Pancakes served cold

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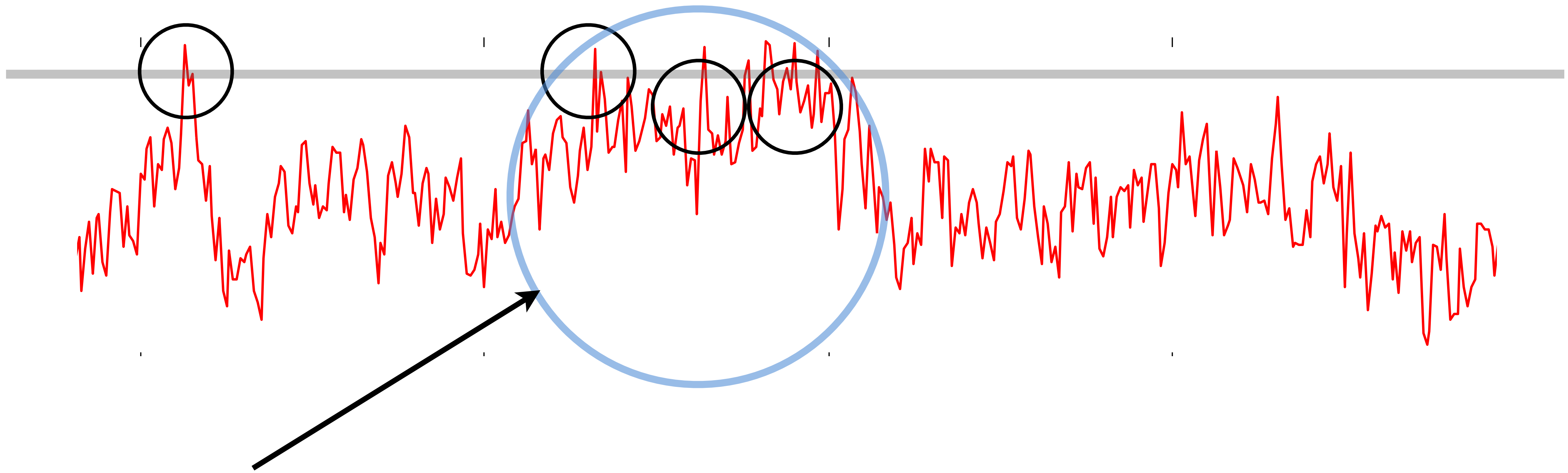
KIPAC/Stanford

Hahn, Dekel, Ceverino, Primack et al., 2011, in prep.

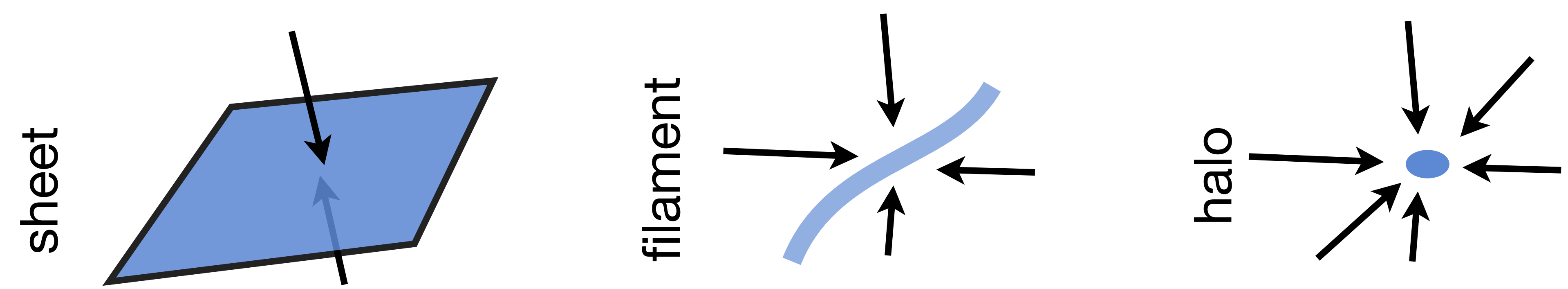
Large vs. small scales: Galaxies and Large-scale Structure

Density fluctuations determine where and how structure forms

Peaks exceeding threshold collapse to form galaxies/haloes



Larger scale fluctuations collapse ‘incompletely’ and subseq. along 3 axes

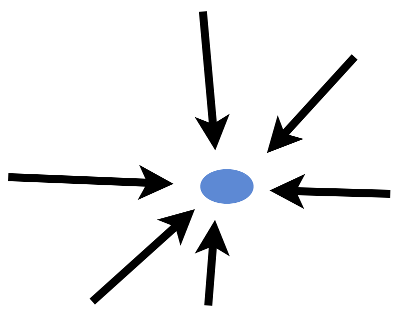


This gives rise to the large-scale structure of the Universe...

cf. also Pauls & Melott (1995), Sheth&Tormen (2002), Shen et al. (2006)

Galaxy formation and large-scale structure

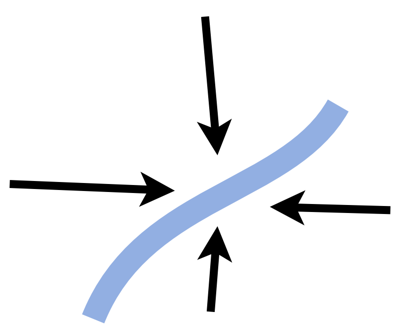
halo



The basic building block of CDM hierarchical galaxy formation theory

Rees & Ostriker 1977, White & Rees 1978

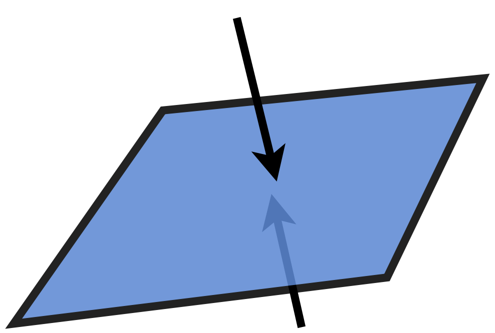
filament



The major player for cold accretion modes "cold streams"

Birnboim & Dekel 2003, Keres et al. 2005

sheet



what...?!?

Zel’dovich pancakes...

- In 1st order Lagrangian perturbation theory, general perturbations collapse subsequently along 3 axes:

$$\rho(\vec{q},t) = \frac{\rho(\vec{q},0)}{[1-D_+(t)\lambda_1]\,[1-D_+(t)\lambda_2]\,[1-D_+(t)\lambda_3]}$$

$$\lambda_k \propto \mathrm{eig}\,(\,\partial_i\partial_j\Phi\,)$$

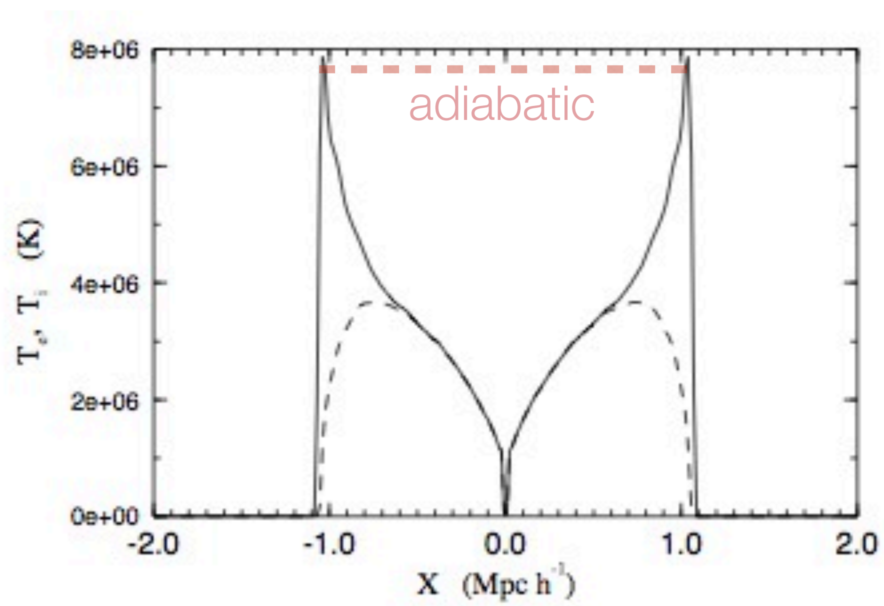
(Zel’dovich 1970)

- “pancake” formation, $\lambda_1, \lambda_2, \lambda_3$ predict asymptotic morphology.
- In reality this is a multi-scale phenomenon.
- halos embedded in filaments embedded in pancakes with increasing scale

Yakov Zel’dovich

Idealized plane wave-collapse

Sinusoidal velocity perturbation along one dimension with self-gravity
-> steepening wave, shock/caustic arising at singularity

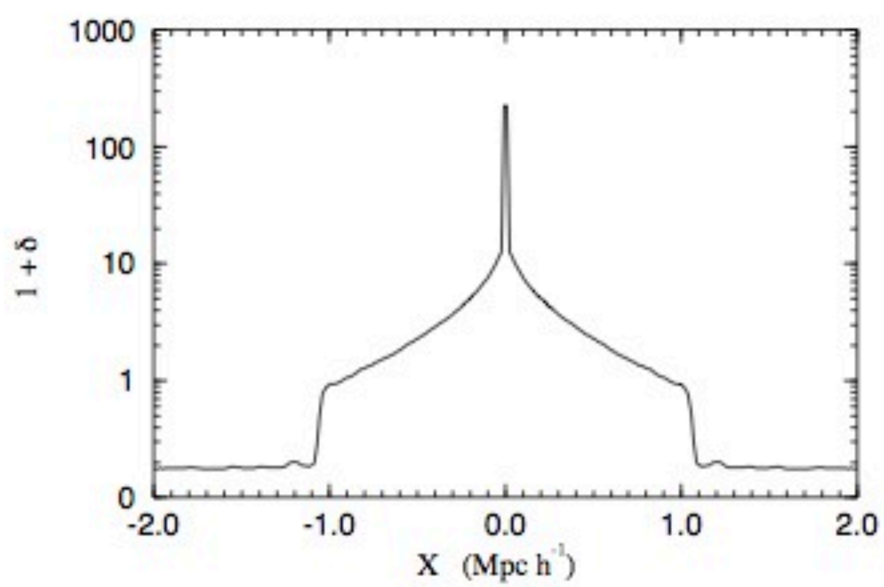


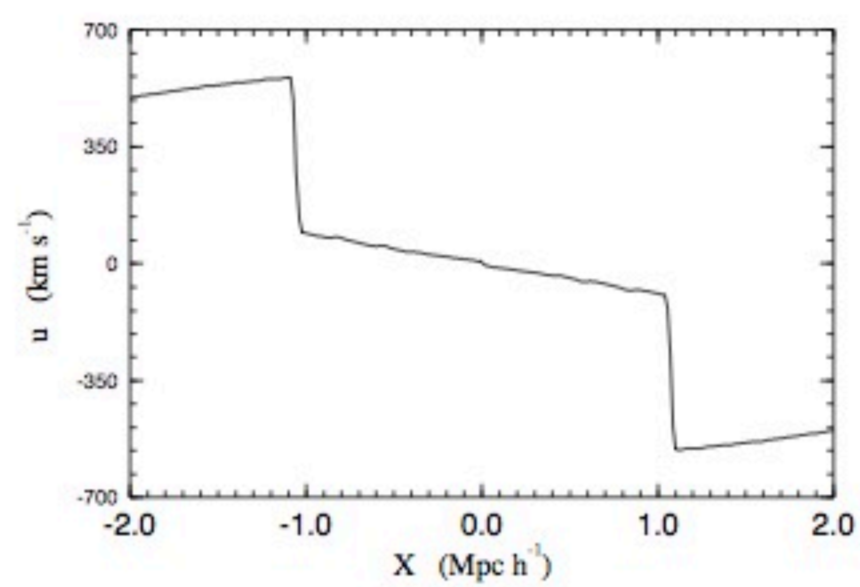
Features of the collisional component:

- outward propagating high Mach number accretion shock
- heated interior
- cold core when cooling

Features of the collisionless component:

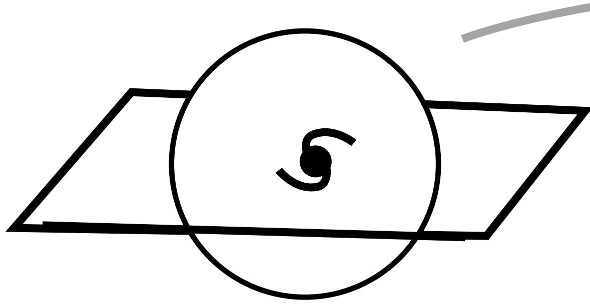
- outward propagating caustic
- high density, velocity dispersion interior



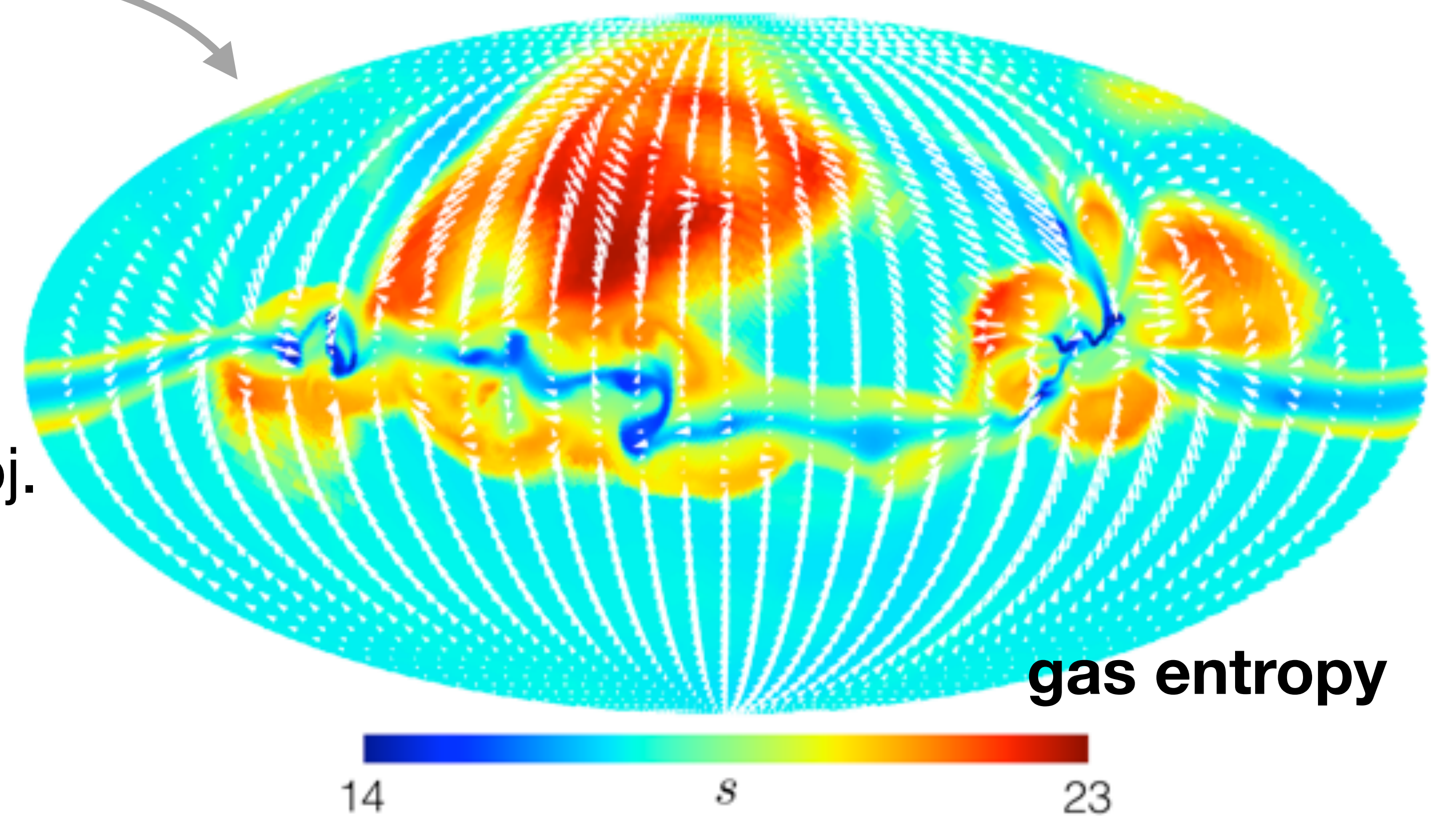


from Teyssier et al. (1998)

...and around massive high-z galaxies?



Thin slice at 2Rvir around $\sim 8\times10^{11}$-$M_\odot$ sized galaxy at z~1.8 in Mollweide proj.



Planar structure

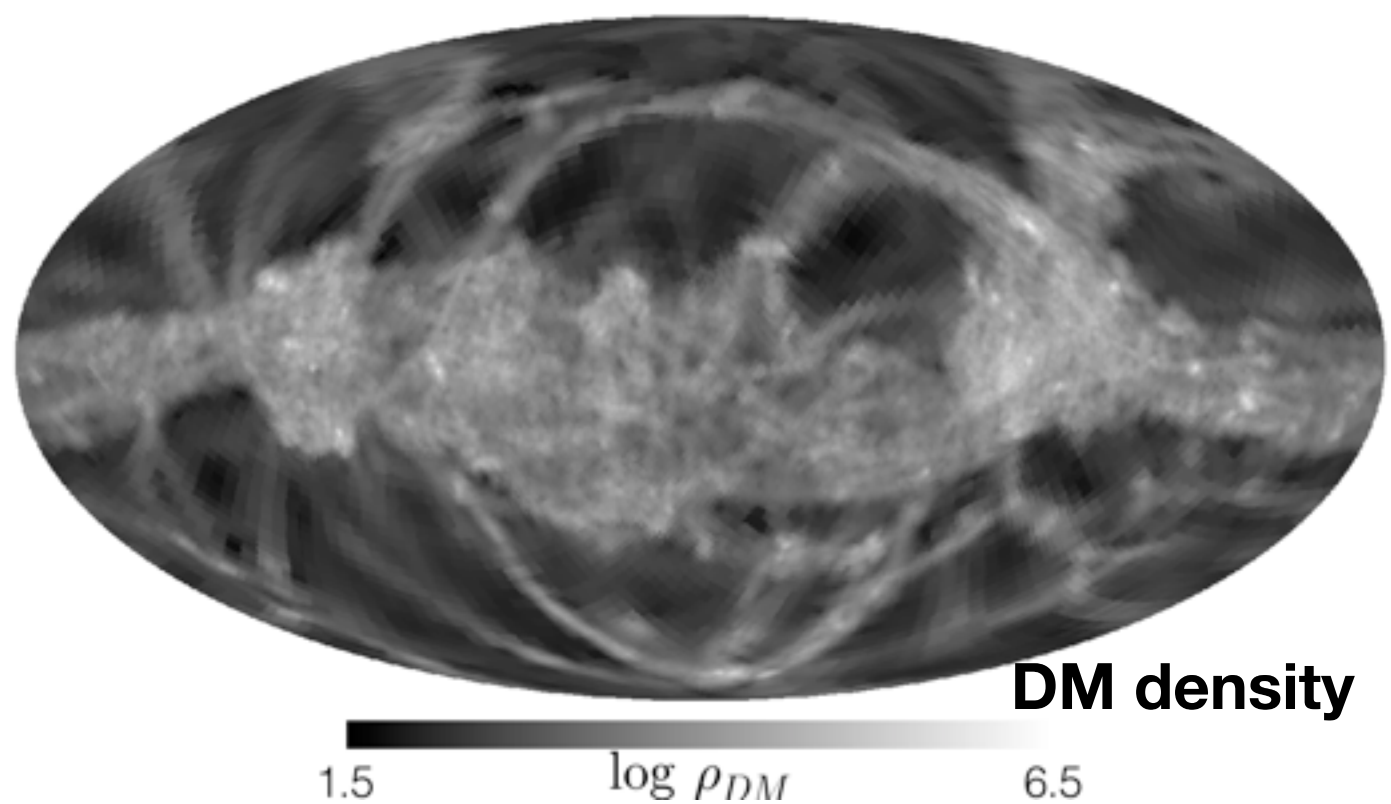
Gas accretes onto plane, then into streams

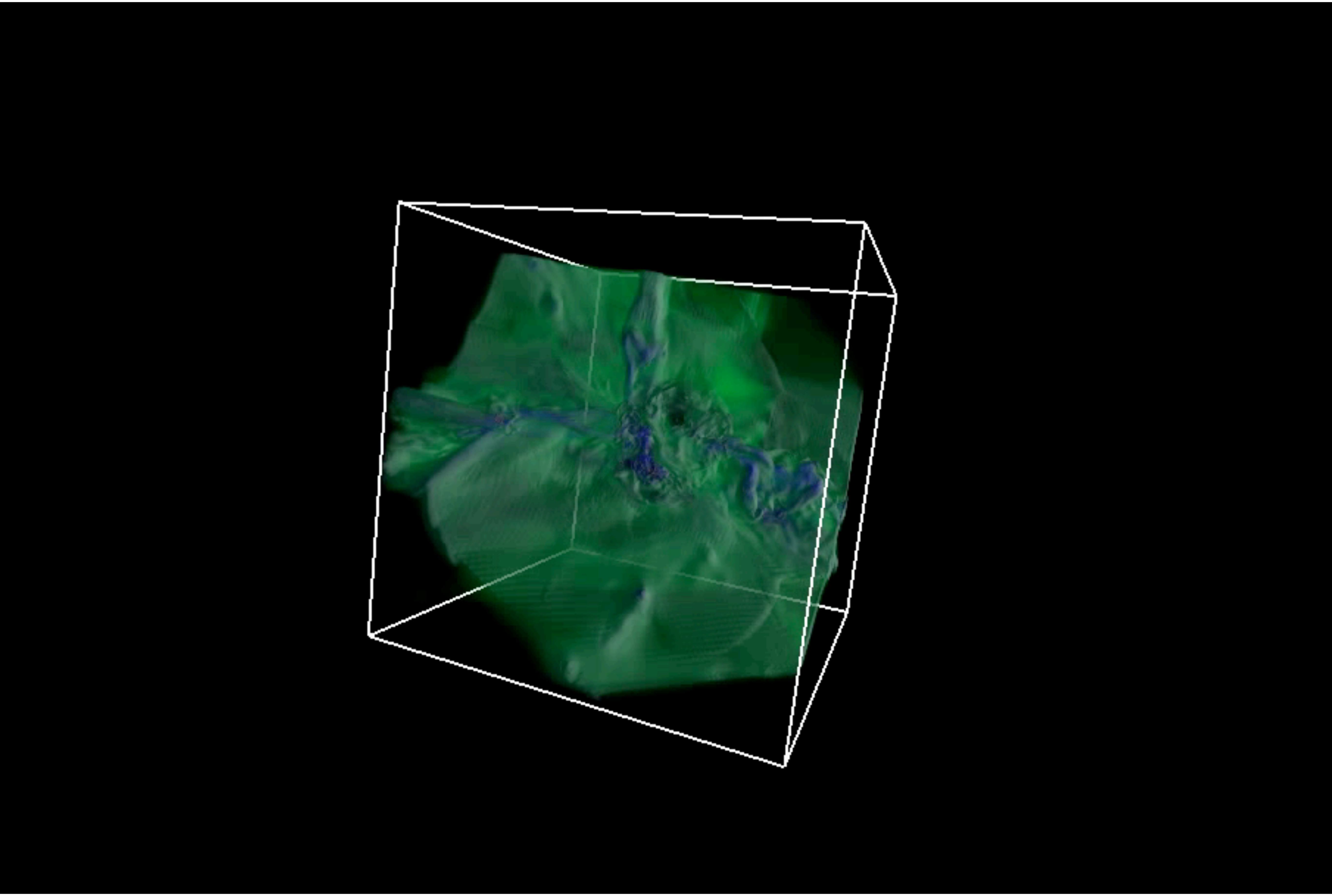
Shocks on both sides

Low entropy 'filling'

Thicker in DM

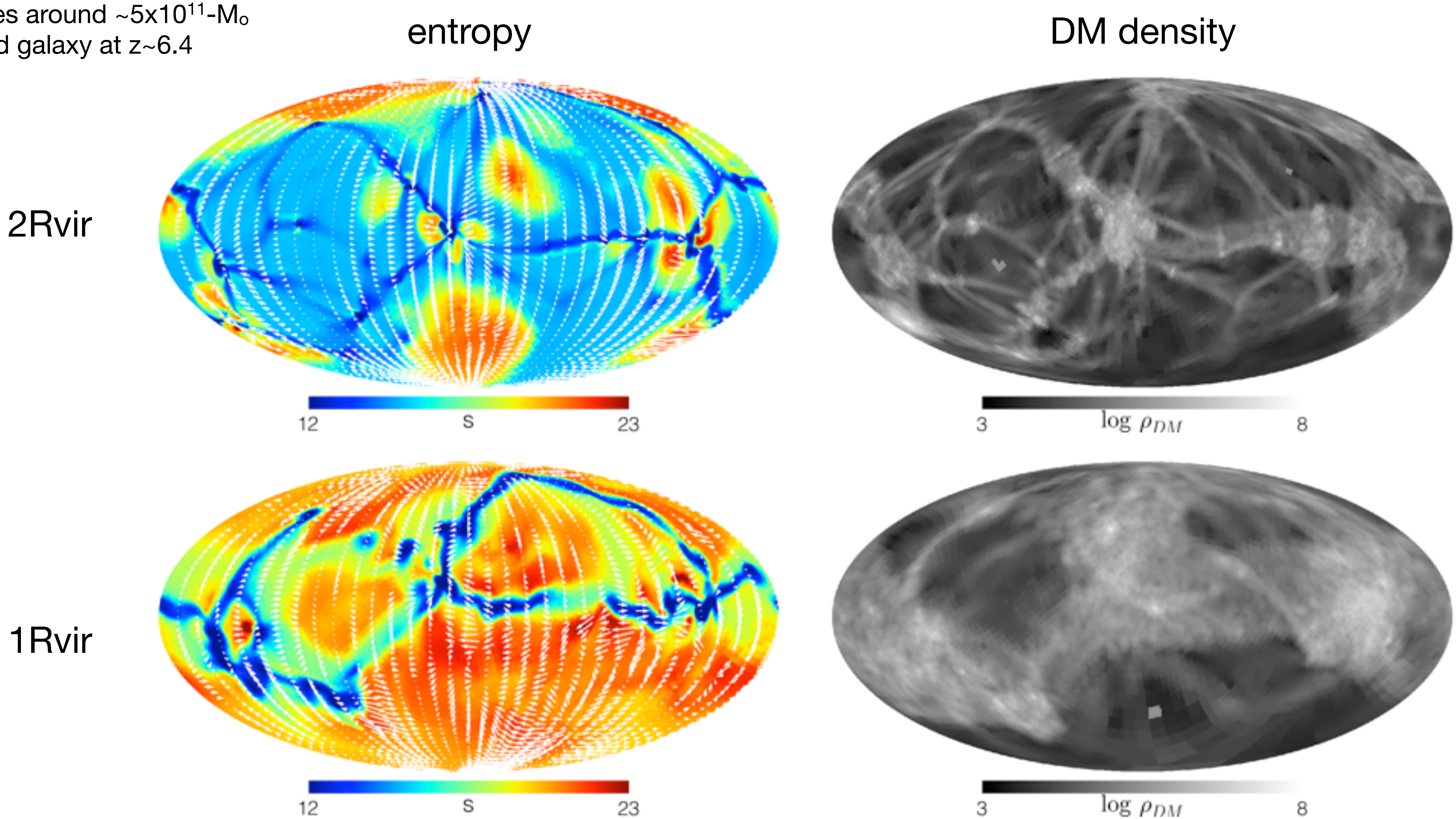
More structures in DM -> still not enough res in gas?




vis. with Ralf Kähler (KIPAC)

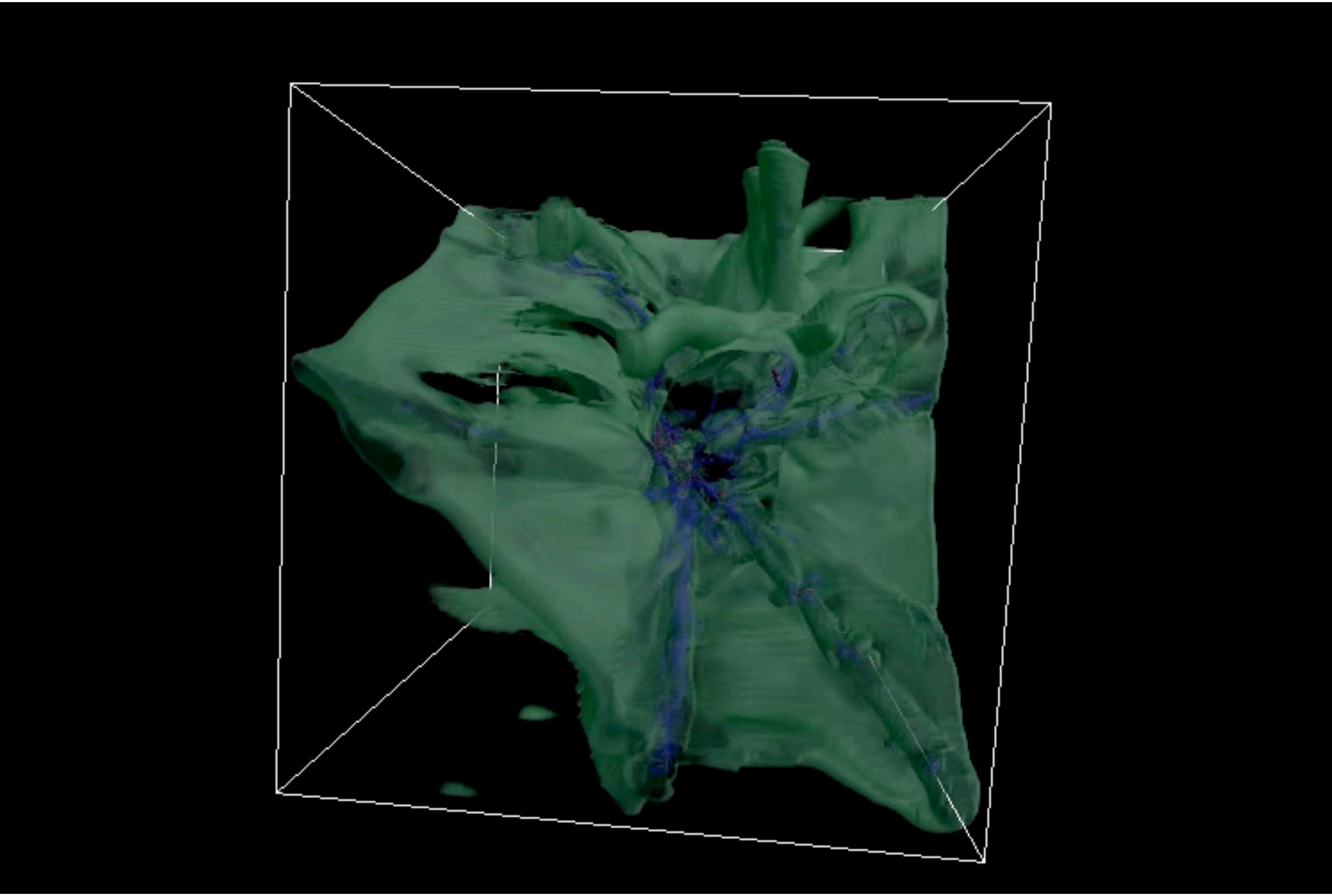
1 pancake, 2 pancakes, 3 pancakes....

Slices around ~5x10^{11}-$M_\odot$ sized galaxy at z~6.4



SFG2

But: plane of strongest influx is not necessarily identical to one of the pancakes
(c.f. also Danovich et al. 2011)



vis. with Ralf Kähler (KIPAC)

...with the right properties?

Pancake profiles...

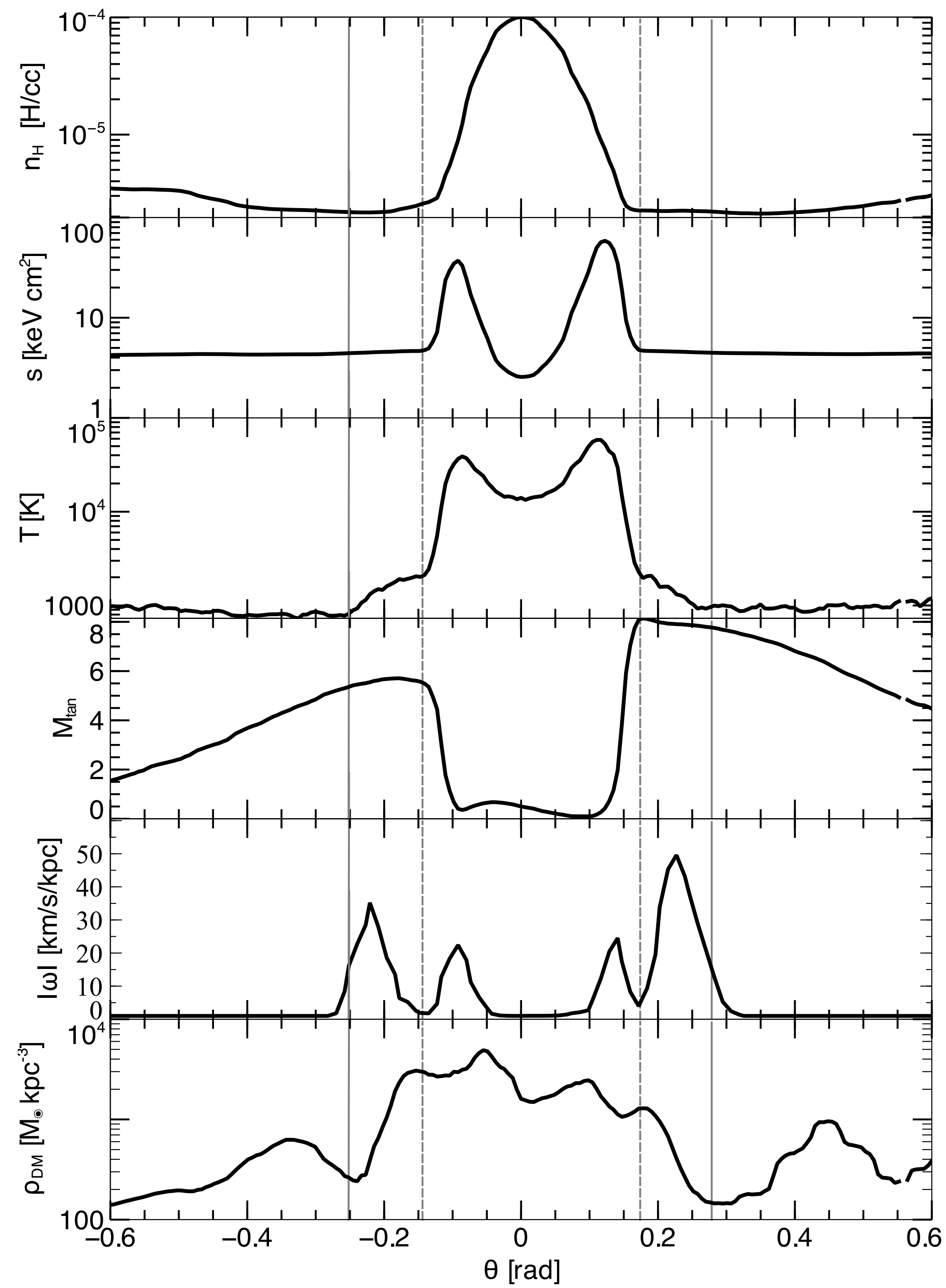
DM caustics (solid gray)
vs.
hydro shocks (dashed gray)

Shandarin & Zeldovich (1989):

$$\frac{x_{\rm sh}}{x_s} = \frac{\gamma - 1}{2}(\gamma + 2)^{1/2} \overset{\gamma=5/3}{\simeq} 0.64$$

we measure

$$\frac{x_{\rm sh}}{x_s} \simeq 0.6$$



Density

Entropy

Temperature

Mach number

Vorticity

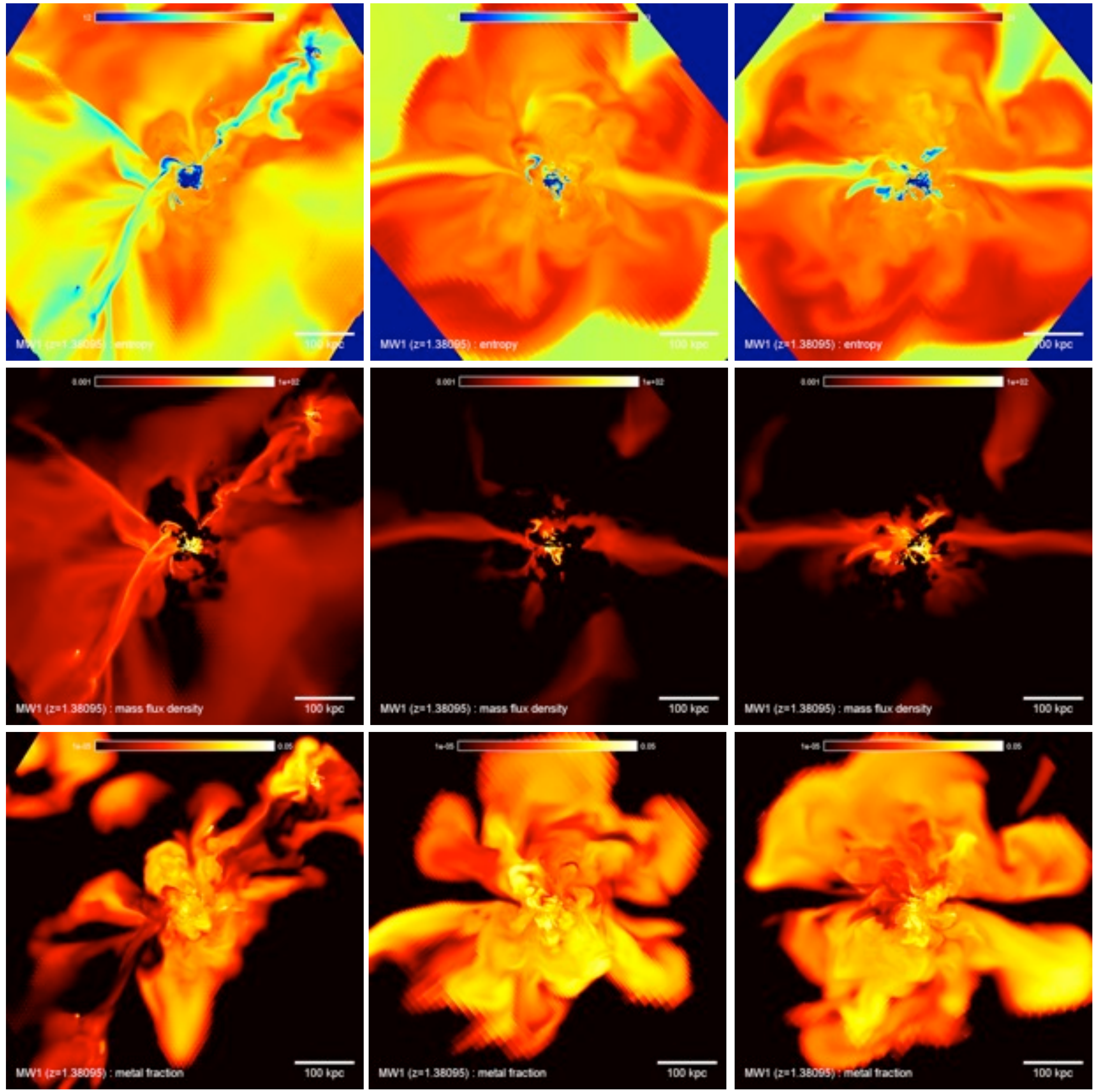
DM density

As the streams, does not shock at Rvir...

Entropy

Flux density

Metal fraction

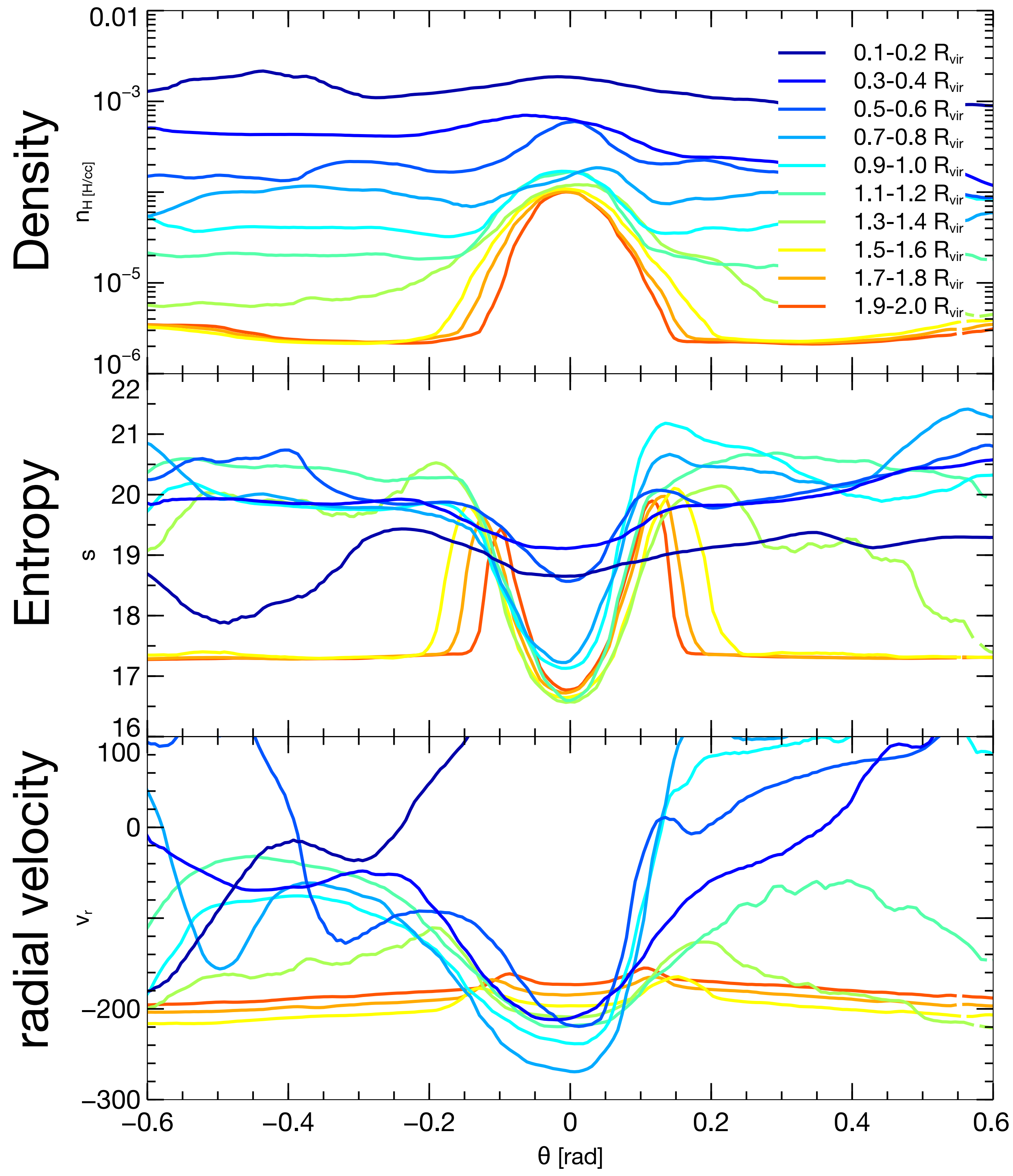


Planar influx into the halo

Pancake profile inside the halo...

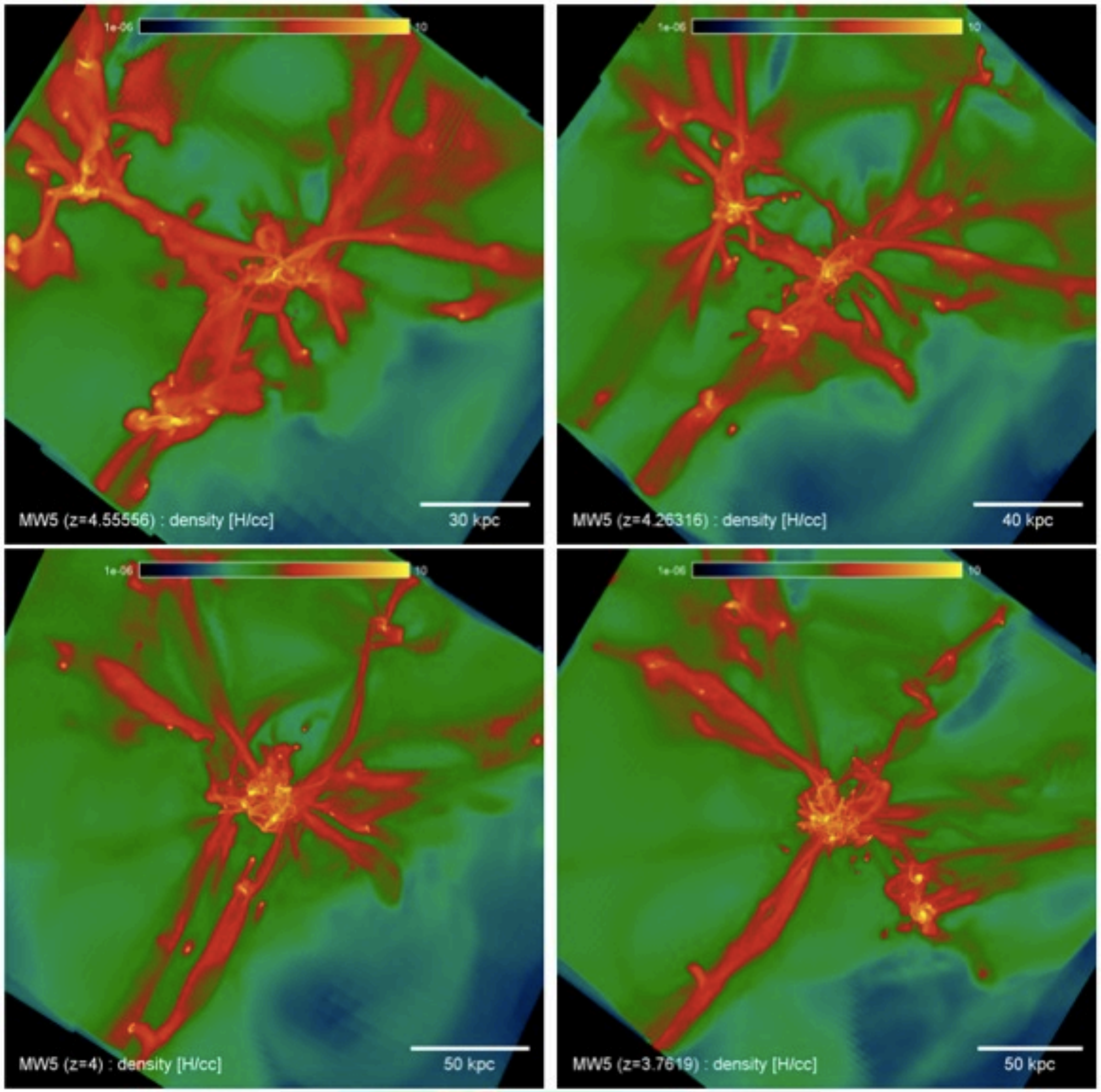
Entropy rises when pancake density becomes comparable to ambient

At all radii higher infall velocity. Infall gets slower when entropy rises ~Rvir/2



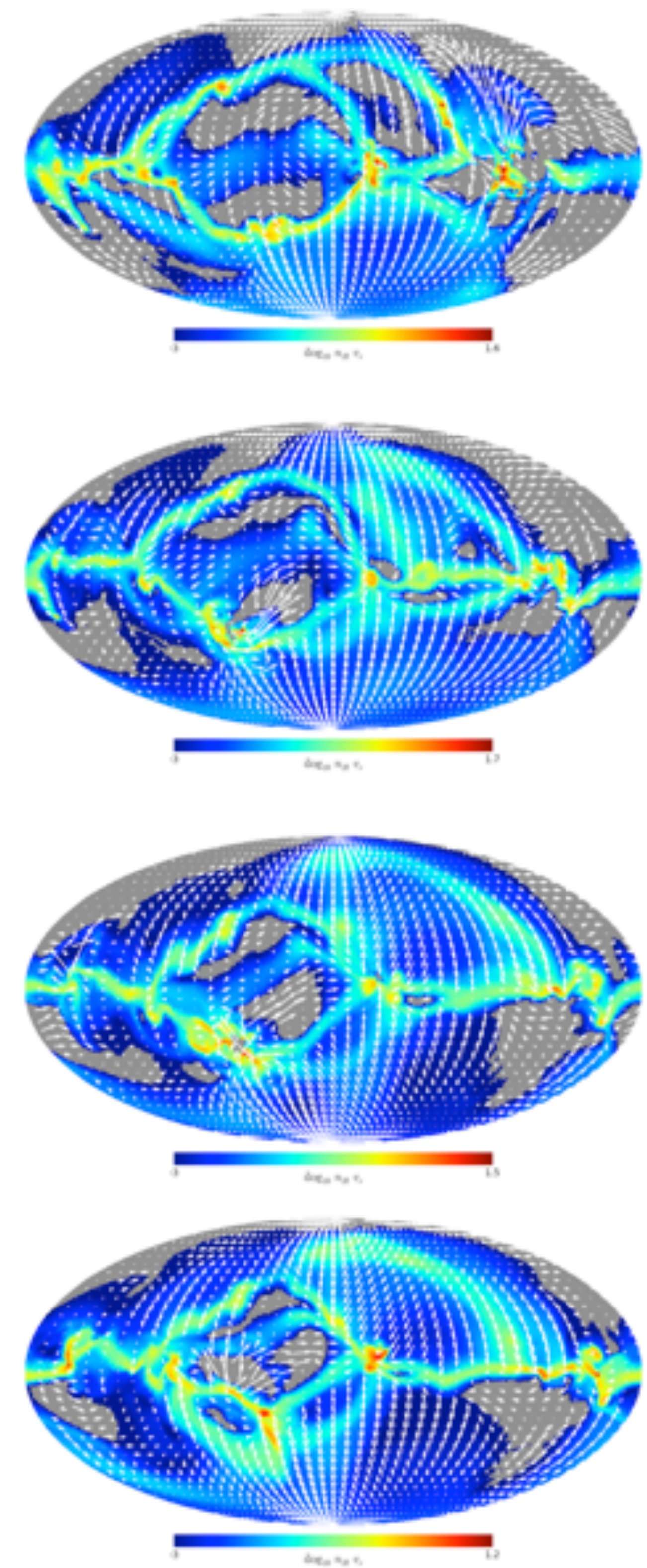
Planar mergers? Stream mergers?

Density



Slice thickness 17kpc - 34kpc

Flux density



What about AM?

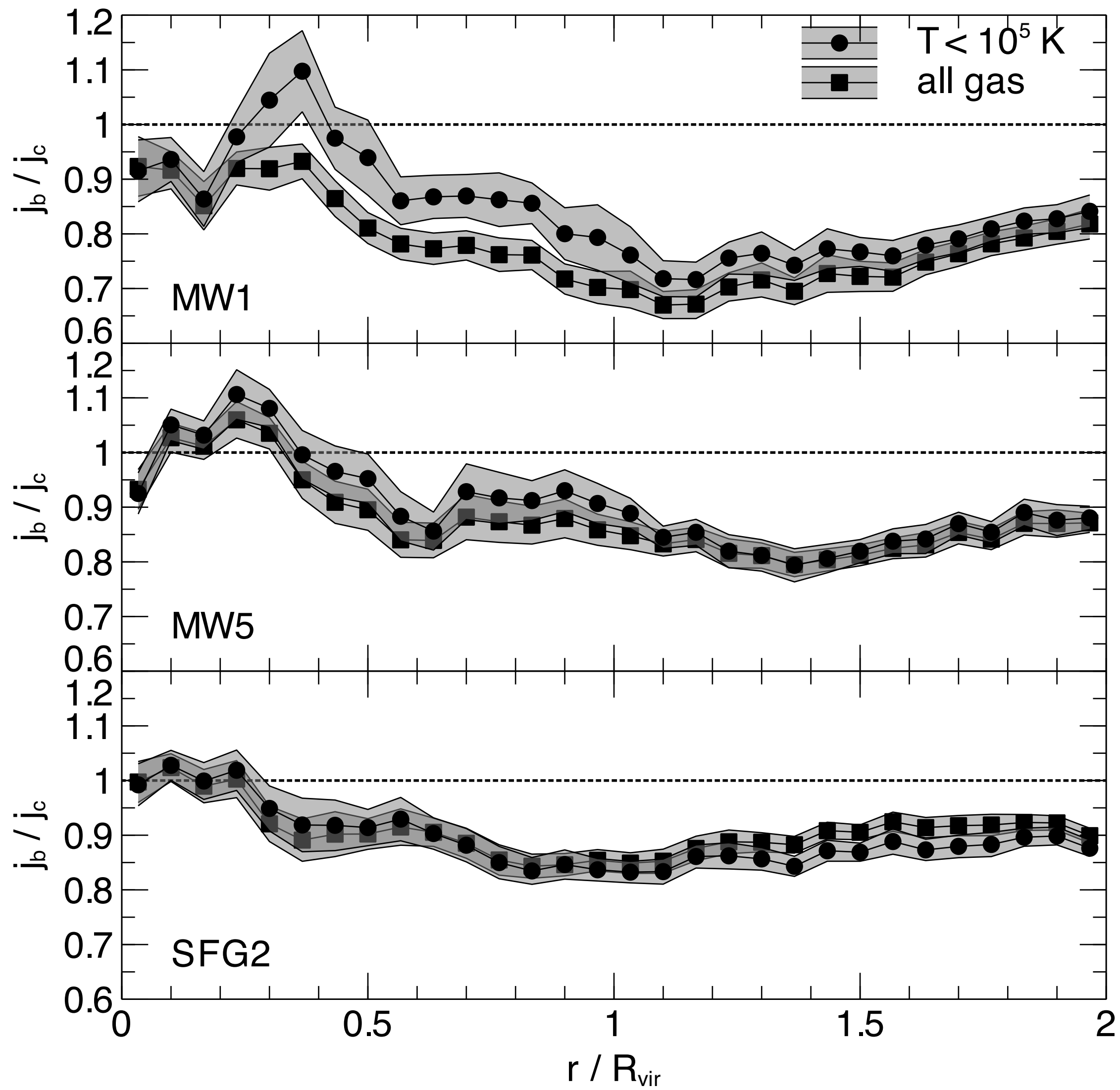
Ratio of gas to CDM specific AM...

Specific AM of gas 10-20% lower than DM outside Rvir

->dissipation

Comparable at ~Rvir/4

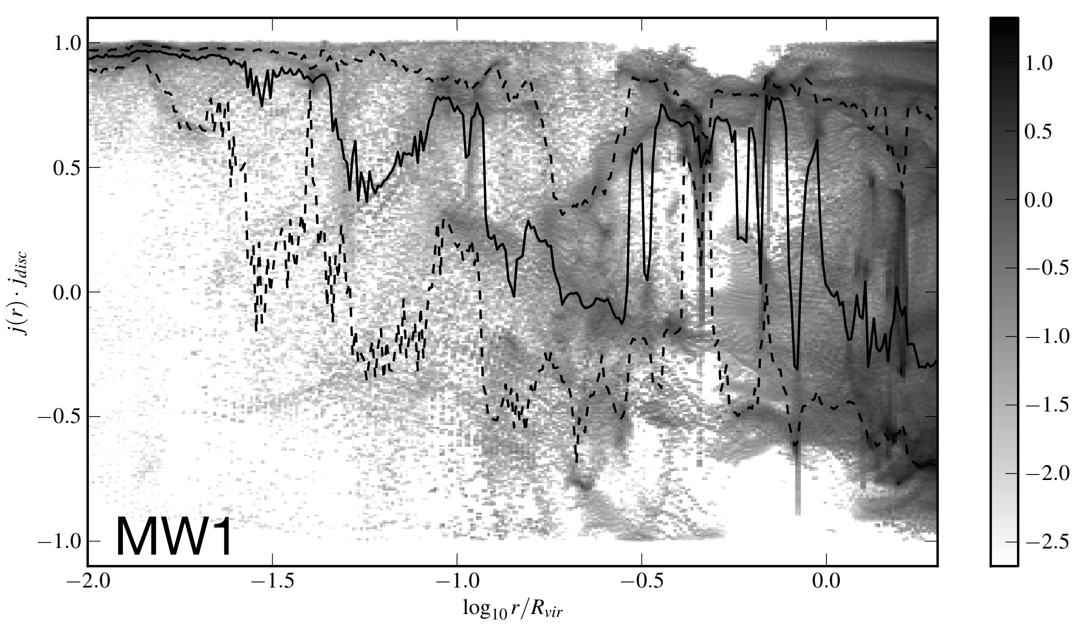
Again dissipation at smaller radii



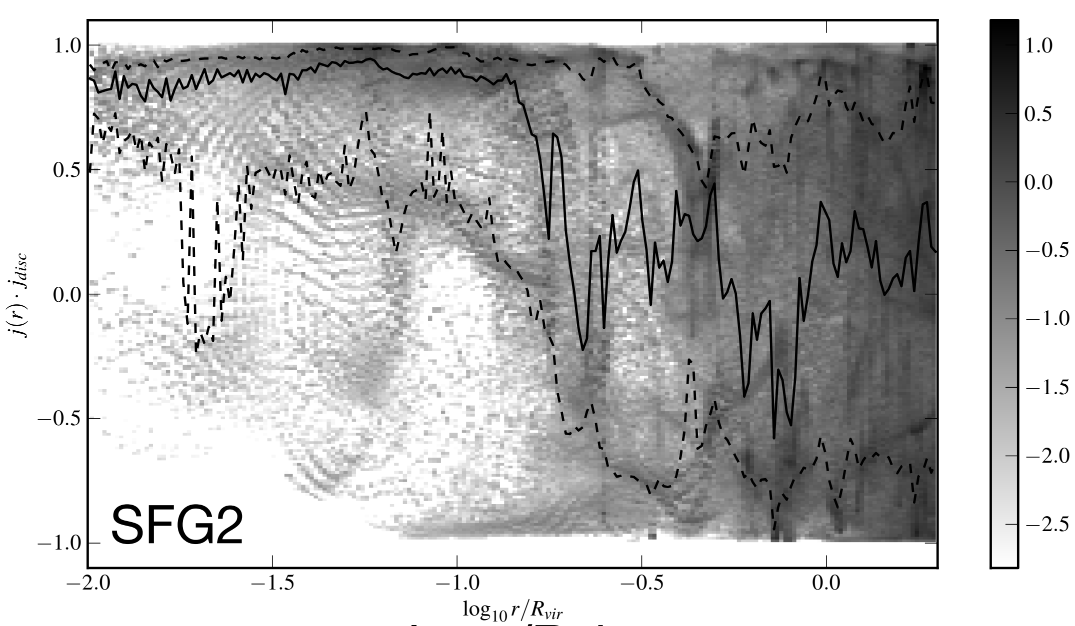
cf. also Kimm et al. (2011)

Coherent AM by pancaking?

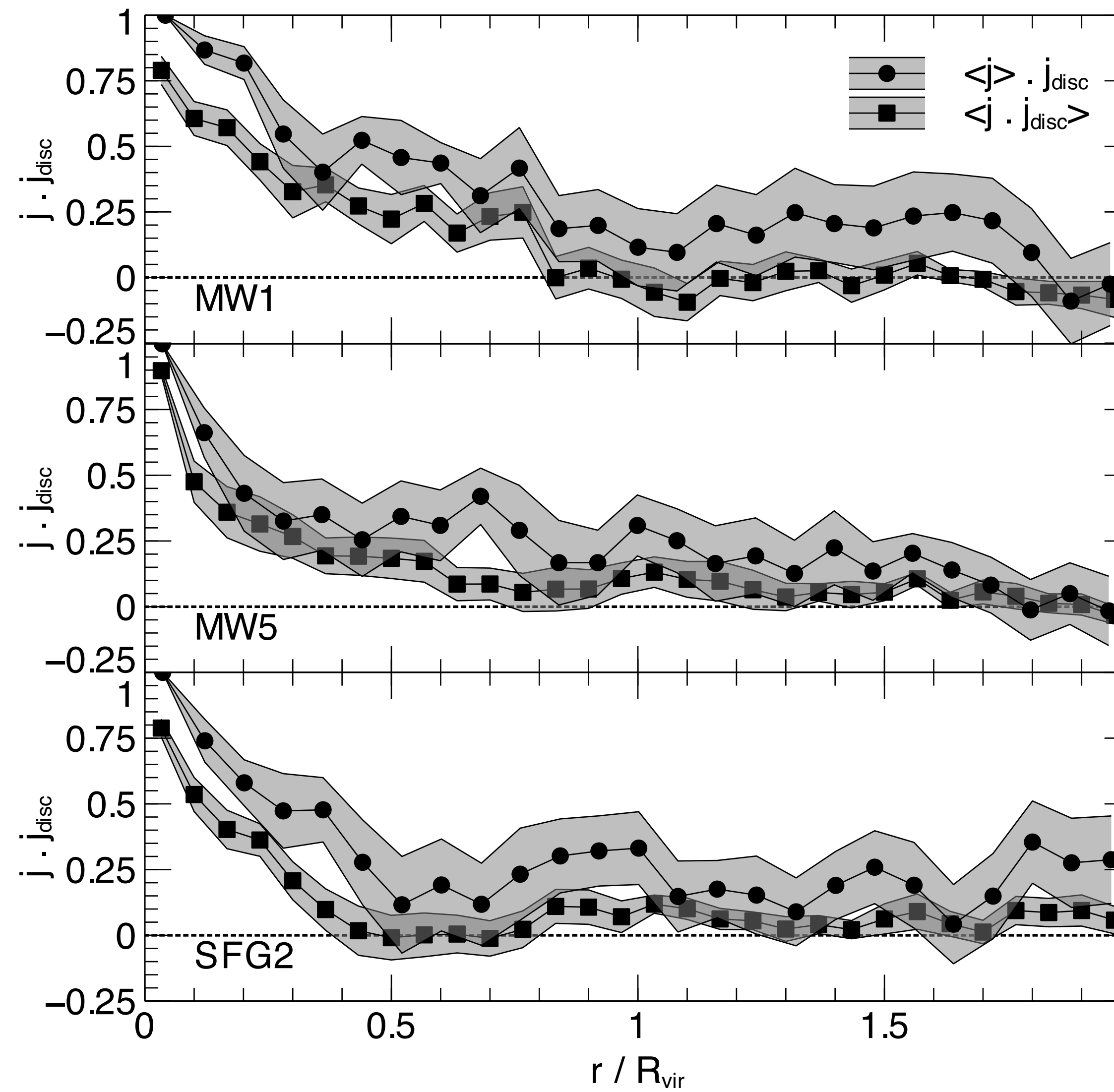
Angle-cosines between disk and cold gas at some radius r



log r/Rvir



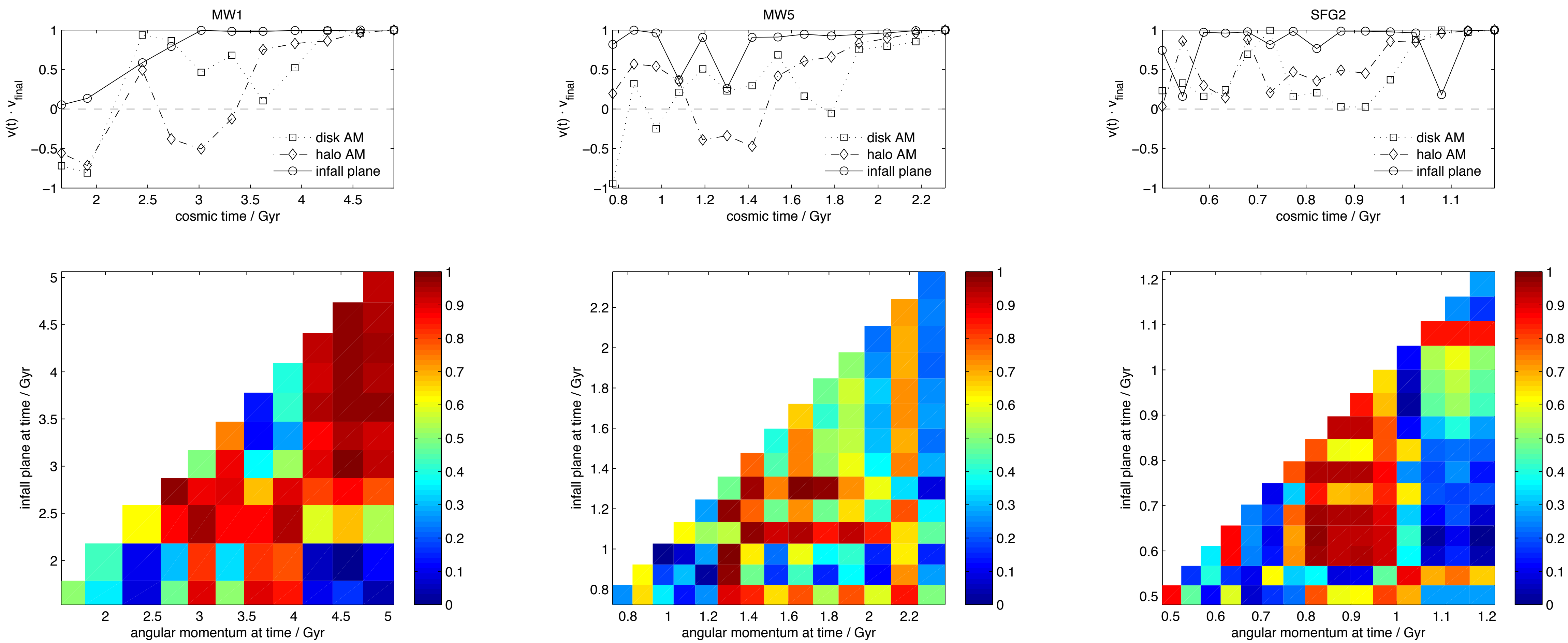
log r/Rvir



Accreting gas becomes aligned inside the halo....

Temporal coherence...

Define pancake by plane of maximum flux within aperture
Very stable over time (Gyrs)
Disk AM less stable



No clear evidence for alignment or anti-alignment, but hard to define plane in cases of several planes.

Summary

- Triaxial collapse leads to planar structures around massive galaxies
- Pancakes contain cooled low metallicity gas within two shocks, extend down to ~Rvir/3
- DM pancakes are more extended
- specific AM is dissipated by LSS formation outside Rvir
- AM <-> large-scale correlations? stay tuned!
- unclear dissipation processes in inner halo... stay tuned!