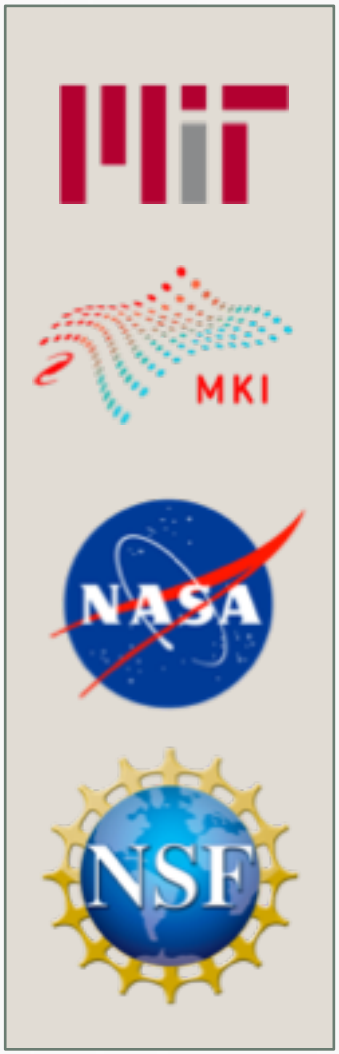
10 Years of Chandra and the South Pole Telescope

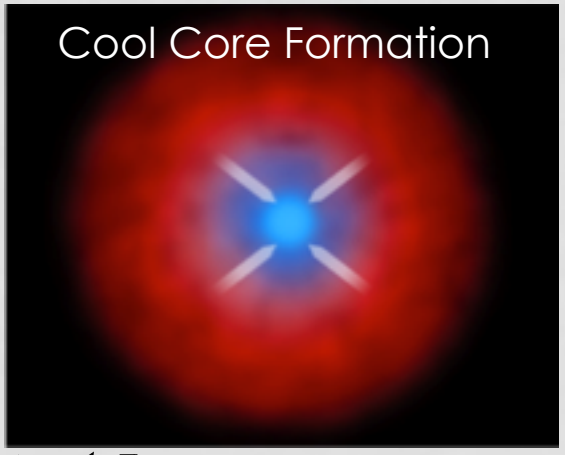
Celebrating 20 Years of Chandra
December 3, 2019

Michael McDonald
Massachusetts Institute of Technology



In collaboration with: The South Pole Telescope Collaboration, M. Bautz (MIT), R. Kraft (CfA), A. Vikhlinin (CfA), B. McNamara (UW), J. Hlavacek-Larrondo (Montreal), A. Edge (Durham), and many others!

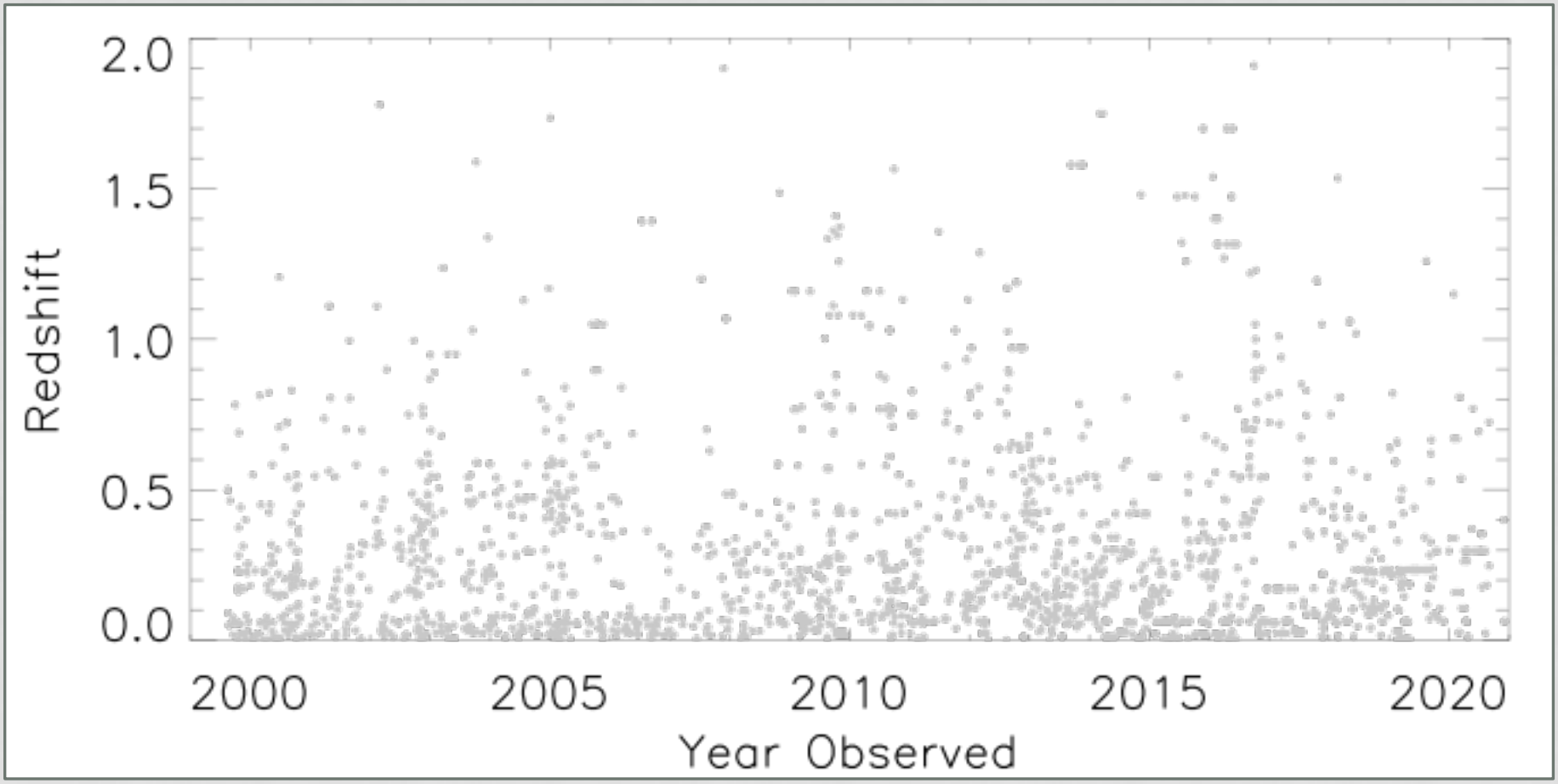
Timing of Major Milestones Remain Uncertain



$z > 3$ $z \sim 2.5$ $z \sim 1.5$

$z \sim 3$ $z \sim 2$ $z \sim 1$

Observing Galaxy Clusters w/ Chandra



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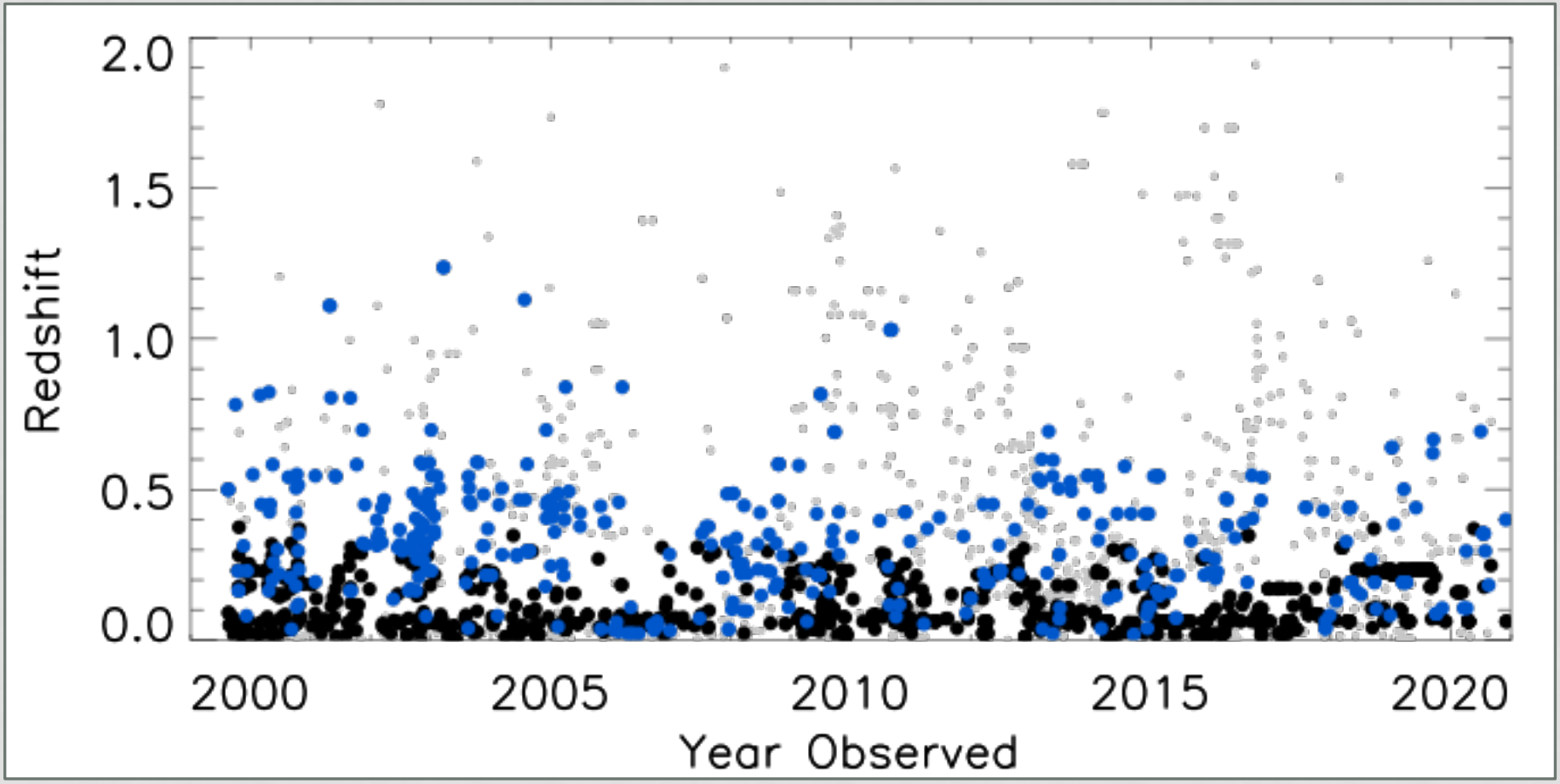

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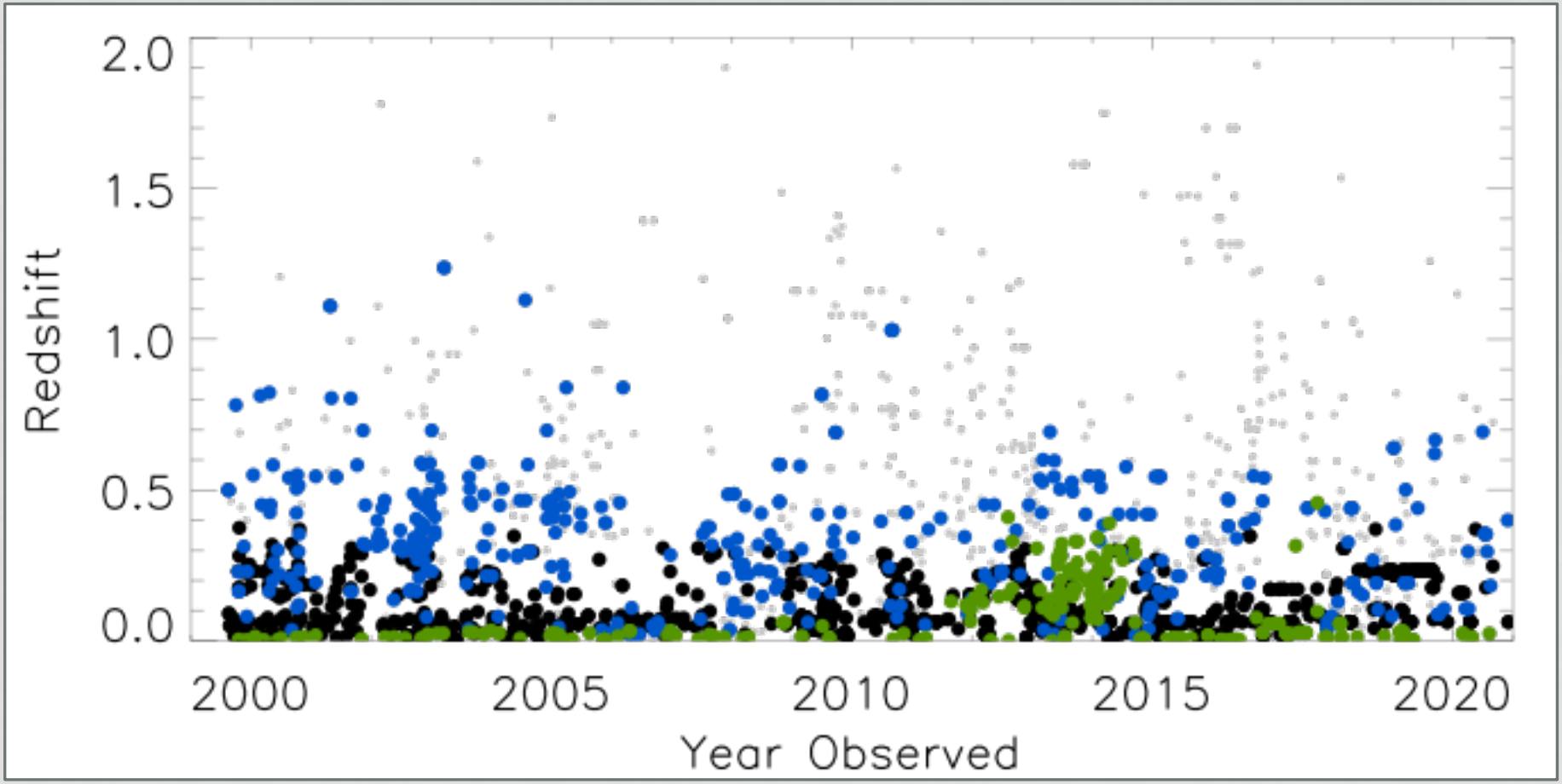

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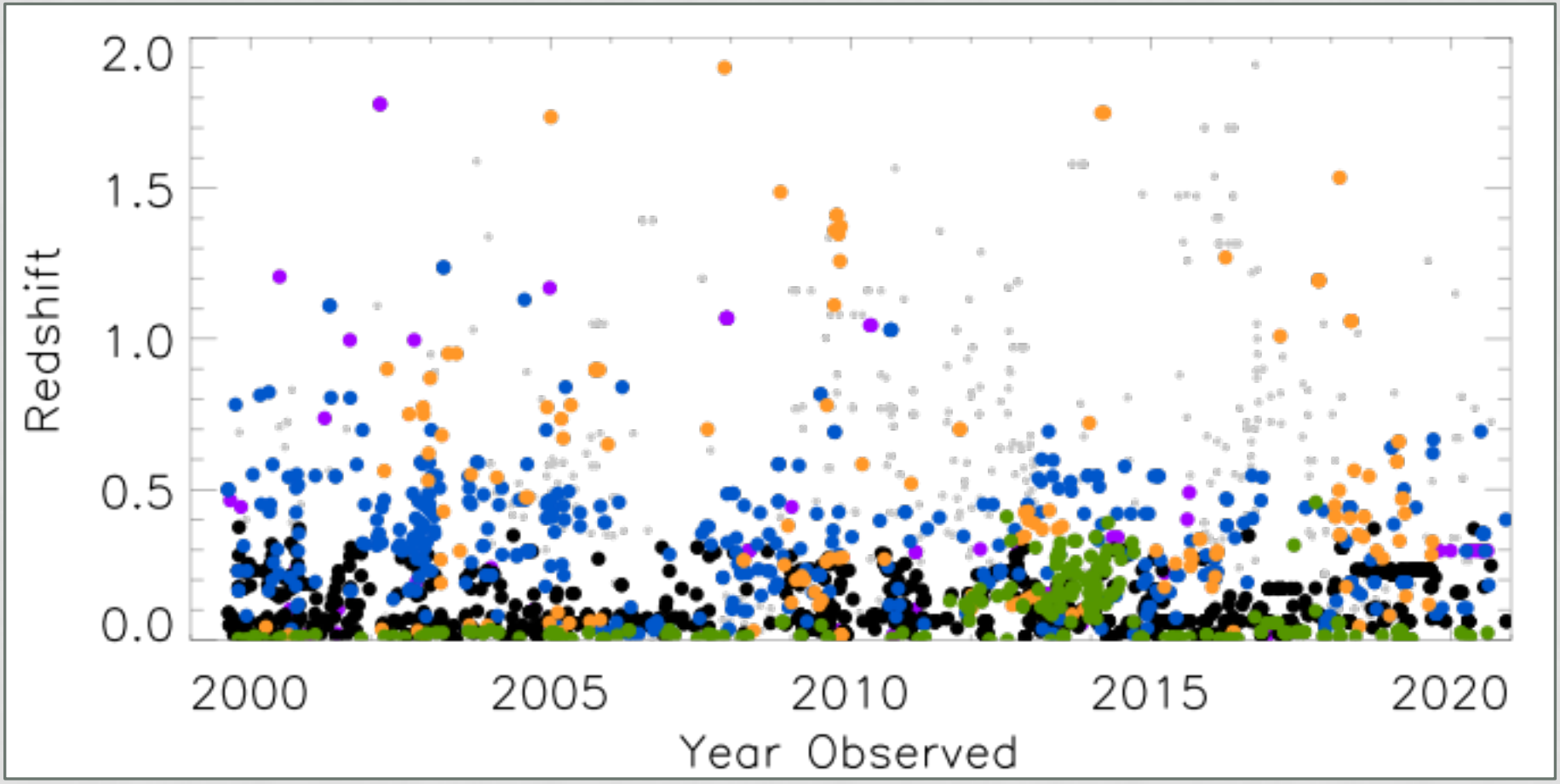

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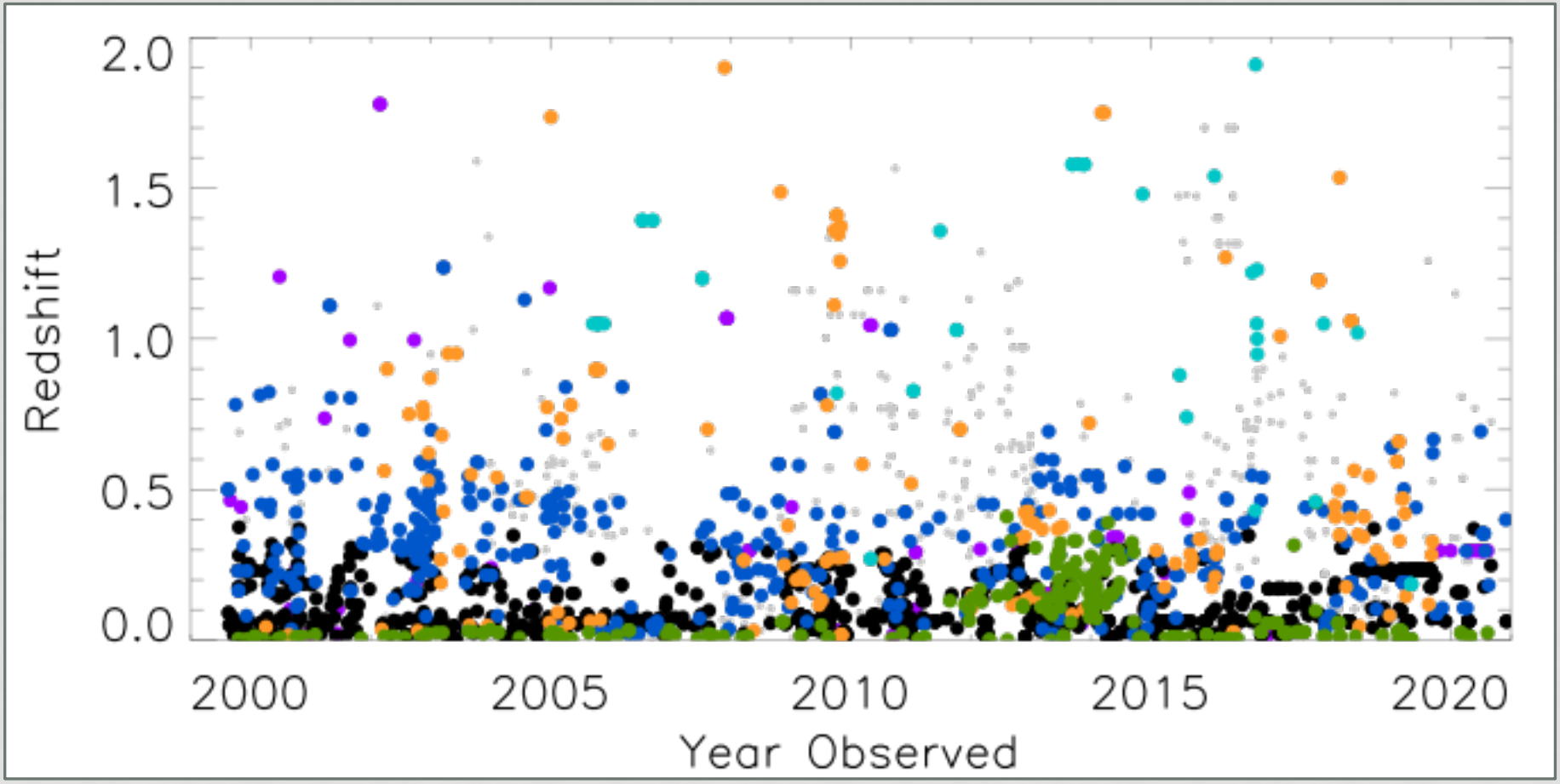

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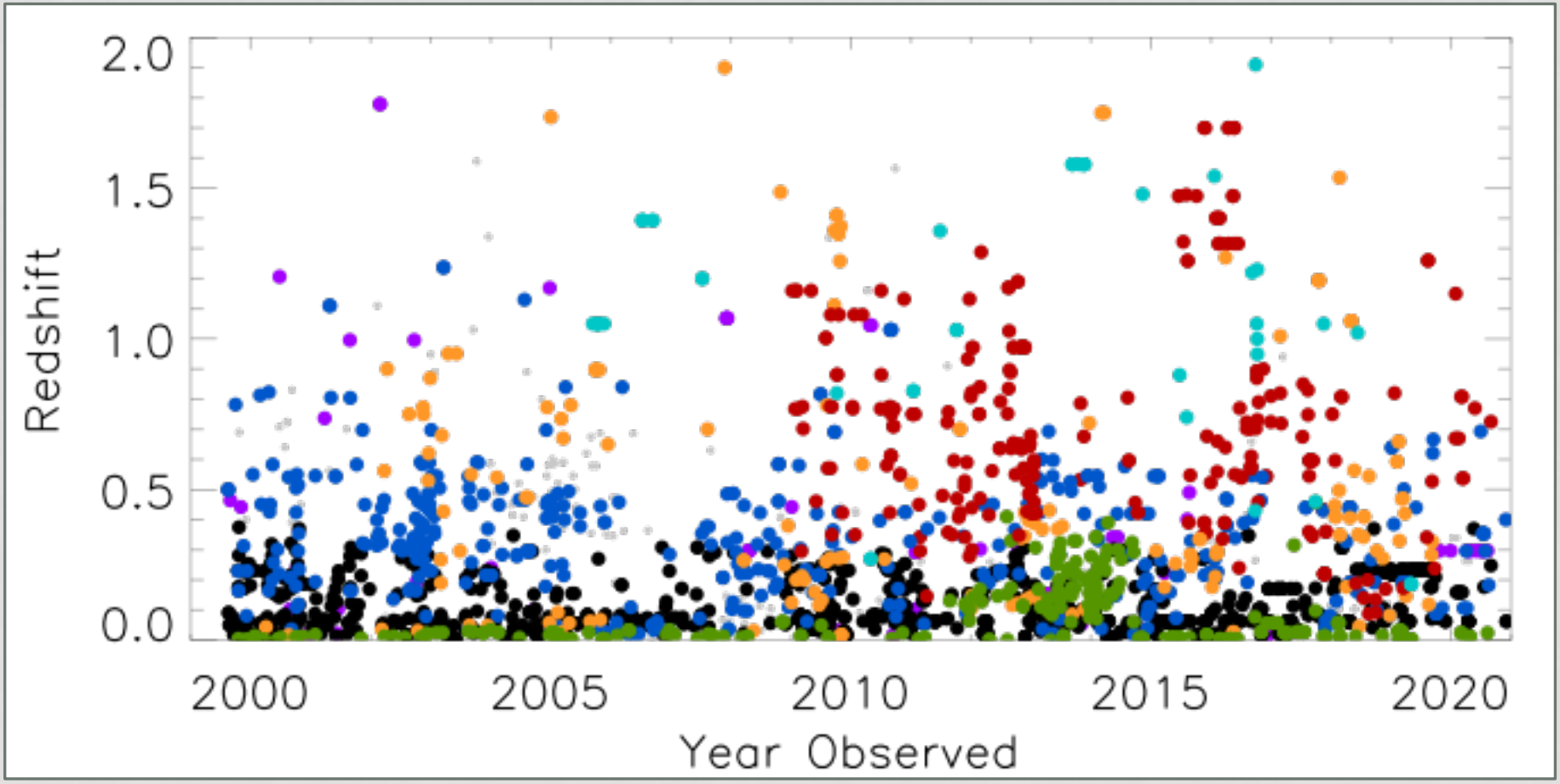

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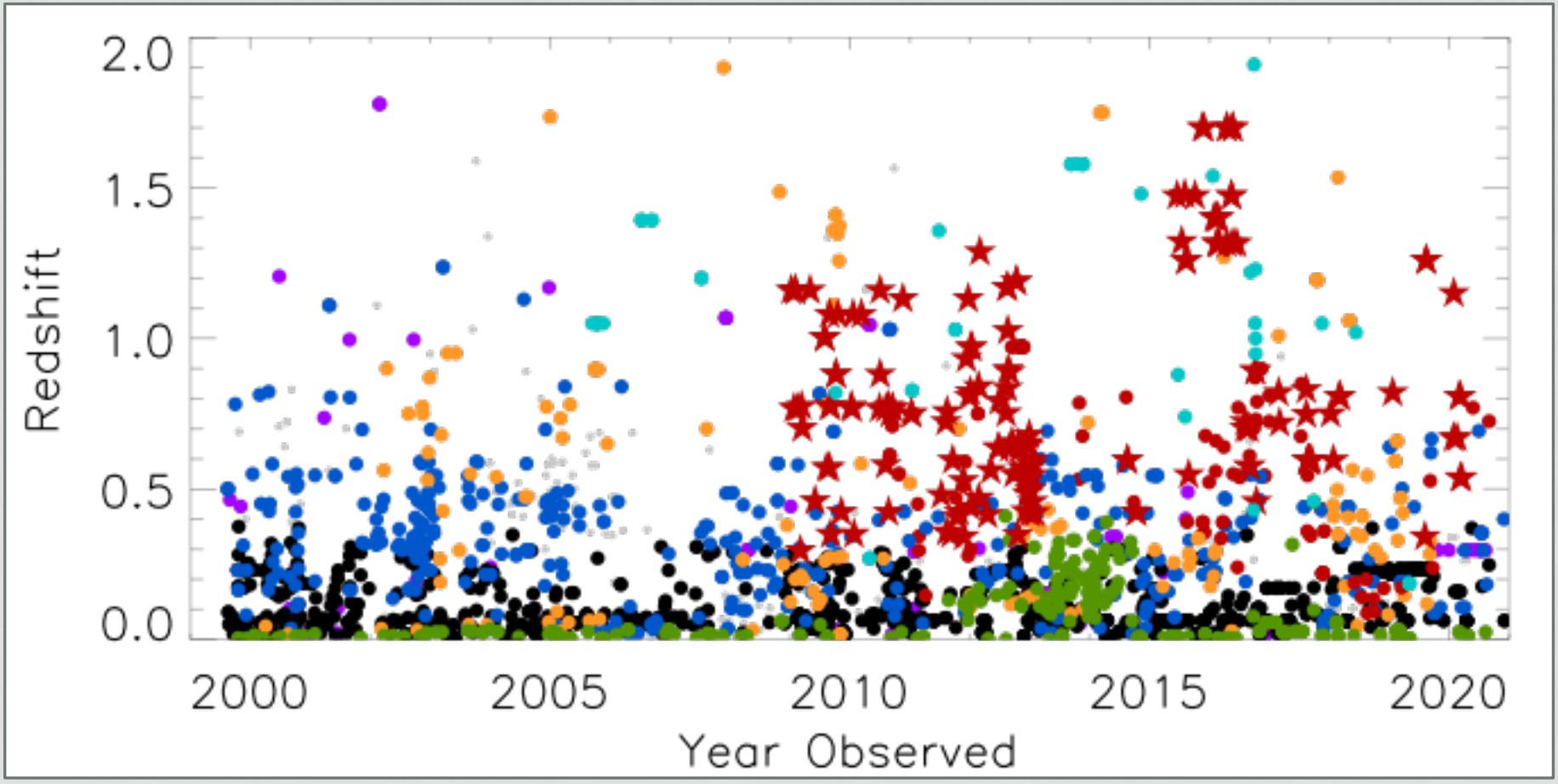
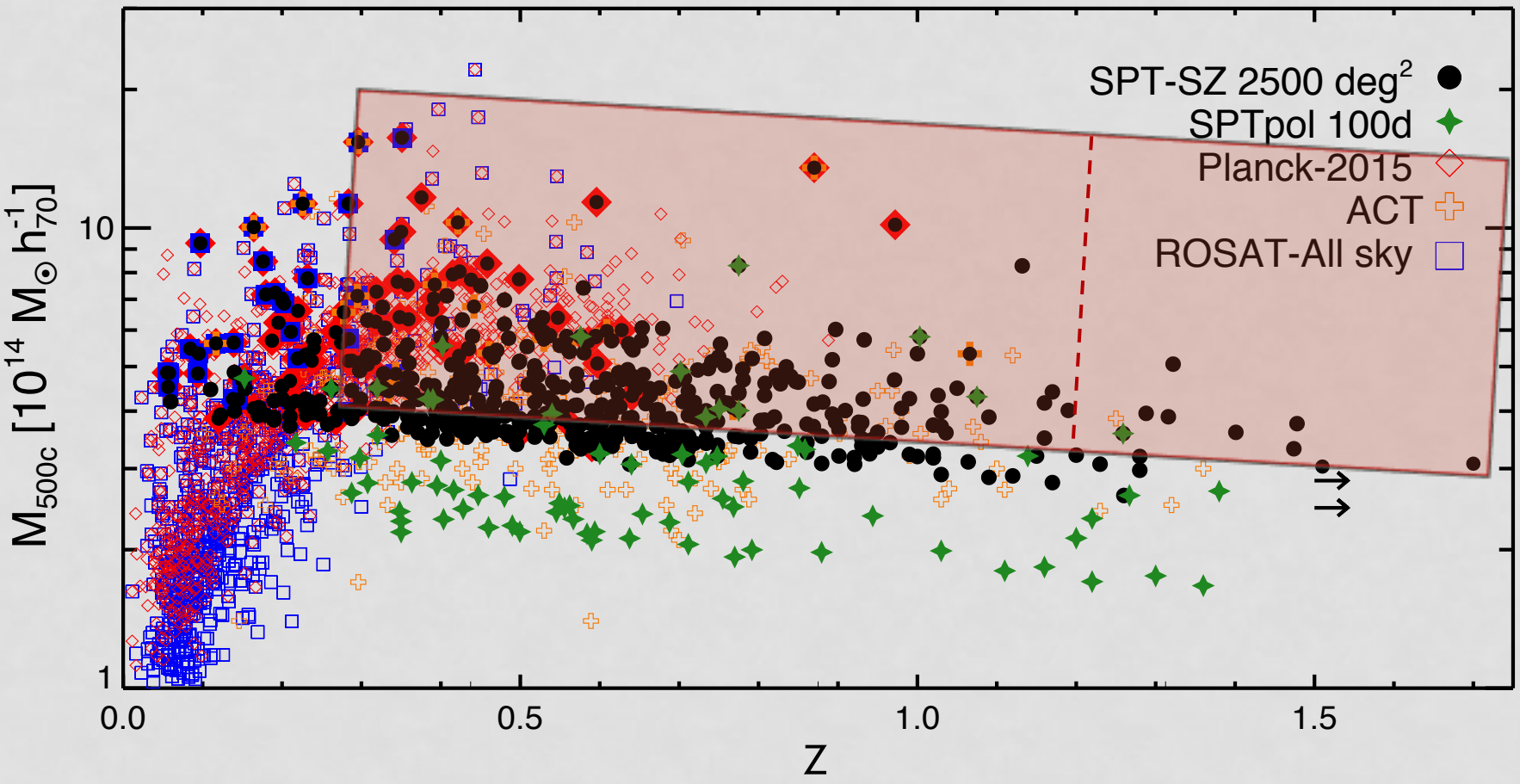
- South Pole Telescope



SPT-Chandra: 10 Years of Follow-up



From 2010-2019:

5.0 Ms GO (XVP + 5 LPs), 2.3 Ms GTO (ACIS+HRC)

>50% of all Chandra observations of clusters @ z > 0.5 were SPT-selected

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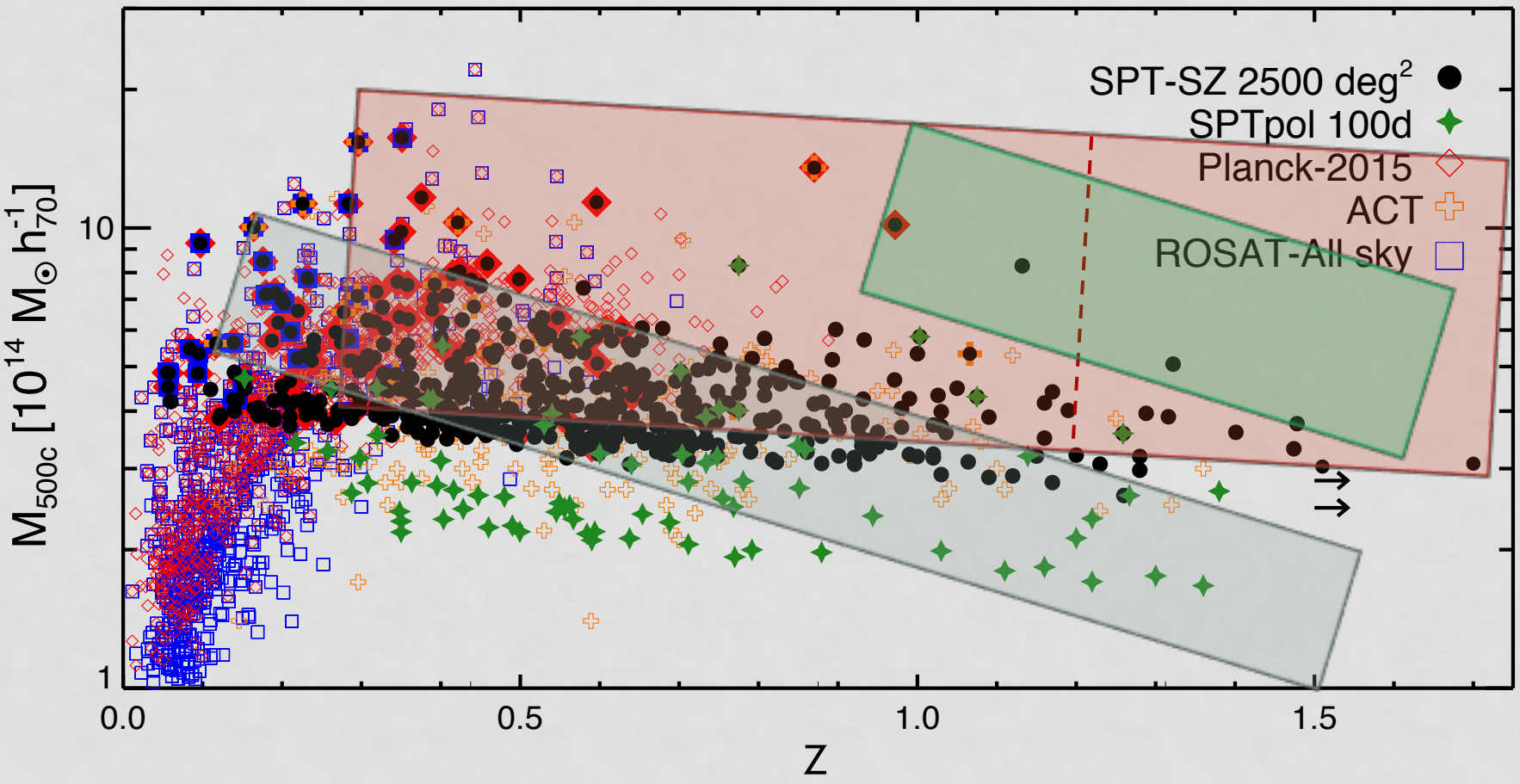

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What Have we Learned Since 2010?

ICM Evolution

- **Radio-mode AGN feedback ongoing and regulating cooling since z ~ 1** *(Hlavacek-Larrondo+15, Gupta+17,19, Calzadilla+19)*
- **Universal pressure profile evolves in core** *(McD+14, Ghirardini+20)*
- **SZ selection is relataively unbiased** *(Lin+15)*
- **Cool cores haven't evolved since z ~ 1** *(Semler+12, McD+13,17)*
- **Cool cores may have started forming at z ~ 1.5** *(McD+17)*
- **Self-similar evolution broken in cluster cores** *(McD+19, Ghirardini+20)*
- **Cooling flows can happen, but it's rare** *(McD+12,13,14,15,19)*
- **Metal content of ICM unchanged since z ~ 1** *(McD+16, Mantz+17)*
- **ICM morphology only weakly dependent on redshift** *(McD+17)*

Galaxy Populations

- **Baryon content is fixed since z > 1** *(Chiu+16,18)*
- **Environmental quenching already there at z~1.5** *(Strazzullo+19)*
- **The red sequence fades at z > 0.6** *(Hennig+17)*
- **Velocity segregation & dynamical friction** *(Bayliss+16a,b)*
- **BCGs were significantly more star-forming at z ~ 1** *(McD+16)*

Cosmology / Scaling relations

- **Cosmology constraints** *(Benson+13, de Haan+16, Bocquet+19)*
- **CMB lensing** *(Baxter+15)*
- **Galaxy lensing** *(High+12, Chiu+16, Schrabback+16)*
- **X-ray scaling relations** *(Saliwanchik+15, Saro+16,Benson+20)*

~40 SPT publications (~2000 citations) utilizing data in ~10 years

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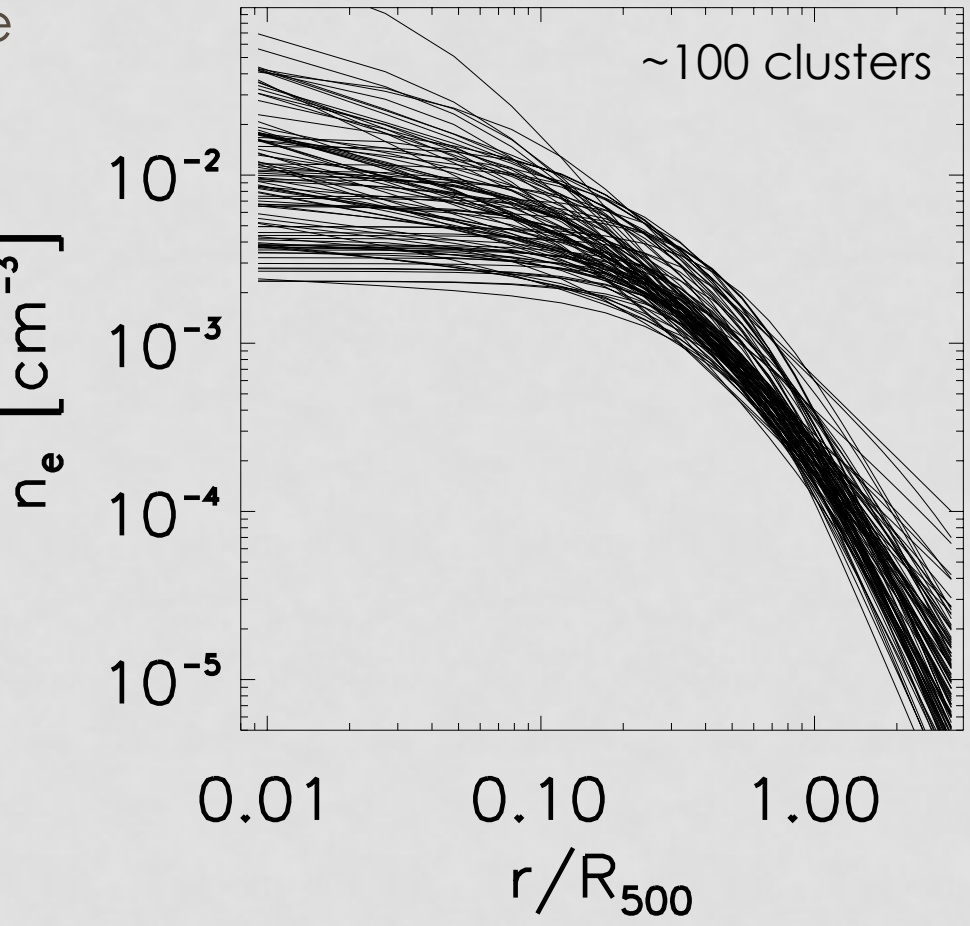
Evolution of ICM Density Profiles

- Consider redshift dependence of density at fixed radius



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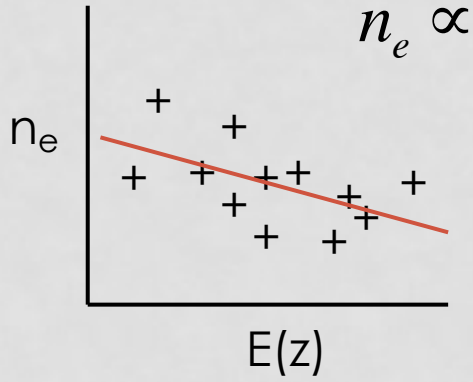
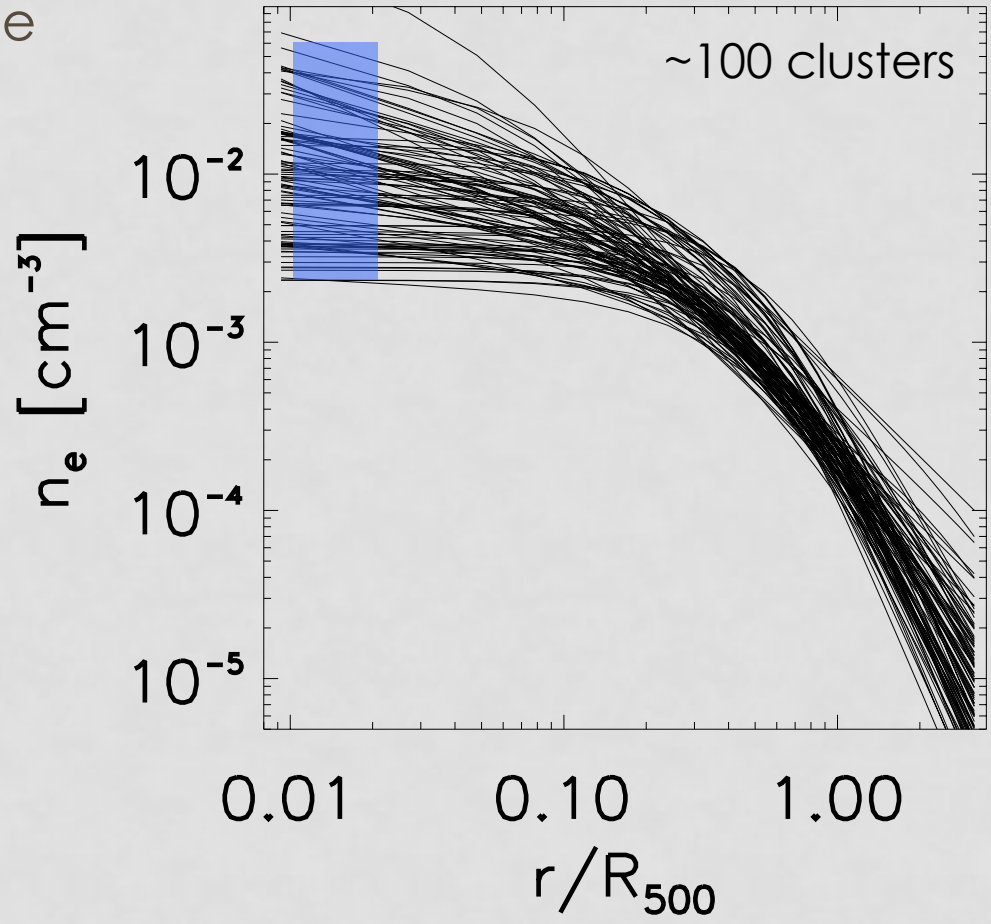
$$n_e \propto E(z)^C$$





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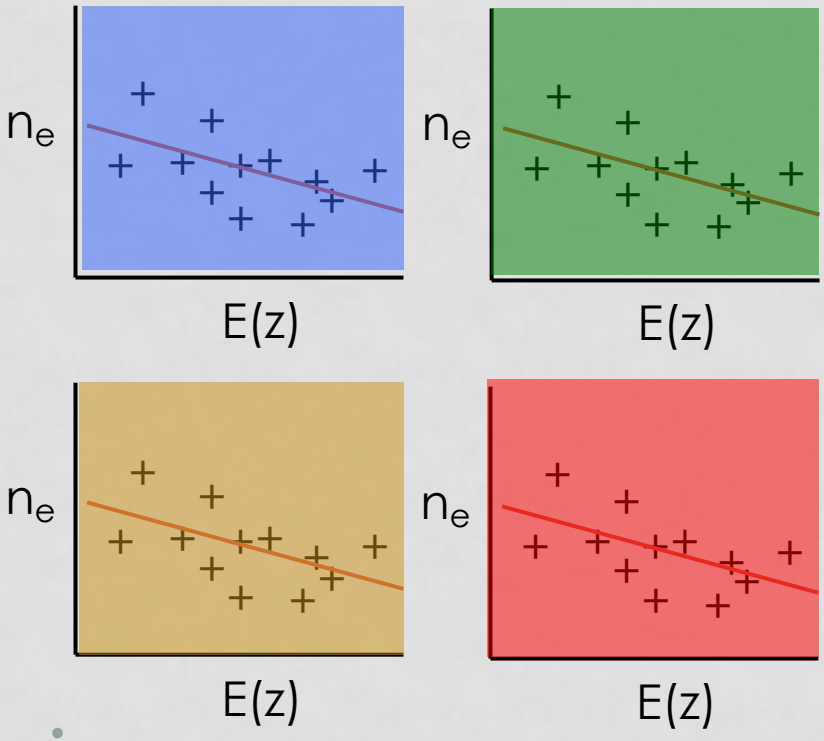
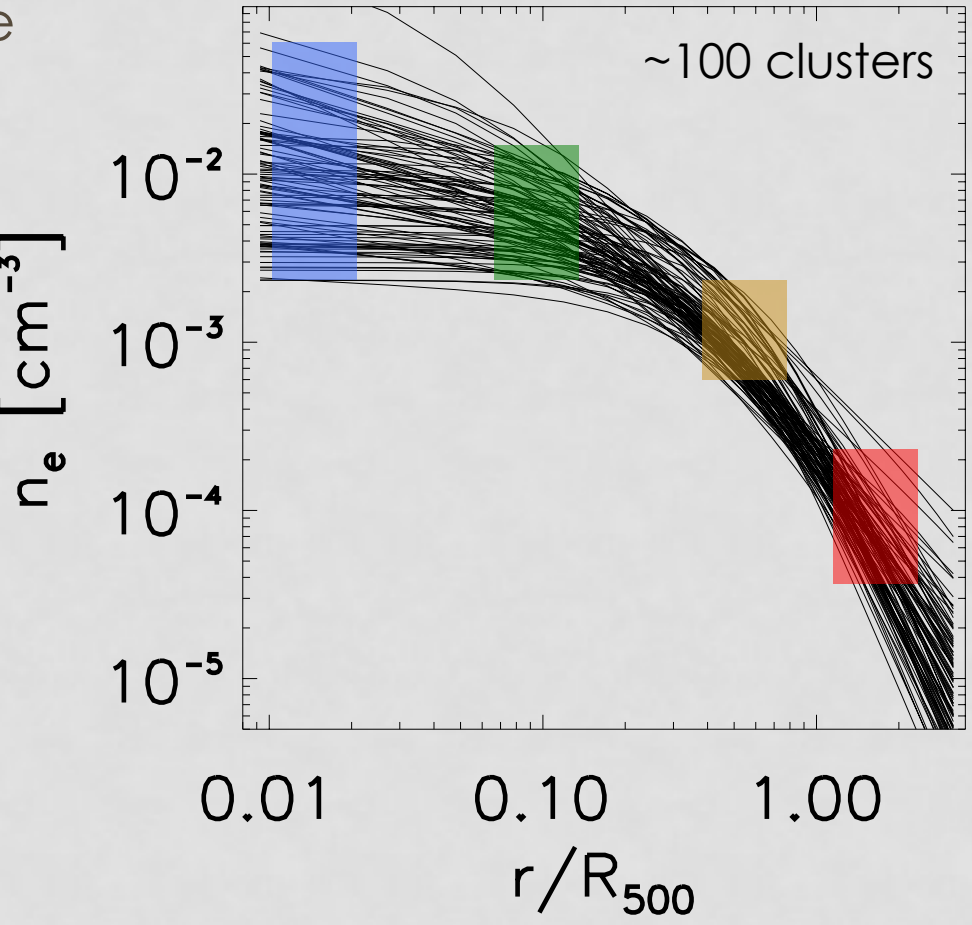




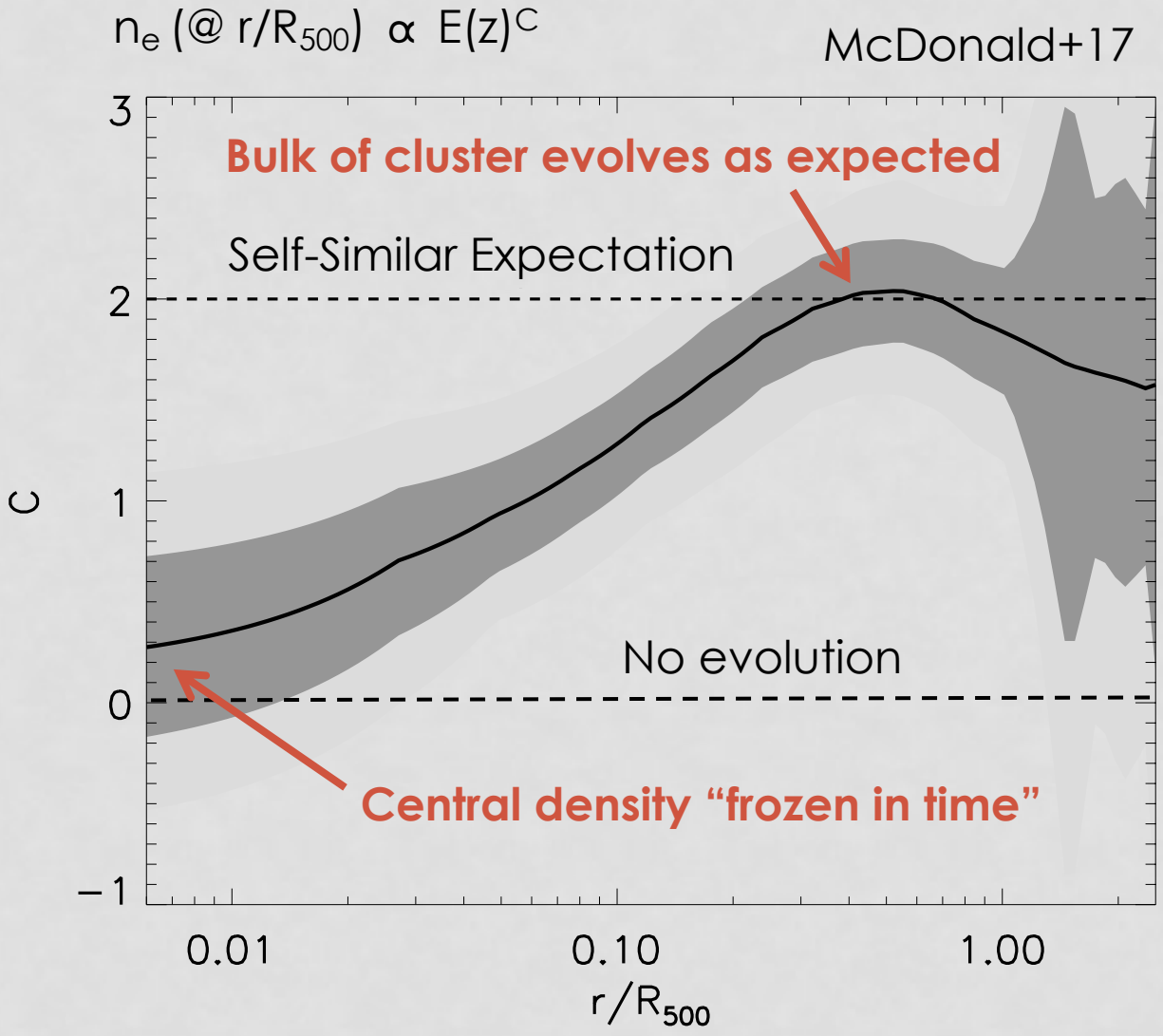
- Ask, how does redshift dependence vary with radius?

$$n_e(r/R_{500}) \propto E(z)^C$$

Deviations from Density Self Similarity

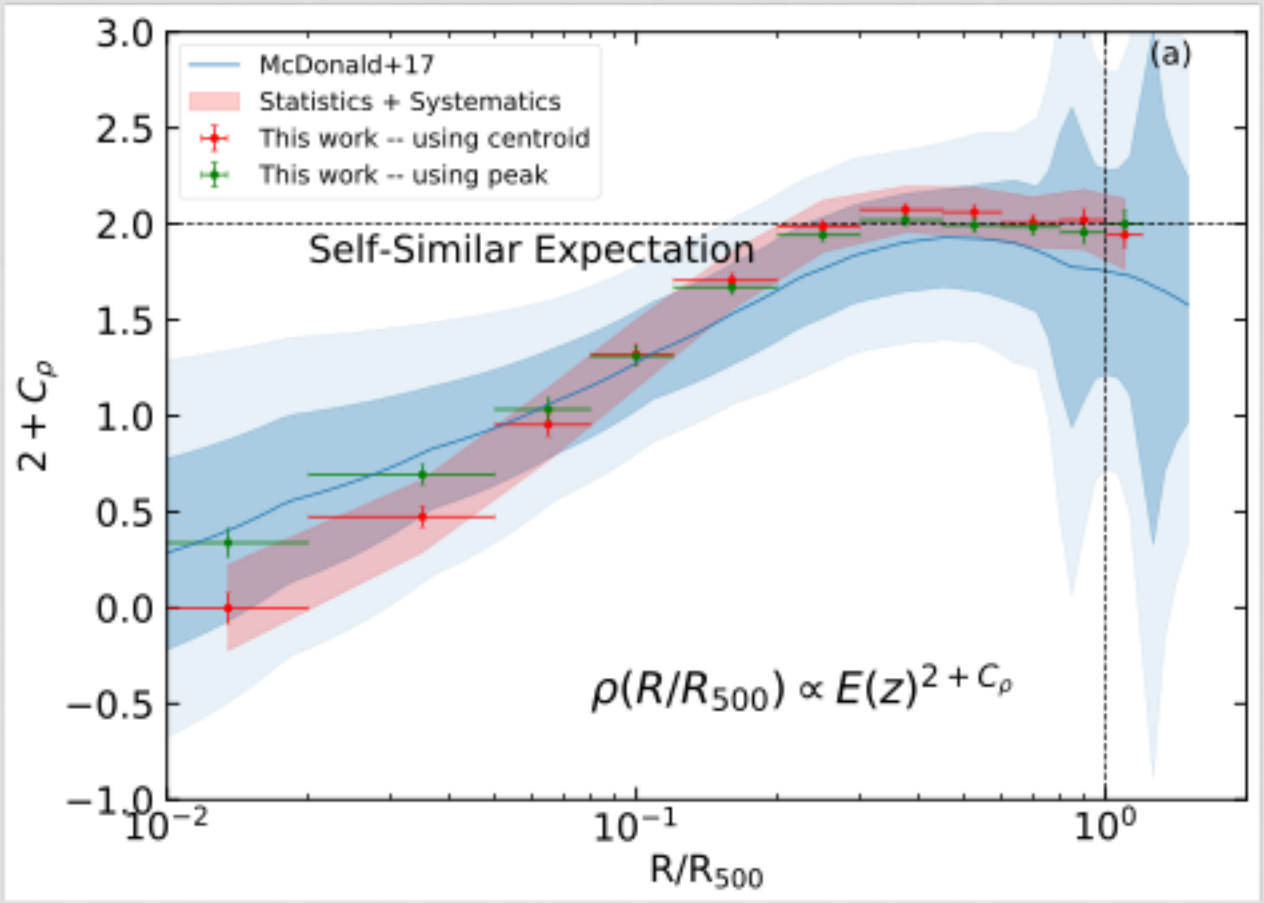
- At large radii, ICM density profile is well-described by gravitational collapse
- At small radii, no apparent redshift evolution in gas density

Dominant physics transitions from gravity (large radii) to feedback (small radii)



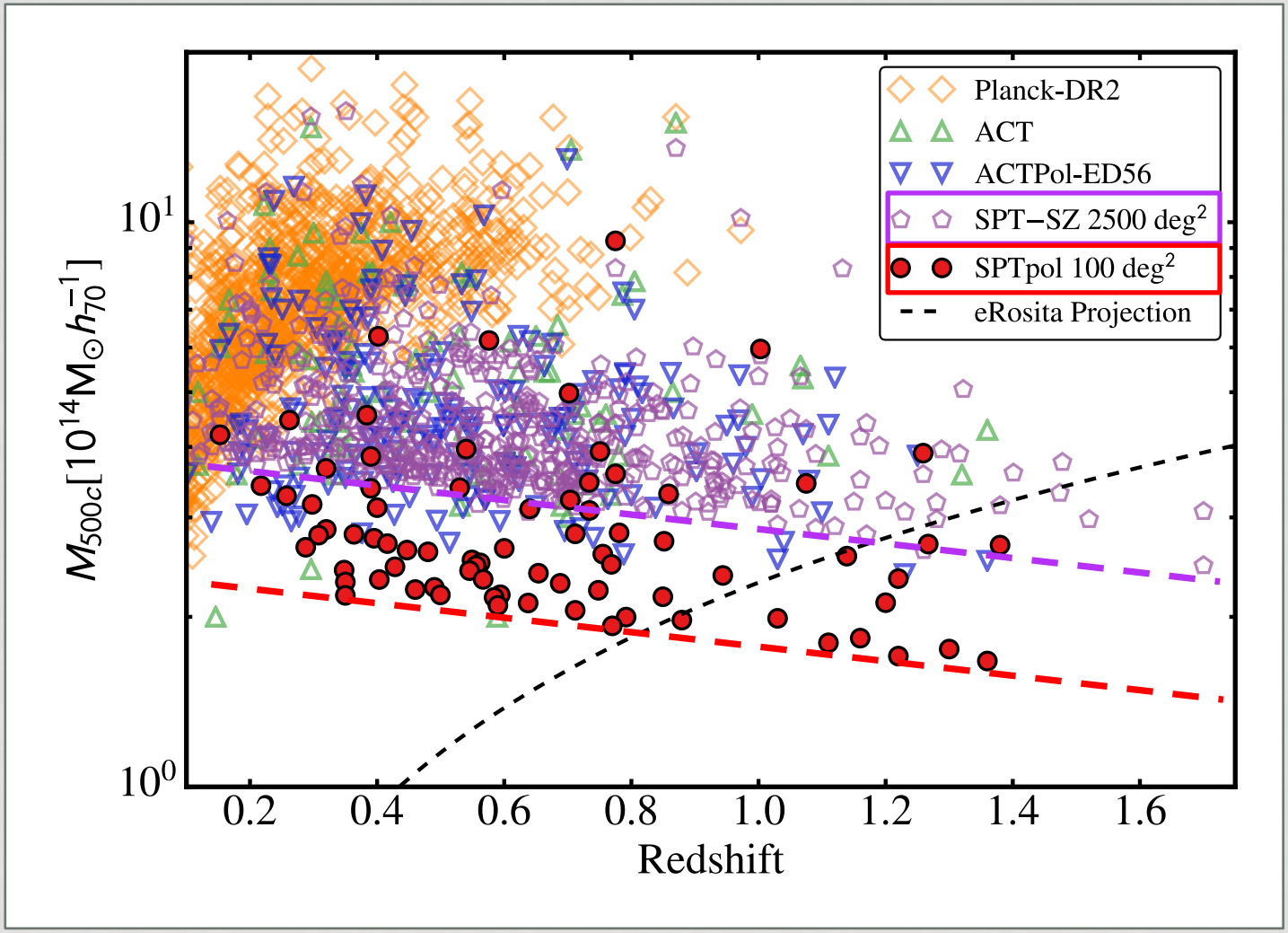
Deviations from Self Similarity

- Density profile evolves self-similarly at large radius
- No measurable evolution within cool core
- Dominant physics transitions from gravity (large radii) to feedback (small radii)



Ghirardini et al. 2019ish

What's Next?



SPTPol (Huang+19)

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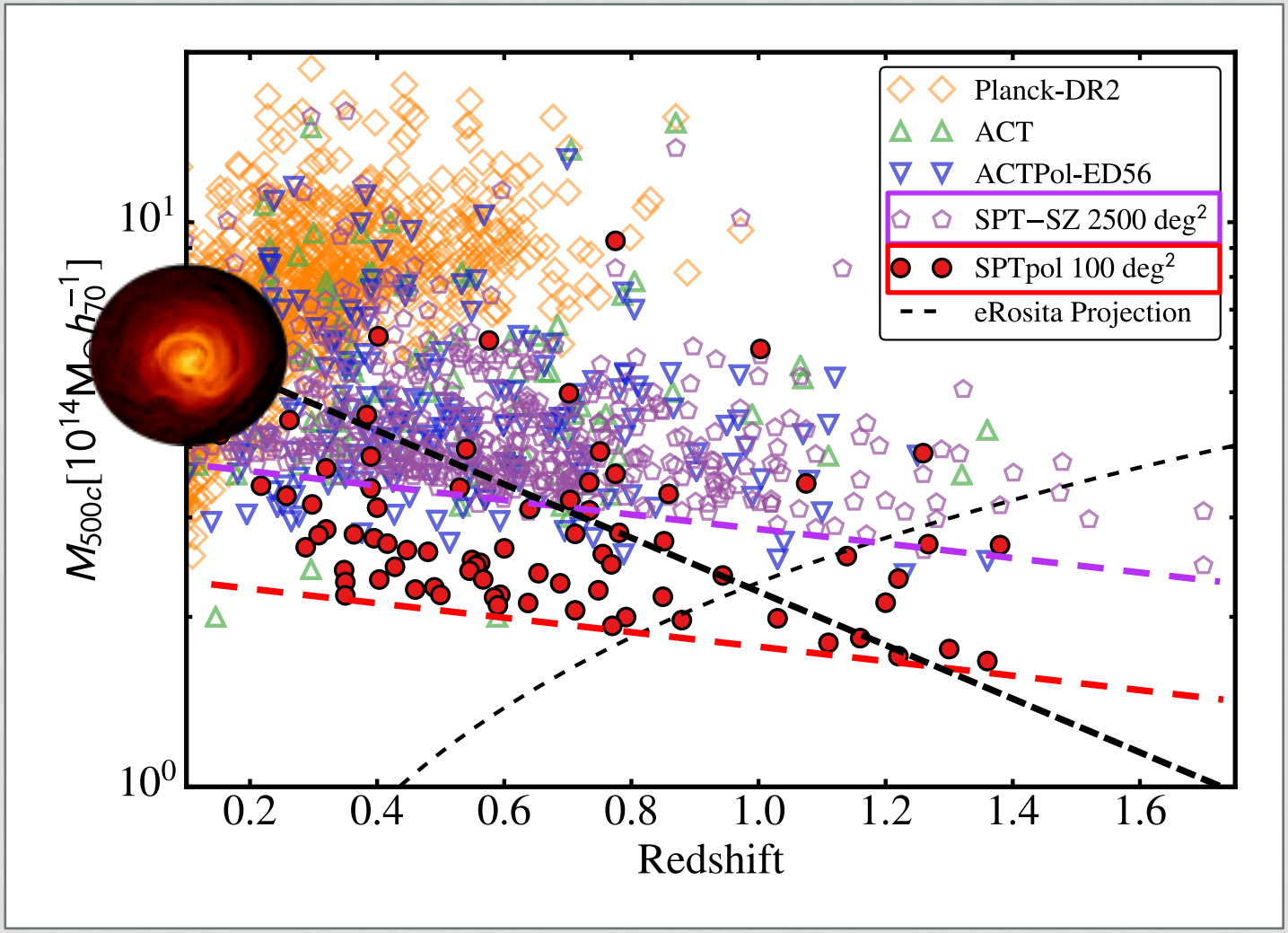

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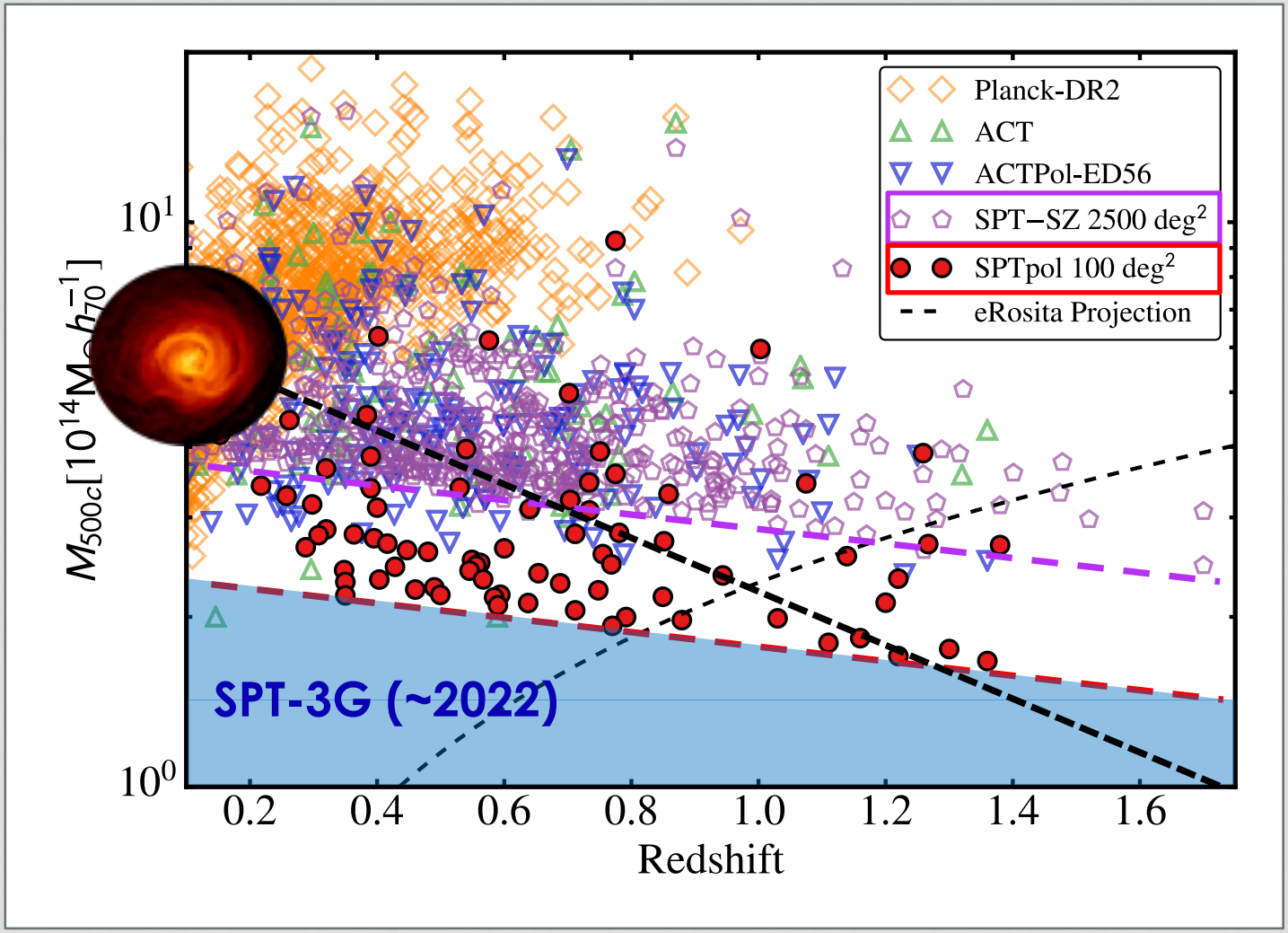
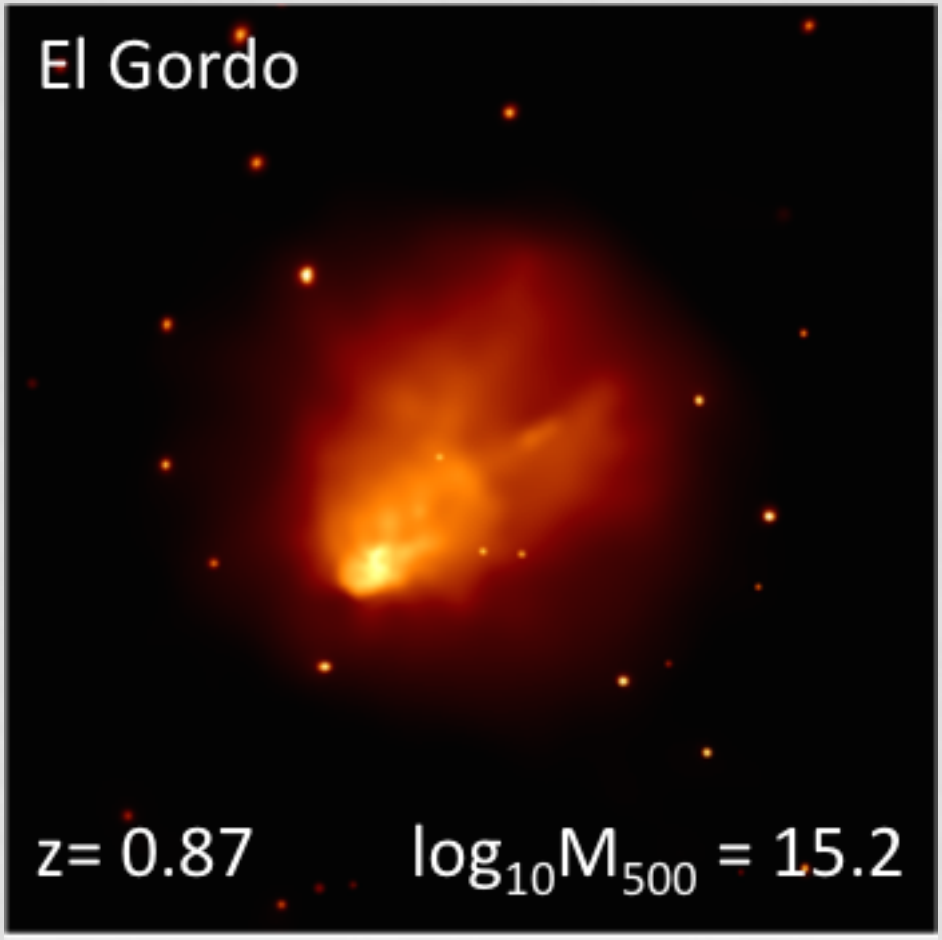


SPT3G (Benson+14)

The Progenitors of Perseus @ z ~2

- At *current* ACIS contamination levels:
  - $M_{500} \sim 10^{14} M_{\odot}$, $z \sim 2$ → $f_X \sim 0.0004$ cts/s (~100 counts in 250ks)



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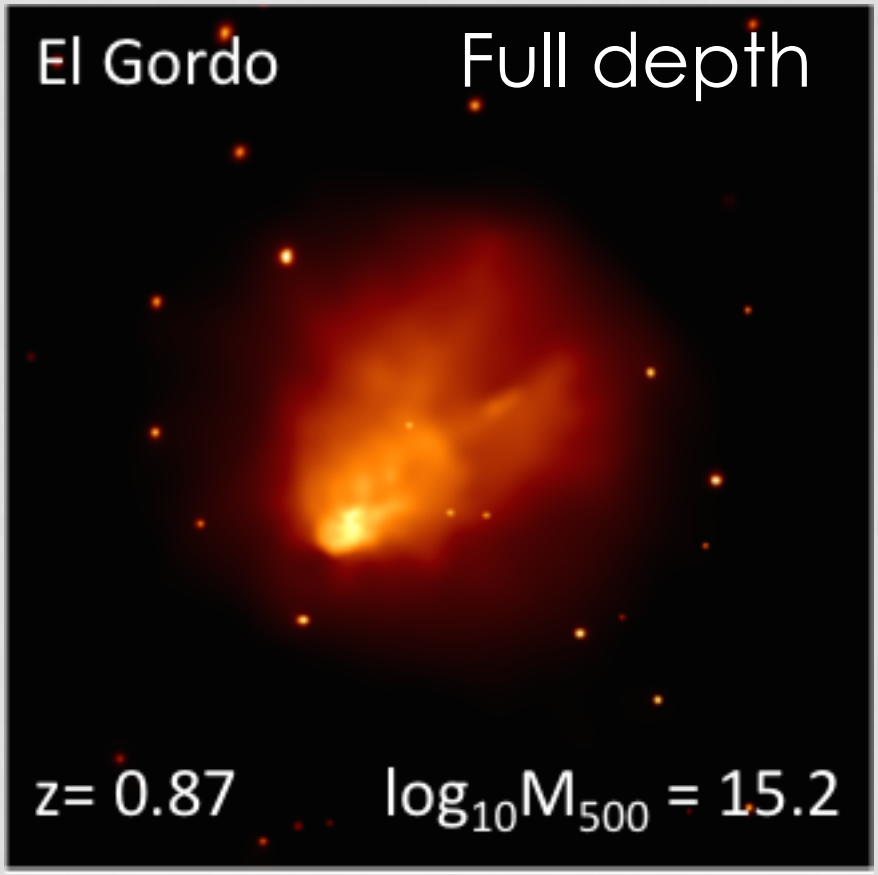

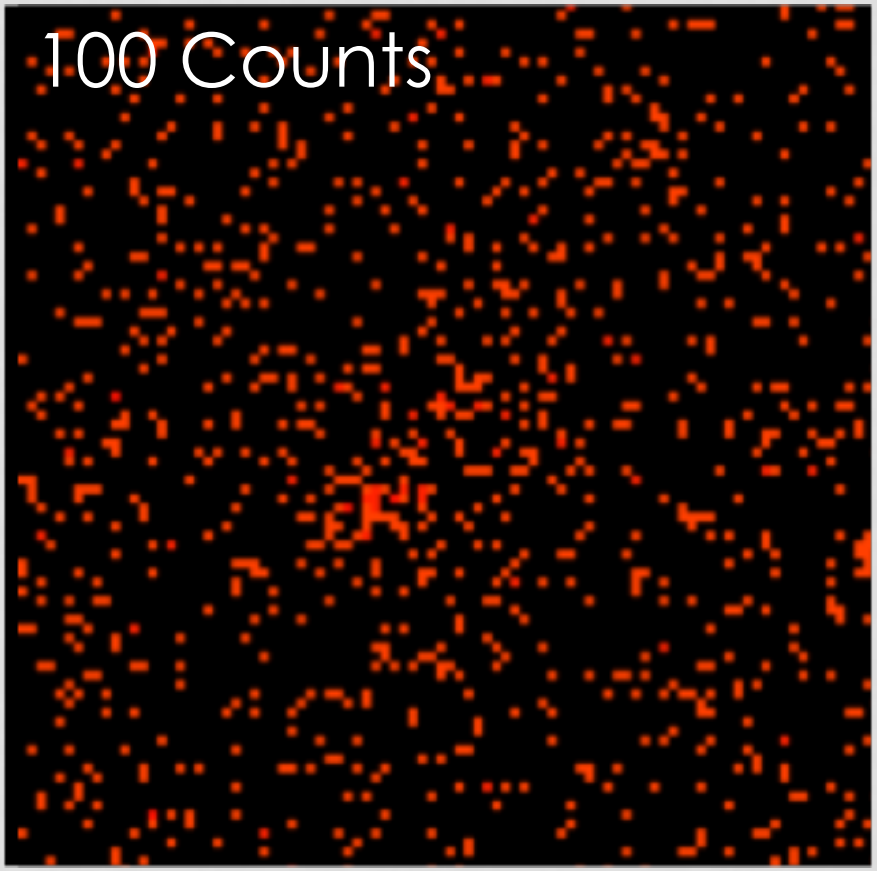

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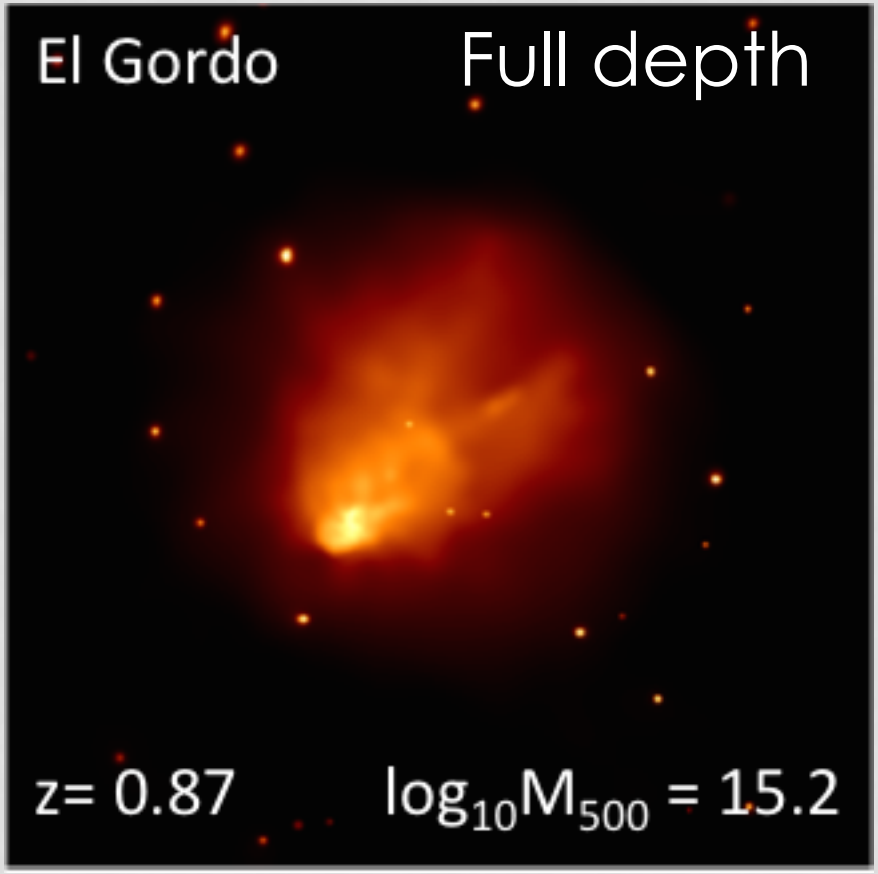

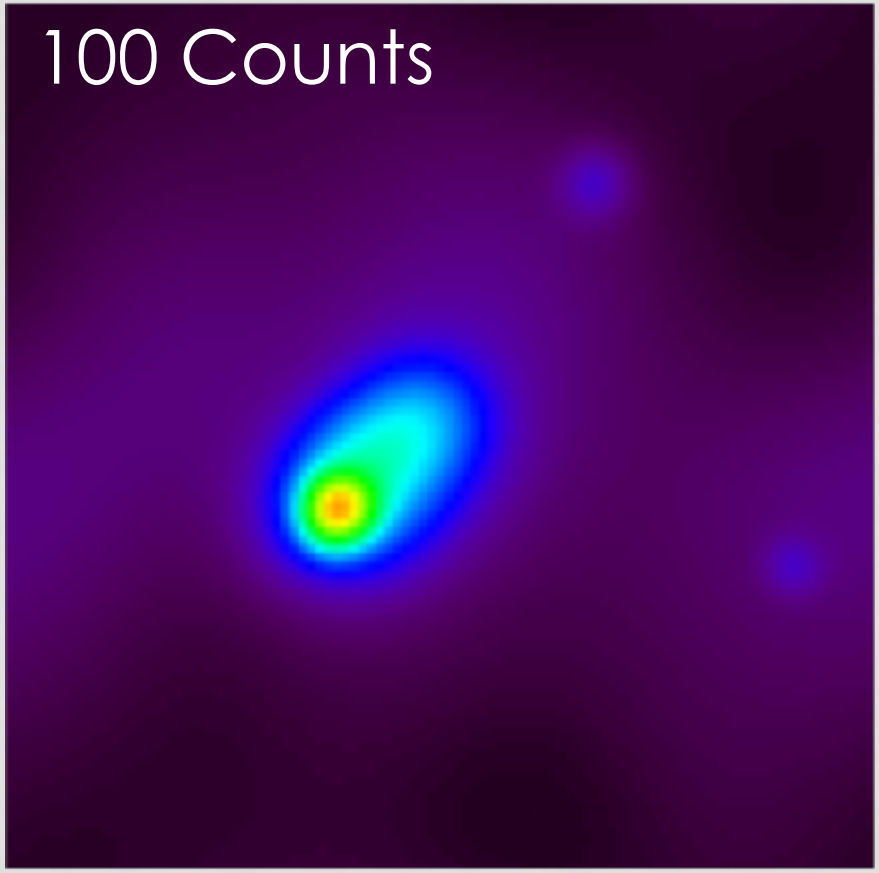

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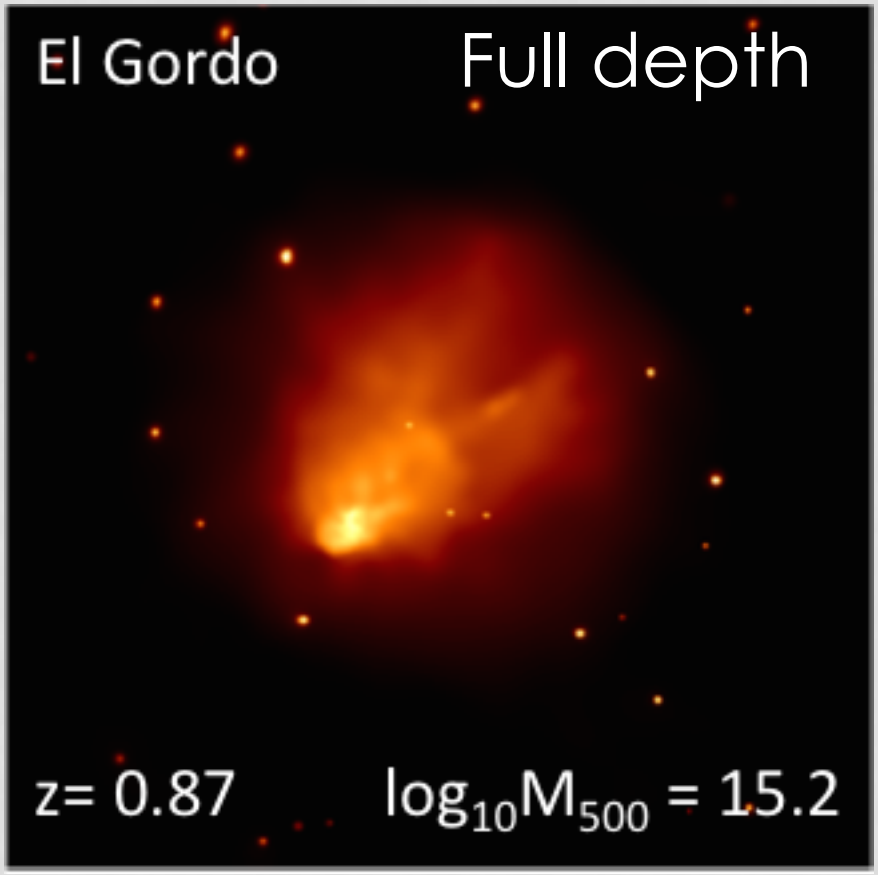
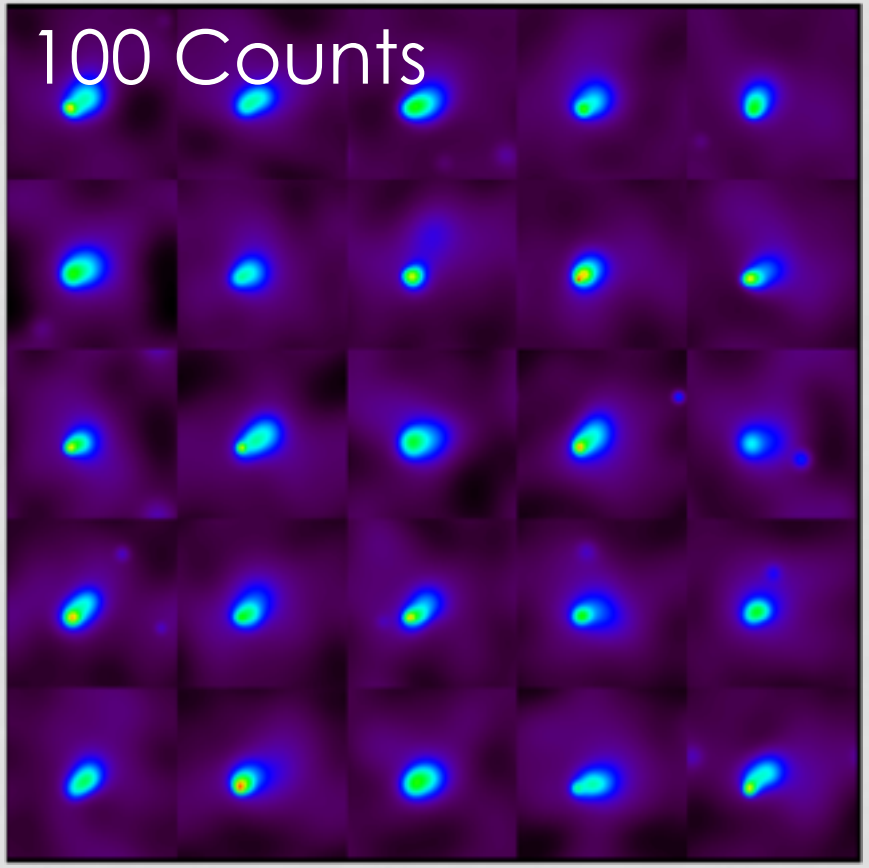




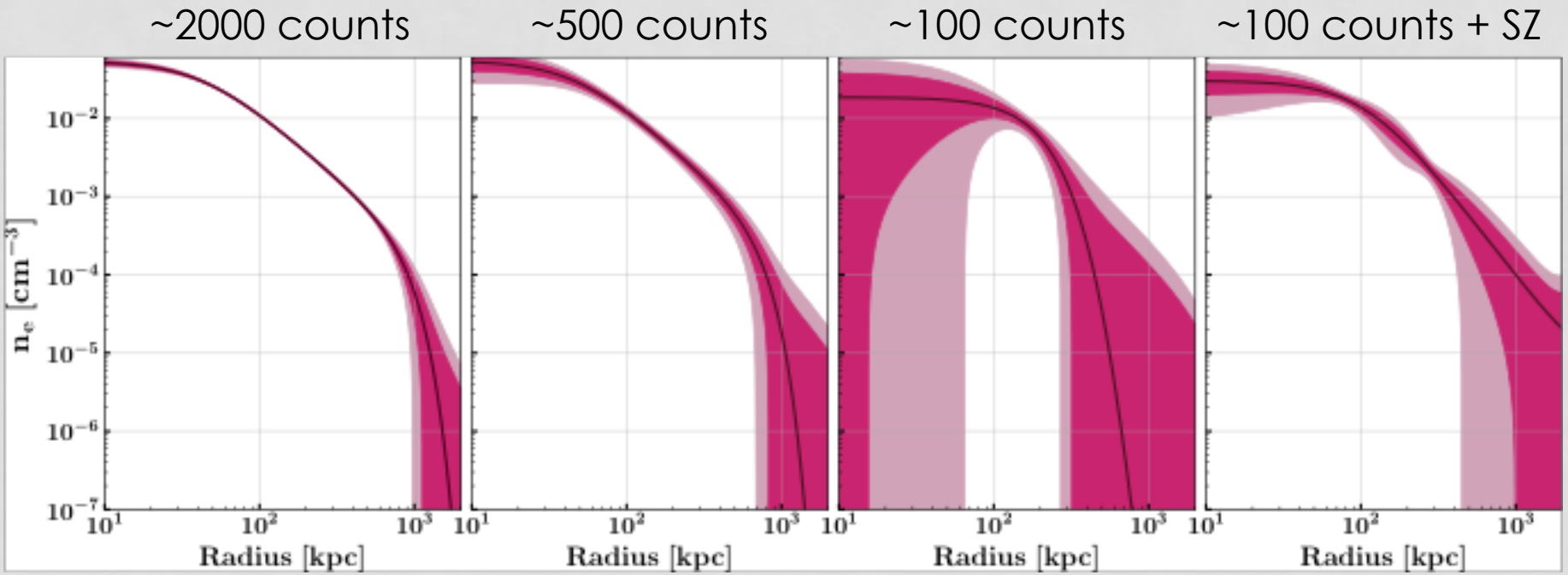
COMBINING SZ + X-RAY

Developing analysis tools to extract more information from limited # of counts

- SZ information probes large-scale P
- Chandra information probes small-scale n_e
- XMM-Newton probes intermediate scale n_e, kT

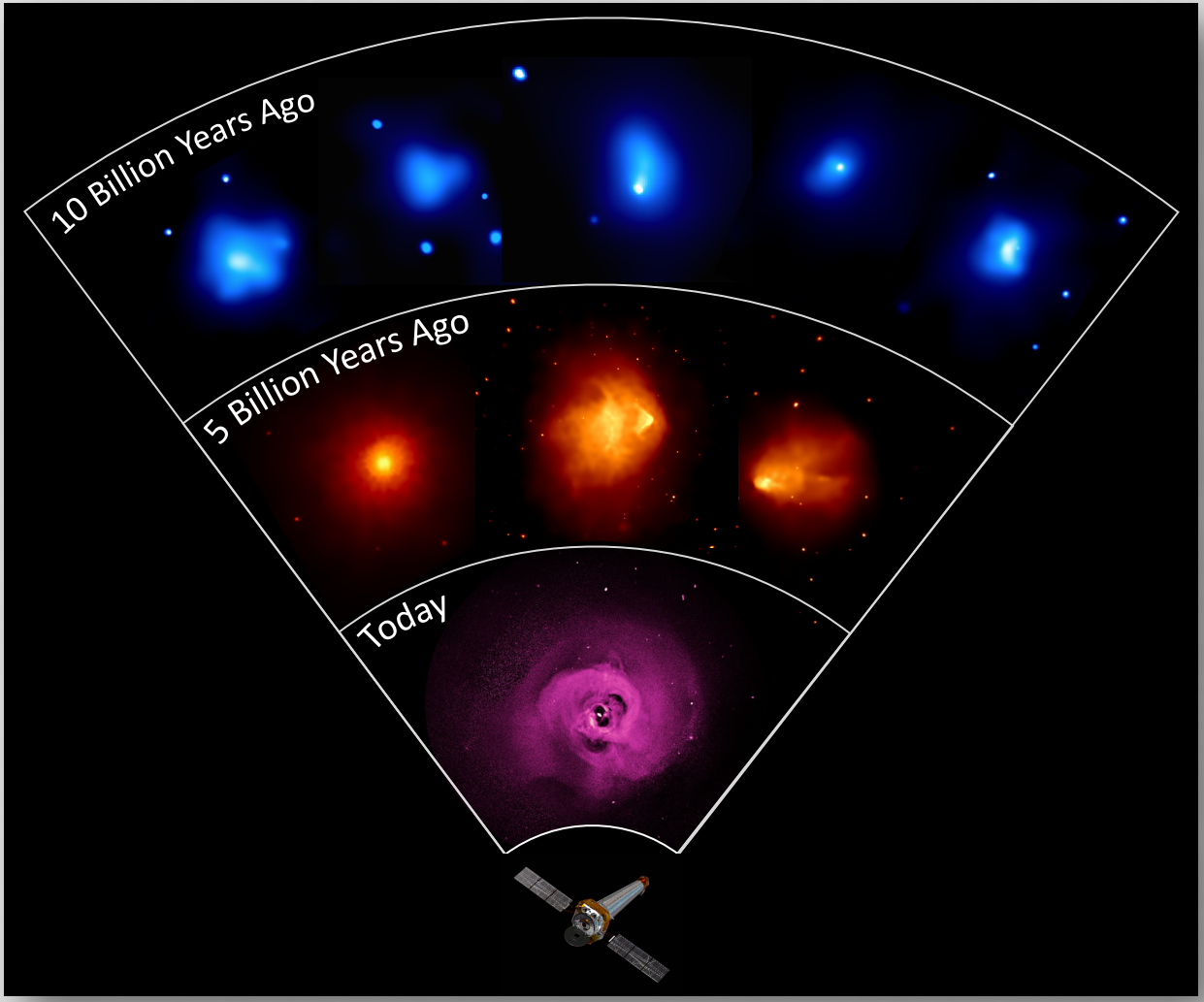
→ **Joint analysis probes n_e, kT on all scales**

See Poster by Florian Ruppin



SUMMARY

- Combined, SPT and Chandra have enabled evolutionary studies of massive galaxy clusters over 10 Gyr
- SZ surveys will continue to push cluster discovery to $z > 2$
- We are doing the best we can with current technology!



Growth of Cool Cores?

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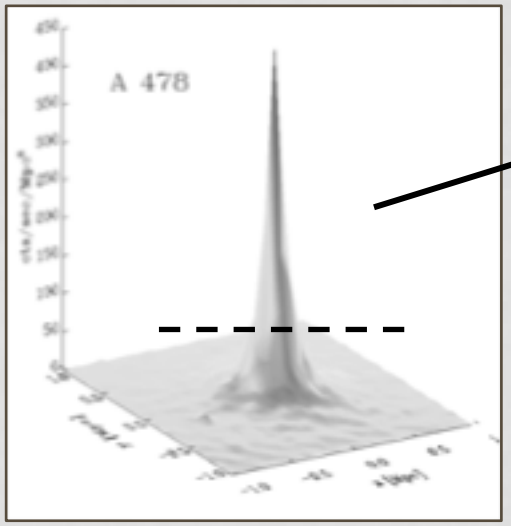
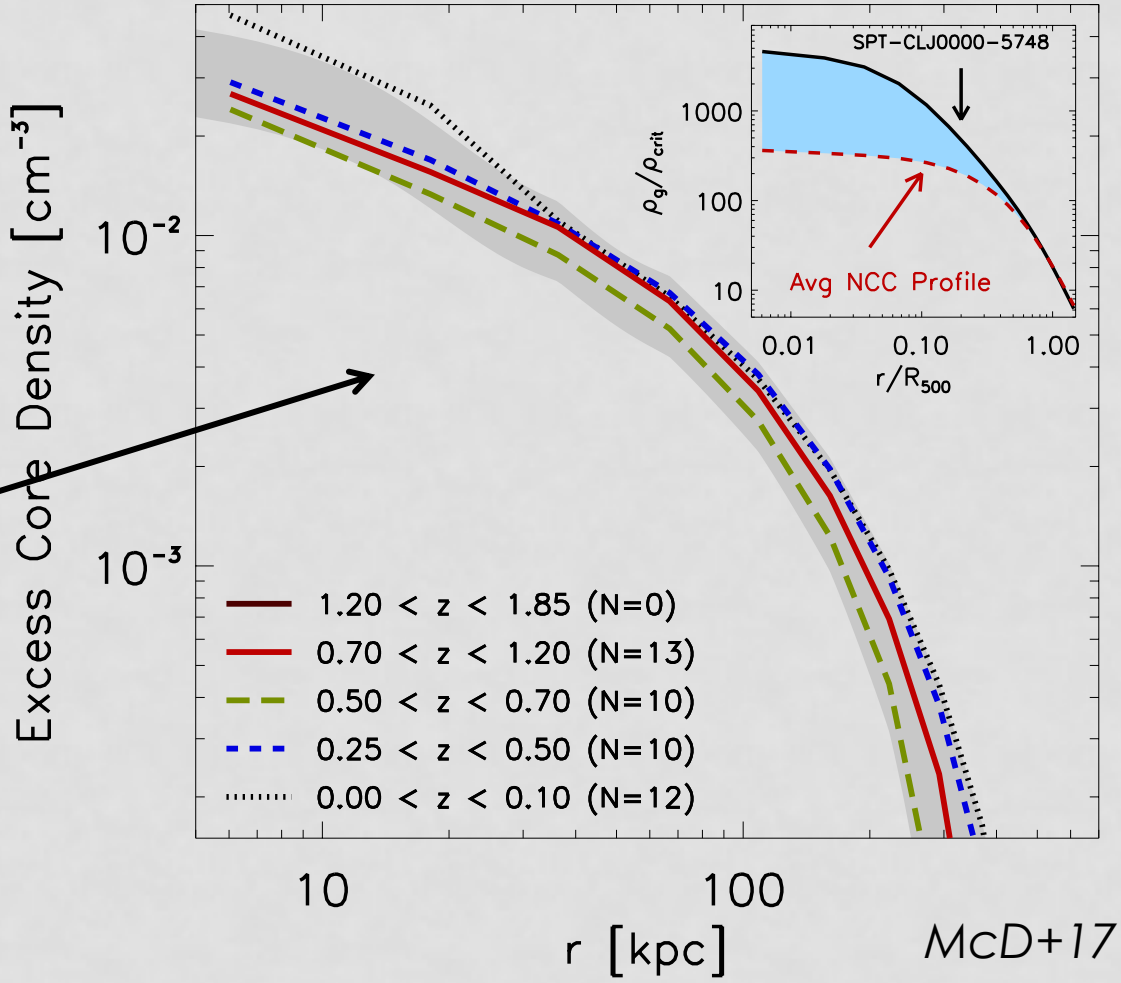
  - Excess is the "cool core"
- No apparent change in cool core shape, size, density over the past ~ 7 Gyr.





McD+17

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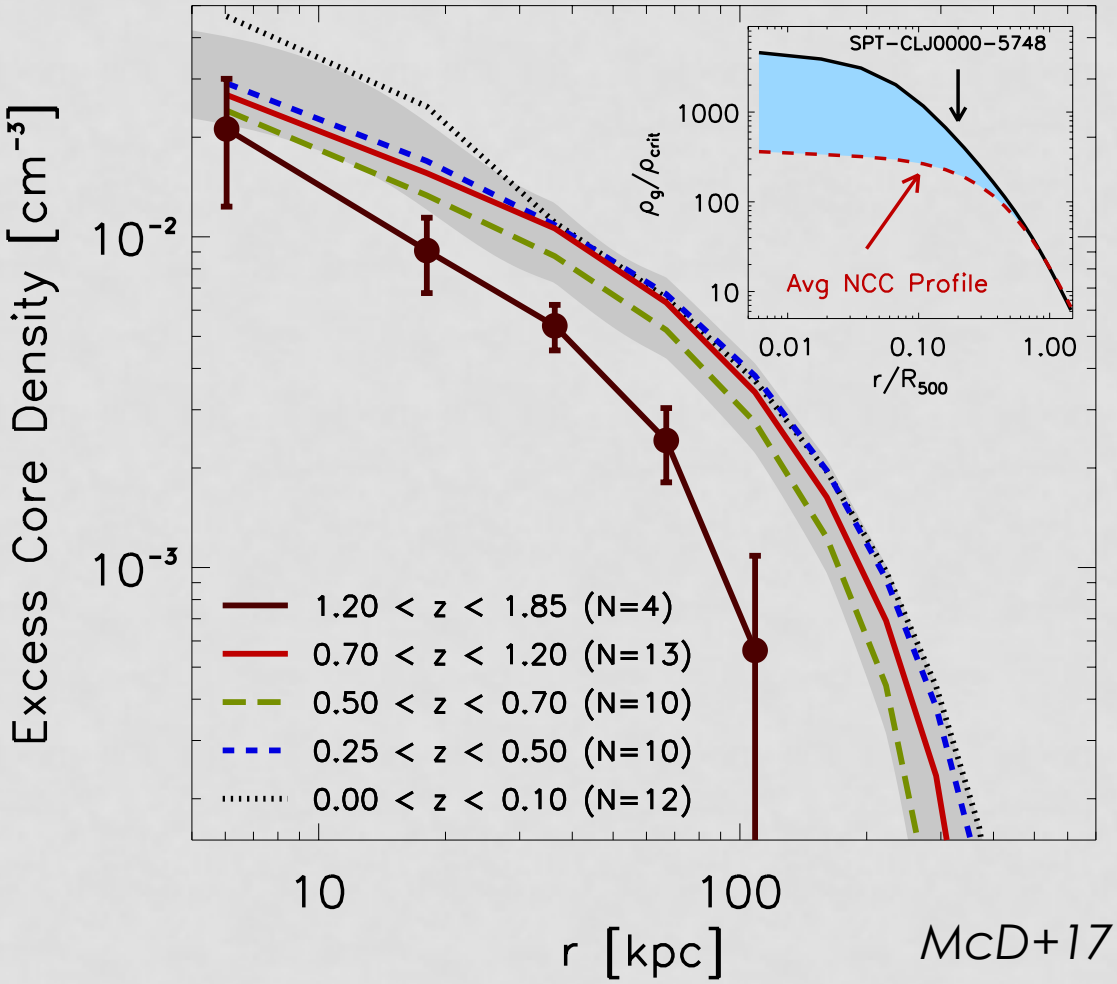
Evidence for long-standing, gentle feedback

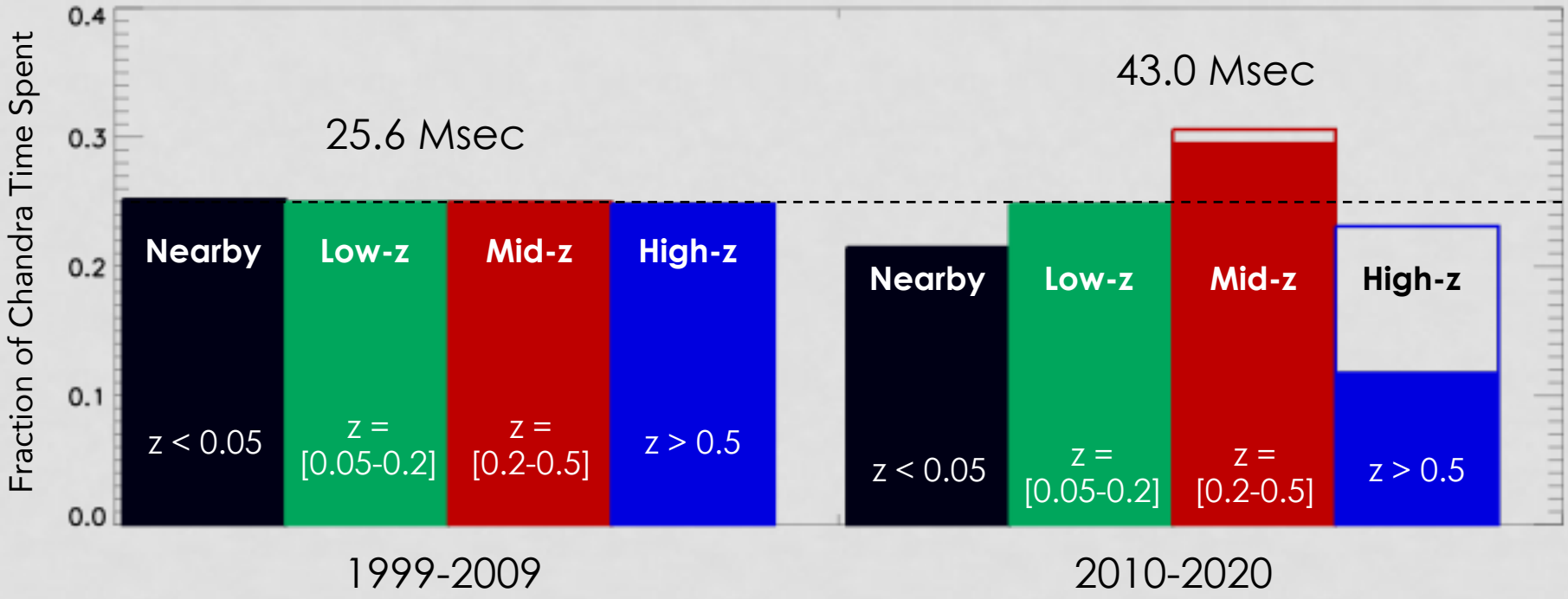
- Some evidence that cool cores began to form at z > 1



McD+17

20 Years of Chandra Cluster Observations

Distribution of Chandra ACIS/HRC observing time spent on galaxy clusters



In first few years, there were already known clusters at z > 1

- Bulk were 3C/4C sources and optically-selected clusters