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Physical mechanisms affecting cluster galaxies

by

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Thanks to: Egidijus Kukstas

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Galaxies

S14a - Quenching cluster galaxies in the cosmic middle ages

Ian G. McCarthy, Liverpool JMU

Outline

- Discussion of environmental processes
- (Some) successes and “failures” of current cosmological simulations
- Future progress

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Environmental processes: an incomplete summary

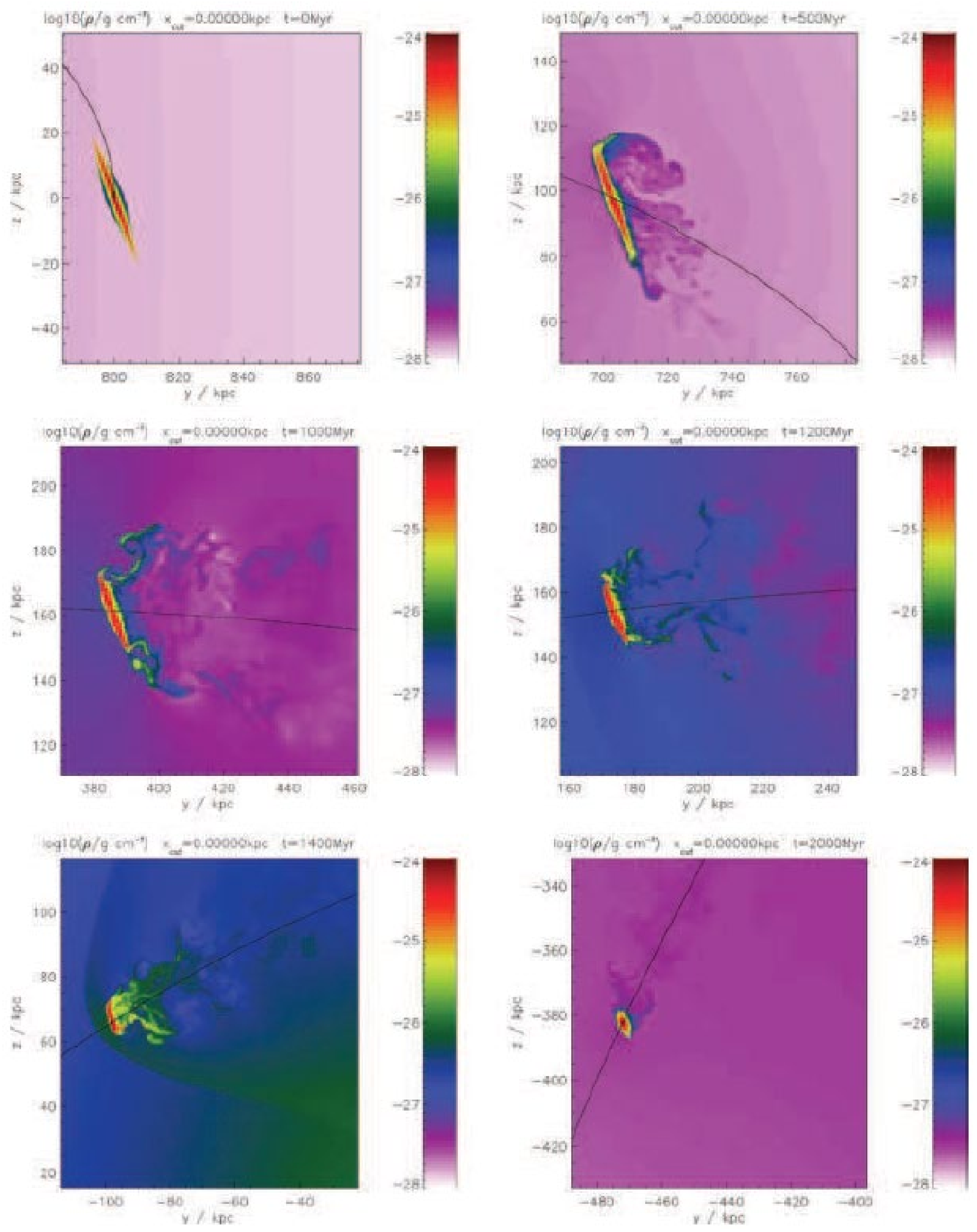
- Ram pressure stripping (cold gas, hot gas, outflows)
- Tidal interactions
- Transport processes: thermal conduction, turbulent and viscous stripping
- Radiative processes

"classical" environment

- Shutting down cosmological accretion
- Pre-processing
- Assembly bias & conformity

"cosmological" environment

Ram pressure stripping: disc gas



Roediger & Bruggen 2007

$$P_{grav} \equiv 2\pi G \Sigma_{gas} \Sigma_{stars}$$

$$P_{ram} \equiv \rho_{ICM} v_{orb}^2$$

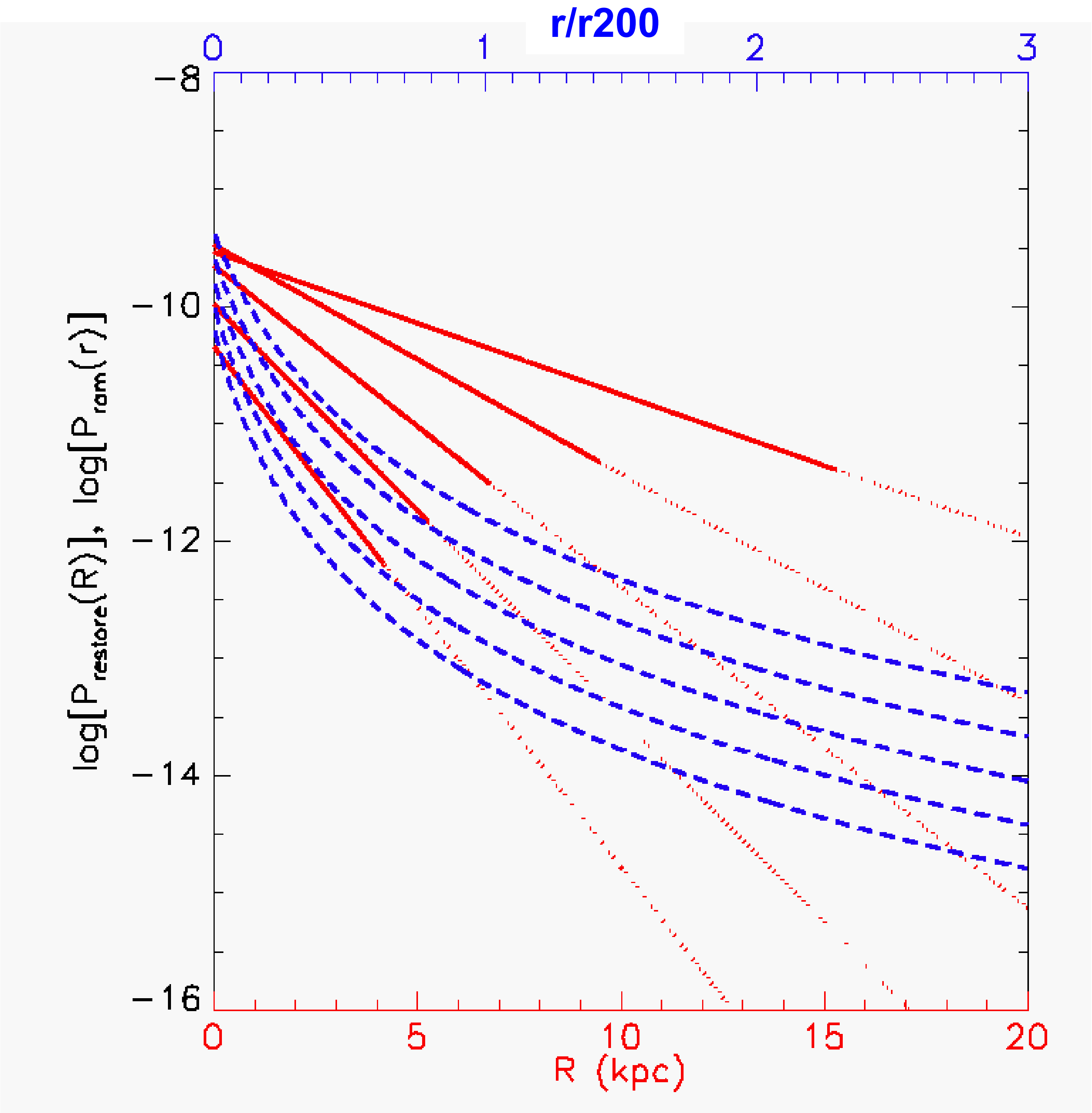
Condition for stripping:

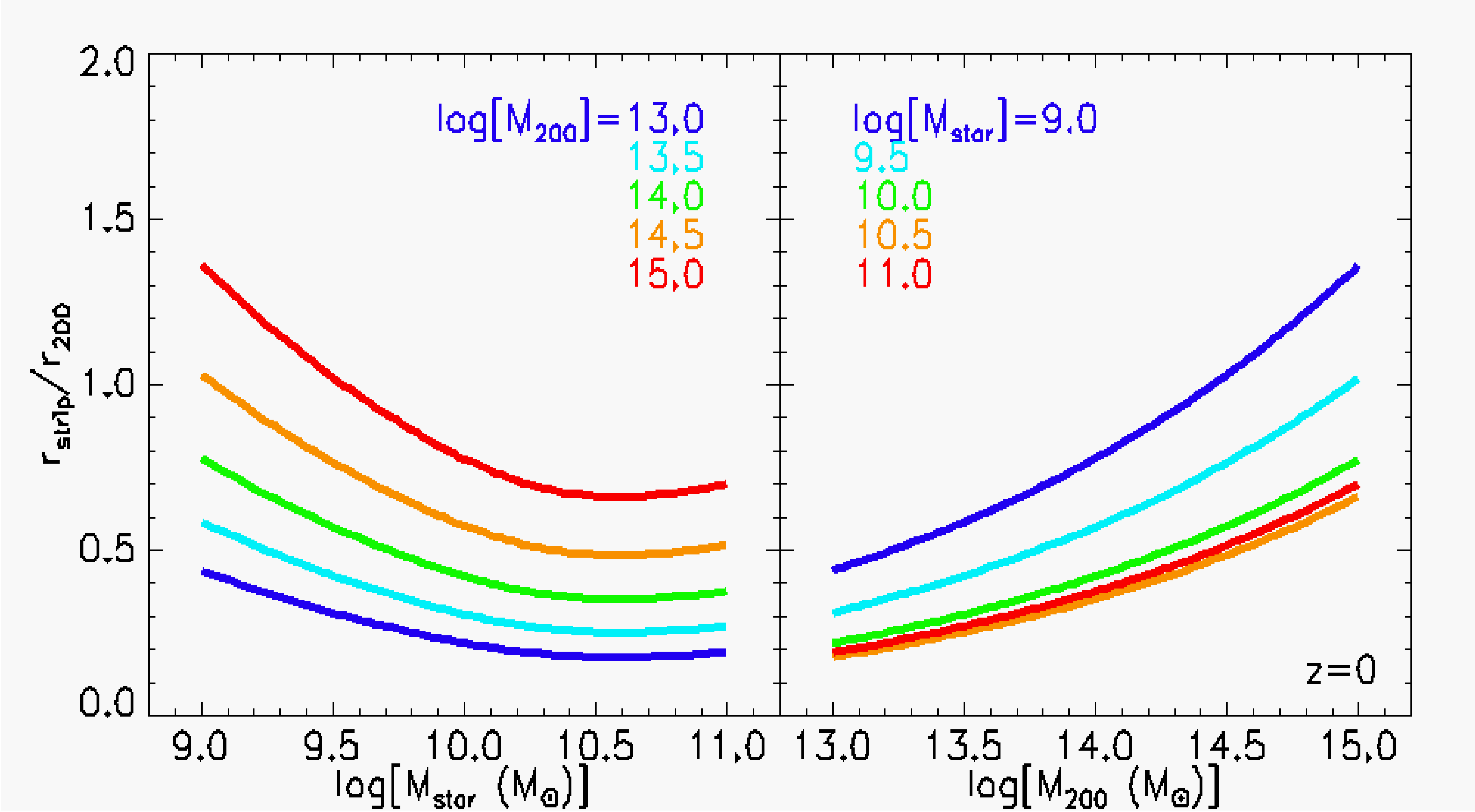
$$P_{ram} > P_{grav}$$

Gunn & Gott 1972

Idealised hydro simulations confirm validity of this simple condition (at least for inviscid, unmagnetized plasmas).

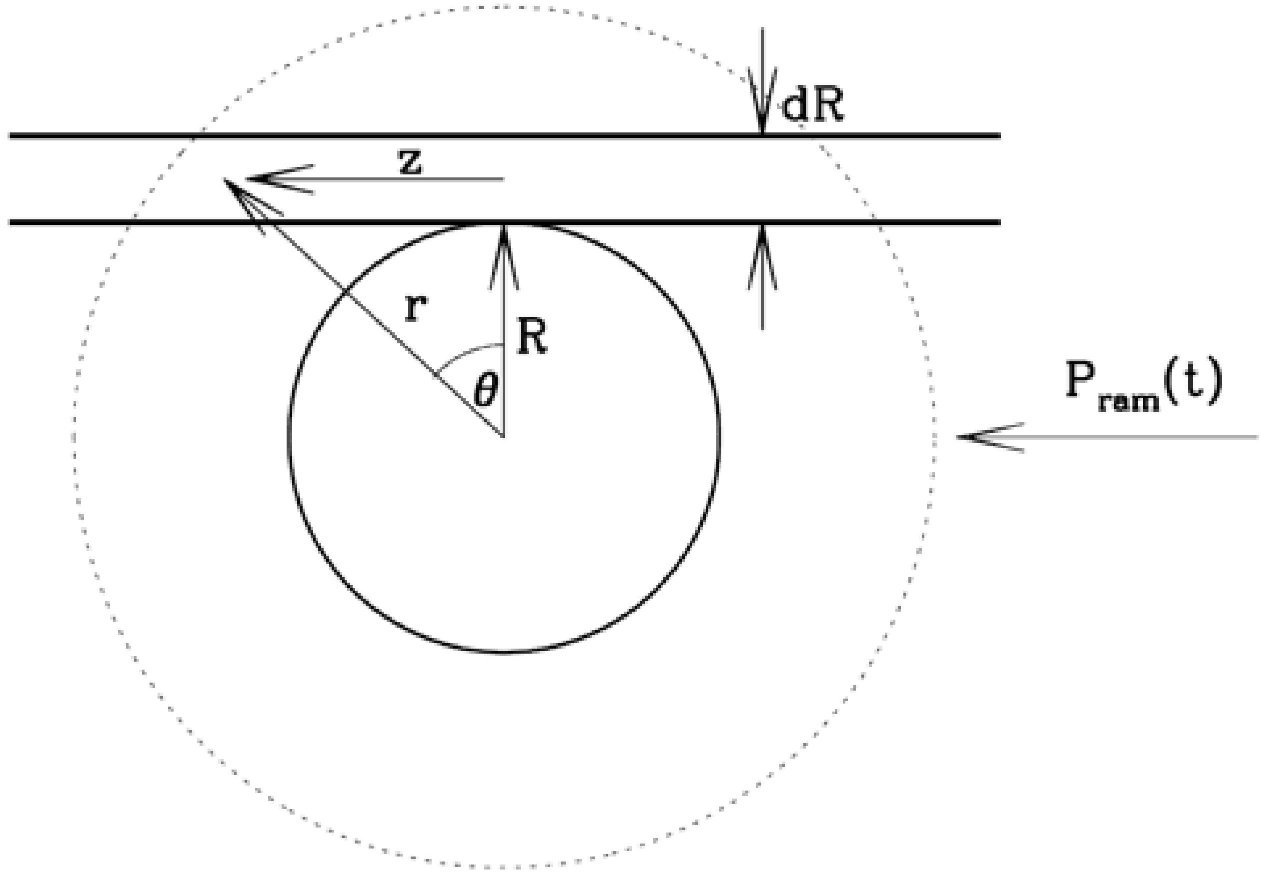
Ram pressure stripping: disc gas





Take empirical mass distributions from local galaxies and assume hot gas traces DM in groups/clusters. Calculate radius where 50% of cold gas would be stripped. (unpublished)

Ram pressure stripping: hot gas



$$P_{ram} \equiv \rho_{ICM} v_{orb}^2$$

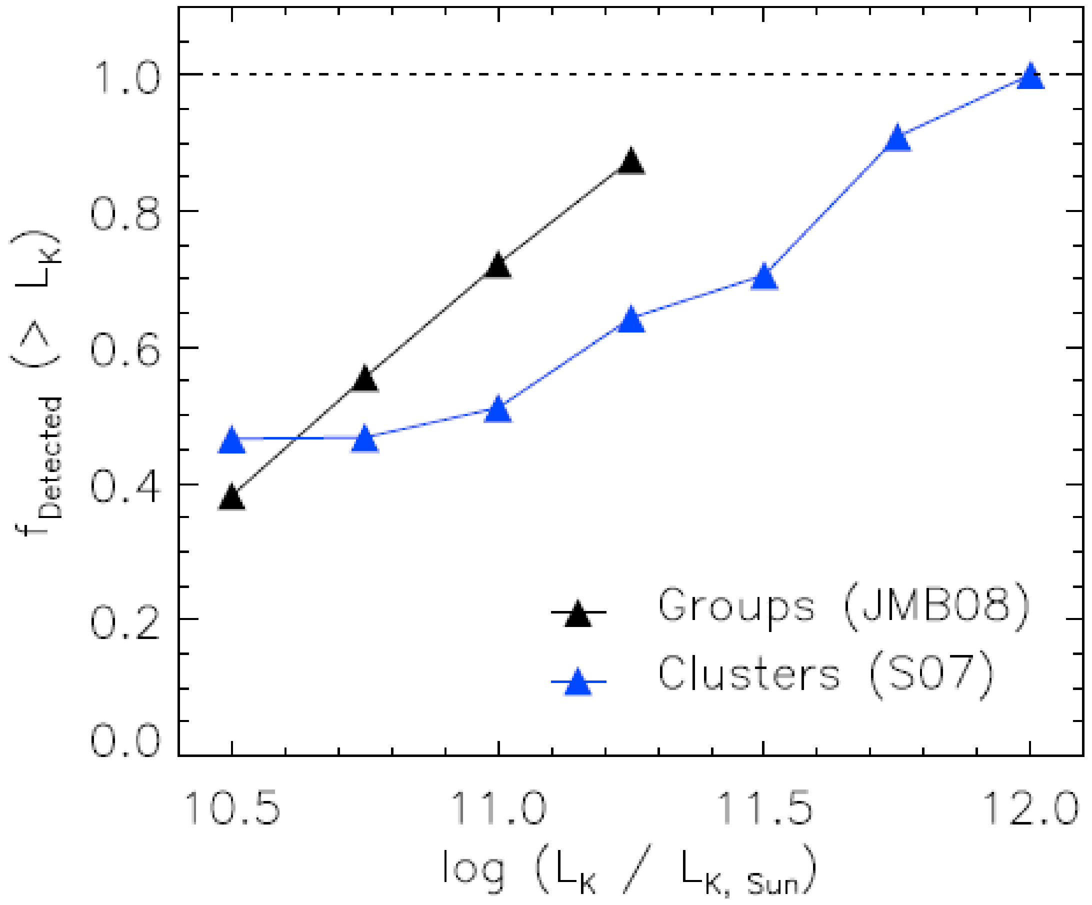
Simple analytic predictions confirmed to high accuracy with idealised simulations .

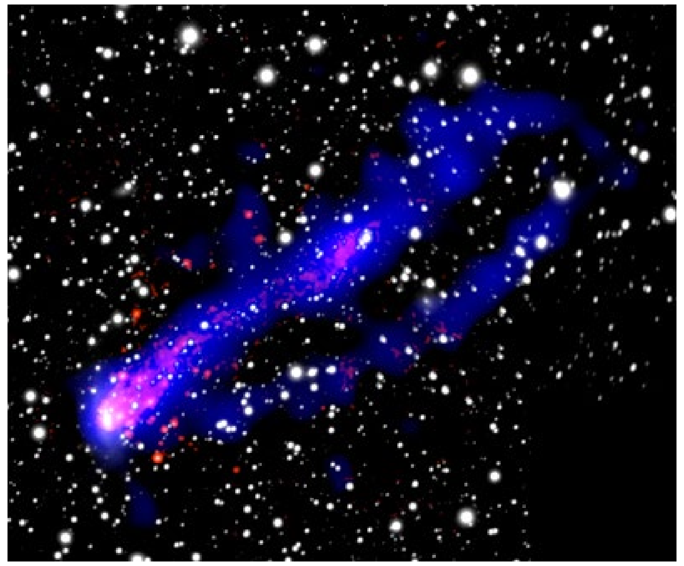
General expectation: lots of hot gas should be quickly stripped. But central ~10-20% may stay intact longer than one orbital time, depending on orbit and mass ratio.

$$P_{grav} \approx g_{\max}(R) \Sigma_{gas}(R)$$

$$= \frac{\pi}{2} \frac{G M_{gal}(R) \rho_{gas}(R)}{R}$$ (for isothermal sphere)

IGM+2008





Ram pressure stripping: outflows

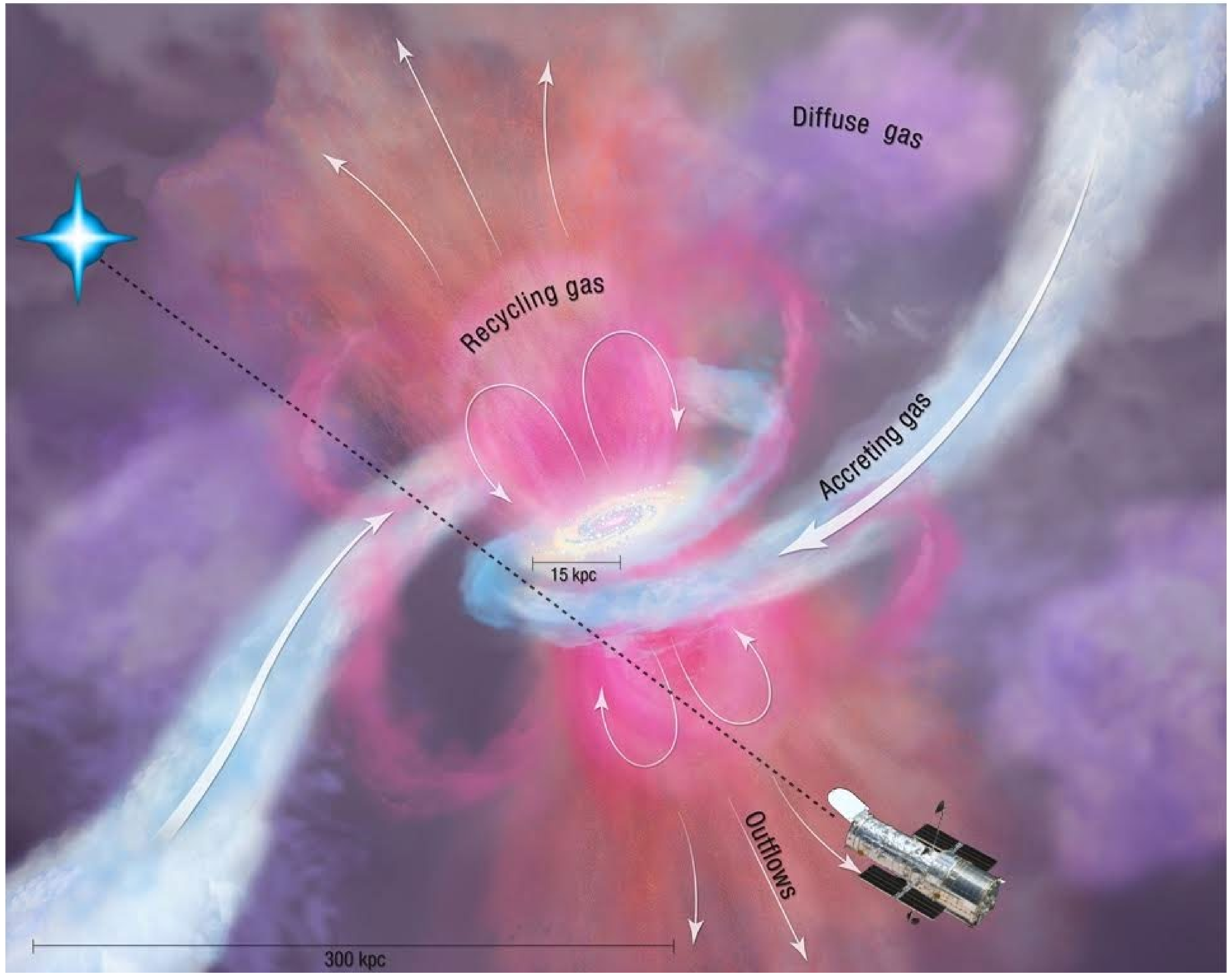


Image credit: Space Telescope Science Institute (by Anne Field)

In the field, galaxies tend to self-regulate their baryon cycles. Cosmological accretion of gas is balanced by star formation, galactic fountains, and outflows (e.g., Davé+2012).

Galactic fountains are more easily stripped than gas in the disc. Removal of fountains is a quick/efficient way to shut down star formation. (Bahe+2015)

We may learn much about the baryon cycle through environmental studies…

Tidal interactions (are probably unimportant for quenching)

$$\frac{r_t}{R} = \left[\frac{M_{gal}(r_t)}{M_{grp}(R)(3 - d\ln M_{grp}/d\ln R)}\right]^{1/3}$$

tidal stripping condition (**King 1962**)

$$\overline{\rho_{gal}(r_t)} = \left(3 - \frac{d\ln M_{grp}}{d\ln R}\right)\overline{\rho_{grp}(R)}.$$

expressed in terms of mean densities

$$\overline{\rho_{gal}(r_t)} < 2\,\overline{\rho_{grp}(R)}.$$

isothermal sphere case

$$\rho_{grp}(R)v_{orb}^2 > \alpha\rho_{gal}(r)v_{c,gal}^2(r).$$

ram pressure stripping condition

$$\overline{\rho_{gal}(r)} < \frac{1}{\alpha}\left(\frac{v_{orb}}{v_{c,gal}}\right)^2\overline{\rho_{grp}(R)},$$

expressed in terms of mean densities

$$F = \frac{1}{2\alpha}\left(\frac{v_{orb}}{v_{c,gal}}\right)^2. \qquad F \sim \frac{1}{4}\left(\frac{M_{grp}}{M_{gal}}\right)^{2/3}$$

So F > 1 requires:

$$\frac{M_{gal}}{M_{grp}} > \sim\frac{1}{8}$$

IGM+2008

Transport processes: I. Thermal conduction

$$\mathbf{Q} = -\kappa \nabla T$$

Heat flux due to temperature gradient (**Spitzer 1956**)

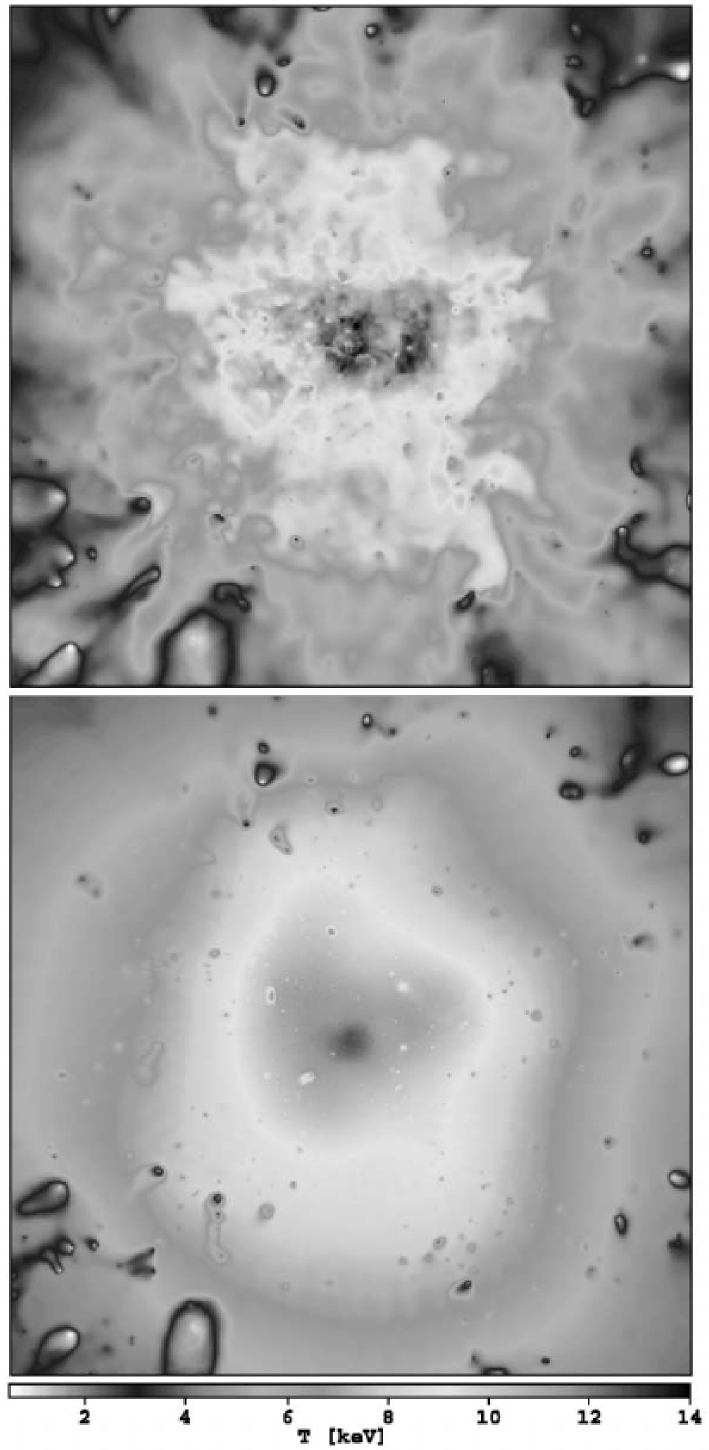
$$\kappa_{\rm Sp} = 20 \left(\frac{2}{\pi}\right)^{3/2} \frac{(k_B T_e)^{5/2}\, k_B}{m_e^{1/2} e^4 Z \ \ln \Lambda},$$

"Spitzer conductivity" (for **unmagnetized** plasma)

Above assumes typical length scale of gradient >> mean free path. Not true for low-density plasmas.

$$Q_{\rm sat} = 0.4 n_e k_B T \left(\frac{2k_B T}{\pi m}\right)^{1/2}$$

Saturated heat flux (**Cowie & McKee 1977**)



Dolag+2004

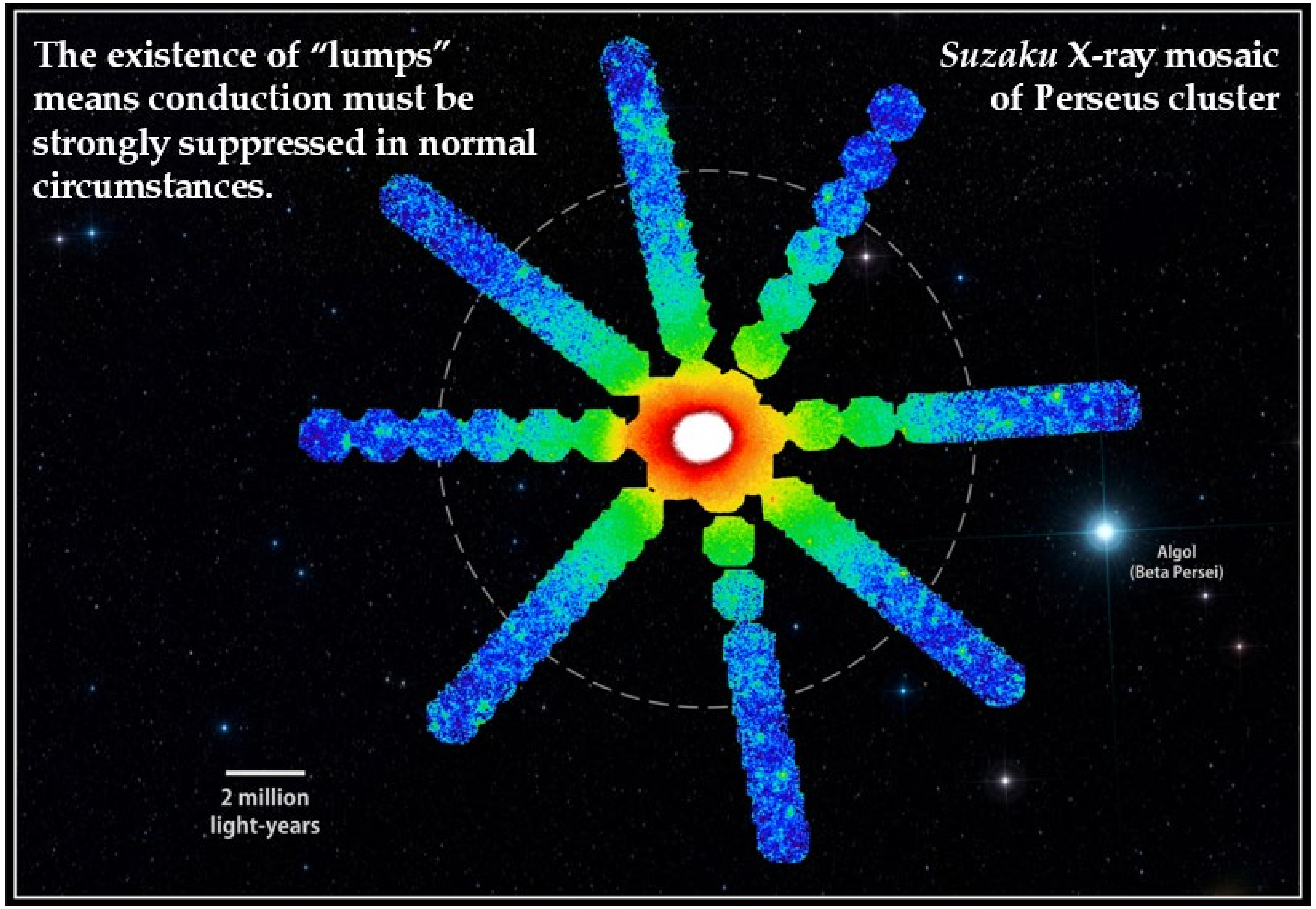
Transport processes: I. Thermal conduction

Typical to assume conductivity is a fraction of full Spitzer rate. This is because magnetic fields (it's a plasma!) inhibit heat transfer perpendicular to field lines.

Previous work (e.g., Narayan & Medvedev 2011) had suggested ~30% full Spitzer rate for "chaotically tangled" fields. This is strong enough to solve "cooling flow problem" in some cases.

Has a massive effect on temperature structure of clusters (smoothing out large-scale gradients), but also evaporates satellite galaxies!!

Conduction proceeds along magnetic field lines. Cosmological MHD simulations with ***anisotropic*** thermal conduction yield results similar to isotropic conduction but with Spitzer conductivity suppressed by a factor of ~100. (**Arth+2015**)

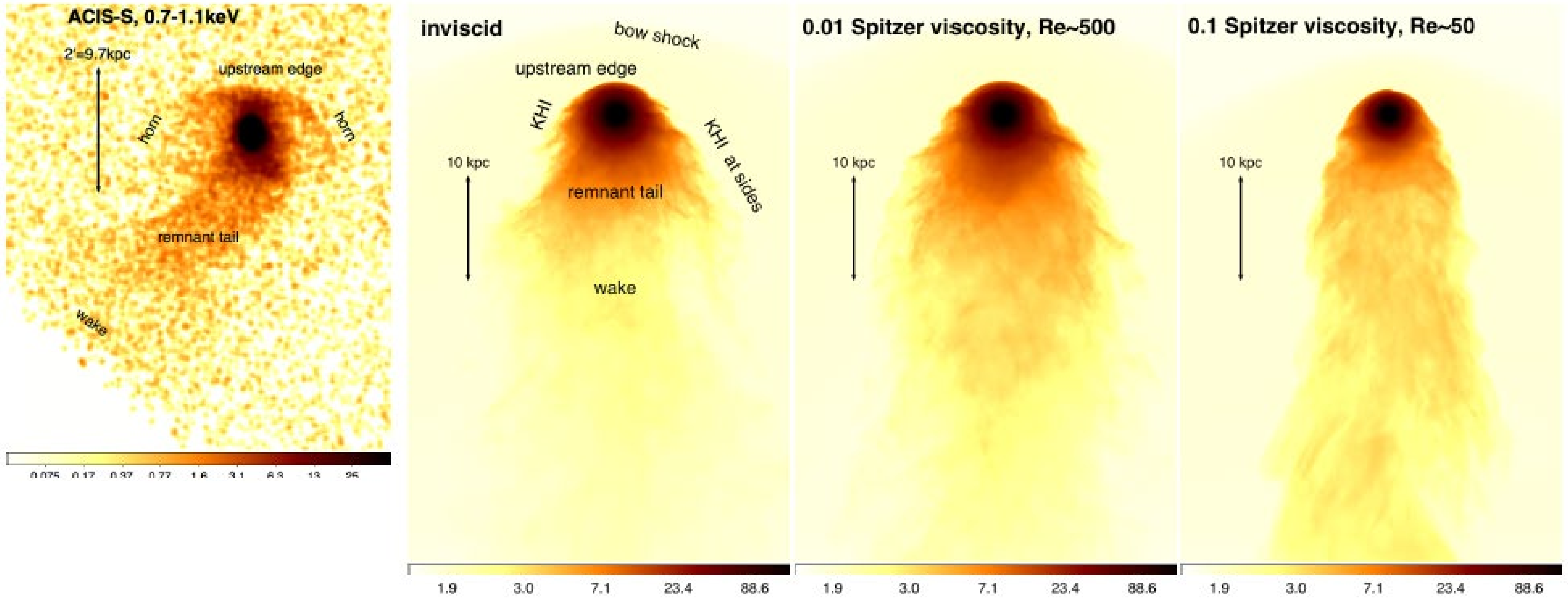


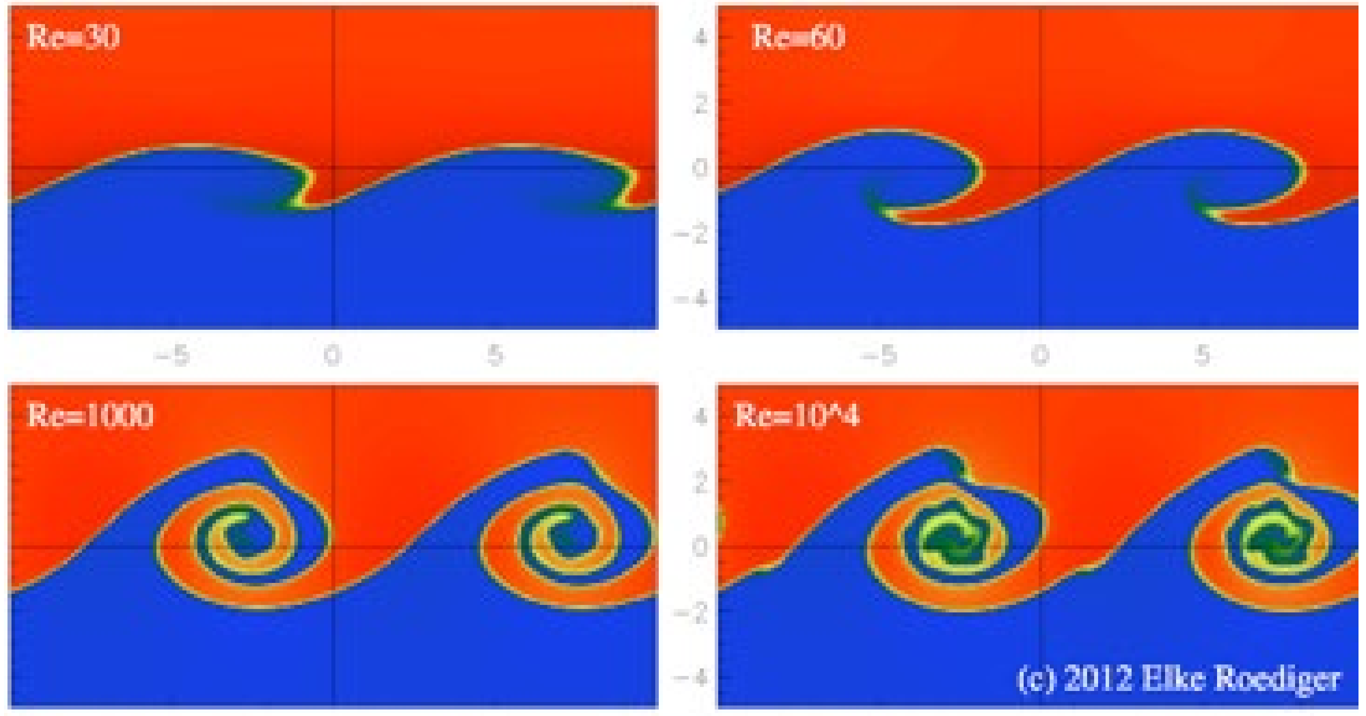
Transport processes: II. turbulent vs. viscous stripping

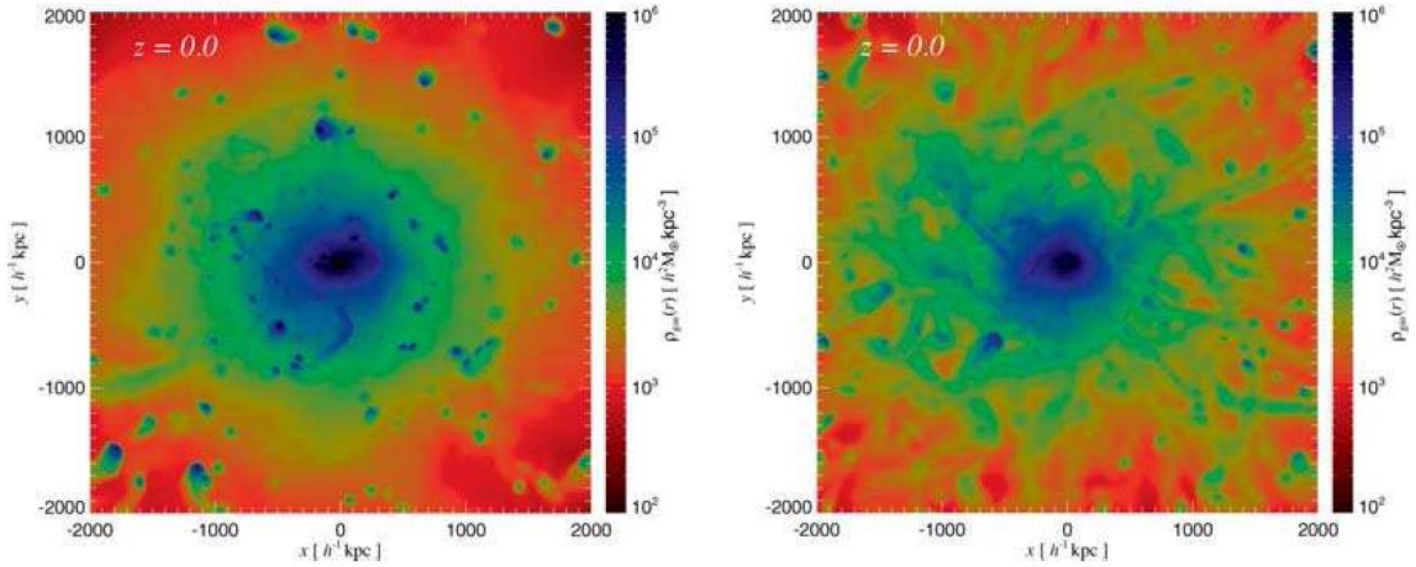
Roediger+2014

For inviscid fluids, turbulent stripping becomes relevant in some cases (e.g., edge on disc). Generally unimportant.

Viscous stripping, on the other hand, can be important if Reynolds number is low (**Nulsen1982**). The effective viscosity, which is ill-constrained, depends sensitively on magnetic field structure of the ICM.

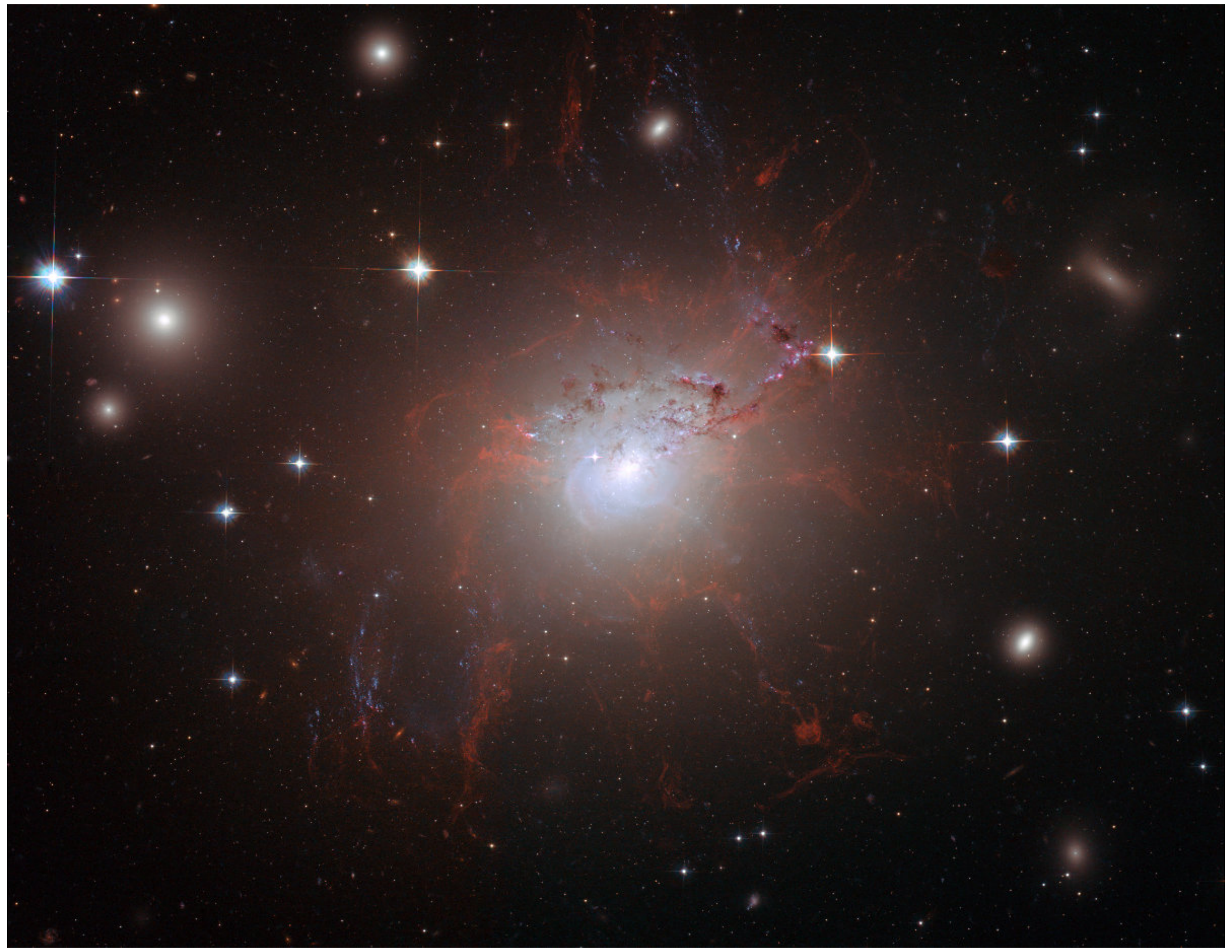






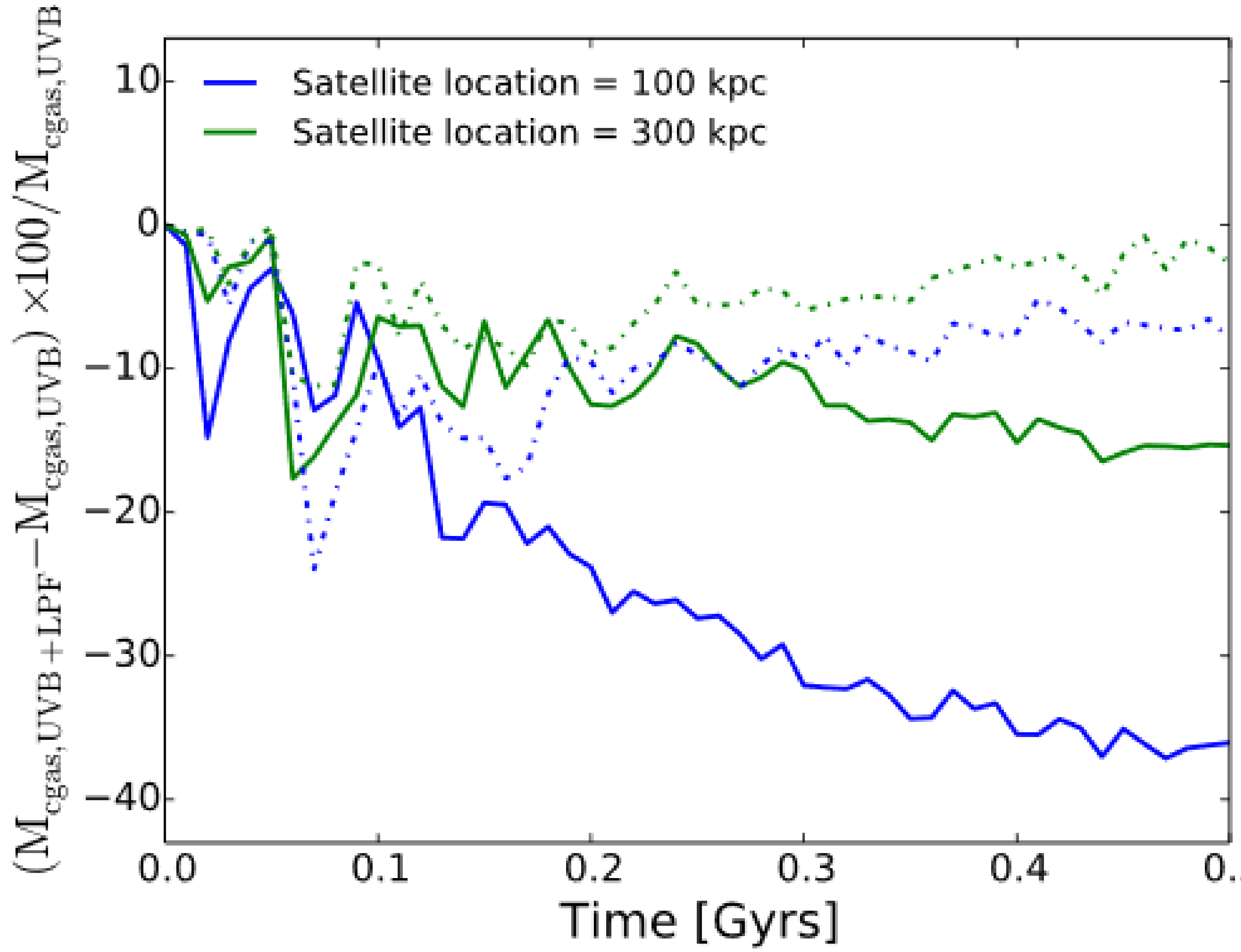
Sijacki & Springel 2006

Radiative processes: photoionization



You sometimes see optical line emission in the central regions of clusters. Photoionization by stars is probably main source (e.g., **Cantalupo 2011**), but secondary electrons from hot ICM can also heat and ionise (e.g., **Fabian et al. 2011**). Filaments appear to need this.

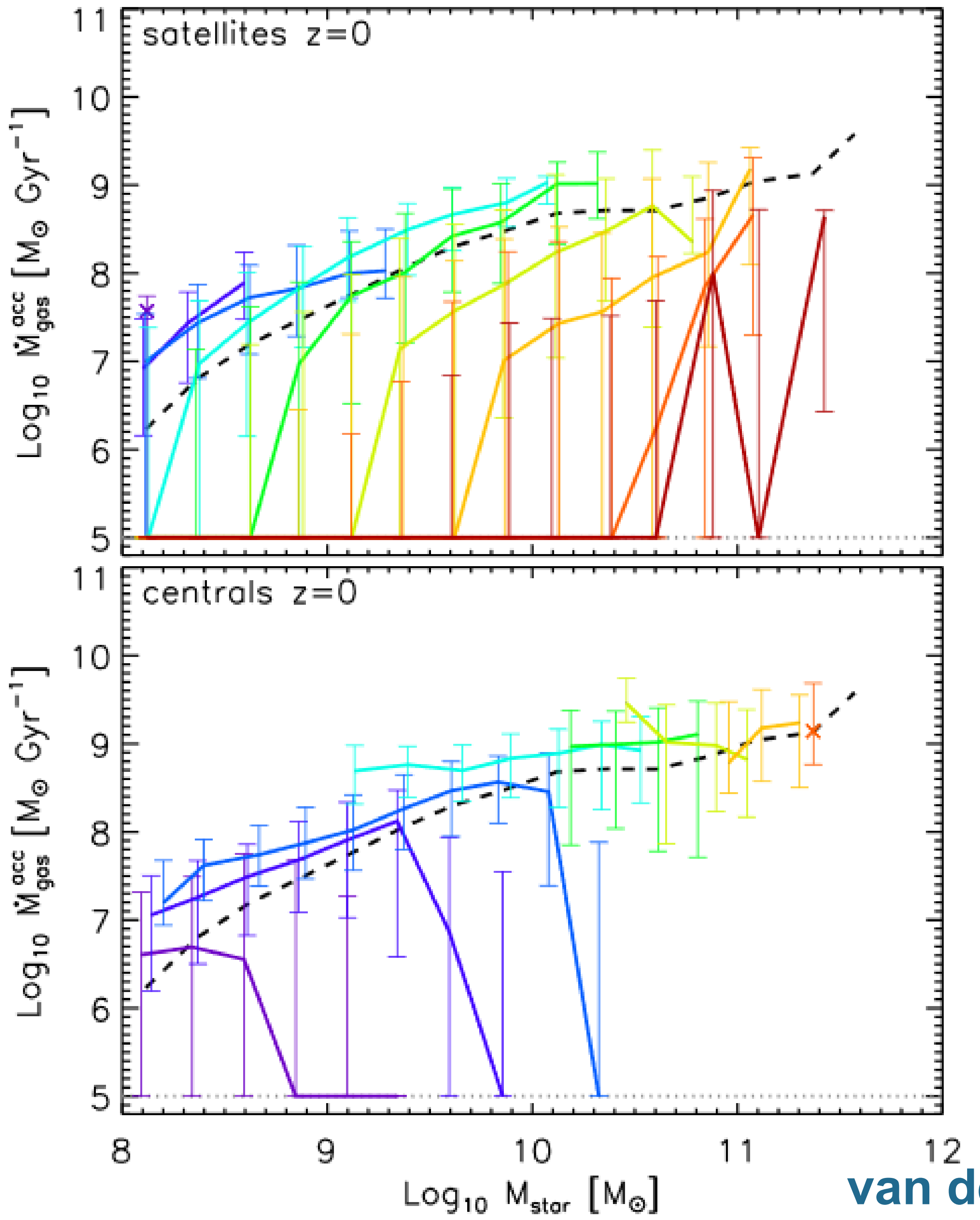
Direct photoionization from ICM photons? (e.g., **Oh 2004**)



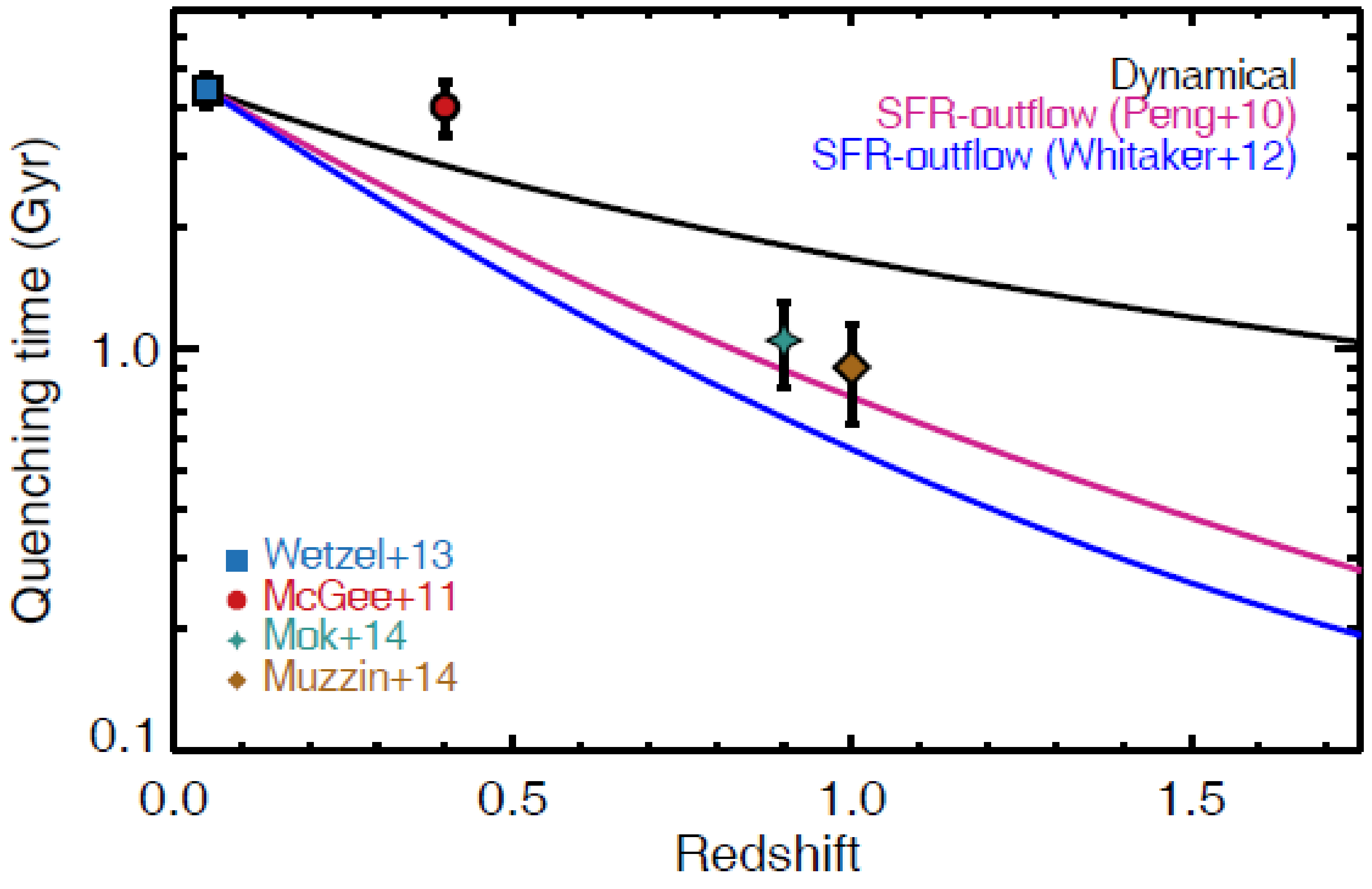
Kannan+2016

Cosmological simulations with local photoionization feedback indeed show an appreciable effect.

"Cosmological" processes: shutting off the accretion



van de Voort+2017



McGee+2014

Cutting off cosmological accretion throws galaxy out of equilibrium. Cold gas is quickly consumed by outflows. "Overconsumption"
Does this effect happen faster than, say, RPS?

Outline

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- Future progress

Cosmological simulations

Clusters are rare, requiring large boxes. Two approaches:

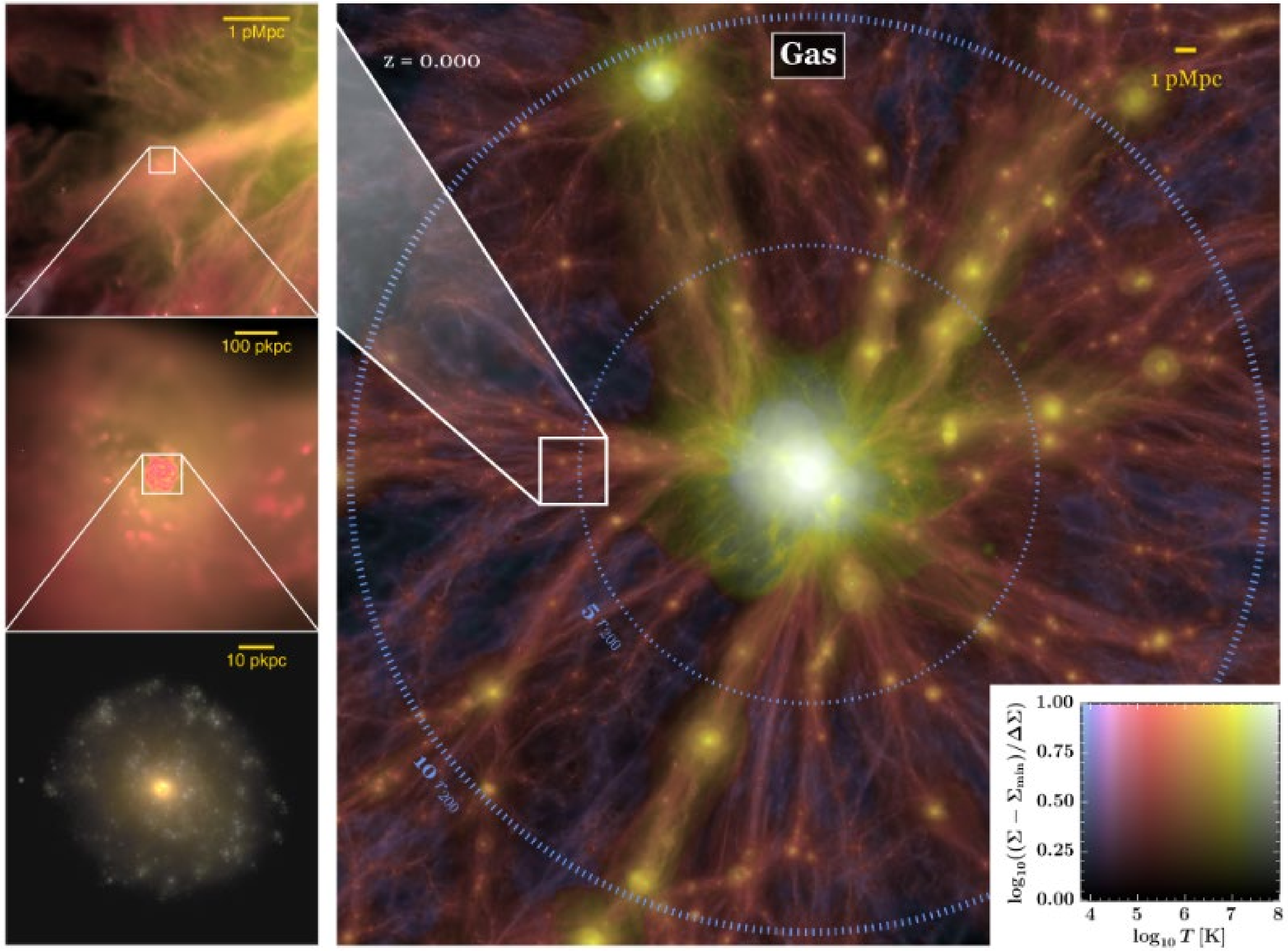
1) low/medium resolution simulations of the full box to generate large samples (e.g., Magneticum, BAHAMAS, IllustrisTNG 300)

2) medium/high resolution “zoom” simulations (e.g., GIMIC, Hydrangea/C-EAGLE, RomulusC, FABLE)

(300 project and MACSIS are half way between)

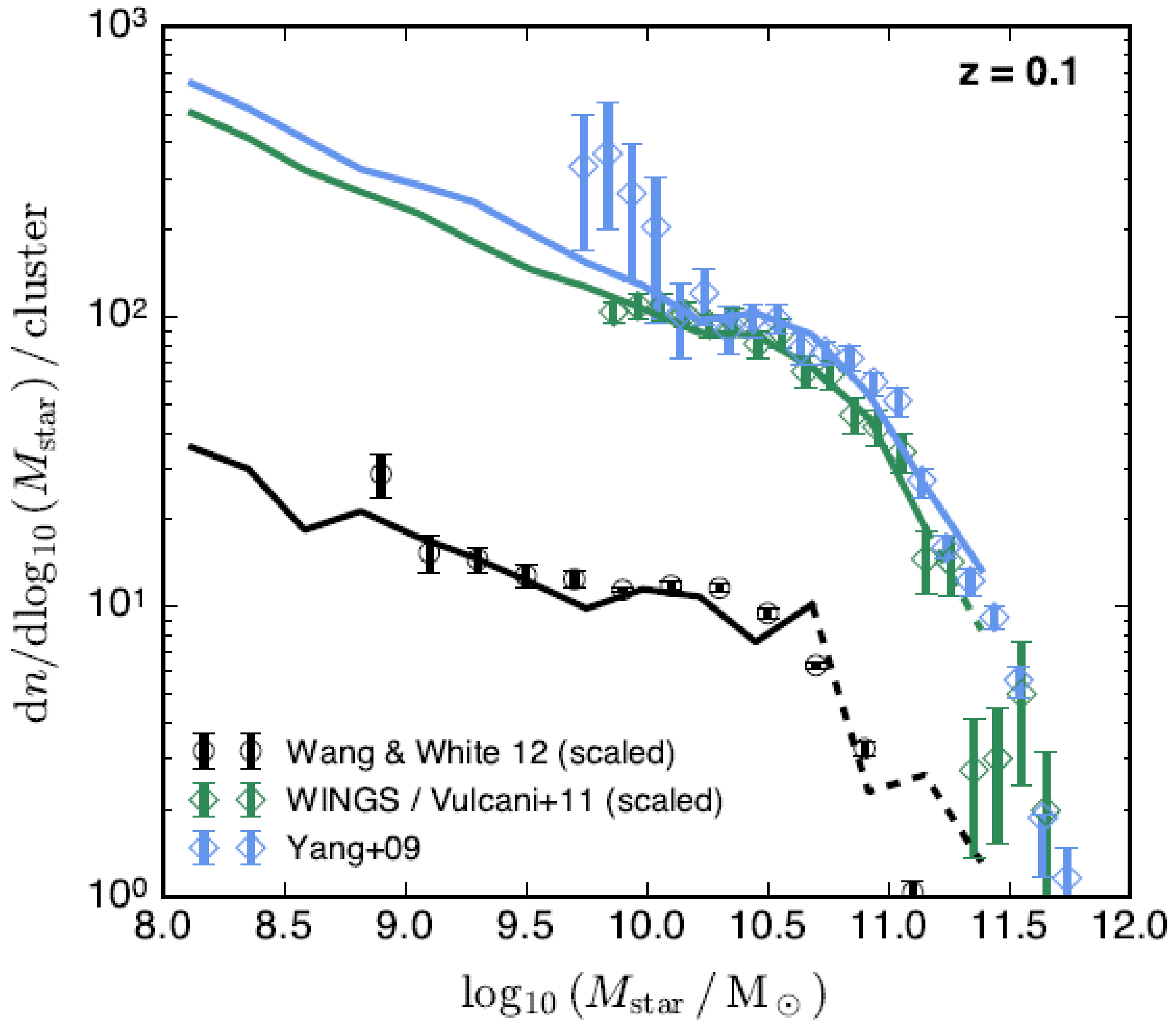
Different resolutions, physics, calibration strategies, and cosmologies.

<u>Environment is a strong test of simulations</u>, as there is no direct control over gravitational or hydrodynamical forces. Feedback is uncertain but is often calibration against the field.

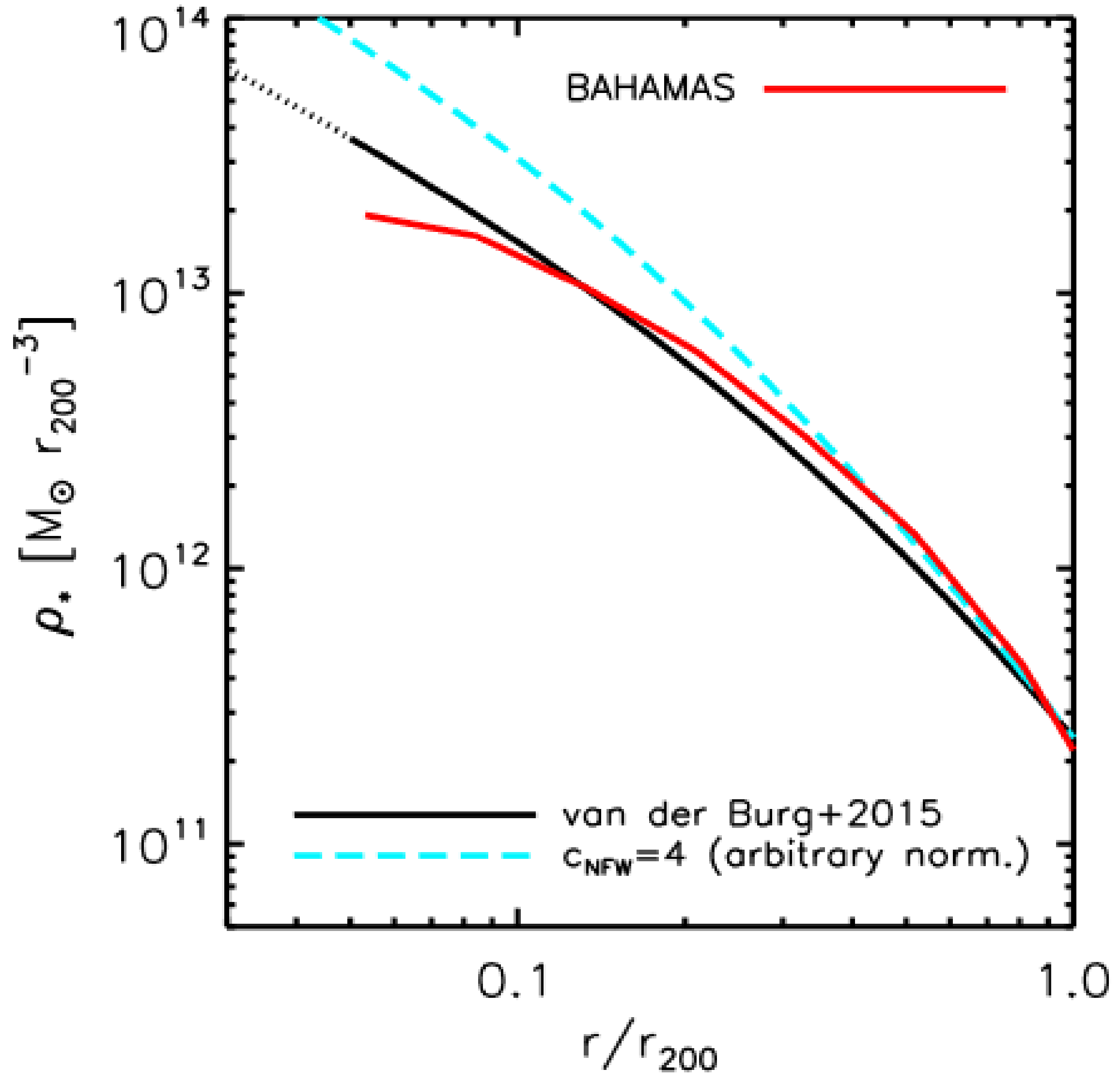


Hydrangea simulations (Bahe+2017)

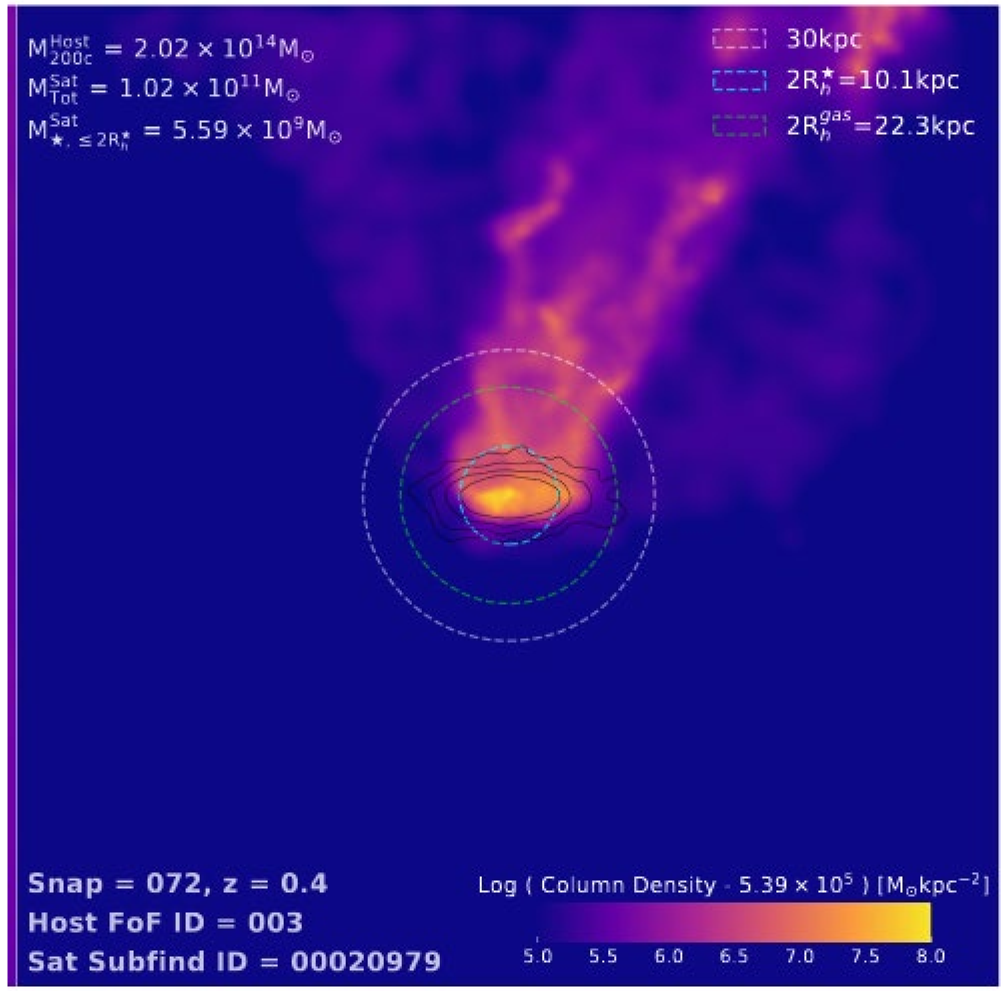
(some) Successes of current simulations



Satellite luminosity functions
(Hydrangea; Bahe+2017)

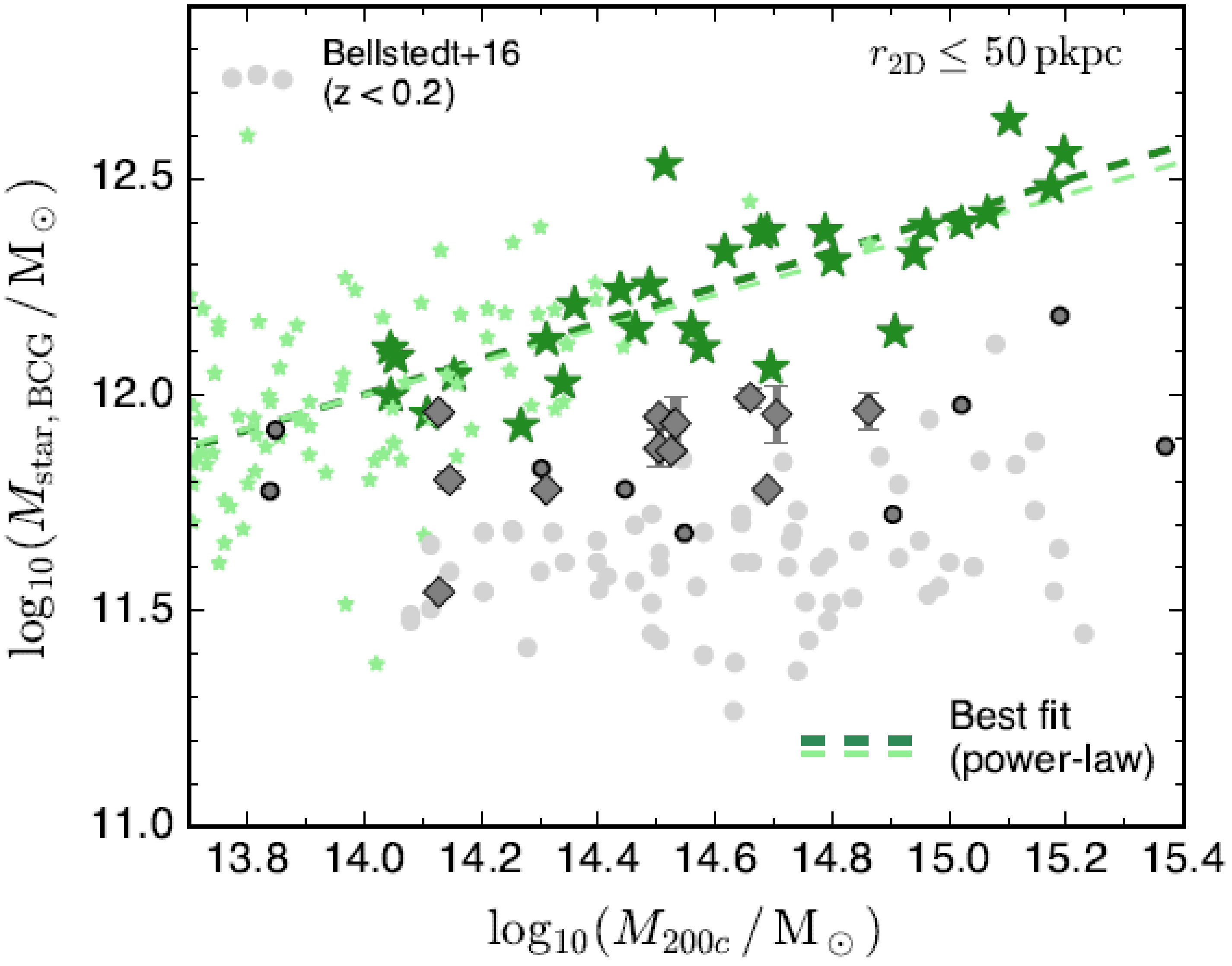


Satellite radial distribution
(BAHAMAS; McCarthy+2017)

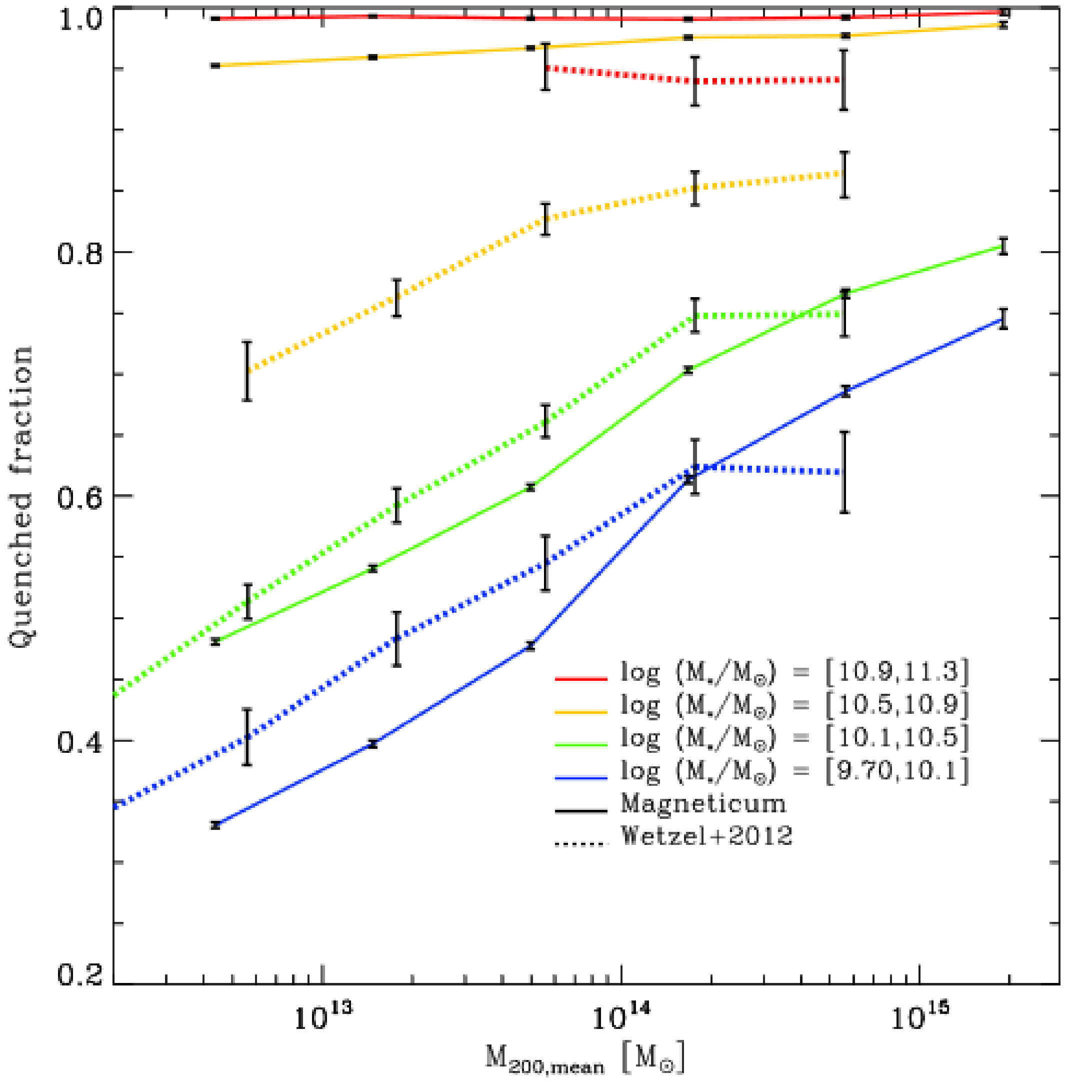


"Jellyfish" galaxies
(IllustrisTNG; Yun+2019)

(some) “Failures” of current simulations



BCG stellar masses
(Hydrangea; Bahe+2017)



Quenched fraction as function of host halo mass
and satellite galaxy mass (Magneticum; Lotz+2019)

Still difficult to regulate cooling flows.

Simulations appear “too good” at quenching sats.

Caveat: comparisons to observations are non-trivial.

Outline

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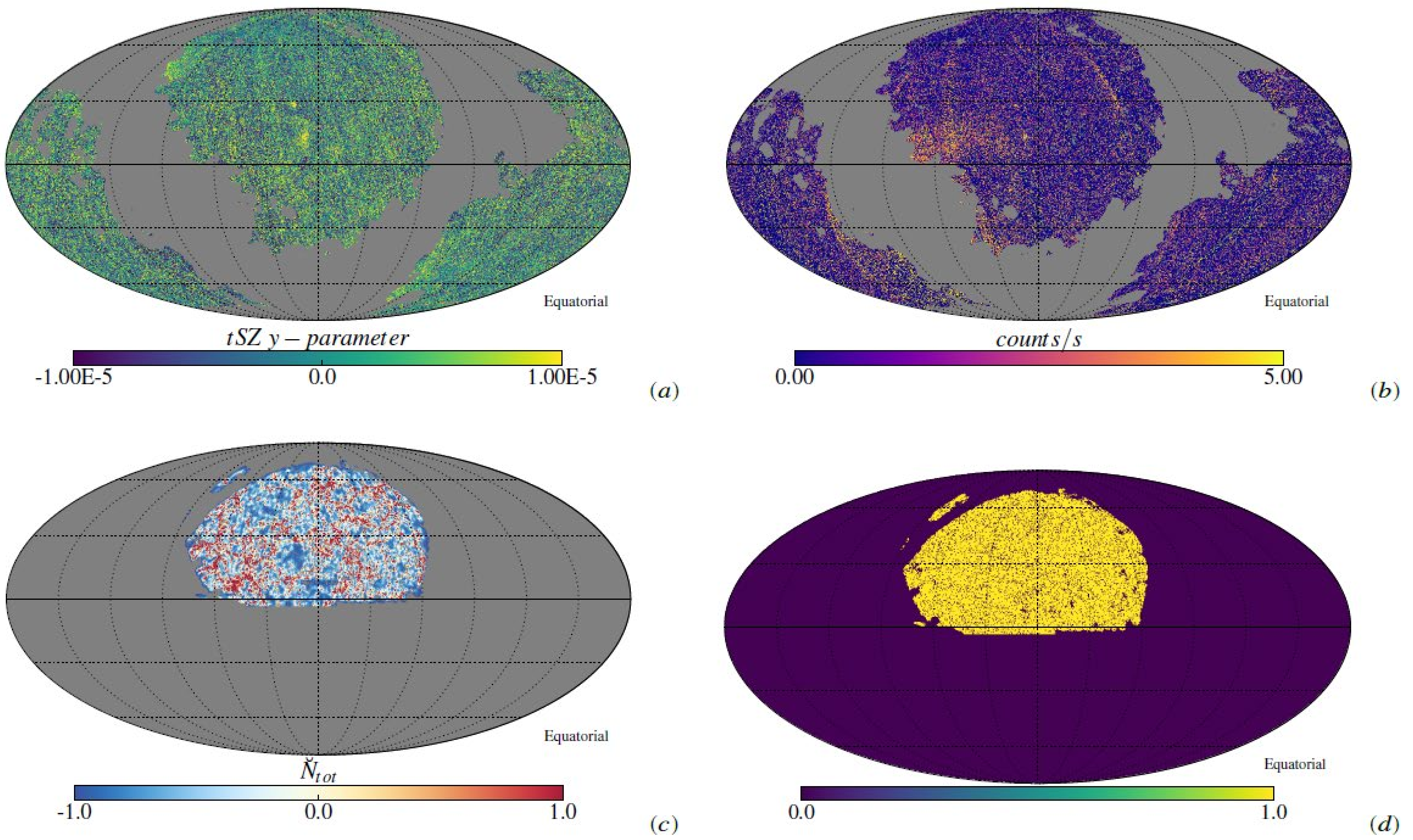
Future progress?: environment meets large-scale structure



To crack the environment problem, we need measurements of the environment! (Not just proxies)

Large-scale structure surveys are available and sample exactly what we need:

- Sunyaev-Zel'dovich effect → ICM pressure
- X-ray flux → ICM density
- Weak lensing → gravitational potential

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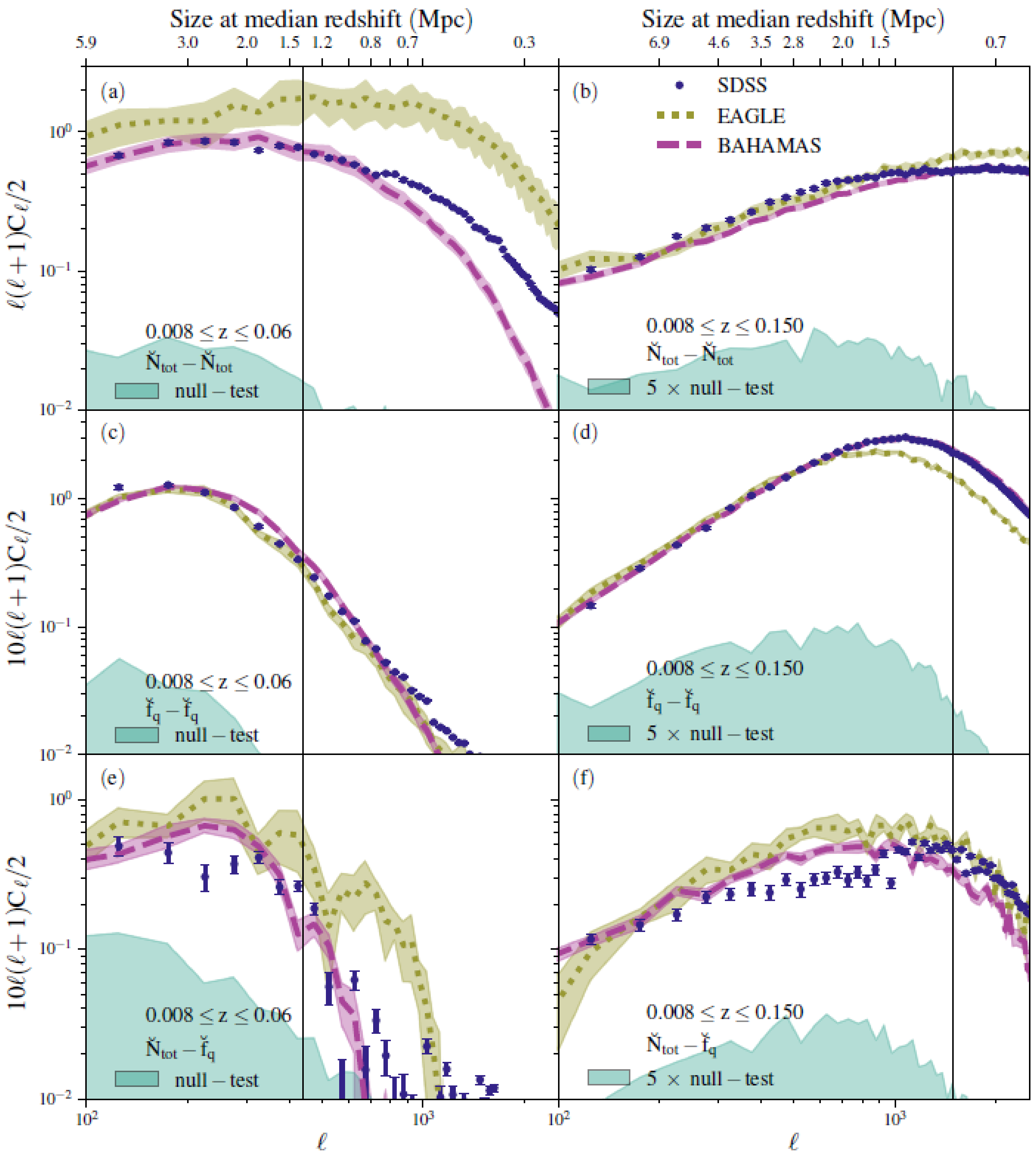
The "power" of spatial cross-correlations



Benefits:

- No need to identify clusters, assign membership, measure masses, etc.
- Directly correlates galaxy properties with "local" environment
- Sources of contamination (e.g., Milky Way dust, background AGN, etc.) all drop out in cross-correlations
- Can use full information from simulations, rather than catalogs/proxies

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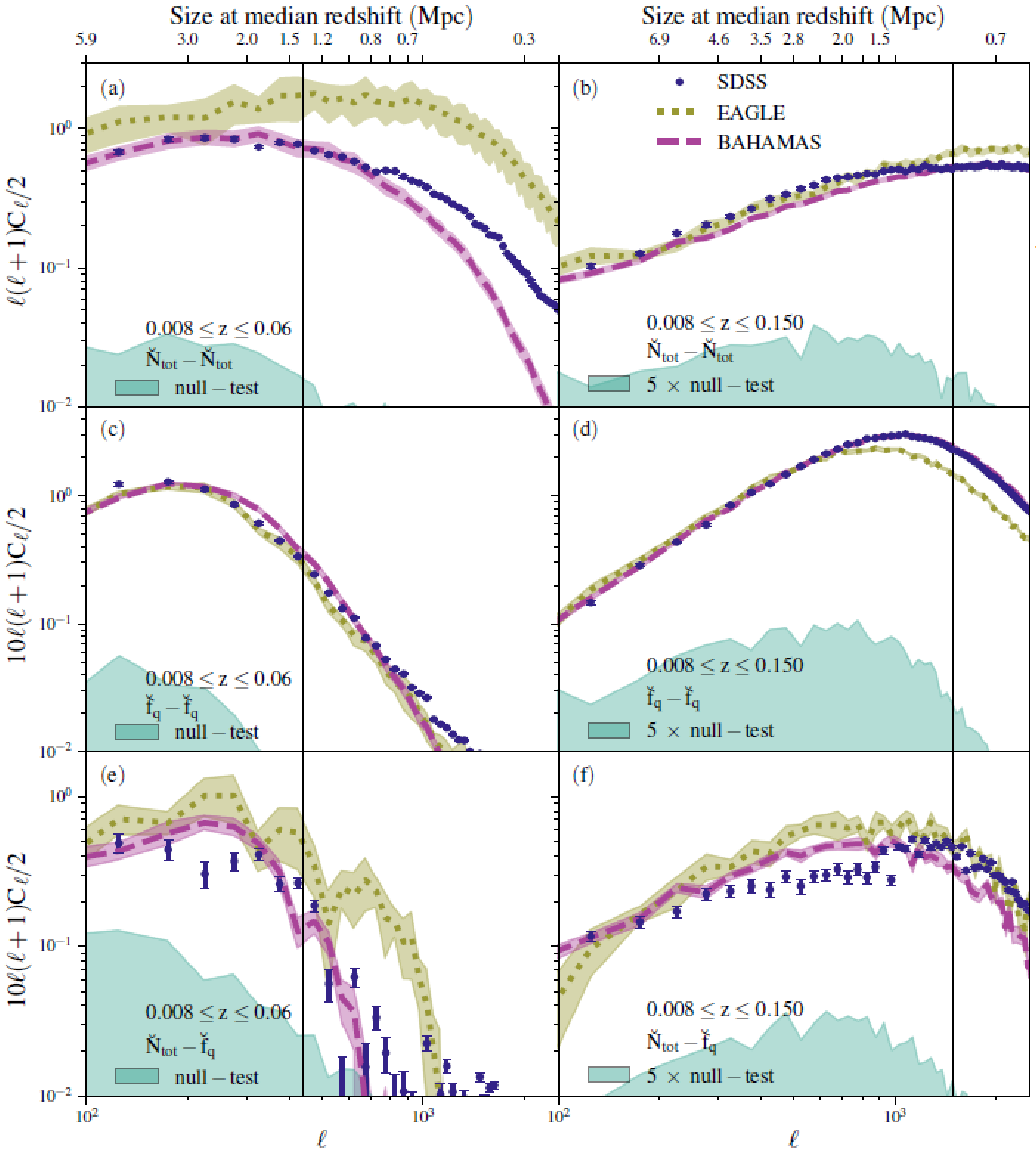
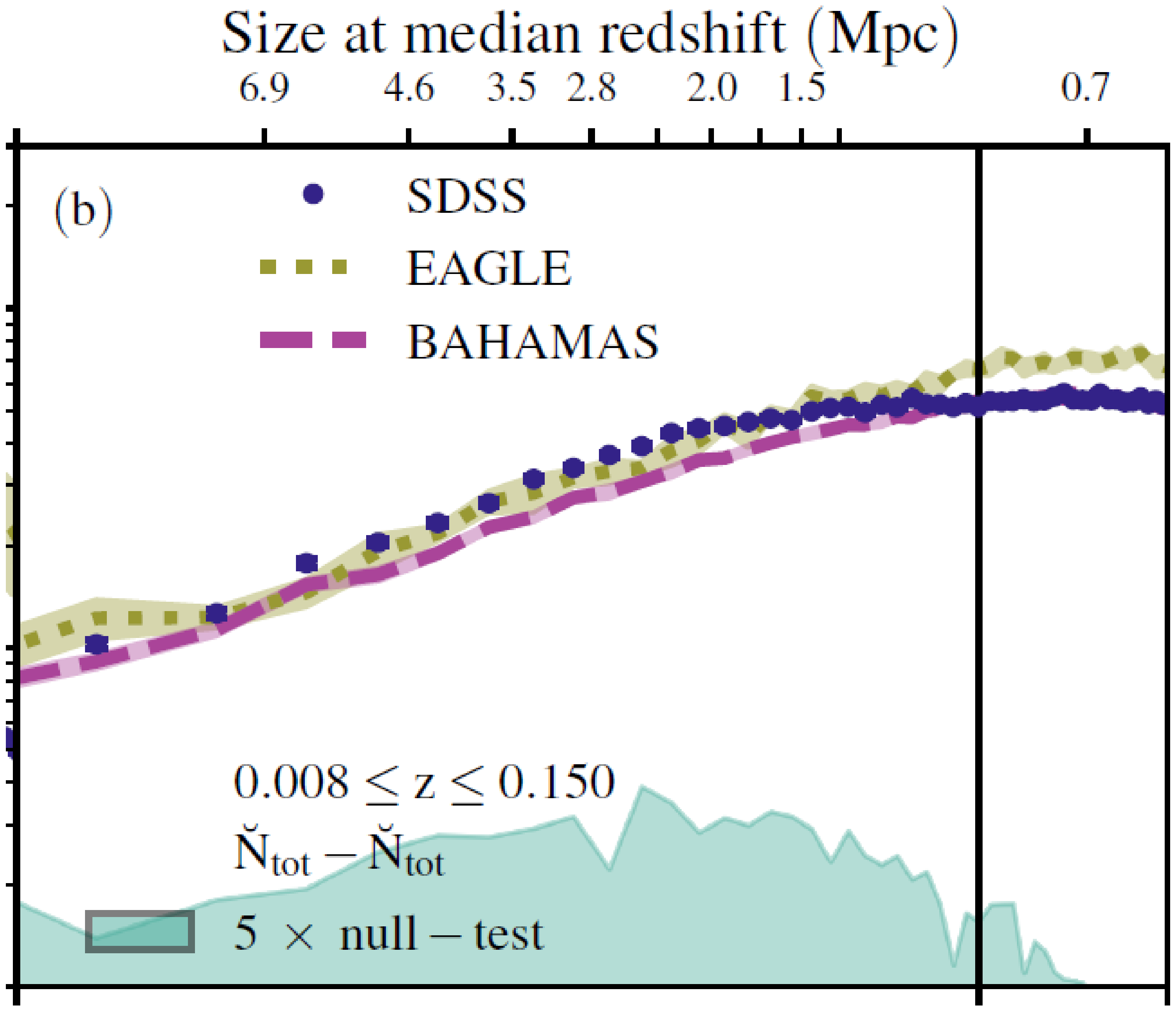
Clustering of galaxies

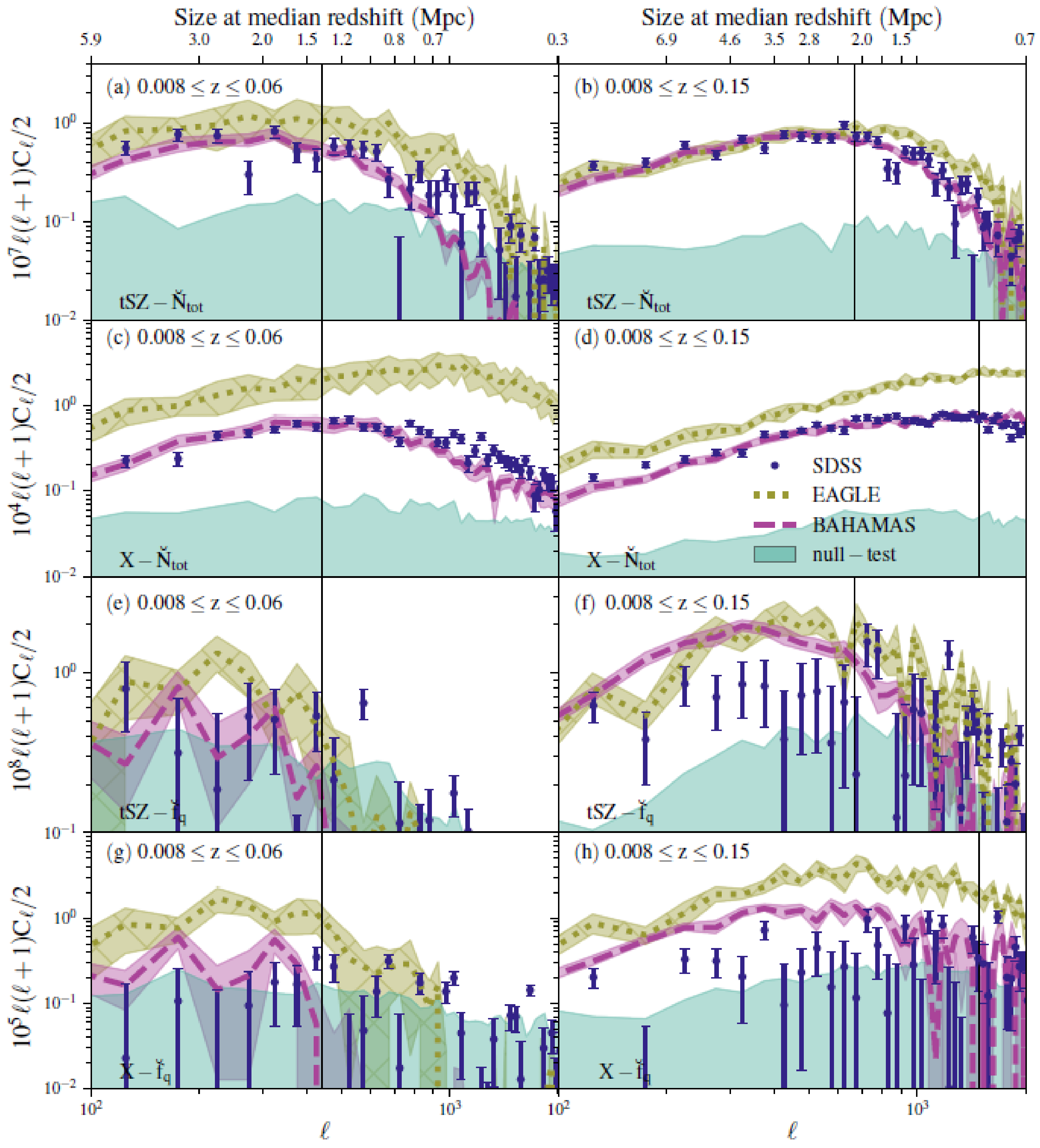




Galaxy overdensity power spectrum

Kukstas, IGM+ 2020

Galaxy and QF – hot gas cross-correlations



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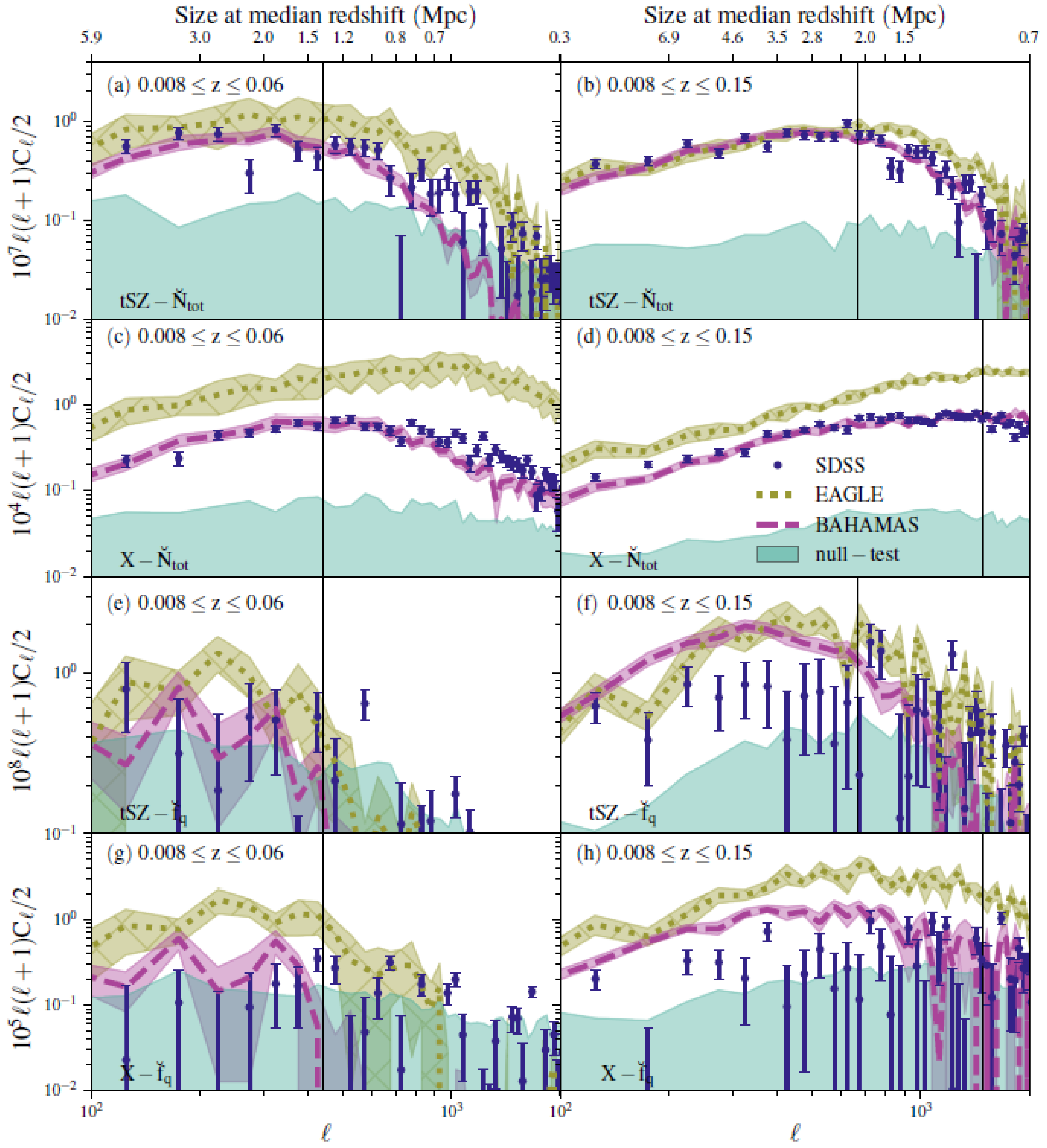
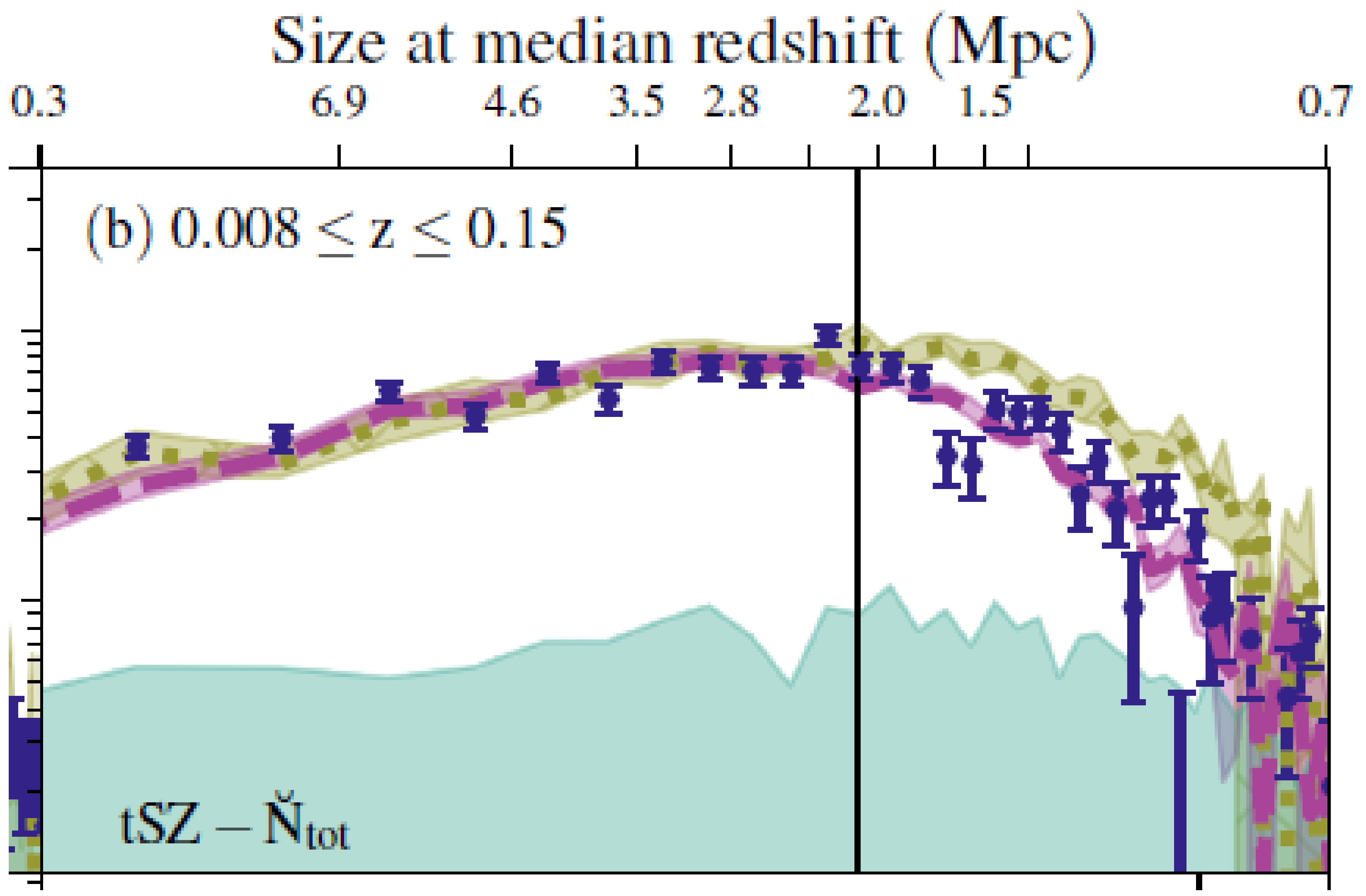
tSZ -- overdensity cross-correlation





tSZ - galaxy overdensity cross-spectrum

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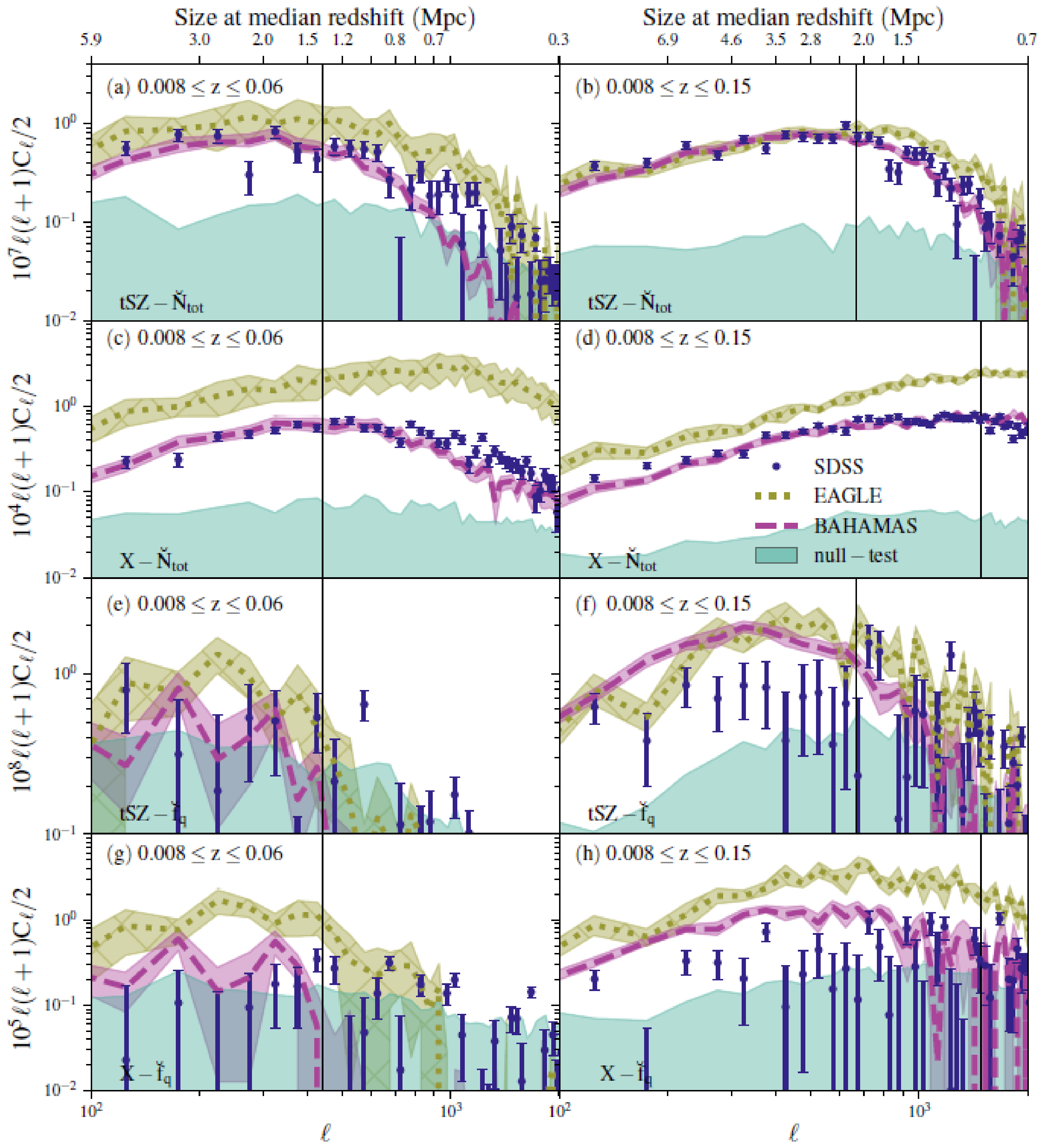
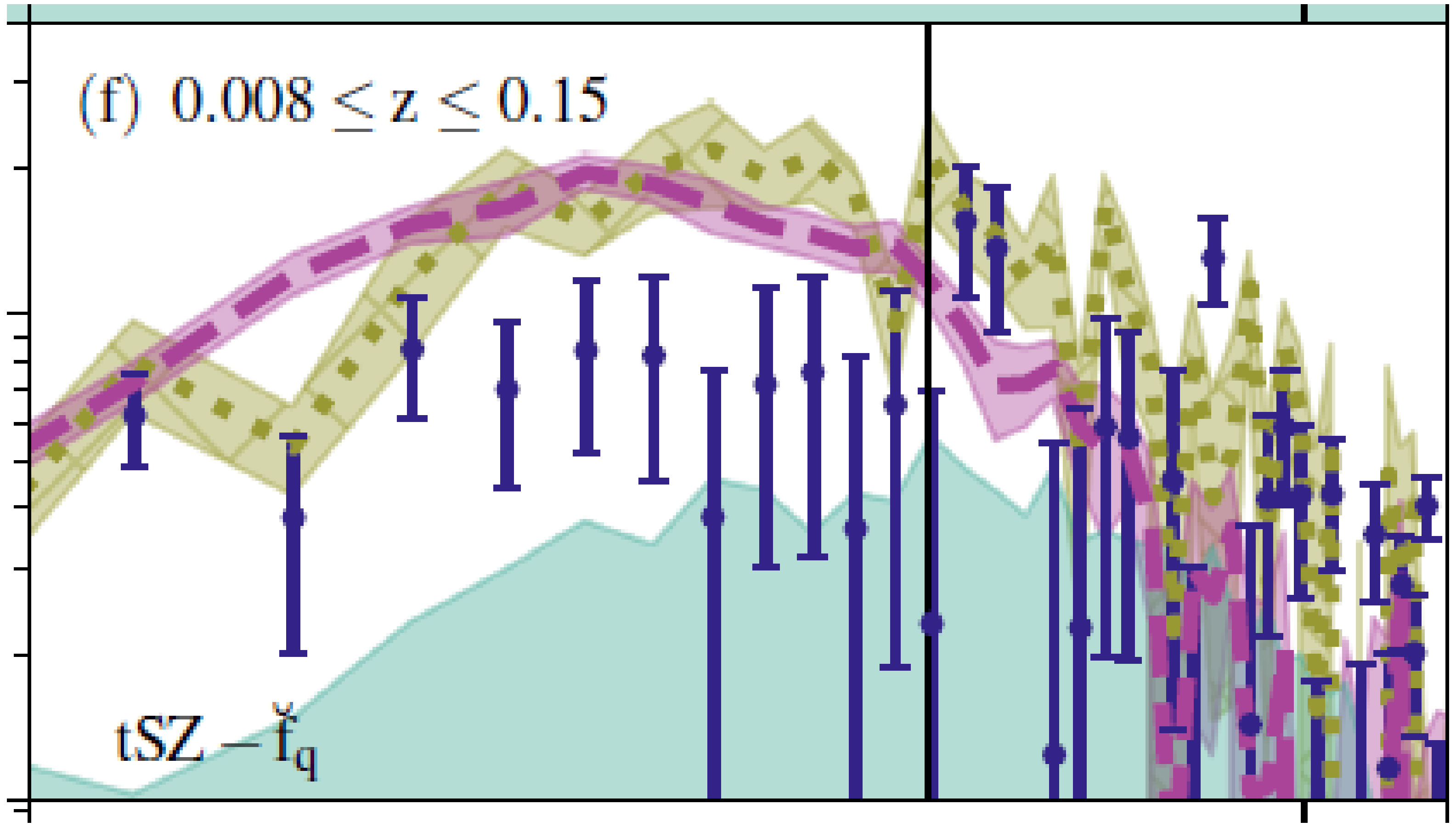
tSZ – quenched fraction cross-correlation





tSZ - QF cross-spectrum

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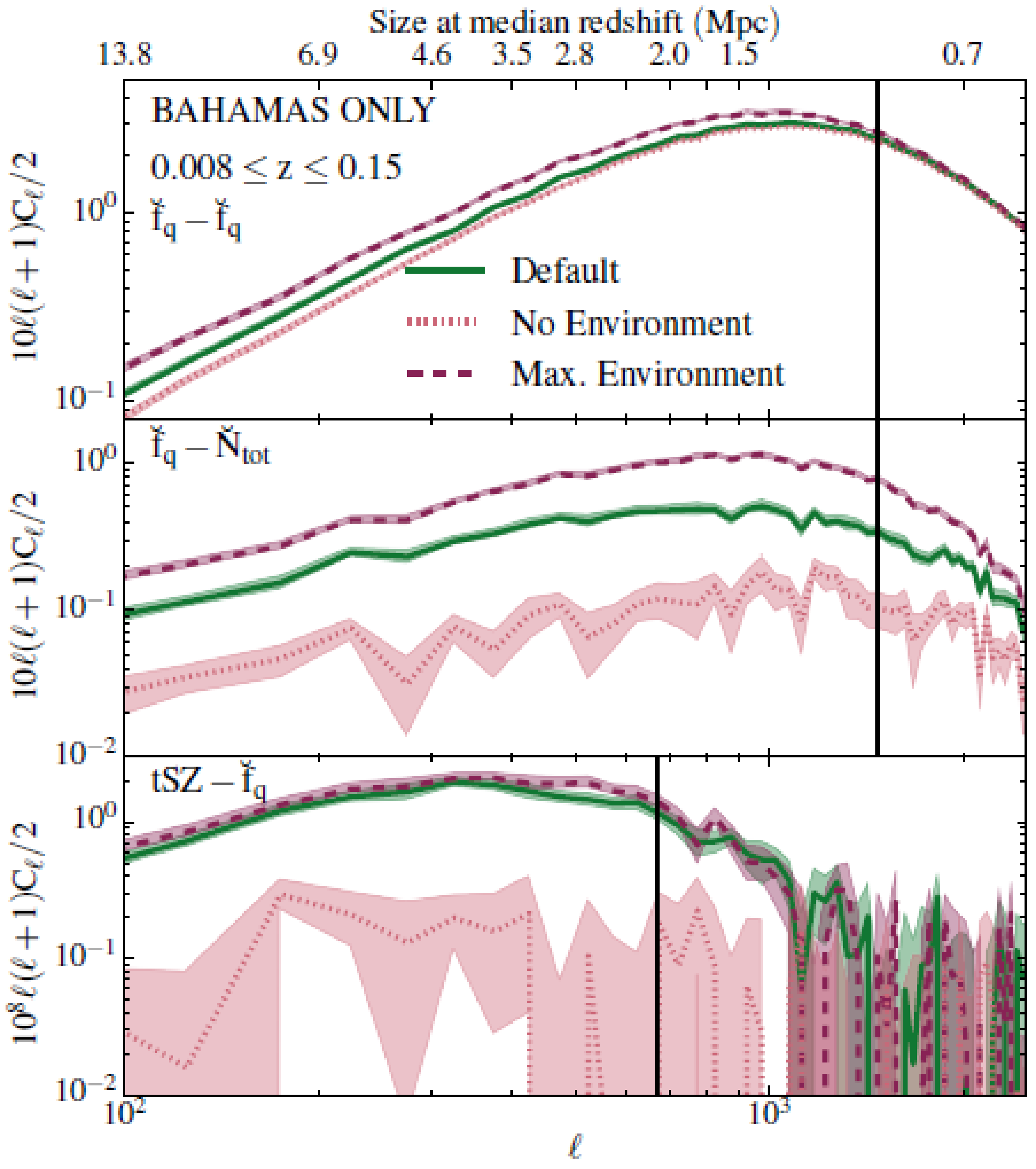
What do the failures mean? Deconstruction



We can artificially remove or maximise environmental effects in the simulations by simply changing the SFRs of satellites by hand.

Clustering of quenched fraction is mostly dominated by central galaxies, so is not particularly sensitive to environment.

Quenched fraction – galaxy overdensity cross receives approx. equal contributions from sats and centrals.

Quenched fraction – tSZ cross is dominated by satellites. EAGLE and BAHAMAS predict too strong of a signal, suggesting satellite quenching is too efficient. Why?

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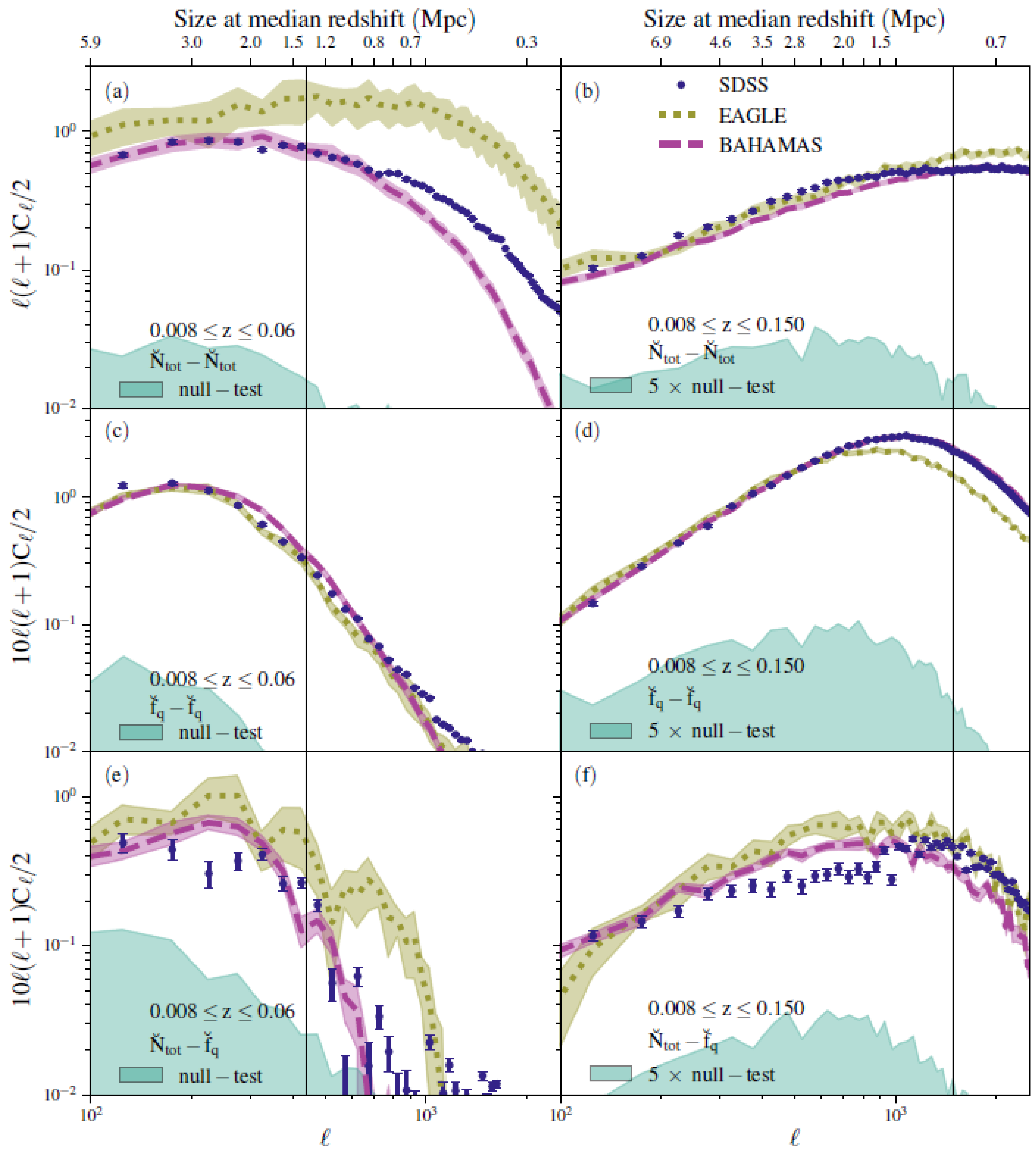
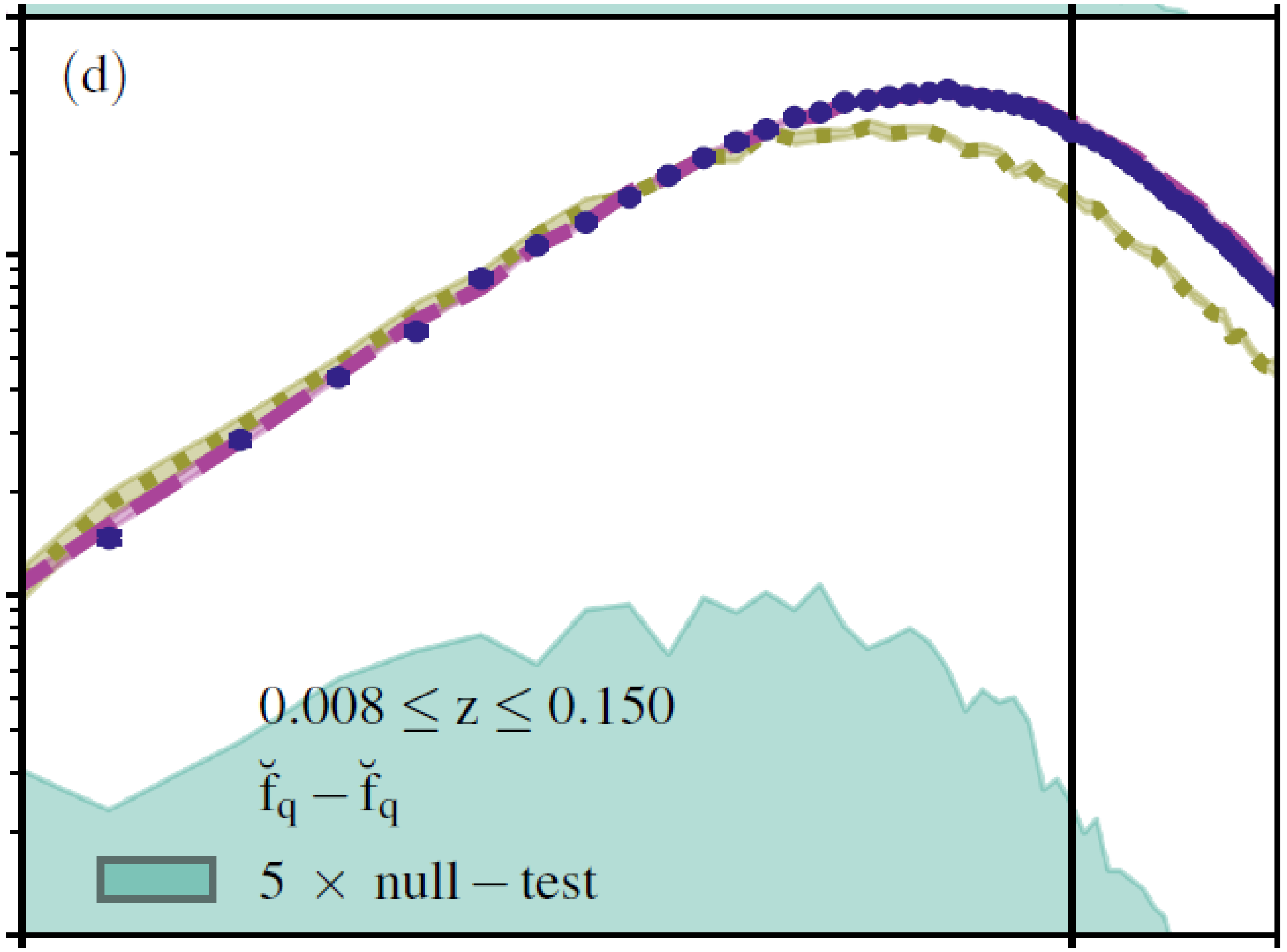
Summary

- Ram pressure stripping of outflows likely to be dominant hydrodynamical effect.
- Shutting down of cosmological accretion dominant gravitational effect.
- Role of radiation field and transport processes still uncertain.
- Cosmological simulations, which generally ignore radiation and transport processes, have some notable successes but also some key shortcomings. New physics? Better comparisons needed?
- Cross-correlations of galaxy surveys with large-scale structure maps (eRosita, LSST, Euclid, future tSZ) should provide valuable clues going forward. Simulations a requirement for interpreting these measurements.

Clustering of quenched fraction





QF overdensity power spectrum

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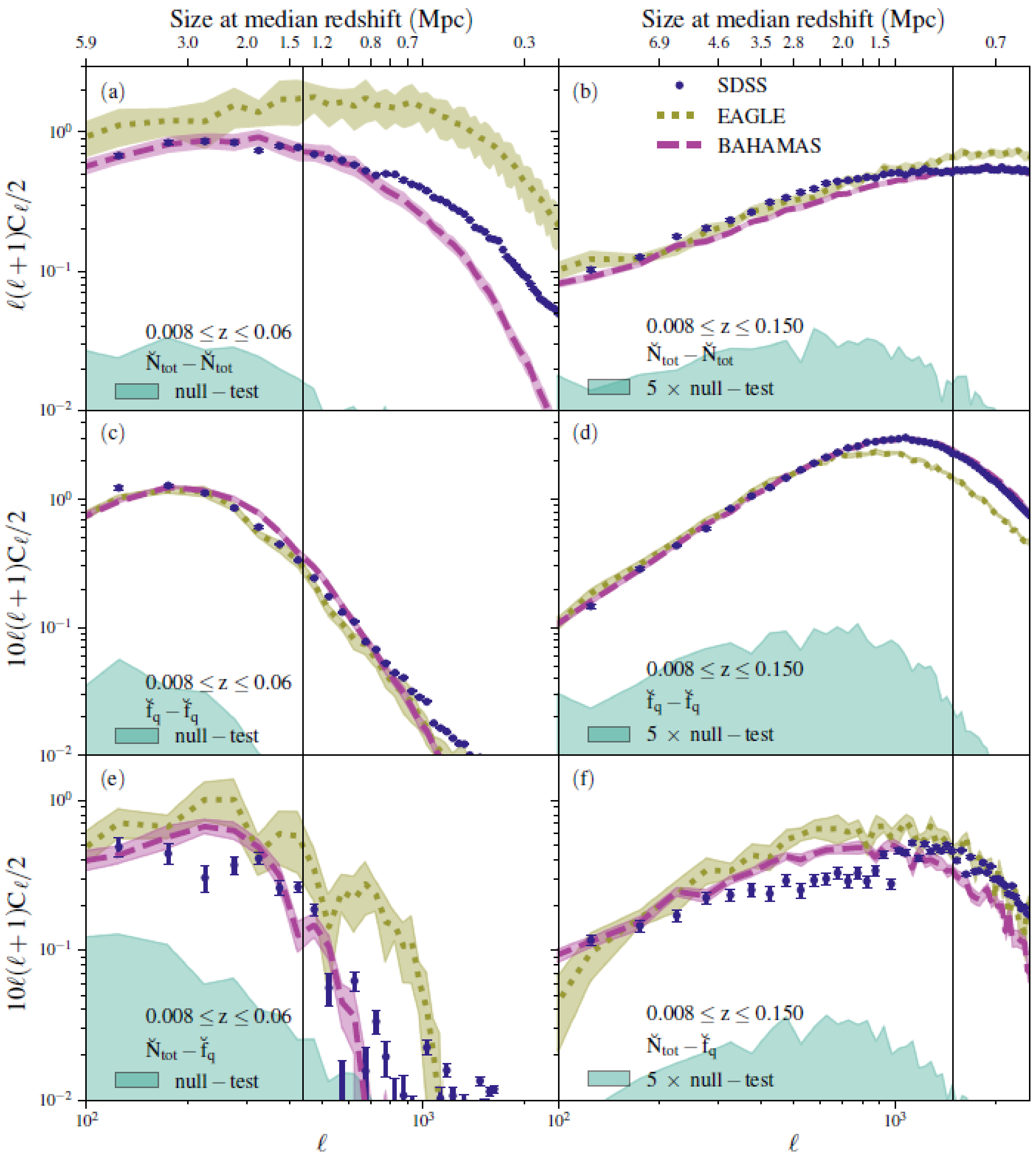
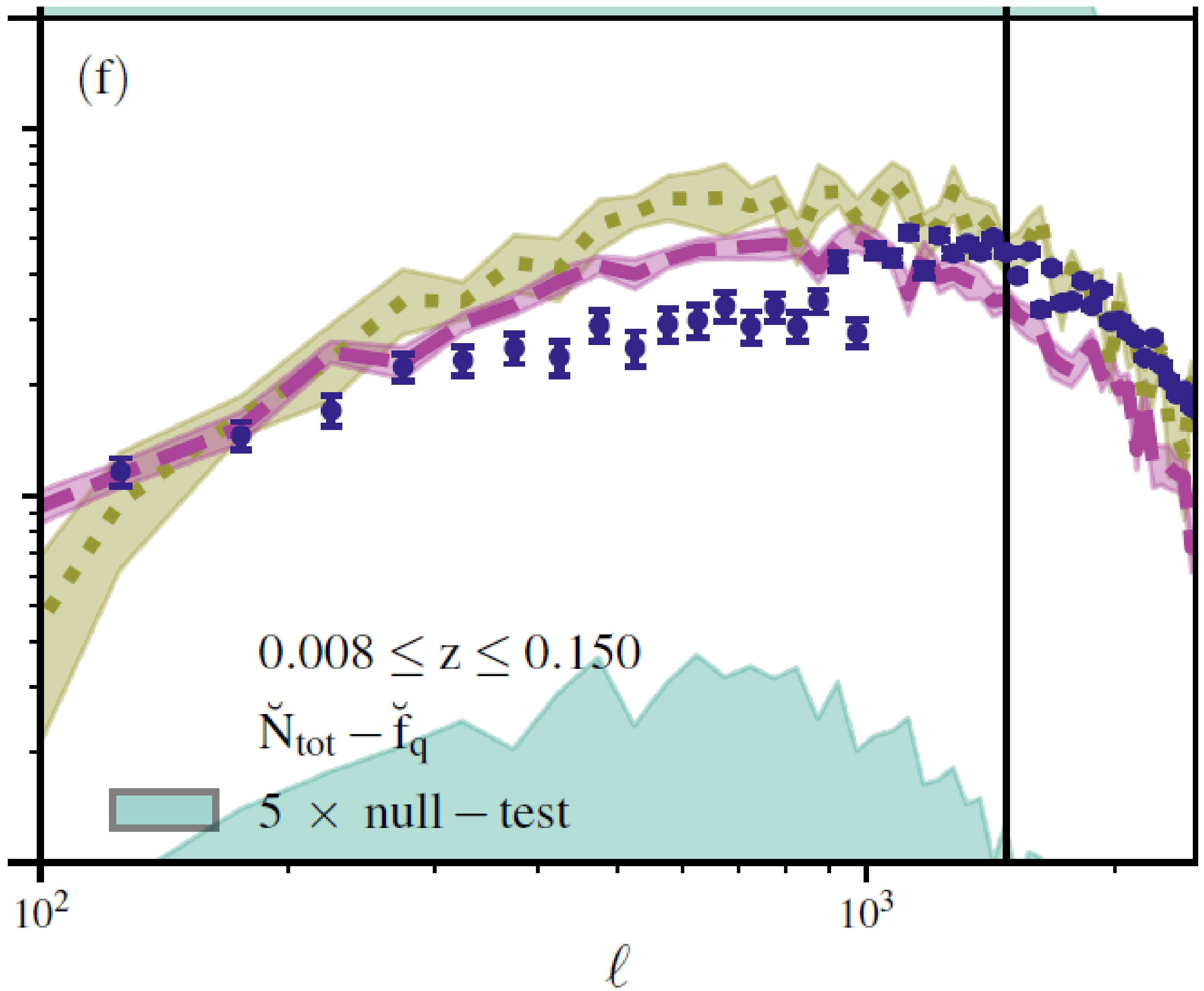
Overdensity – QF cross-correlation





QF-overdensity cross-spectrum

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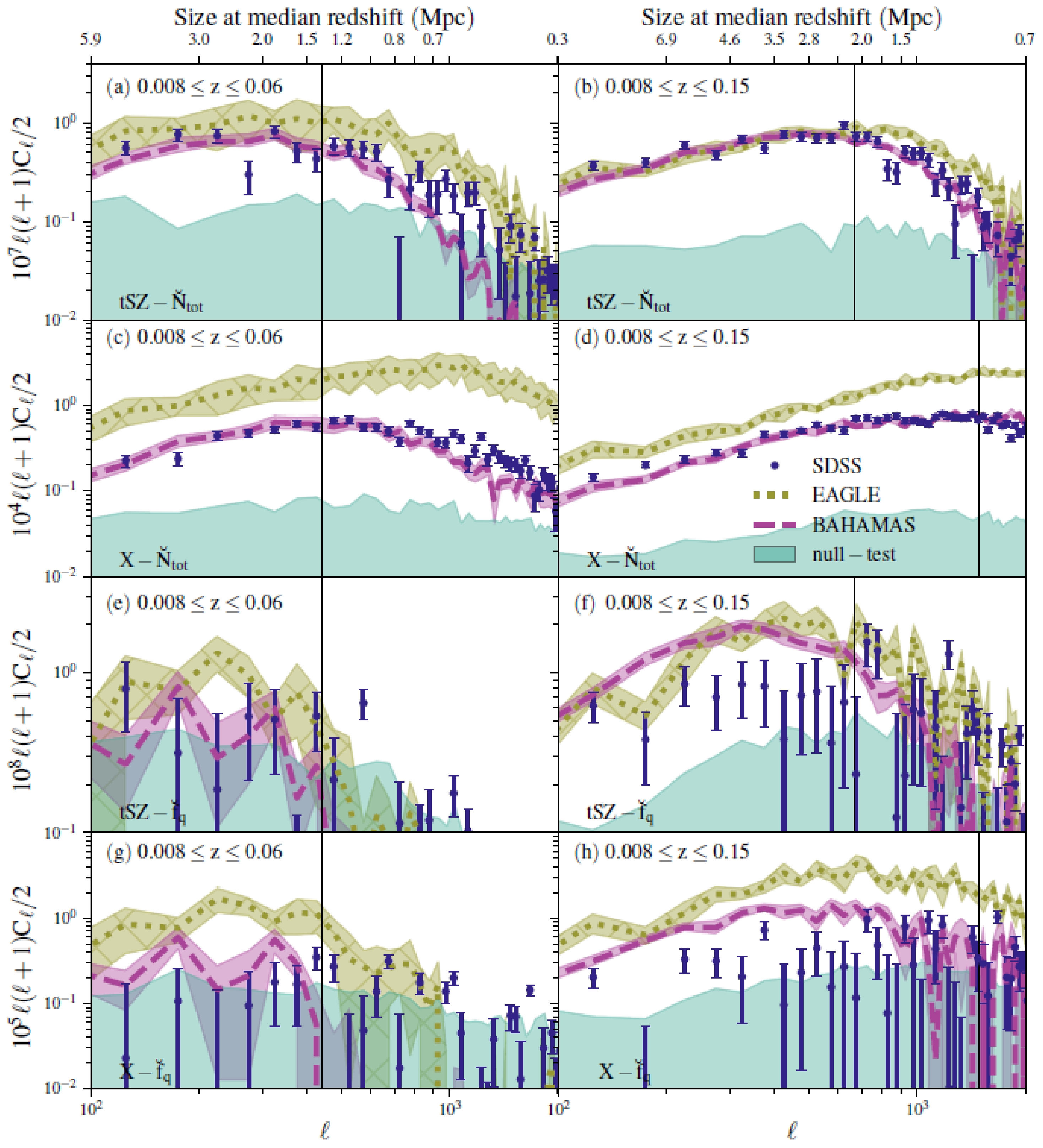
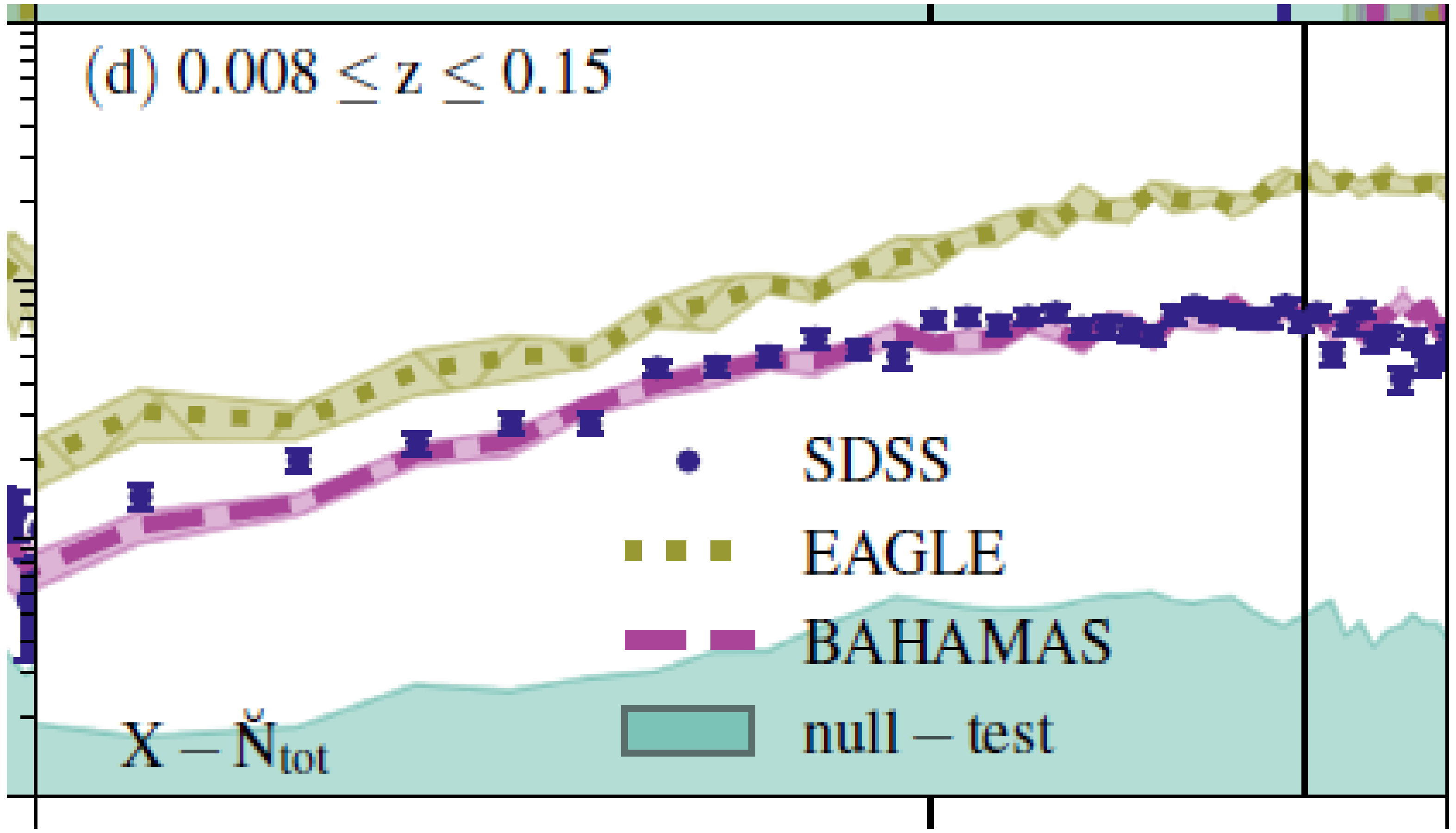
X-ray – overdensity cross-correlations





X-ray - galaxy overdensity cross-spectrum

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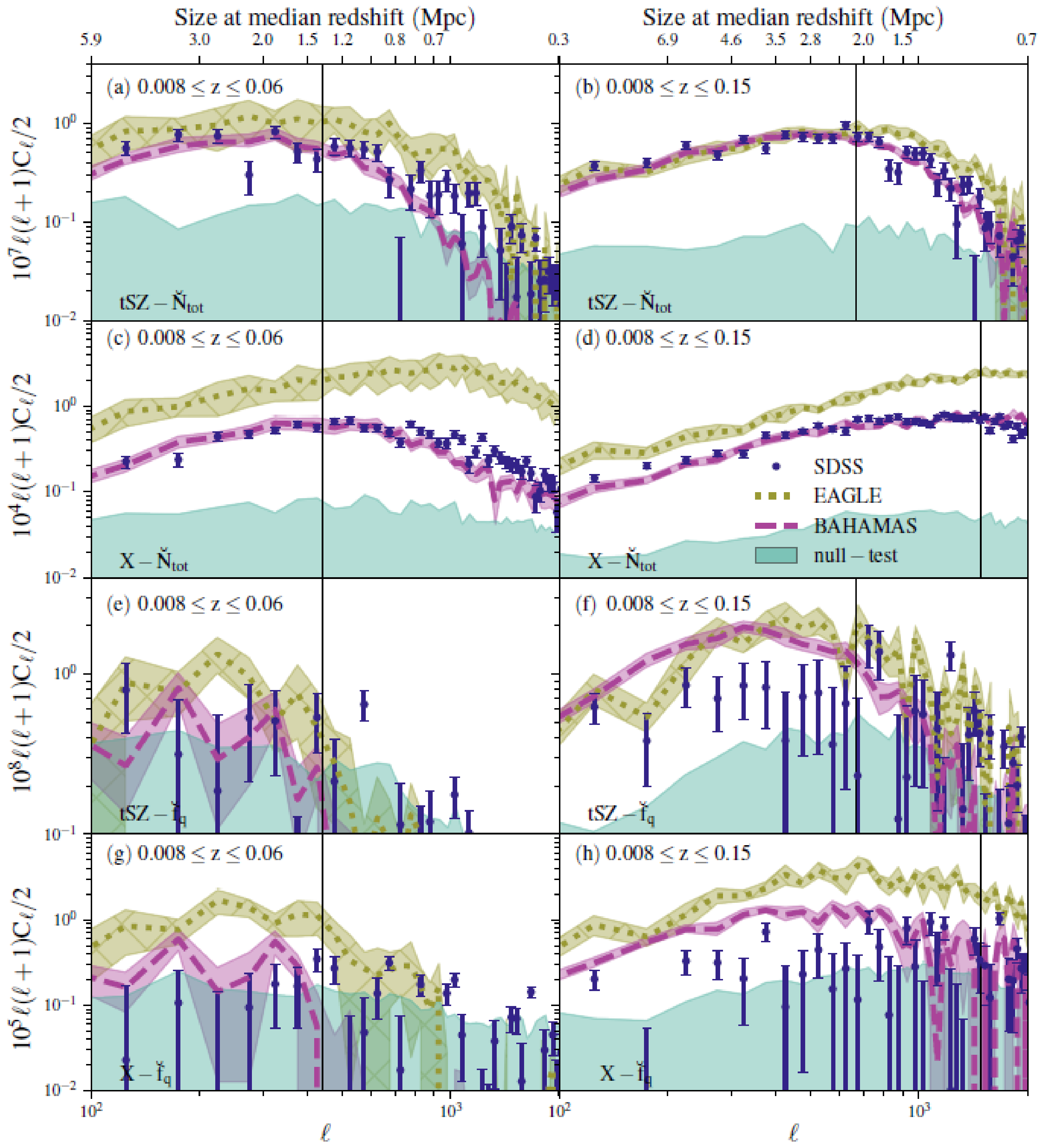
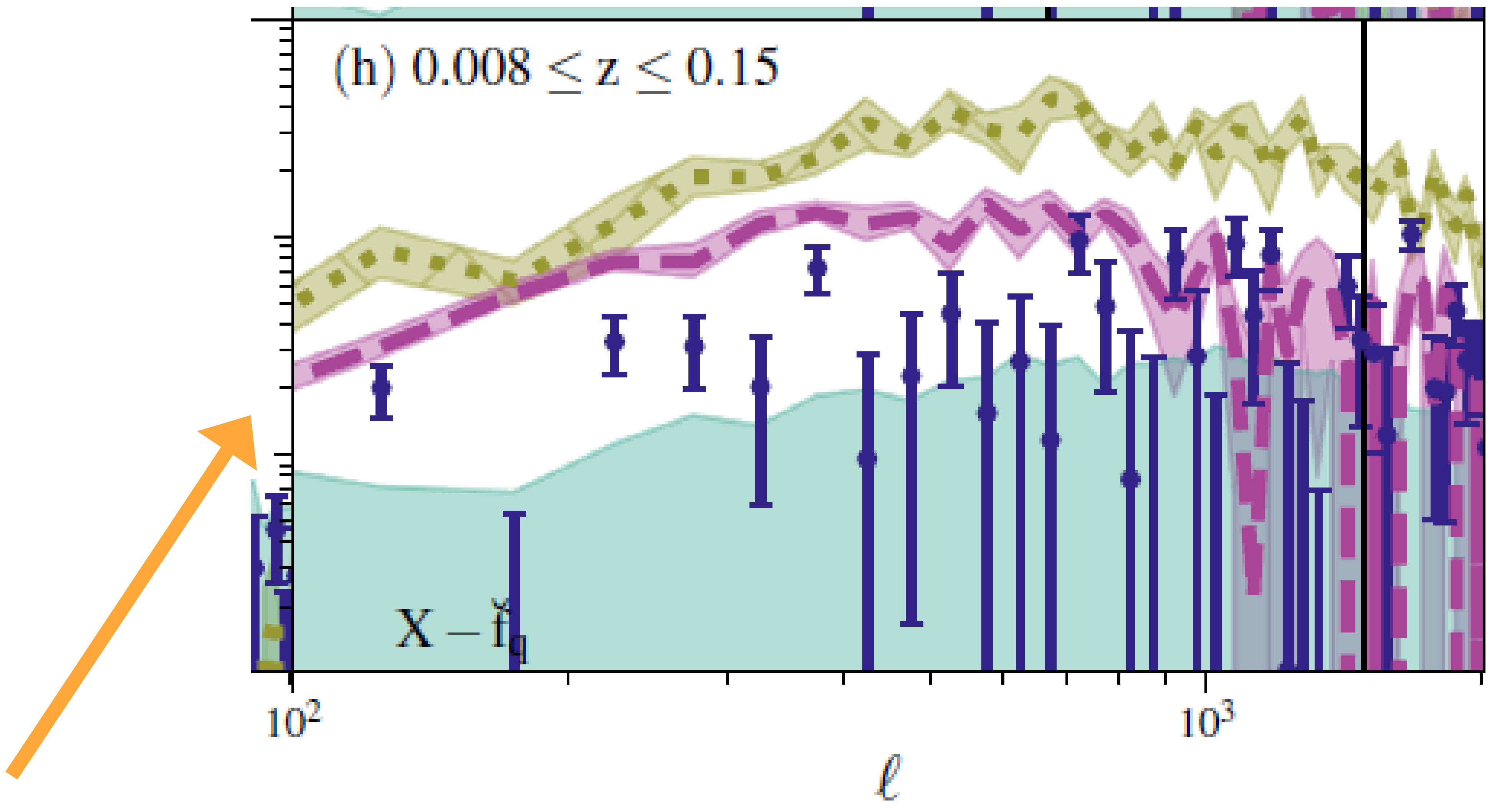
X-ray – quenched fraction cross-correlation





X-ray - QF cross-spectrum

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