Modelling mass profiles in galaxy groups and clusters using X-rays

Alastair Sanderson

University of Birmingham

www.sr.bham.ac.uk/~ajrs

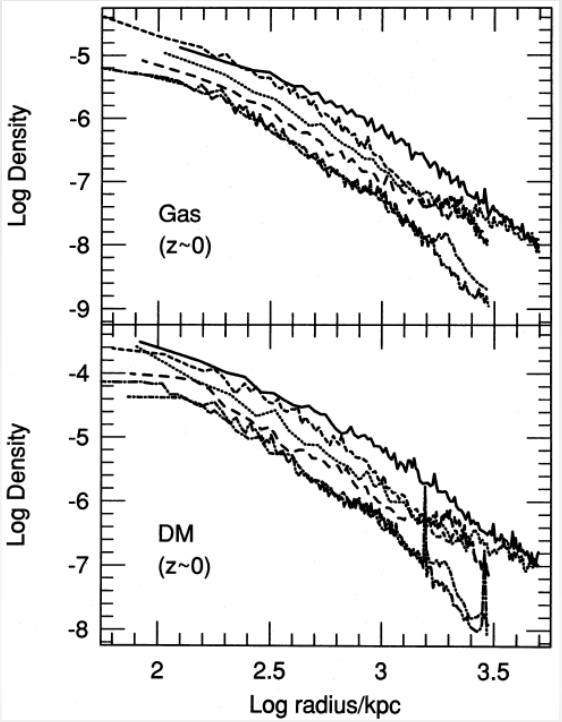
Thanks to: Ewan O'Sullivan, Trevor Ponman & Graham Smith (Birmingham), Anthony Gonzalez (Florida), Suresh Sivanadam (Toronto), Ann Zabludoff & Dennis Zaritsky (Arizona)

Outline

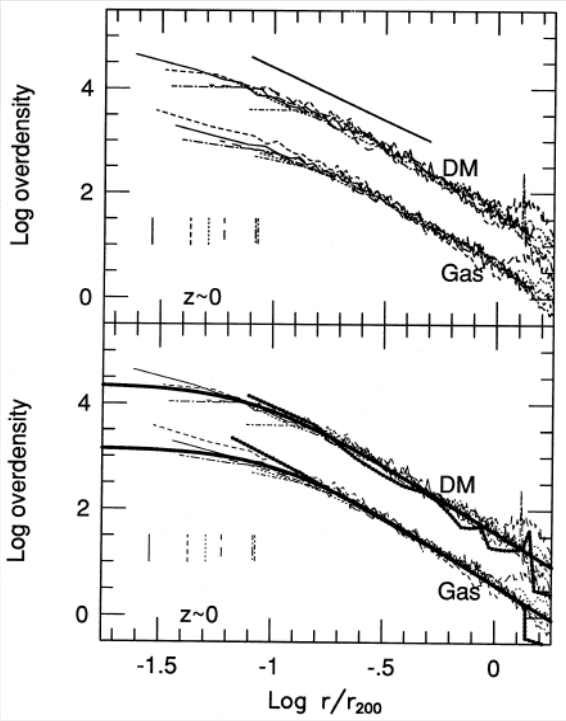
- Why (X-ray) mass?
- Ascasibar & Diego (2008) cluster model
  - application & validation in galaxy clusters
- Baryon fractions in galaxy groups

Why measure mass?

- Cluster scaling
  - Mass provides a normalizing factor *and scaling (e.g. virial) radius*
  - Similarity breaking is a powerful tool for studying cosmic feedback



Scale by mass & virial radius



Navarro, Frenk & White (1995)

X-ray mass measurements

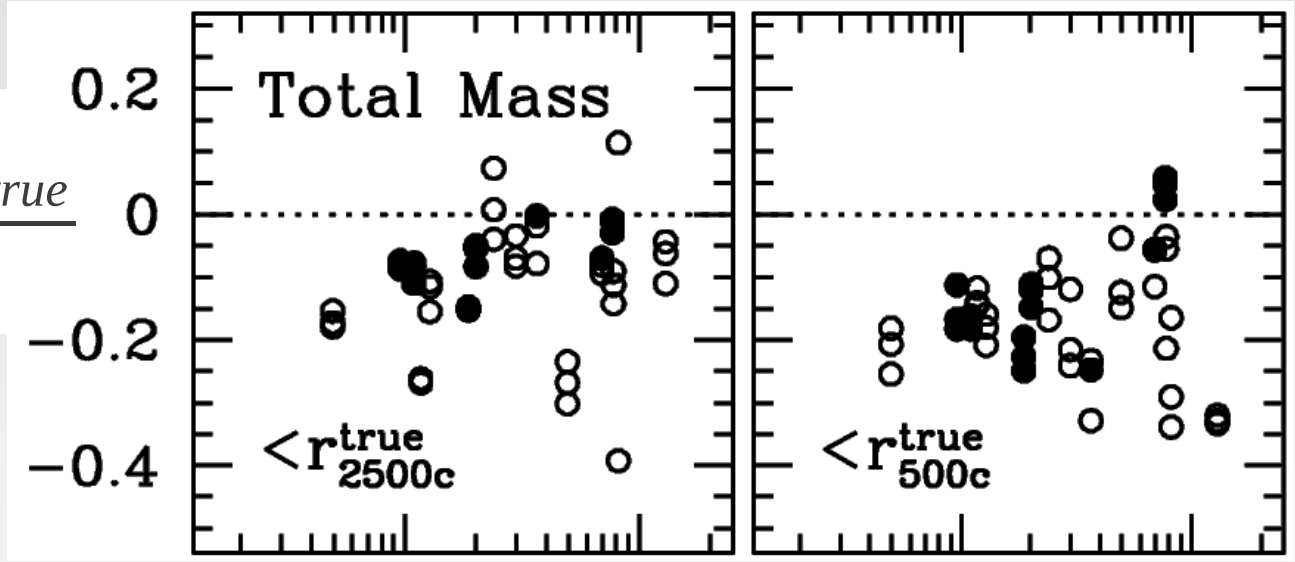
If X-ray emitting gas in hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{G\,M}{r^2}\,\rho$$

measure $T_{gas}(r)$ & $\rho_{gas}(r)$ → $P(r)$ → measure *mass*

$$\frac{M_{est} - M_{true}}{M_{true}}$$

16 simulated clusters at $z = 0$; 3 orthogonal projections



(open) solid points = (un)relaxed morphology

- Small (5 – 20%) bias low in X-ray mass estimates (less for relaxed clusters) due to non-thermal pressure support; *geometry-dependent*

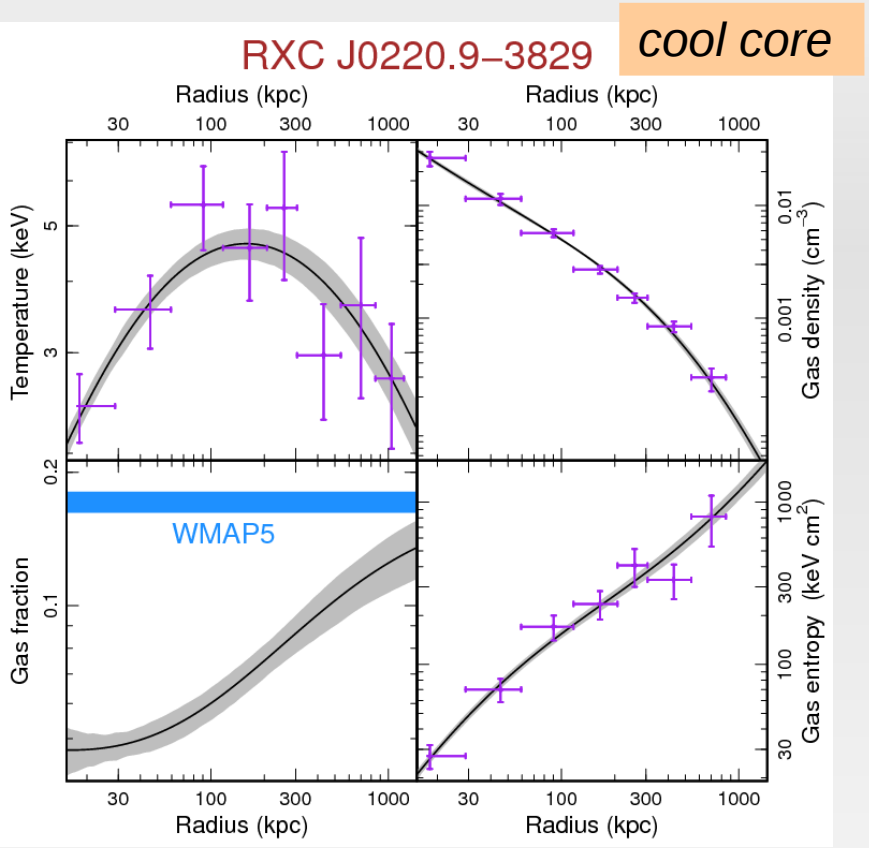
The Ascasibar & Diego (2008) cluster model

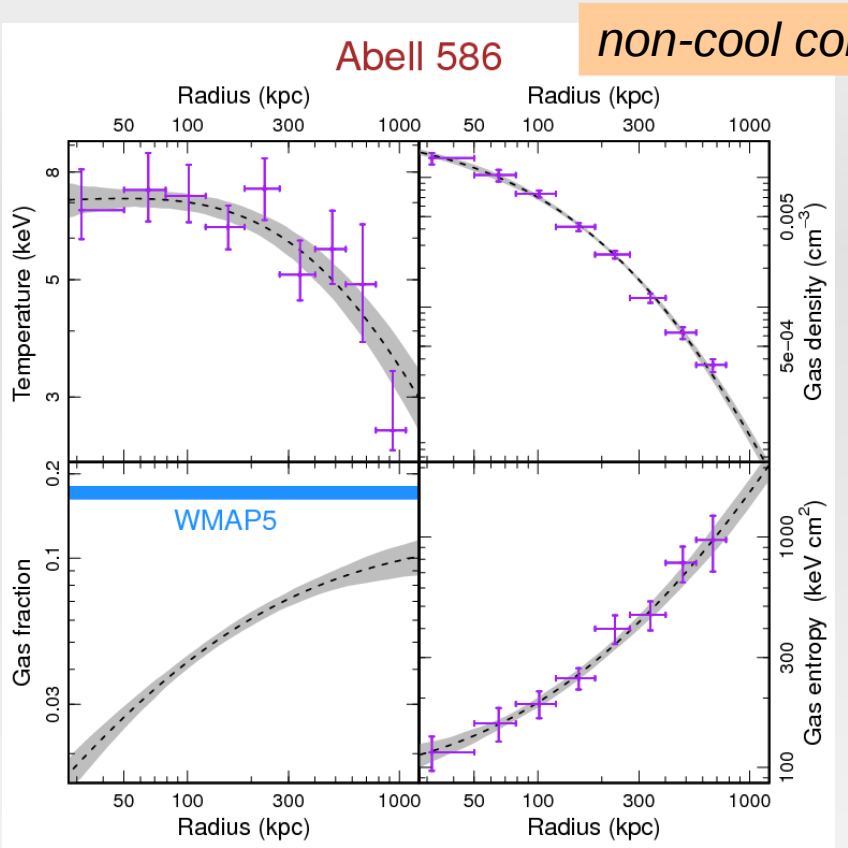
- Assumes polytropic ICM in Hernquist (1990) potential, with additional component to describe (cool) core
  - *yields convergent projected mass (unlike NFW profile): ideal for comparing X-ray masses with those from gravitational lensing*

- 5 parameters, each with a clear physical meaning:
  - T_0 = central gas temperature of baseline (non-cooling) polytropic profile
  - t = actual central gas temperature normalized to T_0 ($0 \leq t \leq 1$)
  - a = dark matter scale radius (typically larger than corresponding NFW r_s)
  - α = cooling radius normalized to scale radius, a
  - f = factor to define gas density normalization *wrt* cosmic baryon fraction ($f = 1$)

See Ascasibar & Diego, 2008, MNRAS, 383, 369 for details

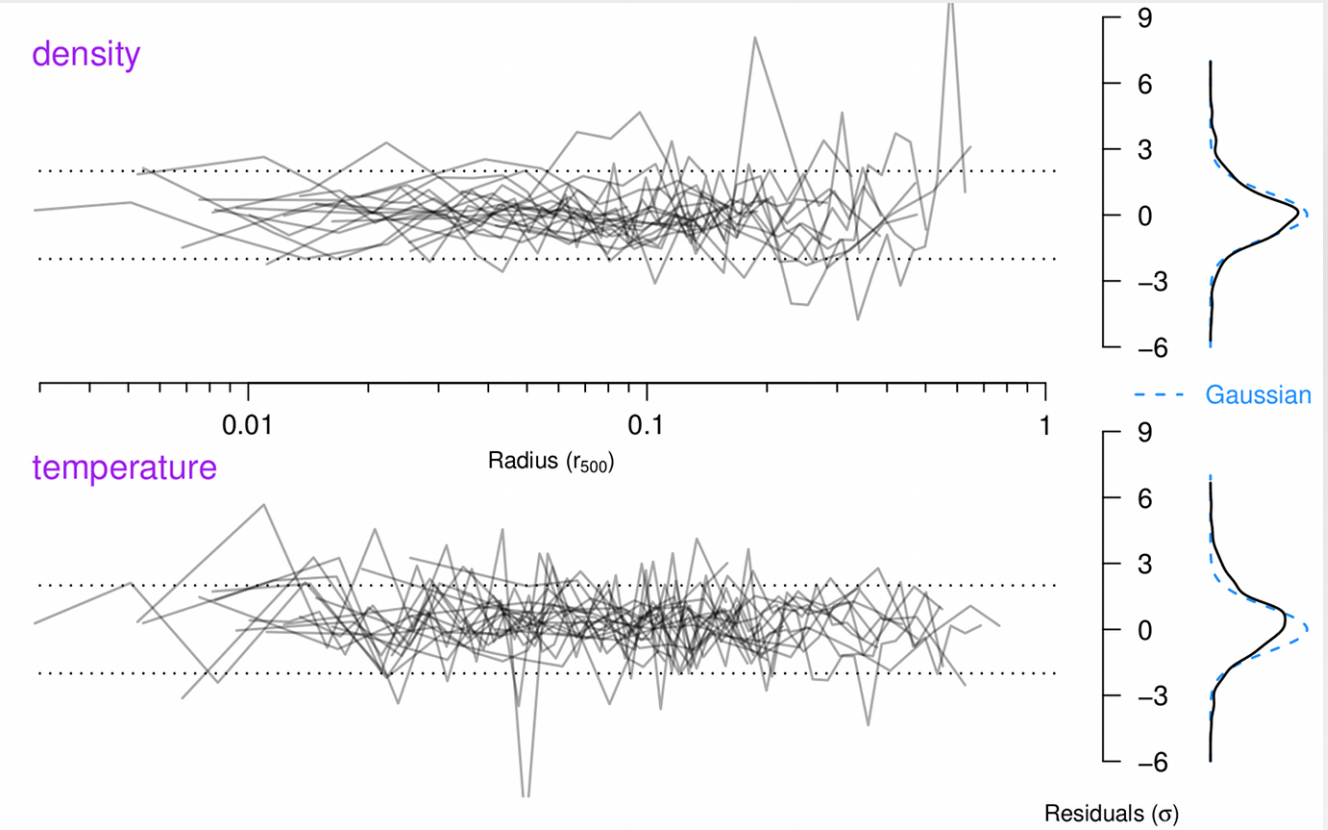
Fitting the model to X-ray data





- Model (solid line) jointly (χ^2) fitted to gas $T(r)$ & $\rho(r)$ data (purple error bars)
- Errors on parameters and all derived quantities from (N = 200) bootstrap resamplings of original data (→ grey 1σ error envelope)
- *Good fit with tight constraints, even with few radial bins*

Testing the model



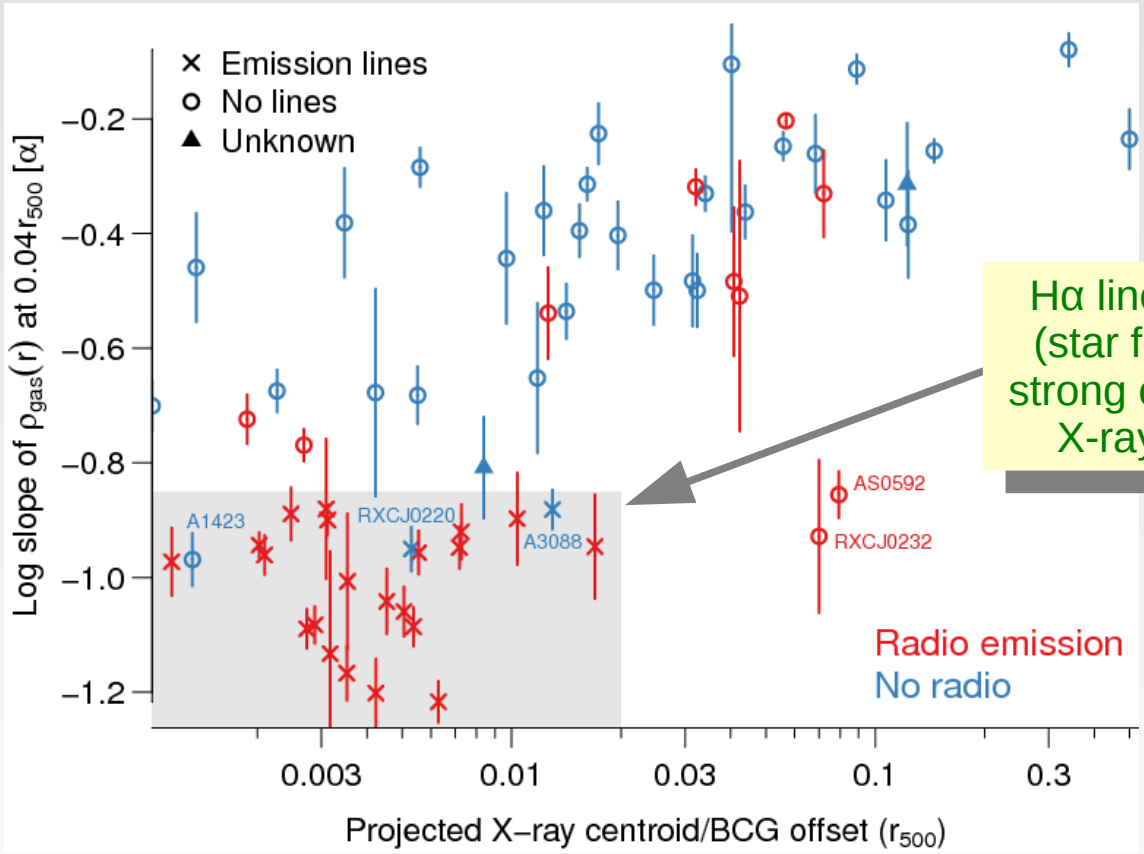
- Residuals (in σ) from model (i.e. normalized by errors) for density and *T* profiles from a statisical sample of 20 clusters (Sanderson, O'Sullivan & Ponman, 2009)
- Marginal distribution shown as kernel smoothed density estimate, compared to a Gaussian of zero mean & unit variance
- *No substantial systematic biases → model is a good representation of the data*

Assumptions & implications

- Spherical symmetry & hydrostatic equilibrium → (inevitable) small underestimate of true mass
- Single potential
  - no subhalos or BCG contribution → typically need to mask out inner ~ 5 – 10 kpc (subclumps excluded from X-ray analysis)
- Hernquist potential
  - $\rho_{tot} \propto r^{-4}$ vs. r^{-3} (NFW) for large r
  - *but, total mass converges → projected mass vs. lensing*
- *Only 5 free parameters for T(r) & ρ(r) → can fit to radial profile with only ≥ 3 bins*

Cluster cooling & dynamical status

- Offset between brightest central galaxy (BCG) & X-ray centroid is a disturbance indicator
- *Clusters without strong central cooling are more dynamically disturbed*



Stronger cooling

More dynamically disturbed

cuspier *ρ(r) (at ~50 kpc)*
→ stronger cooling
(Vikhlinin et al, 2007)

Hα line emitting BCGs (star forming) all have strong cooling & v. small X-ray / BCG offsets

Sanderson, Edge & Smith, 2009

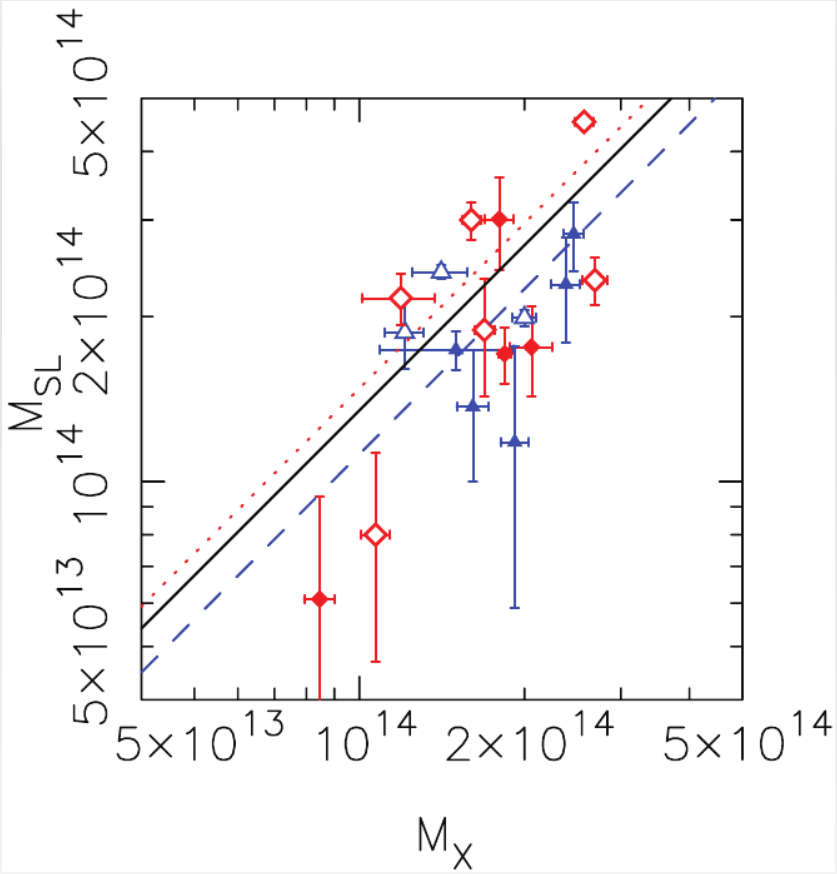
Strong lensing vs. X-ray mass comparison

20 clusters with strong gravitational lensing mass analysis + X-ray mass analysis (Richard et al, 2010)

Projected masses measured near cluster core (250 kpc), using projected X-ray mass from Hernquist (1990) profile in cluster model

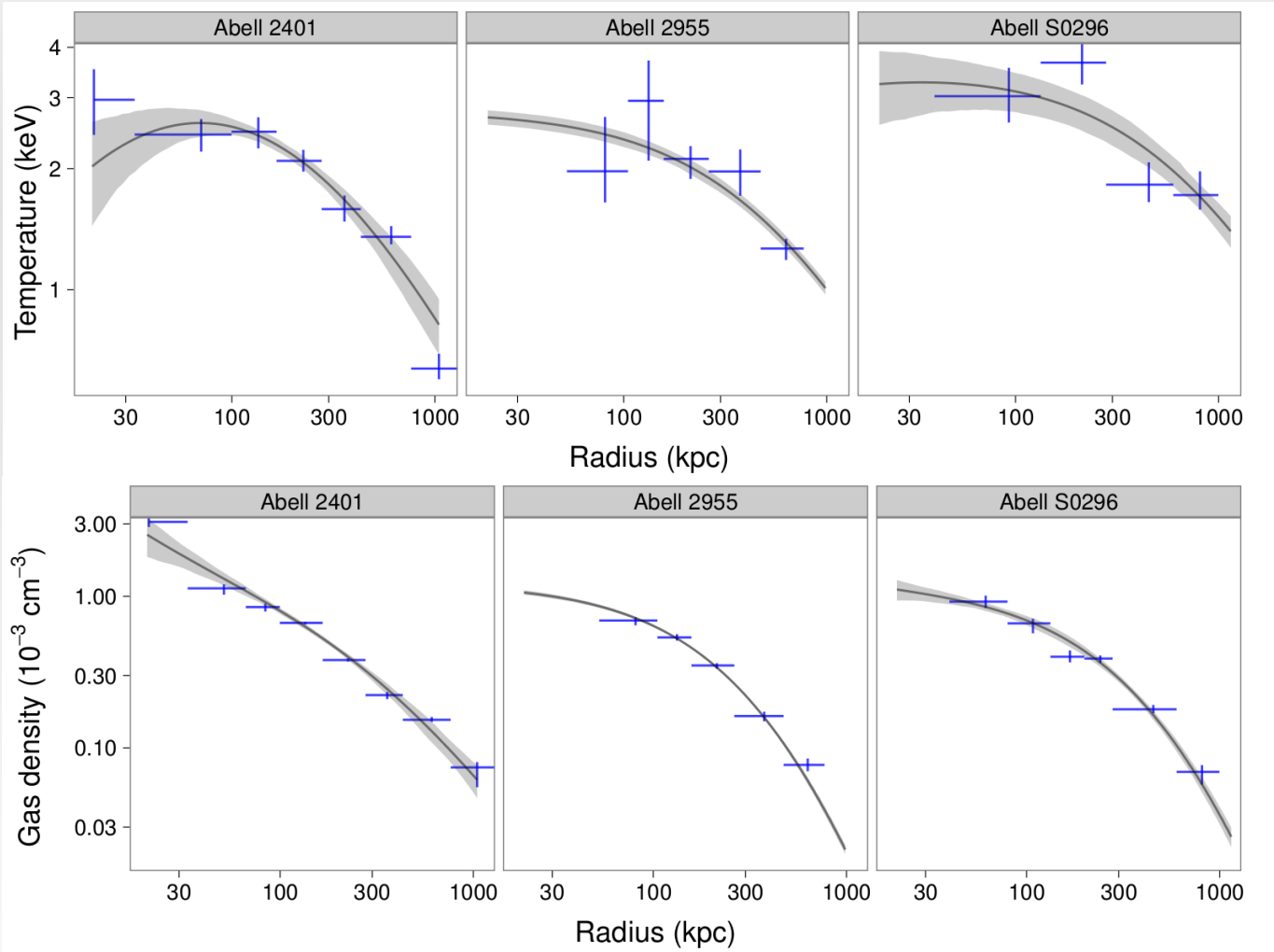
blue = cool core; red = non-CC

dashed blue line is equality

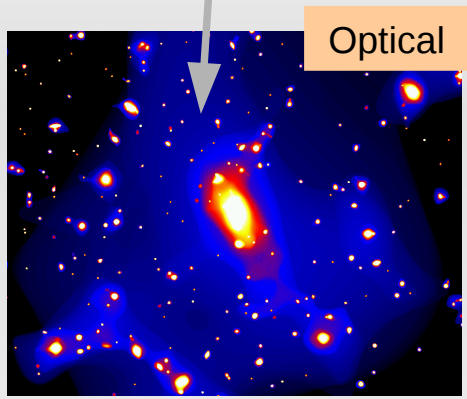


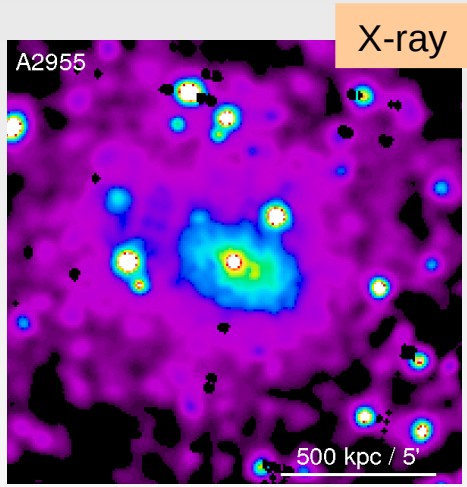
- Generally good agreement between lensing & X-ray masses, especially for cool core clusters (less disturbed)
- Many non-CC clusters have discrepant masses → consistent with non-equilibrium due to recent disruption

Model applied to galaxy groups



intracluster stars

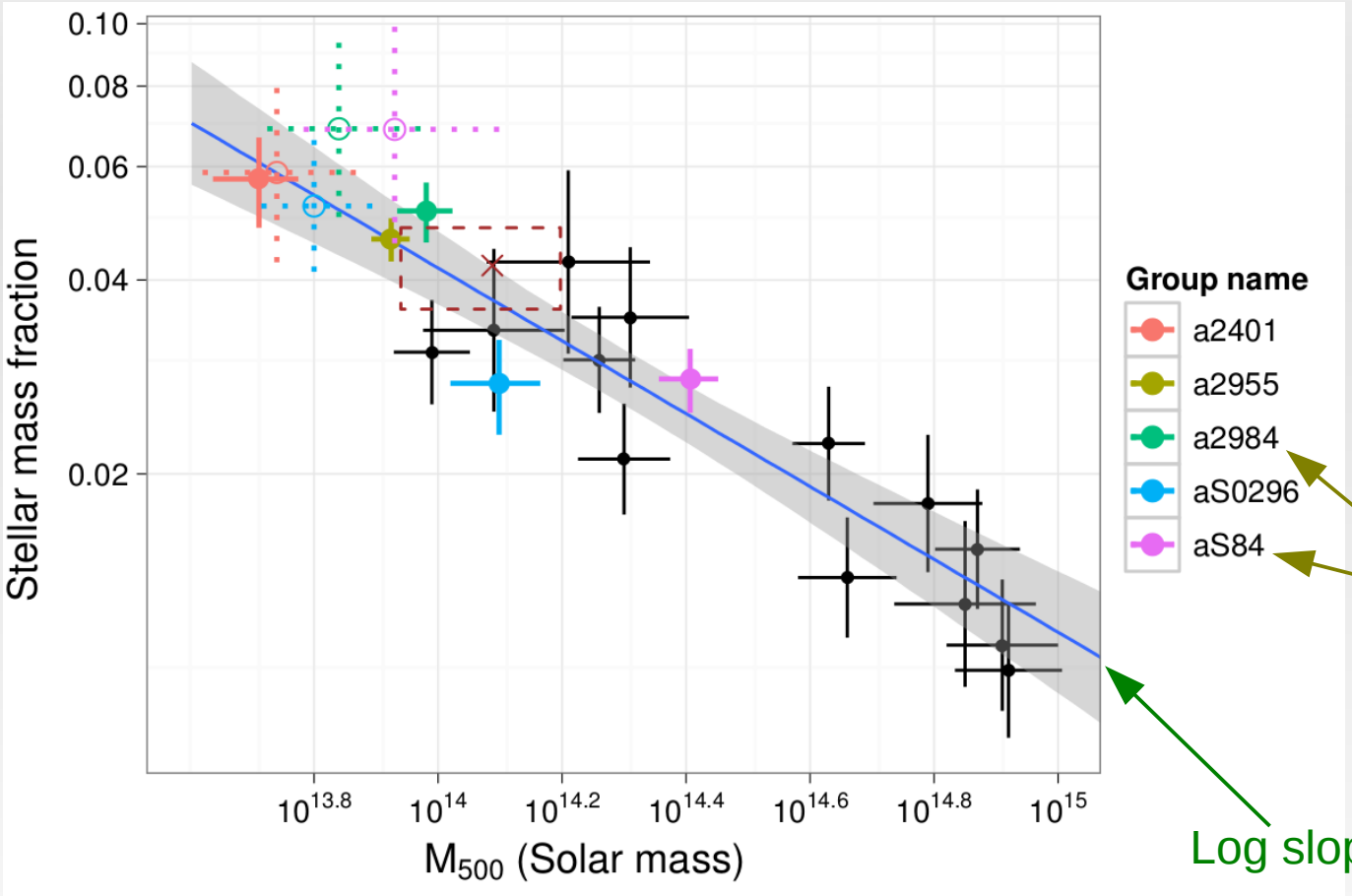




- 3 groups observed with XMM, from sample of Gonzalez+07, with optical mapping of intracluster stars → full baryon census, *with reliable scaling mass and aperture*

Variation in stellar mass fraction

Sanderson, O'Sullivan, Ponman, Gonzalez, +..., in prep.



Black (& dotted) data from Gonzalez+07; masses estimated from velocity dispersion of galaxies

2 more groups added from a companion XMM analysis (Sivanandam et al, in prep.)

Log slope = -0.56 ± 0.06

- Solid coloured lines show new data from X-ray model → optical total mass estimates were biased low, but (steep) trend only slightly flattened
- *Implies ~ ≤ 50% of group optical luminosity in intracluster light...*

Summary

- Measuring cluster masses (→ virial radii) using X-ray data is very effective
- Ascasibar & Diego cluster model is a parsimonious, flexible and effective description of real clusters (& *purely analytic*)
  - fast & easy to fit for even sparse (≥ 3 bins) & noisy data → ideal for use with very large cluster samples
- Scaling with / by cluster mass is a powerful tool for studying cosmology & cosmic feedback → baryon fraction, scaling relations etc.