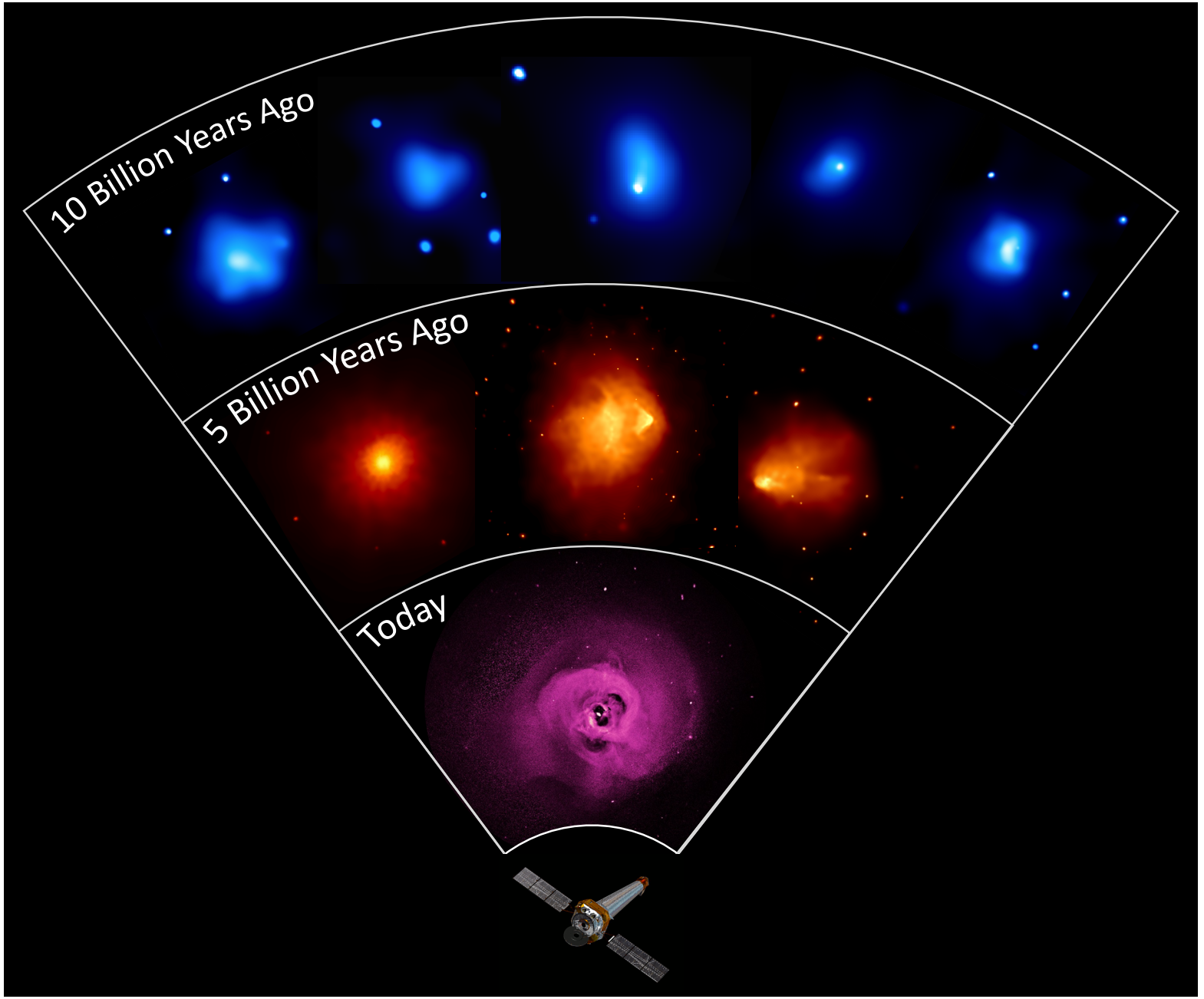
10 Billion Years of Galaxy Cluster Evolution with Chandra



Massachusetts Institute of Technology

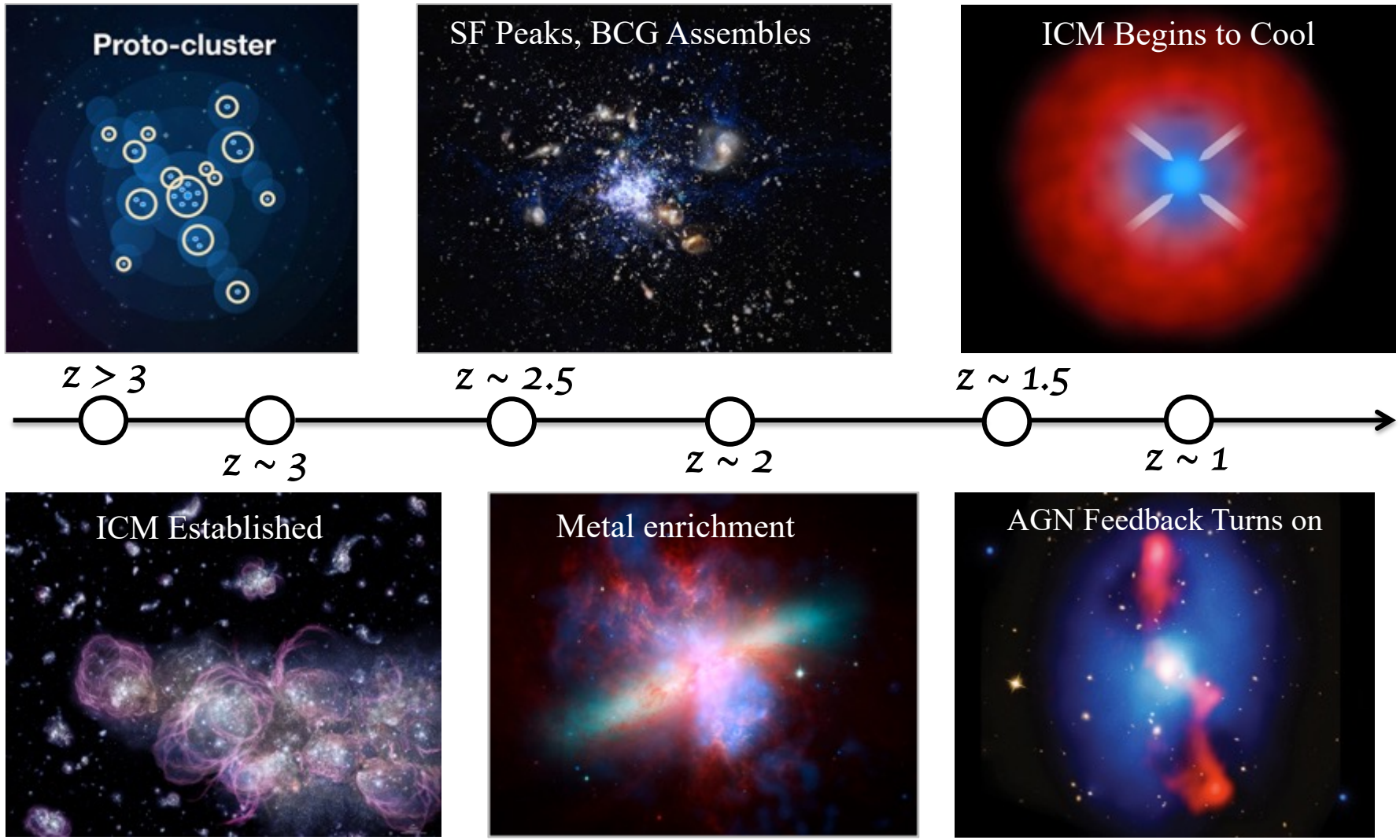
Michael McDonald, MIT

December 4, 2024

Galaxy Cluster Evolution

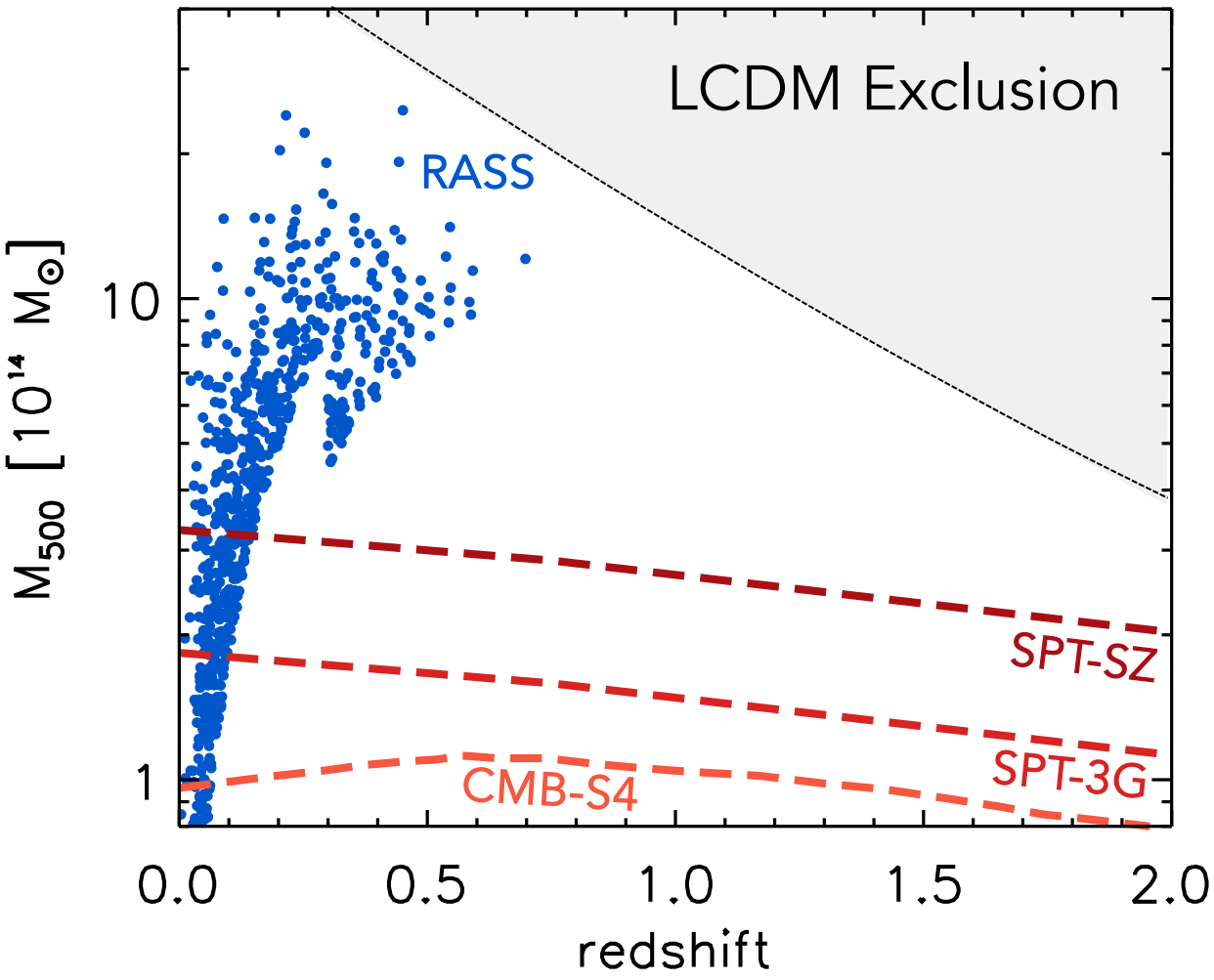
The timing of many major milestones in cluster formation/ evolution remain uncertain

Need well-selected samples of galaxy clusters at z > 1 to understand evolution



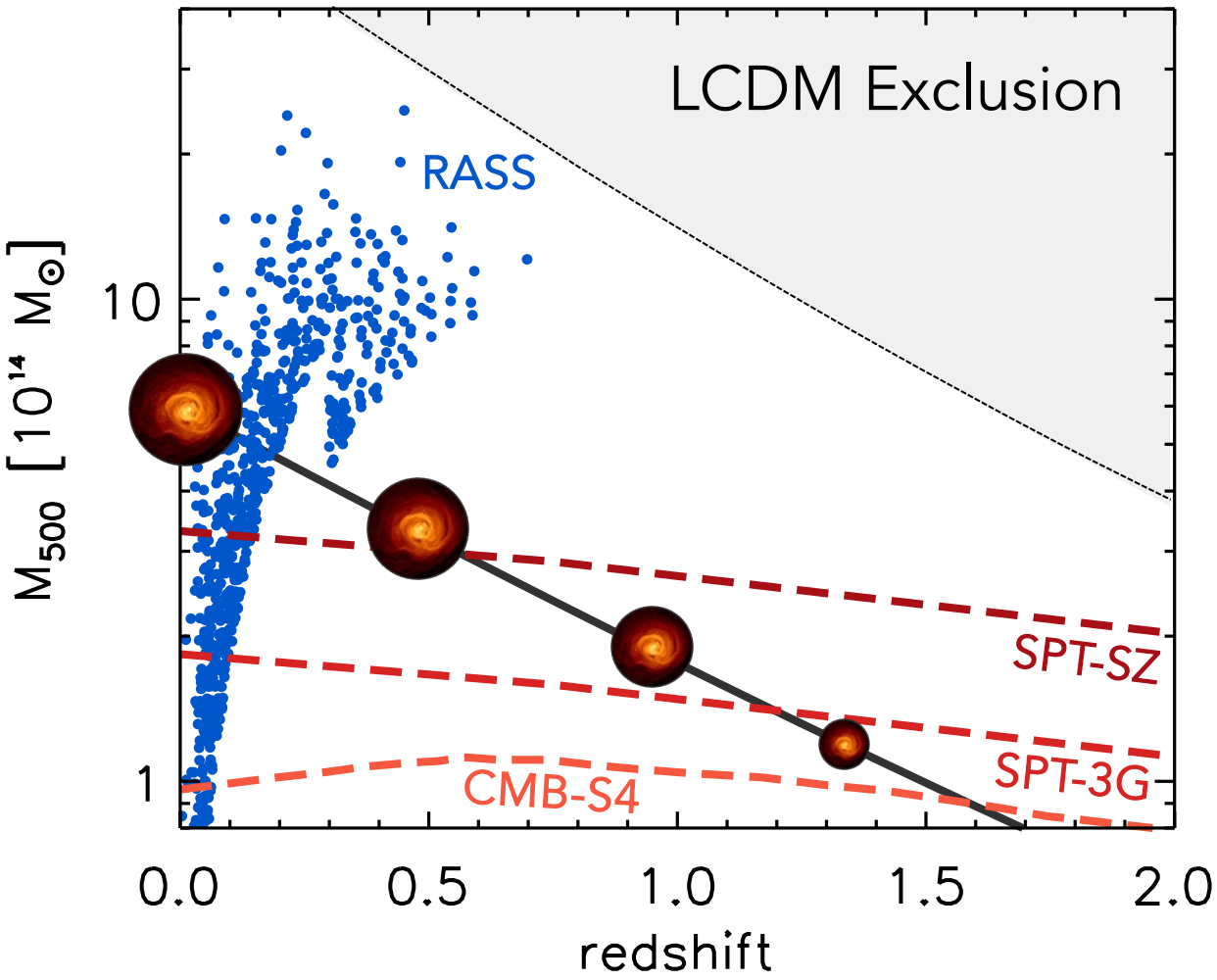
Combining SZ + X-ray Data: Selection

- mm-wave surveys probing the Sunyaev Zel'dovich effect provide our best opportunity to study massive clusters in the early universe
  - Extend to much higher redshift than X-ray surveys
  - Significantly less biased to cluster dynamical state than X-ray



Combining SZ + X-ray Data: Selection

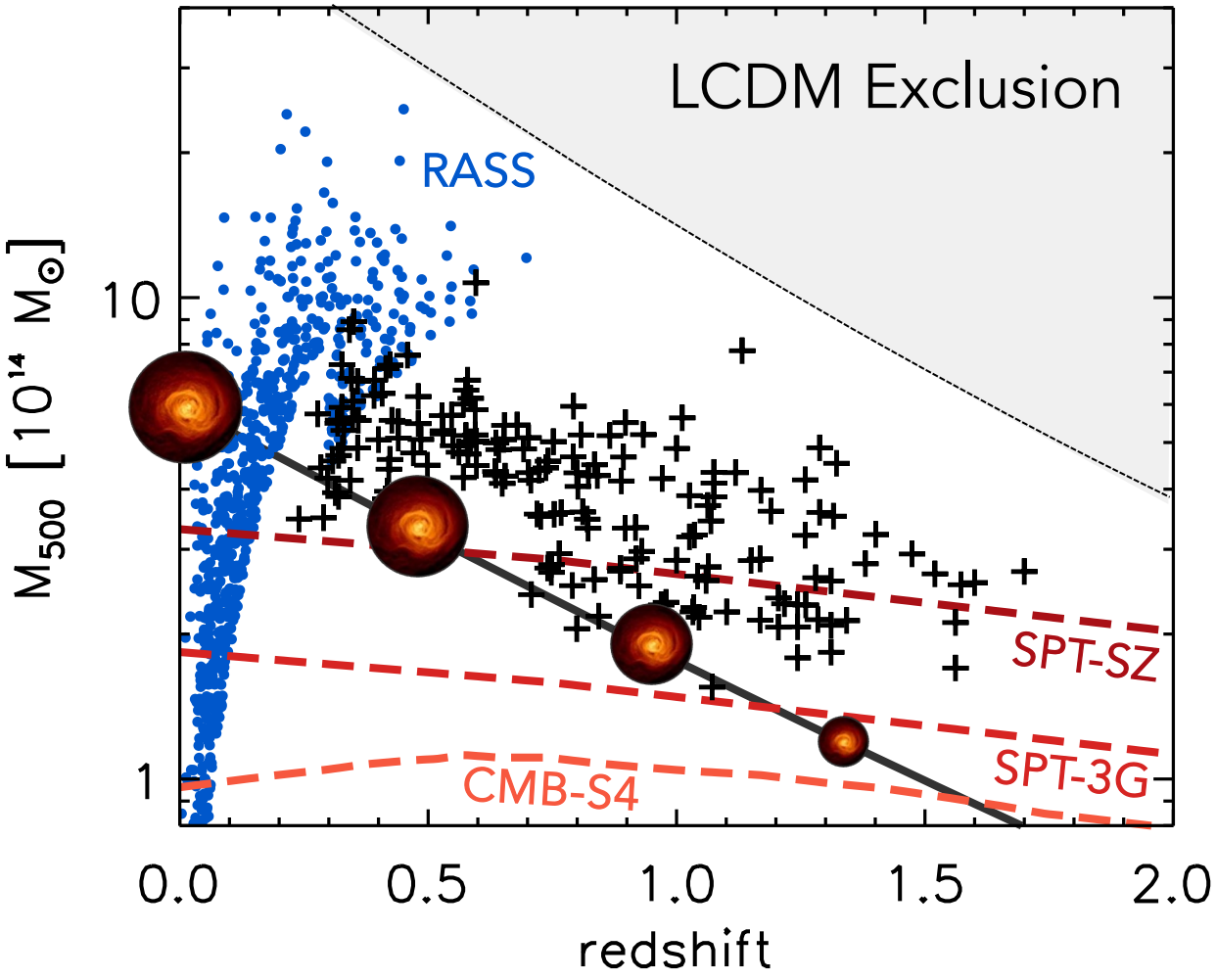
- mm-wave surveys probing the Sunyaev Zel'dovich effect provide our best opportunity to study massive clusters in the early universe
  - Extend to much higher redshift than X-ray surveys
  - Significantly less biased to cluster dynamical state than X-ray



Combining SZ + X-ray Data: Selection

- mm-wave surveys probing the Sunyaev Zel'dovich effect provide our best opportunity to study massive clusters in the early universe
  - Extend to much higher redshift than X-ray surveys
  - Significantly less biased to cluster dynamical state than X-ray

Our strategy (2010-2024):
Follow up most massive SPT-selected clusters at $0.3 < z < 1.7$ with *Chandra*

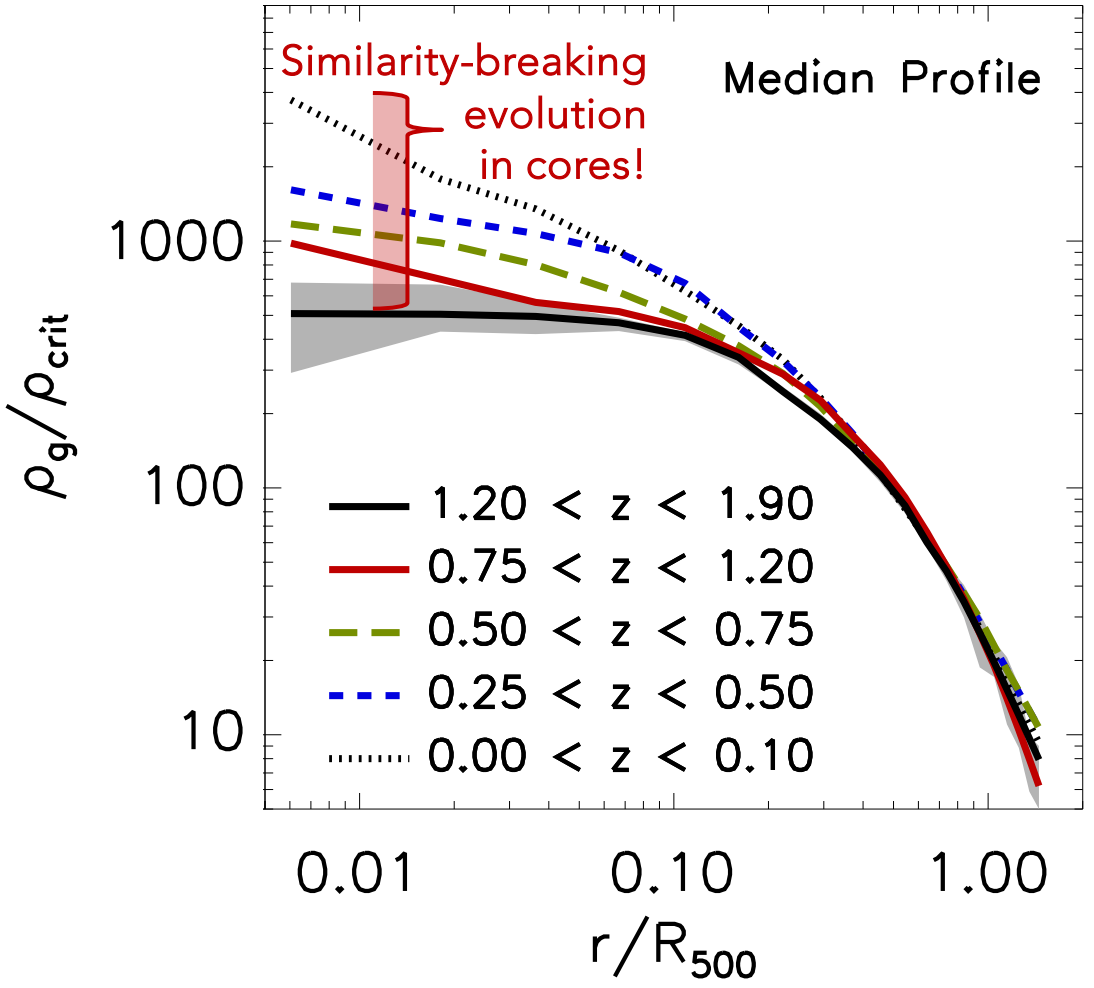


What Have We Learned from SPT-Chandra?

Credit: X-ray: NASA/CXC/Caltech/A.Newman et al/Tel Aviv/A.Morandi & M.Limousin; Optical: NASA/STScI, ESO/VLT, SDSS

MM et al. 2017

(X-ray study of the most distant SZ-selected clusters at z ~ 1.5)

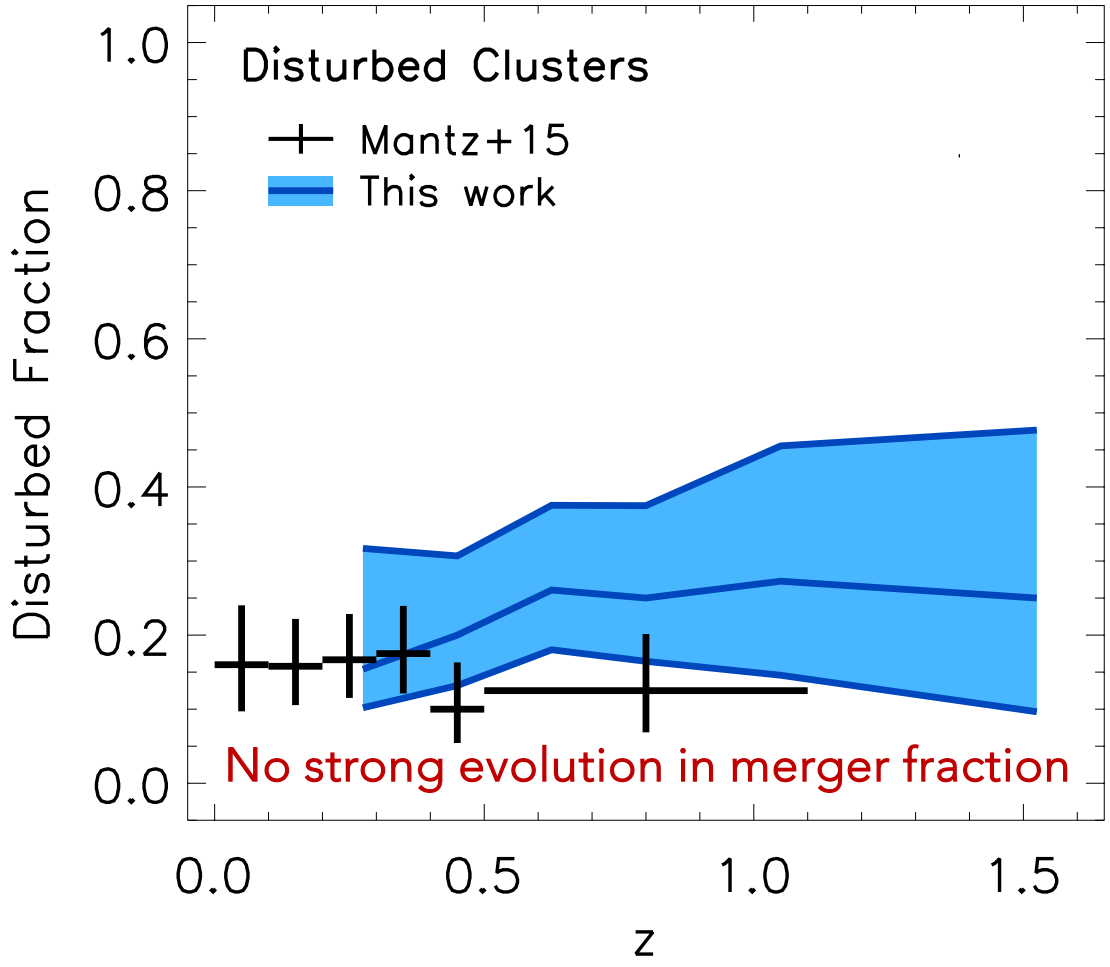


What Have We Learned from SPT-Chandra?

Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

McDonald et al. 2017

(Chandra analysis of `~100 clusters at z=0.3 – 1.7)

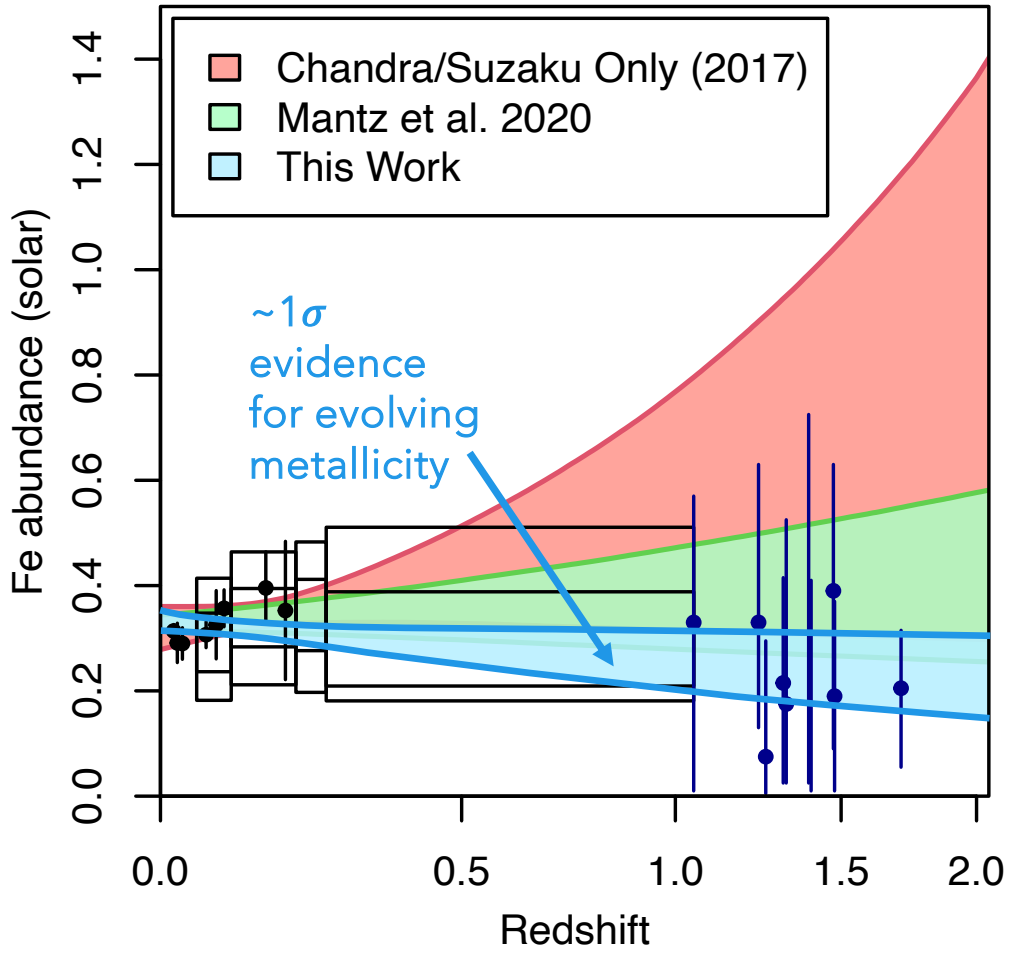


What Have We Learned from SPT-Chandra?

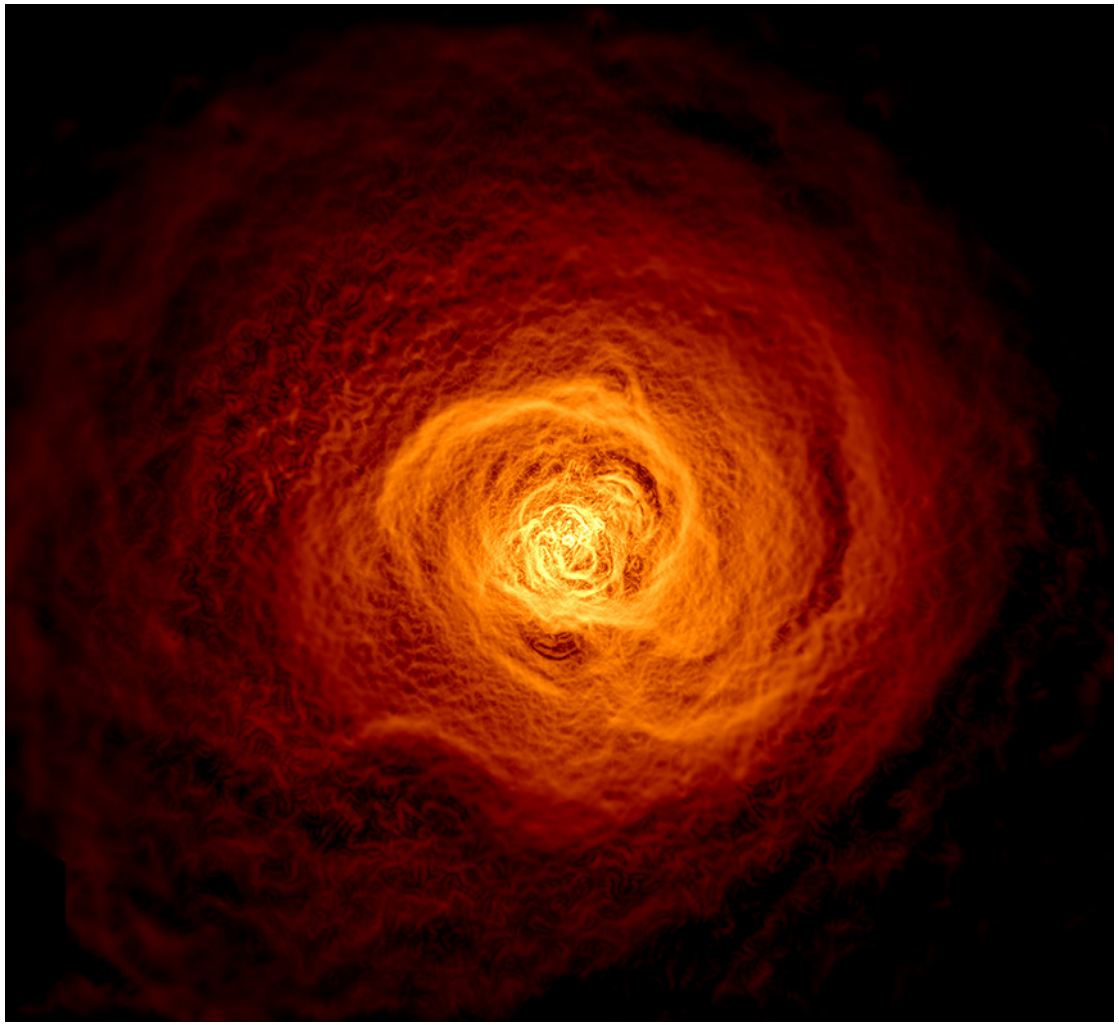
X-ray: NASA/CXC/SAO; Optical: NASA/ESA/STScI; IR: NASA/ESA/CSA/STScI/Milisavljevic et al., NASA/JPL/CalTech; Image Processing: NASA/CXC/SAO/J. Schmidt and K. Arcand

Flores et al. 2021

(XMM-Newton + Chandra analysis of the most distant SZ-selected clusters at z ~ 1.5)



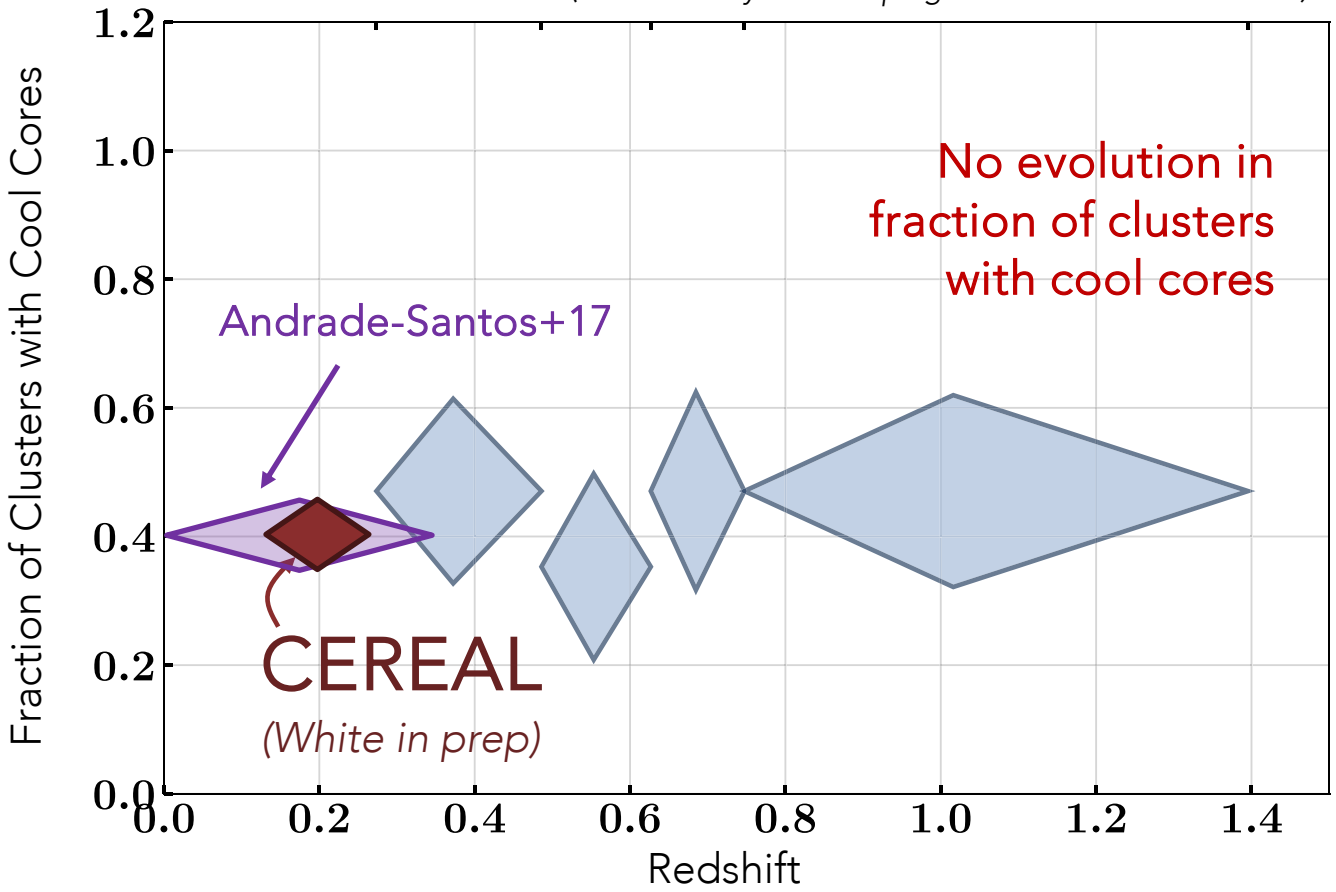
What Have We Learned from SPT-Chandra?



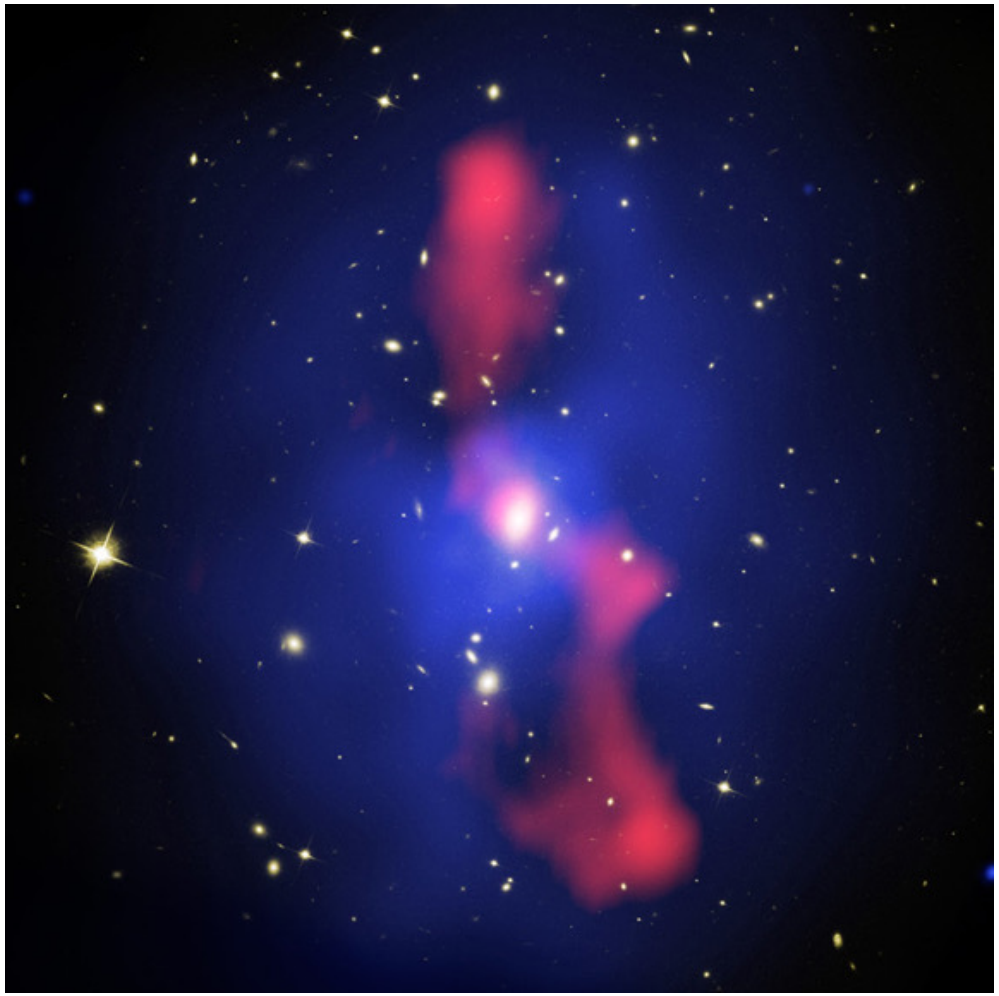
Credit: NASA/CXC/GSFC/S.A.Walker, et al.

Ruppin, MM, et al. 2021

(Chandra analysis of 67 "progenitor-selected" SPT clusters)



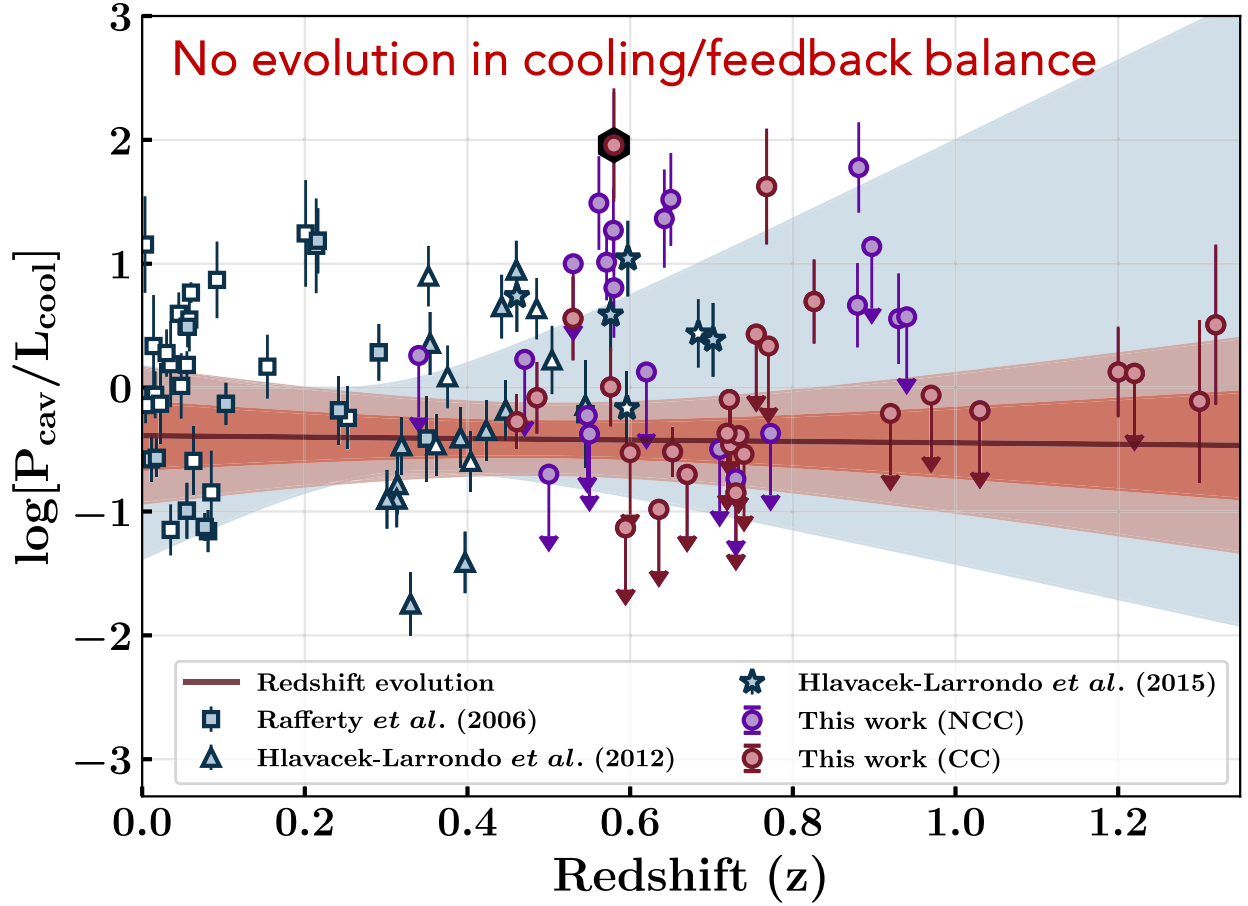
What Have We Learned from SPT-Chandra?



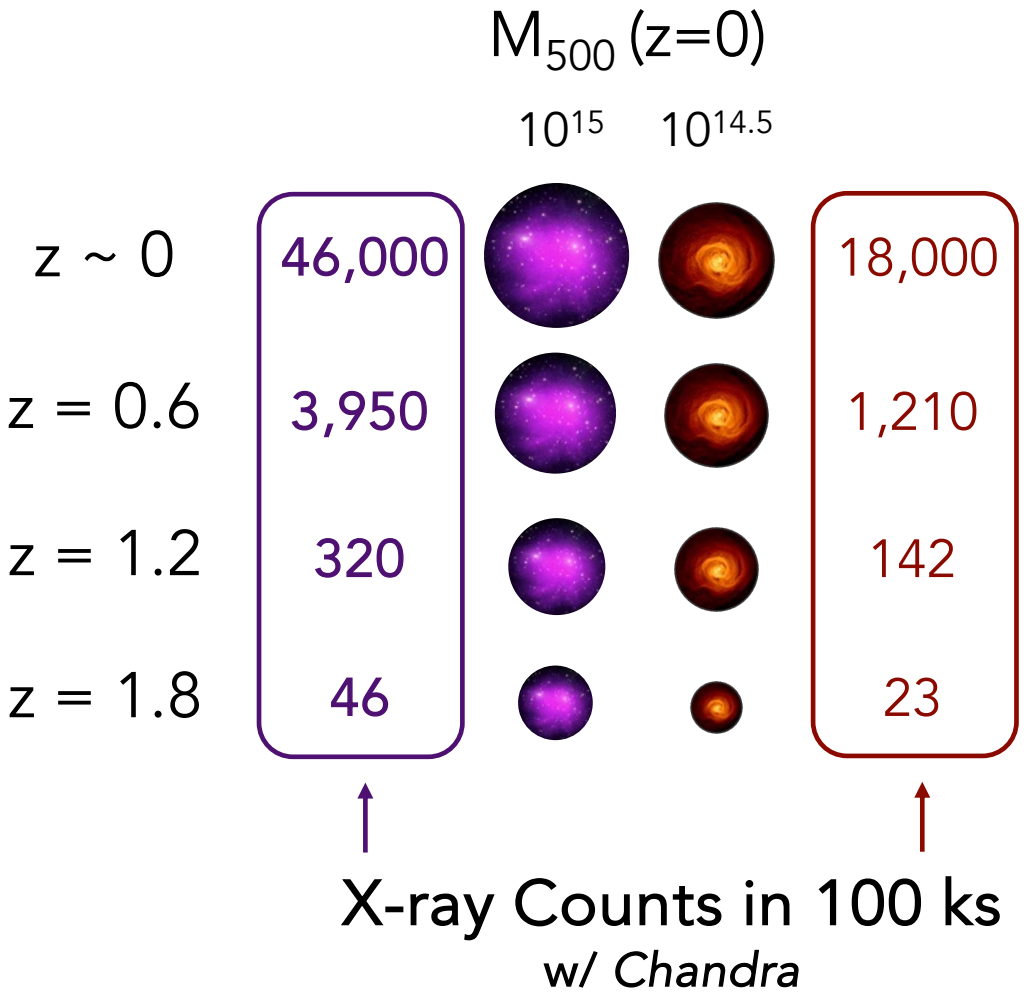
Credit: X-ray: NASA/CXC/Univ. Waterloo/B.McNamara;
Optical: NASA/ESA/STScI/Univ. Waterloo/B.McNamara; Radio: NRAO/Ohio Univ./L.Birzan et al.

Ruppin, MM, et al. 2023

(Chandra+SPT+ATCA analysis of 48 "progenitor-selected" SPT clusters)

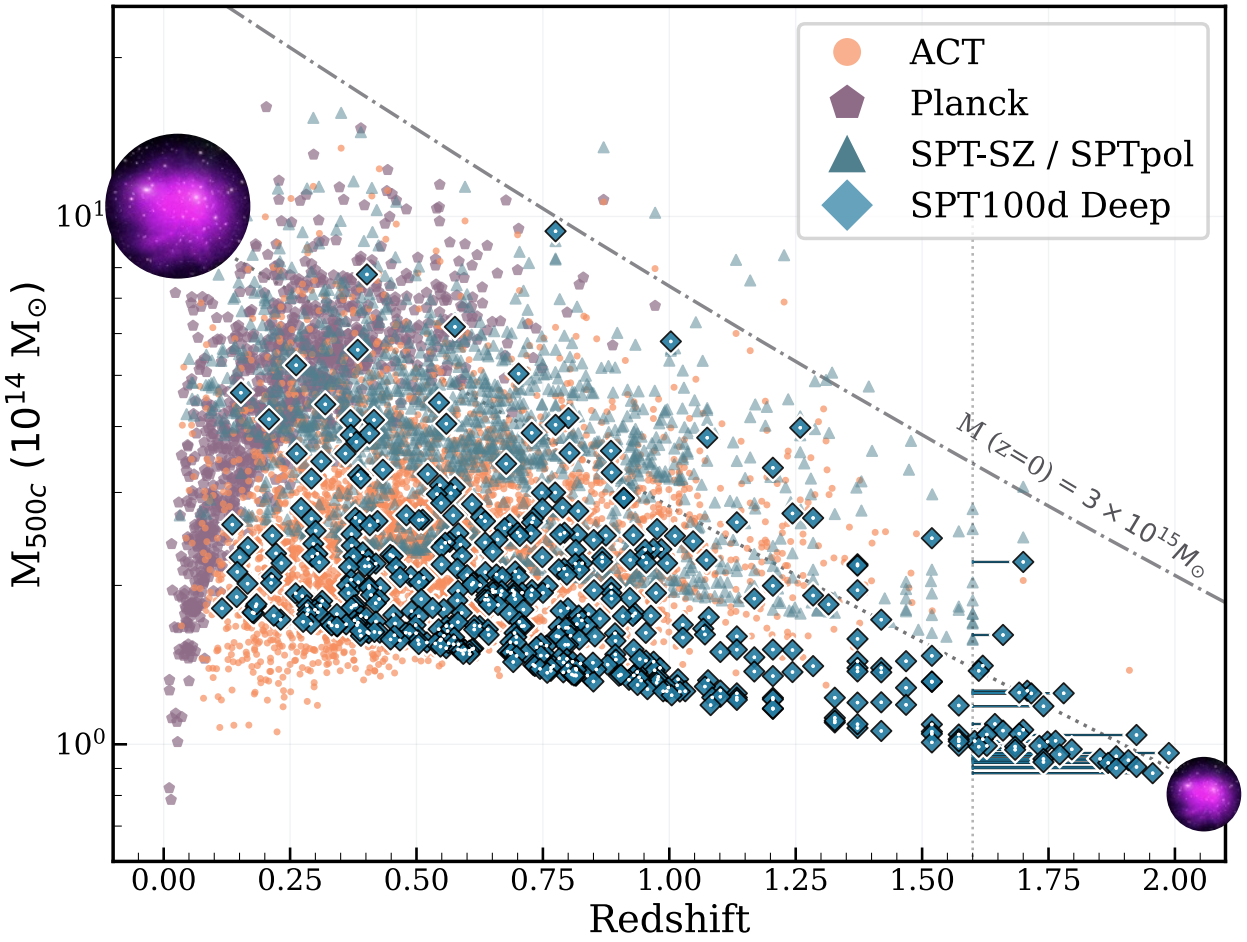


Prospects for the Future: Larger Samples

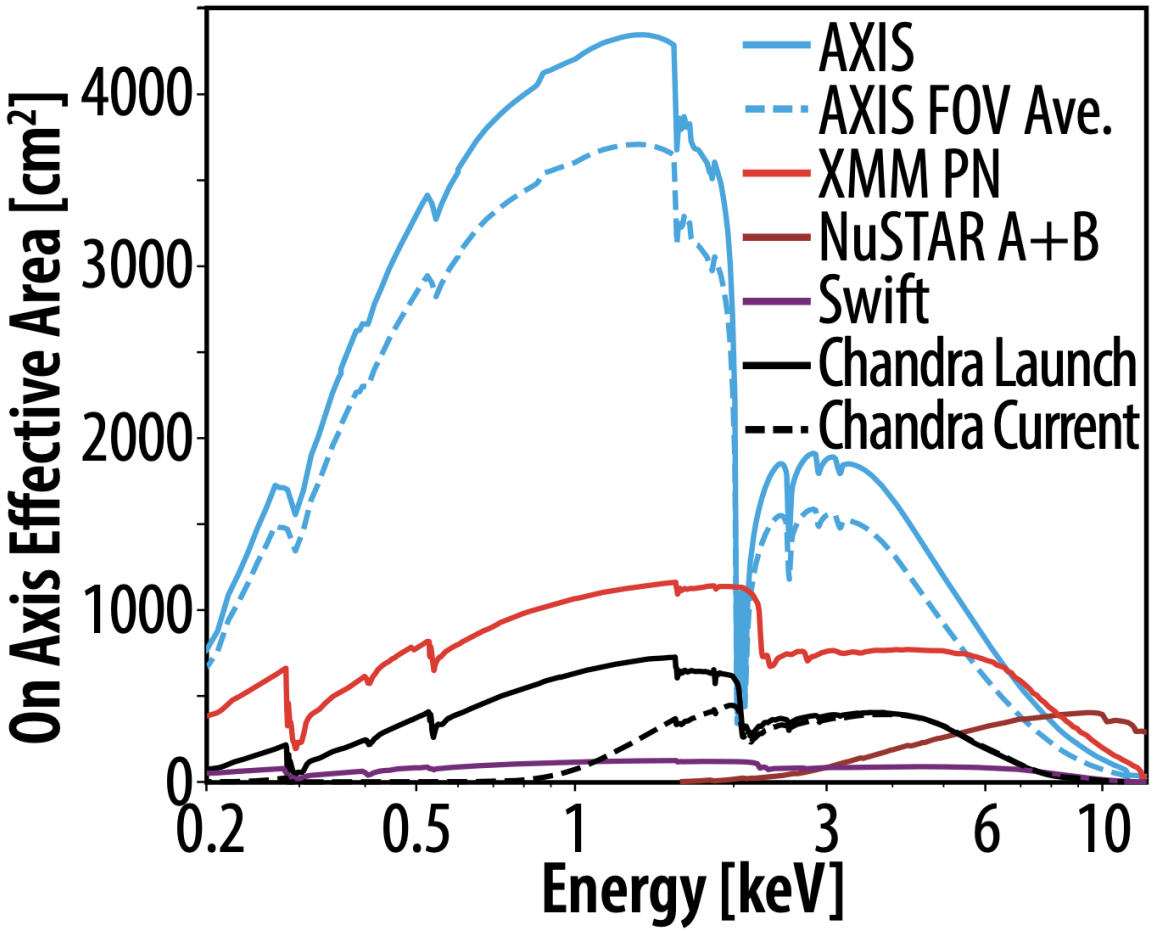


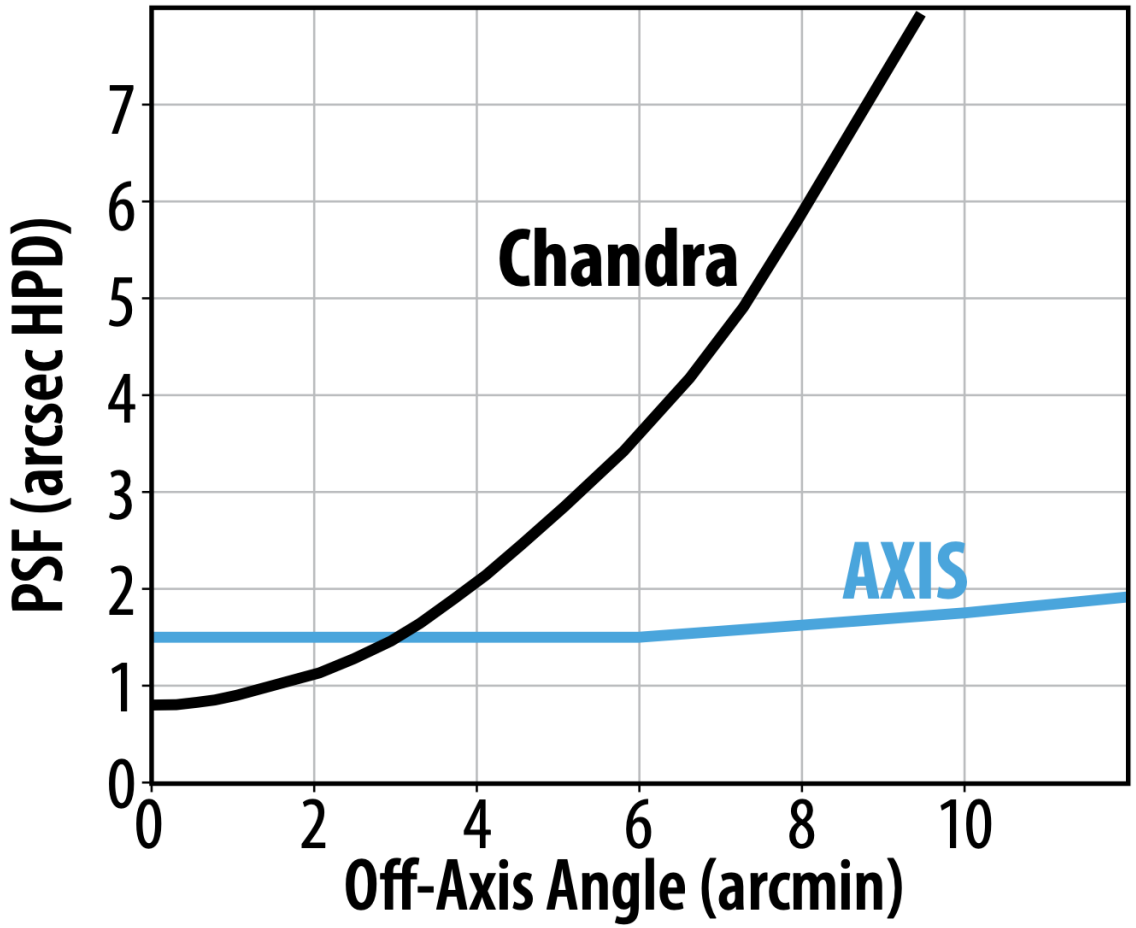
Kornoelje et al. (in prep)

(First results from the SPT-3G galaxy cluster survey)



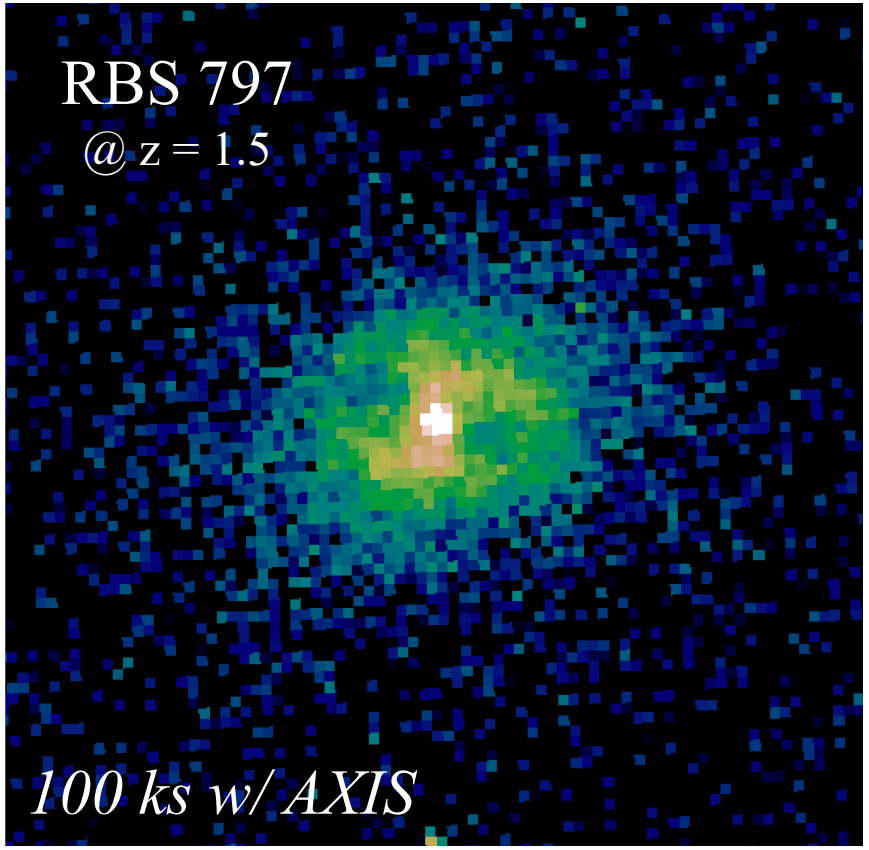
Prospects for the Future: AXIS Probe



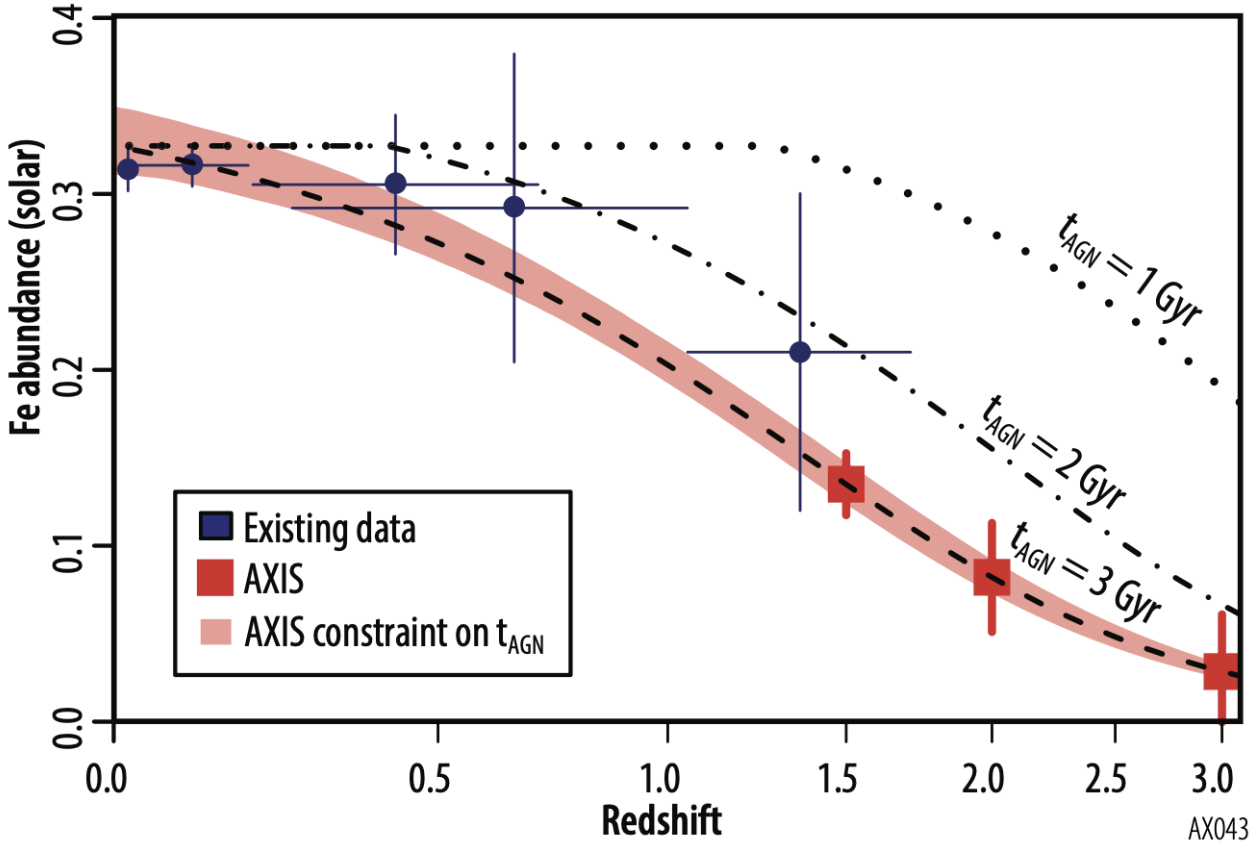


Prospects for the Future: AXIS Probe

Directly Probe Radio-Mode AGN Feedback to z ~ 2

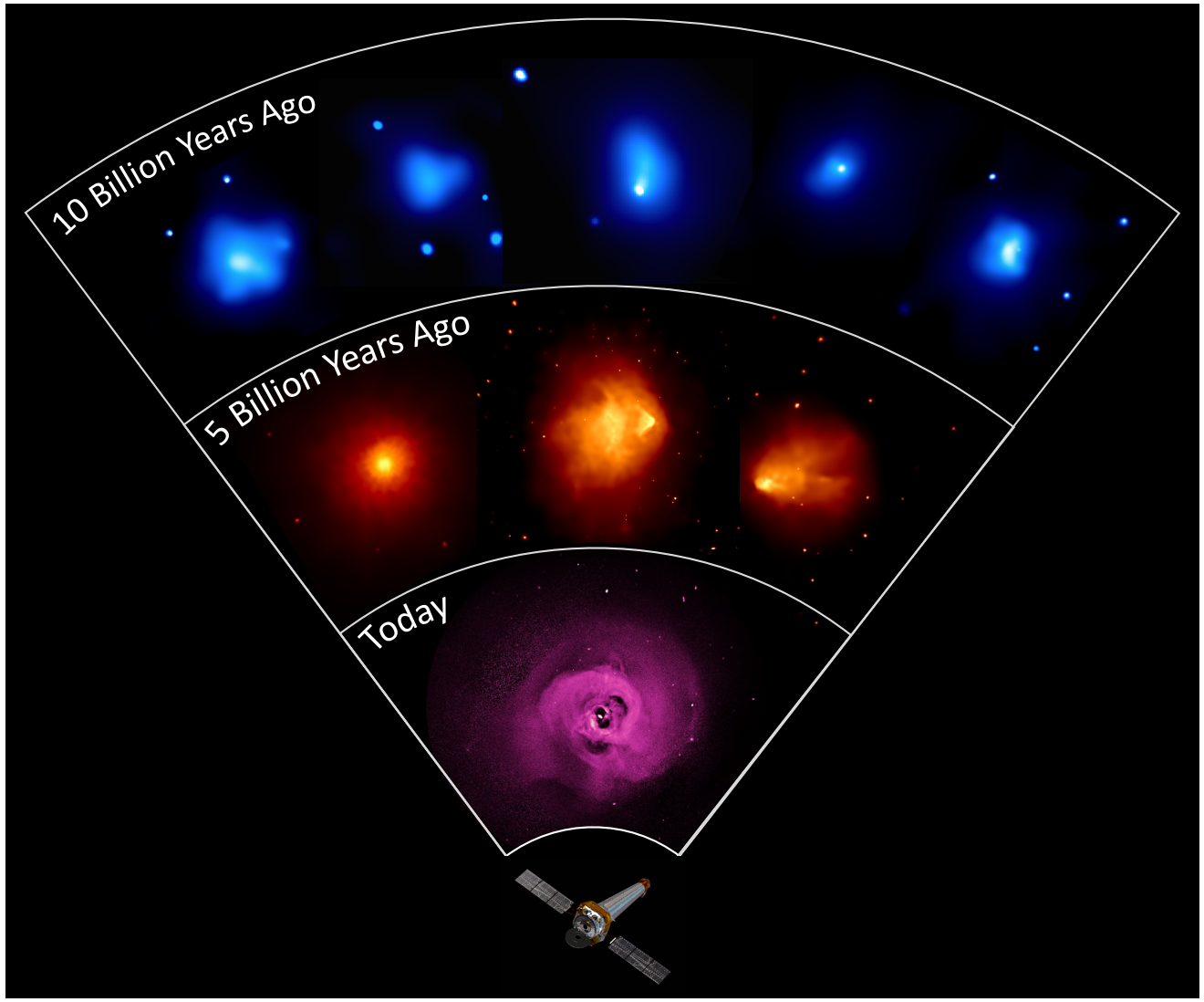


Constrain ICM Metal Enrichment to z ~ 3

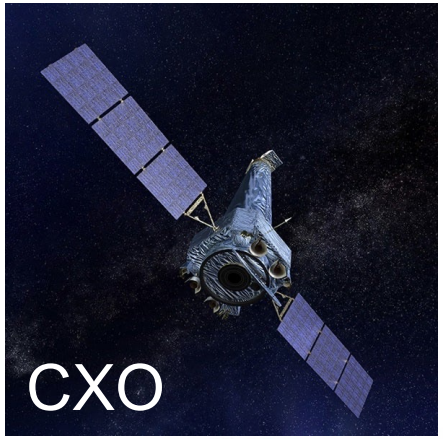


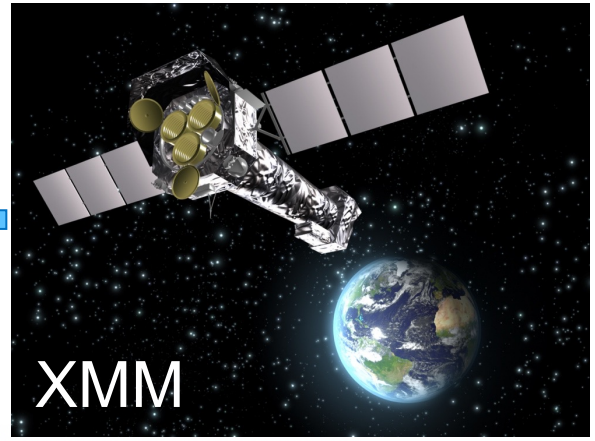
Summary

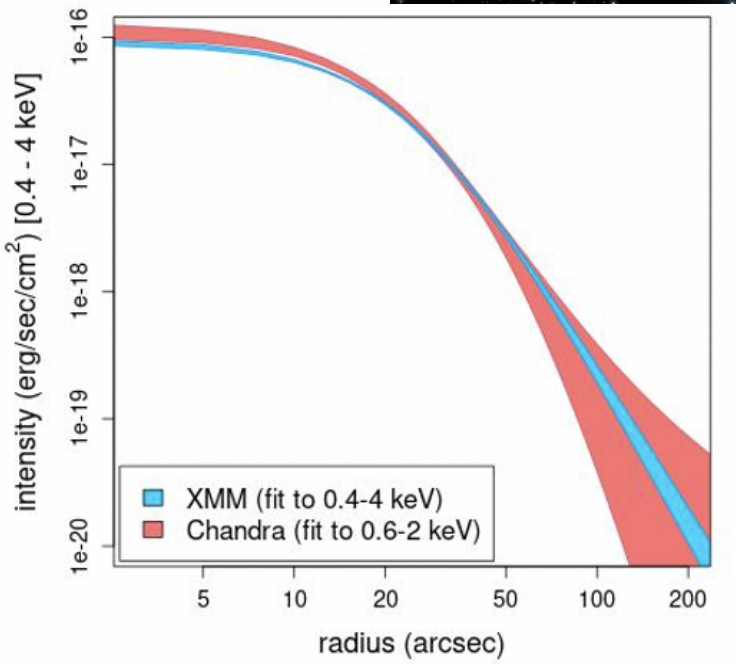
- The combination of mm-wave selection and X-ray follow-up with Chandra has enabled evolutionary studies of the ICM over 10 Gyr
  - *See also talks by Steve Allen, Michael Reefe, Michael Calzadilla*
- In the next 5-10 years we will discover galaxy clusters shortly after their birth (z ~ 3) with SZ surveys.
  - Understanding the physics that governs them requires new methodology/technology

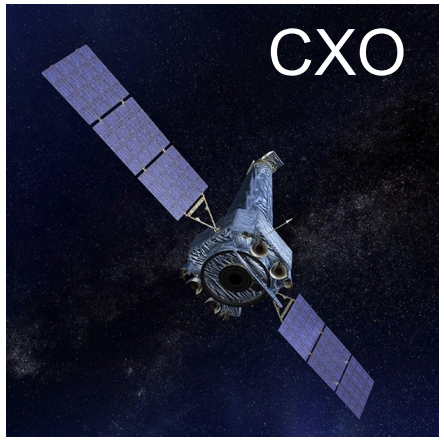


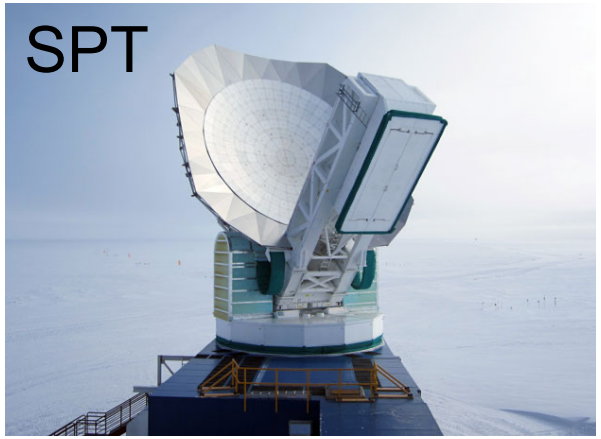
Prospects for the Future: Multi-Observatory

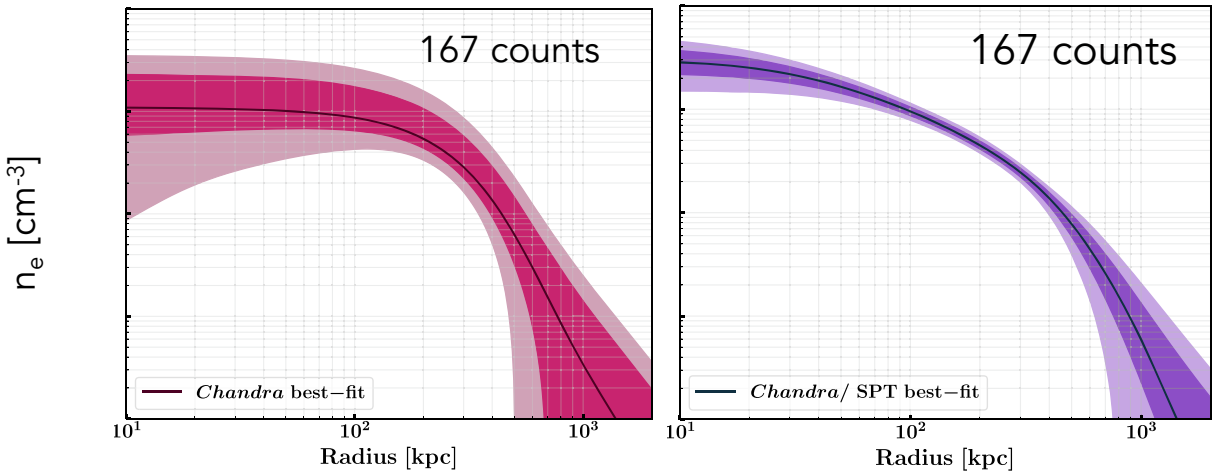




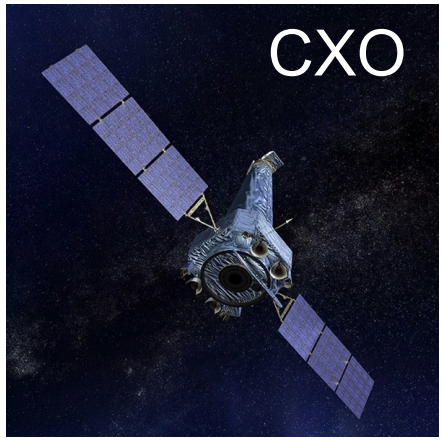




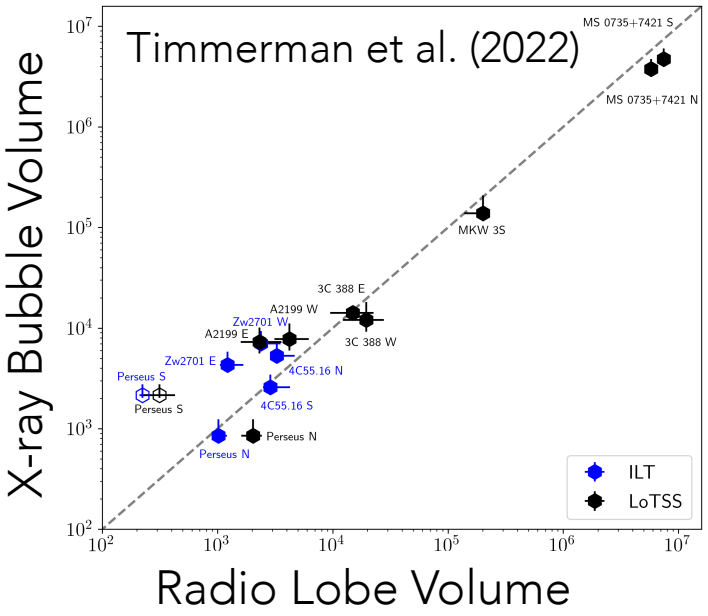


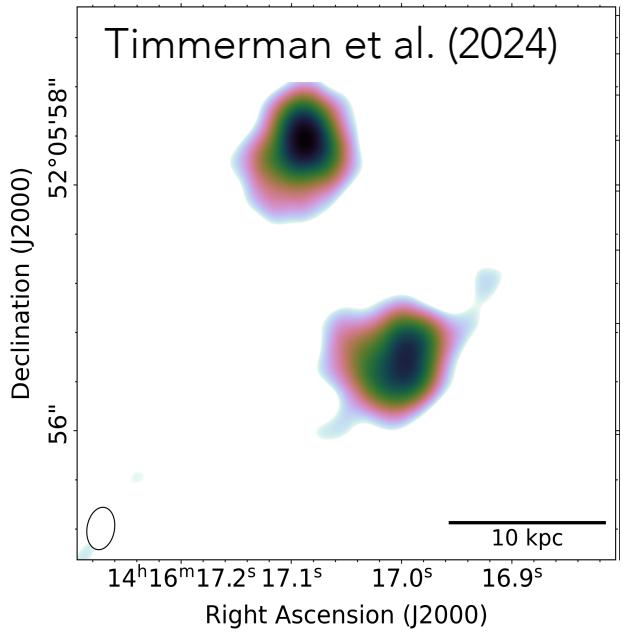


Prospects for the Future: Multi-Wavelength

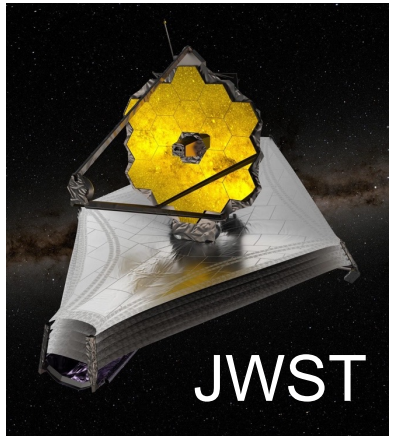


+





+



See talk by Michael Reefe!