Microphysics of ICM from X-ray Images

Effective Equation of State of Gas Fluctuations

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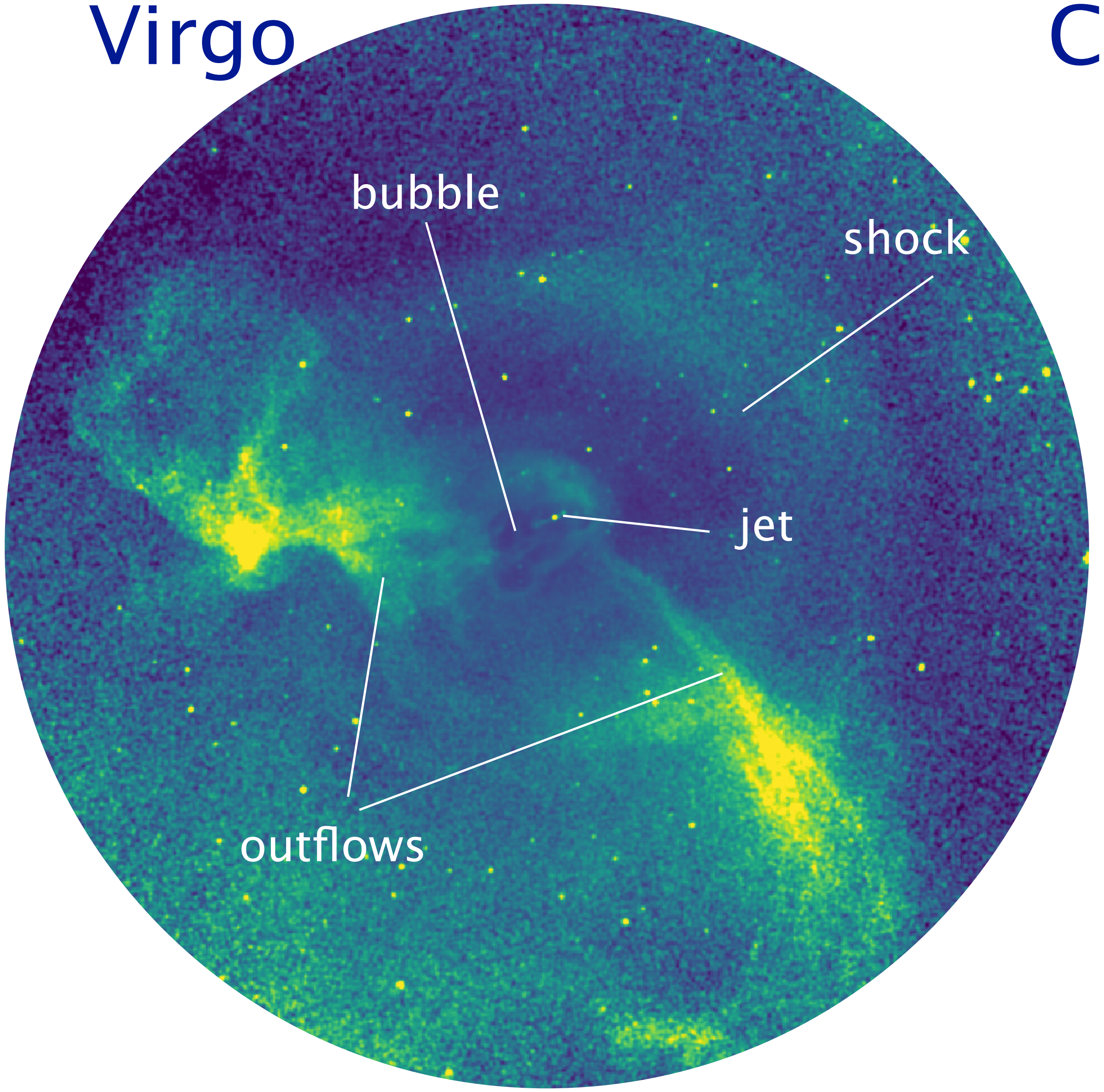
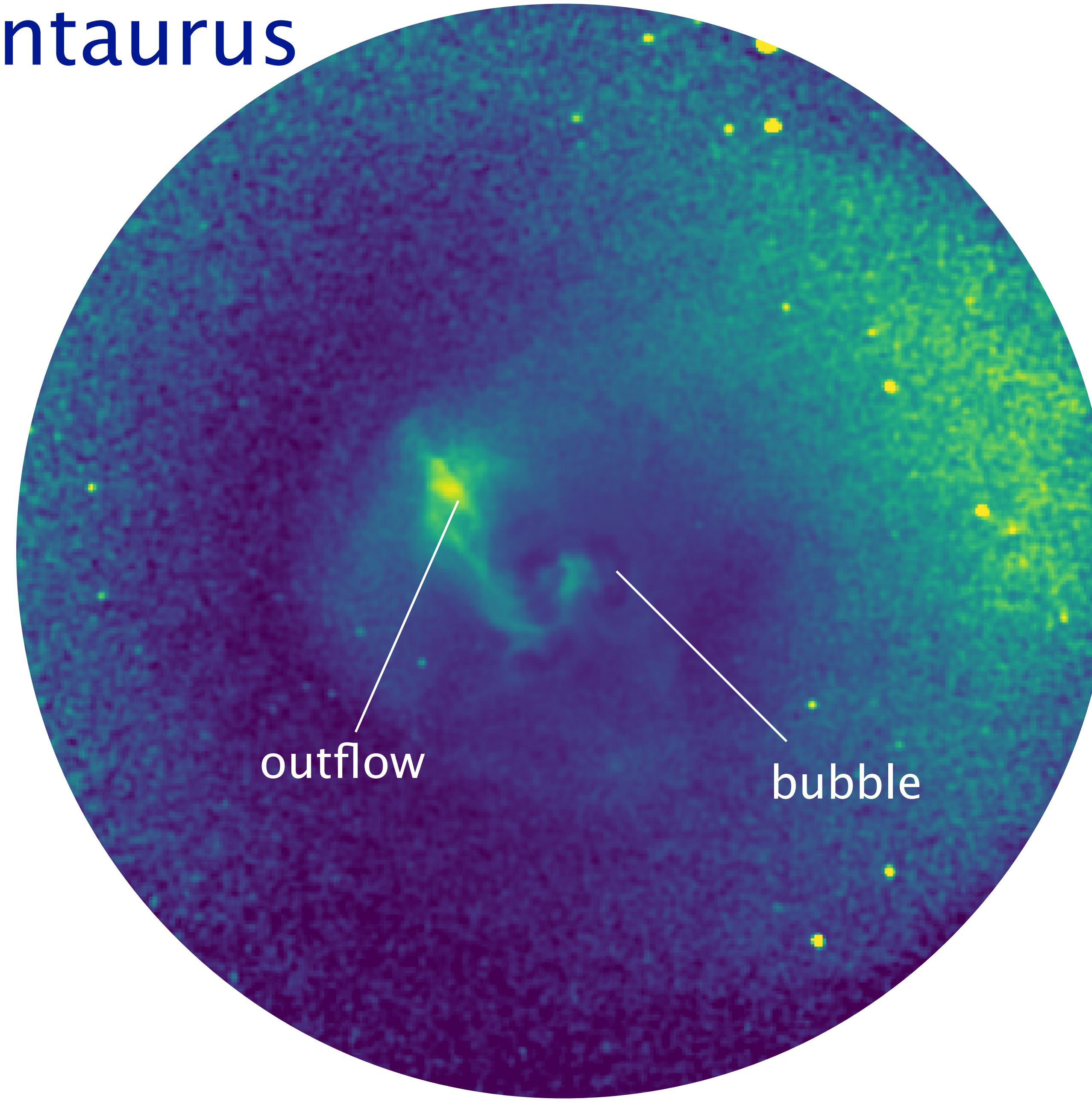
Nature of AGN-driven Perturbations

Virgo



Centaurus



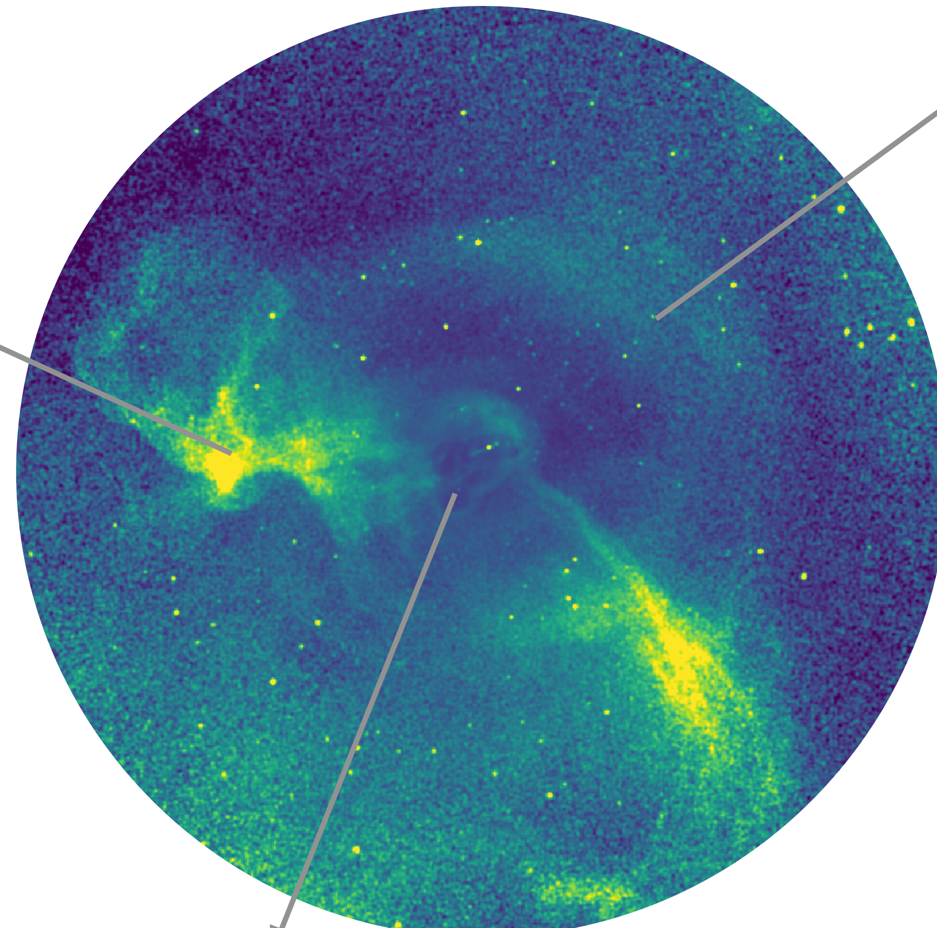
What is the nature and energy content of fluctuations in the bulk of the gas?

Different Types of Fluctuations

ISOBARIC

turbulence
metal outflows
sloshing

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



ADIABATIC

weak shocks
sound waves

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

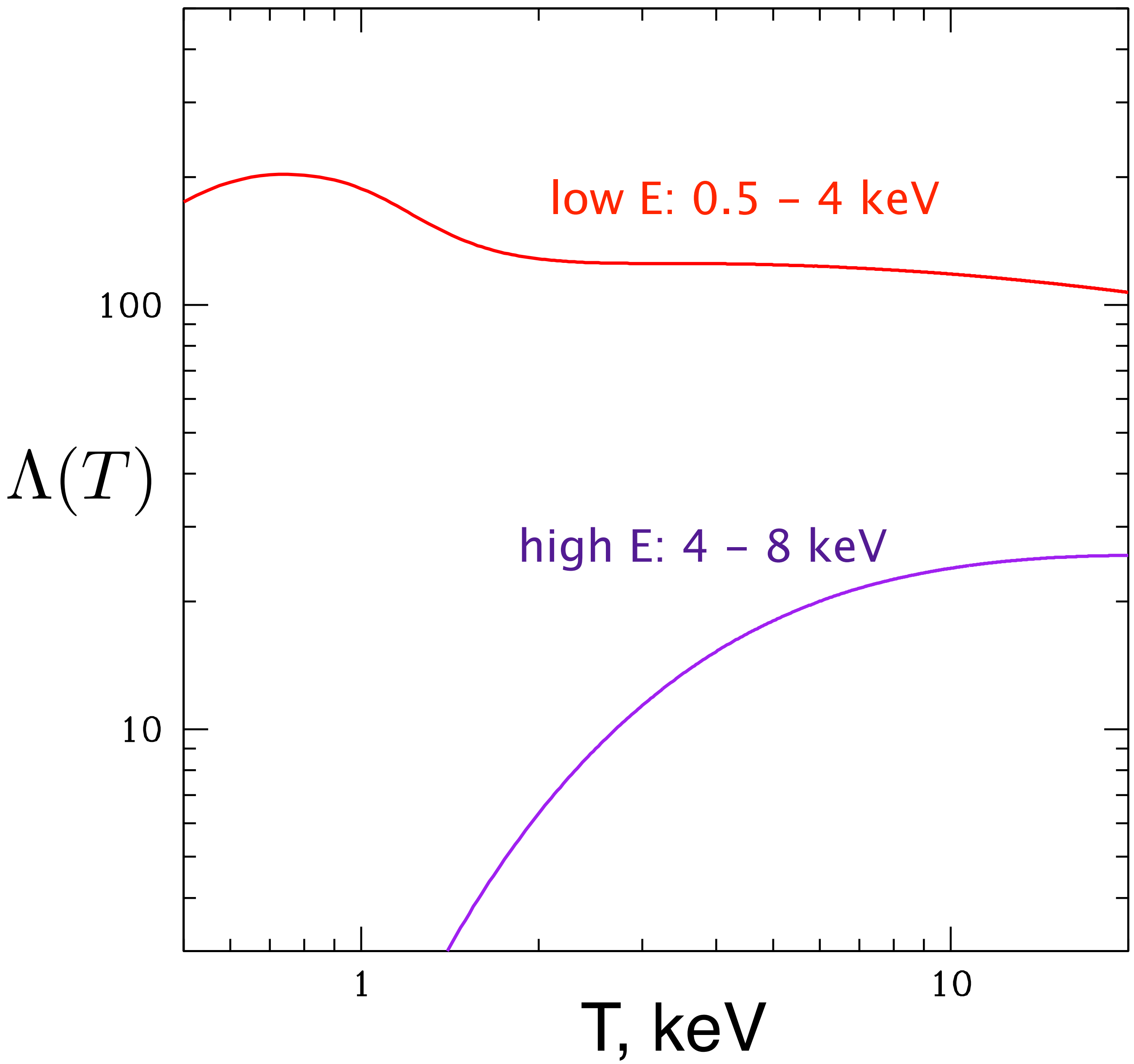
ISOTHERMAL

bubbles
grav. potential

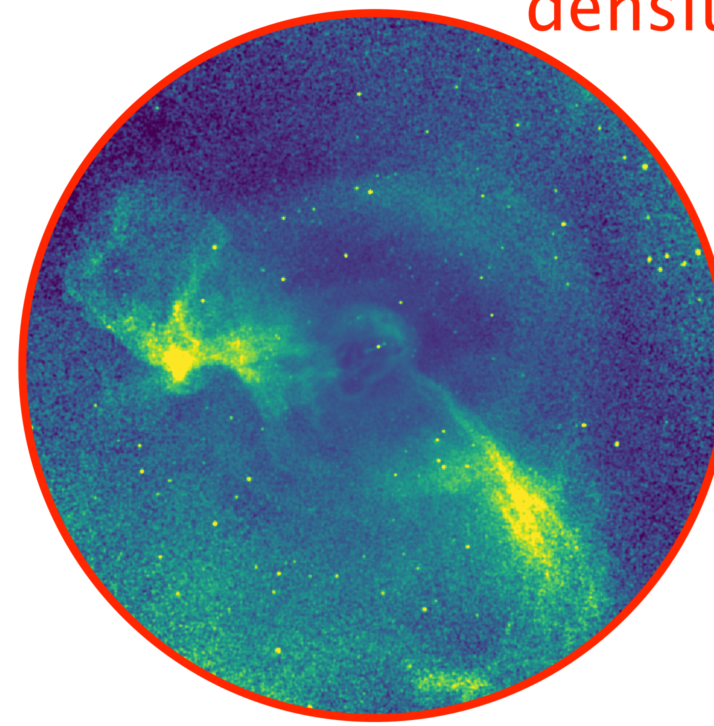
$$\frac{\delta T}{T} = 0 \cdot \frac{\delta n}{n}$$

Different Types of Fluctuations: X-ray response

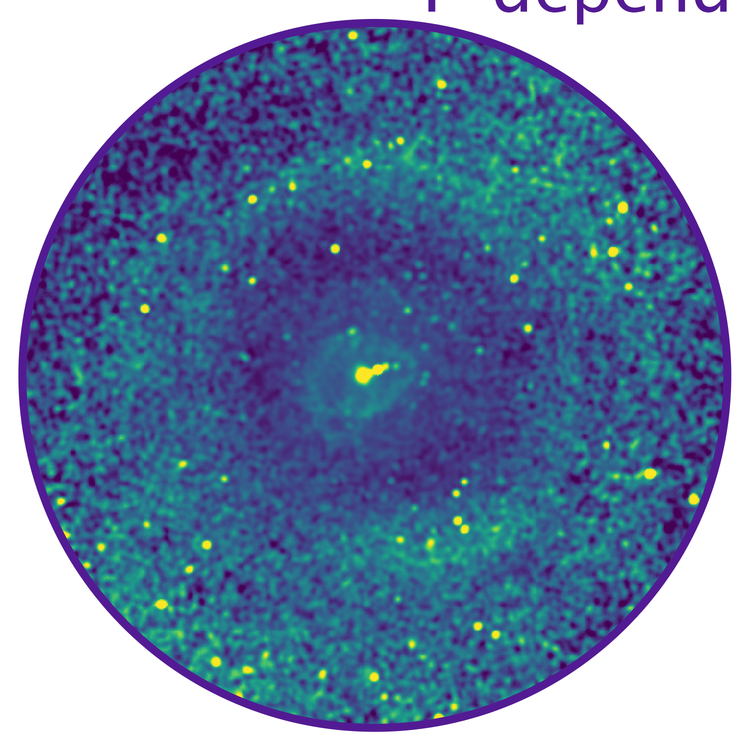
$$f \propto n^2 \Lambda(T)$$



“density” band



“T-dependent” band



Different Types of Fluctuations: X-ray response

$$f \propto n^2 \Lambda(T)$$

$$n = n_0 \left(1 + \frac{\delta n}{n_0}\right)$$

$$T = T_0 \left(1 + \frac{\delta T}{T_0}\right)$$

$$\frac{\delta T}{T_0} = \alpha \frac{\delta n}{n_0}$$

a/d: $\alpha = 2/3$

i/b: $\alpha = -1$

i/t: $\alpha = 0$

if density and temperature perturbations are small:

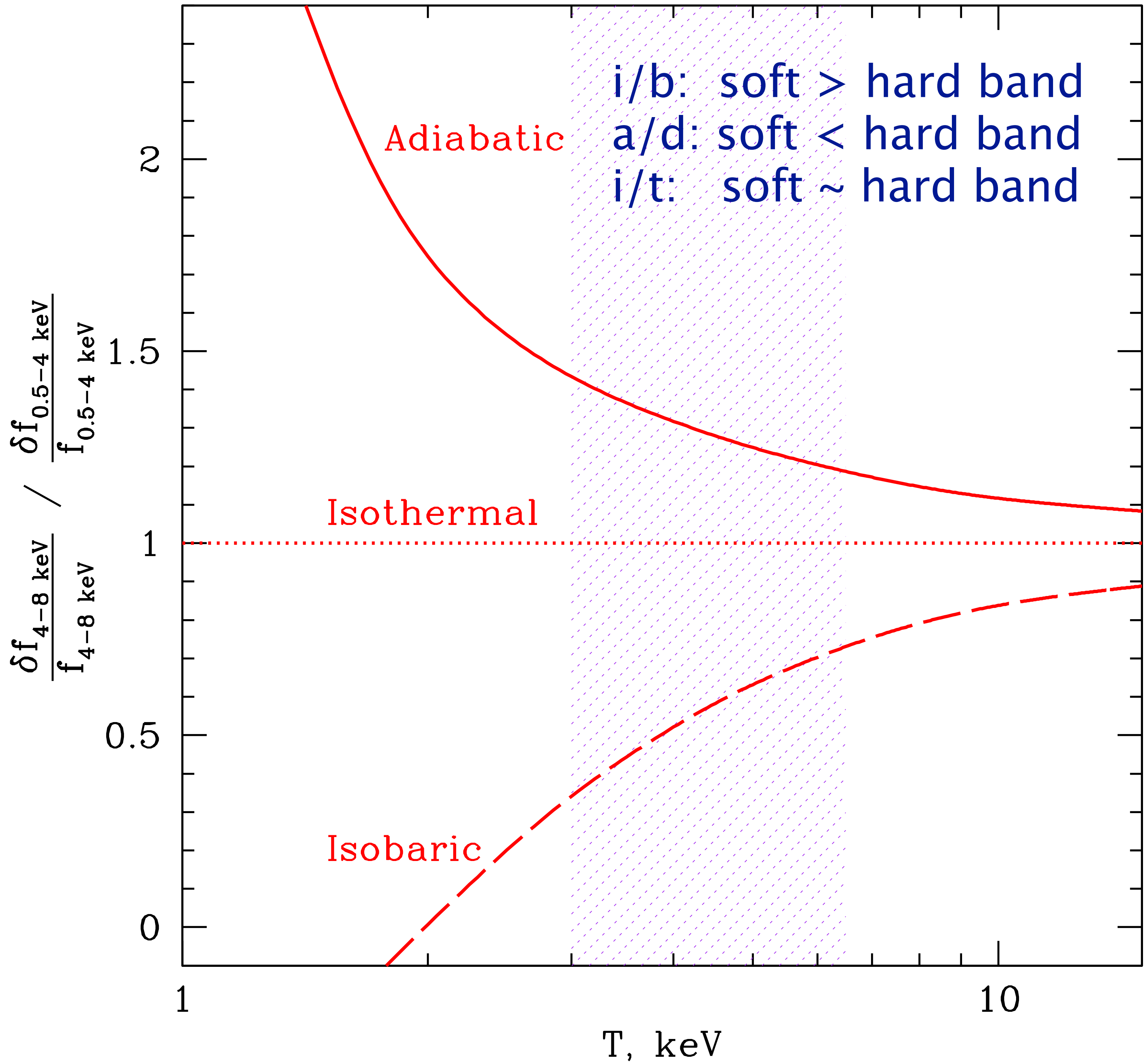
$$\frac{\delta f}{f} = \frac{\delta n}{n_0} \left(2 + \alpha \frac{d \ln \Lambda}{d \ln T}\right)$$

X-ray response of different type of perturbations:

$$(\delta f/f)_a / (\delta f/f)_b$$

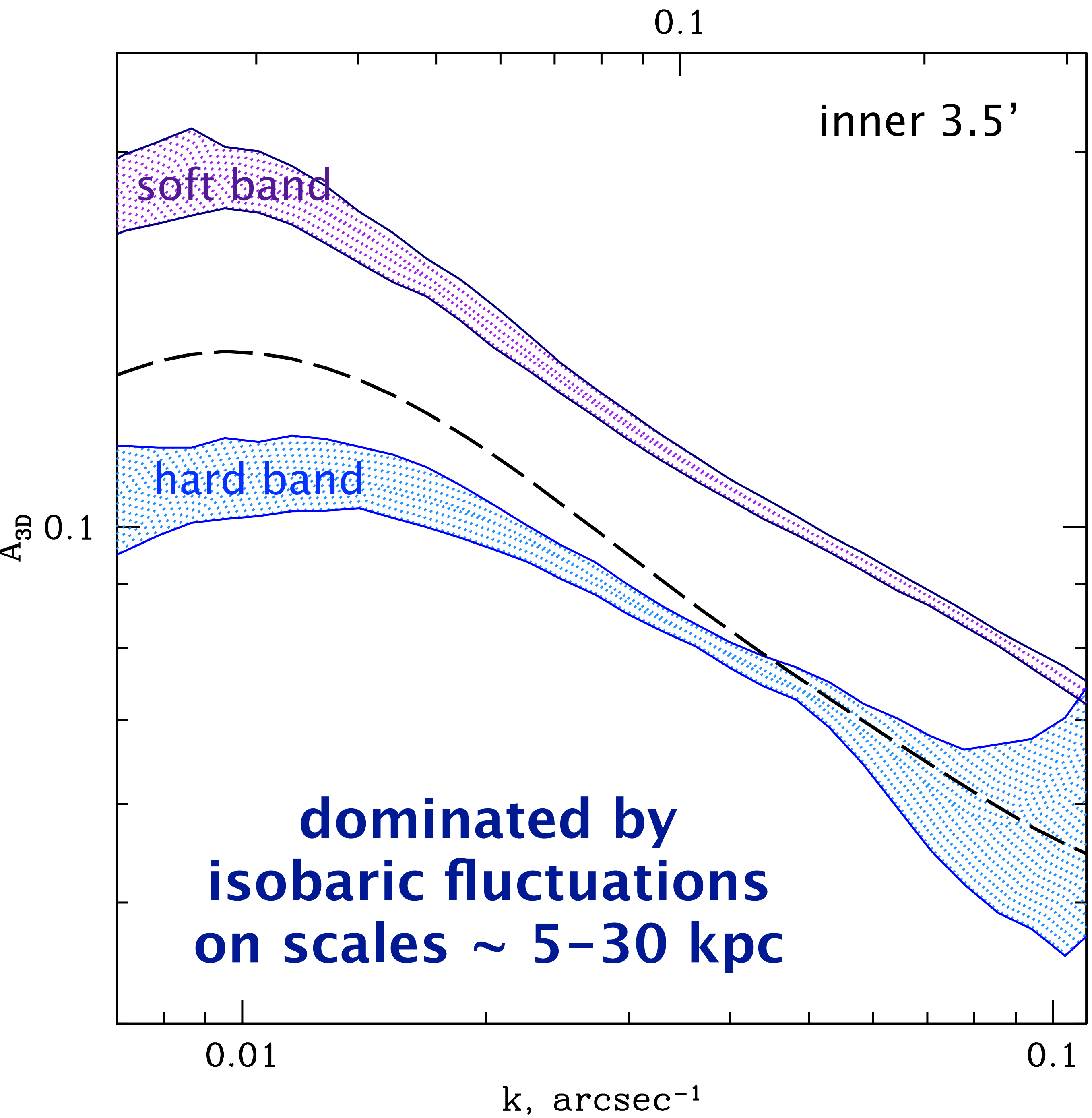
a, b – two different energy bands [e.g. 0.5–4 keV and 4–8 keV]

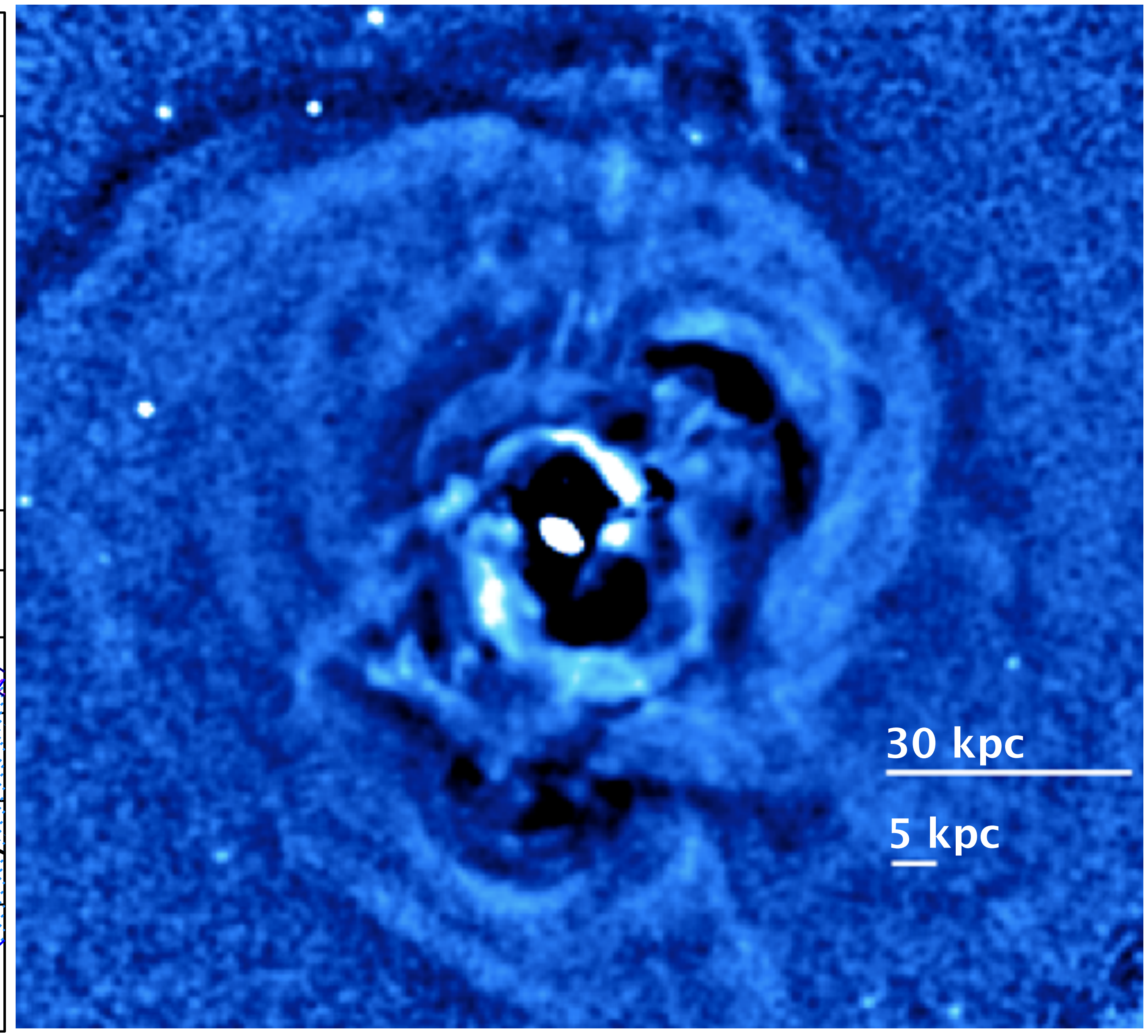
Different Types of Fluctuations: X-ray response



Nature of AGN-driven Perturbations

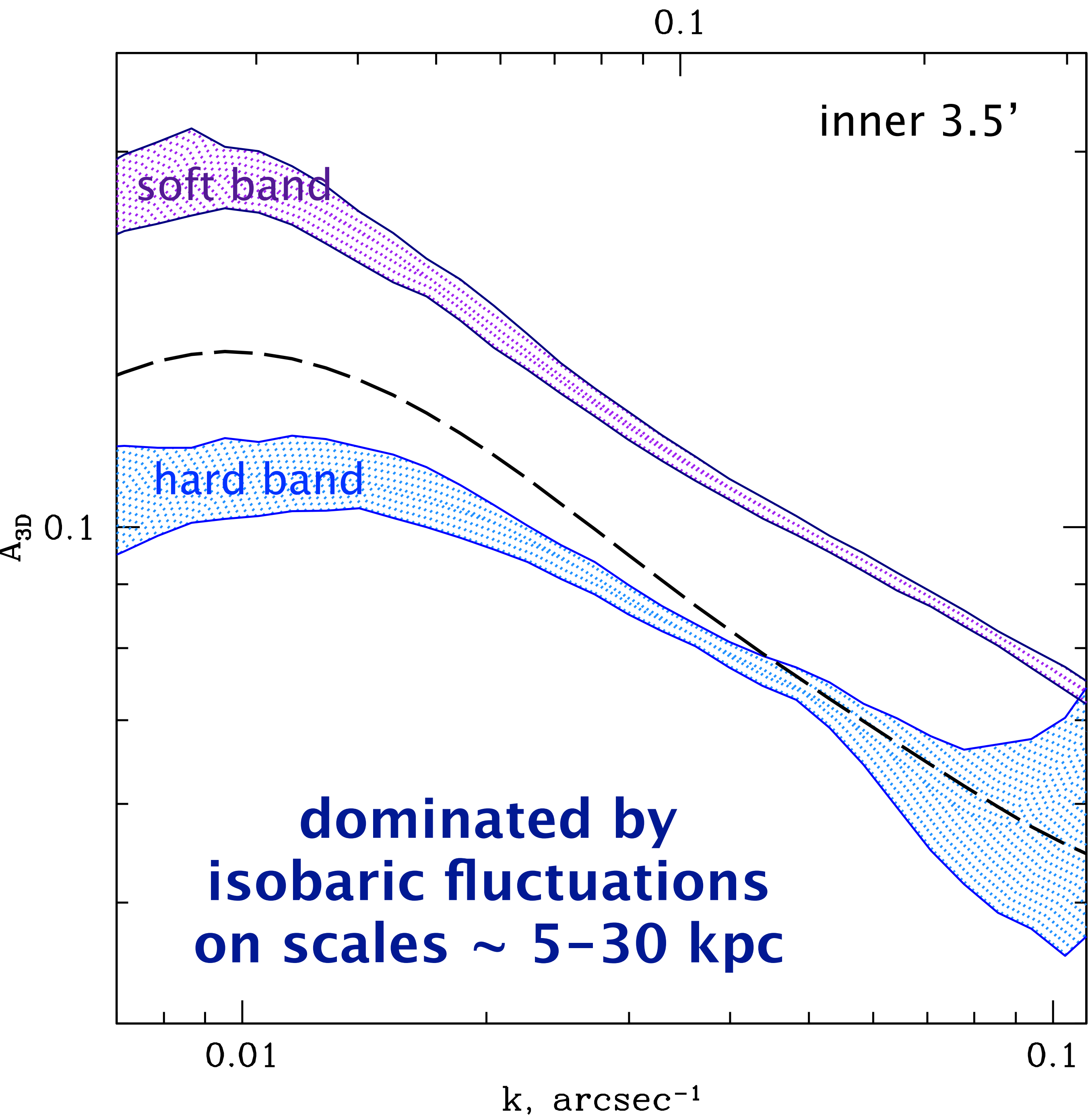
Perseus Cluster





Nature of AGN-driven Perturbations

Perseus Cluster



Centaurus Cluster

in preparation

Mixture of different types of fluctuations

One process or multiple? —> Coherence

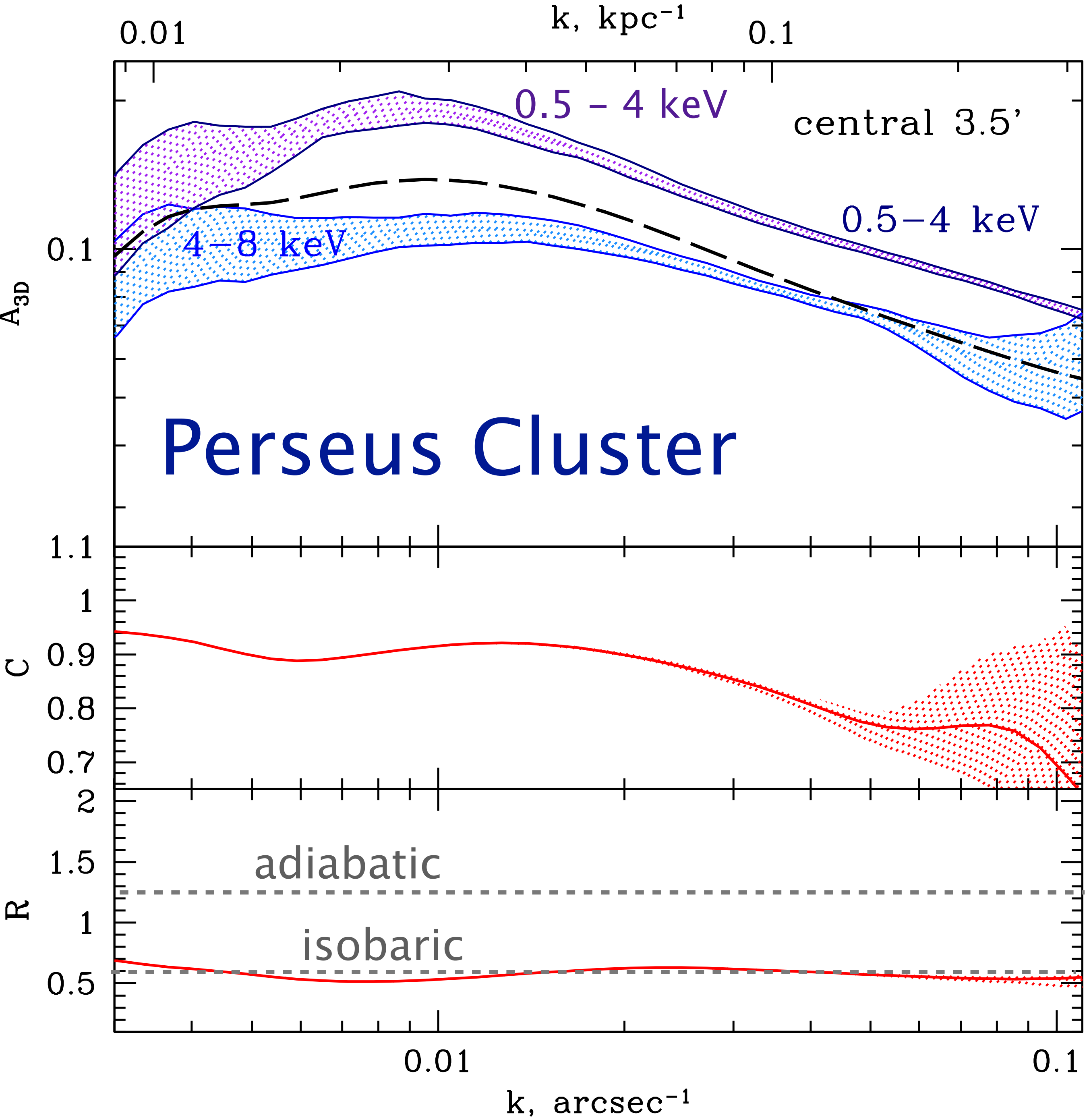
$$C = \frac{P_{12}}{\sqrt{P_1 P_2}}$$

Which process dominates? —> Ratio

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

For a given T and any combination of i/b, a/d, i/t fluctuations we predict C and R and compare them with observations

Nature of AGN-driven Perturbations



energy partition:
~ 80% isobaric
~12% isothermal
~ 8% adiabatic

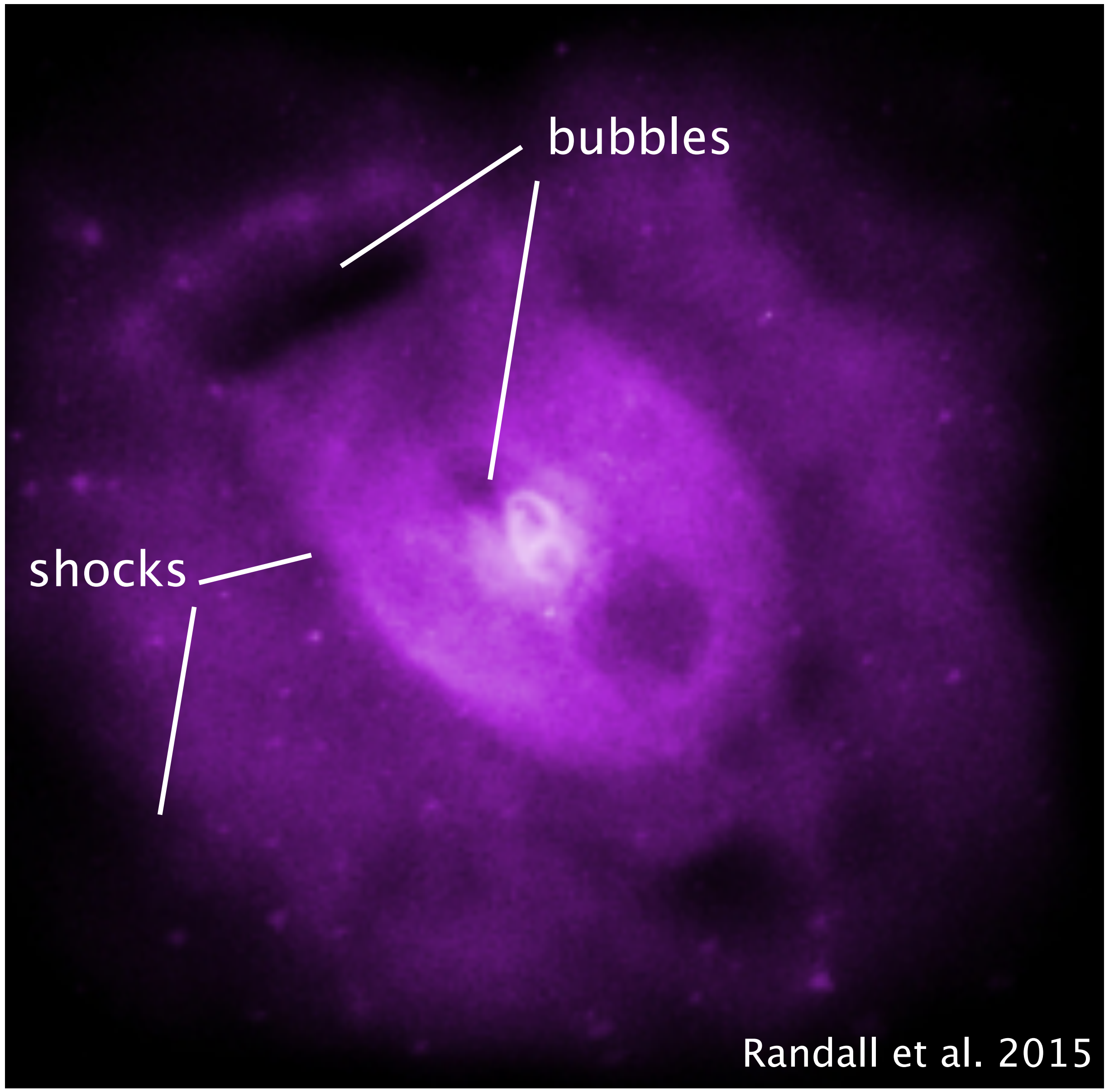
Centaurus Cluster

in preparation

[Arevalo+16; IZ+16a; IZ+16b in prep.]

Nature of AGN-driven Perturbations

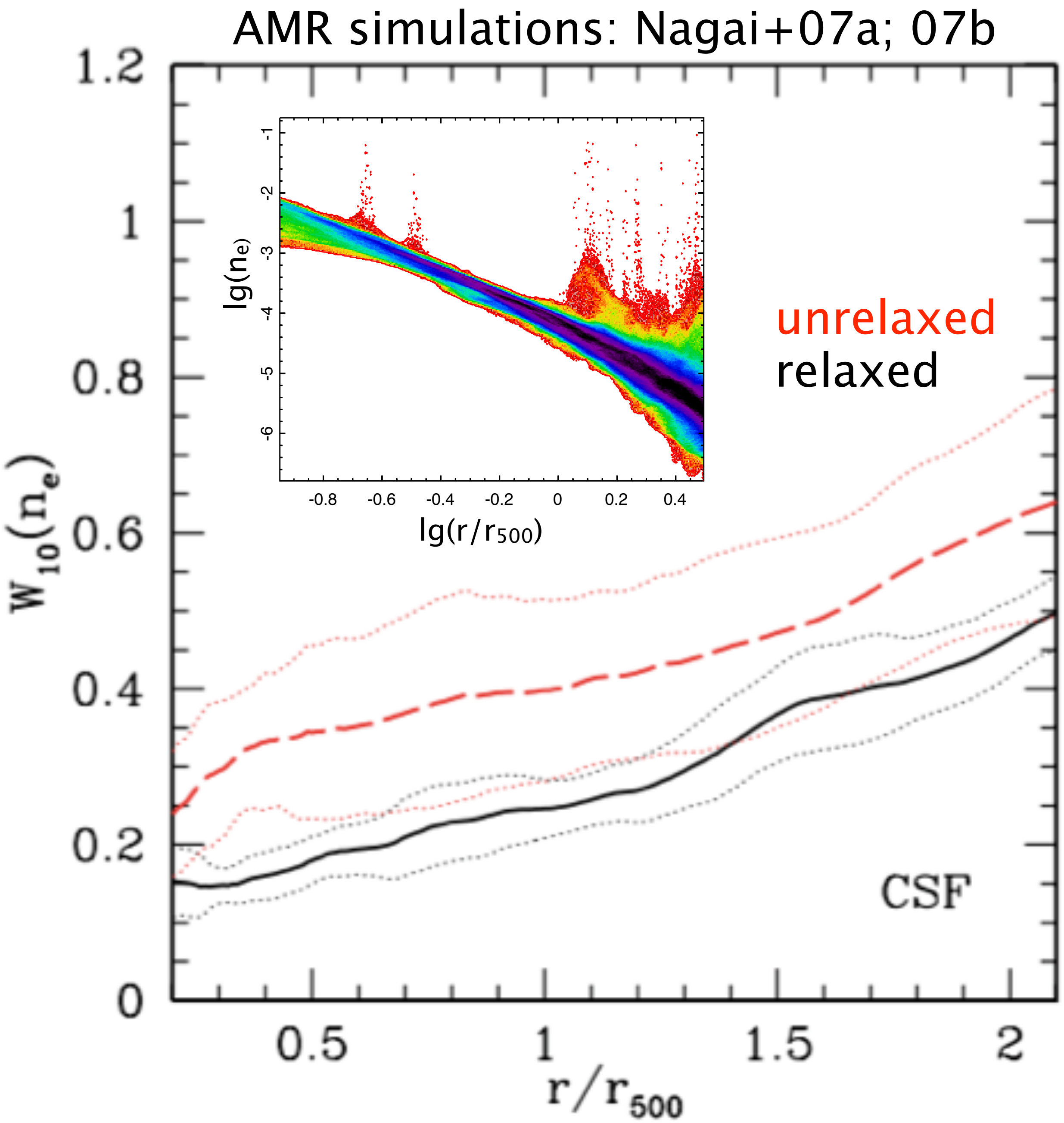
interesting exception: NGC5813

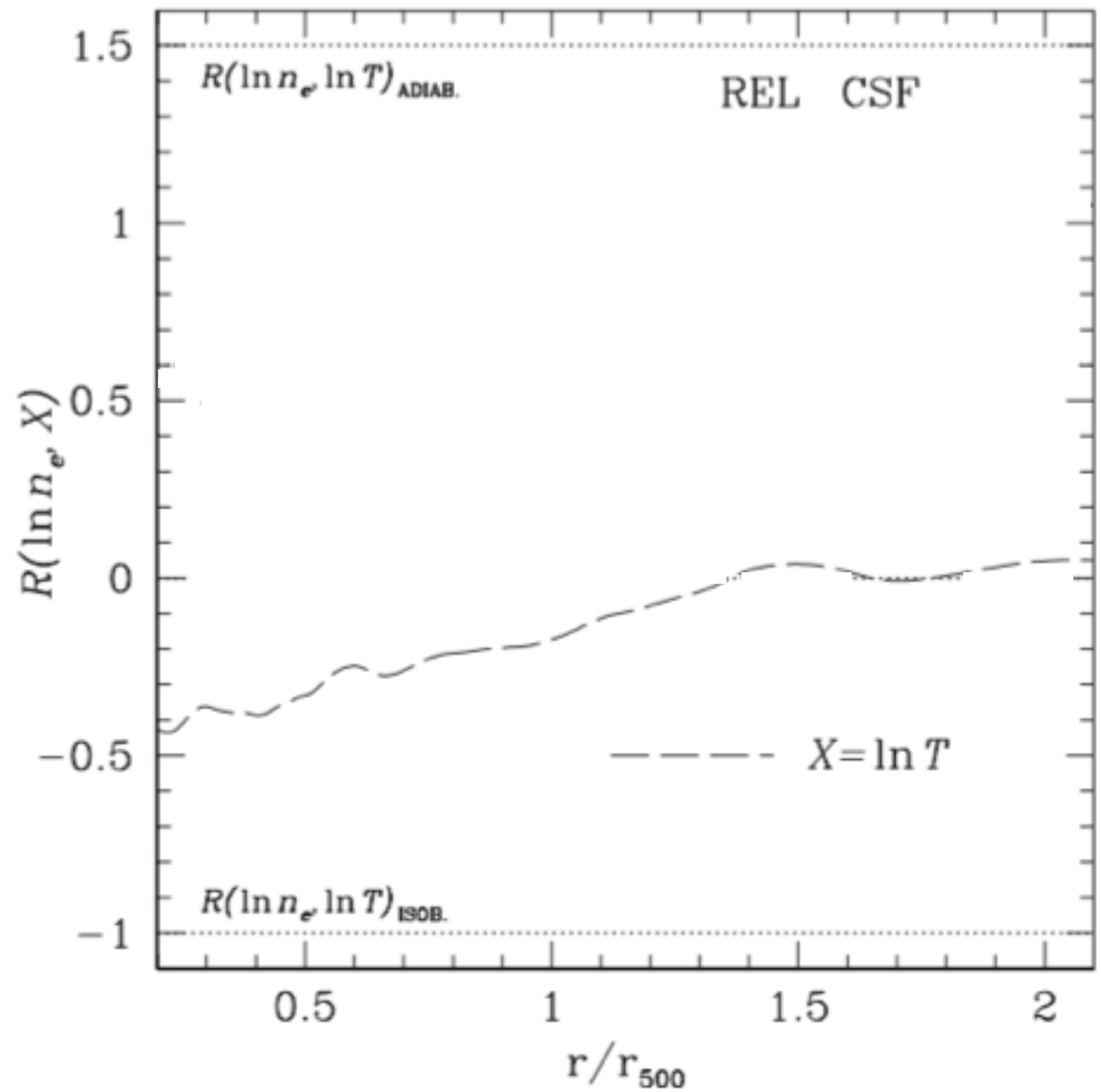


in preparation

[IZ+16b, in prep.]

Nature of Perturbations: simulations

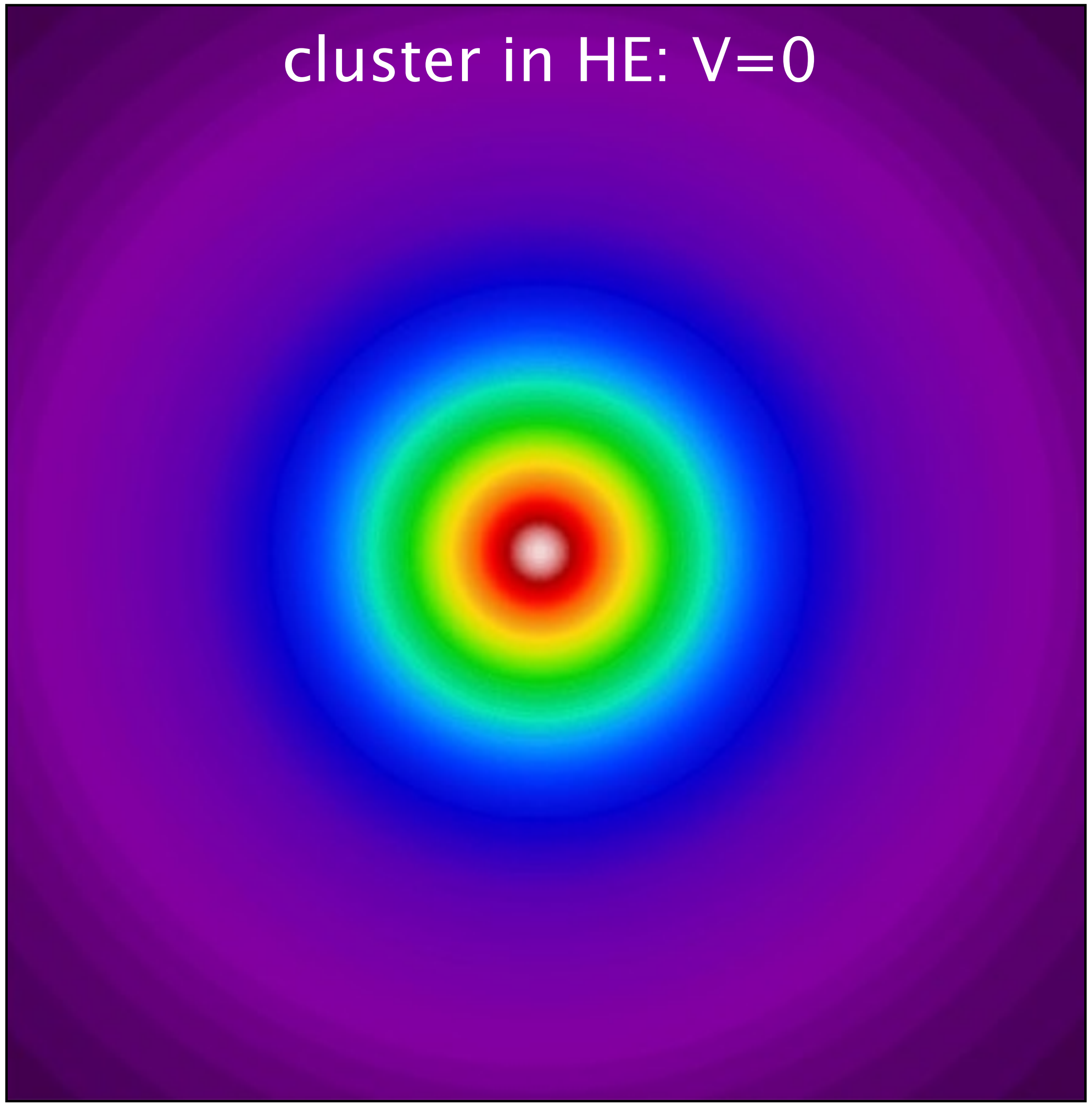


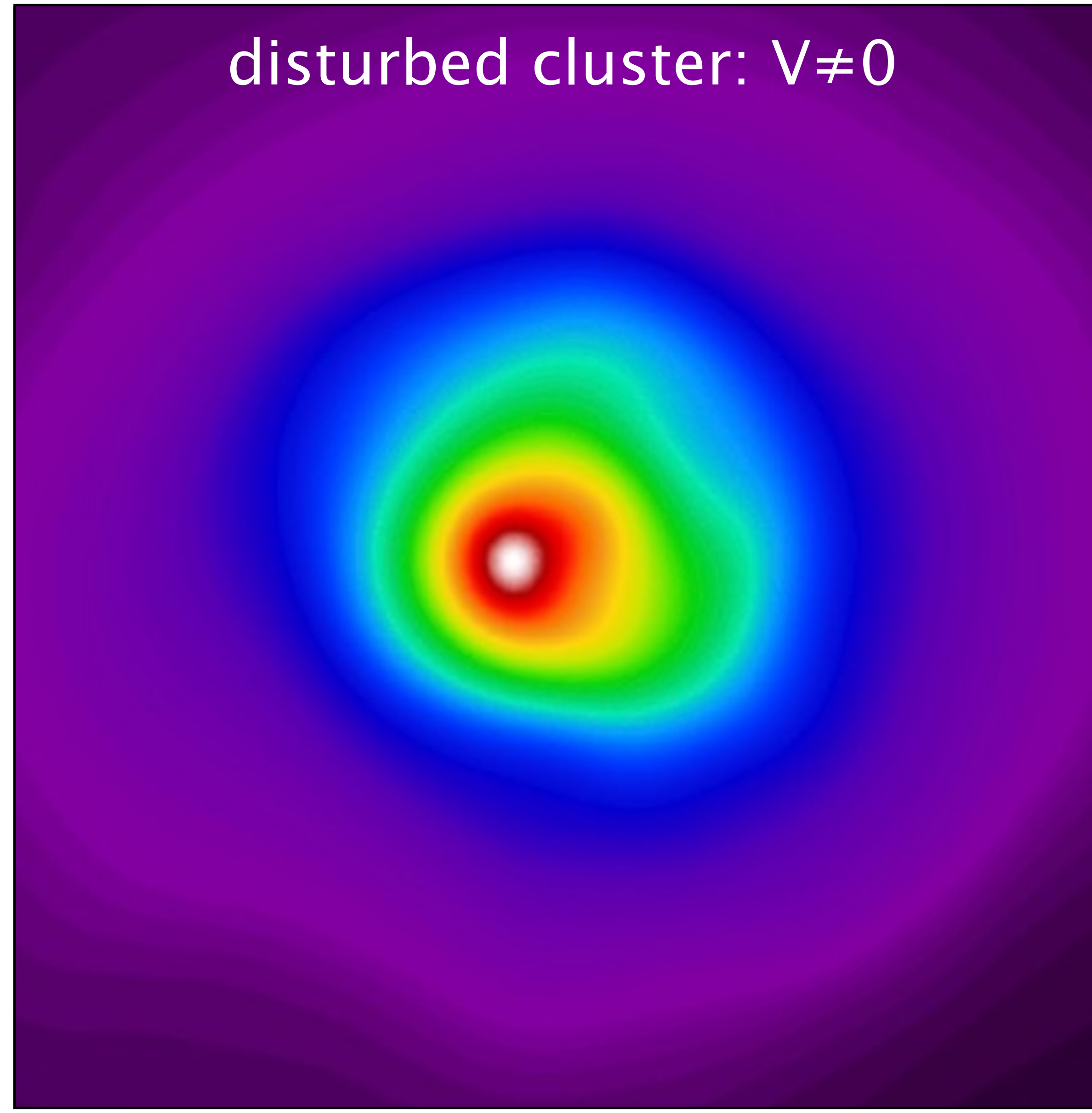


- density fluctuations < 10–20 % in the core
- no pure isobaric or adiabatic fluctuations
- in the core: closer to isobaric

[IZ+13]

Isobaric Fluctuations —> Velocity



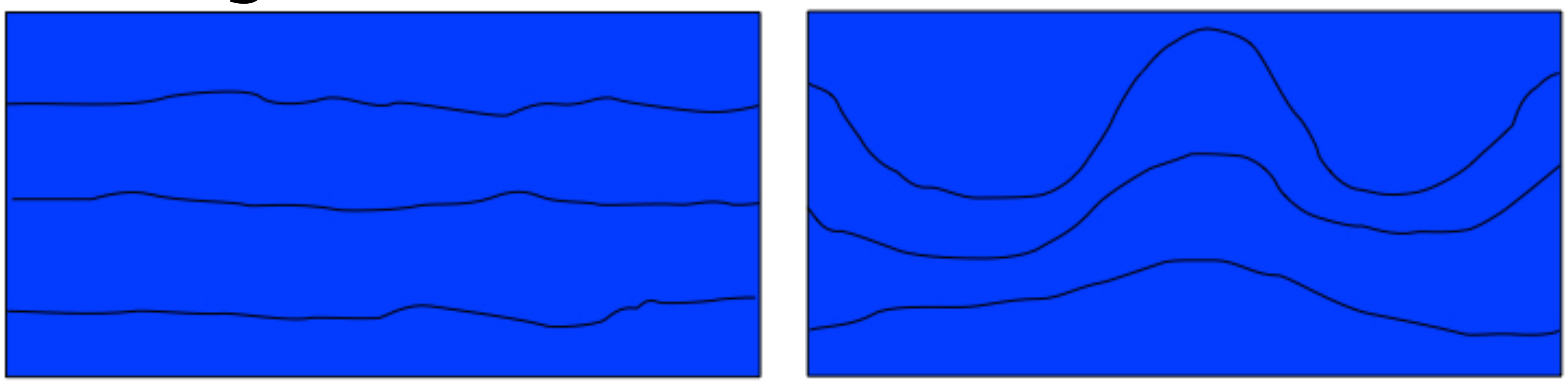


X-ray images in soft band —> $\delta n/n$

we need to understand: $\delta n/n$ —> V?

δn/n —> V Relation

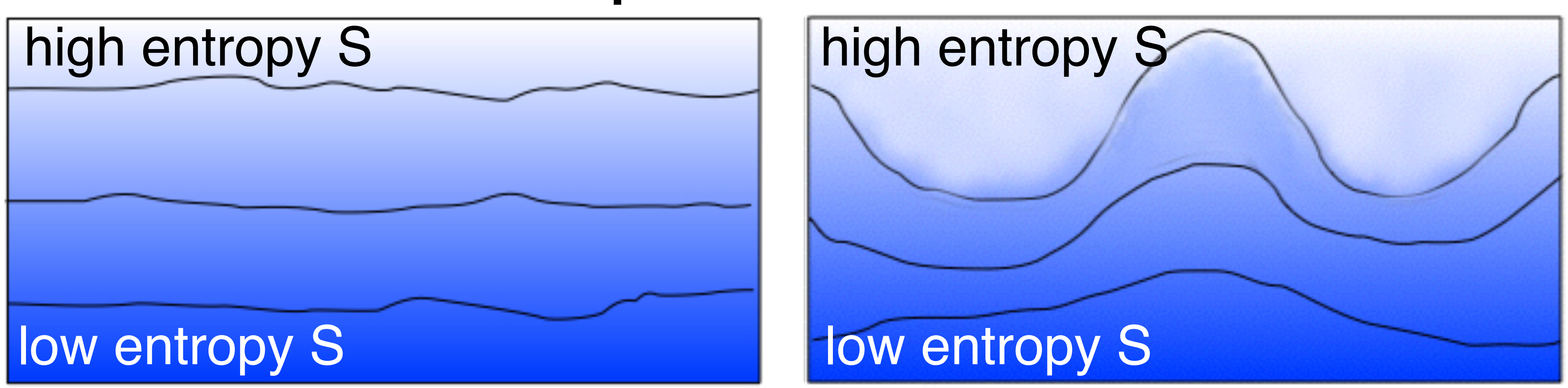
homogeneous box



$$\delta\rho \propto M^2$$

from Bernoulli's equation

stratified atmosphere



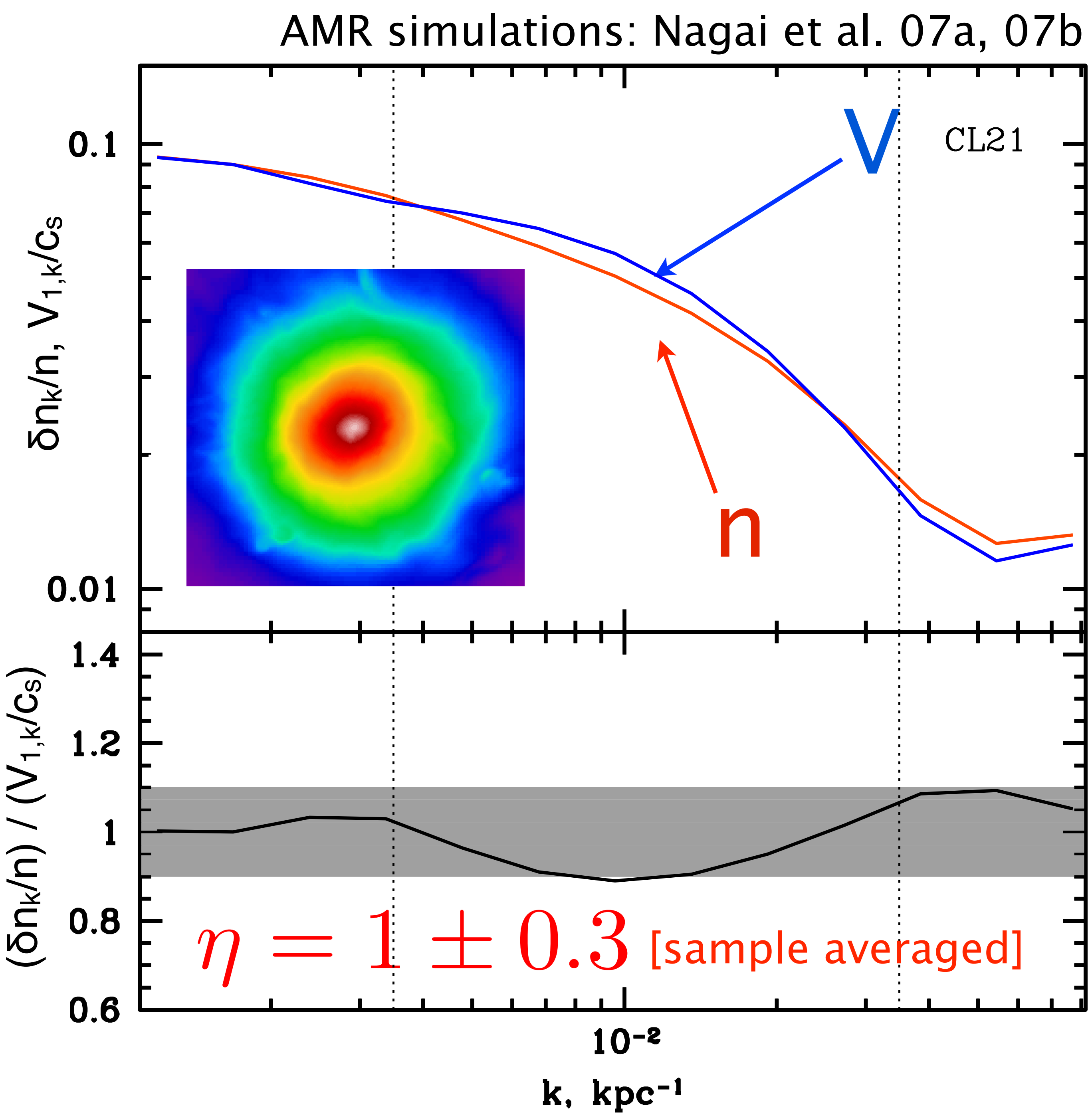
on each scale 1/k:

$$\frac{\delta n_k}{n} = \eta \frac{V_k}{c_s}$$

$$\eta \approx 1$$

* in pure hydro case without conduction and viscosity

Verifying the Coefficient in δn/n–V Relation

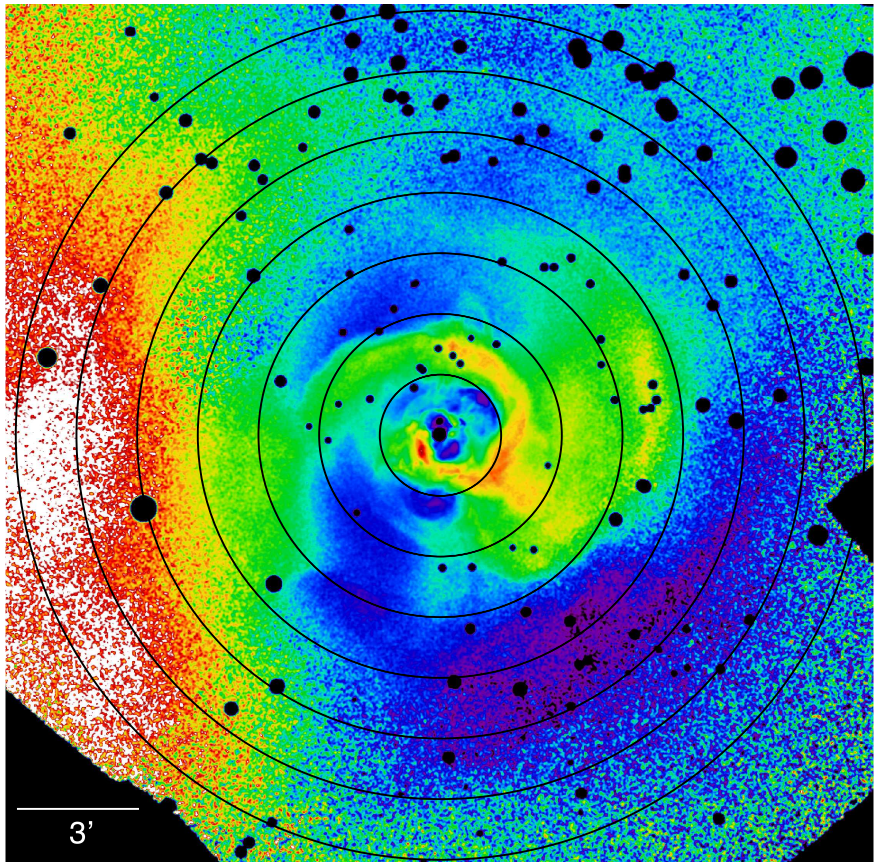


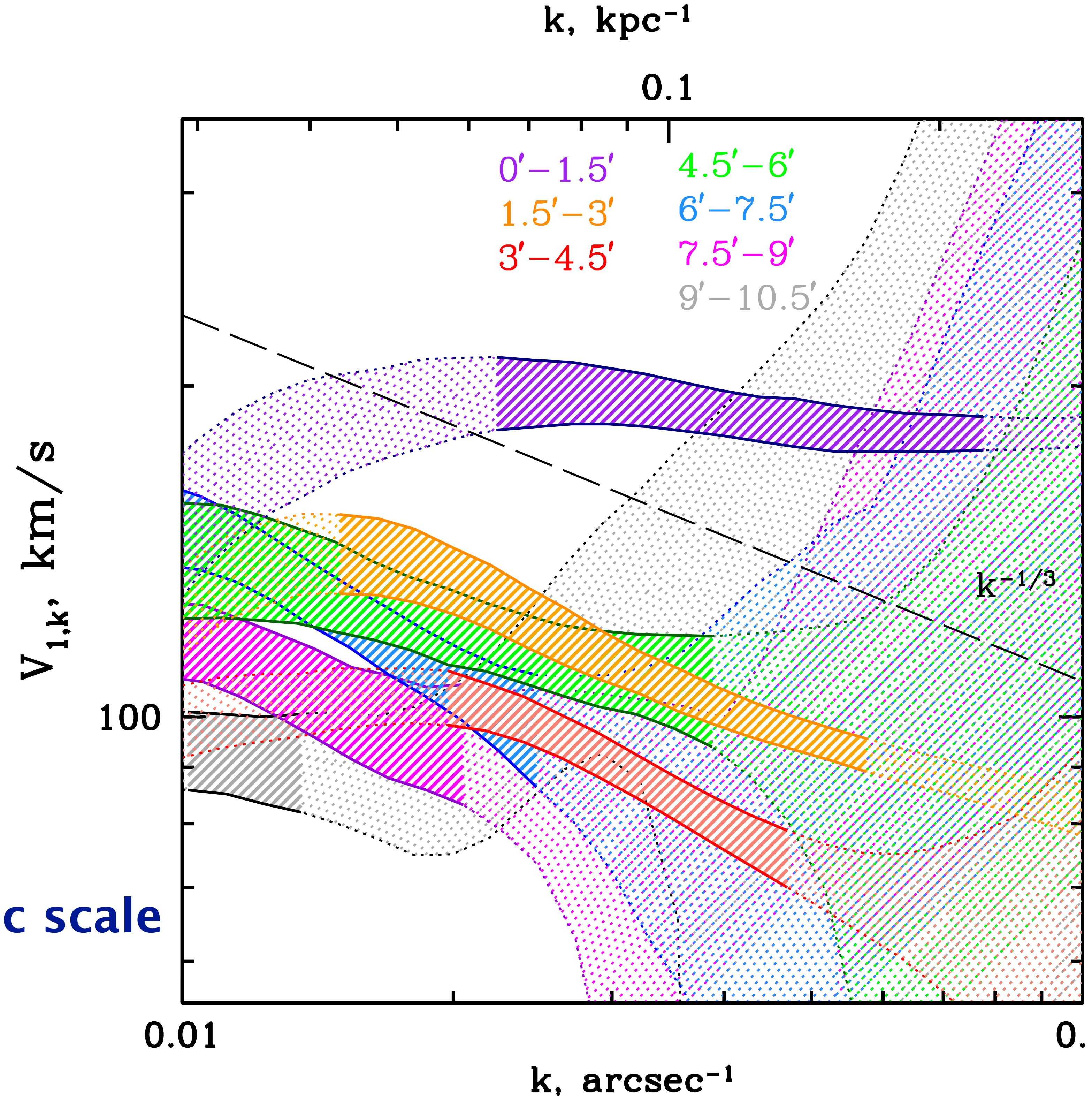
[IZ+14a]

hydro simulations: η ~1 w/o conduction [Gaspari+14]

δn/n–V works in simulated galaxy clusters

Velocity Power Spectrum in Perseus

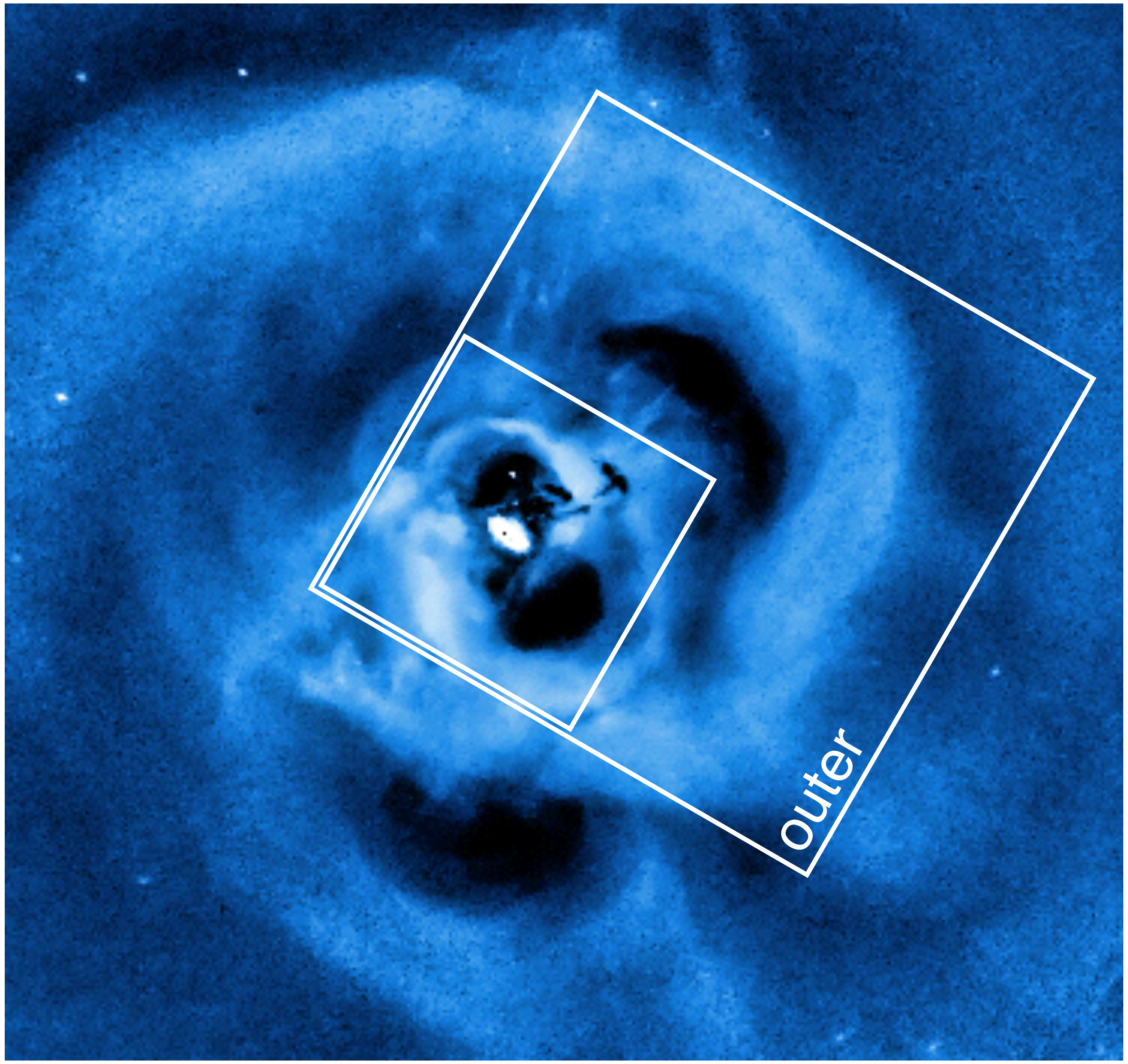




V<200-150 km/s on 5-30 kpc scale

[IZ+15]

Velocity Measurements:
Hitomi (Direct) vs Chandra (Indirect)



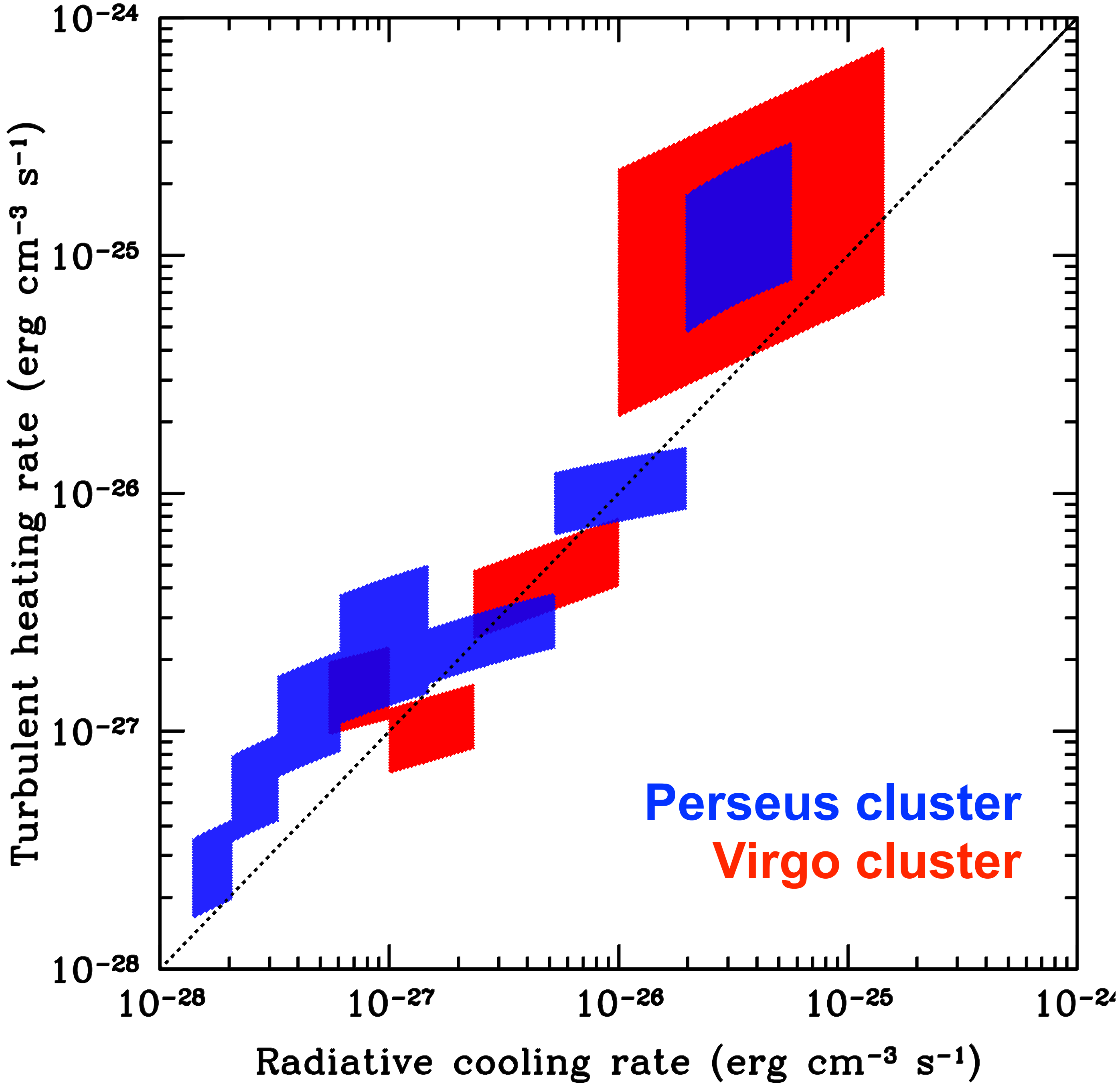
in preparation

Hitomi (line broadening) ≈ Chandra (I_x fluctuations)

But: 1) have to measure injection scale
2) factor of 2 uncertainty from fluctuations

Turbulent Heating vs Cooling in Cluster Cores

$$H(k) = C_H \rho V_{1,k}^3 k \qquad C = n_e n_i \Lambda_n(T)$$



in preparation

Turbulent Heating ~ Cooling

[IZ+14b; IZ+16b in prep.]

Summary:

- AGN-induced gas fluctuations are predominantly isobaric (/isothermal)

- Adiabatic fluctuations dominate in specific regions, in some galaxies

- Simulations: mixture of fluctuations, R approaches isobaric predictions

- Sample of nearby clusters: V_{1D}<220 km/s @ 50 kpc scales
  V_{1D}~few 10s km/s @ <5 kpc scales

- Cooling vs turbulent heating: approximate balance
  [though scatter and uncertainties are large]

Wish list of things to do [simulations]:

- Measure effective EoS of gas fluctuations and compare it with observations

- Further verify density-velocity relation, accounting for additional physics