X-ray mass analysis of LoCuSS* clusters with Chandra

**Local Cluster Substructure Survey*

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X-ray mass analysis overview

1) Deprojection

- gas temperature & density profiles

2) Mass modelling

- $M(r)$, $f_{gas}(r)$, $\rho_{tot}(r)$ etc.

3) Estimation of parameter errors

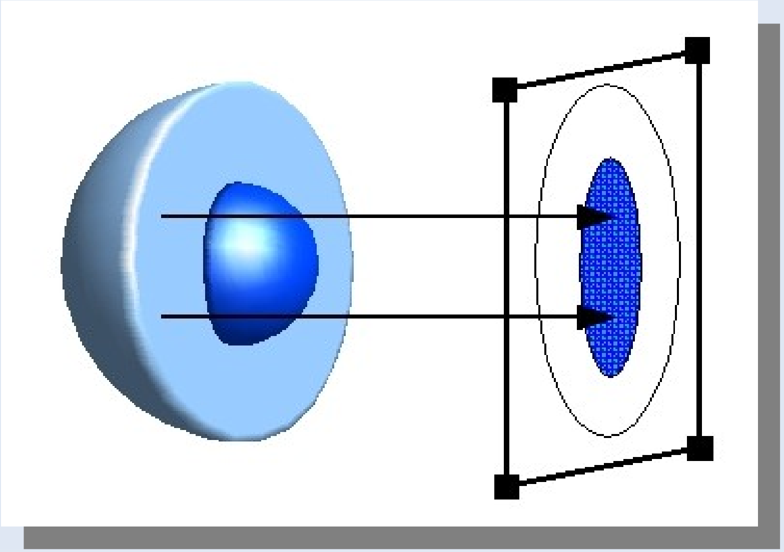
- also need errors on any derived quantities

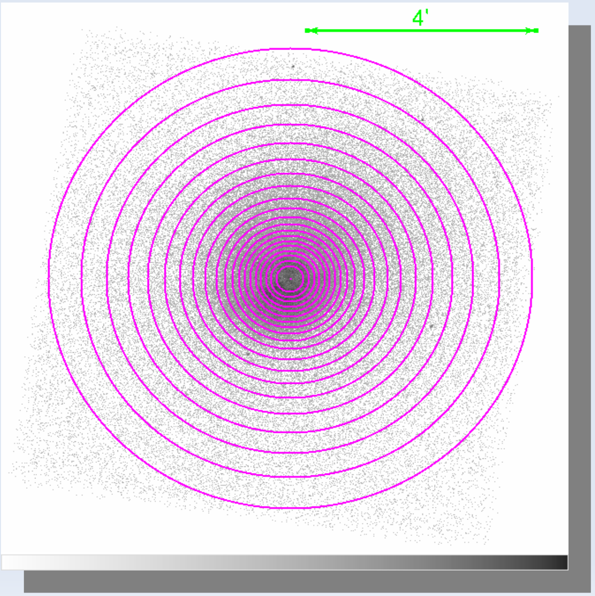
X-ray analysis stages:
1) Deprojection

- Using XSPEC "*projct*" model
- Non-parametric deprojection
- Assume spherical geometry
- Ignore spectral bias & PSF blurring

- Exclude "obvious" subclumps
- Fix metallicity and galactic absoprtion at projected values
- Sometimes also need to fix temperature at projected values (ok if ~isothermal)
- No soft excess bg modelling

3d shells map onto 2d annuli





X-ray spectrum in each annulus

Model parameters for each shell ***fitted simultaneously***

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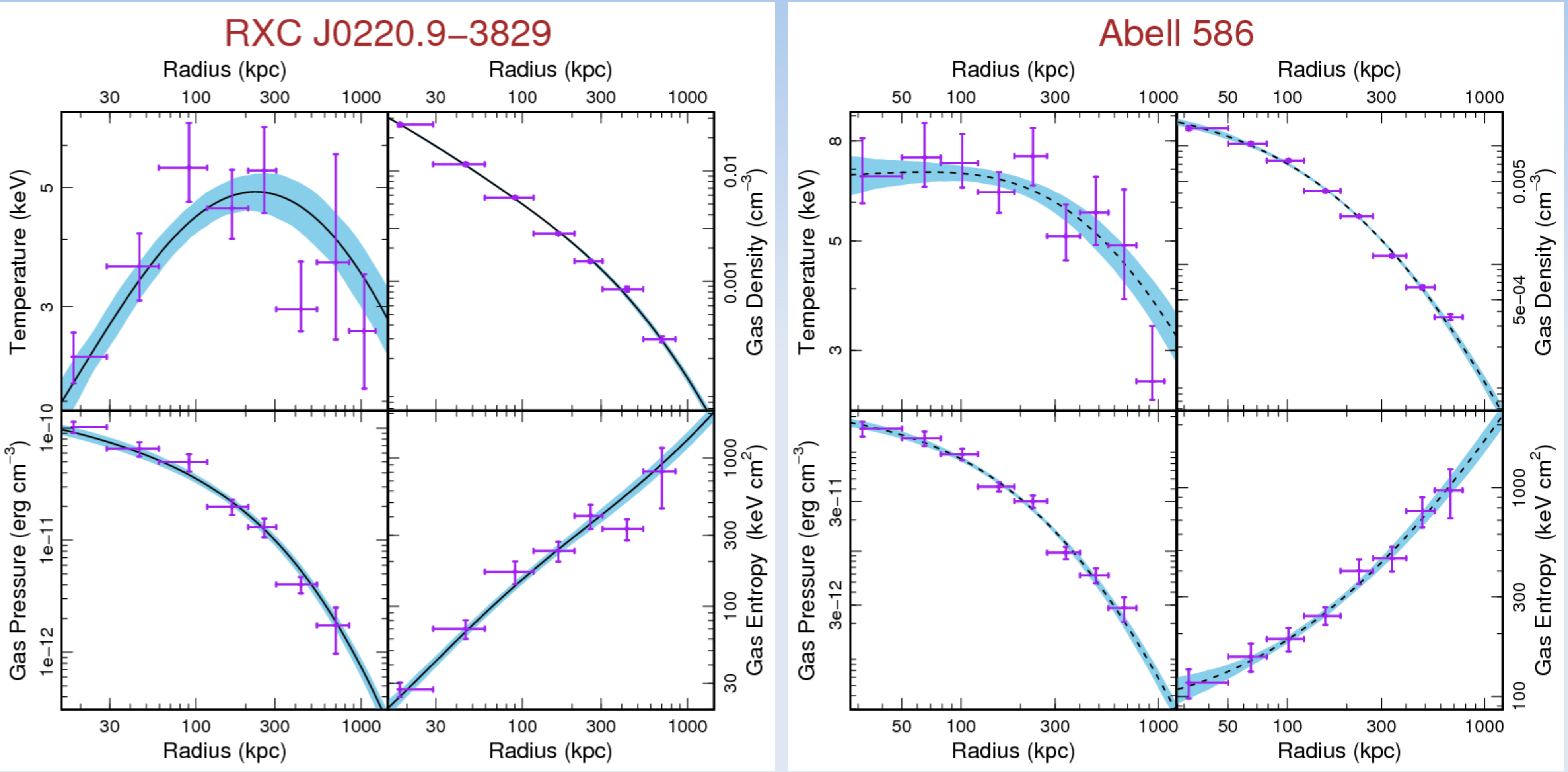
The Ascasibar & Diego (2008) cluster model

- Hernquist $M_{tot}(r)$
- Polytropic gas with variable cool-core component: specifies $T(r)$ & $\rho_{gas}(r)$ in full
- 5 parameters, each with a clear physical meaning:
  - T_0 = central gas temperature of non-cool core polytropic profile
  - t = actual central gas temperature normalized to T_0
  - a = dark matter scale radius [NB ~ 2x NFW r_s]
  - α = cooling radius normalized to scale radius, a
  - f = scaling factor to define gas density normalization wrt cosmic baryon fraction (f = 1)

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

Examples of model fits



Examples of a cool-core and non-cool core cluster with relatively few bins; errorbars are the deprojected data & line is best-fit Ascasibar & Diego model + 1σ error envelope (in both cases the model determines r_{500} to ~5% accuracy)

Ascasibar & Diego cluster model pros & cons

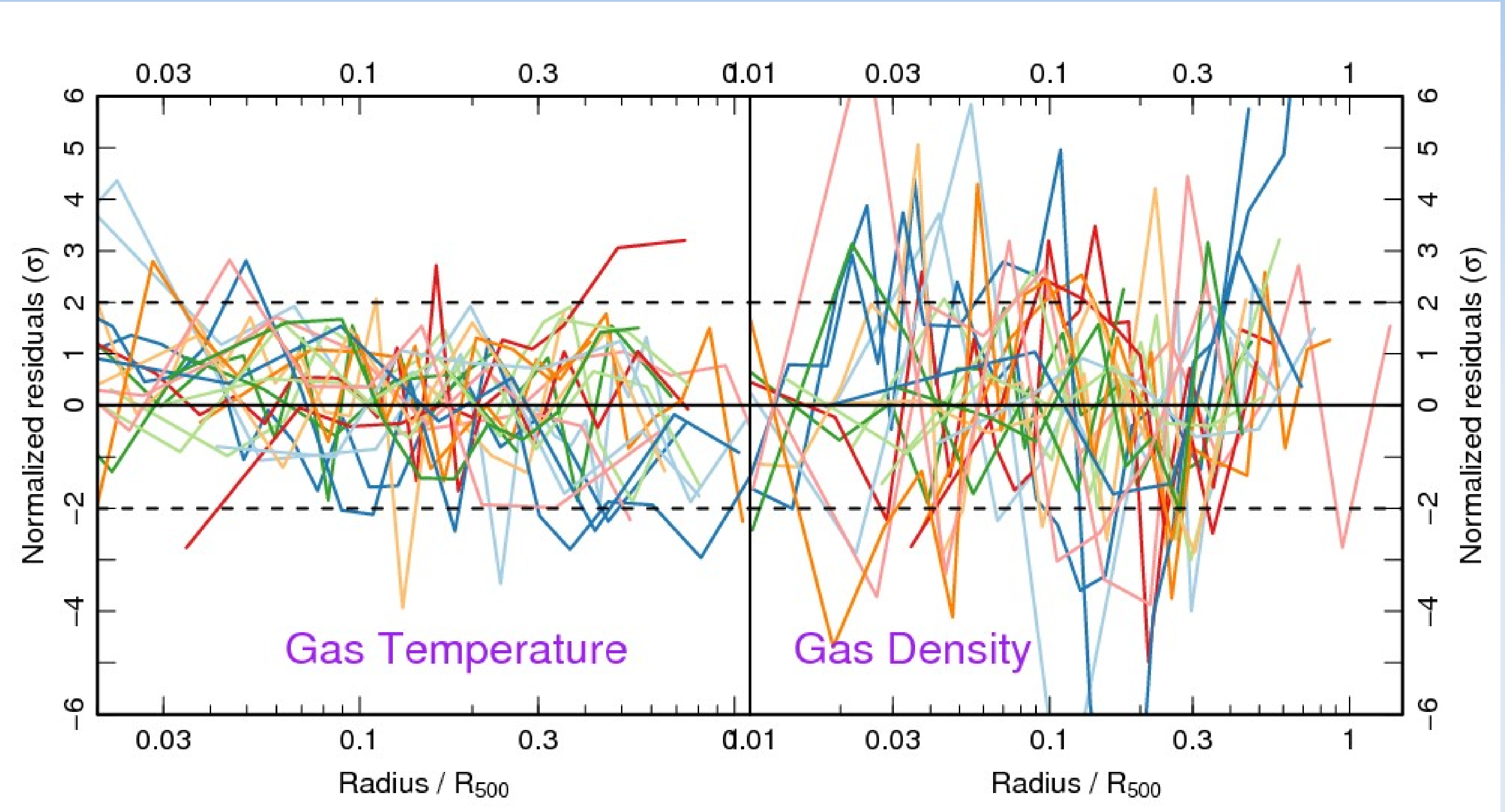
Strengths

- Physically-motivated and well behaved: e.g. no negative $T(r)$
- Simple (won't overfit the data), yet reasonably flexible
- Mass is modelled directly
- Stable & easy to fit, even with sparse & noisy data
  - no need for gradient estimates to get $M(r)$
  - will yield fairly sensible results even for “problem” clusters

Limitations

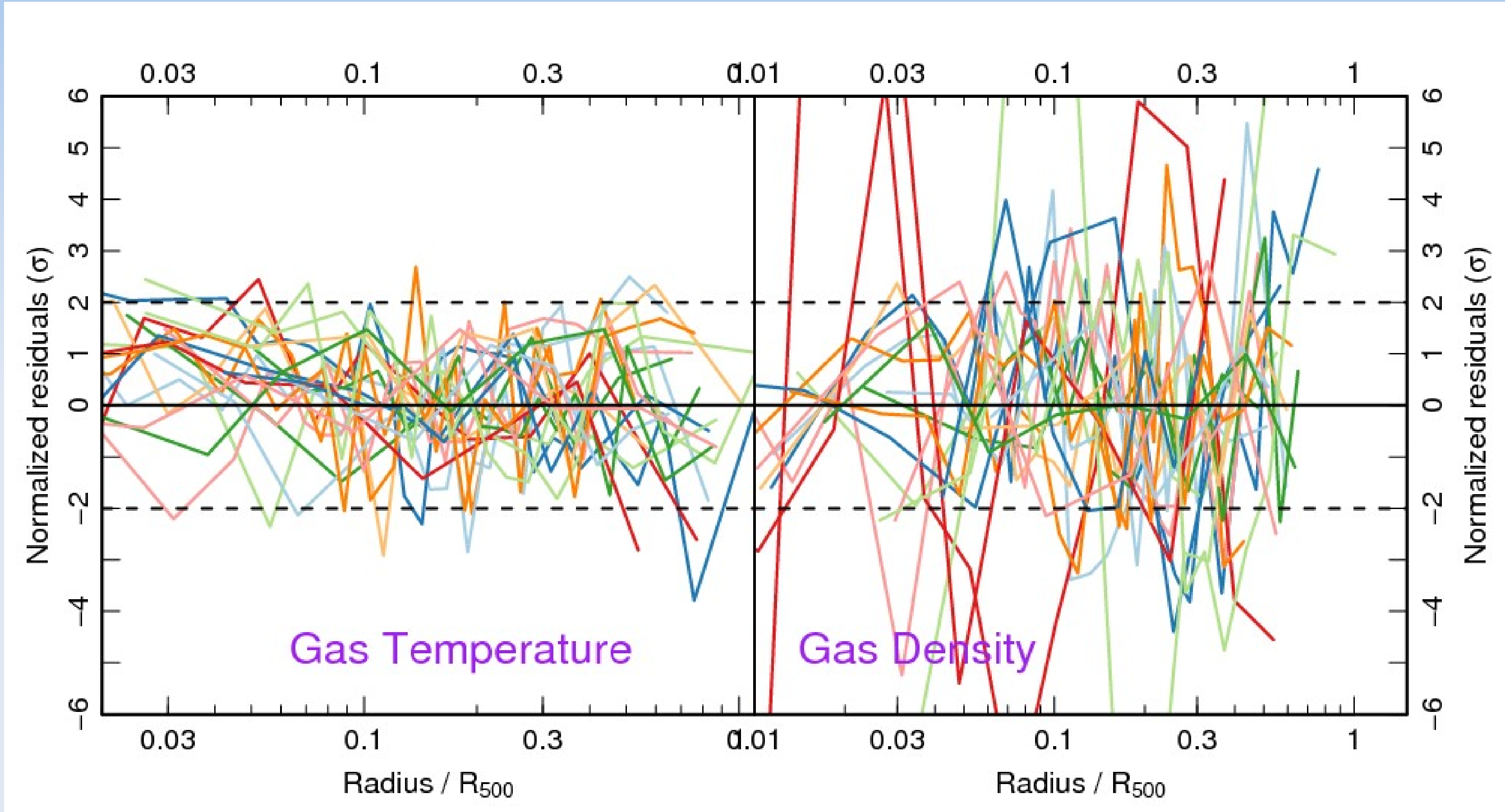
- Fixed (Hernquist) $M(r)$ – e.g. can't investigate inner slope
- Potential lack of flexibility
  - use bootstrap resampling to determine errors
  - need to monitor residuals & ignore innermost data (< 5-10 kpc)

Model residuals vs. scaled radius (coolest clusters)



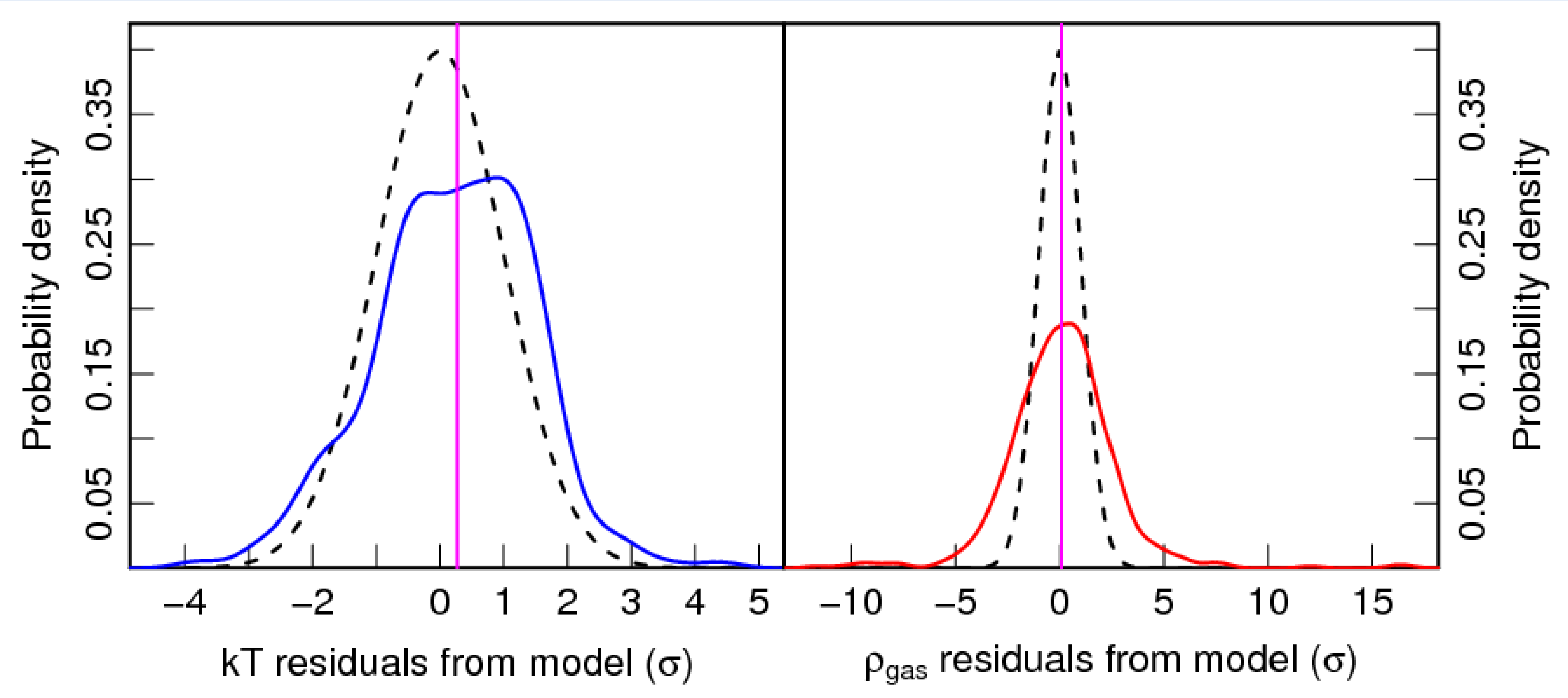
- Only 21 coolest clusters shown (half the sample)
- No significant radial trends in residuals

Model residuals vs. scaled radius (hottest clusters)



- Only 21 hottest clusters shown (half the sample)
- No significant radial trends in residuals

Model residuals probability density plots



- No bias in density residuals; but some (symmetric) outliers – intrinsic scatter due to density substructure, non-equilibrium etc.
- Temperature residuals slightly biased high (i.e. model underpredicts data), but fewer outliers

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Model fitting procedure

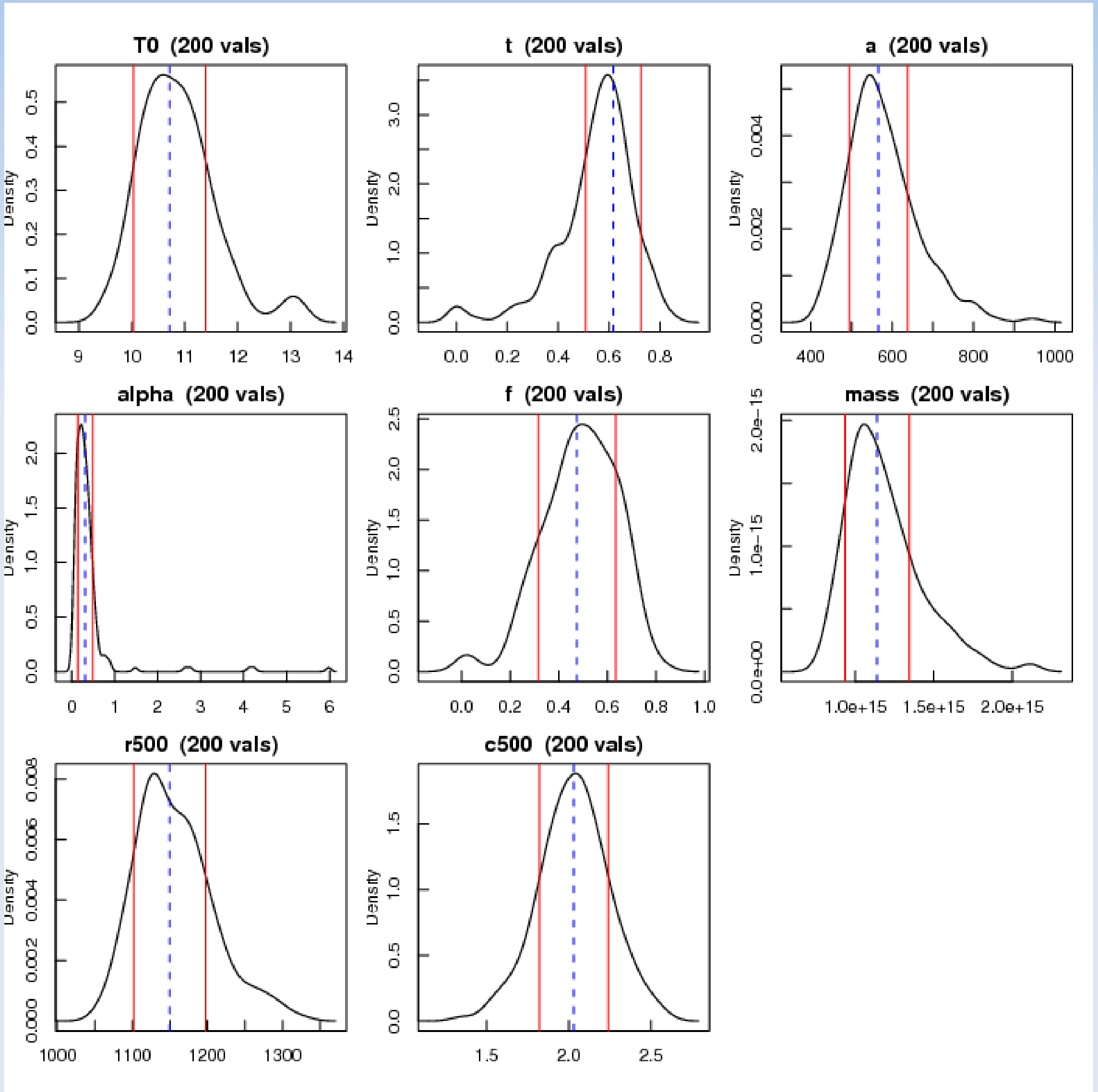
- Joint chi-squared fit to (independently binned) $T(r)$ & $\rho_{gas}(r)$ with asymmetric errors

Error estimates

- Separate bootstrap resampling of temperature and density profiles – 200 Monte Carlo realizations of the original data
  - model fitted to each MC realization
- Use median absolute deviation to estimate σ, as robust to outliers – equivalent to median vs. mean
  - can use any quantile or other statistic as necessary
- A MC realization of every derived quantity can be obtained
  - no error propagation => fully allows for parameter correlations

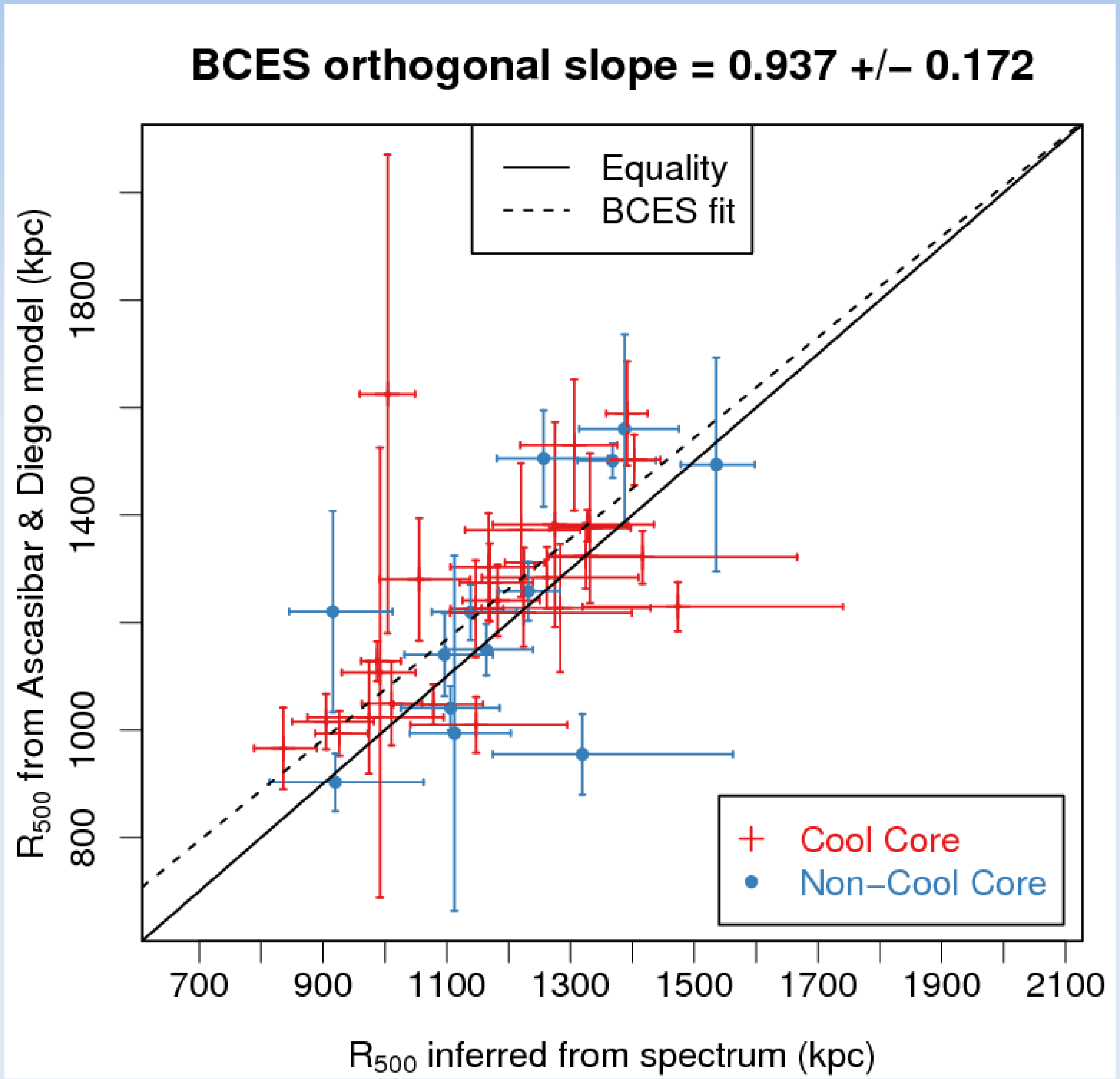
Bootstrap error diagnostics: probability density plots

- Example case of the cluster A586.
- Black curve is kernel-smoothed density plot;
- Dashed blue line is best-fit value
- Red lines are +/- 1 sigma errors (200 Monte Carlo realizations in total).

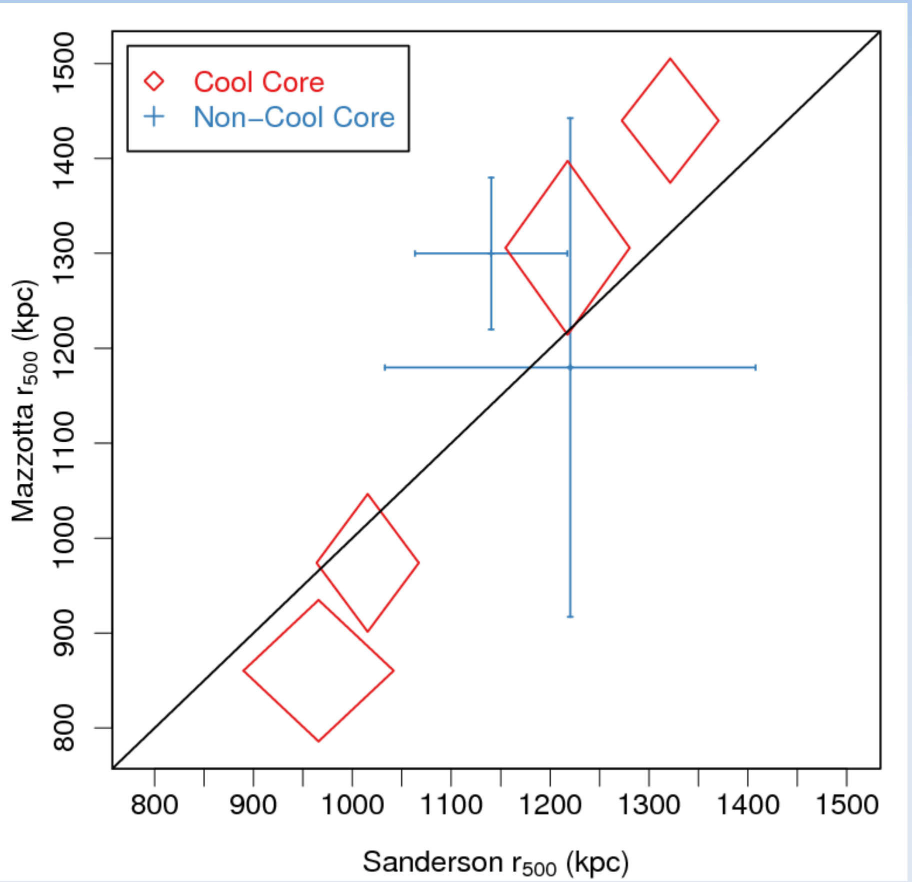


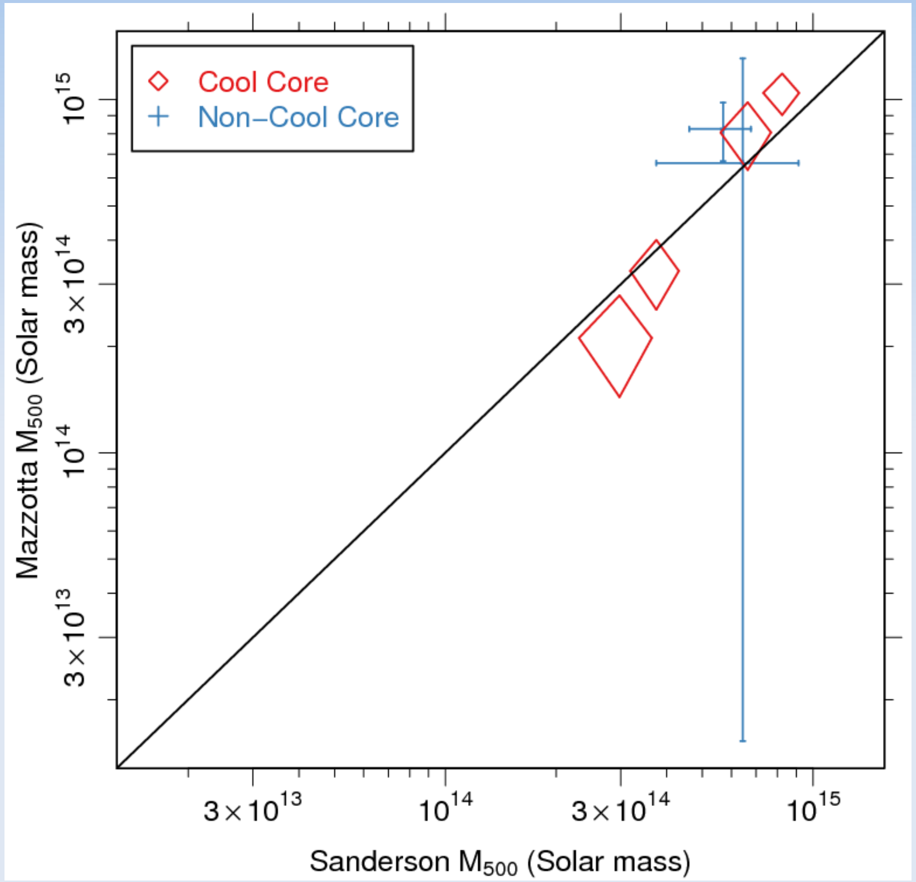
Testing the model: R_{500} comparison

- Weighted orthogonal regression (BCES: Akritas & Bershady, 1996)
- Good agreement between r_{500} estimated from spectrum and r_{500} determined by mass modelling



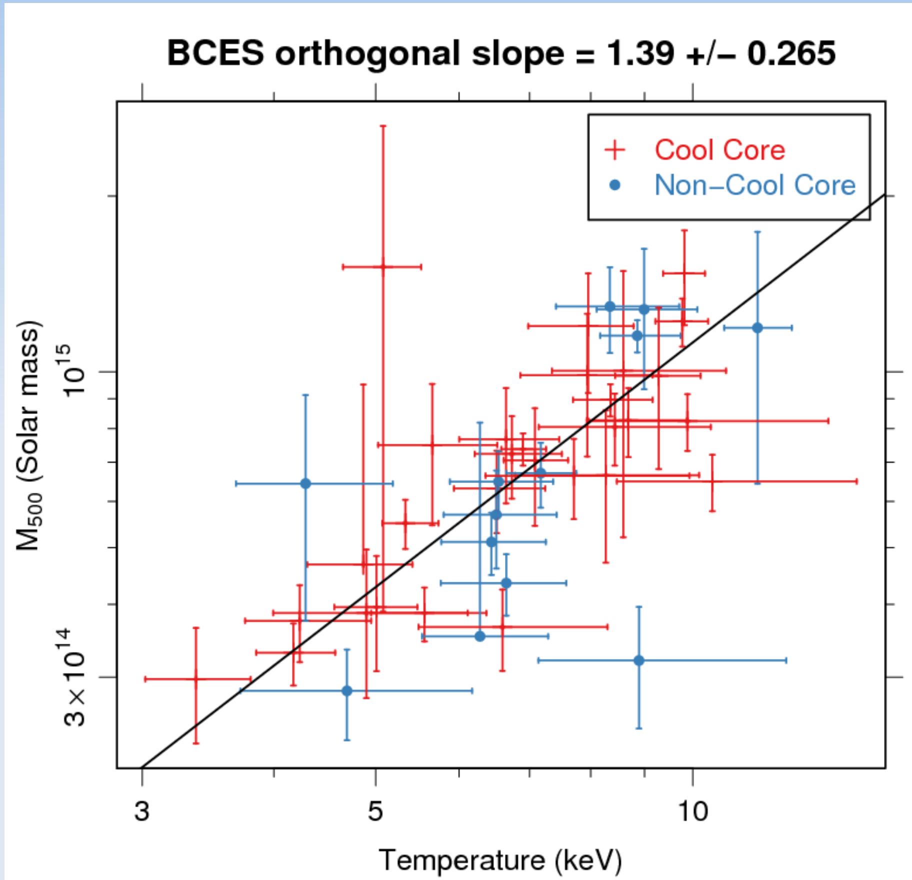
Comparison of mass analysis methods: r_{500} & M_{500}

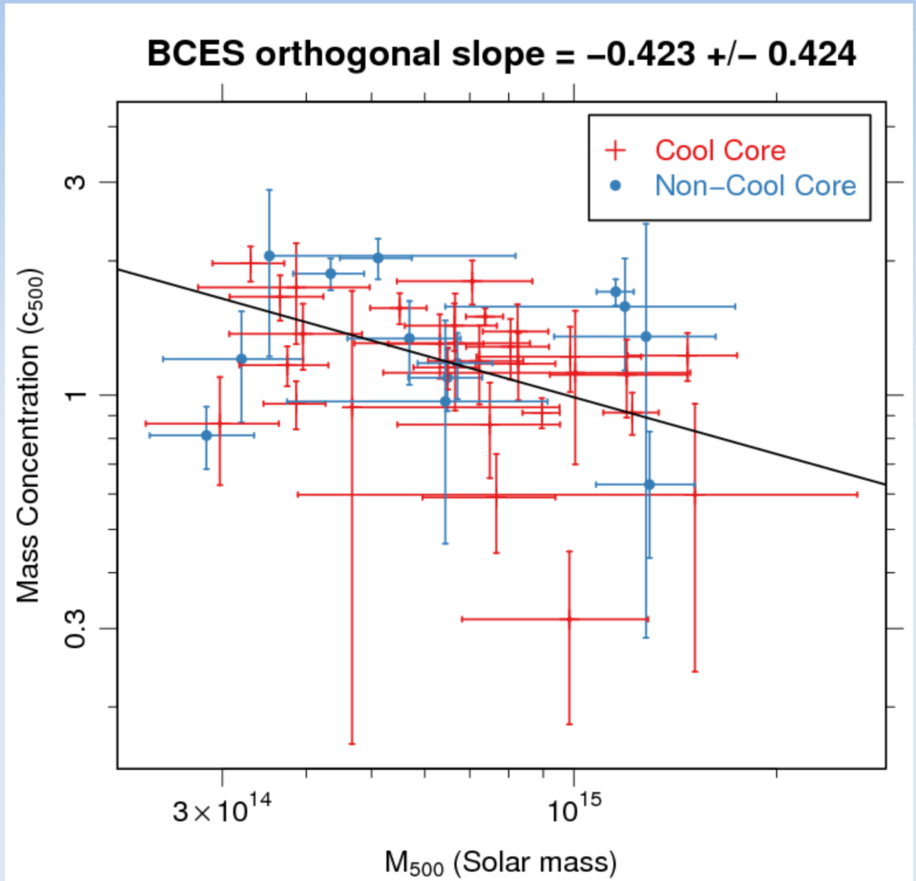




- Same Chandra data, analysed differently by Pasquale Mazzotta (*y* axis) & me (*x* axis)
- 6 LoCuSS clusters observed in 2008 (all 20ks, so fairly shallow)

Some preliminary scaling relation results: c_{500} & M_{500}

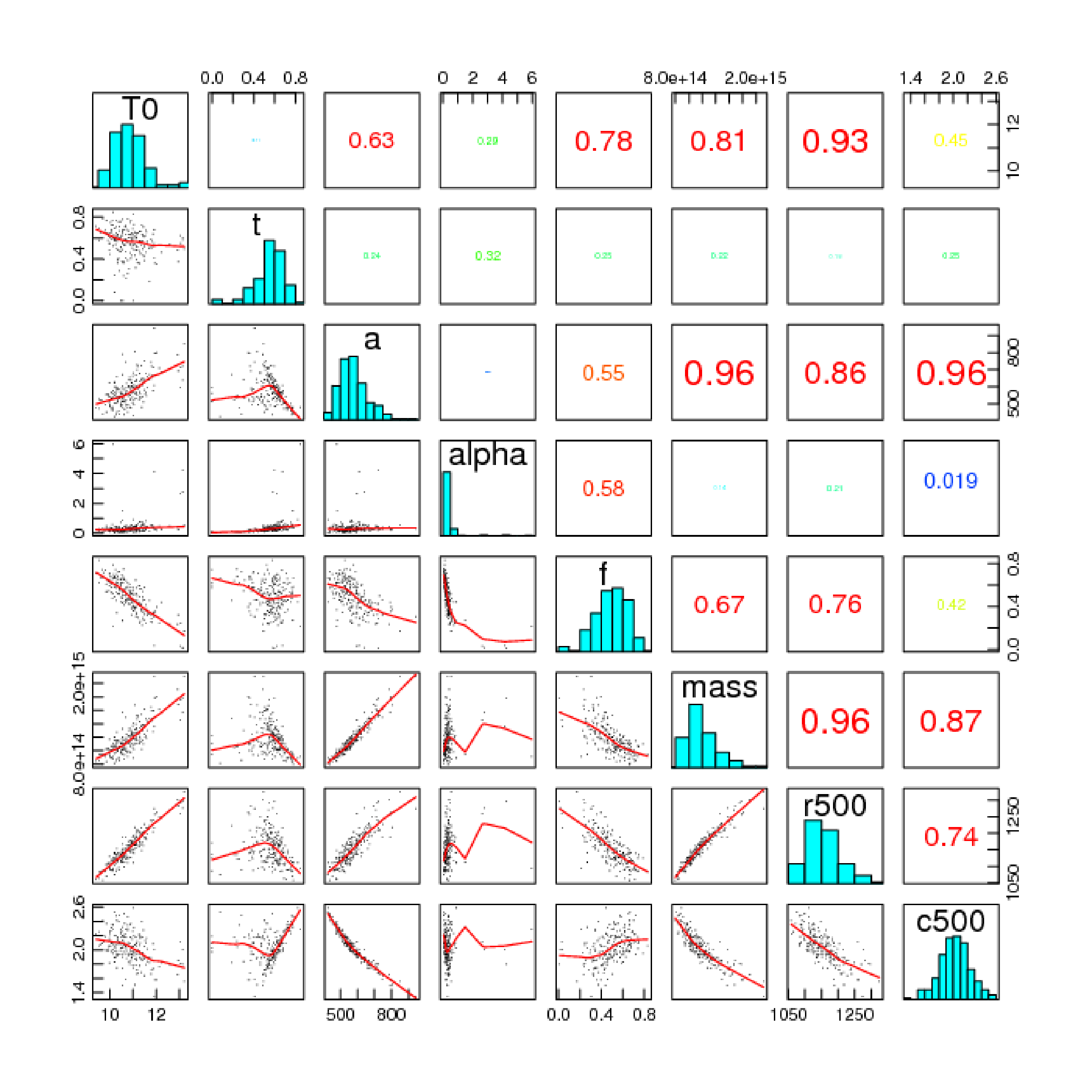




- 42 LoCuSS clusters with Chandra data (NB c_{500} ~ 0.5 x NFW value for Hernquist model)
- Fairly narrow dynamic range & large scatter => large errors on slopes

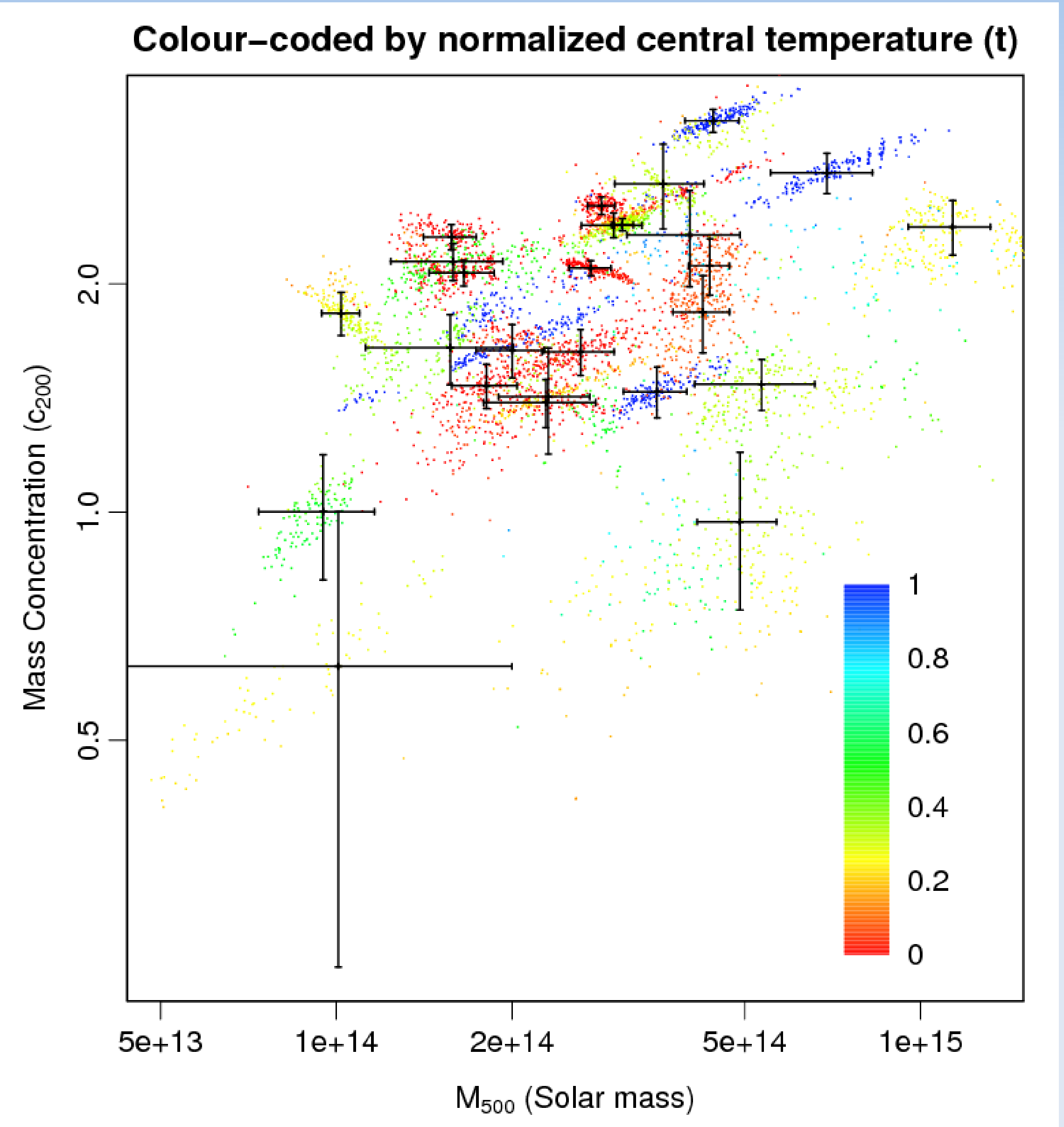
Bootstrap error diagnostics: parameter correlations

- Matrix of scatterplots of parameters (for cluster A586)
- Many correlations evident (red numbers highlight strongest correlations)



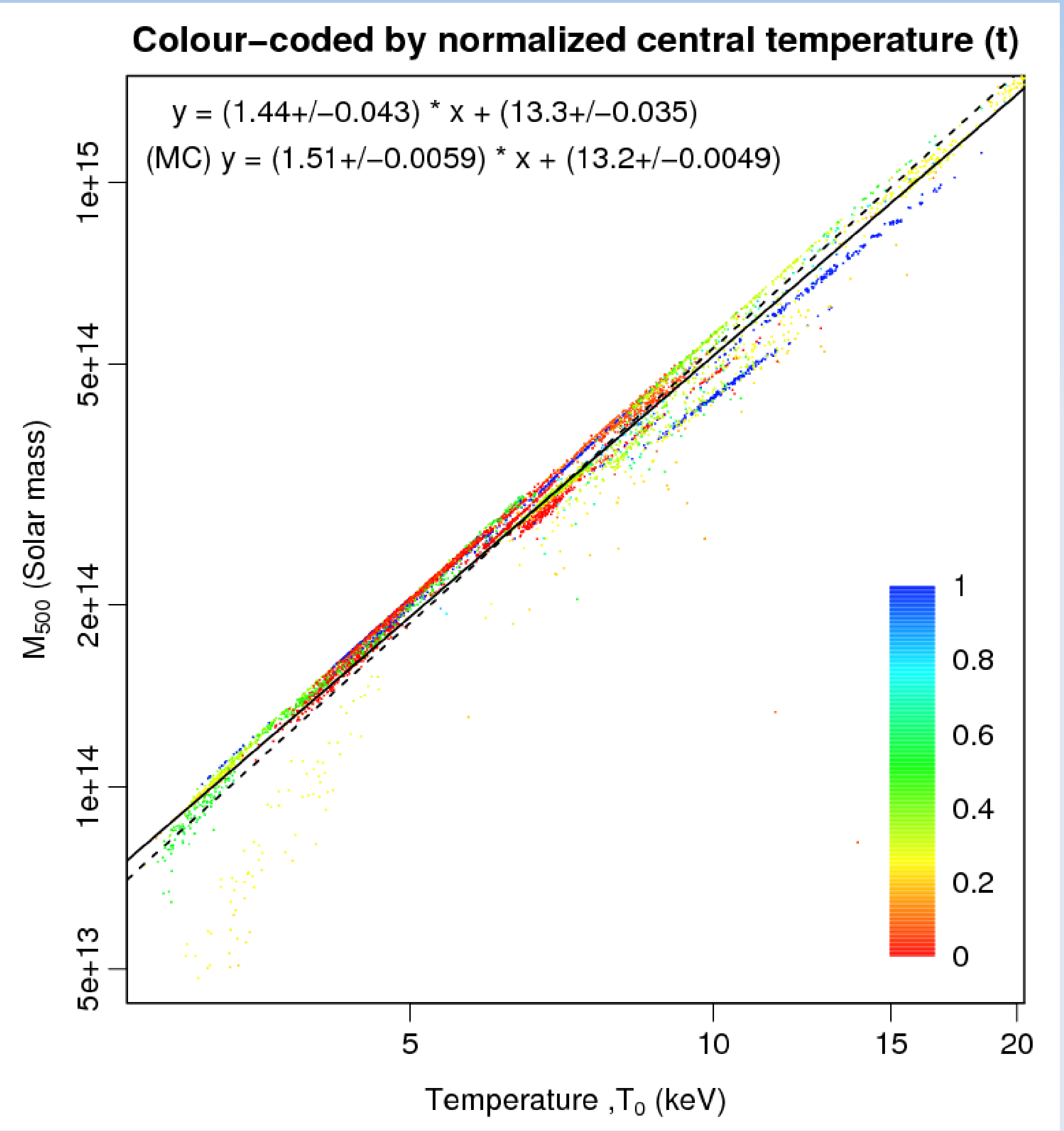
Parameter correlations: M_{500}-c_{200} relation

- Parameters are not independent!
- Intrinsic correlation highly variable
- Hot core clusters show strong correlation
- Cool core clusters show anti-correlation
- **Need to deal with these correlations in fitting global scaling relations**



Parameter correlations: M_{500} - T_0 relation

- Parameters very highly correlated
- Hot core clusters flatten the relation
- Bootstrap realizations sample probability space & capture the correlation
- Dashed line is <u>unweighted</u> fit to all Monte Carlo points
  - steeper => internal correlation flattens
  - **automatically handles intrinsic scatter**
- Orthogonal regression needed...



Summary

- XSPEC projct is a simple & effective scheme for non-parametric X-ray deprojection
  - Some issues with instabilities in recovered $T(r)$, especially for hotter clusters
- Ascasibar & Diego (2008) model effective at determining $M(r)$, especially with sparse/noisy data
  - Less suitable for detailed studies with v. high quality data
- Bootstrap resampling of mass models is ideal for error estimation and handling of parameter correlations
- Need detailed comparison of methods (inc. lensing) for 10's of clusters to establish best approach