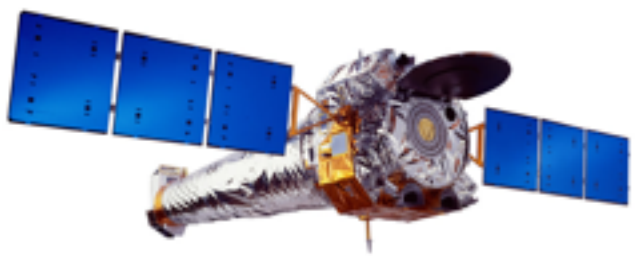
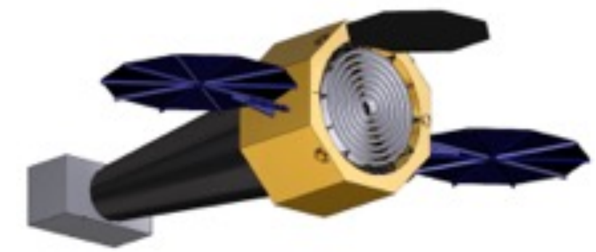
Measuring effective equation of state of diffuse gas in galaxy clusters





from Chandra to X-ray Surveyor

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X-ray Vision Workshop: Probing the Universe in Depth and Detail with the X-ray Surveyor
Oct 6-8, 2015 Washington DC

Big Questions

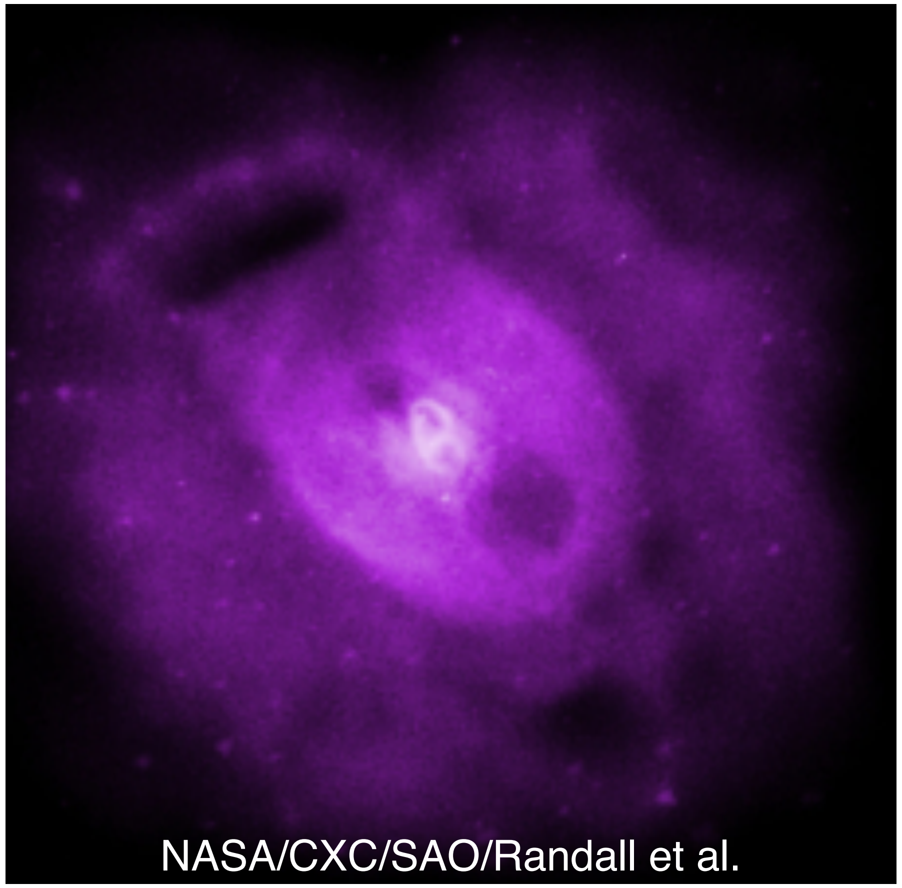
How is the energy from central AGN partitioned between different feedback channels (e.g. bubbles, shocks, turbulence etc.)?

How is the energy from AGN dissipated in the ICM?

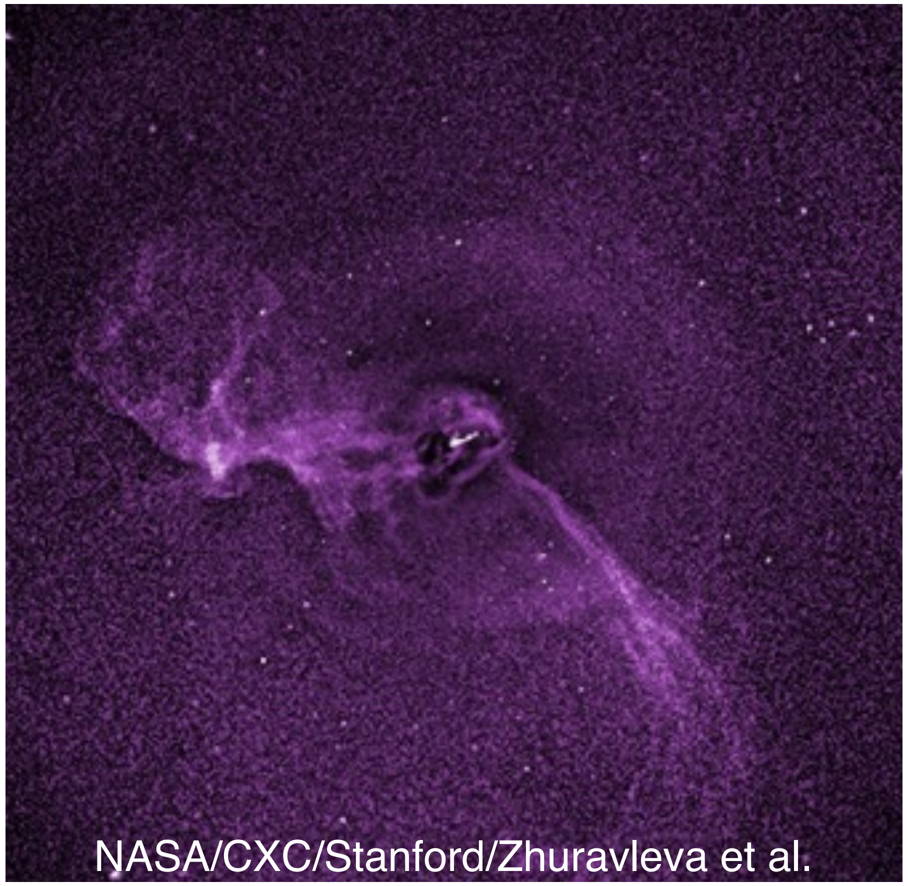
Radio-mode feedback can be best addressed in X-rays

AGN-driven perturbations: X-ray view

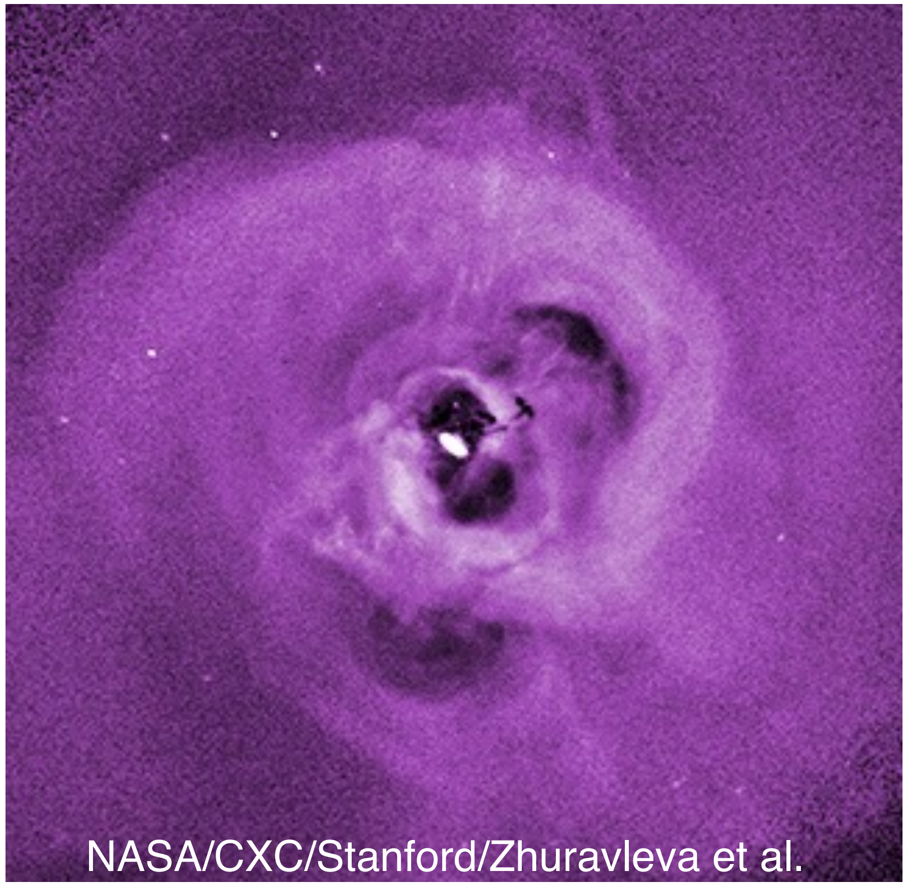
NGC5813



Virgo/M87

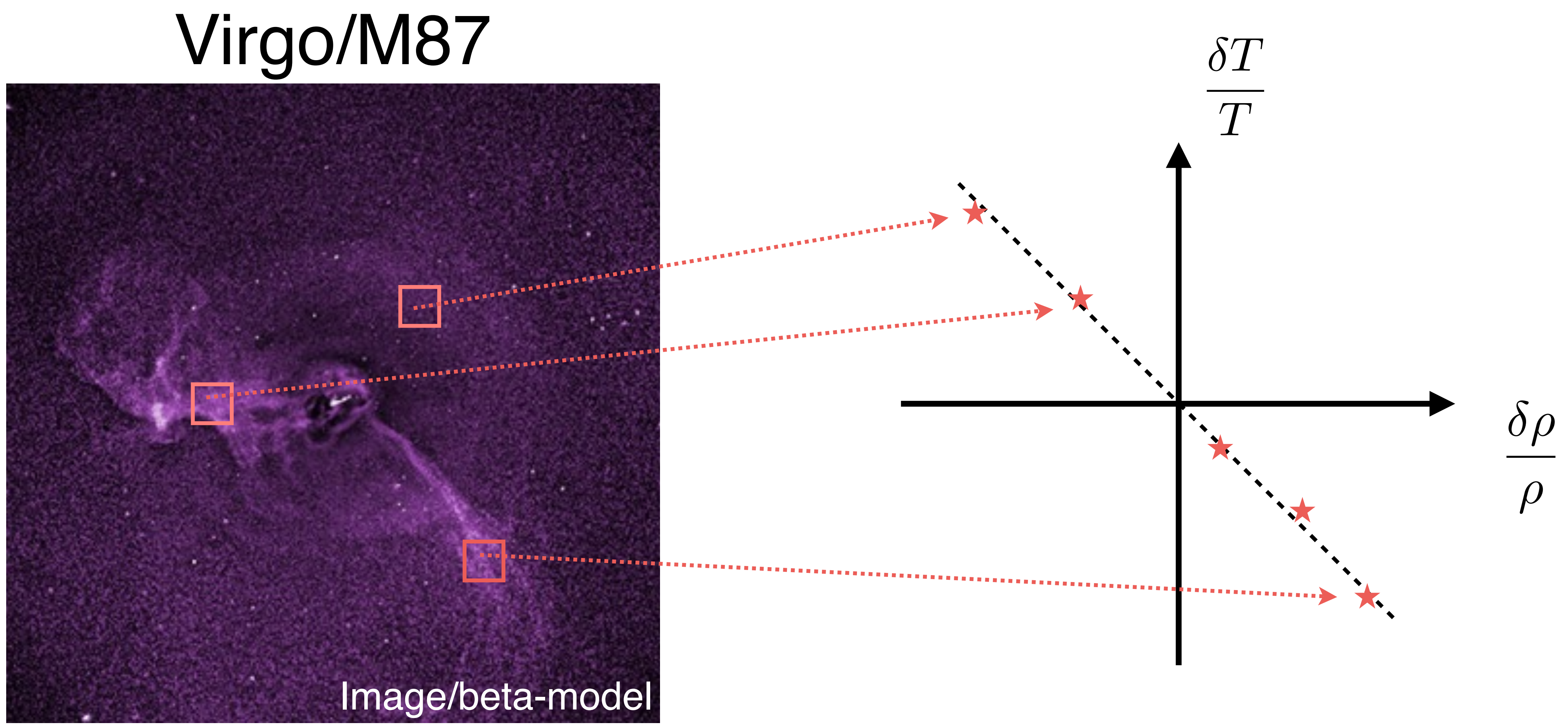


Perseus



What is the nature of AGN-driven perturbations?
What fraction of the AGN energy is in each type of perturbations?

Effective equation of state of perturbations



- Characterizes fluctuations relative to the mean value
- It does not reflect the true equation of state of the gas

Types of perturbations

isobaric

slow displacements of gas
gas in P equilibrium

$$\frac{\delta T}{T} = -1 \cdot \frac{\delta n}{n}$$

adiabatic

weak shocks, sound waves
do not change gas S

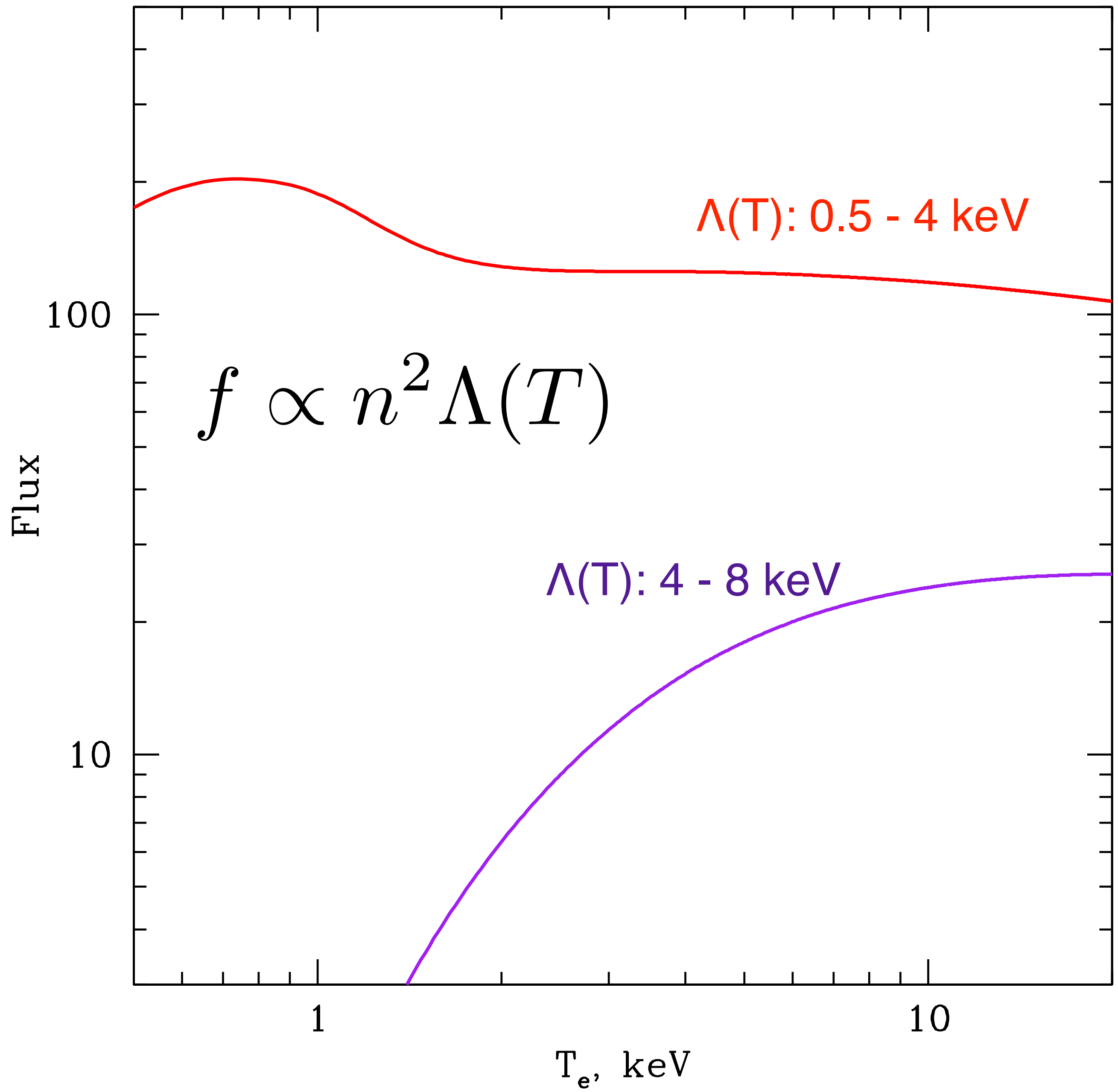
$$\frac{\delta T}{T} = \frac{2}{3} \cdot \frac{\delta n}{n}$$

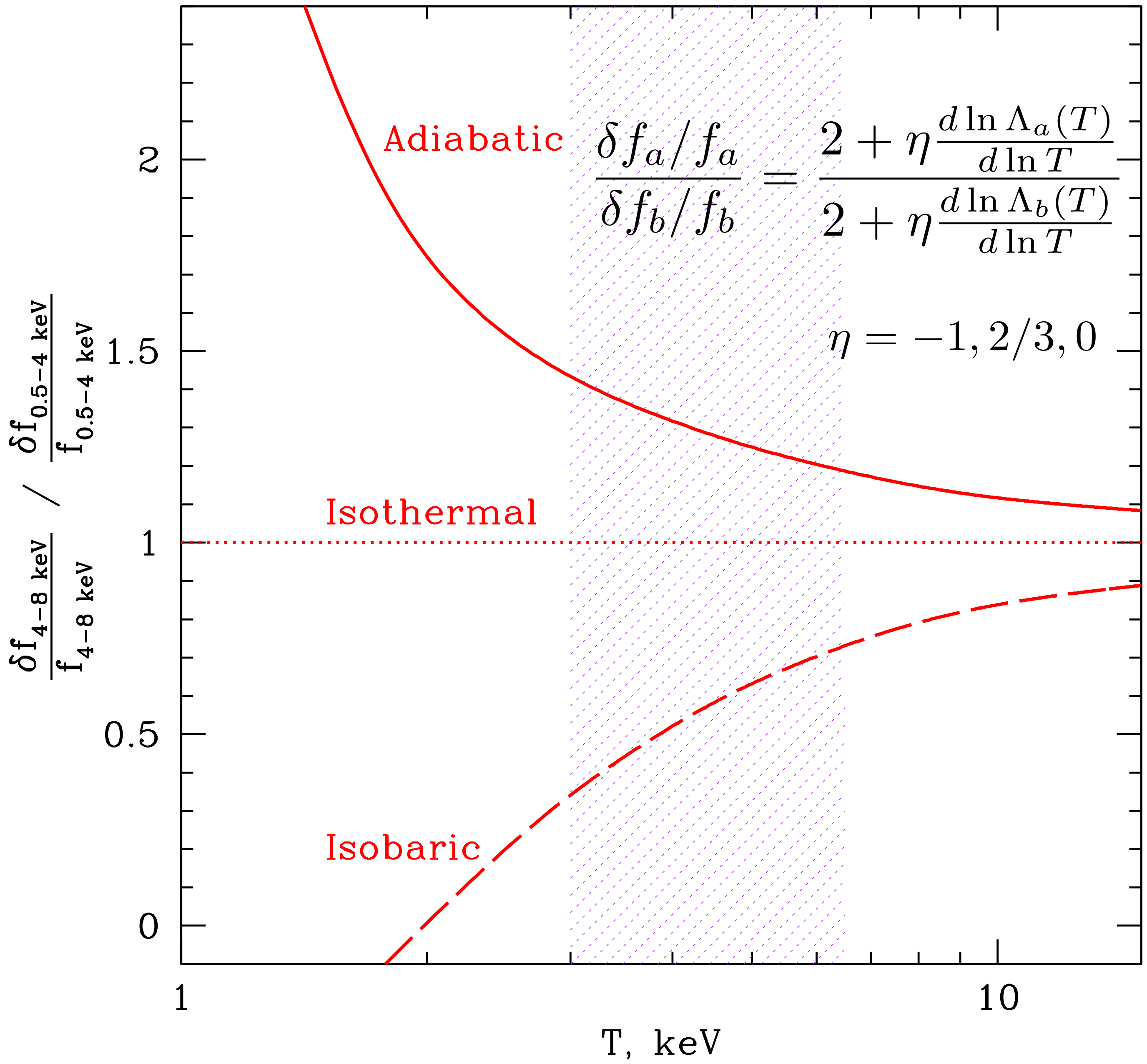
isothermal

bubbles of relativistic plasma
ρ variations at constant T

$$\frac{\delta T}{T} = 0 \cdot \frac{\delta n}{n}$$

X-ray response of perturbations

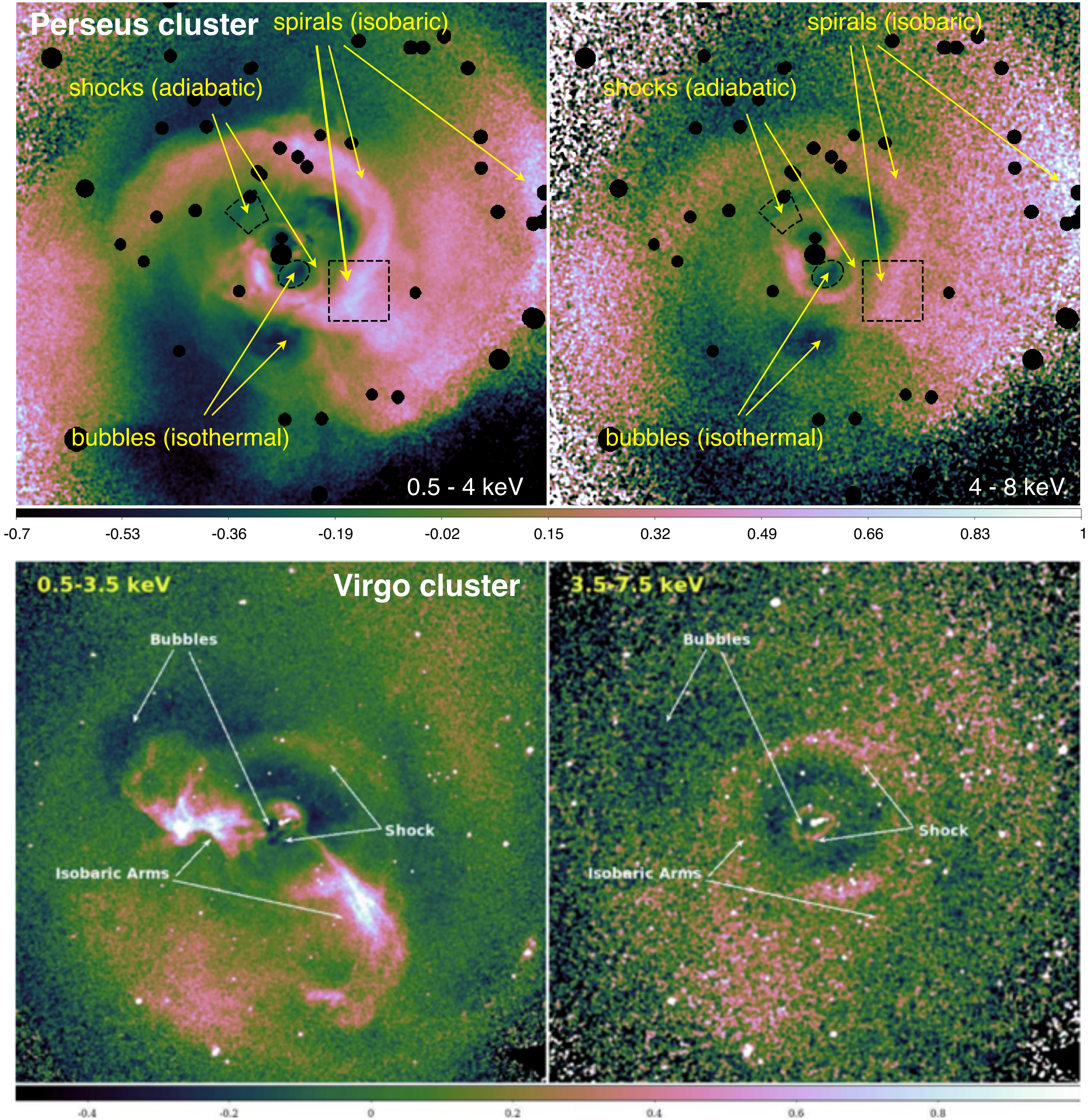




isobaric: $(\delta f/f)_{soft} > (\delta f/f)_{hard}$

adiabatic: $(\delta f/f)_{soft} < (\delta f/f)_{hard}$

isothermal: $(\delta f/f)_{soft} \cong (\delta f/f)_{hard}$



X-arithmetic, Churazov et al. in prep.

Cross-spectra analysis

Power spectra of emissivity fluctuations in different bands:

P_1, P_2

Cross-spectrum of fluctuations:

P_{12}

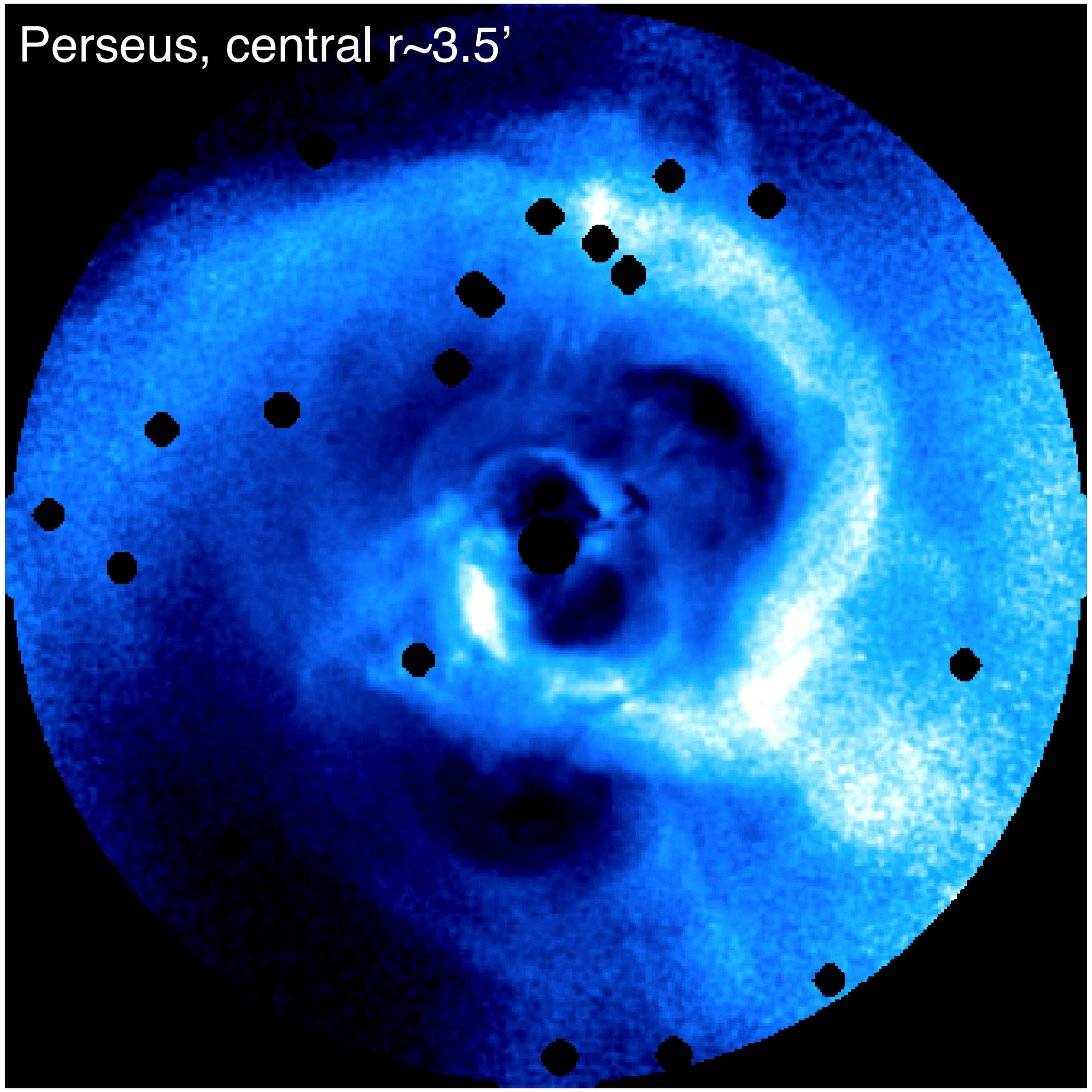
One process or multiple? —> Coherence

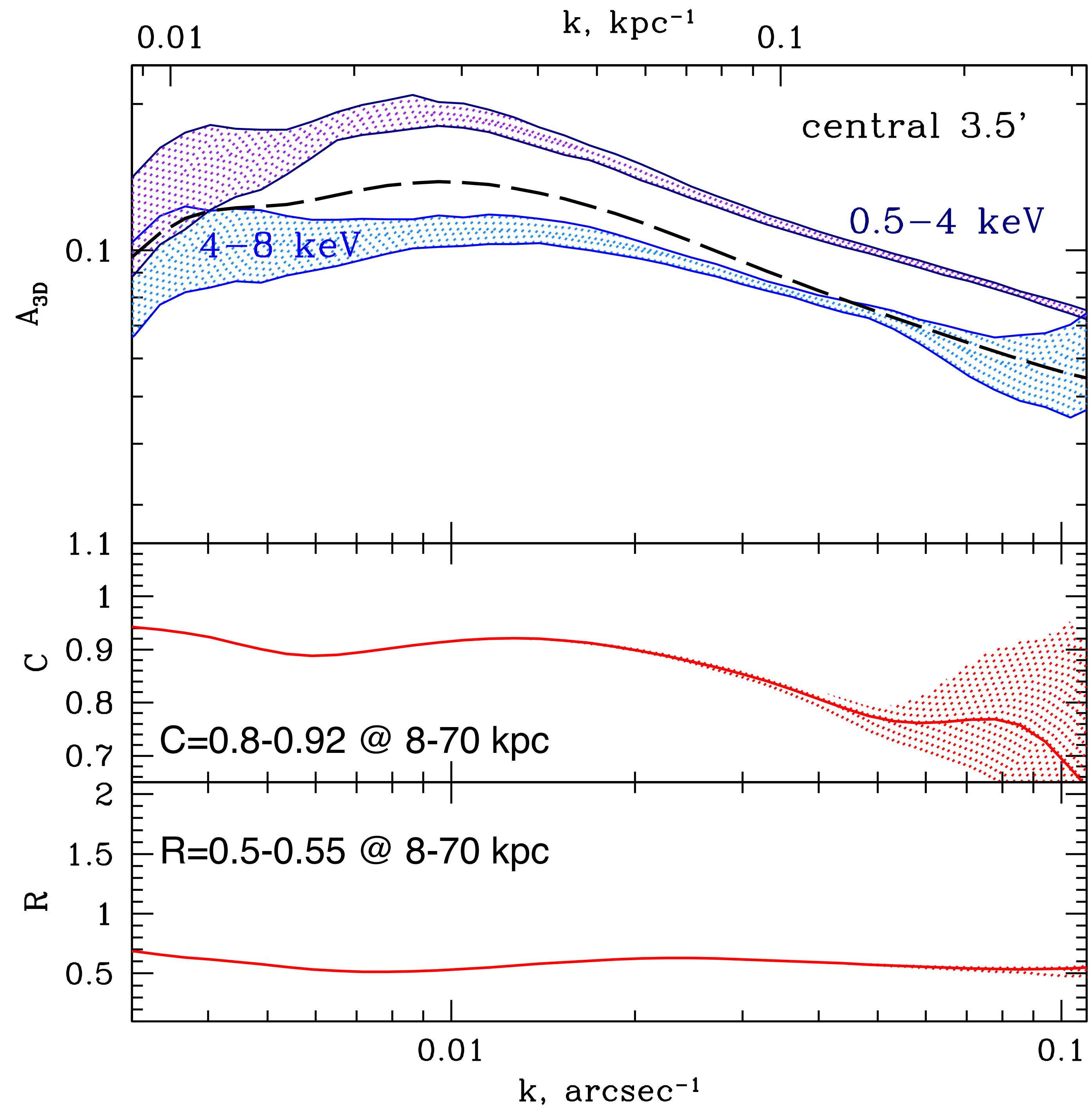
$$C = \frac{P_{12}}{\sqrt{P_1 P_2}}$$

Which process dominates? —> Ratio

$$R = \frac{P_{12}}{P_1}$$

Nature of perturbations in Perseus: inner r~3.5'



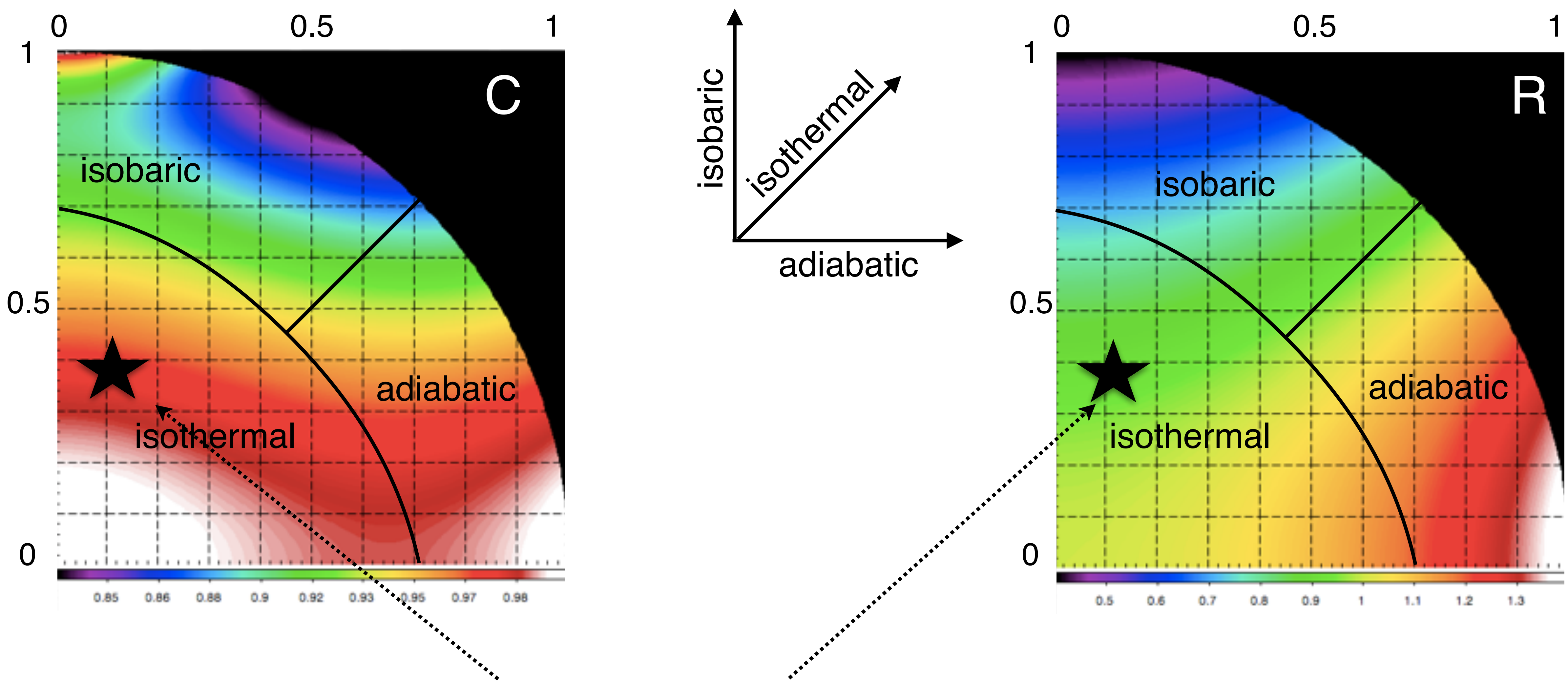


C and R for a mixture of processes

Any combination of three processes:

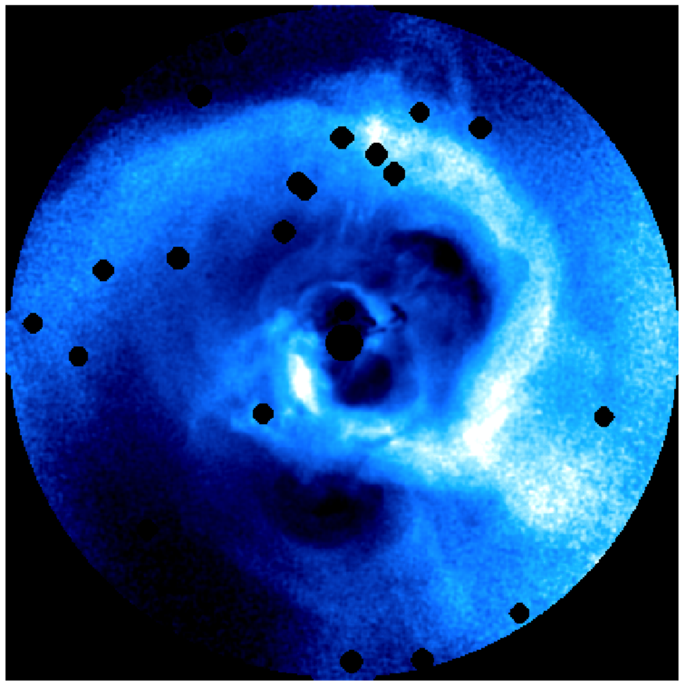
$$\alpha_1^2 X_{\text{adiab.}}^2 + \alpha_2^2 X_{\text{isob.}}^2 + \alpha_3^2 X_{\text{isoth.}}^2$$

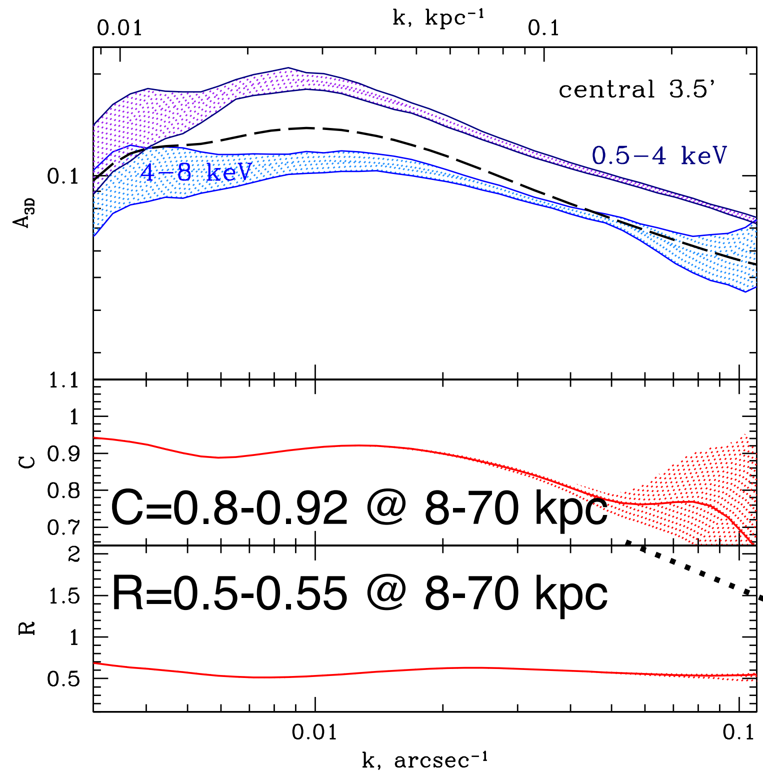
$$X = \frac{\delta f_a / f_a}{\delta f_b / f_b} \qquad \sqrt{\alpha_1^2 + \alpha_2^2 + \alpha_3^2} = 1$$



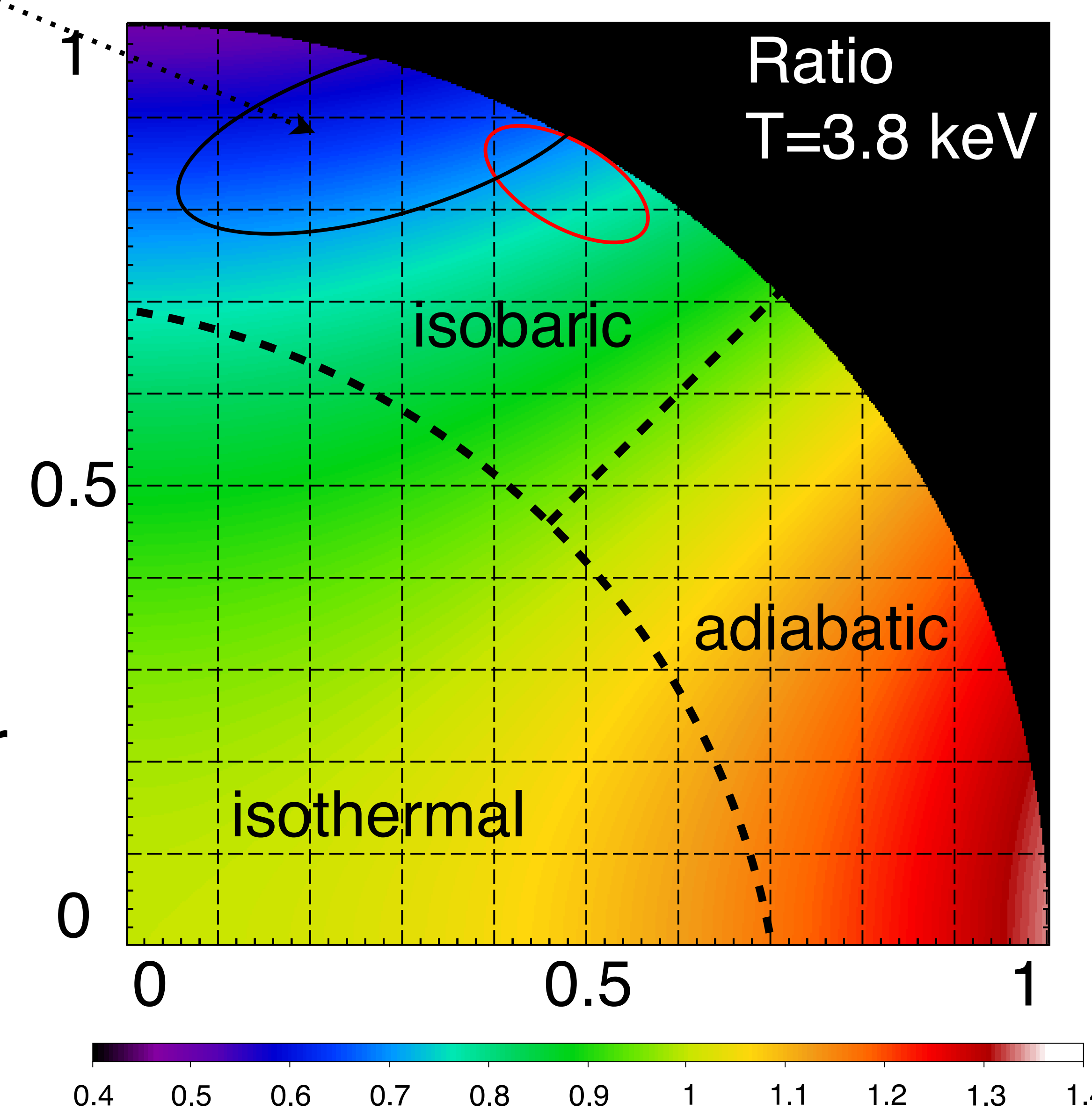
C~0.98, R~0.9 => isothermal

Nature of perturbations in Perseus: inner r~3.5’





inner 3.5’, scales 8-70 kpc:
~ 90% of the total variance
—> dominated by isobaric



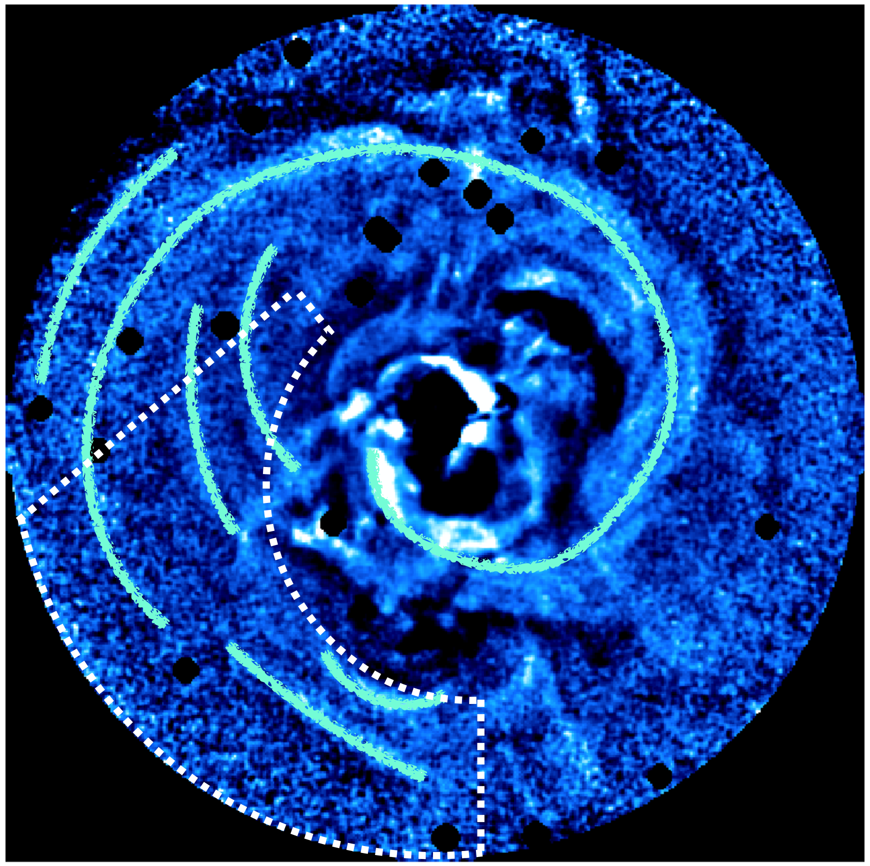
$E_{pert}=E_b+E_{sw}+E_{gw}$ $E_i/E_{therm} \sim (\delta\rho/\rho)_i^2$

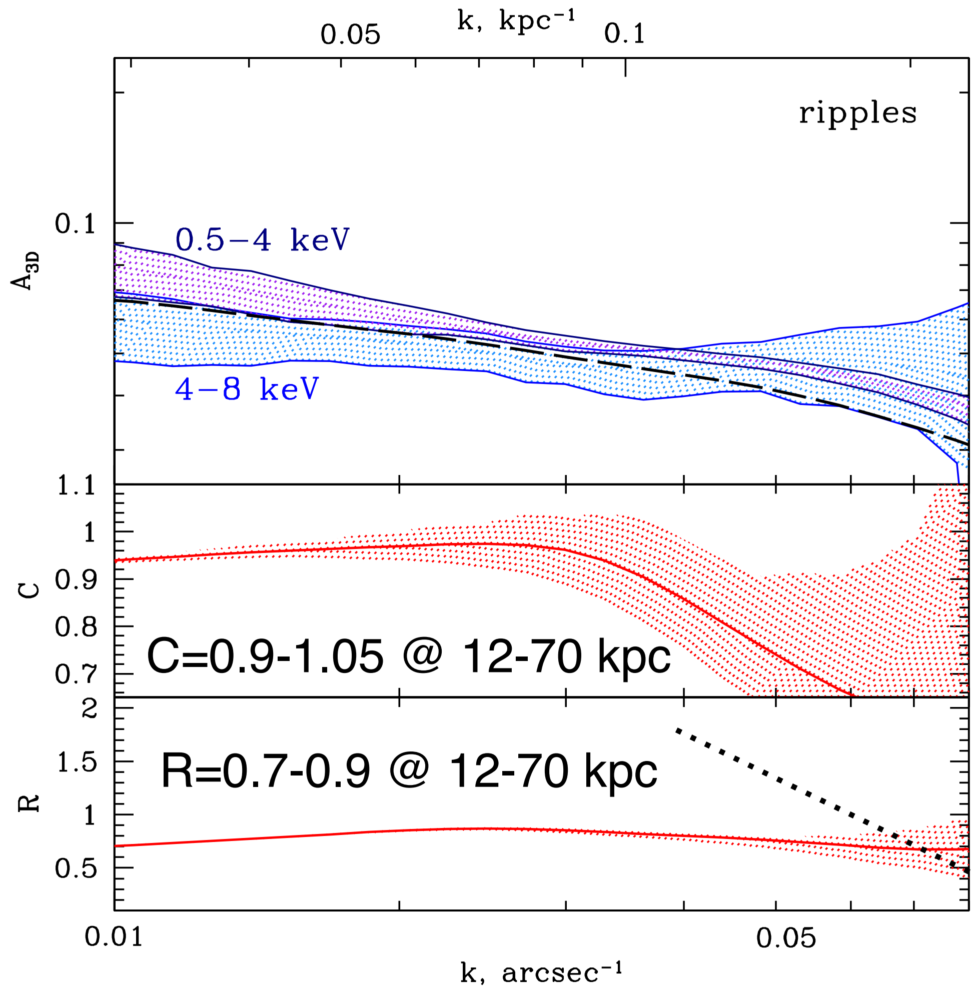
$E_{pert}/E_{therm} \sim 11\%$

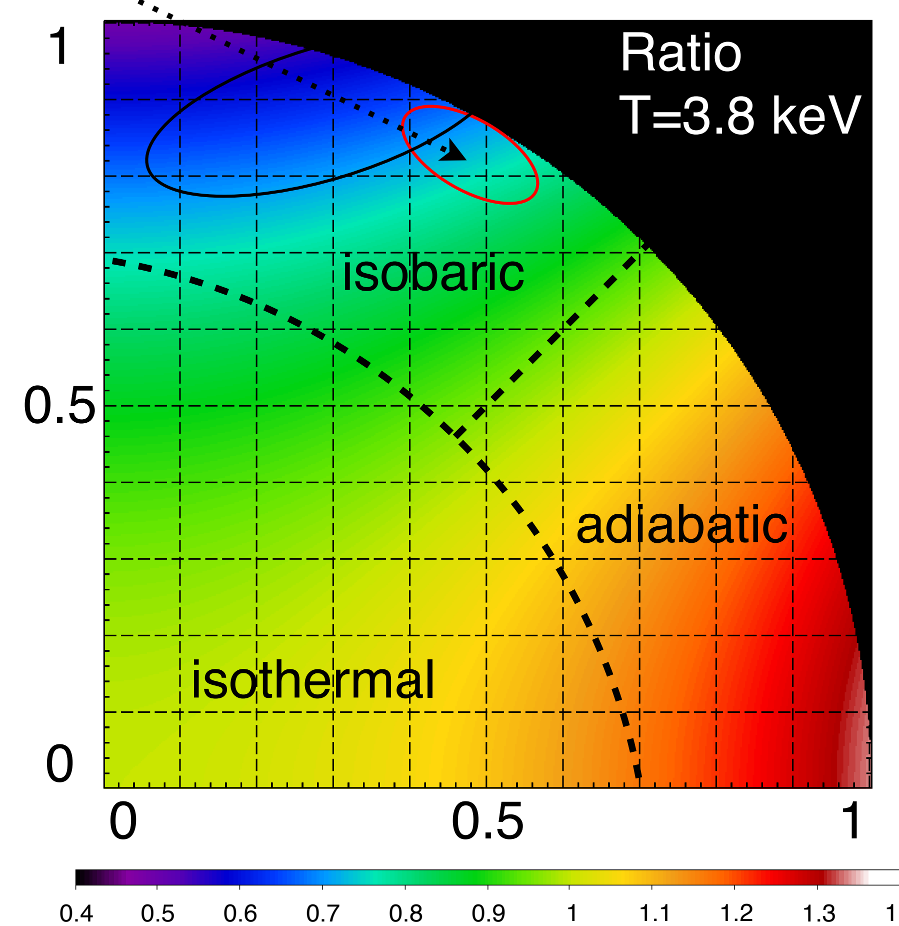
if cooling ~ heating => $t_{diss} \sim 5{\cdot}10^7 - 3{\cdot}10^8$ yr

Zhuravleva et al., in prep.

Nature of perturbations in Perseus: ripples



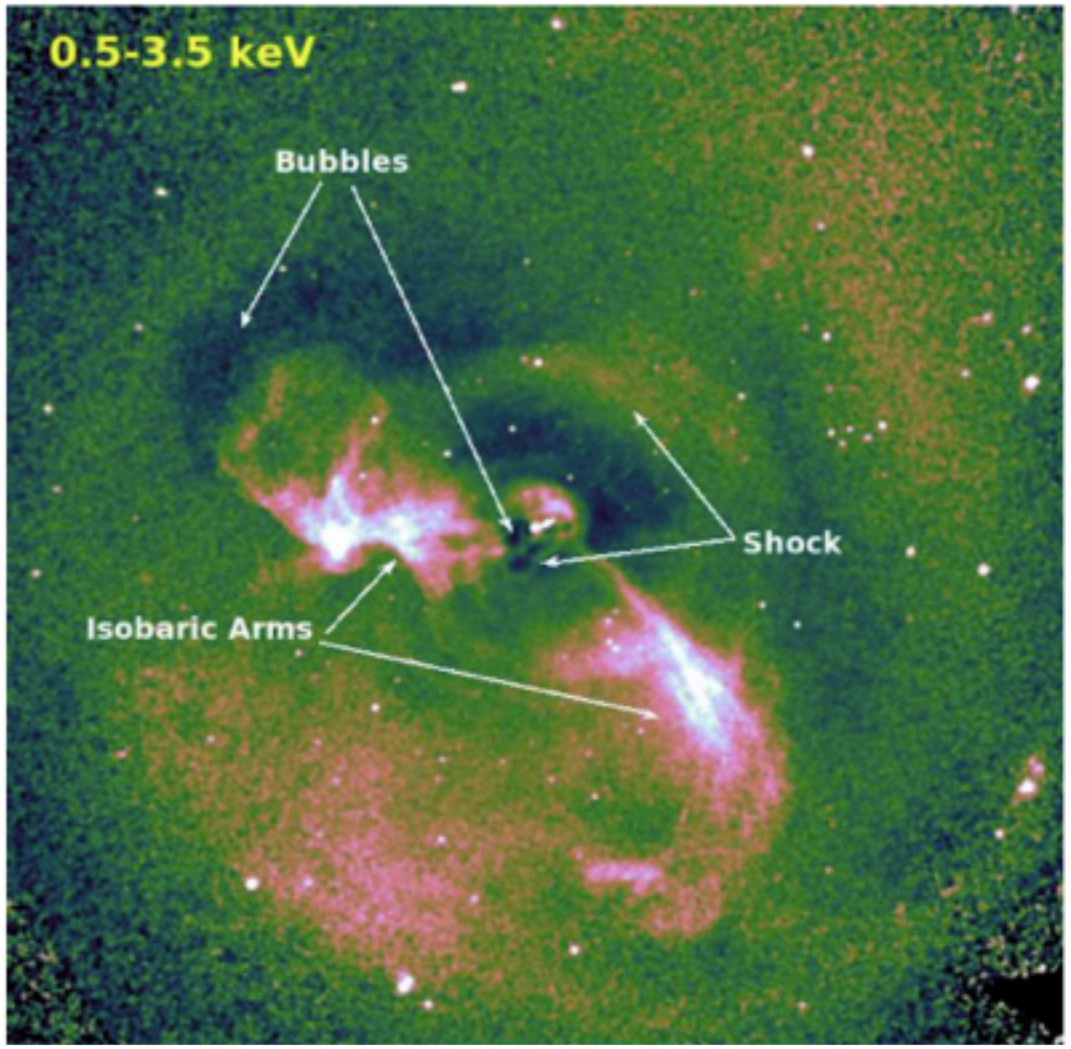




Ripples, scales 12-70 kpc:
~ 50-60% of the total variance —> isobaric
~ 30% —> isothermal
~15 % —> adiabatic

Zhuravleva et al., in prep.

Nature of perturbations in Virgo/M87 cluster



central 14':
dominated by isobaric "arms"

central 14', no arms, 5-10 kpc scale:
~70 % isothermal
~15 % adiabatic
~15% isobaric

on scales > 30 kpc —> isobaric

$E_{pert}/E_{therm} \sim 5\%$

if cooling ~ heating => $t_{diss} \sim 5 \cdot 10^7$ yr

supports AGN feedback model mediated by bubbles

Arevalo et al. 2015, submitted

Main limitation:

- Low number of counts, especially in hard band

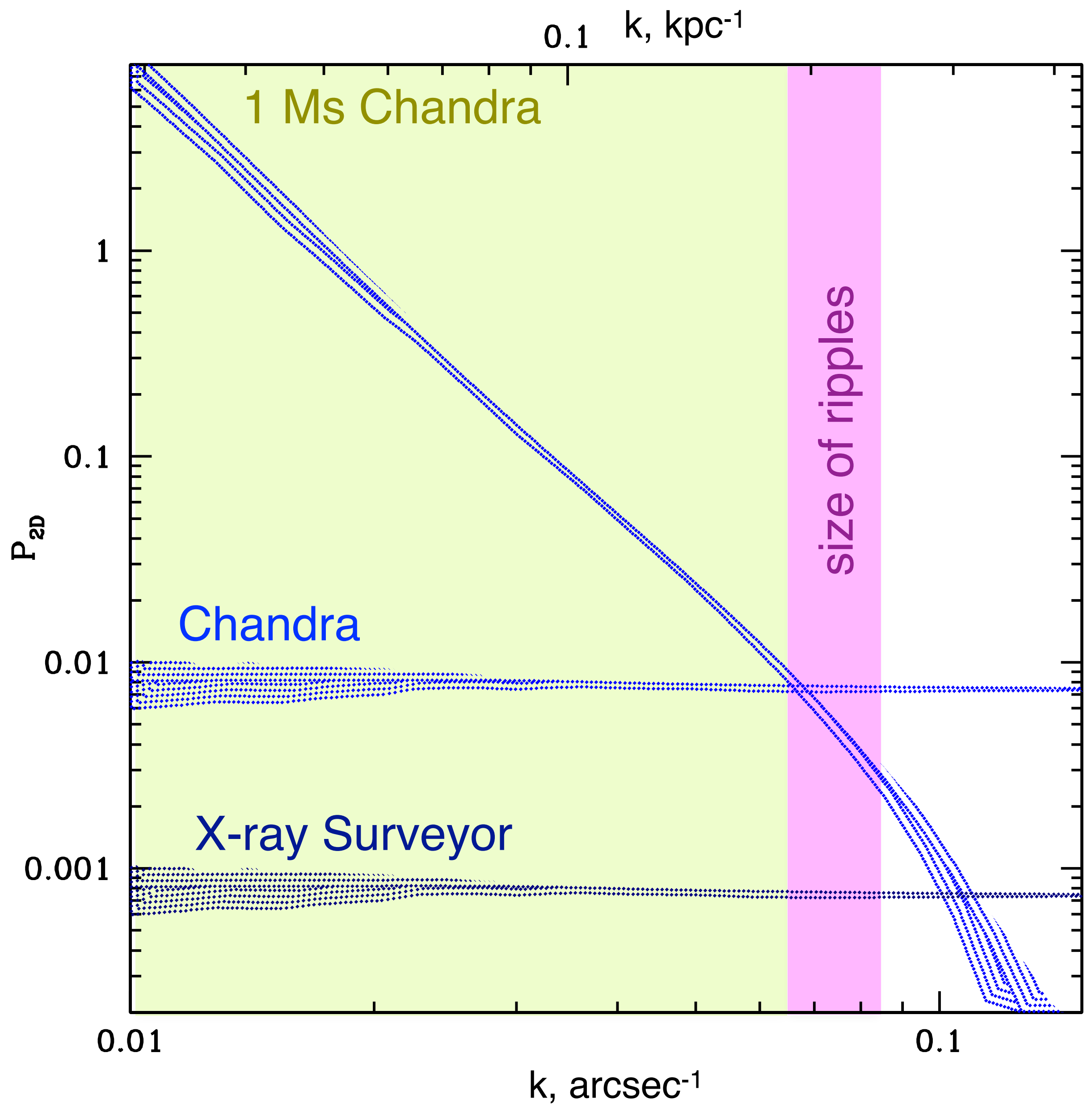
X-ray Surveyor:

- large effective area —> reduce the Poisson noise
- high angular resolution
  —> probe small-scale fluctuations
  —> resolve point sources
- high spectral resolution —> direct information on V

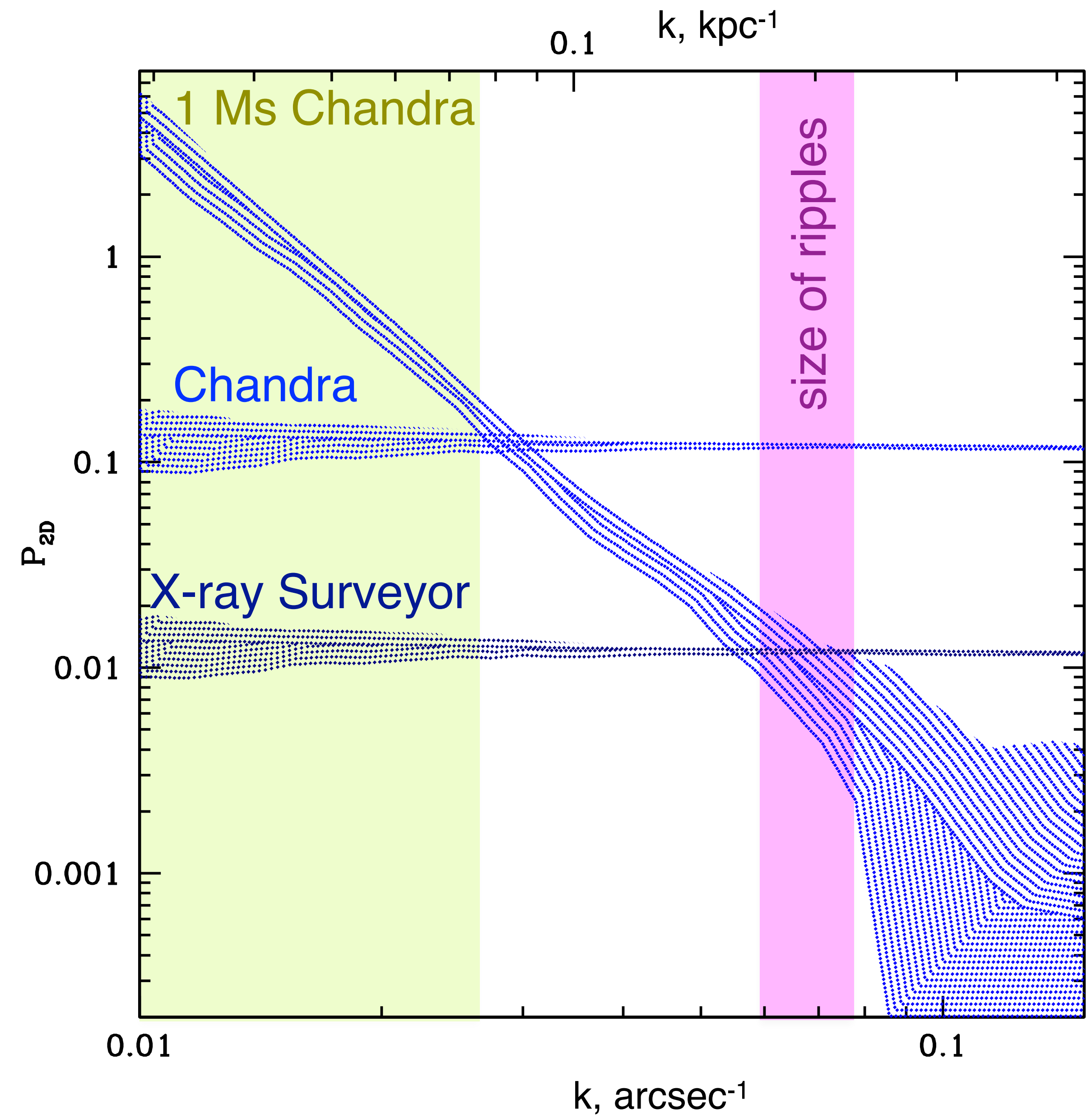
Future with X-ray Surveyor: effective area + FoV

Poisson ~ $1/N_{phot}$

Perseus, ripples: 0.5 - 4 keV band



Perseus, ripples: 4 - 8 keV band

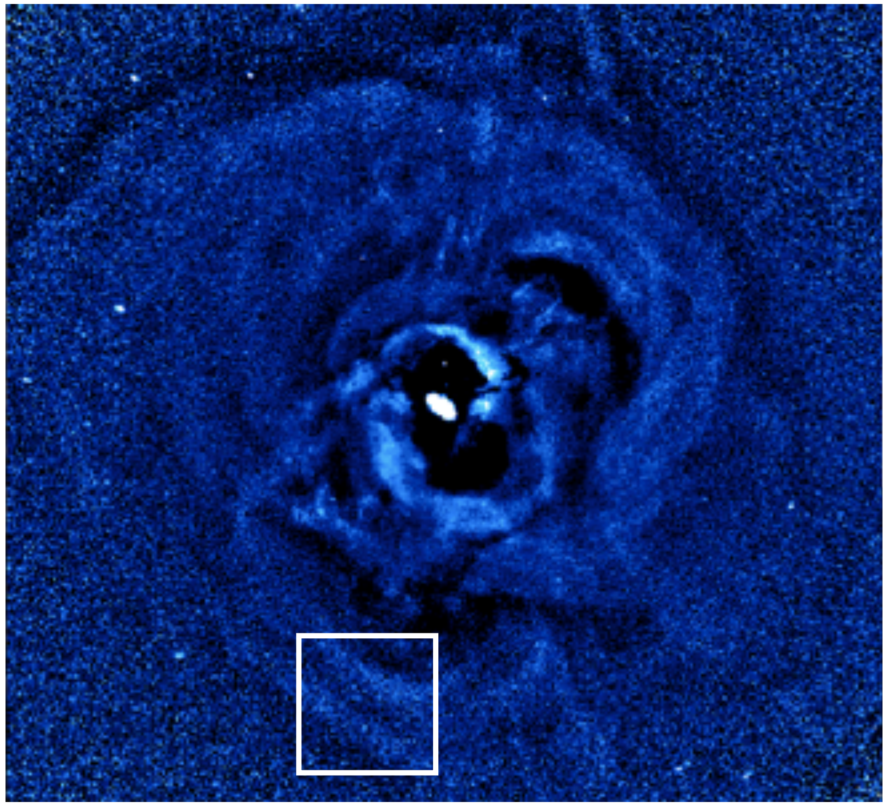


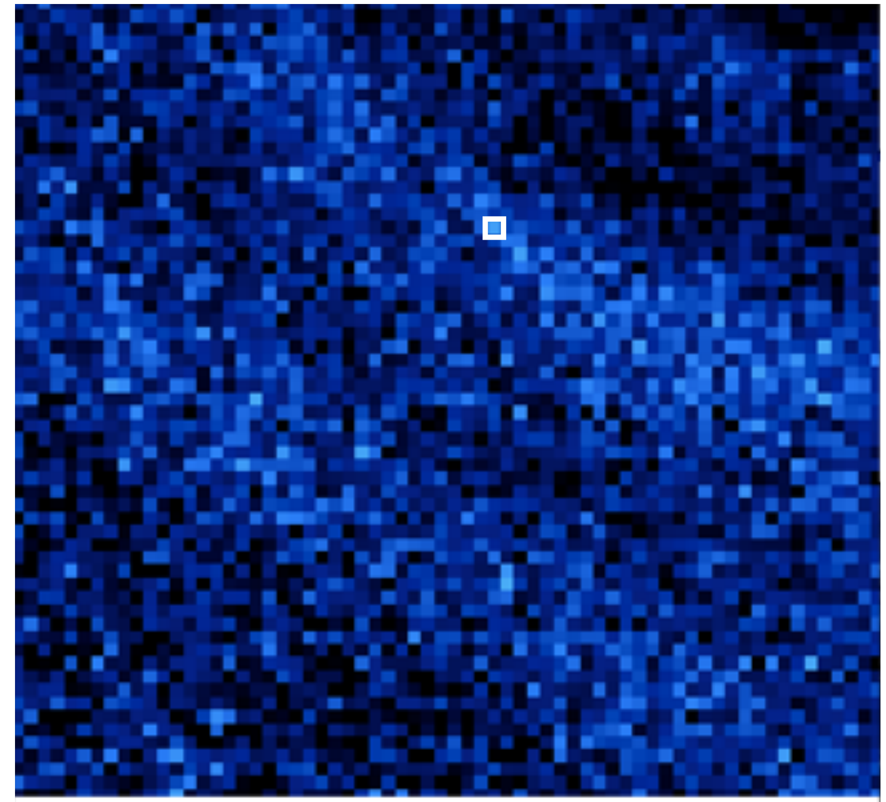
the smallest scales we can reach with
Chandra: ~ 5 kpc
X-ray Surveyor: < 2 kpc

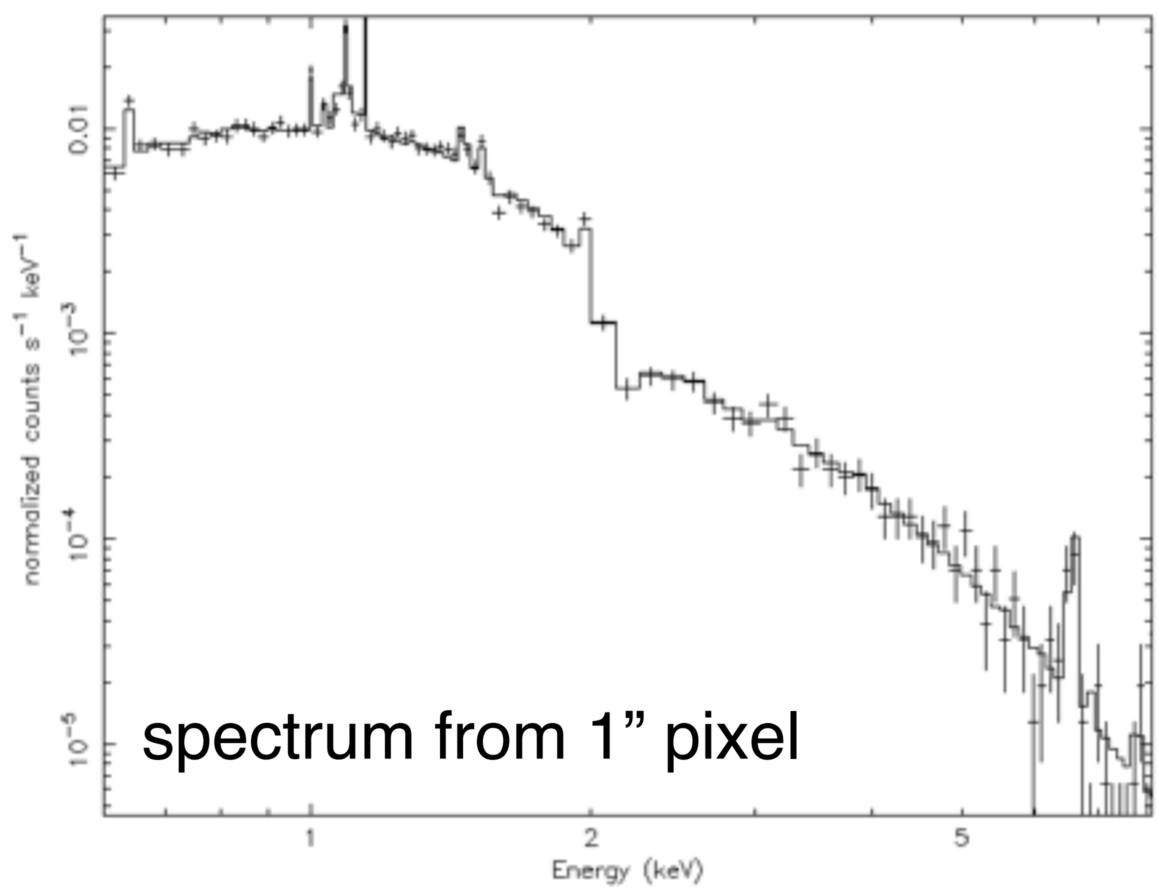
the smallest scales we can reach with
Chandra: ~ 12 kpc
X-ray Surveyor: ~ 5 kpc

X-ray Surveyor will probe fluctuations ~ 5 kpc even in **hard** X-ray band

Future with X-ray Surveyor: spectral + angular resolutions







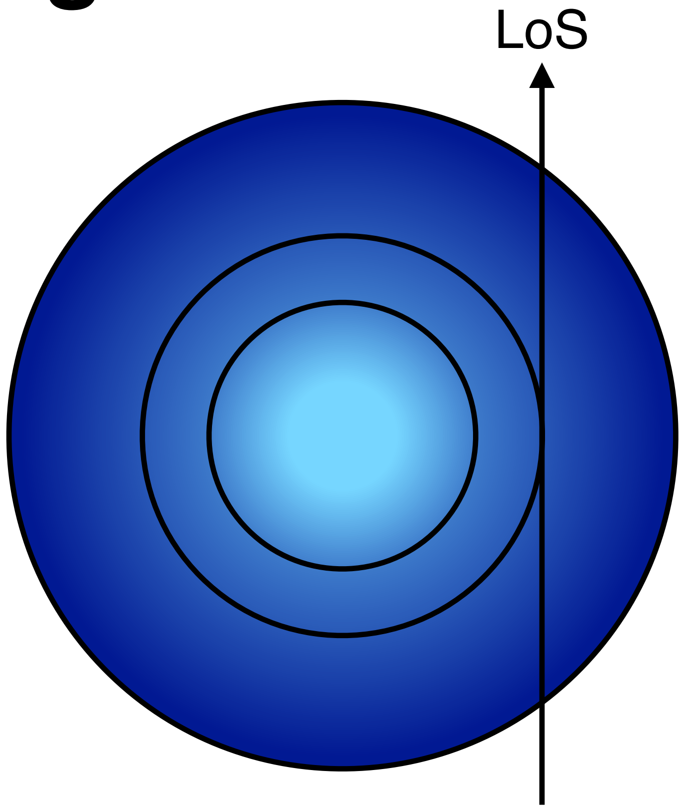
if V~300 km/s
line broadening: ± 52 km/s
centroid shift: ± 30 km/s

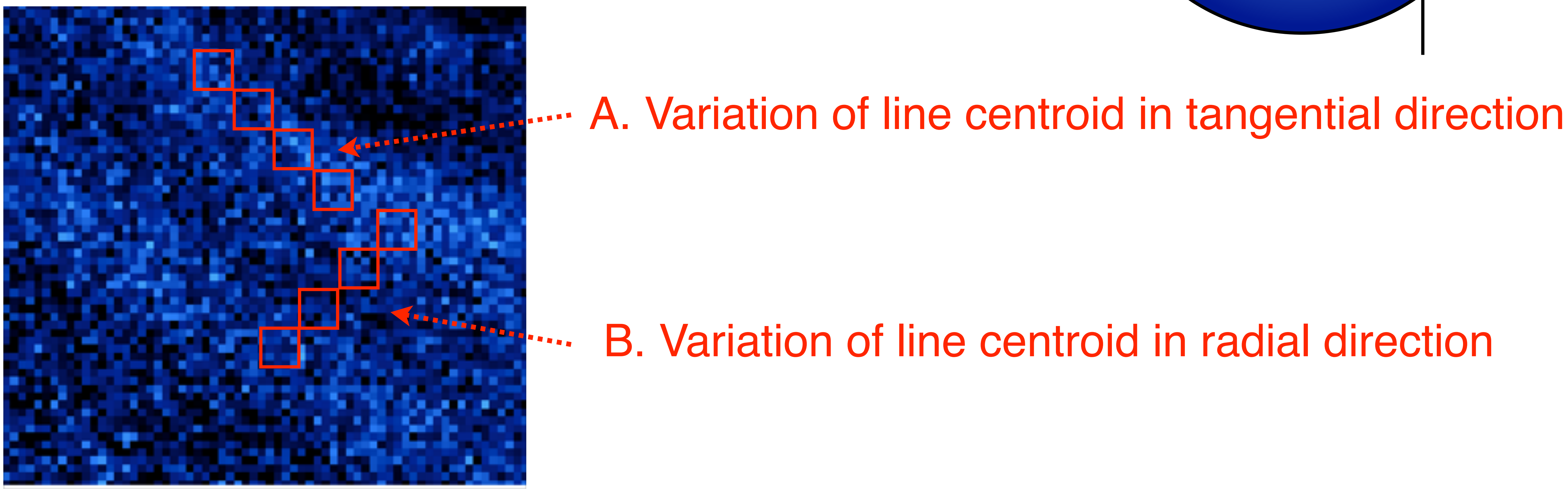
X-ray Surveyor will spatially and spectrally resolve the tiniest structures

Future with X-ray Surveyor: spectral + angular resolutions

Sound waves or stratified turbulence?

X-ray surface brightness of clusters is peaked in the core => at some distance from the center we probe mostly tangential motions of gas





if A < B => turbulent eddies are correlated in tangential direction and not in radial => stratified turbulence

Summary

Chandra:

- Cross-spectra analysis allows us to obtain the dominant processes responsible for the observed fluctuations in the ICM;
- Perseus, inner r~3.5’: dominated by isobaric nature of perturbations on scales 8-70 kpc;
- Perseus, region with ripples: ~ 50% of the total variance is associated with isobaric fluctuations, ~30% with isothermal on scales 12-70 kpc;
- Virgo: dominated by isobaric arms, the rest of fluctuations - mostly isothermal.

X-ray Surveyor:

- Large effective area and spatial resolution —> probe < 2 kpc scales in soft band and down to 4-5 kpc in hard band;
- High spectral and spatial resolution —> resolve internal structure of ripple-like fluctuations, proving independent probes of their nature and energetic;
- Powerful physics lab with new capabilities .