EVOLUTION OF THE COOLING FLOW PROBLEM IN GALAXY CLUSTERS

Michael Calzadilla

PhD Candidate w/Prof. Mike McDonald
Massachusetts Institute of Technology

with the SPT Collaboration

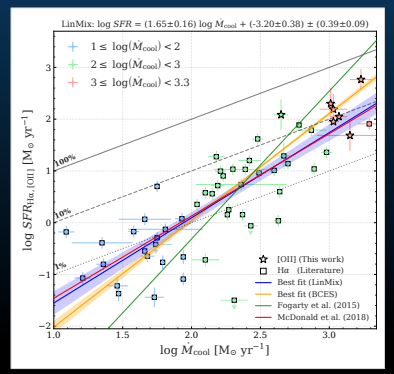
OVERVIEW

Background

- Cooling flow problem
- AGN feedback: black holes as thermostats

The New Cooling Flow Problem

- Testing the limits of AGN feedback with the most extremely cooling systems
- What governs the effectiveness of AGN feedback?



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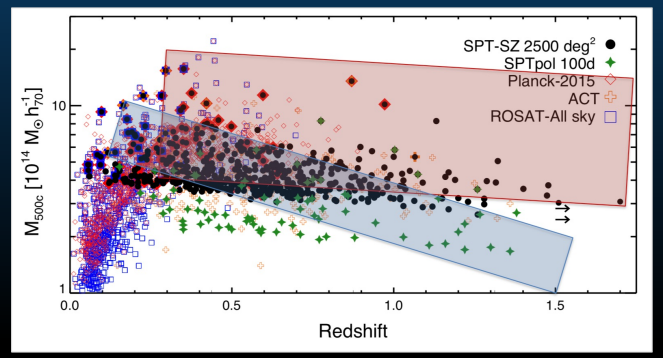
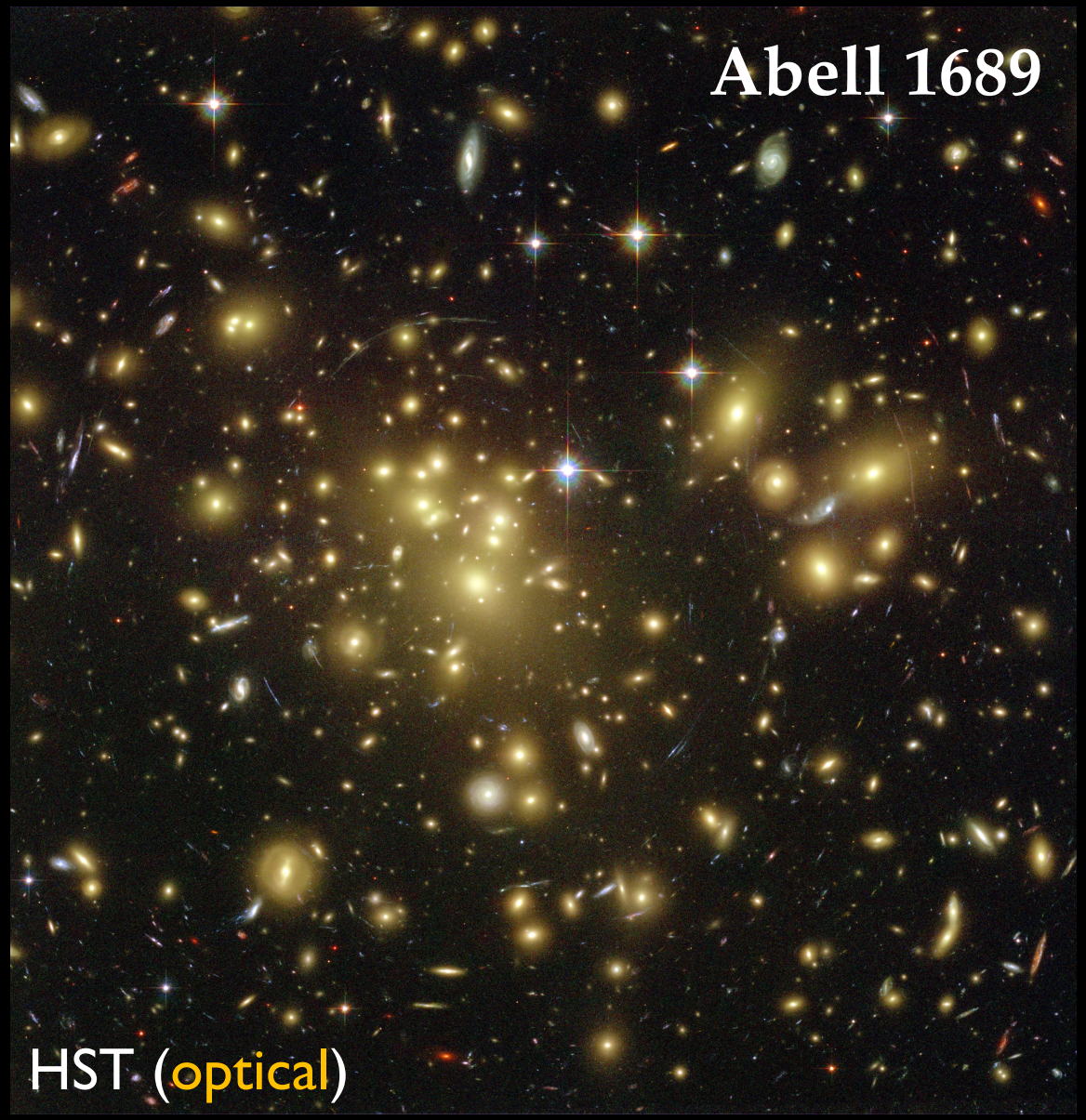
- Using a large multi-λ sample of SPT clusters spanning $0.3 < z < 1.7$



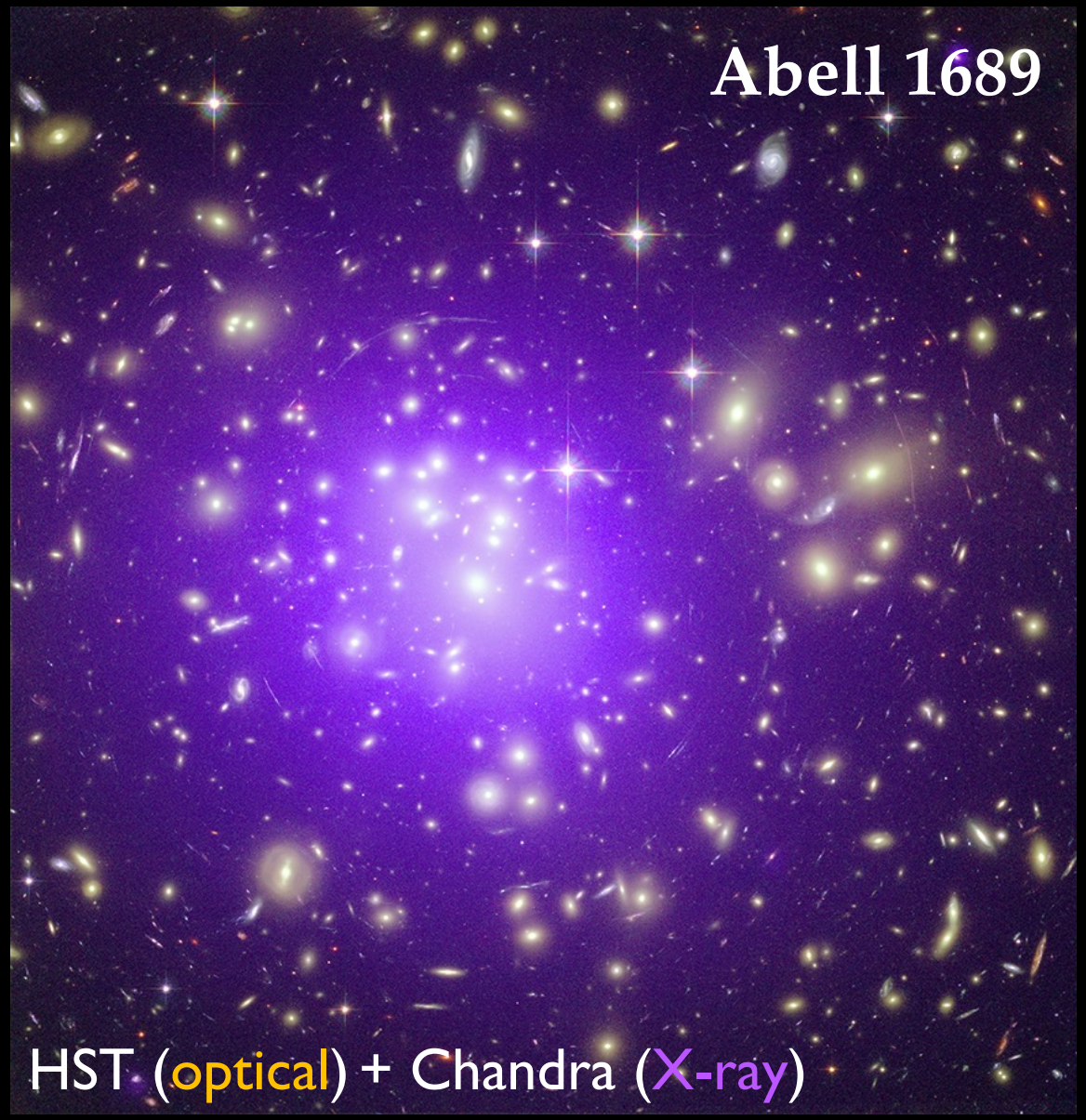
GALAXY CLUSTERS

- Largest objects in Universe™
- 100s – 1000s of galaxies, often dominated by a brightest cluster galaxy (BCG)
- ~10^{14} – 10^{15} $M_\odot$ (mostly dark matter)



GALAXY CLUSTERS

- Largest objects in Universe™
- 100s – 1000s of galaxies, often dominated by a brightest cluster galaxy (BCG)
- ~10^{14} – 10^{15} $M_\odot$ (mostly dark matter)
- Hot (10^7 K) **intracluster medium** (ICM) makes up most (≳80%) of the luminous matter
- Gives off X-rays via radiative cooling (e.g. Bremsstrahlung)



THE COOLING FLOW PROBLEM

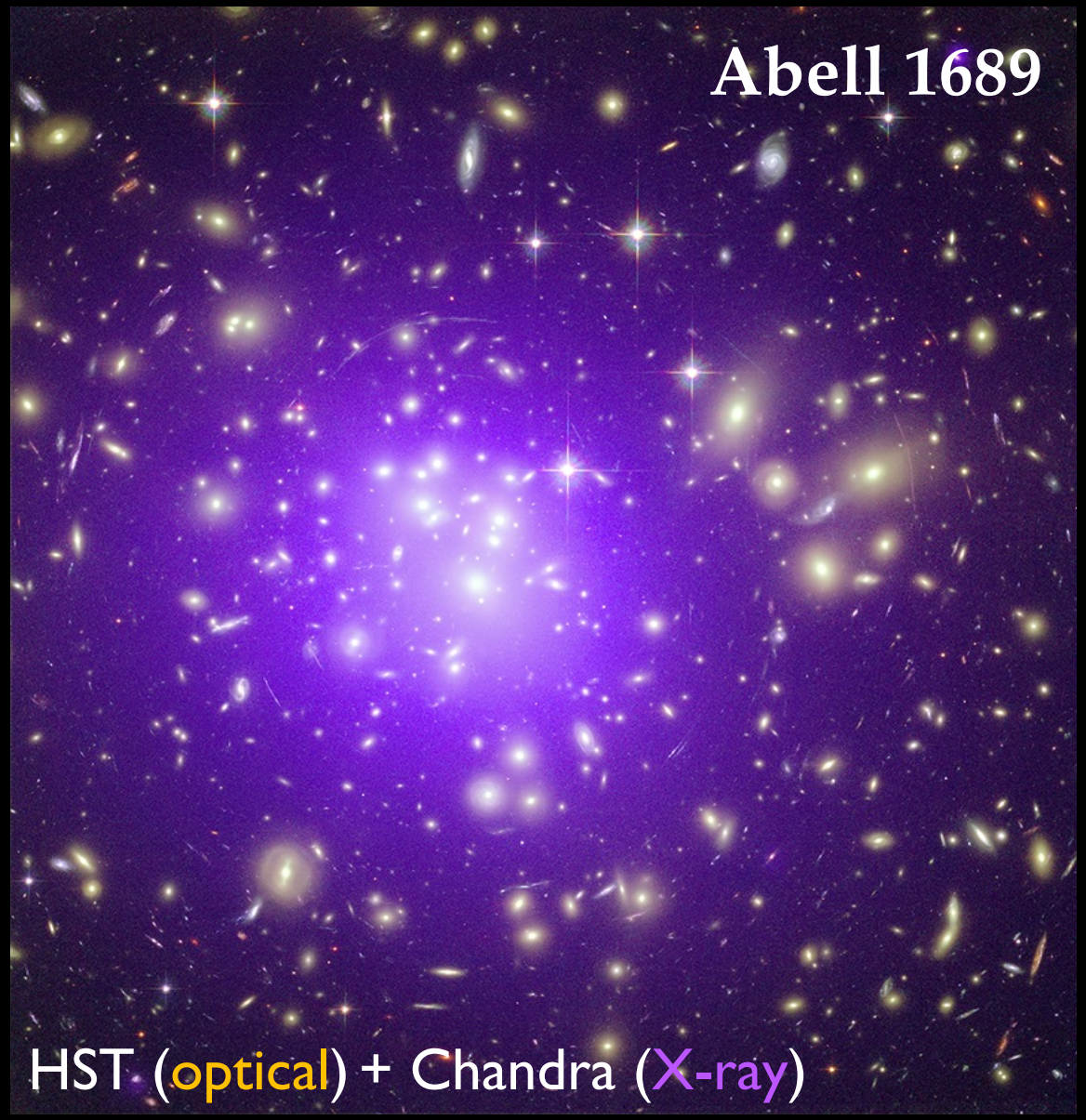
X-ray flux $\propto n_e^2 / \sqrt{T}$

$\Downarrow$

Cold and dense core

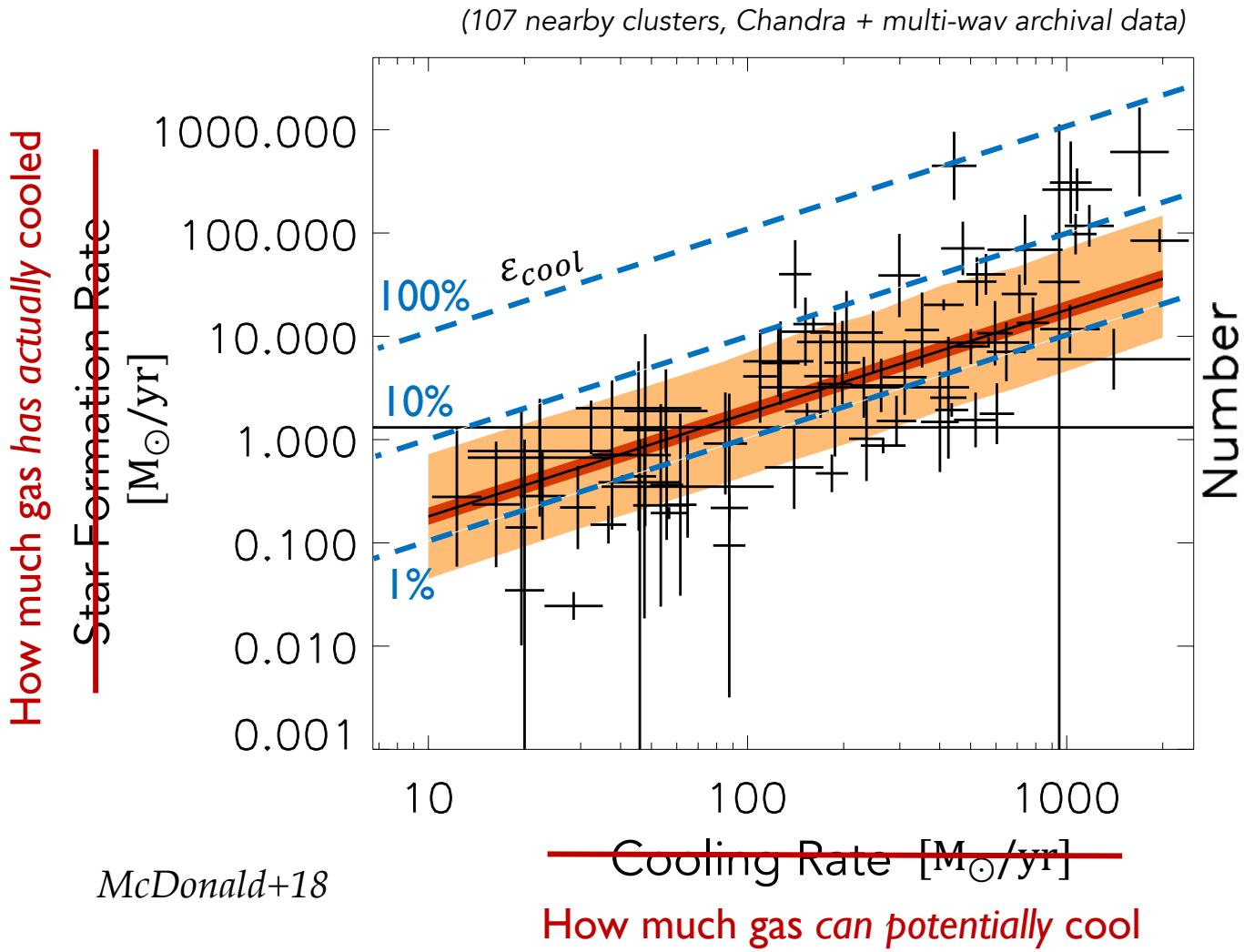
$\Downarrow$

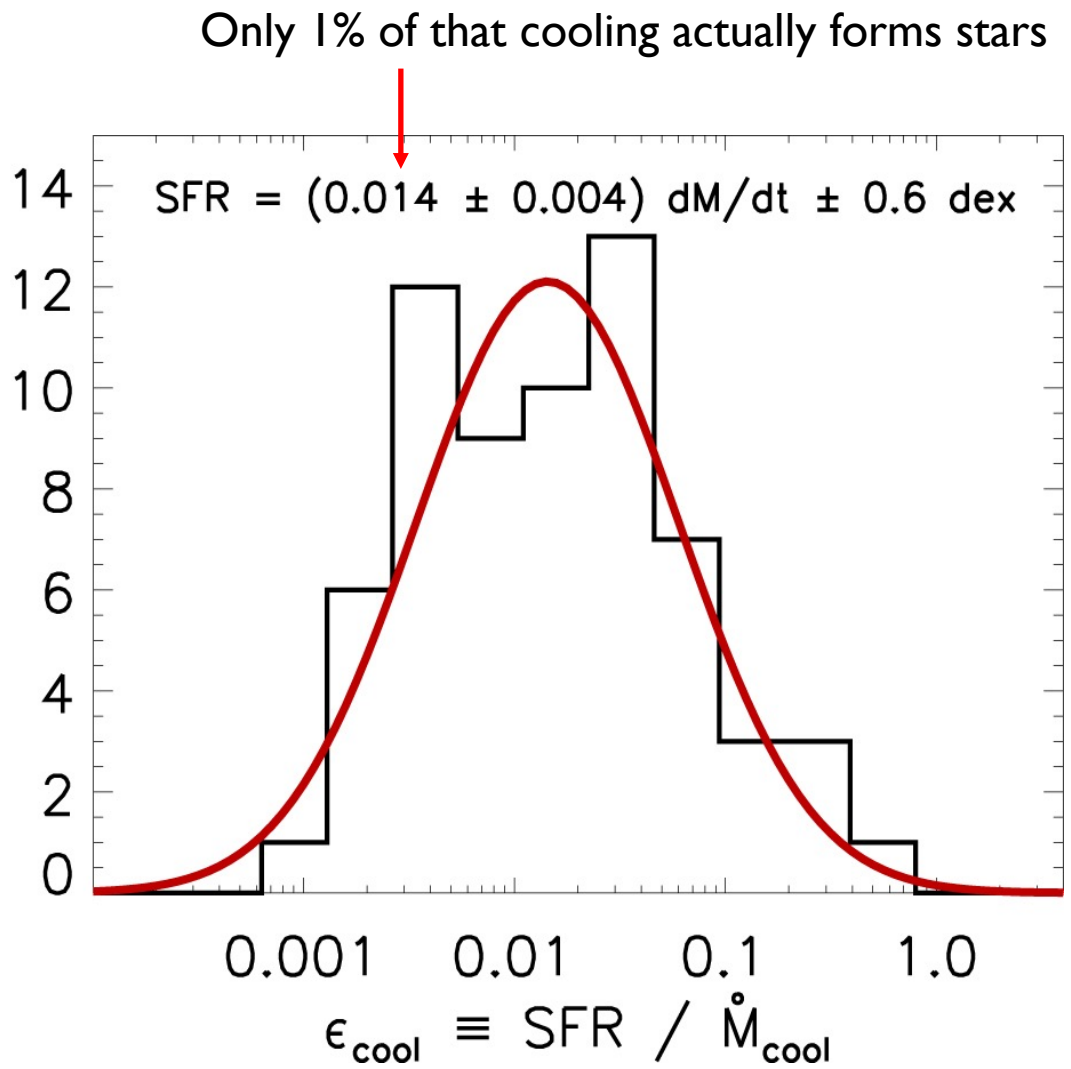
Expect high star formation rates (SFRs) in BCGs



BCGs are "red and dead"

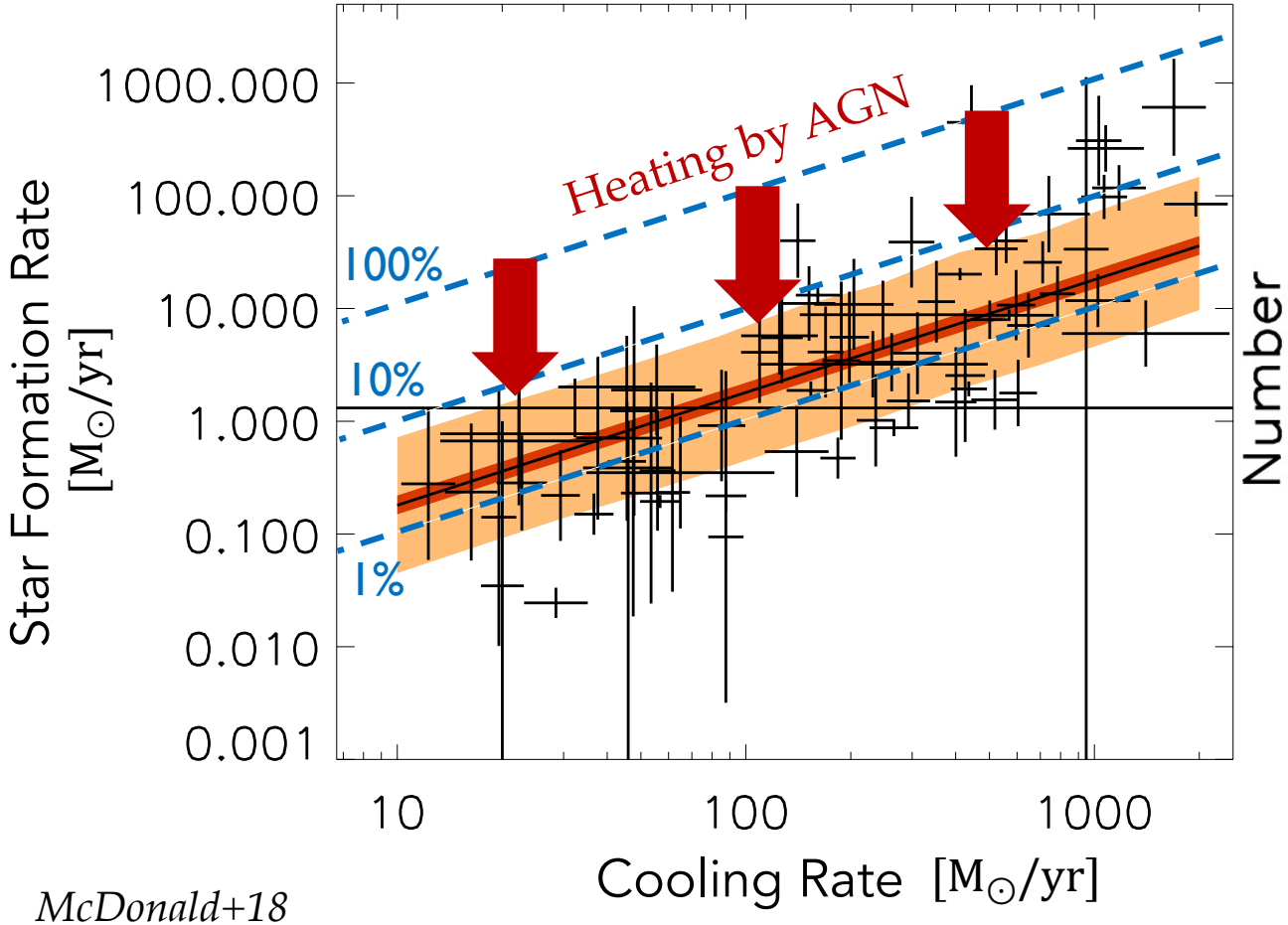
THE COOLING FLOW PROBLEM





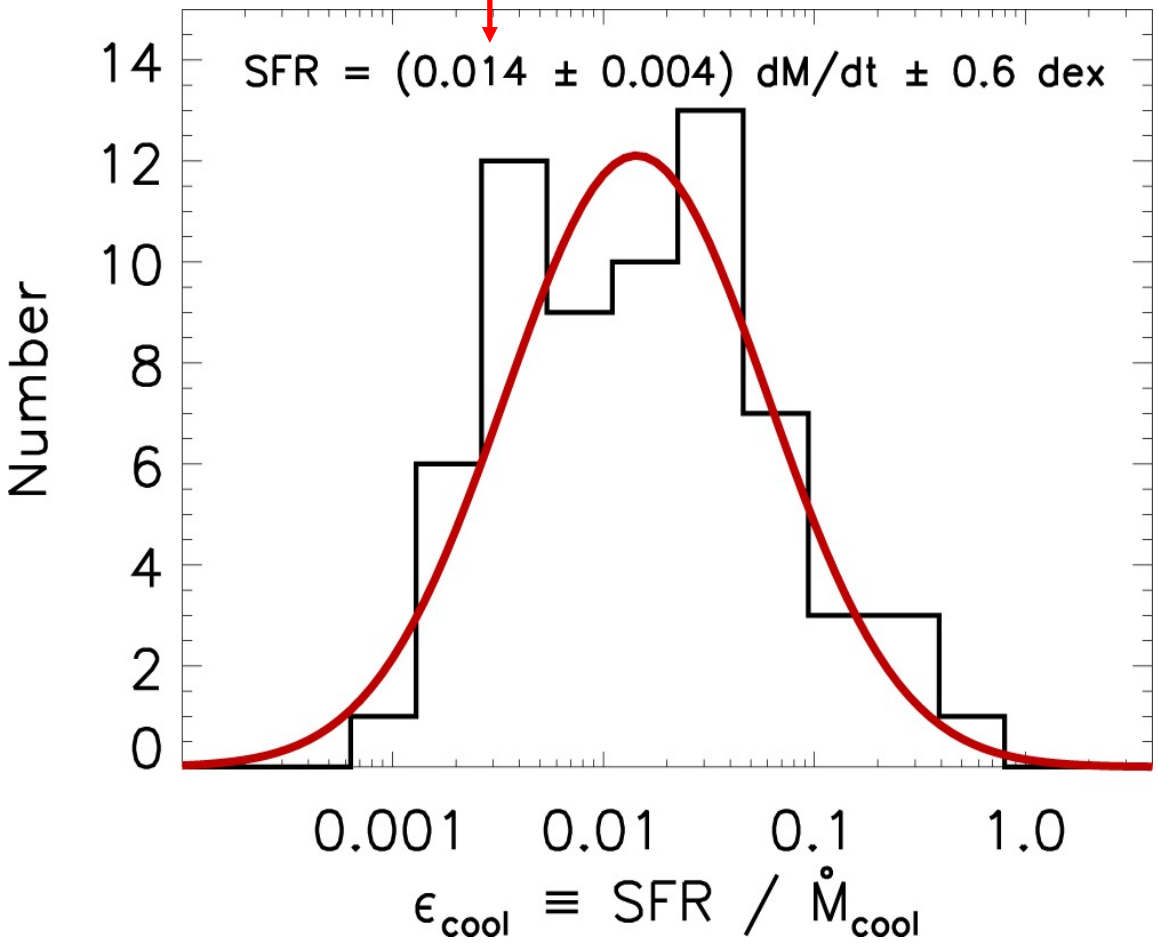
AGN FEEDBACK ACTS AS A THERMOSTAT

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



McDonald+18

Only 1% of that cooling actually forms stars



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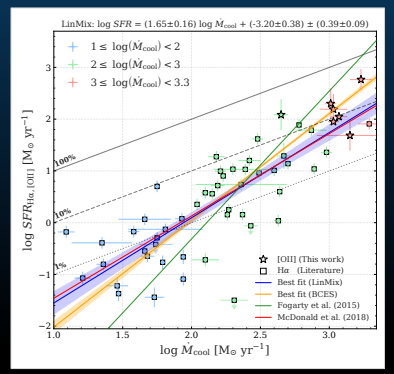

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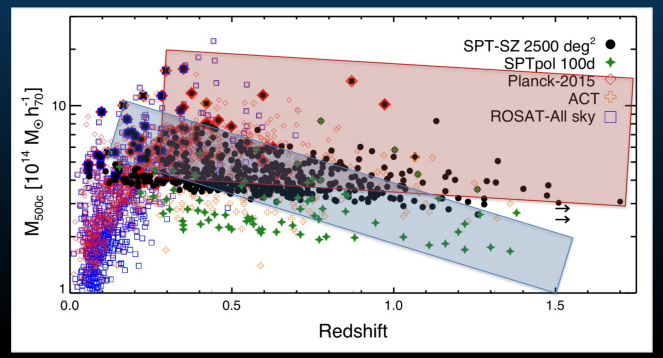

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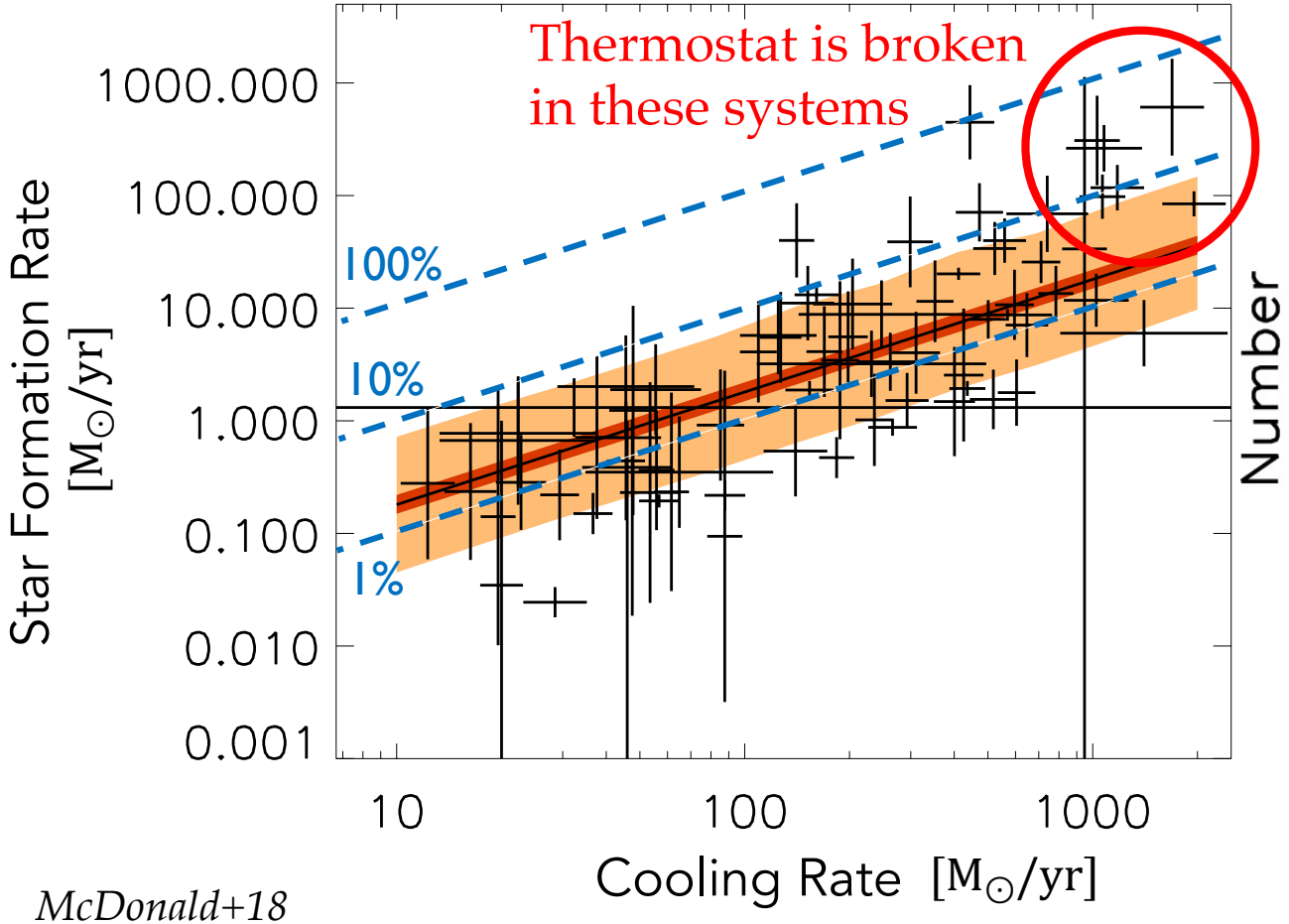

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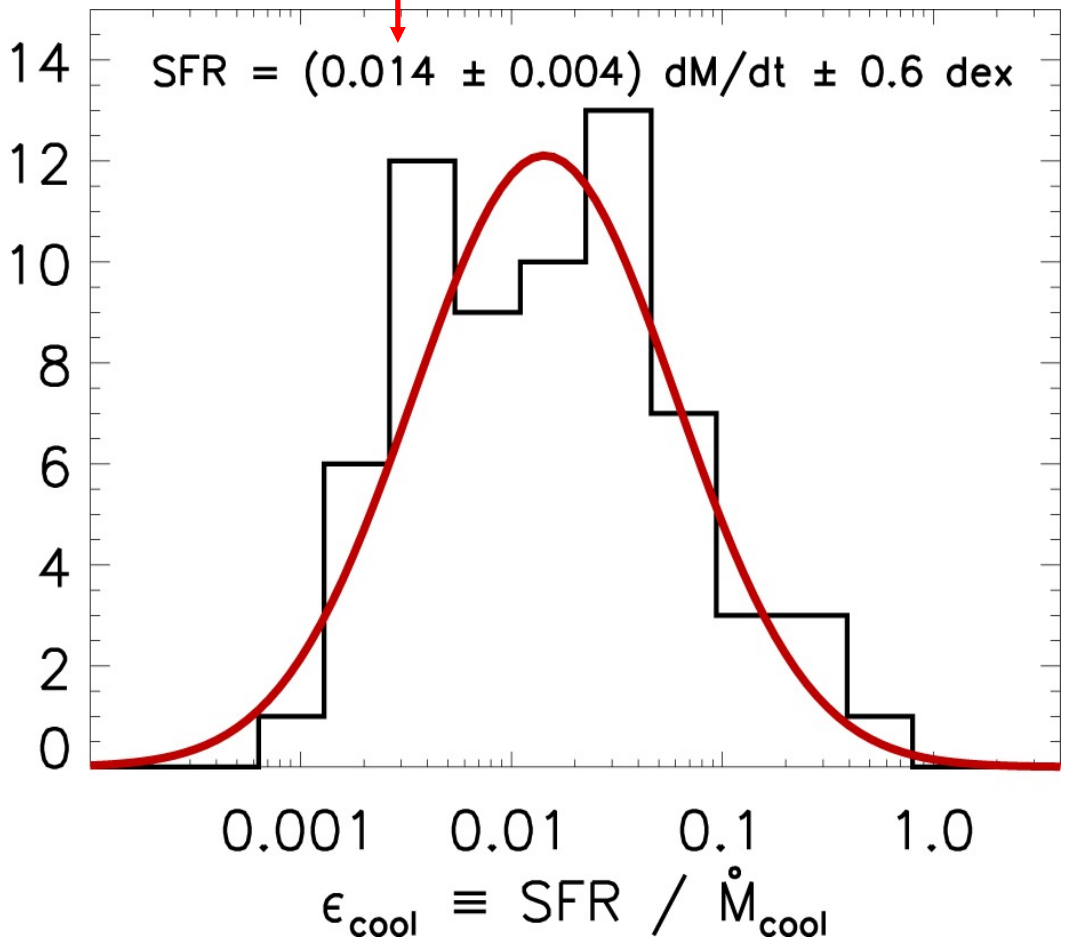
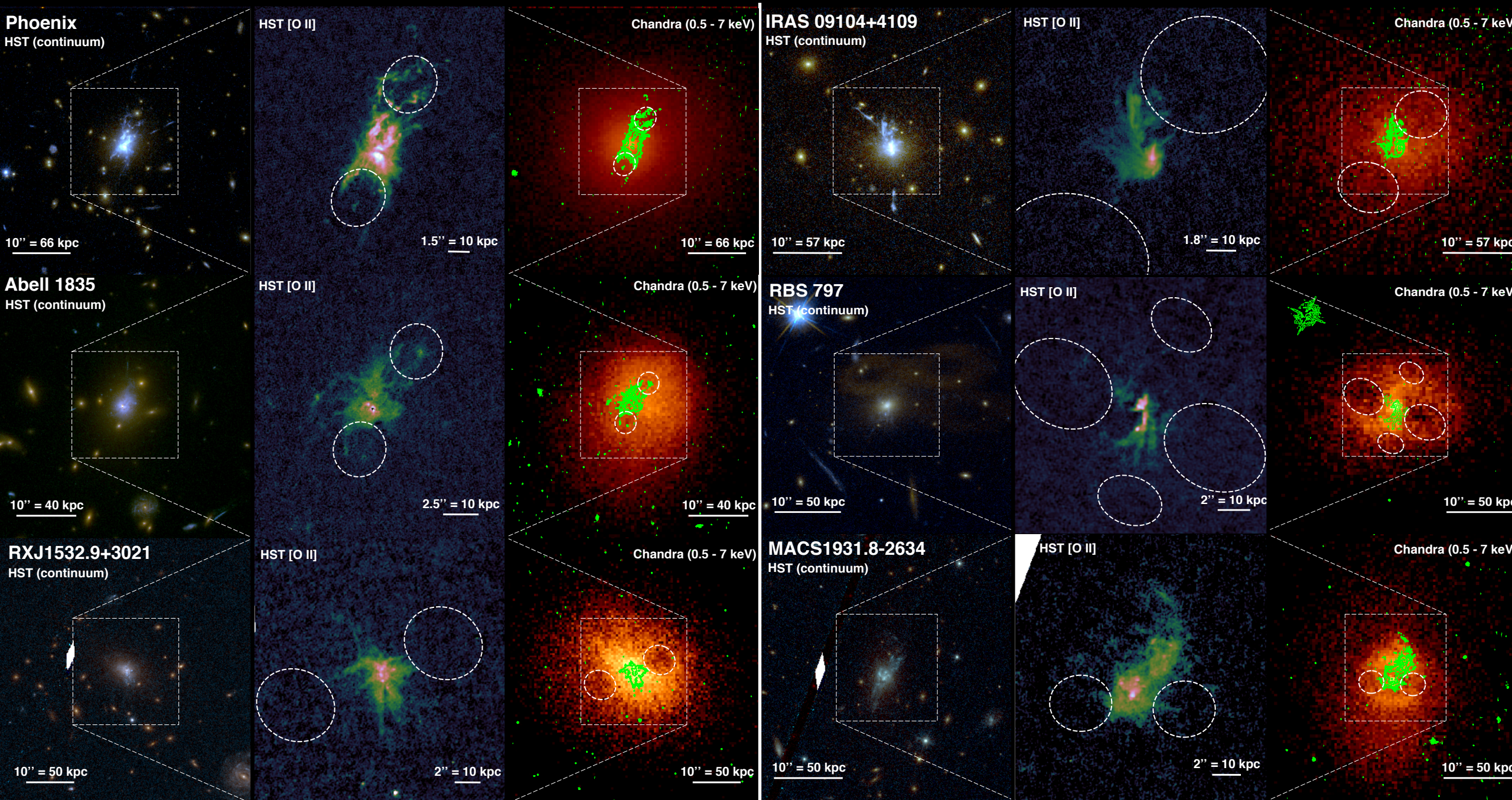
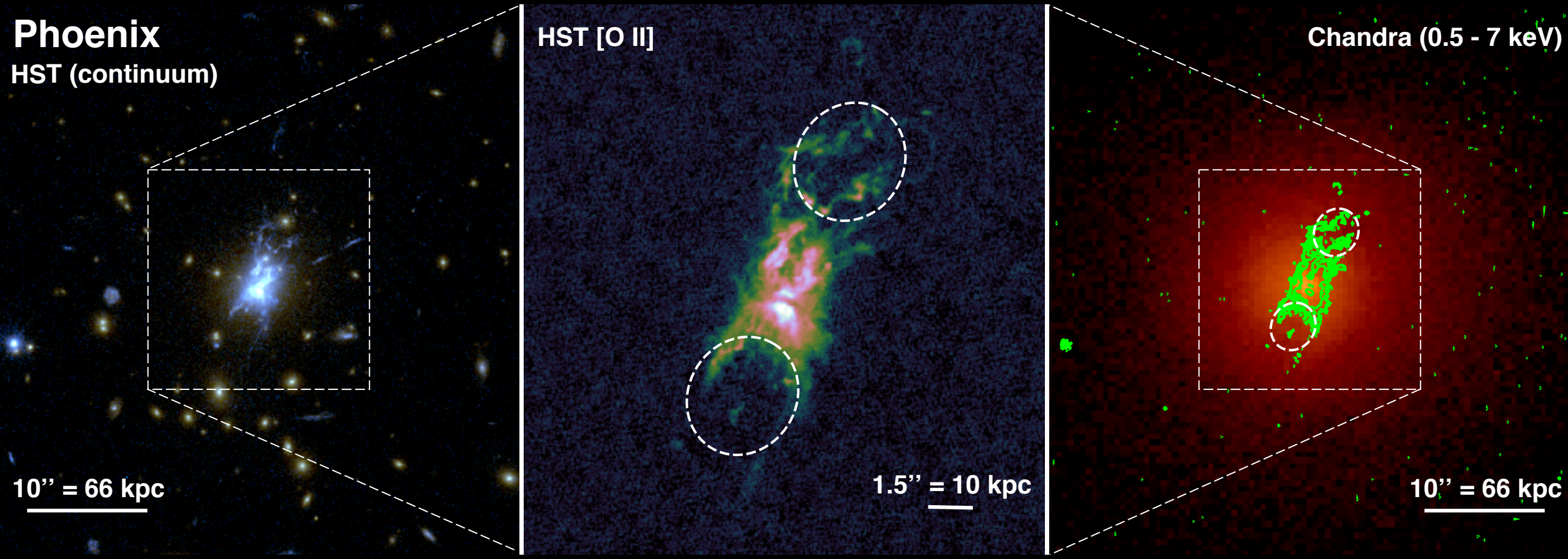
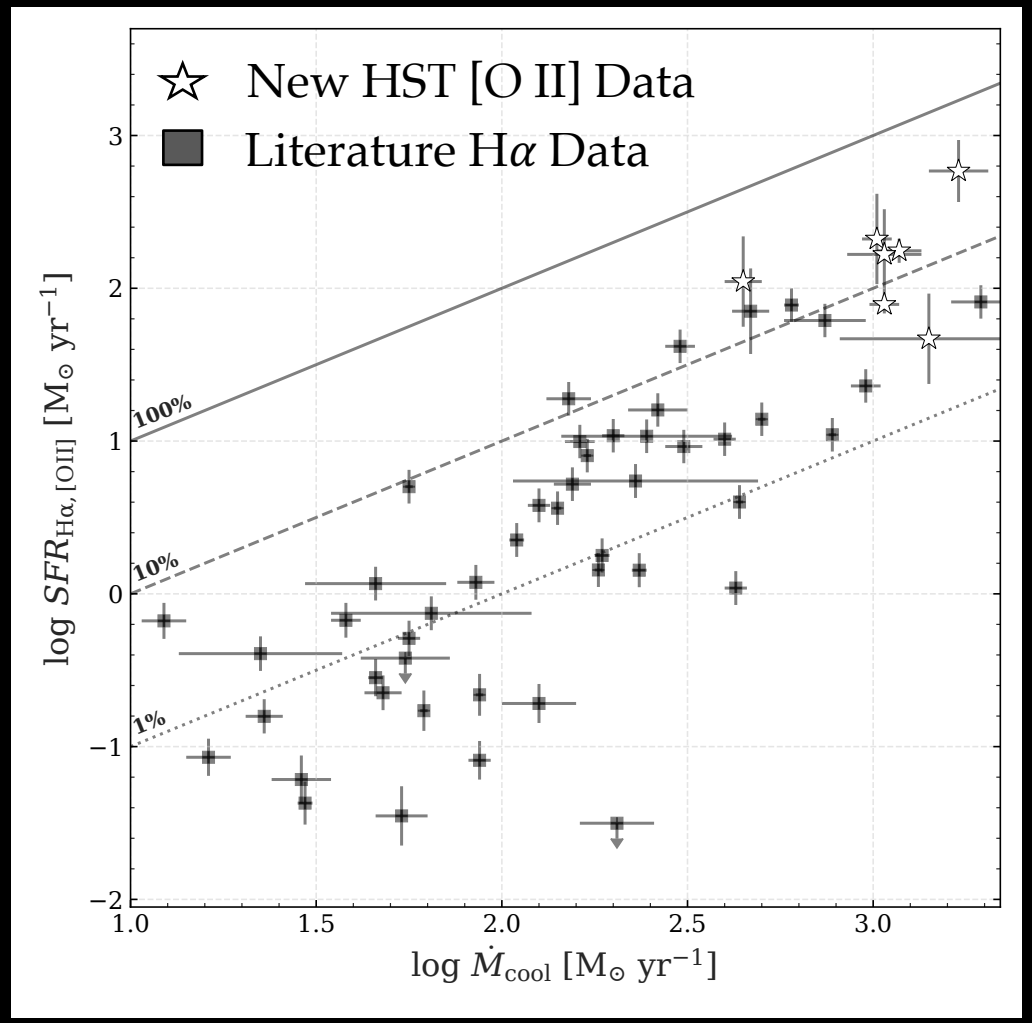


EXTREME COOLING SAMPLE: OPTICAL (*HST*) + X-RAY (*Chandra*)




Phoenix
HST (continuum)
10'' = 66 kpc
HST [O II]
1.5'' = 10 kpc
Chandra (0.5 - 7 keV)
10'' = 66 kpc

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



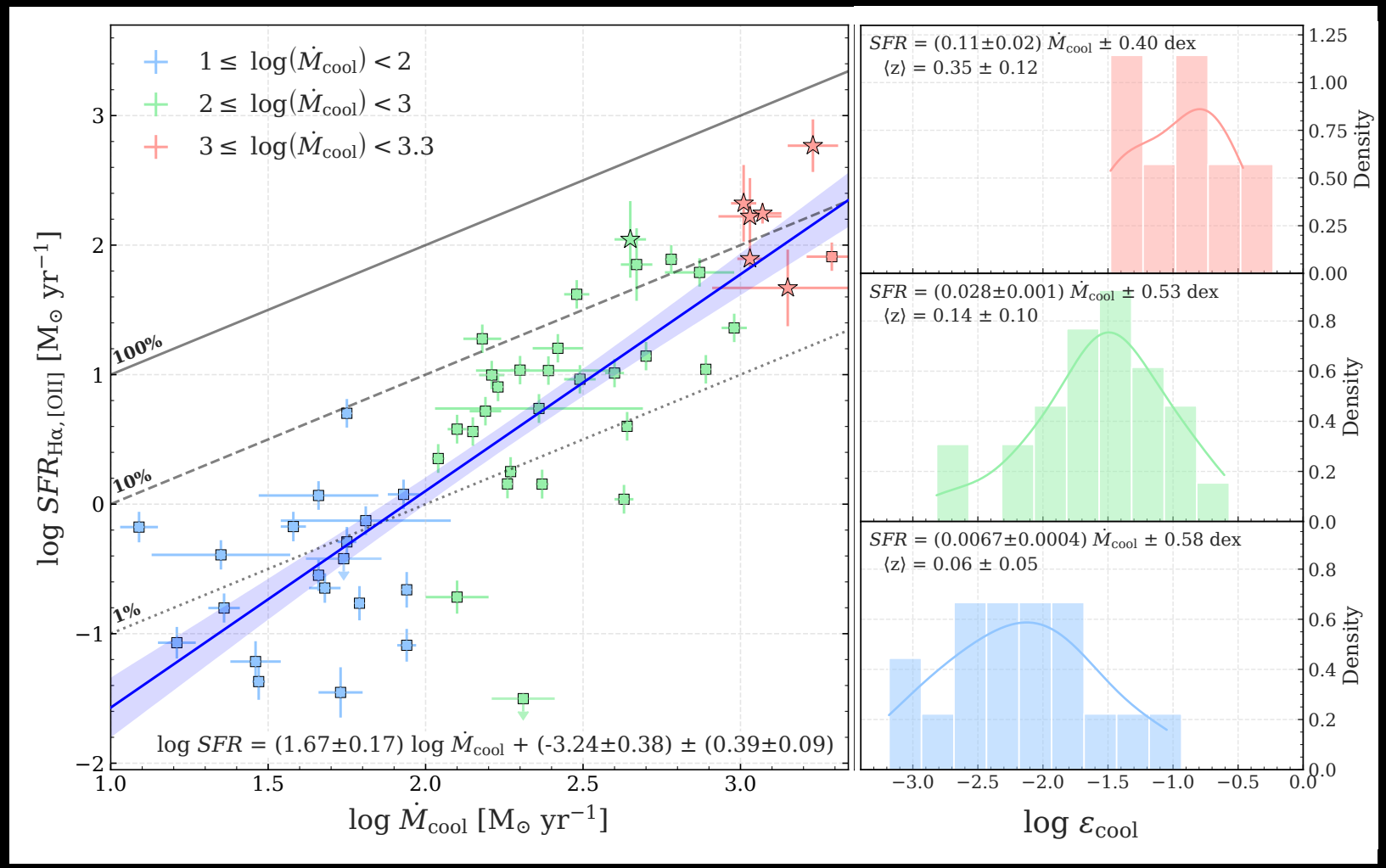
- Calculate SFRs using Kewley+04:

$$SFR_{[\mathrm{OII}]} = 6.58 \times 10^{-42}\, L_{[\mathrm{OII}]} \;\; \mathrm{M}_\odot\ \mathrm{yr}^{-1}$$

- Homogenization of Hα data from the literature (*Hamer+16, McDonald+10, Crawford+99*, etc.)
- Corrected for:
  - Cosmological parameter choices
  - Intrinsic (based on *Crawford+99*) and Galactic extinction
  - Evolved star contributions

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

Calzadilla+22



- Relaxing assumption of constant cooling efficiency:

→ Find steeper-than-unity relation b/w SFR and $\dot{M}_{cool}$

→ Gradual decrease in effectiveness of feedback

GRADUAL SATURATION OF AGN FEEDBACK

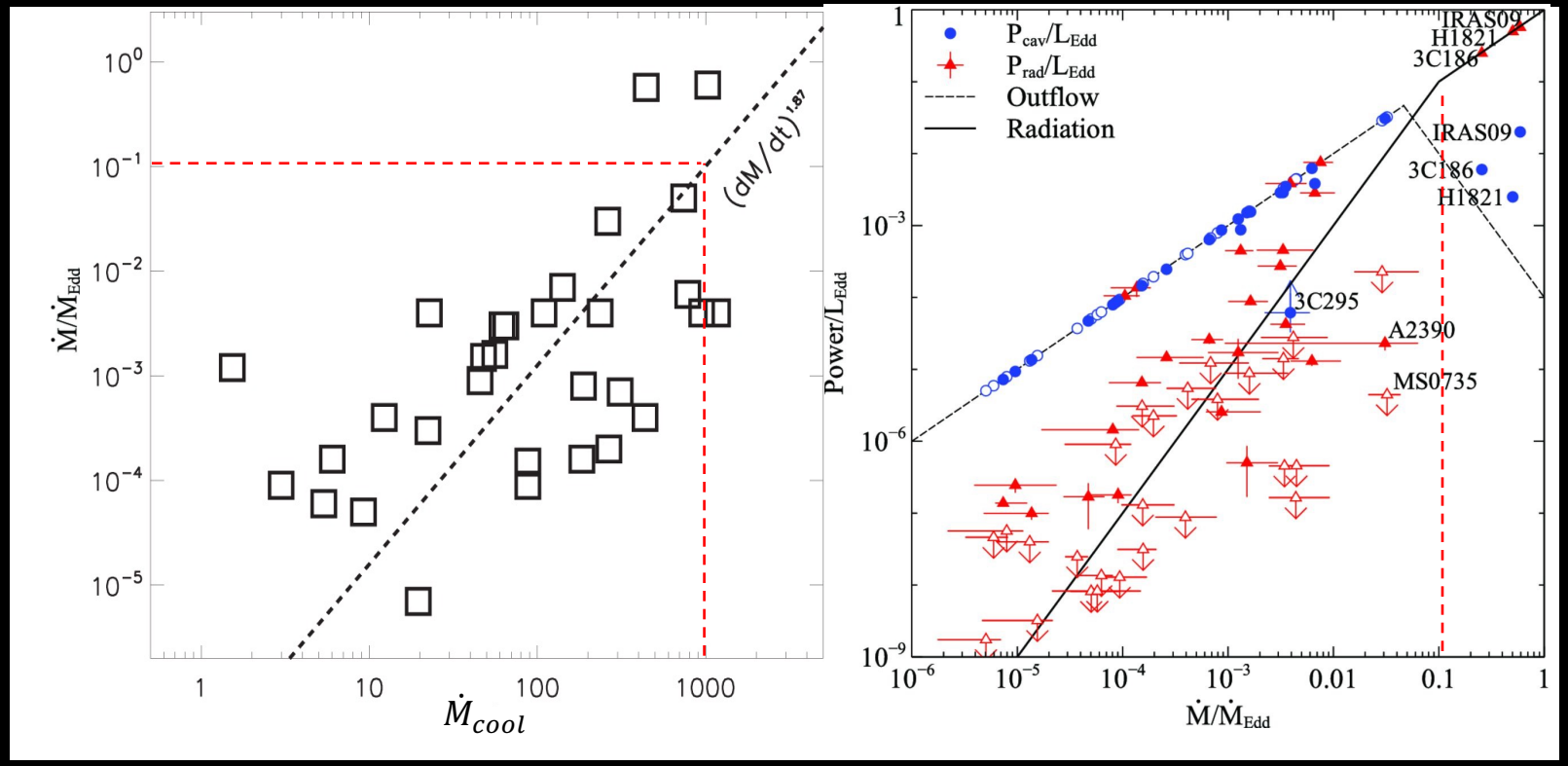
Russell+13, Churazov+05

- SMBH growth rate proportional to cooling rate:

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

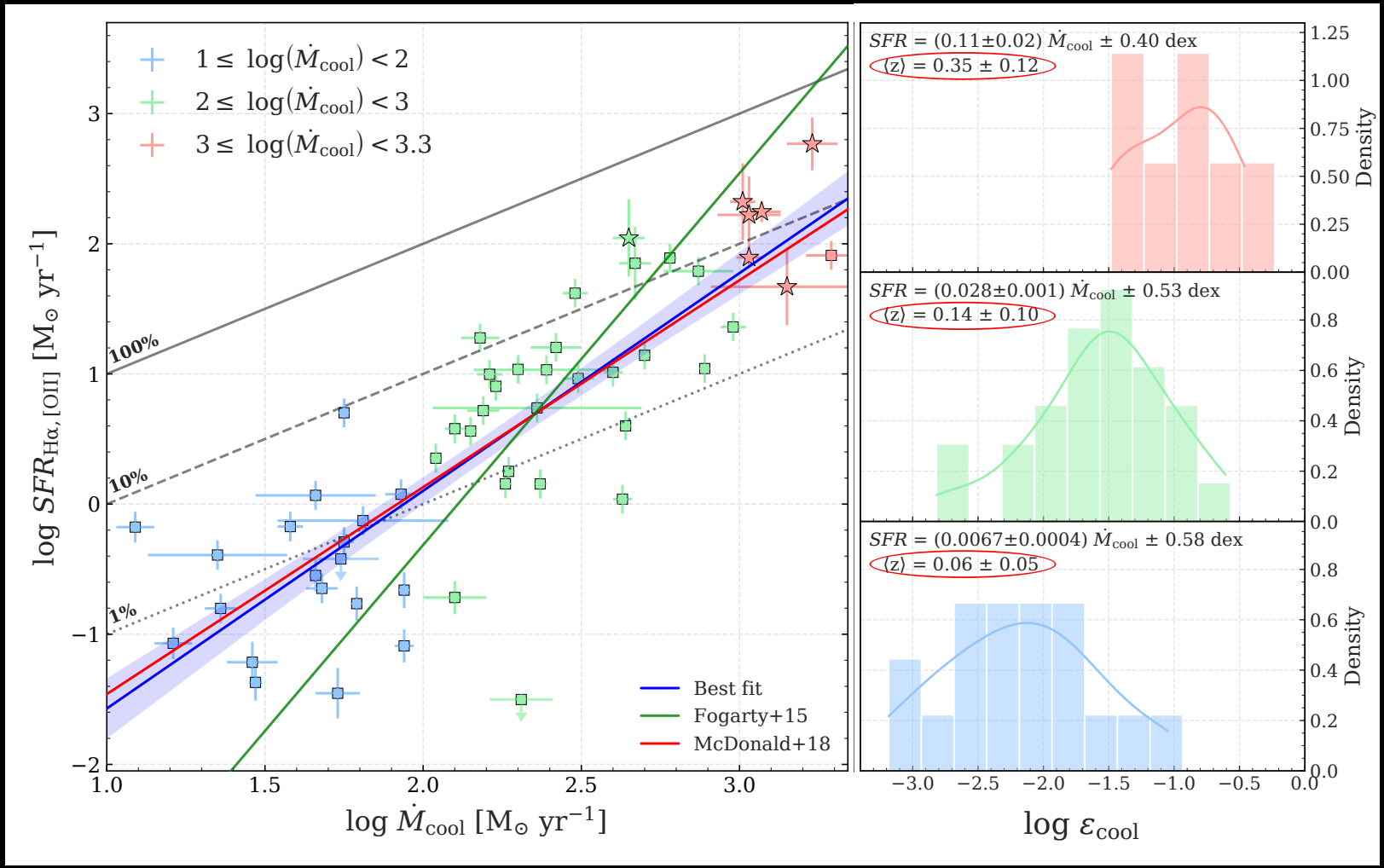
- Cap on LHS, but not RHS
- Halos can grow via mergers/accretion faster than their SMBHs, resulting in undermassive SMBHs

  → effect of overwhelming your thermostat



SFR VS $\dot{M}_{cool}$: REDSHIFT DEPENDENCE?

Calzadilla+22



Are we looking at an evolutionary trend?

→ Need bigger, more representative sample

→ Leverage SZ surveys

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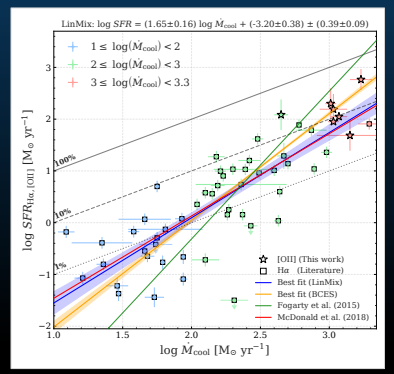

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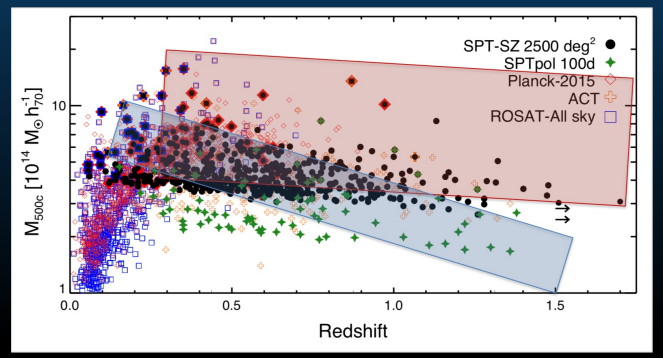
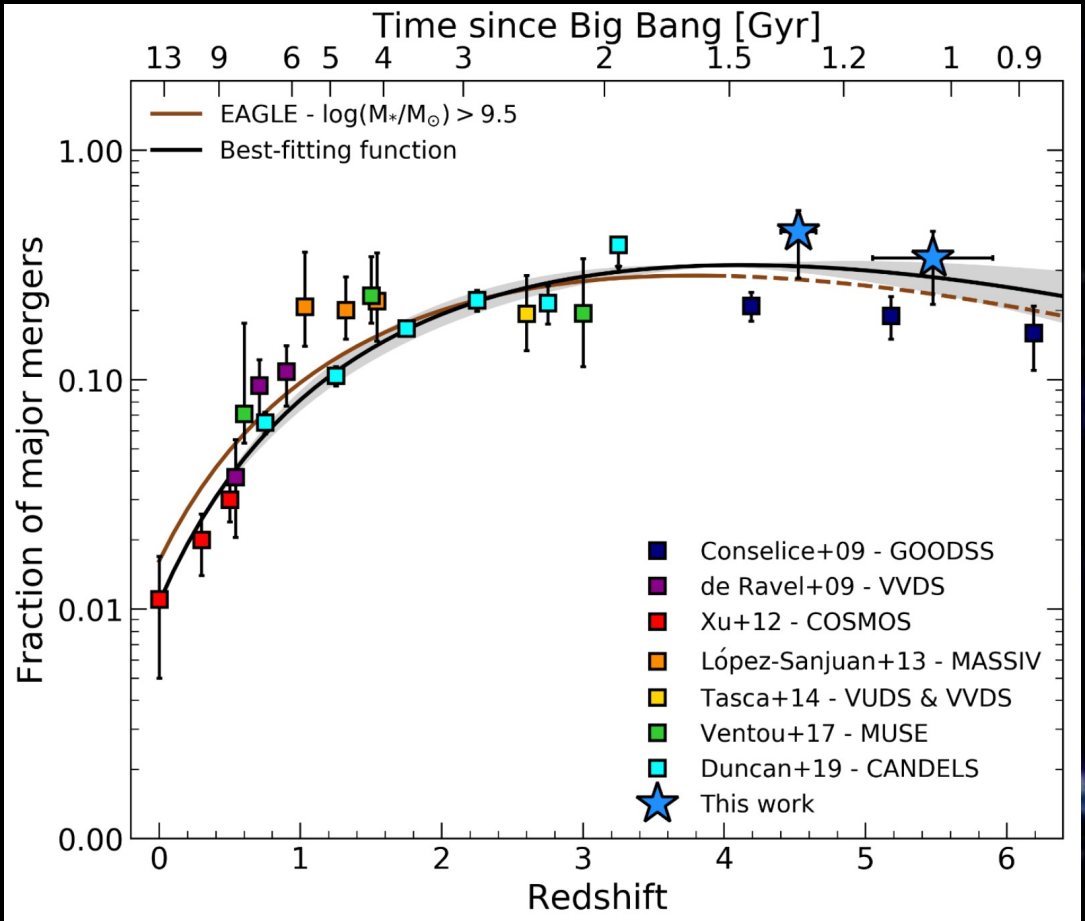


HOW HAS THE COOLING/FEEDBACK CYCLE EVOLVED?

- Why should we expect feedback/cooling to look any different at higher redshifts?
  - Higher merger rates (e.g. Romano+21, Brodwin+13)
  - Higher availability of gas



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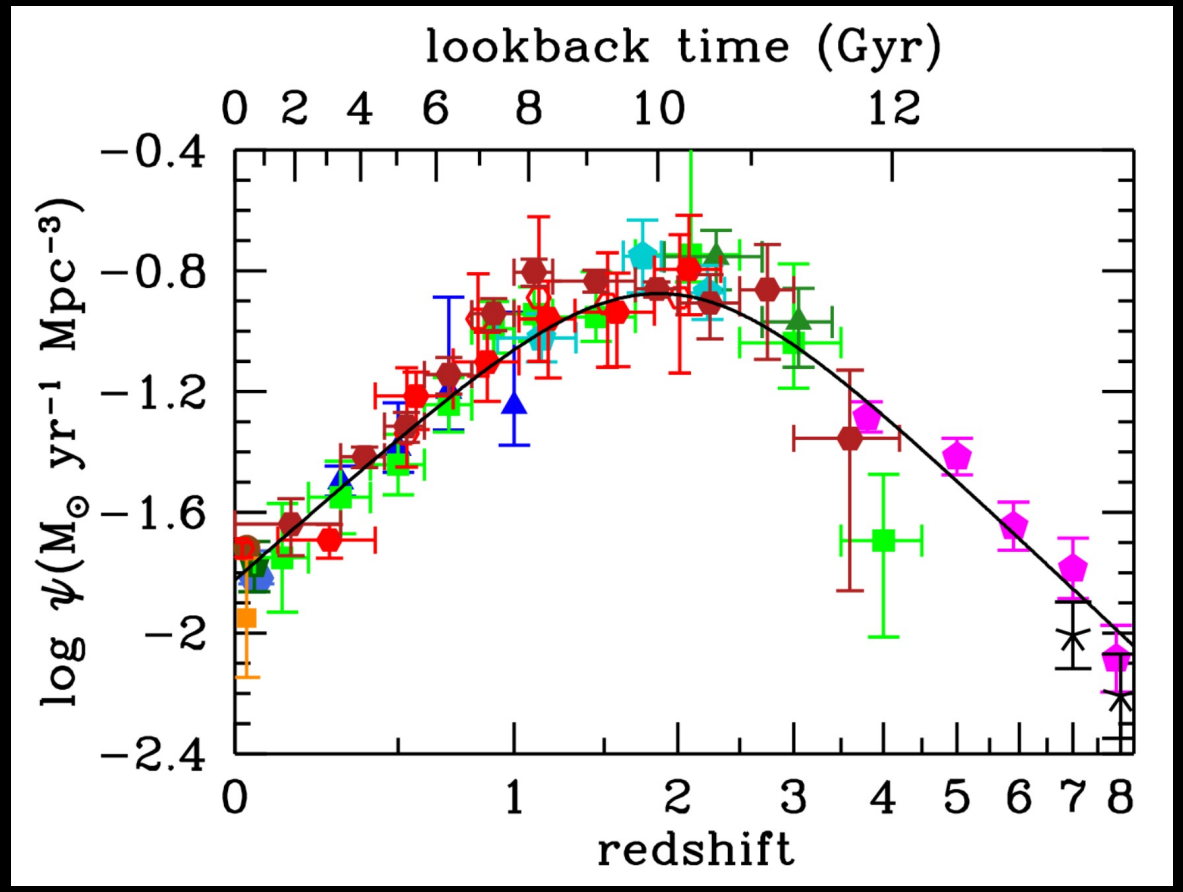

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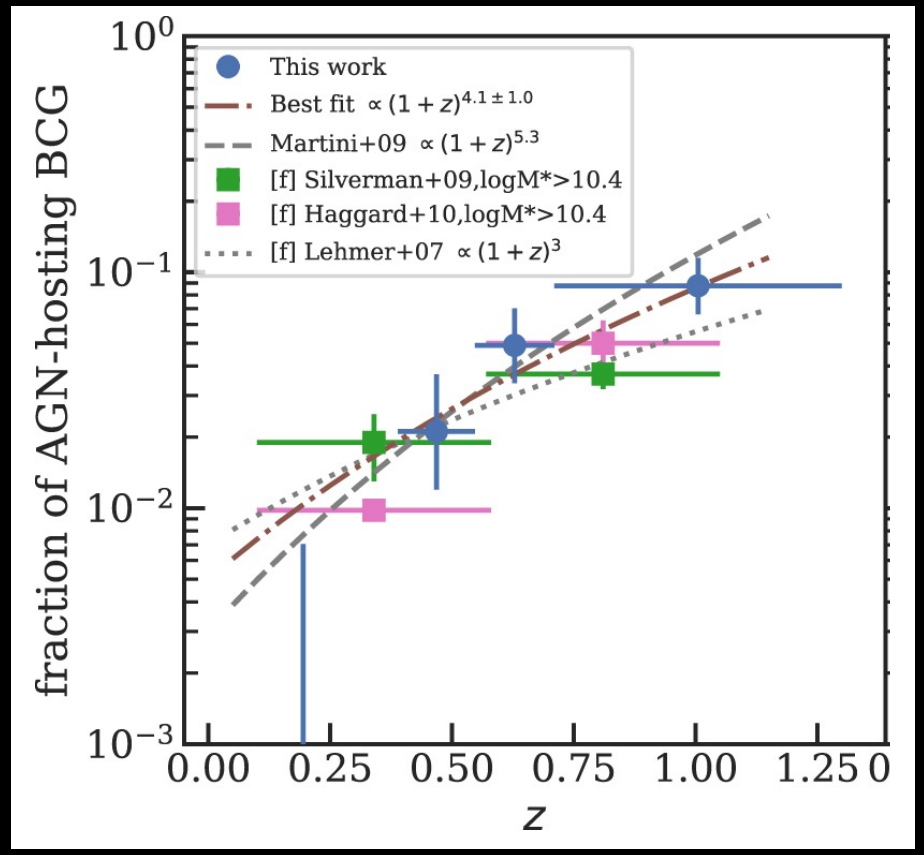
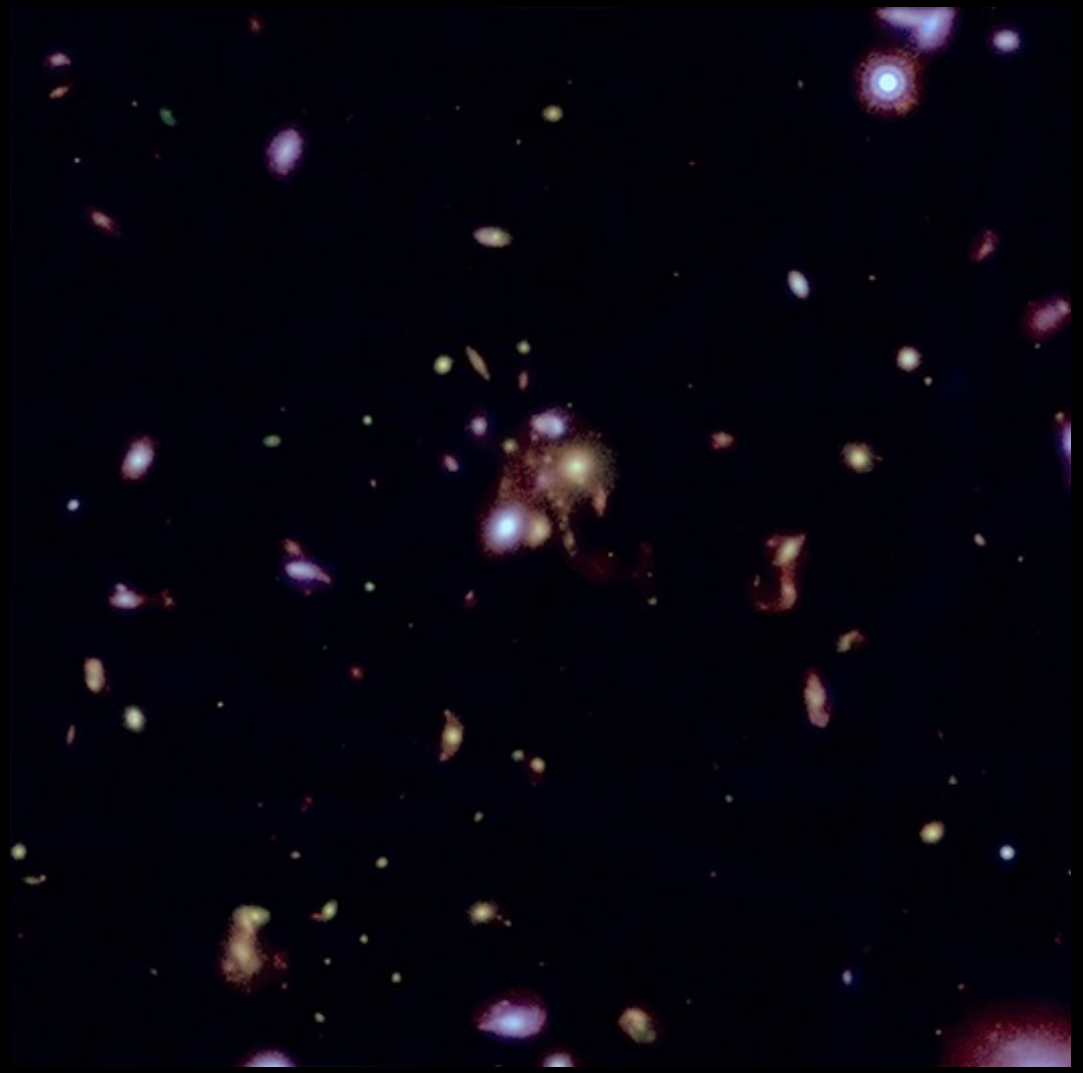
  - Higher availability of gas
  - Higher SFRs (Madau & Dickinson 14)
  - Higher AGN/quasar fraction (e.g. Somboonpanyakul+22, Hlavacek-Larrondo+13)



NOTABLE EXAMPLES OF EXTREME HIGH-Z COOLING

- SpARCS 1049
  - $z = 1.7$, $M = 3\times10^{14}\ M_\odot$
  - Massive starburst: ~860 $M_\odot$/yr (Webb+15a,b)



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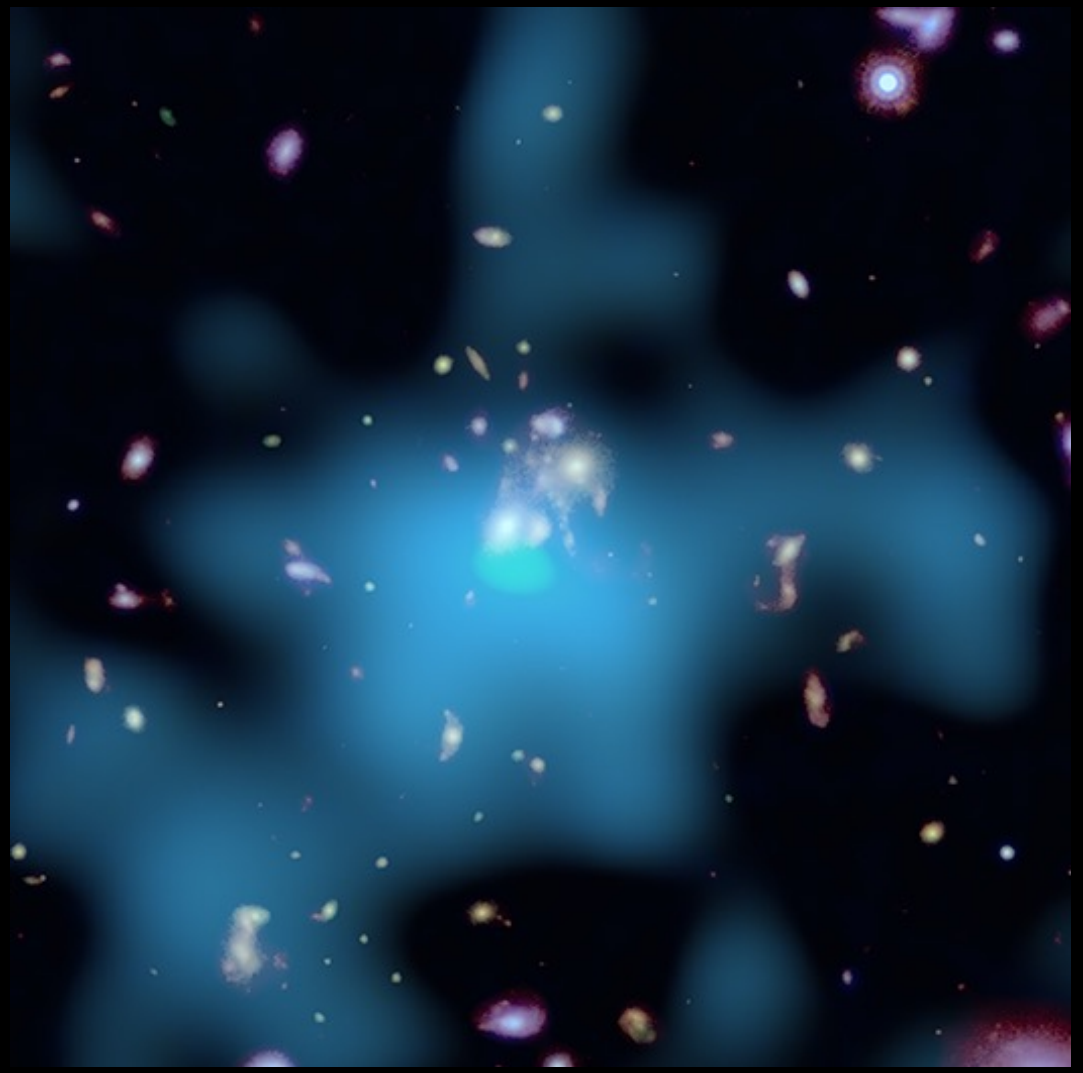
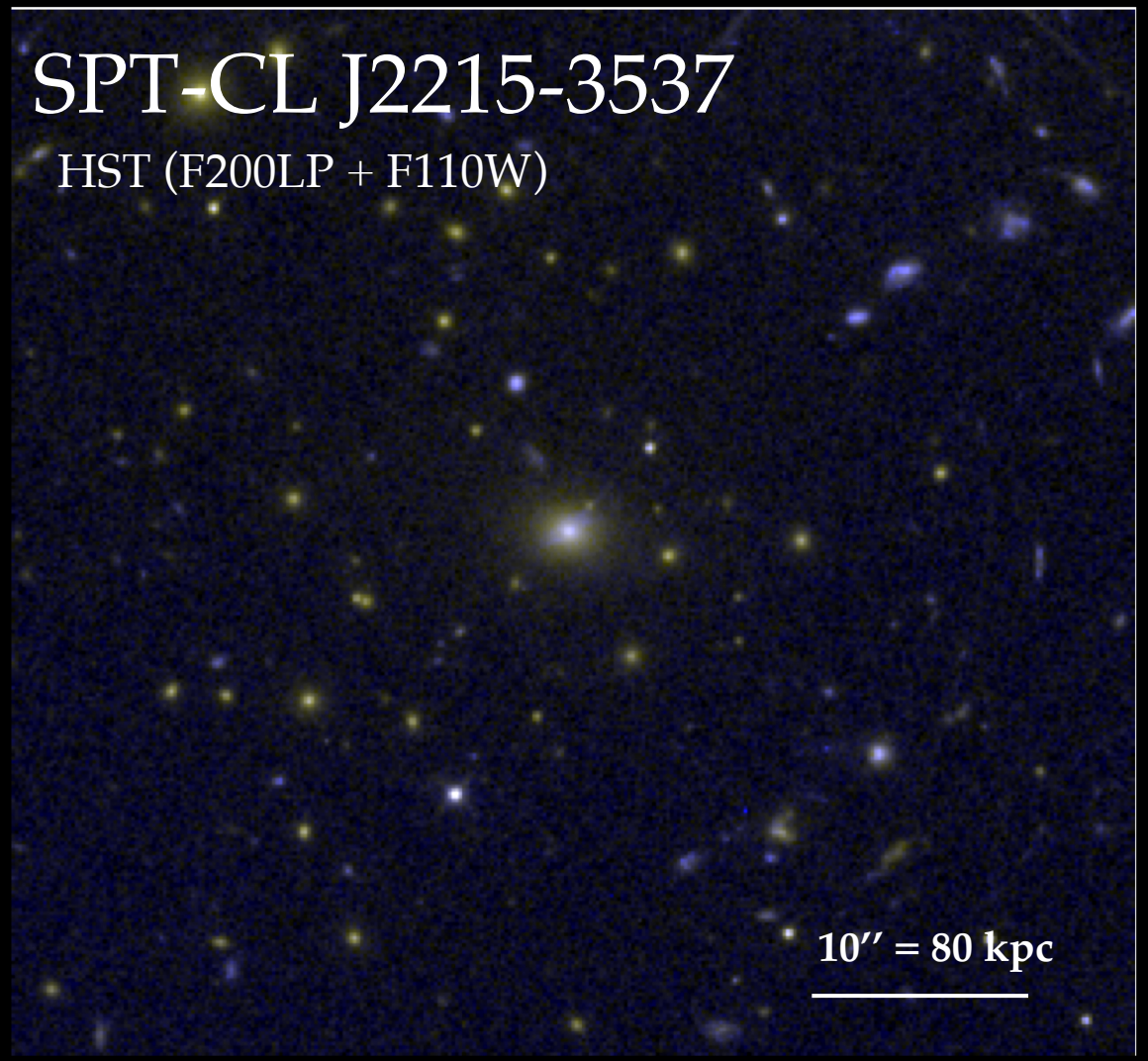
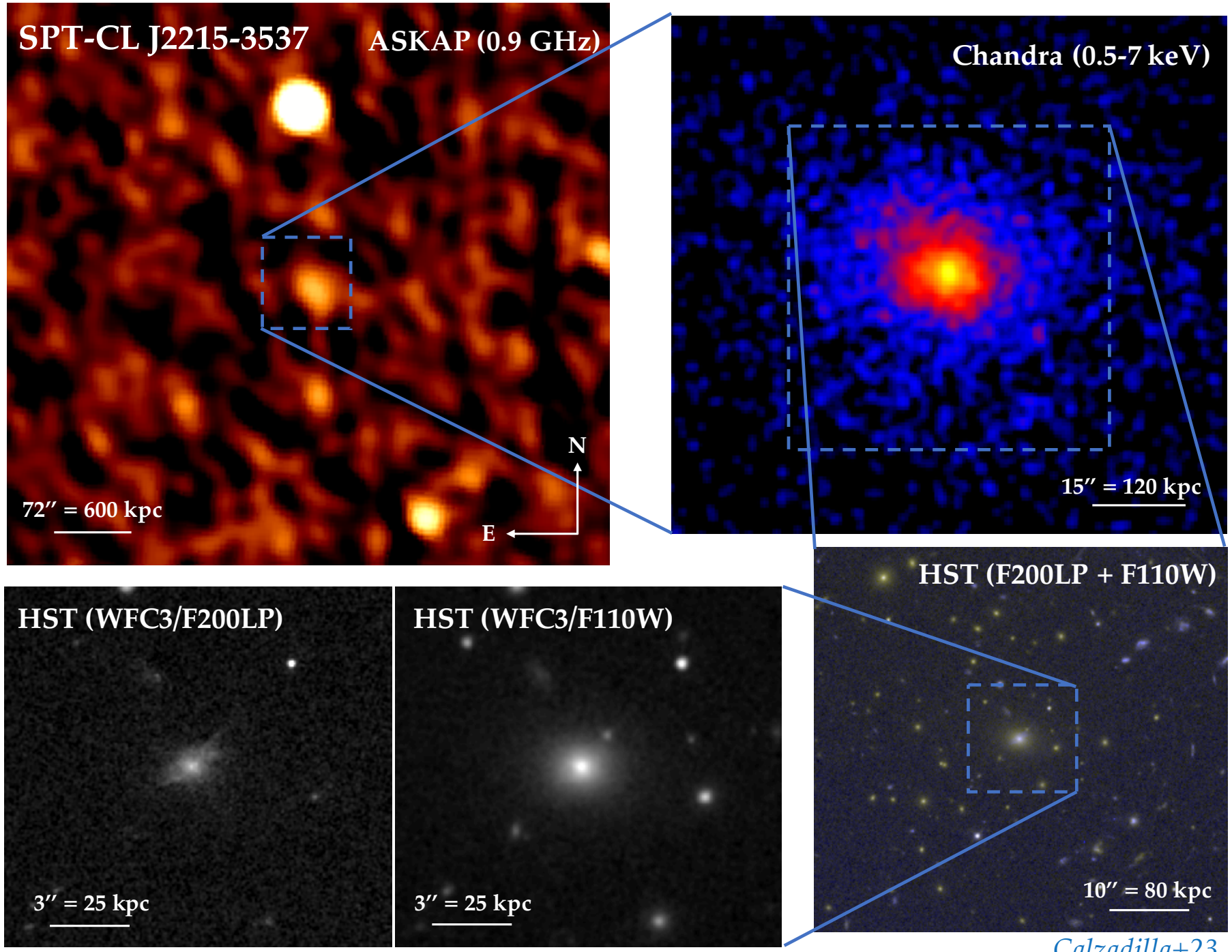
  - ICM and SF not centered on BCG → no feedback (Hlavacek-Larrondo+20)



NOTABLE EXAMPLES OF EXTREME HIGH-Z COOLING

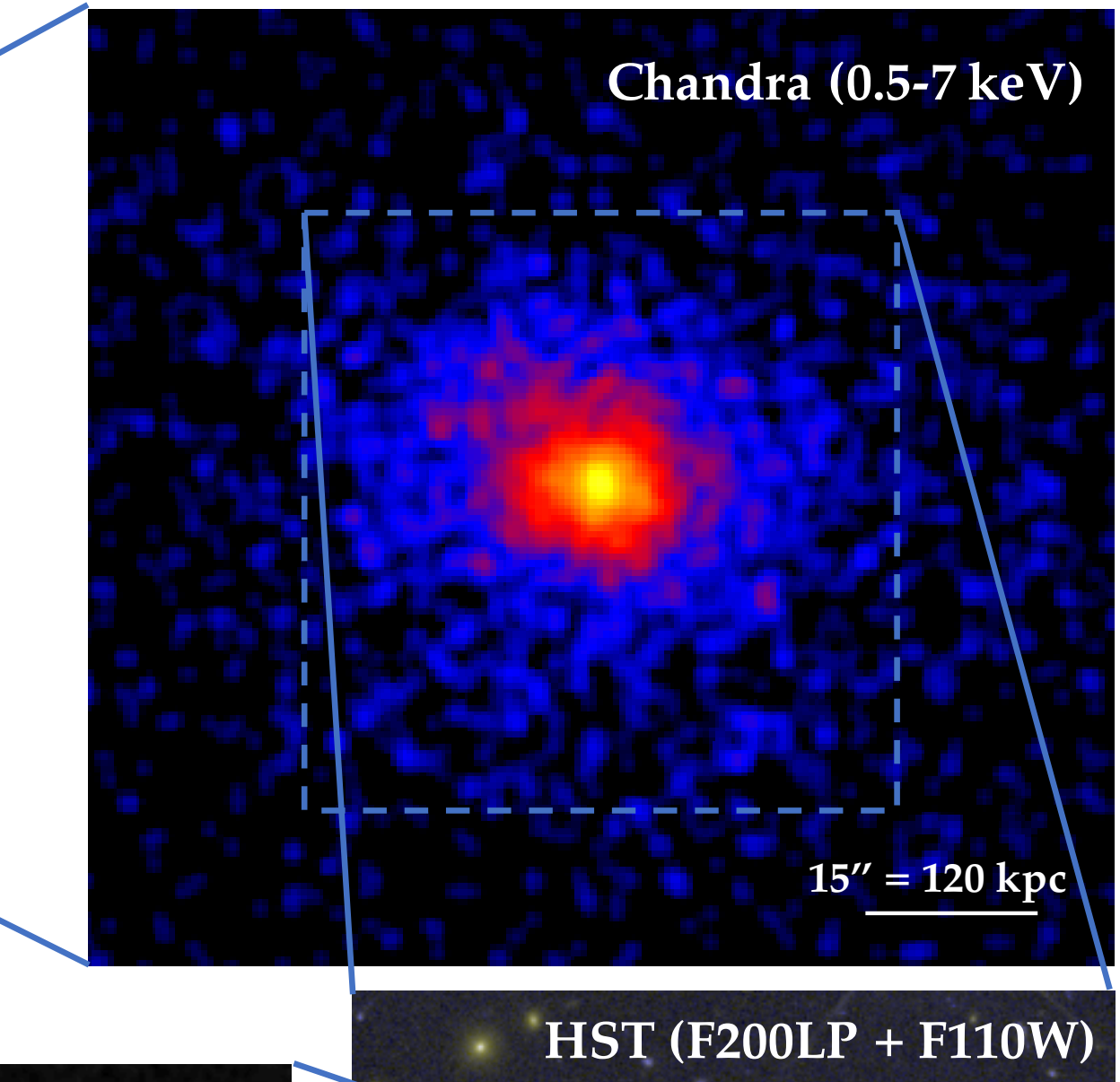
- SPT 2215 (Calzadilla+23)
  - $z = 1.2$, $M = 7\times10^{14}\ M_\odot$
  - Exceptionally isolated and relaxed
  - Massive starburst: ~320 $M_\odot$/yr at the center of one of the most distant relaxed clusters



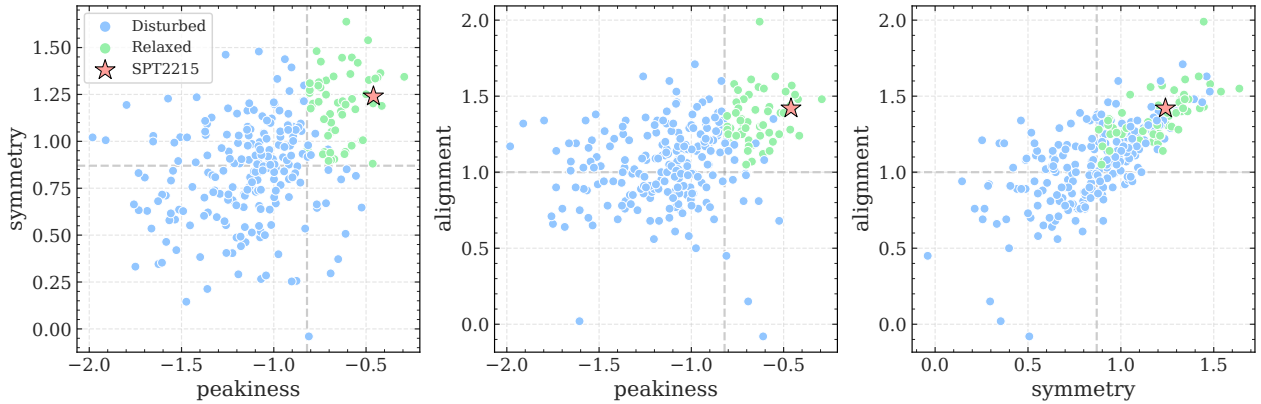


Calzadilla+23

X-RAY CHARACTERISTICS



- Extremely relaxed (Mantz+22)



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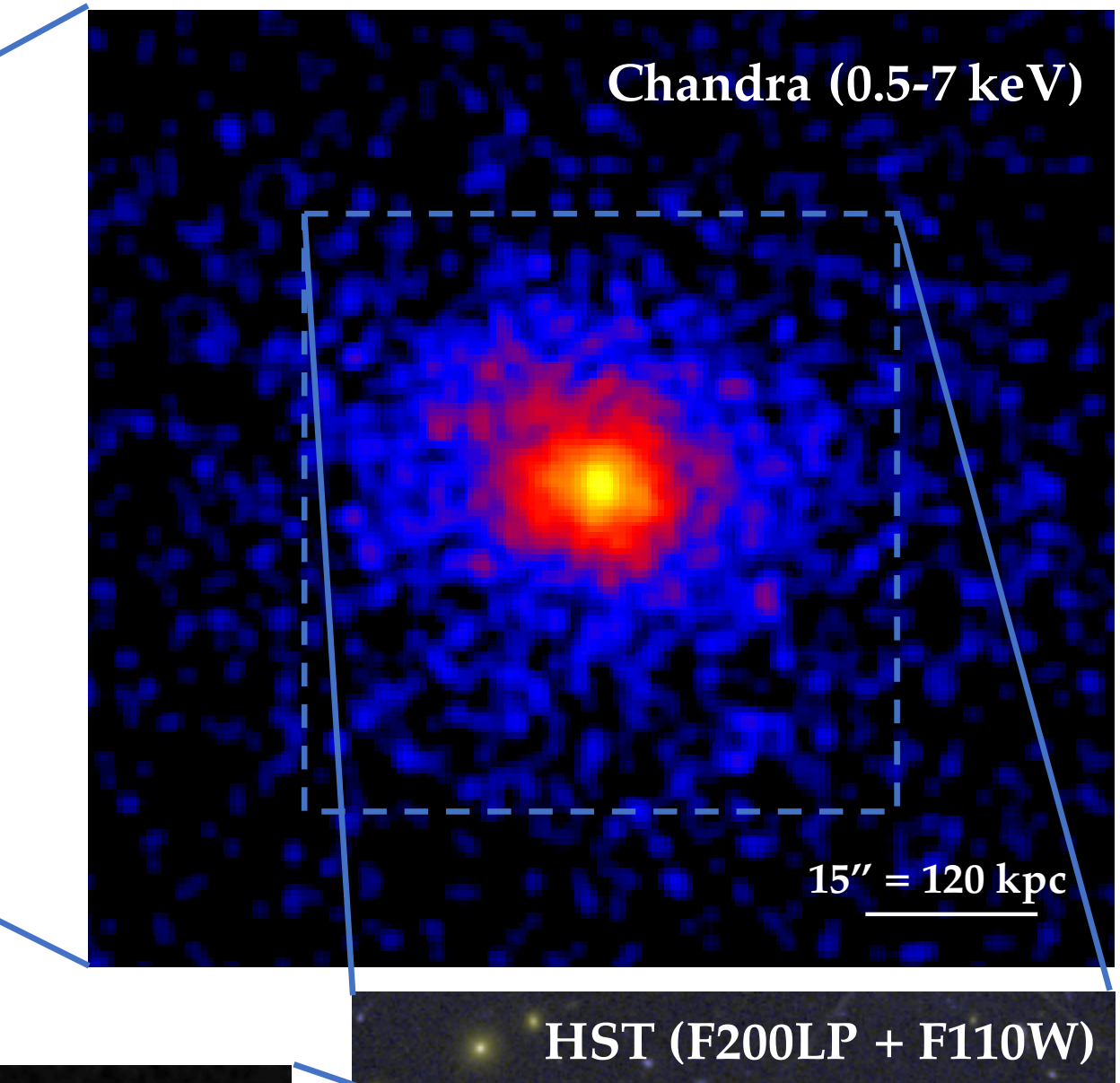
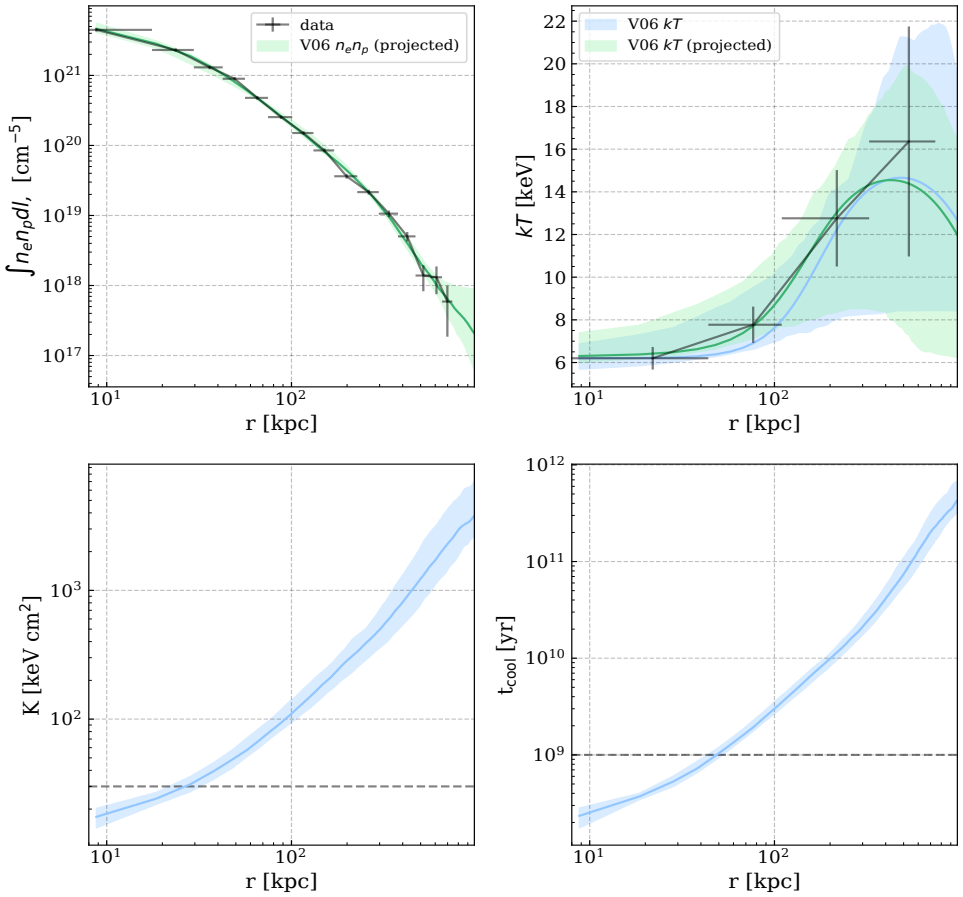


- Extremely relaxed (Mantz+22)
- Strong cool core



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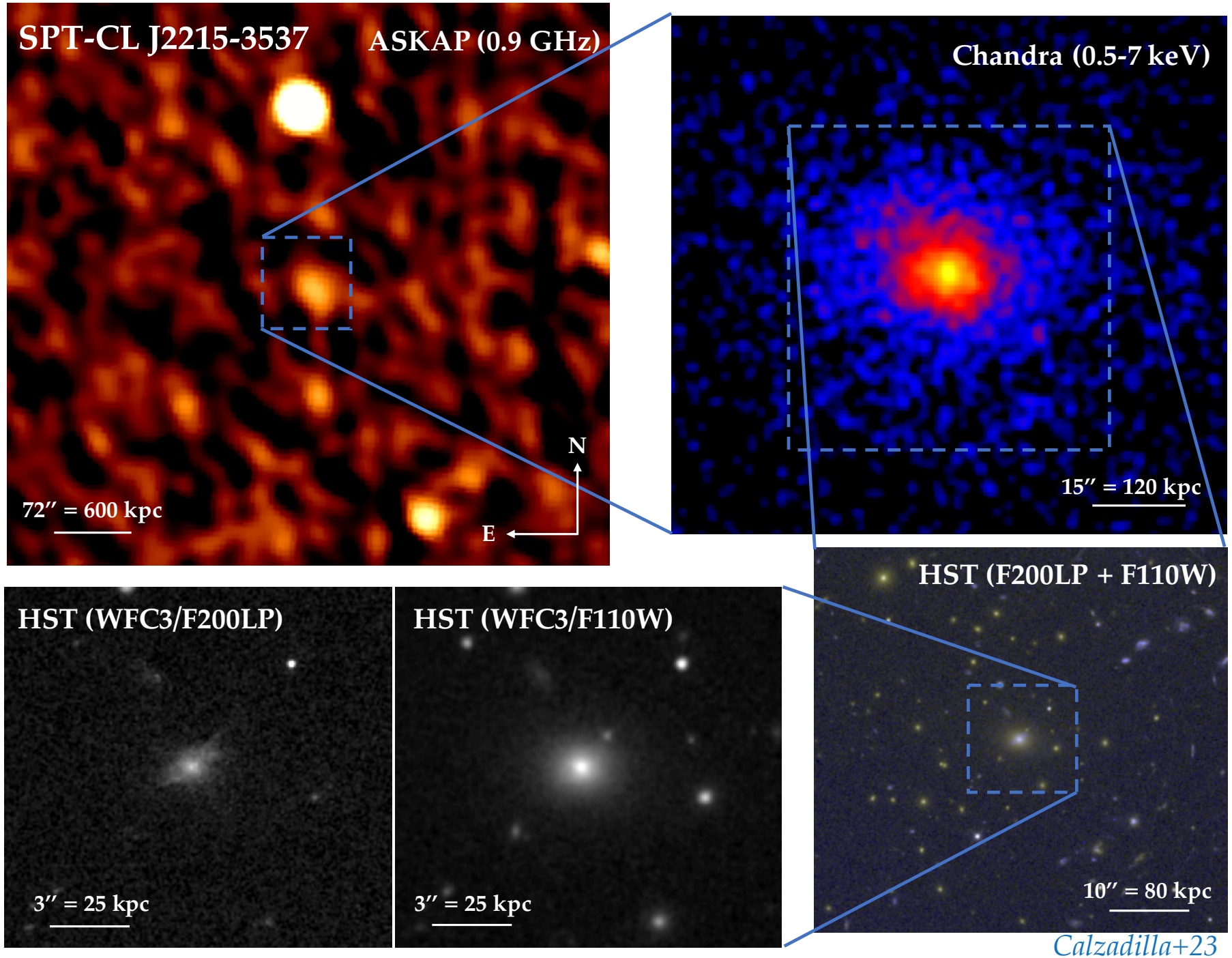

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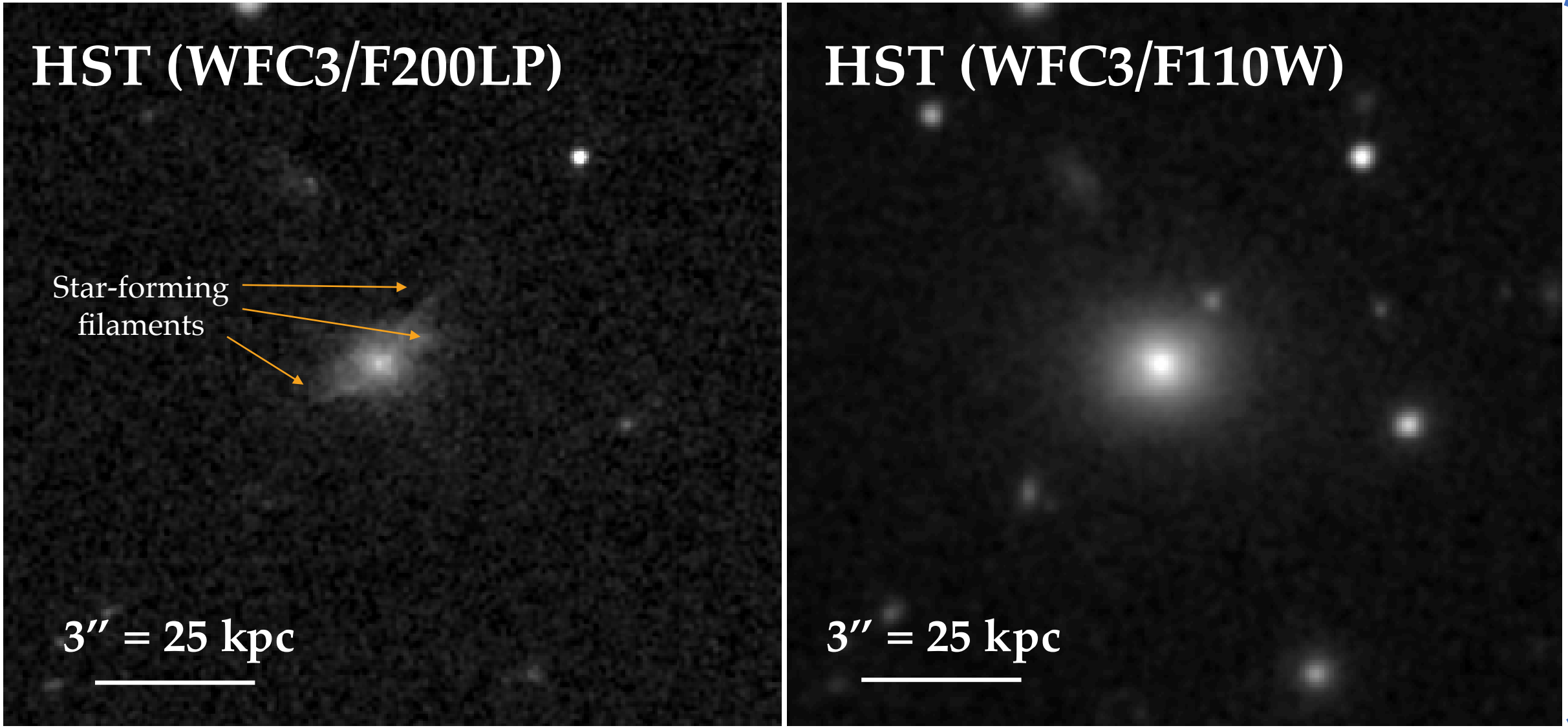
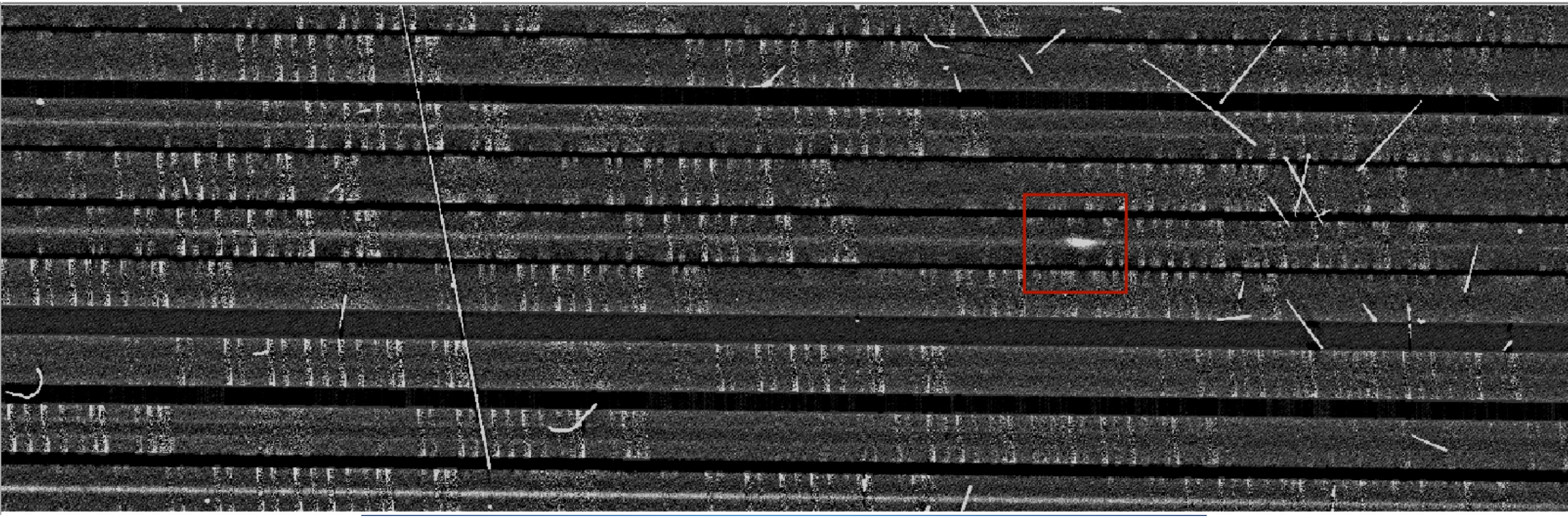
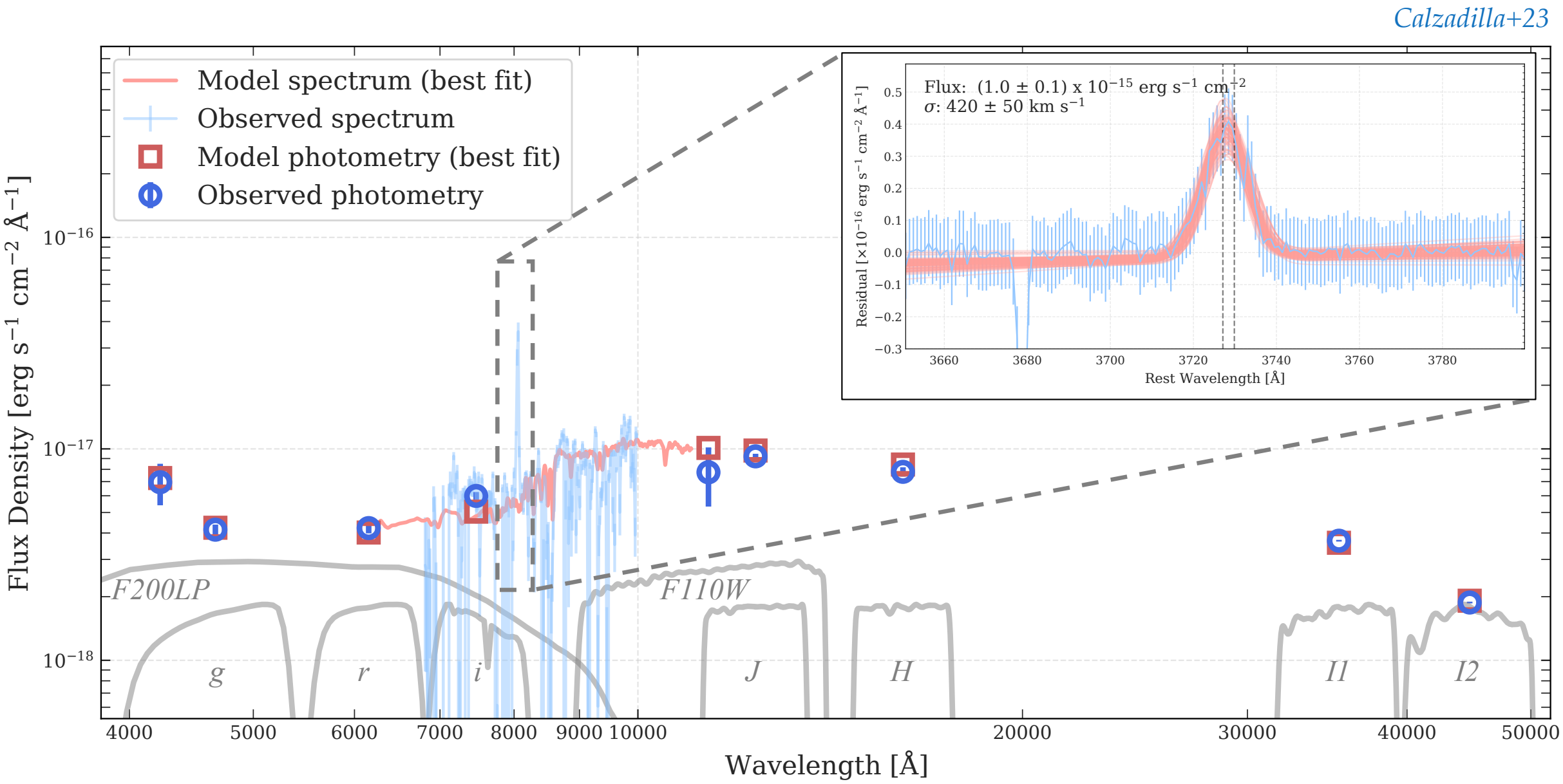
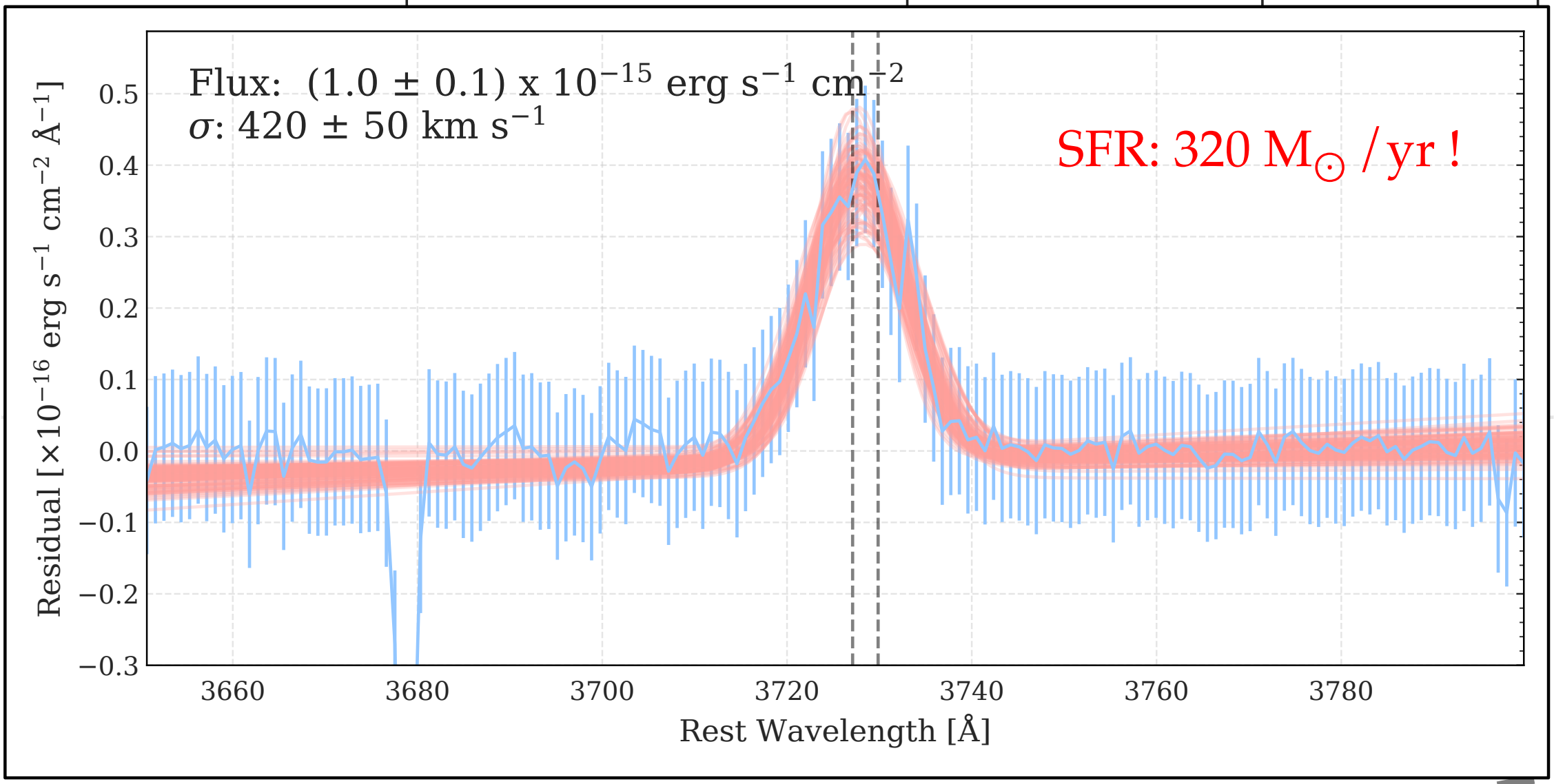

HST (WFC3/F200LP)
Star-forming filaments
3″ = 25 kpc
HST (WFC3/F110W)
3″ = 25 kpc

AN EXTREMELY HIGH SFR

- 2.3 hours of Magellan/LDSS3 spectroscopy + photometry from *HST*, PISCO, *Spitzer*
  - Strong [O II]$\lambda\lambda$3726,3729Å emission
- MCMC-based SPS and SED fitting of spectrophotometry with *Prospector*



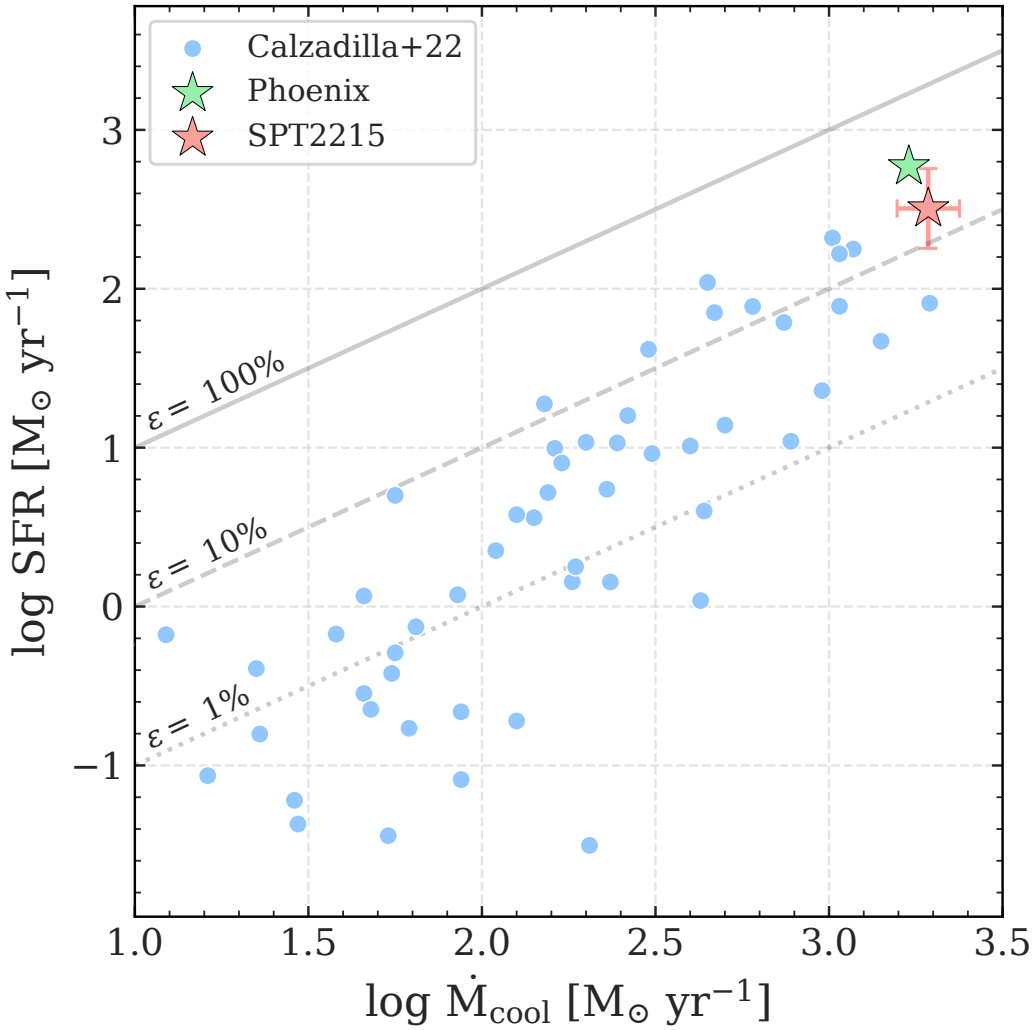

Calzadilla+23
Model spectrum (best fit)
Observed spectrum
Model photometry (best fit)
Observed photometry
Flux Density [erg s^{-1} cm^{-2} Å^{-1}]
Wavelength [Å]
F200LP
F110W
g
r
i
J
H
I1
I2
Flux: (1.0 ± 0.1) x 10^{-15} erg s^{-1} cm^{-2}
σ: 420 ± 50 km s^{-1}
Residual [×10^{-16} erg s^{-1} cm^{-2} Å^{-1}]
Rest Wavelength [Å]


Flux: (1.0 ± 0.1) x 10^{-15} erg s^{-1} cm^{-2}
σ: 420 ± 50 km s^{-1}
SFR: 320 $M_\odot$ / yr !
Residual [$\times 10^{-16}$ erg s^{-1} cm^{-2} $Å^{-1}$]
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
3660
3680
3700
3720
3740
3760
3780
Rest Wavelength [Å]

WHY SUCH A HIGH SFR?

- Highly efficient conversion from hot (10^7 K) to warm (10^4 K) ionized gas

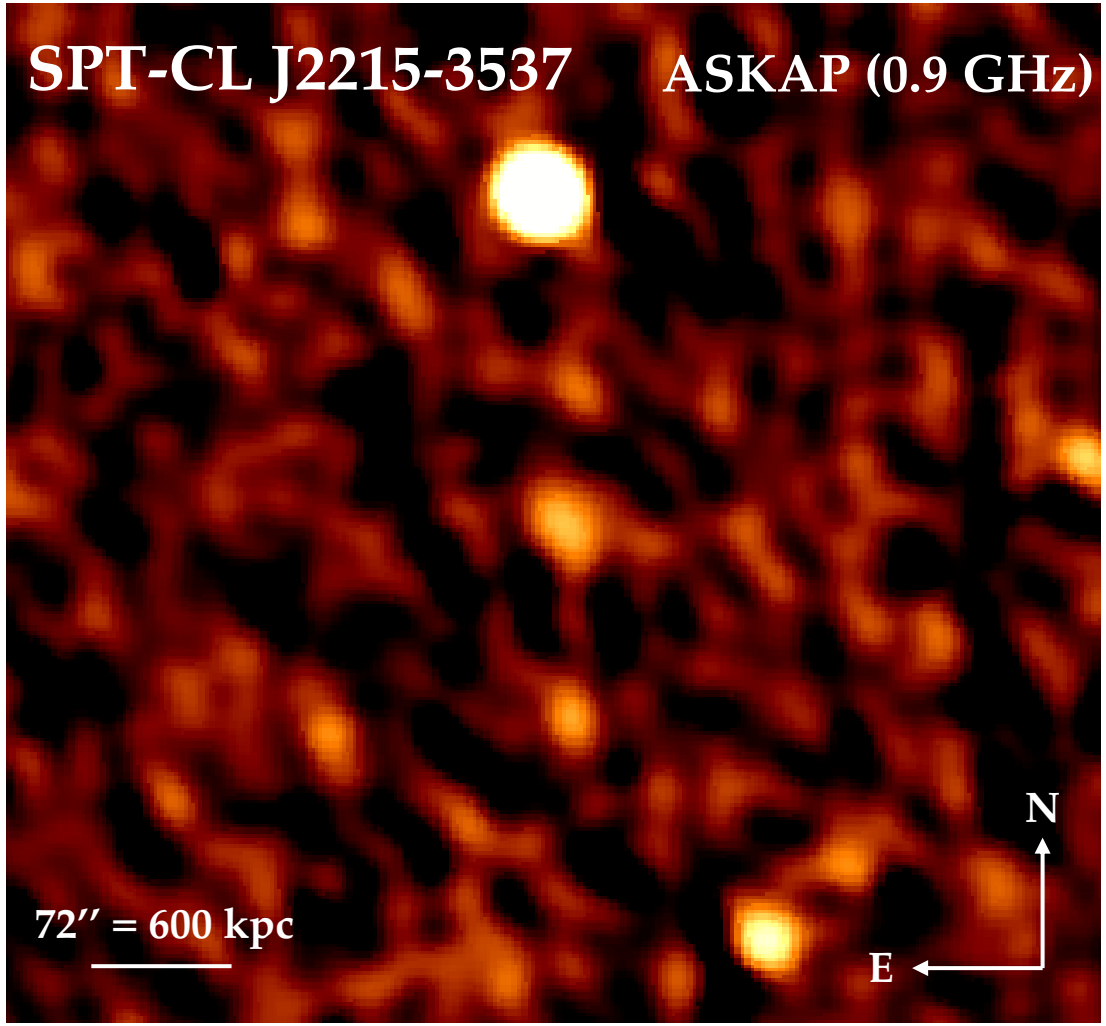
Calzadilla+23



WHY SUCH A HIGH SFR?

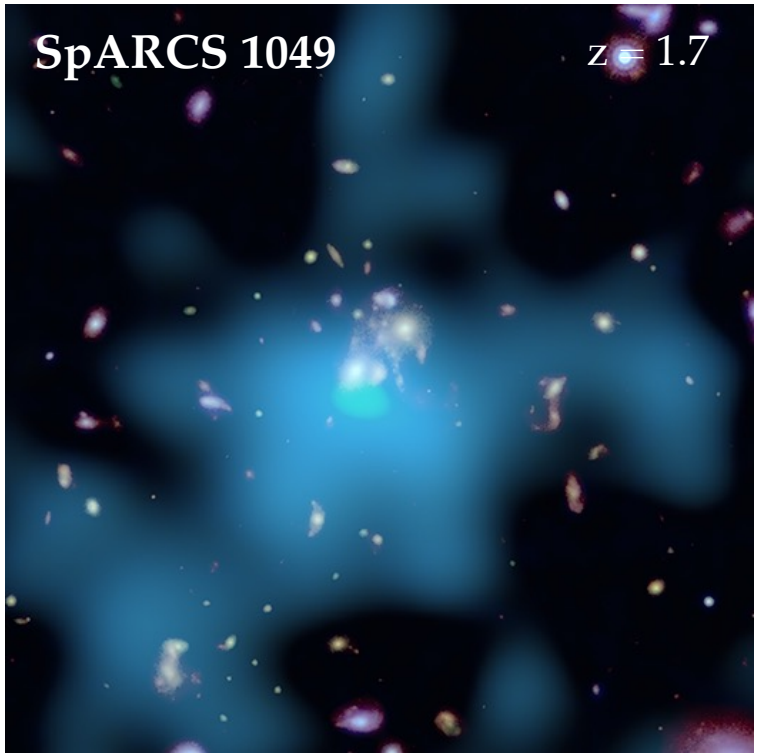
Calzadilla+23

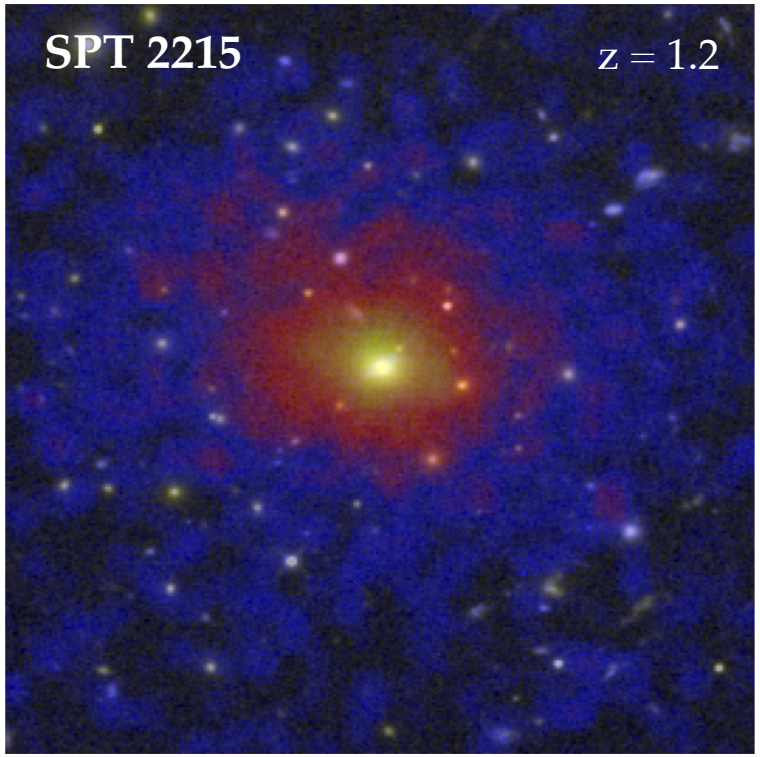
- Highly efficient conversion from hot (10^7 K) to warm (10^4 K) ionized gas
- Weak radio source ($L_{0.8\,\mathrm{GHz}} = 2$ mJy)
  - Cooling > heating ($P_{cav}/L_{cool} = 0.1$)
  - Recently "activated" AGN?

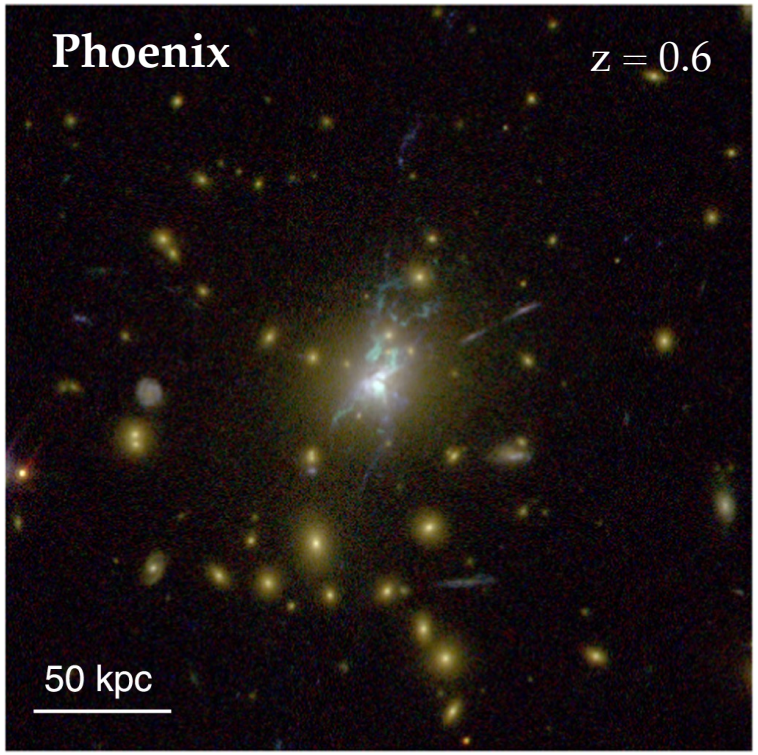


IMPLICATIONS FOR EVOLUTION OF FEEDBACK

- Descendant of SpARCS 1049-like system?
- High-z analog of Phoenix cluster







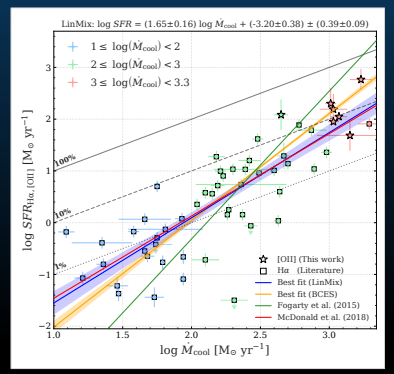
OVERVIEW

Background

- Cooling flow problem
- AGN feedback: black holes as thermostats

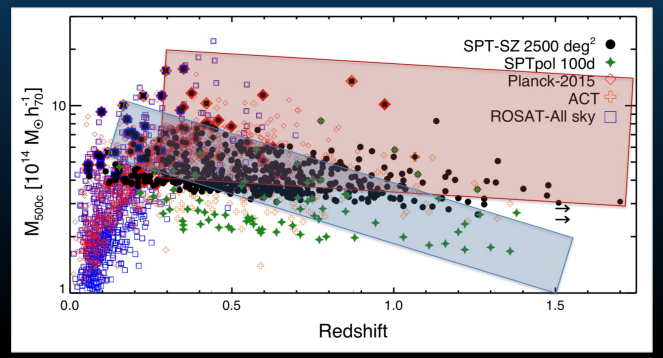
The New Cooling Flow Problem

- Testing the limits of AGN feedback with the most extremely cooling systems
- What governs the effectiveness of AGN feedback?

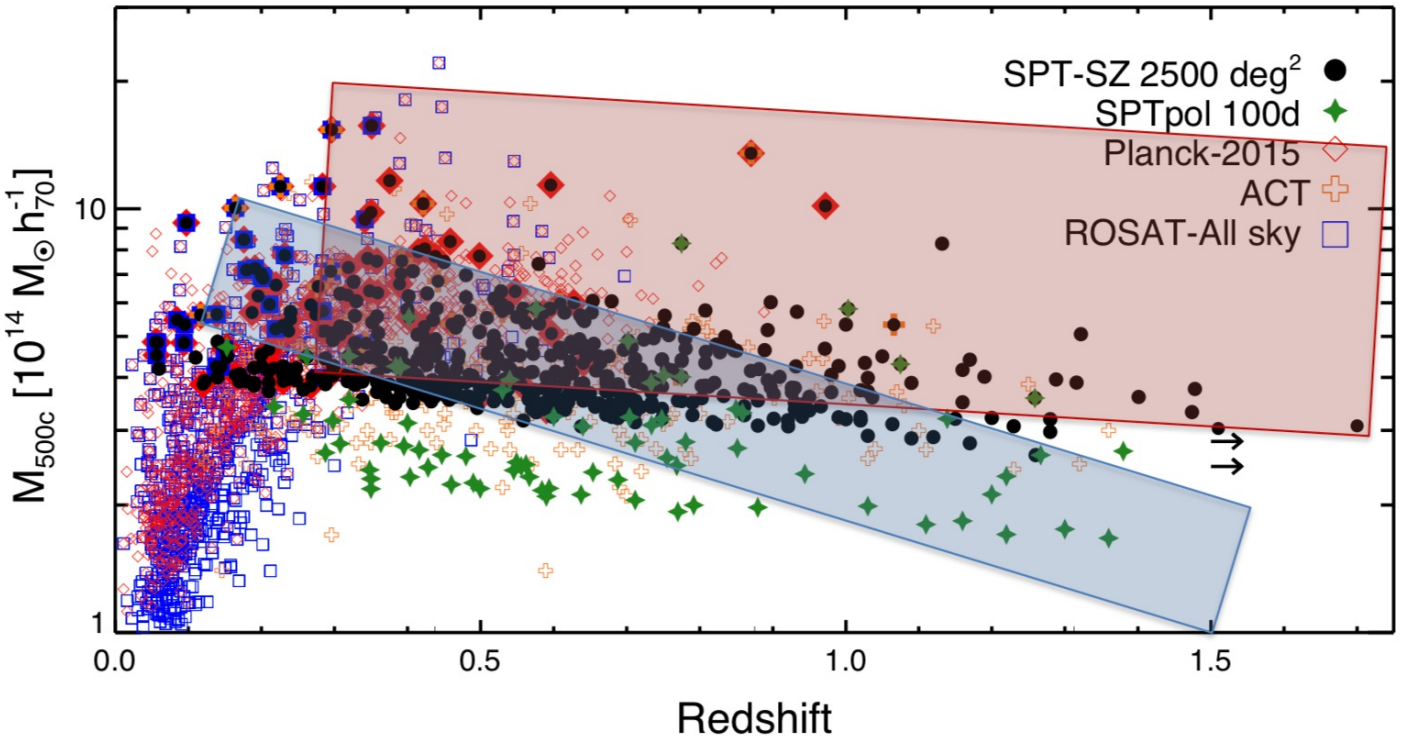


Evolution of the Cooling Flow Problem

- What does the cooling-feedback balance look like at high-z?
- Using a large multi-λ sample of SPT clusters spanning $0.3 < z < 1.7$



SPT MULTI-λ 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

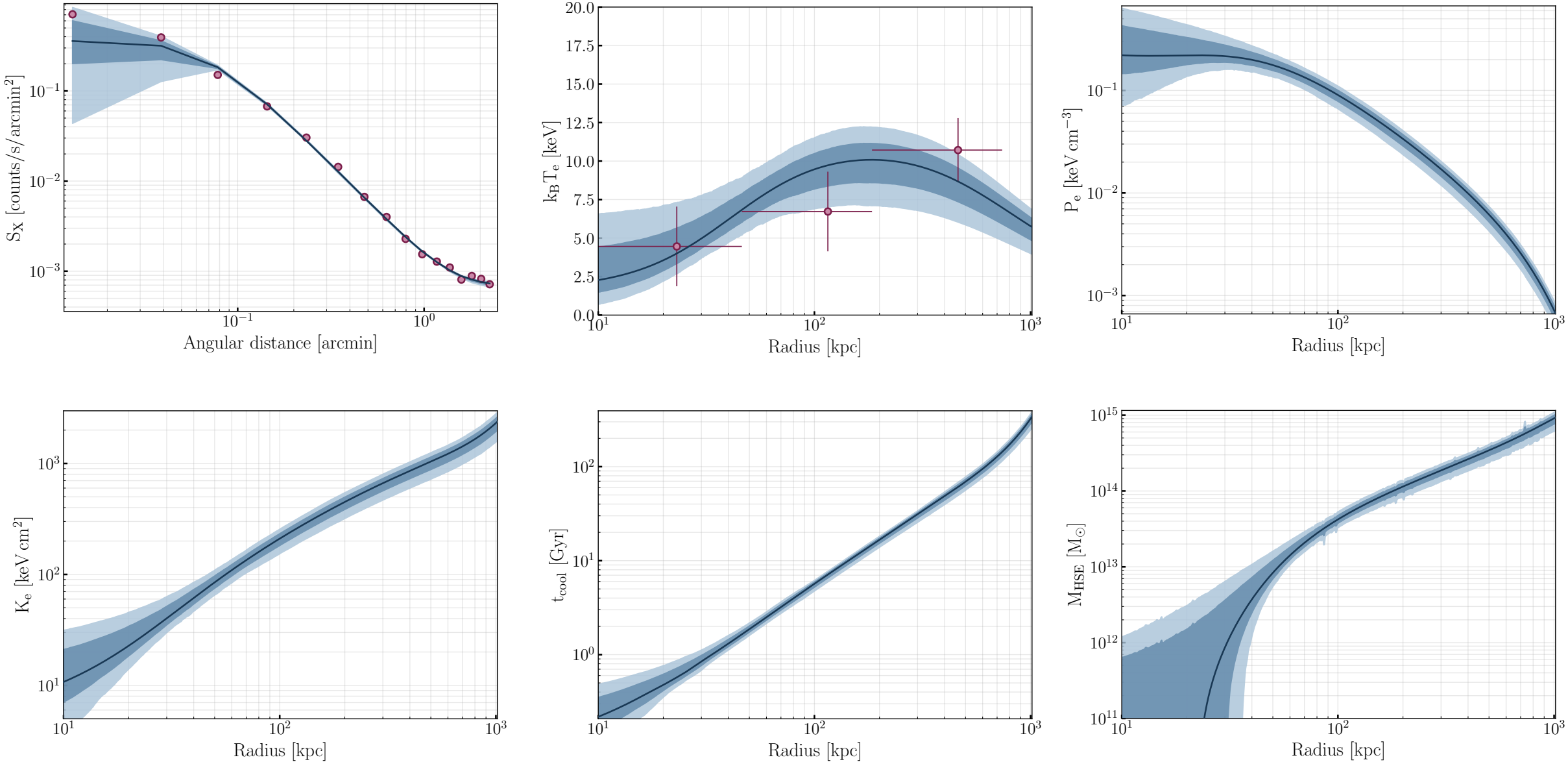
→ (see e.g. Ruppin+21, 23)

- Multiwavelength follow-up:

X-ray + Radio + Optical/IR spectra

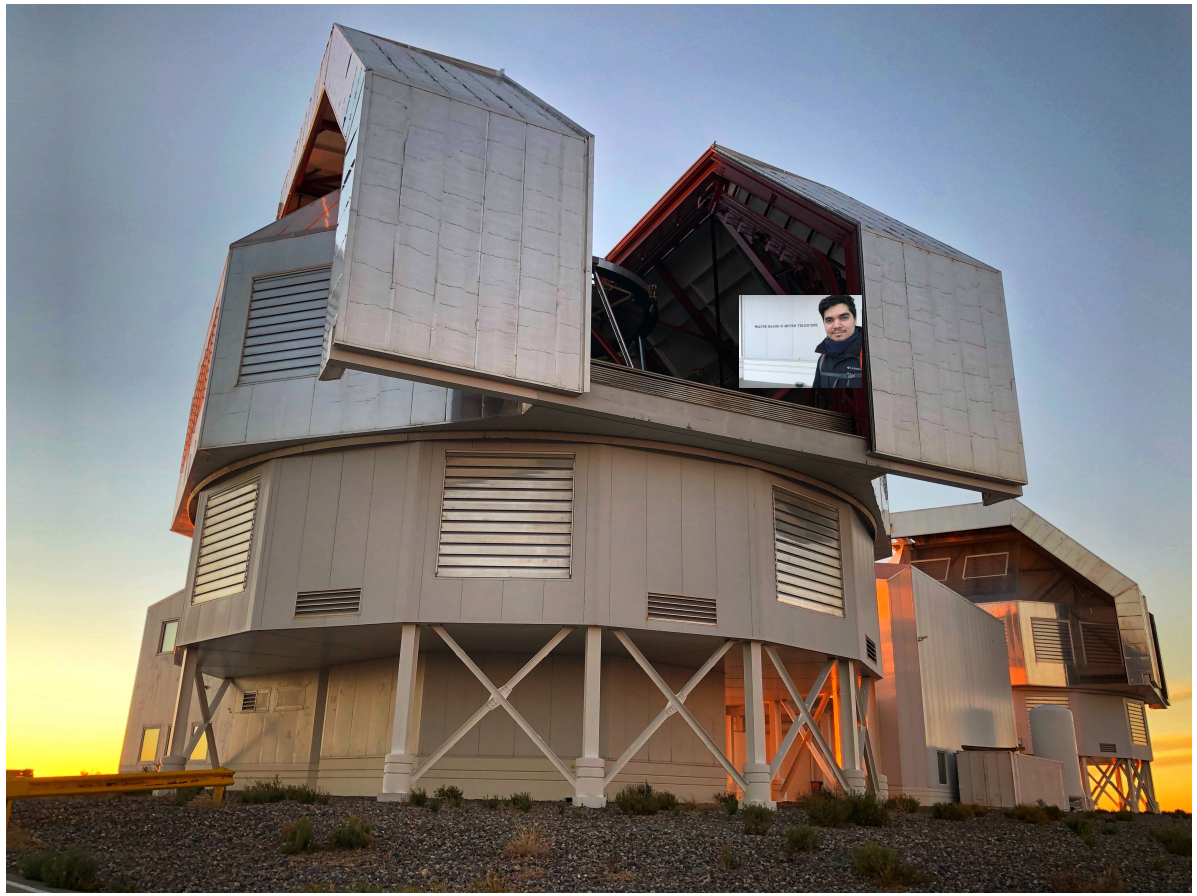
ICM "fuel" → AGN activity / Star formation

X-RAY ANALYSIS



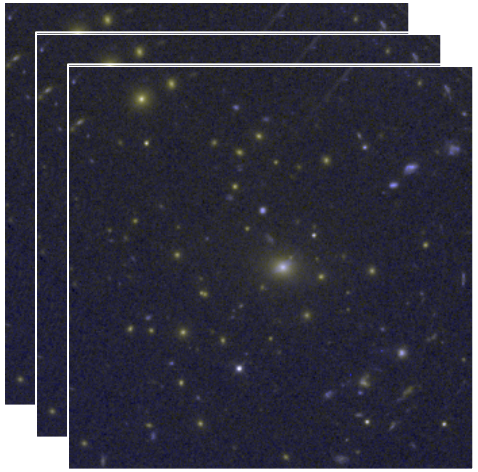
MAGELLAN OBSERVING CAMPAIGN

- MOS & long-slit spectra covering [O II], [O III] and 2-3 of the Hβ, Hγ, Hδ lines to get:
  - Spectroscopic redshifts
  - Extinction-corrected SFRs
  - SF vs AGN diagnostics
- Magellan reduction pipeline (IMACS & LDSS3)



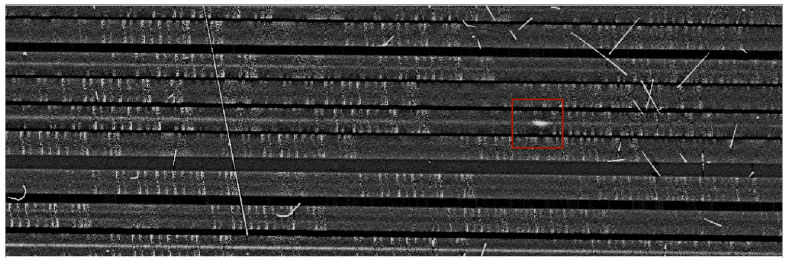
SED FITTING WITH prospector

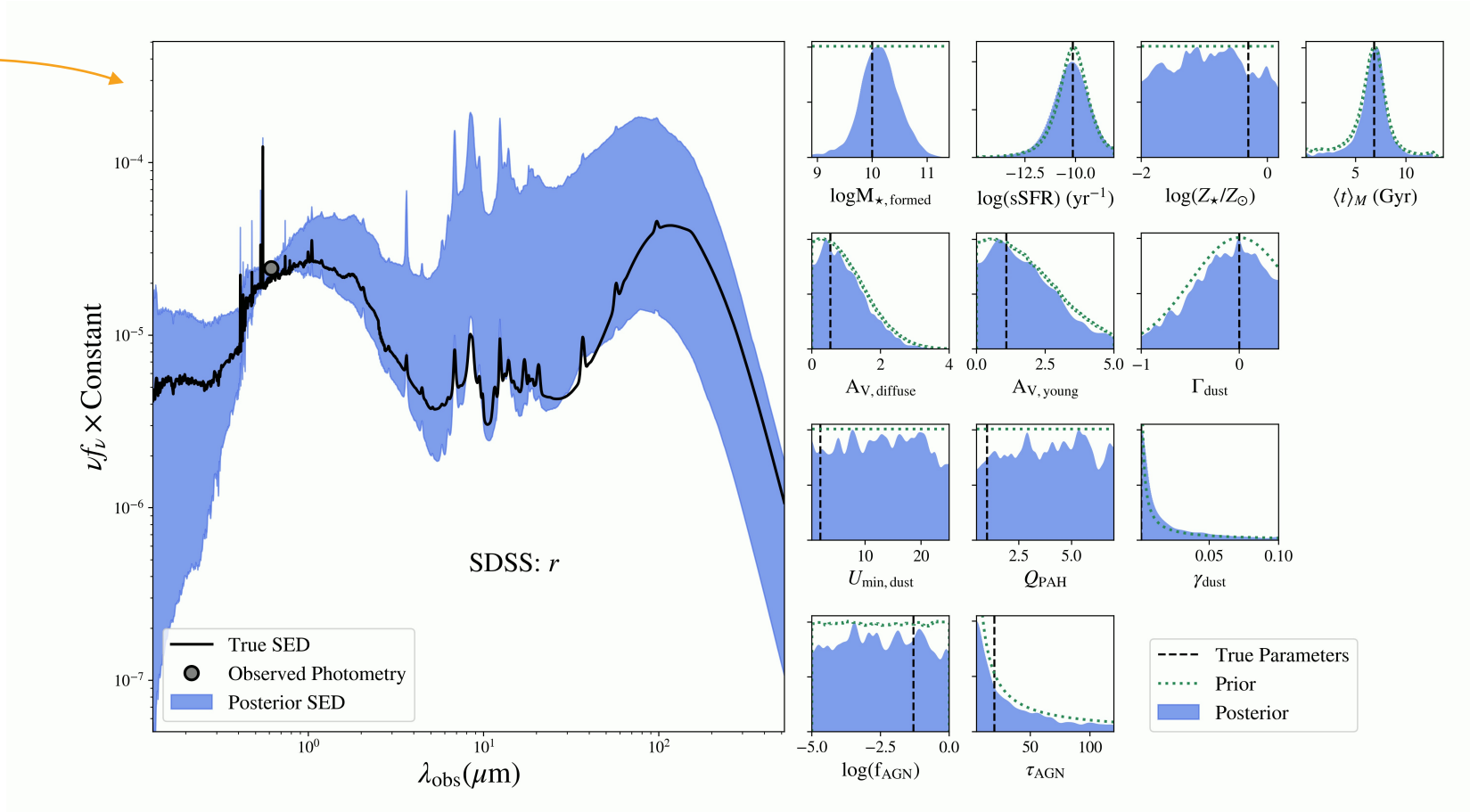
photometry



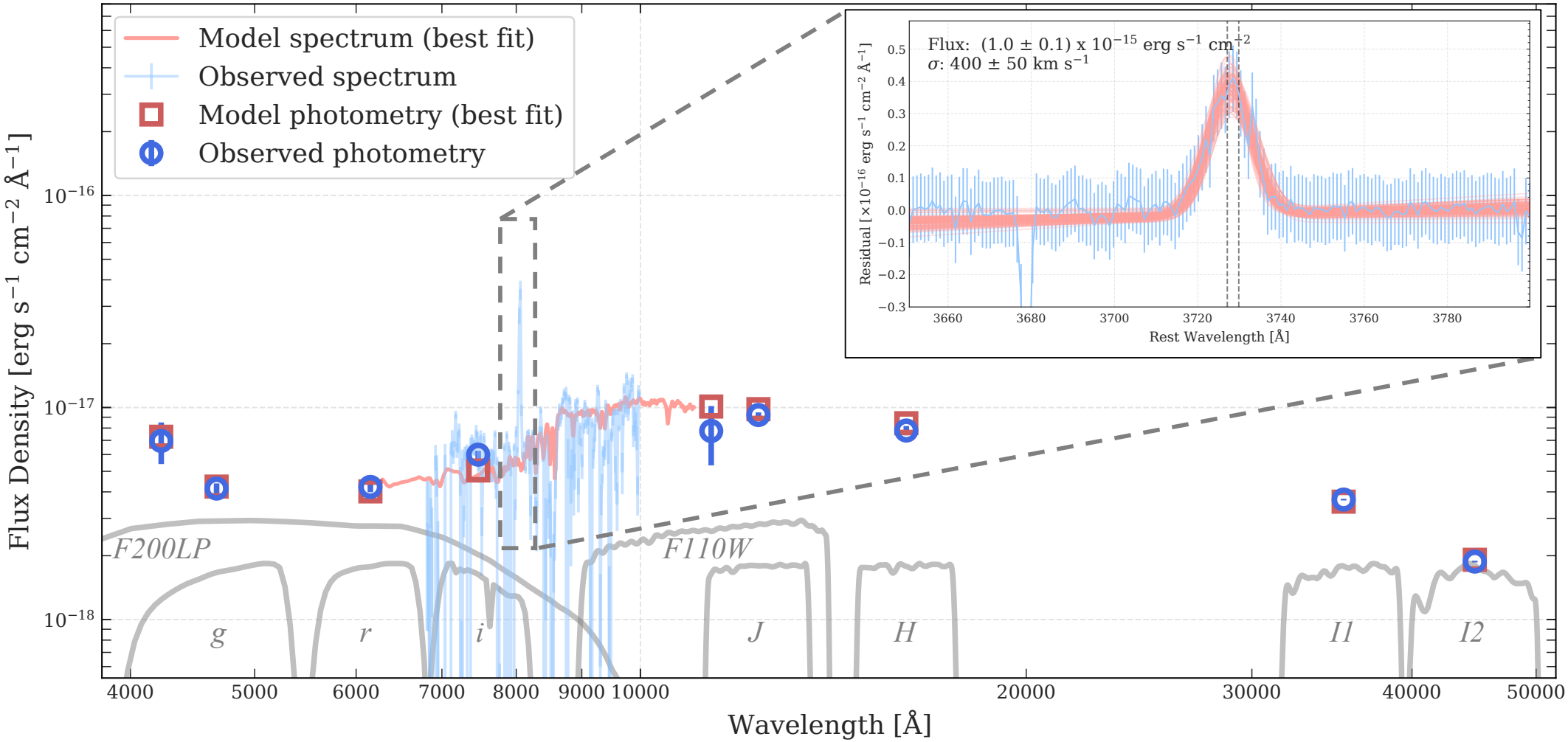
x100

+ spectra



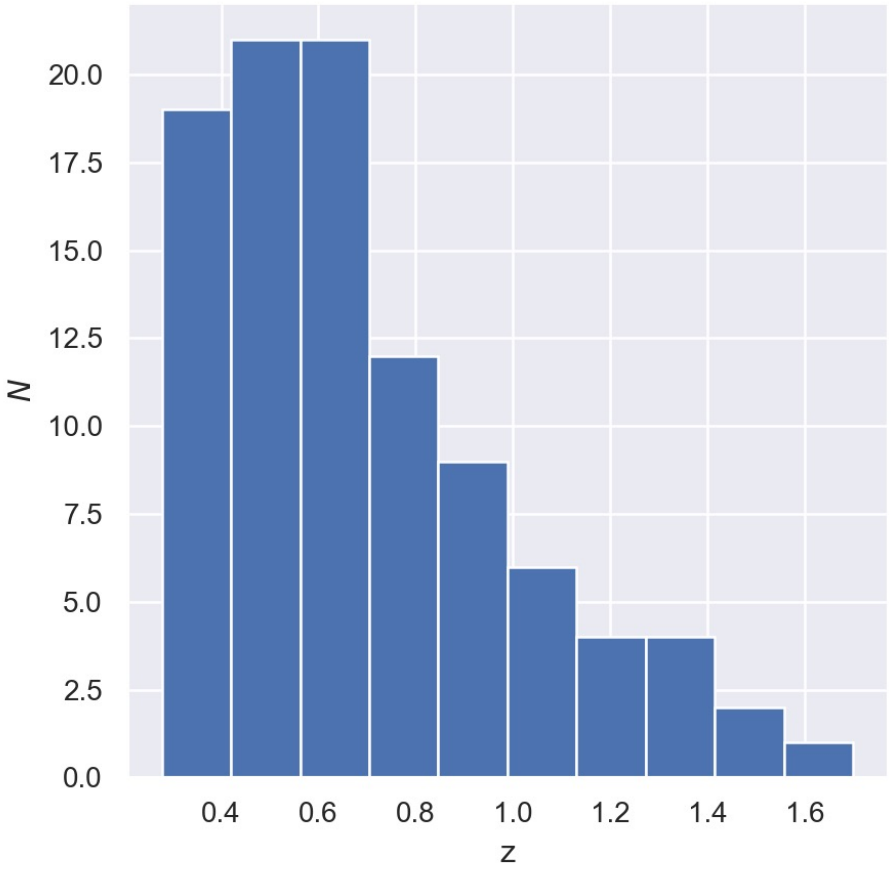


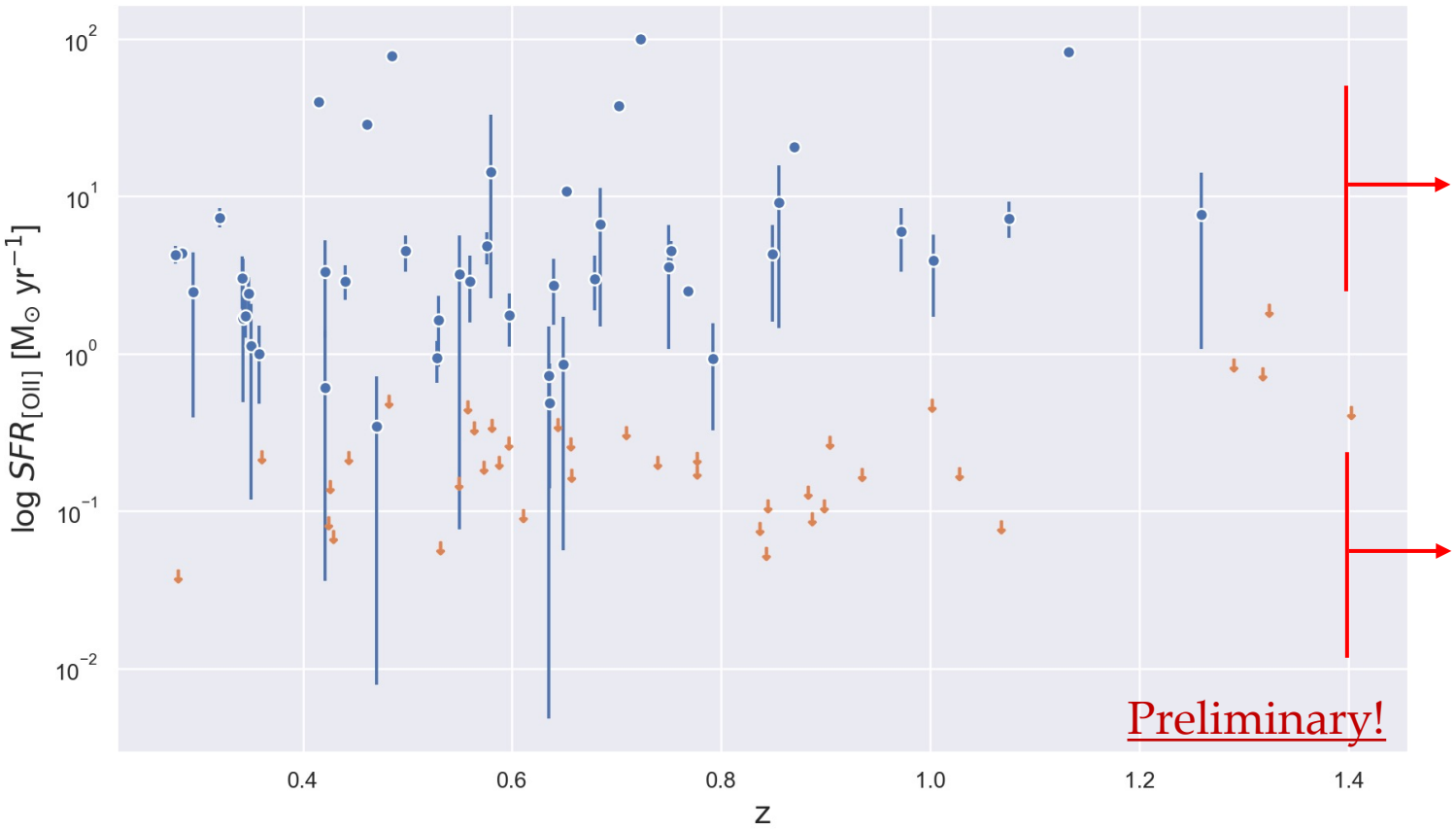
SED FITTING WITH PROSPECTOR



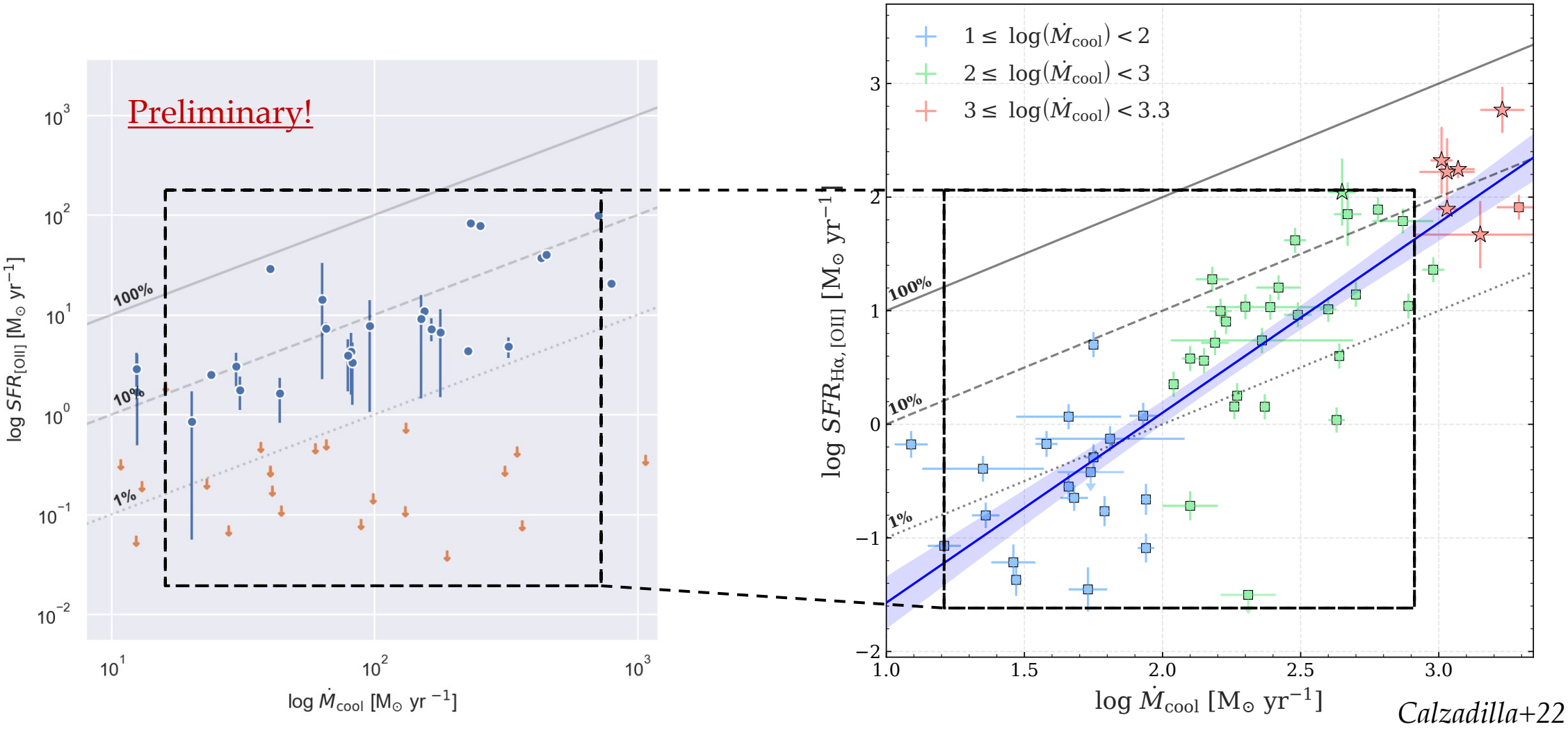
Calzadilla+23

PRELIMINARY RESULTS: SPECTROSCOPY



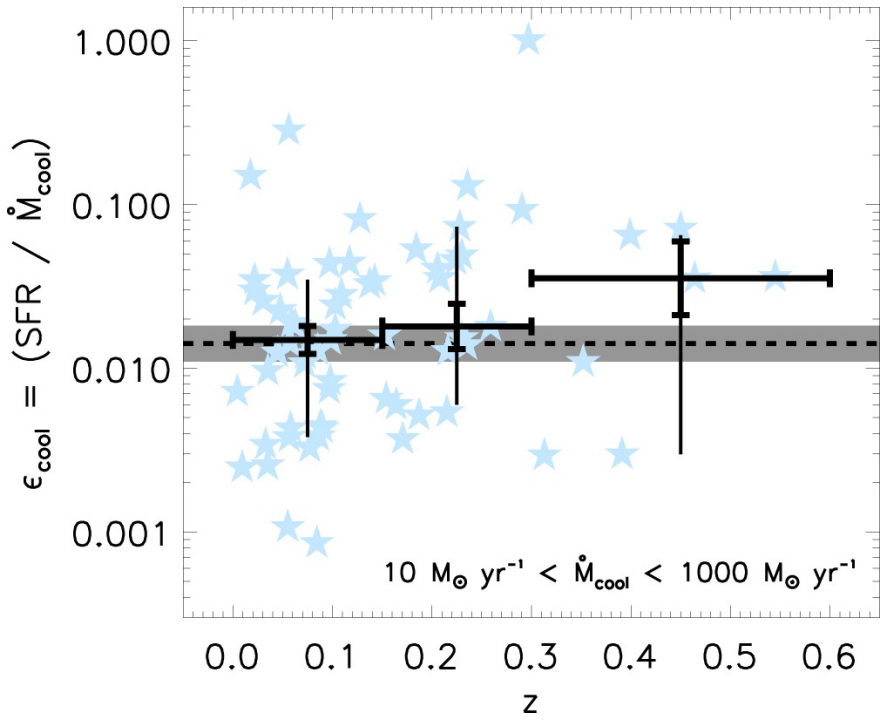


SFR VS $\dot{M}_{cool}$

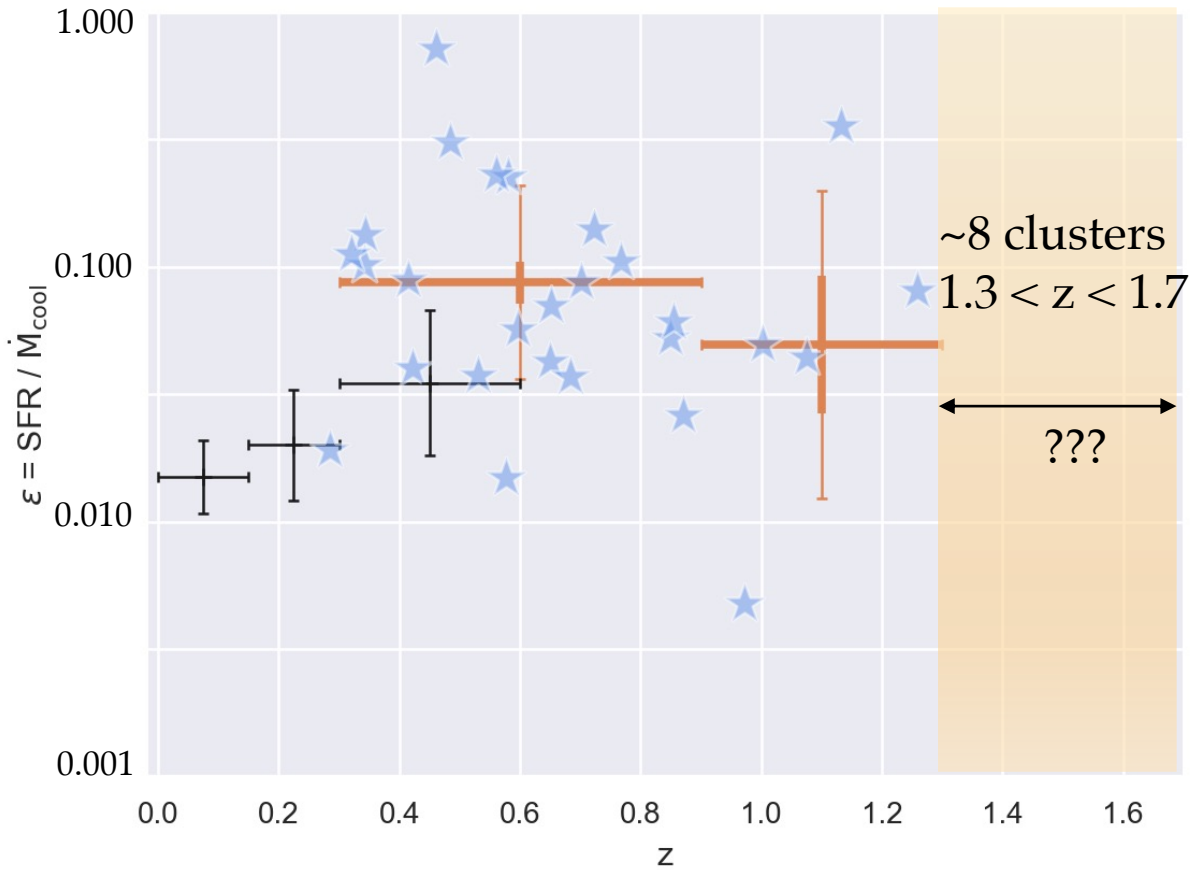


Calzadilla+22

SFR VS $\dot{M}_{cool}$



McDonald et al. 2018



→ Adding ~50 cool cores to 0.3 < z < 1.8

→ previously N=7 at 0.3 < z < 0.6

Preliminary!

EVOLUTION OF FEEDBACK

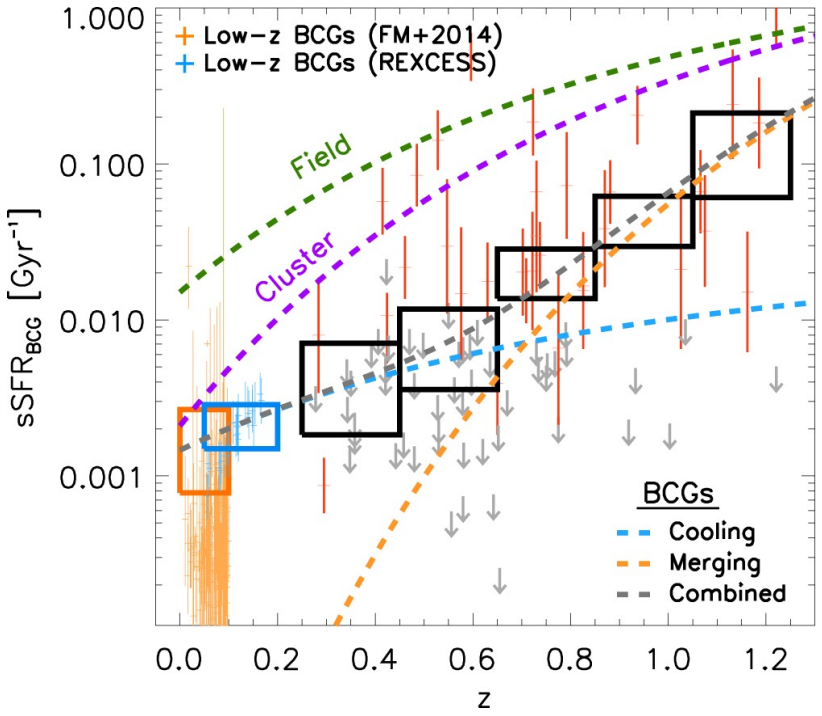
- Star-forming efficiency of hot gas seems to increase in more massive systems
  - Maybe due to dominant mode of feedback
- Some high-z clusters are consistent with this behavior
  - Extreme and efficient cooling and star formation in SPT2215, Sp1049
- We will investigate this effect in an unbiased, SZ-selected sample of ~100 galaxy clusters spanning 10 Gyr of evolution
- Preliminary: avg. cooling efficiency hasn't changed much since z~1.2
- Our multi-λ dataset will also help answer:
  - How did the largest galaxies assemble?
  - Have thermal instability criteria for cooling evolved?
  - Was AGN feedback always as gentle in the past?

Stay tuned!

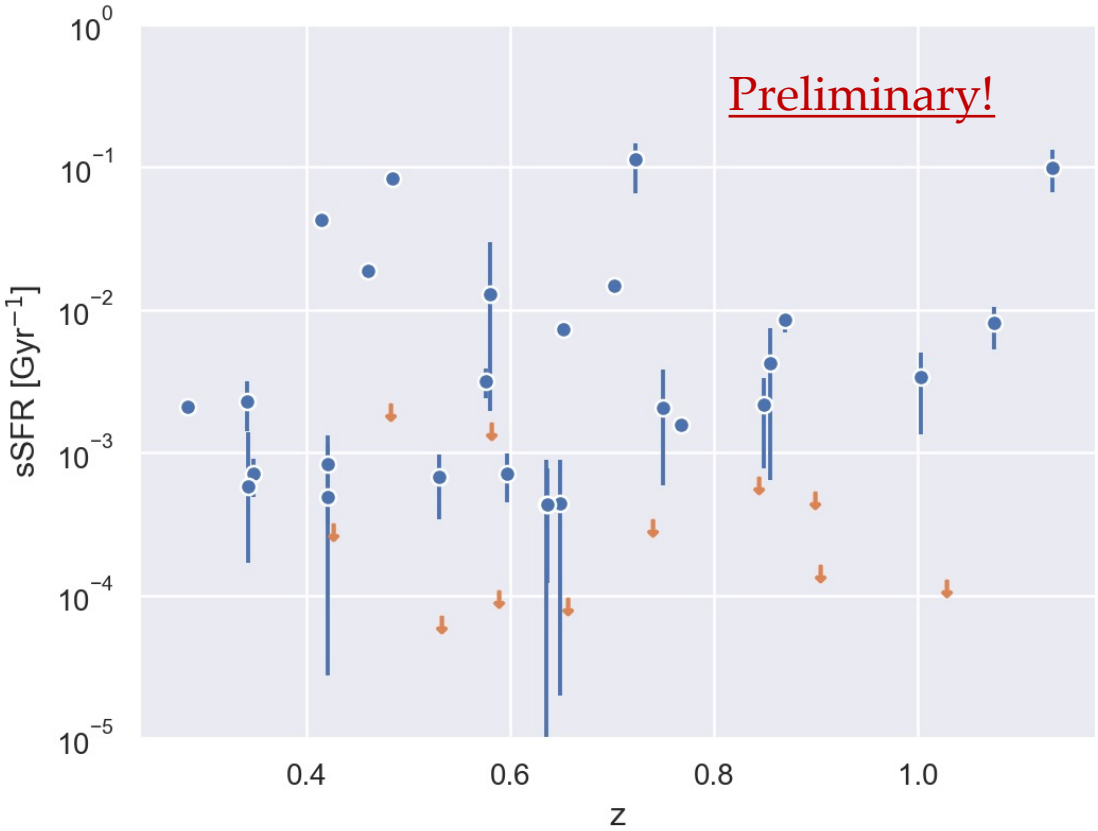
FURTHER TOPICS

that we will be able to address with this sample

HOW DID THE LARGEST GALAXIES ASSEMBLE?

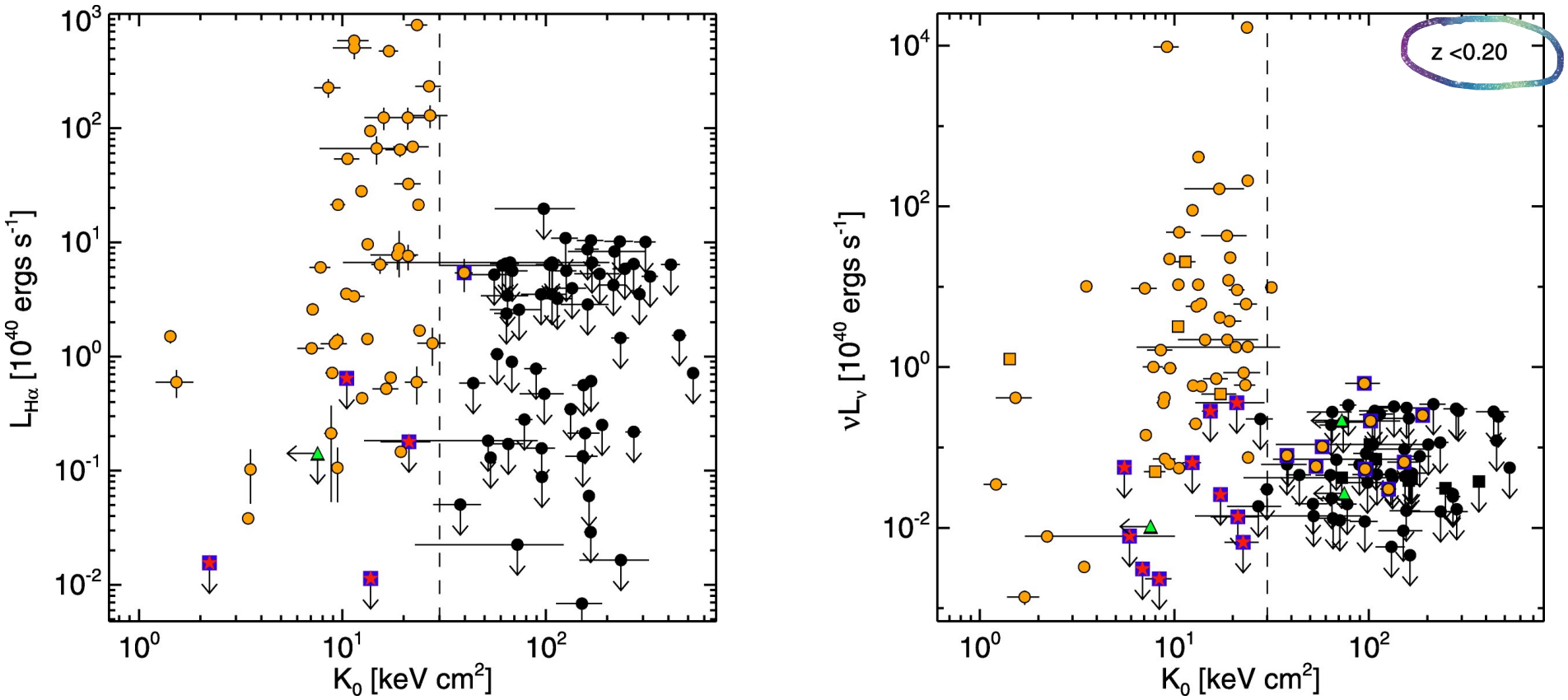


McDonald et al. 2016



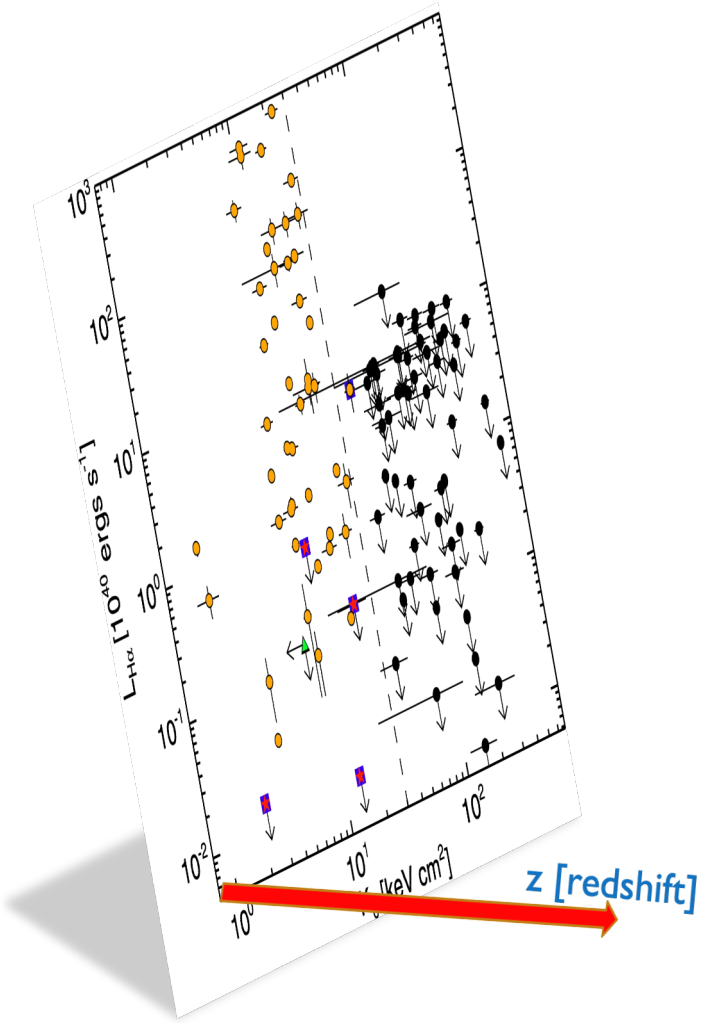
→ Improve measurement uncertainties by factors of several, and reduce upper limits by 2 orders of magnitude, on average

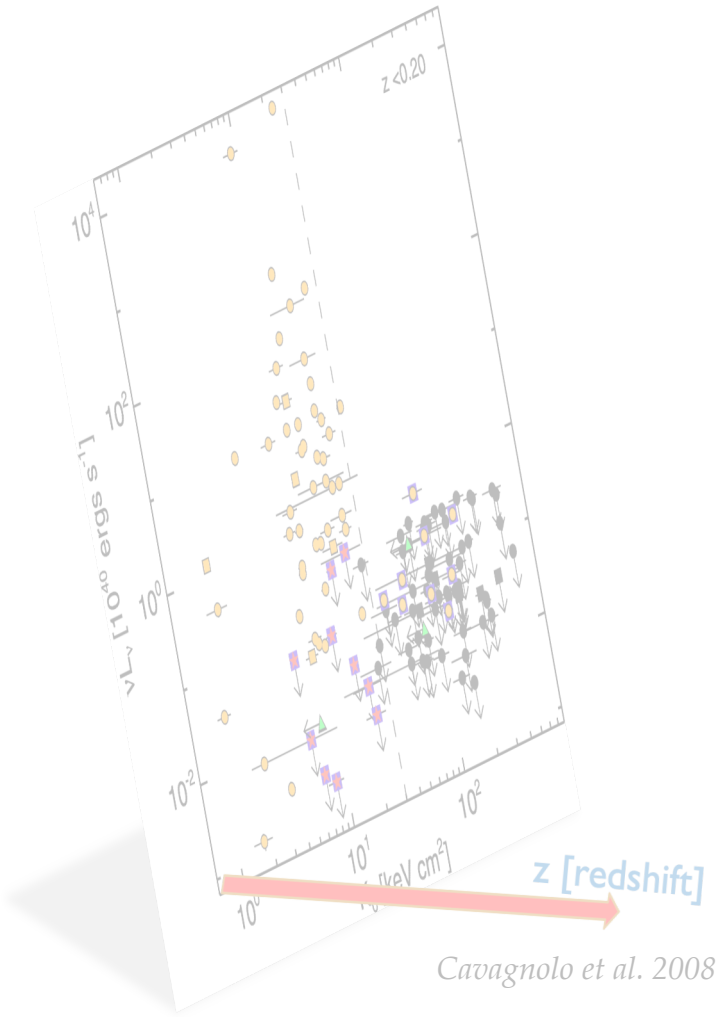
HAVE THE CONDITIONS FOR COOLING EVOLVED?



Cavagnolo et al. 2008

HAVE THE CONDITIONS FOR COOLING EVOLVED?

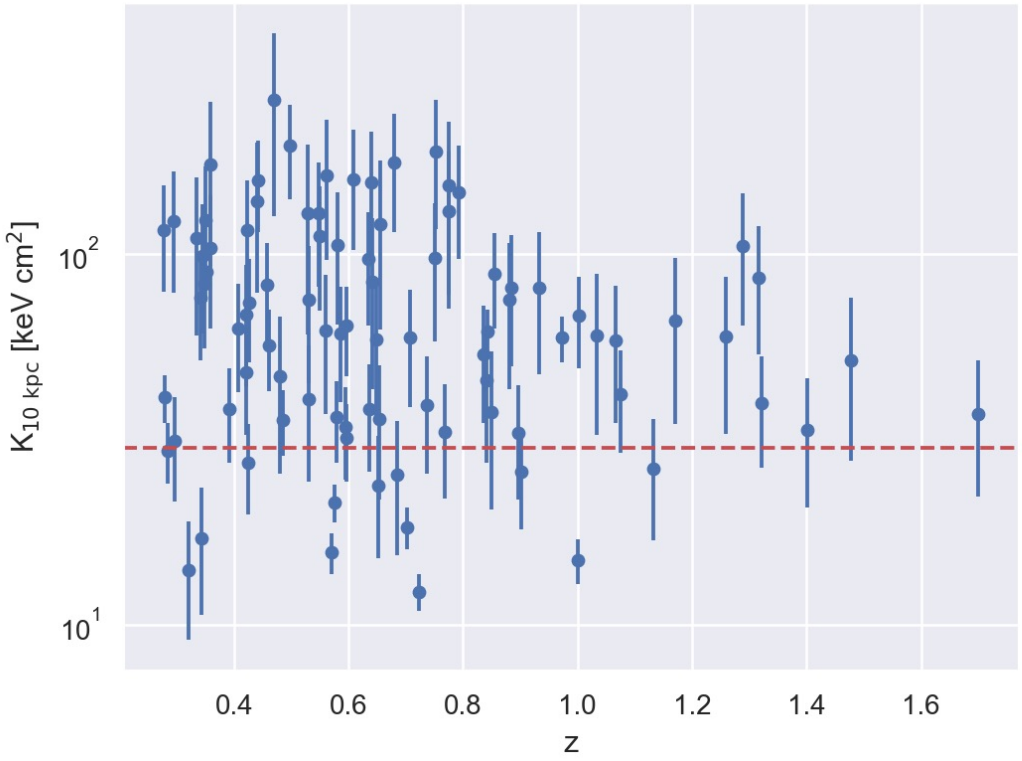


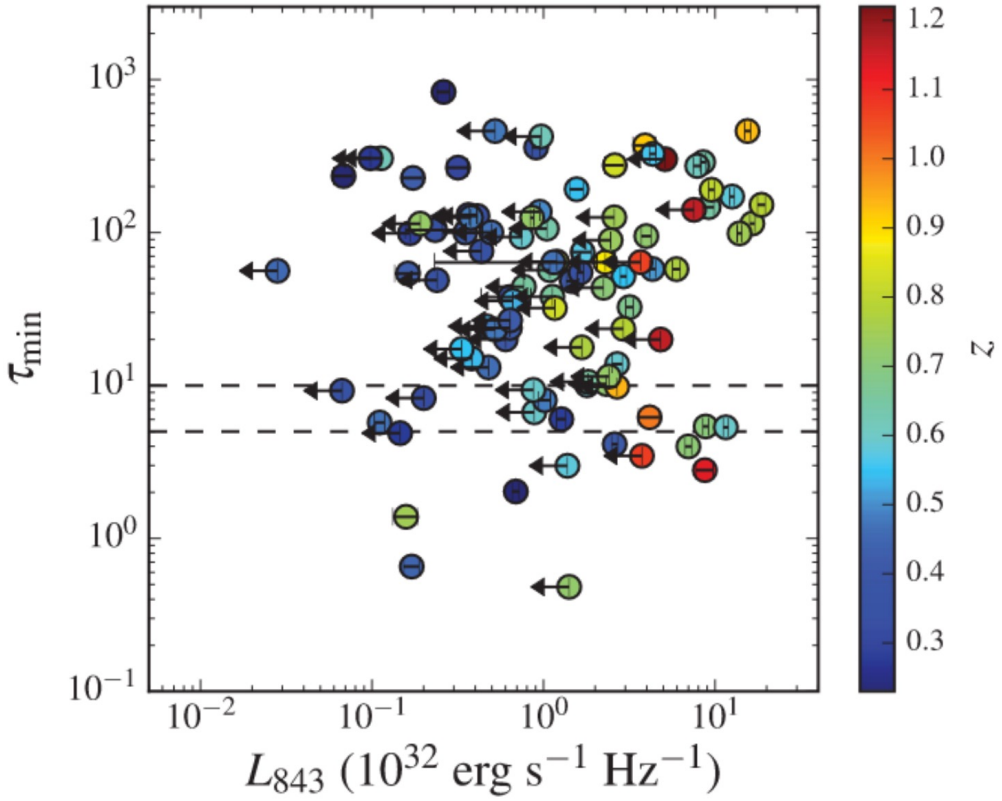


Cavagnolo et al. 2008

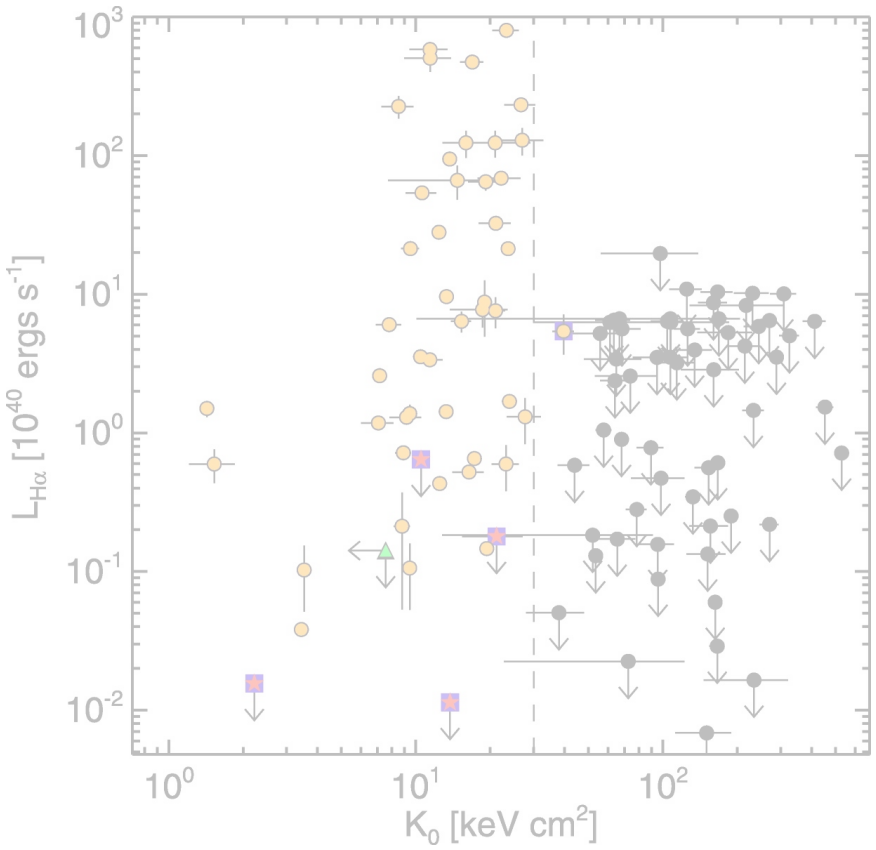
HAVE THE CONDITIONS FOR COOLING EVOLVED?

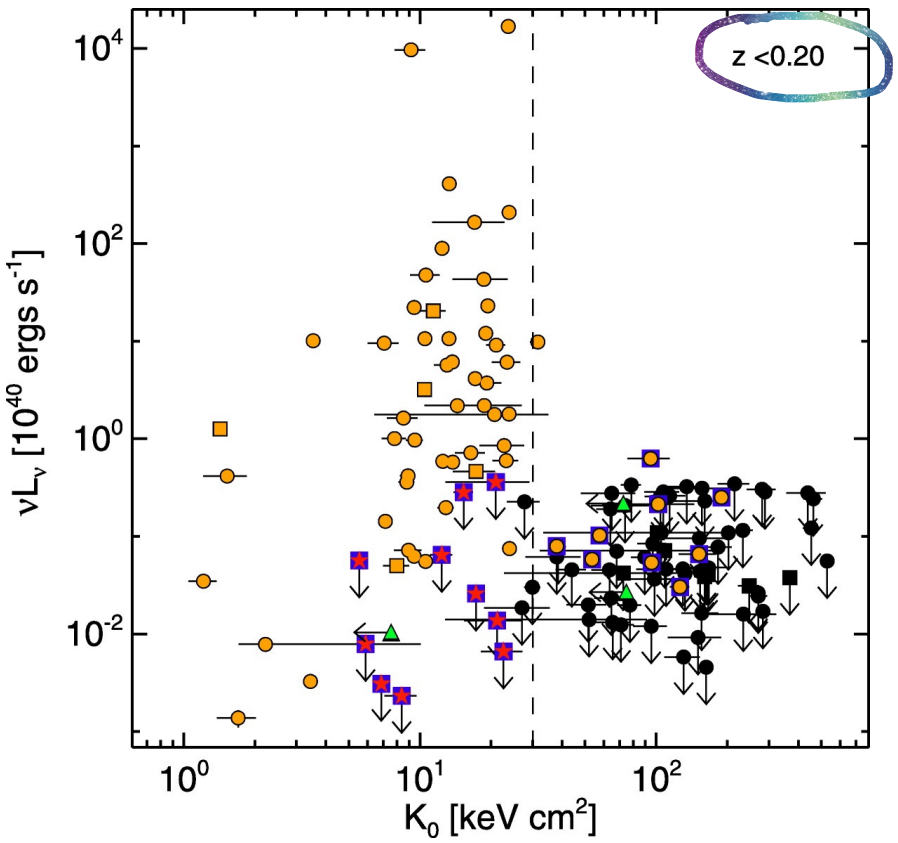
- Has the entropy threshold changed with time?
- Consistent with findings of Birzan+17: no distinction in AGN radio luminosity b/w CC and non-CC





HAVE THE CONDITIONS FOR COOLING EVOLVED?

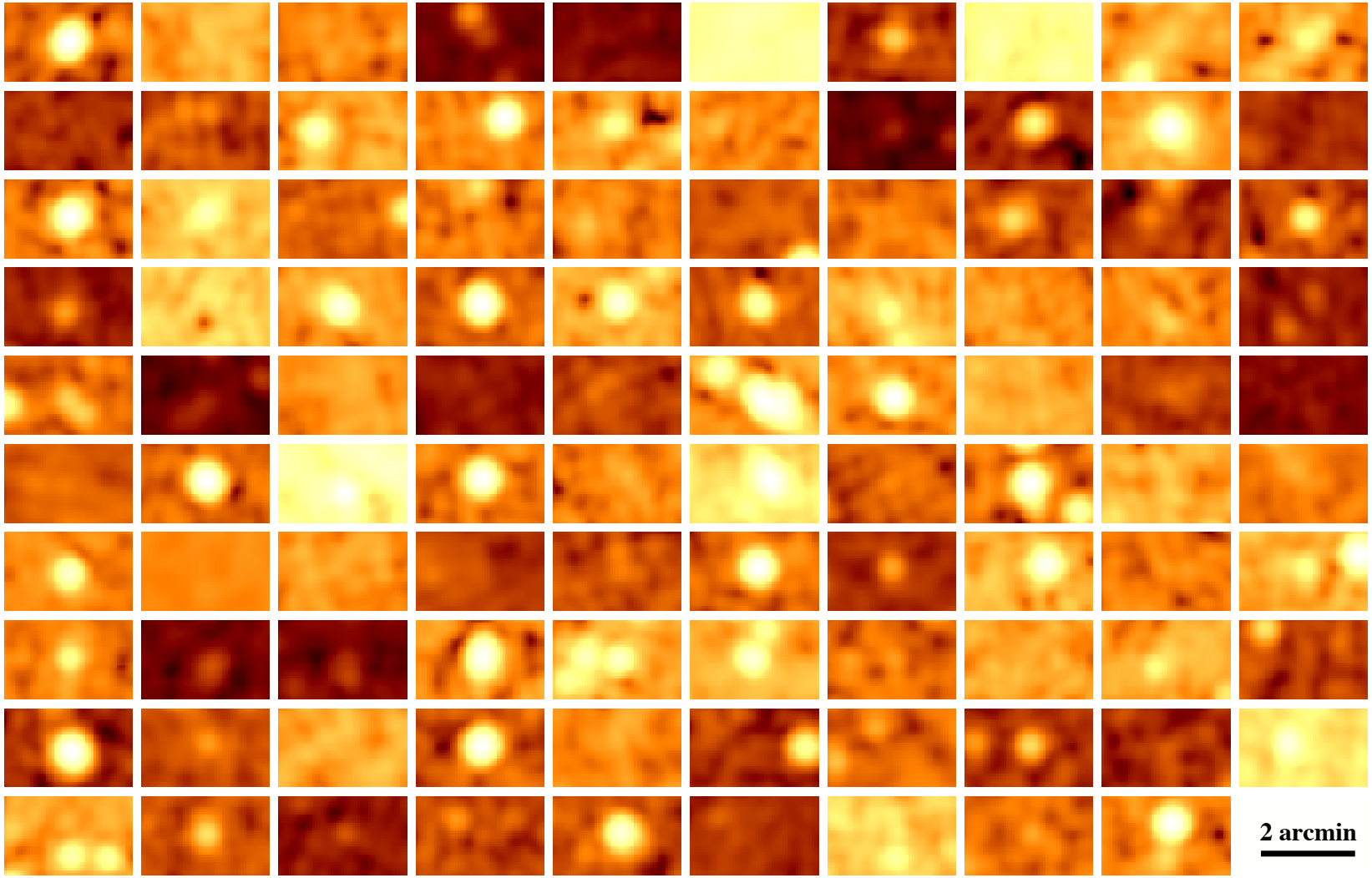




Cavagnolo et al. 2008

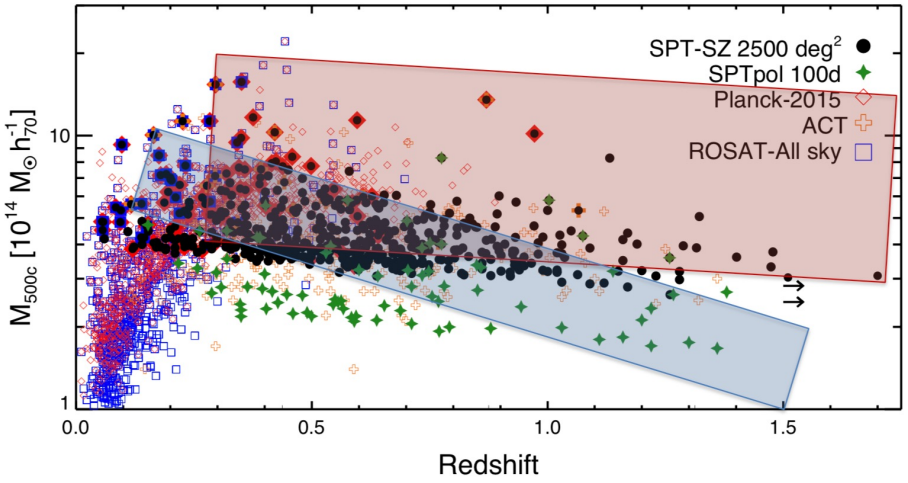
PRELIMINARY RESULTS: RADIO DETECTIONS

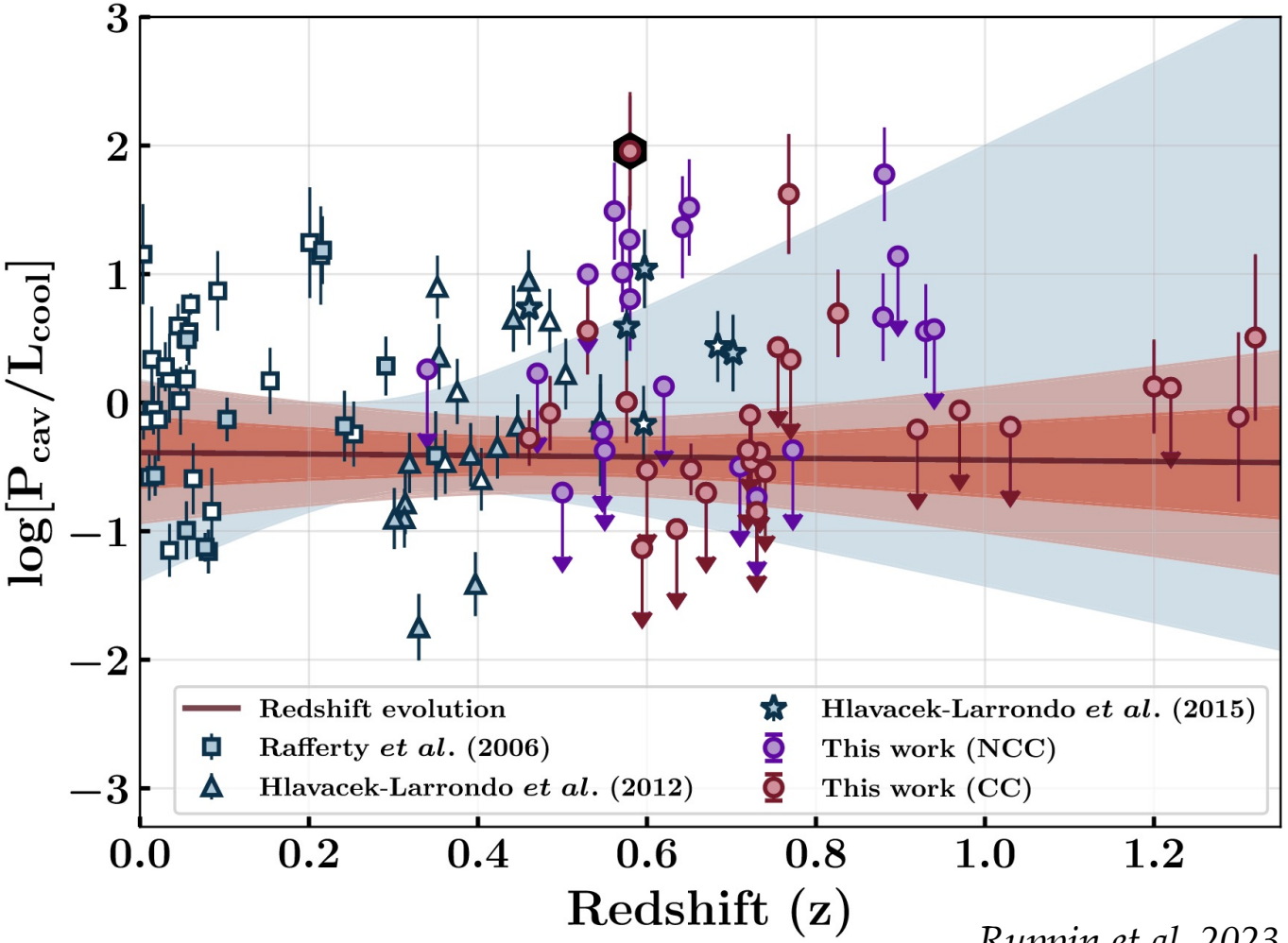
- Uniform ASKAP 0.9 GHz radio data for entire sample from RACS + multi-channel ATCA data



AGN FEEDBACK AS A FUNCTION OF REDSHIFT

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





Ruppin et al. 2023

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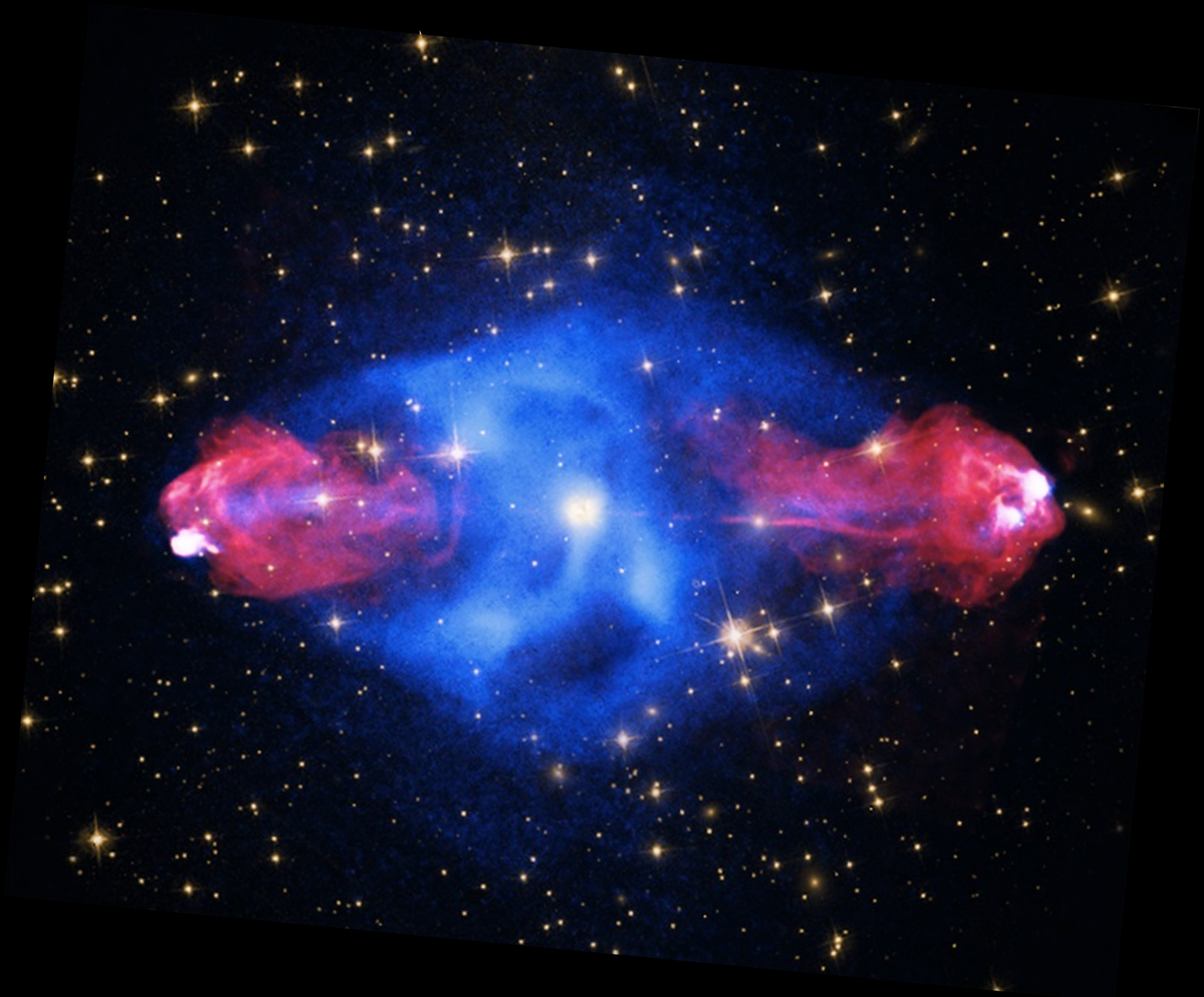
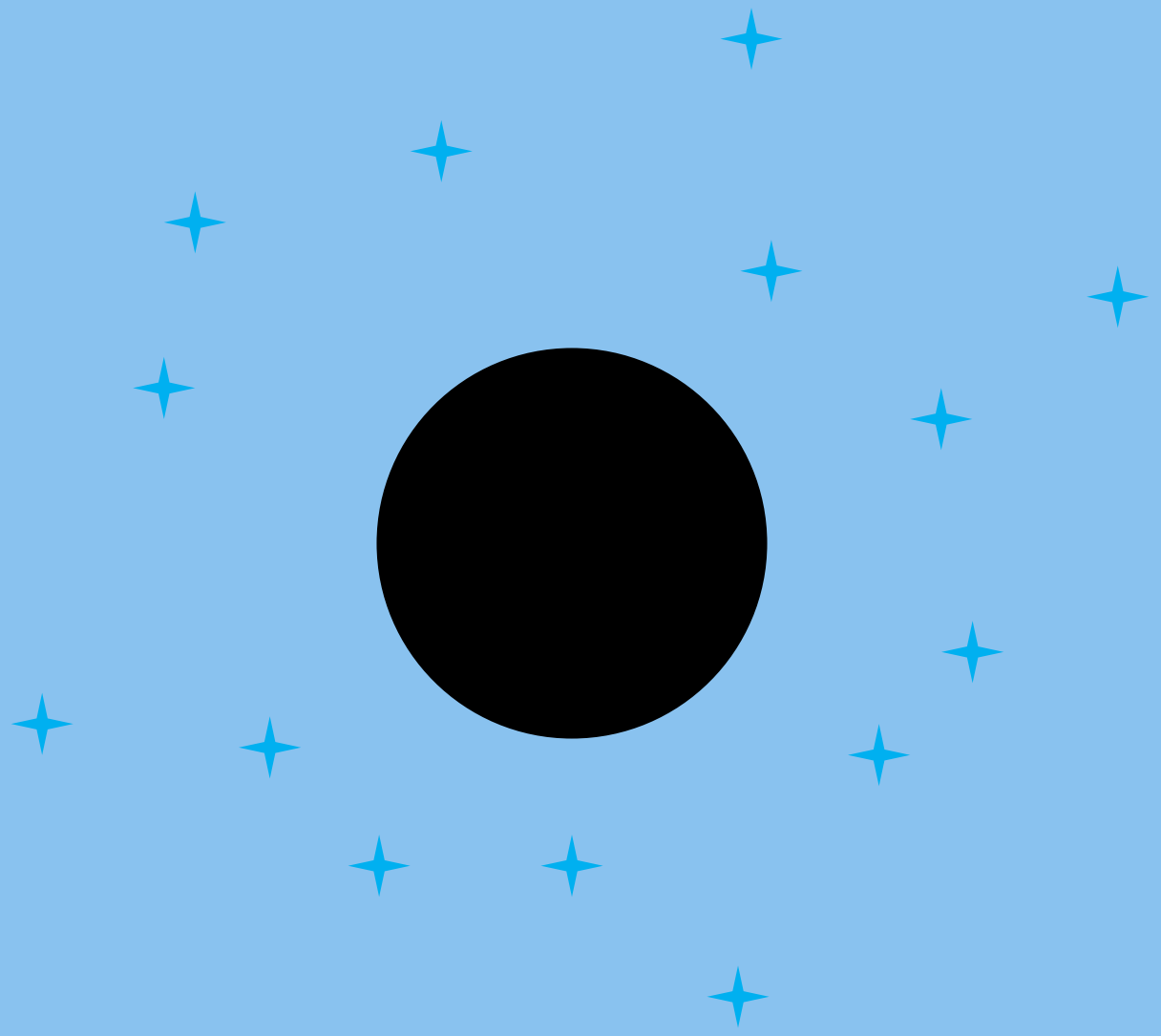
Stay tuned!



THE AGN FEEDBACK CYCLE

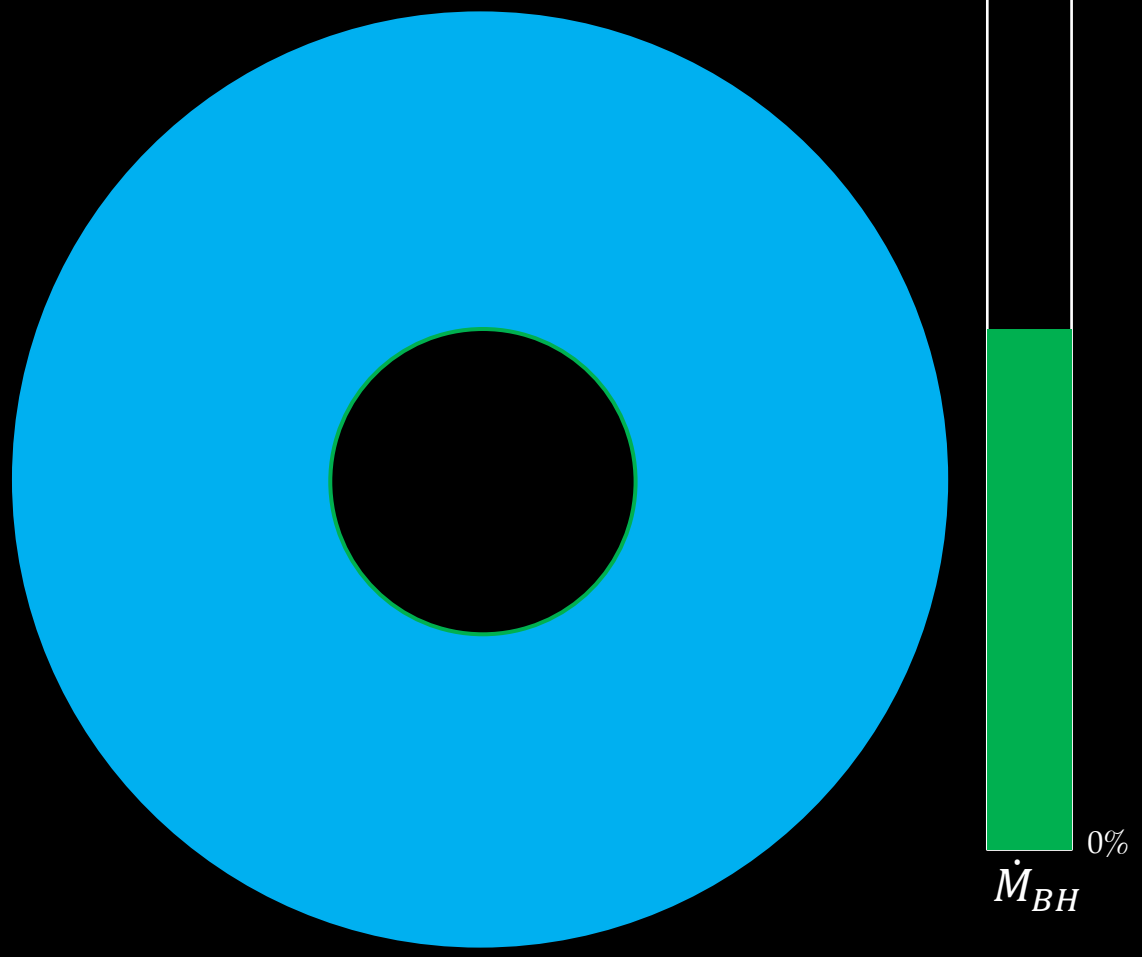


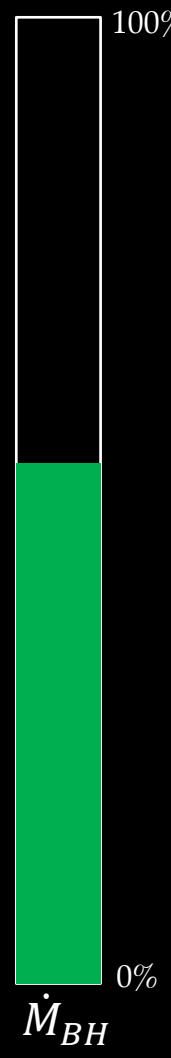
4.3 Black Hole Growth and Feedback in Galaxy Clusters

BH and ICM not to scale

Radio Mode Feedback

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

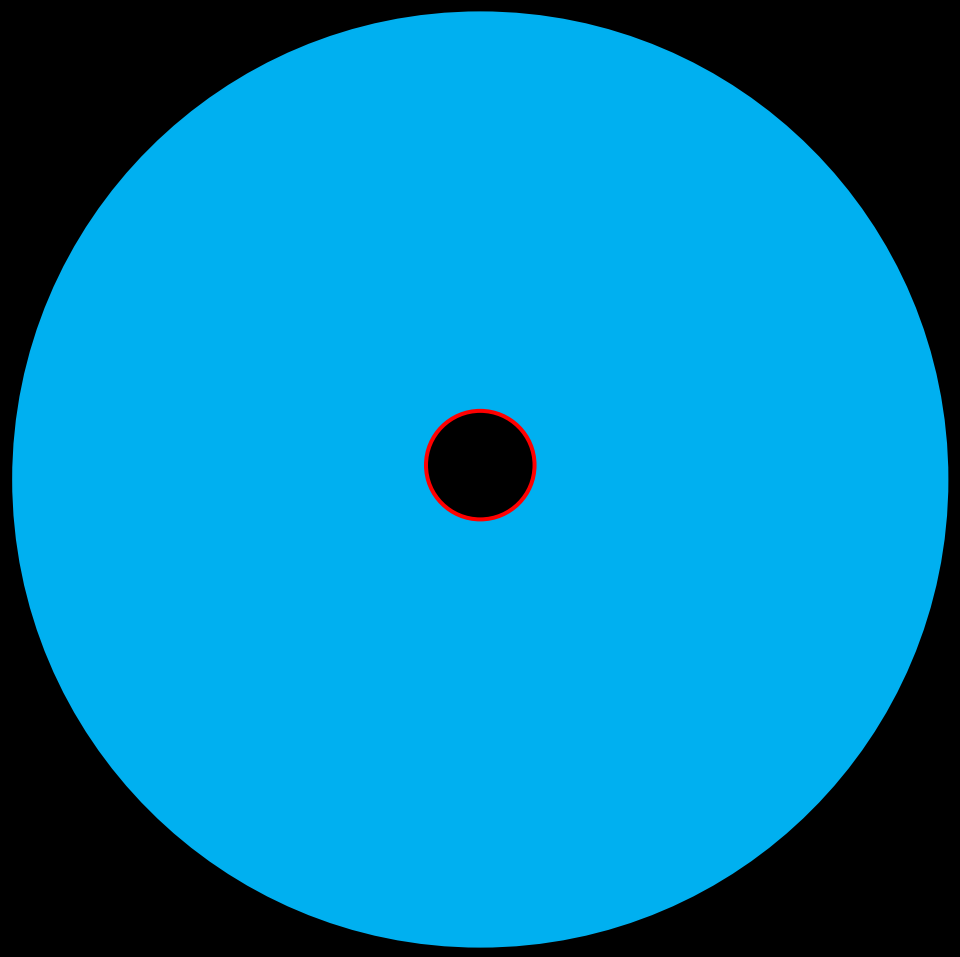


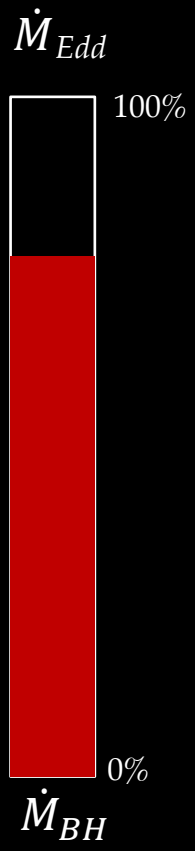


vs

Quasar Mode Feedback

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





Radio Mode Feedback

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

Feedback is jet dominated

More effective at suppressing cooling

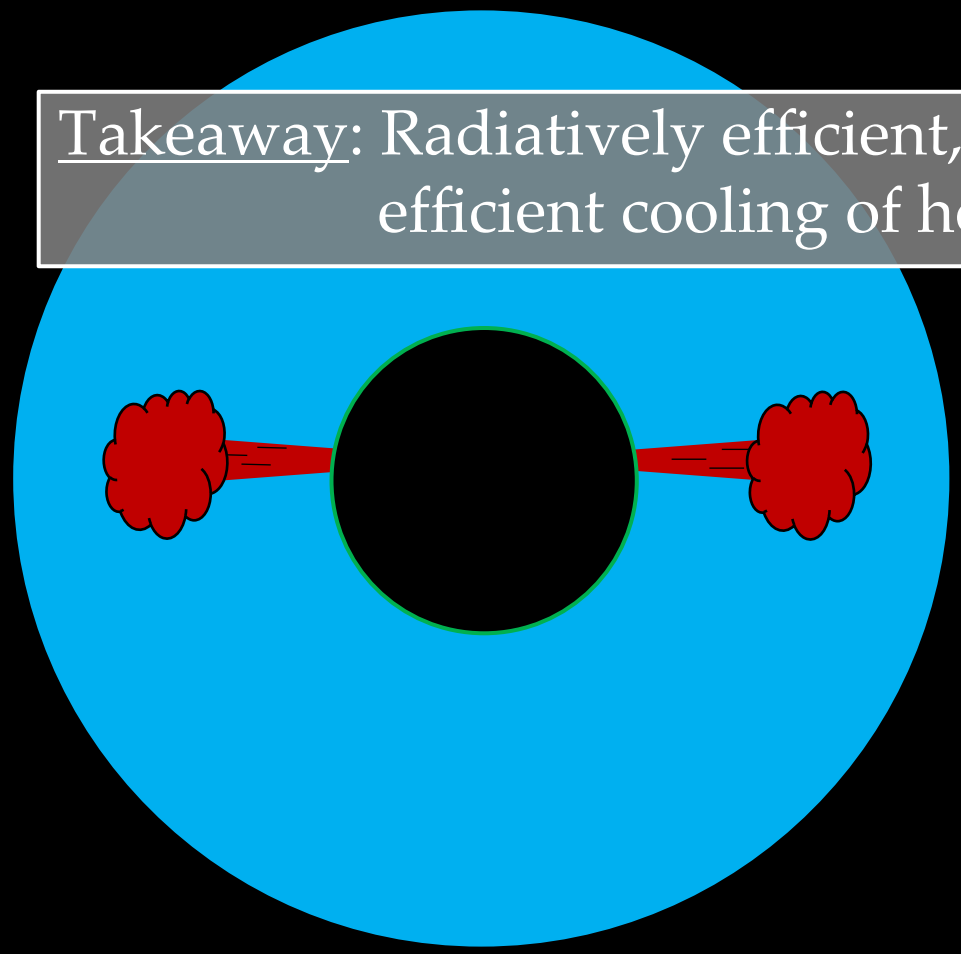
vs

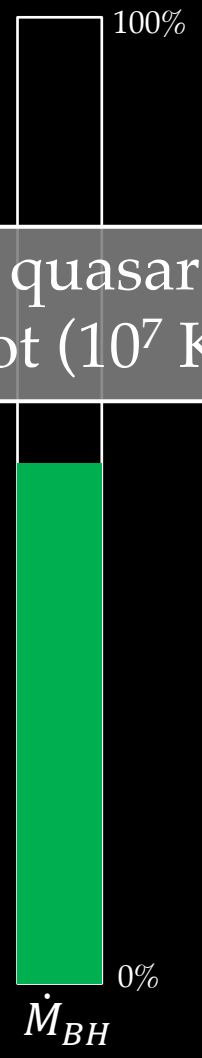
Quasar Mode Feedback

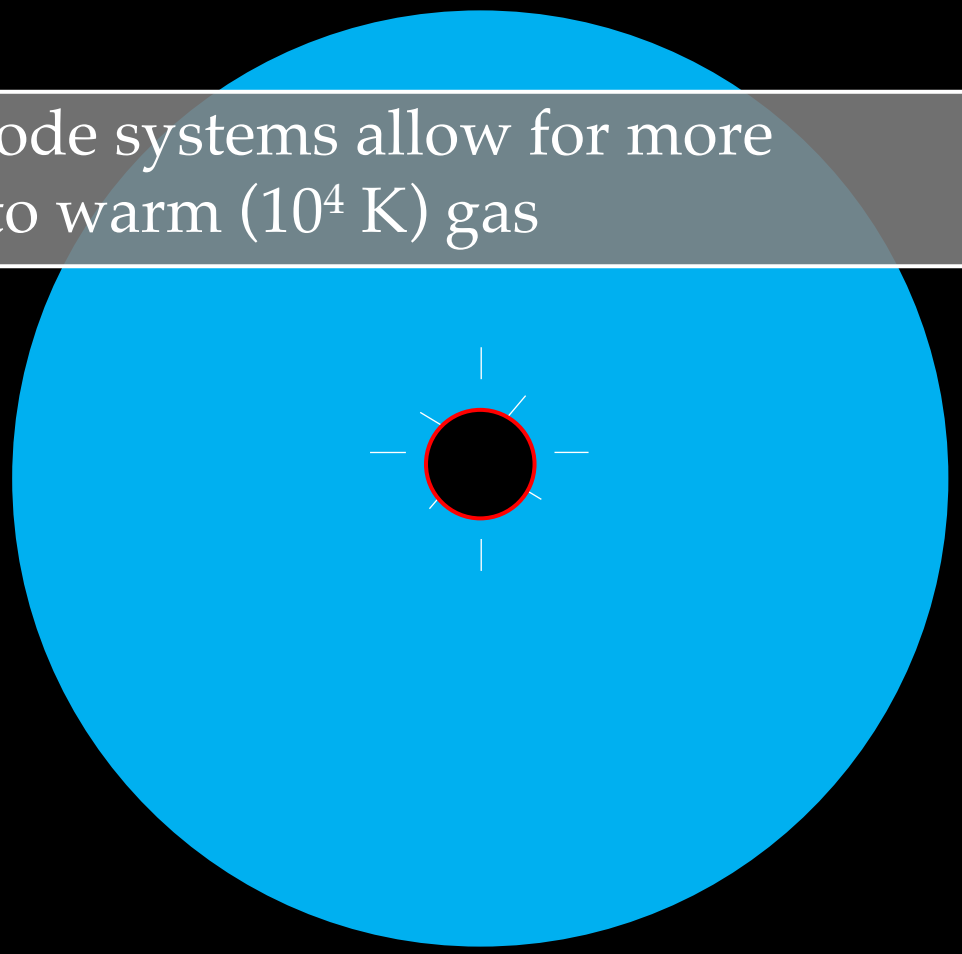
$\dot{M}_{BH} \gtrsim 0.1\,\dot{M}_{Edd}$

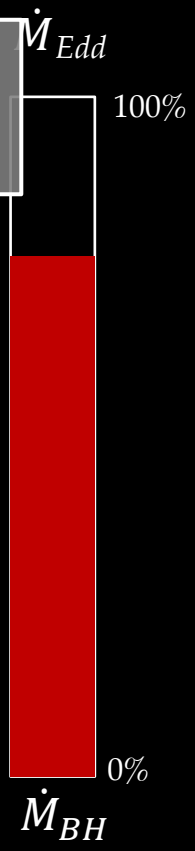
Feedback is radiation dominated

Not as effective at suppressing cooling





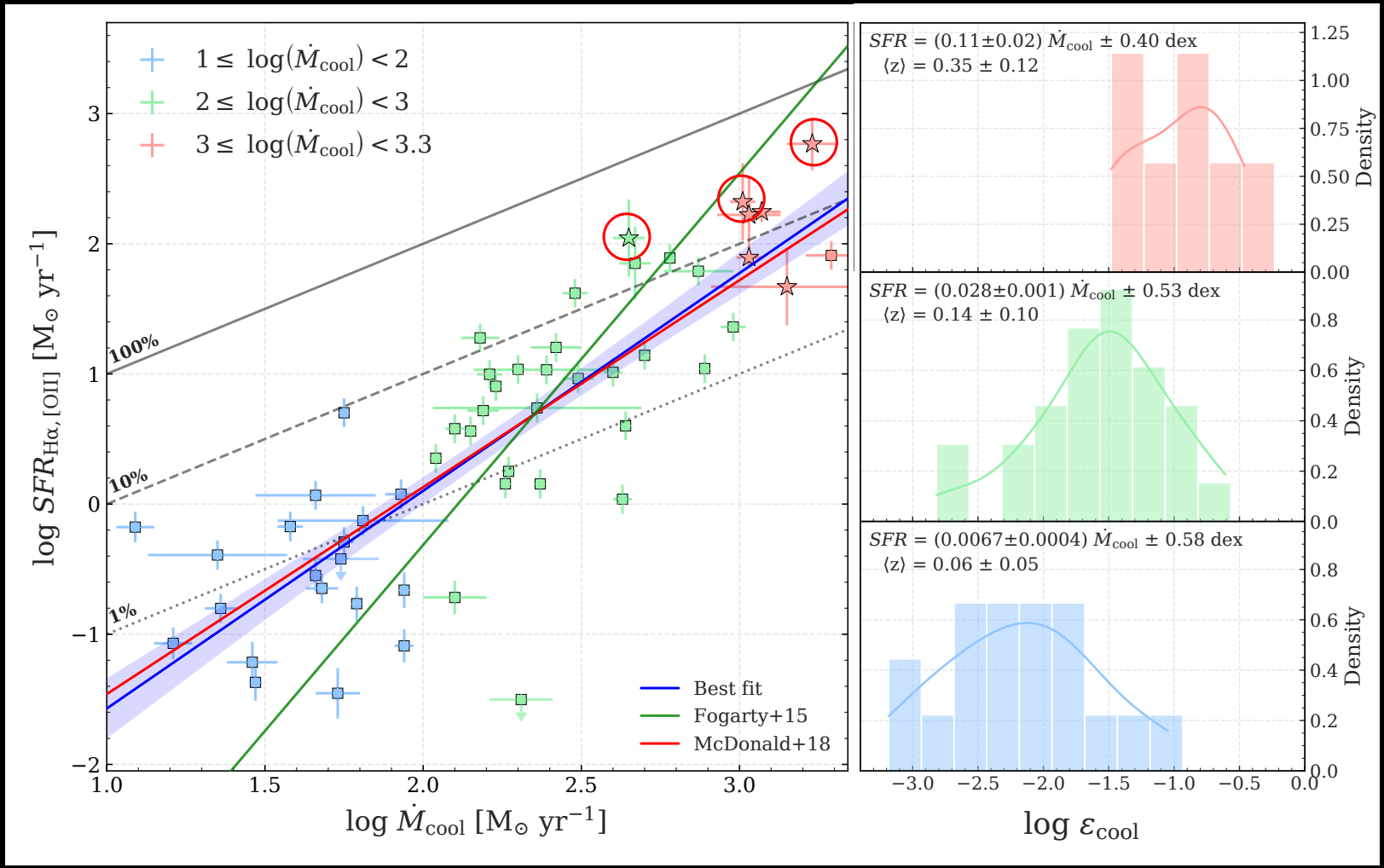




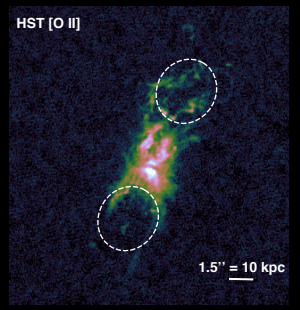
Takeaway: Radiatively efficient, quasar mode systems allow for more efficient cooling of hot (10^7 K) to warm (10^4 K) gas

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

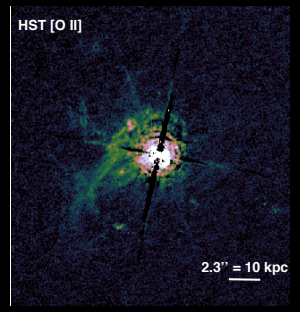
Calzadilla+22



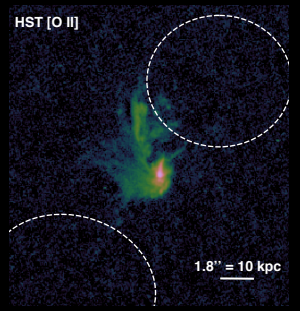
Not a coincidence that our quasar sources are cooling most efficiently



Phoenix



H1821+643



IRAS 09104+4109

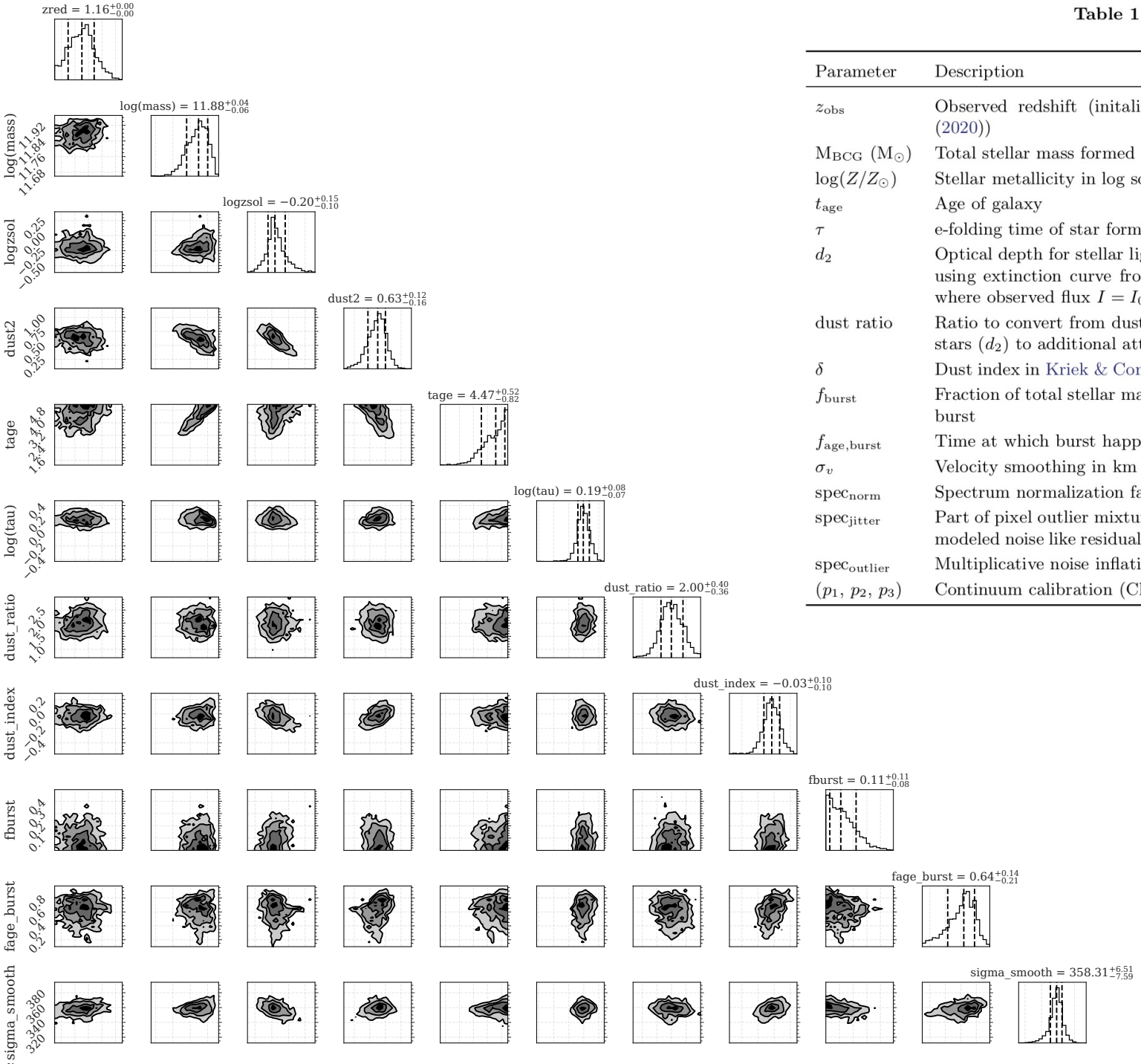
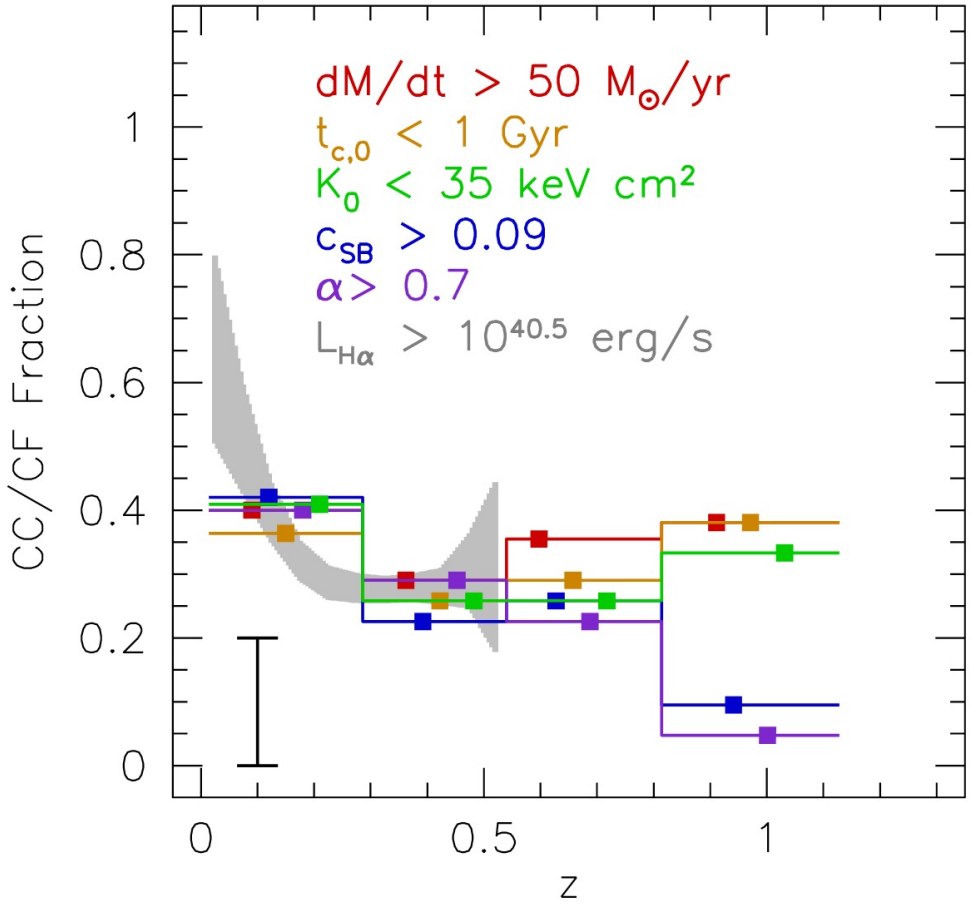
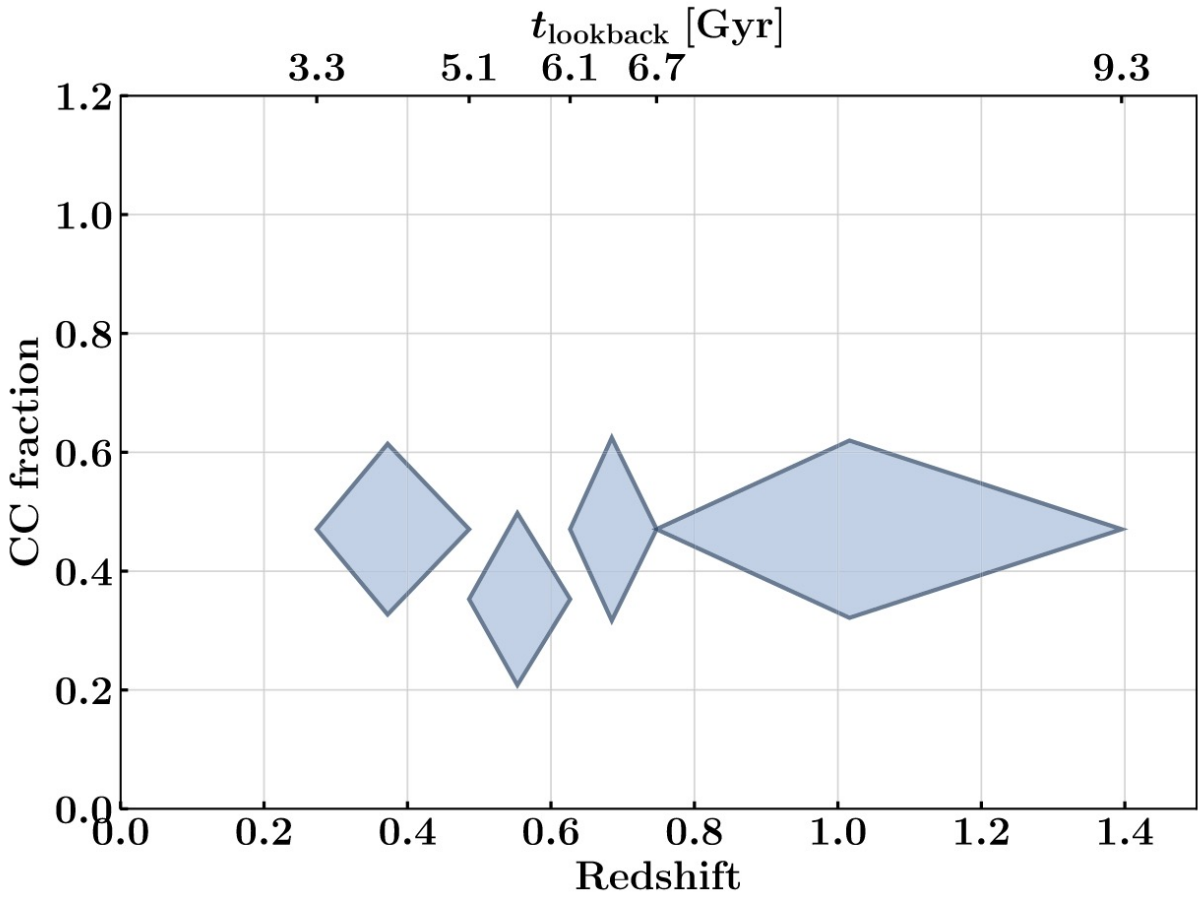


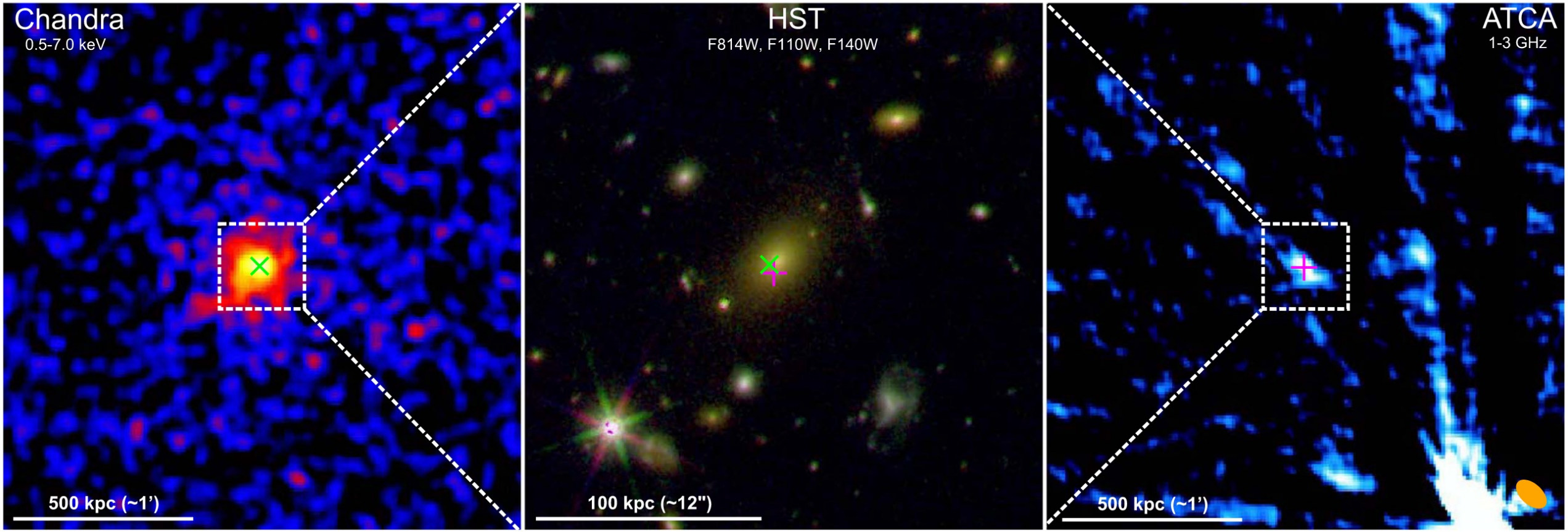
Table 1. Free parameters used in `Prospector` SED fitting

Parameter	Description	Priors
$z_{\rm obs}$	Observed redshift (initalized to mean z from Bleem et al. (2020))	TopHat: $[z-0.001,\, z+0.001]$
$\mathrm{M_{BCG}}$ ($\mathrm{M_\odot}$)	Total stellar mass formed	$\mathrm{Log_{10}}$ uniform: $[10^9, 10^{13}]$
$\log(Z/Z_\odot)$	Stellar metallicity in log solar units	Clipped normal: $\mu = 0.0$, $\sigma = 0.3$, range=$[-2.0, 0.5]$
$t_{\rm age}$	Age of galaxy	TopHat: [0, age of universe at $z_{\rm obs}$]
τ	e-folding time of star formation history in Gyr	$\mathrm{Log_{10}}$ uniform: $[0.01, 3.0]$
d_2	Optical depth for stellar light attenuation by dust for old stars using extinction curve from Kriek & Conroy (2013, eqn. 1), where observed flux $I = I_0 e^{-d_2}$	TopHat: $[0, 20]$
dust ratio	Ratio to convert from dust attenuation optical depth from old stars (d_2) to additional attenuation for young stars	Clipped normal: $\mu = 2.3$, $\sigma = 0.3$, range=$[0, 3.0]$
δ	Dust index in Kriek & Conroy (2013) extinction curve (eqn. 1)	TopHat: $[-2.0, 0.5]$
$f_{\rm burst}$	Fraction of total stellar mass formed in a recent star formation burst	TopHat: $[0, 0.5]$
$f_{\rm age,burst}$	Time at which burst happens, as a fraction of $t_{\rm age}$	TopHat: $[0.1, 1]$
σ_v	Velocity smoothing in km $\mathrm{s^{-1}}$	TopHat: $[150, 500]$
$\mathrm{spec_{norm}}$	Spectrum normalization factor to match photometry	$\mathrm{Log_{10}}$ uniform: $[0.005, 5.0]$
$\mathrm{spec_{jitter}}$	Part of pixel outlier mixture model, to marginalize over poorly modeled noise like residual sky lines or missing absorption lines	TopHat: $[1, 10]$
$\mathrm{spec_{outlier}}$	Multiplicative noise inflation term	TopHat: $[0.0001, 1]$
$(p_1,\, p_2,\, p_3)$	Continuum calibration (Chebyshev) polynomial	TopHat: n=3: $[-0.2/(n+1), 0.2/(n+1)]$


dM/dt > 50 M⊙/yr
t_c,0 < 1 Gyr
K_0 < 35 keV cm²
c_SB > 0.09
α > 0.7
L_Hα > 10^40.5 erg/s
CC/CF Fraction
z
0
0.2
0.4
0.6
0.8
1
0
0.5
1

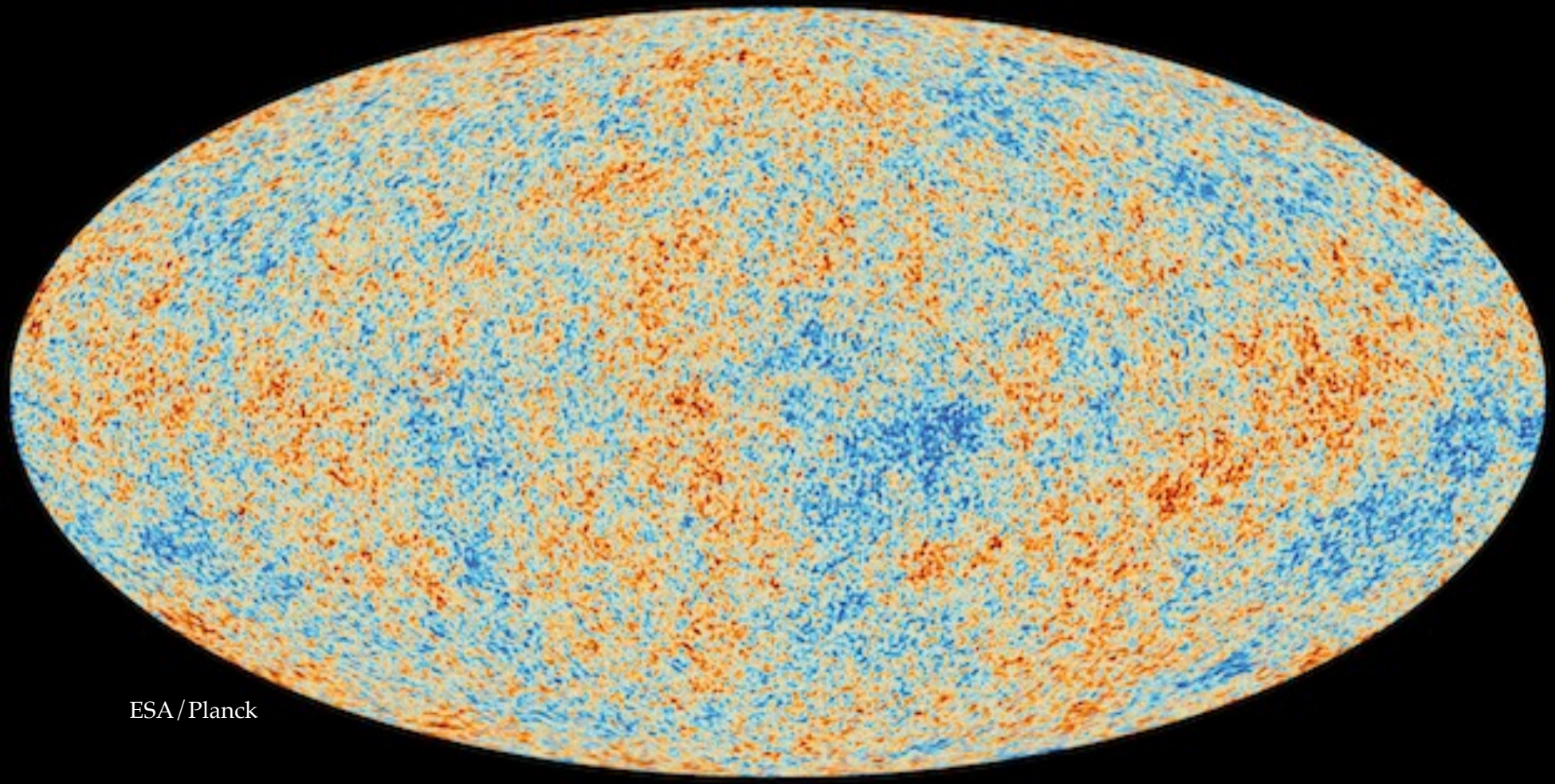

t_lookback [Gyr]
3.3
5.1
6.1
6.7
9.3
CC fraction
Redshift
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

EXTREME COOLING DOESN'T ALWAYS LEAD TO HIGH SFR



Masterson+23

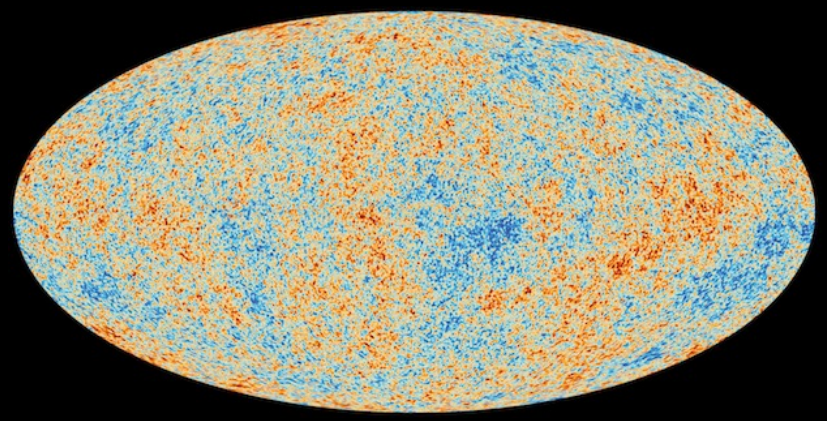
Sunyaev-Zel'dovich (SZ) EFFECT



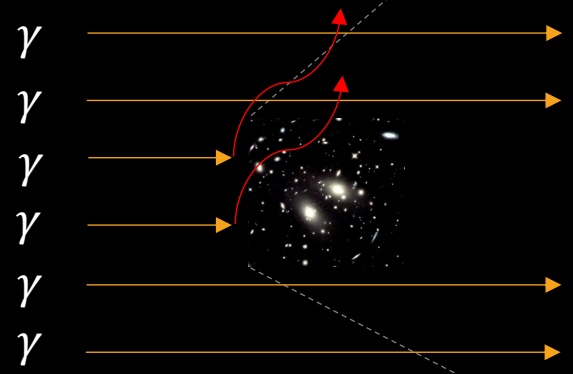
ESA/Planck

Sunyaev-Zel'dovich (SZ) EFFECT

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

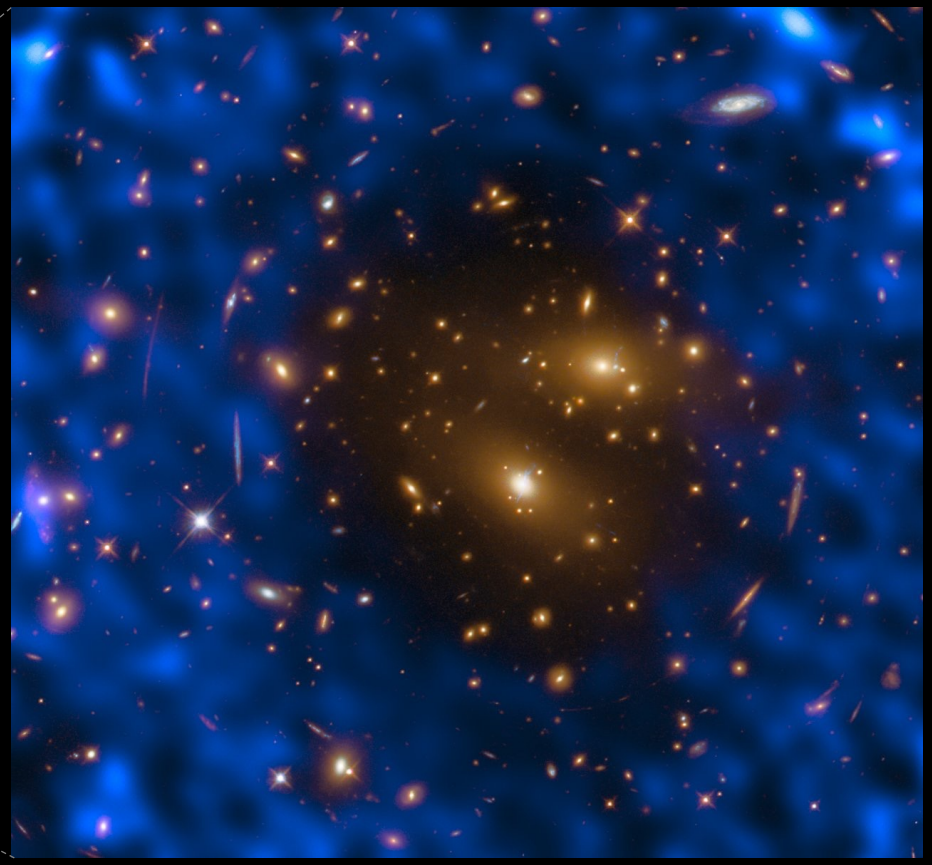


ESA/Planck



z_{CMB}

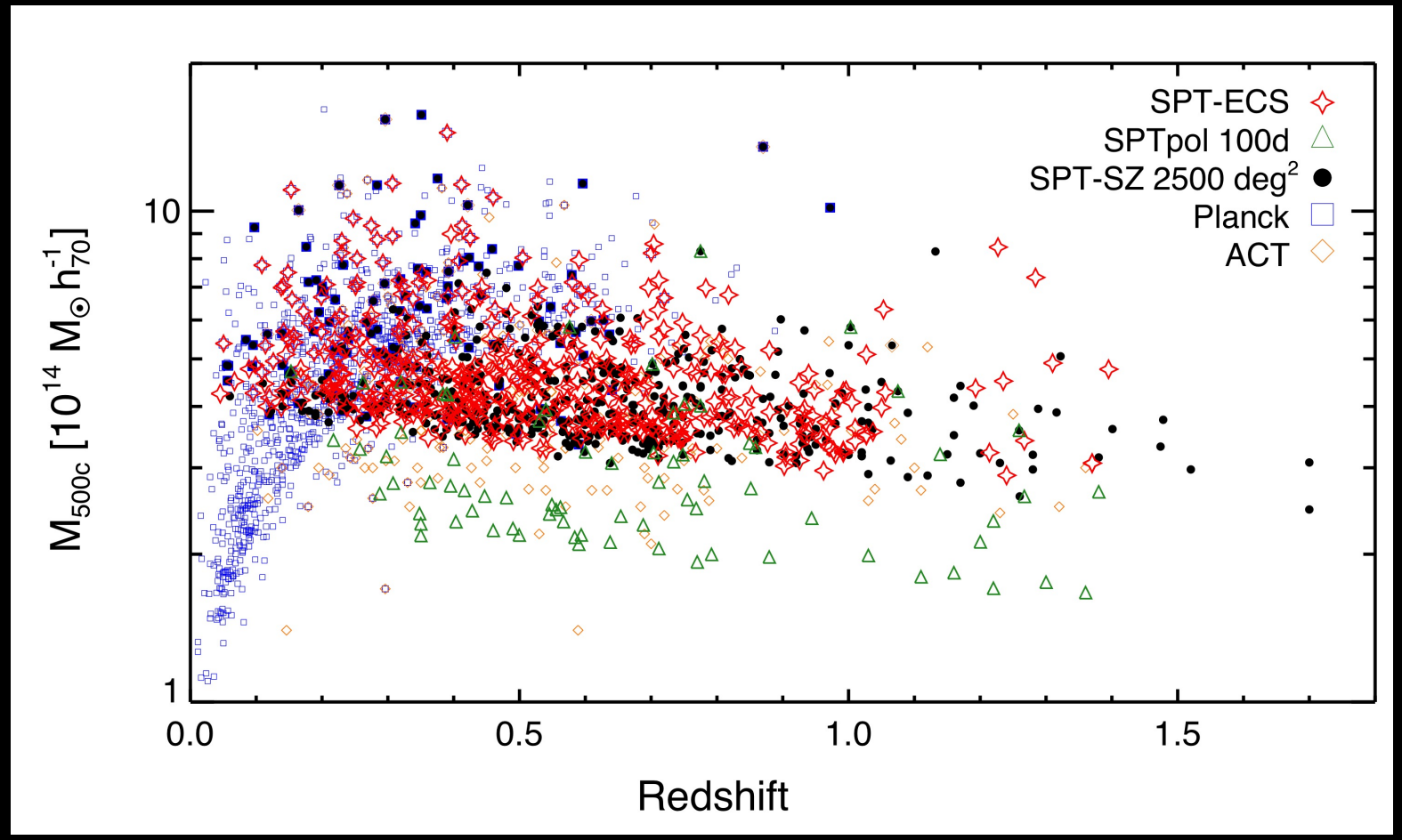
$z = 0$



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

SZ CLUSTER SURVEYS

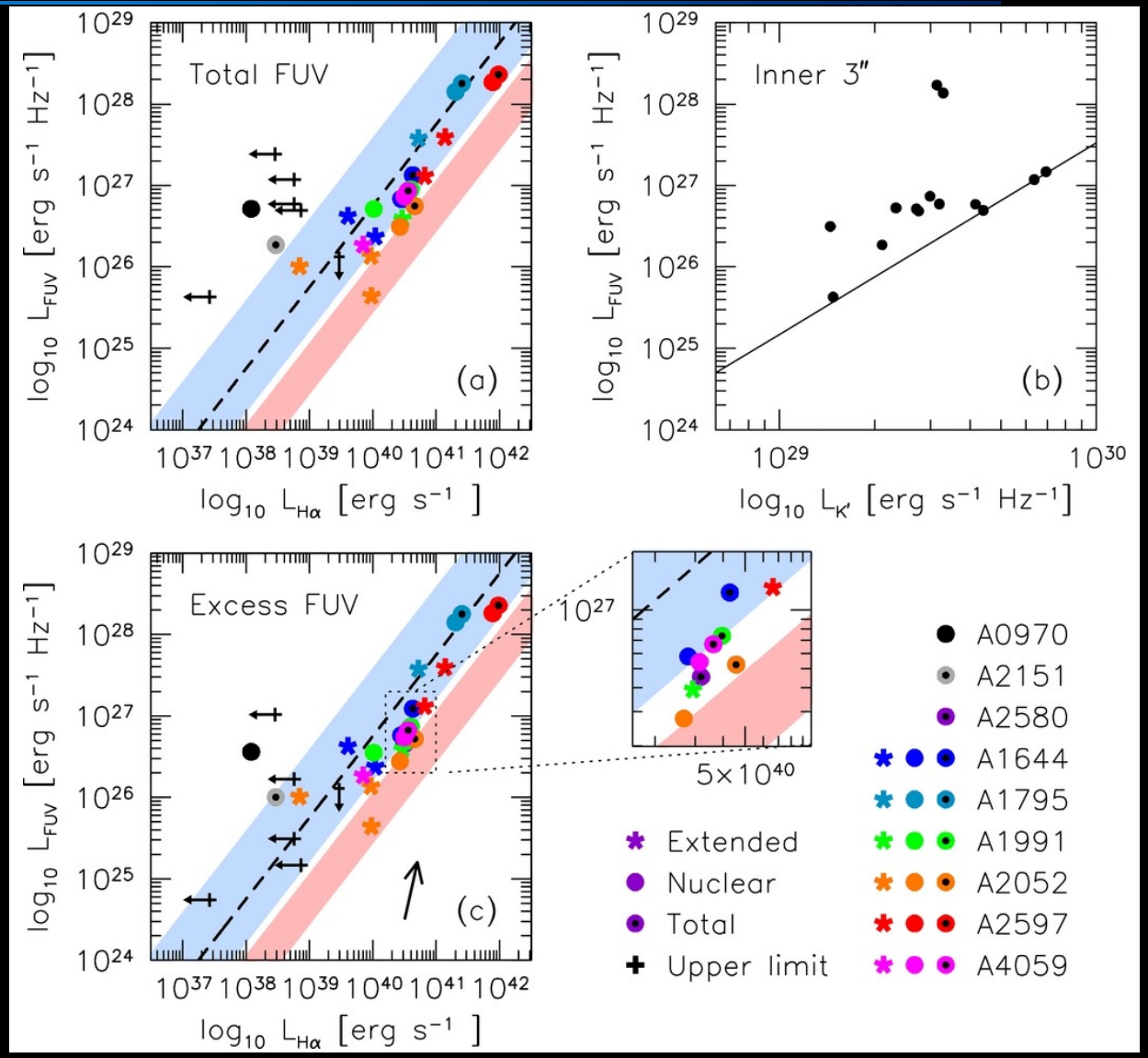
- SPT (Bleem+15,19; Huang+19)
  - SPT-SZ: 539
  - SPTPol: 79
  - SPT-ECS: 448
- Planck Collaboration (13,15,16):
  - 1094 clusters
- ACT (Marriage+11; Hasselfield+13; Hilton+17,21):
  - 220 clusters



Bleem+19

USING [OII] TO MEASURE SFRS

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



McDonald+11