Diagnostics of turbulence and bulk motions in ICM

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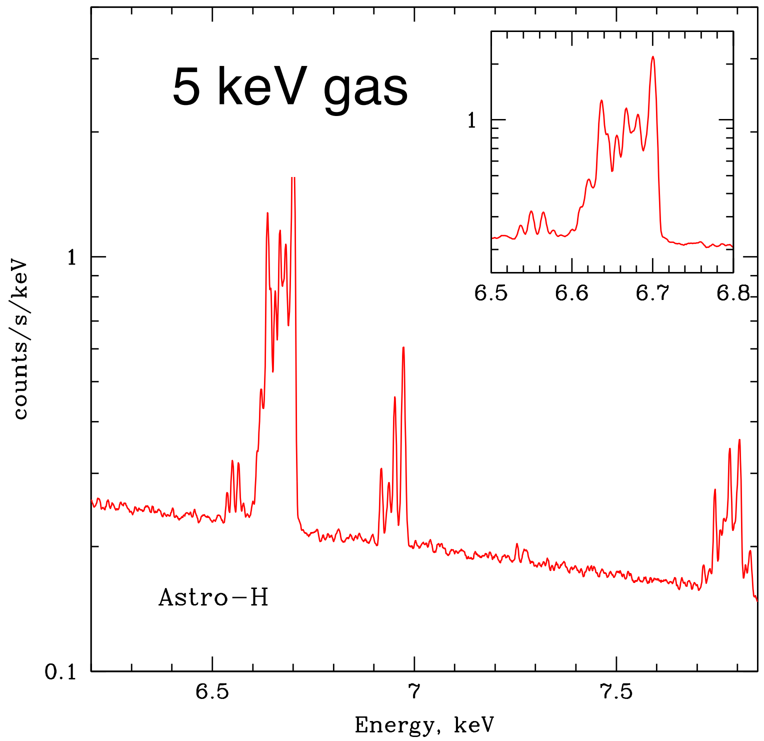
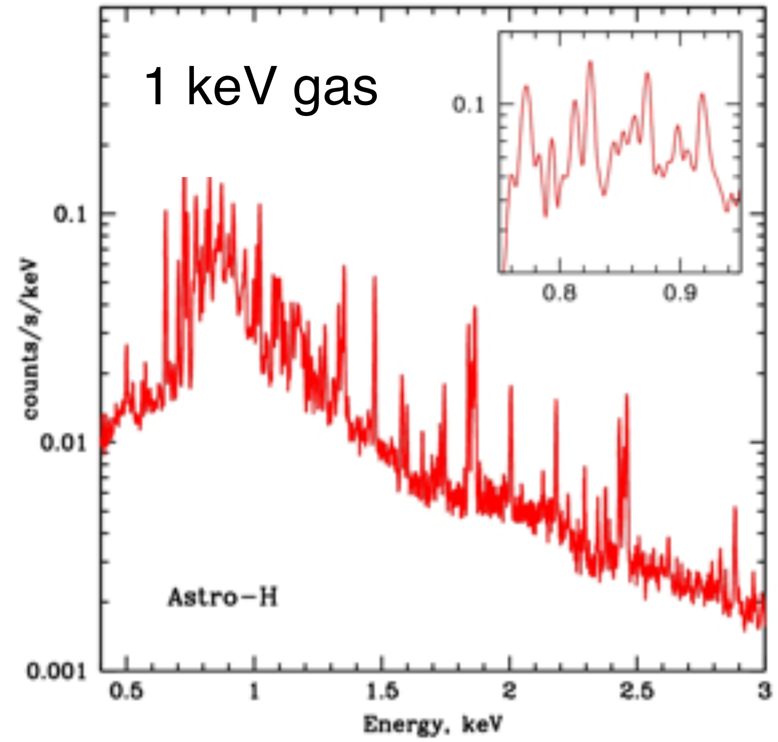
for this talk:
turbulence=motions of gas

ICM physics and modeling, Garching, June 15-17

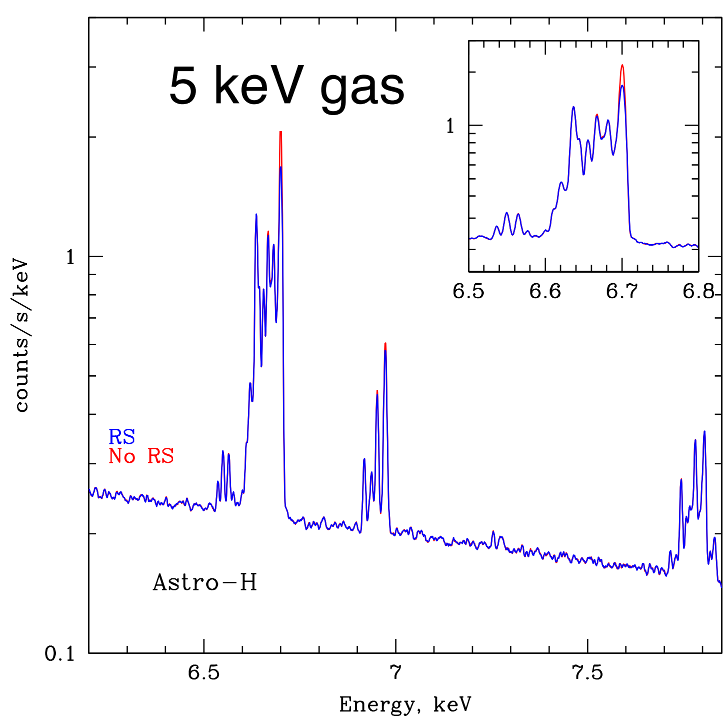
Amplitude I: line broadening and shift

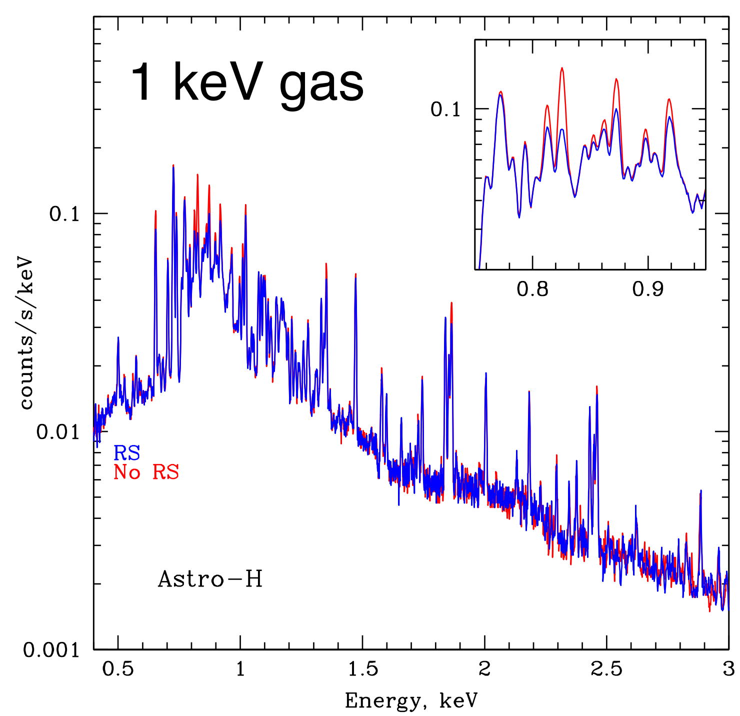




RGS measurements:
Sanders+10,11,13; Bulbul+12;
Pinto+15

Amplitude II: resonant scattering





Gilfanov+87, Churazov+10;

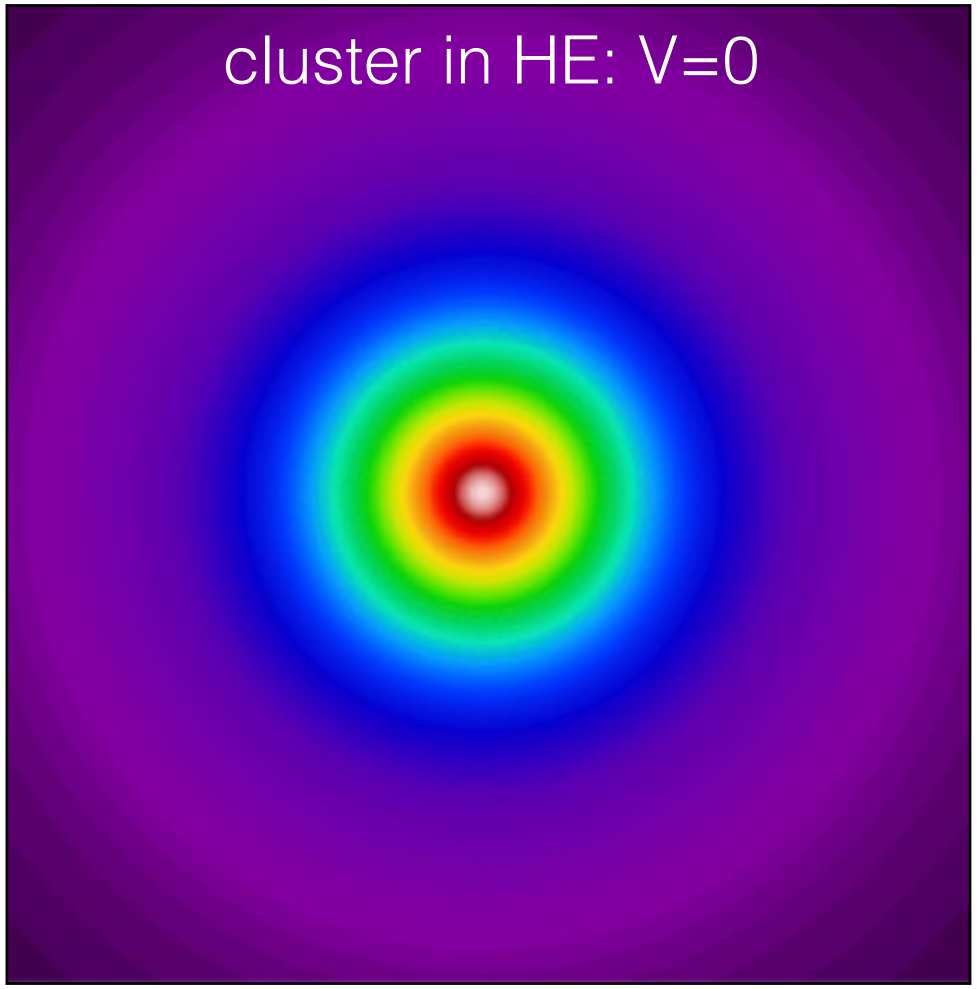
RGS measurements:
e.g. Xu+02; Kahn+03; Werner+09; de Plaa+12

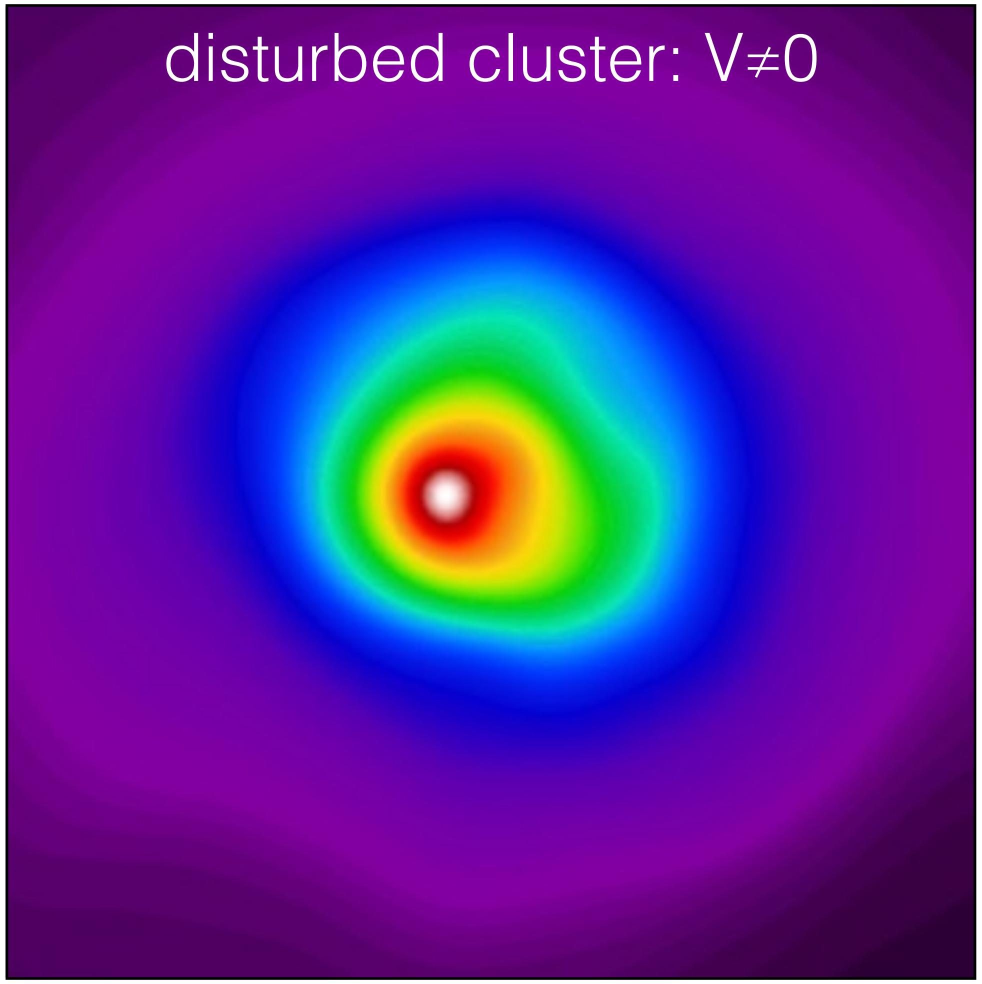
Chandra and XMM measurements:
e.g. Molendi+98; Akimoto+99; Churazov+04; Sanders+04; Gastaldello+04; Zhuravleva+13

Amplitude III: mixture modeling

Shang & Oh12

Indirect constraints of velocity amplitude as a function of spatial scale

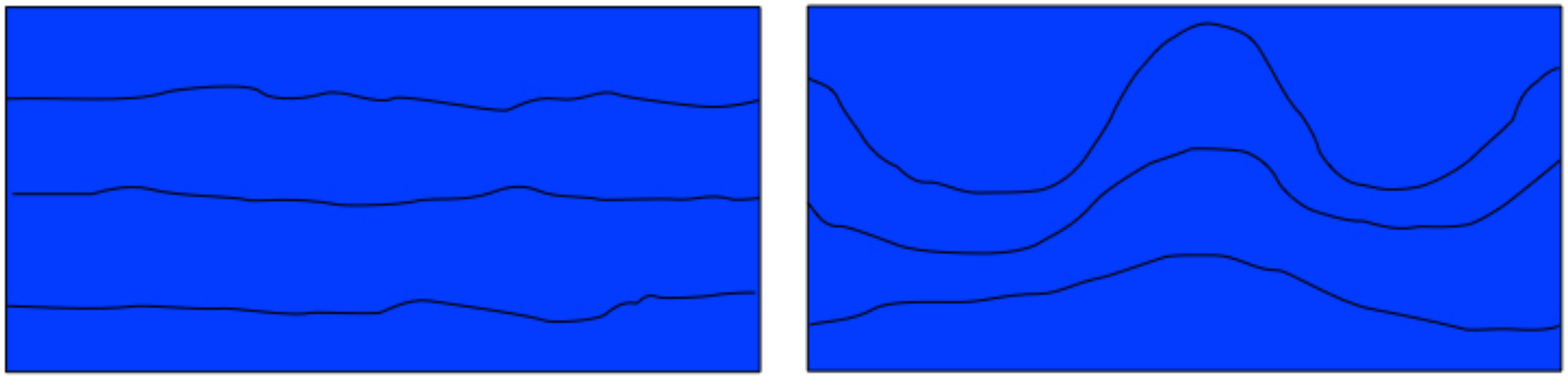




δρ —> V?

How do density perturbations scale with the velocity field?

homogeneous box

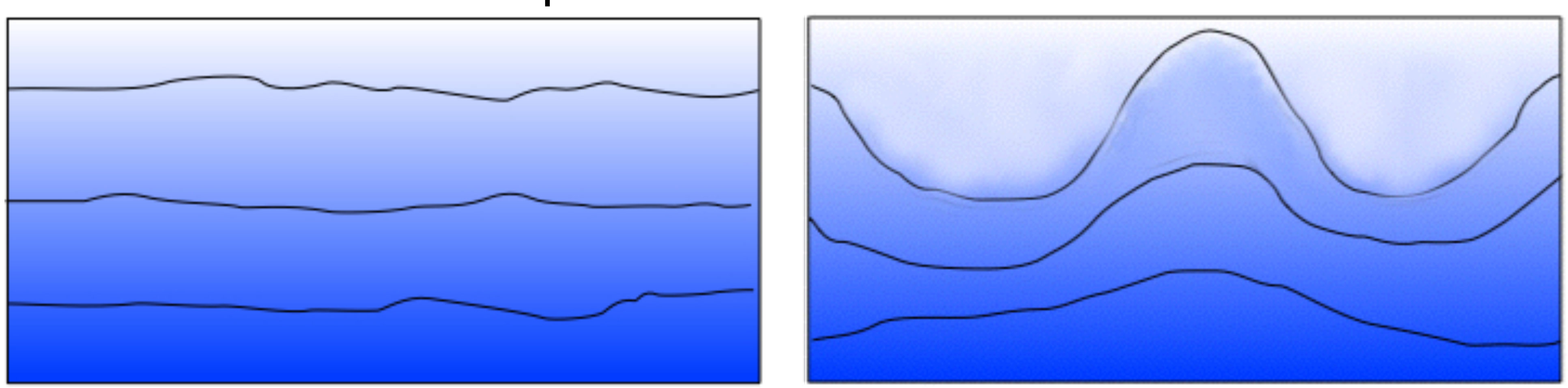


$\delta\rho \propto M^2$

Bernoulli's principle

(solenoidal motions)

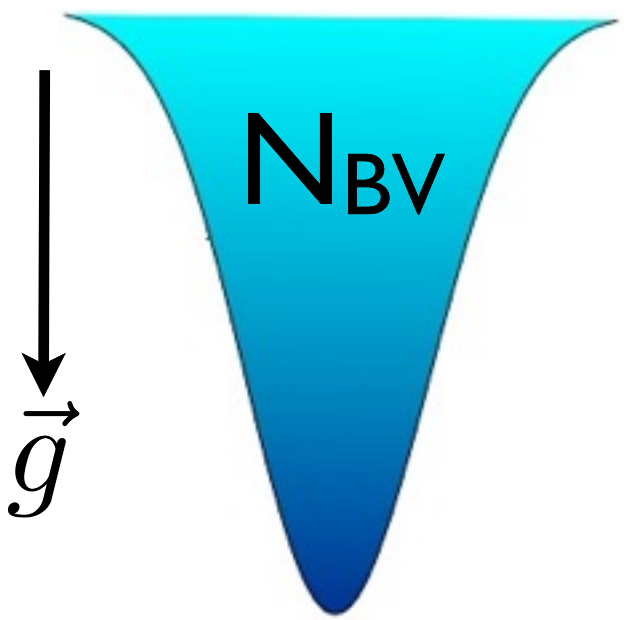
stratified atmosphere

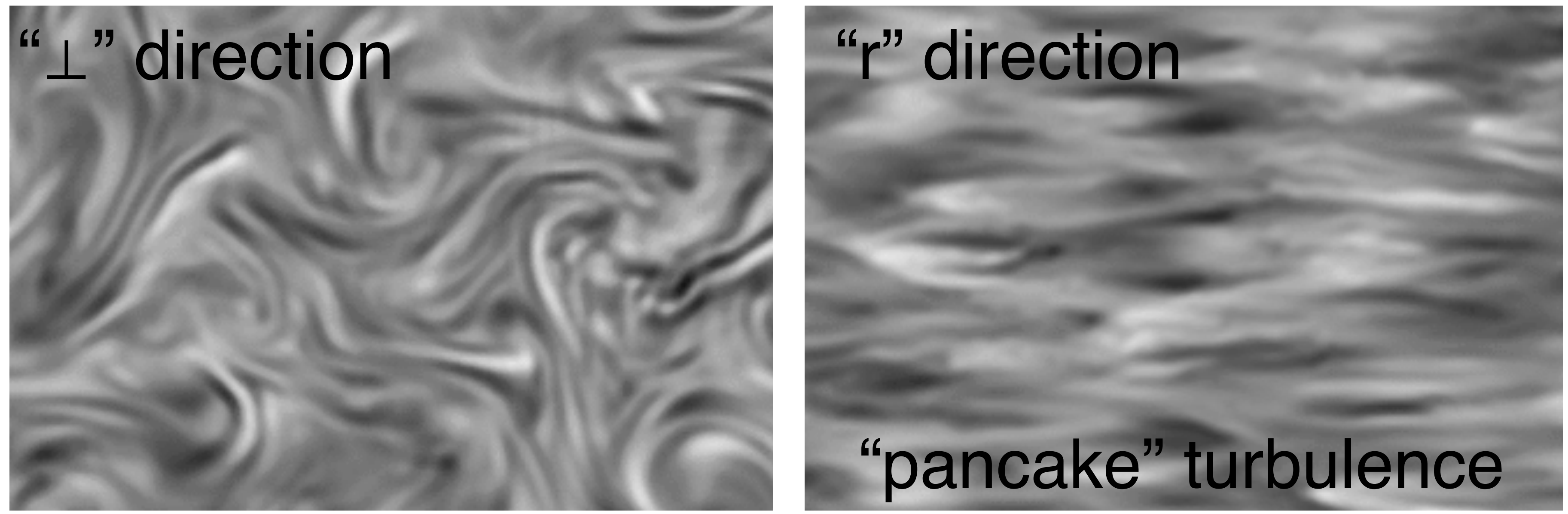


?

Stratified turbulence

slow perturbations, $\omega \ll N_{BV}$ => g-modes => stratified turbulence

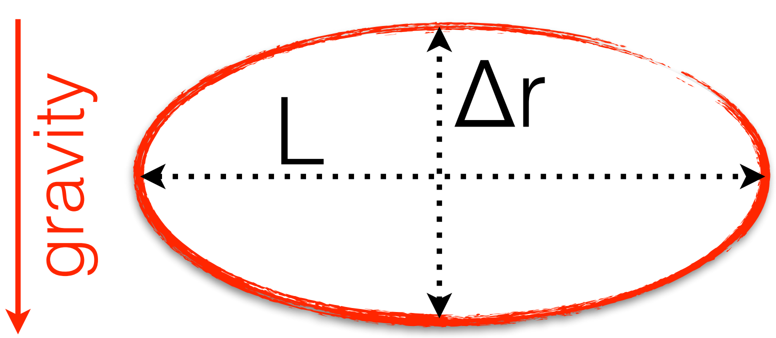




Waite & Bartello 2006

on large scales V is dominated by $V_\perp$

Turbulent eddy at injection scale L :



$V_r \ll V_\perp \sim V$

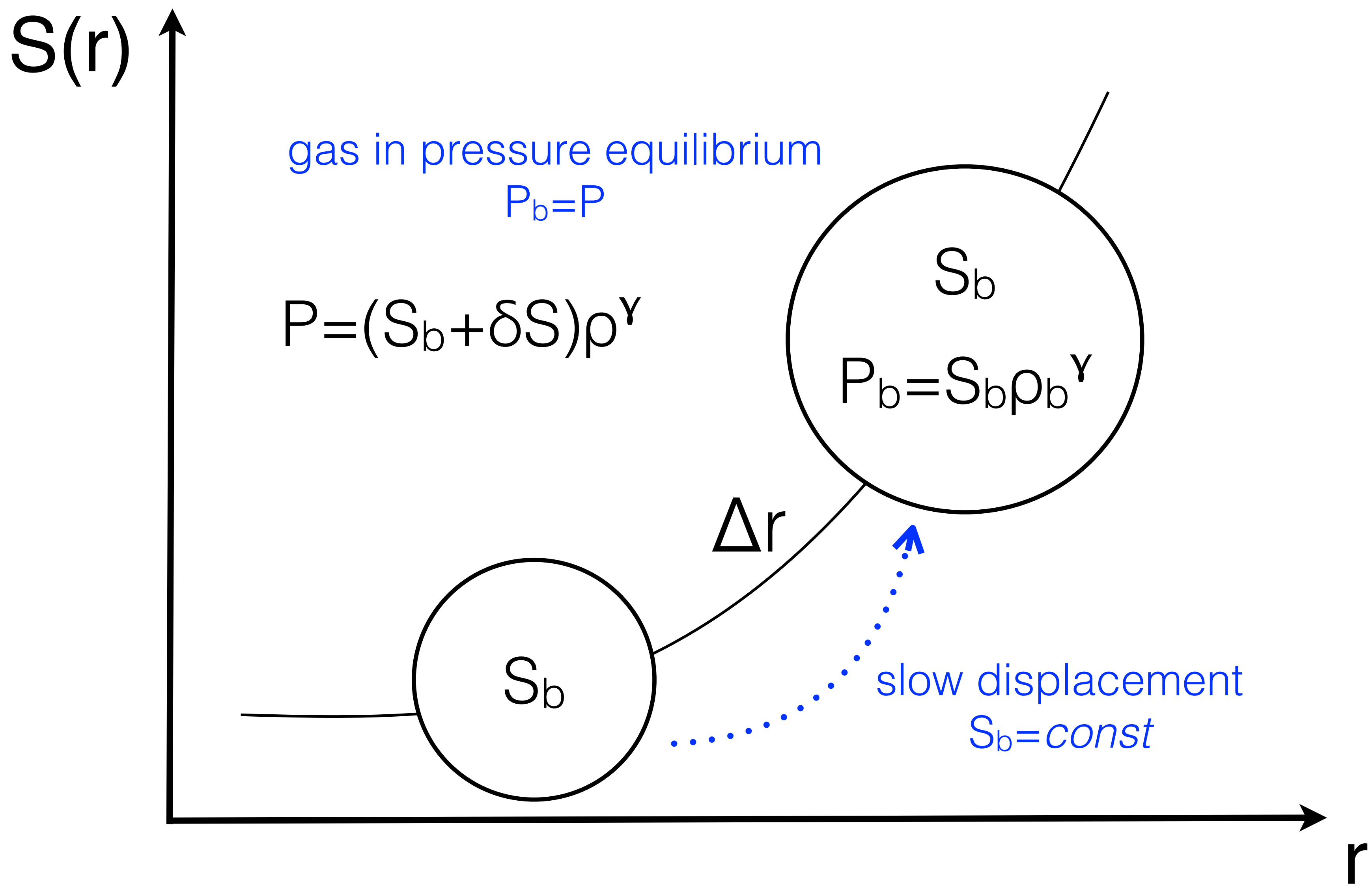
$$\frac{\Delta r}{L} \approx \frac{\omega}{N_{BV}}$$

$$V_\perp = L\omega \sim V$$

$$V = N_{BV} \Delta r$$

gravity provides V - Δr relation

Gas displacement and density contrast



density contrast after (slow) gas displacement:

$$\frac{\delta\rho}{\rho} = \frac{1}{\gamma}\frac{\delta S}{S} \approx \frac{1}{\gamma}\frac{\Delta r}{H}$$

entropy scale height

entropy gradient gives δρ - Δr relation

Buoyancy-dominated regime of motions

entropy gradient:

$$\frac{\delta\rho}{\rho} = \frac{1}{\gamma}\frac{\Delta r}{H_s}$$

gravity:

$$V = N_{BV}\Delta r$$

$$N_{BV} = \frac{c_s}{\gamma\sqrt{H_s H_p}}$$

$$\frac{\delta\rho}{\rho} = \eta\frac{V}{c_s}$$

$$\eta = \sqrt{\frac{H_p}{H_s}} \sim 1$$

valid on large, buoyancy-dominated scales

on small scales:

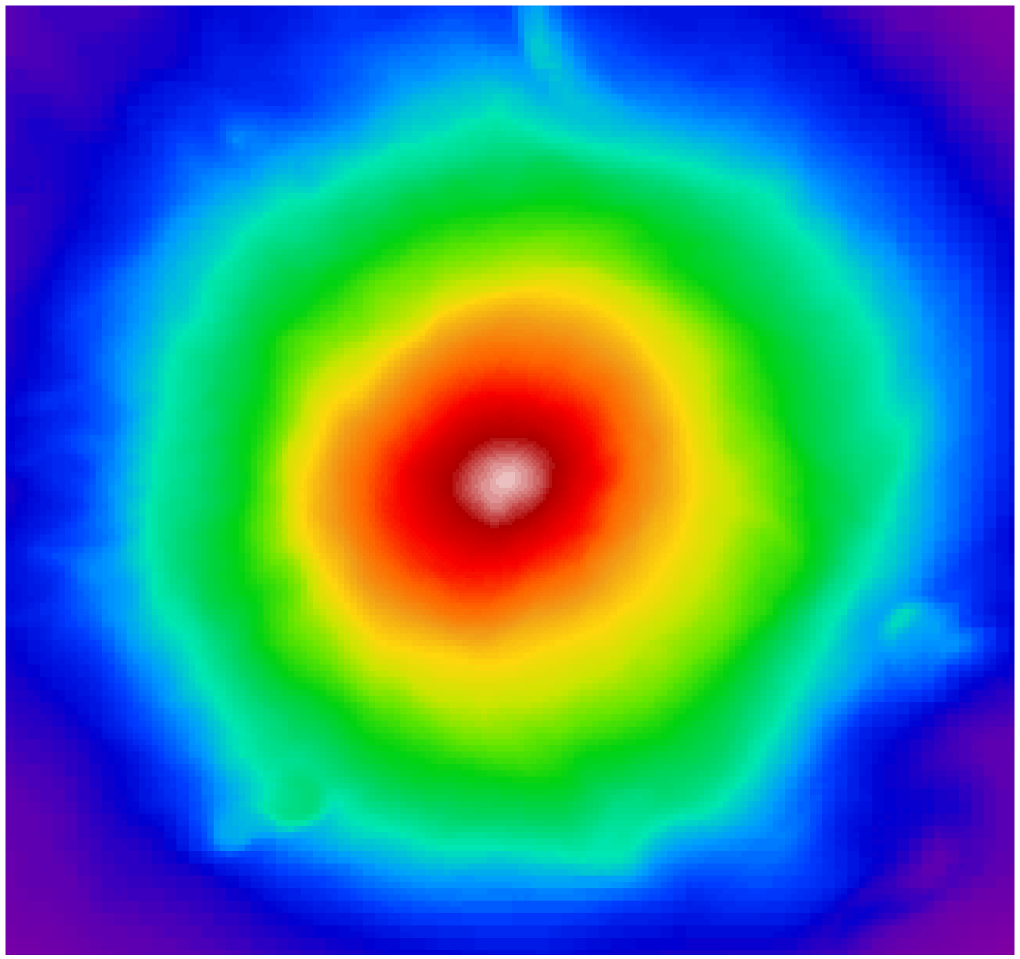
the relation retains since density is a passive scalar

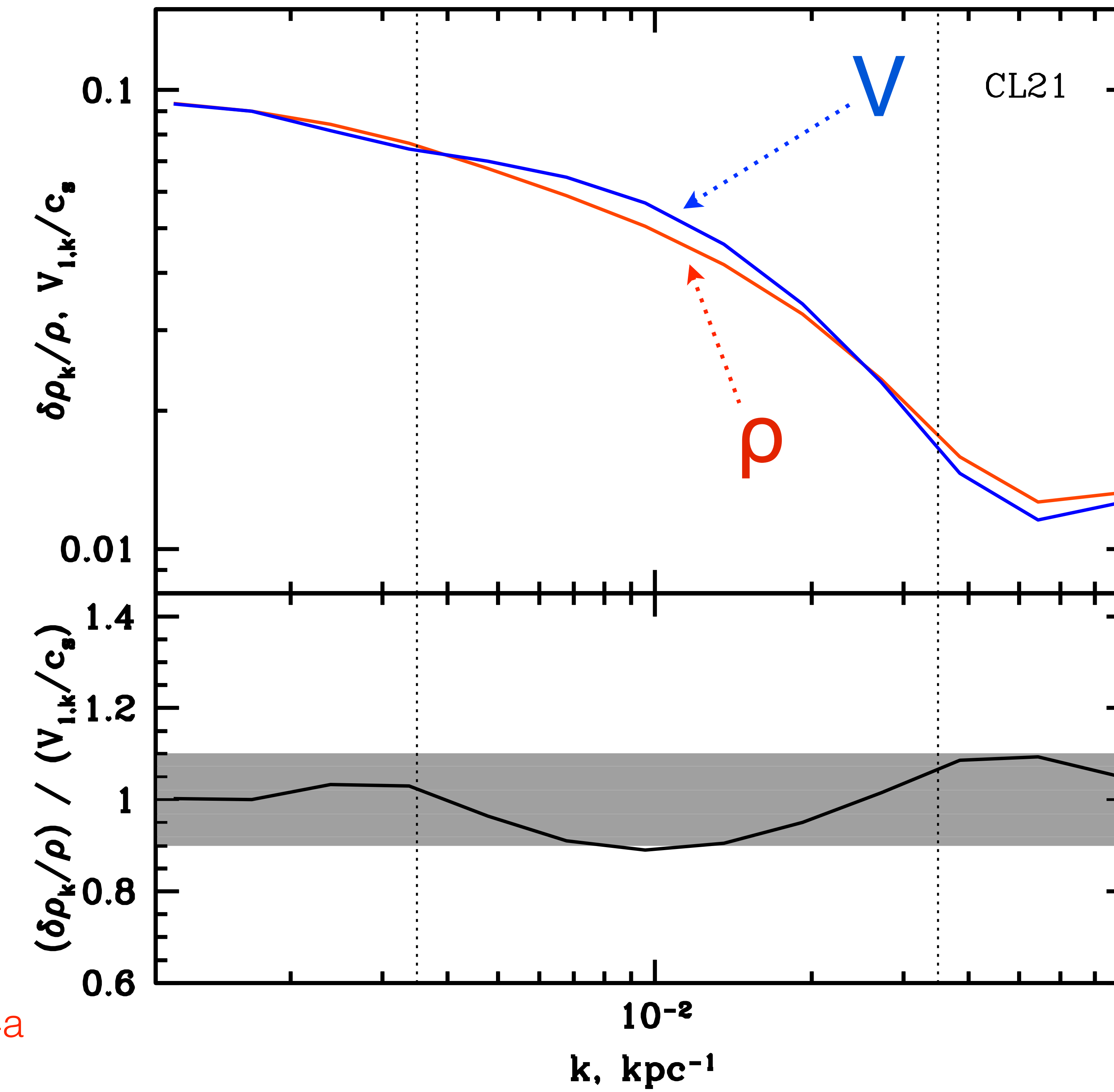
(Obukhov 49; Corrsin 51)

Verifying the coefficient η

AMR cosmological simulations, NR runs, relaxed clusters

Kravtsov+99;03; Nagai+07a; Nelson+14





sample averaged

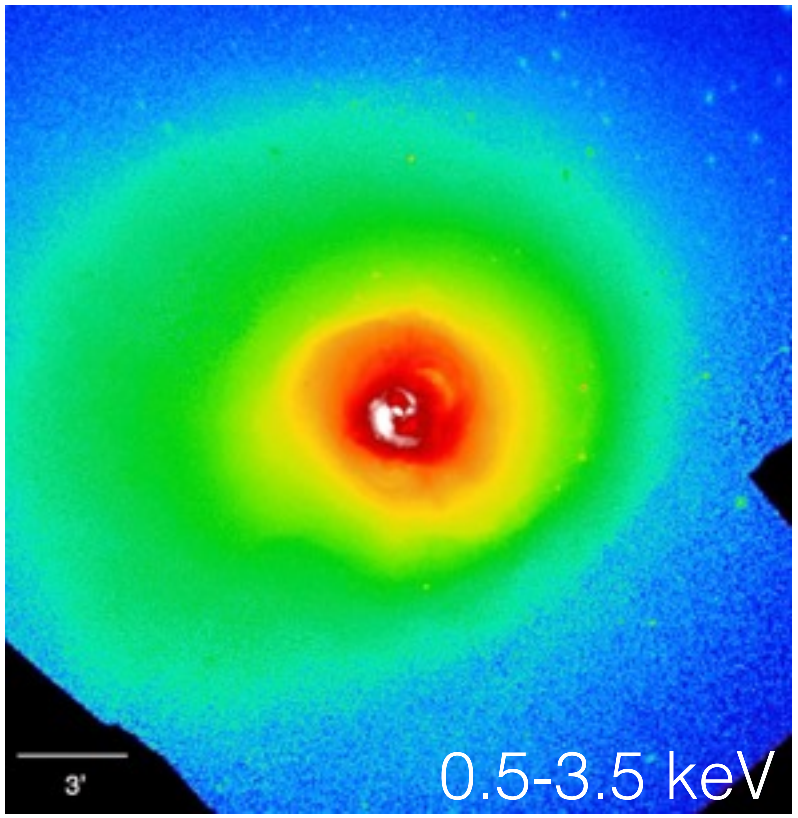
$$\eta = 1 \pm 0.3$$

Zhuravleva+2014a

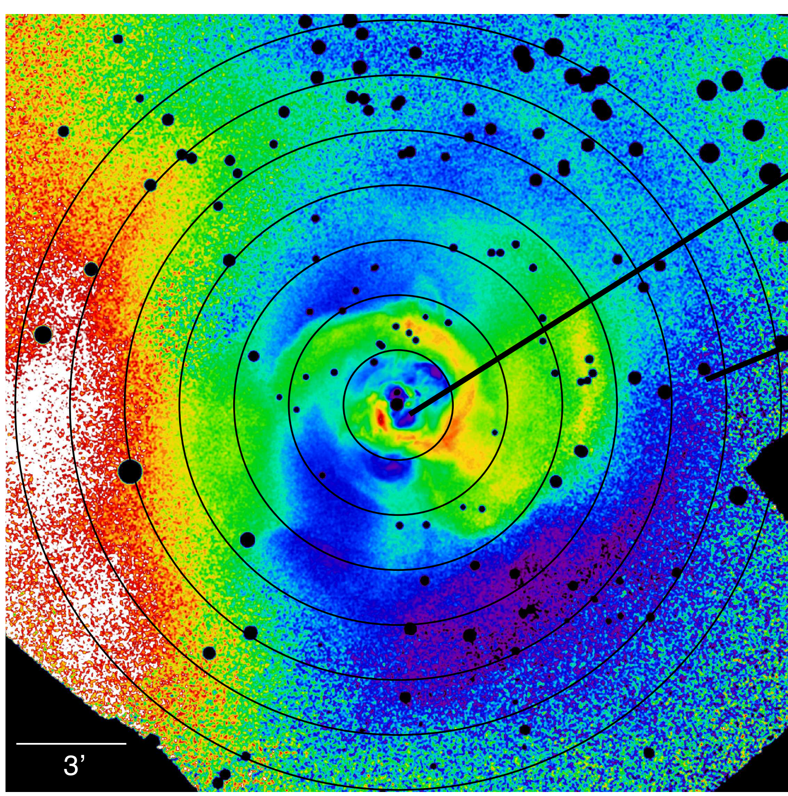
hydro simulations: η ~1 w/o conduction

Gaspari+2014

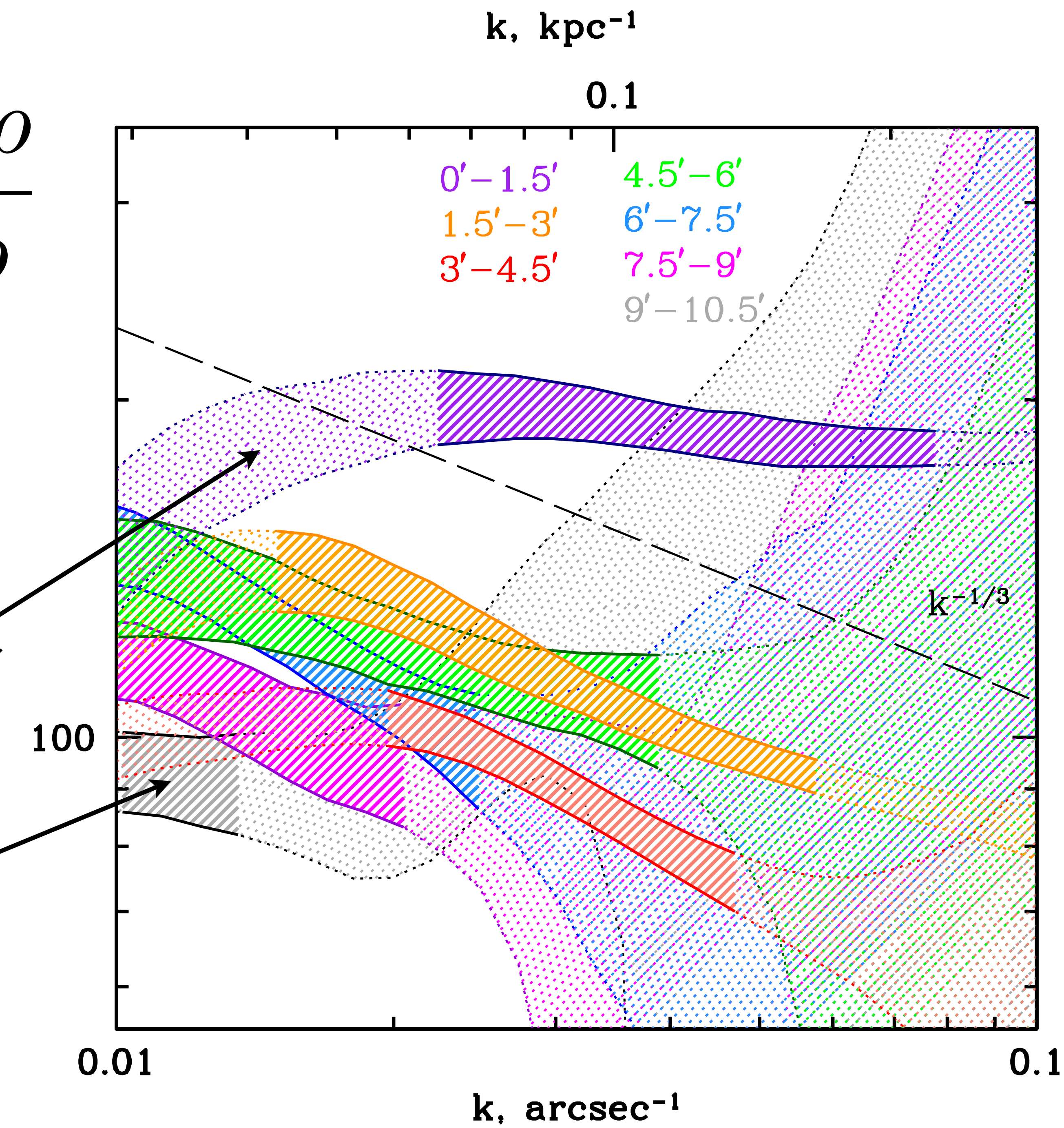
Velocity power spectrum in the Perseus cluster



⟵ 400 kpc ⟶



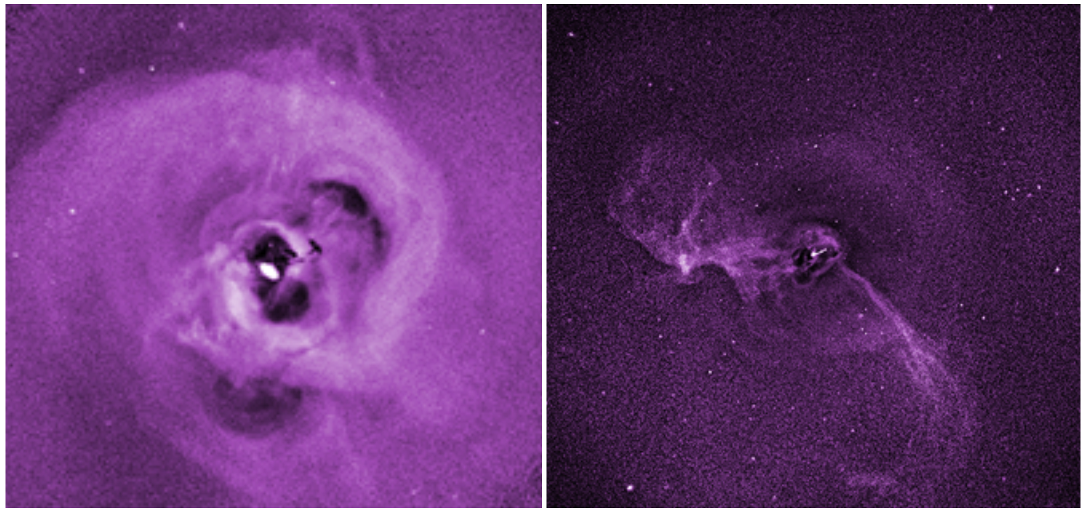
$$V_k = c_s \frac{\delta\rho}{\rho}$$

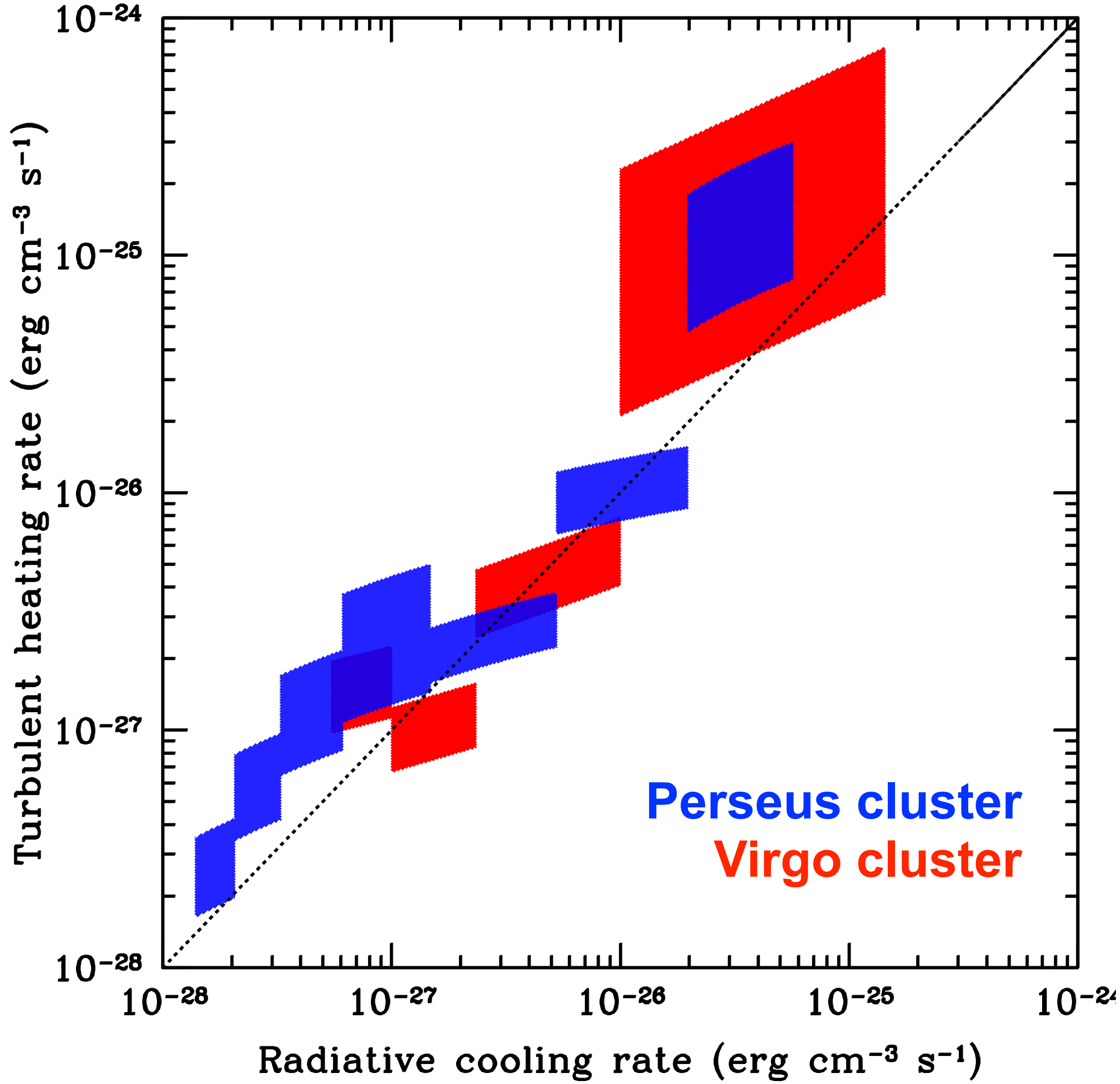


- V higher towards center —> power injection from center
- larger V on smaller k —> consistent with cascade turbulence
- 70 km/s < $V_{1,k}$ < 200 km/s on scales 6-30 kpc

Zhuravleva+15a

Turbulent dissipation in AGN feedback





cooling rate:

$$C = n_e n_i \Lambda_n(T)$$

heating rate:

$$H(k) = C_H \rho V_{1,k}^3 k$$

locally: cooling ~ heating

AGN —> Bubbles —> g-modes—> Turbulent dissipation —> Heat

Zhuravleva+14b

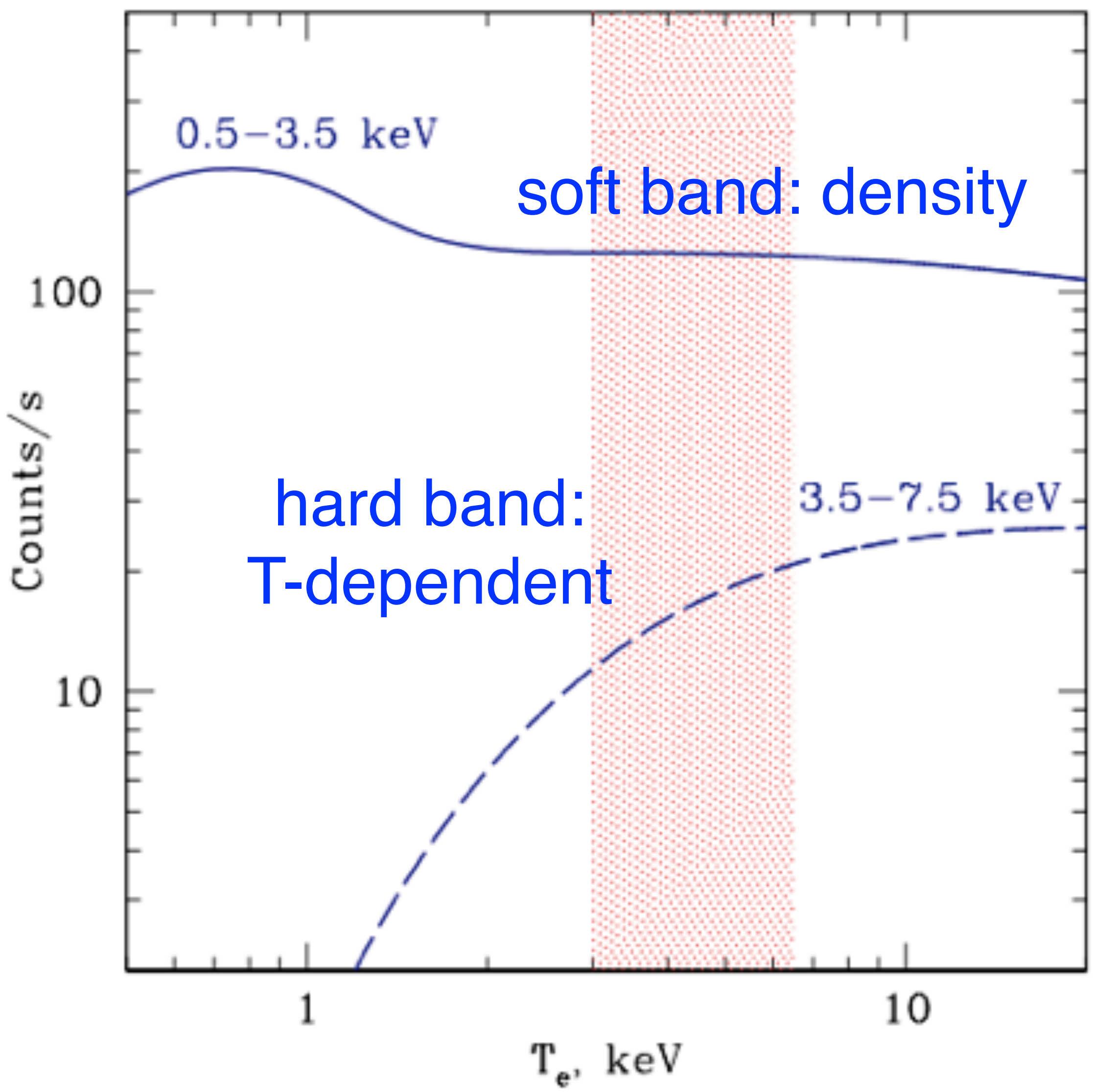
Types of fluctuations

"effective" equation of state: $$\frac{\delta T}{T} = (\gamma - 1)\frac{\delta n}{n}$$

γ=0: isobaric
slow displaced gas

γ=5/3: adiabatic
weak shocks
sound waves

γ=1: isothermal
bubbles



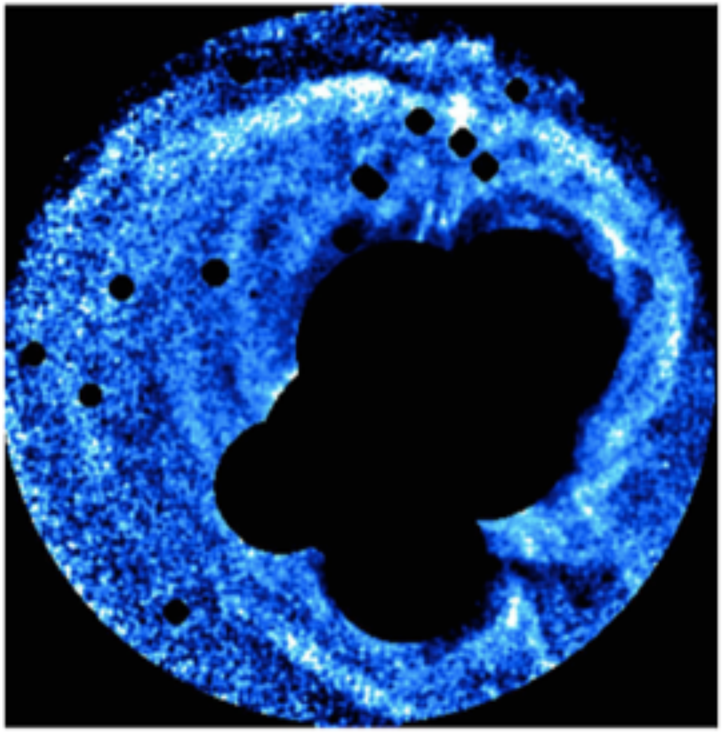
in preparation

Response of two bands to different types of perturbations

if mixture of processes:

$P=\alpha_1 P_{adiab.} + \alpha_2 P_{isob.} + \alpha_3 P_{isoth.}$ $(\alpha_1^2+\alpha_2^2+\alpha_3^2)^{1/2}=1$

in preparation



Nature of ripples in the Perseus cluster

sound waves or stratified turbulence?

(Fabian+03; Sanders+07) (Zhuravleva+14; 15)

in preparation

- **dominated by isobaric fluctuations**
- **consistent with slow displacement of gas: sloshing, turbulence, g-modes**

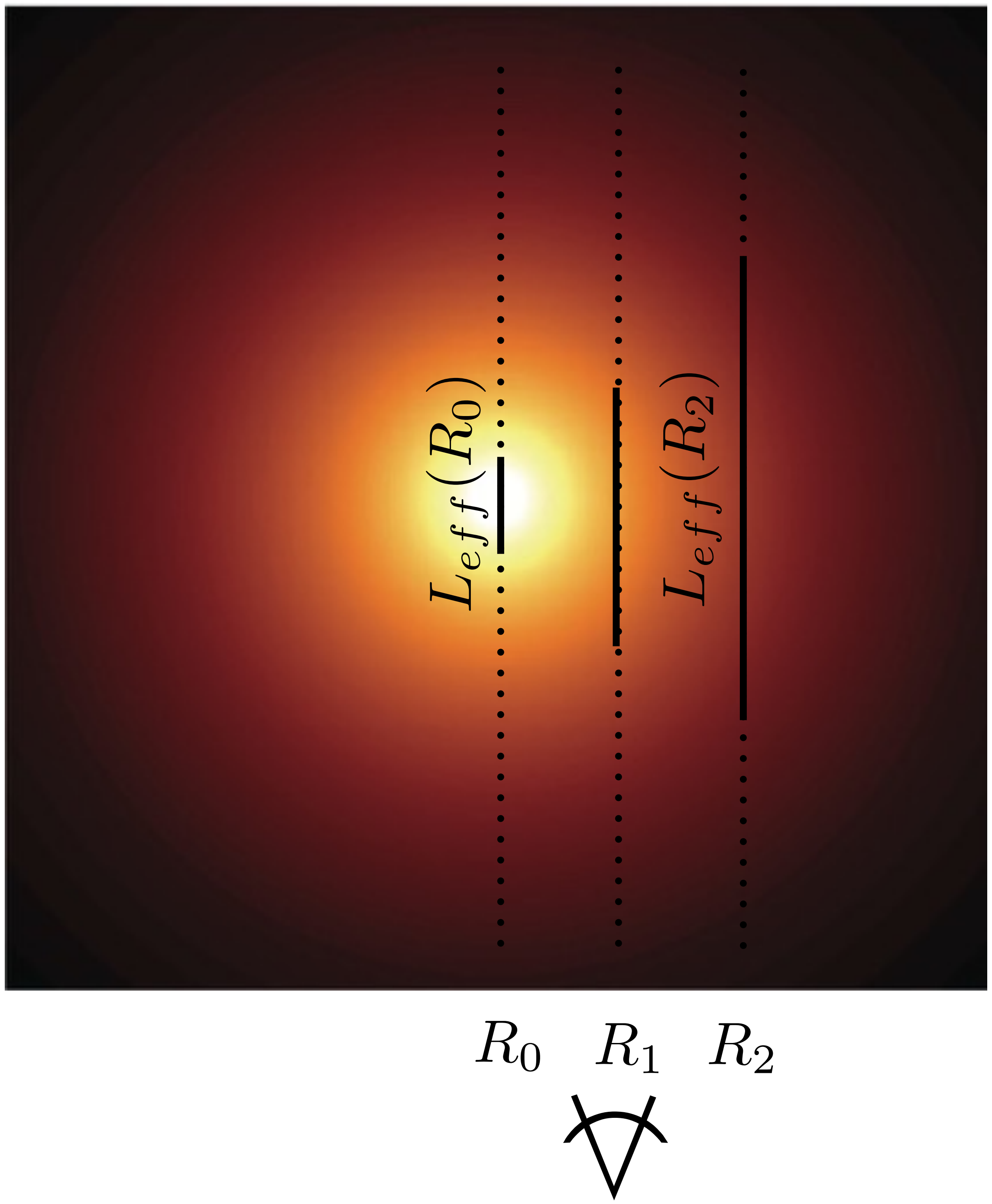
Zhuravleva+15b in prep.; Arevalo+15 in prep.; Churazov+15 in prep.

Indirect constraints of velocity power spectrum

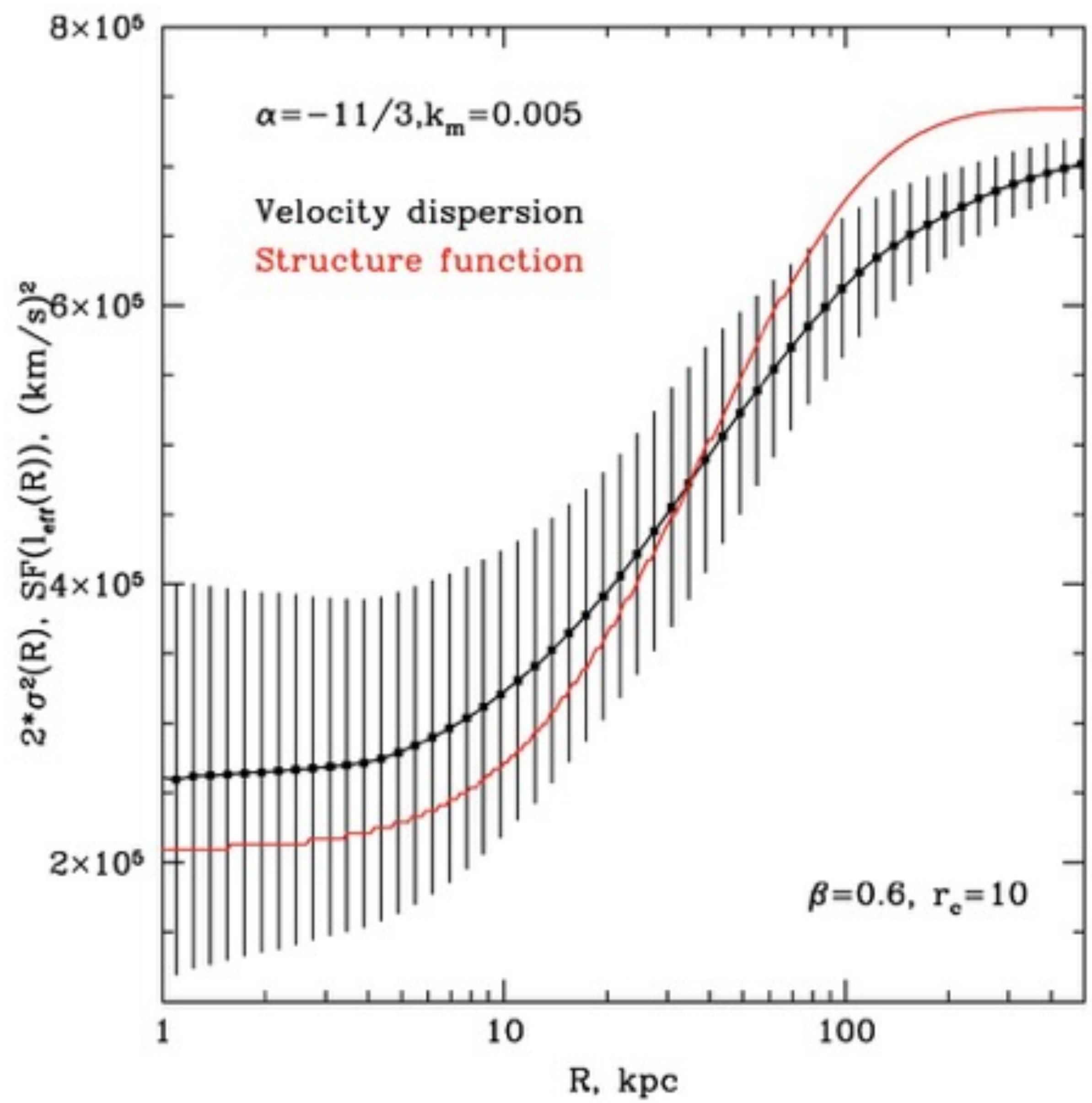
- cross-spectrum analysis —> fraction of isobraic fluctuations
- spectrum of density fluctuations —> velocity spectrum
- calibrate with Astro-H direct measurements

Observed σ and structure function

$$\mathrm{SF}(\Delta r) = \langle (V(r) - V(r+\Delta r))^2 \rangle$$



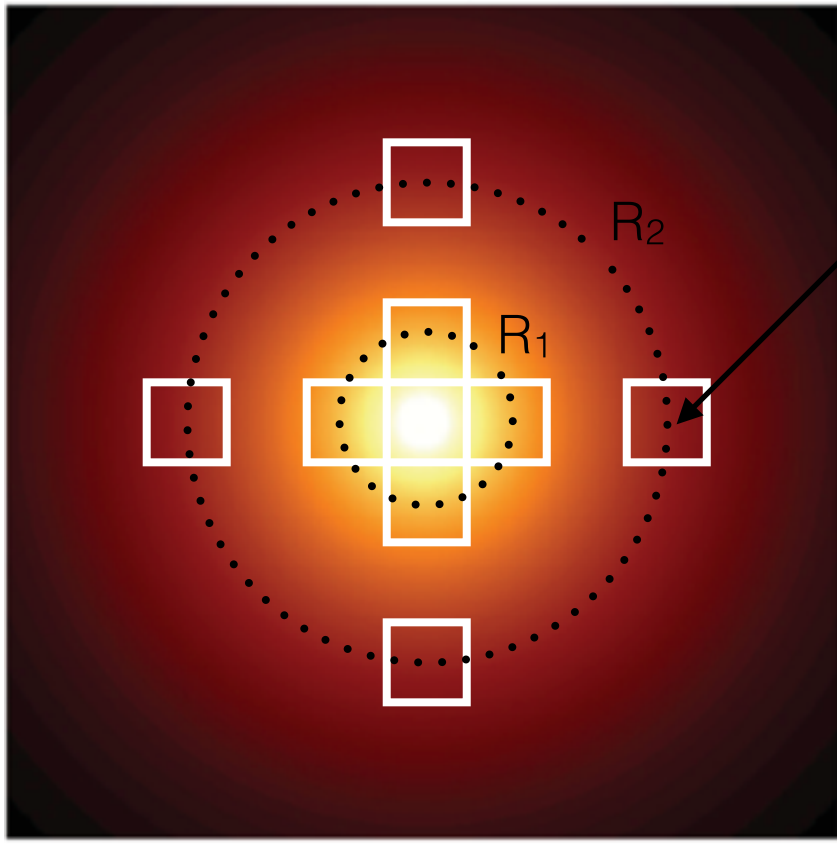
At a given R an interval L_{eff} ~ R contributes to the line flux (width)



Observed σ(R) ≈ structure function (L_{eff})

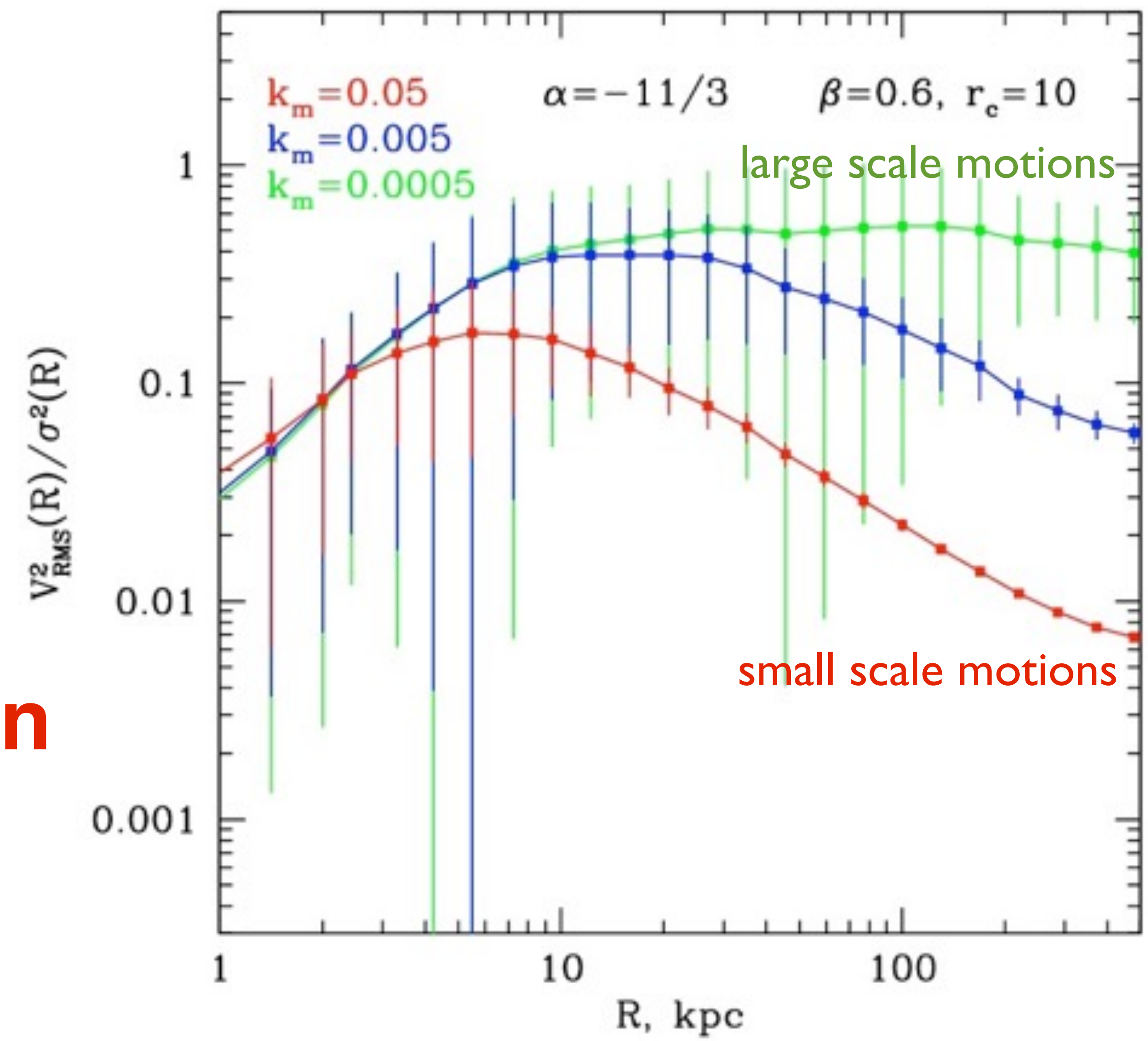
Zhuravleva+12

RMS of centroid shift and injection scale



σ; V

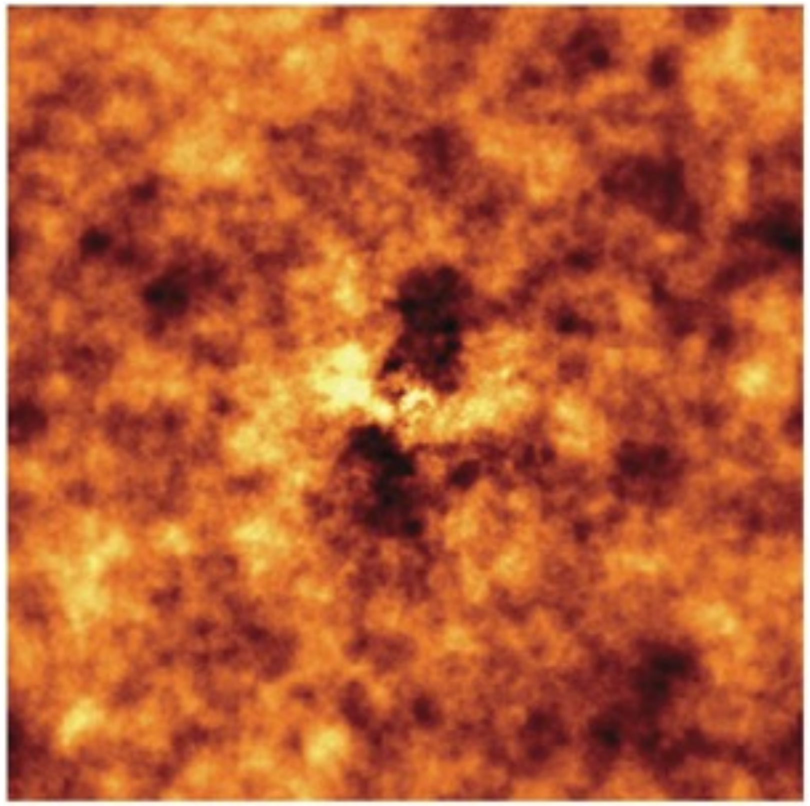
$$\frac{\mathrm{RMS}(V(R))}{\sigma(R)} \longrightarrow k_{inj}$$



cosmic variance is the main source of uncertainties

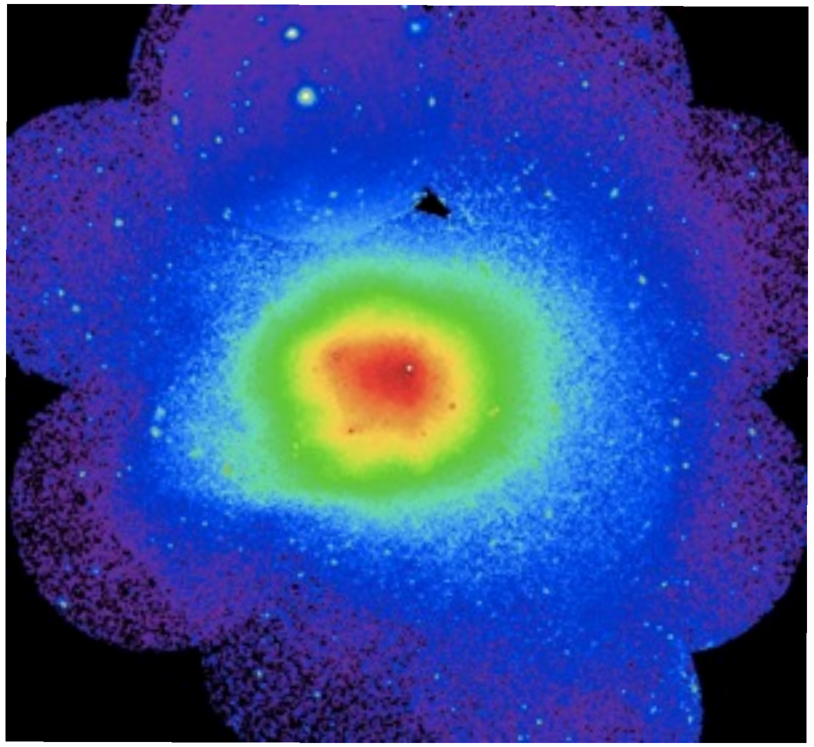
Zhuravleva+12

V(x,y) and power spectrum of V3D



$$\rightarrow V(x,y) \rightarrow P_{\rm 2D}(k)$$

$$P_{\rm 2D}(k) \rightarrow P_{\rm 3D}(k)$$



for Coma-like clusters
(flat surface brightness)

$$(k >> 1/L_{eff})$$

$$P_{\rm 2D}(k) \approx P_{\rm 3D}(k) \int P_{\rm EM}(k_z, x, y) dk_z$$

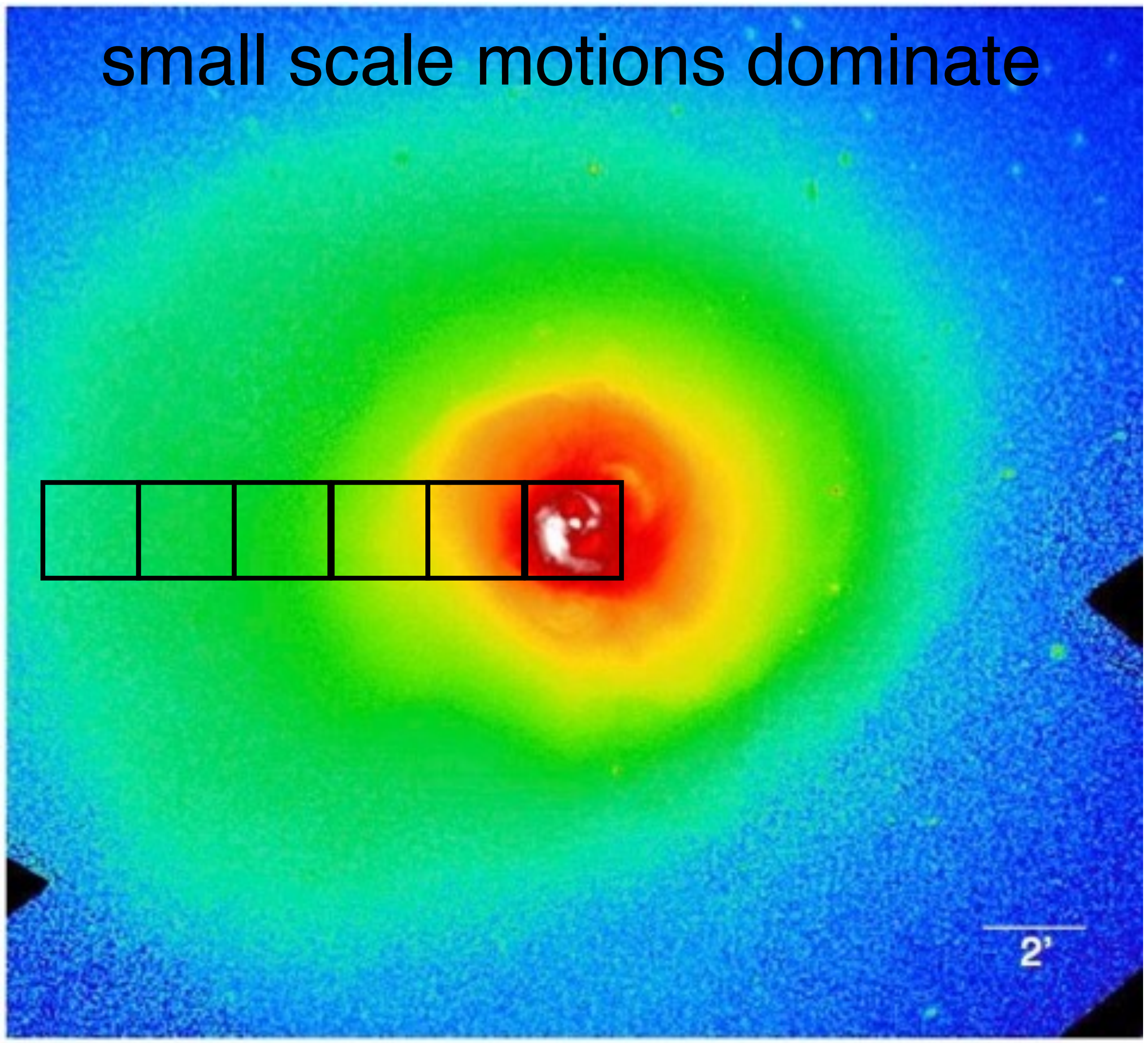
Zhuravleva+12

for detailed analysis of Coma structure function see ZuHone+15

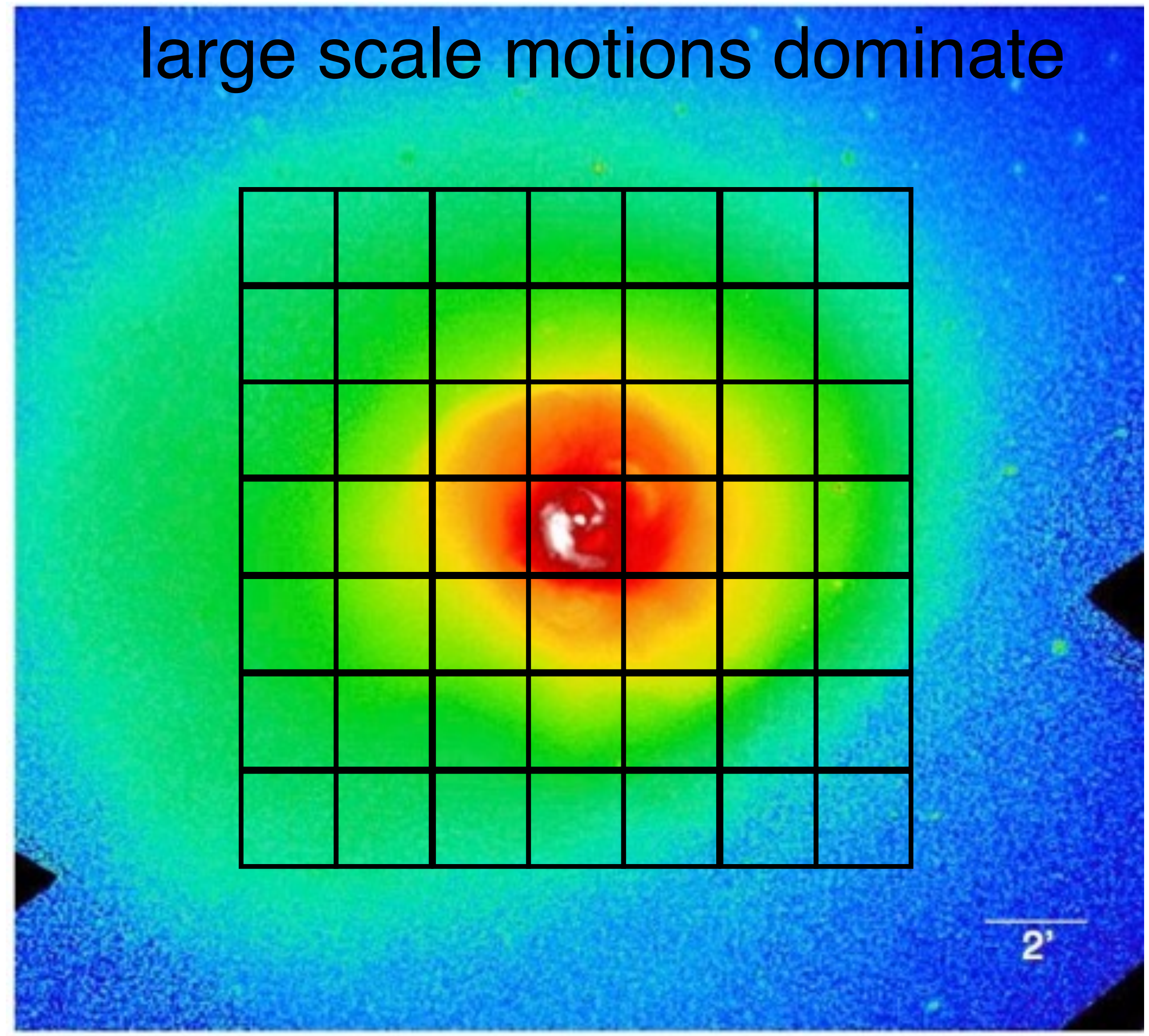
“cosmic variance” of turbulence

First things to do:

1. take two pointings (central and at distance r)
2. measure σ and RMS(V) using these two observations
3. ratio RMS(V)/σ will show whether motions are dominated by large or small scales



σ(R) ≈ constant
small cosmic variance



cosmic variance dominate
mapping will decrease the variance

Zhuravleva+12; ZuHone+15

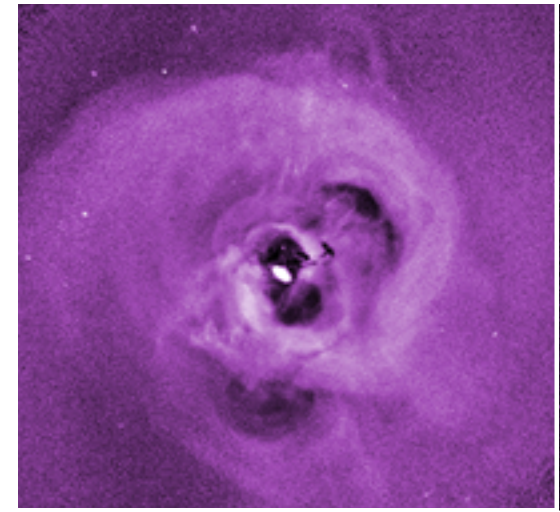
Direct constraints of velocity amplitude(scale) with Astro-H

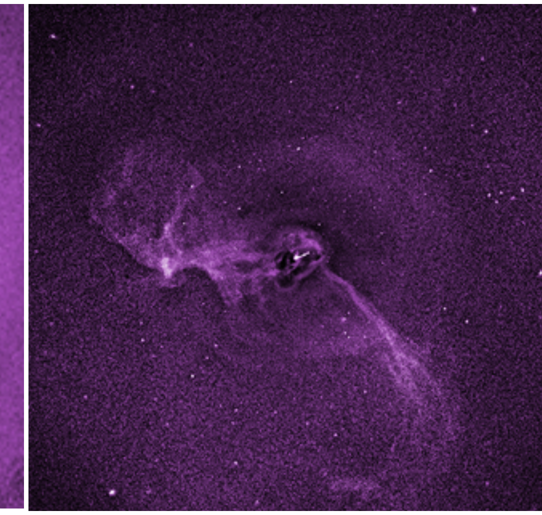
- injection scale: possible
- dissipation scale: impossible
  (unless it is impossibly large)
- distinguish between different slopes: impossible
  (unless they differ from physically motivated models)
- cosmic variance

Summary

$$\frac{\delta\rho_k}{\rho} = \eta \frac{V_{1,k}}{c_s}$$

- relaxed clusters
- subsonic motions
- simplest approach





V measurements on different scales:

- Perseus: 70 km/s $< V_{1,k} <$ 200 km/s on 6 - 30 kpc (within ~ 200 kpc)
- Virgo: 40 km/s $< V_{1,k} <$ 90 km/s on 2 - 10 kpc (within ~40 kpc)

AGN-feedback:

- turbulence dissipation is sufficient to offset cooling locally at each r
- AGN —> Bubbles —> g-modes—>Turbulent dissipation —> Heat

Nature of fluctuations in Perseus:

dominated by isobaric fluctuations (turbulence, sloshing, g-modes)

Astro-H (end 2015), Athena (2028), Smart-X (?):

- direct measurements (amplitude, anisotropy, scales)
- verification of the linear relation, importance of microphysics