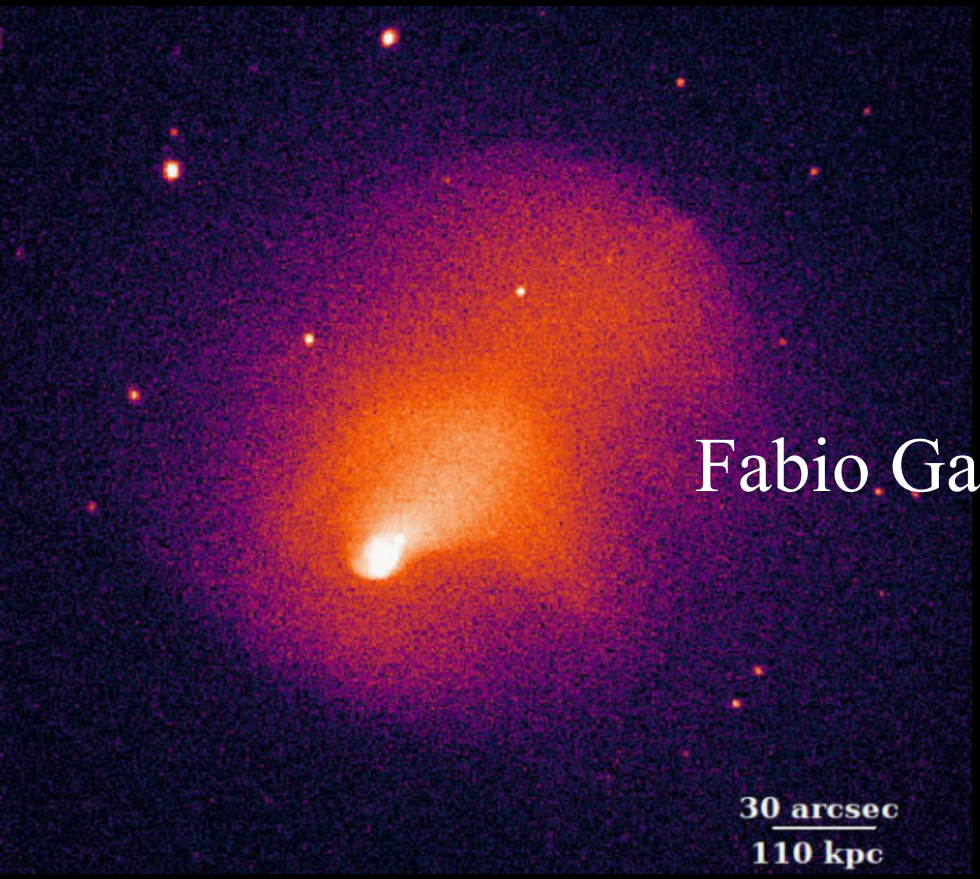
# The X-ray view of mergers in Galaxy Clusters

Fabio Gastaldello (INAF-IASF Milano)



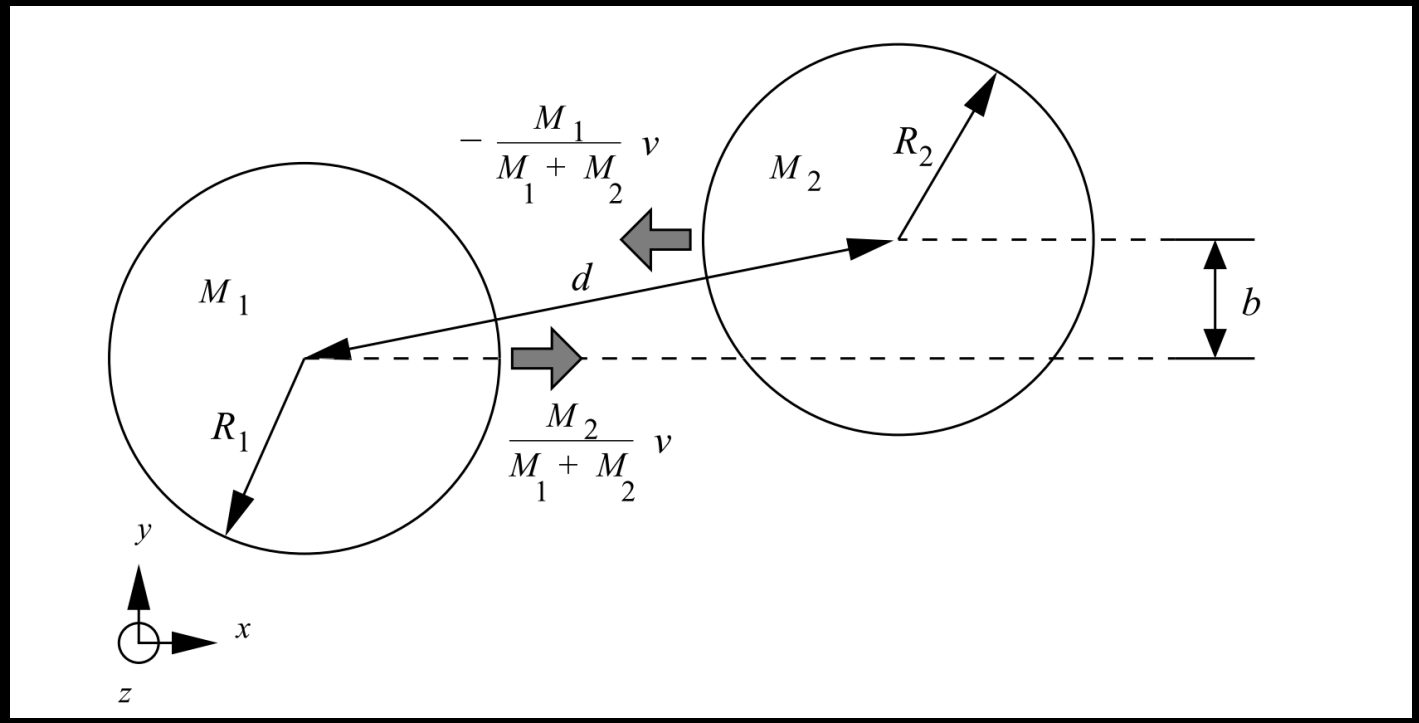

A2146 Chandra image Russell+22

A2142 XMM-Newton image Rossetti+13

# Outline of the lesson

- The features of dynamically relaxed cool core clusters (CC) and merging clusters (NCC)
- X-ray morphology as a dynamical indicator
- Cold Fronts by merging and sloshing cold fronts
- Shock Fronts
- The XRISM revolution: turbulence and bulk motions in the ICM

# The most energetic events since the Big Bang




Relative velocities can be derived from conservation of energy and momentum in a cosmological setting and it brings to velocities of the order of 2000-3000 km/s and impact parameters b of the order of 100 kpc.

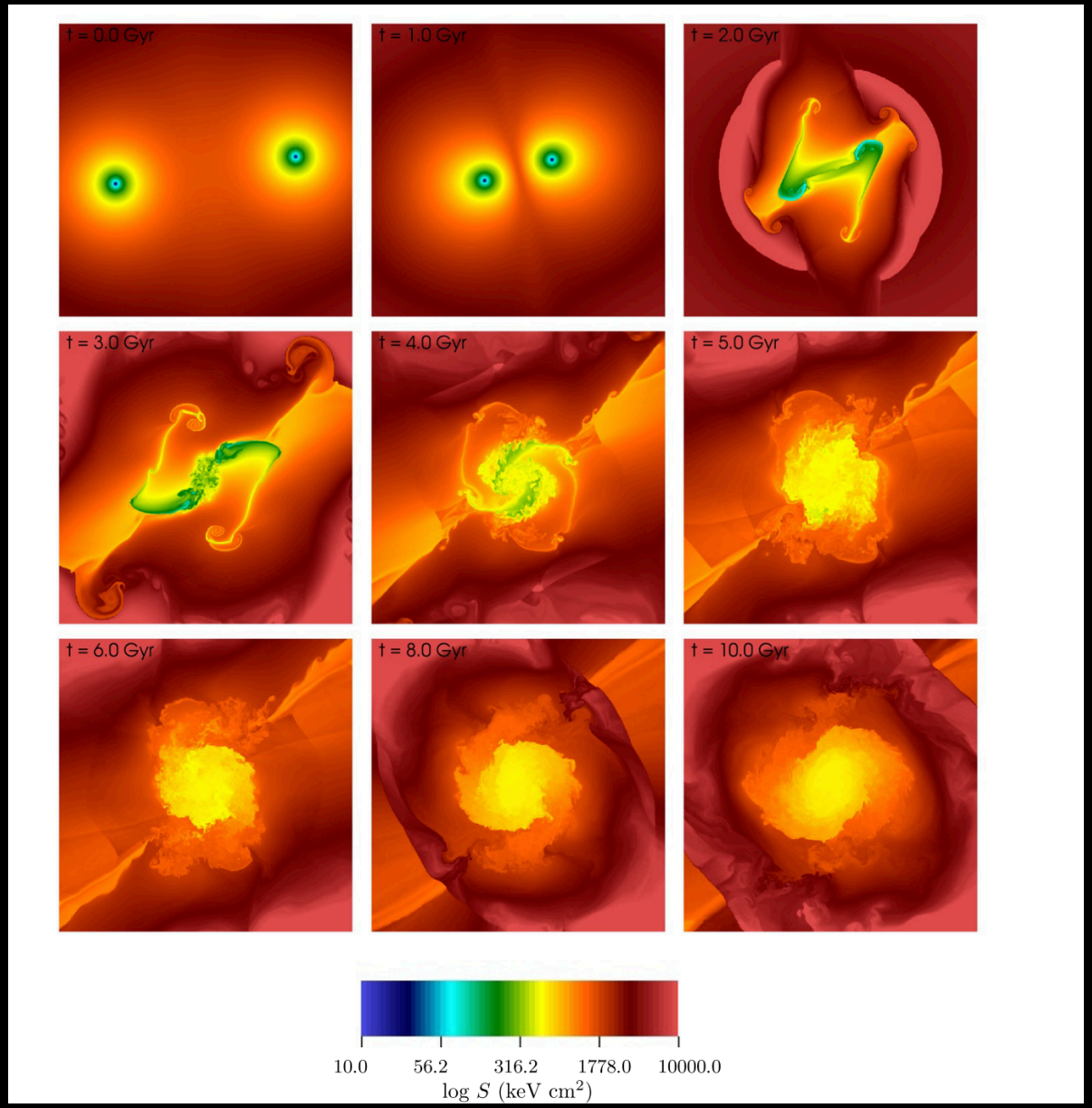
Major meregers are the **most energetic events** since the Big Bang and it can release up to $10^{64}$-$10^{65}$ on a time-scale of 1-2 Gyr.

They release their energy through shocks, turbulence and (re)acceleration of relativistic particles and amplification of magnetic fields

$$E \approx 9 \times 10^{63} \left(\frac{M}{10^{14} M_\odot}\right) \left(\frac{v}{3000\,\mathrm{km\,s^{-1}}}\right)^2 \mathrm{erg}$$

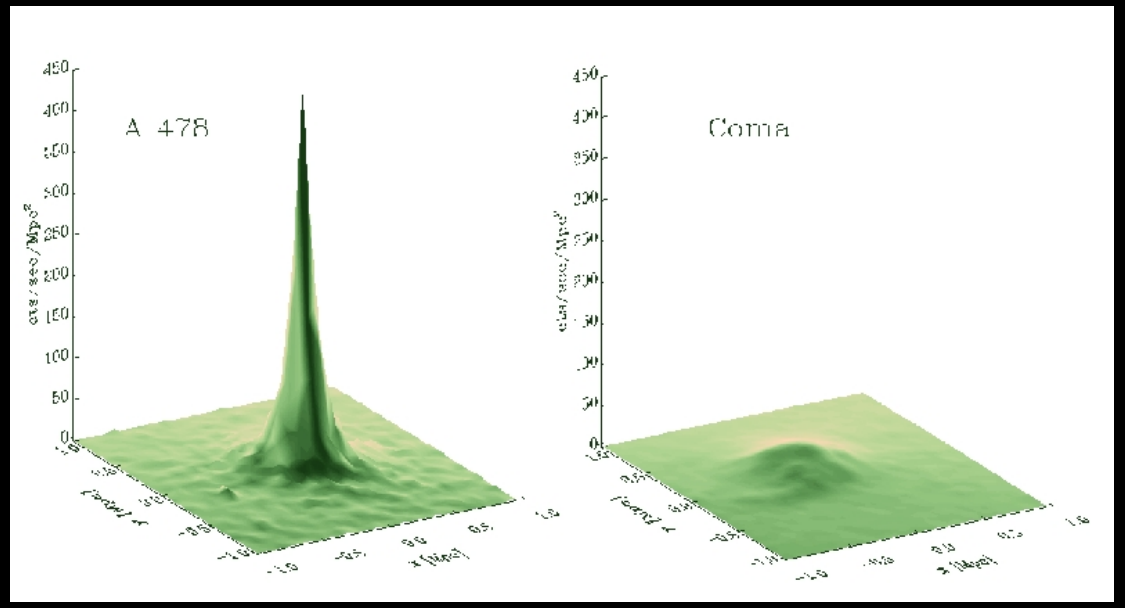
Sarazin 01

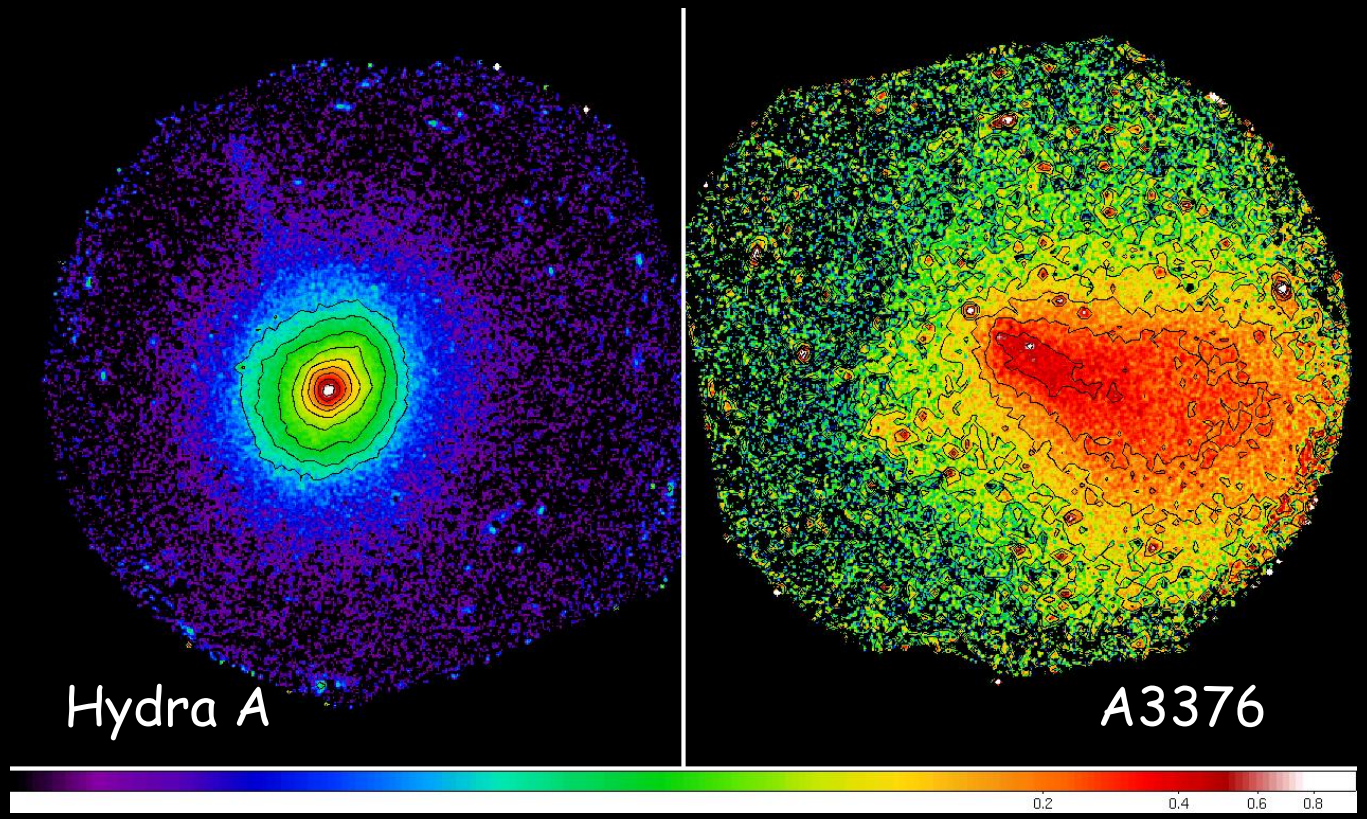
# The most energetic events since the Big Bang




ZuHone+11

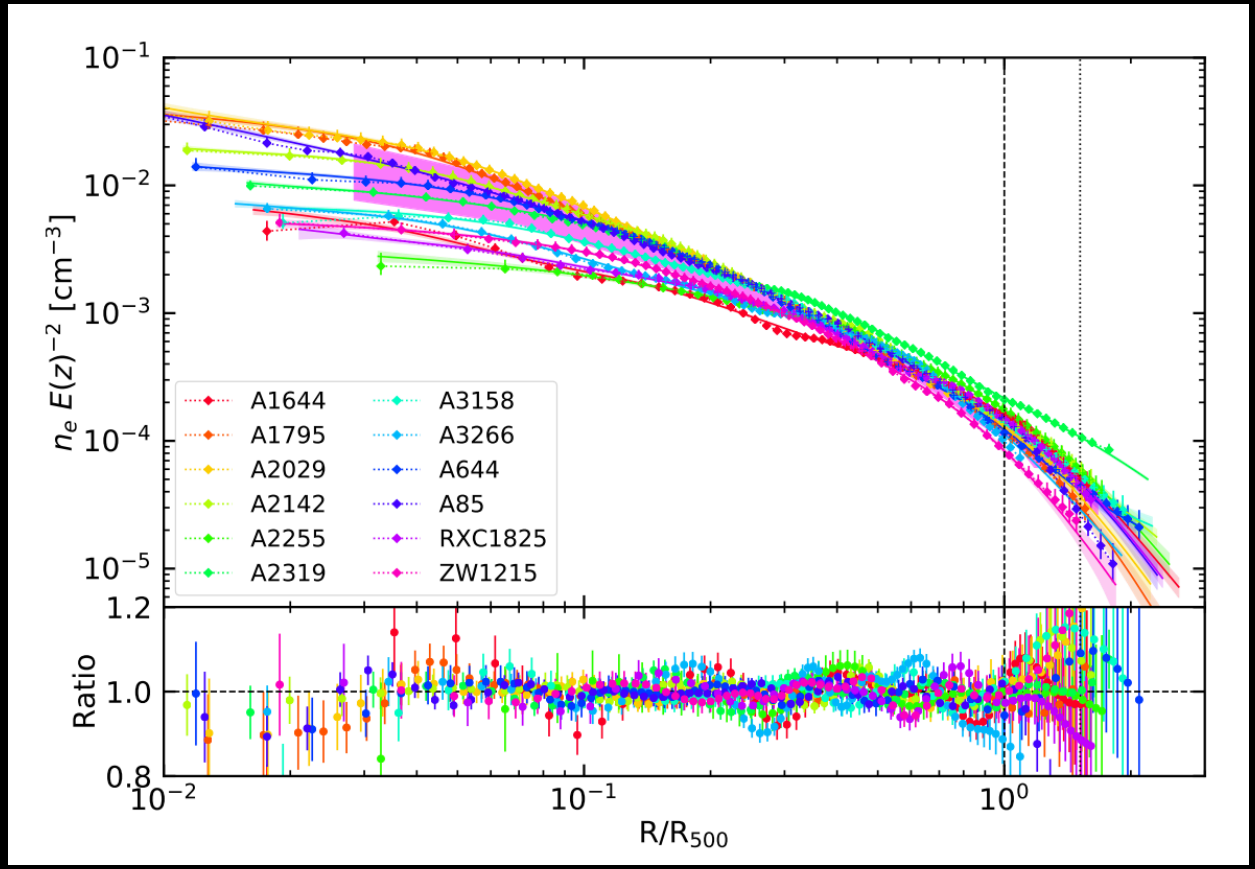
# CC (relaxed) vs NCC (mergers) clusters



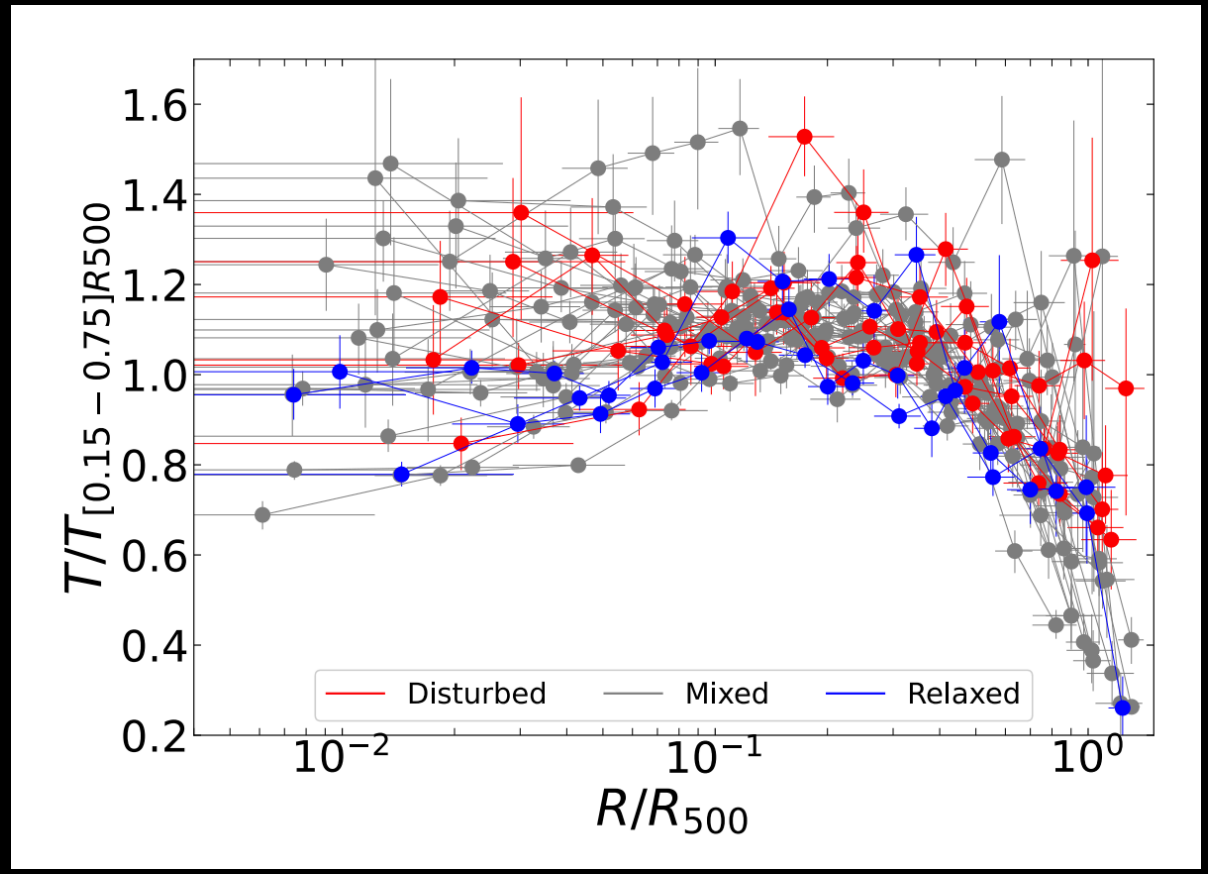




CC peaked surface brightness and regular isophotes, NCC no peak and irregular isophotes. XMM flux images (erg $cm^{-2}$ $s^{-1}$) scaled by the maximum value, same scale, same contours levels

# CC (relaxed) vs NCC (mergers) clusters



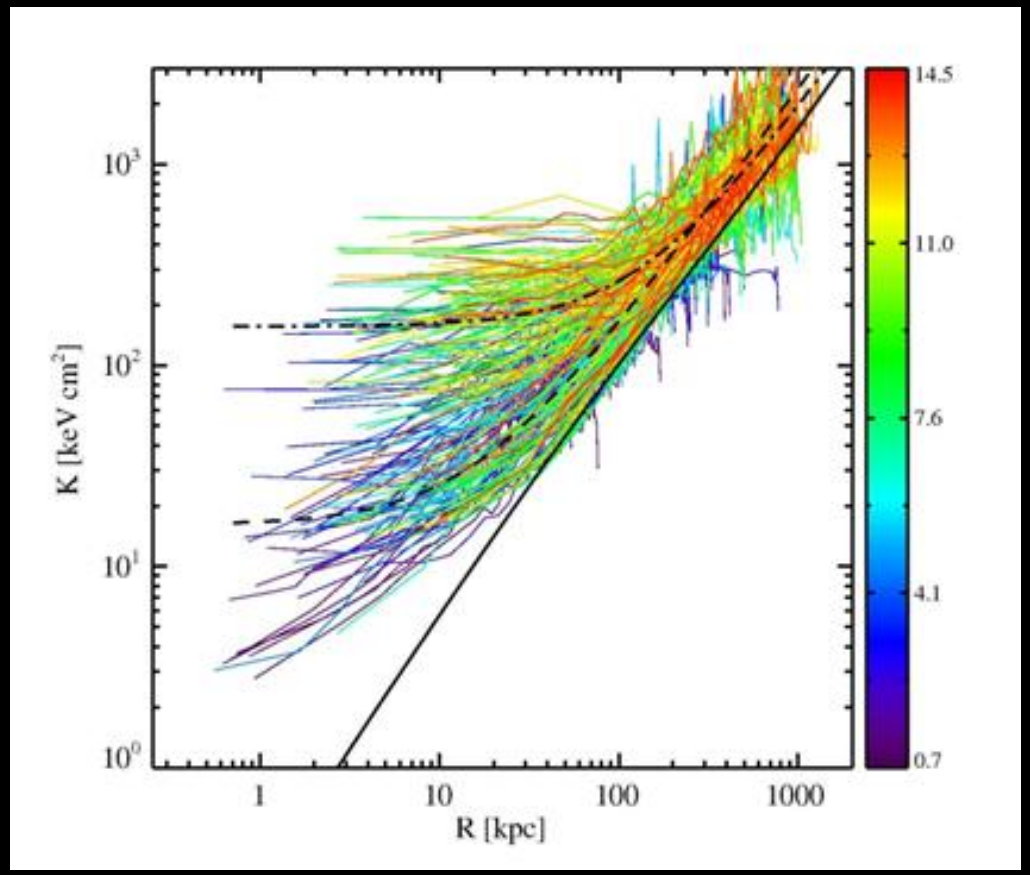

XCOP sample Ghiradini+19

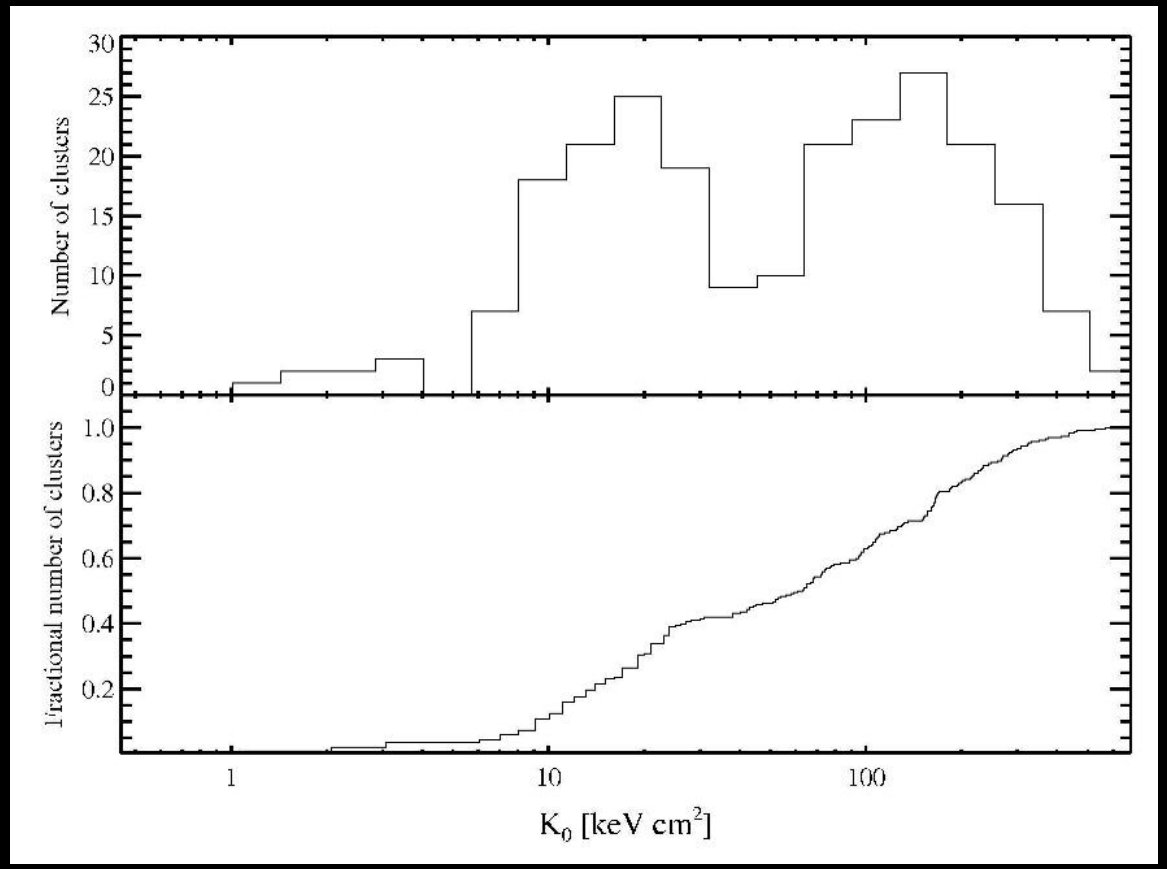



CHEXMATE sample Rassoetti+24

Scatter in the core (< 0.3 $r_{500}$), due to presence or absence of the cool core, more uniform at larger radii both in density and temperature

# CC (relaxed) vs NCC (mergers) clusters



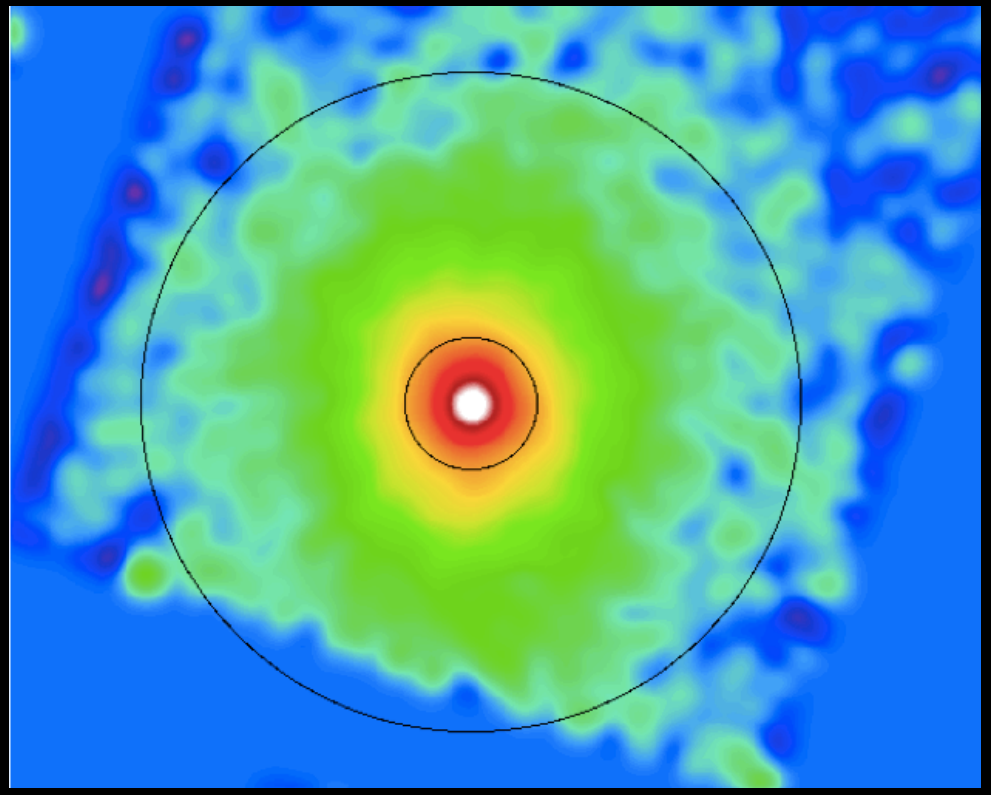



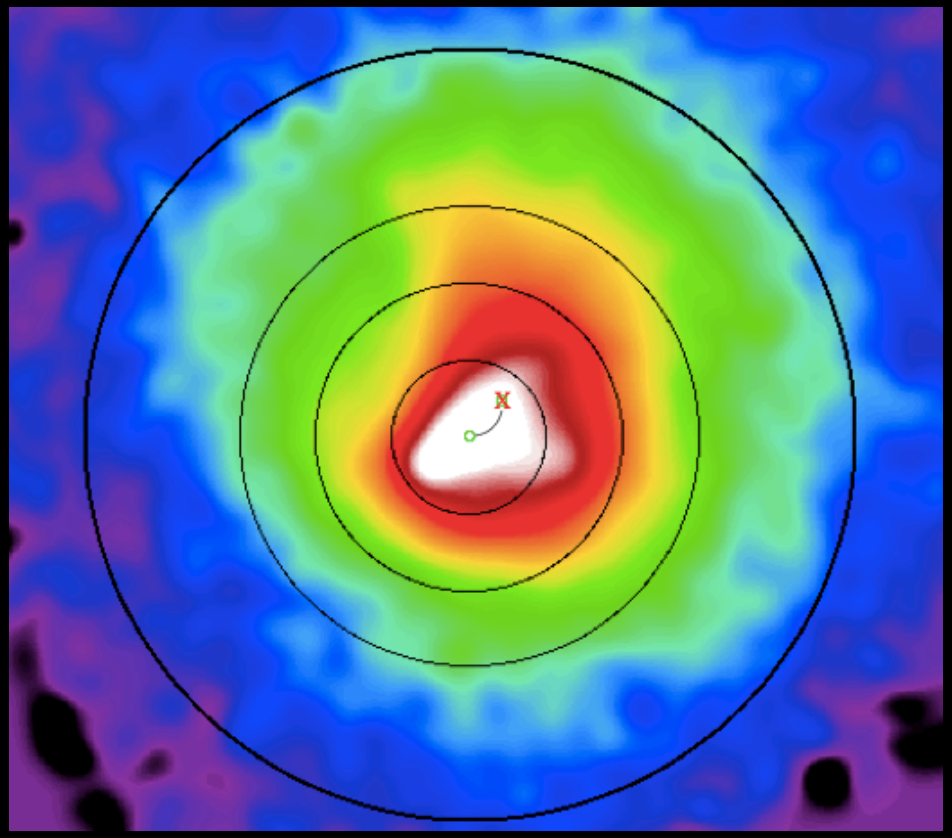

Cavagnolo+09

$$K(r) = K_0 + K_{100}\left(\frac{r}{100\ kpc}\right)^{\alpha}$$

The way to encode that is in the entropy profiles with a clead difference in the core entropy

# X-ray morphology as a dynamical state indicator



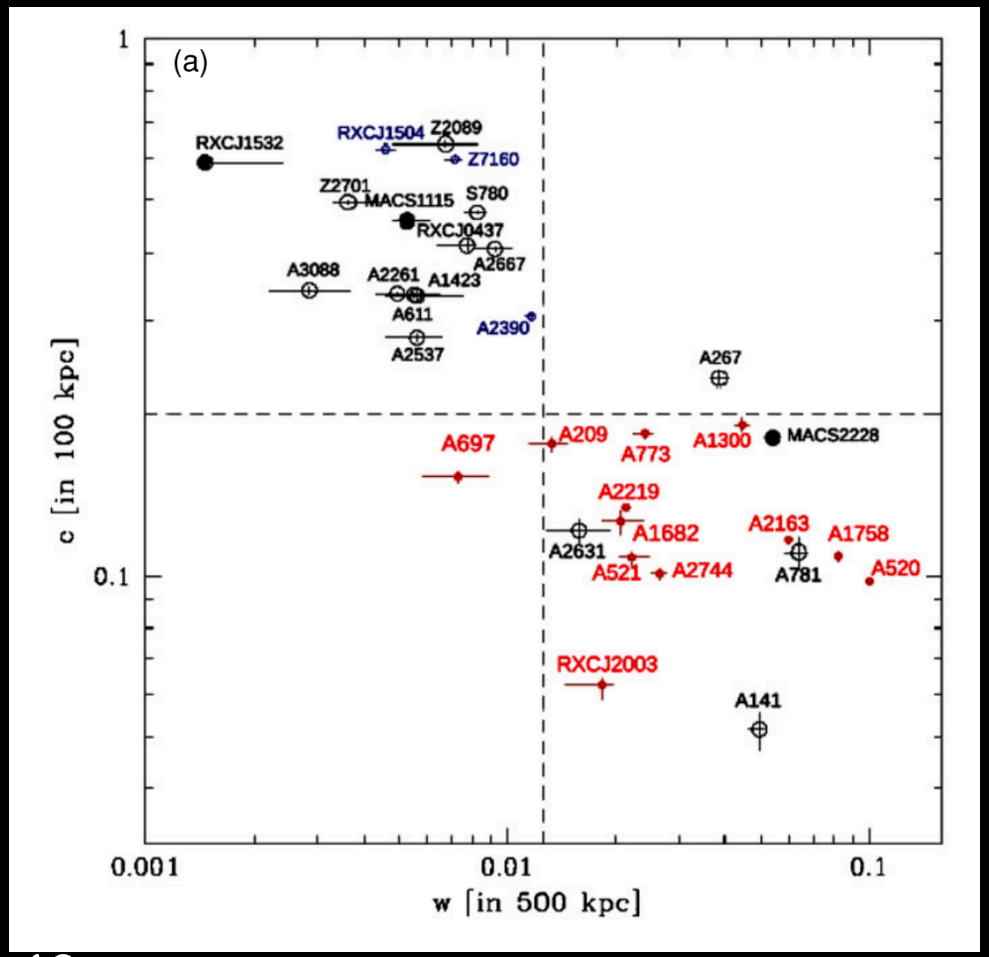


$$c = \frac{SB(r < 100kpc)}{SB(r < 500kpc)}$$

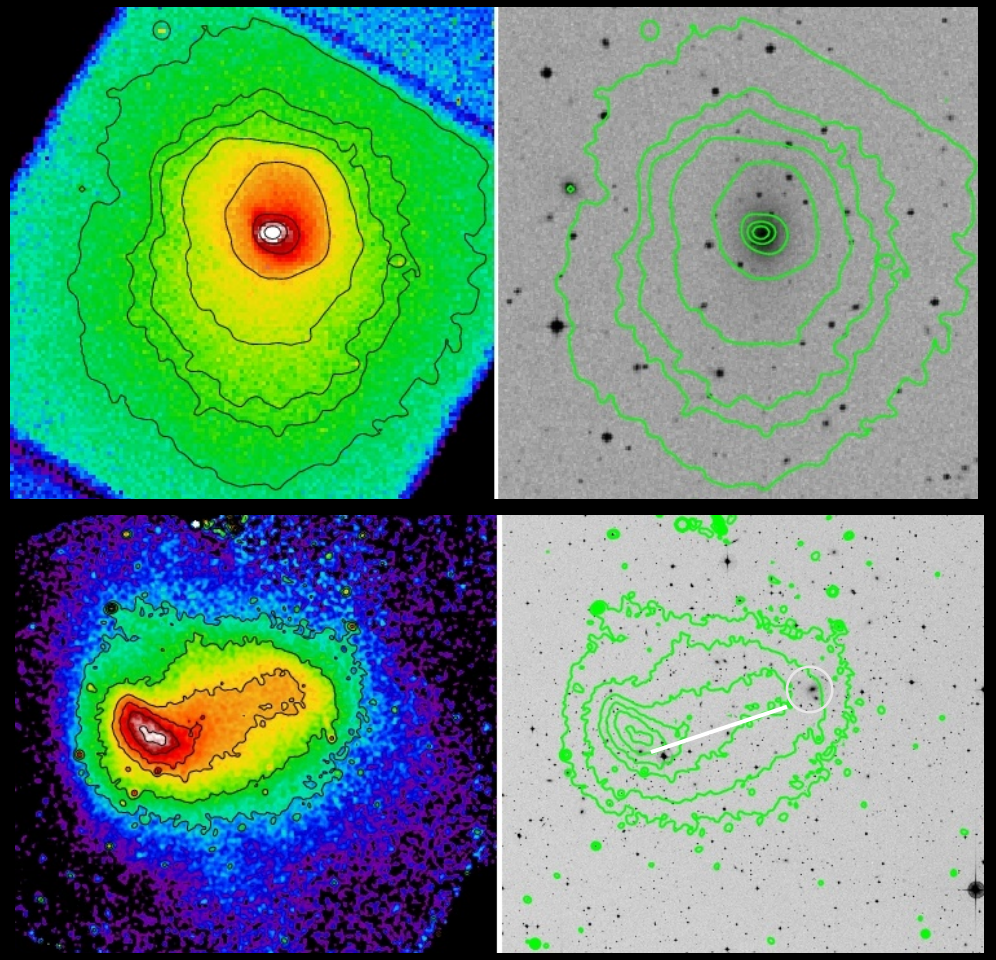
$$w = \left[ \frac{1}{N-1} \sum_{i=1}^{N} (\Delta_i - \langle \Delta \rangle)^2 \right]^{\frac{1}{2}} \times \frac{1}{R_{ap}}$$

The sufficient parametrization is to have a parameter quantifying the presence of the core and another characterizing the distribution of the X-ray isophotes

# X-ray morphology as a dynamical state indicator



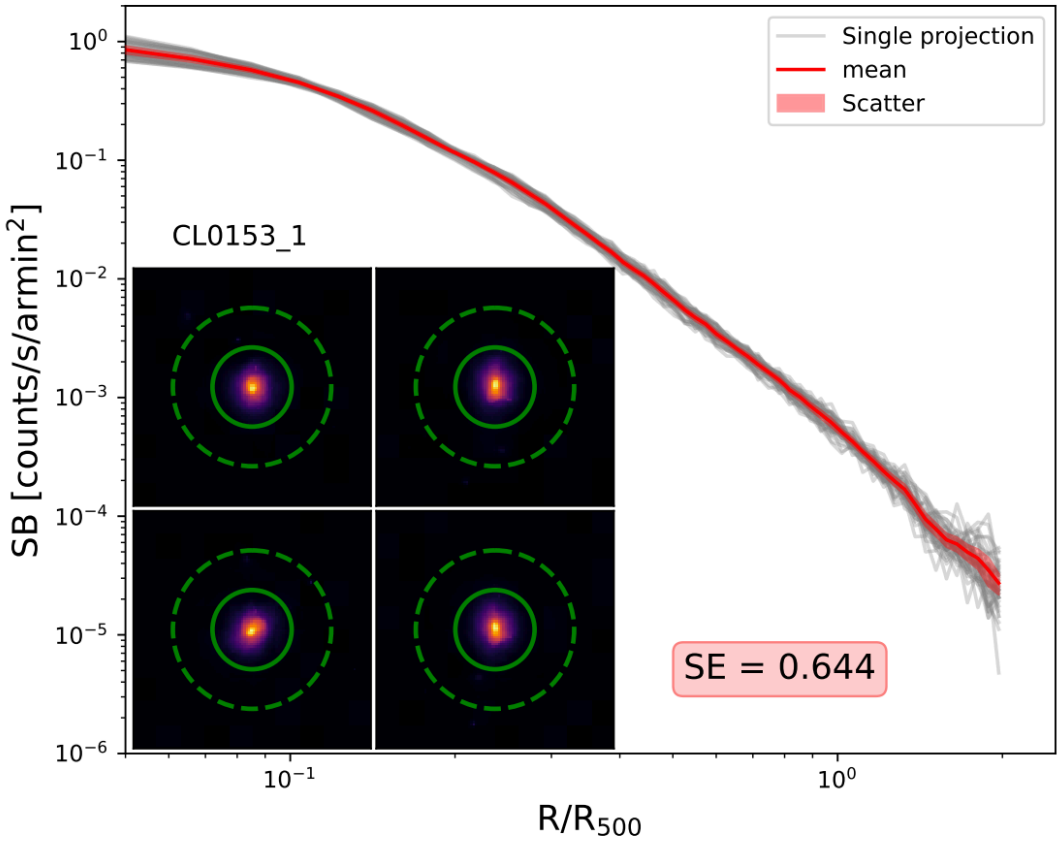

Cassano+10

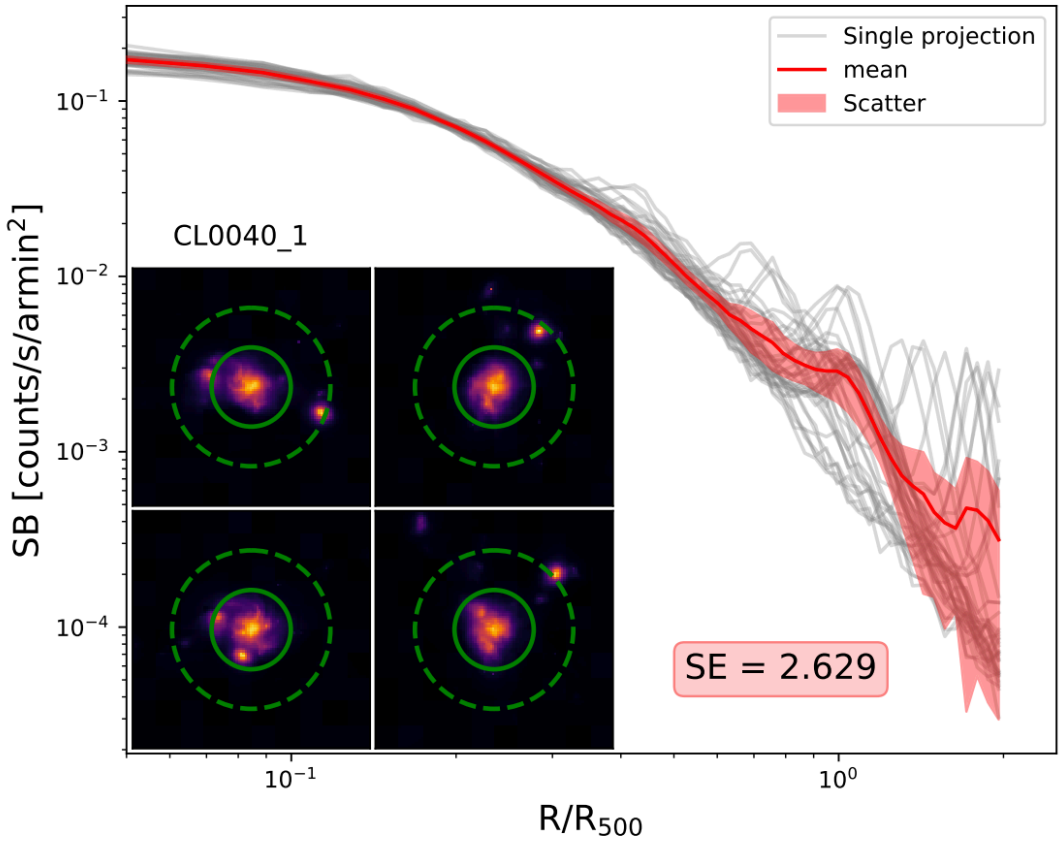


Rossetti+16

X-ray morphology correlates well with other signs of dynamical disturbance, such as presence of giant radio halos, presence of optical substructure, X-ray peak-BCG offset

# X-ray morphology: caveats

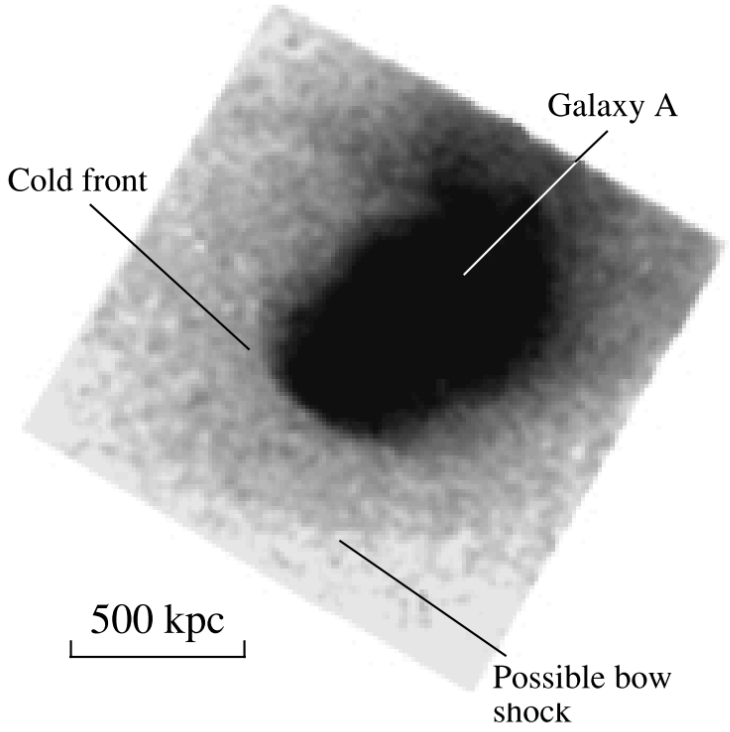


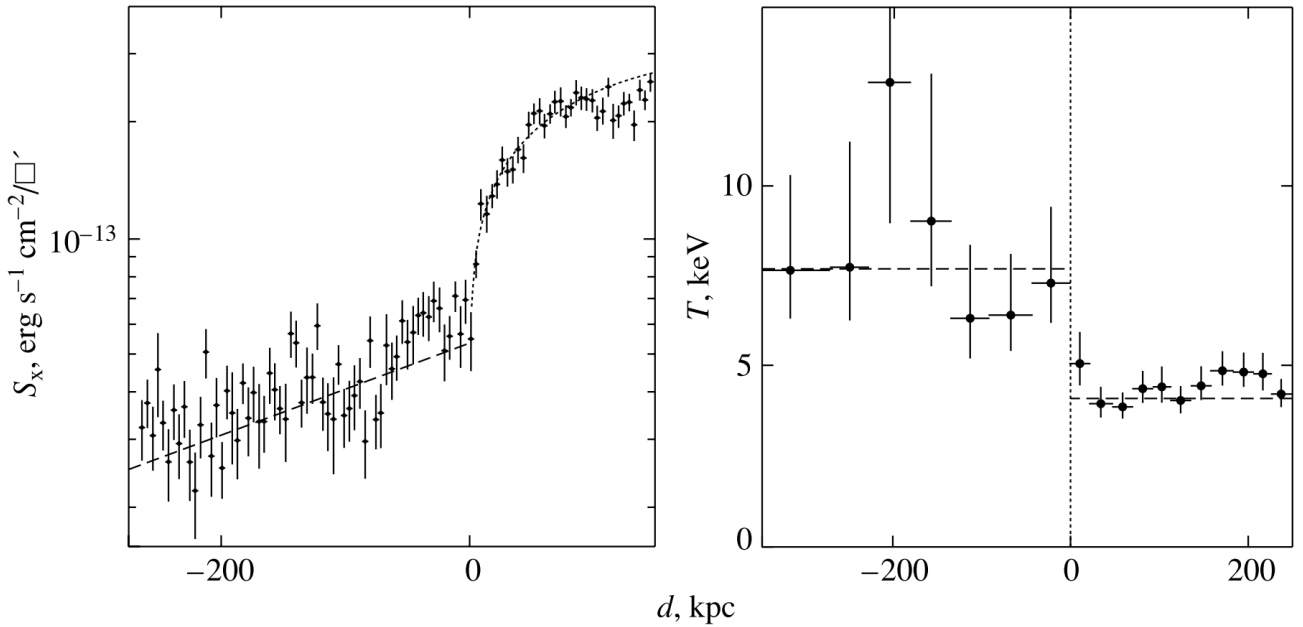




Veronesi+25

Systematics due to projection effects, sensitivity to 1-2 Gyr around pericenter passage

# Cold Fronts

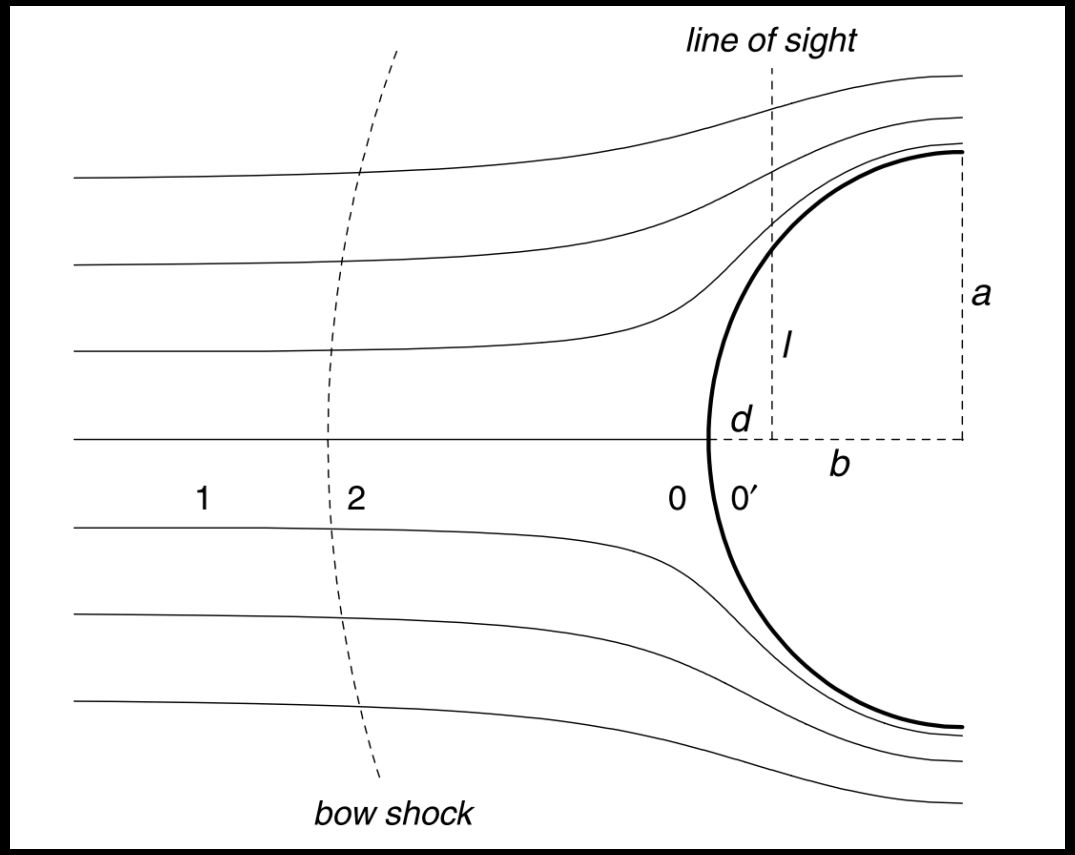


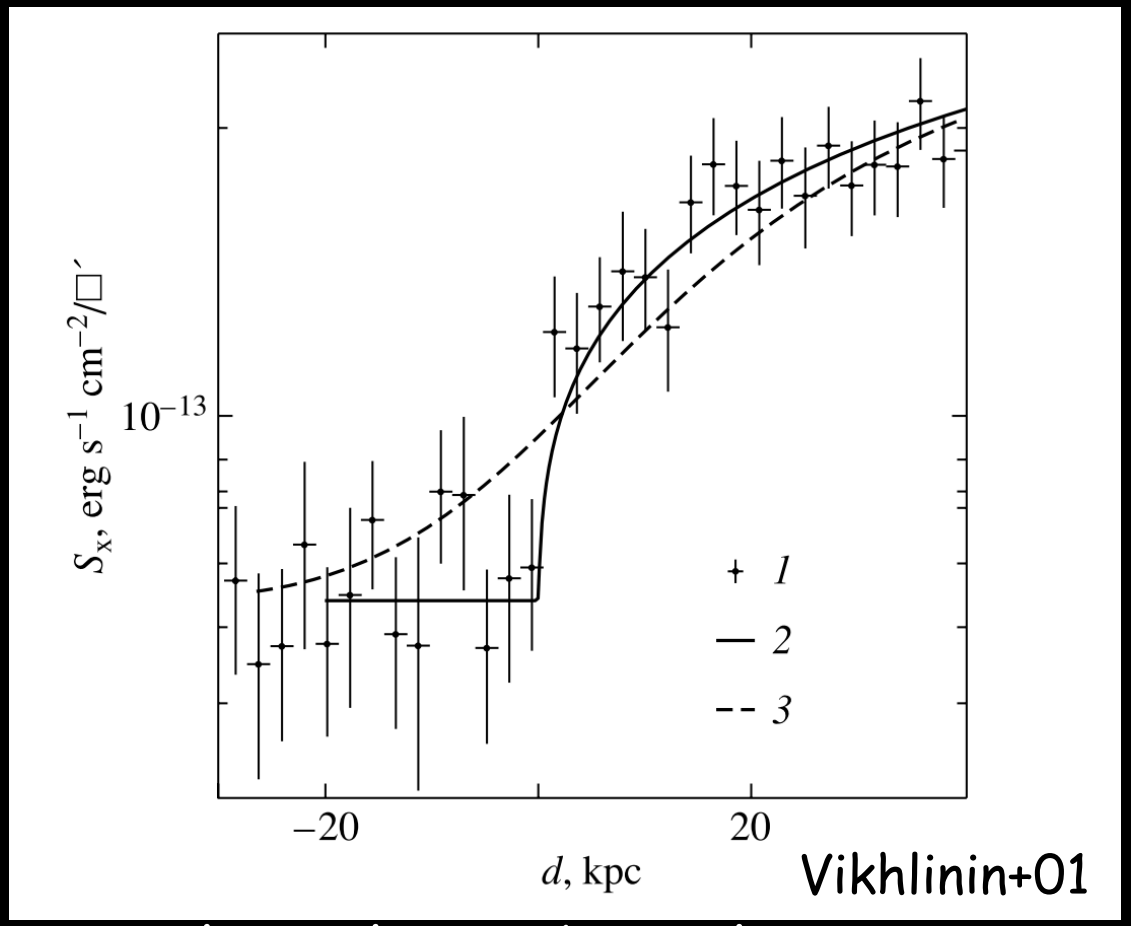




Vikhlinin+01

The high quality Chandra images showed routinely sharp surface brightness discontinuities (i.e density jumps) but with the "wrong" sign of the temperature jump

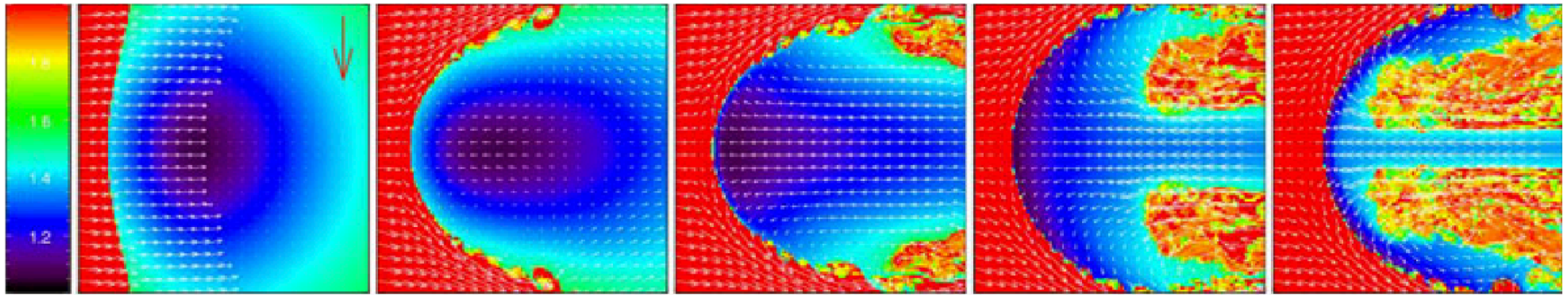
# Cold Fronts

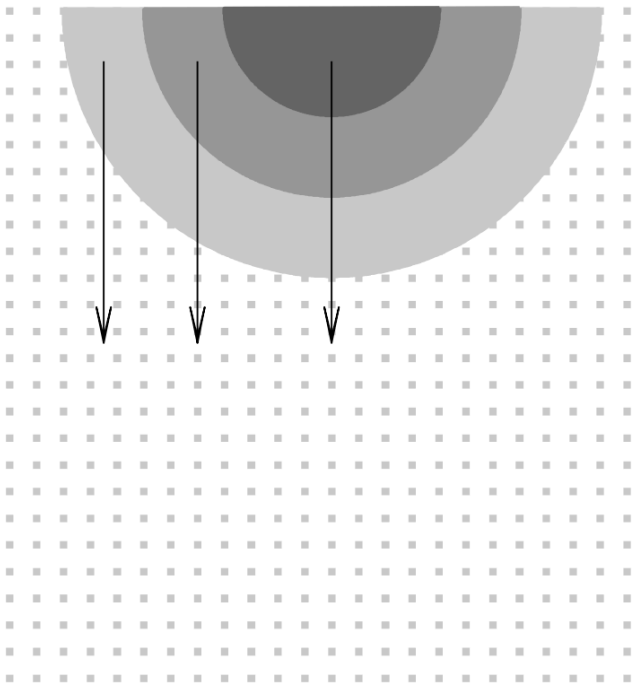


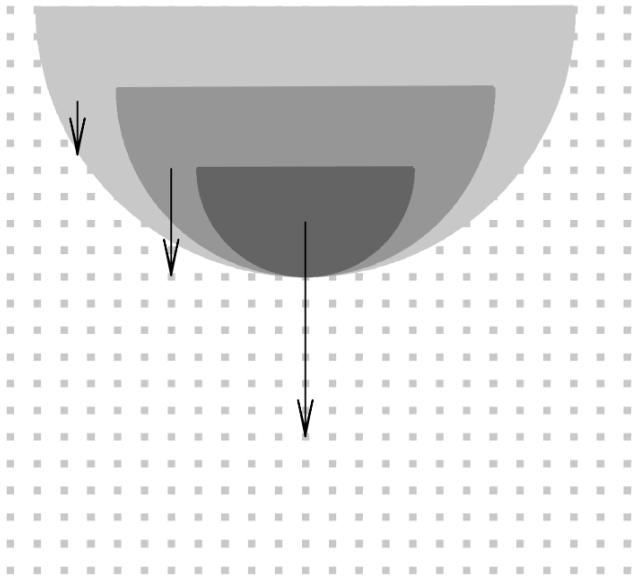




They form when a galaxy, group or cluster moves through a ambient hotter plasma and the resulting head wind strips off the outer layer of its atmosphere. They are interesting probes of plasma physics, they are very narrow of the order of few kpc, smaller than the Coulomb mfp.

# Cold Fronts



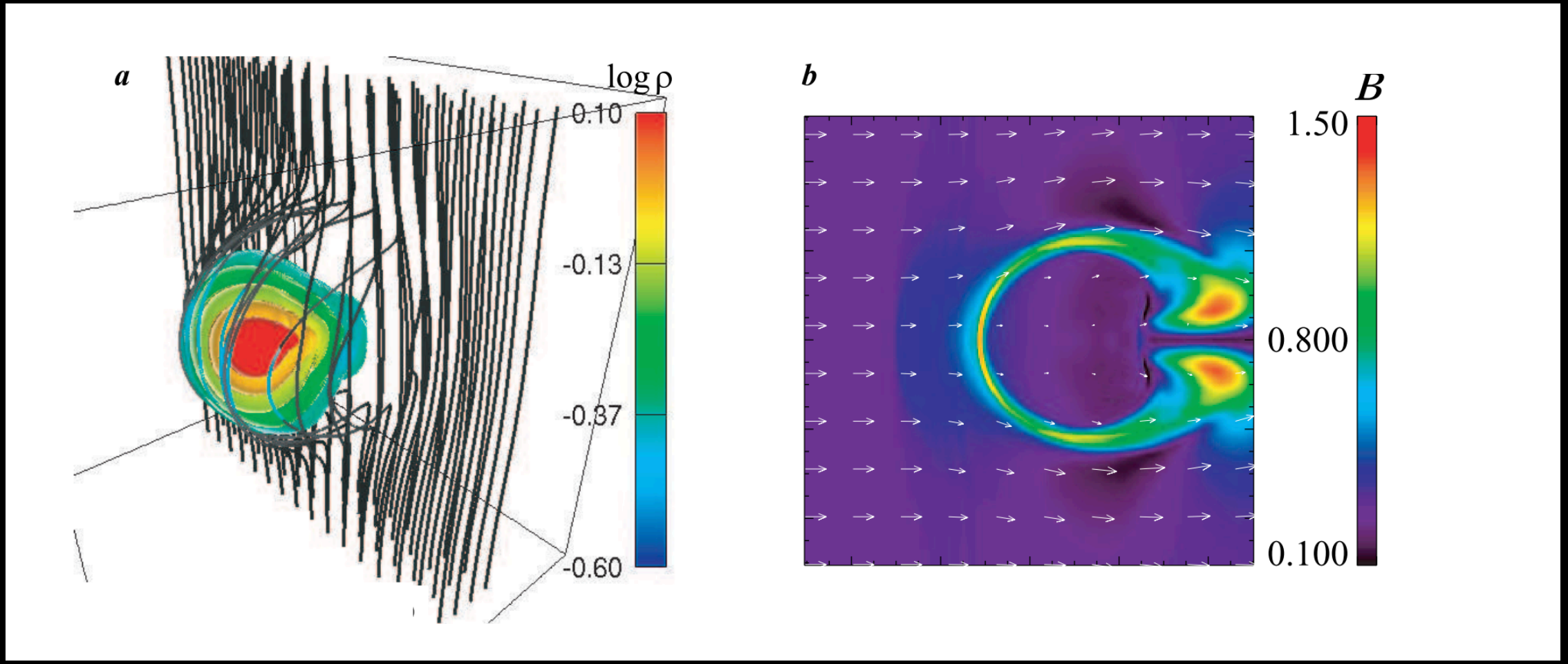





Heinz+03

They are a pure hydrodynamical phenomenon as the area-proportional drag force causes differente deceleration of gas at different densities which brings the densest gas forward

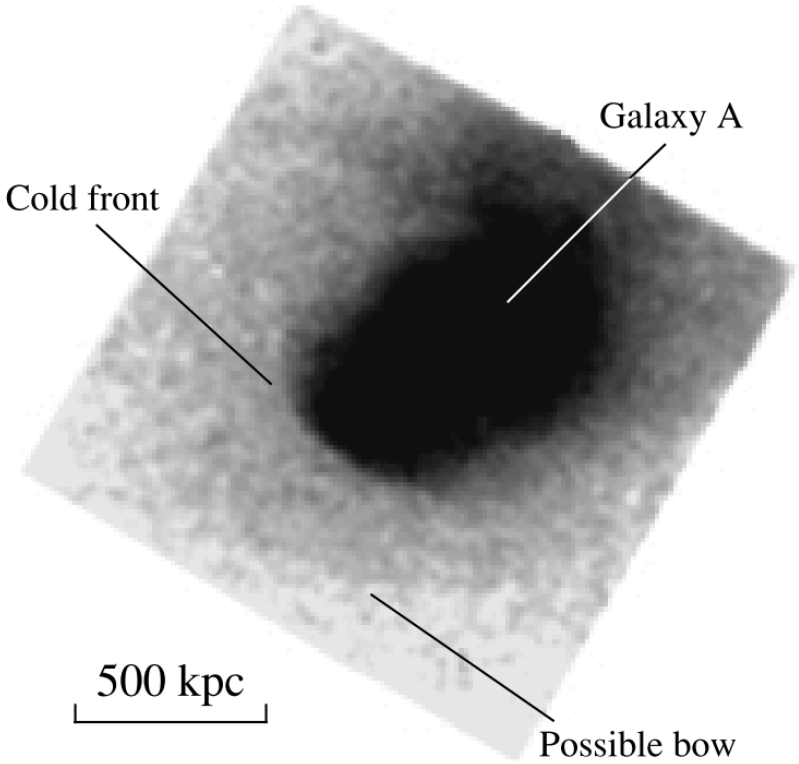
# Cold Fronts




Asai+05

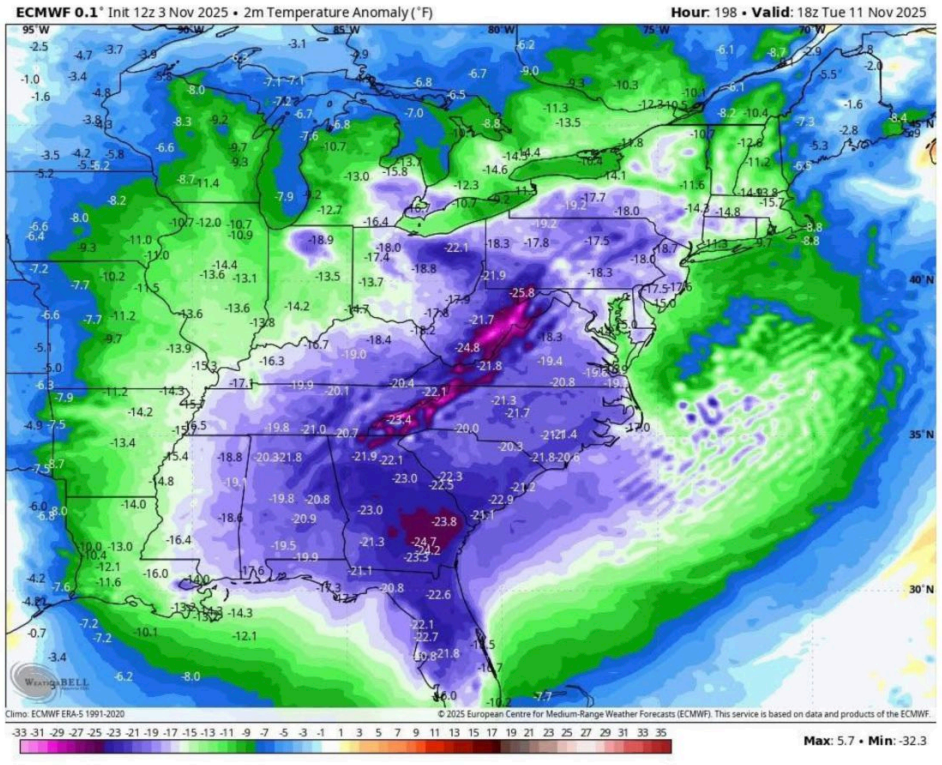
However the sharpness of cold front is better explained by a magnetic field "draping" the cold front

# Cold Fronts

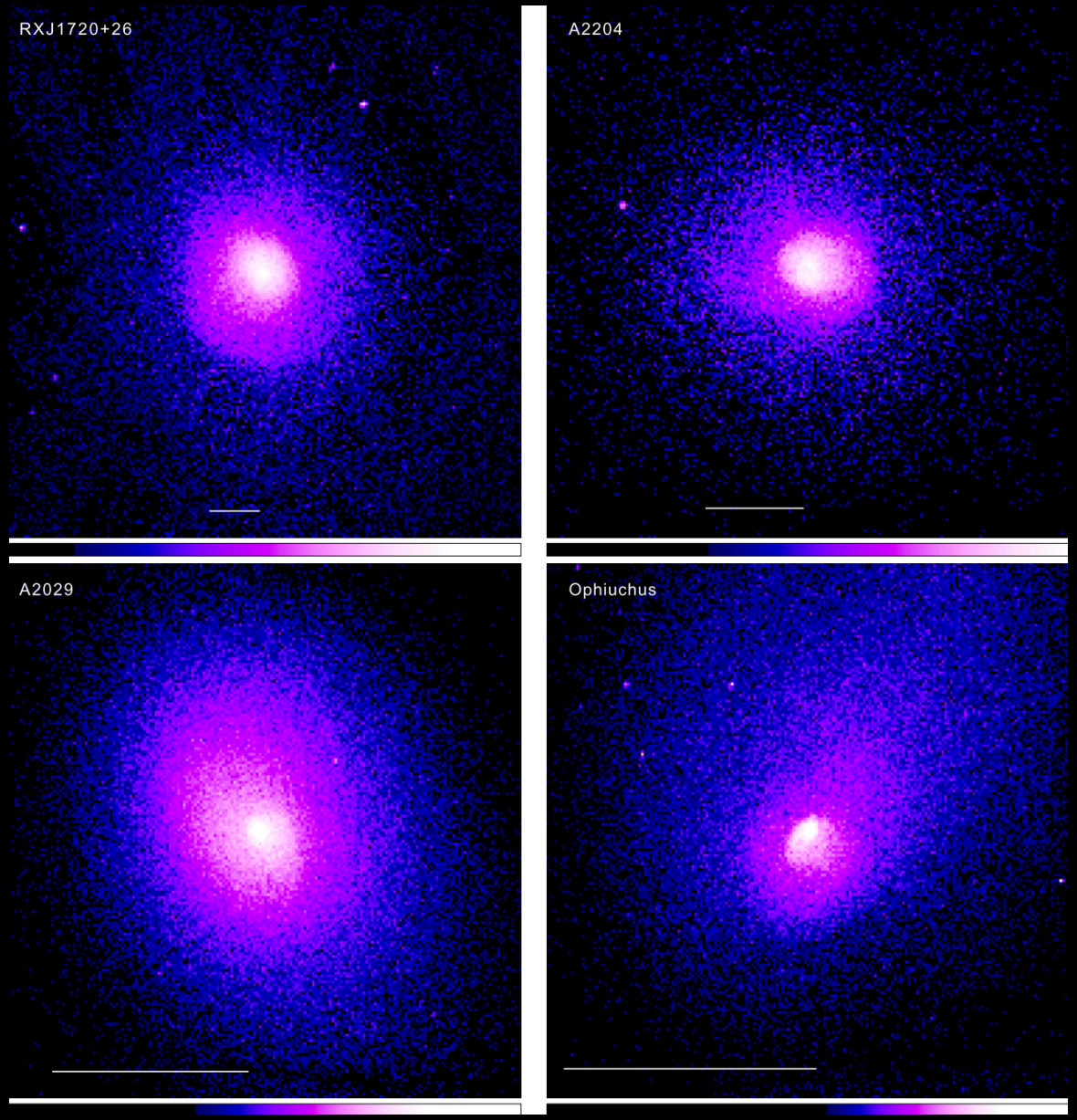



## Winter Weather Map Shows 'Big-Time Cold Front' Set To Hit US

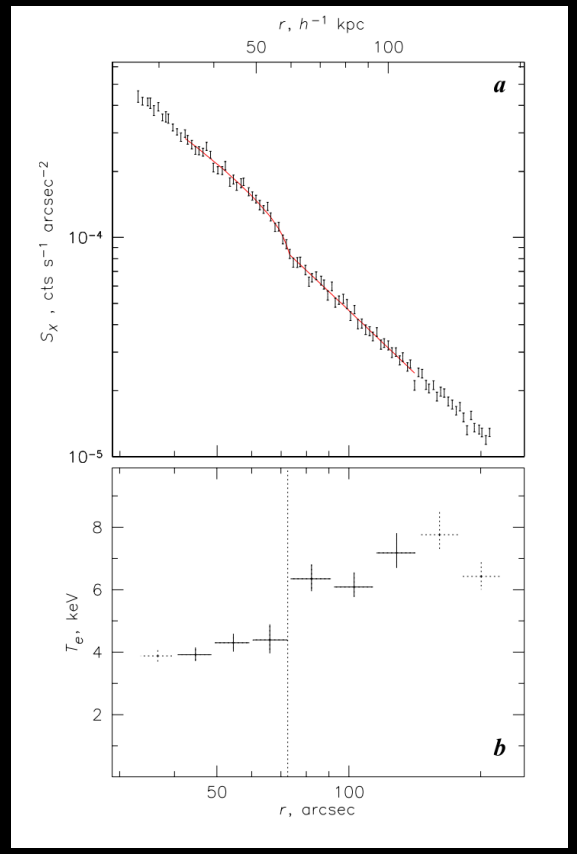
PUBLISHED
NOV 04, 2025 AT 08:17 AM EST



# Sloshing Cold Fronts




Puzzling evidence that cold fronts are present also in CC, dinamically relaxed clusters !



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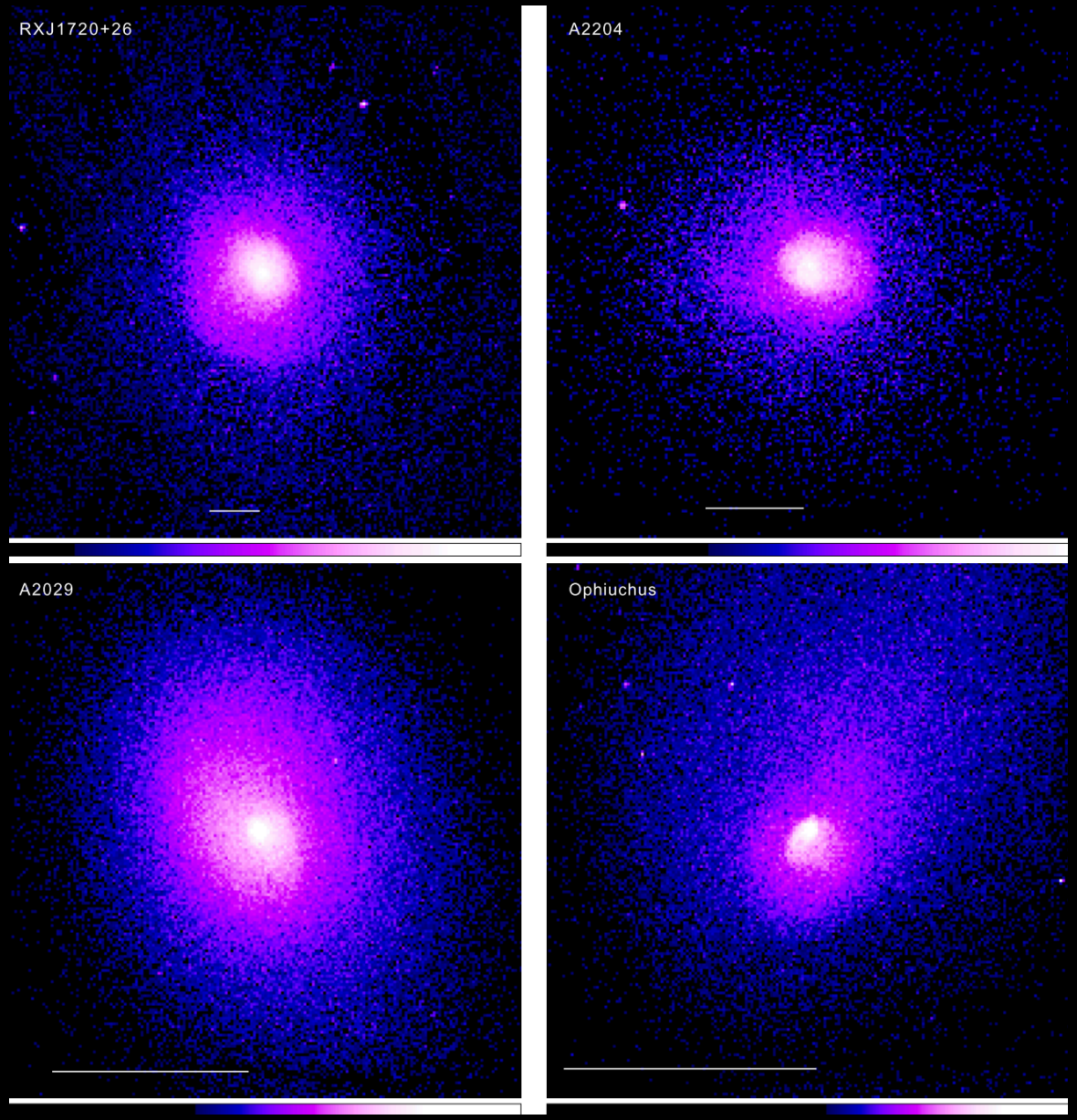
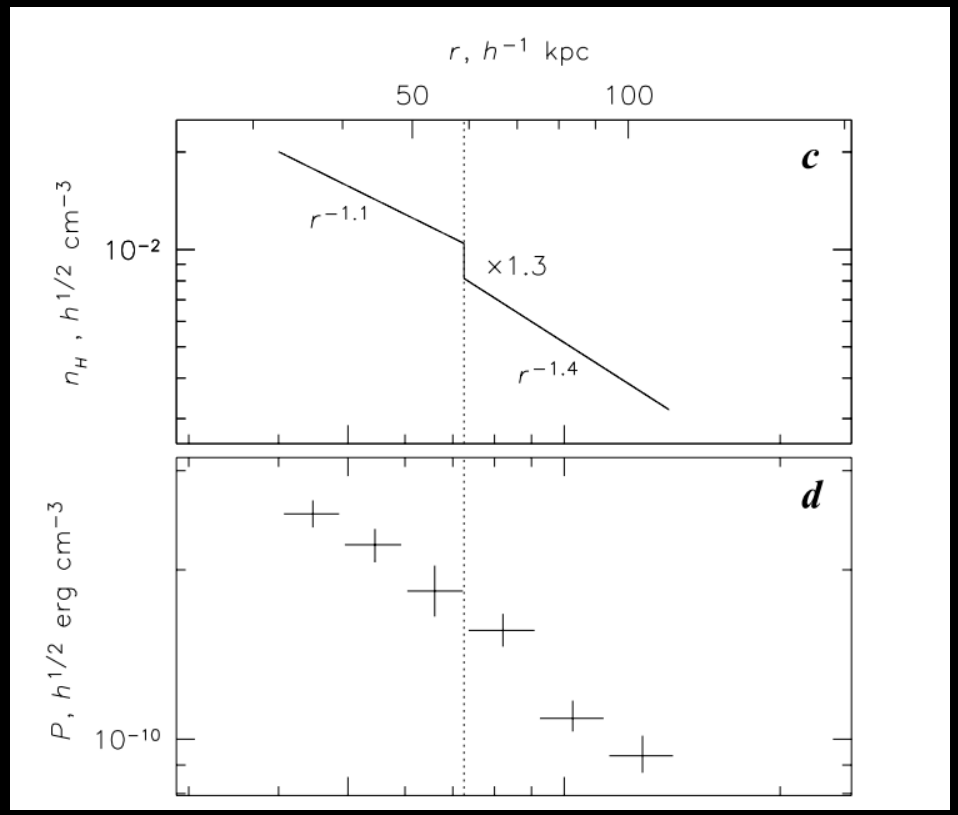
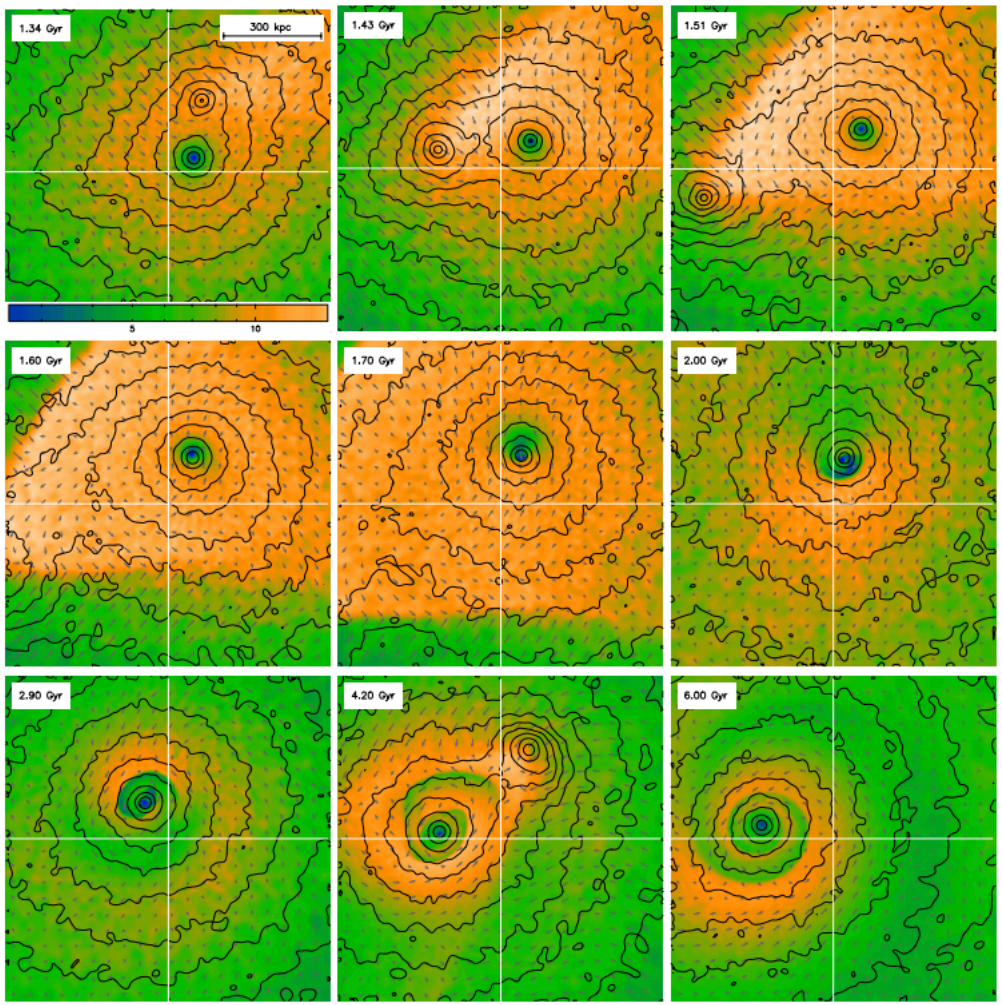



Pressure is continuous across the front



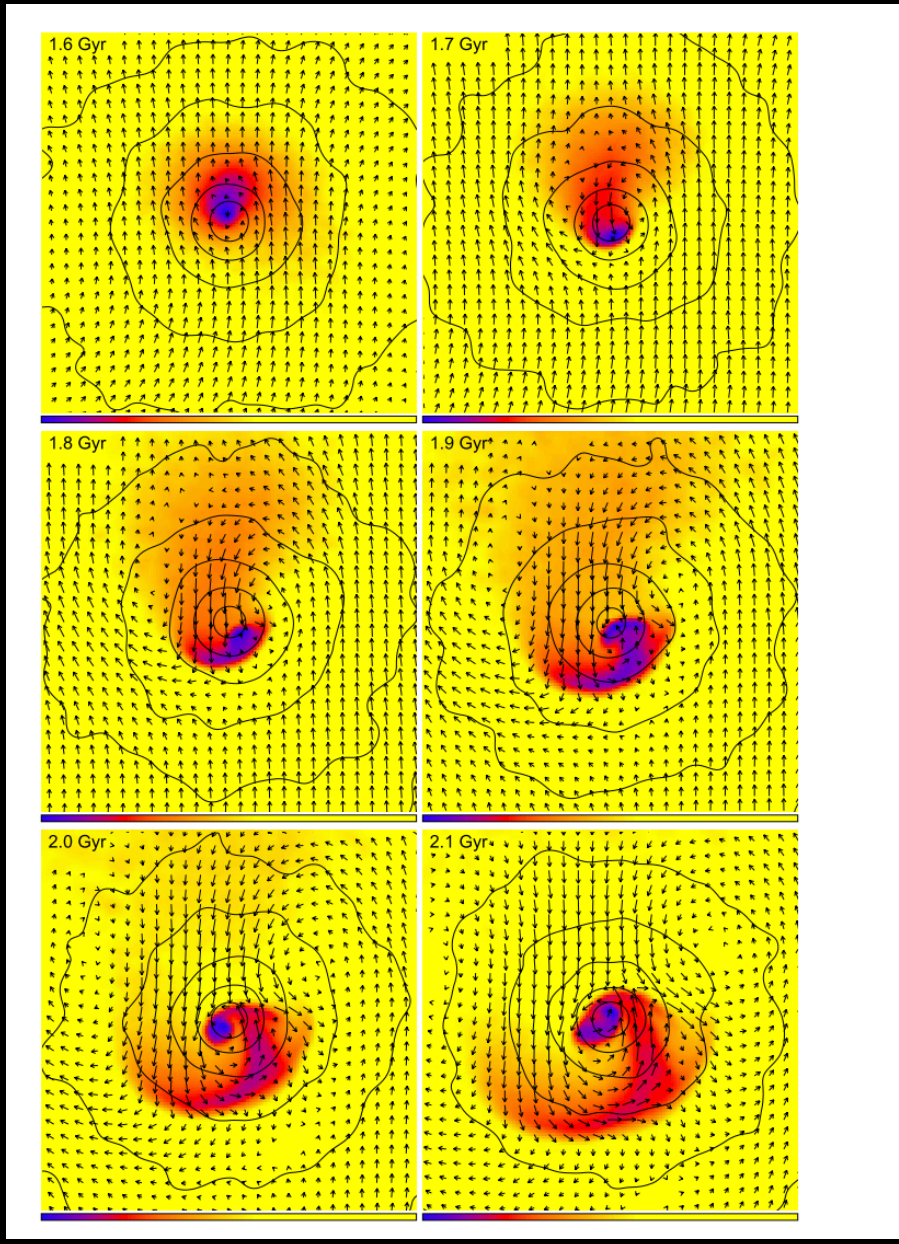
# Sloshing Cold Fronts




Ascasibar

&

Markevitch 06




Off-axis minor mergers make the gas oscillates, "sloshing" around the equilibrum position

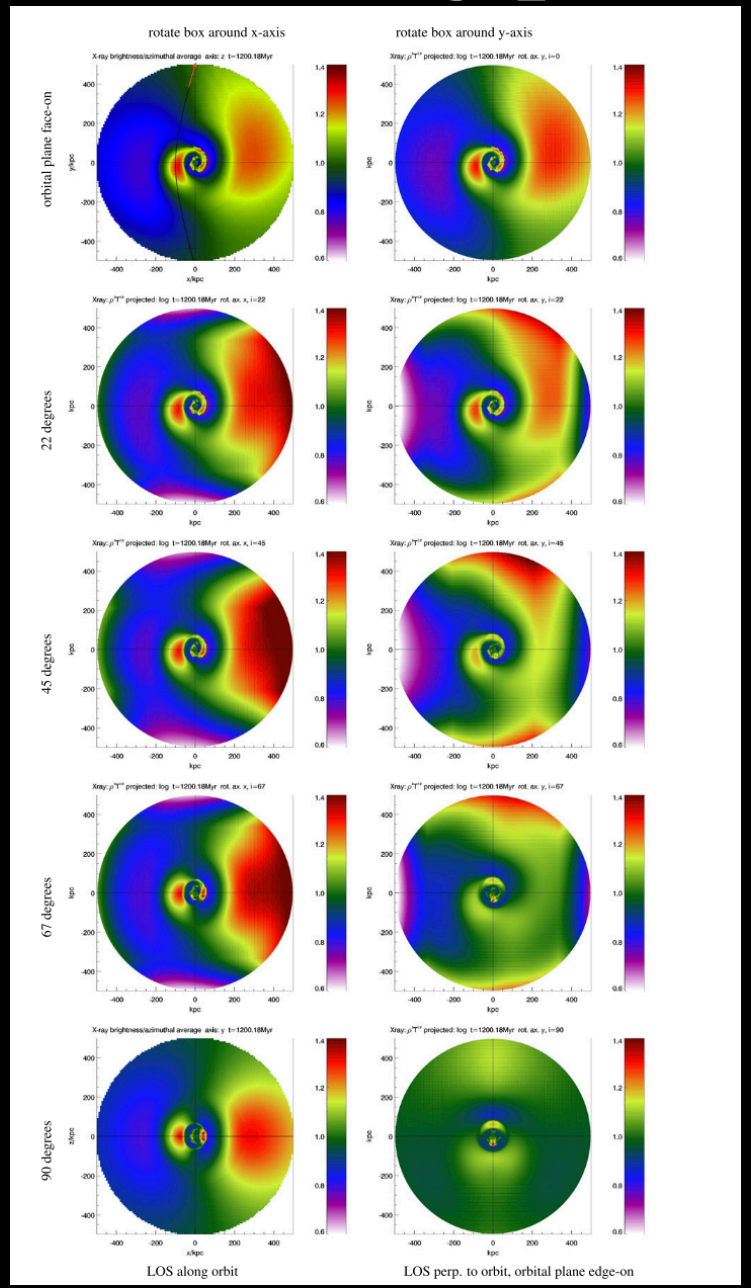
# Sloshing Cold Fronts

Fig. 16. The origin of cold fronts in the dense cluster cores.

Markevitch & Vikhlinin 07

Clearly just an analogy, but possibly a better way to remember it

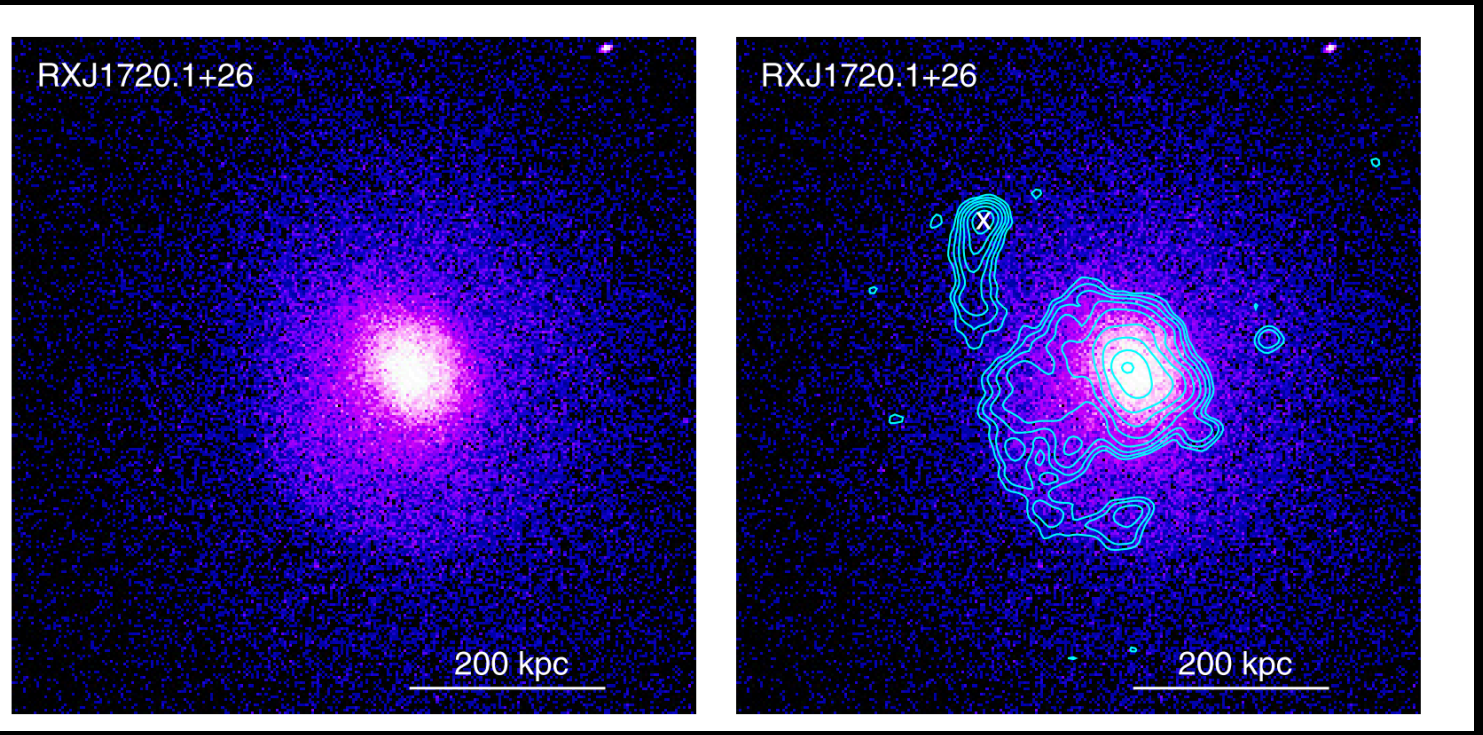
# Sloshing pattern as a record of the merger

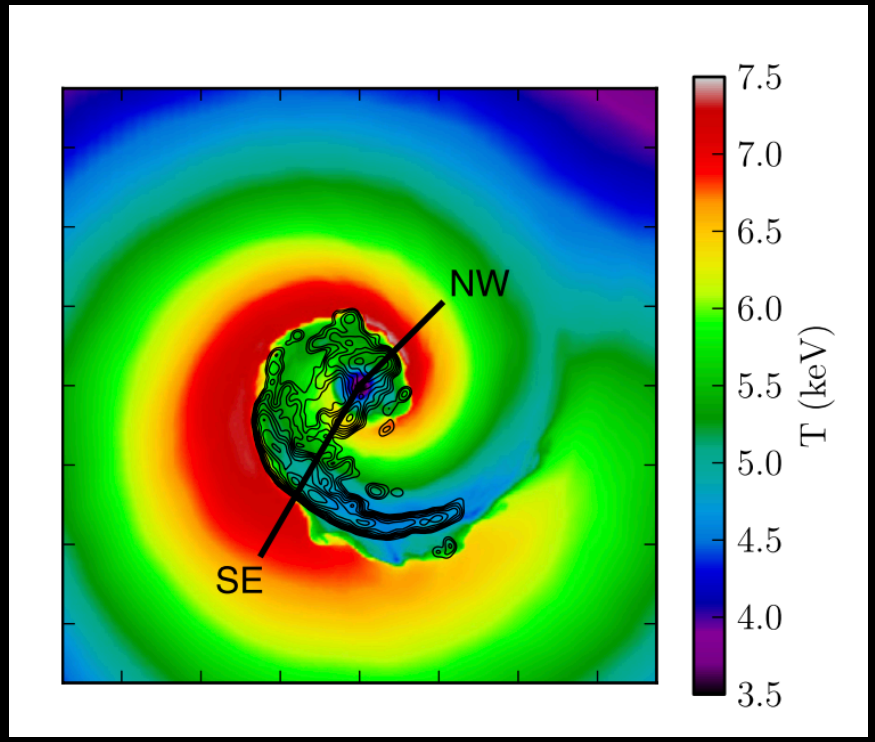



The combination of sloshing, angular momentun and viewing angle determines wether cold fronts are arranged in a spiral or in staggered arcs on opposite sides of the cluster core. They are visible out to 1-2 Gyr

Credits: E. Roediger

# Sloshing and mini-radio halos

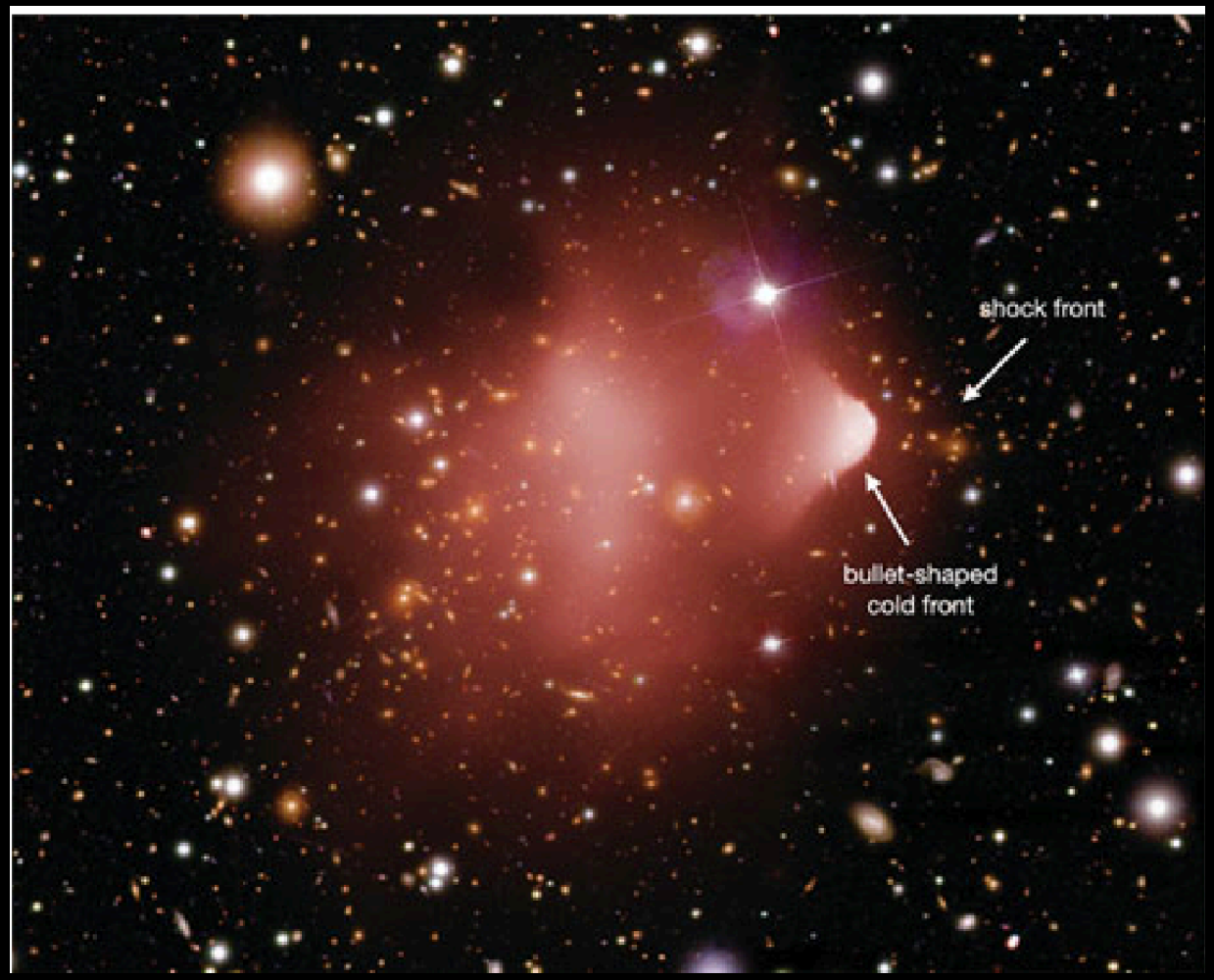


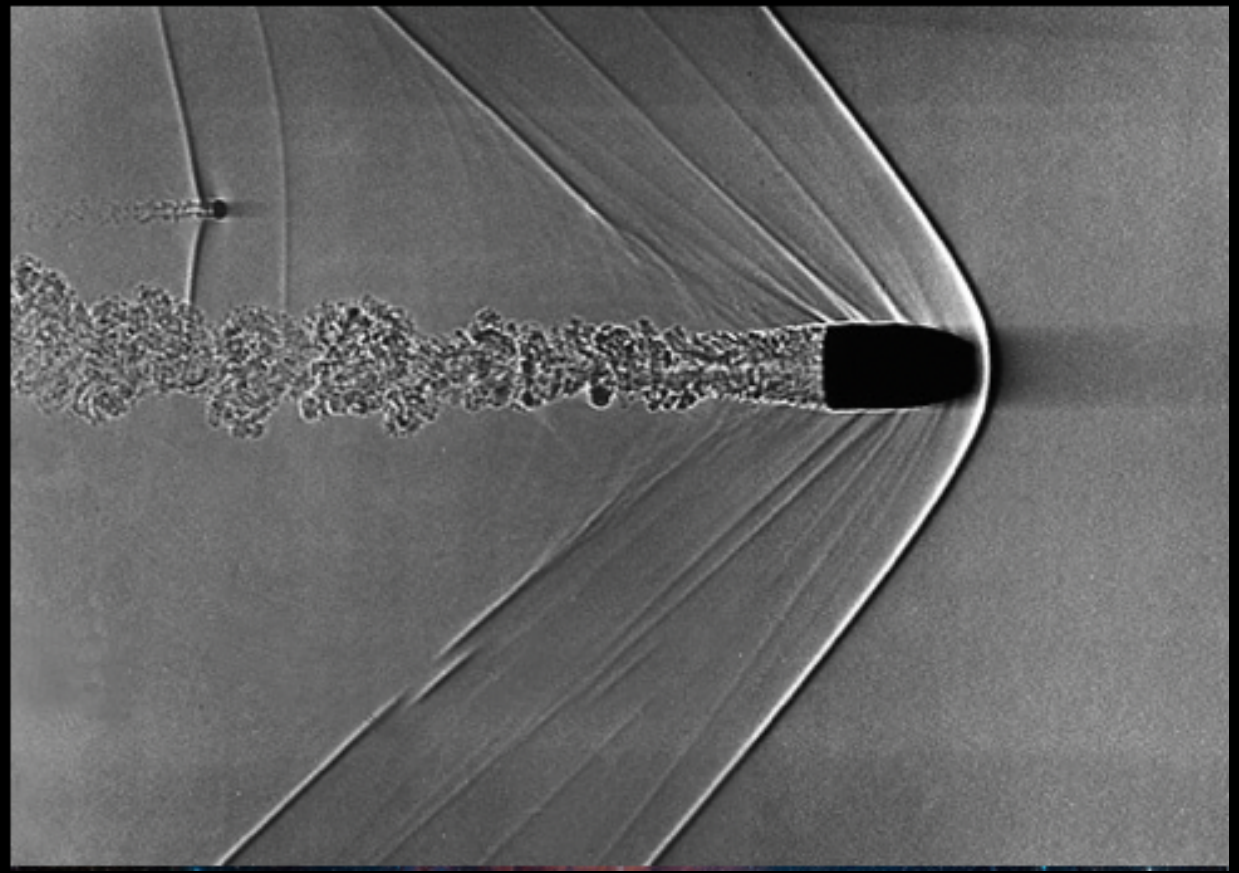




ZuHone+11

Mini-halos are though to be generated by the reaccleeration of electrons caused by turbulence generated by sloshing motions. MHD simulations have shown that sloshing motions generate turbulence with velocities of the order 50-200 km/s on spatial scales of 100 kpc and is able to turbulent reaccelerate seed electrons.

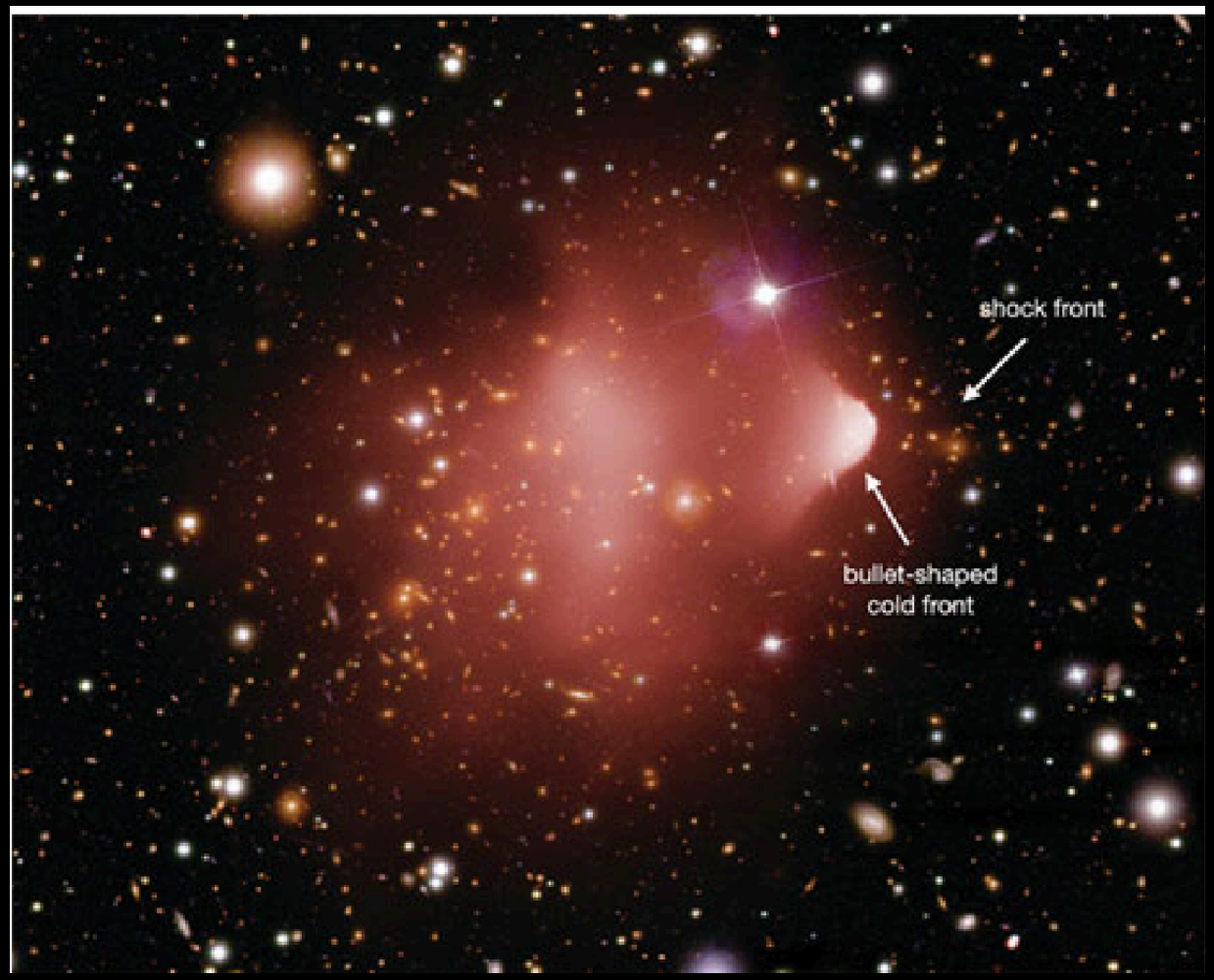
# Shock Fronts

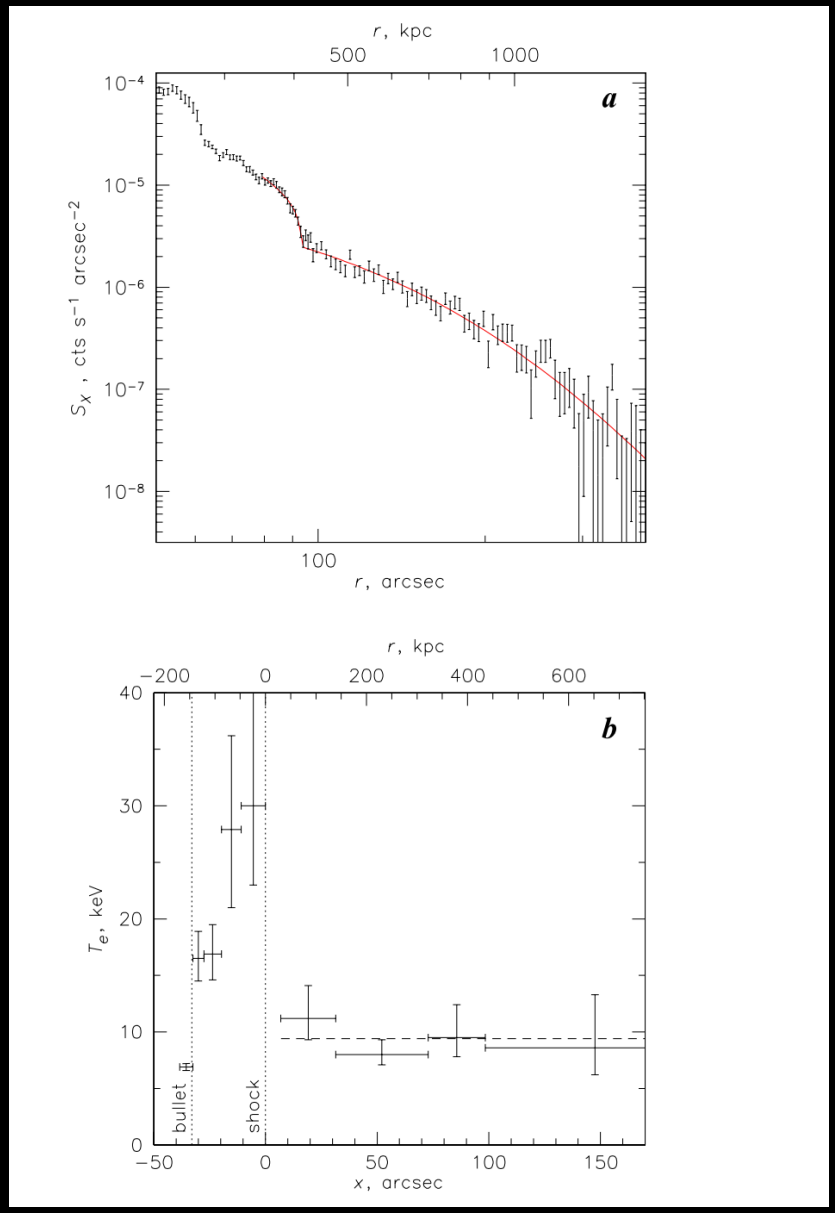


Markevitch & Vikhlinin 07

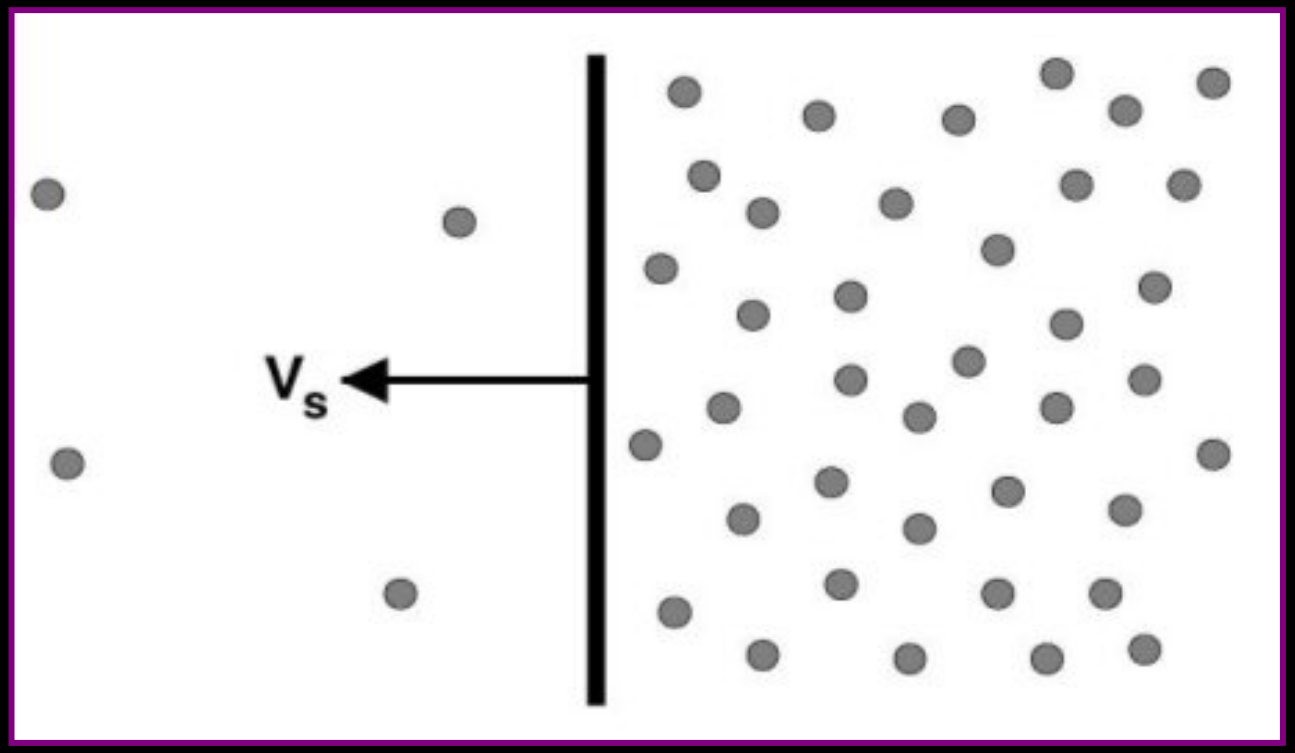
# Shock Fronts




Markevitch & Vikhlinin 07

# Shock Fronts



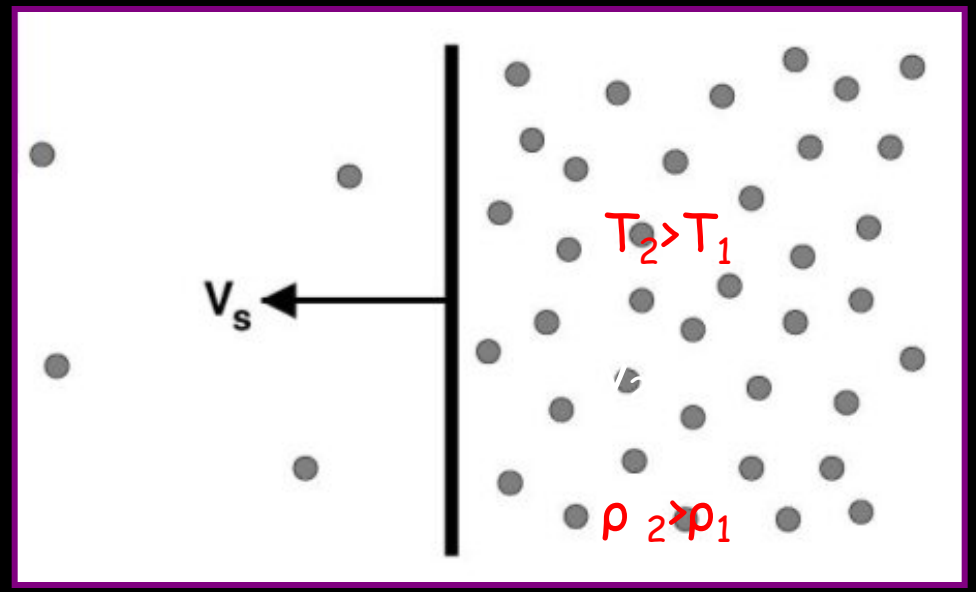

The "power" of the shock is measured by the Mach number

$$M=v_s/c_s$$

where $v_s$ is the velocity of the shock and $c_s$ is the speed of sound in the pre-shock, unperturbed ICM

$$c_s=(5/3\ P/\rho)^{1/2}$$

# Shock Fronts




If the ICM behaves as a perfect fluid, the RH jump condition can be rewritten as:

$$\frac{\rho_d}{\rho_u} = \frac{4\mathcal{M}_{\rm SB}^2}{\mathcal{M}_{\rm SB}^2 + 3}$$

$$\frac{T_d}{T_u} = \frac{5\mathcal{M}_{\rm kT}^4 + 14\mathcal{M}_{\rm kT}^2 - 3}{16\mathcal{M}_{\rm kT}^2}$$

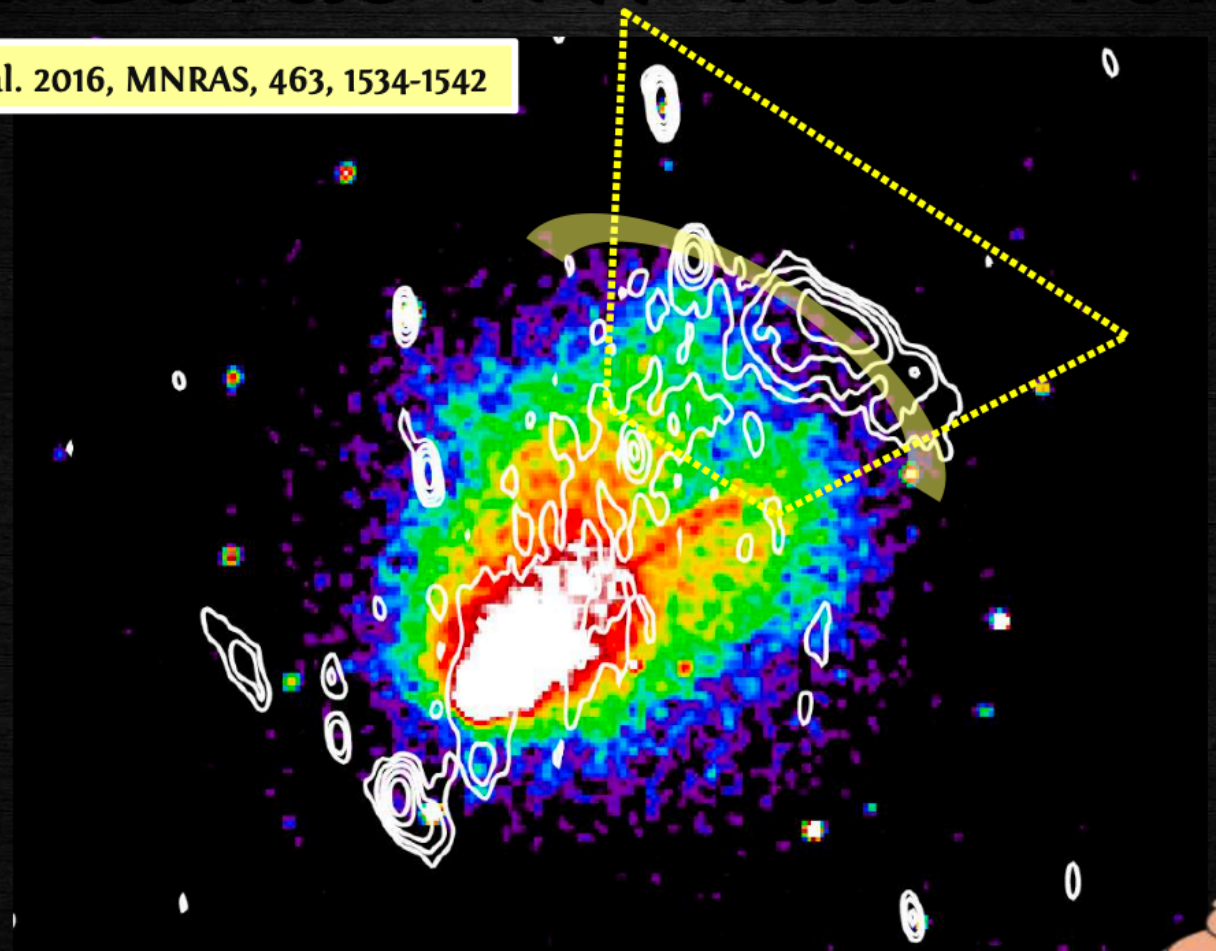
Measuring the density (SB ~$n^2$) and temperature discontinuity across the front, the speed of the shock can be calculated

The shock compression can be measured directly from the X-ray image, but we need temperature measurements:

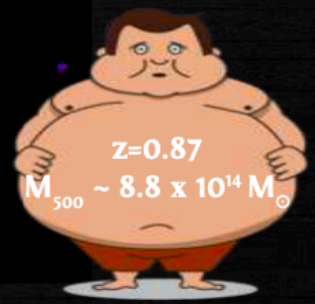
- to measure the velocity of the front and not only M
- to know that it is a shock and not a cold front

# El Gordo NW radio relic

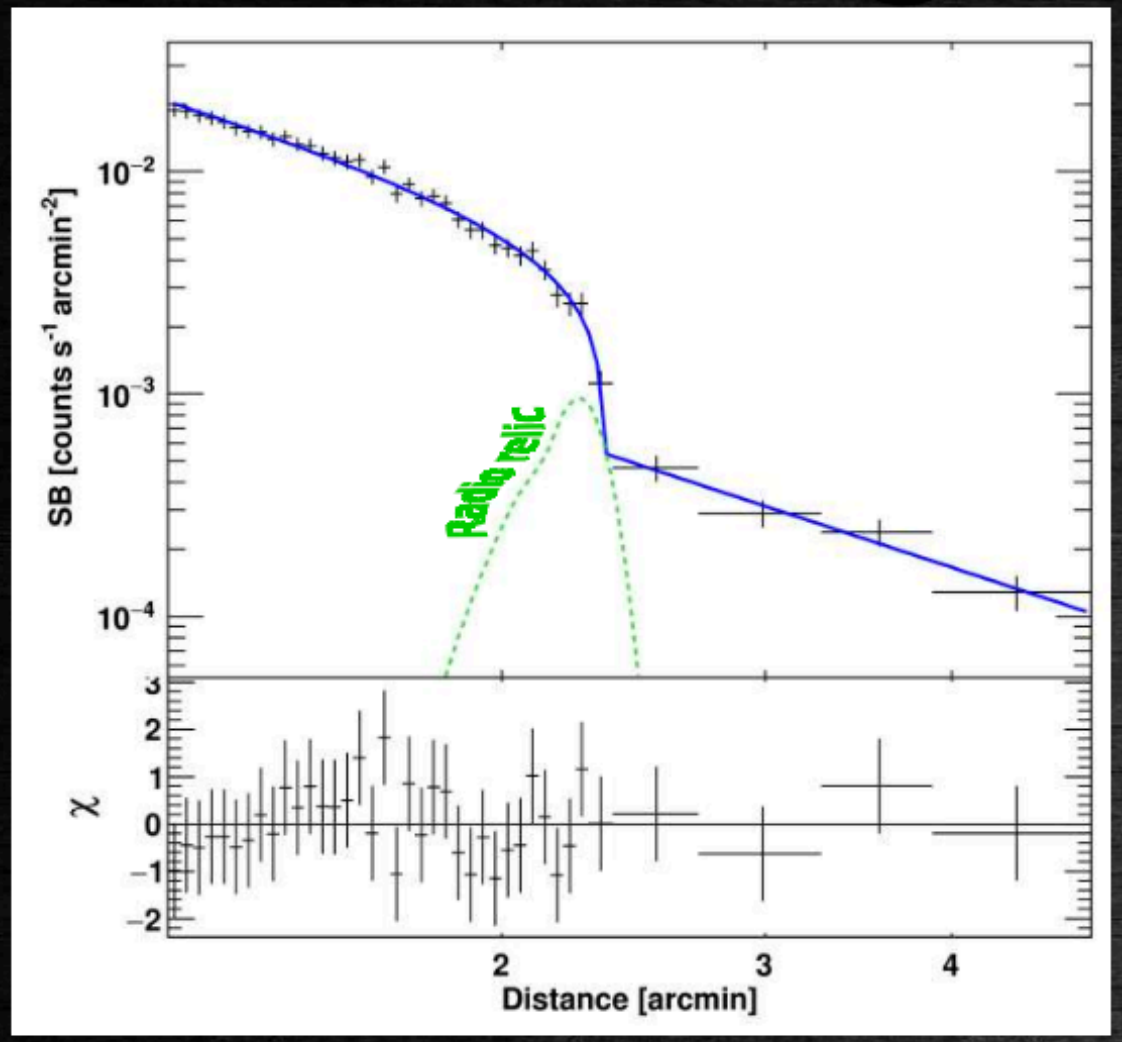
Botteon et al. 2016, MNRAS, 463, 1534-1542

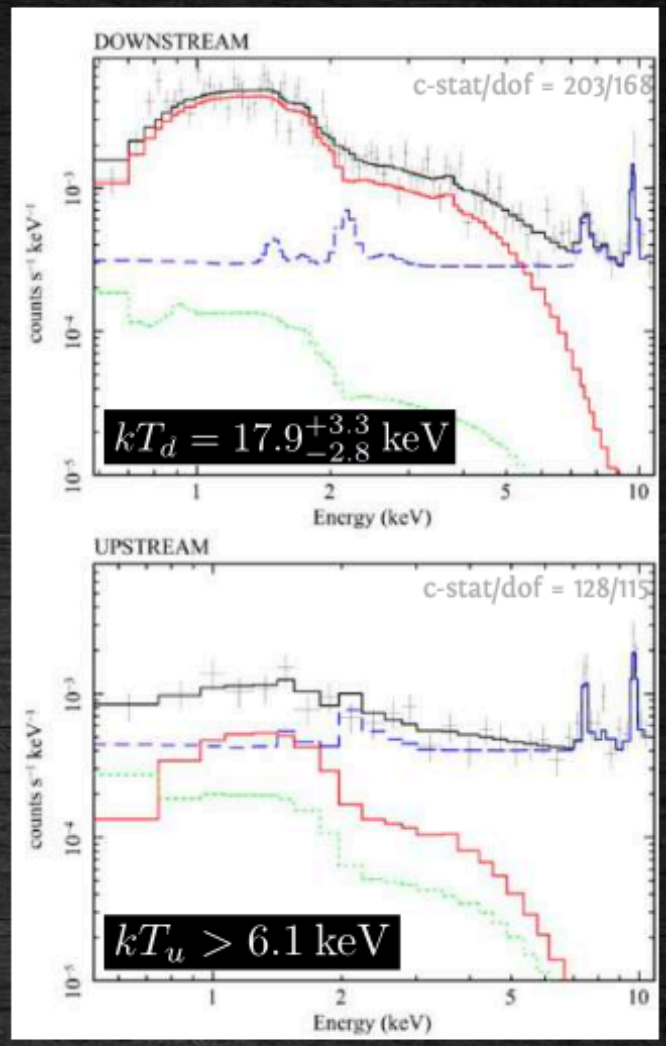


- Discovered by SZ signal (Marriage+11)
- Complex merger state (Menanteau+10,12)
- Halo and double relics (Lindner+14)
- Numerical simulations (Donnert14, Molnar+Broadhurst15, Ng+15, Zhang+15,18)




Credits: Botteon

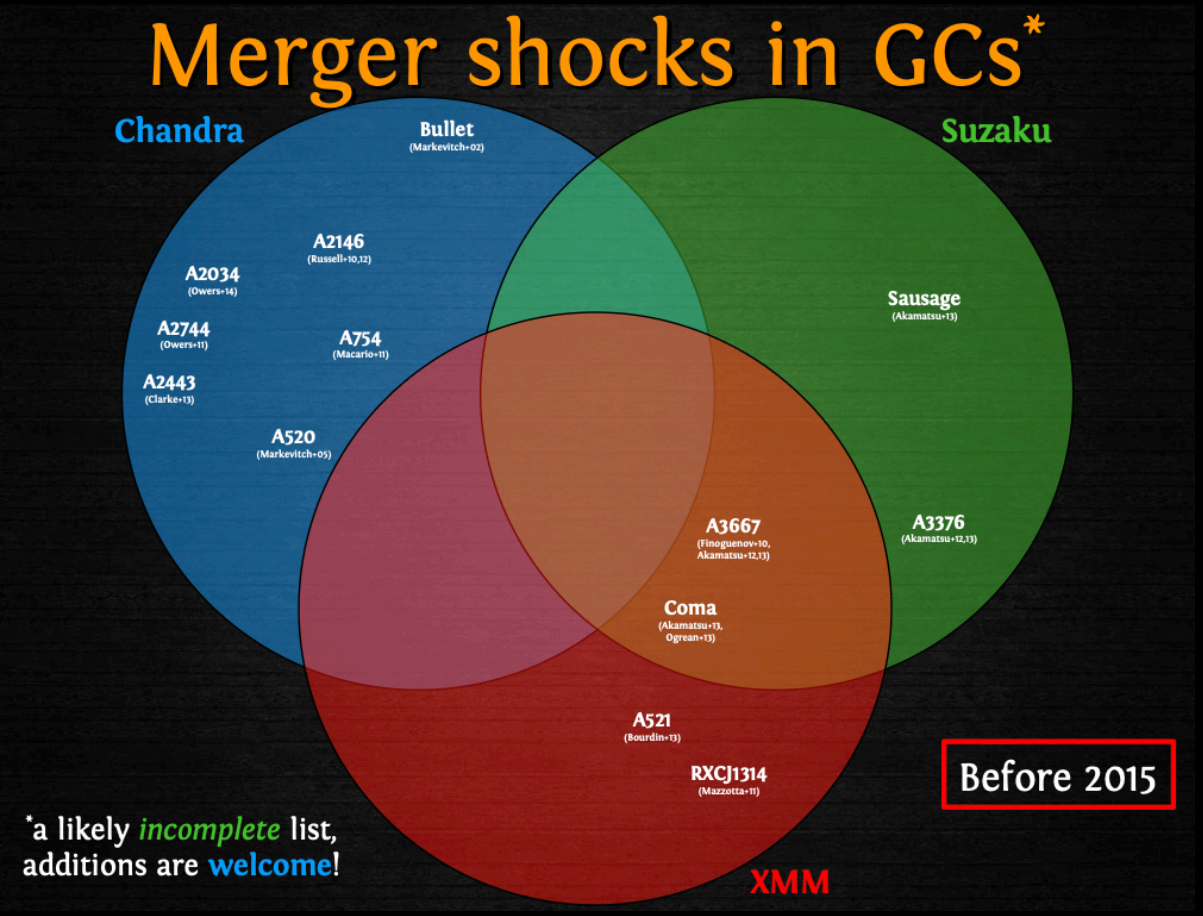


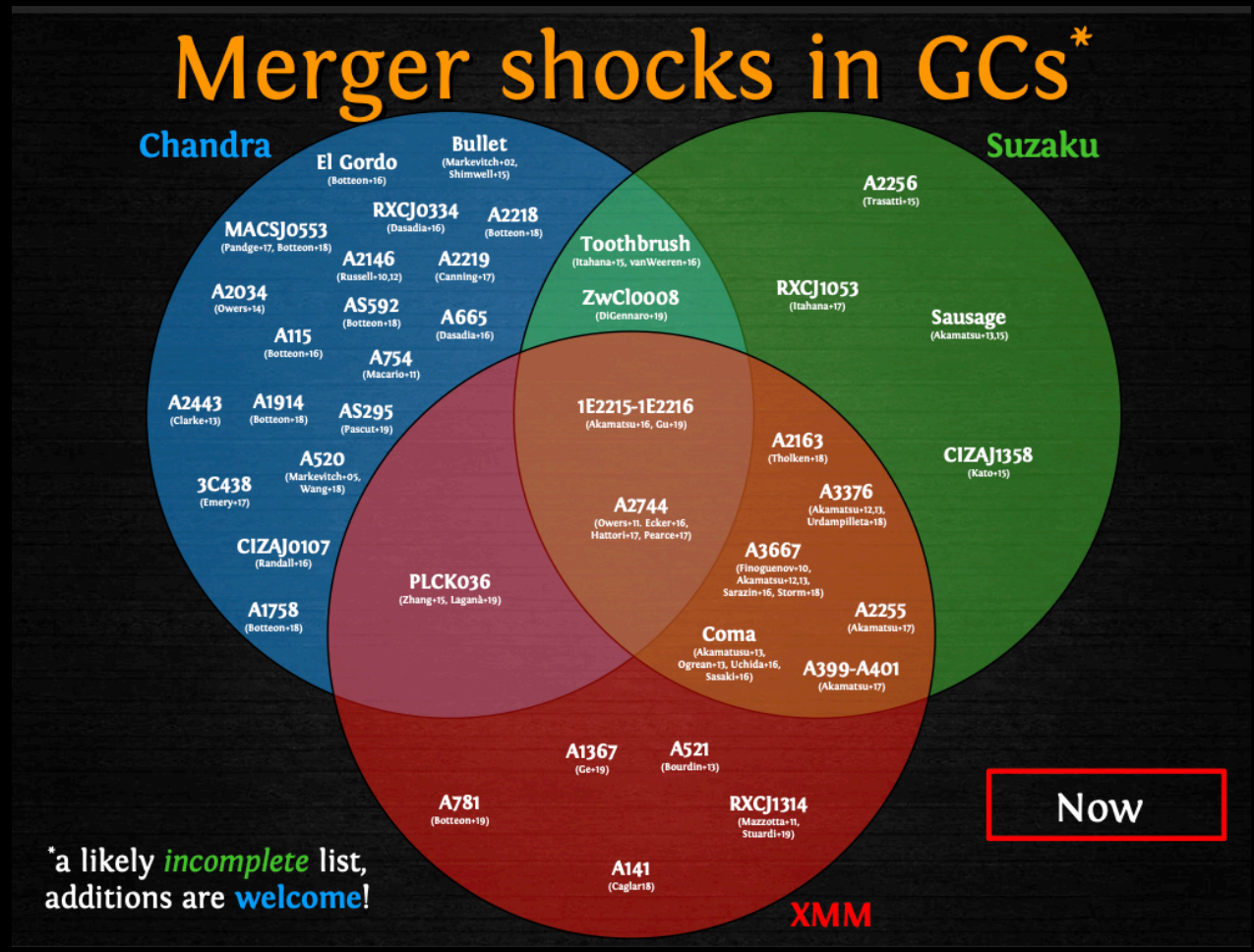




Credits: Botteon

A M>3 shock by density jump. Difficult measurement of the temperature due to low surface brightness and high temperatures. Projection effects are important: shocks are preferentially seen in the plane of the sky

# Shock Fronts

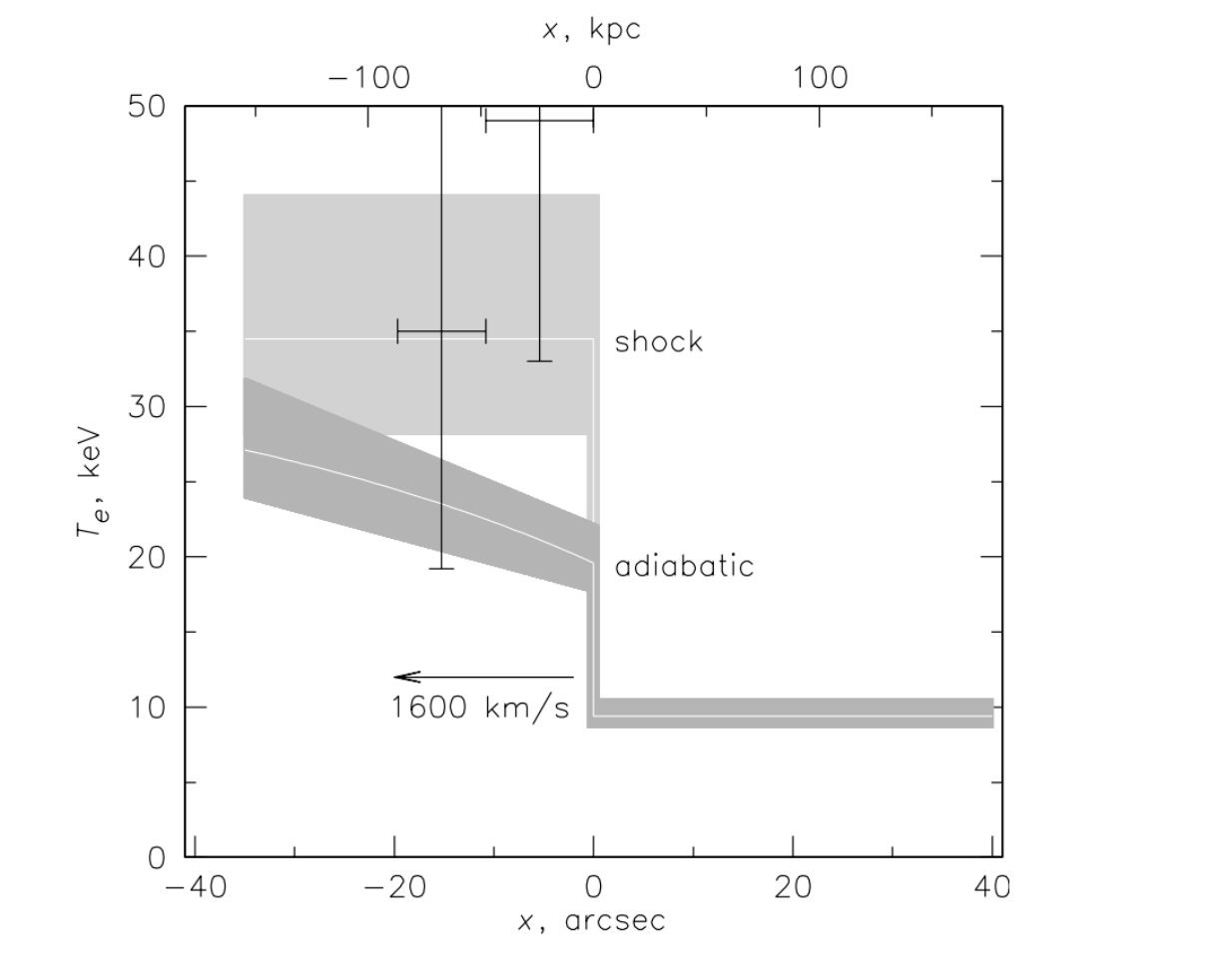



Credits: Botteon

A fair number of detected shocks thanks to X-ray satellites working in this century

# Electron-ion equilibration timescale




In a collisional plasma electron need the Coulomb time to reach the thermal equilibrium with protons that are heated dissipatively. But these are collisionless shocks so electrons might be heated in a different way (solar wind shock). Difficult measurement and not consistent results among the very few measurements in 2/3 cases

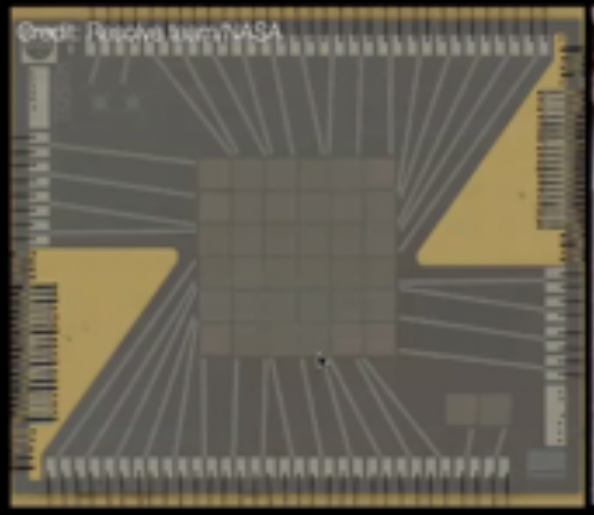
Markevitch & Vikhlinin 07

# XRISM

## Xtend

CCD: 38'x38' FoV

## Resolve

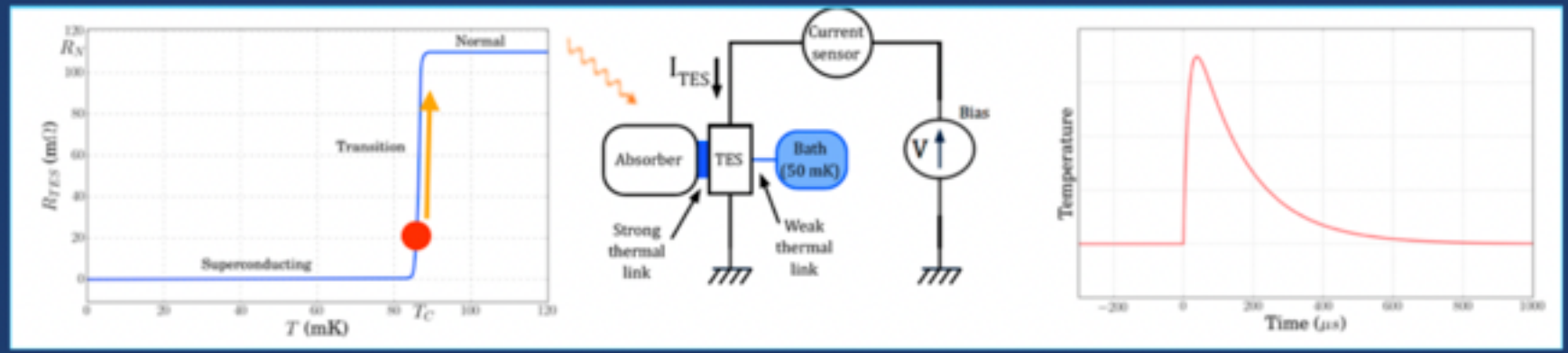



Microcalorimeter: 35 pixels, 3'x3' FoV

## XMA

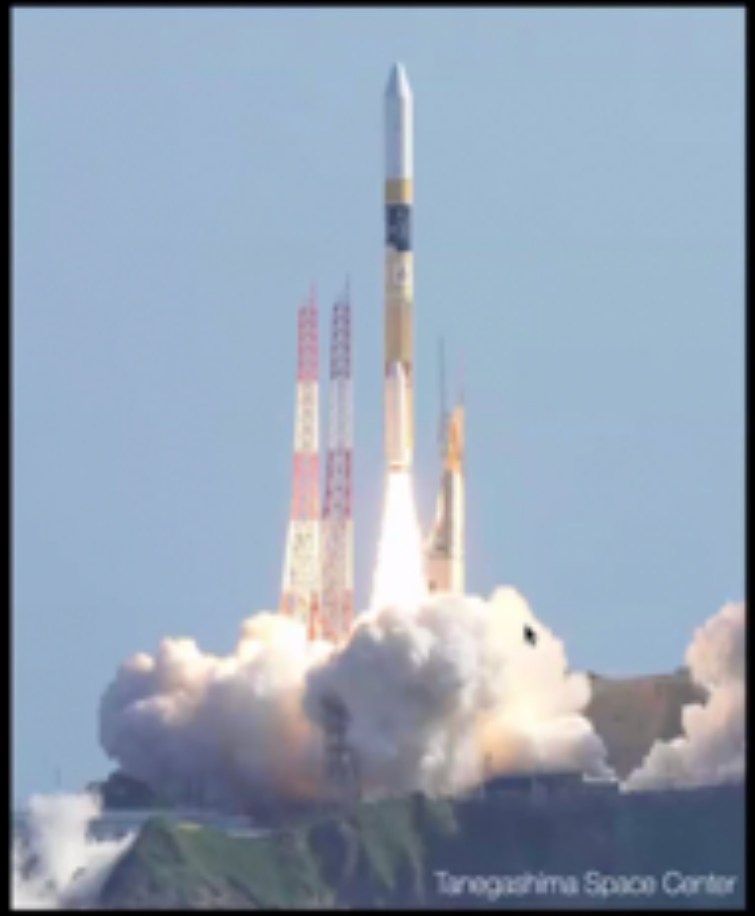
Two identical X-ray mirrors: 1.3' HPD

## Transition Edge Sensor principle



XRISM

# Milestones




- Launched: September 2023
- Commissioning completed: February 2024

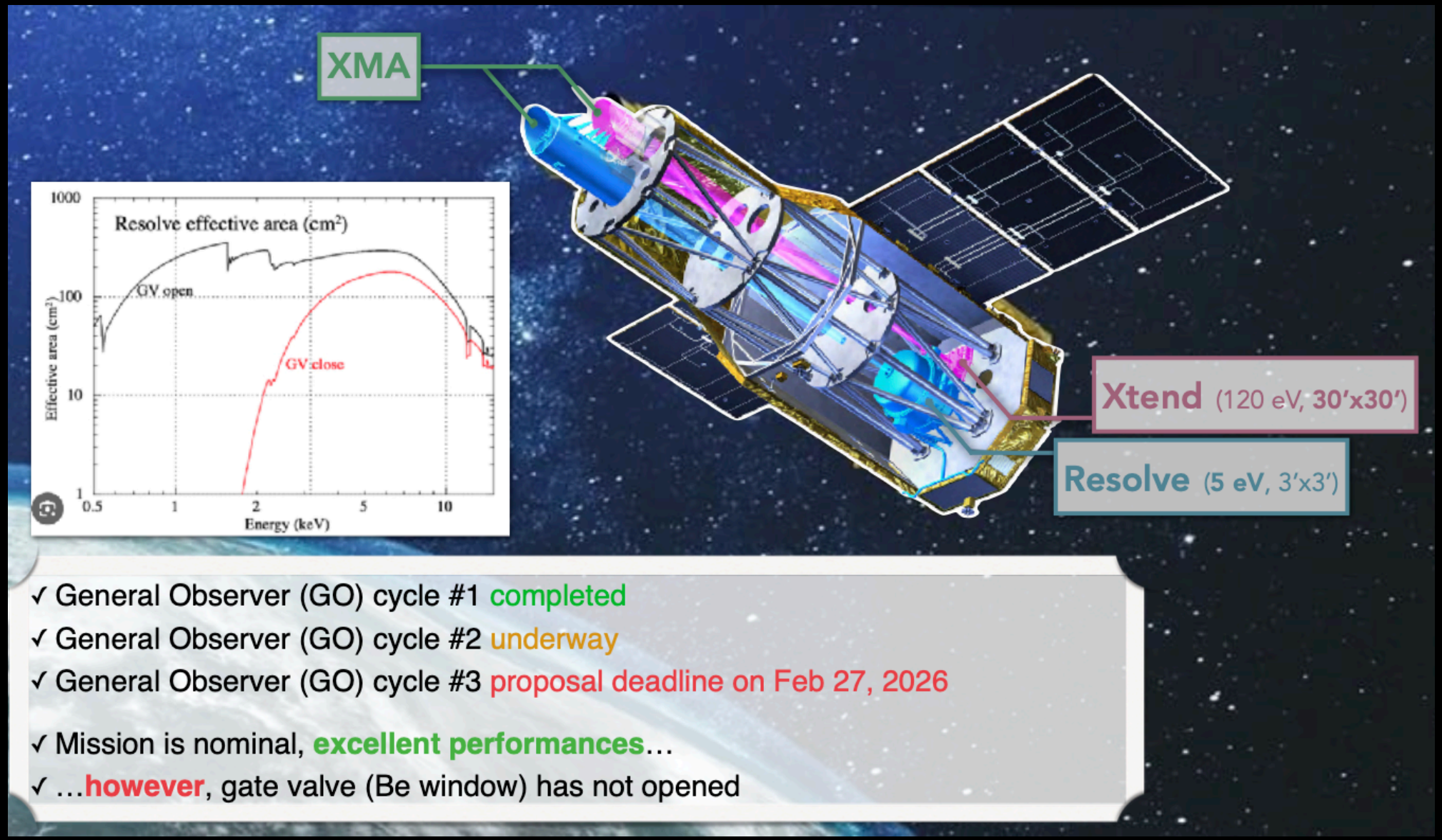
***Resolve* (X-ray microcalorimeter):**

- Non-dispersive spectrometer
- $A_{eff}$ @ 1 keV: ~ 200 $cm^2$
- Energy resolution: < 5 eV (E/dE ~ 1500 @Fe-K)
- Spatial resolution: 1.3'
- 2-17 keV energy band

- Performance verification and in-flight calibration observations: public release in August 2025
- GO cycle 1 observations under way
- **GO cycle 2 deadline: May 15, 2025** ←

Credits: I. Zhuravleva

# XRISM

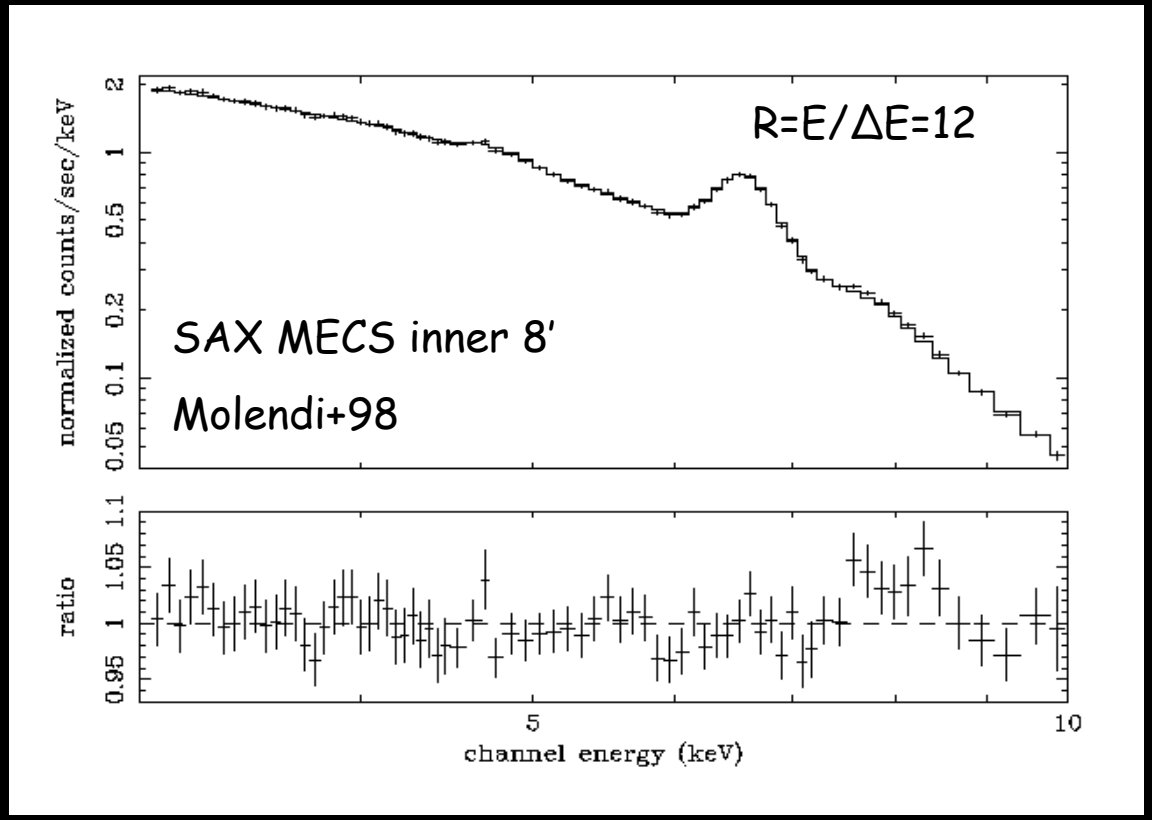


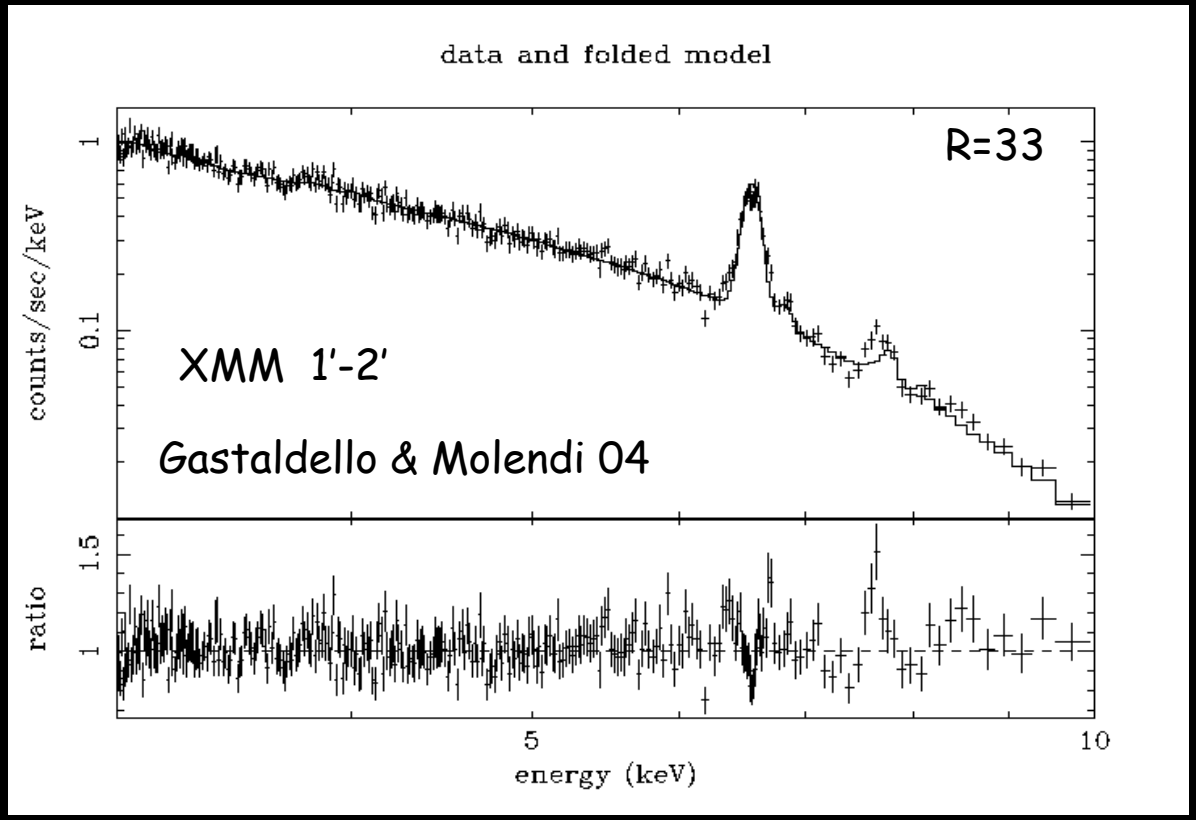

- ✓ General Observer (GO) cycle #1 completed
- ✓ General Observer (GO) cycle #2 underway
- ✓ General Observer (GO) cycle #3 proposal deadline on Feb 27, 2026

- ✓ Mission is nominal, excellent performances…
- ✓ …however, gate valve (Be window) has not opened

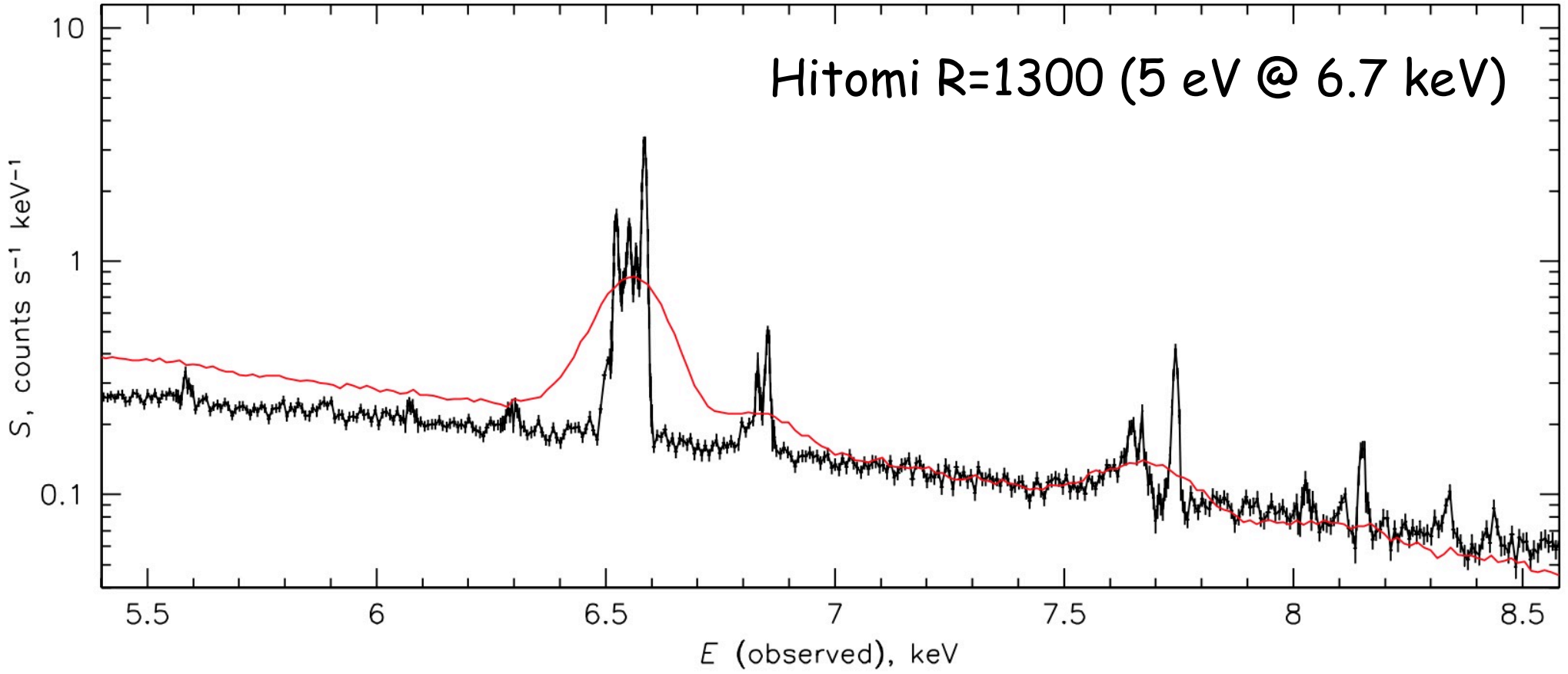
Credits: F. Mernier

# Incresing spectral resolution



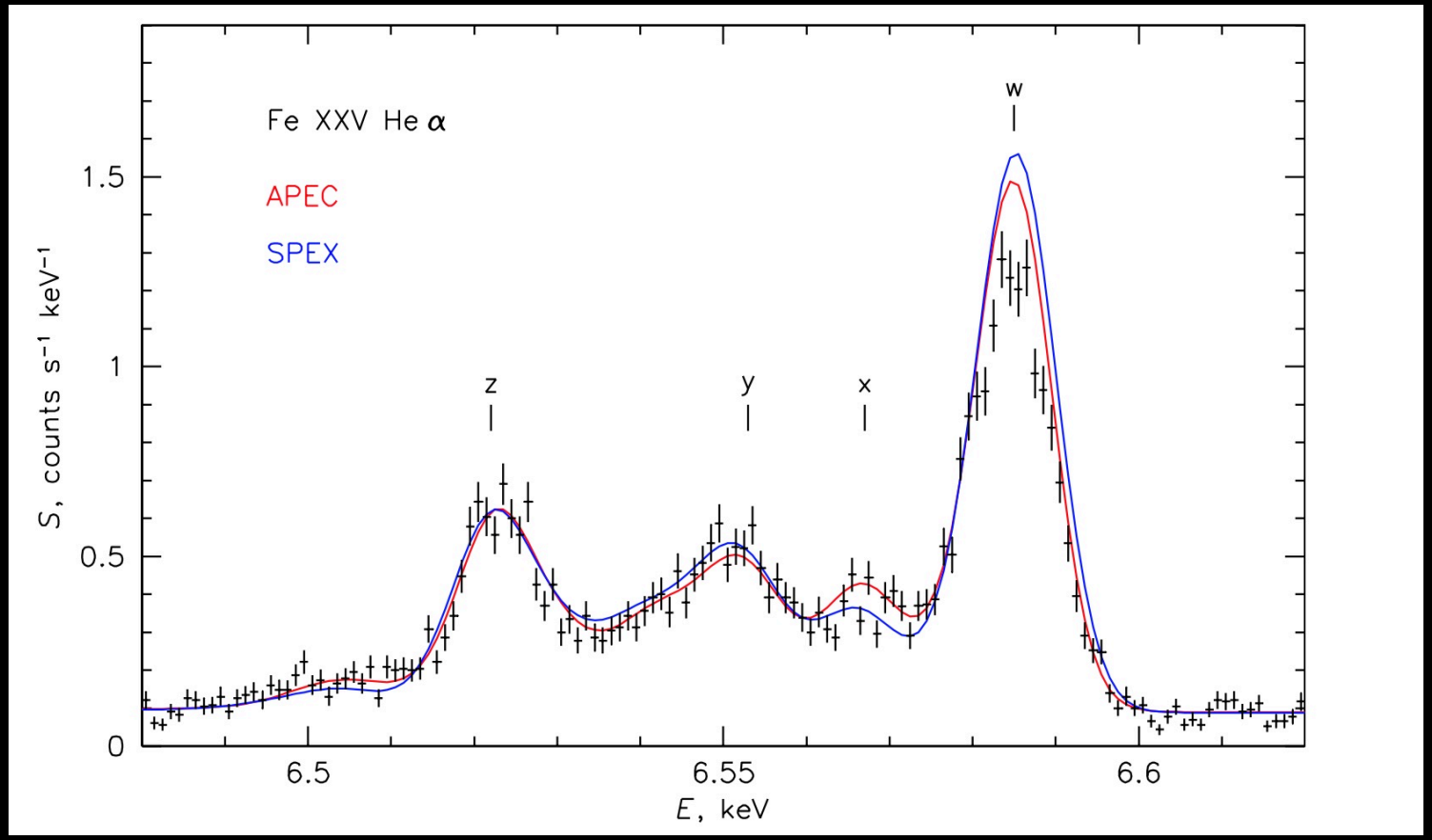
# Incresing spectral resolution




**Extended Data Figure 1 | SXS spectrum of the full field overlaid with a CCD spectrum of the same region.** The CCD is the Suzaku X-ray imaging spectrometer (XIS) (red line); the difference in the continuum slope is due to differences in the effective areas of the instruments.

Hitomi Coll.+16

# The He-alpha complex at 6.7 keV




Hitomi Coll.+16

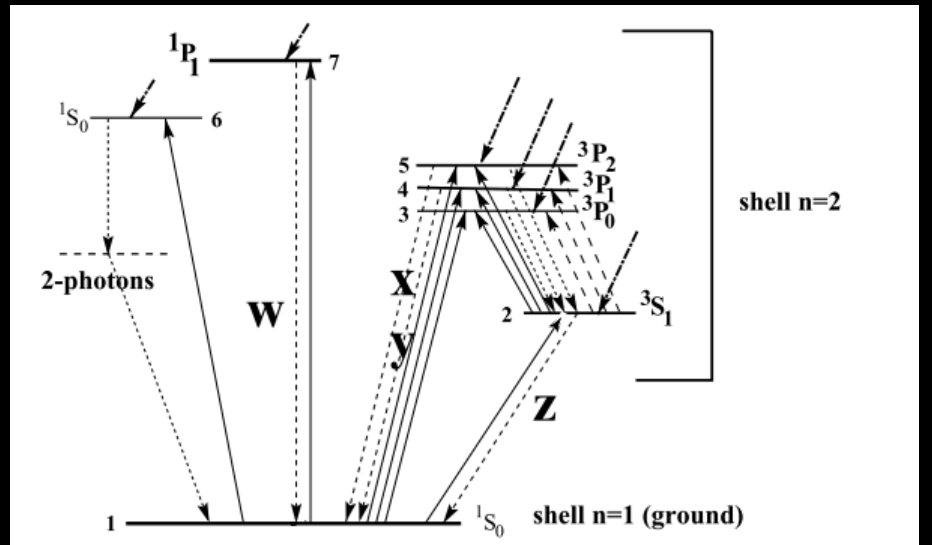
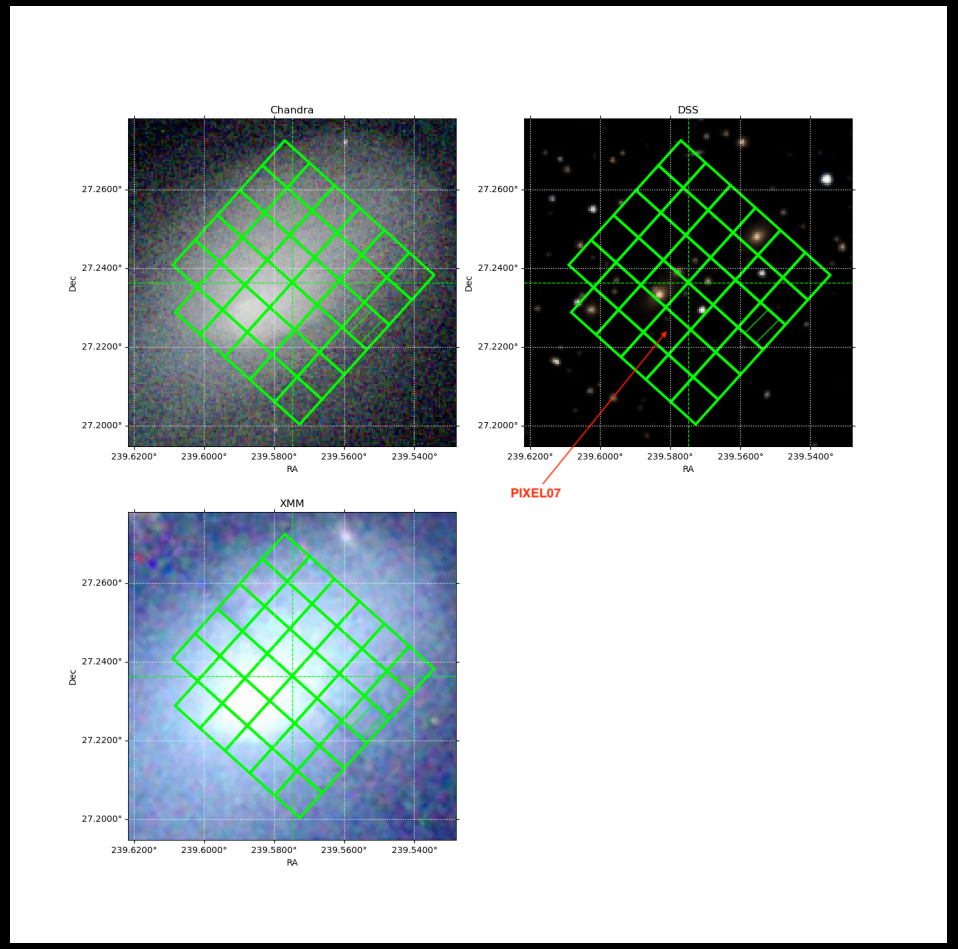
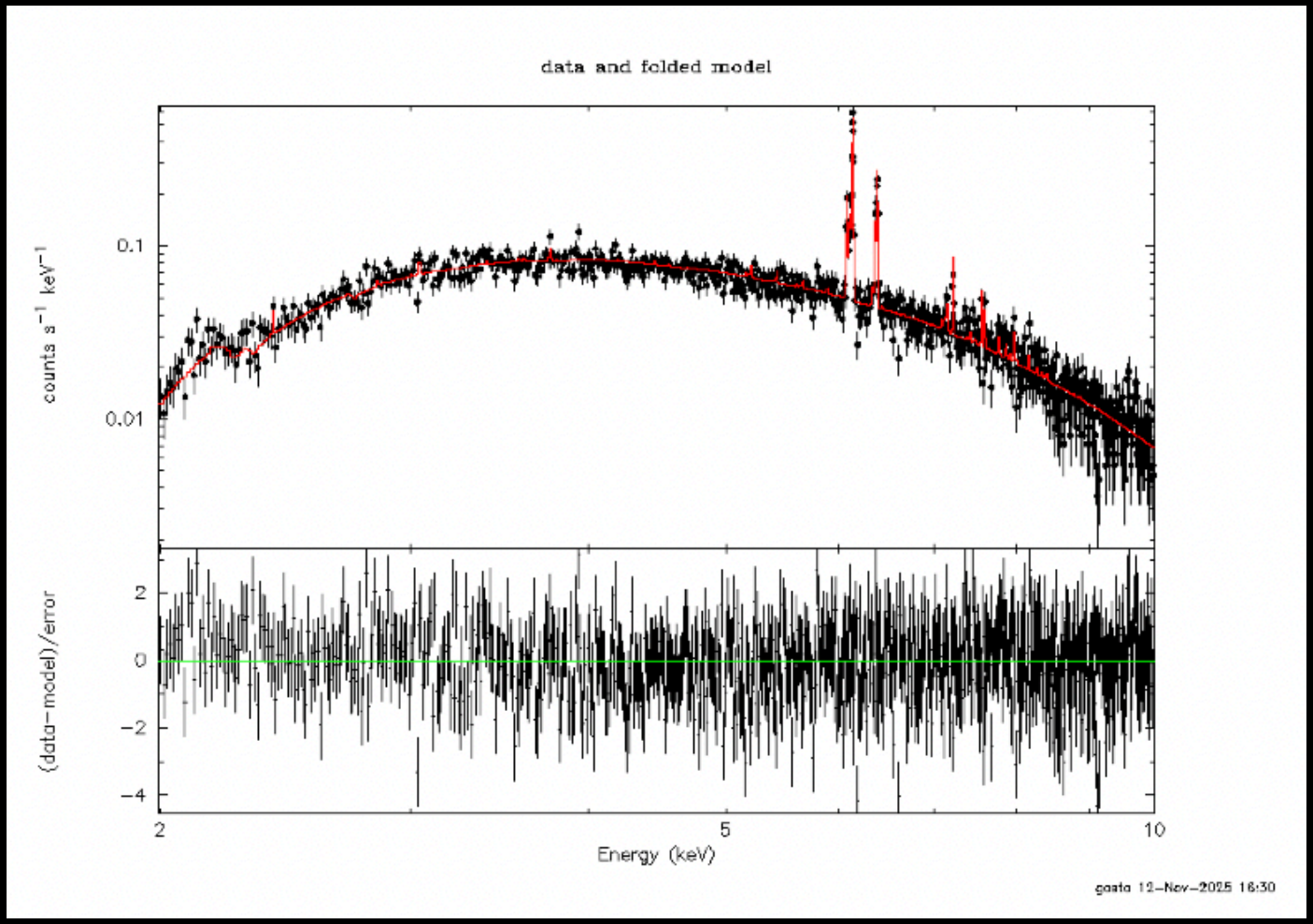



**Fig. 1.** Simplified level scheme for helium-like ions. $w$ (or r), $x$, $y$ (or i), and $z$ (or f): resonance, intercombination, and forbidden lines, respectively. *Full upward arrows*: collisional excitation transitions, *broken arrows*: radiative transitions (including photo-excitation from $2\,^3S_1$ to $2\,^3P_{0,1,2}$ levels, and 2-photon continuum from $2\,^1S_0$ to the ground level), and *thick skew arrows*: recombination (radiative and dielectronic) plus cascade processes.

Porquet+01

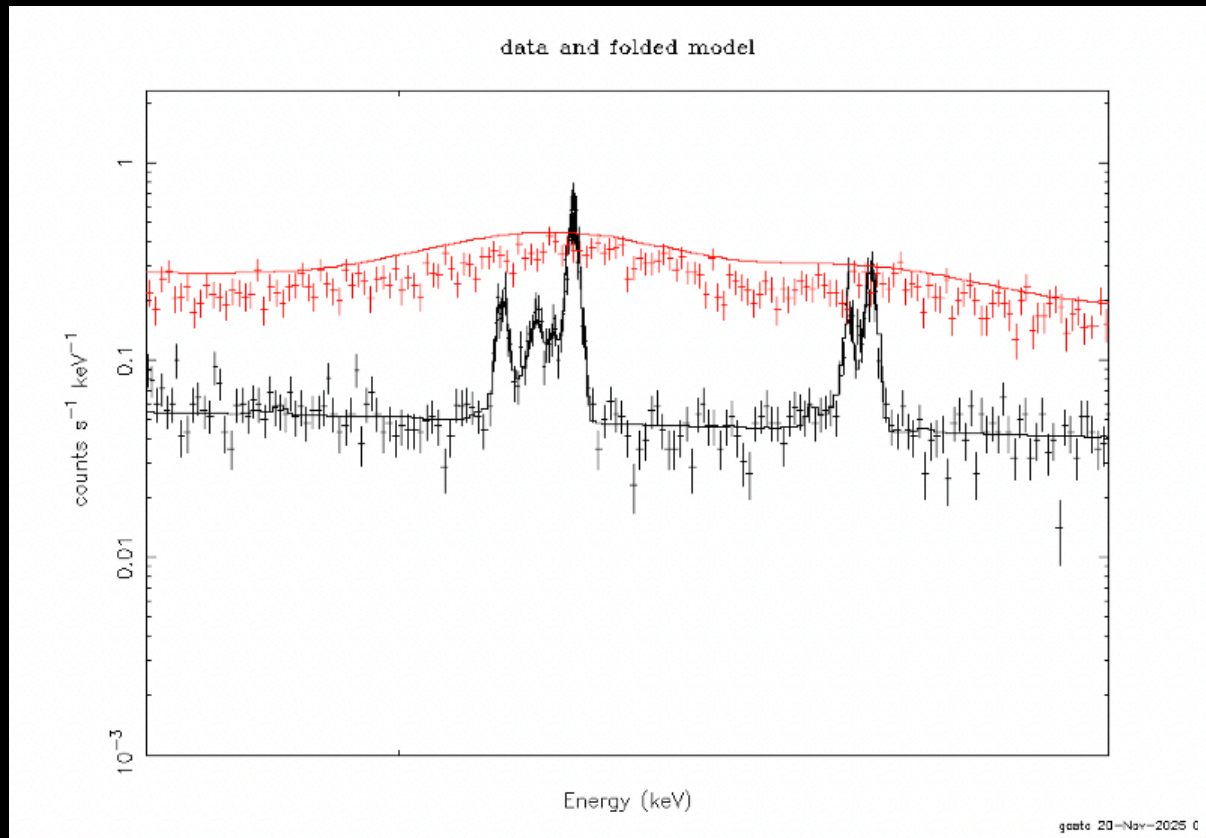
# XRISM OBSERVATION OF A2142

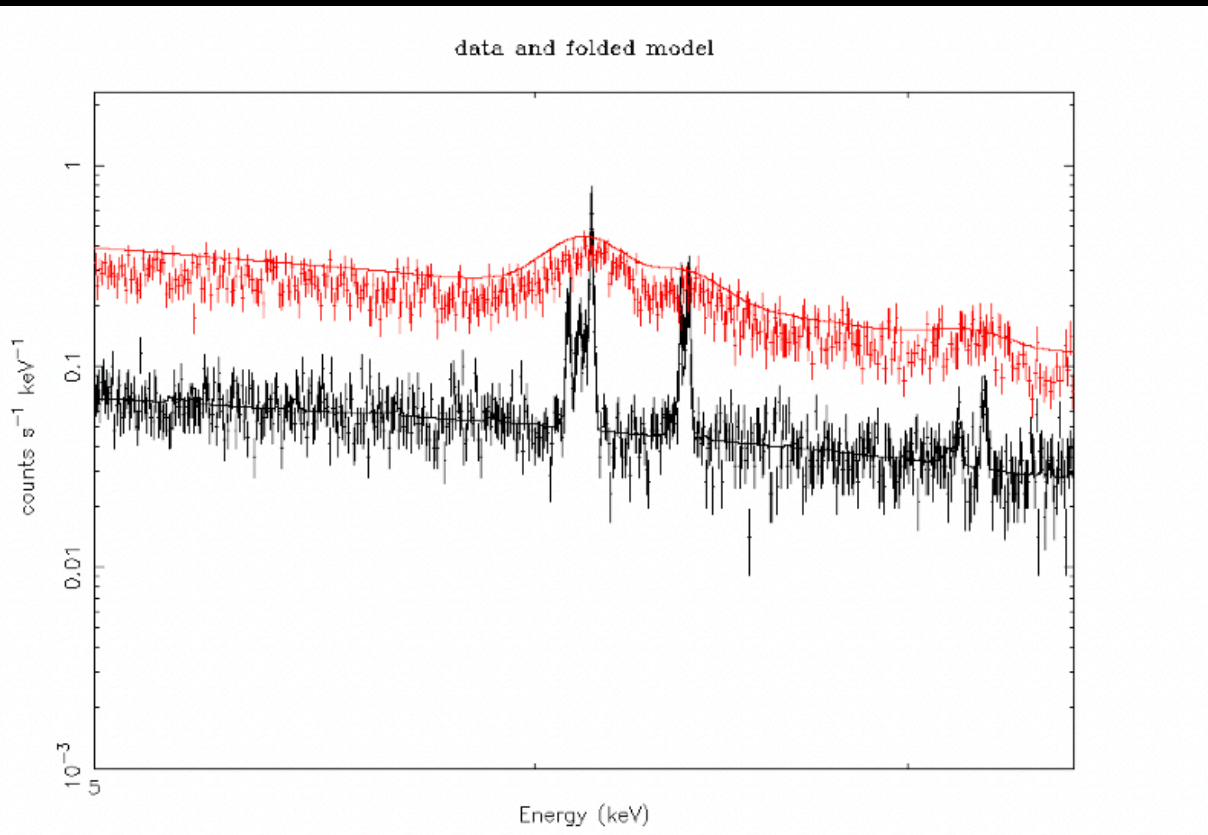



XRISM observation of the core of A2142 taken in august this year

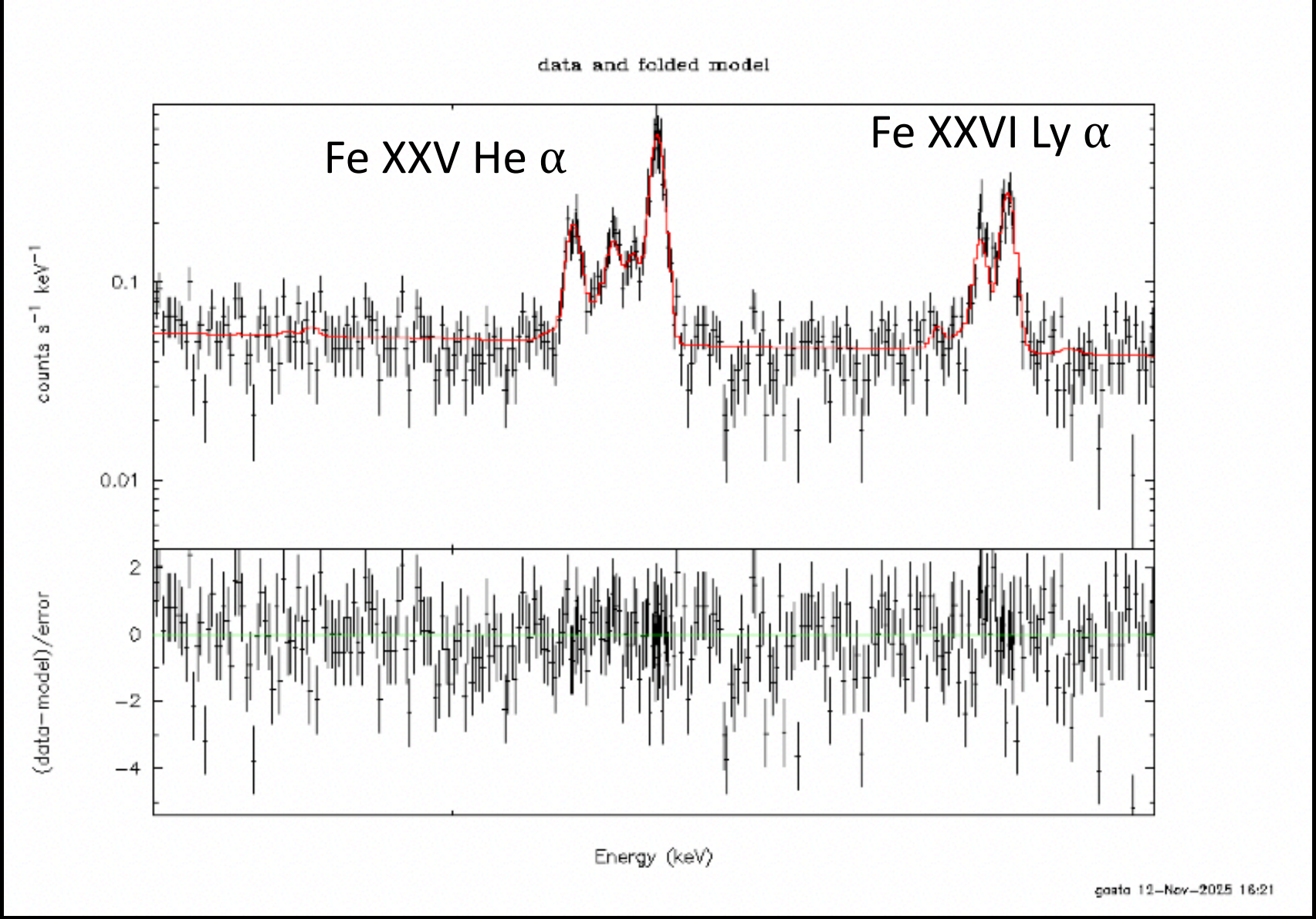
# XRISM OBSERVATION OF A2142



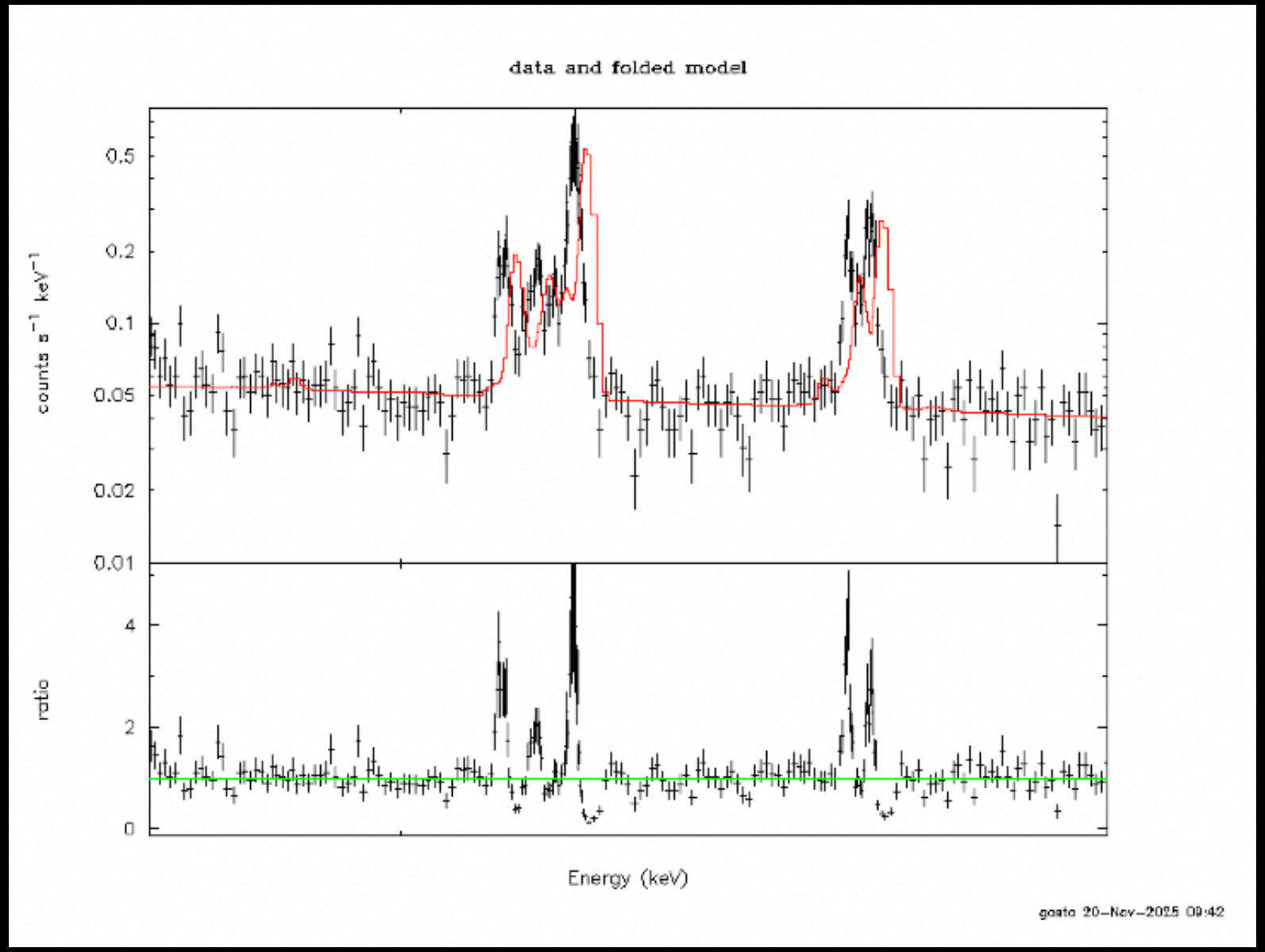

Comparison with XMM/CCD spectra

# XRISM OBSERVATION OF A2142



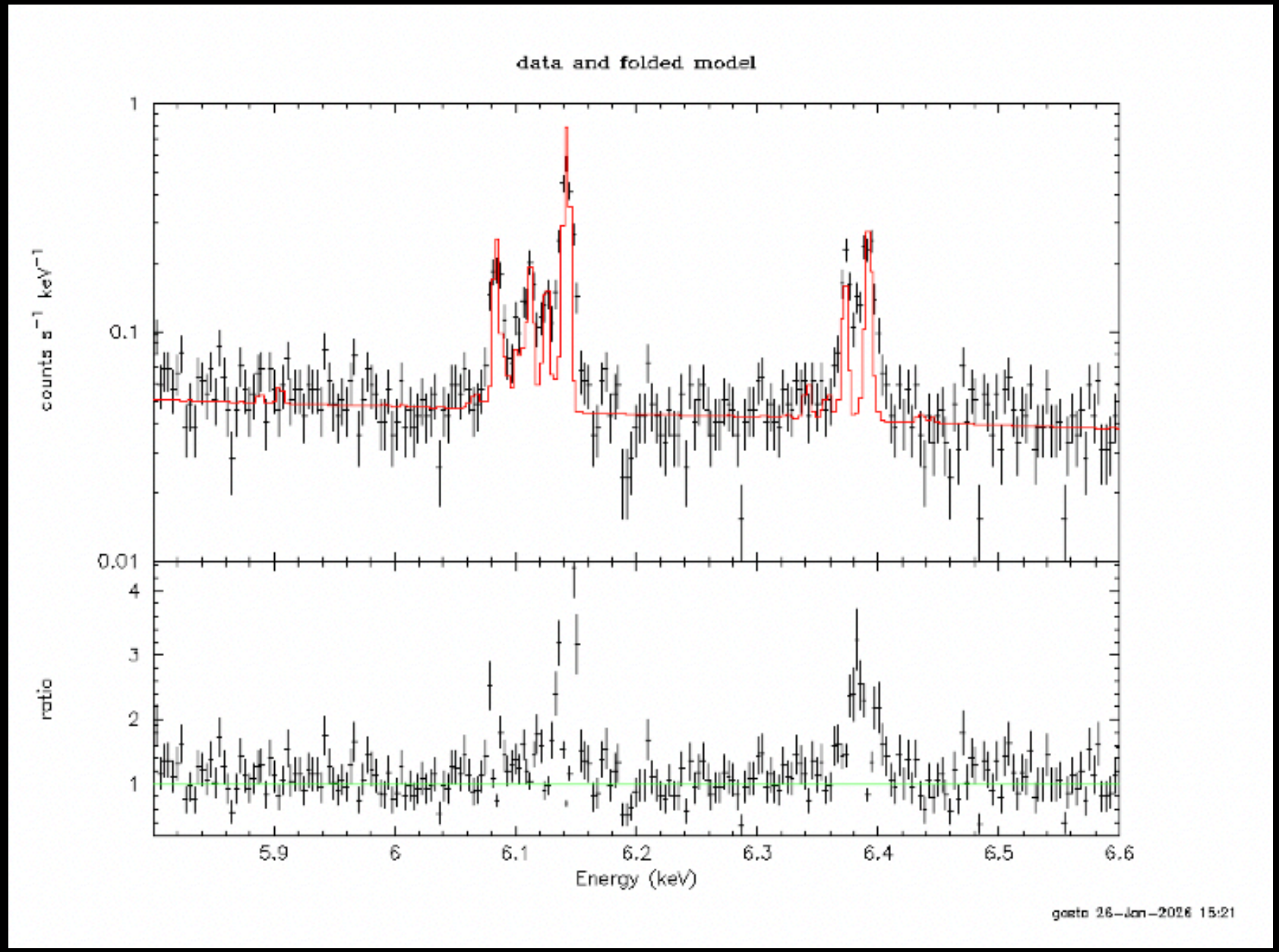

Zoom in in the Fe line (He “triplet” and H double line)
Bulk motion (wrt BCG1, consistent with the overall distribution of the galaxies along the los) of 140 (+/-10) km/s (redshifted) [based on z=0.090 in Owers+11], dispersion velocity of 170 (+/- 10) km/s

# Line Shifts – Bulk motions




You can measure with high significance line shifts. Here the residuals if you fix the redshift at the optical redshift of the BCG

# Line Broadening – turbulent motions




You can measure with high significance line broadening. Here the residuals if you fix the broadening to 0. Usually you assume that this is pure turbulence but it could be broadening due to unresolved bulk motions

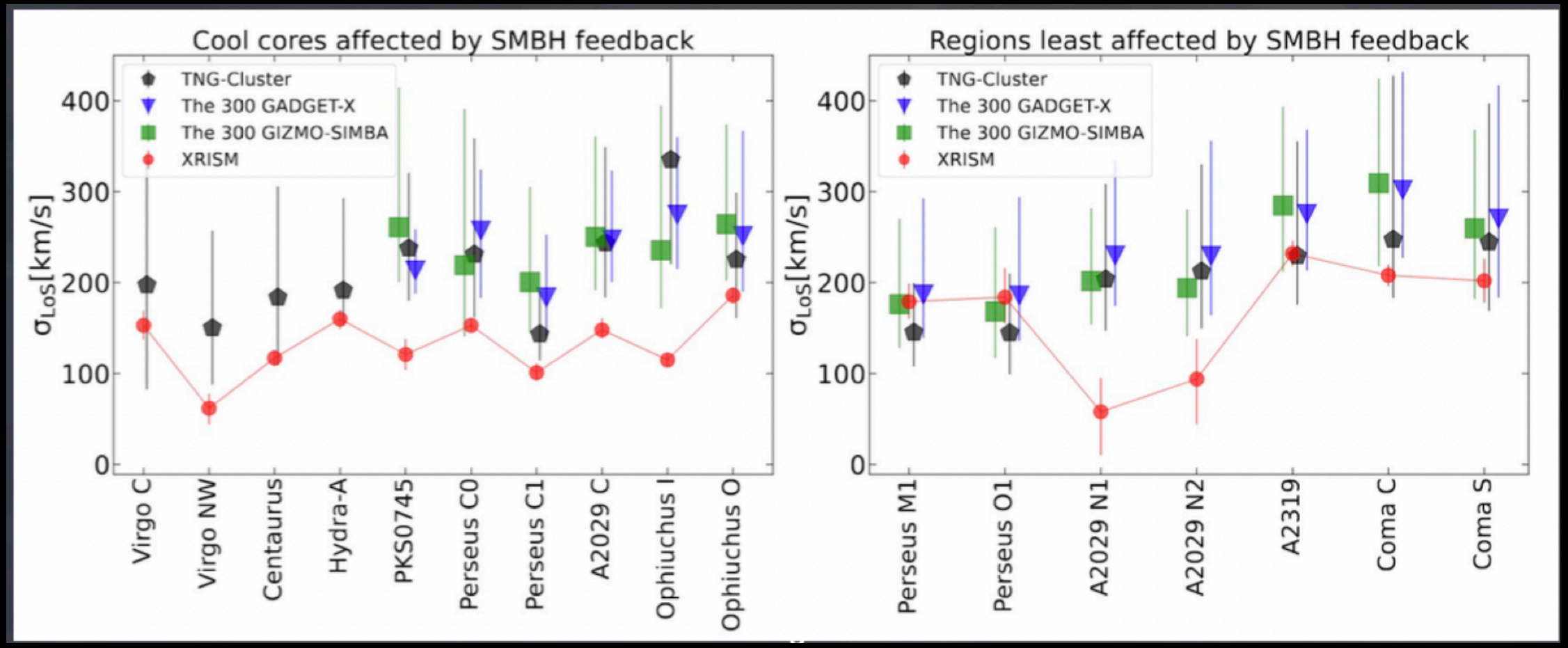
# NT PRESSURE IN A2142

$$M_{3D} = \frac{\sqrt{3}\sigma_{1D}}{c_s} \qquad c_s = \sqrt{\frac{\gamma\, kT}{\mu\, m_p}} \qquad \frac{P_{NT}}{P_{tot}} = \frac{M_{3D}^2}{M_{3D}^2 + 3/\gamma}$$

$\sigma_{1D}$=170 ± 10 km/s

| | $M_{3D}$ | $P_{NT}/P_{tot}$ |
|---|---|---|
| T= 7.18 ± 0.11 keV | 0.216 (0.013) | 2.5 (±0.3) % |

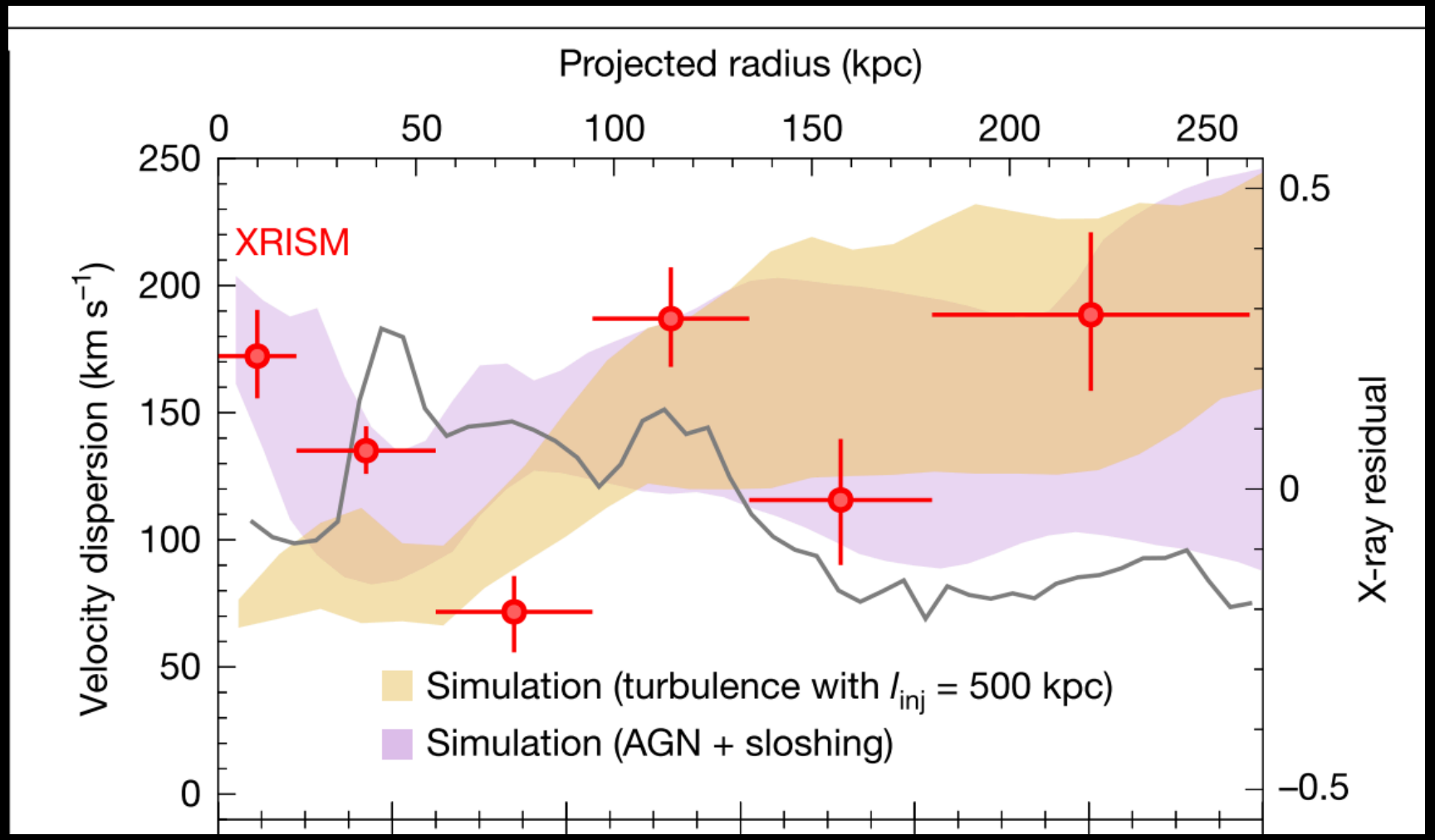
# LOW VELOCITY DISPERSIONS




XRISM COLL.+25a

Velocity dispersions in the range 100-200 km/s ale **lower** than the predictions from hydrodynamical simulations

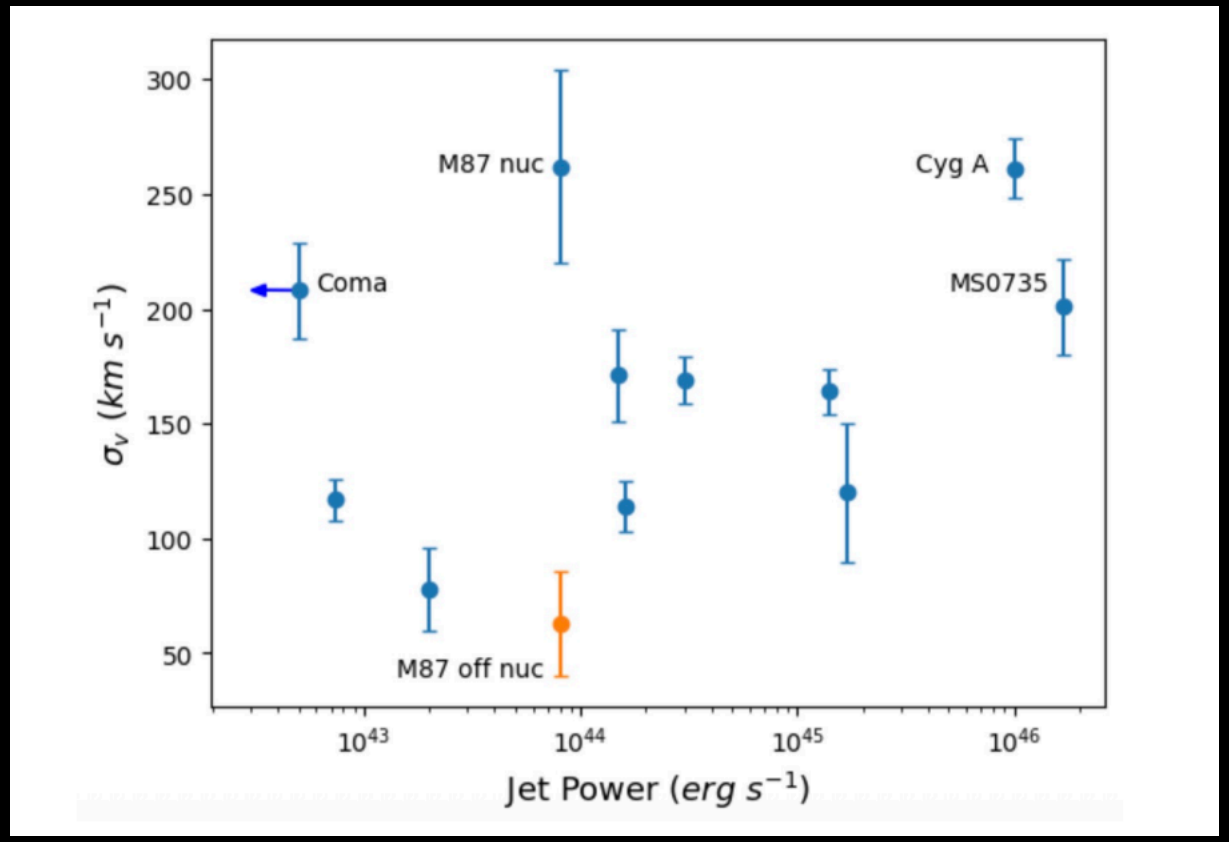
# TWO TURBULENCE DRIVERS

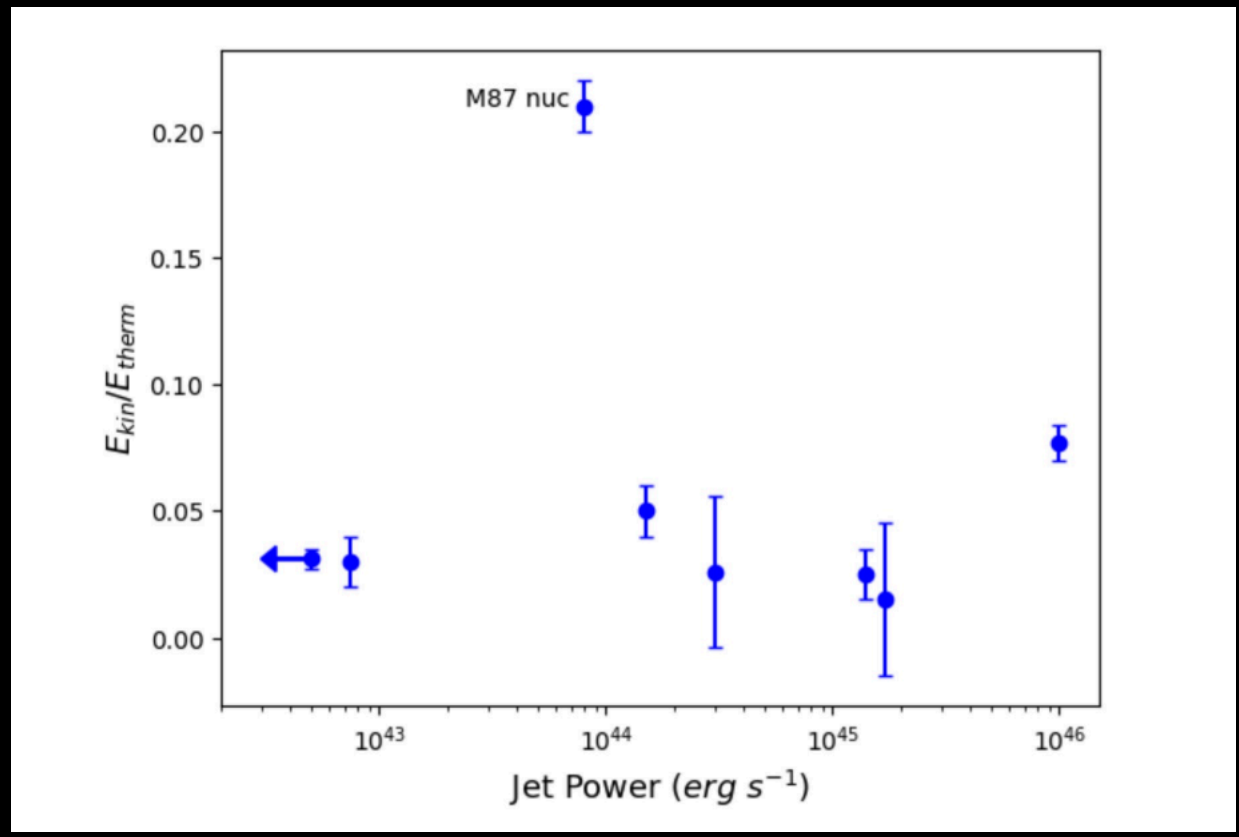



XRISM COLL.+25b

Two dominant drivers of gas motions: a small scale driver in the inner core due to AGN feedback and a large scale one powered by mergers

# IMPLICATIONS FOR TURBULENCE BY AGN



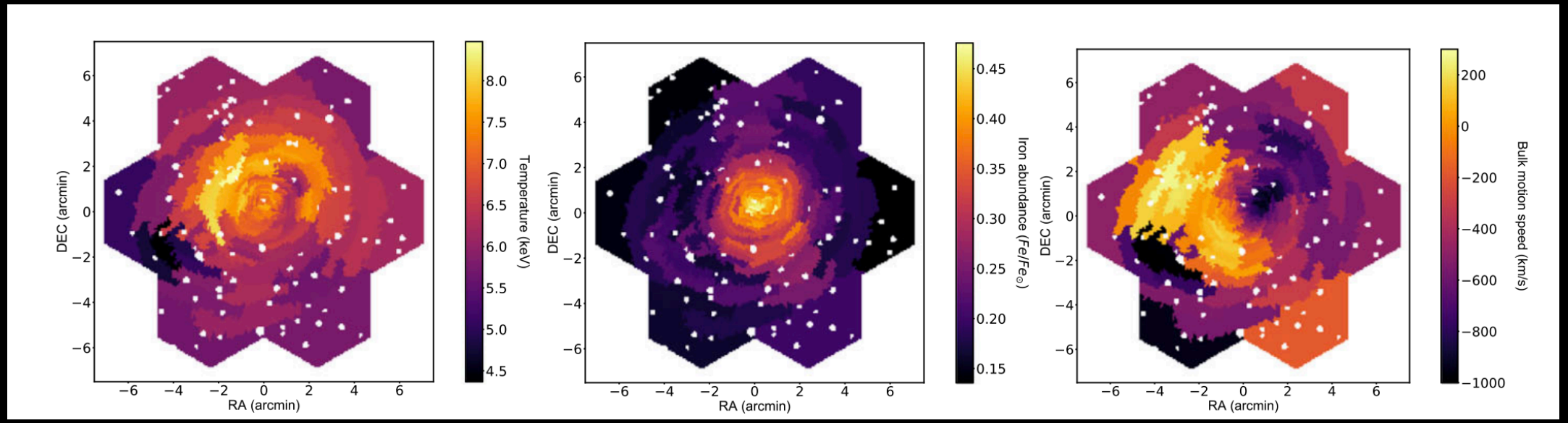




MCNAMRA+26

No trend between jet power and velocity dispersion over 4 decades of jet power. Heating by jets and cavities is gentle. Objects like M87 might be dominated by bulk motions. Severe challenge for contribution of turbulence to heating

# OPEN QUESTIONS

- How are cool cores disrupted by merger ?
- How shocks really heat the gas and (re)accelerate particles ?
- The ICM seems to be dominated by bulk motions and with indications of low turbulence. How does this affect  our understandig of many aspects such as hydrostatic equilibrium, radio halos generation and turbulence induced by AGNs ?
- We clearly need a better instrument and the X-IFU on board NewAthena will be able to tackle in depth those questions




Barret+23