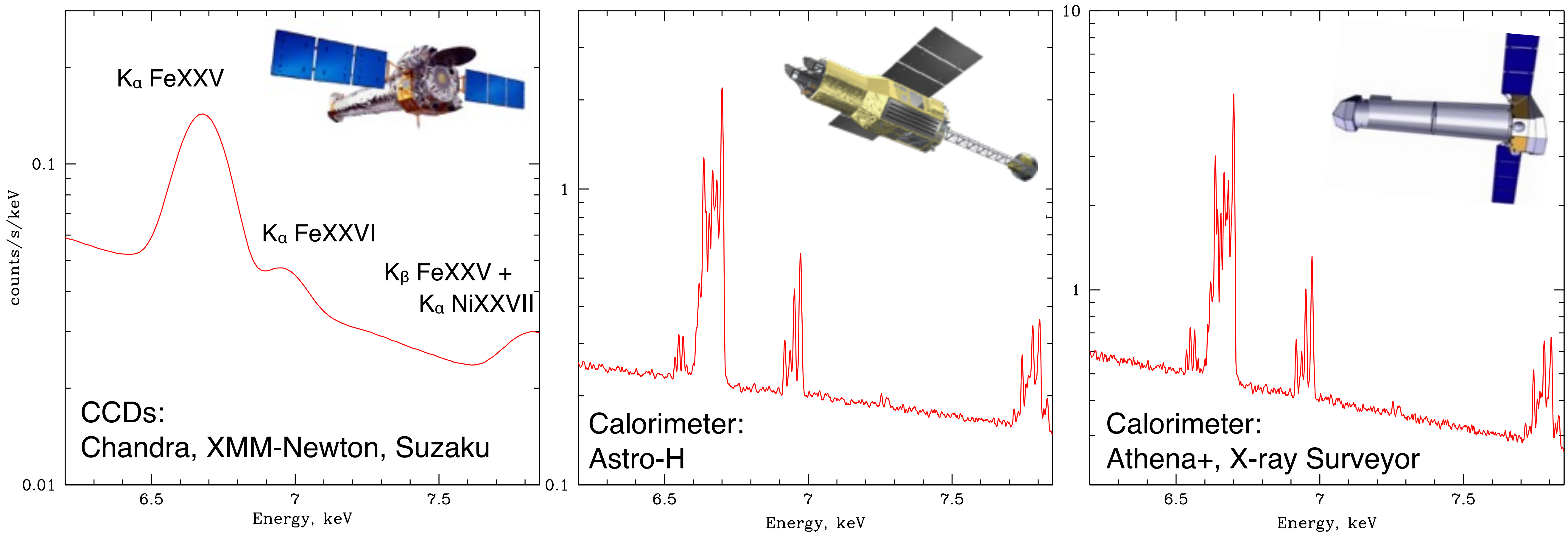
Measuring Gas Dynamics in Galaxy Clusters



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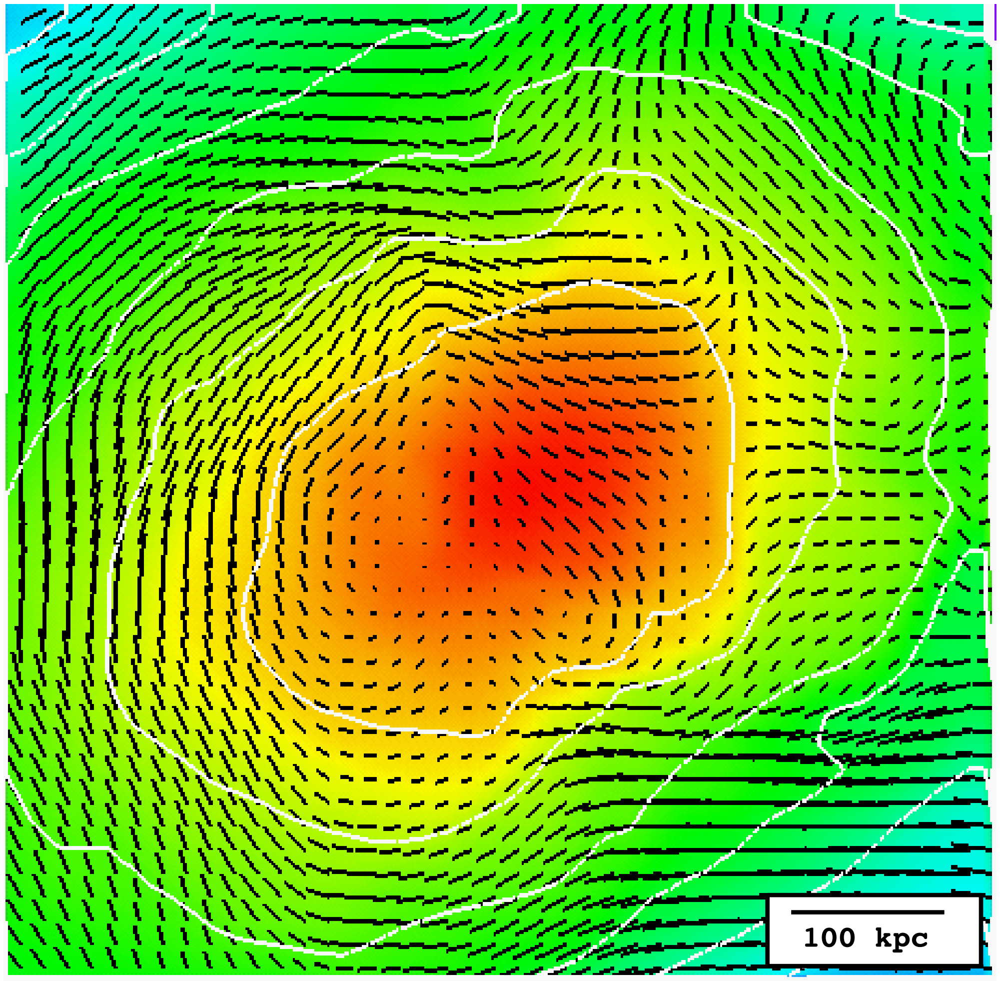
E. Churazov, S. Allen, P. Arevalo, J. de Plaa, W. Forman, A. Kravtsov, E. Lau, D. Nagai, A. Ogorzalek, A. Schekochihin, R. Sunyaev, A. Vikhlinin, N. Werner

The Universe in High-resolution X-ray Spectra, Cambridge, MA, Aug 19-21, 2015

ICM gas dynamics: expectations and motivation



V_{max}=520 km/s Bryan et al. 1999

cosmology:
- contribution of non-thermal P
- correction on hydrostatic M_{tot}

astrophysics & microphysics:
- radio-mode AGN feedback
- cosmological heating
- particle re-acceleration, origin of radio halos
- amplification of magnetic fields
- transport process

What would we like to measure?

- velocity amplitudes
- velocity anisotropy
- velocity power spectrum:
  - injection scale
  - slope of cascade
  - dissipation scale

Important!

- V amplitude and **scale** associated with it are needed for many astrophysical applications
- crucial for the estimates of **stochastic uncertainties** of measured V amplitude

Amplitude I: line broadening and shift

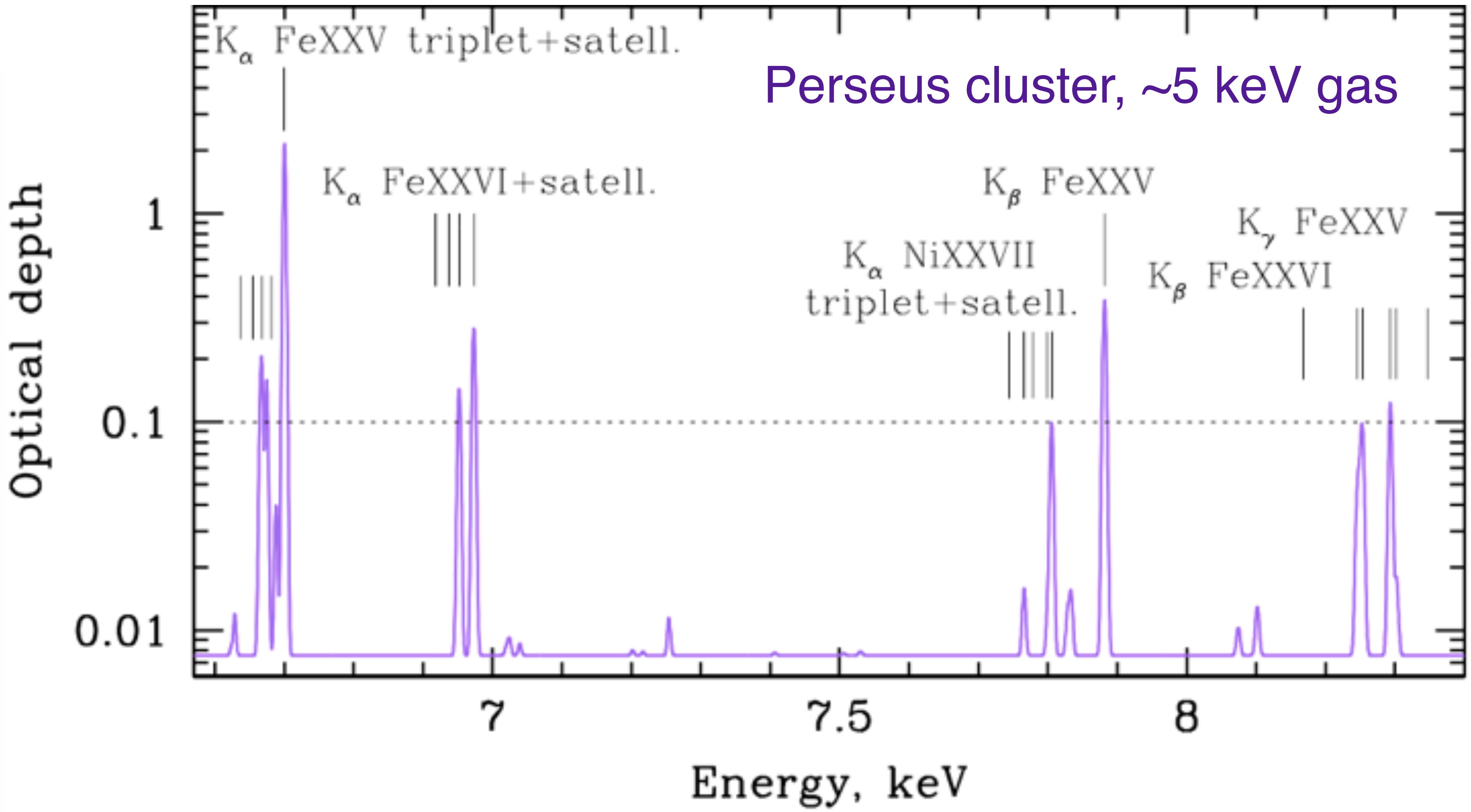
CCDs: state-of-the-art measurements of the Doppler shift (20-30 eV) of Fe-shell lines
ASCA, Chandra: Centaurus & Perseus clusters, bulk velocity difference few$\cdot 10^3$ km/s (Dupke et al. 01a, 01b, 06)
ASCA: the Perseus cluster, no significant velocity gradient (Ezawa et al. 01)
Suzaku: the Centaurus cluster, velocity difference ~1400 km/s (Ota et al. 07)
A 2319, 2000 km/s (Sugawara et al. 09)
A2256, 1500 km/s (Tamura et al. 11)

XMM-Newton RGS: only for central bright cores in clusters and elliptical galaxies
Several objects V~ few hundred km/s, mostly upper limits
(see e.g. Sanders et al. 10,11,13; Bulbul et al. 12; Pinto et al.15)

Need high-resolution X-ray spectroscopy:
Astro-H (2016), Athena+ (2028), X-ray Surveyor (2030?)

Amplitude II: resonant scattering

Optical depth ~ few in some lines in galaxy clusters (Gilfanov et al. 87)



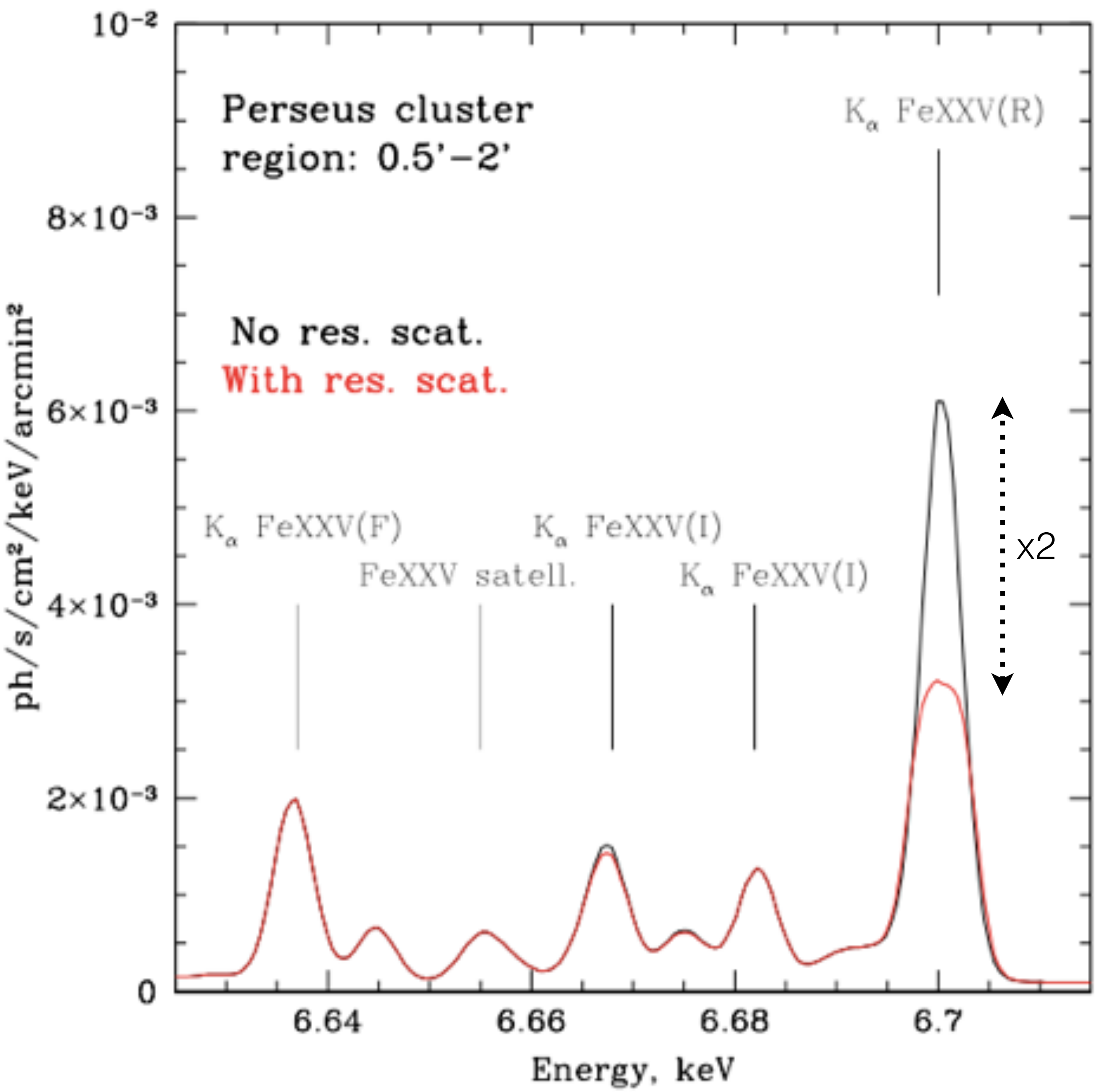
$$\mathrm{RS} \propto \tau \propto \frac{1}{\Delta E_{\mathrm{D}}} \propto \frac{1}{(V_{\mathrm{therm}}^2 + V_{\mathrm{turb}}^2)^{1/2}}$$

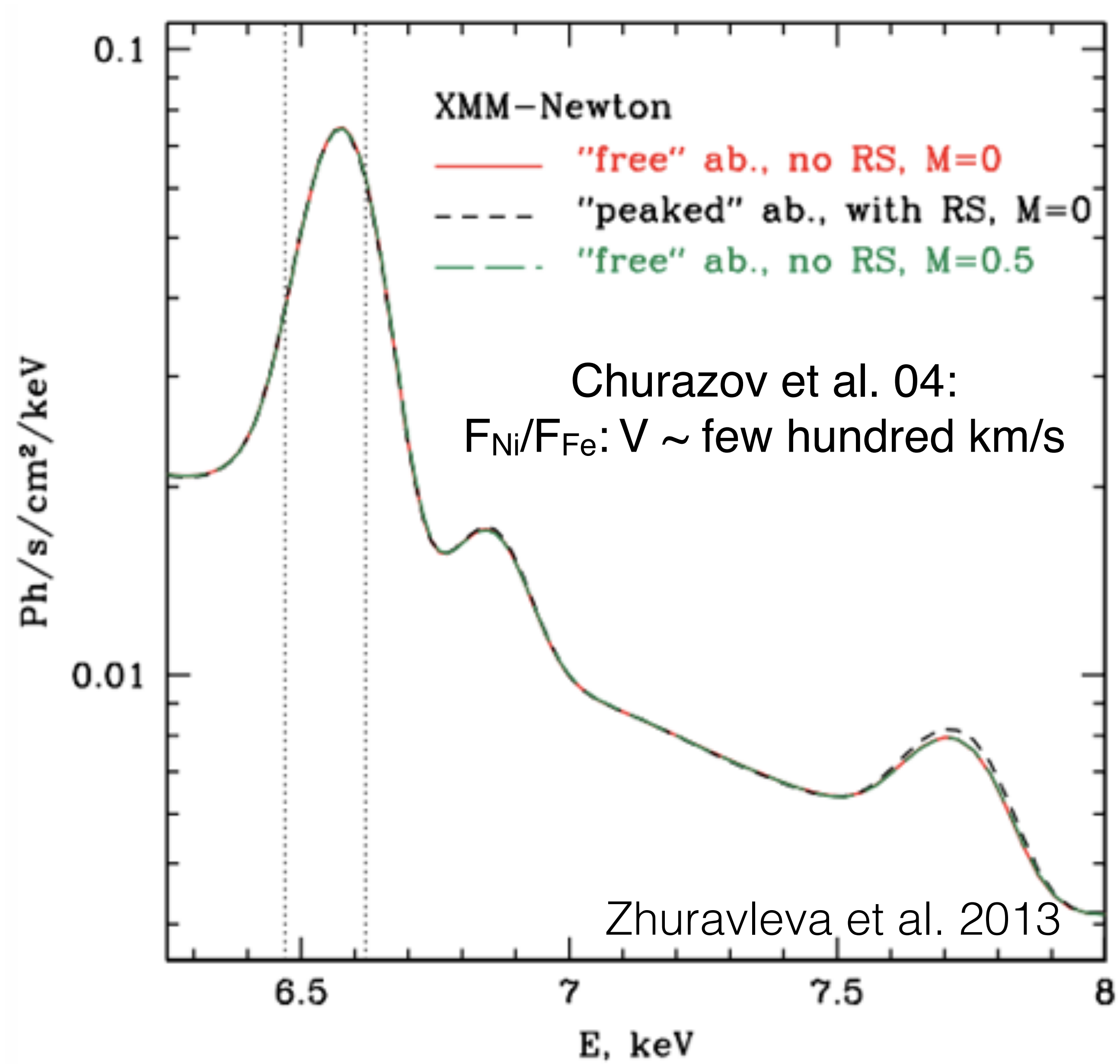
see also Krolik+88; Molendi+98; Shigeyama+98; Akimoto+99; Kaastra+99; Churazov+01; Mathews+01; Bohringer+01; Sakelliou+02; Xu+02; Sazonov+02a; Sazonov+02b; Kahn+03; Churazov+04; Gastaldello+04; Sanders+04; Saders+06; Molnar+06; Werner+09; Hayashi+09; Zhuravleva+10a; Zhuravleva+10b; Churazov+10; de Plaa+12; Shang+13; Zhuravleva+13.

Amplitude II: resonant scattering

simulations: APEC + Monte Carlo radiative transfer

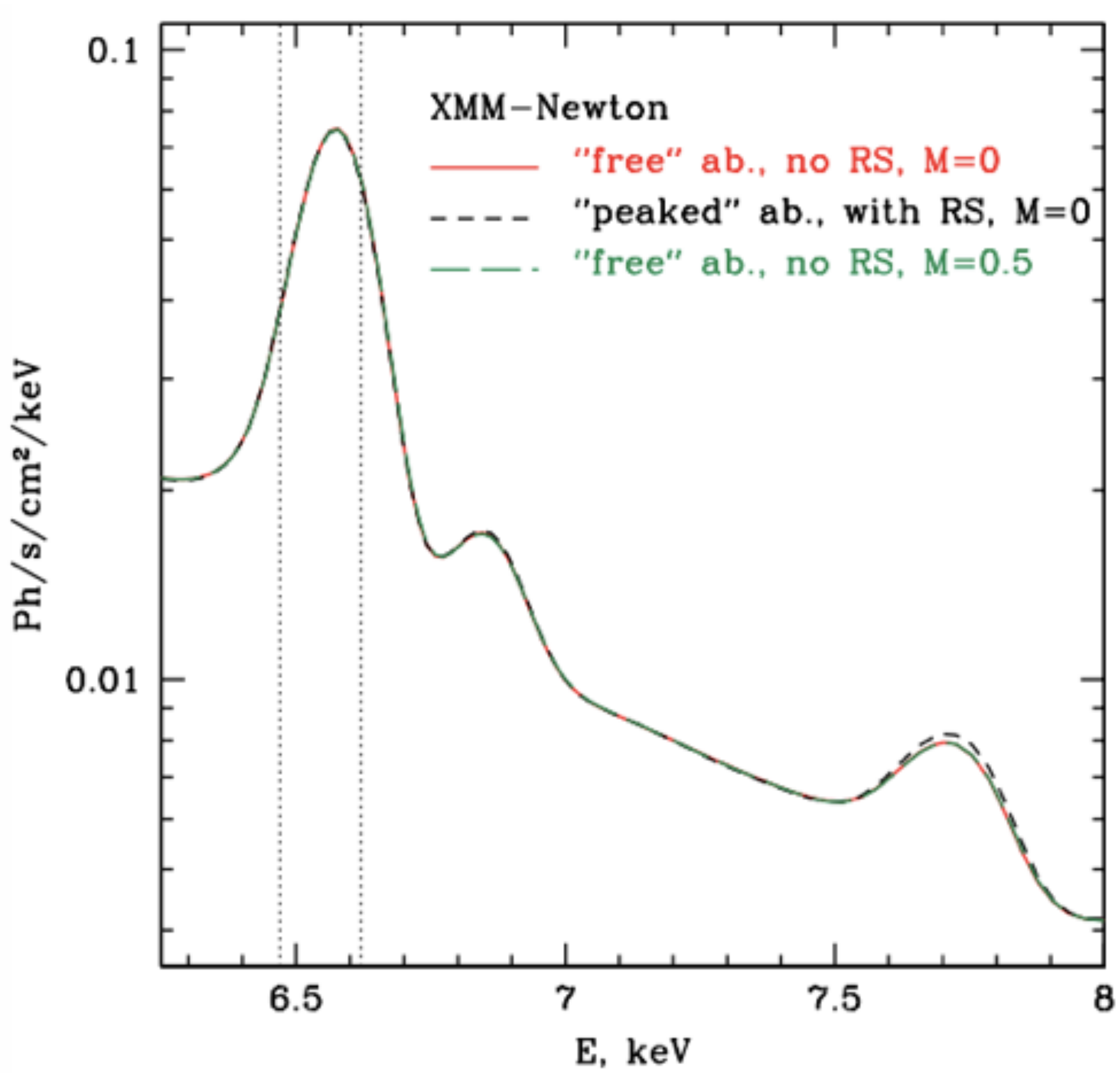
Sazonov et al. 02; Zhuravleva et al. 10,13

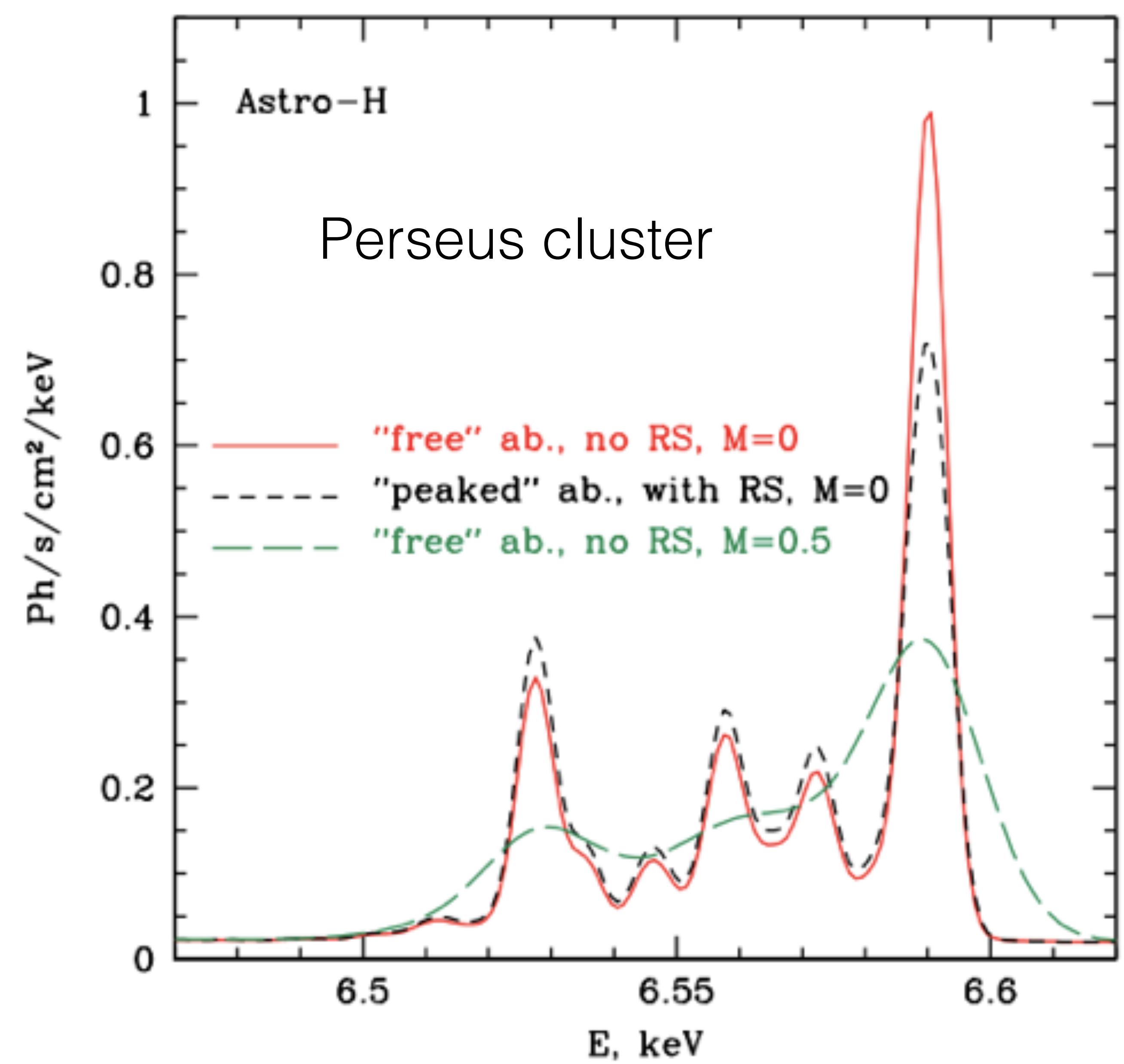




Amplitude II: resonant scattering

Future with Astro-H

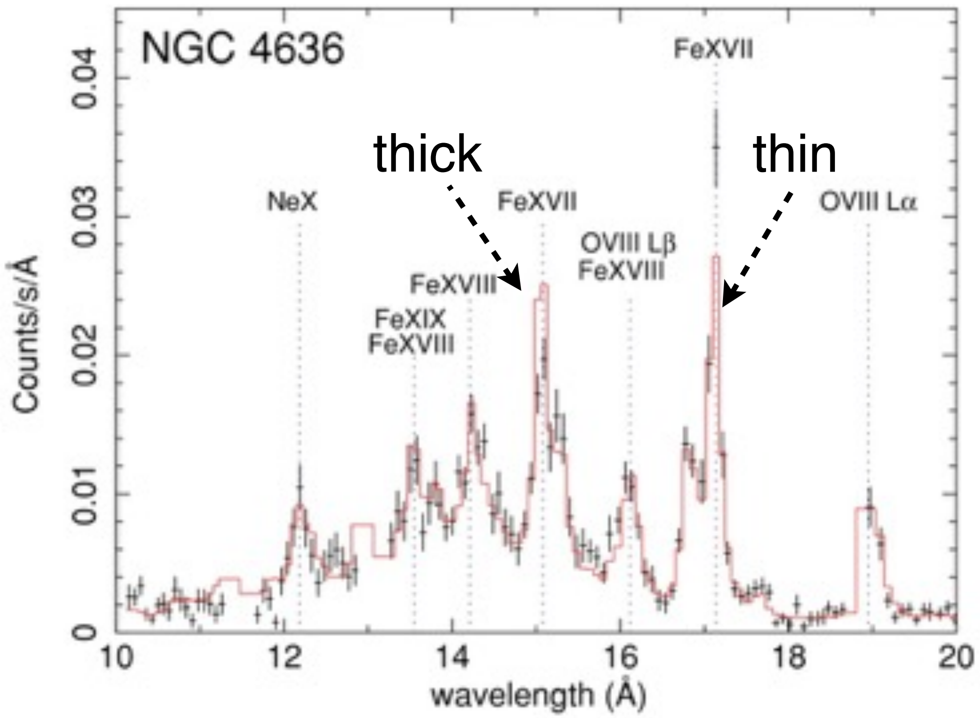


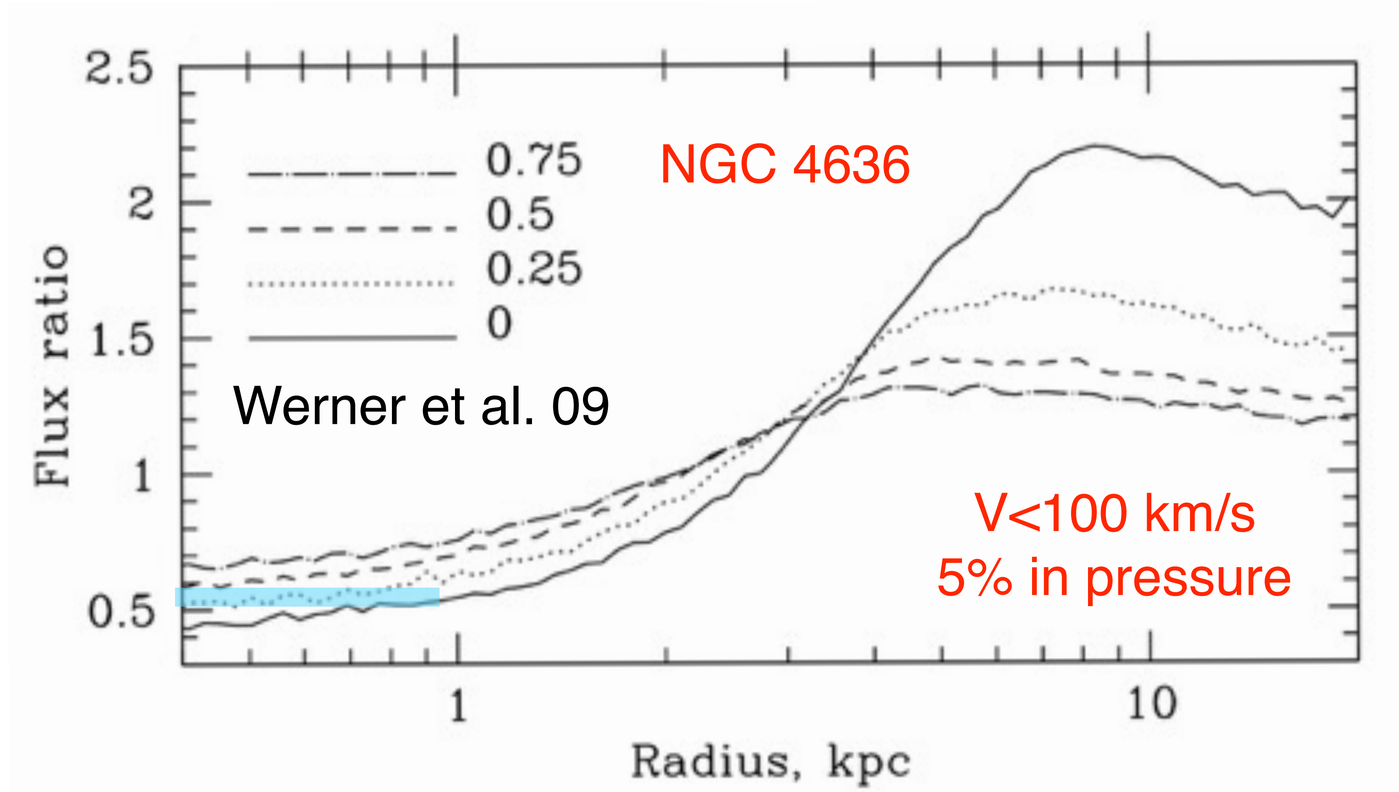


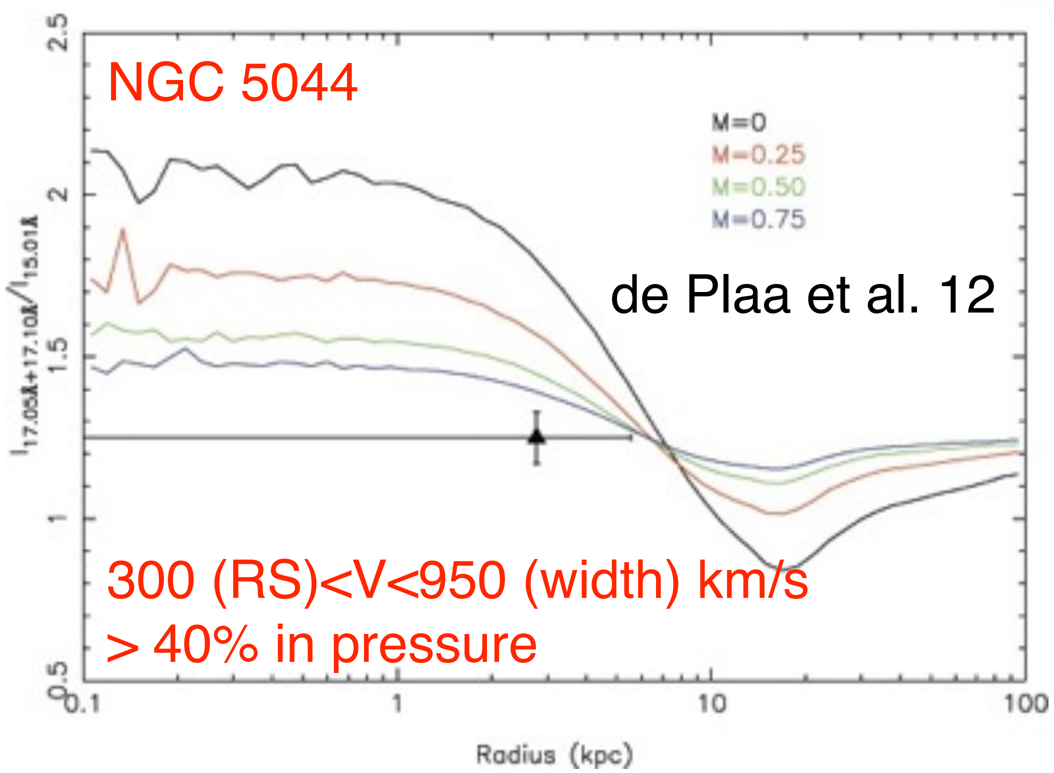
Zhuravleva et al. 2013

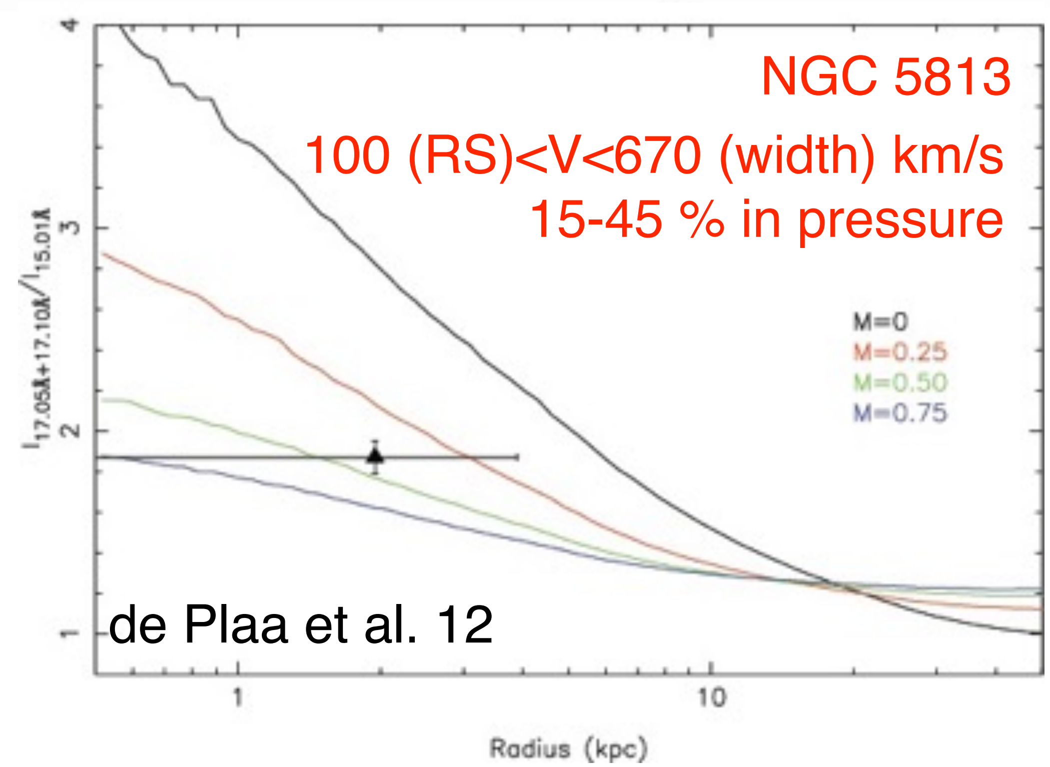
Amplitude II: resonant scattering

RGS XMM Newton, FeXVII lines, F_{thin}/F_{thick} -> V







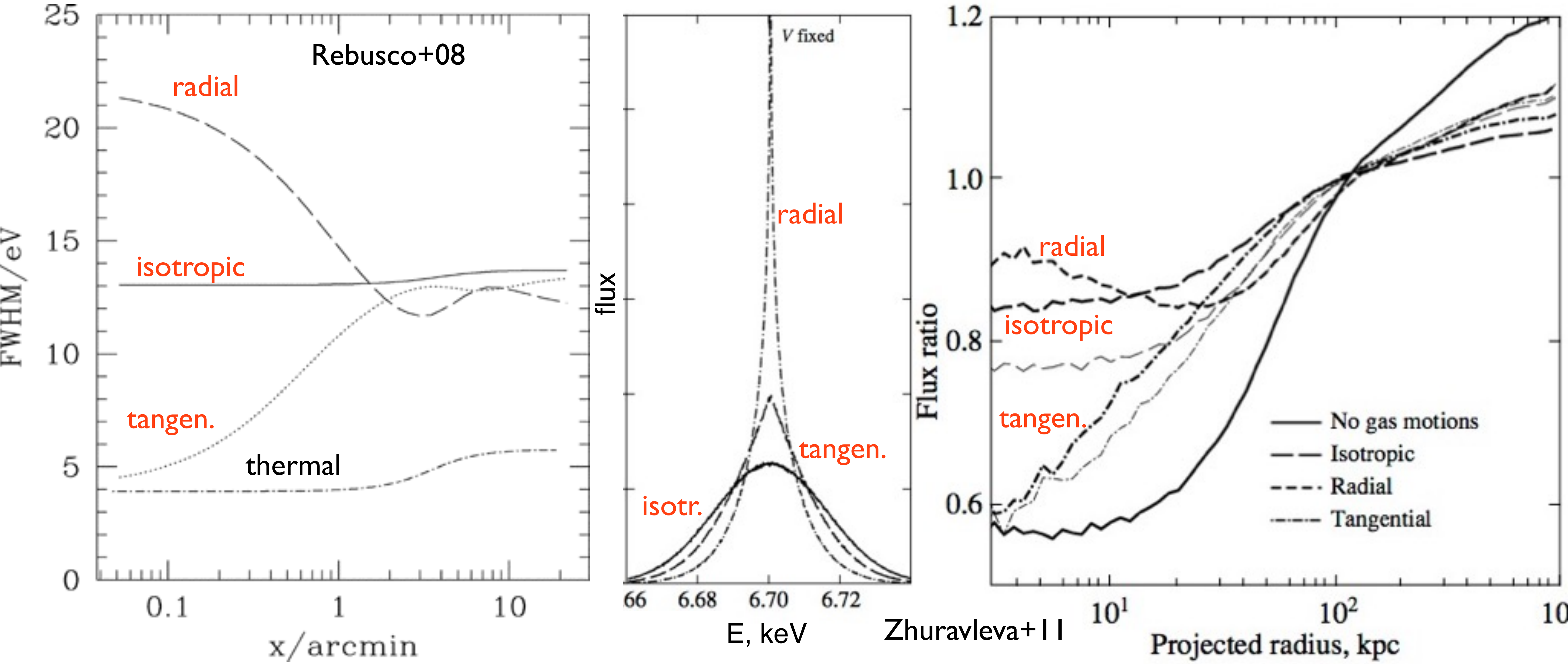


more to come: analysis of CHEERS sample

see also talks by J. de Plaa, S. Roberts, poster by J. Ahoranta

Anisotropy: line width + RS + line profile

Three observables are sensitive to anisotropy of motions:



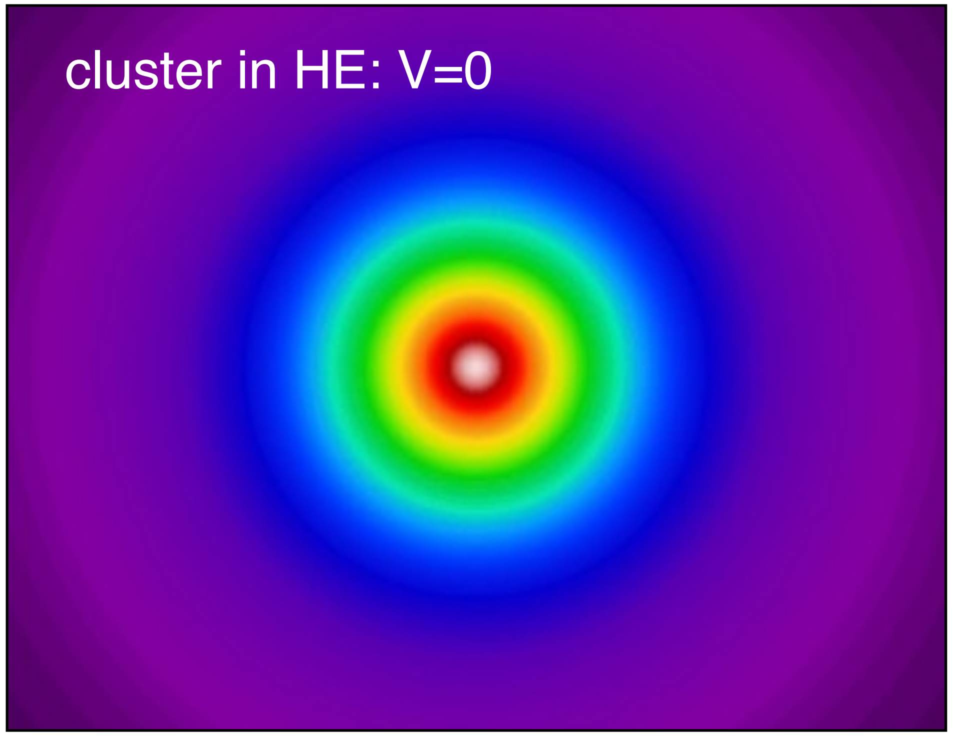
What would we like to measure?

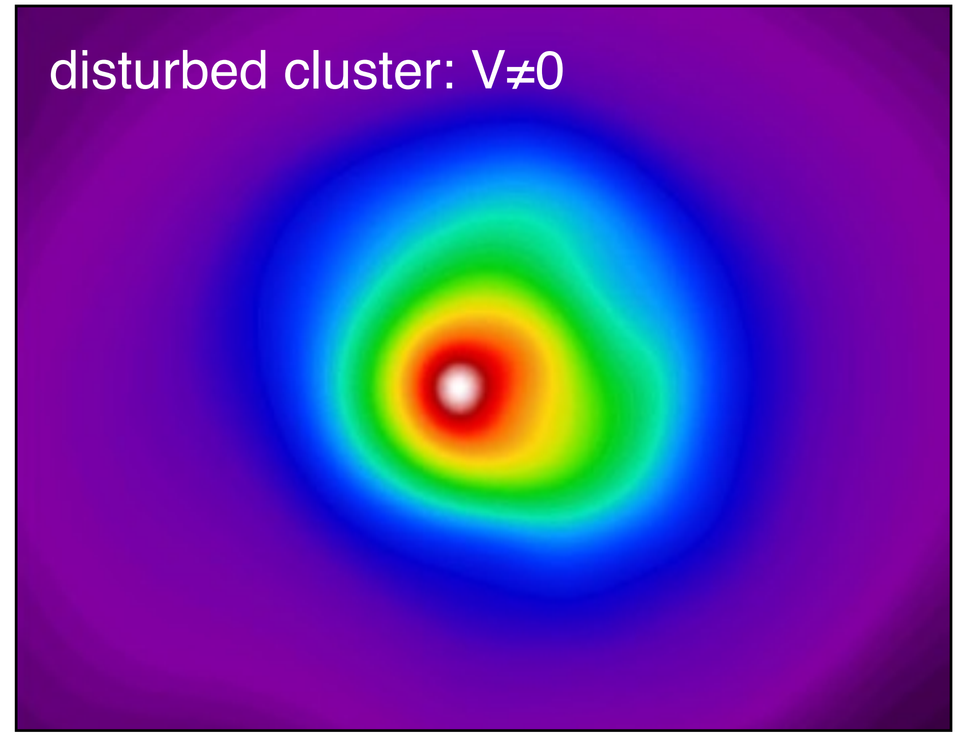
✓ velocity amplitudes
✓ velocity anisotropy

velocity power spectrum:

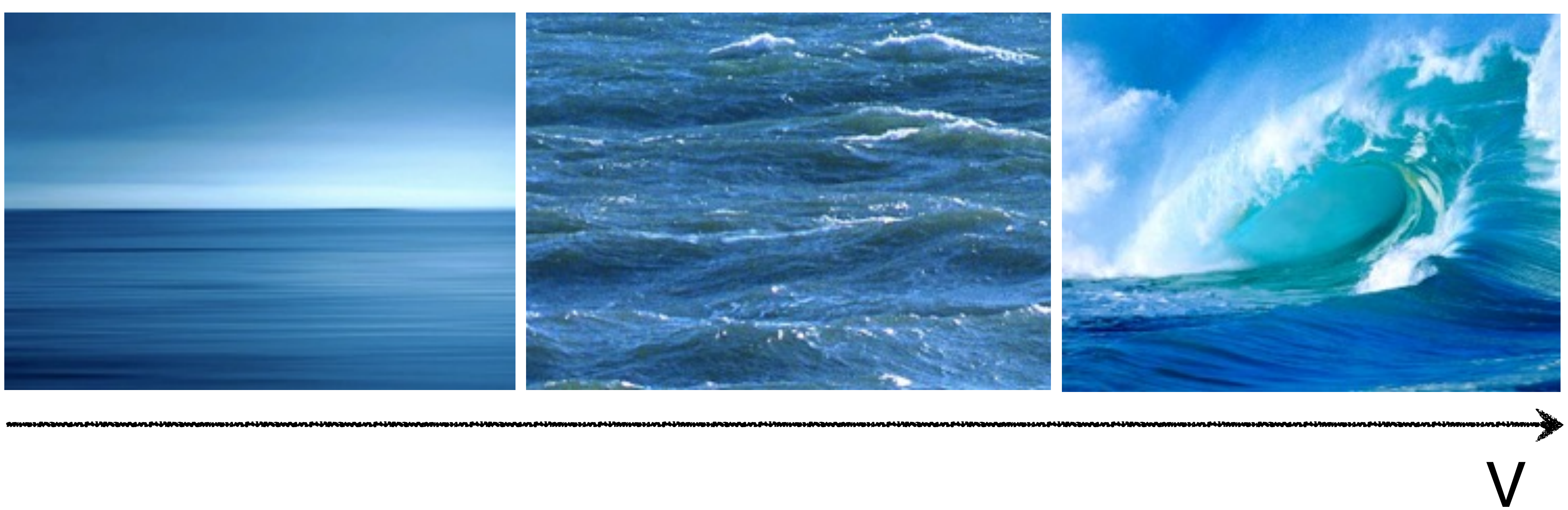
I. indirect measurements (Chandra)
II. future direct measurements

Power spectrum I: surface brightness fluctuations

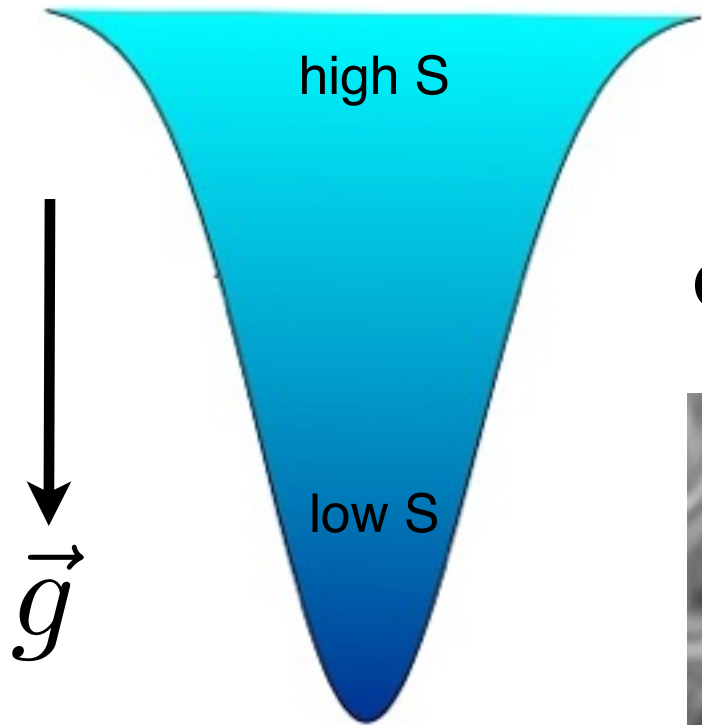




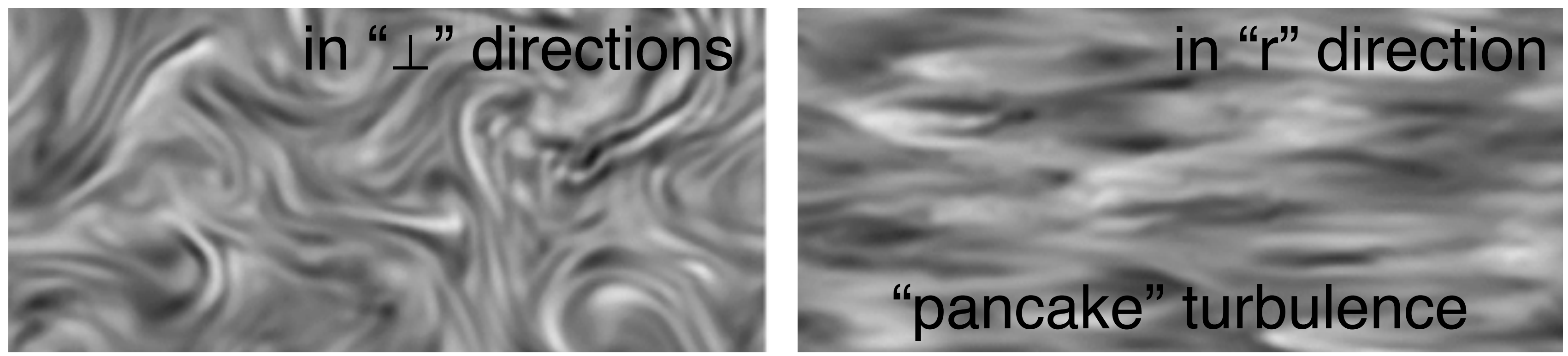
$\delta\rho$ —> V?



Power spectrum I: surface brightness fluctuations



on large scales (buoyancy scale): **dominated by $V_{\perp}$**



Waite & Bartello 2006

on small scales: isotropic V

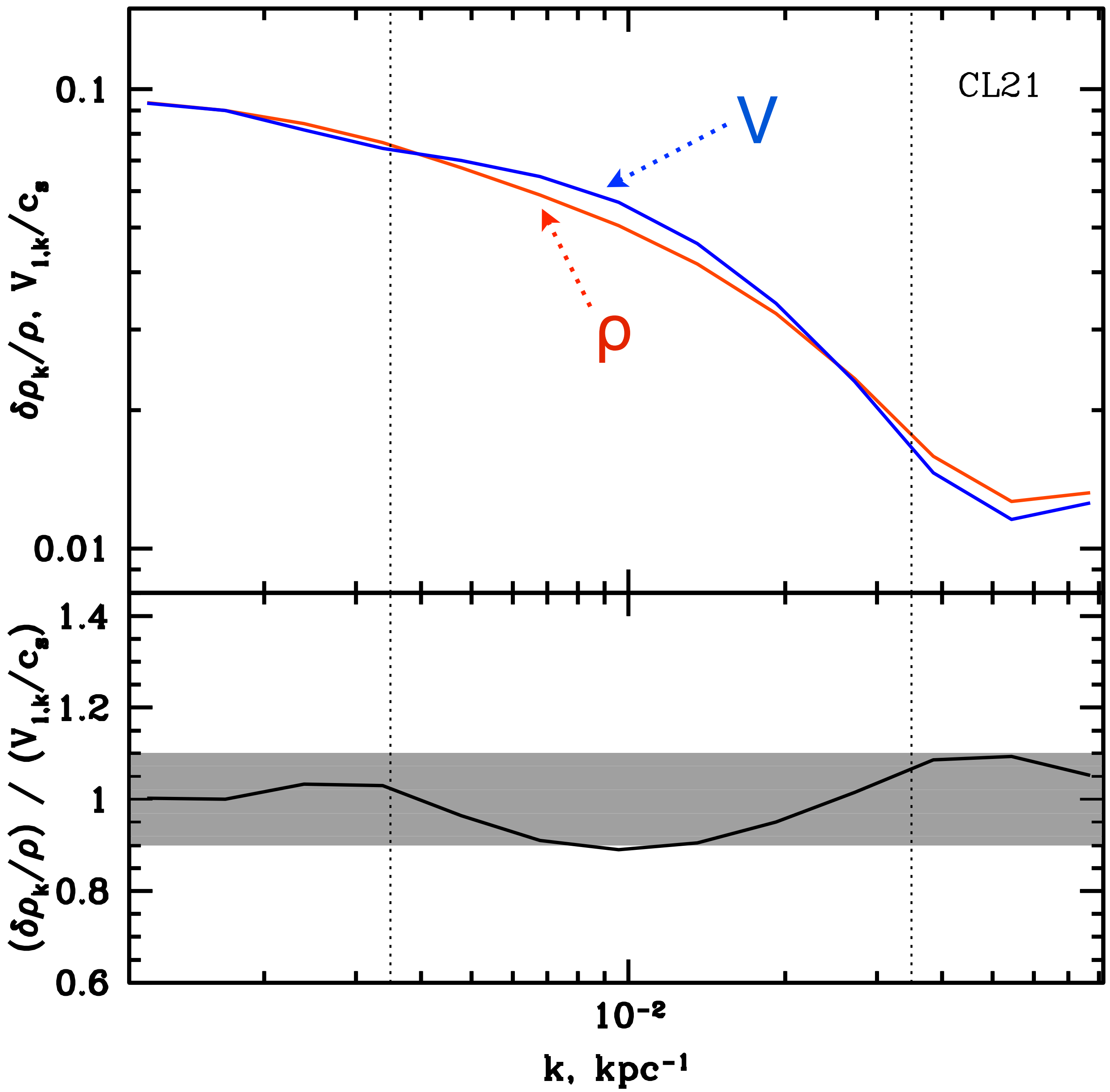
$$\frac{\delta\rho_k}{\rho} = \eta\frac{V_k}{c_s}$$

in inertial range of scales
no magnetic fields
no plasma effects

Zhuravleva et al. 2014a

Power spectrum I: surface brightness fluctuations

Simulations are provided by D. Nagai, E. Lau, A. Kravtsov



sample-averaged:

$$\eta = 1 \pm 0.3$$

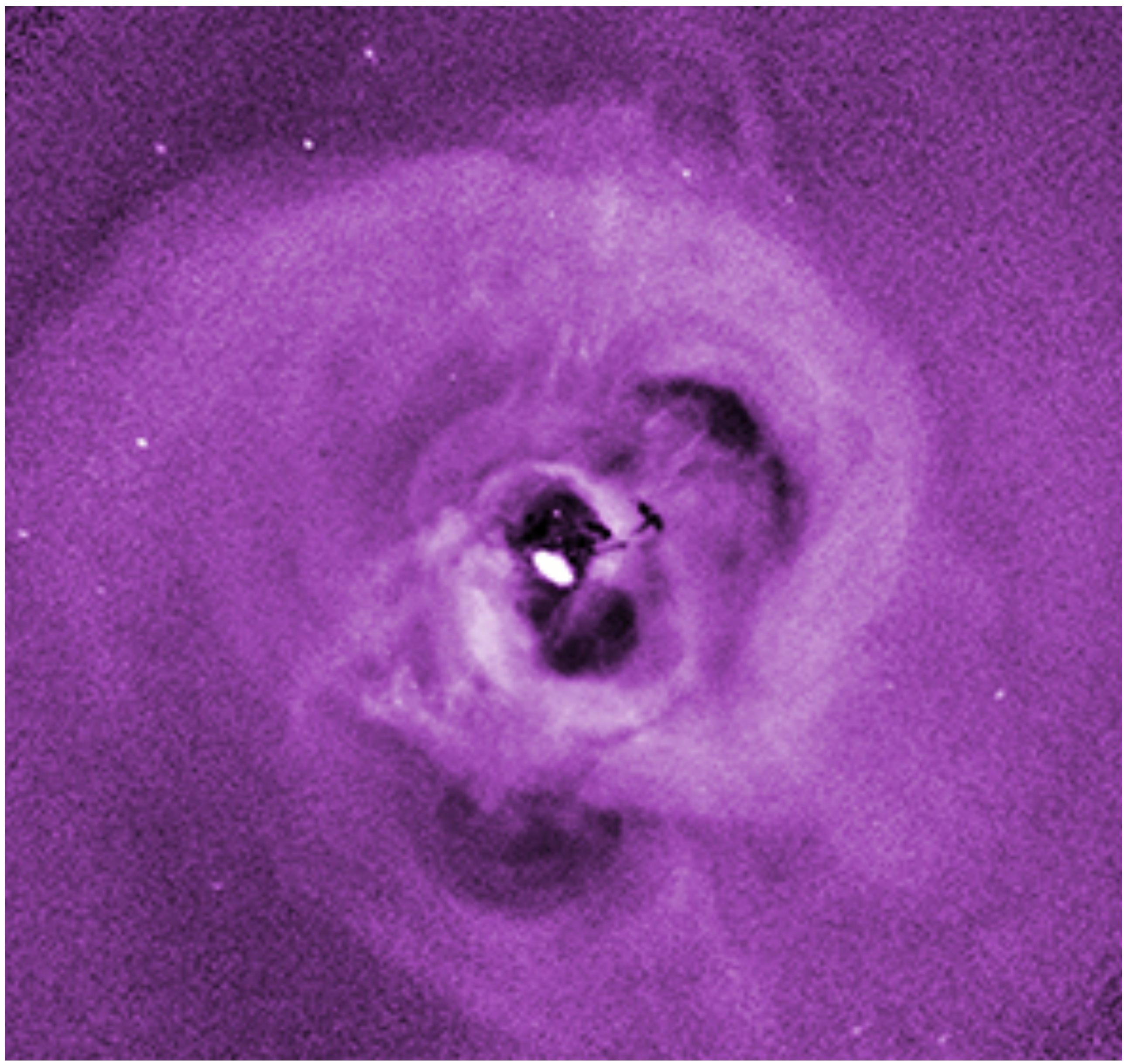
Zhuravleva et al. 2014a

see also Gaspari et al. 2014
for hydro simulations

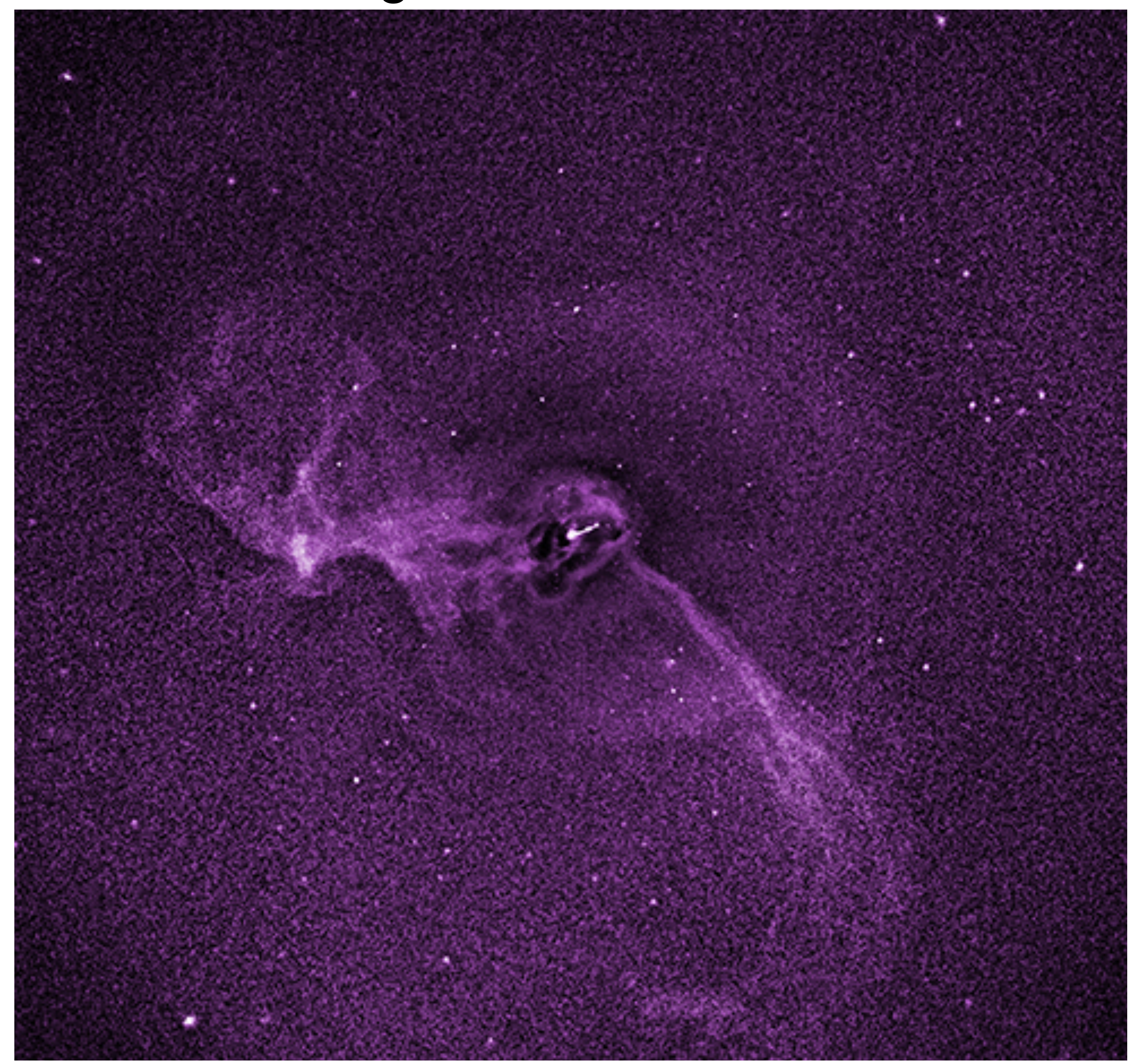
Power spectrum I: surface brightness fluctuations

Deep Chandra observations:

Perseus cluster: 1.4 Ms



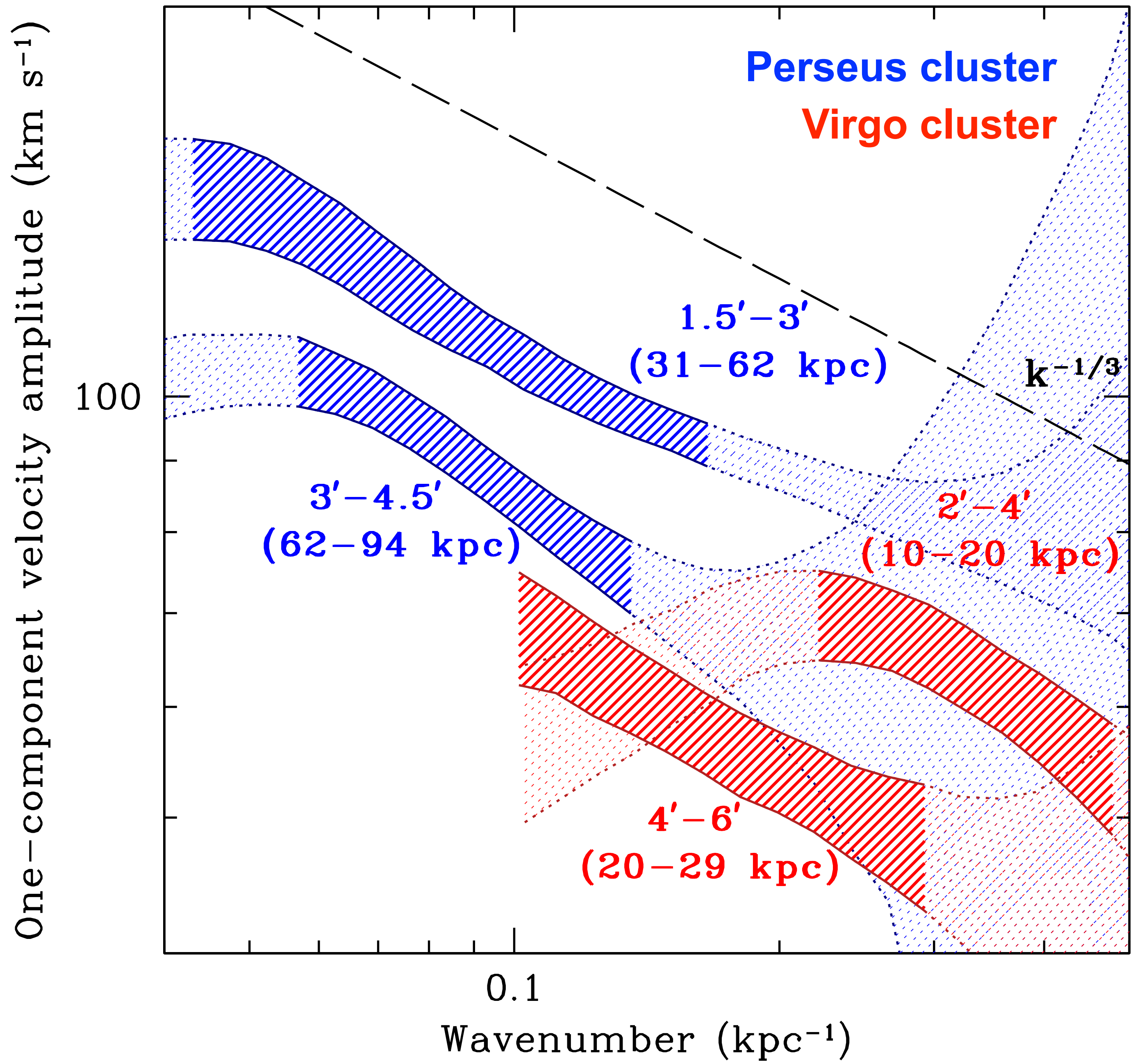
Virgo cluster: 600 ks



P_k of SB fluctuations -> P_k of density fluctuations -> velocity P_k

see also Schuecker et al. 04, Sanders et al. 12, Churazov et al. 12, Zhuravleva et al. 14, Zhuravleva et al. 15, Arevalo et al. 15, Walker et al. 15

Power spectrum I: surface brightness fluctuations



Zhuravleva et al. 14b, 15

see also Schuecker et al. 04, Churazov et al. 12, Walker et al. 15

- Perseus: 70 - 210 km/s on scales 6-30 kpc (within central 200 kpc)
- Virgo/M87: 40 - 140 km/s on scales 2-10 kpc (within central 40 kpc)

Power spectrum I: turbulent heating

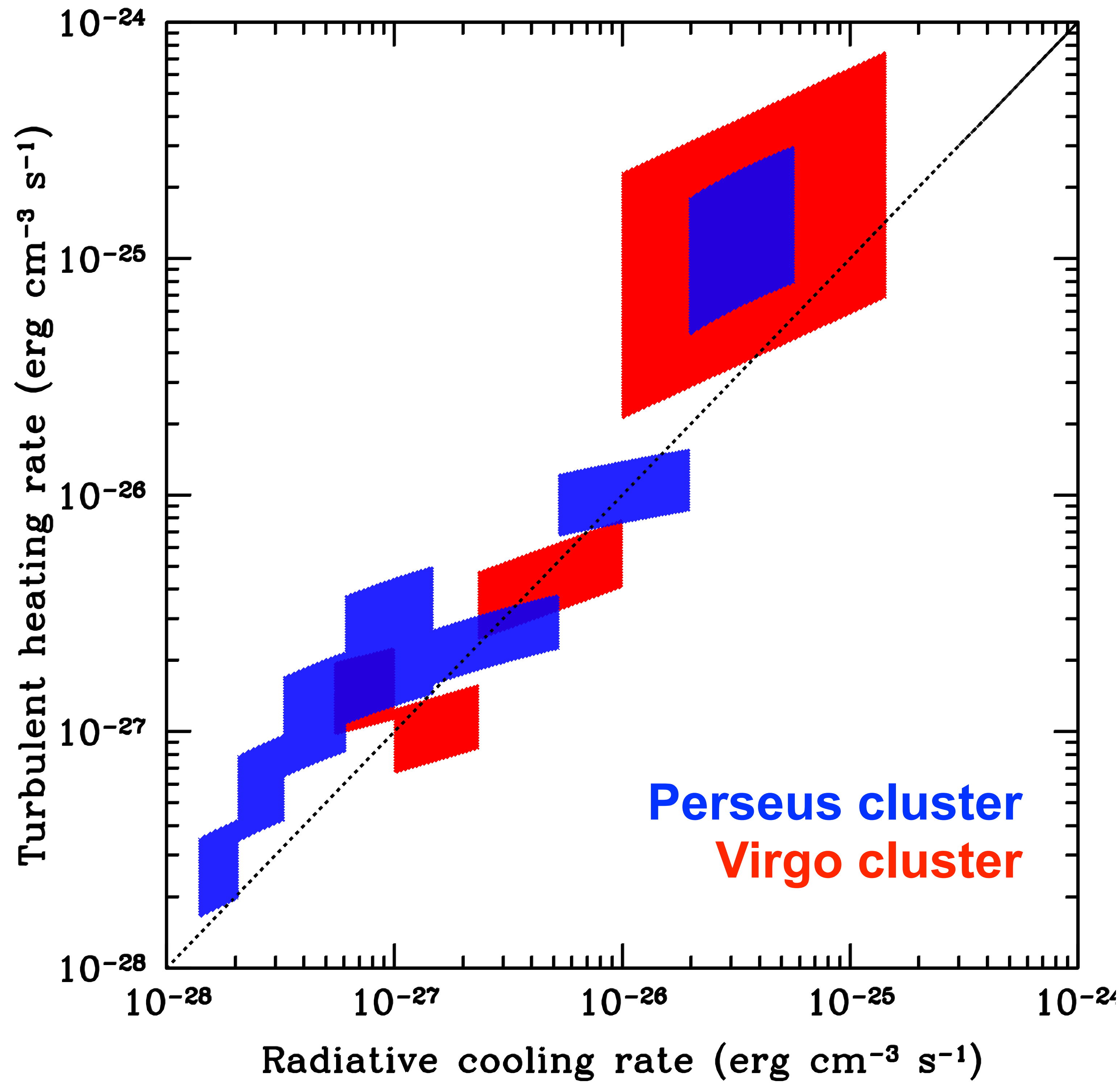
cooling rate:

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

heating rate:

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

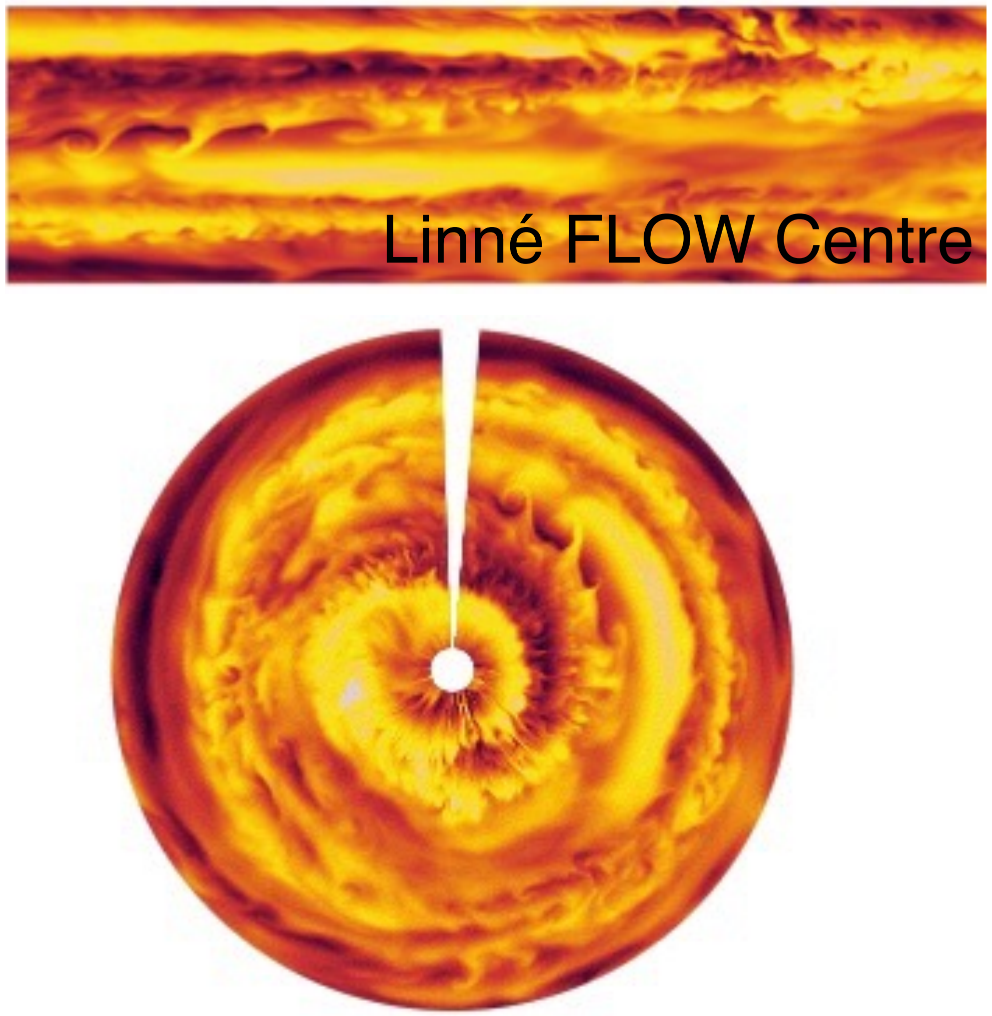
locally: cooling ~ heating

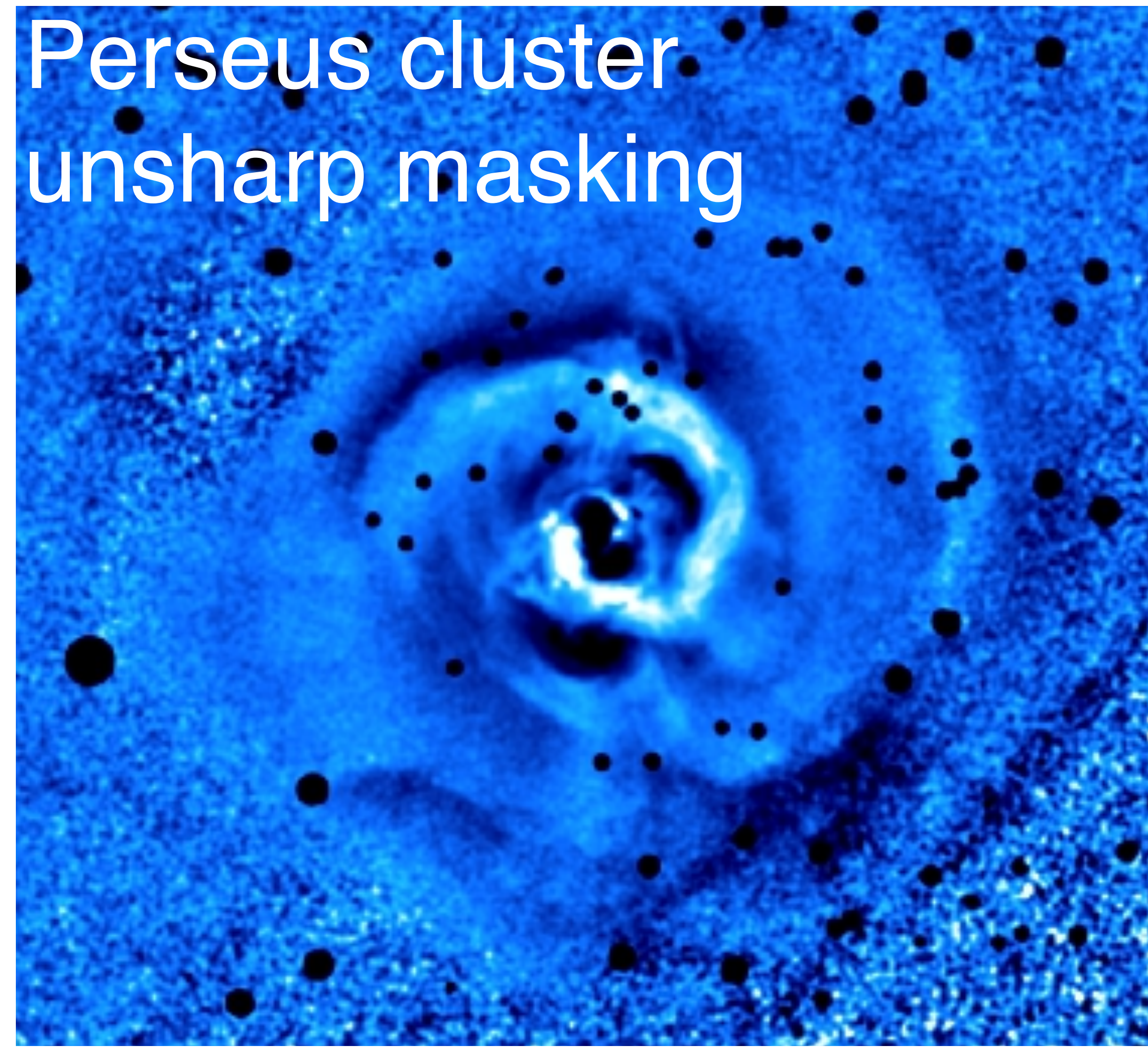


AGN —> Bubbles —> Turbulent dissipation —> Heat

Zhuravleva et al. 14b

Power spectrum I: surface brightness fluctuations





linear size of ripples: $\Delta r \sim 10$ kpc

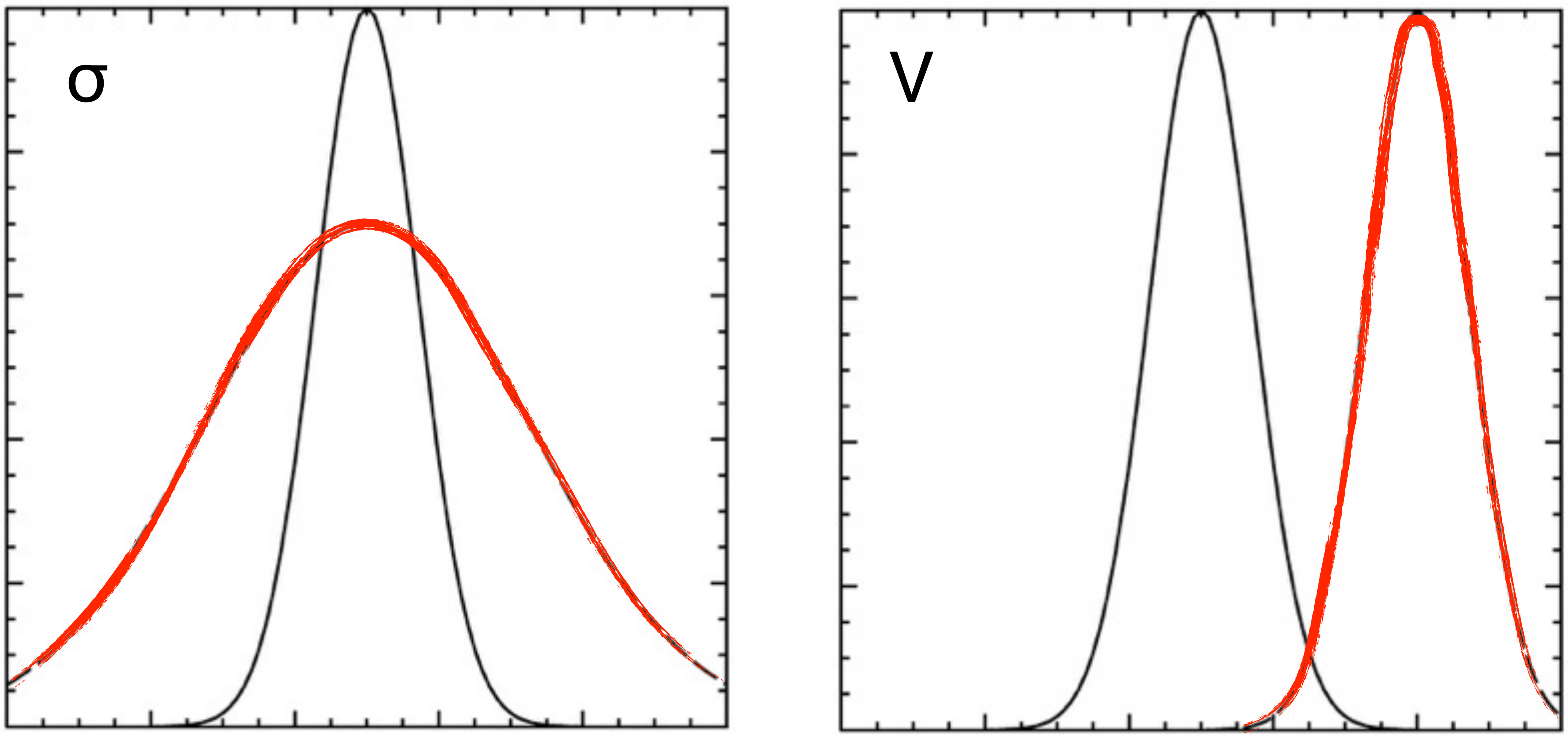
Ripples, two possibilities:

- sound waves (Fabian et al. 03, 06; Sanders et al. 07)
- stratified turbulence (Zhuravleva et al. 14, 15)

Need high angular and spectral resolutions:
X-ray Surveyor

Power spectrum II: direct measurements with Astro-H

Two new observables:

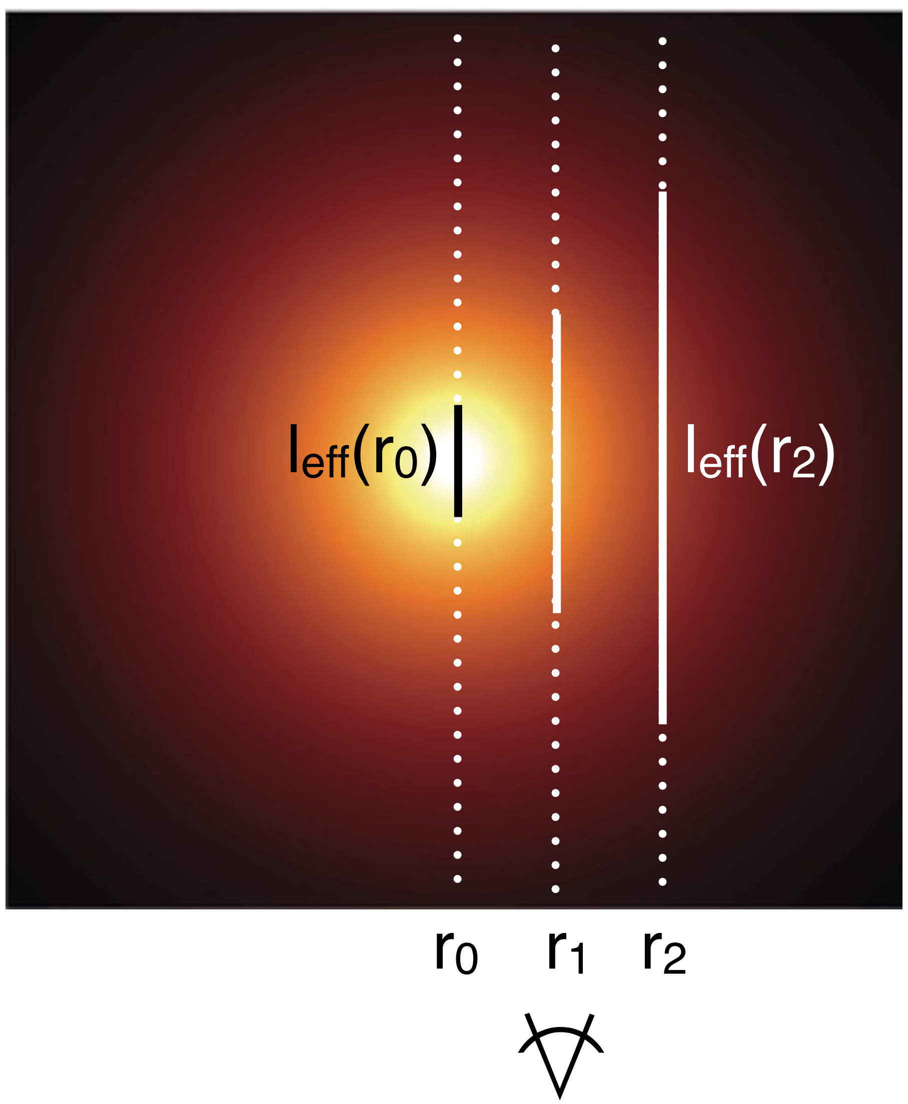


How to extract statistical information about the velocity field using these observables?

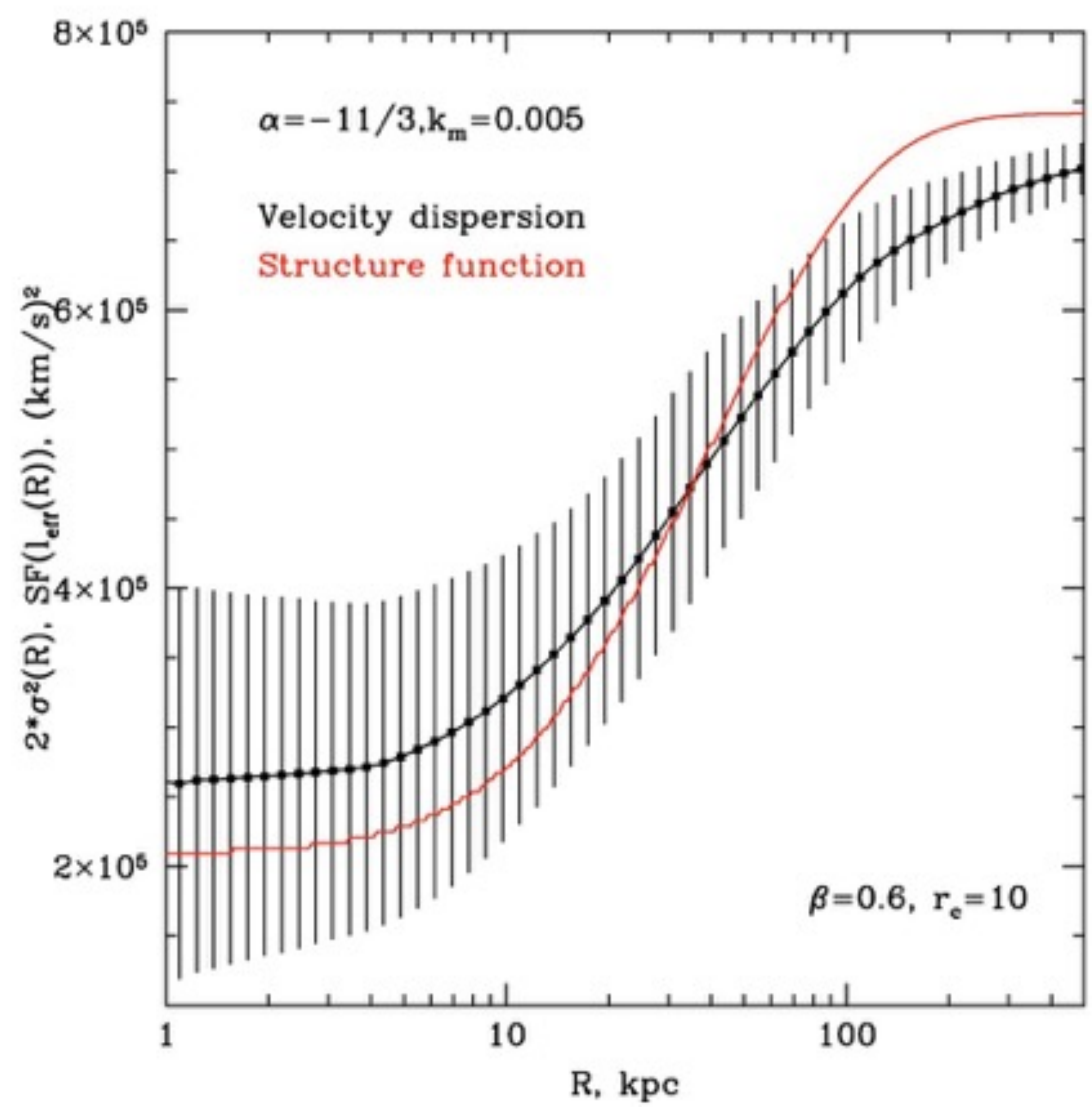
Power spectrum II: direct measurements with Astro-H

Structure function in cool-core clusters

At a given r an interval $l_{eff} \sim r$ contributes to the line flux



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

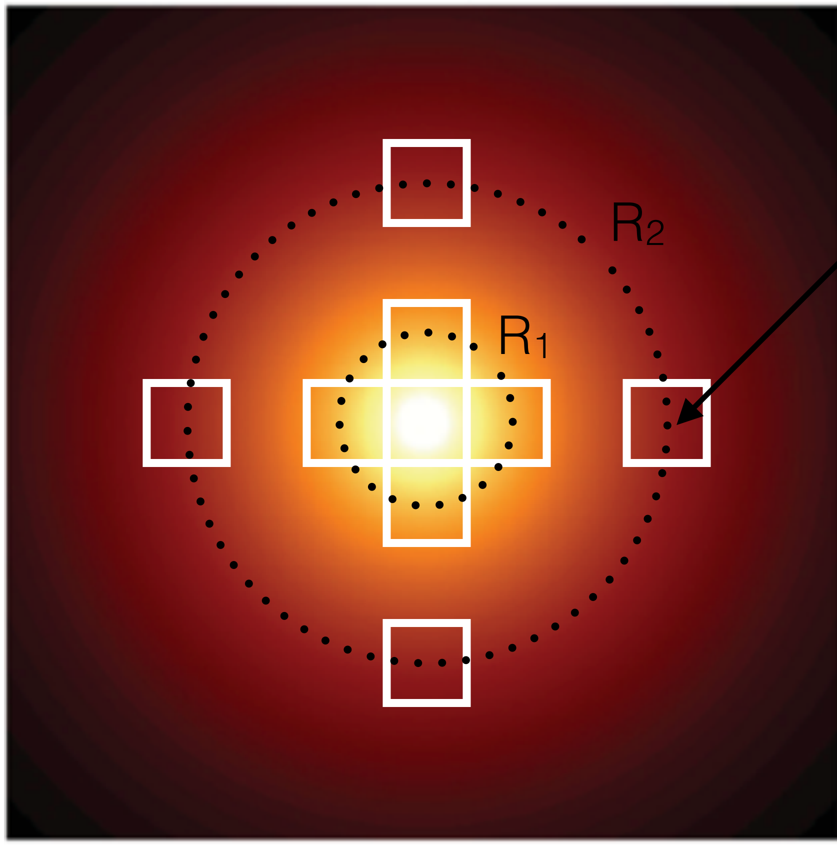


Observed $\sigma(r) \approx$ structure function (l_{eff})

Zhuravleva+12

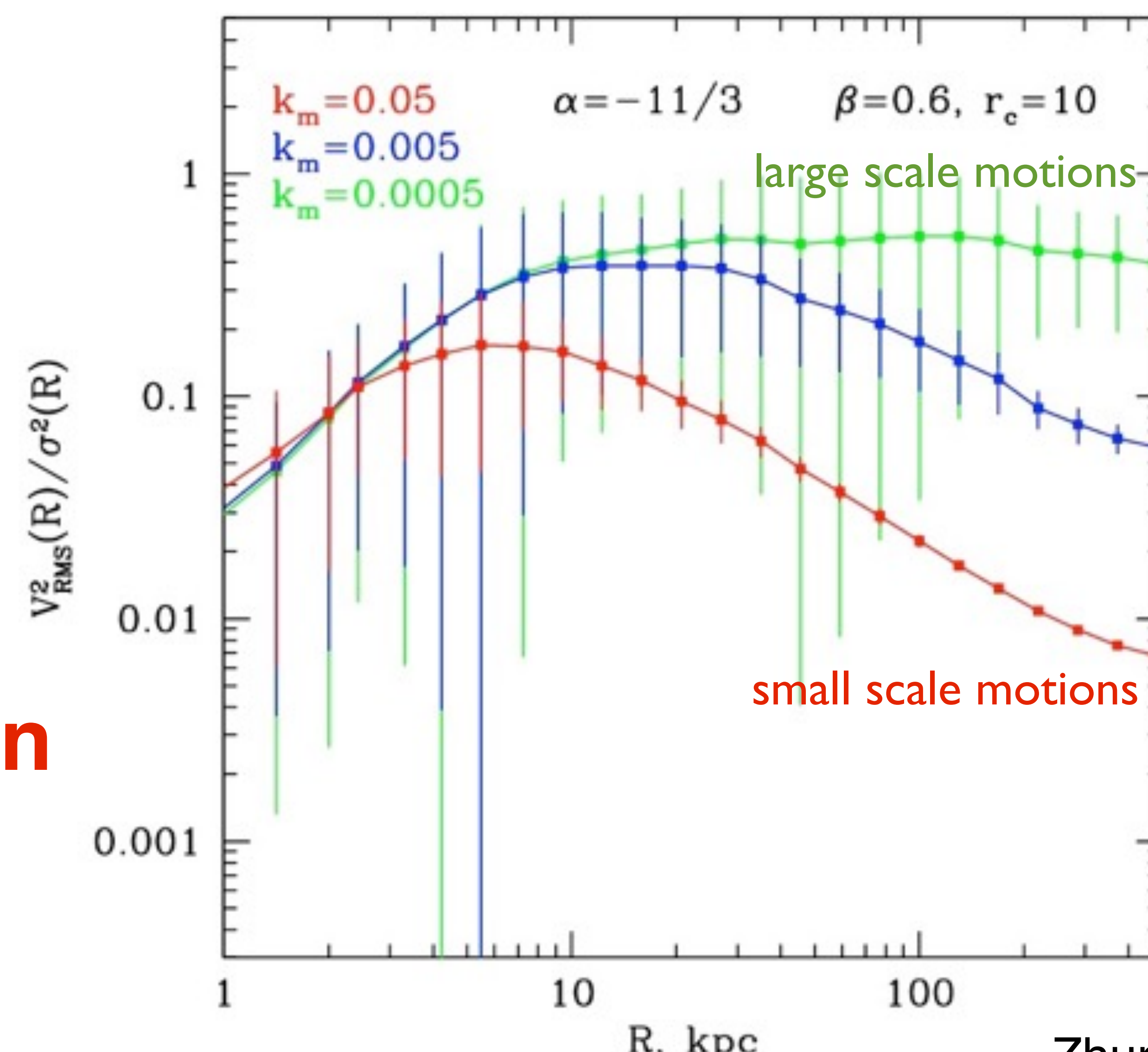
Power spectrum II: direct measurements with Astro-H

Constraints on injection scale



σ; V

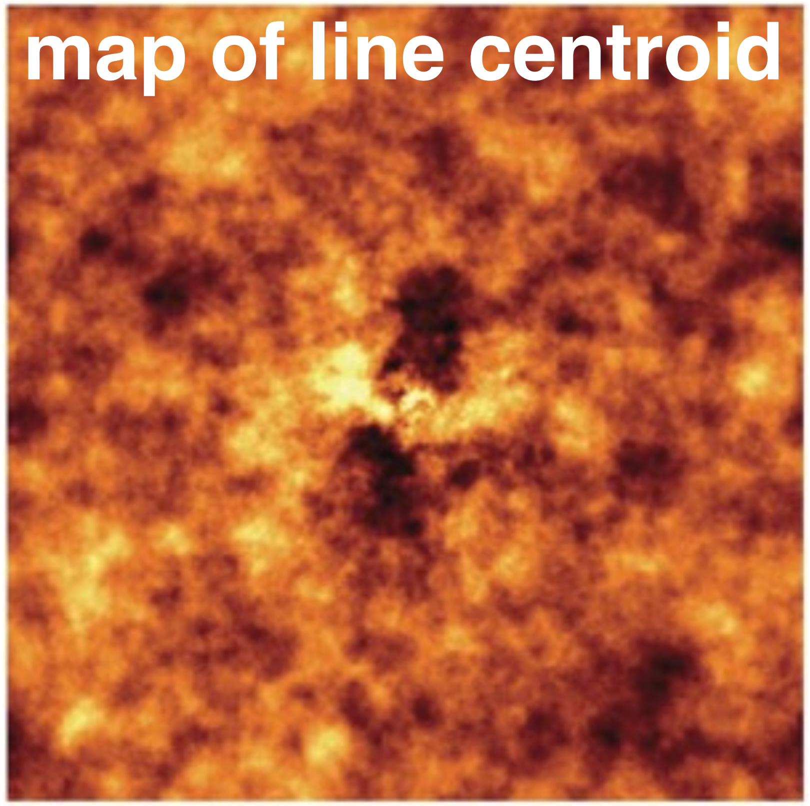
$$\frac{RMS(V(R))}{\sigma(R)} \longrightarrow k_{inj}$$



cosmic variance is the main source of uncertainties

Zhuravleva+12

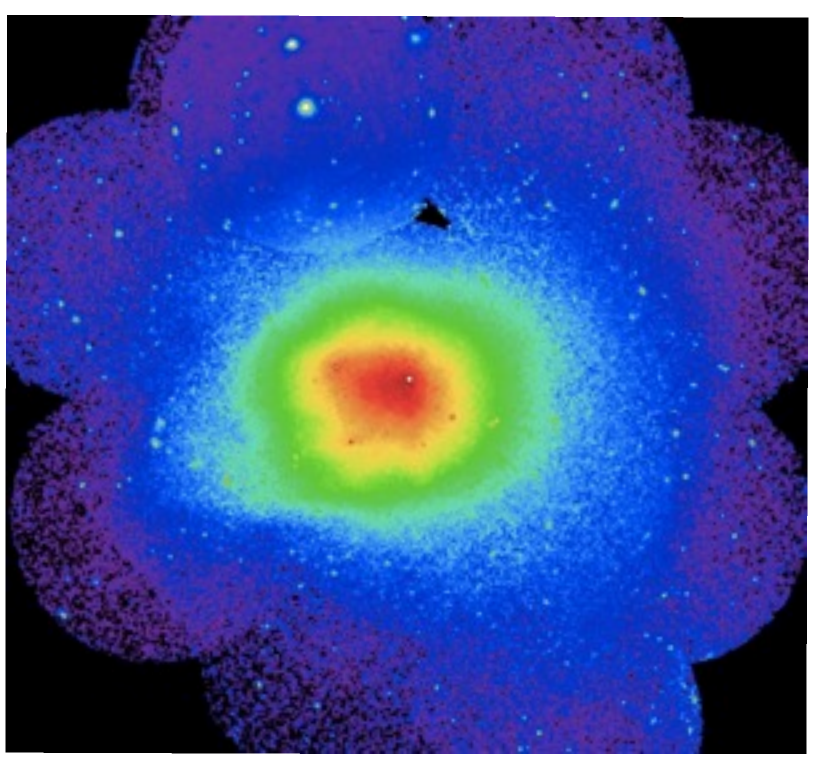
Power spectrum II: direct measurements with Astro-H



Power spectrum in non-cool-cores

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

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



for Coma-like clusters
(flat surface brightness)

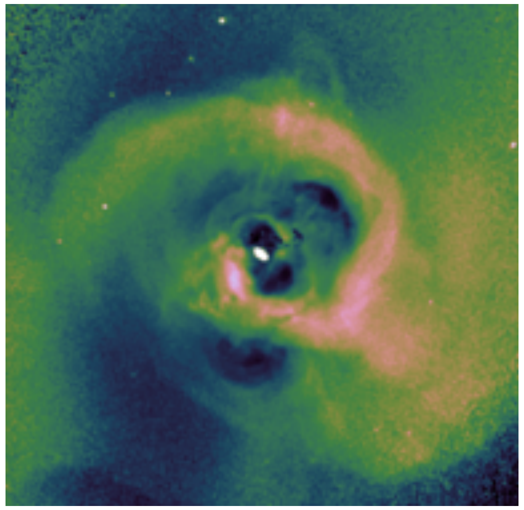
$$(k >> 1/L_{eff})$$

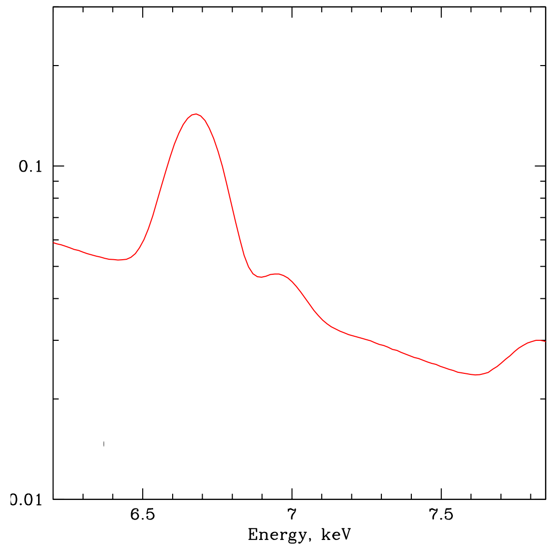
$$P_{\rm 2D}(k) \approx P_{\rm 3D}(k) \int P_{\rm EM}(k_z, x, y) dk_z$$

Zhuravleva et al.12
ZuHone et al. 15

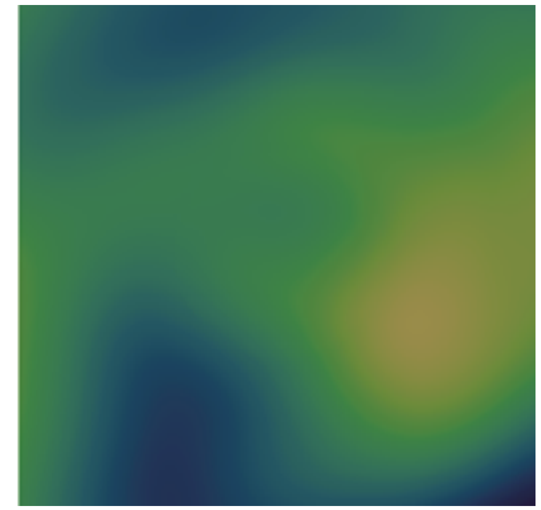
Summary

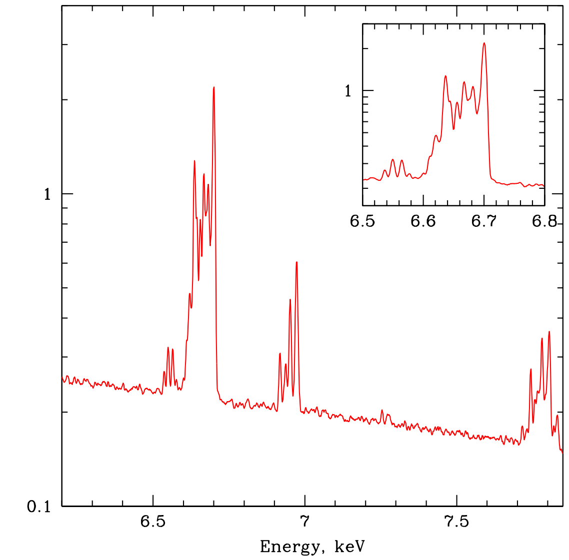
Chandra: imaging





Astro-H: spectroscopy





+

= bright near future of X-ray astronomy

Amplitude

Chandra and XMM: mostly upper limits, for several objects V~100-200 km/s in cores

Astro-H: line broadening, shift, resonant scattering

Anisotropy

Astro-H: broadening(R)+shape+resonant scattering

Power spectrum

Chandra: $\delta\rho_k/\rho \sim V_{1,k}/c_s$ -> Perseus: V=70-200 km/s on 6-30 kpc scale; Virgo: V=40-90 km/s on 2-10 kpc scale

Astro-H: broadening(R) -> structure function

rms(V)/broadening -> injection scale

V map -> P_{2D} -> $P_{3D}=P_{2D}/f(\text{emissivity})$

Chandra and Astro-H: calibration of $\delta\rho_k/\rho \sim V_{1,k}/c_s$ and application on a large sample