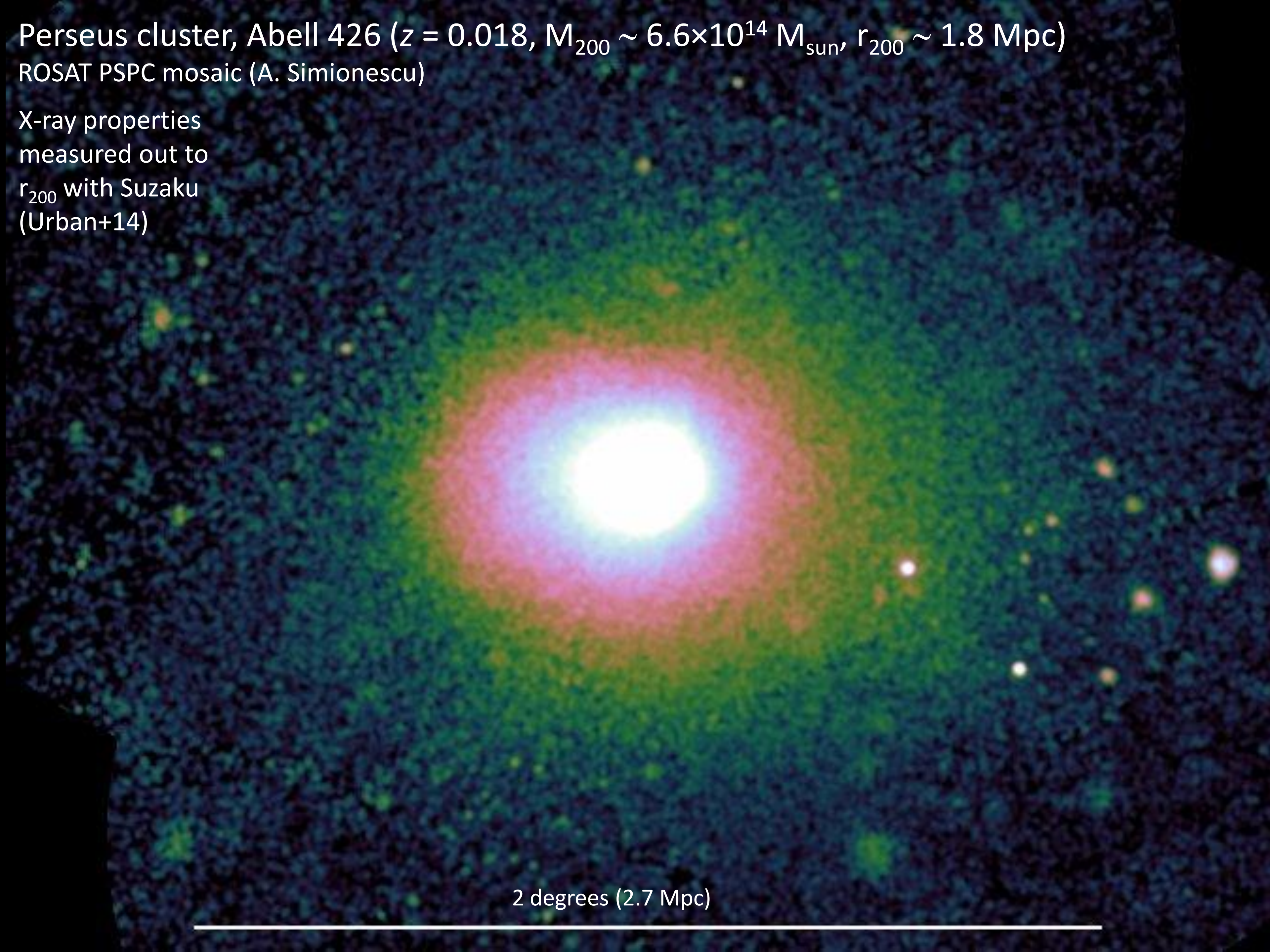
The deep Chandra view of the core of the Perseus cluster

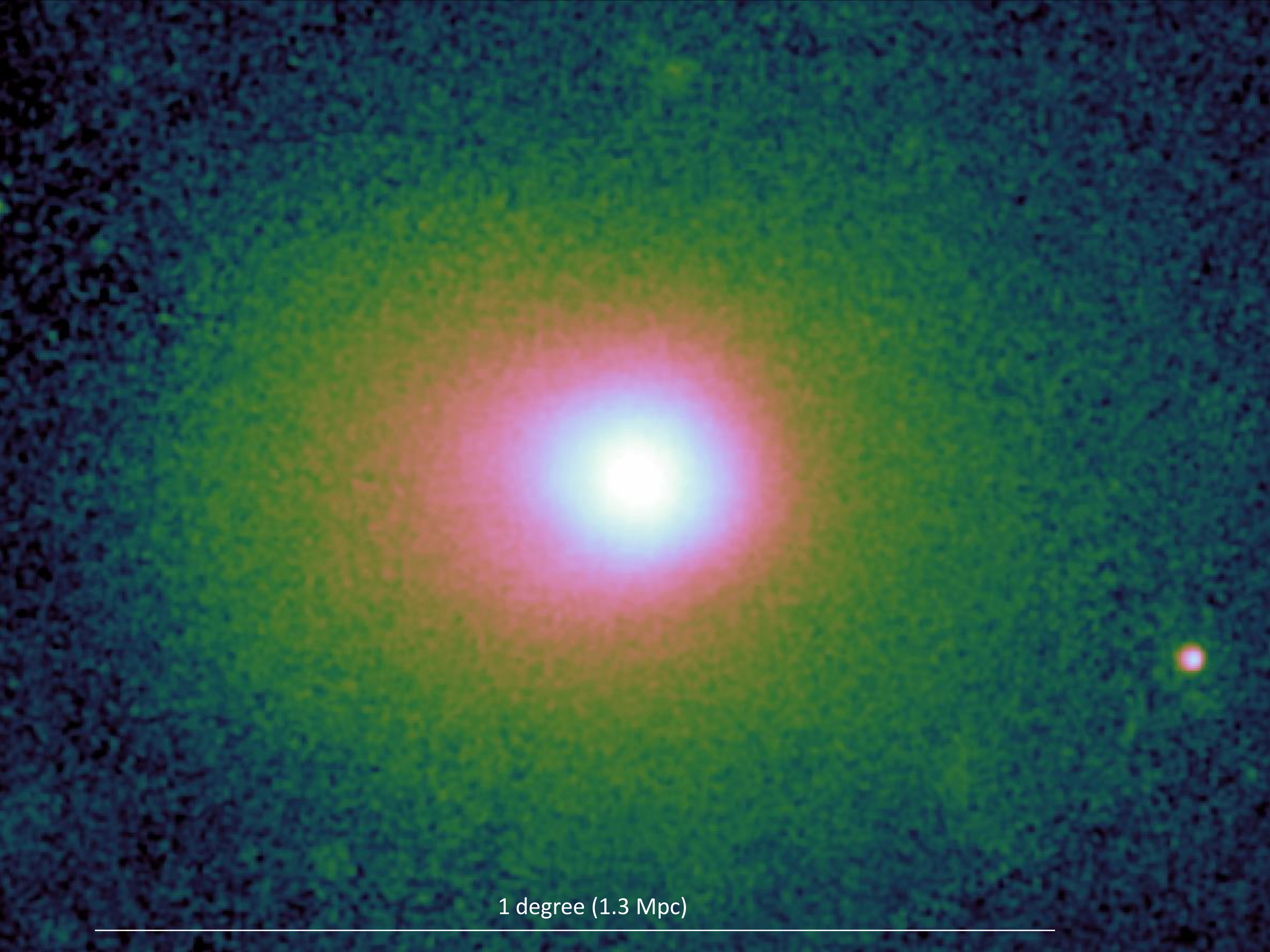
Jeremy Sanders

Max Planck Institute for Extraterrestrial Physics (MPE)

Thanks to: Andy Fabian, Helen Russell, Katherine Blundell, Stephen Walker and a long list of co-authors

JOURNEY TO THE CENTRE OF THE PERSEUS CLUSTER

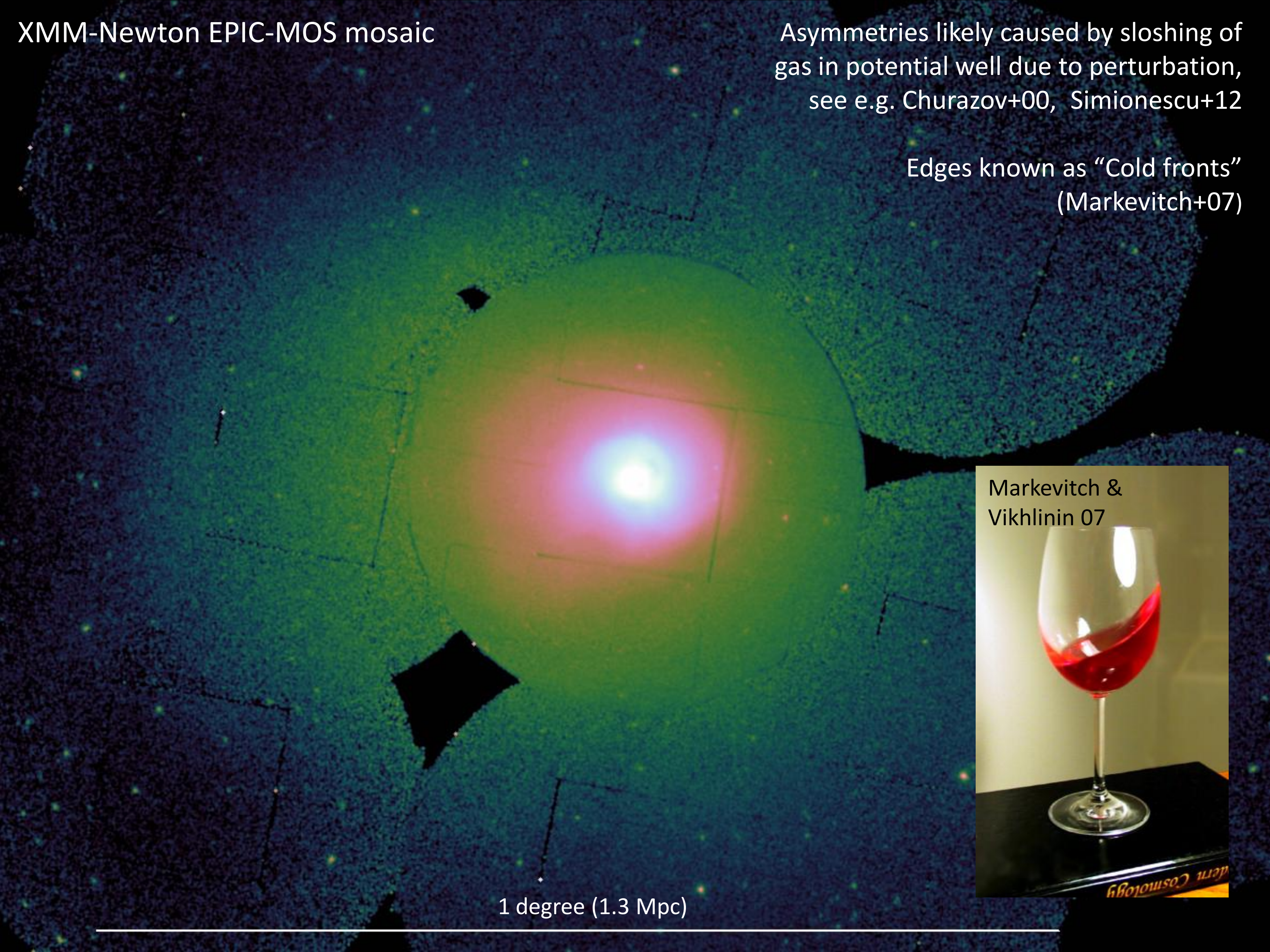

Perseus cluster, Abell 426 (z = 0.018, $M_{200} \sim 6.6\times10^{14}\ M_{sun}$, $r_{200} \sim 1.8$ Mpc)
ROSAT PSPC mosaic (A. Simionescu)
X-ray properties measured out to r_{200} with Suzaku (Urban+14)
2 degrees (2.7 Mpc)


1 degree (1.3 Mpc)

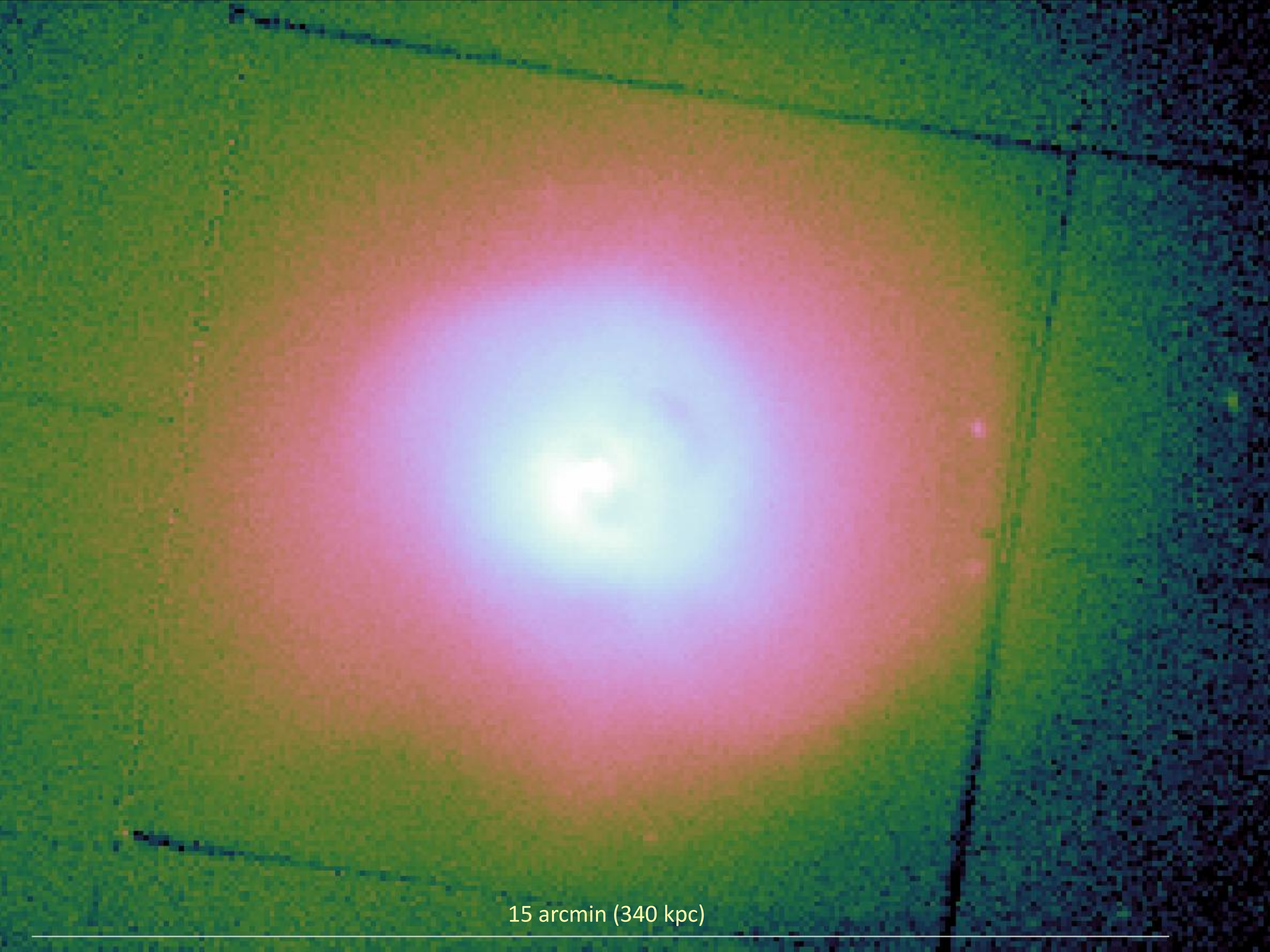
XMM-Newton EPIC-MOS mosaic

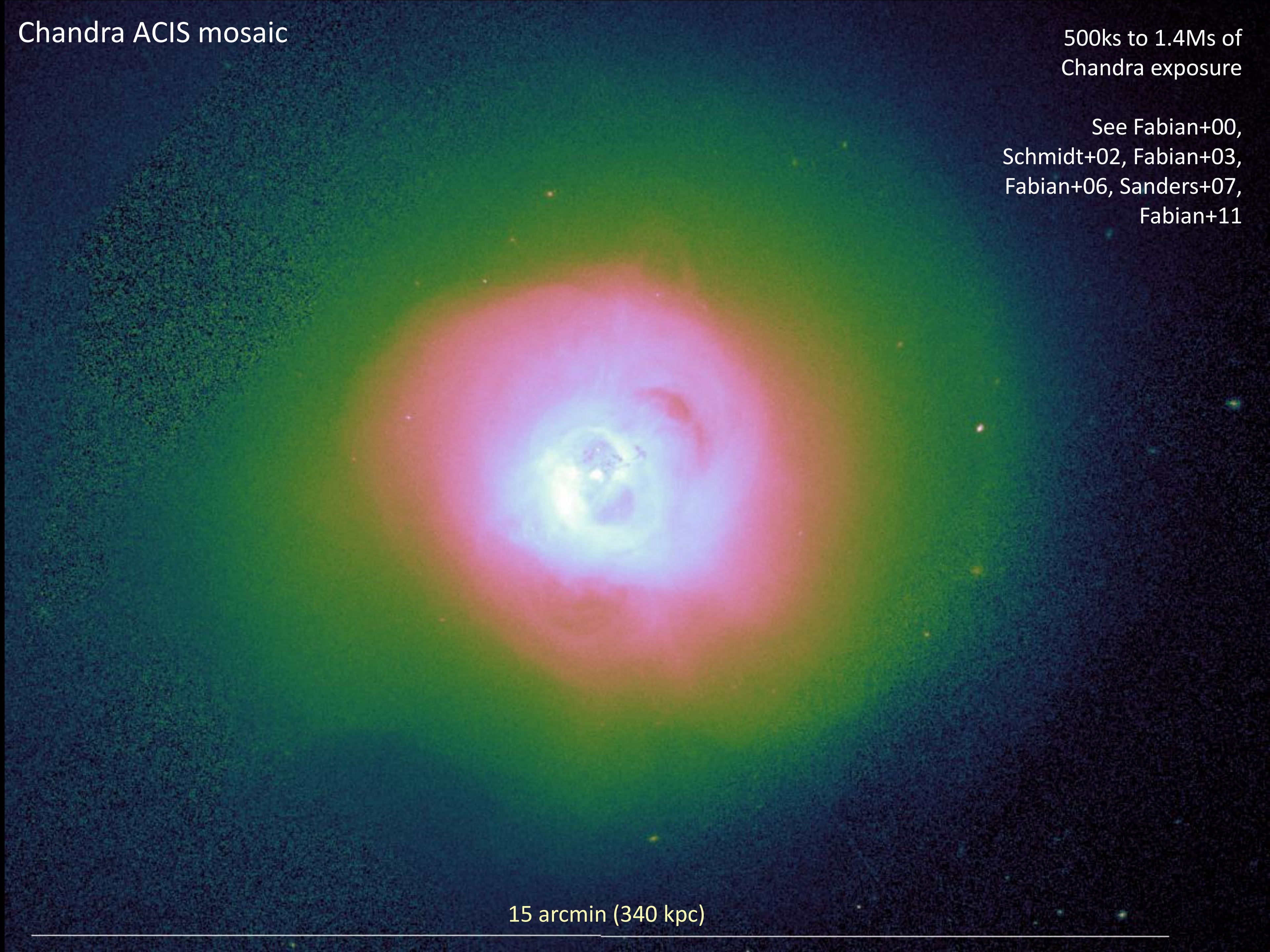
Asymmetries likely caused by sloshing of gas in potential well due to perturbation, see e.g. Churazov+00, Simionescu+12

Edges known as “Cold fronts” (Markevitch+07)

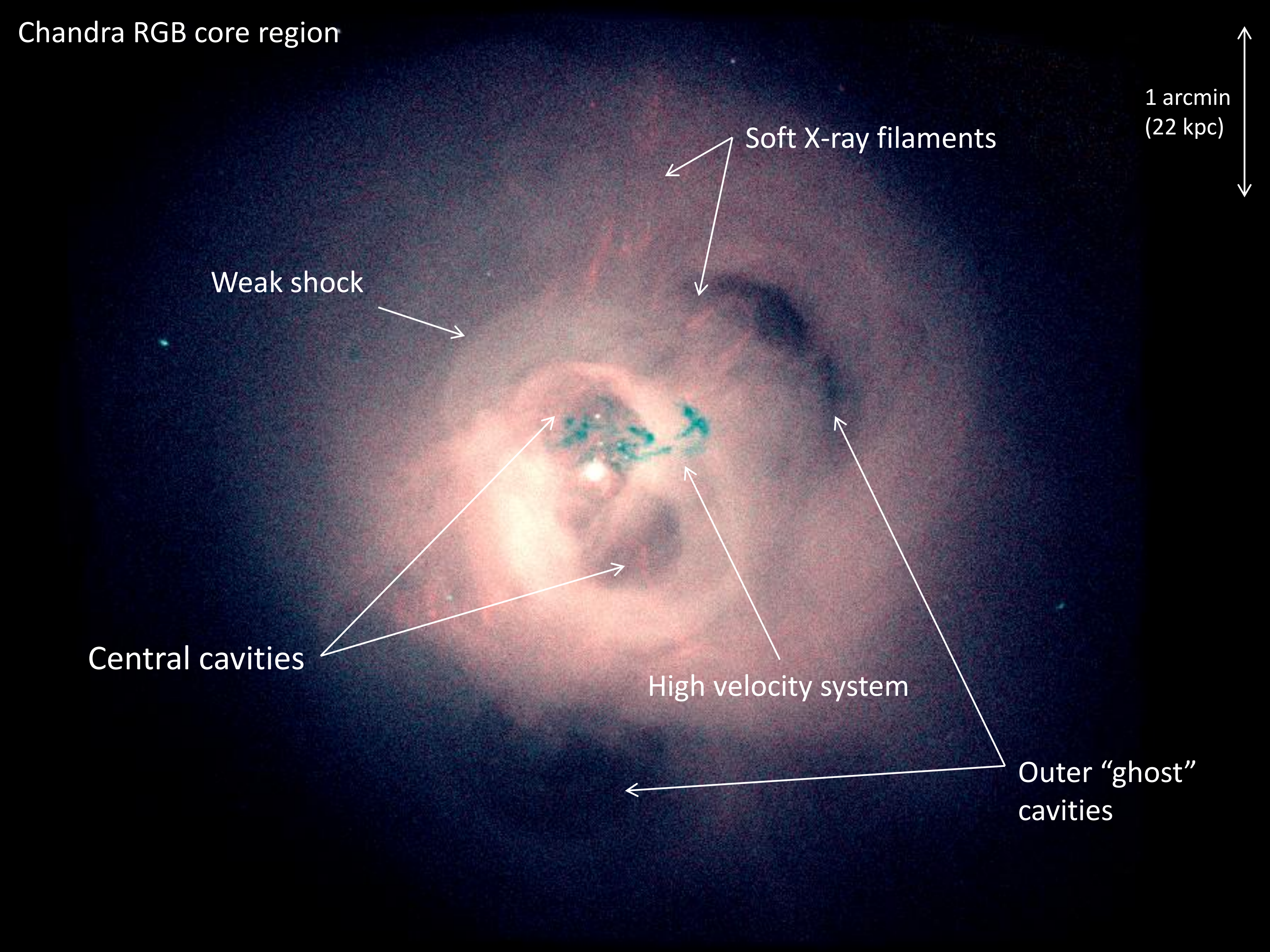


Markevitch & Vikhlinin 07

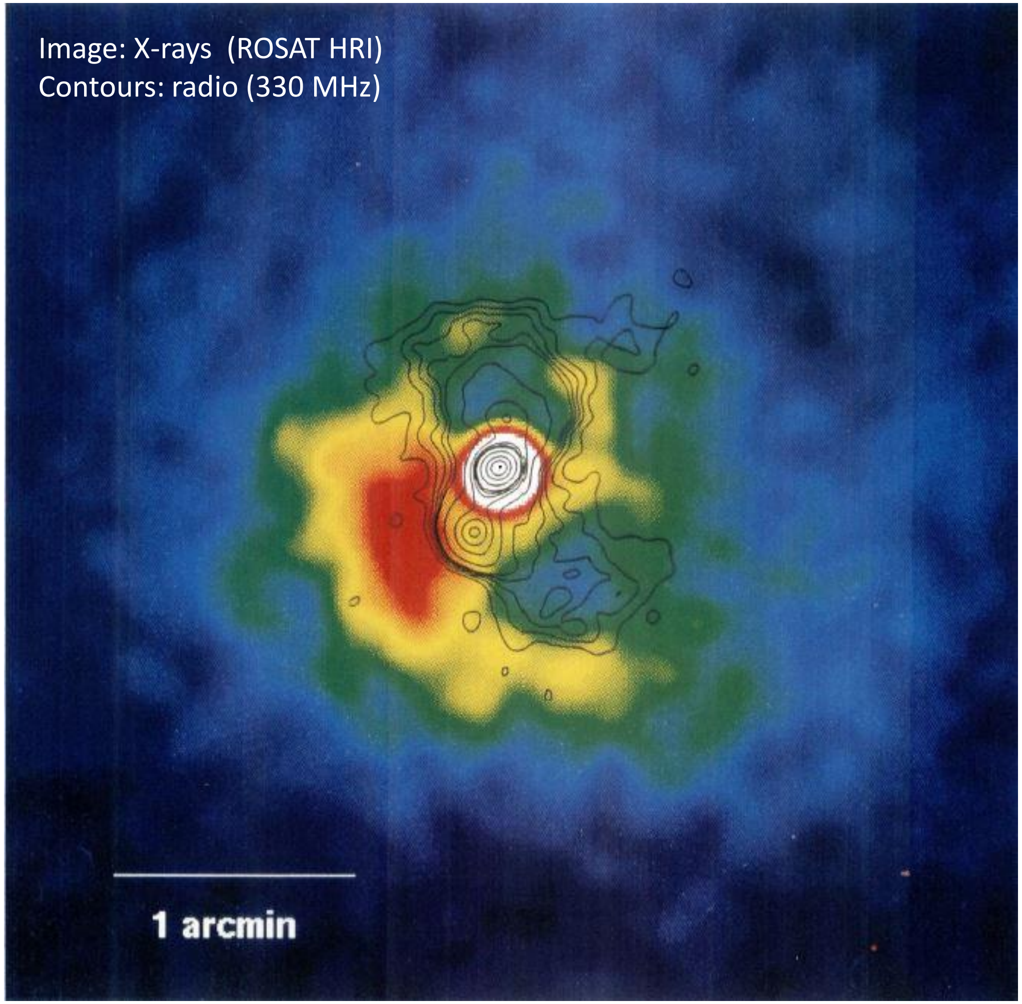

15 arcmin (340 kpc)


Chandra ACIS mosaic
500ks to 1.4Ms of
Chandra exposure
See Fabian+00,
Schmidt+02, Fabian+03,
Fabian+06, Sanders+07,
Fabian+11
15 arcmin (340 kpc)

Chandra RGB core region


Chandra RGB core region
1 arcmin
(22 kpc)
Soft X-ray filaments
Weak shock
Central cavities
High velocity system
Outer “ghost”
cavities

Evidence for feedback in Perseus

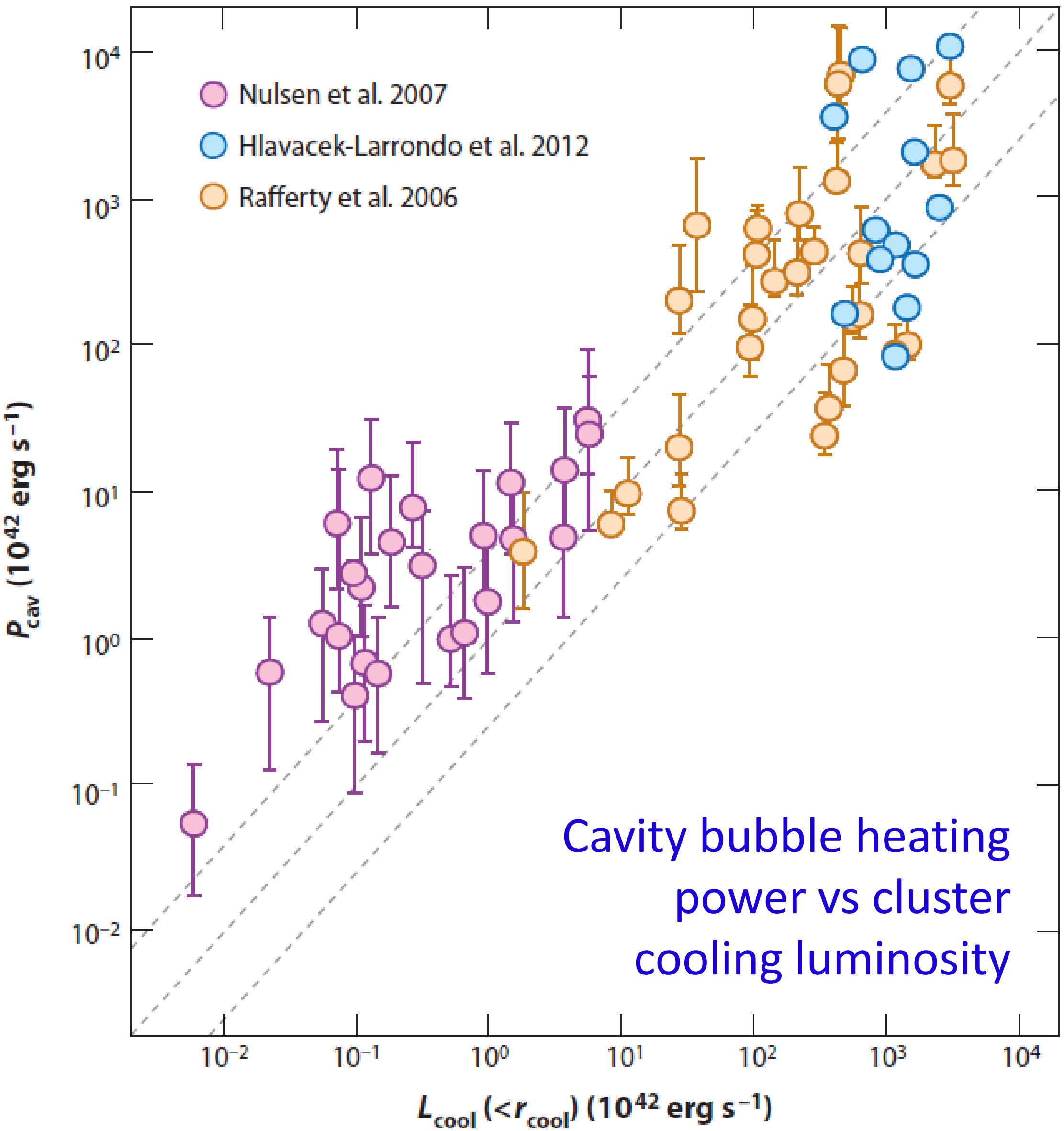


Böhringer+93

- ROSAT first saw the interaction of AGN jets and bubbles with the intracluster medium
- X-ray emitting gas displaced by non-thermal plasma
- Not until the launch of Chandra that they were seen to be widespread

Heating power vs cooling luminosity

from J. Hlavacek-Larrondo (in Fabian 2012)



Heating power estimated from bubble enthalpy (4PV) and timescale for heating, Churazov+02

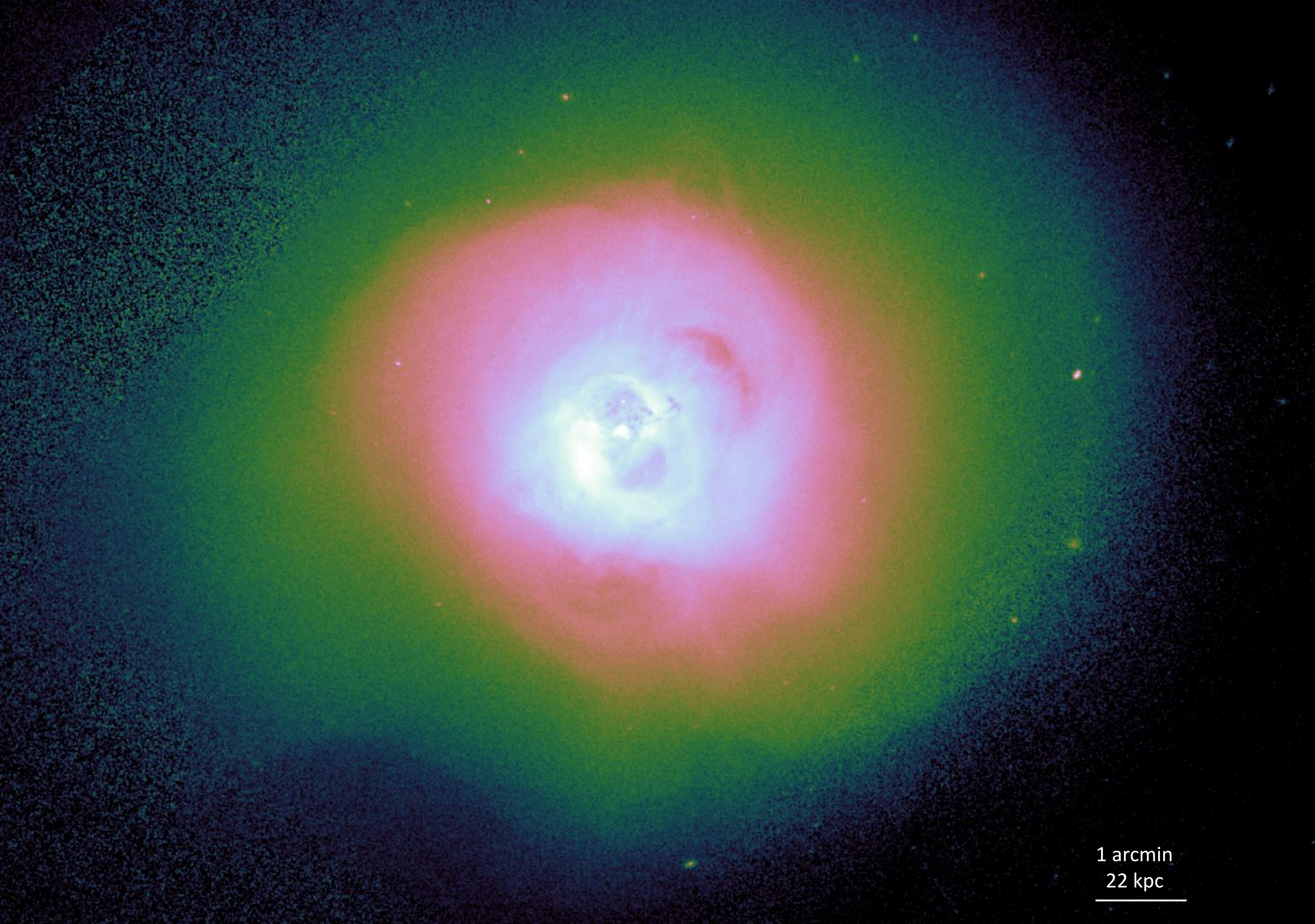
Energetically, AGN can prevent cooling in majority of objects over a wide range in X-ray luminosity

>80% clusters with cooling times <0.5 Gyr have cavities (Panagoulia+14)

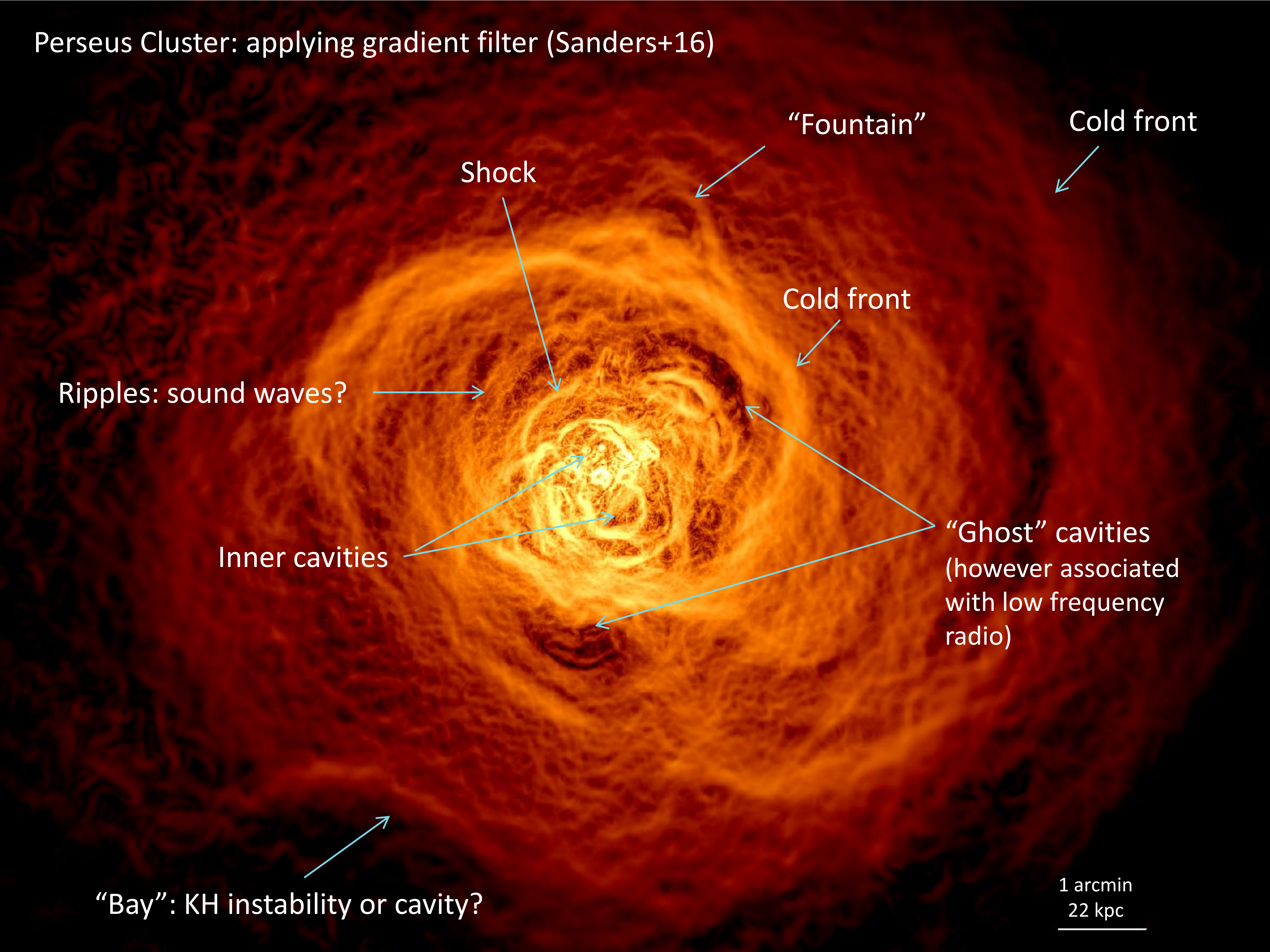
How does AGN feedback work in detail?

How is the energy distributed from cavities?

Perseus Cluster: Chandra mosaic

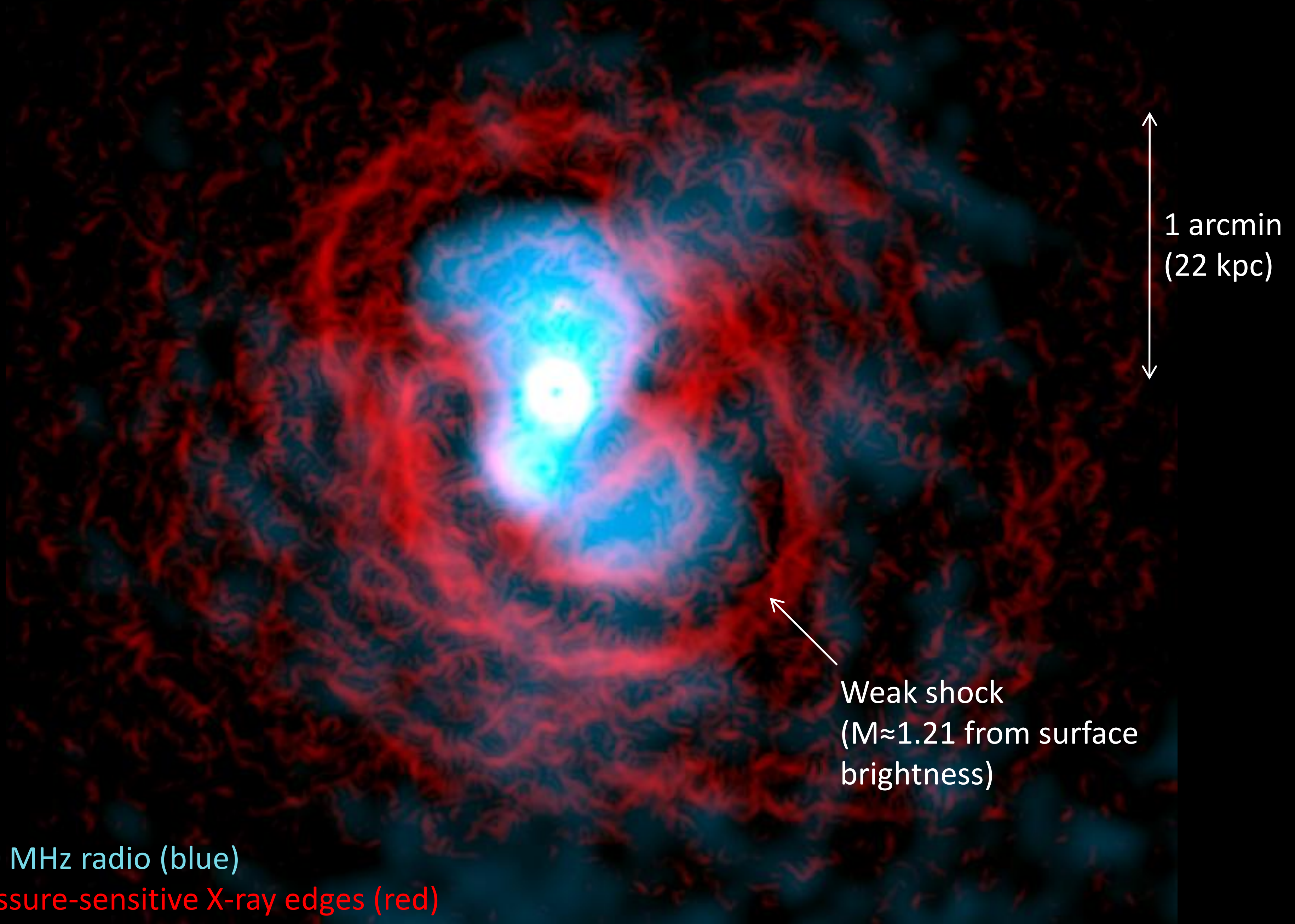


Perseus Cluster: applying gradient filter (Sanders+16)


Perseus Cluster: applying gradient filter (Sanders+16)
"Fountain"
Cold front
Shock
Cold front
Ripples: sound waves?
"Ghost" cavities
(however associated
with low frequency
radio)
Inner cavities
"Bay": KH instability or cavity?
1 arcmin
22 kpc

Weak shocks in Perseus

Fabian+06, Graham+08, Sanders+16



330 MHz radio (blue)

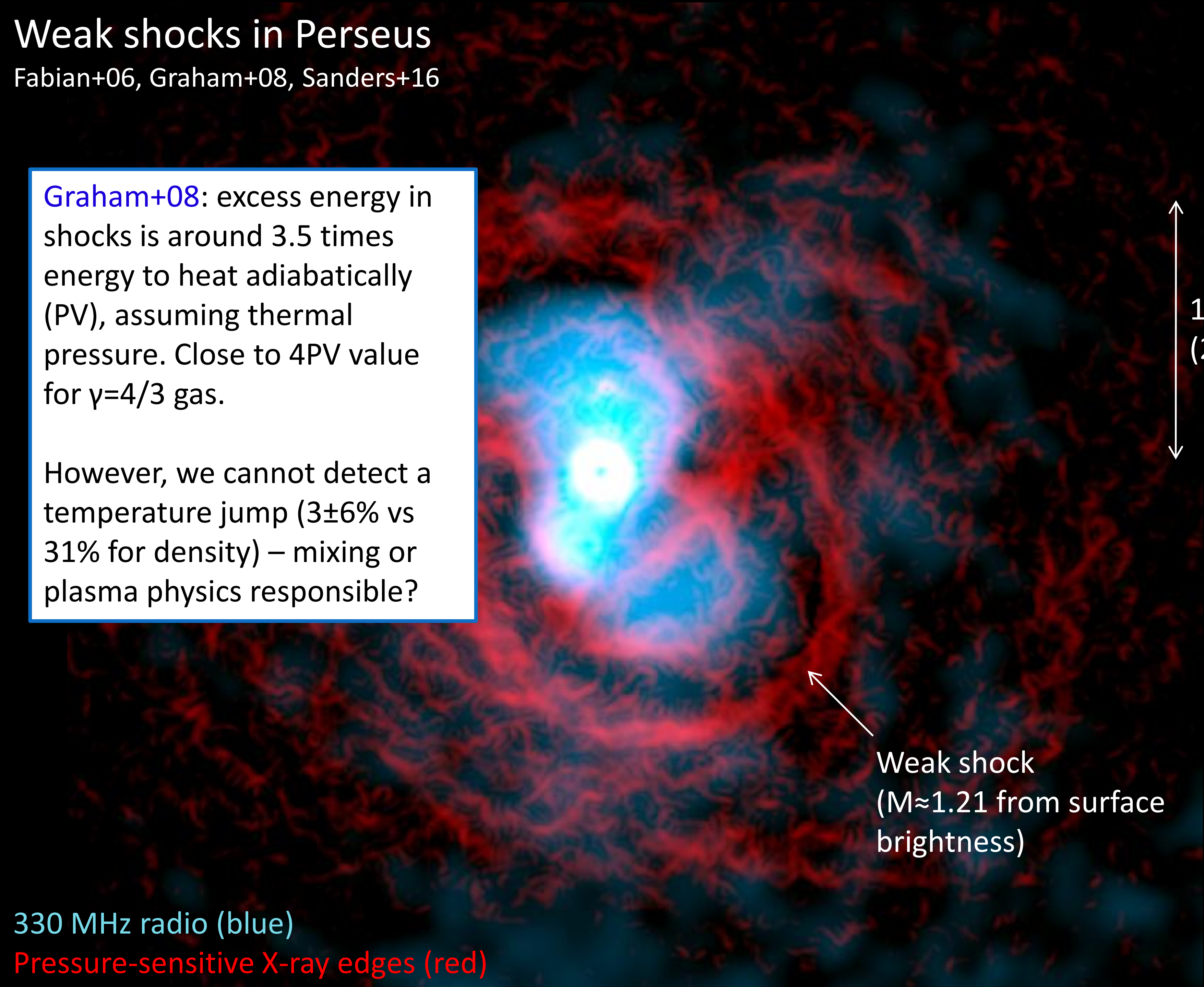
Pressure-sensitive X-ray edges (red)

Weak shocks in Perseus

Fabian+06, Graham+08, Sanders+16

Graham+08: excess energy in shocks is around 3.5 times energy to heat adiabatically (PV), assuming thermal pressure. Close to 4PV value for γ=4/3 gas.

However, we cannot detect a temperature jump (3±6% vs 31% for density) – mixing or plasma physics responsible?



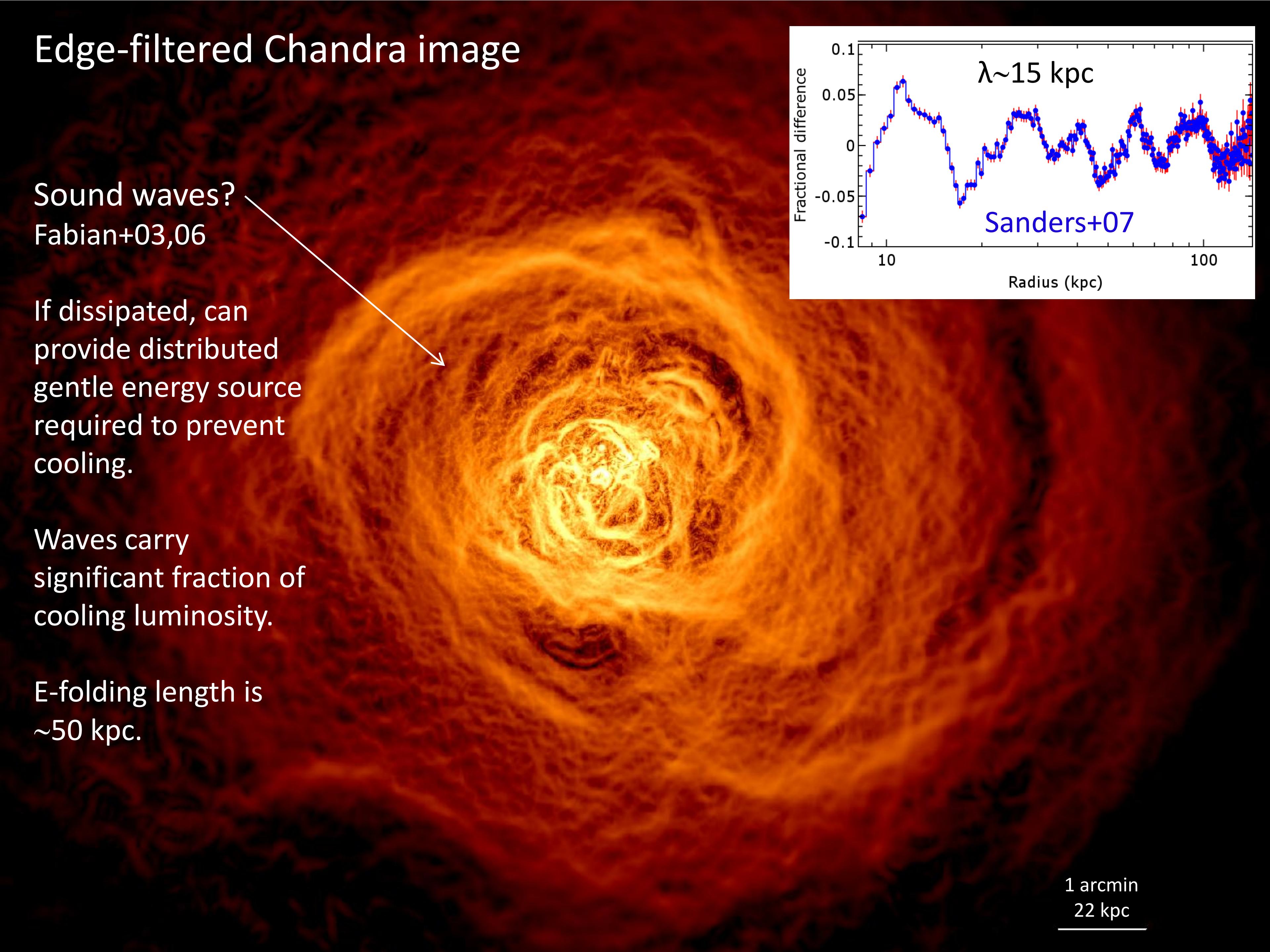
330 MHz radio (blue)

Pressure-sensitive X-ray edges (red)

Centaurus cluster (Abell 3526)

Chandra image of nuclear region (Sanders+16b)

Edge-filtered Chandra image



Sound waves?
Fabian+03,06

If dissipated, can provide distributed gentle energy source required to prevent cooling.

Waves carry significant fraction of cooling luminosity.

E-folding length is ~50 kpc.

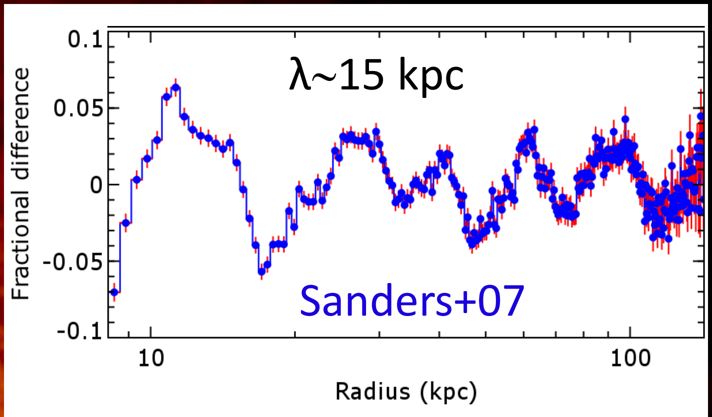
Edge-filtered Chandra image

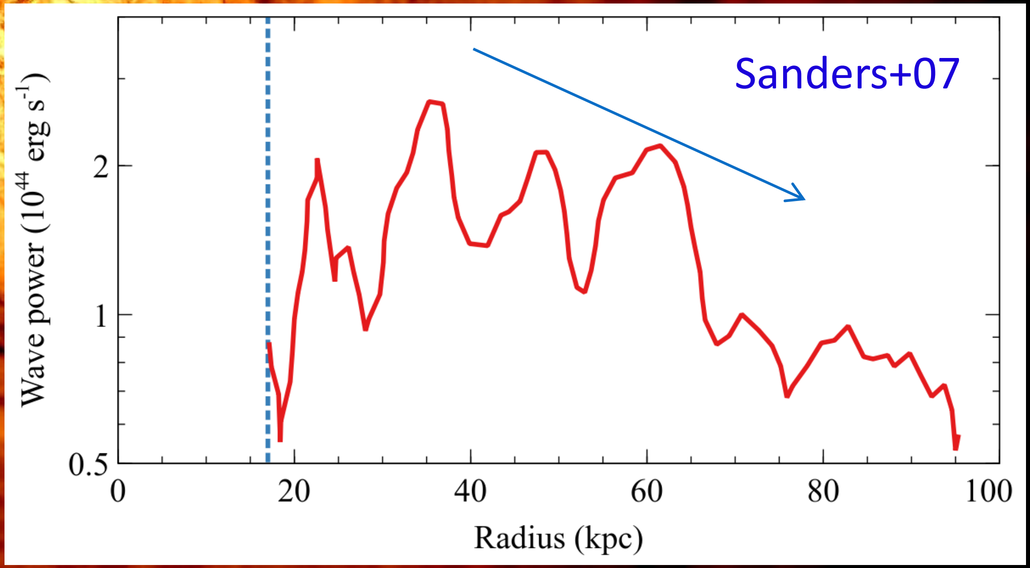
Sound waves?
Fabian+03,06

If dissipated, can provide distributed gentle energy source required to prevent cooling.

Waves carry significant fraction of cooling luminosity.

E-folding length is ~50 kpc.



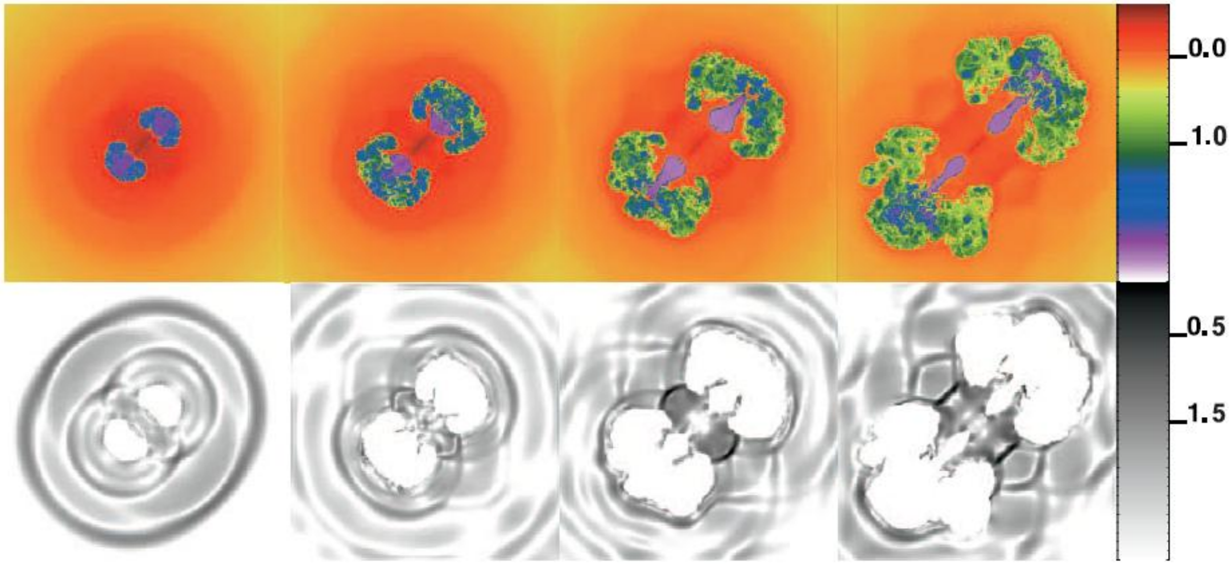


1 arcmin
22 kpc

Waves seen in simulations with viscosity

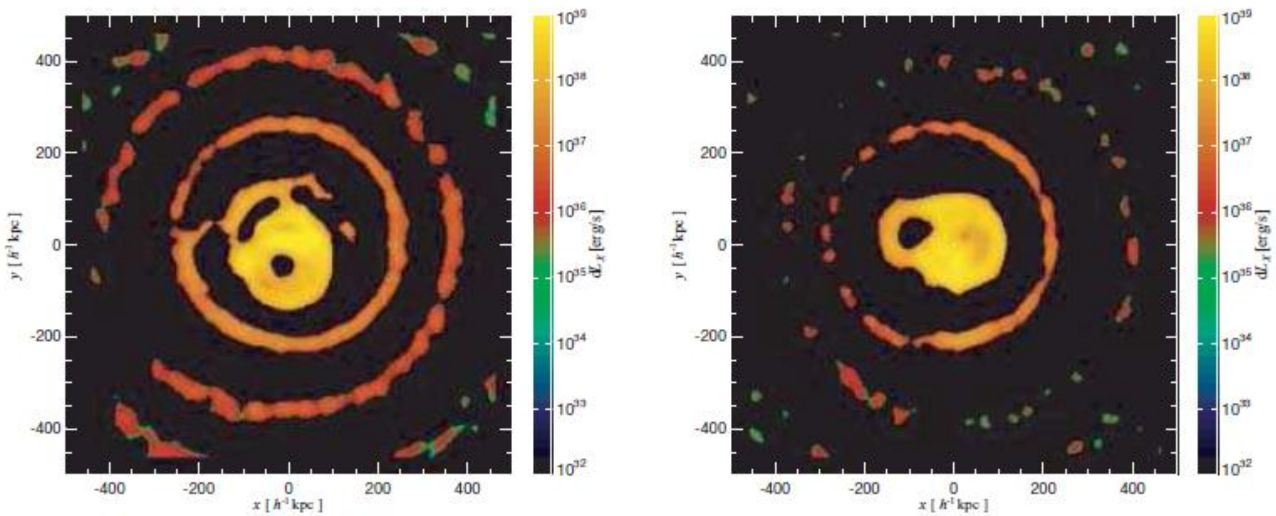
Density

Dissipation



time

Ruszkowski+04

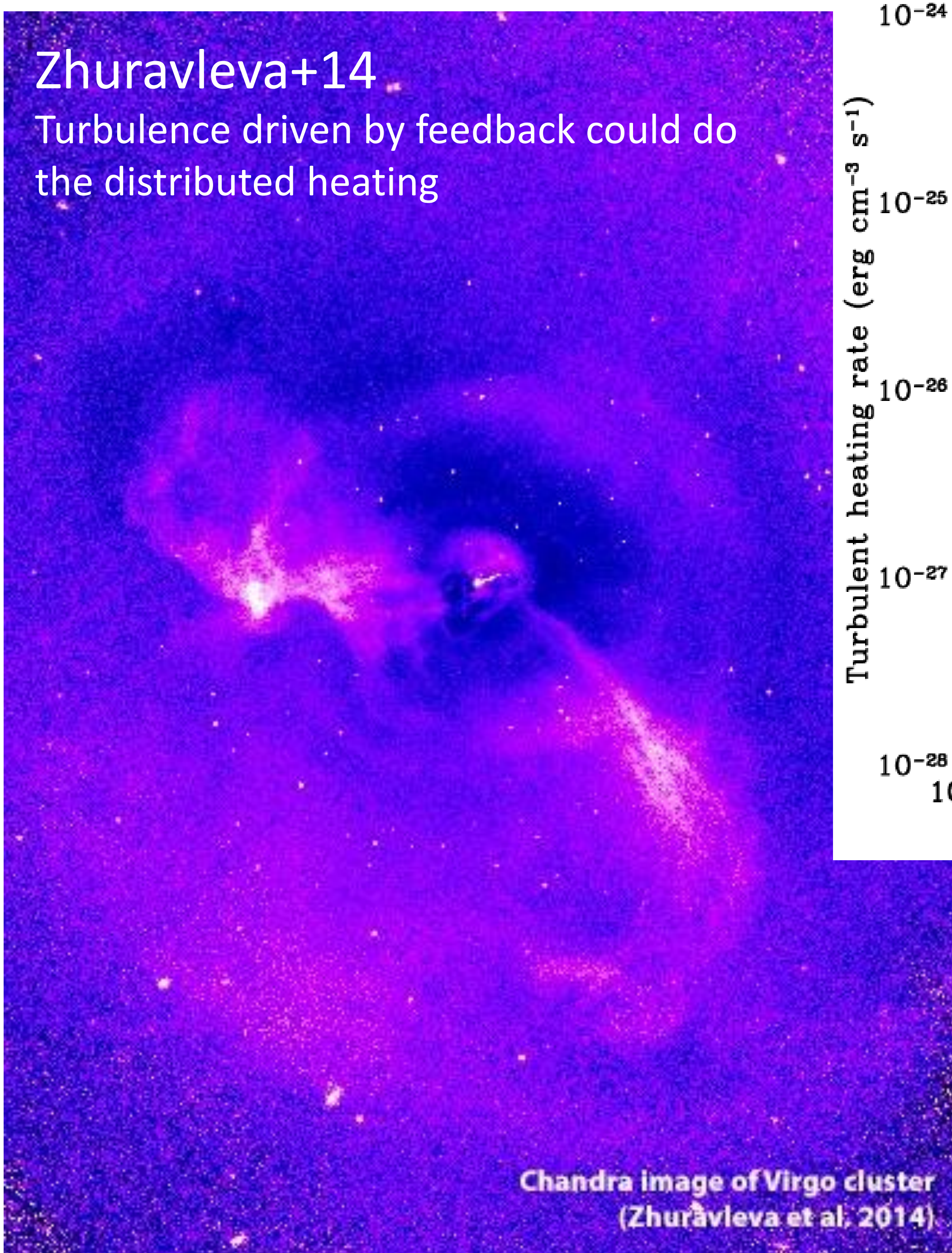


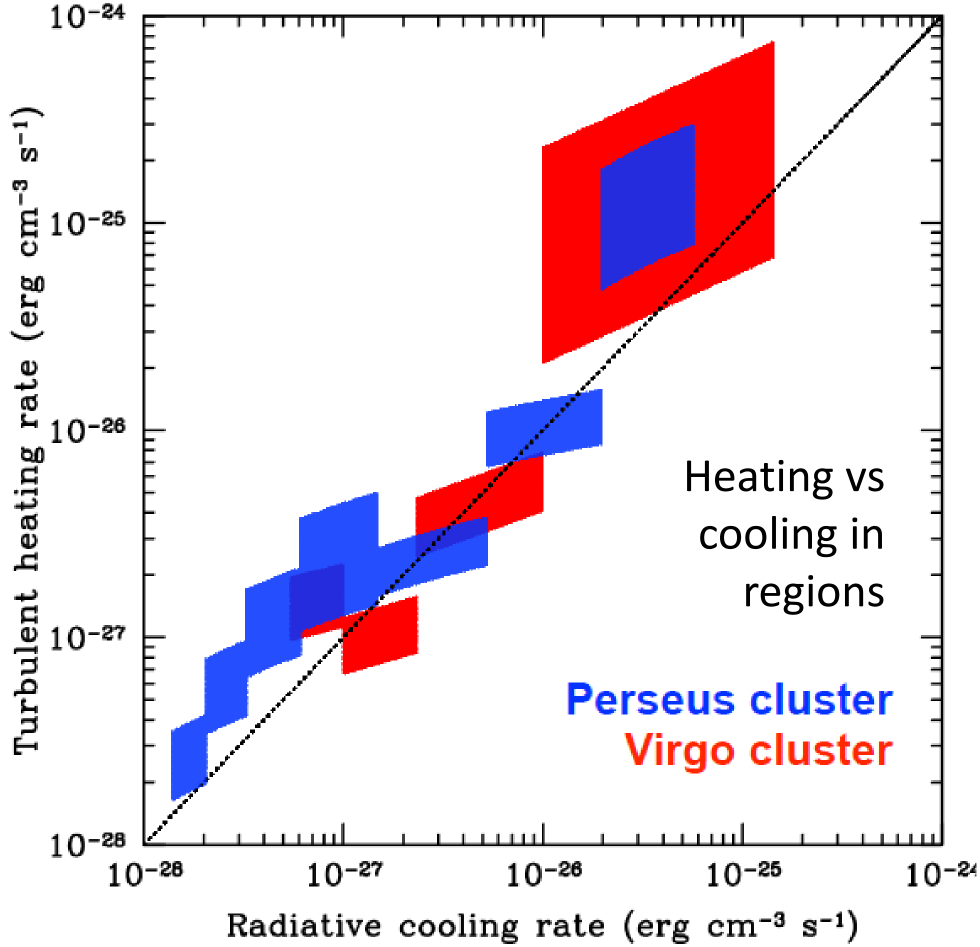
Sijacki+08

Unsharp-masked X-ray filtered images for two different viscosities

Zhuravleva+14

Turbulence driven by feedback could do the distributed heating



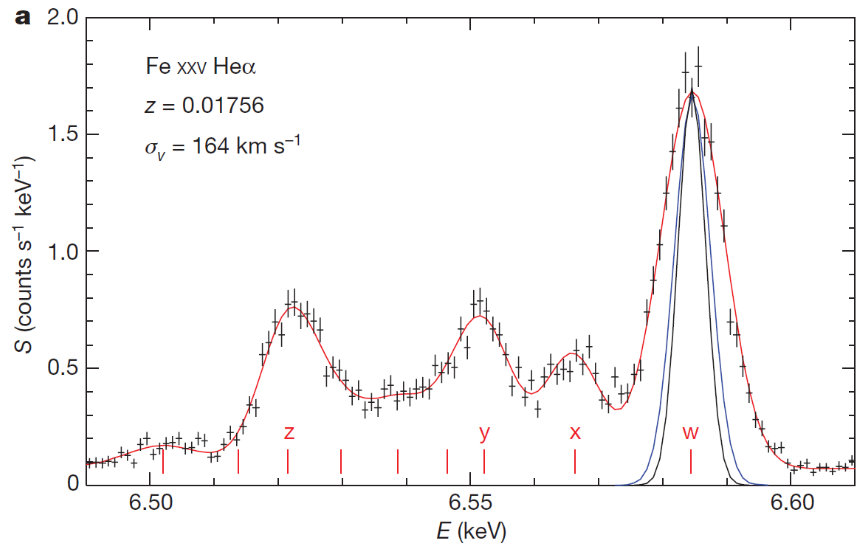


Surface brightness fluctuations, sensitive to density, are used to infer the turbulent velocity, based on simulations

Can turbulence combat cooling in Perseus?

- **Fabian+16:**
  - Energy in turbulence accounts for only 80 Myr worth of core X-ray emission
  - *g*-modes (which drive turbulence) only able to travel at ≤70 km s^{-1}, and could only travel 13 kpc in that time
  - Sound waves are able to travel much further, covering cooling region at 1000 km s^{-1}
  - Velocity amplitude of sound waves consistent with Hitomi

Hitomi collaboration (2016)



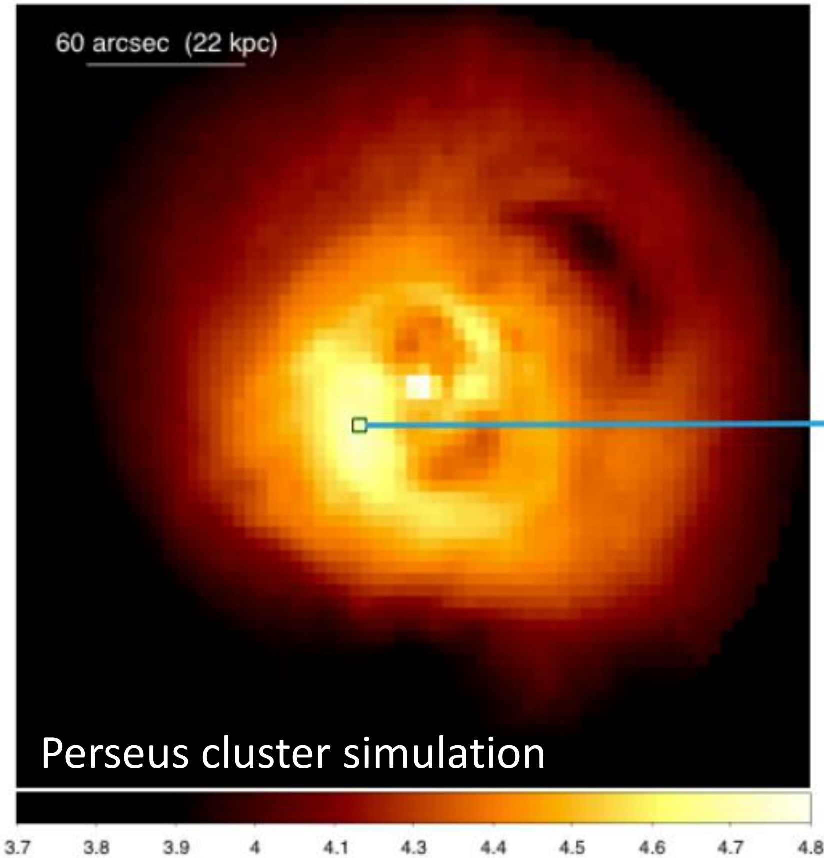
Line of sight velocity dispersion: 164 ± 10 km s^{-1}

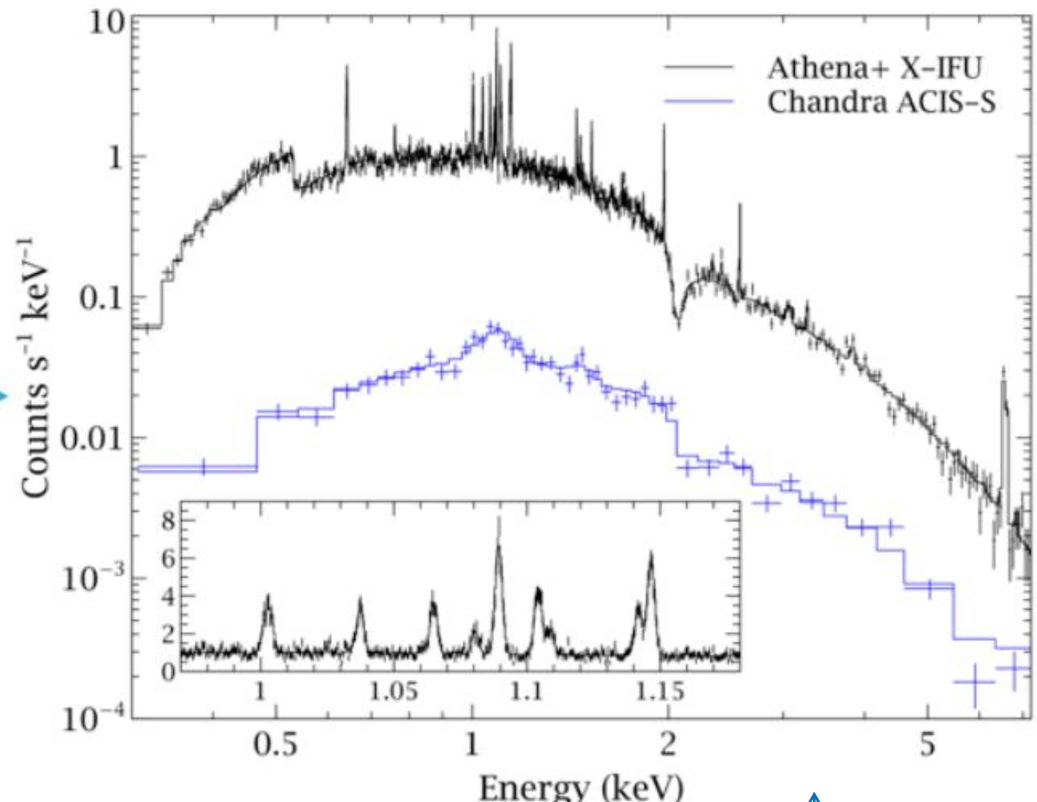
Future X-ARM and Athena observations will be vital.

Deep Chandra observations could measure temperature variations of sound waves

The Future: *Athena* (early 2030s)

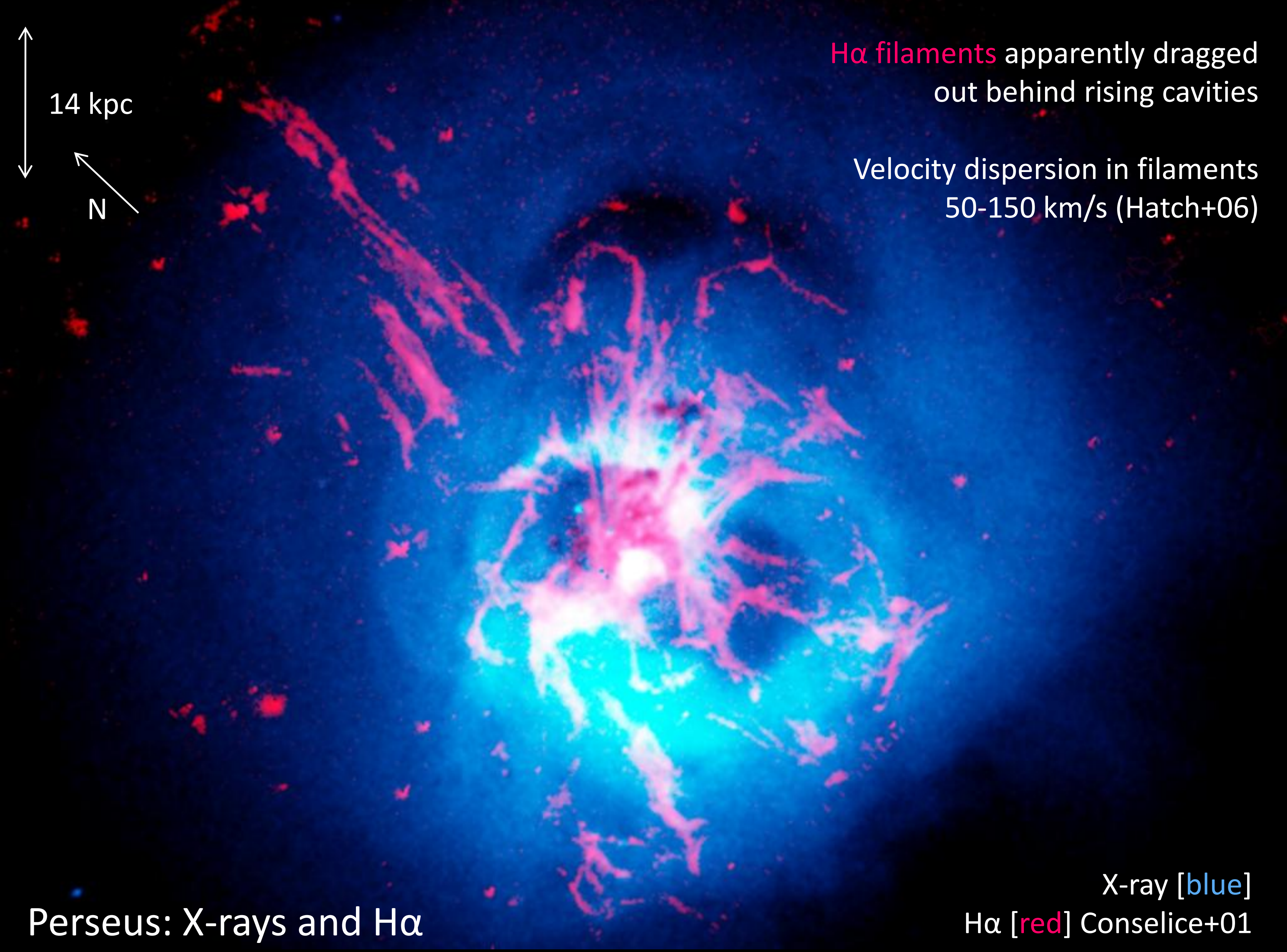
See Croston, Sanders, et al., 2013, *Athena+* supporting paper
70 ks simulated observation with X-IFU

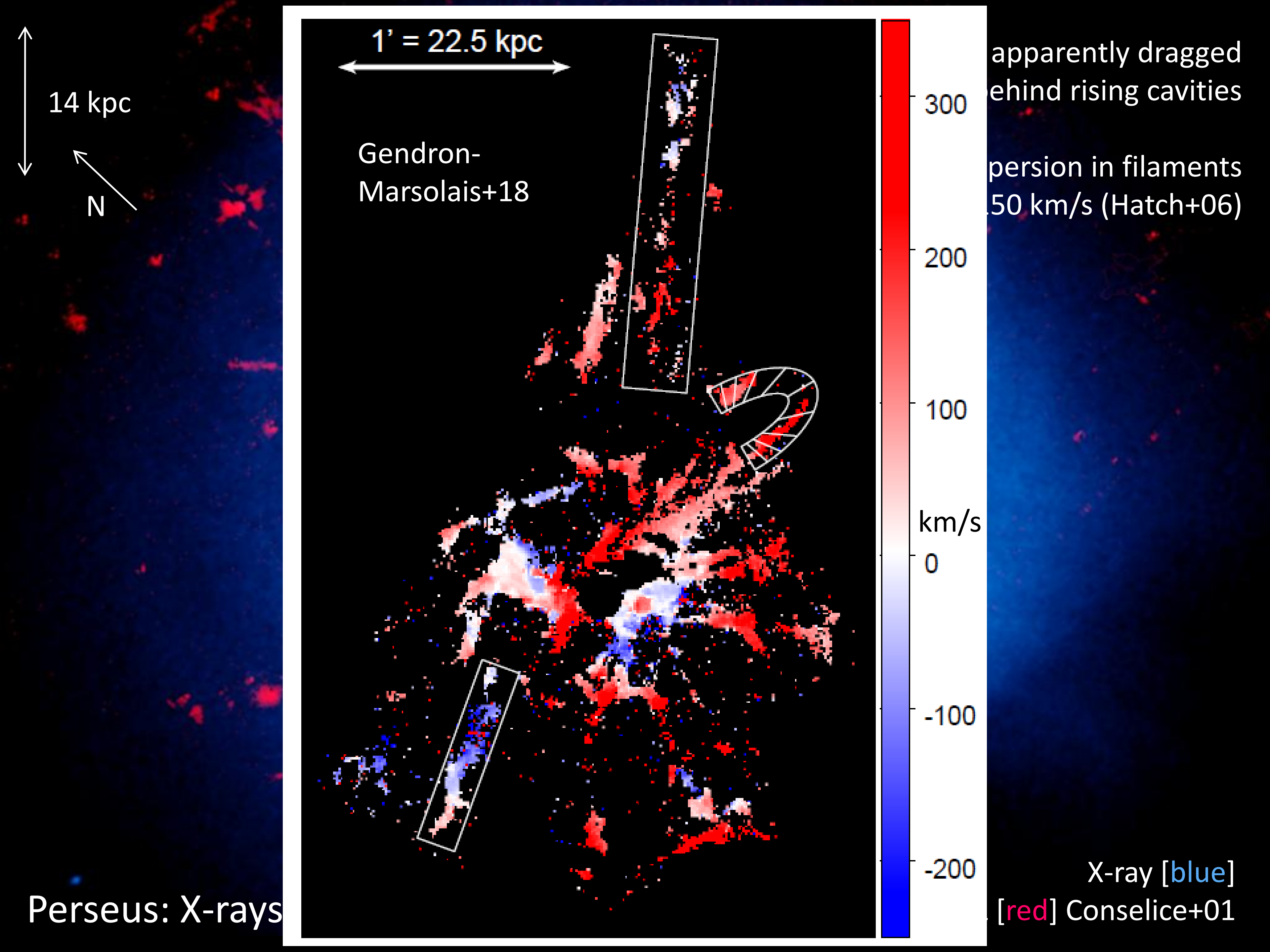




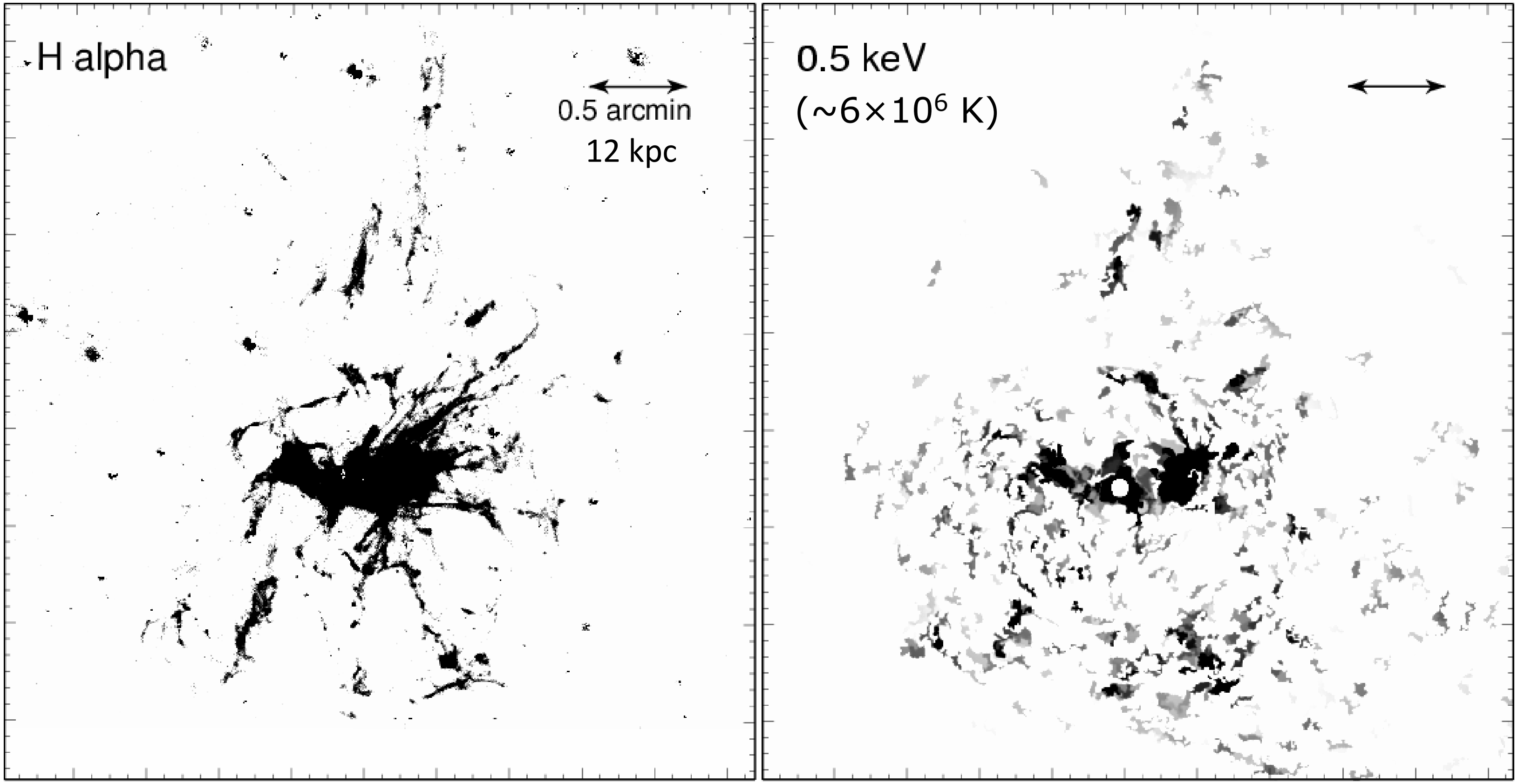
Velocities measured to 10s km s^{-1} in each 5 arcsec bin

Concept:
5 arcsec spatial resolution, 1.4 m^2 collecting area @ 1 keV
X-IFU (2.5eV spectral resolution, 5 arcmin FoV)
WFI (standard spectral resolution, 40 arcmin FoV)


14 kpc
N
Hα filaments apparently dragged out behind rising cavities
Velocity dispersion in filaments 50-150 km/s (Hatch+06)
Perseus: X-rays and Hα
X-ray [blue]
Hα [red] Conselice+01

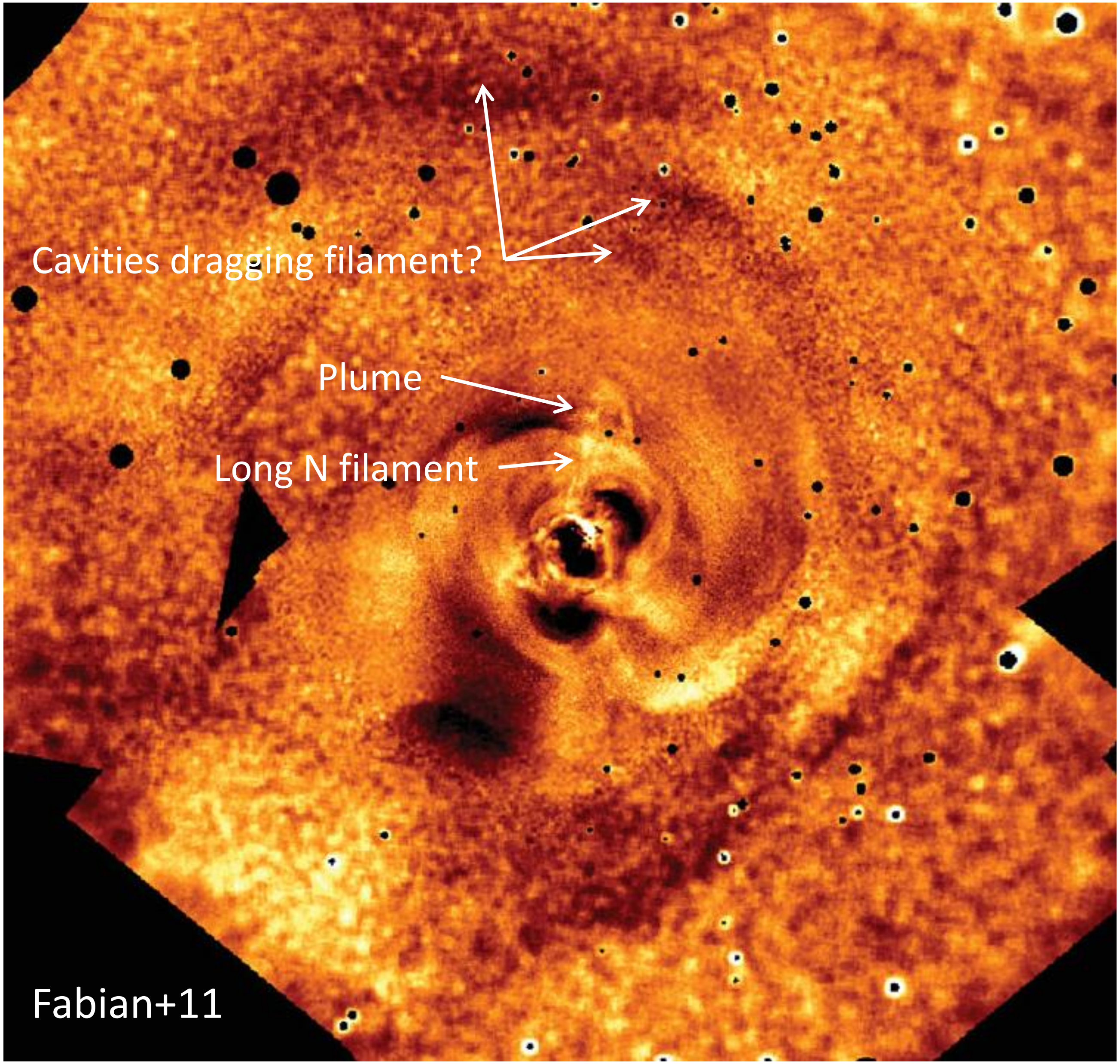

14 kpc
N
1' = 22.5 kpc
Gendron-
Marsolais+18
300
200
100
km/s
0
-100
-200
apparently dragged
ehind rising cavities
persion in filaments
.50 km/s (Hatch+06)
X-ray [blue]
[red] Conselice+01
Perseus: X-rays

Multiphase filament structure



10^9 $M_\odot$ of X-ray gas associated with the filaments
However, the molecular gas mass dominates (up to 10^{11} $M_\odot$; Salomé+08)

Further depressions to the north



Ratio to X-ray surface brightness model.

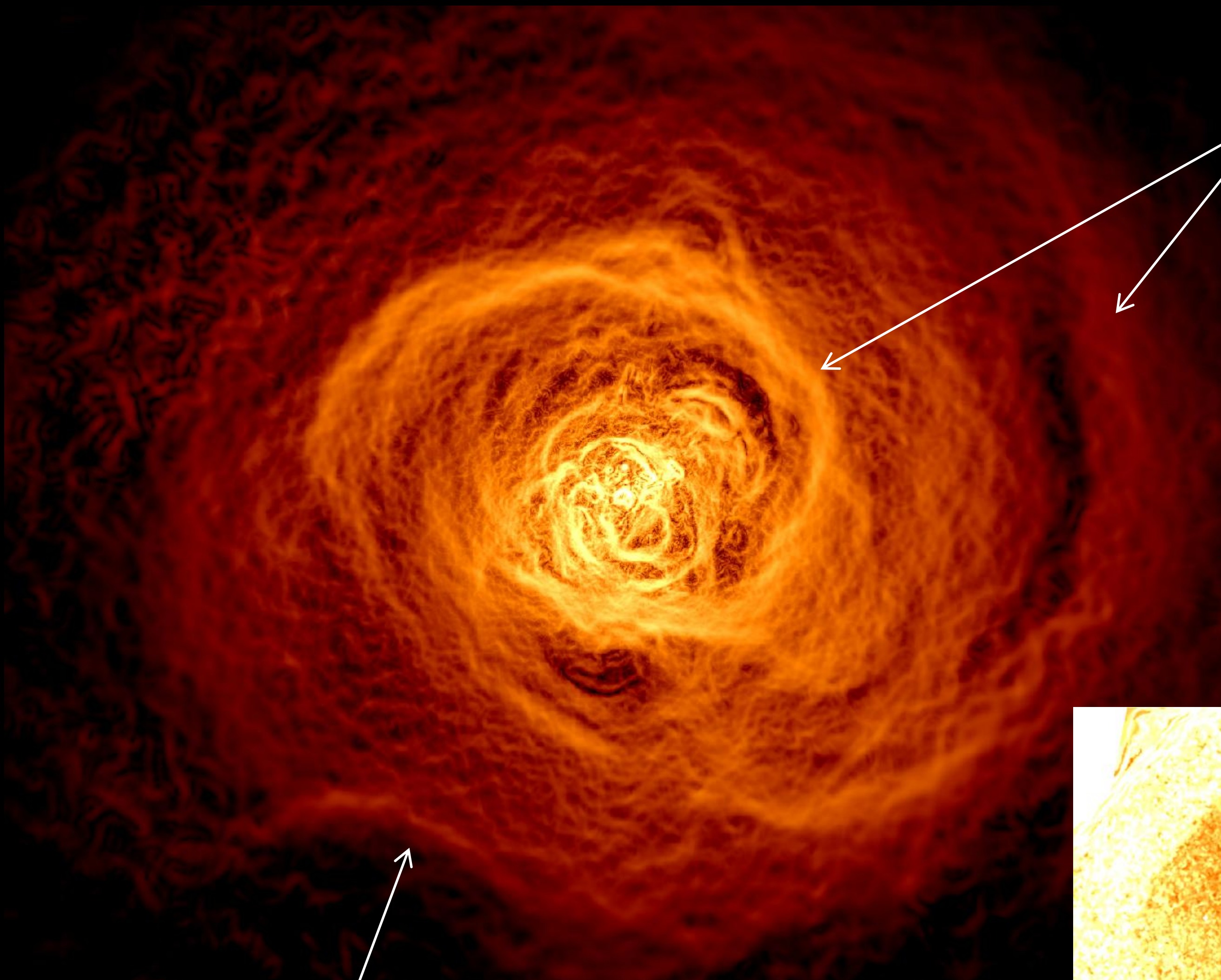
Depressions to the north at 220 kpc radius.

Minihalo extends along direction (Sijbring+93)

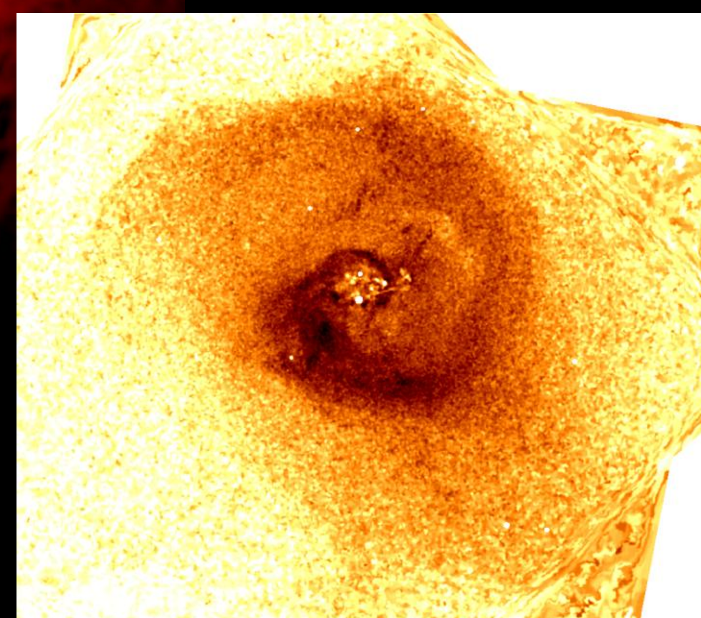
If cavities, suggests that they can survive for very long time periods.

Outburst energies ~10 times larger than inner cavities.

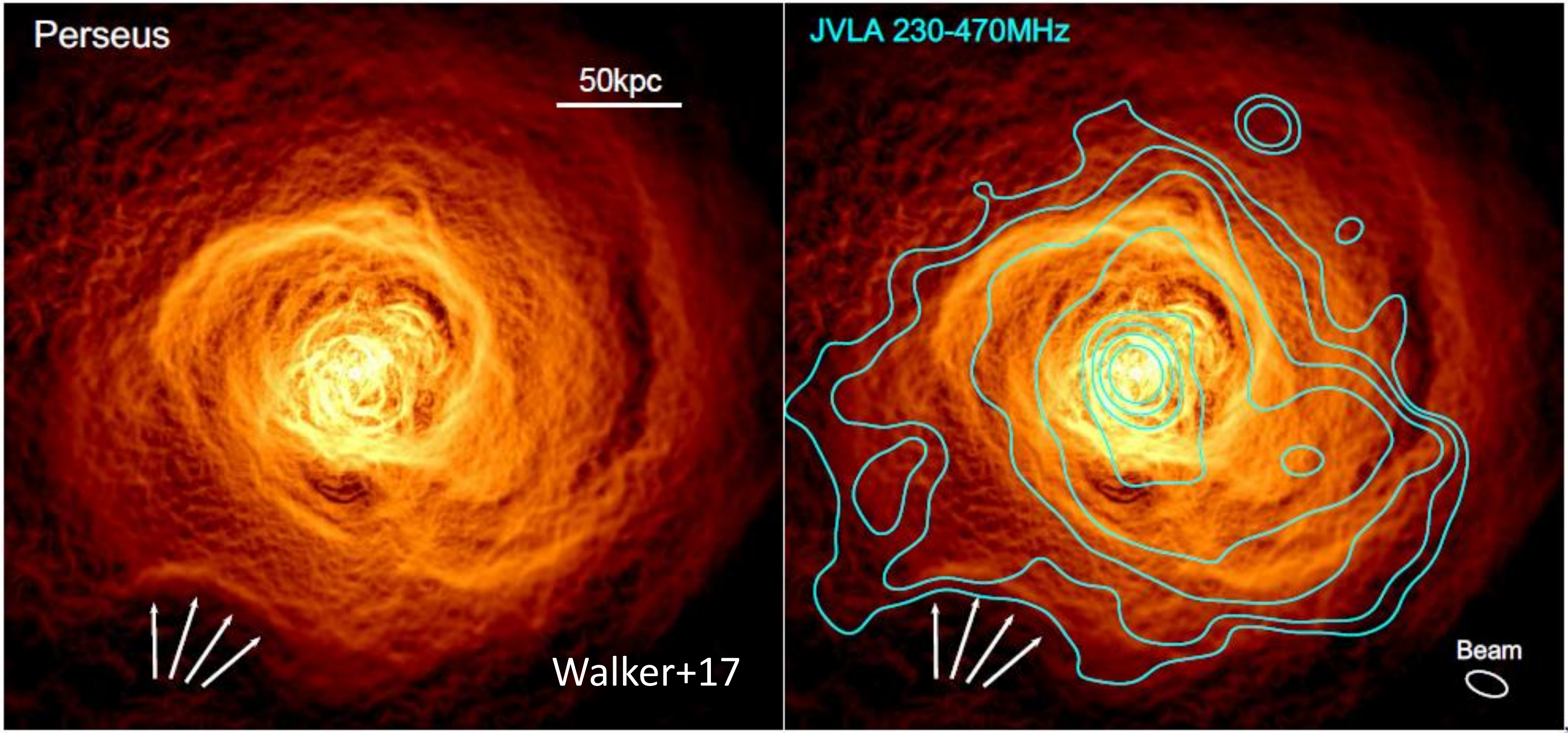
Accumulation of several cavities? Instabilities?



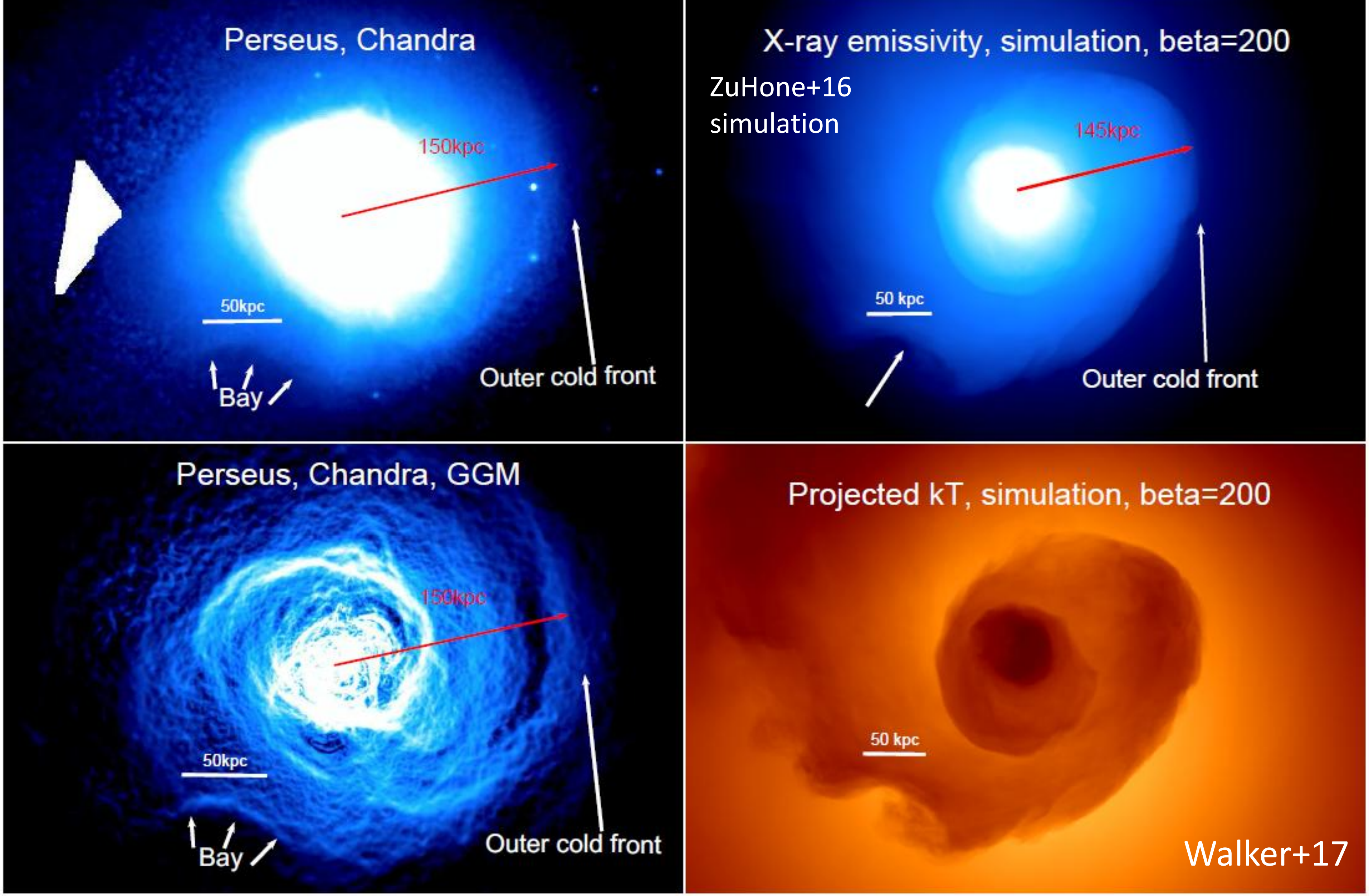
Chandra temperature map



Possible Kelvin-Helmholtz instability?

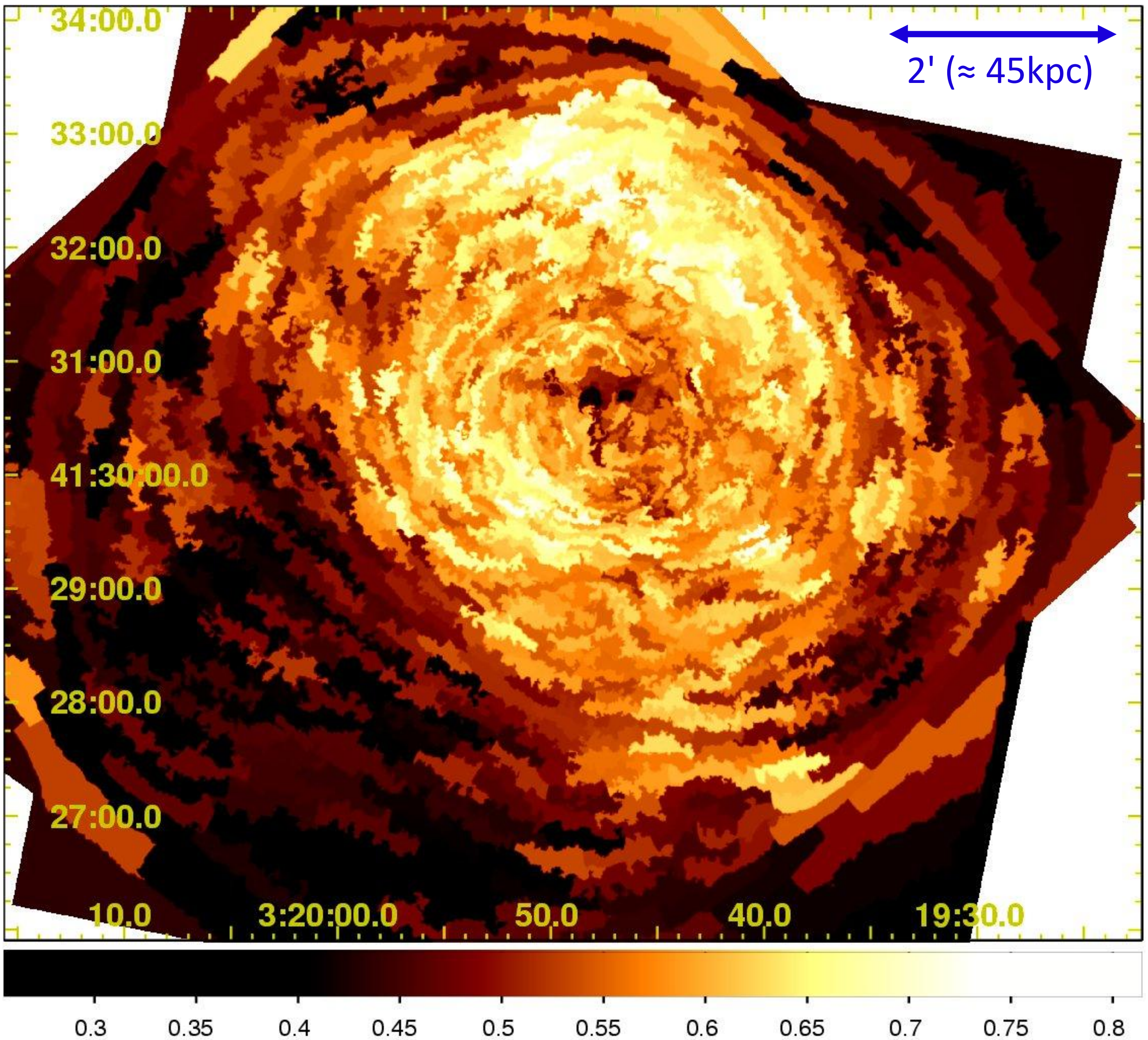


- Negatively curved edge to the south, near the outer cold front edge, named “the bay”
- Low frequency radio avoids feature (Gendron-Marsolais+17), suggesting it’s not a cavity



Structures too strong in simulations if initial β=1000, but missing if β=100, potentially constraining magnetic field pressure

Perseus metallicity map



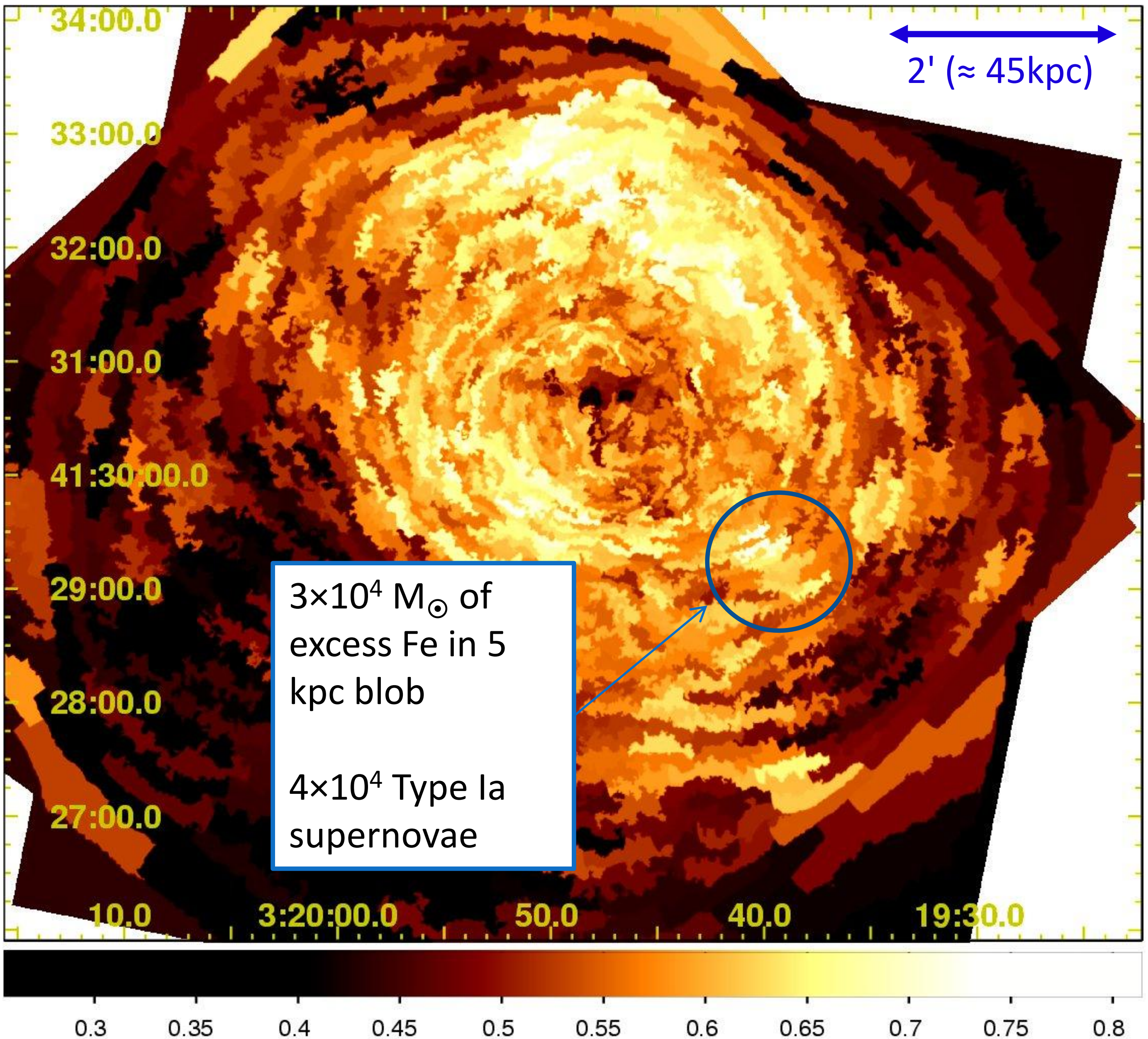
Sanders+07

High metallicity regions are able to survive in the intracluster medium (see also Rebusco+05)

Likely rising cavities can drag these out (see e.g. Kirkpatrick+15)

Intrinsically these should be stronger due to projection

Perseus metallicity map



Sanders+07

High metallicity regions are able to survive in the intracluster medium (see also Rebusco+05)

Likely rising cavities can drag these out (see e.g. Kirkpatrick+15)

Intrinsically these should be stronger due to projection

Conclusions

- Deep X-ray observations of the X-ray brightest cluster give us a wealth of information about cluster physics
- Several different processes could be important for AGN feedback (bubbles, shocks, sound waves, turbulence…)
- Studying images and spectra in detail can tell us about the microphysics of the intracluster medium