Suppressed Effective Viscosity in the Bulk Intergalactic Plasma

Irina Zhuravleva (UChicago)
E. Churazov (MPA), A. Schekochihin (Oxford)
S. Allen (Stanford), A. Vikhlinin (CfA/Harvard), N. Werner (MTA-Eötvös)

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Image: NASA/CXC/SDSS/I. Zhuravleva

UCSB KITP / Connecting Micro and Macro Scales in Astrophysical Plasmas / Sep 09, 2019

Intergalactic / Intracluster Medium

T ~ 7 keV $n_e \sim 10^{-3}\ \mathrm{cm}^{-3}$

Coulomb mean free path:

$$\lambda_{\mathrm{mfp}} = 15\,\mathrm{kpc}\left(\frac{T}{7\,\mathrm{keV}}\right)^2\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)$$

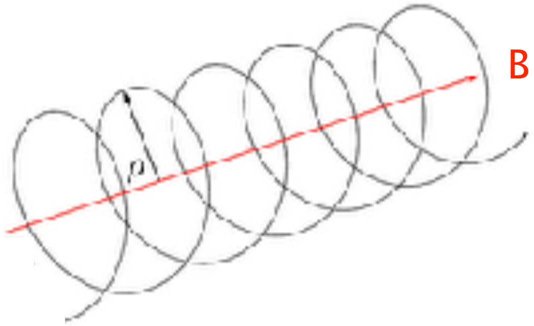
$$\sim 1 - 100\,\mathrm{kpc}$$

B ~ 1 μG $\beta \sim P/P_B \sim 100$

Gyroradius of particle:

$$r_g = \frac{mV_\perp}{|q|B} \sim 3 \cdot 10^{-14}\,\mathrm{kpc}\,(\sim 1000\,\mathrm{km})$$

$r_g \ll \lambda_{mfp}$



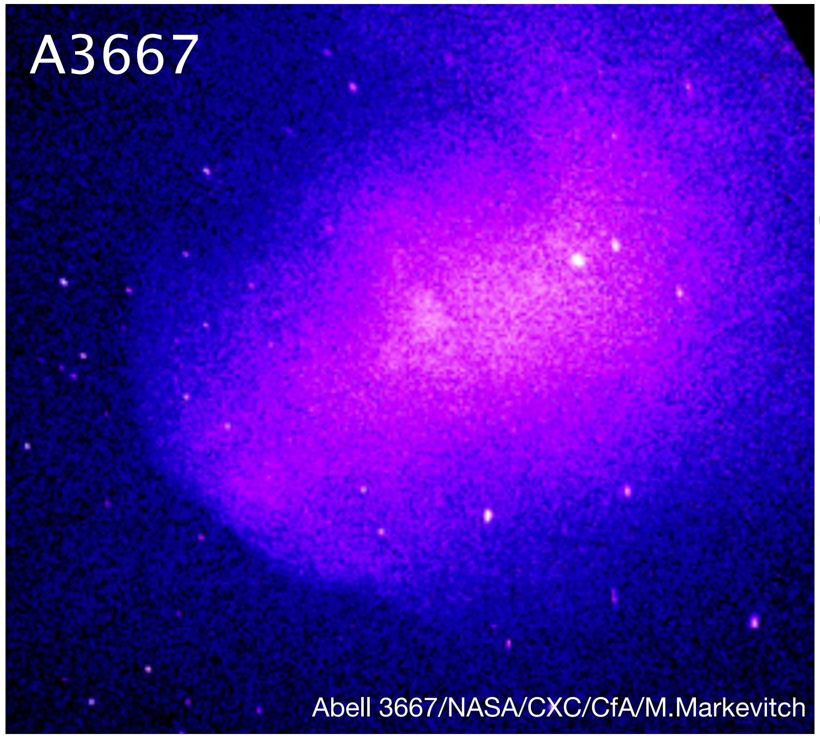
- *weakly-collisional plasma*
- *high-β plasma*

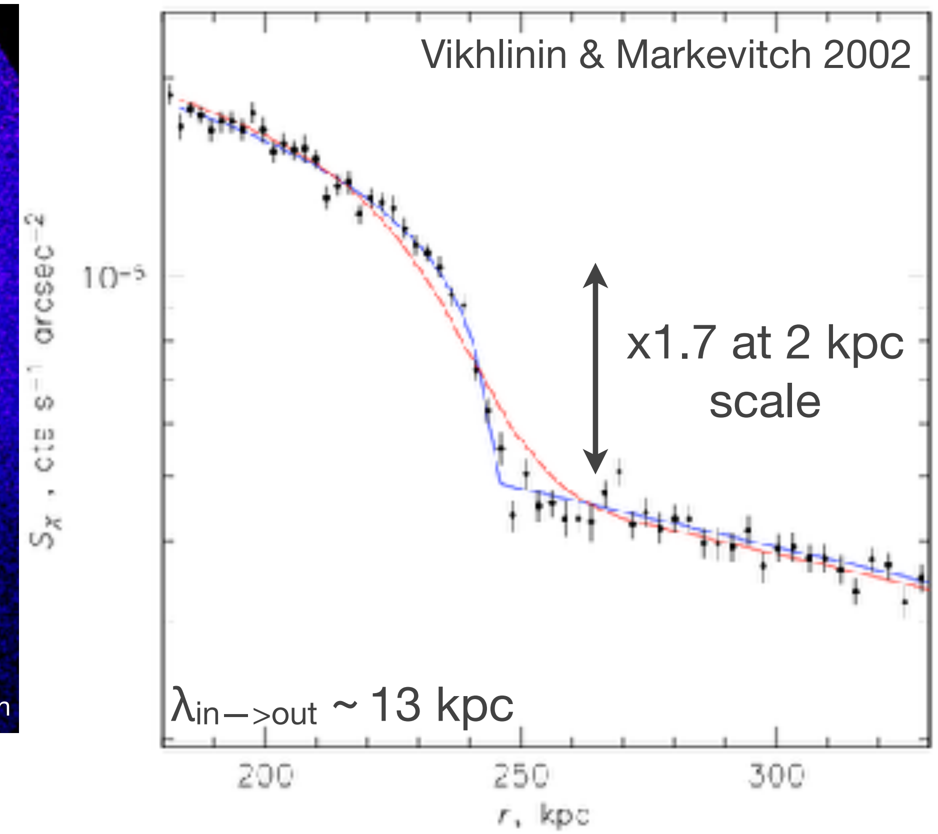
Do clusters follow the hydrodynamic description on micro scales?

Do magnetic fields and plasma instabilities change the properties of the ICM? How?

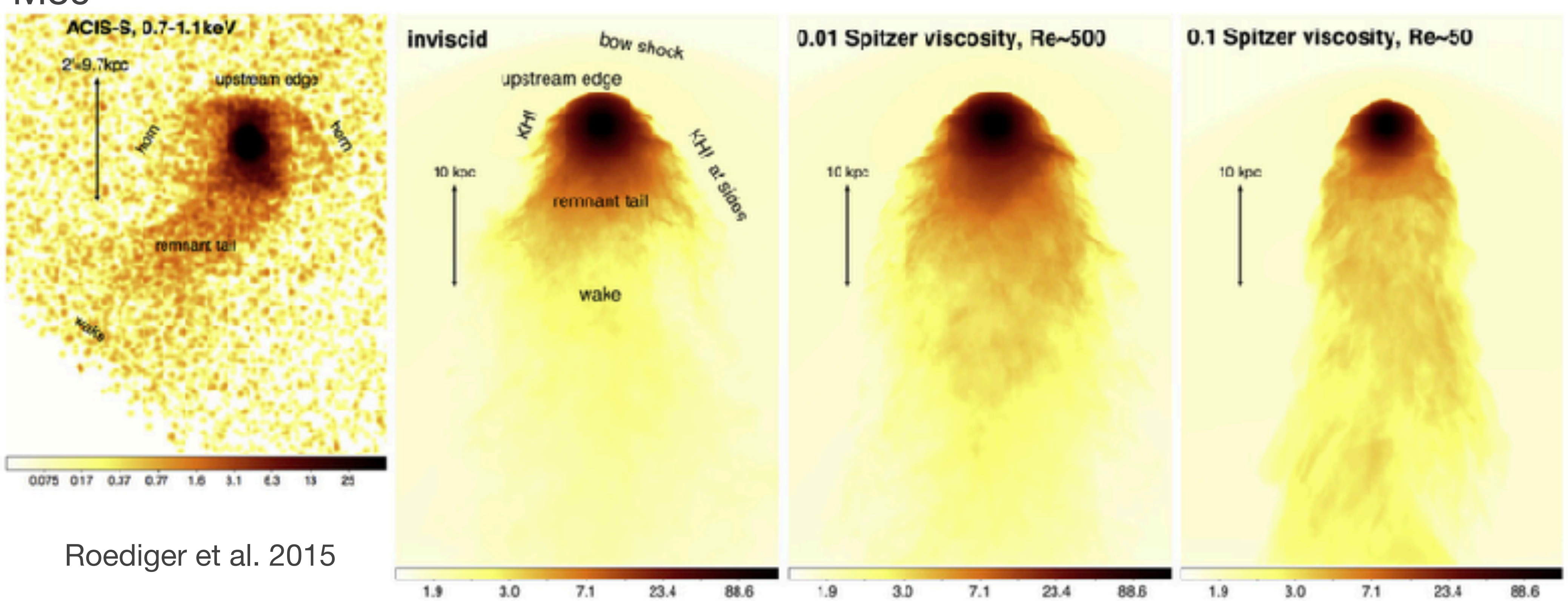
What are the transport properties of the hot intergalactic plasma?

Suppressed Transport Process in the ICM





M89



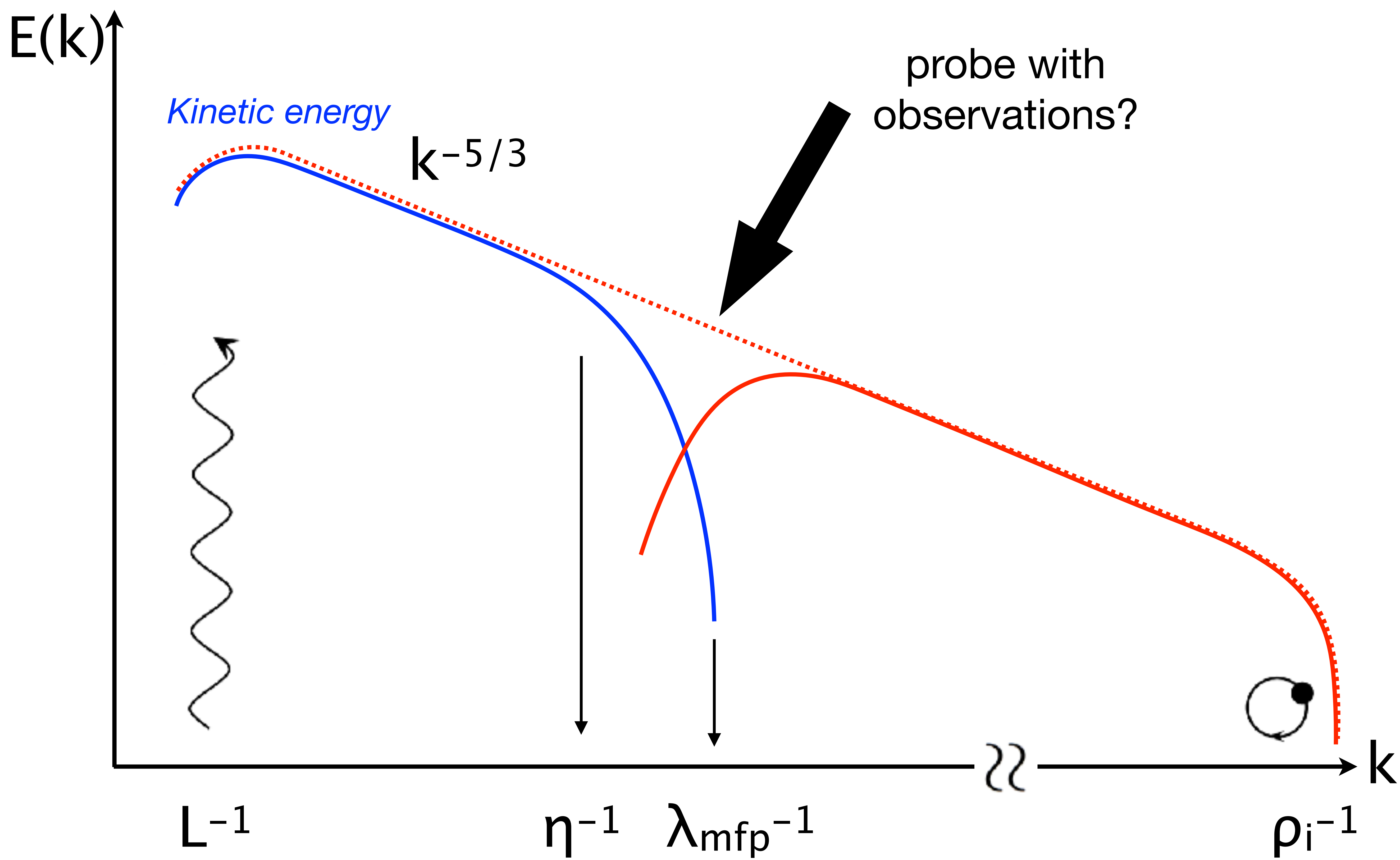
Roediger et al. 2015

see also Markevitch & Vikhlinin 07, Machocek et al. 05, Roediger et al. 12, ZuHone et al. 11,13,15, Werner et al. 16, Su et al. 17 etc.

Transport processes in the bulk of the gas?

Does ICM follow basic hydrodynamic model on microscales?

Weakly-collisional Plasma

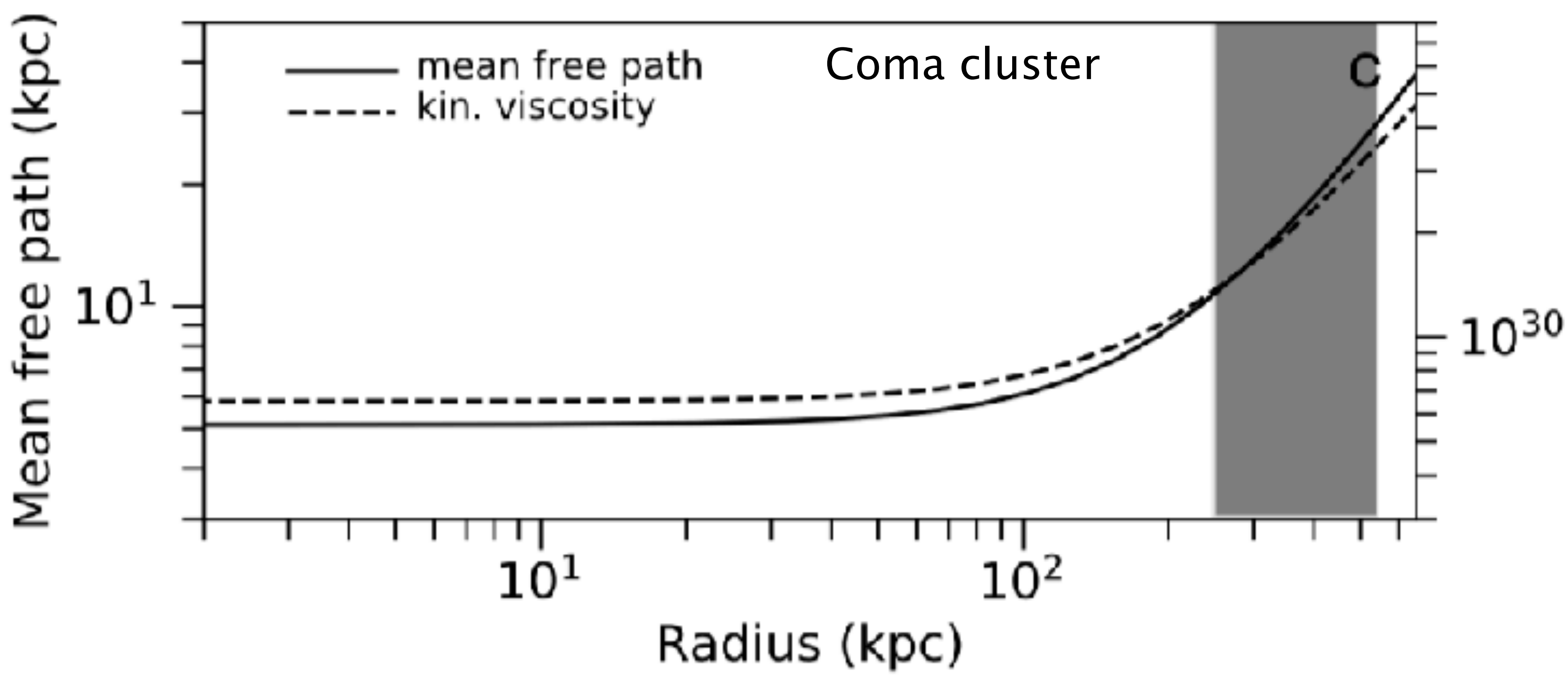


e.g., Schekochihin et al. 2010, Kunz et al. 11, Melville et al. 2016

Challenge I: small mfp

bright cluster cores
λ_{mfp} < few kpc

non-cool-cores, off the center
$\lambda_{mfp} \sim T^2 n^{-1}$, 10s of kpc



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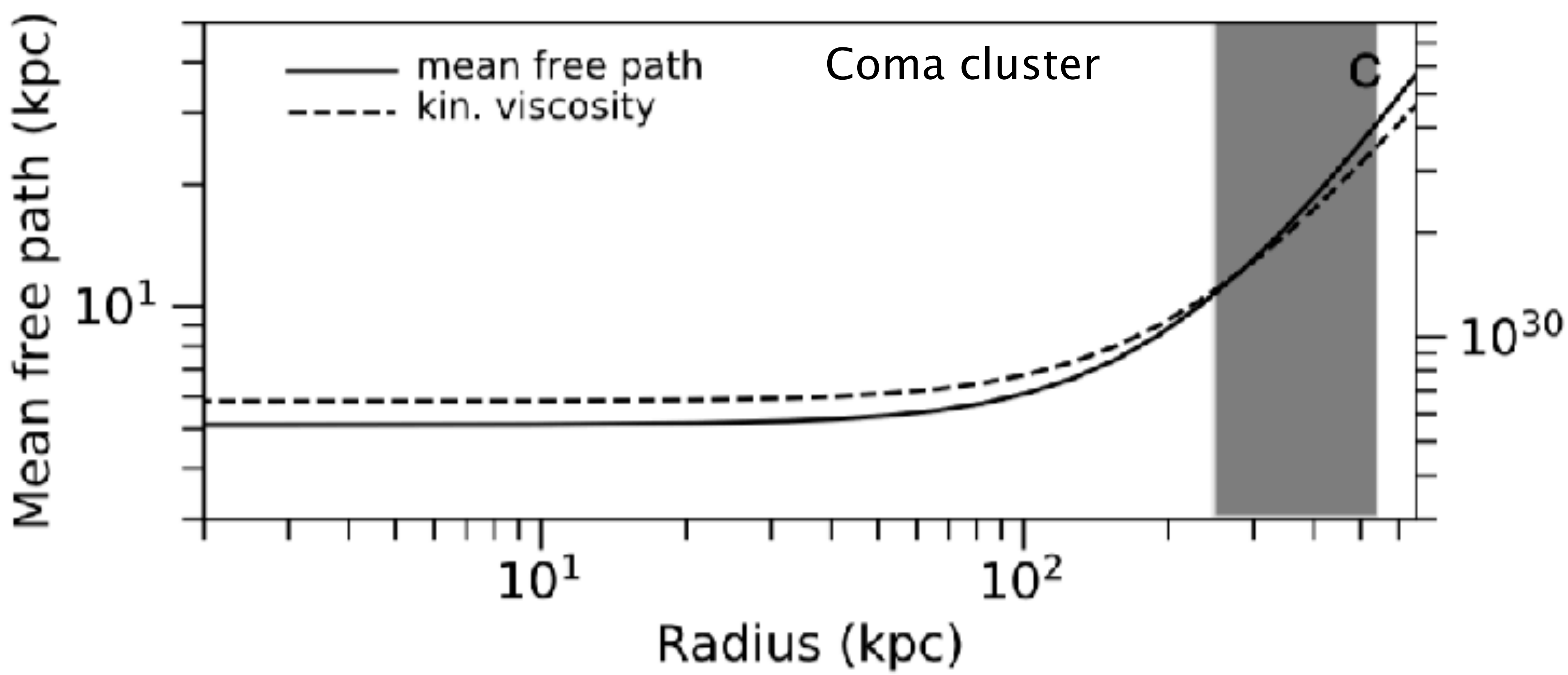


Challenge II: no direct V measurements

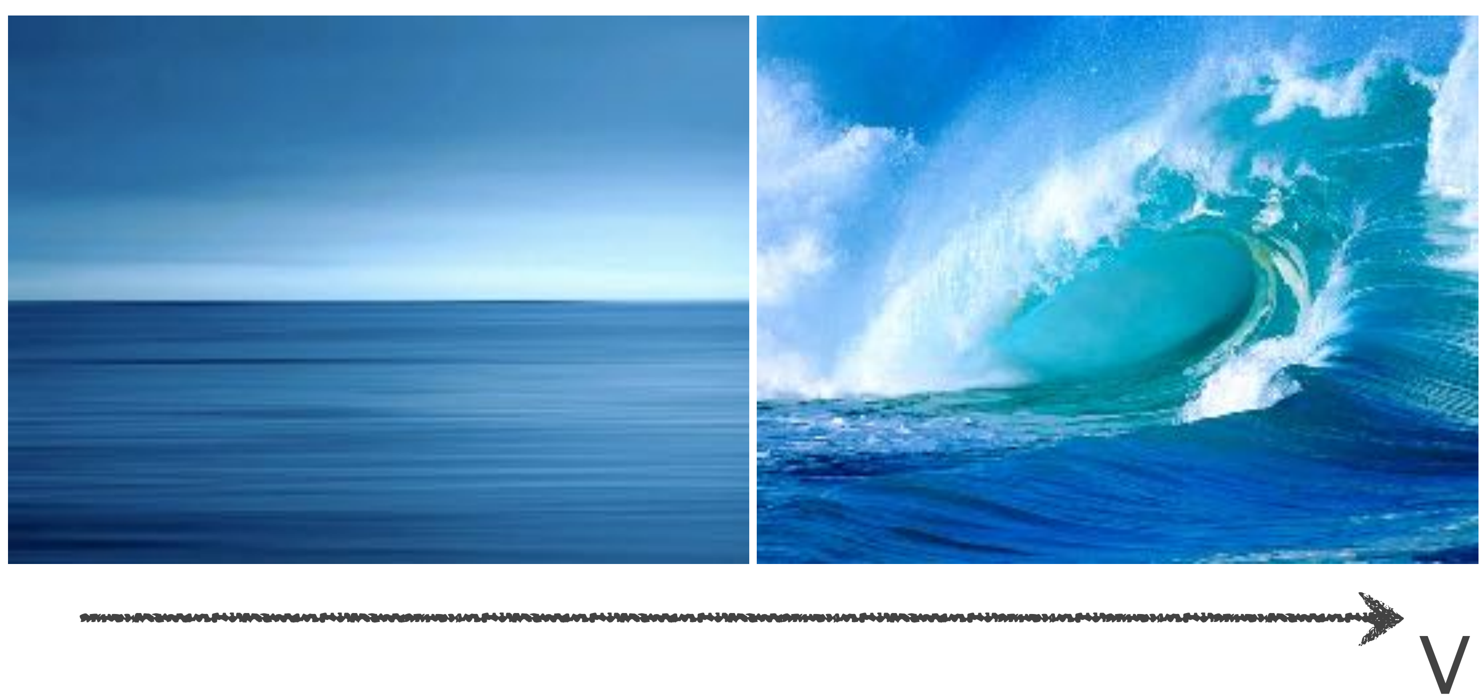
Indirect Measurements of Velocity Power Spectrum

- stratification
- subsonic motions
- motions are generated on large, buoyancy-dominated scales

$$\longrightarrow \quad \frac{\delta\rho_k}{\rho} = \eta \frac{V_k}{c_s}$$

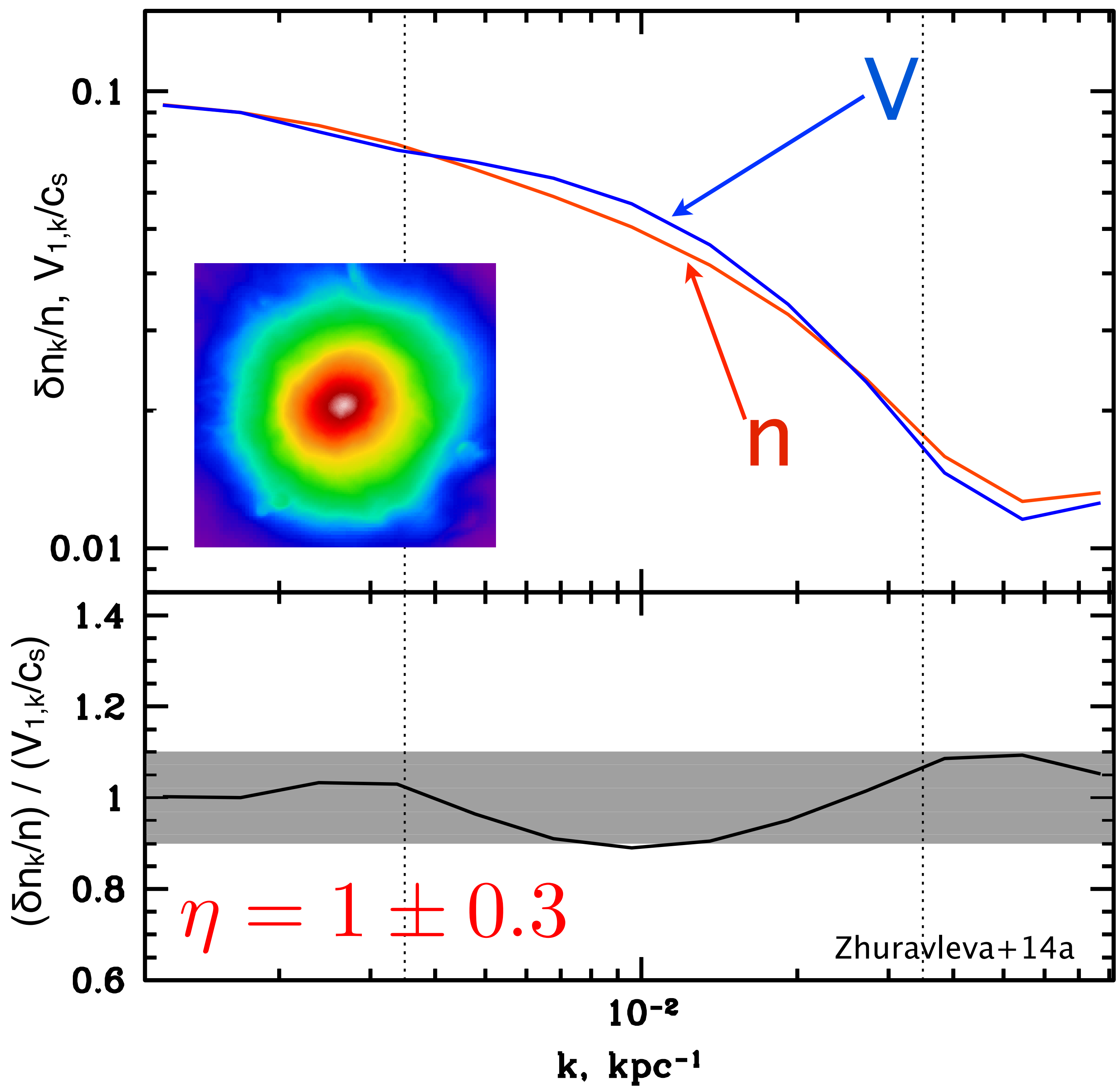
$$\eta = \sqrt{\frac{H_p}{H_s}} \sim 1$$

Zhuravleva et al. 2014a
Gaspari et al. 2014



Verifying Density-Velocity Relation

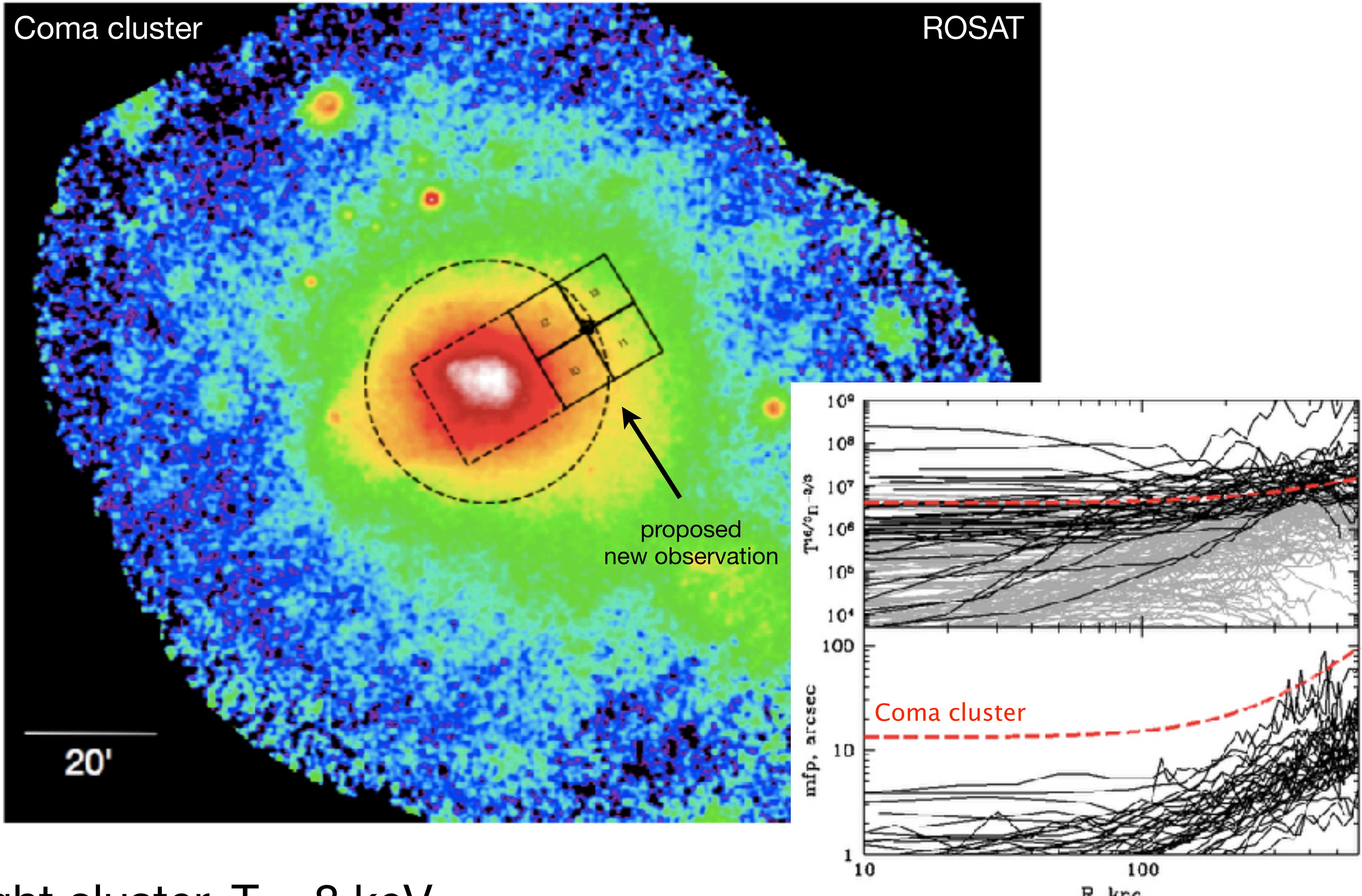
sample of relaxed clusters from cosmological simulations:
ART N-body+gas dynamics Kravtsov+06, Nagai+07a



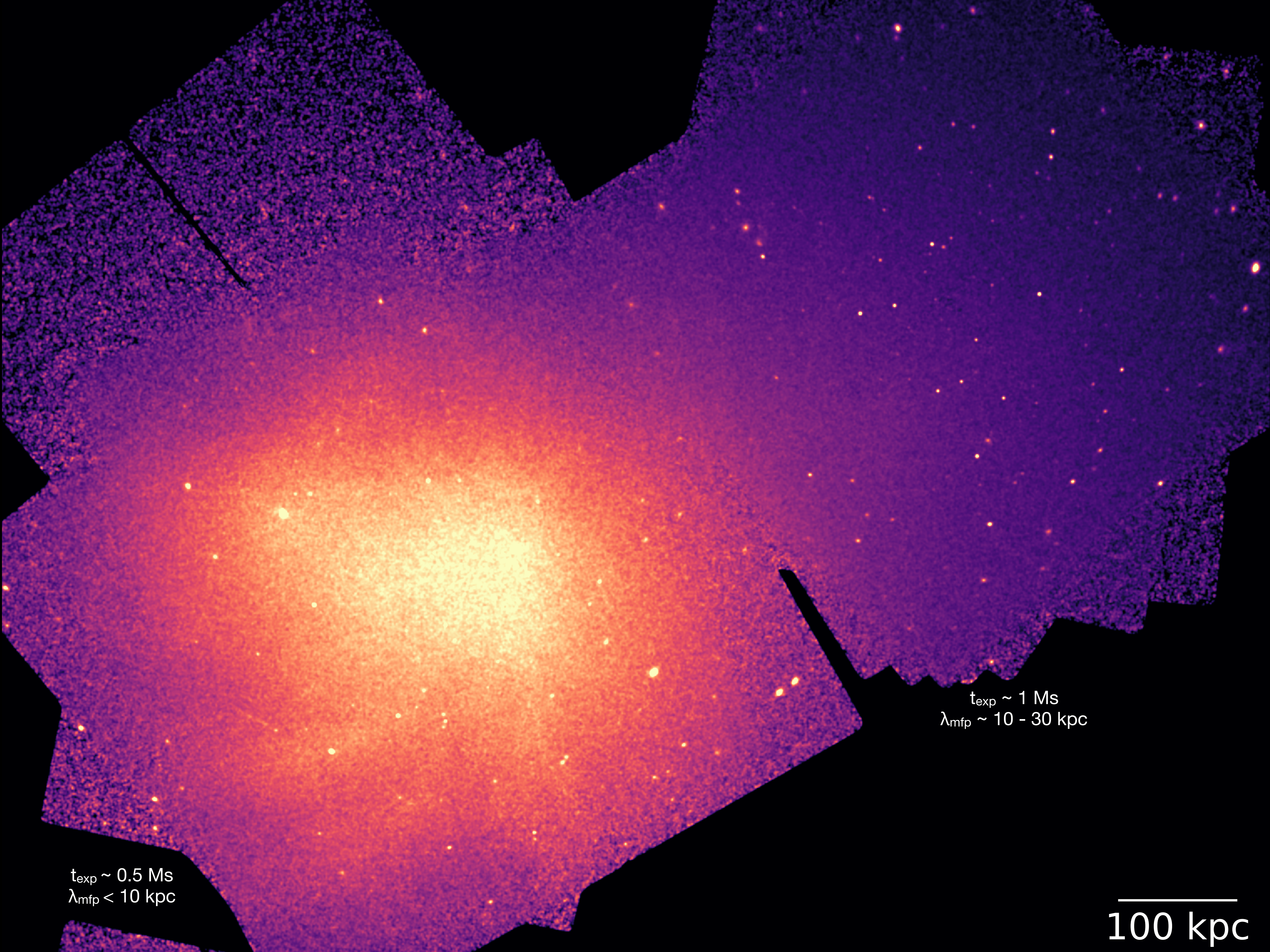
Hitomi V are consistent with V from fluctuations in Perseus:
V ~ 100-200 km/s

Hitomi collaboration 2016, 2018

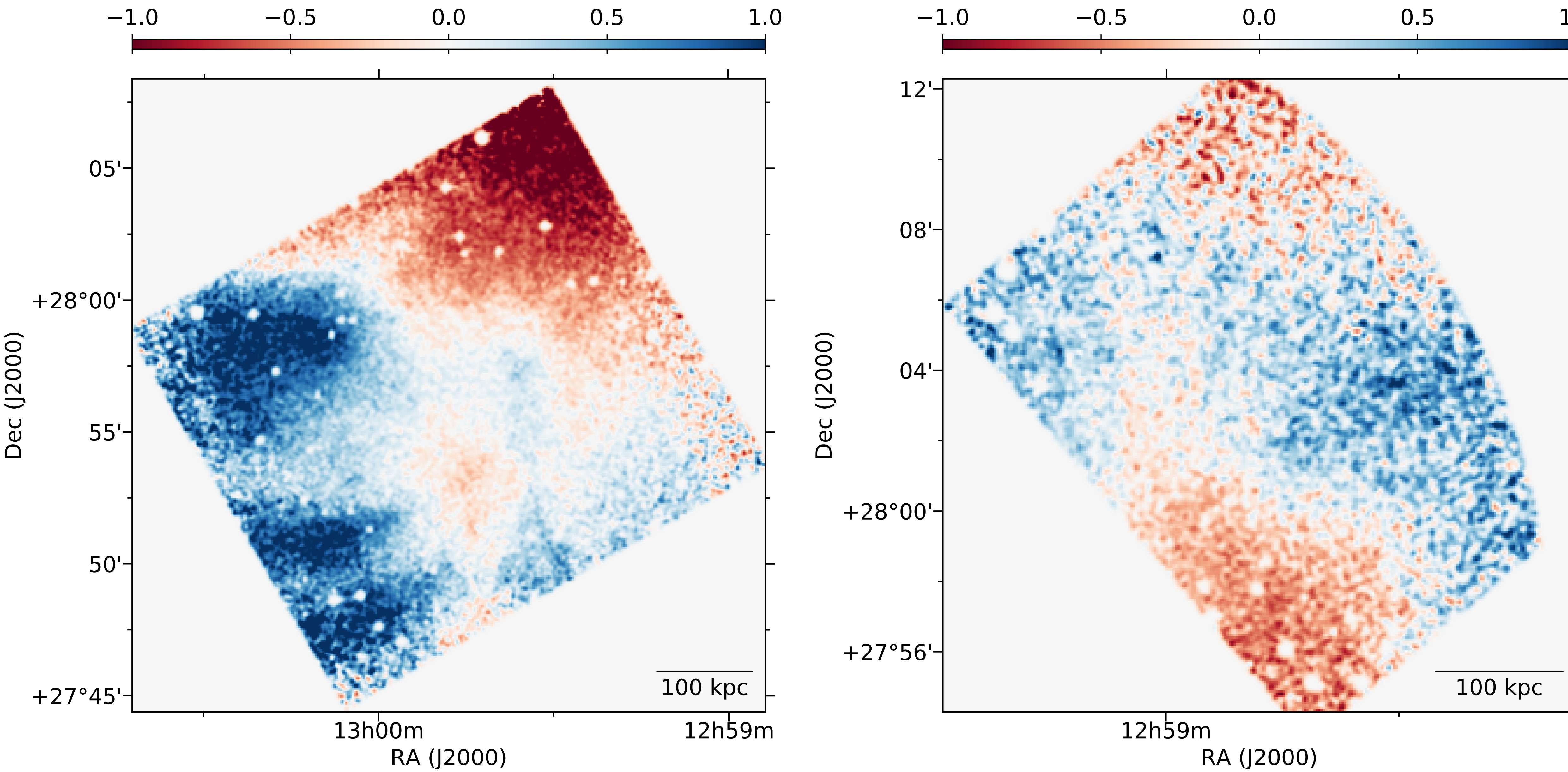
Best Cluster for the mfp Measurements



- hot bright cluster, T ~ 8 keV
- mfp < few kpc in the center and few 10s outside the center
- not an extreme merger


t_{exp} ~ 1 Ms
λ_{mfp} ~ 10 - 30 kpc
t_{exp} ~ 0.5 Ms
λ_{mfp} < 10 kpc
100 kpc

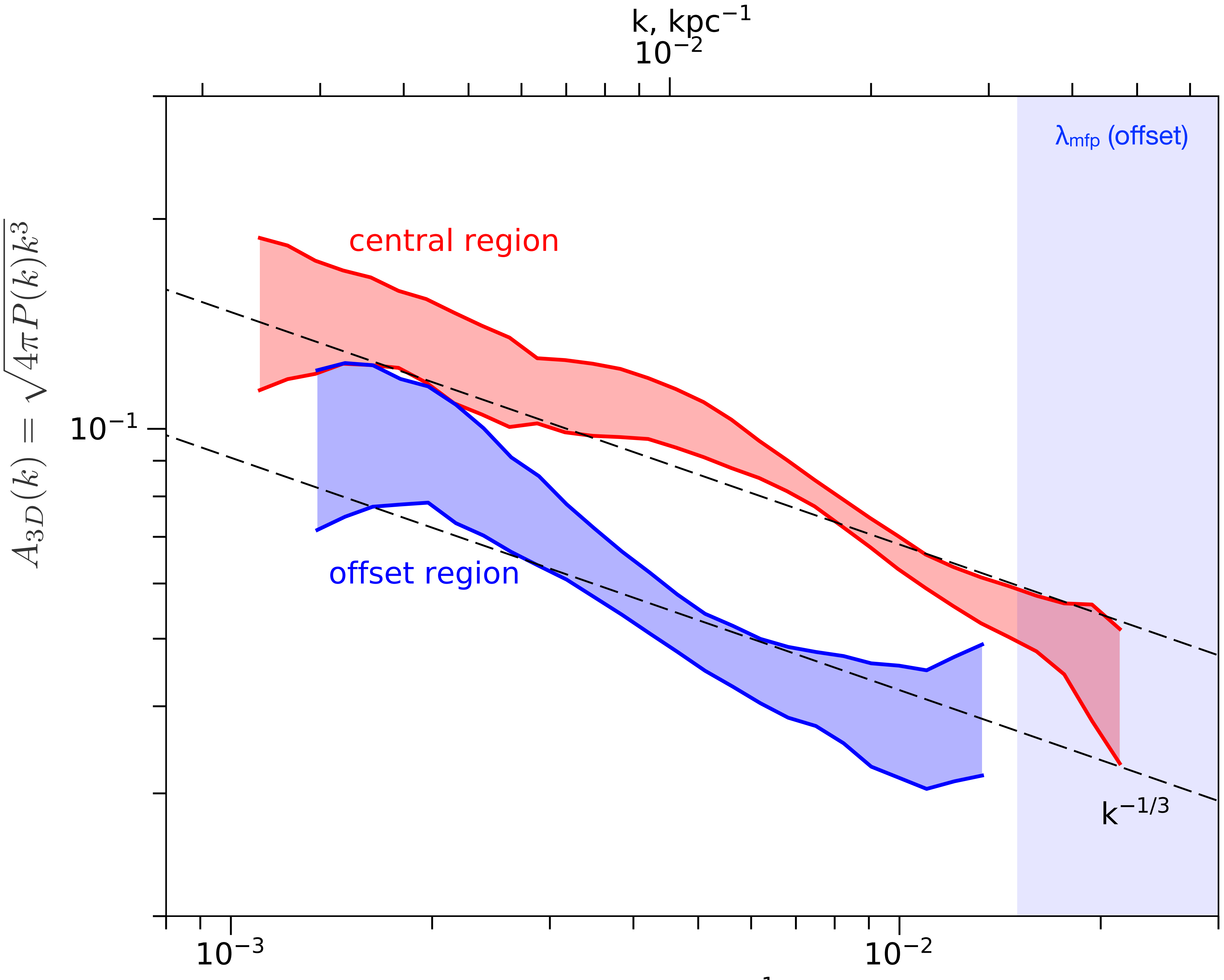
Surface Brightness Fluctuations in Coma



$$\frac{\delta I_X}{I_X} \rightarrow P_{2D}(k) \rightarrow C \times P_{3D}(k) \rightarrow \frac{\delta \rho}{\rho} \rightarrow \frac{V_{1D}}{c_s}$$

Arevalo et al. 2012, Churazov et al. 2012, Zhuravleva et al. 2014b, 2015, 2018 +

Power Spectrum of Density Fluctuations in Coma



Zhuravleva et al. 2019, in press

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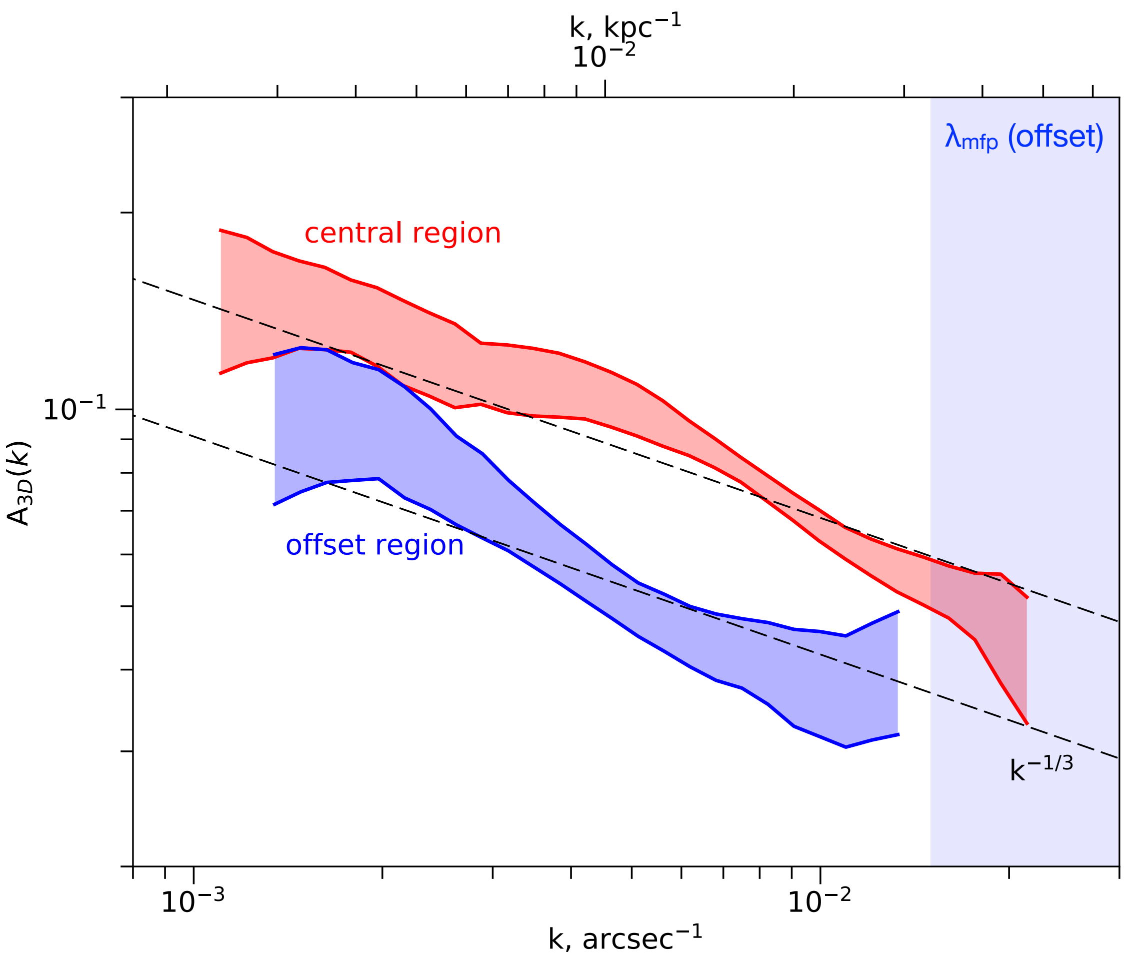
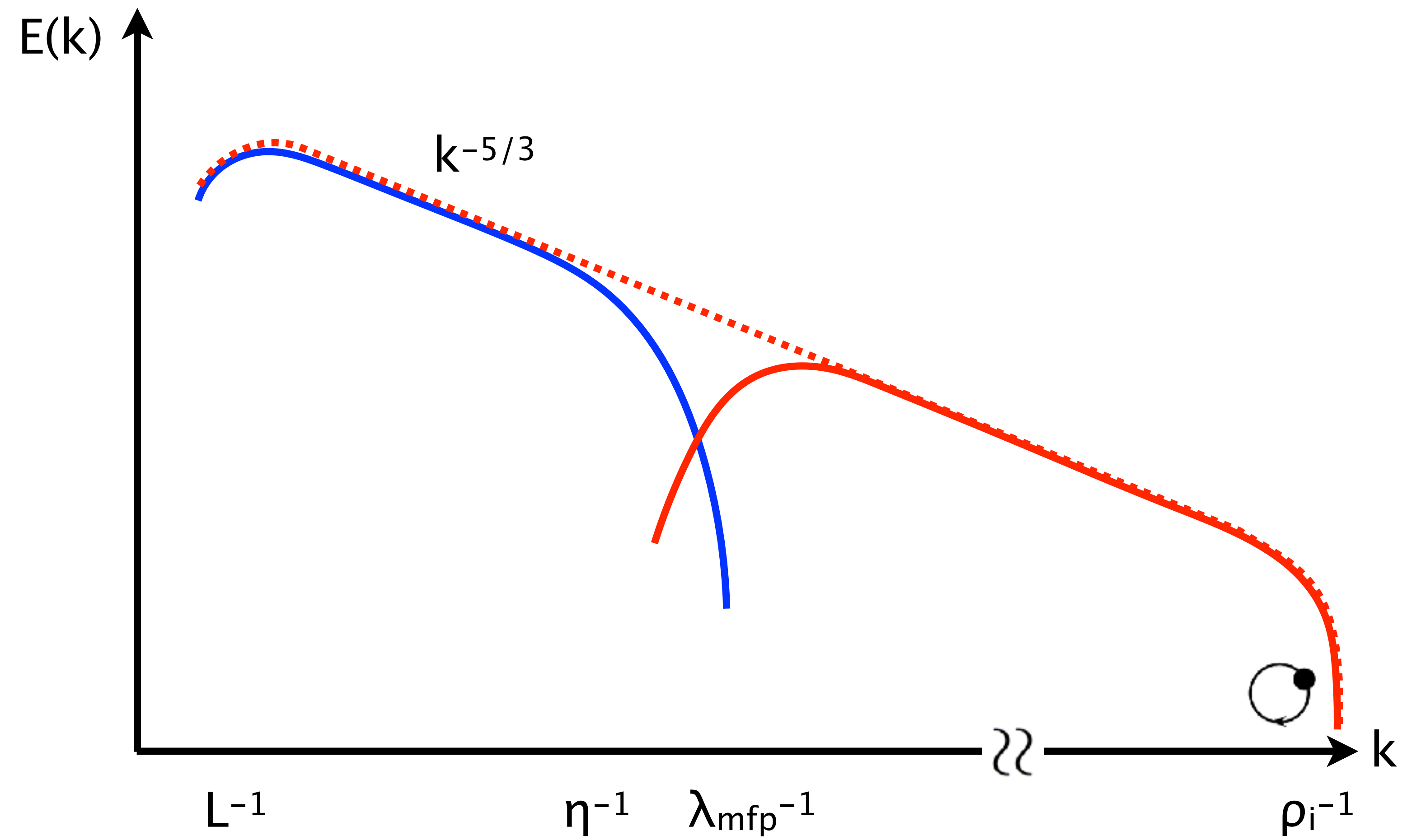




Hydrodynamic models with pure Coulomb collisions do not describe intracluster plasma

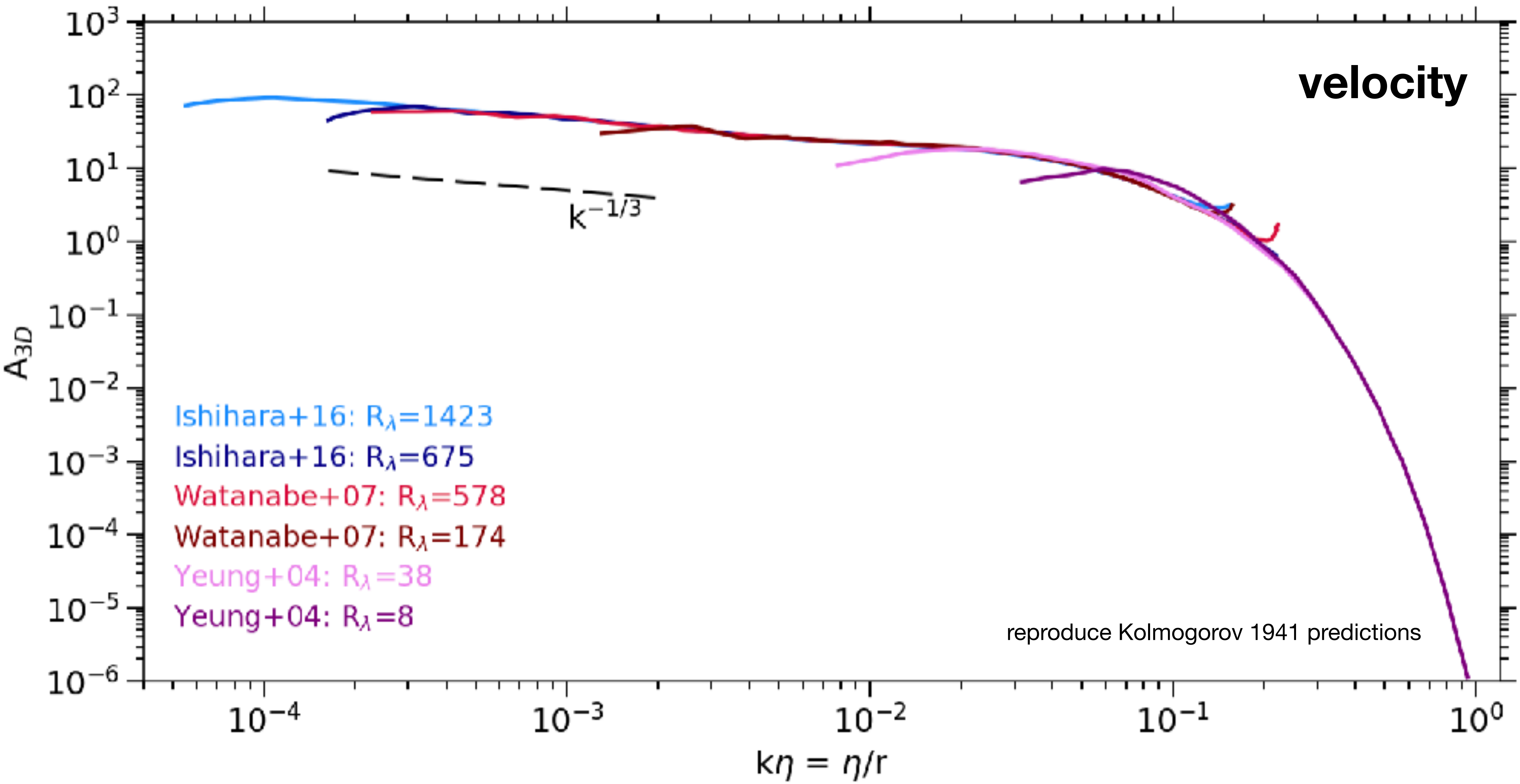
- Due to particle scattering off microfluctuations produced by plasma instabilities

  e.g., Schekochihin et al. 2010, Kunz et al. 11, Melville et al. 2016

- Possible modification of plasma turbulence by anisotropic transport processes with respect to local magnetic fields

  Squire, Schekochihin, Quataert, Kunz 2019, “magneto-immutable” turbulence

Direct Numerical Simulations (DNS) of Hydrodynamic Turbulence



Dissipation (Kolmogorov) scale: $\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$

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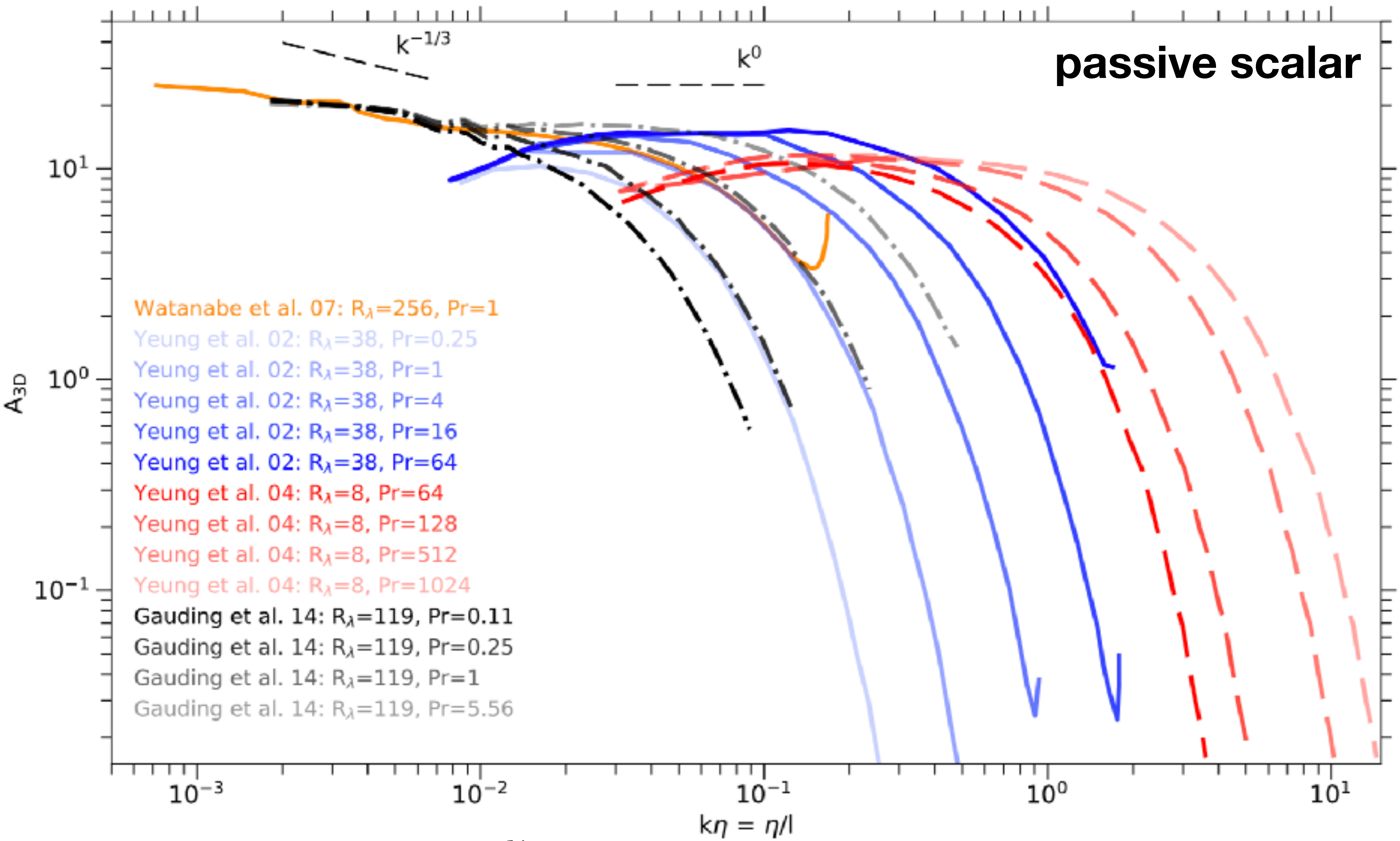


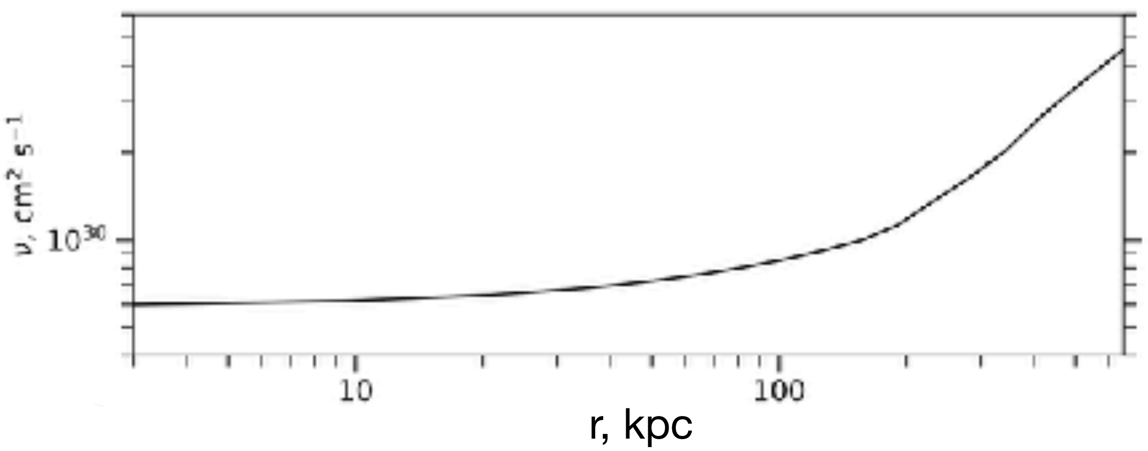
Thermal Prandtl number: $Pr = \dfrac{\nu}{\alpha}$

reproduce Batchelor 1959 predictions

Kolmogorov (Dissipation) Microscale in Coma

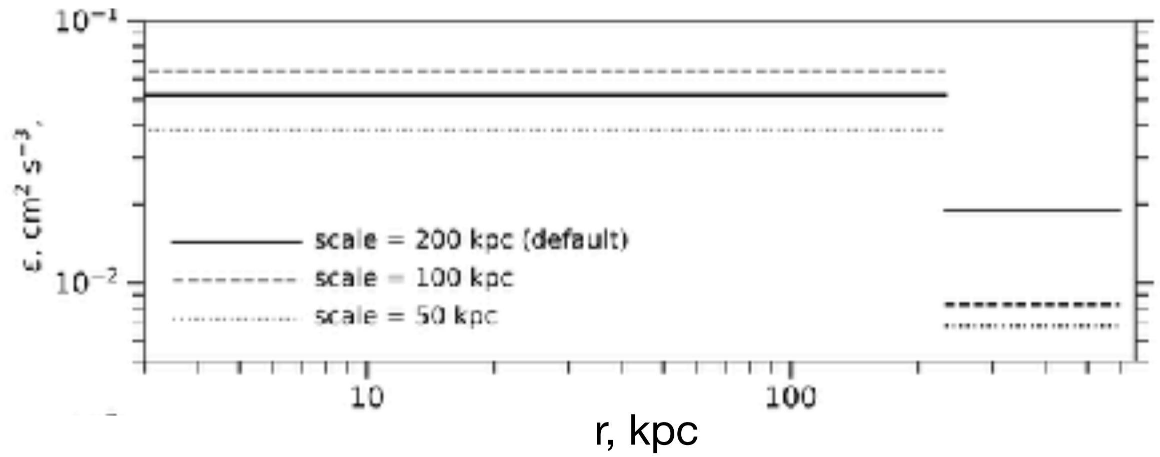
$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$$

$\nu \propto \lambda_{\rm mfp} V_{th} = f(n, T)$



ϵ directly from $A_{3D}(k)$: $\left(\frac{\delta\rho}{\rho}\right)_k = \frac{V_{1,k}}{c_s}$

$\epsilon = C_Q V_{1,k}^3 k$



$\eta \sim$ 20 kpc (central region)
50 kpc (offset region)

$$\eta = L_{\rm inj} Re^{-3/4}$$

$$Re = 3ML/\lambda_{\rm mfp}$$

M = 0.2 – 0.5
L_{inj}=200–500 kpc

$\eta \sim$ 10 – 40 kpc (central region)
40 – 90 kpc (offset region)

Diffusivity of the Passive Scalar in ICM

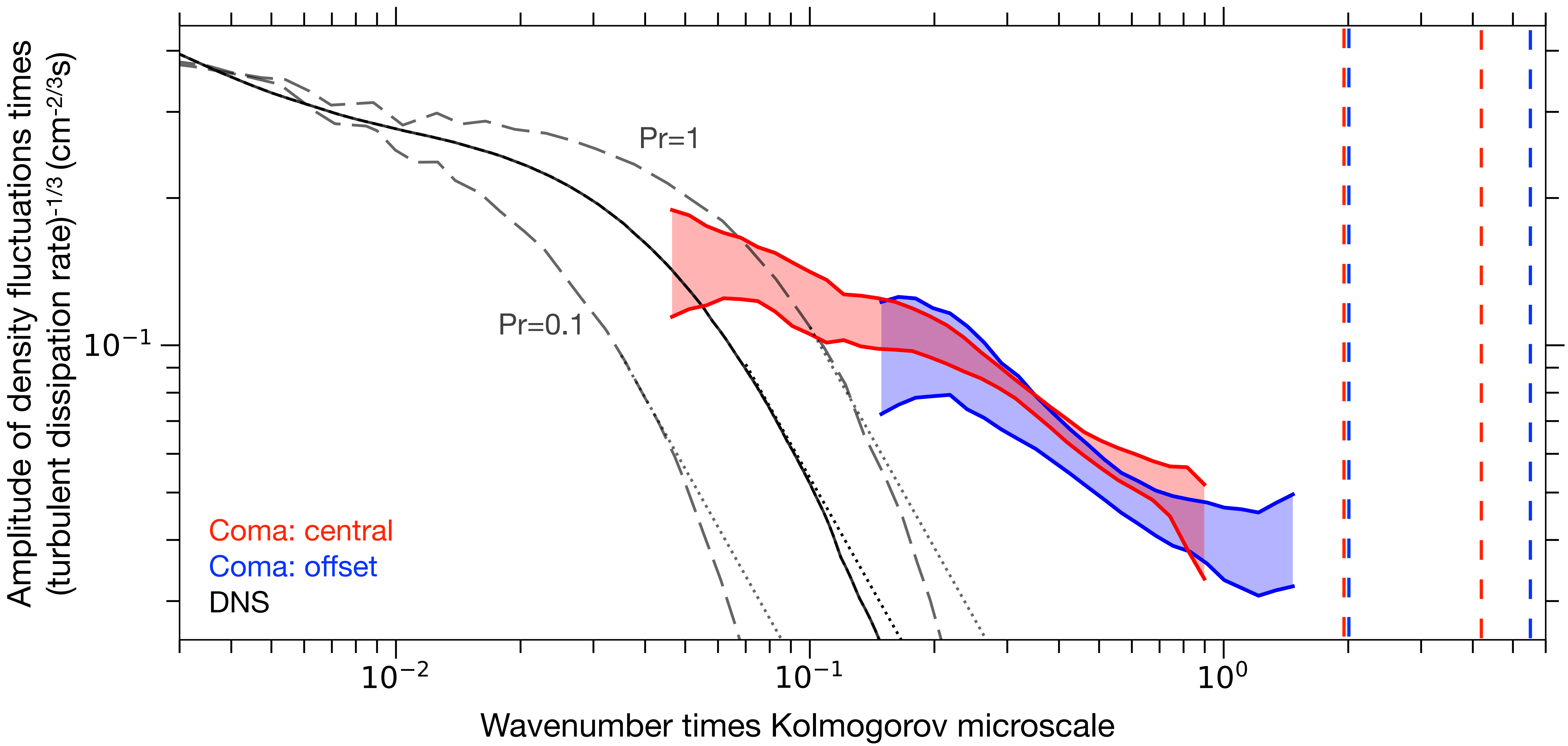
Stratified medium, low viscosity and conduction, small scales:
entropy fluctuations ~ passive scalar =>
density fluctuations ~ passive scalar

For subsonic motions, P remains smooth =>
ρ fluctuations are compensated by T fluctuations

T fluctuations are subject to thermal conduction =>
parametrized by the thermal Prandtl number

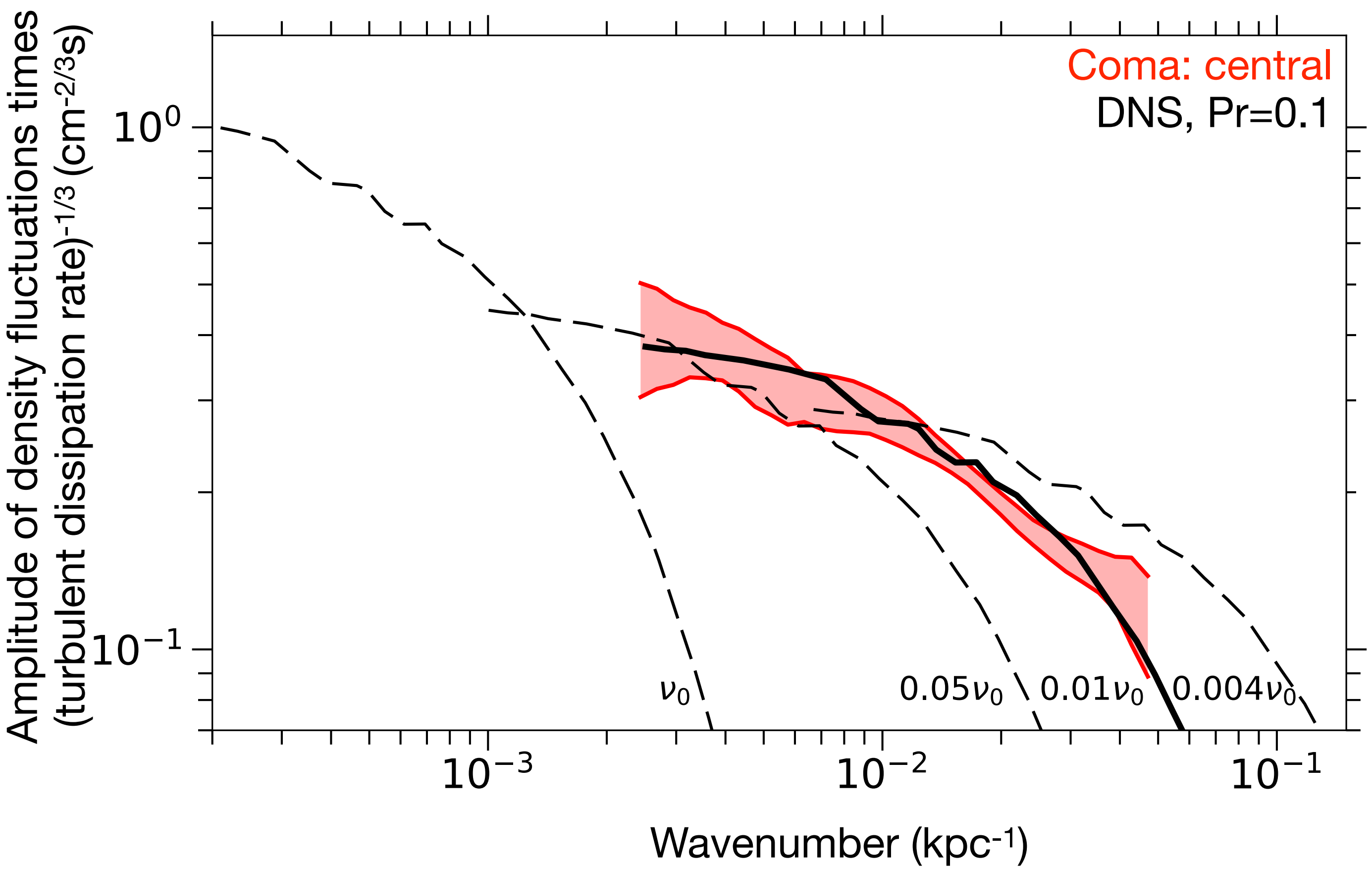
$$Pr \approx \frac{V_{\rm i}}{V_{\rm e}} = \left(\frac{m_{\rm e}}{m_{\rm i}}\right)^{1/2} \approx 0.02$$

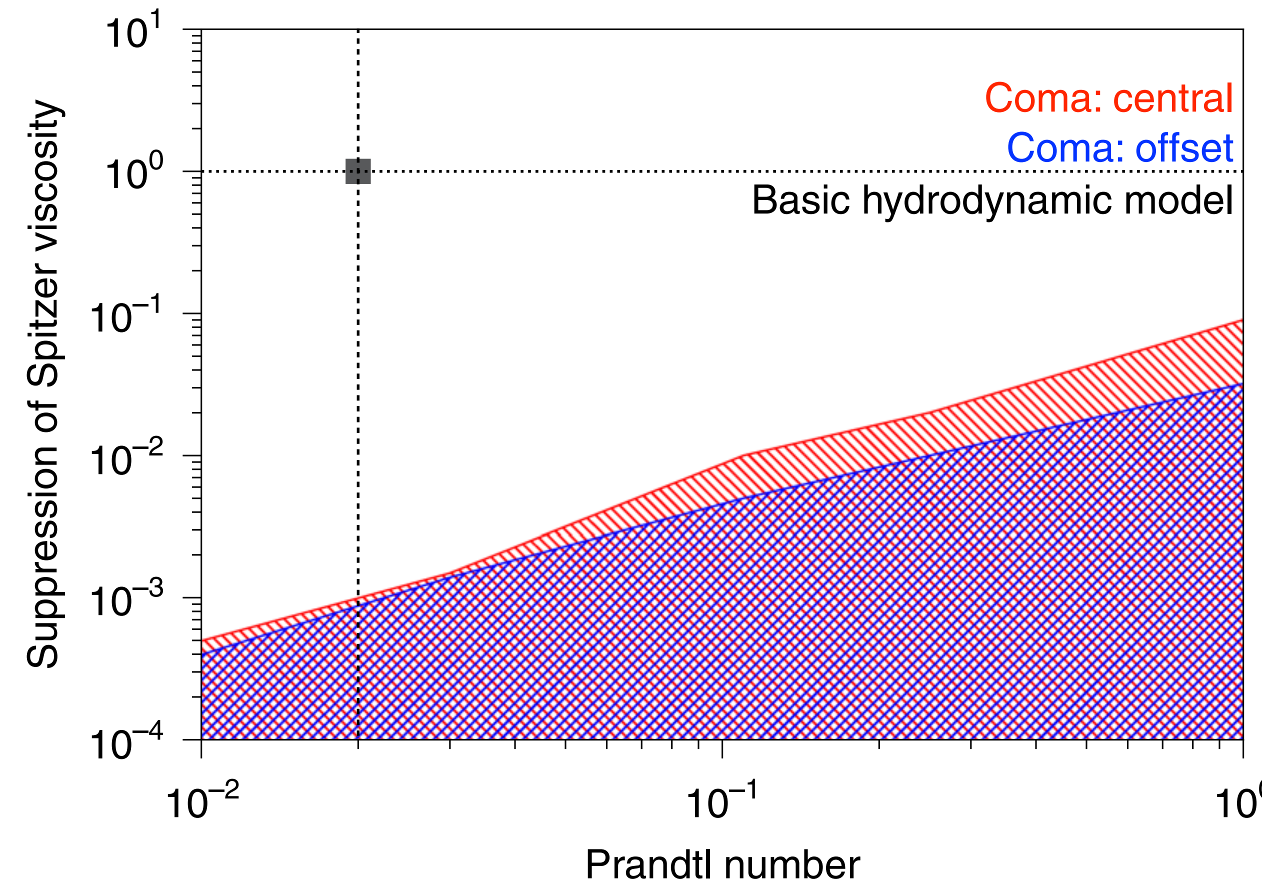
Coma Observations and DNS Comparison



- Hydrodynamic model with Coulomb collisions does not describe the ICM plasma
- Effective isotropic viscosity is suppressed in the bulk ICM

Coma Observations and DNS Comparison: Constraints on Viscosity

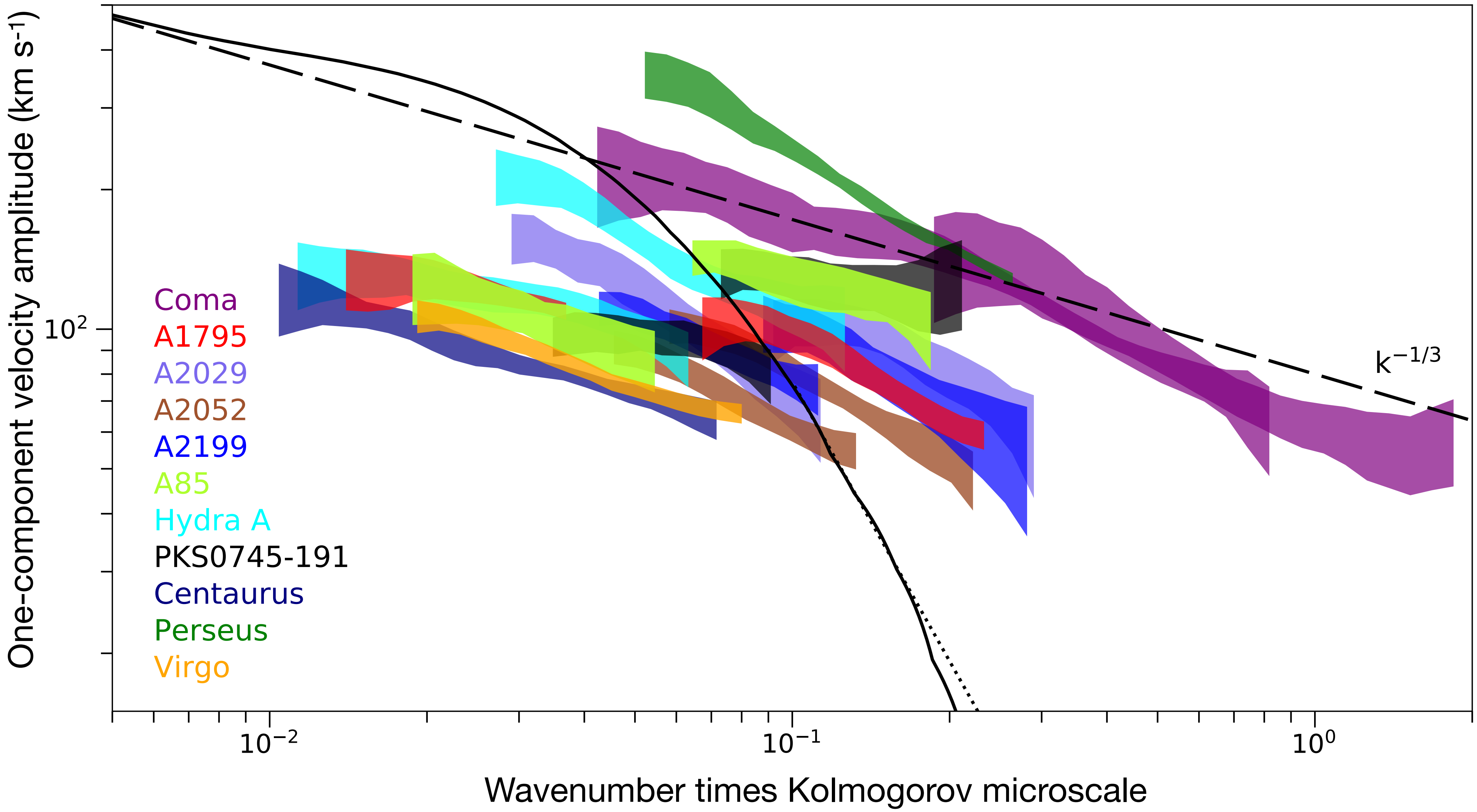




*Isotropic viscosity is suppressed in the **bulk** gas by at least a factor of ~ 10-1000 for Pr = 1-0.02*

Zhuravleva et al. 2019, in press

Other Galaxy Clusters

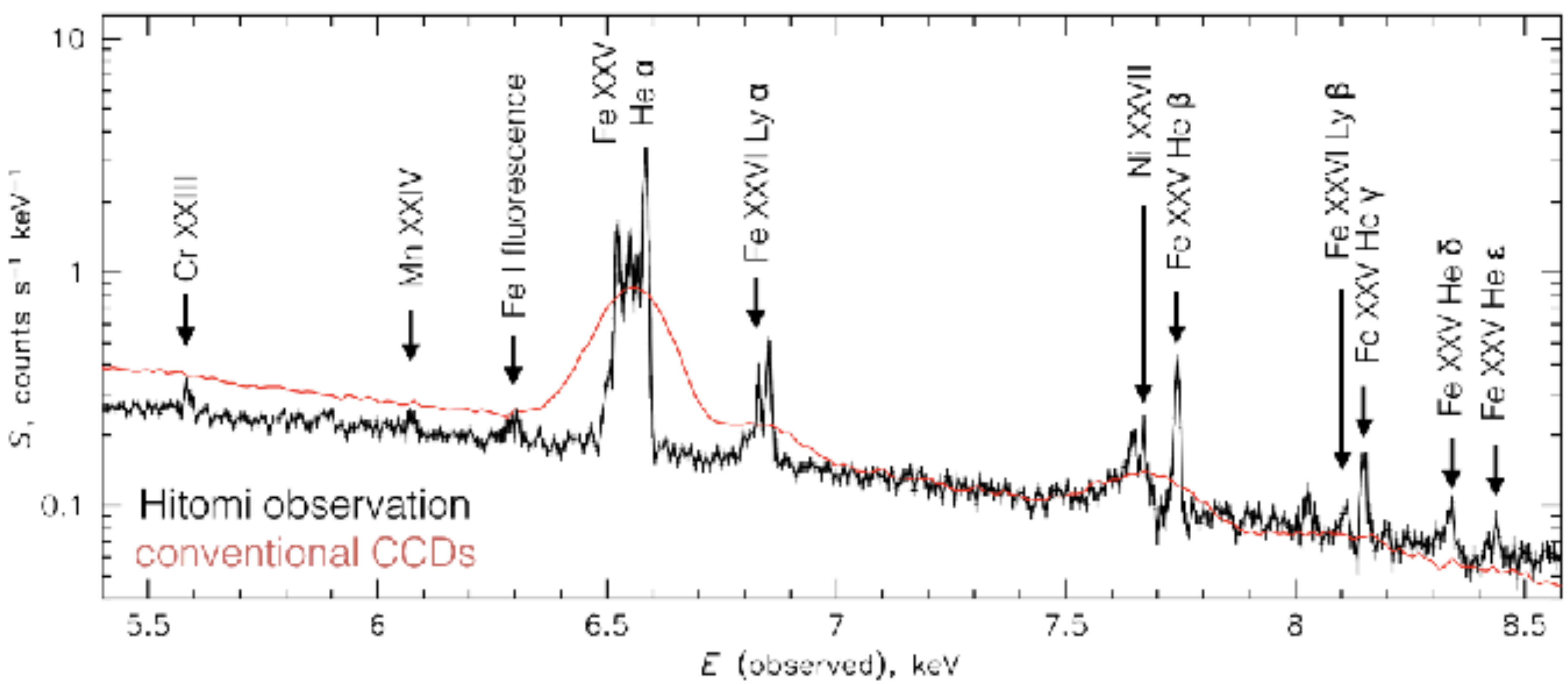


In many cool cores, DNS simulations with Spitzer viscosity cannot describe power spectra of ICM fluctuations, however for robust conclusions k-range should be larger

Zhuravleva et al. 2019, in press

Uncertainties

No direct velocity measurements —> XRISM (2022), Athena, Lynx



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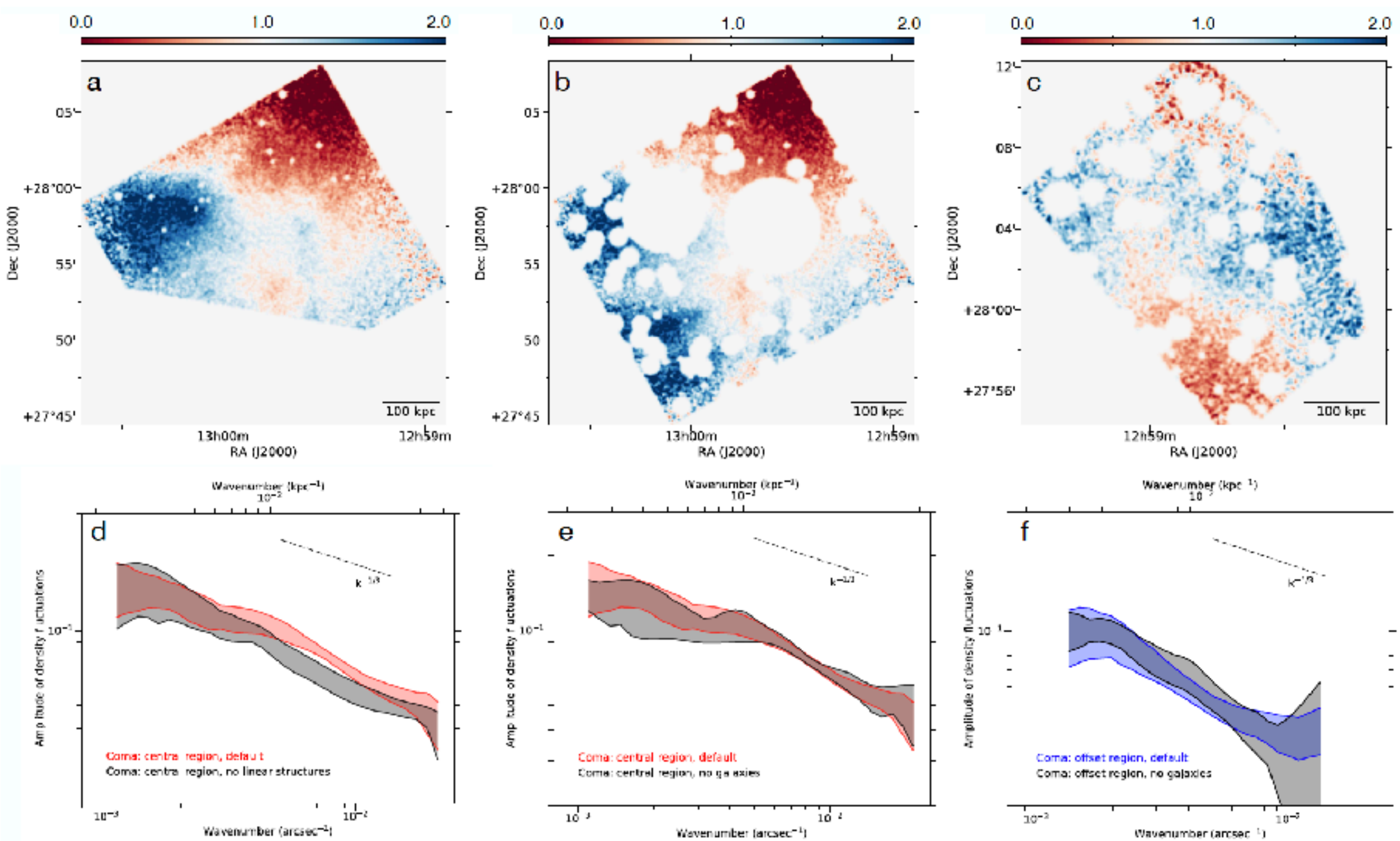
Additional structures associated with low-entropy gas, cD and normal galaxies —> no significant changes



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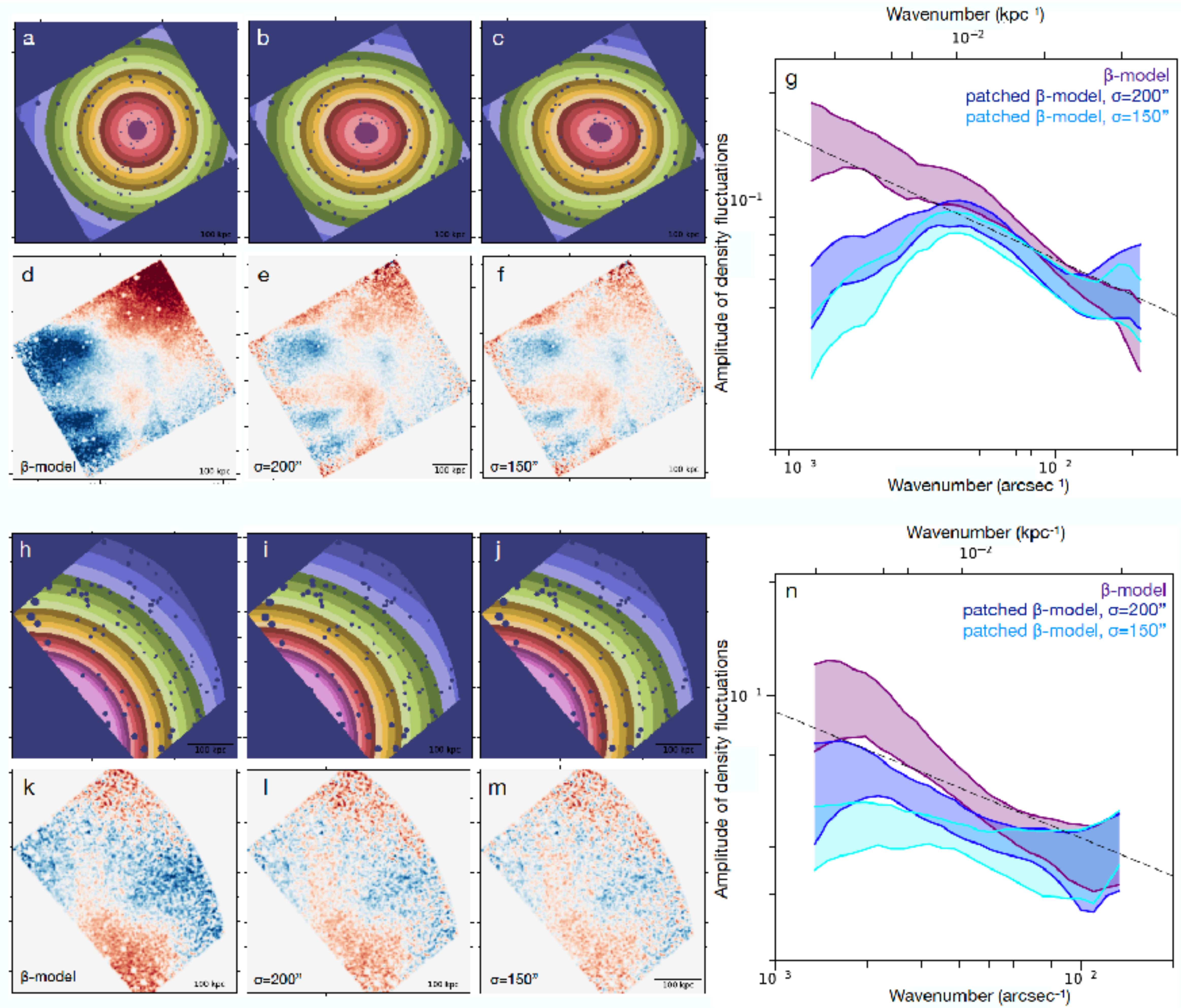
Choice of underlying model —> does not steepen the observed spectra, amplitude of fluctuations on mfp remains the same



a
b
c
d
e
f
β-model
σ=200"
σ=150"
100 kpc
g
β-model
patched β-model, σ=200"
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Wavenumber (kpc⁻¹)
Amplitude of density fluctuations
Wavenumber (arcsec⁻¹)
h
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Uncertainties on mfp, Kolmogorov microscale, etc —> a factor of a few on viscosity, the main conclusions remain unchanged

Summary:

- Observations started probing mfp scale of the ICM
- Weakly-collisional, high-β plasma in galaxy clusters is inconsistent with hydrodynamic fluid with Spitzer transport coefficients
- Consistent with the presence of plasma instabilities that, by interacting with particles, increase the plasma collision rate, and/or with the establishment of a new type of turbulence in which motions adjust to be immune to the locally anisotropic plasma viscosity
- If isotropic transport processes: effective Re is large in the bulk ICM, viscosity is suppressed at least by a factor of 10 regardless of the level of thermal conduction
- Numerical simulations should use the lowest-possible viscosity