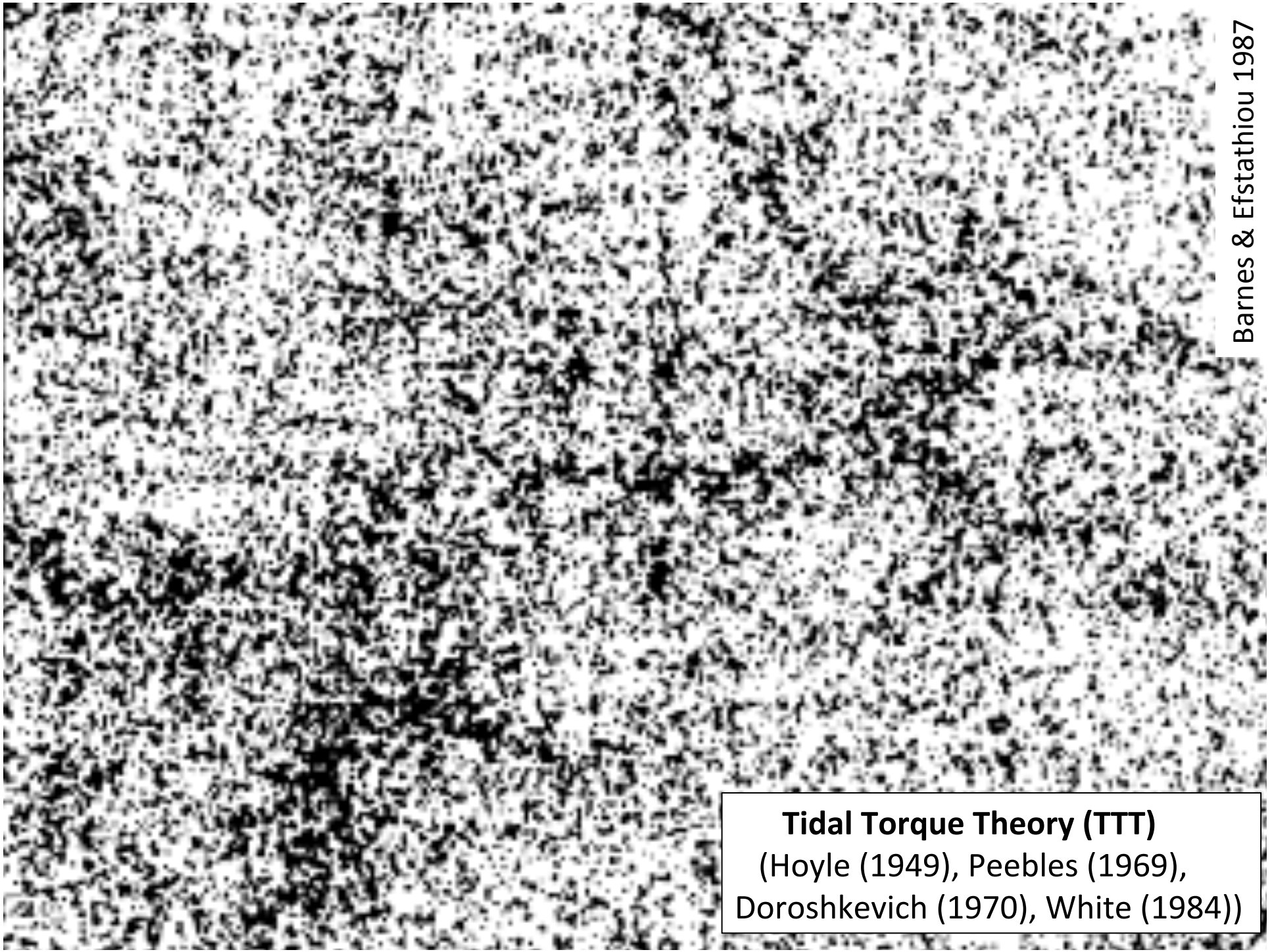
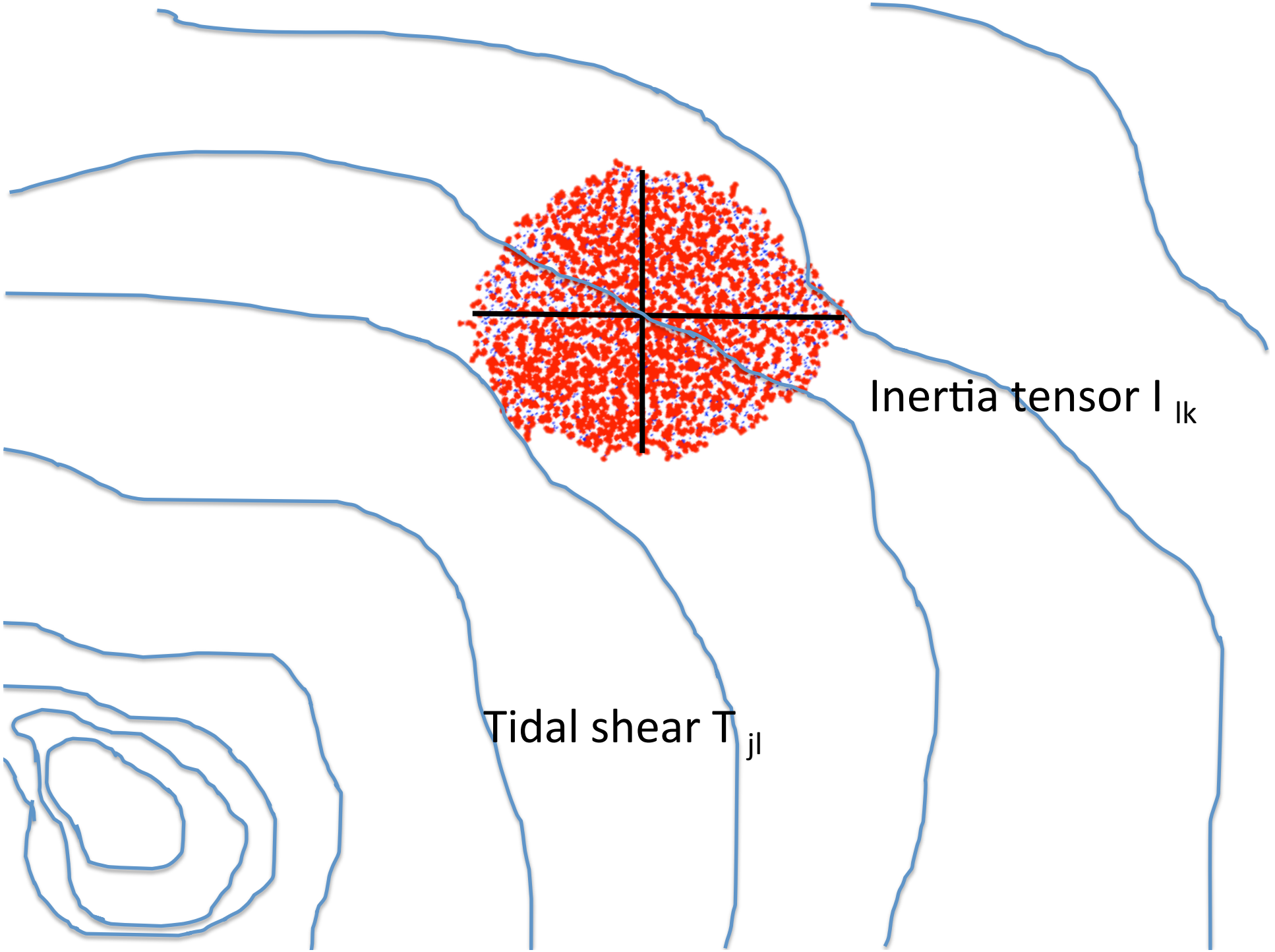
The Origin of Disk Angular Momentum

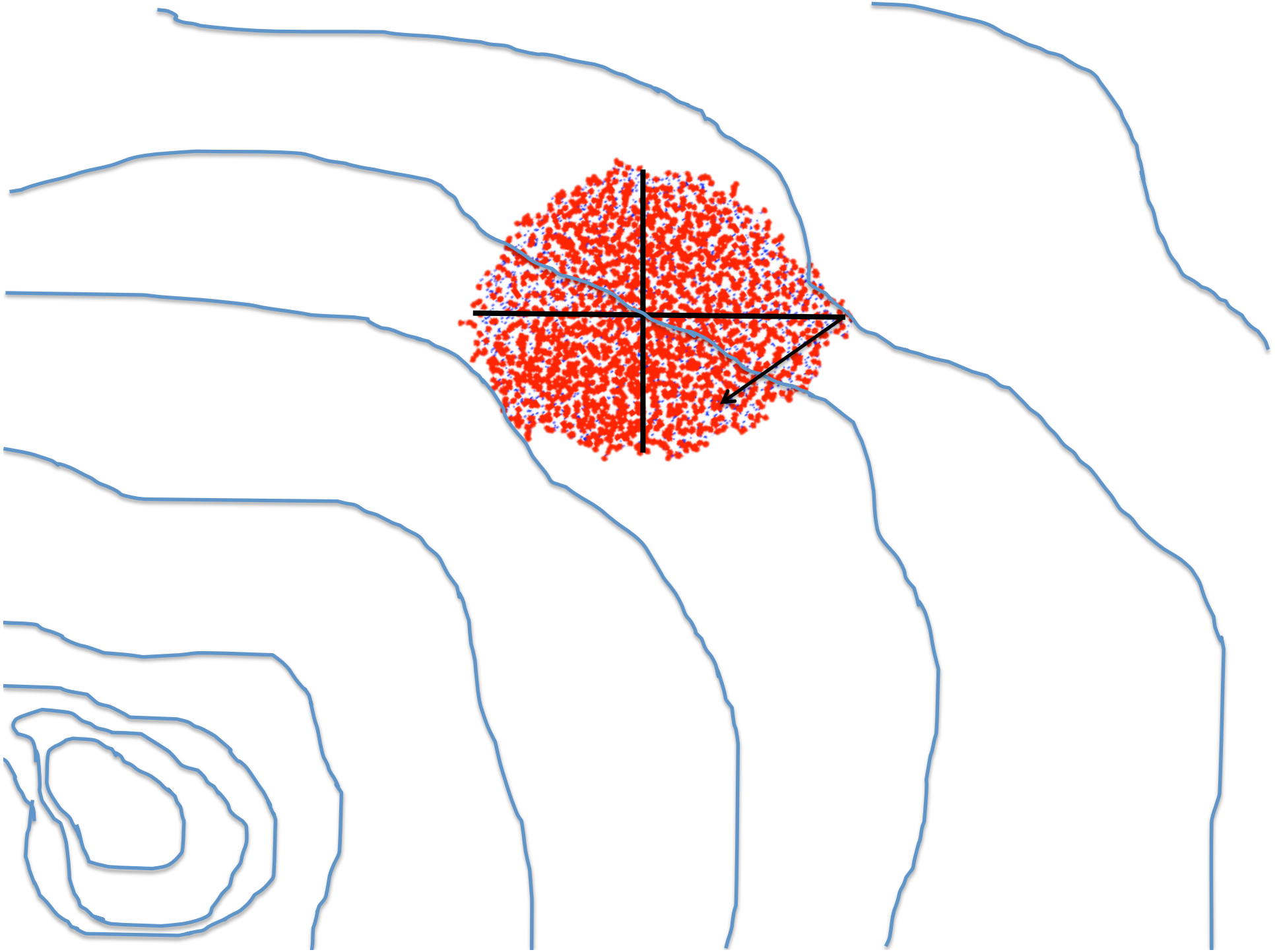
Adrianne Slyz
University of Oxford

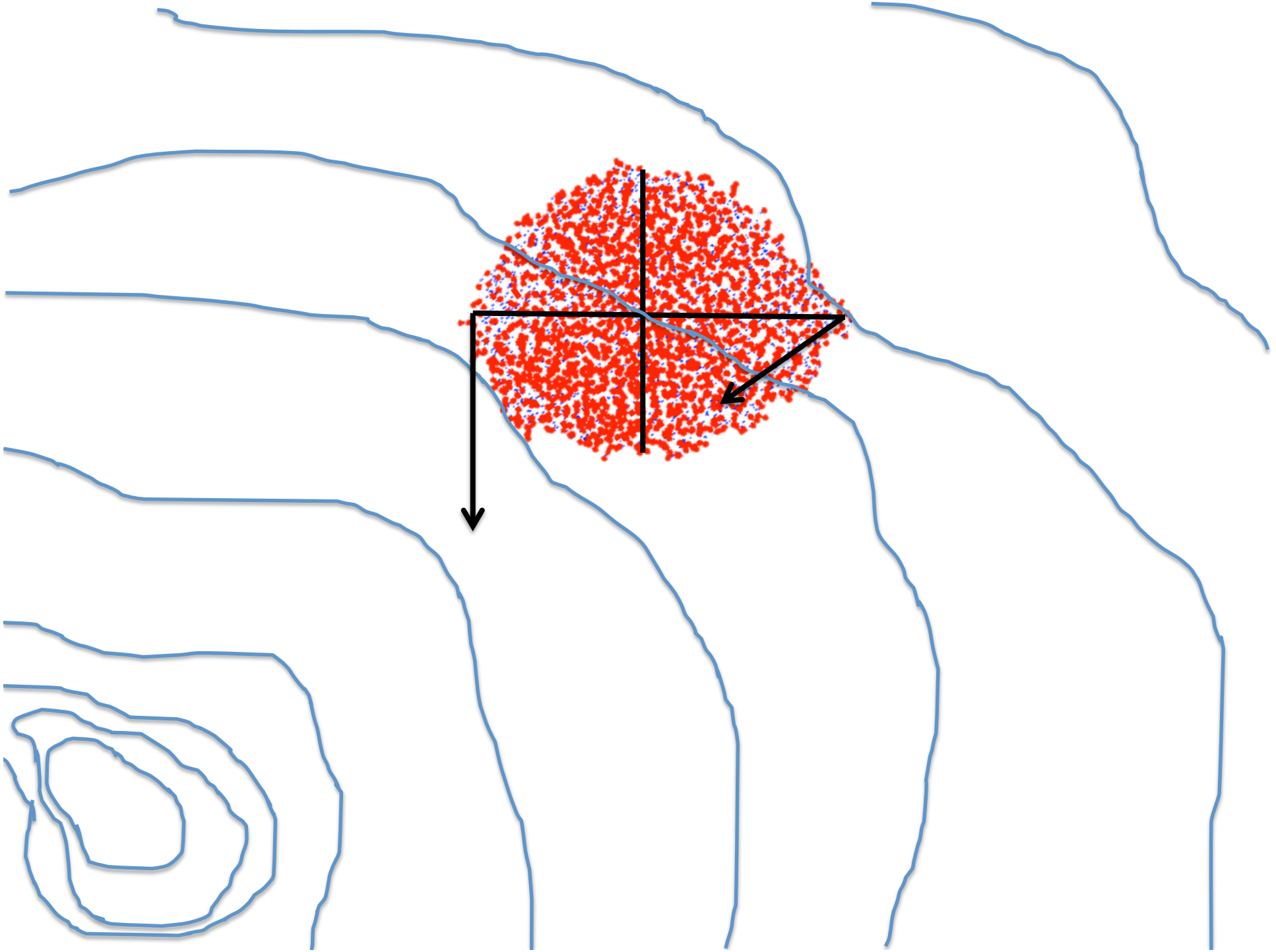
with (in alphabetical order): Sandrine Codis (IAP), Julien Devriendt (Oxford),
Yohan Dubois (IAP), Taysun Kimm (Princeton), Clotilde Laigle (IAP),
Christophe Pichon (IAP), Dmitri Pogosyan (Univ. of Alberta), Thierry Sousbie (IAP),
Henry Tillson (Oxford), Charlotte Welker (IAP) + Horizon collaboration

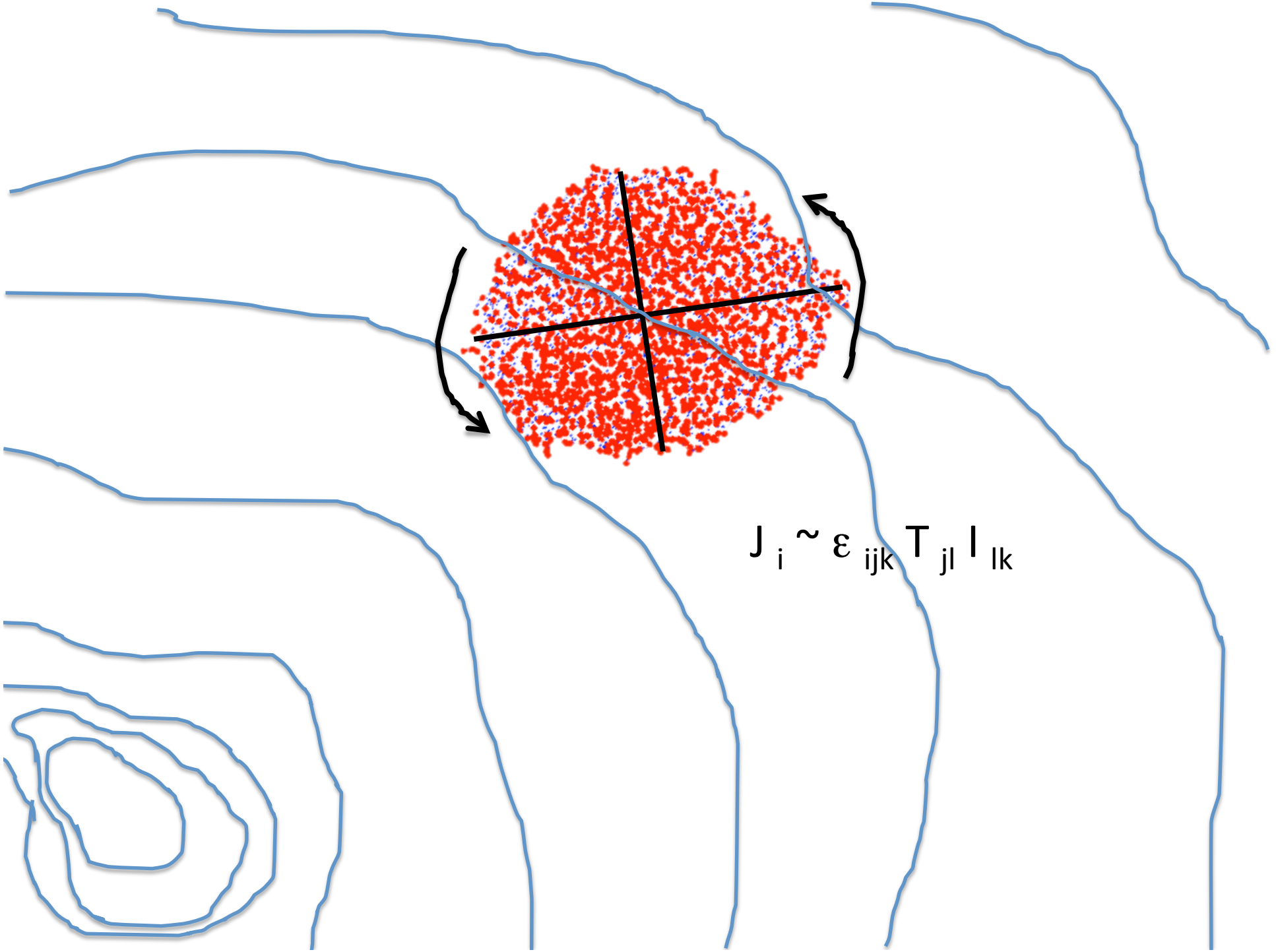


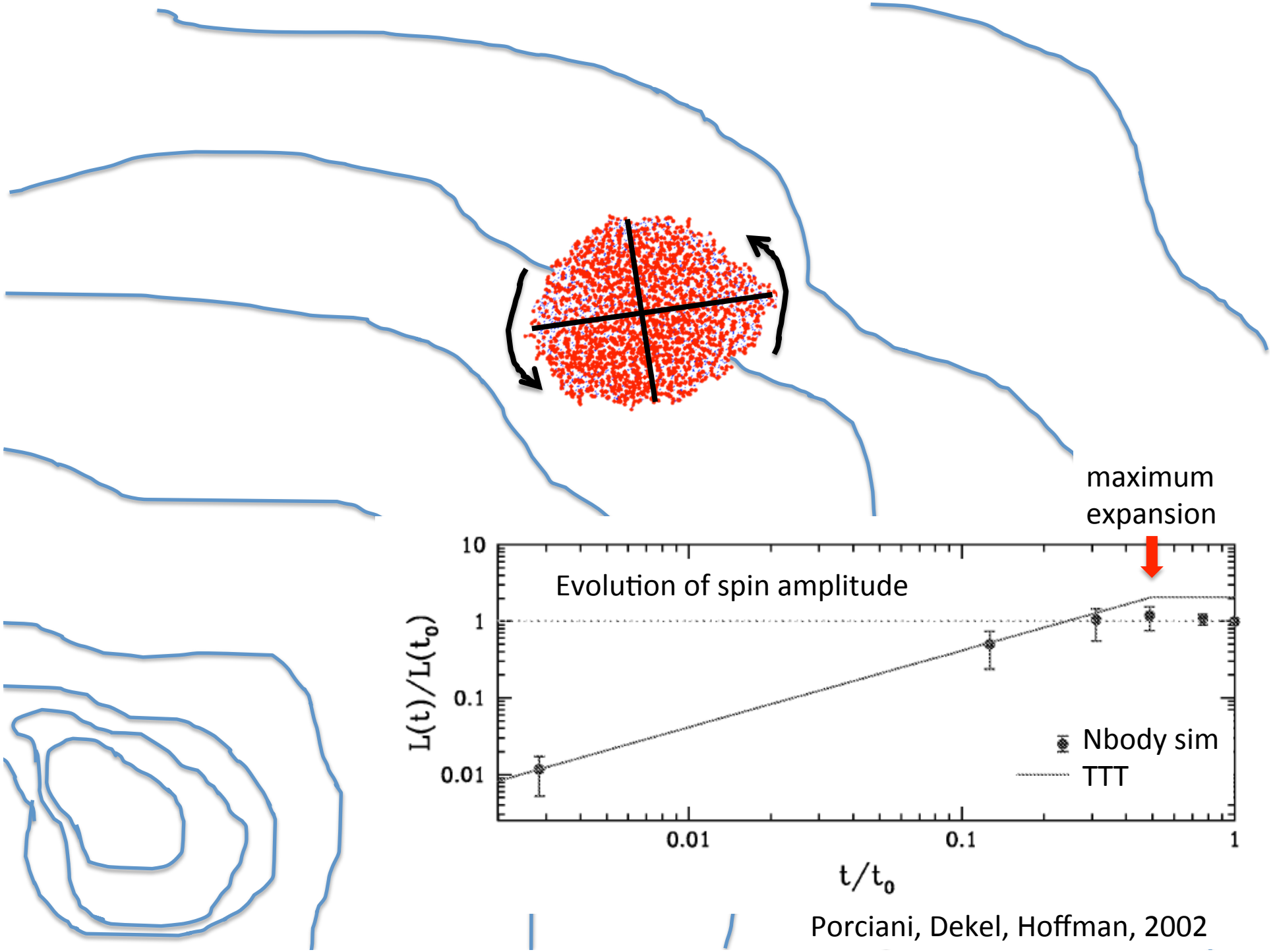
Tidal Torque Theory (TTT)
(Hoyle (1949), Peebles (1969),
Doroshkevich (1970), White (1984))


Inertia tensor I_{lk}
Tidal shear T_{jl}





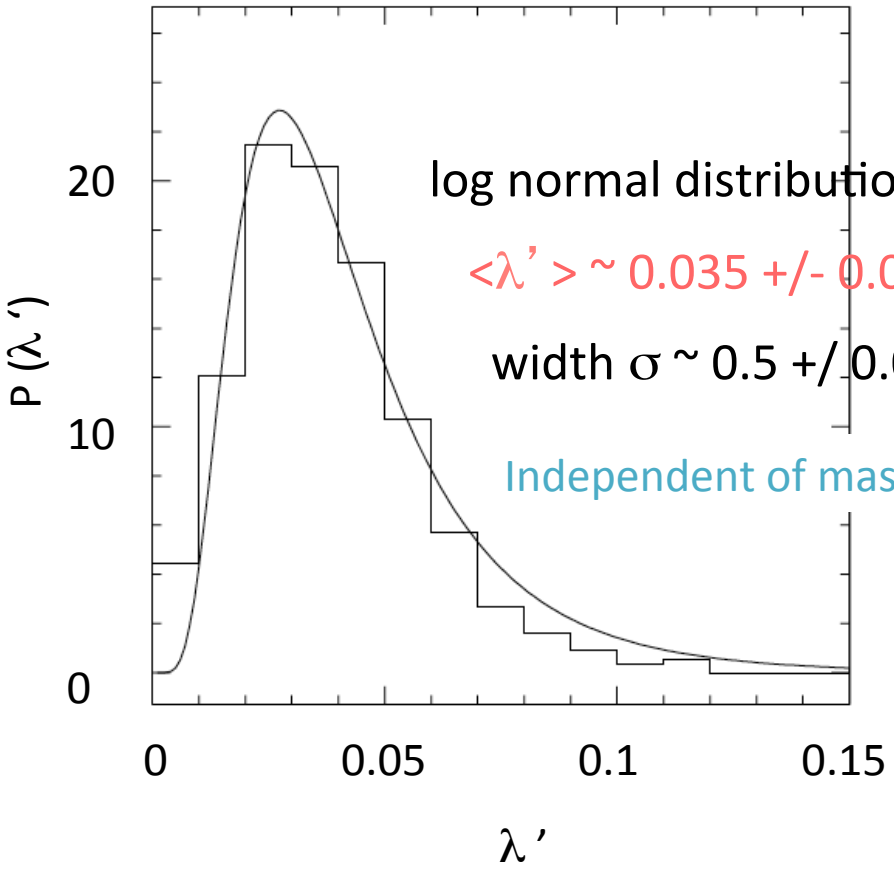

$J_i \sim \varepsilon_{ijk} T_{jl} I_{lk}$



Porciani, Dekel, Hoffman, 2002

How much do dark matter halos spin?

Distribution of the spin parameter



$$\lambda' \equiv \frac{J}{\sqrt{2}MVR}$$

log normal distribution

$<\lambda'> \sim 0.035 +/- 0.005$

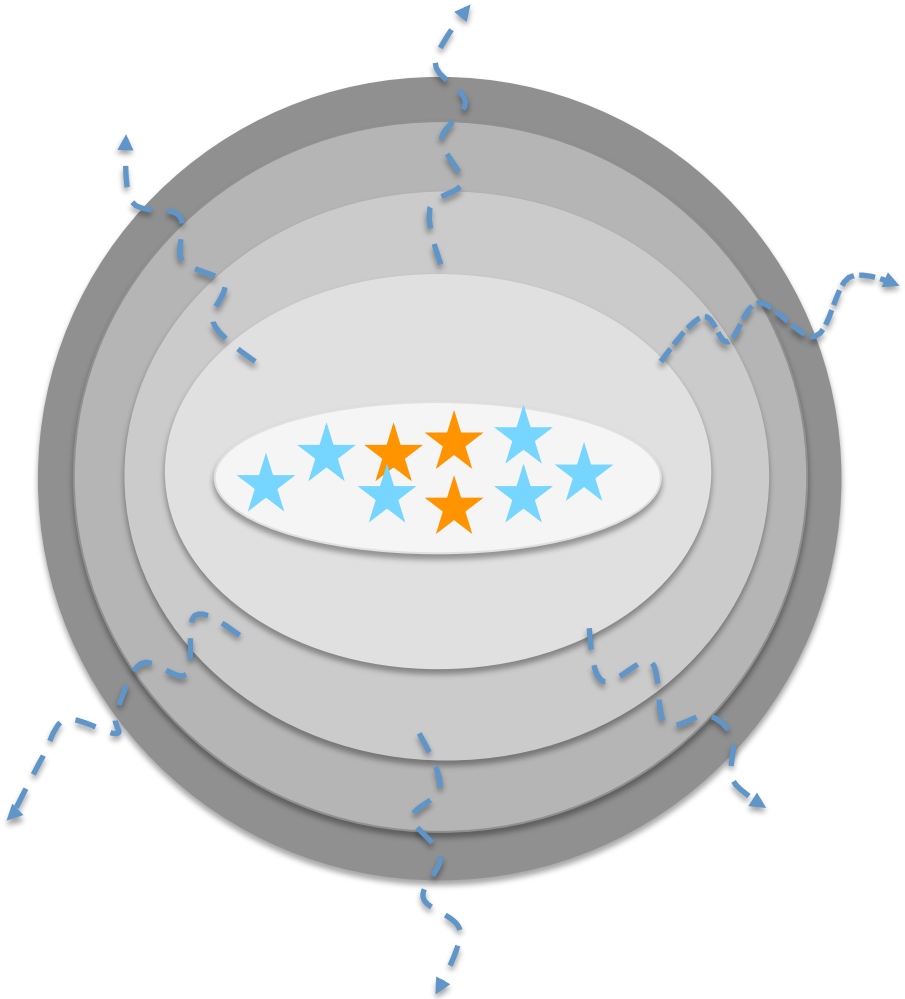
width $\sigma \sim 0.5 +/- 0.03$

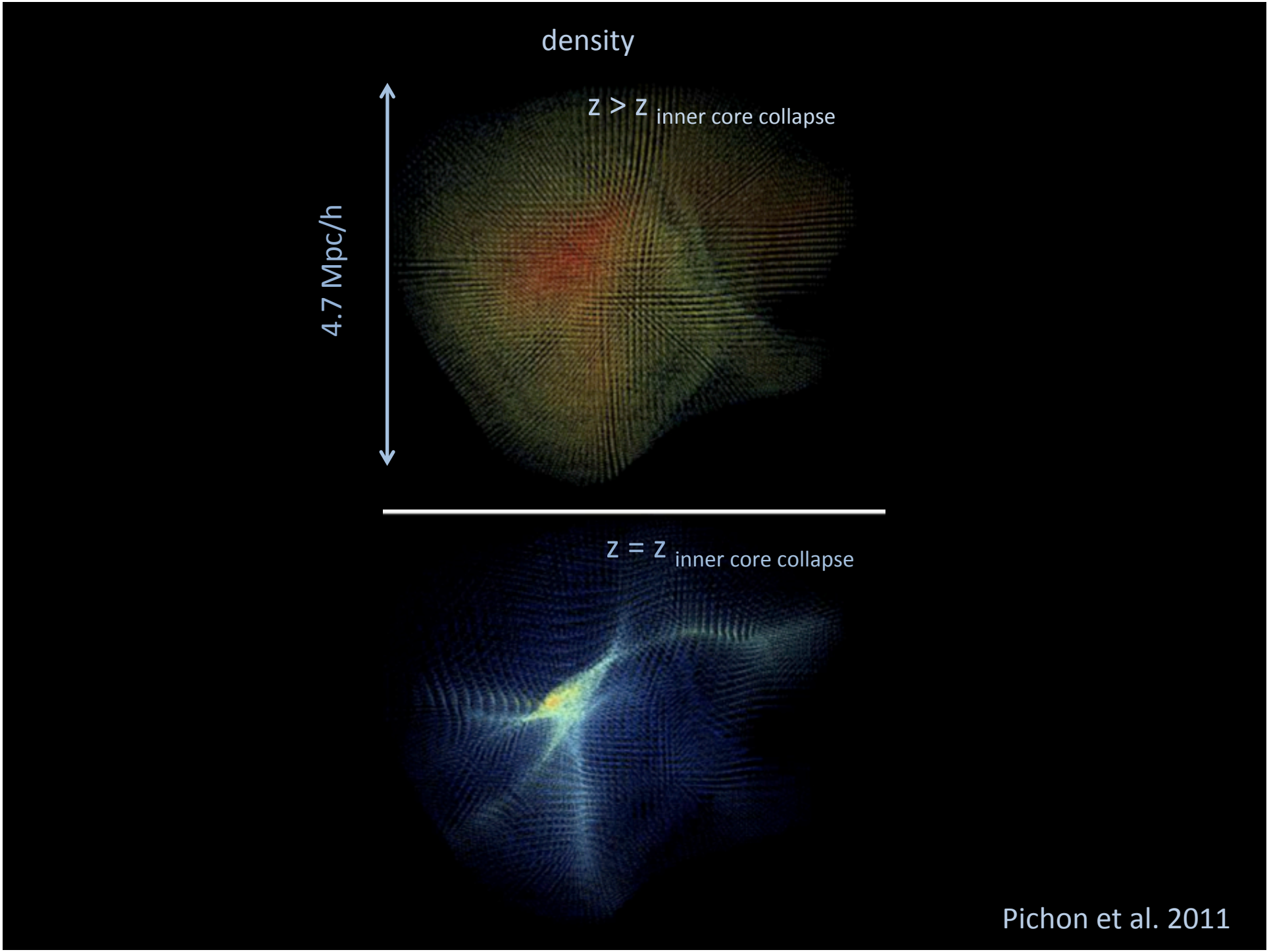
Independent of mass, redshift, cosmology

Bullock et al. 2001,see also Barnes & Efstathiou 1987, Ryden 1988, Warren et al 1992
Steinmetz & Bartelman 1995, Cole & Lacey 1996, Gardner 2001, Maccio et al. 2006

Why do disk galaxies spin more?

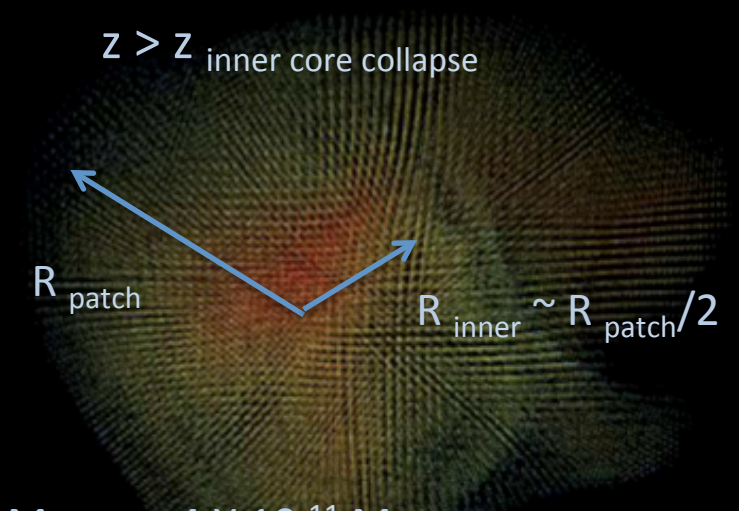
Fall & Efstathiou 1980; Dalcanton, Spergel, Summers, 1997; Mo, Mao & White 1998




density
z > z inner core collapse
4.7 Mpc/h
z = z inner core collapse
Pichon et al. 2011

density

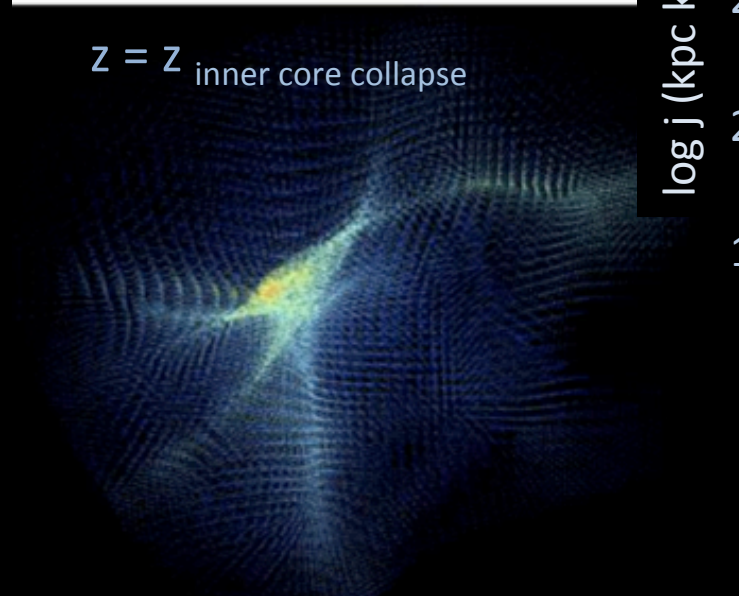
$z > z_{\text{inner core collapse}}$



$M_{\text{patch}} = 4 \times 10^{11} M_{\text{sun}}$

$M_{\text{inner}} = 5 \times 10^{10} M_{\text{sun}}$

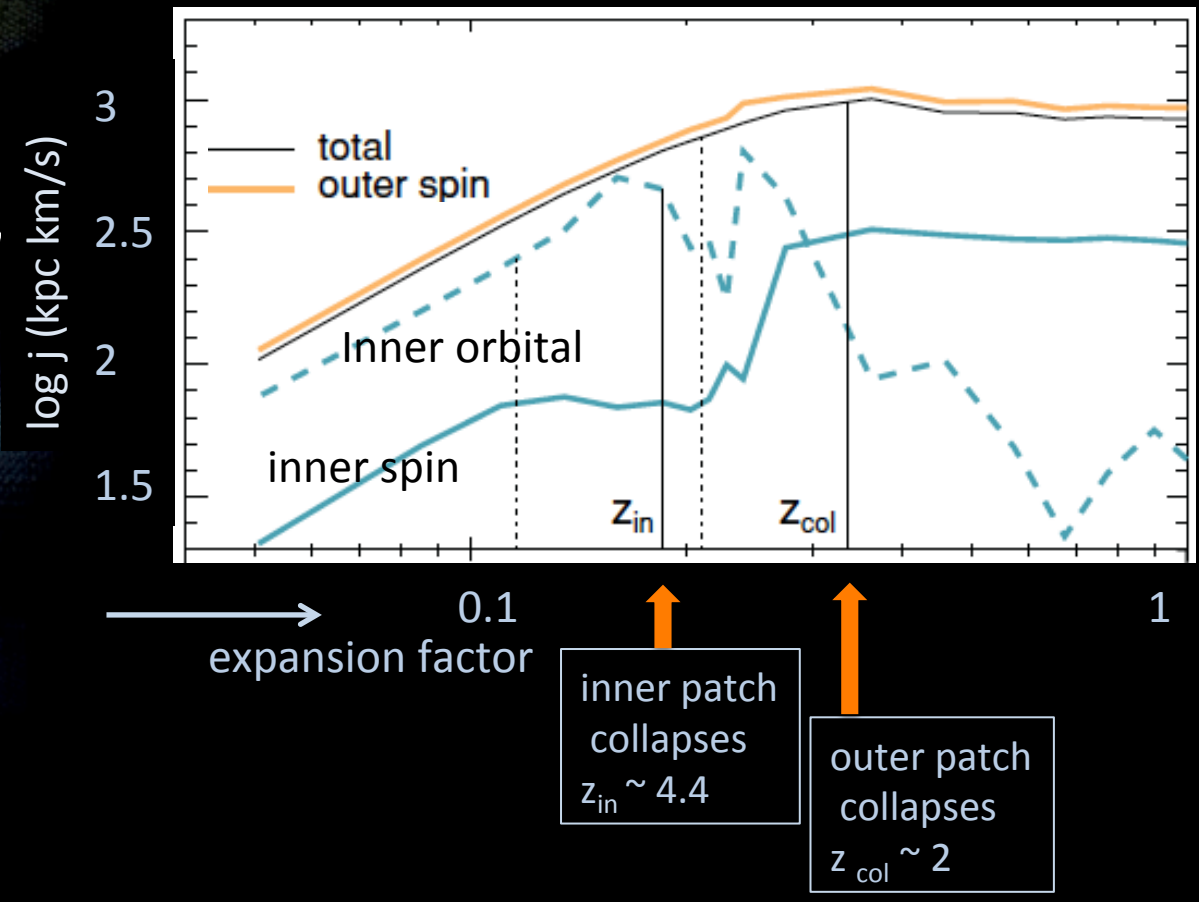
$z = z_{\text{inner core collapse}}$



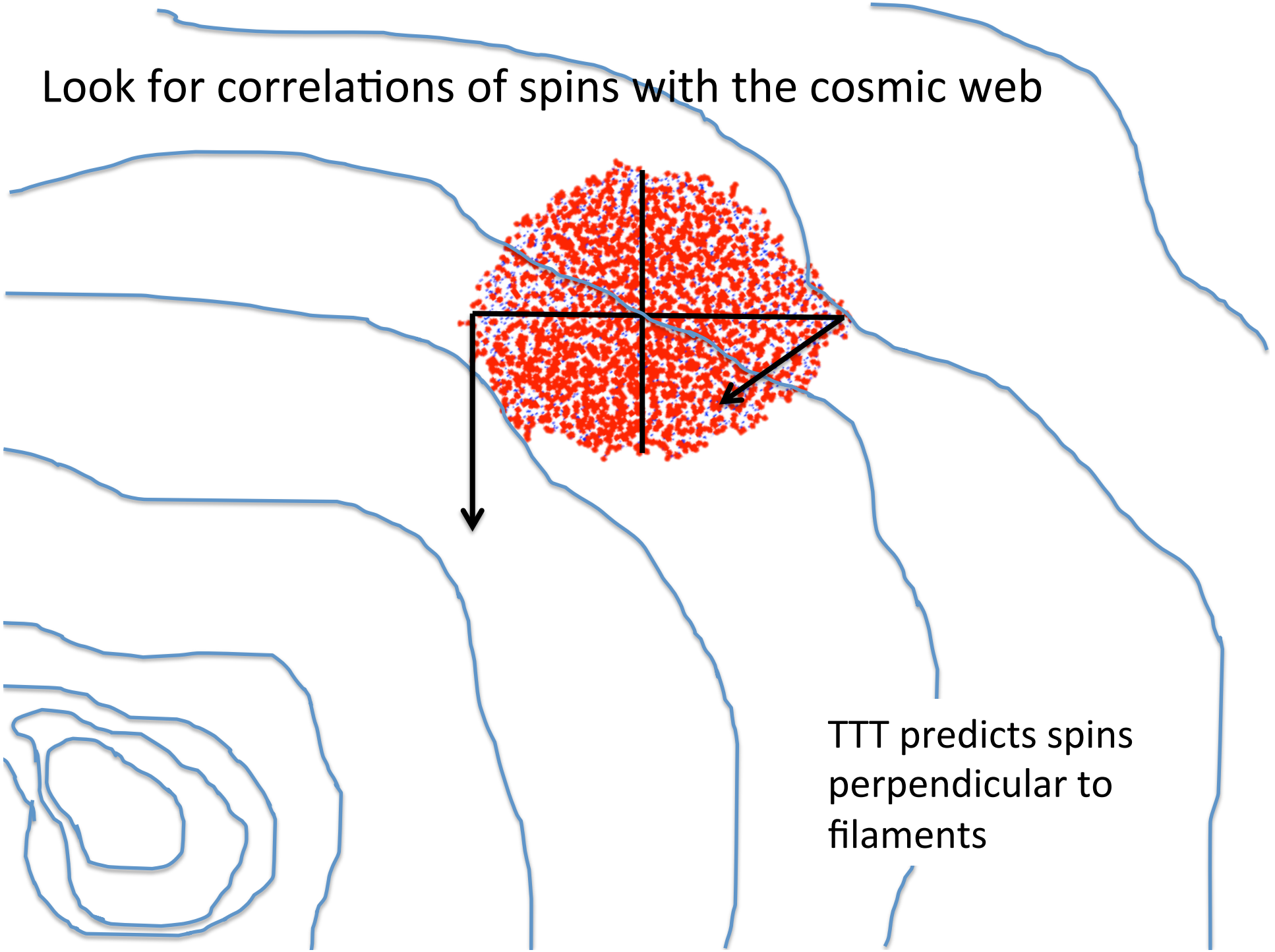
Pichon et al. 2011

What do we mean by "secondary infall"?

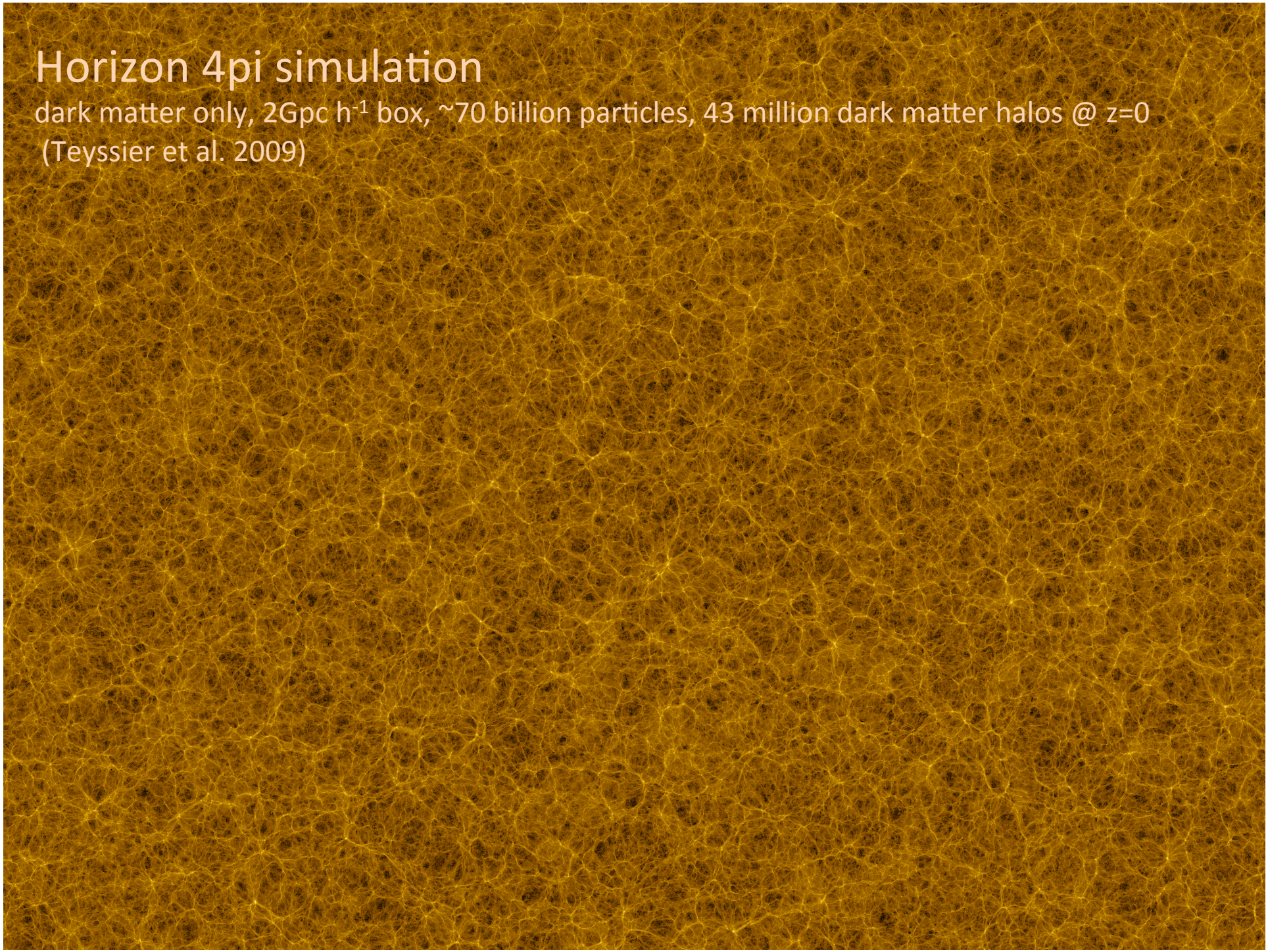
Evolution of specific angular momentum



Look for correlations of spins with the cosmic web

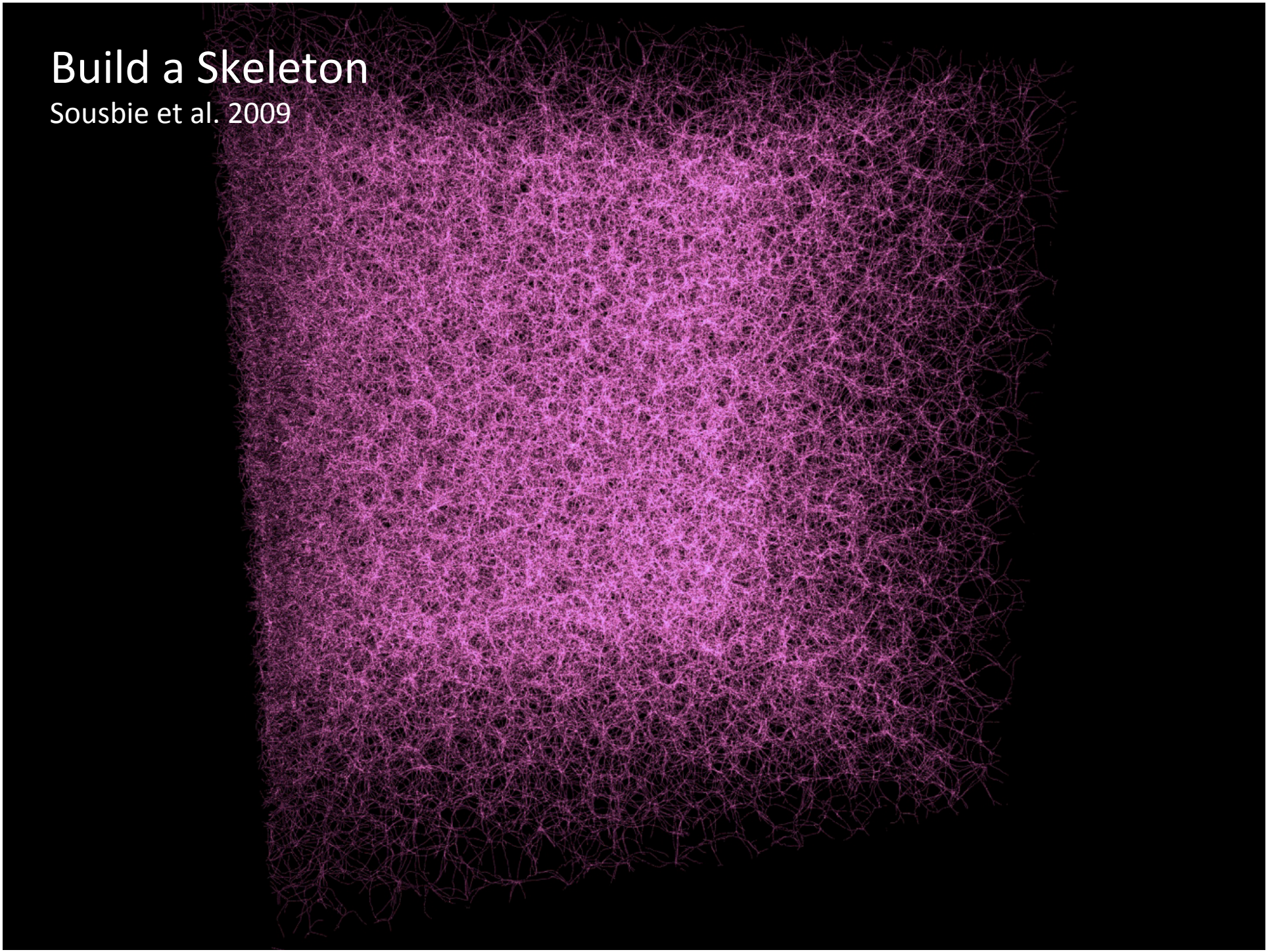


TTT predicts spins perpendicular to filaments

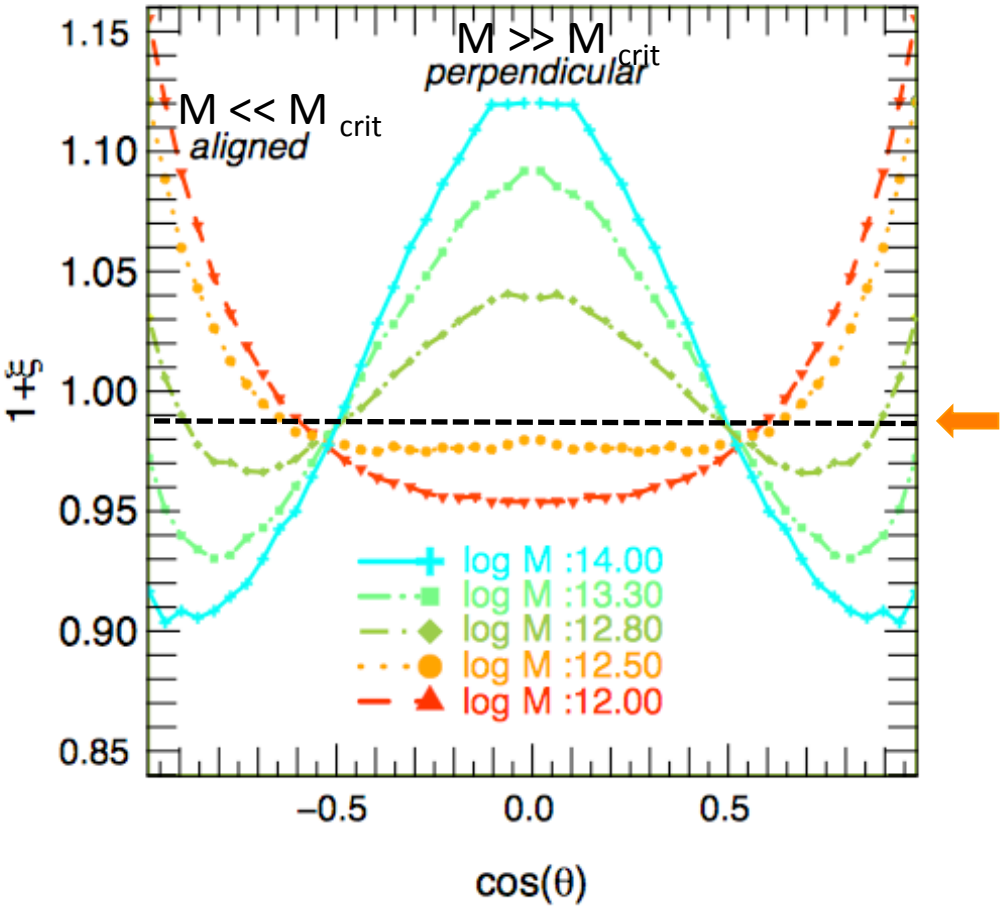

Horizon 4pi simulation
dark matter only, 2Gpc h^{-1} box, ~70 billion particles, 43 million dark matter halos @ z=0
(Teyssier et al. 2009)

Build a Skeleton

Sousbie et al. 2009



Excess probability of alignment between spins of dark matter halos and their nearest filaments



random orientations

Mass transition:

$M_{crit} \sim 4 \times 10^{12} M_{sun}$

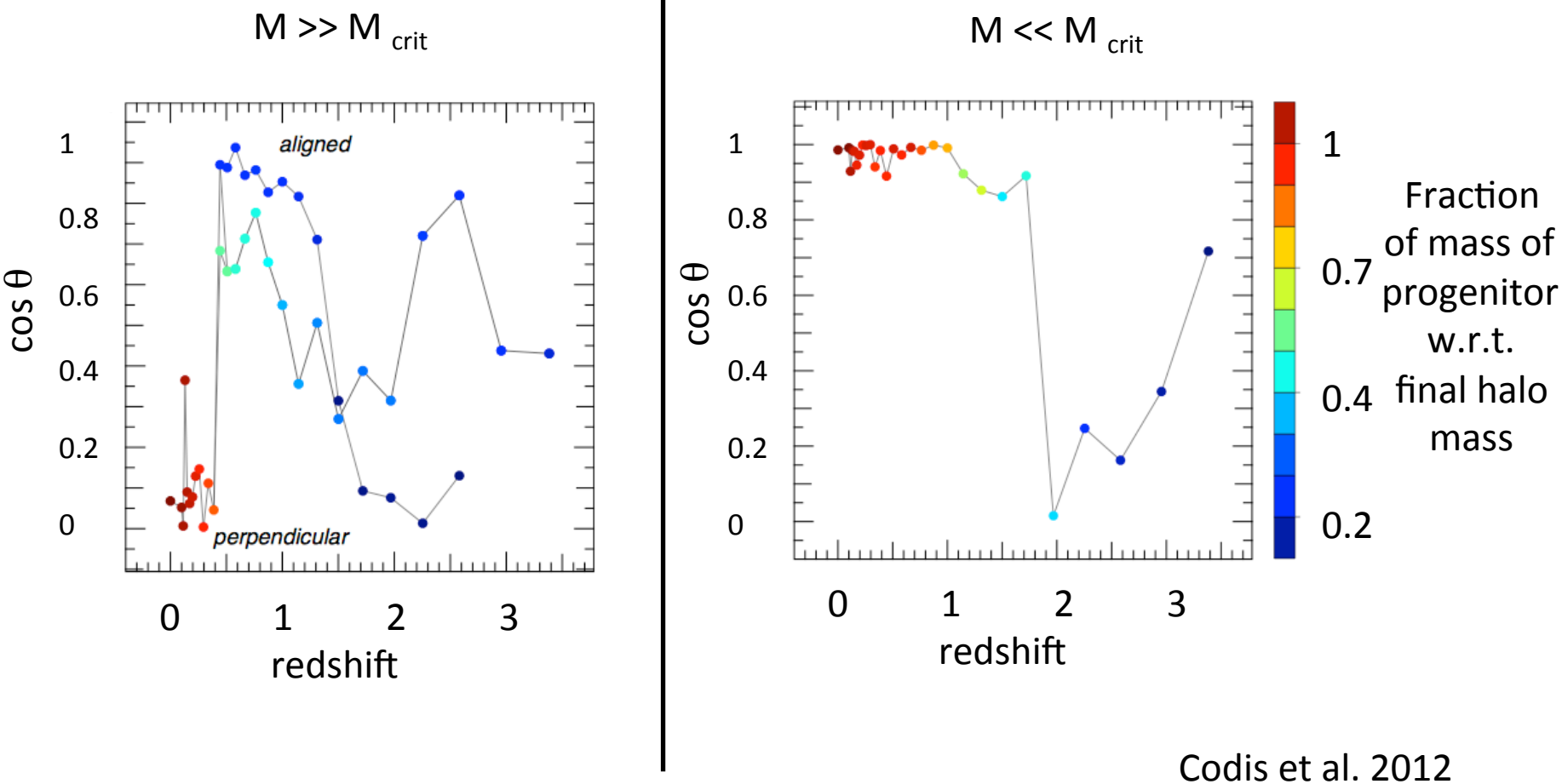
$M < M_{crit}$ aligned

$M > M_{crit}$ perpendicular

Codis et al. 2012 (see also Bailin & Steinmetz 2005, Aragon-Calvo et al. 2007, 2013, Hahn et al. 2007, Paz et al. 2008, Libeskind et al. 2013, Trowland et al. 2013)

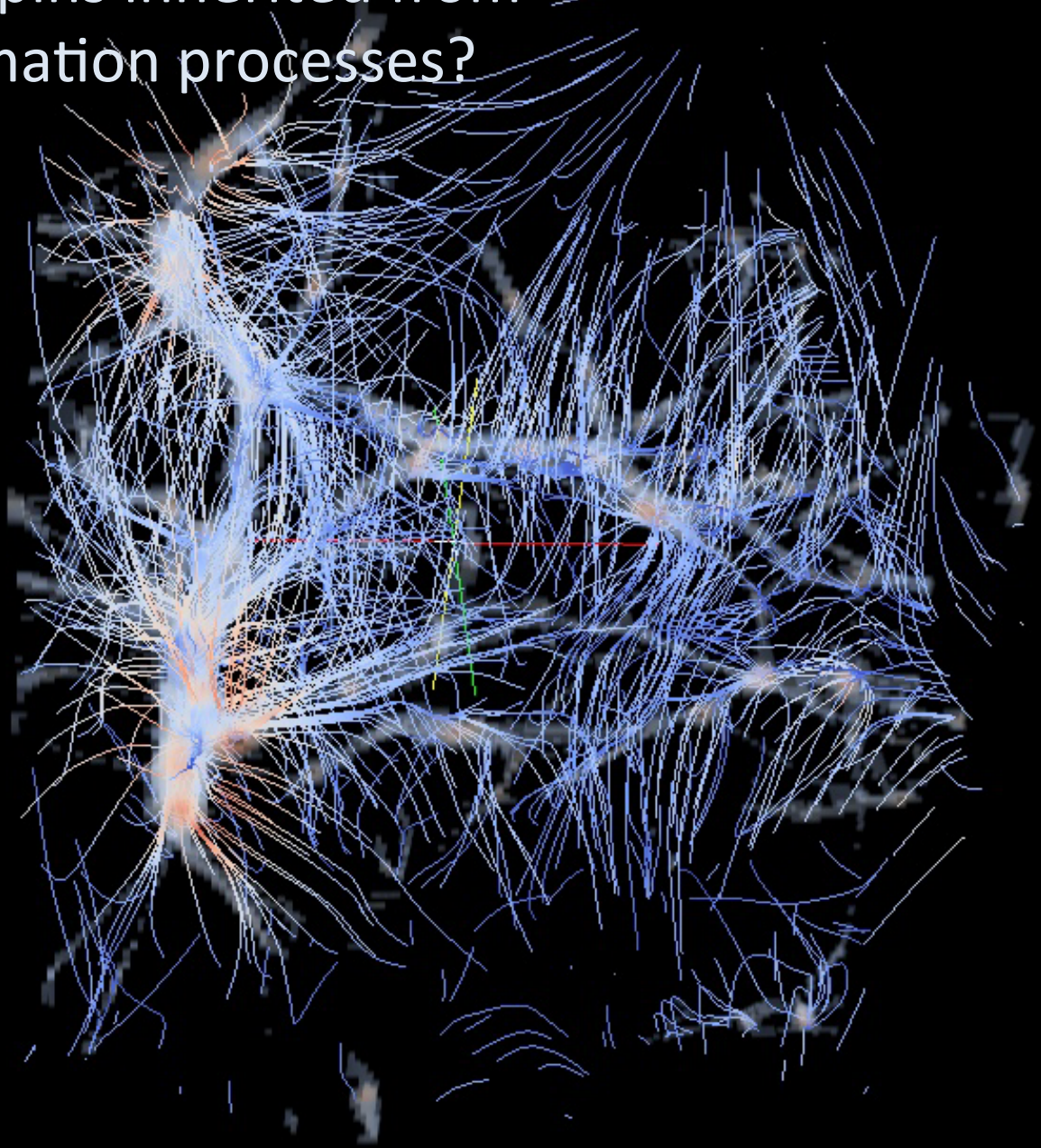
Is mass transition a reflection of accretion history onto a dark matter halo?

Time evolution of angle between closest filament and the spin of a DM halo

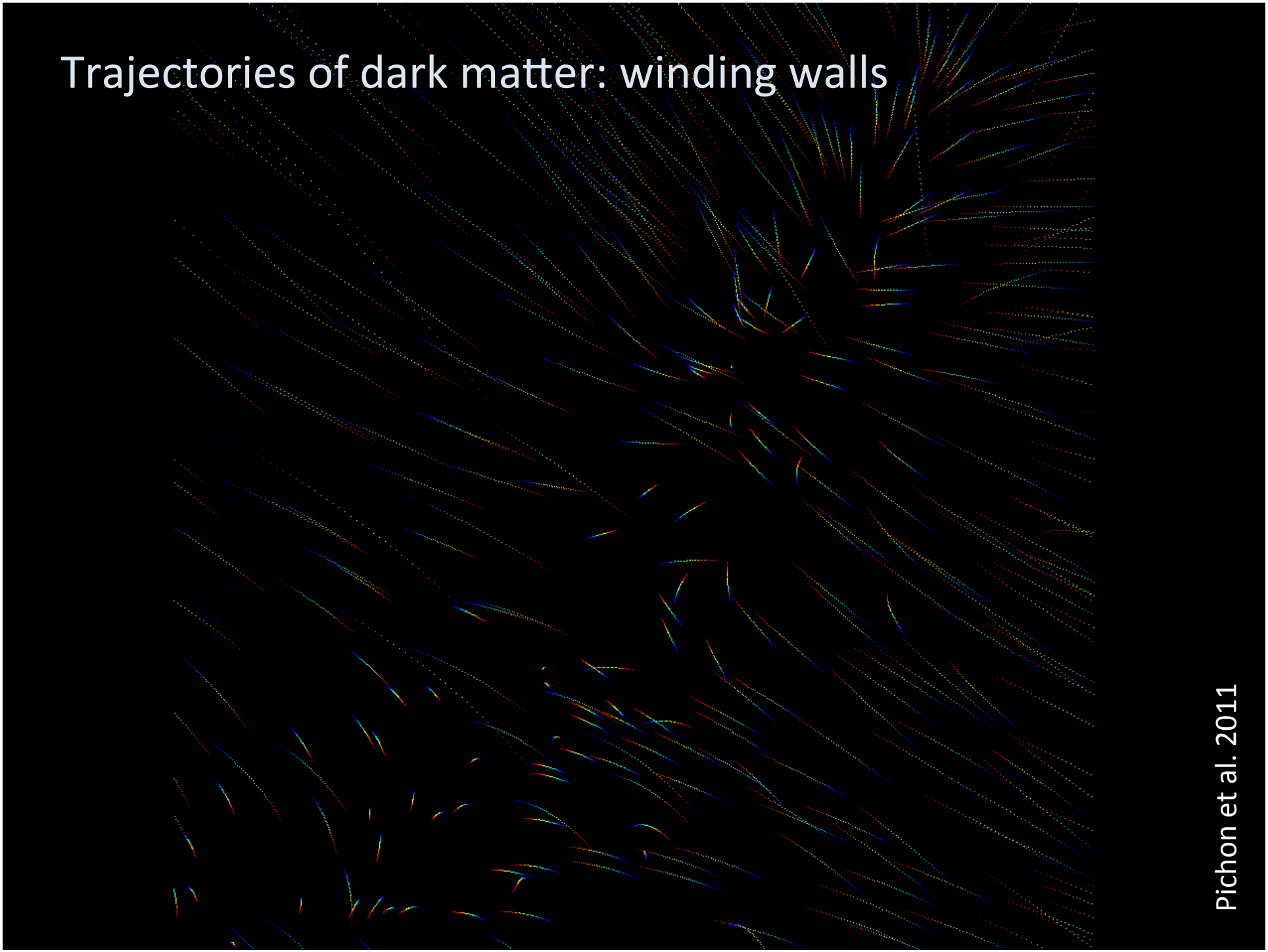


Codis et al. 2012

Are aligned spins inherited from filament formation processes?

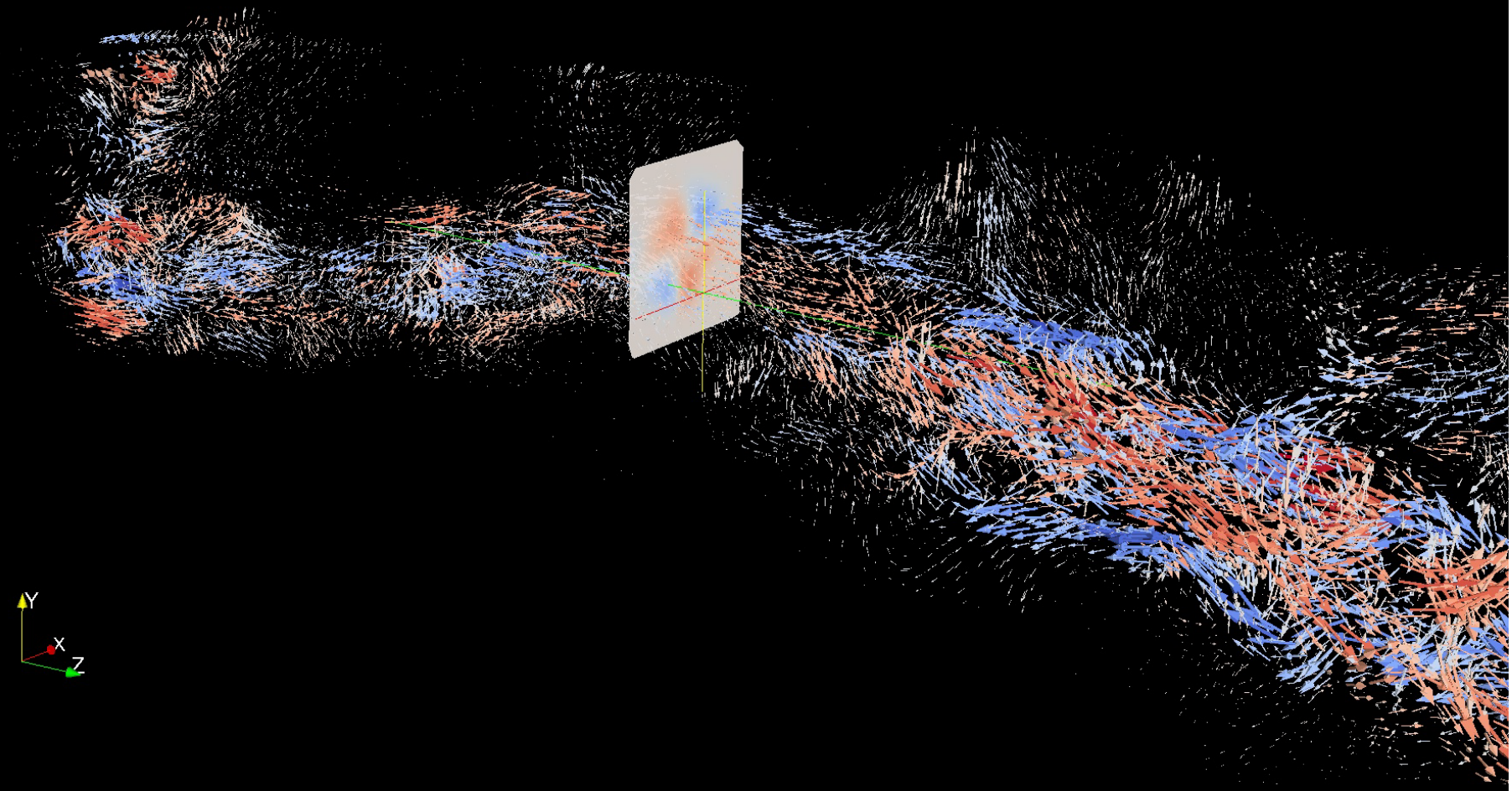


Trajectories of dark matter: winding walls

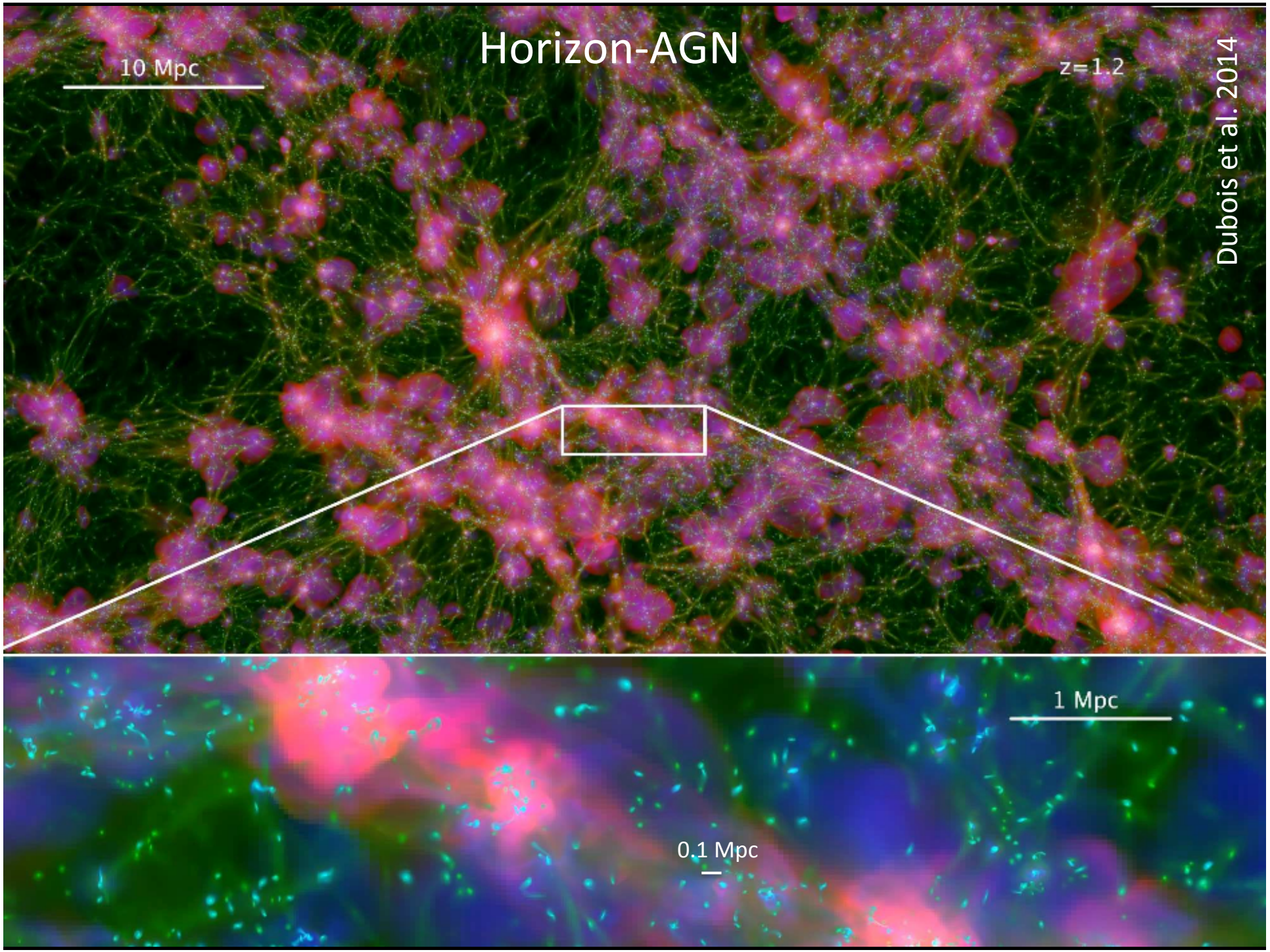


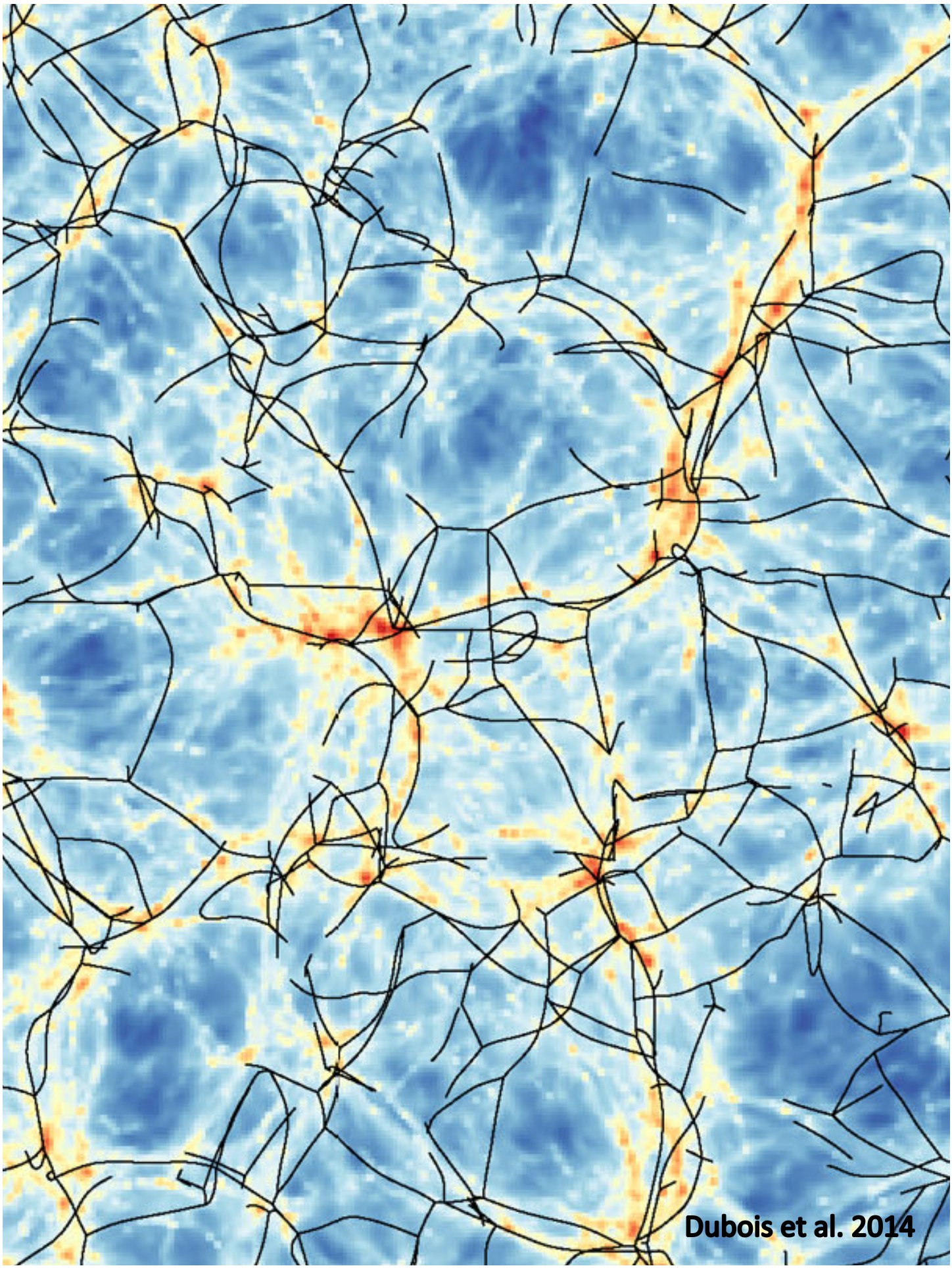
Pichon et al. 2011

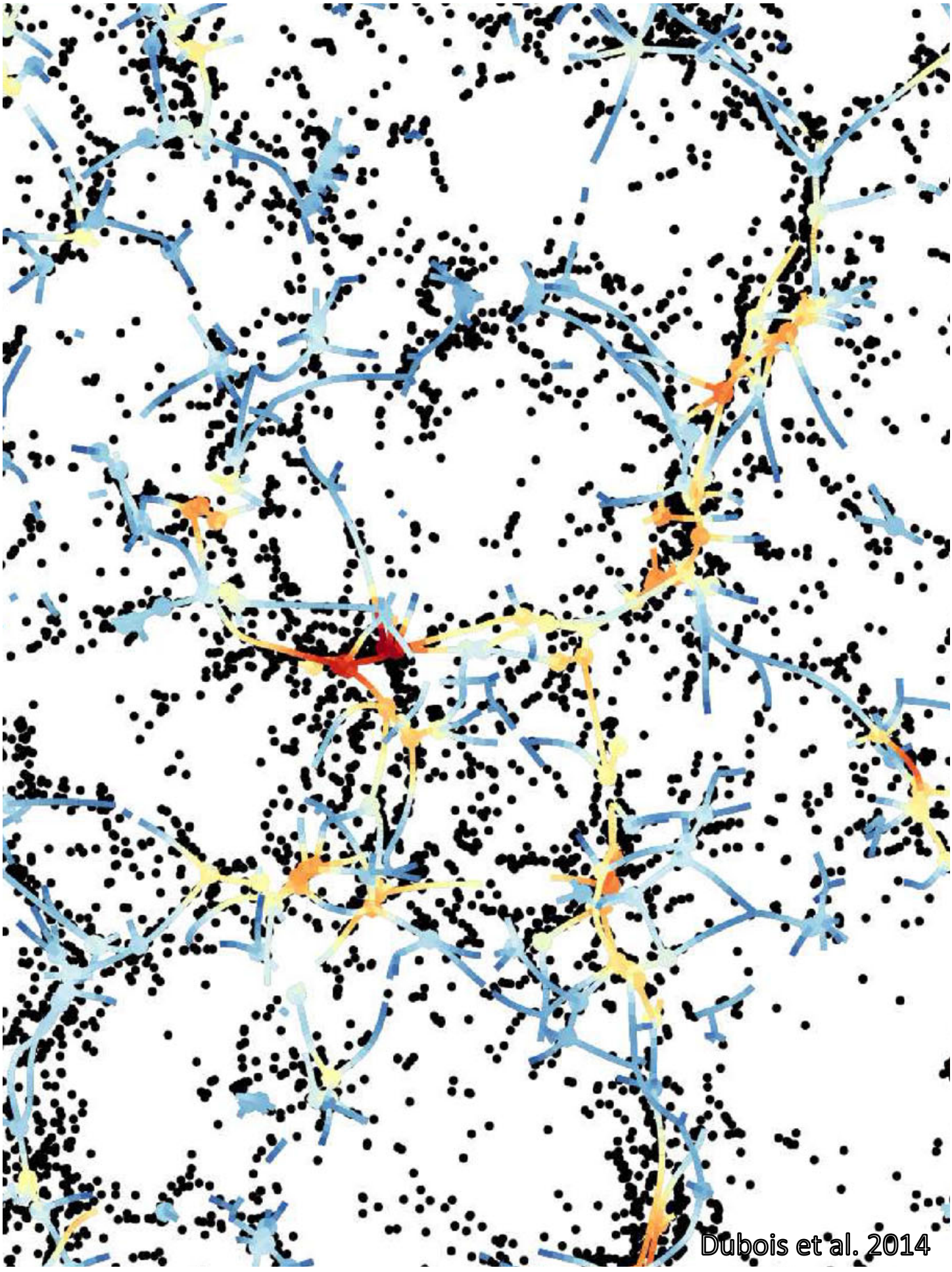
Vorticity field near a filament



Laigle et al. 2014


Horizon-AGN
10 Mpc
z=1.2
Dubois et al. 2014
1 Mpc
0.1 Mpc

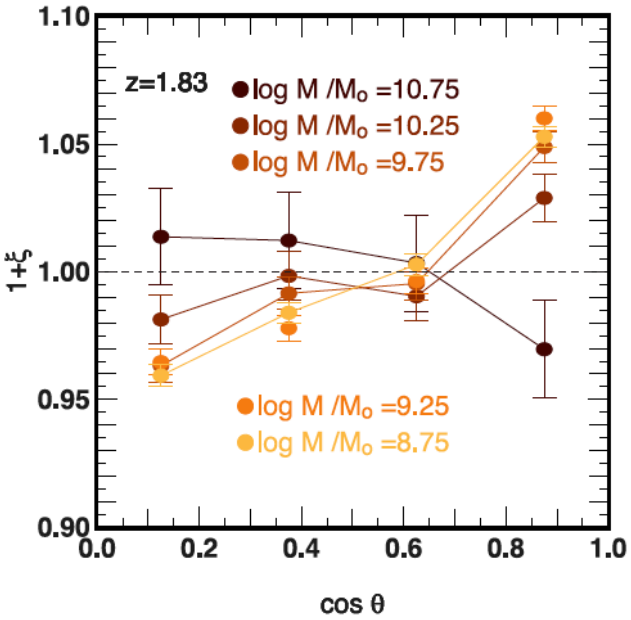

Dubois et al. 2014


Dubois et al. 2014

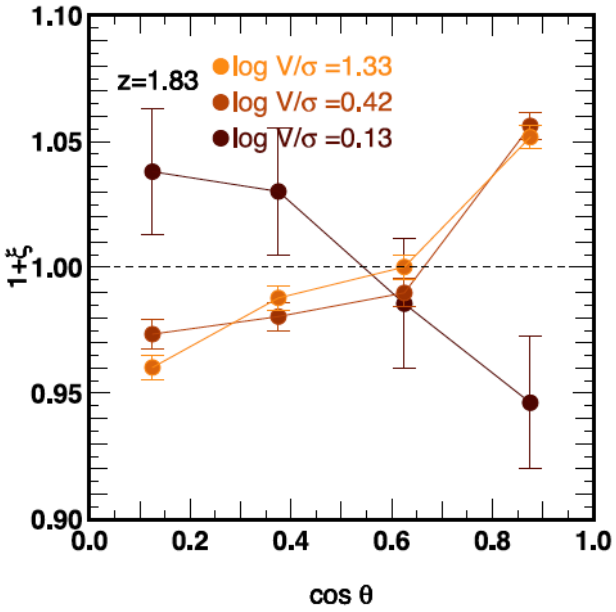
Morphology of simulated galaxies is correlated to the cosmic web at z = 1.83

Excess probability of alignment between galaxy spin & closest filament as function of:

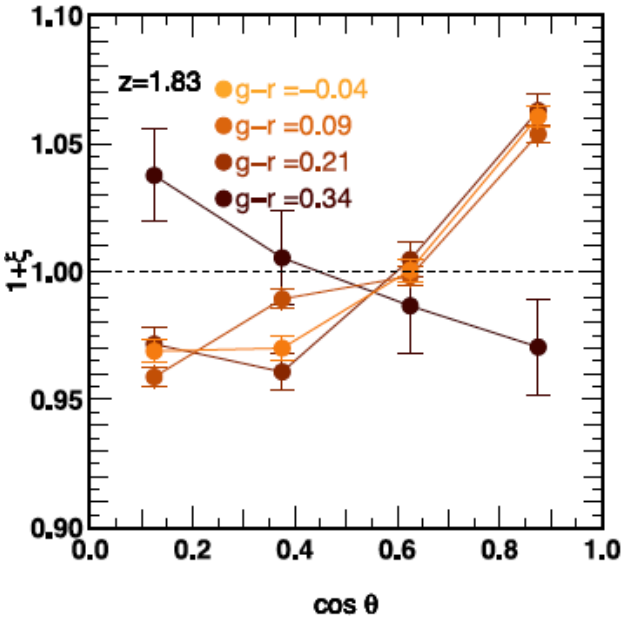
mass



kinematics (V/s)

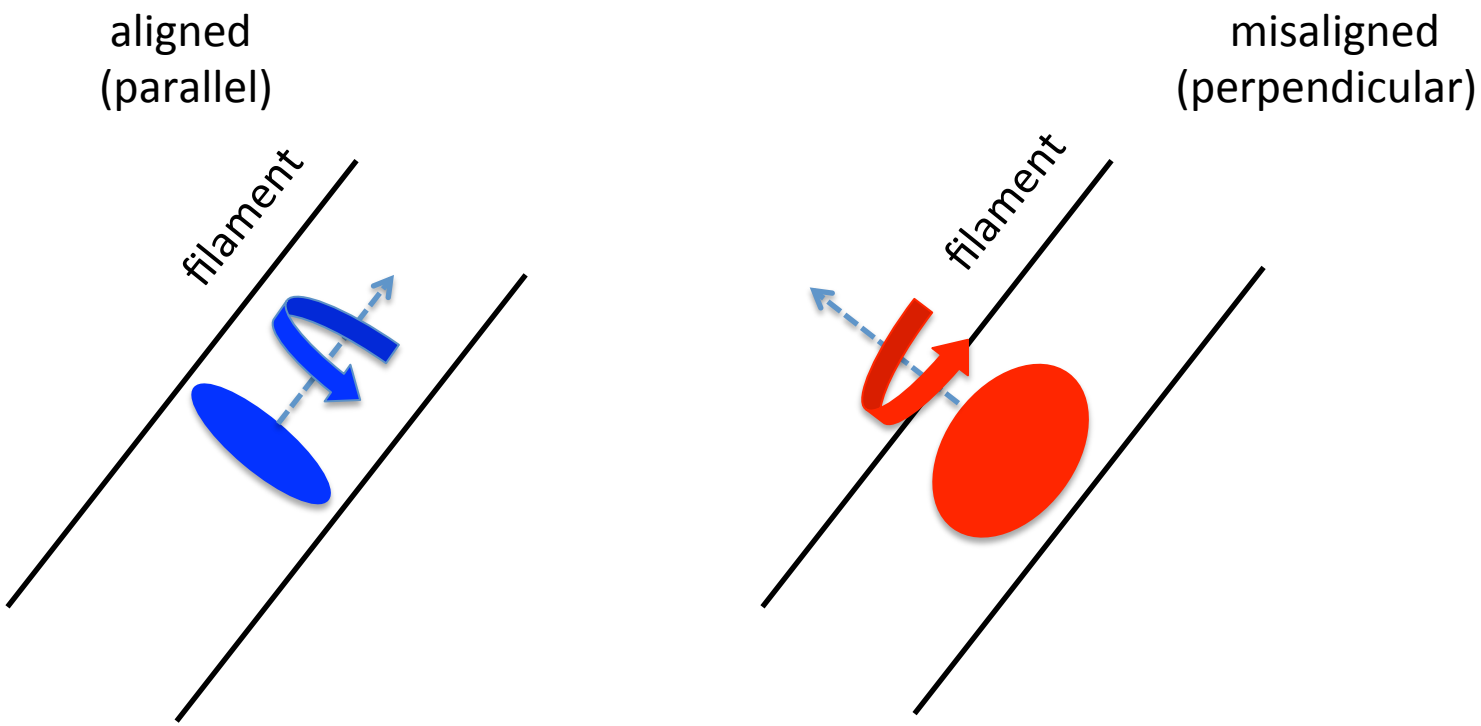


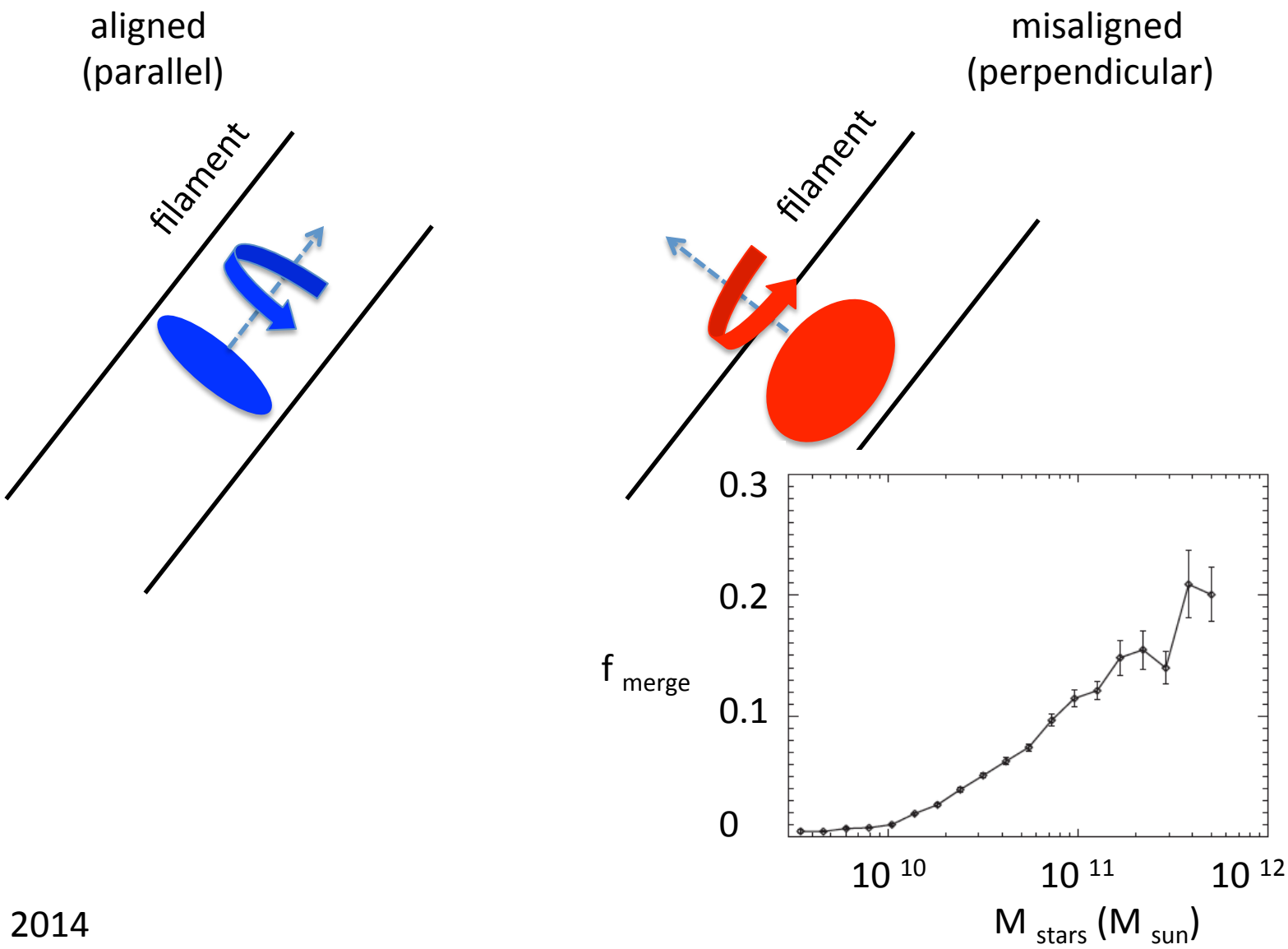
color (g-r)



Mass transition
M_{stars} ~ 3 X 10^{10} M_{sun}
compatible with Codis et al. 2012
M_{DM} ~ 5 X 10^{11} M_{sun} at z=1.83

Dubois et al. 2014

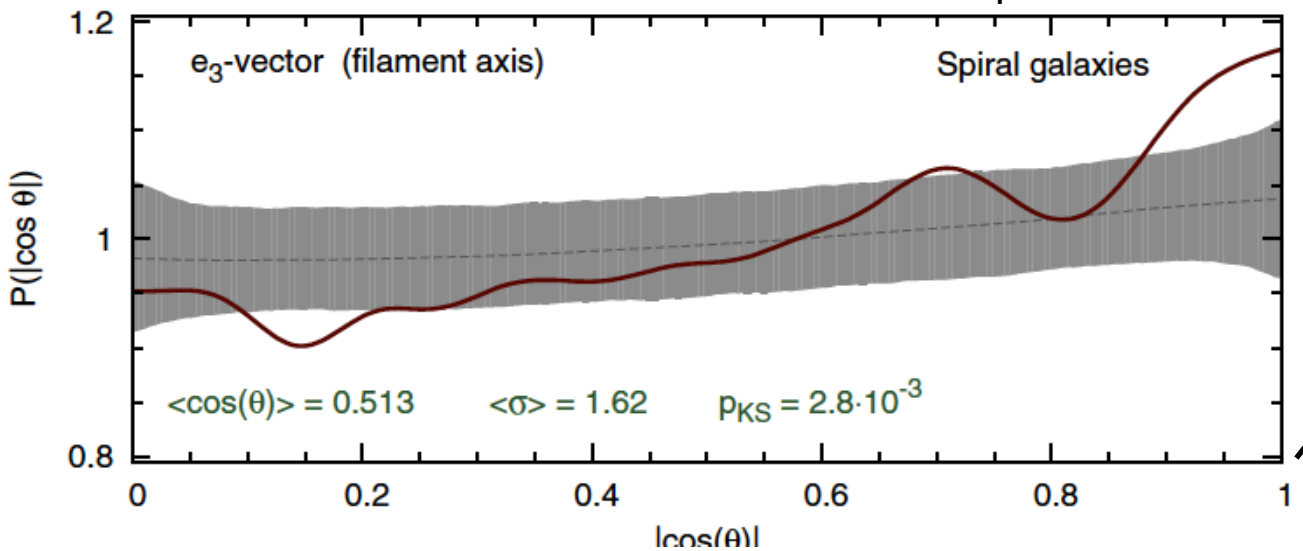

aligned
(parallel)
filament
misaligned
(perpendicular)
filament

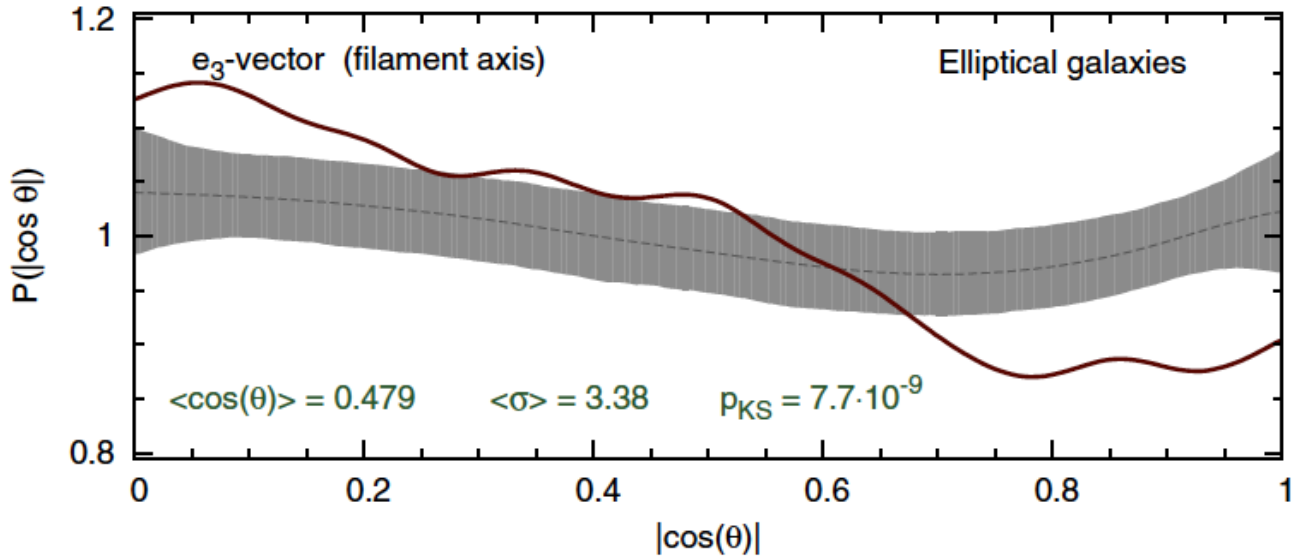


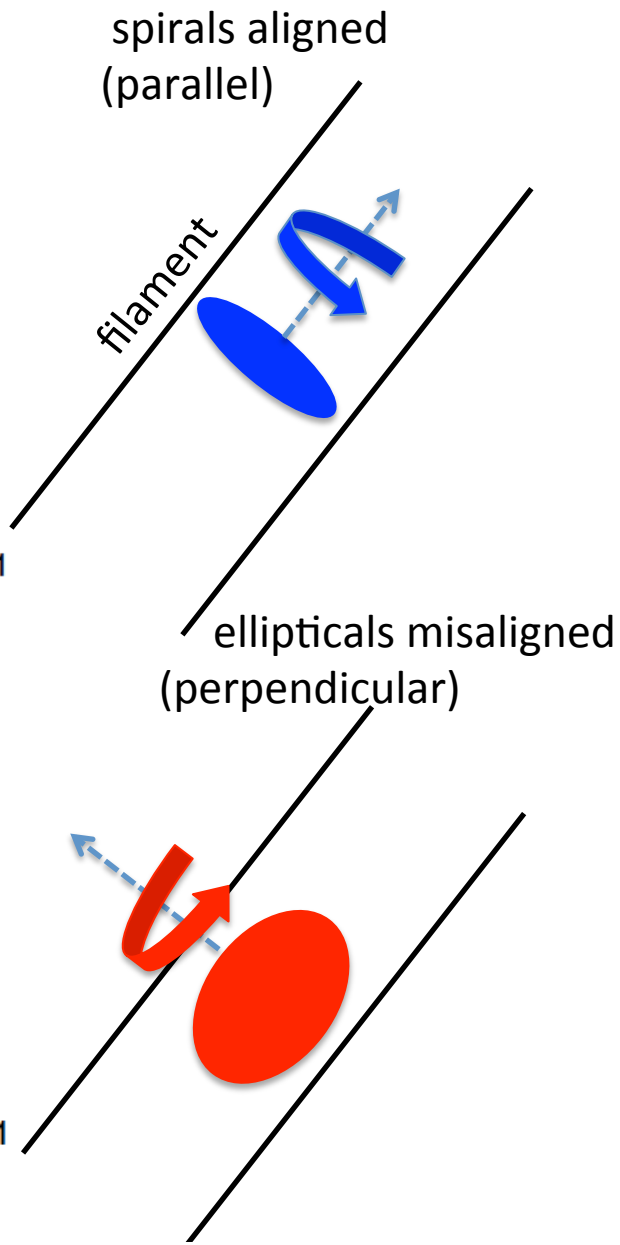
Dubois et al. 2014

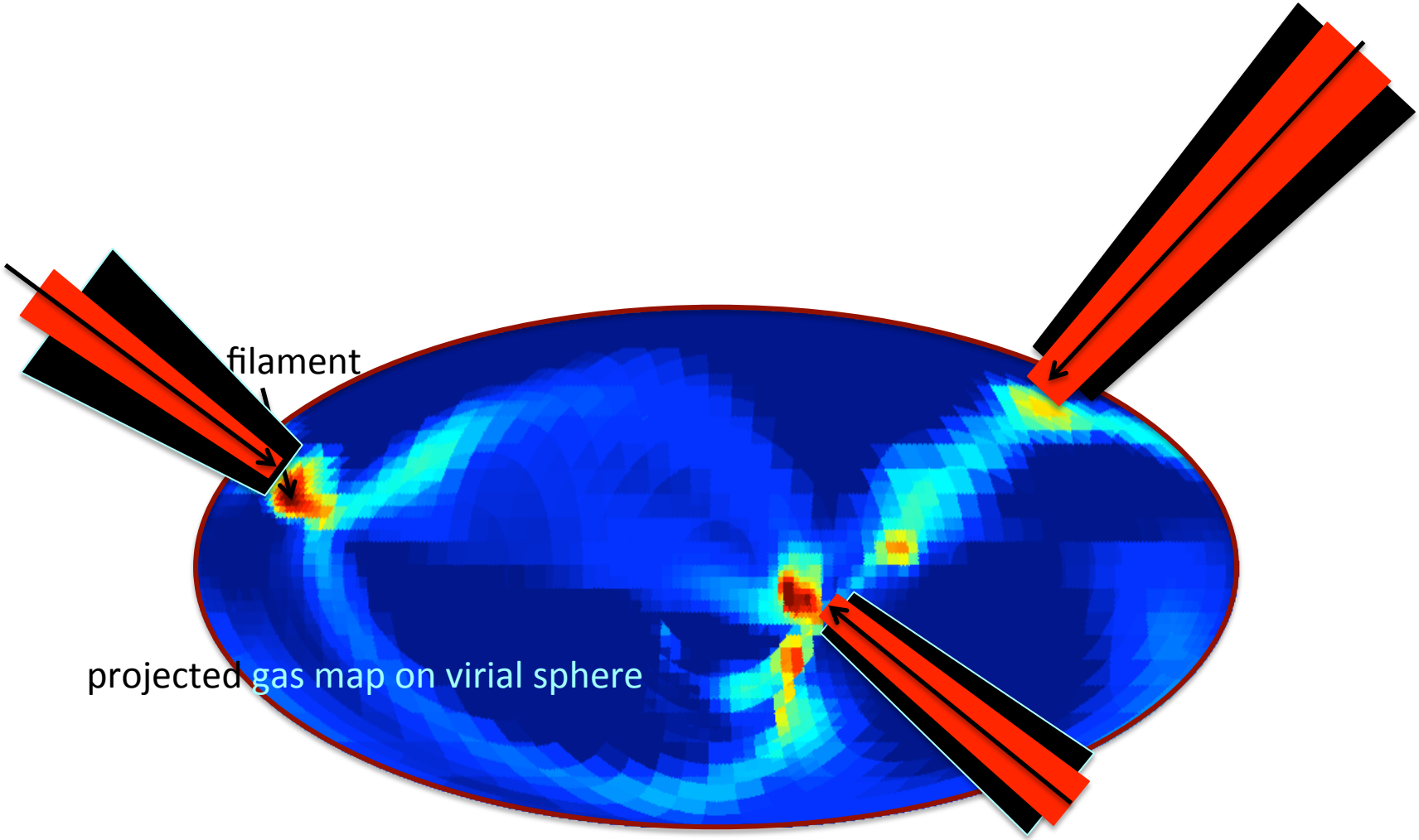
Morphology of observed SDSS galaxies might be correlated to the cosmic web…

Temple et al. 2013

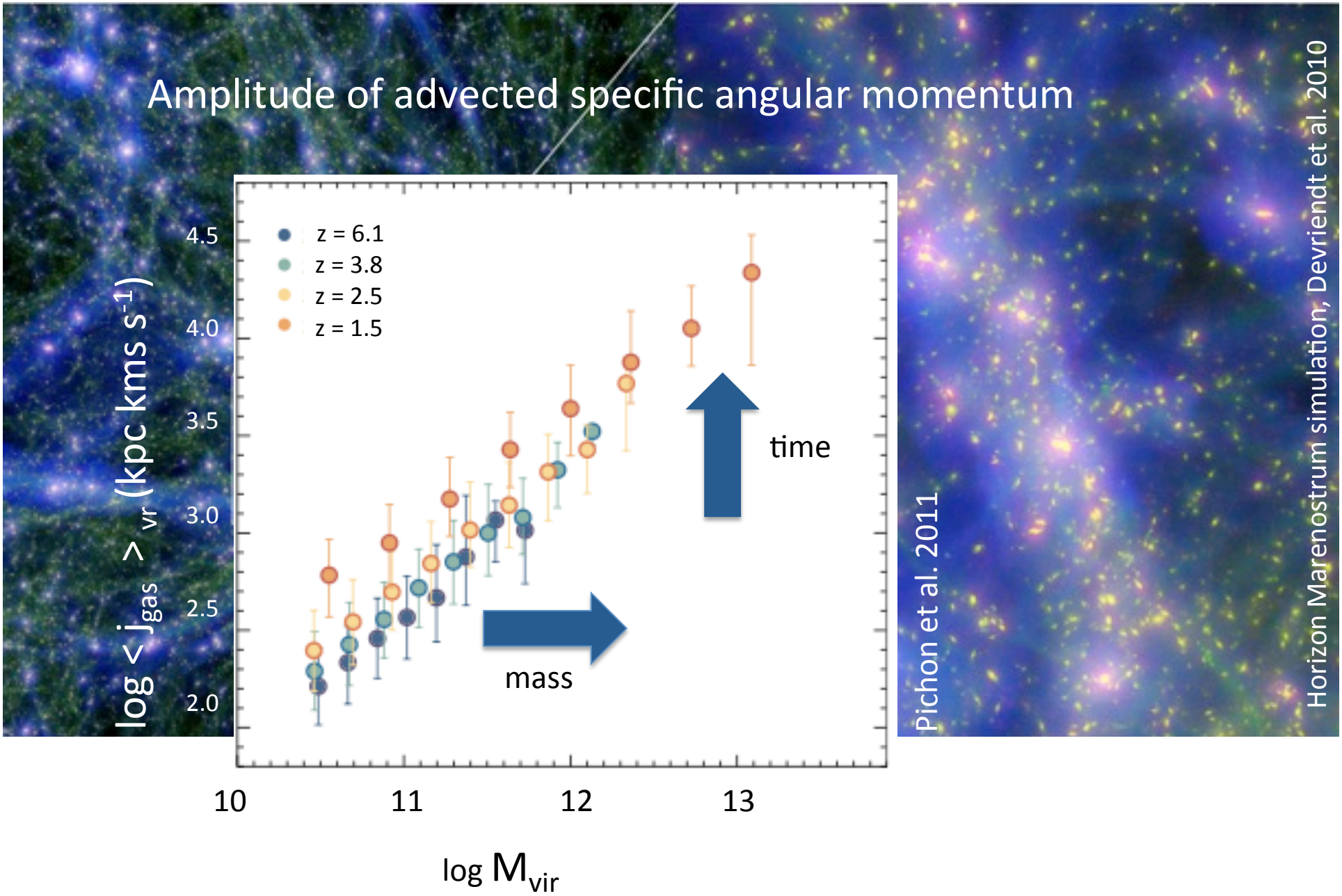


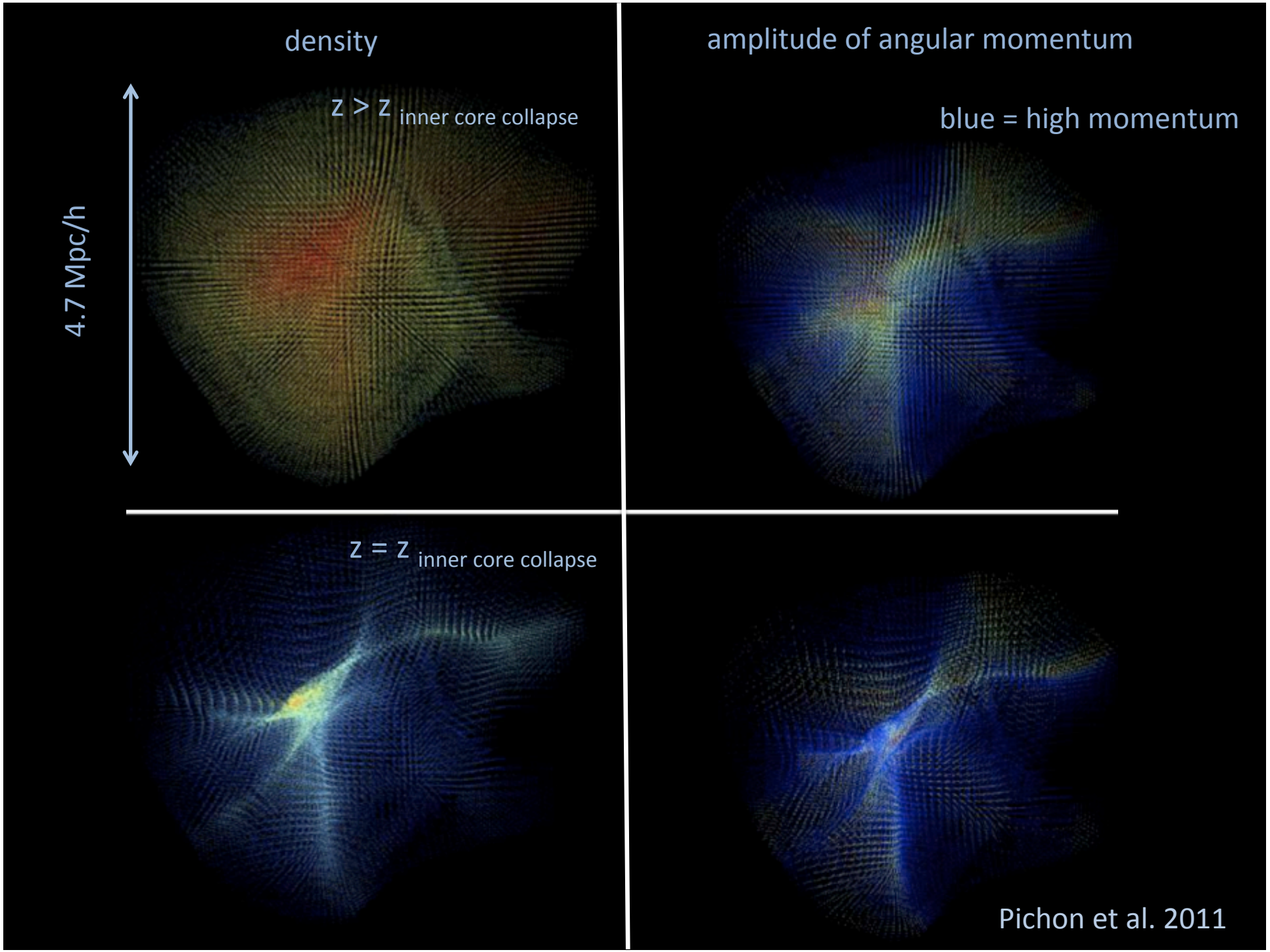






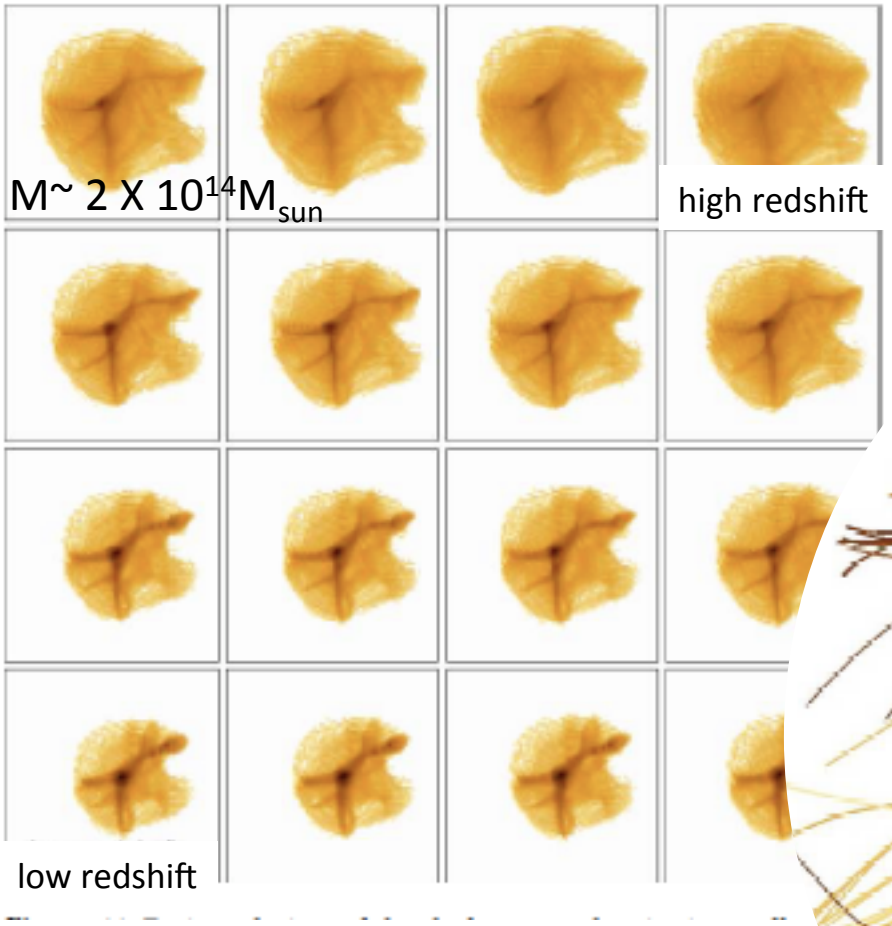
e.g. Dekel et al. 2009, Pichon et al. 2011, Danovich et al.2012


Amplitude of advected specific angular momentum
z = 6.1
z = 3.8
z = 2.5
z = 1.5
time
mass
log < j_gas >_vr (kpc kms s^-1)
4.5
4.0
3.5
3.0
2.5
2.0
10
11
12
13
log M_vir
Pichon et al. 2011
Horizon Marenostrum simulation, Devriendt et al. 2010


density
amplitude of angular momentum
z > z inner core collapse
blue = high momentum
4.7 Mpc/h
z = z inner core collapse
Pichon et al. 2011

“Sweeping skeleton”

$100h^{-1}$ Mpc ΛCDM simulation with 256^3 dark matter particles

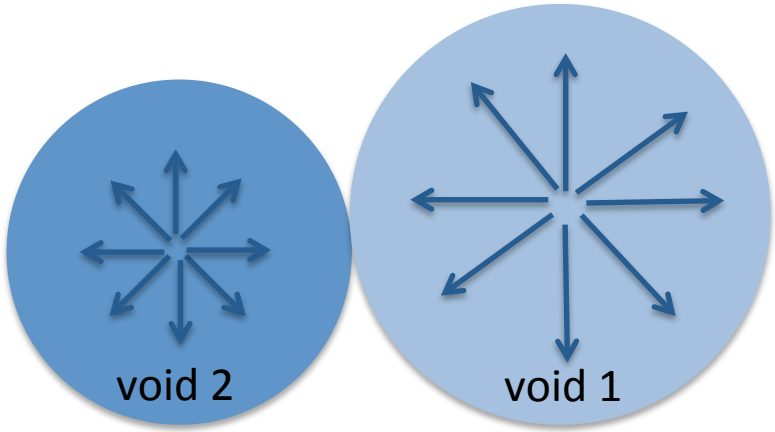


dark: high z
light: low z

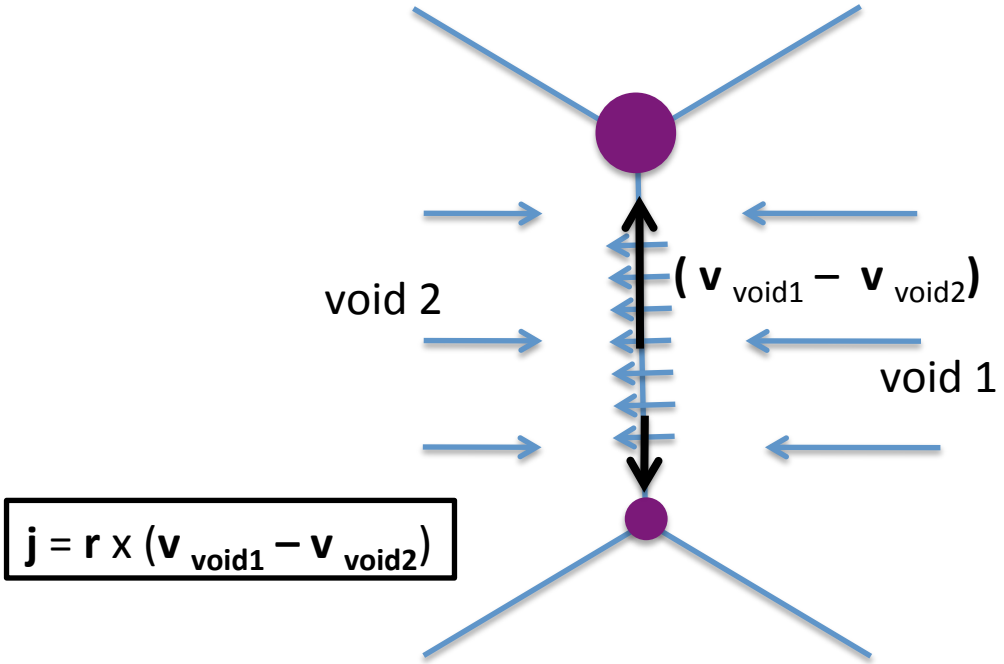
Pichon, Pogosyan, Kimm, Slyz, Devriendt, Dubois 2011

Why later infall carries more angular momentum

2 adjacent asymmetric voids

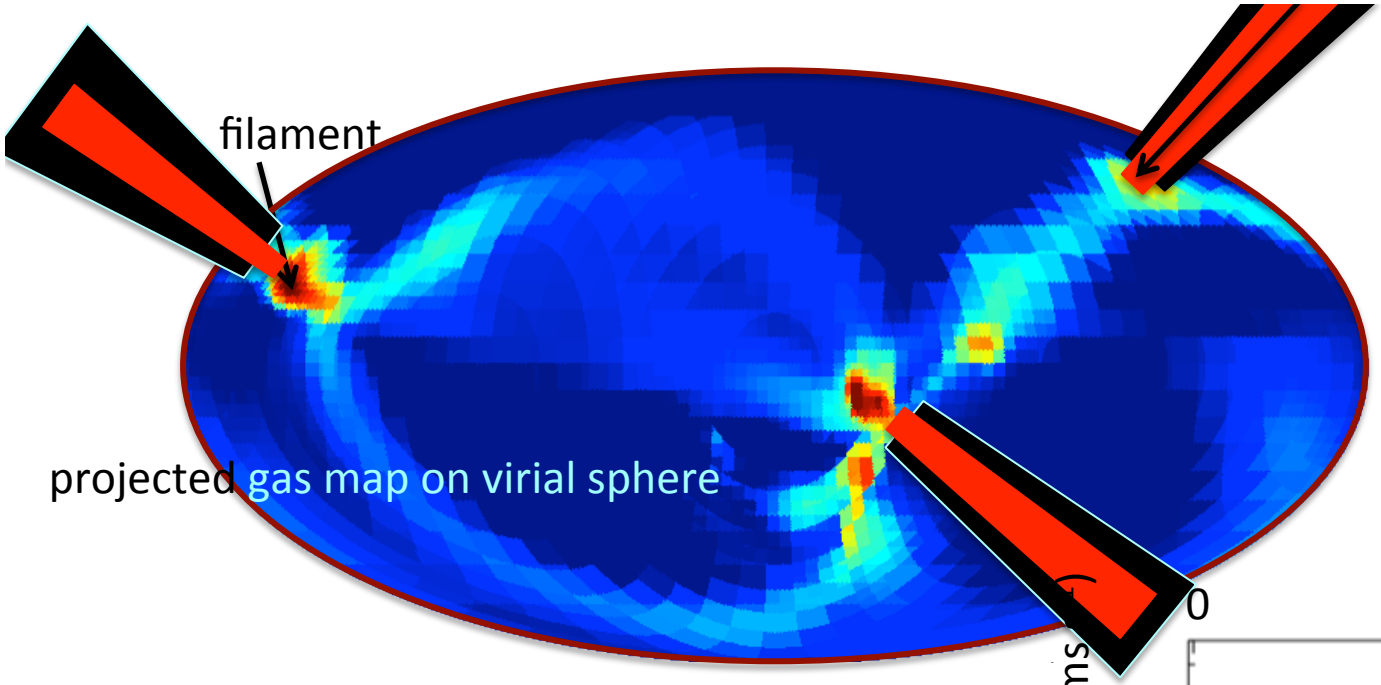


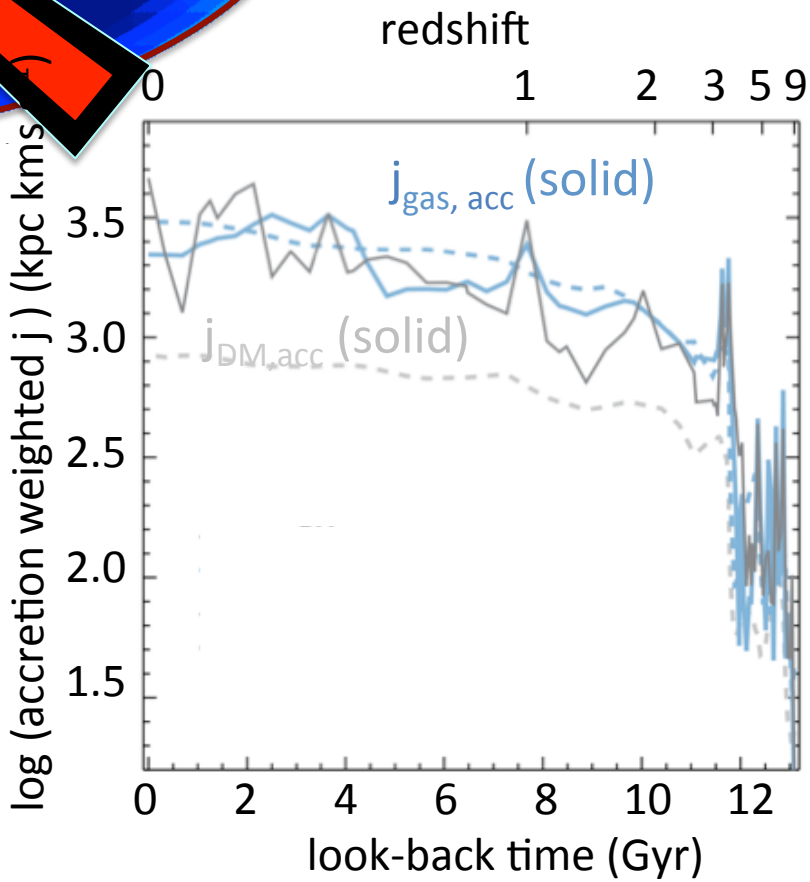
in 2 dimensions



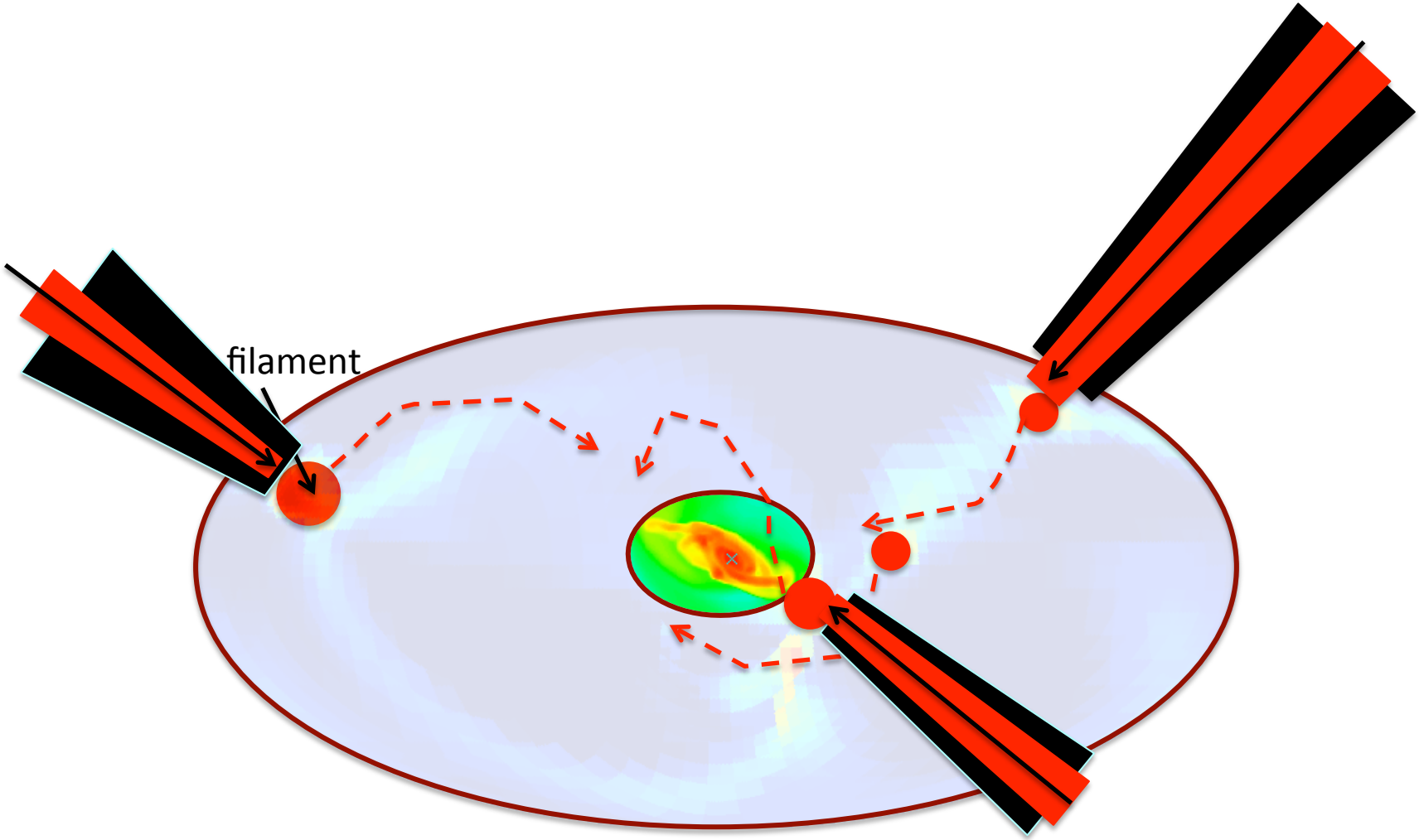
$$\mathbf{j} = \mathbf{r} \times (\mathbf{v}_{\text{void1}} - \mathbf{v}_{\text{void2}})$$

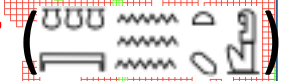
Pichon, Pogosyan, Kimm, Slyz, Devriendt, Dubois 2011



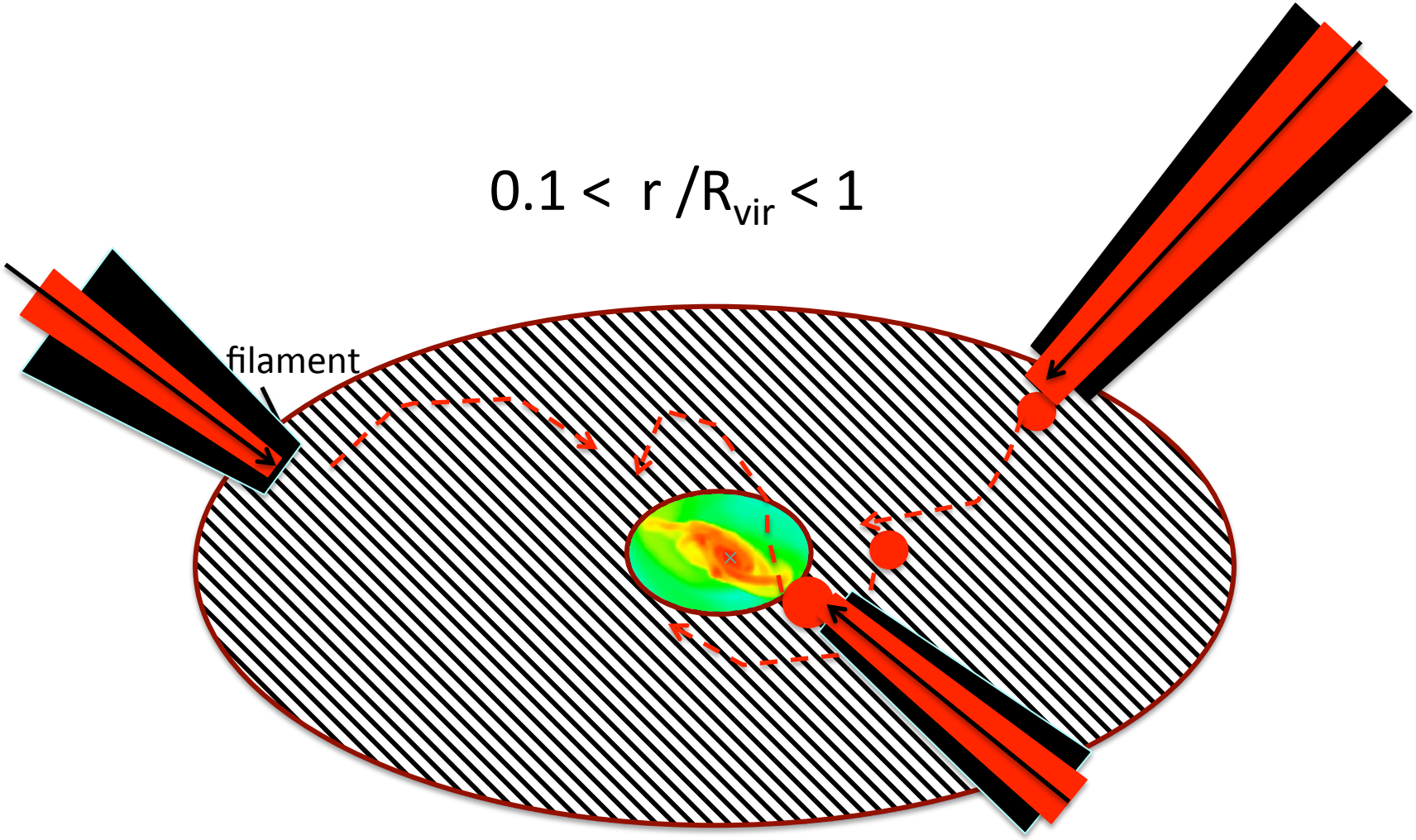


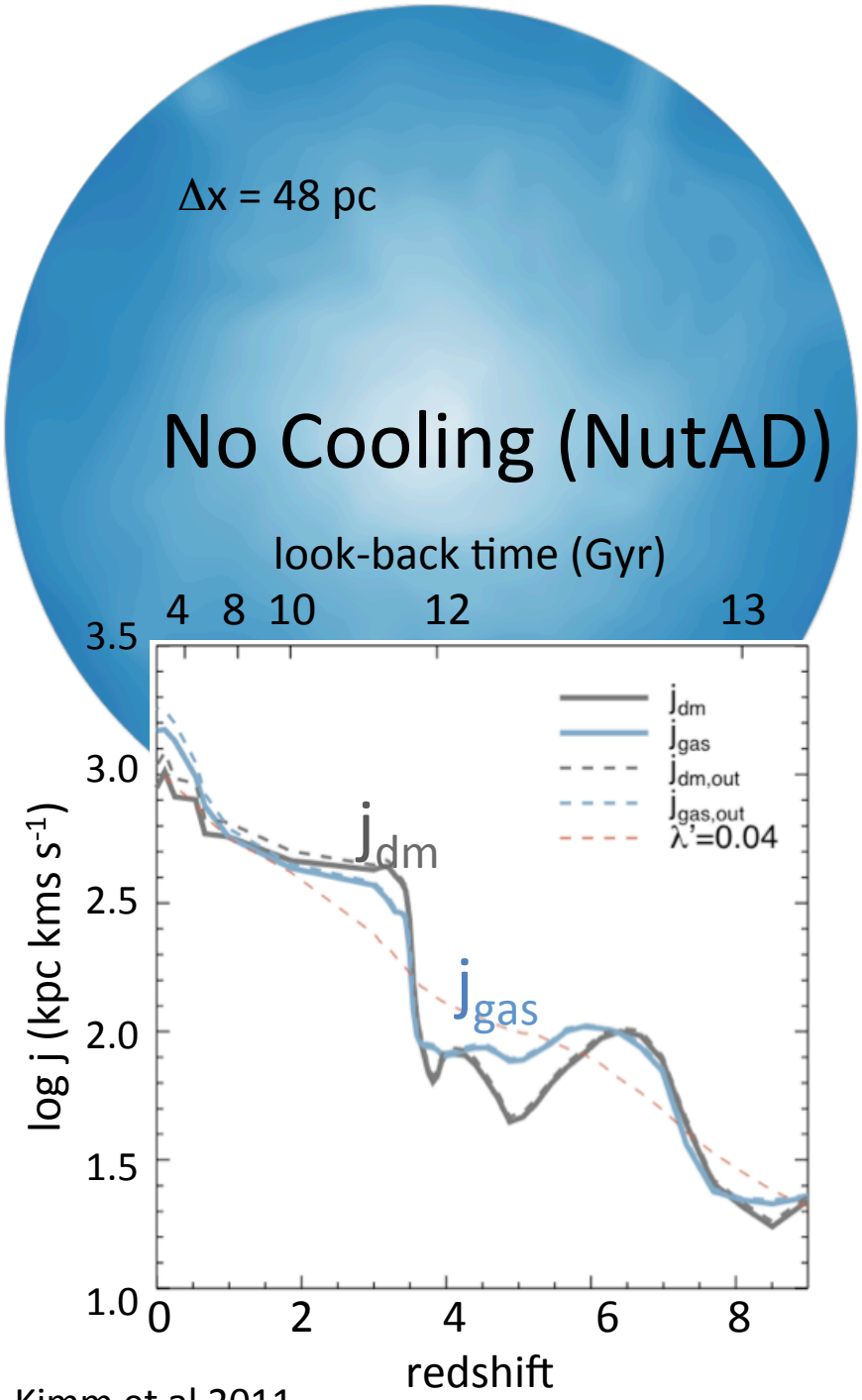
Kimm, Devriendt, Slyz, Pichon, Kassin, Dubois, 2011


filament

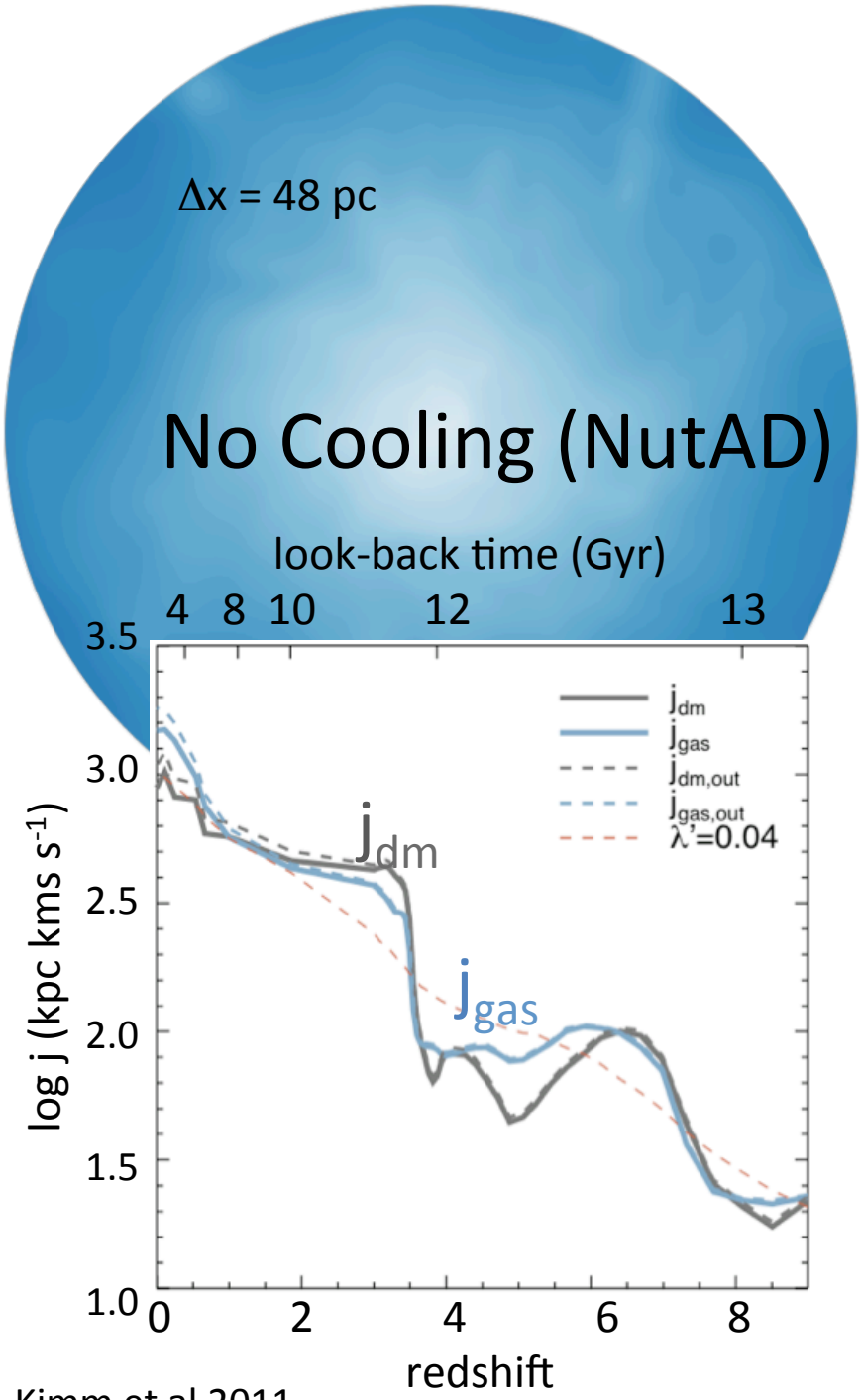
Inside halos with the AMR NUT () « re-simulations » …

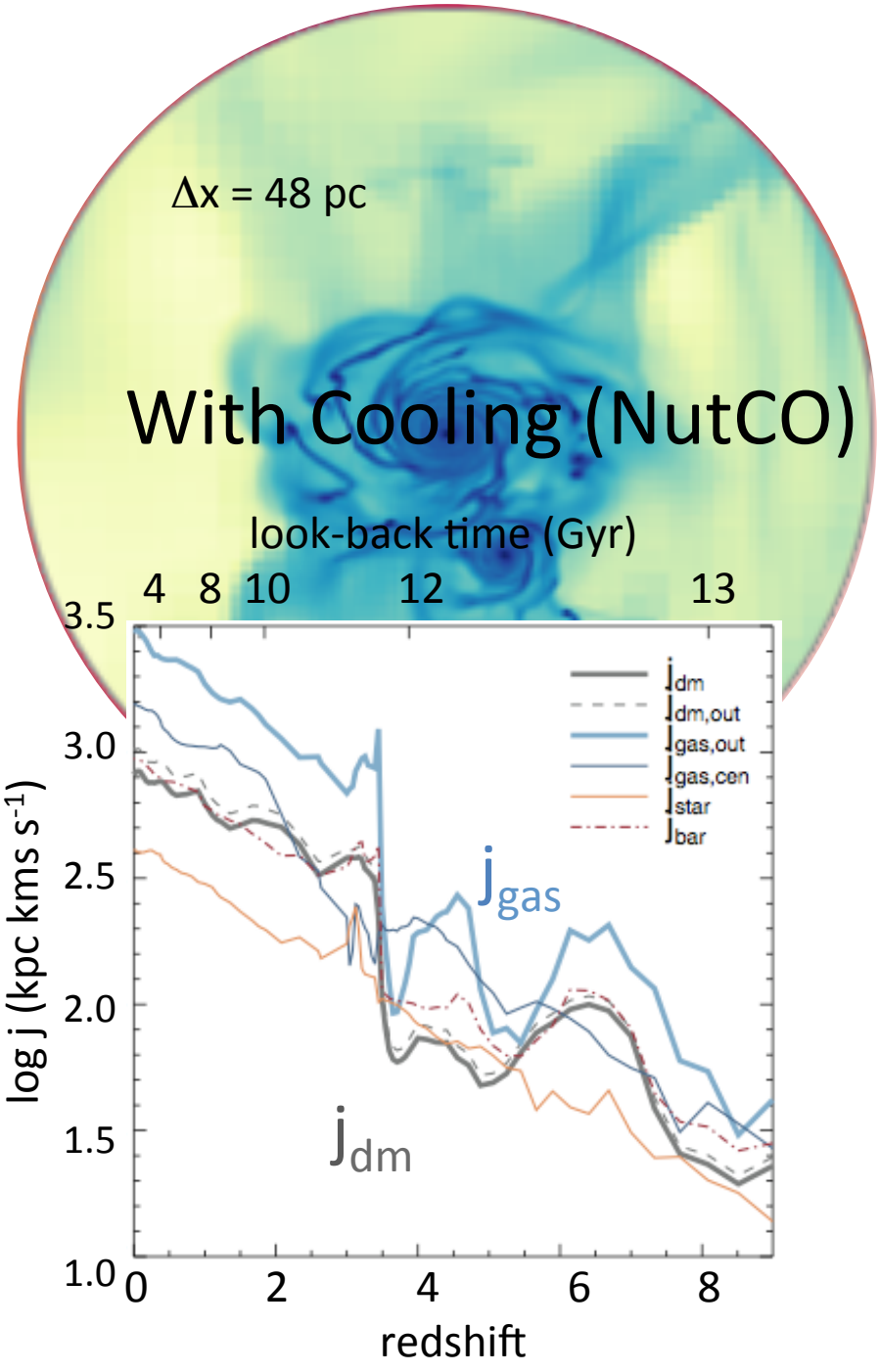
RAMSES code (Teyssier, 2002) with 128 root grid,
3 nested grids
8-15 AMR refinement levels
Identical simulations (IC / DM particle mass res → 5 x 10^4 $M_\odot$) with different physics implemented (adiabatic, cooling, star formation, SN feedback, RT, stellar winds, MHD …)


0.1 < r /R_vir < 1
filament

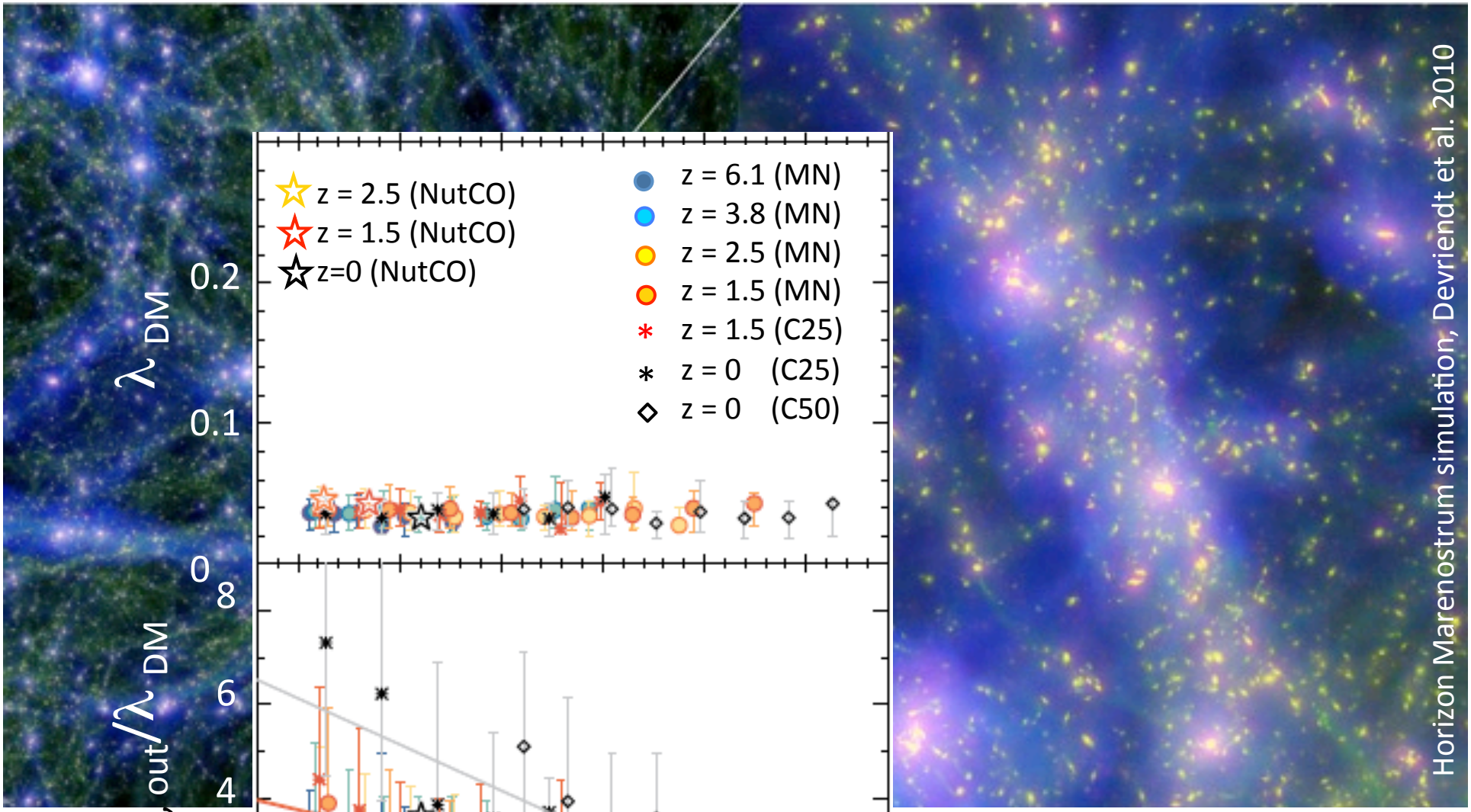


Kimm et al 2011

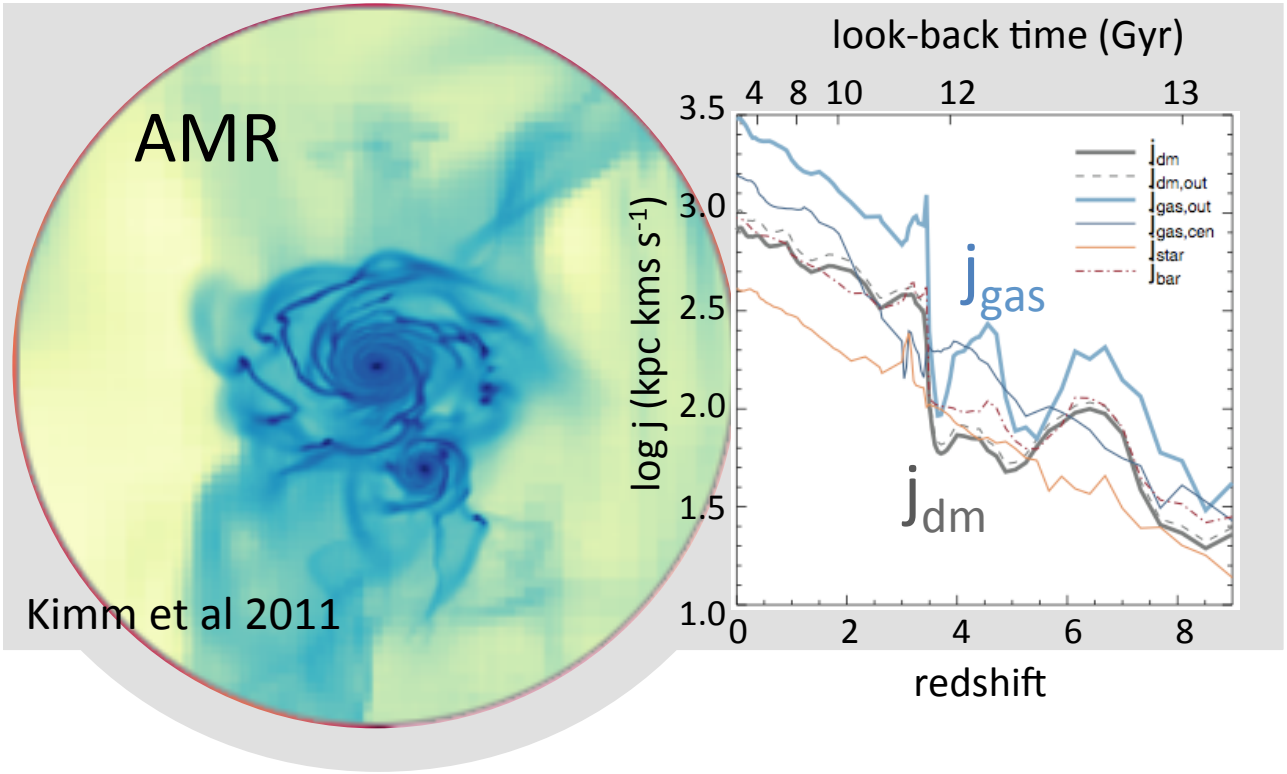




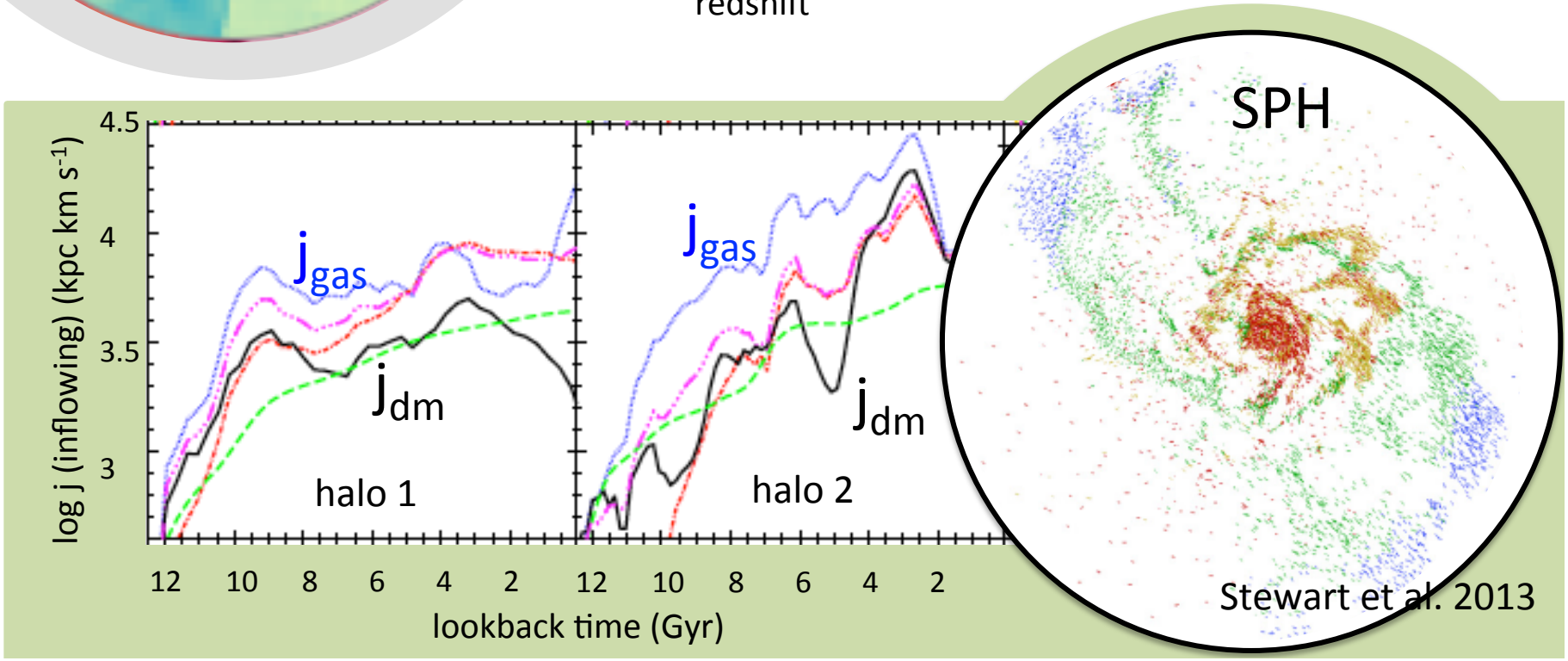
Kimm et al 2011

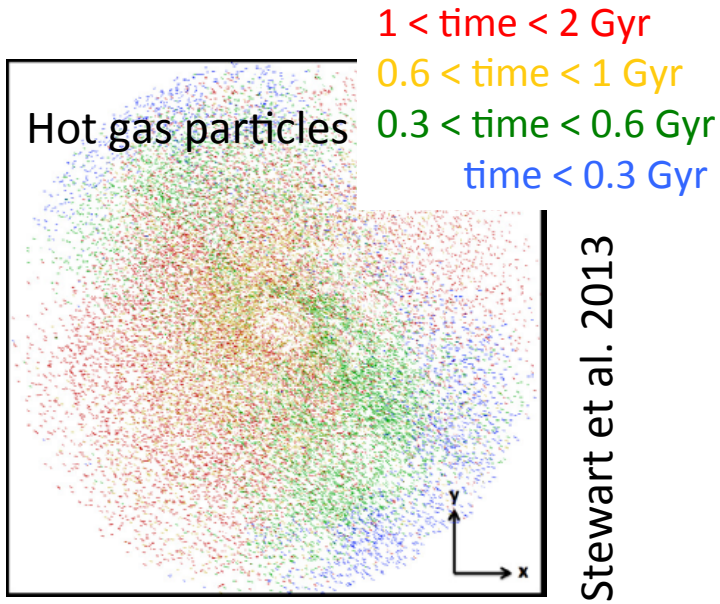


Kimm et al 2011

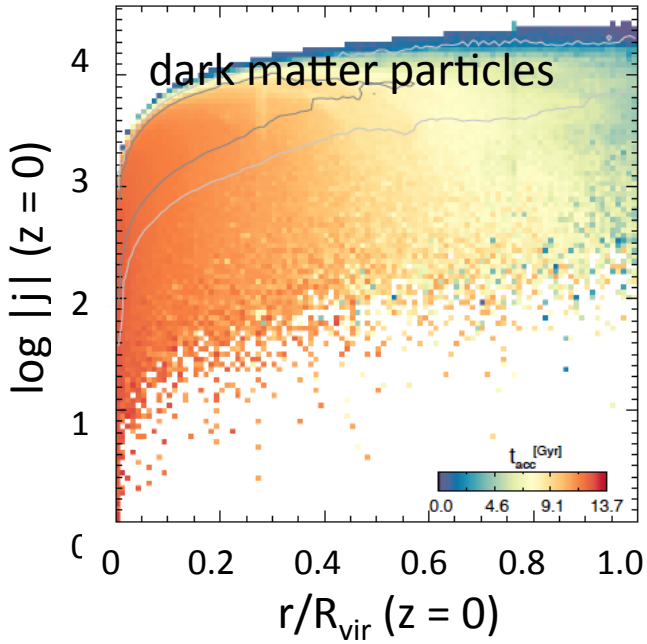


see also Danovich et al. 2014

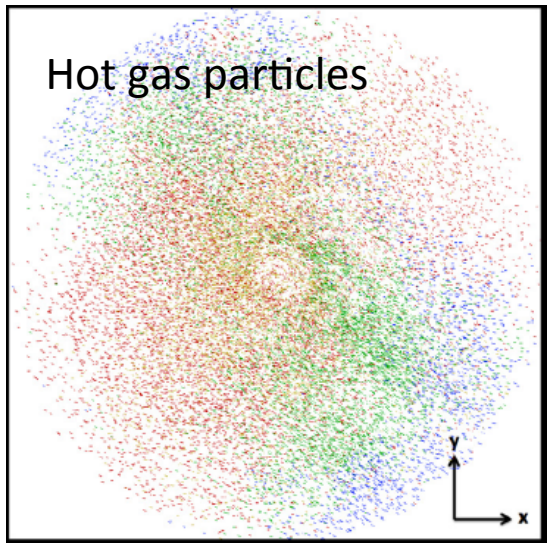




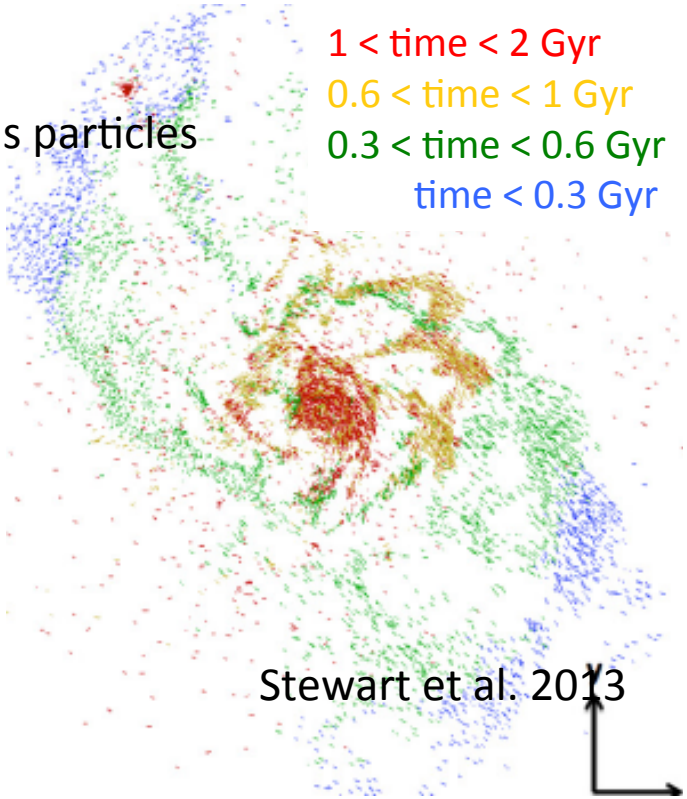
Stewart et al. 2013

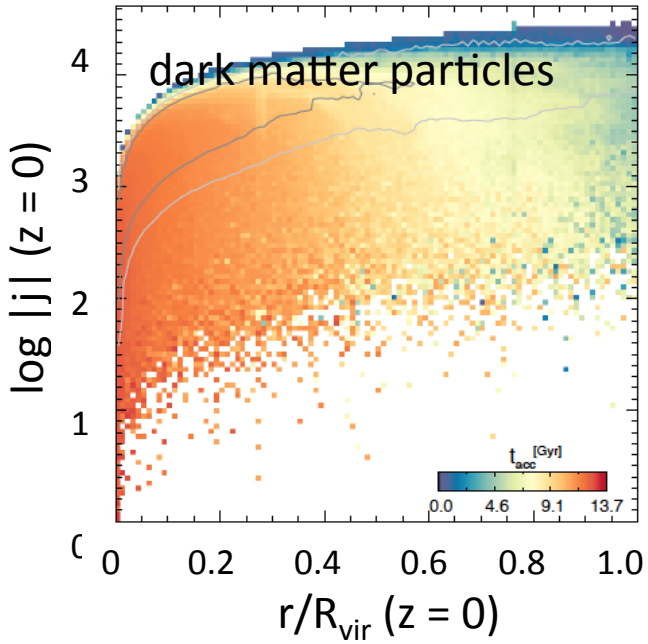


Kimm et al 2011

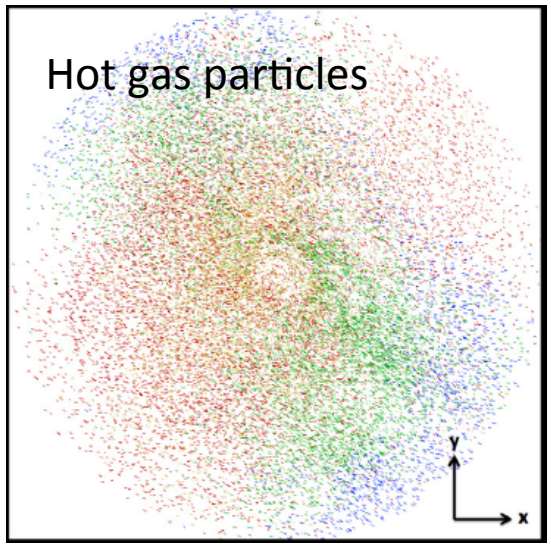


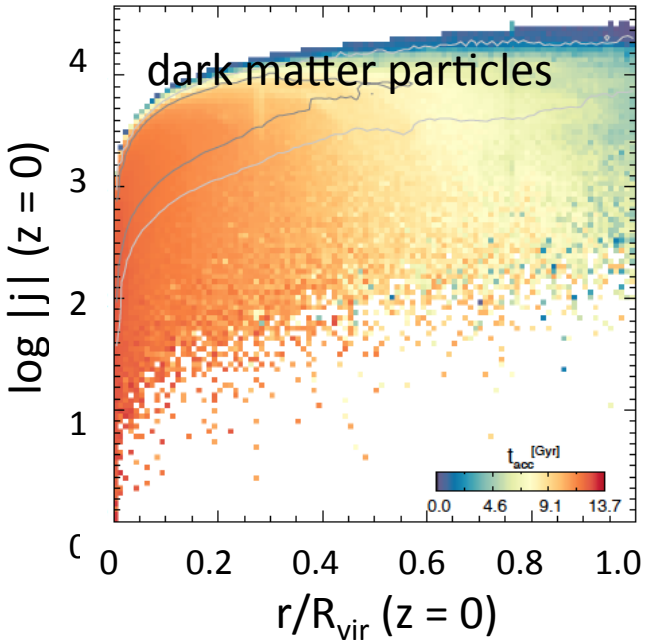
Stewart et al. 2013





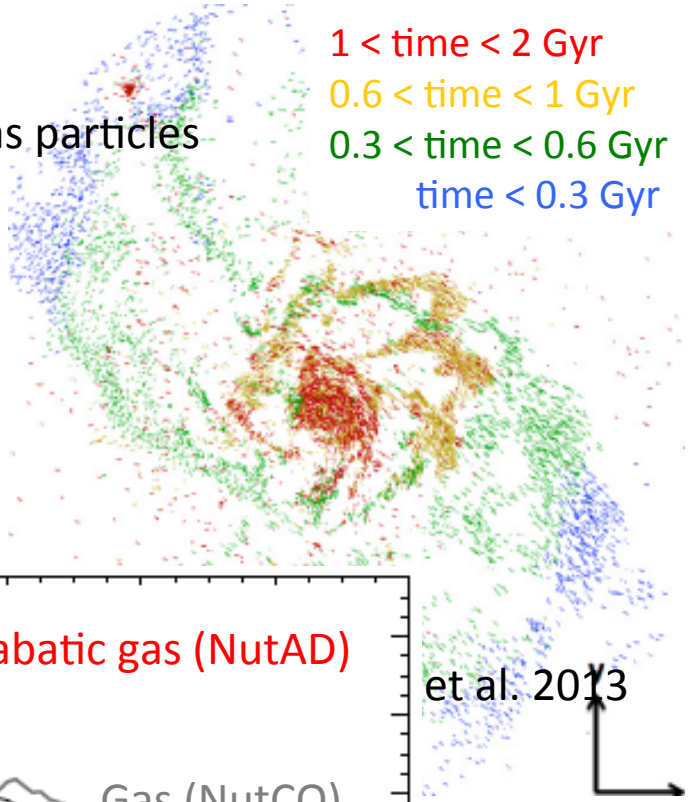
Kimm et al 2011

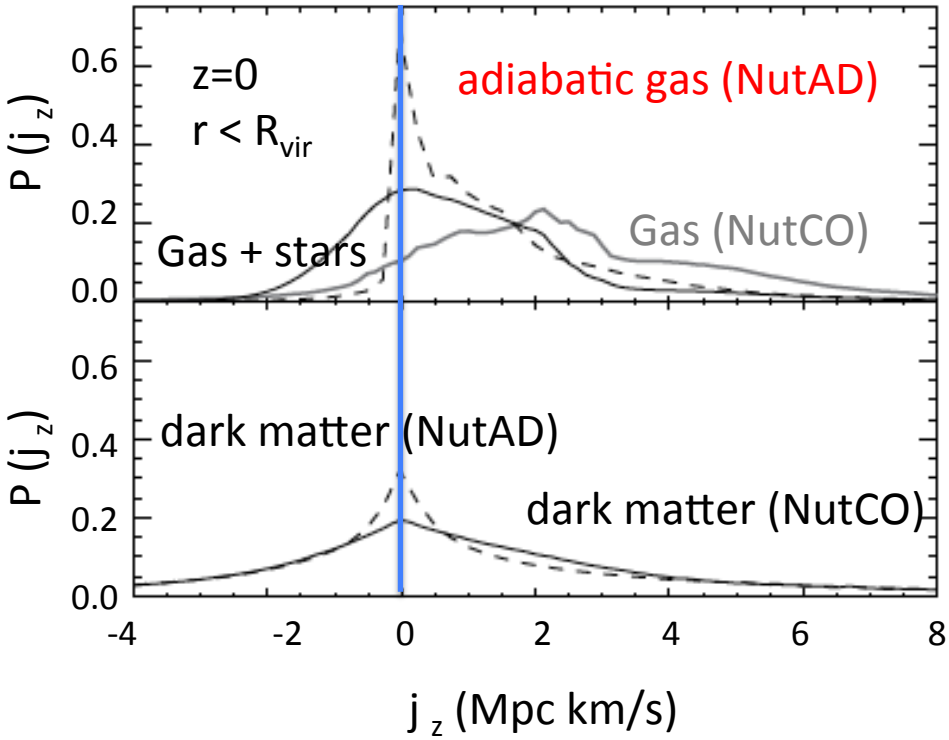




Kimm et al 2011

Stewart et al. 2013

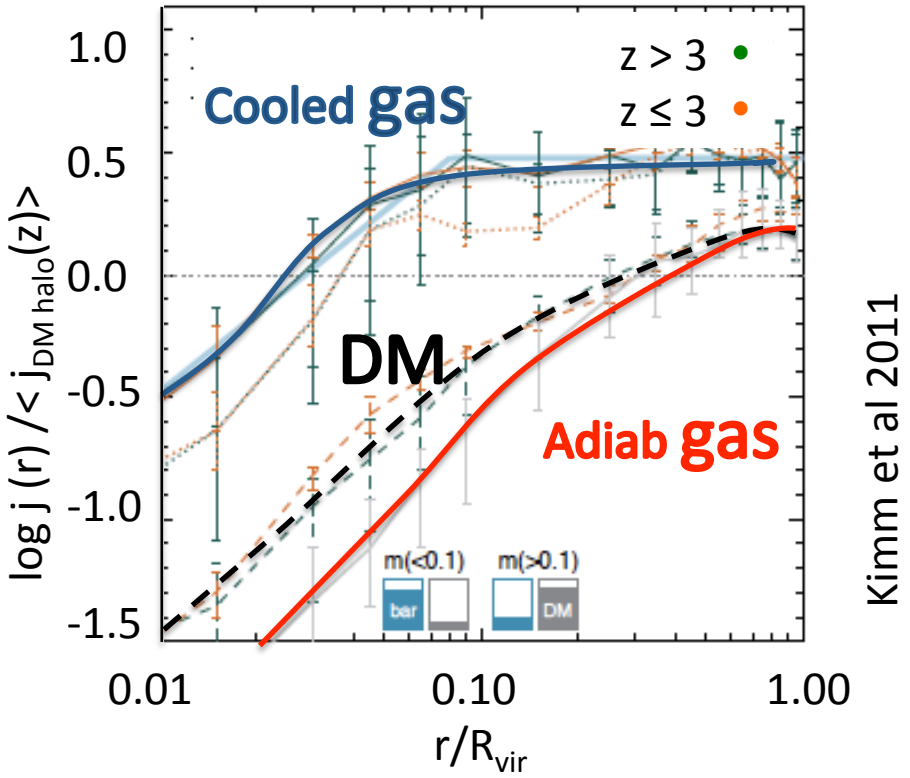




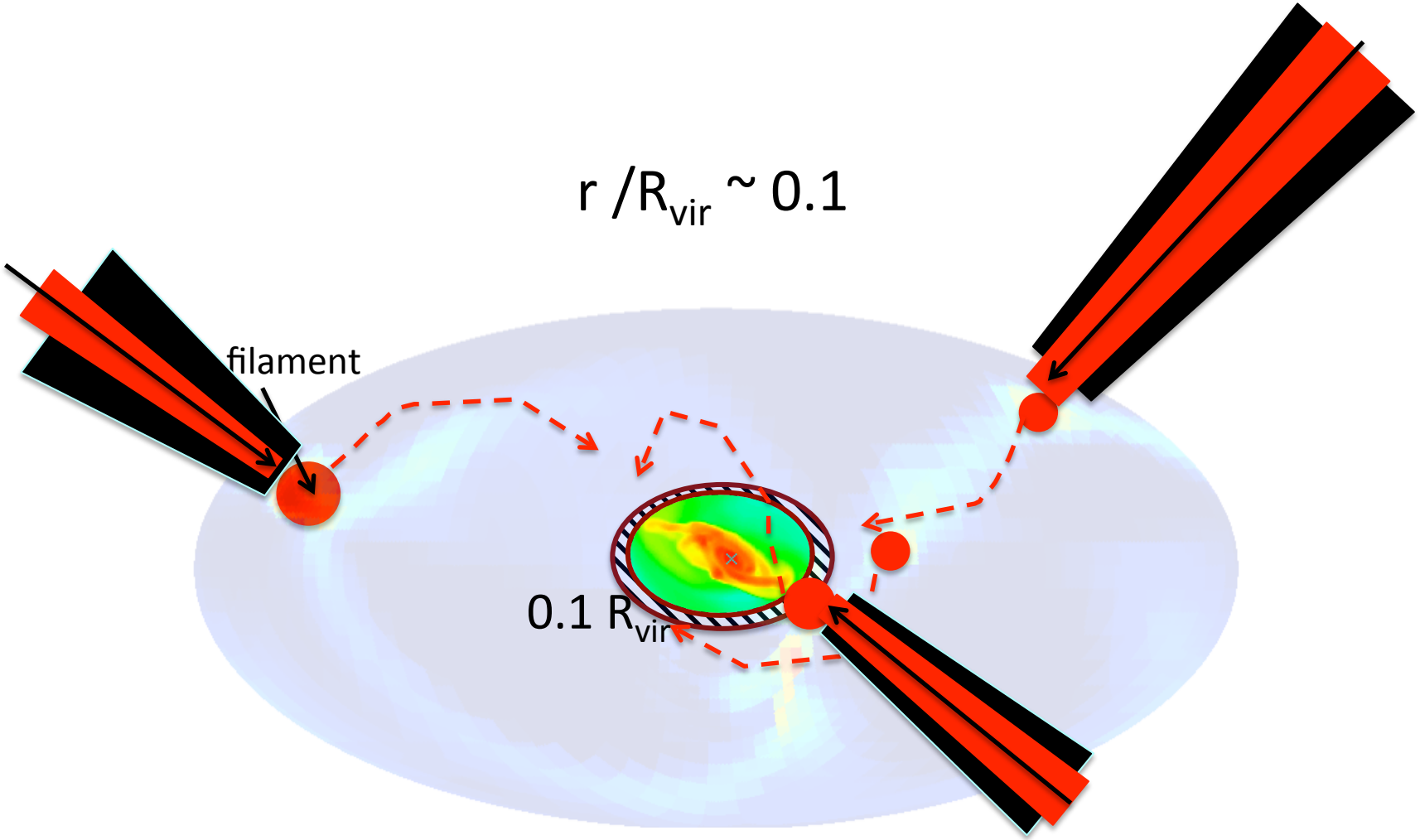
Kimm et al 2011

see also Sharma & Steinmetz2005

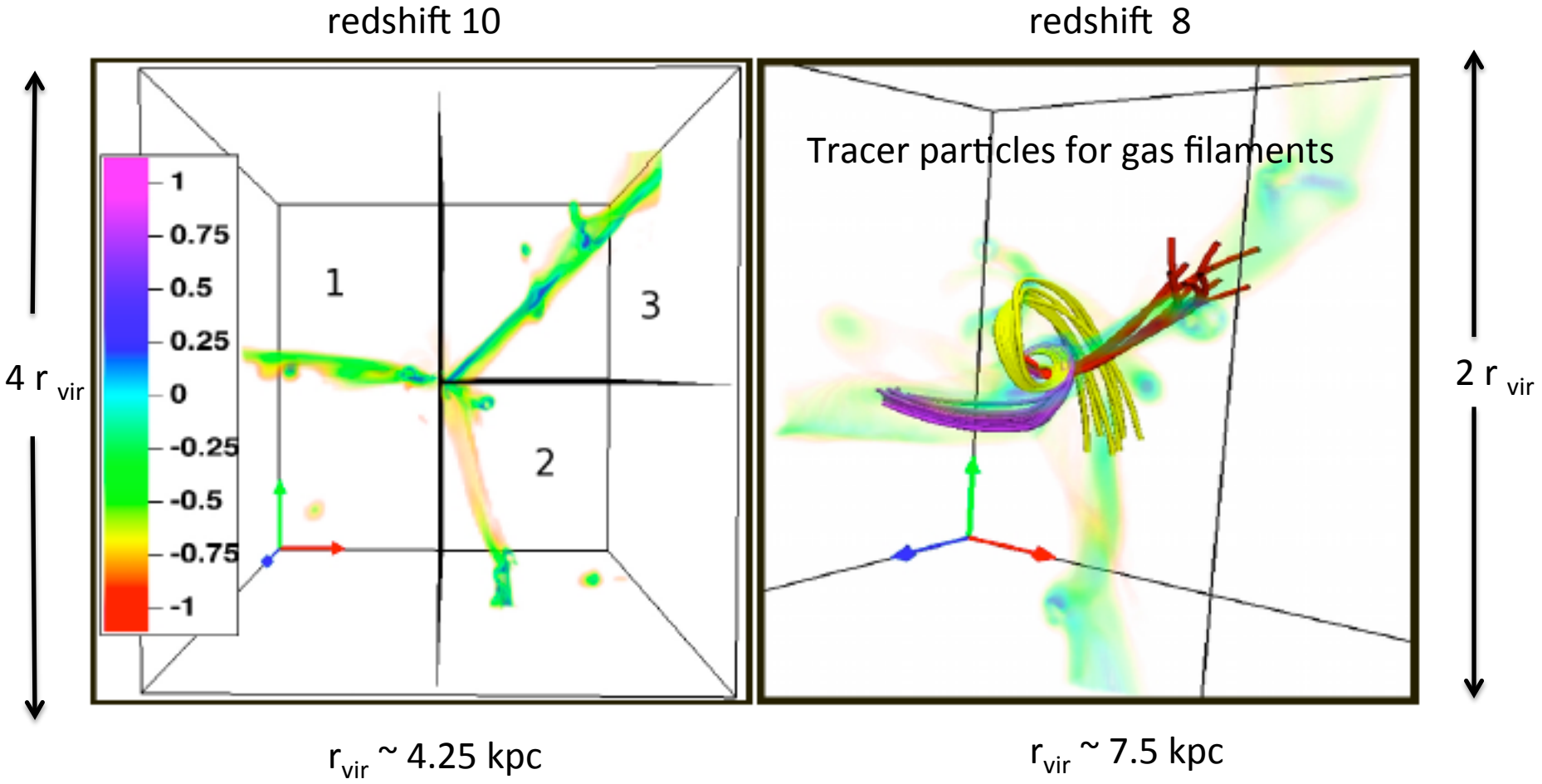
Do dark matter and gas share same specific angular momentum profile?



Stacked specific angular momentum profiles from NutCO & Nut-Adiabatic sims ($\Delta x \sim$ 48 pc)

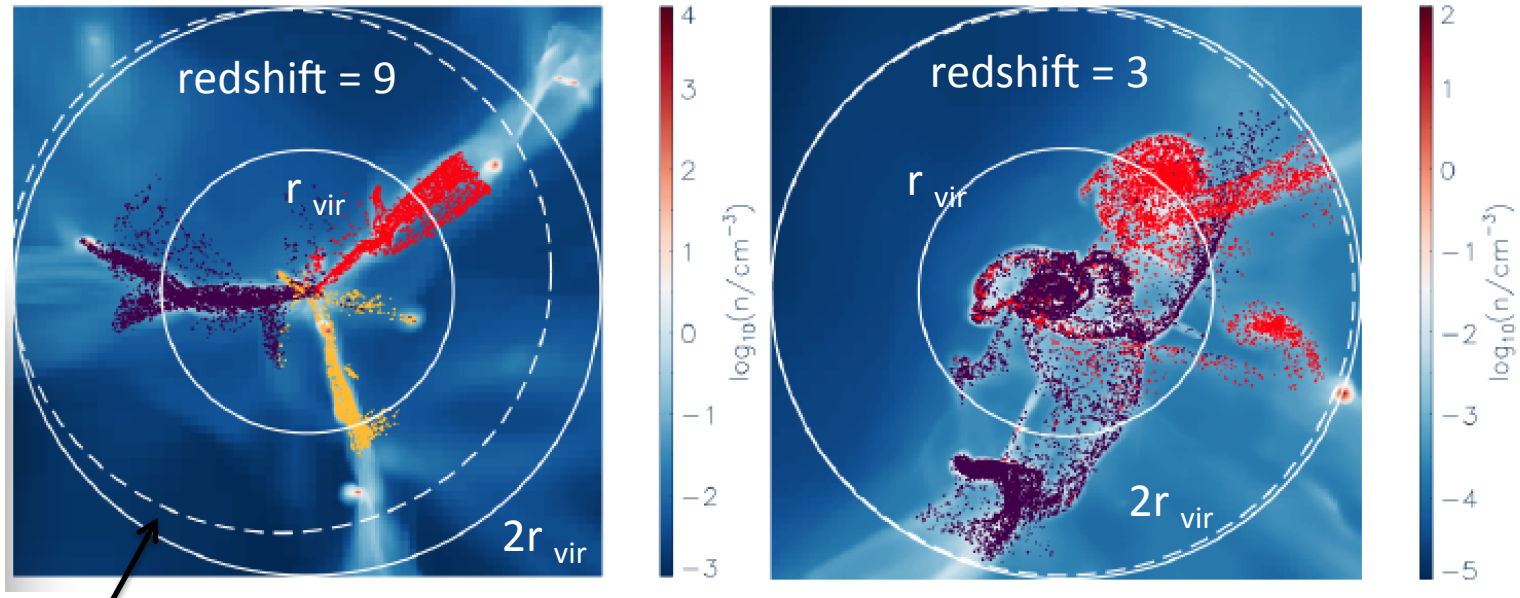

r /R_vir ~ 0.1
filament
0.1 R_vir

How much gas mass and angular momentum enter disk galaxy via filaments?

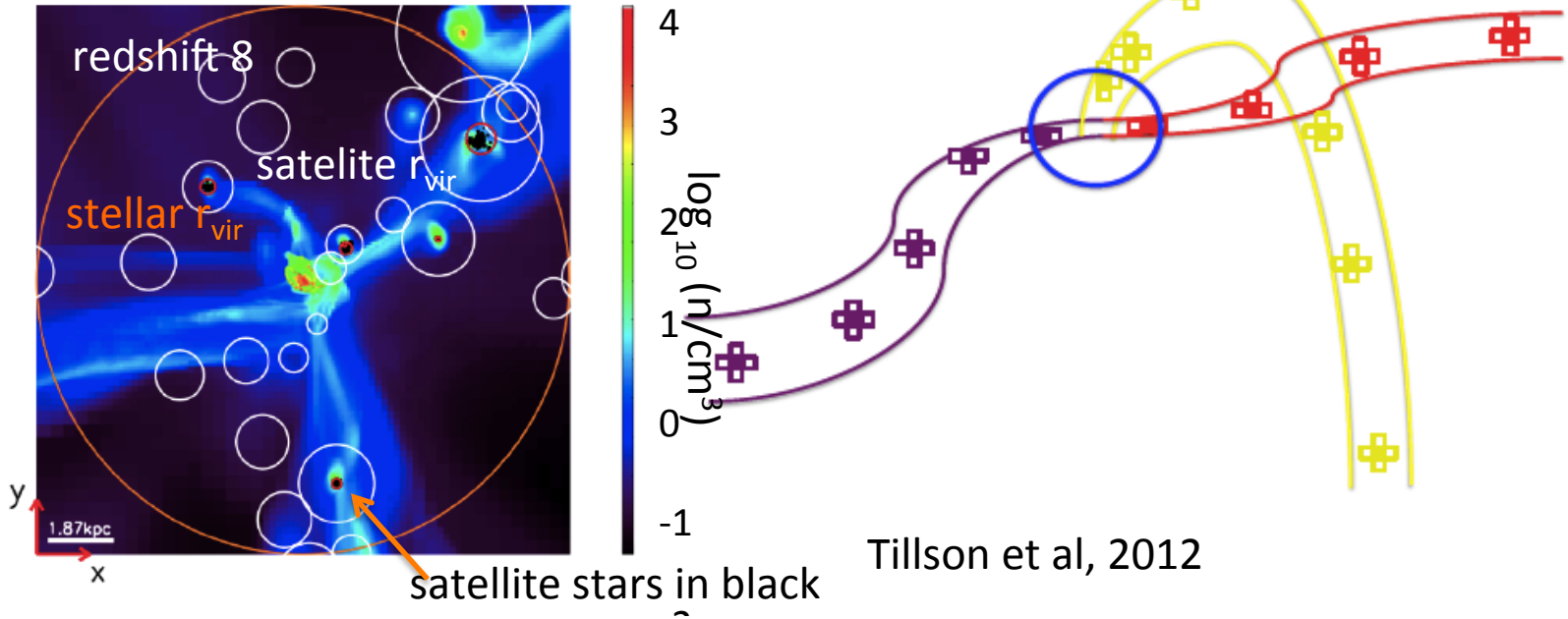


Tillson, Devriendt, Slyz, Miller, Pichon 2012

Tracer particles for gas filaments



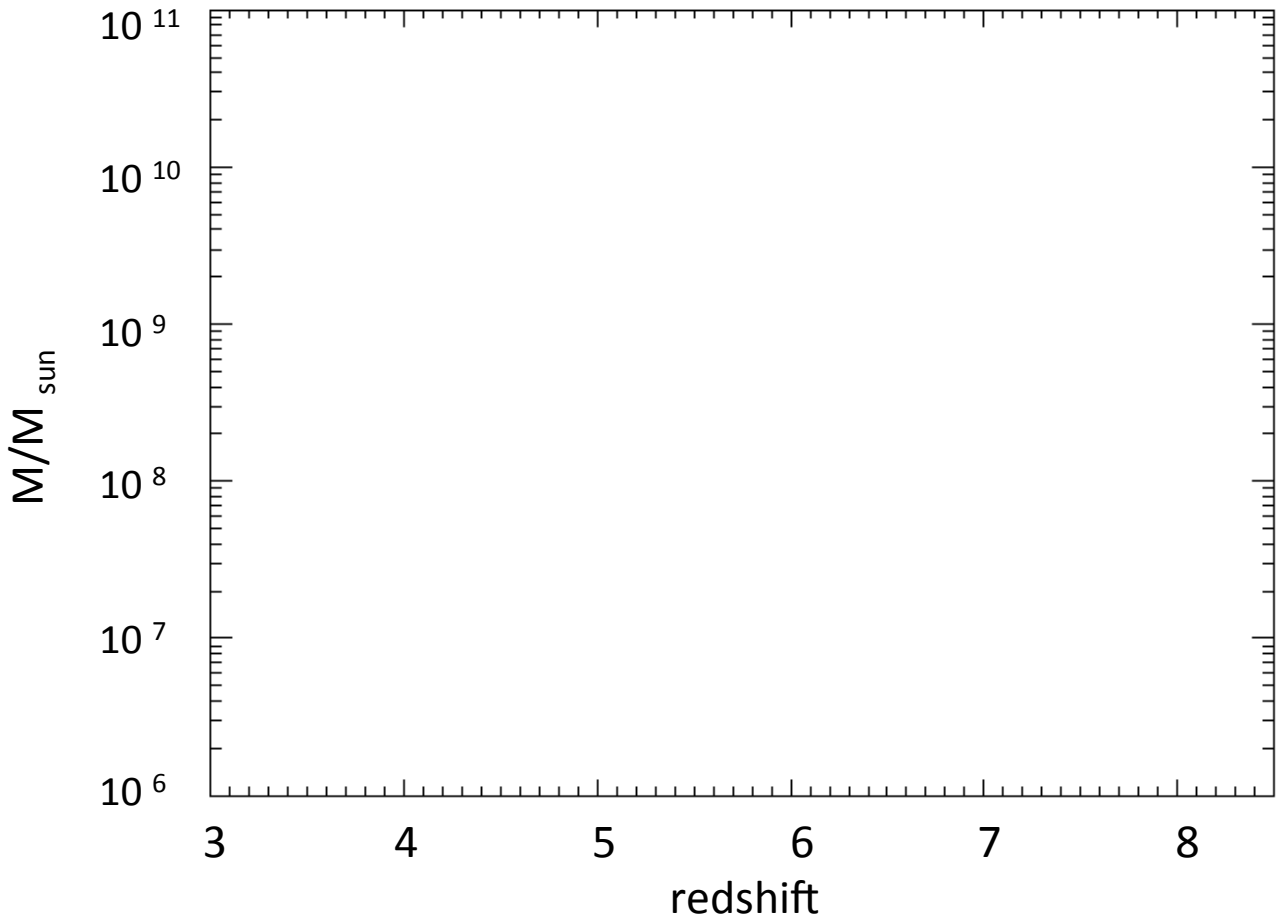
2r $_{vir}$ at previous time output



satellite stars in black

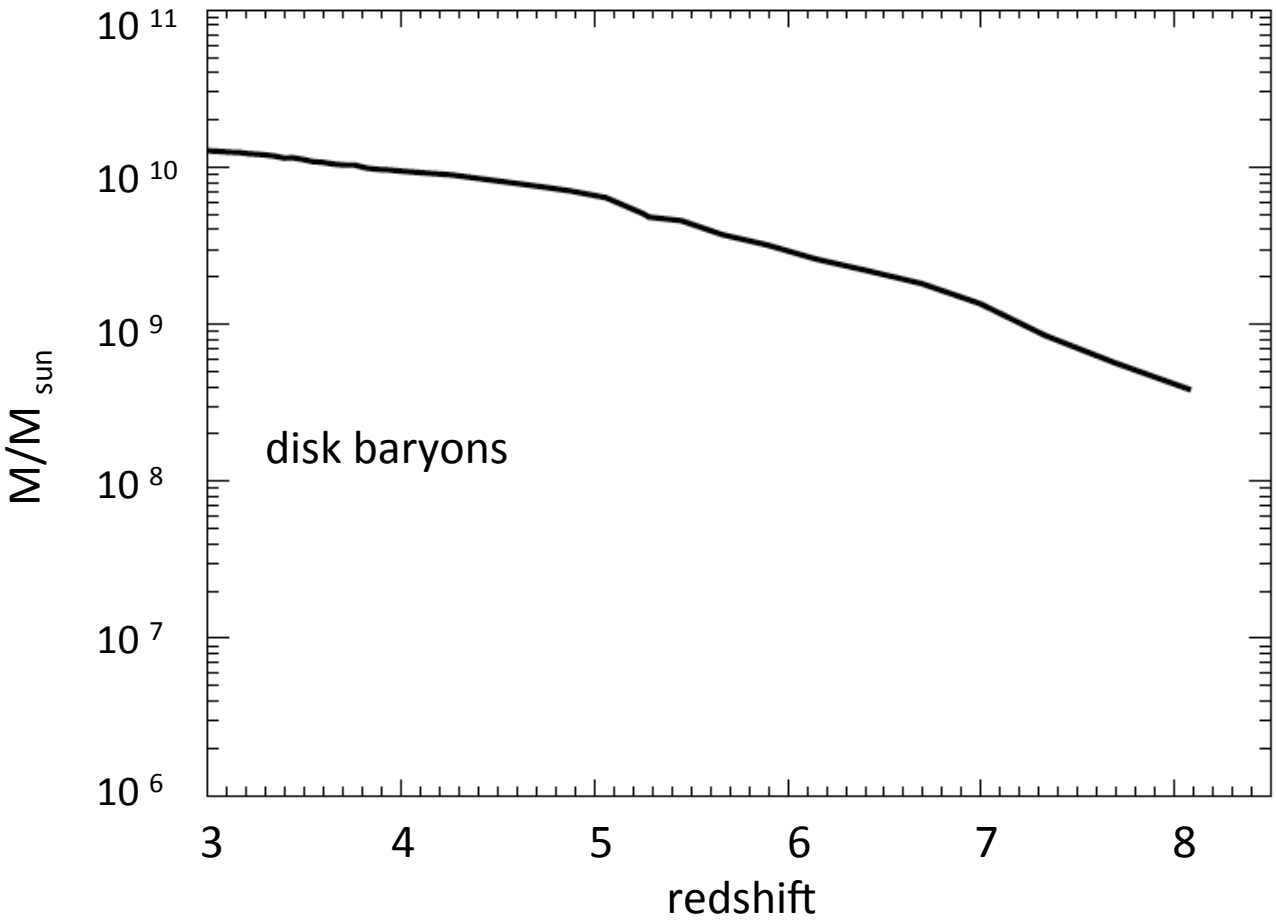
Tillson et al, 2012

What sets the mass budget
of the disk?



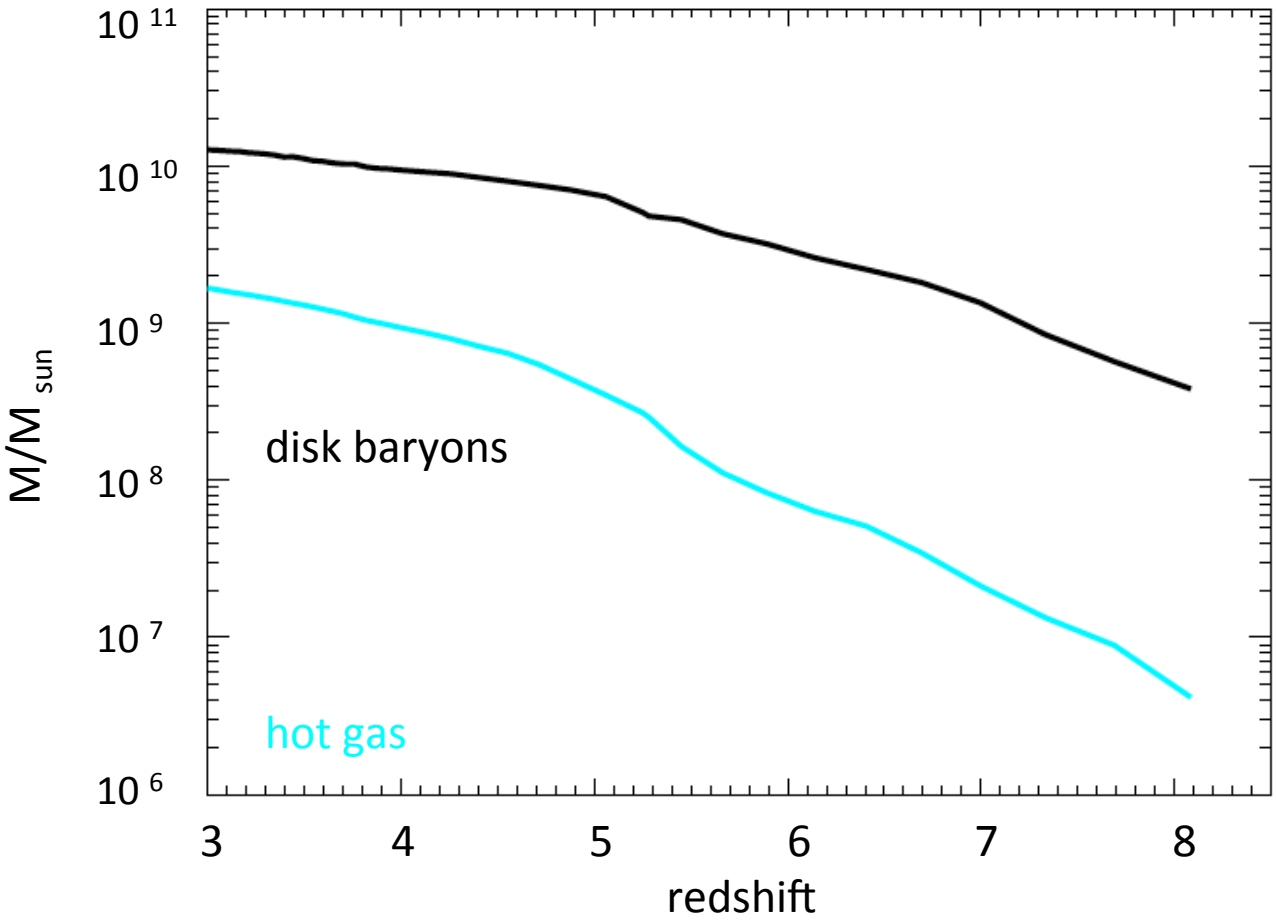
Tillson et al, 2012

What sets the mass budget
of the disk?



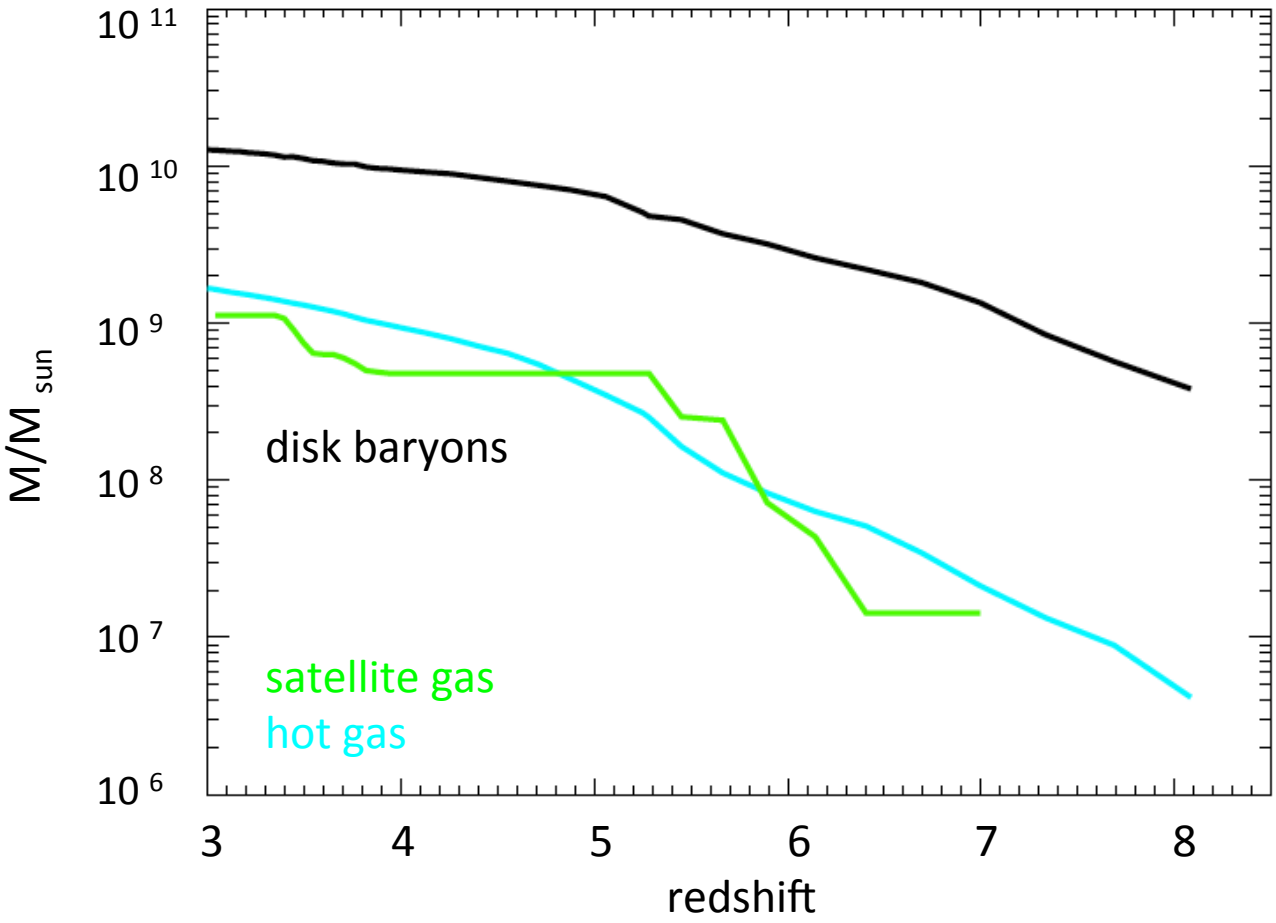
Tillson et al, 2012

What sets the mass budget
of the disk?



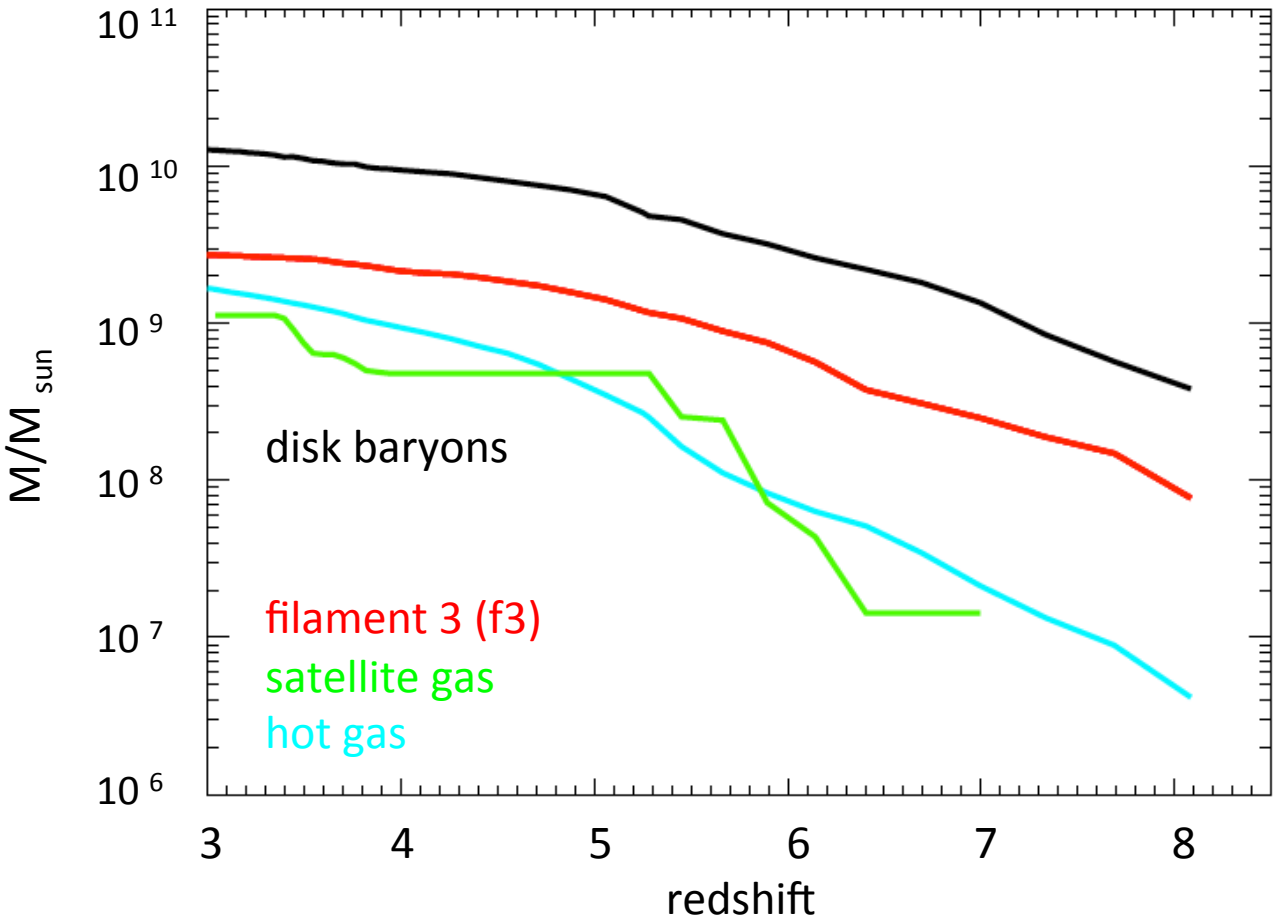
Tillson et al, 2012

What sets the mass budget
of the disk?



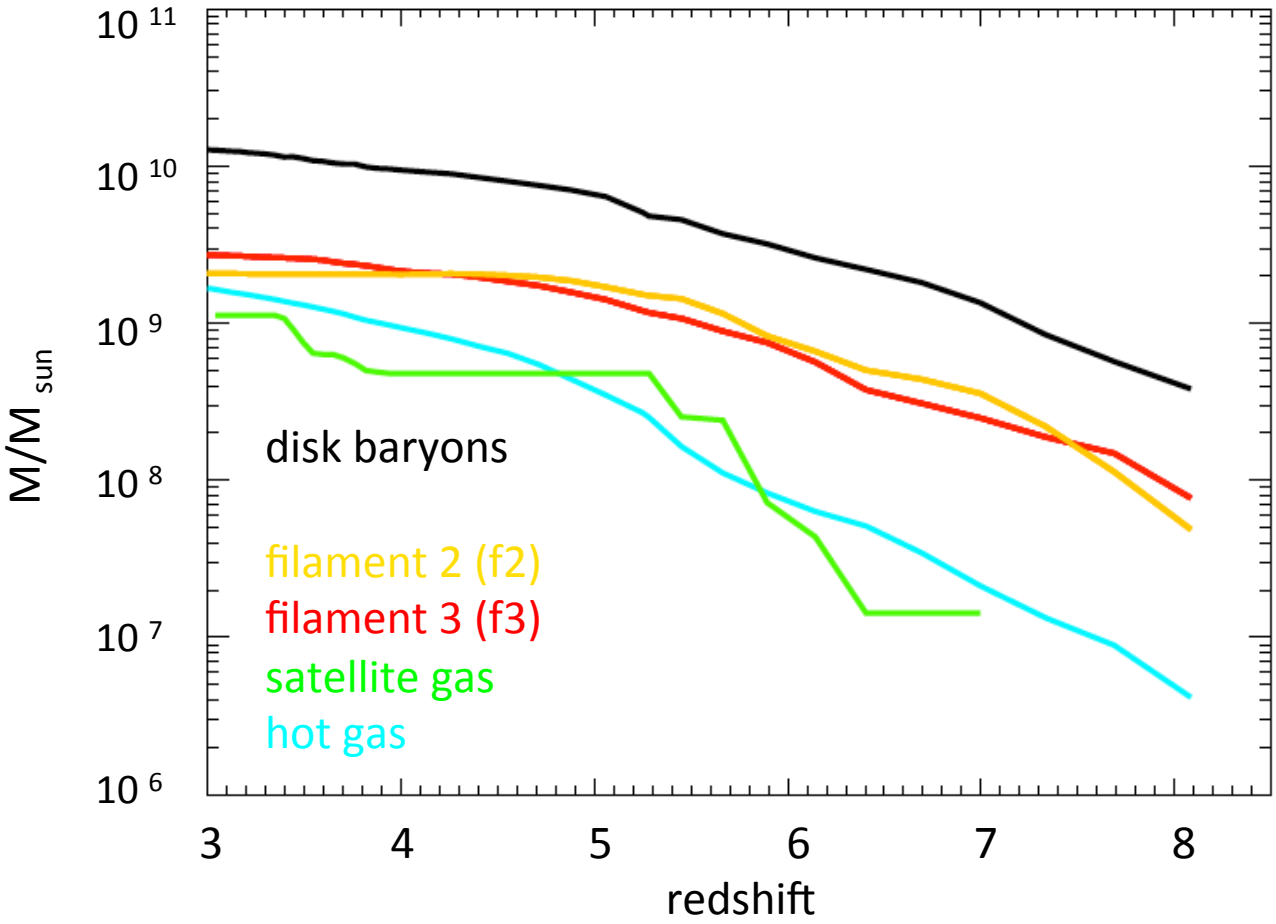
Tillson et al, 2012

What sets the mass budget
of the disk?



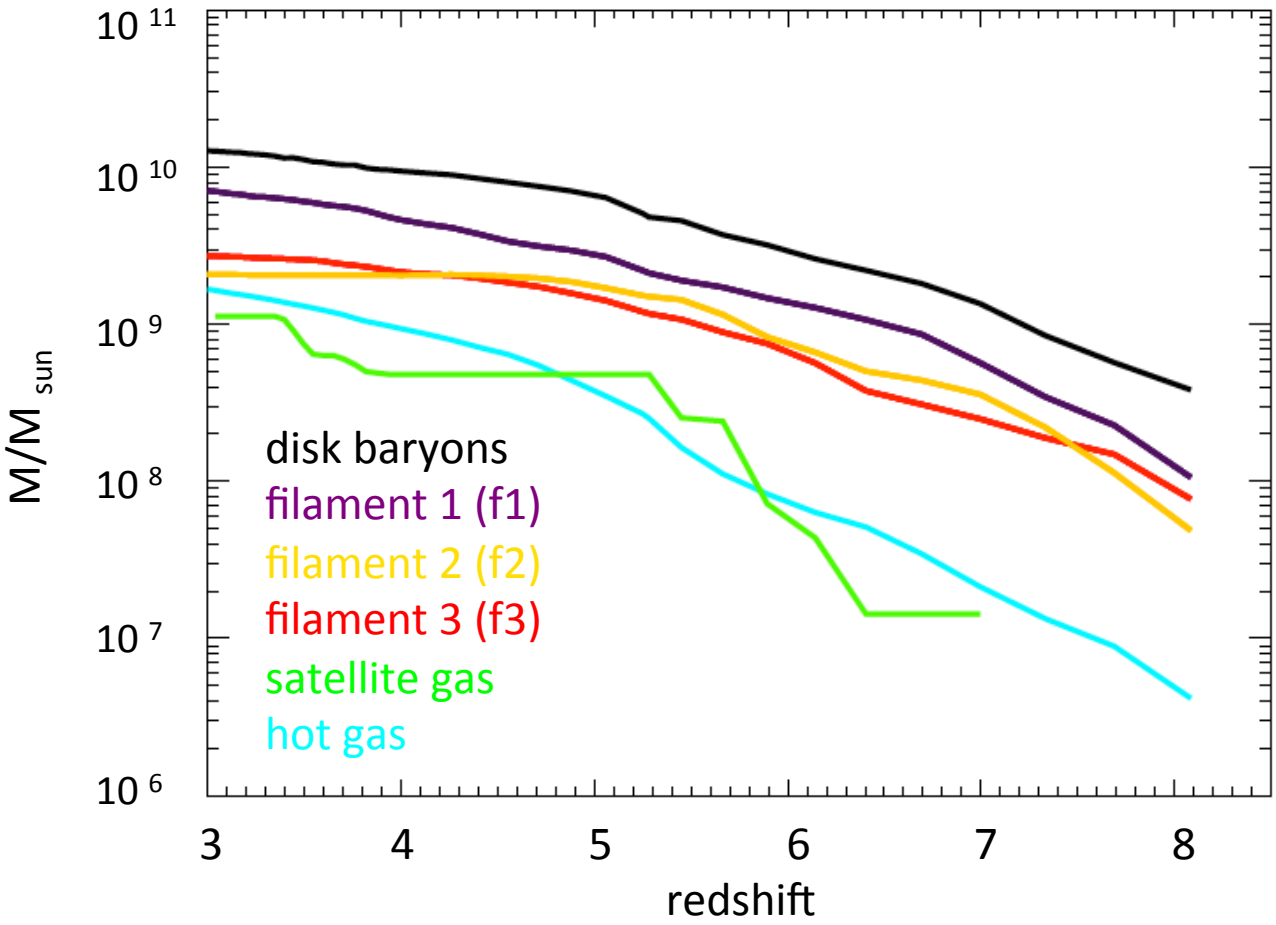
Tillson et al, 2012

What sets the mass budget
of the disk?

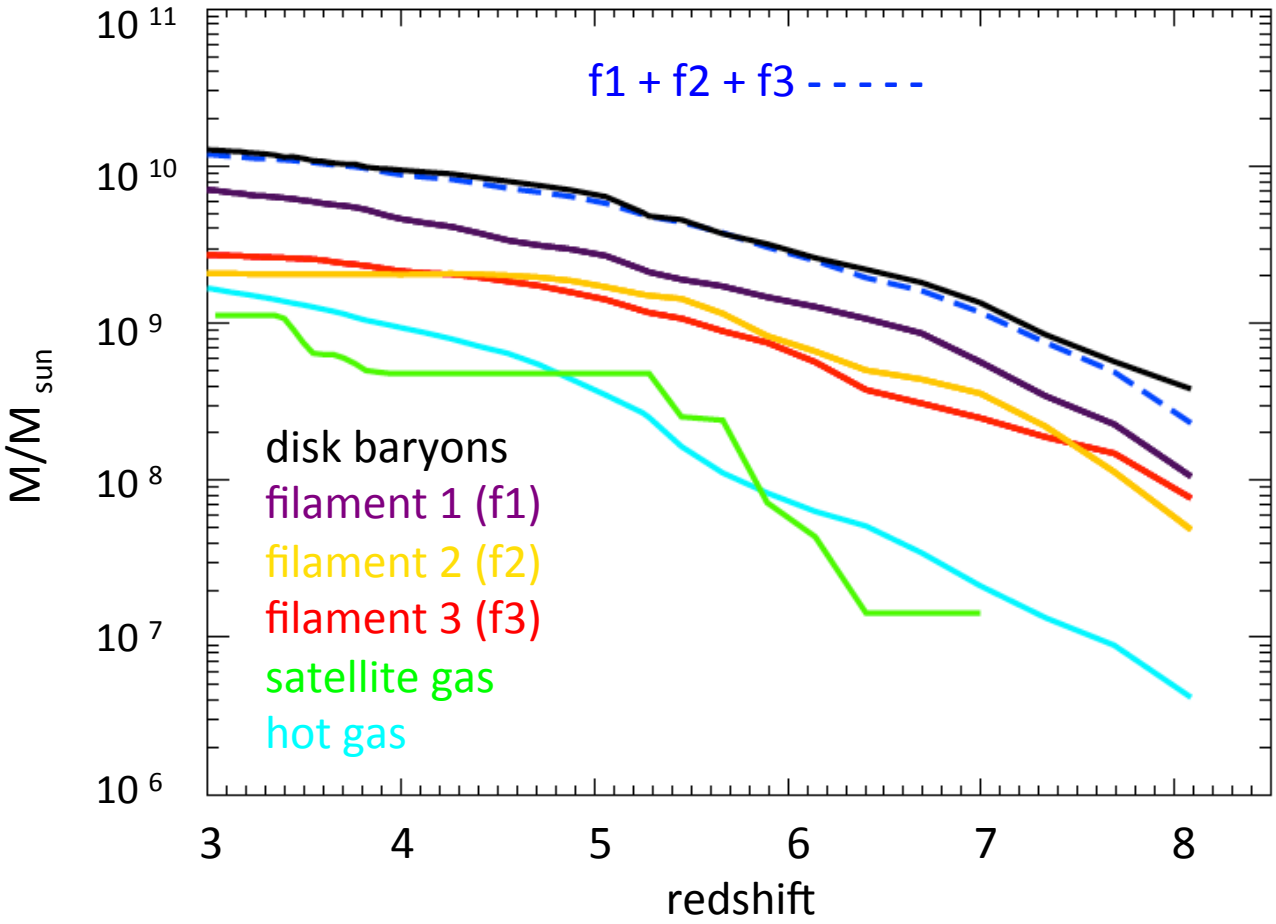


Tillson et al, 2012

What sets the mass budget
of the disk?

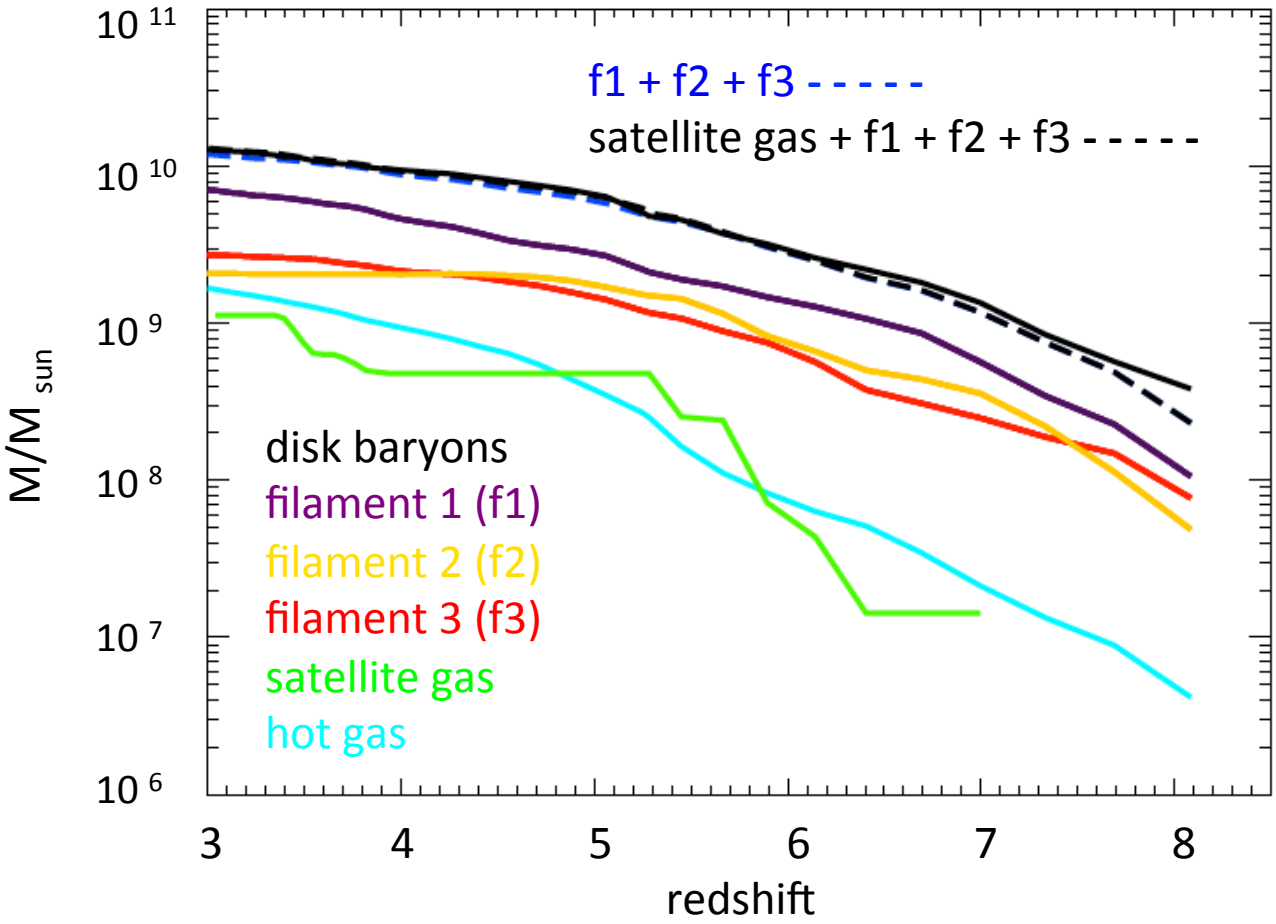


What sets the mass budget
of the disk?



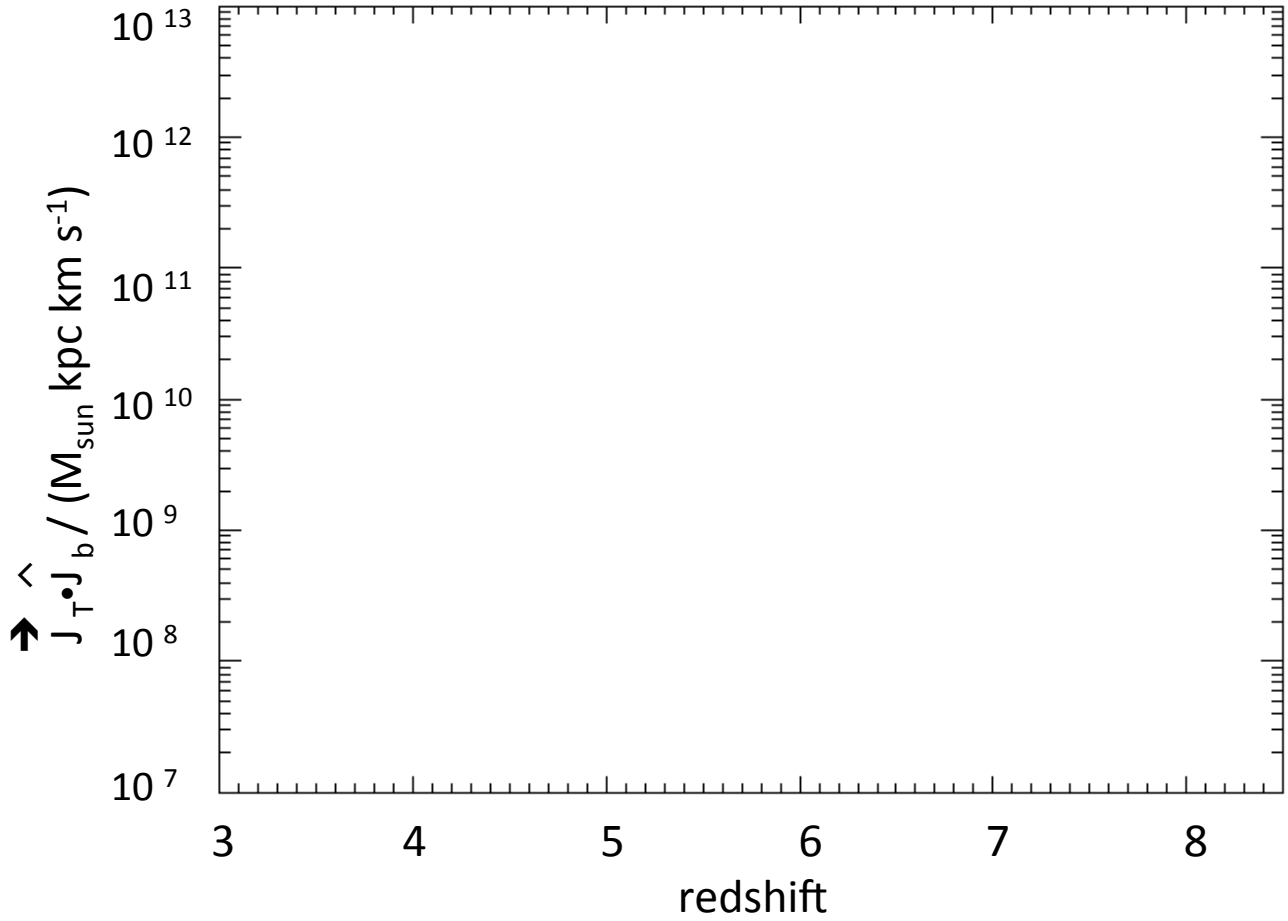
Tillson et al, 2012

What sets the mass budget
of the disk?

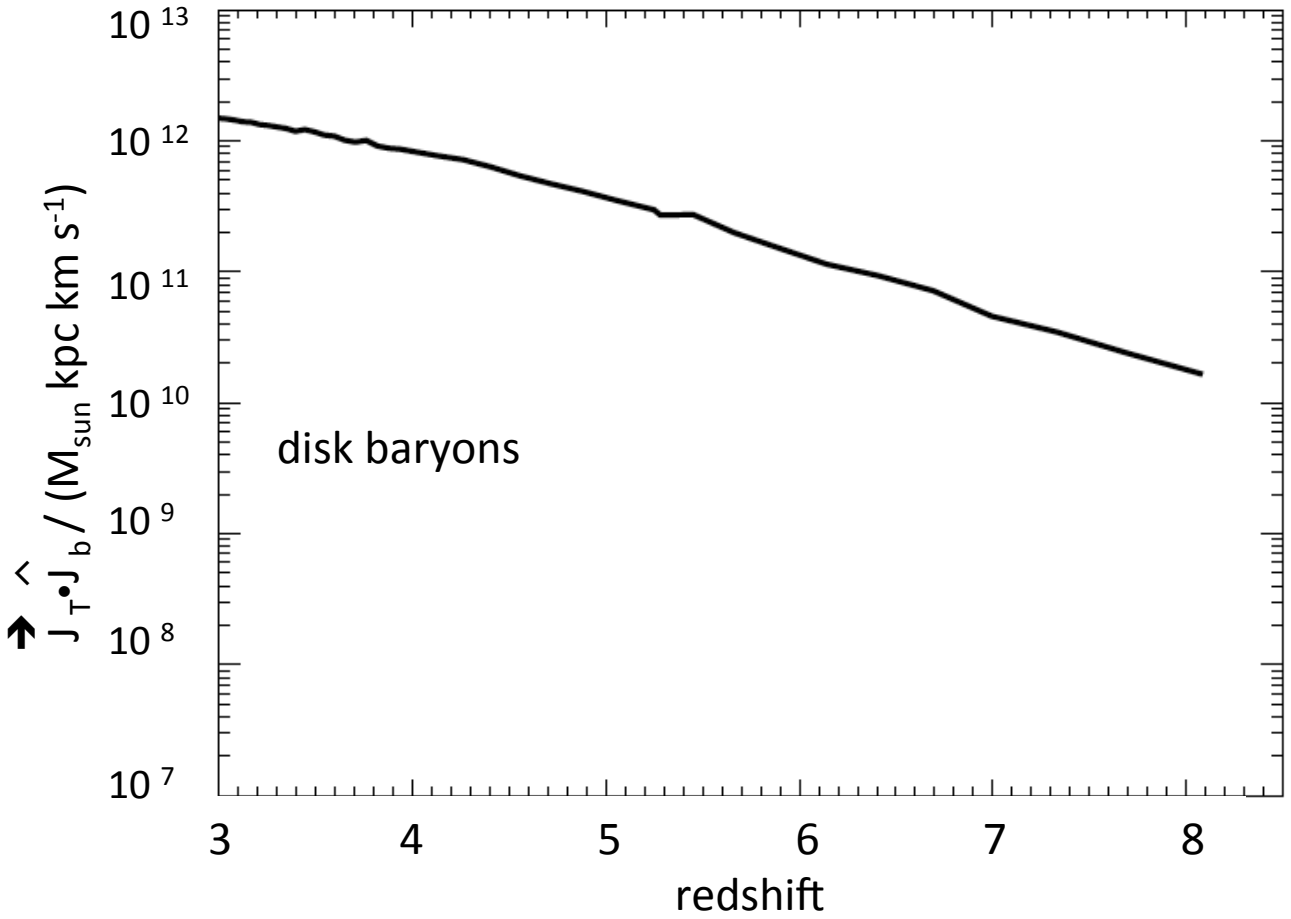


Tillson et al, 2012

What sets the angular momentum budget of the disk?

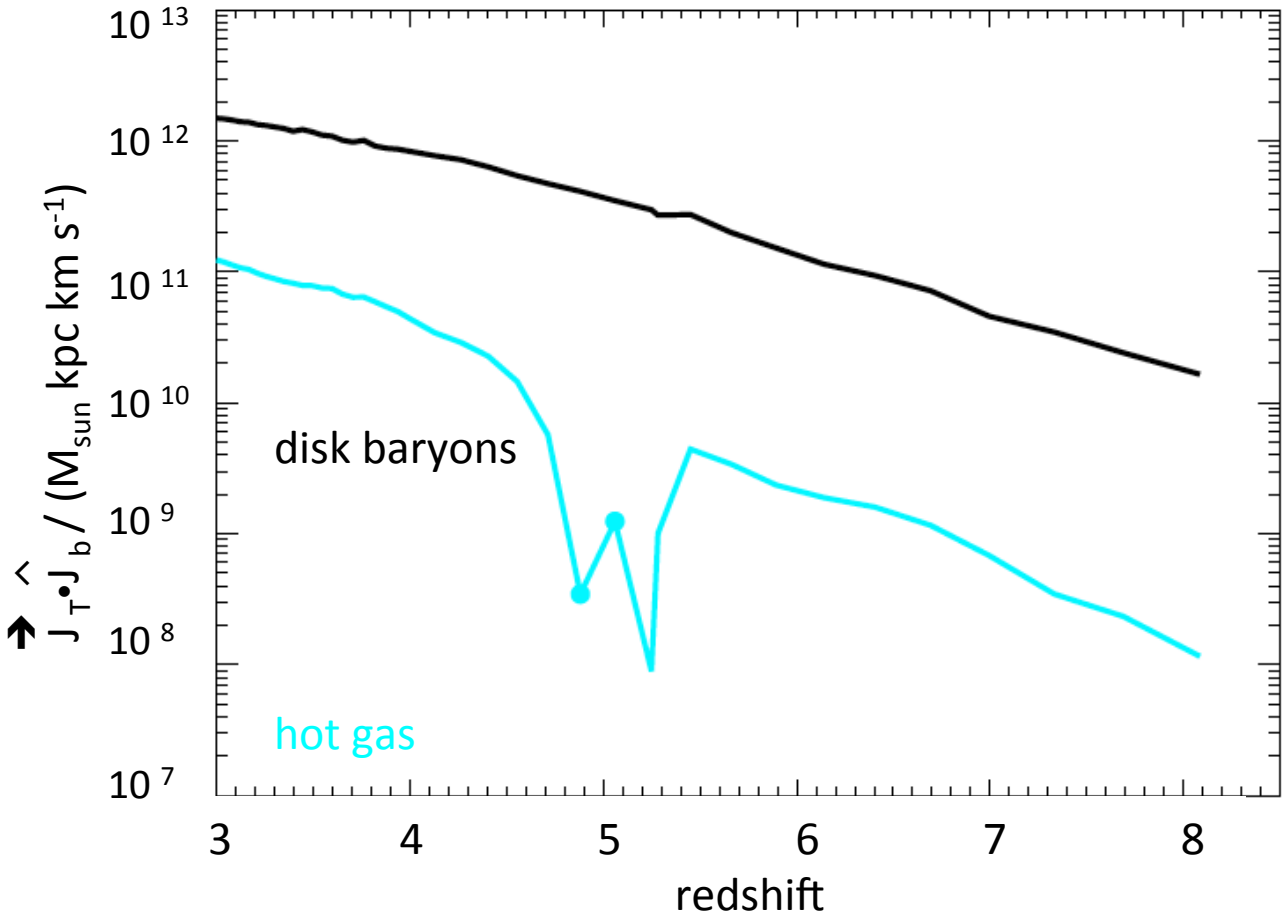


What sets the angular momentum budget of the disk?



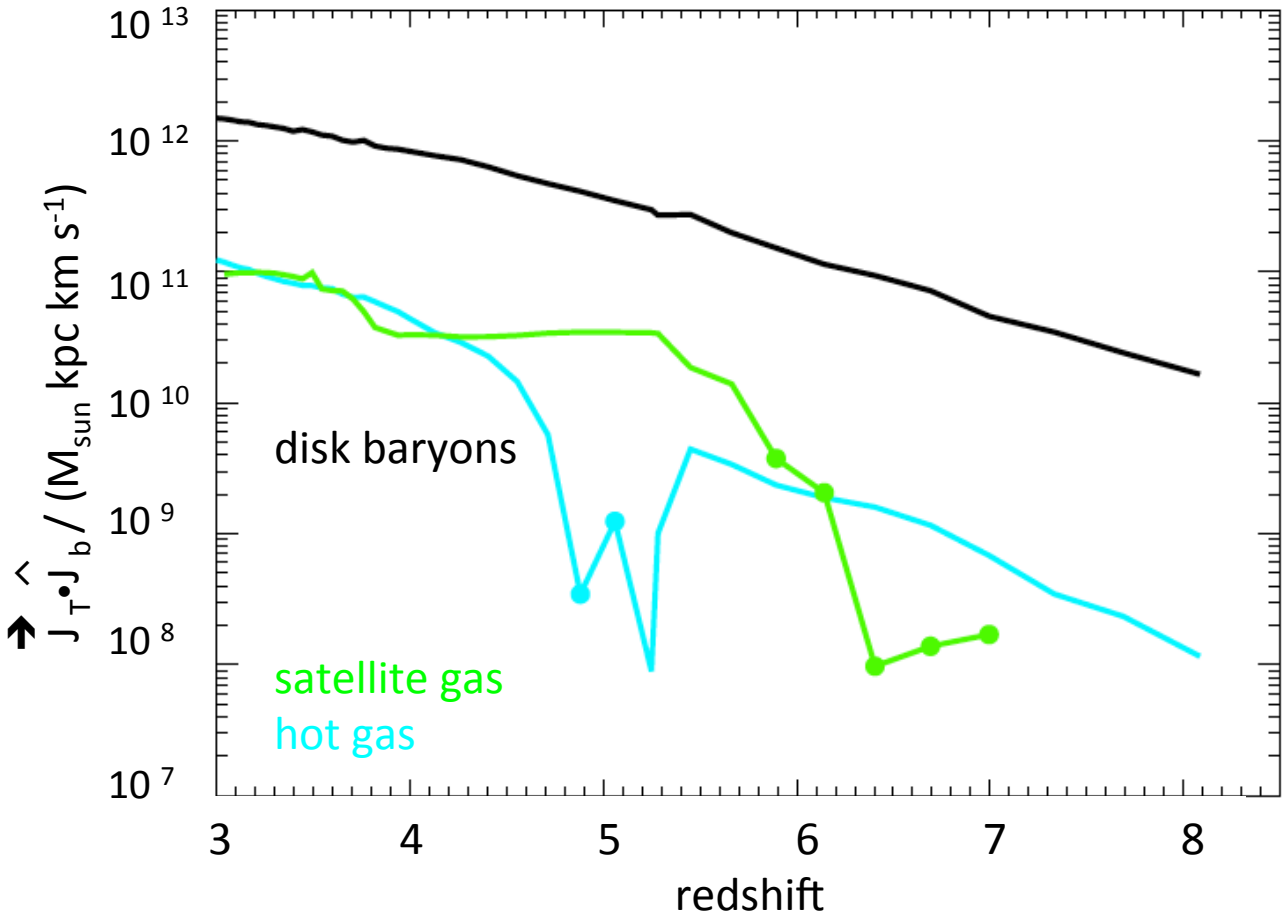
Tillson et al, 2012

What sets the angular momentum budget of the disk?



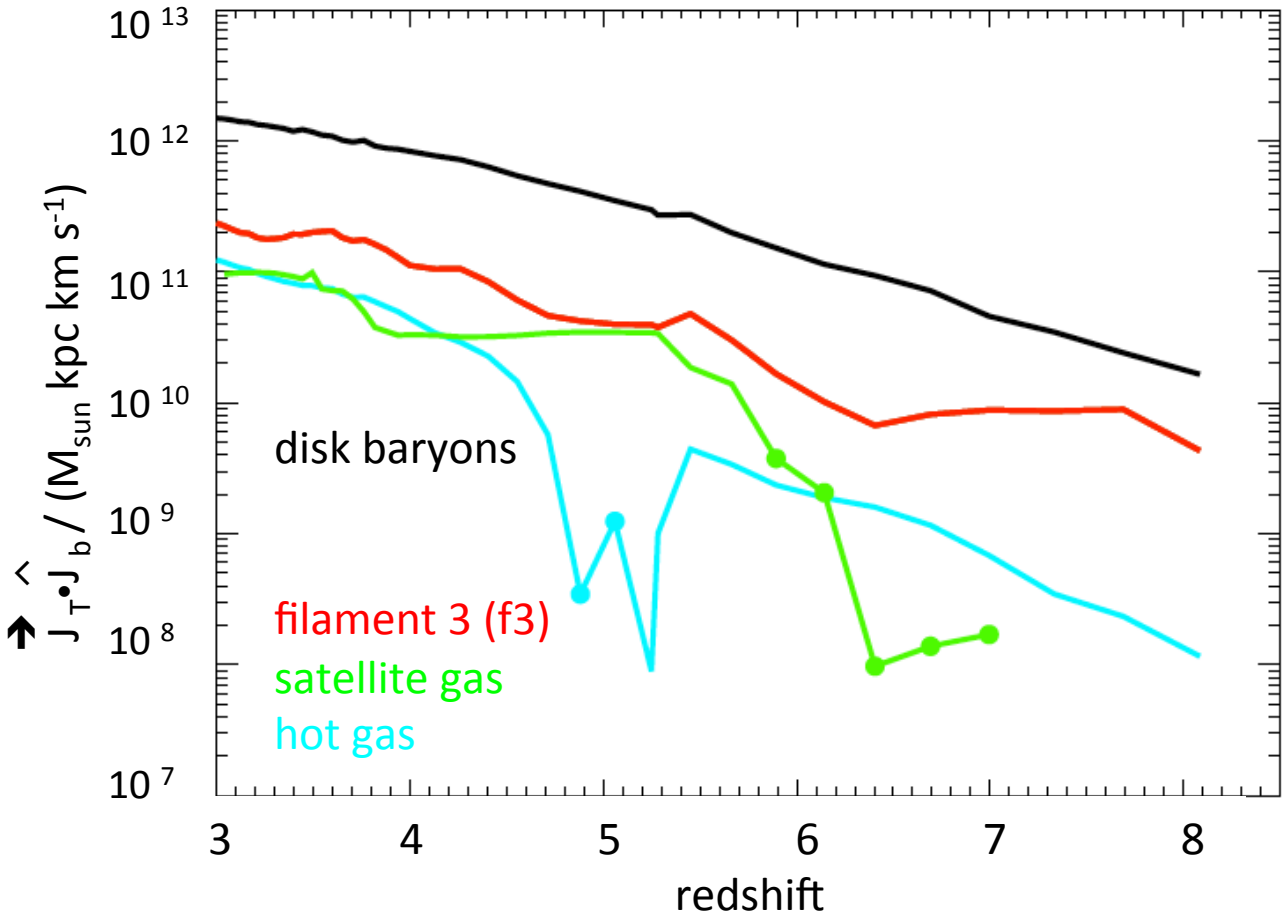
Tillson et al, 2012

What sets the angular momentum budget of the disk?



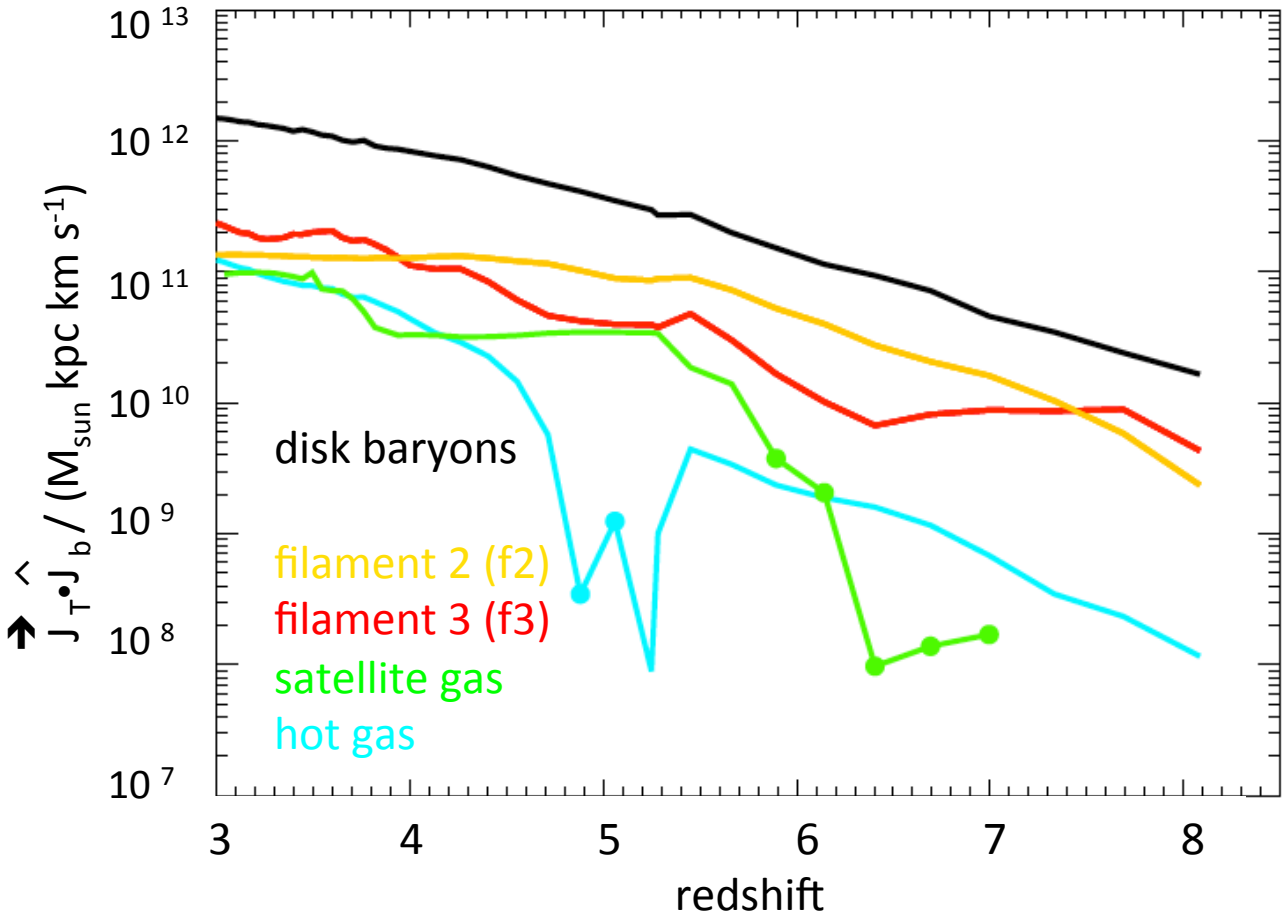
Tillson et al, 2012

What sets the angular momentum budget of the disk?

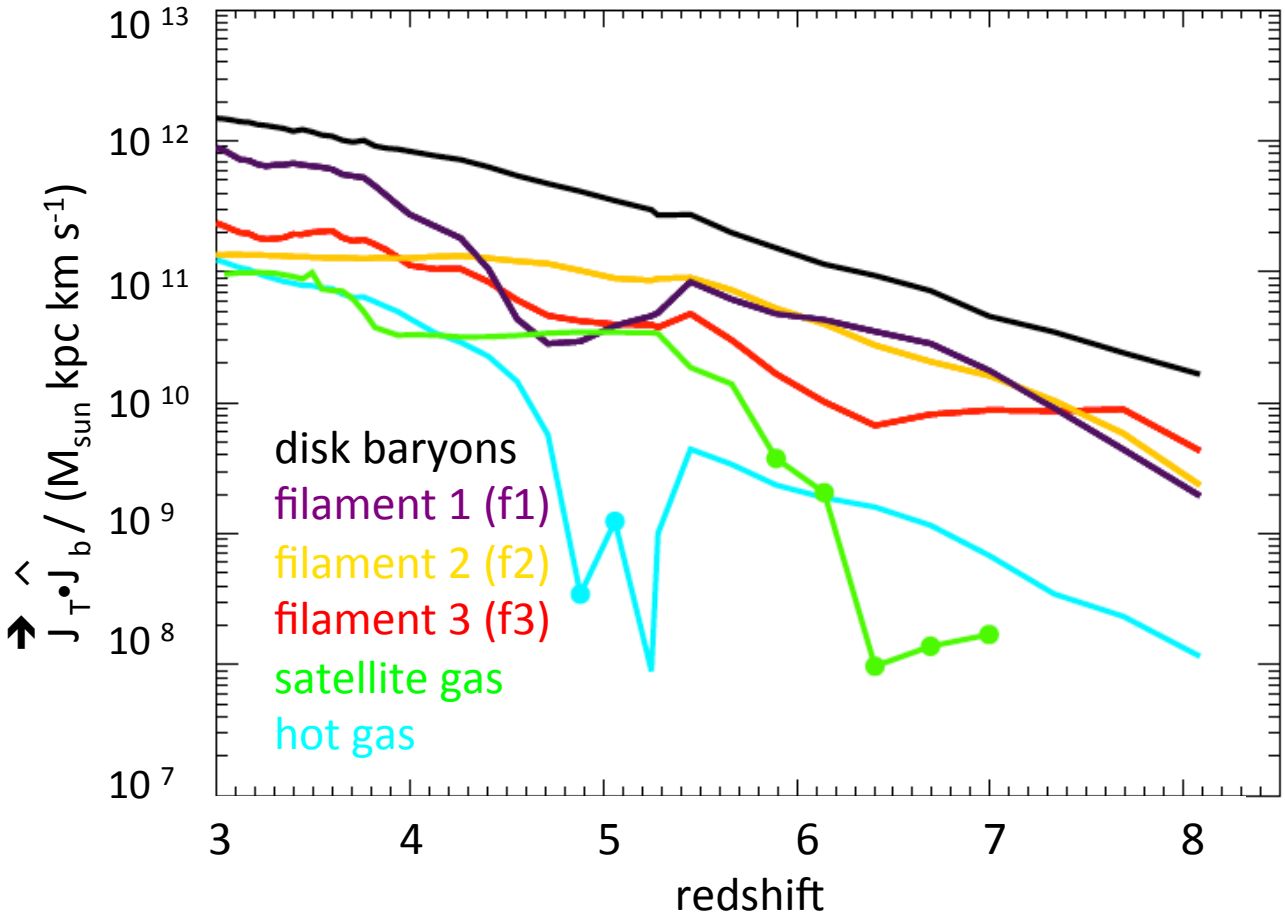


Tillson et al, 2012

What sets the angular momentum budget of the disk?

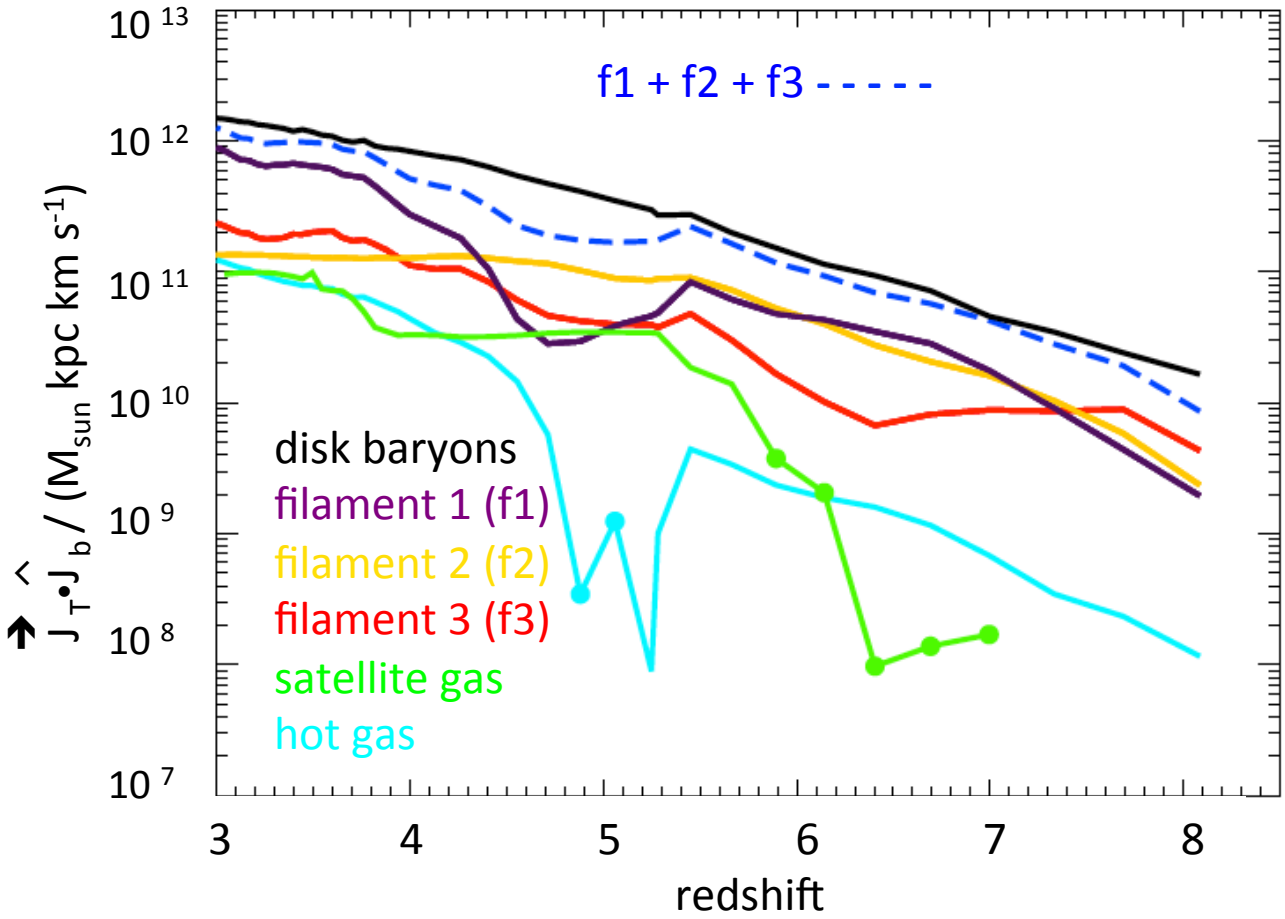


What sets the angular momentum budget of the disk?



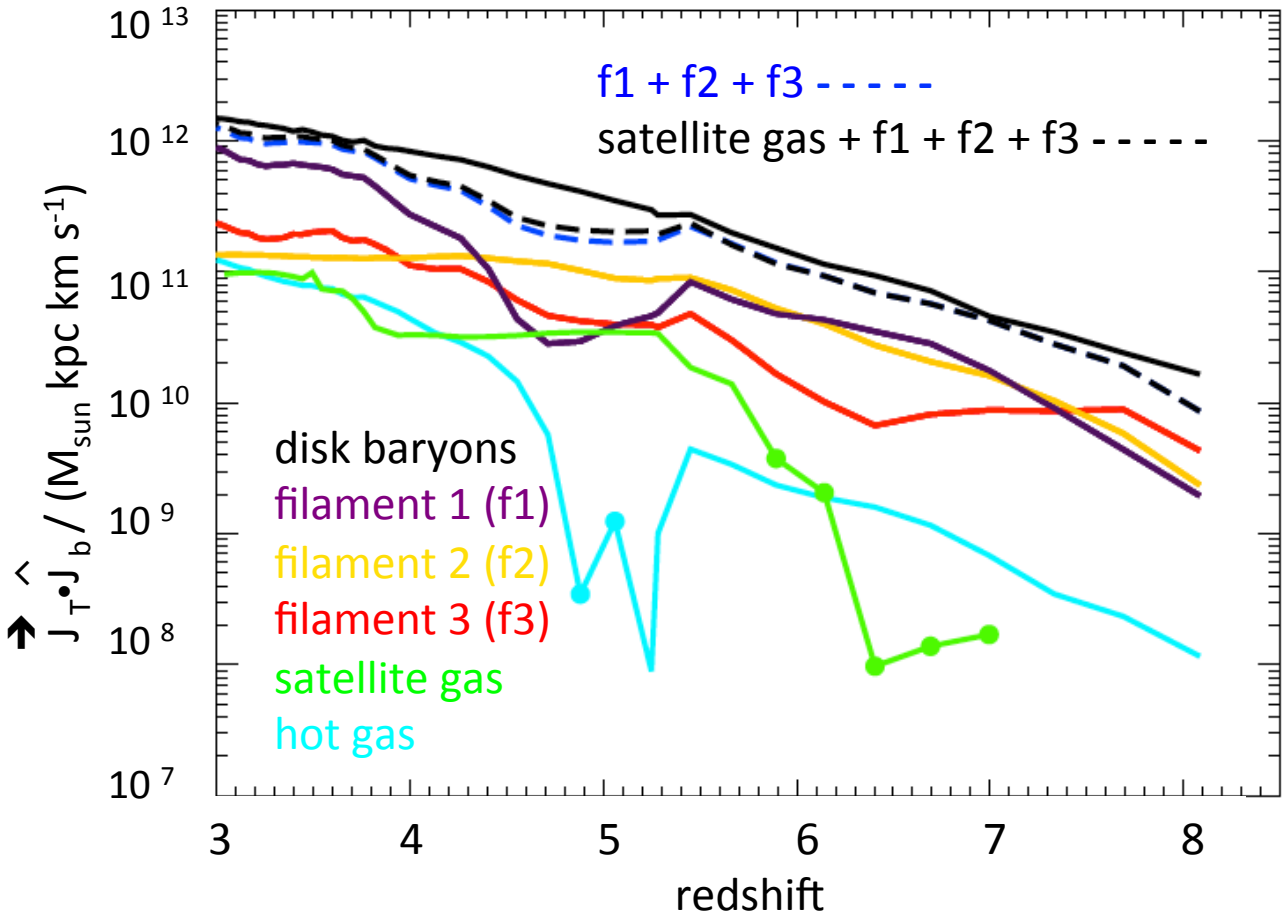
Tillson et al, 2012

What sets the angular momentum budget of the disk?



Tillson et al, 2012

What sets the angular momentum budget of the disk?



Tillson et al, 2012

Summary of findings beyond Tidal Torque Theory

A mass transition separates aligned from perpendicular halos in dark matter simulations. High mass halos have perpendicular spins because they are results of mergers; low mass halos have parallel spins because they acquire mass from accretion in the vorticity-rich neighborhood of filaments.

Massive, dispersion dominated, passive, red, smooth, metal-rich and old galaxies tend to have spins perpendicular to filaments.

Low mass, centrifugally supported, star forming, blue, irregular, metal poor and young galaxies tend to align with filaments.

Gas and dark matter have the same angular momentum when they are accreted at the virial radius. However, for simulations with cooling, gas specific angular momentum within the virial radius is always higher by at least a factor of 2 than that of the dark matter.

The specific angular momentum of profile of gas within the virial radius never matches the profile for dark matter.

At high redshift, the cold filament gas phase dominates the mass and angular momentum budgets of the disk as a function of time. The luminous satellites account for at most $1/10^{th}$ of the disk mass and angular momentum budget at any given epoch.