Shocks and Caustics — and their importance for galaxy formation

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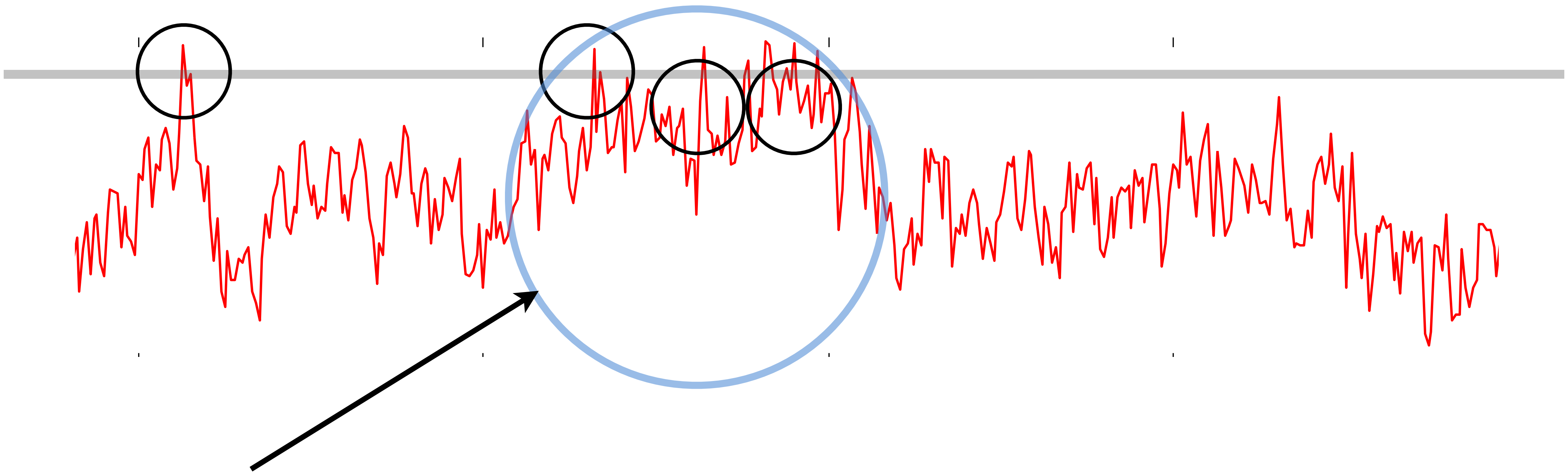
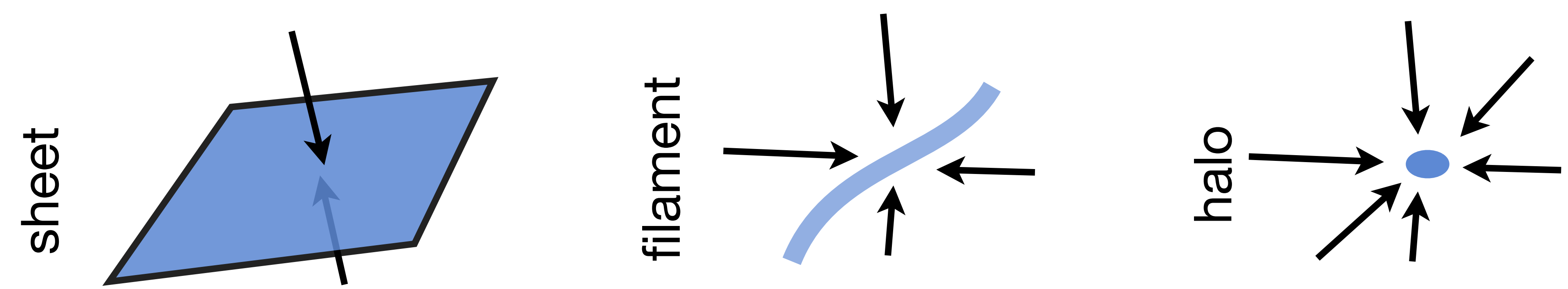
Anisotropic Collapse in Random Fields

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



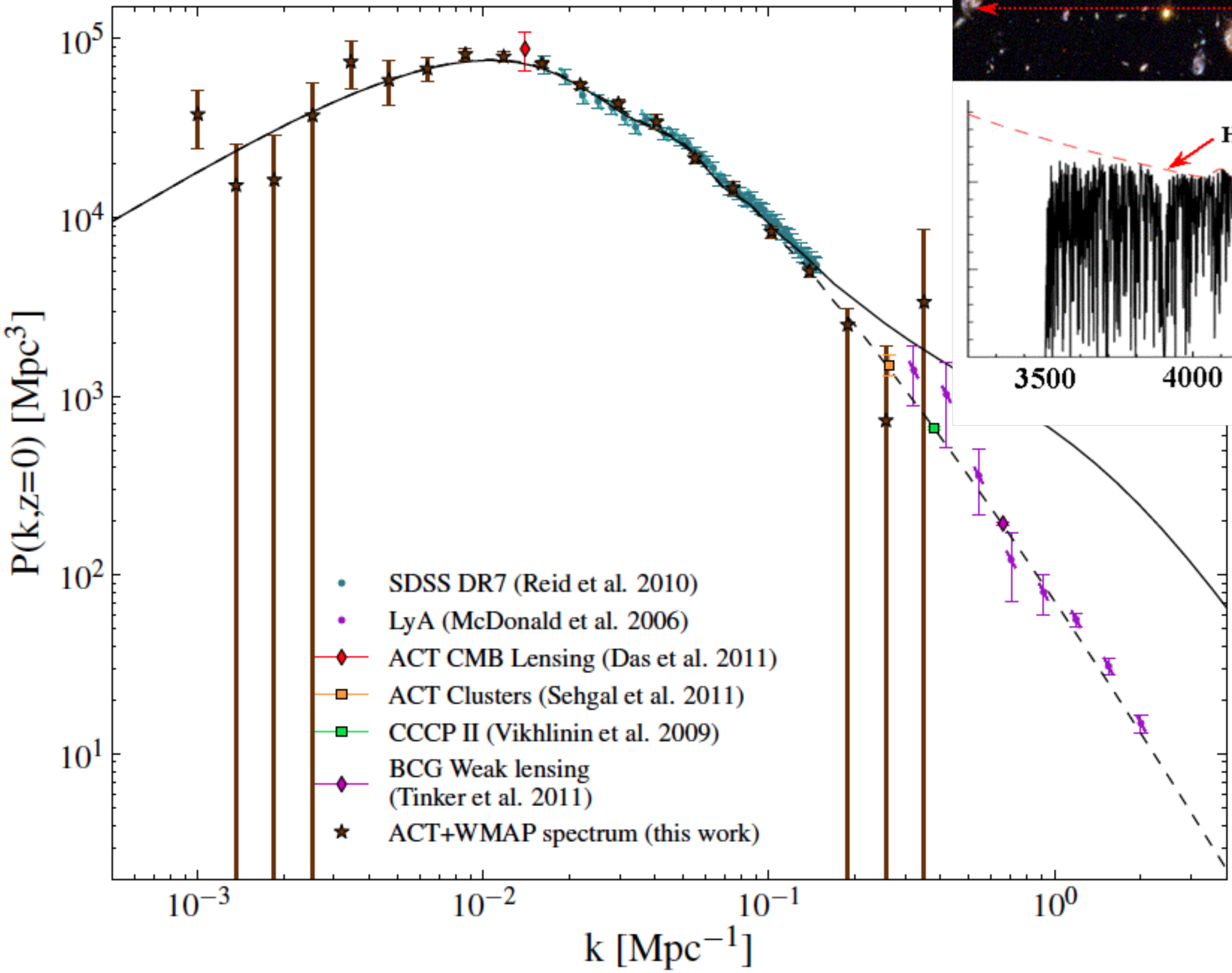
This gives rise to the large-scale structure of the Universe...

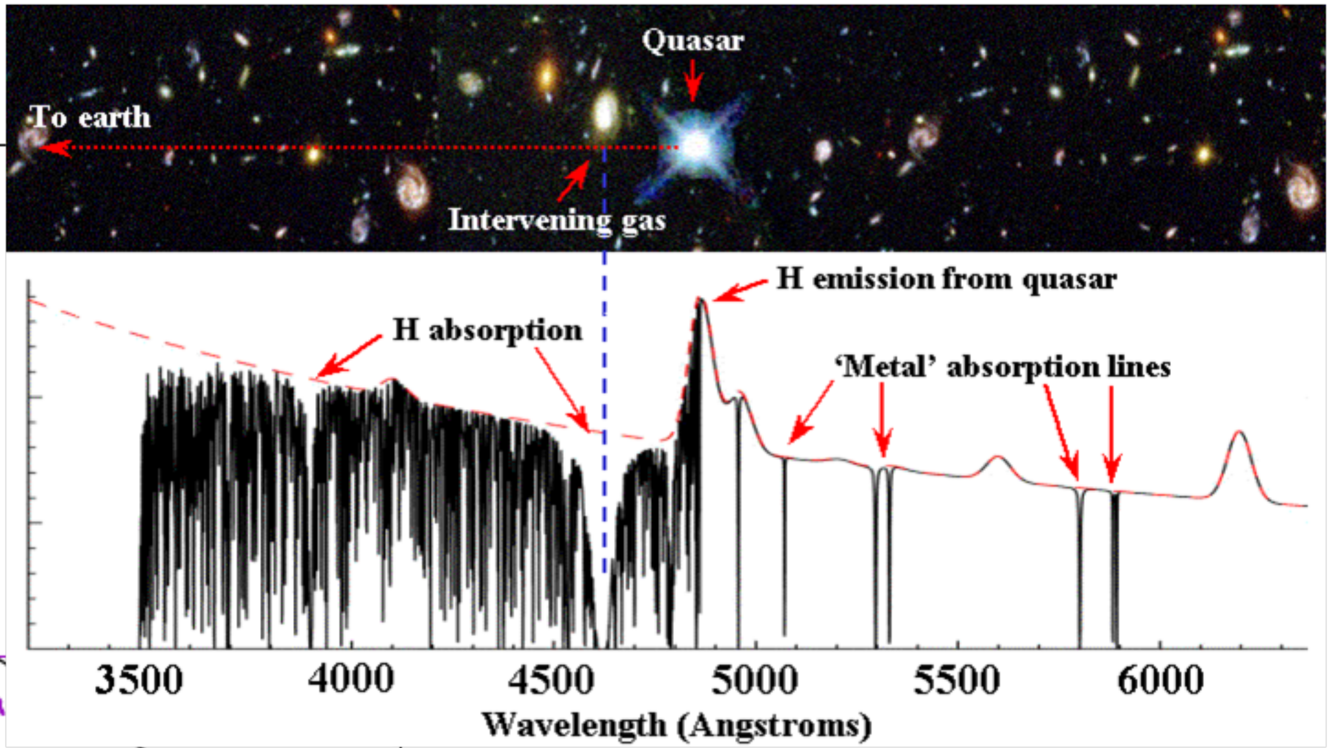
cf. also Zeldovich(1970), White+(1987), Pauls & Melott (1995), Bond+(1996)

Temperature sets the small scales

- **DM kinetic temperature must be cold(ish)**
- **gas temperature set by UV background (lower-z), or CMB (first stars)**

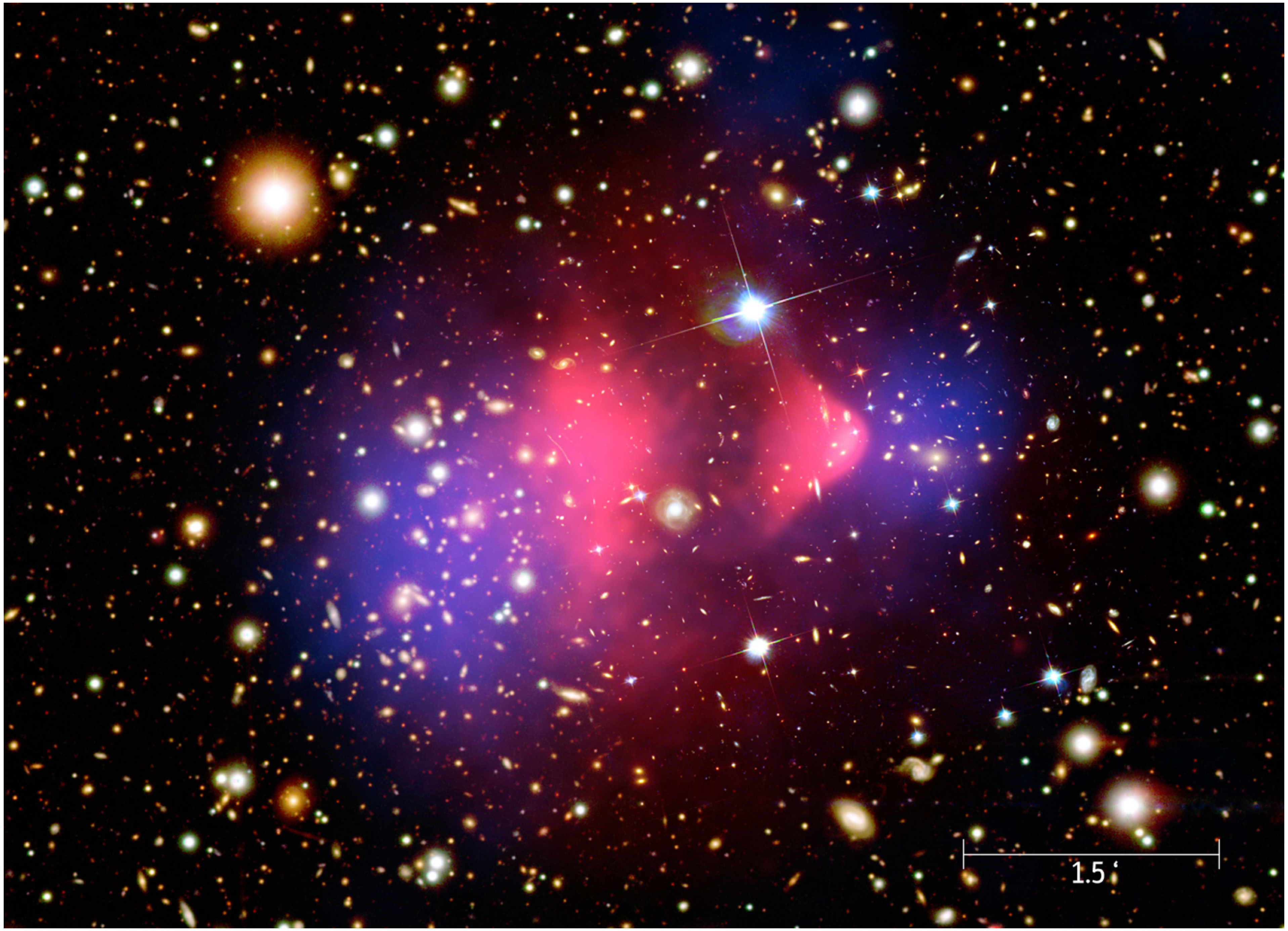
Hlozek et al. 2012





- best DM temperature constraints from Ly-α forest (e.g. Viel et al. 2013) >~ 5keV
- constrains WDM, FDM

Collisional vs collisionless dynamics



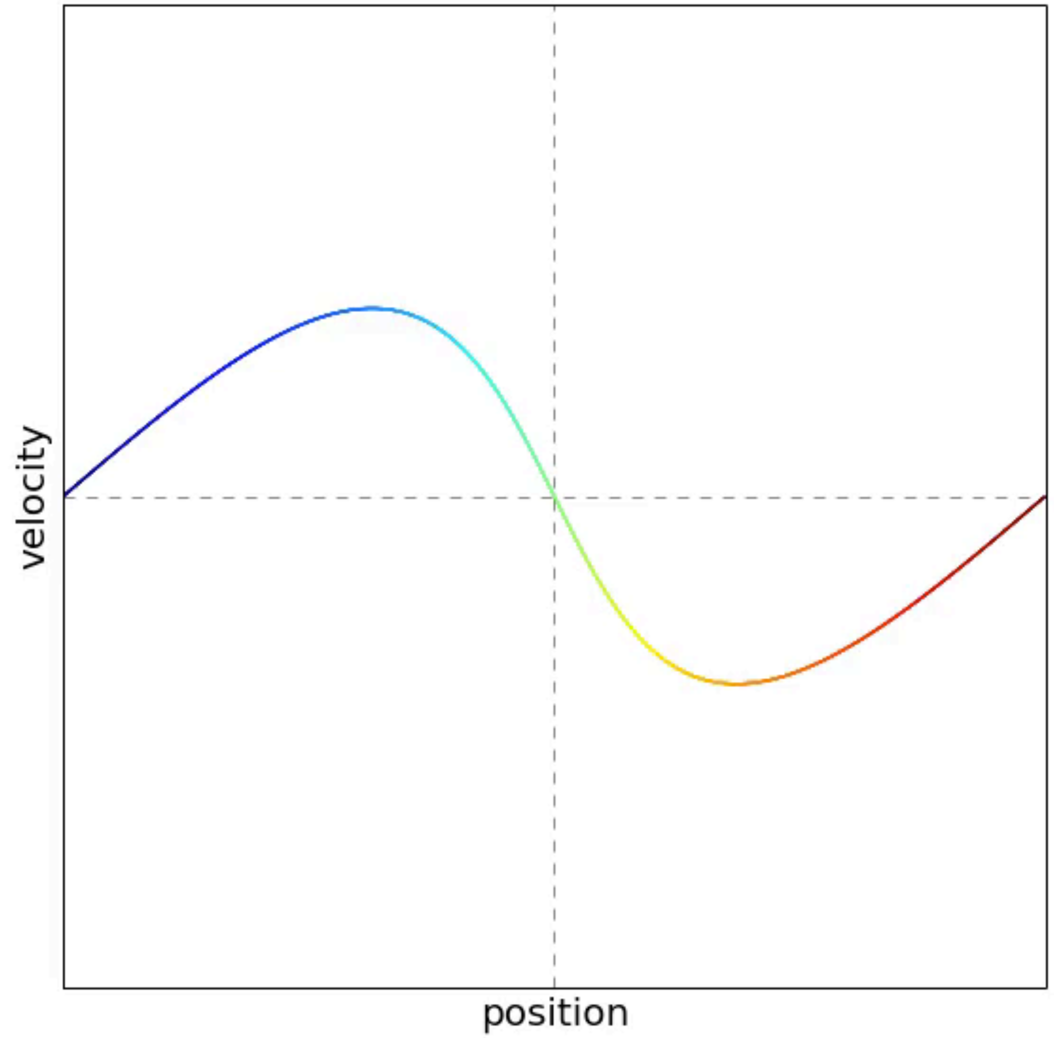
NASA/CXC/M. Weiss

Collisional and Collisionless Evolution

Evolution governed by **Boltzmann equation**

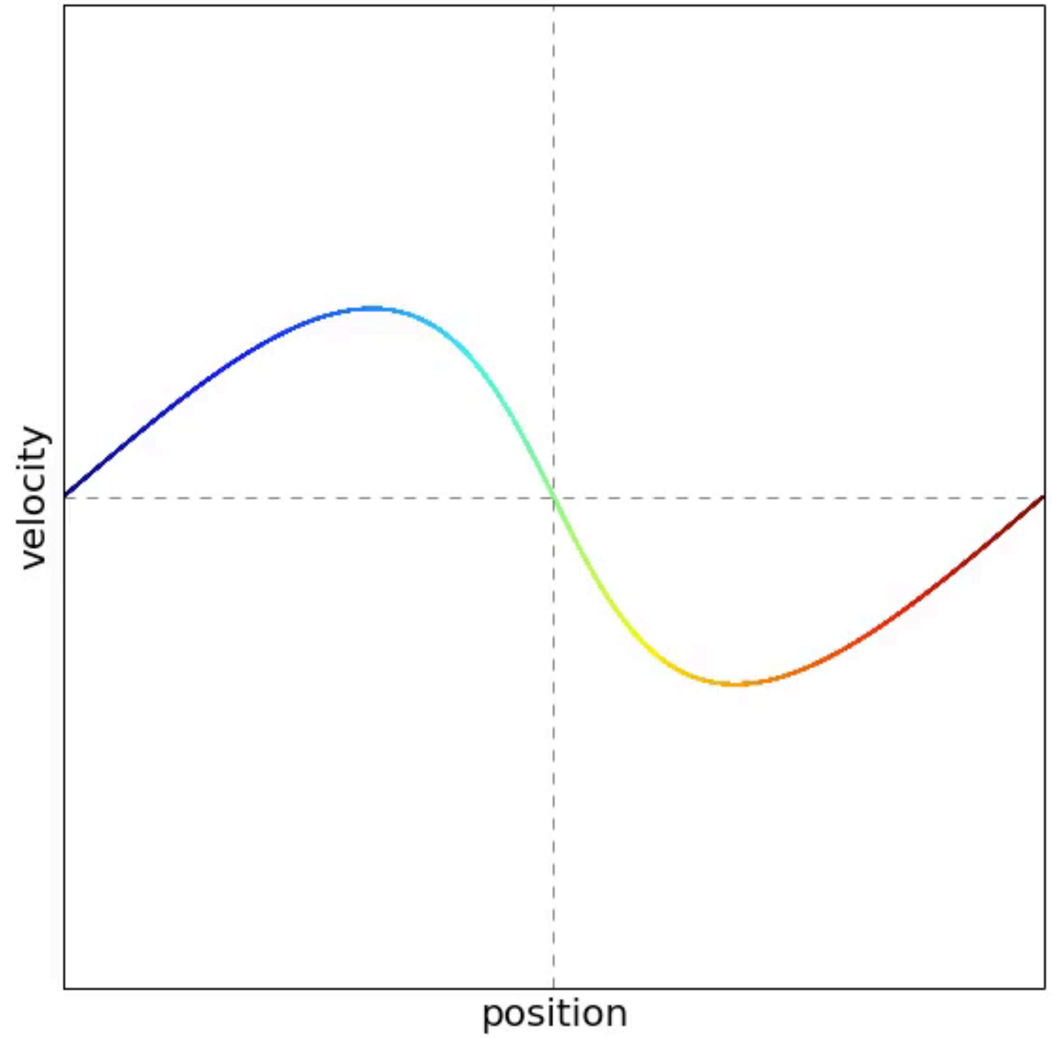
$$\frac{\partial f}{\partial t} + \frac{\mathbf{v}}{a^2} \cdot \boldsymbol{\nabla}_{\mathbf{x}} f - \boldsymbol{\nabla}_{\mathbf{x}} \phi \cdot \boldsymbol{\nabla}_{\mathbf{v}} f = C[f]$$

cold-collisionless case



always reversible -> multi-stream

cold-collisional case



entropy production -> MB dist.

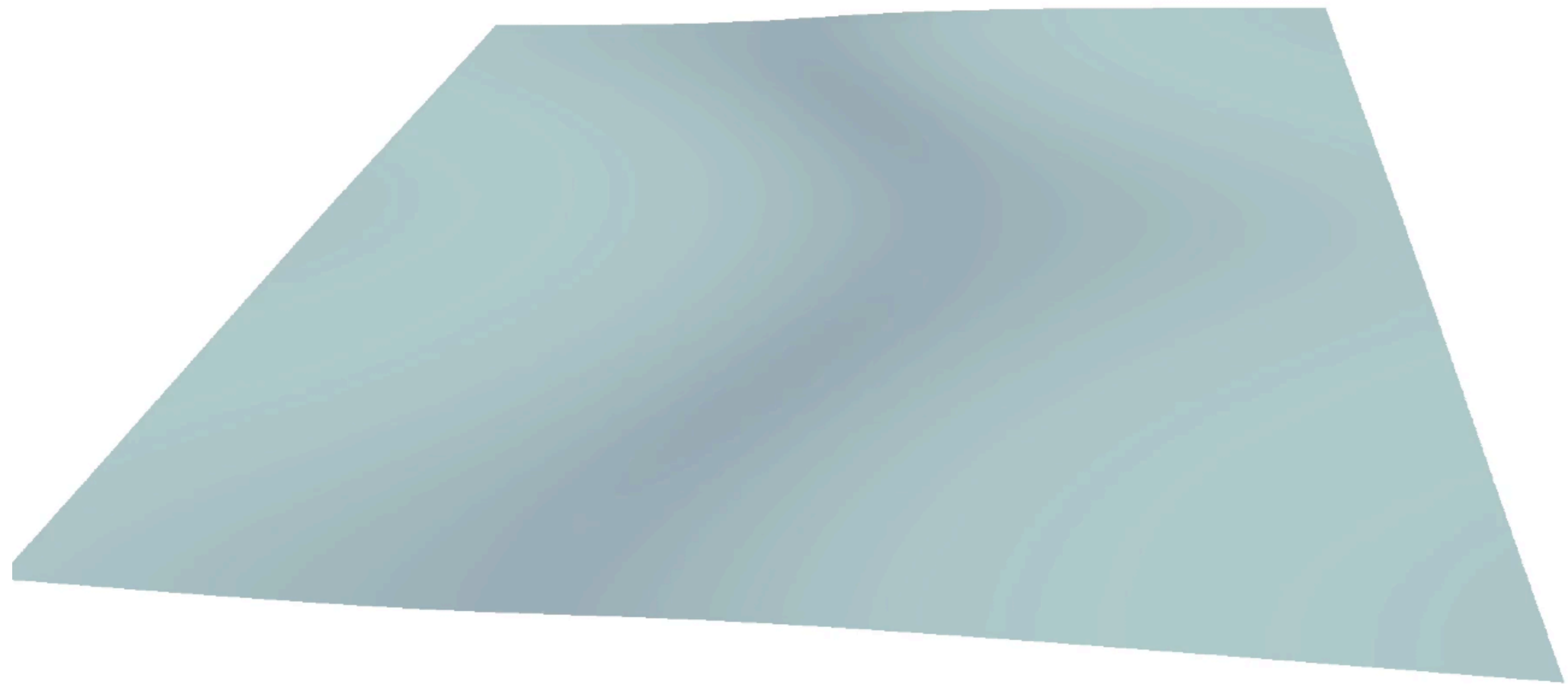
Higher-Dimensional Folding…

Shape of potential determines dynamics

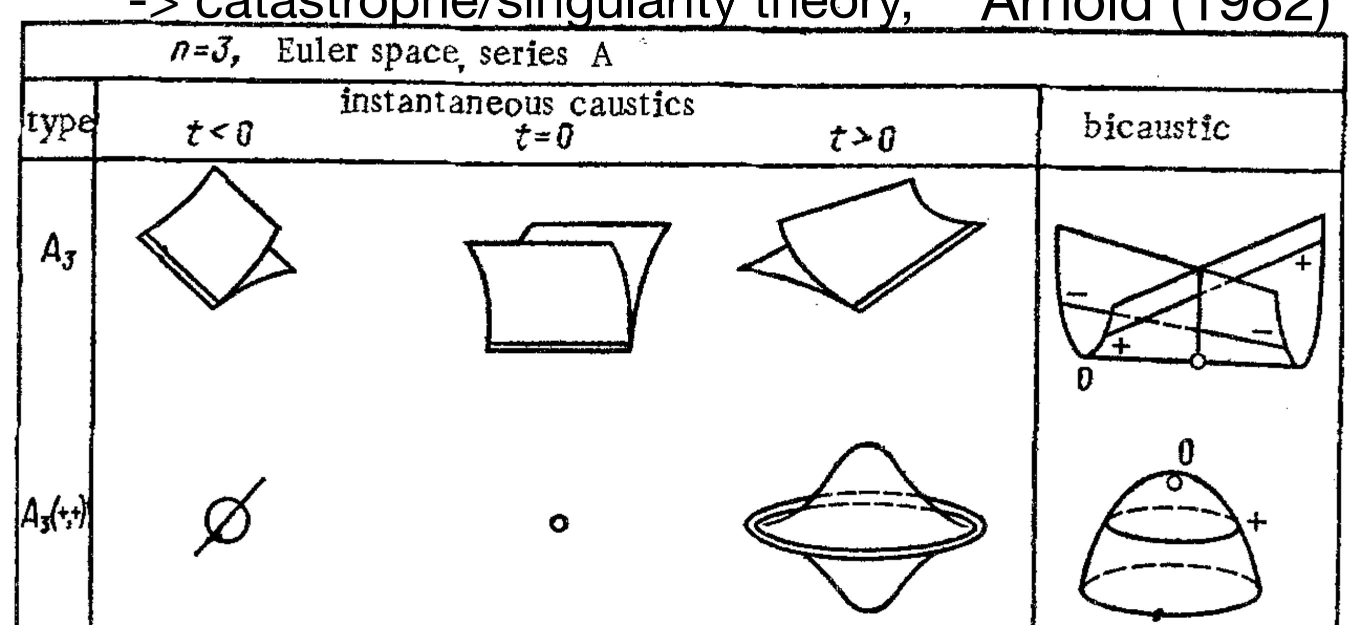
collisionless case:

phase space sheet winds up, but never tears

Phase space (2+1 cut)



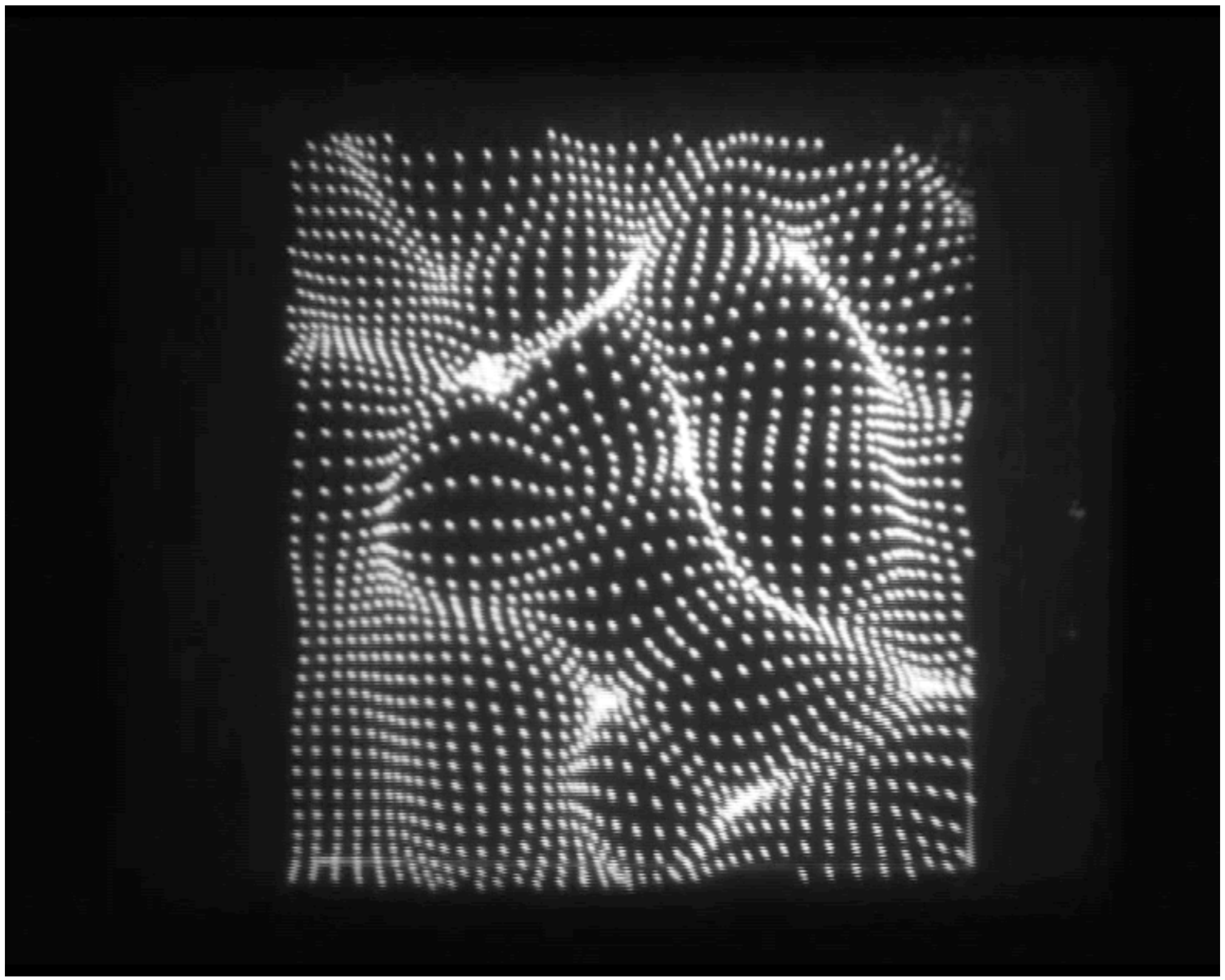
-> catastrophe/singularity theory, Arnold (1982)



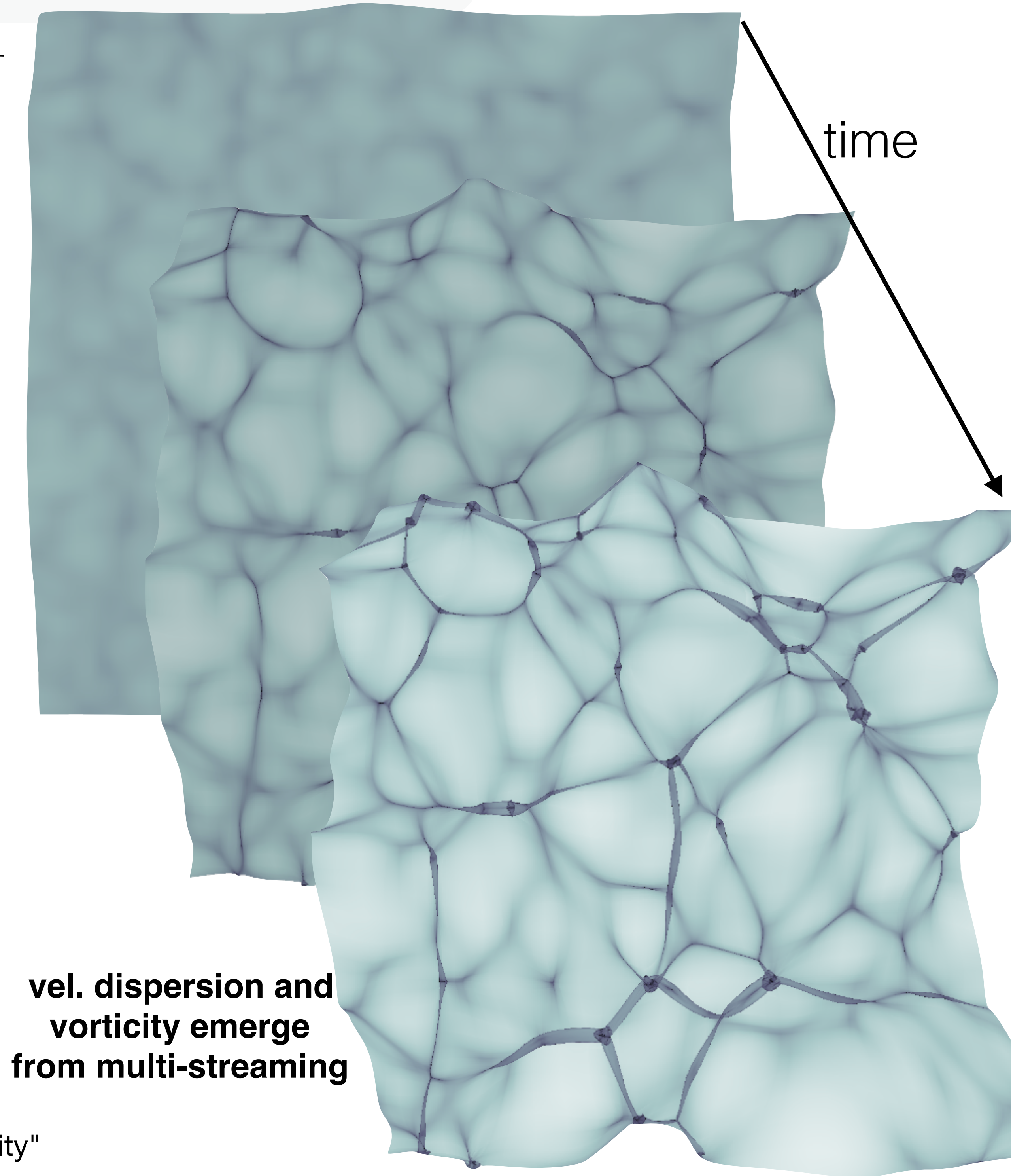
Cosmic web formation/singularities

Formation of structure from catastrophes… Zeldovich pancakes…

$$\rho = m_{\rm DM} \left| \frac{\partial x_i}{\partial q_j} \right|^{-1} \simeq m_{\rm DM} \prod \left(1 + {\rm eig} \left\{ \frac{\partial v_i}{\partial q_j} \right\} \right)^{-1}$$



A. G. Doroshkevich, E. V. Kotok, S. F. Shandarin **1977**:
B. "Evolution of the Density Field according to the Theory of Gravitational Instability"
Can be found on webpage of Jaan Einasto

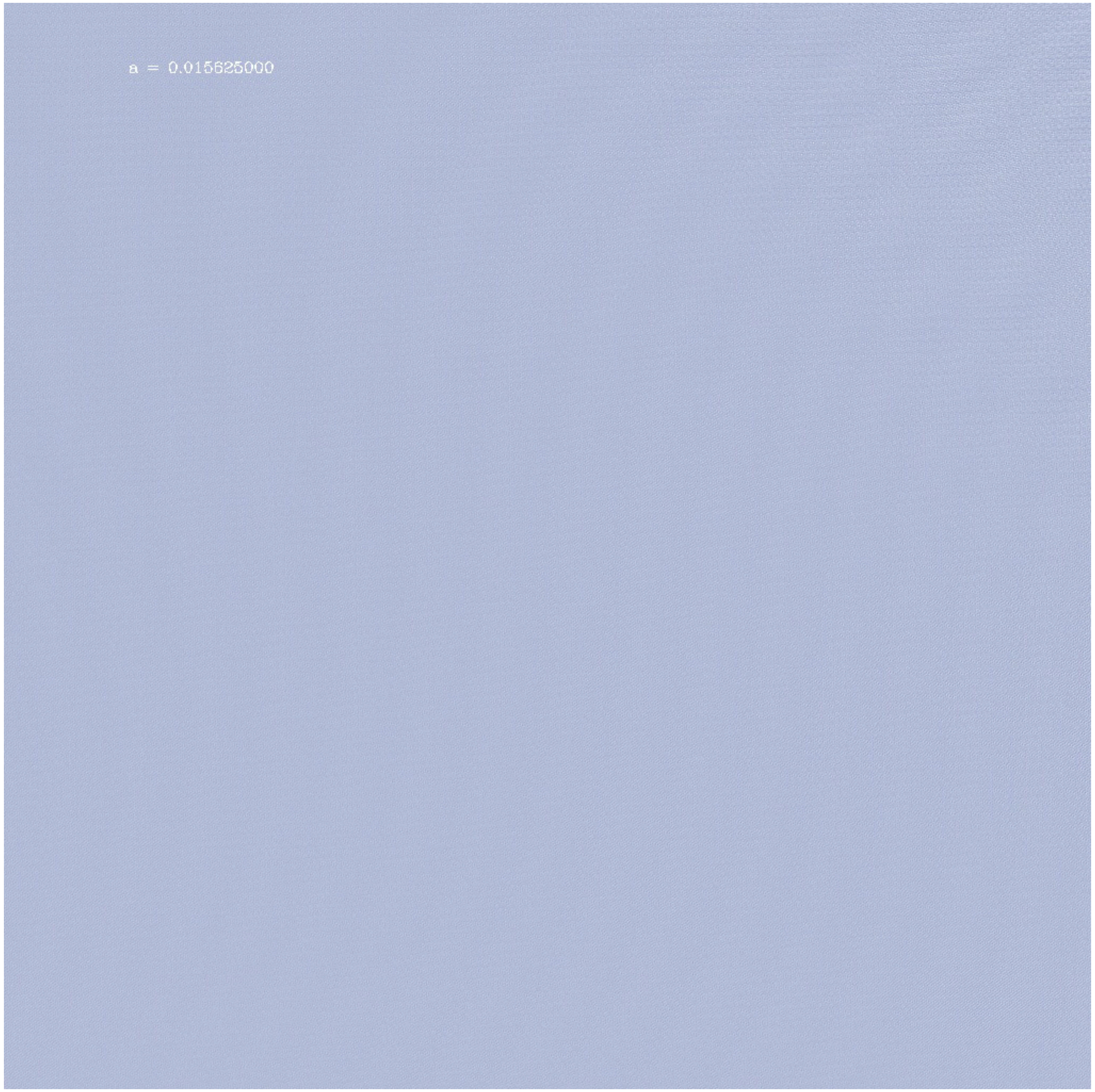


today's version… (run on the fly)

Halo/galaxy formation, CDM-WDM

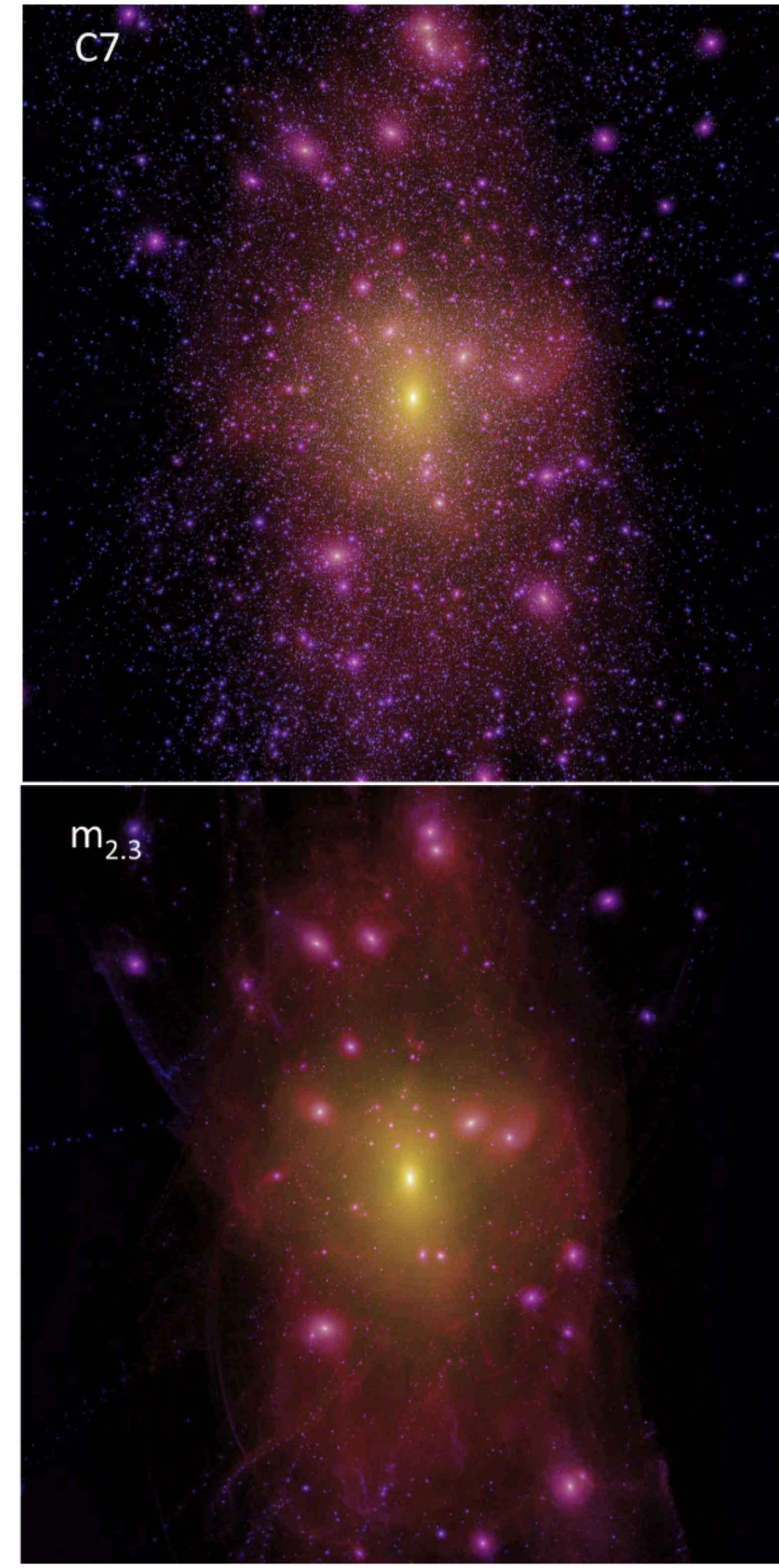
WDM -> introduce a small-scall cut-off to perturbations

monolithic formation of haloes at the free-streaming scale



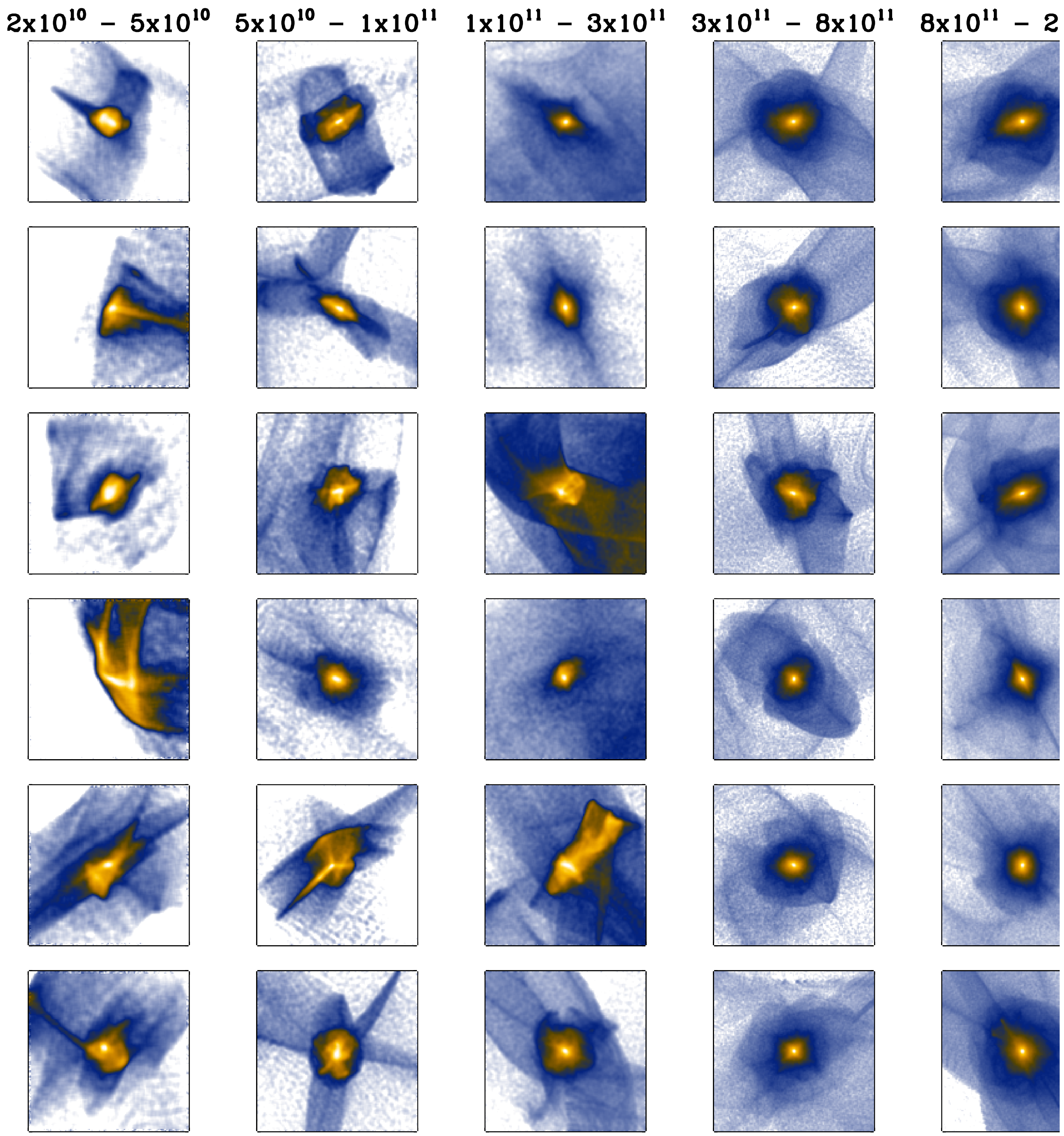
movie: with R. Angulo

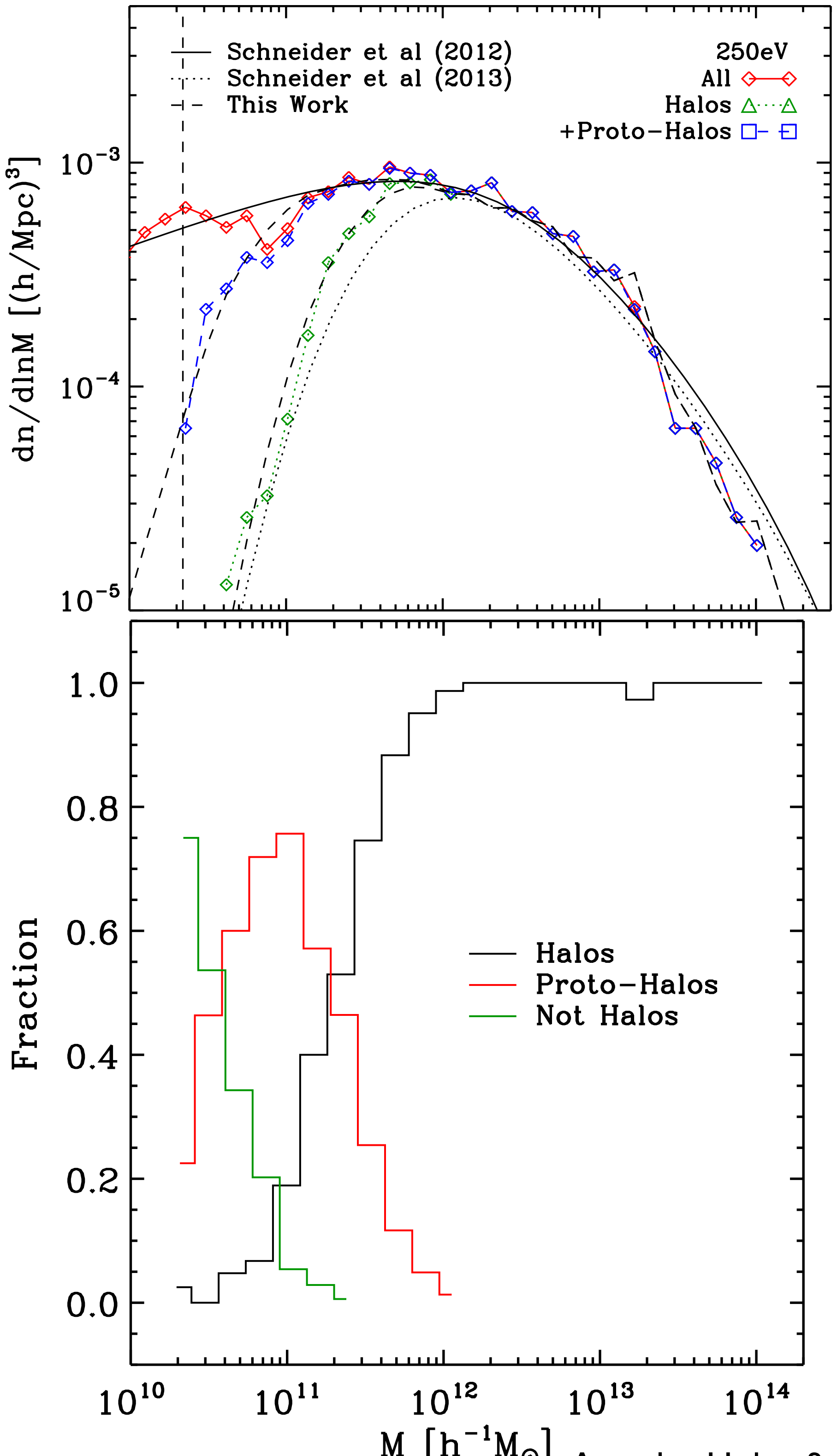
Milky-Way in CDM and WDM



Lovell+2013

Halo/galaxy formation in WDM

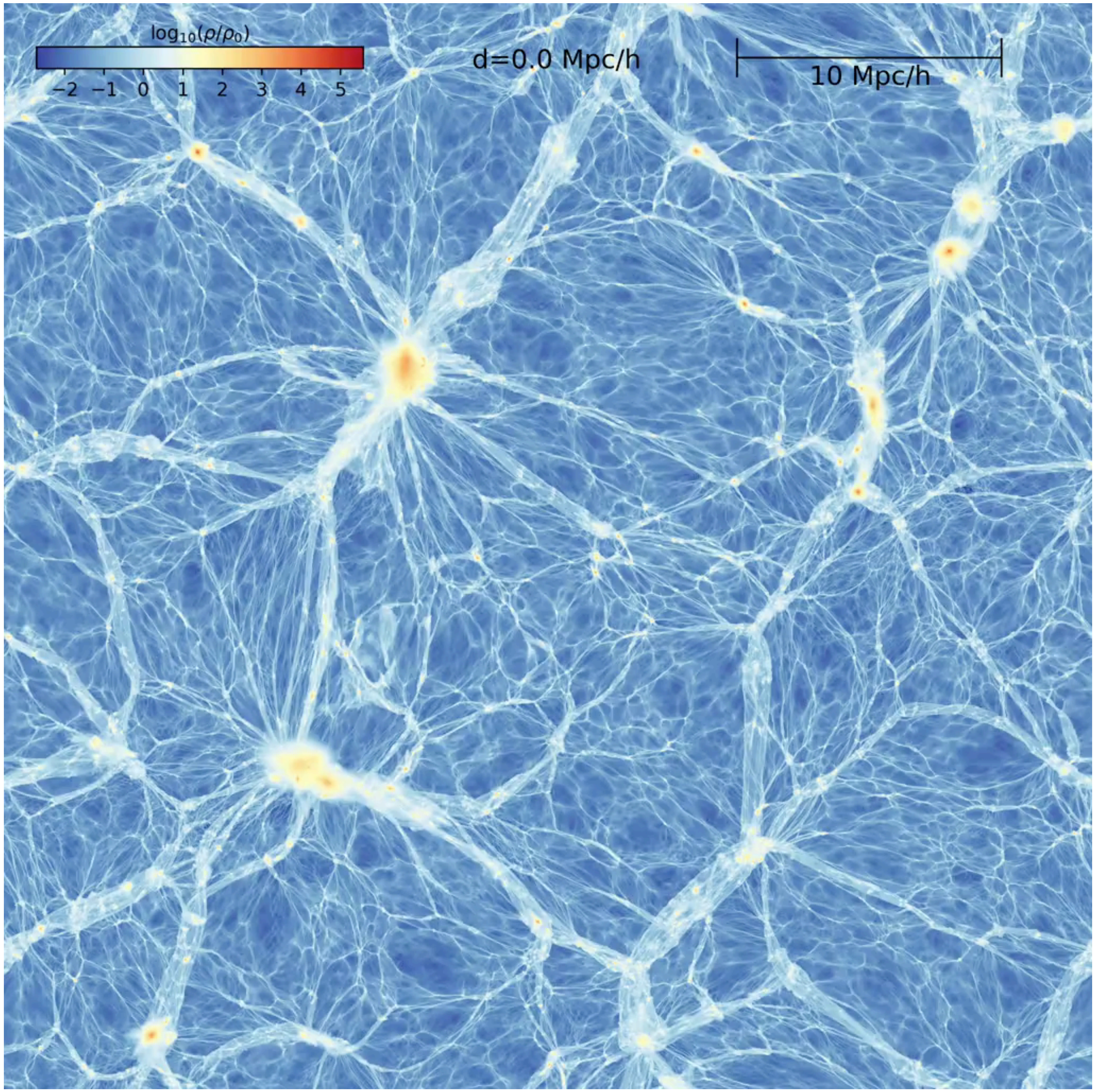




Angulo, Hahn & Abel 2013

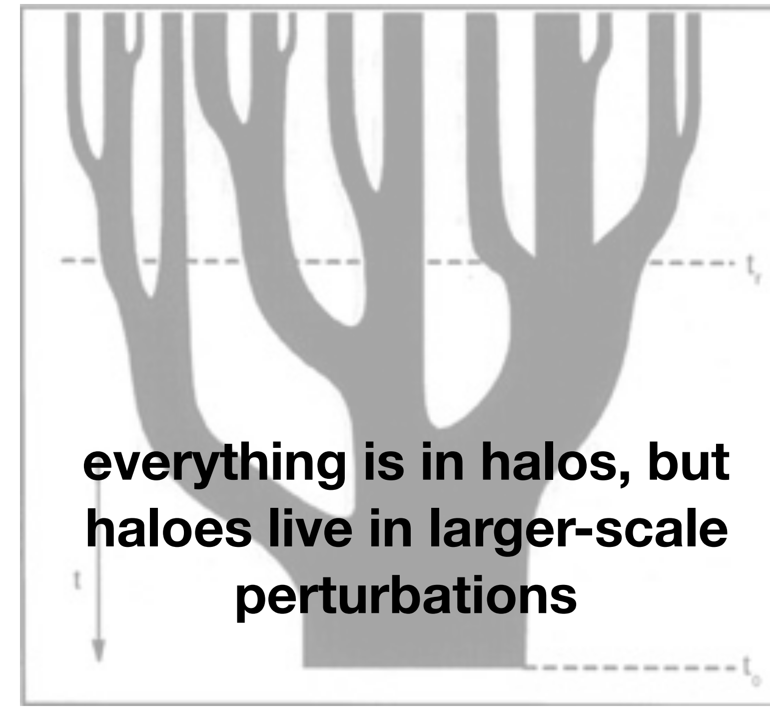
Mass=evolutionary stage,
no progenitors below some mass

Haloes/galaxies in the LSS



moving slice through cosmological volume (by J. Stuecker, cf. Stuecker+2017)

How to reconcile with LCDM hierarchical formation?



everything is in halos, but haloes live in larger-scale perturbations

largest scale turning non-linear determines LSS

-> many haloes in clusters, few in voids (e.g. Kaiser 1984)

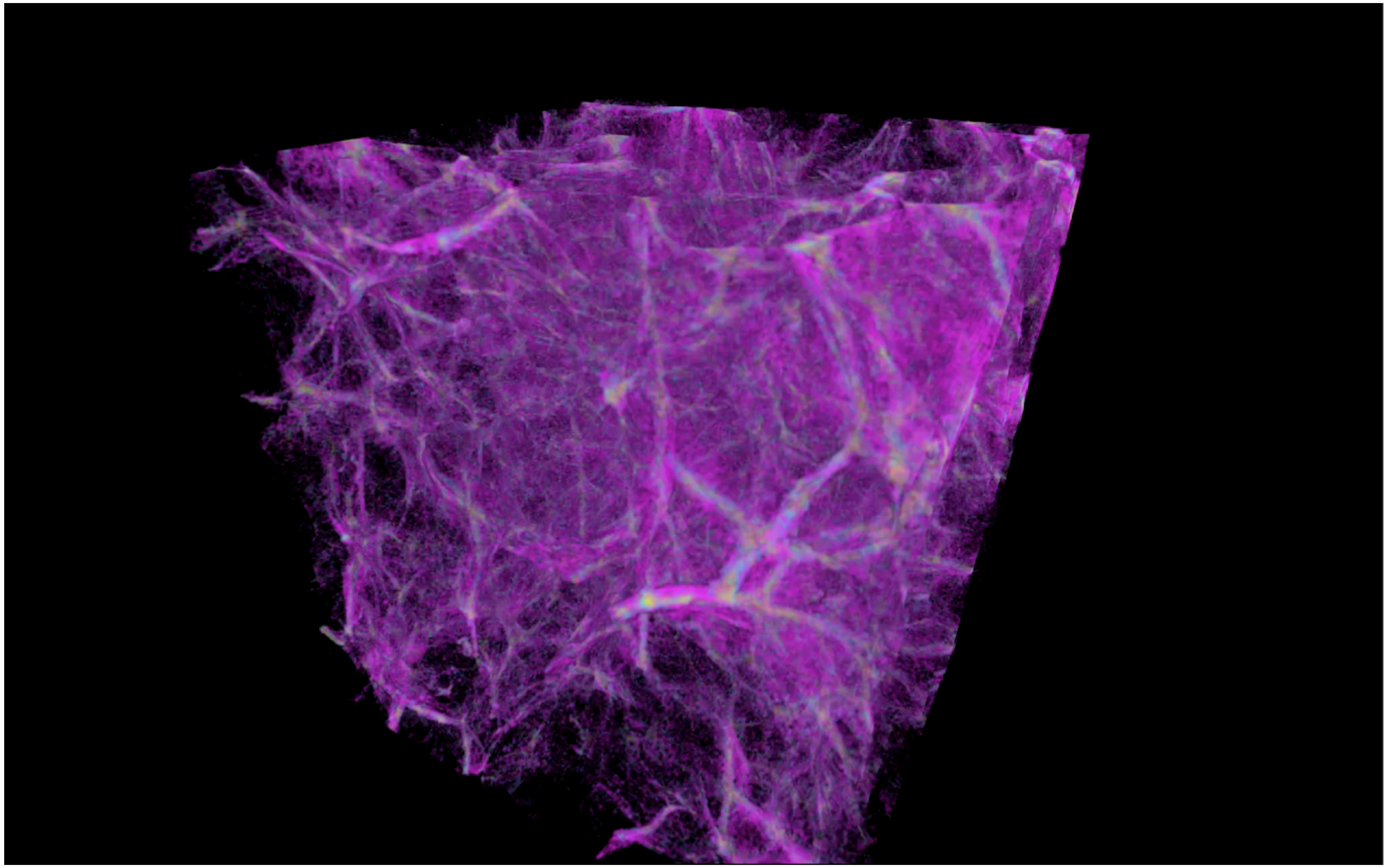
and galaxies?

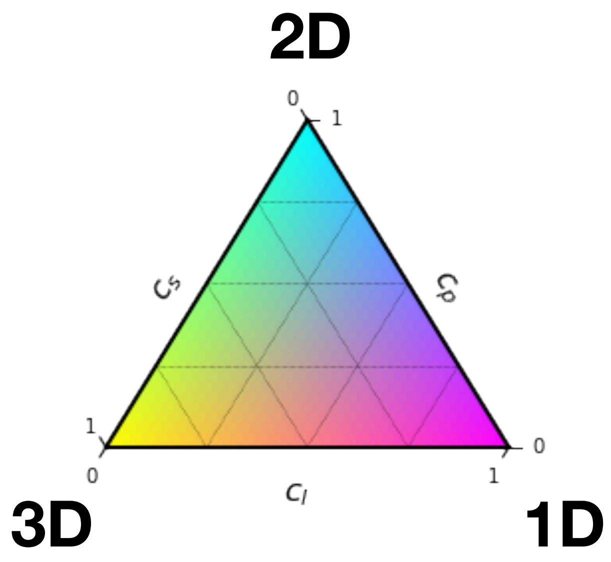
form inside DM haloes, but from dissipative processes

do galaxies care about LSS beyond halo mass?

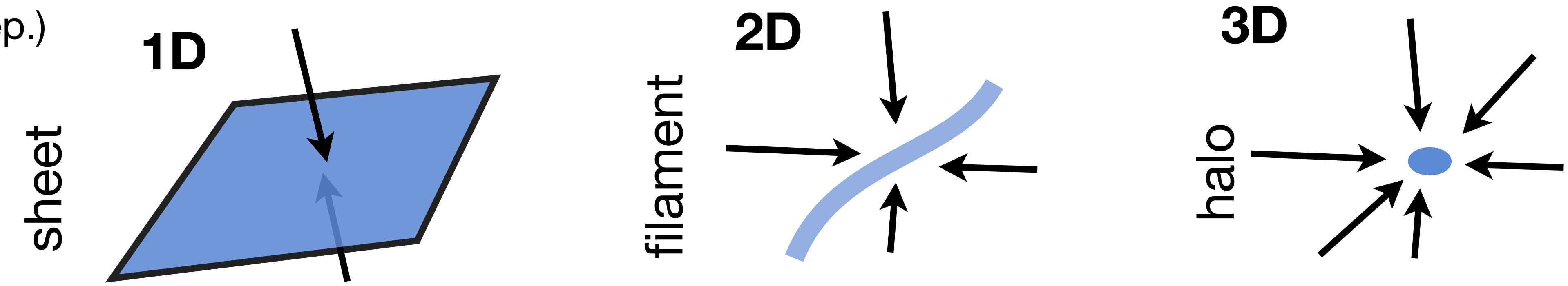
Collisionless component (DM, galaxies) does not isotropize

Velocity dispersion in collapsed regions retains memory of collapsed dimension





Buehlmann&OH (2018,in prep.)

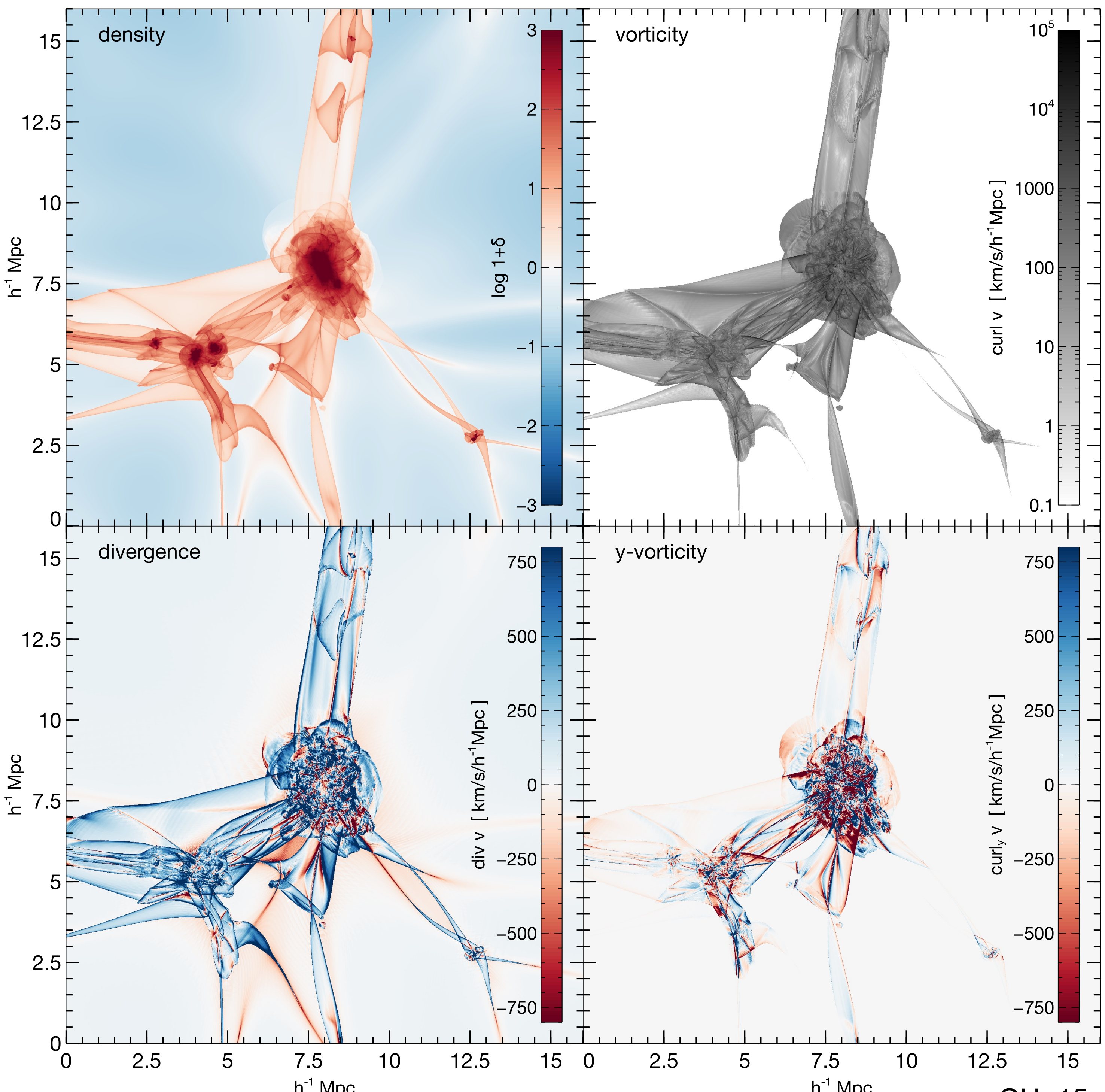


A zoom in on multi-stream regions

- Vorticity for std. gravity pure multi-stream phenomenon!!

$$\nabla \cdot \langle \mathbf{v} \rangle = \left\langle (\nabla \log \rho) \cdot (\mathbf{v} - \langle \mathbf{v} \rangle) \right\rangle + \langle \nabla \cdot \mathbf{v} \rangle$$

$$\nabla \times \langle \mathbf{v} \rangle = \left\langle (\nabla \log \rho) \times (\mathbf{v} - \langle \mathbf{v} \rangle) \right\rangle + \langle \nabla \times \mathbf{v} \rangle$$



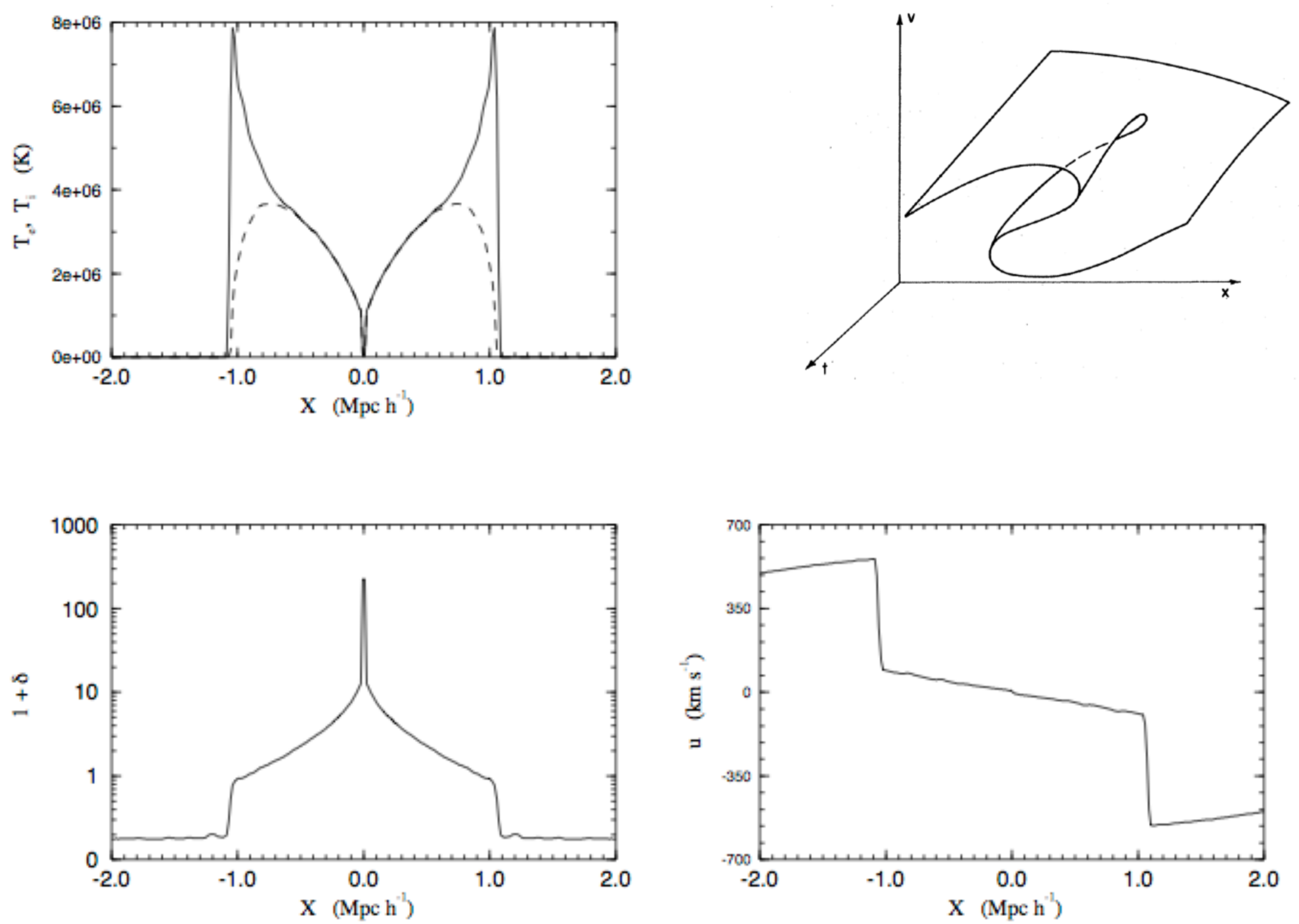
OH+15

Shell-crossing breaks the trivial coupling between density and velocity divergence

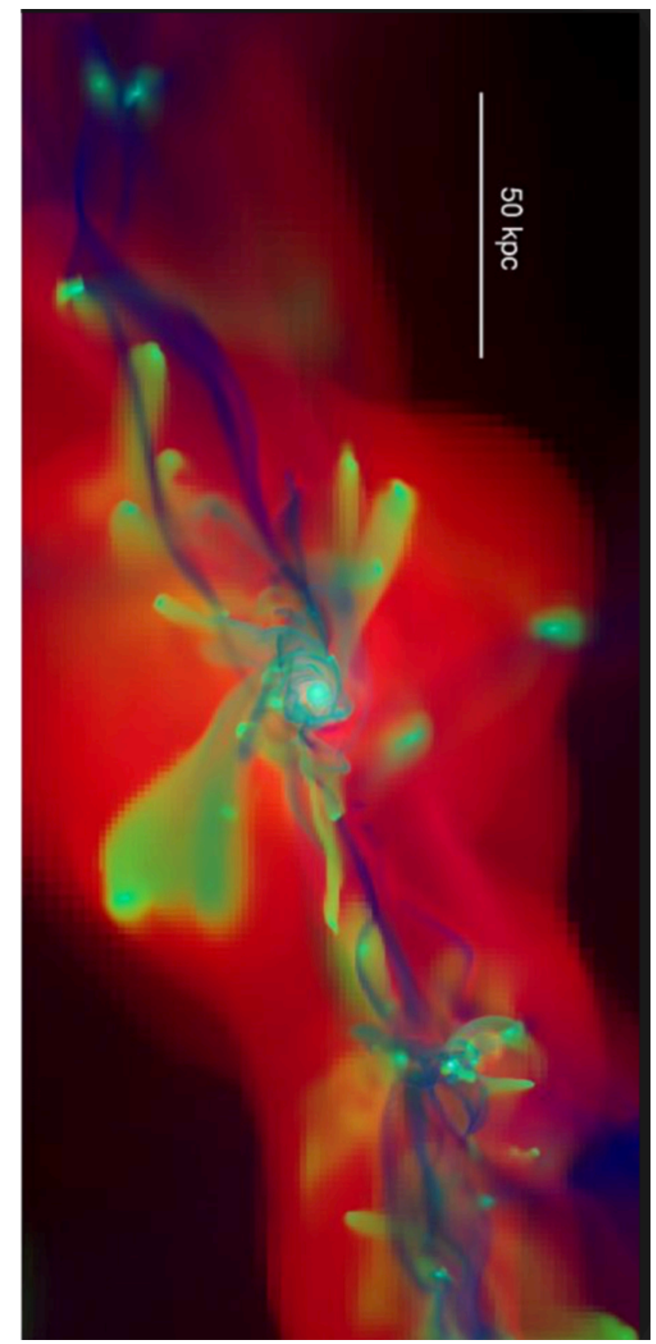
Collisionless component will retain some memory of its initial conditions, but gas…?

Gas: Shock Formation, Cooling…

Phenomenology similar to DM, but produce shocks instead of caustics
cooling possible due to increased density in collapsed region

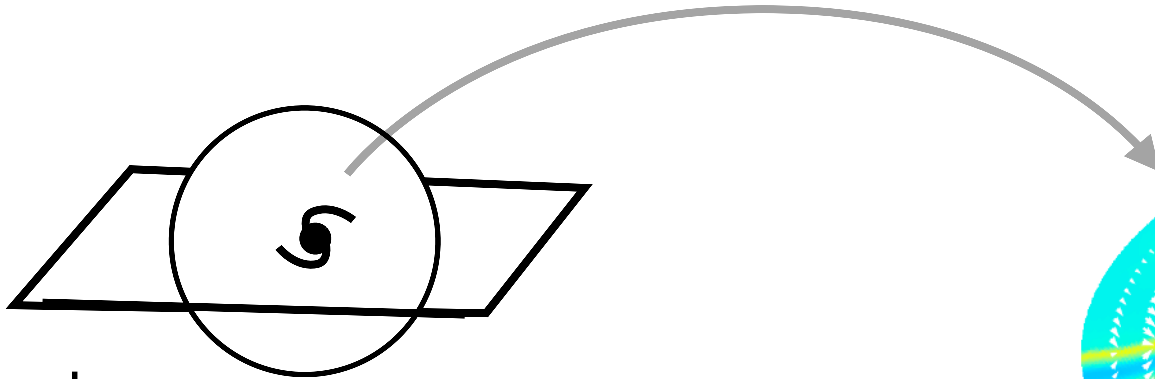


from Teyssier et al. (1998)



Agertz+2009

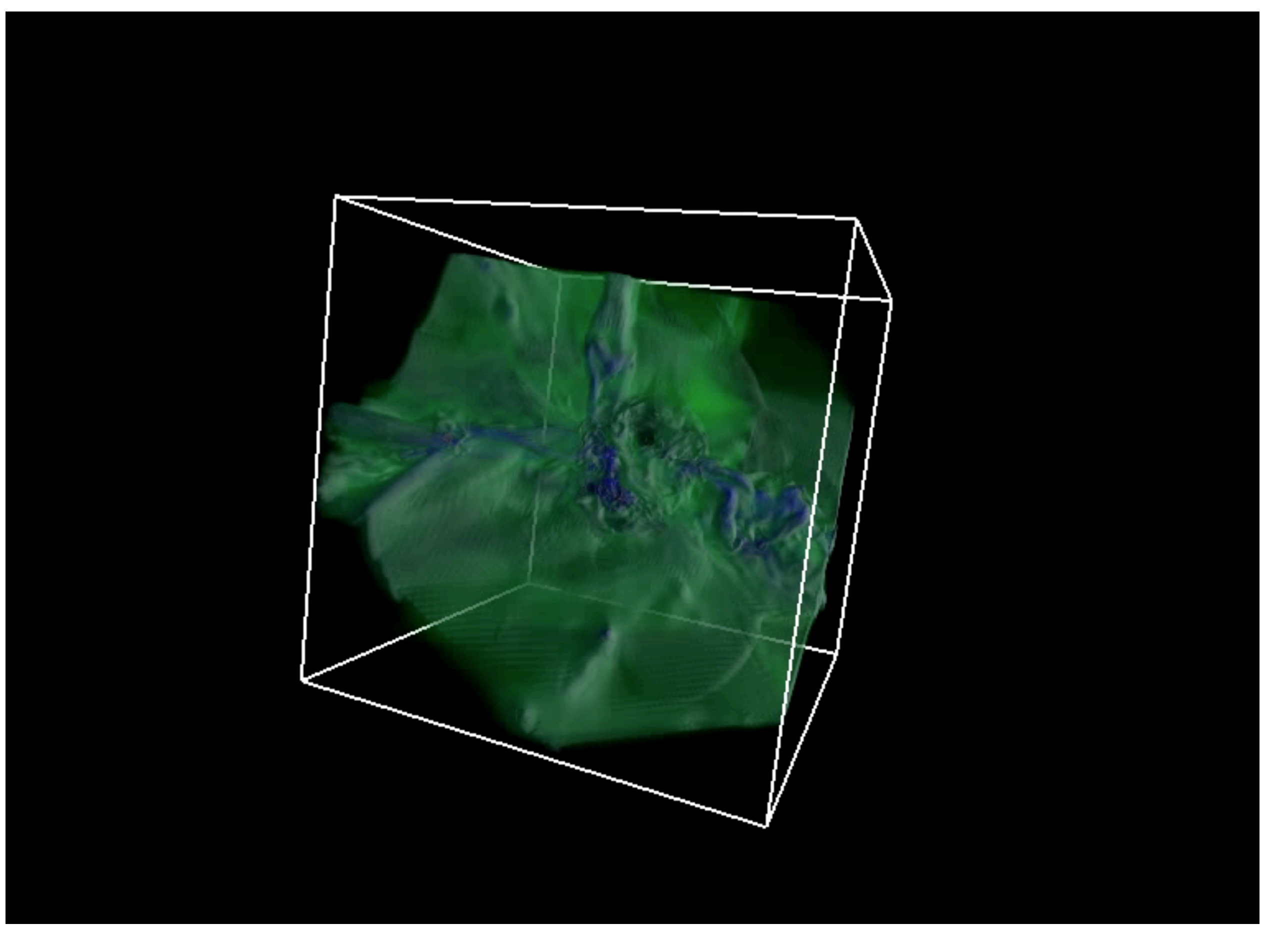
Gas around high-z galaxies



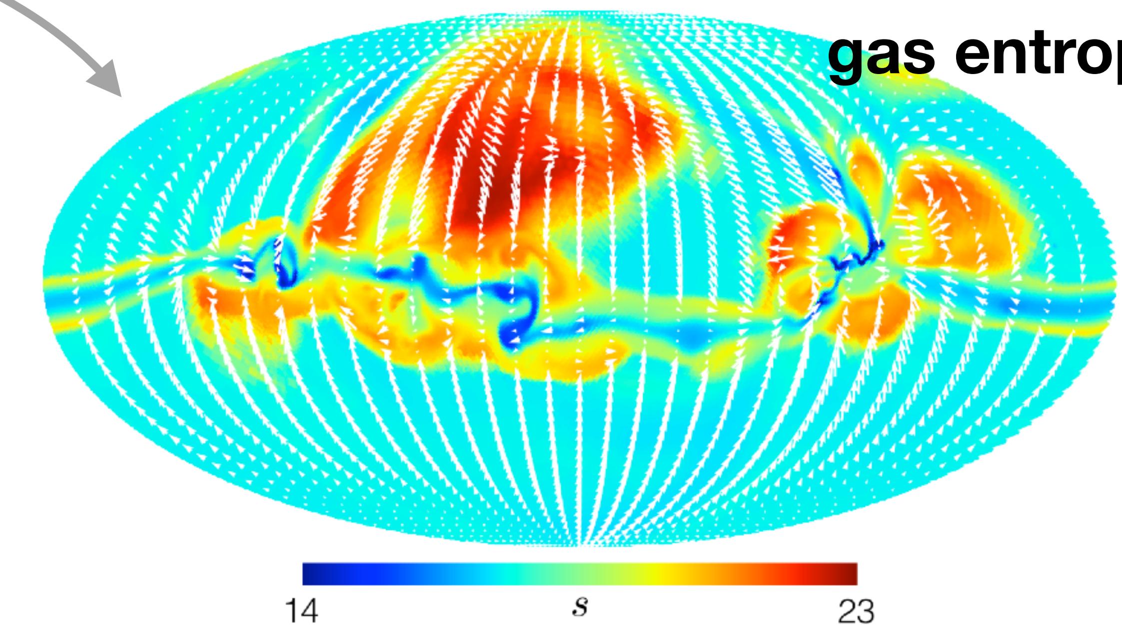
Planar structure

Gas accretes onto plane,
then into streams

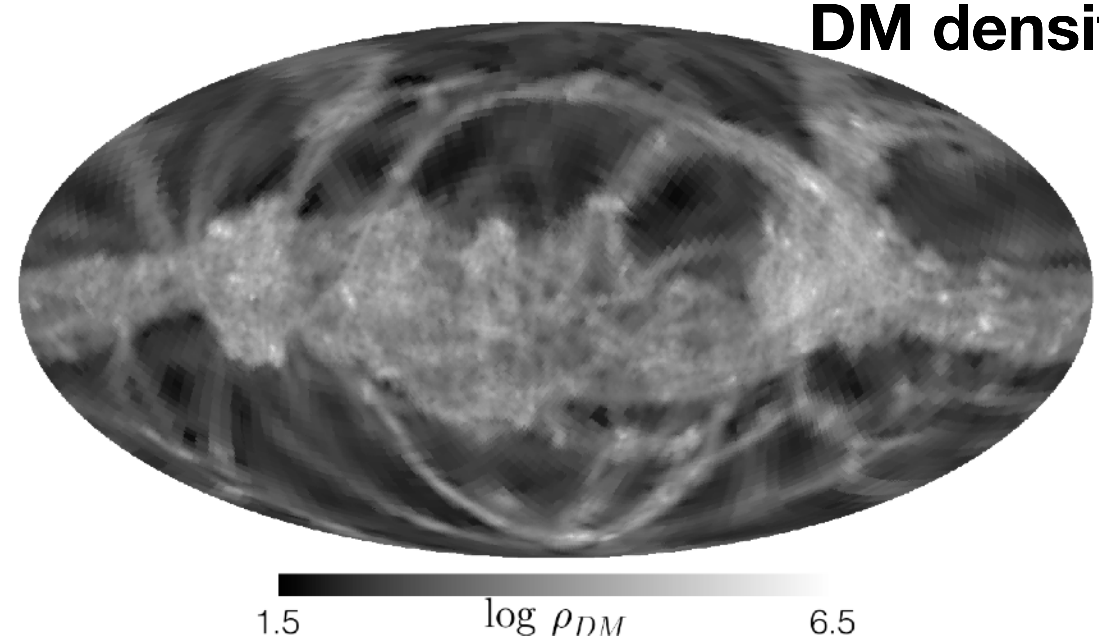
Shocks on both sides



gas entropy



DM density



cold streams (cf. Keres+2005, Dekel+2009,…)
embedded in extended pancakes
(e.g. Danovich 2012,15)

Structure of high-z pancakes

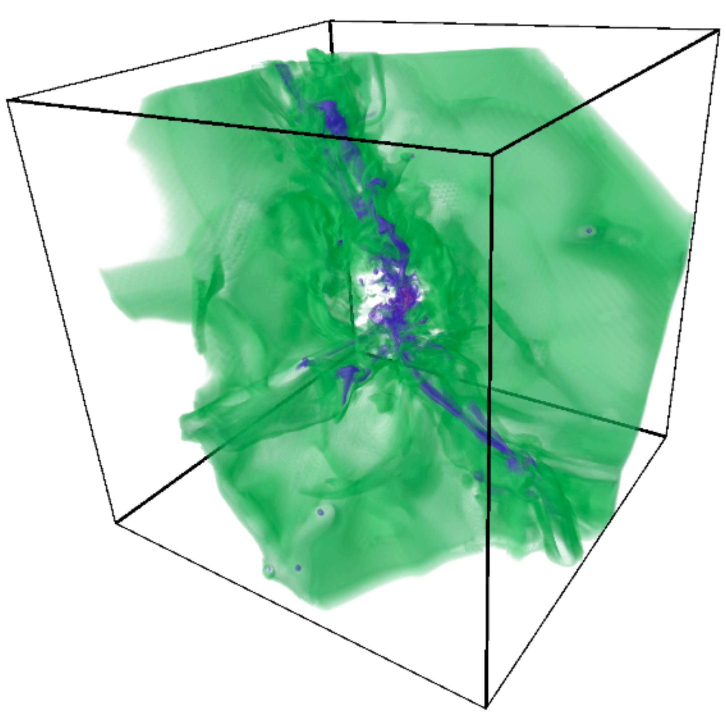
DM caustics (solid gray)
vs.
hydro shocks (dashed gray)

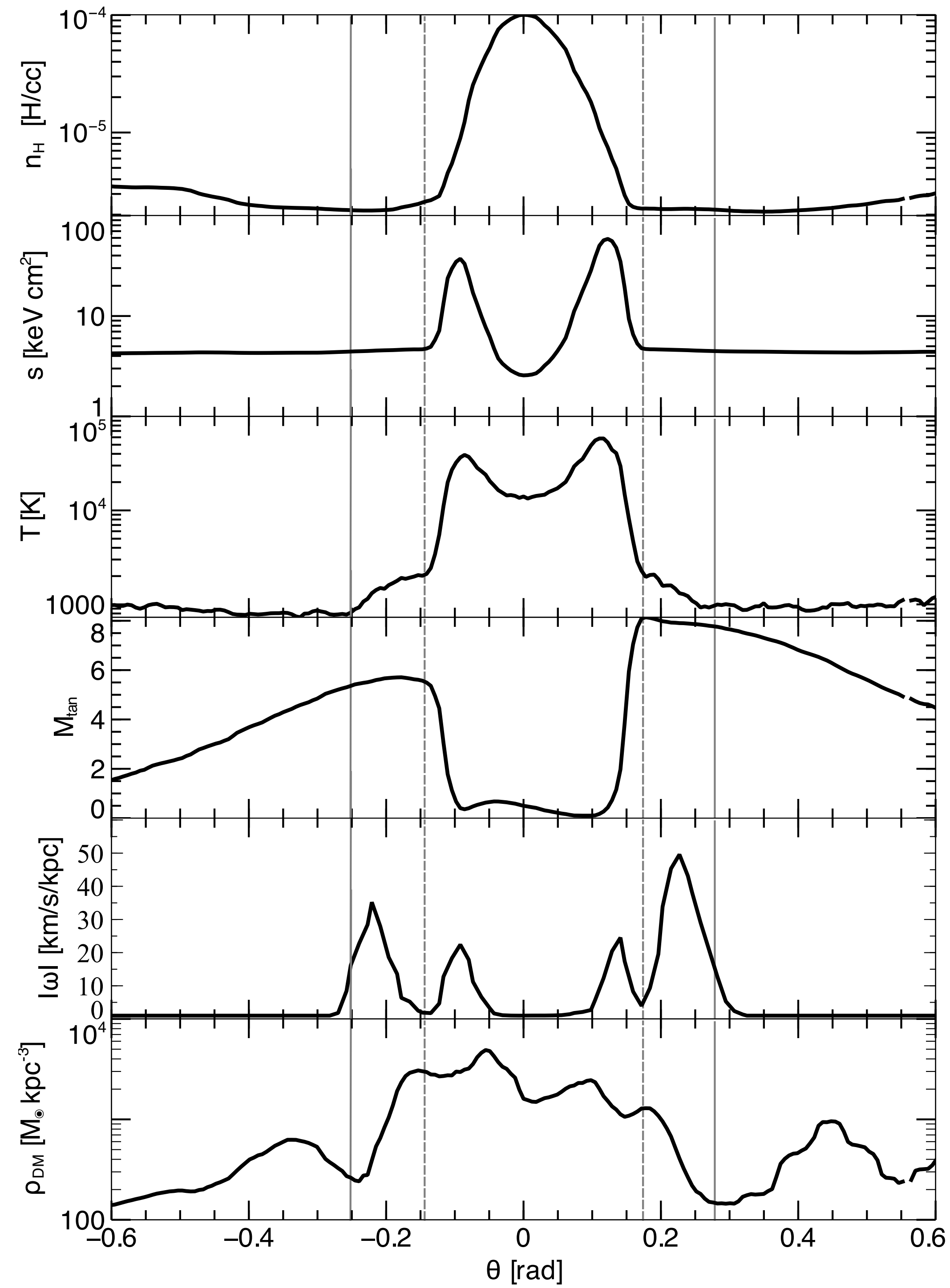
Shandarin & Zeldovich (1989):

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

one measures

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





Density

Entropy

Temperature

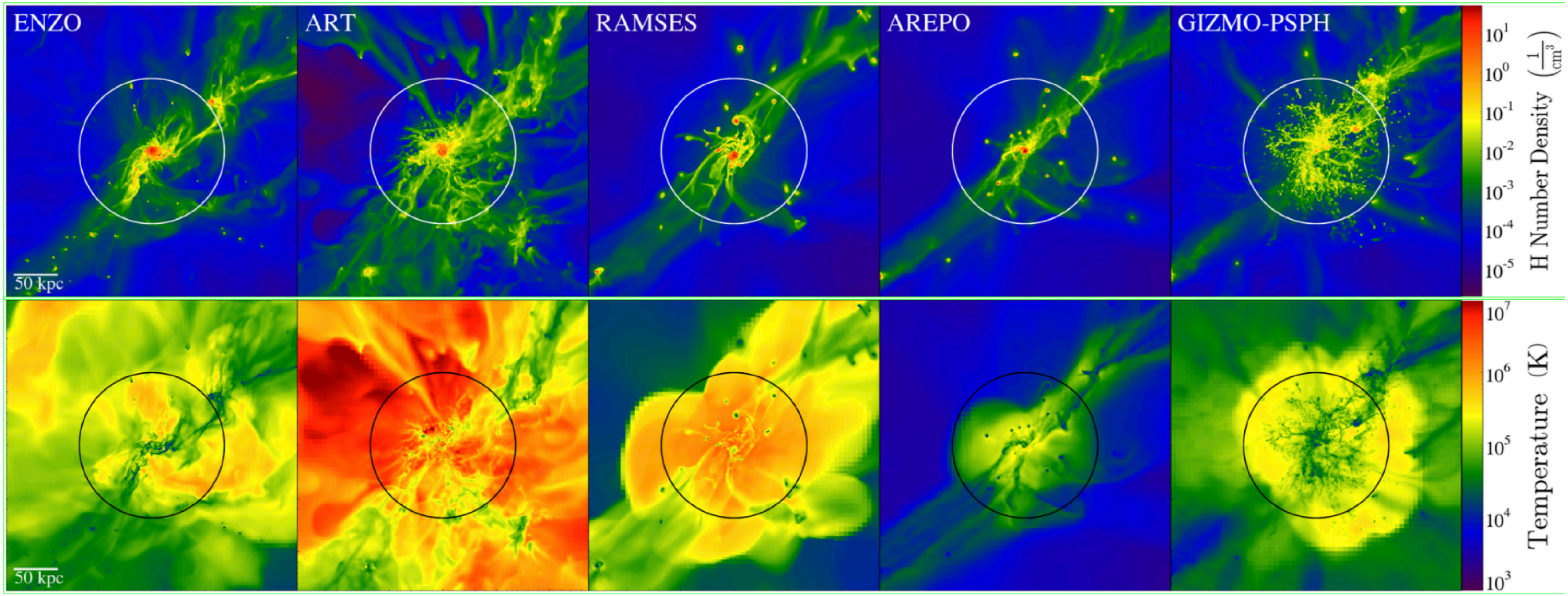
Mach number

Vorticity

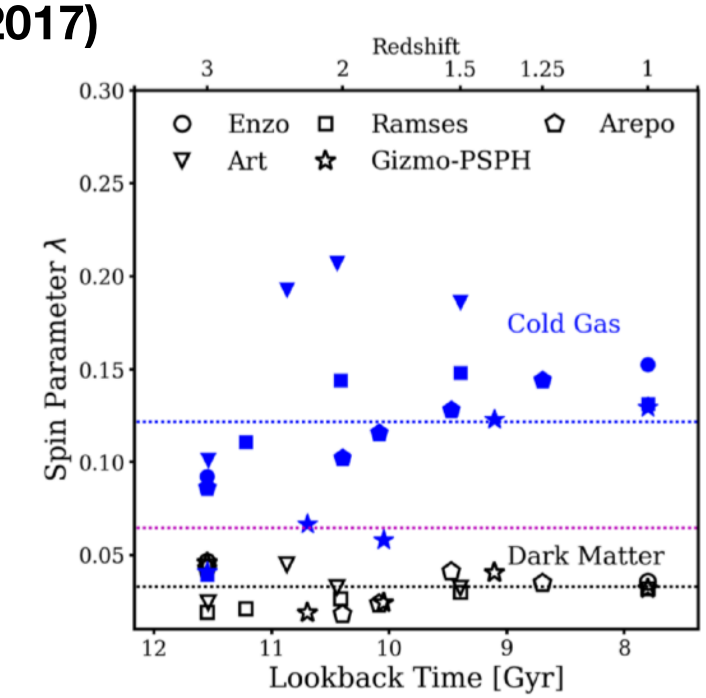
DM density

(unpublished, with A. Dekel)

Anisotropic accretion onto galaxies at high-z



Stewart+(2017)



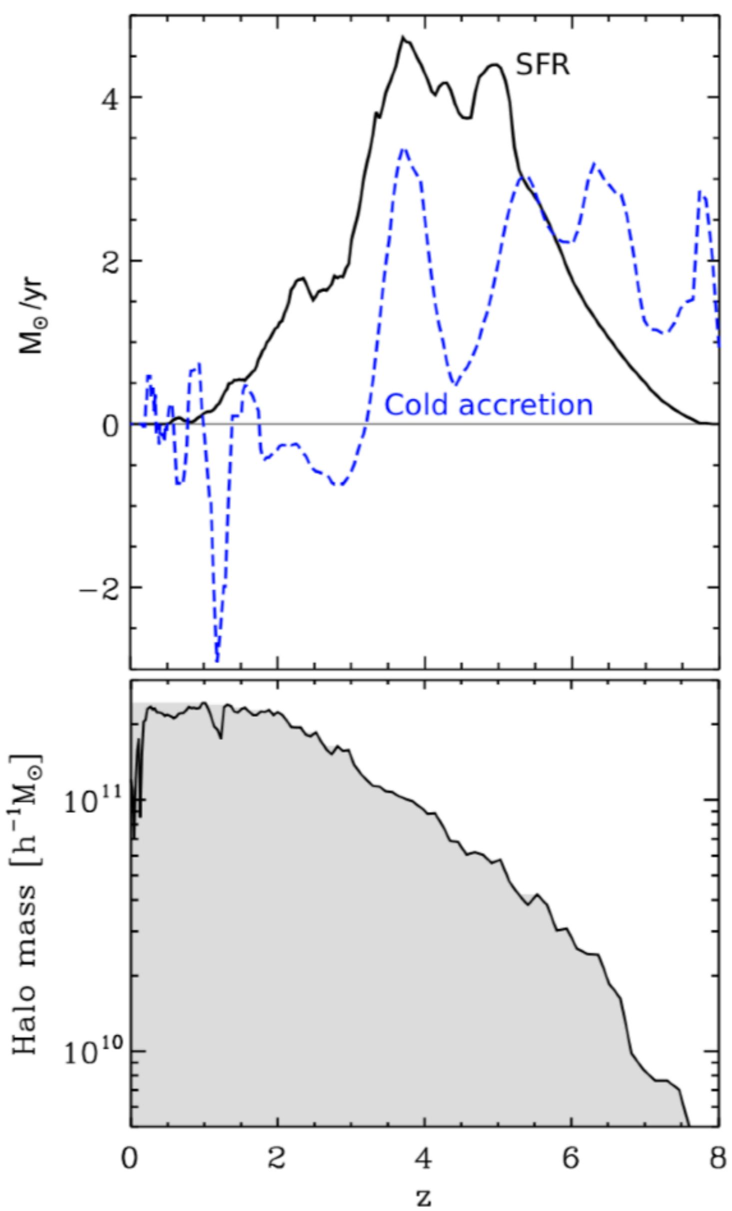
In principle streams dump very efficiently gas into CGM at high z.

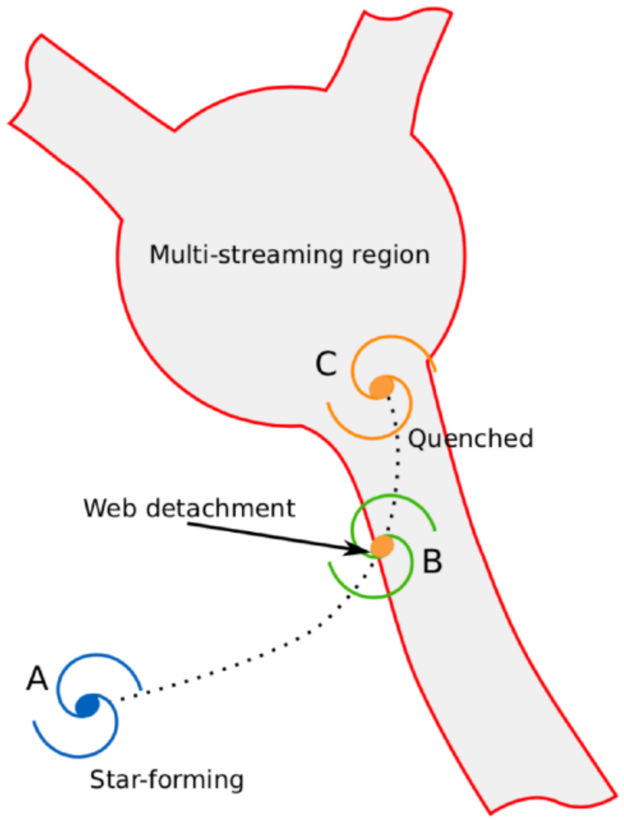
Role of galactic process (outflows) can counteract this…

(and galaxy formation is just so inefficient…)

LSS influencing galaxy evolution?

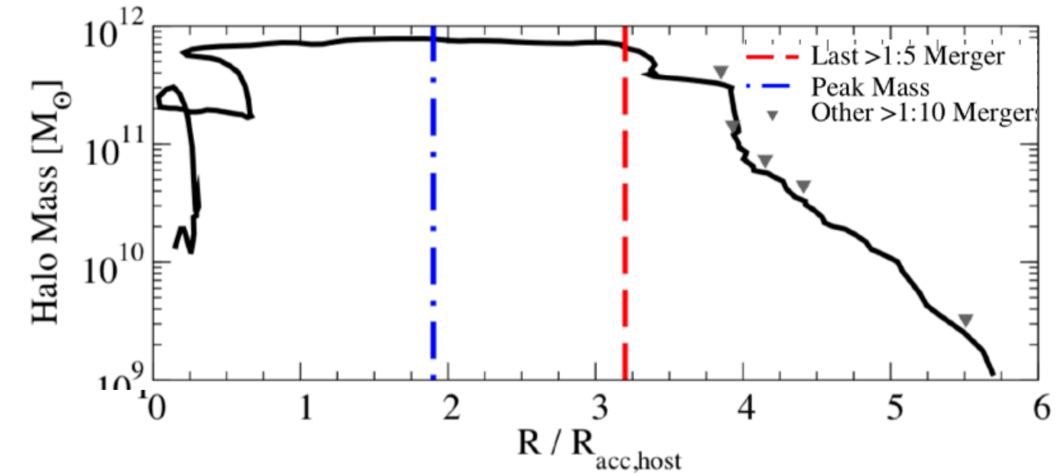
“Cosmic web detachment” drives quenching?
Aragon-Calvo+2016





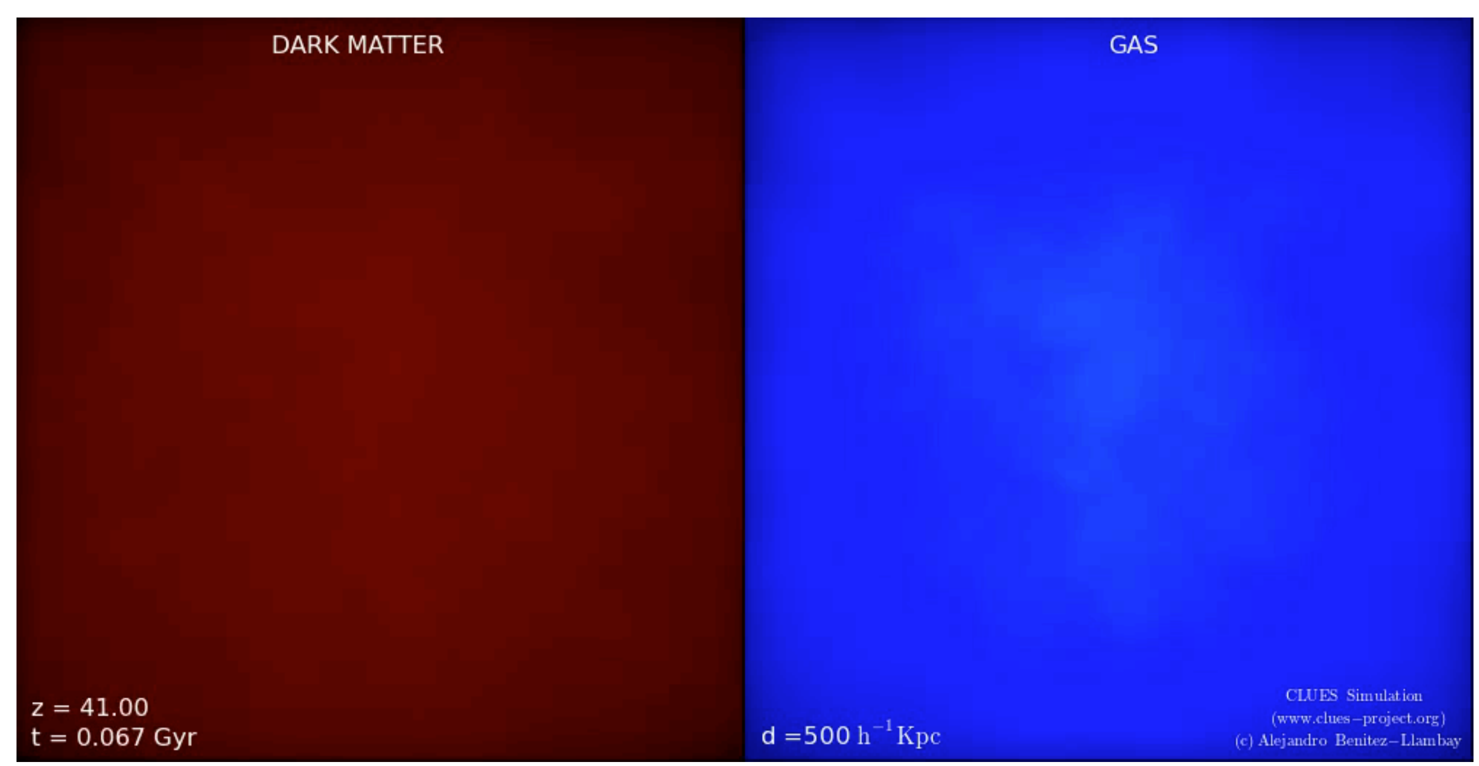
->Assembly bias

Mergers and Accretion end well outside virial radius
Behroozi+2014 (see also OH+09, Bahé+13)



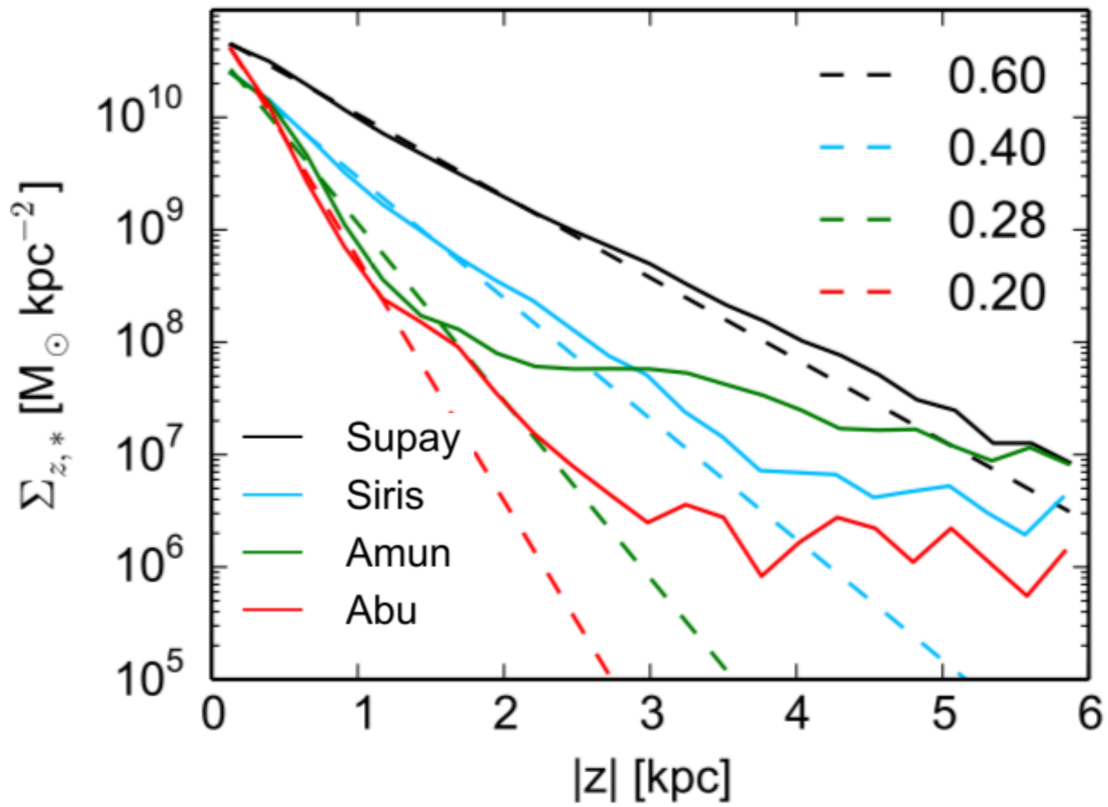
+ ram-pressure in filaments? (Bahé+13)

Stripping of MW satellites in filaments/pancakes?
Benitez-Llambay+(2013)



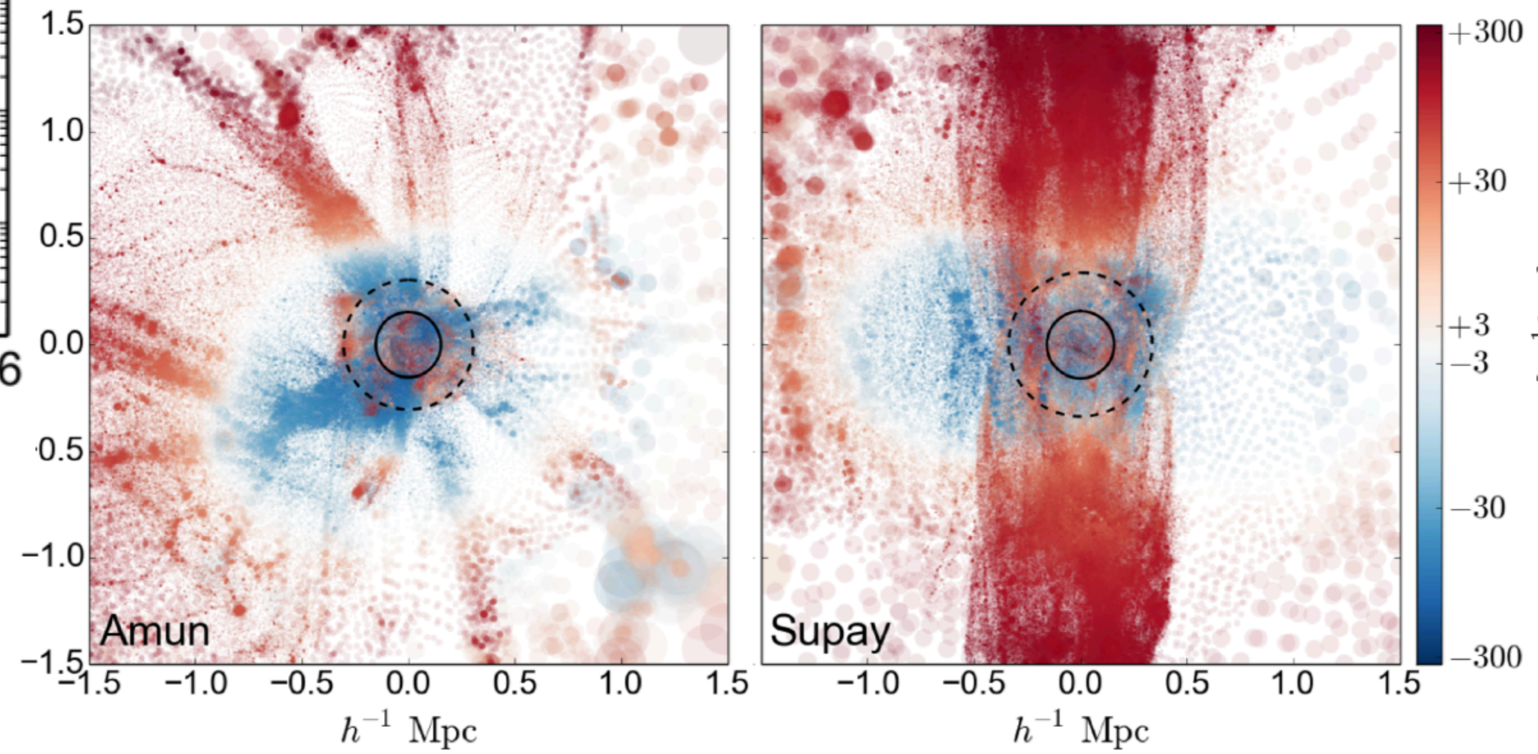
Differences in galaxy assembly?

Dedicated zooms of early and late forming halos indicate possibly puffier disks and older stellar populations at fixed halo mass



Romano-Diaz+2017

At fixed halo mass, accretion rate depends whether halo is `locally dominant`. This sets also ratio of radially to tangentially accreted material (see also Faltenbacher&White 2010)



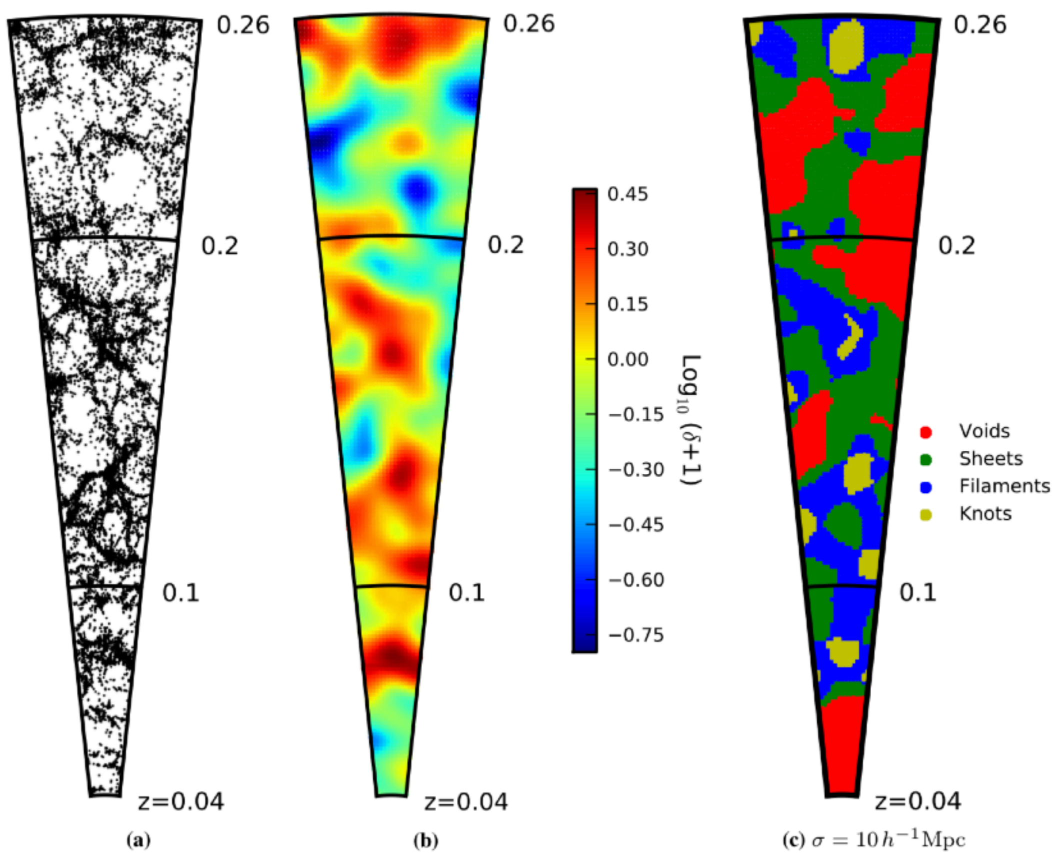
Borzyszkowski+2017

can one test this in observations?

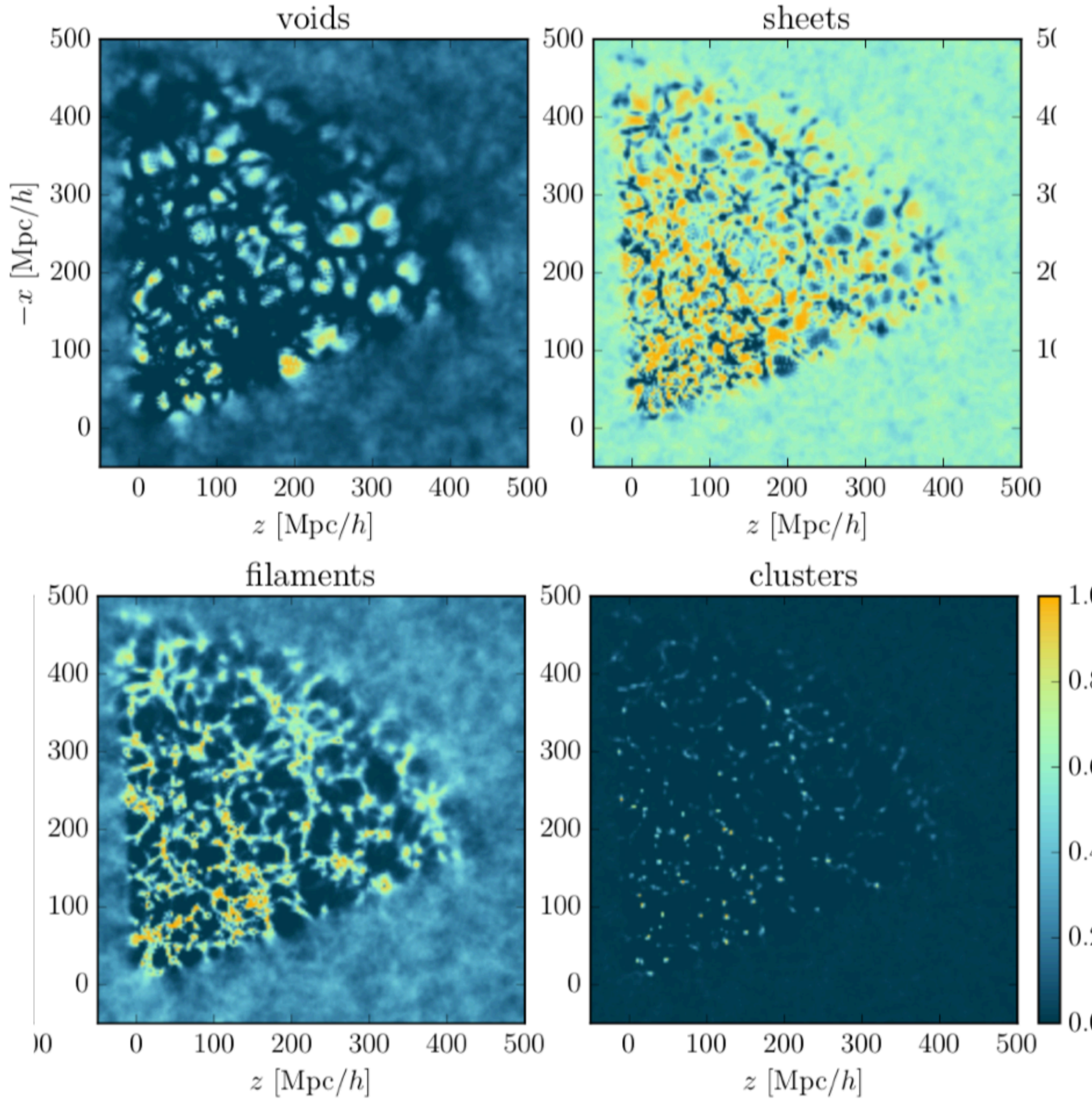
How to quantify the cosmic web in observations?

Usually: from density field estimate

- then eigenvalue signature of Hessian of potential (OH+2007) or density (Aragon-Calvo+2007)
- or Morse properties of smoothed density field (Sousbie 2011),
- or …



Eardley+(2015), GAMA data



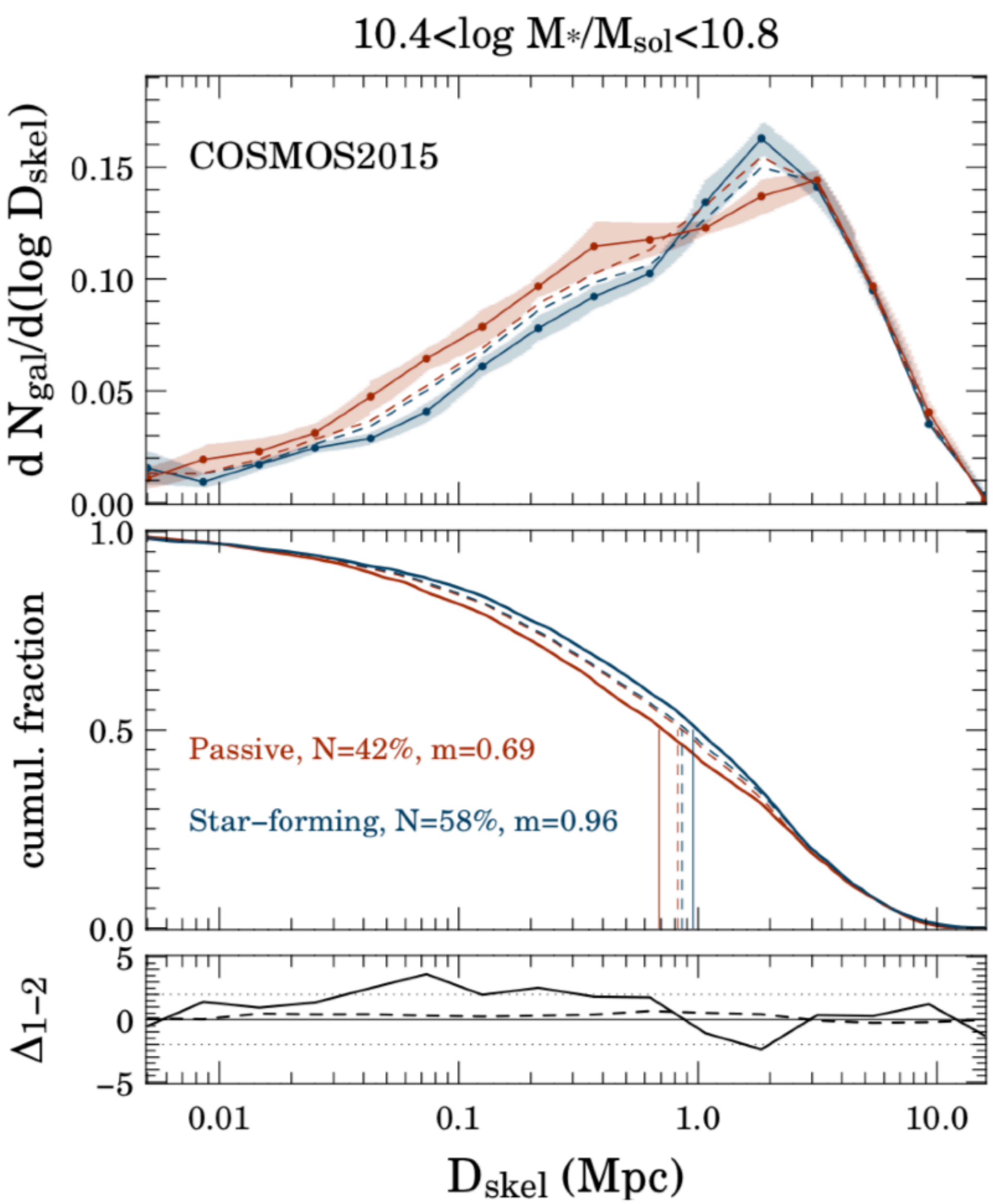
Leclercq+(2016), forward modelling of SDSS data

see also review on different methods by Libeskind+2018

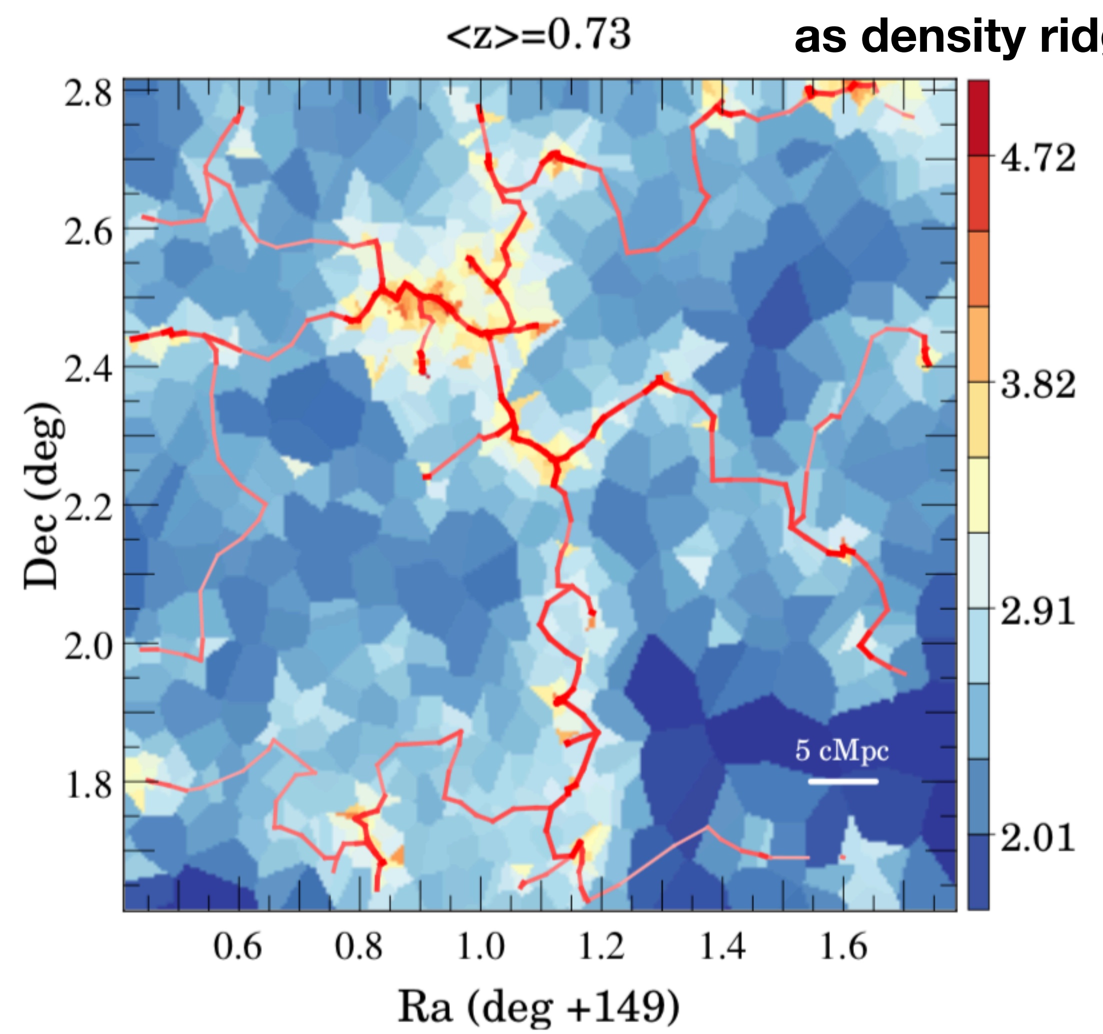
Environmental Dependence of Galaxy Formation

Anything `beyond halo mass` ?

Segregation of passive/star-forming galaxies towards filament centers, but is this driven by halo mass or by LSS environment?



skeleton defines filaments as density ridges

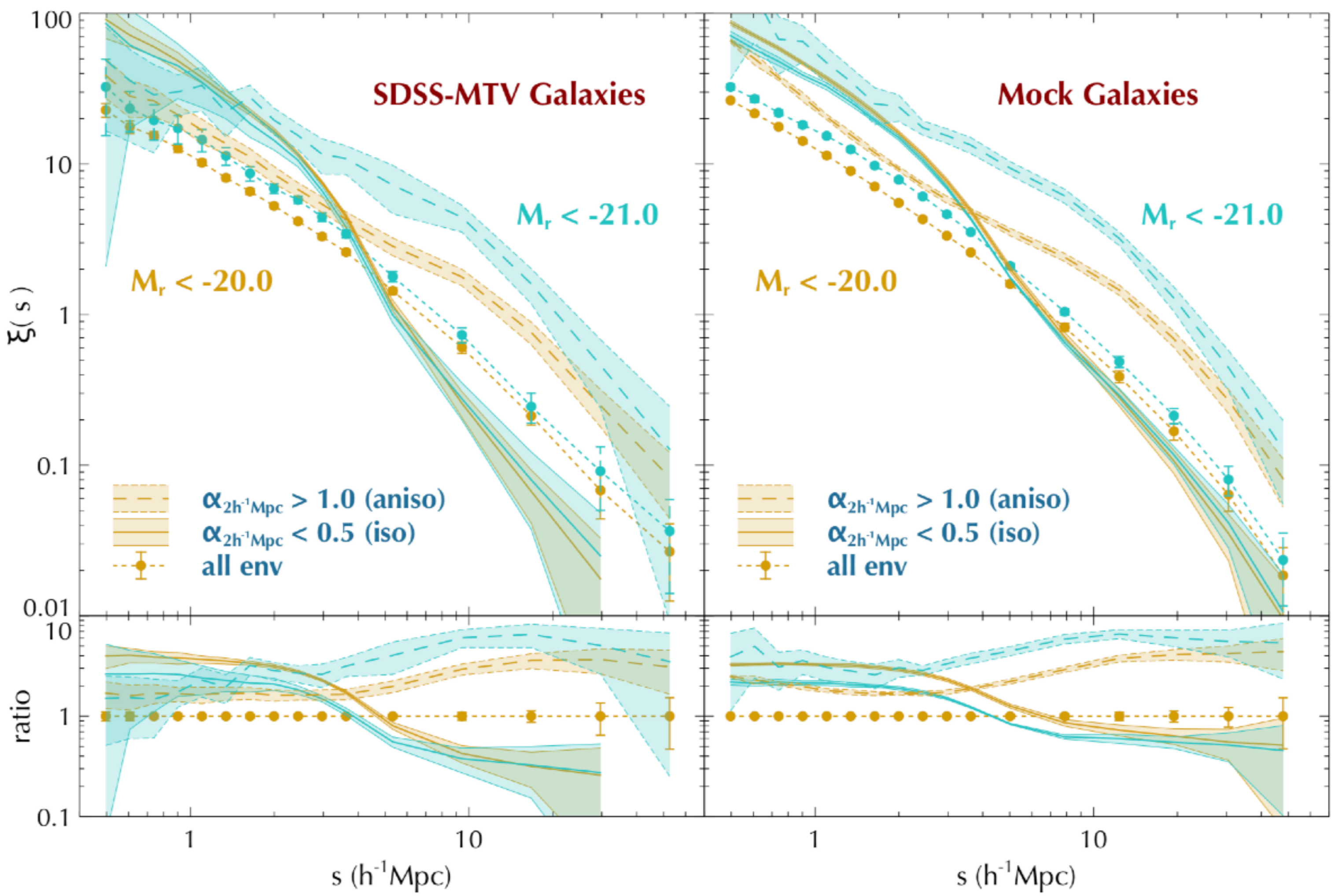


Laigle+2017, skeleton identification on photometric COSMOS2015 data

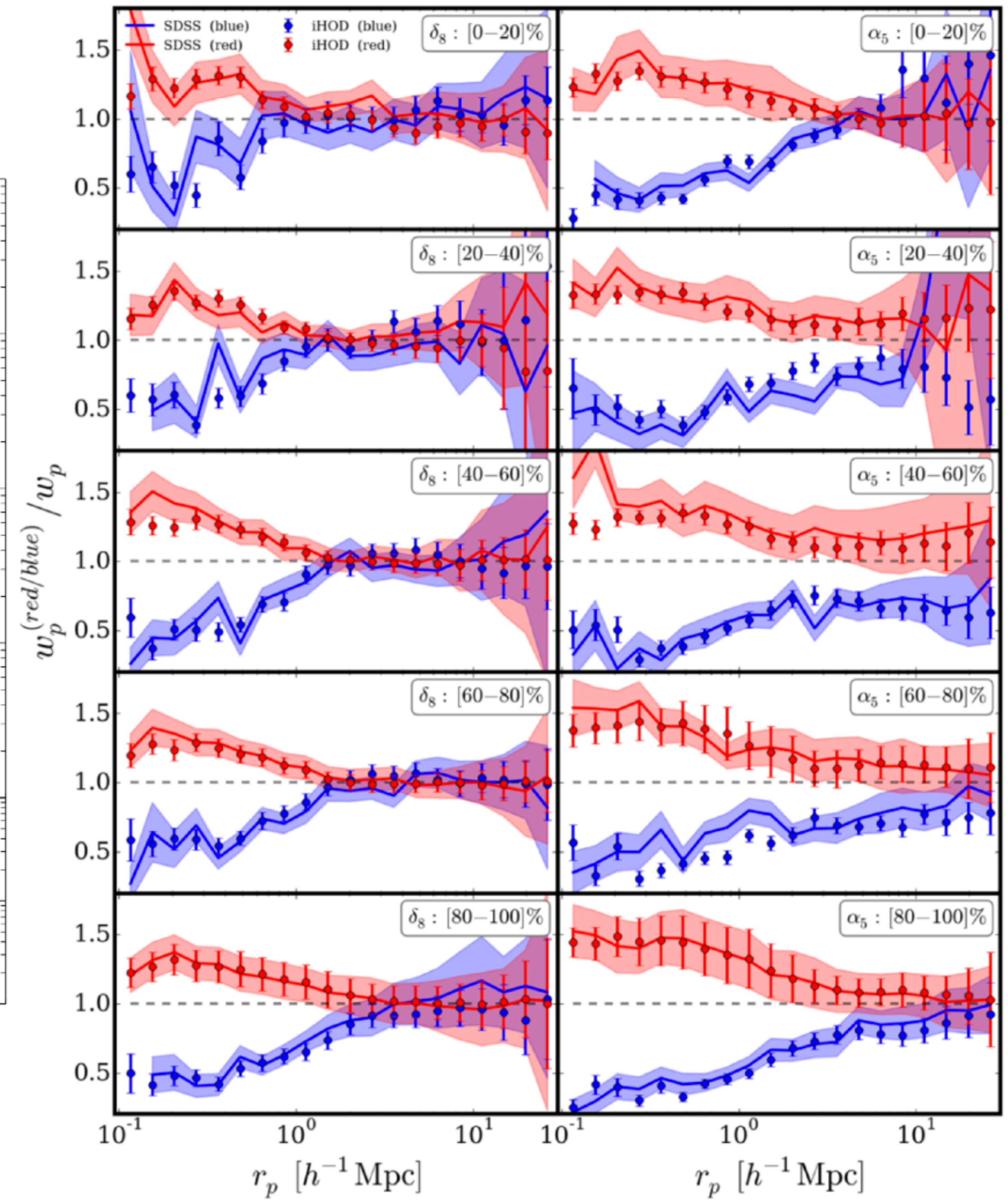
Environmental Dependence of Galaxy Formation

Anything `beyond halo mass` ?

in SDSS, galaxy colour appears only driven by halo mass,
LSS differences through different halo mass function
at different LSS density



Paranjape, OH, Sheth 2018



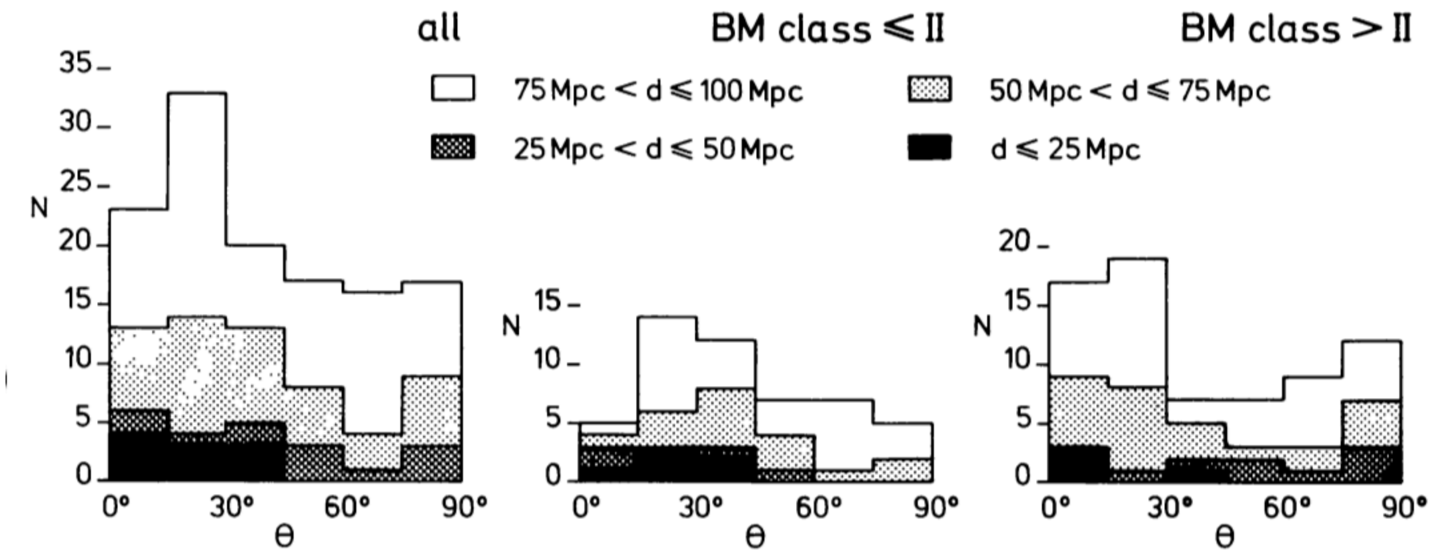
Alam et al. 2018

In regime currently accessible (low z, ~5Mpc), seems halo mass drives everything!

see also Yan,Fan & White (2013)

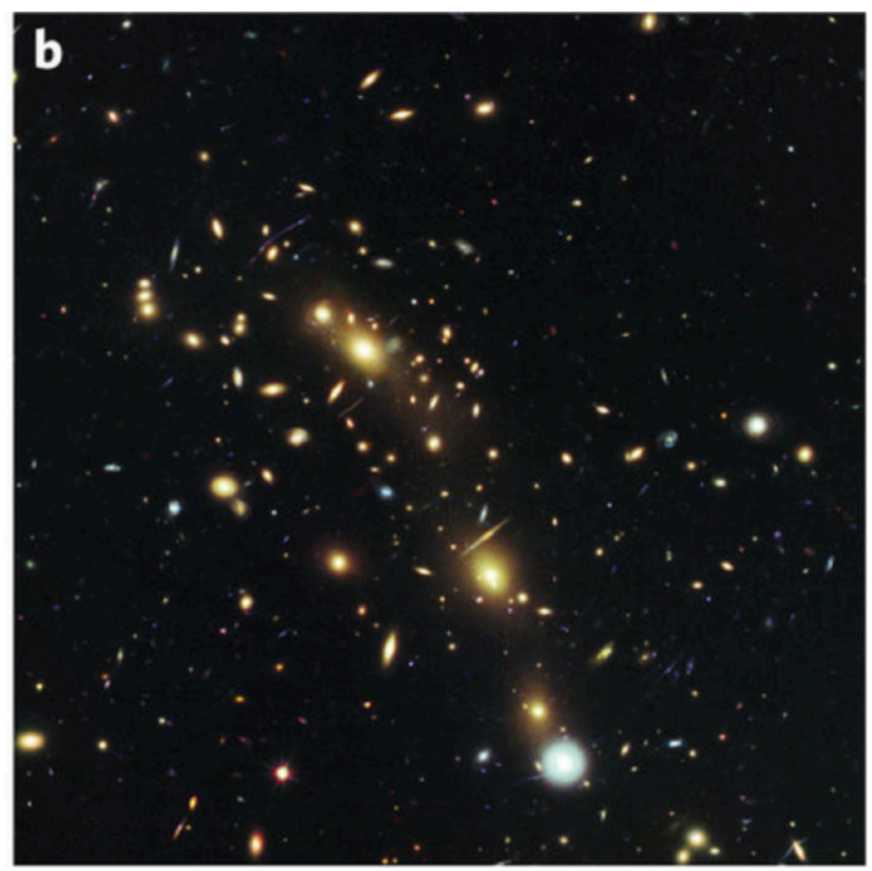
Anisotropic mergers — BCG alignment

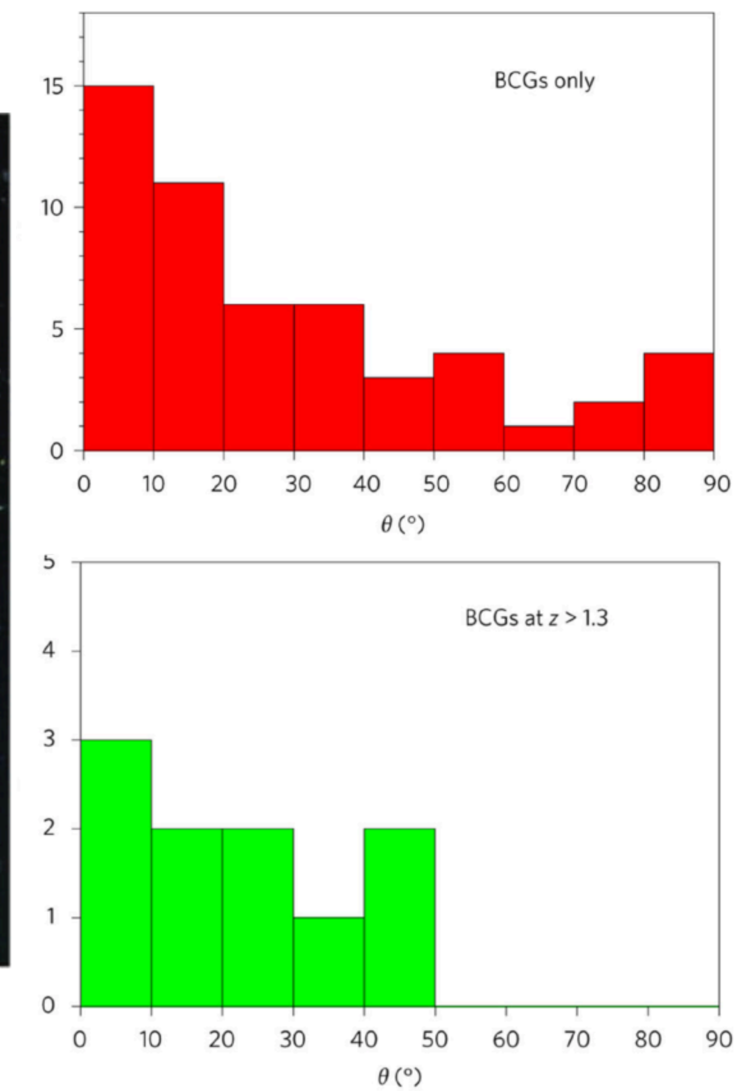
Binggeli effect — alignment of central cluster galaxies



(Binggeli 1982)

BCGs are aligned with the host cluster, and with direction to neighbouring cluster



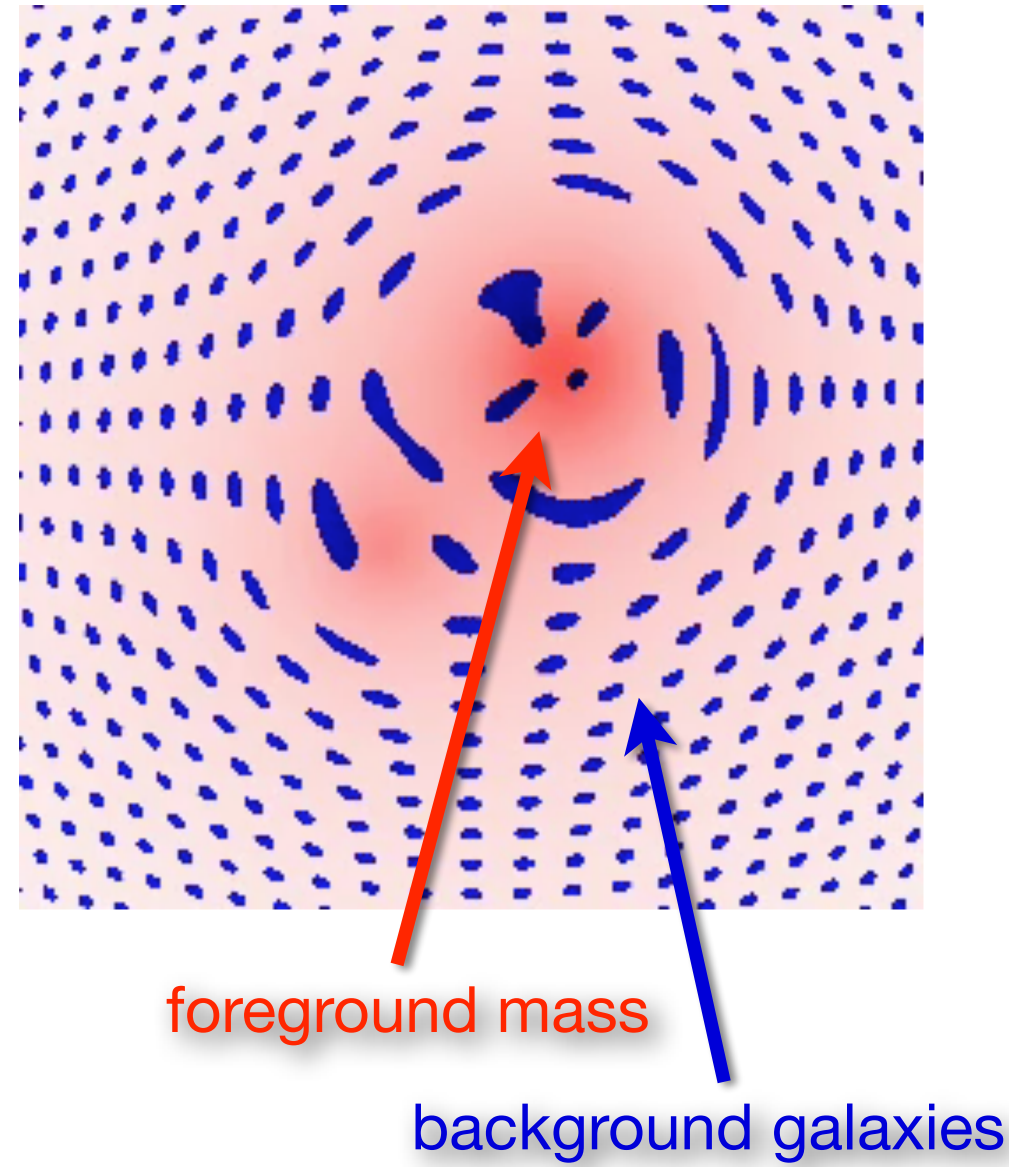


West+2017

Intrinsic Alignments from Lensing

Lensing potential

$$\phi(\boldsymbol{\theta}, \chi_s) = \frac{2}{c^2} \int_0^{\chi_s} \mathrm{d}\chi \frac{d_A(\chi_s - \chi)}{d_A(\chi_s) d_A(\chi)} \Phi(\chi, d_A(\chi)\boldsymbol{\theta})$$



weak shear is a weighted integral
of the **tidal field**:

$$\begin{aligned} \gamma_1 &= \frac{1}{2}(\phi_{,11} - \phi_{,22}) \\ \gamma_2 &= \phi_{,12} \end{aligned}$$

Observable is total ellipticity

$$\epsilon_{\rm obs} = \gamma + \epsilon_I$$

Correlation function thus becomes

$$\langle \epsilon_{\rm obs} \epsilon'_{\rm obs} \rangle = \langle \gamma\, \gamma' \rangle + \langle \gamma\, \epsilon'_I \rangle + \langle \epsilon_I\, \gamma' \rangle + \langle \epsilon_I\, \epsilon'_I \rangle$$

structure **GI** II

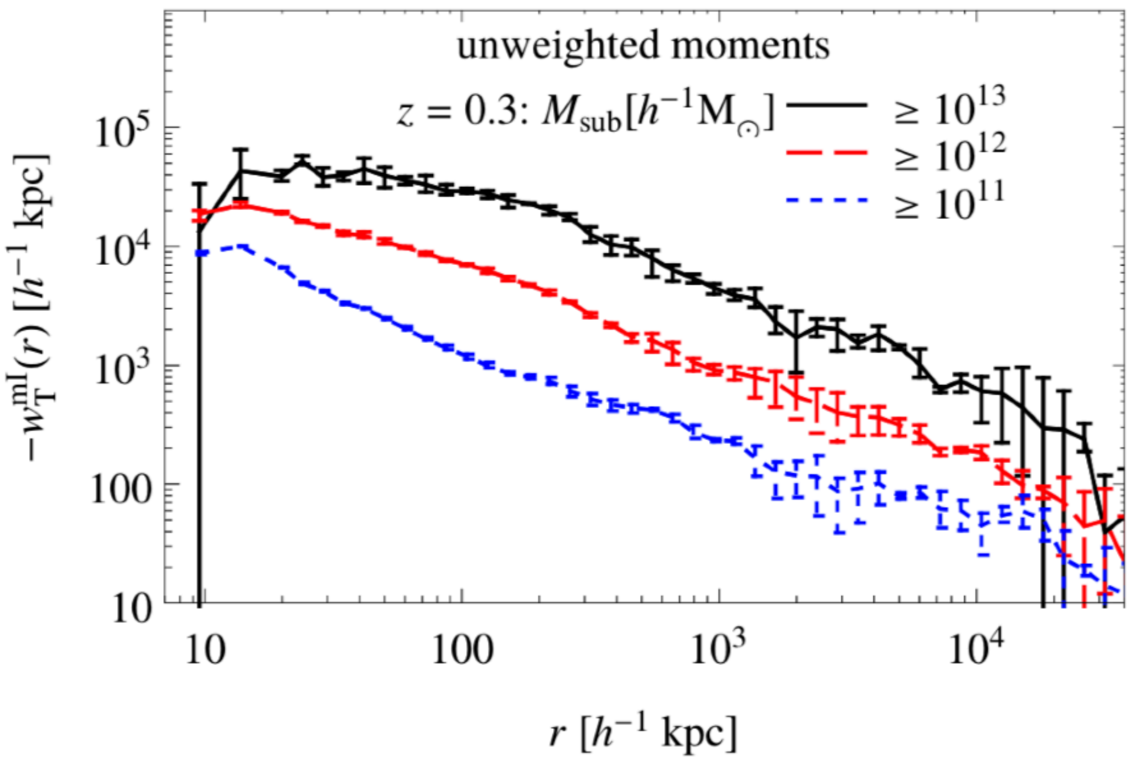
→ Contaminant for dark energy obs.

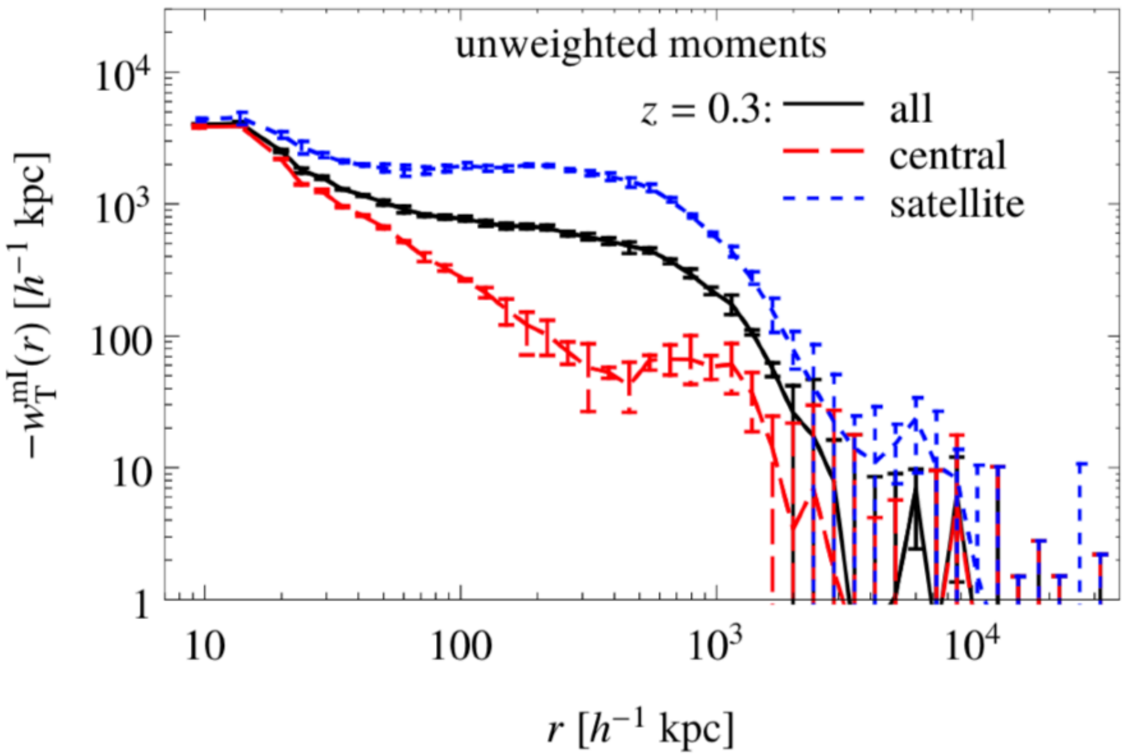
→ **Signal for galaxy formation**

Intrinsic Alignments from Lensing

Illustris simulation (Hilbert+2017)

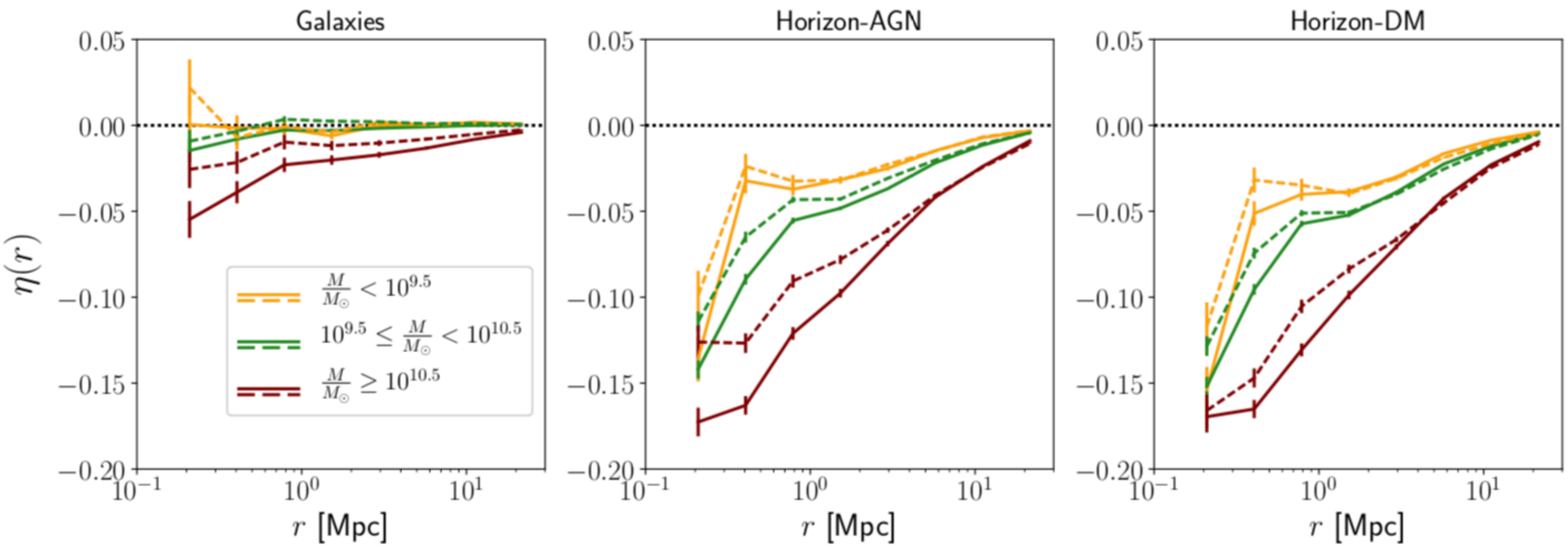
massive galaxies and satellites most aligned





Horizon-AGN simulation (Chisari+2017)

haloes more aligned than galaxies! (mergers!!!)



Summary

- **shocks and caustics ubiquitous in large-scale structure**
- **galaxies evolve as part of cosmic web**
- **not clear (at low z) if web has any importance when dissipative processes (gas!) is involved, or halo mass determines everything (galaxy formation is inefficient!)**
- **high-z observations: we'll see**
- **effect on collisionless dynamics has been demonstrated at high significance (BCG/LRG alignment)**