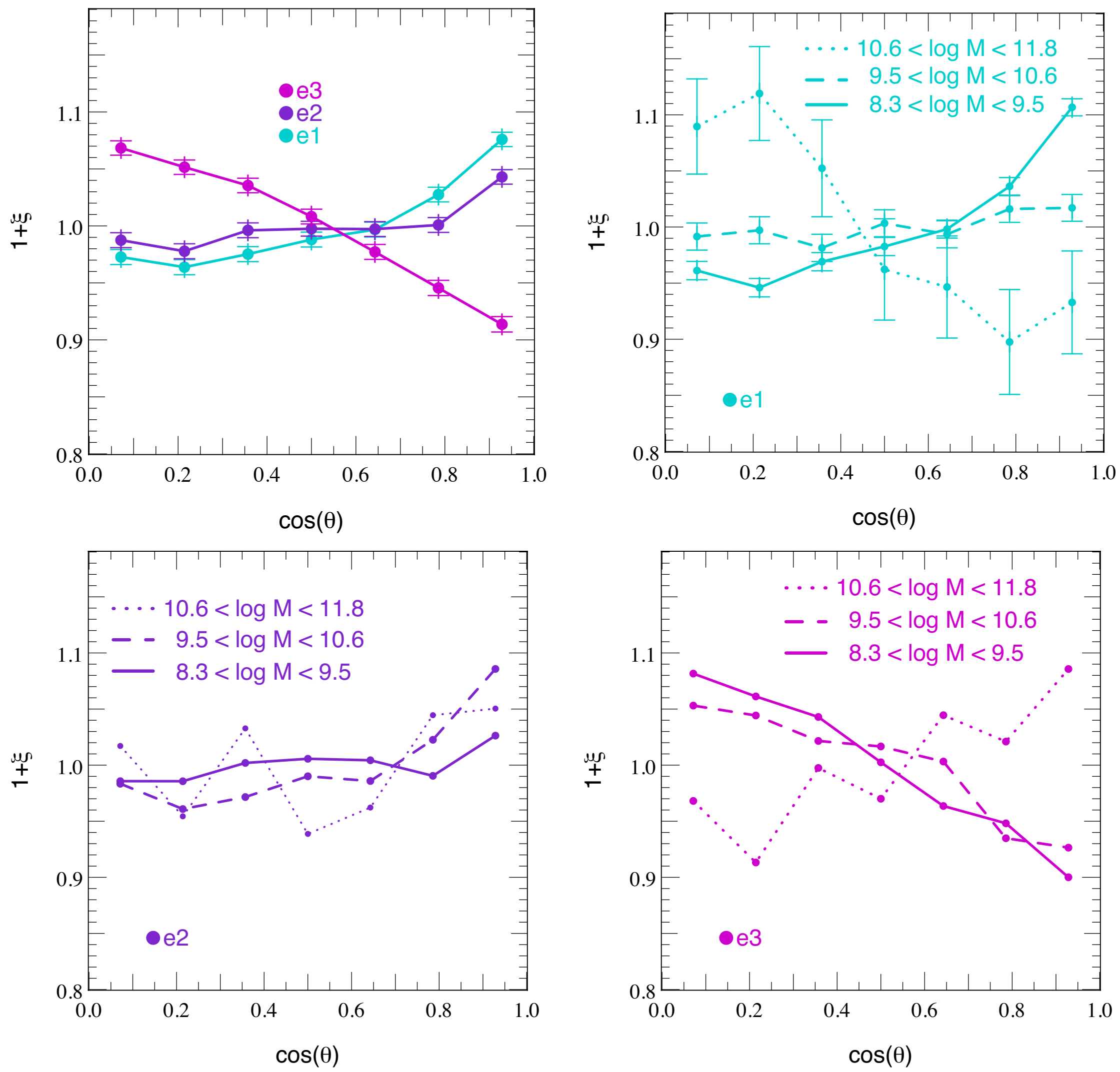
$$T_{ij} = \partial_{ij}\phi - \frac{1}{3}\Delta\phi\delta_{ij}$$

ϕ: gravitationnal potential

$$\lambda_1 \leq \lambda_2 \leq \lambda_3$$



Mass decomposition



Codis et al, arXiv:1406.4668C

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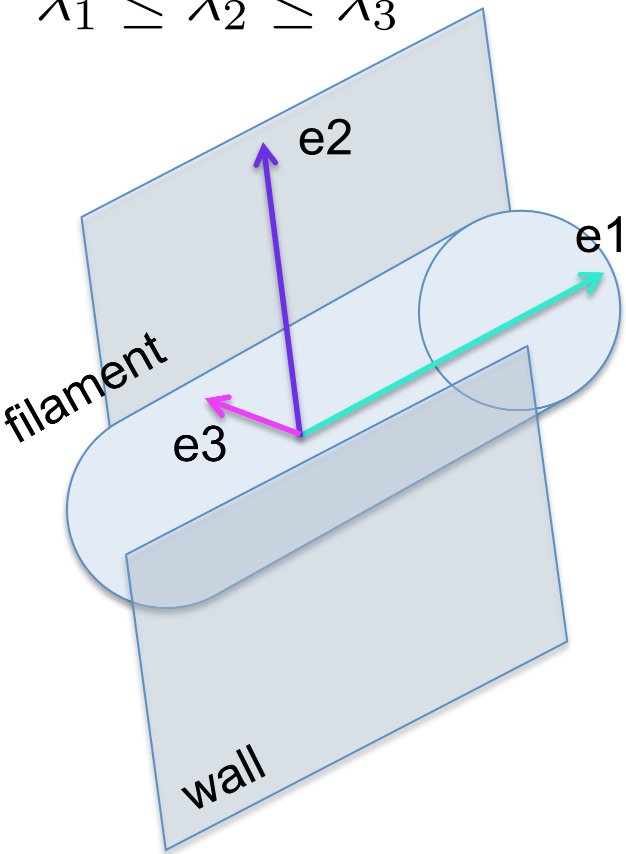
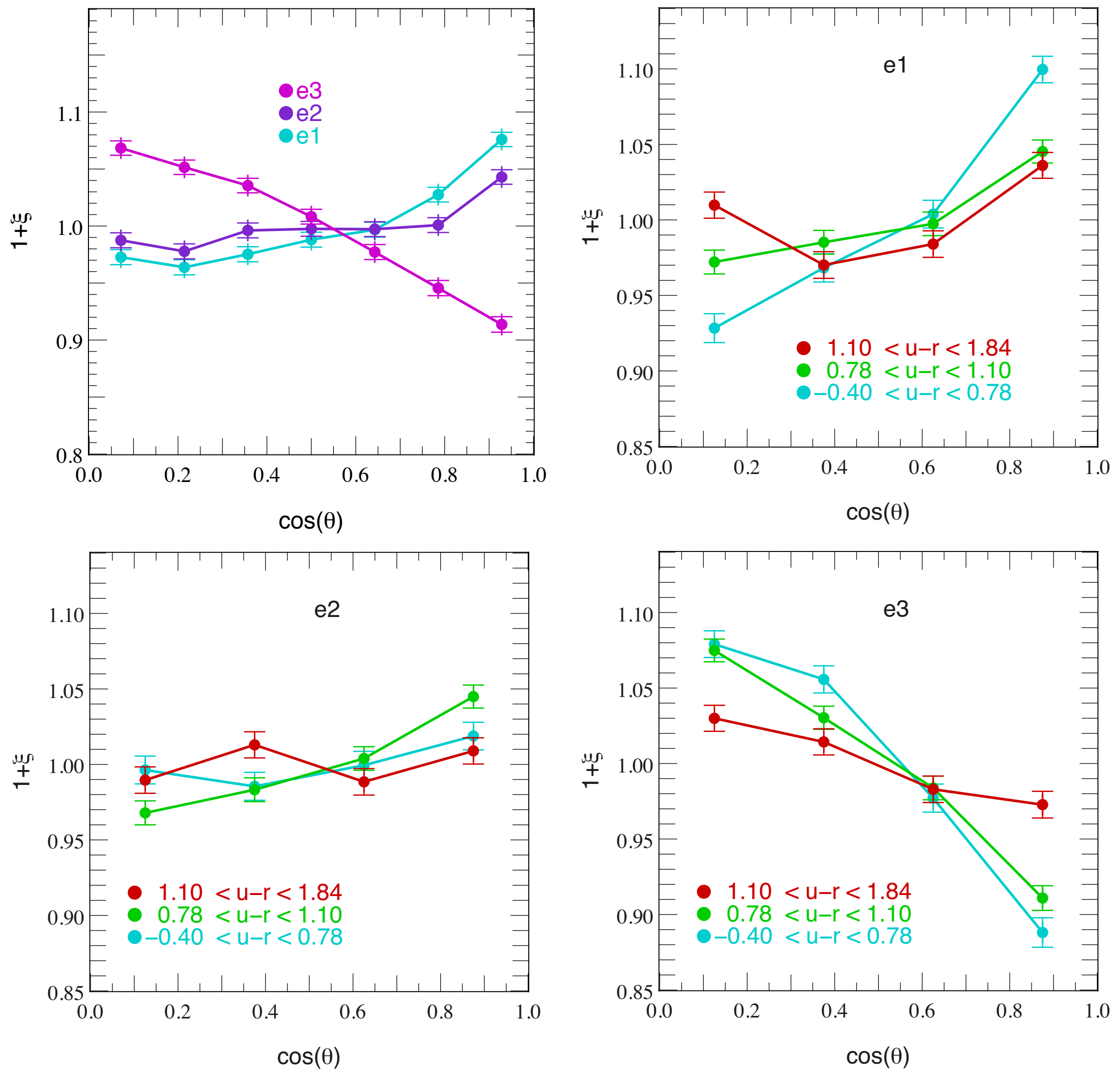
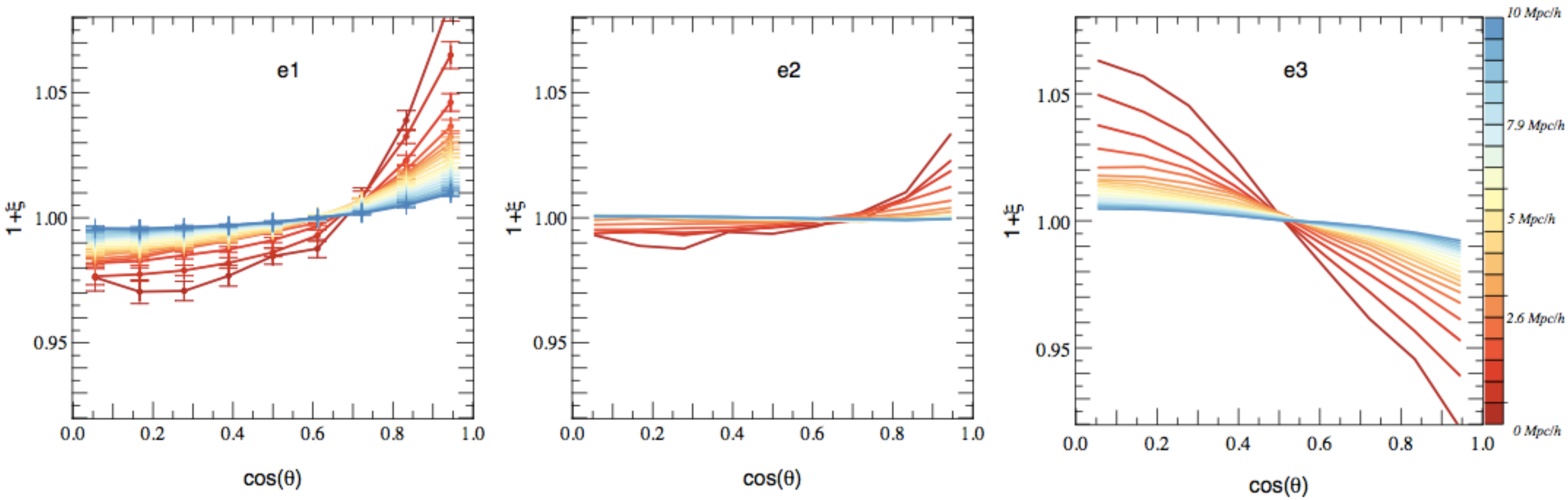


Color decomposition



Codis et al, arXiv:1406.4668C

Spin-shear alignement (IG) signal (2-point)



Codis et al, arXiv:1406.4668C

The Horizon-noAGN simulation

- Simulation content (S. Peirani)
  - Run with Ramses (AMR) *Teyssier (2002)*
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8x10^7$ 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
  - Standard outputs ~200 Myrs
  - Star particles are backed up every 10-20 Myr
  - 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=1.1 using ~1 Mhours on 4096 cores
- 150 000 galaxies per snapshot (> 50 part.)
- 7.10^9 leaf cells (more than Illustris or EAGLE)

http://www.horizon-simulation.org/