The morphology of clusters of galaxies in eRASS1

Jeremy Sanders

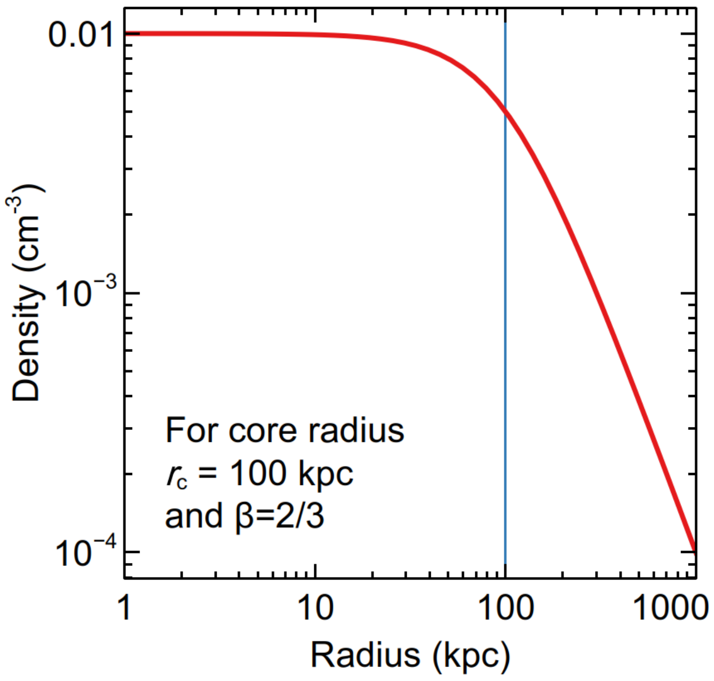
Max Planck Institute for Extraterrestrial Physics

Y. E. Bahar, E. Bulbul, V. Ghirardini, A. Liu, F. Balzer, N. Clerc, J. Comparat, M. Kluge, F. Pacaud, M. Ramos-Ceja, T. Reiprich, X. Zhang

Cluster morphologies

- In X-rays we are observing the dominant baryonic component of clusters of galaxies
- This hot atmosphere, the intracluster medium, ICM, is still often assumed to be spherical, with a profile following a beta model:

$$n(r) = n_0\,[1 + (r/r_c)^2]^{-3\beta/2}$$

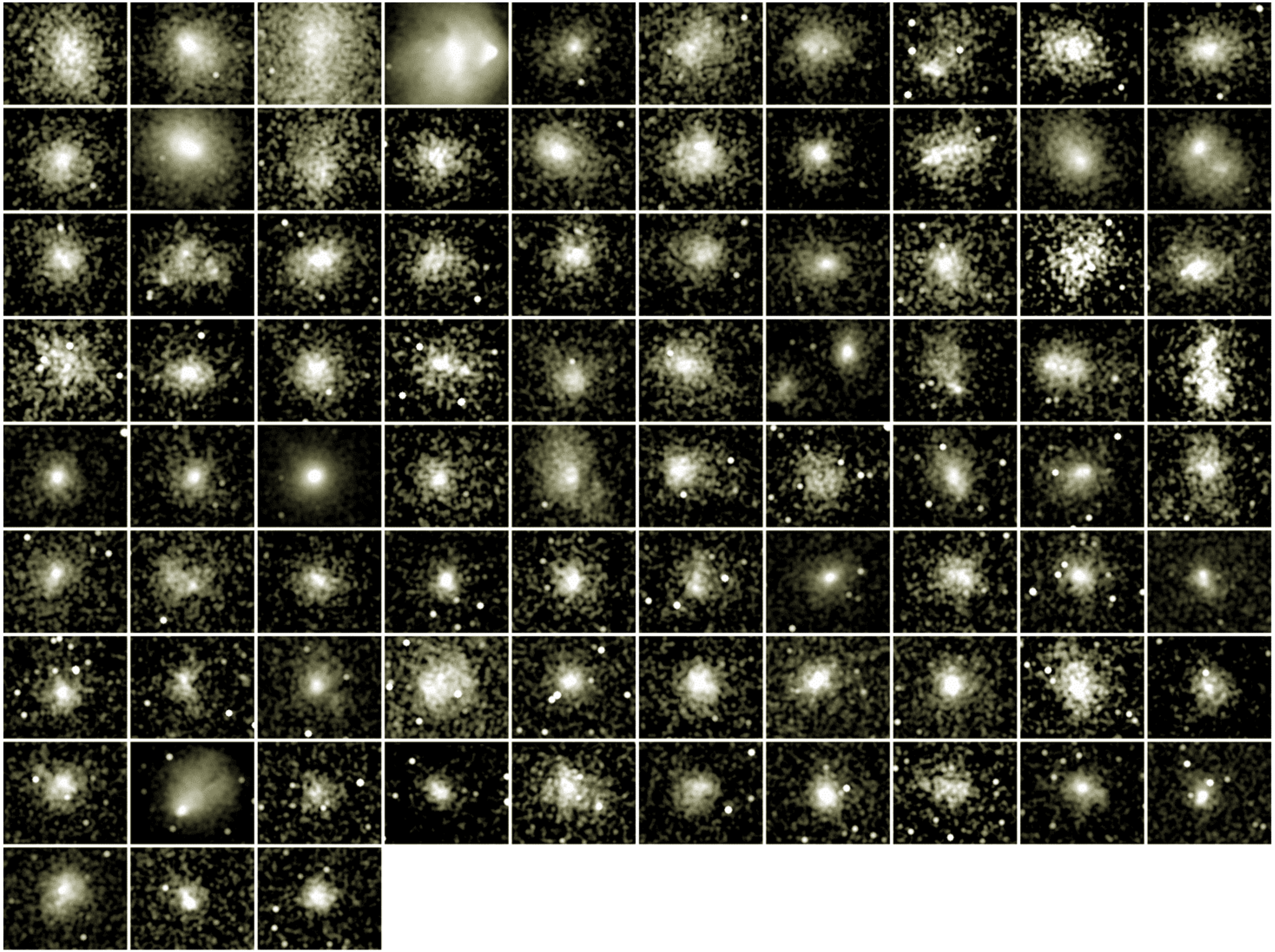


- However, that's a very simplified view of clusters

Chandra observations of clusters selected by the SPT telescope

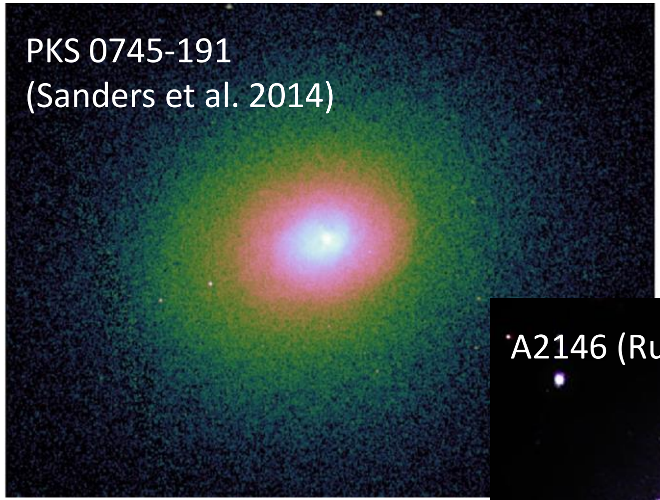
Redshift order (0.28 to 1.2, median ~0.6)

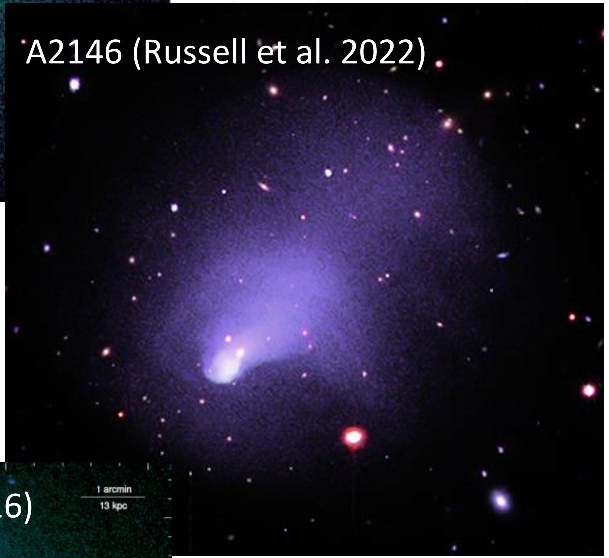
4.5x3.5 arcmin regions

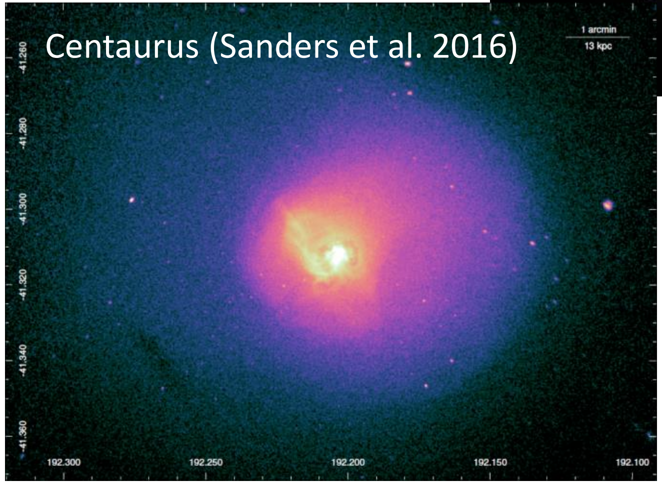


Cluster morphologies

- In particular, many clusters have a steeply peaked X-ray and density profiles – cool core clusters (e.g. Fabian 2012)
  - These clusters are also more likely to be relaxed and symmetric
- Merging clusters disturb the 2D shape of the object – see Bullet cluster (e.g. Clowe et al. 2004)
- Minor mergers give rise to sloshing (‘cold front’; Markevitch & Vikhlinin 2007)


PKS 0745-191
(Sanders et al. 2014)


A2146 (Russell et al. 2022)



Centaurus (Sanders et al. 2016)

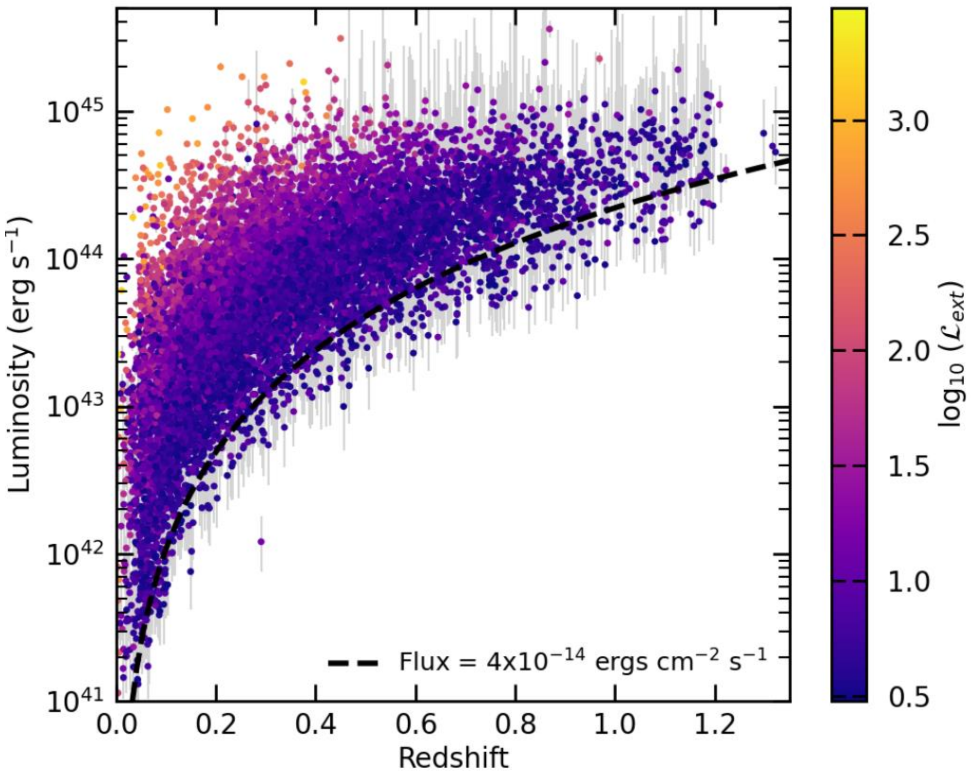
Why are they interesting?

- Morphology is connected to global properties of clusters, e.g. cool core clusters have higher luminosities
- Morphology might affect mass determinations, if observable is affected by morphology
- We might want to study astrophysics and evolution of clusters, including mergers and cool cores
- Morphology can affect how cluster is selected in an X-ray survey

Our cluster sample

- Over 12,000 optically confirmed clusters have been found in eRASS1 (Bulbul et al. 2024)
- Spans redshifts from 0.003 to 1.32
- Masses from 5×10^{12} to 2×10^{15} M_{sun}
- Largest sample of X-ray observed clusters which can be used to study morphlogy

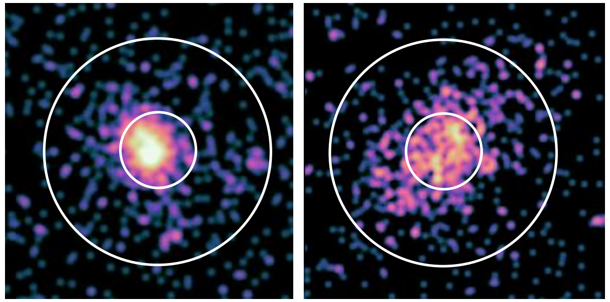
Bulbul et al. 2024



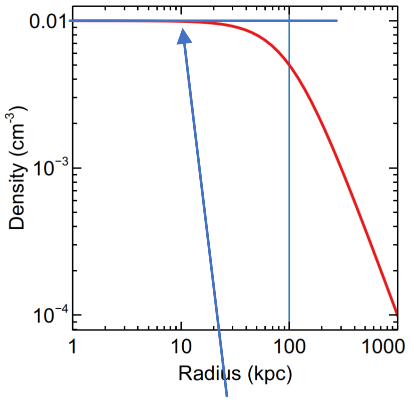
Morphological parameters

- We can characterise cluster morphology using a number of different measurements (i.e. parameters)
- These are sensitive to different aspects of a cluster morphology and are not equivalent to each other

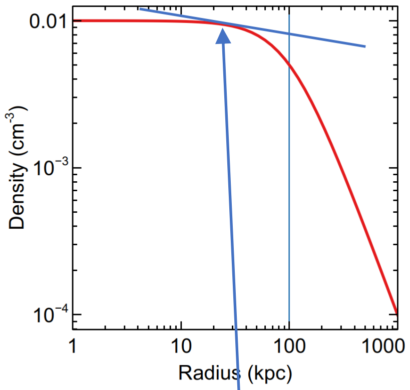
Morphological parameters



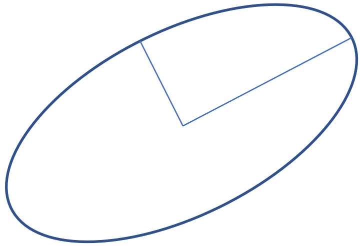
Concentration (c): fraction of flux in a small vs large aperture (e.g. $0.1R_{500} \rightarrow R_{500}$ or 80→800 kpc)



Central density (n_0): density or scaled density at some radius



Inner slope/ Cuspiness (α)

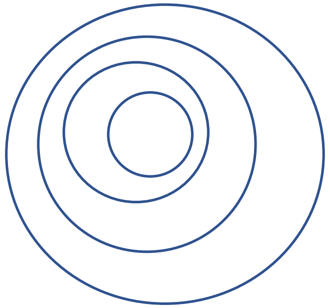


Ellipticity ($\varepsilon = b/a$): ratio of minor to major axis

Obtained by forward modelling (MBProj2D)

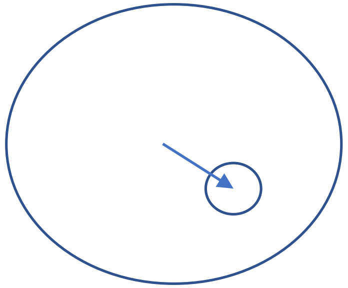
Image based – dependent on PSF+noise

Centroid shift (w): variance of centroid with different apertures

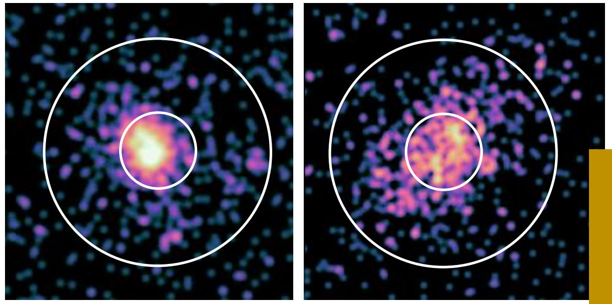


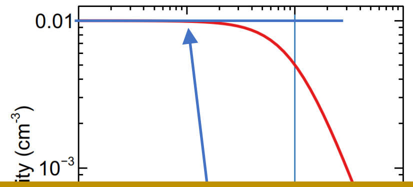
- Photon asymmetry (A_{phot}): how asymmetric are photons around centre?
- Gini coefficient (G): economic measure applied to measure how peaky the cluster is
- Power ratios (P_{10}, P_{20}…): decompose clusters into multipoles and calculate power from each relative to 0 order

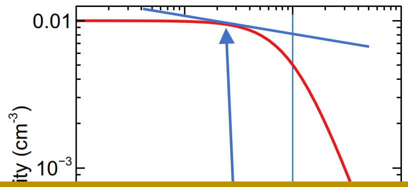
Fit-peak offset (F): offset between cluster fit position and X-ray peak



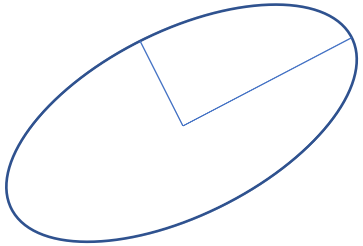
Morphological parameters







Concentration (c): fraction of flu
in a small vs large aperture (e.g.
$0.1R_{500} \rightarrow R_{500}$ or 80→800 kpc)



Ellipticity ($\varepsilon = b/a$): ratio of minor to major axis

Obtained by forward modelling (MBProj2D)

However:

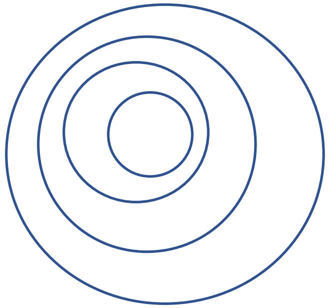
Several of these parameters depend on the choice of the centre of the cluster!

If so, we both fit for the centre with a global model, or use the X-ray peak (denoted *)

And, for some we measure at fixed physical radii and scaled radii (relative to R_{500})

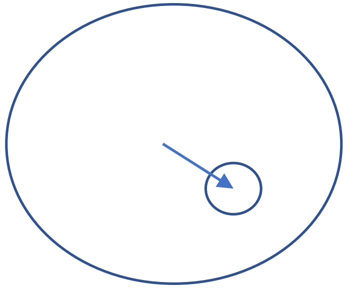
Image based – dependent on PSF+noise

Centroid shift (w): variance of centroid with different apertures

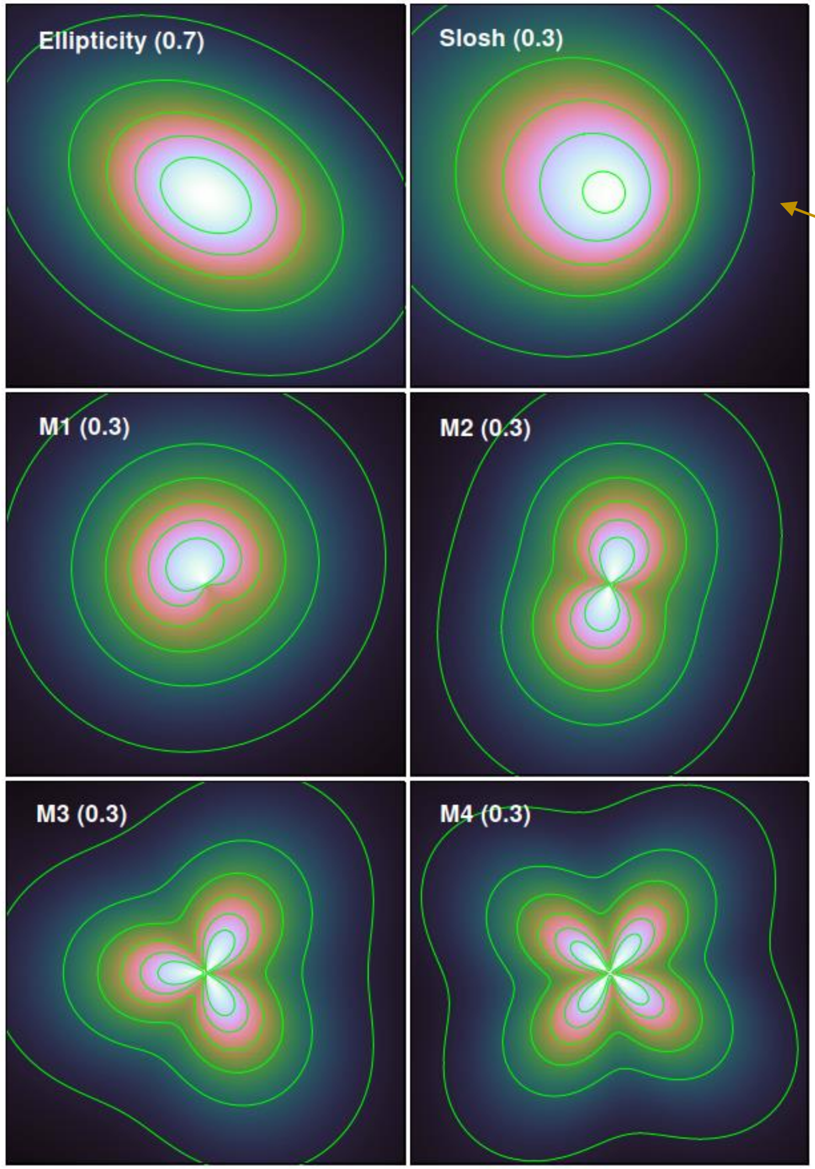


- Power ratios (P_{10}, P_{20}…): decompose clusters into multipoles and calculate power from each relative to 0 order

Fit-peak offset (F): offset between cluster fit position and X-ray peak



New forward-modelled parameters



Introduce new forward-modelled parameters for 2D shape

- Slosh (H): looks like a sloshing cluster, where

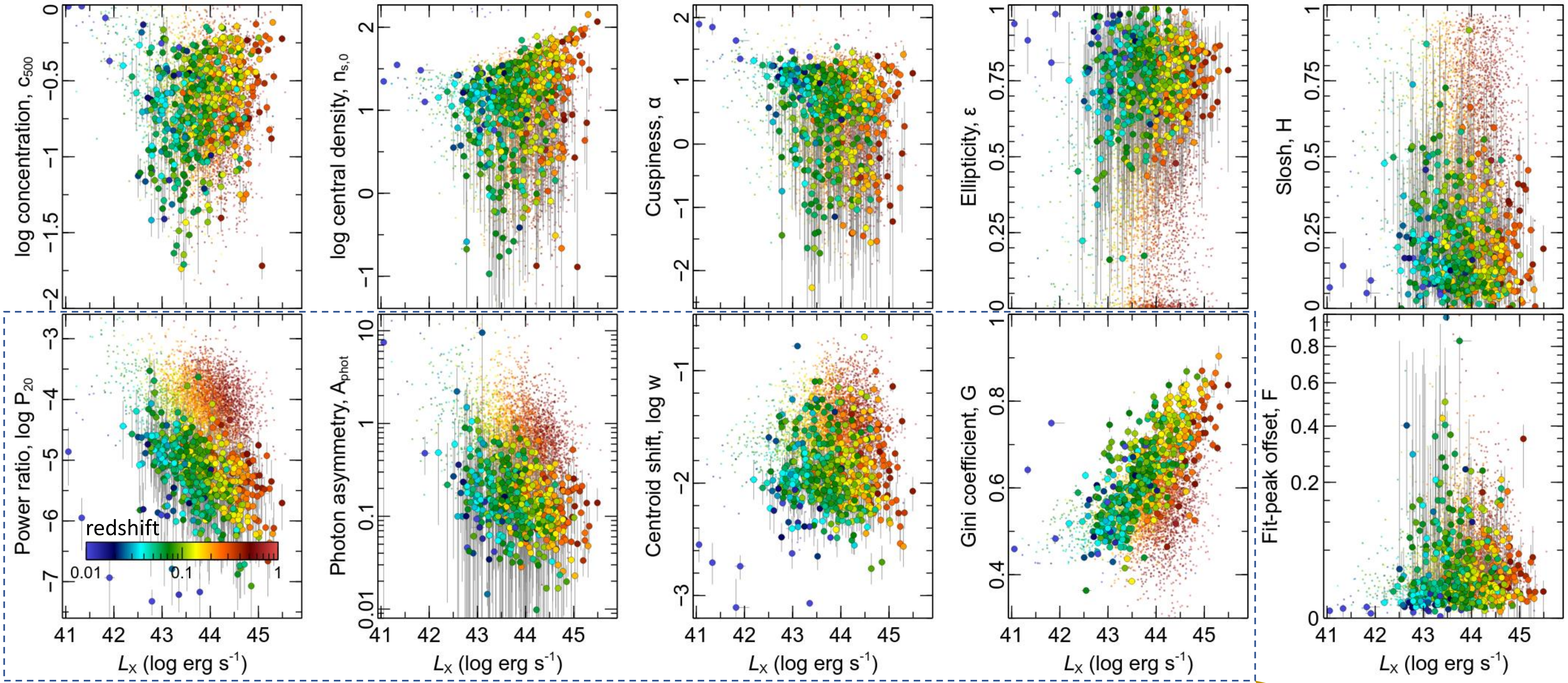
$$S'(r, \theta) = A(H)\, S(r\, [1 + H \cos(\theta + \theta_0)])$$

- Multipole magnitude (M_m) – similar to power ratios – where

$$S'(r, \theta) = [1 + M_m \sin(m\theta + \theta_0)]\, S(r)$$

for m = 1-4

Results: parameters as function of L_X



Subset of parameters, where big markers have >300 counts and small points have >25 counts

Markers coloured by redshift

Image-derived quantities show large systematics related to number of counts

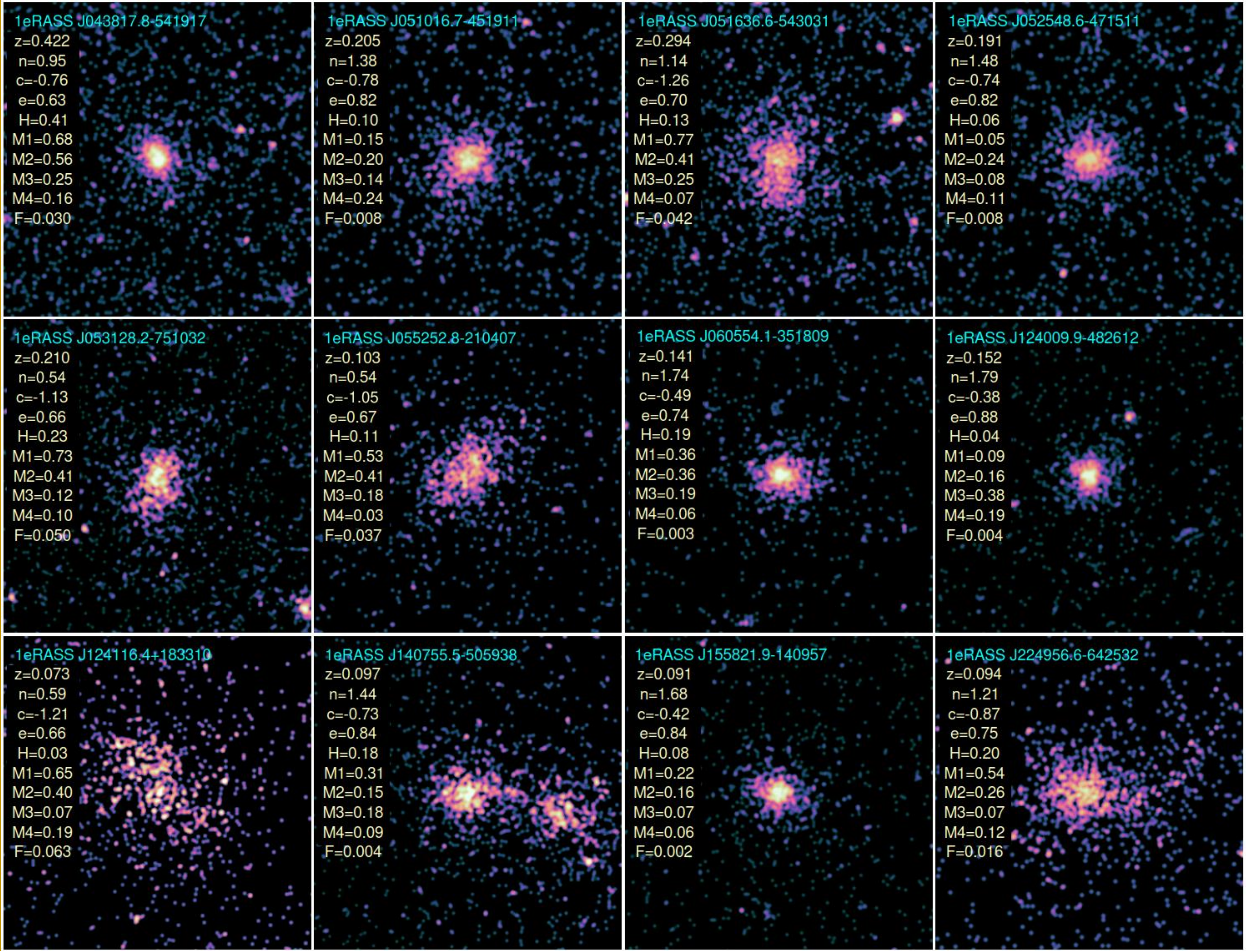
Example clusters

Clusters with ~ 1000 counts

Shown are:

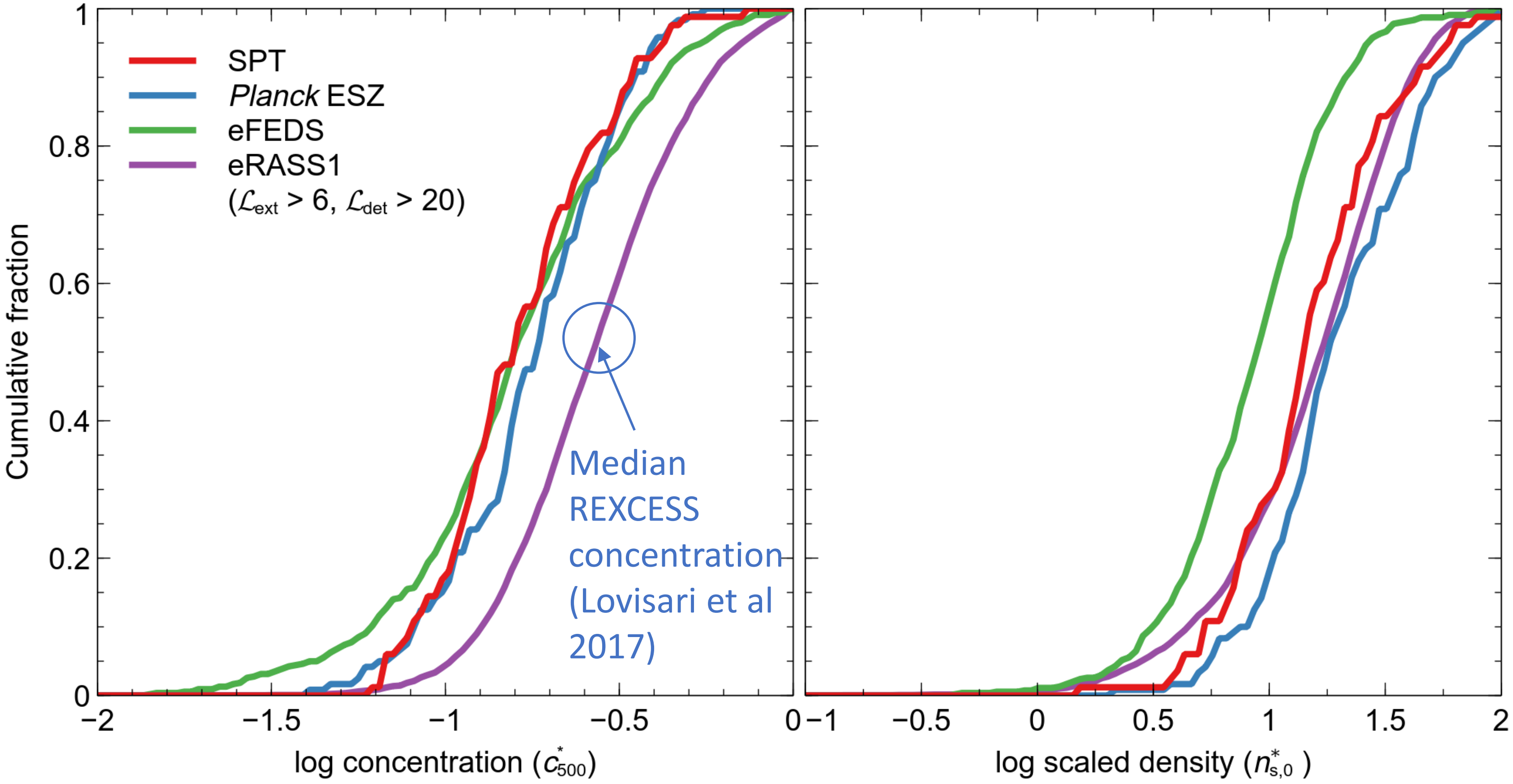
- *Redshift*
- *Log central density*
- *Log concentration*
- *Ellipticity*
- *Slosh*
- *Multipole magnitudes*
- *Peak-fit offset*

Catalogue contains 29 measurements for each of the 12,000 clusters in the sample



Comparisons with other samples

There is reasonable agreement on individual objects with previous measurements, however samples differ…

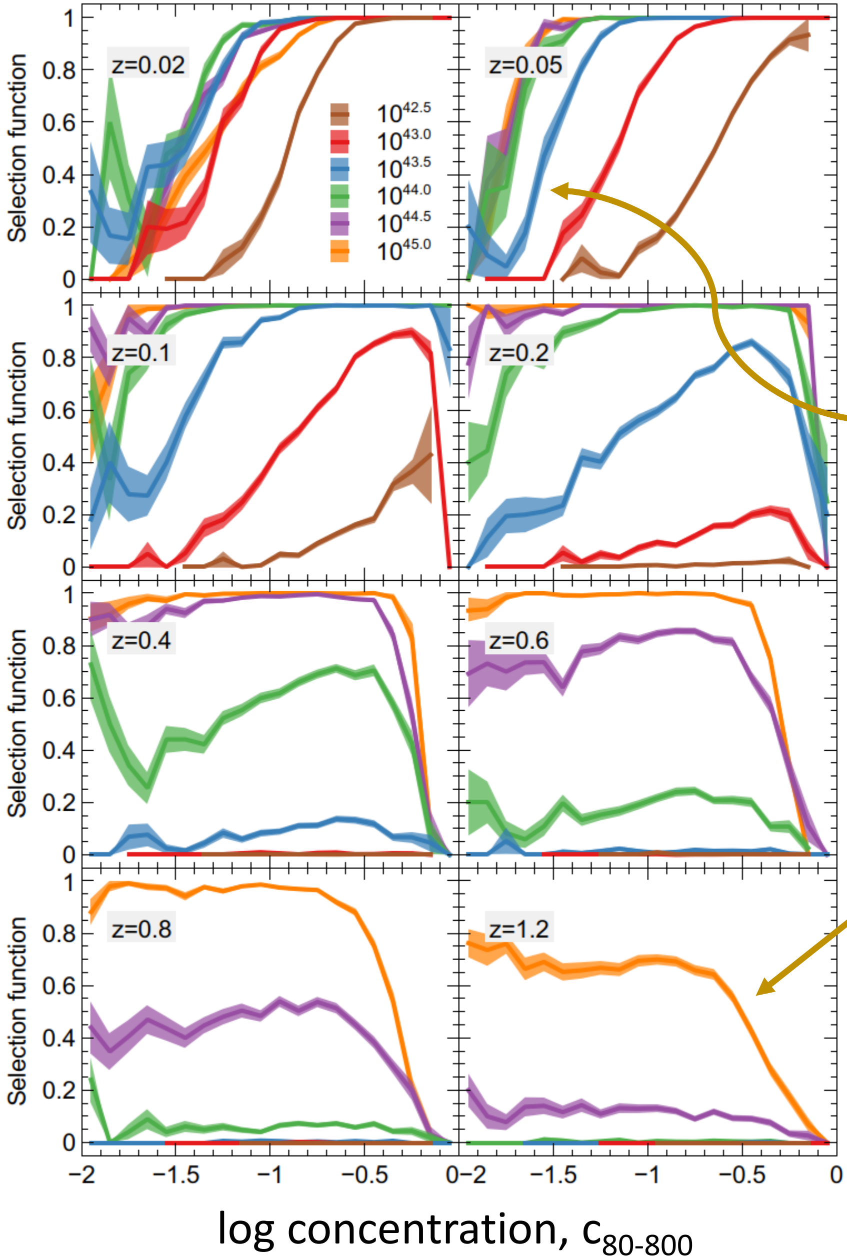


- Comparisons with
  - Planck-selected ESZ sample (Lovisari et al 2017)
  - SPT-selected sample (Bleem et al. 2015)
  - eROSITA-selected eFEDS sample (Liu et al. 2022), measured by Ghirardini et al. (2022)

- eRASS1 clusters more concentrated than the other samples, but have similar central density to SPT and Planck clusters

Selection and which subset of cluster population studied ($z/M/L_X$) is important.

Cluster selection is important

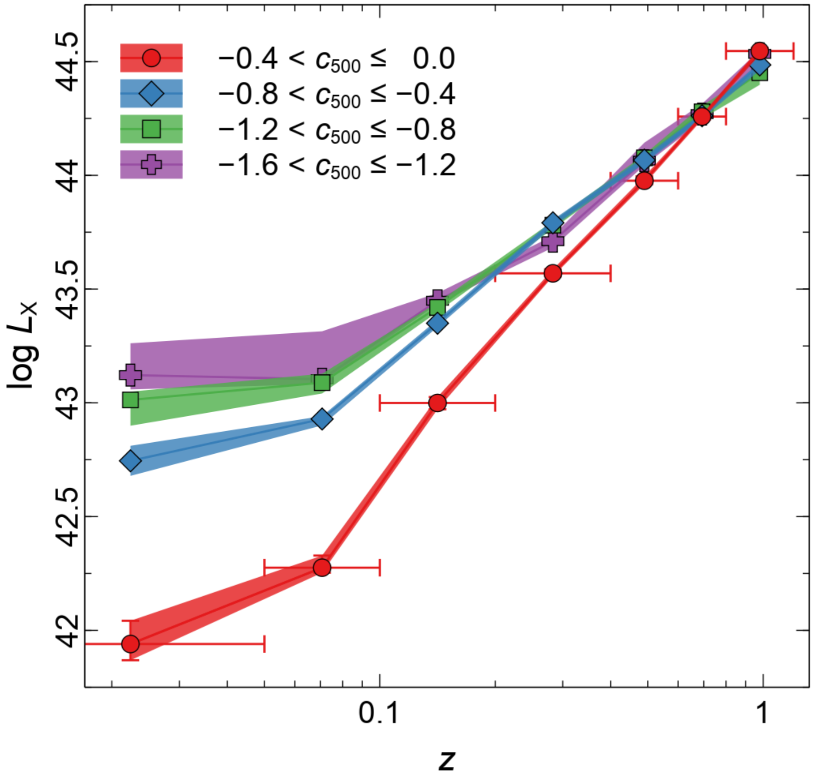


Selection function obtained from simulations, showing probability of detecting a cluster with the properties listed

Miss low concentration objects at low redshift

Miss high concentration objects at high redshift

Luminosities of clusters in bins of concentration and redshift



Low concentration objects have higher L_X at low z, and the opposite at high z

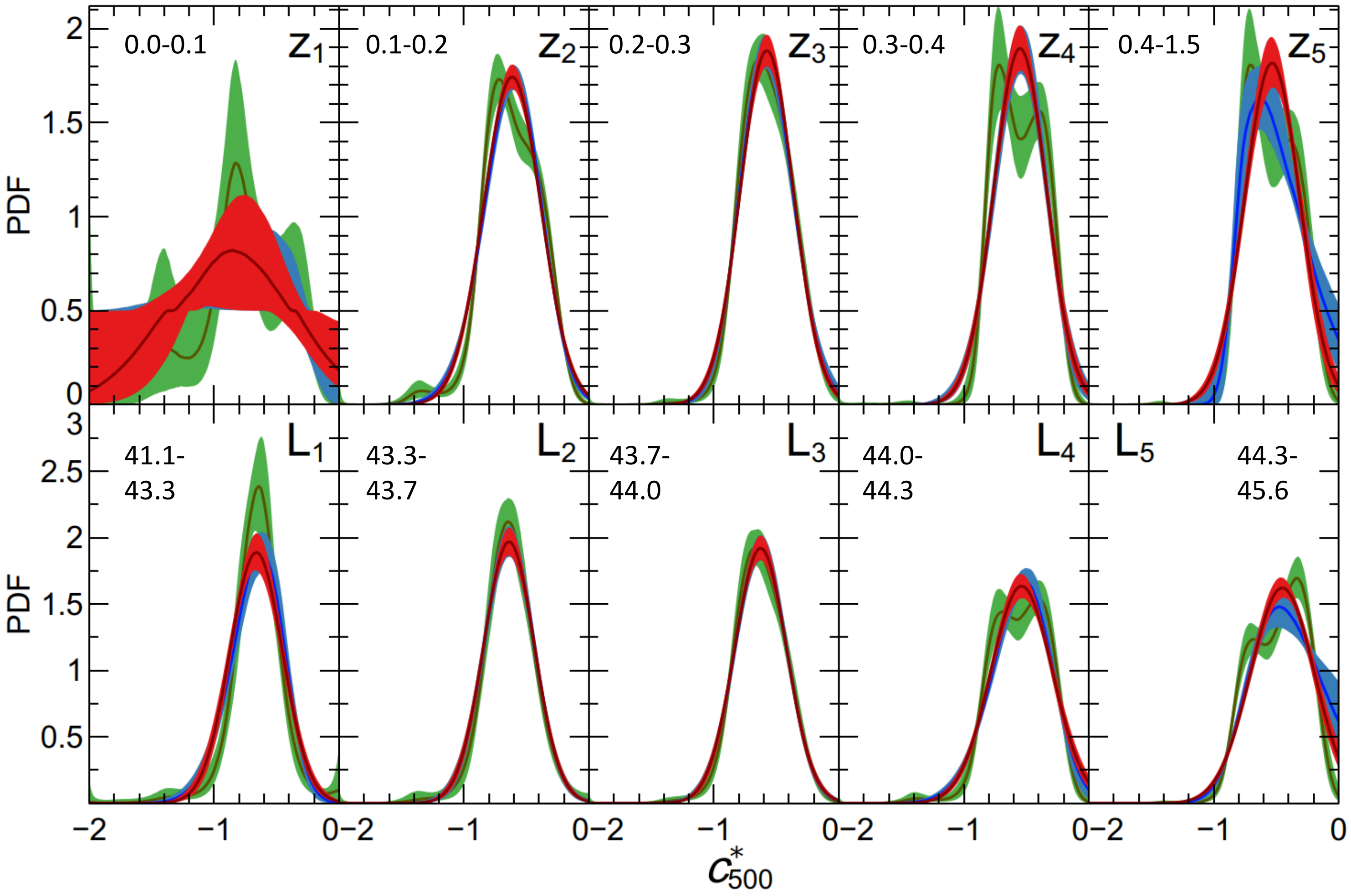
Modelling the distributions

Preliminary!

To properly understand the distributions, we have constructed a Bayesian model including the selection function and mass function of clusters

Evolution coming soon…

Measure distributions in redshift and X-ray luminosity bins, here for normal, skew and interpolated distributions

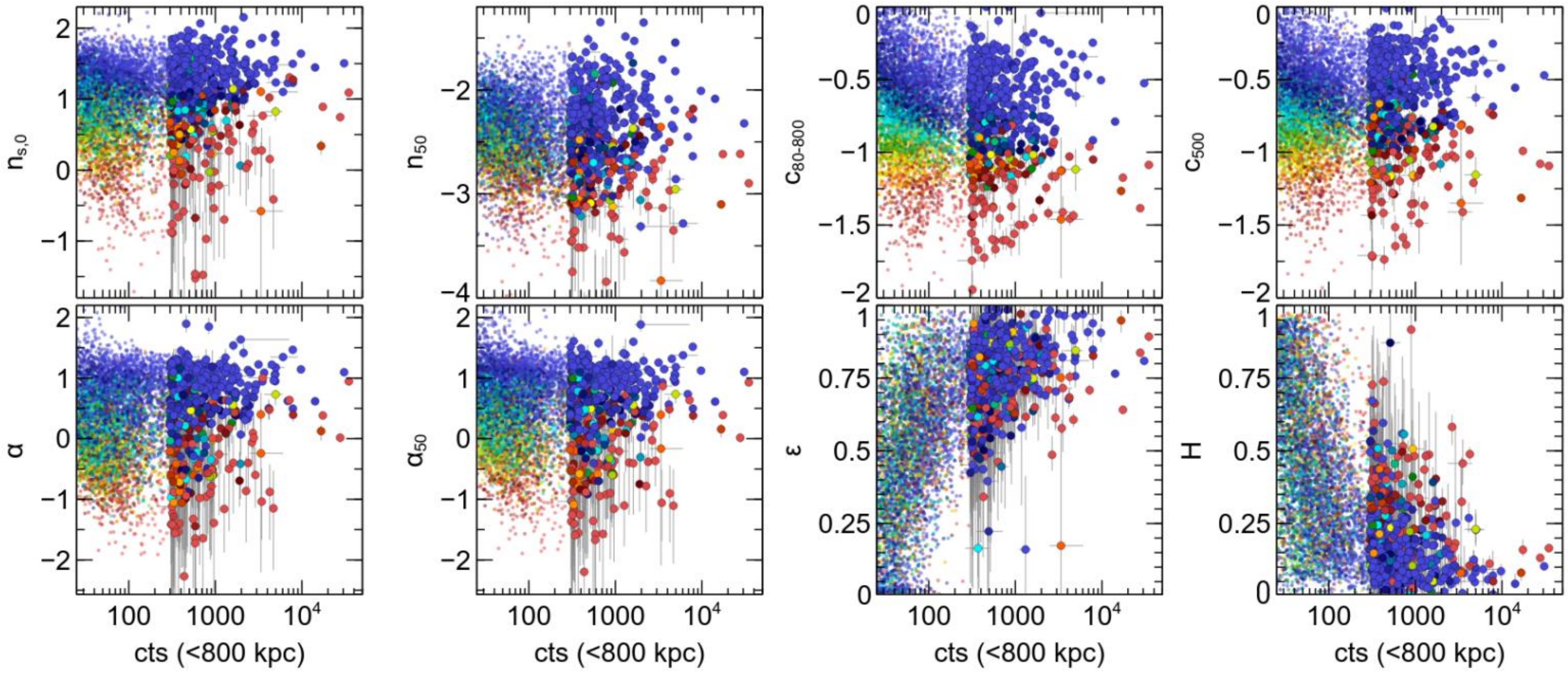


log concentration, using peak position

Normal distribution is statistically preferred in all these bins.

Not the case for all other parameters…

Identifying relaxed systems



We fit a two-component Gaussian Mixture Model to a set of forward-modelled parameters.

Blue= relaxed
Red = unrelaxed

Model prefers 3/4 of objects in a 'relaxed' component and 1/4 in an 'unrelaxed' component

Conclusions

- Measured morphological properties of >12000 clusters
- Reasonable agreement with other measurements of the same clusters
- Forward modelled parameters less subject to bias and noise than image-derived parameters
- eRASS1 clusters are more concentrated than those found by SZ surveys
- Majority of systems classified as relaxed
- We are modelling the distribution of parameters and evolution, taking into account the selection functions