Radio-Mechanical Feedback and the Origins of Galaxy Clusters

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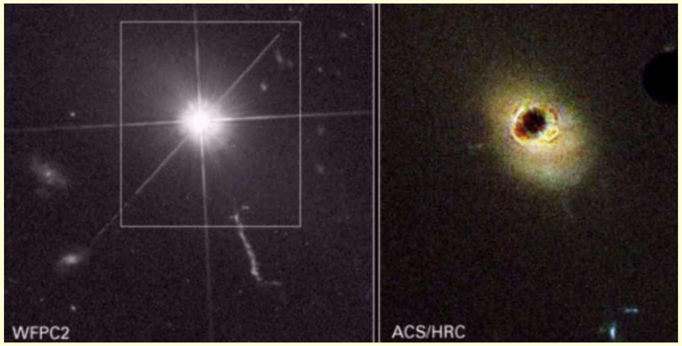
Two topics: 1) Molecular cloud lifting 2) Evolution of CC/NCC
understanding both relies much on simulation

6^{th} ICM Computation Workshop

(wistfully) Copenhagen August 16, 2022

Two types of AGN Feedback

Quasar mode: early universe



winds, radiation
Fast outflows (X-ray), ionized winds, molecular flows

regulate growth of galaxies and SMBHs
M-σ relation
Energy balance: $M_{bh} \sim \sigma^5$ Silk & Rees 98
Momentum: $M_{bh} \sim \sigma^4$ Fabian 99, 12, King 03
Murray + 05

Radio/mechanical mode: Largest most massive, most efficient lifting

Heating & outflows driven by jets & radio bubbles past > 8 Gyr

red and dead galaxies
cosmic “downsizing”
diffuse baryon glut

Both modes presumably operate over the life of a massive galaxy

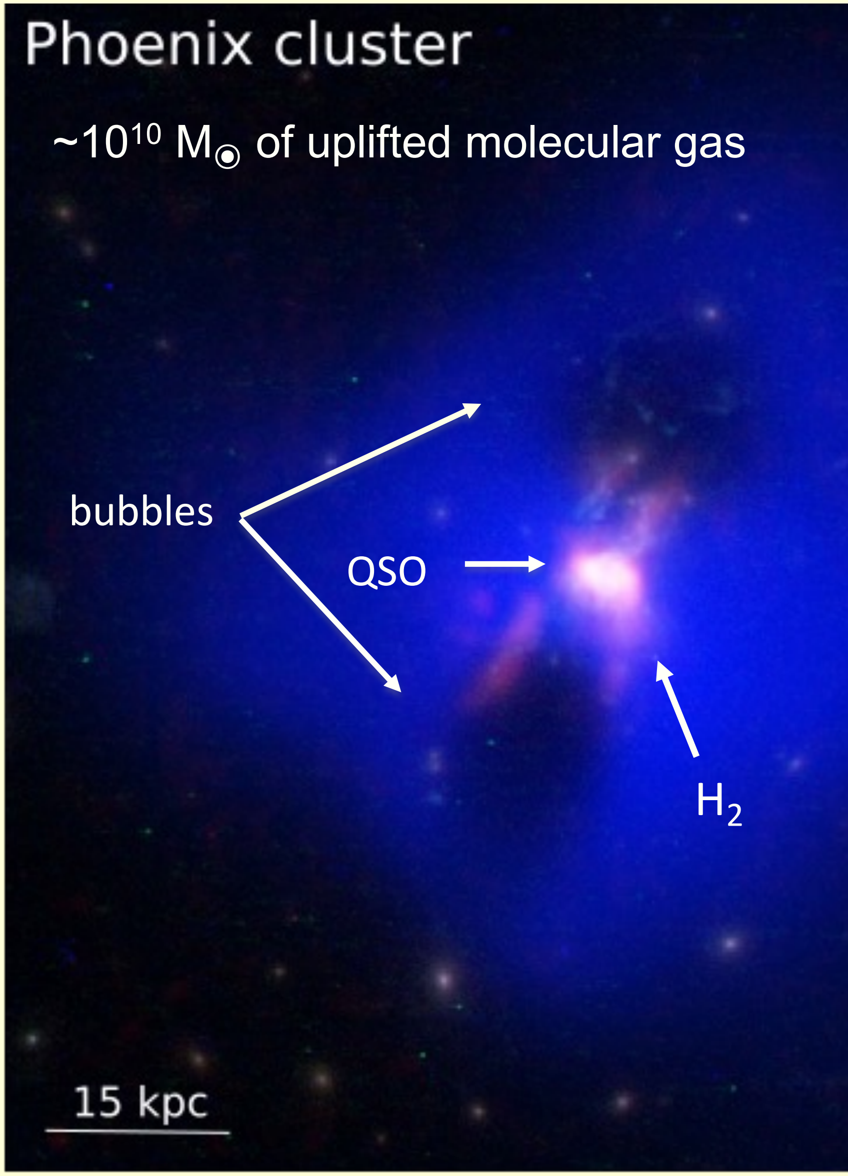
Quasar mode early -- radio/mechanical mode late?

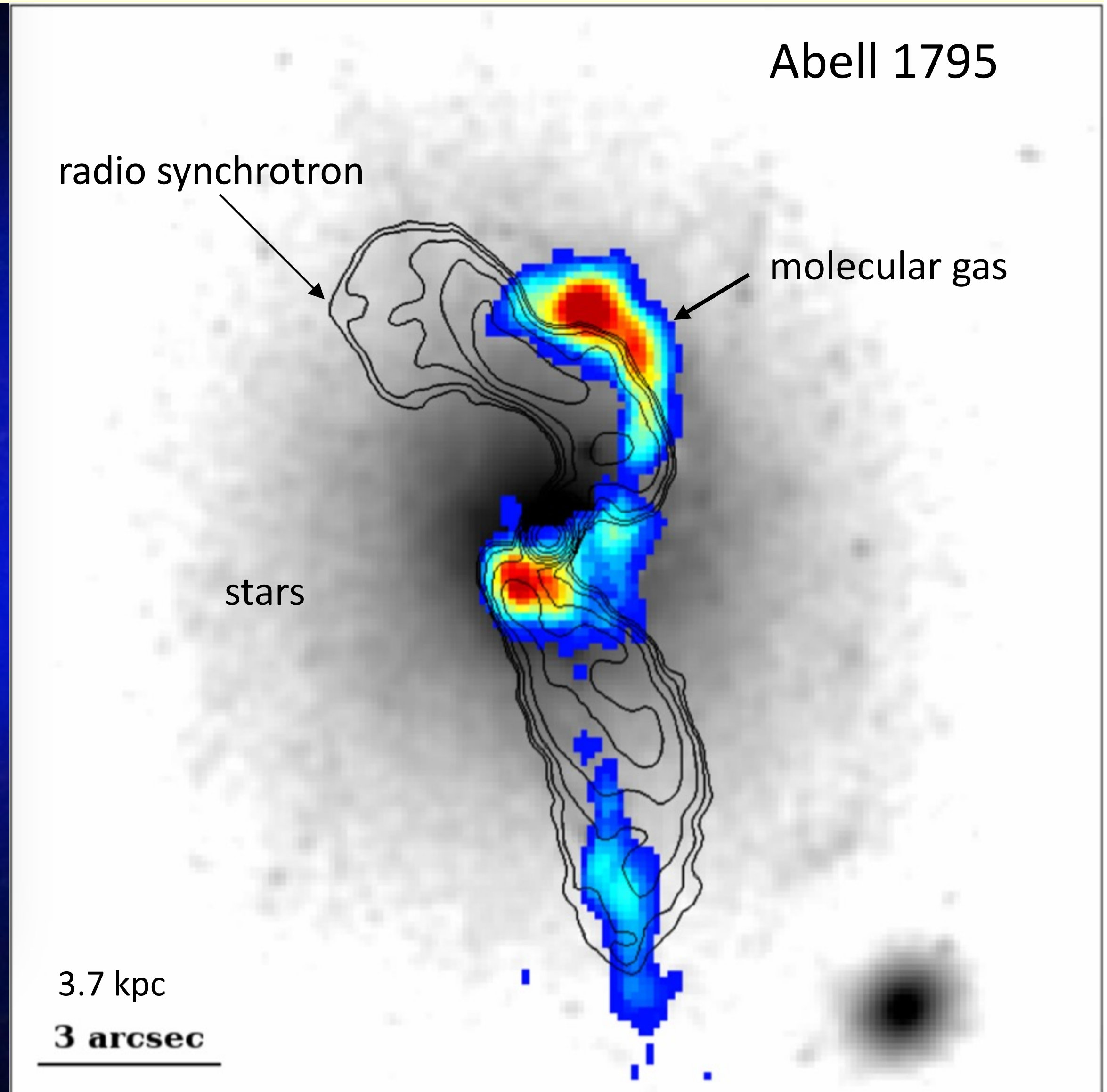
What drives galaxy evolution when radio & QSO mechanisms operate contemporaneously?

Much of what we know relies on difficult simulations

What do observations reveal?

Lifting: Molecular Gas is filamentary, off nucleus, behind radio bubbles





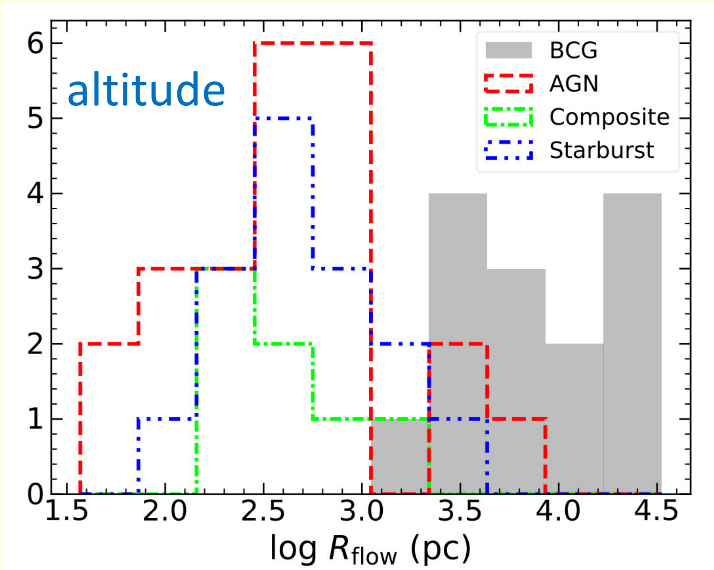
Russell + 17a

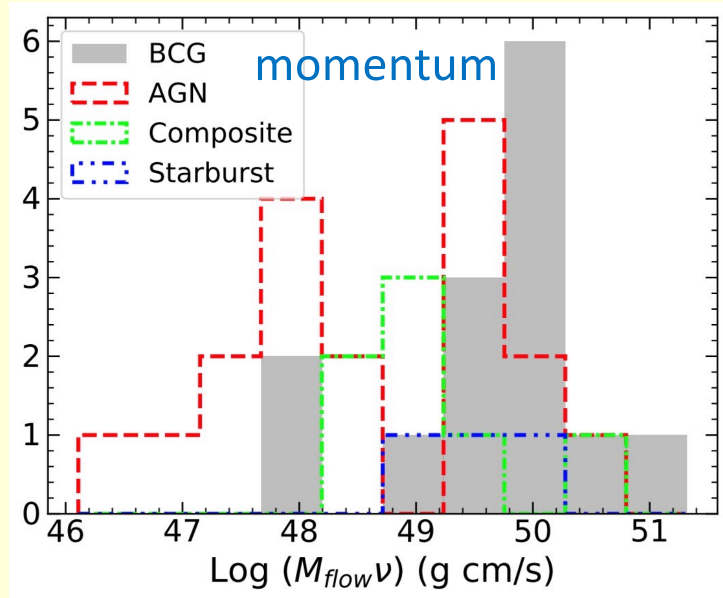
Russell + 19
Olivares + 19

Russell + 17b

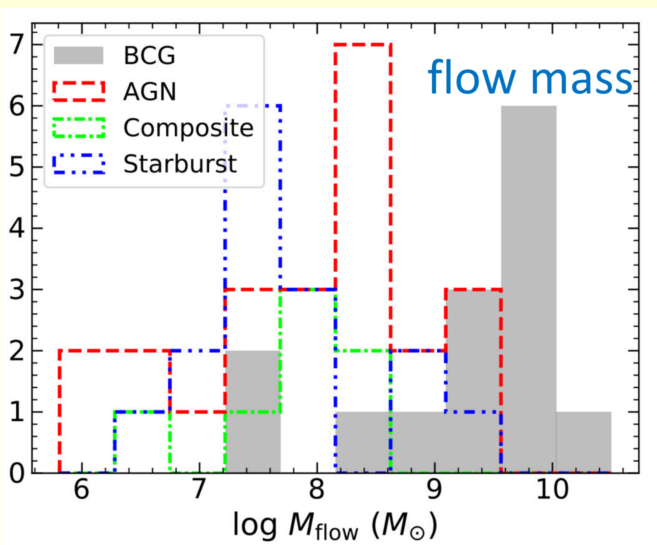
How do Cluster Central RGs Stack up?

AGN=Seyfert/QSO, Composite=Liner, Starburst=H2 galaxies – Fluetsch + 18





Tamhane + 22



High flow masses $>10^9$ $M_{\odot}$

Low flow velocities ~100s km s^{-1}

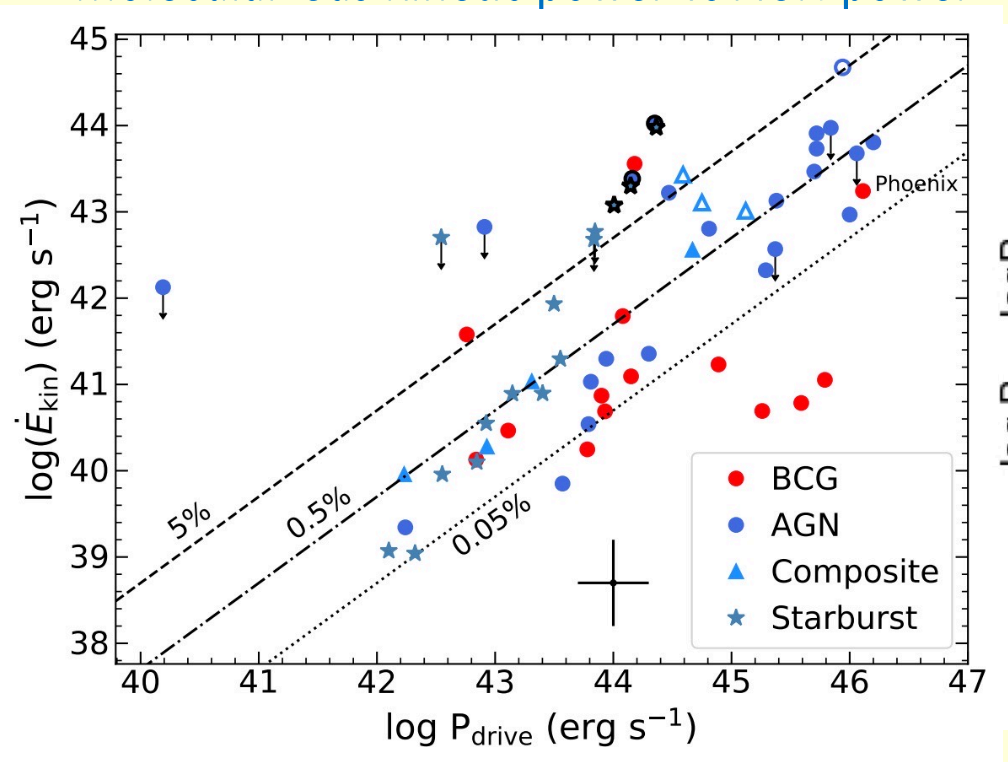
Large flow sizes. ~10 kpc

High Momenta

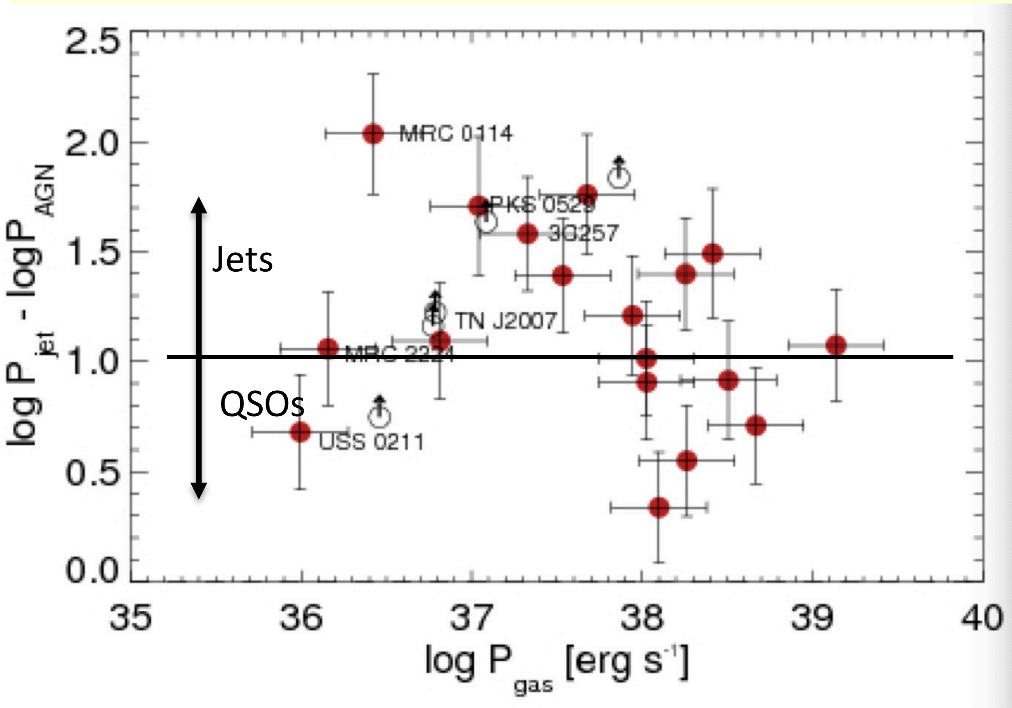
Tamhane + 22, sample: Hogan+17, Pulido+18

How do HZRG/QSO composites compare at z=2-3

Molecular Gas Kinetic power vs AGN power



HZRG/QSO P_{jet}/P_{QSO} vs Gas Momentum



Tamhane+22

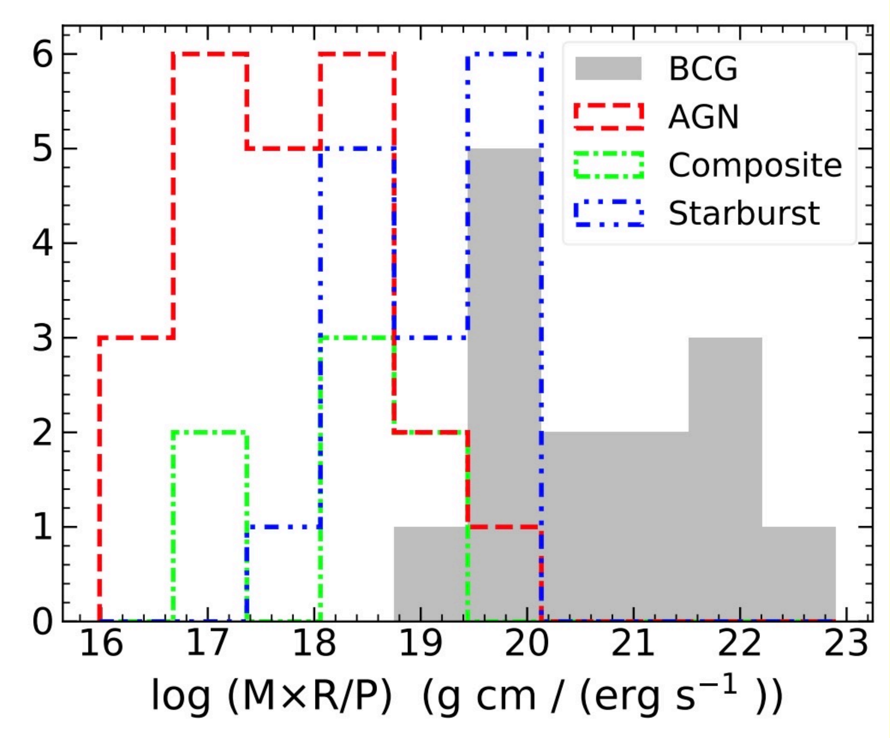
Nesvadba+17
Z=2-3

-less than ~1% AGN power transferred to gas kinetic energy

-jet usually dominates QSO imparting gas momentum in HZRGs (Phoe

Radio-mechanical feedback likely important since early universe
but uncertainties: do all QSOs have jet phase?

Large Lifting Factor – (gas mass x altitude)/driving power



Is gas lifted hot, cold, both?

McNamara+16

Tamhane + 22

Fluetsch + 18

Radio-mechanical feedback far more capable of driving gas away from galaxies in contemporary AGN

Buoyancy, large surface area, large volume in mature atmospheres

Jets capable in HZRGs. How mature are their atmospheres?

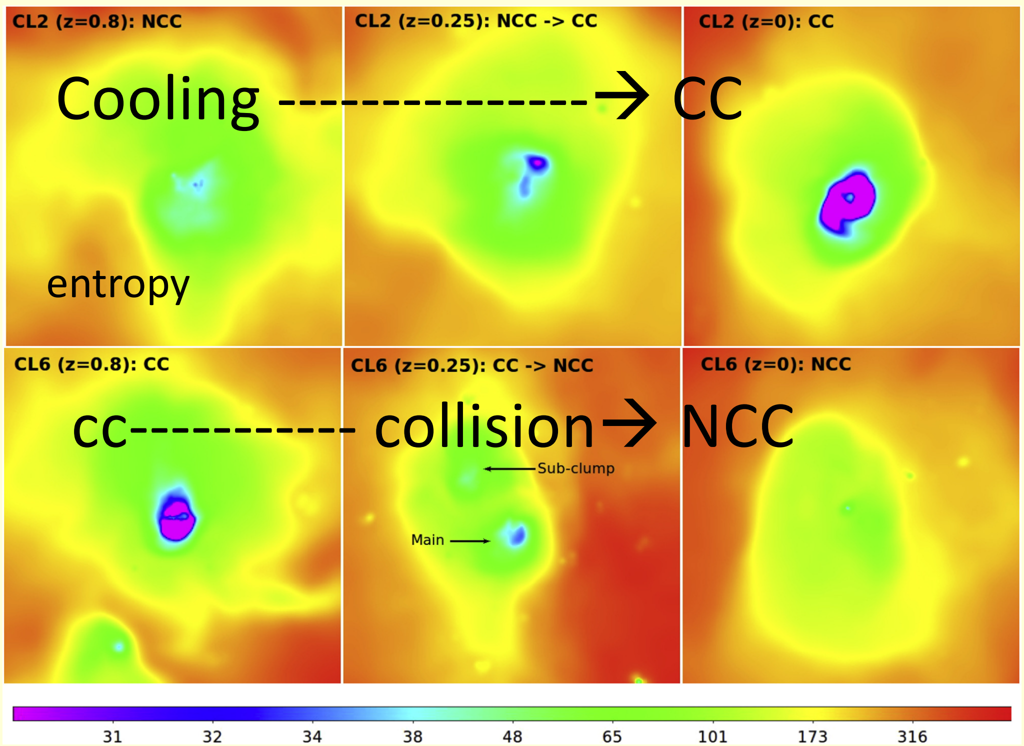
A note on CC/NCC evolution

How did contemporary clusters separate into two types?

-- understanding relies on simulation

Two broad scenarios: mergers or initial conditions

CCs initially followed by low angular momentum mergers destroy CC's => NCC
CC/NCC initially – variations in preheating/pre-enrichment?



Evolution z=0.8-0

Realistic simulations sensitive to:

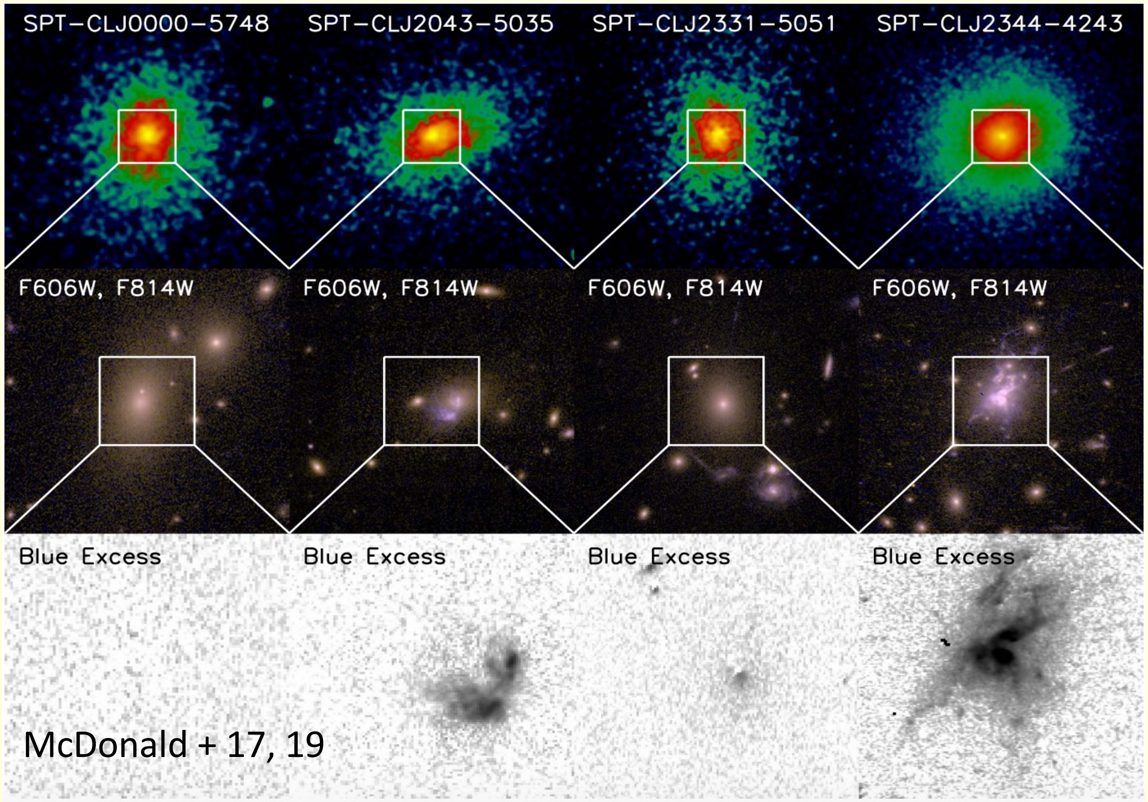
metallicity
preheating/pre-enrichment
feedback Evrard 90, Loewenstein 13

constraints: feedback, cc mass

Rasia +15

Rasia+15, Planelles+14, Hahn+17

Evolution of cool cores from *z=1-0,* or 8 Gyr



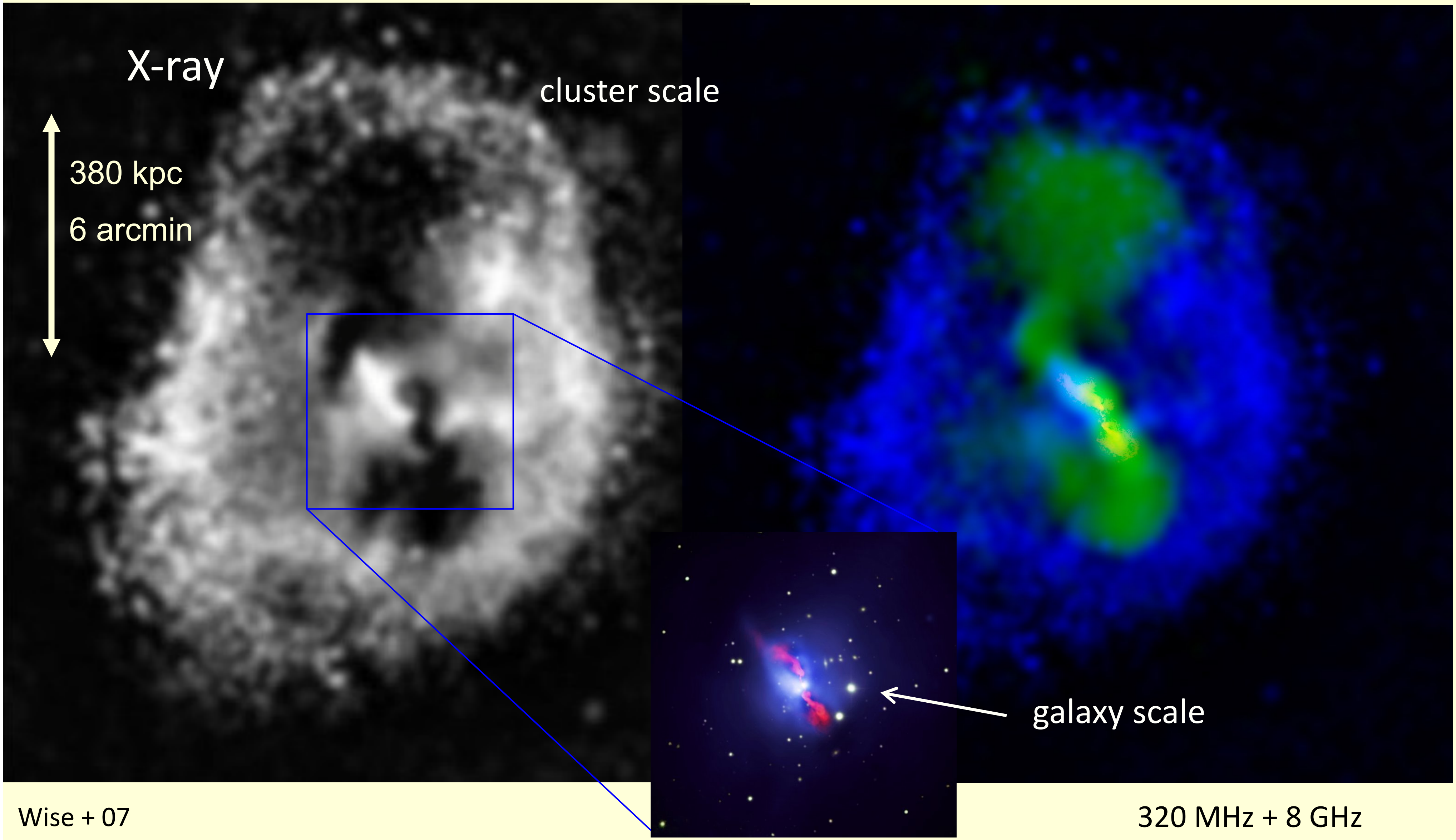
SZ Clusters from the South Pole Telescope

McDonald+13

- CC's cooler by 30% at z=1
- Gas <u>entropy profiles constant</u>, despite time to cool
- CCs growing in time; AGN feedback maintains atmosphere
- Beyond 0.3 R_{500} cluster atmospheres evolve self-similarly

Hydra A Cluster: Jets impact hundreds of kpc

$E_{mech} > 10^{61}$ erg



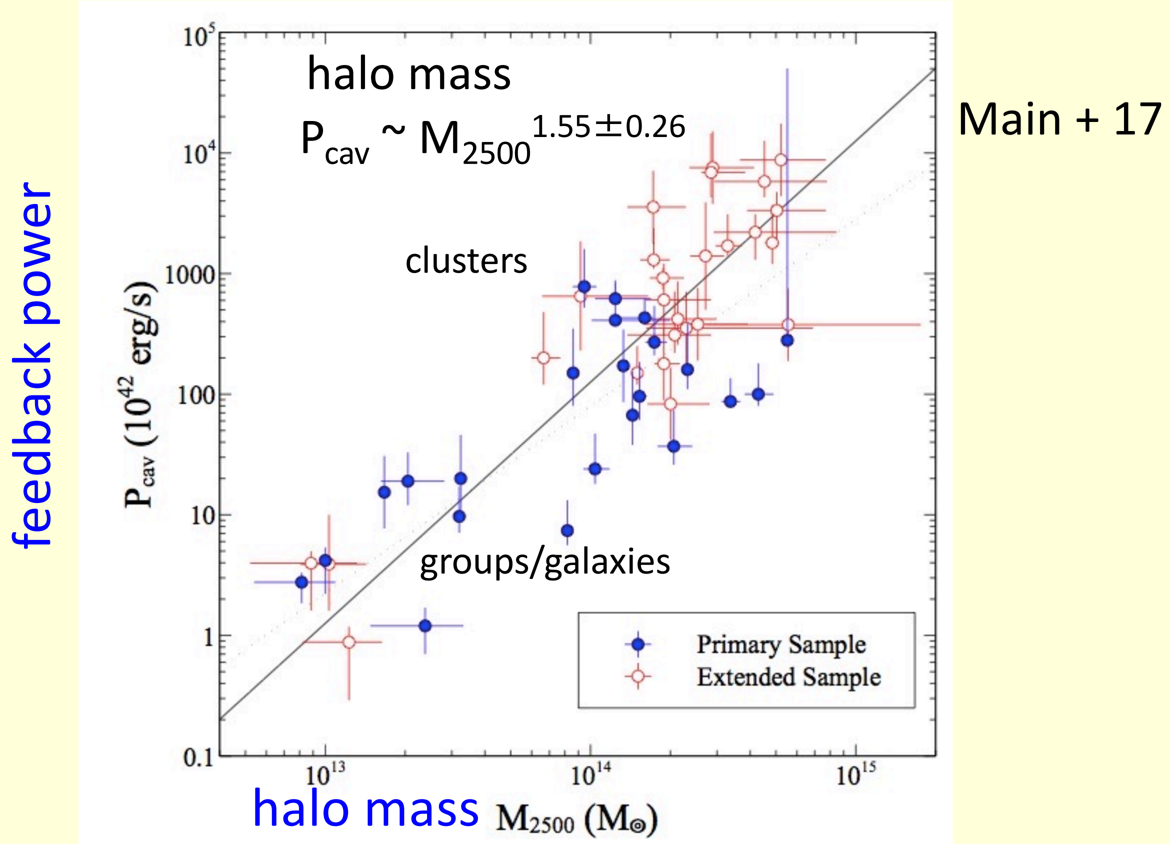
Wise + 07

Nulsen + 05

McN + 00

320 MHz + 8 GHz

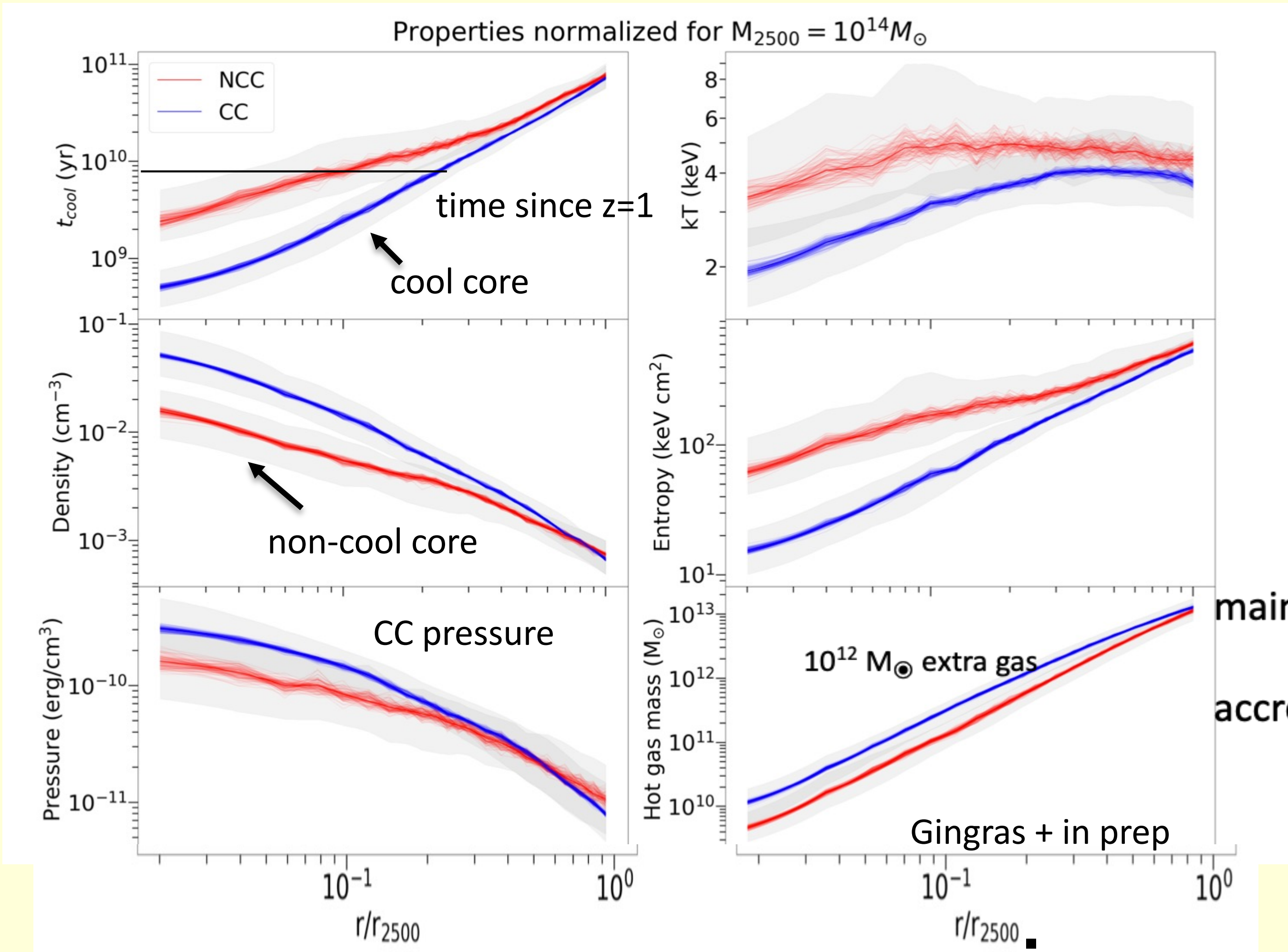
Feedback Power scales with halo mass
when the *central cooling time < 1 Gyr*



Scaling is consistent with M-σ relation: $M \sim \sigma^5$
assuming $P_{jet} \sim L_{cool} \sim M^{1.75}$, *and assuming jets powered by feedback*

Trend vanishes in halos with central cooling times ≥ 1 Gyr
cooling time/entropy instability threshold– Cold Accretion

Cluster Atmospheres: Two thermodynamic classes



CC-feedback active

NCC-feedback minimal

← Entropy

maintained by feedback
since z~1
accreted ~10^{12} $M_\odot$ extra gas

-- *Preliminary* result: M_{gas} (CC) ~0.01 M_{2500} Implies M~ 130 $M_\odot$ yr^{-1}

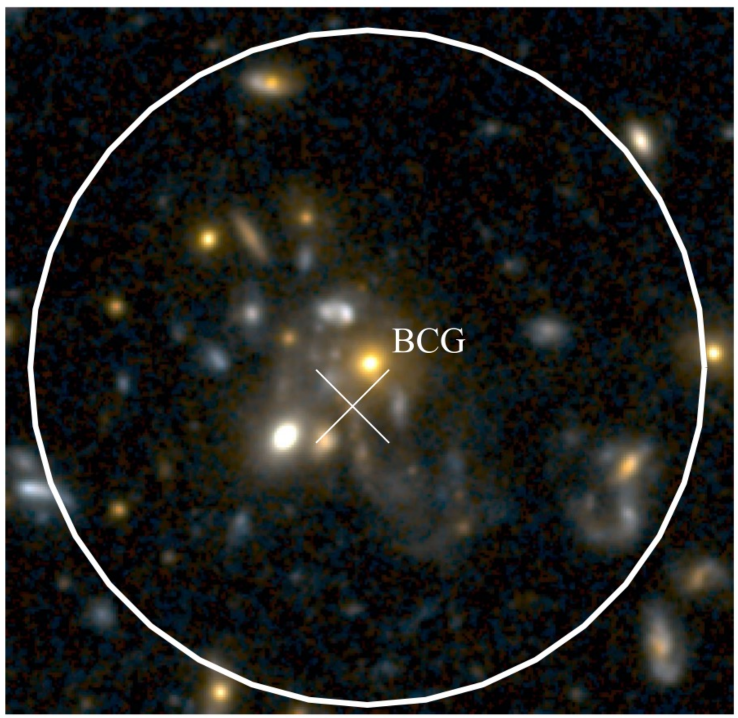
Consistent with McDonald+13: 150 $M_\odot$ yr^{-1} since z=1 in SPT clusters

-- Clarification: I did not intend to suggest the pressure "excess" is due to feedback (that would be crazy!). The pressure profile is the product of the temperature and density profiles giving the expected high central pressure. I intended to suggest there may be more pressure than required to support the extra weight of the CF gas when integrating to large radii. Thus "extra" pressure. Hydrostatic equilibrium is baked into the mass profile.

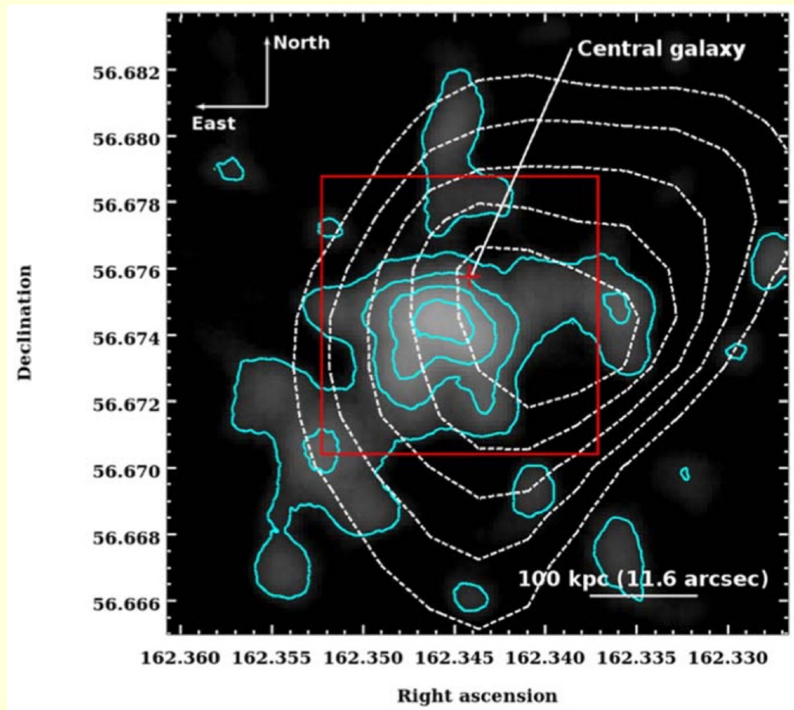
Clearer picture emerging at z>2

SpARCS1049+56 z = 1.7 natal cluster 9 Gyr ago,

Nascent BCG



Nascent cluster atmosphere



Webb + 15, Hlavacek-Larrondo + 20

Just assembling. Radio AGN feedback has not been established

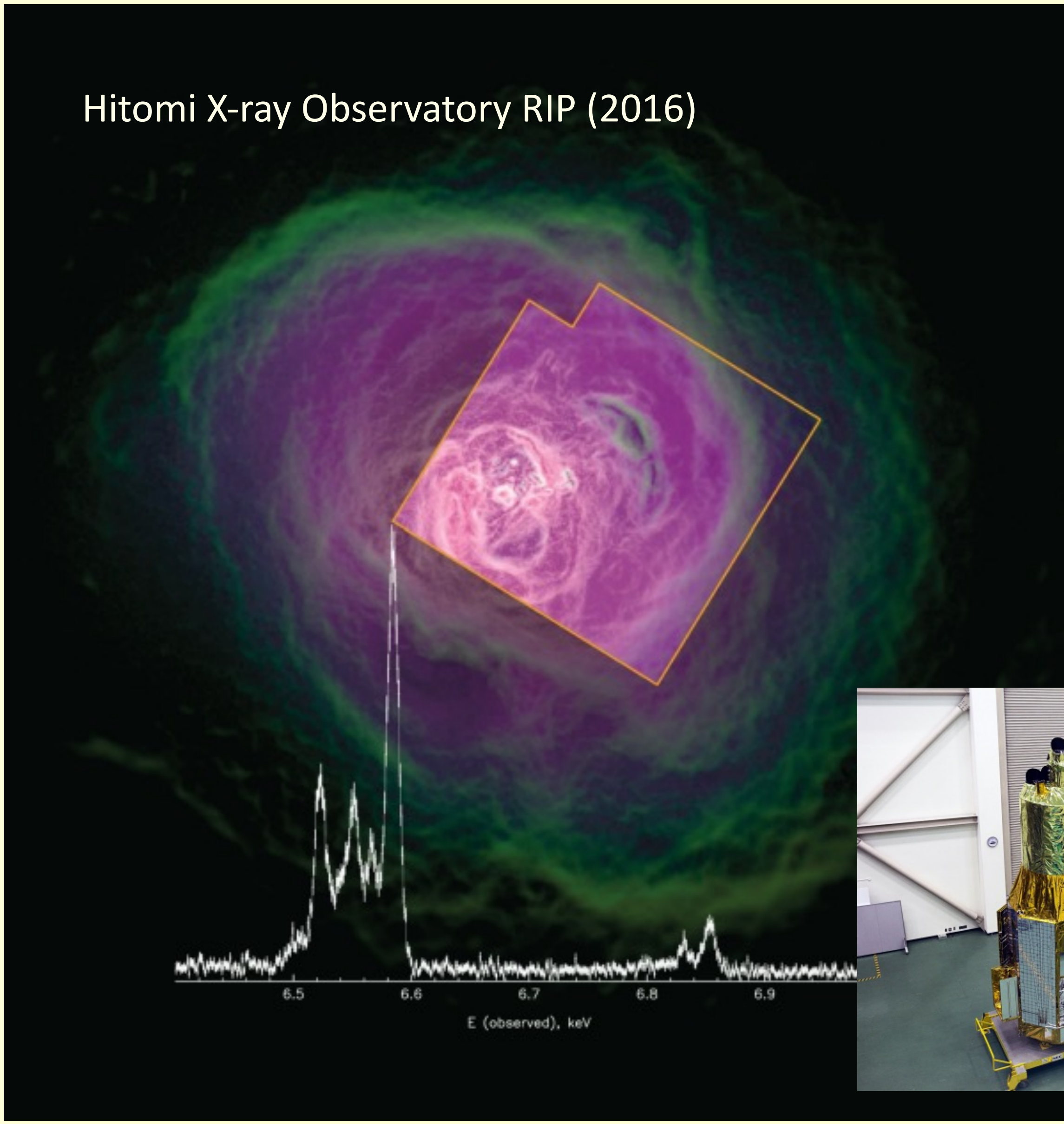
Approaching the preheating, pre-enrichment epoch

Evrard 90, Evrard & Henry 91, Bialek+01, Borgani+02, Loewenstein 13

Future: High resolution X-ray spectroscopy

Metallicity: cooling, star formation history, pre-enrichment

Mernier+18, Gastaldelo+18
Simionescu+ 2019



<5 eV resolution
Turbulent/bulk velocities <10 km/s

Energy transport
Turbulent heating
Chemical enrichment histories

XRISM (2023-)
Athena (2035)
Lynx (2040)

summary

-- Radio mechanical feedback, when operating, appears to dominate other feedback mechanisms as far as Z=2-3

High Lifting factors: $L = (m_{gas} \times R_{gas})/P_{AGN}$

-- Contemporary cluster thermodynamic profiles roughly consistent with cooling over past 8 Gyr.

-- We still don't know the origin of most of the atmospheric metals

Metallicity key observable when X-ray calorimeters fly