Galaxy cluster observations: structure and dynamics of the intracluster medium

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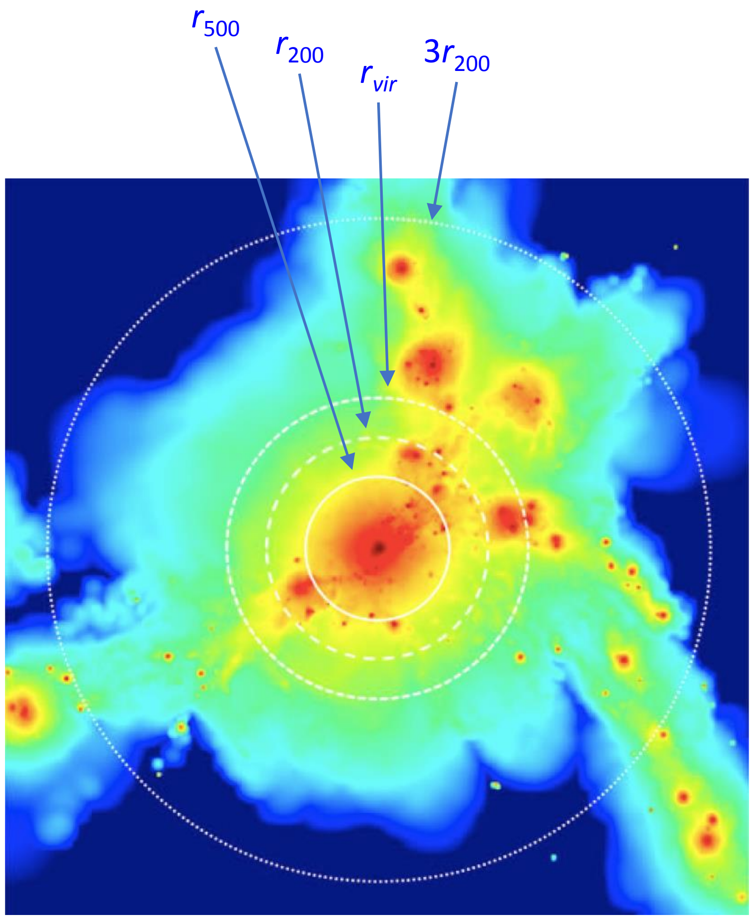
D. Eckert, T. Tamura, F. Hofmann

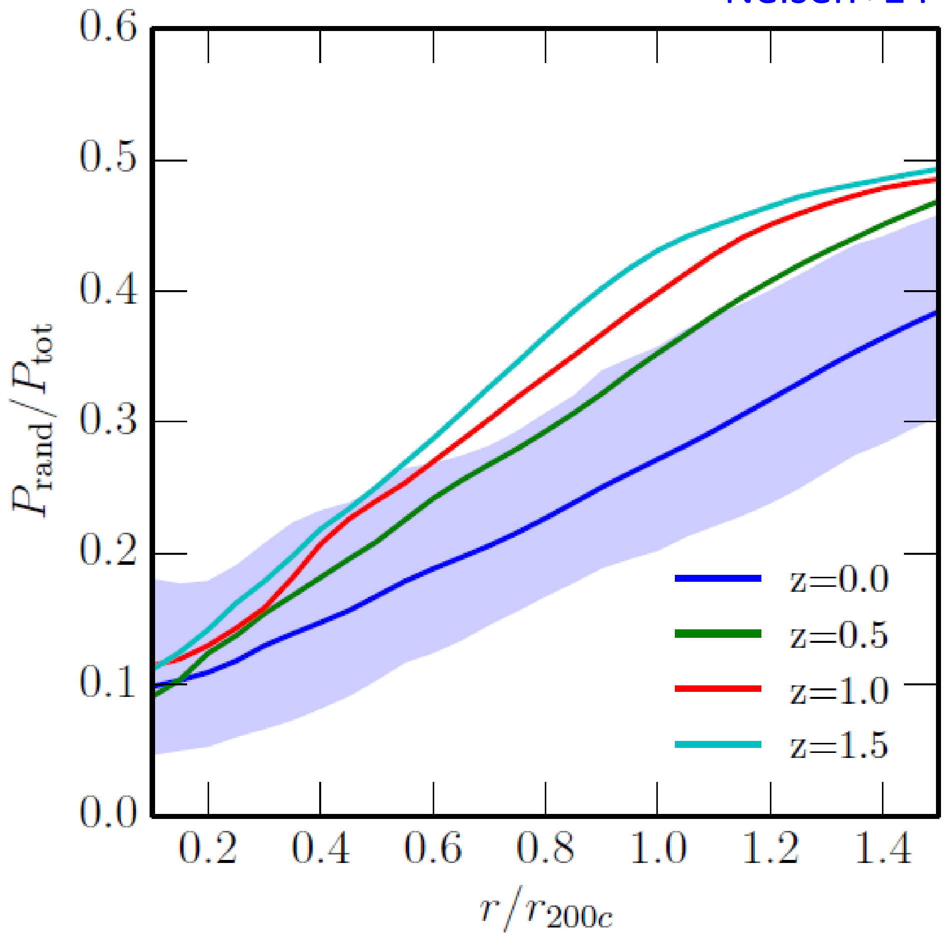
Clusters on large scales



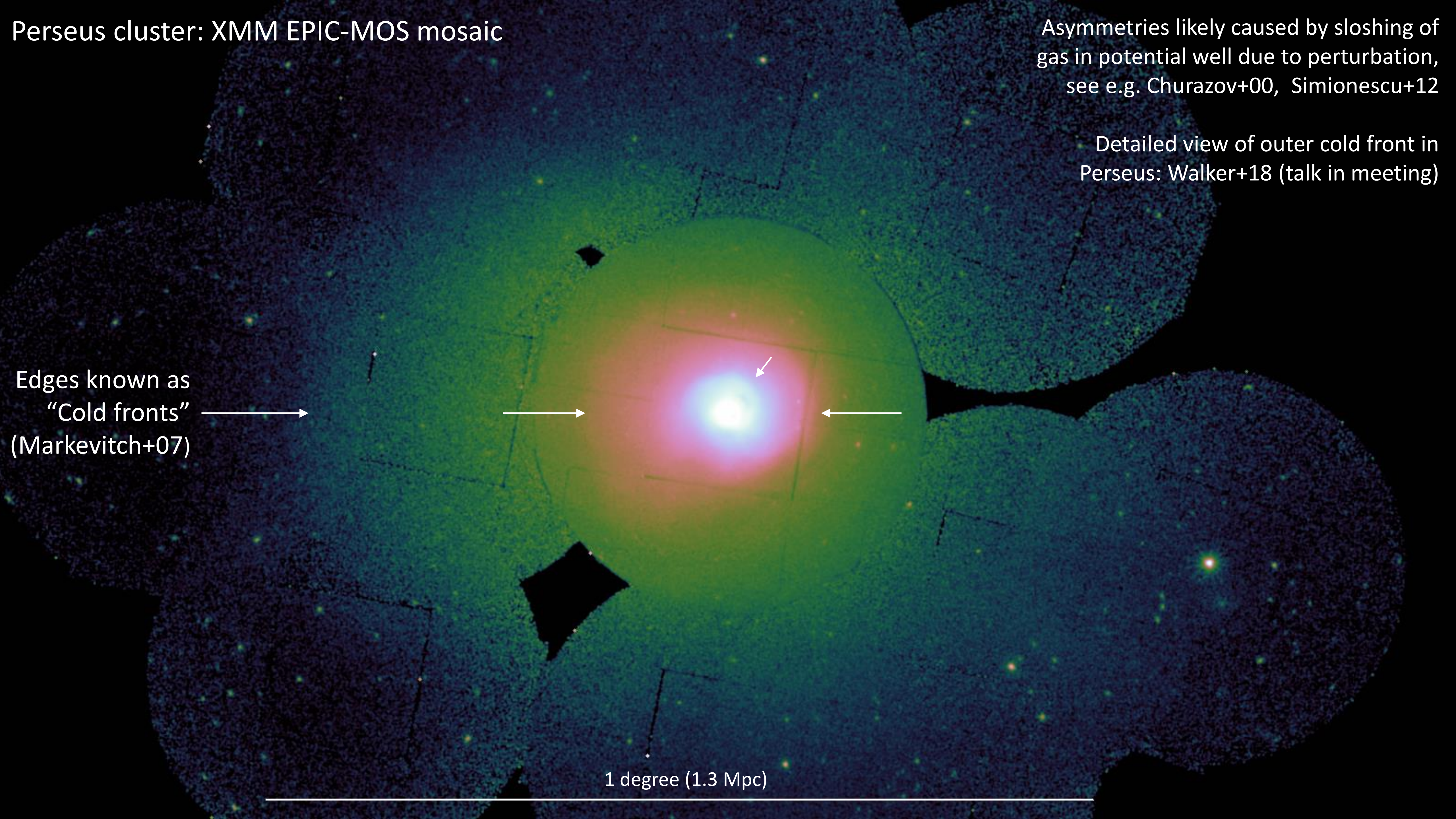
Reiprich+13

Outer parts of clusters should be increasingly disturbed/turbulent due to merging subclumps

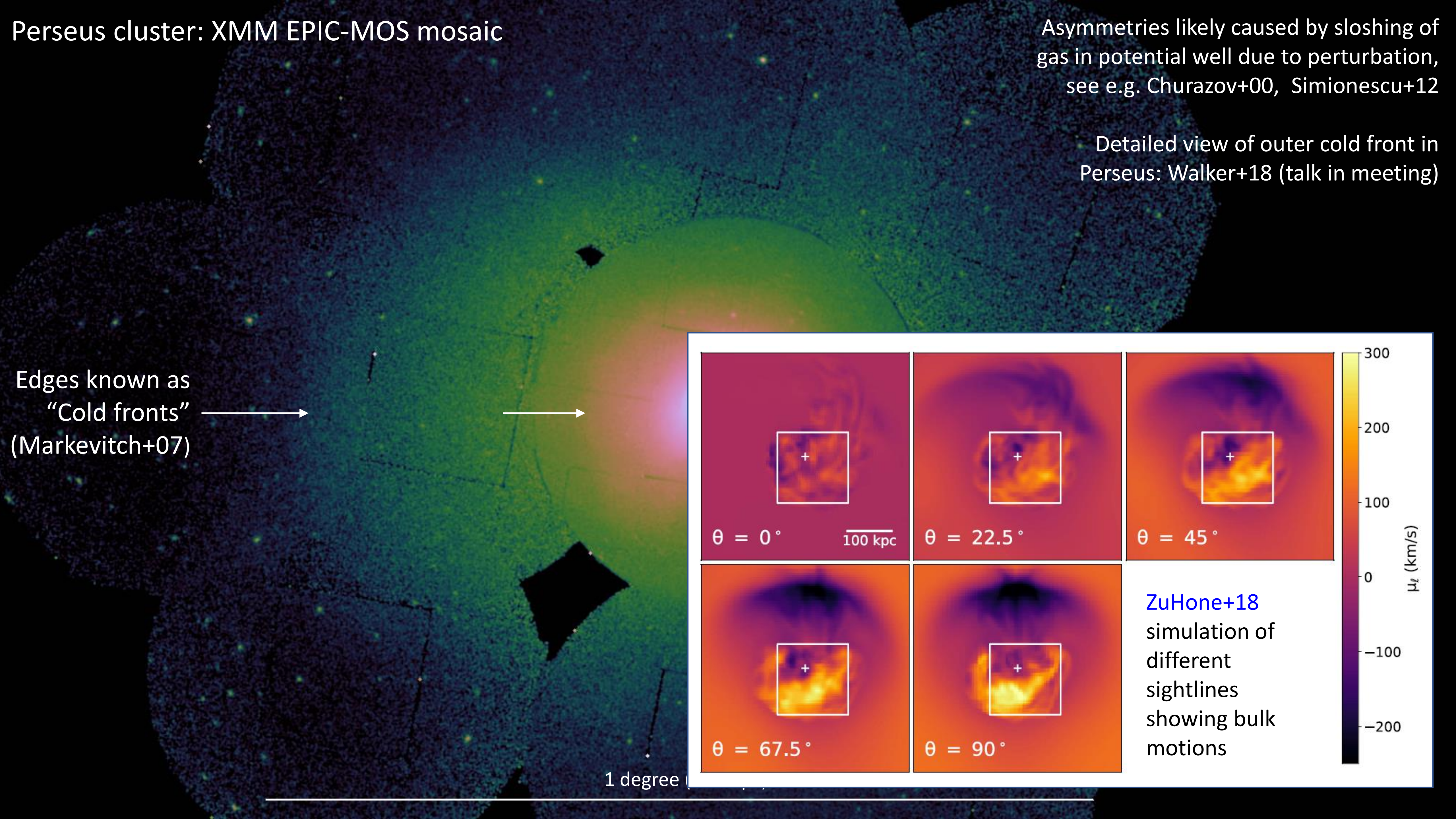
Nelsen+14



The turbulence in the intracluster medium (ICM), the main baryonic cluster component, should increase with radius



Perseus cluster: XMM EPIC-MOS mosaic
Asymmetries likely caused by sloshing of gas in potential well due to perturbation, see e.g. Churazov+00, Simionescu+12
Detailed view of outer cold front in Perseus: Walker+18 (talk in meeting)
Edges known as “Cold fronts” (Markevitch+07)
1 degree (1.3 Mpc)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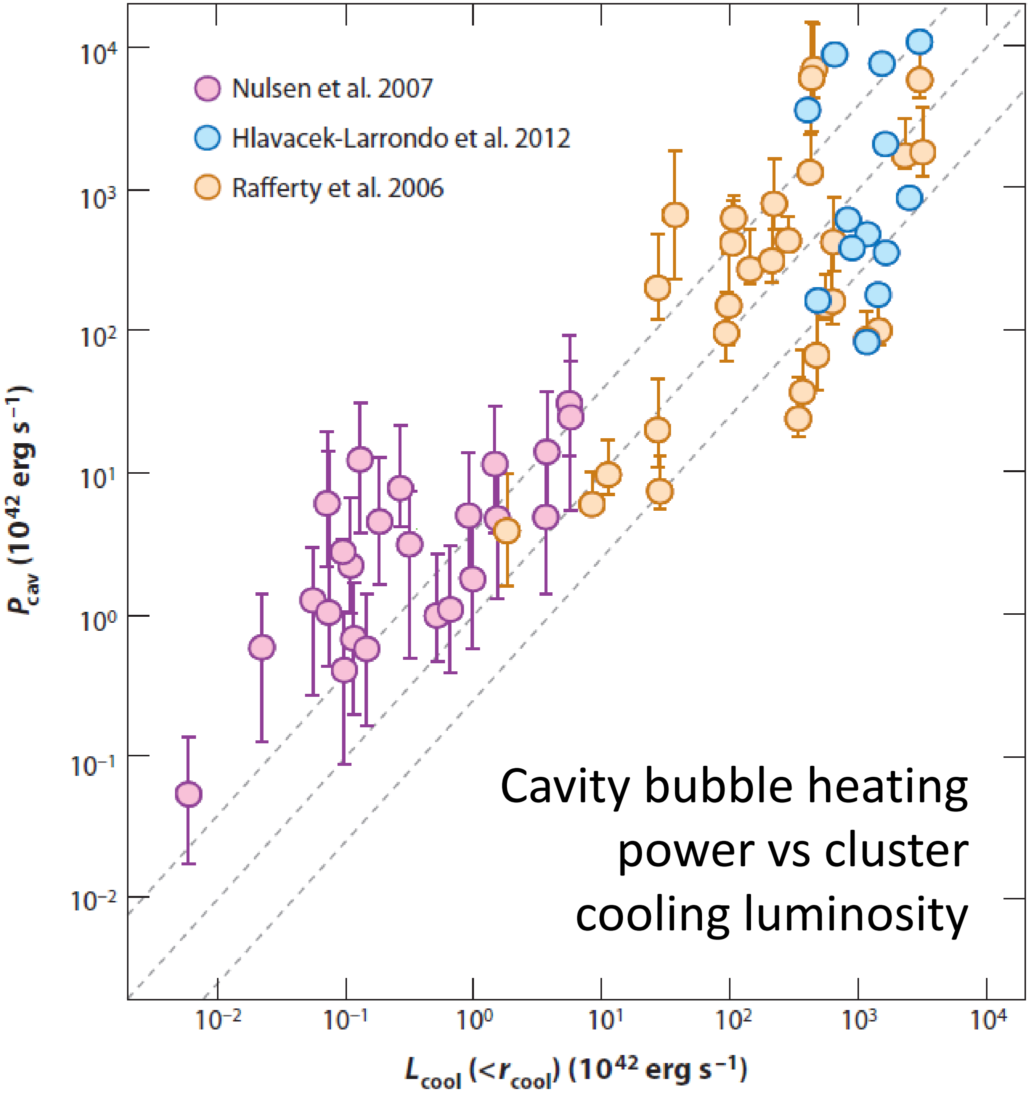
Detailed view of outer cold front in Perseus: Walker+18 (talk in meeting)
Edges known as “Cold fronts” (Markevitch+07)
θ = 0 °
100 kpc
θ = 22.5 °
θ = 45 °
θ = 67.5 °
θ = 90 °
ZuHone+18 simulation of different sightlines showing bulk motions
300
200
100
0
−100
−200
μ_ℓ (km/s)
1 degree

AGN feedback in clusters

from J. Hlavacek-Larrondo (review in Fabian 2012)

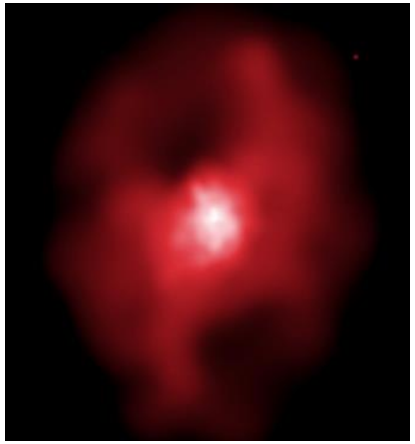


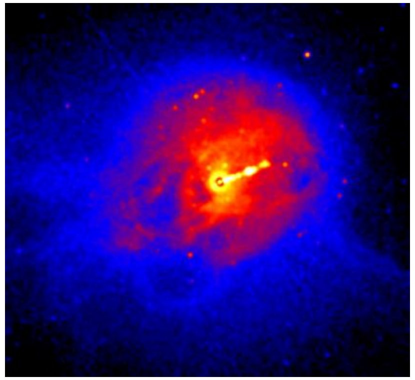
Many clusters show short cooling times in their cores – would rapidly cool if emitted energy not replaced

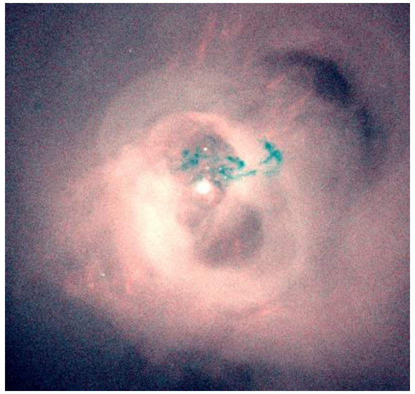
Feedback is seen in the form of cavities generated by AGN jets in most clusters with short cooling times (e.g. Panagoulia+14)

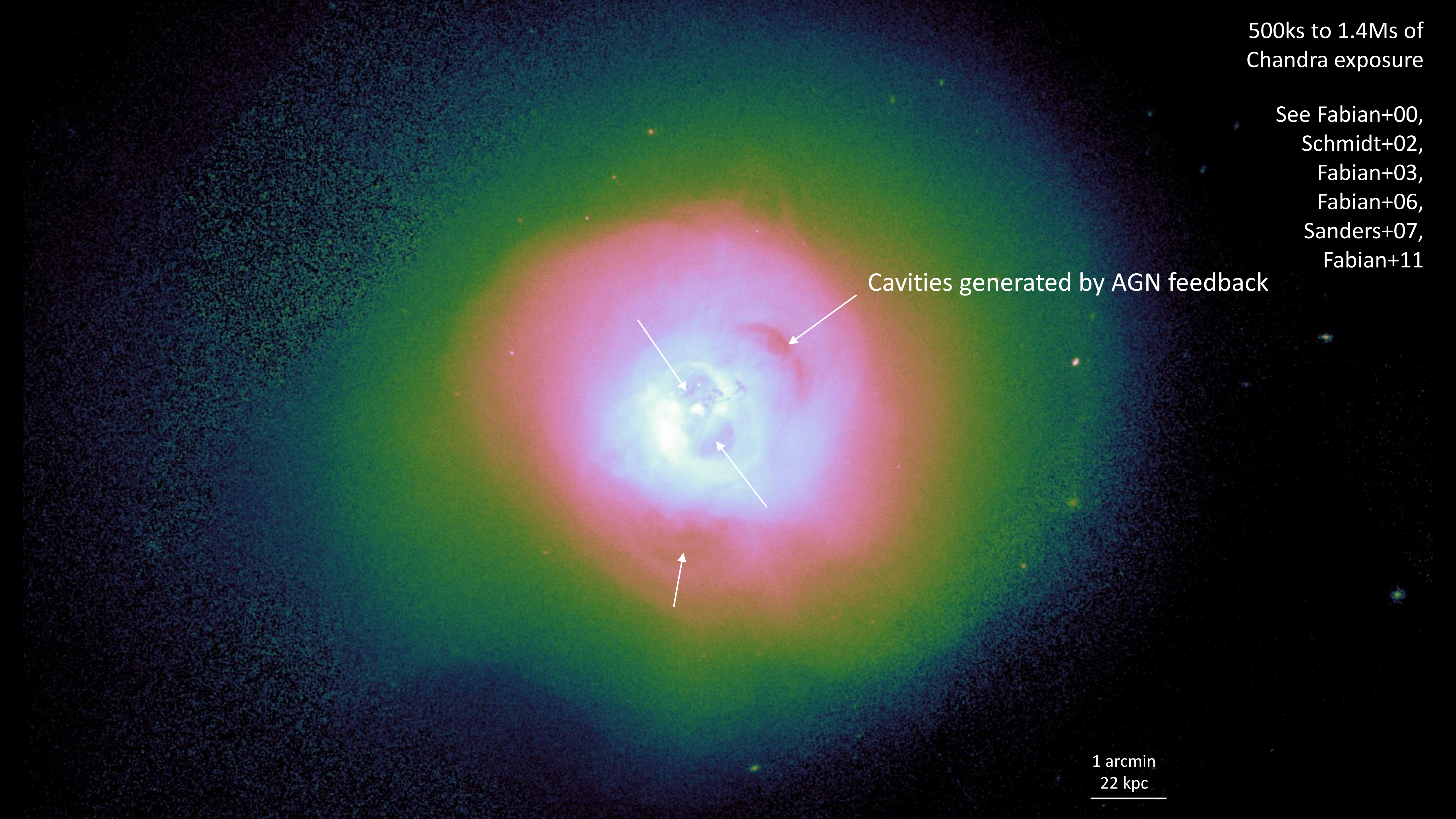
Energetically, AGN can prevent cooling in majority of objects over a wide range in X-ray luminosity

- *How does AGN feedback work in detail?*
- *How is the energy distributed from cavities?*

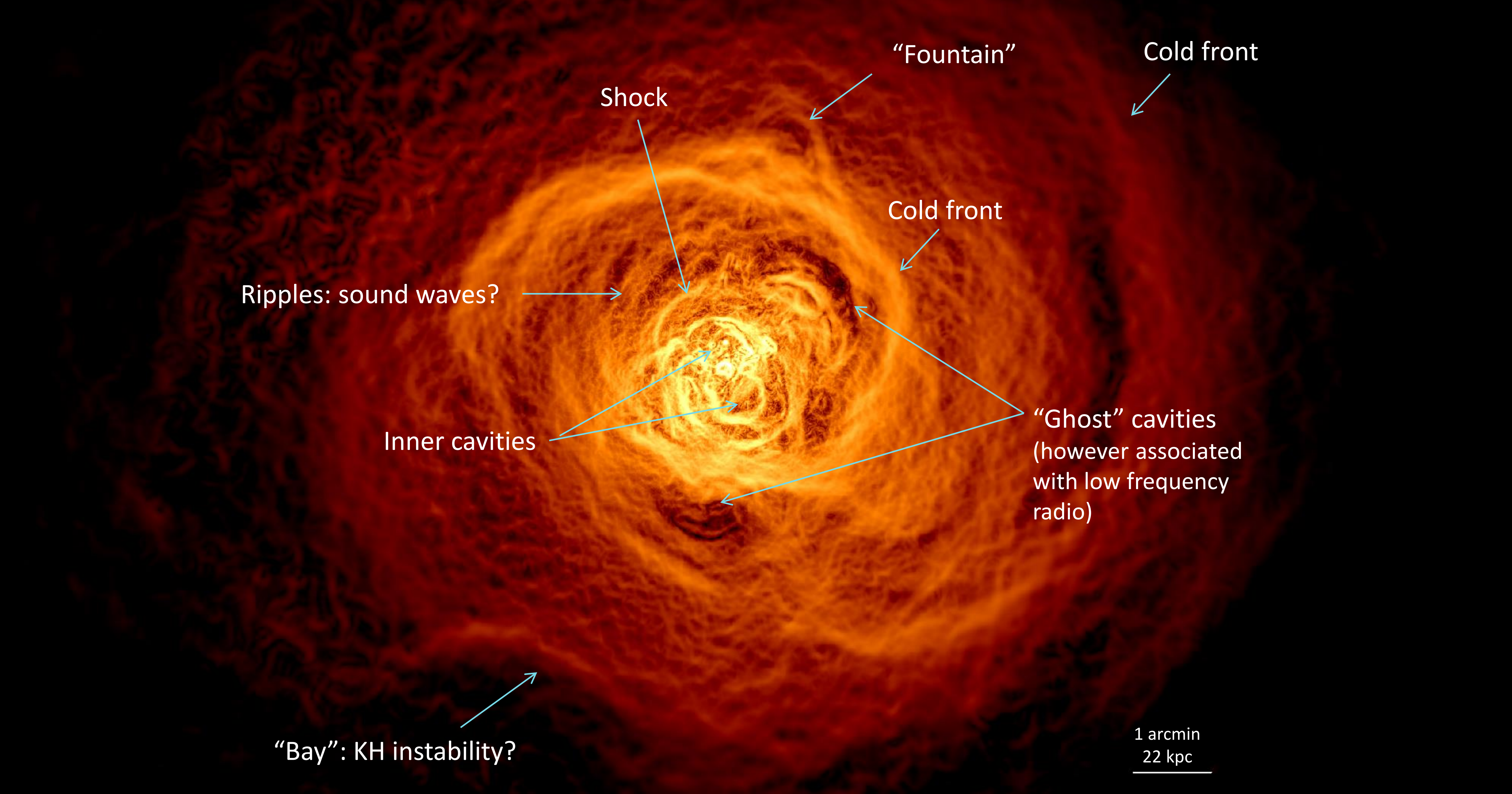




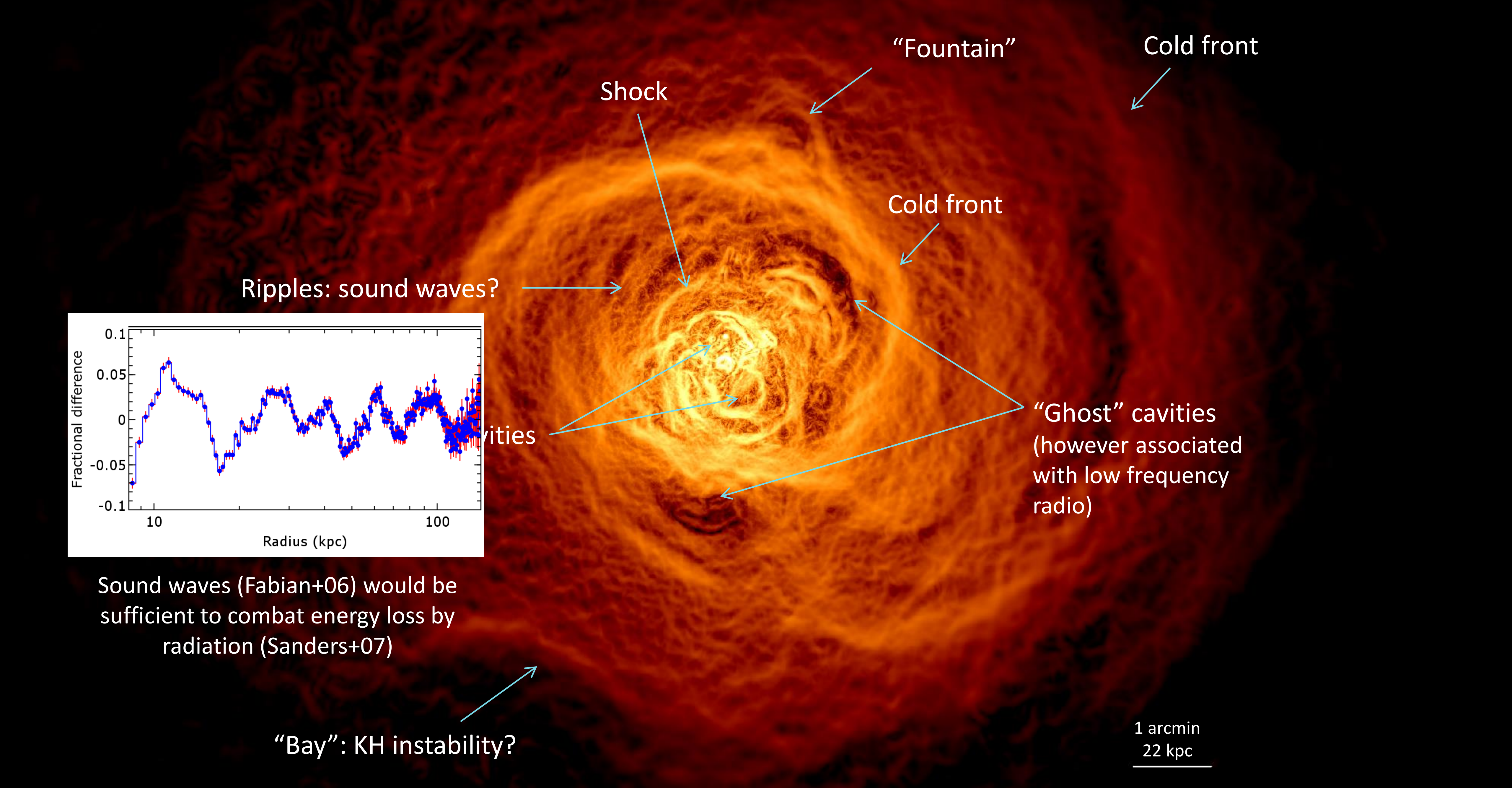


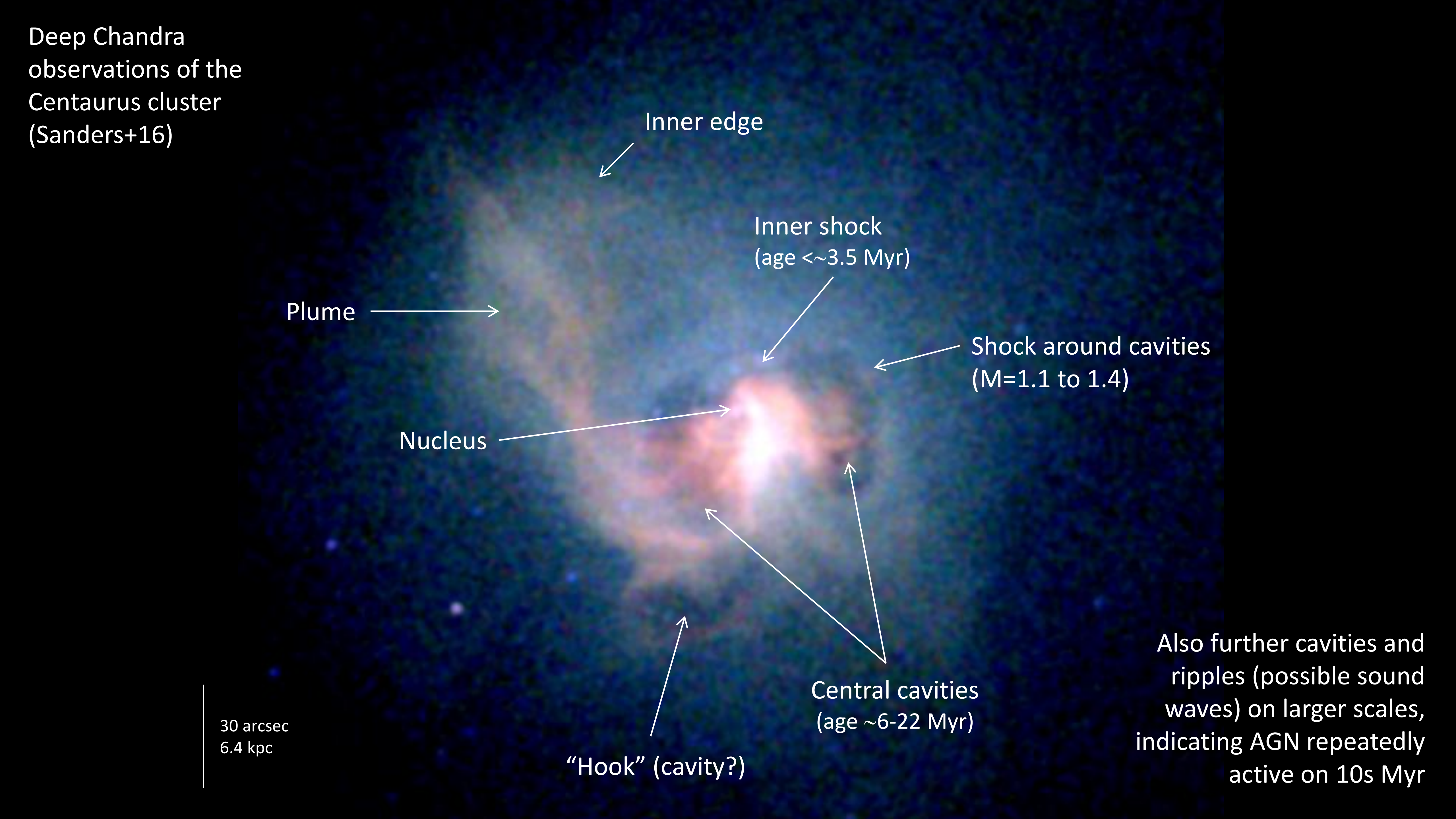

500ks to 1.4Ms of
Chandra exposure
See Fabian+00,
Schmidt+02,
Fabian+03,
Fabian+06,
Sanders+07,
Fabian+11
Cavities generated by AGN feedback
1 arcmin
22 kpc

Perseus Cluster: applying gradient filter (Sanders+16)

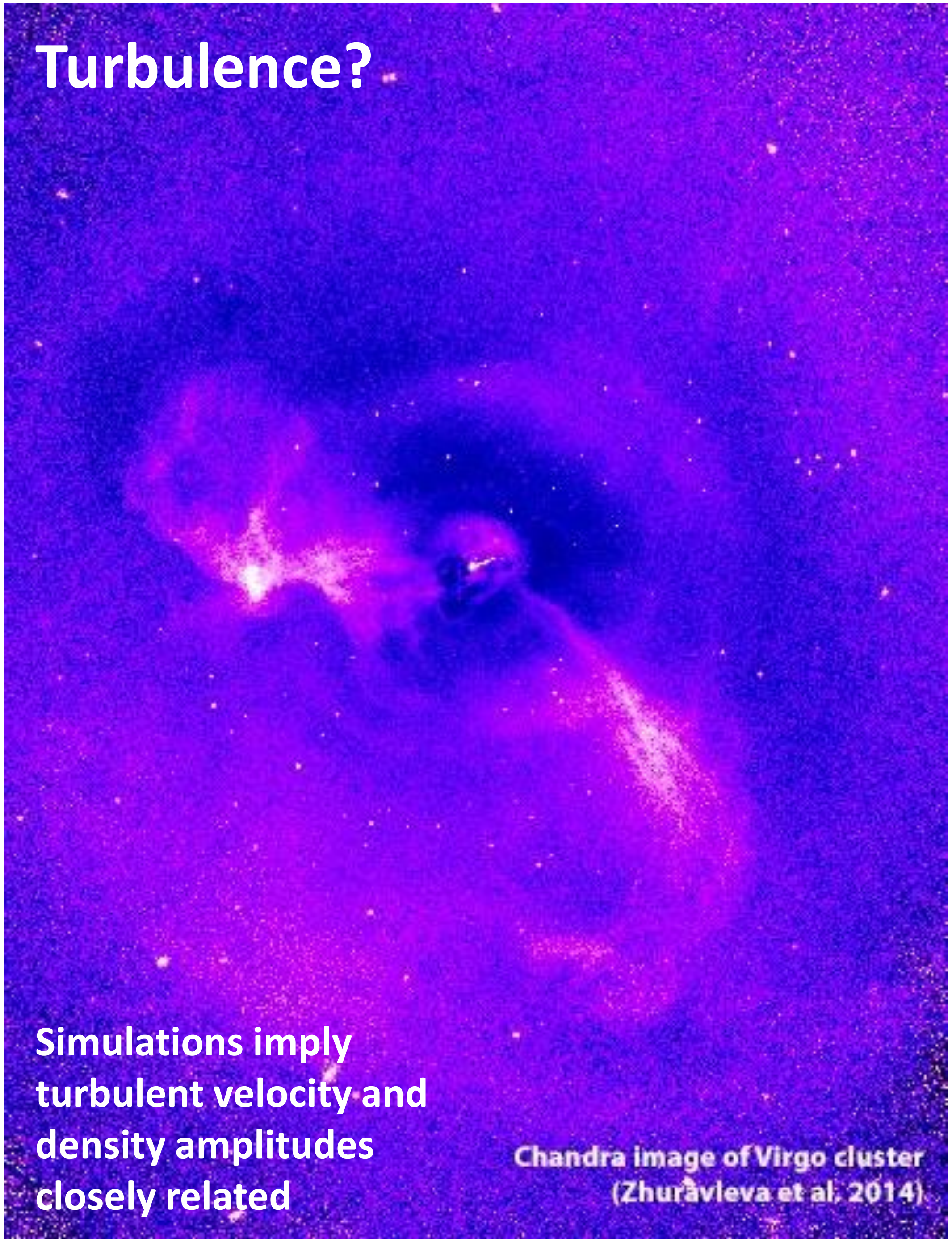


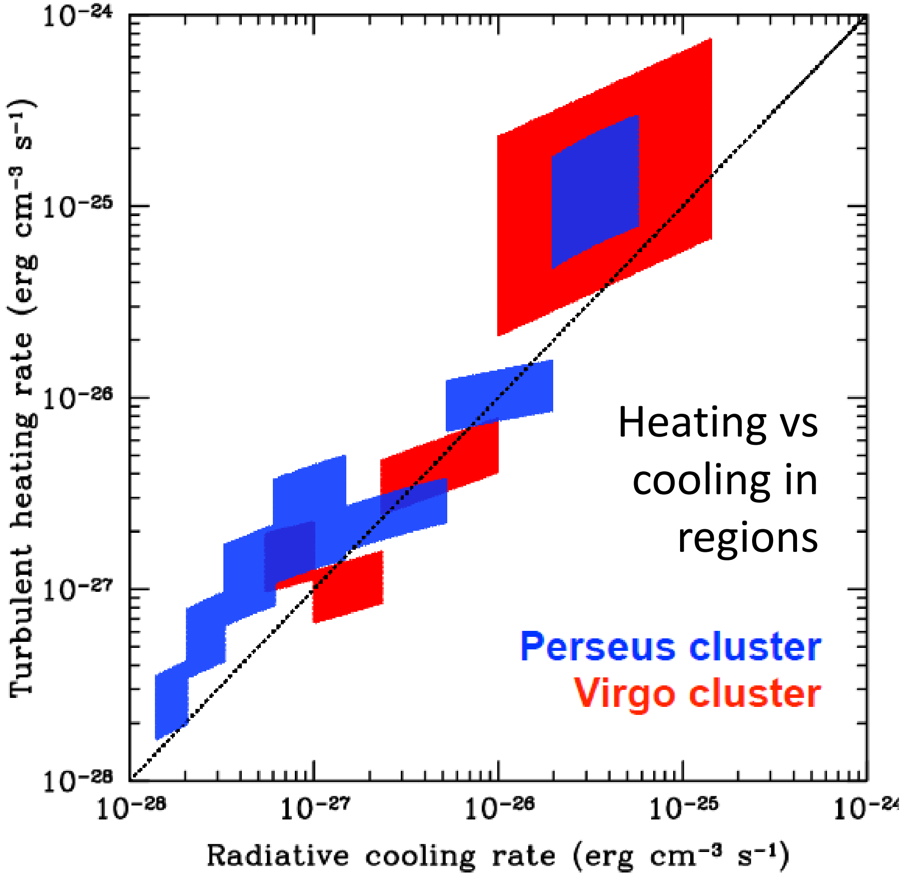
Perseus Cluster: applying gradient filter (Sanders+16)




Deep Chandra observations of the Centaurus cluster (Sanders+16)
Inner edge
Inner shock
(age <~3.5 Myr)
Plume
Shock around cavities
(M=1.1 to 1.4)
Nucleus
"Hook" (cavity?)
Central cavities
(age ~6-22 Myr)
30 arcsec
6.4 kpc
Also further cavities and ripples (possible sound waves) on larger scales, indicating AGN repeatedly active on 10s Myr

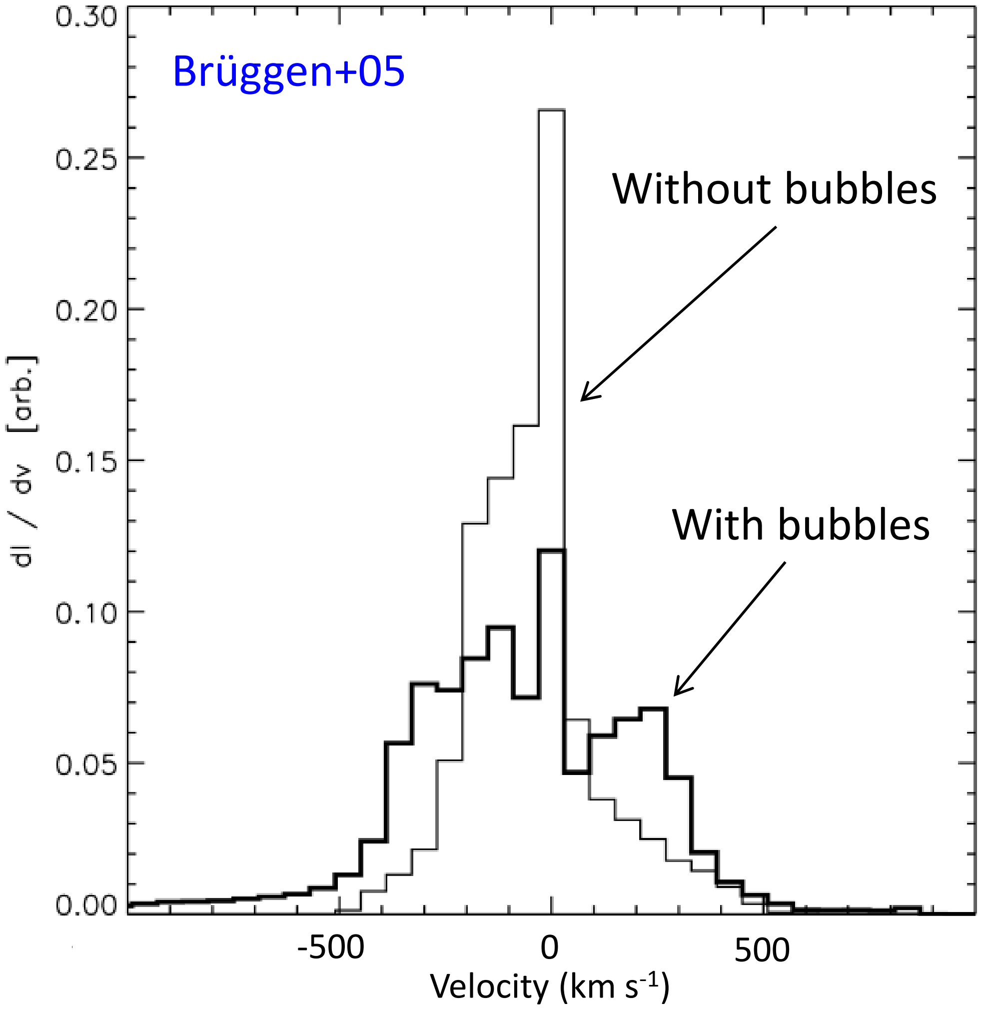
Turbulence?





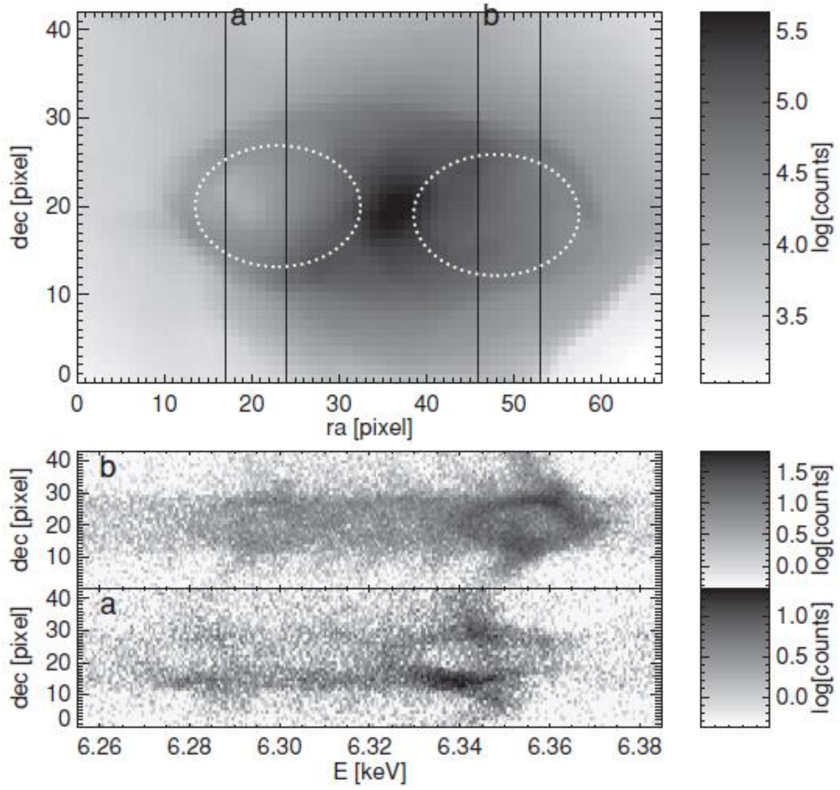
- If density fluctuations are turbulence, then it could energetically do the heating: Zhuravleva+14
- However, (non-AGN) sloshing can be a significant contribution to the signal: Walker+18
- Possible issues with transport and efficiency: e.g. Fabian+16, Yang+16, Bambic+18

Feedback in simulations



Emission-weighted velocity centred on bubble.
Feedback can give motions of 100s km s^{-1}

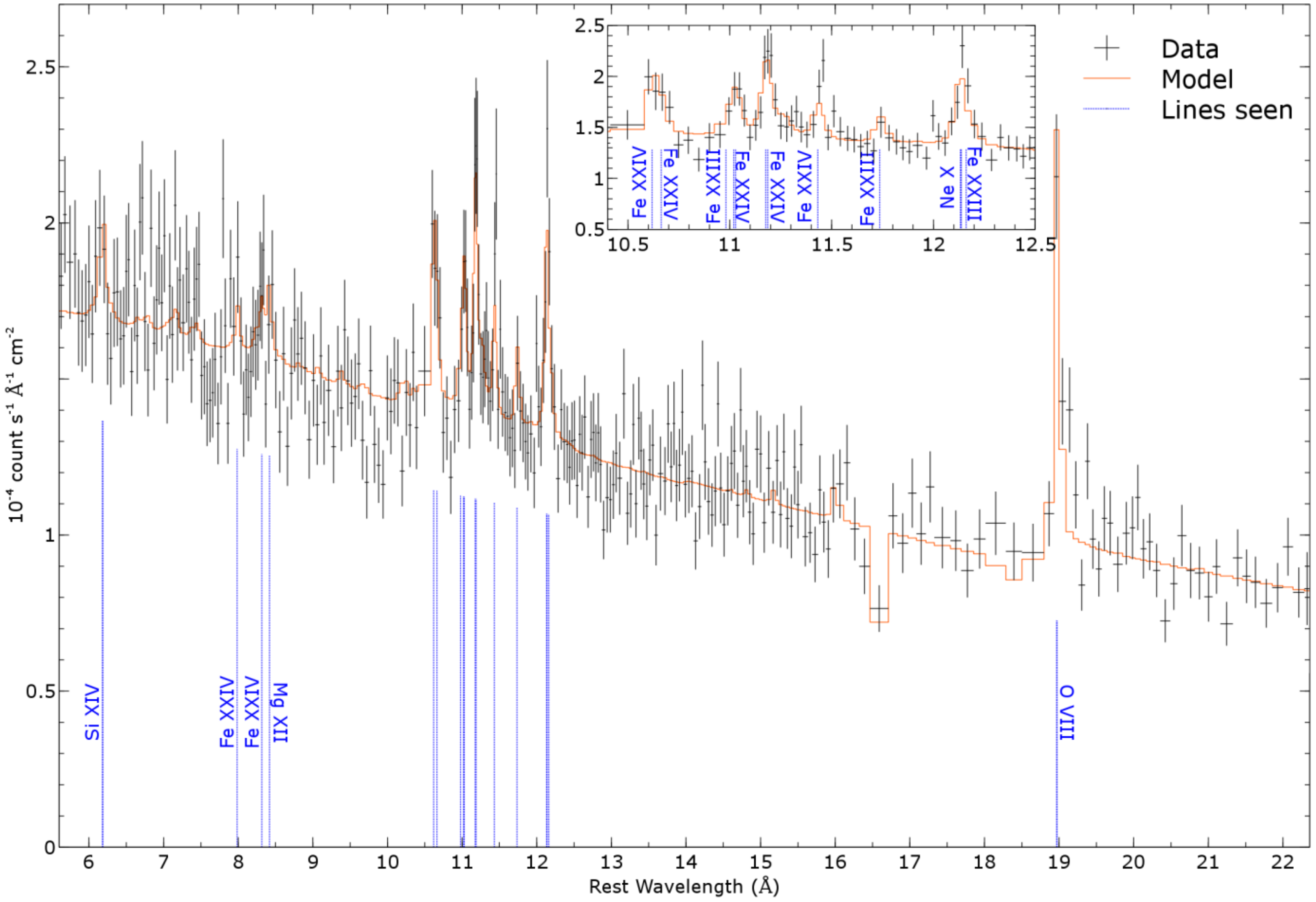
Heinz+10 Also see Bourne+17



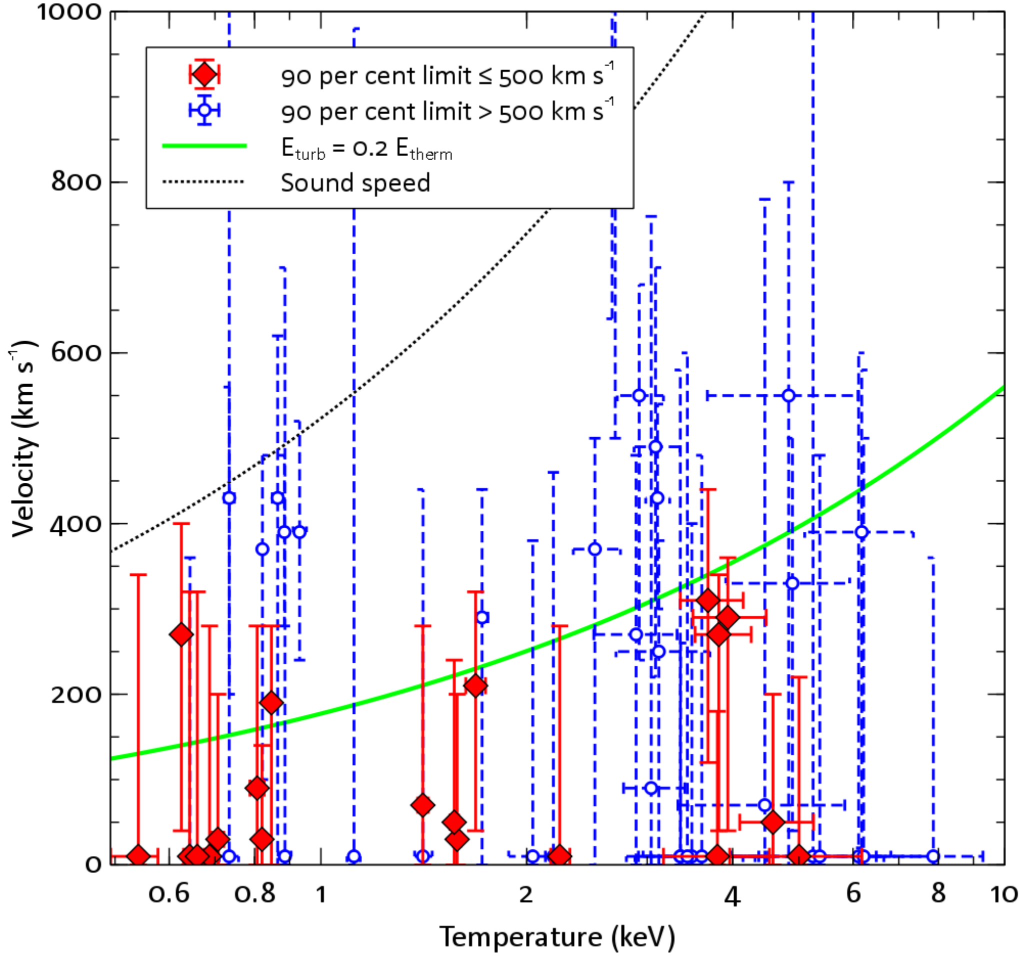
Directly measuring velocities crucial to understanding AGN feedback (including dissipation of energy), sloshing and cluster evolution

XMM-RGS measurements of velocities

Sanders+10: Abell 1835, line-of-sight $v_{turb} < 274$ km s^{-1}



Sanders+13



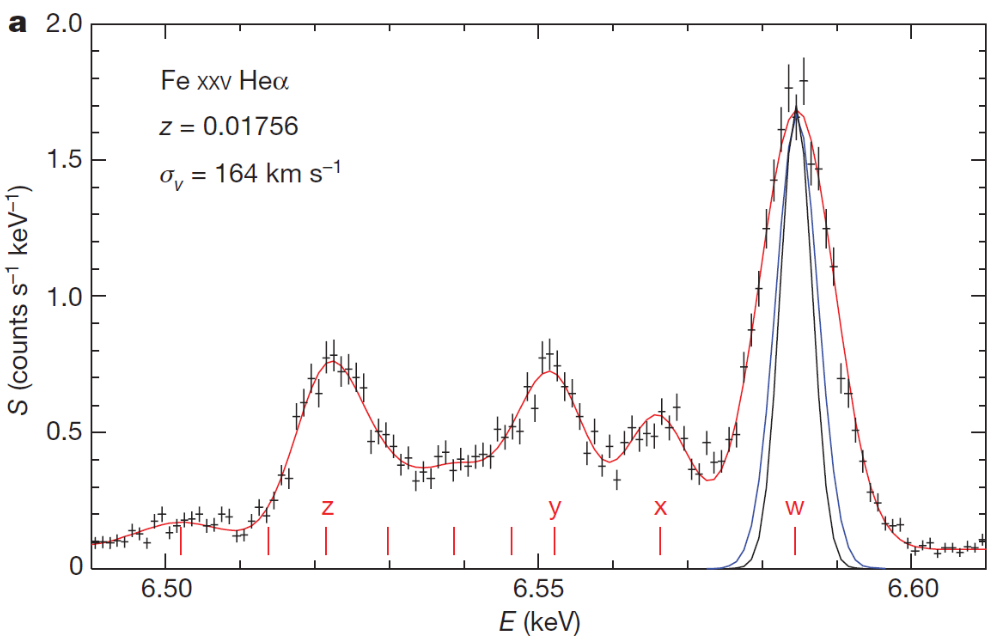
Many cool core clusters with AGN feedback show line width limits < 500 km s^{-1}

Similar results found in a nearby sample in Pinto+15 (see his talk)

Hitomi and the Perseus cluster

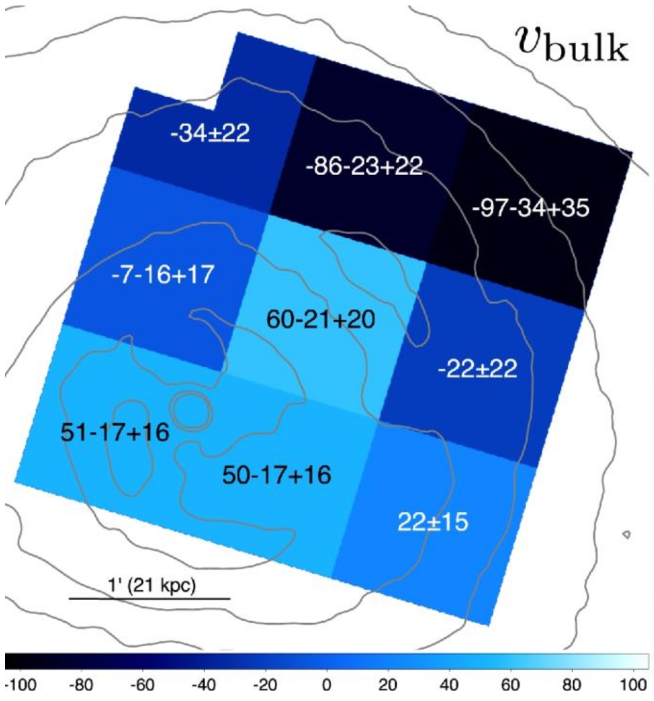
Before its loss, Hitomi observed Perseus, obtaining high resolution spectra measuring the velocity structure.
Little evidence for strong turbulence or motions.

Hitomi+16

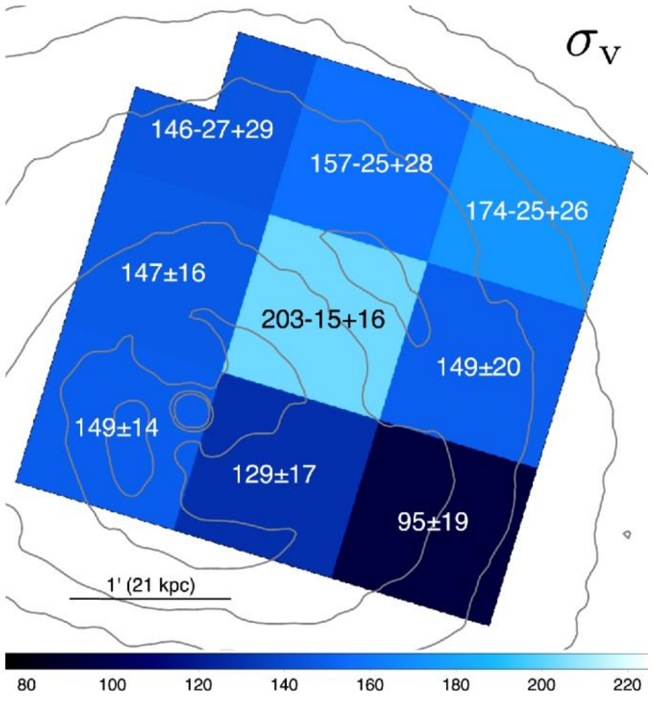


Line widths imply line-of-sight velocity dispersion of 164±10 km s^{-1}

Hitomi+18



Bulk LoS velocity (km s^{-1})

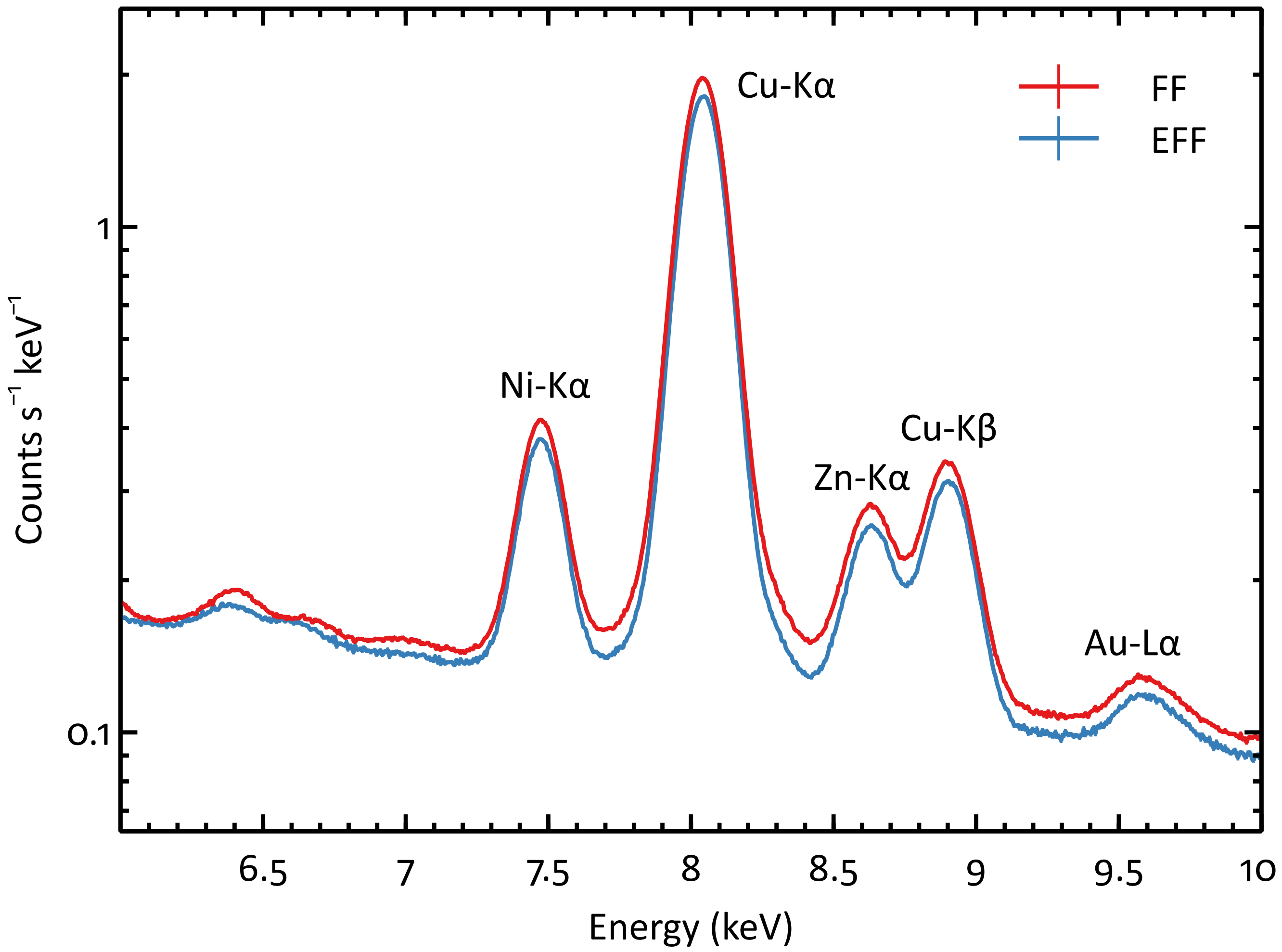


LoS velocity dispersion (km s^{-1})

Measuring bulk flows using CCD detectors

- Measuring velocities important for understanding AGN feedback and the growth of clusters
- Unfortunately, we will need to wait until XRISM to get new Hitomi-quality ICM velocity measurements
- Although CCD detectors have a relatively low spectral resolution, can measure velocities using Fe-K redshift if the energy scale is well-calibrated
- Previous analyses with Suzaku include Tamura+14 and Ota+16
  - Limits or hints of motion at the level of several 100 km s^{-1}

Improving the calibration of XMM-Newton EPIC-pn



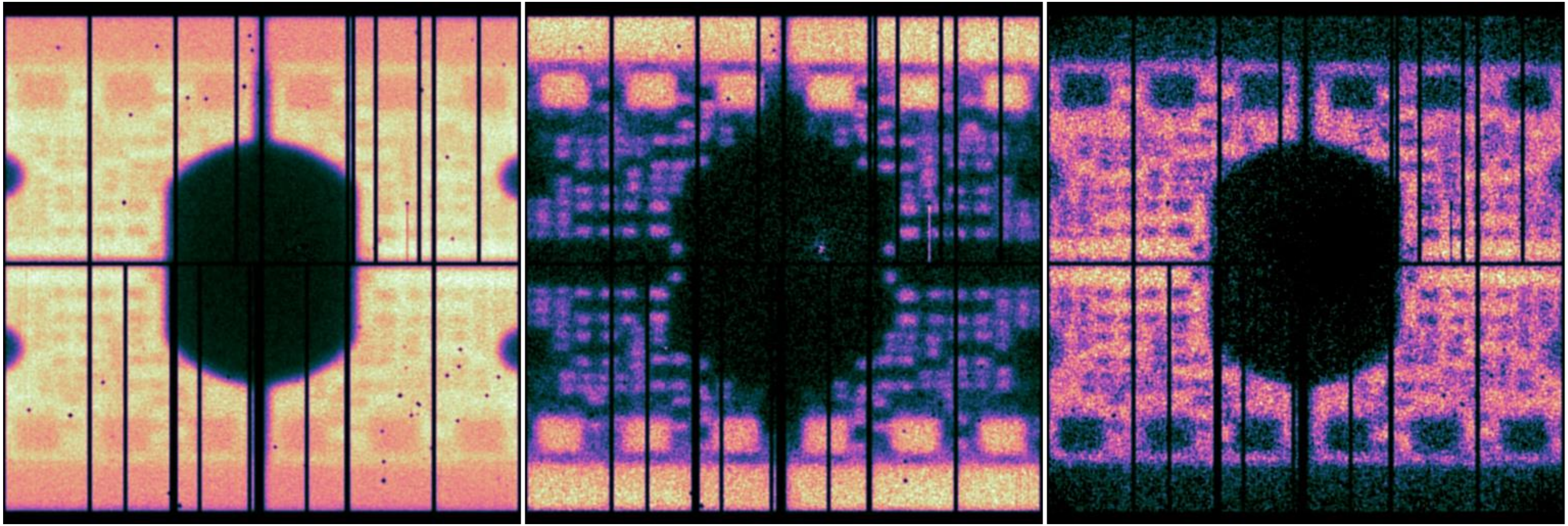
The EPIC-pn detector on XMM-Newton has a detector background including bright fluorescent lines, in particular Cu-Kα

As we know these line energies from lab measurements, we can improve the energy calibration of the detector

FF and EFF are the two full-frame detector modes
33 and 20 Ms of stacked spectra, respectively

Images of EPIC-pn in different background lines

Stacked images after subtracting instrumental background. Signal comes from electronics boards (Freyberg+01).



Cu-Kα

Ni-Kα

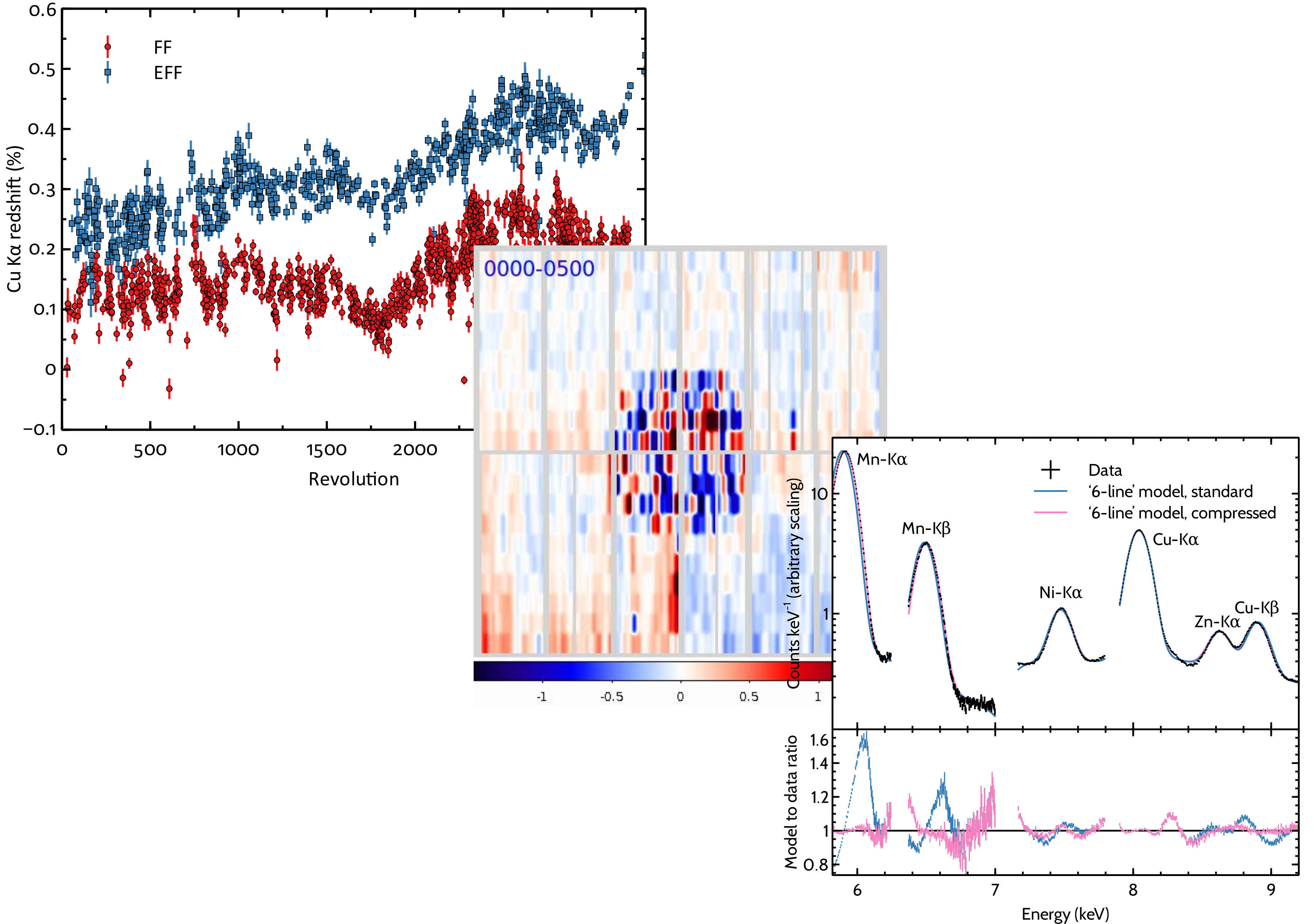
Zn-Kα + Cu-Kβ

Can only calibrate outer parts of detector using these lines!

EPIC-pn energy calibration improvement procedure

- Considerable work into improving energy calibration

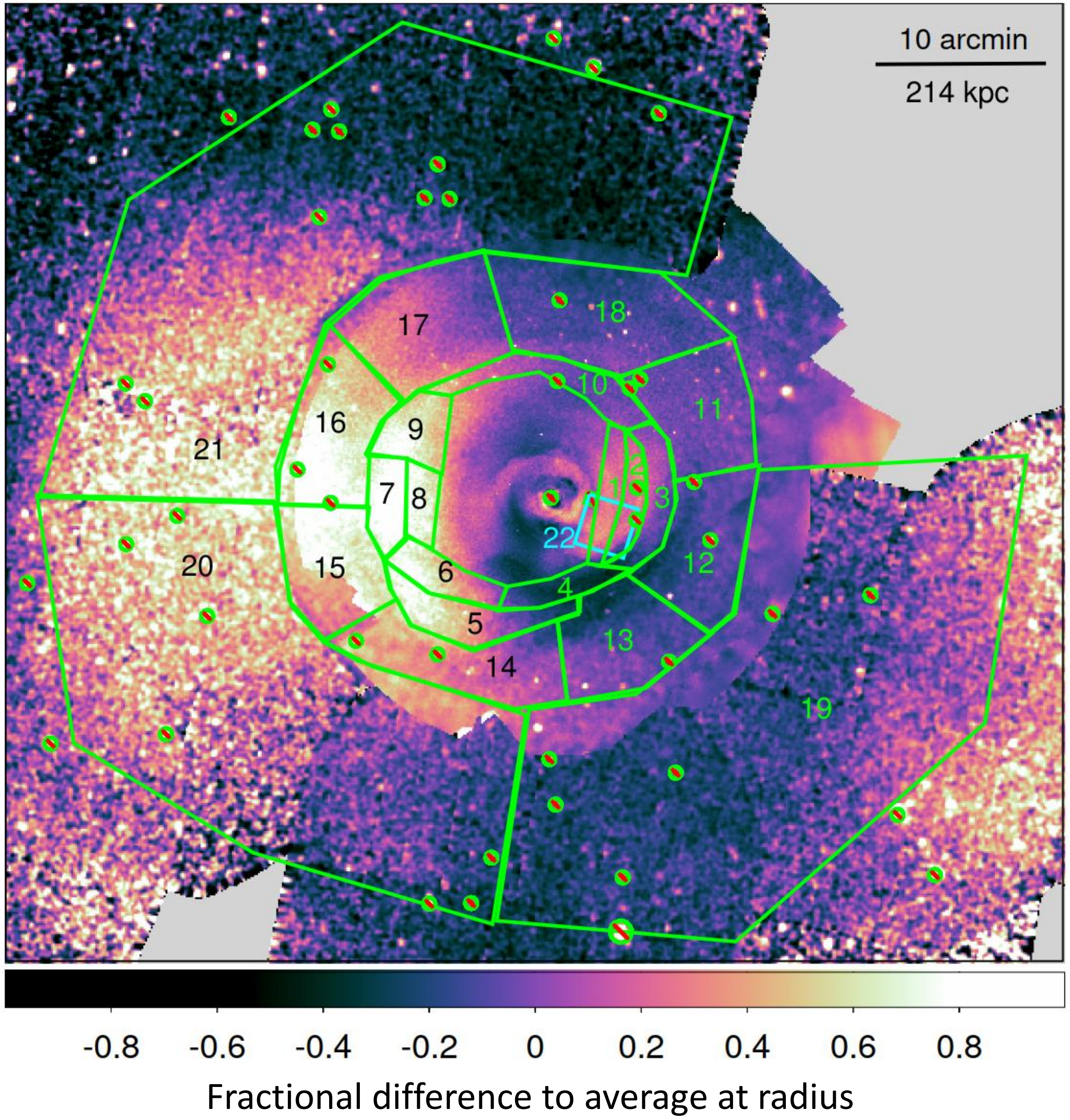
- 3 stage approach to correcting the energy of X-ray events in addition to the standard calibration
  - Stage 1: correct average gain
  - Stage 2: correct detector position-dependent gain
  - Stage 3: correct energy scale



Results after correction

- Examine dispersion of energy correction factor in corrected individual (unstacked) calibration and astrophysical observations
- Implies energy scale is good to 100-200 km s^{-1} at Fe-K
- May be better when combining observations of different epochs and aimpoints

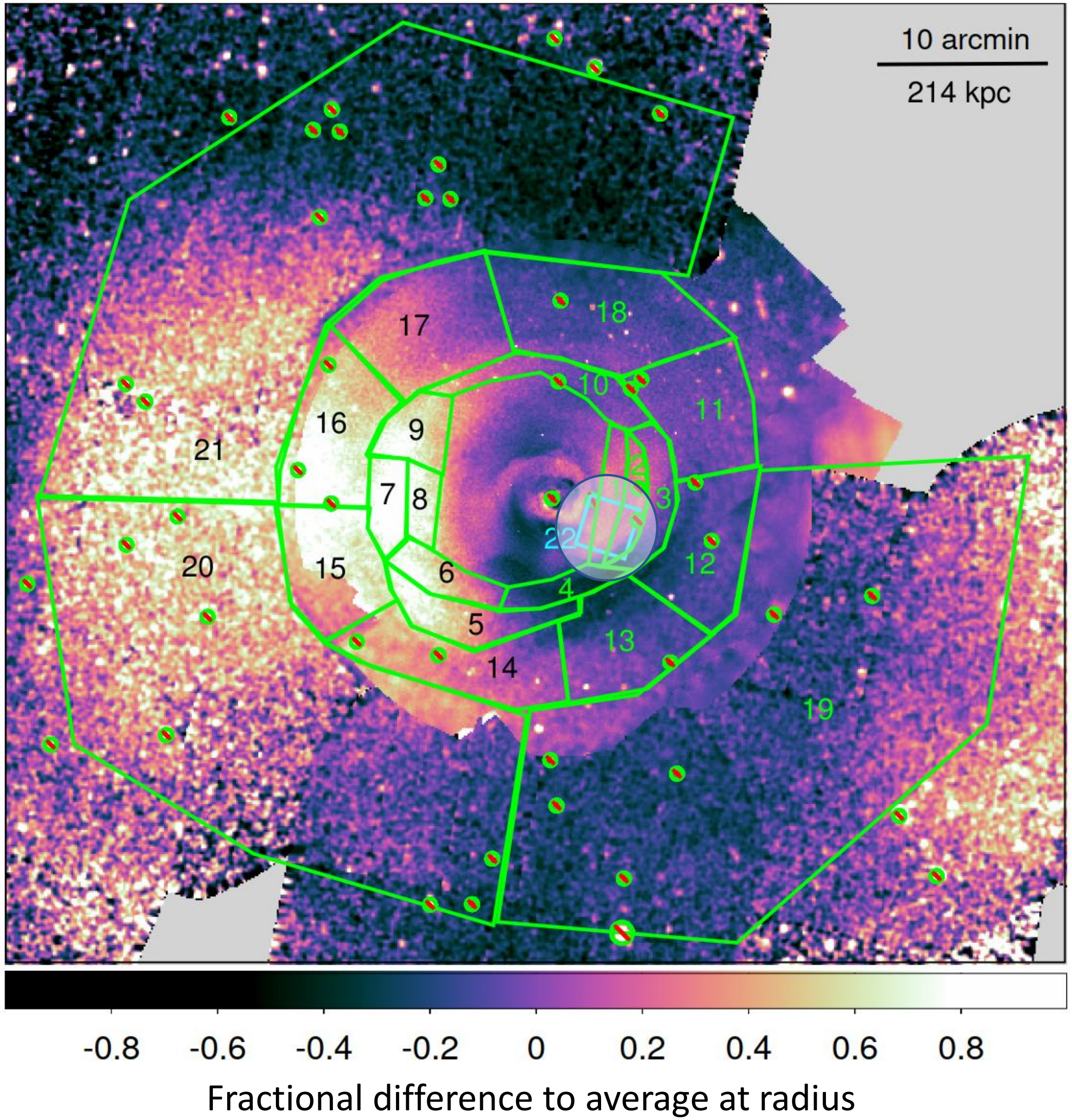
Perseus cluster velocity measurements

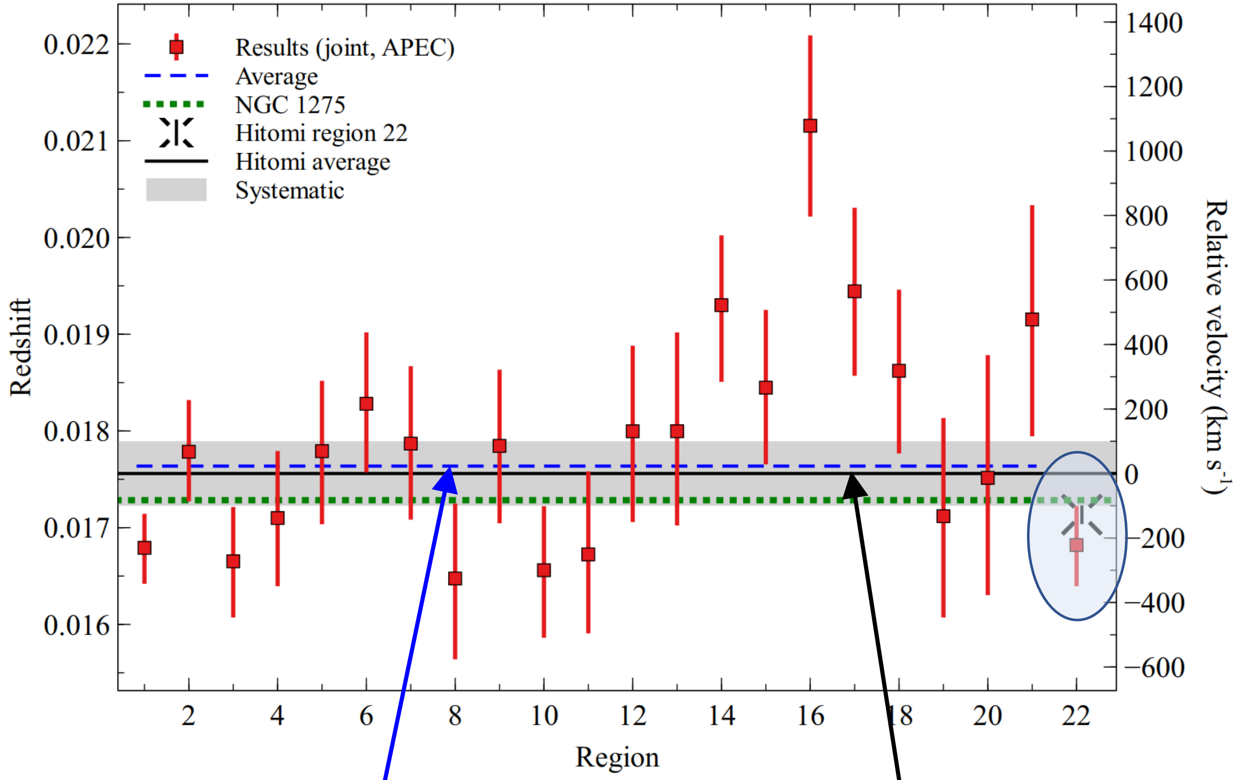


- Independent spatial regions following surface brightness (created by hand)
- No central regions!
- Also Hitomi comparison region (Region 22)

- Fit spectra between 4 and 9.25 keV with cluster plus background model

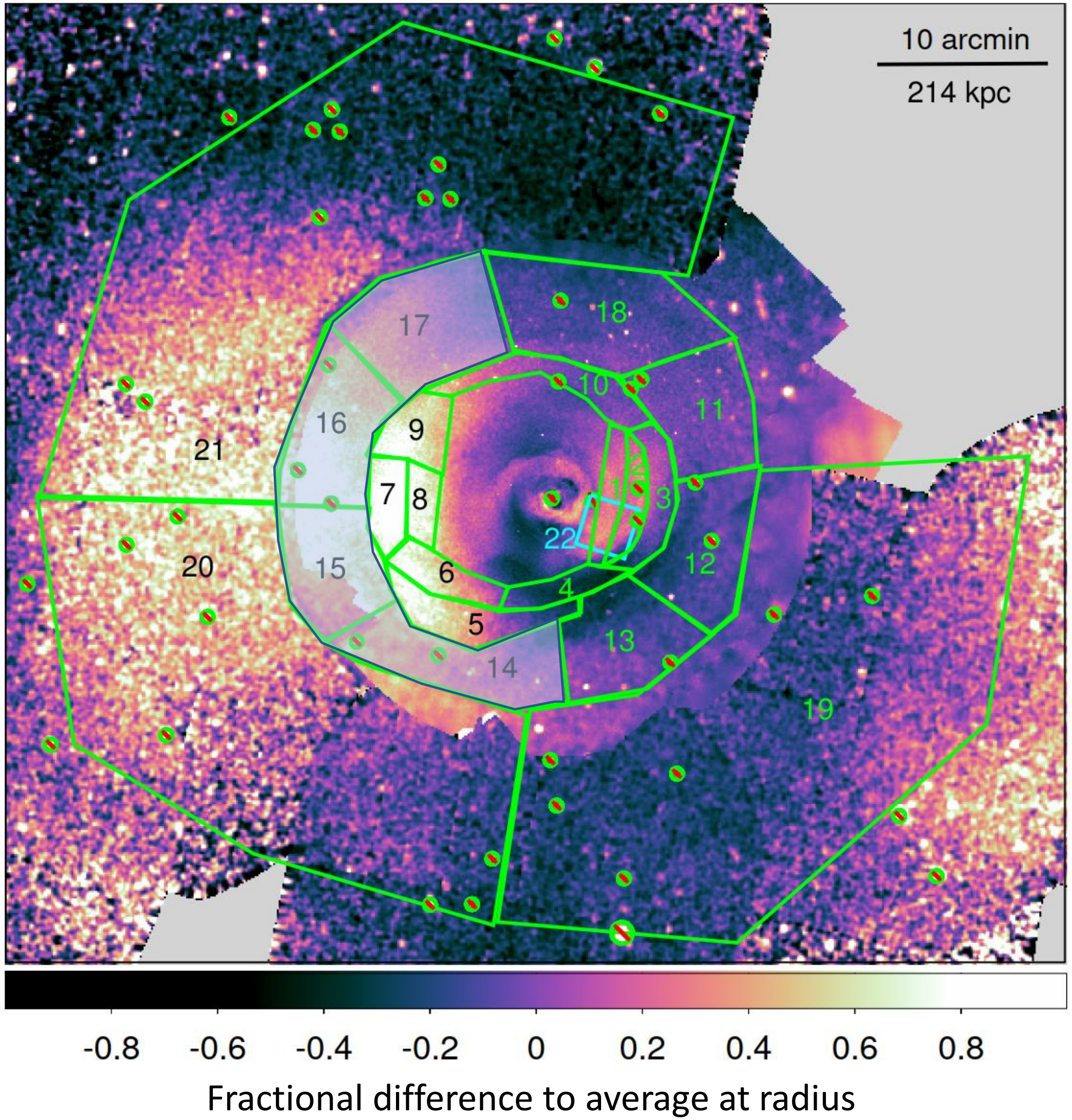
Perseus cluster velocity measurements

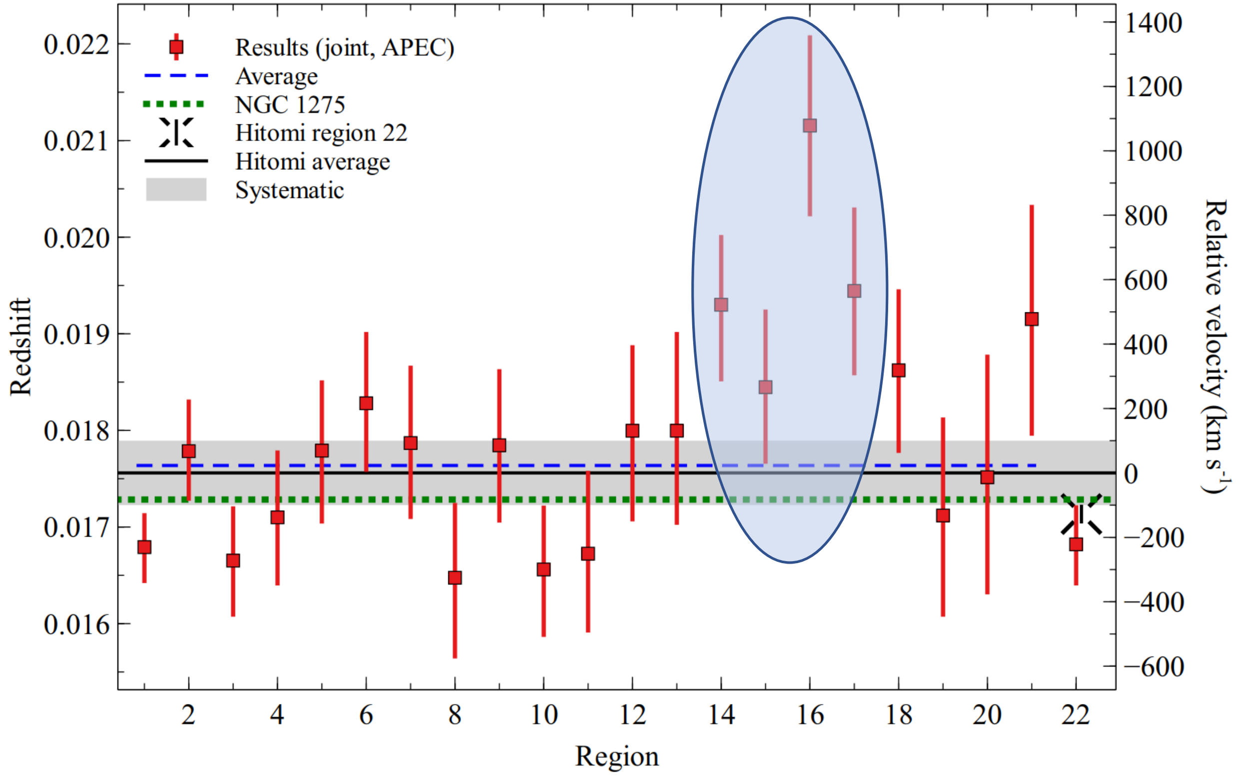




- Our average velocity and the Hitomi average velocity are very close (<< systematics)
- Consistent velocity obtained in Hitomi comparison region (Region 22)

Perseus cluster velocity measurements

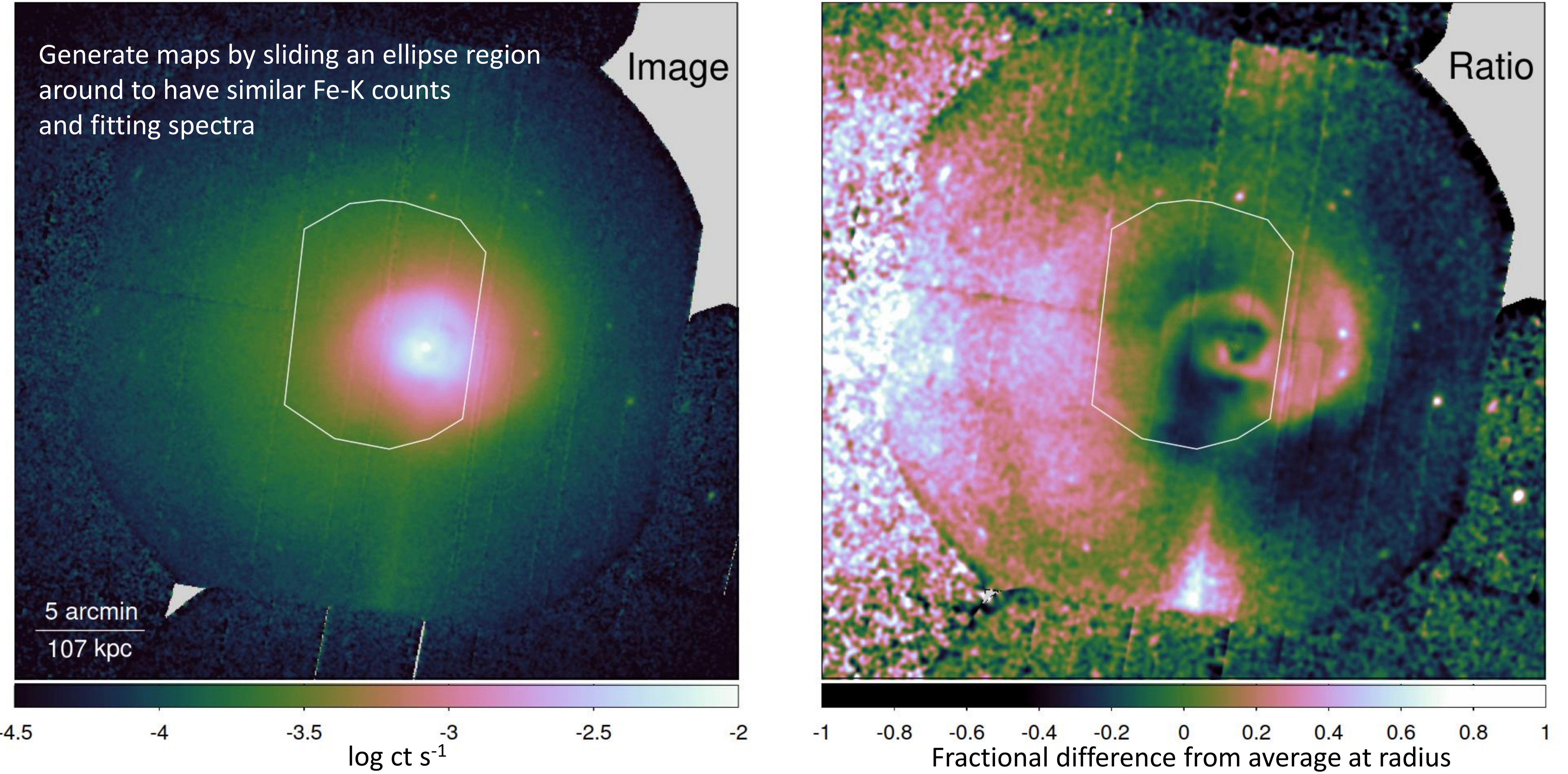




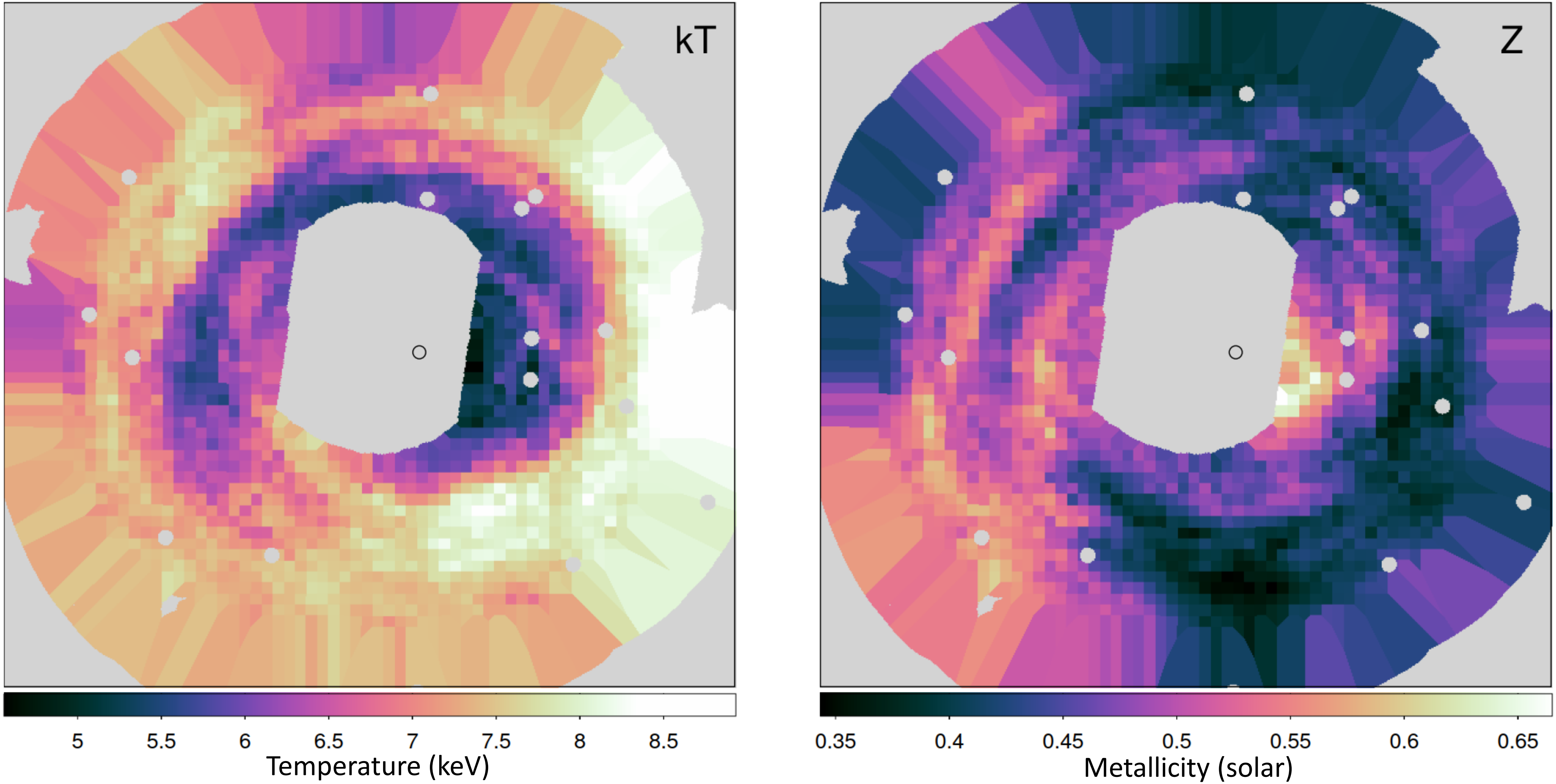
- Evidence for sloshing at 500±100 km s^{-1} to east of core where there is a cold front (excl. systematic)
- Assuming distribution is Gaussian, LoS width of all points (except 22) is 260±90 km s^{-1}
- Excluding sloshing region, obtain width <220 km s^{-1}, similar to Hitomi in region without feedback

Perseus cluster maps: surface brightness

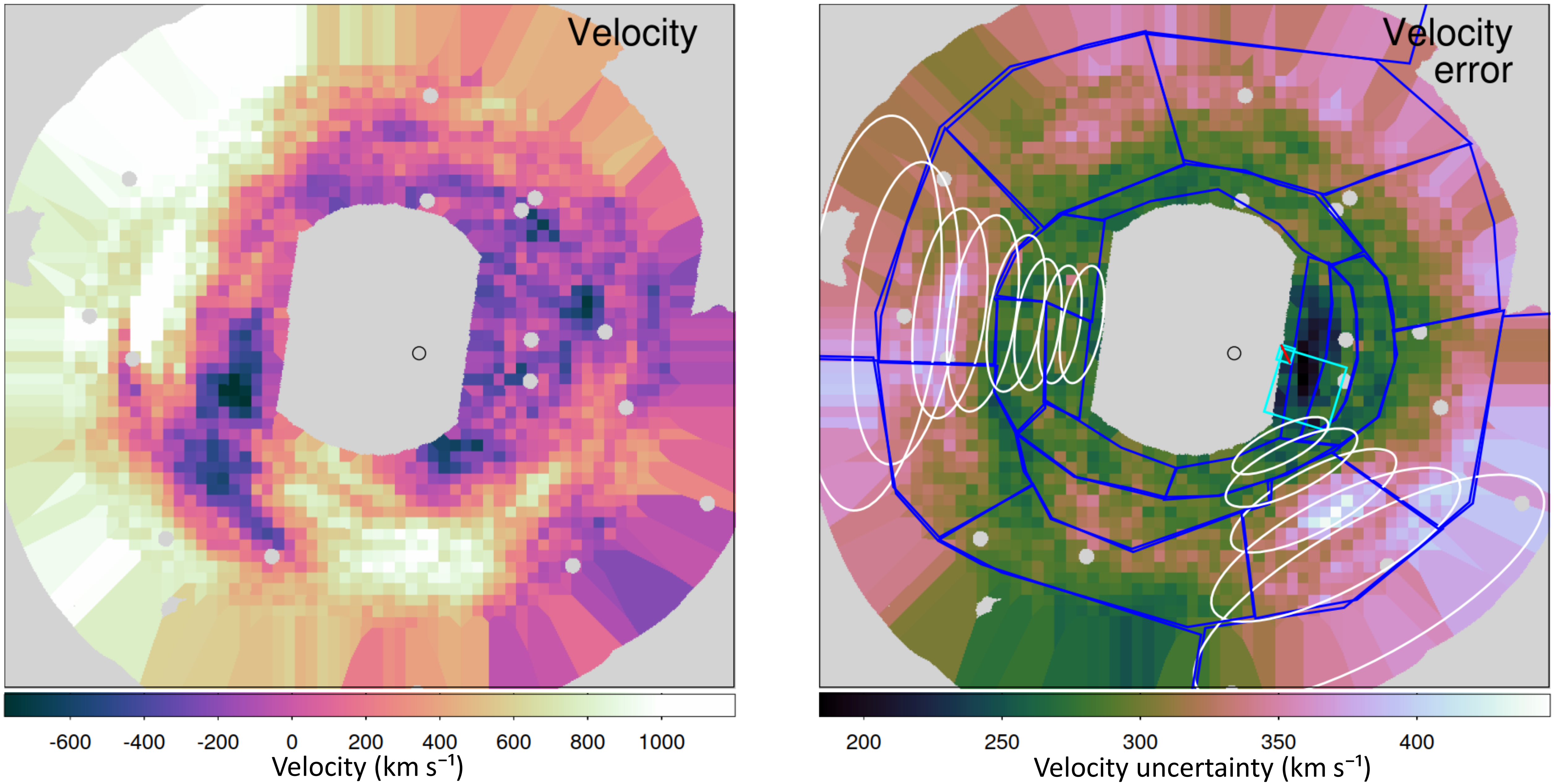
Generate maps by sliding an ellipse region around to have similar Fe-K counts and fitting spectra



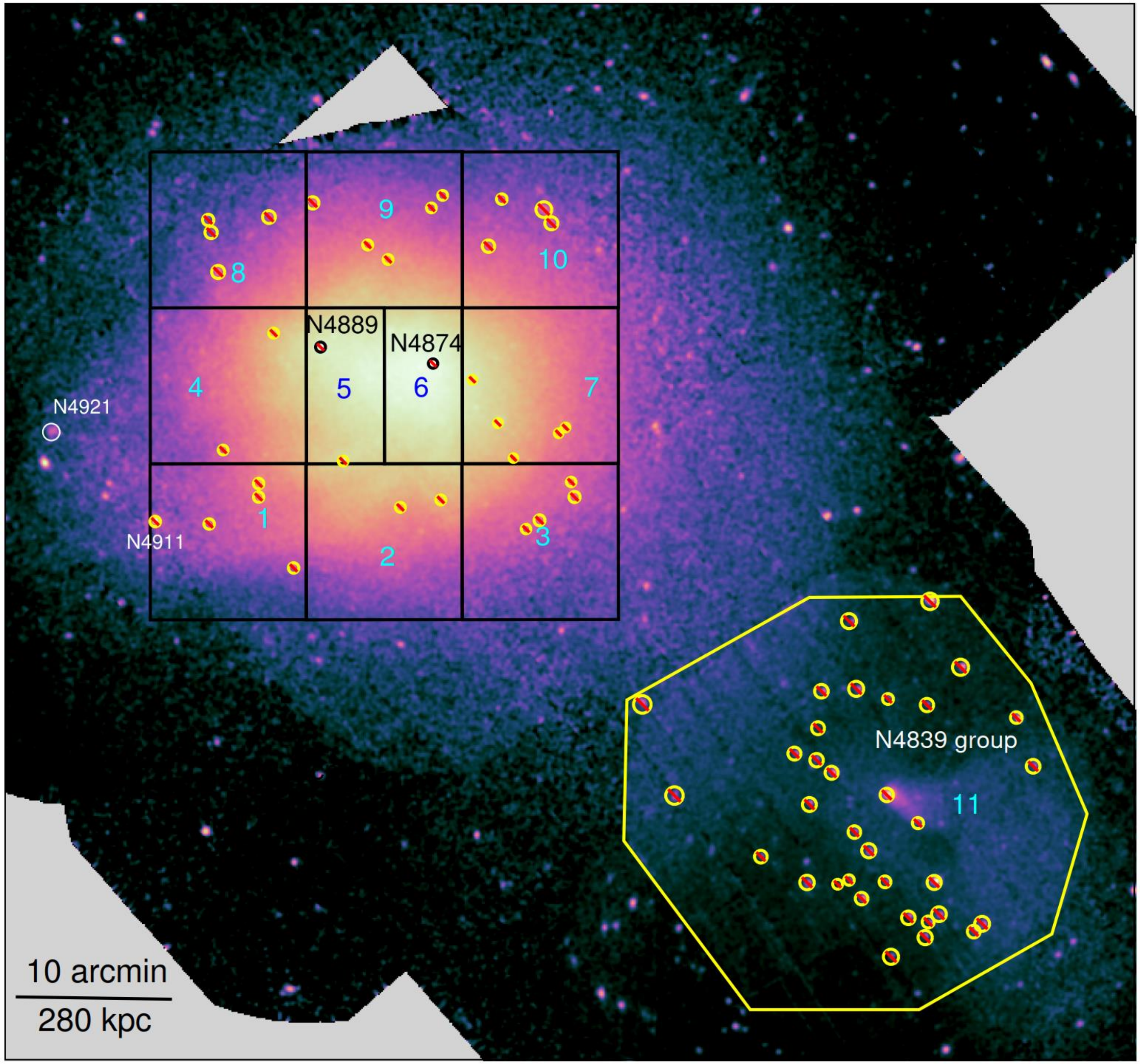
Perseus cluster maps: temperature and metallicity



Perseus cluster maps: velocity and uncertainty

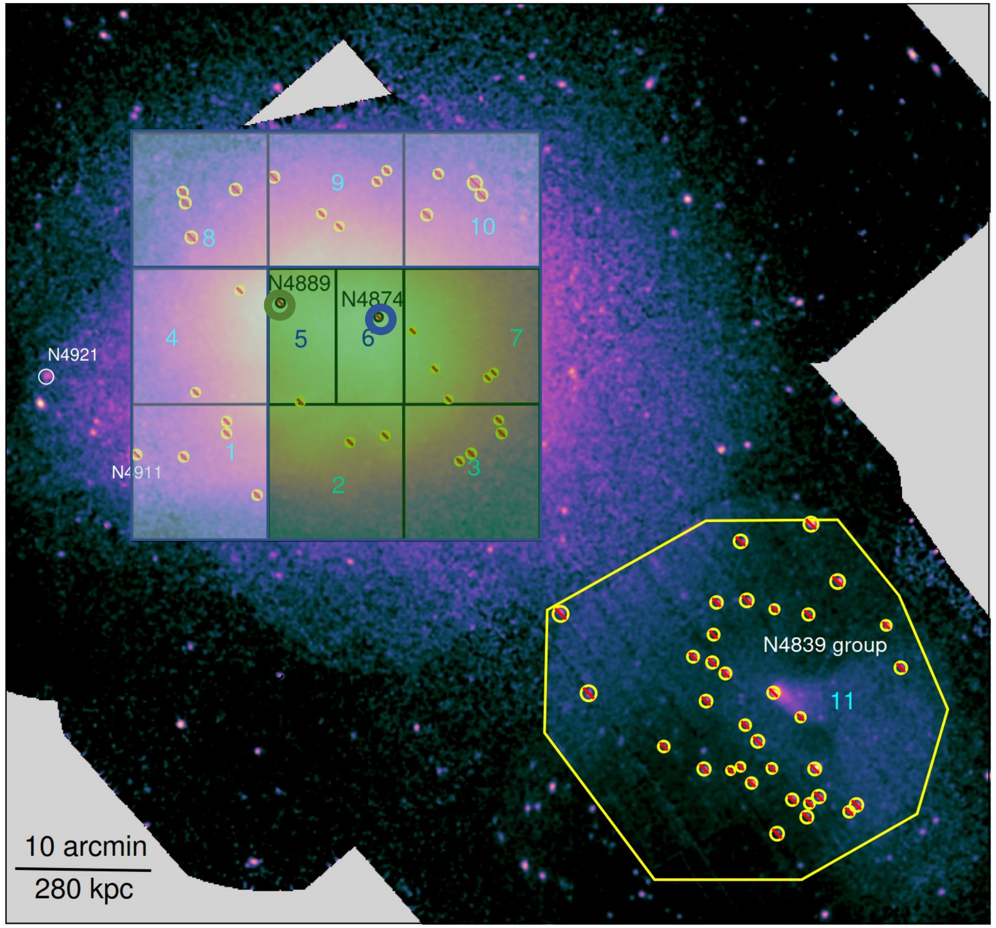


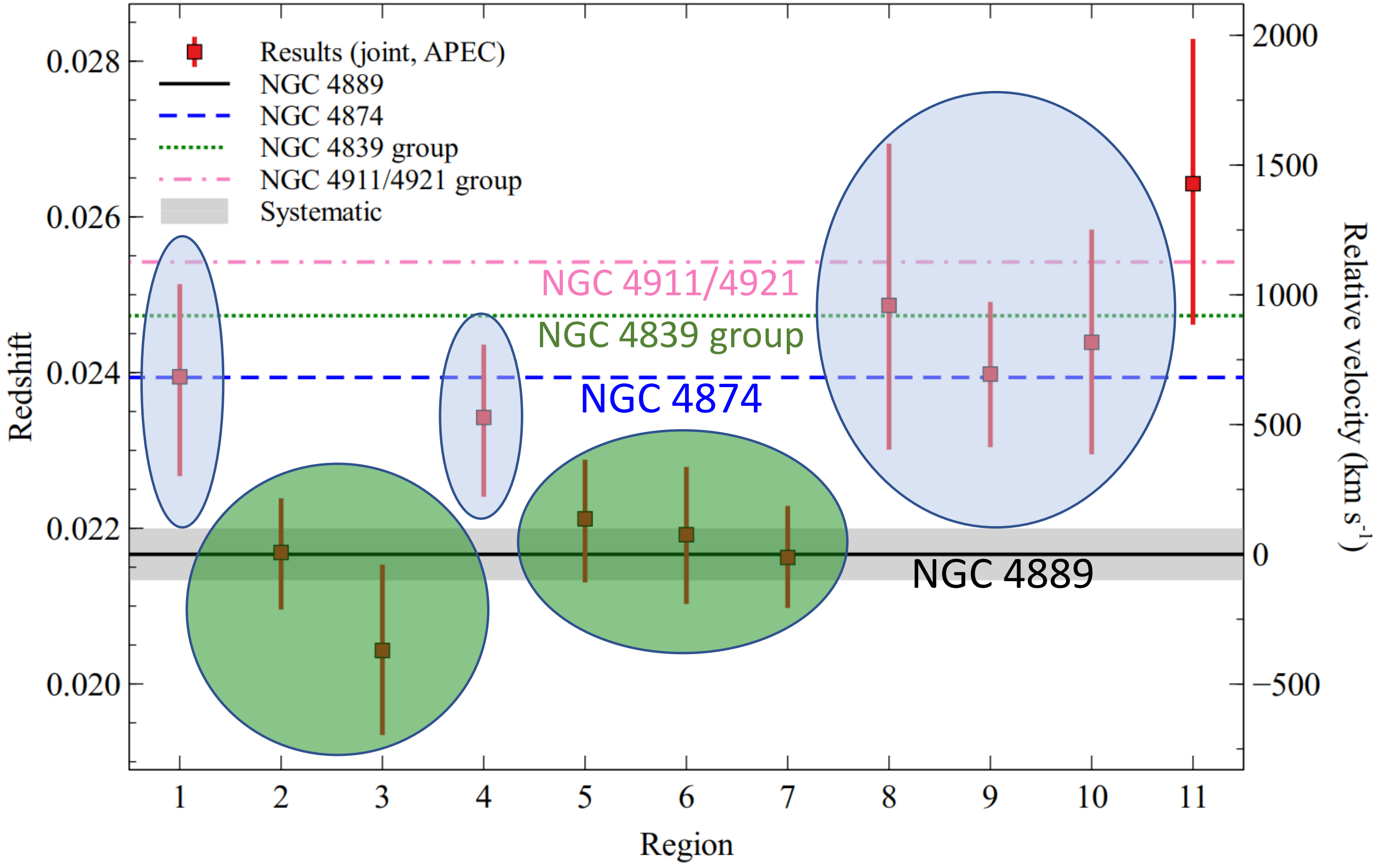
Coma cluster



- Merging system
- Two central galaxies: NGC 4874 and NGC 4889
- Merging NGC 4839 group in south west. Neumann+01 claim likely has not passed through cluster.
- Second NGC 4921/4911 group to east, likely showing colder stripped gas from group (Neumann+03) into cluster core (Sanders+13)
- Construct 10 central regions and one for NGC 4839 group

Coma cluster – velocity results

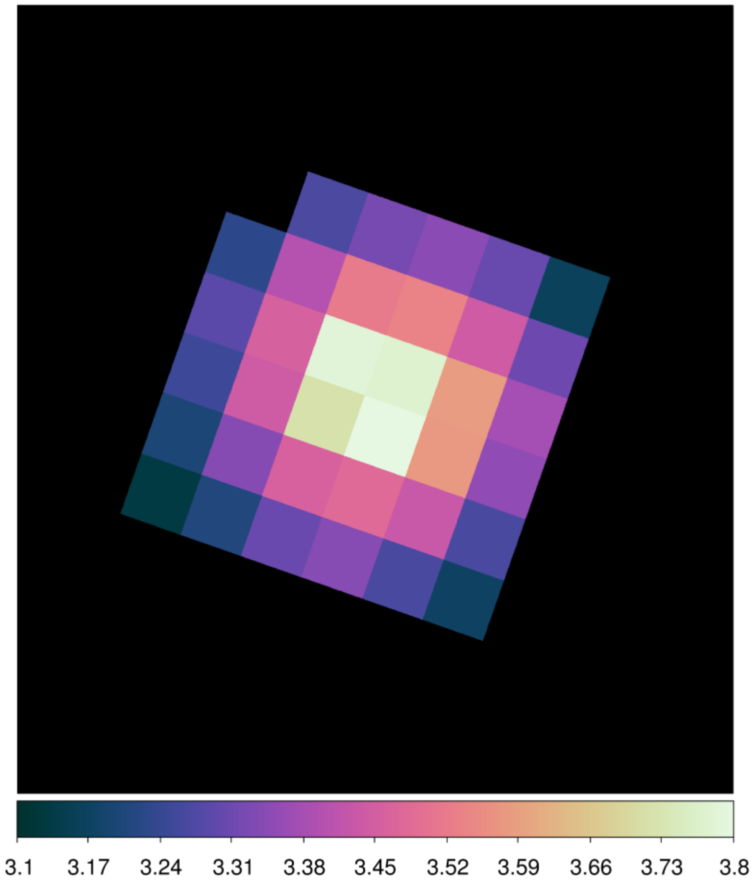




- Coma ICM velocities match that of the central galaxies
- Material in centre and S, W and SW matches NGC 4889
- ICM velocity to N, E, NE and SE matches NGC 4874
- NGC 4839 group gas velocity consistent with optical

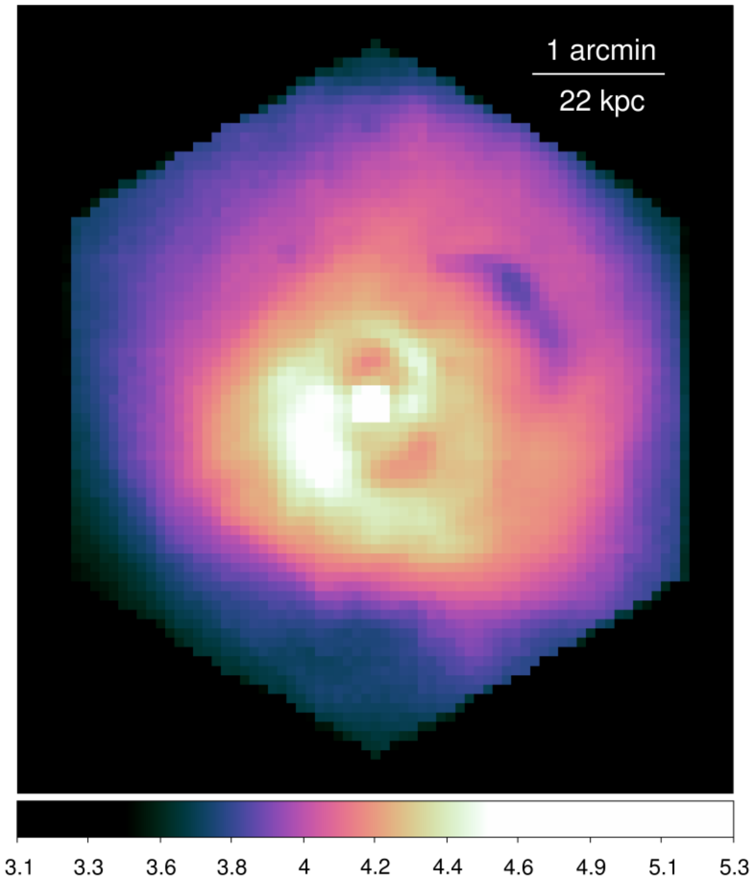
Future high resolution X-ray spectroscopy

Hitomi / XRISM (2021)

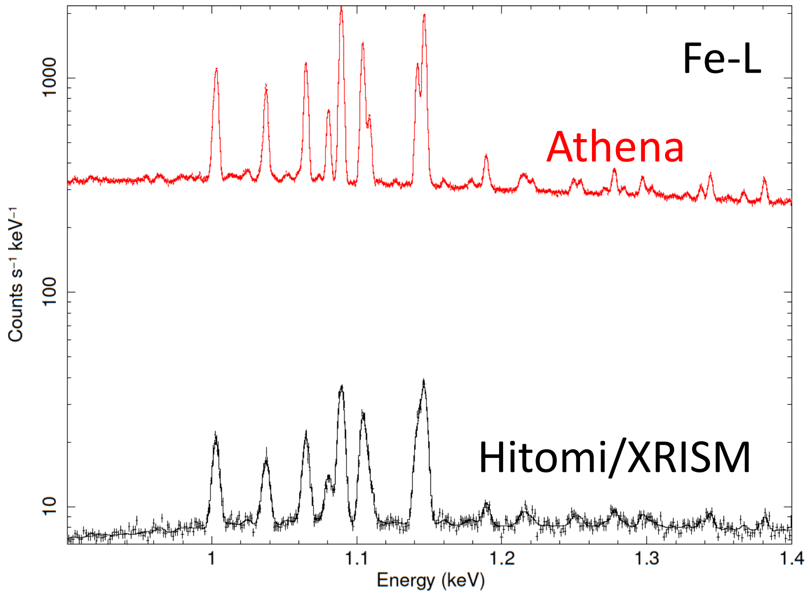


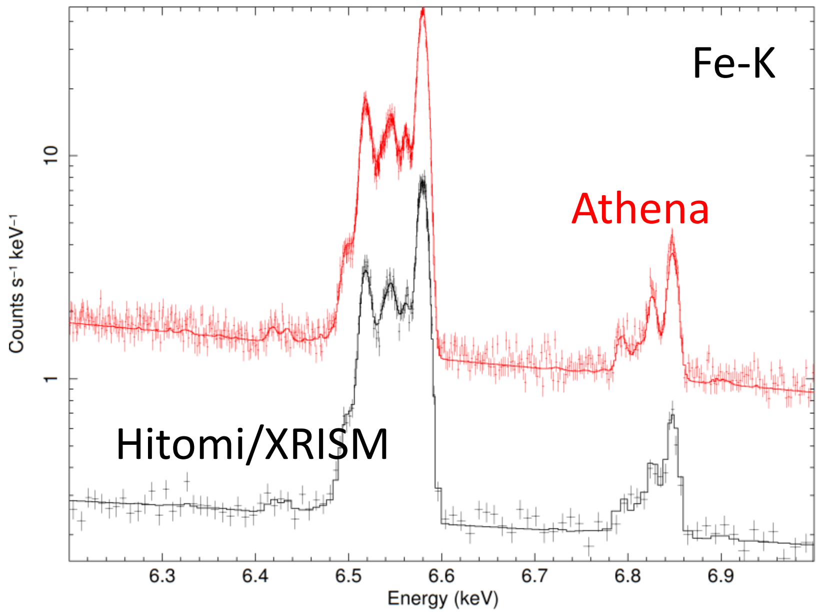
log cts pixel^{-1}

Athena (2031)



log cts pixel^{-1}





Perseus: 50 ks observations – real Hitomi vs simulated Athena

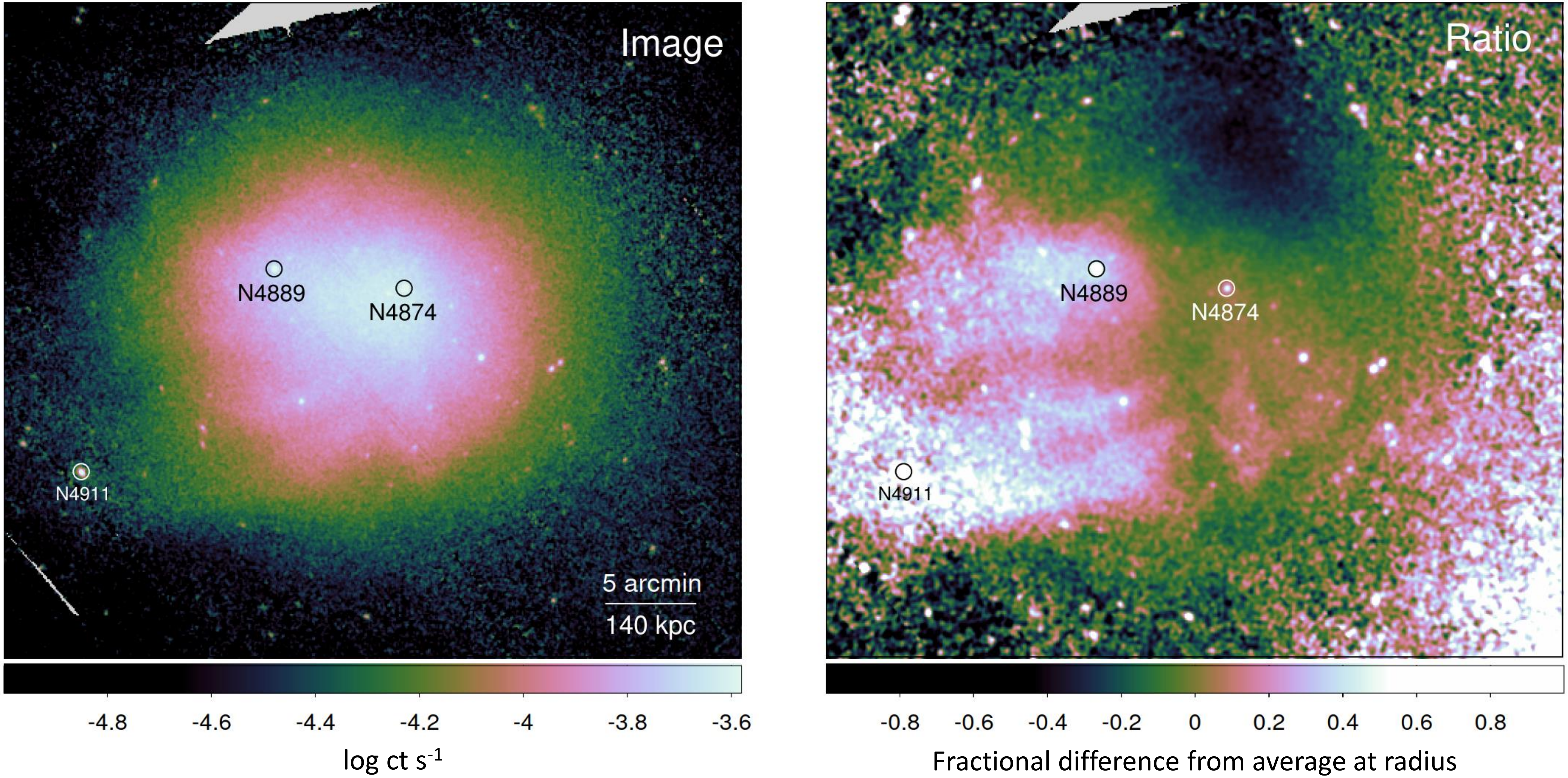
XRISM will be great, but Athena will allow the study of scales on size of cavities

Conclusions

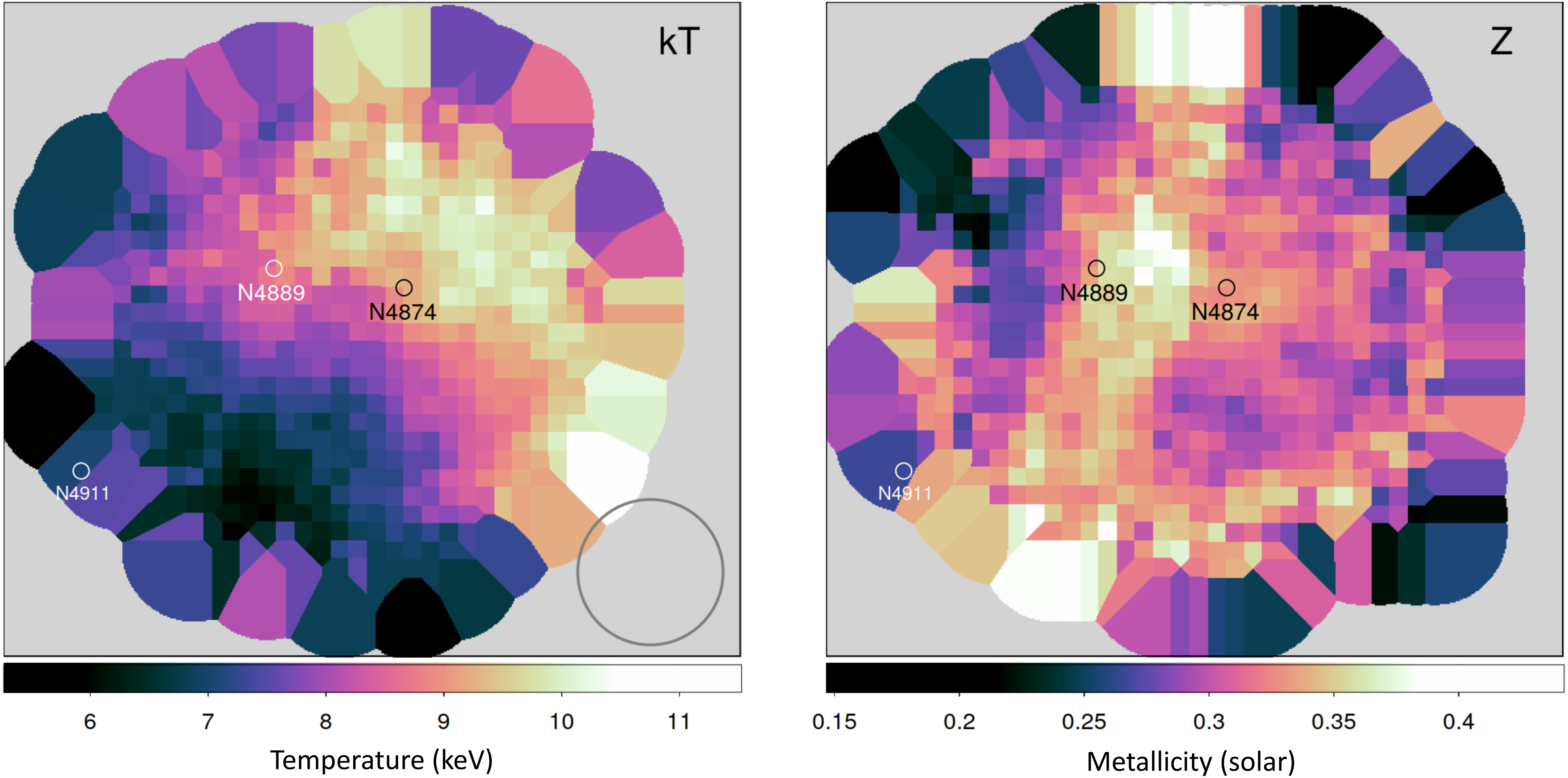
- Cores of clusters seem to have low levels of turbulence
- We developed a new technique for measuring bulk motions with XMM-Newton
- Good agreement with Hitomi measurement in Perseus
- Detect sloshing signal in the Perseus cluster
- See the gas velocity matches velocity of central galaxies in Coma

- Upcoming analyses with new offset observations:
  - Virgo cluster / M87
  - Centaurus cluster

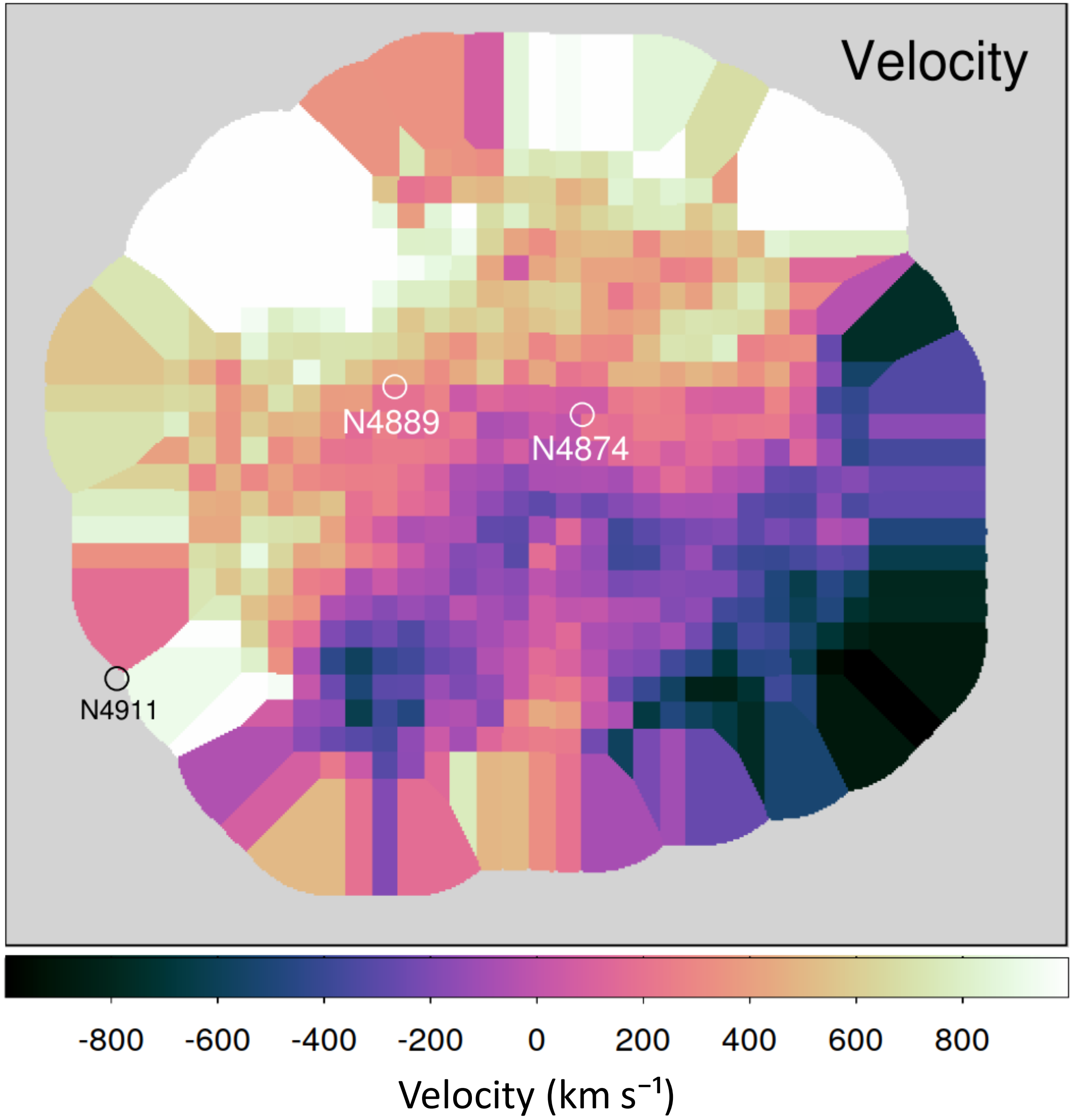
Coma cluster – surface brightness images

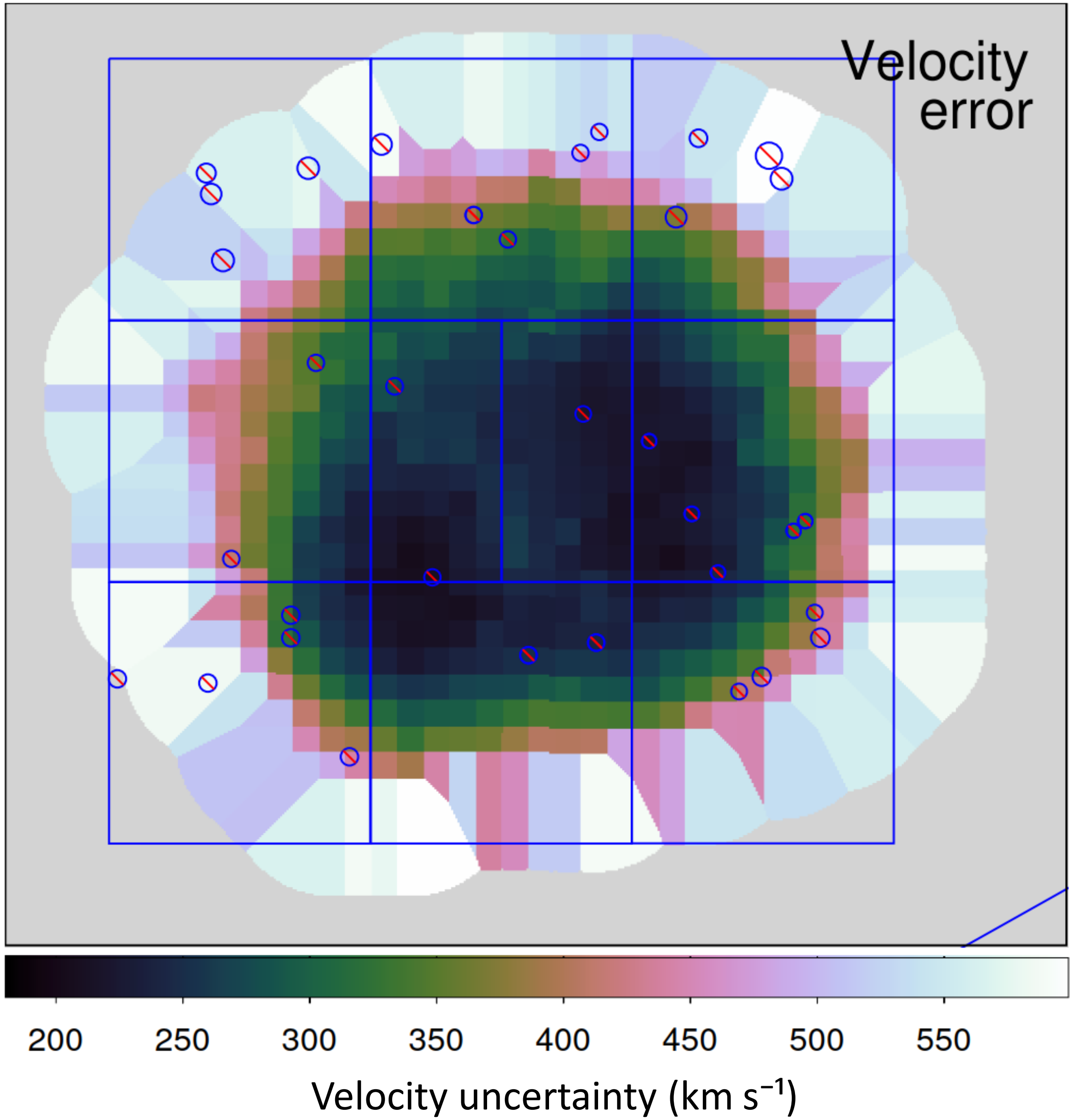


Coma cluster – temperature and metallicity maps

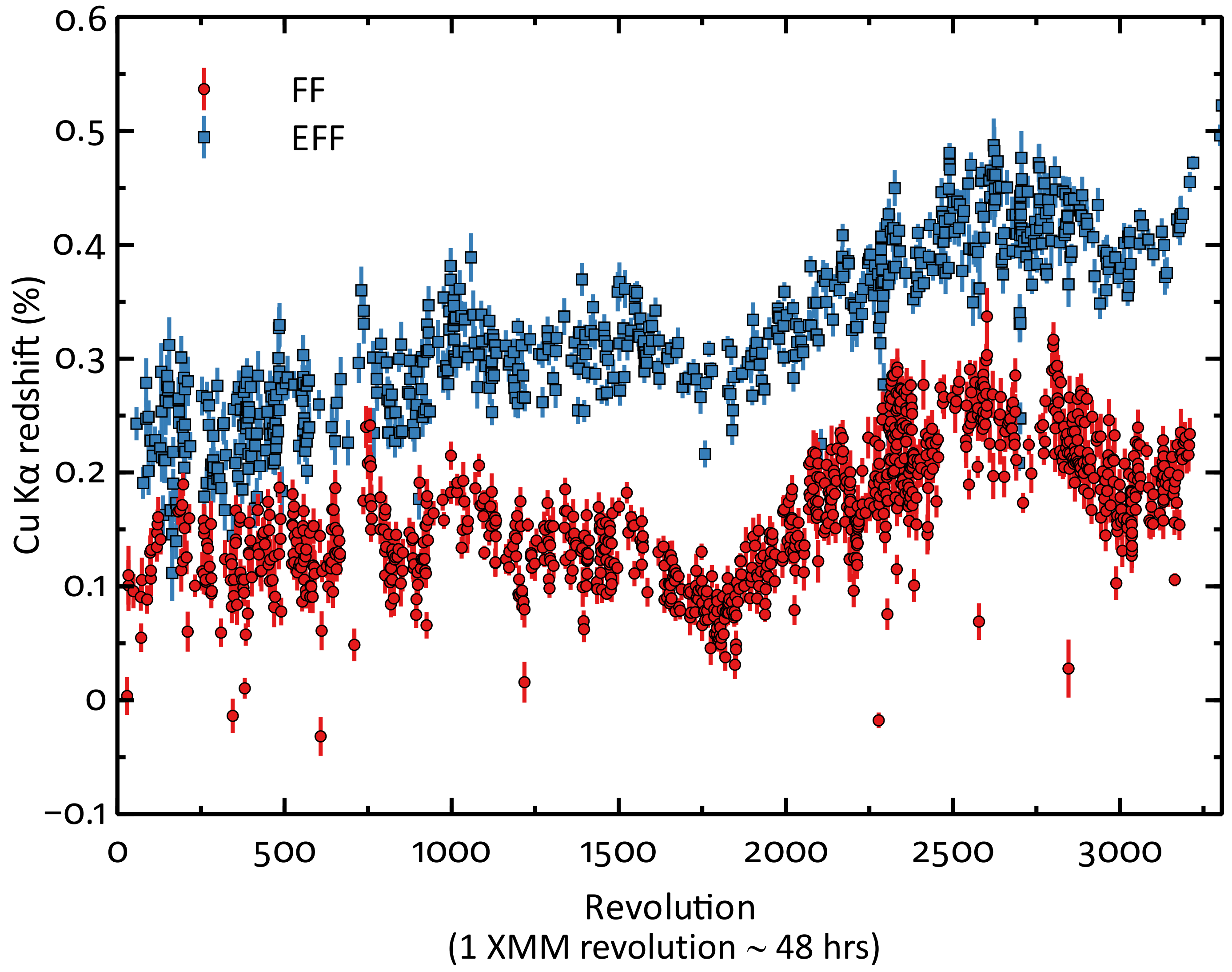


Coma cluster – velocity map





Stage 1: correcting for average gain shift

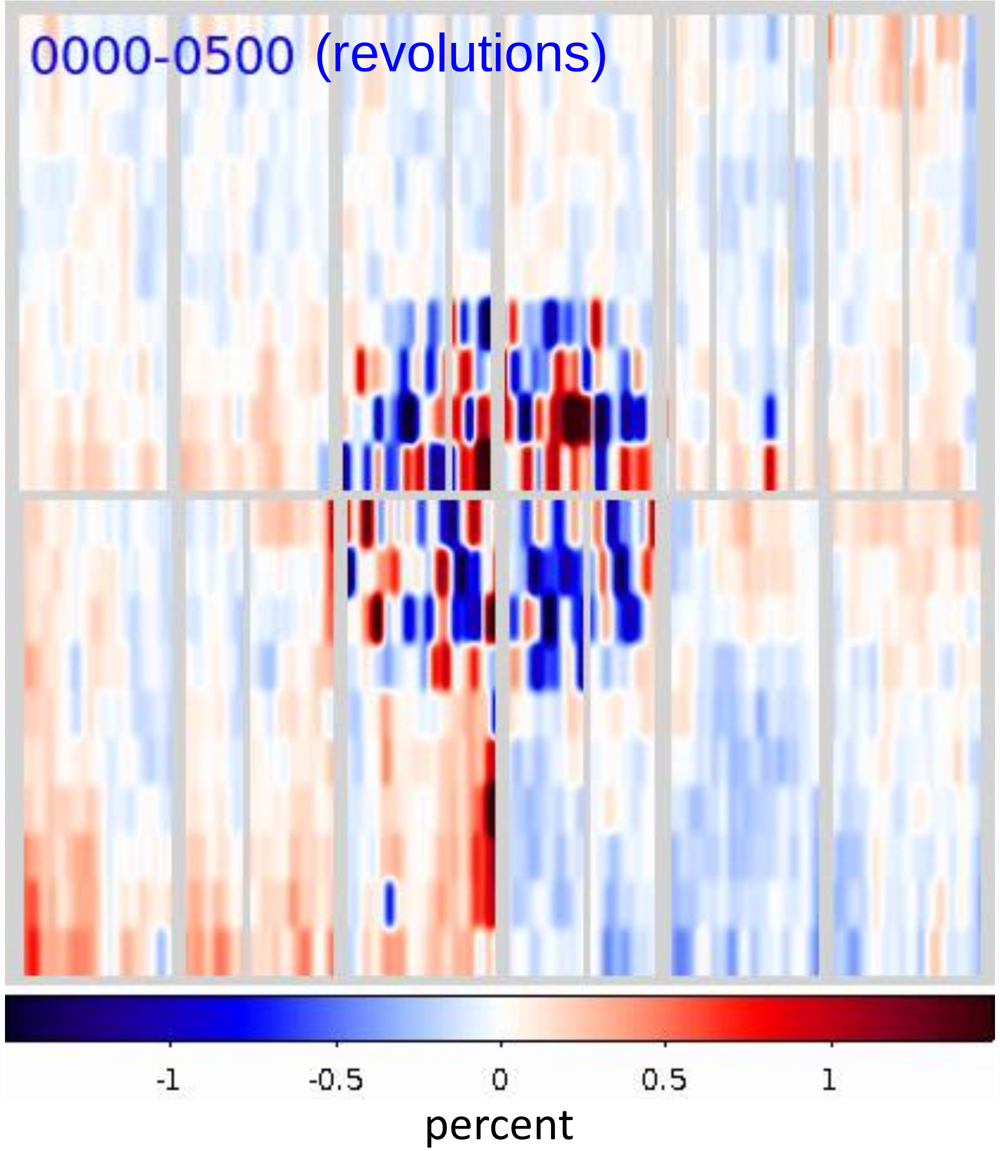


- Measure Cu-Kα line ‘redshift’ (should be zero)
- Correct X-ray event energies to make redshift zero

0.1% = 8eV at Cu-Kα = 300 km s^{-1} at Fe-K

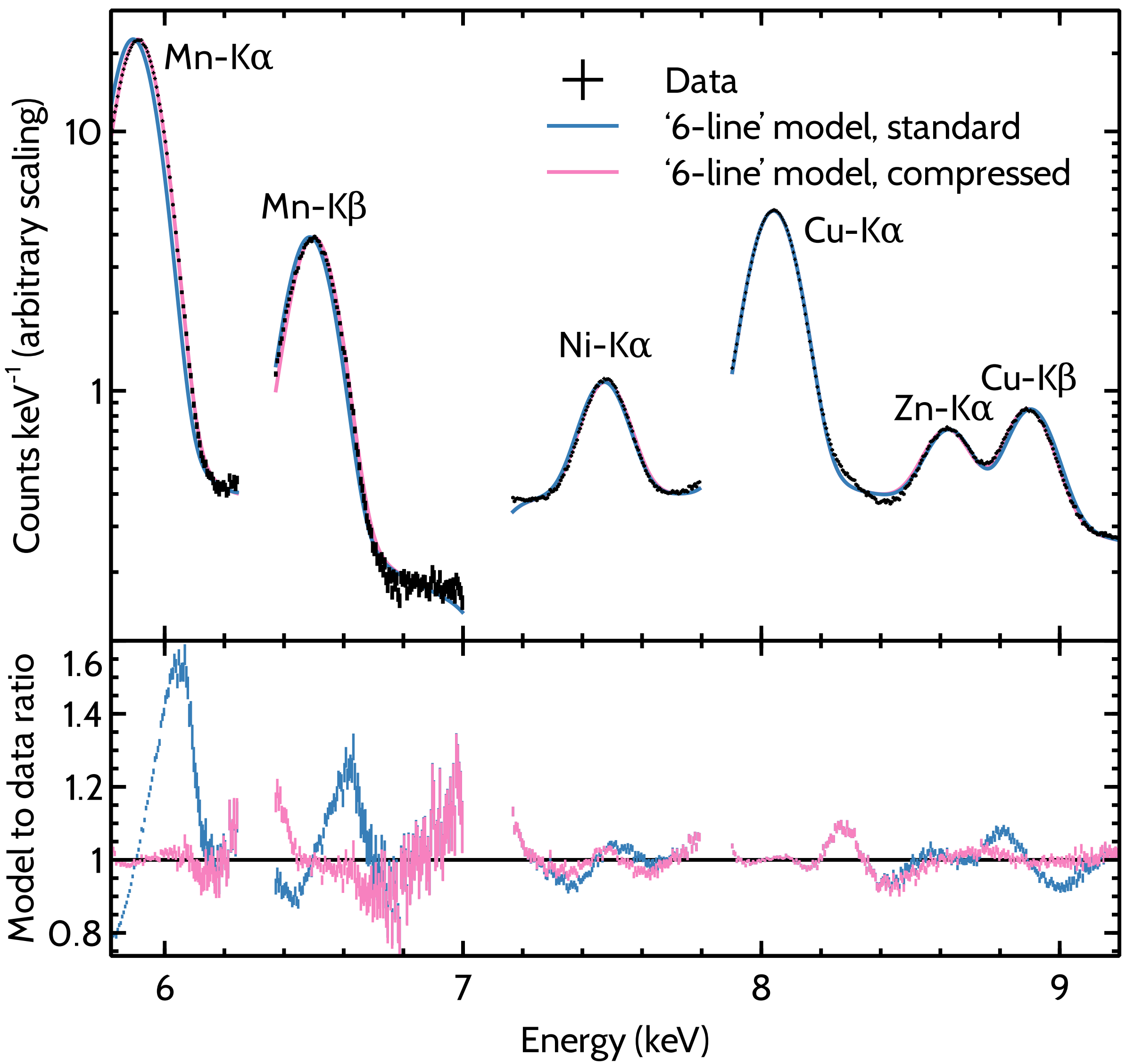
Stage 2: correcting for position-dependent gain

Centre part of detector noisy because of lack of signal



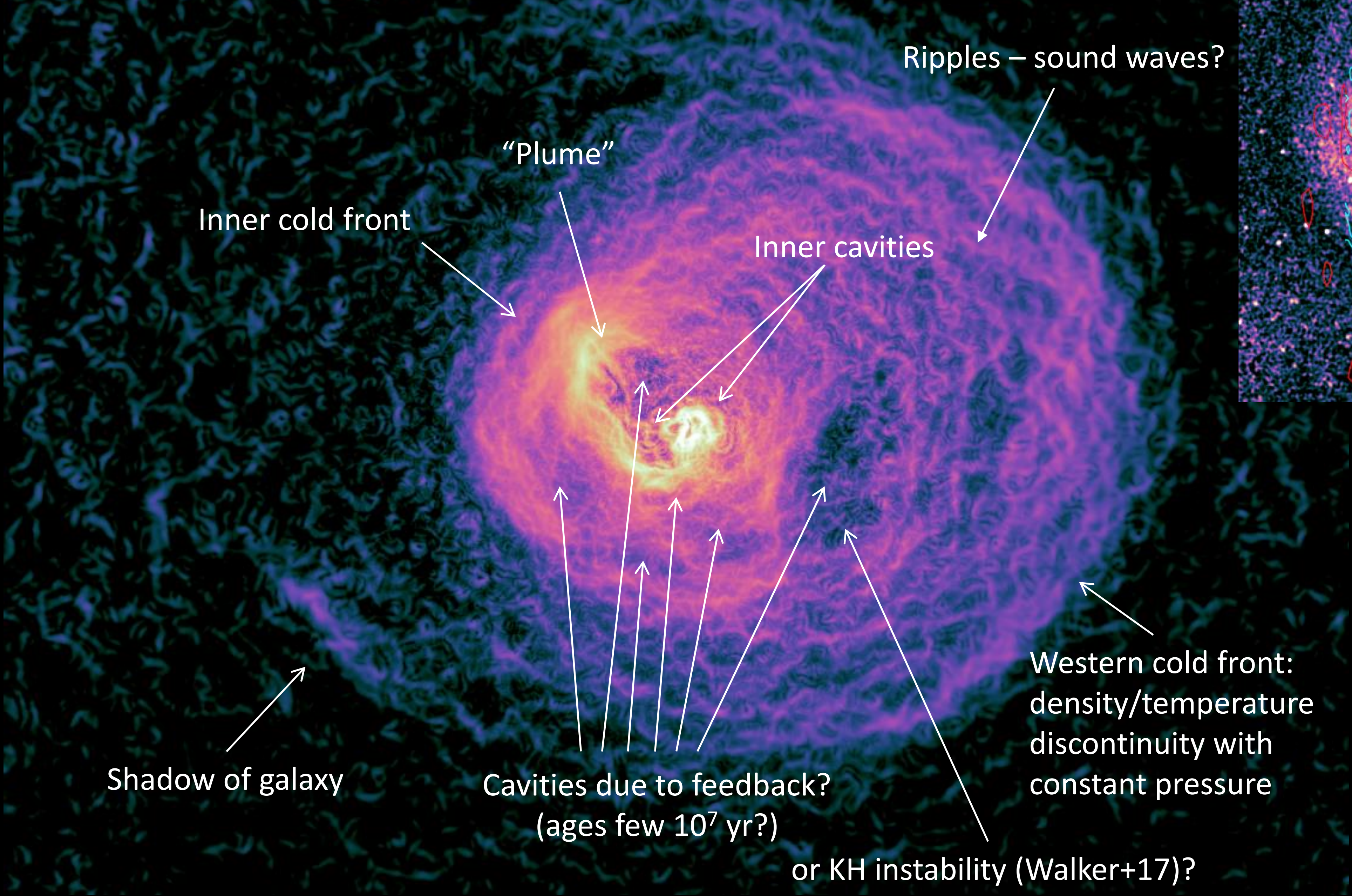
- Stack astrophysical observations
- Measure Cu-Kα redshift as a functions of detector position and time
- Apply gain correction to events to remove spatial variation

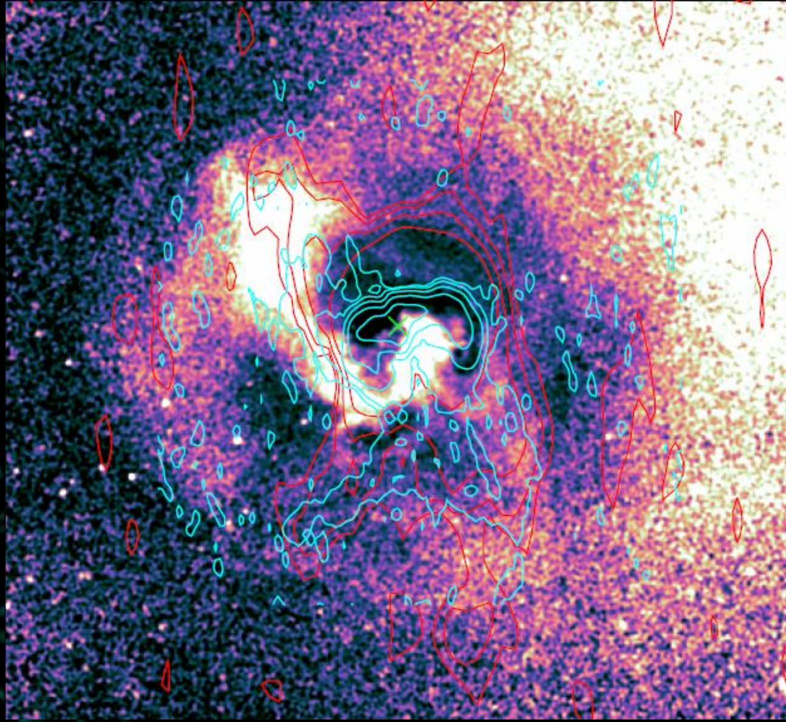
Stage 3: correcting energy scale



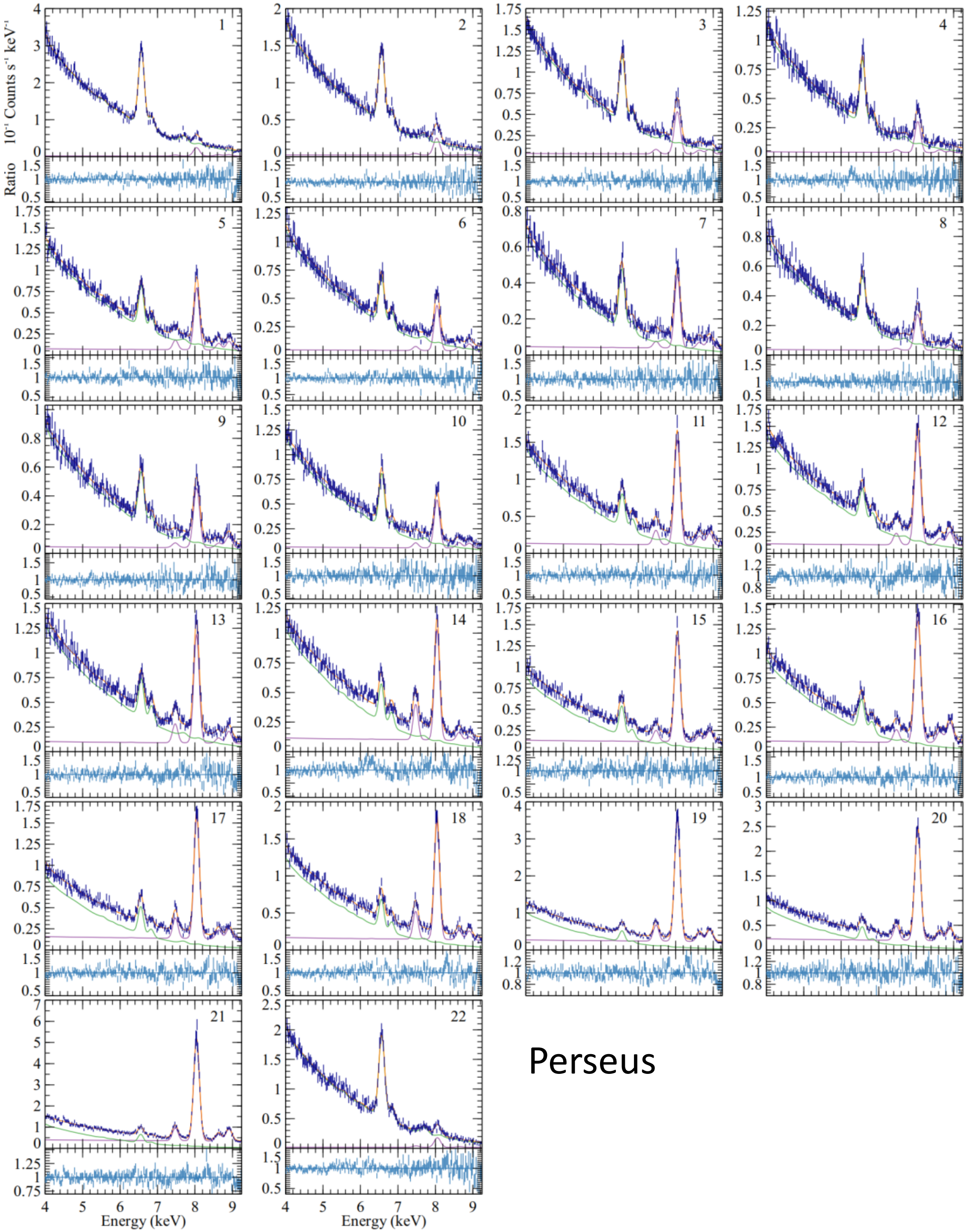
- Energies of other background lines and calibration lines showed an energy scale correction was required
- Linear scaling model as a function of energy difference (δE/E) from Cu-Kα applied to stacked spectra
- Position dependent with linear increase in time

Centre of the Centaurus cluster
Applying GGM gradient filtering

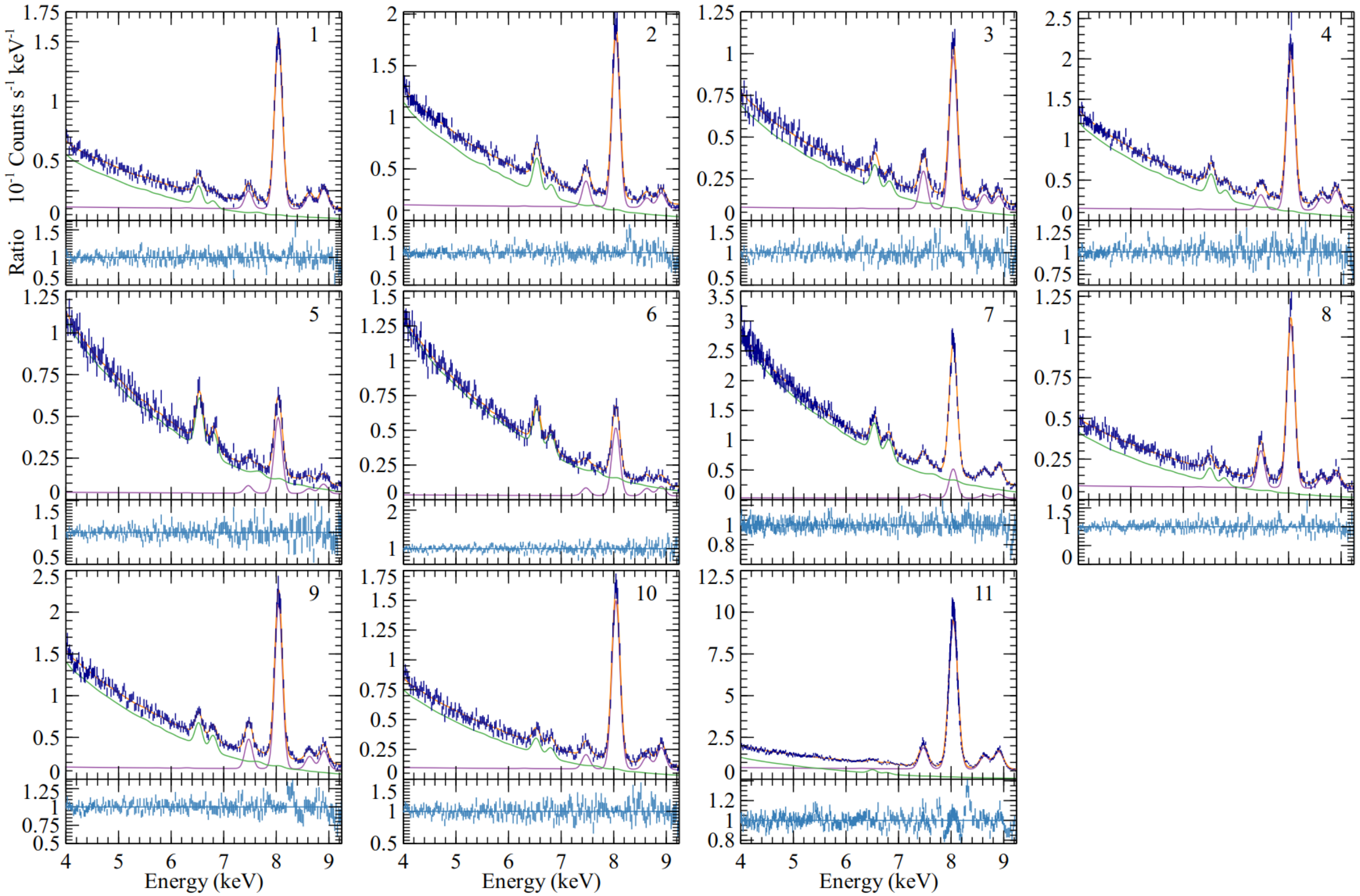




AGN appears repeatedly active on timescales of 10s of Myr



Perseus



Coma