

# EVOLUTION OF THE AGN FEEDBACK CYCLE IN GALAXY CLUSTERS

Michael Calzadilla

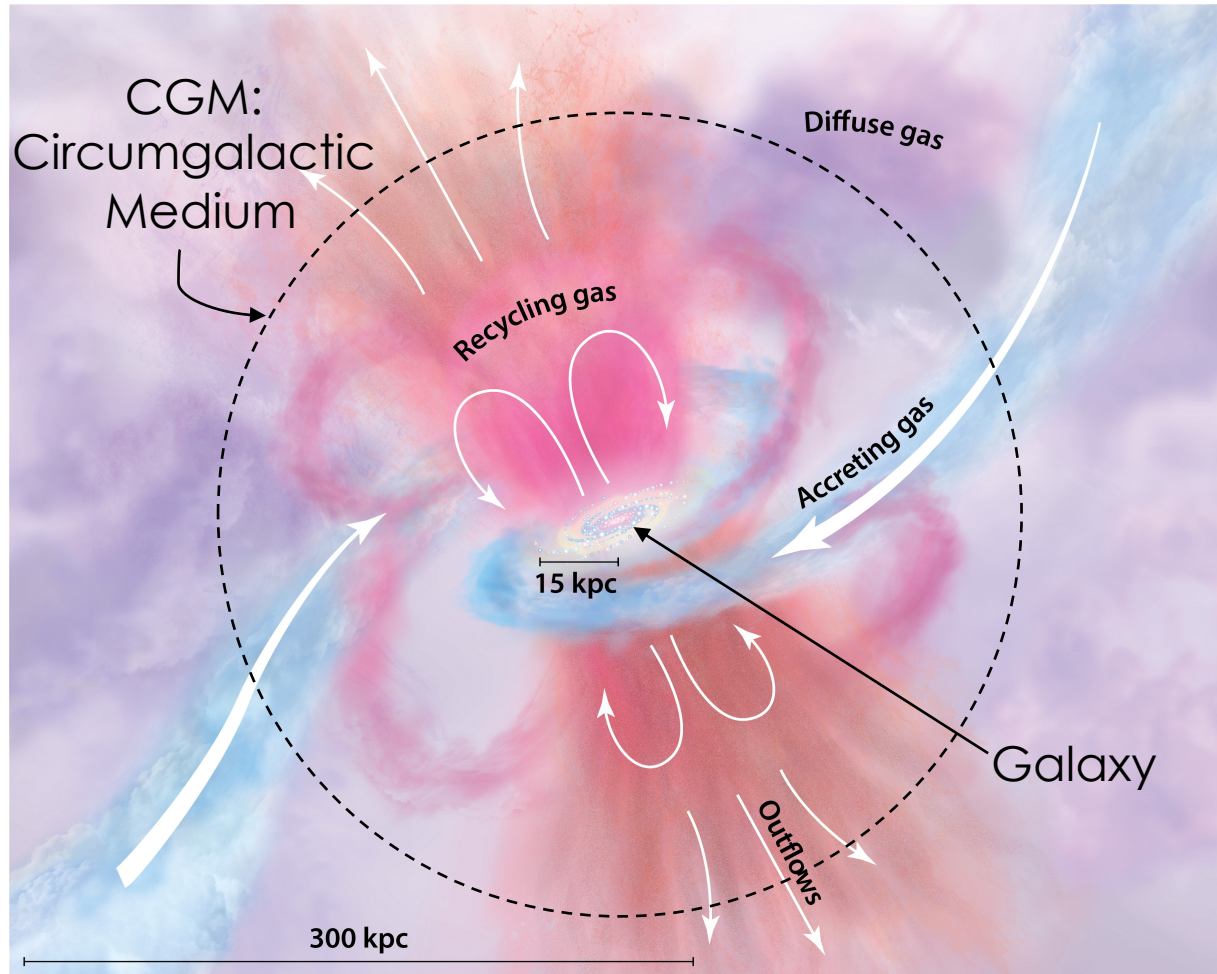
NASA Hubble Fellow  
NHFP Symposium 2024



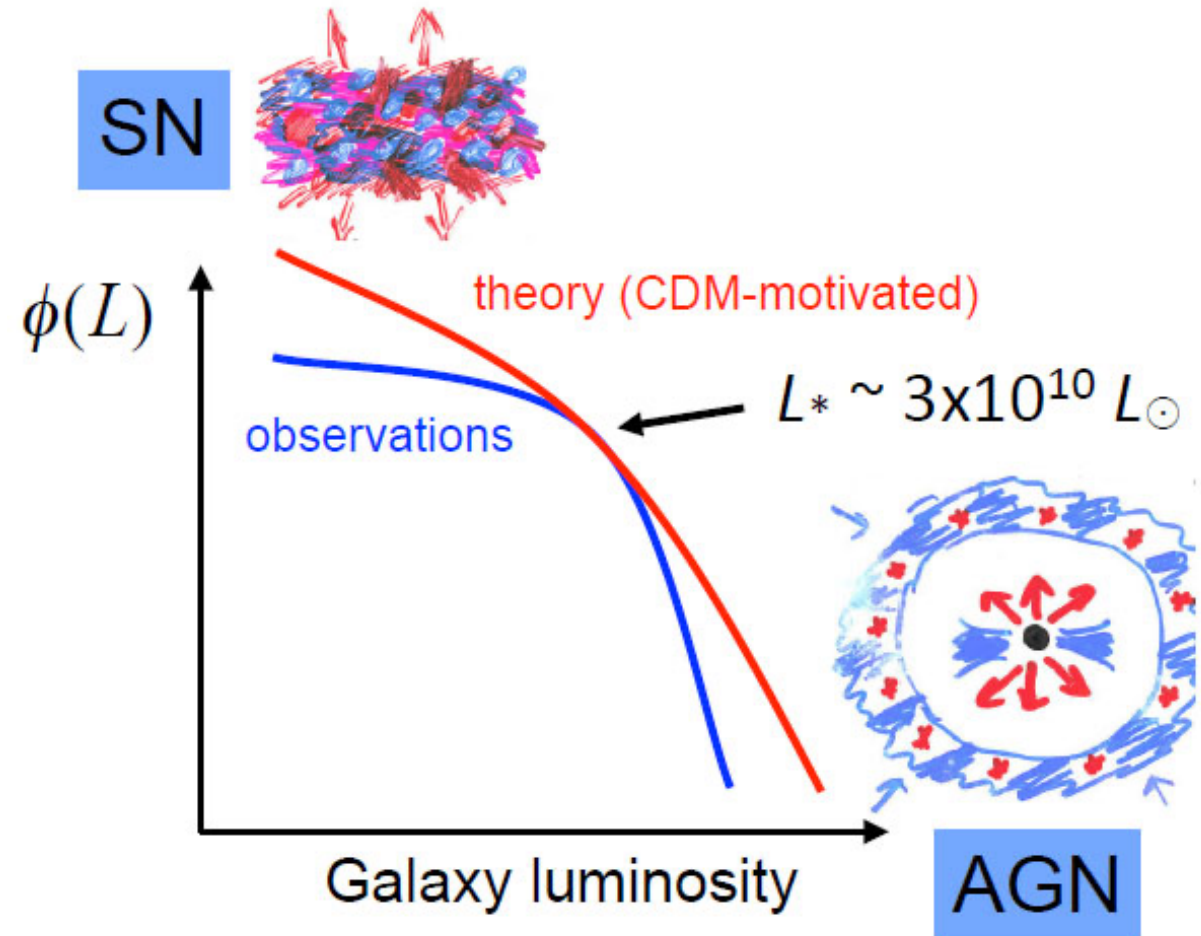
CENTER FOR  
ASTROPHYSICS  
HARVARD & SMITHSONIAN



# THE BARYON CYCLE, FEEDBACK, AND GALAXY EVOLUTION



Tumlinson+17

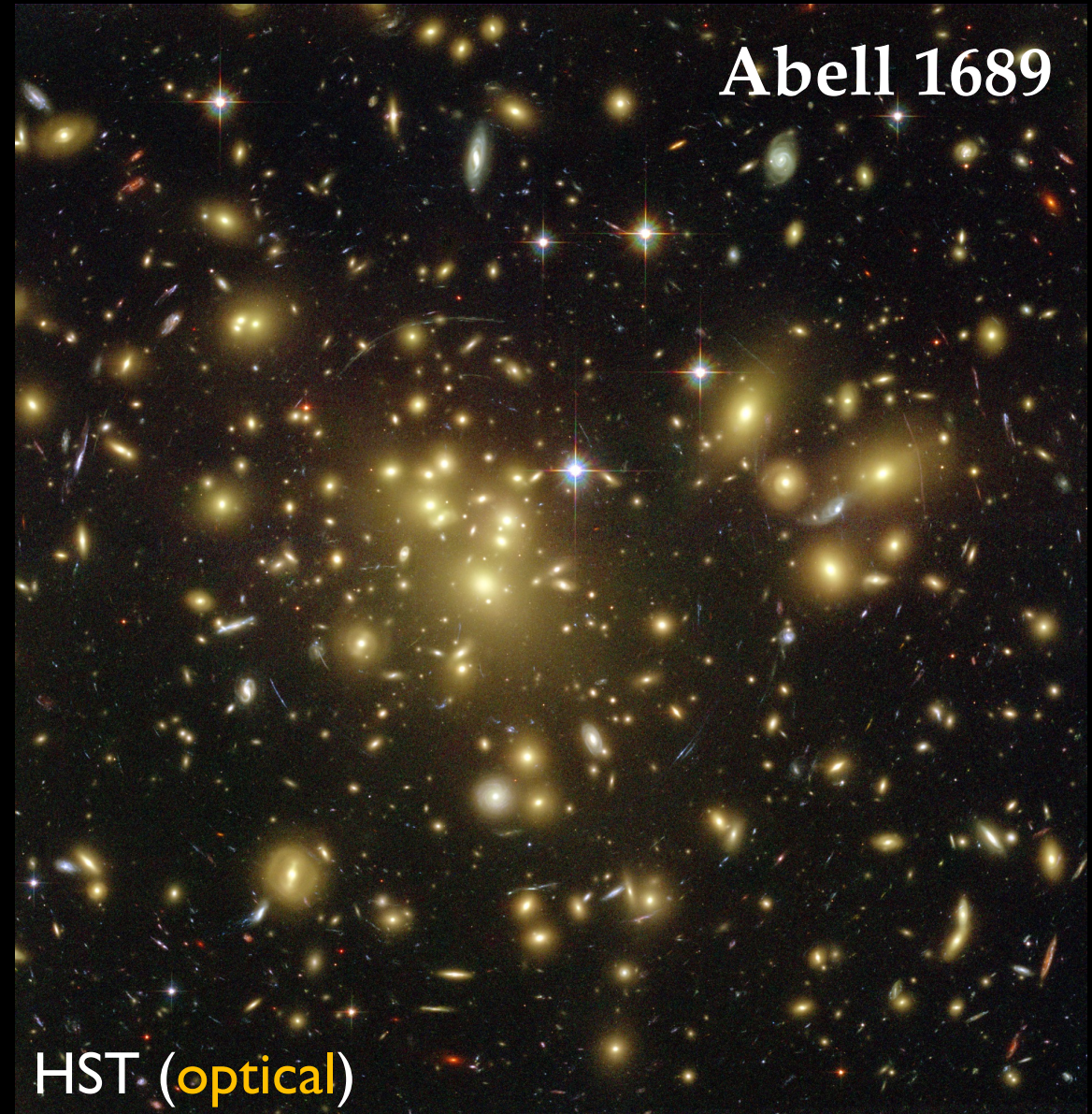


Silk & Mamon+12



# GALAXY CLUSTERS

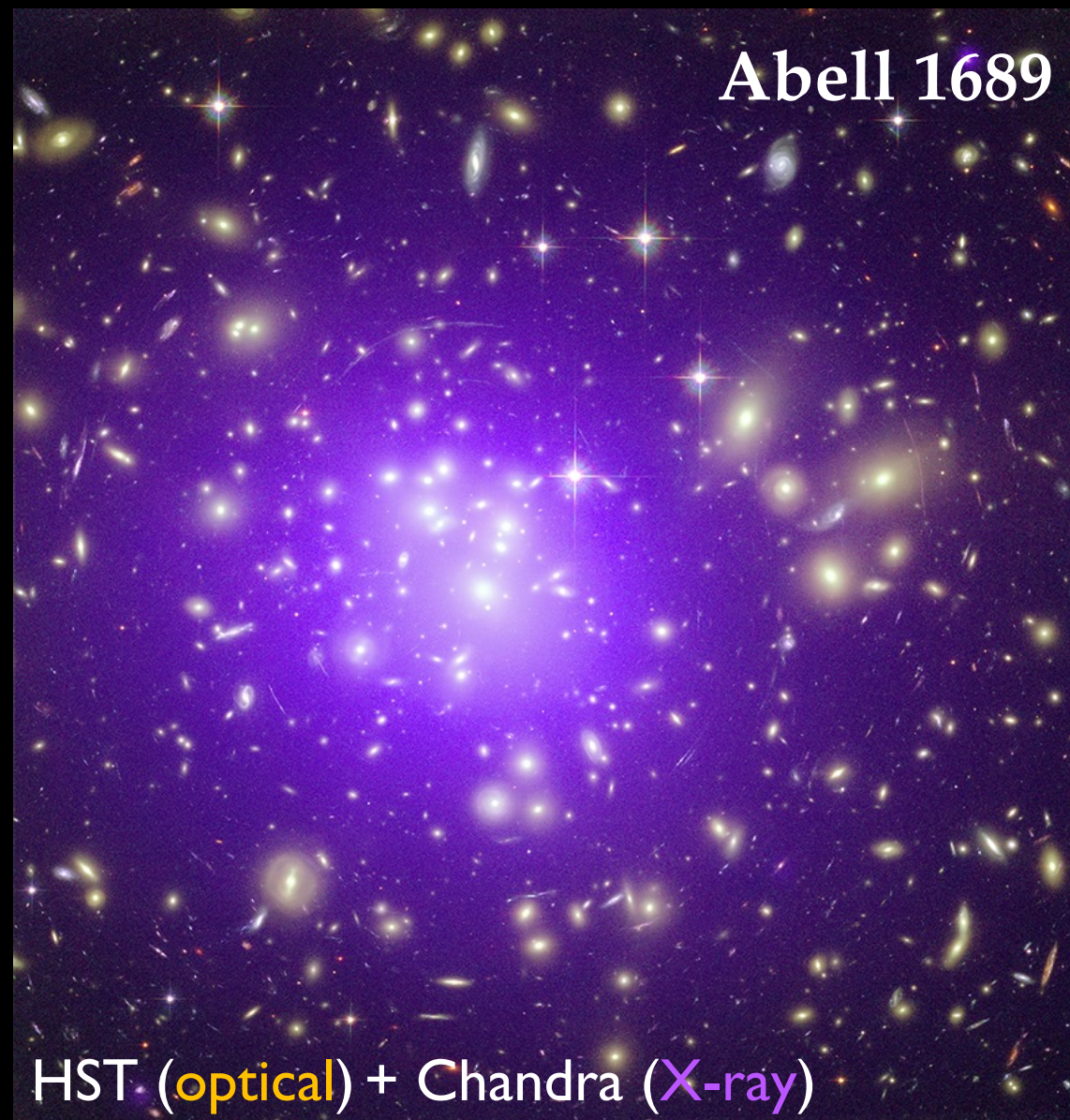
- Largest objects in Universe<sup>TM</sup>
- 10s – 100s of **galaxies**, often dominated by a brightest cluster galaxy (BCG)
- $\sim 10^{14} - 10^{15} M_{\odot}$





# GALAXY CLUSTERS

- Largest objects in Universe<sup>TM</sup>
- 10s – 100s of **galaxies**, often dominated by a brightest cluster galaxy (BCG)
- $\sim 10^{14} - 10^{15} M_{\odot}$
- Hot ( $10^7$  K) **intracluster medium** (ICM) makes up most (>90%) of the luminous matter
  - Inner ICM = CGM of BCG
- Gives off **X-rays** via radiative cooling (e.g. Bremsstrahlung)





# THE COOLING FLOW PROBLEM

$$\text{X-ray flux} \propto n_e^2 / \sqrt{T}$$



Cold and dense core



Expect high star formation rates  
(SFRs) in BCGs



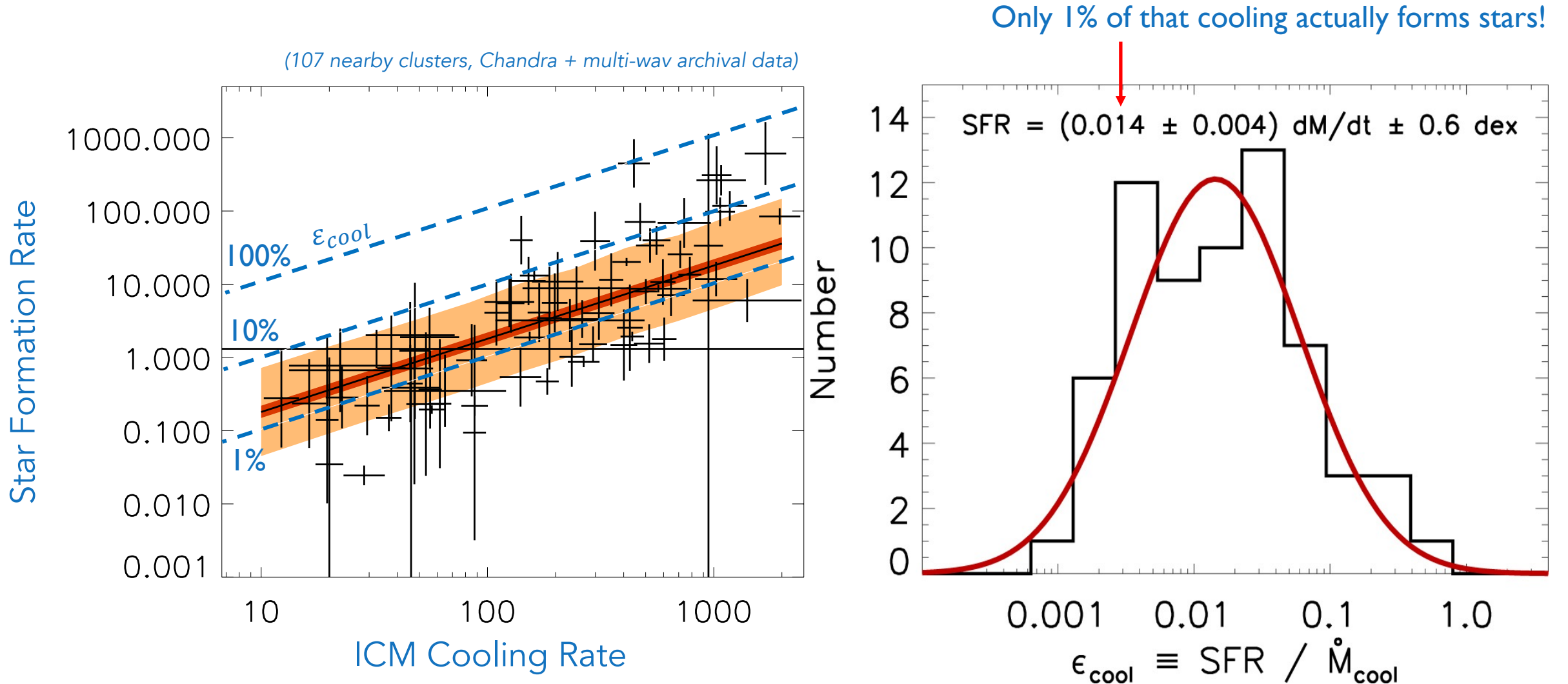




BCGs are “red and dead”

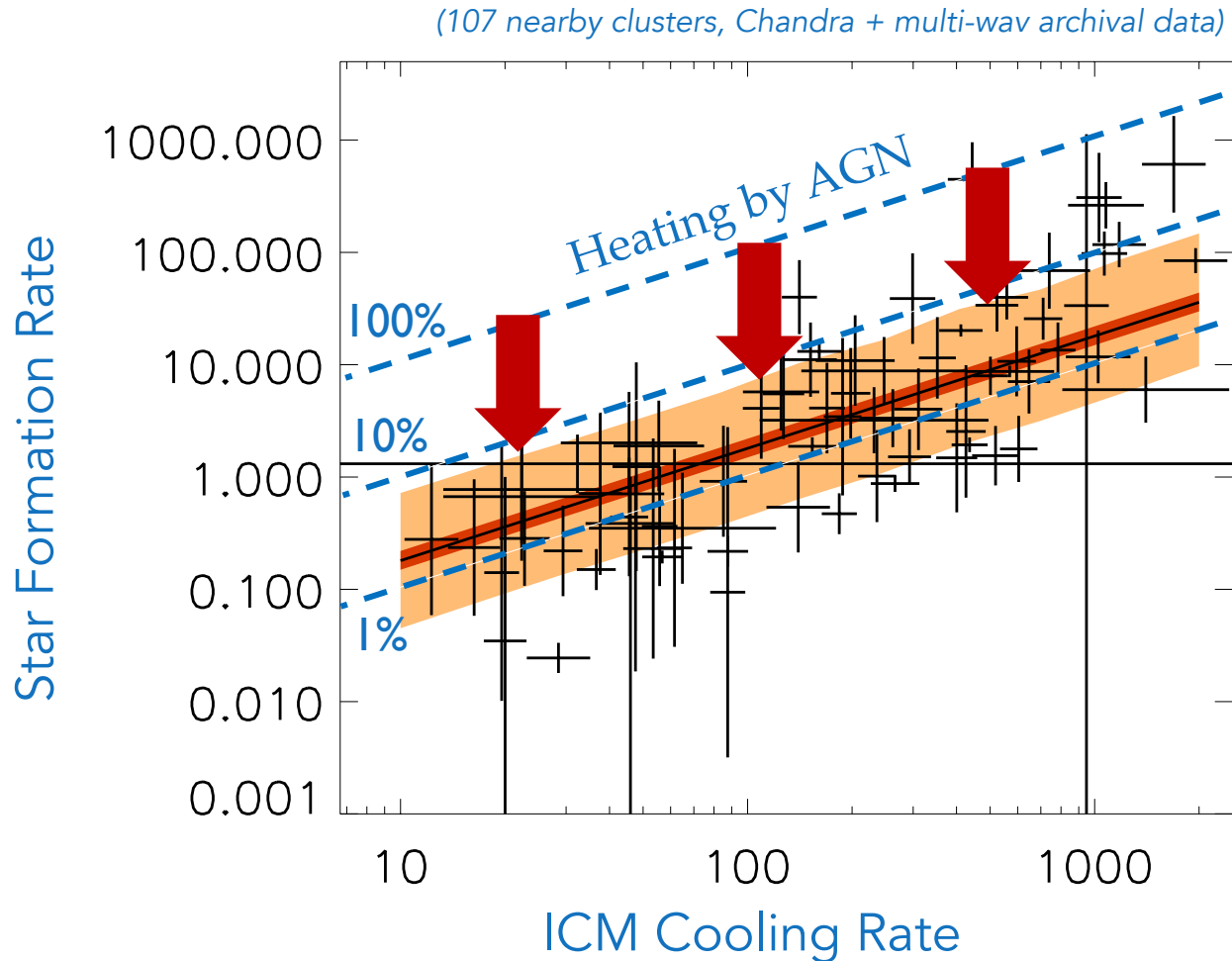


# THE COOLING FLOW PROBLEM





# SOLUTION: AGN FEEDBACK

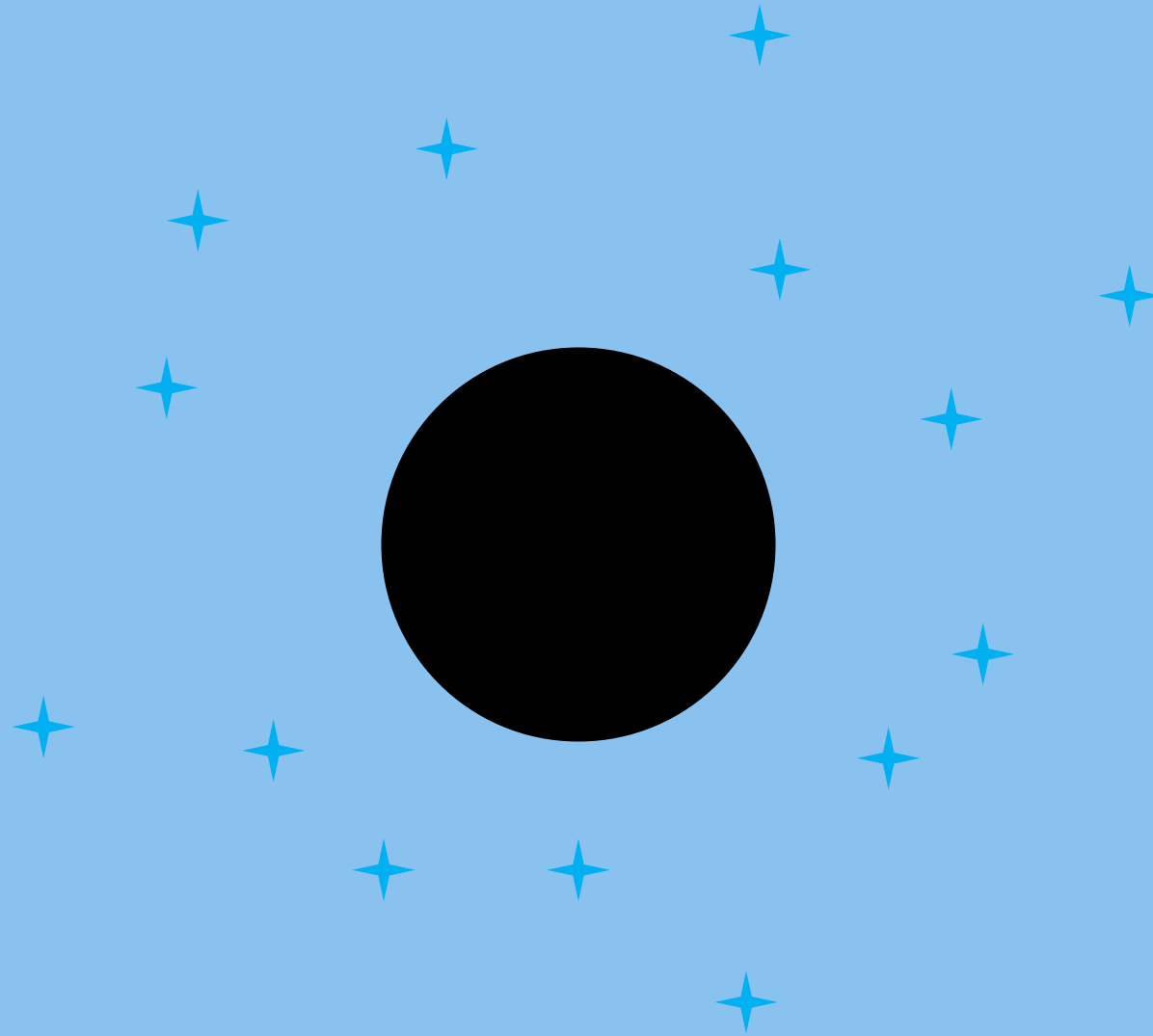


AGN (Active Galactic Nucleus) aka: an actively accreting / feeding supermassive black hole at the center (nucleus) of a galaxy





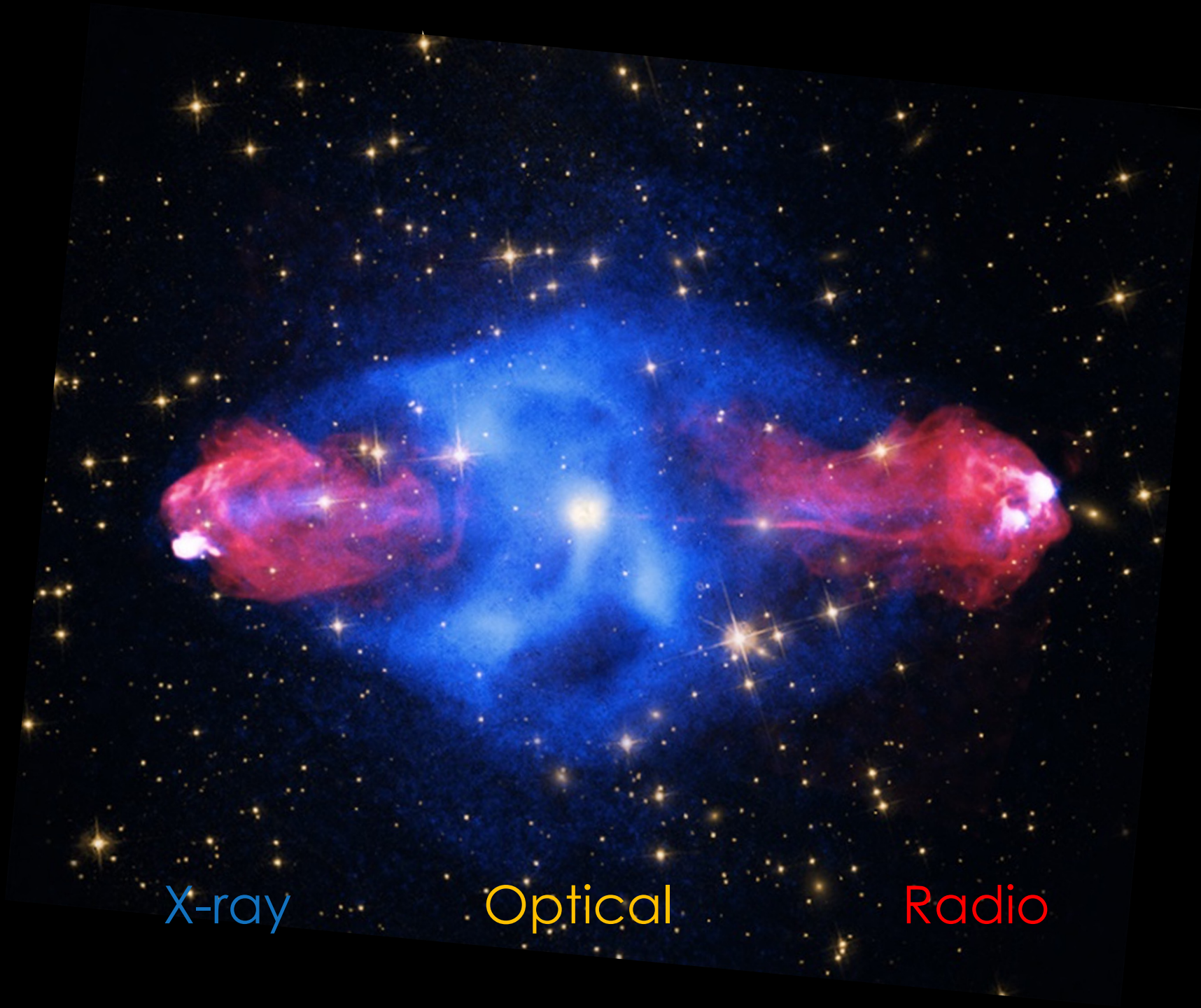
# THE AGN FEEDBACK CYCLE



4.3 On the Cooling Flow and the Massive Black Hole Feedback Loop

*BH and ICM not to scale*





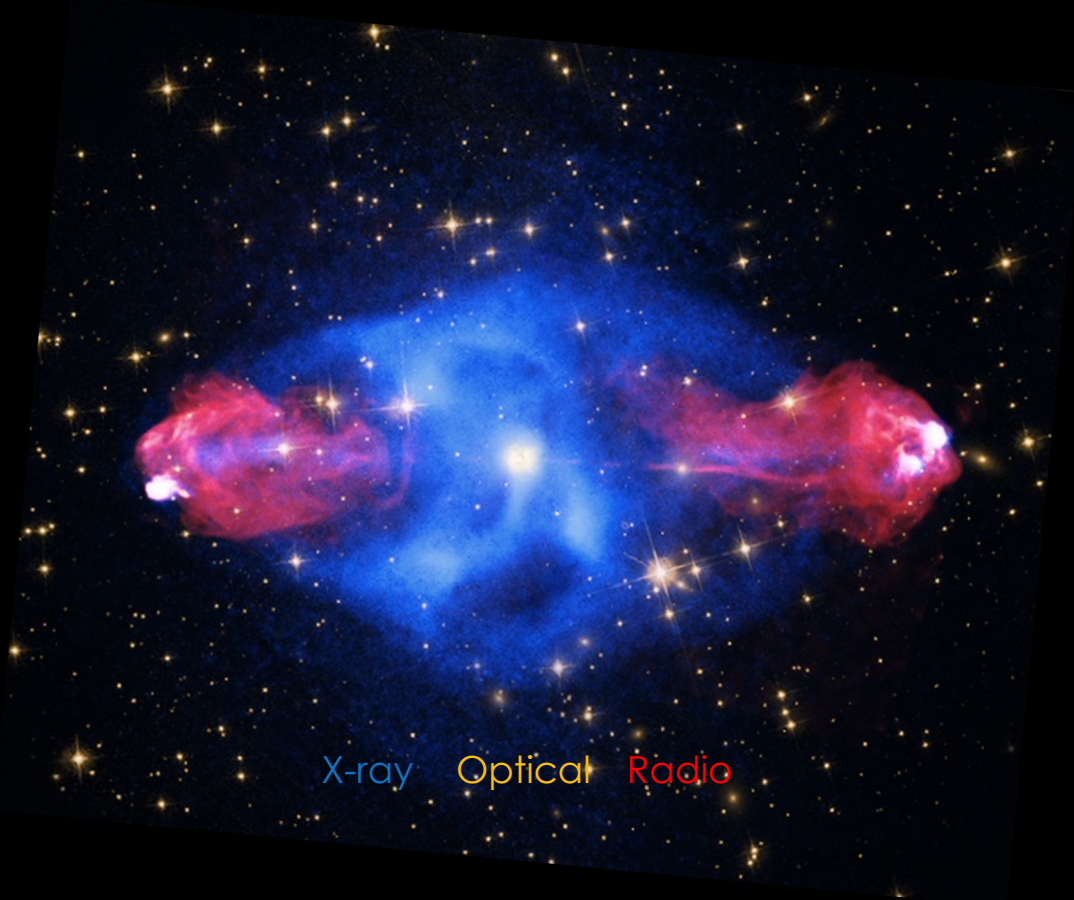
X-ray

Optical

Radio



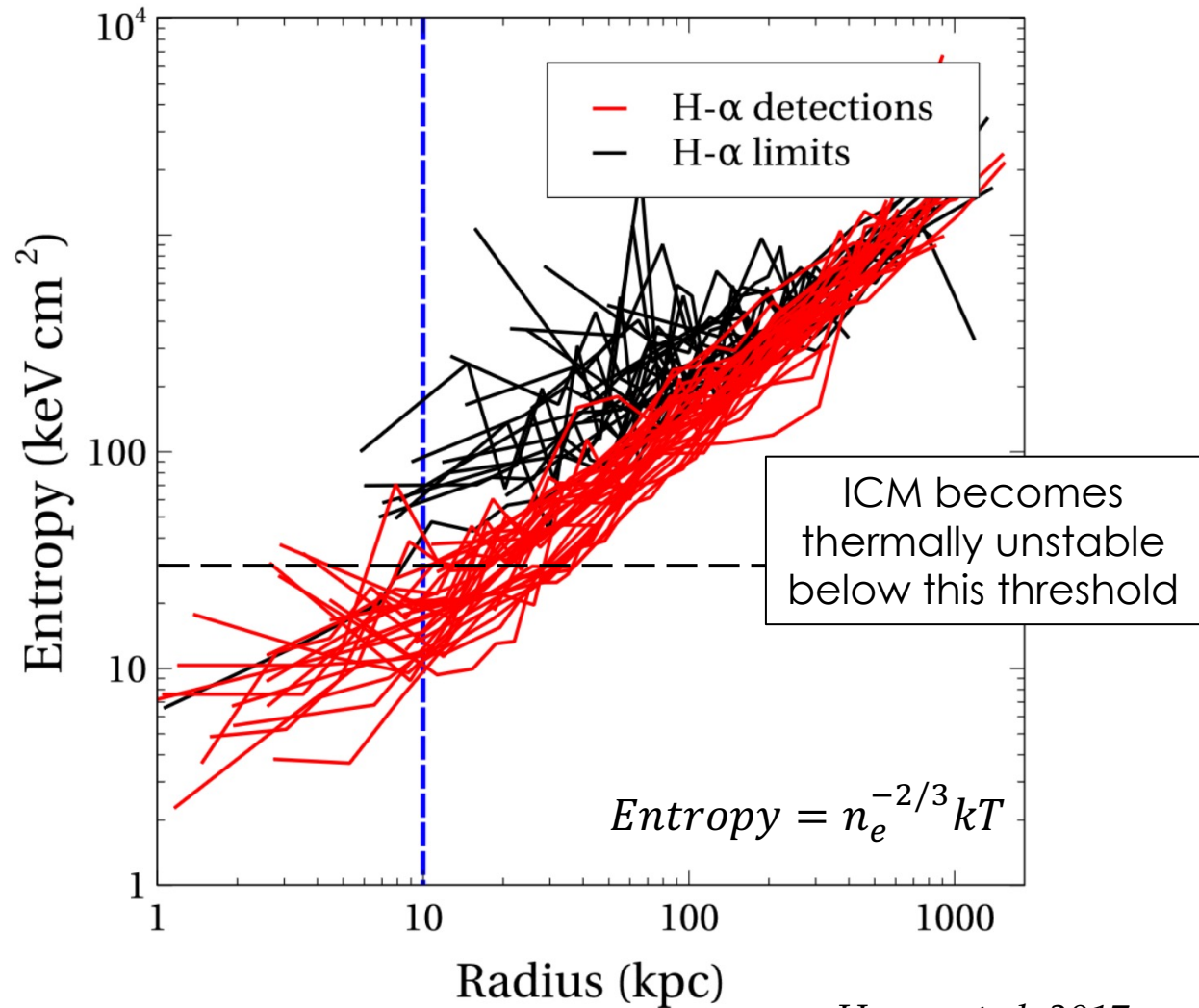
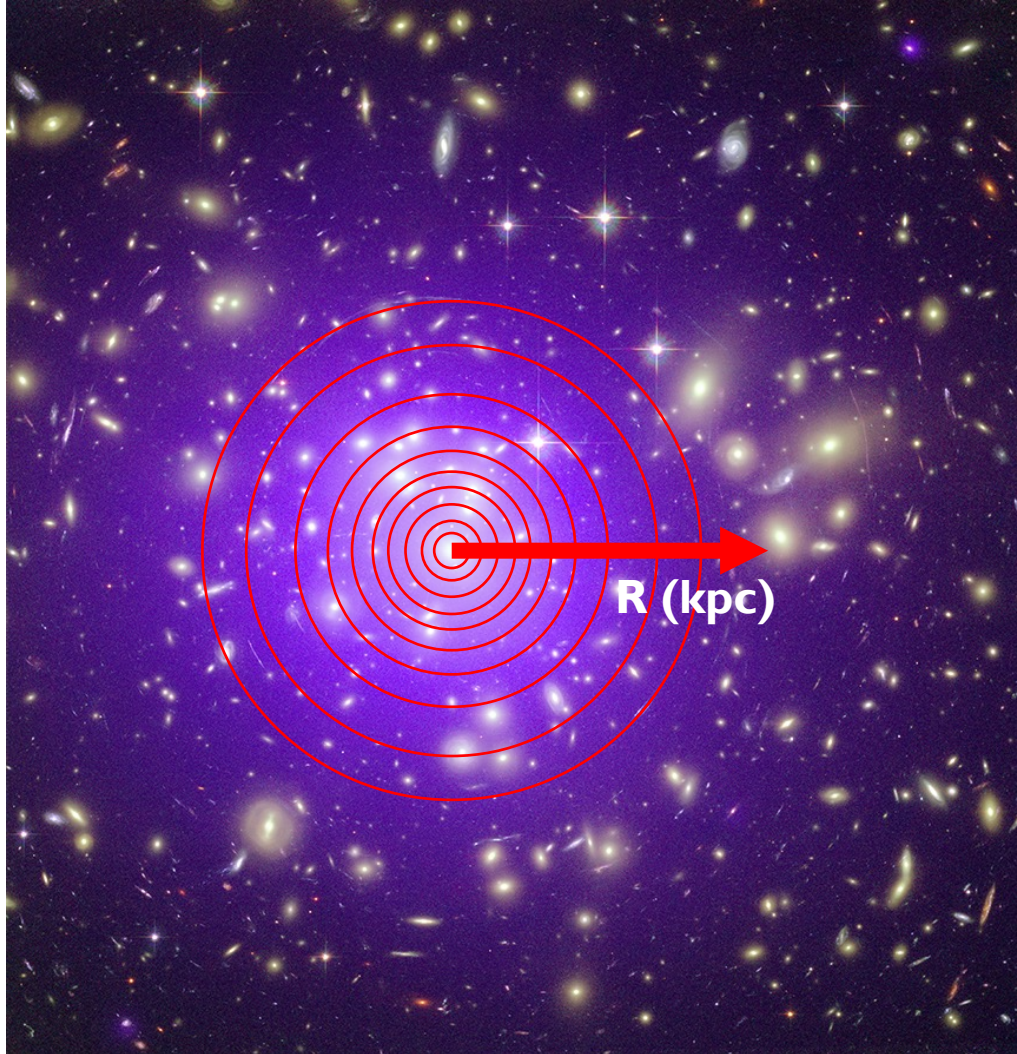
# EVOLUTION OF THE AGN FEEDBACK CYCLE



- Multi-wavelength observations of galaxy clusters best way to see entire baryon cycle in largest galaxies
- AGN feedback biggest driver of BCG evolution
- Some remaining questions:
  - How long has this balance been in place?
  - Have the conditions for triggering cooling and feedback evolved?
  - Has feedback's effectiveness changed with time?
- Only recently able to start addressing these



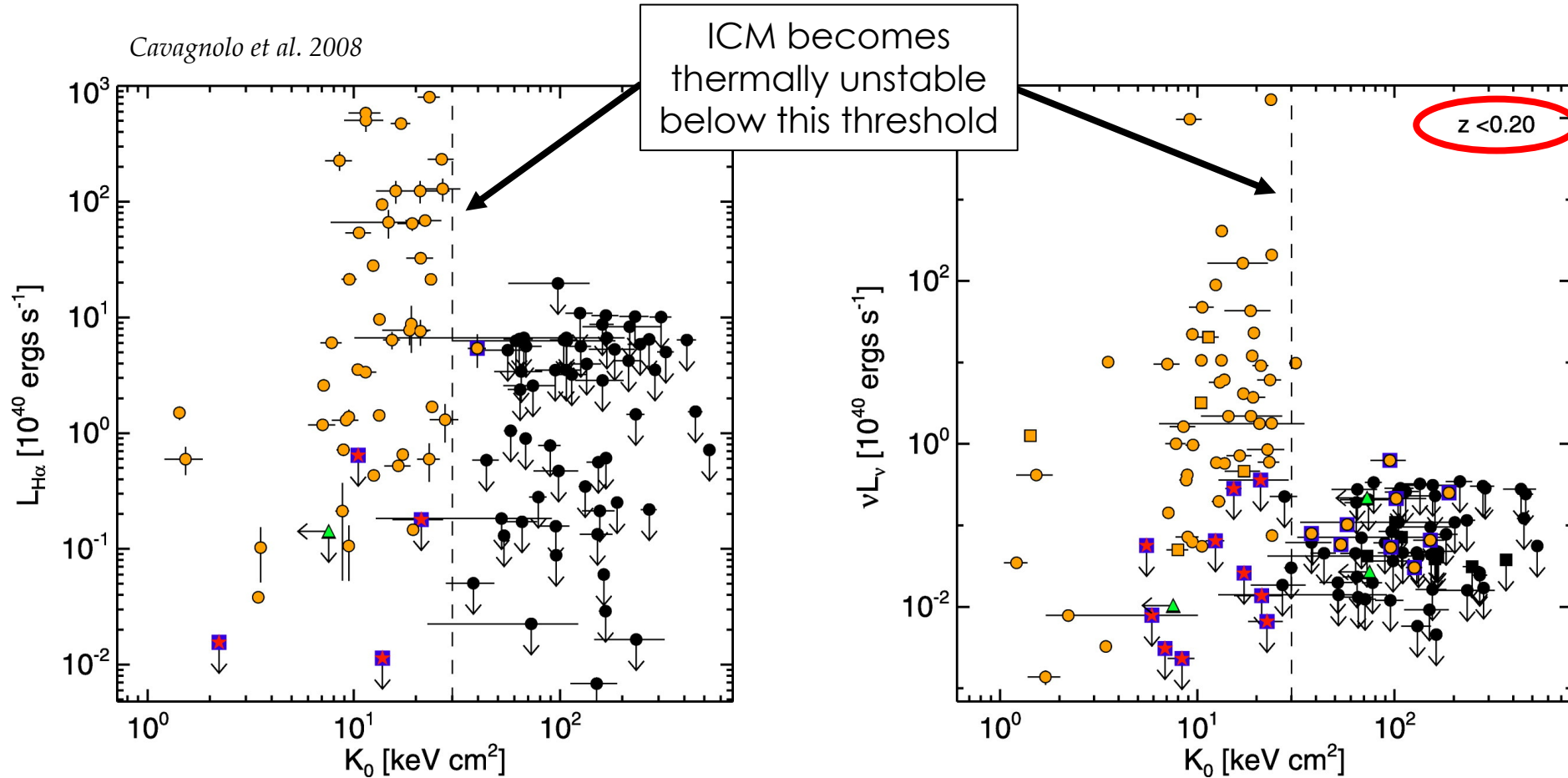
# ENTROPY THRESHOLD FOR TRIGGERING COOLING AND FEEDBACK



*Hogan et al. 2017*



# ENTROPY THRESHOLD FOR TRIGGERING COOLING AND FEEDBACK



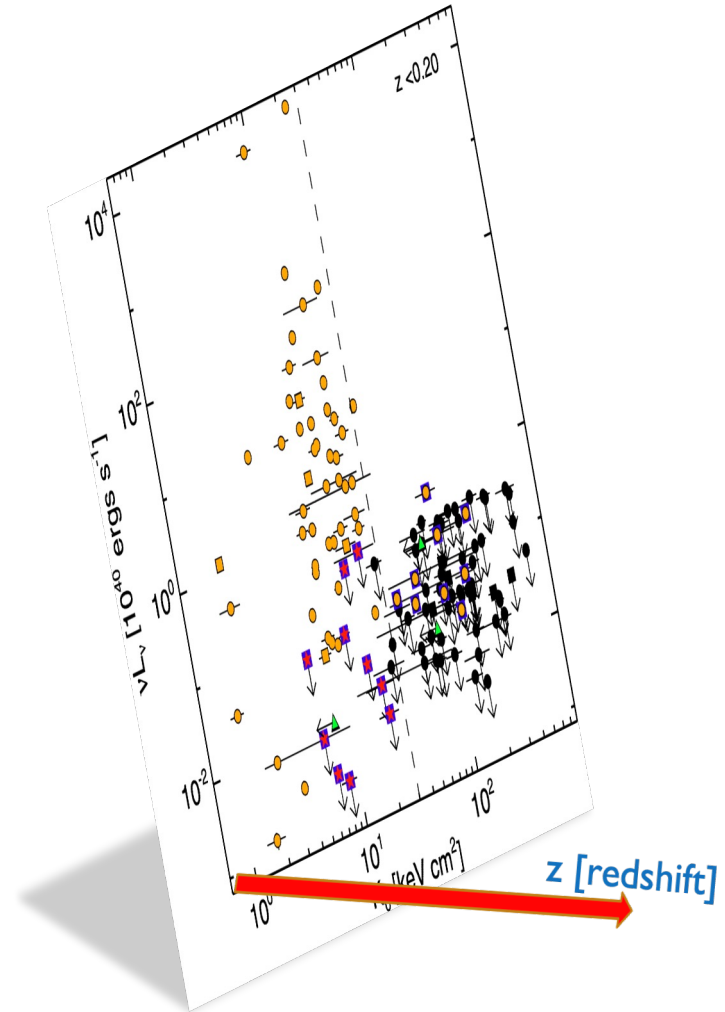
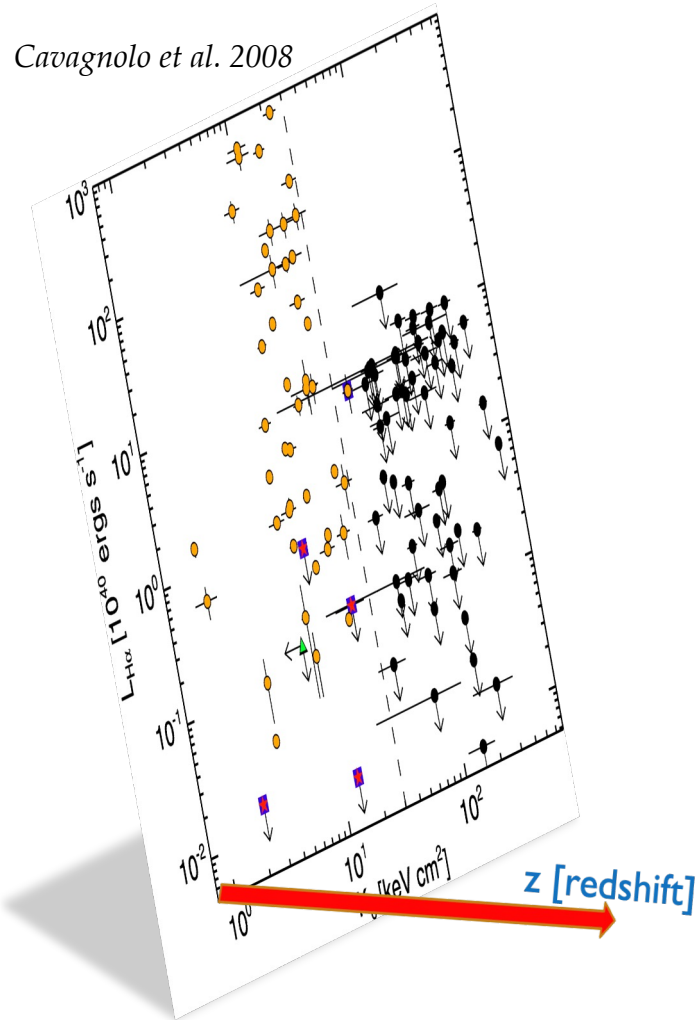
which triggers **star formation**

and

**AGN feedback**



# HAVE THE CONDITIONS FOR TRIGGERING COOLING AND FEEDBACK EVOLVED?





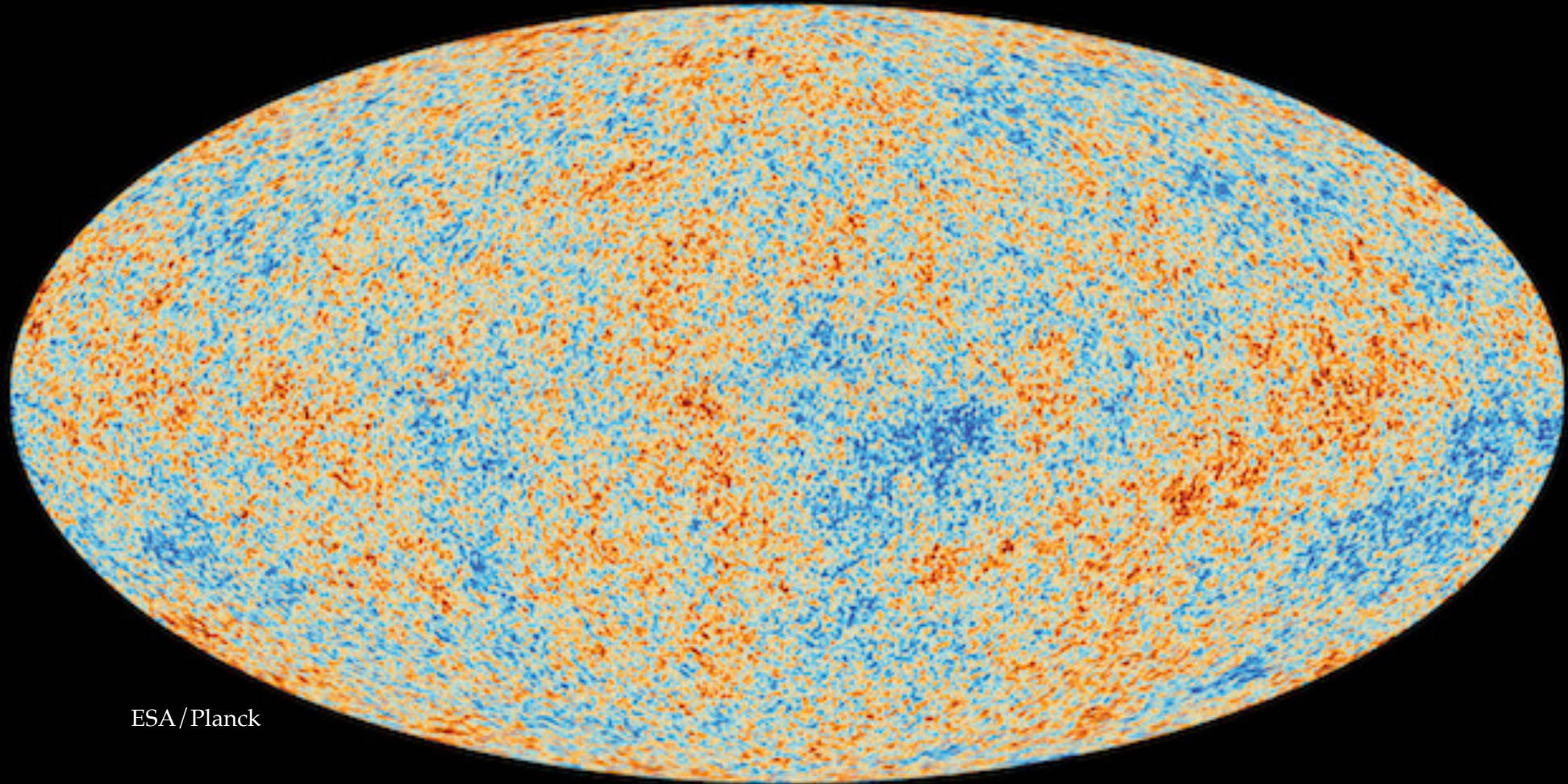
# SOUTH POLE TELESCOPE





# Sunyaev-Zel'dovich (SZ) EFFECT

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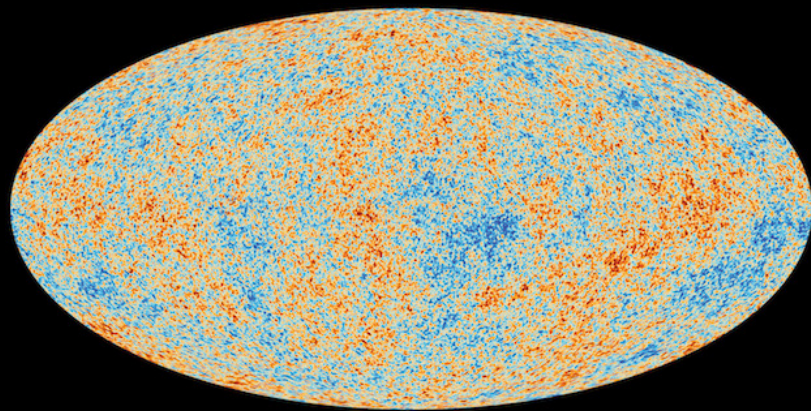


ESA/Planck

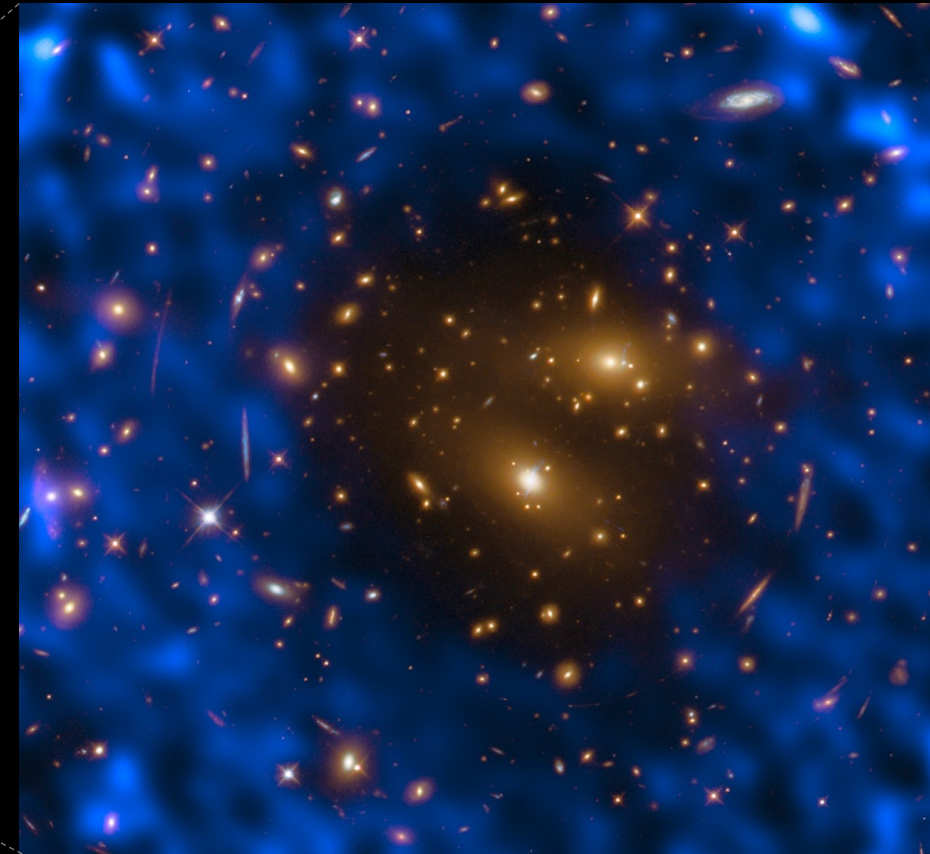
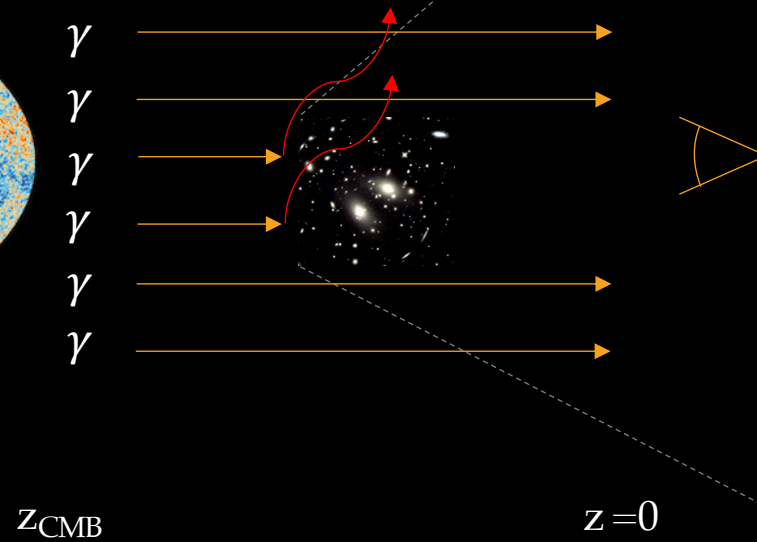


# Sunyaev-Zel'dovich (SZ) EFFECT

- Redshift-independent detection of galaxy clusters
- Enables evolutionary studies

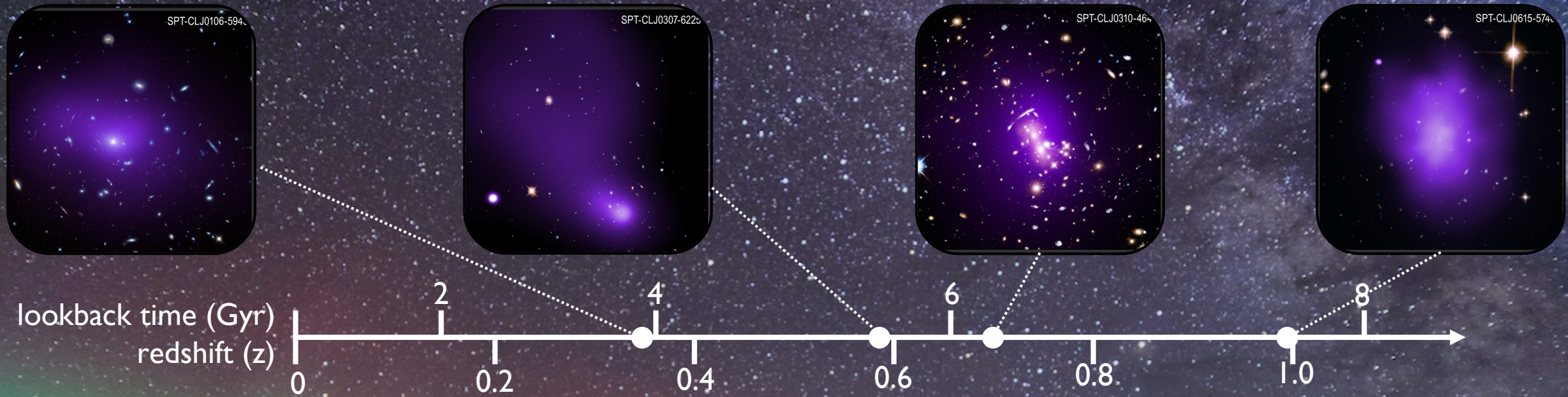


ESA/Planck



ALMA (ESO/NAOJ/NRAO)/T. Kitayama, ESA/Hubble & NASA





## SPT-Chandra sample:

Unbiased sample of 95 clusters spanning 10 Gyr in evolution

Multiwavelength followup:

~4 Ms Chandra (X-ray)

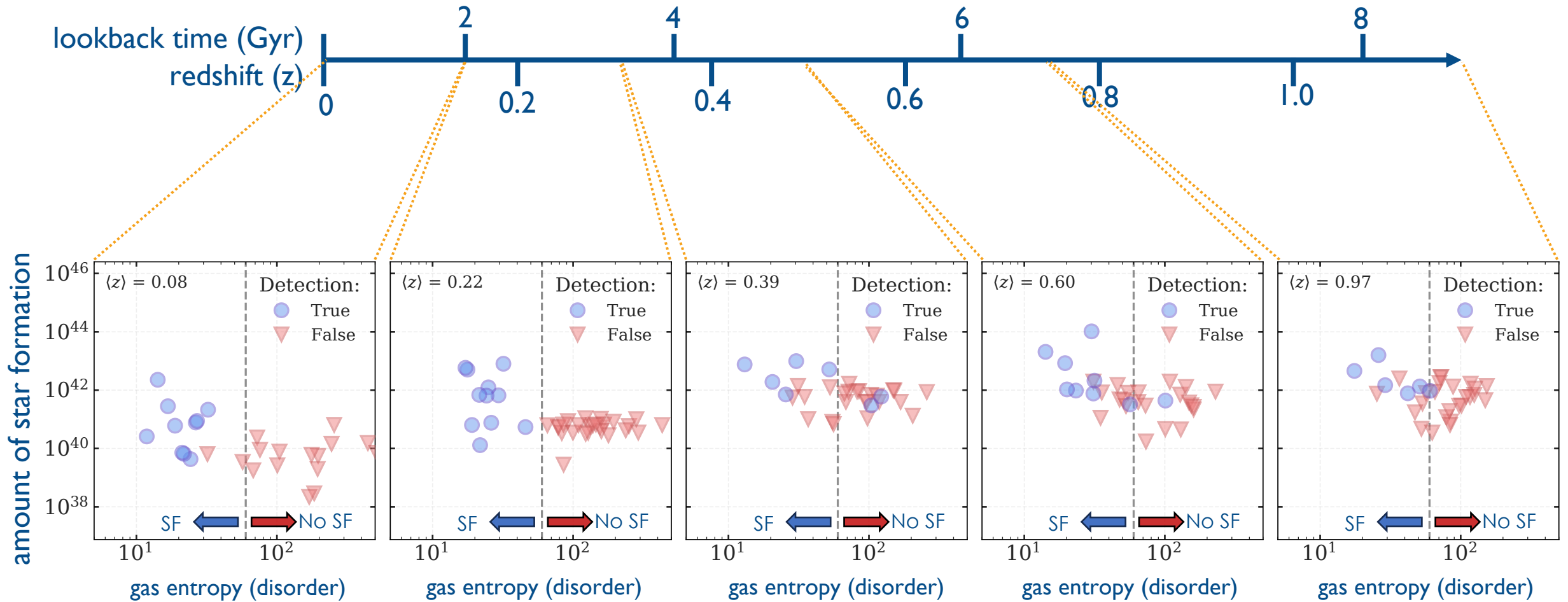
~30 nights optical spectroscopy

-- Full radio coverage



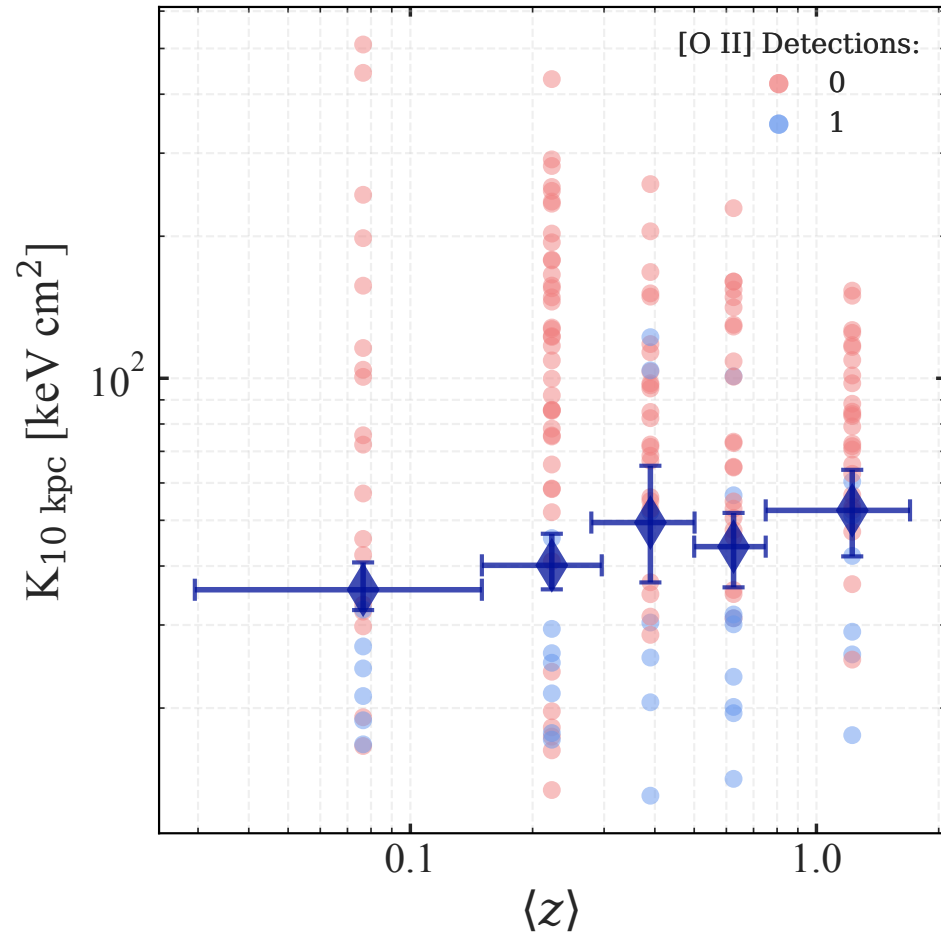


# TRIGGER FOR STAR FORMATION PERSISTS FOR 10 GYR





# CONDITIONS FOR MULTIPHASE COOLING

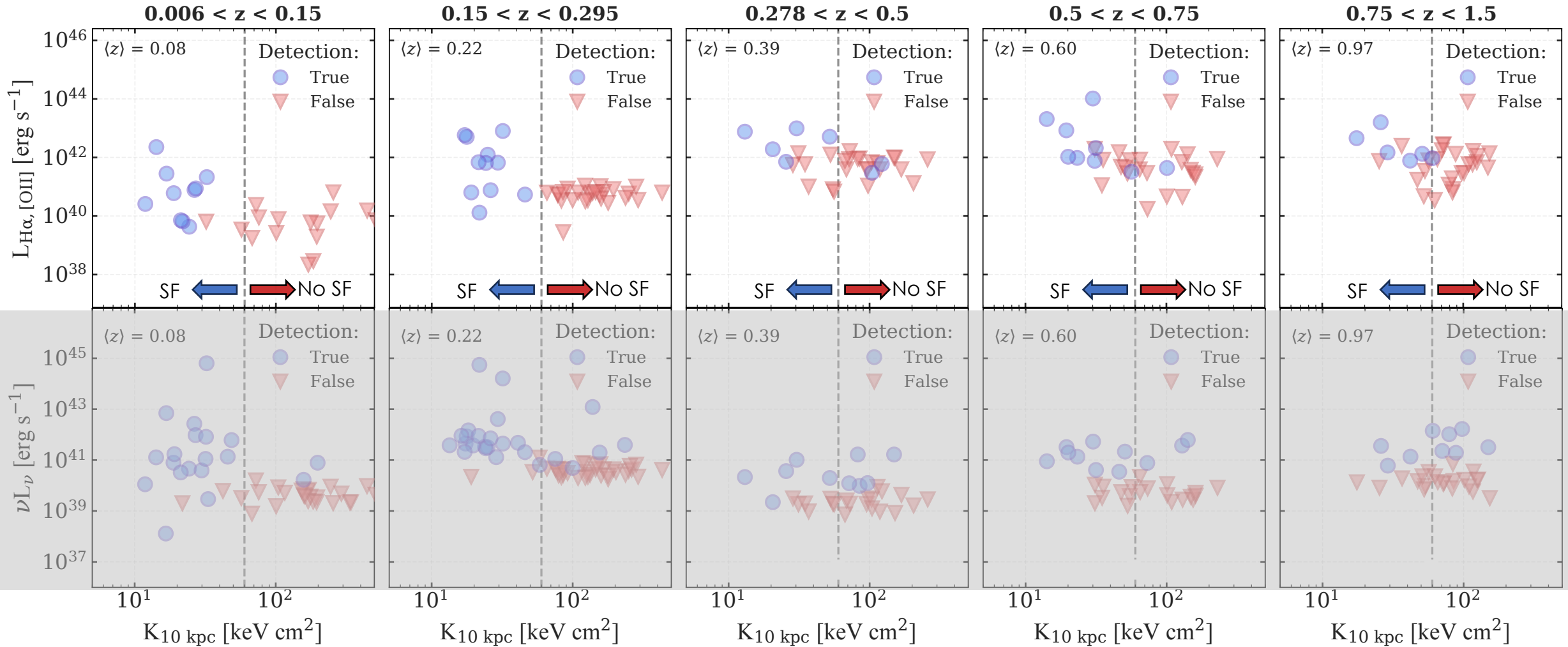


No significant evolution  
in threshold value

Strong, long-lived connection  
between ICM cooling and SF



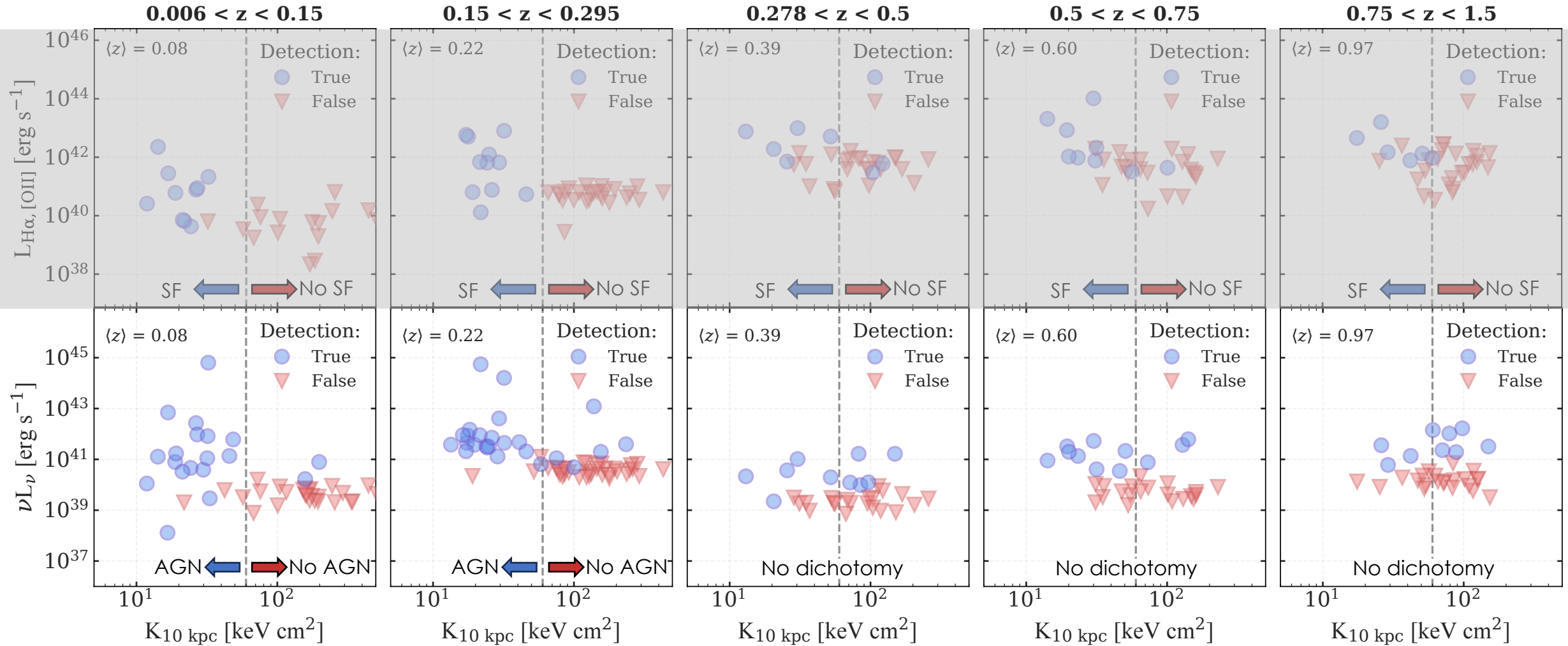
# HAVE THE CONDITIONS FOR COOLING EVOLVED?



*Calzadilla et al. 2024a*



# HAVE THE CONDITIONS FOR FEEDBACK EVOLVED?



Calzadilla et al. 2024a

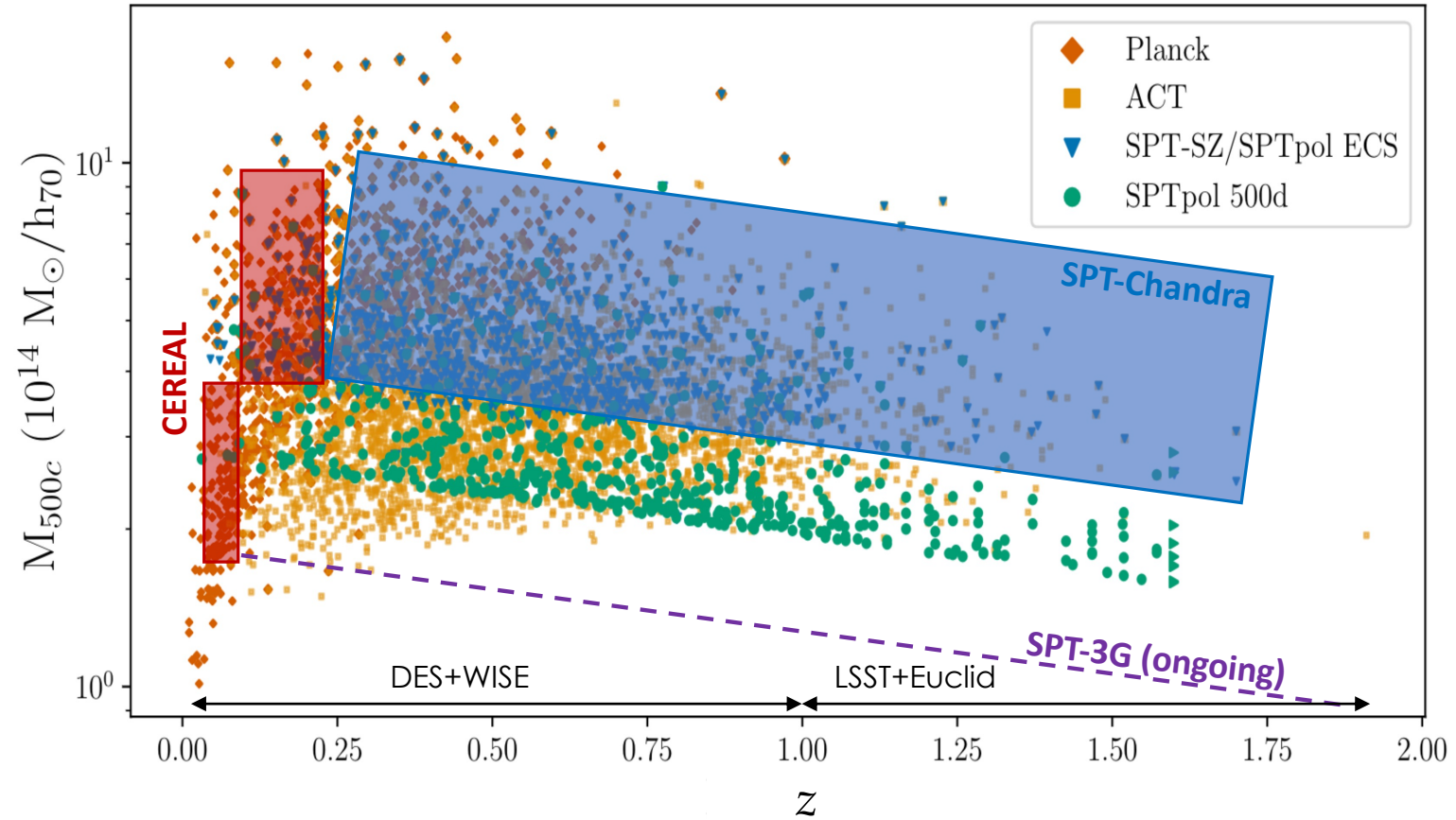


# FUTURE WORK

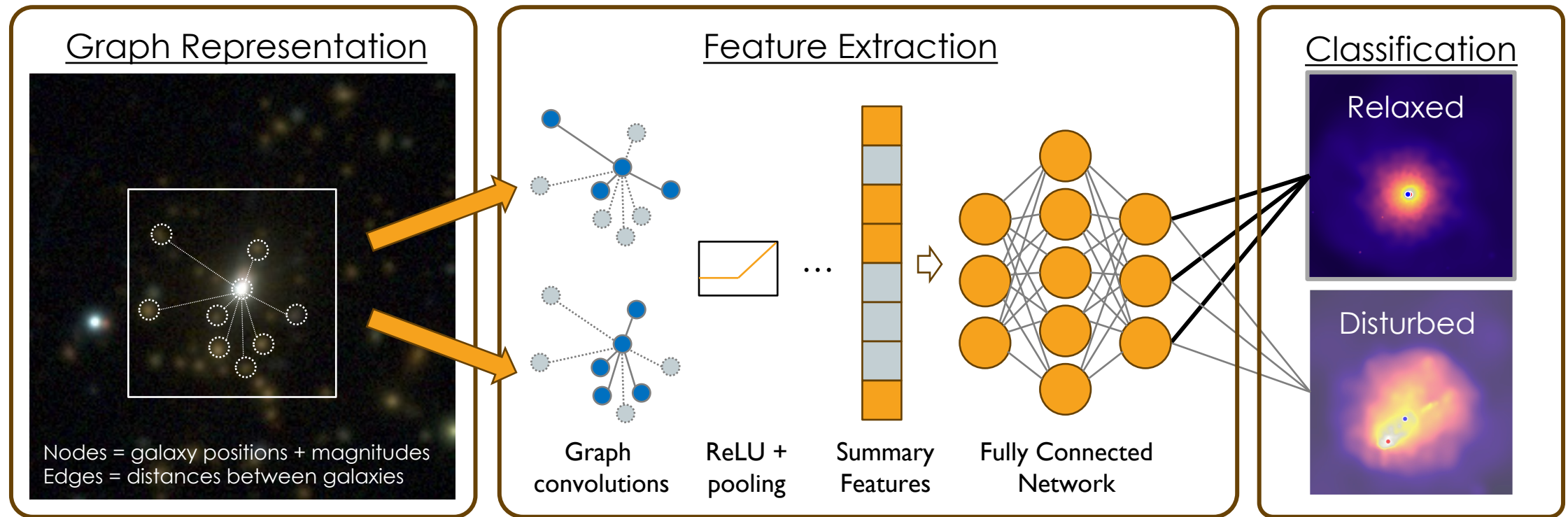
SPT-3G: ~5000 clusters out to  $z \sim 2$

→ Will use ML to characterize

→ Subset of hundreds of clusters with X-ray+optical+radio to probe beginnings of AGN feedback cycle



# MACHINE LEARNING CLUSTER DYNAMICAL STATES



Train on simulation → apply to real SPT-3G sample  
Disentangle BCG growth and BH fueling mechanism from evolution



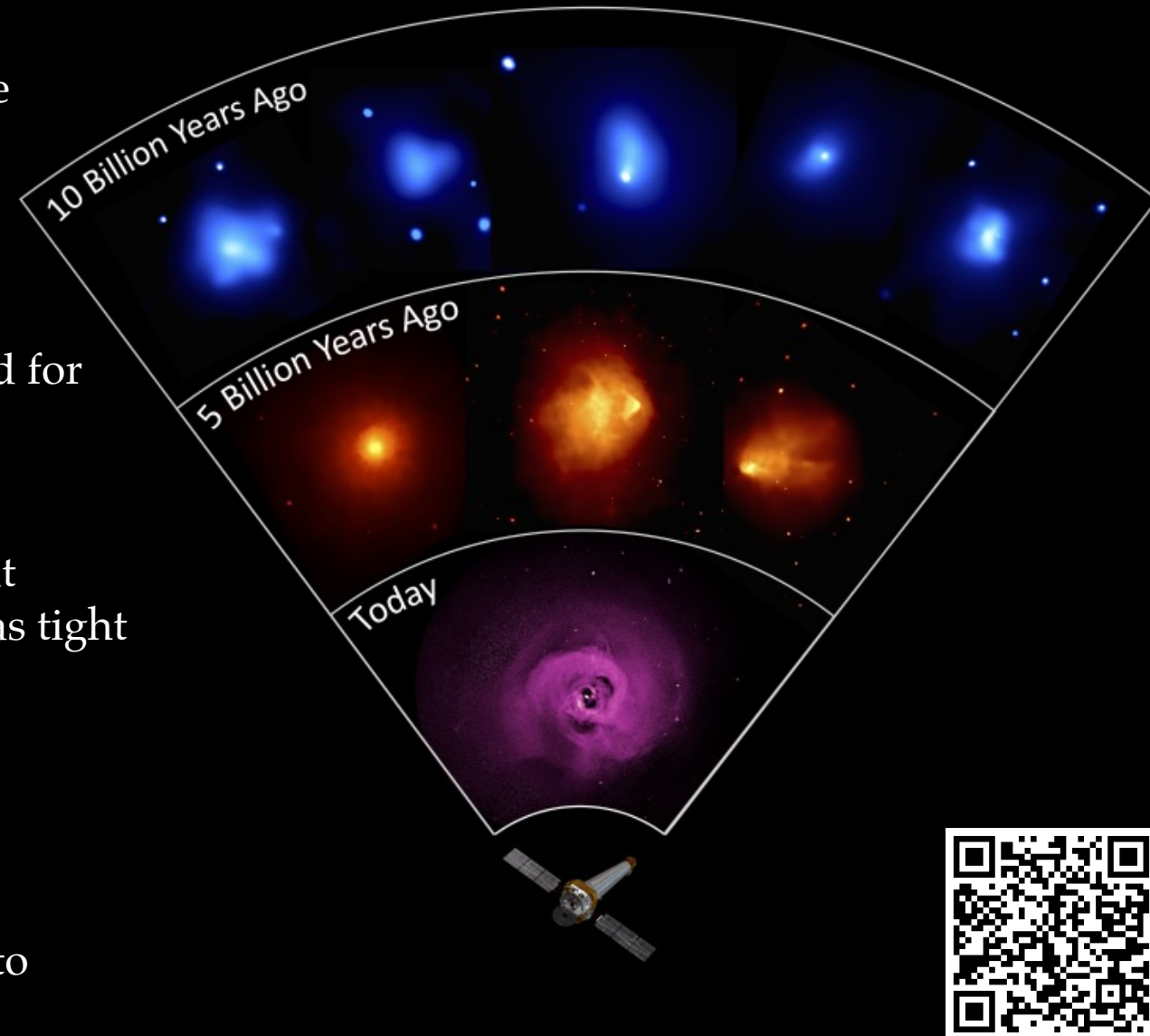
# EVOLUTION OF AGN FEEDBACK CONDITIONS IN GALAXY CLUSTERS

(arXiv:2311.00396)

- Clusters are a great way to see entire baryon cycle
- AGN feedback drives evolution of BCGs
- At low- $z$ , feedback is triggered when ICM central entropy drops below a certain threshold
- Show for the first time that this entropy threshold for cooling persists out to  $z > 1$
- No significant evolution in this threshold value
- Entropy threshold for AGN activity disappears at higher- $z$   $\rightarrow$  cooling-feedback connection wasn't as tight

**Stay tuned for follow-up papers!**

- Evolution of cooling / feedback efficiency
- Machine Learning Cluster Dynamical States
- BCG+AGN fuel supply transition from mergers to ICM cooling

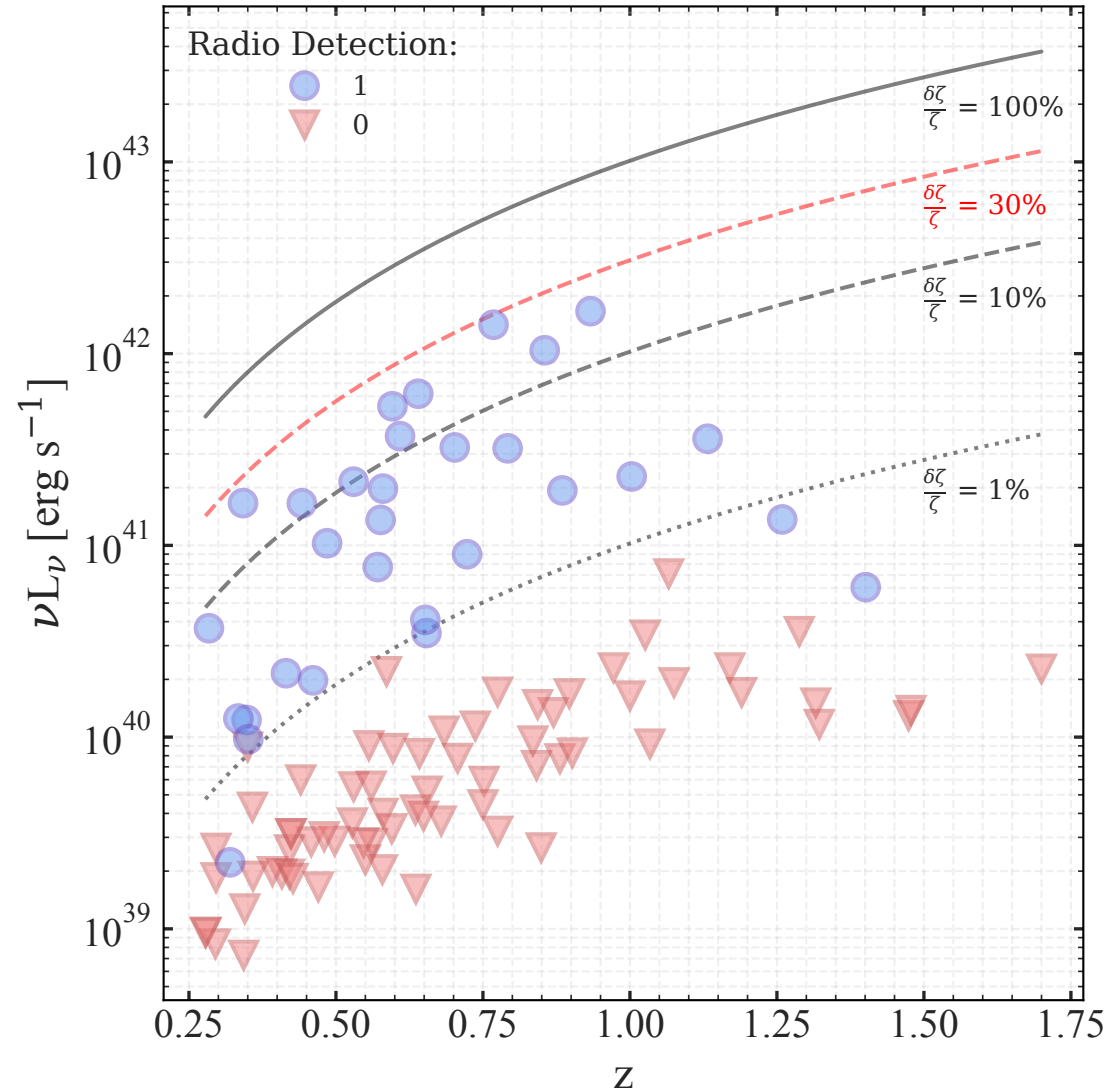


# MISSING HIGH POWER RADIO SOURCES

Only missing ~4% of high power sources expected from low-z

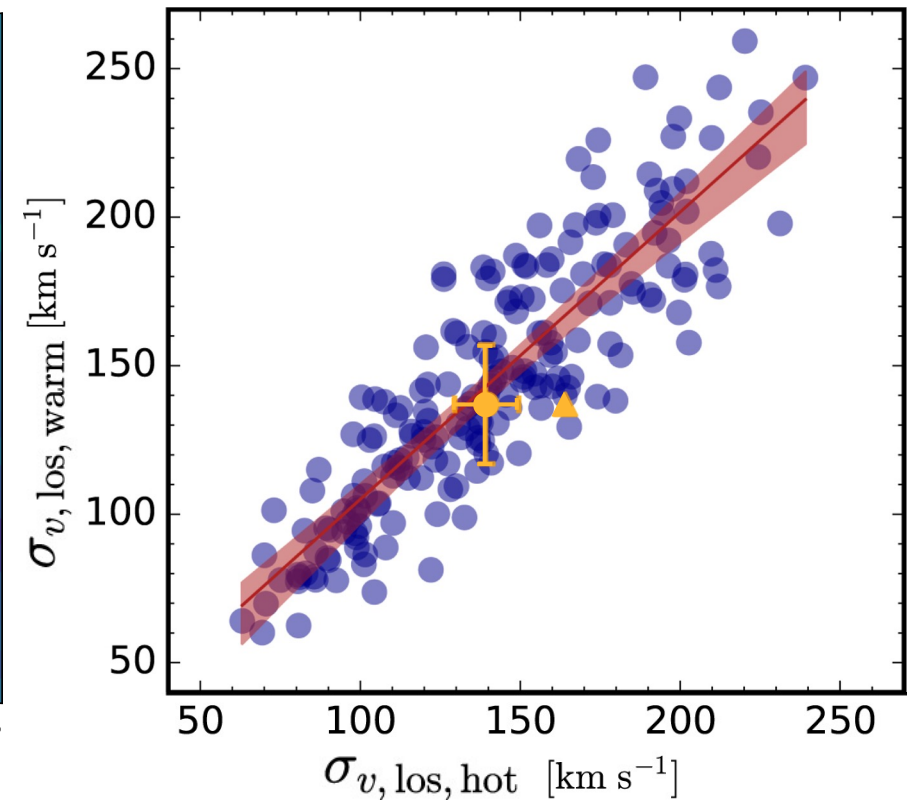
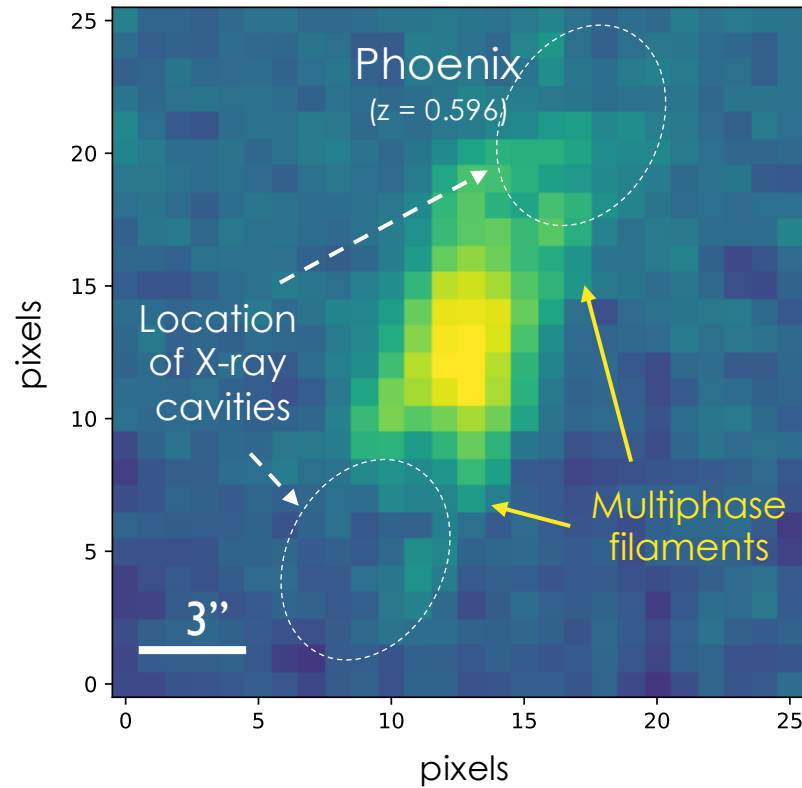
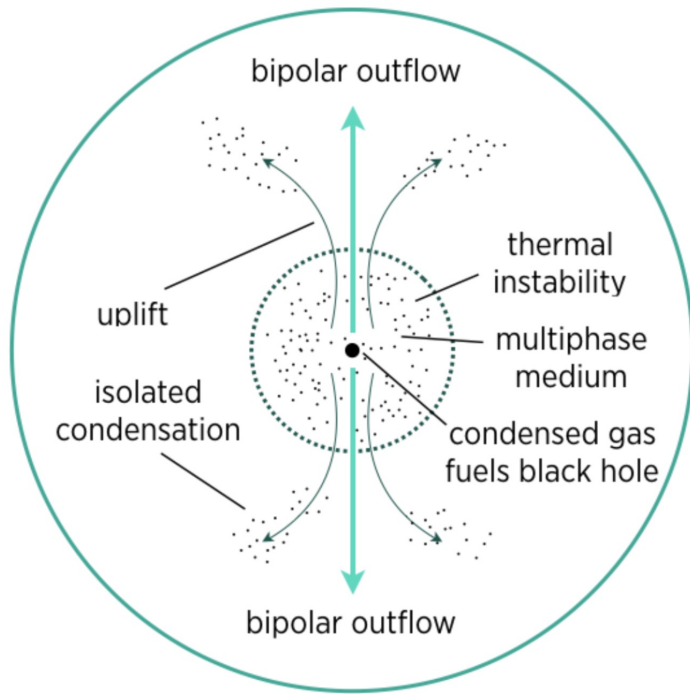
Radio bias to SZ signal:

$$\langle \delta\zeta/\zeta \rangle = -0.03 \left( \frac{\nu_{\text{SZ}}}{1.4 \text{ GHz}} \right)^{-\alpha_s} \left( \frac{S_{1.4}}{\text{mJy}} \right) \left( \frac{M_{500}}{10^{14} M_{\odot}} \right)^{-1}$$

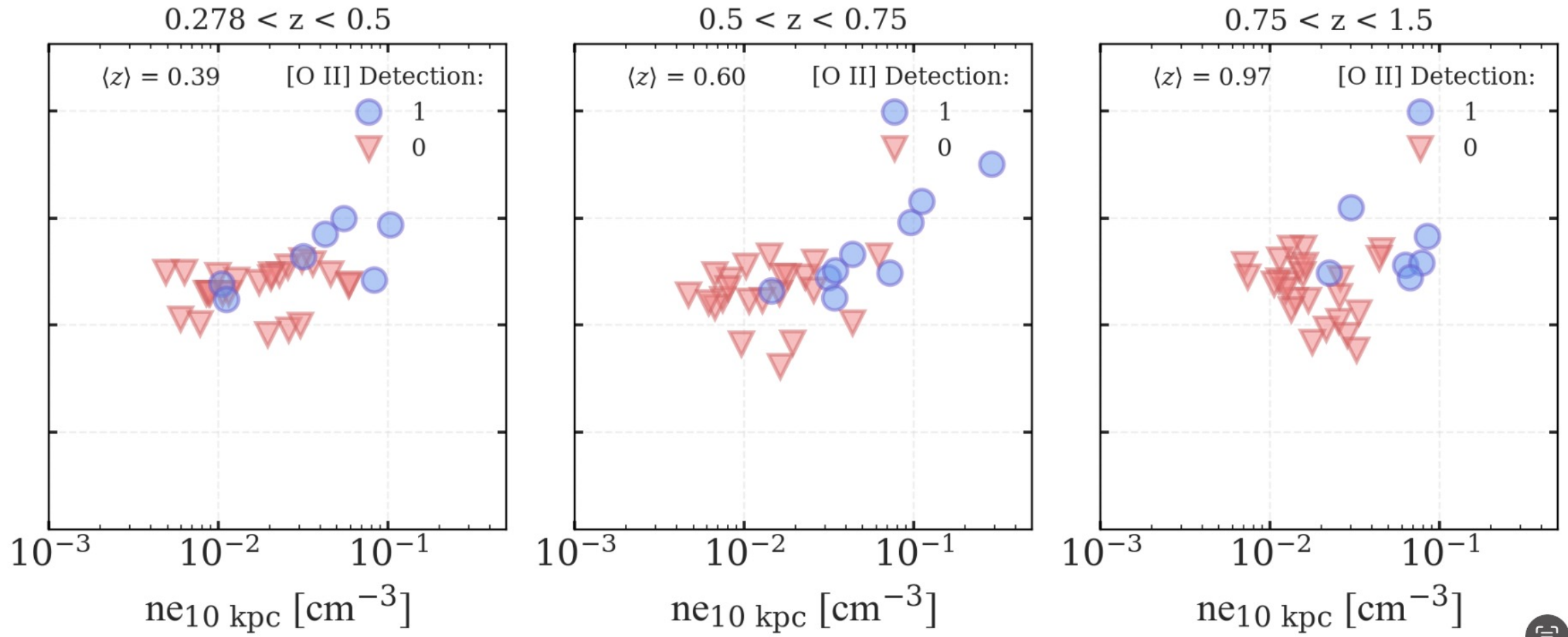




# FUTURE DIRECTIONS



# USING DENSITY RATHER THAN ENTROPY





# USING [OII] TO MEASURE SFRS

- [OII] probes similar ionization energy to  $H\alpha$ , which is  $\propto UV$
- All consistent with photoionization by young stars
- Spatially-resolved maps which allows us to avoid AGN contamination

