Observational signatures of turbulence in ICM

How to measure it?

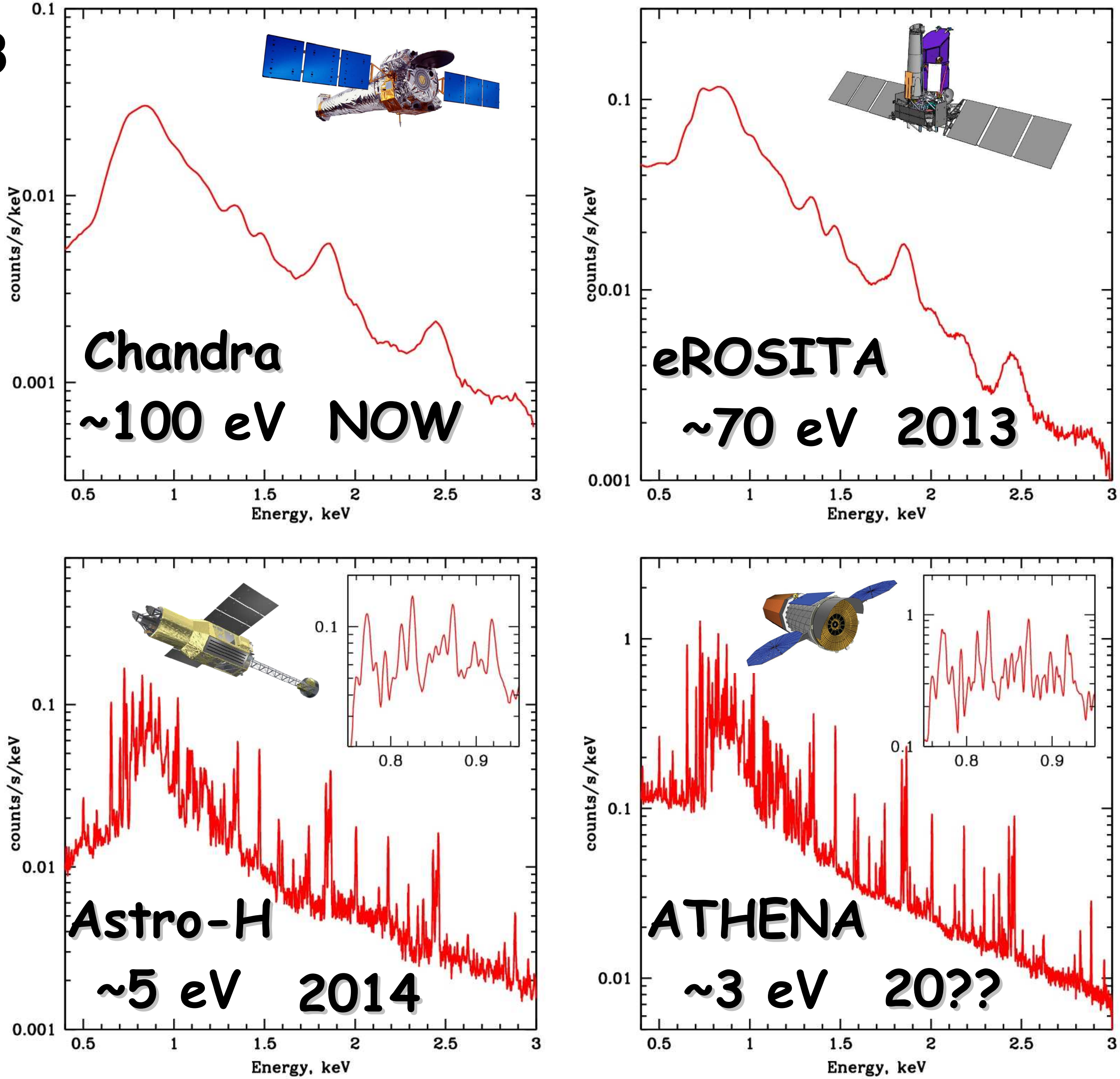
I. Zhuravleva, E. Churazov, R. Sunyaev, N. Werner, S. Sazonov, J. de Plaa, A. Kravtsov, W. Forman, K. Dolag, R. Smith

First eROSITA International Conference, Garmisch 2011

Background picture: Vazza+11

ICM turbulence: direct measurements

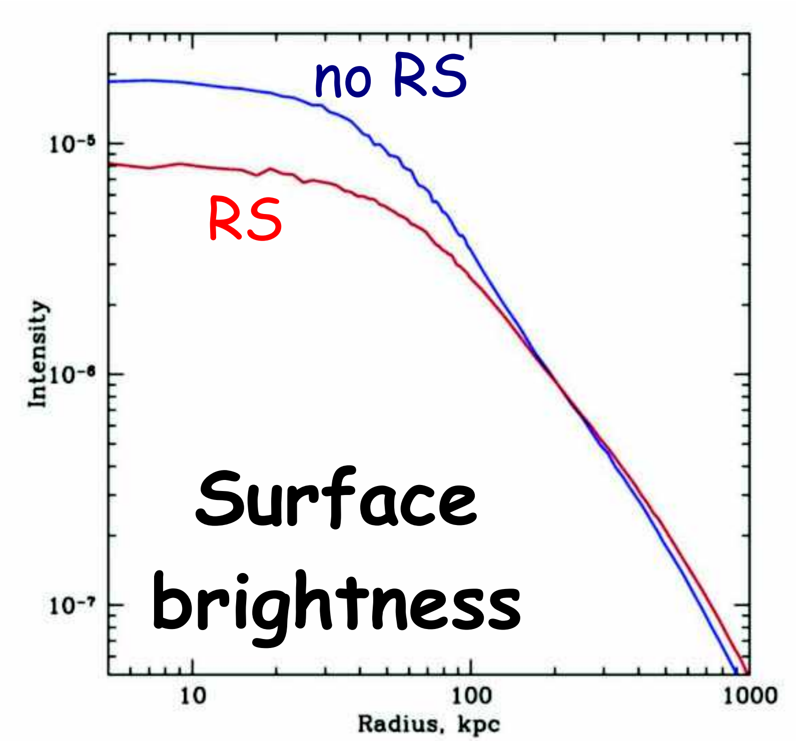
NGC 5813
1 Ms obs.

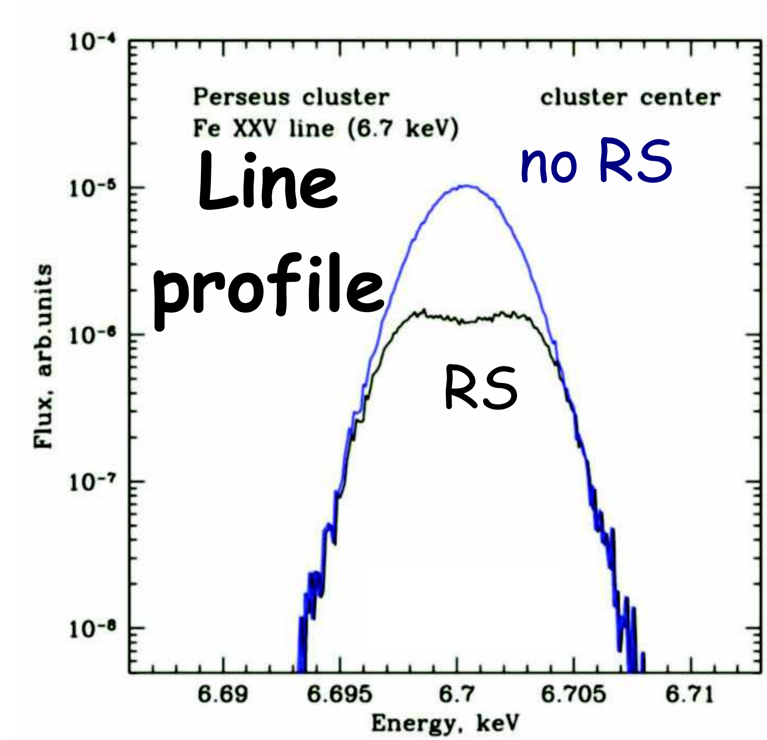


RGS/XMM weak upper limits (Sanders+10)

ICM turbulence: indirect measurements
resonant scattering (RS)

optical depth in resonant lines can be ~ 1 (Gilfanov+87)

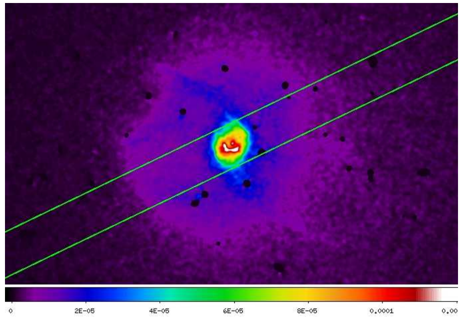




$$RS \propto \tau \propto \frac{1}{\Delta E_{\rm D}} \propto \frac{1}{(V_{\rm therm}^2 + V_{\rm turb}^2)^{1/2}}$$

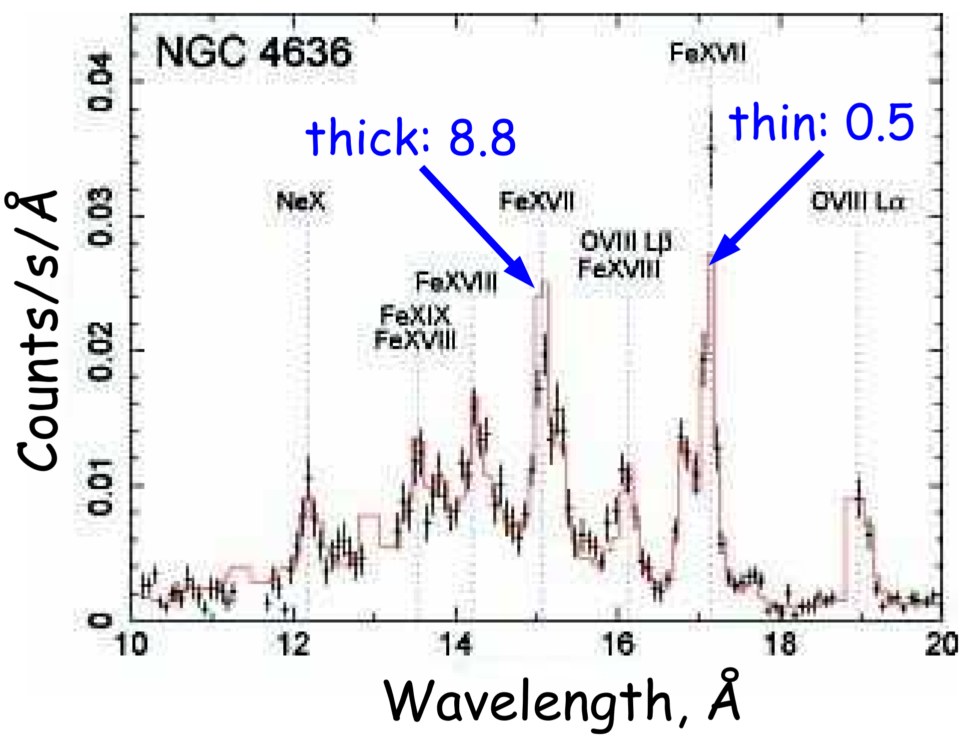
See review Churazov, IZ+10

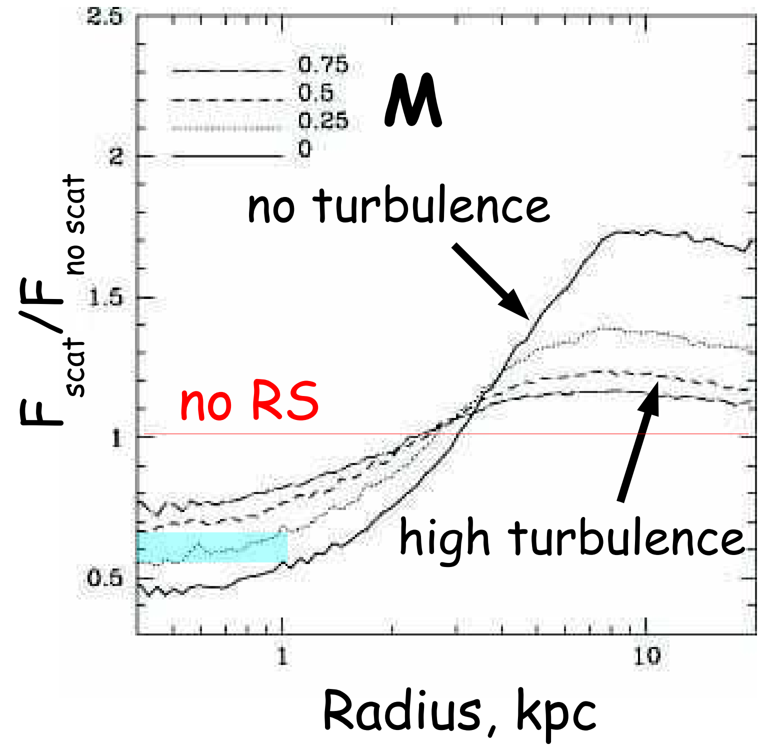
Resonant scattering: NGC4636



$$F_{thin} / F_{thick} \longrightarrow V$$

RGS XMM Newton 0.5 arcmin

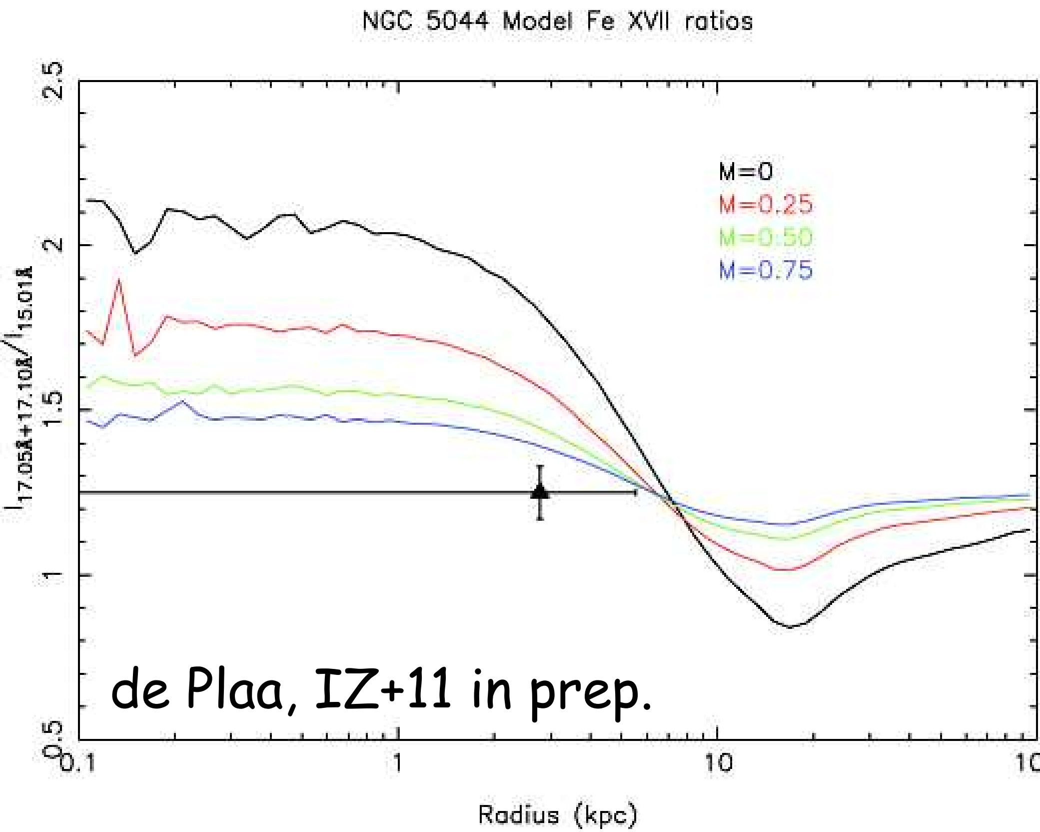


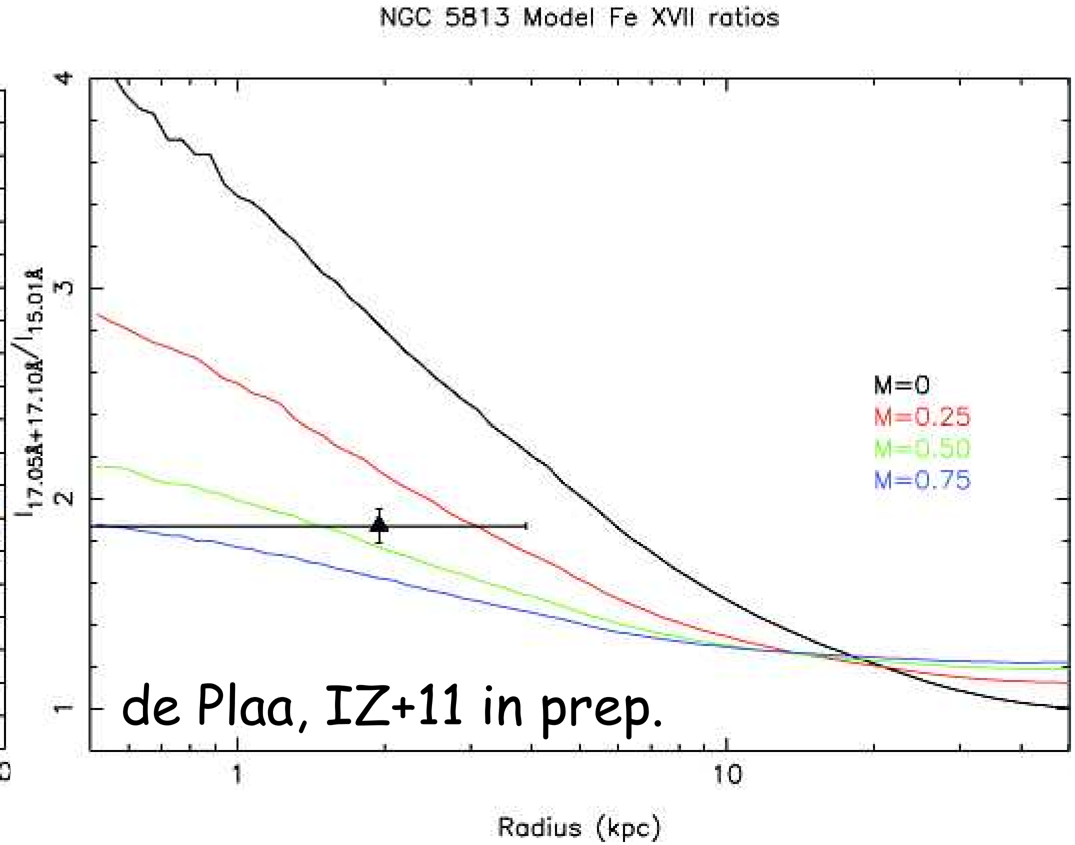


V in the core < 100 km/s

Werner, IZ+ 09

RS: NGC 5044 and NGC 5813



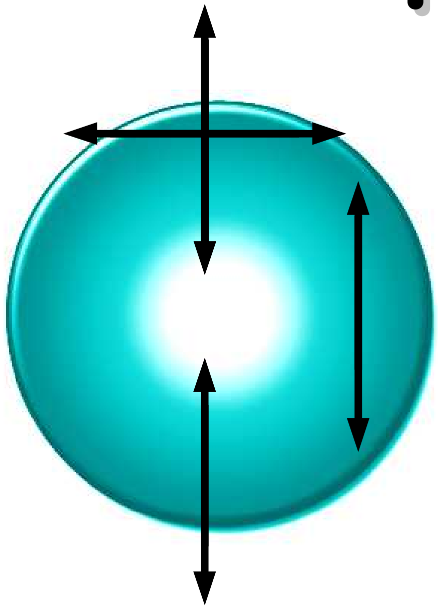


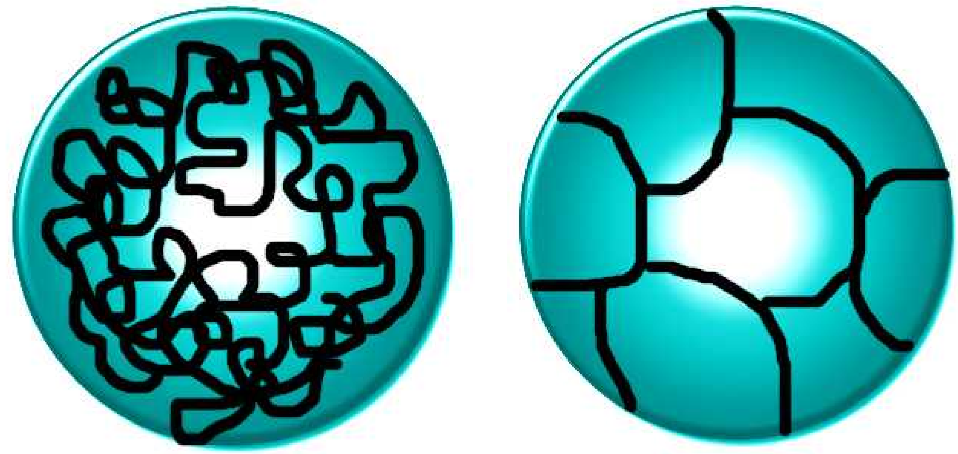
NGC 5044: 300 (RS) < V < 950 (width) km/s

NGC 5813: 100 (RS) < V < 670 (width) km/s

Crucial point: uncertainties in atomic data

RS: anisotropy + correlation length



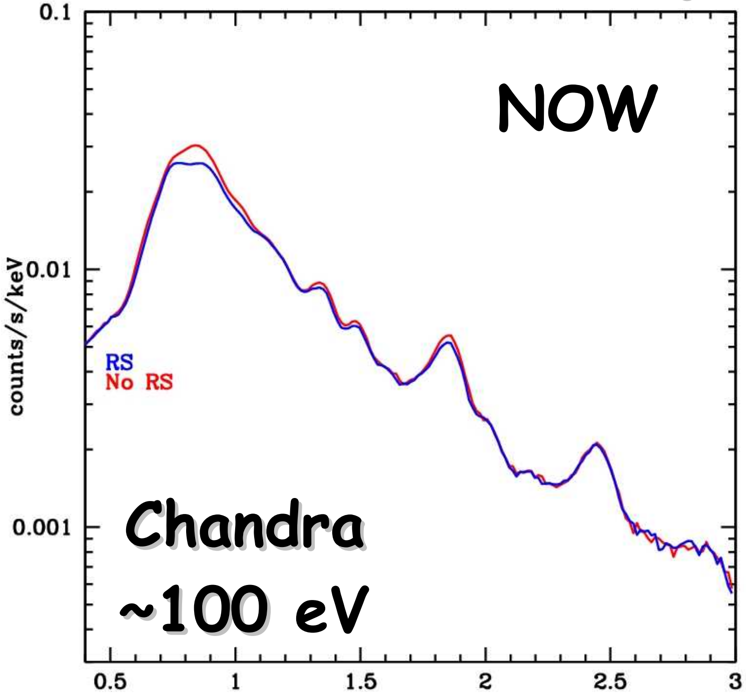


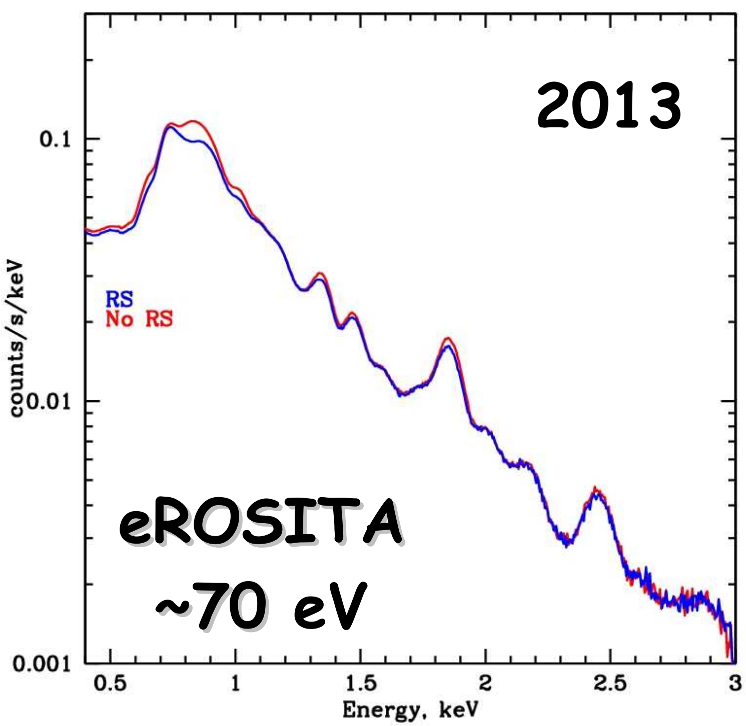
RS is mostly sensitive to:

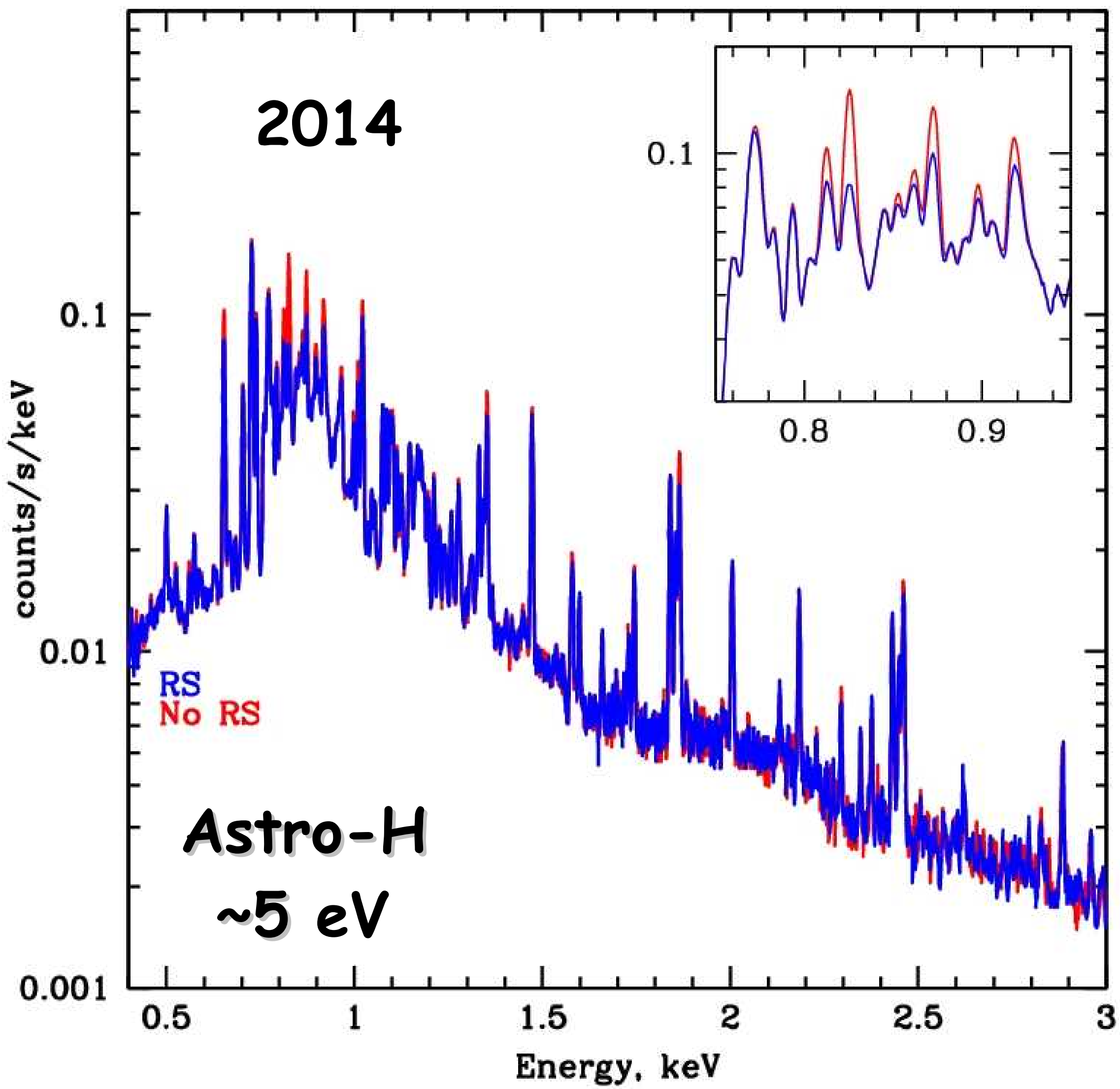
- radial motions
- small scale motions

IZ+11a

RS: future prospects

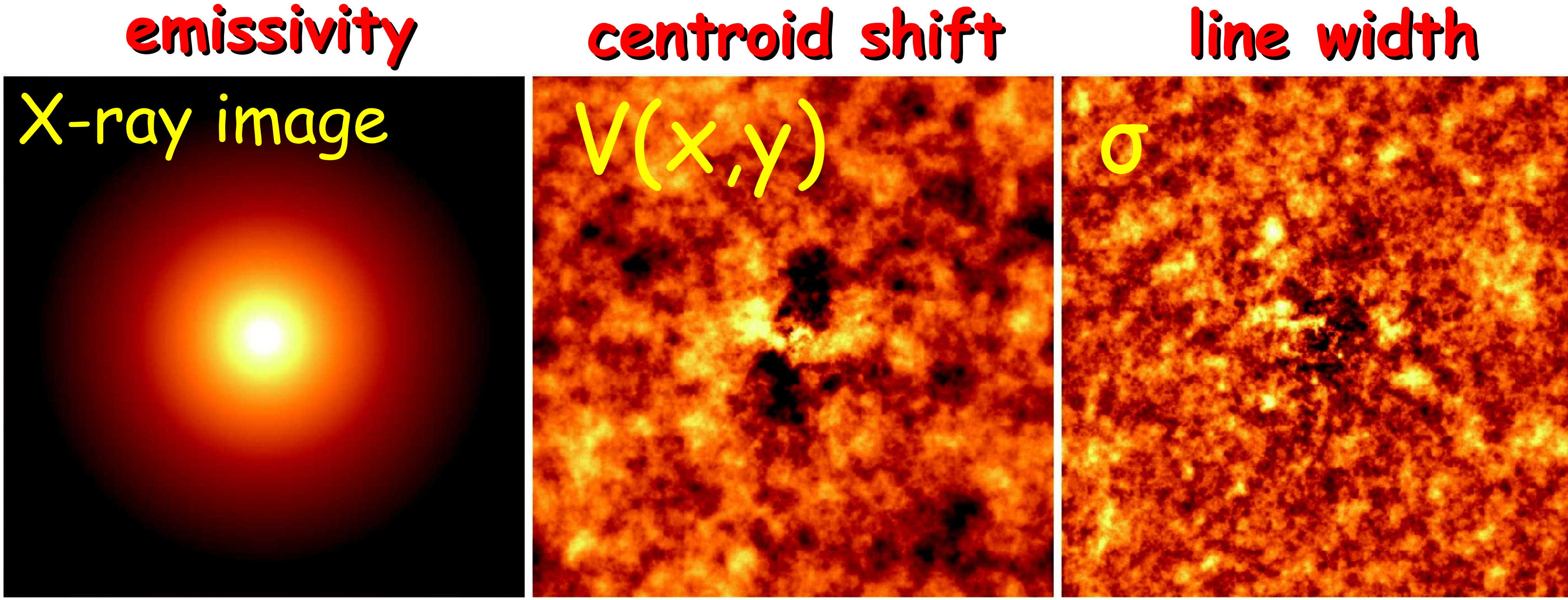






simulations: NGC 5813 1 Ms obs.

Direct measurements: future prospects



Emissivity-weighted V and σ

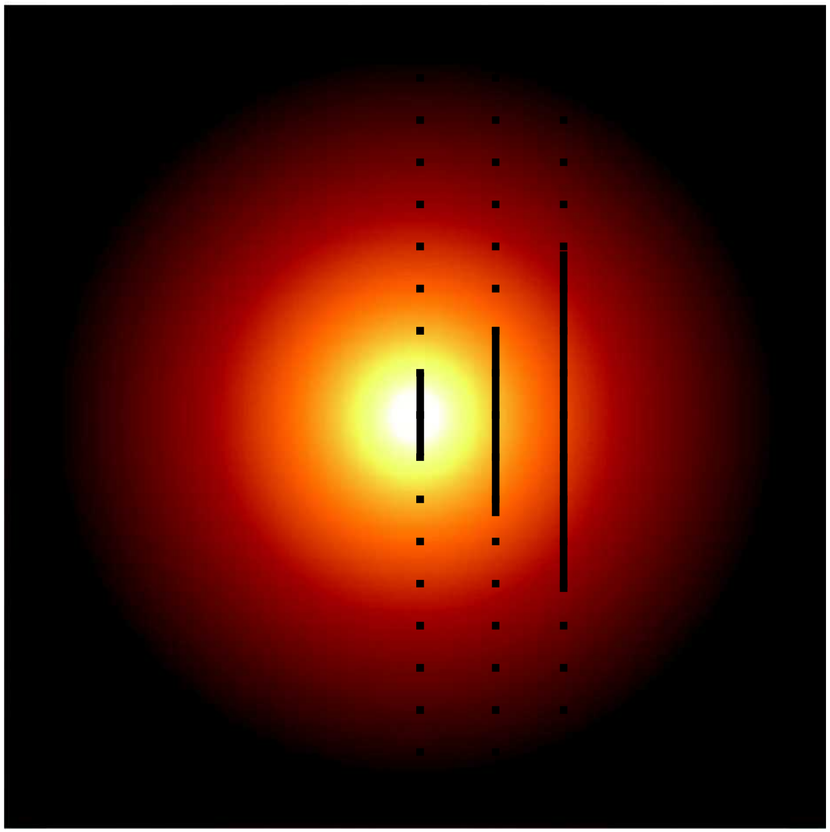
σ(R) → structure function of turbulence

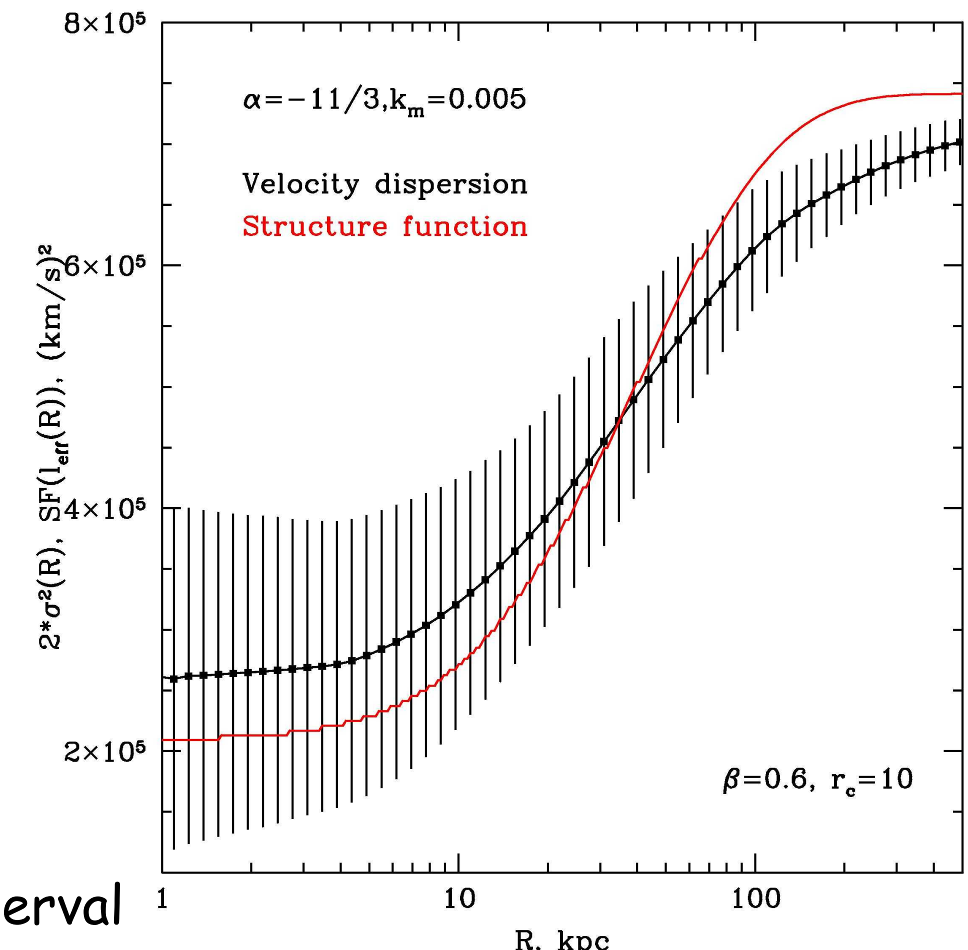
RMS(V)/σ → correlation length of velocity field

IZ+11b, submitted

Observed σ and structure function

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





At a given projected distance R an interval $l_{eff} \sim R$ contributes to the line flux (and width)

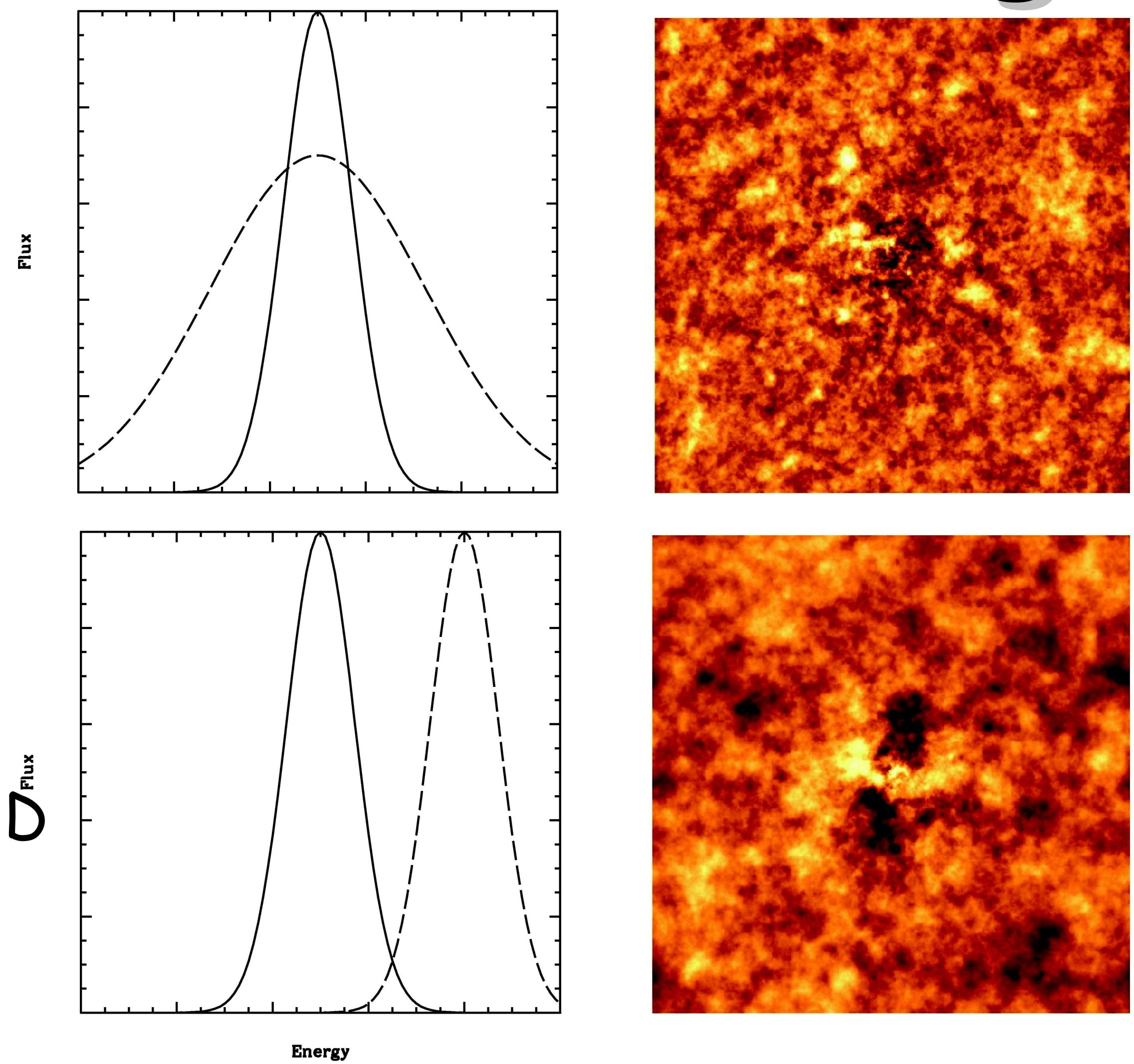
Observed σ(R) ≈ structure function (l_{eff})

IZ+11b, submitted

RMS(V) and correlation length

V_{3D} → $L < L_{eff}$: σ

V_{3D} → $L > L_{eff}$: V_{2D}



RMS(V)/σ — proxy of correlation length

IZ+11b, submitted

Conclusions

How to constrain properties of the ICM velocity field?

NOW

•Grating + RS → lower limits on amplitudes

•Grating + line width → upper limits on amplitudes

SOON

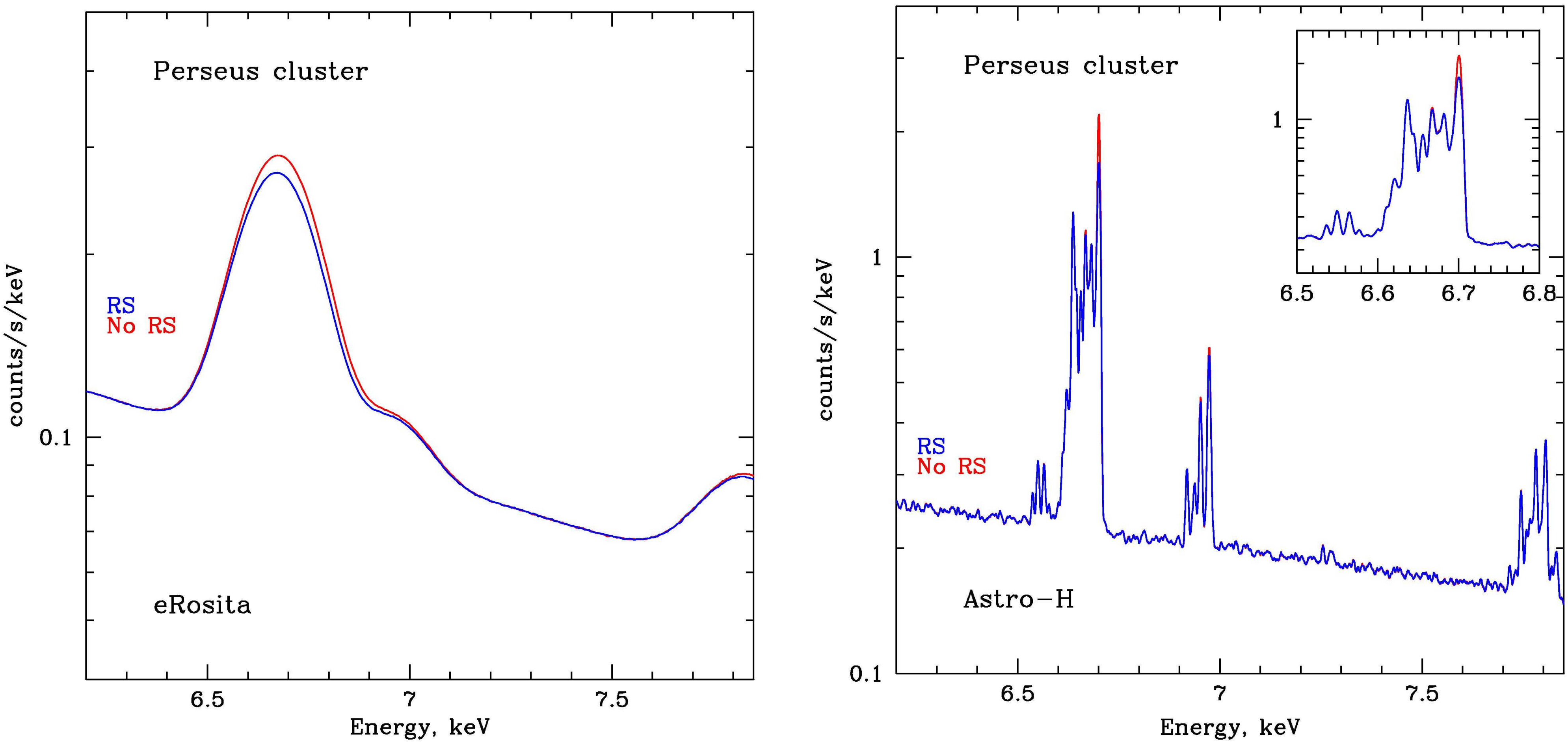
•eROSITA + RS → constraints from CCD

•Astro-H + line width and centroid shift+ RS → amplitudes, anisotropy, spatial scales, 3D velocity power spectrum

FUTURE

•ATHENA+ line width and centroid shift+ RS → amplitudes, anisotropy, spatial scales, 3D velocity power spectrum

•X-ray polarimeters → transverse gas motions



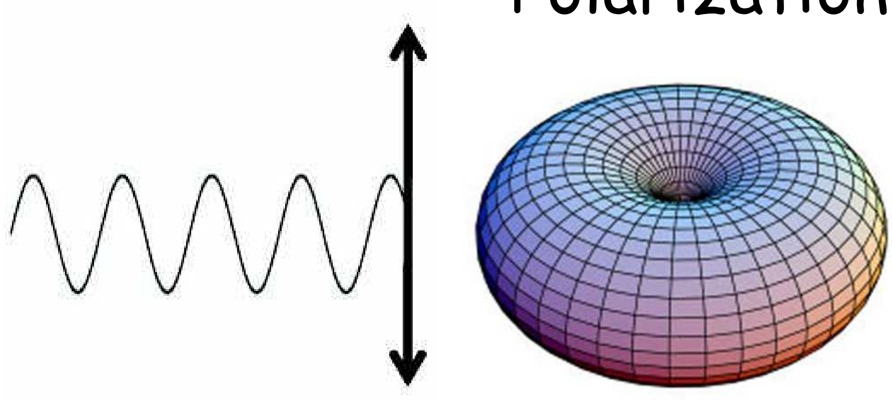
Perseus cluster
RS
No RS
eRosita
counts/s/keV
0.1
6.5
7
7.5
Energy, keV
Perseus cluster
RS
No RS
Astro-H
counts/s/keV
1
0.1
6.5
7
7.5
Energy, keV
1
6.5
6.6
6.7
6.8

RS: polarization in strong lines

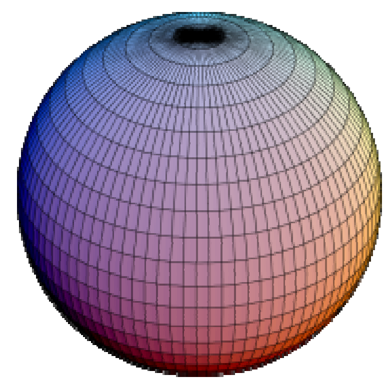
Scattering phase function=

Rayleight + Isotropic

Polarization



No polarization



Non zero weight of Rayleight weight

(Chandrasekhar 1950, Hamilton 1947)

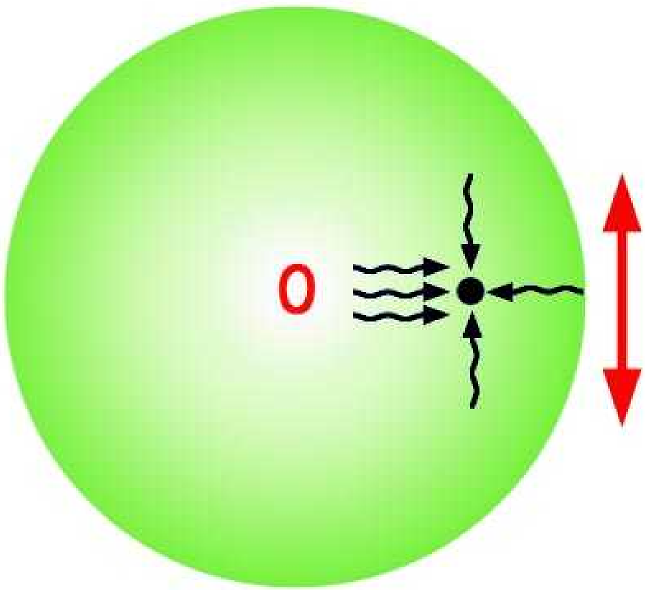
He-like ions: $1s^2\,(^1S_0) - 1s2p\,(^1P_1)$ **=>** W_R**=1**

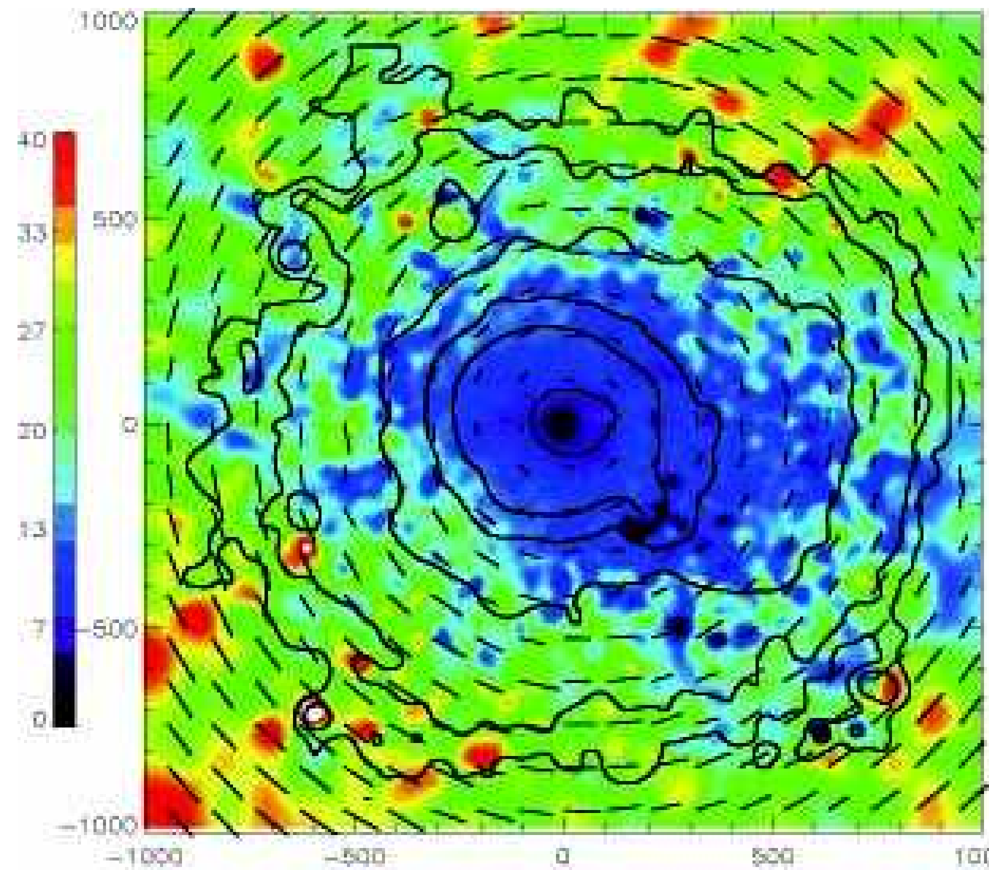
(e.g. 6.7 keV line)

RS: polarization in strong lines

Rayleight phase function + quadrupole moment = polarization

simulated cluster



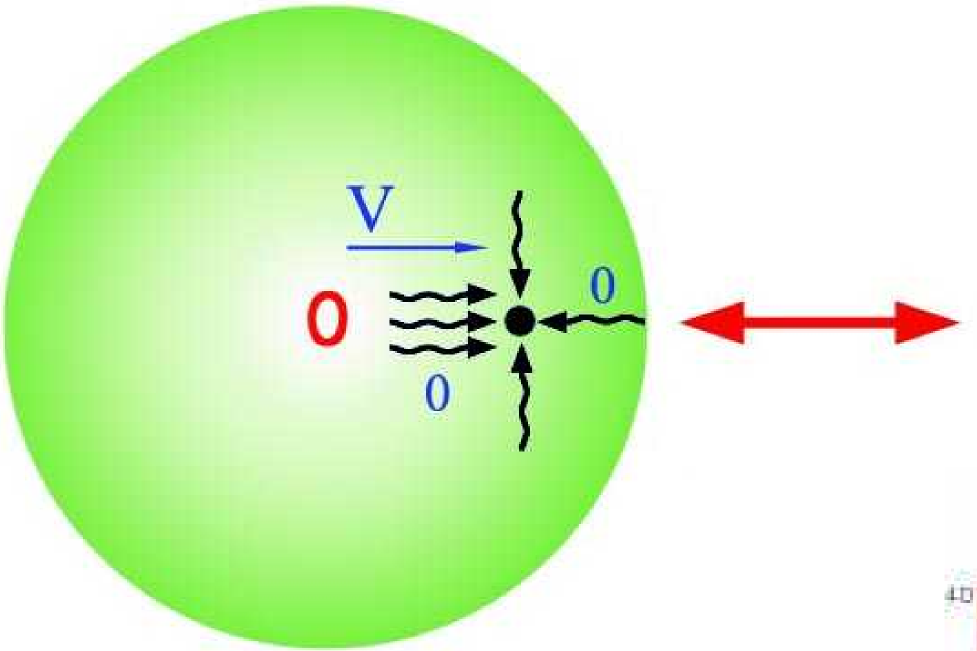


6.7 keV line

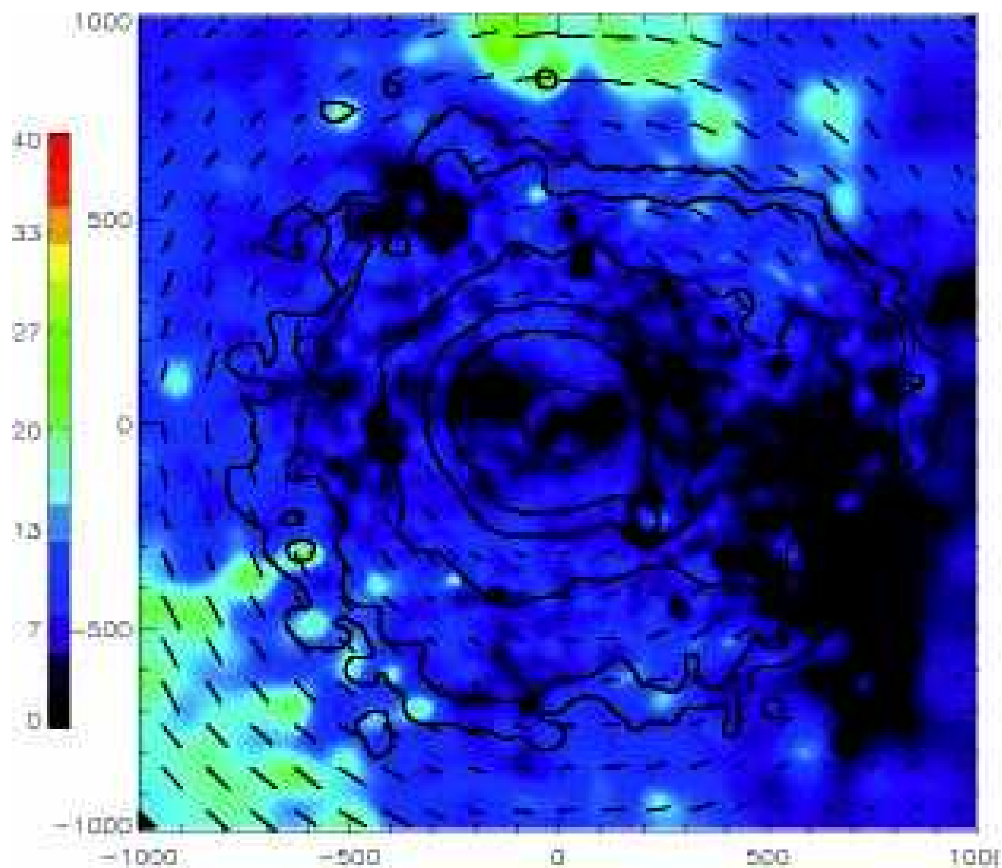
P ~ 25%

Sazonov et al. 2002, Zhuravleva et al.2010a

Polarization: transverse motions



P ~ 15%



Zhuravleva et al. 2010a

RS: optical depths

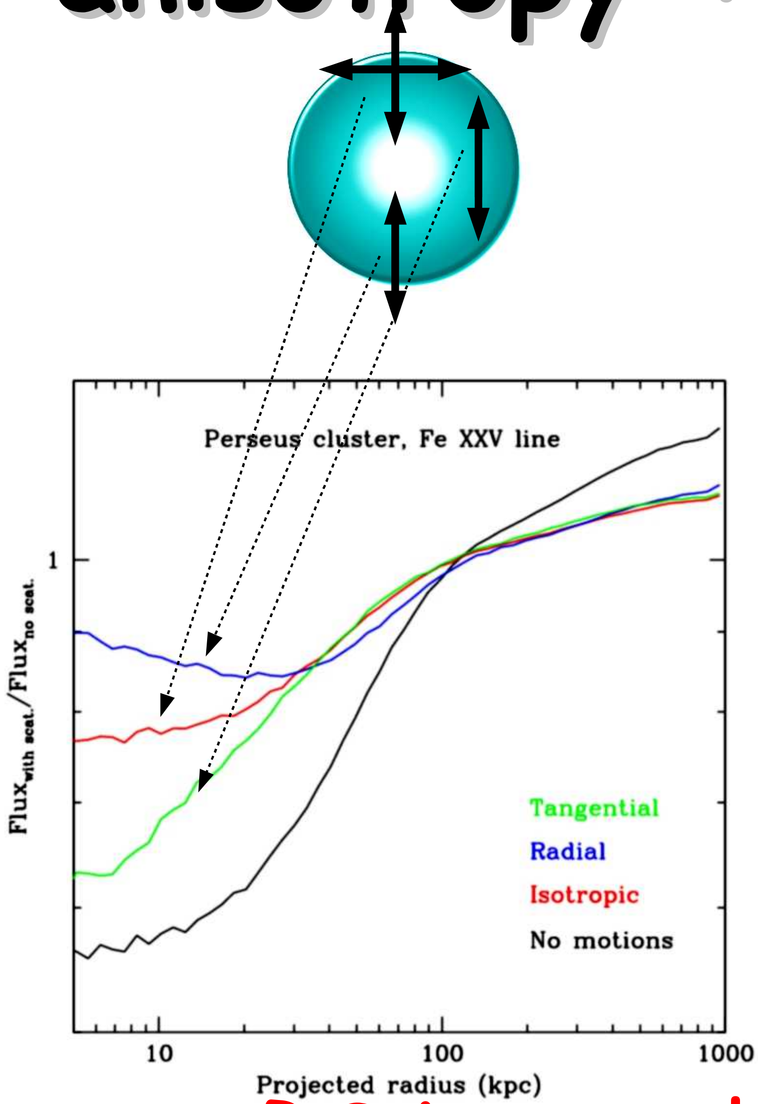
Ion	E, keV	f	τ, NGC 4636	τ, Virgo/M87	τ, Perseus
O VIII	0.65	0.28	1.2	0.34	0.19
Fe XVII	0.83	2.73	8.8	0.0005	$2.8\cdot10^{-8}$
Fe XVIII	0.87	0.57	1.3	0.0007	$1.5\cdot10^{-7}$
Fe XXIII	1.129	0.43	0.016	1.03	0.16
Fe XXIV	1.168	0.245	0.002	1.12	0.73
Fe XXV	6.7	0.78	0.0002	1.44	2.77

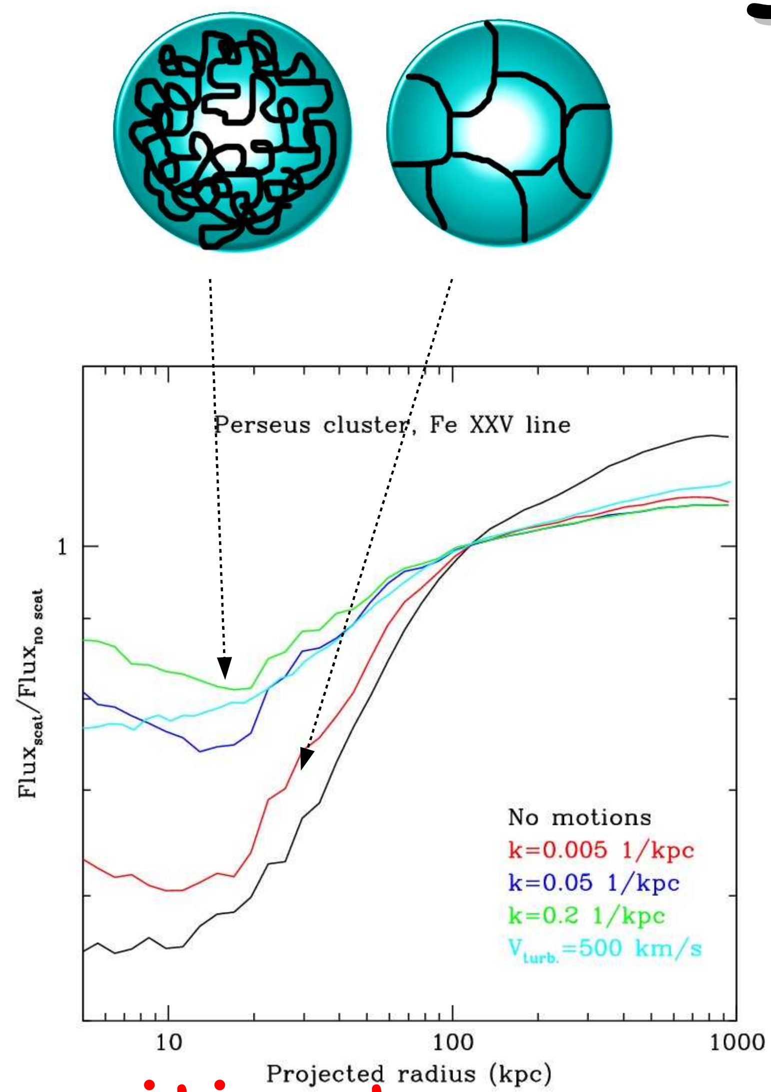
$$RS \propto \tau \propto \frac{1}{\Delta E_{\rm D}} \propto \frac{1}{(V^2_{\rm therm} + V^2_{\rm turb})^{1/2}}$$

Sensitive to velocity of gas motions

RS can be used as a diagnostic of turbulence in the ICM

RS: anisotropy + correlation length





RS is mostly sensitive to:

- radial motions
- small scale motions

IZ+11a

Direct/Indirect measurements

	XMM-Newton	Chandra	Astro-H (2014)
Width and shift of lines	Weak upper limits on amplitudes (Sanders+11)	-	Amplitudes, spatial scales (Zhuravleva+11b)
Resonant Scattering	Upper limits on amplitude (e.g. Werner+09, Churazov+04) talk by Jelle de Plaa		Amplitudes, spatial scales, anisotropy (Zhuravleva+11a)
Pressure fluctuations	Spatial scales (Schuecker+04)	-	-
SB fluctuations	Spatial scales talk by E. Churazov		-
Diffusion of heavy elements	Amplitudes, spatial scales Rebusco+06		-

+ X-ray polarization: transverse gas motions (Zhuravleva+10)
+ Kinetic SZ: amplitudes

Resonant Scattering: spatial scales and anisotropy

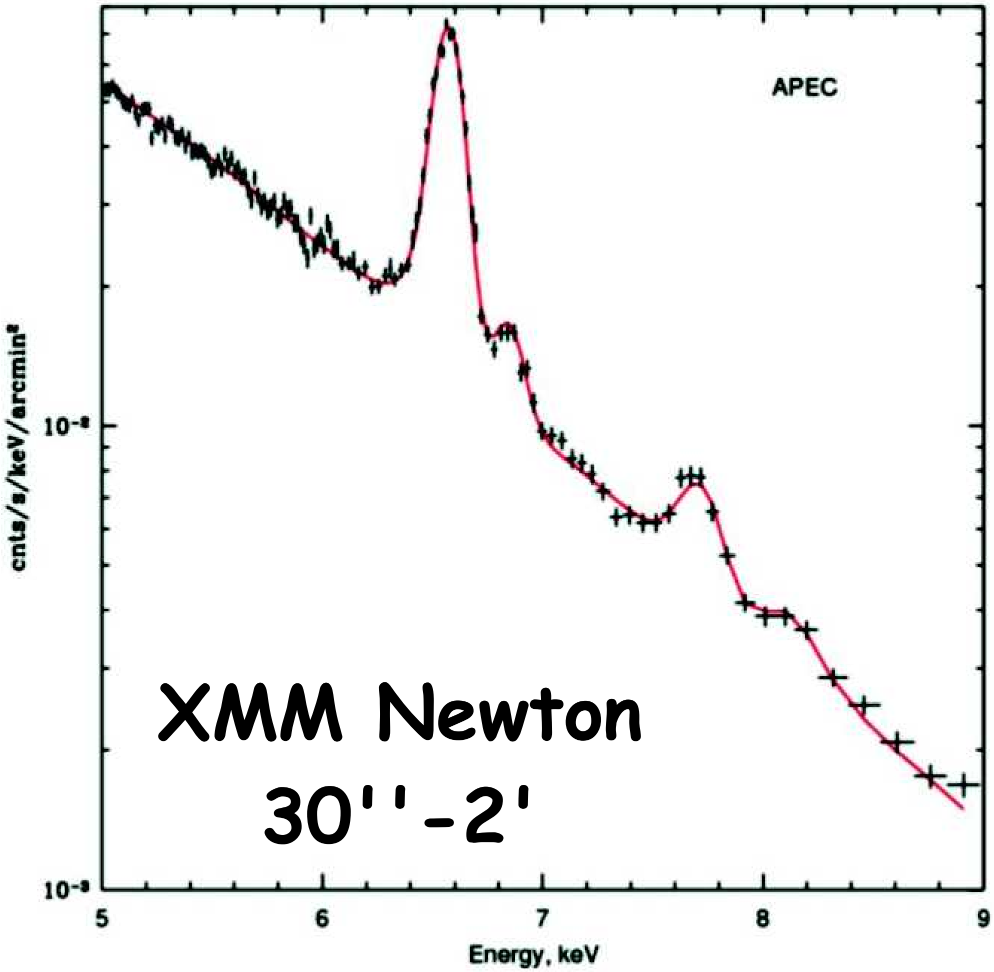
Perseus, $r<10$ kpc		Perseus, $r<30$ kpc	
Isotropic:	V=500 km/s	Isotropic:	V=500 km/s
Radial:	V=200 km/s	Radial:	V=300 km/s
Tangential:	V=1500 km/s	Tangential:	V=1200 km/s

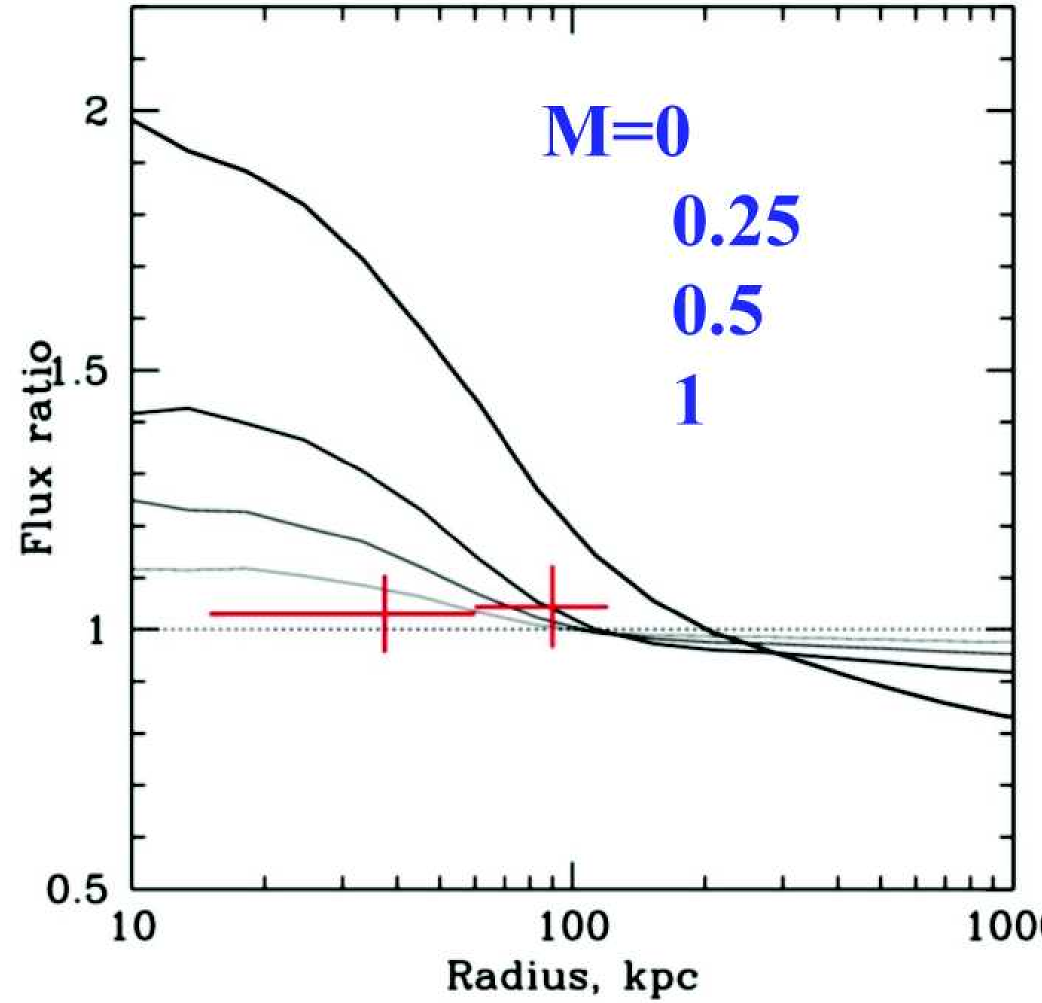
Zhuravleva+11a

Resonant scattering: Perseus

He-like Fe 6.7 keV line, optical depth ~3

F_{Ni}/F_{Fe}



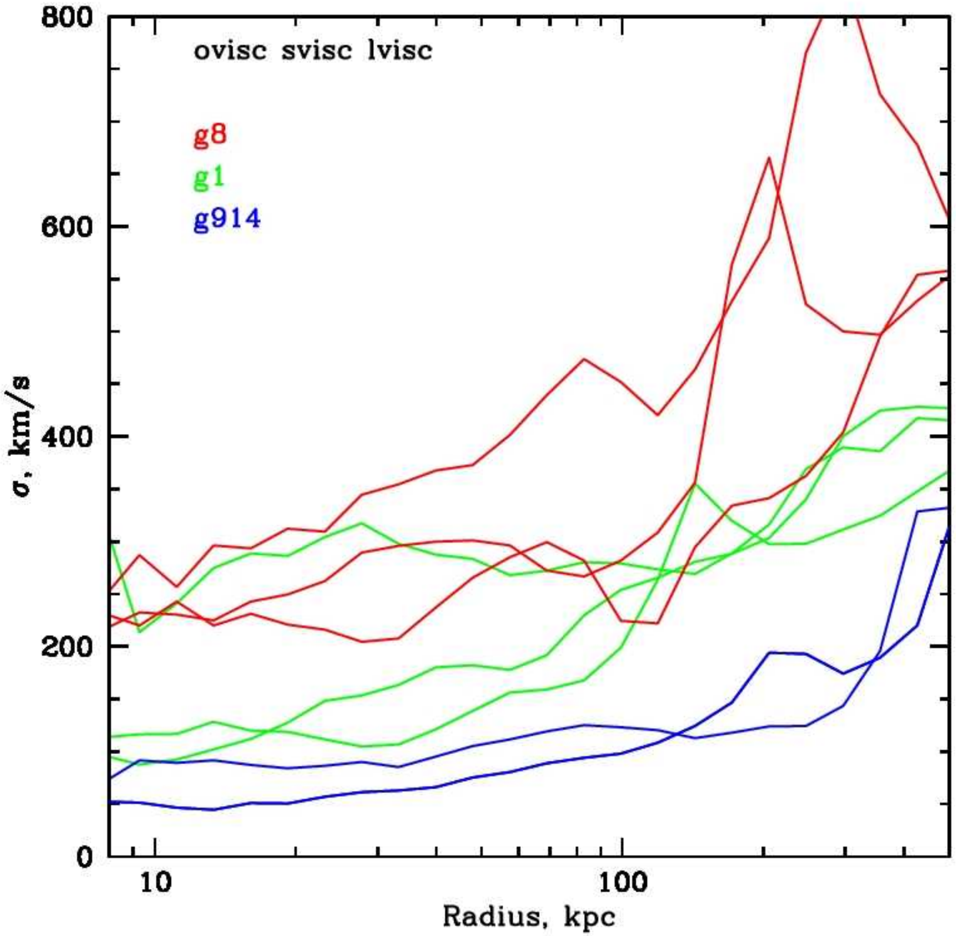


6.7 keV line is not supressed → V>400 km/s

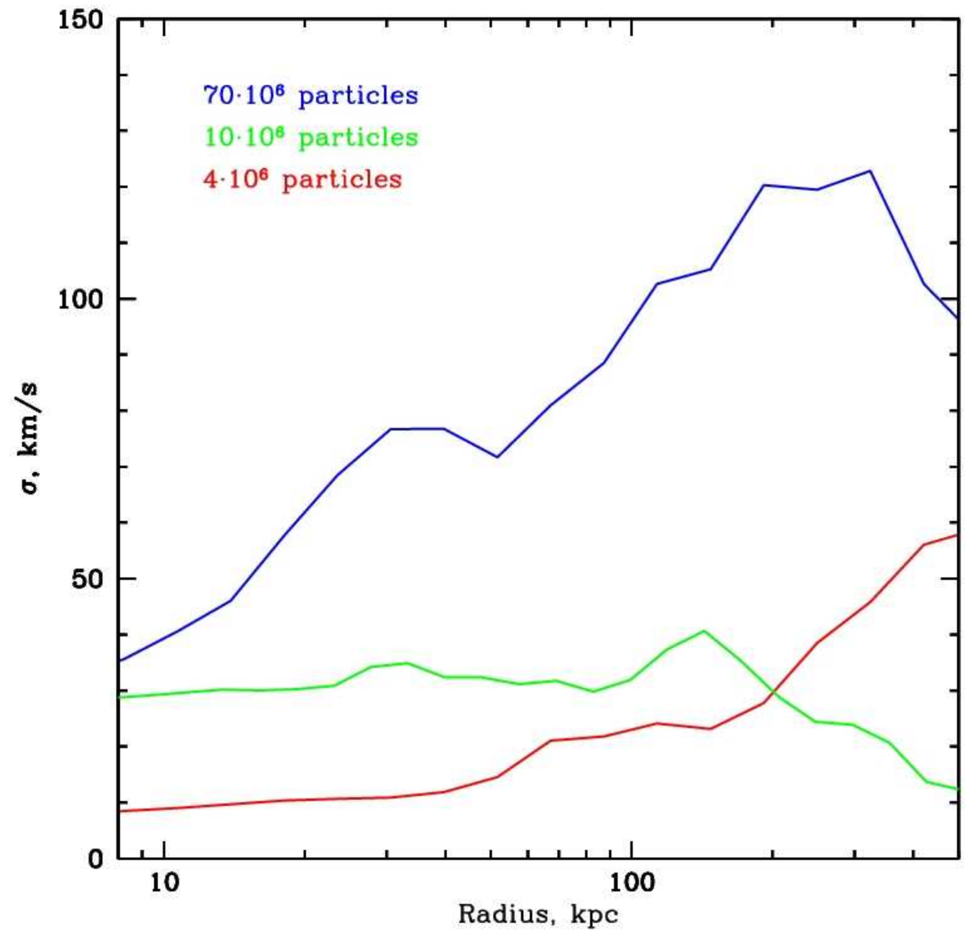
Churazov et al. 2004

Velocity field in SPH simulations: main problems

Numerical viscousity

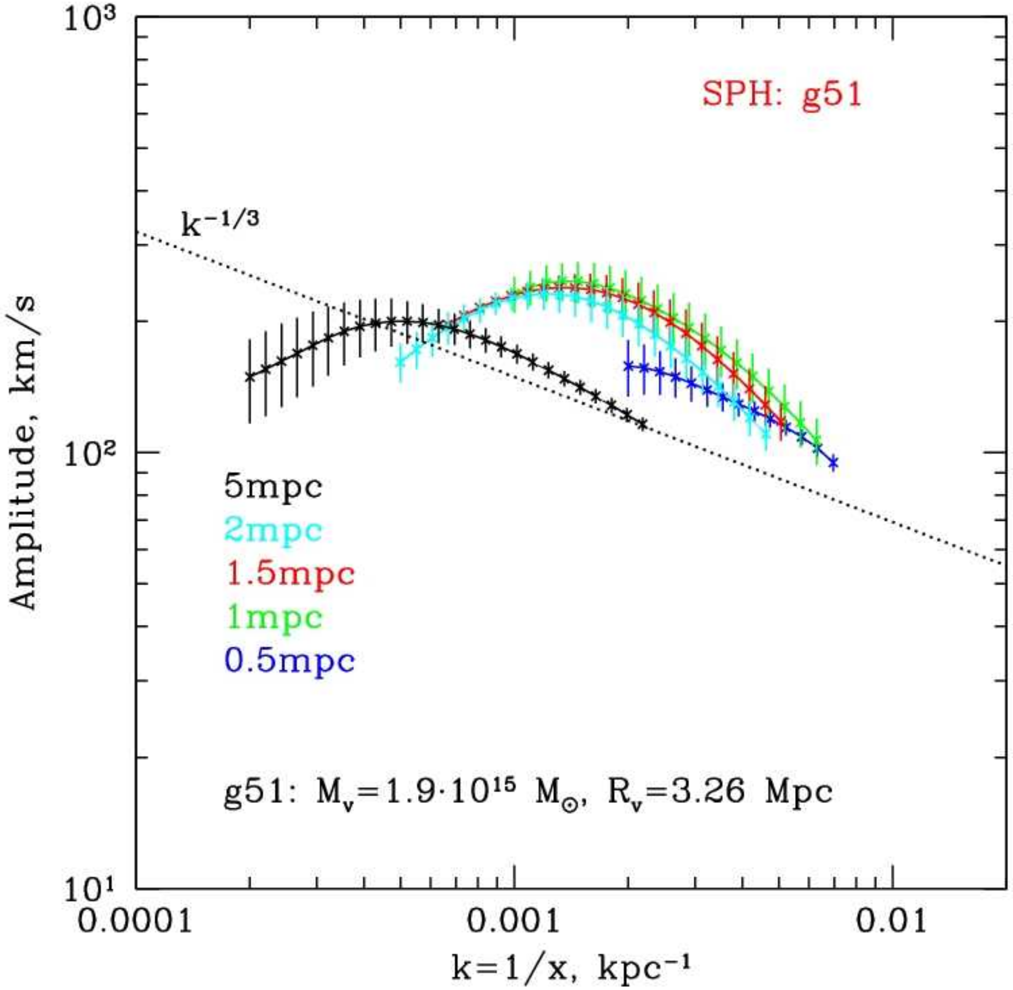


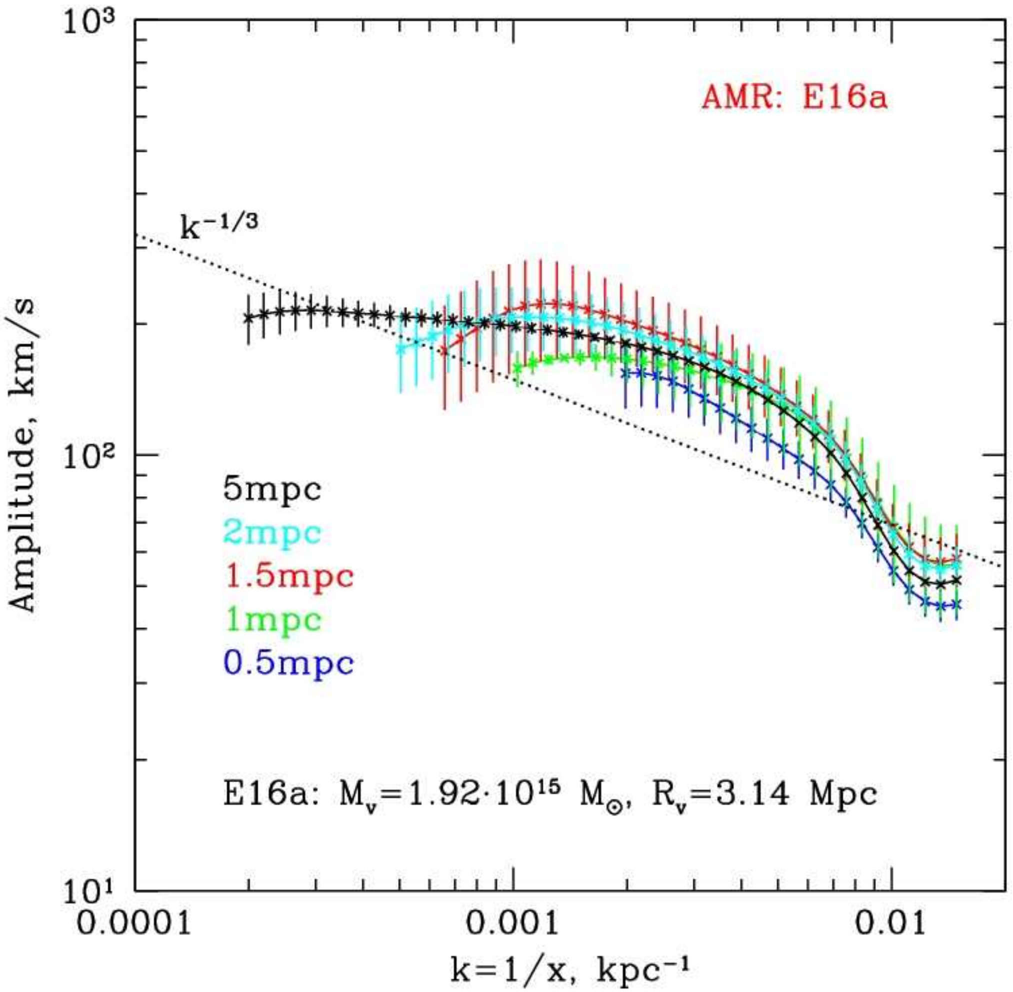
Resolution



Simulations by Dolag et al. 2005

3D velocity power spectrum





Deviations from Kolmogorov PS

Dependence on considered volume

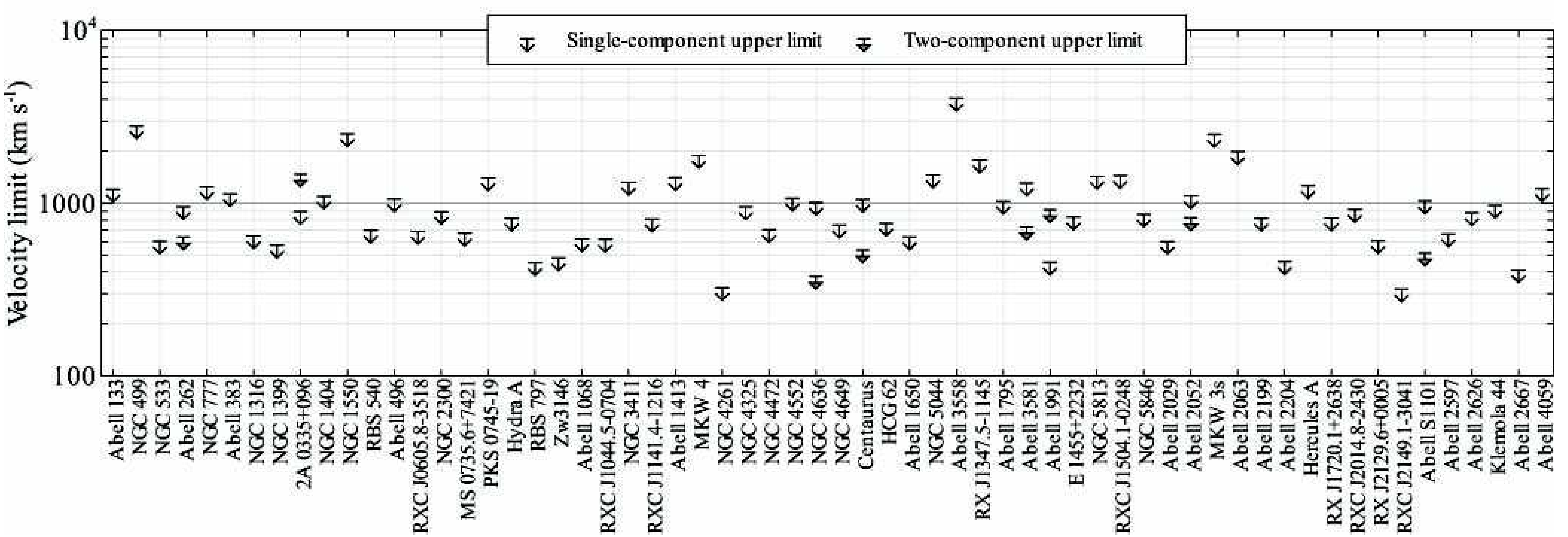
SPH and AMR show similar behaviour

Gas motions: observations

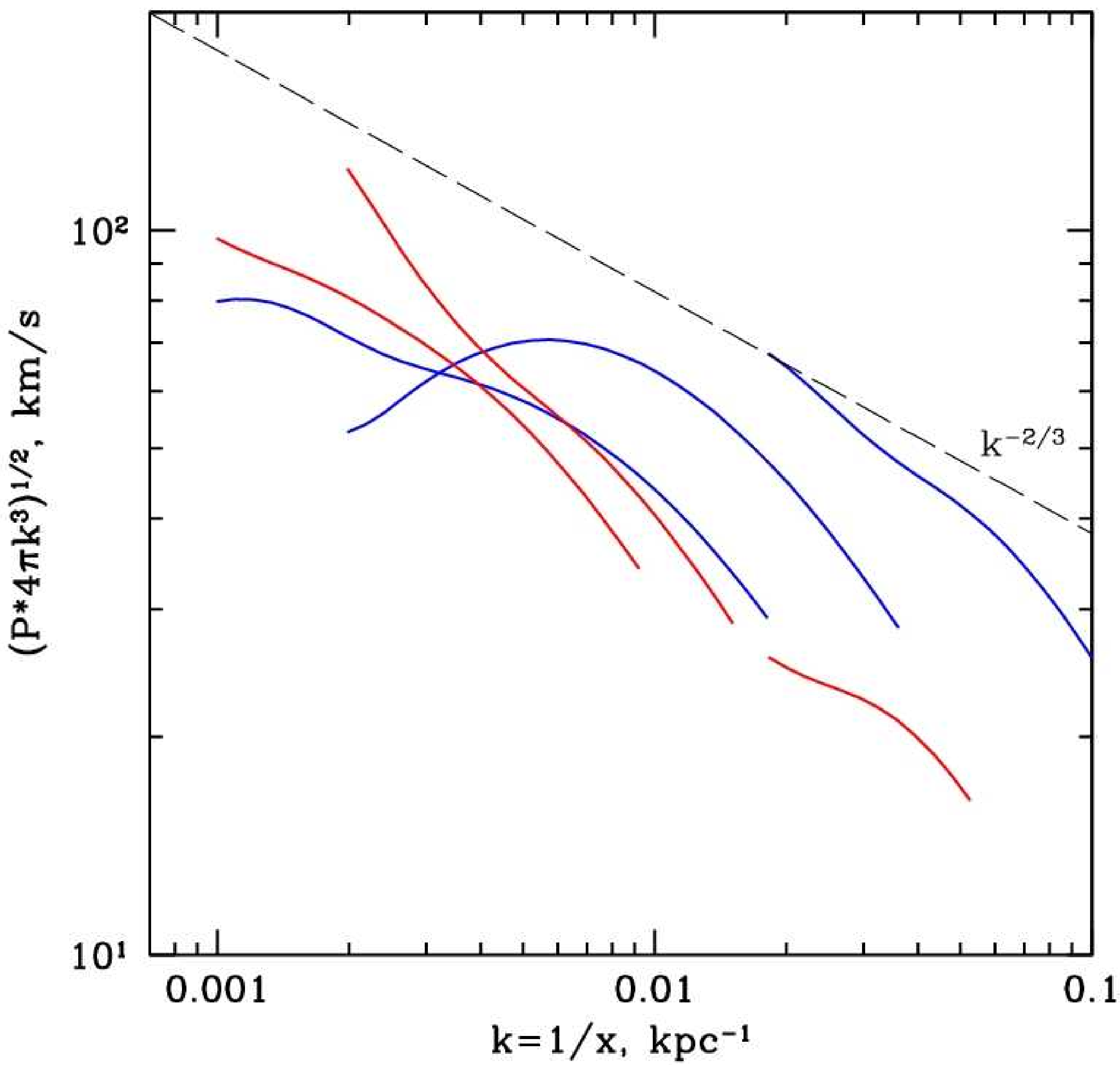
Broadening and shift of line: amplitude, dispersion

RGS XMM Newton : upper limits on V

(Sanders et al. 2010)



3D velocity power spectrum: resolution of simulations



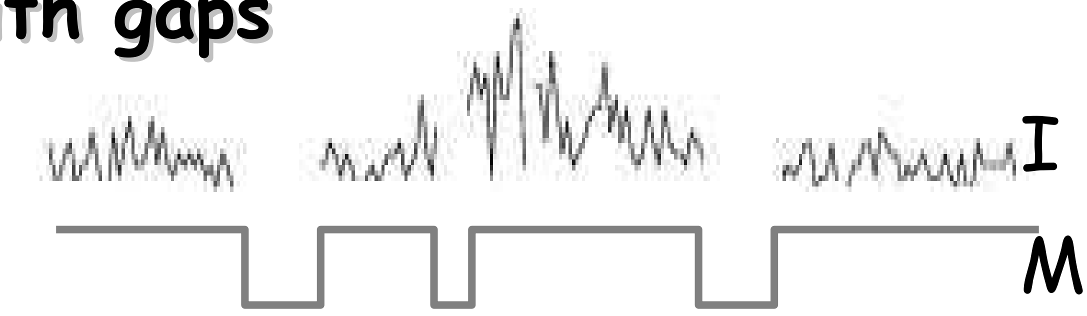
A Mexican Hat with holes:

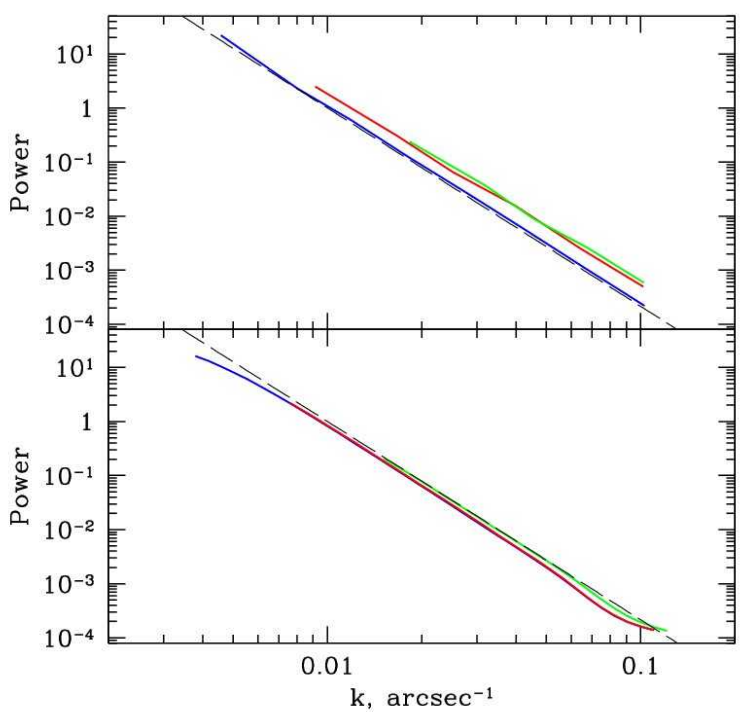
a method to calculate low resolution PS from data with gaps

Arevalo et al. 2010 in prep.

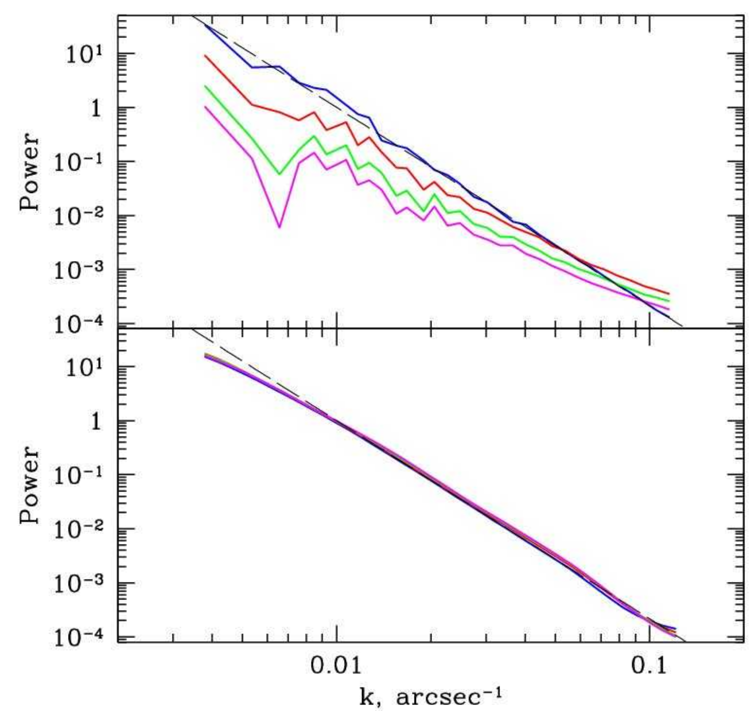
i) $$I_c(k) = \frac{G_{\sigma 1} * I}{G_{\sigma 1} * M} - \frac{G_{\sigma 2} * I}{G_{\sigma 2} * M}$$

ii) variance of $I_c(k)$





trimming of boxes

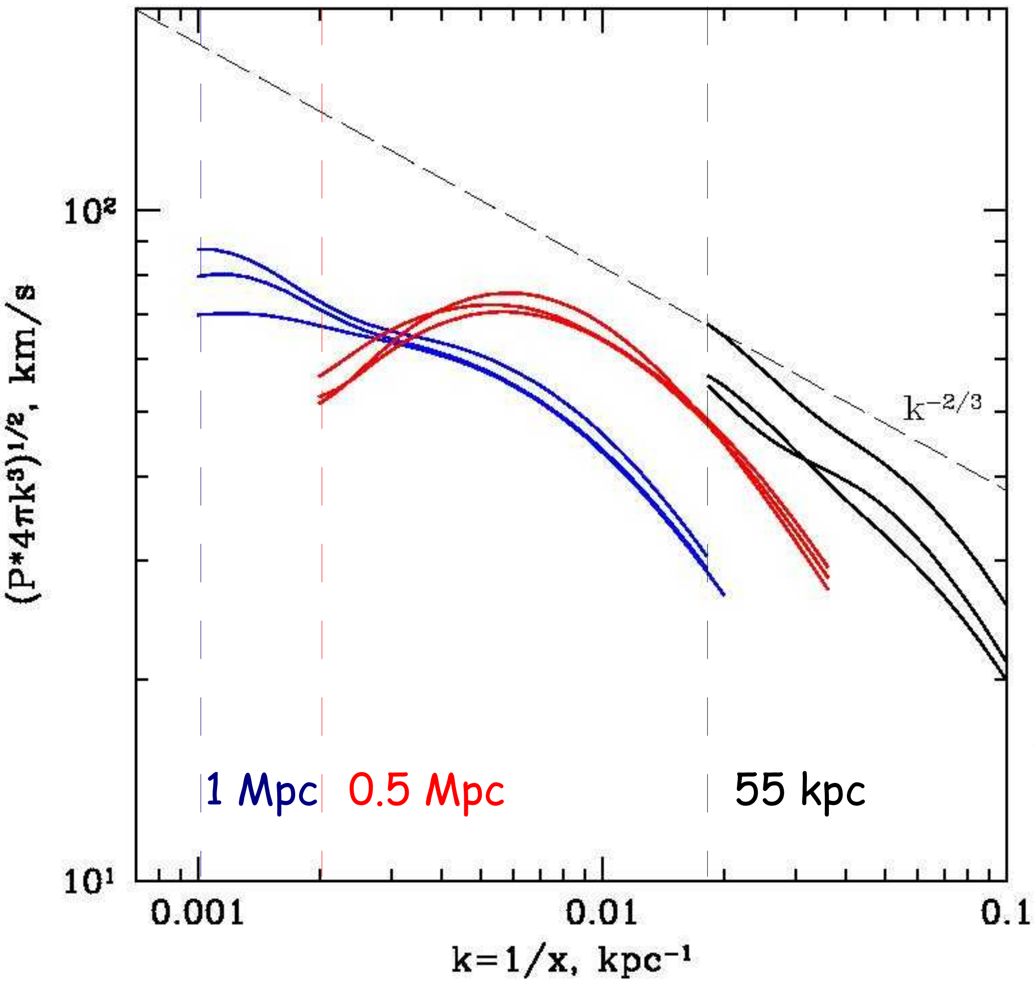


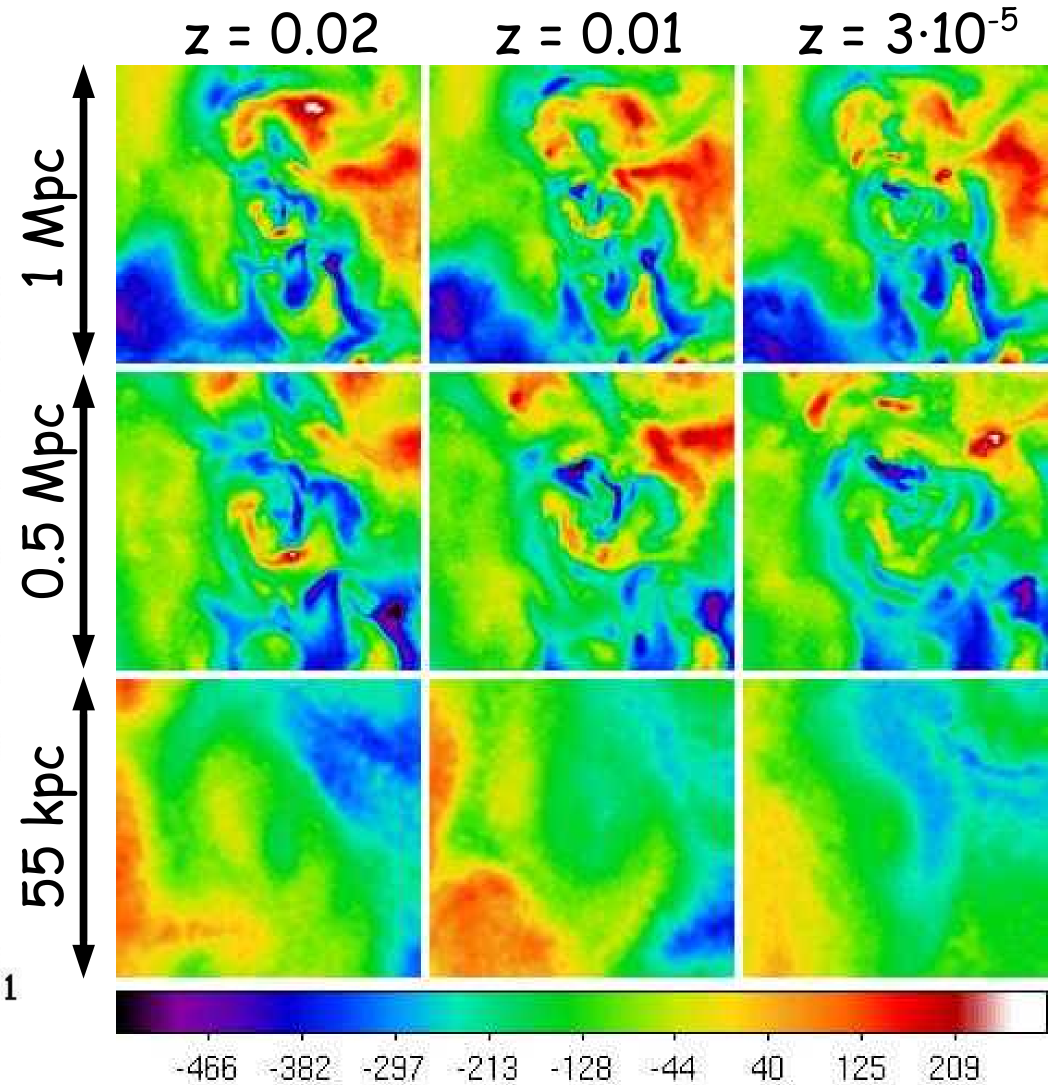
data with gaps

3D velocity power spectrum

SPH simulations by K. Dolag (Dolag et al. 2005) , ~ $70 \cdot 10^6$ particles

g676 cluster: $M_{vir} = 1.6 \cdot 10^{14}\ M_{sun}$, $R_{vir} = 1.43$ Mpc





Does PS depend on considered volume of cluster?