Studying the physics of clusters of galaxies using X-ray observations

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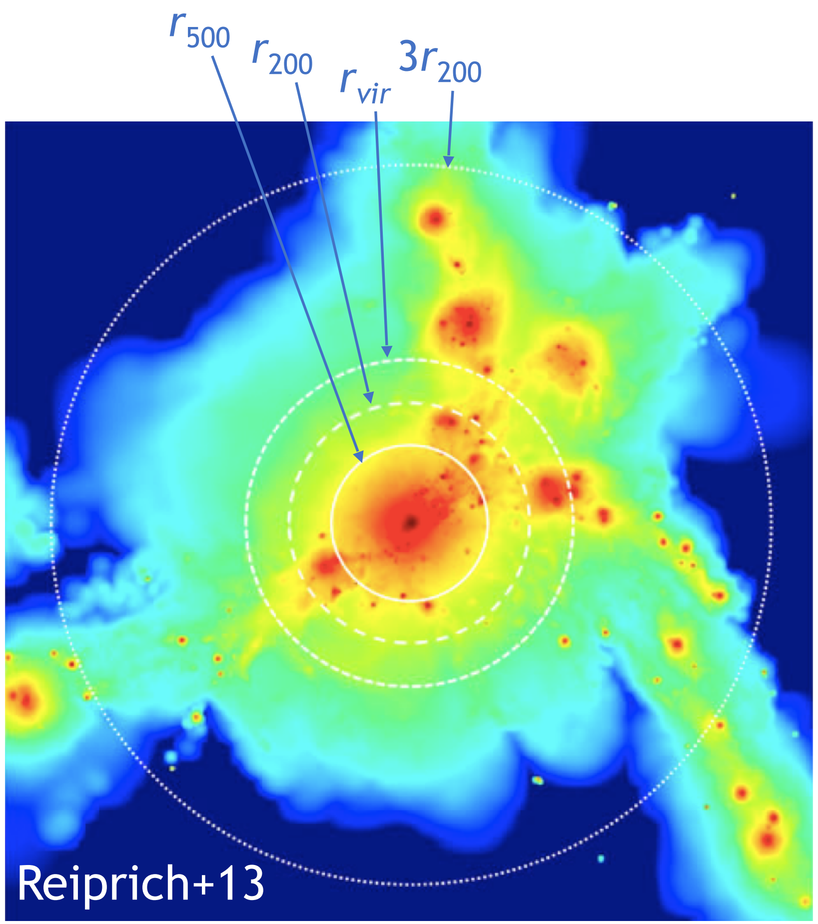
[AGN feedback and velocities in the intracluster medium]

Physics in clusters seen by X-rays

- The intracluster medium, ICM, is the dominant baryonic component in clusters
- Temperature ~ few 10^7 K (or few keV)
- Directly visible in X-ray band (bremsstrahlung)

- Many different physical processes we can study
  - AGN feedback and ICM cooling
  - Mergers
  - Hydrostatic equilibrium
  - Gas sloshing
  - Enrichment
  - Turbulence, microphysics, transport properties, magnetic fields
  - …

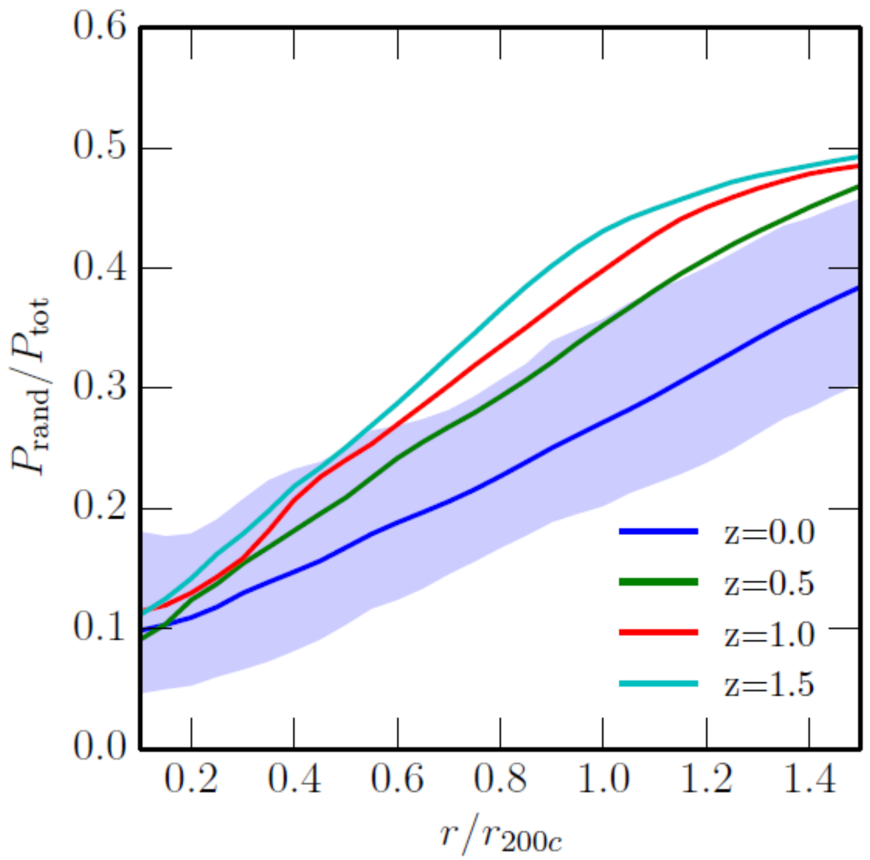


R_{500} is routinely accessible to X-ray observations, though increasingly R_{200} can be (e.g. Suzaku, X-COP, …)

Turbulence in the outskirts

Fraction of pressure in random motions

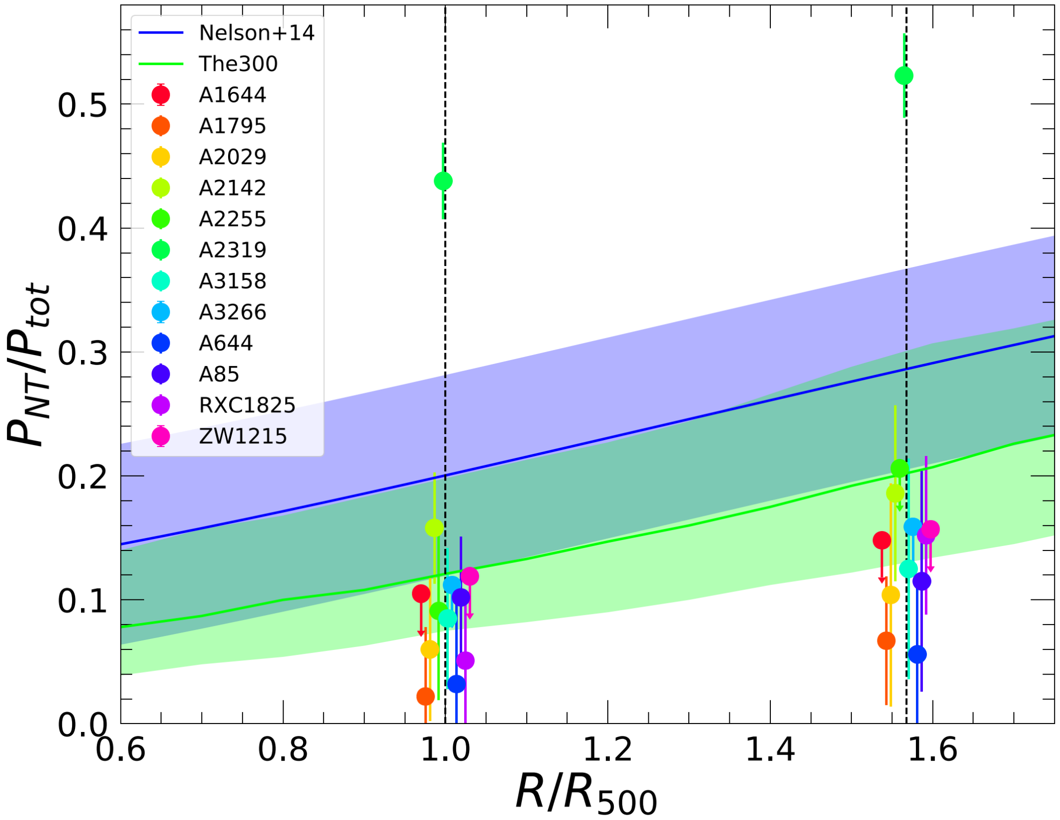
Nelsen+14 (simulations)



Turbulence predicted to increase with radius by simulations [important for hydrostatic masses]

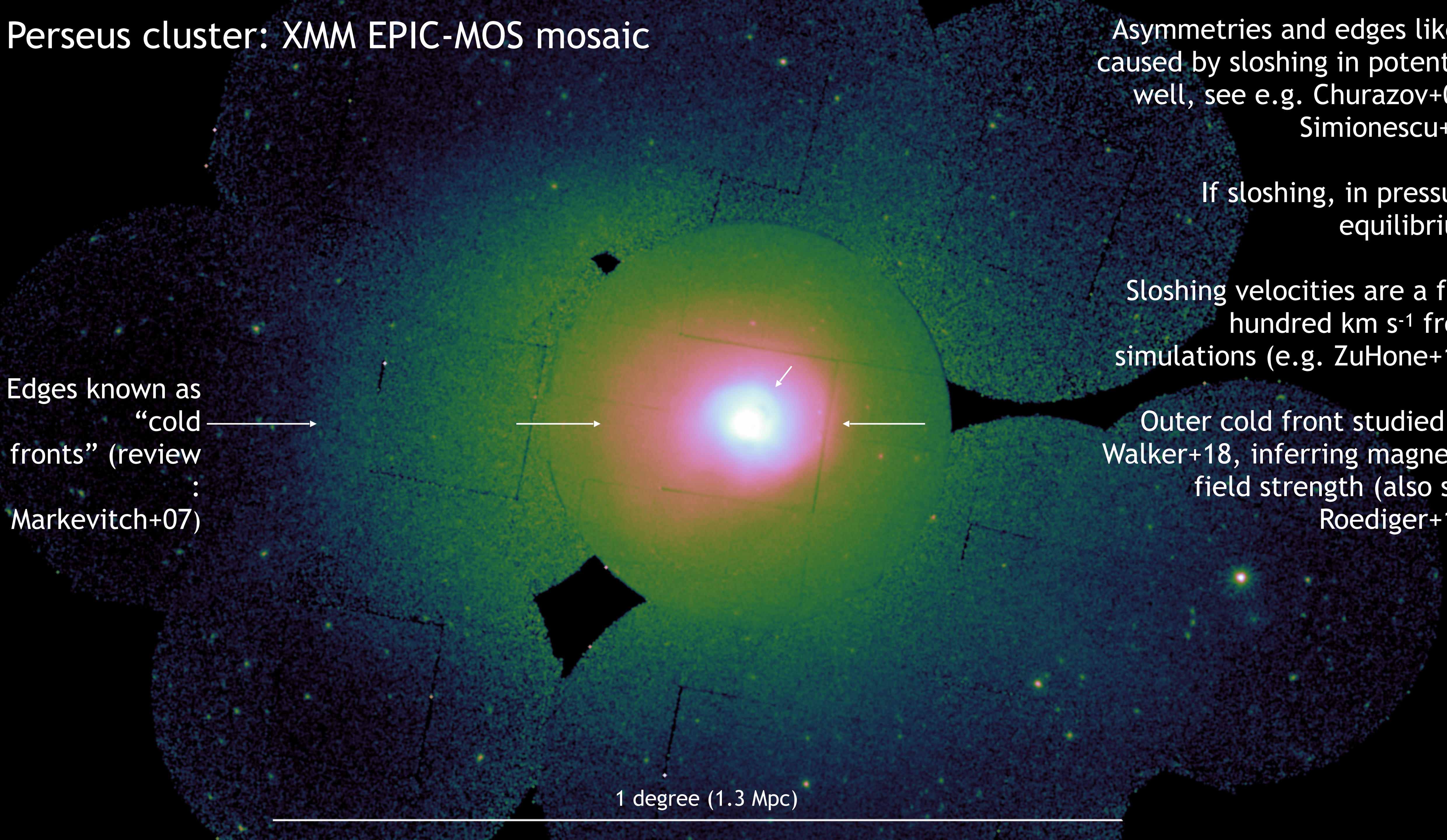
Non-thermal pressure fraction

Eckert+19 (recent observations)



However, X-COP observations found around 10% pressure contribution at R_{200} using fgas

Perseus cluster: XMM EPIC-MOS mosaic



Edges known as “cold fronts” (review : Markevitch+07)

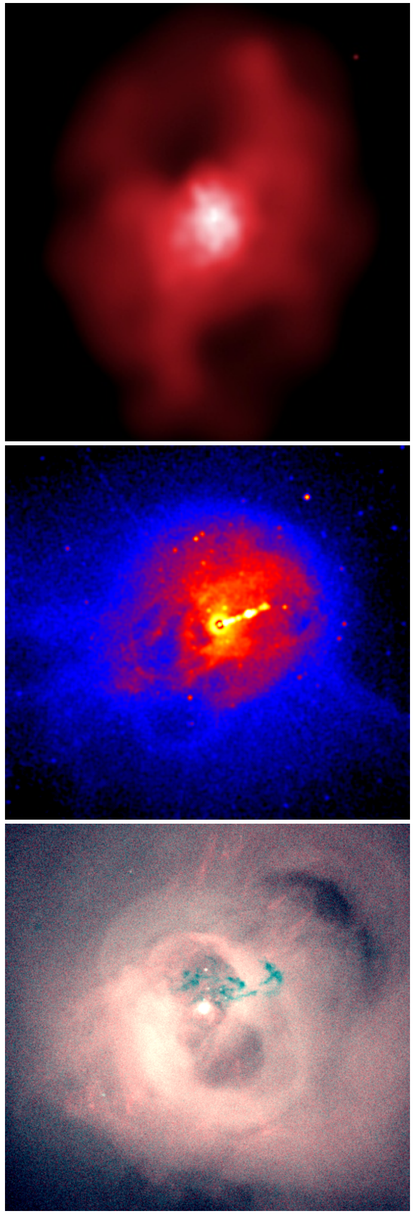
Asymmetries and edges likely caused by sloshing in potential well, see e.g. Churazov+00, Simionescu+12

If sloshing, in pressure equilibrium

Sloshing velocities are a few hundred km s^{-1} from simulations (e.g. ZuHone+18)

Outer cold front studied by Walker+18, inferring magnetic field strength (also see Roediger+13)

AGN feedback in clusters



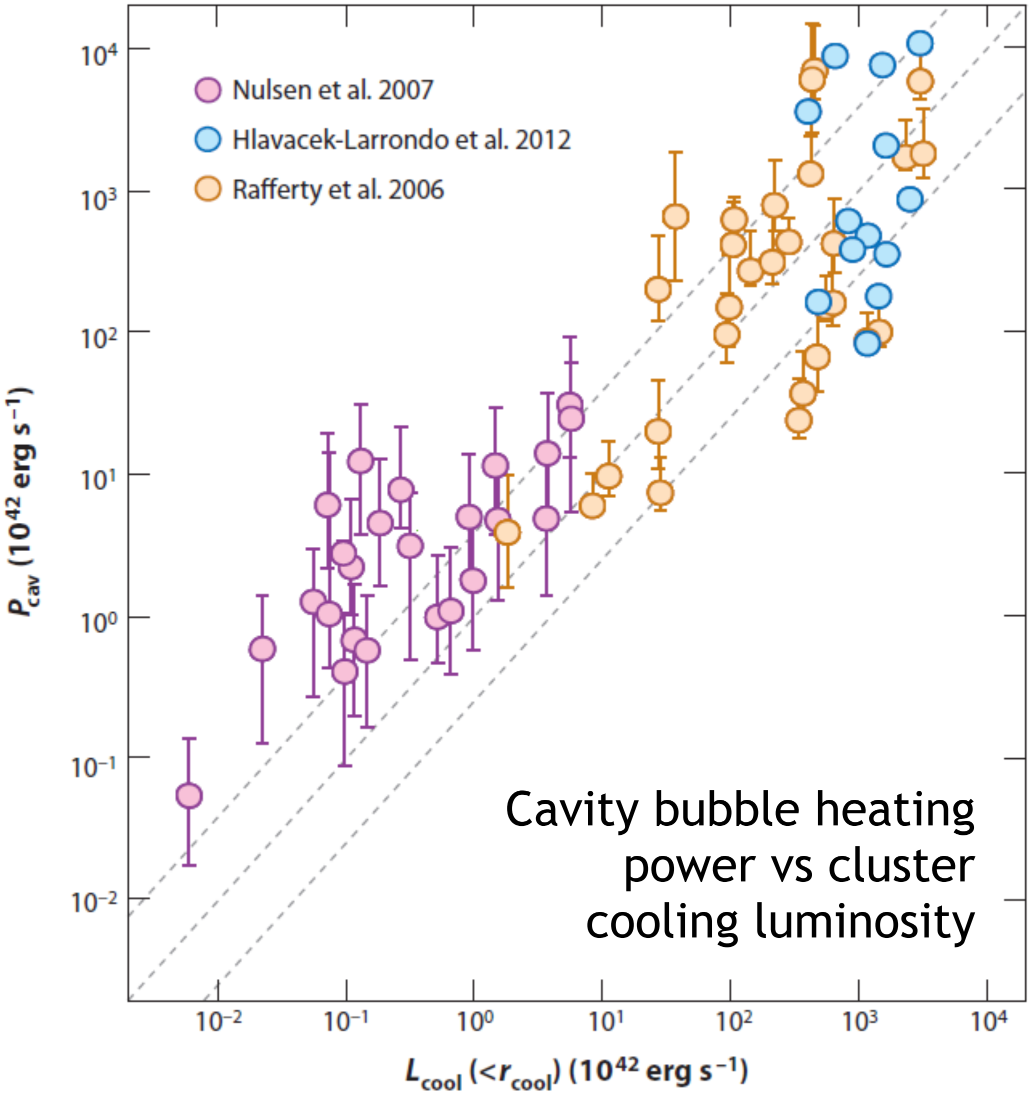
Many clusters show short cooling times in their cores – would rapidly cool if emitted energy not replaced

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 over a wide range in X-ray luminosity (see Fabian+12)

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

Fabian+12

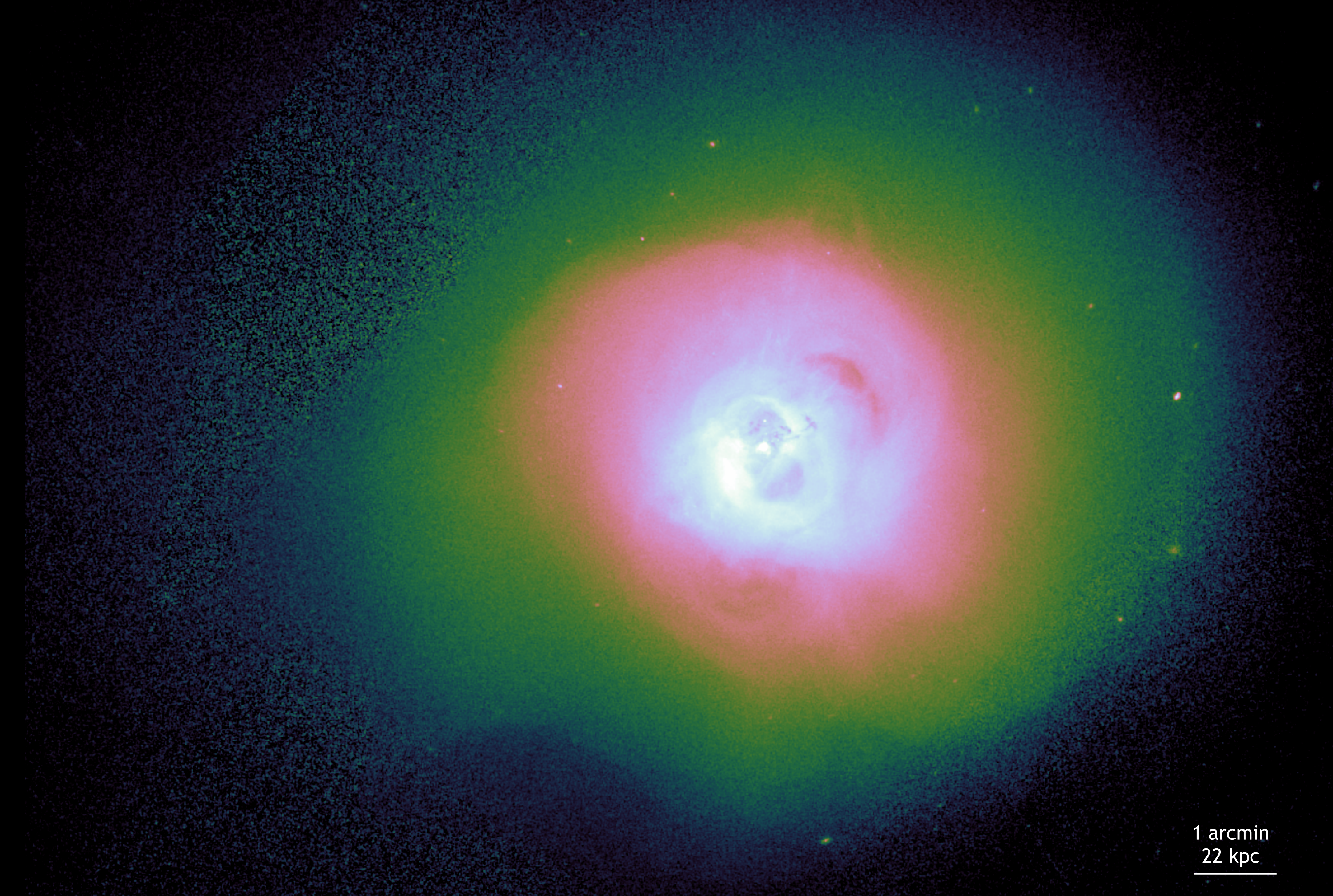


Cavity bubble heating power vs cluster cooling luminosity

Perseus cluster

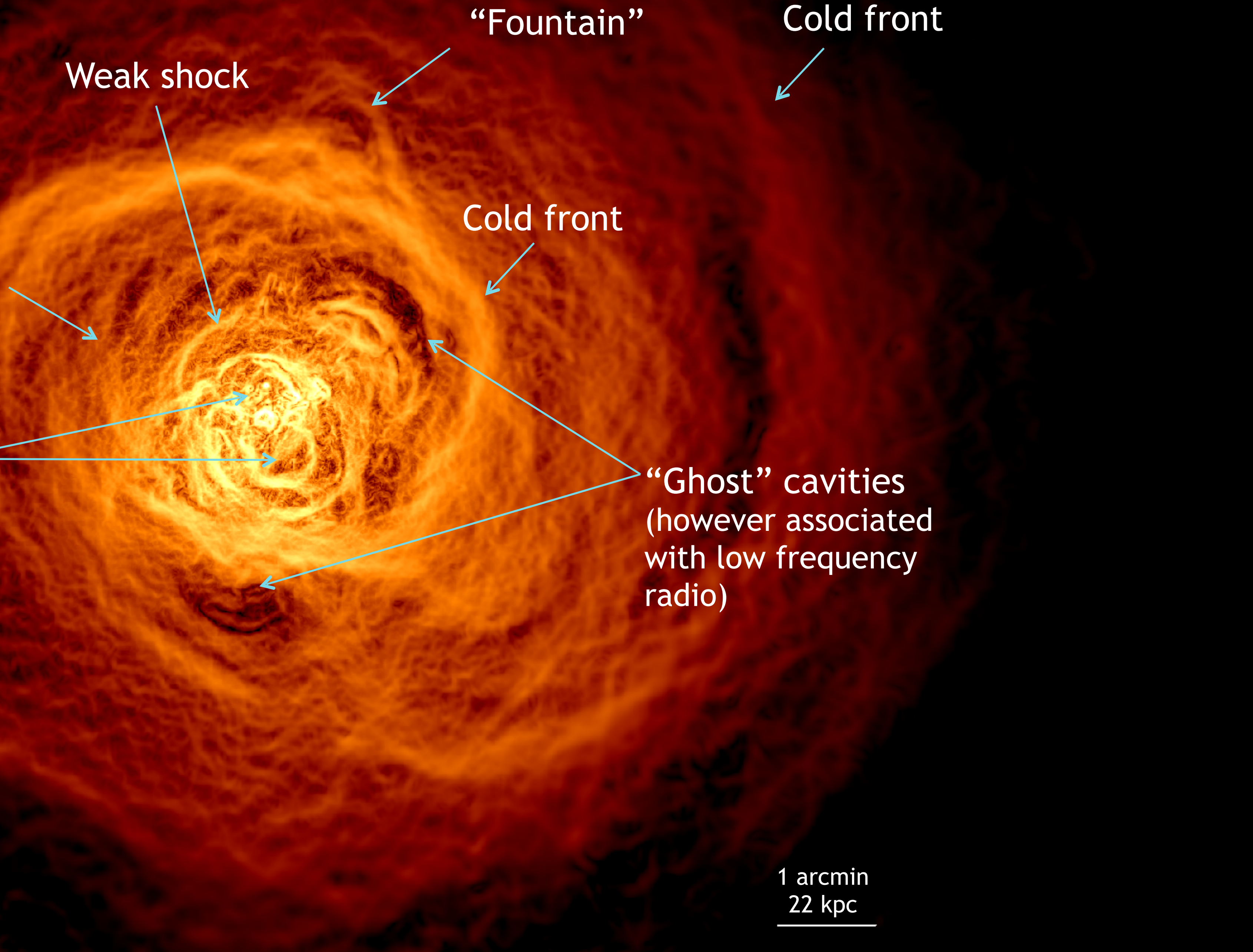
Up to 1.4Ms of Chandra exposure

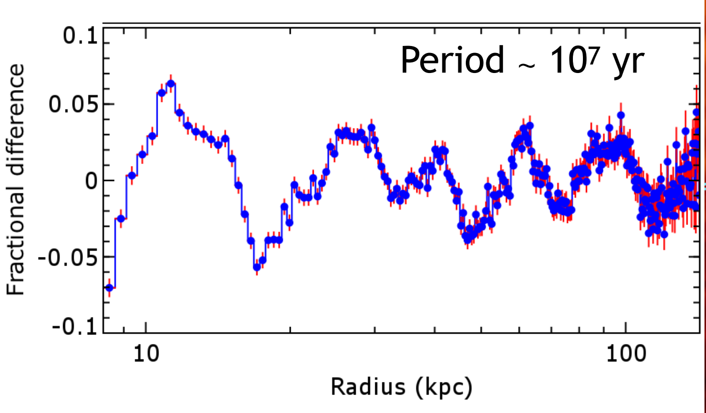
See Fabian+00, Schmidt+02, Fabian+03, Fabian+06, Sanders+07, Fabian+11



Perseus Cluster: applying gradient filter

Sanders+16b

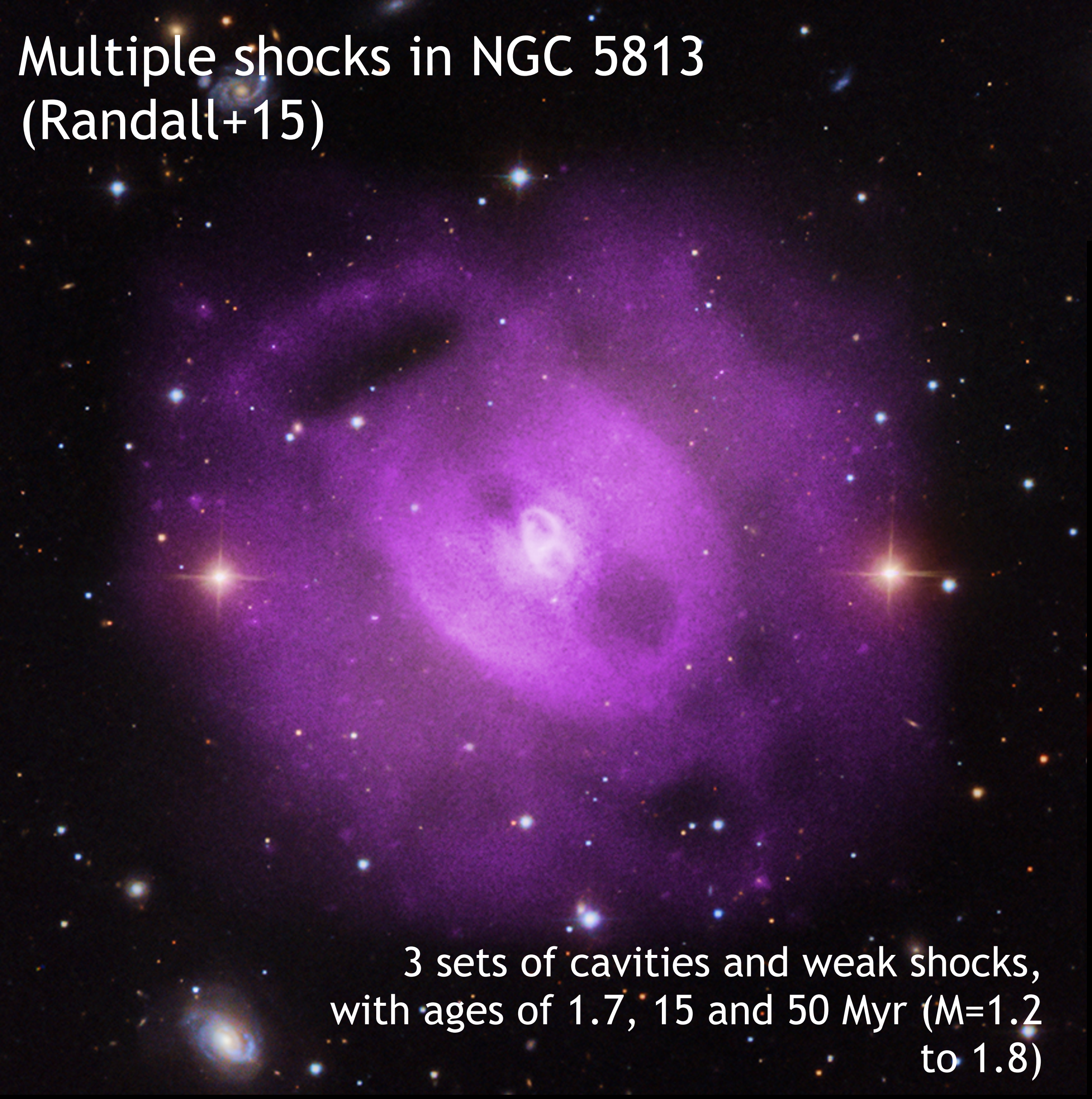




Sound waves (Fabian+06) would be sufficient to combat large fraction of energy loss by radiation (Sanders+07)

Weak central shock contains significant fraction of energy required to combat cooling in centre (Graham+08)

Multiple shocks in NGC 5813 (Randall+15)

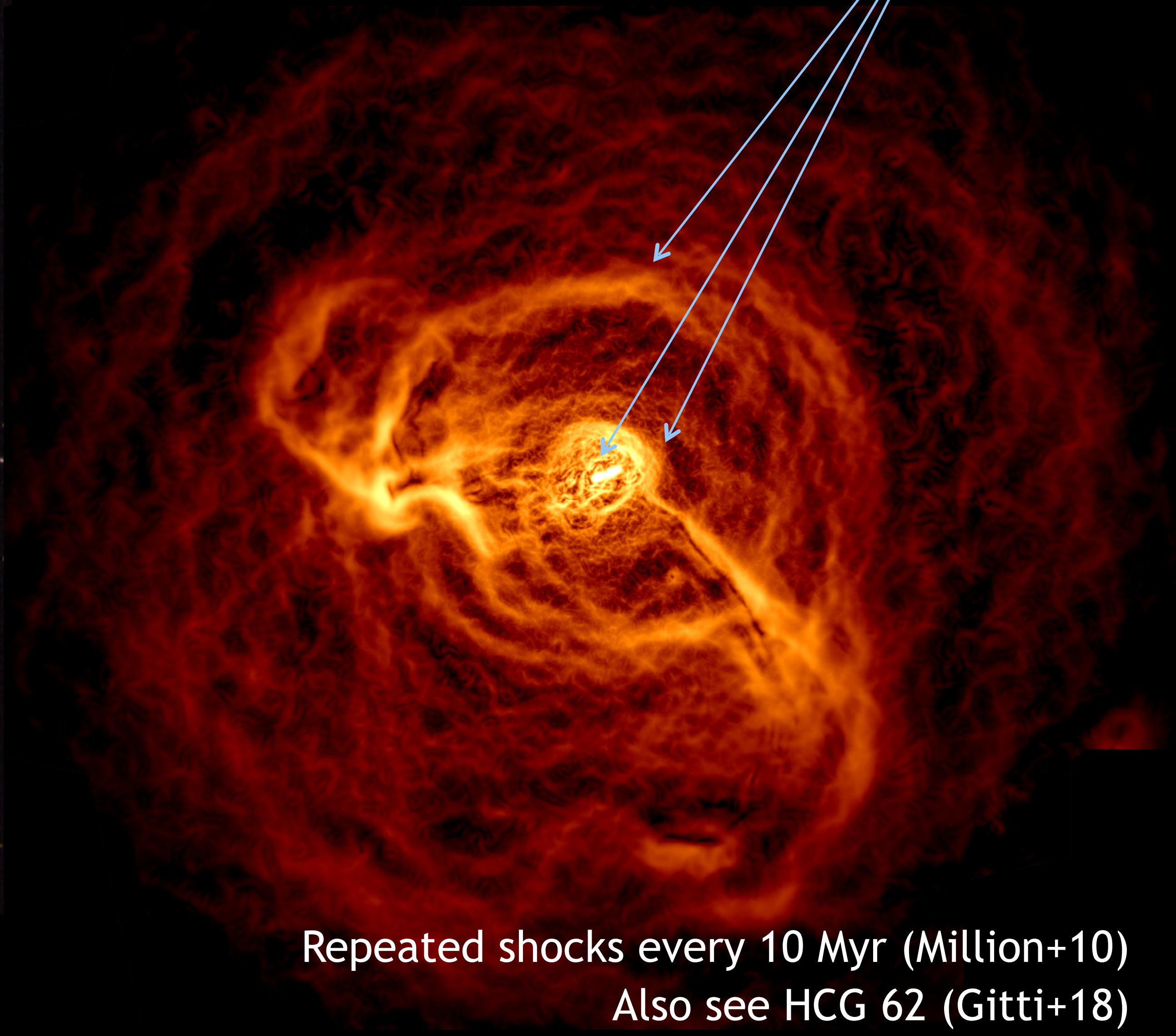


3 sets of cavities and weak shocks, with ages of 1.7, 15 and 50 Myr (M=1.2 to 1.8)

Cooling rates and shock heating rates balanced for each front

M87 in Virgo cluster (Forman+07)

Chandra image with gradient filtering (Sanders+16b)

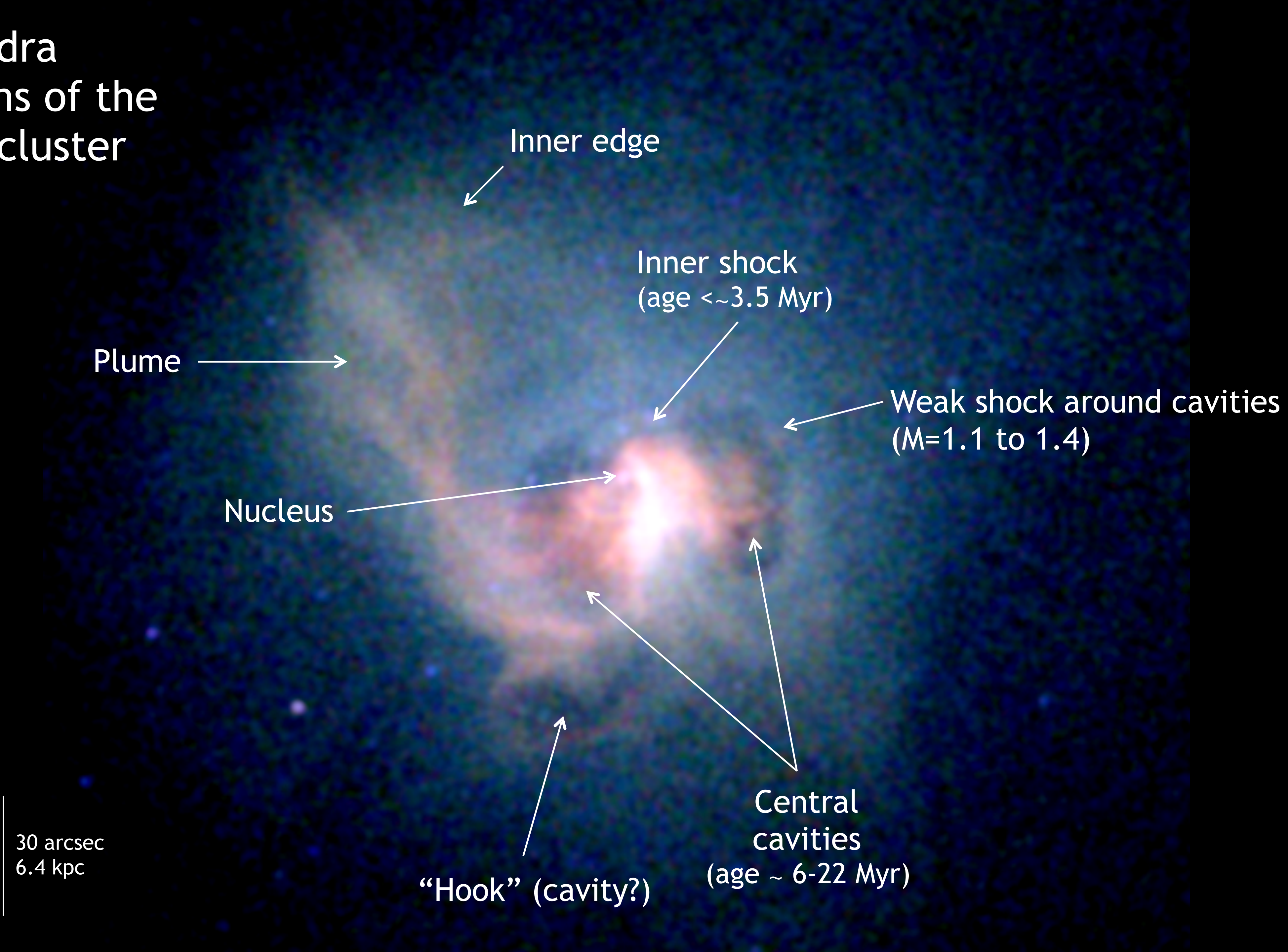


Repeated shocks every 10 Myr (Million+10)

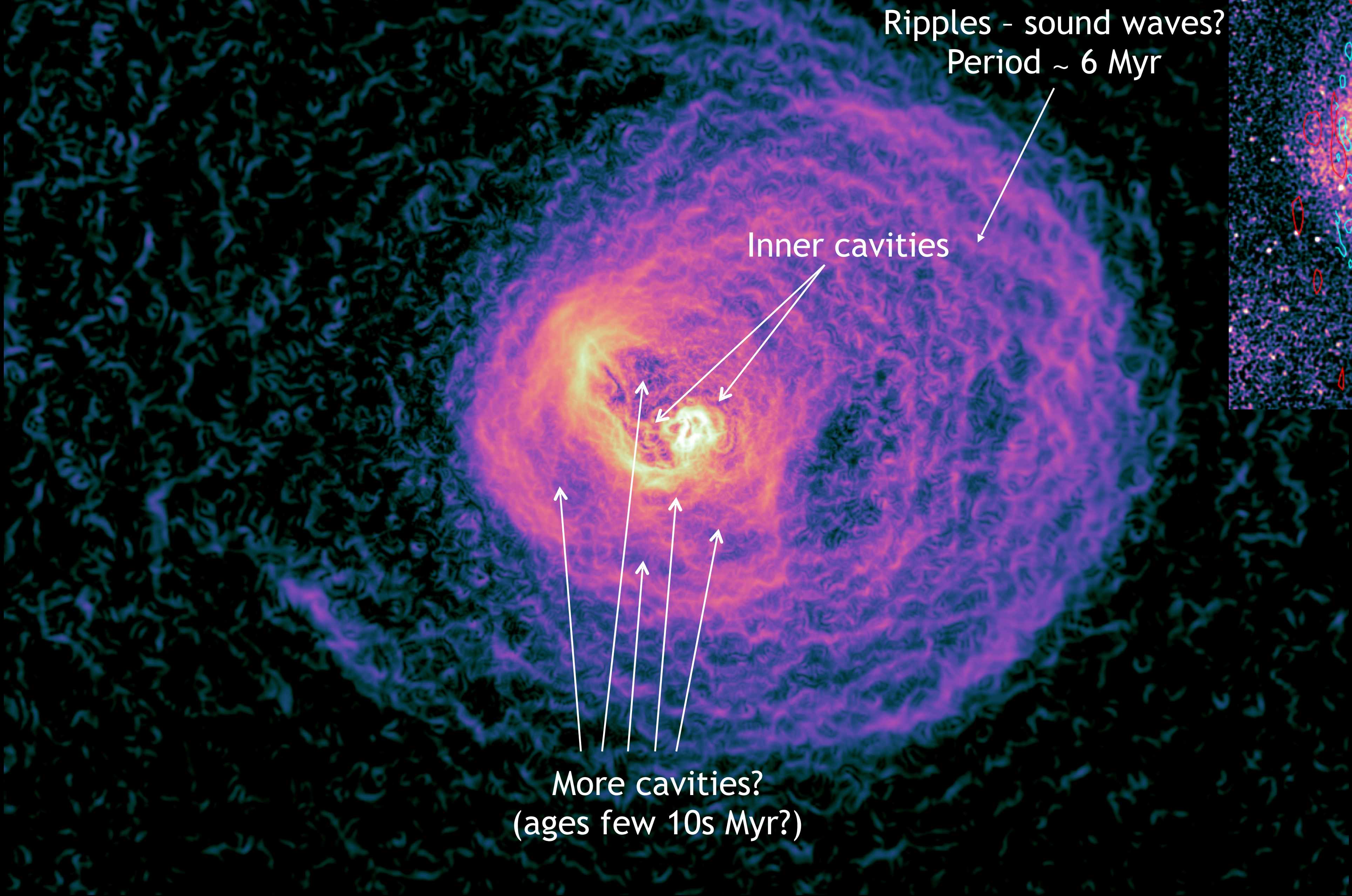
Also see HCG 62 (Gitti+18)

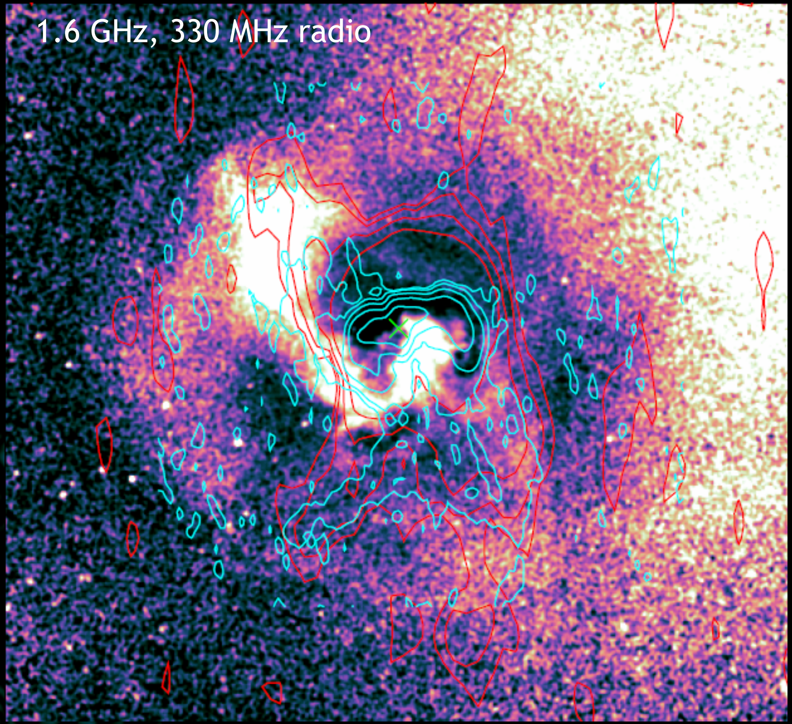
Deep Chandra observations of the Centaurus cluster

Sanders+16a



Centre of the Centaurus cluster
Applying gradient filtering

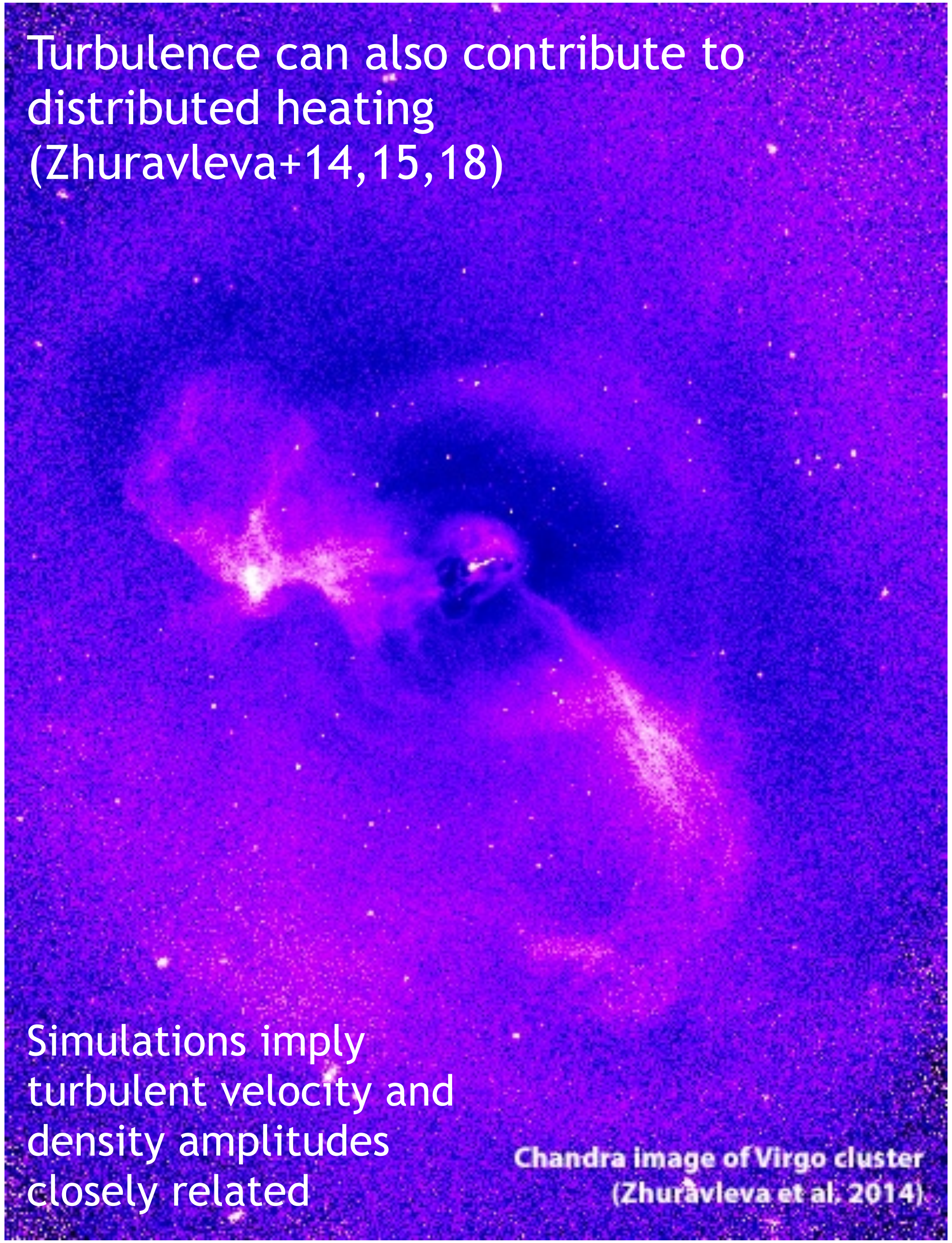




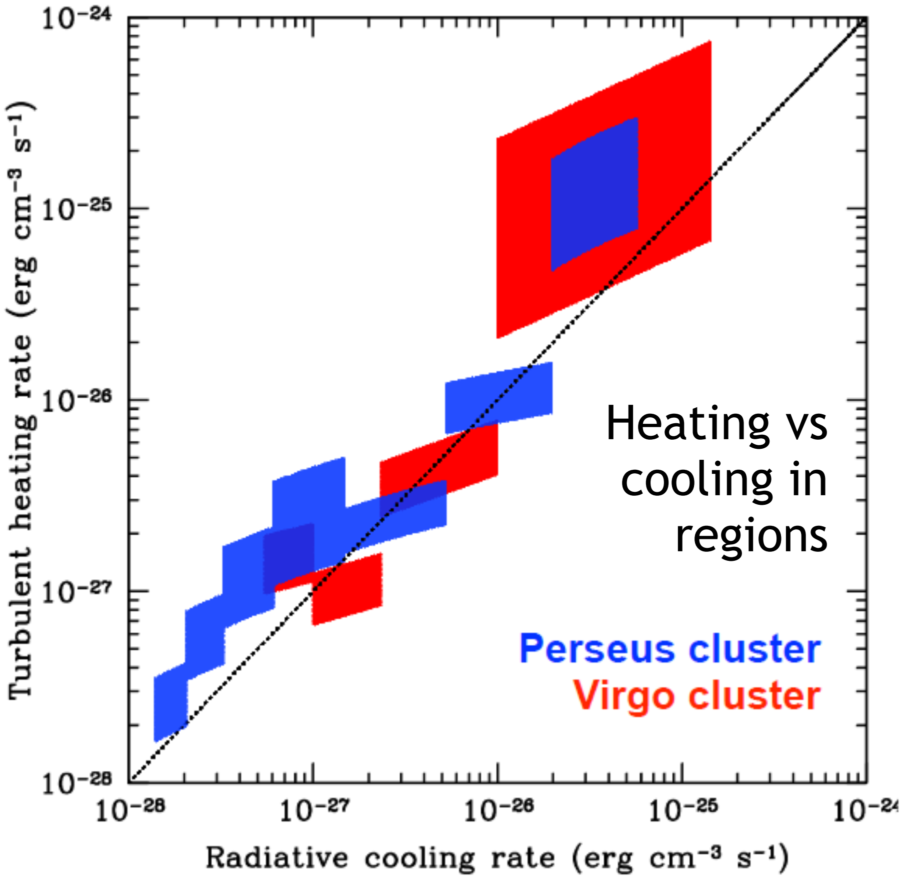
AGN appears repeatedly active on timescales of few to 10s of Myr (see also M87: Forman+07)

Weak shocks and sound waves could produce the distributed heating required to prevent rapid cooling

Turbulence can also contribute to distributed heating (Zhuravleva+14,15,18)



Simulations imply turbulent velocity and density amplitudes closely related



Also see:
Schuecker+04
Walker+15
Hofmann+16

- If density fluctuations are due to turbulence, then could energetically heat the cool core: Zhuravleva+14
- However, (non-AGN) sloshing can be a significant contribution to the signal: Walker+18
- Potential issues with transport of energy (Fabian+16, Bambic+18) and its heating efficiency

Directly measuring velocities crucial to understanding

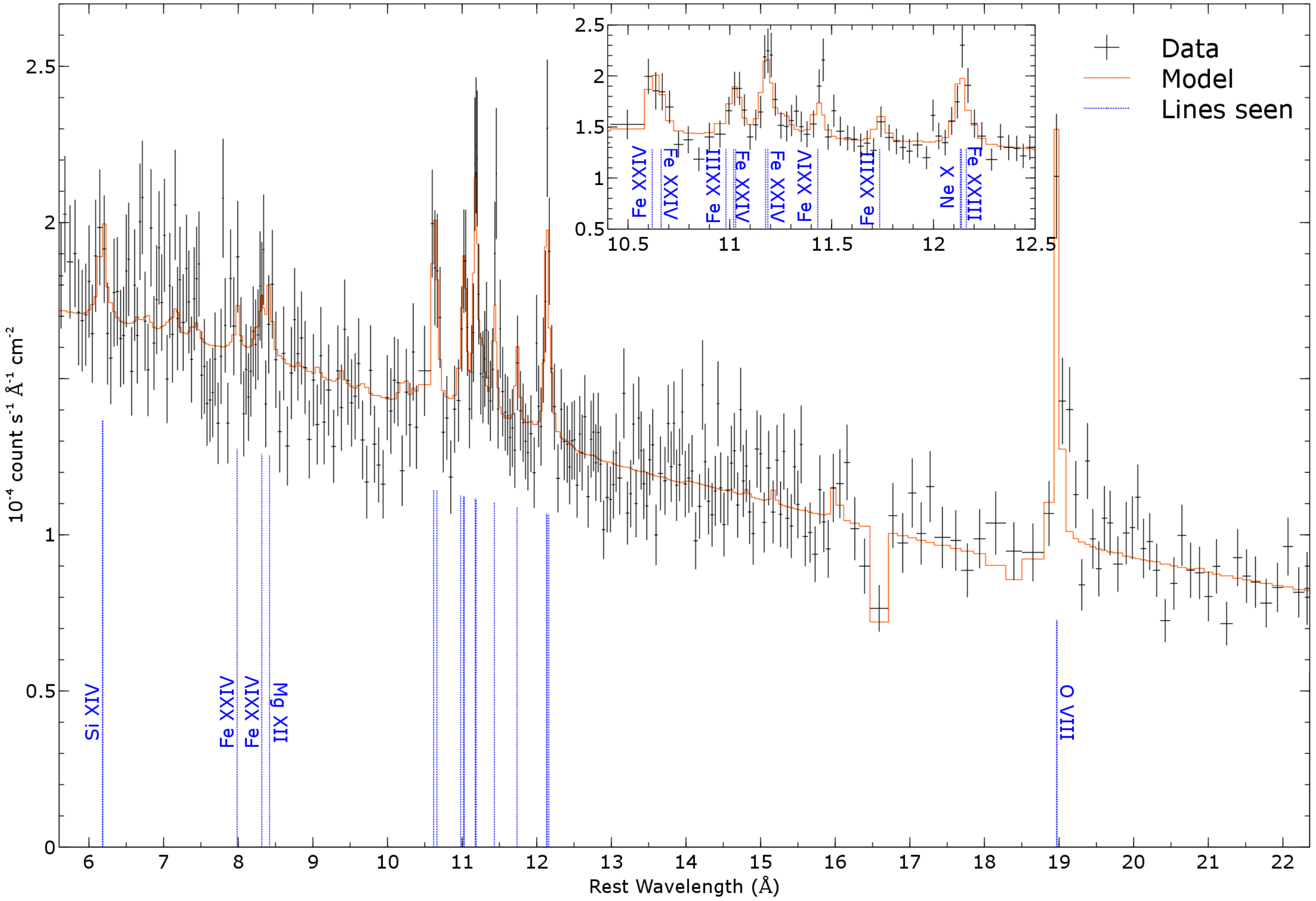
- *AGN feedback (including dissipation of energy)*
- *Cluster growth / evolution*
- *Mergers and sloshing*
- *Hydrostatic bias*
- *Microphysics*

Indirect methods include:

- Resonant scattering (e.g. Xu+02, Churazov+04, Werner+09, Ahoranta+16, Ogorzalek+17, Hitomi+18)
- Density/pressure fluctuations (e.g. Schuecker+04, Zhuravleva+14,15,18, Walker+15, Hofmann+16)
- X-ray vs optical potential: Churazov+08
- Baryon fraction in outskirts: Eckert+19
- Metallicity variation: Rebusco+05, Graham+06, Churazov+03, Simionescu+08, Kirkpatrick+09,11

XMM-RGS velocity upper limits

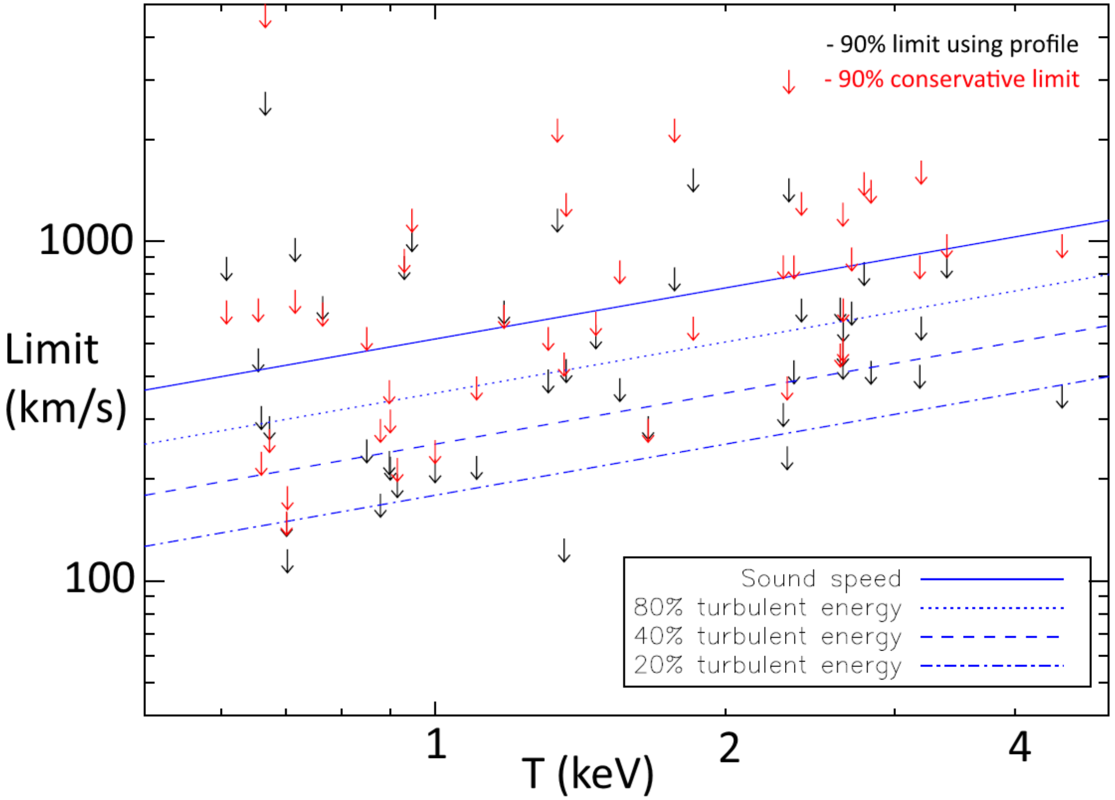
Sanders+10: A1835, LoS v_{turb} < 274 km s^{-1} (turb. pressure <13%)



Many cool core clusters with AGN feedback show line width limits < 500 km s^{-1} (and some < 300 km s^{-1})

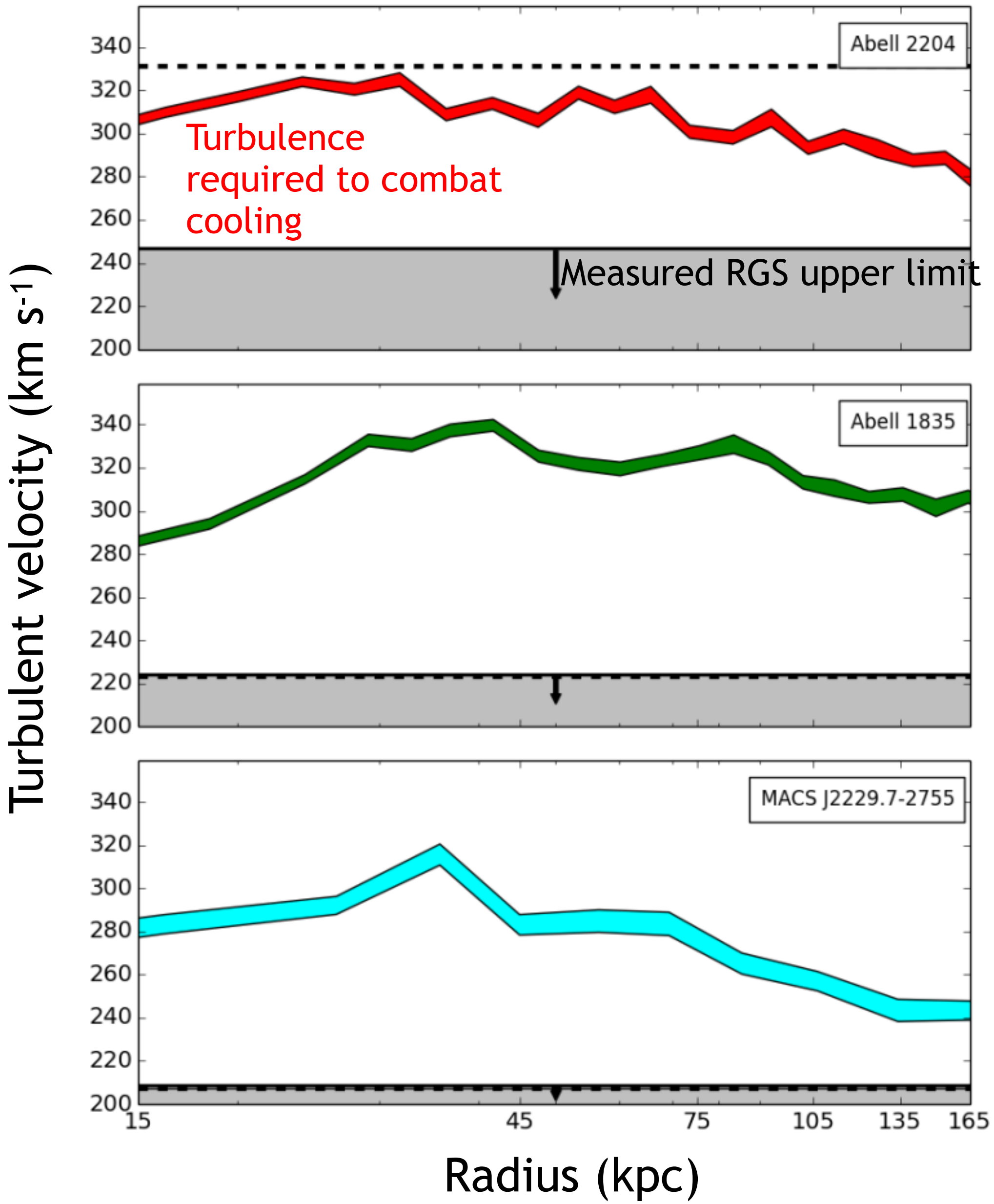
Also see: Bulbul+12 for A3112 (< 205 km s^{-1}, modelling-

Pinto+15 (CHEERS sample)



Similar results found in a more compact sample and different modelling in Sanders+13, also finding a couple of detections

Measured upper limits and required turbulence



Bambic+18

Examined three cool core clusters with good constraints on turbulent velocity

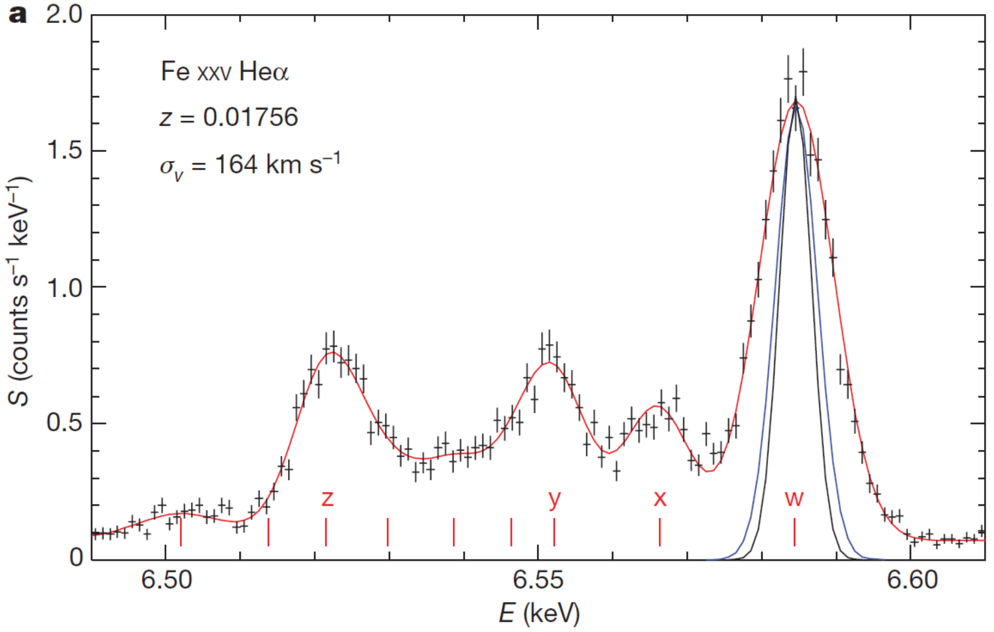
If the upper limits measured are the turbulent velocity, too low to be able to transport sufficient energy radially to combat cooling.

Would need to inject turbulence at each radius.

Hitomi and the Perseus cluster

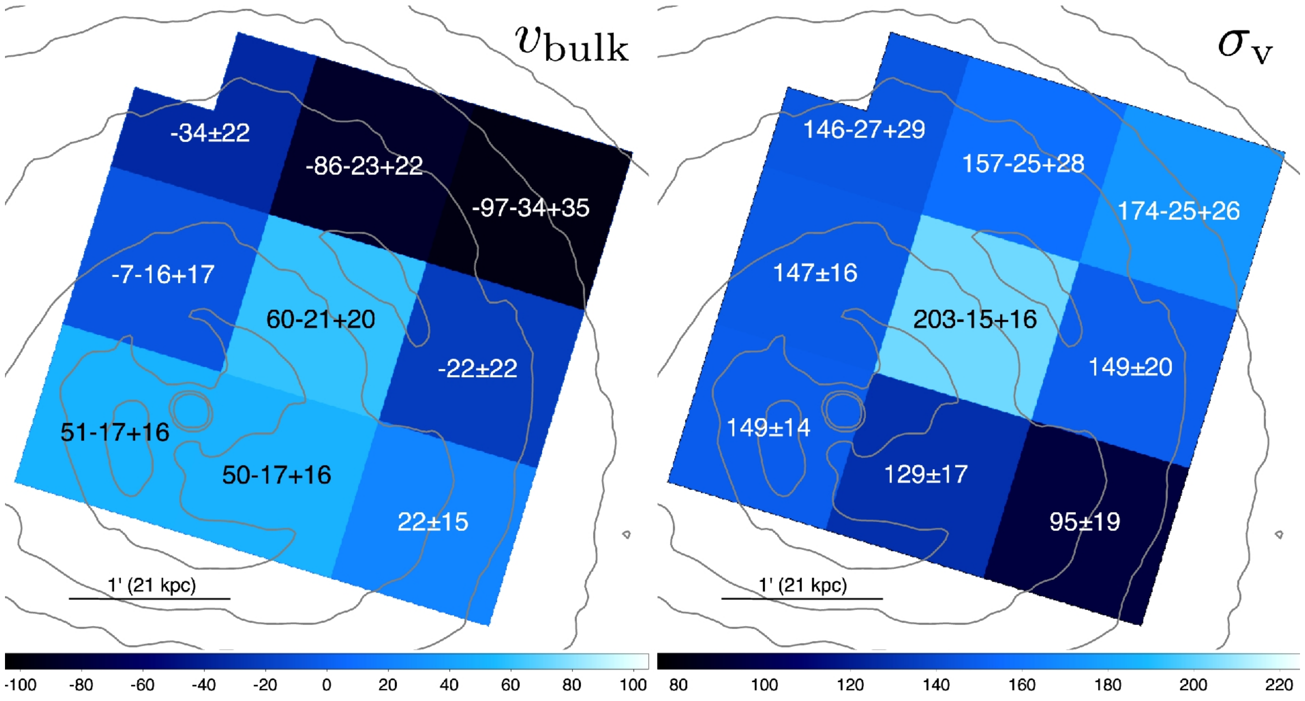
Before its loss, Hitomi observed Perseus, obtaining high resolution spectra measuring the velocity structure. Little evidence for strong turbulence or motions, confirming the RGS results.

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

- Unfortunately, we will need to wait until XRISM to get new Hitomi-quality ICM velocity measurements

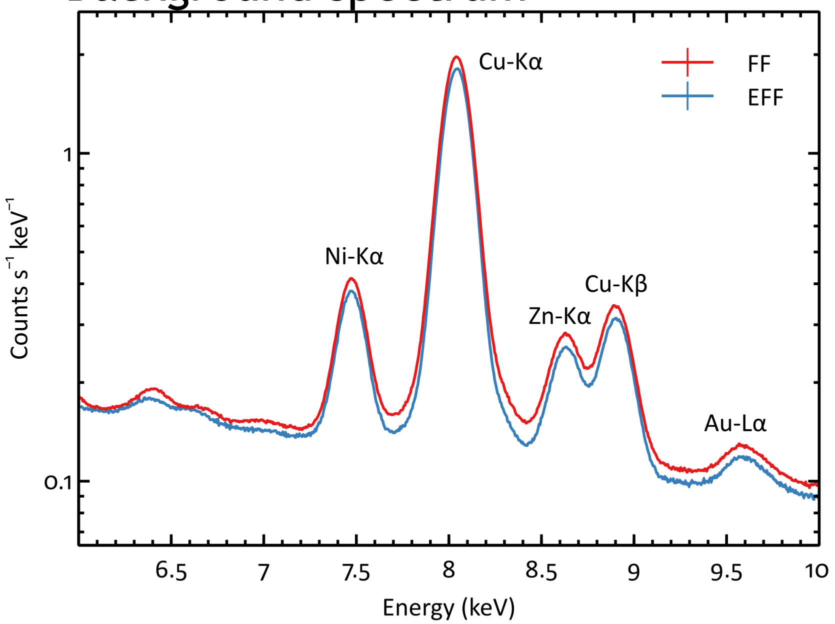
- Although CCD detectors have a relatively low spectral resolution, we can measure bulk velocities using Fe-K redshifts, if the energy scale is well-calibrated

- Previous analyses with Suzaku include Tamura+14 and Ota+16
  - Limits or hints of motion at the level of several 100 $\mathrm{km\,s^{-1}}$

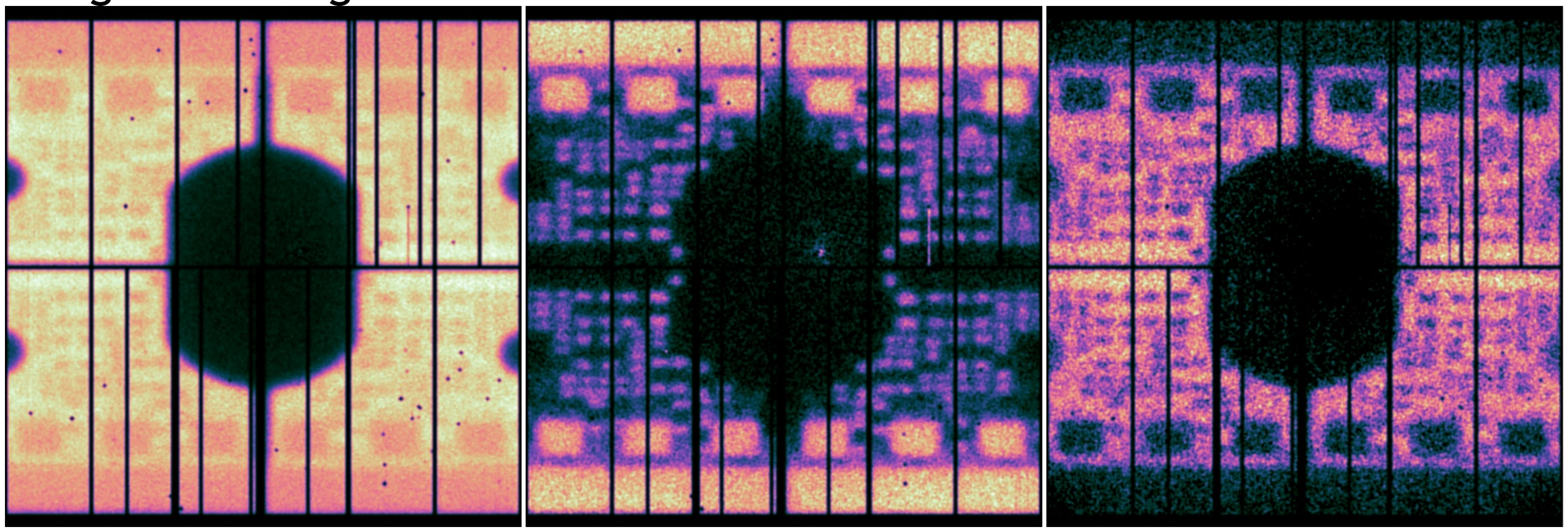
Improving energy calibration of XMM EPIC-pn

Sanders, Dennerl, Russell, Eckert, Pinto, Fabian, Walker, Tamura, ZuHone, Hofmann, A&A, submitted

Background spectrum



Background images



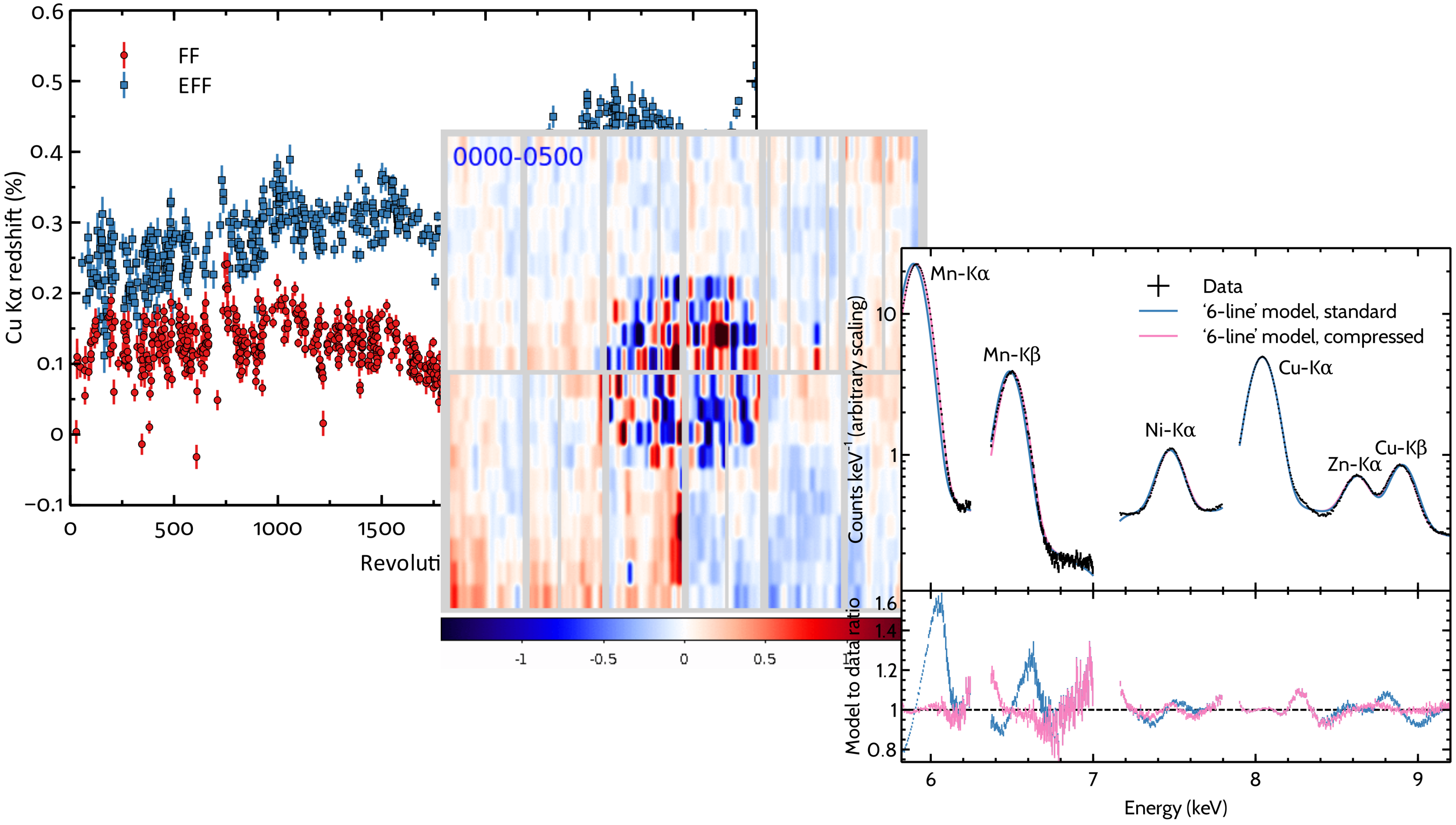
Cu-Kα   Ni-Kα   Zn-Kα + Cu-Kβ

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 use these as a reference (except in detector centre)

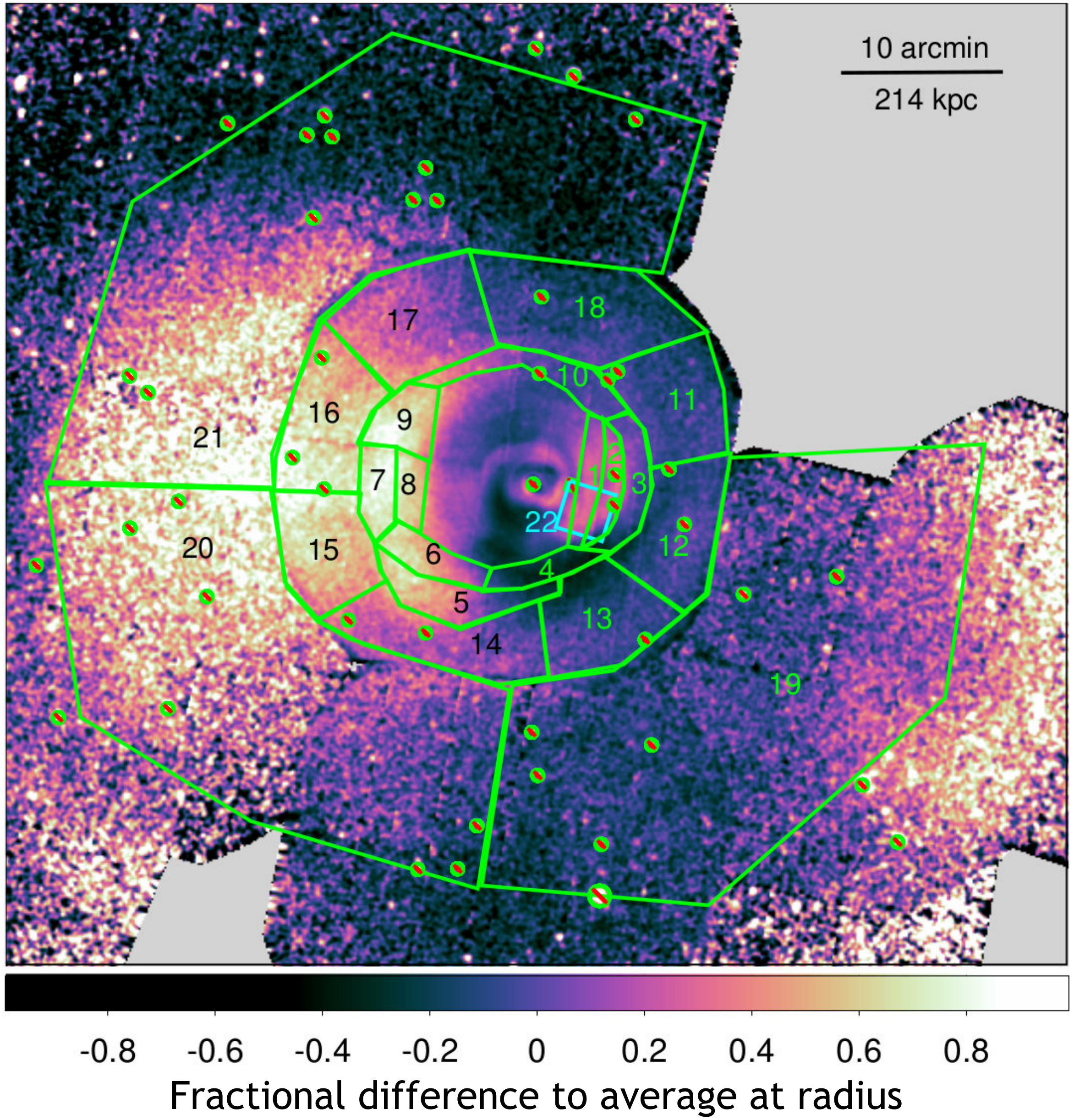
XMM EPIC-pn correction procedure

- Large effort into energy calibration procedure, using large fraction of XMM archive
- 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



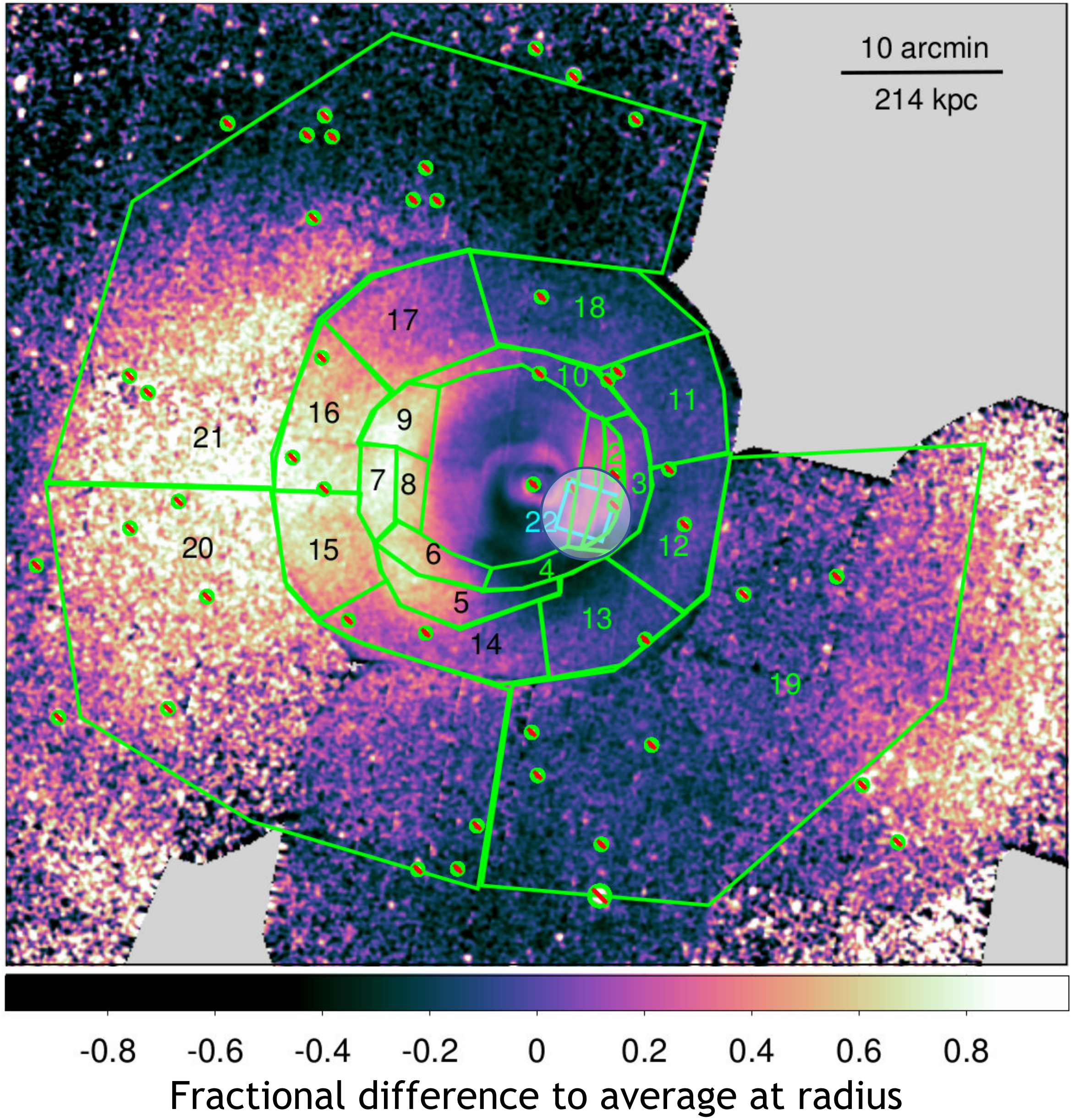
After correction, we look at the dispersion between observations, which implies our velocities are accurate to 150 km s^{-1} at Fe-K energies

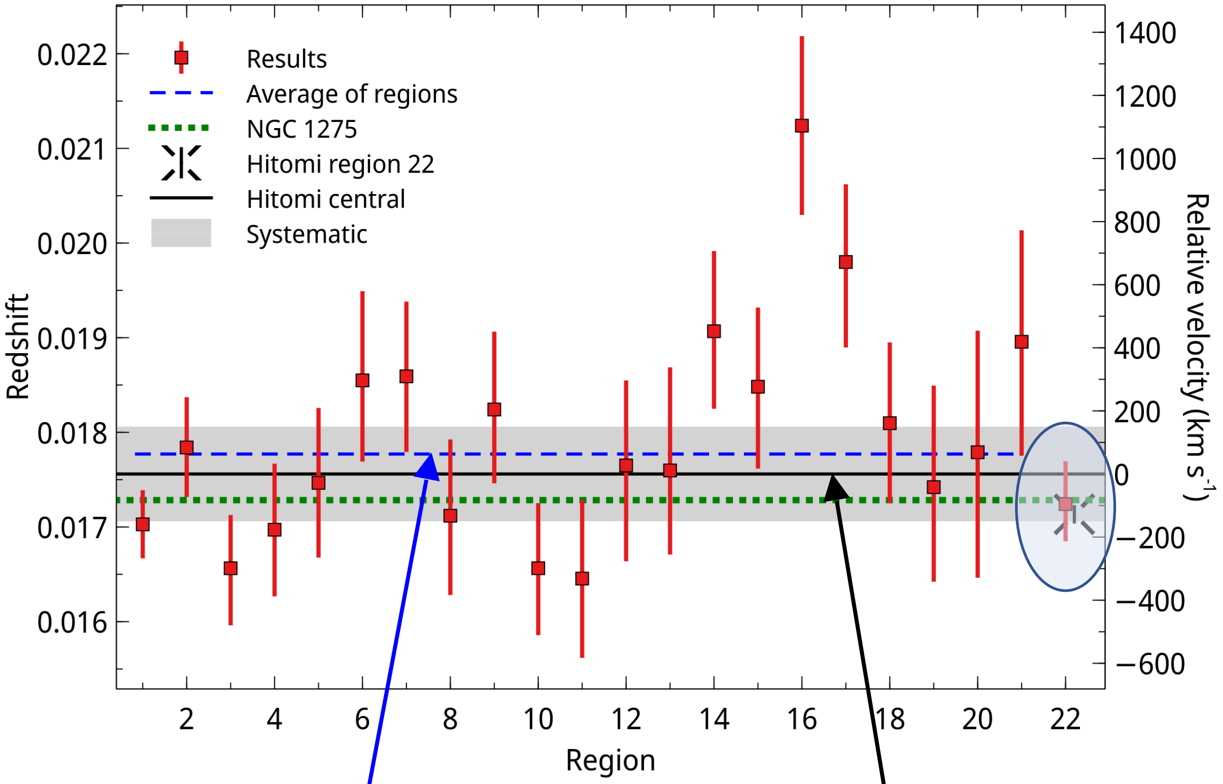
Perseus cluster velocity measurements



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

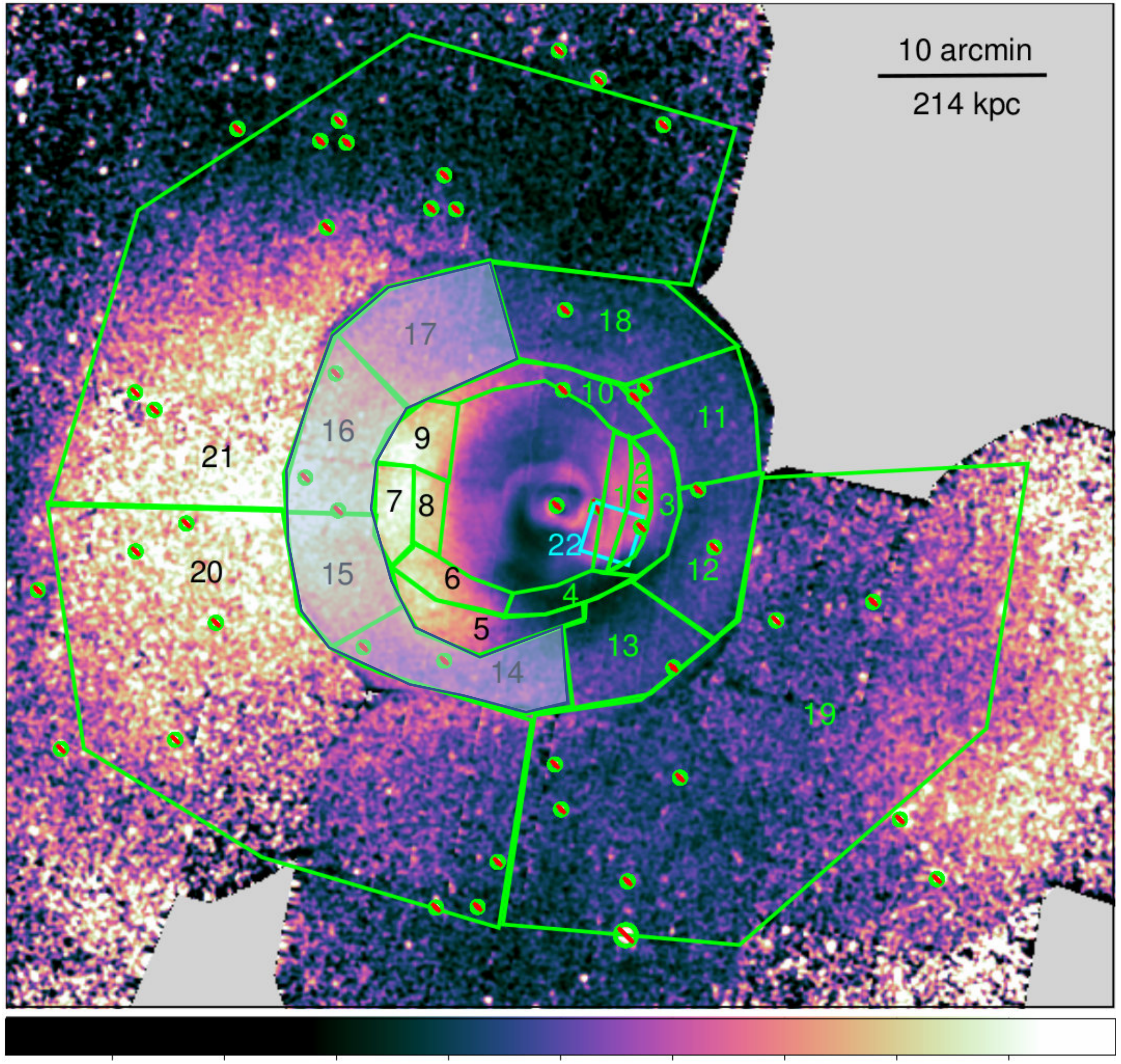
Perseus cluster velocity measurements

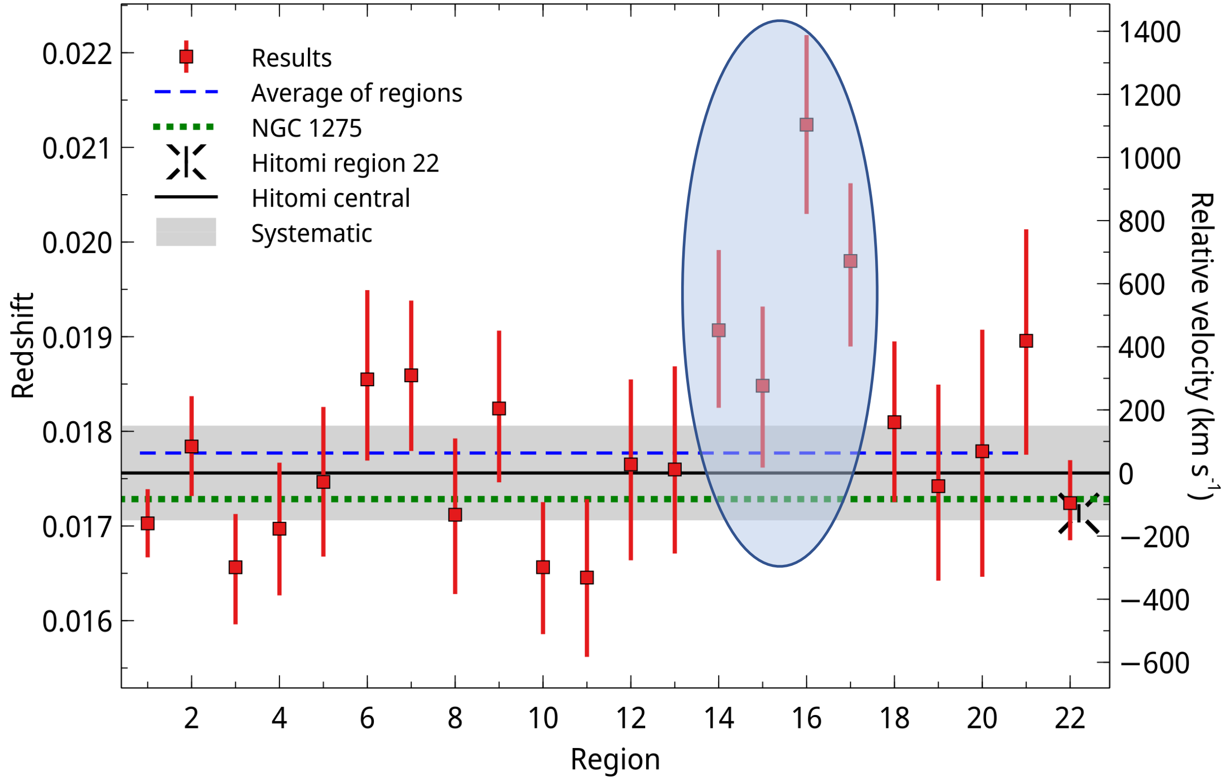




- Our average velocity and the Hitomi average velocity are very close (<< systematics)
- Consistent velocity obtained in Hitomi comparison region (Region 22)

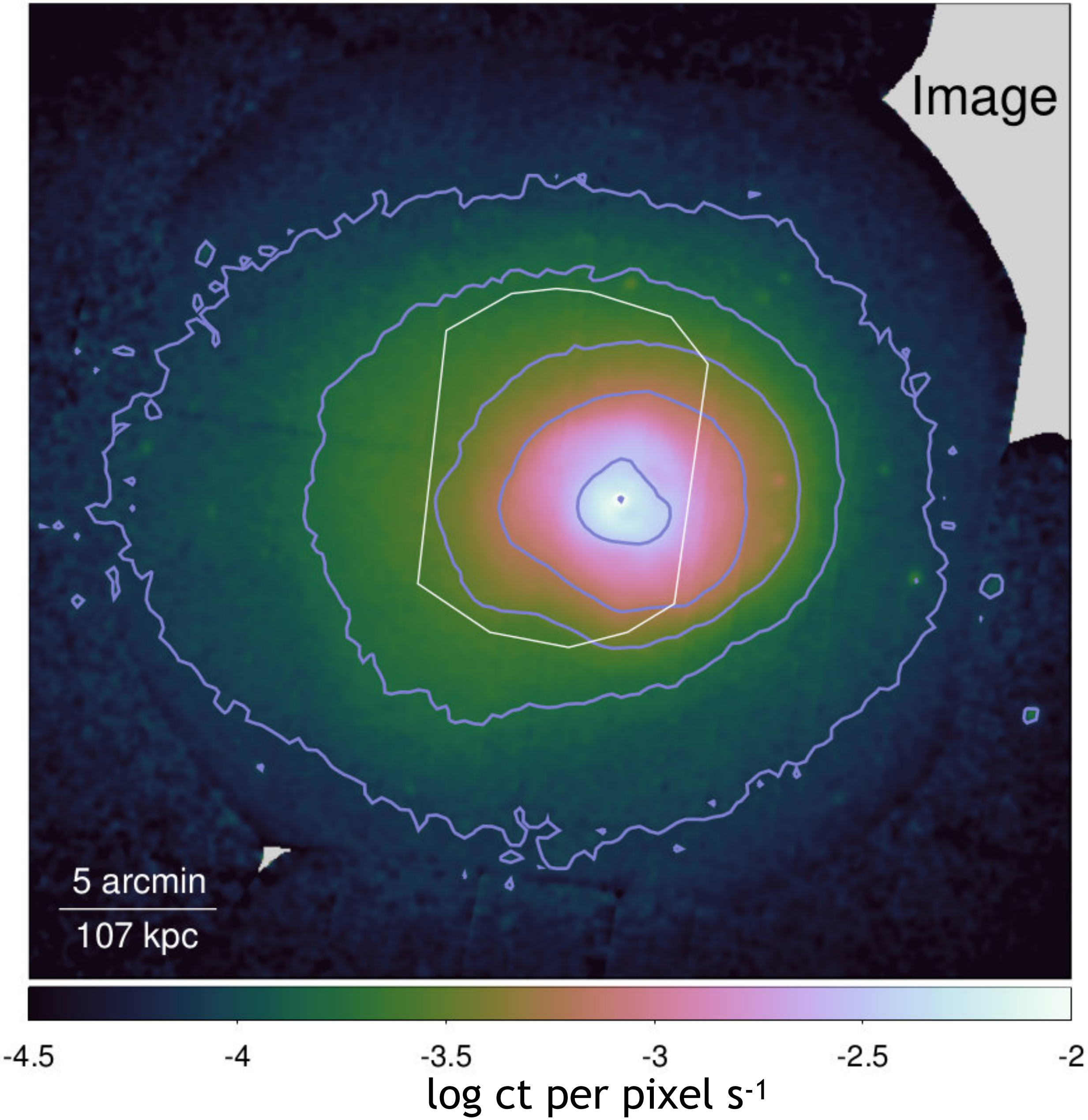
Perseus cluster velocity measurements

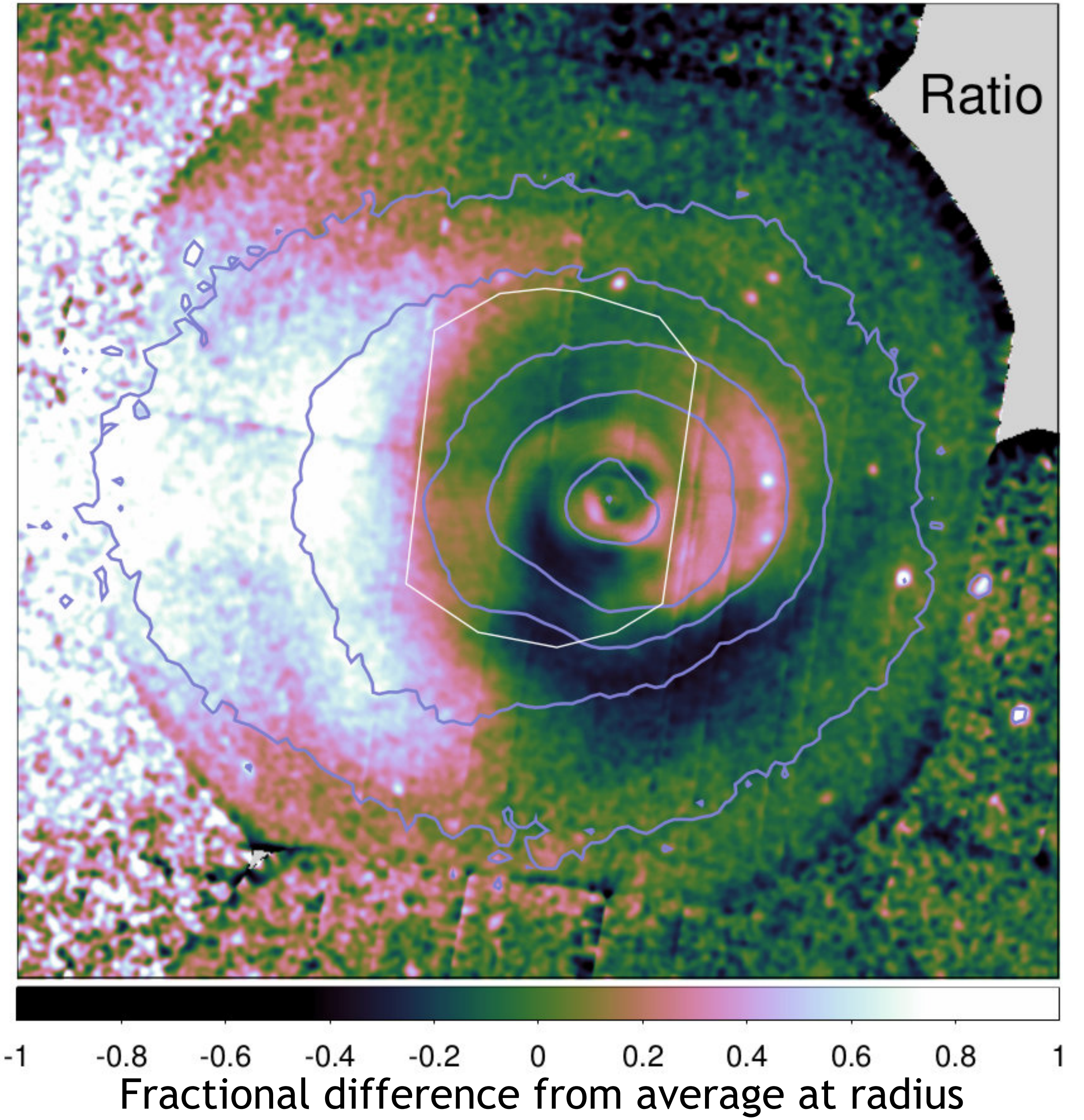




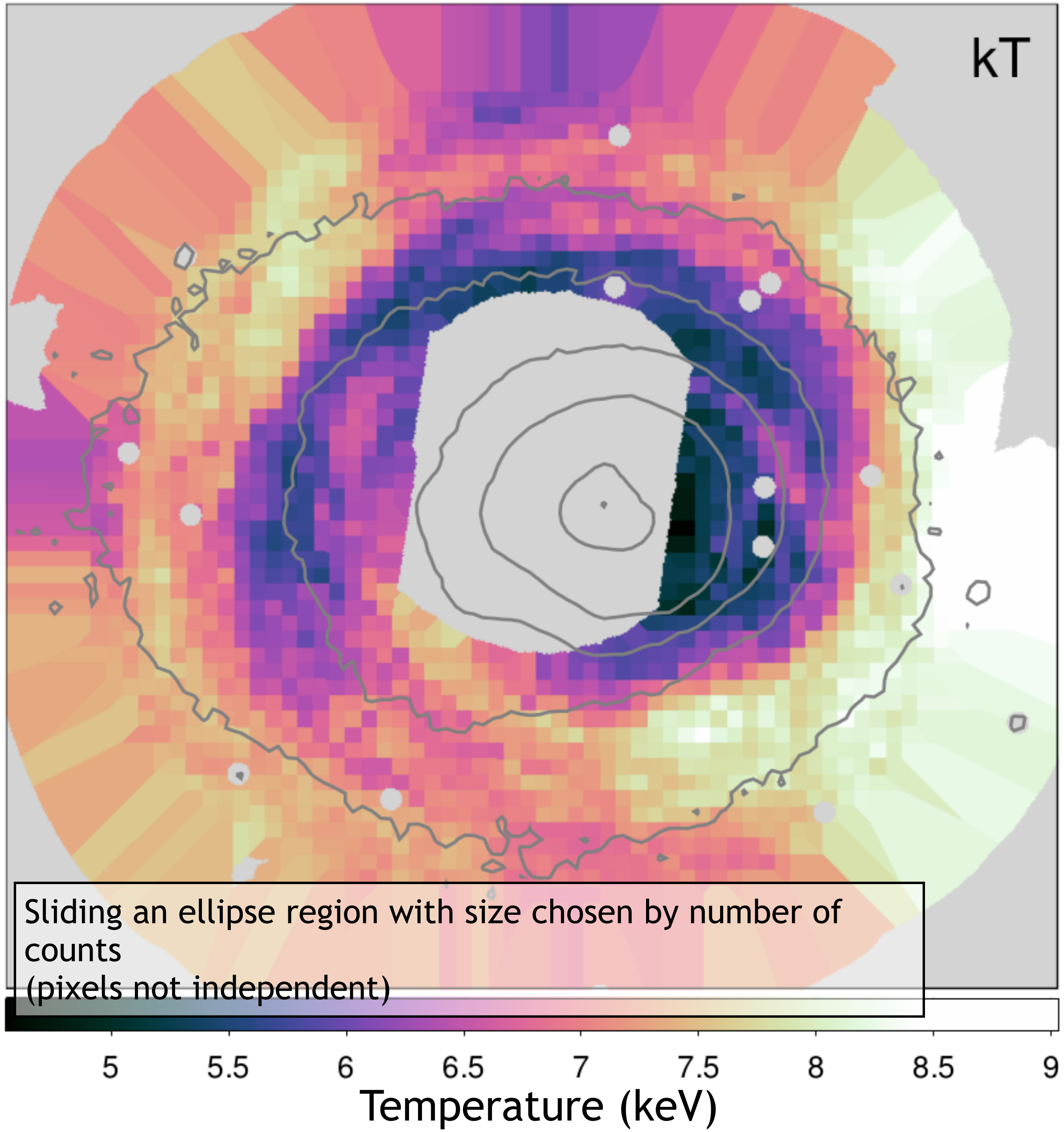
- Evidence for sloshing at 500±100 km s^{-1} to east of core where there is a cold front (excl. systematic)
- Line-of-sight width excluding sloshing region < 220 km s^{-1}, assuming a Gaussian

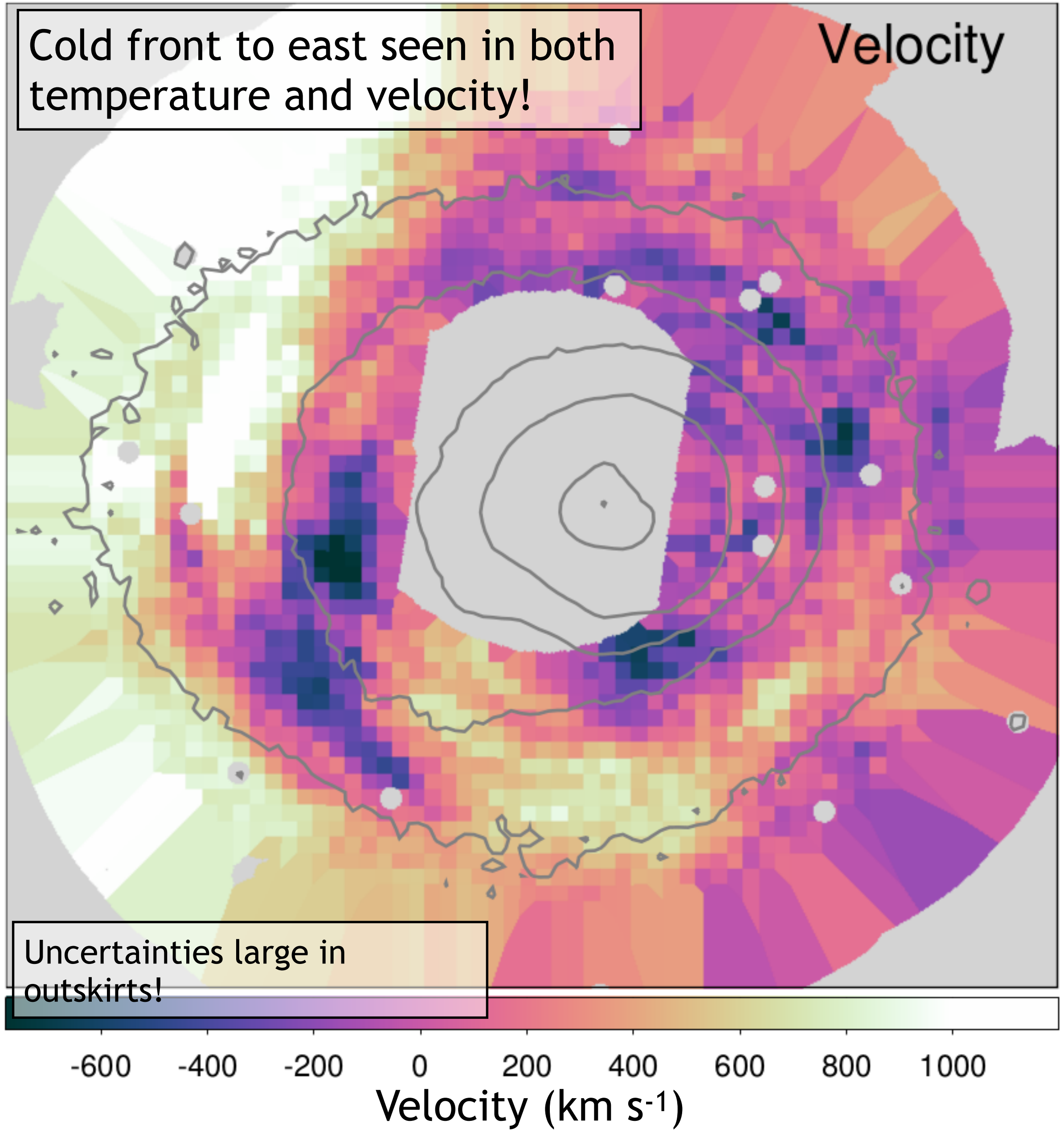
Perseus maps: surface brightness



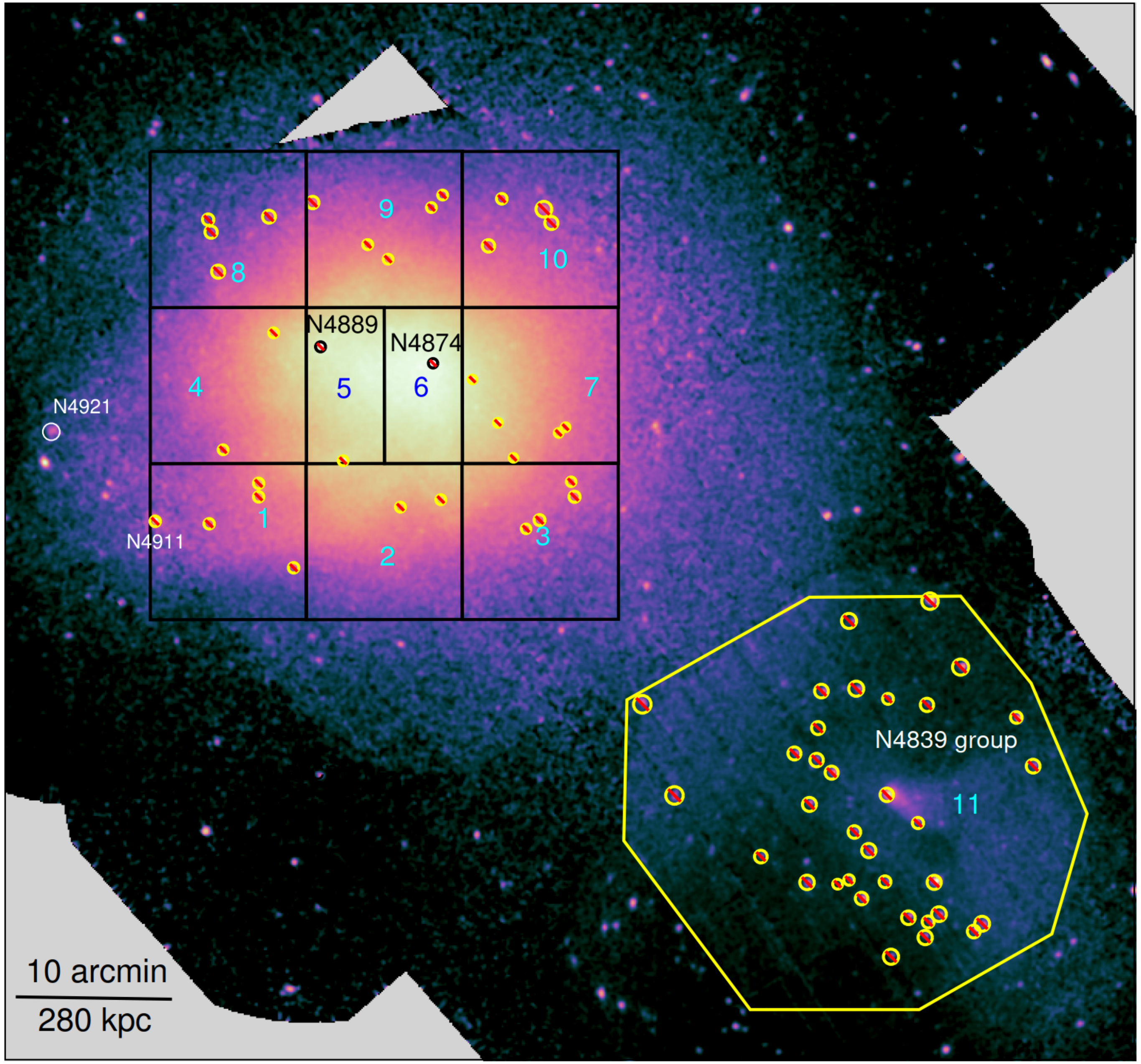


Perseus maps: temperature and velocity



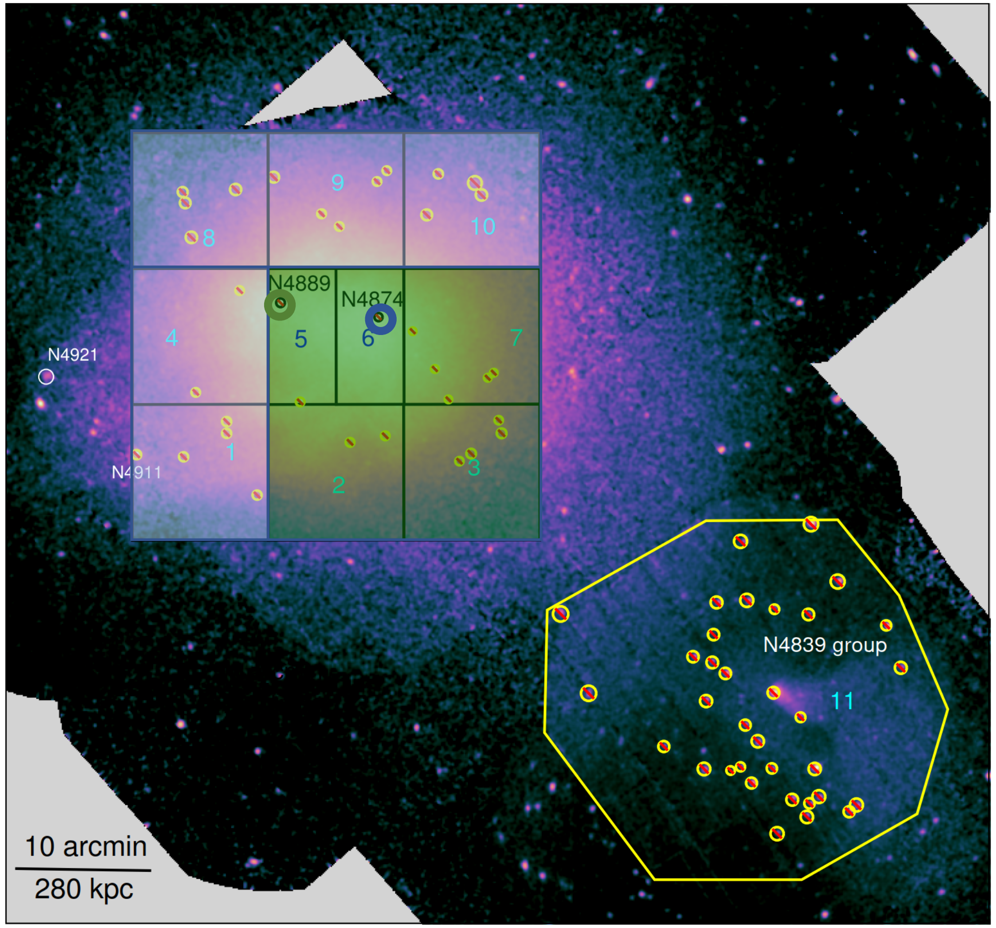


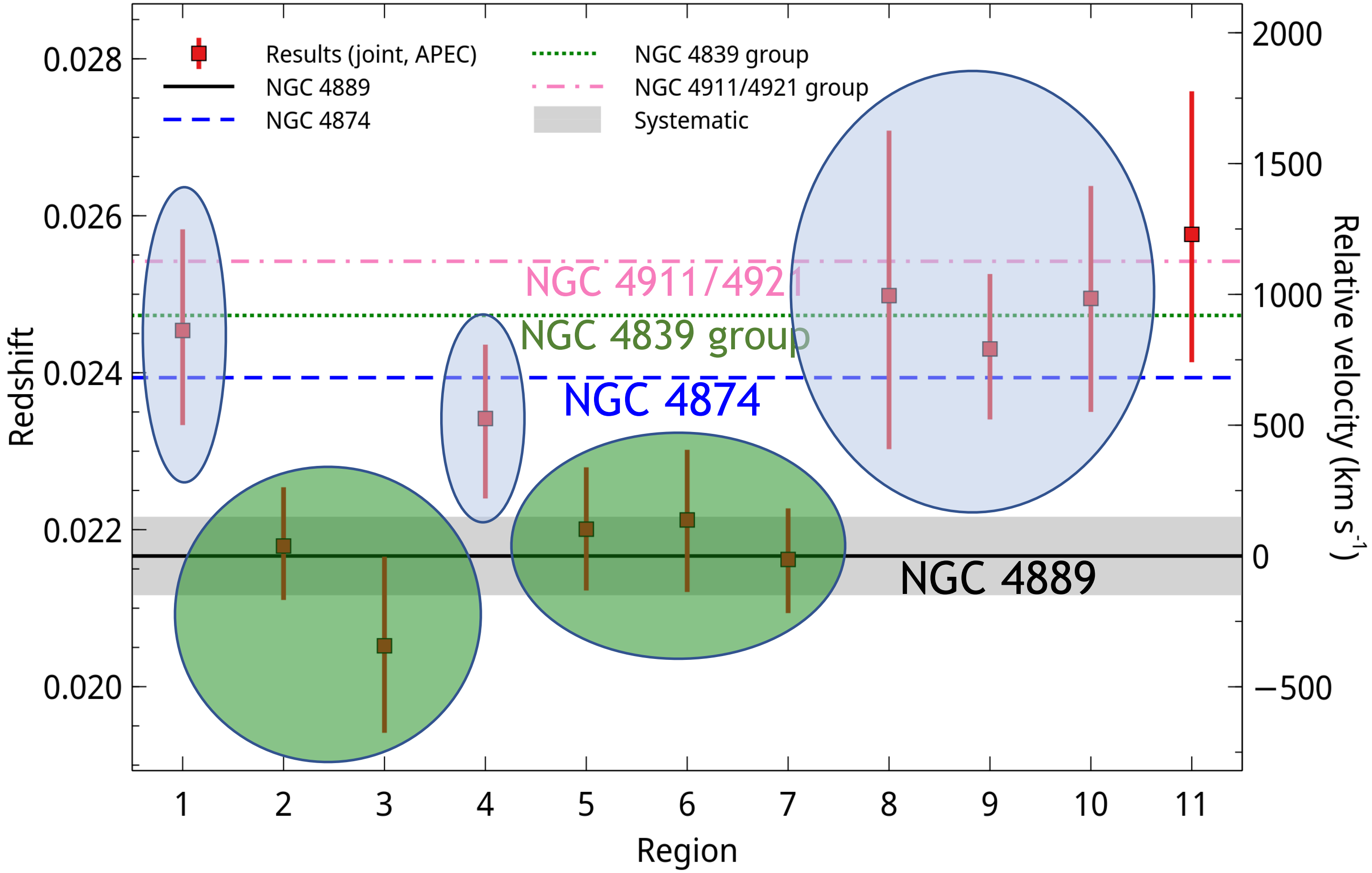
Coma cluster



- Merging system
- Two central galaxies: NGC 4874 and NGC 4889
- Merging NGC 4839 group in south west
- Second NGC 4921/4911 group to east
- Construct 10 central regions and one for NGC 4839 group

Coma cluster – velocity results

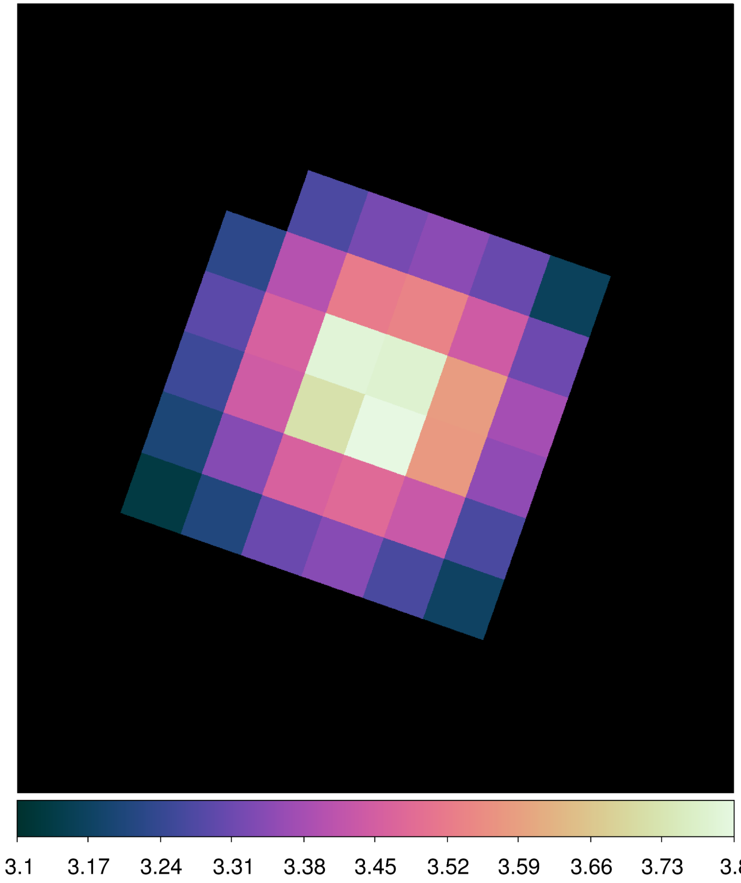




- Coma ICM velocities match that of the central galaxies
- Material in centre and S, W and SW matches NGC 4889
- ICM velocity to N, E, NE and SE matches NGC 4874
- NGC 4839 group gas velocity consistent with optical

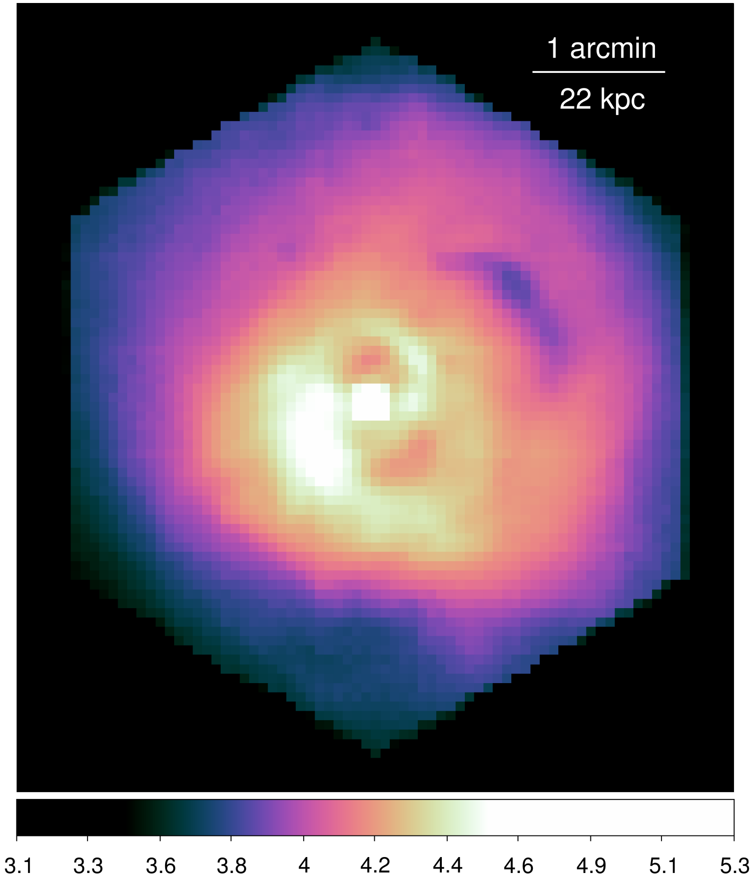
Future high resolution X-ray spectroscopy

Hitomi / XRISM (2021)

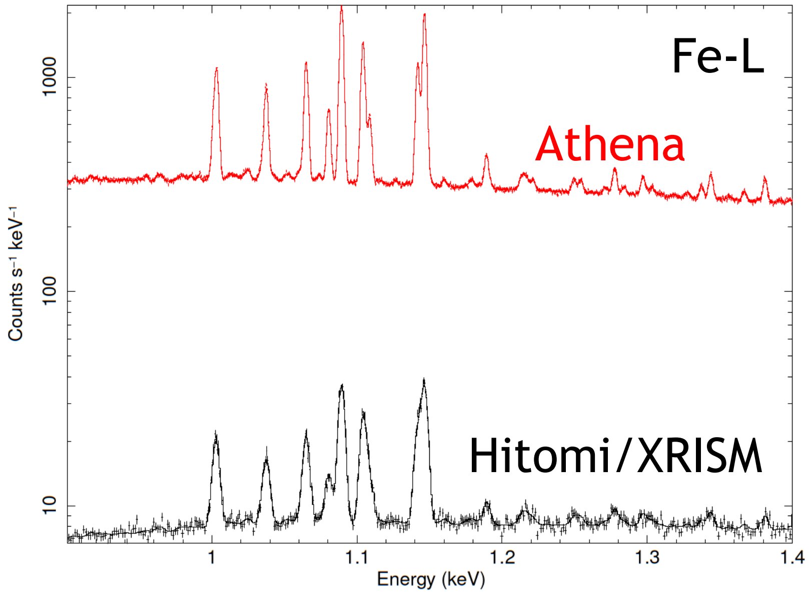


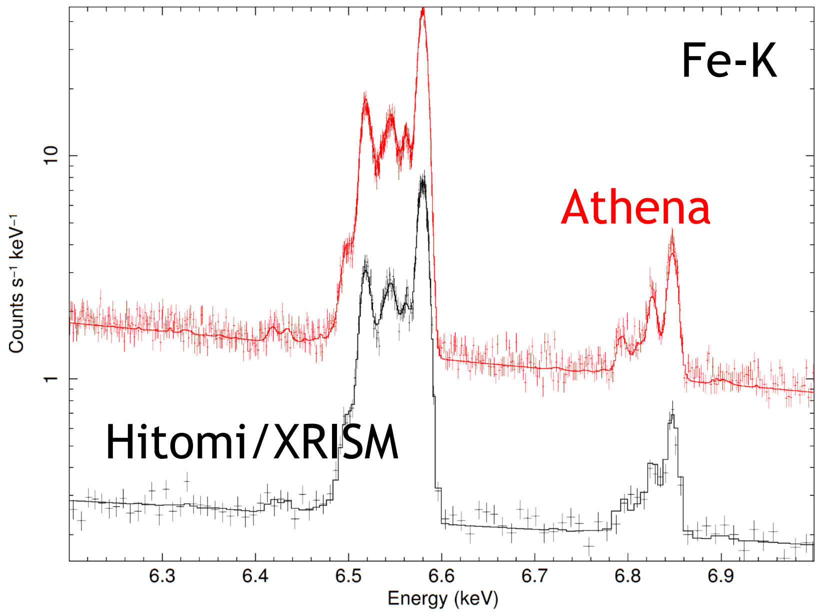
log cts pixel^{-1}

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

- AGNs in nearby clusters show evidence for repeated frequent feedback events over 10s of Myr producing weak shocks and possible sound waves
- Centres of cool core clusters appear to have low levels of turbulence
- Developed a new technique for measuring bulk motions with XMM
- 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, indicating gas hasn't mixed and is still streaming at the sub-cluster velocities

- Upcoming analyses with new offset observations for Virgo and Centaurus