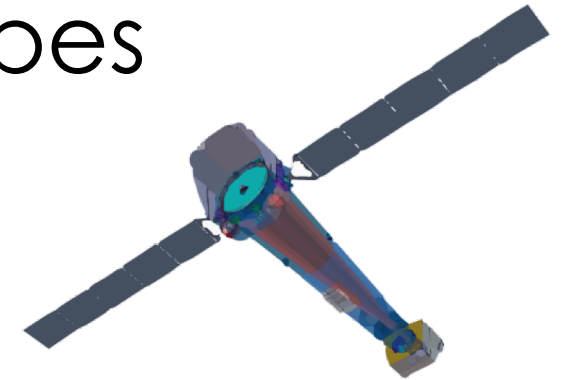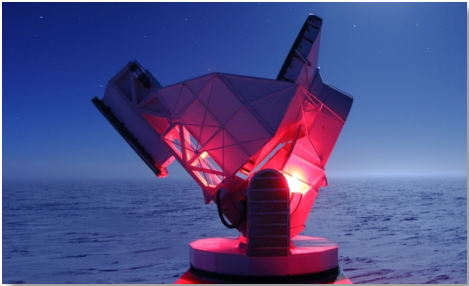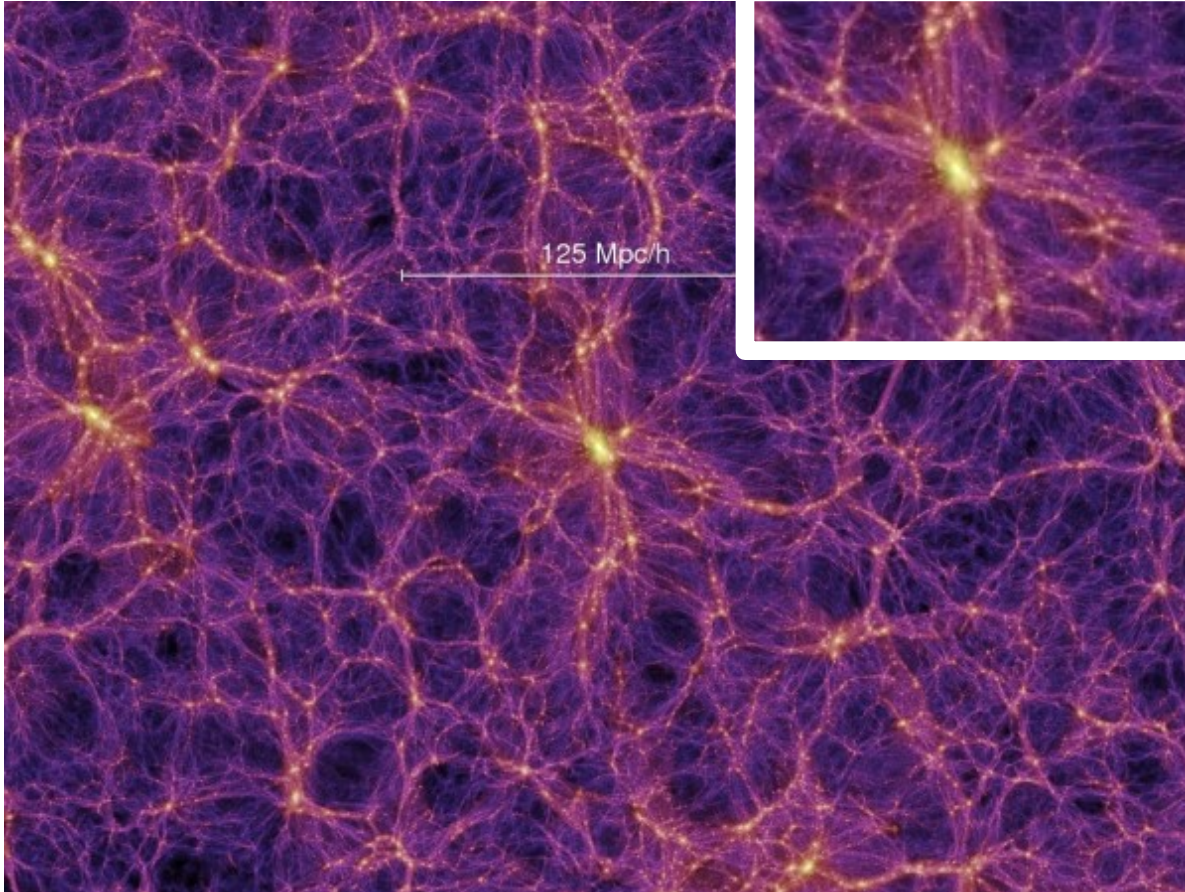# Measuring Gas Motions in Cluster Outskirts with ATHENA and Synergies with SZ Telescopes

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and

J. ZuHone, M. Gaspari, B. Benson, L. Bleem, N. Clerc, E. Cucchetti, B. Forman, R. Kraft, P. Nulsen, E. Pointecouteau, and R. Smith

Large Scale Motion in Clusters

Credit: Volkar Springel, Virgo Consortium

- Clusters are dynamic and evolving objects
- Fed by accretion along the filament connecting clusters
- Accretion generates large scale motion and turbulence in cluster outskirts
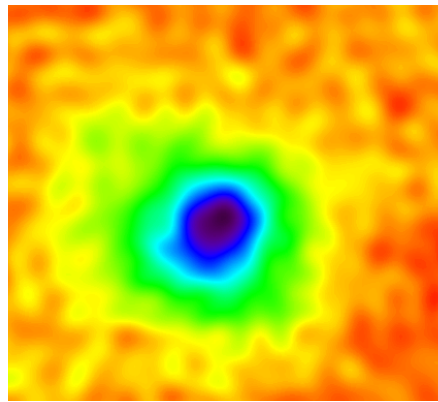- Turbulence → non-thermal pressure support at cluster outskirts

Measurements of Velocity Field
with SZ and X-rays

Inverse Compton Scattering
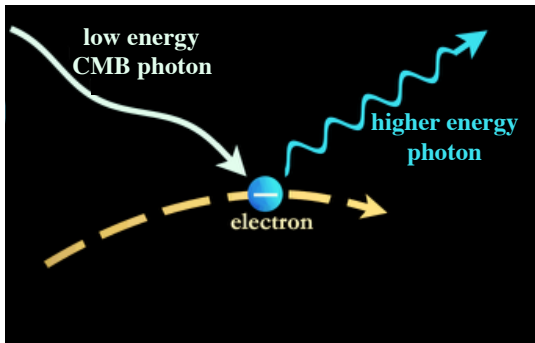
SZ Effect

X-rays

Thermal Bremsstrahlung

A2744 (SPT)
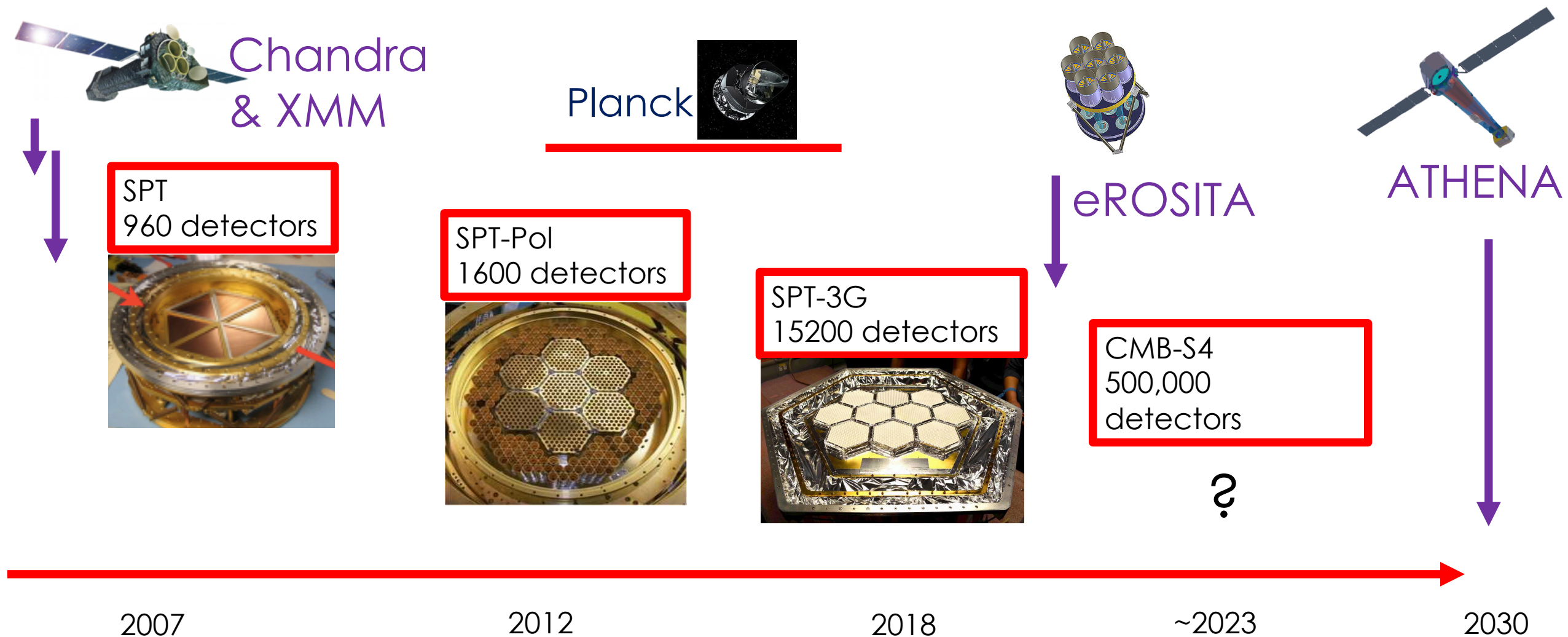
A2744 (Chandra)

$Y_{SZ} \propto \int n_e k_B T_e \, dl$
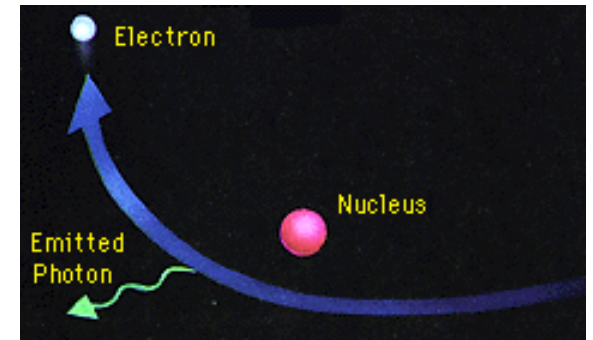
$S_x \propto \int n_e^2 \Lambda(T_e) \, dl$

Indirect Detection: Density and Pressure Fluctuations → ATHENA WFI
and SZ Observations
Direct Detection: Line Shifts, Shapes, and Broadening → ATHENA XIFU

Current and Future SZ and X-ray Observatories

Chandra & XMM

Planck
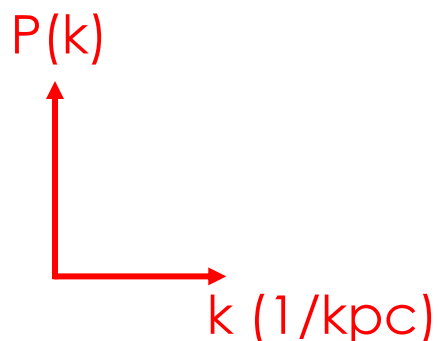
eROSITA

ATHENA

SPT
960 detectors

SPT-Pol
1600 detectors

SPT-3G
15200 detectors

CMB-S4
500,000
detectors

?

2007   2012   2018   ~2023   2030

Indirect Detection

Large Scale Motion
Faster Speed
Line Shifts

Injection
Scale

$P(k) \propto k^{-\alpha}$

Dissipation
Scale

P(k)

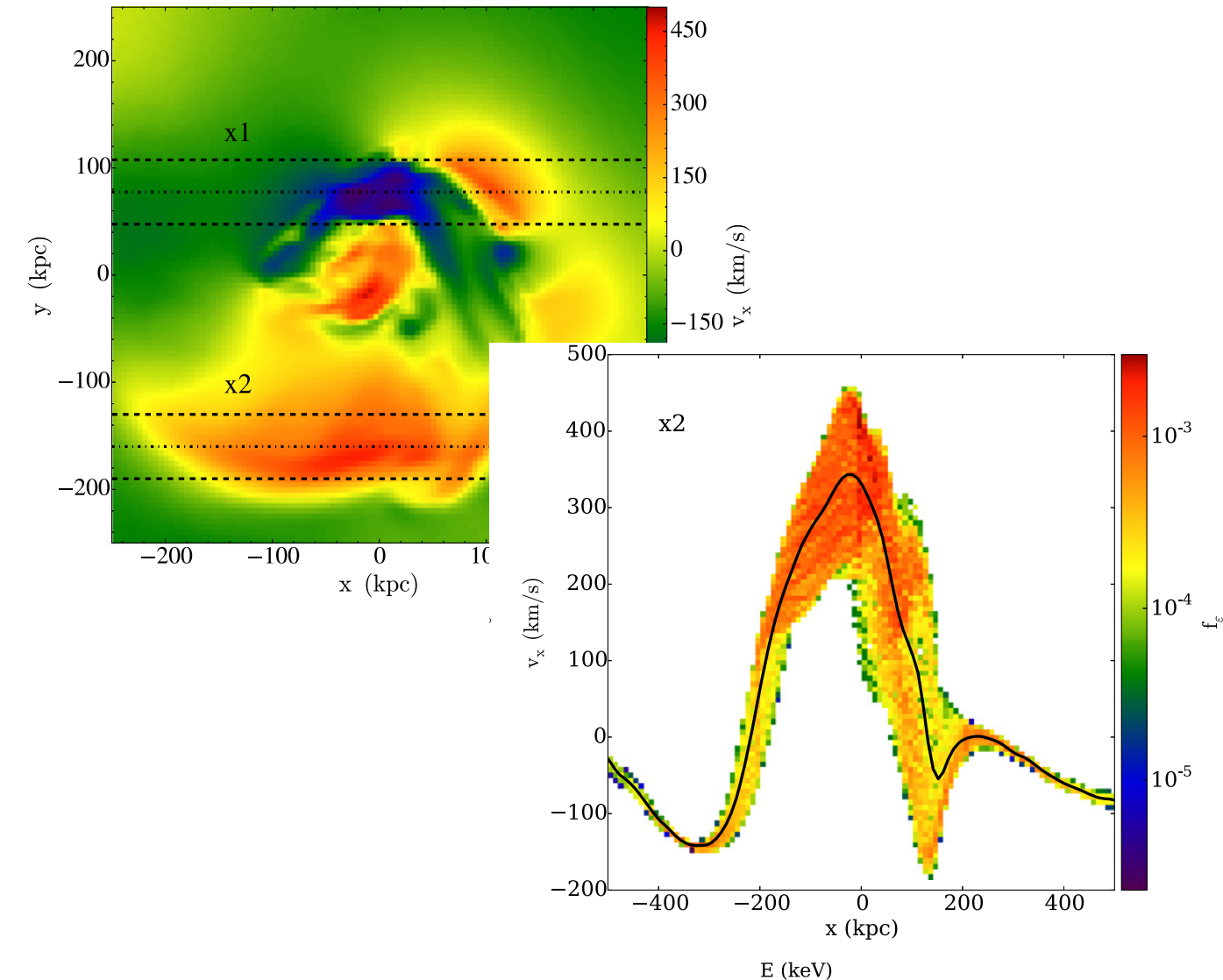k (1/kpc)

Small Scale Motion
Slow Speed
Line Broadening

- Imaging
- Density, pressure fluctuations → normalization of the velocity spectrum
- Dissipation scale of the turbulent cascade → the effective "viscosity" of the ICM

$$\frac{\delta\rho}{\rho} \approx M^2$$

$$E_{turb} \approx \frac{1}{2}\gamma(\gamma - 1)M^2 E_{th}$$
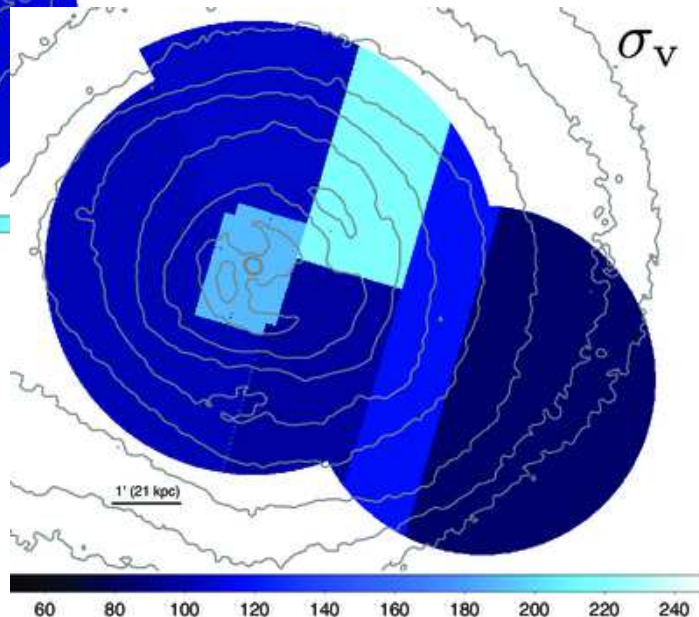
Direct Measurements

- High resolution spectroscopy
- Velocity Broadening → turbulence
- Line shifts →line of sight velocities over the face of a cluster
- Line shapes → size and number of Eddies along the line of sight

First Direct Measurements with Hitomi

Line Shifts

Line Broadening

v_{bulk}

σ_v

Hitomi+2016,2018
ZuHone+2018
Bulbul+2012,
Sanders+13,
Pinto+15
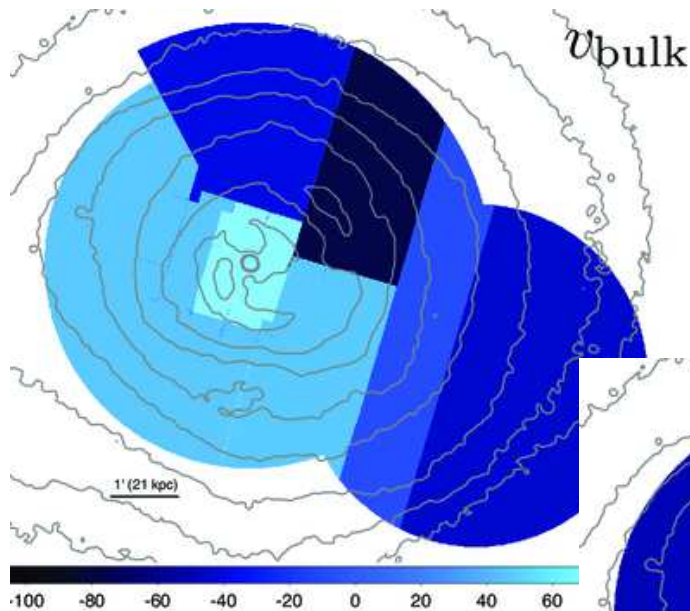
- First direct measurement velocity broadening and line shifts from 200ks observations of the Perseus cluster
- Velocity dispersion→ ~ 220 km s^{-1}
- Bulk velocity→ -70 to +70km s^{-1}
- Line shapes→ No significant departures from Gaussianity

First indirect Measurements
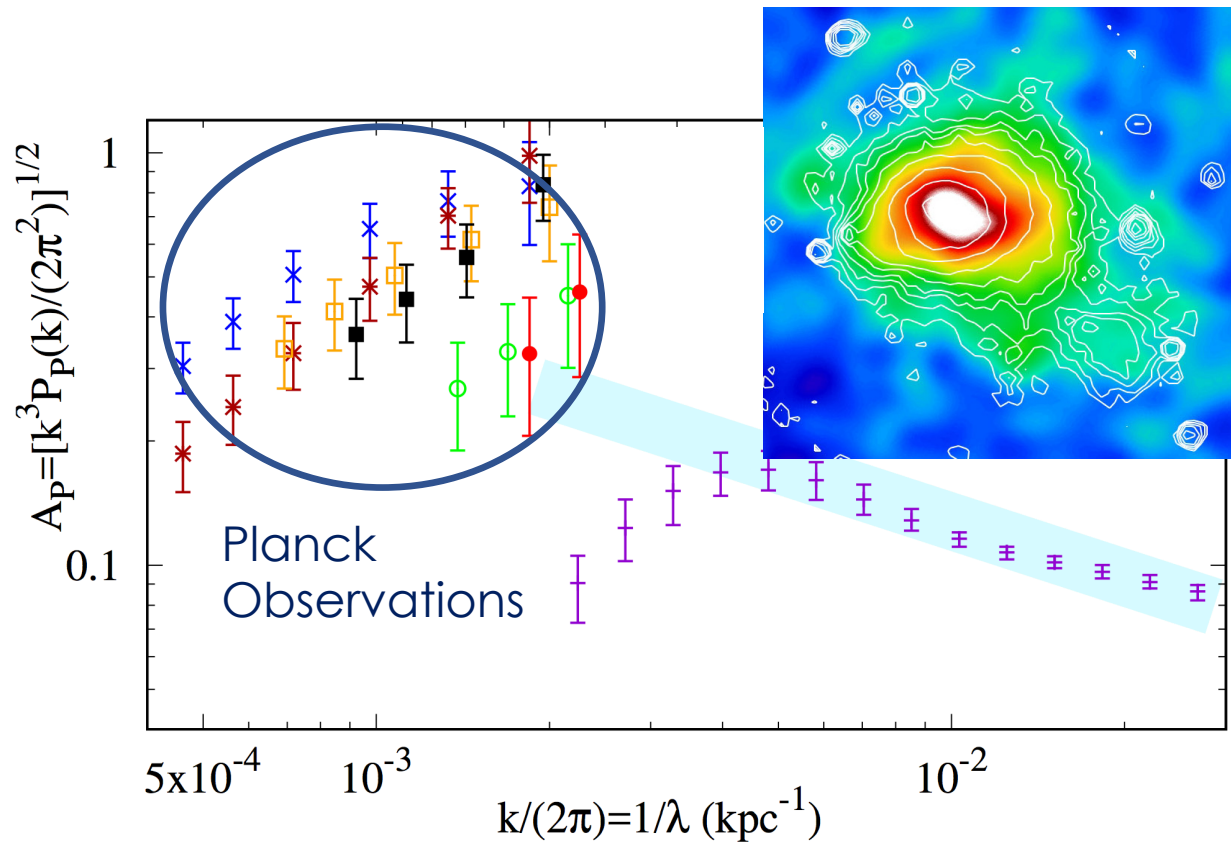
- Coma Center: density Fluctuations in the order of ~5-10% in the cores (Churazov+2012)
- Coma Outskirts: $\delta P/P$ = 33 ± 12% and 74 ± 19% at15′ and 40′ away from the core (Khatri & Gaspari 2016)
- 3D Mach number of 0.8 ± 0.3
- Extend this study with higher resolution SZ telescopes

See also Zhuravleva+2013,2014

Hydrodynamical Simulations of a Coma-Like Cluster


Hydrodynamical Simulations of a cluster at z=0.1
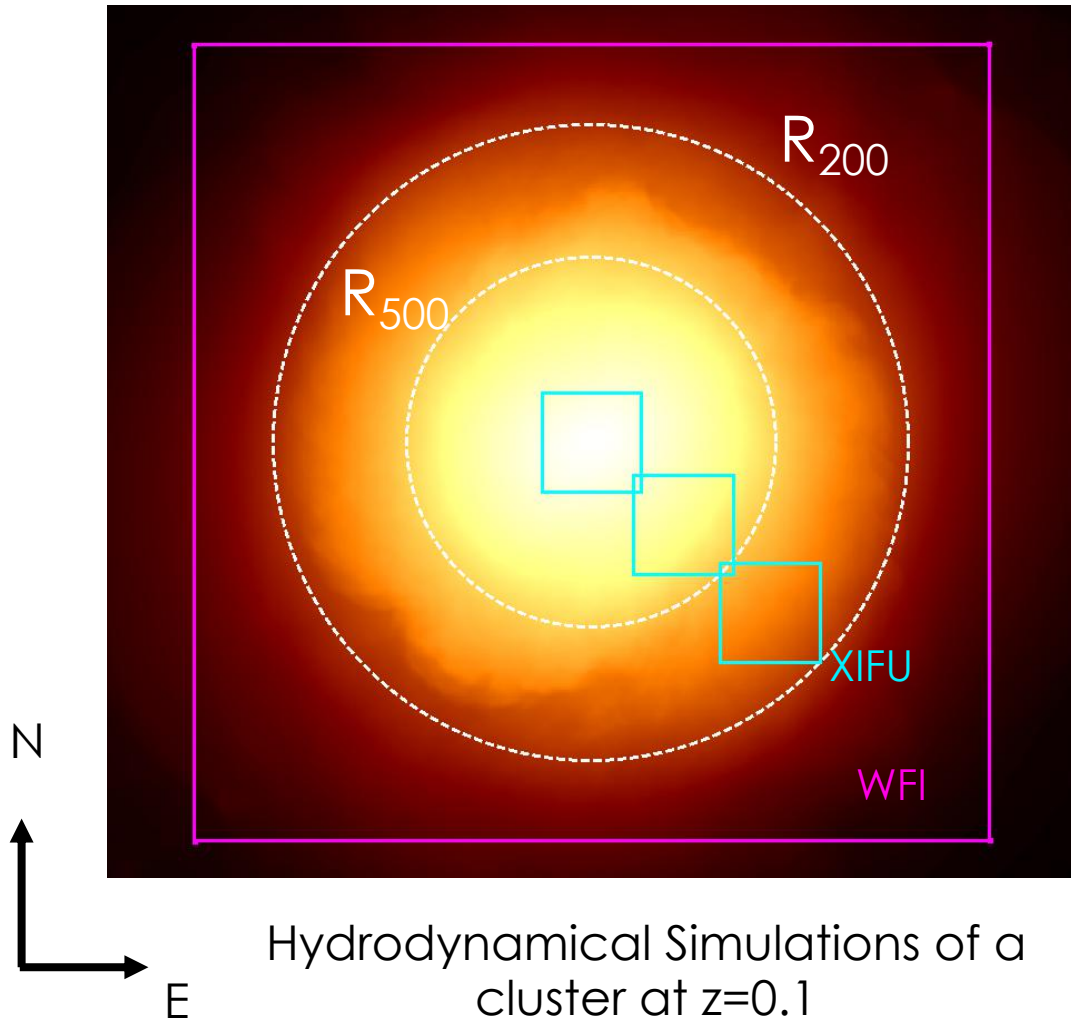
- Hydrodynamical simulations of a Cluster at z=0.1
- Mock Athena WFI and XIFU Observations out to R_{200}
- Exposure Time 100ks with SIXTE
- R_{200} = 16 arcmin
- M_{200} = 6 x 10^{14} M_{sun}
- Work in Progress!

Direct Measurements with ATHENA XIFU

R_{200}

kT = 2.7 keV

kT = 6 keV

R_{500}

kT = 9 keV

E

N
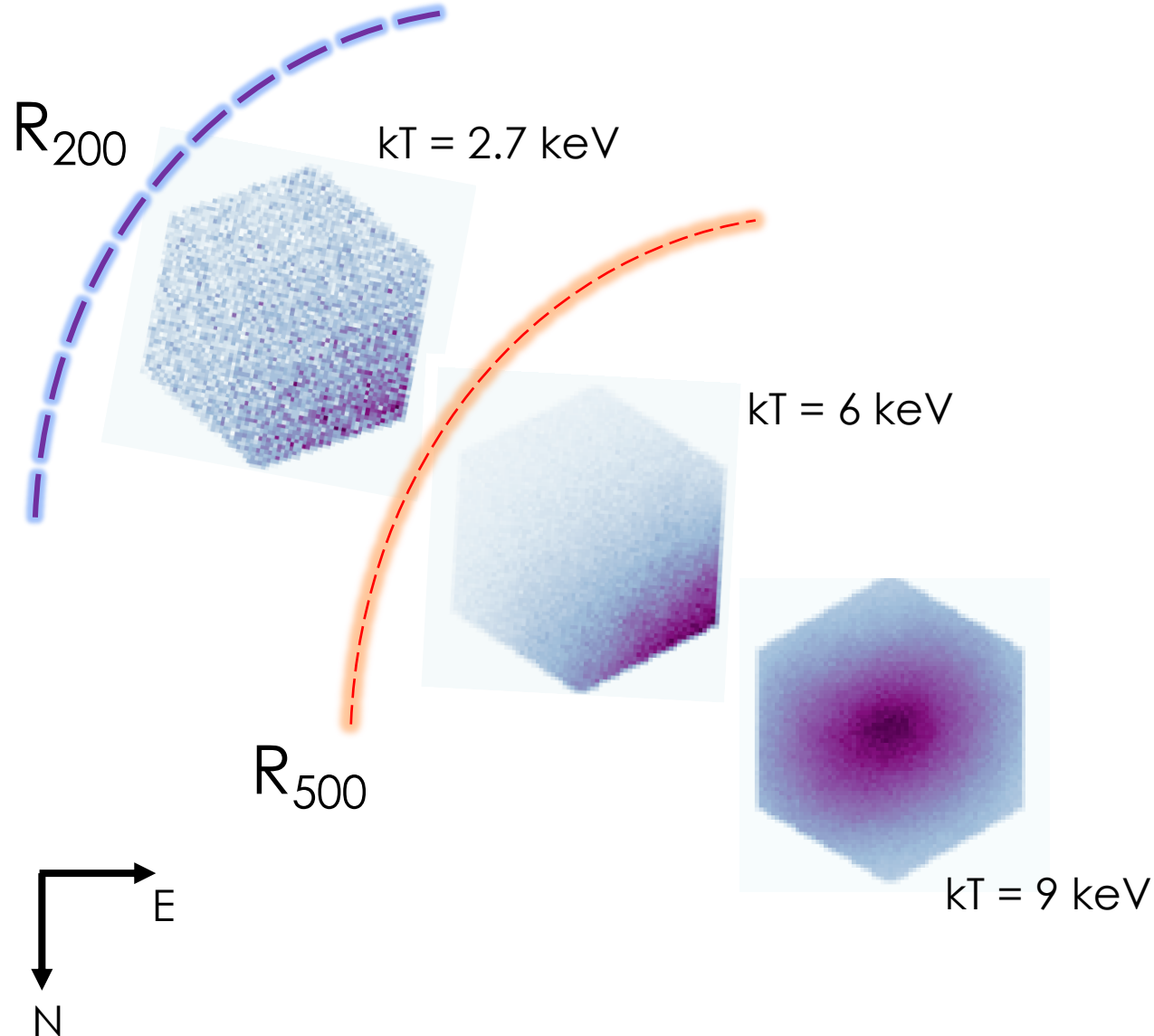
- ATHENA XIFU will be the most sensitive instrument to determine turbulence and bulk motion from cluster cores out to large radii over a large range of redshifts
- Initial estimates ✓
- See also Roncarelli+2018

Direct Measurements with ATHENA XIFU
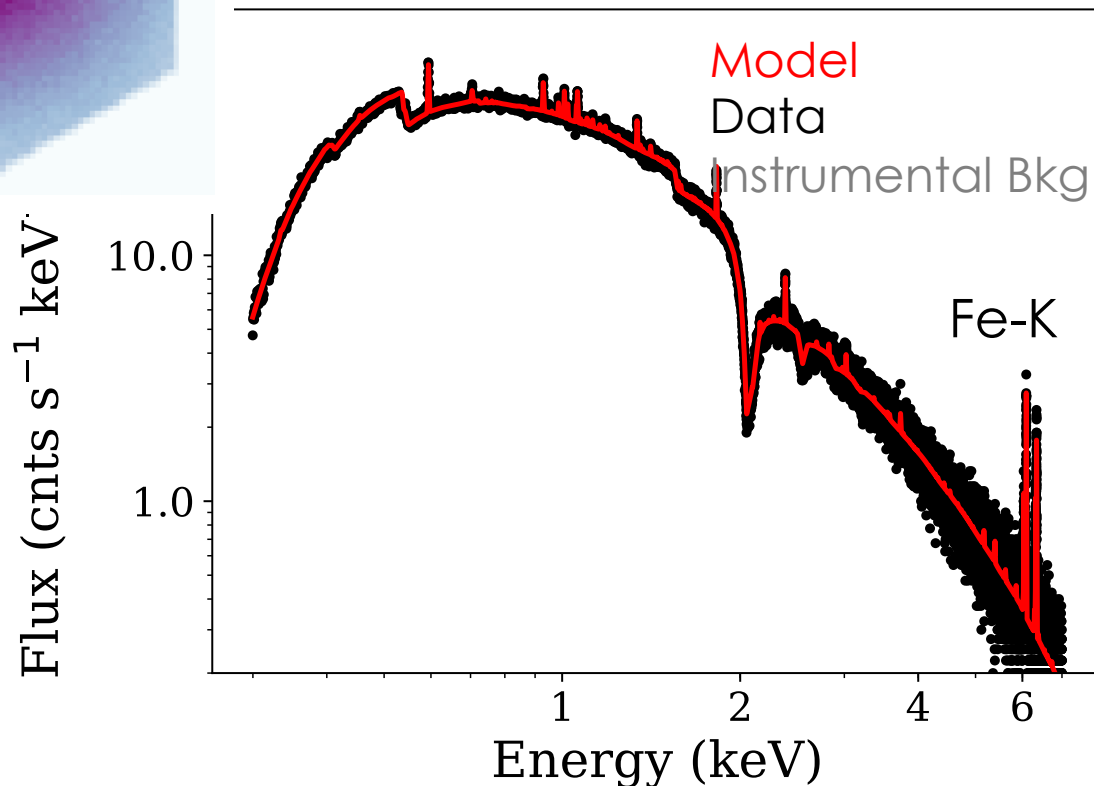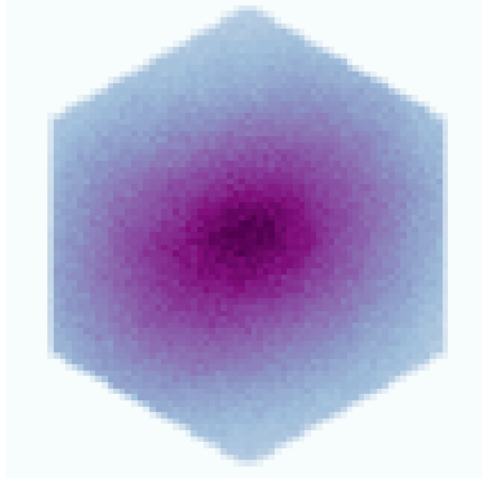
- $V_{turb} = 160 \pm 10$ km s^{-1}
- $V_{bulk} = -17 \pm 4$ km s^{-1}
- Line broadening and shift is significantly detected
- In the central region significant detection of the line broadening and shift

Direct Measurements with ATHENA XIFU
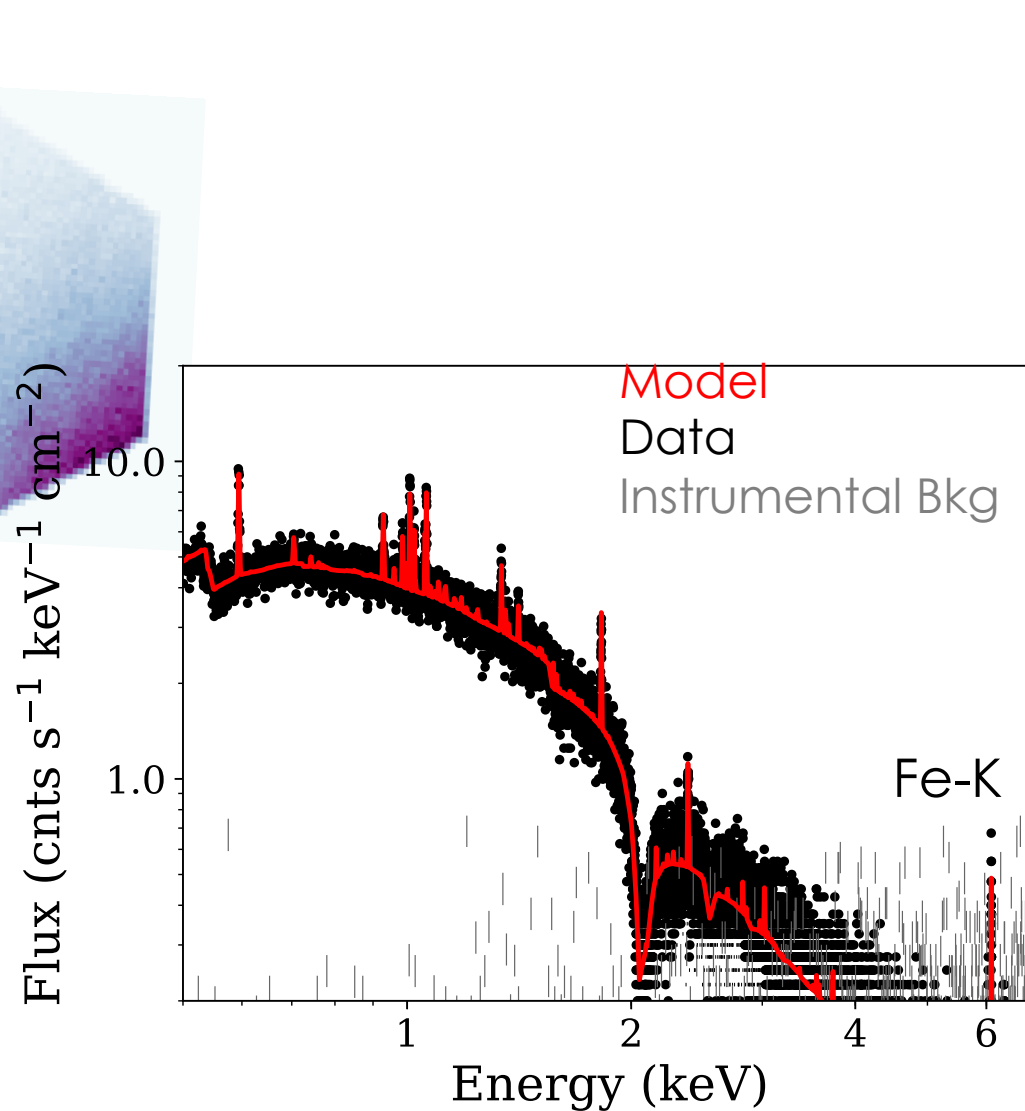
R_{500}

- Region: $R_{2500} < R < R_{500}$
- $V_{turb} = 170 \pm 20$ km s^{-1}
- $V_{bulk} \rightarrow$ no significant detection (due to the geometry of the source)
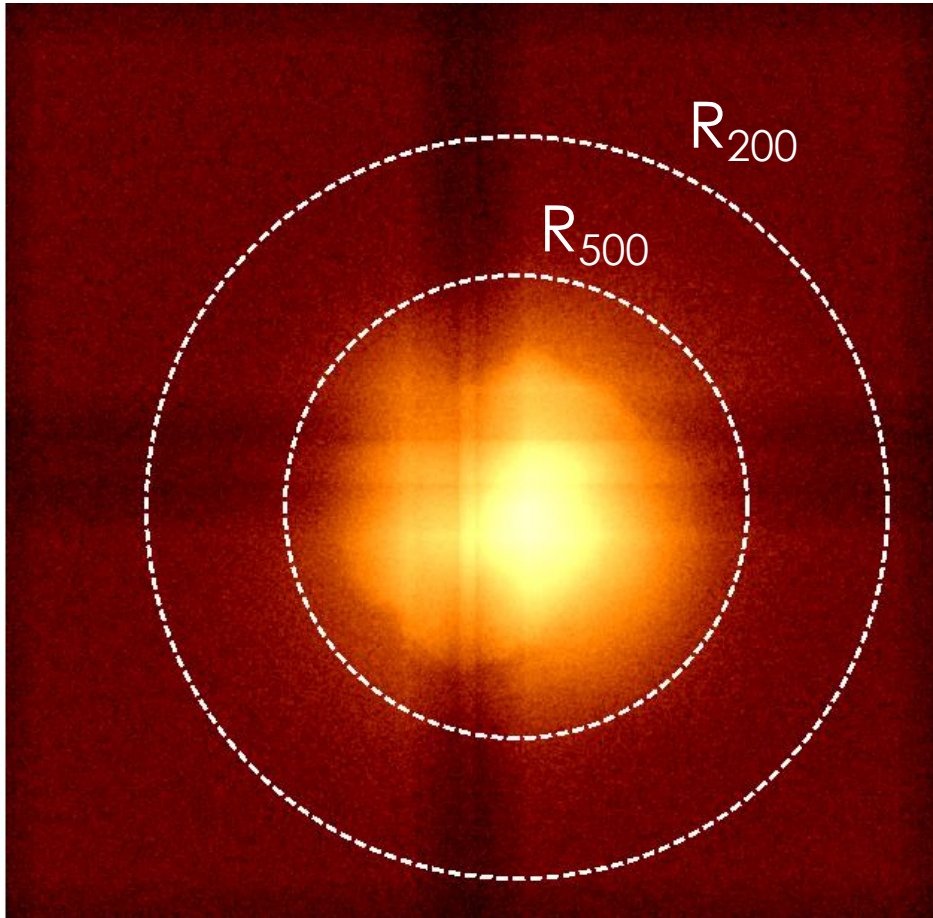- Line broadening is significantly detected!

Direct Measurements with ATHENA XIFU

R_{200}

R_{500}

Flux (cnts s^{-1} keV^{-1} cm^{-2})

Model
Data
Instrumental Bkg

Energy (keV)
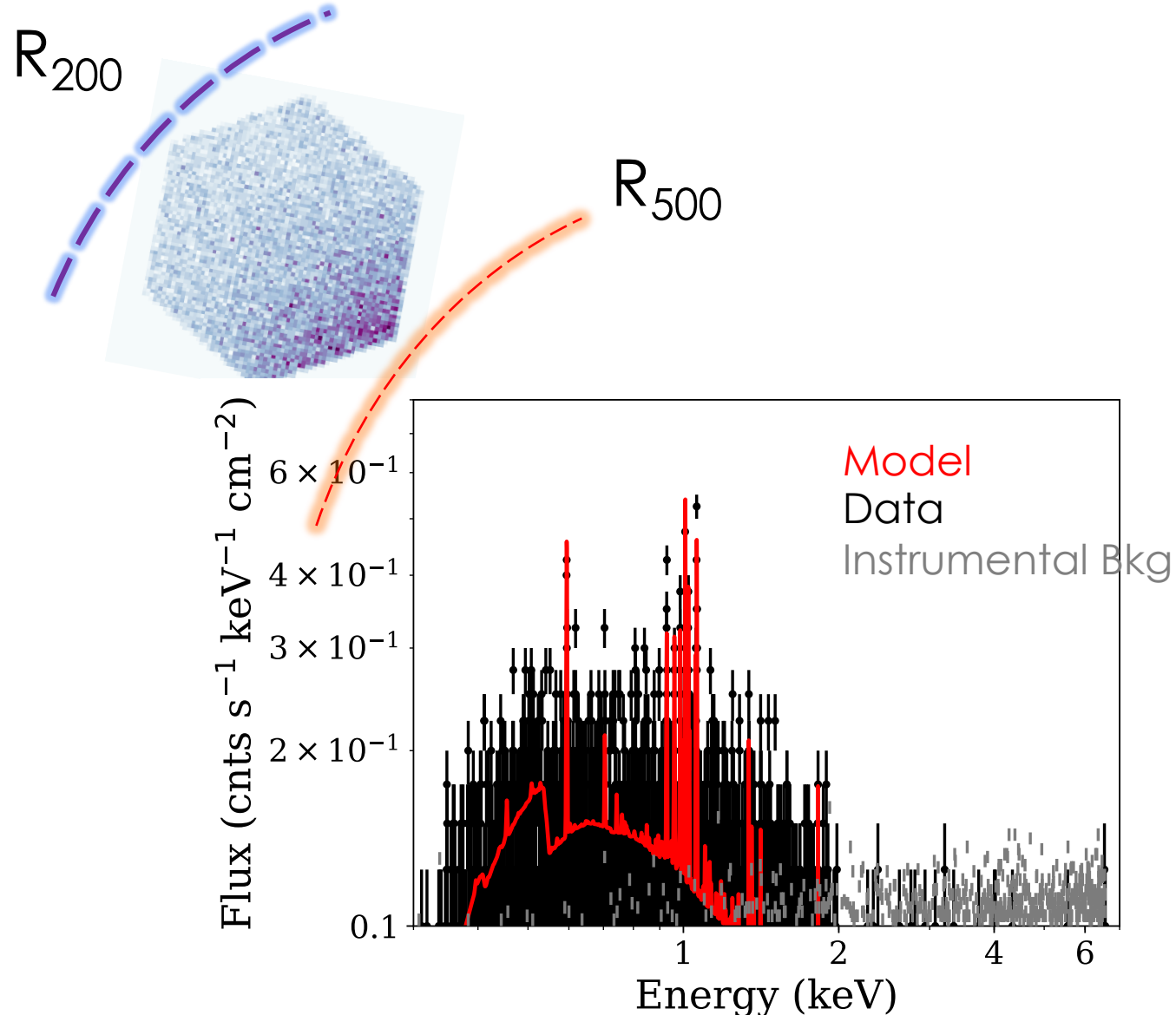
- In the outskirts between R_{500} and R_{200}:
- Spectra becomes noise dominated
- V_{turb} = 110 ± 60 km s^{-1}
- V_{bulk} → no significant detection
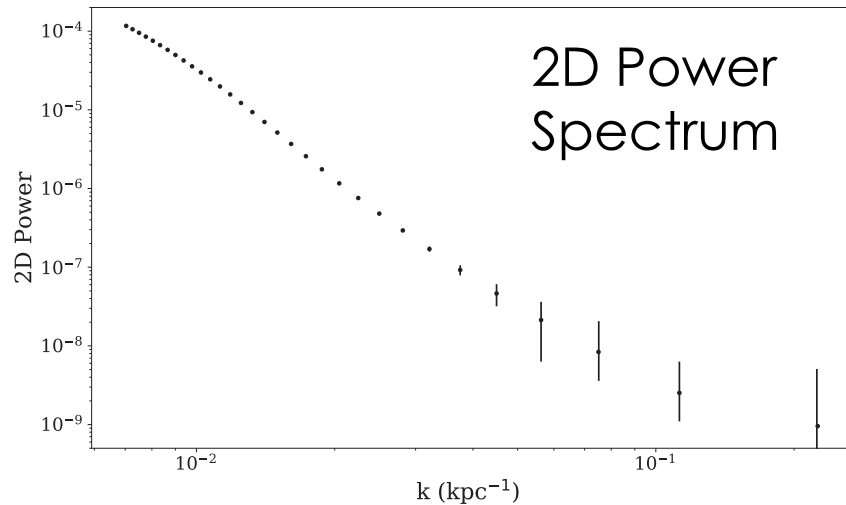- Line broadening is detected with 2σ
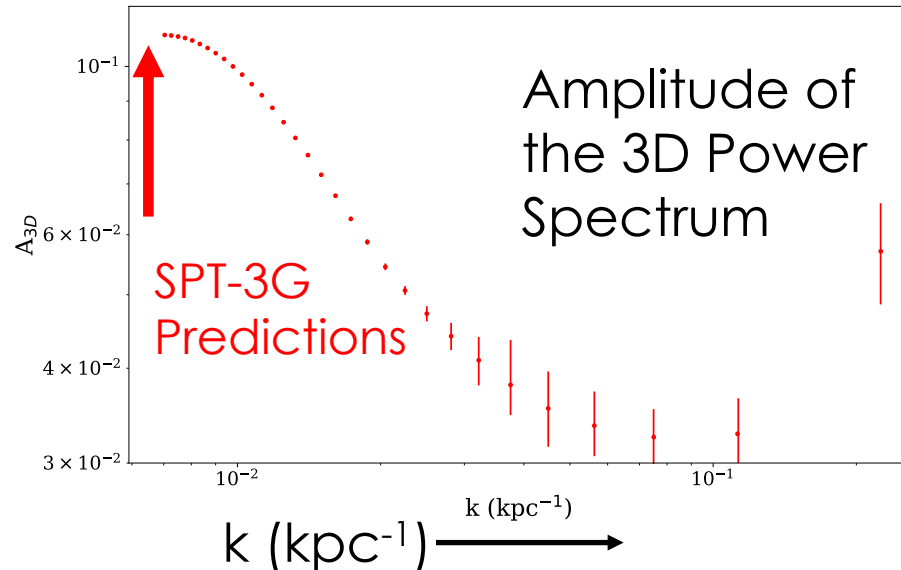
Mock ATHENA WFI Observations

Preliminary

- Dithered WFI Observations for 100ks
- Large FOV covers the entire cluster out to R_{200}
- Obtained exposure maps, surface brightness profile, and performed fluctuation analysis
- $P_{2D} \rightarrow P_{3D} \rightarrow A_{3D}$

Fluctuation Analysis with ATHENA WFI

2D Power Spectrum

k (kpc⁻¹) →

SPT-3G Predictions

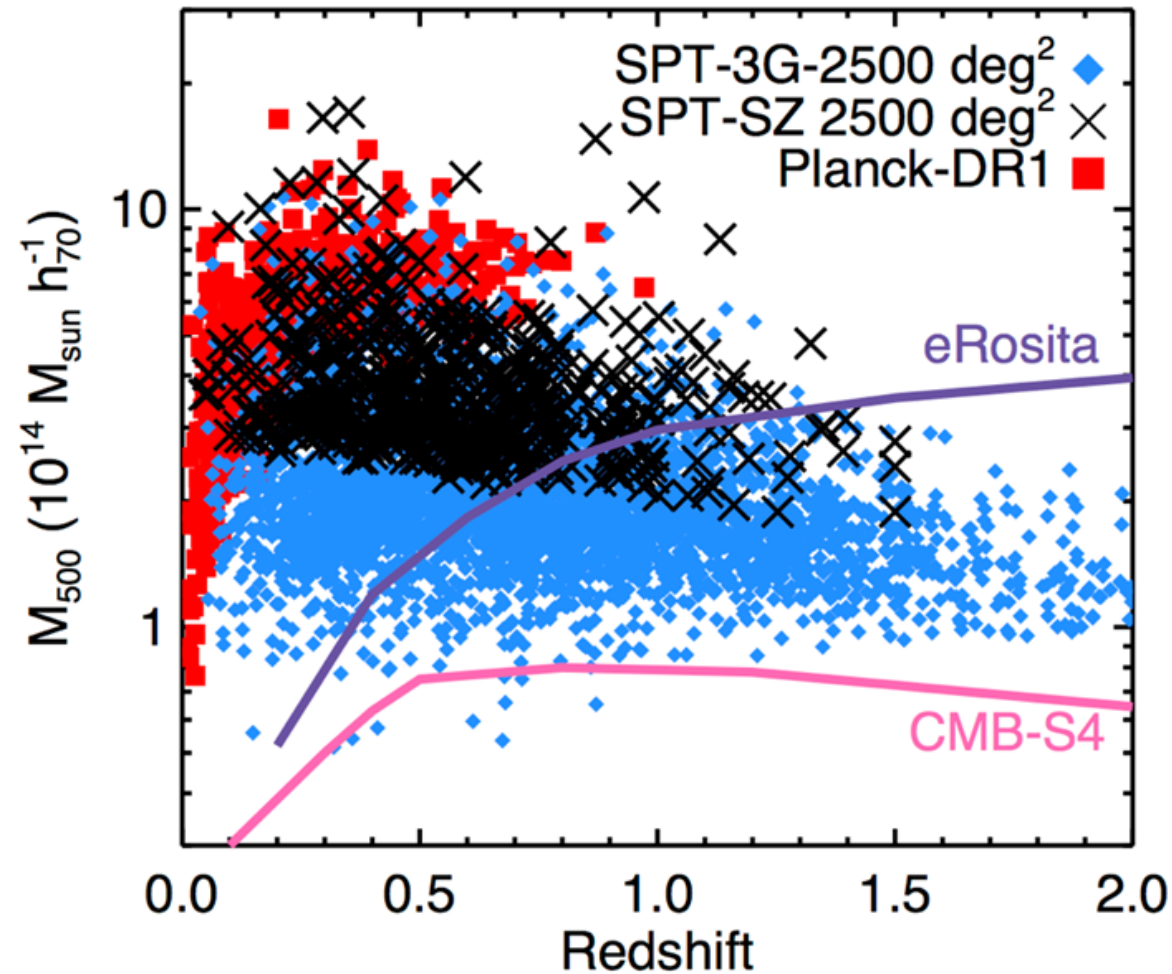Amplitude of the 3D Power Spectrum

k (kpc⁻¹) →

- Work in progress!
- Convolve y-maps with SPT beam size and noise

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

- Calculate Mach Number, hydrostatic bias
- Repeat the analysis for a few relaxed clusters

Summary

- A pathfinder study of the SPT selected clusters with XMM+Chandra and SPT observations is underway!
- Combined ATHENA XIFU and WFI and SZ observations are essential for complete understanding of ICM thermodynamics
- Potential observing Strategy: Find interesting systems with WFI +SZ and follow-up with XIFU