# Twenty Years of Chandra Cluster Phenomenology

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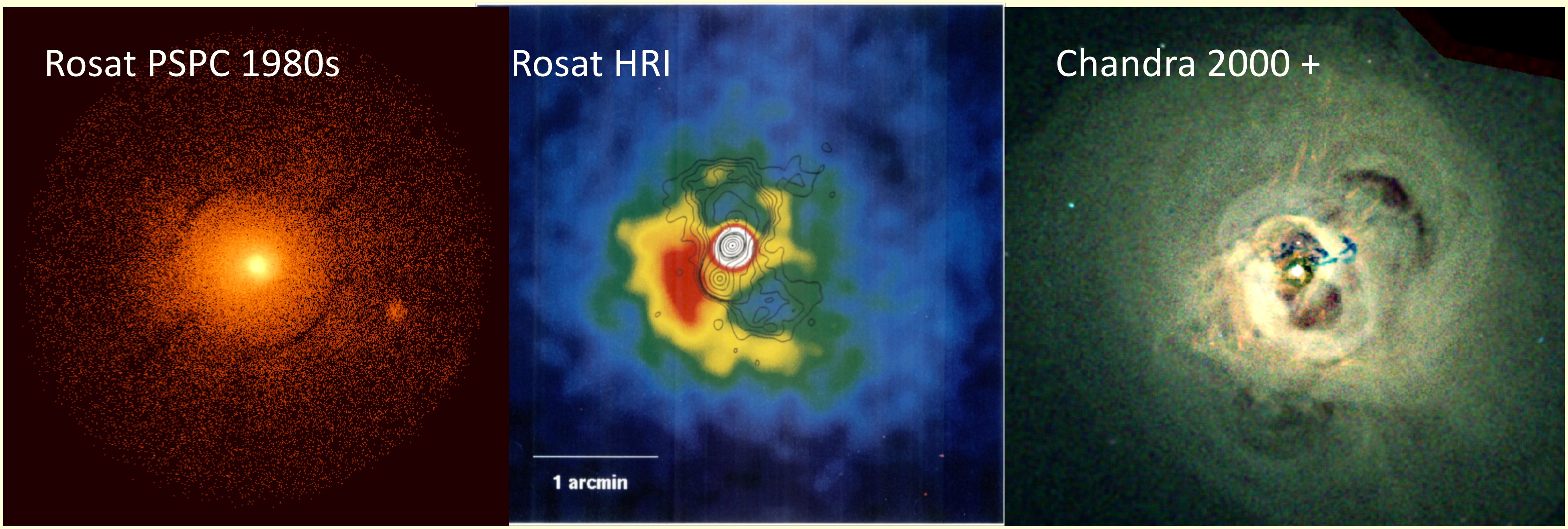
See Nulsen + 2019, 20 Years of Chandra, Chapter 9, Groups and Clusters of Galaxies

# X-ray Universe in sharp focus: precision thermodynamics




Sharp imaging: (~25x HRI, ~600x PSPC) + moderate spectral resolution

+

Synergy: Hubble, VLA, LOFAR, GMRT, ALMA, computer simulation

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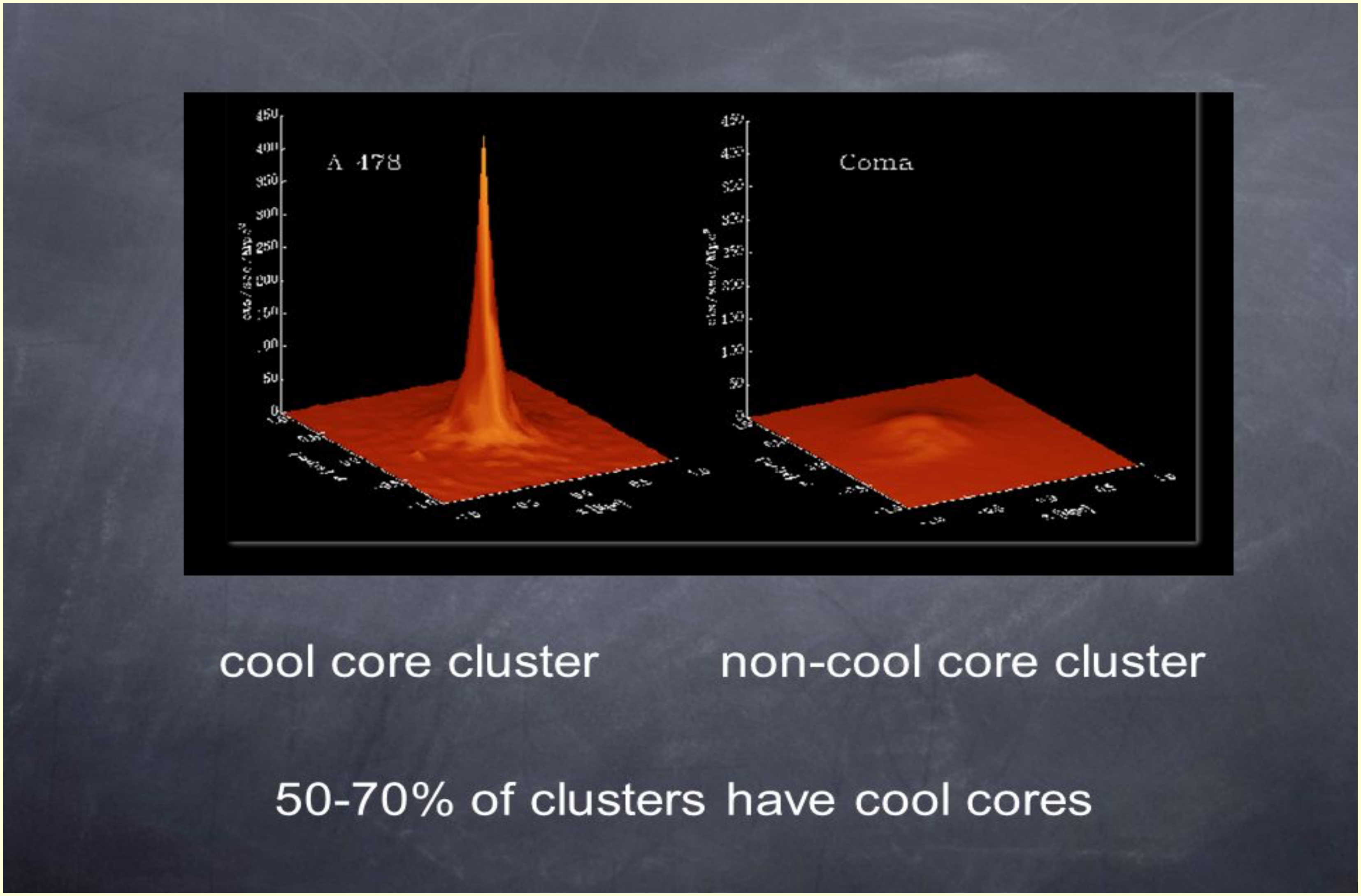
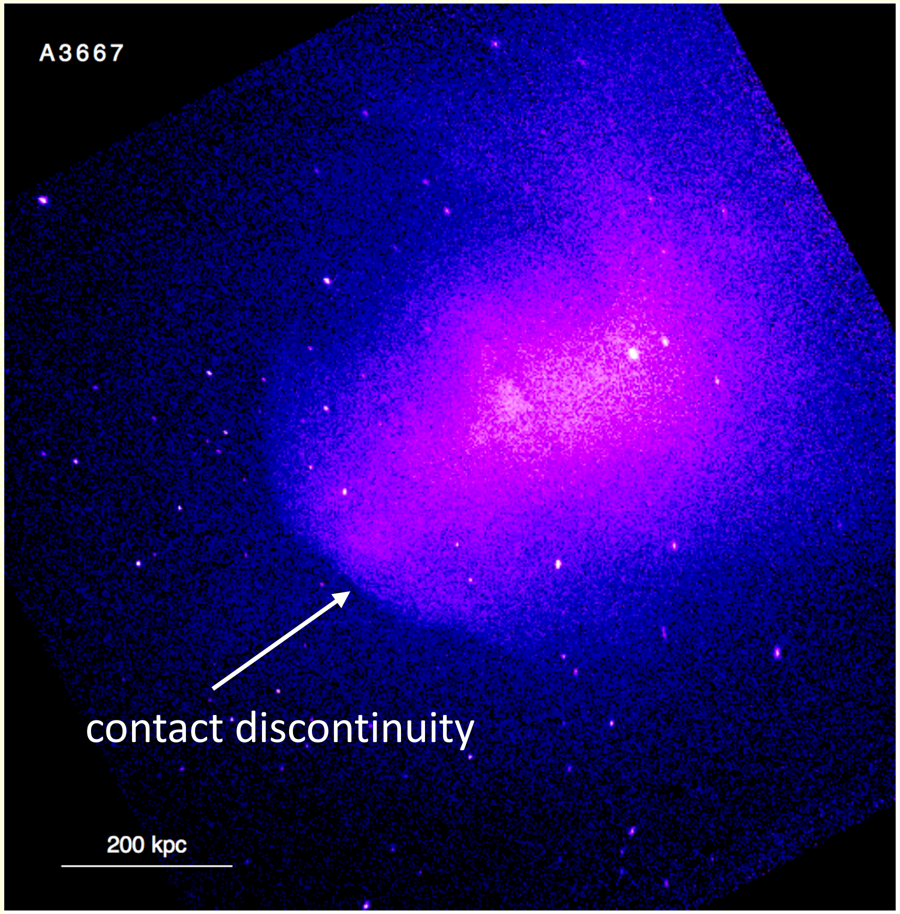
A great leap forward: Universe shaped by gravity, black holes, magnetic fields

# Cluster Basics

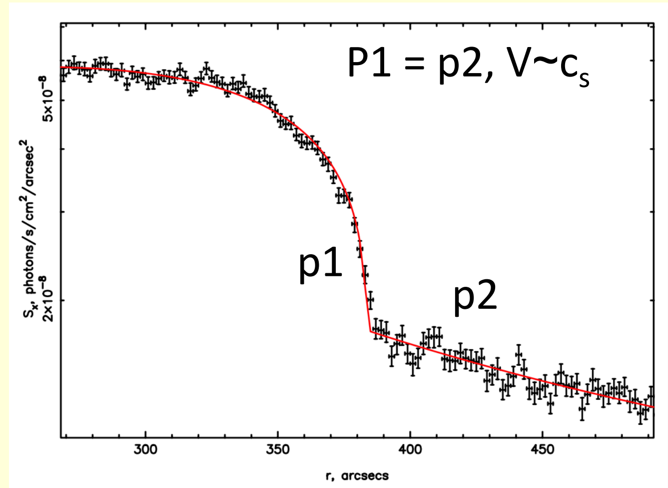
90% dark matter 9% atmosphere 1% stars
atmospheres T ~ $10^7$ - $10^8$ K



# Merger Cold Fronts: Galaxy Cluster Assembly




dense sub-cluster ablated by ram pressure



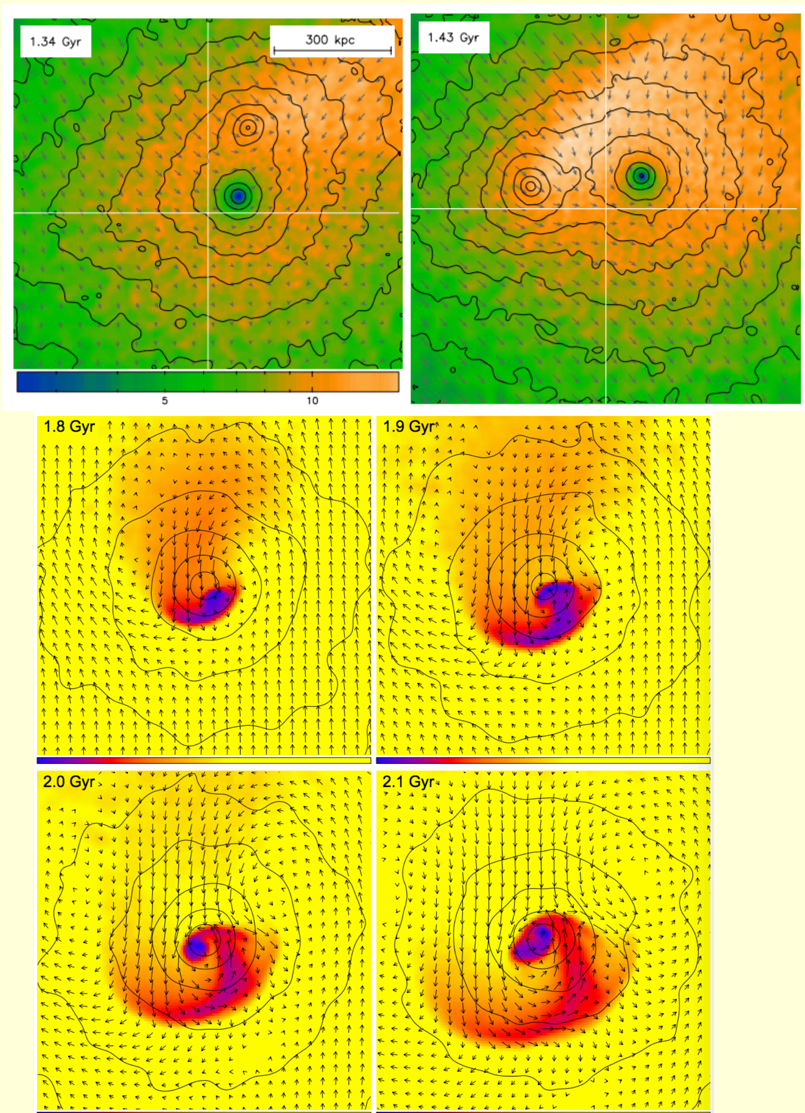

Cold fronts: window to cluster physics

- Suppressed instabilities (KH, RT)
-- magnetic field enhanced
-- thermal conductivity suppressed
-- viscosity
-- flow dynamics

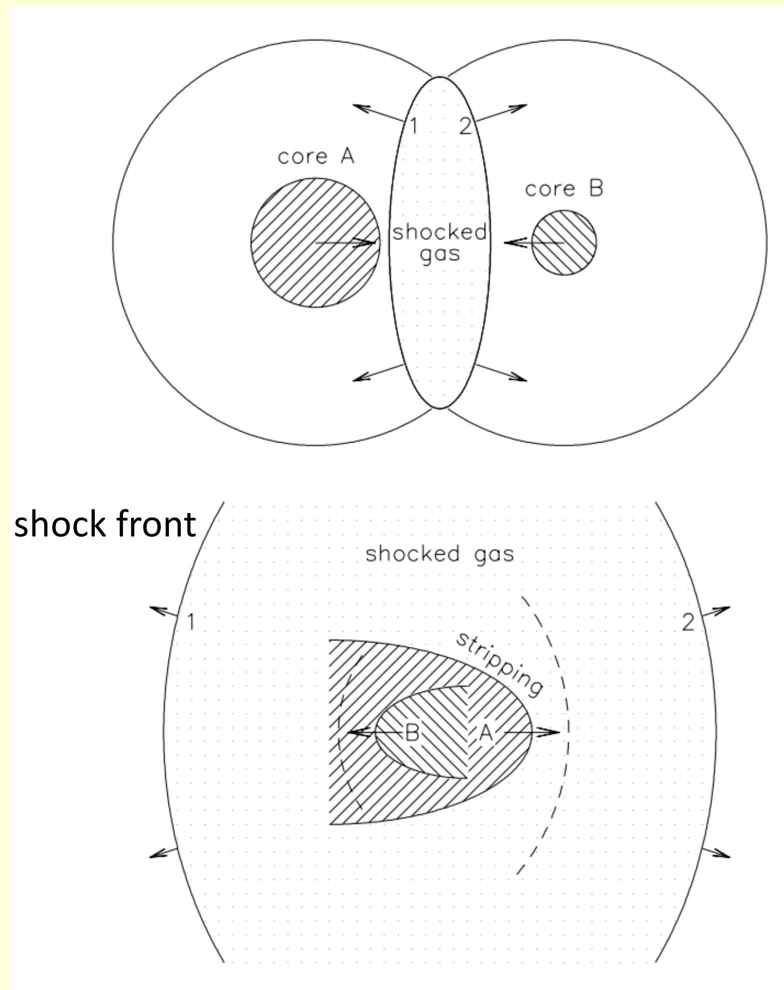
B ~ 10 $\mu G$

dynamics: thermal pressure + ram pressure

## Sloshing Cold Front

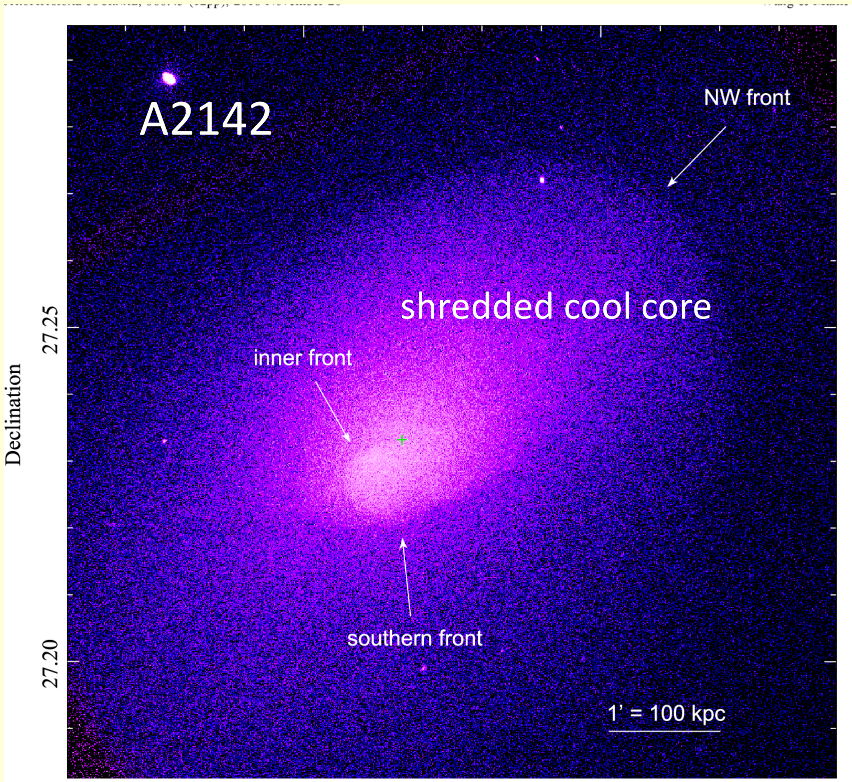


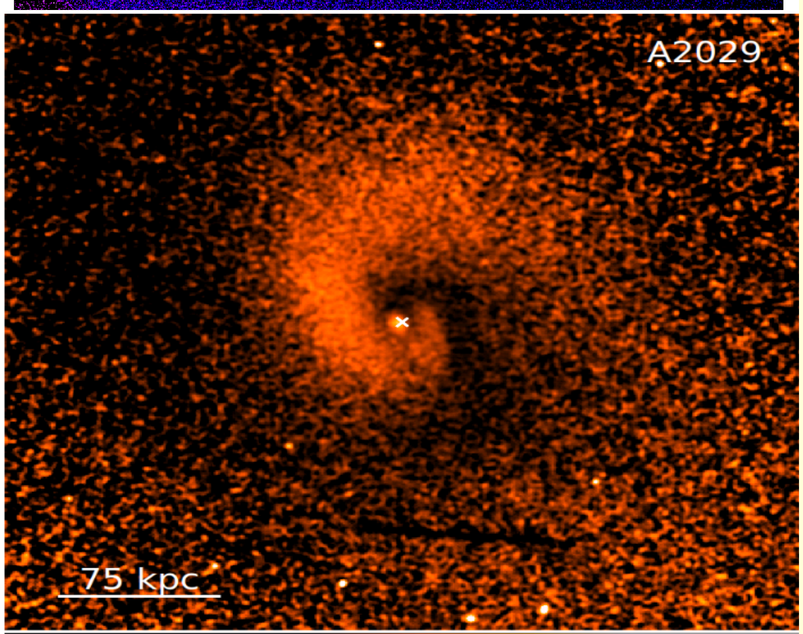

## Merger (remnant core) Cold Front

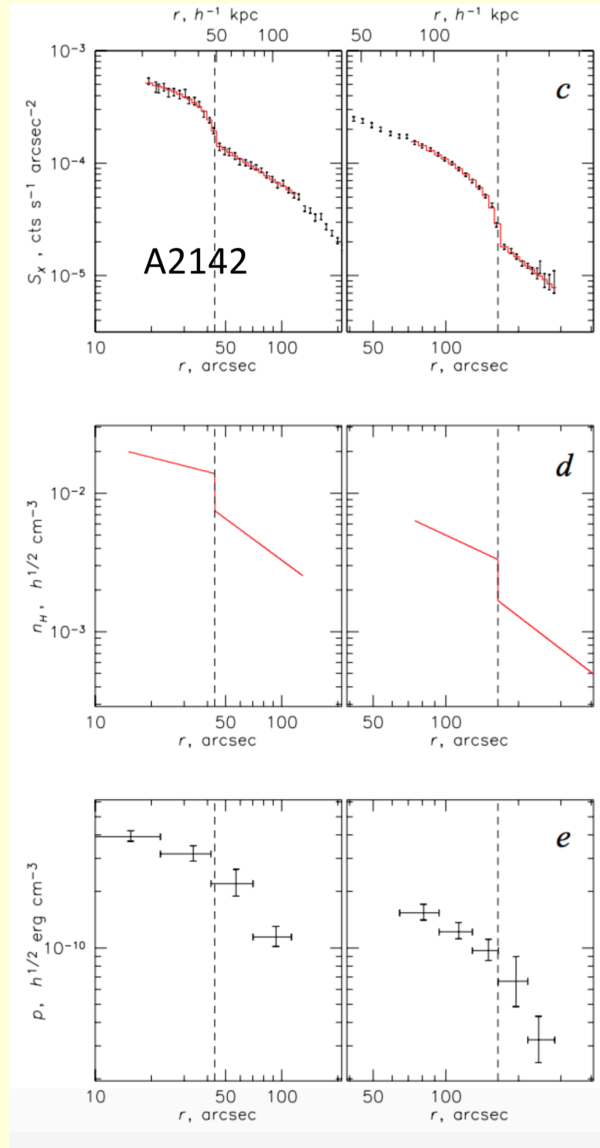



Markevitch & Vikhlinin 07, Zuhone & Roediger 16 for reviews

# Sloshing Cold Fronts

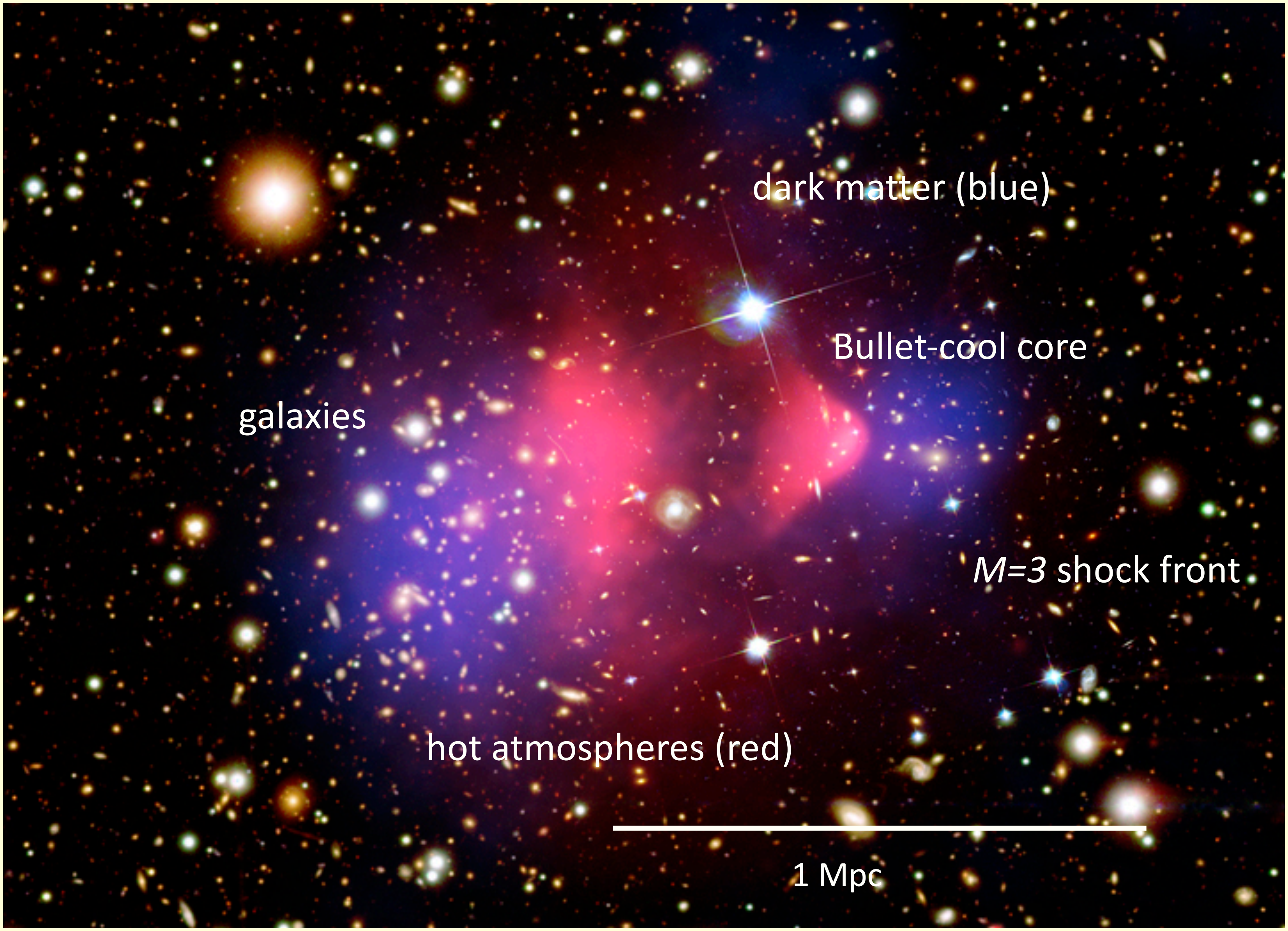


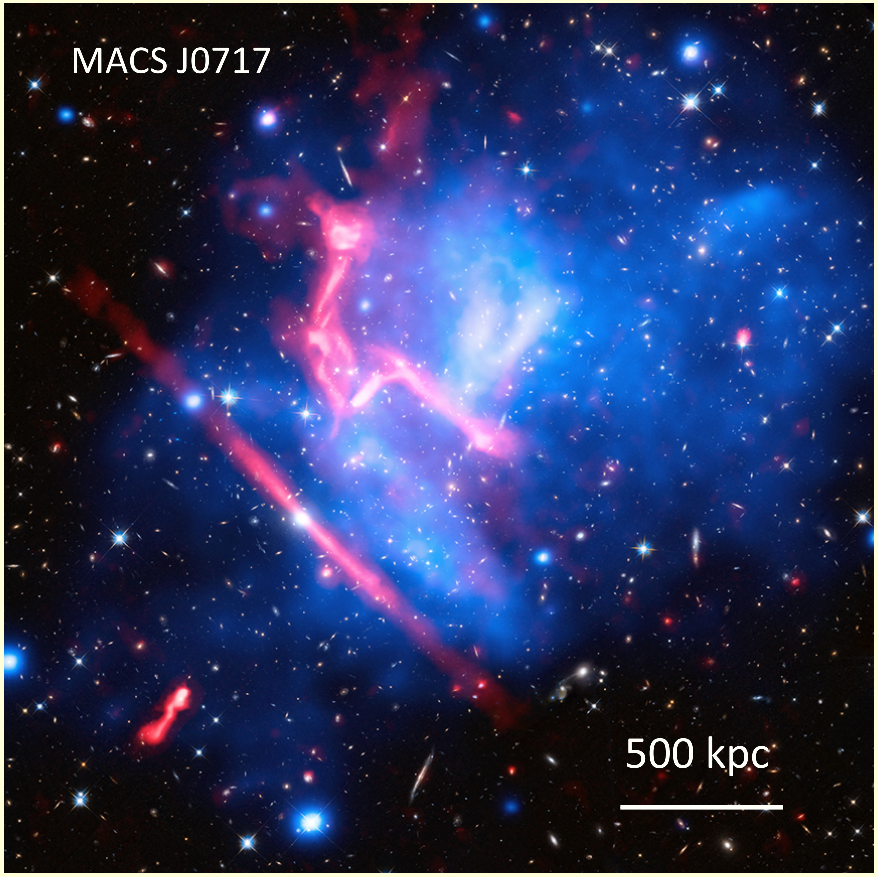



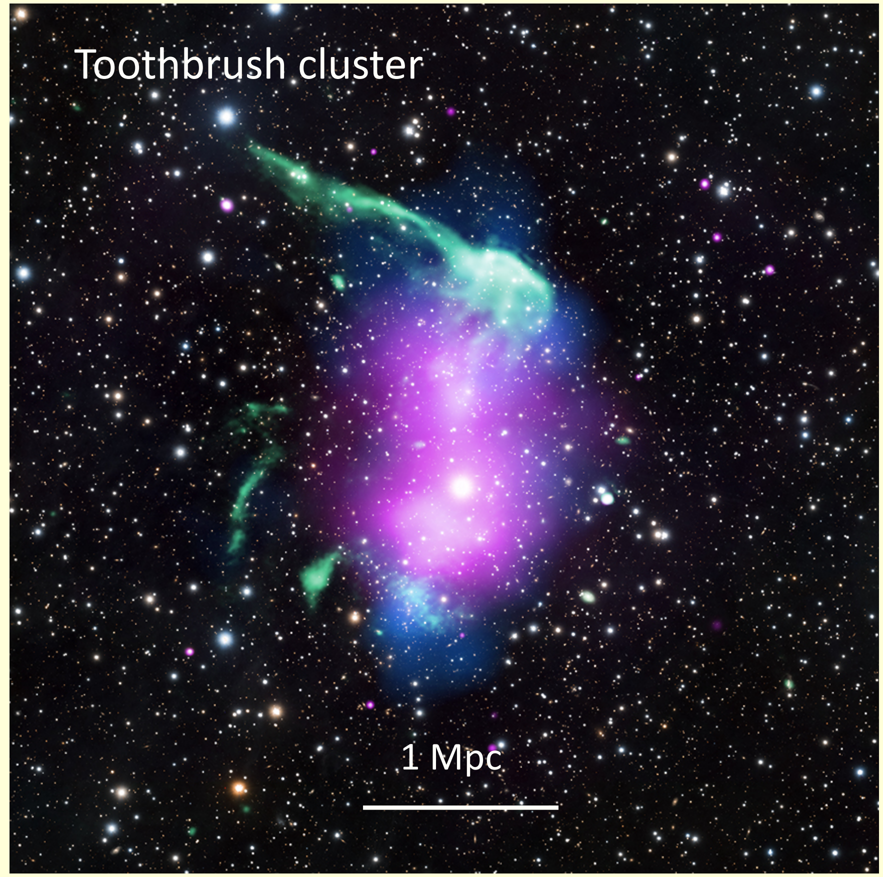

angular momentum, gravity, buoyancy = spiral

# Clusters assemble by mergers



# Radio Relics – energized by violent collisions



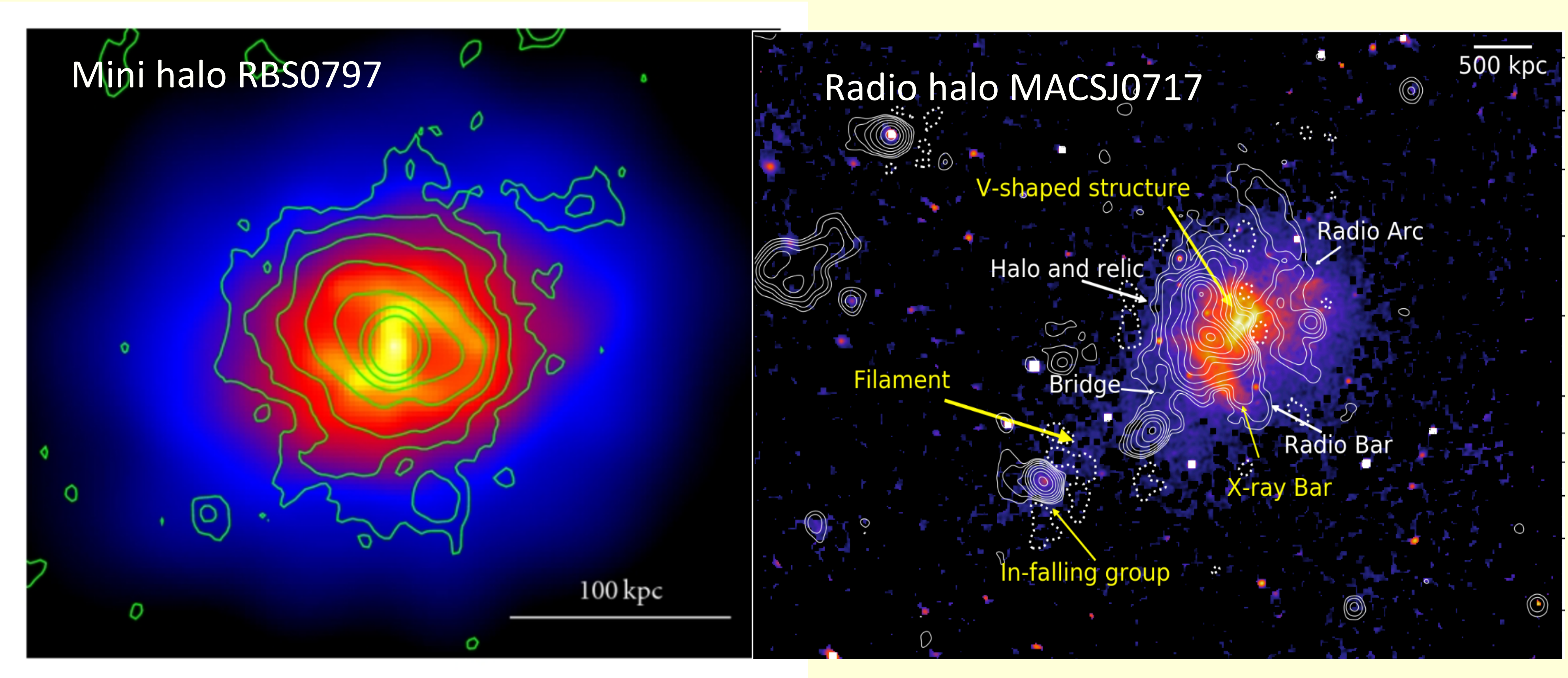




four clusters colliding

M=2-3 shock fronts

Problems: electron (re) acceleration: turbulence, shocks?
thermal electrons? relativistic electrons from radio galaxies reenergized?

# Radio Halos & Mini-halos




<u>Mini-halo</u>: Located in cool cores -- relic relativistic electrons from central galaxy radio source reaccelerated by atmospheric turbulence & sloshing

<u>Radio Halo</u>: Faint, diffuse, large-scale, unpolarized, powered by turbulence, shocks

# Takeaway Points

-- dynamic clusters: collisions, sloshing

-- Surprise: edges in pressure balance, cold fronts

-- edge/shock morphology sensitive to merger history: mass, orbit, speed

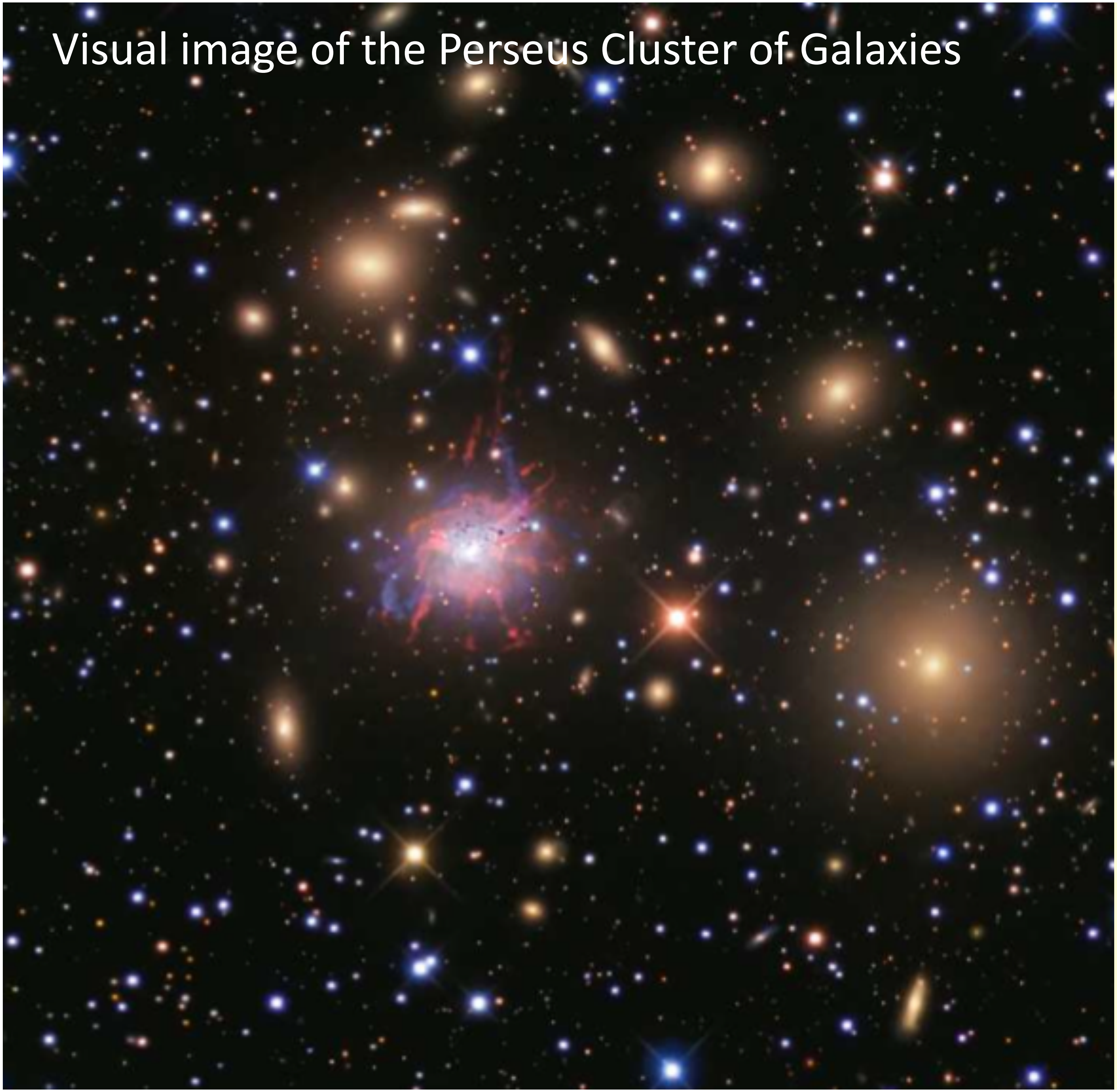
-- modern simulations capture this physics well

-- sharp discontinuity: magnetic draping suppresses KHI & thermal conduction.

-- longer term evolution: swirls -- sensitive to plasma viscosity

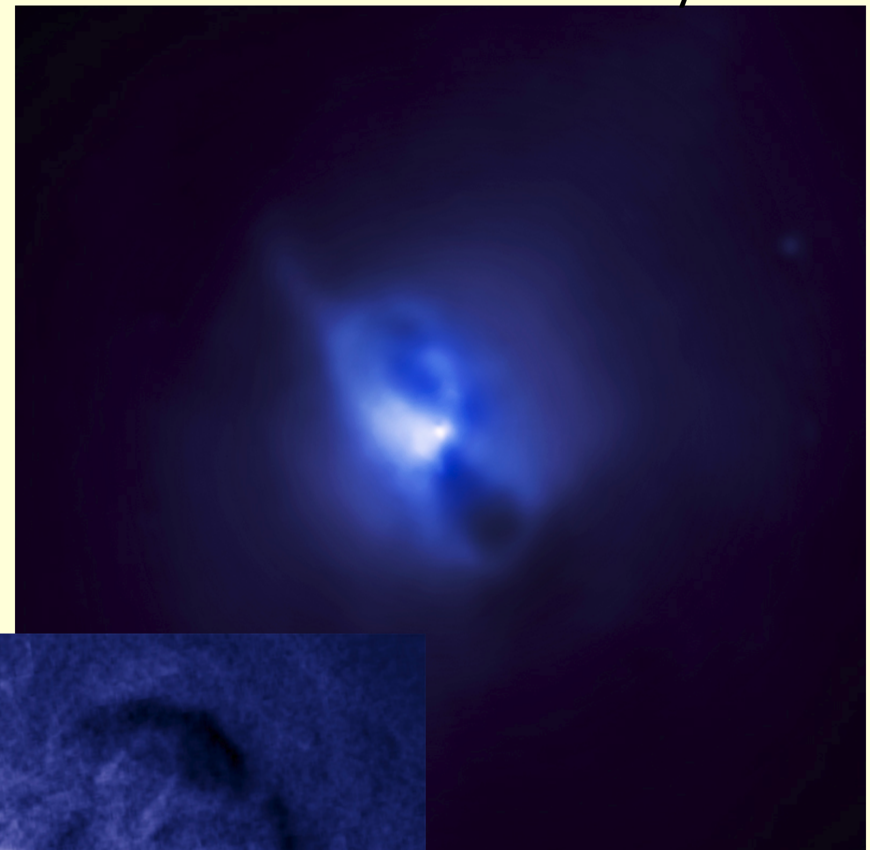
-- electron/ion equilibration timescales measured in violent collisions


X-rays from 100 M degree gas permeating the Perseus cluster

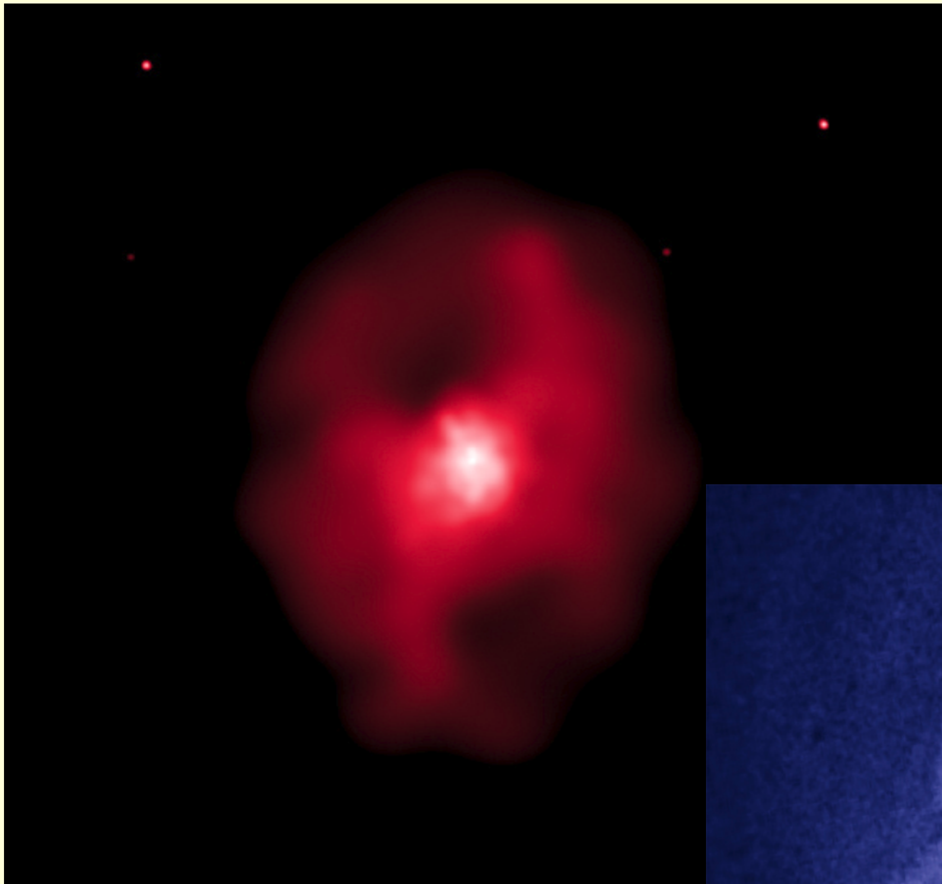

Visual image of the Perseus Cluster of Galaxies

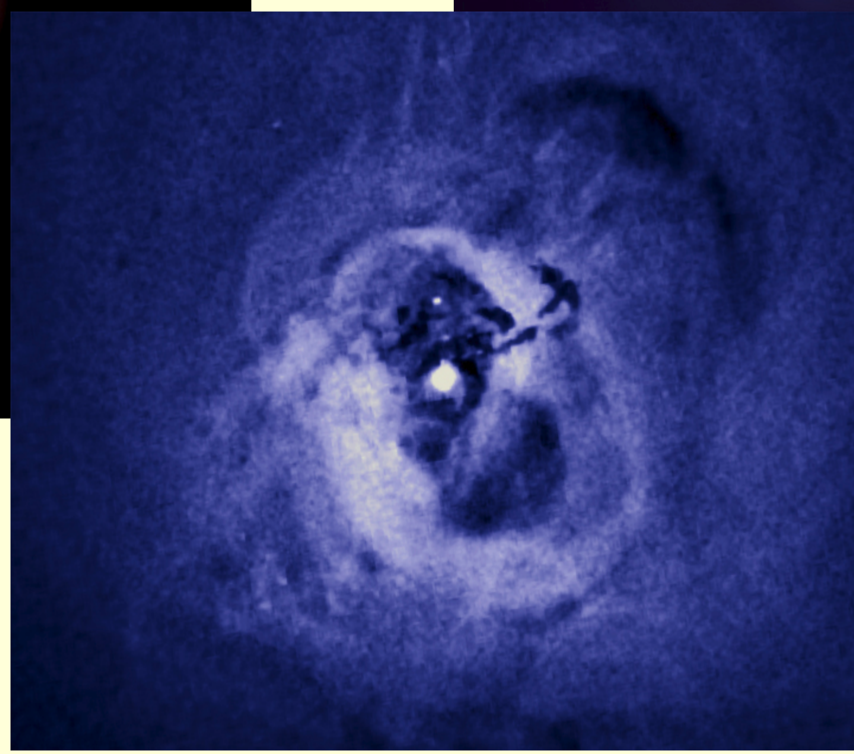
Zoom to cluster cores: Radio Mode feedback stabilizes cooling

Hydra A



MS0735

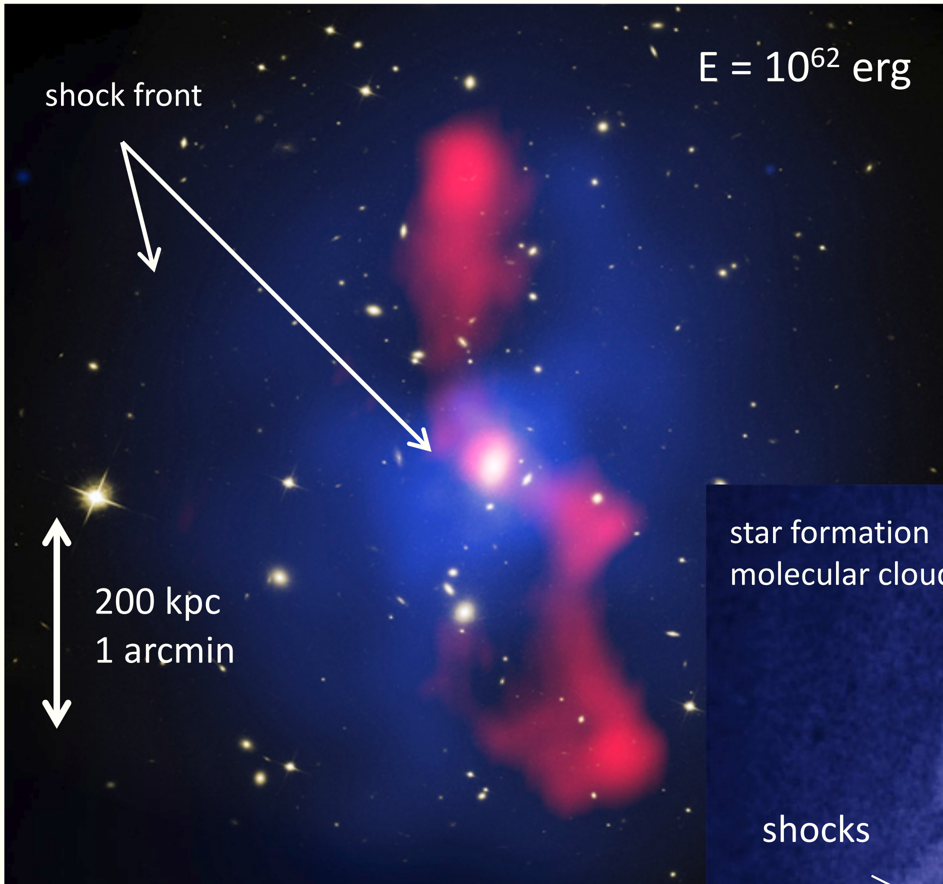




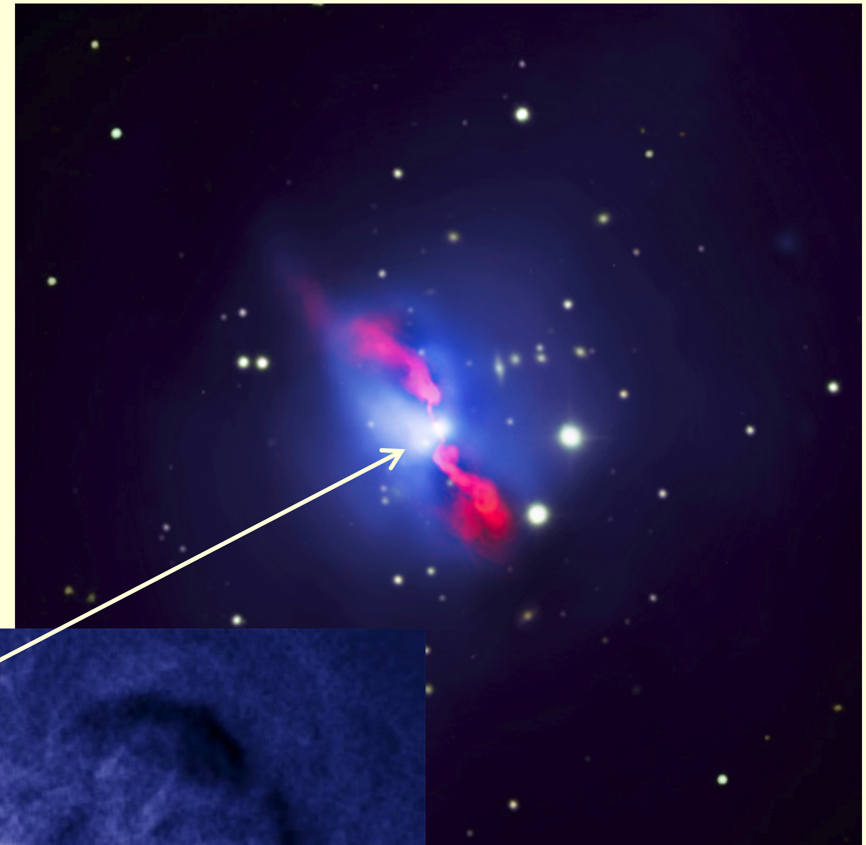
Perseus

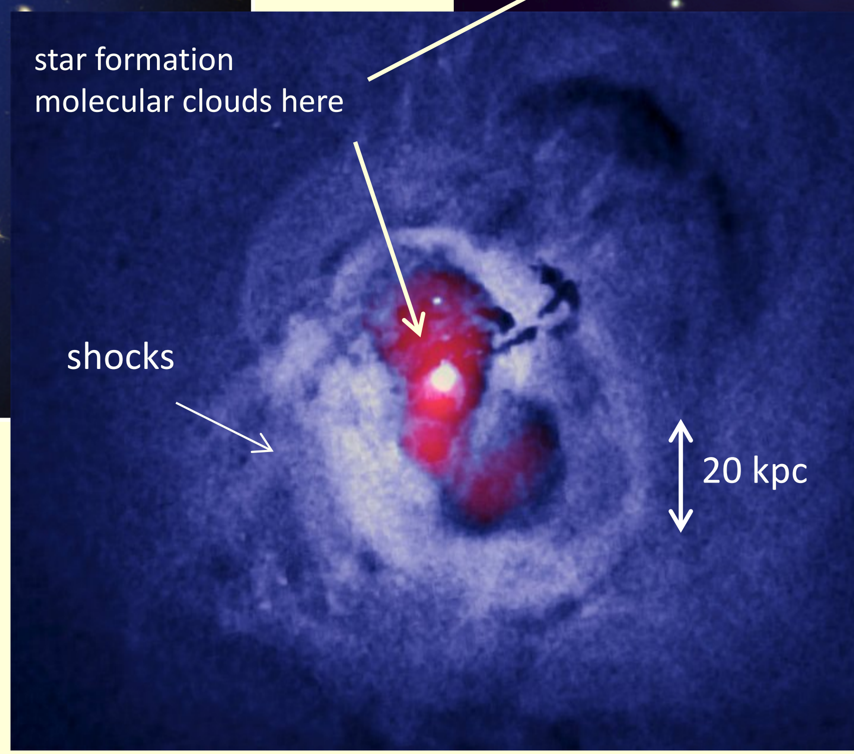
# X-ray + radio = mechanical feedback

MS0735




Hydra A



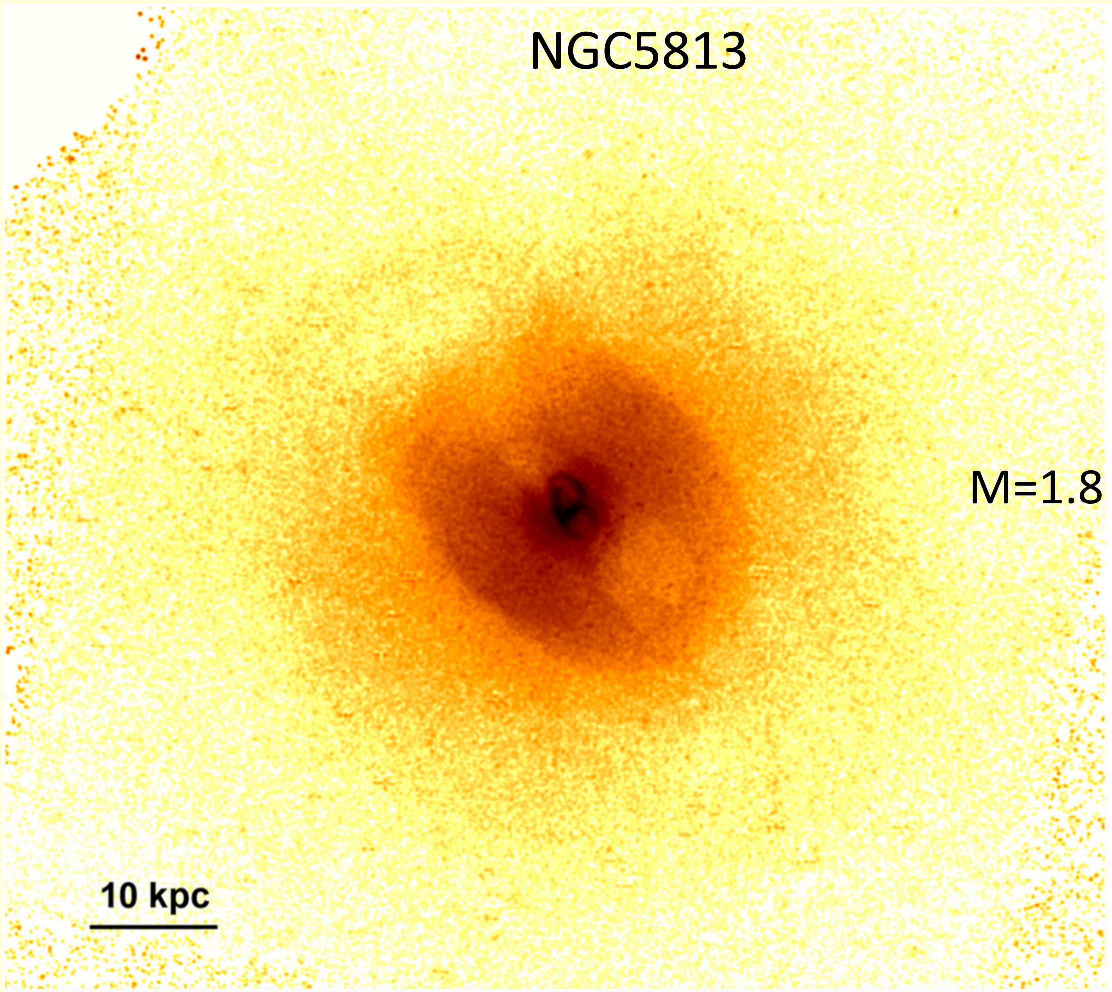



Perseus

Prescient paper:
Gull & Northover 1973

Radio-mode feedback seen also in groups, ellipticals
a common phenomenon, Key:
<u>short central cooling time</u>

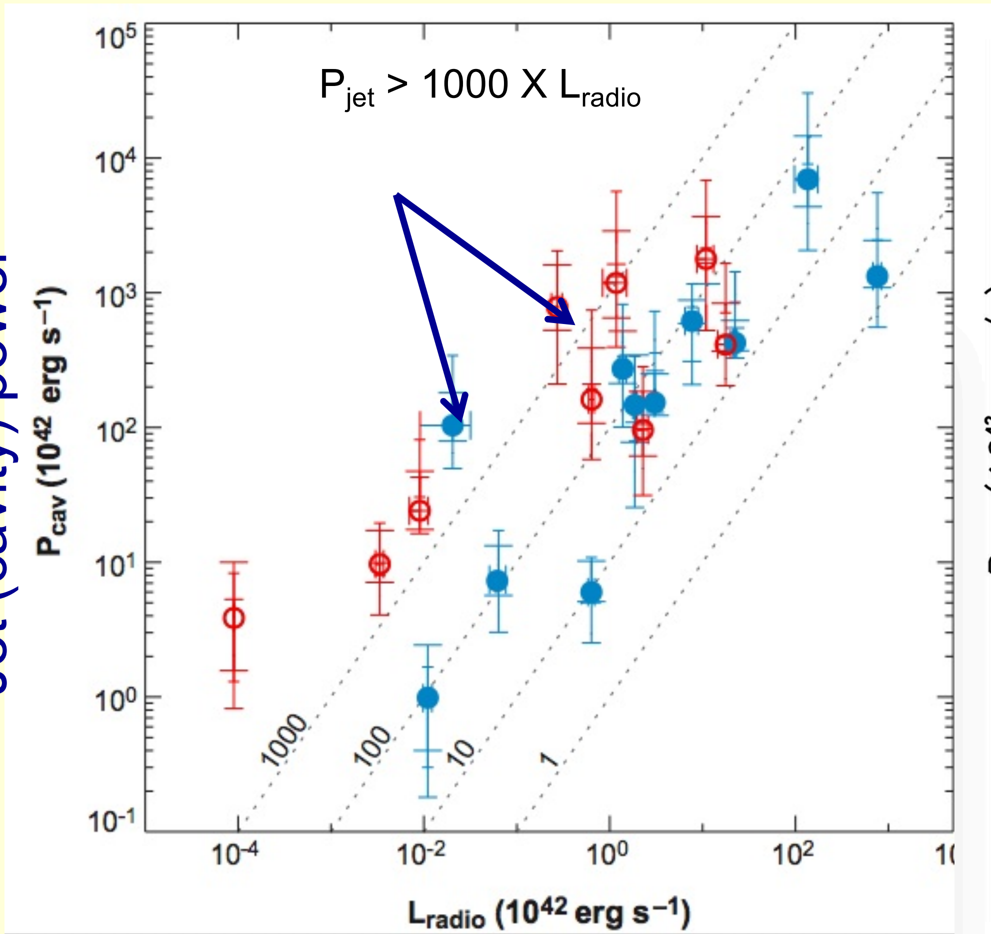
NGC5813



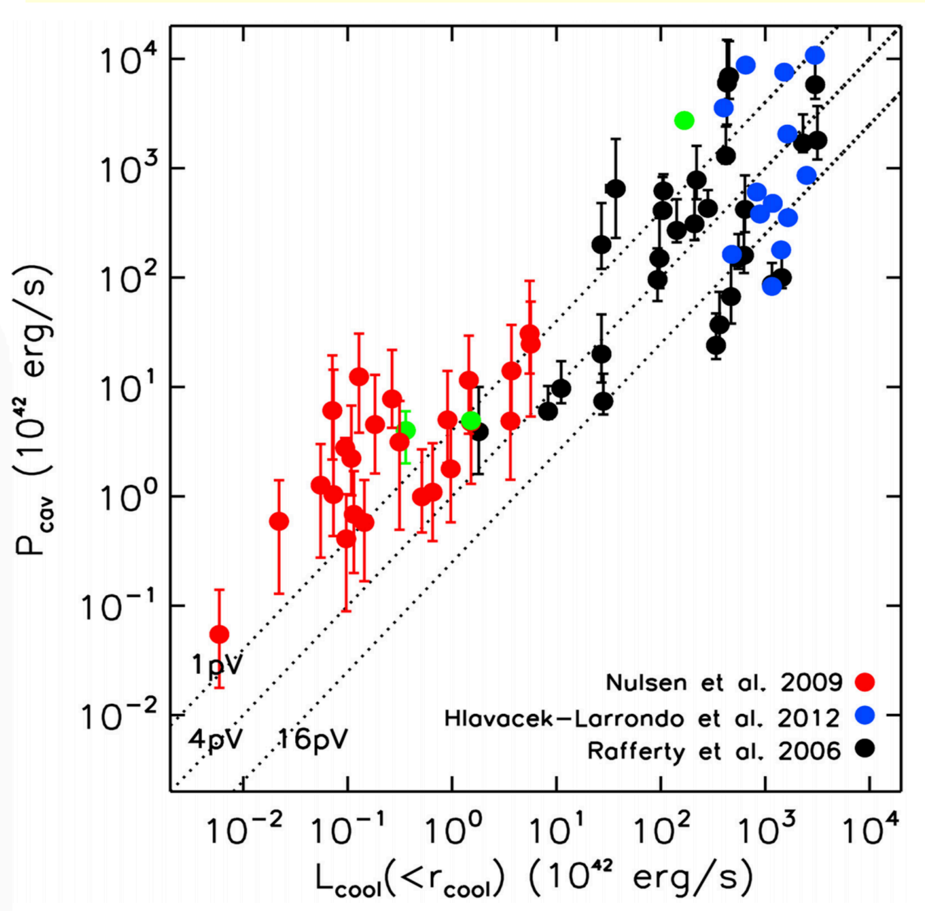

M=1.8 cocoon shock

# Jet (cavity) power vs radio power & Cooling Luminosity

Jet (cavity) power




Radio Luminosity



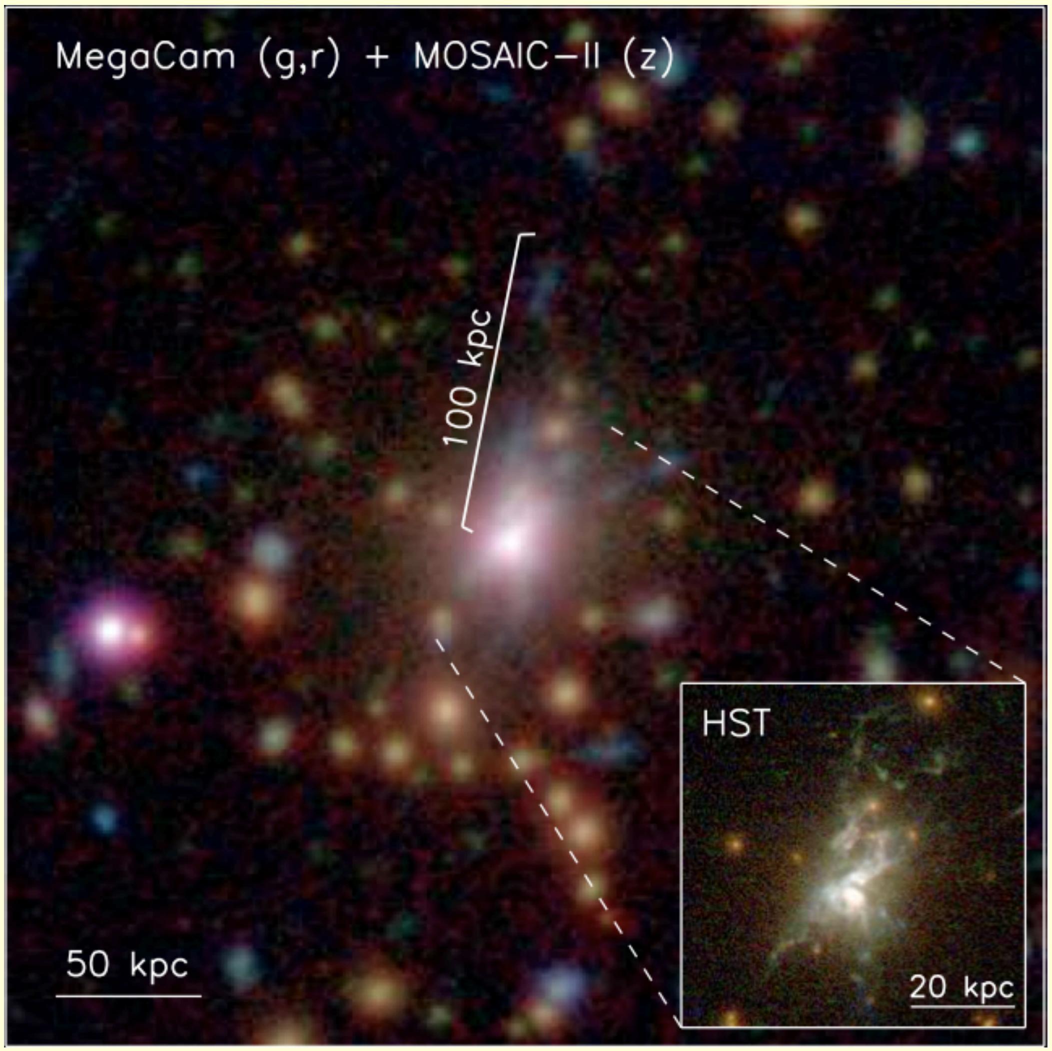

X-ray Cooling Luminosity

Chandra Key insight: even weak radio sources are mechanically powerful enough power to regulate cooling, lift enormous amounts of gas

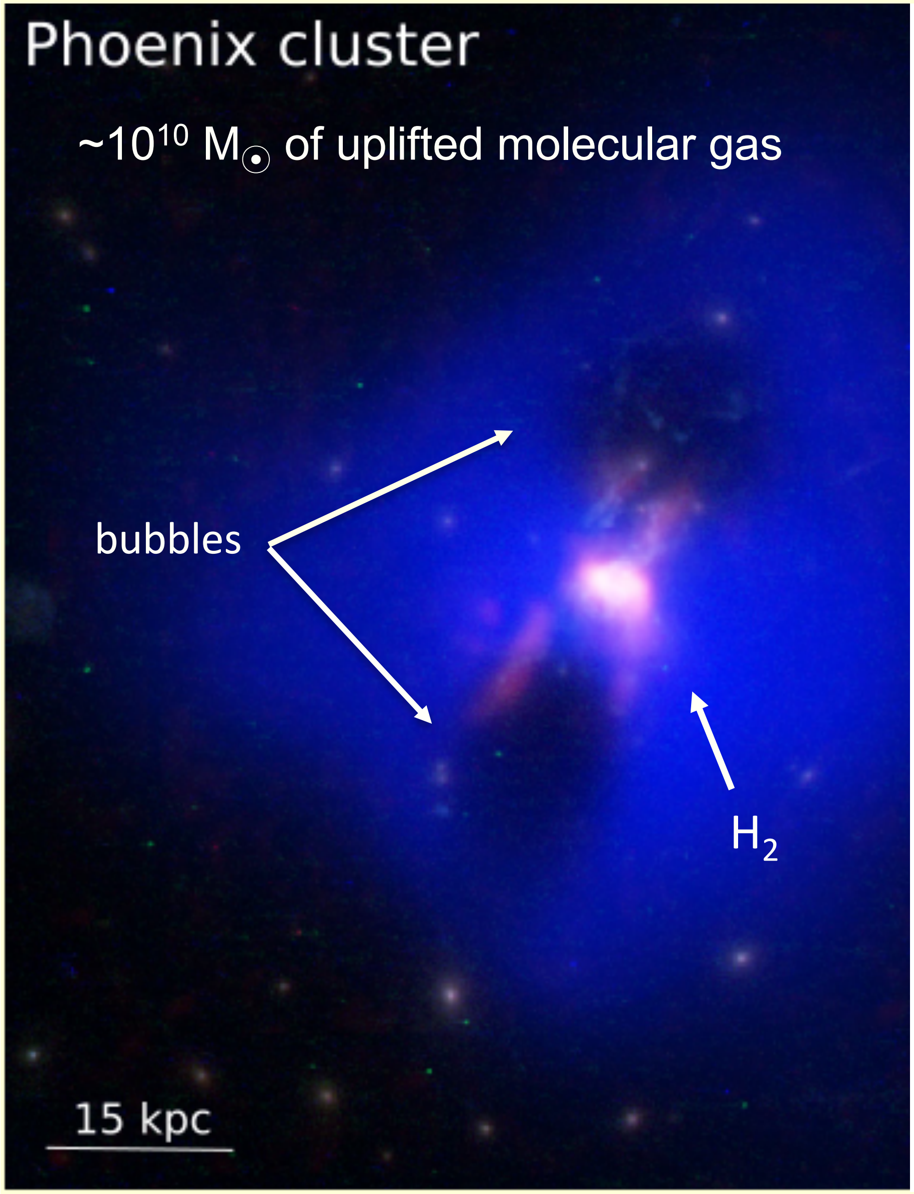
Phoenix Cluster: A burgeoning Central Galaxy at z = 0.6

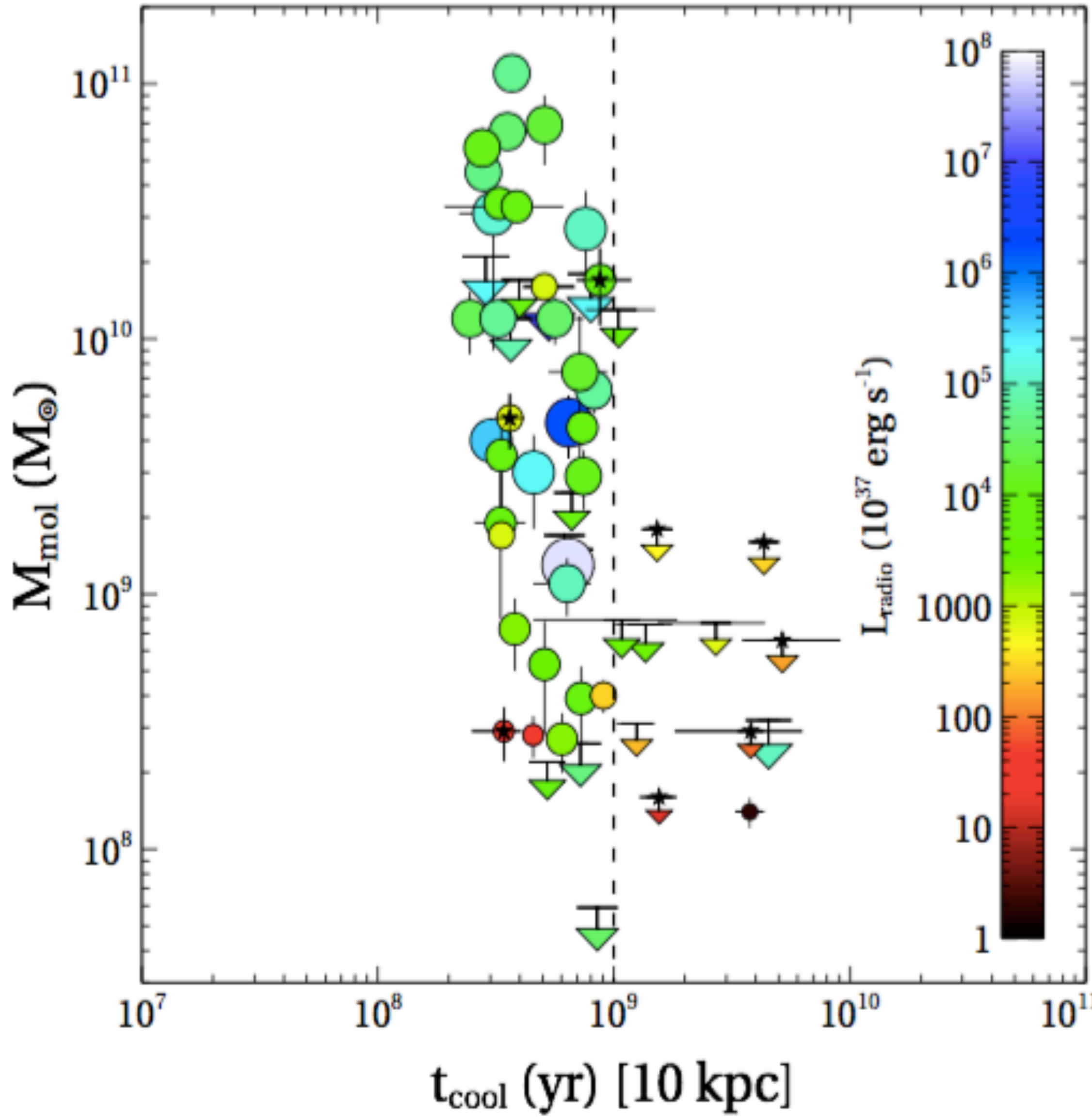
SFR ~ 800 $M_\odot$ $yr^{-1}$ $M_{mol}$ ~ $10^{11}$ $M_\odot$

What fuels star formation and AGN in this and others?



Lifting: Molecular Gas is filamentary, off nucleus, behind radio bubbles
clearly seen in Perseus -- may stimulate thermally unstable cooling




Chandra in blue, Alma in pink

# Takeaway Points

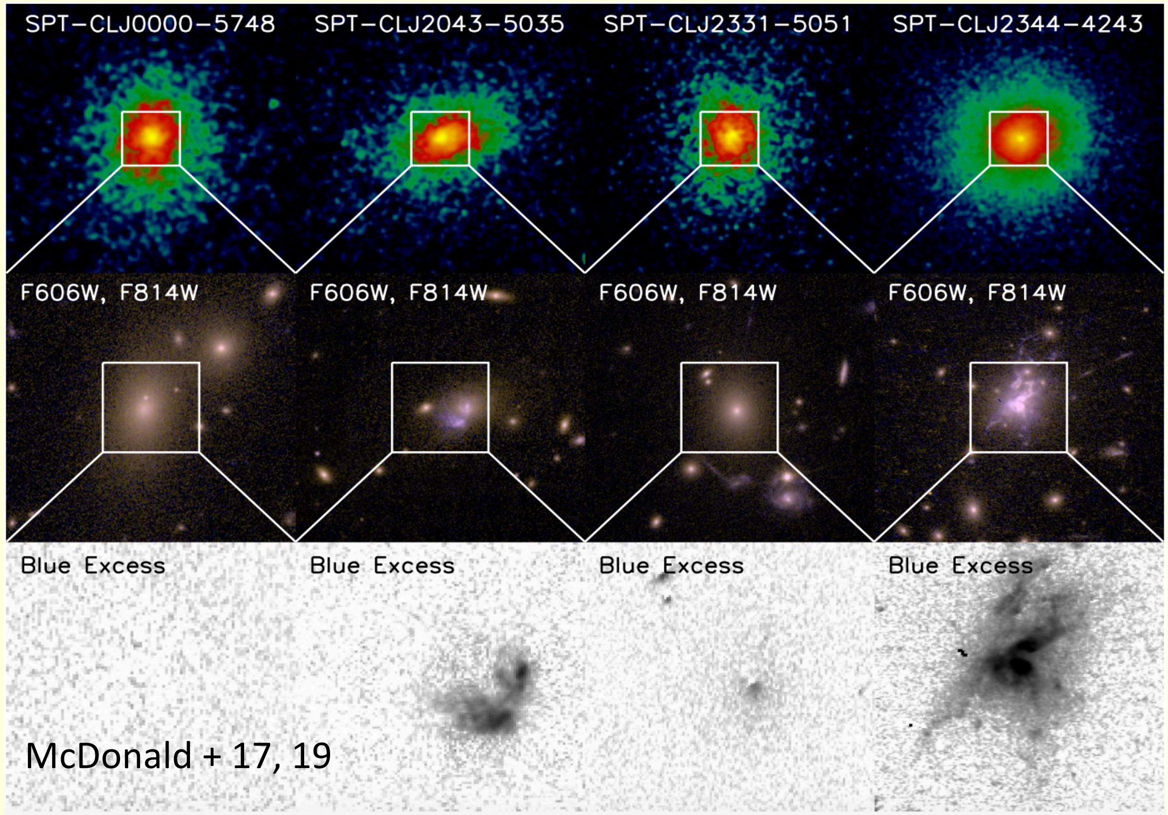
Cavity & Shock Calorimetry reveal:

-- <u>Surprise</u>: Cavity rims cool, displaced gas, not shocked gas
-- Cavity enthalpy & shock energy consistent to 2-3x
-- <u>Surprise</u>: Mechanical power exceeds radio synchrotron power by ~100-1000X
-- On large scales, radio plasma dominated by heavy particles: protons?

-- Jet power comparable to cooling power: quenches cooling flows– <u>solved by Chandra</u>
-- data reveal directly AGN outburst *history* (e.g. M87), unavailable in other AGN
-- Feedback is a gentle process- not captured well in simulation
-- Radio mode feedback has been active and effective for billions of years

-- Radio jets/lobes drive molecular outflows more efficiently than any other AGN type
-- Lifting cool, atmospheric gas, feedback stimulates cooling, feeding star formation AGN

# Evolution of cool cores from *z=1-0,* or 5 Gyr

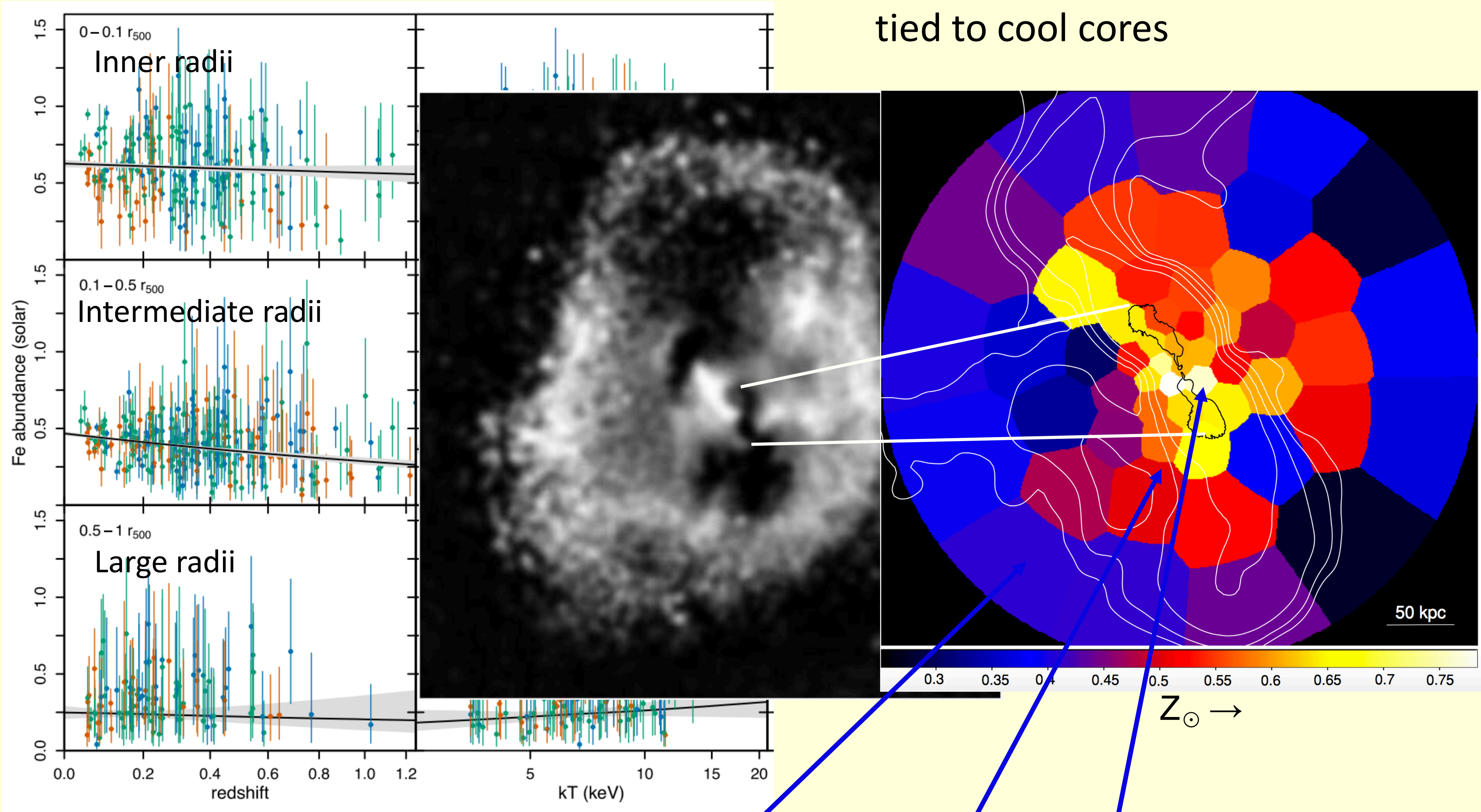



## SZ Clusters from the South Pole Telescope

- 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

# Chemical Evolution of Hot Atmospheres since z~1

tied to cool cores



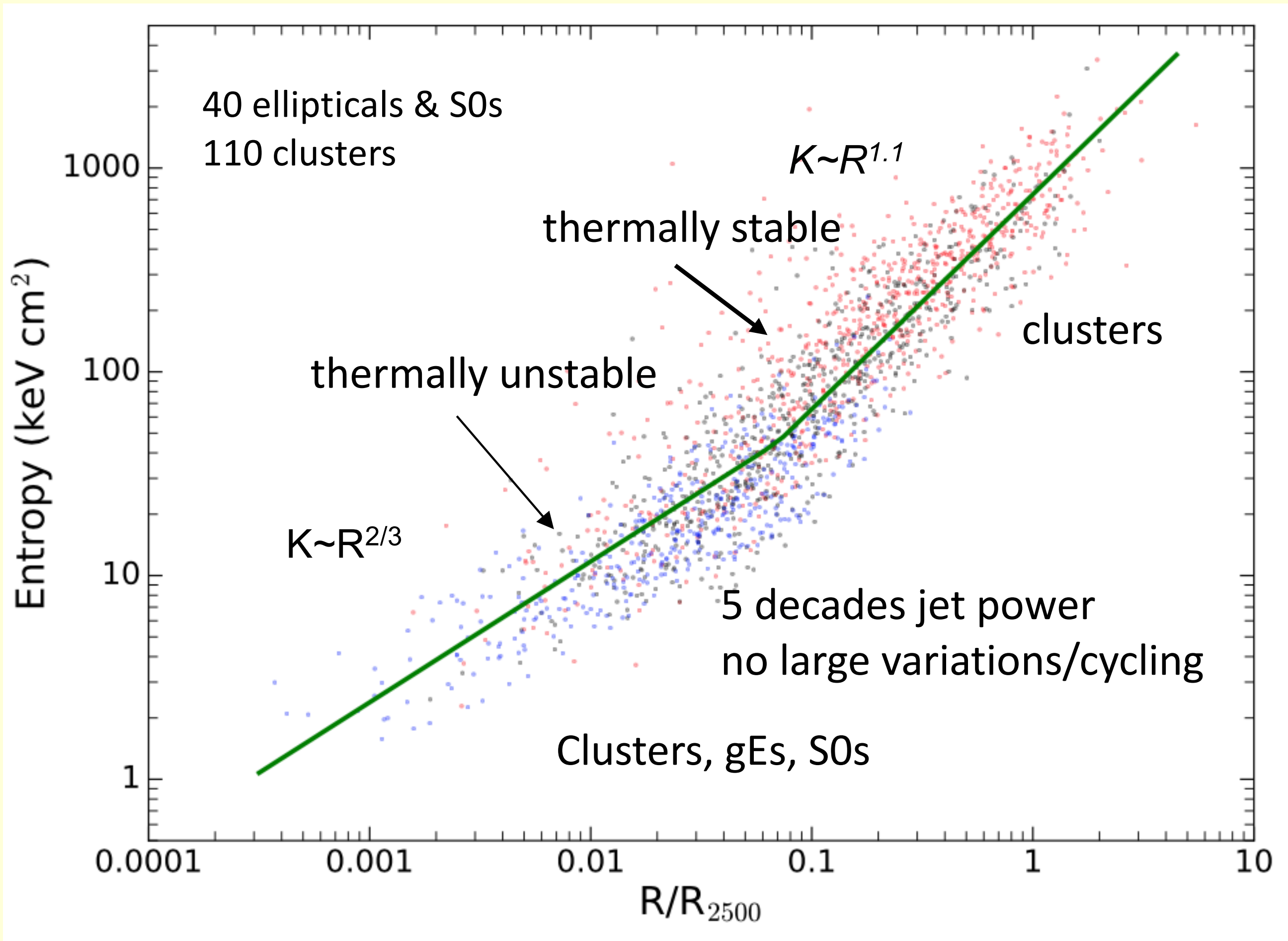

$Z_\odot \rightarrow$

Outer radii –constant metallicity $z/z_\odot$ ~0.3 pre-enriched

Intermediate radii – late-time enrichment, mixing by sloshing, AGN

Inner radii – approach solar metallicity – enrichment from central galaxy

# Feedback has imprinted nearly universal entropy distribution since z~1



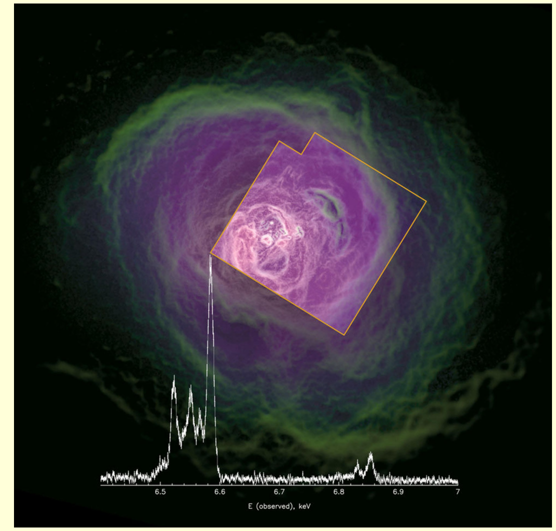

$K\sim R^{1.1}$  $R > 0.1R_{2500}$

$K\sim R^{2/3}$  $R < 0.1R_{2500}$

-- Low scatter in the central region: Gentle feedback, 5 decades jet power!

# The Future

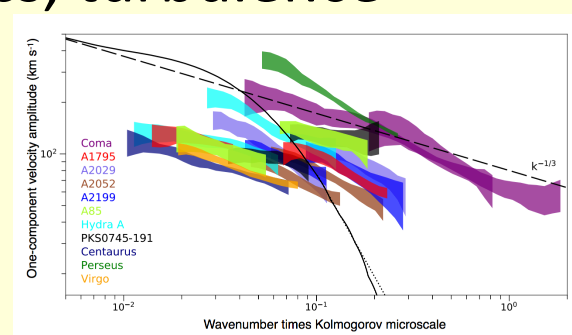
High spectral resolution calorimetry spectroscopy
XRISM  Athena




Large cluster surveys – eRosita

<u>High Spatial & Spectral resolution calorimetry</u>:  Lynx

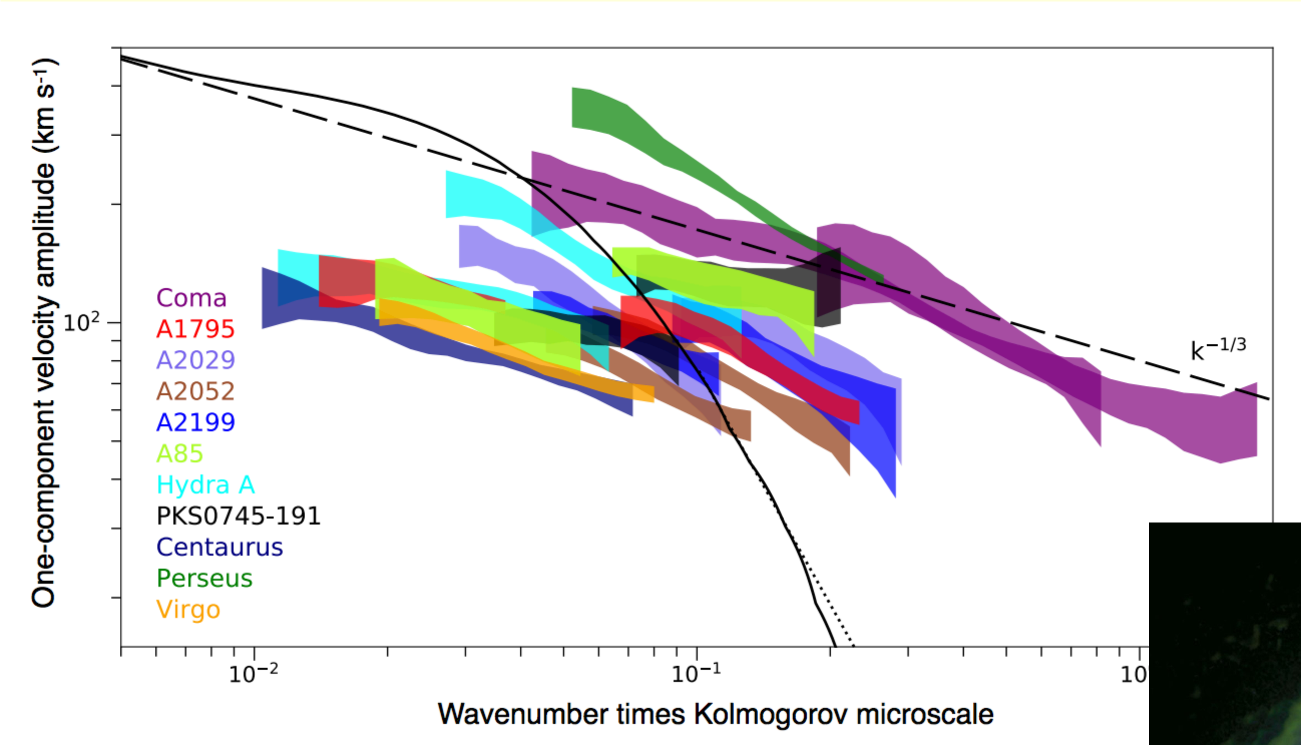
-- precision dynamics: feedback, bubble expansion/motion
thermally unstable cooling lines, plasma physics, turbulence
black hole winds within the Bondi sphere




-- cluster & massive black hole assembly

Thank you to all who dreamed of, conceived, designed, built, and operated Chandra overt the past 40 years

# Future: understanding atmospheric turbulence




Particle acceleration

Plasma physics

Heating?

Accelerated cooling?