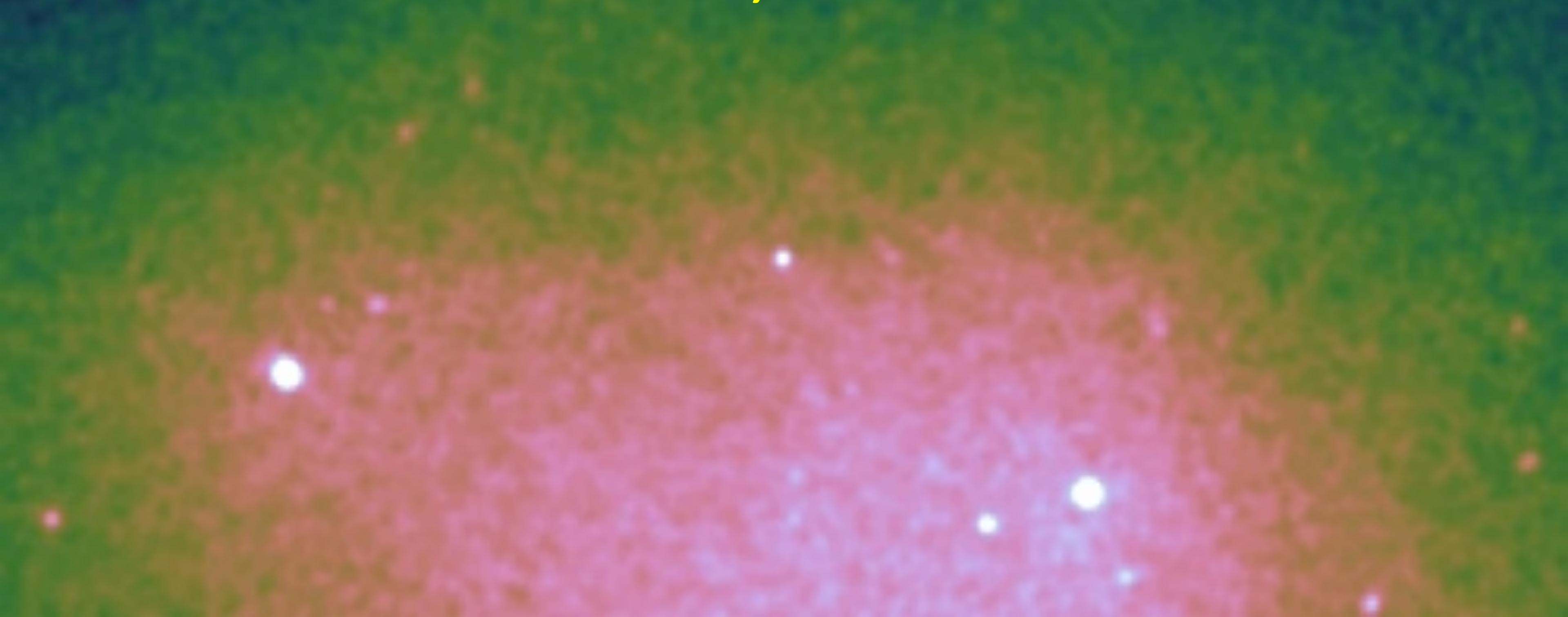
Diffuse hot gas in galaxy clusters at high spatial and spectral resolution

E.Churazov (MPA, IKI)

P.Arevalo, W. Forman, C. Jones, A.Schekochihin, A.Vikhlinin, I.Zhuravleva



Diffuse Hot Gas in Galaxy Clusters at High Spatial and Spectral Resolution

1. Measure velocity power spectrum
2. Go to scales smaller than mean-free-path
3. Measure total mass of cold gas in cluster cores

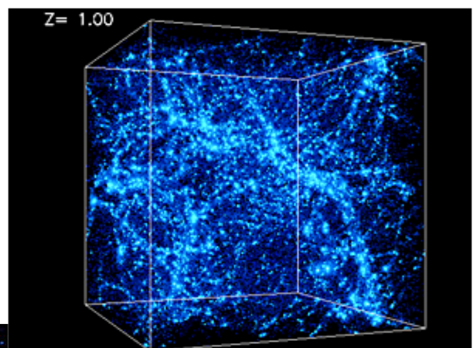
Measurements	Implications for …
Velocity Power Spectrum	Mass correction, gas heating
Velocity & X-ray SB Power Spectra	Conduction, V – δρ relation
X-ray SB Power Cross-Spectra in 2 bands	Nature of perturbations (e.g., sound waves vs solenoidal turbulence vs bubbles)
Anisotropy of velocity power spectra	Nature of perturbations
+ (high-res) SZ maps and power spectra	Nature of perturbations
Power spectrum of metalicity variations	Turbulence, diffusivity of (heavy) ions
Scales smaller than mean free path	Plasma physics
+ Faraday Rotation Measure Spectra ($B*n_e$)	Plasma physics
Mass of the cold gas	Gas cooling, AGN Feedback

Fourier Projection-Slice Theorem

In N dimensions, the projection-slice theorem states that the Fourier transform of the projection of an N-dimensional function f(r) onto an m-dimensional linear submanifold is equal to an m-dimensional slice of the N-dimensional Fourier transform of that function consisting of an m-dimensional linear submanifold through the origin in the Fourier space which is parallel to the projection submanifold.

$$I(x,y)=\int F(x,y,z)\,dz$$

$$\hat{I}(k_x,k_y)=\int\int e^{i2\pi k_x x+i2\pi k_y y}\,dx\,dy\int F(x,y,z)\,dz=\hat{F}(k_x,k_y,k_z=0)$$



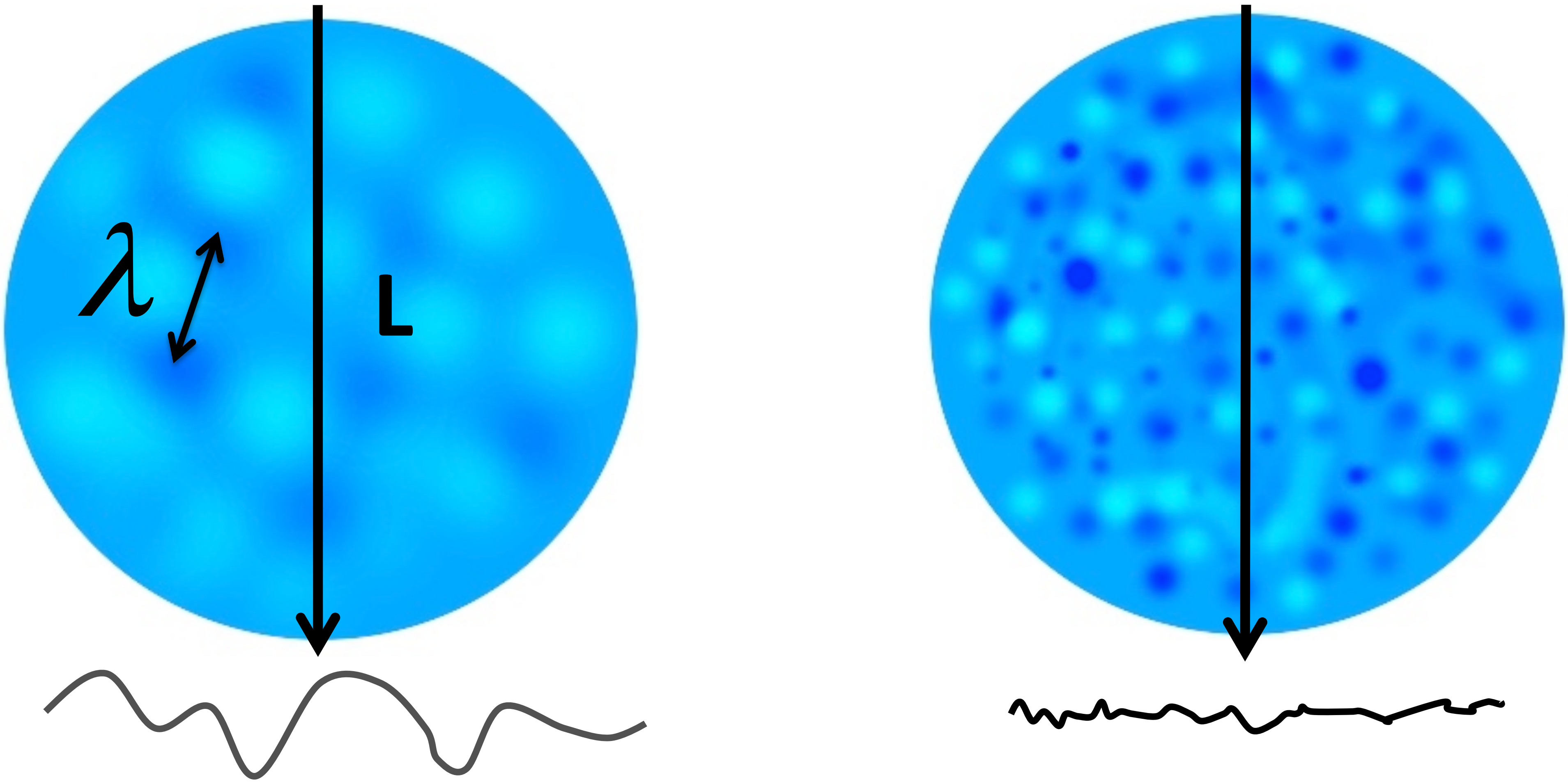
$I(x,y)$

$F(x,y,z)$

$$\hat{I}(k_x,k_y)=\hat{F}(k_x,k_y,0)$$

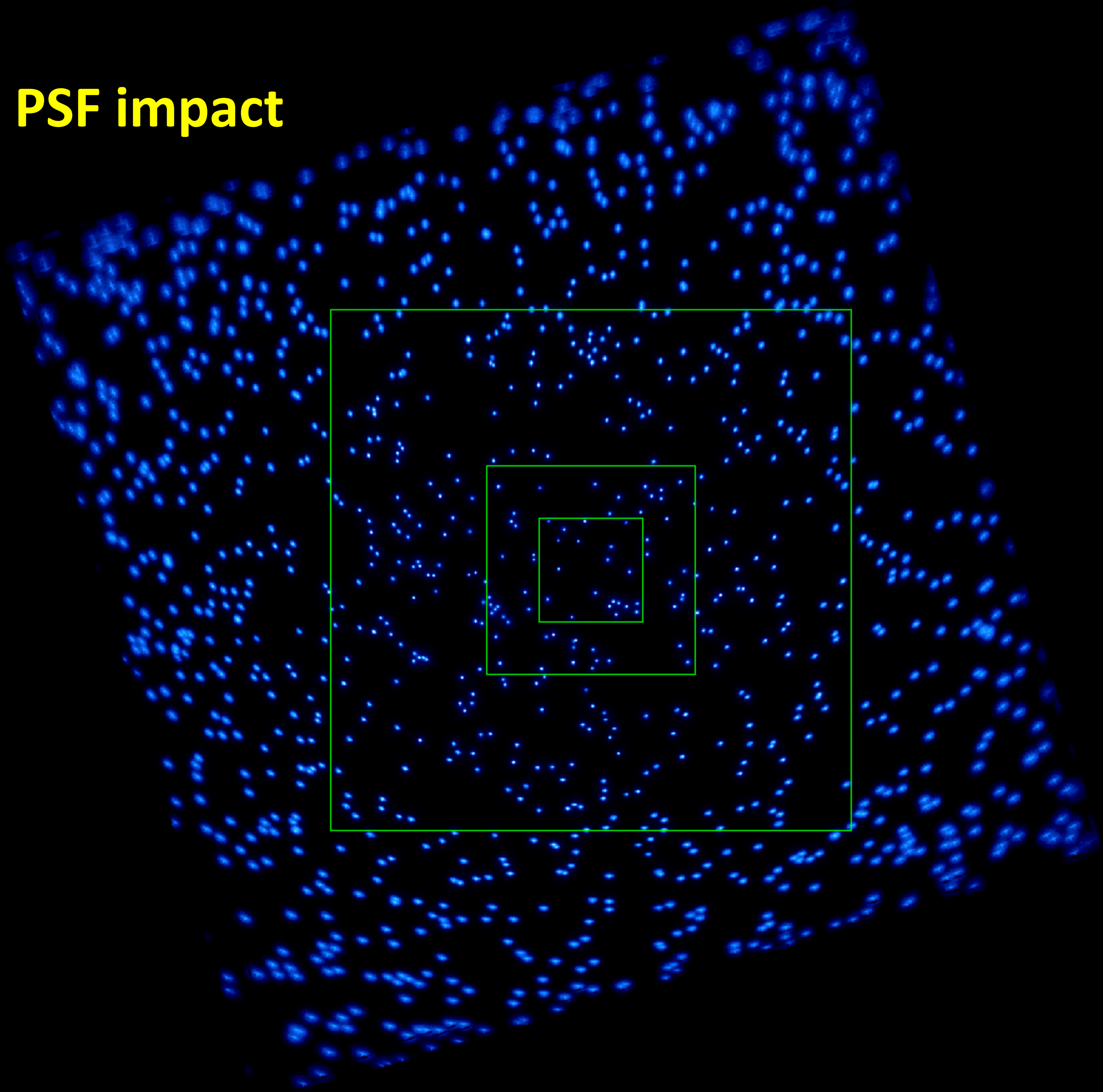
$$P_{2D}(k)=C\times P_{3D}(k)$$

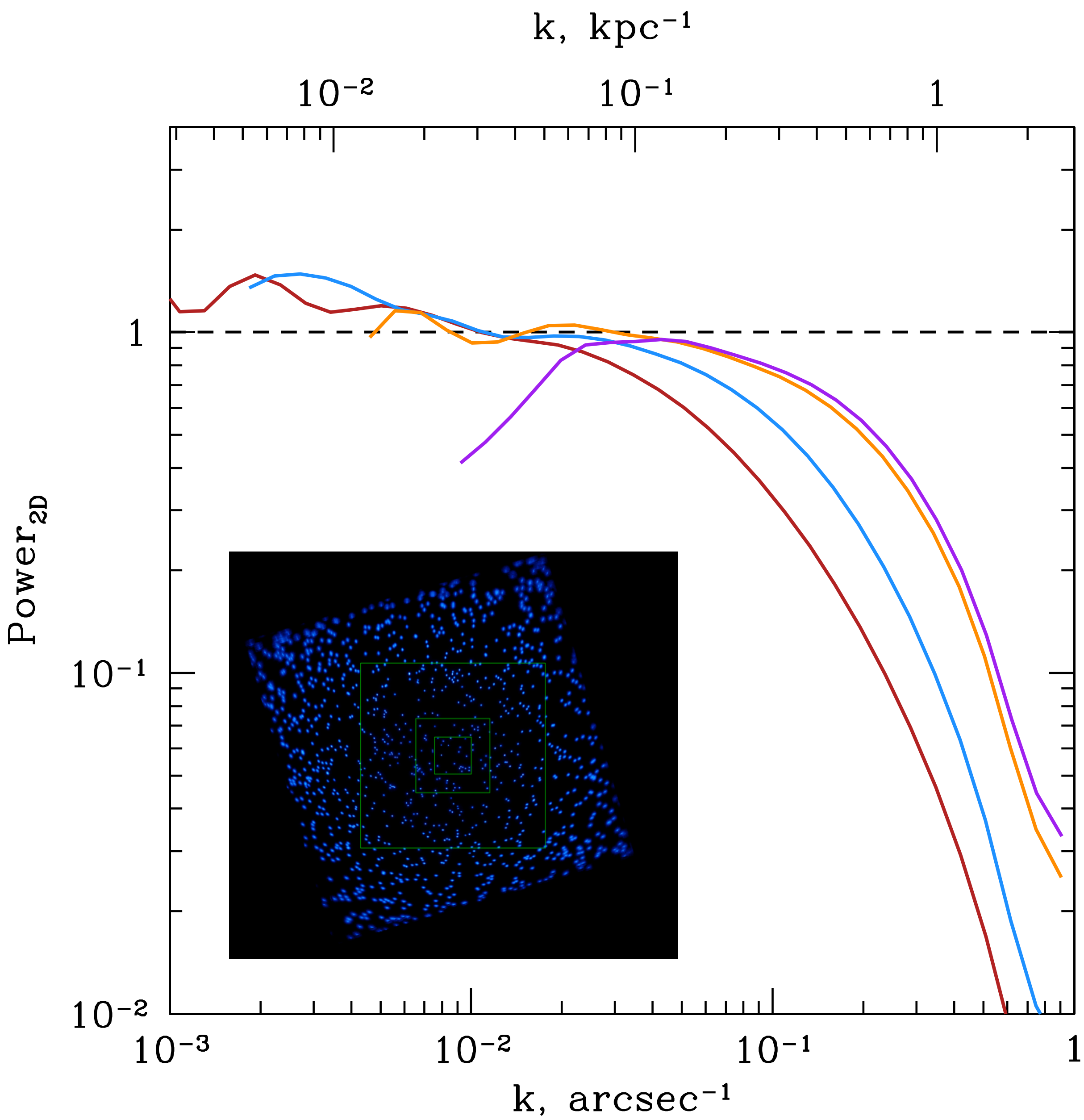
Reconstructing 3D power spectrum from 2D spectrum



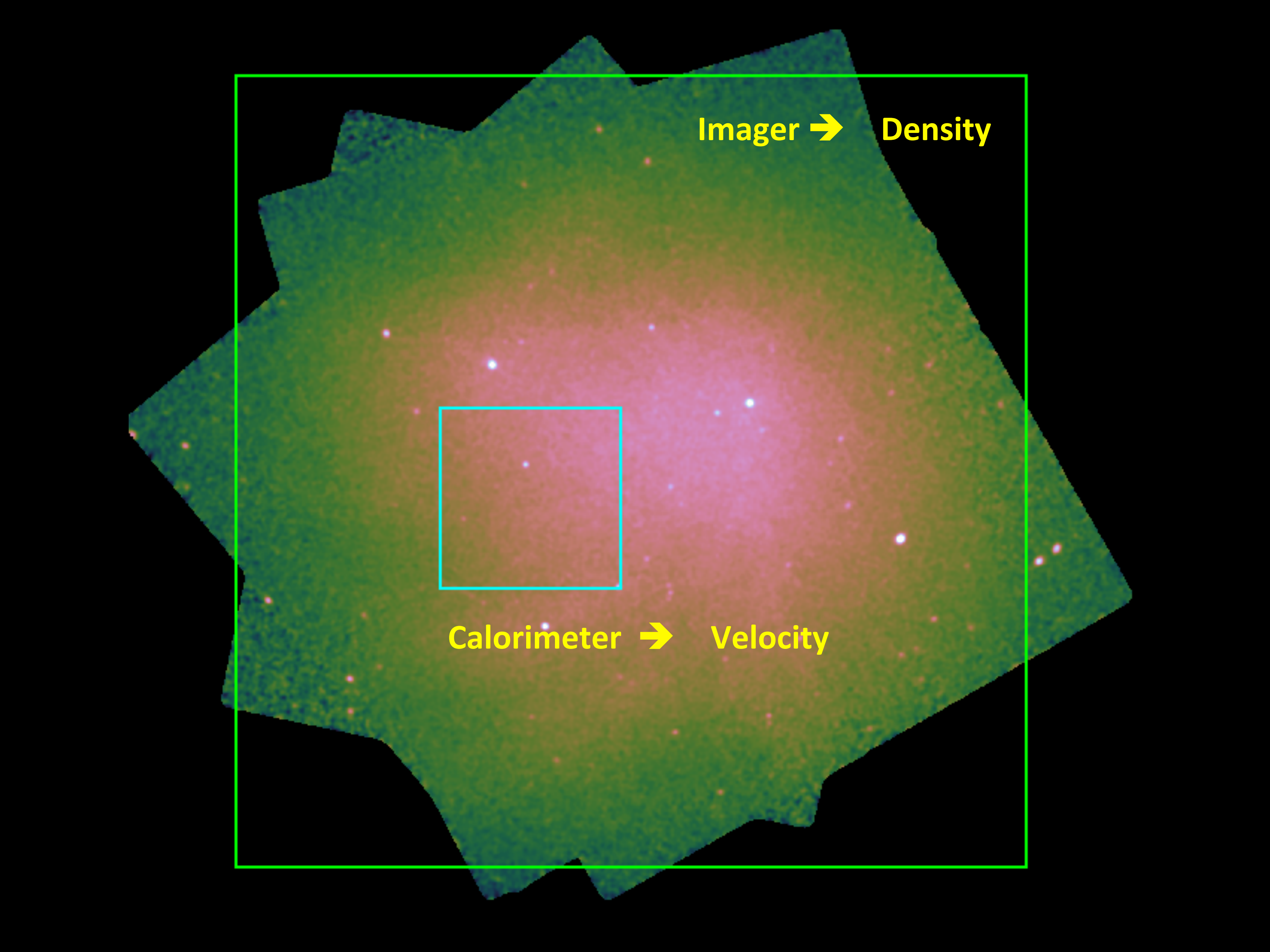
$$A_{2D} \propto A_{3D} \times \sqrt{\frac{1}{N}} = A_{3D} \times \sqrt{\frac{\lambda}{L}} \quad \Rightarrow \quad P_{3D} = \frac{1}{C} \times P_{2D}$$

PSF impact

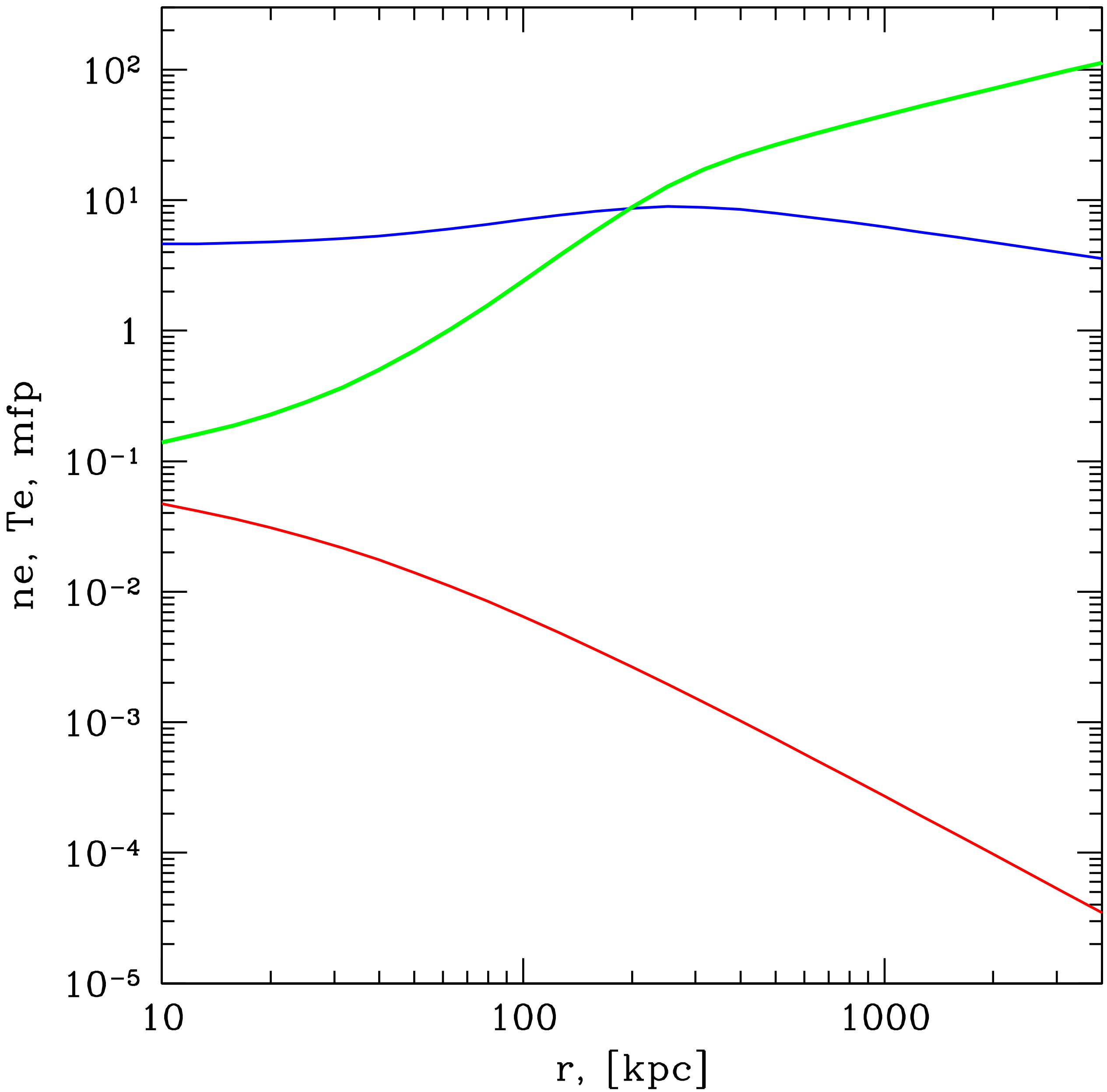


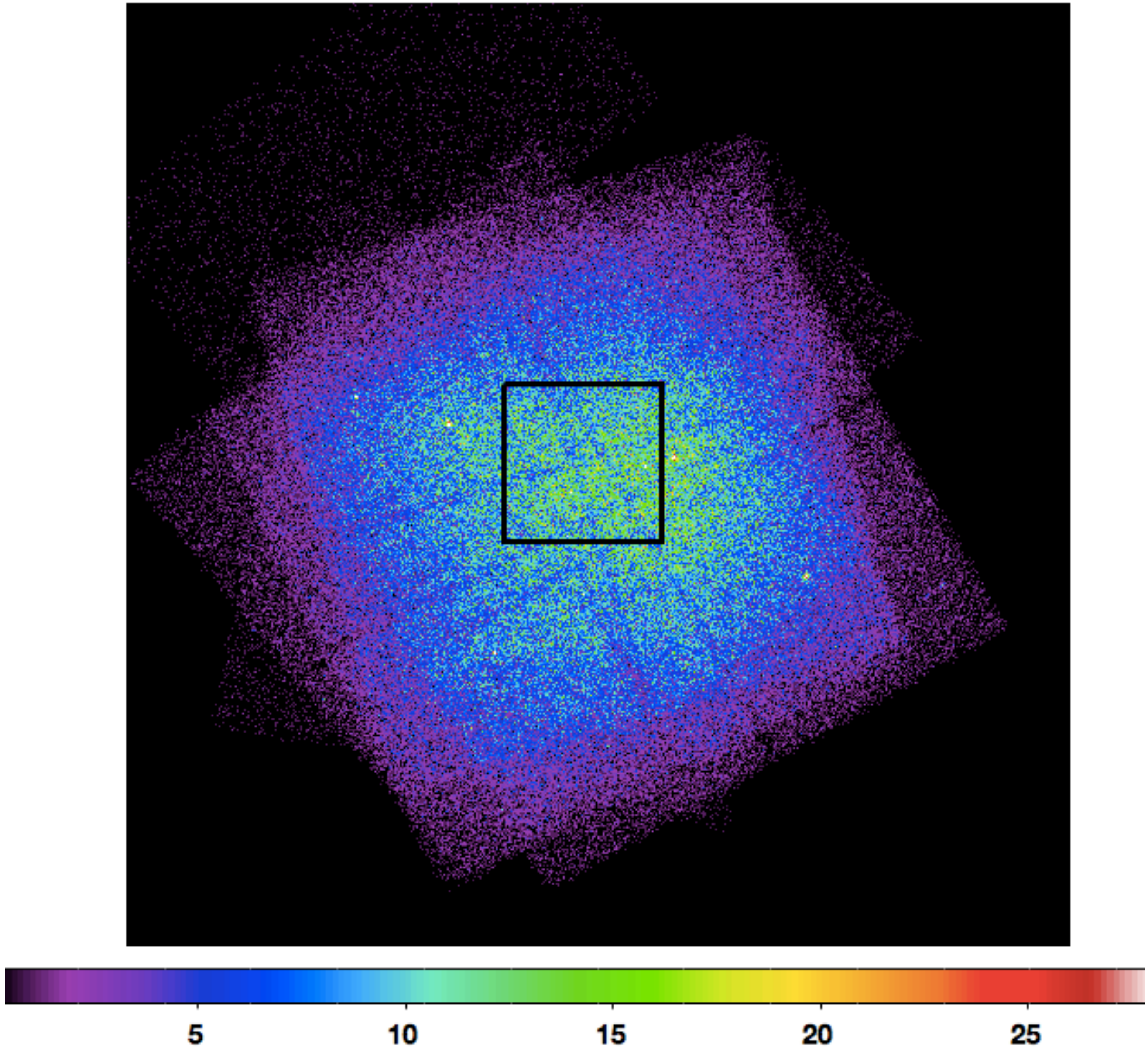


k, kpc⁻¹
10^{-2}
10^{-1}
1
Power$_{2D}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
k, arcsec⁻¹


Imager → Density
Calorimeter → Velocity

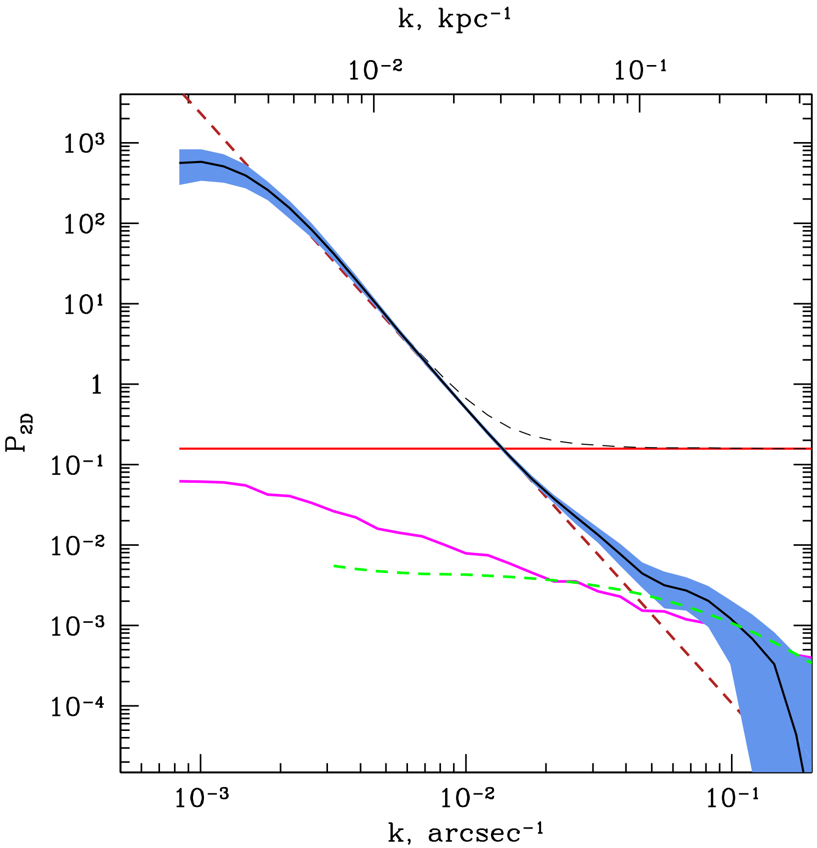
Coma cluster; mean free path

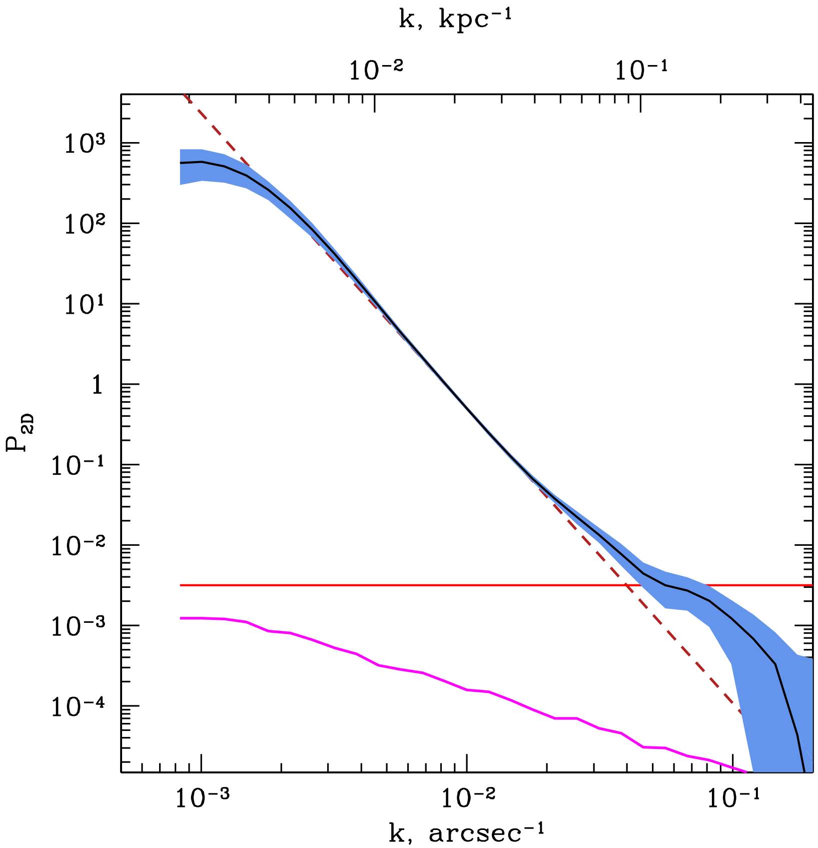




5
10
15
20
25

Scaling from Chandra to X-ray Surveyor (density power spectrum)



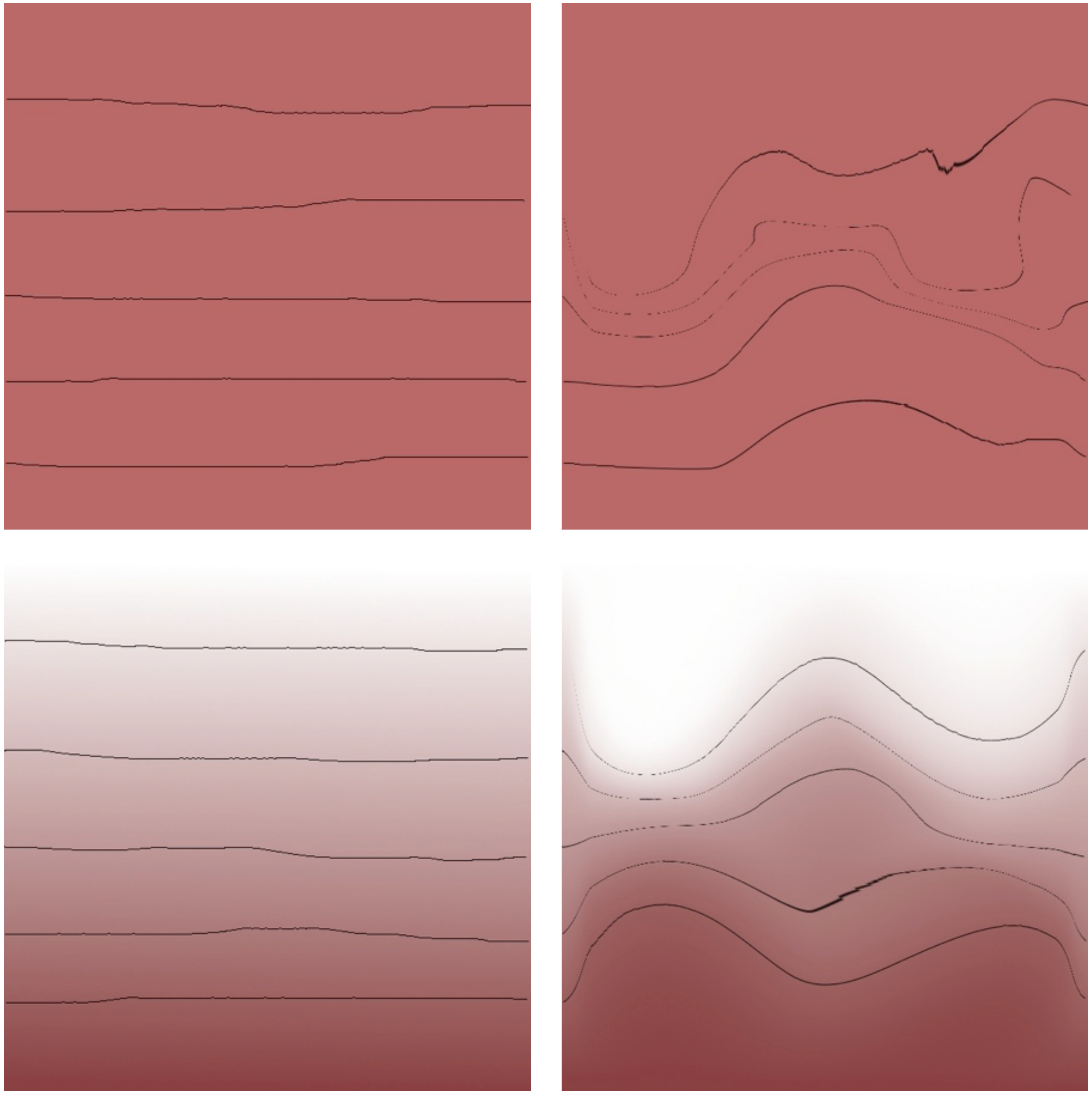


1) Unresolved background AGN
2) PSF over FoV
3) Poission noise -> 1/50

Relation between density and velocity power spectra

Entropy (and metalicity) gradients make gas motions visible

Scaling of density perturbation with velocity



Uniform gas

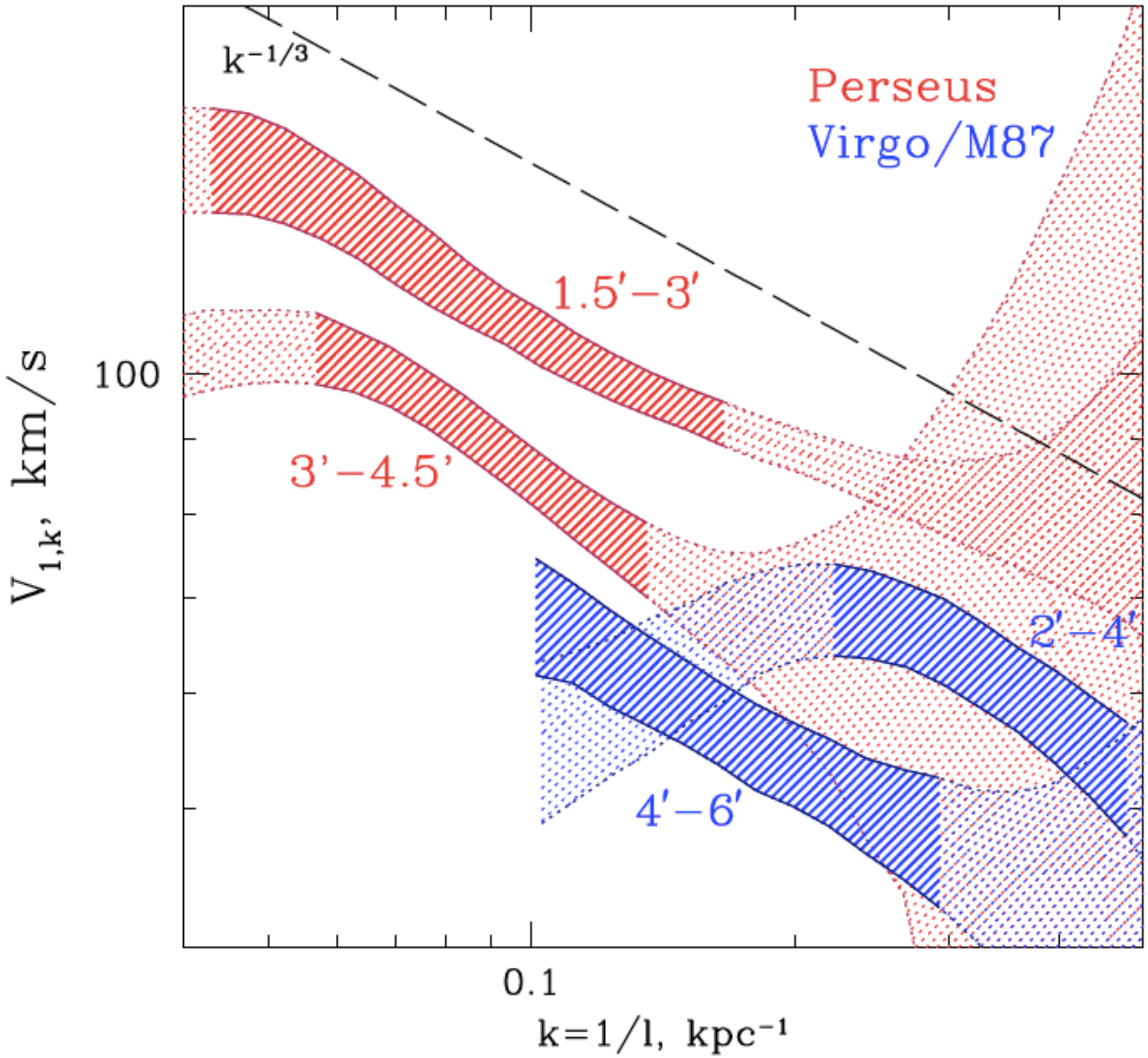
$$\delta\rho \propto M^2$$

Stratified ICM in clusters

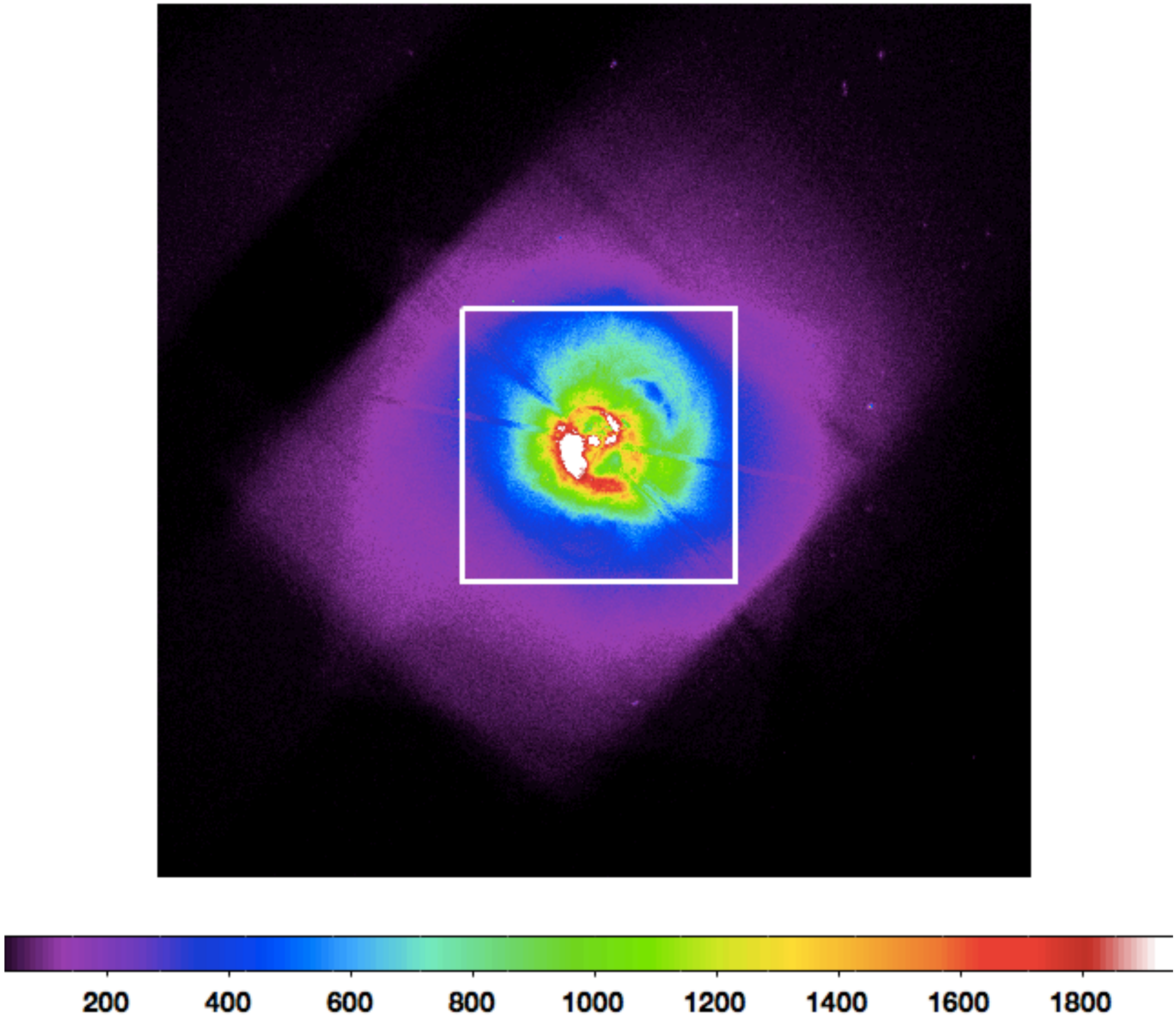
$$\delta\rho \propto M$$

$$\frac{\delta\rho}{\rho} \sim \frac{\mathrm{v}}{c_s}$$

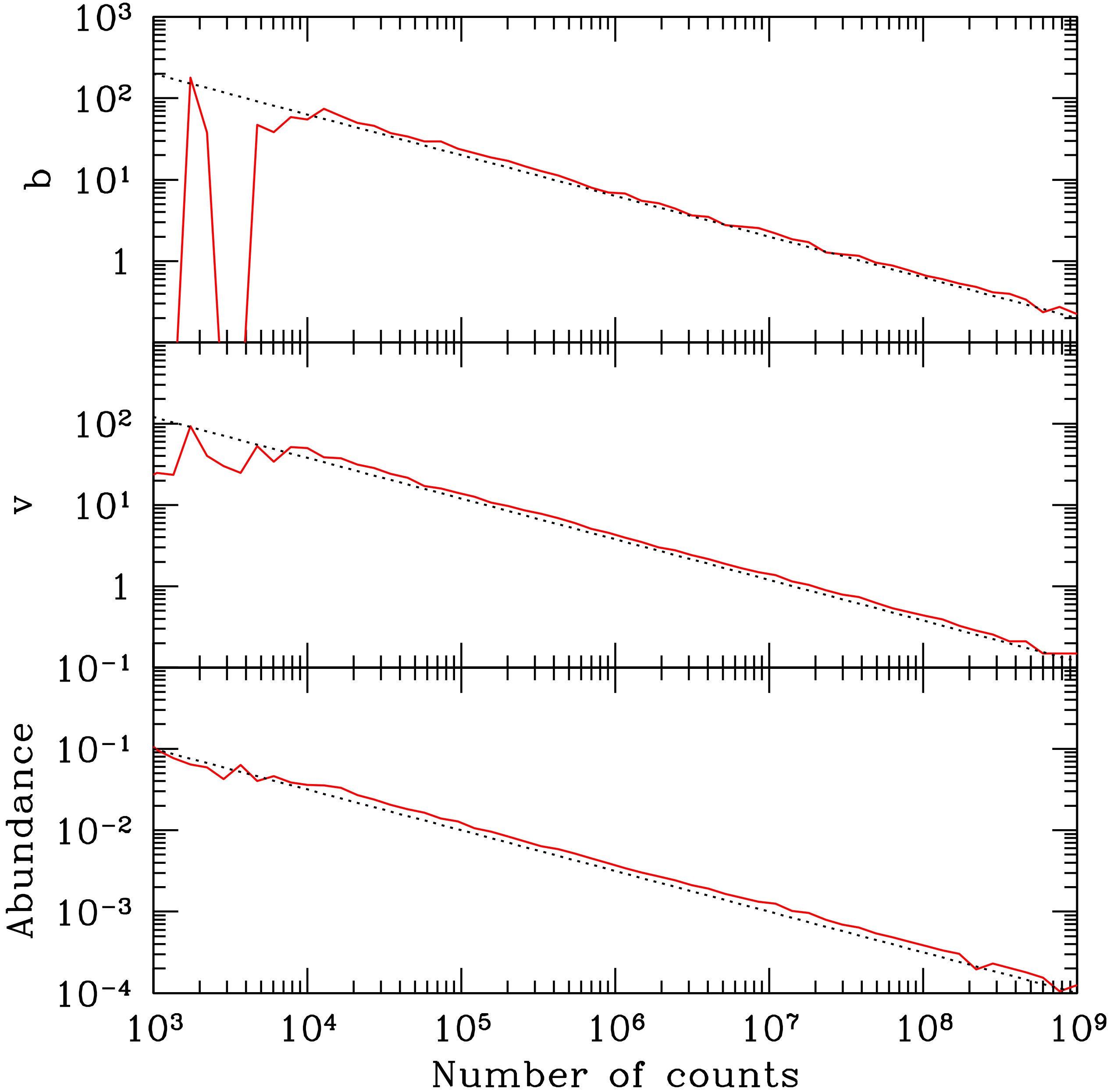
Velocity power spectra in Perseus and M87



Zhuravleva+, 2014


200
400
600
800
1000
1200
1400
1600
1800

(Formal) 1σ uncertainty on velocity and broadening

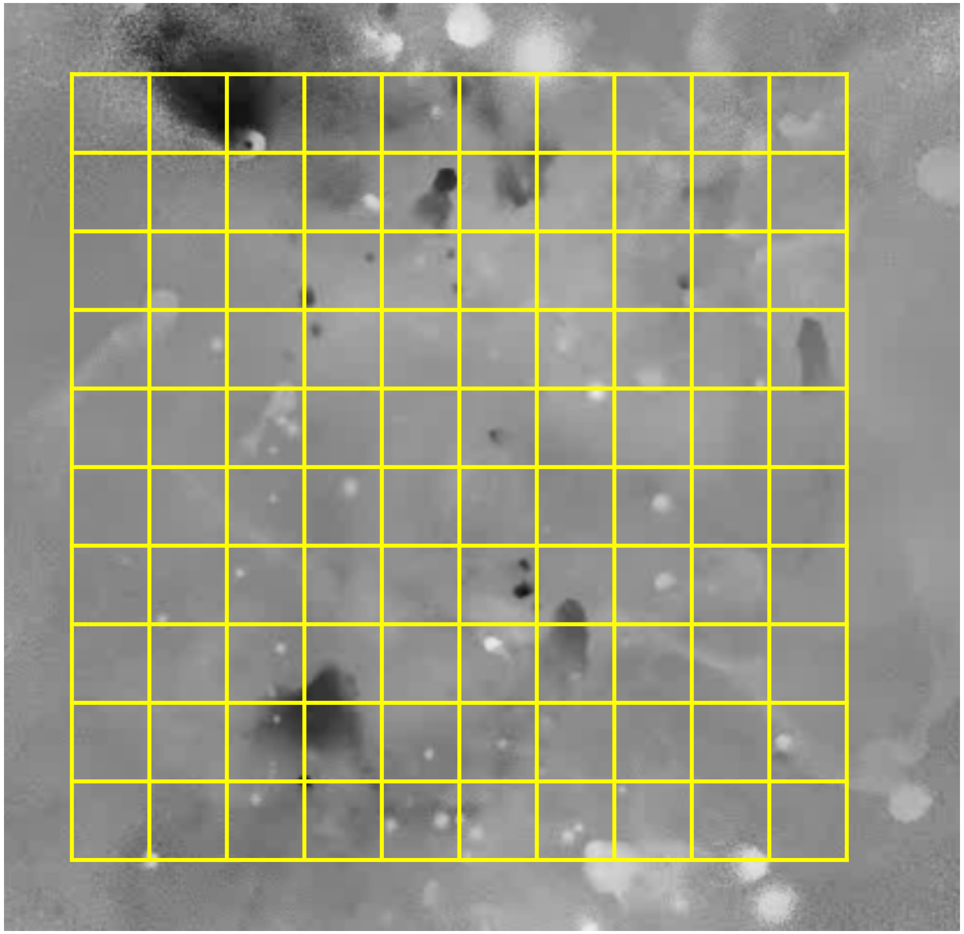


$$b = 200\sqrt{\frac{10^3}{N_{cts}}}\ \text{km/s}$$

$$\text{v} = 120\sqrt{\frac{10^3}{N_{cts}}}\ \text{km/s}$$

$$A = 0.1\sqrt{\frac{10^3}{N_{cts}}}$$

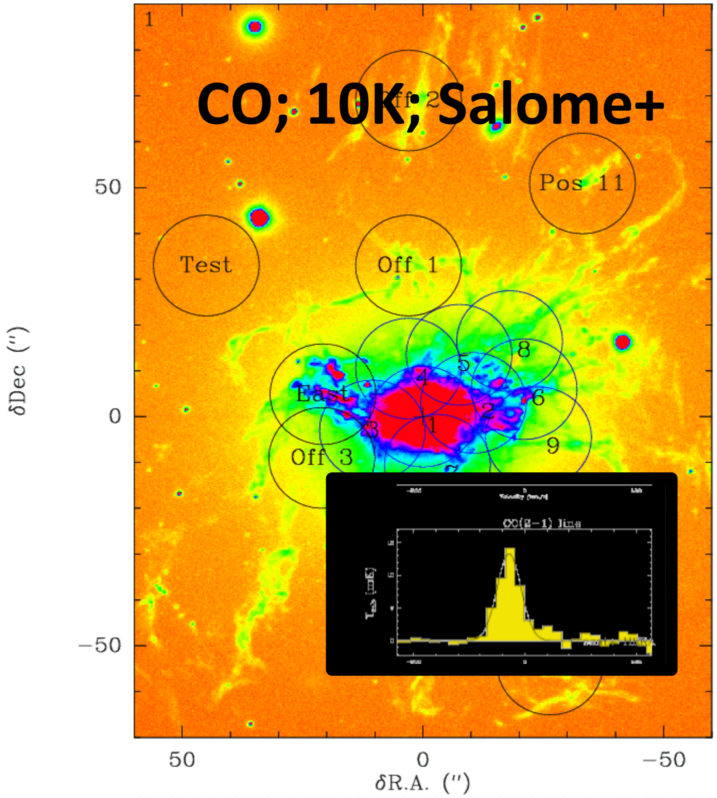
Uncertainty in measuring the velocity field

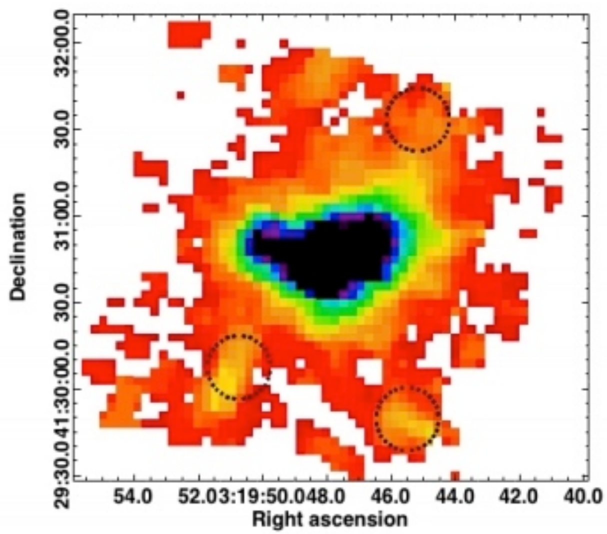


Error in one pixel
Total number of pixels

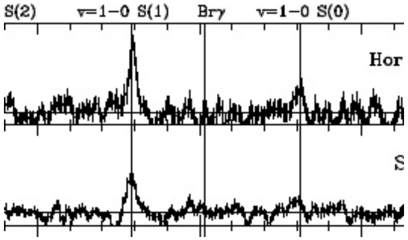
$$\sigma_I \approx \sqrt{\frac{1}{N_{counts}}}$$

$$\sigma_{v/cs} \approx 4\sqrt{\frac{1}{N_{counts}}}$$

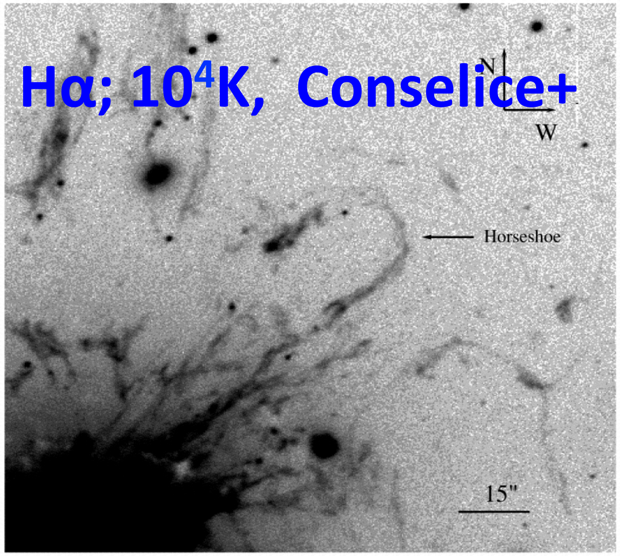




CII; 100K; Mittal+



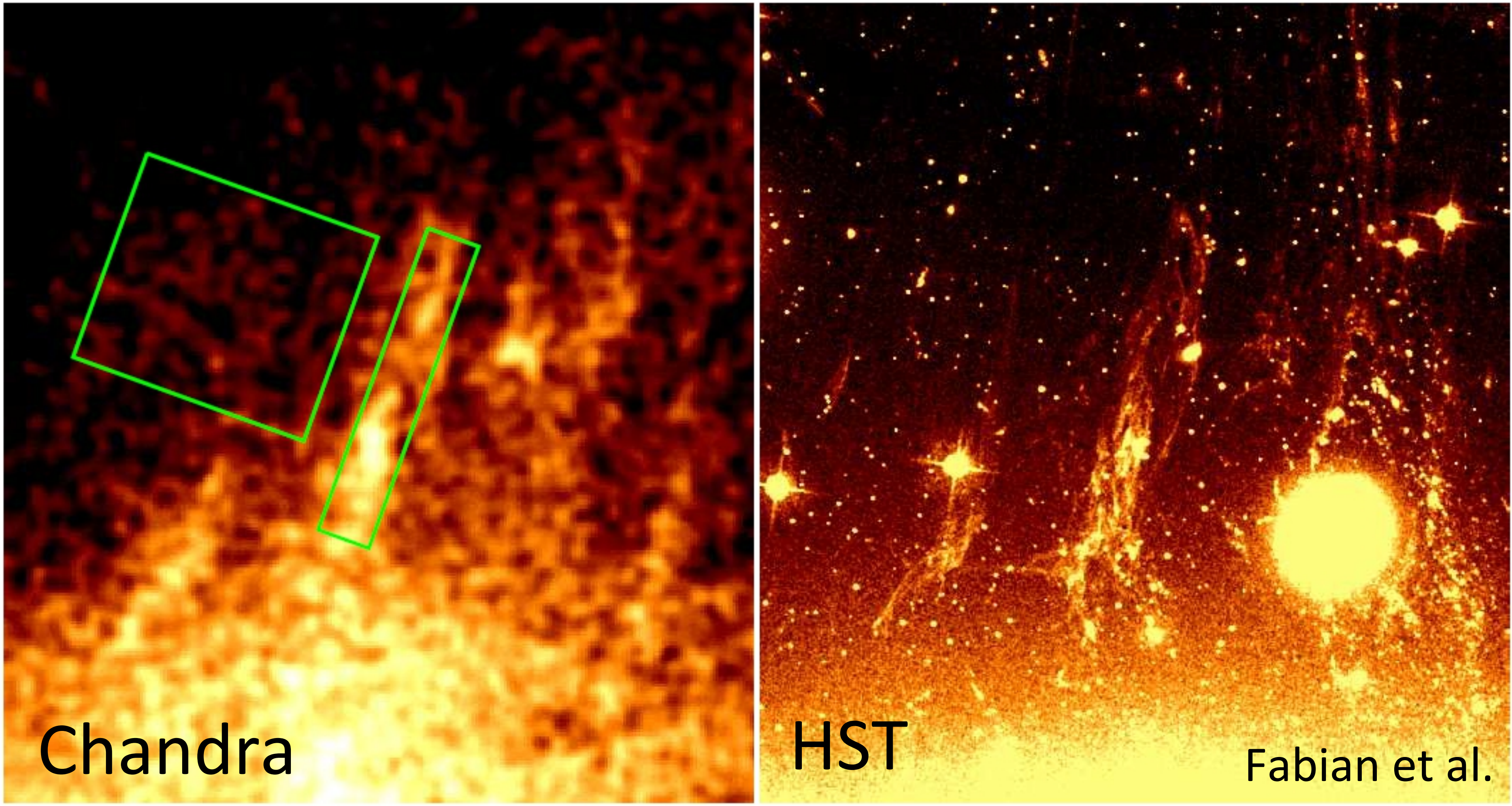
H_2; 2000 K; Hatch+



Lots of cold gas

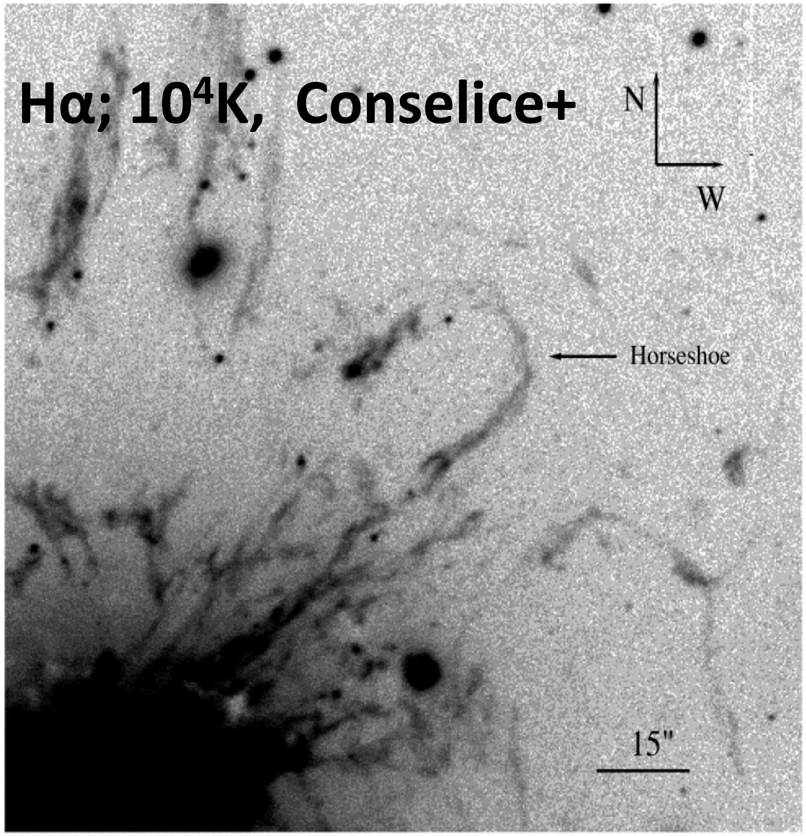
Conversion to mass is uncertain

Soft X-ray emission



Soft $L_X < L_{Opt}$

Can we use X-rays to measure total mass of cold gas?

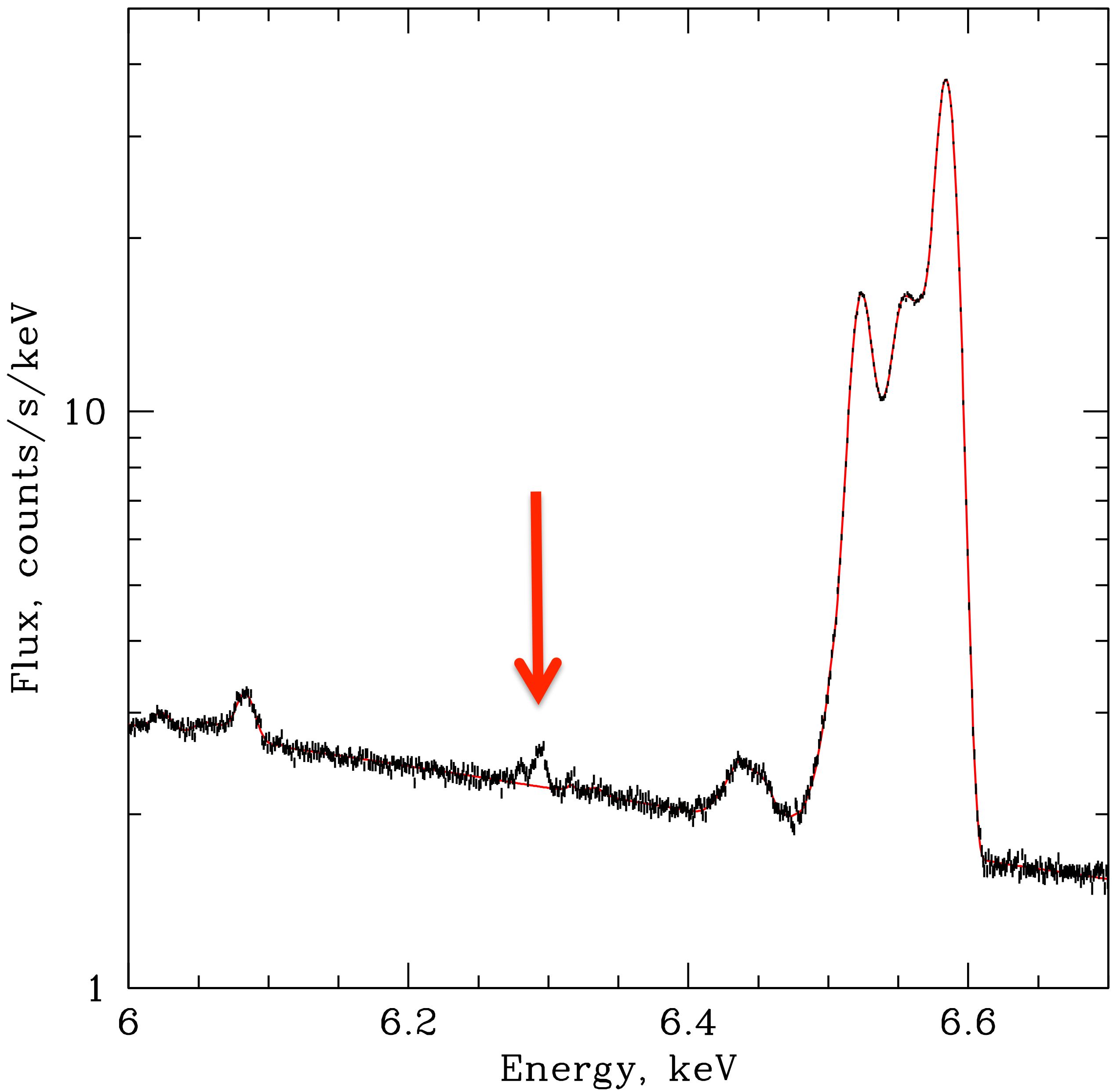


$$F_{6.4\,\mathrm{keV}} \propto M_{gas} Z_{Fe} Y_{6.4} \int_{7.1\ \mathrm{keV}} I_X(E)\sigma_{ph}(E)\,dE$$

Iron fluorescent emission from cold gas exposed to known radiation field => Gas mass

EC et al., 1998

Expected spectrum integrated over central region (Perseus cluster)



Conclusions

Power spectra of density fluctuations can be measured down to few ”
Velocity spectrum can be measured down to scales ~3 times larger

Marginally resolved mean free path (in velocities).
Signs of the spectrum steepening should be present at scales larger than m.f.p.

Depends on the calibration of gain (of pixels) and uniformity of QE

The mass of the cold gas (at any T, even if it not visible) can be measured
via fluorescent iron line at 6.4 keV