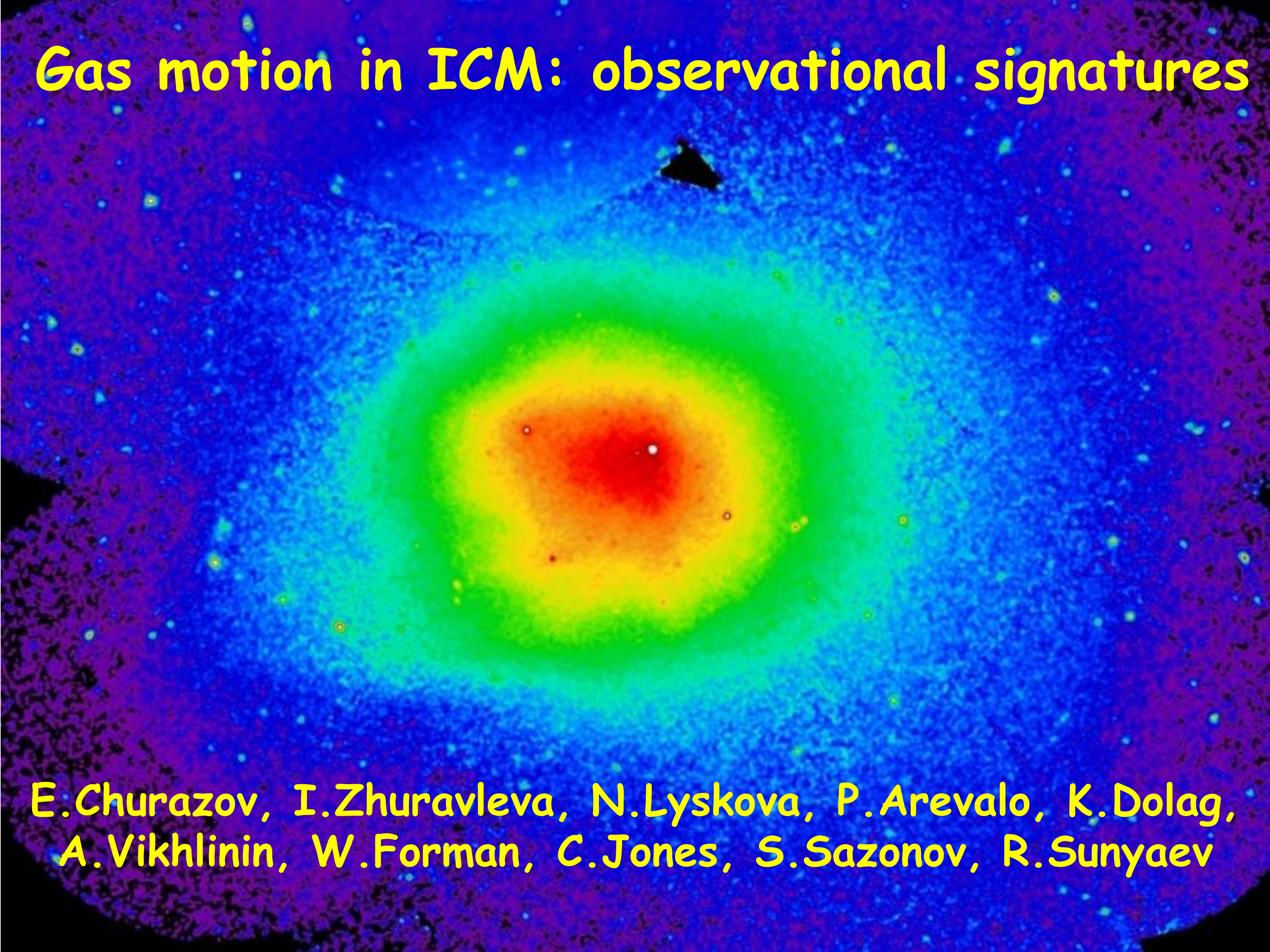
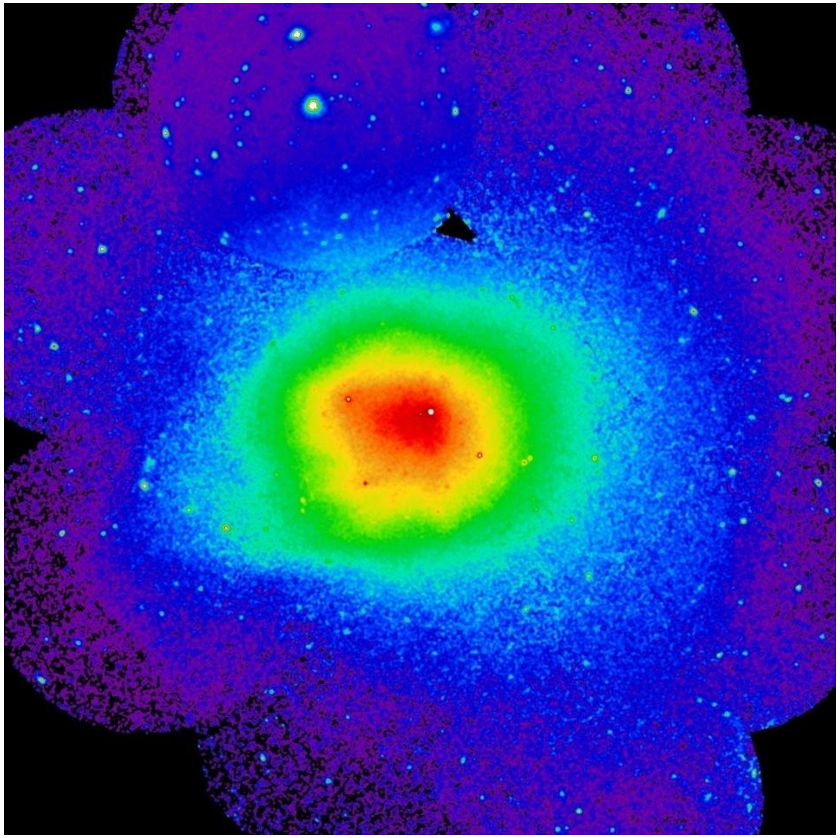
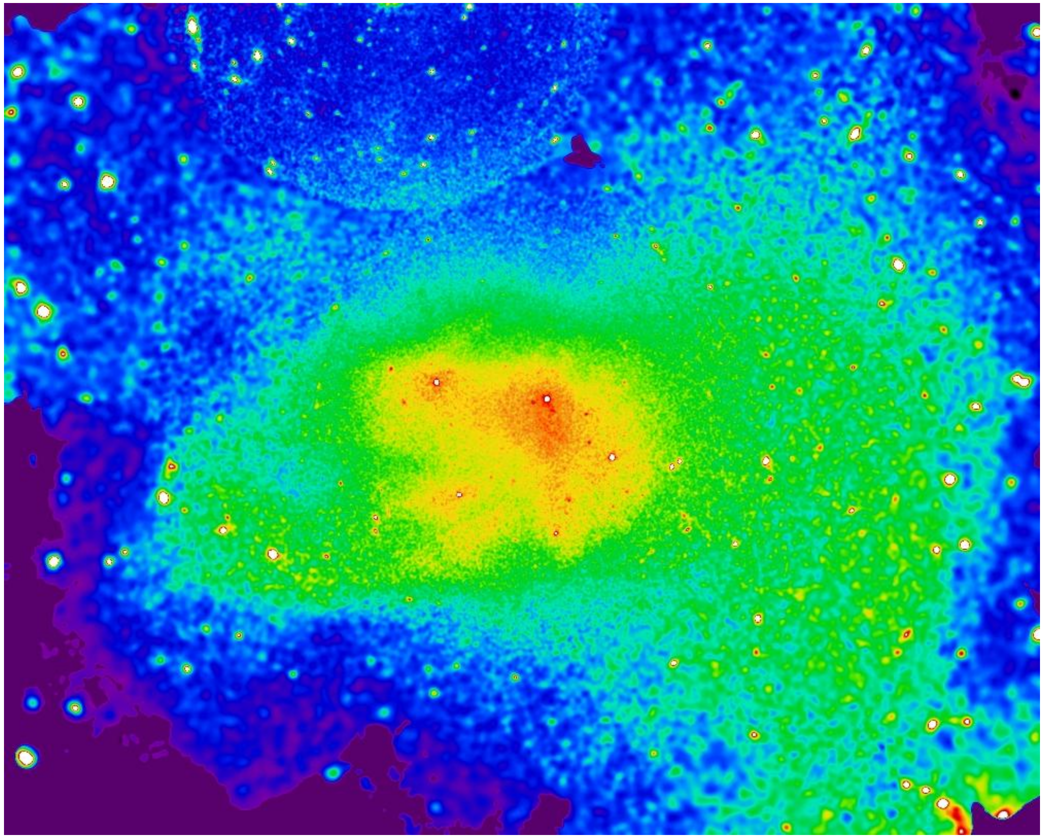
Gas motion in ICM: observational signatures



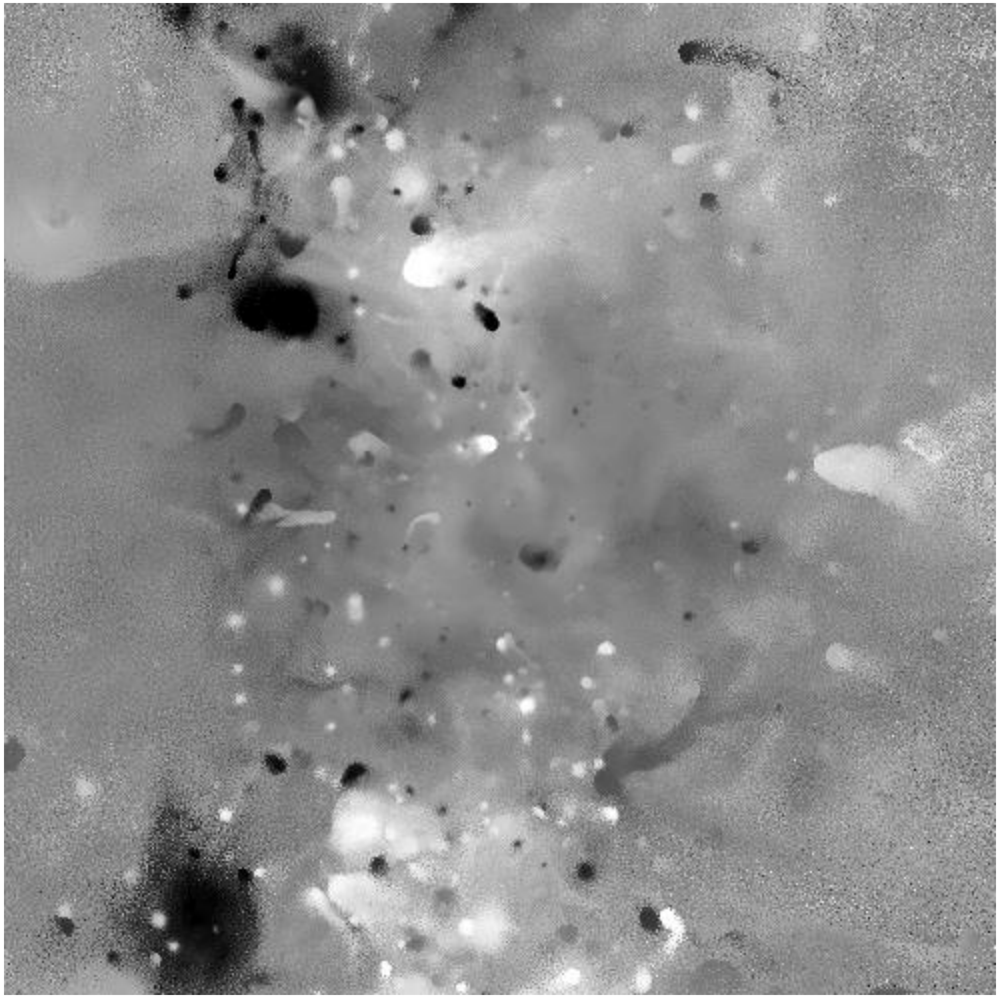
E.Churazov, I.Zhuravleva, N.Lyskova, P.Arevalo, K.Dolag, A.Vikhlinin, W.Forman, C.Jones, S.Sazonov, R.Sunyaev

Coma
X-ray image and residuals from symmetric model





Gas is not at rest!



We want to "measure" hot ICM velocity field

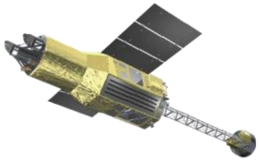
How to measure?

How we characterize the velocity field and observables?

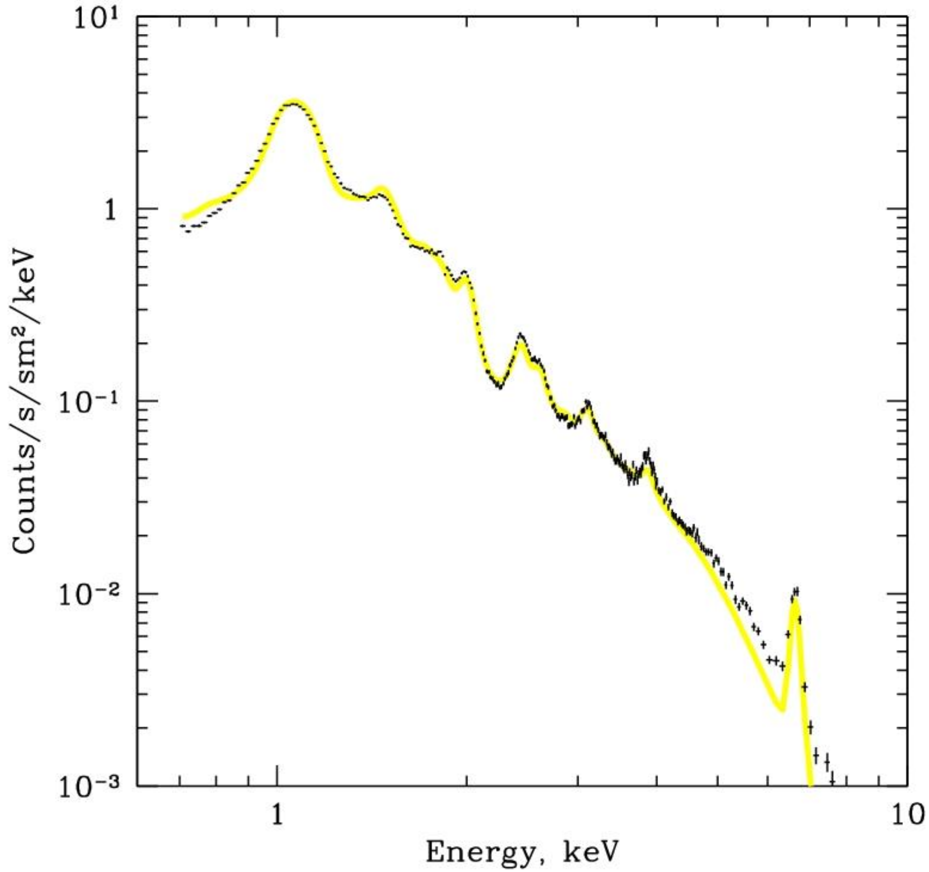
Using simulations to calibrate observables

Any differential gas motions
Gaussian isotropic random field

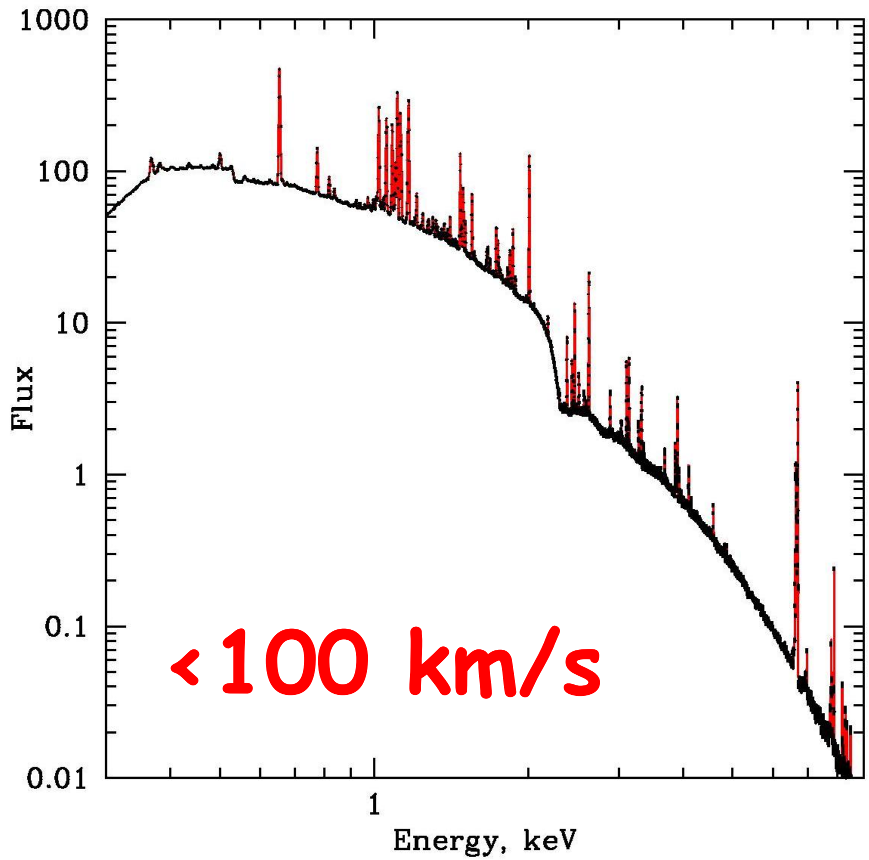
Direct velocity measurements



Chandra

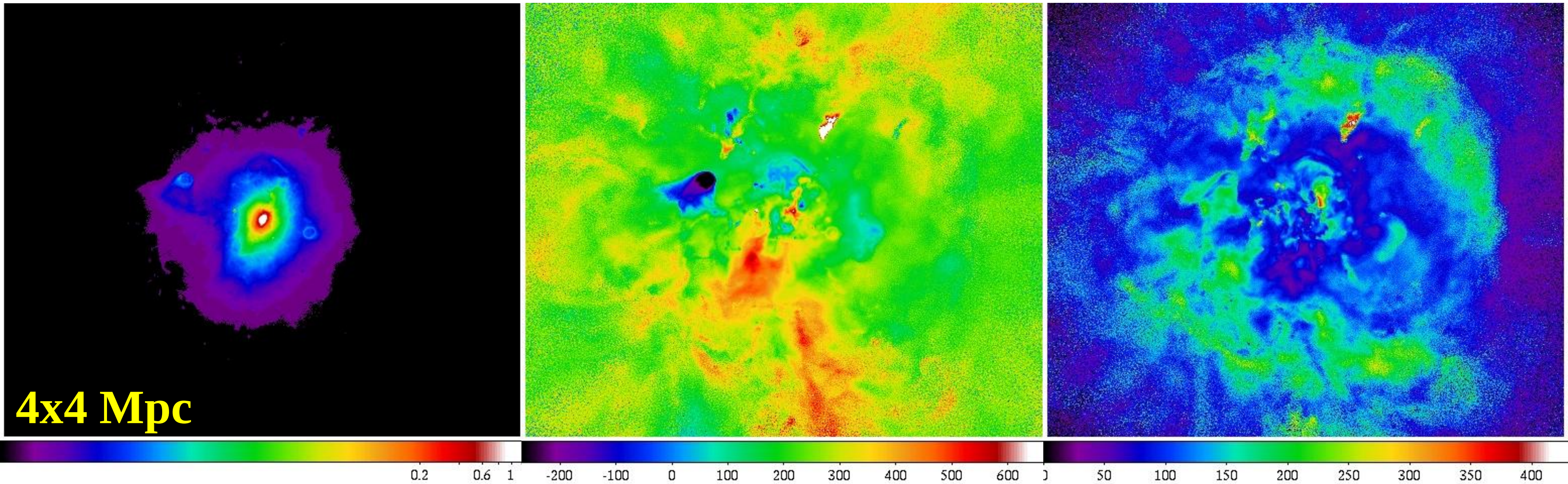


Astro-H, 2013



XMM/RGS, broadening < 200 km/s [1D] (Sanders+10,11)

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



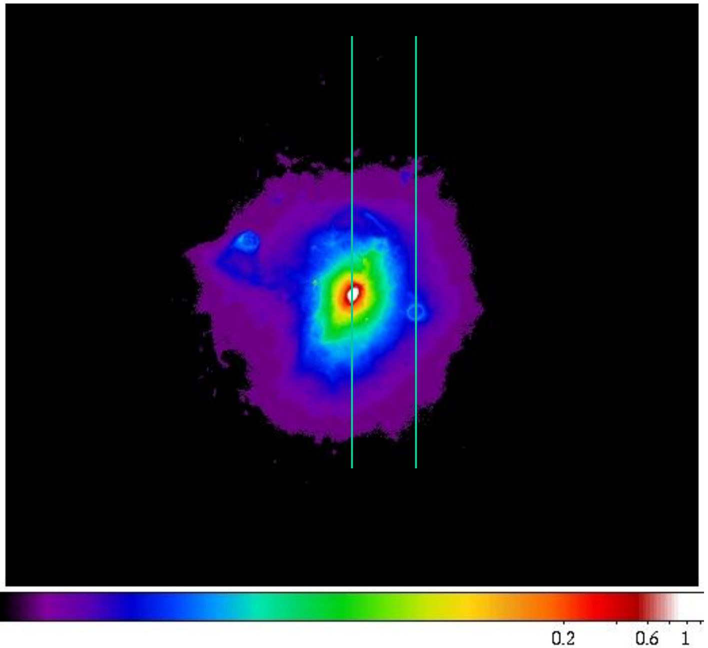
Observables: n_e, emission measure weighted v_z, σ

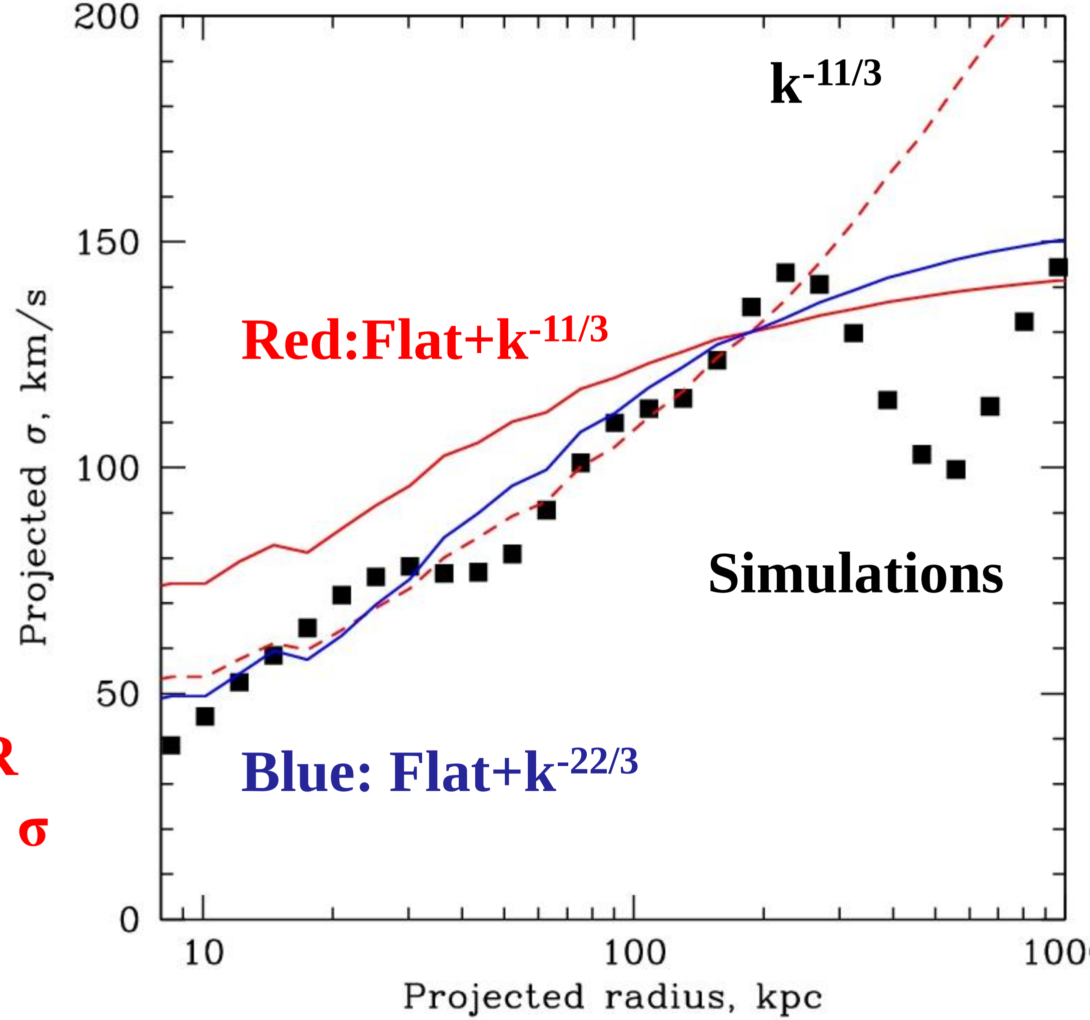
$$\mathrm{v}_{2D} = \int \mathrm{v}_{3D} n_e^2(z) dz$$

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

Projected velocity dispersion ≈ Structure Function

$$S(\Delta x) = \left\langle \left(v(x+\Delta x) - v(x) \right)^2 \right\rangle$$





At a given projected radius R an interval ~R contributes to σ

$\sigma^2 \approx$ structure function

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

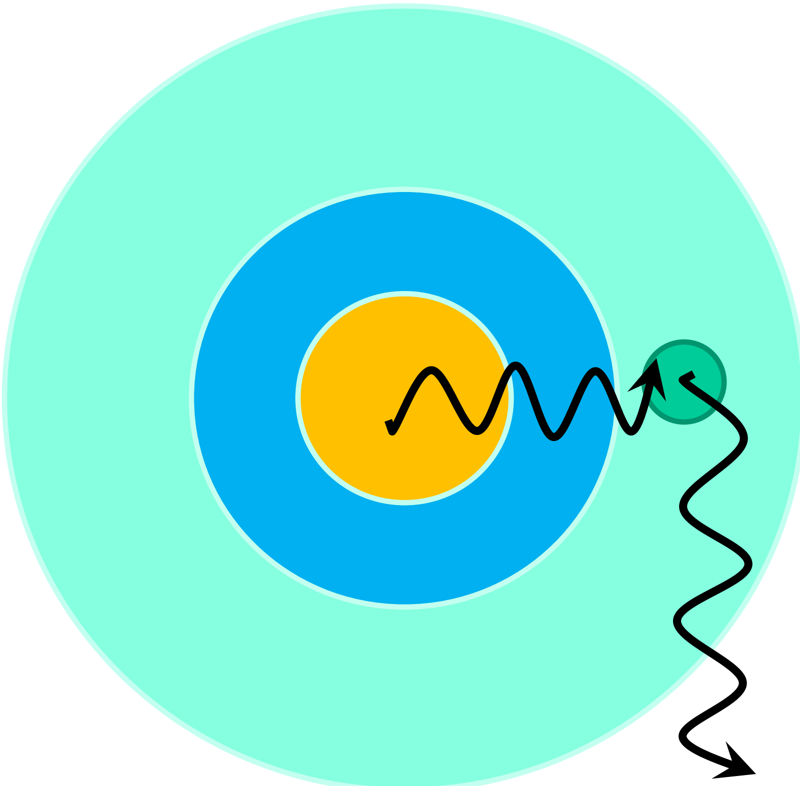
Zhuravleva, 2011

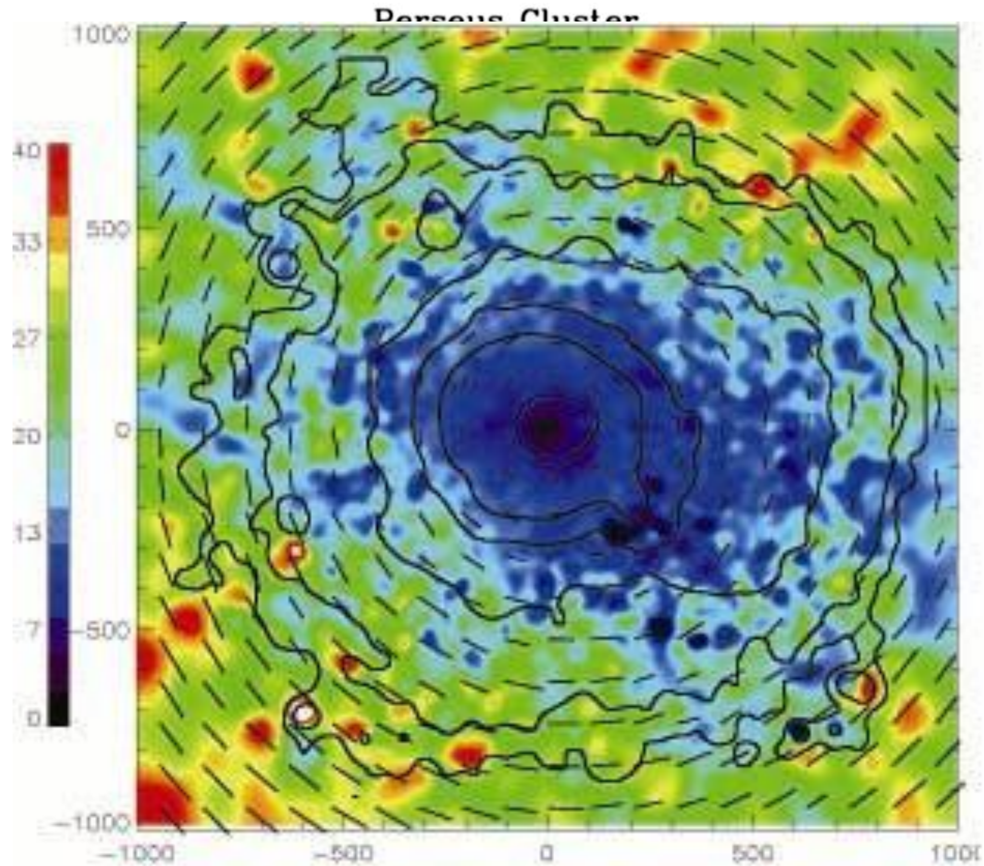
Less direct ways of measuring ICM velocities.

Kinetic SZ effect	<V>, ΔV	Benson+03 Osborne+11
Resonant scattering	ΔV, PS(V)	Werner+09, Hayshi+09, Zhuravleva+11
Polarization due to resonant scattering	V, ΔV	Zhuravleva+10
Faraday Rotation	PS(B)->V	Vogt+03, Bonafede+10
H_α filaments	V	Fabian+03
Pressure fluctuations	PS(P)->V	Schuecker+04
SB fluctuations	PS(n_e)	

Polarization of 6.7 keV Iron line

Rayleigh phase function + Quadrupole = Polarization





100% polarized

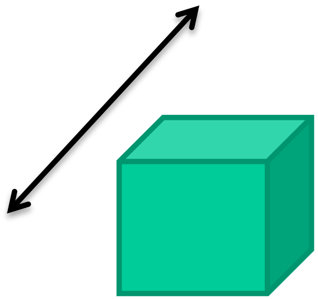
Center: 0%
Outskirts: 10%

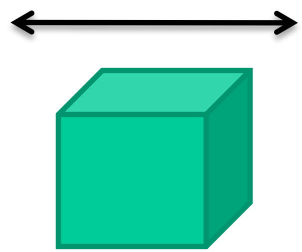
Sazonov+ 2002; Zhuravleva+ 2010

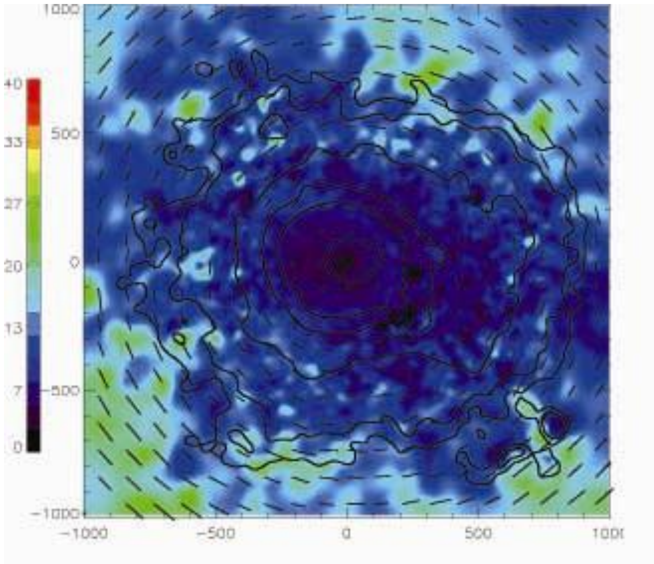
Transverse ICM velocities and polarization

Quadrupole component can be induced by gas motions!

Motion along l.o.s. **Motion transverse l.o.s.**







Doppler shift
No polarization

No Doppler shift
Polarization

1) On average gas motions reduce optical depth
2) But can cause polarization in the cluster core

Very indirect ways of measuring ICM velocities.

Turbulent Diffusion of metals	D~VL	Rebusco+05
Cool Cores: Heating=Cooling	Heating~V^3/L	
Correction to mass from hydrostatic equilibrium	V^2	EC+08,10
Many more…		

Combinations provide both V, L

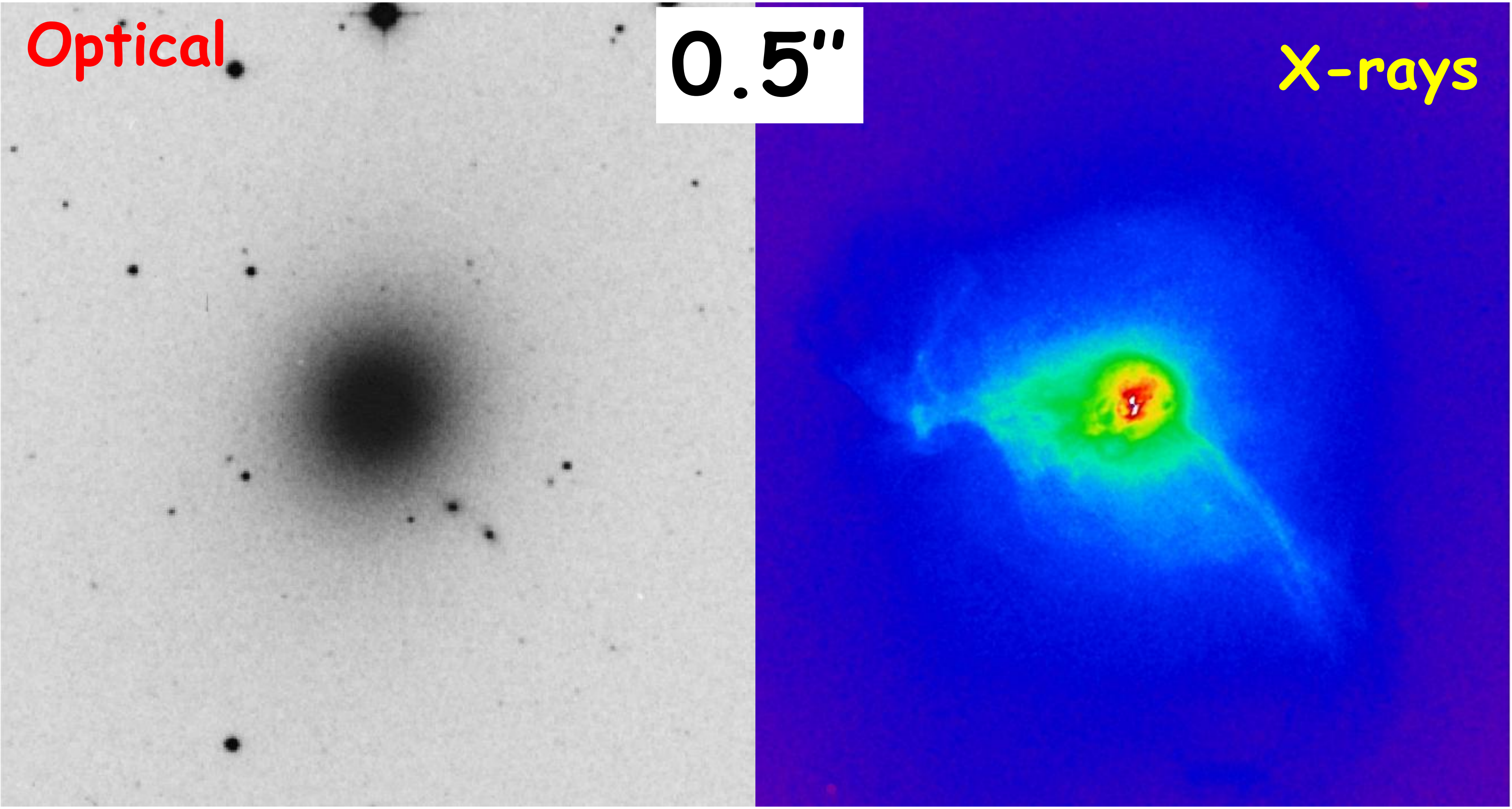
$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM}{r^2}$$

$$P = nkT + P_{CR} + \frac{B^2}{8\pi} + P_{turb}$$

Thermal pressure (easy to measure)

Non-thermal pressure (invisible)

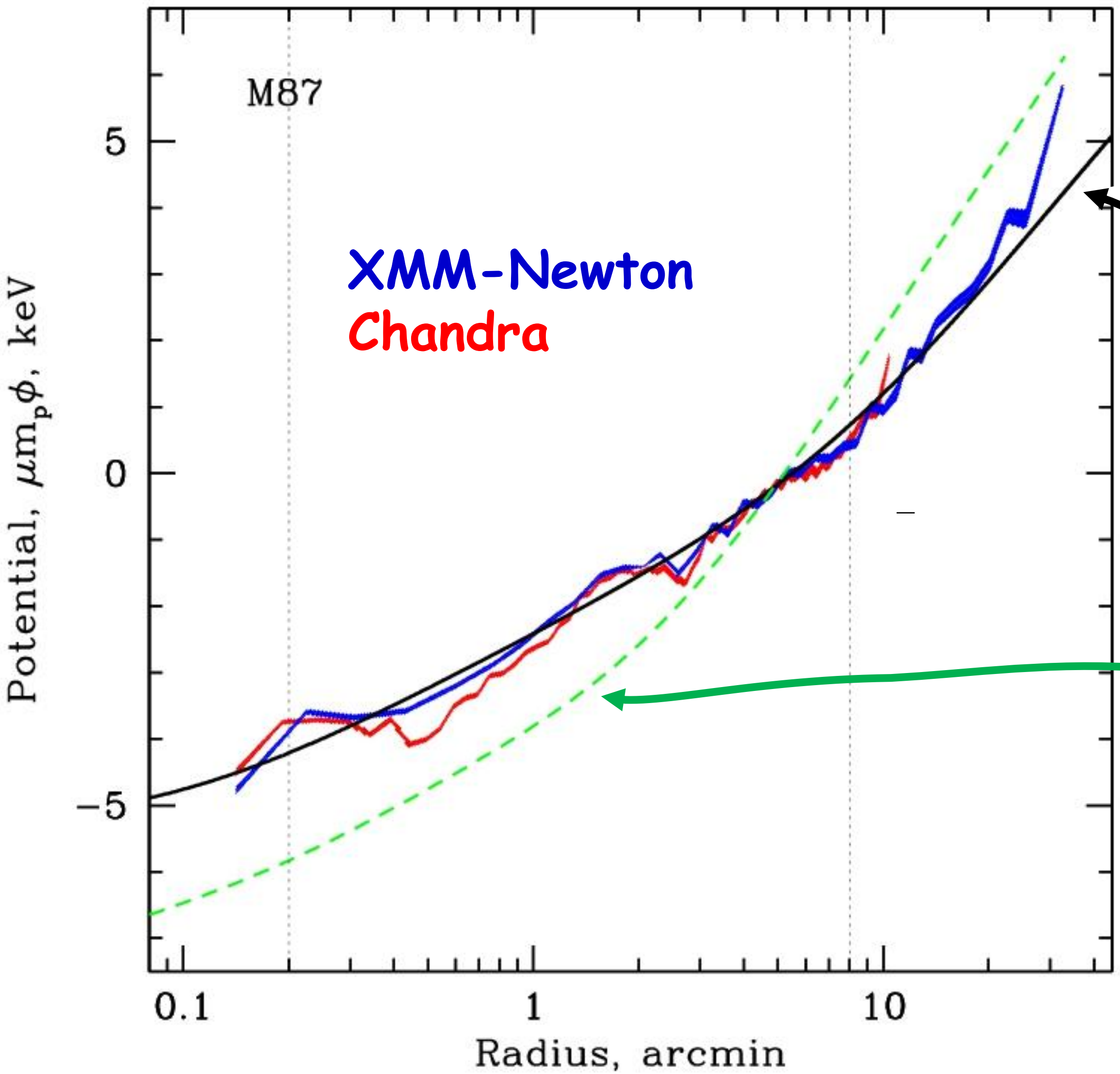
M87



Stars: gravity only (anisotropy)

Gas: gravity, magnetic fields, cosmic rays, turbulent motions, non-stationarity

M87: X-rays + stellar kinematics



Romanowsky & Kochanek, 2001

$$\frac{P_{nt}}{P_{gas}} \leq 0.1$$

Gebhardt & Thomas, 2010

$$\frac{P_{nt}}{P_{gas}} \approx 0.35$$

V~few 100 km/s -> Power Spectra

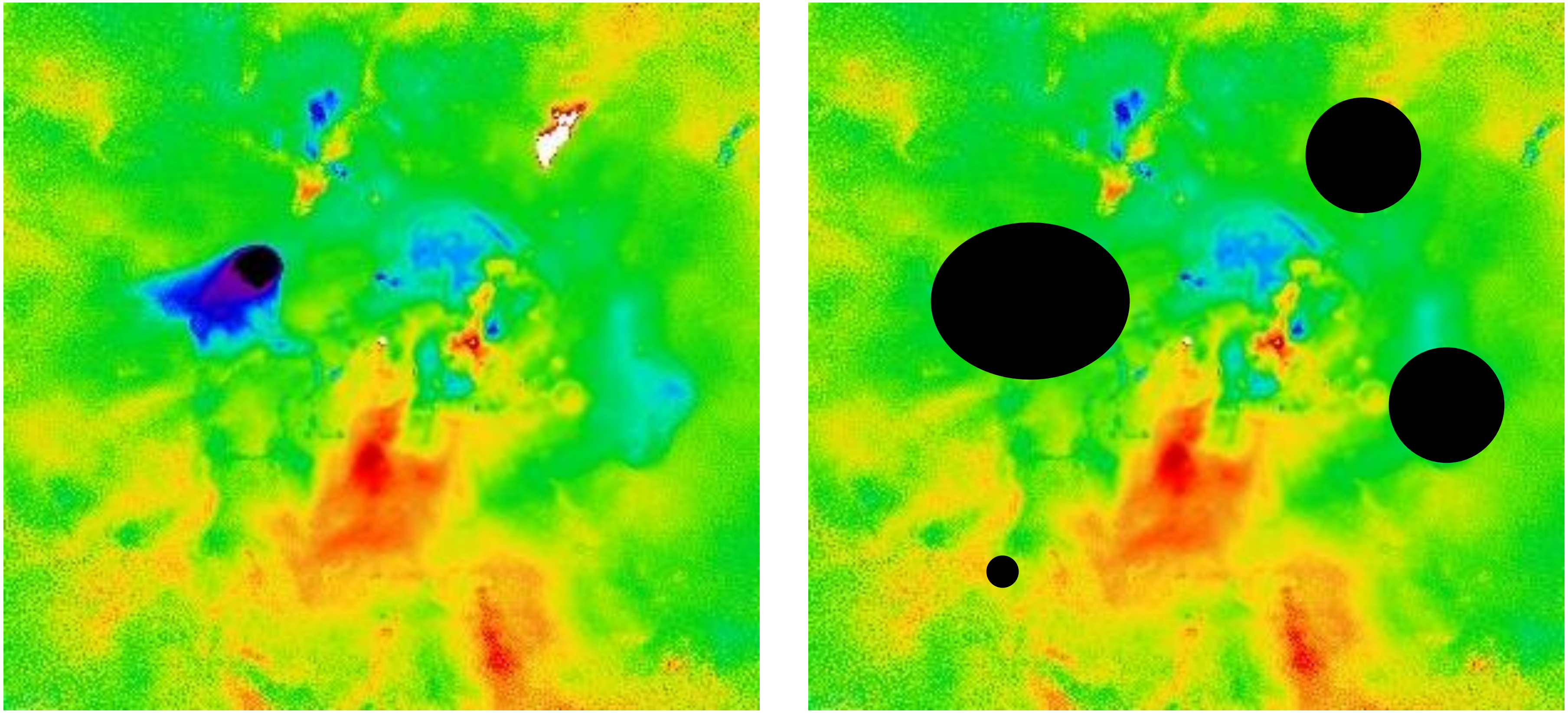
Characterizing ICM velocity field (3D simulations, RM maps, etc)

Calculating Power Density Spectra for featureless continuum

Calculating characteristic amplitude associated with a given spatial scale

Calculating Power Density Spectrum for the data with holes (making Fourier transform of the velocity map)

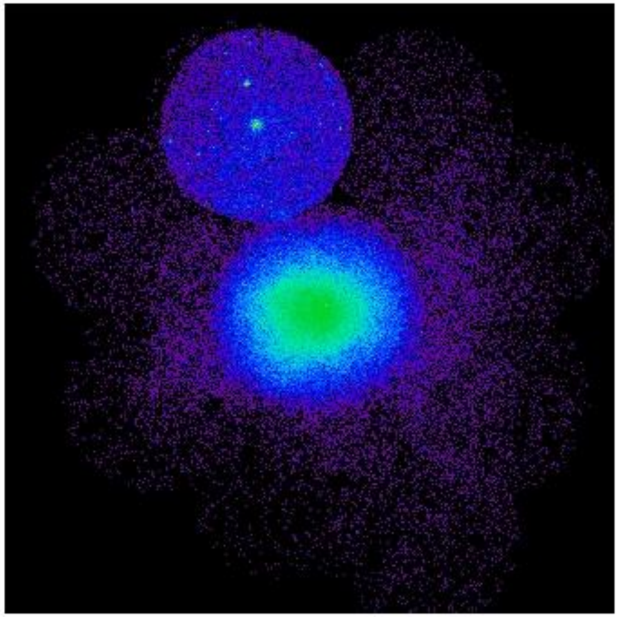
1. Non-periodic
2. Missing data (points sources, gaps between CCDs,…)



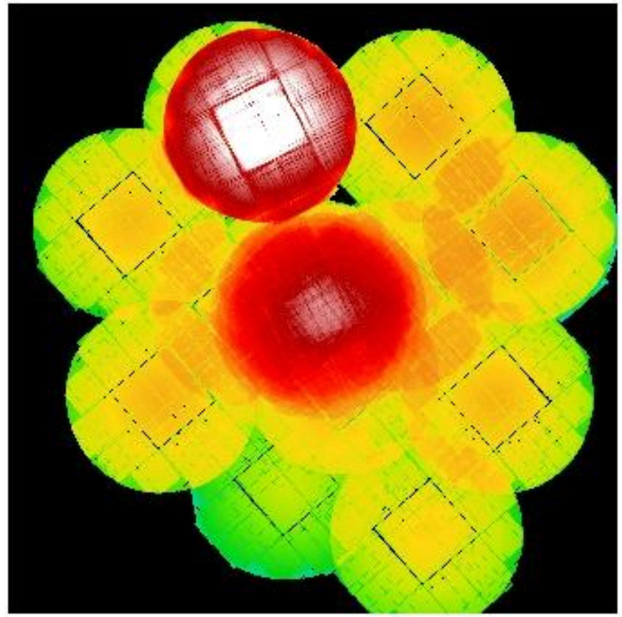
Fourier is tuned for periodic arrays without gaps

Smoothing of X-ray images

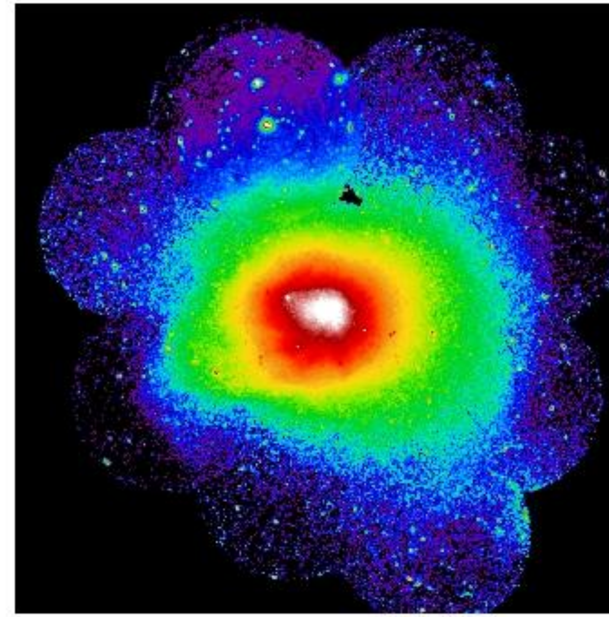
Raw image



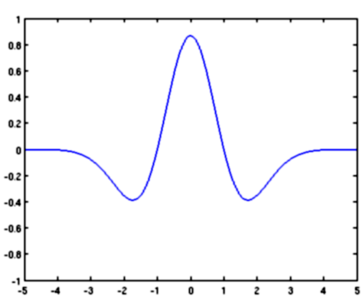
Exposure map



S(Images)/S(E_map)



$$G_{\sigma_1} \circ I = \frac{G_{\sigma_1} \circ I}{G_{\sigma_1} \circ M}$$

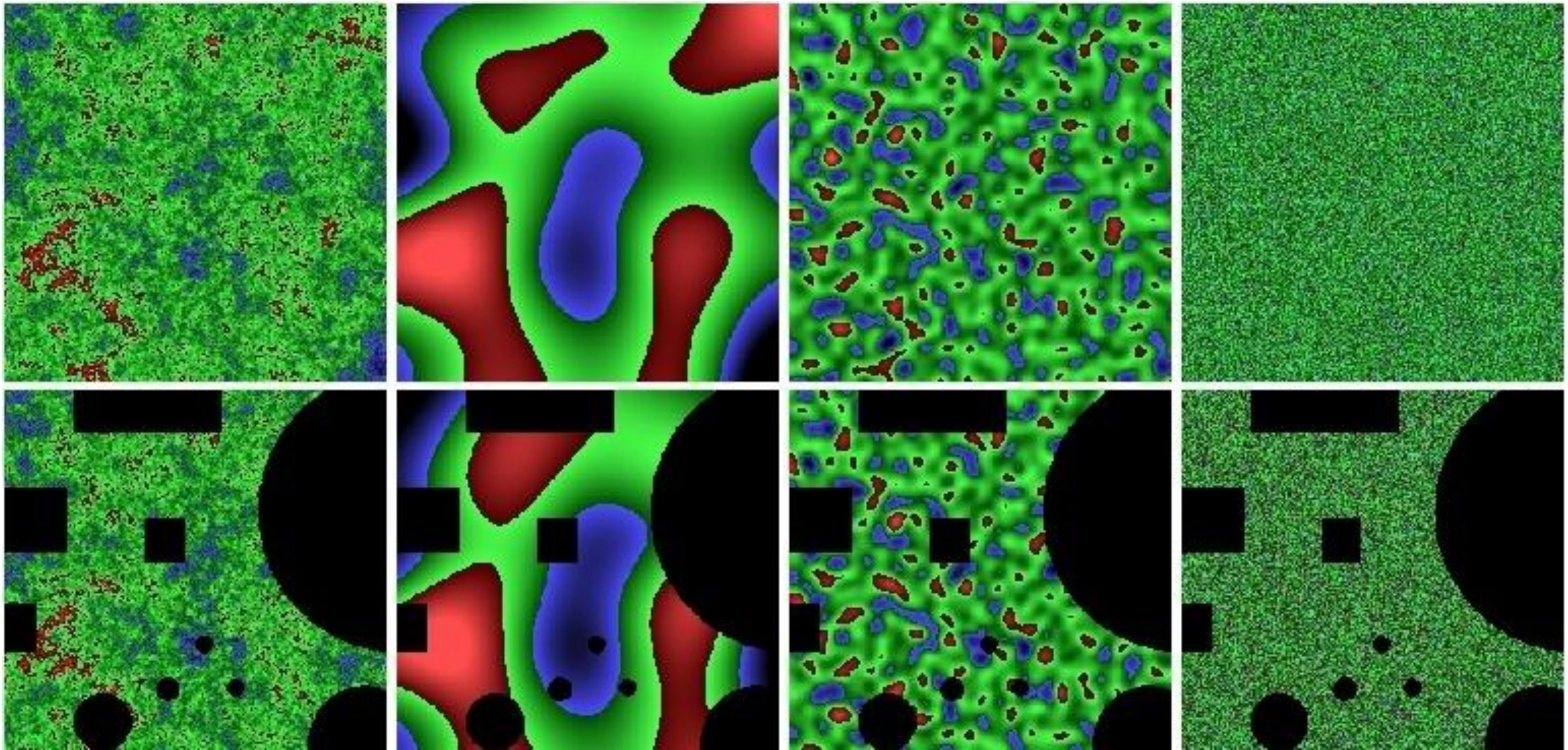


$G_{\sigma_1} \circ I - G_{\sigma_2} \circ I$ **= Mexican Hat Filter**

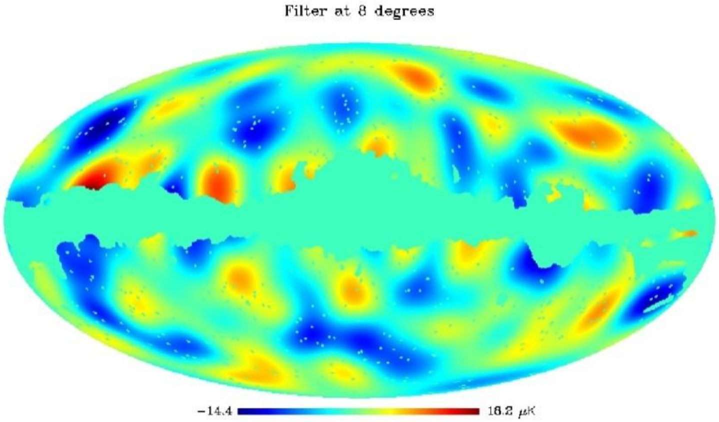
Modified Mexican Hat Filter for data with gaps

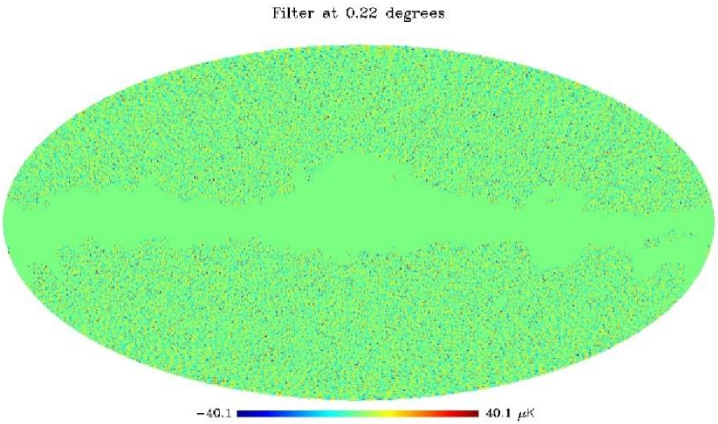
$$\tilde{F} \circ I = \frac{G_{\sigma_1} \circ I}{G_{\sigma_1} \circ M} - \frac{G_{\sigma_2} \circ I}{G_{\sigma_2} \circ M}$$

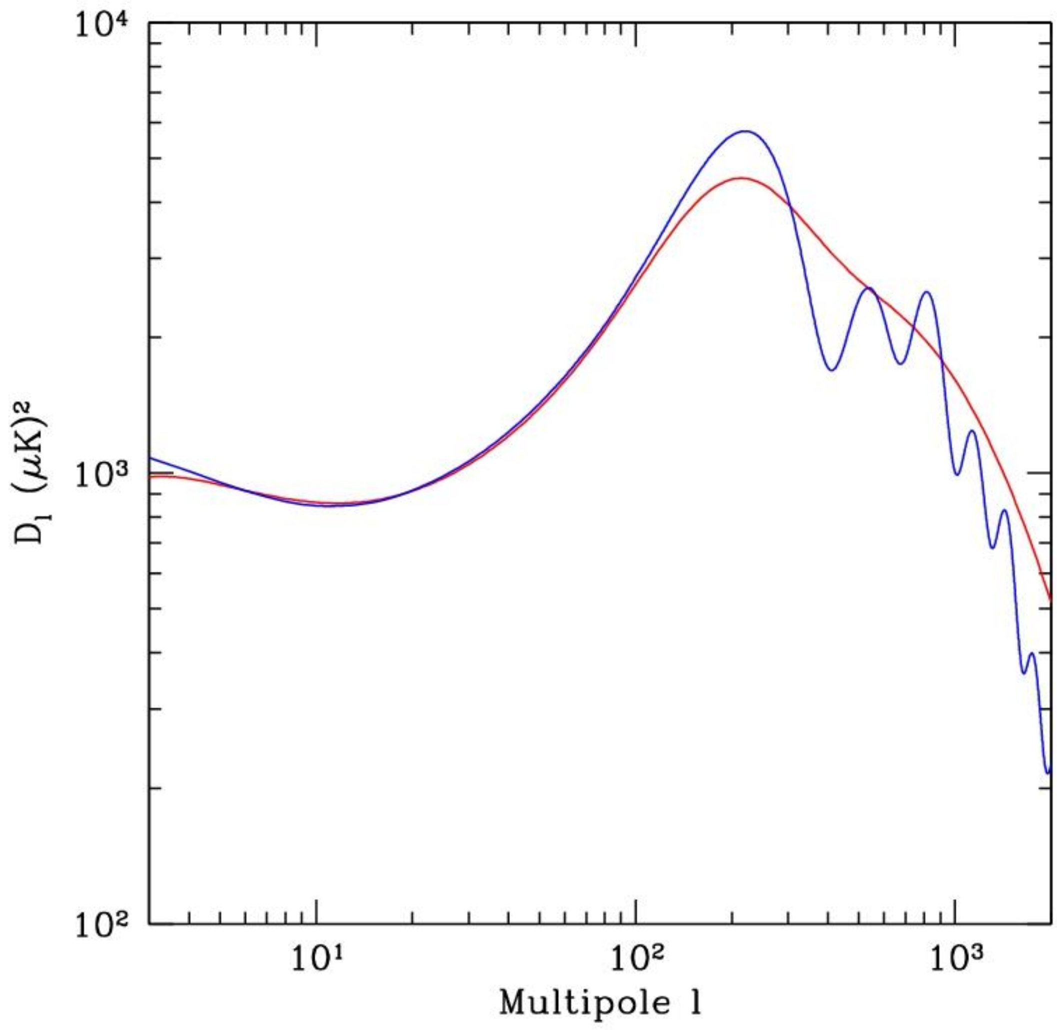
(Arevalo et al, submitted, see also Ossenkopf+08)



CMB: Works fine for low resolution PS



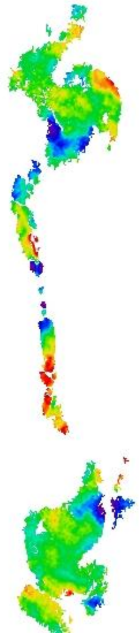


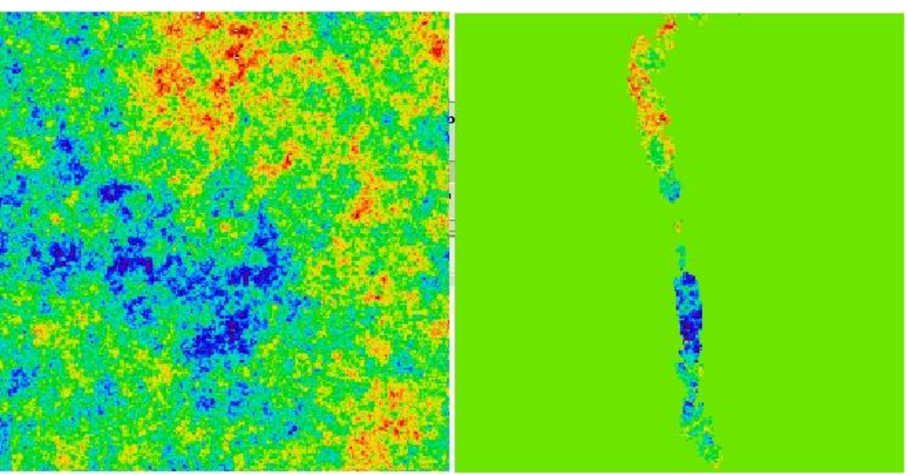


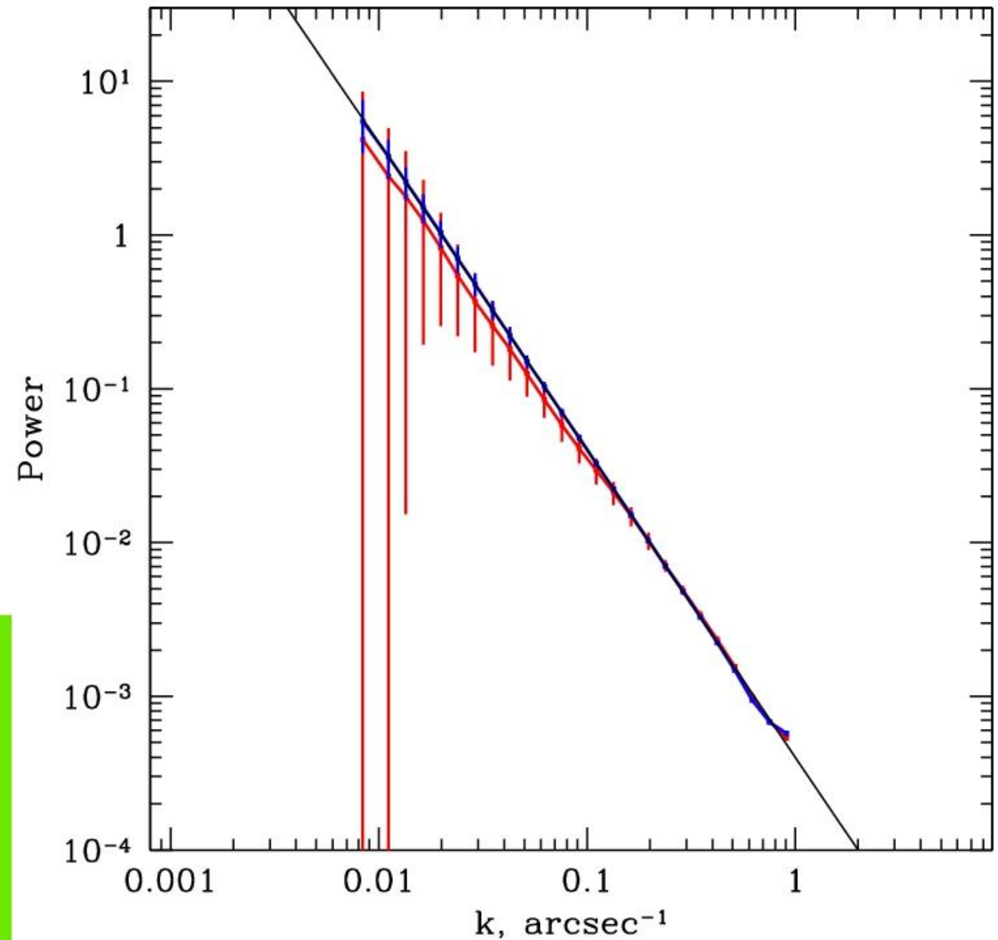
Arevalo+, submitted

Faraday Rotation Measure

$$\int n_e B_{||} dl$$

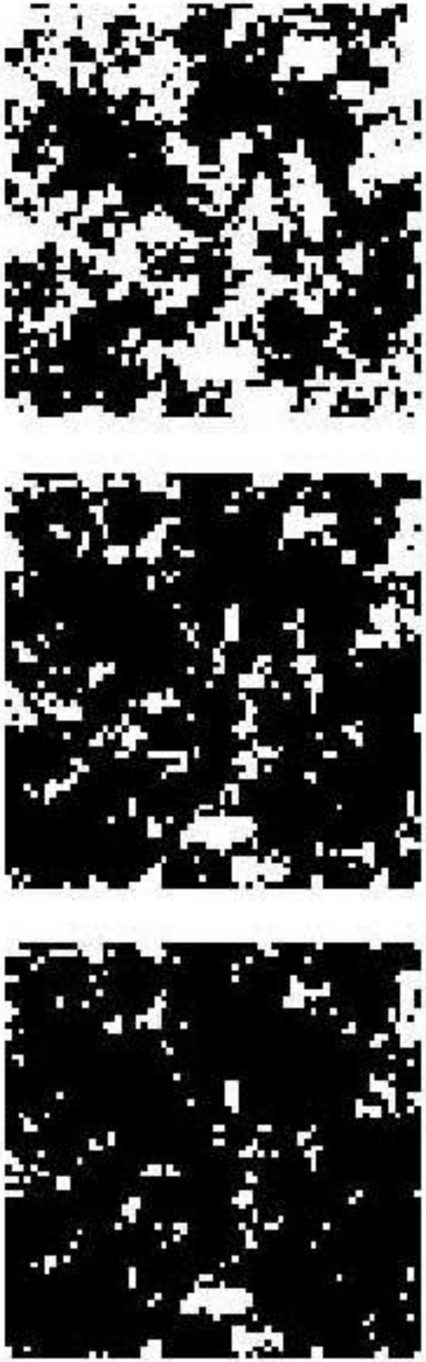






Lyskova+

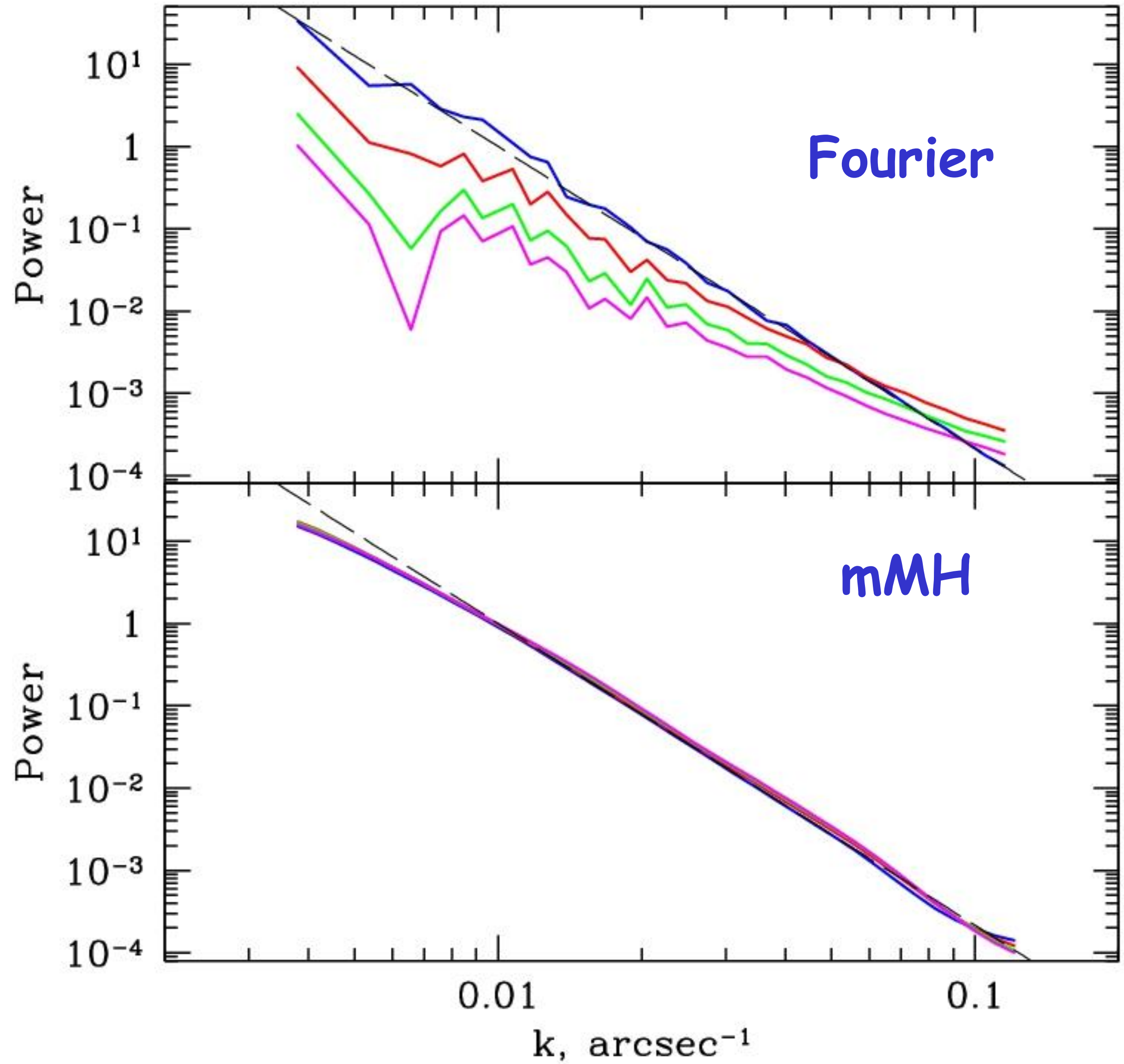
Simulated 3D velocity cube



50%

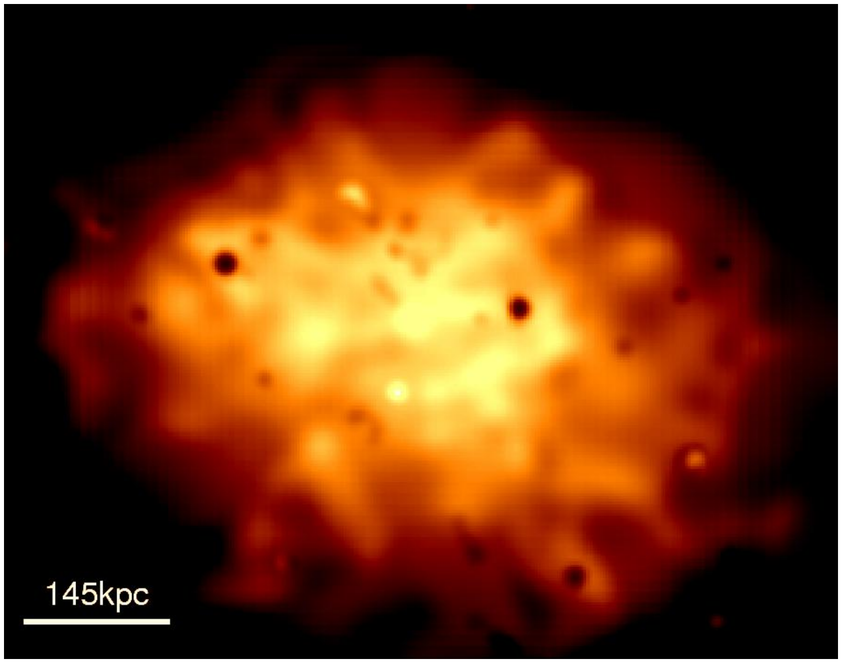
75%

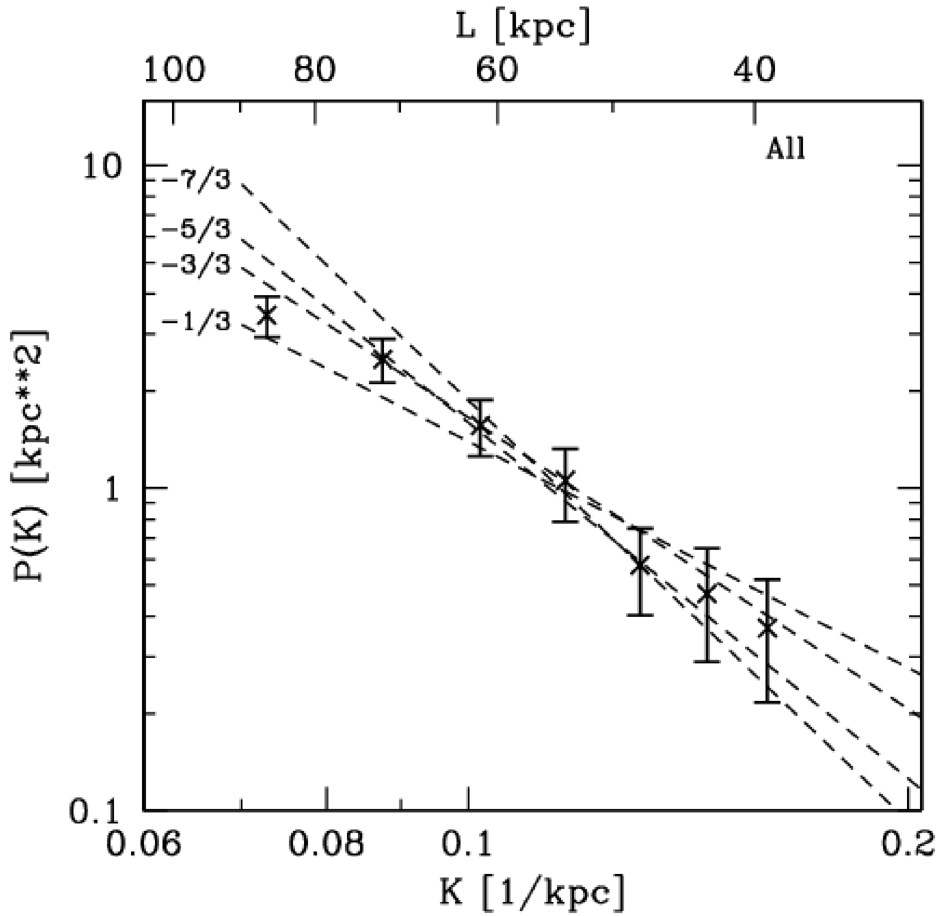
85%



Zhuravleva+

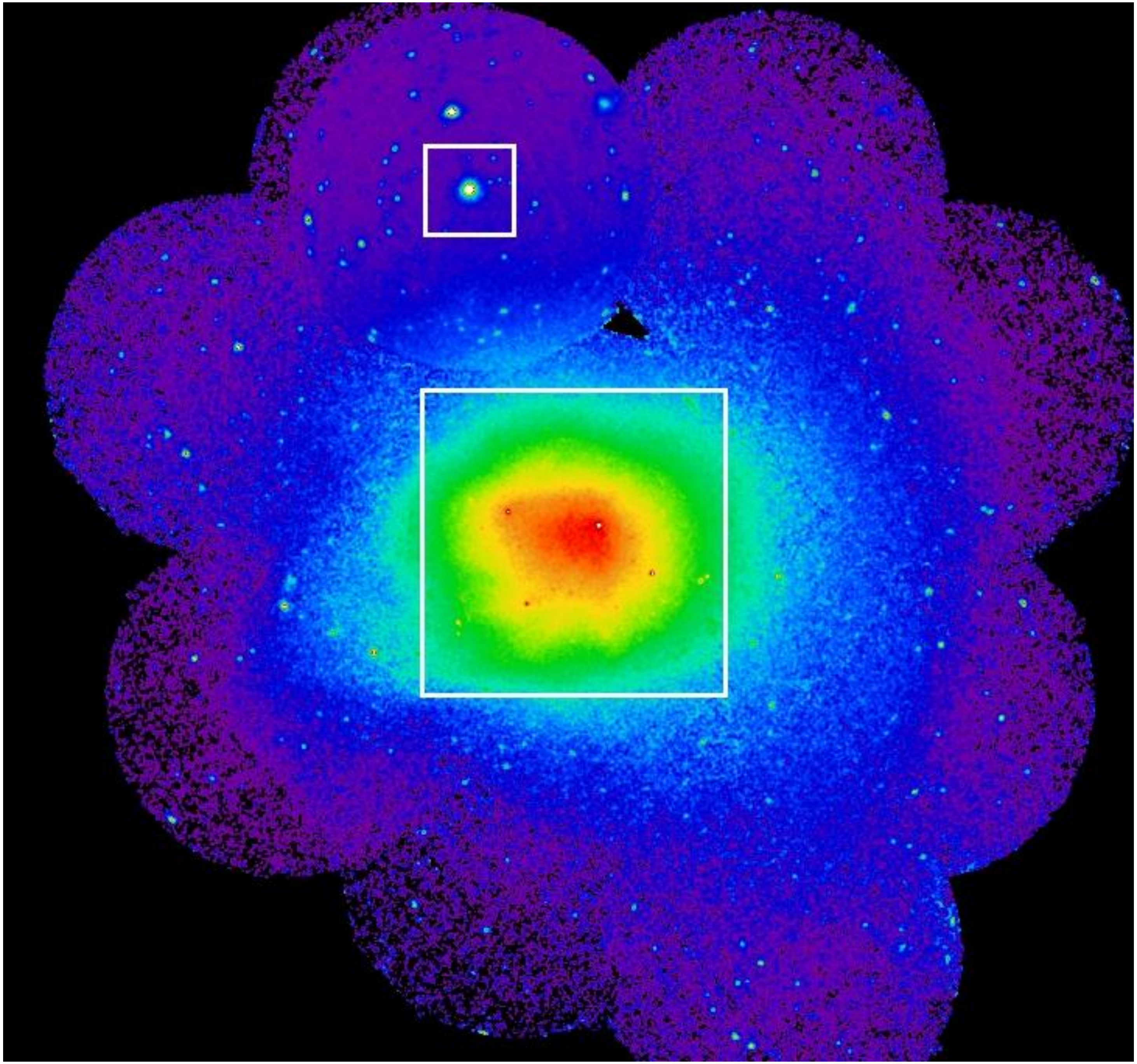
Pressure fluctuations in Coma



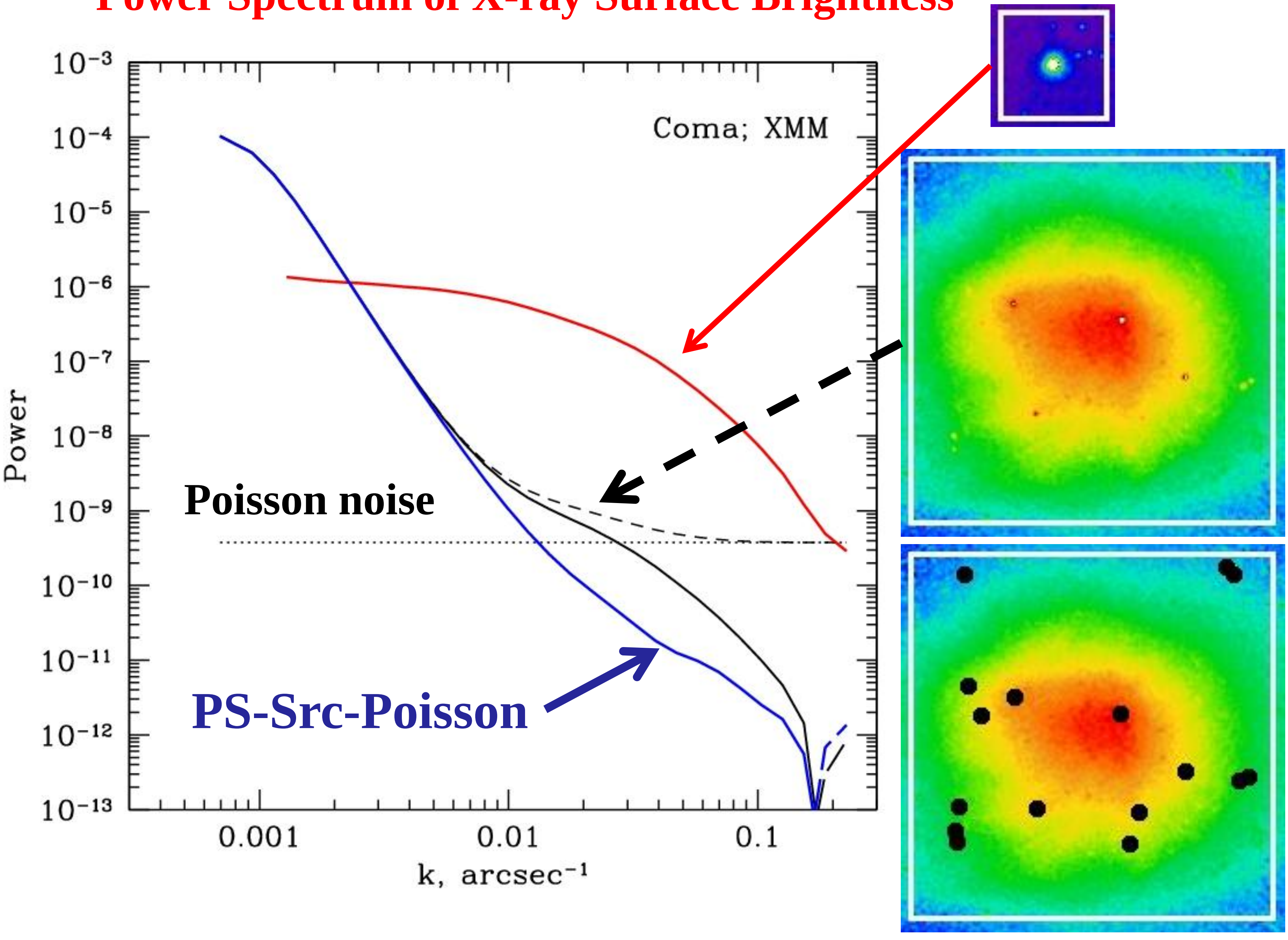


Schuecker et al. (2004)

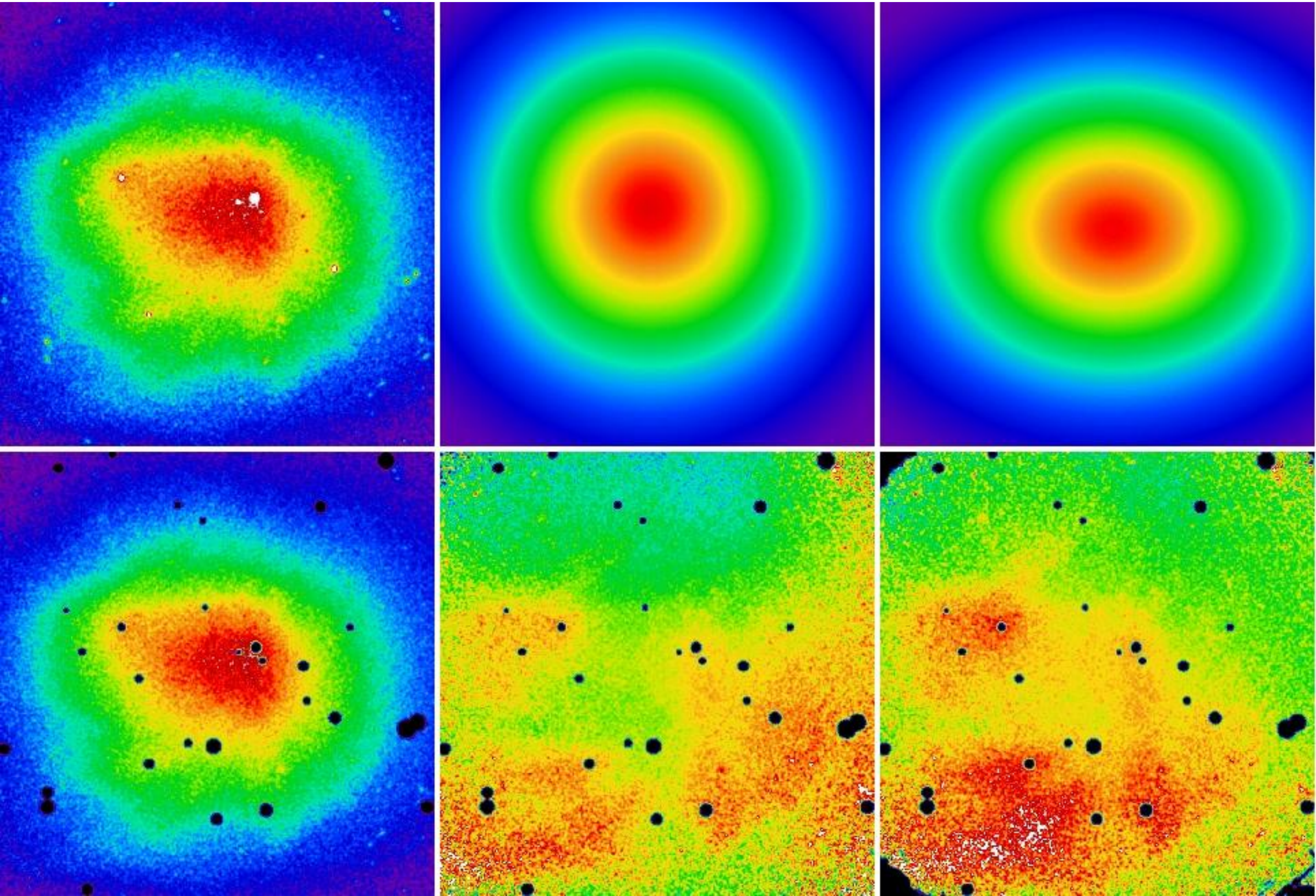
Let us do SB fluctuations



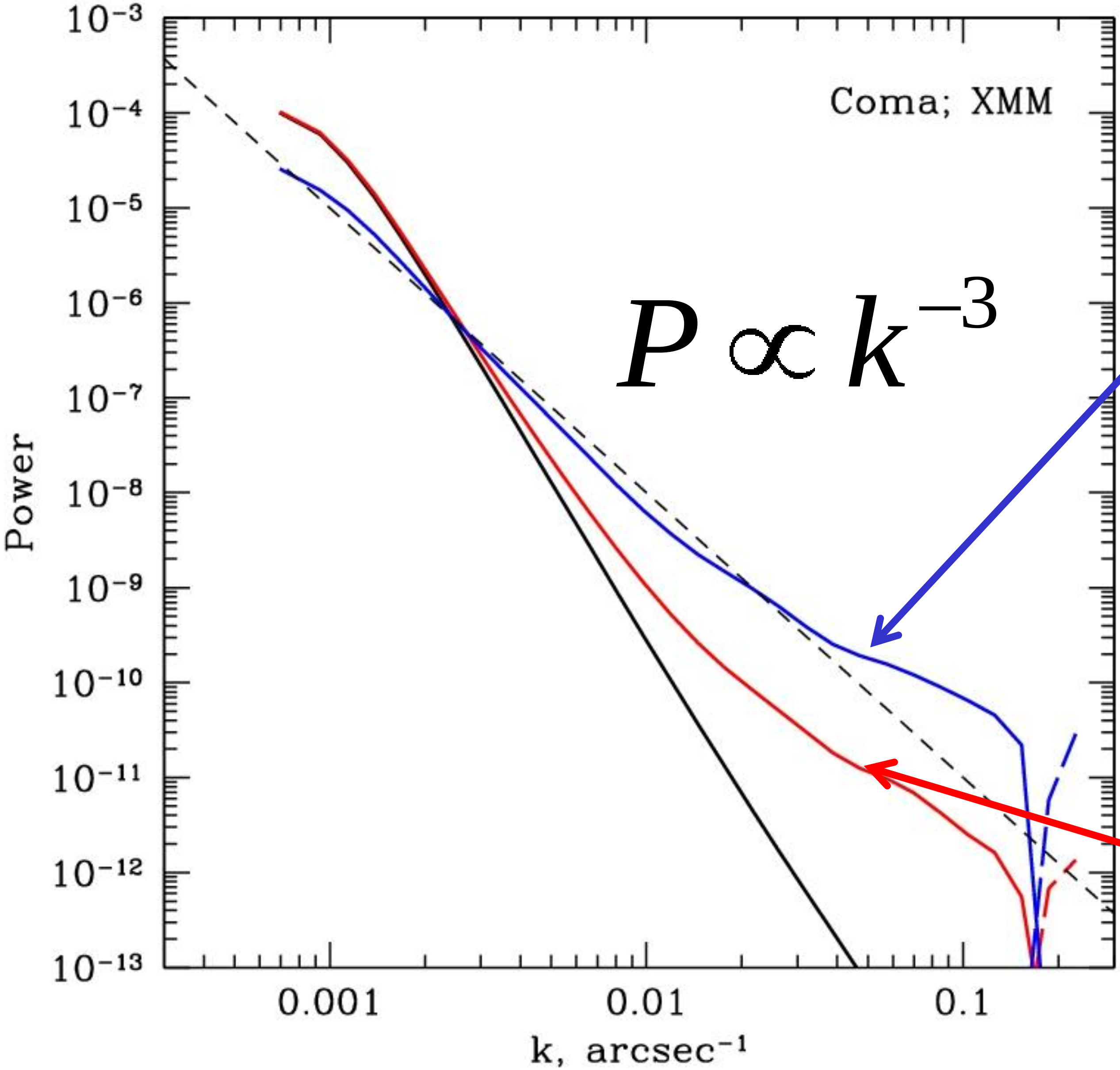
Power Spectrum of X-ray Surface Brightness



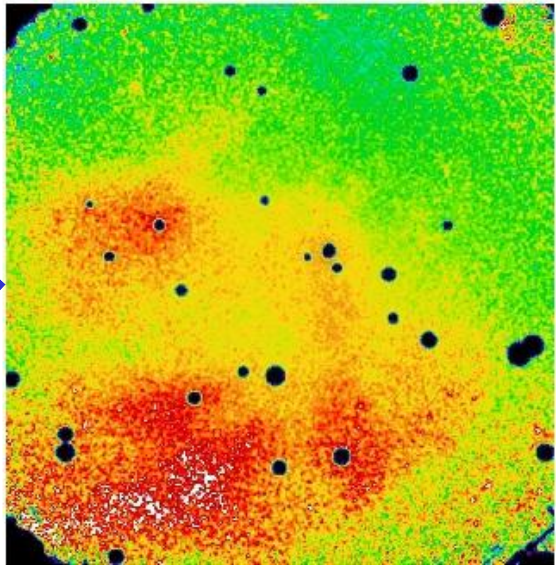
Removing global Coma profile

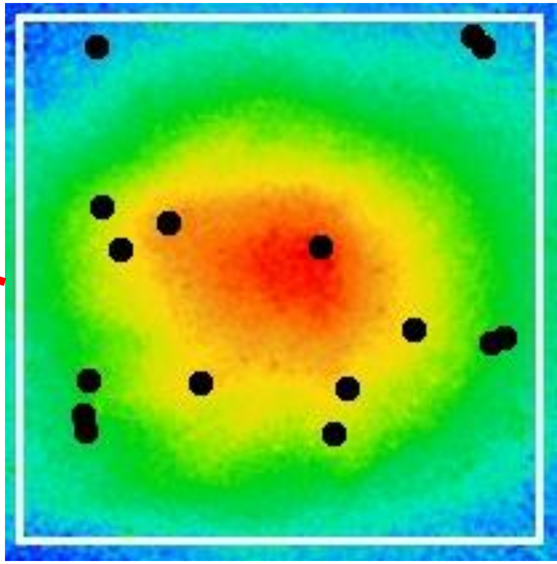


Coma divided by the β model



$$P \propto k^{-3}$$



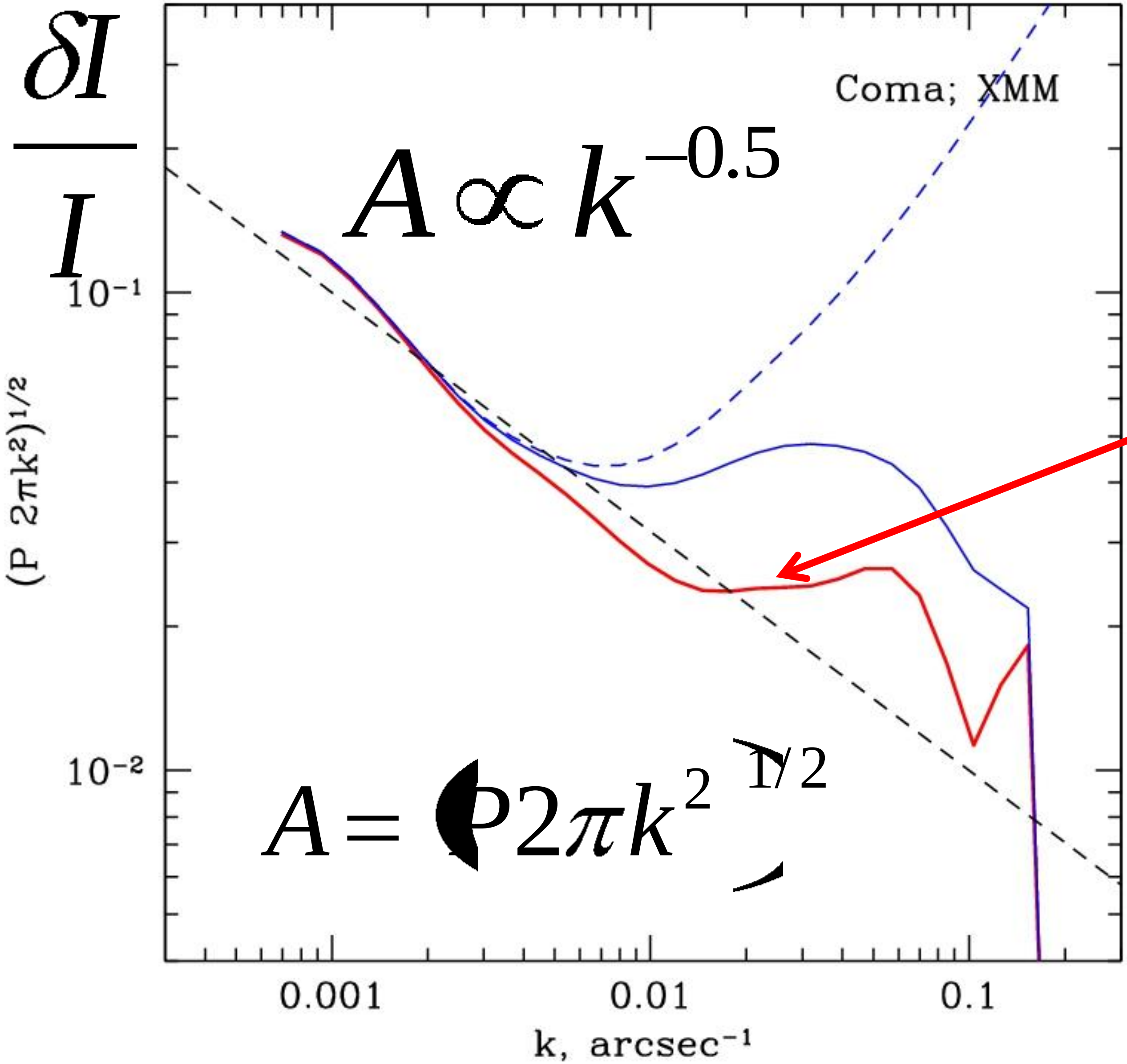


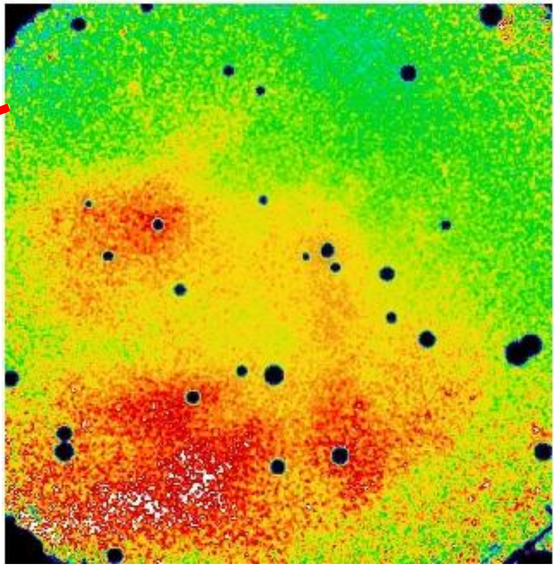
Converting to Amplitudes

$$\frac{\delta I}{I}$$

$$A \propto k^{-0.5}$$

$$A = \left(P 2\pi k^2\right)^{1/2}$$





Relating 3D and 2D power spectra

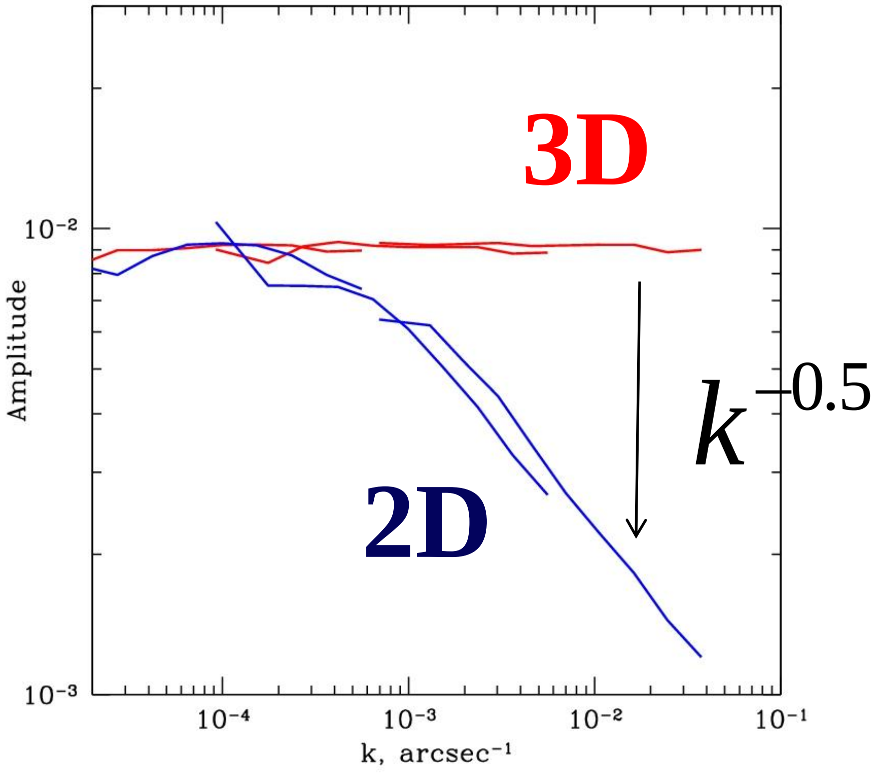
$$I(x,y) = \int \delta(x,y,z) n_e^2(x,y,z) dz$$

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

$$W = P_1[n_e^2(z)]$$

$$k >> \frac{1}{l_z} \Rightarrow P_{2D} = aP_{3D}$$

$$k << \frac{1}{l_z} \Rightarrow P_{2D} = aP_{3D} \times k$$

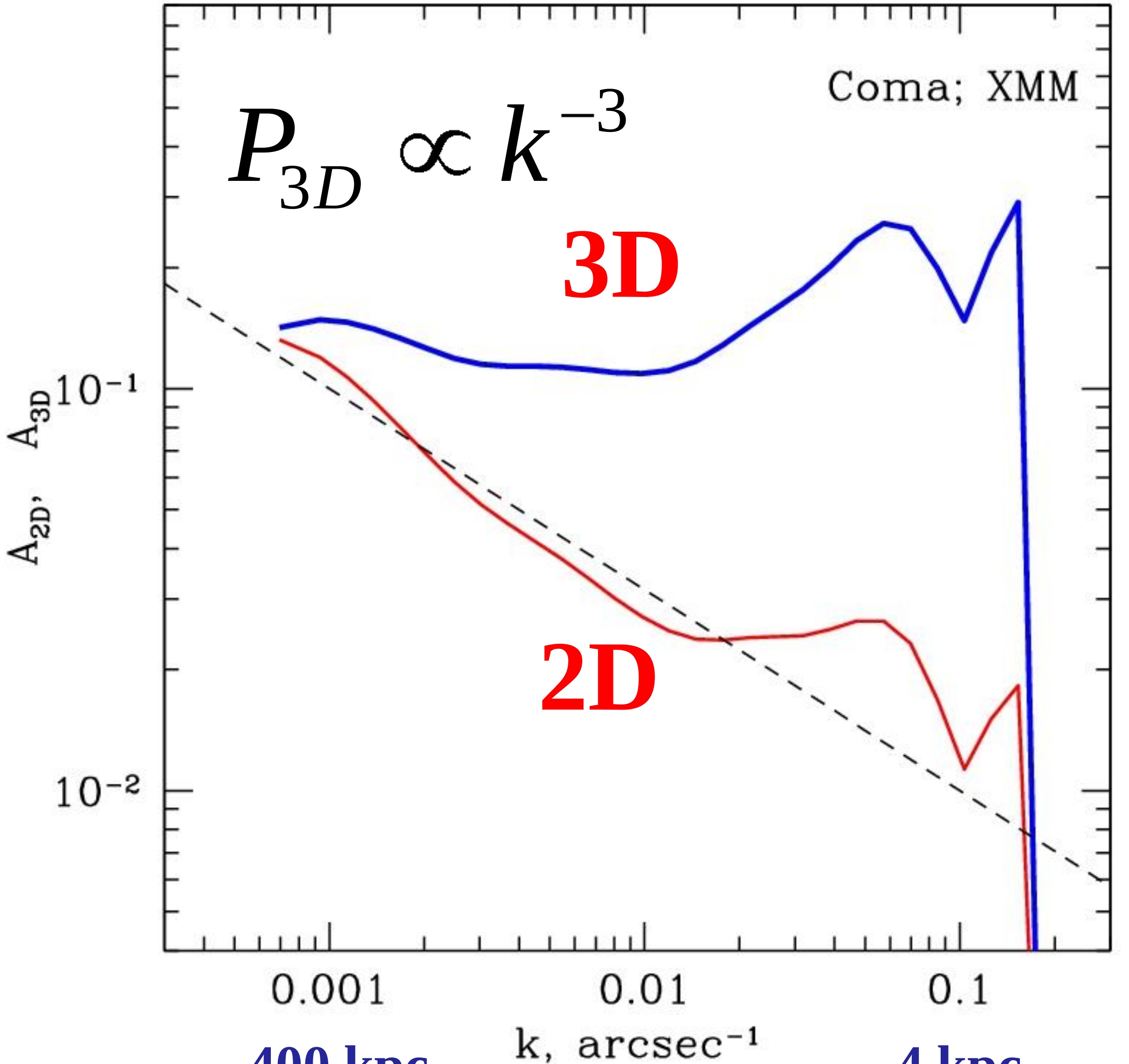


3D Density fluctuations in Coma

$$2\frac{\delta n_e}{n_e}$$

$$\frac{\delta I}{I}$$

$$P_{3D} \propto k^{-3}$$

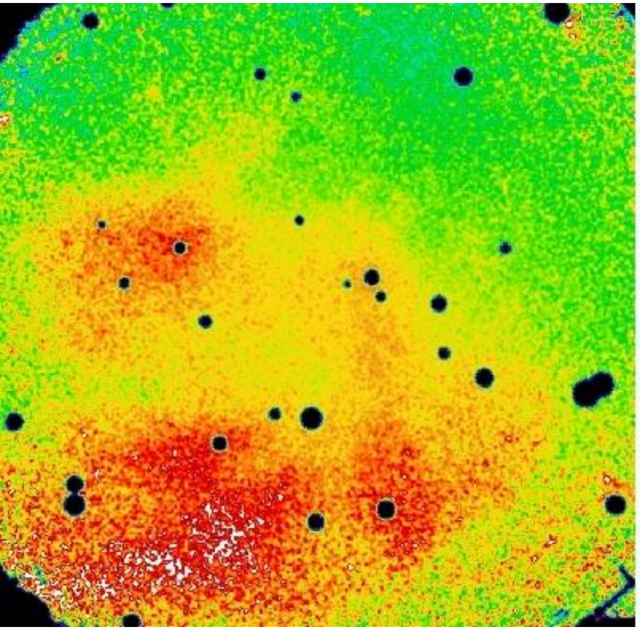
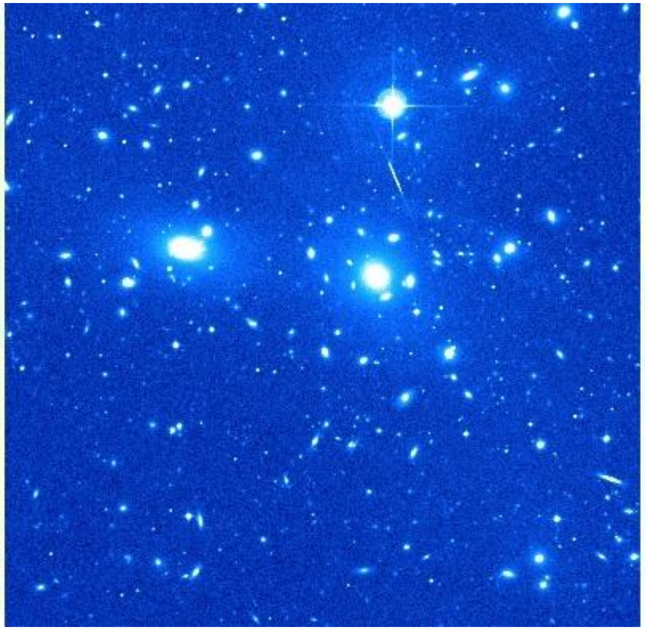
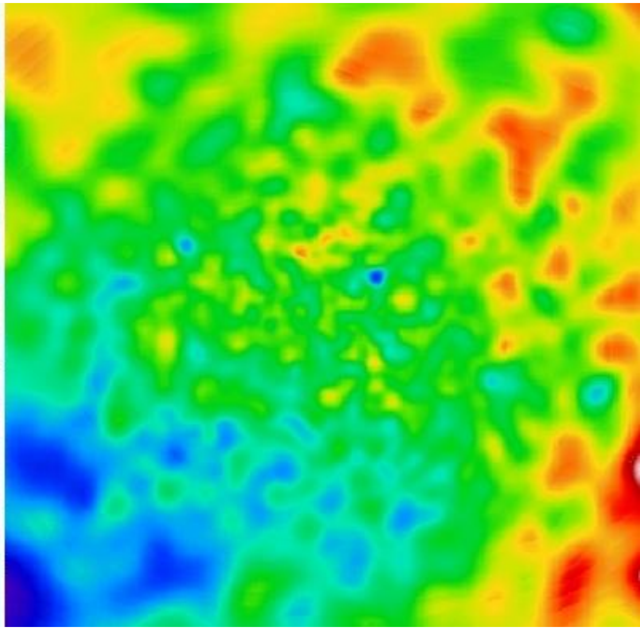


400 kpc

4 kpc

Density fluctuations ~5-10% on scales 4-400 kpc

X-Image/β **Optical** **Gas T-map**

~5-10% density fluctuations include (4-400 kpc):
potential perturbation (big galaxies)
entropy fluctuations (infalling groups)

$$P_{3D} \propto k^{-3}$$

Conclusions

ICM velocities ~ few 100 km/s
[except for mergers]

Direct V measurements ->
structure function

Modified MH method provides robust
measure of V(k)

We are approaching "precision ICMology"