X-ray Surface Brightness Fluctuations in Galaxy Clusters

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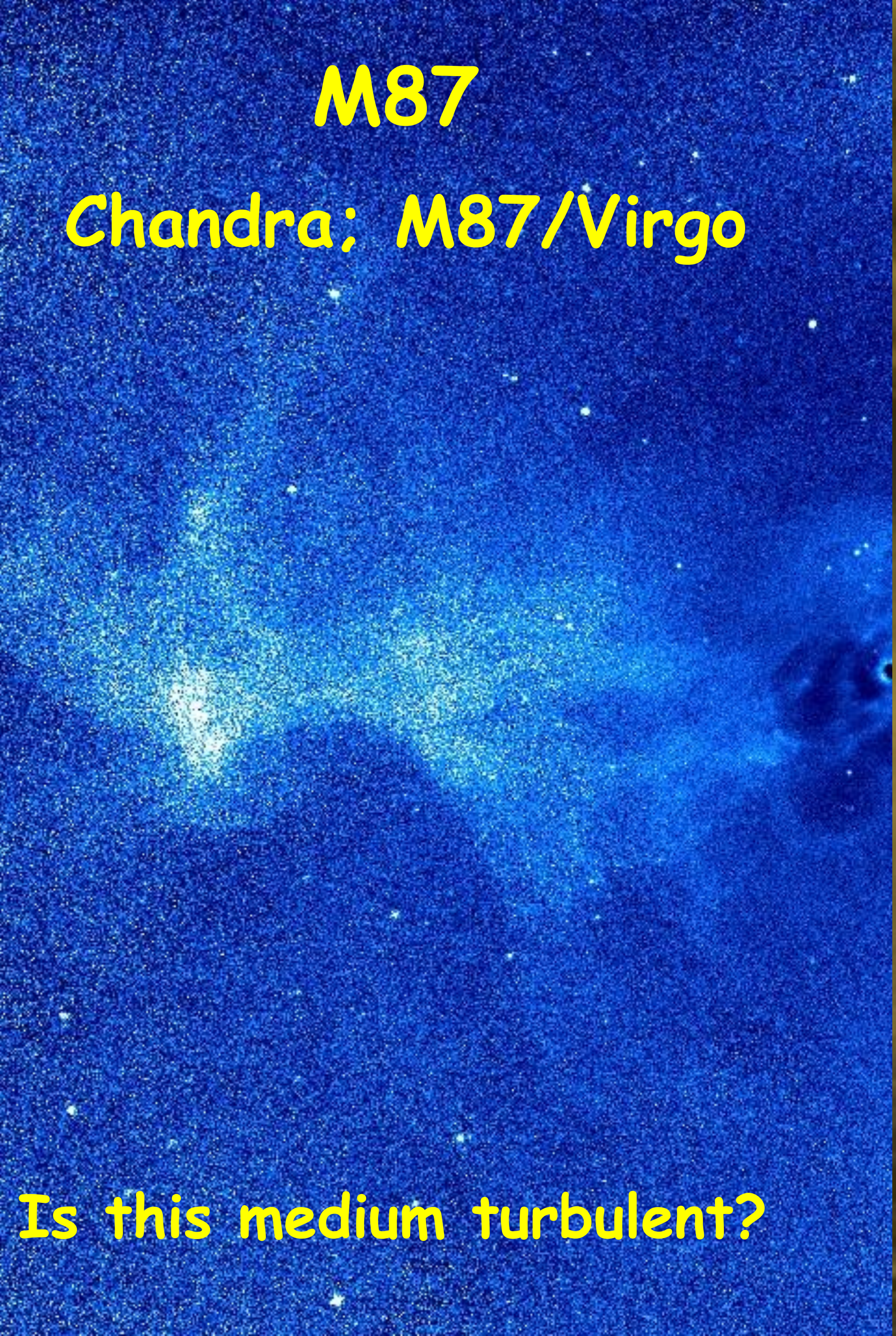
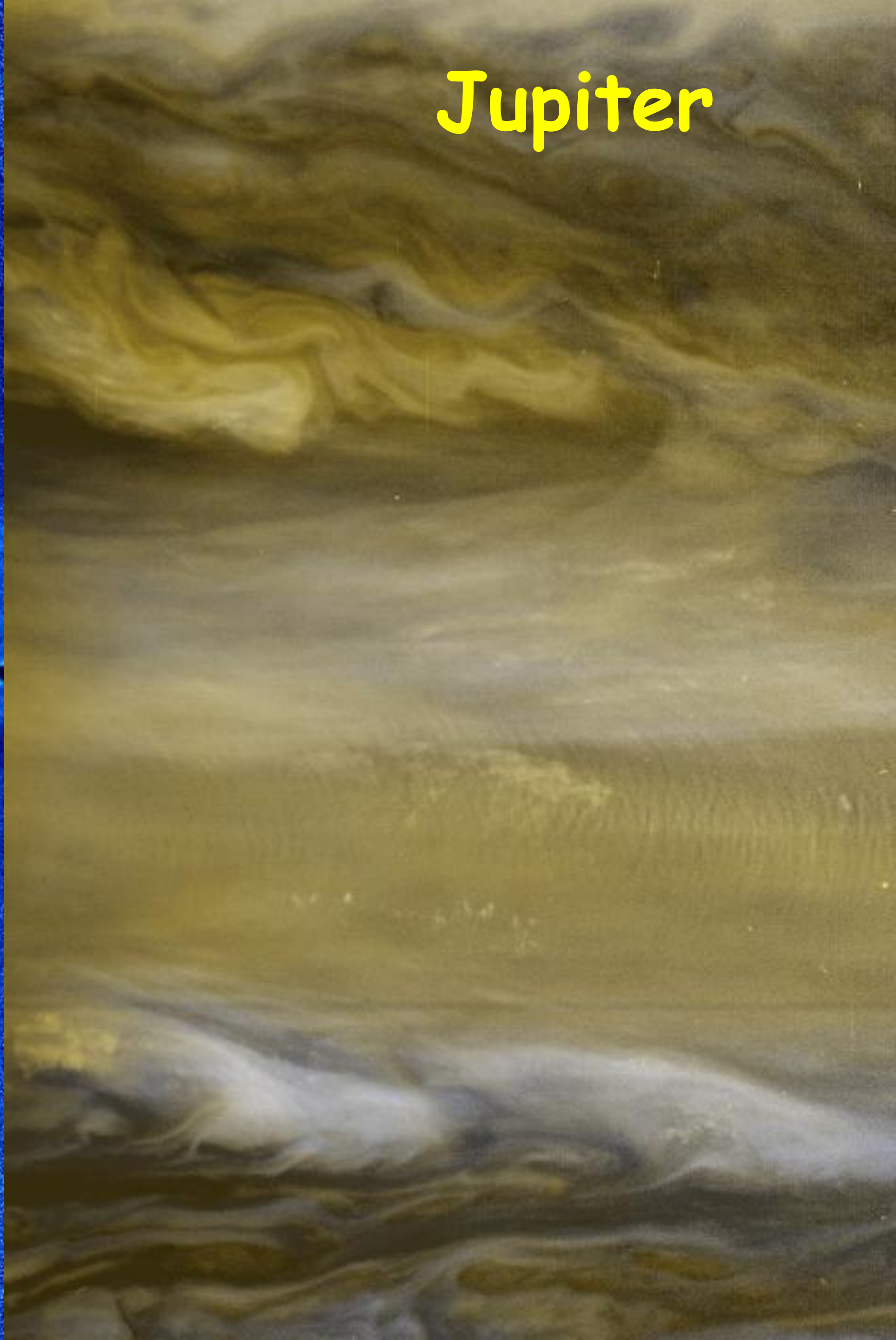
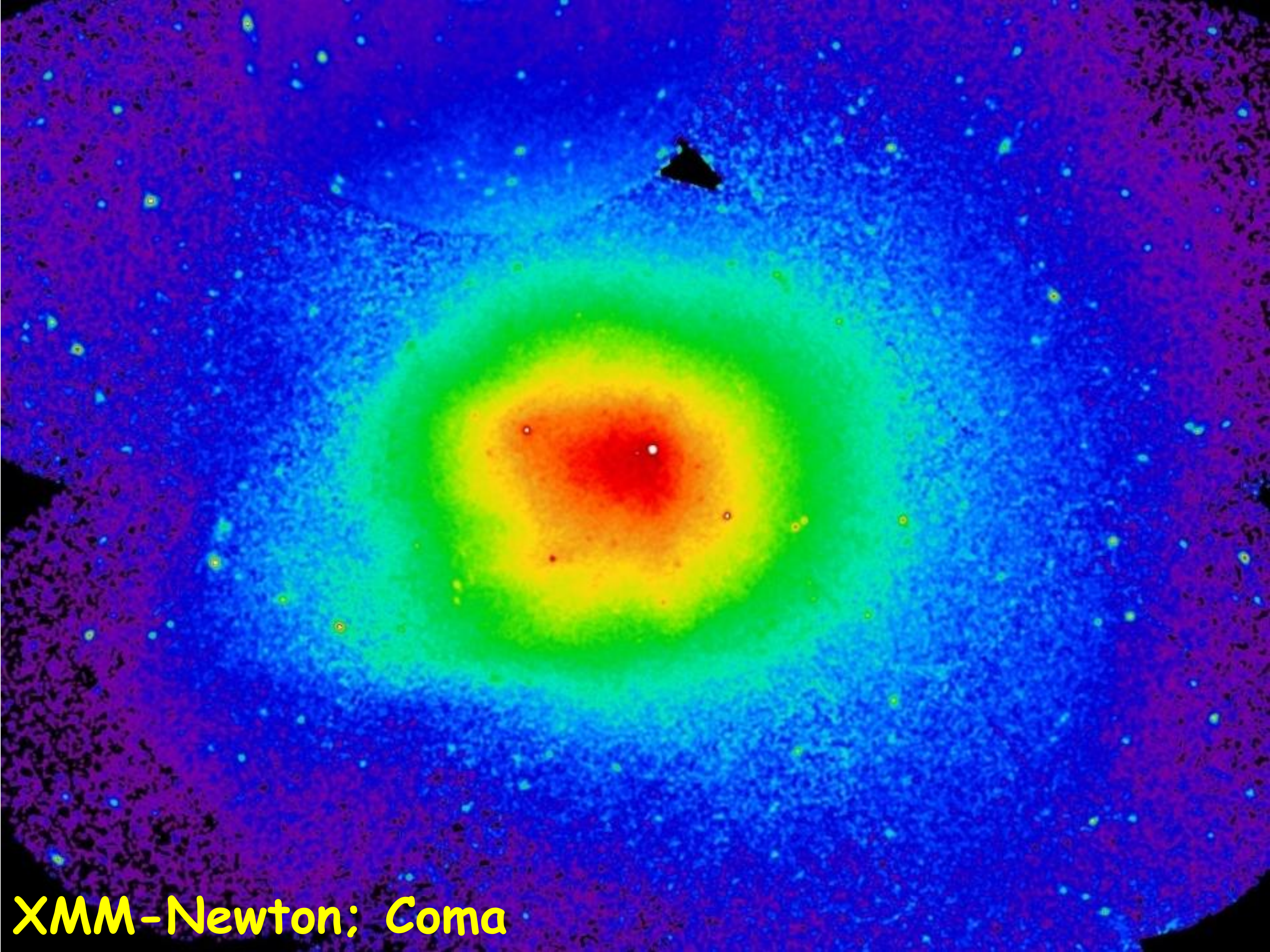
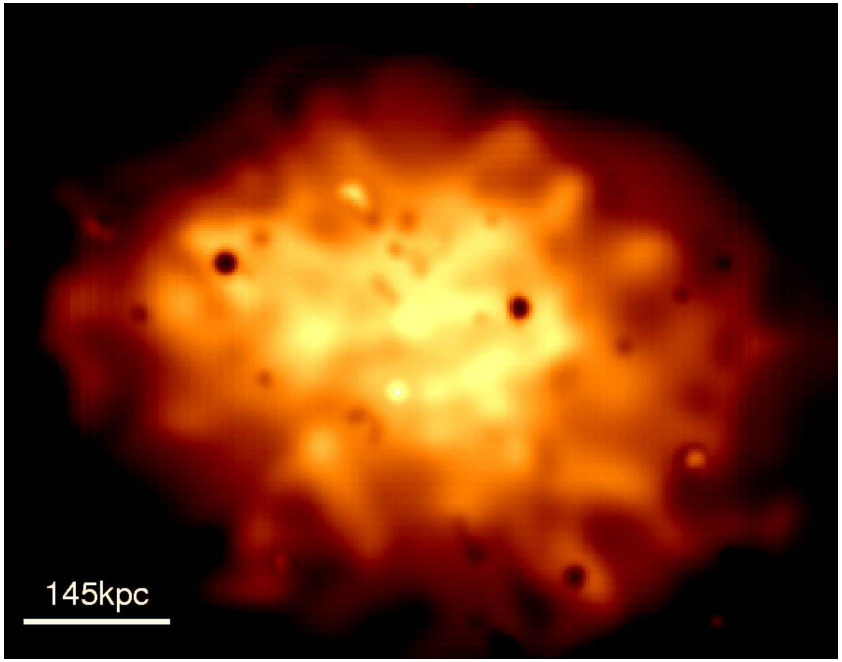
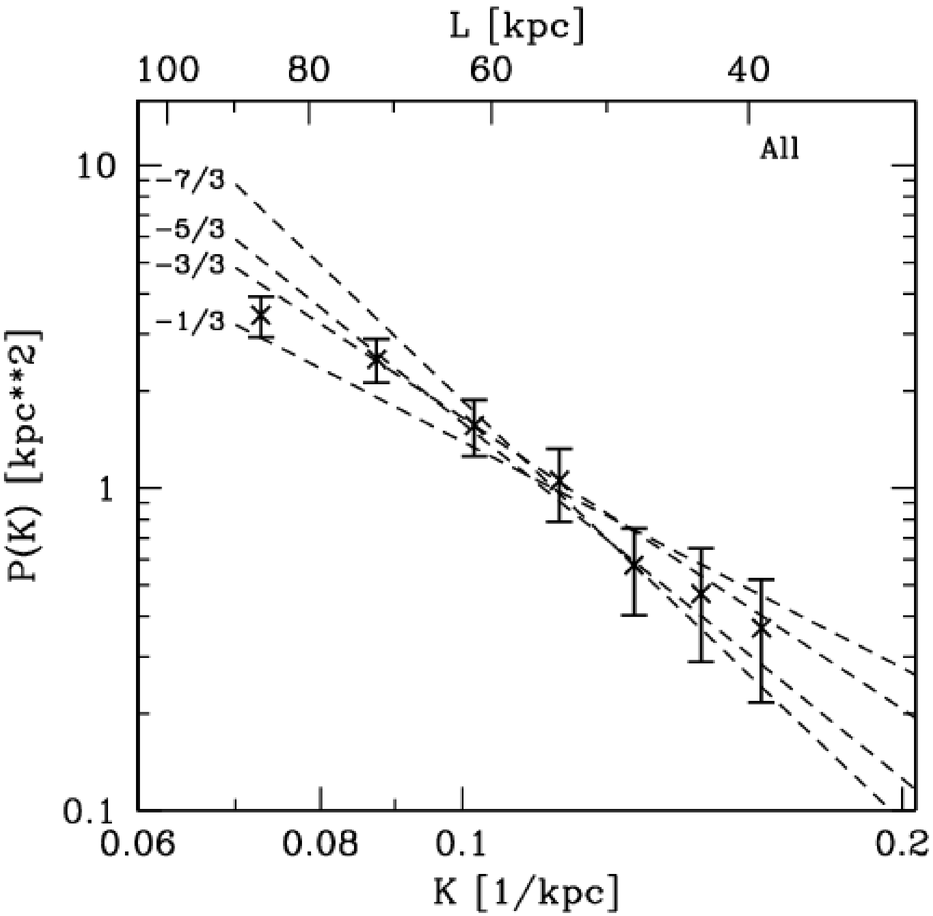

M87
Chandra; M87/Virgo
Is this medium turbulent?


Jupiter


XMM-Newton; Coma

Pressure fluctuations in Coma



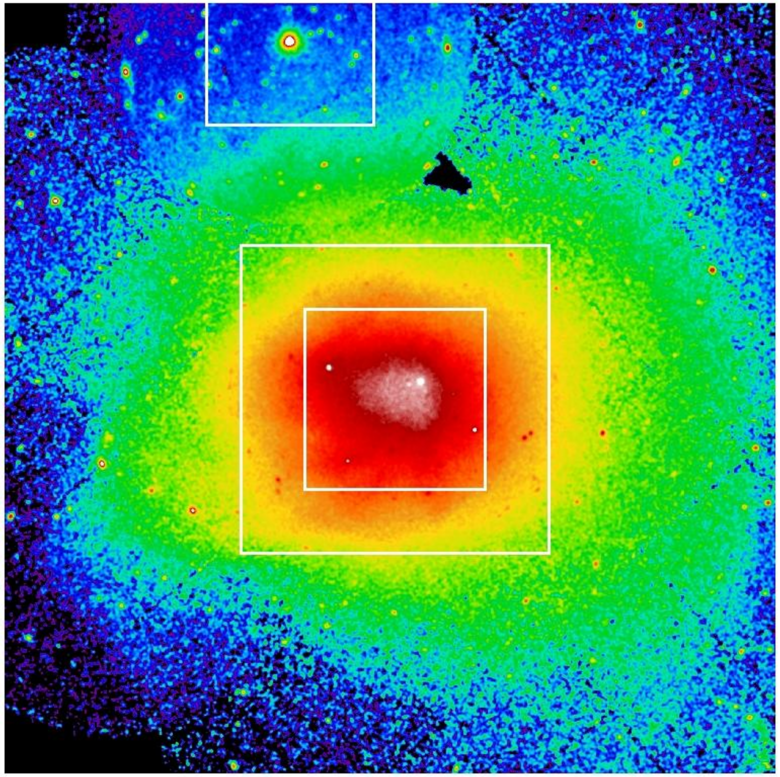


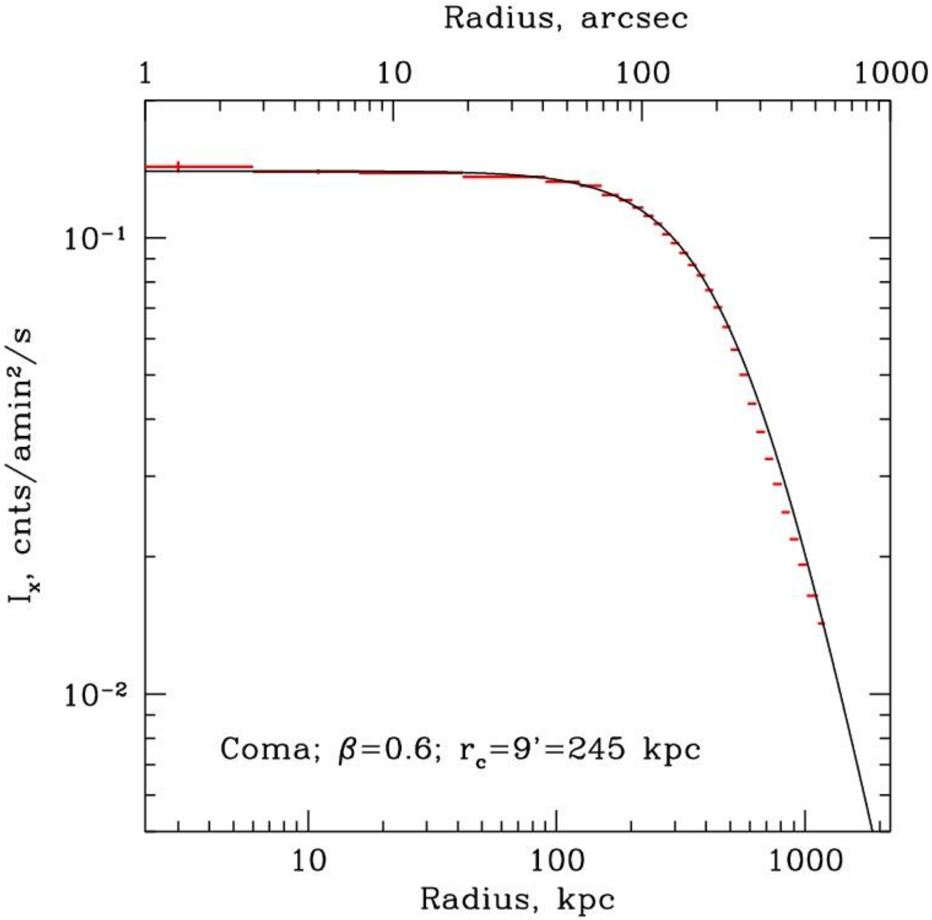
Schuecker et al. (2004)

Why Surface Brightness Fluctuations?

1. Most easy to measure
2. Accurate account for Poisson noise

3. Constraints on temperature variations
4. Proxy to turbulence
5. Transport processes in ICM

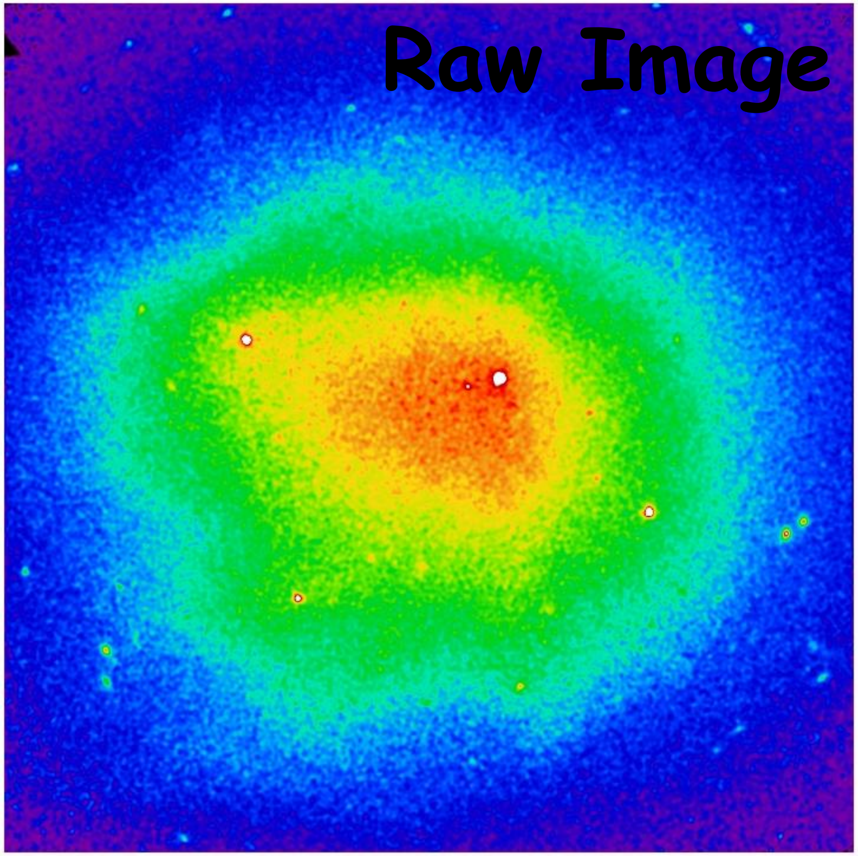


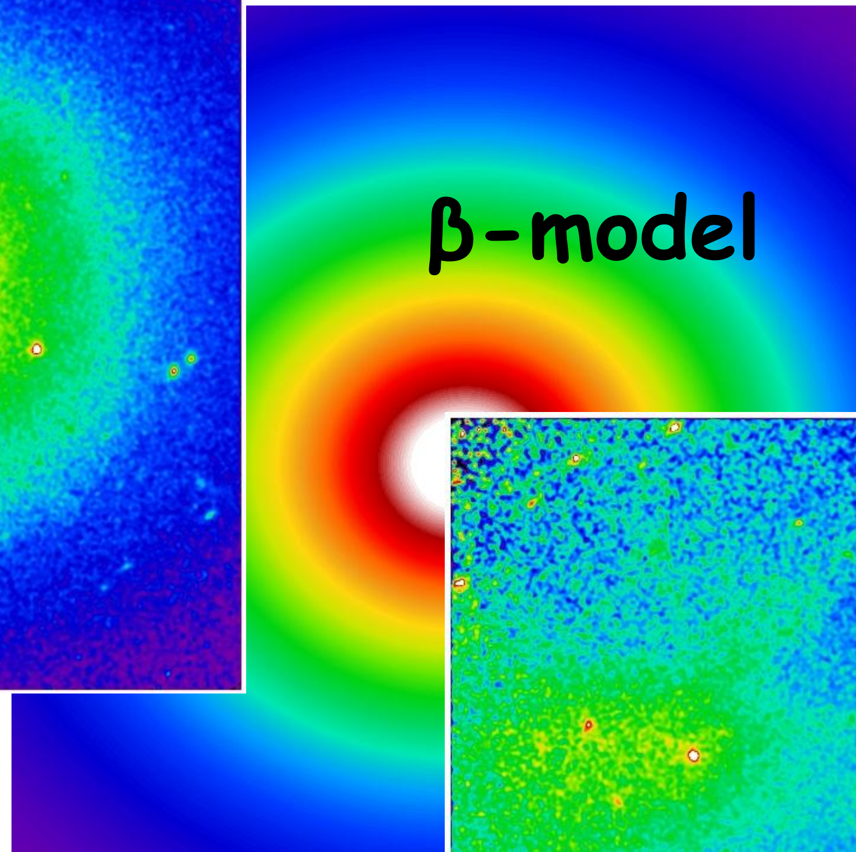


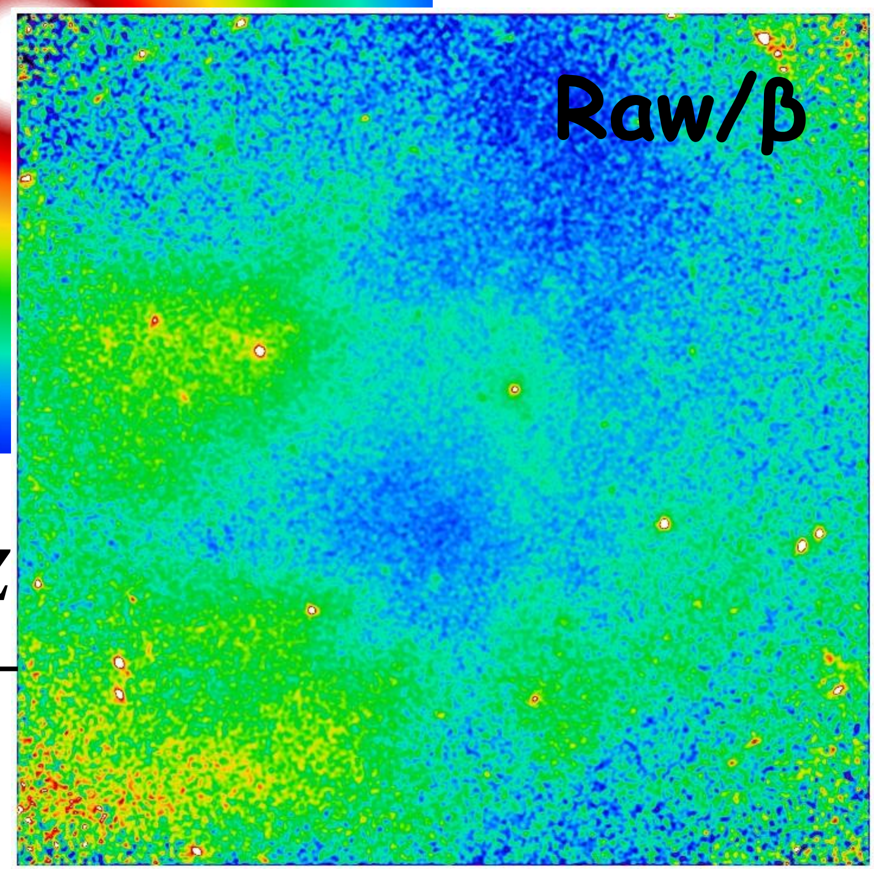
$$n = n_0(x,y,z)[1+\delta(x,y,z)]$$

$$\delta(x,y,z)$$

Random Isotropic/Homogeneous Field : Power Spectrum

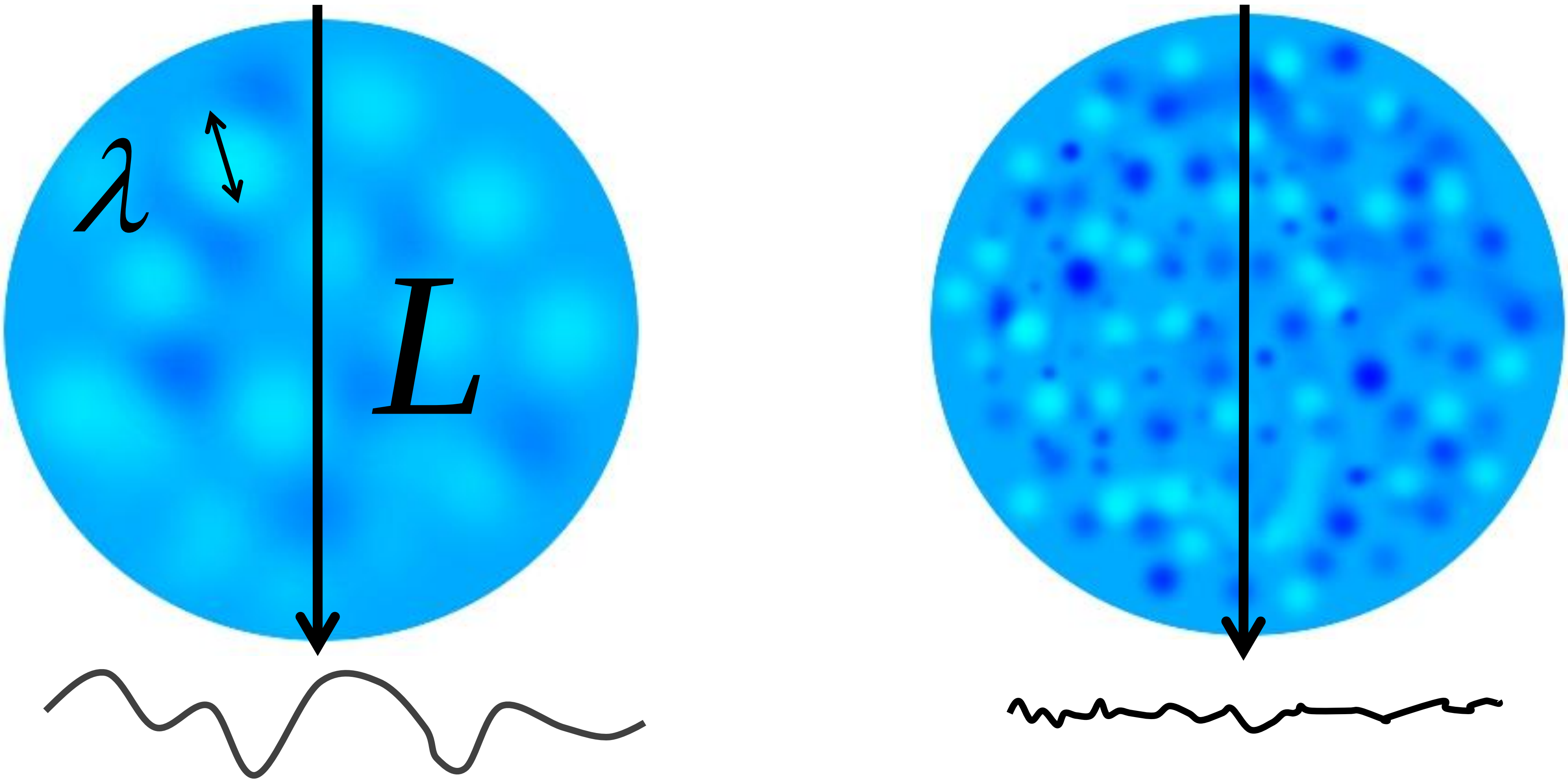






$$\frac{\int 2\delta(x,y,z)\,n_e^2(x,y,z)\,dz}{\int n_e^2(x,y,z)\,dz}$$

Projection of density fluctuations



$$A_{2D} \propto A_{3D} \times \sqrt{\frac{1}{N}} = A_{3D} \times \sqrt{\frac{\lambda}{L}}$$

Relating 3D and 2D power spectra

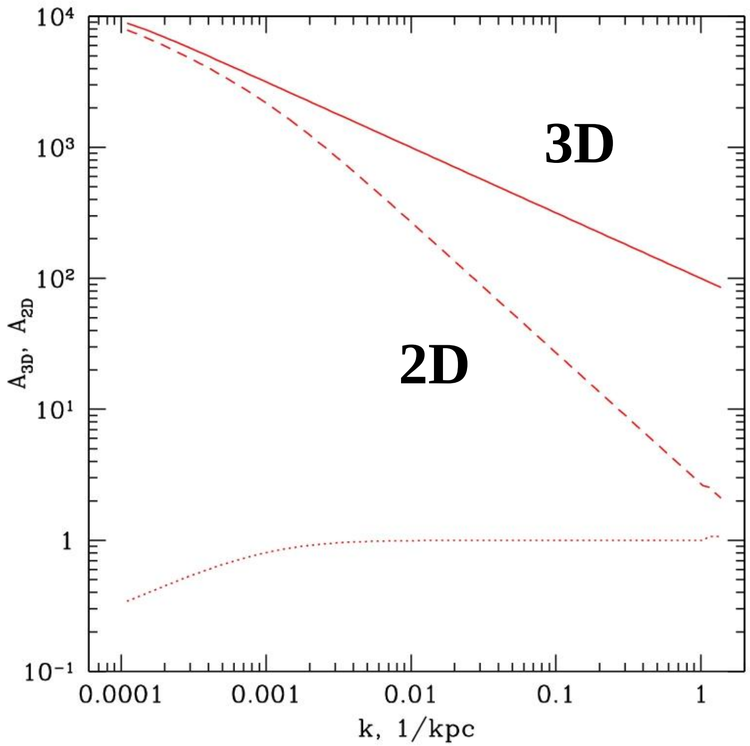
$$I(x,y)=\int \delta(x,y,z)n_e^2(x,y,z)dz$$

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

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

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

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

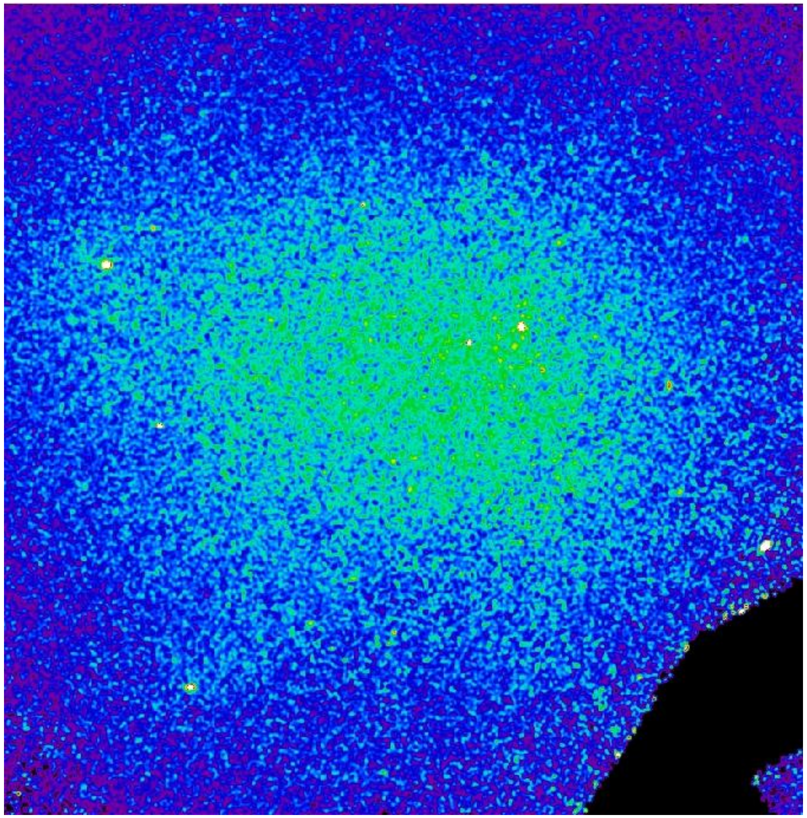


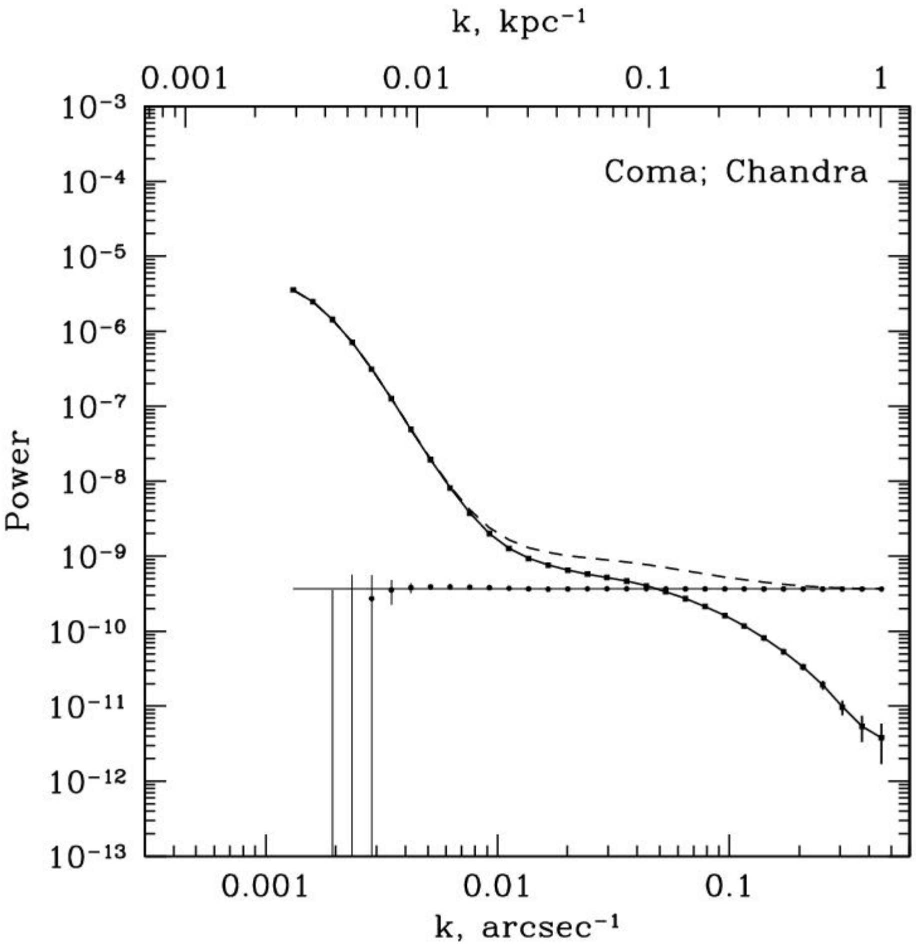
1. Measure 2D power spectrum of SB fluctuations

2. Use known density and temperature profiles to calculate 3D->2D transformation

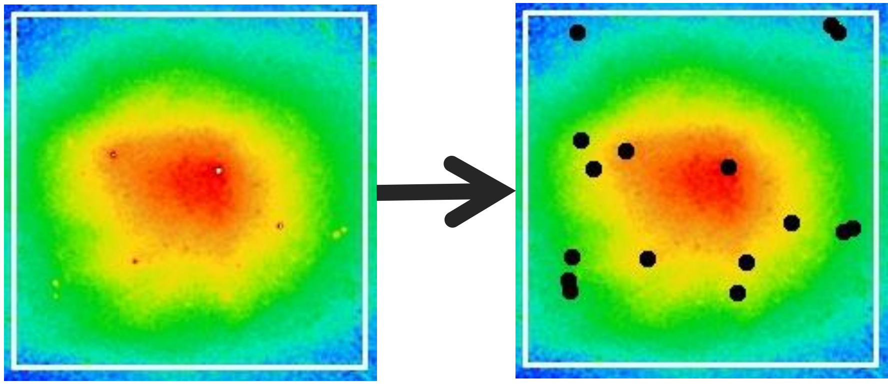
3. Convert 2D Power Spectrum into 3D

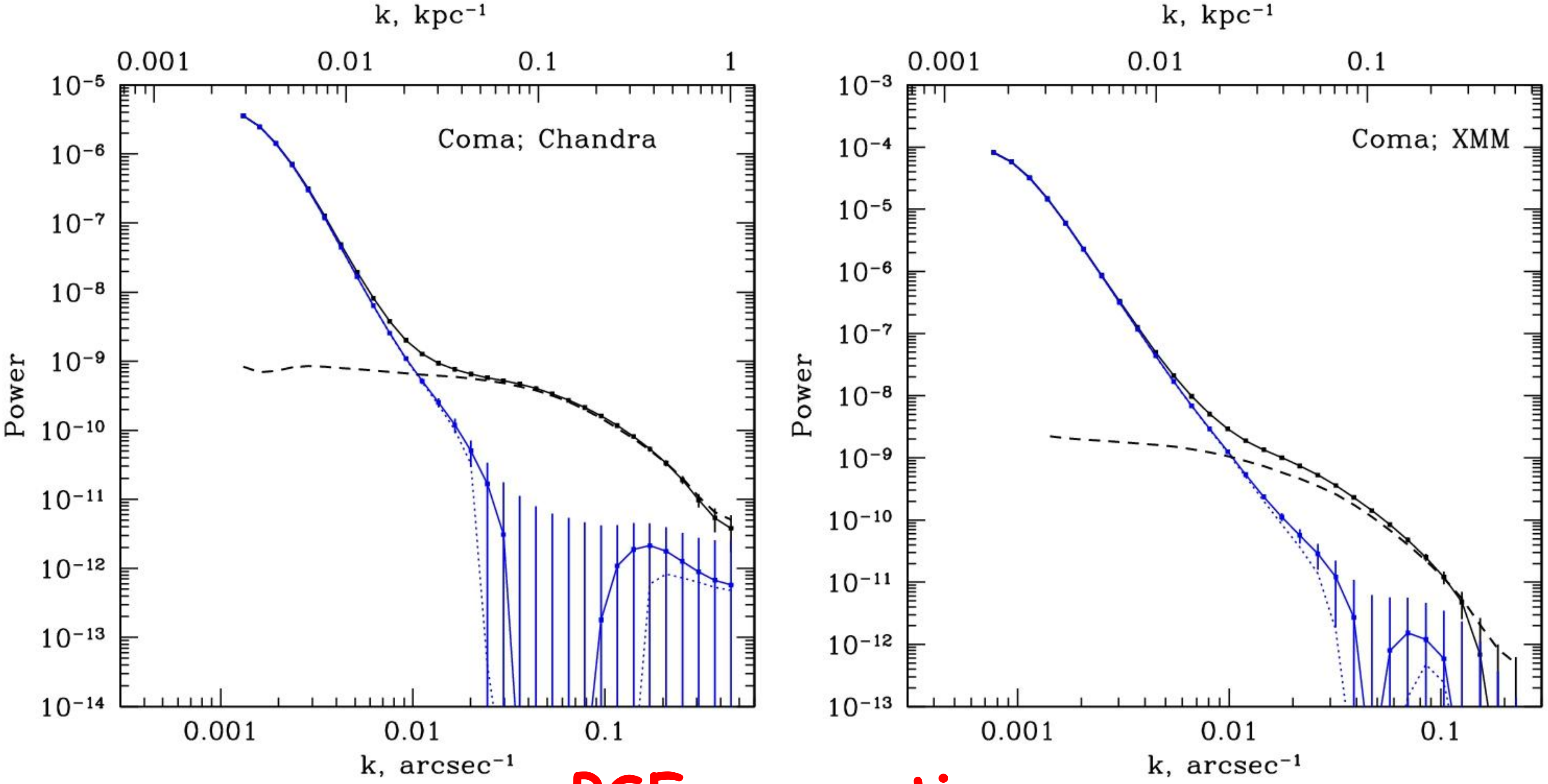
Raw 2D Power Spectrum of Coma





Removing point sources



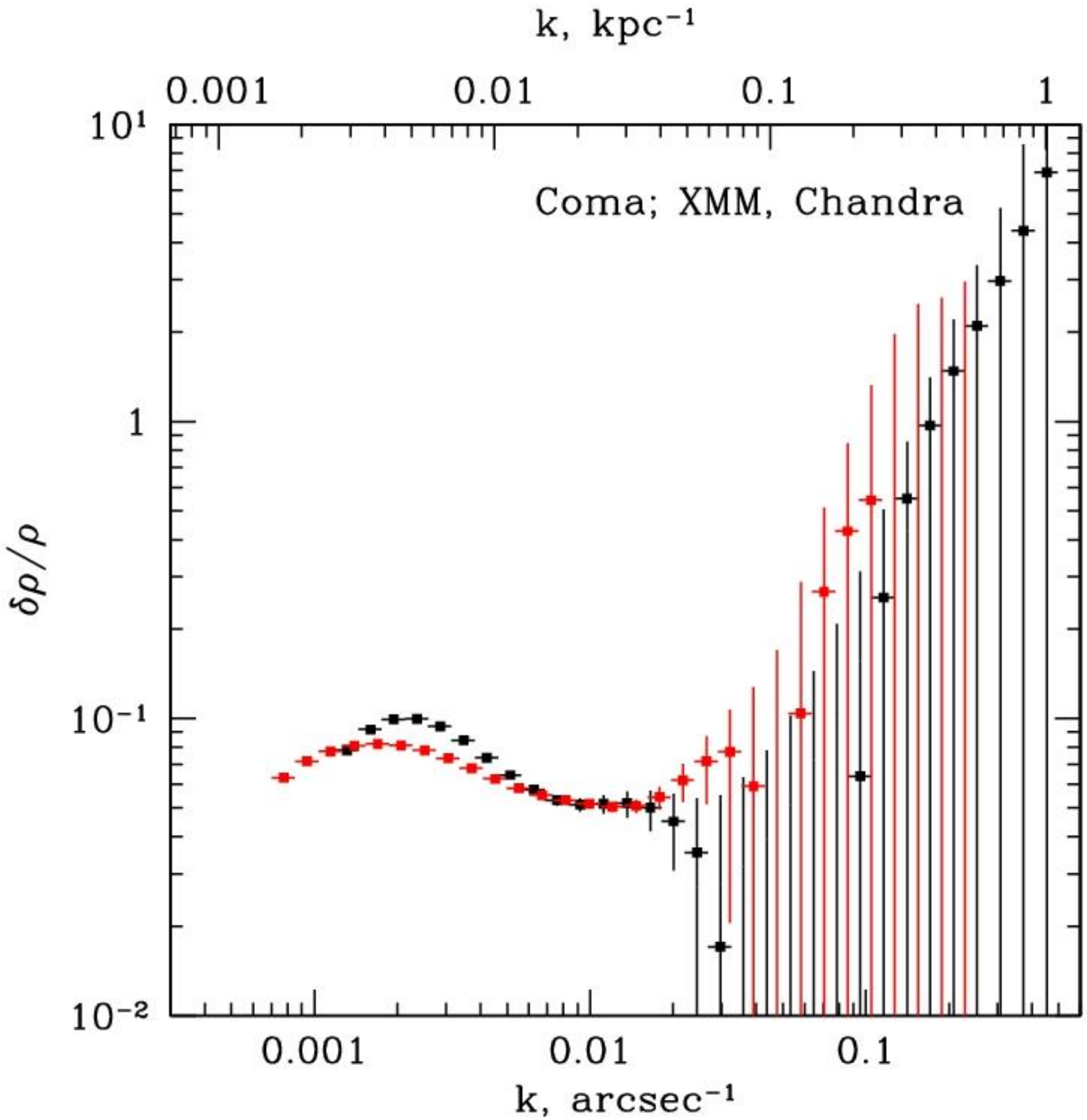


PSF correction

Major steps of the analysis

Divide the image by a suitable model
Remove compact sources
Calculate 2D Power Spectrum
Remove Poisson noise
Correct for PSF
Convert 2D $\rightarrow$3D

3D gas density perturbations in Coma



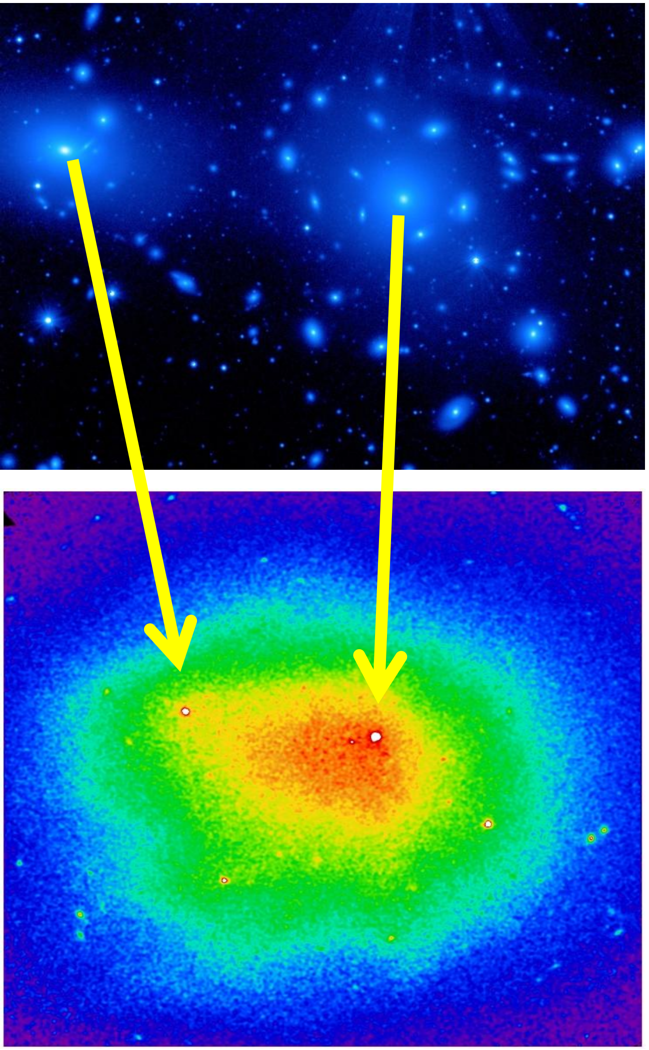
$$k = \frac{1}{x}$$

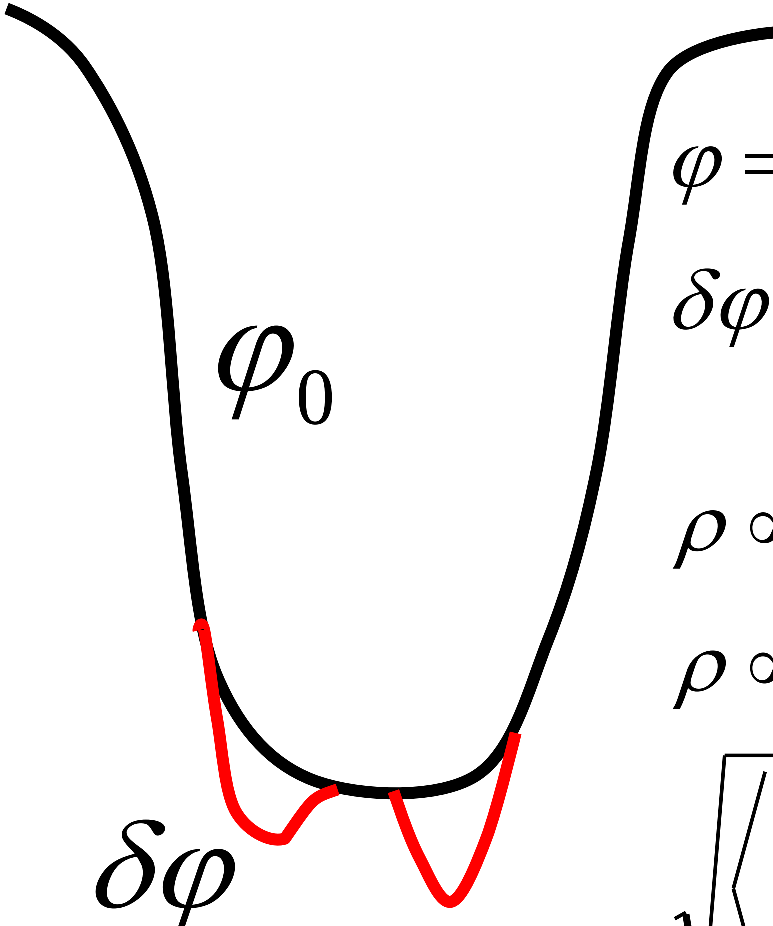
Density fluctuates by 5-10% at scales 30-1000 kpc

What is the origin of ~5-10% density fluctuations?

Perturbations of the potential
Entropy variations
Sound waves
Pressure variations in eddies
Metalicity variations
Global model is not perfect

Perturbations of the potential





$$\varphi = \varphi_0 + \delta\varphi$$

$$\delta\varphi = \mathrm{v}_c^2 \ln(r)$$

$$\rho \propto e^{-\frac{\mu m_p \mathrm{v}_c^2 \ln(r)}{kT}} - 1$$

$$\rho \propto r^{-0.15}$$

$$\sqrt{\left\langle \frac{\delta\rho^2}{\rho^2} \right\rangle} \approx 0.03$$

Turbulent Variations of v,T,P,ρ

$$\frac{\delta\rho}{\rho} \approx \frac{\mathrm{v}^2}{2}\frac{\mu m_p}{\gamma}\frac{1}{kT}$$

V~450 km/s => 5% density fluctuations
V~650 km/s => 10% density fluctuations

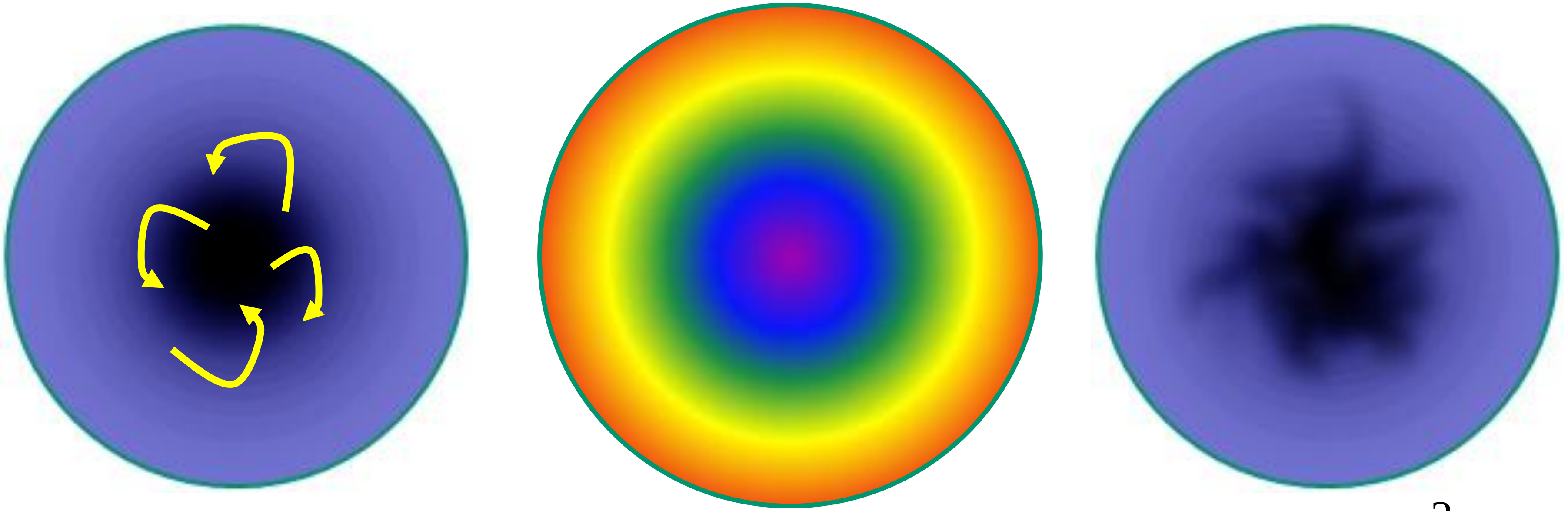
Sound waves due to turbulence?

$$\frac{\delta\rho}{\rho} \approx \frac{u_s}{c_s} \quad \Rightarrow \quad u_s \approx 72\,\mathrm{km/s} \Rightarrow \frac{\delta\rho}{\rho} \approx 5\%$$

$$\varepsilon \approx \frac{\mathrm{v}^8}{c_s^5 l} \quad \Rightarrow \quad u_s \approx \sqrt{\varepsilon t_s} = \mathrm{v}\left(\frac{\mathrm{v}}{c_s}\right)^3 \sqrt{\frac{R}{l}} \approx 30\,\mathrm{km/s}$$

Too weak?

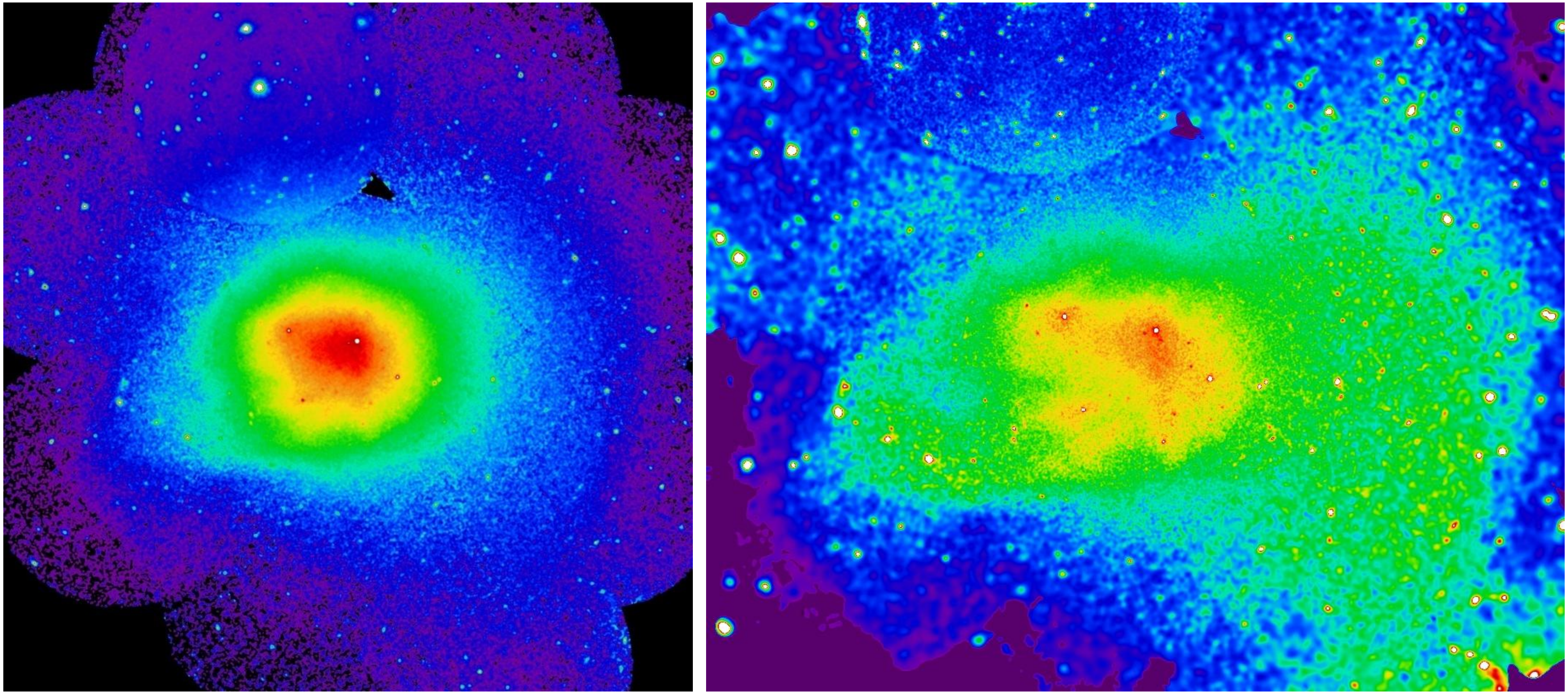
Entropy variations due to gas motions



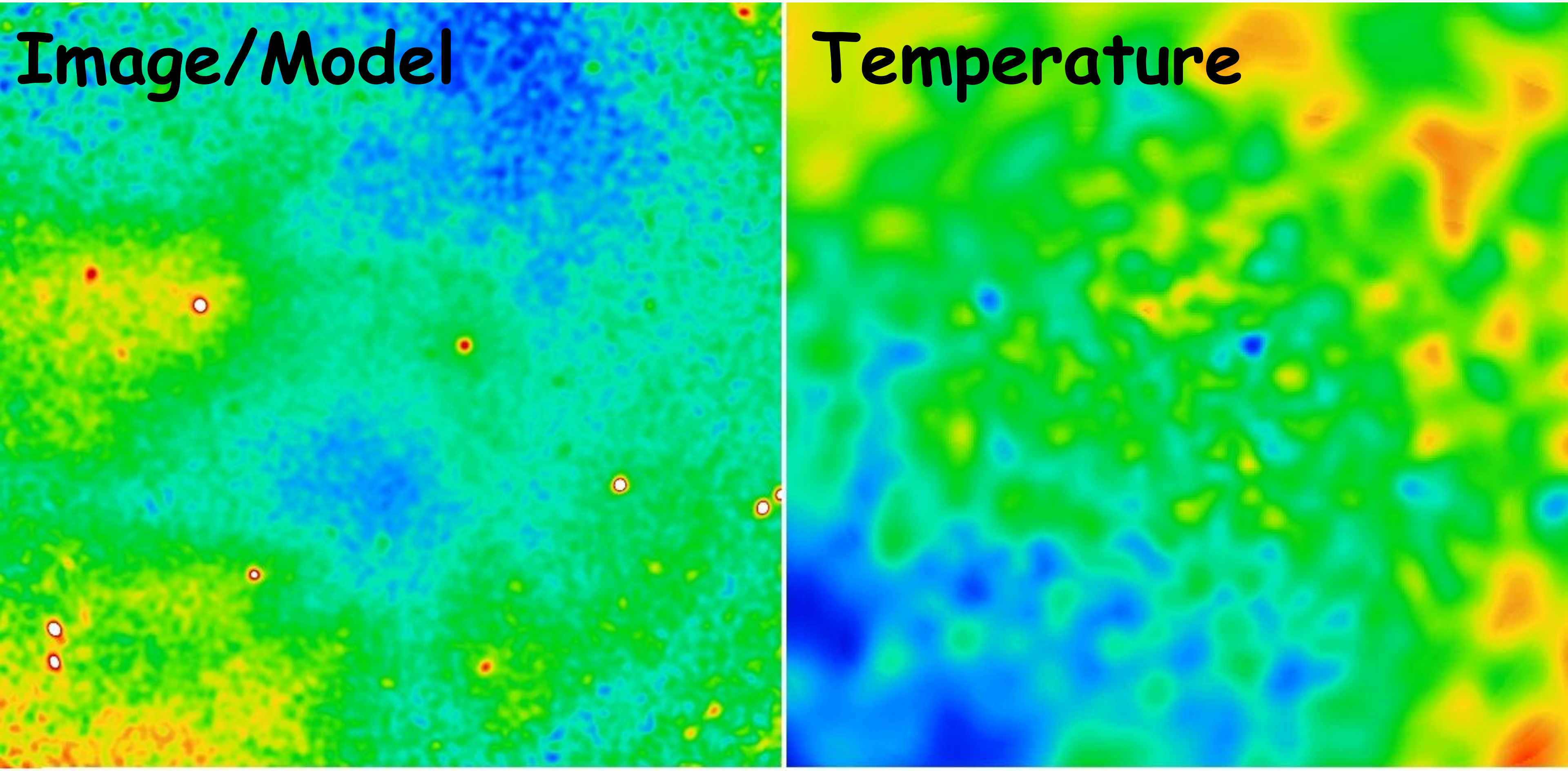
$$P \propto \rho^{5/3}; \quad \frac{\delta\rho}{\rho} \approx \frac{3}{5}\frac{\delta P}{P} \approx -\frac{3}{5} 3\beta \left(\frac{\delta r}{r}\right) \frac{\left(r/r_c\right)^2}{1+\left(r/r_c\right)^2}$$

$$\frac{\delta r}{r} \sim 10\% \quad \Rightarrow \quad \frac{\delta\rho}{\rho} \sim 5\%$$

Coma
X-ray image and residuals from symmetric model



Entropy variations due to mergers



$$\frac{\delta\rho}{\rho} \approx \frac{\delta T}{T} \sim 5\%$$

Conclusions - I

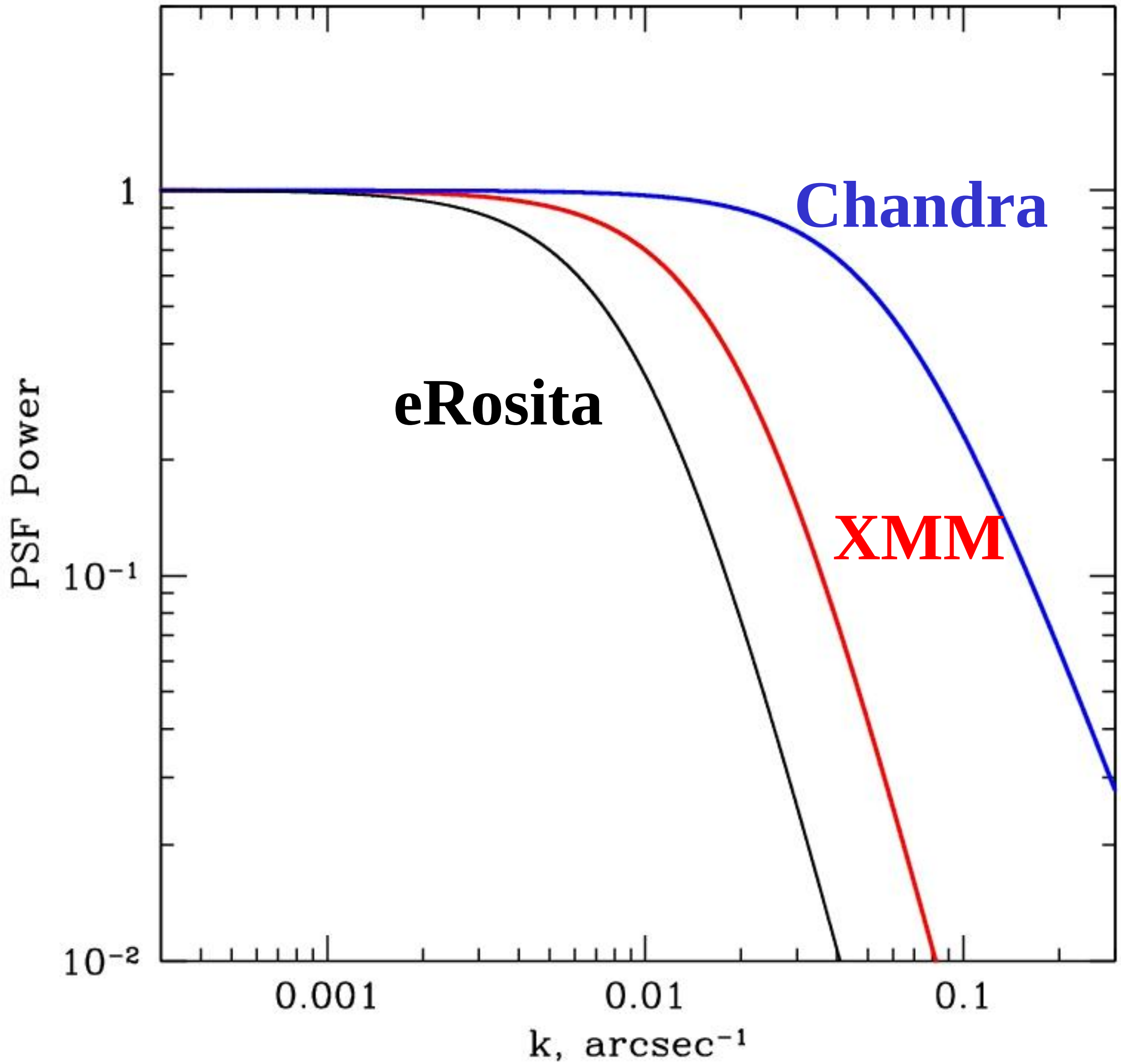
3D density variations - few % – 10 % on scales 30-1000 kpc

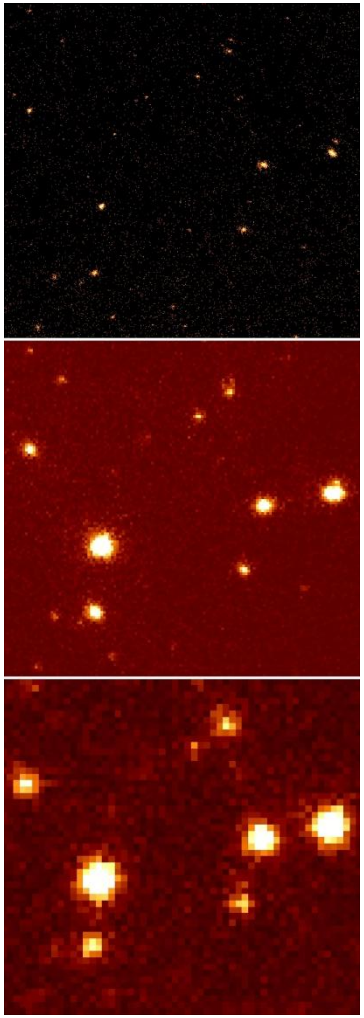
Perturbations of the potential and low temperature infalling gas – plausible contributors

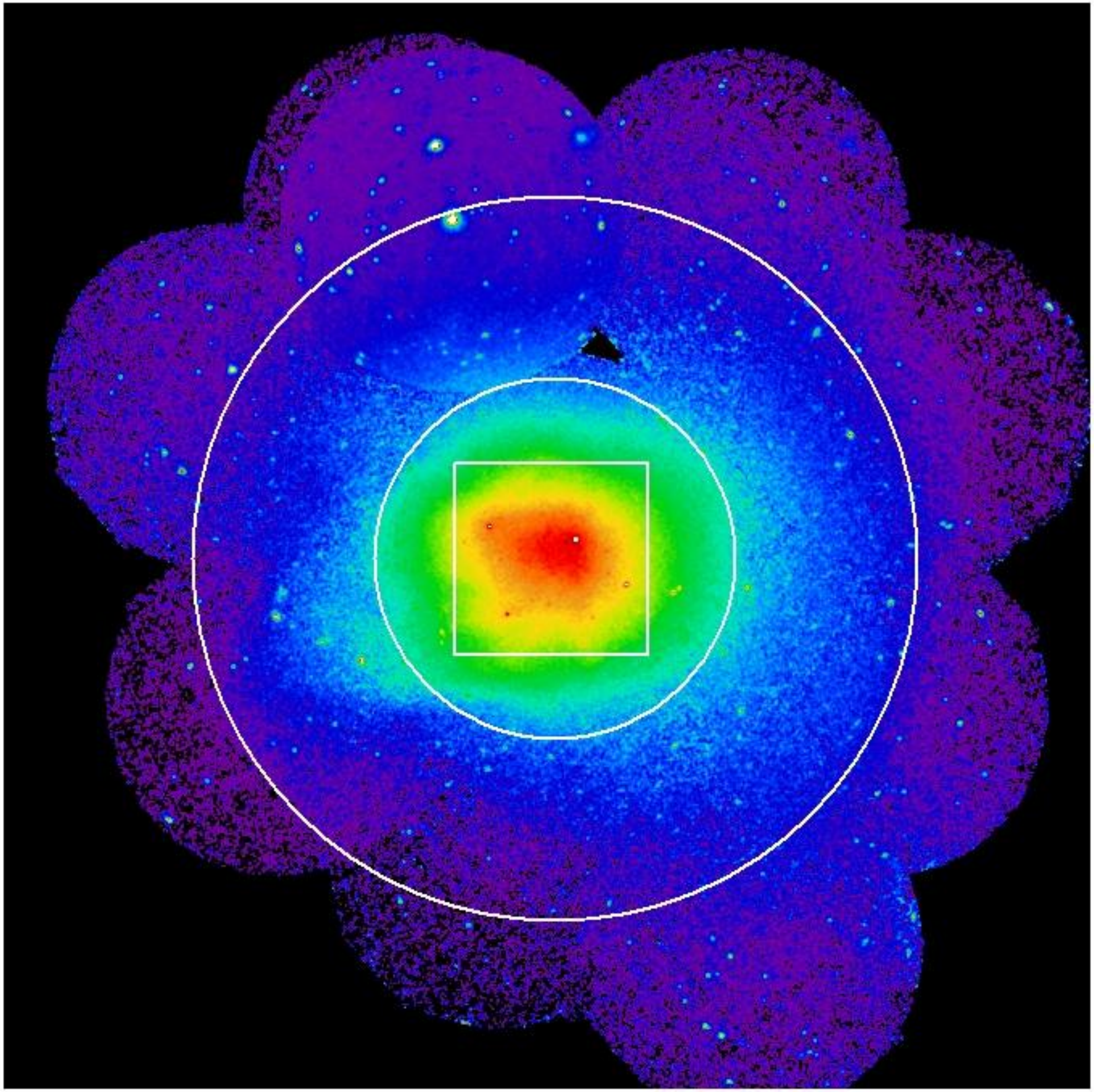
Mean free path scales are not resolved, but it is possible with Chandra

What about eRosita?

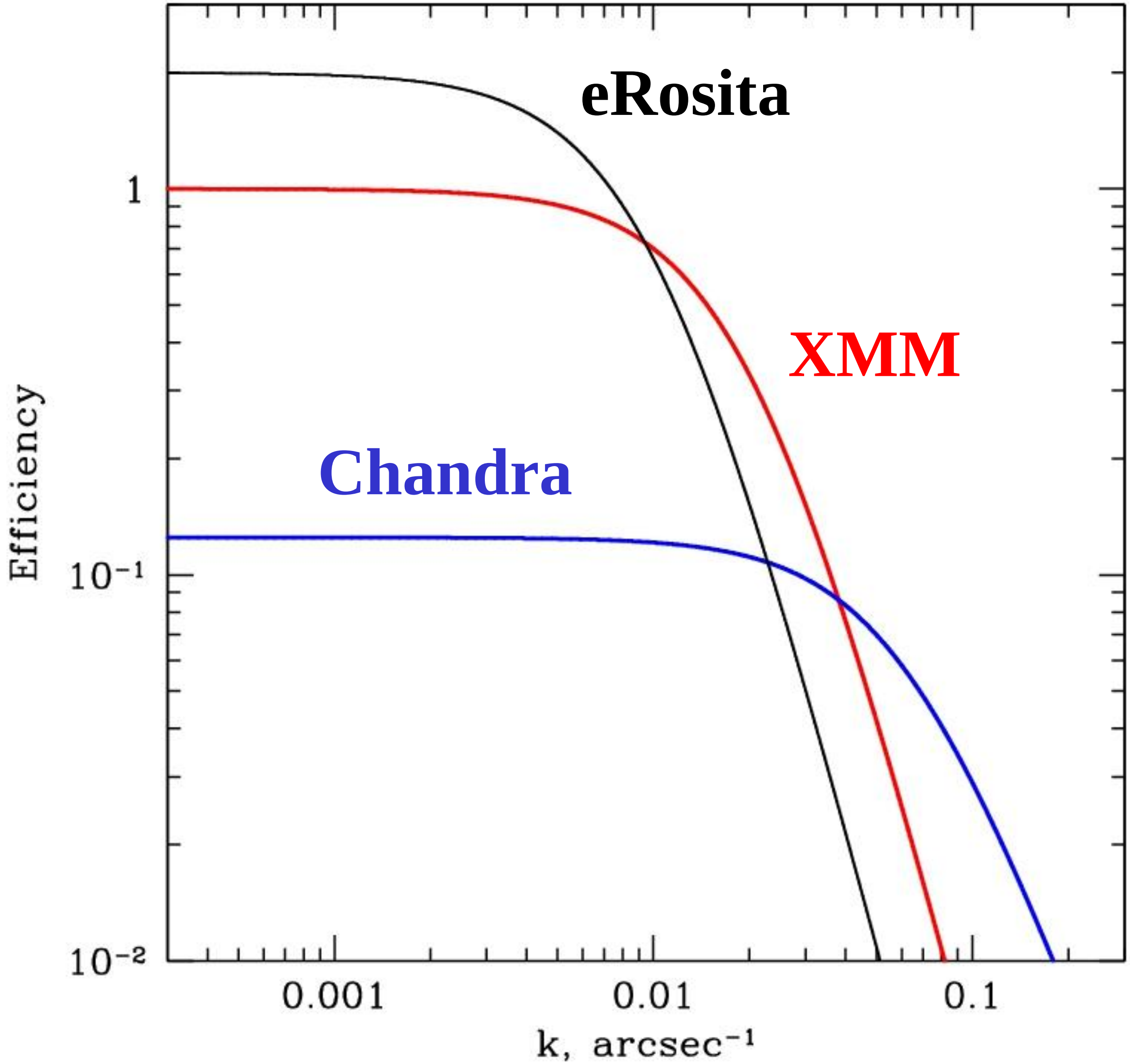
PSF Power Spectra







Efficiency for Power Spectra



Conclusions - II

eRosita is the best on scales larger than 100''
(outskirts of clusters)

X-Rays + SZ – measure of unresolved fluctuations