# X-ray Spectral Deprojection of Galaxy Clusters

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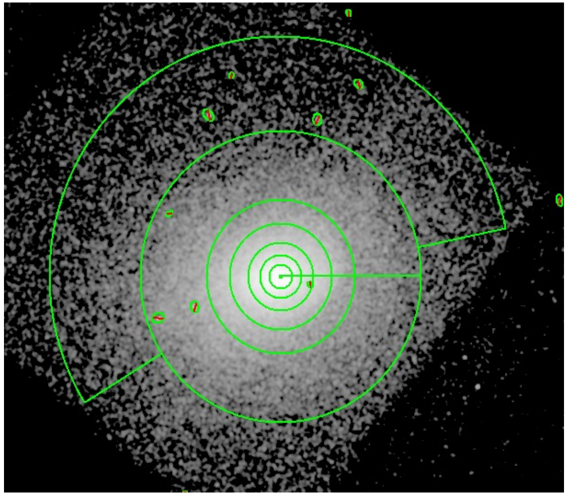
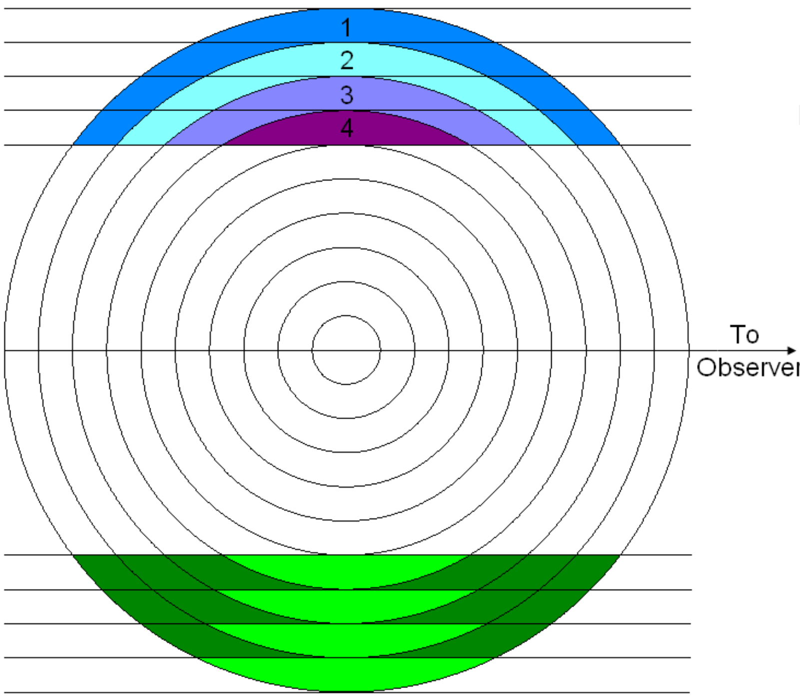
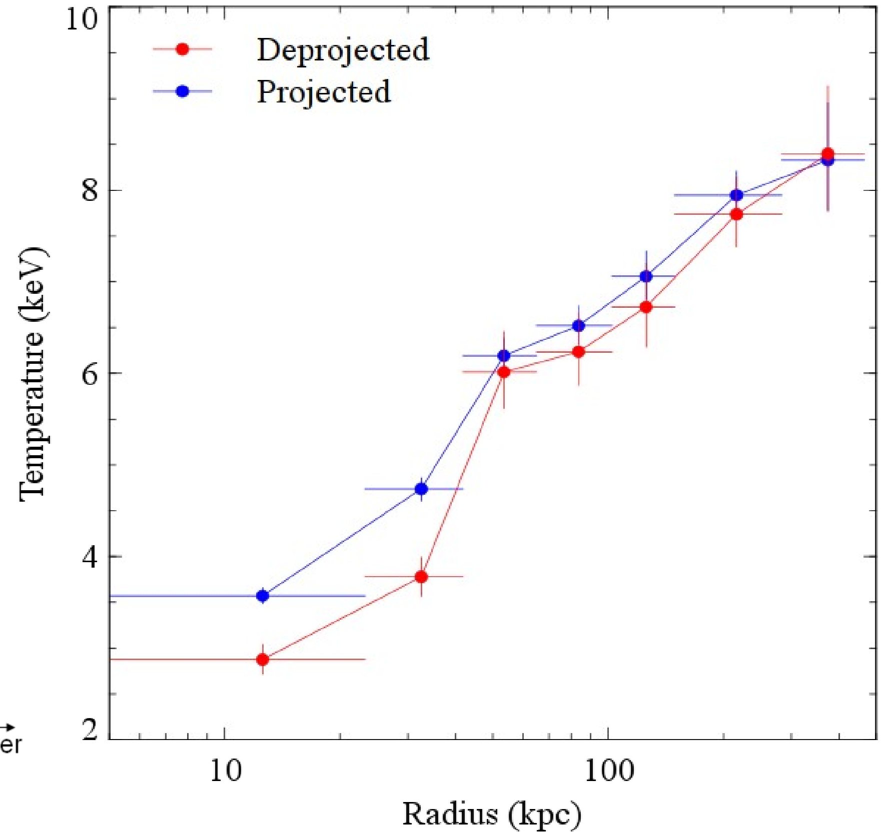
# Outline

- Galaxy cluster deprojection in X-rays
  - Model-dependent methods: Projct
  - Model-independent methods: DSDeproj
- Mass profiles
- PKS 0745-191

# Deprojection



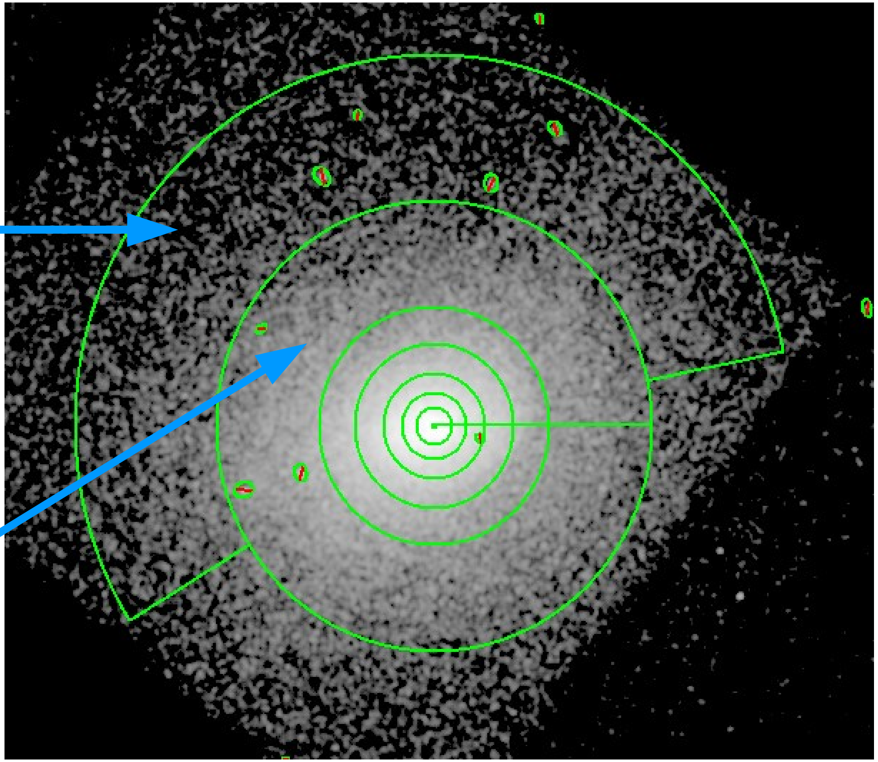


# Galaxy Cluster Deprojection

- Assume spherical symmetry
- Model-dependent method
  - Projct in Xspec

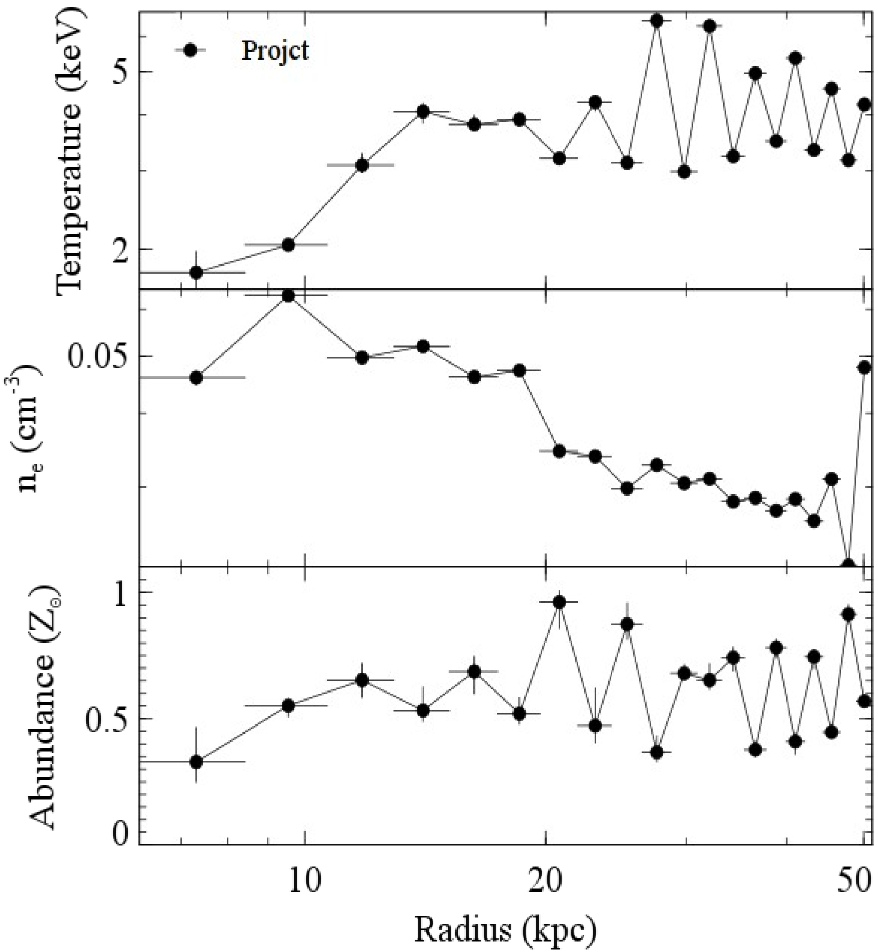
1 model + 0 models of projected emission



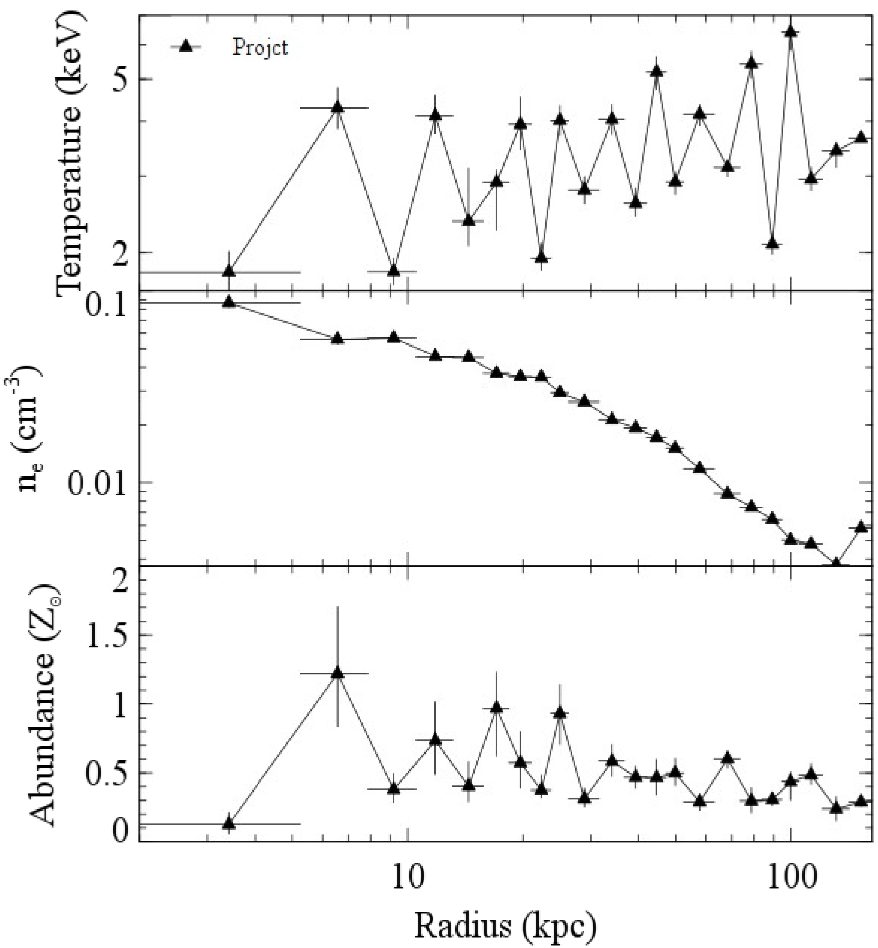
1 model + 1 model of projected emission

# Projct

## PERSEUS CLUSTER

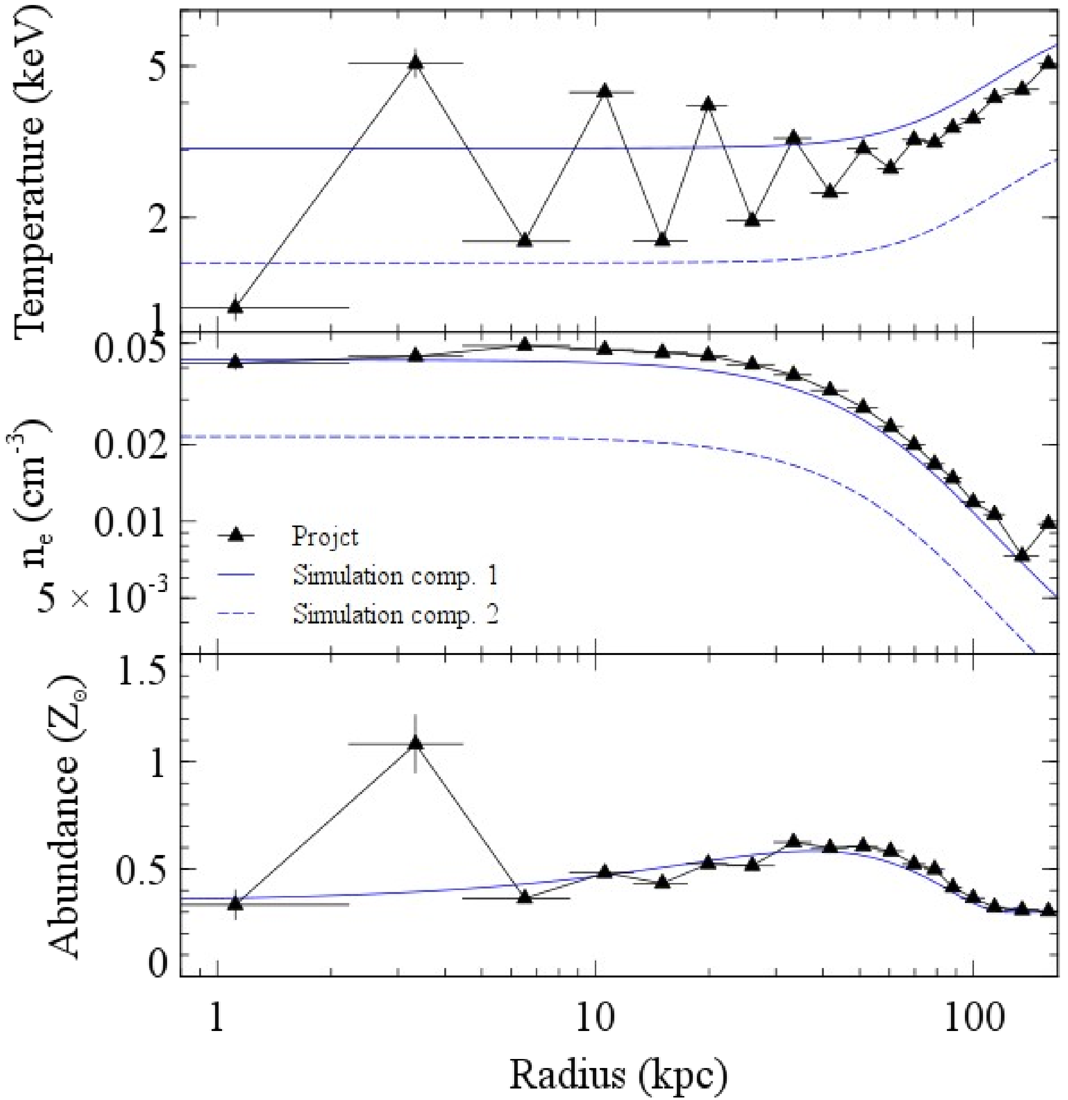



## HYDRA A



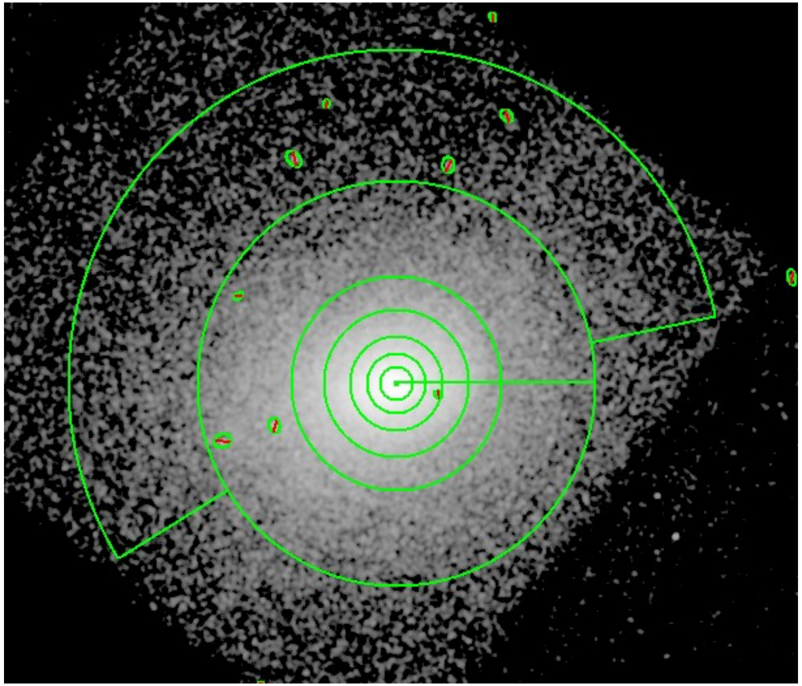
# Projct

- Simulated clusters
  - Two temperature components fitted with single temperature model
  - Data does not generally support two temperature model fits



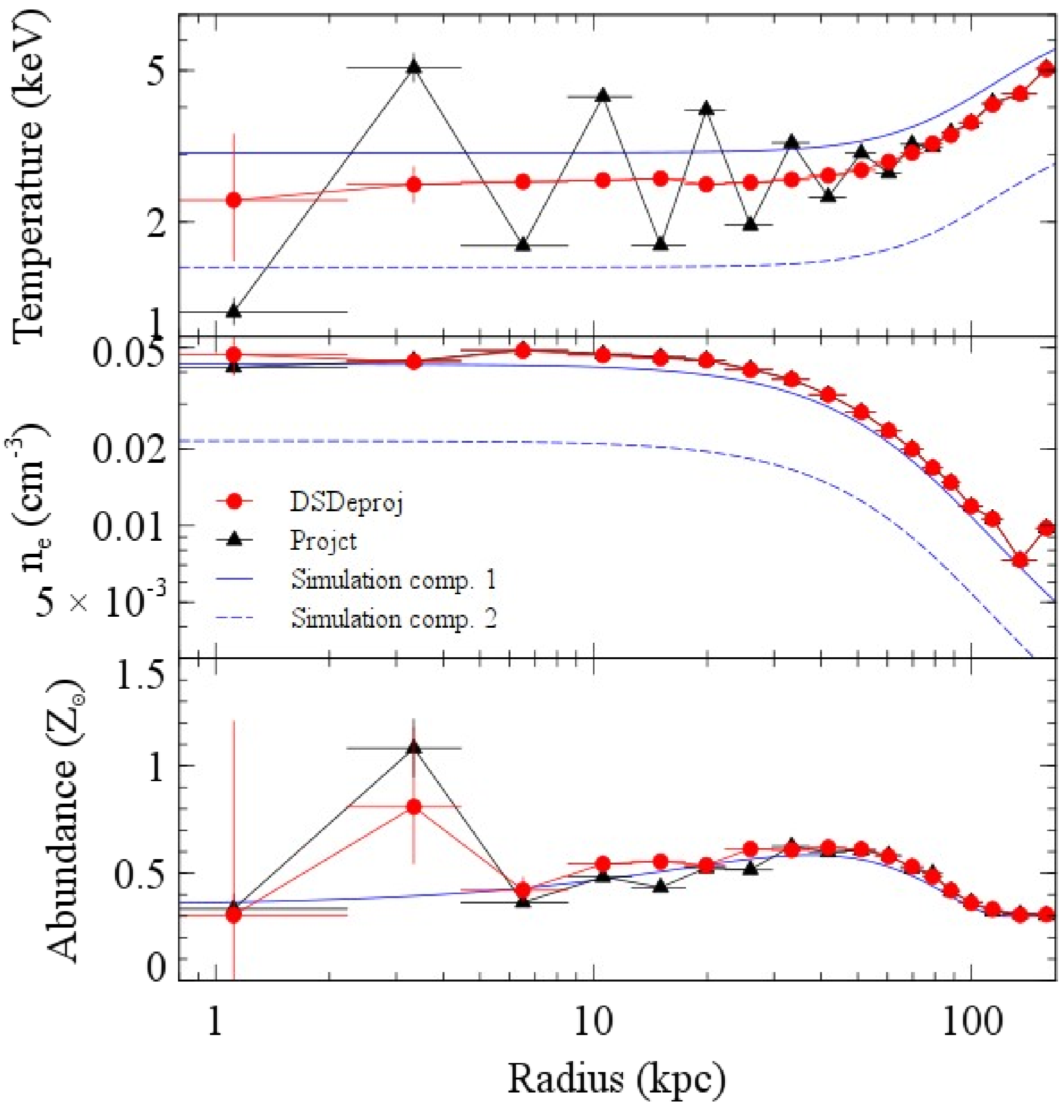
# Spectral Deprojection

- Model-independent method – DSDeproj (Sanders & Fabian 2007, Russell et al. submitted)
- Uses a geometrical procedure to subtract off the projected emission in a series of shells (similar to Nulsen & Bohringer 1995)
- A Monte Carlo technique was used to calculate the uncertainties on each deprojected spectrum.

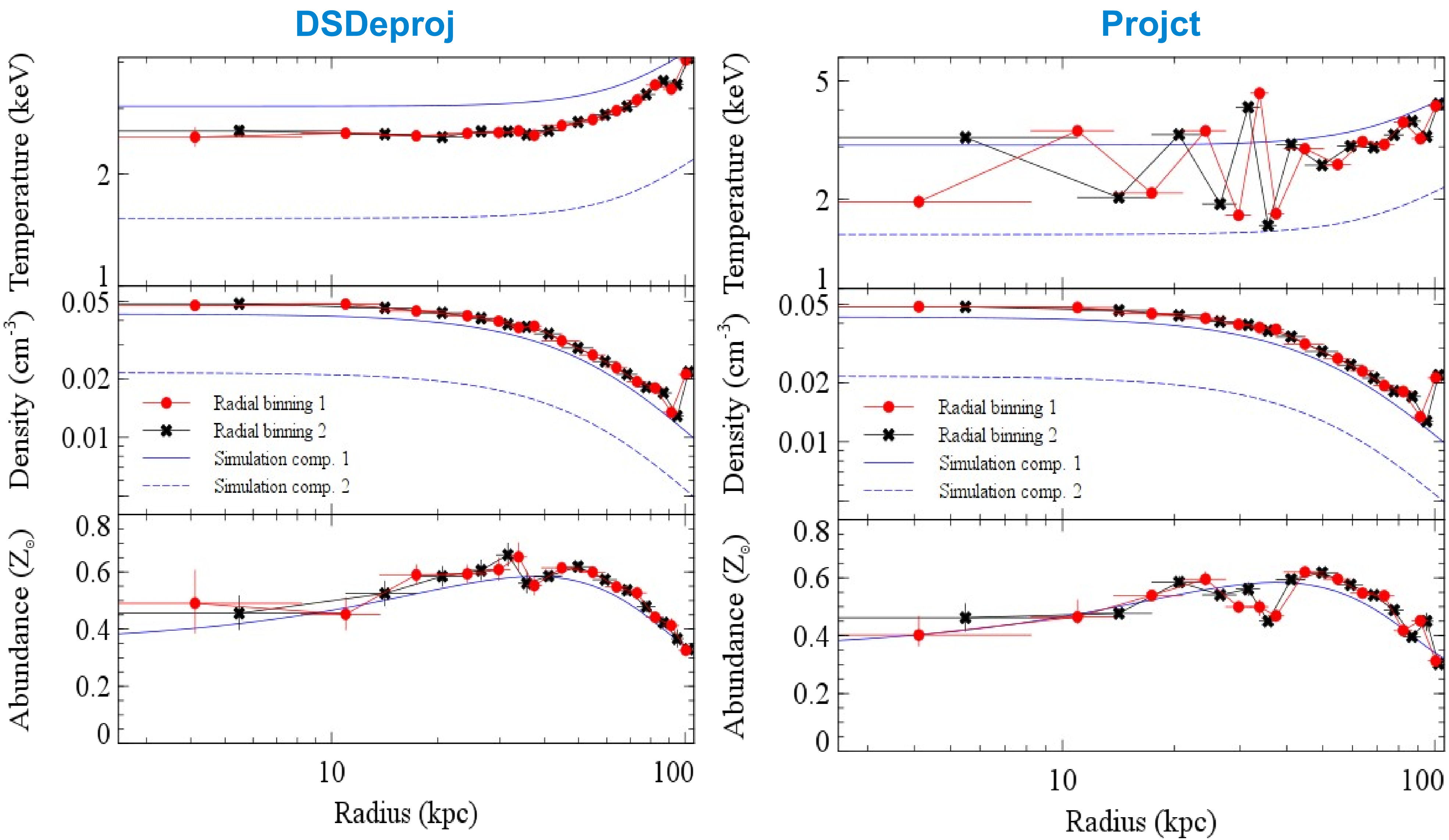


# DSDeproj

- DSDeproj produces a smooth temperature profile that is average of the two separate components (weighted by emission)



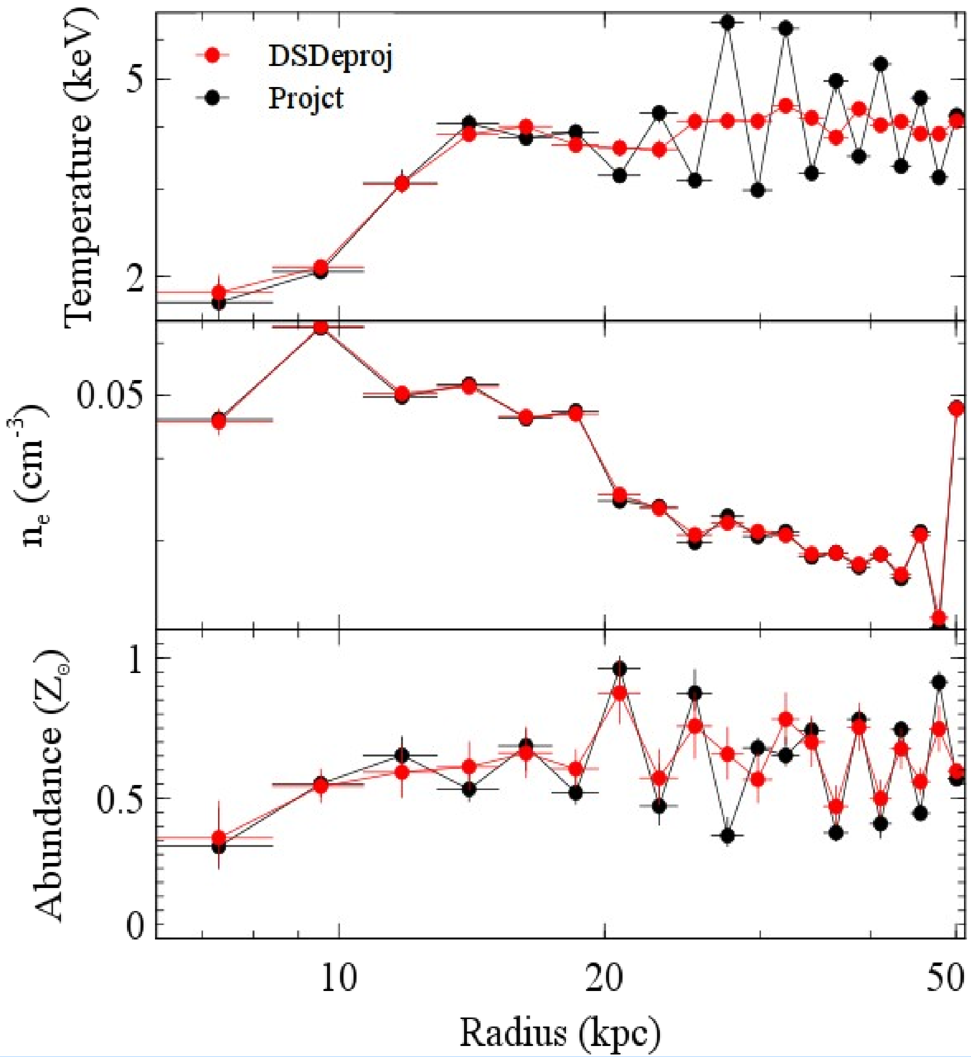
# DSDeproj

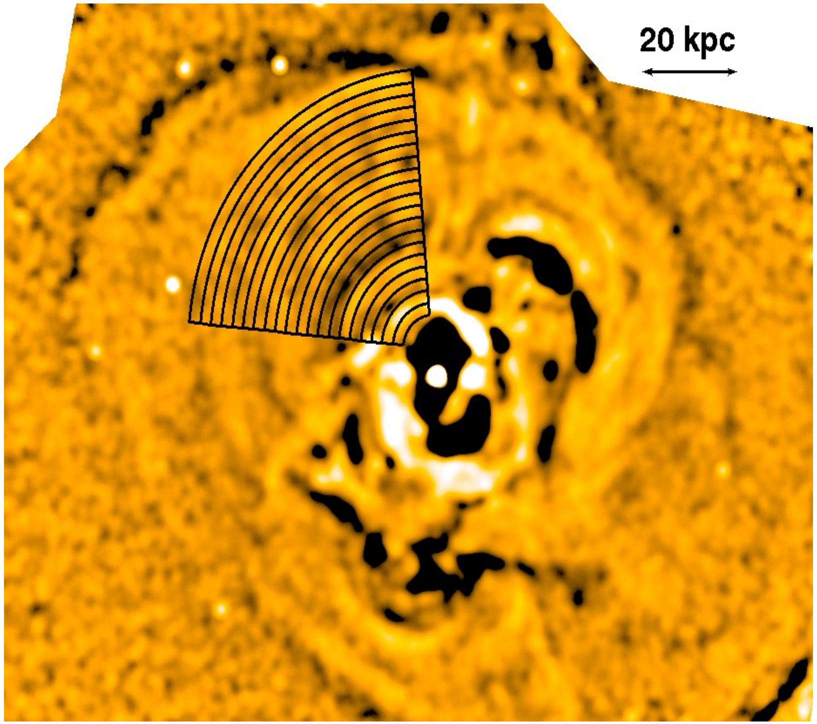


DSDeproj
Projct
Temperature (keV)
Density (cm-3)
Abundance (Z⊙)
Radius (kpc)
Radial binning 1
Radial binning 2
Simulation comp. 1
Simulation comp. 2
5
2
1
0.05
0.02
0.01
0.8
0.6
0.4
0.2
0
10
100

# DSDeproj

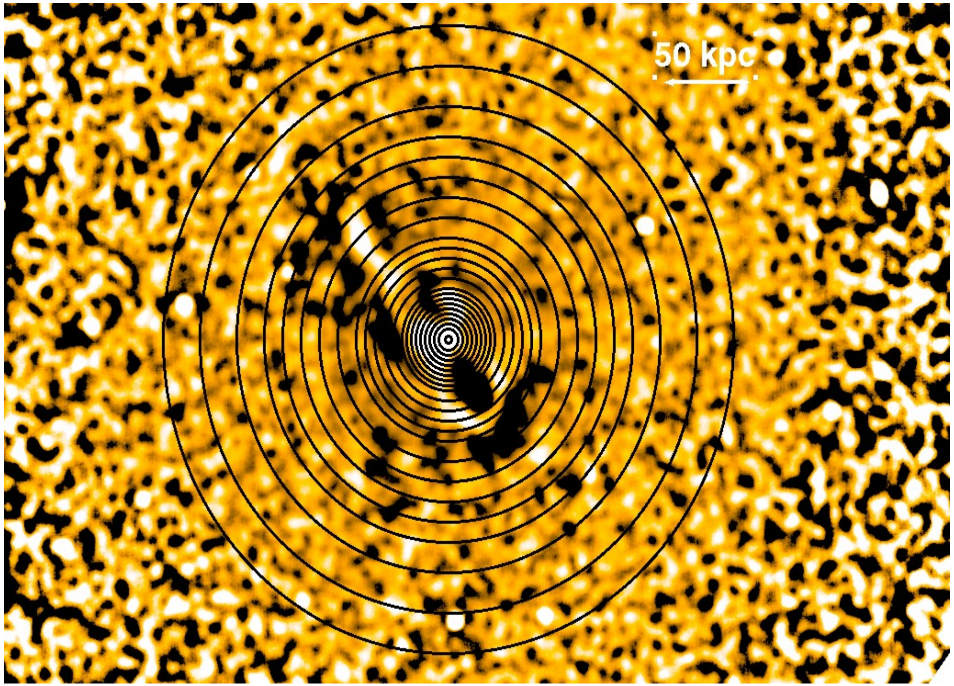
## PERSEUS CLUSTER



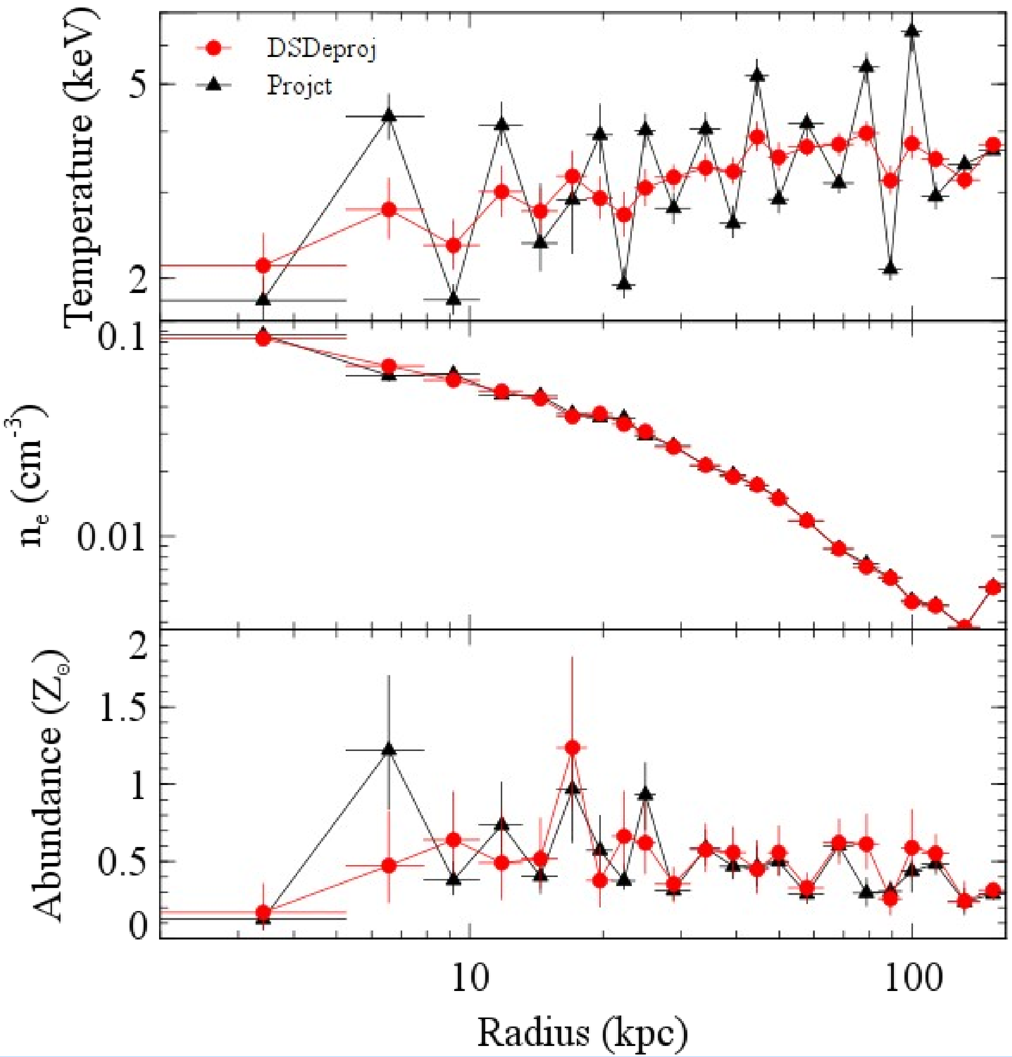

Fabian et al. 2006

# DSDeproj




Nulsen et al. 2002

**HYDRA A**



# Mass Profile

- To derive a mass profile, assume:
  - Gas properties are spherically symmetric
  - Gravitational potential dominated by dark matter
  - Cluster is in hydrostatic equilibrium

$$\frac{dP}{dr} = \frac{k_B}{\mu m_H}\left(\rho_{gas}\frac{dT}{dr} + T\frac{d\rho_{gas}}{dr}\right) = \frac{-GM(<r)\rho_{gas}}{r^2}$$

- Temperature and $\rho_{gas}$ profiles $\rightarrow$ Mass profile?

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- Temperature and $\rho_{gas}$ profiles $\rightarrow$ Mass profile?

Assume the total density distribution can be described by an **NFW profile**

# Mass Profile

- Use an NFW model and the observed $\rho_{gas}$ to predict a temperature in each annulus.

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}$$

$$c_{200} = r_{200}/r_s$$

Schmidt & Allen (2007)

# Mass Profile

- Use an NFW model and the observed $\rho_{gas}$ to predict a temperature in each annulus.

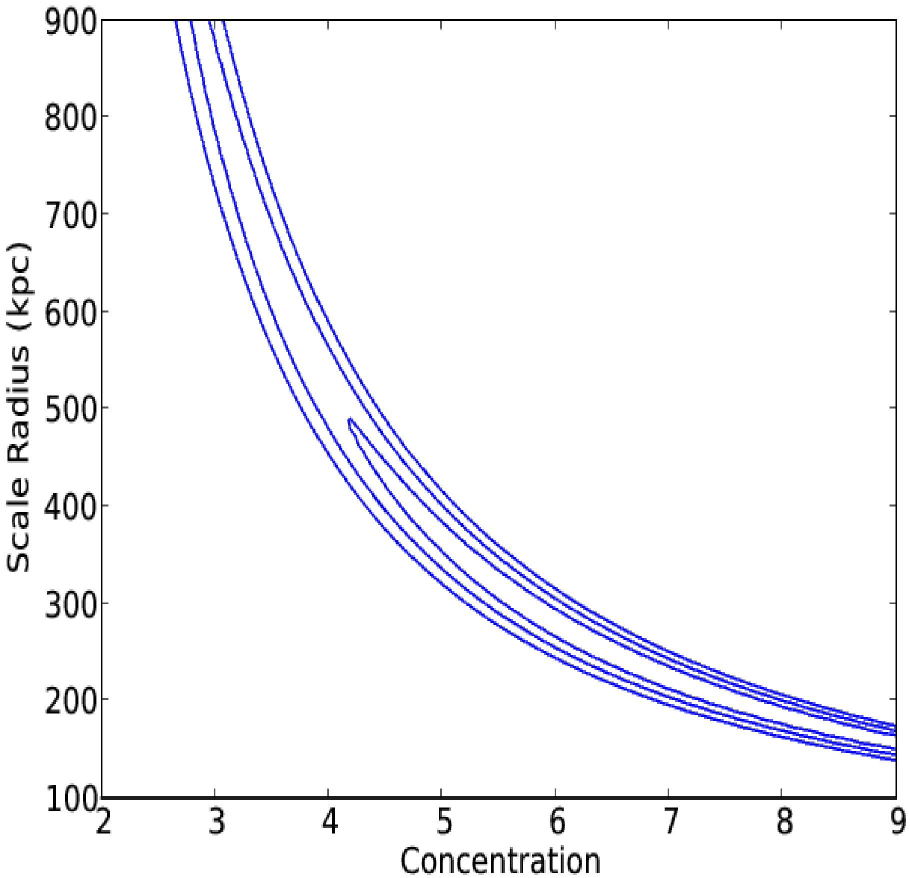
$$\frac{k_B}{\mu m_H}\left(\rho_g \frac{dT}{dr} + T\frac{d\rho_g}{dr}\right) = \frac{-G M \rho_g}{r^2}$$

Schmidt & Allen (2007):

$$r_s = 360^{+130}_{-110}\, kpc \qquad c = 5.85^{+1.55}_{-1.07}$$

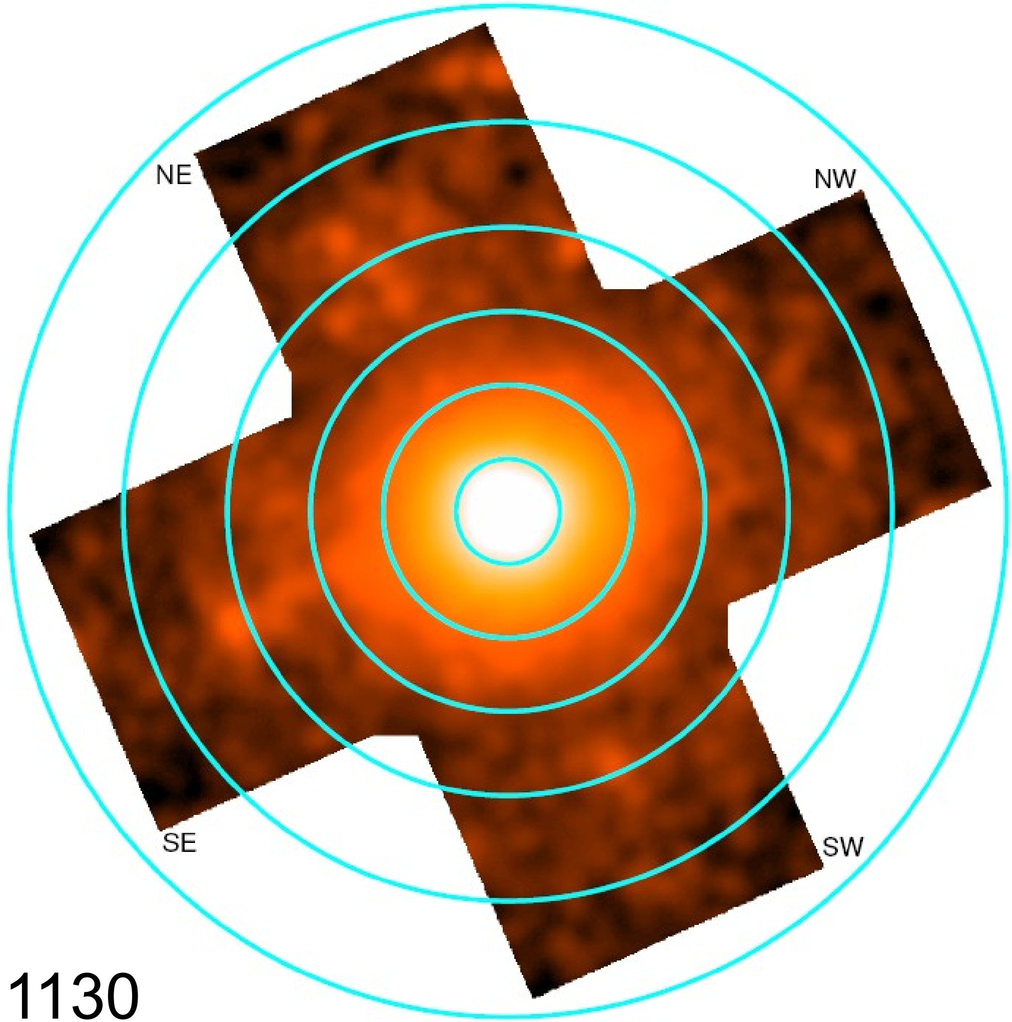
Pointecouteau et al. (2005):

$$r_{200} = 1999 \pm 77\, kpc \qquad c = 5.12 \pm 0.40$$



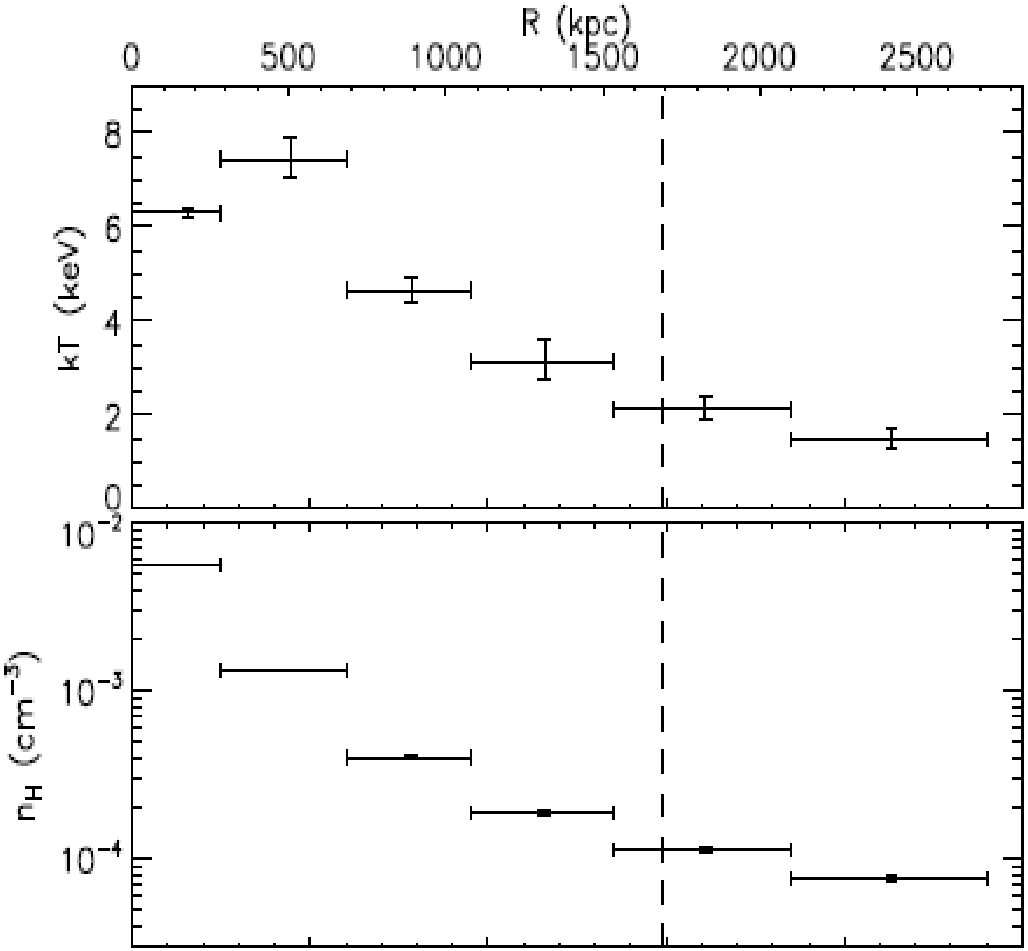
# PKS 0745-191

- 5 separate fields of 32ks each
- Observation reaches nearly 24' (2.7 Mpc)

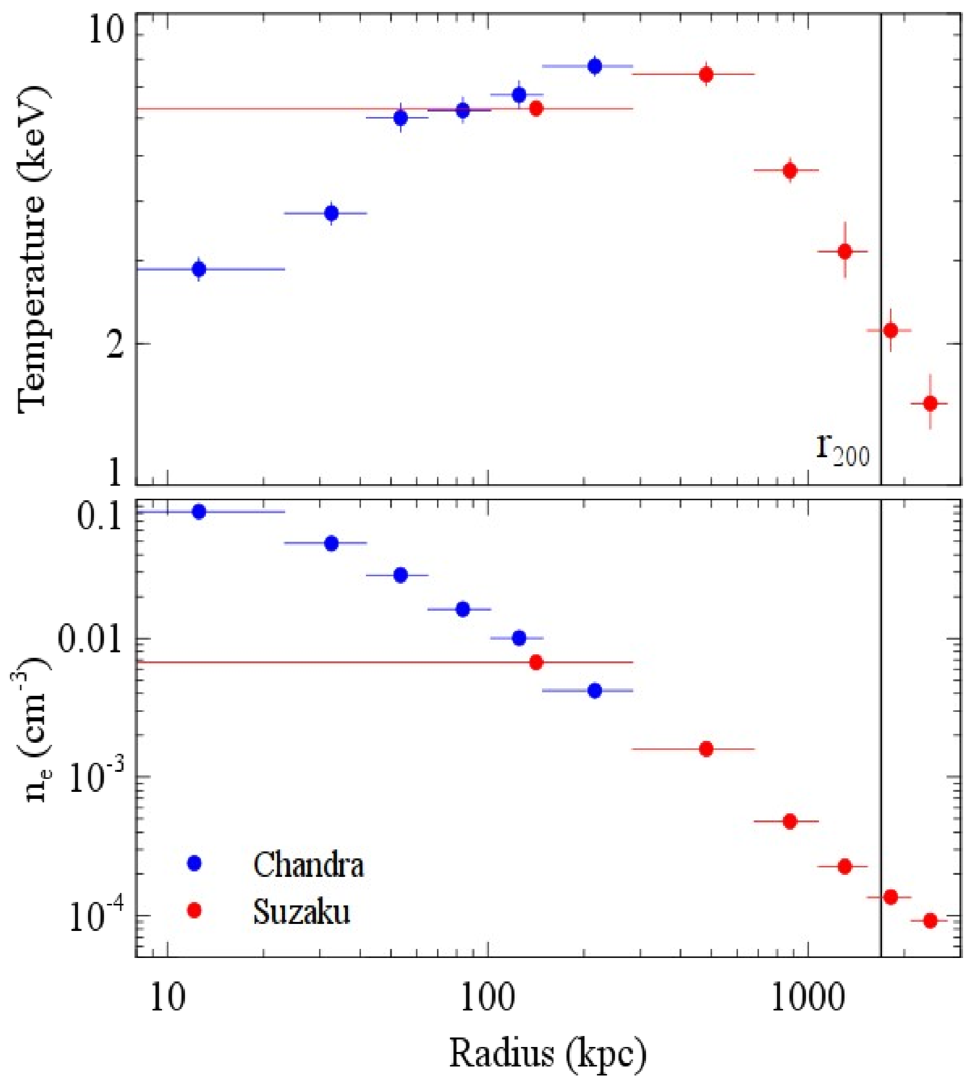



George et al. (2008) arXiv:0807.1130

# Mass Profile: Chandra + Suzaku




$r_{200}$

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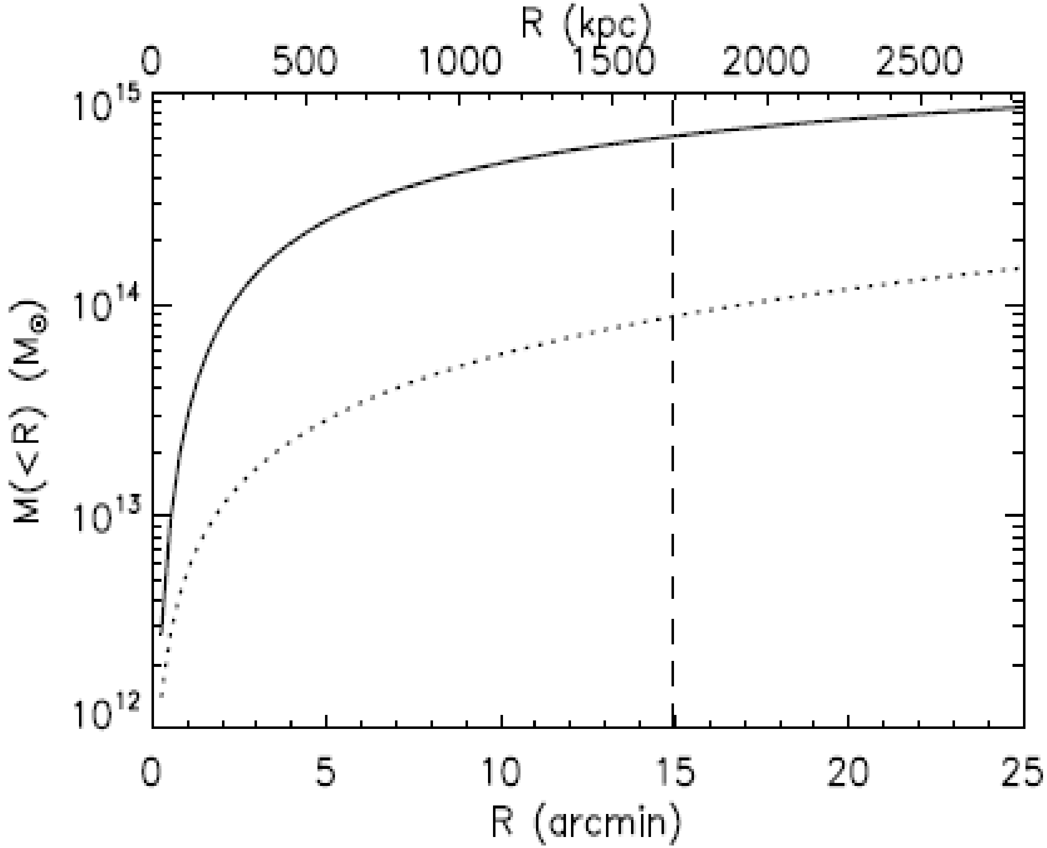


$$r_s = 280^{+50}_{-40}\,kpc$$

$$c_{200} = 6.1^{+0.9}_{-0.8}$$

$$r_{200} = c_{200}\, r_s = 1.69^{+0.06}_{-0.05}\,Mpc$$

$$M_{200} = 6.1^{+0.7}_{-0.6} \times 10^{14}\, M_\odot$$

Schmidt & Allen (2007):

$$M_{200} = 11.8^{+4.70}_{-3.55} \times 10^{14}\, M_\odot$$

Pointecouteau et al. (2005):

$$M_{200} = 10.0^{+1.2}_{-1.2} \times 10^{14}\, M_\odot$$

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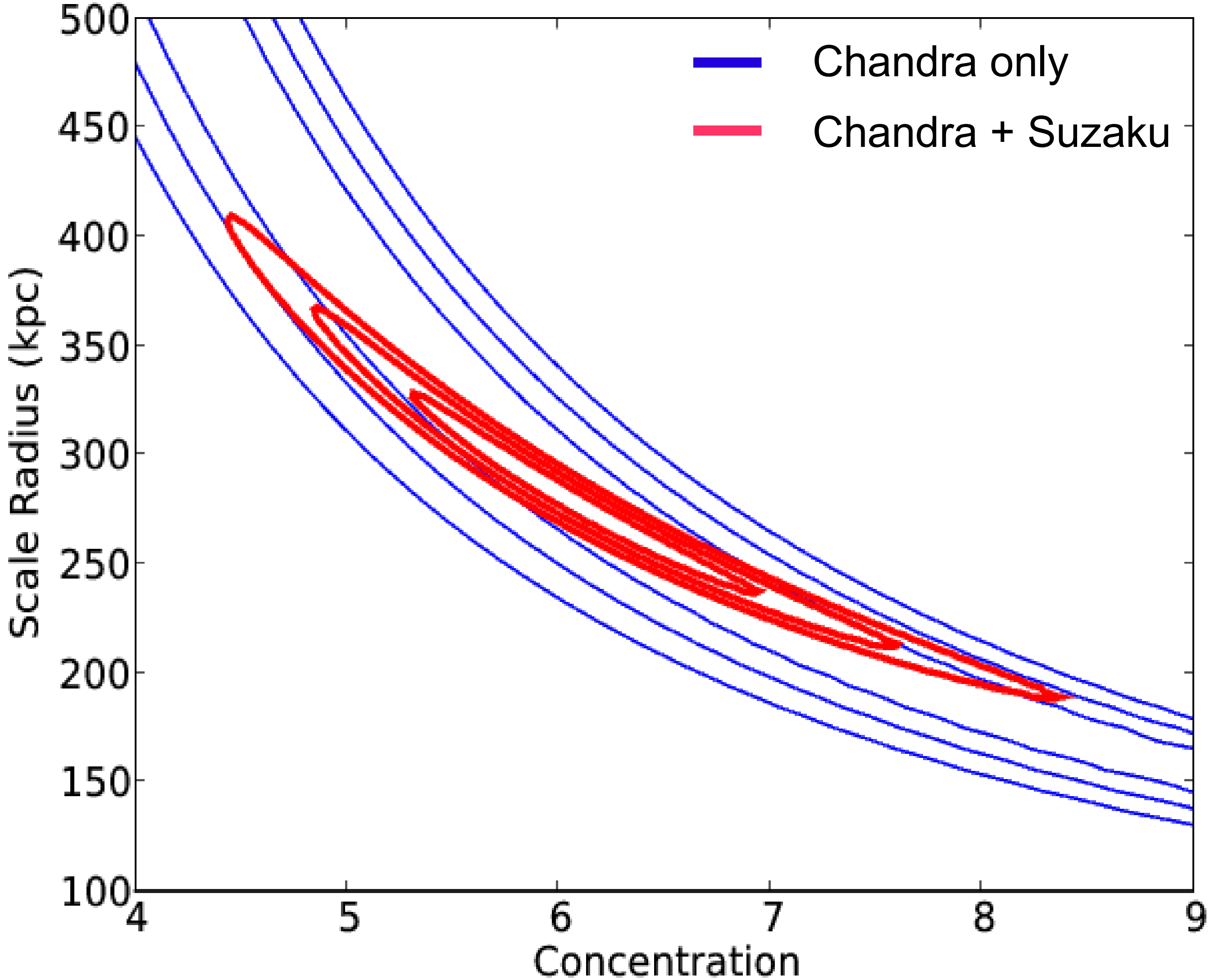


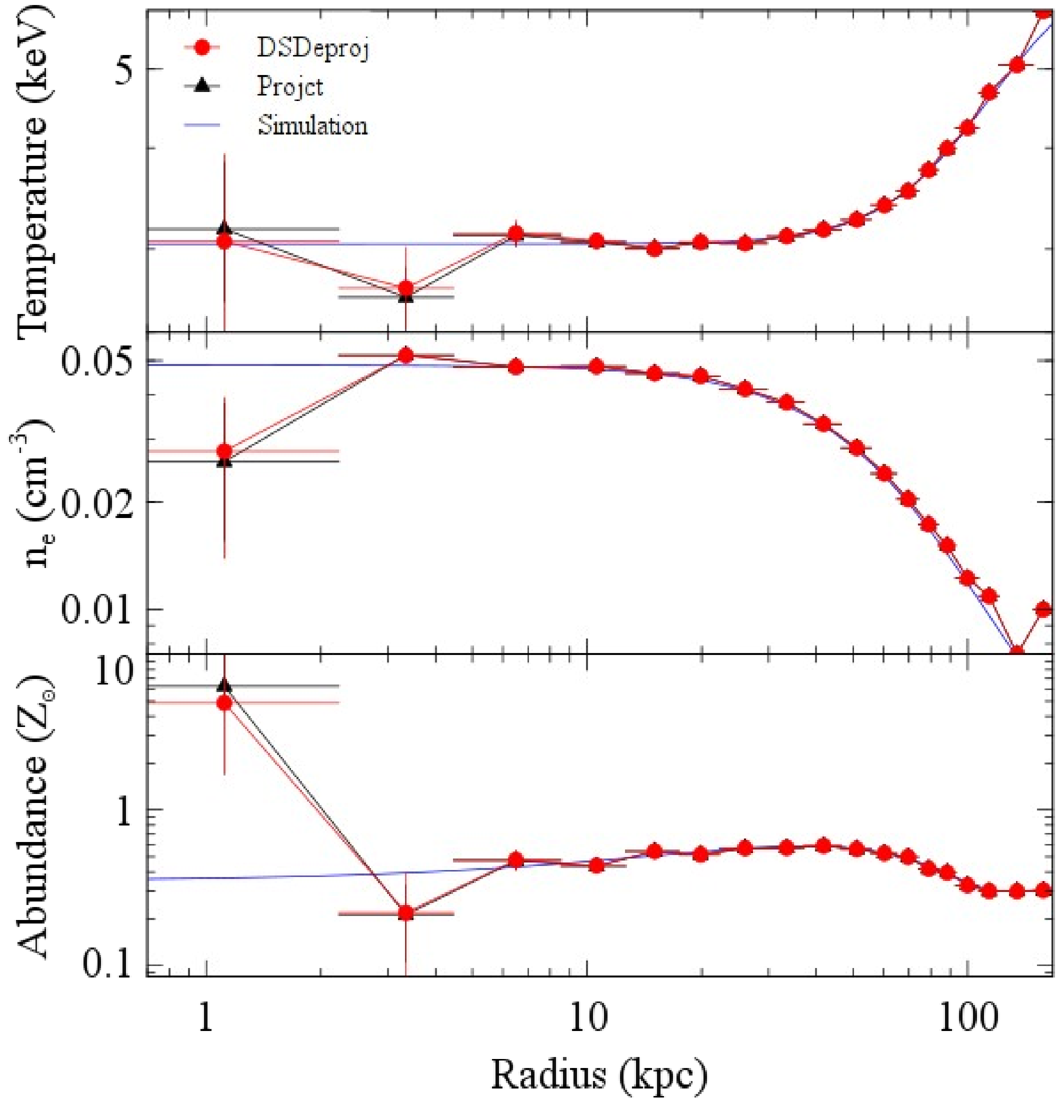
# Summary

- Multi-temperature gas causes unstable, oscillating temperature profiles for model-dependent deprojection routines.
- Model-independent methods can alleviate this problem.
- Assuming hydrostatic equilibrium and NFW profile, can calculate mass profiles for galaxy clusters.
- Cluster observations out to greater radii produce better constrained mass profiles.

DSDeproj is available at: www-xray.ast.cam.ac.uk/papers/dsdeproj

# Non-spherical Cluster

- Cluster stretched by a third along the line of sight.
- Central radial bin is poorly constrained because of residuals from incorrect subtraction of outer layers.

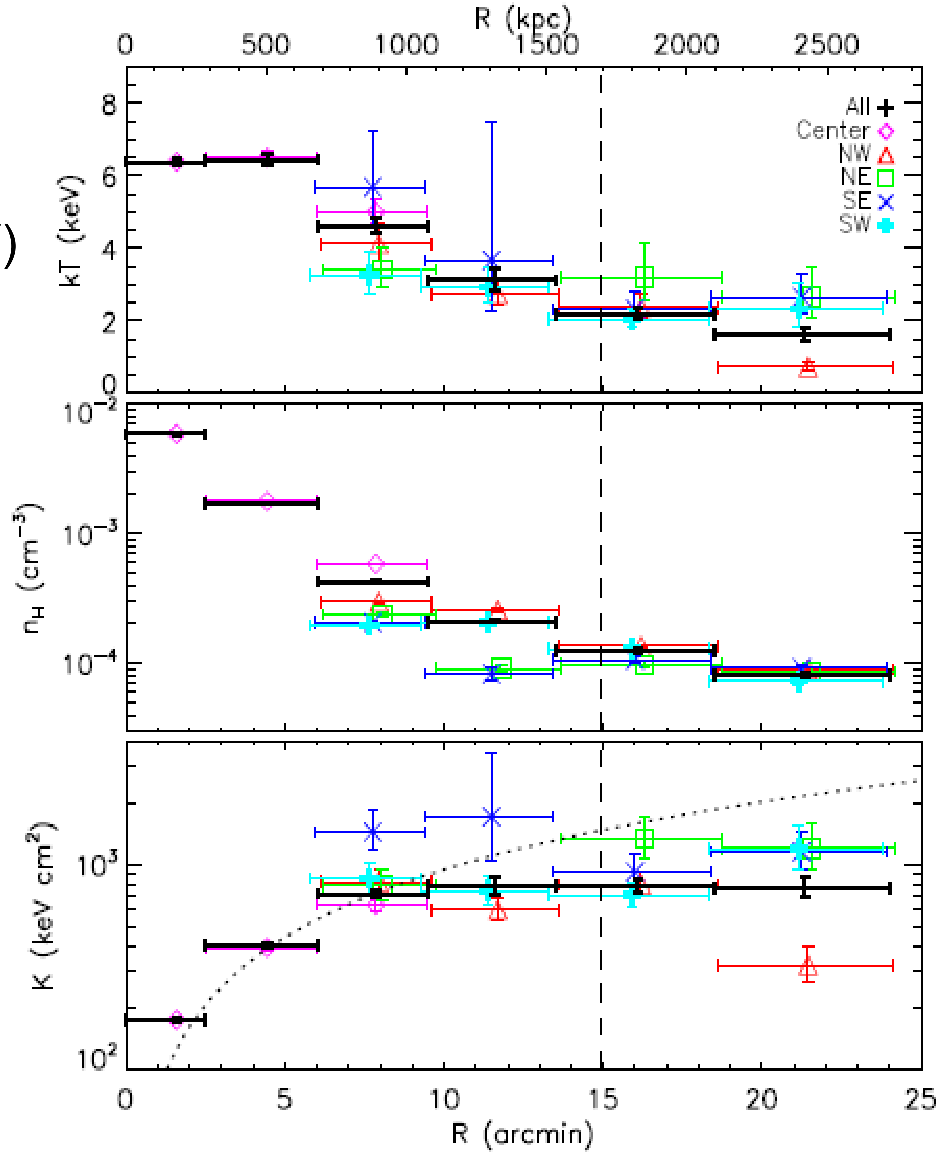


# Non-spherical Cluster

Temperature (keV)

$n_H$ (cm$^{-3}$)

Entropy (keV cm$^2$)

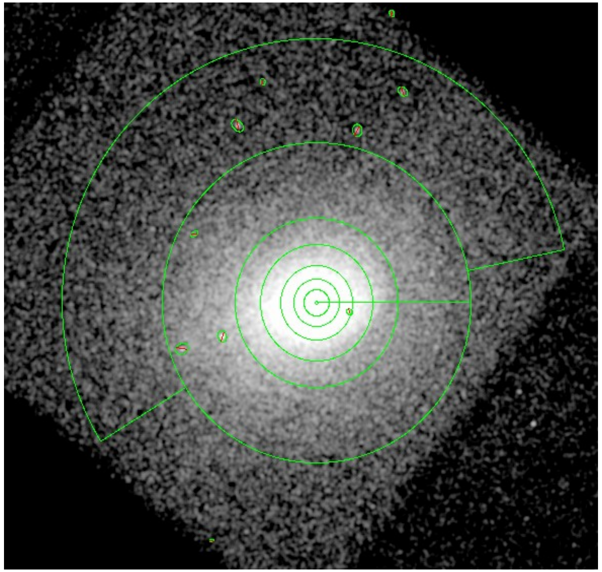


# Error Budget

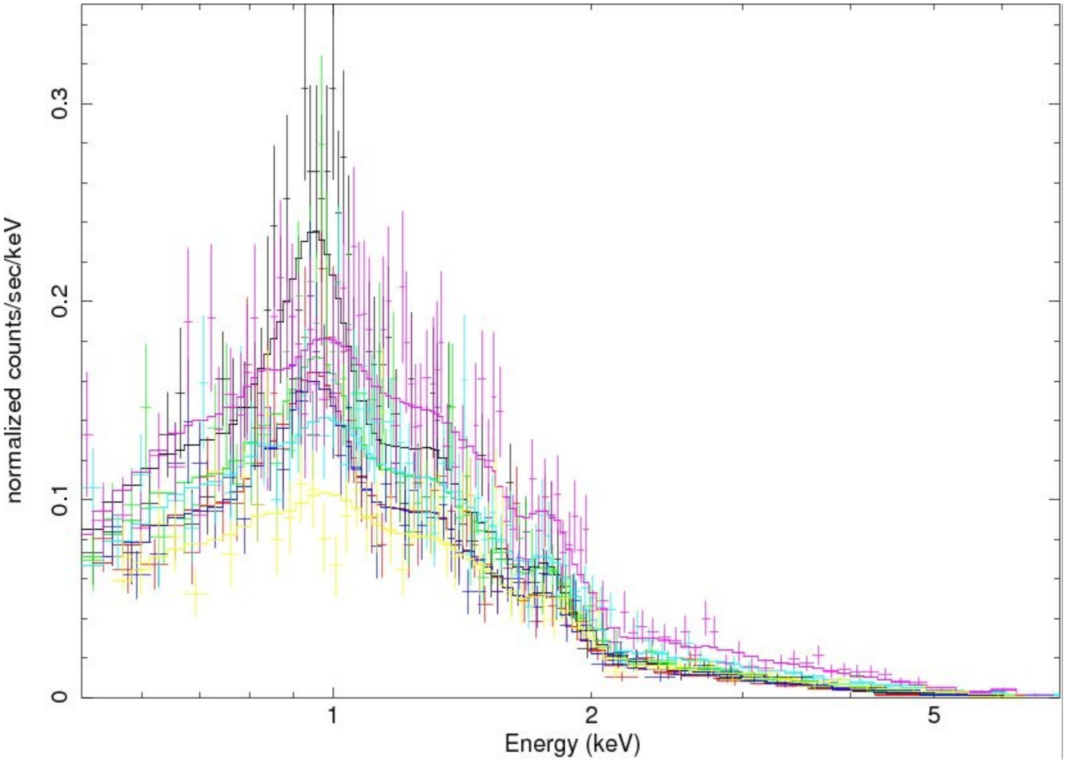
| Radius (′) | kT (keV) | Stat. | No PSF | NXB ±3% | CXB ±10% | Gal. ±50% | $N_H$ ±10% | Z $0.2 - 0.4 Z_\odot$ |
|---|---|---|---|---|---|---|---|---|
| 0–2.5 | 6.30 | $^{+0.10}_{-0.10}$ | +0.08 | < 0.005 | < 0.005 | < 0.005 | 0.59 | < 0.005 |
| 2.5–6.0 | 7.43 | $^{+0.45}_{-0.40}$ | −0.99 | 0.01 | < 0.005 | 0.01 | 0.74 | 0.02 |
| 6.0–9.5 | 4.65 | $^{+0.29}_{-0.26}$ | −0.05 | 0.03 | 0.03 | 0.02 | 0.40 | 0.03 |
| 9.5–13.5 | 3.13 | $^{+0.47}_{-0.38}$ | −0.01 | 0.09 | 0.14 | 0.06 | 0.26 | 0.01 |
| 13.5–18.5 | 2.13 | $^{+0.23}_{-0.21}$ | +0.06 | 0.08 | 0.19 | 0.06 | 0.13 | 0.09 |
| > 18.5 | 1.49 | $^{+0.22}_{-0.18}$ | +0.14 | 0.10 | 0.18 | 0.06 | 0.10 | 0.08 |

**Table 3.** Estimated uncertainties in the radial temperature profile due to removing PSF-corrections or changing normalizations of background components and spectral model parameters within the ranges given. Each parameter is varied independently and we present only the maximum of the upward and downward temperature shifts (in keV) for clarity. Best-fitting PSF-corrected temperatures and their statistical uncertainties are included for comparison.

# Projected Quantities

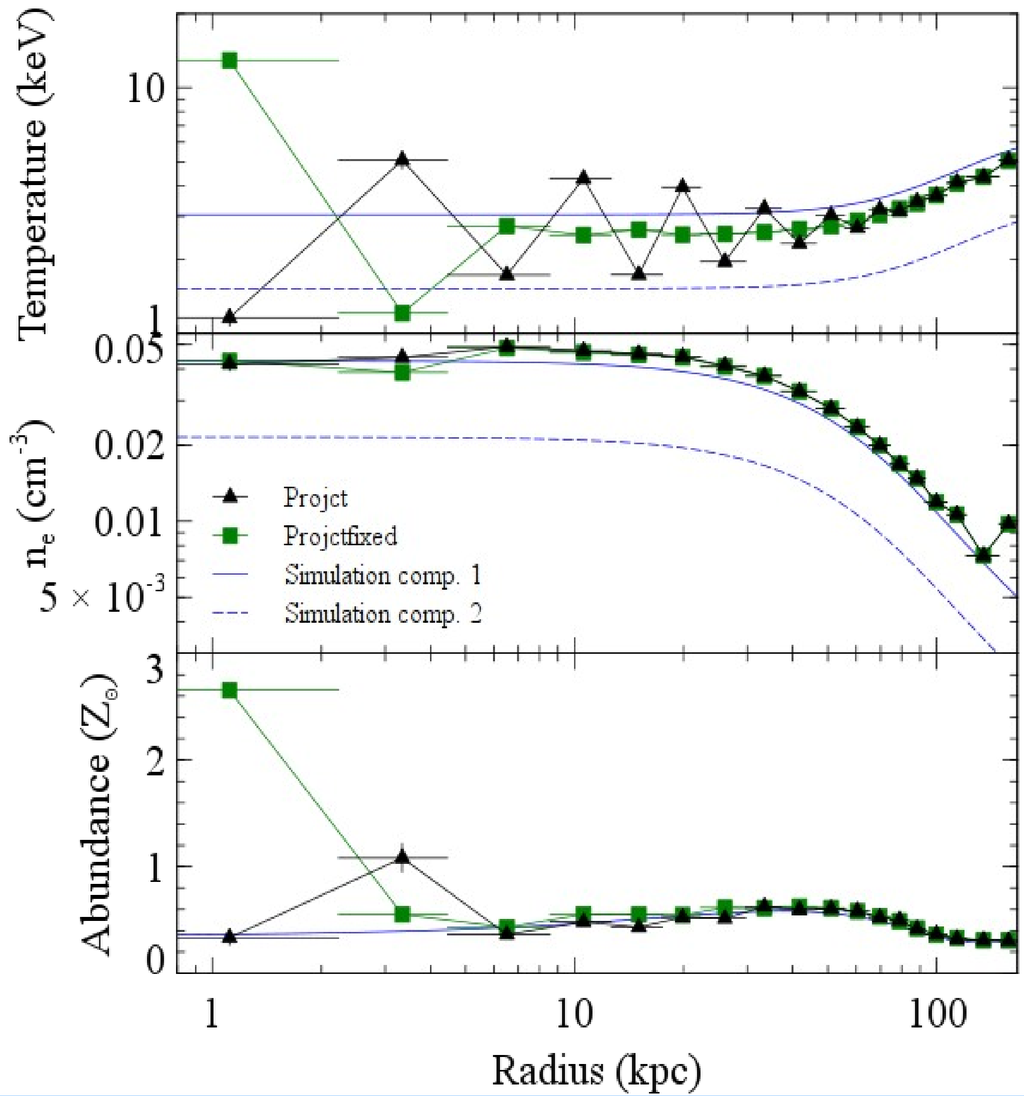


- Determine temperature, density and metallicity in a series of concentric annuli



# Projct

- Sequentially fix parameters from the outside in.
  - Prevents the poorly modelled spectra near the centre affecting the results in the outer annuli
  - Underestimates uncertainties



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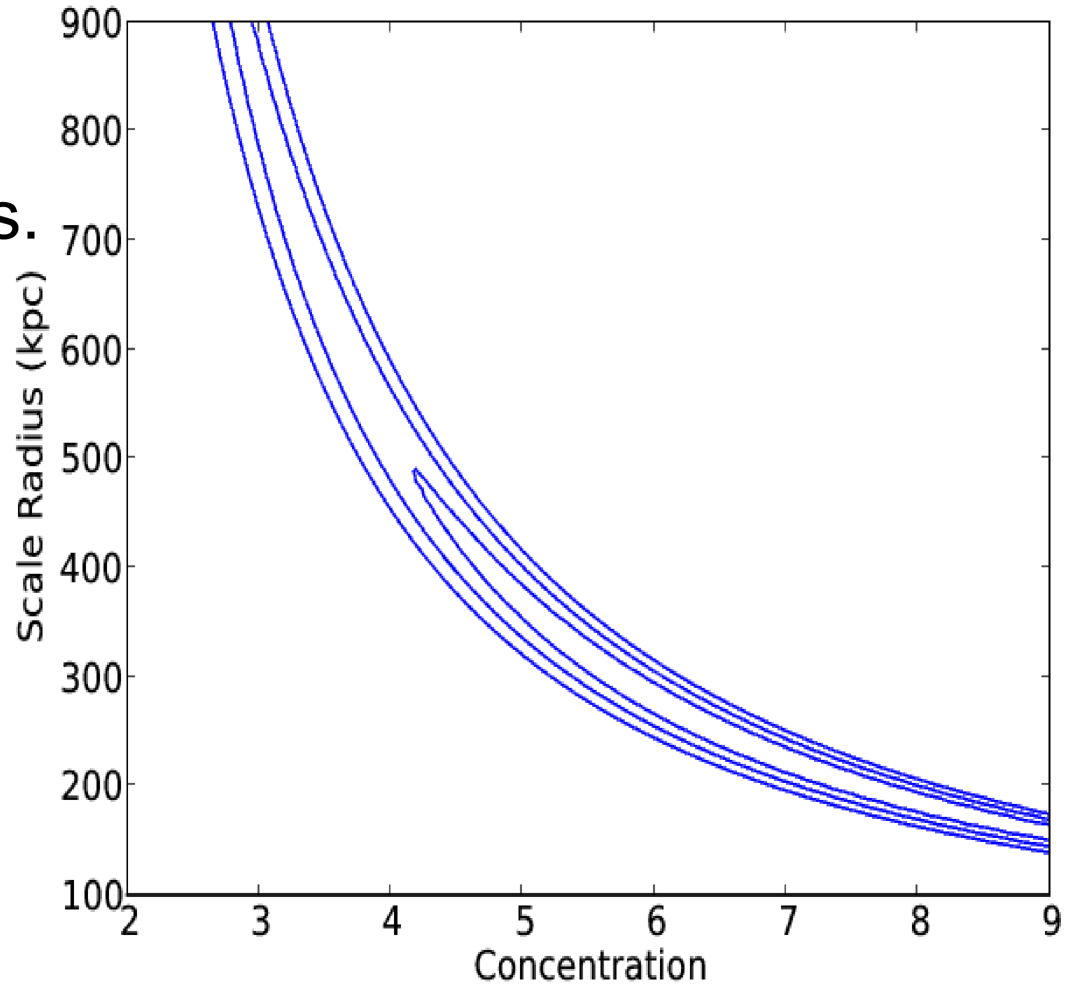


Need profiles **out to larger radii**