EVOLUTION OF THE COOLING-FEEDBACK CYCLE IN BRIGHTEST CLUSTER GALAXIES

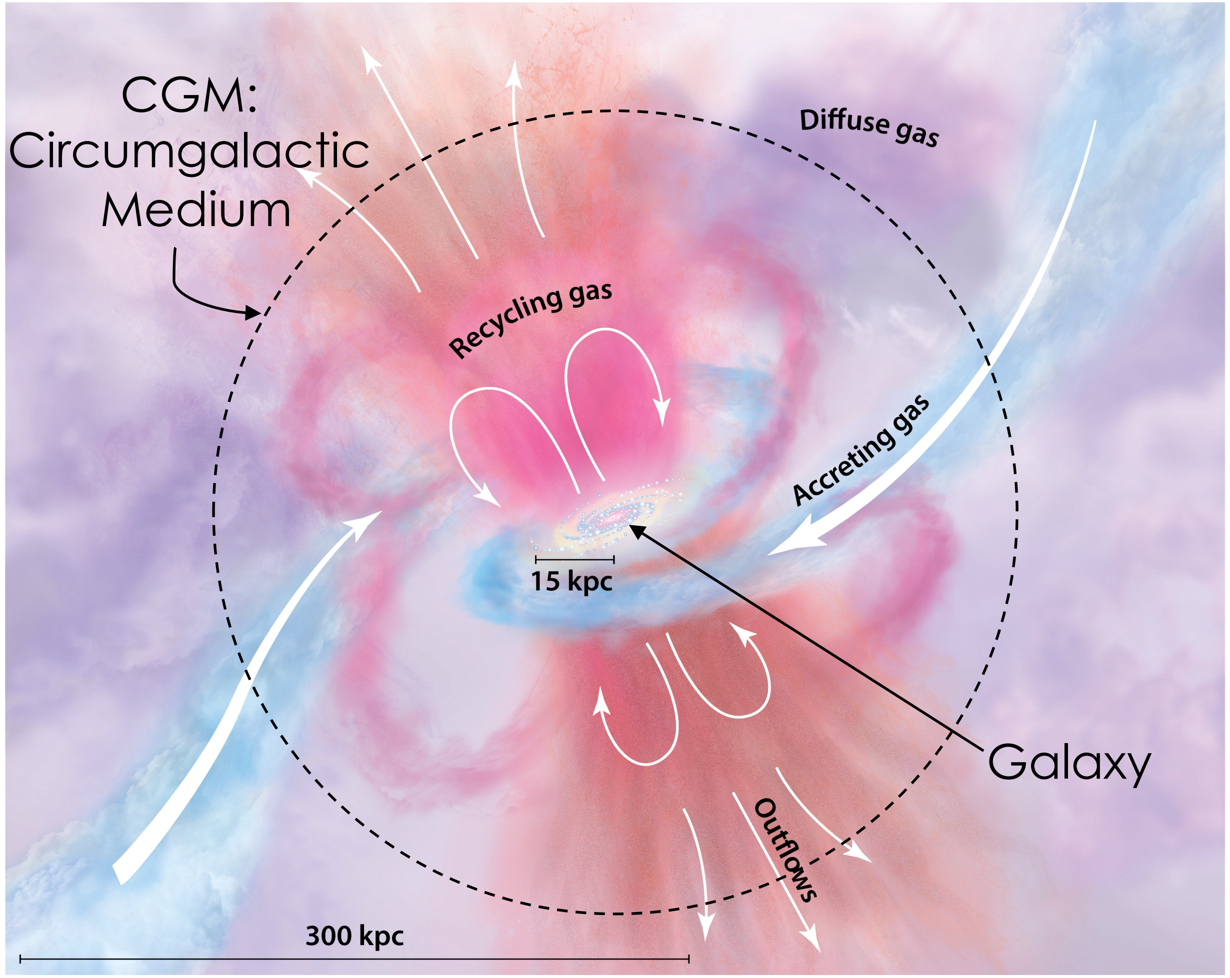
Michael Calzadilla

NASA Hubble Fellow

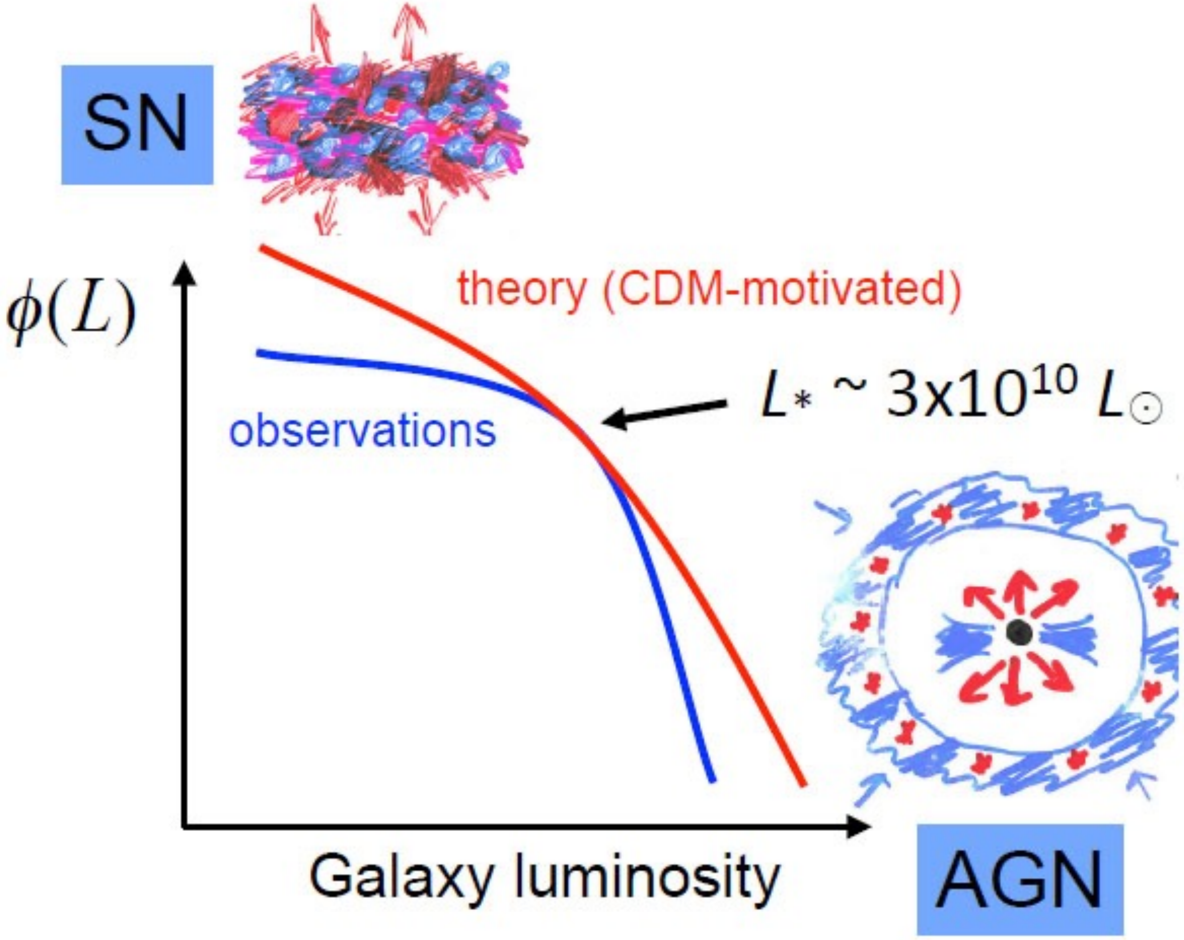
Center for Astrophysics | Harvard & Smithsonian

25 Years of Chandra Symposium

THE BARYON CYCLE, FEEDBACK, AND GALAXY EVOLUTION



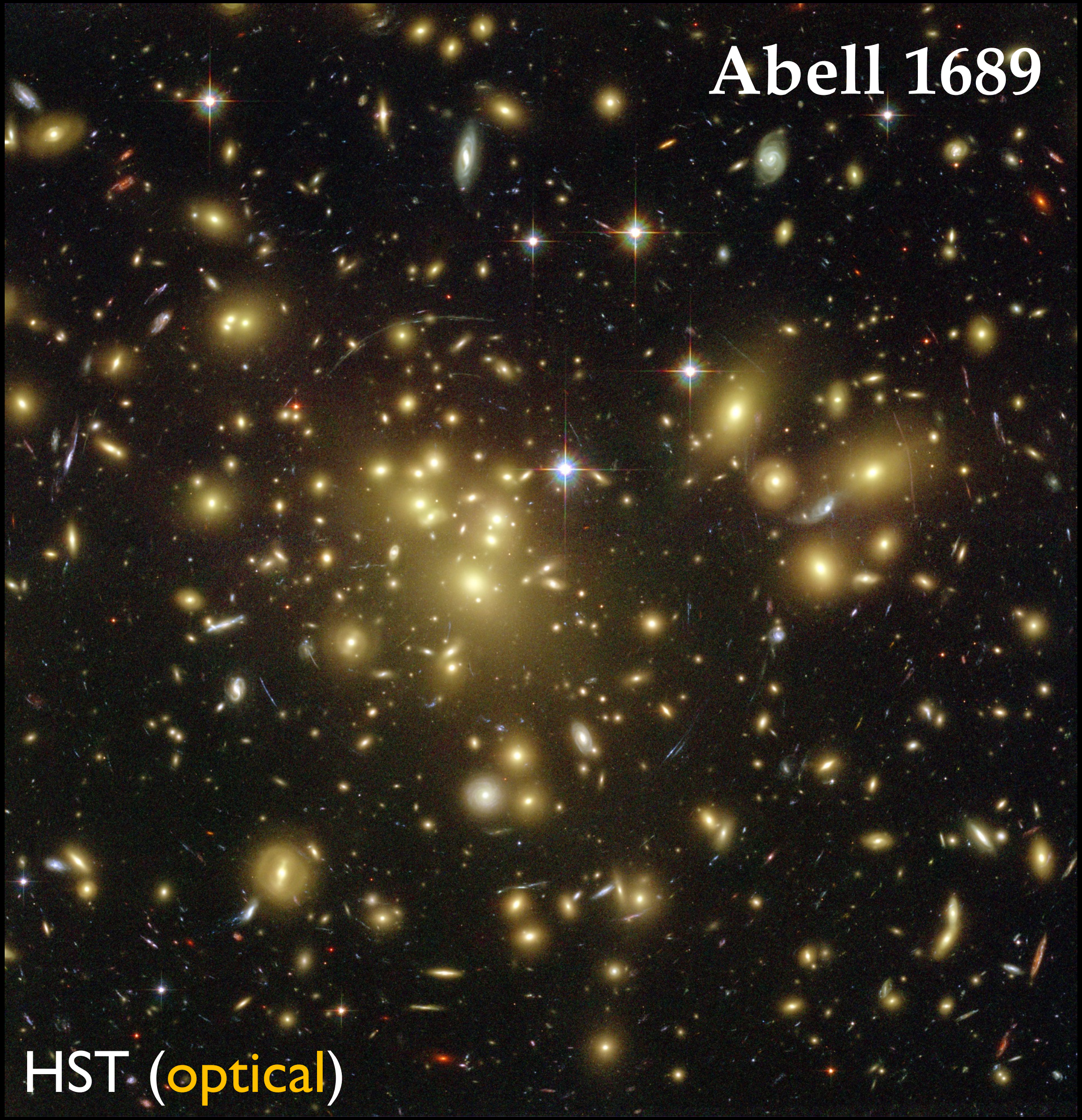
Tumlinson+17



Silk & Mamon+12

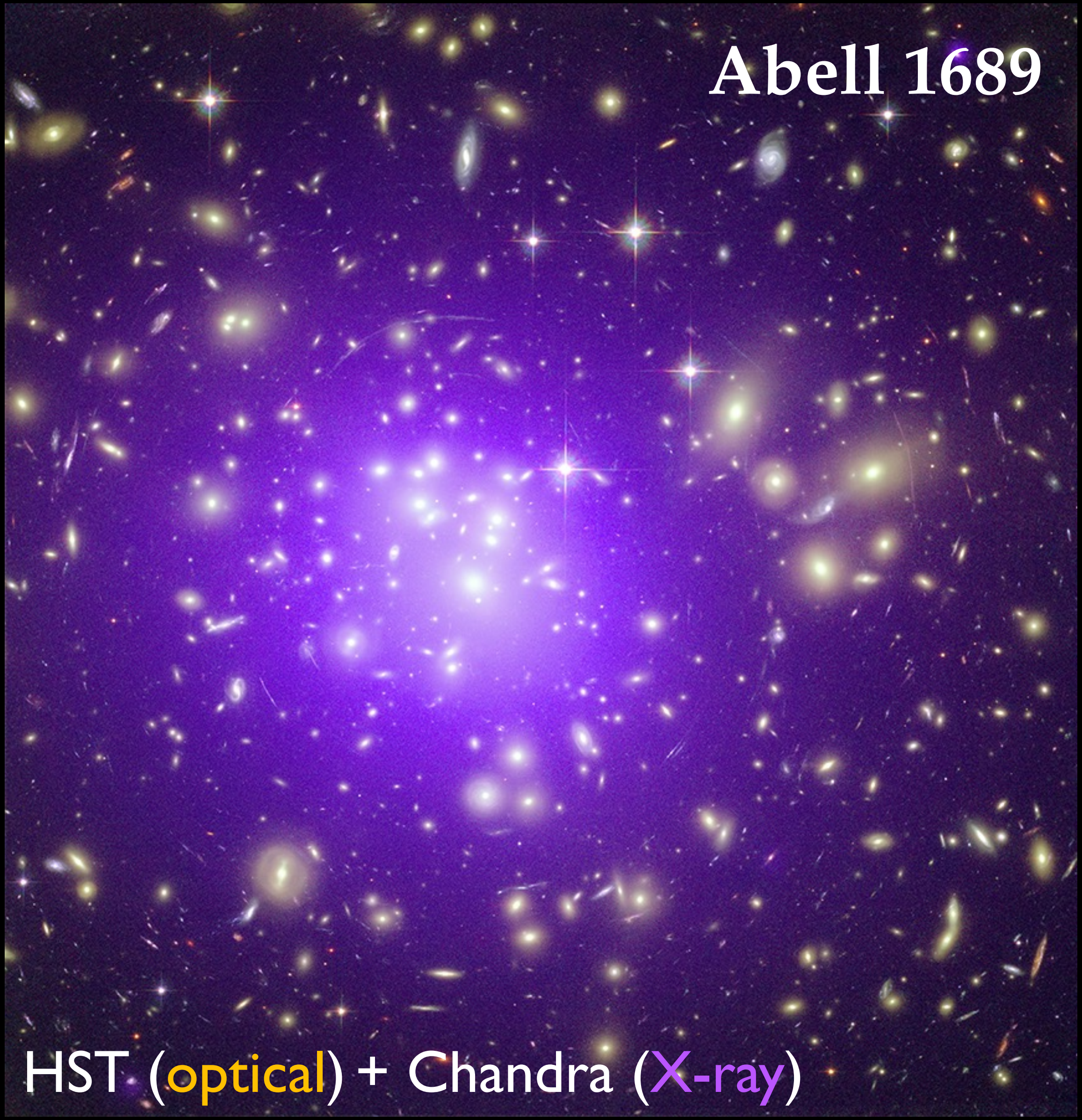
GALAXY CLUSTERS

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



GALAXY CLUSTERS

- Largest objects in Universe™
- 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

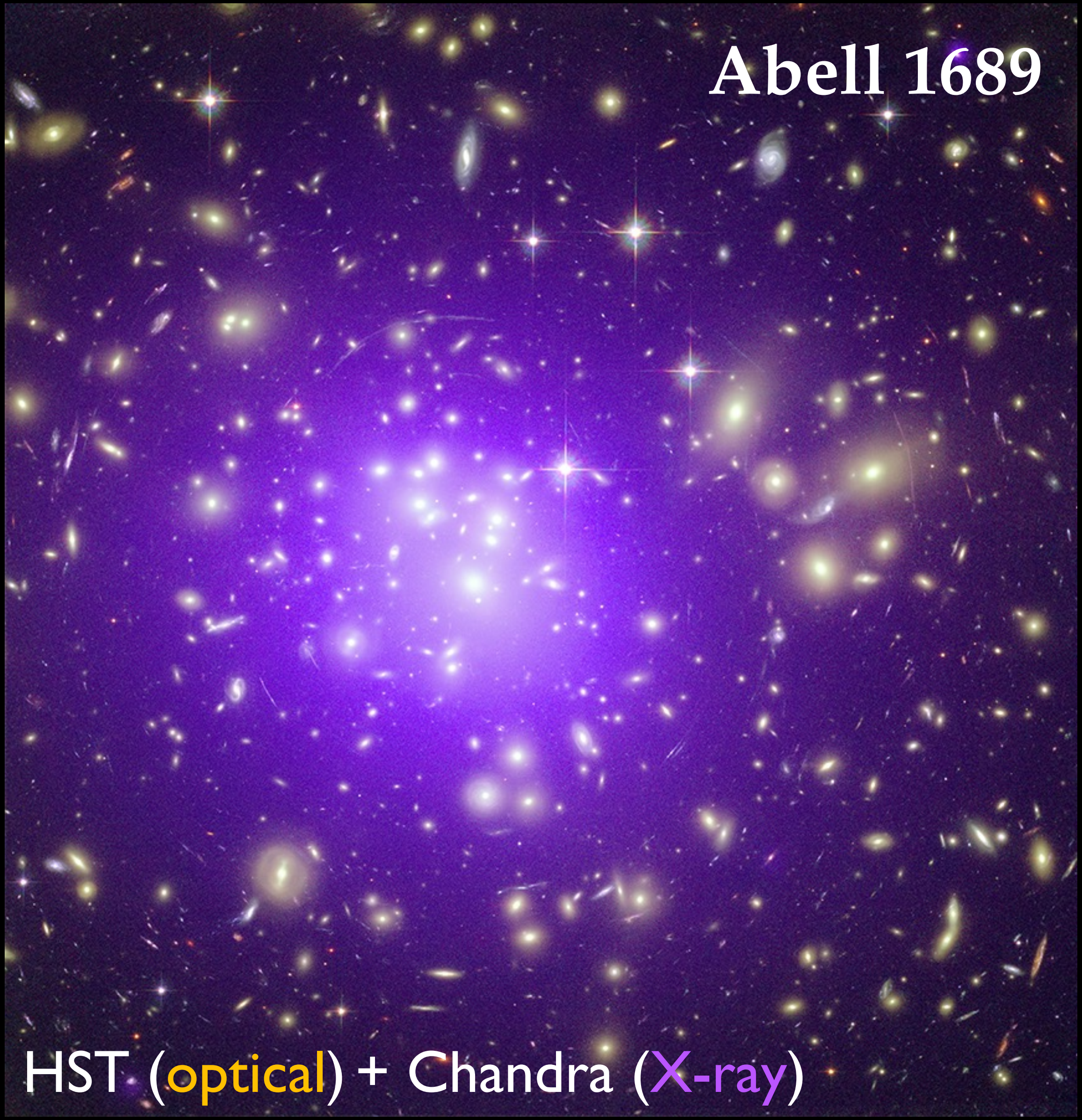
X-ray flux $\propto n_e^2 / \sqrt{T}$

$\Downarrow$

Cold and dense core

$\Downarrow$

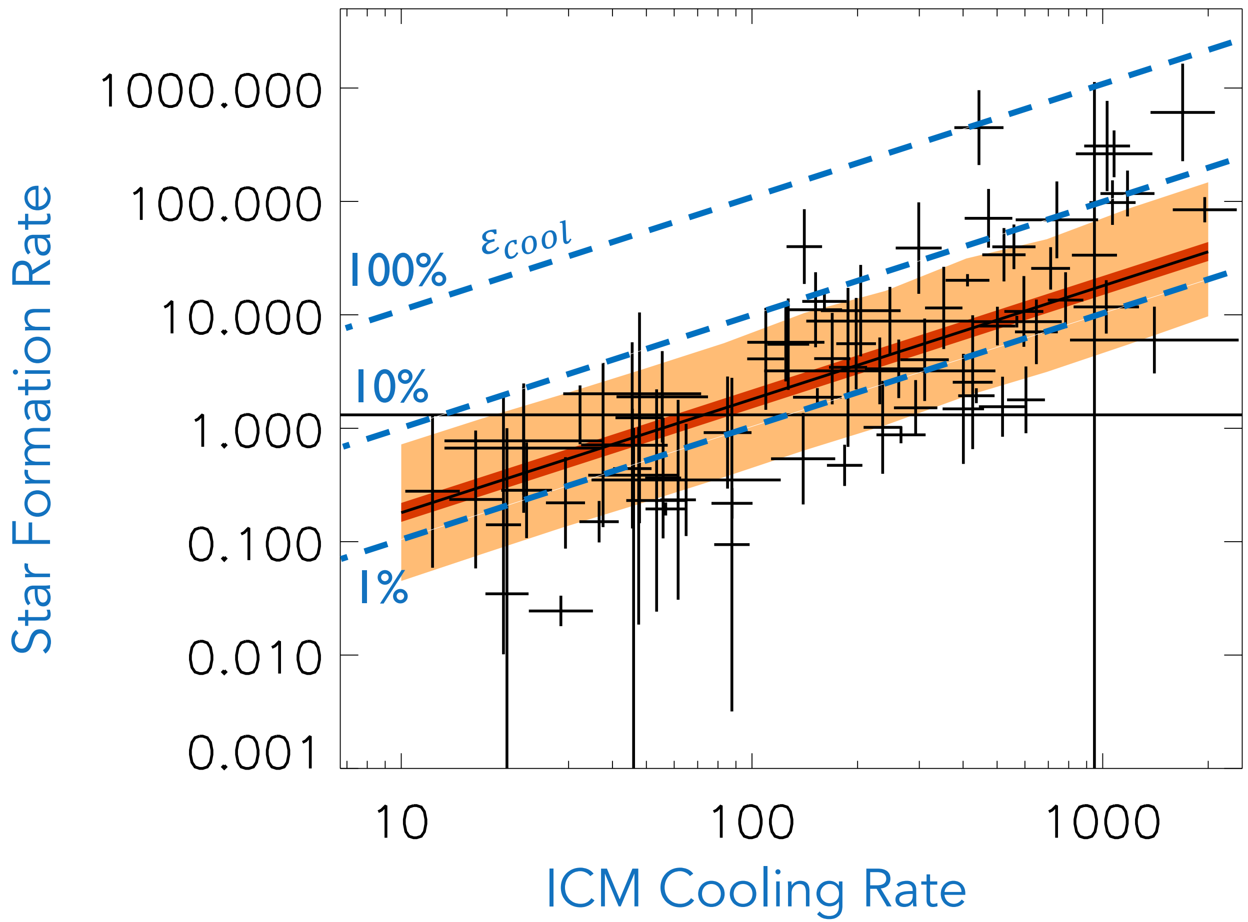
Expect high star formation rates (SFRs) in BCGs



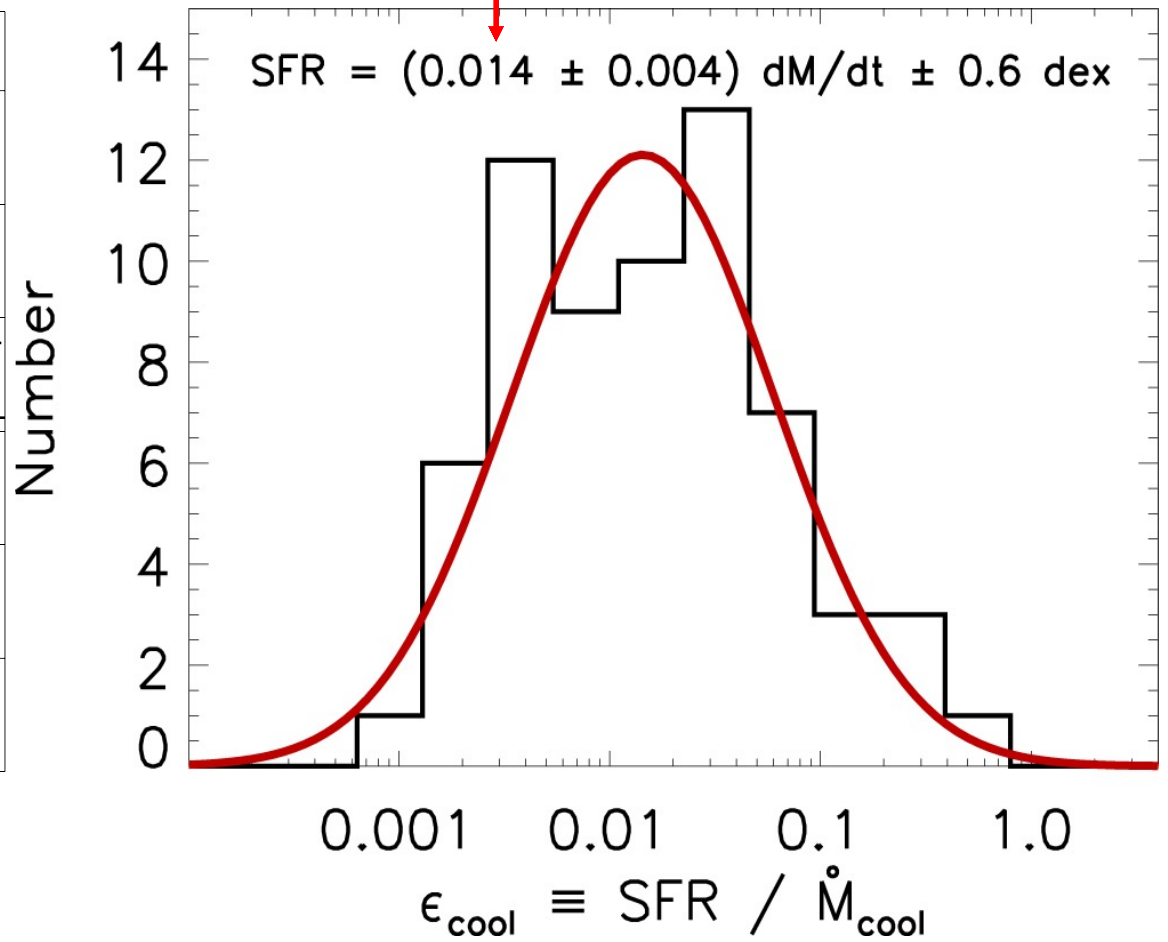

BCGs are “red and dead”

THE COOLING FLOW PROBLEM

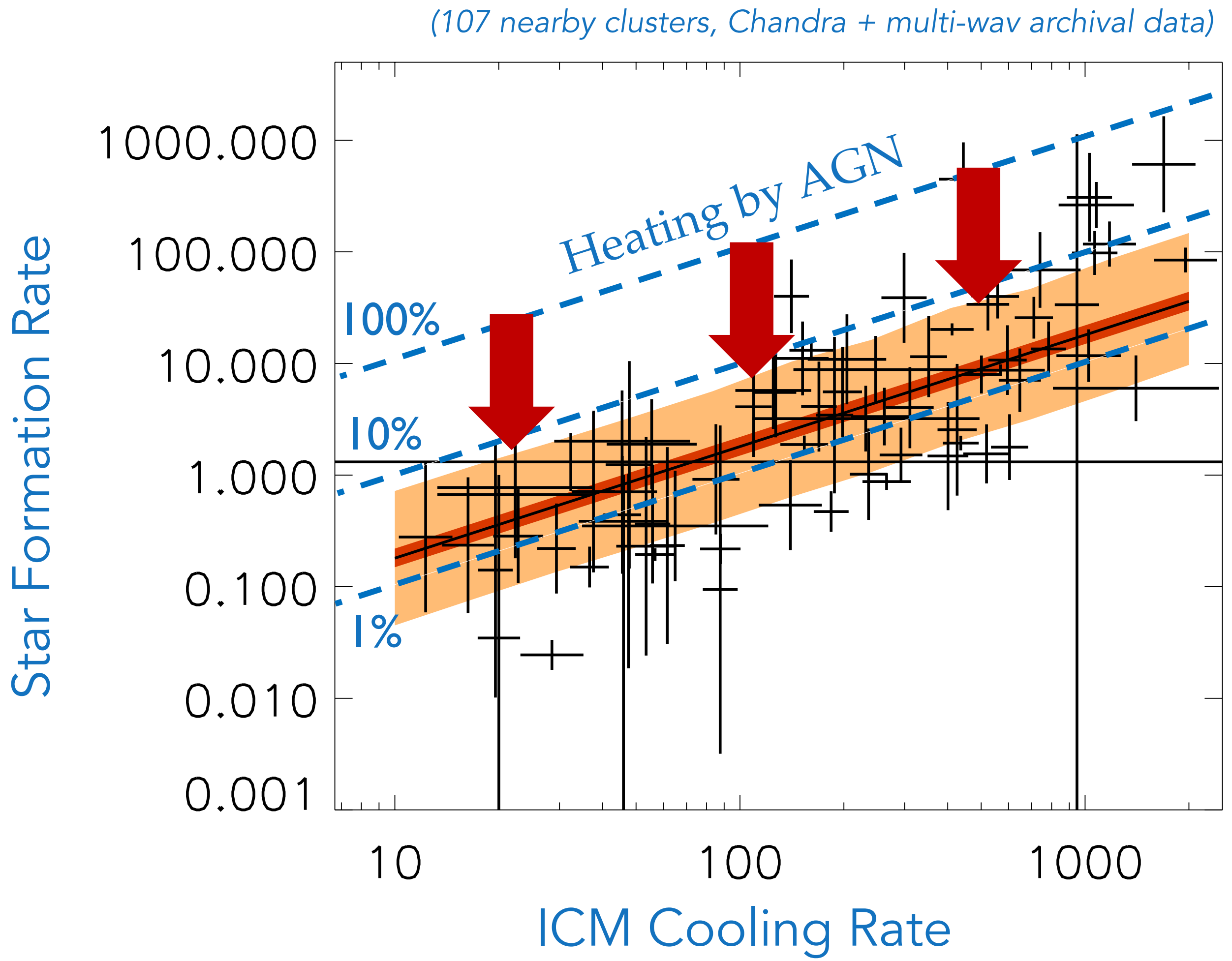
(107 nearby clusters, Chandra + multi-wav archival data)

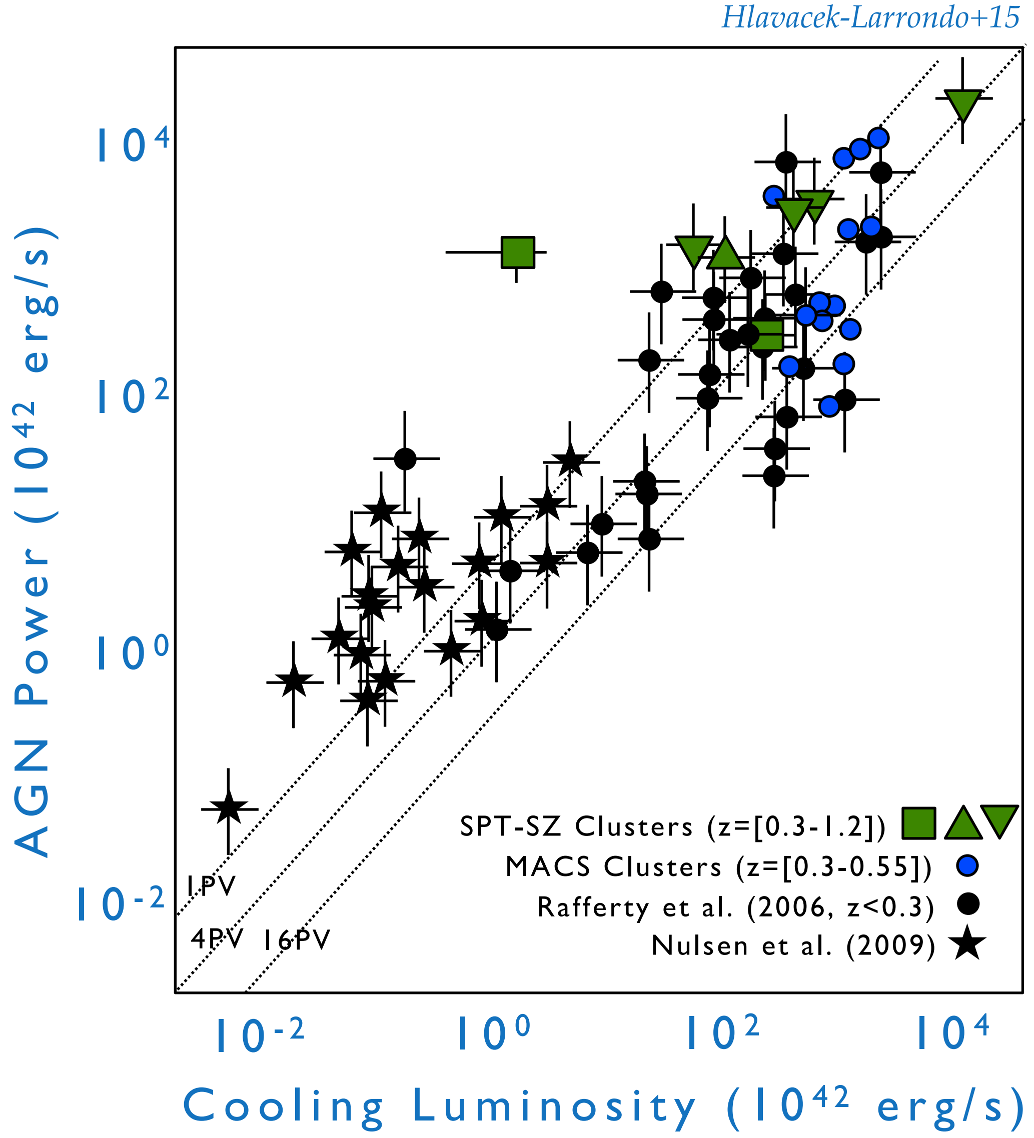


Only 1% of that cooling actually forms stars!

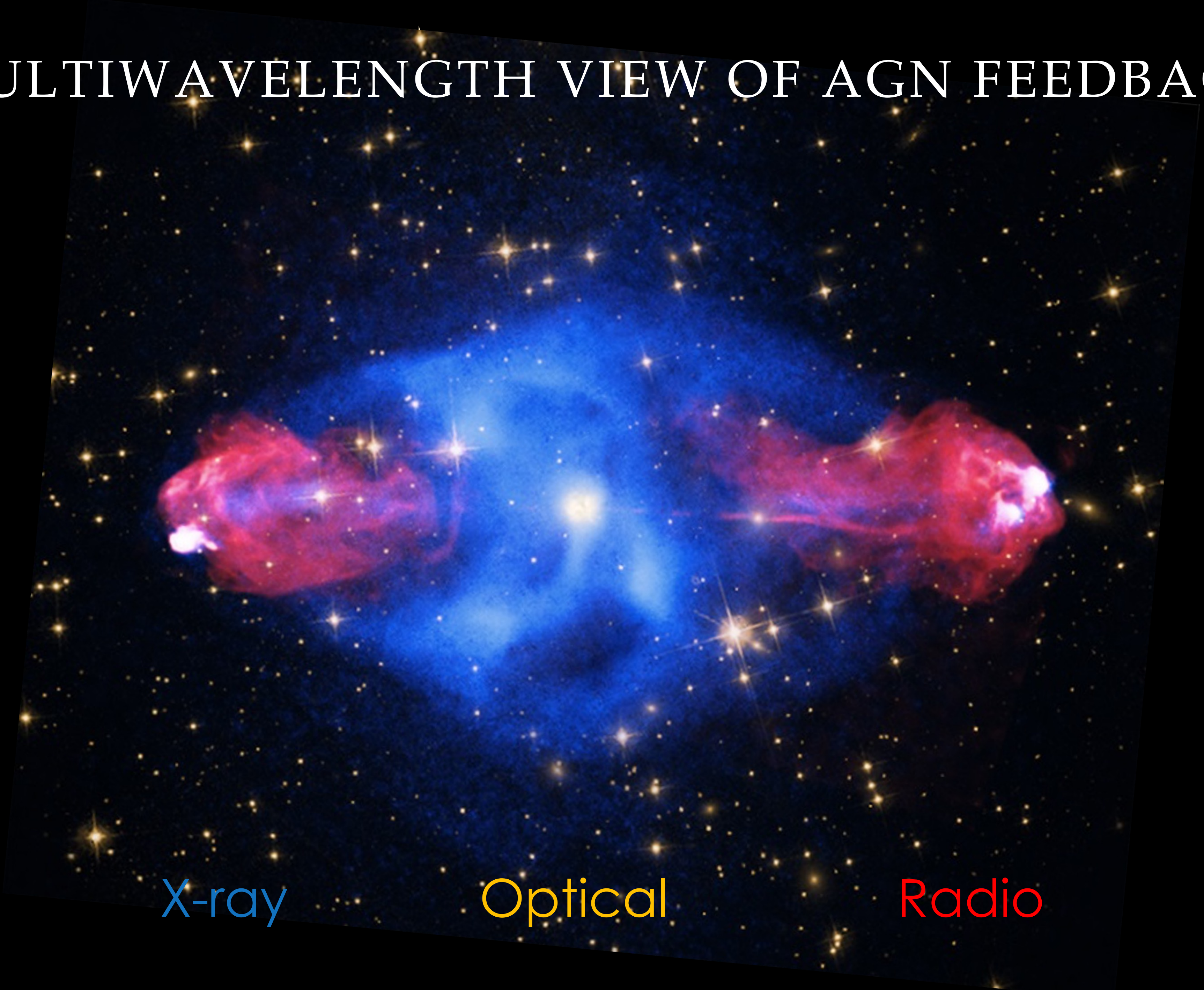


SOLUTION: AGN FEEDBACK AS A THERMOSTAT

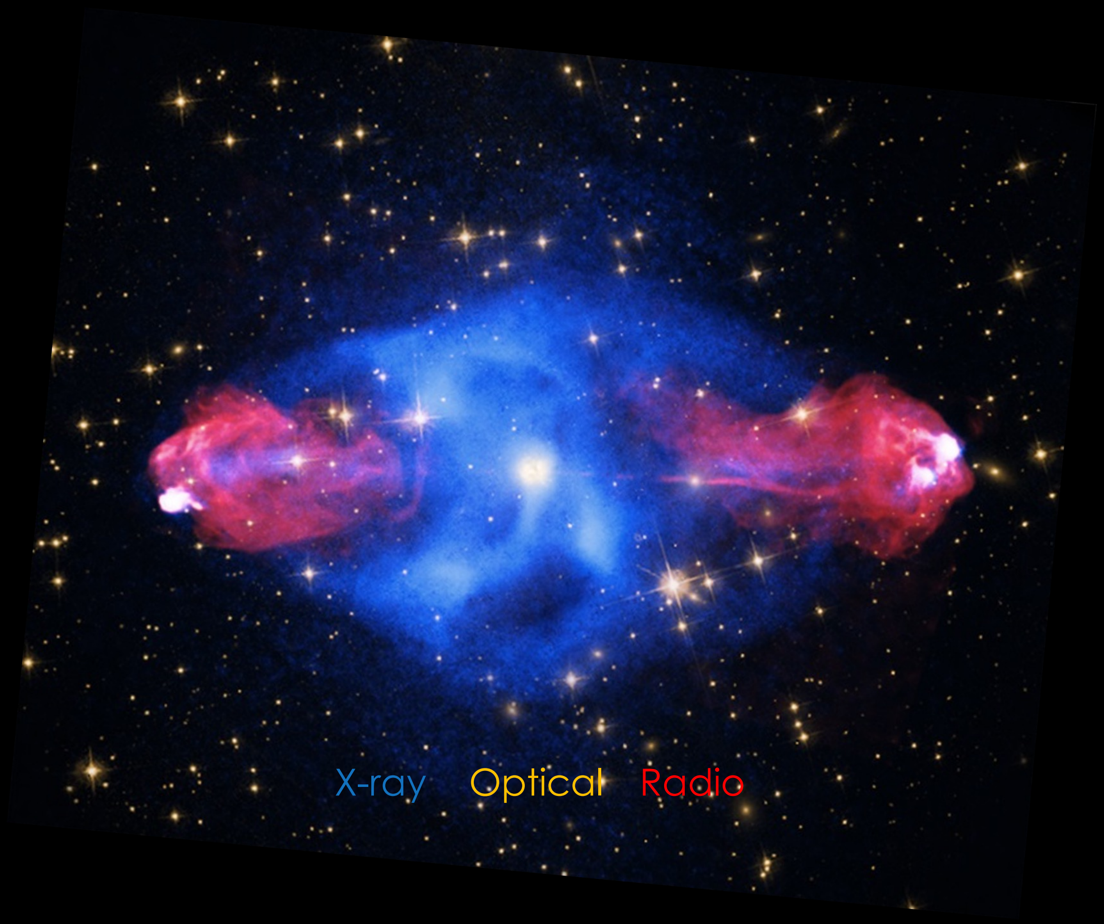




MULTIWAVELENGTH VIEW OF AGN FEEDBACK

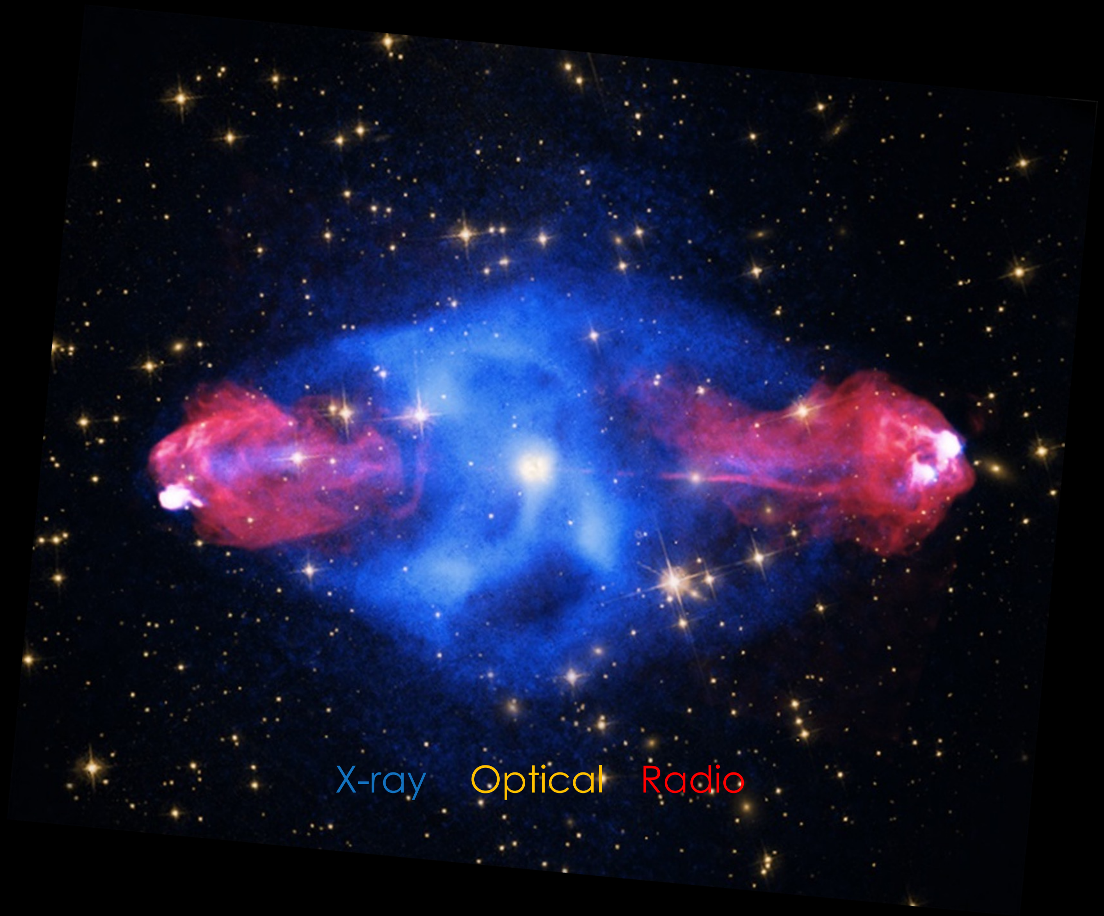


EVOLUTION OF THE AGN FEEDBACK CYCLE



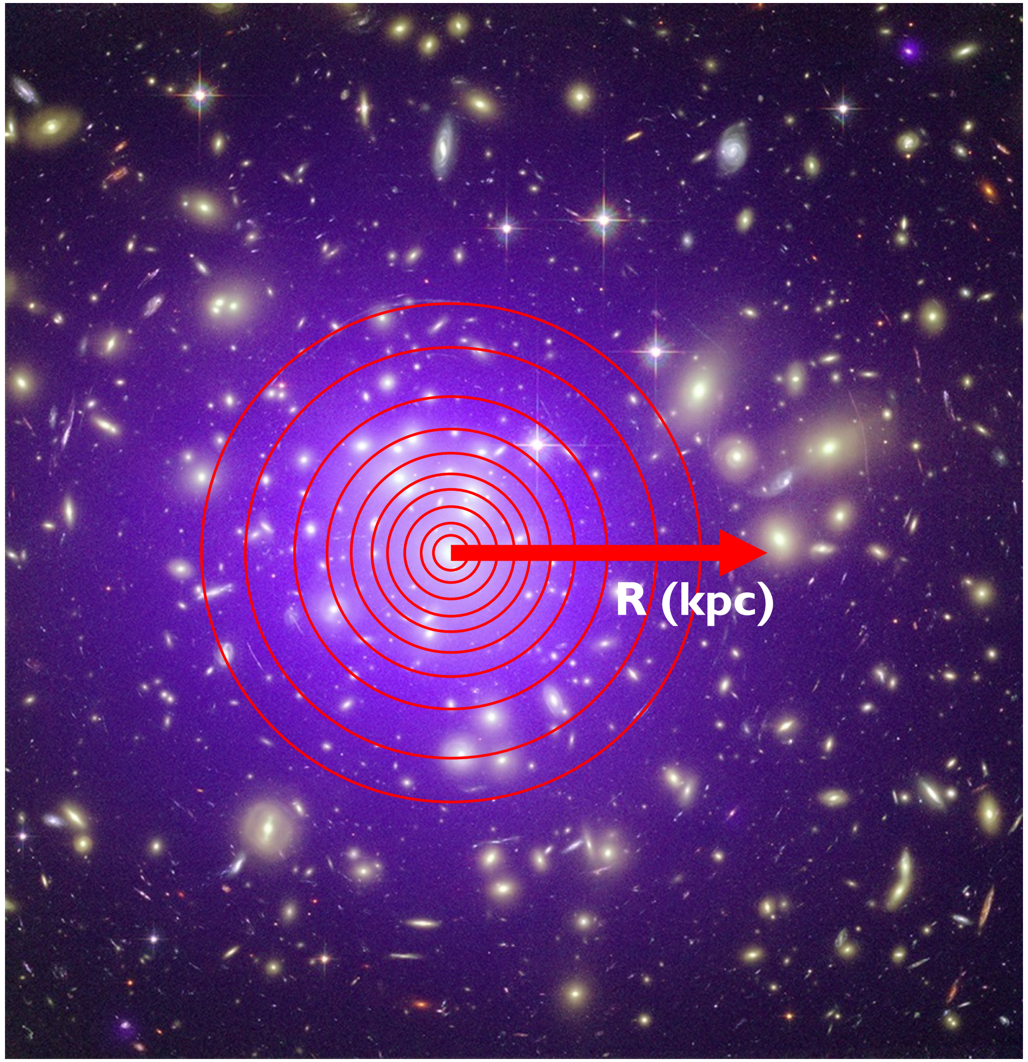
- Multi-wavelength observations of galaxy clusters best way to see entire baryon cycle in largest galaxies
- AGN feedback biggest driver of BCG evolution
- Some remaining questions:
  - How long has this balance been in place?
  - Have the conditions for triggering cooling and feedback evolved?
  - Has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

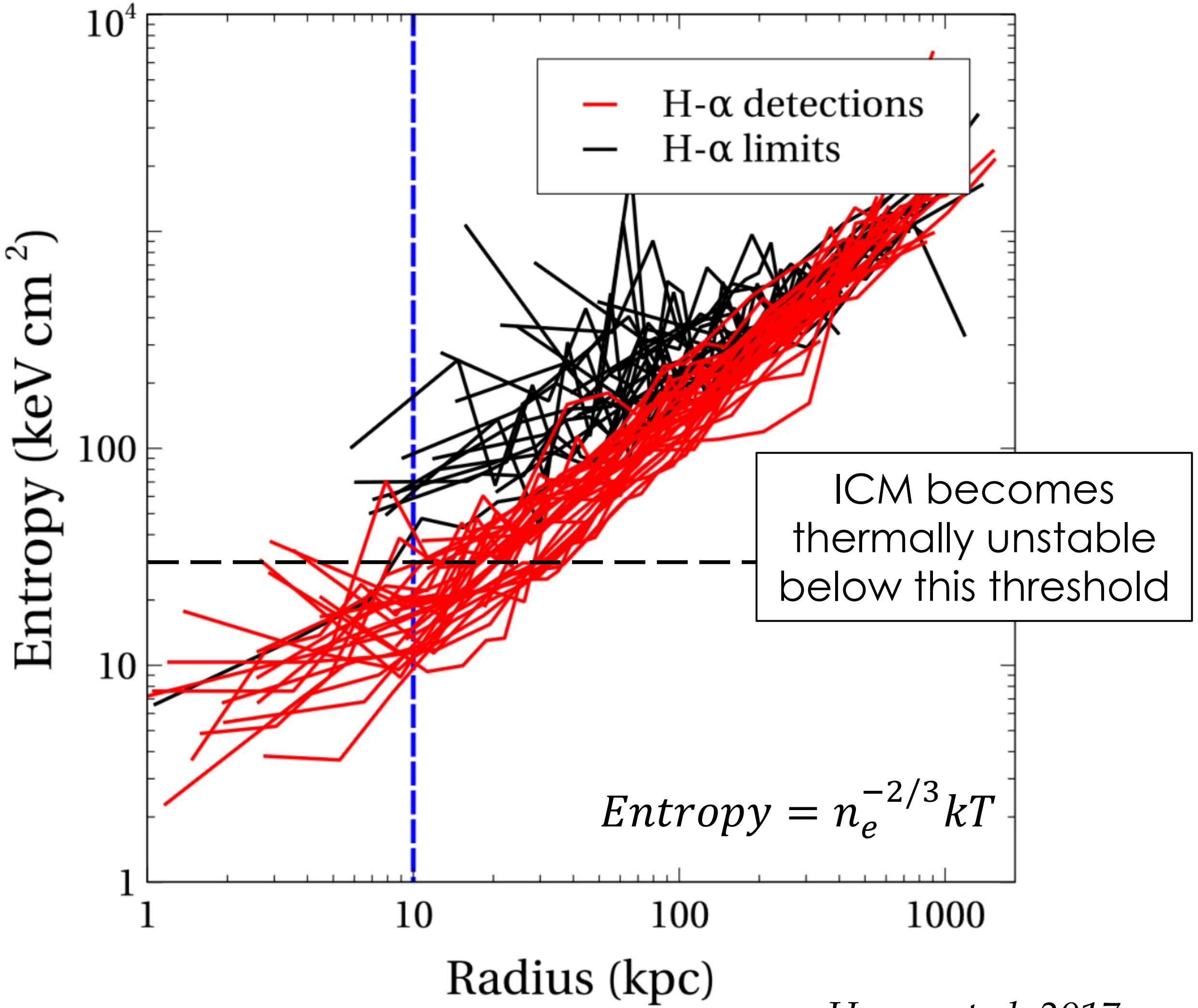
EVOLUTION OF THE AGN FEEDBACK CYCLE



- 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 thanks to SZ surveys

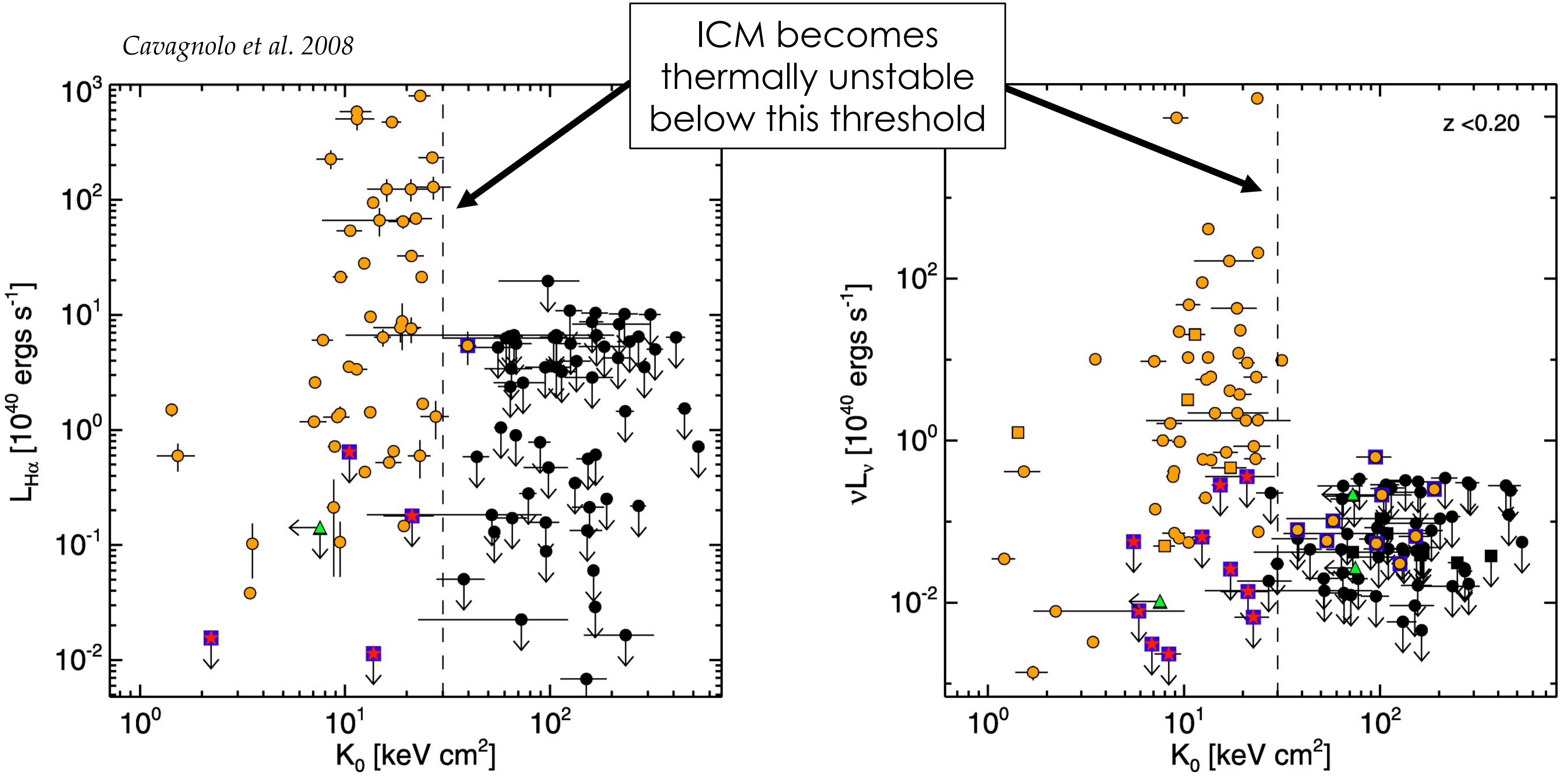
ENTROPY THRESHOLD FOR TRIGGERING COOLING AND FEEDBACK





Hogan et al. 2017

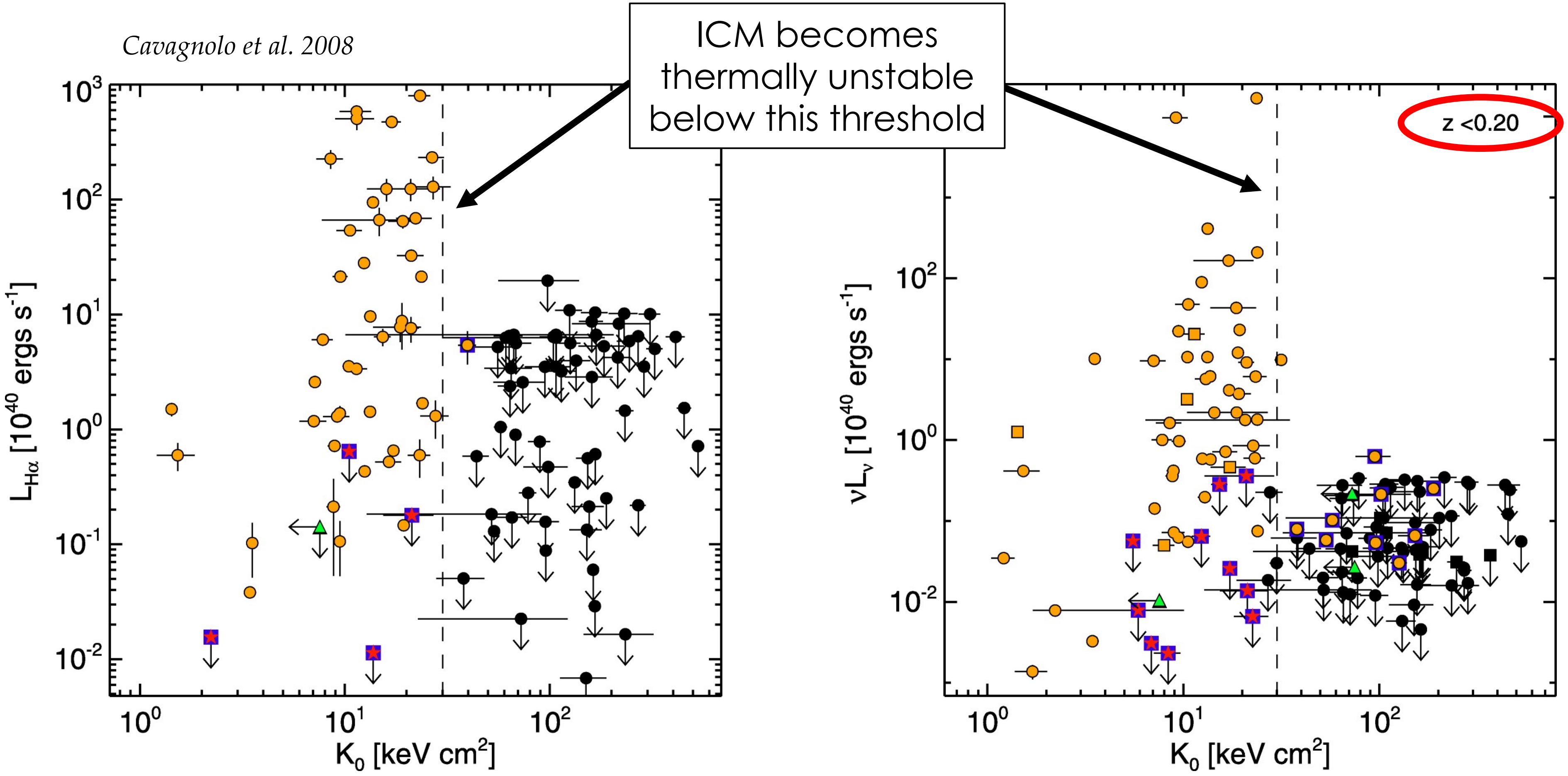
ENTROPY THRESHOLD FOR TRIGGERING COOLING AND FEEDBACK



which triggers star formation and AGN feedback

ENTROPY THRESHOLD FOR TRIGGERING COOLING AND FEEDBACK

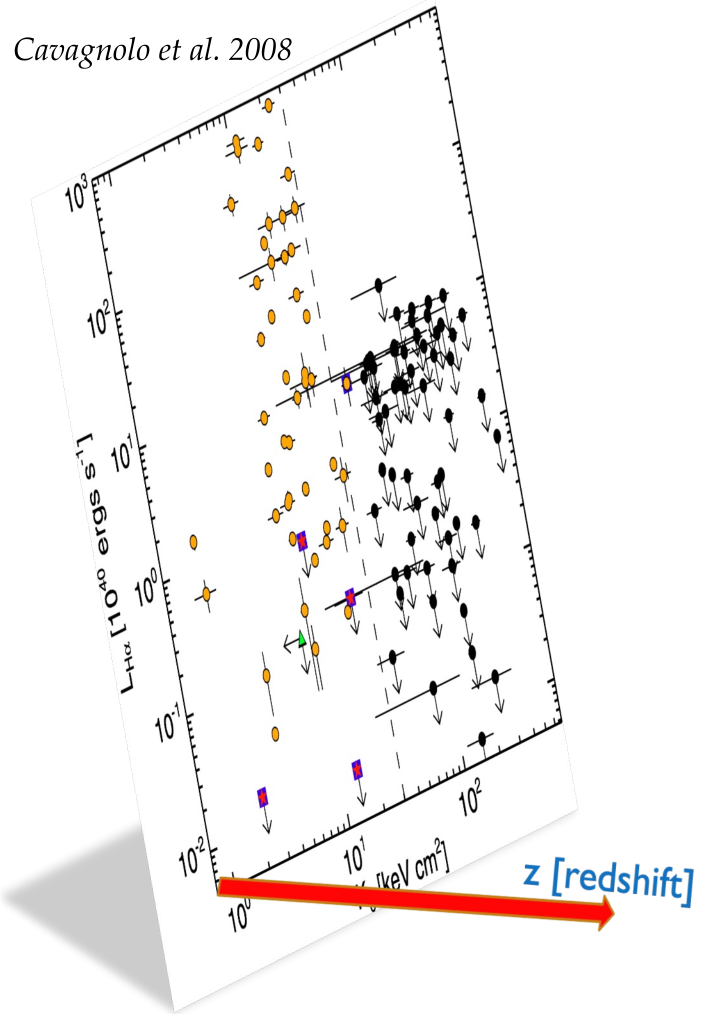
Cavagnolo et al. 2008

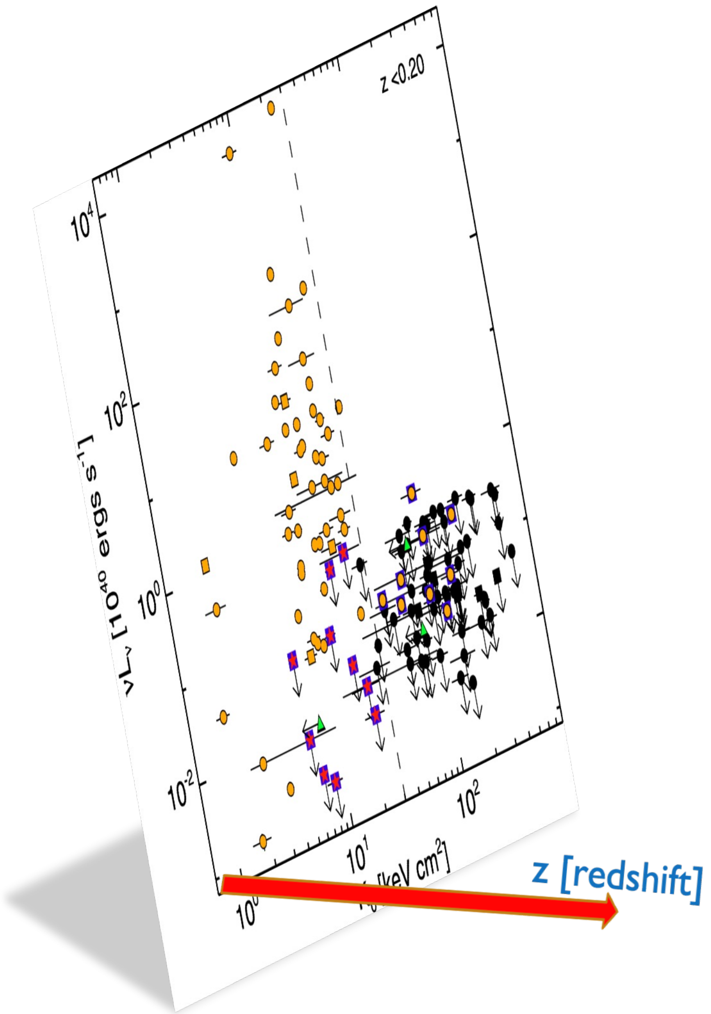


which triggers star formation and AGN feedback

HAVE THE CONDITIONS FOR TRIGGERING COOLING AND FEEDBACK EVOLVED?

Cavagnolo et al. 2008

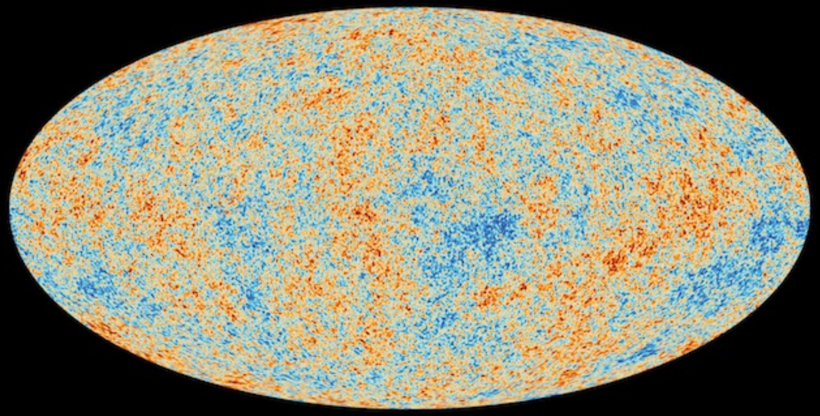




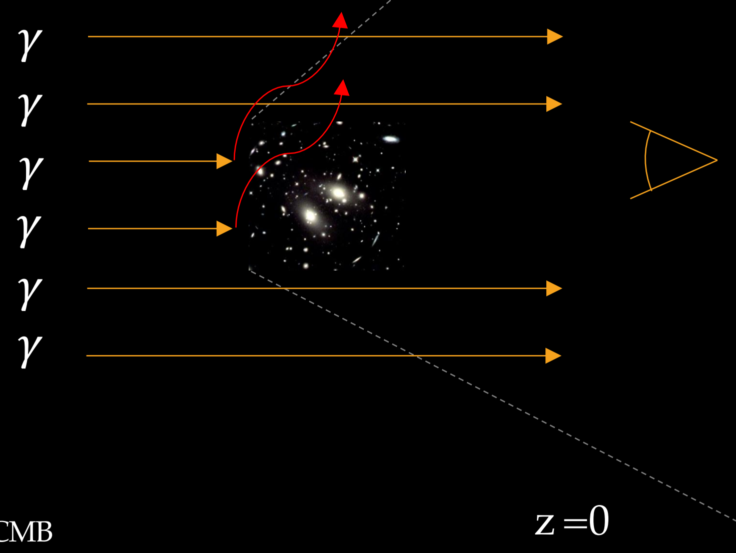
SOUTH POLE TELESCOPE

Sunyaev-Zel'dovich (SZ) EFFECT

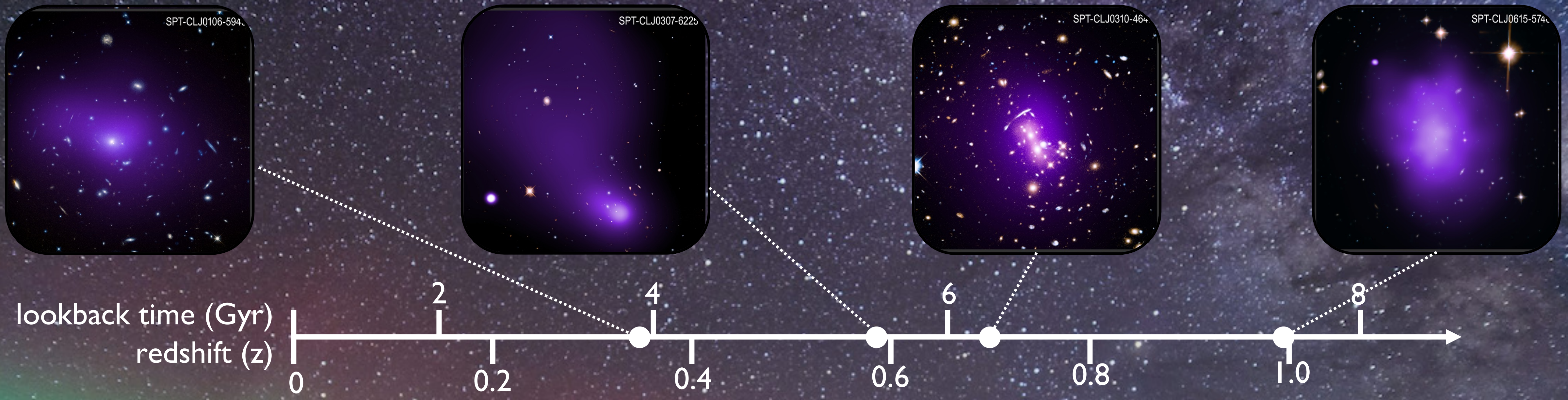
- Redshift-independent detection of galaxy clusters
- Enables evolutionary studies



ESA/Planck



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



SPT-Chandra BCG sample:

Unbiased sample of 95 clusters spanning 10 Gyr in evolution

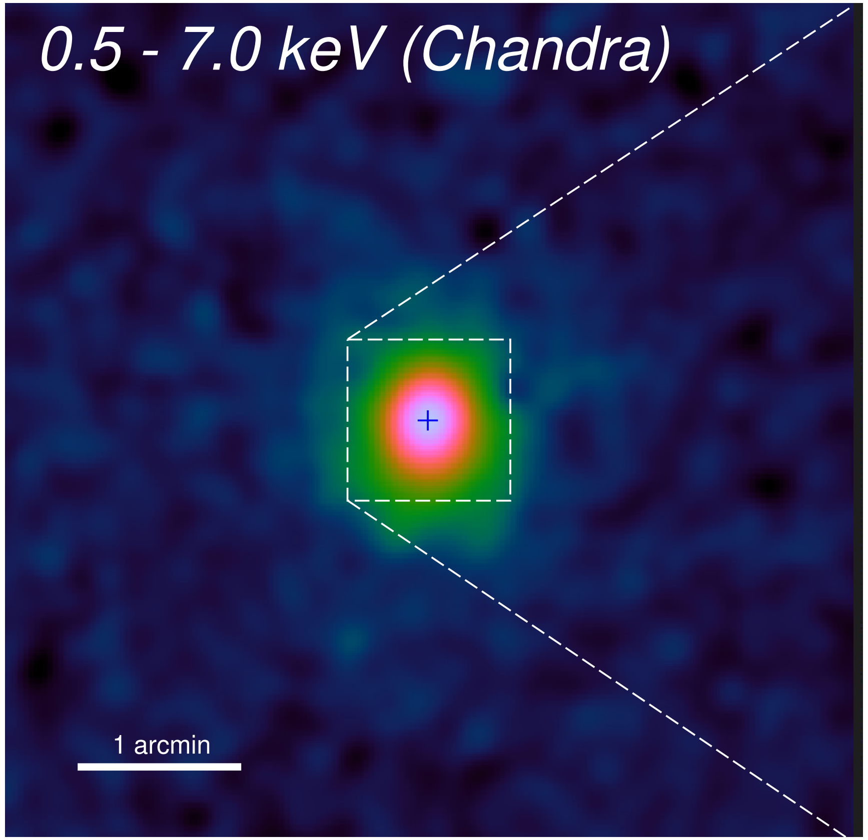
Multiwavelength followup:

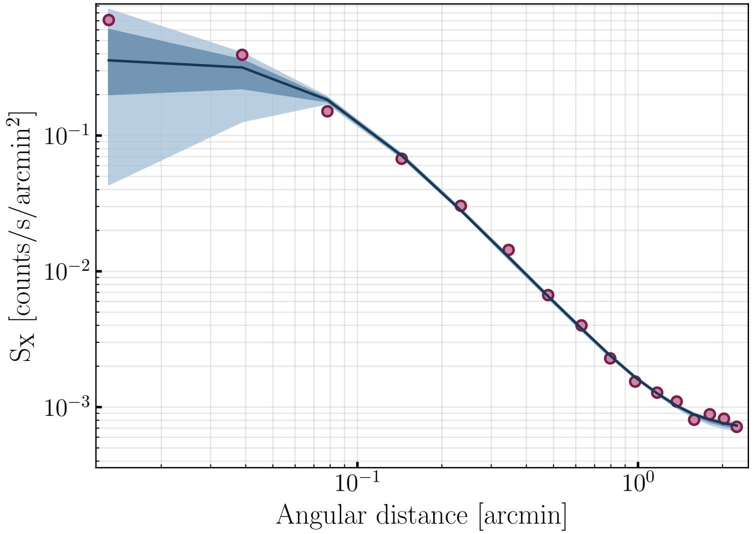
~4 Ms Chandra (X-ray)

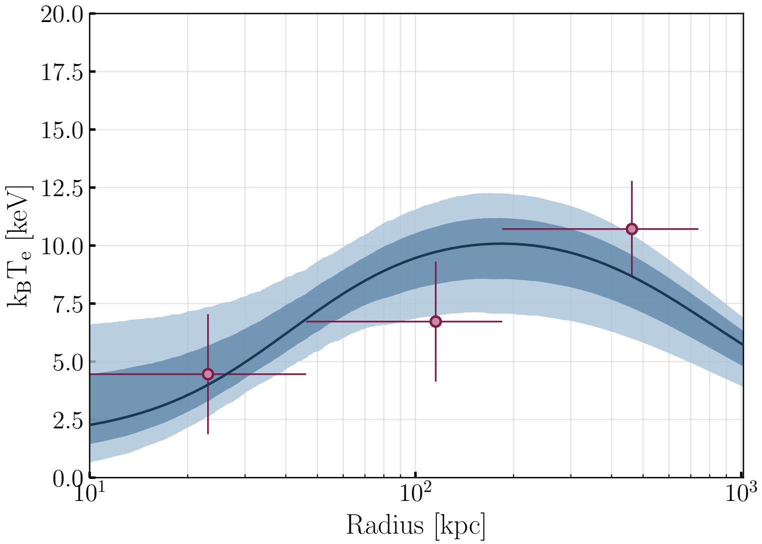
~30 nights optical spectroscopy

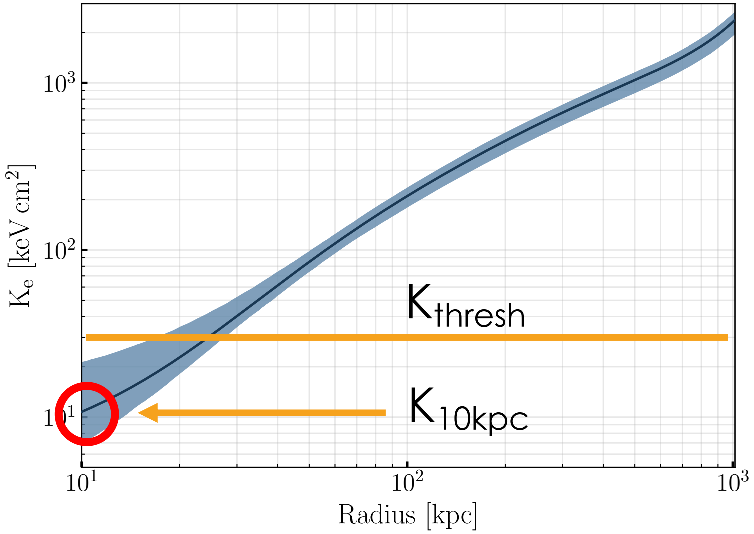
-- Full radio coverage

MULTIWAVELENGTH DATA





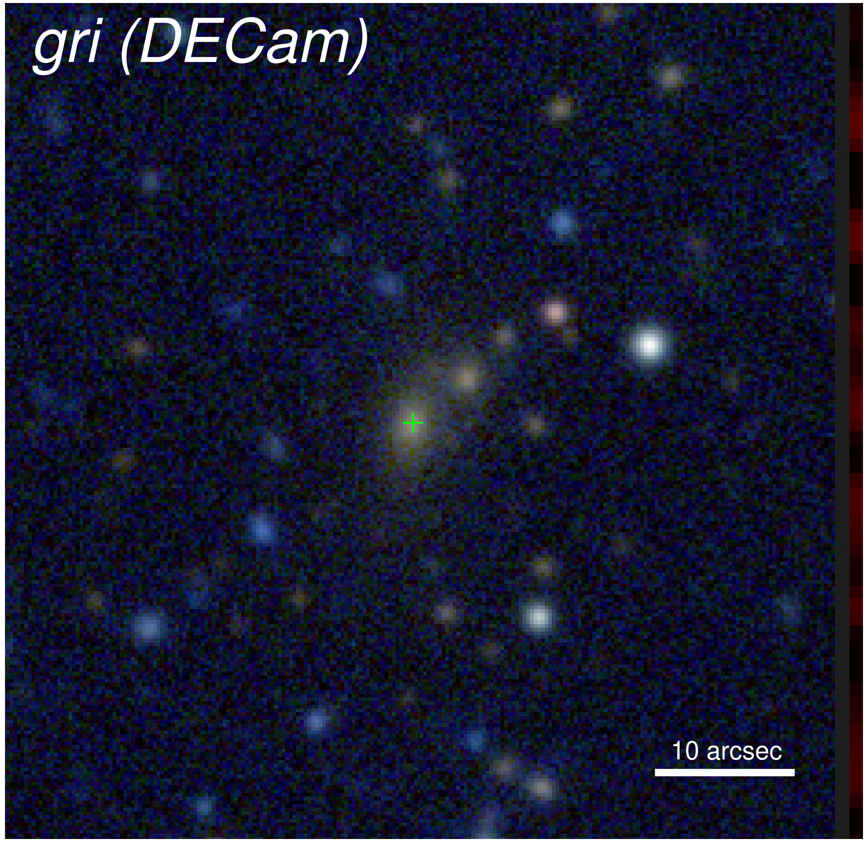


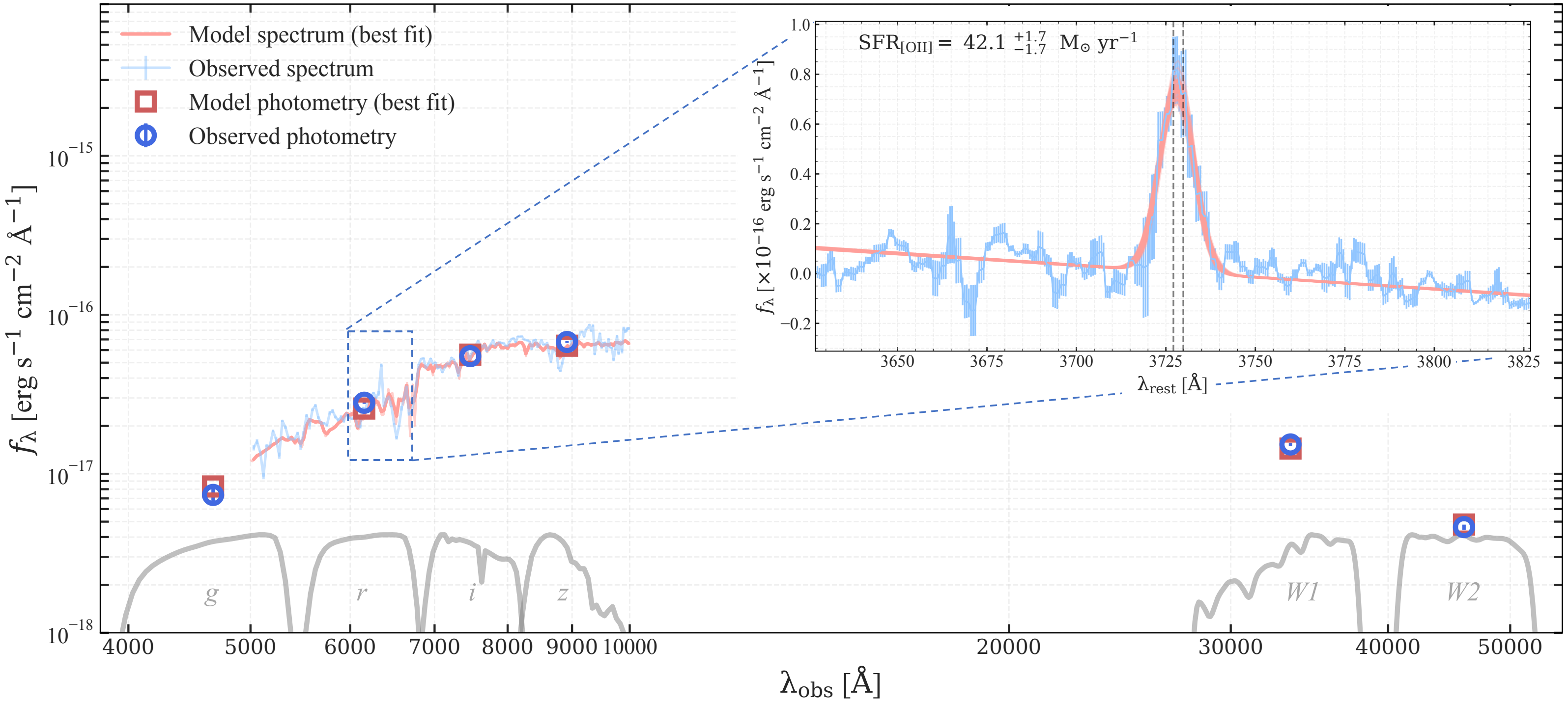


Multiphase cooling if $K_{10kpc} < K_{thresh}$

ICM "fuel" → Star formation / AGN activity

MULTIWAVELENGTH DATA

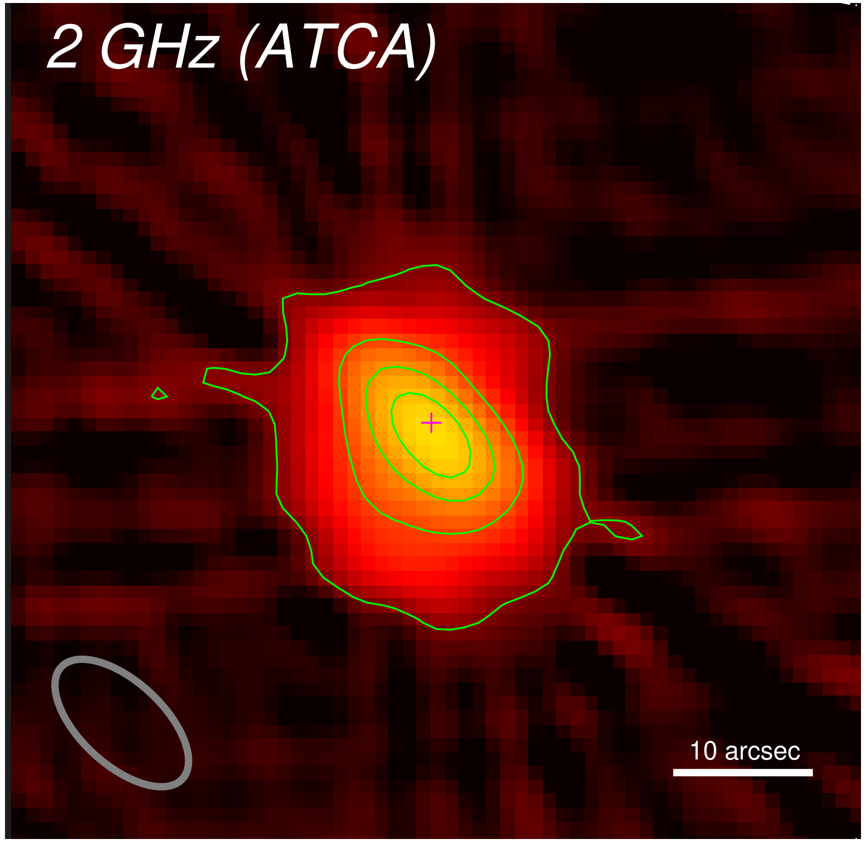


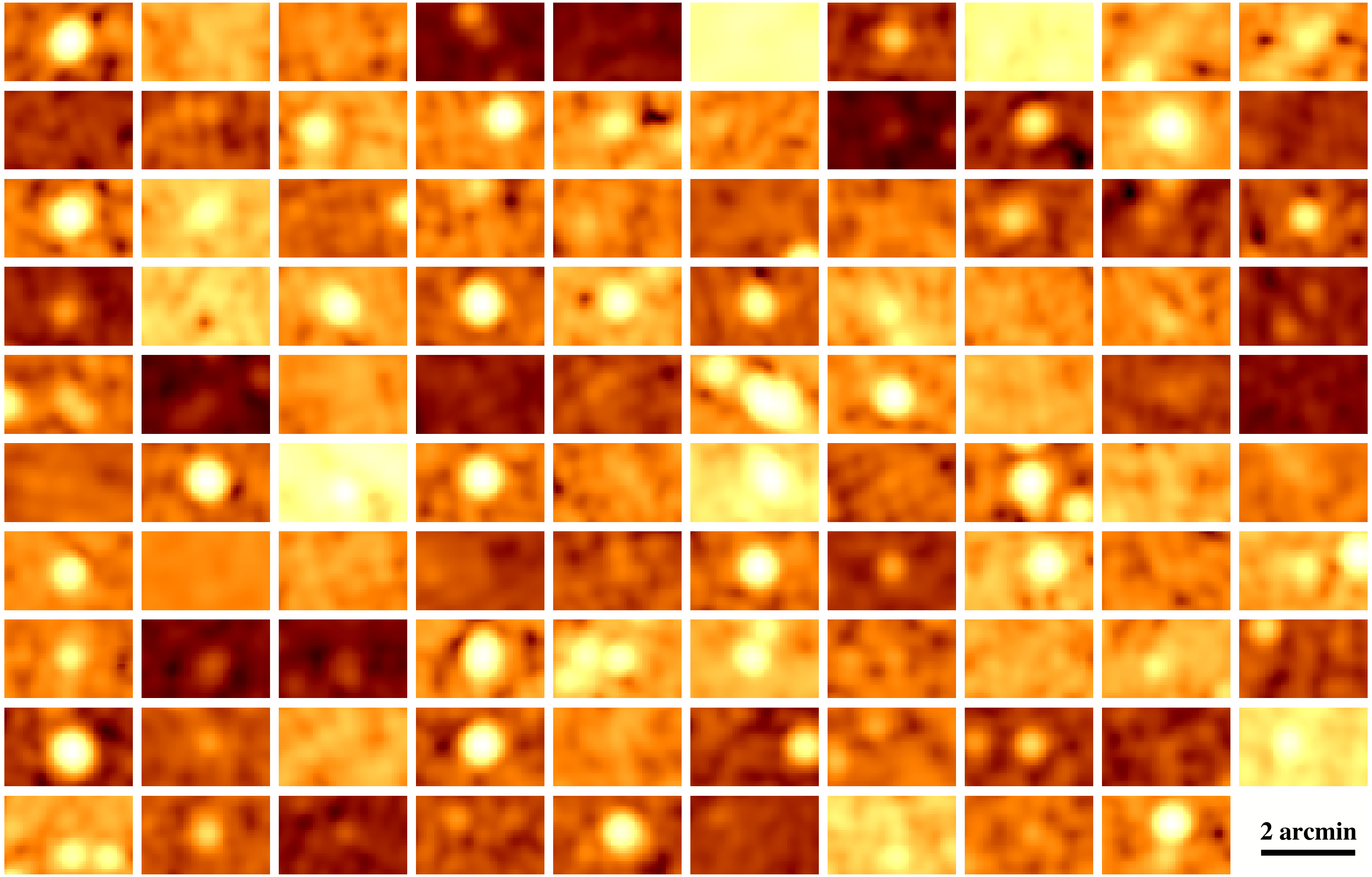


ICM "fuel" → Star formation / AGN activity

Look for detection of [O II] emission

MULTIWAVELENGTH DATA

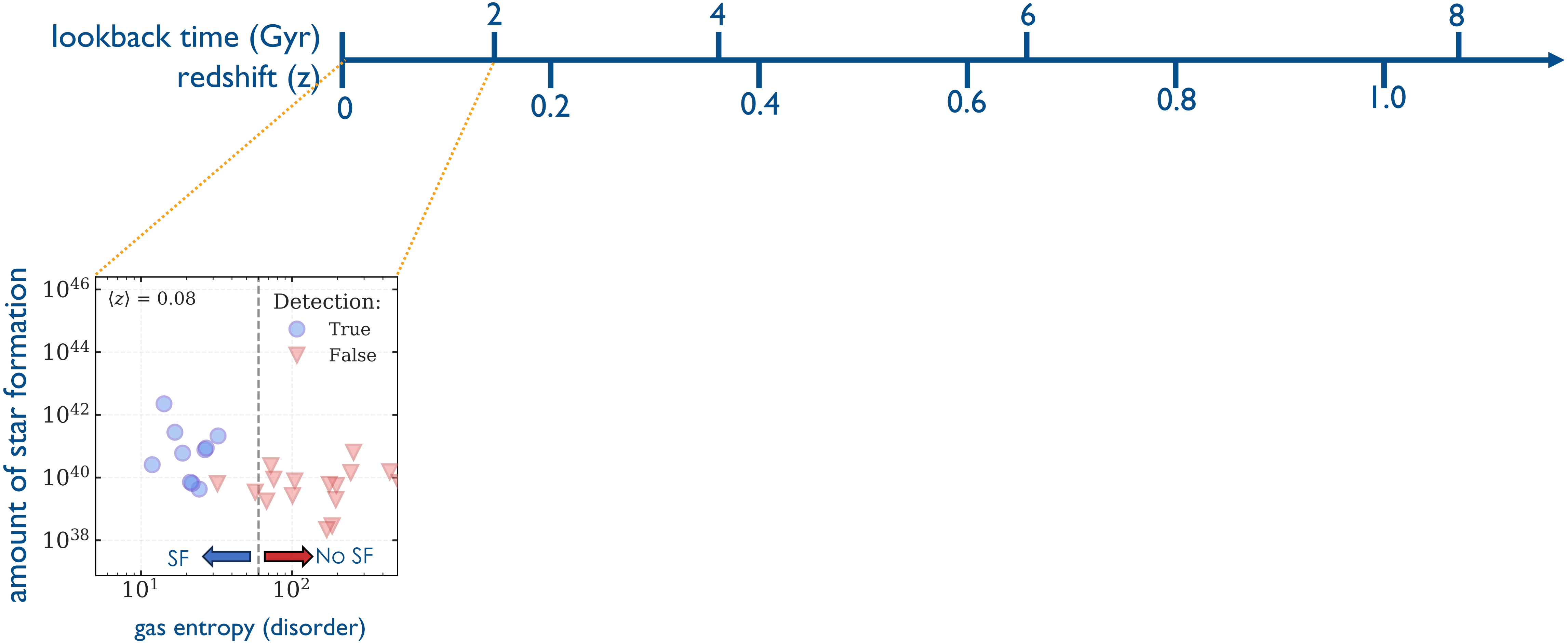




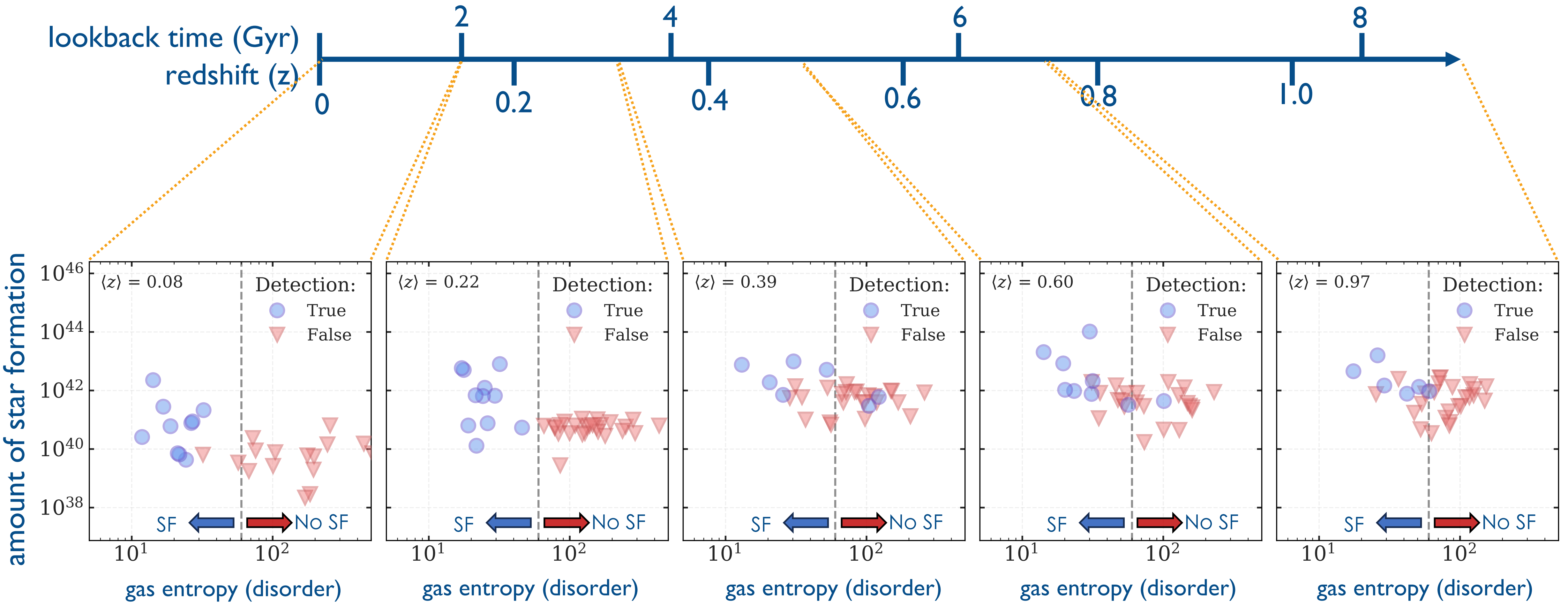
ICM “fuel” → Star formation / AGN activity

Look for detection of radio source

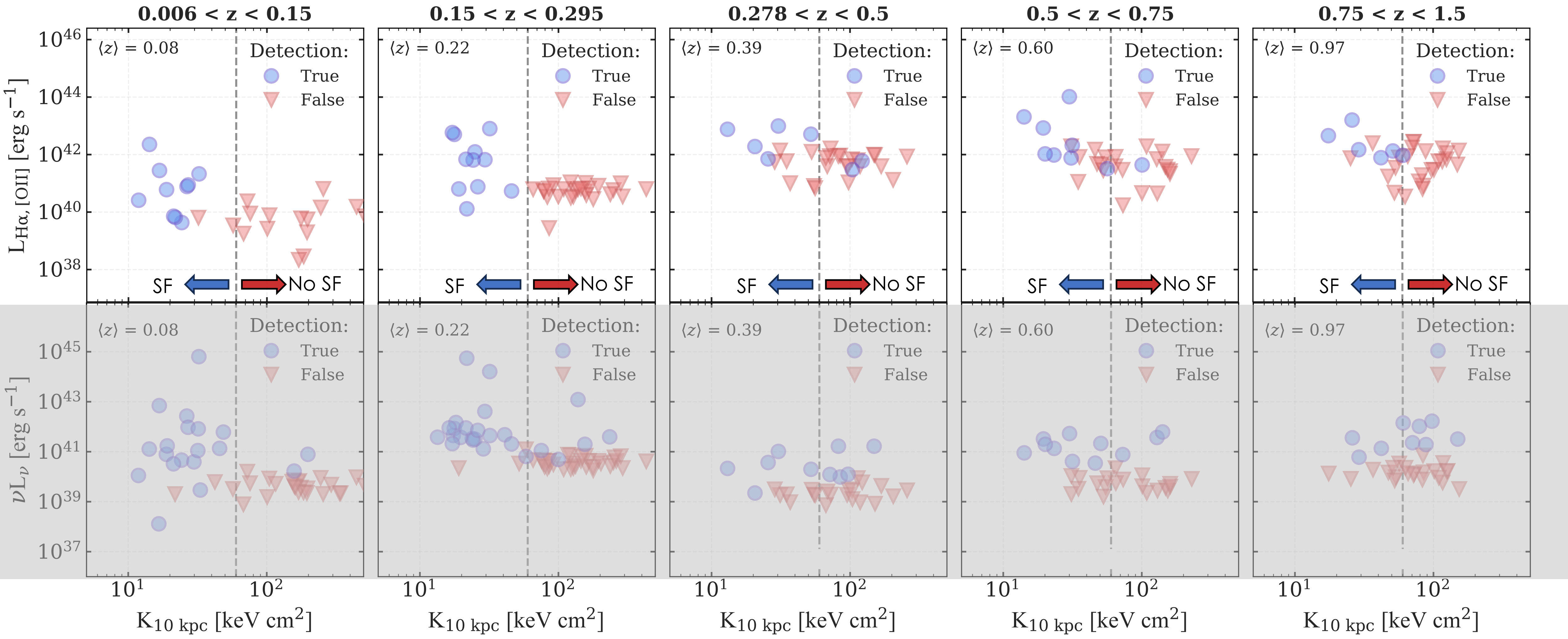
TRIGGER FOR STAR FORMATION PERSISTS FOR 10 GYR



TRIGGER FOR STAR FORMATION PERSISTS FOR 10 GYR

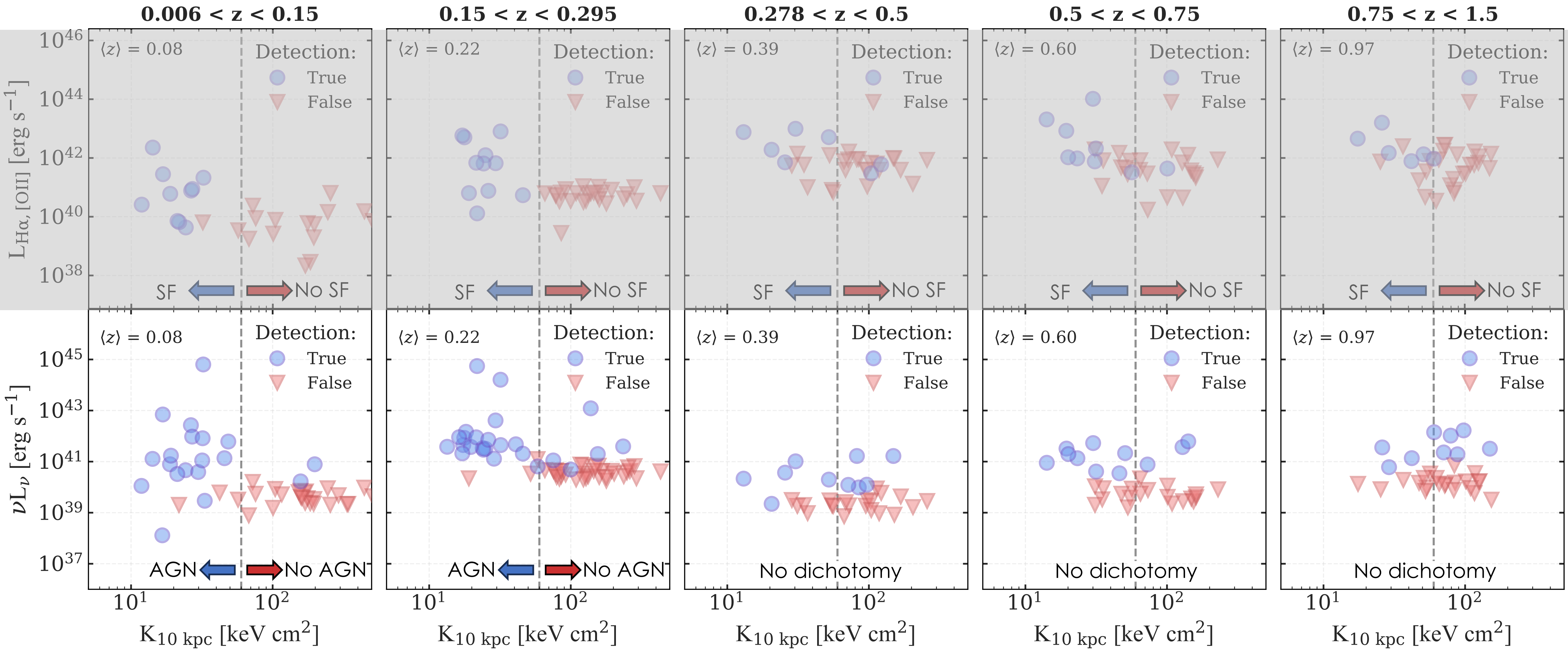


HAVE THE CONDITIONS FOR COOLING EVOLVED?



Calzadilla et al. 2024a

HAVE THE CONDITIONS FOR *FEEDBACK* EVOLVED?

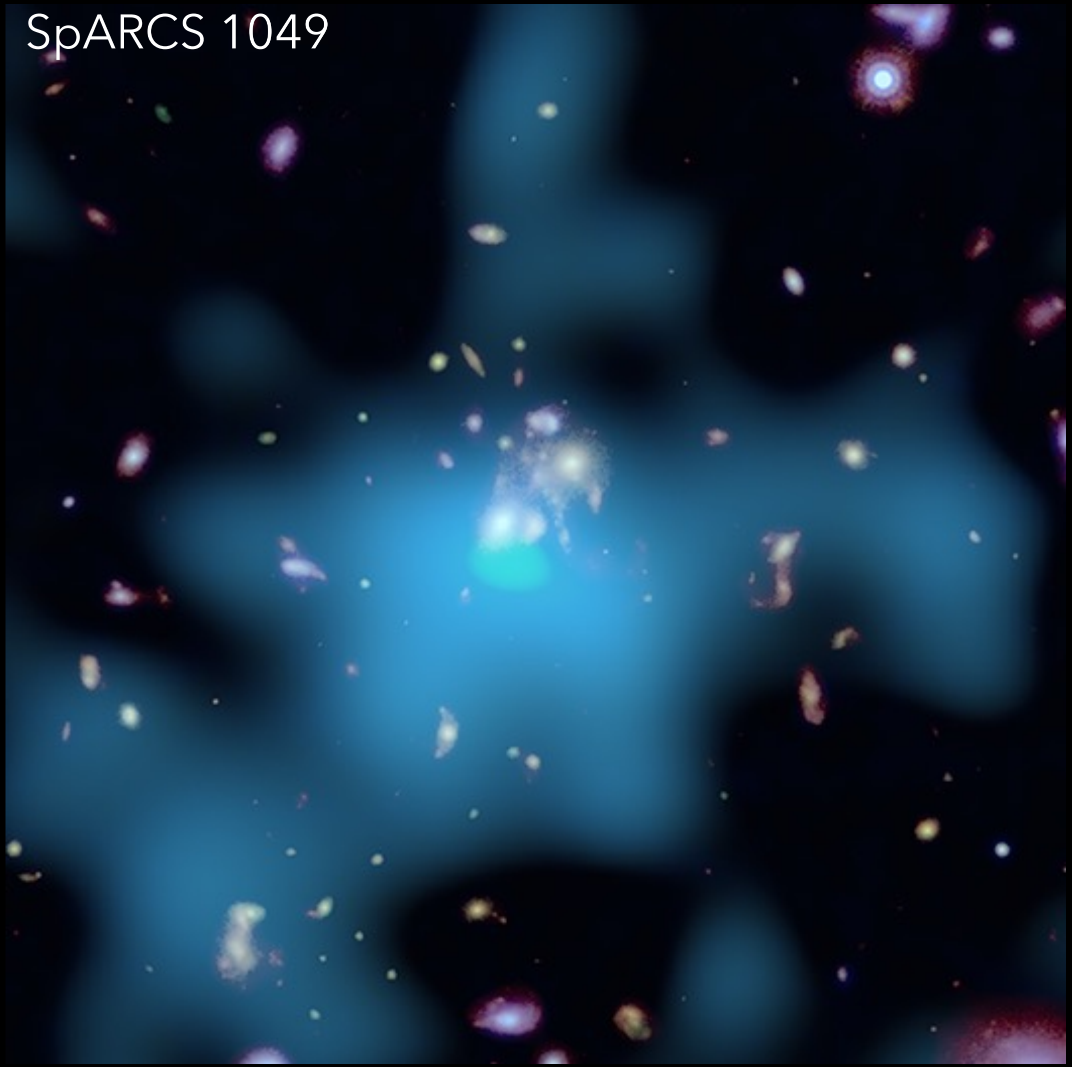


Calzadilla et al. 2024a

COOLING-FEEDBACK CONNECTION AT HIGH-Z

- Not as tight in the past as it is today *(Birzan+17)*
- Conditions in the past:
  - Higher merger rate *(e.g. Brodwin+13, Lotz+13)*
  - Higher gas availability and SFRs *(e.g. Madau & Dickinson 14)*
  - Higher quasar fraction rather than radio mode AGN *(Somboonpanyakul+22, Hlavacek-Larrondo+13)*

- Case study: SpARCS 1049
  - $z = 1.7$, $M = 3\text{x}10^{14}\ M_\odot$
  - Massive starburst: ~860 $M_\odot$/yr *(Webb+15a,b)*
  - ICM and SF not centered on BCG → no feedback *(Hlavacek-Larrondo+20)*

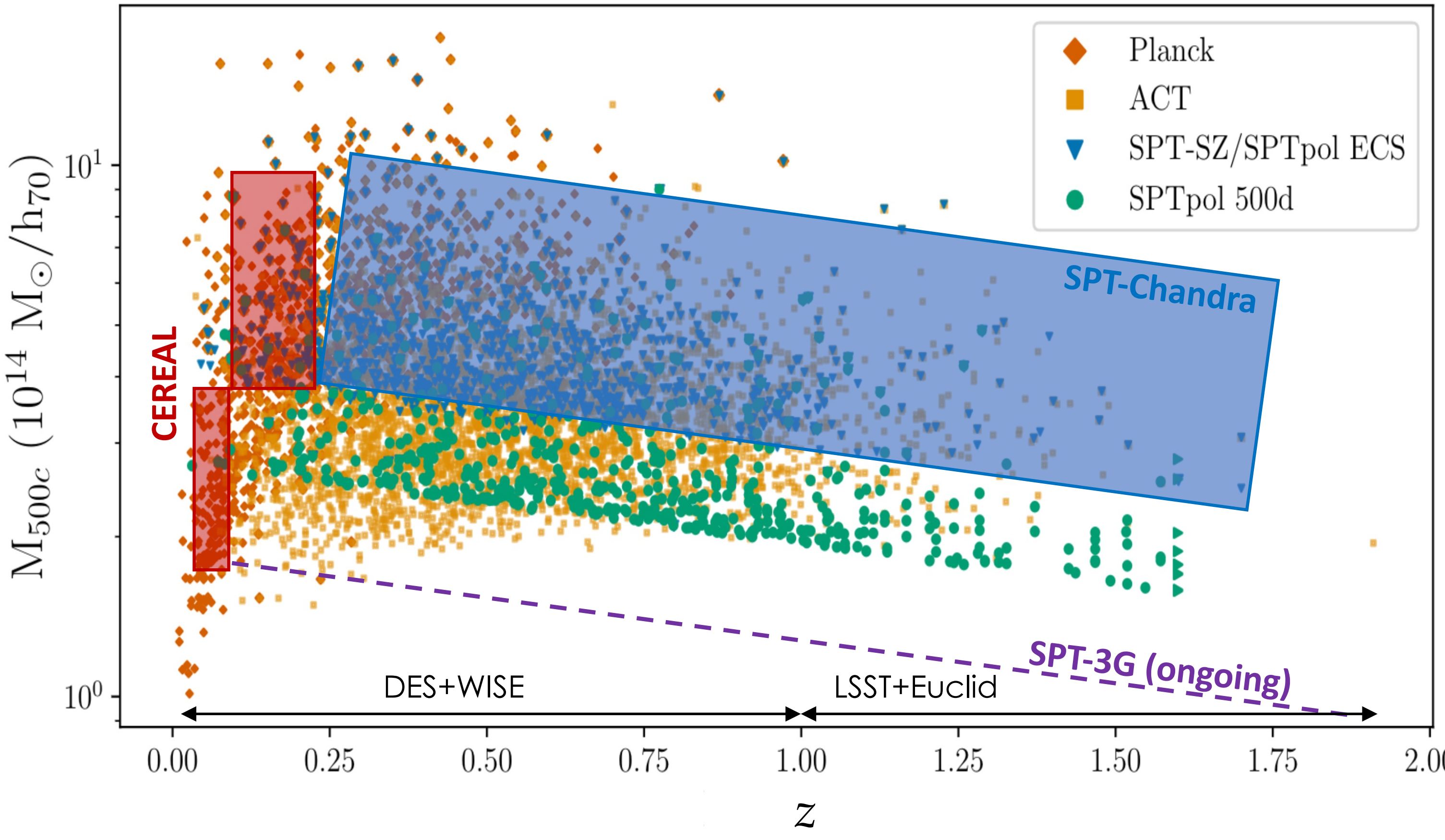


FUTURE WORK

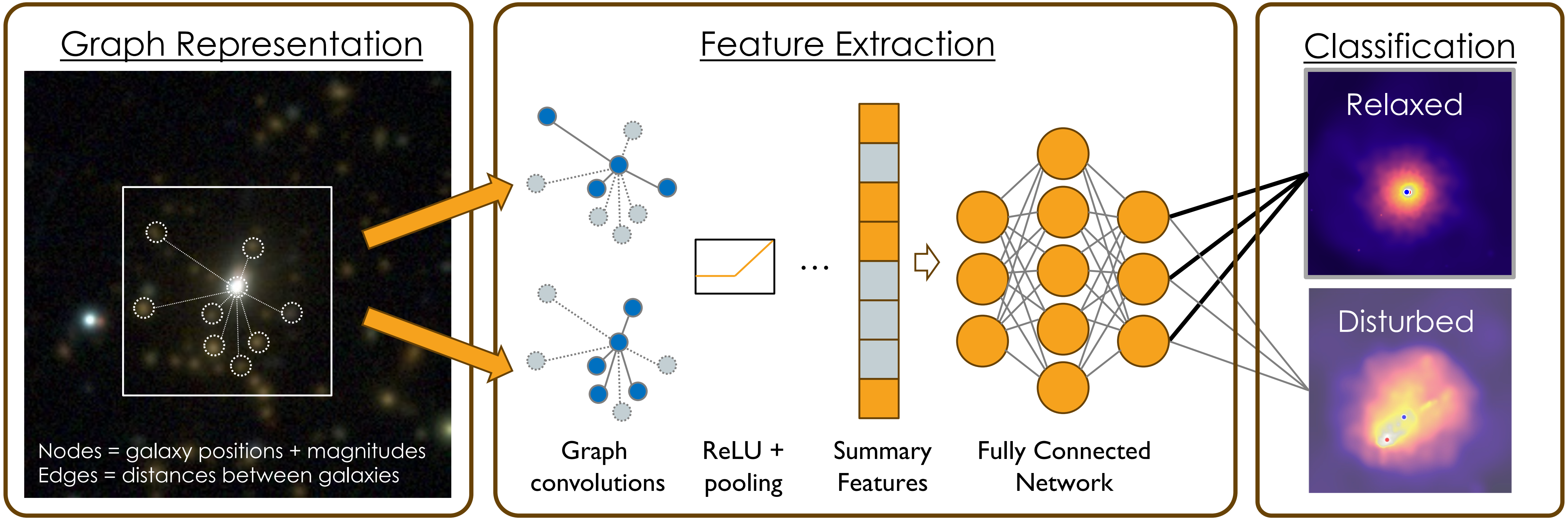
SPT-3G: ~5000 clusters out to z~2

→ Will use ML to characterize

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



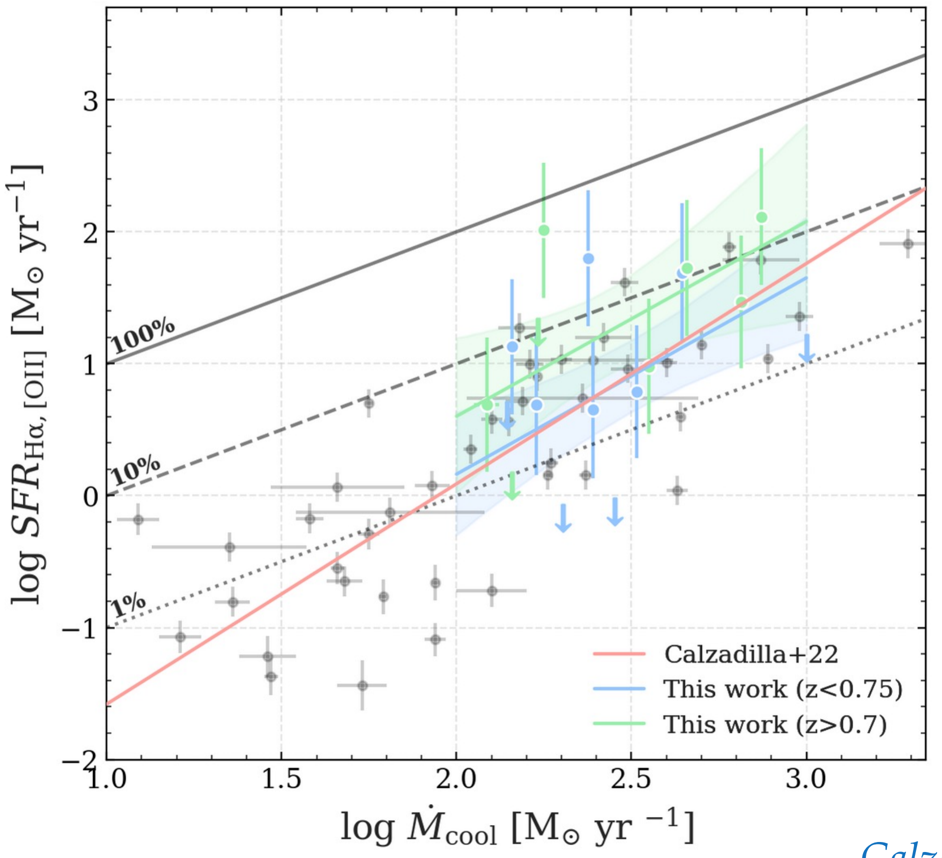
MACHINE LEARNING CLUSTER DYNAMICAL STATES

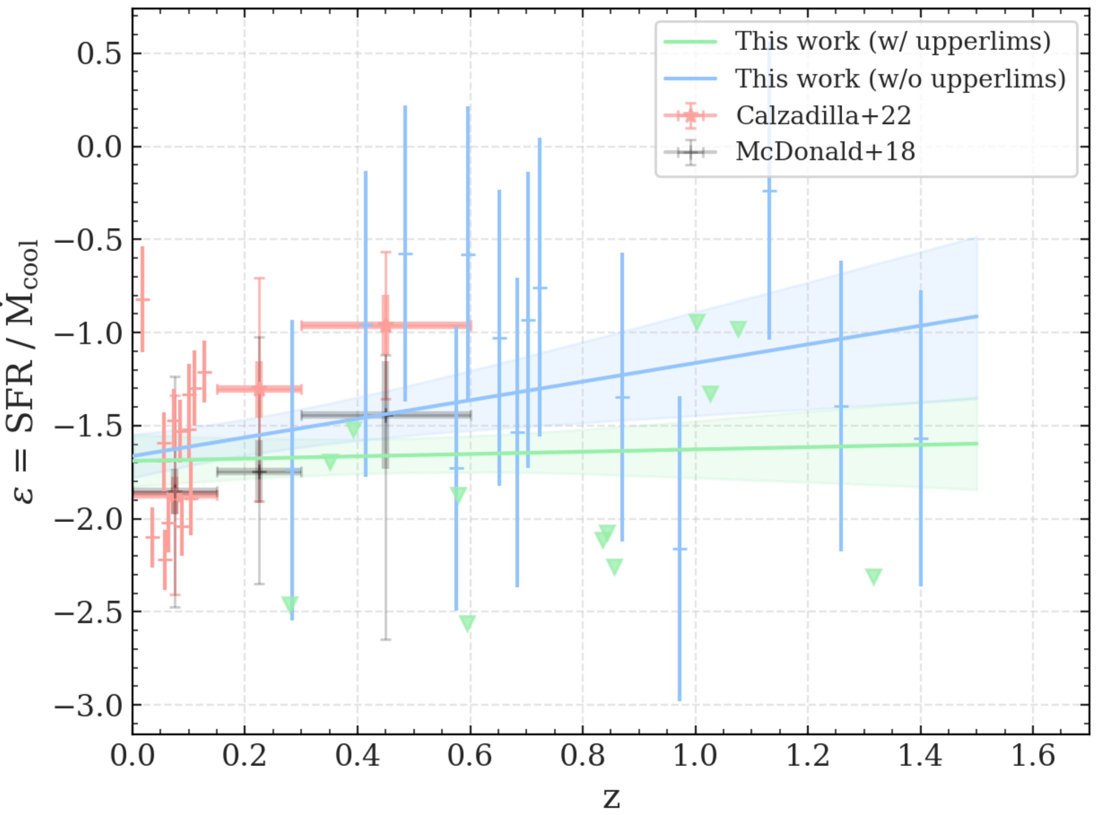


Train on simulation → apply to real SPT-3G sample
Disentangle BCG growth and BH fueling mechanism from evolution

PRELIMINARY: EVOLUTION OF FEEDBACK EFFECTIVENESS

Steeper-than-unity slope out to high-z, but no significant evolution in average efficiency





Calzadilla+24b (in prep.)

EVOLUTION OF AGN FEEDBACK CONDITIONS IN GALAXY CLUSTERS

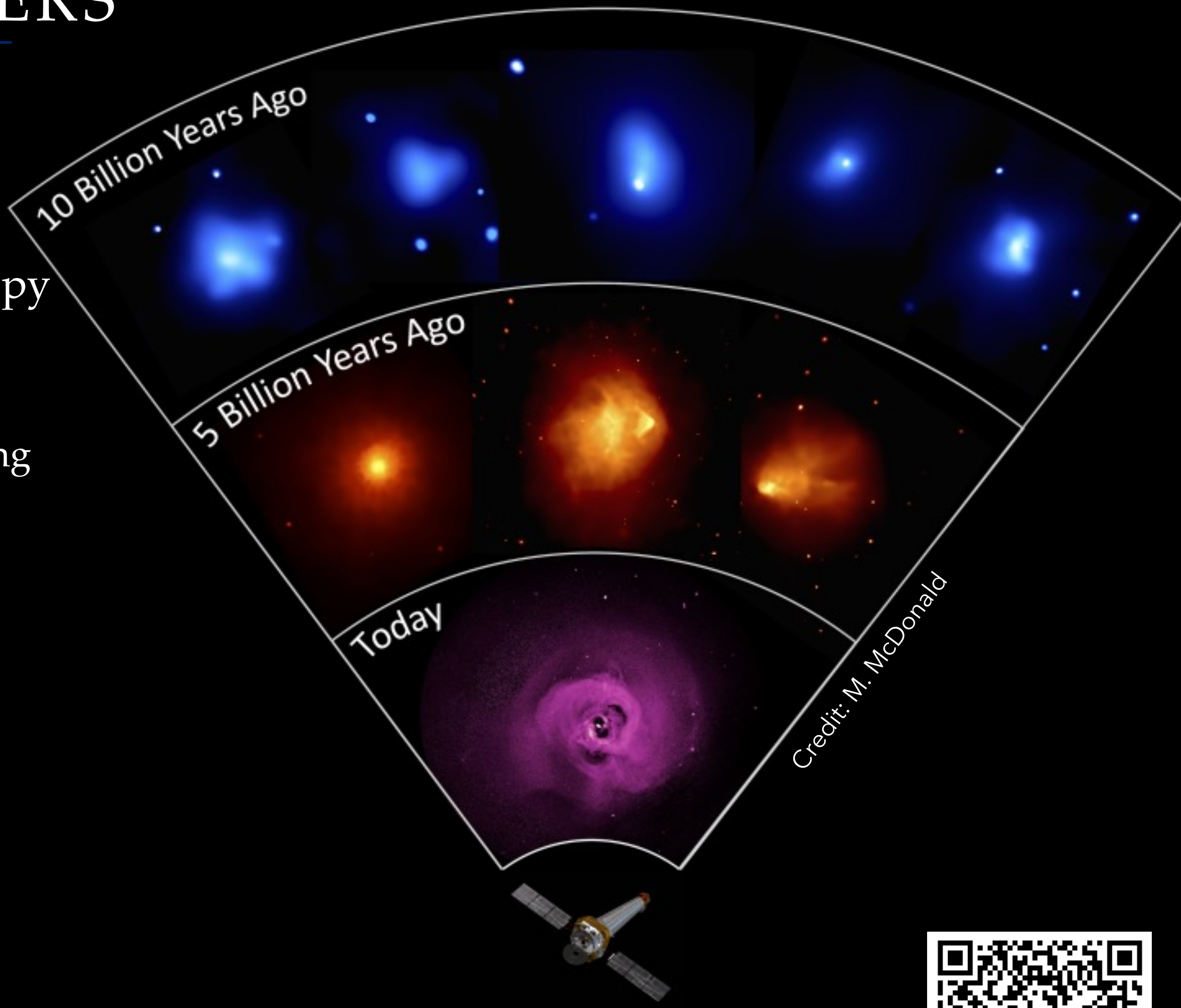
(arXiv:2311.00396)

- 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
- Chandra synergy with Optical + SZ + Radio dataset:
  - 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

    → cooling-feedback connection wasn't as tight

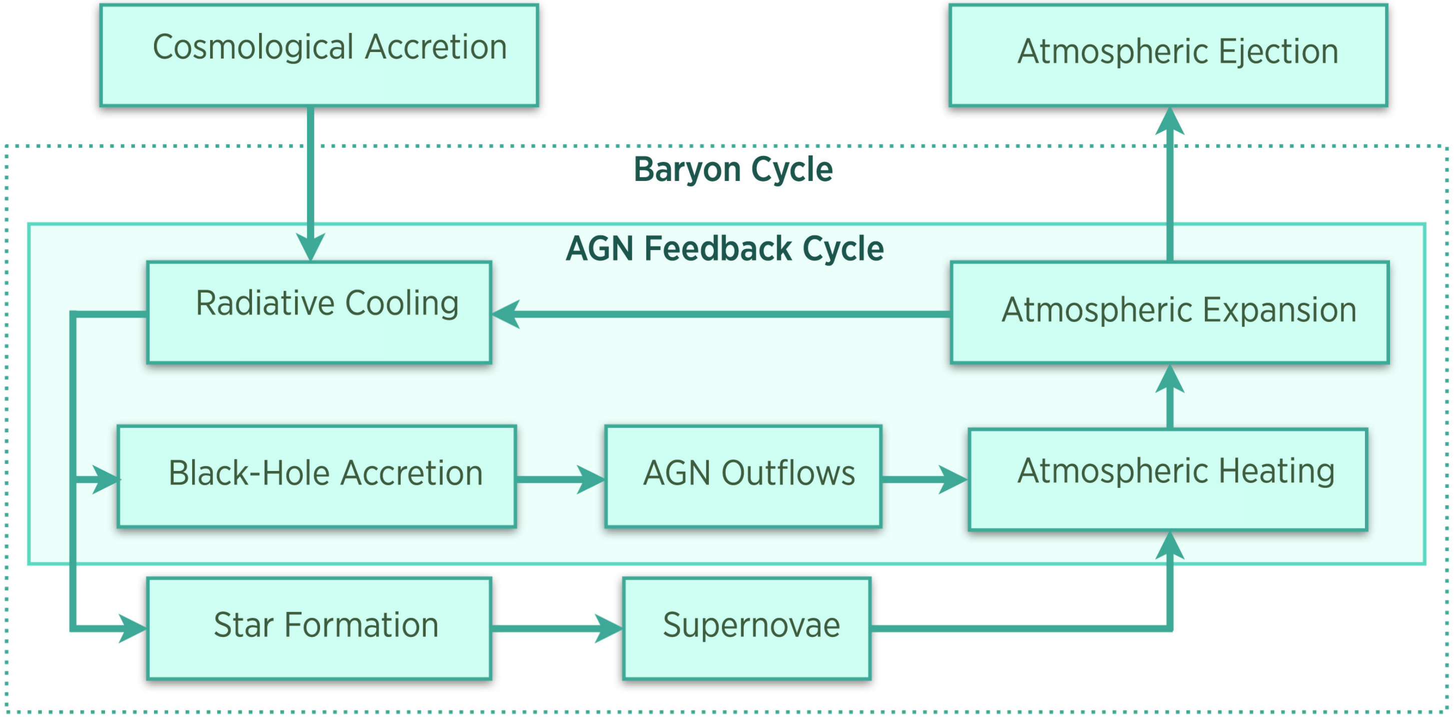
Stay tuned for follow-up papers!

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

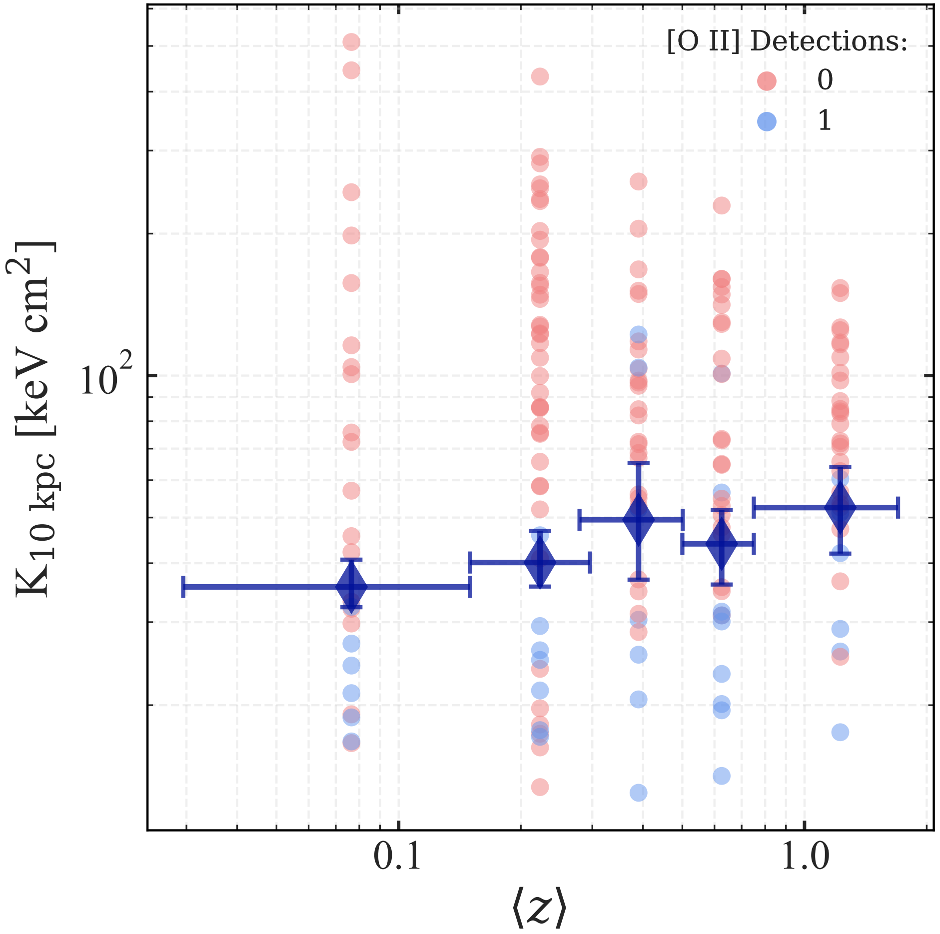


BACKUP SLIDES

BARYON CYCLE



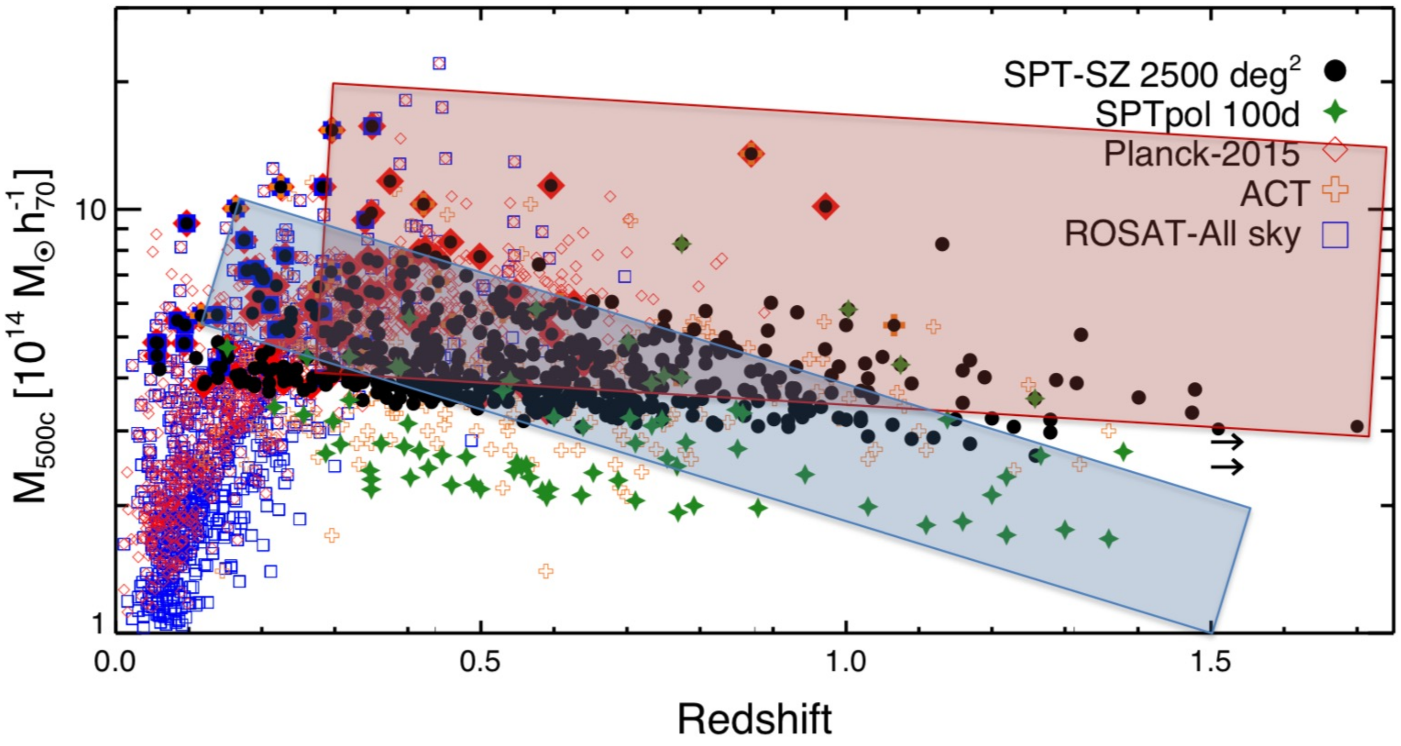
CONDITIONS FOR MULTIPHASE COOLING



No significant evolution in threshold value

Strong, long-lived connection between ICM cooling and SF

SPT MULTI-WAVELENGTH CLUSTER SAMPLE



Bleem + 19

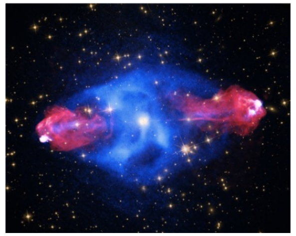
"XVP" or "SPT-Chandra" or "SPT-100":
~100 clusters spanning 0.3 < z < 1.7

"Progenitor sample" or "100d-Chandra":
~50 clusters spanning 0.3 < z < 1.4

→ (see e.g. Ruppin+21, 23)

- Multiwavelength follow-up:

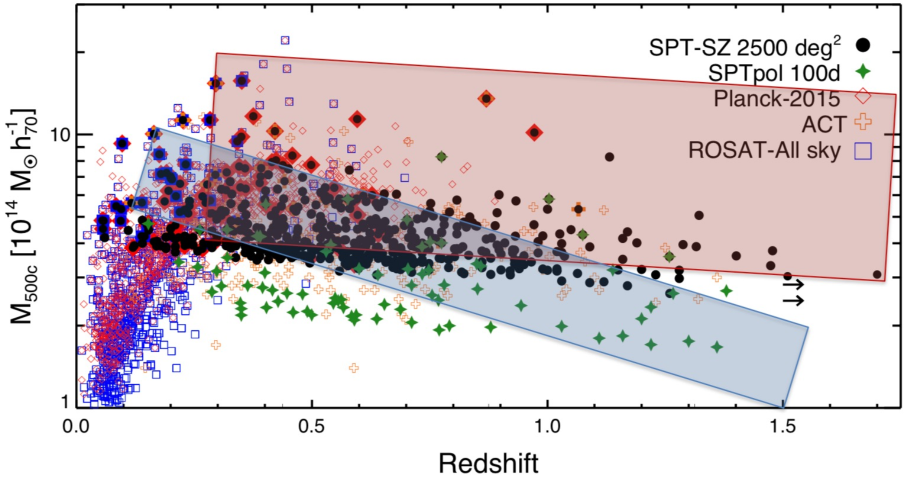
  X-ray + Radio + Optical/IR spectra

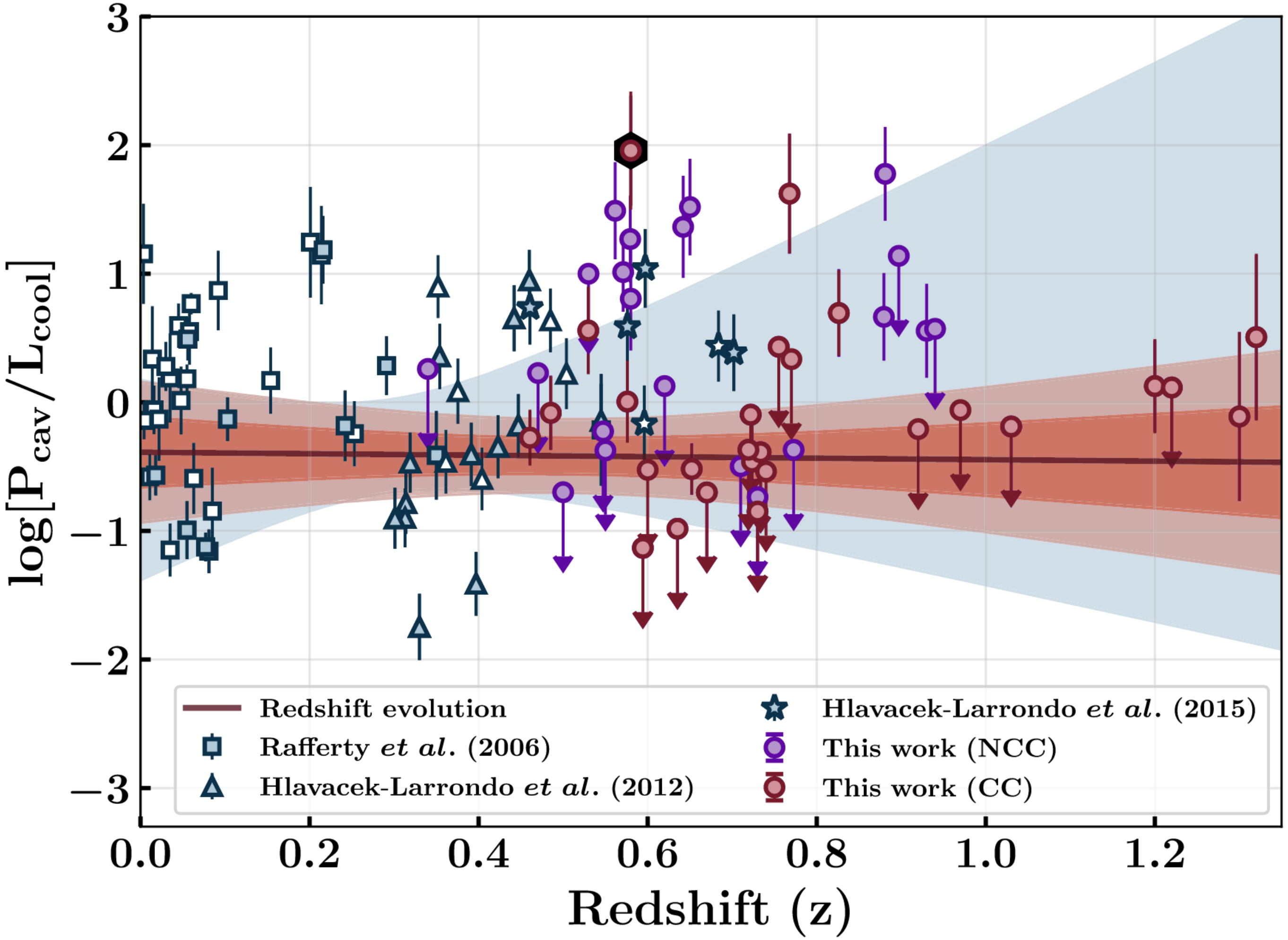


AGN FEEDBACK AS A FUNCTION OF REDSHIFT

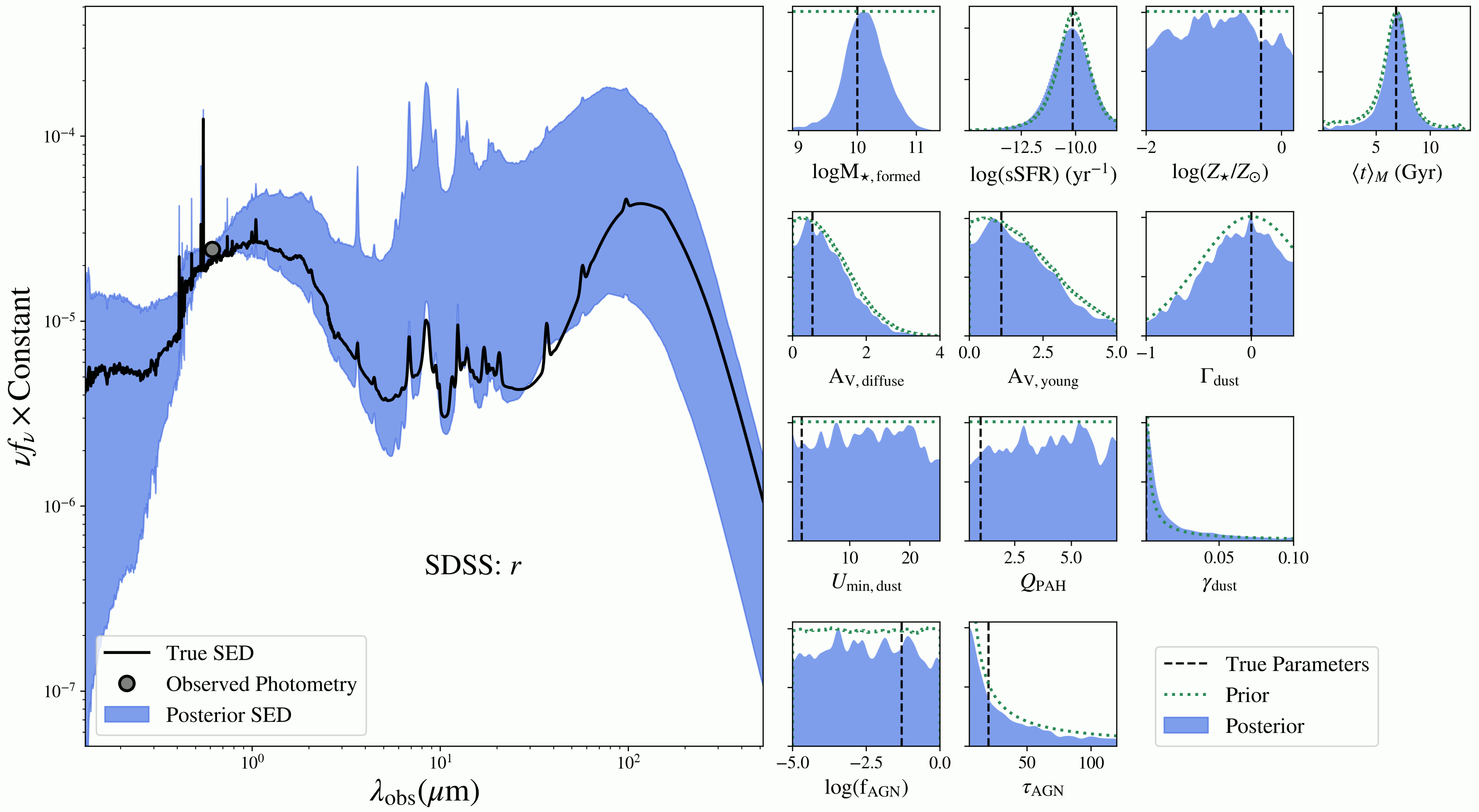
Ruppin et al. 2023

- Was feedback more violent in the past?
- "Radio-mode" feedback has been operating for 9+ Gyr
- No significant evolution up to z~1.3



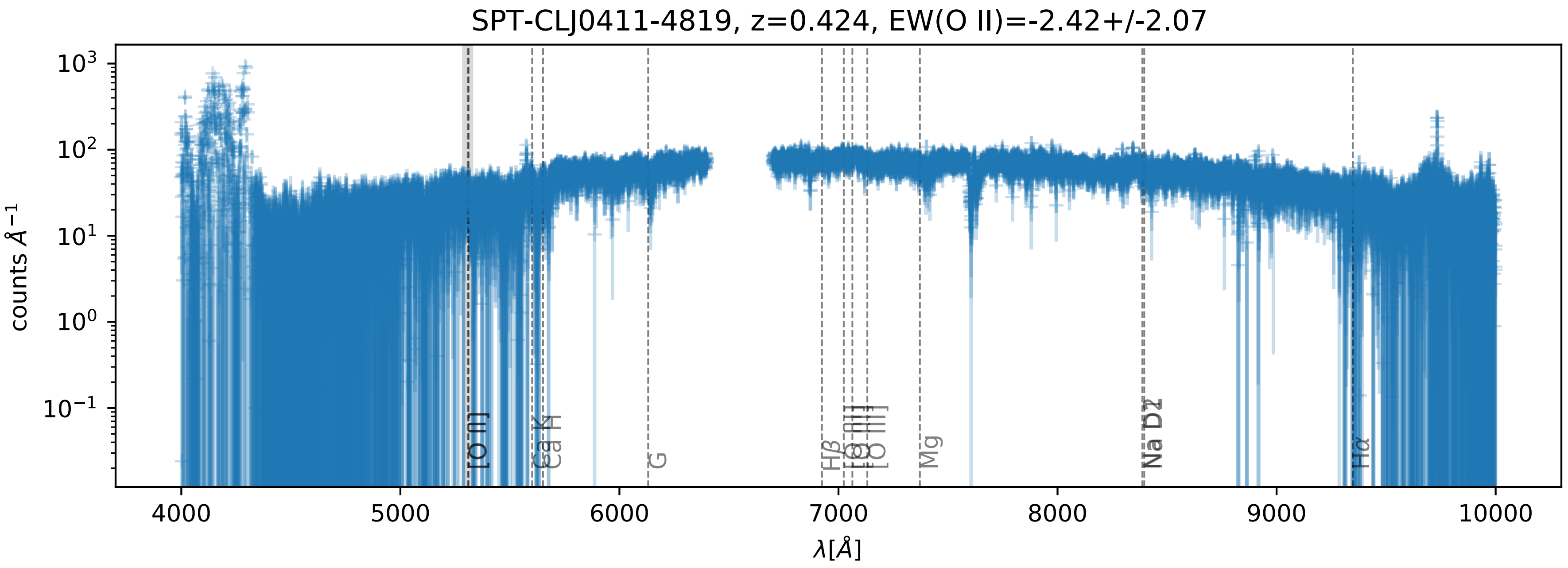


SED FITTING WITH PROSPECTOR



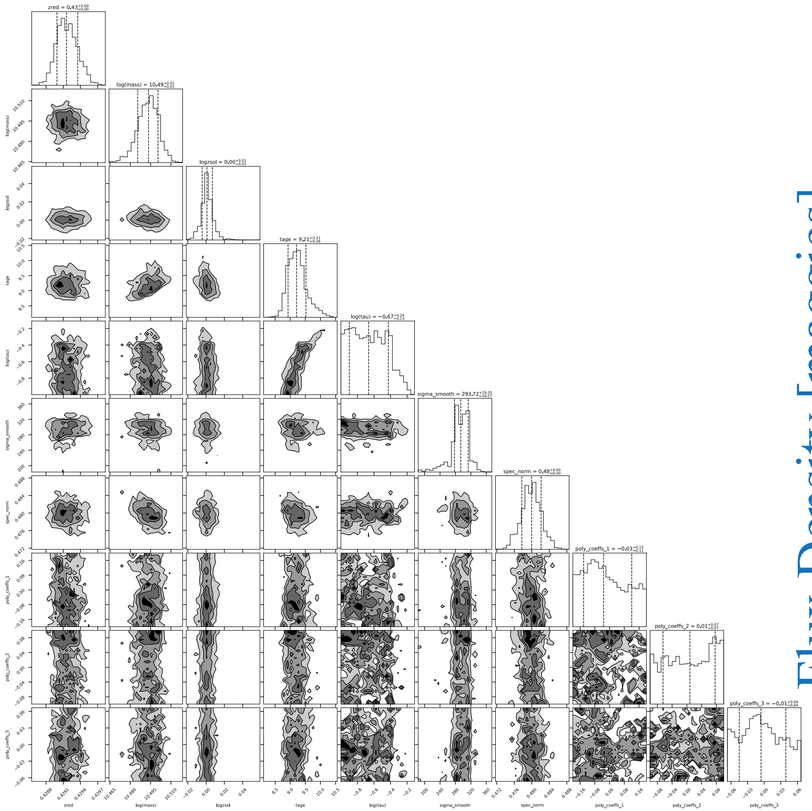
SED FITTING WITH PROSPECTOR

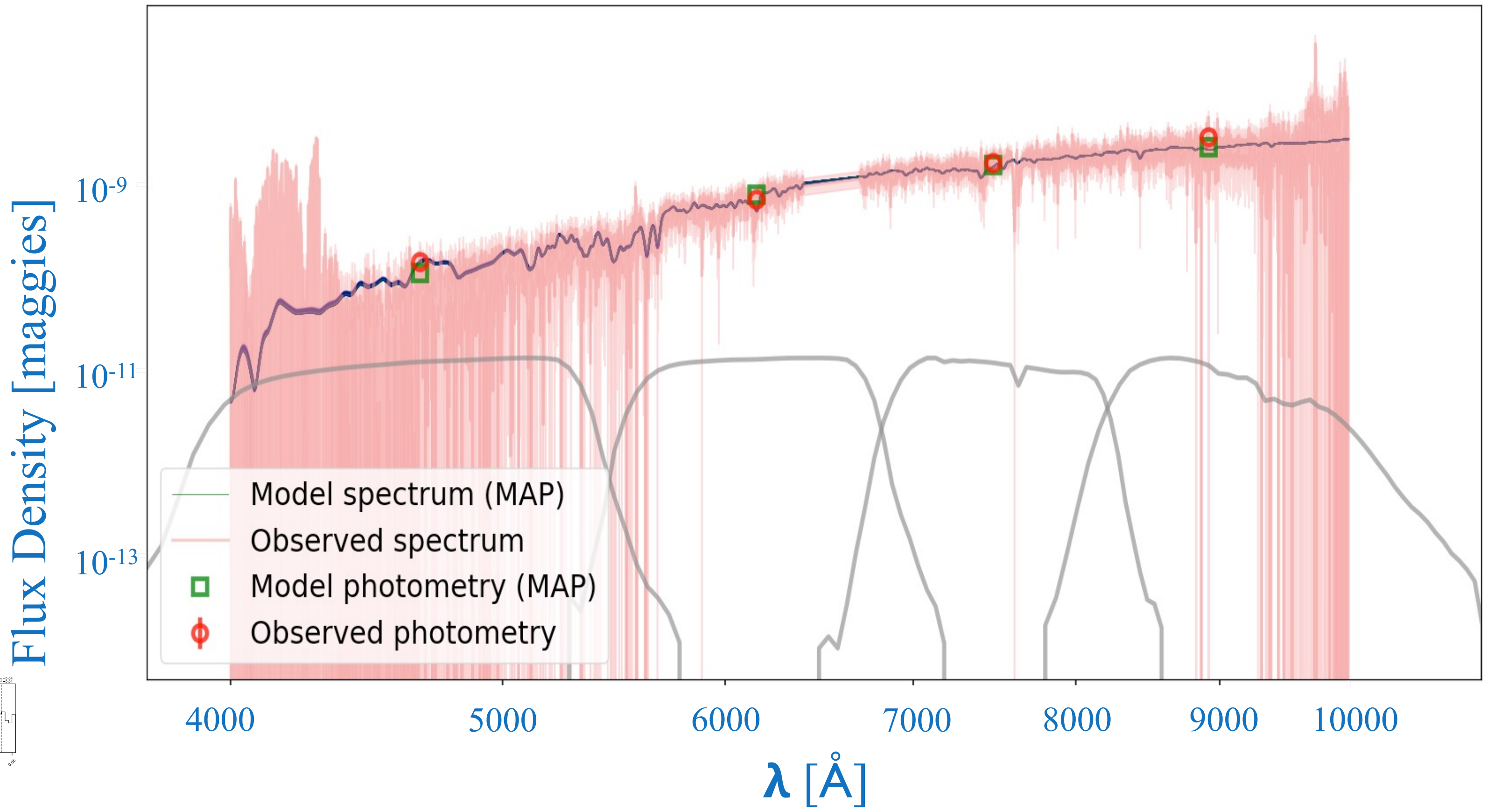
- Flux calibrate spectrum using calibrated photometry



SED FITTING WITH PROSPECTOR

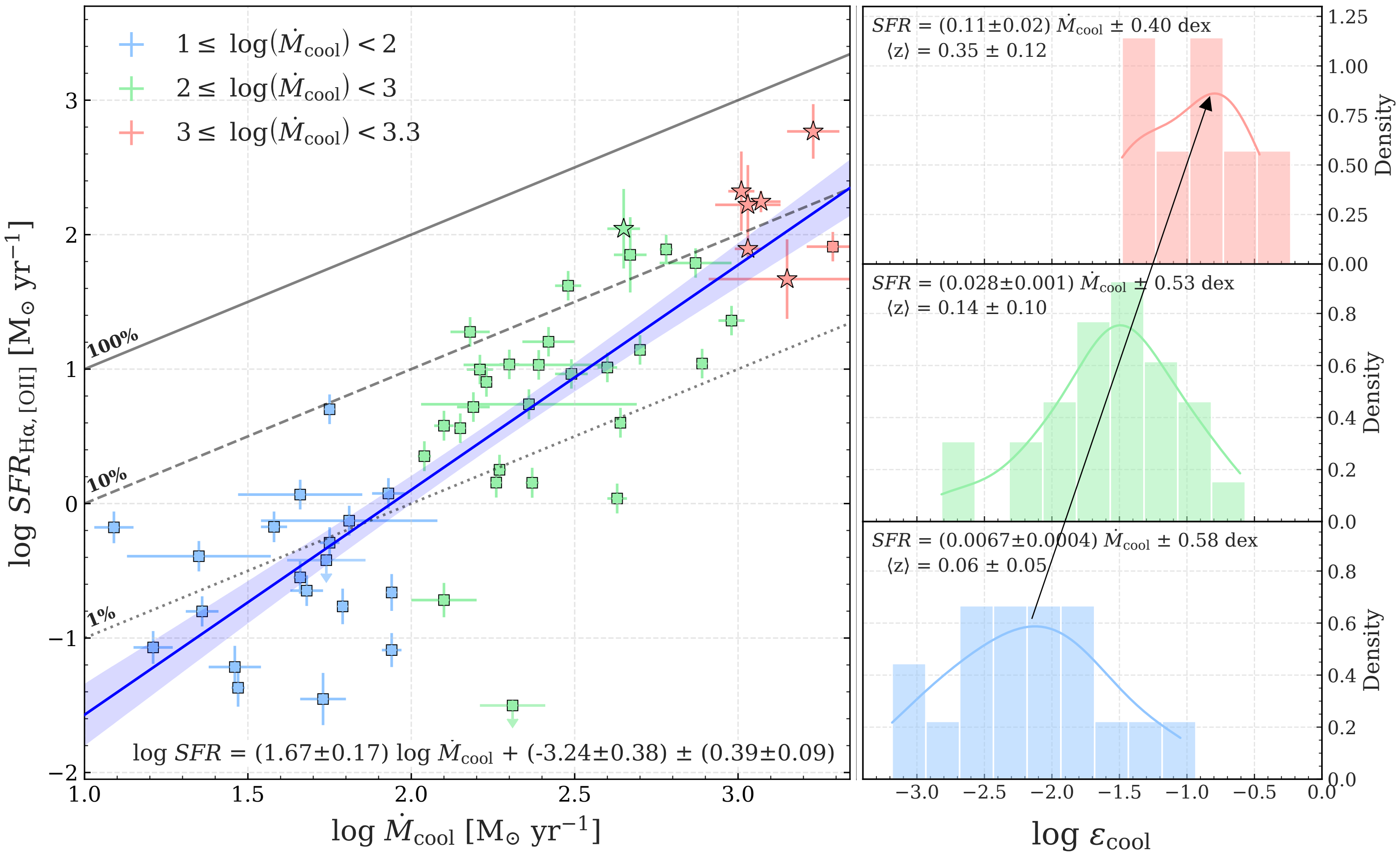
- Fit with delayed-tau SFH plus additional SF burst





SATURATION POINT FOR AGN FEEDBACK?

Calzadilla+22



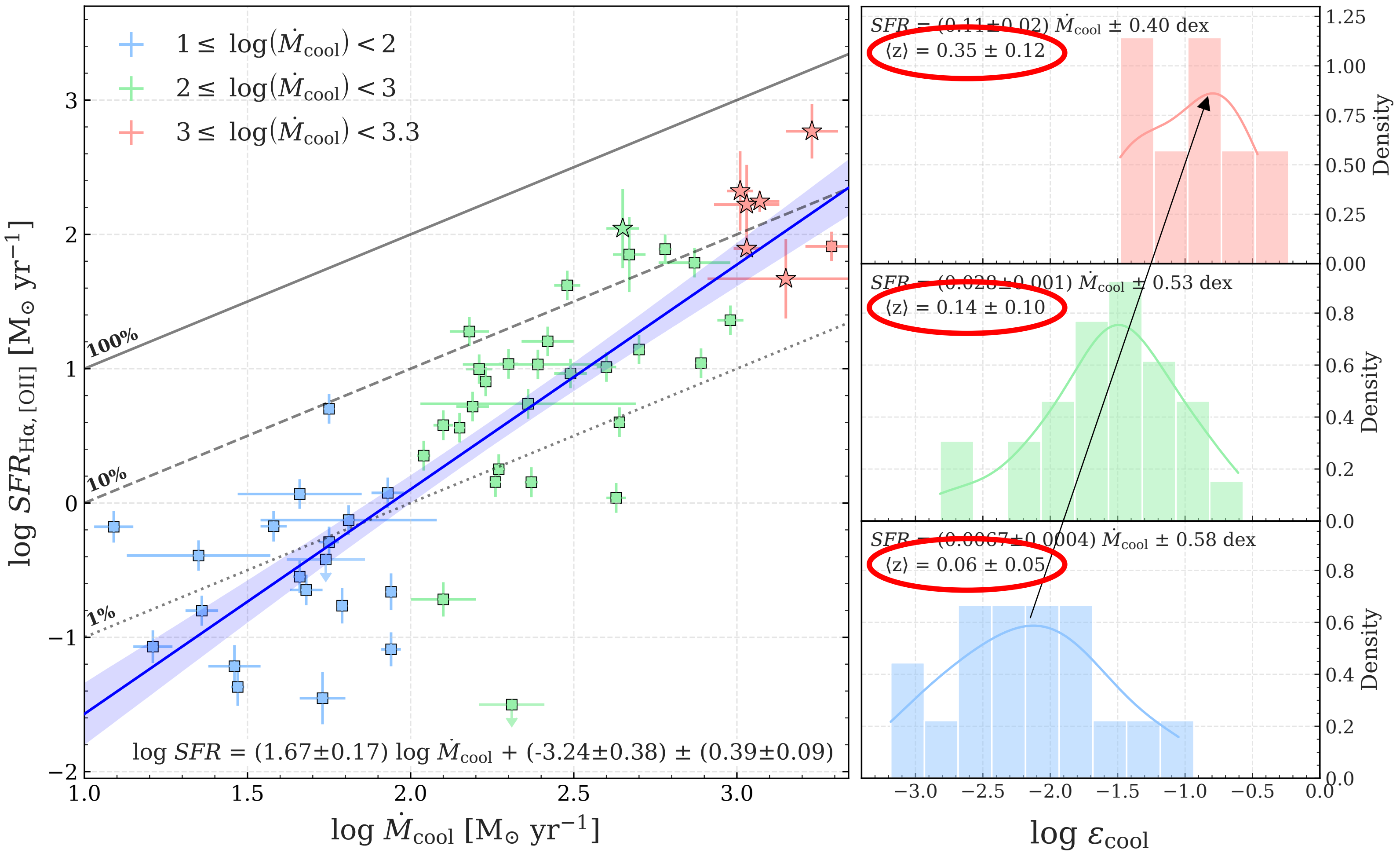
- Relaxing assumption of constant cooling efficiency:

→ Find steeper-than-unity relation b/w *SFR* and M_{cool}

- Gradual *increase* in cooling efficiency ⇔ Gradual *decrease* in effectiveness of feedback

HAS THE EFFECTIVENESS OF FEEDBACK EVOLVED?

Calzadilla+22



Redshift dependence?

Need representative sample to assess

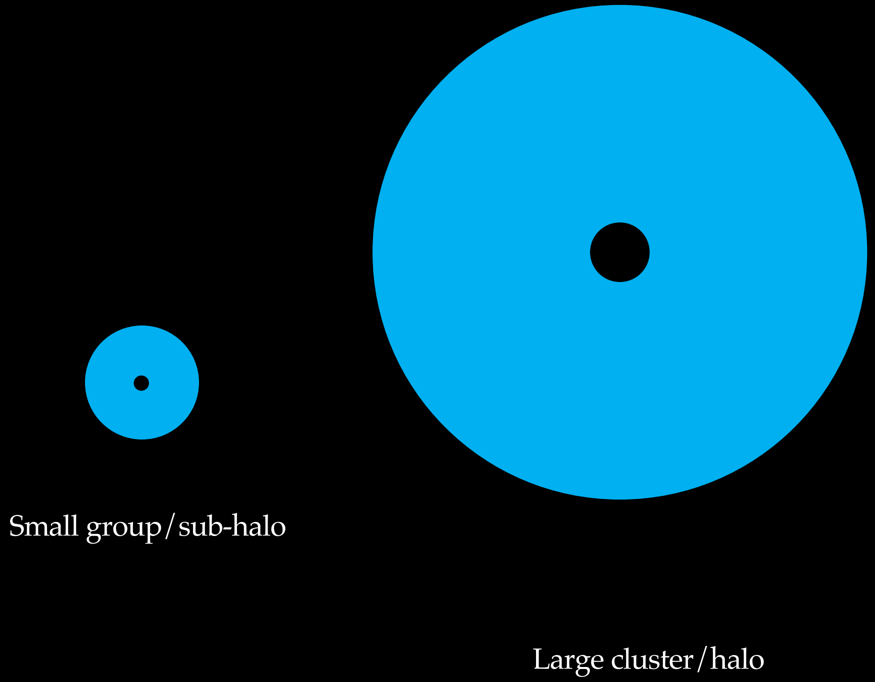
GRADUAL SATURATION OF AGN FEEDBACK

- SMBH growth rate proportional to cooling rate:

$$\frac{\dot{M}_{BH}}{\dot{M}_{Edd}} \propto \dot{M}_{cool}^{1.87}$$

- Cap on LHS, but not RHS
- Halos can grow via mergers/accretion, resulting in undermassive SMBH

→ affects mode of AGN feedback

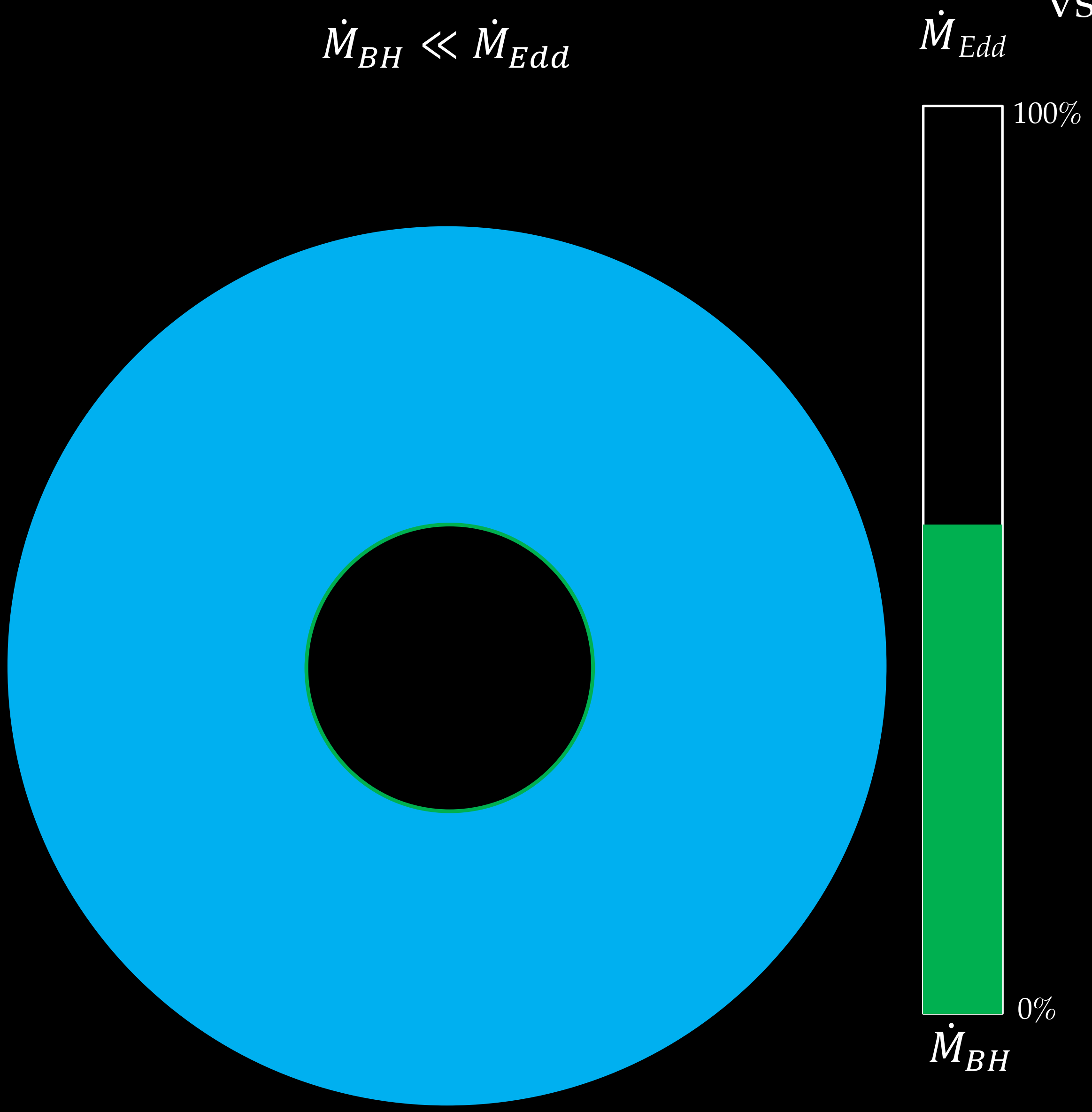


Radio Mode Feedback

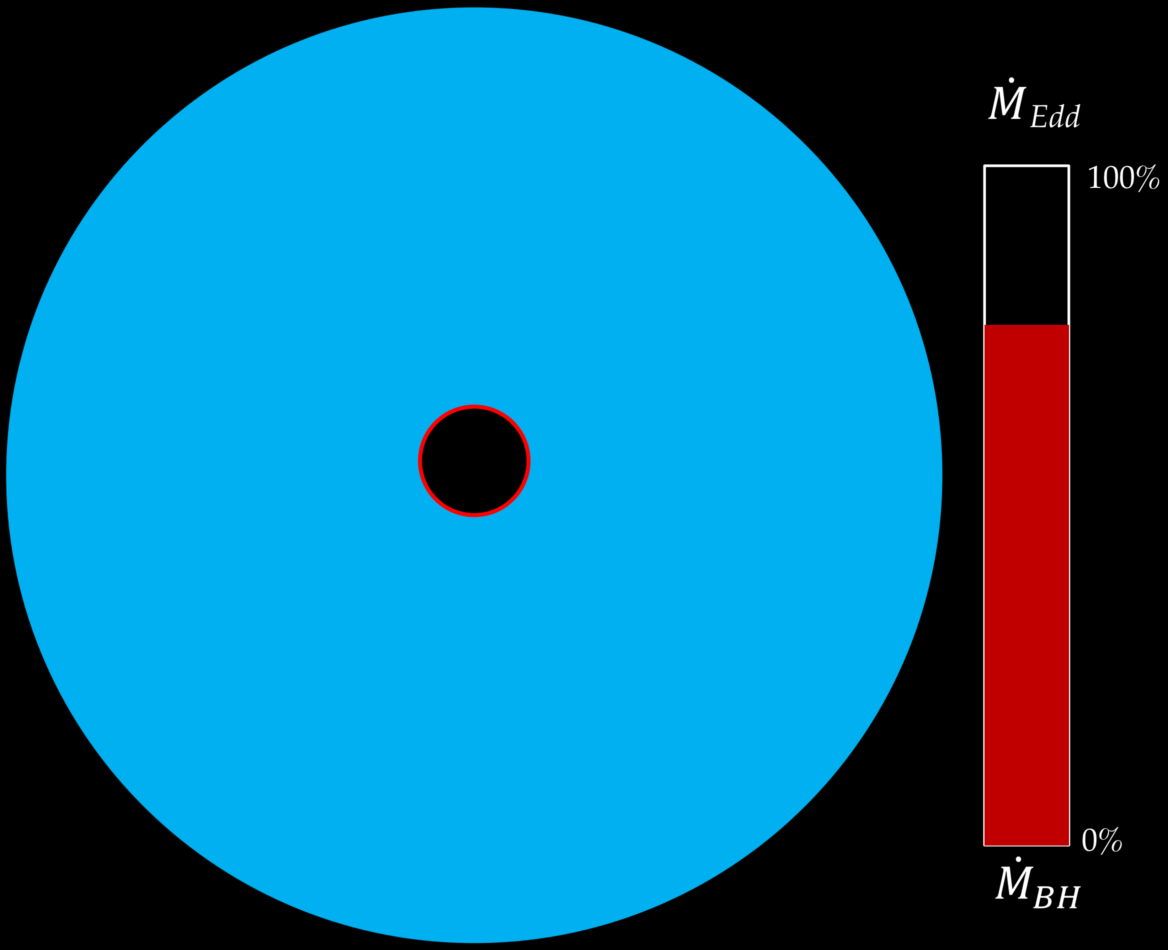
vs

Quasar Mode Feedback

$\dot{M}_{BH} \ll \dot{M}_{Edd}$



$\dot{M}_{BH} \gtrsim 0.1\,\dot{M}_{Edd}$



Radio Mode Feedback

vs

Quasar Mode Feedback

$\dot{M}_{BH} \ll \dot{M}_{Edd}$

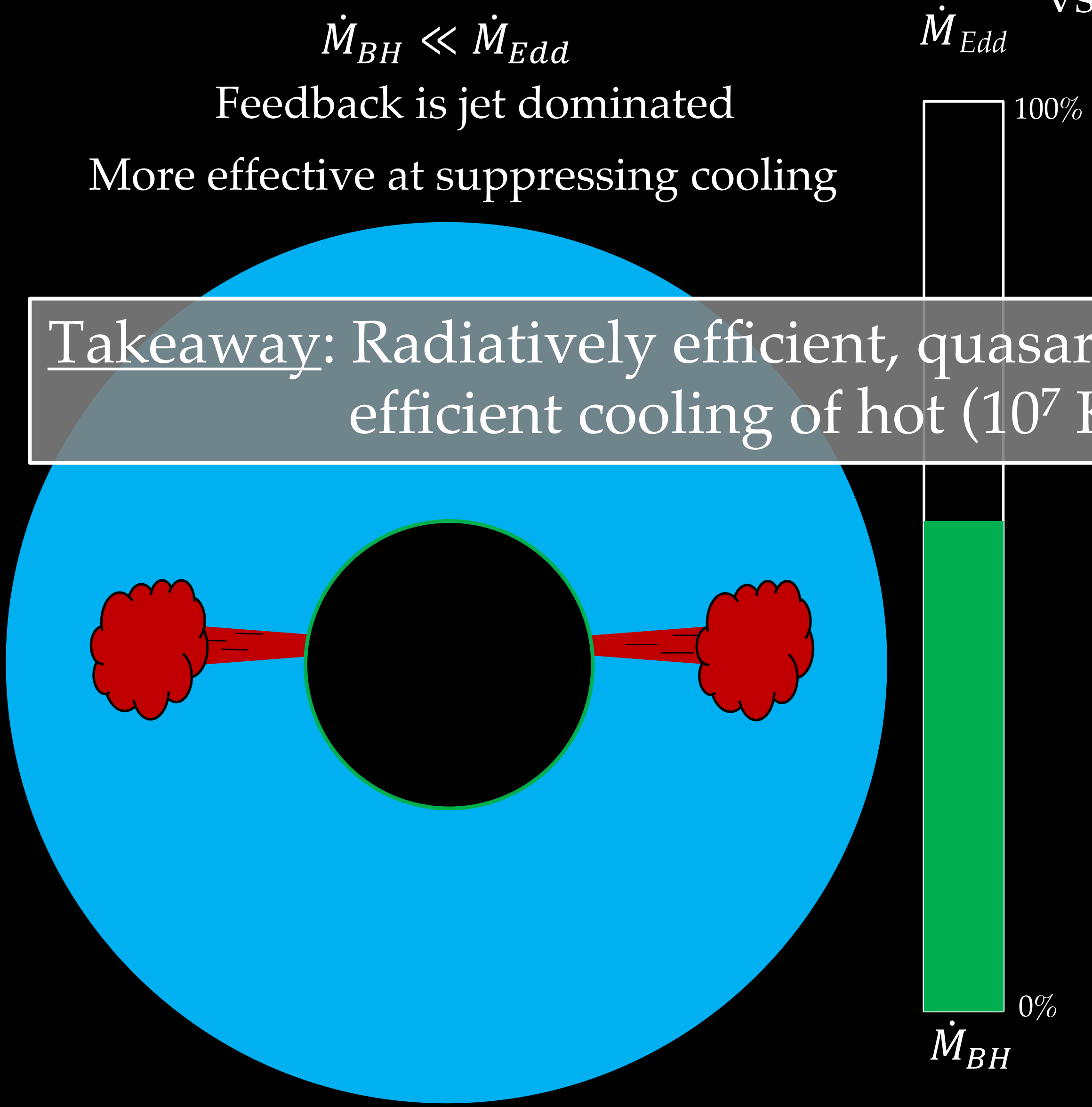
Feedback is jet dominated

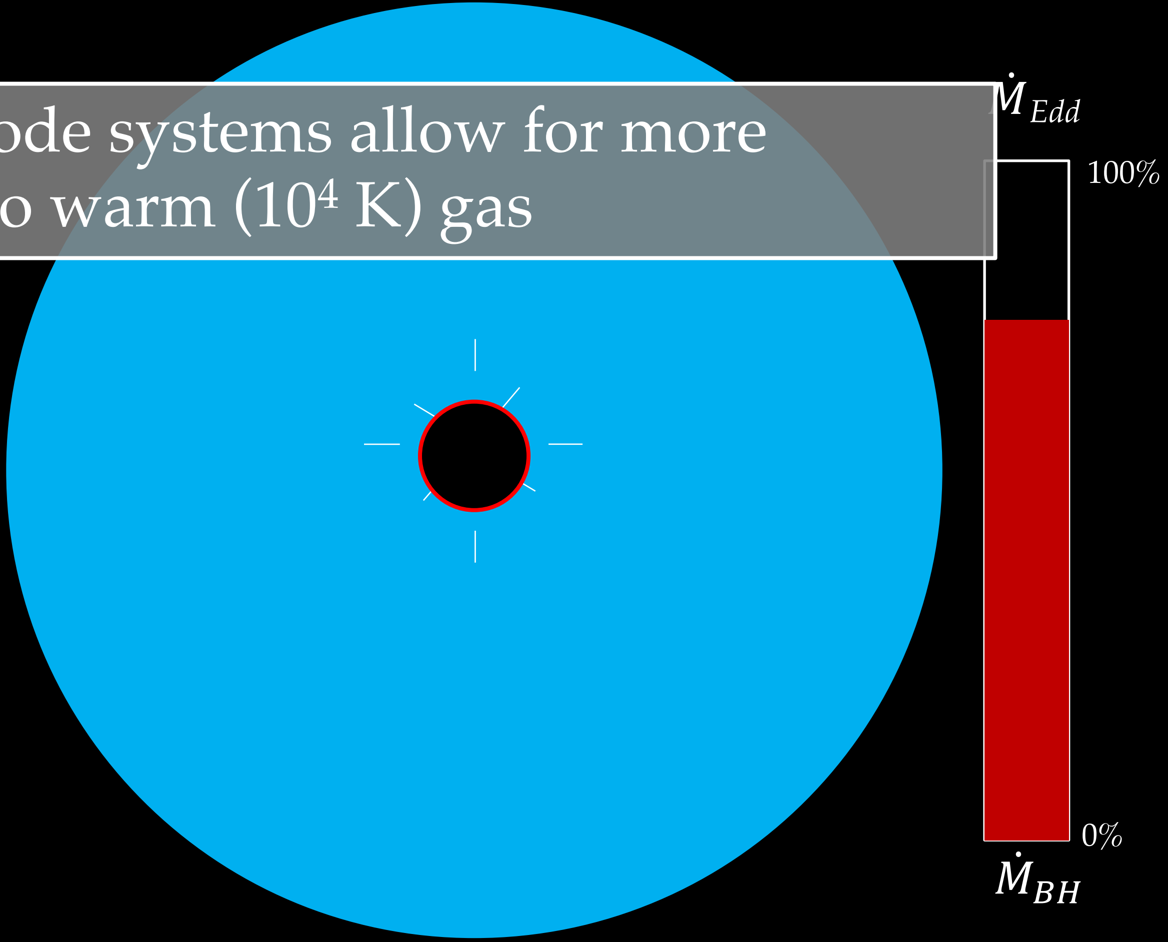
More effective at suppressing cooling

$\dot{M}_{BH} \gtrsim 0.1\,\dot{M}_{Edd}$

Feedback is radiation dominated

Not as effective at suppressing cooling



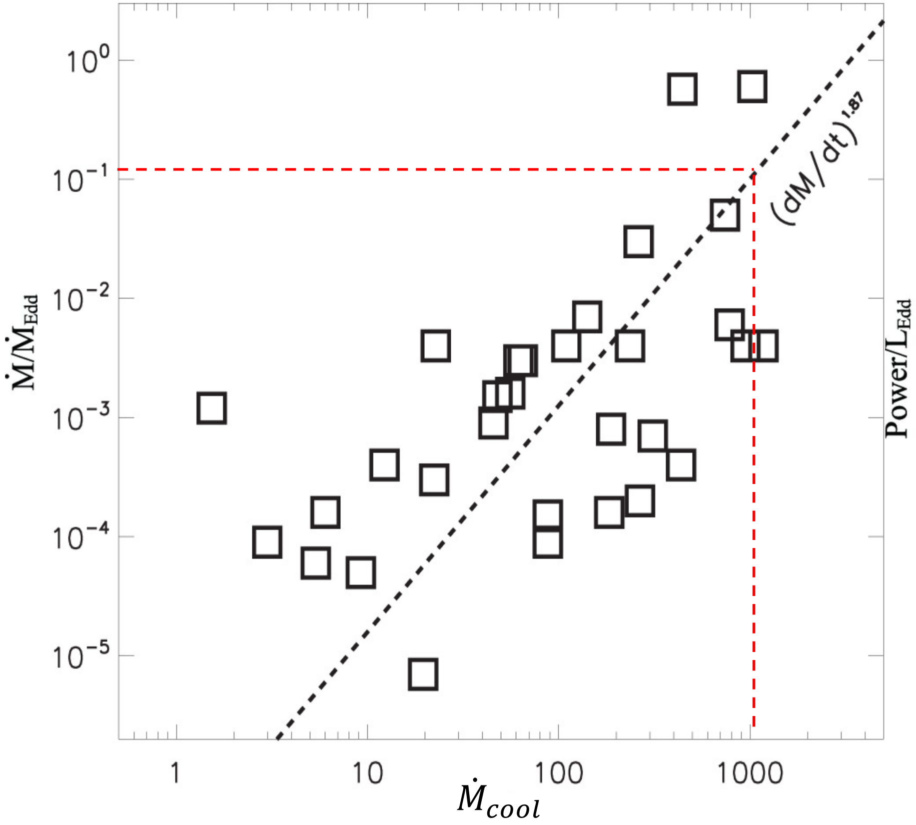


Takeaway: Radiatively efficient, quasar mode systems allow for more efficient cooling of hot (10^7 K) to warm (10^4 K) gas

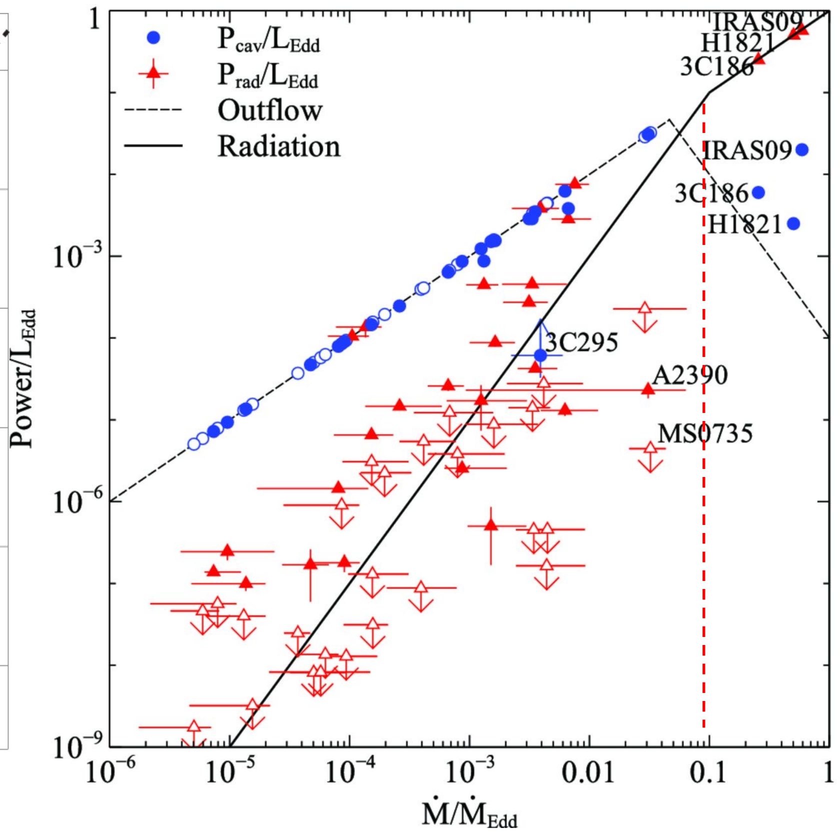
GRADUAL SATURATION OF AGN FEEDBACK

- Gradual transition from mechanical to radiative feedback at high $\dot{M}/\dot{M}_{Edd}$
  - Not as effective at offsetting cooling in clusters
- How then do you stop cooling?

McDonald+18

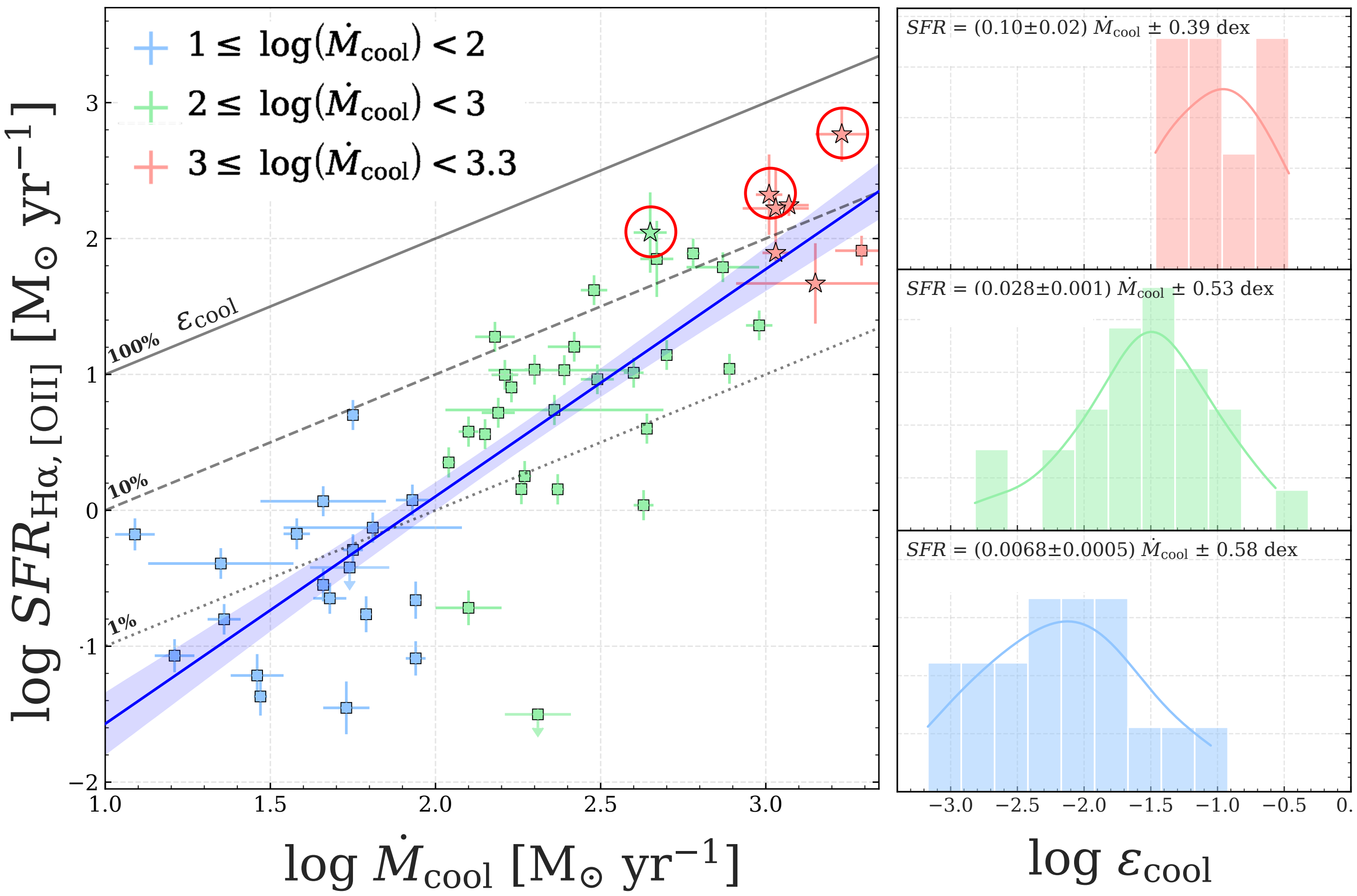


Russell+13, Churazov+05

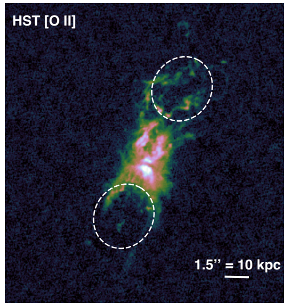


SFR VS $\dot{M}_{cool}$: GRADUAL SATURATION OF AGN FEEDBACK?

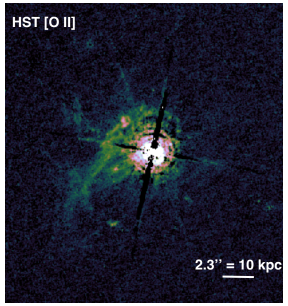
Calzadilla et al. 2022



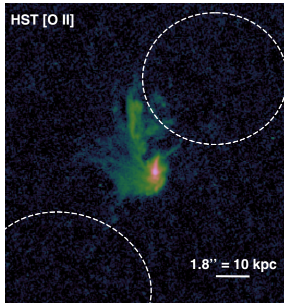
Not a coincidence that our quasar sources are cooling most efficiently



Phoenix



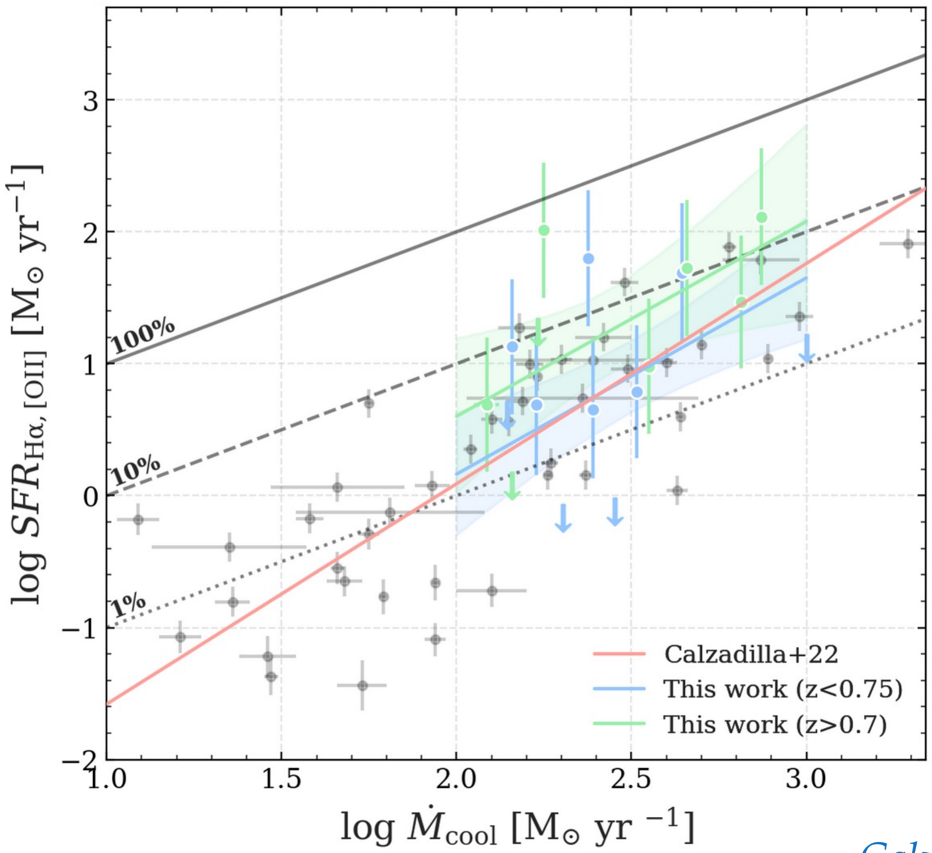
H1821+643

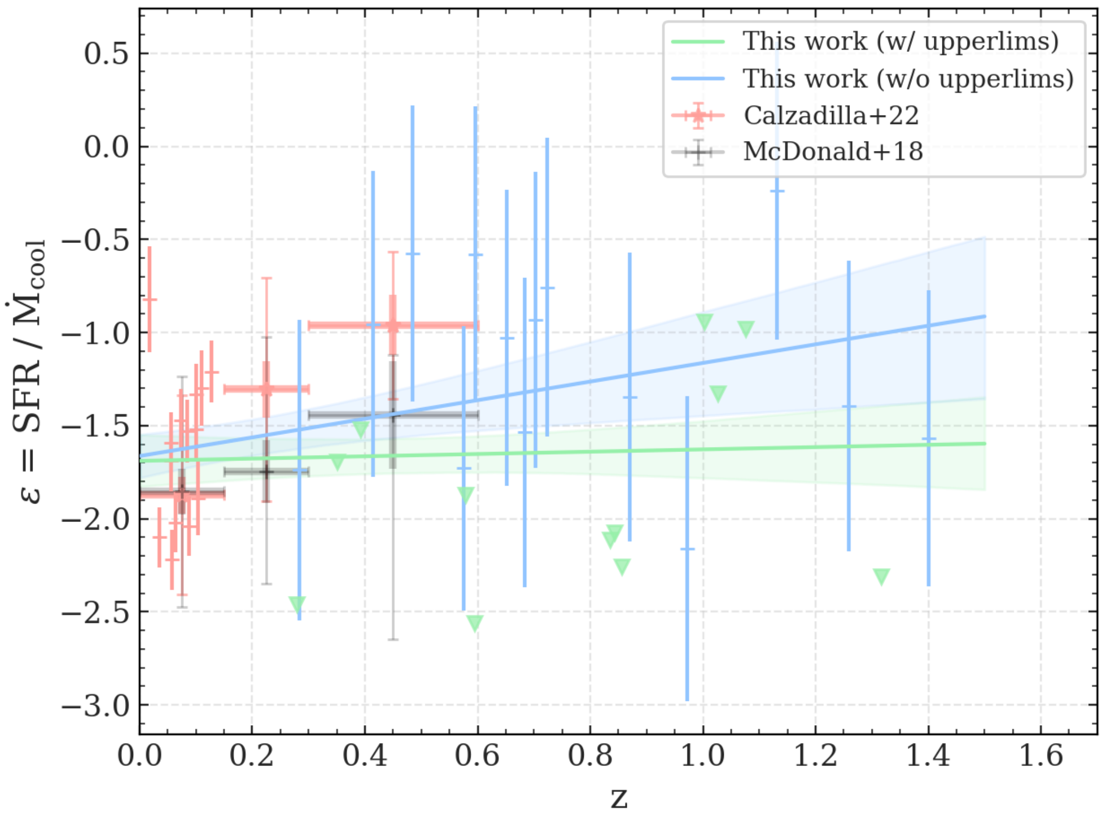


IRAS 09104+4109

PRELIMINARY: EVOLUTION OF FEEDBACK EFFECTIVENESS

Steeper-than-unity slope out to high-z, but no significant evolution in average efficiency





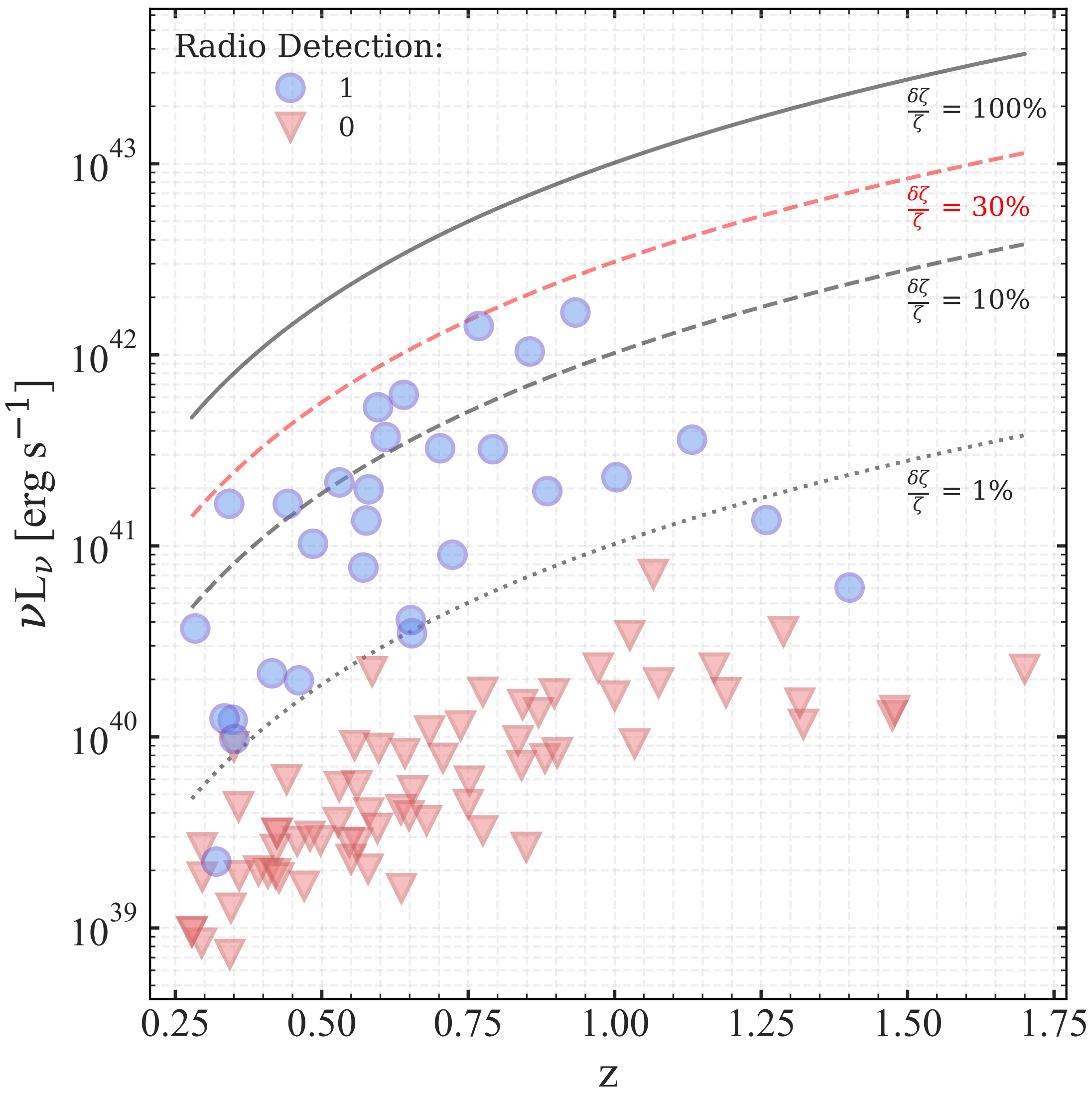
Calzadilla+24b (in prep.)

MISSING HIGH POWER RADIO SOURCES

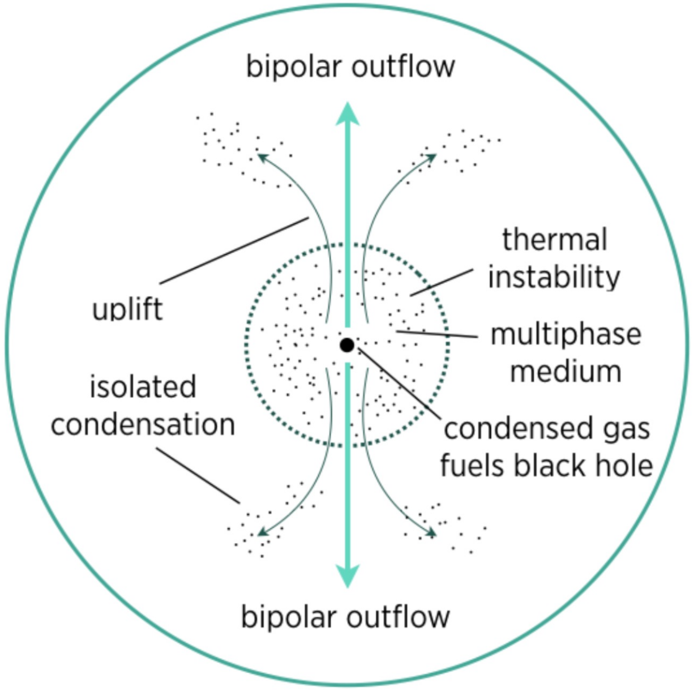
Only missing ~4% of high power sources expected from low-z

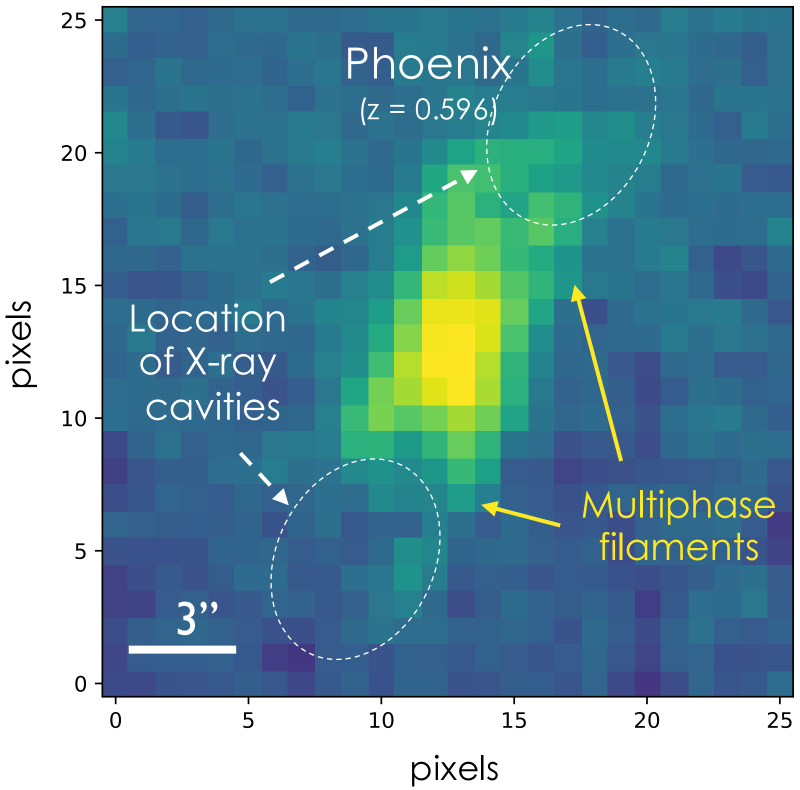
Radio bias to SZ signal:

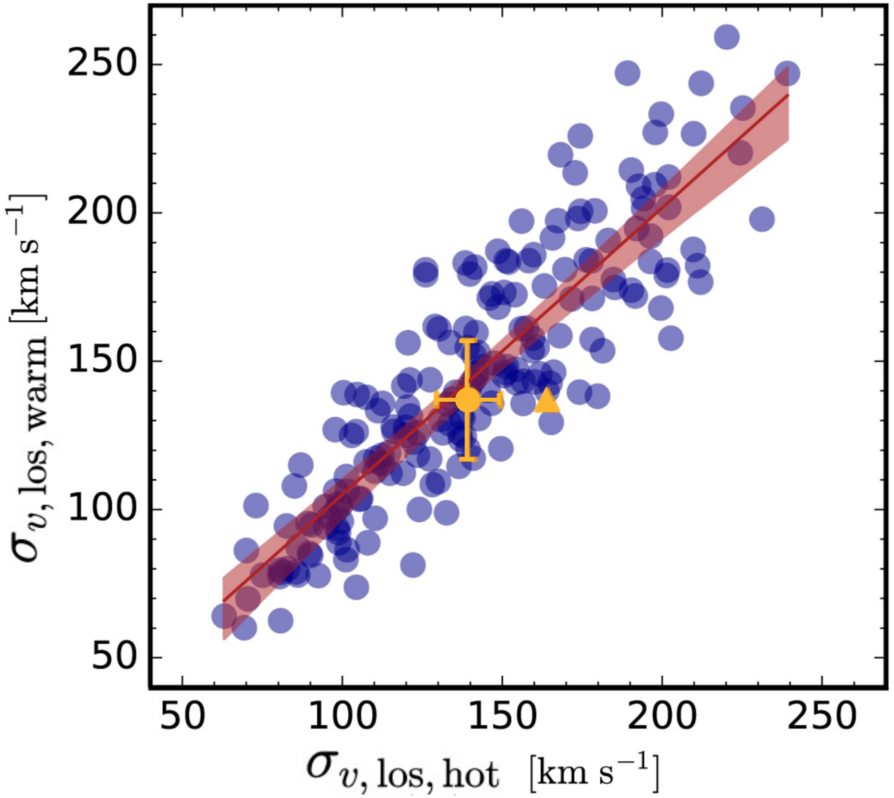
$$\langle \delta\zeta/\zeta \rangle = -0.03 \left(\frac{\nu_{\rm SZ}}{1.4\ {\rm GHz}} \right)^{-\alpha_s} \left(\frac{S_{1.4}}{\rm mJy} \right) \left(\frac{M_{500}}{10^{14}\ M_\odot} \right)^{-1}$$



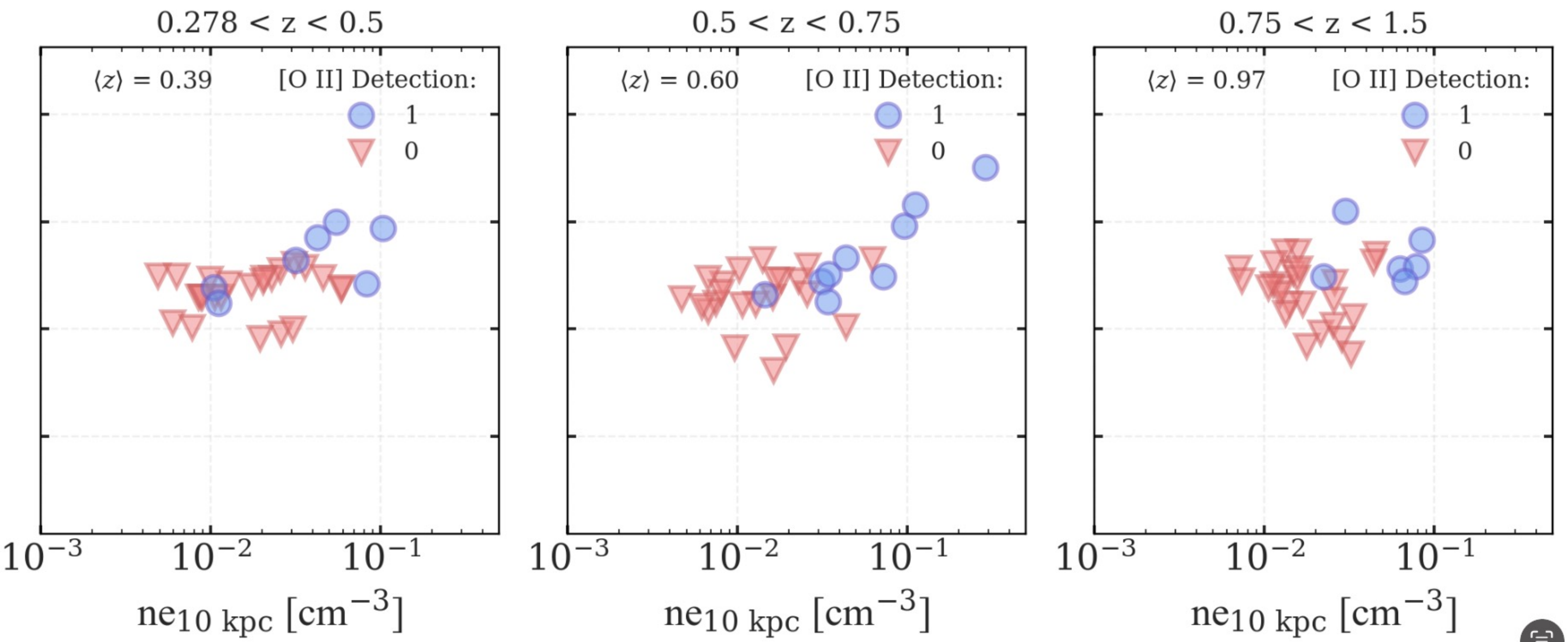
FUTURE DIRECTIONS





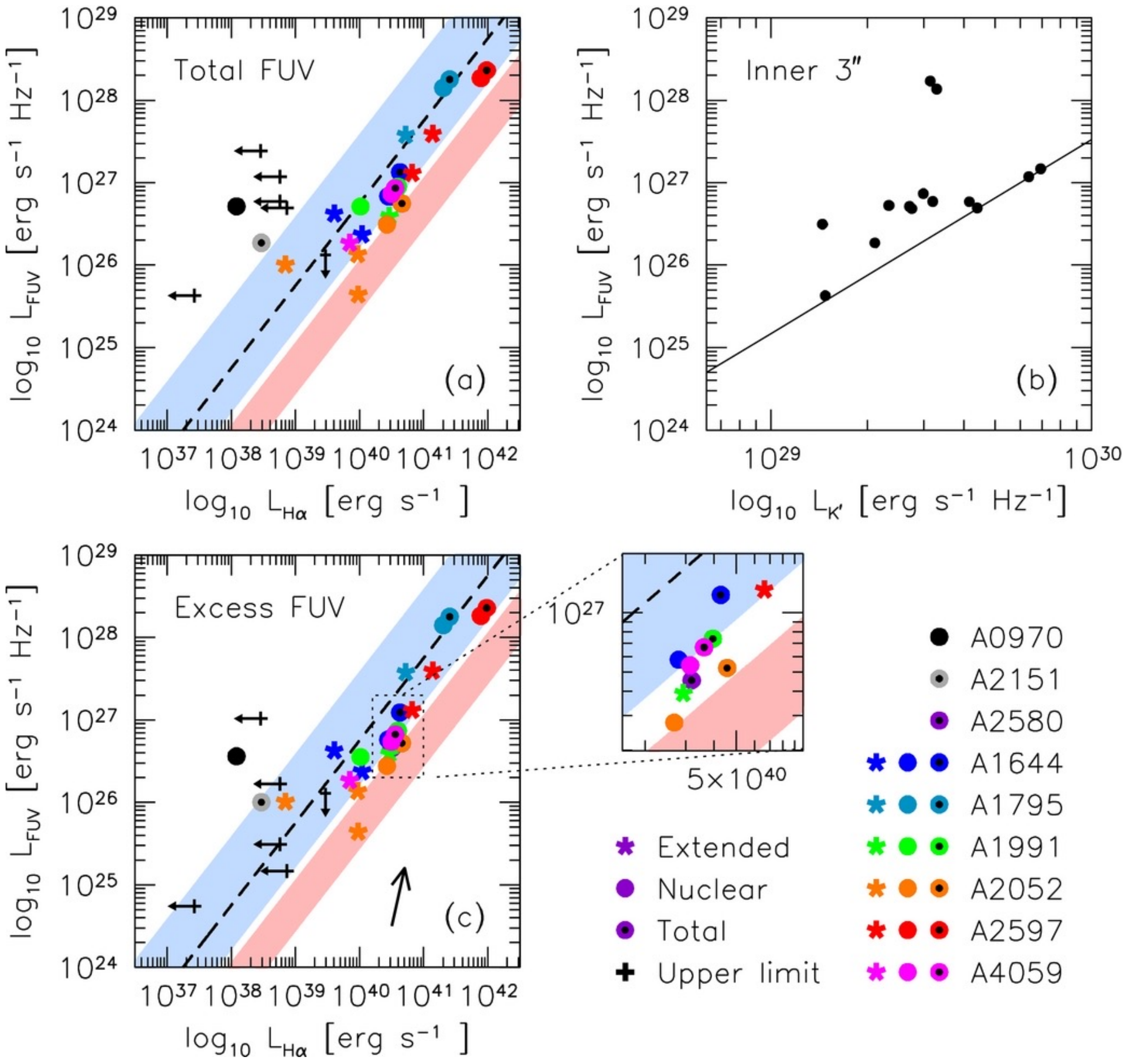


USING DENSITY RATHER THAN ENTROPY



USING [OII] TO MEASURE SFRS

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



McDonald+11