Estimating (proto-)cluster masses and dynamical states

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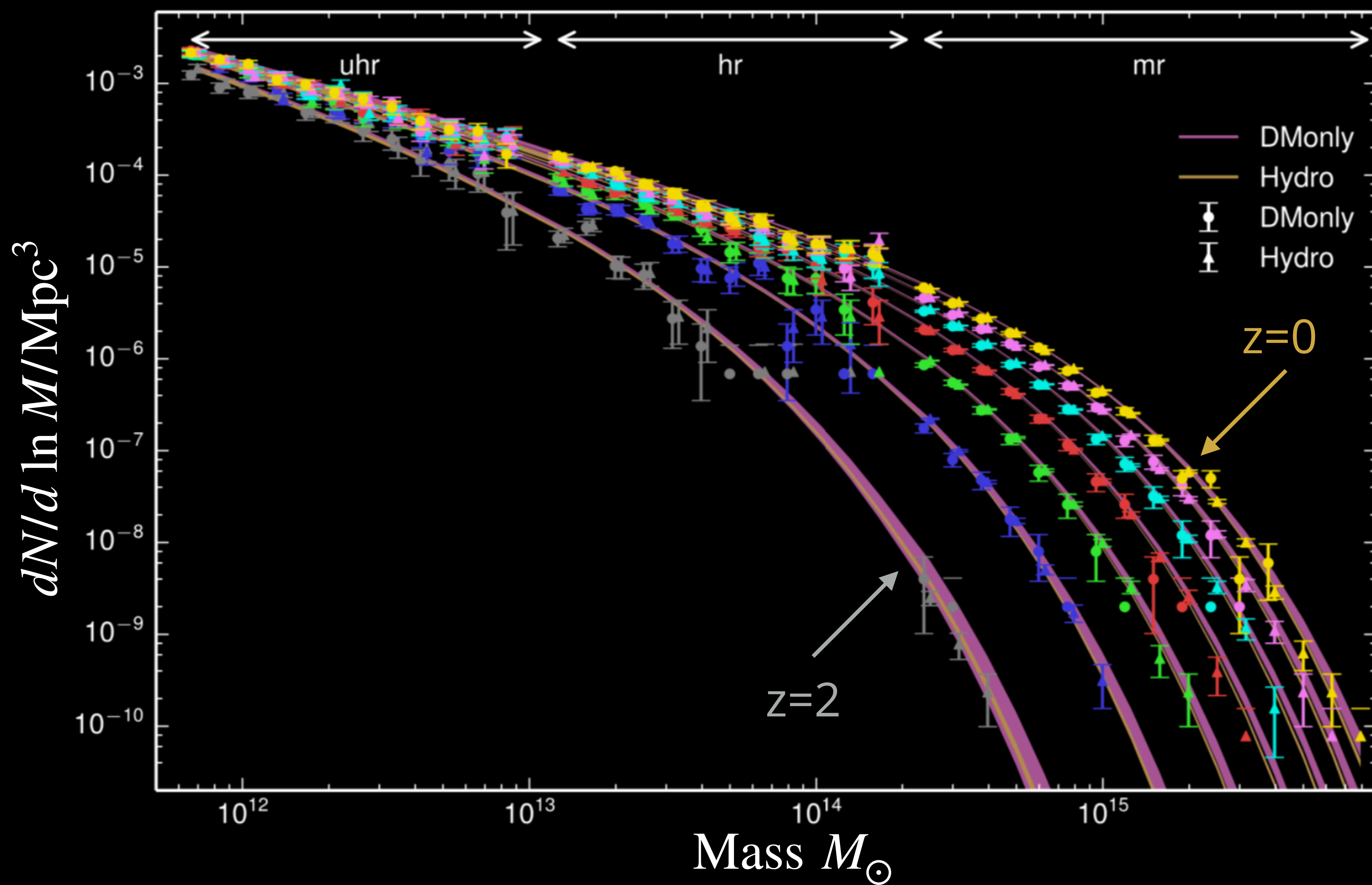
The halo mass function



BOCQUET ET AL. 2016

- This is what we're looking at…but you can't measure the mass of every cluster in the Universe…

A three-parameter population

- Structure forms through dark matter-driven gravitational coalescence
  - like it or not, dark matter seems to be the dominant component

- The mass and redshift
  - are the fundamental parameters that allow us to link observation and theory

- The dynamical state
  - we have a single snapshot of a cluster from the entirety of its assembly history, lasting billions of years
  - affects cluster detectability in every wavelength range
  - affects our ability to reconstruct the mass using every method at our disposal

Masses & dynamical state

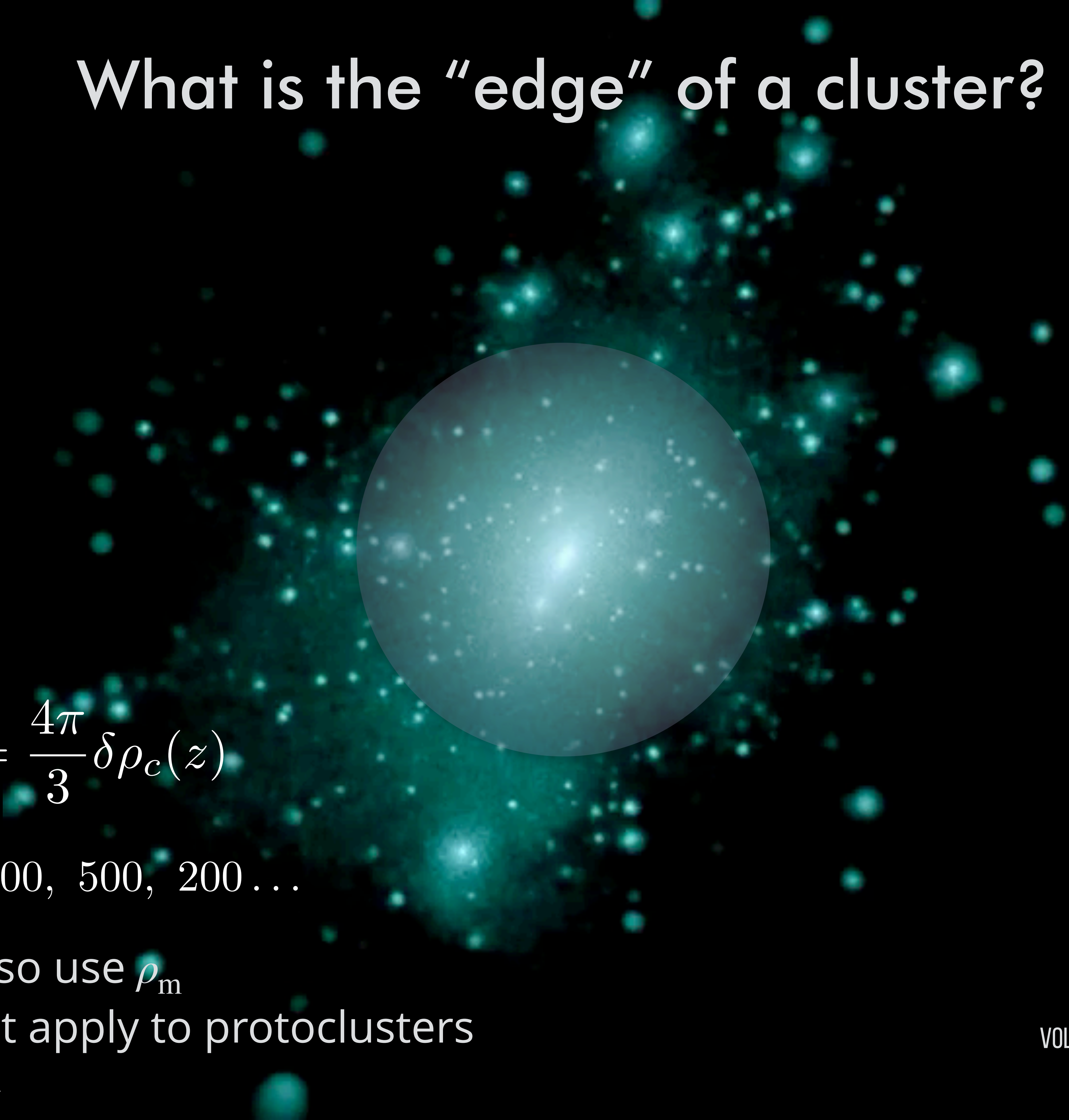
- Vast subject, cannot hope to do it justice in <20 mins
  - (thanks, SOC…)

- For masses, the tracers are:
  - cluster galaxies (dynamical, caustic)
  - background galaxies (weak & strong lensing)
  - ICM (X-rays, SZ)
  - CMB anisotropies (CMB lensing)
  - each has its own advantages & disadvantages (see last slide)

- For the dynamical state:
  - cluster galaxies (but need spectra of a lot of galaxies to do this well)
  - ICM (X-rays, mm/SZ if you have the angular resolution)
  - (presence of large-scale non-thermal emission)

Dark matter

What is the “edge” of a cluster?



VOLKER SPRINGEL

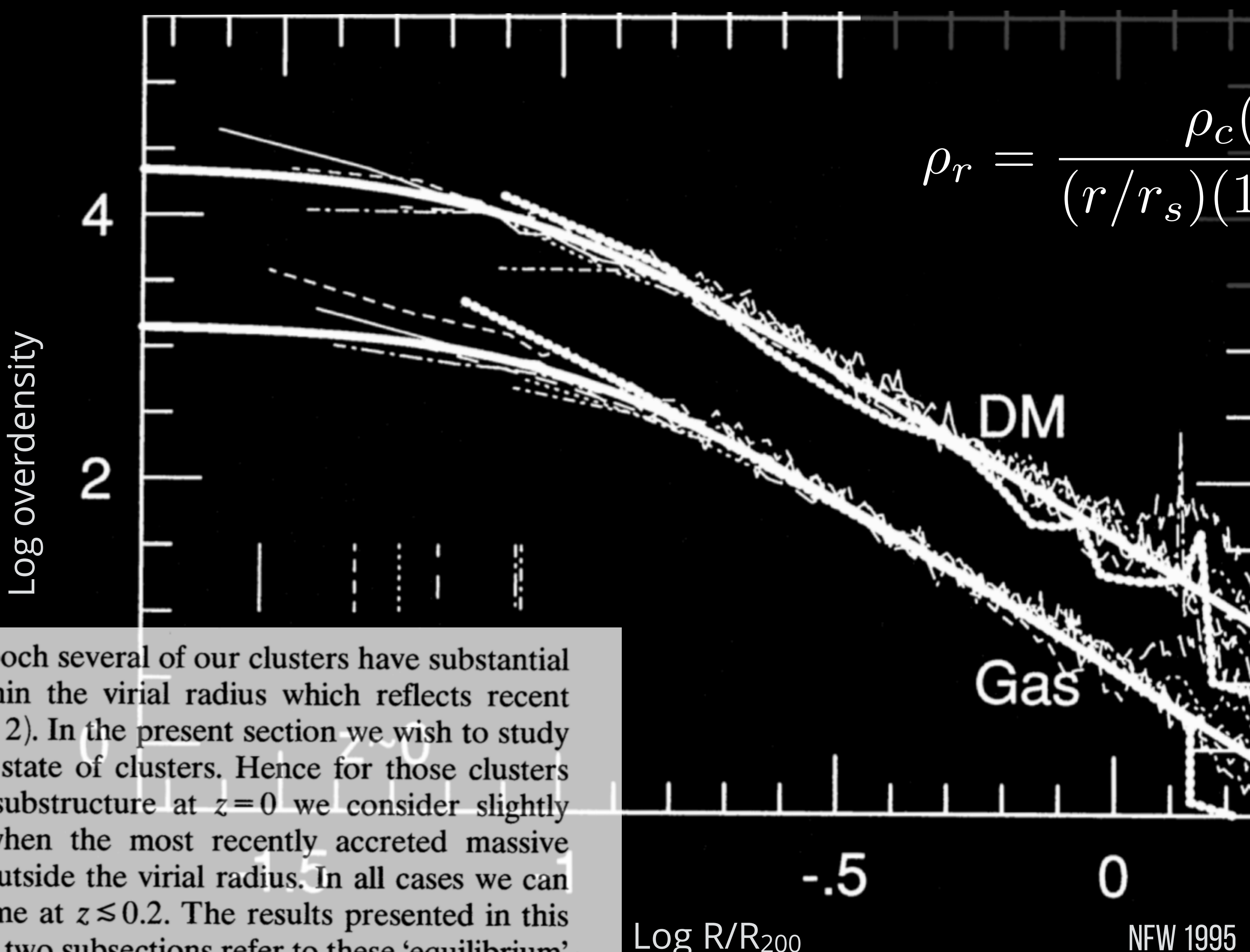
$$\frac{M_\delta}{R_\delta^3} = \frac{4\pi}{3}\delta\rho_c(z)$$

$$\delta = 2500,\ 500,\ 200\ldots$$

Can also use $\rho_{\rm m}$

Cannot apply to protoclusters

The NFW profile

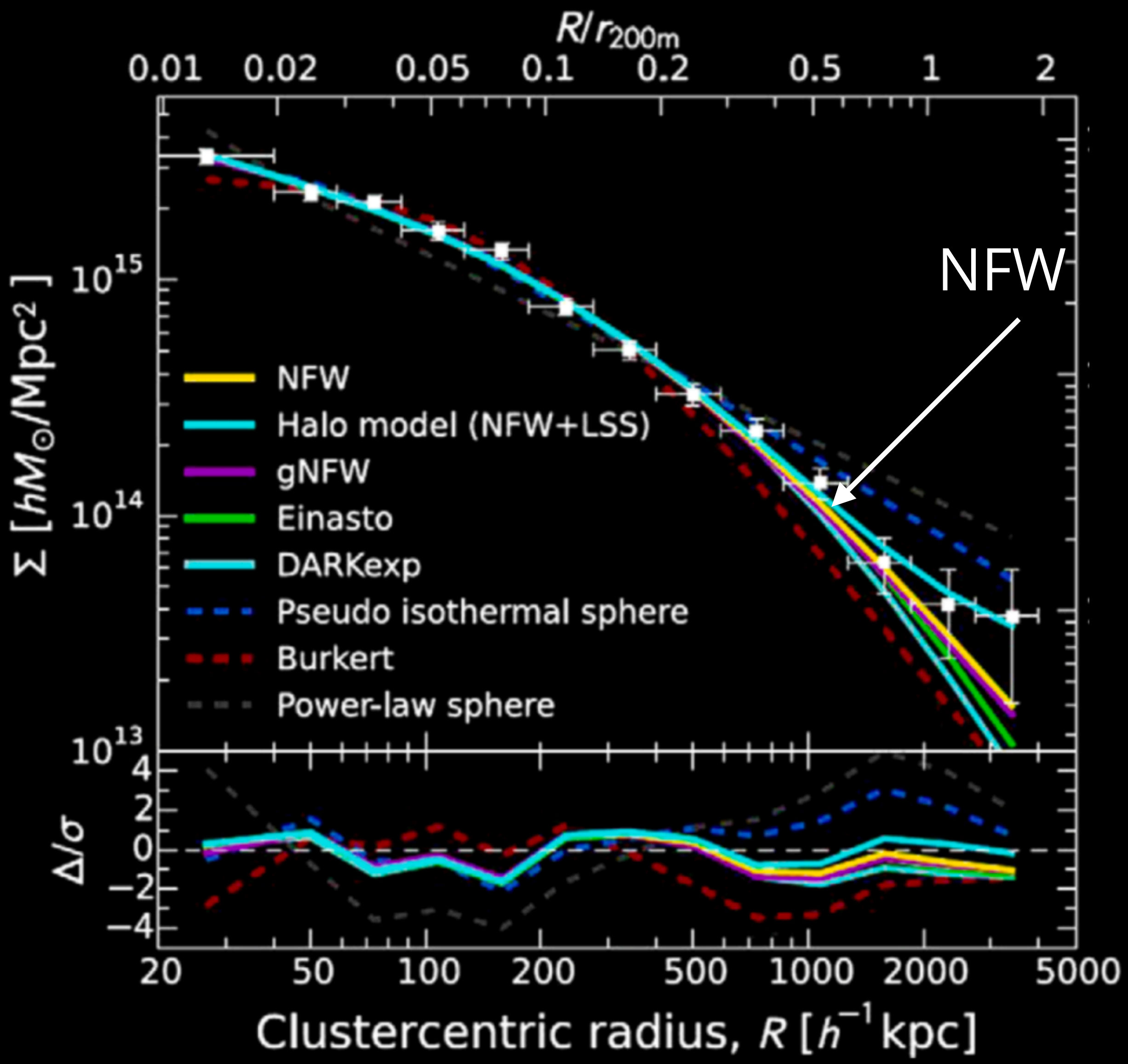


NFW 1995

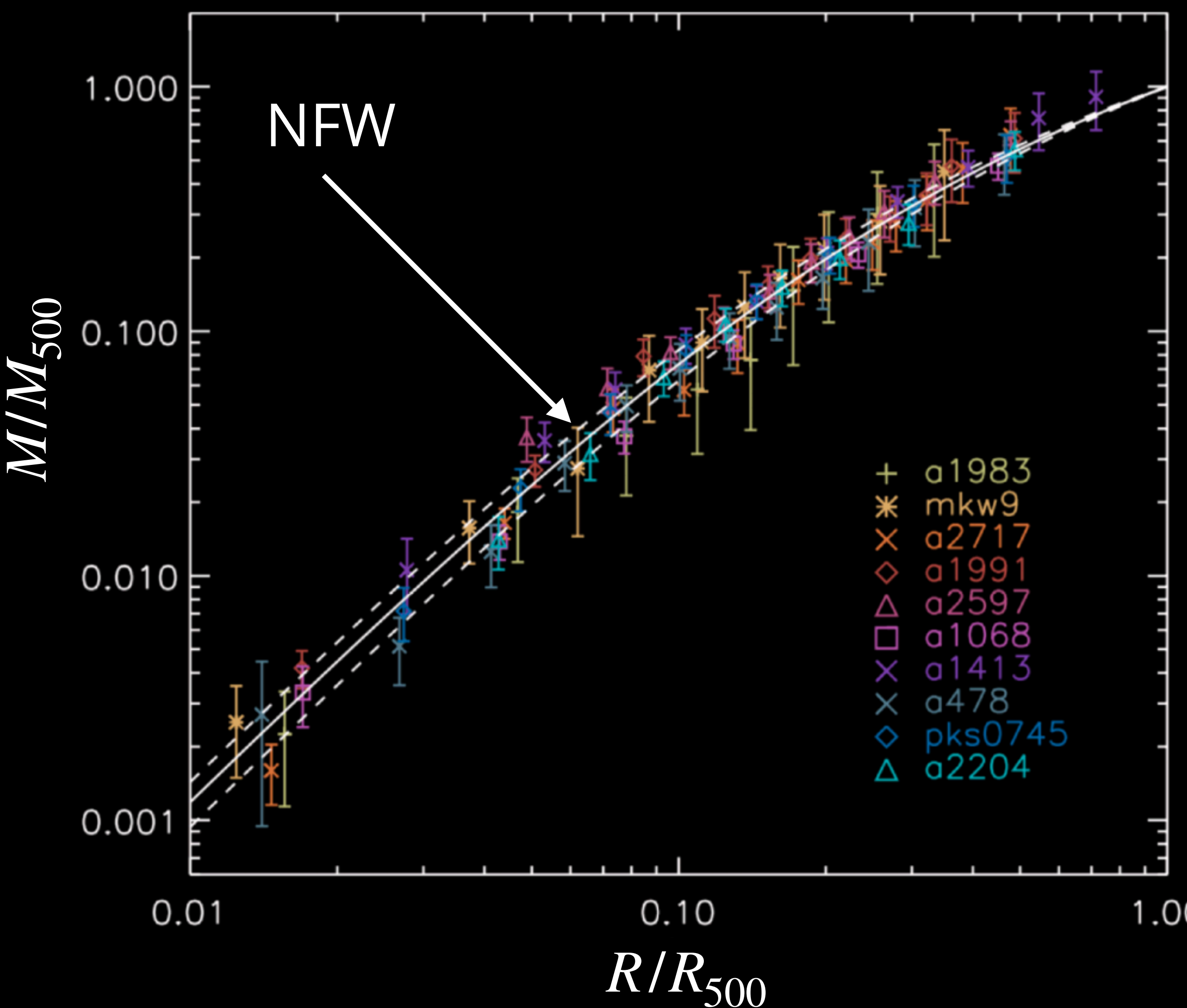
$$\rho_r = \frac{\rho_c(z)\delta_c}{(r/r_s)(1+r/r_s)^2}$$

At the present epoch several of our clusters have substantial substructure within the virial radius which reflects recent mergers (see Fig. 2). In the present section we wish to study the 'equilibrium' state of clusters. Hence for those clusters with significant substructure at $z=0$ we consider slightly earlier epochs when the most recently accreted massive clump was still outside the virial radius. In all cases we can choose such a time at $z \lesssim 0.2$. The results presented in this and the following two subsections refer to these 'equilibrium' configurations. It is important to note that they cannot be considered typical of nearby clusters; rather, they are typical of nearby *regular* clusters, which may be a minority of all clusters.

Total density and mass profiles



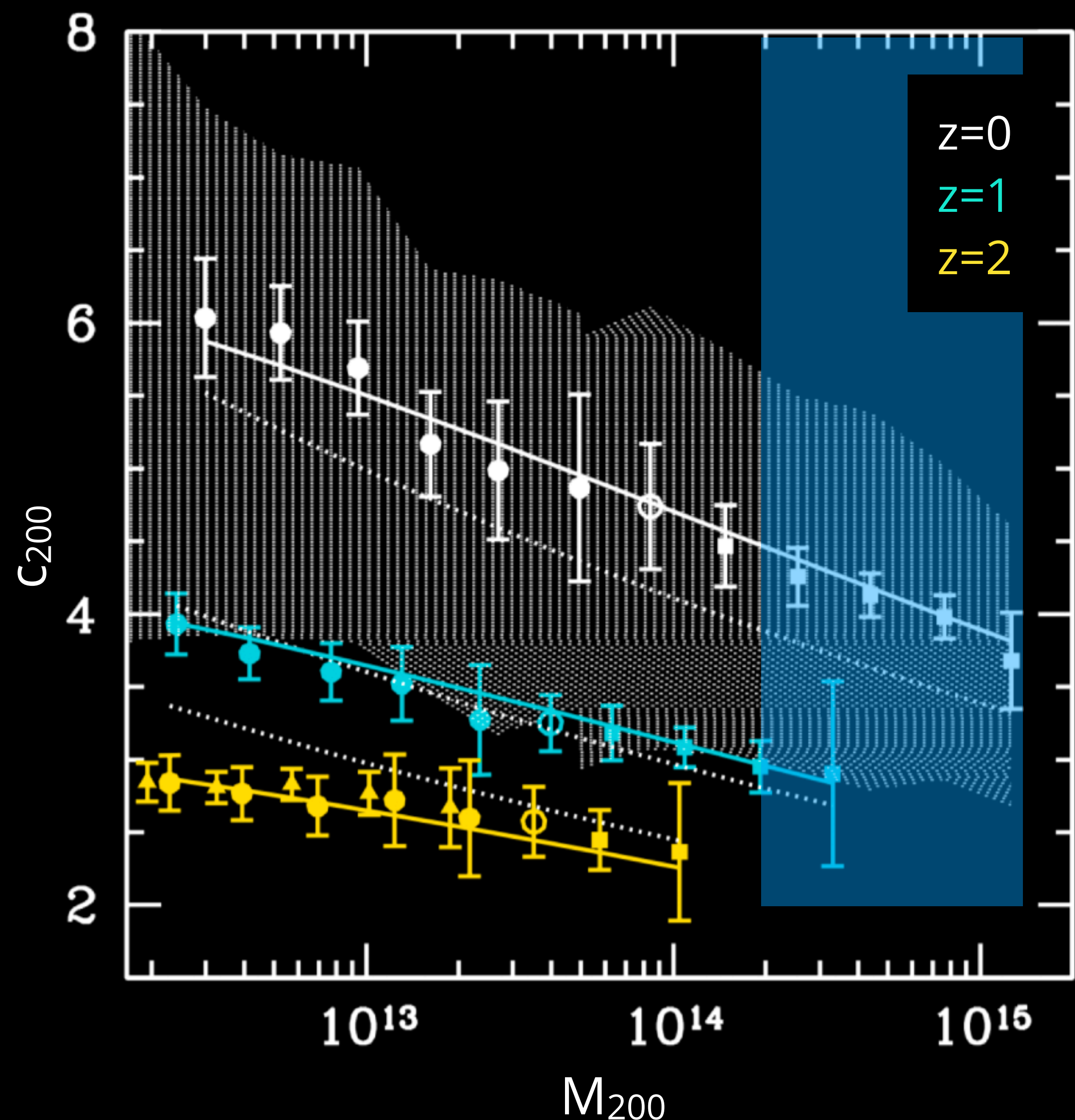
UMETSU ET AL. 2016, X-RAY SELECTED SYSTEMS



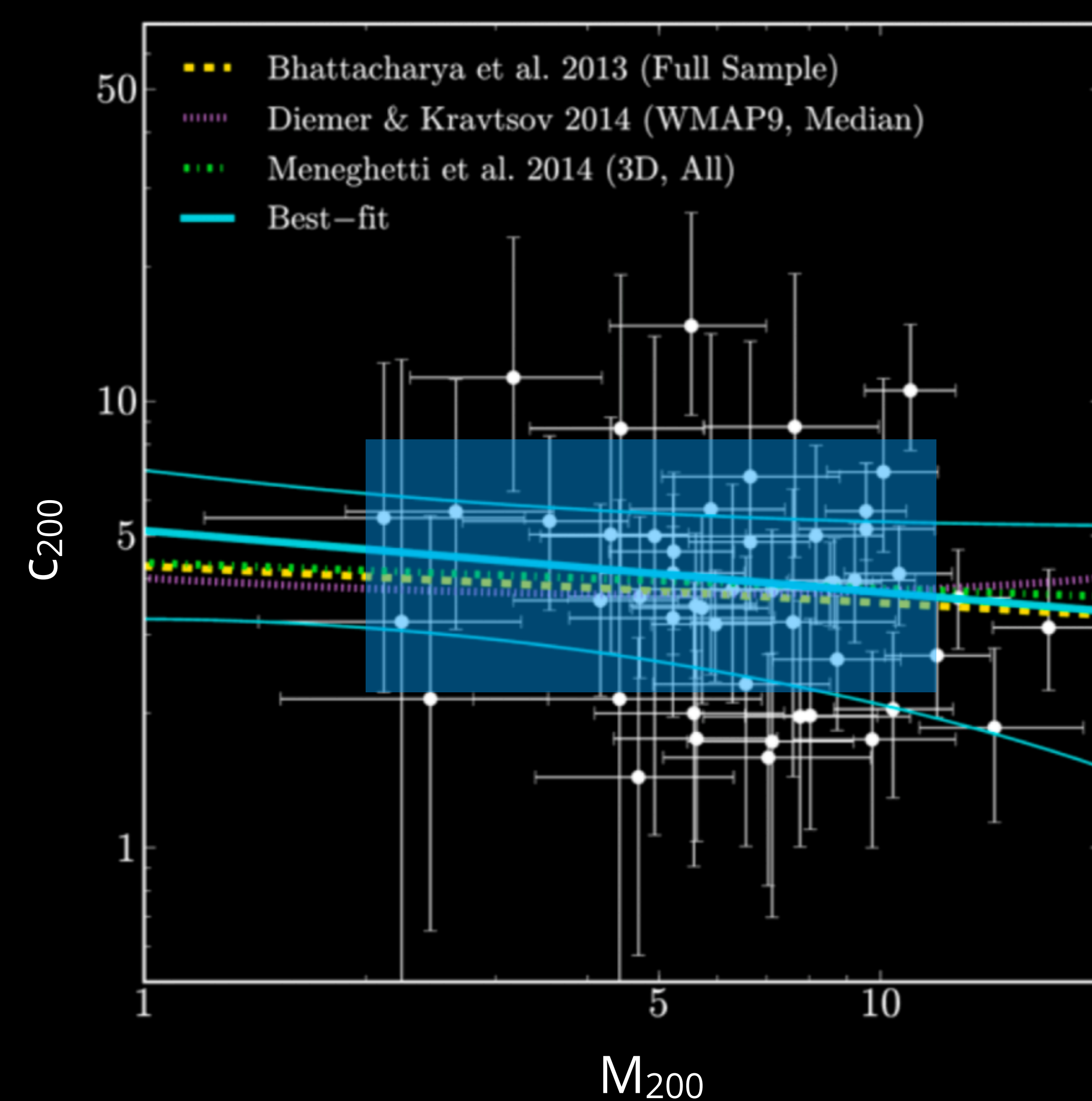
POINTECOUTEAU ET AL. 2005, X-RAY HE MASSES OF RELAXED SYSTEMS
SEE ALSO VIKHLININ ET AL. 2006

- In the best-observed systems, most observations (velocity dispersions, WL, SL, X-ray…) indicate NFW-type profiles

The c-M relation



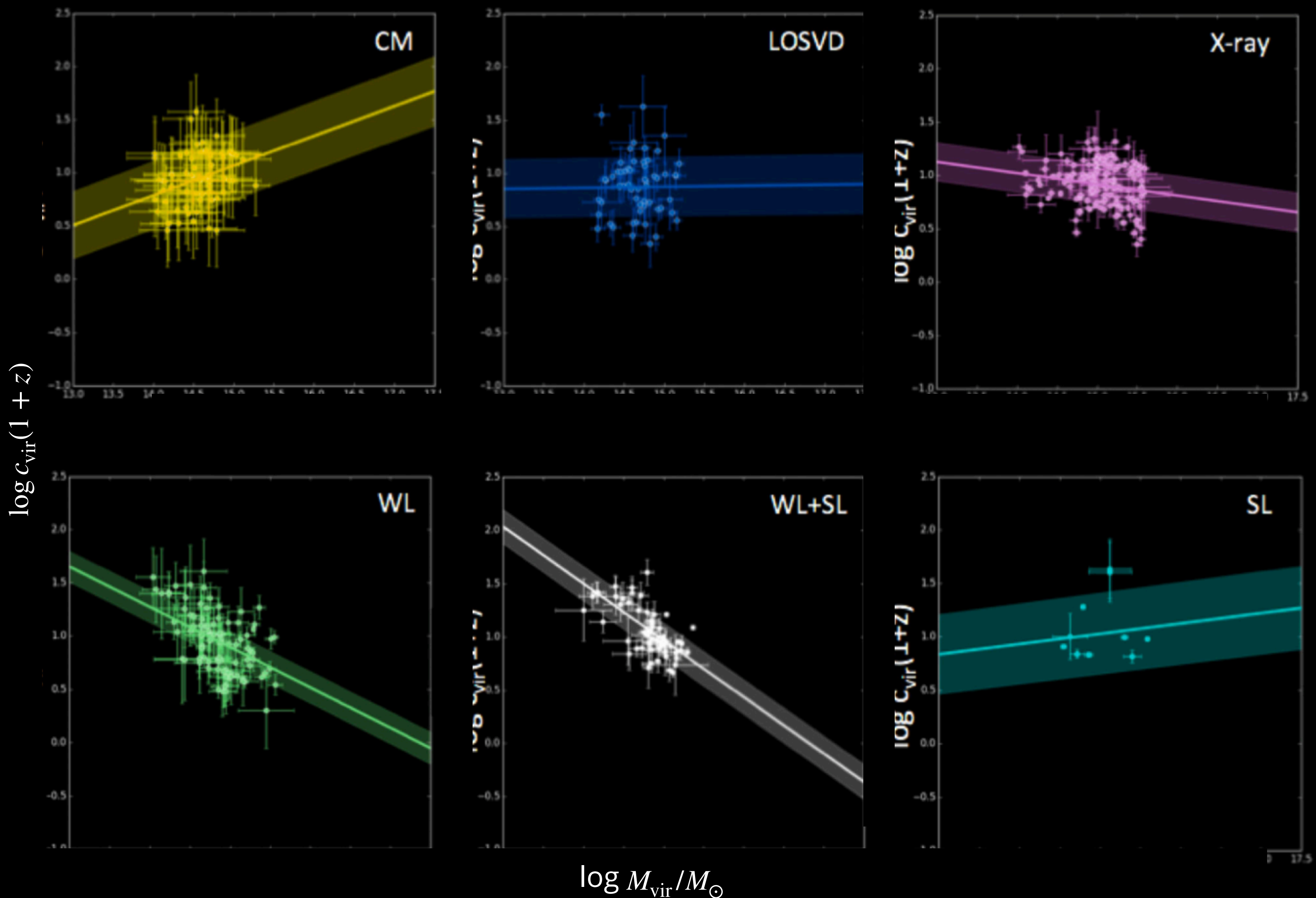
BHATTACHARYA ET AL. 2013, SEE ALSO E.G. DOLAG ET AL 2004, DIEMER & KRAVTSOV 2014, AND MANY OTHERS



OKABE & SMITH 2016, SEE ALSO POINTECOUTEAU ET AL. 2005, VIKHLININ ET AL . 2006, MERTEN ET AL. 2015, BIVIANO ET AL. 2017, AND MANY OTHERS

- Large dispersion in simulations comes from differences in formation times, mass accretion histories, and dynamical state
- c also depends on fitted radial range (Neto et al. 2007, Wu et al. 2013)
- In observations, it's mostly dominated by measurement uncertainties

The c-M relation



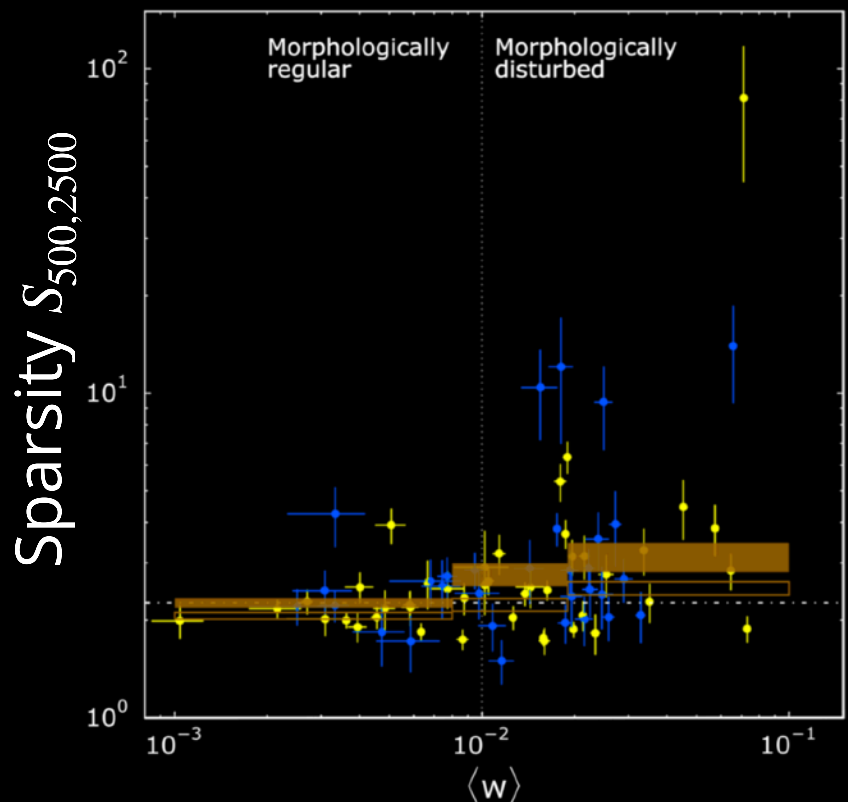
COMPILATION OF C-M MEASUREMENTS BY GROENER ET AL. 2016

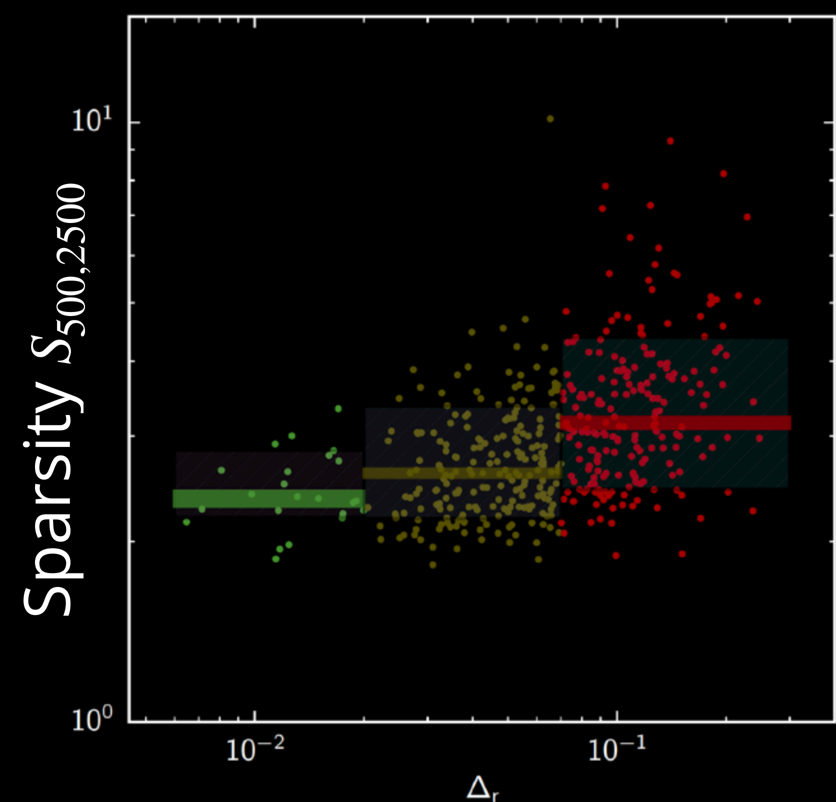
- Large variety in c-M relations between methods
- But large uncertainties, primarily linked to selection effects
- The c-M may not be the optimum test

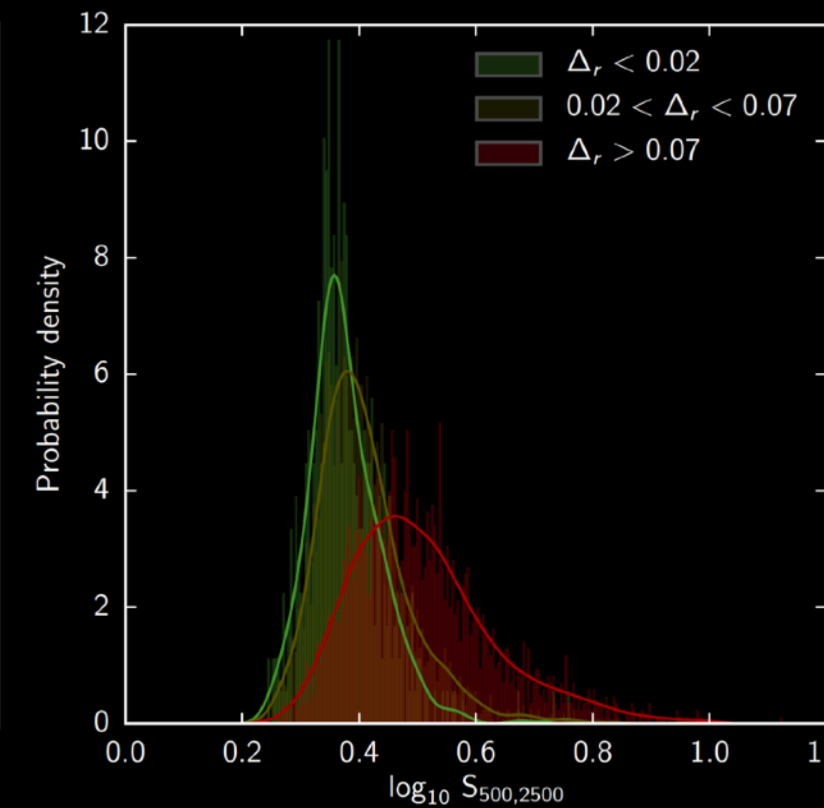
Halo sparsity

observations

simulations







BARTALUCCI ET AL 2019

ARNAUD ET AL IN PREP

- Sparsity (Balmès et al. 2014) is a non-parametric measure of halo shape
- Easy to observe: it is a mass ratio (e.g. M_{2500}/M_{500})
- Directly related to NFW profile for regular haloes, but better captures properties of haloes that are not well-fitted by NFW profiles
- Sparsity depends distinctly on dynamical state - trends observed in observations and simulations

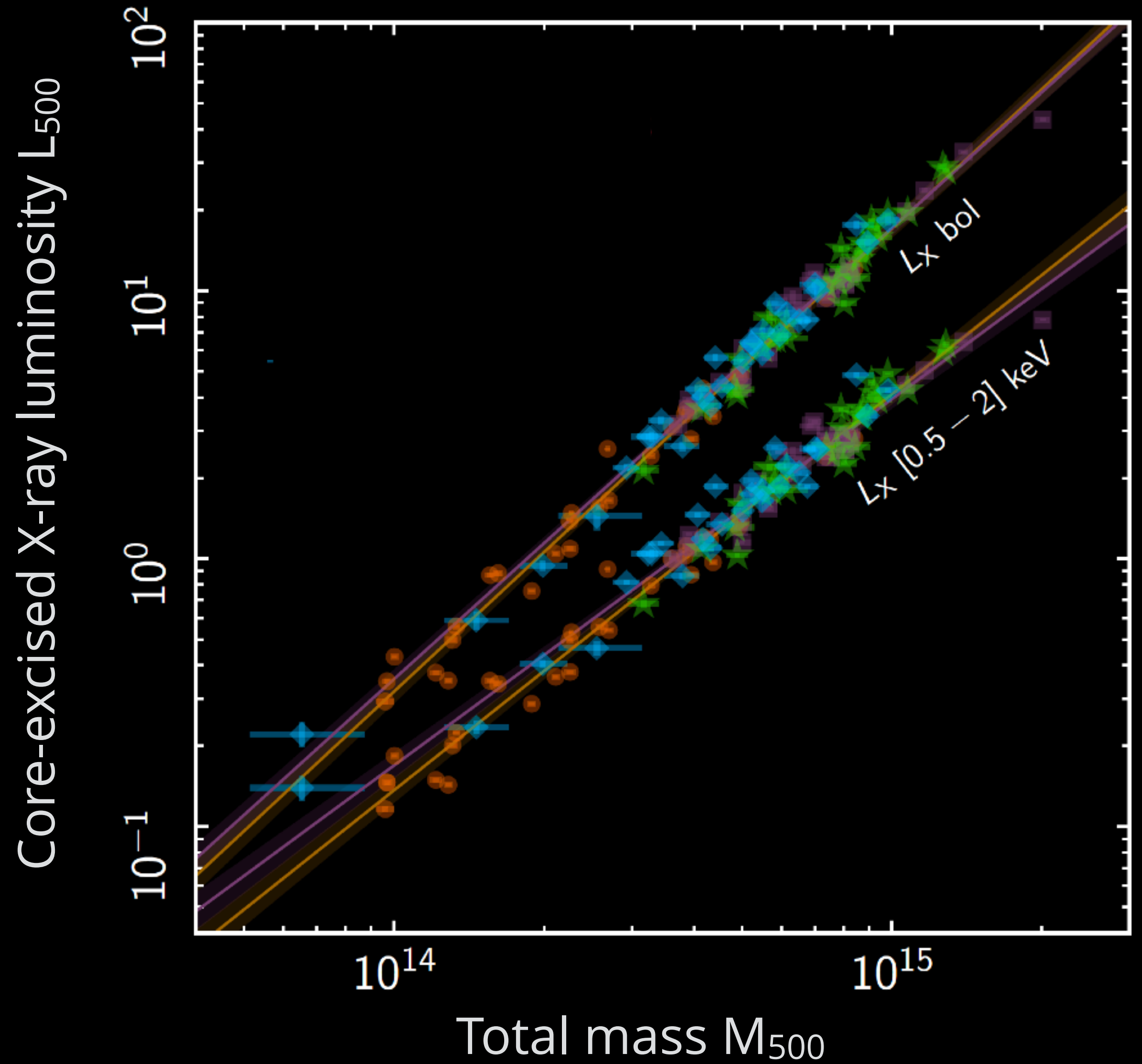
Mass proxies

The cluster population

Individually complex…

globally simple

MARKEVITCH ET AL 2002, 2004

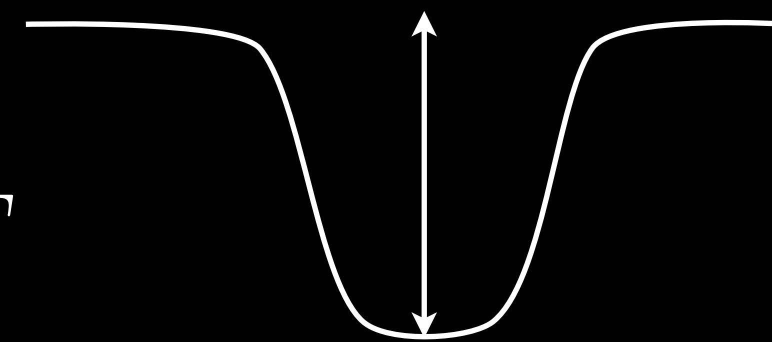


GWP ET AL

Scaling laws

- Virial theorem:
  - X-ray temperature reflects depth of potential

$$\frac{GM_\delta}{R_\delta} \propto kT$$



- Clusters are essentially closed boxes
  - Constant gas mass fraction

$$f_{\rm gas} = \frac{M_{{\rm gas},\delta}}{M_\delta} = {\rm const}$$

- Evolution via mean dark matter (gas) density

$$\overline{\rho_{\rm gas}} \propto \overline{\rho_{\rm DM}} \propto \rho_{\rm c}(z) \propto E^2(z)$$

⇒ Scaling laws for global properties to leverage statistical samples

$$T_\delta \propto M\delta/R_\delta \propto E(z)R_\delta^2 \propto E(z)M_\delta^{2/3}$$

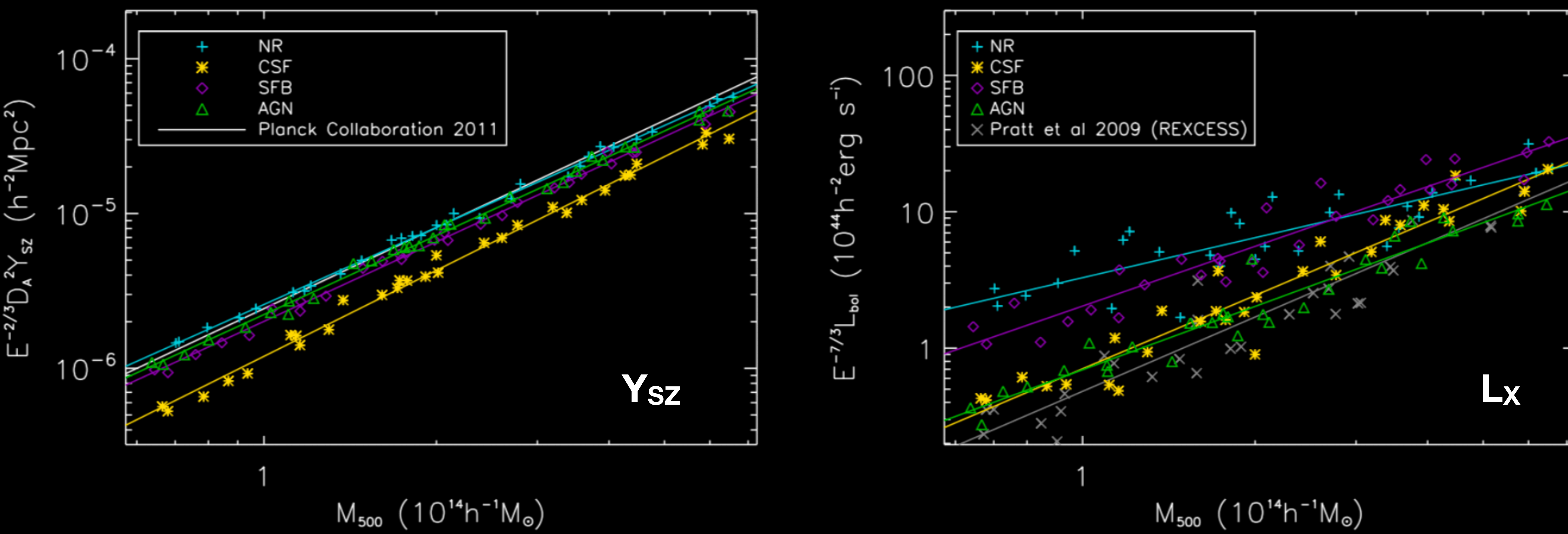
$$L_\delta \propto E(z)\,T_\delta^2 \quad ; \quad L_\delta \propto M_\delta^{4/3}$$

(assuming Bremsstrahlung)

+ M_{gas}, Y_X, optical richness λ, Y_{SZ}, etc

FUNDAMENTAL REFERENCES: BERTSCHINGER 1985, KAISER 1986, BRYAN & NORMAN 1998

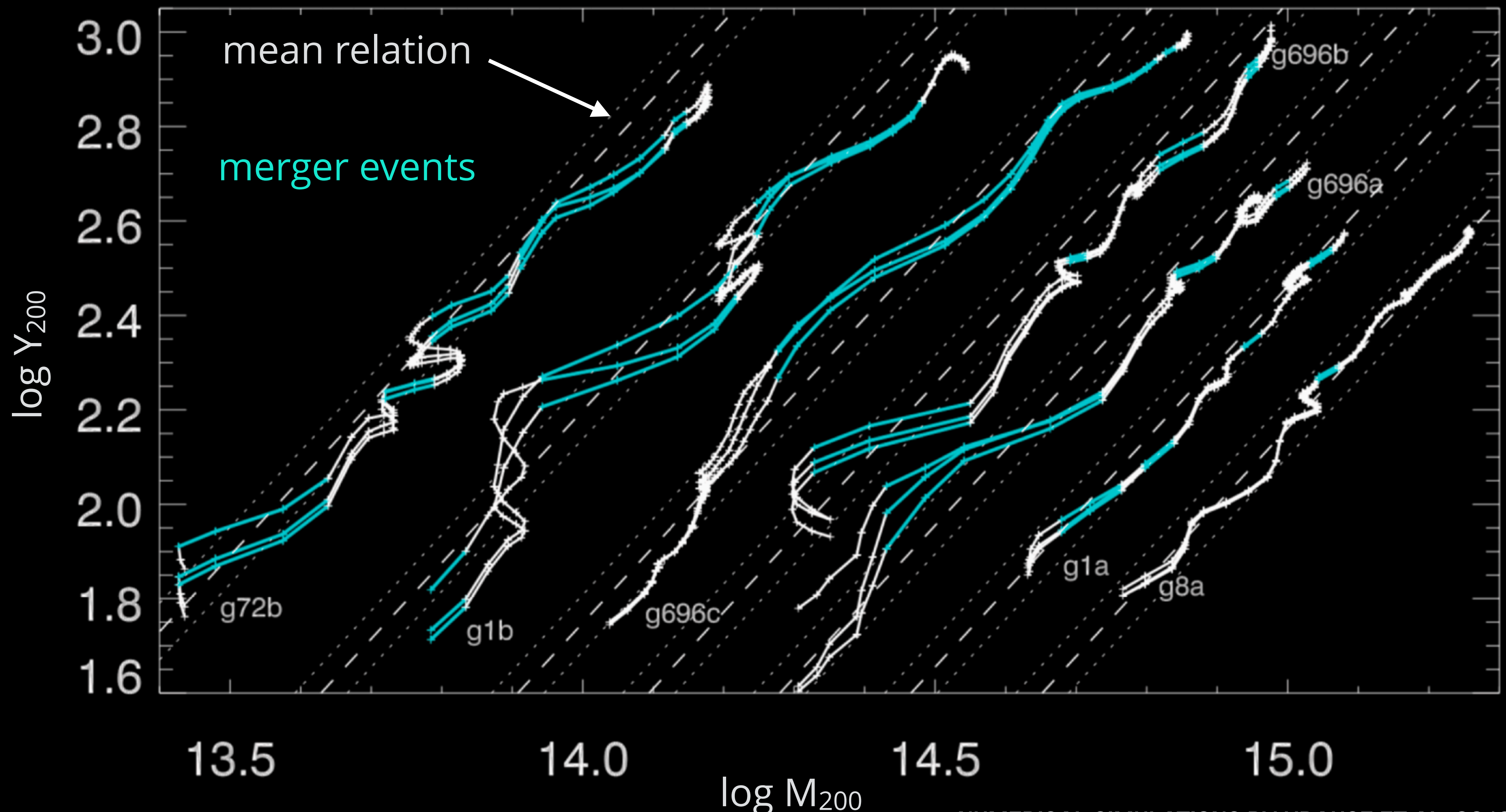
Scaling laws



NUMERICAL SIMULATIONS BY PIKE ET AL. 2014

- Some integrated quantities reflect the underlying mass better than others
- The (3D) SZ signal is a particularly good proxy
- Optical and X-ray quantities have a higher scatter...

Dynamical state

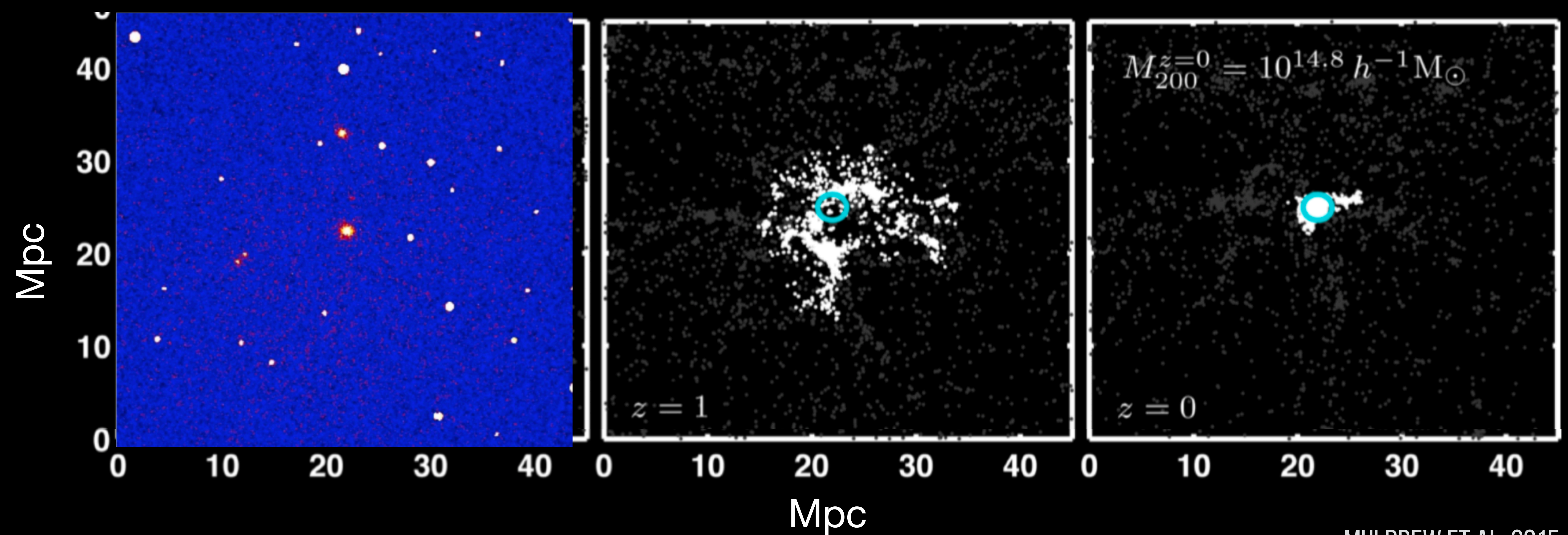


NUMERICAL SIMULATIONS BY KRAUSE ET AL. 2012

- Dynamical state affects the position of clusters on any scaling relation
- This affects detectability…

Protoclusters & the future

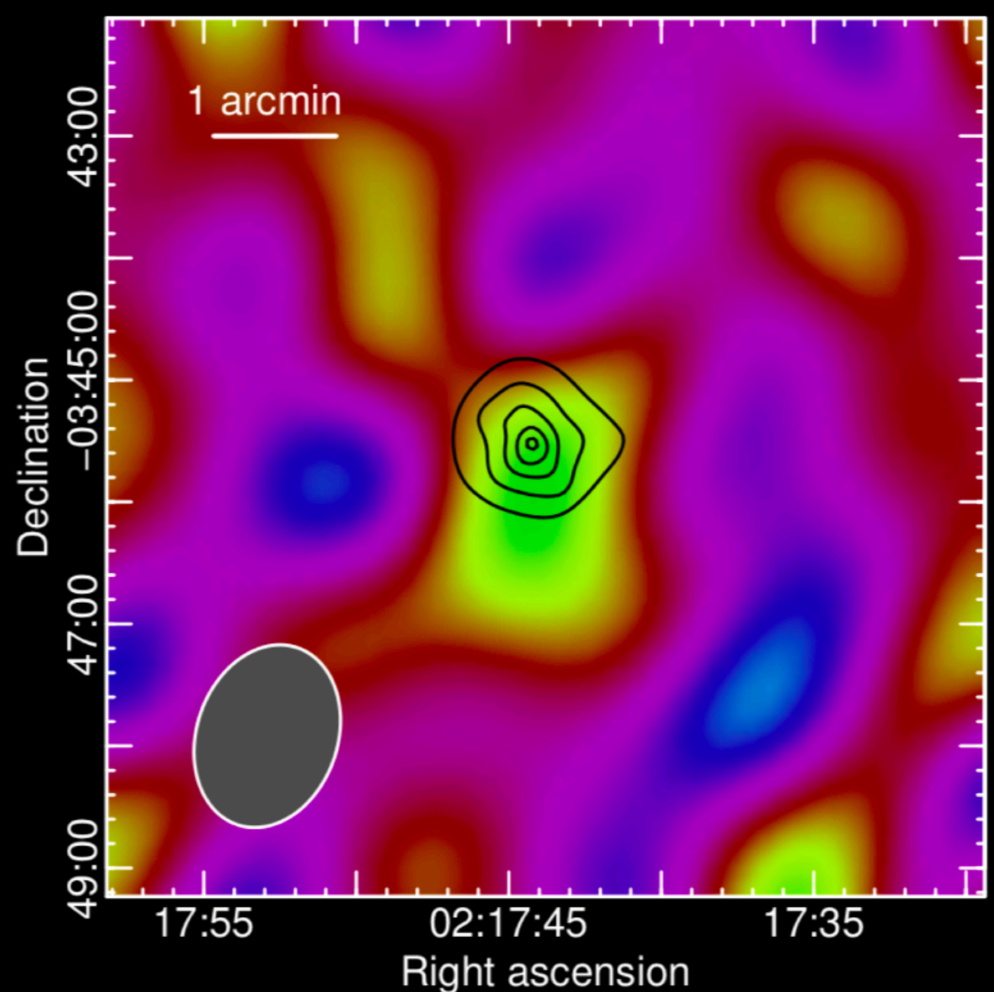
Protoclusters

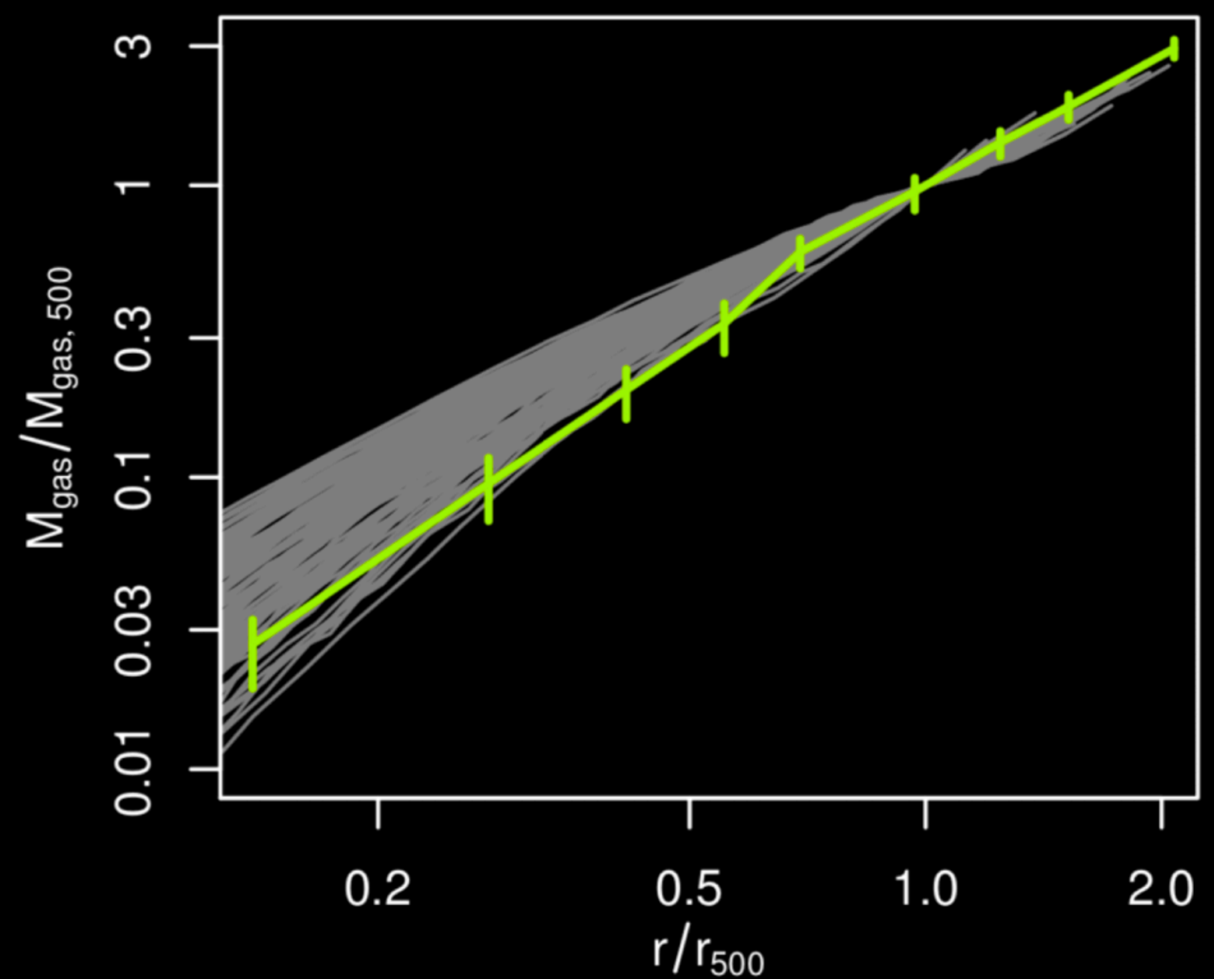


MULDREW ET AL. 2015

- By definition, unvirialised
- In X-rays, SZ, you will only ever see the **densest regions**
- Current instruments require long exposures to obtain meaningful constraints on ICM properties

Characterisation with current instruments



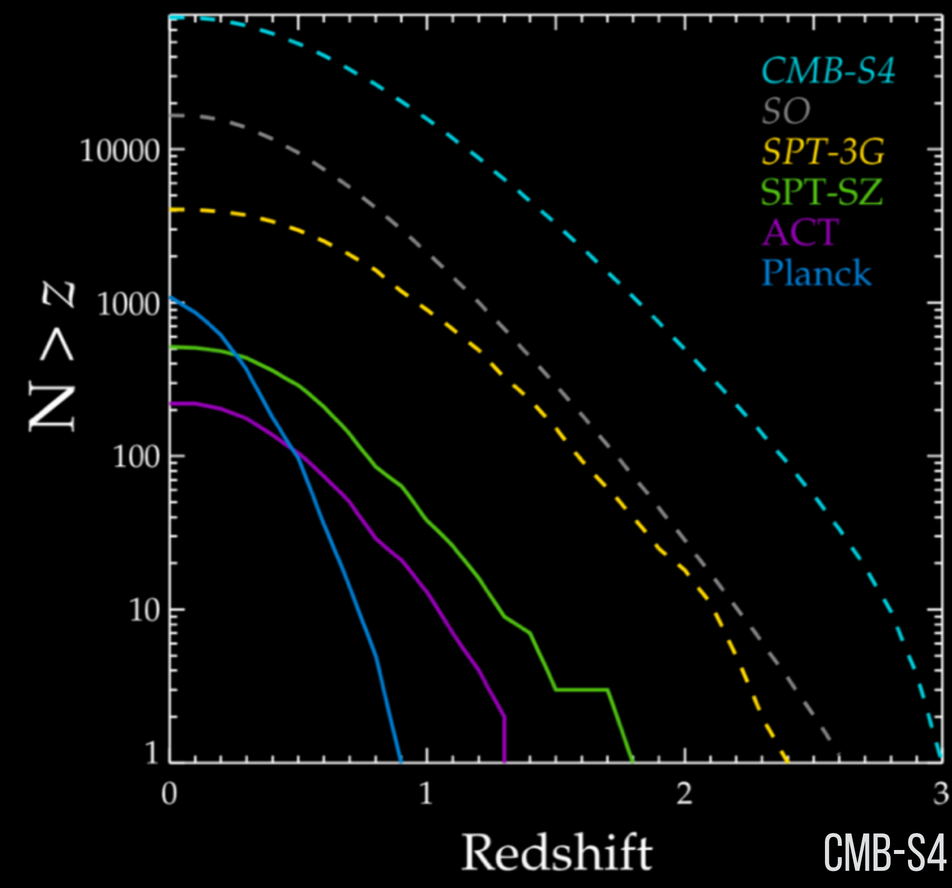


MANTZ ET AL. 2018, XLSSC 122, >500 KS EXPOSURE TIME

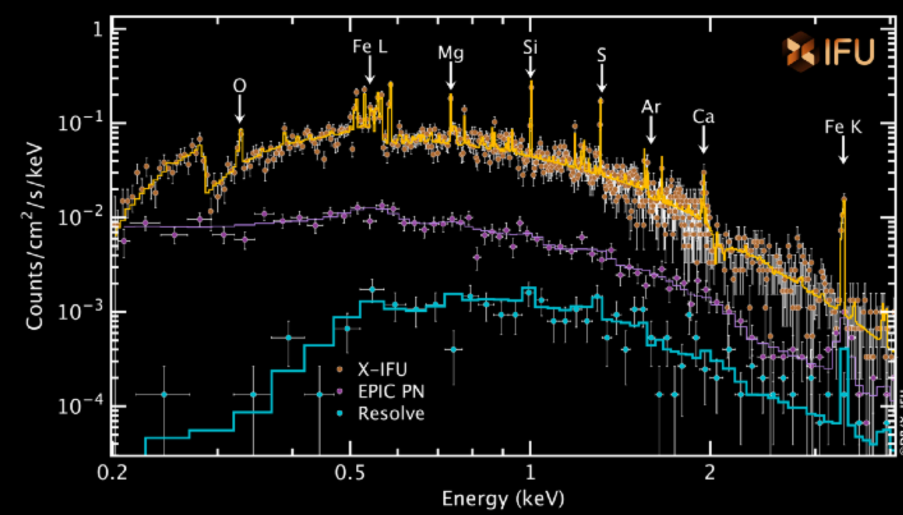
- Indications of dynamical state from large X-ray / SZ peak offset
- Mass from (strong) hypotheses regarding f_{gas}, can also use extrapolation of “local” scaling relations using global X-ray or SZ quantities (dangerous?)

The future

- Many tens of thousands of clusters and protoclusters will be detected in the coming years
  - Insert your favourite survey/instrument here
  - the challenge will be to characterise them
- What we have detected thus far is *atypical* and cannot be generalised
  - the challenge is to understand the underlying population
- We should be method- and waveband-agnostic
  - use all possible measurements



CMB-S4



ATHENA (Z=1 CLUSTER)

Measuring the mass of an individual object

Pratt et al. (2019, SSRV, 215, 25) for a review

	tracer	local S/N (contrast)	radial range	z range	typical uncertainty	assumptions
dynamical	cluster galaxies	depends on n_{gal}	~R_{200}	starts to get difficult at z>0.6	~30% for 100 members	NFW / King, spherical symm.
caustic	cluster galaxies	depends on n_{gal}	>R_{200}	~local	~20% for 200 members	spherical symm.
weak lensing	background galaxies	low; depends on $n_{gal,bkg}$	> R_{2500}	< 1 - 1.2 (even with HST)	~30% at best	NFW, spherical symm.
X-rays	gas	high	<R_{500}	~1.2	~10 -20%	HE, spherical symm.
SZ	gas	low	<R_{200}	~1.5 (with X-ray)	~10 -20% (with X-ray)	HE, spherical symm.
CMBLens	CMB anisotropies	very low	<R_{200}	all	>100% now <100% with CMBS4	Stacking, spherical symm.