# Indirect Turbulence Measurements in Galaxy Clusters with Hitomi and Chandra

Irina Zhuravleva
KIPAC, Stanford University

**Diffuse Synchrotron Emission in Clusters of Galaxies – What's Next?**
**Leiden | 24 Oct, 2017**

# Indirect Turbulence Measurements in Galaxy Clusters with Hitomi and Chandra

Irina Zhuravleva
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1. Resonant scattering velocity measurements with Hitomi
on behalf of Hitomi collaboration

2. Velocity power spectra measurements with Chandra
in collaboration with S. Allen, P.Arevalo, E. Churazov, W. Forman, A. Schekochihin

**Diffuse Synchrotron Emission in Clusters of Galaxies – What's Next?**
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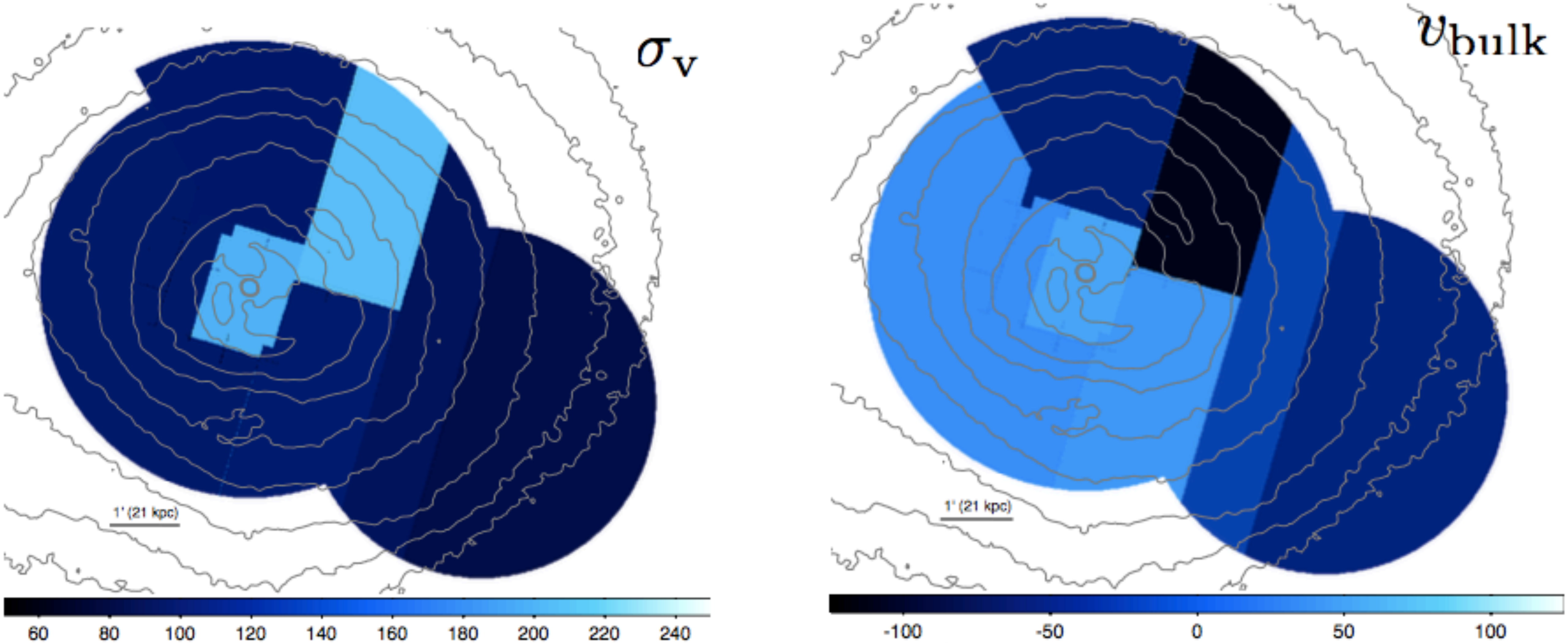
# Doppler broadening velocity measurements with Hitomi



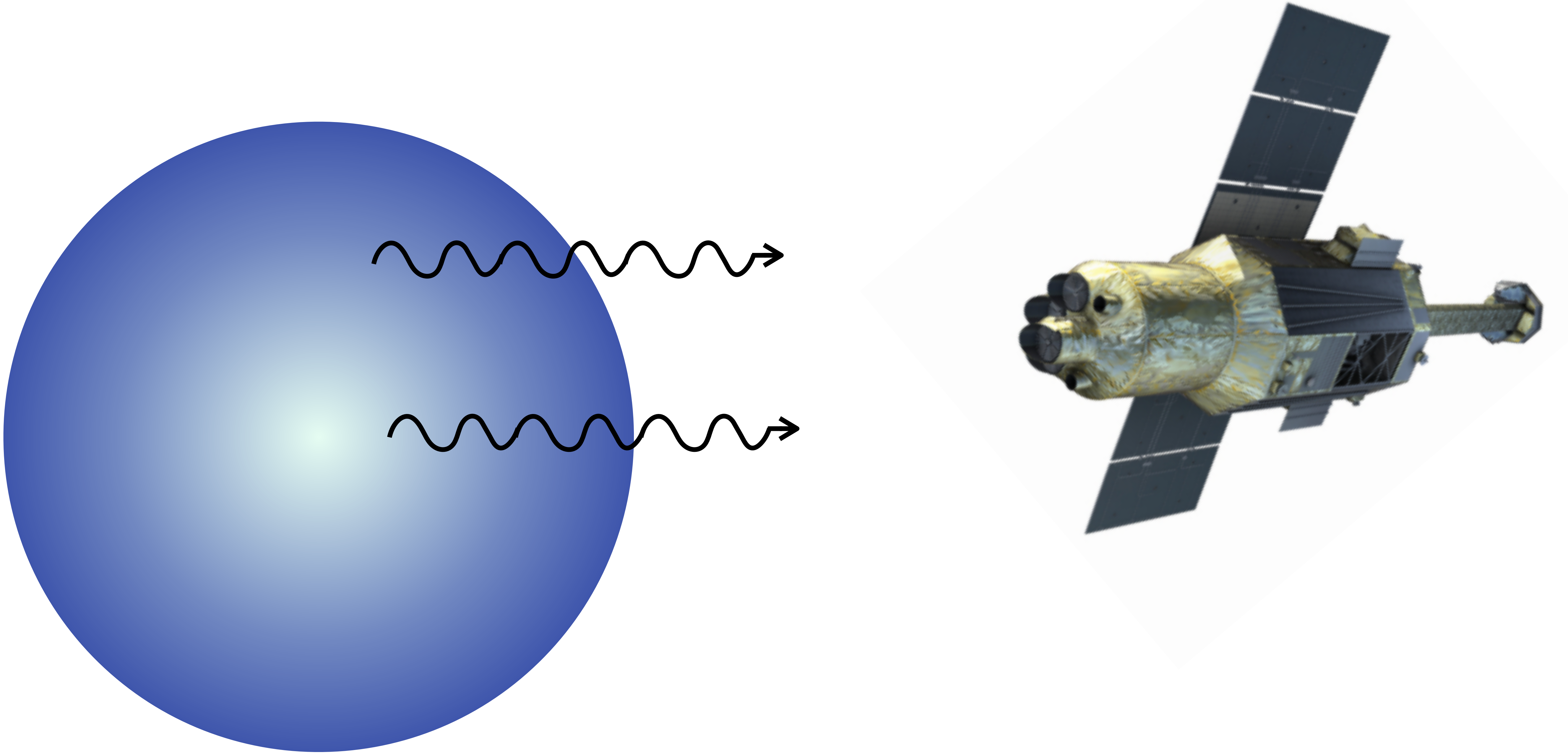

see talk by M. Markevitch

**$V_{tot}$~ 300 – 430 km/s or M~0.3–0.4 —> subsonic motions**

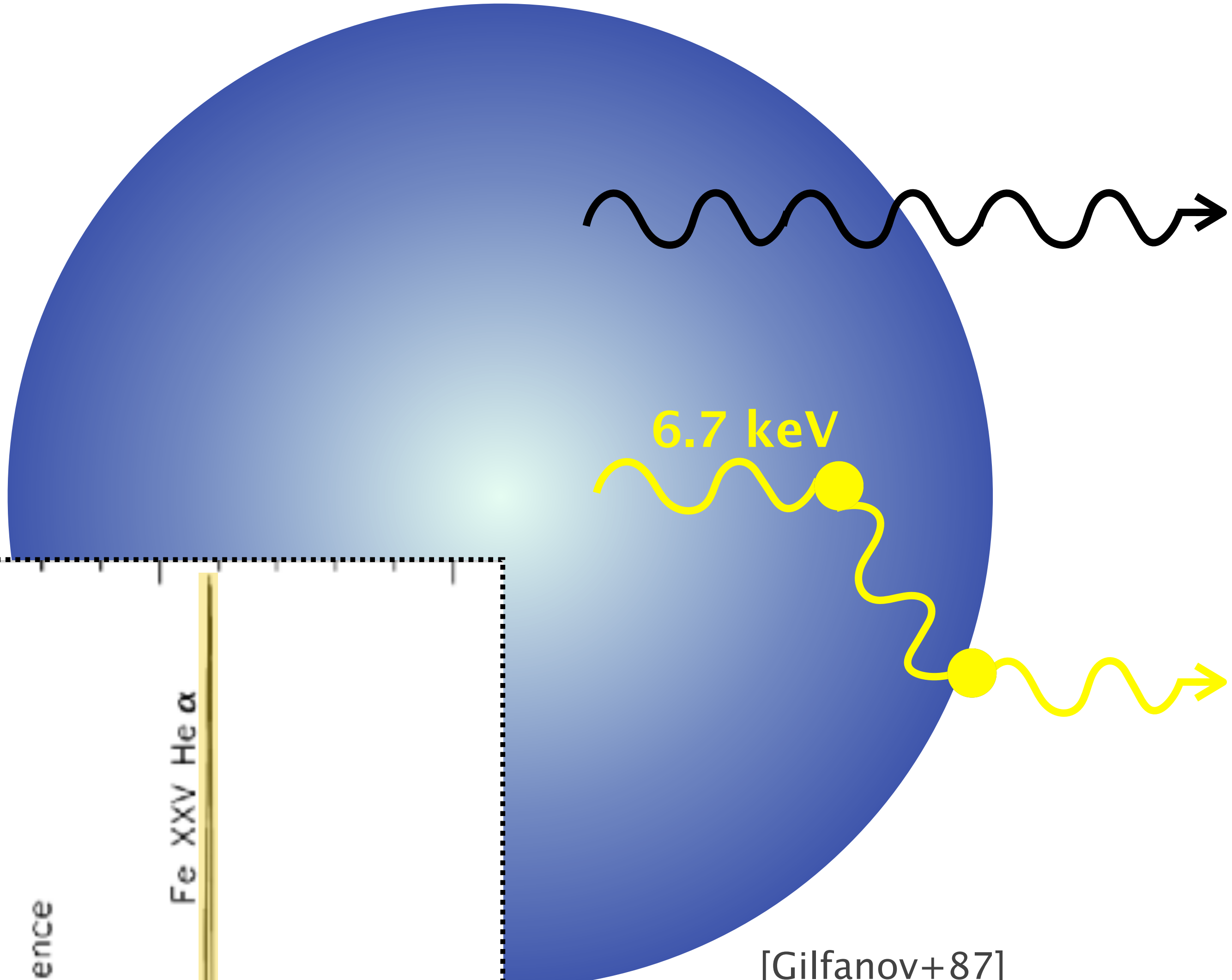
[Hitomi collaboration: velocity paper, 2017, submitted]

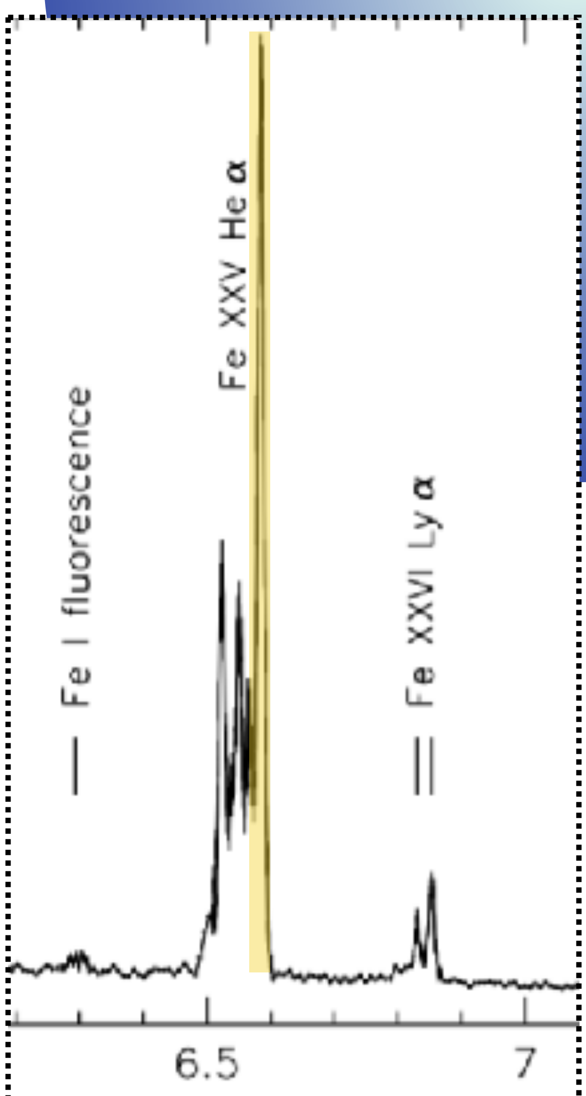
# Resonant scattering velocity measurements with Hitomi

# Resonant scattering



# Resonant scattering



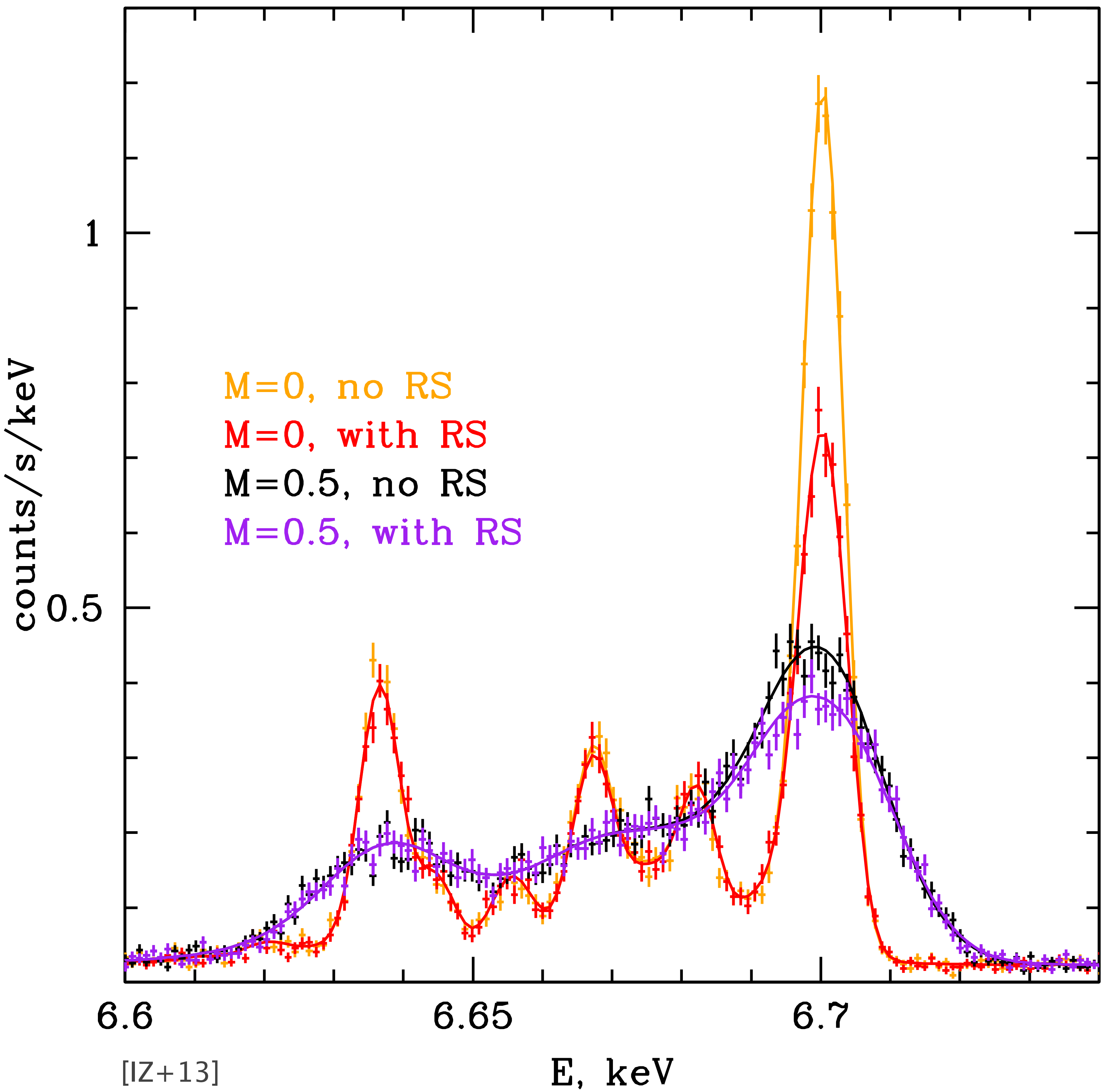




[Gilfanov+87]

- RS changes the flux of the strongest line
- RS ~ optical depth ~ (line width)$^{-1}$ —> $V_{turb}$

# Resonant scattering

Radiative transfer simulations for the Perseus cluster
mock Hitomi spectrum: 100 ks



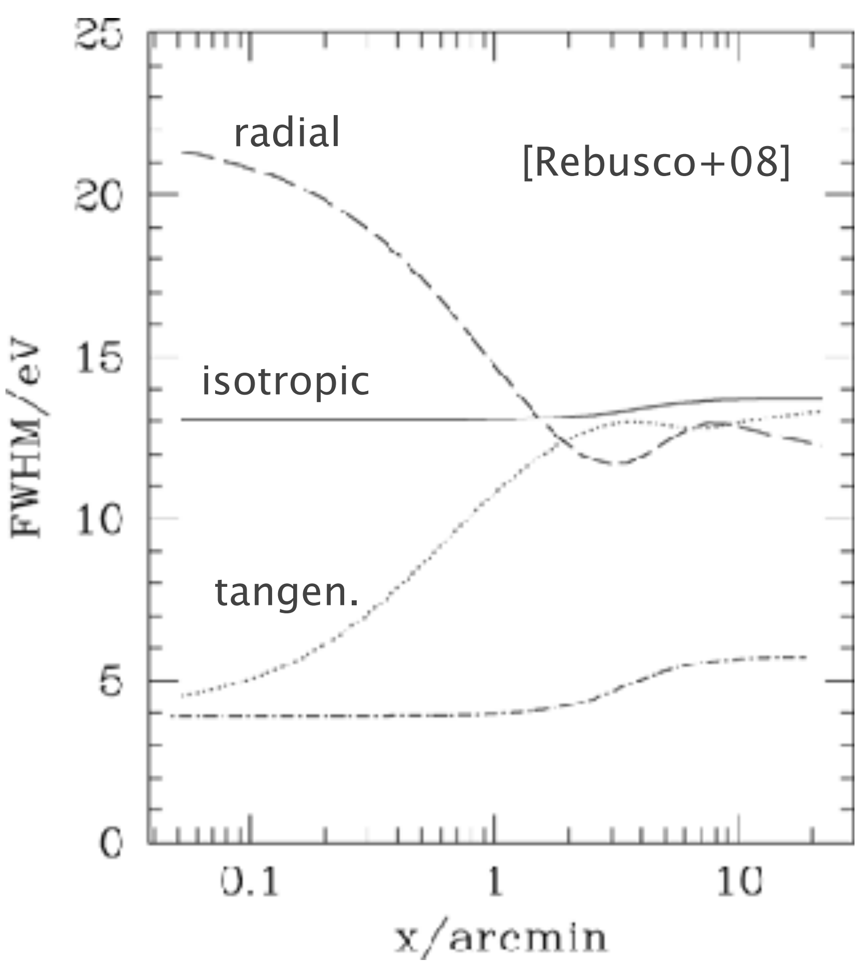

[IZ+13]

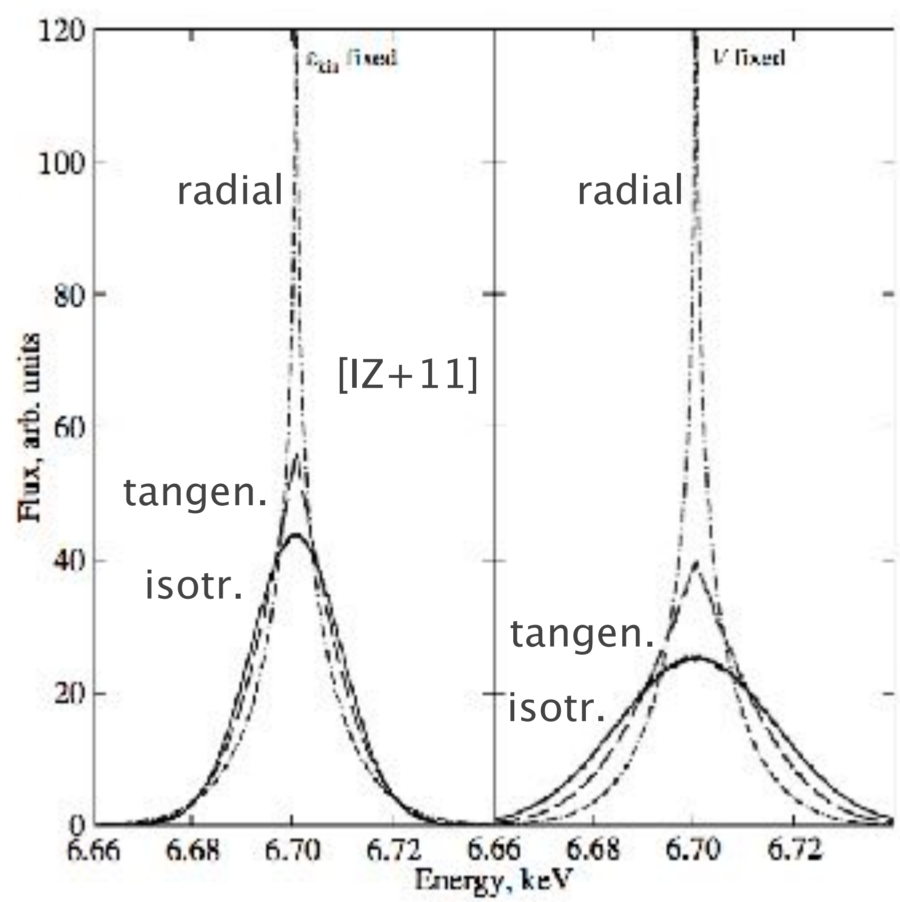
# Doppler Broadening and Resonant Scattering

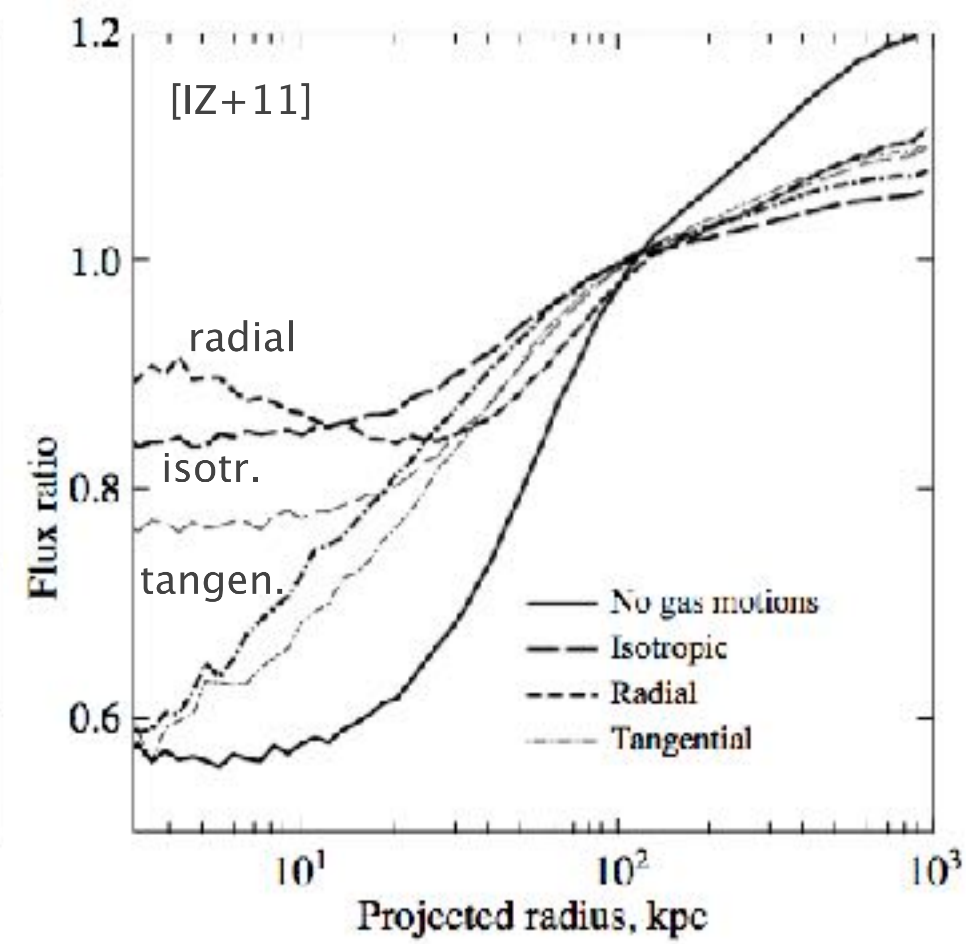
complementary, non-redundant constraints on the V field

1. $\mathrm{DB} \propto \int V \cdot n^2 dl \qquad \mathrm{RS} \propto \int V \cdot n dl$

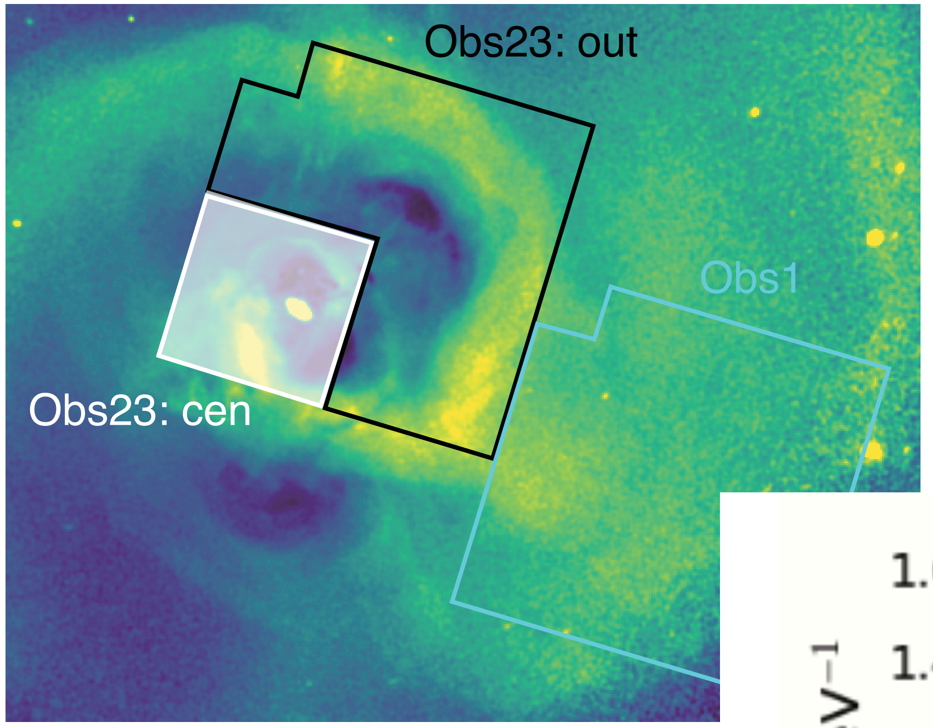
2. anisotropy of motions

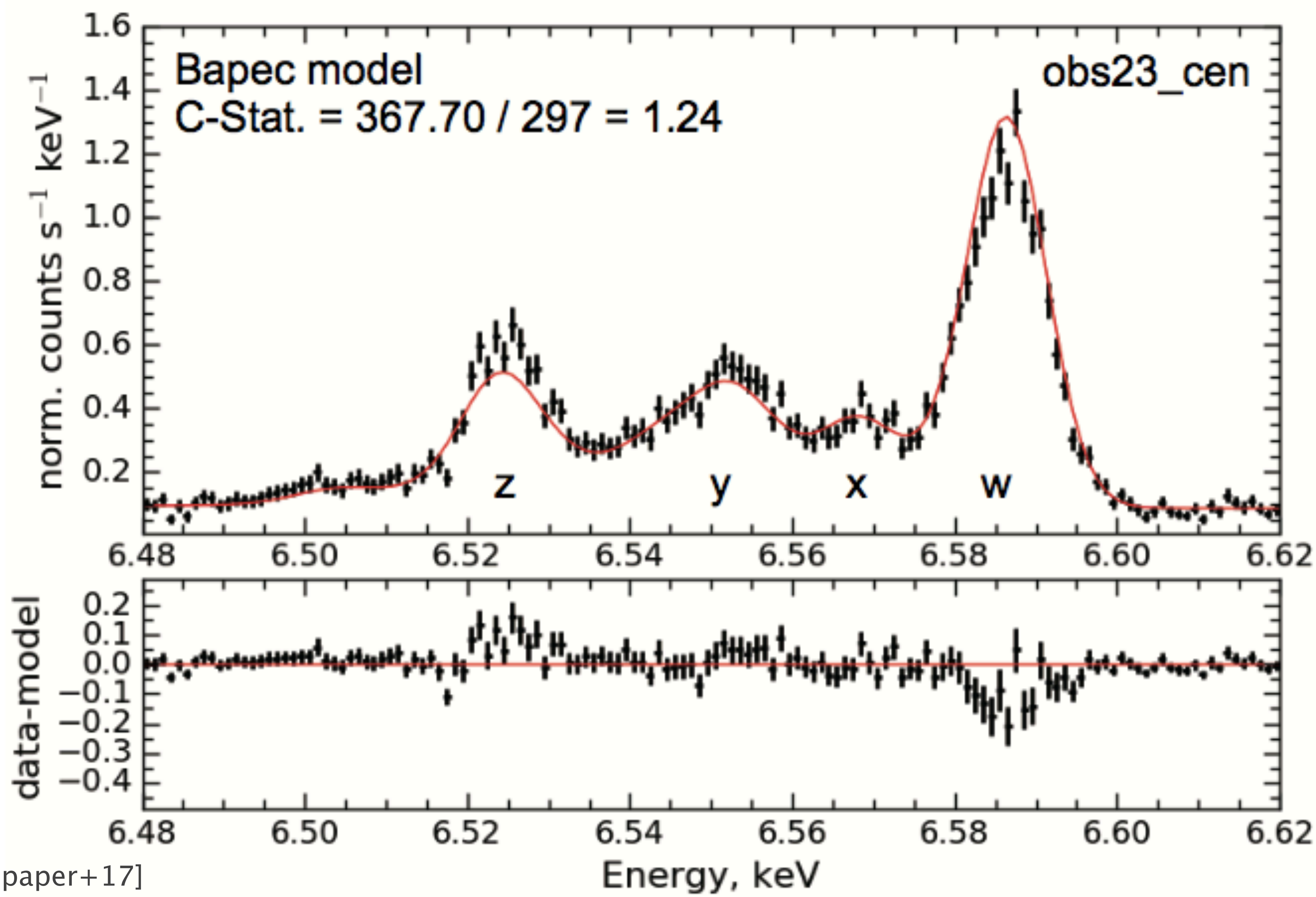


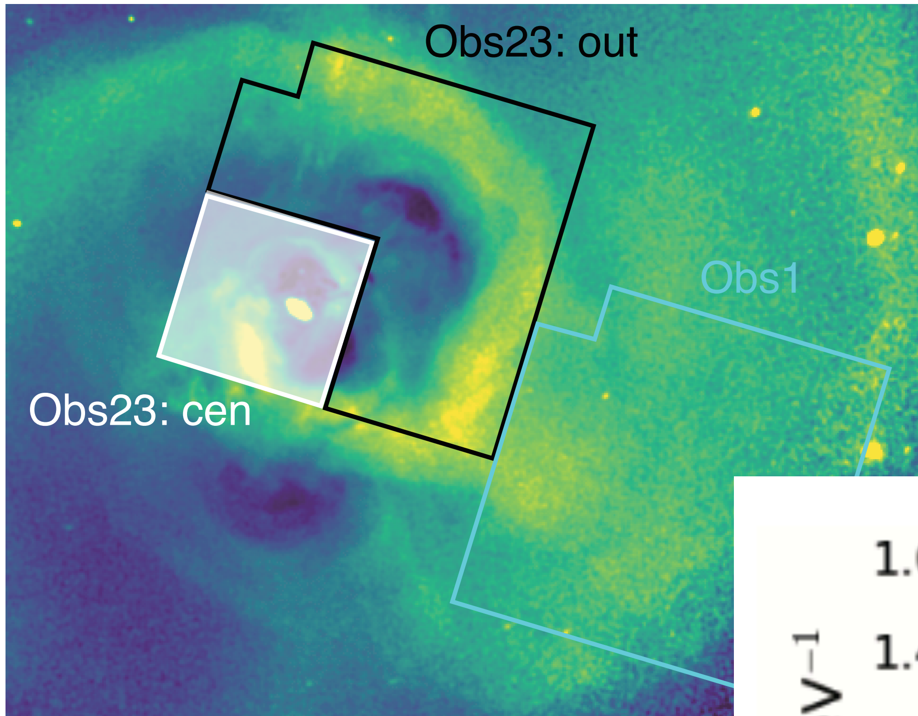
# Did Hitomi see the scattering?

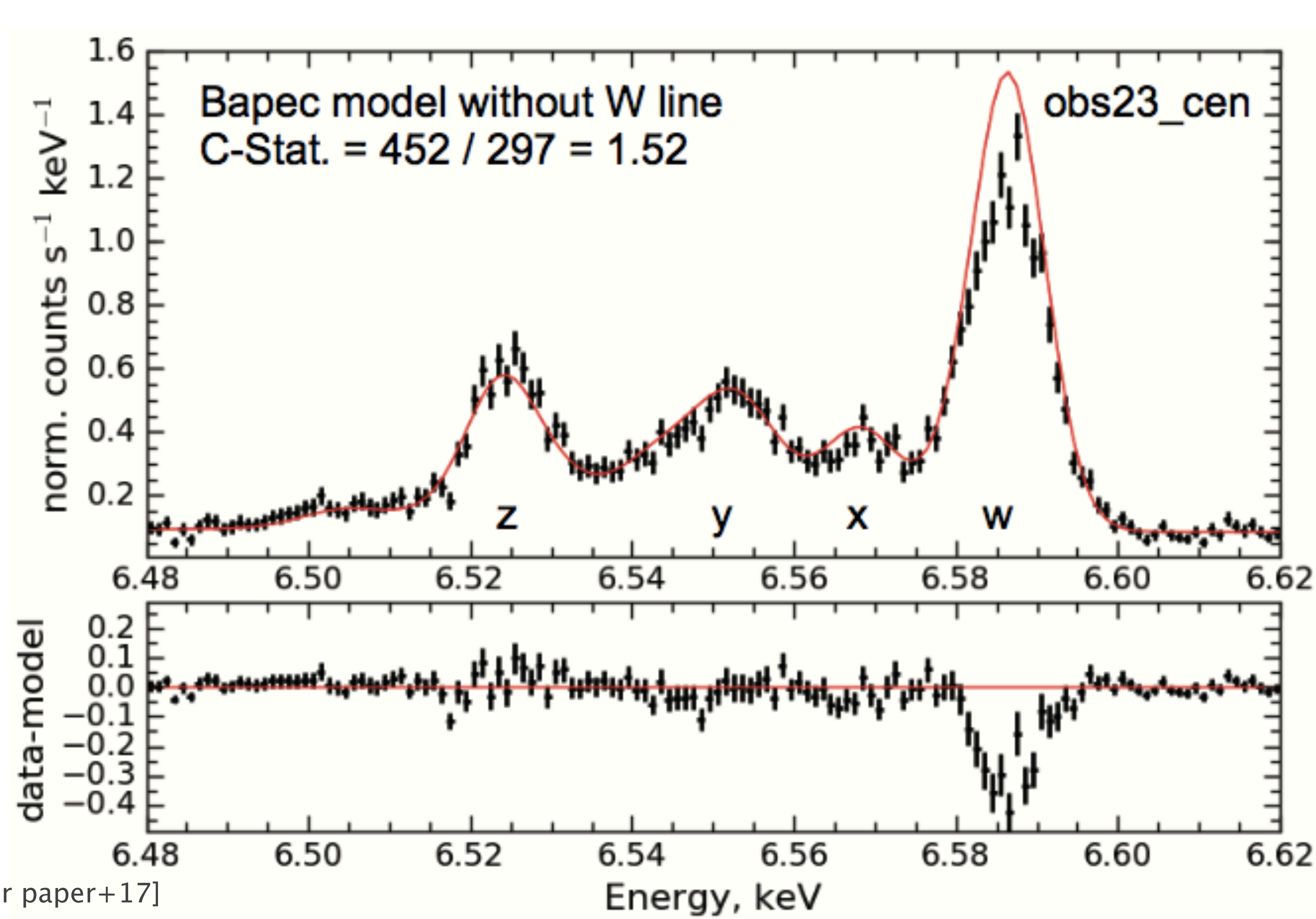



[Hitomi collaboration: radiative transfer paper+17]

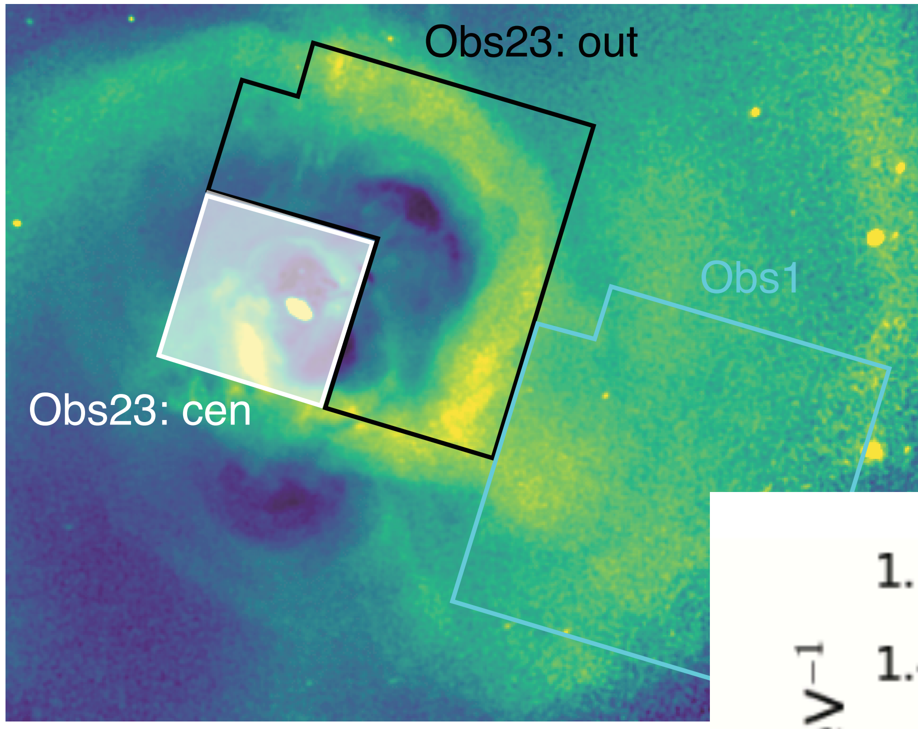
# Did Hitomi see the scattering?

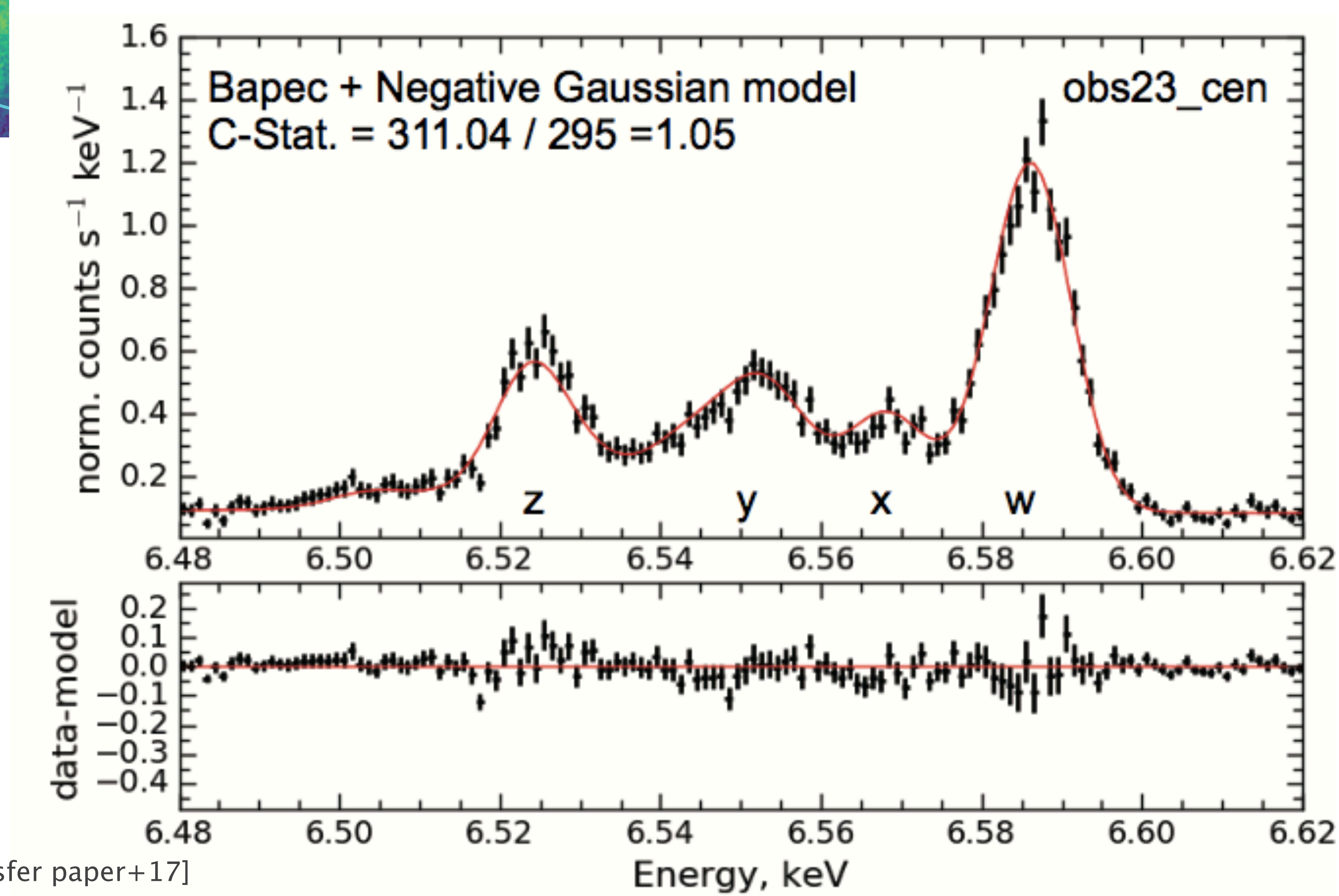



[Hitomi collaboration: radiative transfer paper+17]

# Did Hitomi see the scattering?

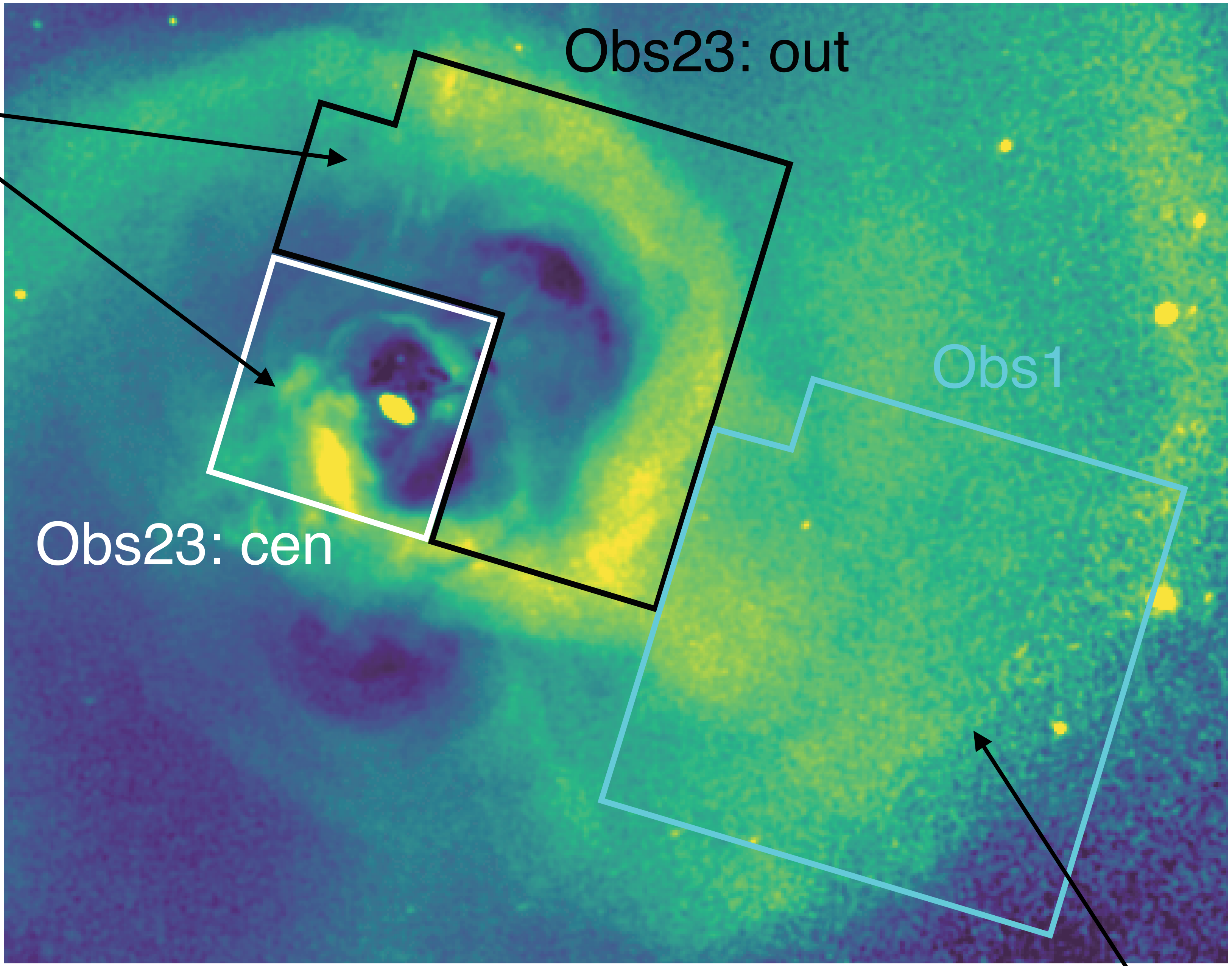



[Hitomi collaboration: radiative transfer paper+17]

# Hitomi observations of RS in Perseus

line is suppressed by a factor of ~ 1.3



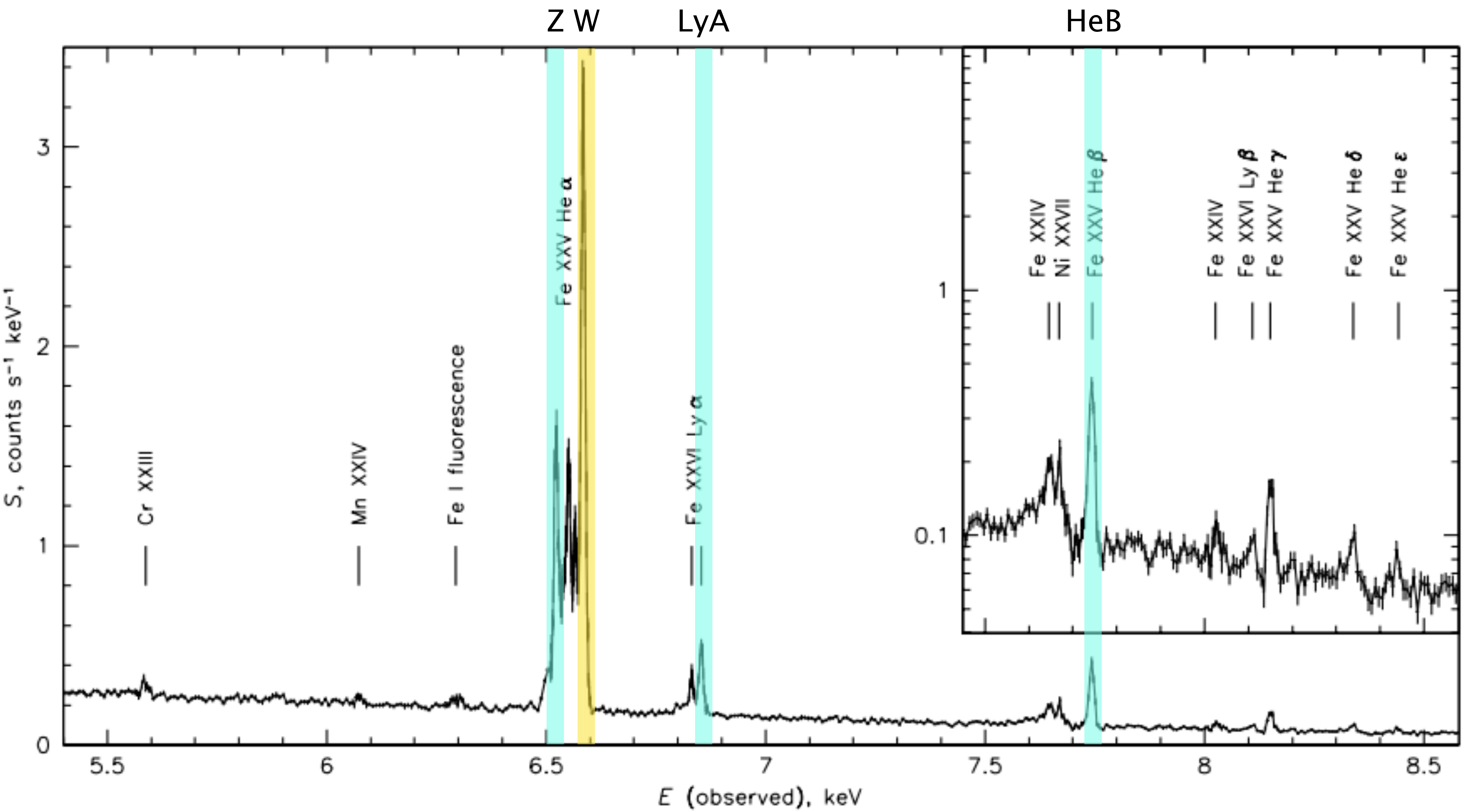

line is suppressed by a factor of ~ 1.15

**Consistent with theoretical predictions!**

[Gilfanov+87; Churazov+04; IZ+11 & 13]

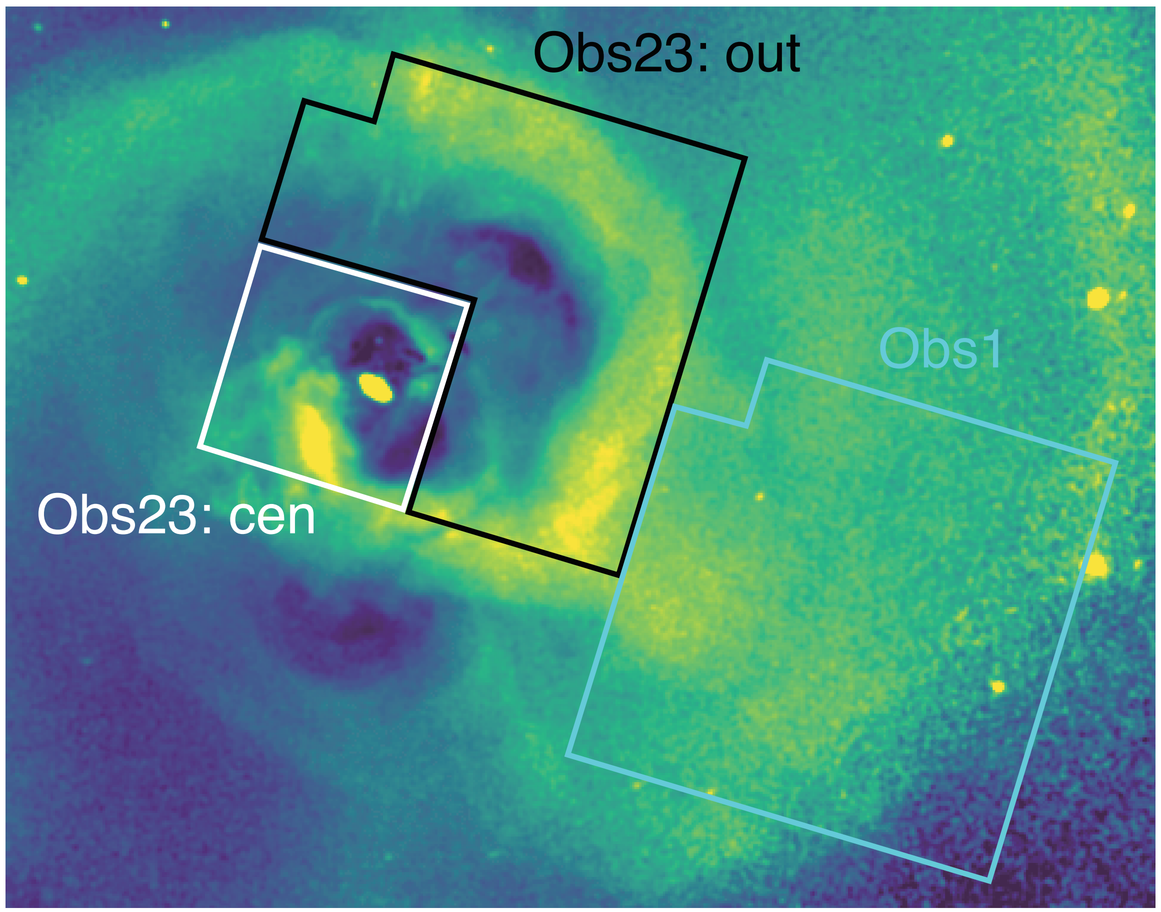
[Hitomi collaboration: radiative transfer paper+17]

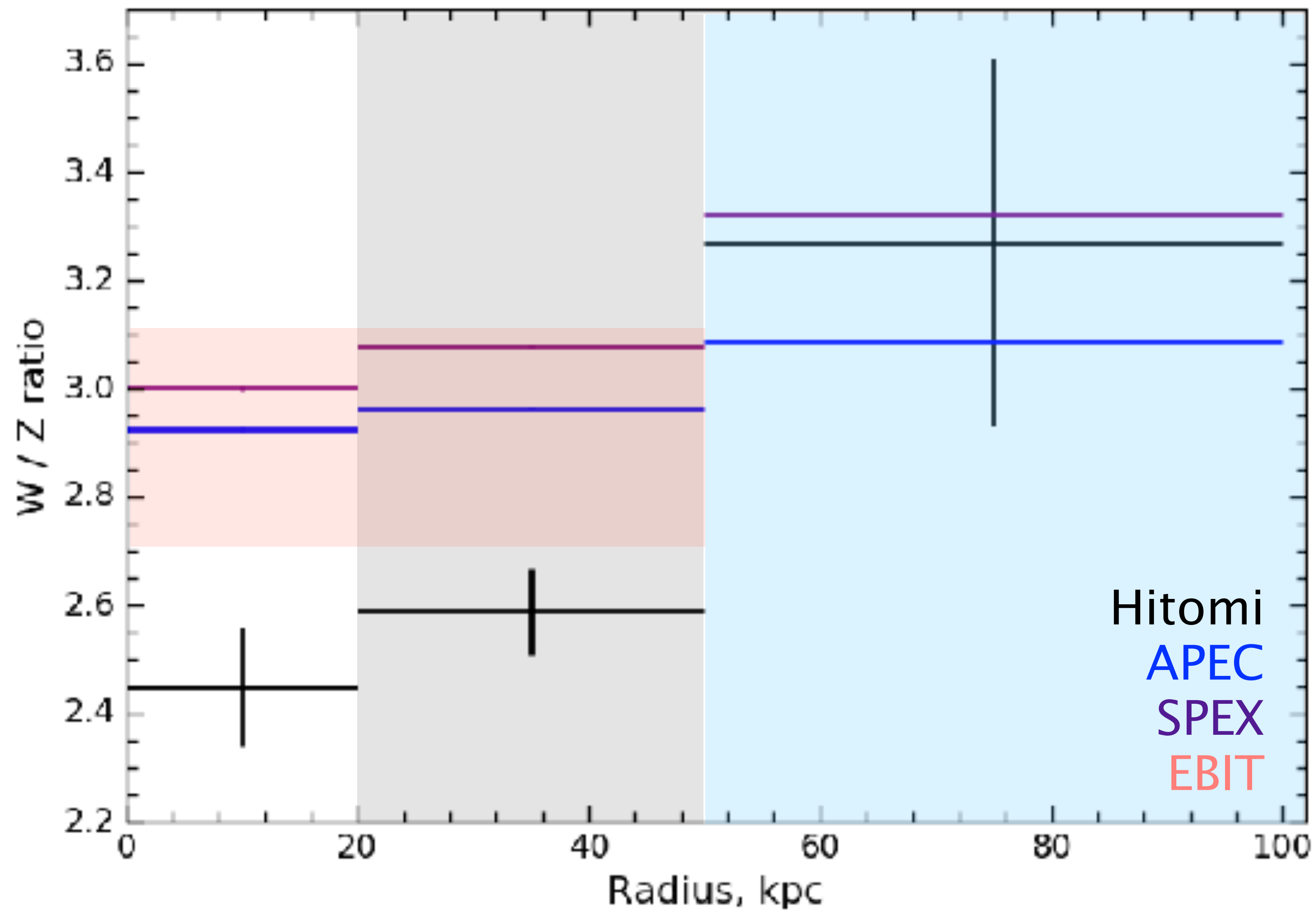
# RS velocity measurements with Hitomi




Bapec model with excluded W, Z, LyA and HeB lines + Gaussians
Measure the ratios of fluxes in W/Z, W/LyA, W/HeB

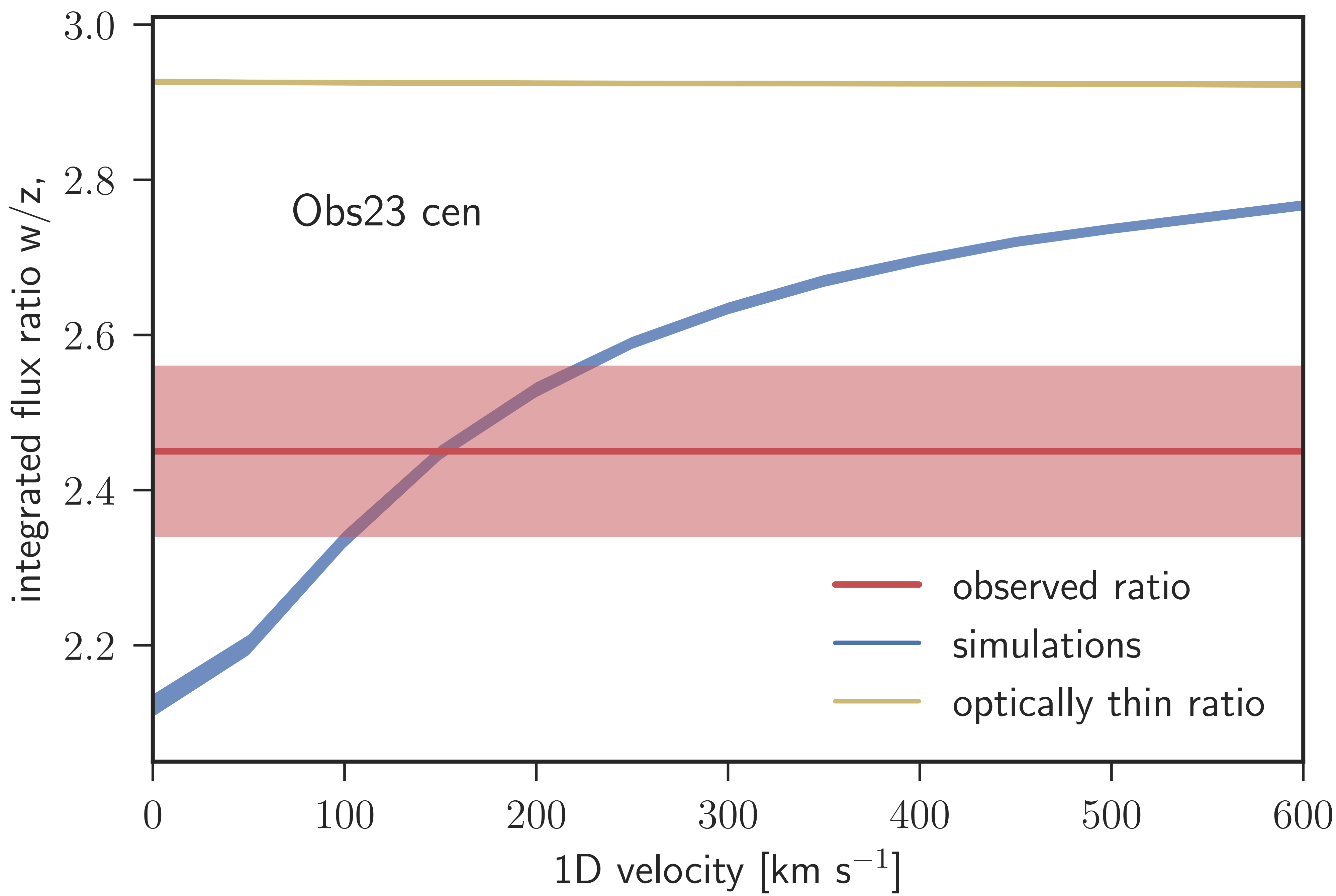
# RS velocity measurements with Hitomi



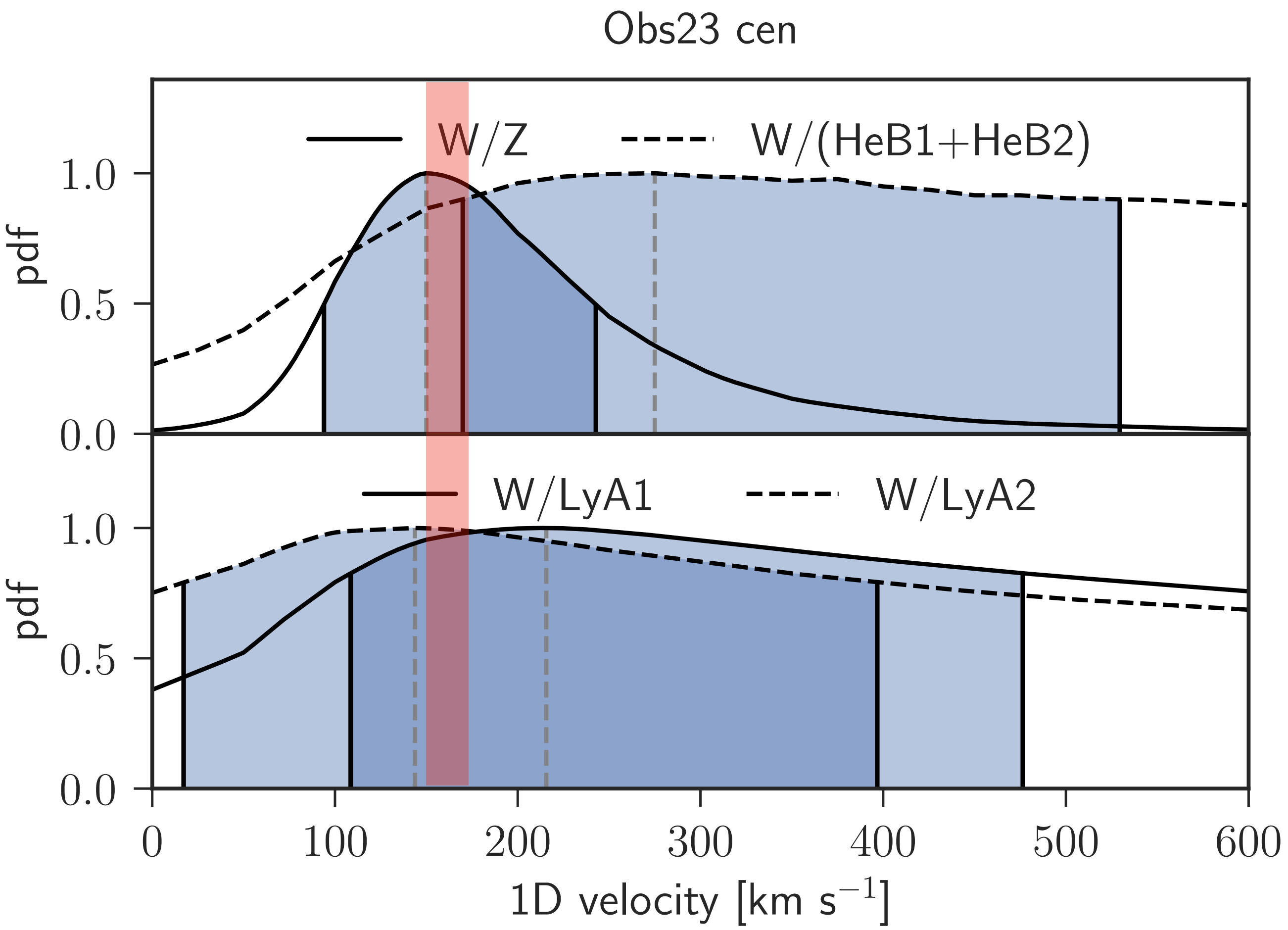

[Hitomi collaboration: radiative transfer paper+17]

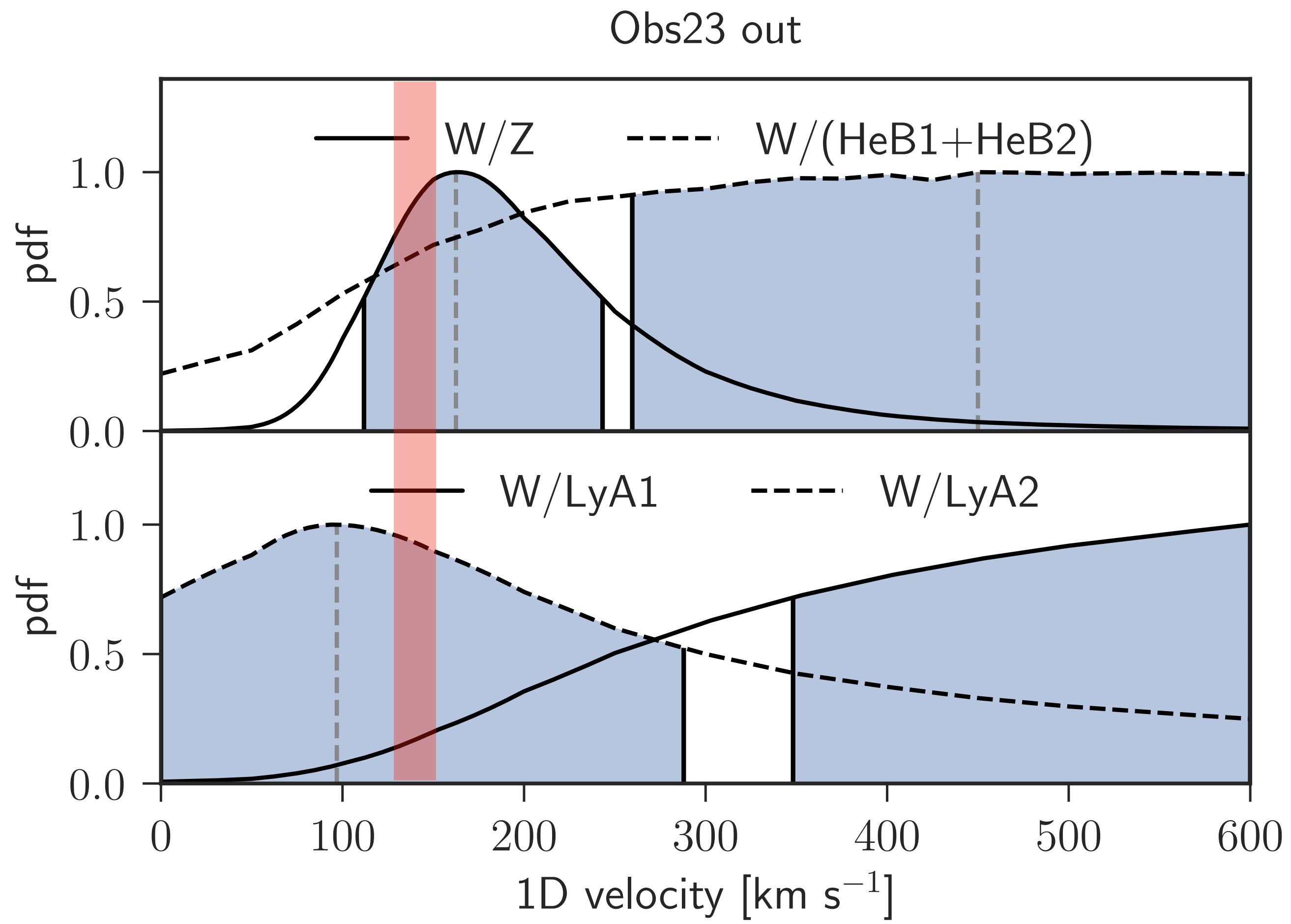
# RS velocity measurements with Hitomi




[for the method see IZ+13, Ogorzalek, IZ+17]

# RS velocity measurements with Hitomi




$$\mathrm{W/Z}: 150^{+80}_{-56}\,\mathrm{km/s}$$

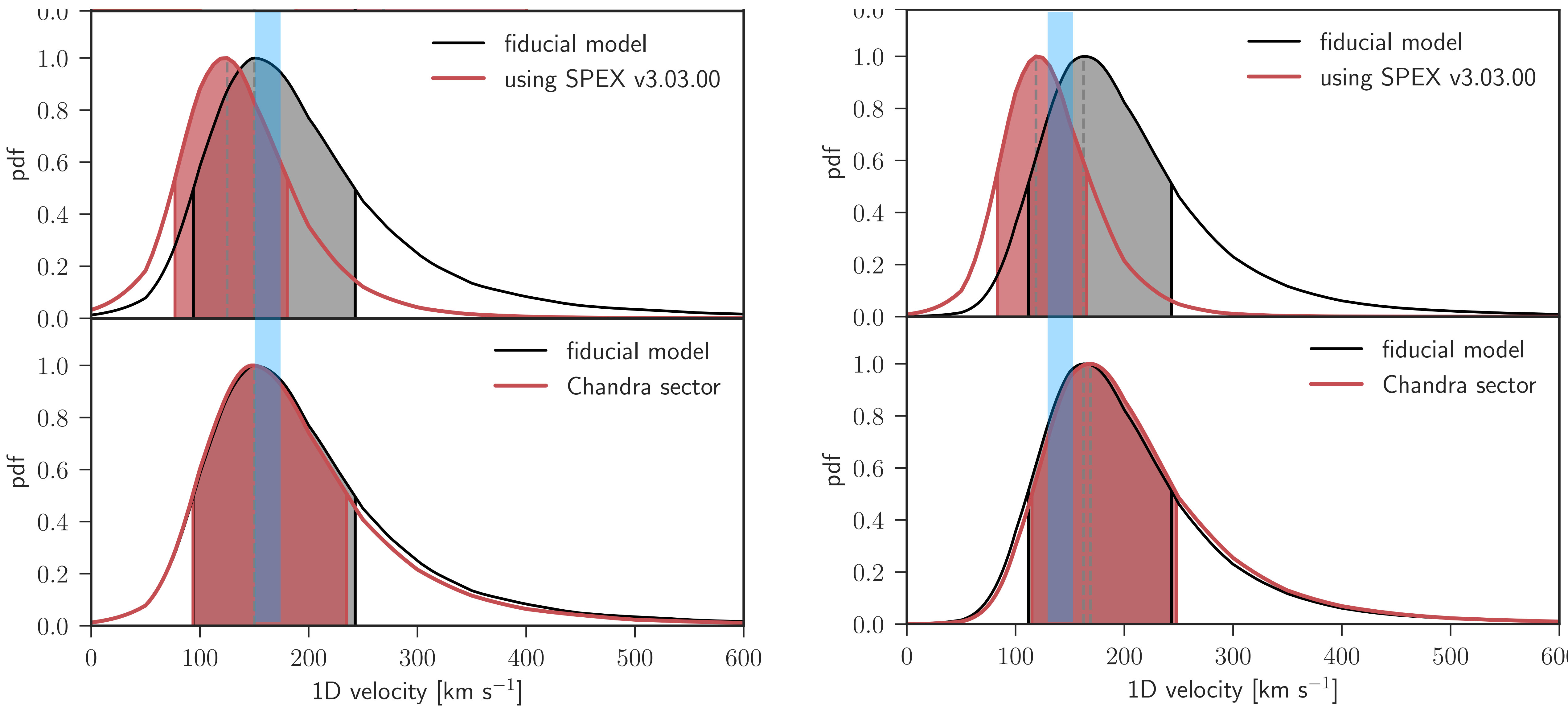
$$\sigma: 155 \pm 7\,\mathrm{km/s}$$

$$\mathrm{W/Z}: 162^{+78}_{-50}\,\mathrm{km/s}$$

$$\sigma: 141 \pm 5\,\mathrm{km/s}$$

[Hitomi collaboration: radiative transfer paper+17]

# RS velocity measurements with Hitomi

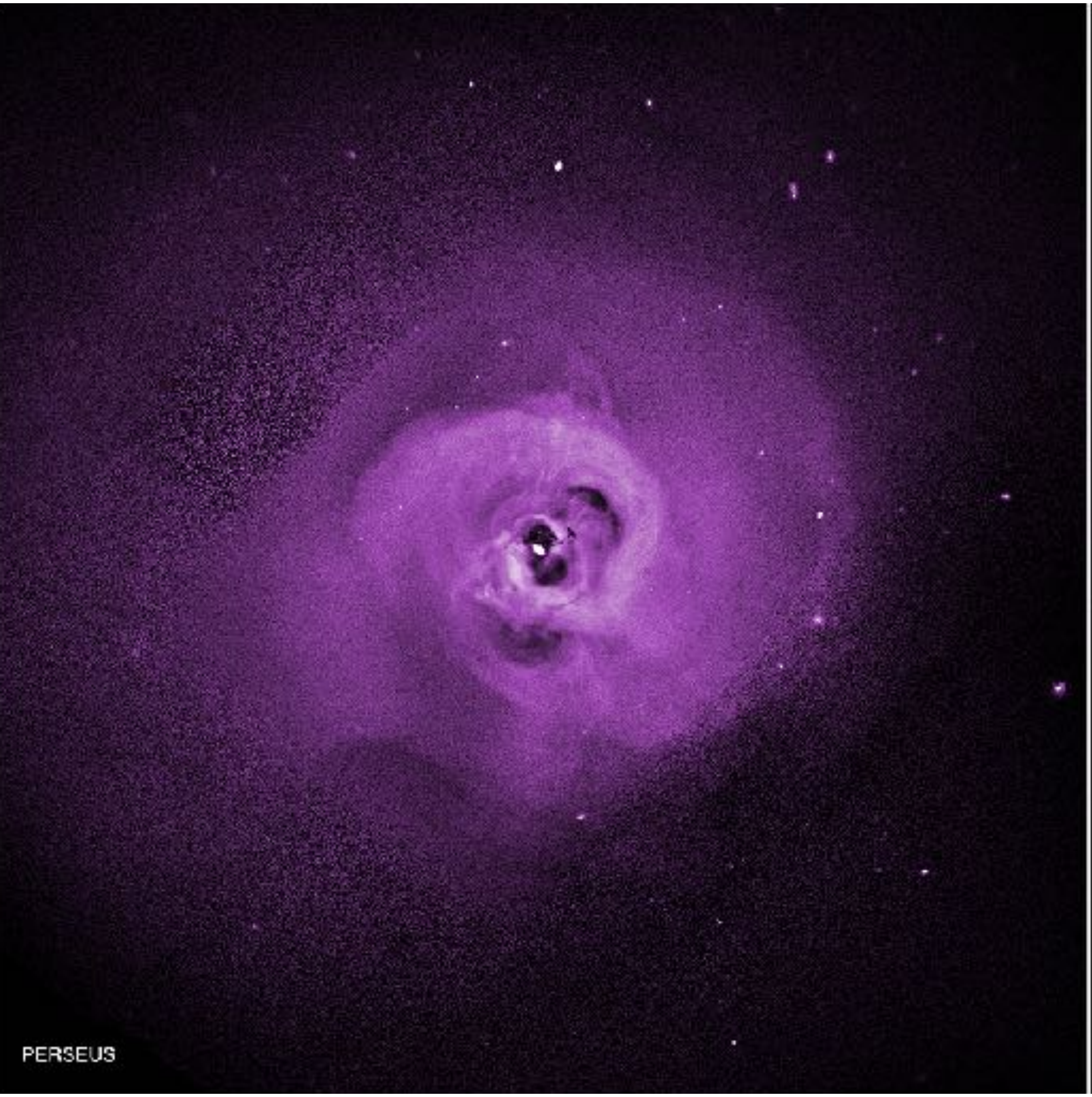


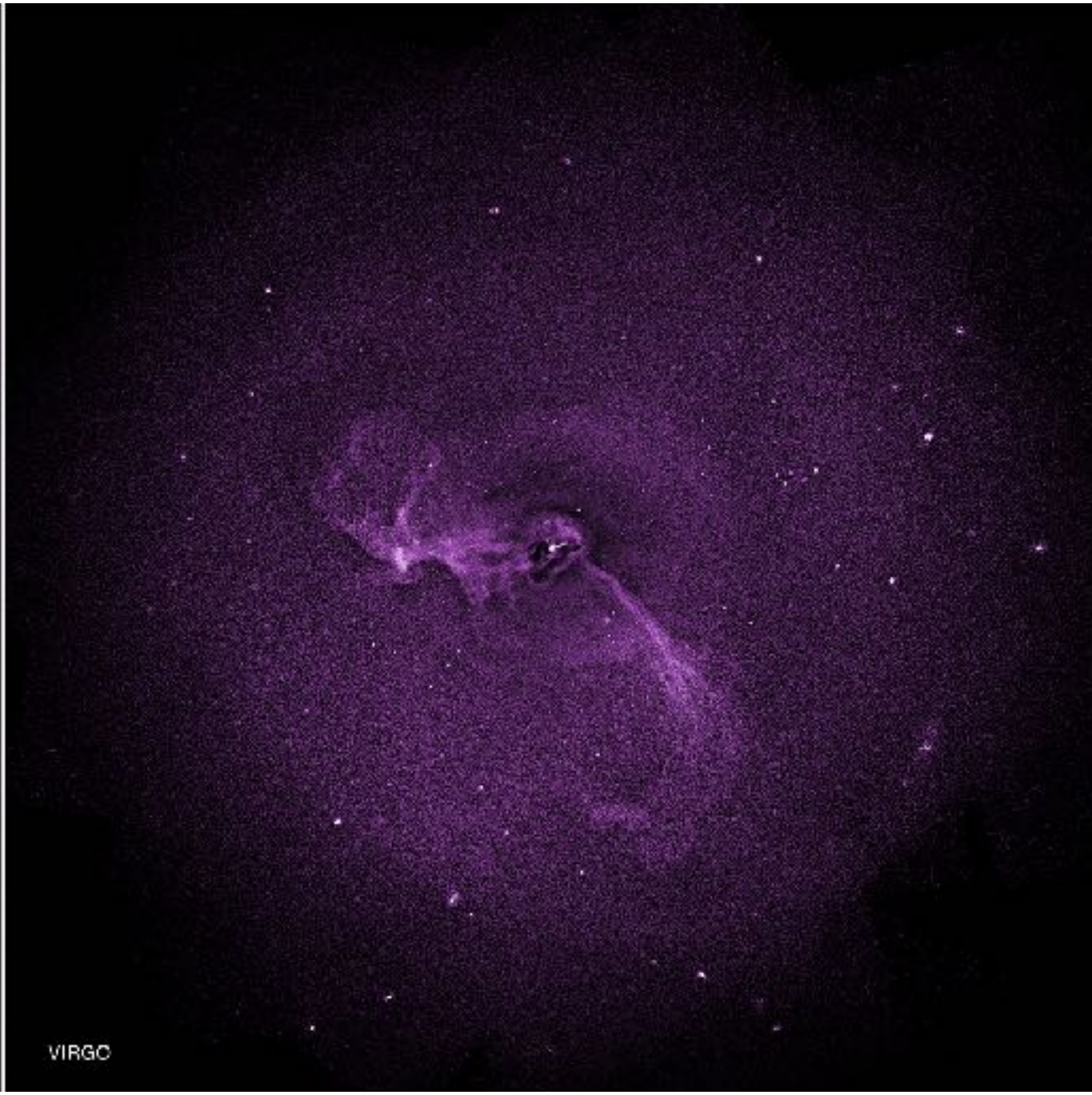

- DB and RS give consistent results
- anisotropy measurements require longer, Hitomi-like observations
- and better agreement between optically thin line emissivities

[Hitomi collaboration: radiative transfer paper+17]

# Velocity power spectra measurements with Chandra

# High-resolution X-ray Images —> Velocities?

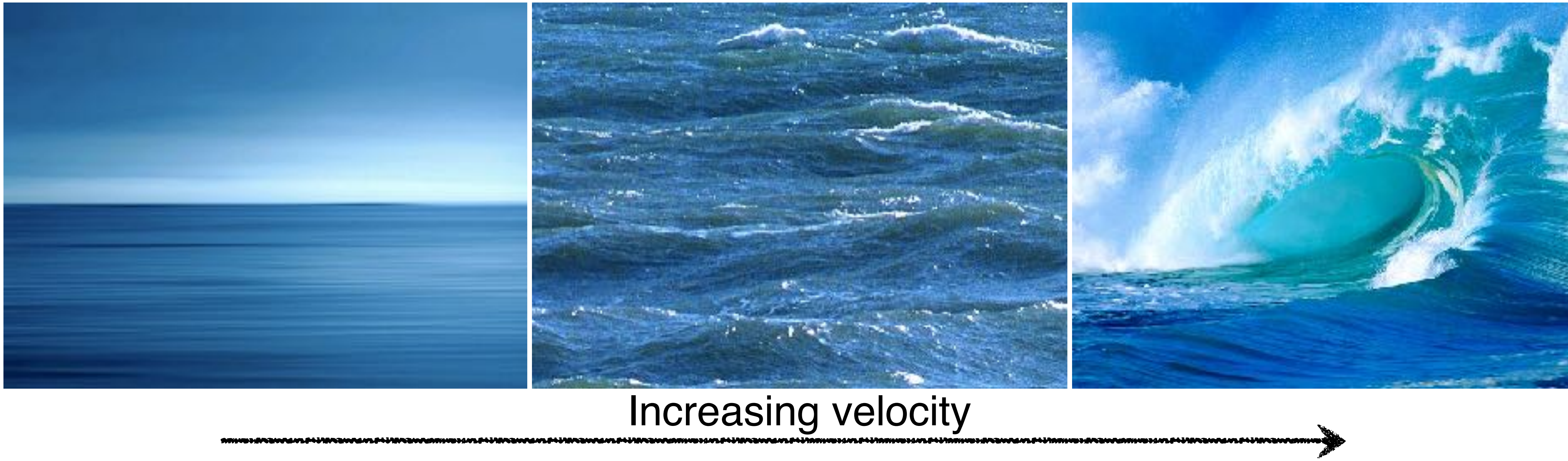



[NASA/CXC/Stanford/I.Zhuravleva]

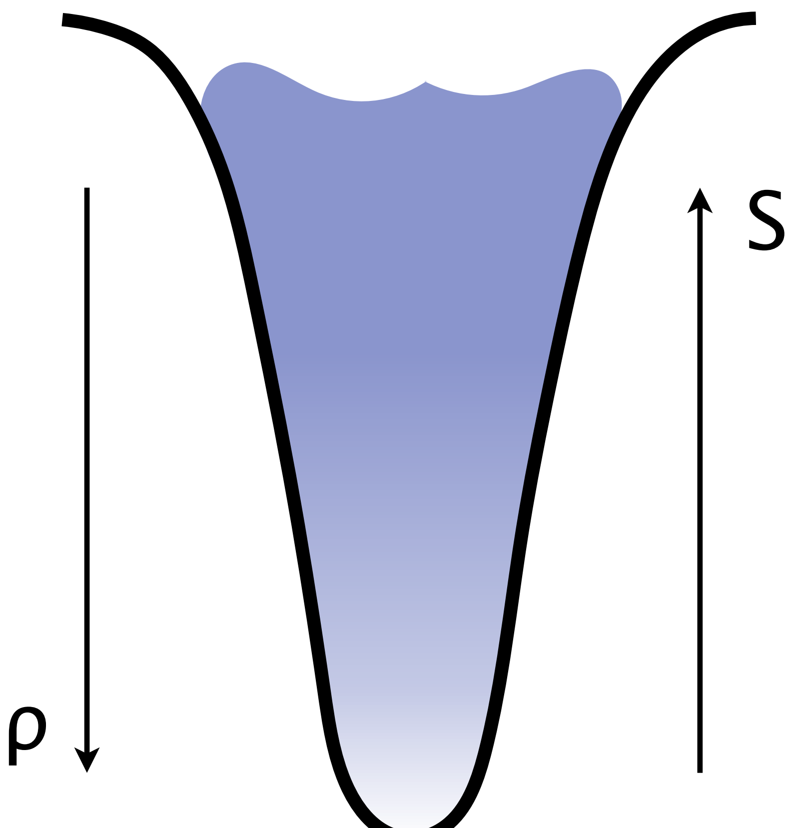
$I_X \sim n_e^2$ [in soft band]

# High-resolution X-ray Images —> Velocities?



# High-resolution X-ray Images —> Velocities?

Increasing velocity




stratification —> $\frac{\delta\rho}{\rho} = \frac{1}{\gamma}\frac{\Delta r}{H_s}$

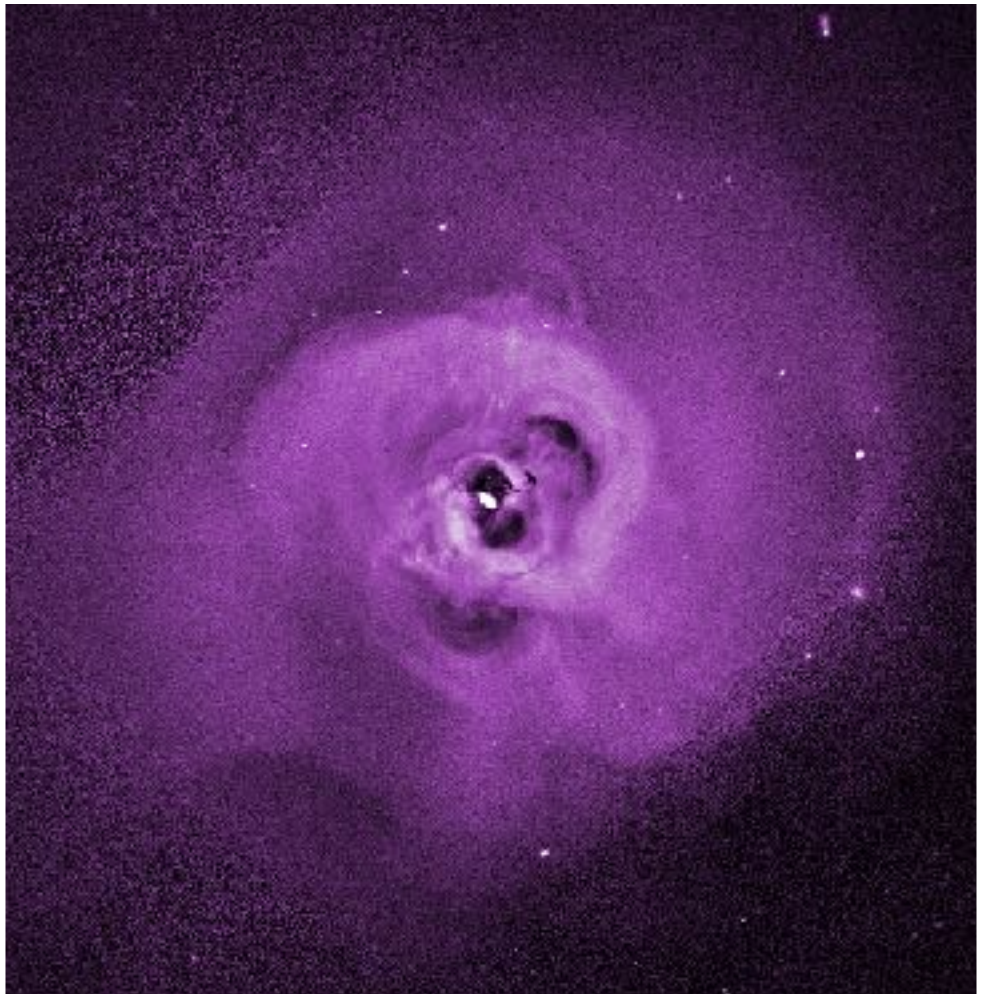
critical balance —> $V \sim V_\perp >> V_r$

$V = N_{BV}\Delta r$

$$\frac{\delta\rho_k}{\rho} = \eta\frac{V_k}{c_s} \qquad \eta = \sqrt{\frac{H_p}{H_s}} \sim 1$$

[IZ+14a]

# High-resolution X-ray Images —> Velocities?



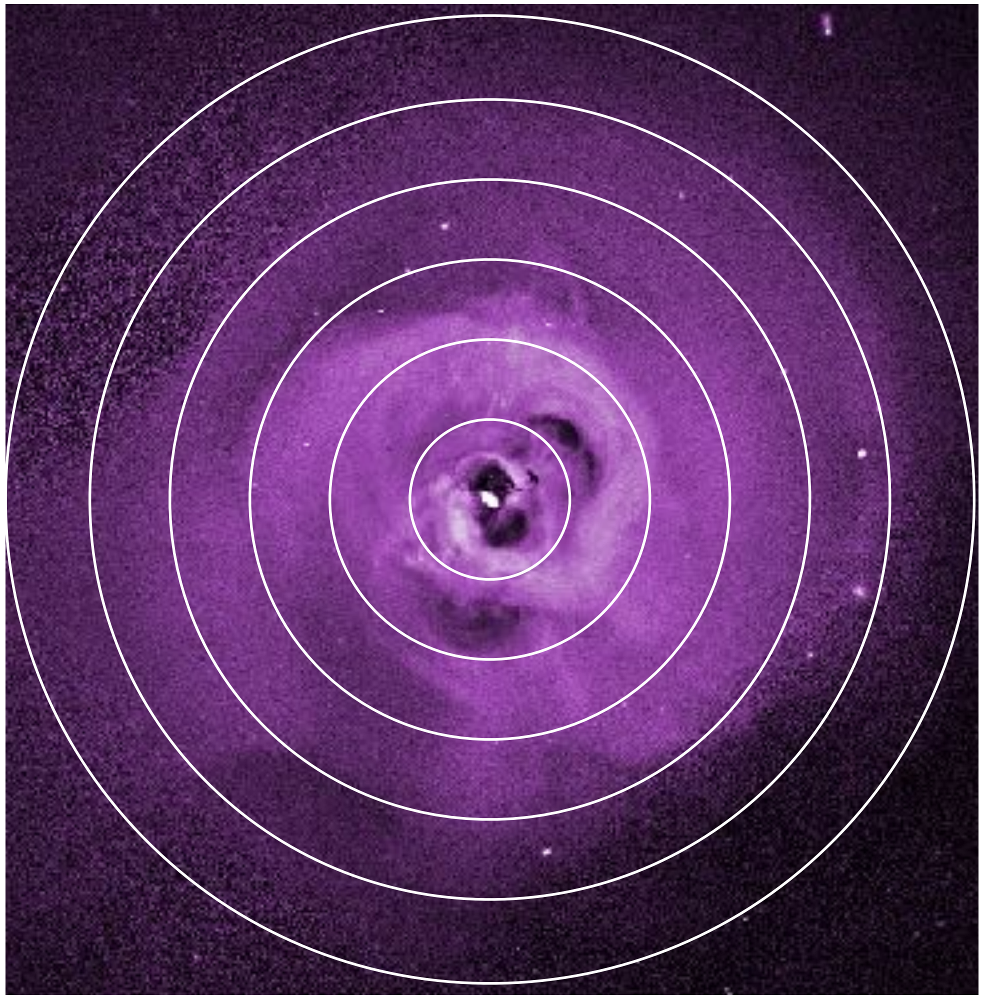
$$\frac{\delta I_X}{I_X} \rightarrow P_{2D}(k) \rightarrow$$

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

[Arevalo+2012, Churazov+2012, IZ+15]

[for other clusters see Walker+13, Arevalo+16, Werner+16, IZ+17]

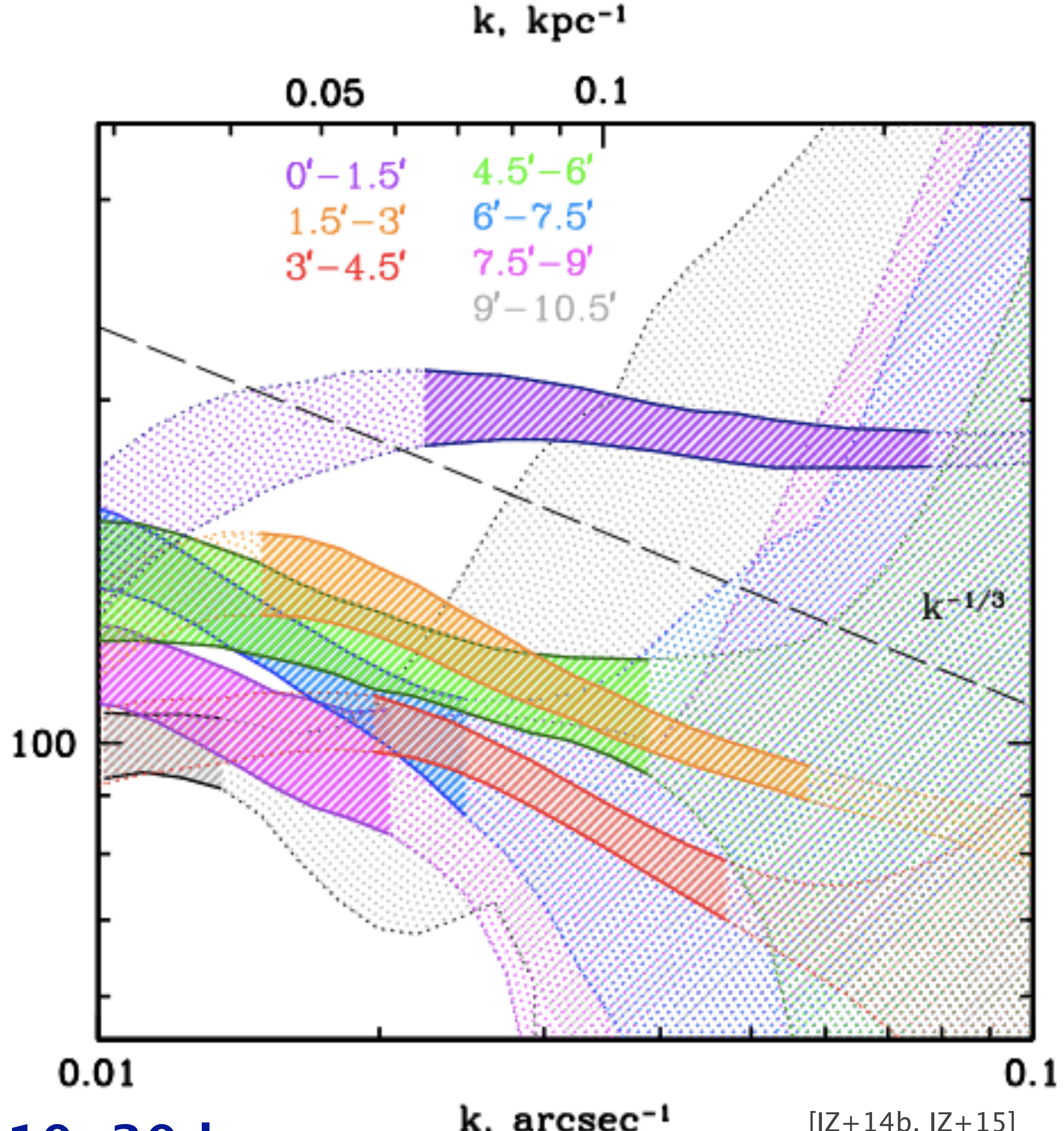
# High-resolution X-ray Images —> Velocities?



$$\frac{\delta I_X}{I_X} \rightarrow P_{2D}(k) \rightarrow$$

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

[Arevalo+2012, Churazov+2012, IZ+15]

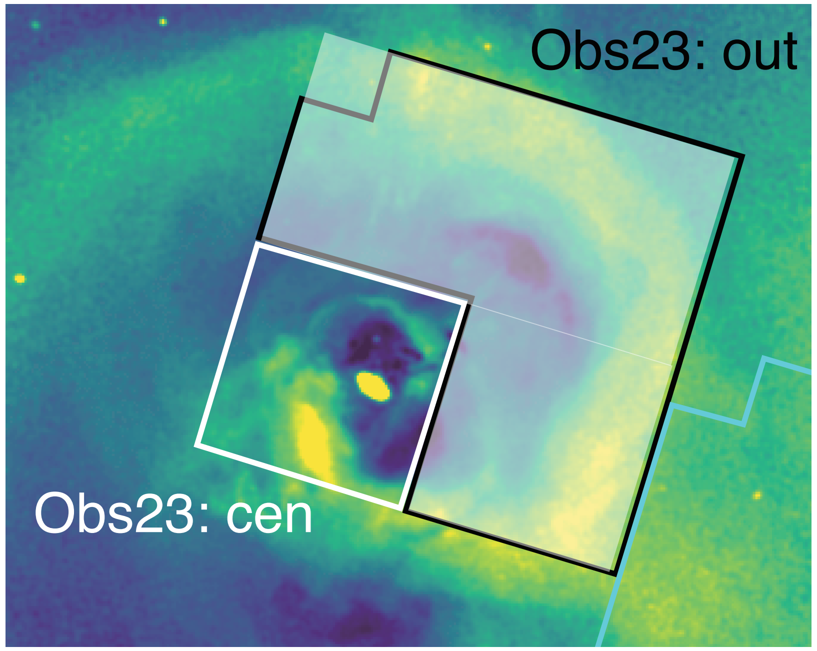


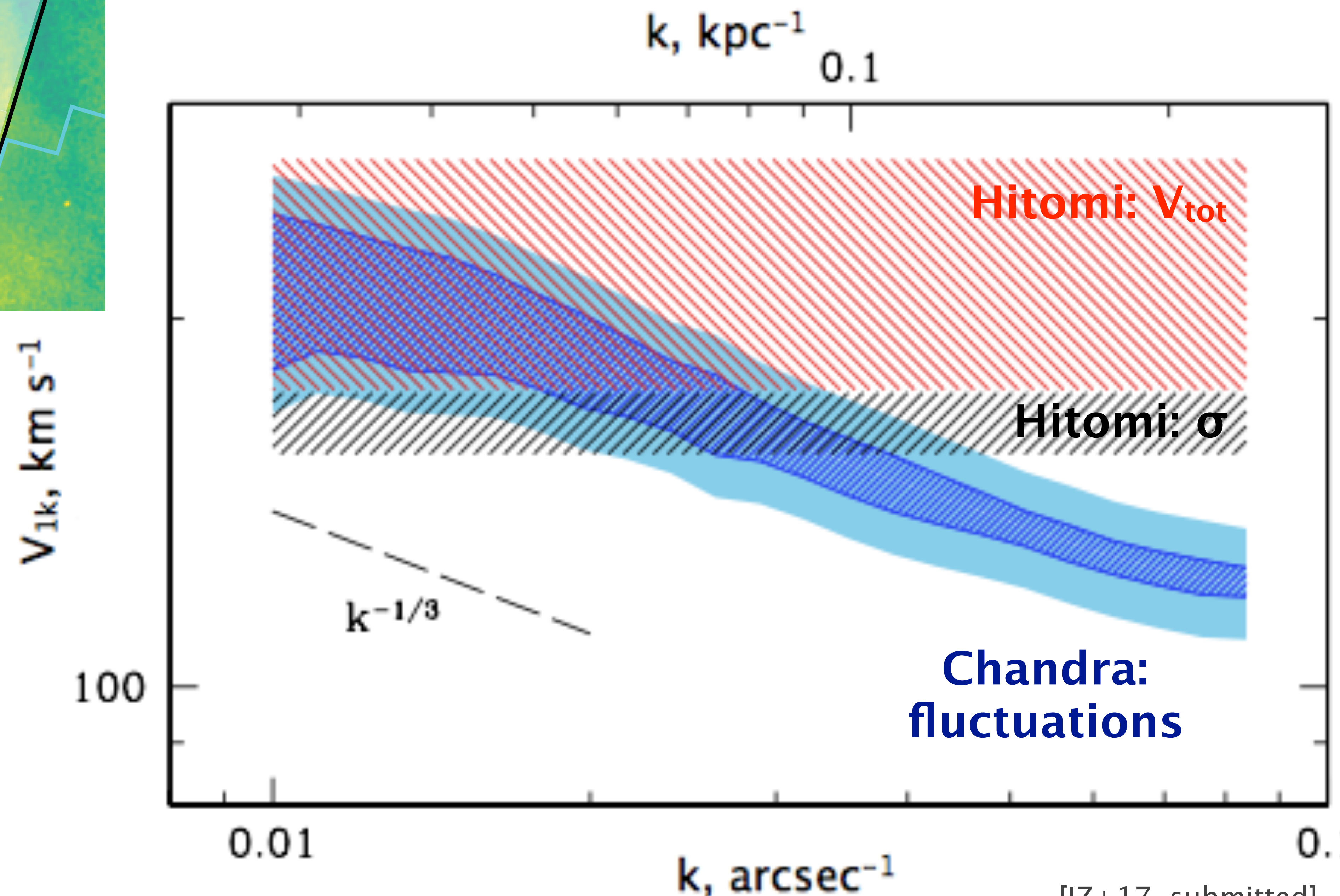

[IZ+14b, IZ+15]

**V=80-150 km/s on scales 10-30 kpc**

[for other clusters see Walker+13, Arevalo+16, Werner+16, IZ+17]

# Velocities from fluctuations vs Hitomi results

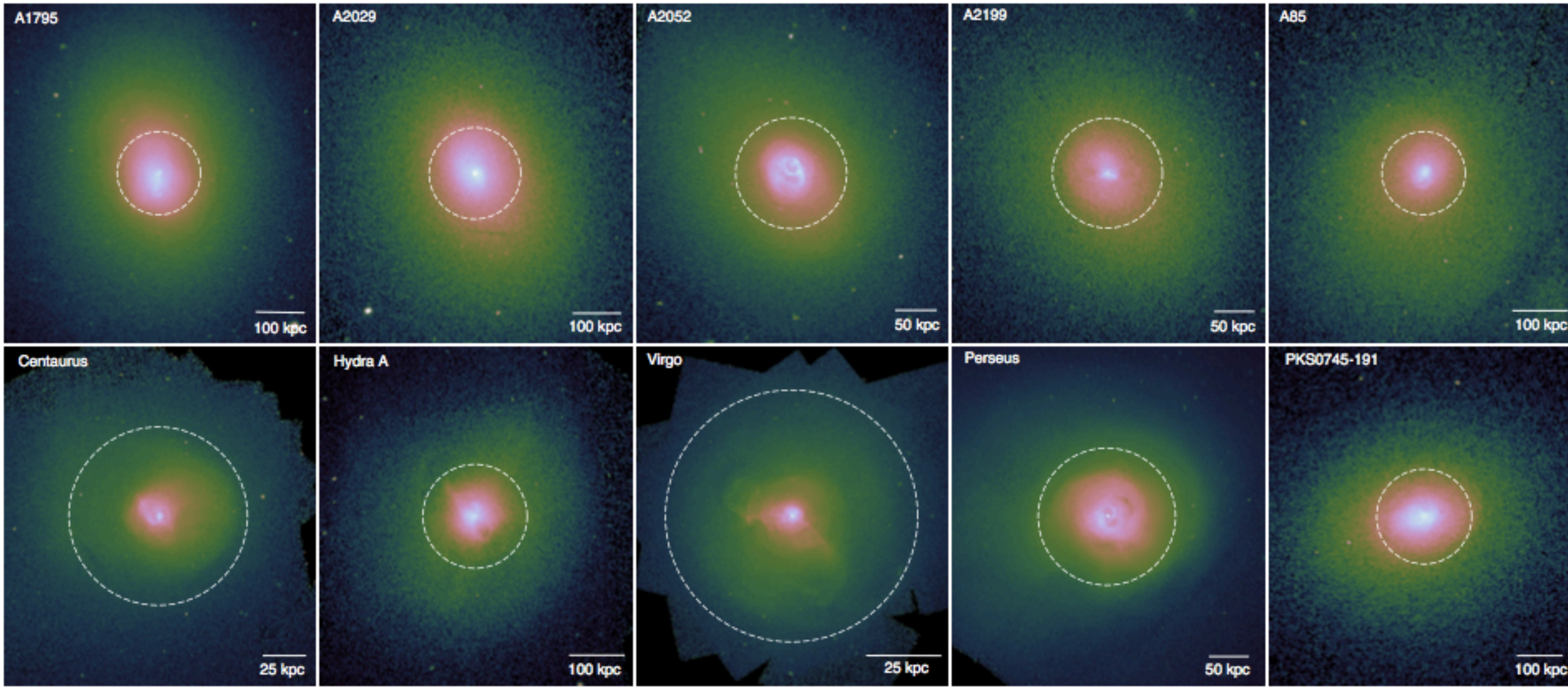


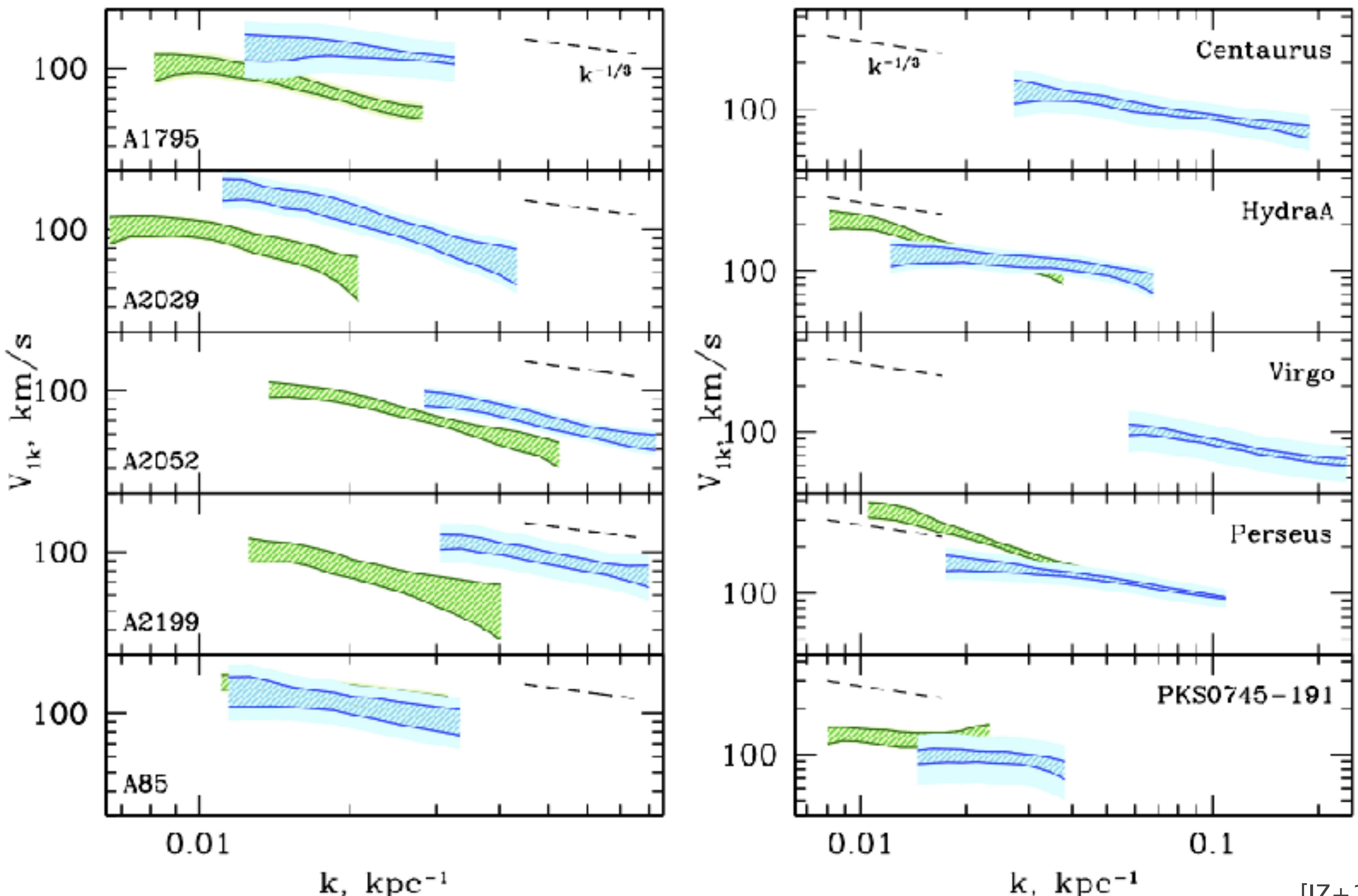

[IZ+17, submitted]

**if 7 < $L_{inj}$ < 150 kpc in the 30–60 kpc region there is a consistency between Hitomi and Chandra results**

# High-resolution X-ray Images —> Velocities?



# Velocity measurements with Chandra




[IZ+17, submitted]

**in the core regions in clusters:**
**V ~ 100-150 km/s on scales < 50 kpc**
**up to ~ 300 km/s on scale ~ 100 kpc**

# What's Next?

XARM (2021+)

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

η ~ 1 [theory] [IZ+14a]

η ~ 1 ± 0.3 [cosmological simualtions] [IZ+14a]

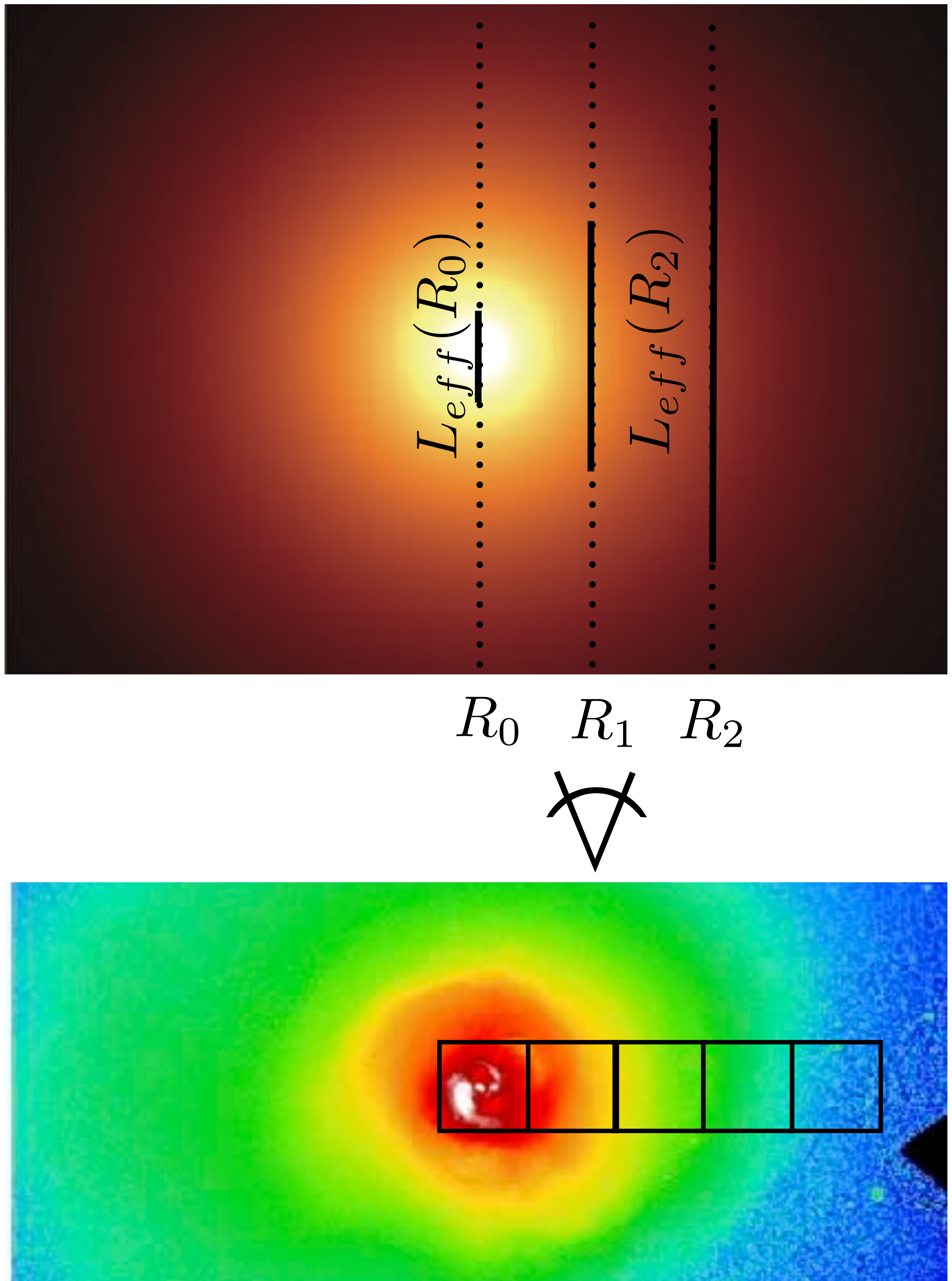
η ~ 1 [hydro simulation] [Gaspari+14]

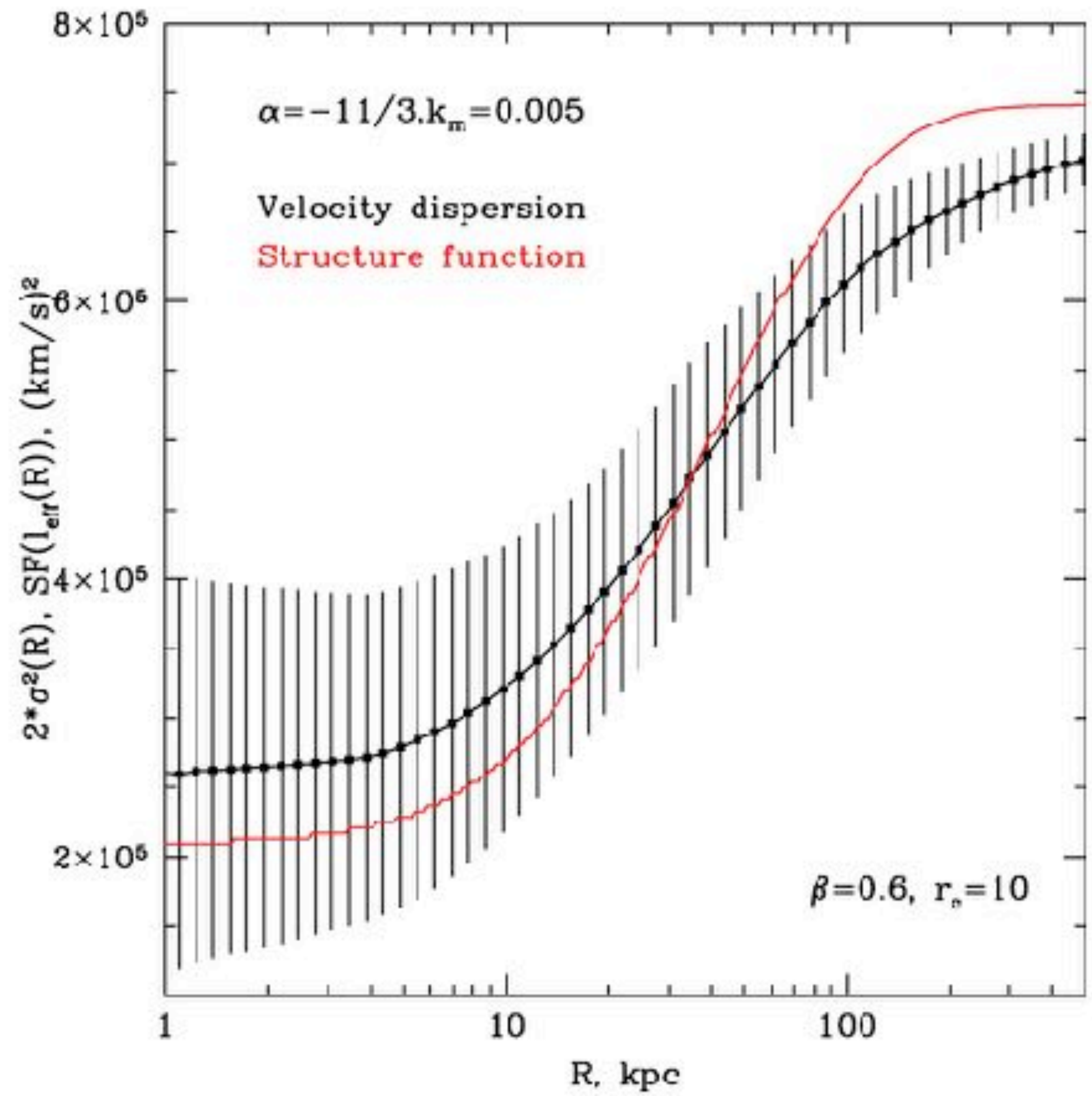
Need to calibrate density-velocity relation
using XARM observations

if η ~ 1 —> effective method to measure power spectra in large sample of clusters [IZ+14a]

if η ≠ 1 —> constrain microphysics [viscosity, conduction] [Gaspari+14]

# How to measure velocity power spectra from line broadening and centroid shift?



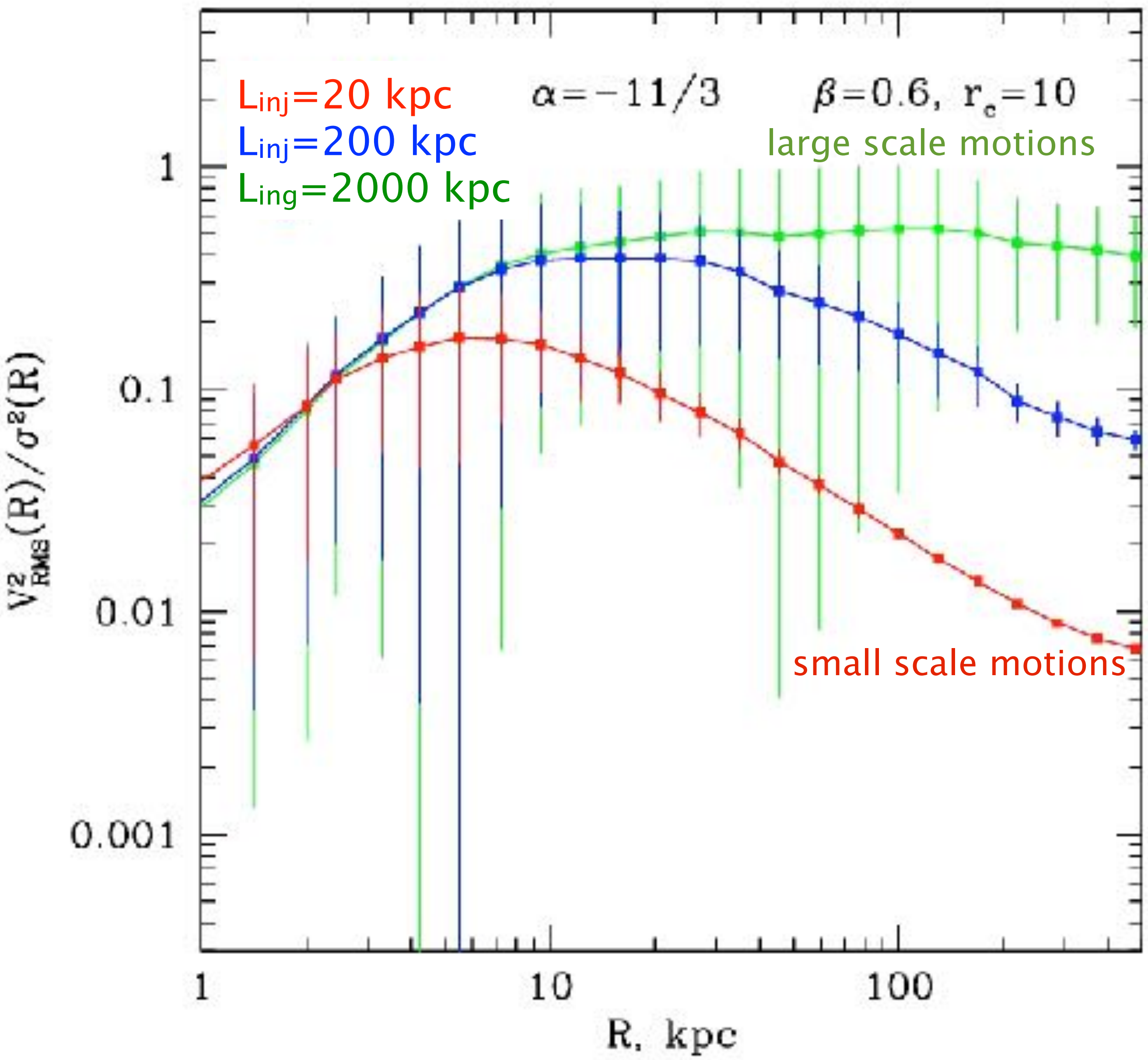



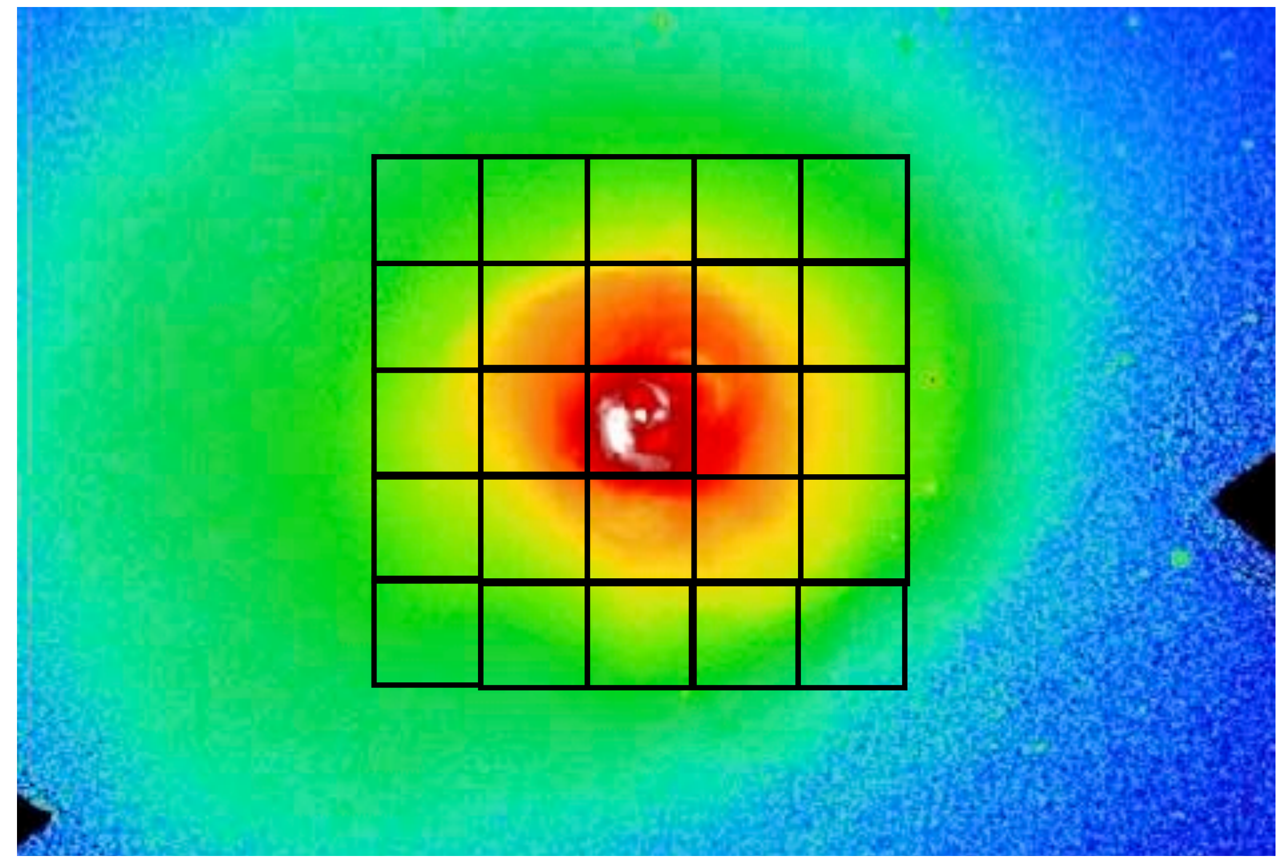

Observed σ(R) ≈ structure function (Leff)

[IZ+12]

[for Coma-like clusters see ZuHone+16]

# How to measure velocity power spectra from line broadening and centroid shift?



[IZ+12]

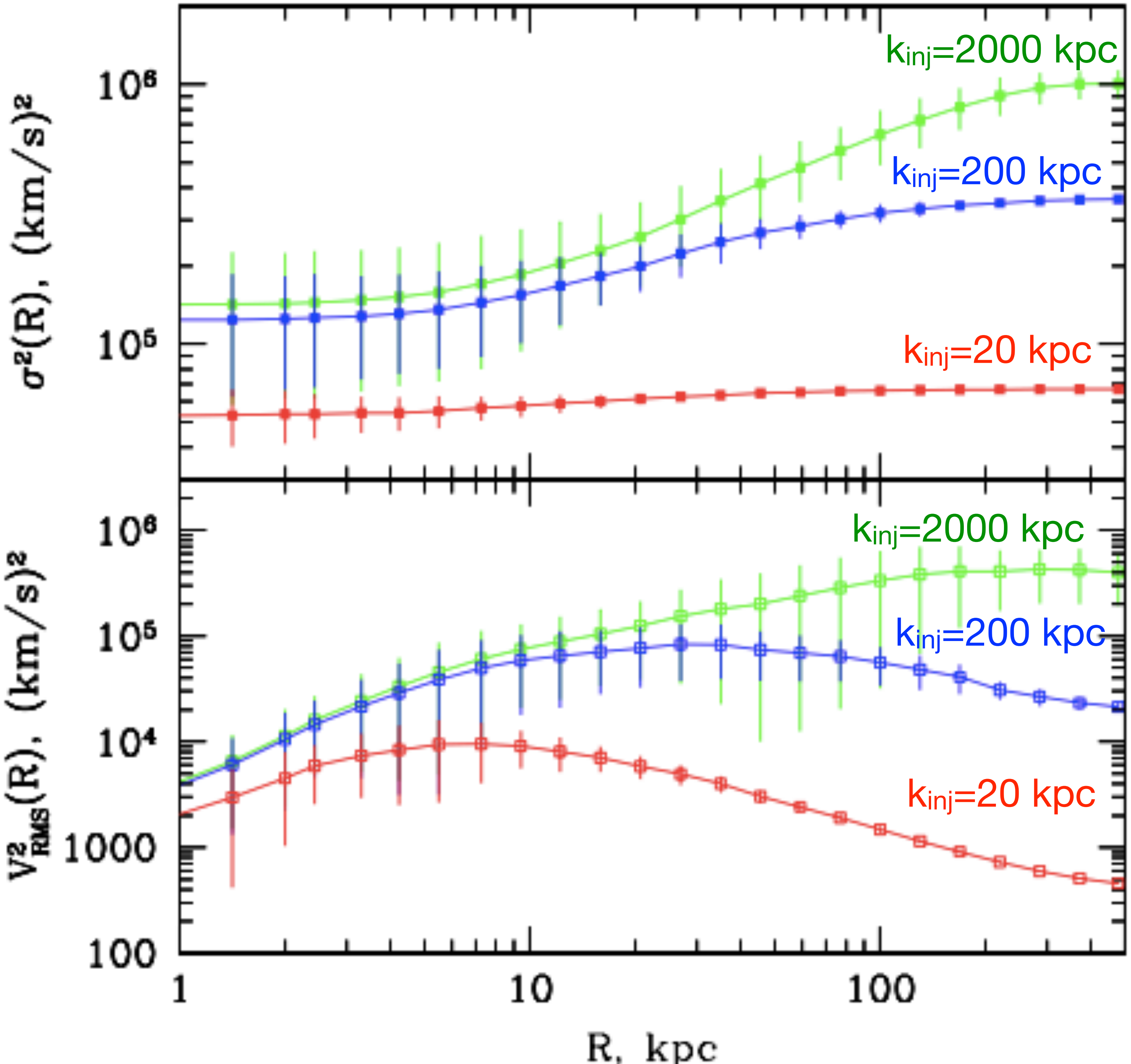
[for Coma-like clusters see ZuHone+16]

# Summary

1. **Resonant scattering velocity measurements with Hitomi**
    - first detection in the cluster core
    - velocities measured with DB and RS are consistent
    - anisotropy measurements require longer, Hitomi-like observations and improvements in atomic data and plasma models

2. **Velocity power spectra measurements with Chandra**
    - currently the only way to measure velocity power spectra
    - consistent with direct Hitomi measurements in Perseus
    - can be easily extended on other clusters/regions [but requires careful checks on large scales]
    - the main limitation on small scales: Poisson noise - reducible with deeper Chandra observations

# Doppler broadening velocity measurements with Hitomi




[IZ+12]

From Hitomi observations: driving scale is less than few 100 kpc

[Hitomi collaboration: velocity paper, 2017, submitted]

# Uncertainties

Oscillator strength:
depends on the upper level's oscillator strength —> directly related to the natural line width
for w line: $E_{nat,APEC}$=0.308 eV, $E_{nat, SPEX}$=0.301 eV, $E_{nat, lab}$=0.311 eV (Rudolf et al. 2013)
error on oscillator strength < 5%

error on the total electron impact excitation rate for w line: < 10%

uncertainties in fluxes of unresolved satellite lines: contribute less than few % to the line suppression

charge exchange: could account for a suppression of 6 %, but only in the innermost region