Measuring ICM velocities: resonant scattering and X-ray polarization

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Galaxy Clusters: the Crossroads of Astrophysics and Cosmology
Santa Barbara 2011

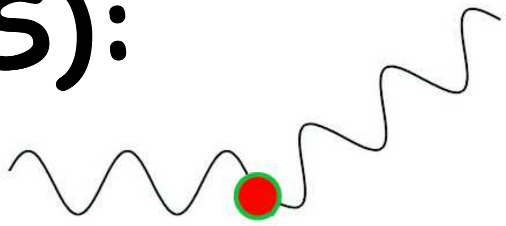
We know	We don't know
Temperature	Velocity field
Density	Magnetic fields
Abundance	Thermal conduction

(1) Constraints on velocity field with resonant scattering: amplitudes, spatial scales, anisotropy

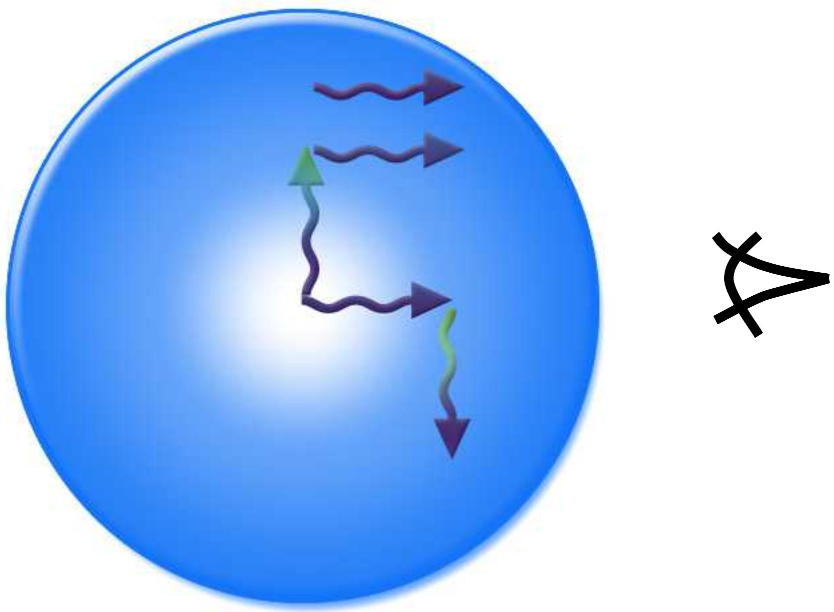
(2) Constraints on transverse gas motions: X-ray polarimetry

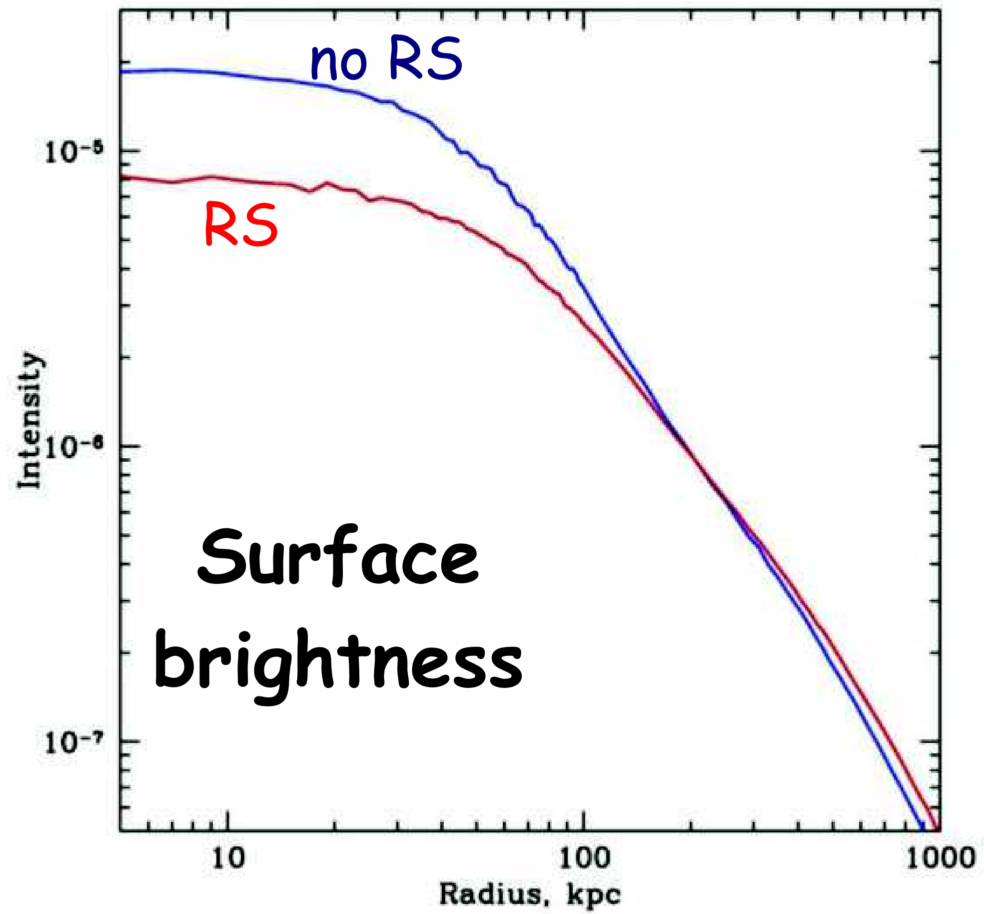
(3) Observables → 3D velocity field

Resonant Scattering (RS): absorption+emission

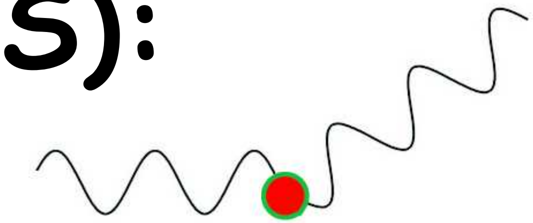


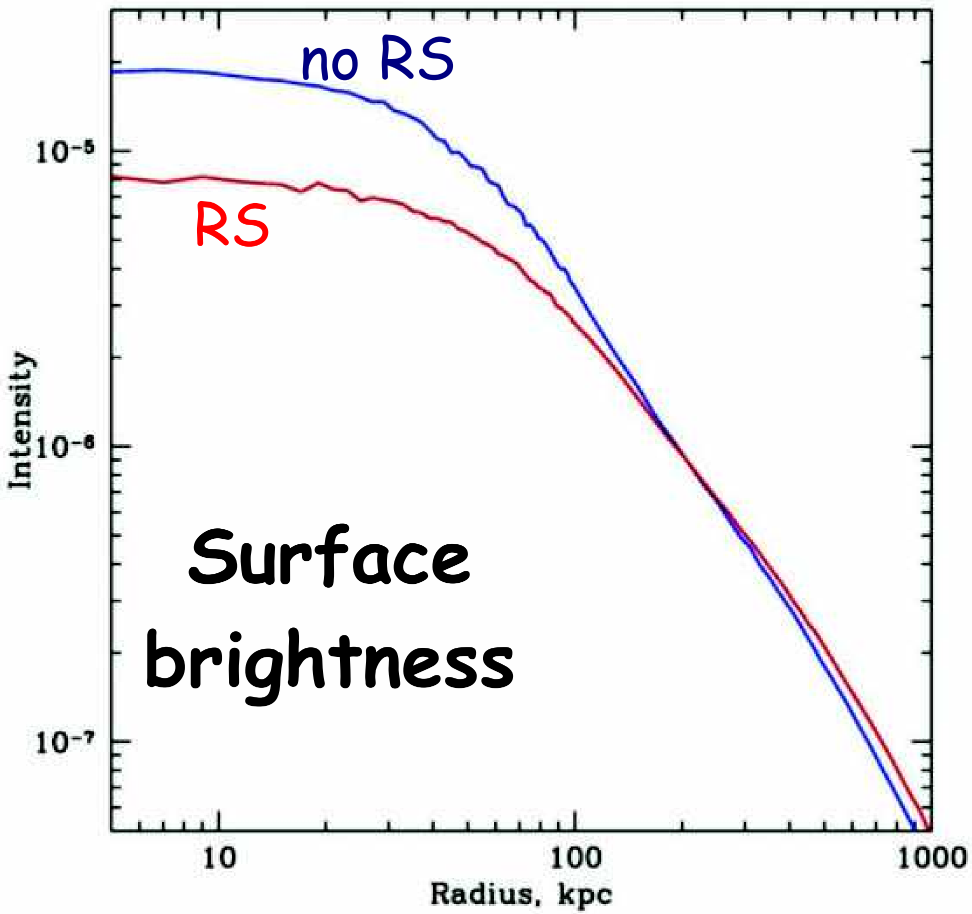
Gilfanov, Sunyaev & Churazov (1987) :
optical depth in resonant lines can be ~ 1

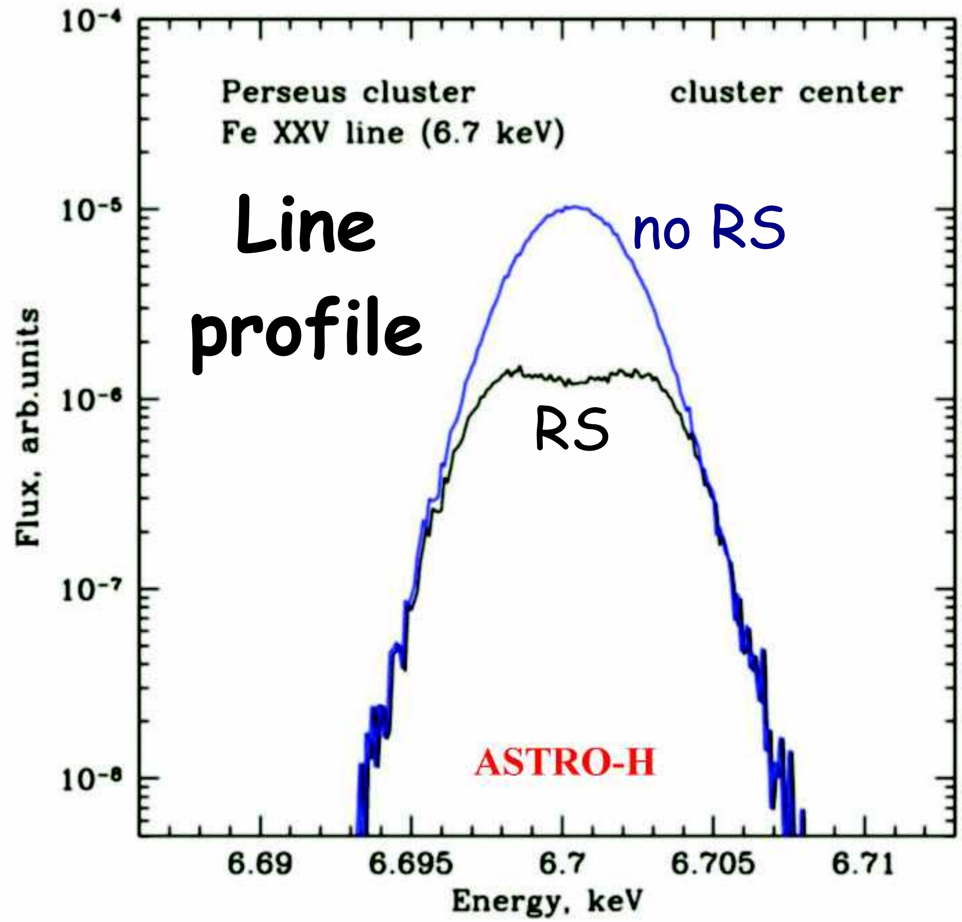




Resonant Scattering (RS): absorption+emission







Optical depth in X-ray lines

$$\tau = \int \frac{\sqrt{\pi} h r_e c f_{ik}}{\frac{E_0}{c}\sqrt{\frac{2kT_e}{Am_p} + V_{\rm turb}^2}} n_i dl$$

$$n_i = n_p Z \delta_i$$

Large oscillator strength of the transition

Appreciable ion fraction

Abundant elements

Small line width

Heavy elements (thermal broadening)

Sazonov et al. 2002; IZ et al. 2010

Optical depth in X-ray lines

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	$2.8 \cdot 10^{-8}$
Fe XVIII	0.87	0.57	1.3	0.0007	$1.5 \cdot 10^{-7}$
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

Resonant scattering in clusters

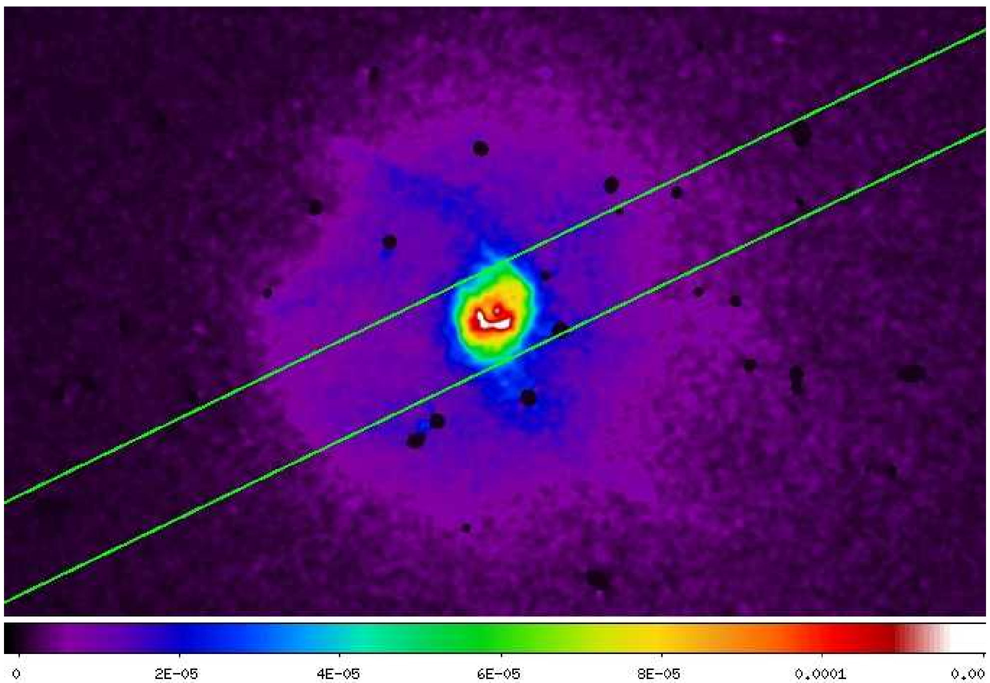
Gilfanov+, 1987; Krolik & Raymond, 1988; Molendi+, 1998;
Shigeyama 1998; Akimoto+, 1999; Kaastra+, 1999;
Churazov+, 2001; Mathews+, 2001; Bohringer+, 2001;
Sakelliou+ 2002; Xu+, 2002; Sazonov+,2002a;
Sazonov+, 2002b; Kahn+, 2003; Churazov+, 2004;
Gastaldello & Molendi, 2004; Sanders+, 2004;
Sanders & Fabian, 2006; Molnar+, 2006;
Werner+, 2009; Hayashi+, 2009; Zhuravleva+, 2010a,b;

See our recent review on RS:
EC+, 2010

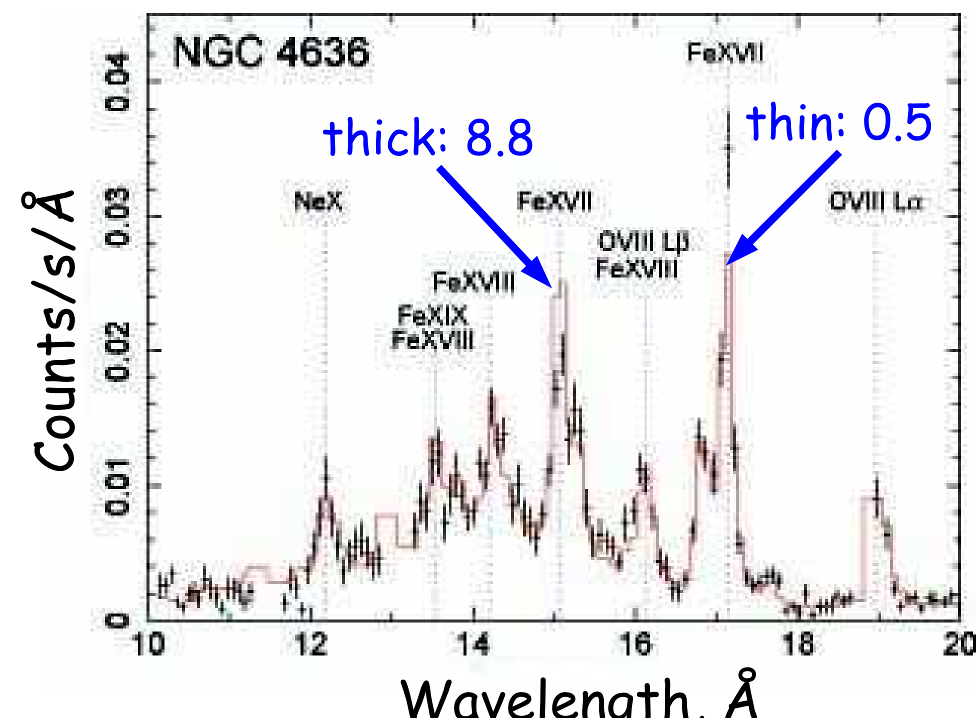
Resonant scattering: NGC4636

$$\Delta E_D = E_0\left[\frac{2kT}{Am_pc^2}+\frac{V_{turb}^2}{c^2}\right]^{1/2} \rightarrow F_{thin}/F_{thick} \rightarrow V$$

NGC4636



RGS XMM Newton 0.5 arcmin

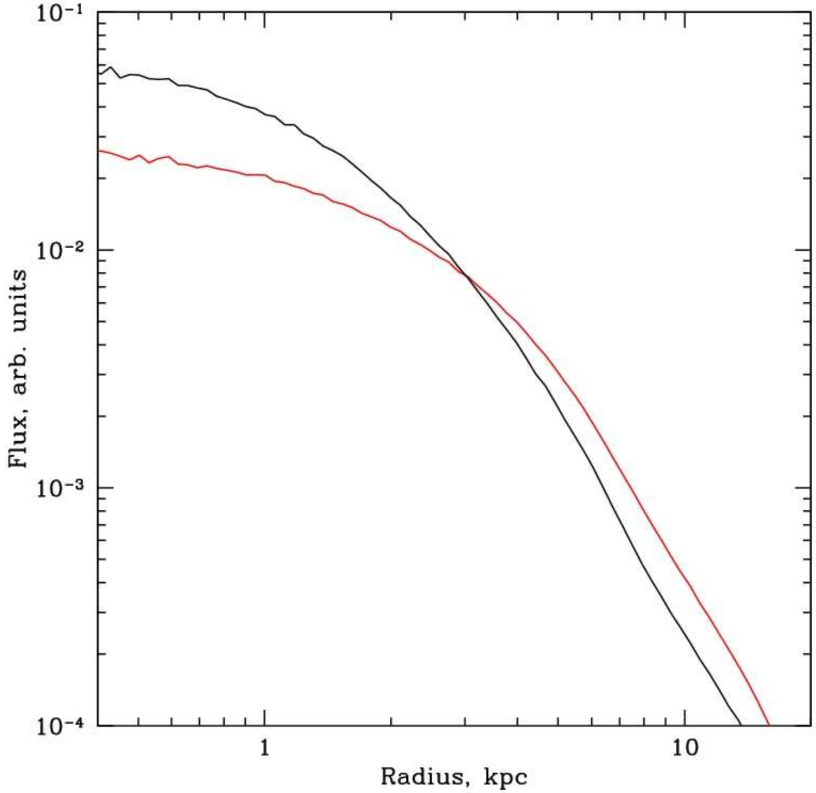


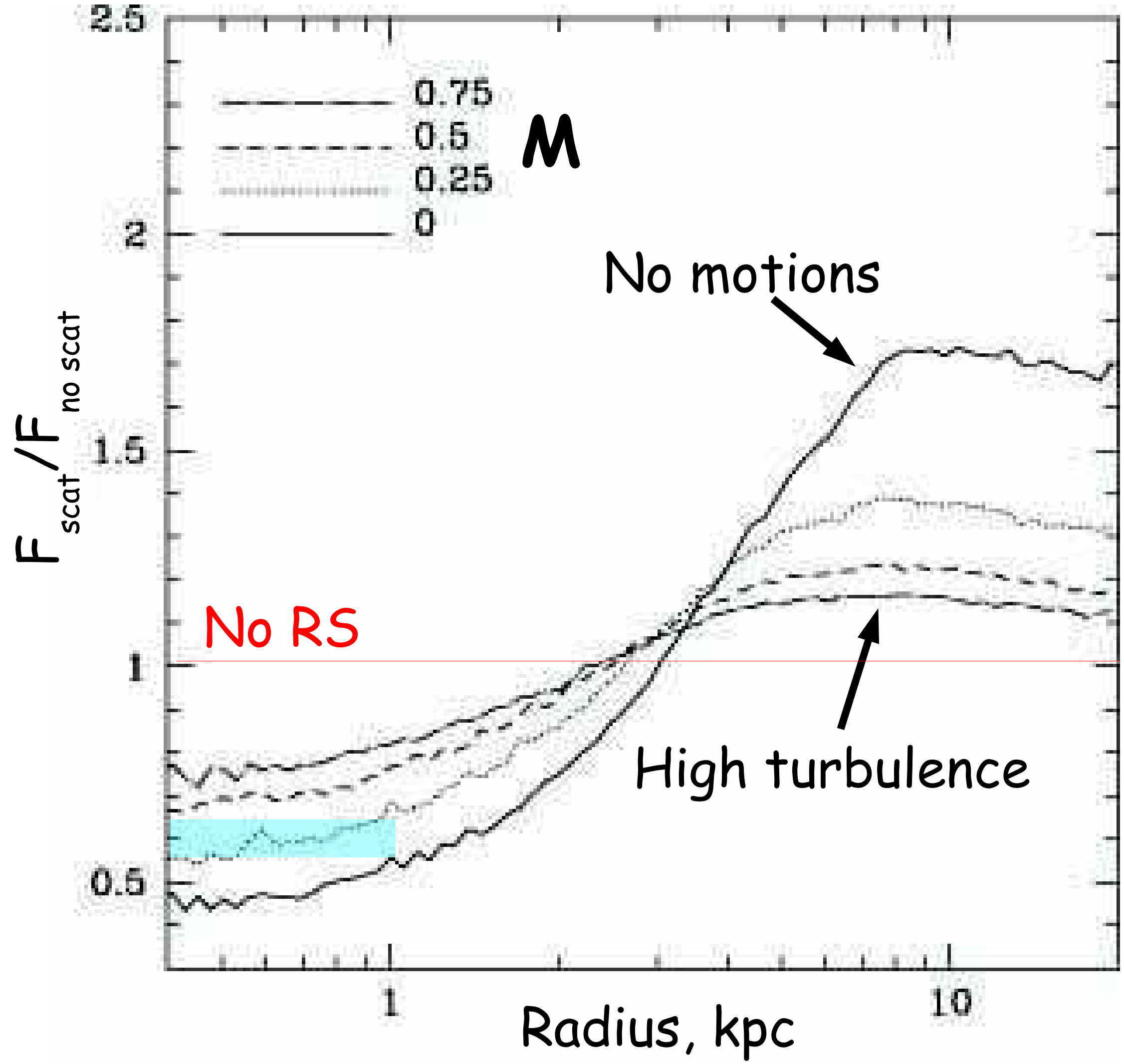
Observations: $F_{17Å}/F_{15Å}=2.04\pm0.21$

Prediction: $F_{17Å}/F_{15Å}=1.31$

Werner, IZ et al. 2009

Resonant scattering: NGC4636





V in the core < 100 km/s

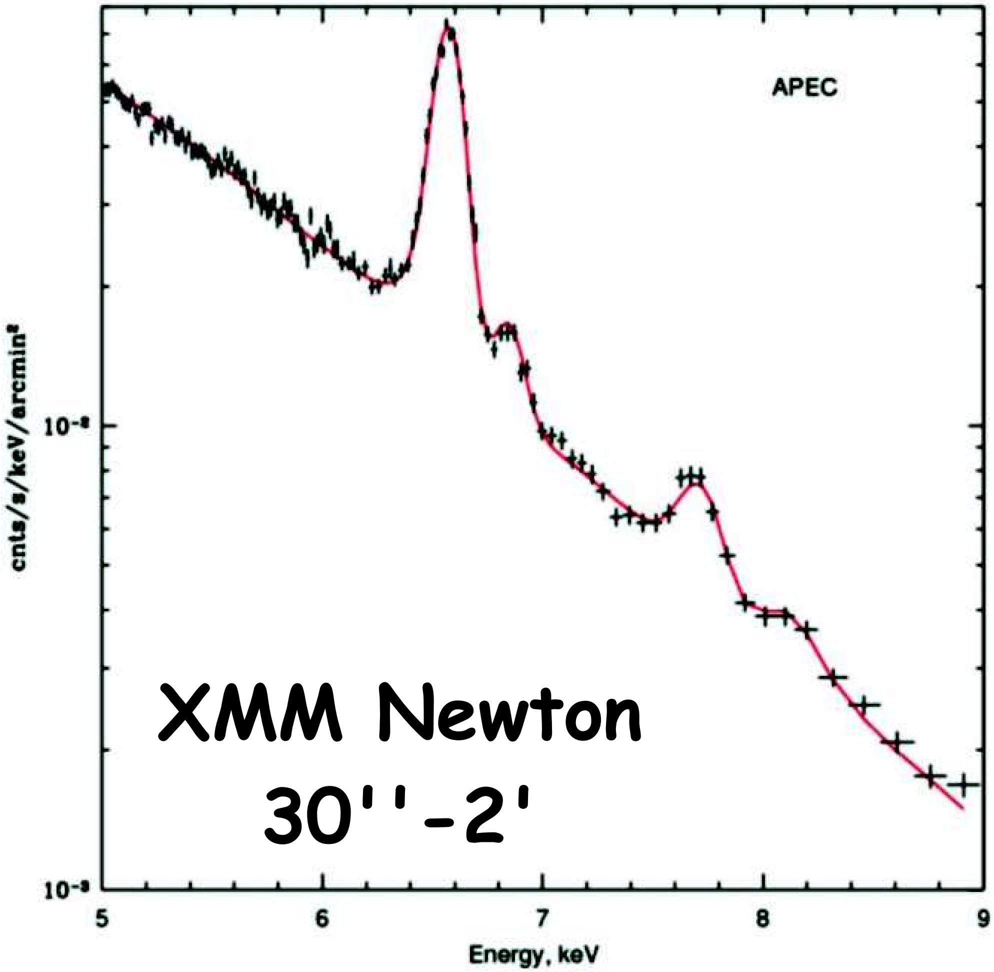
Pressure support < 5% of the thermal P

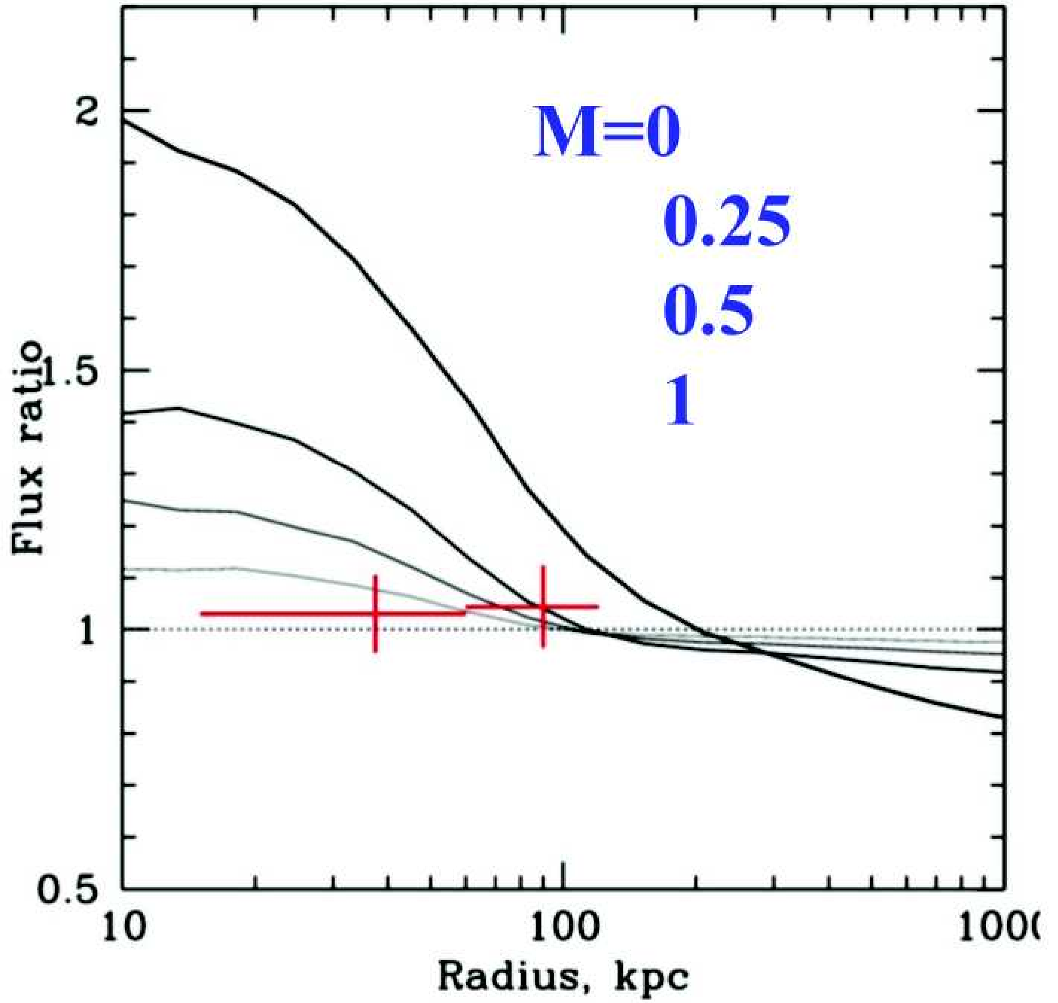
Werner, IZ et al. 2009

Resonant scattering: Perseus

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

F_{Ni}/F_{Fe}



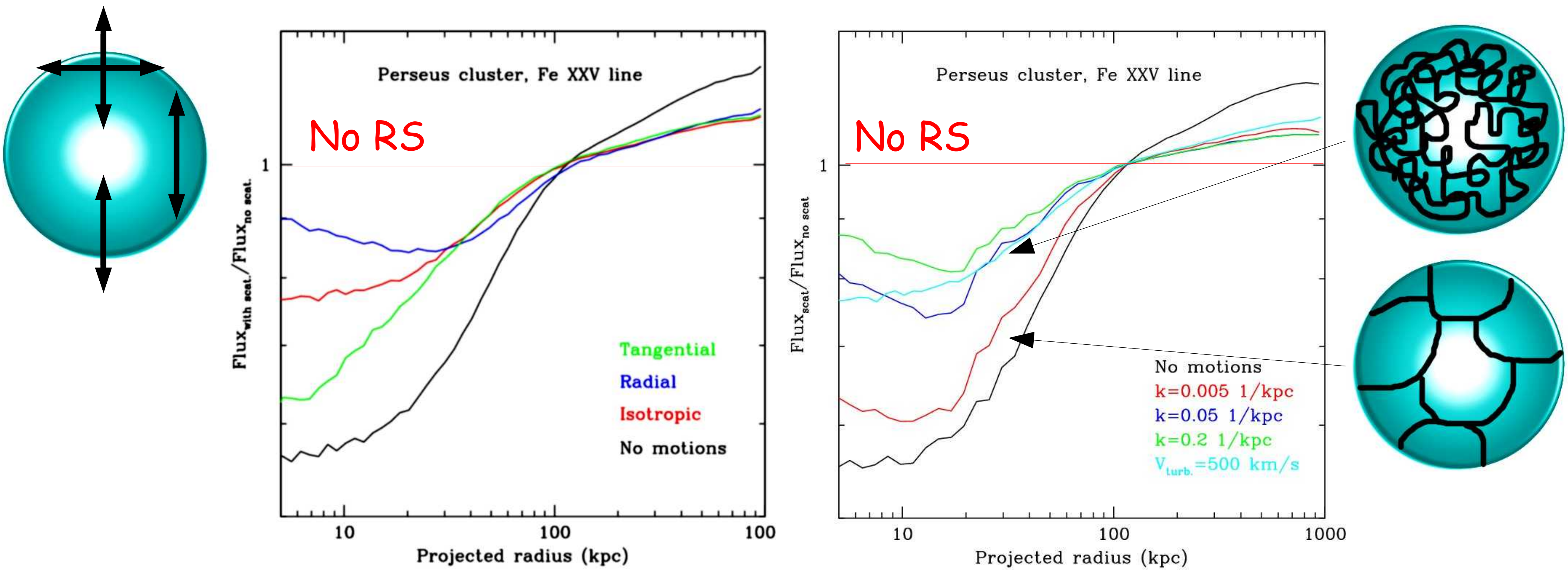


6.7 keV line is not supressed → V>400 km/s

Churazov et al. 2004

Resonant Scattering: spatial scales and anisotropy

Optical depth depends on the character of motions



RS is mostly sensitive to:

(1) radial motions

(2) small scale motions

IZ et al. 2011

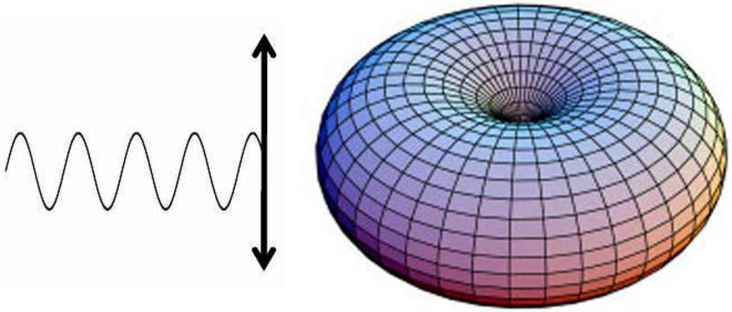
I. X-ray polarization in strong lines

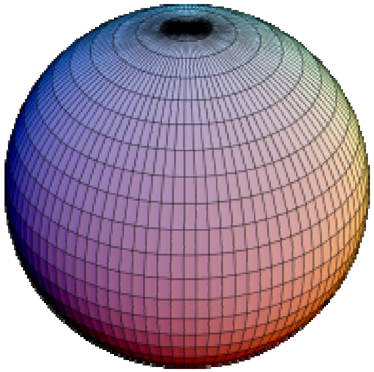
Scattering phase function:

Rayleight (w1) + Isotropic (w2)

w1+w2=1

Polarization | No polarization





Non zero weight of Rayleight scattering

(Chandrasekhar 1950, Hamilton 1947)

$$\text{He-like } K_\alpha \ \ (1s^2 - 1s2p(^1P_1)) \ : \ J=0, \Delta J=1 \Rightarrow W_1=1$$

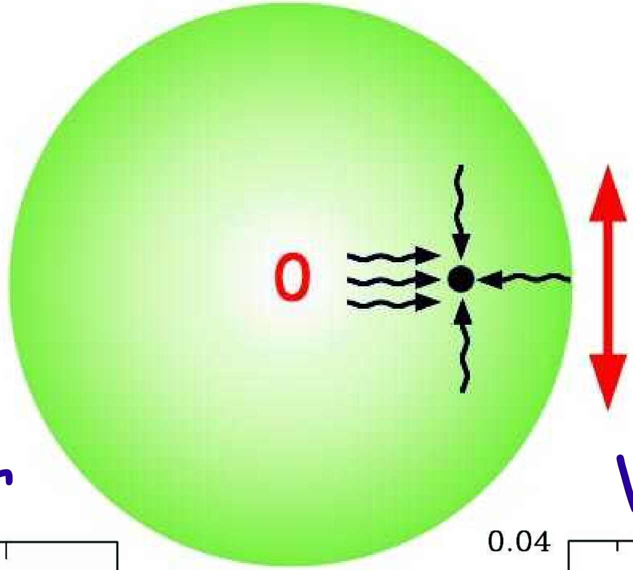
$$\text{H-like } K_\alpha \ \ (1s - 2p(^1P_{1/2})) \ : \ J=1/2, \Delta J=0 \Rightarrow W_1=0$$

$$\text{H-like } K_\alpha \ \ (1s - 2p(^1P_{3/2})) \ : \ J=1/2, \Delta J=1 \Rightarrow W_1=0.5$$

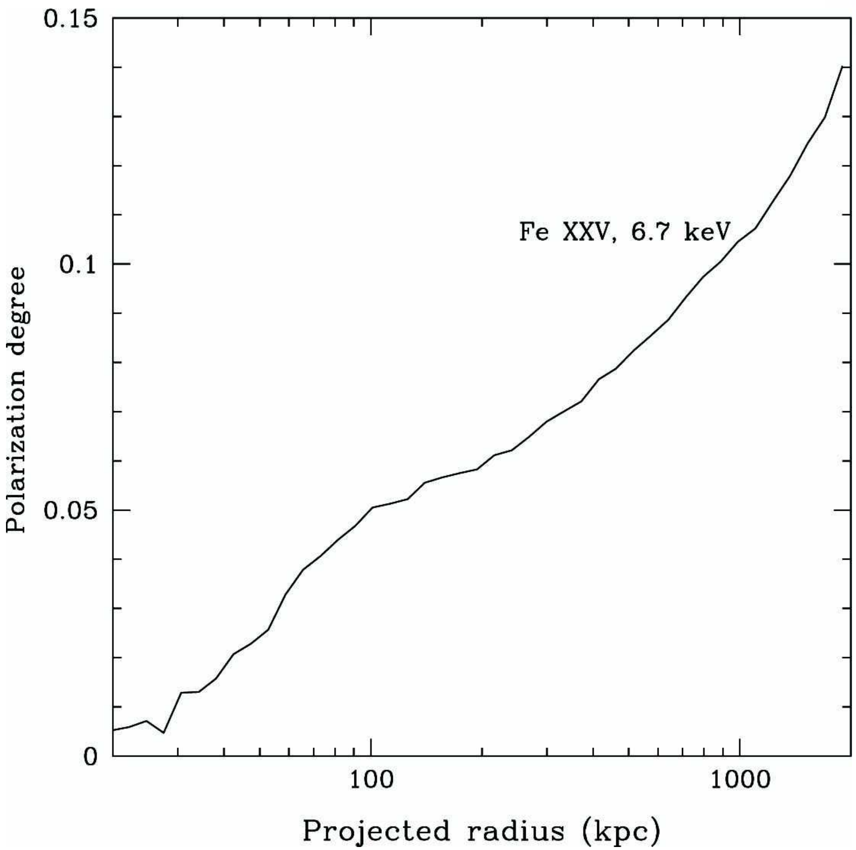
II. X-ray polarization: quadrupole moment

Rayleigh phase function + quadrupole moment = polarization

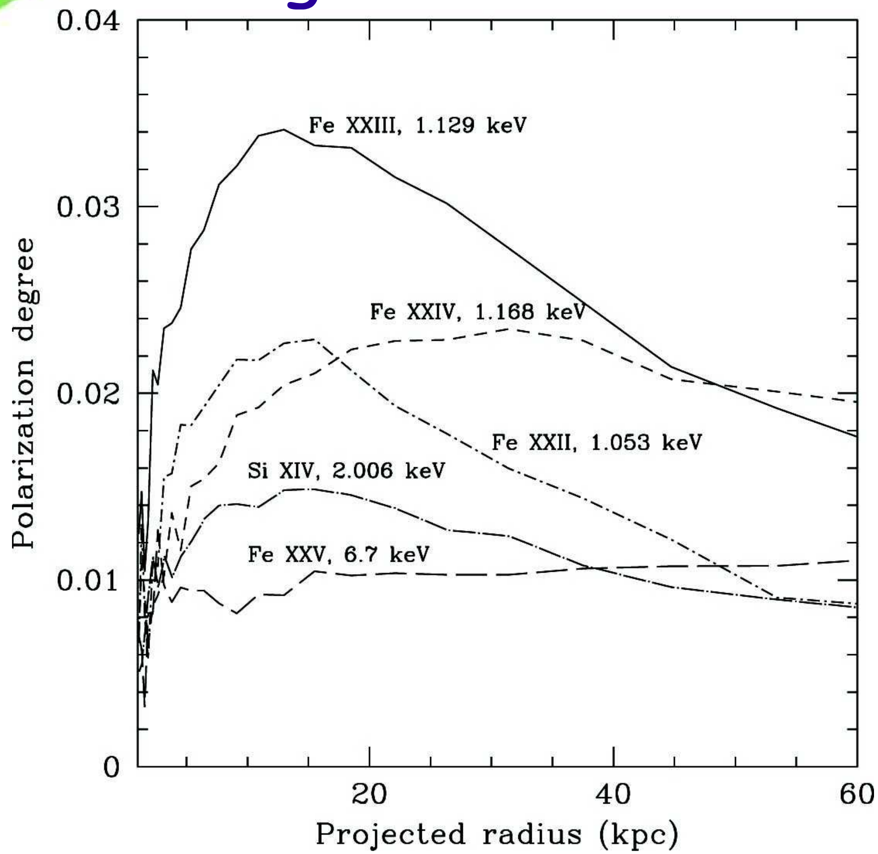
Sazonov et al 2002;
IZ et al. 2010



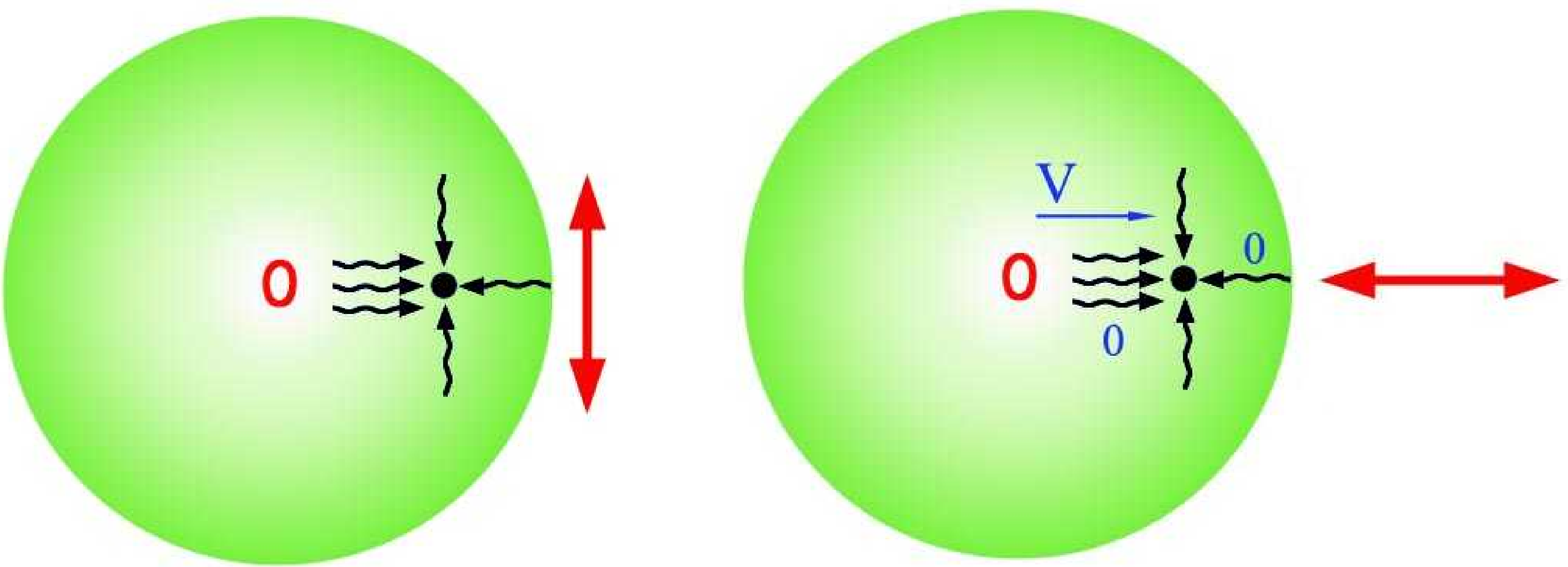
Perseus cluster



Virgo/M87 cluster

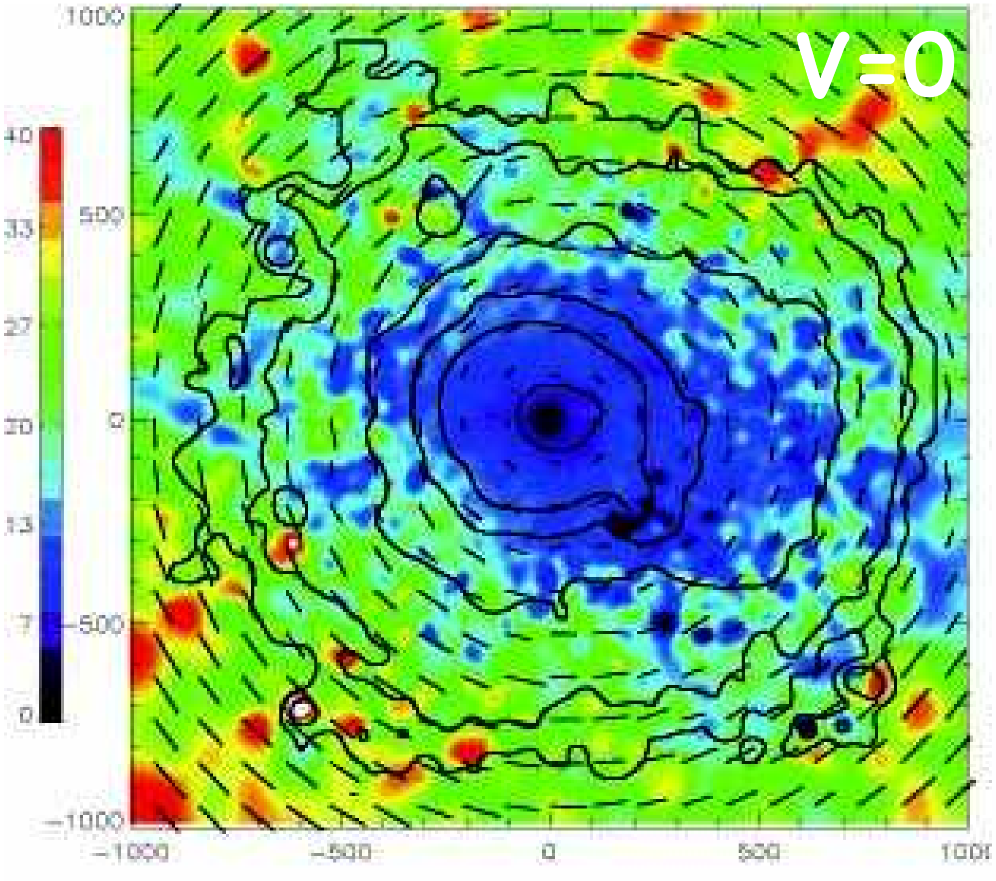


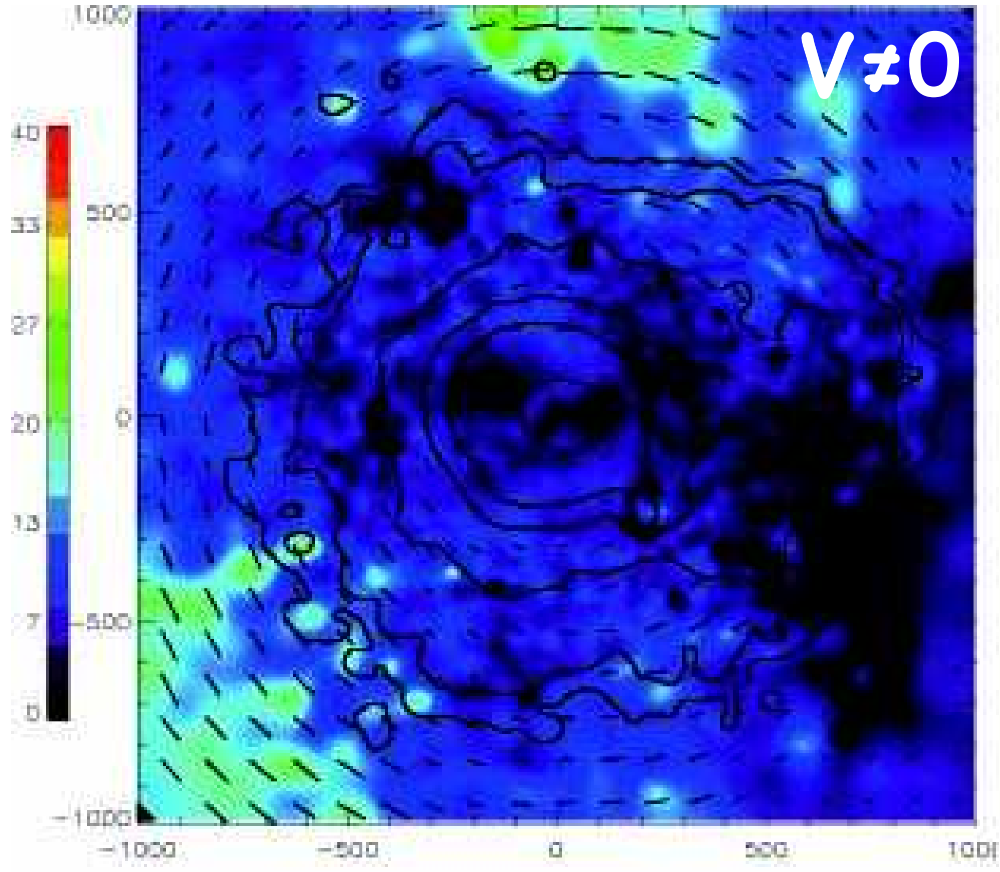
X-ray polarization: transverse gas motions



X-ray polarization: transverse gas motions

6.7 keV line, optical depth ~ 3.6



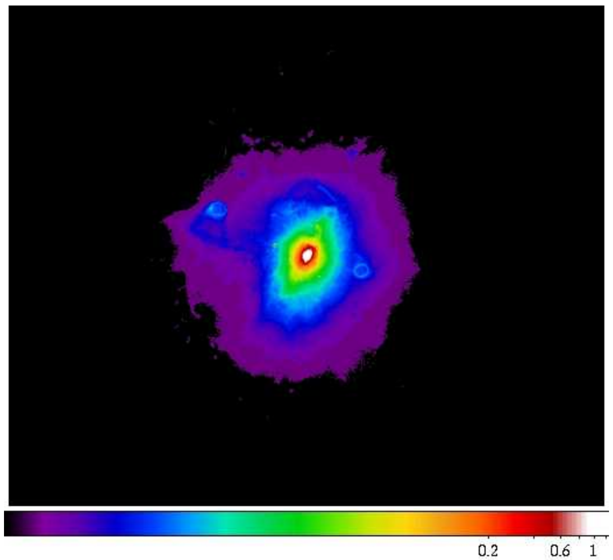


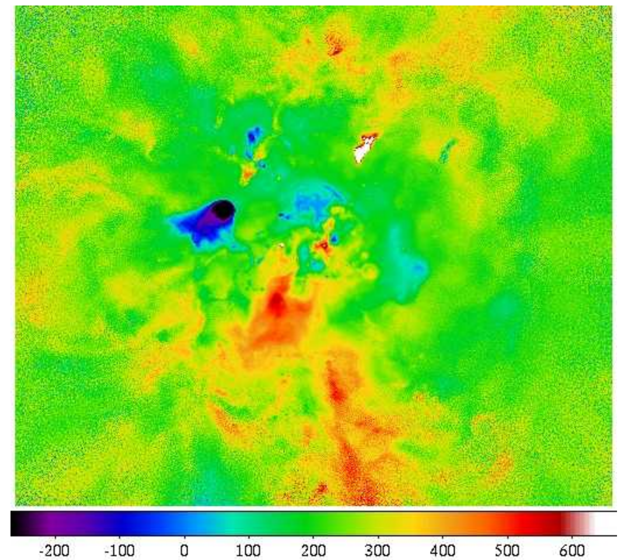
P ~ 25% at r=500 kpc **P ~ 15% at r=500 kpc**

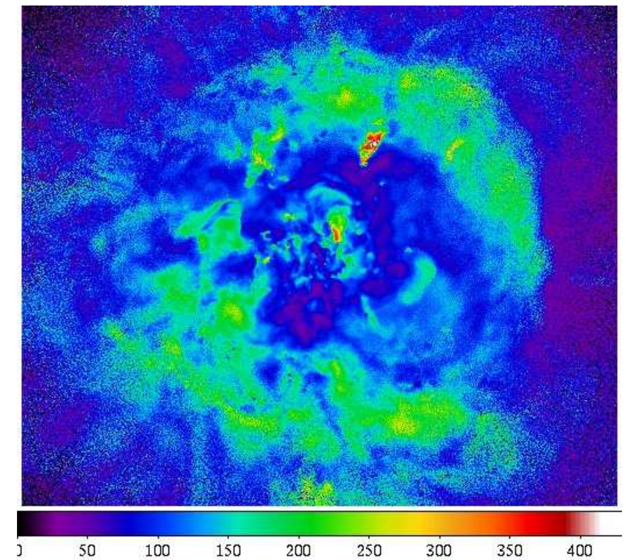
IZ et al. 2010

3D velocity PS and observables

$\int n_e^2 dl$ | $\langle \mathrm{v}_z \rangle_l$ | $\sqrt{\langle v_z^2 \rangle_l - \langle v_z \rangle_l^2}$







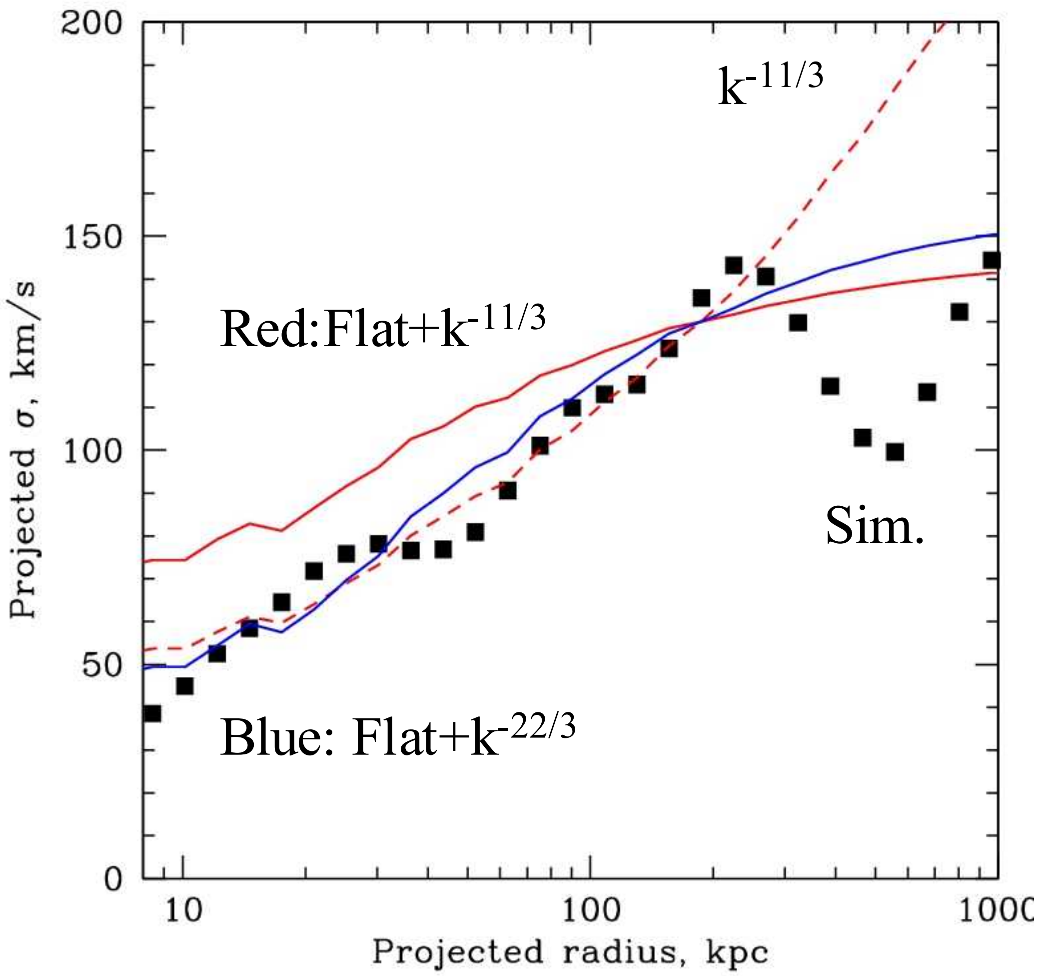
Emission measure weighted Vz and σ

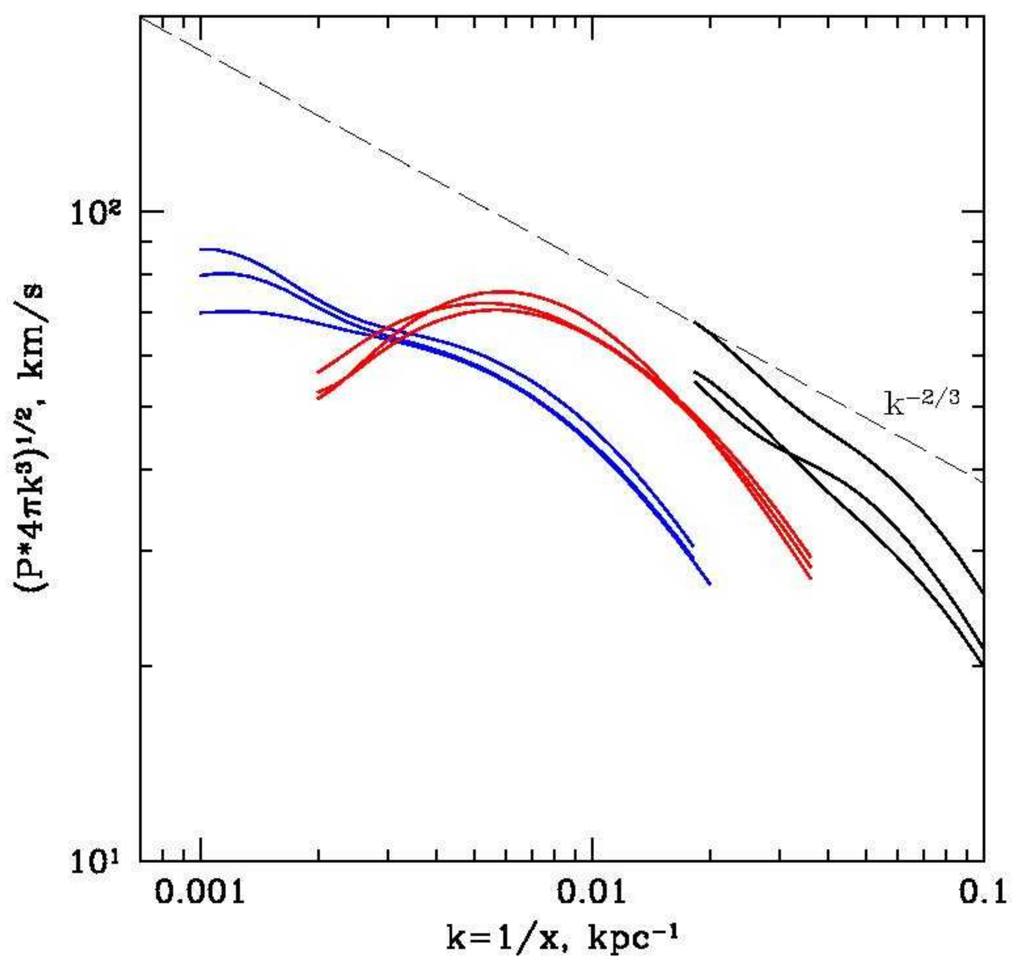
$$v_{2D} = \int v_{3D} n_e^2(z) dz \Big/ \int n_e^2(z) dz$$

$$P_{2D}(k) = \int P_{3D}\left(\sqrt{k^2 + k_z^2}\right) W^2(k_z) dk_z$$

Velocity dispersion and structure function

$$\sigma^2 = \int P_{3D}\left[1 - W^2(k_z)\right] dk_z dk_x dk_y$$





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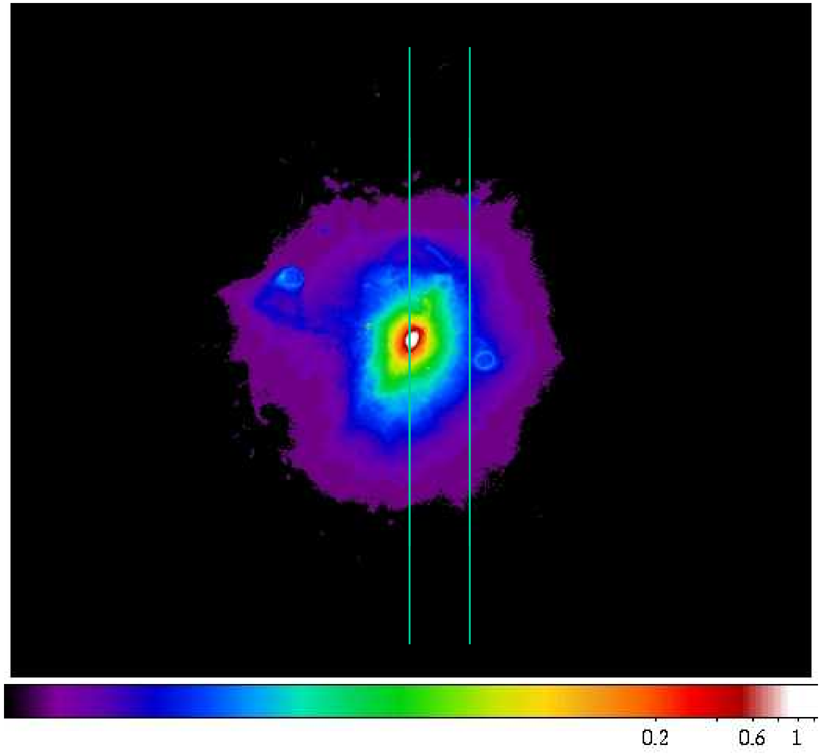

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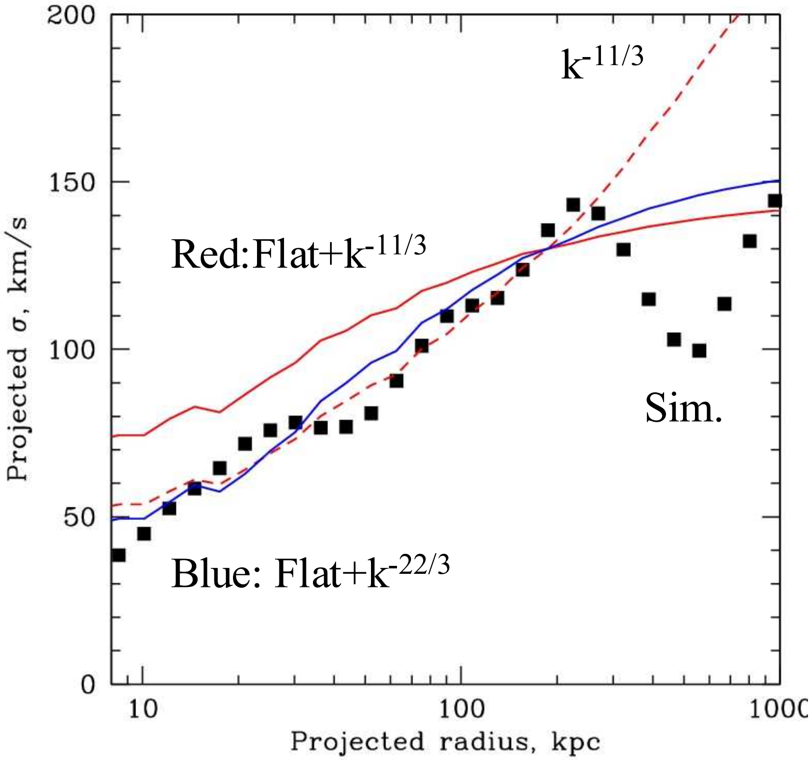

At a given radius R
interval ~ R
contributes to σ

Conclusions

Observables Vz and σ constrain amplitude and shape of 3D velocity PS, structure function

RS is a powerful tool to study gas motions: amplitudes, spatial scales, anisotropy

Astro-H

X-ray polarization: constraints on transverse gas motions

Requirements for X-ray polarimeters:

- Energy resolution: for 6.7 keV line P↓50% if ΔE=50 eV.
- Angular resolution: ~ arcmin.
- Large effective area and field-of view, faint X-ray sources

IXO