What

<u>**Clusters of galaxies**</u>

~100s-1000s of Mpc away
~ few Mpc virial radius

~ 1e-1 to 1e-4 cm^-3
~ 10s of pc to kpc mean free path

~ 10^7-10^8 K
~thousands of km/s sound speed

~ B-field several μG
~ nanoparsec Larmor radii

fully dissociated plasma
(mostly) in collisional ionization equilibrium (although mfp is large!)
(mostly) optically thin
but often approximated as ideal fluid (so far…)

Why

Open questions

~ average level of turbulent to thermal pressure support vs. radius, mass, time

~ is turbulence in the ICM actually responsible for (re)accelerating cosmic ray component of these objects?

~ importance of turbulence for magnetic field amplification

~ how much heat is actually generated by dissipating turbulent motions?

~ what is the role of turbulence in regulating feedback from supermassive black holes?

~ role of turbulence for spreading chemical elements throughout cluster volume

~ what is the effective viscosity of the ICM? What does that imply for the physics on nanoparsec scales that cannot be resolved (or even physics below the mfp)?

Why

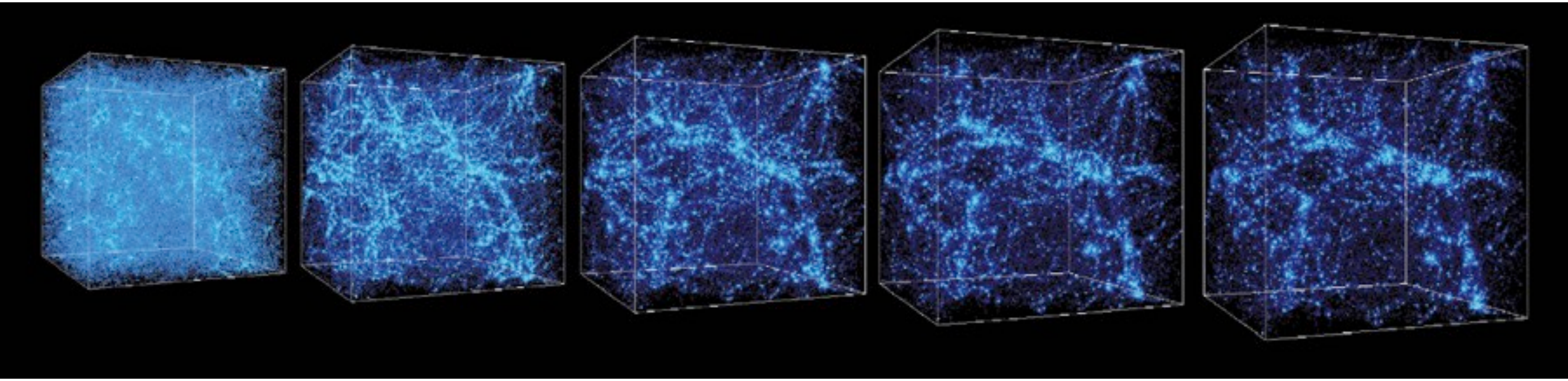
<u>Open questions</u>

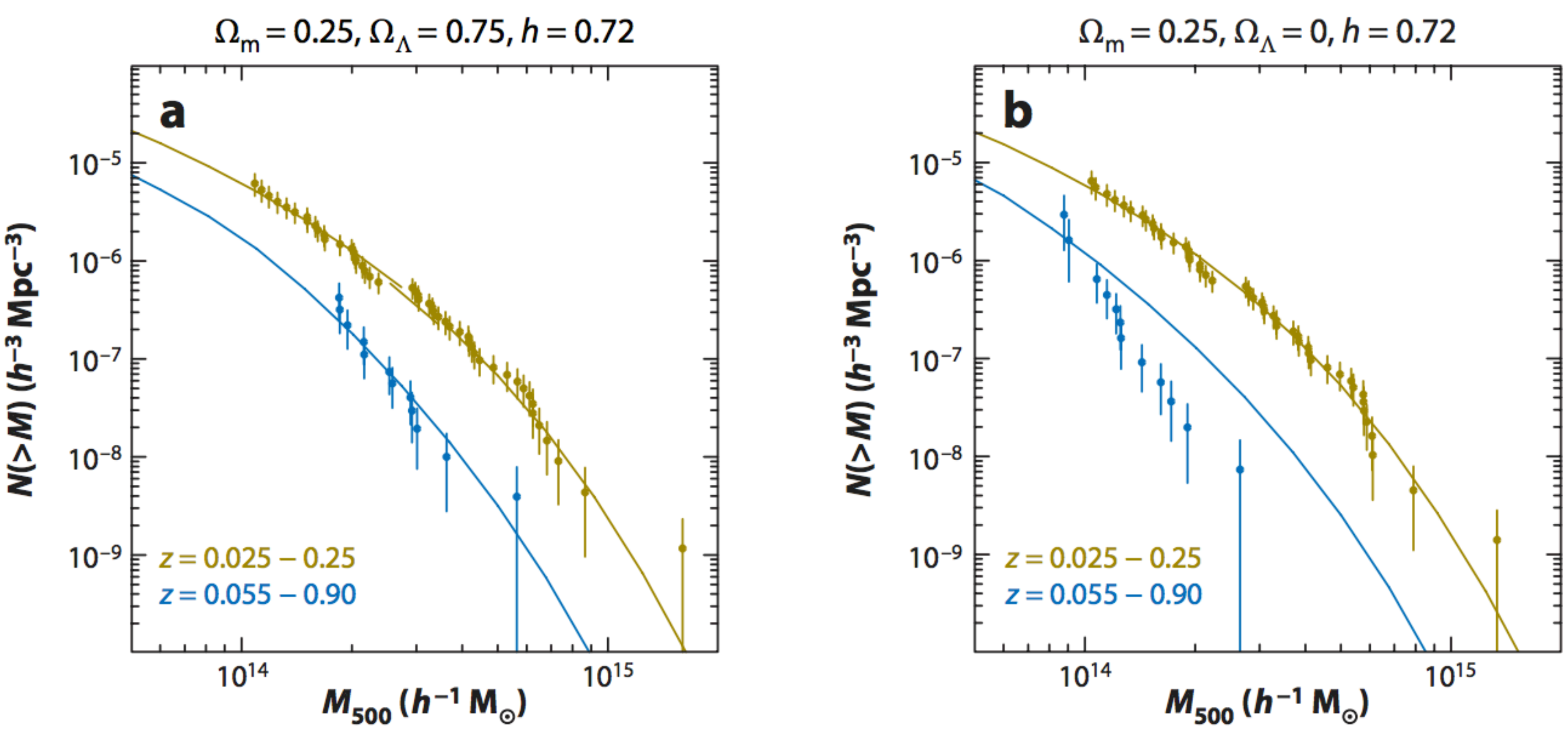
~ average level of turbulent to thermal pressure support vs. radius, mass, time, etc [how wrong is the hydrostatic equilibrium assumption used to infer cluster masses for cosmology?]

~ how much heat is actually generated by dissipating turbulent motions?

~ what is the role of turbulence in regulating feedback from supermassive black holes?

~ is turbulence in the ICM actually responsible for (re)accelerating cosmic ray component of these objects?

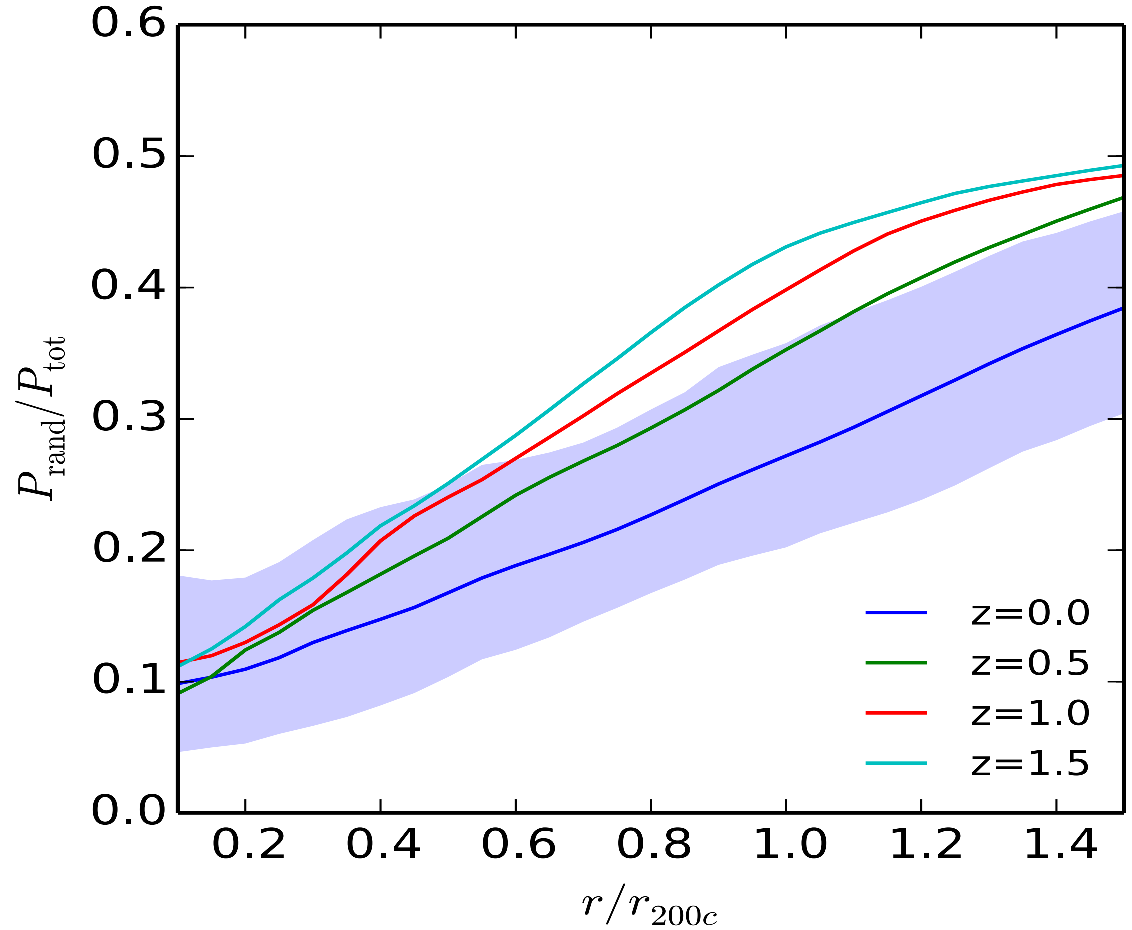




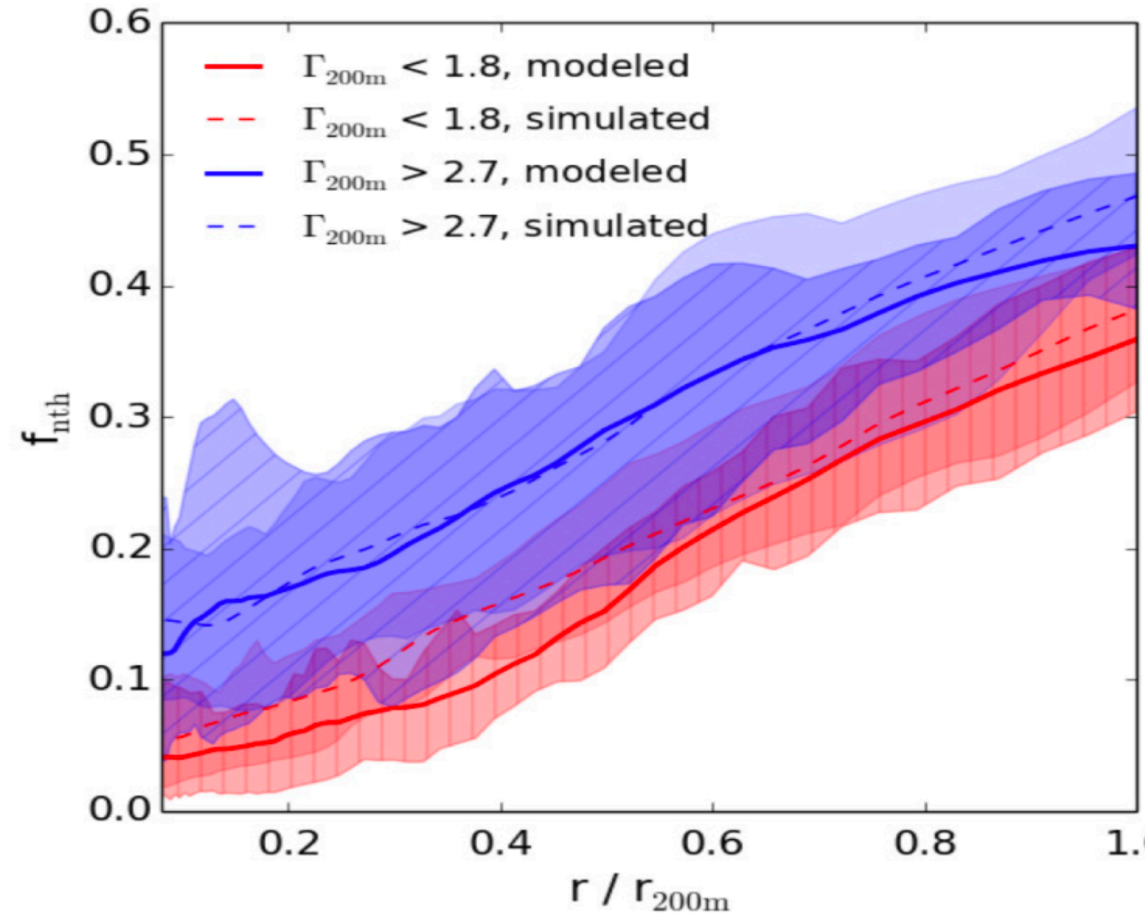
$$\frac{dP_{\rm gas}}{dr} = -\rho_{\rm gas}\frac{GM_{\rm HSE}(<r)}{r^2}$$

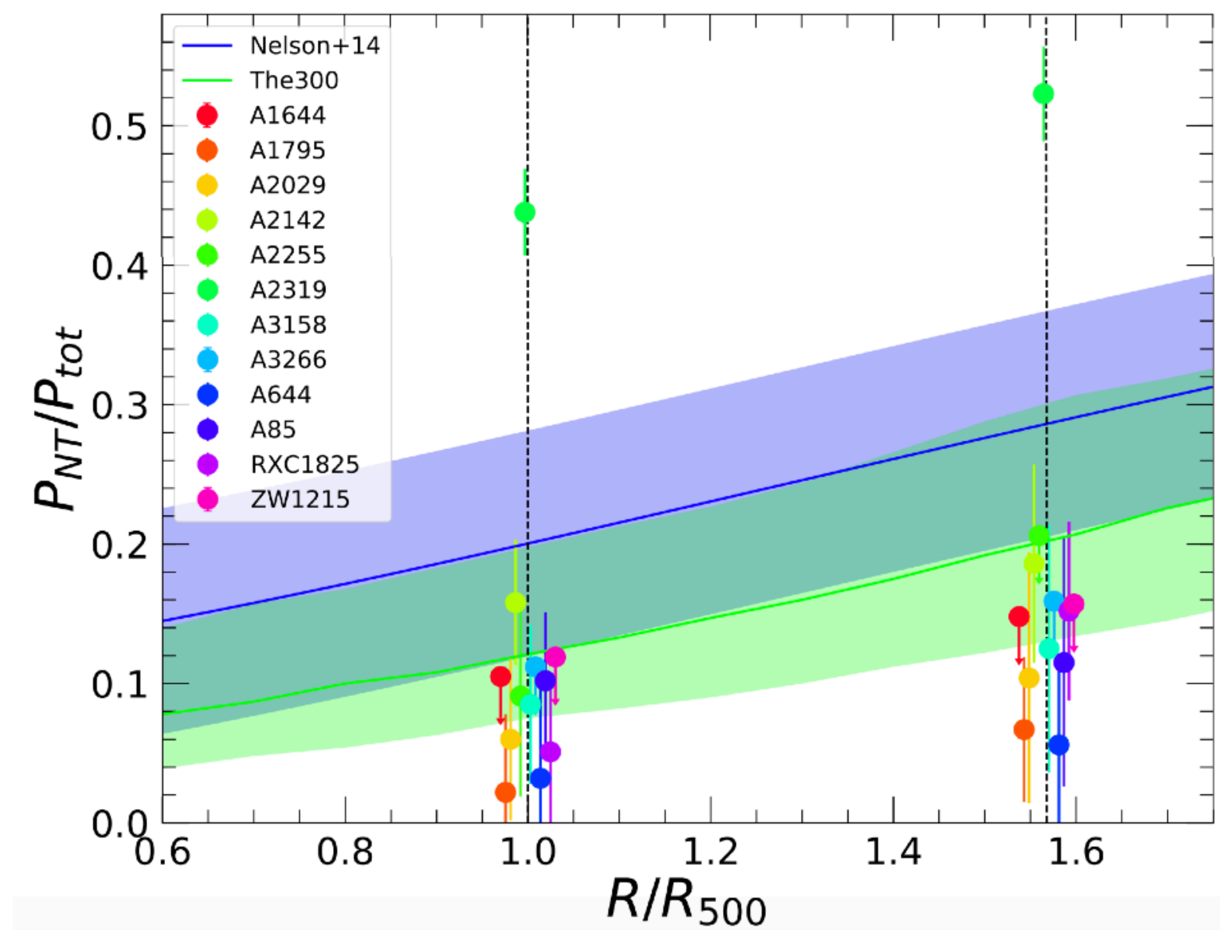
Vikhlinin et al. 2009

Nelson et al. 2014



Shi et al. 2015





Eckert et al. 2019

Why

Open questions

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~ how much heat is actually generated by dissipating turbulent motions?

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[see notes by Mateusz]

~ is turbulence in the ICM actually responsible for (re)accelerating cosmic ray component of these objects?

How to measure the gas velocity

~ X-ray surface brightness fluctuations

$$\frac{\delta\rho_k}{\rho_0} = \eta_1 \frac{V_{1,k}}{c_s}$$

~ Doppler shifts and widths of X-ray lines (both of order eV)

$$\Delta E = E_{\rm line} \times v_{\rm bulk}/c \qquad W_{\rm therm} = \frac{\nu_0}{c}\sqrt{\frac{k_B T}{A m_p}} \qquad W_{\rm turb} = \frac{\nu_0}{c}\sigma_{v||}$$

~ Resonant scattering

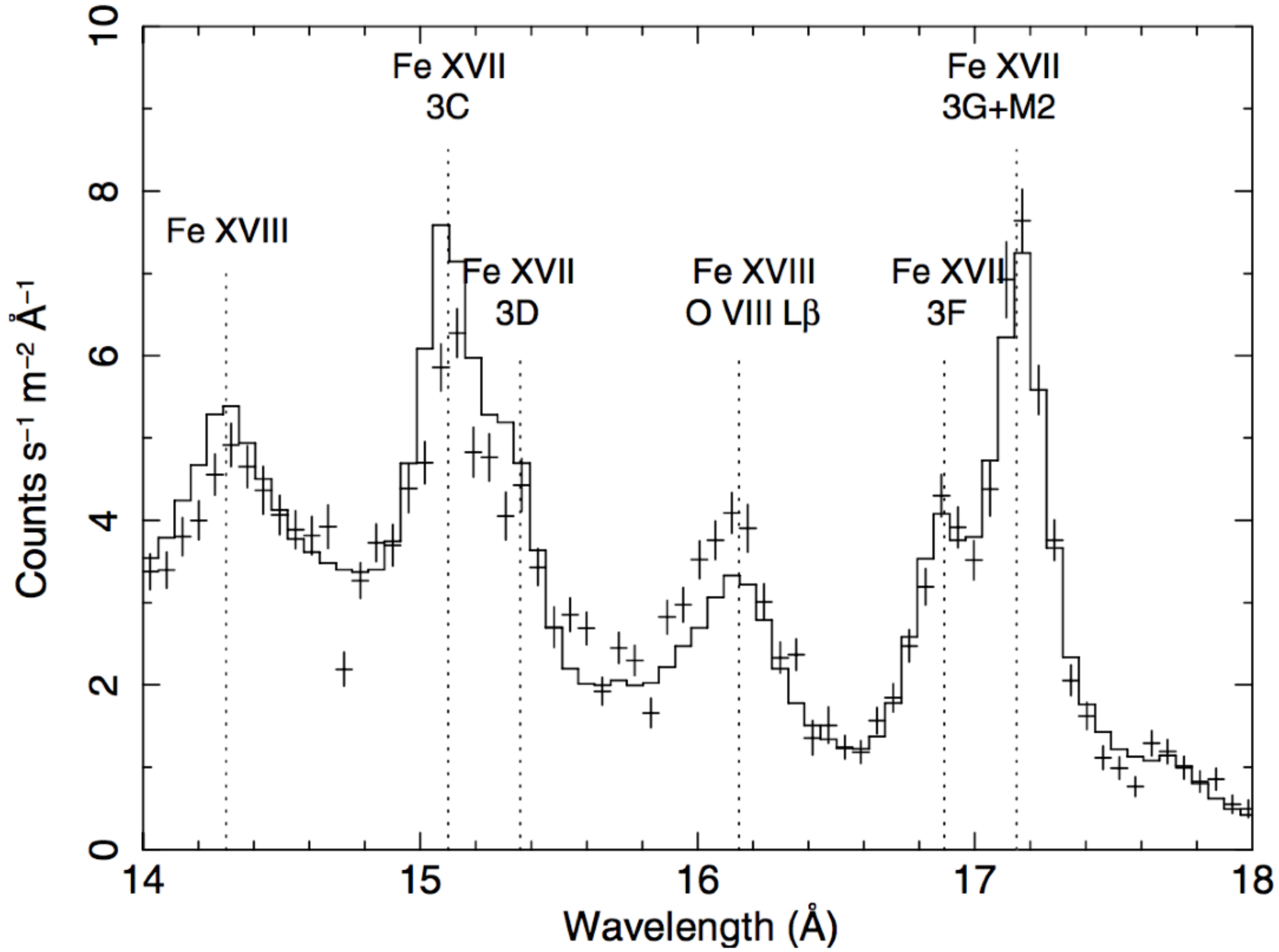
$$\tau = \int_0^\infty \frac{\sqrt{2\pi} h r_e c f}{\sigma} n_p Z \delta_i dr$$

~ kinematic SZ (sub-dominant to thermal SZ unless v reaches ~ thousands of km/s)

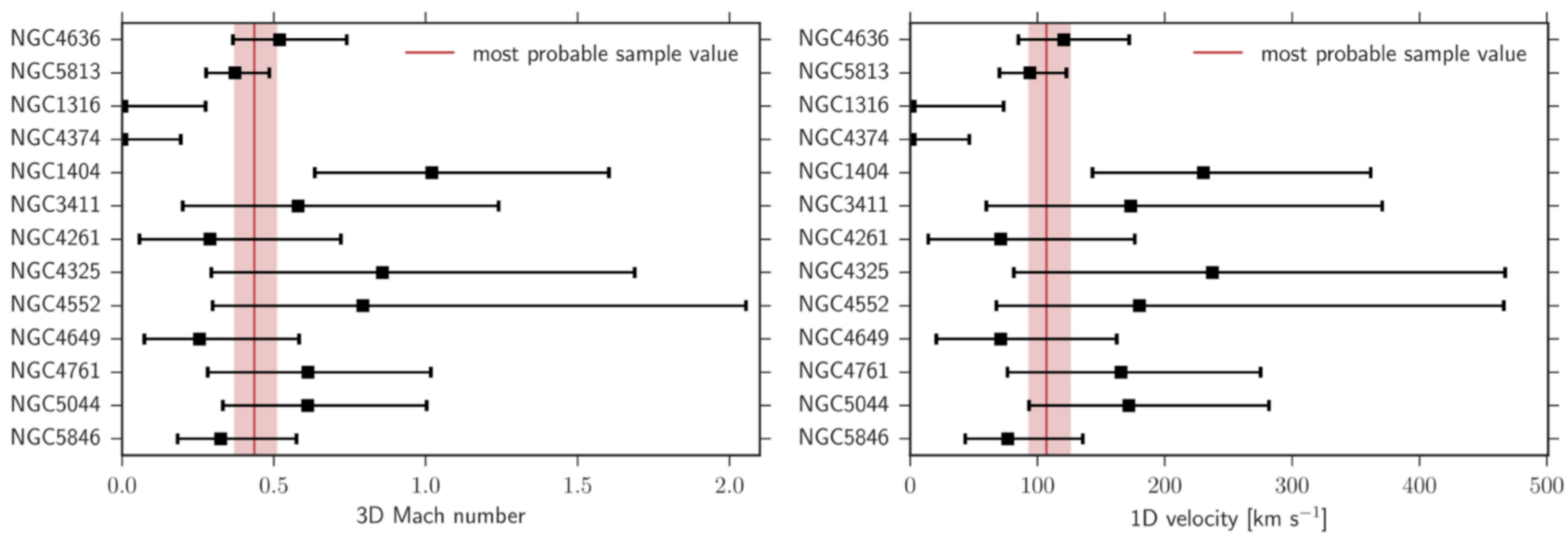
$$\frac{\Delta T}{T} = -\sigma_{\rm T} \int n_e \boldsymbol{\beta} d\ell$$

~ use optical line emitting nebulae as tracers of hot phase?

XMM-Newton RGS

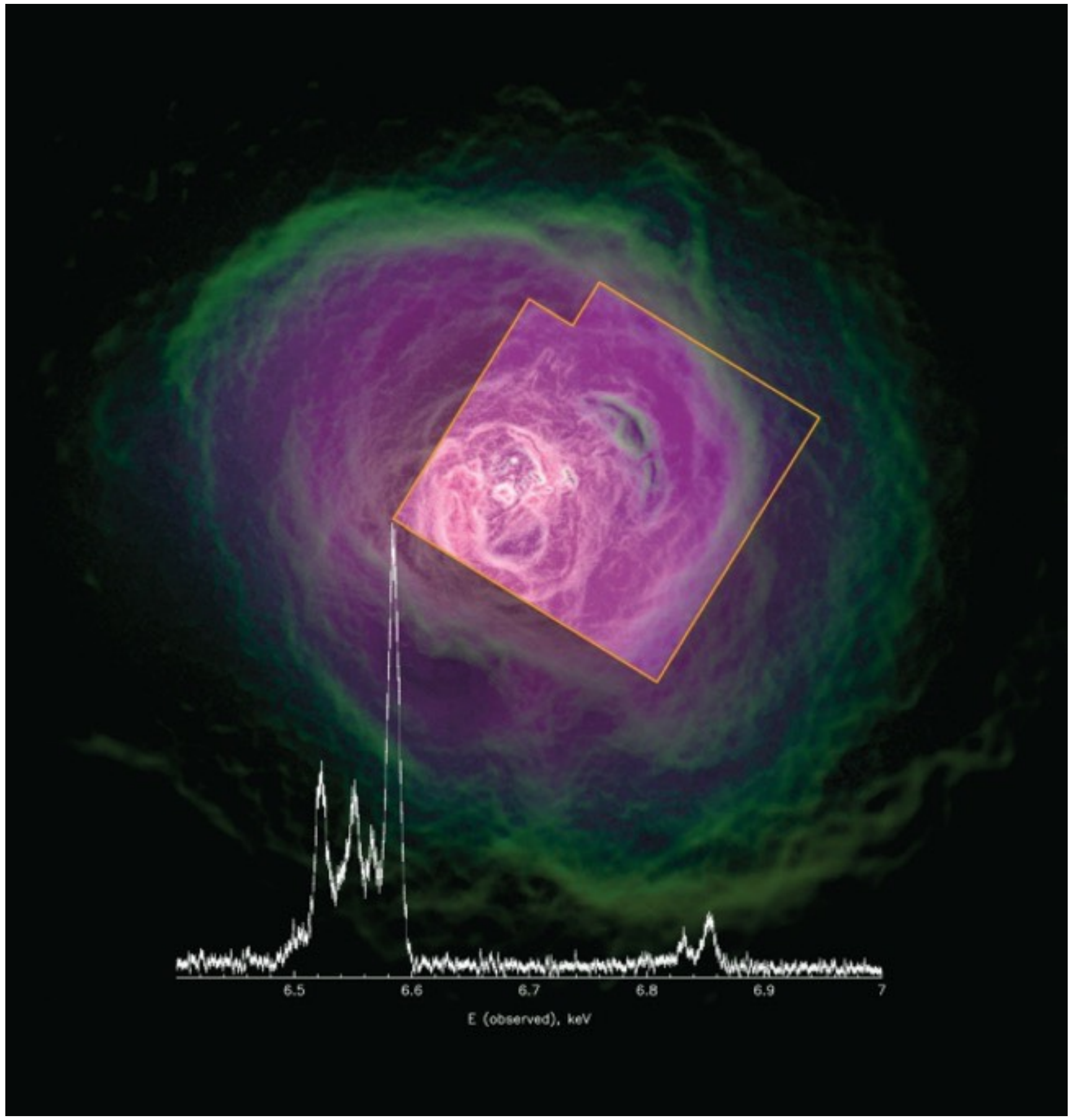


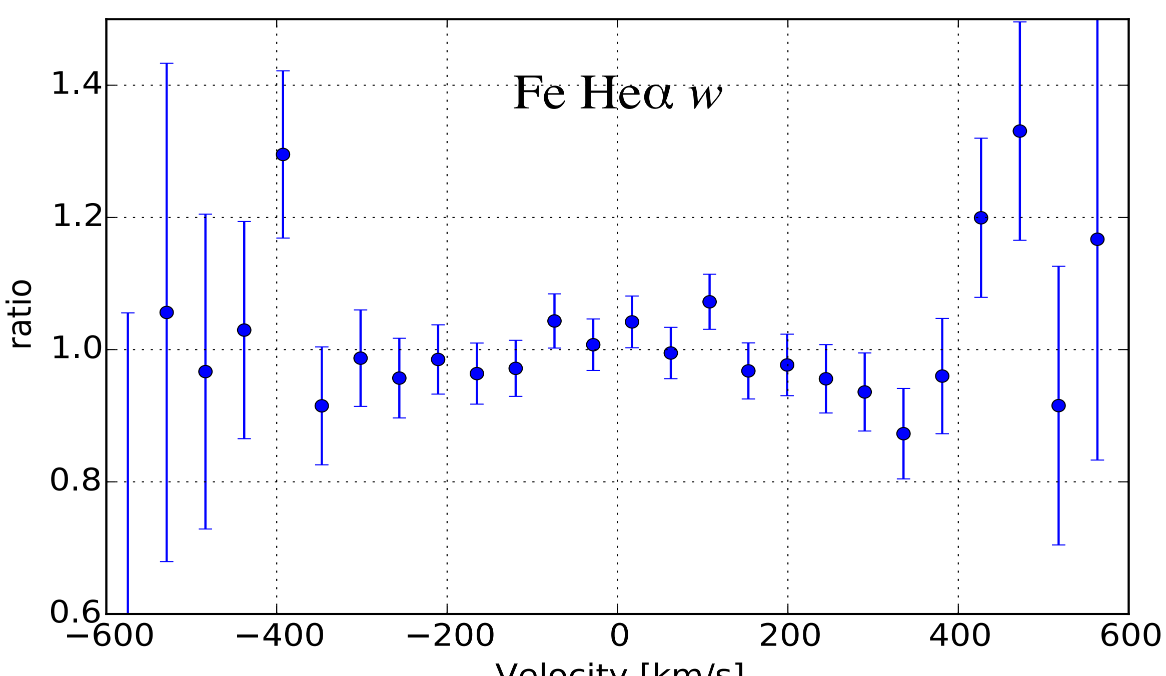
de Plaa et al. 2012
NGC5813

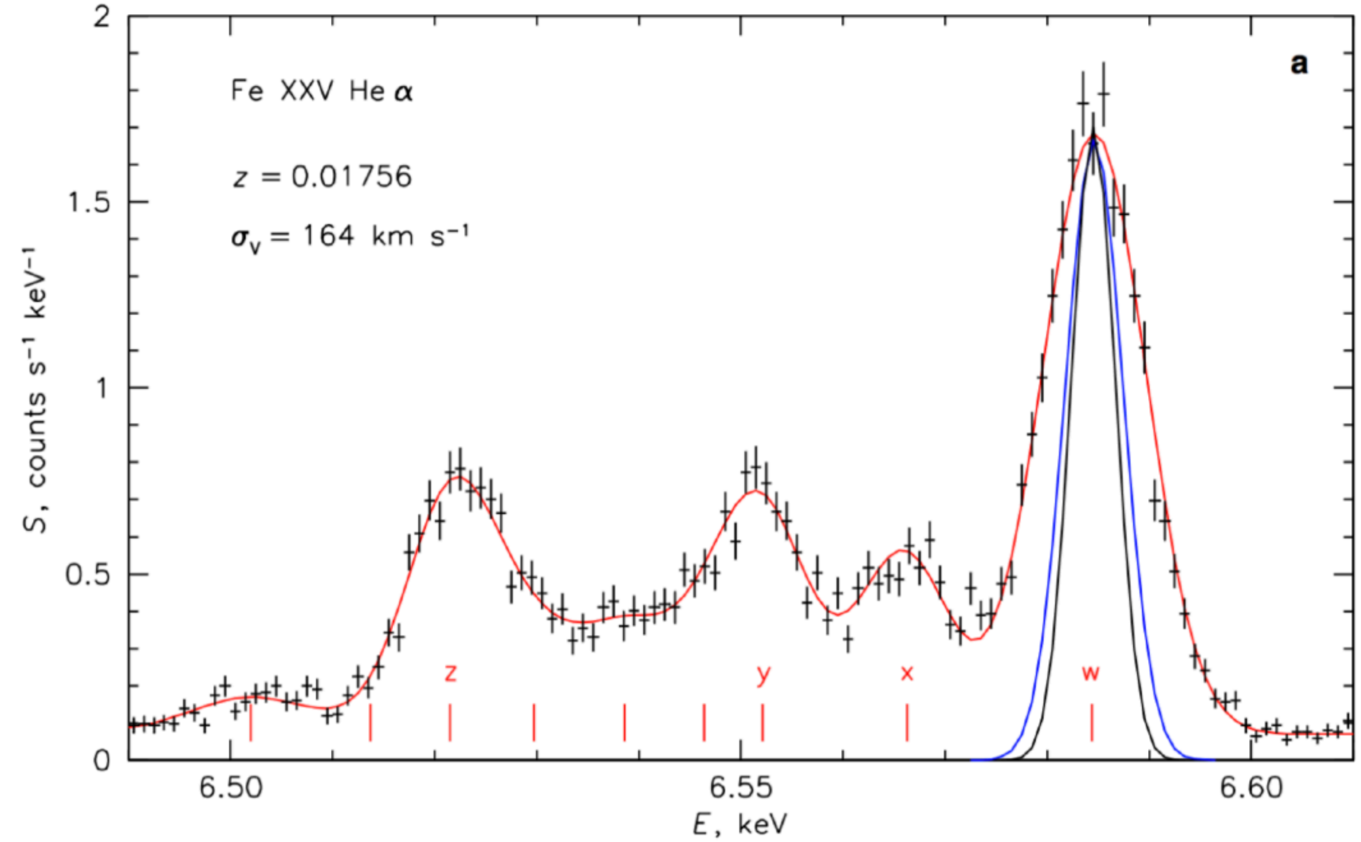


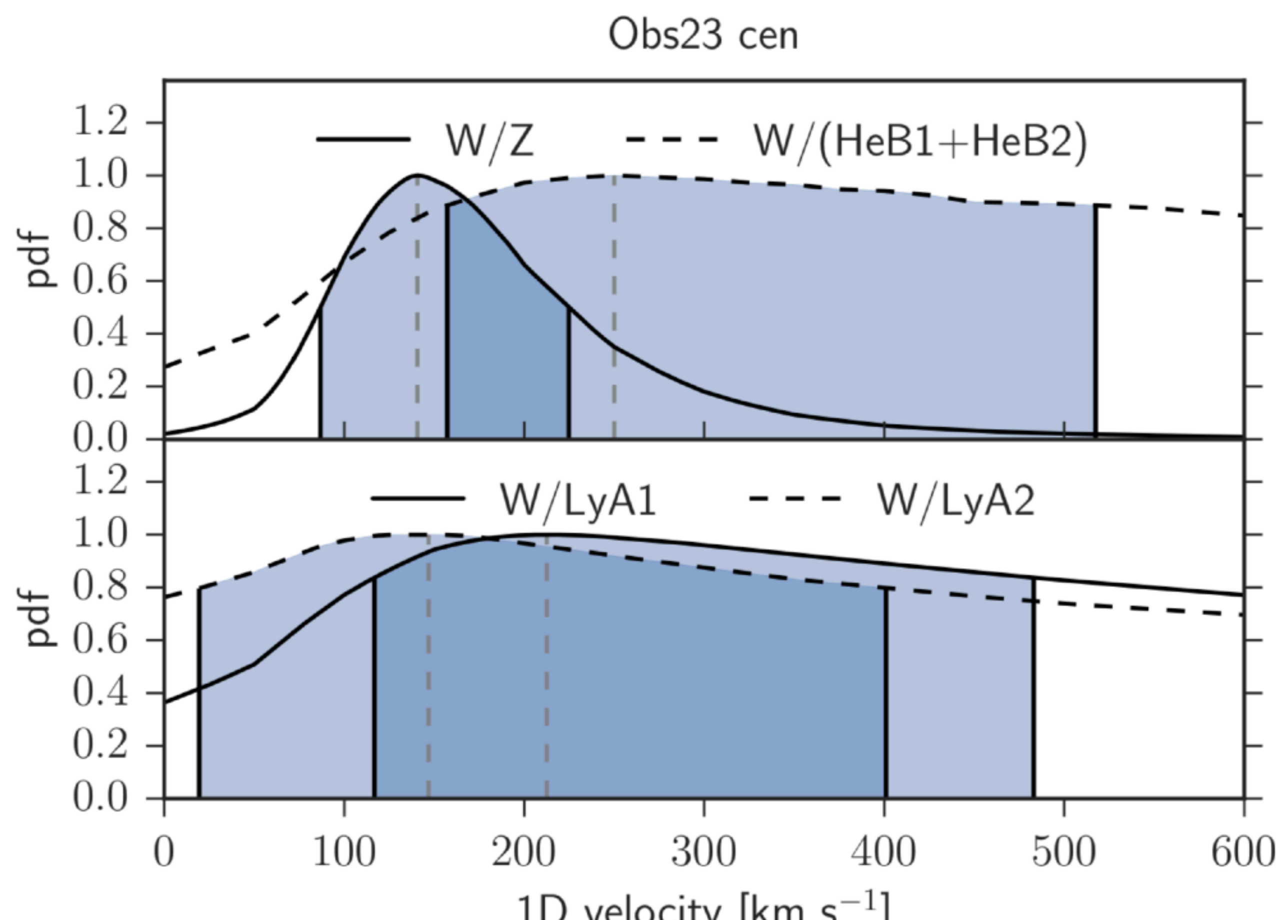
Ogorzalek et al. 2017

Perseus

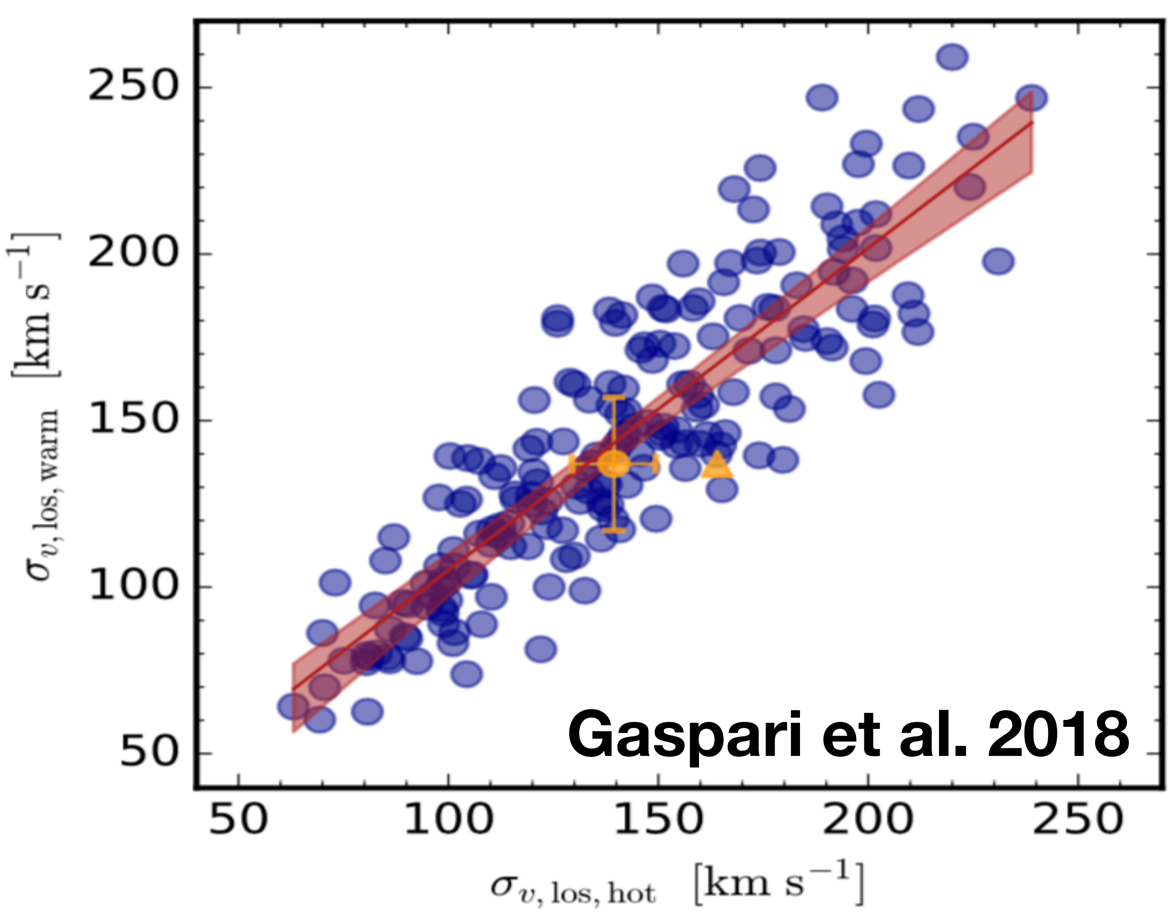

6.5
6.6
6.7
6.8
6.9
7
E (observed), keV

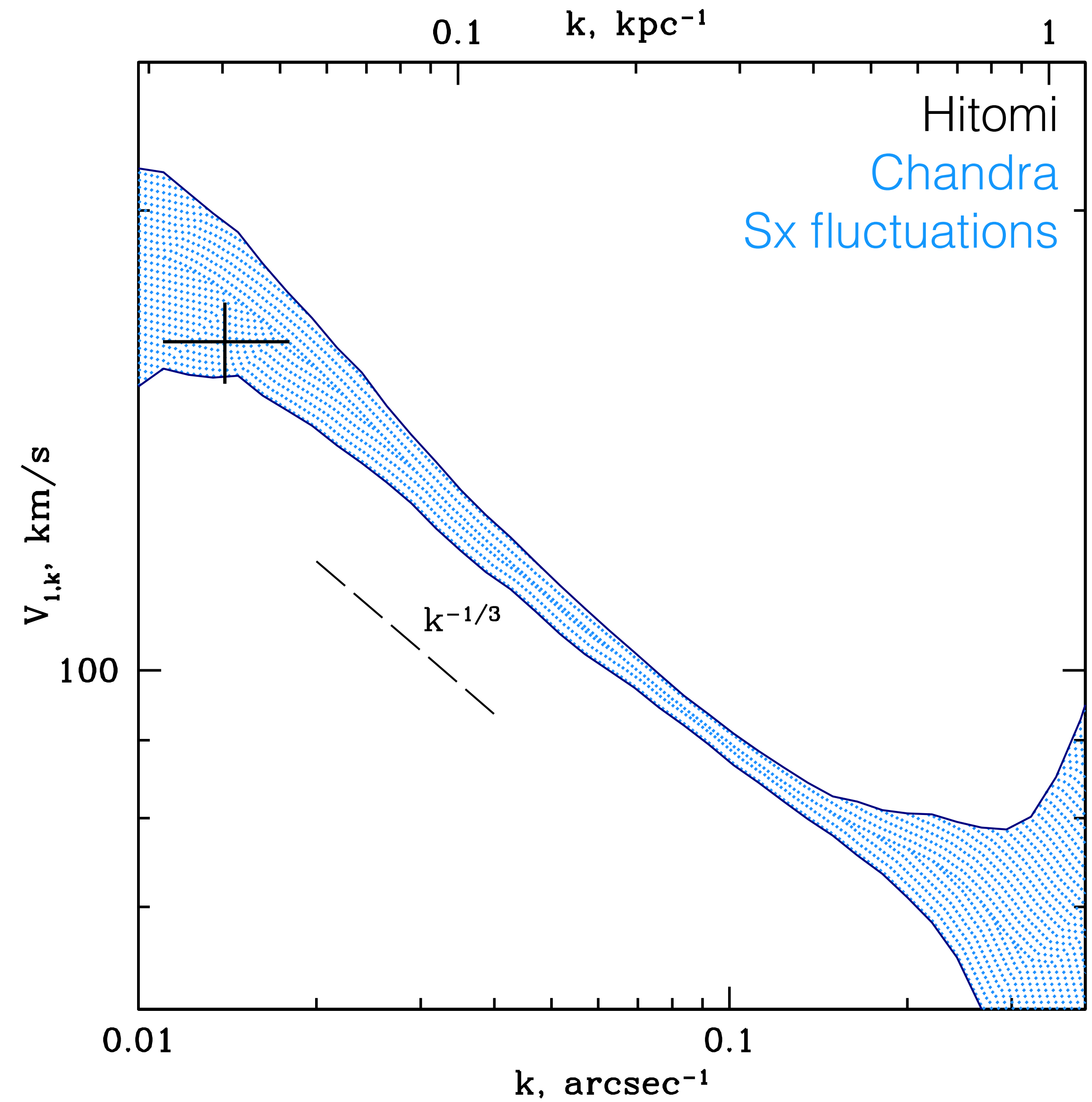

Fe Heα w
ratio
1.4
1.2
1.0
0.8
0.6
−600
−400
−200
0
200
400
600
Velocity [km/s]


Fe XXV He α
z = 0.01756
σv = 164 km s⁻¹
a
S, counts s⁻¹ keV⁻¹
2
1.5
1
0.5
0
z
y
x
w
6.50
6.55
6.60
E, keV


Obs23 cen
W/Z
W/(HeB1+HeB2)
W/LyA1
W/LyA2
pdf
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
600
1D velocity [km s⁻¹]

Perseus direct vs. indirect velocity measurements





The fine print

Drivers of turbulence in the intracluster medium

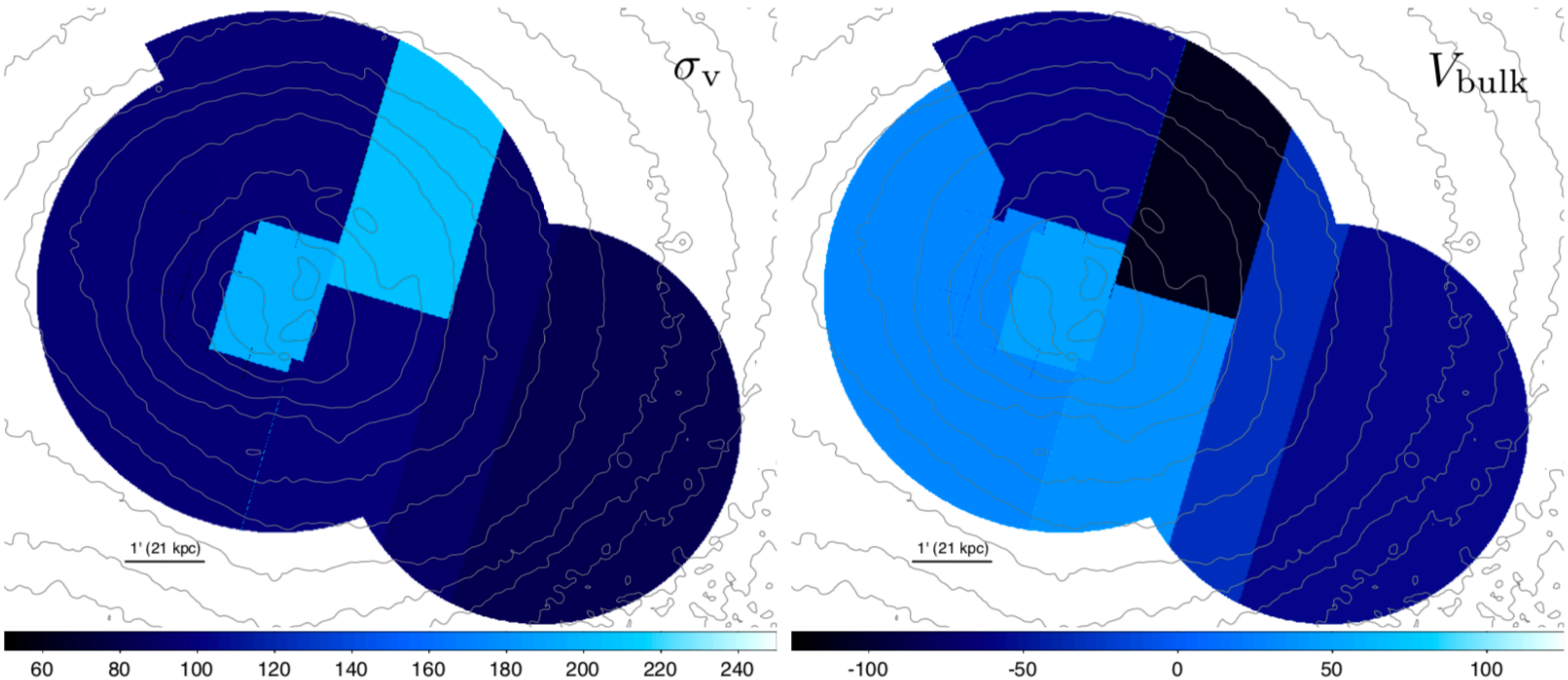
~ integrated history of large-scale structure growth
~ recent accretion and mergers
~ feedback from supermassive black holes
~ motions of member galaxies through ICM

All of these are at play and all are predicted to drive turbulence at the ~few 100 km/s level

+we are necessarily integrating along the line of sight and over a pretty large region of space!

How do we distinguish what is the contribution from each physical mechanism?

Perseus, spatially resolved (kind of)



Turbulence higher in regions that have AGN bubbles.
What does that imply for the physics of AGN feedback?
[further discussion by Mateusz]