# Physics of Galaxy Clusters:

## *a brief (and biased) review of recent results*

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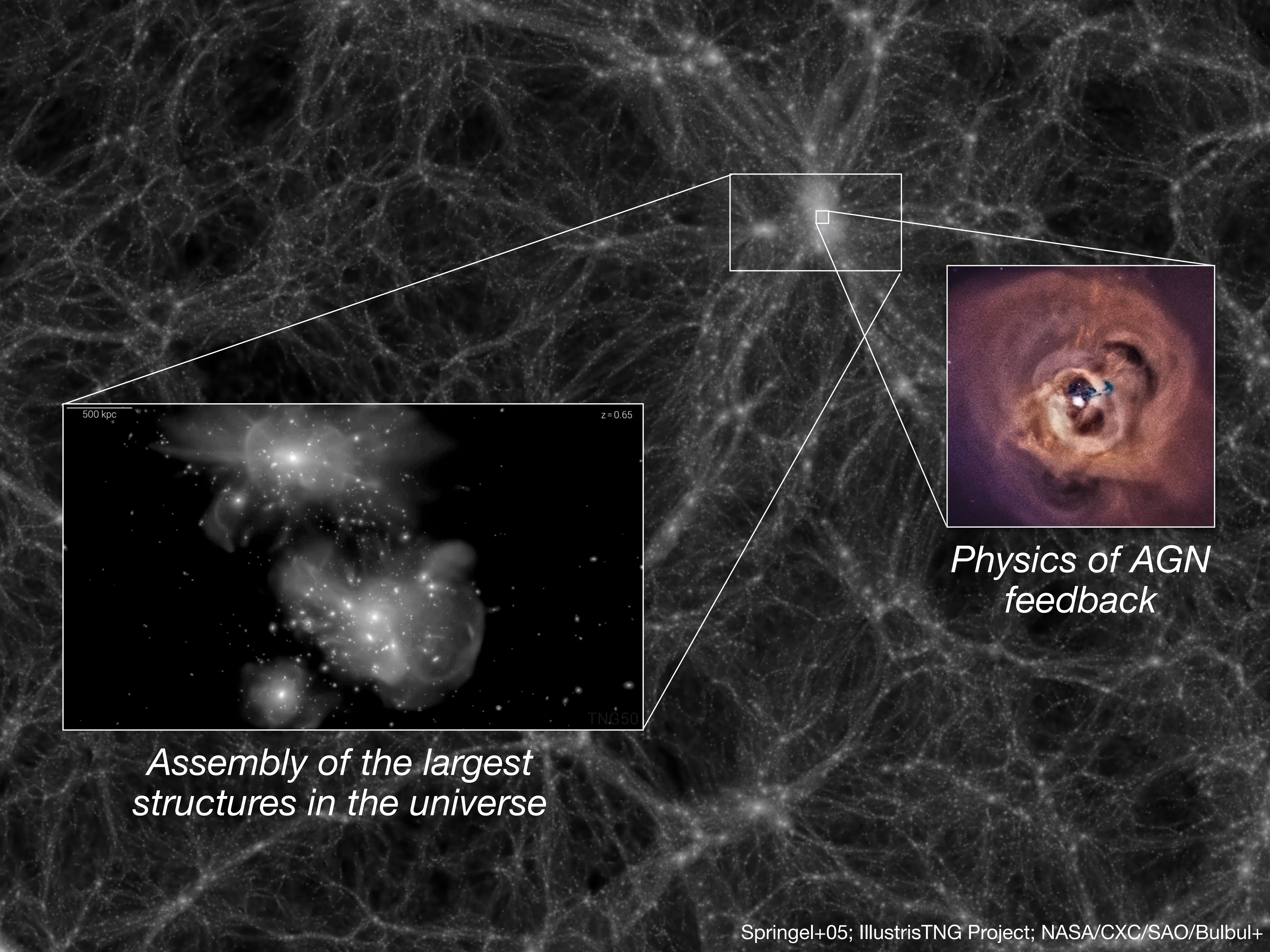
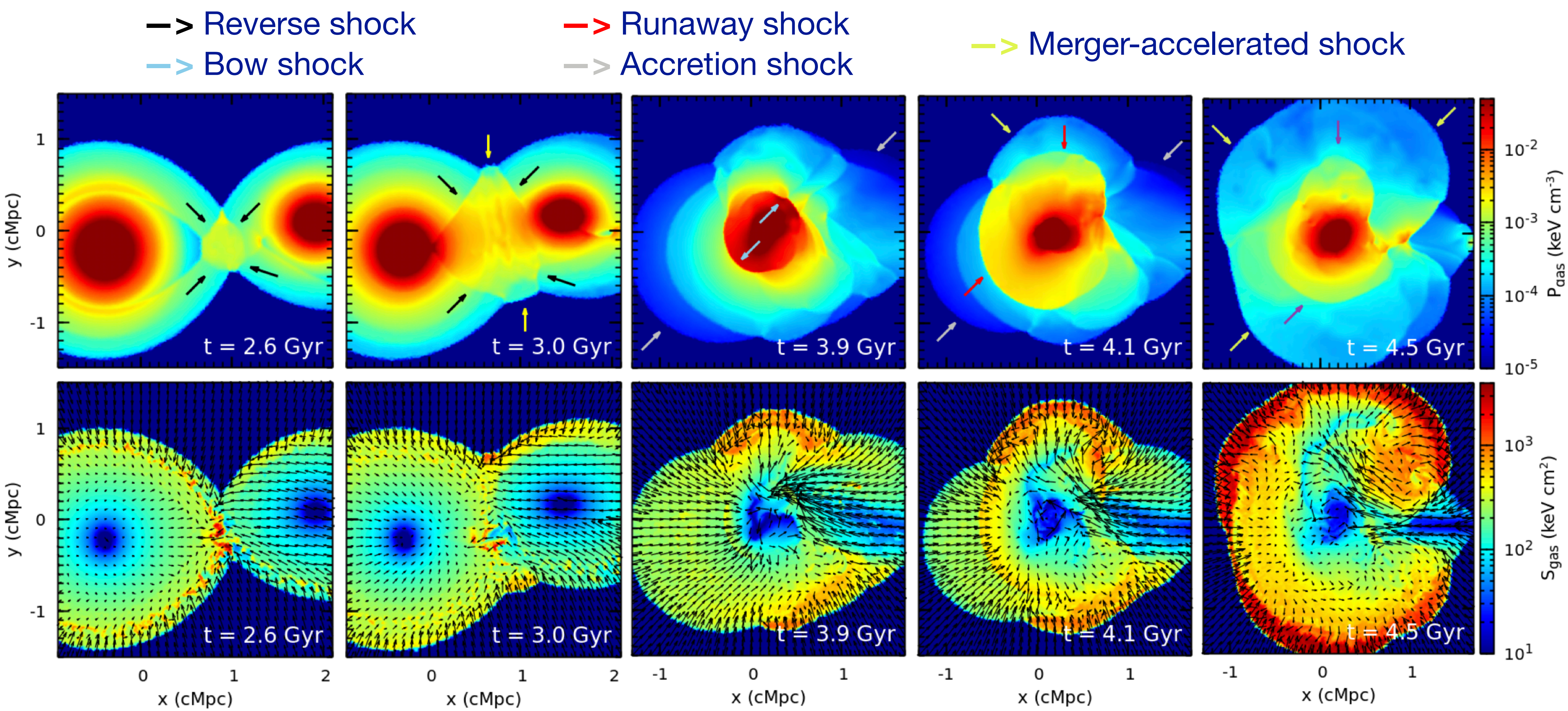
First Results from the SRG/eROSITA All-Sky Survey: from Stars to Cosmology | Garching | 09/18/2024




Springel+05; IllustrisTNG Project; NASA/CXC/SAO/Bulbul+

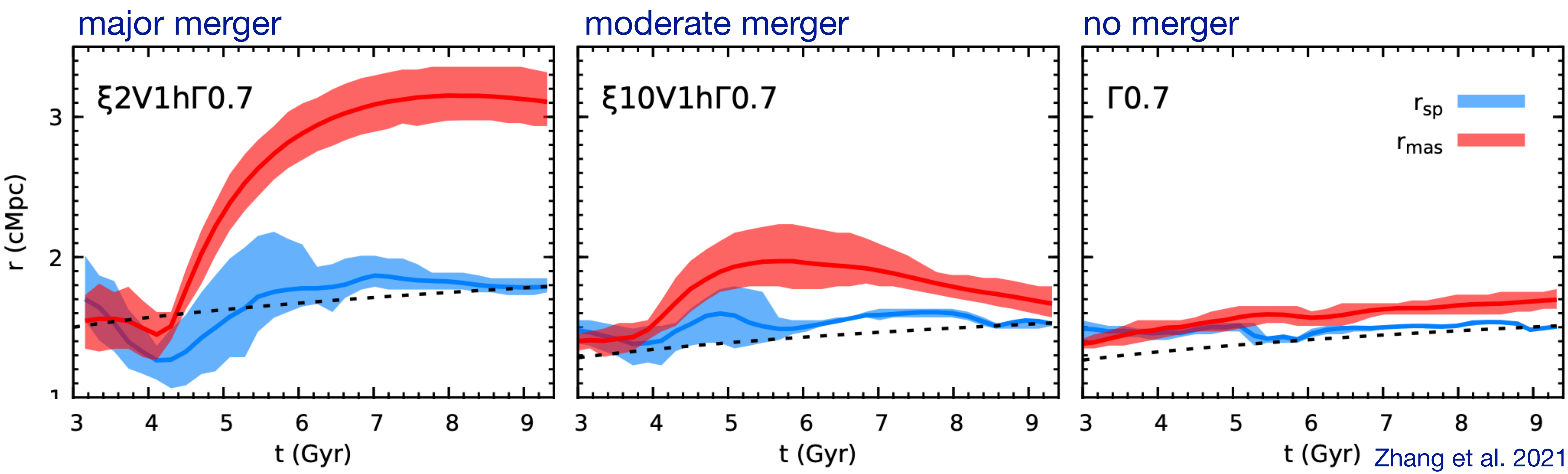
# Merging Clusters in *Idealized* Cosmological Background

- Cluster is modeled by a self-similar solution of the spherical collapse model
- The mass evolution follows: $M(z) = M(z_\mathrm{i})\left[a(z)/a(z_\mathrm{i})\right]^{\Gamma_\mathrm{s}}$
- Outermost DM caustic and accretion shock are automatically included and well-resolved
- High computational efficiency, ideal for exploring parameter space, full control of the merging process

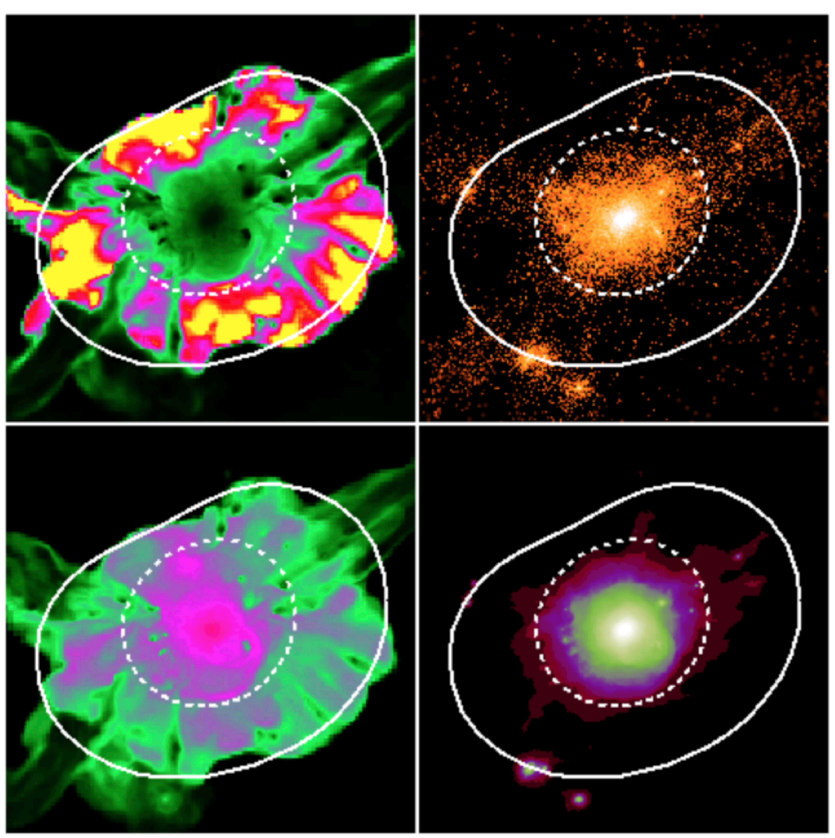



Zhang et al. 2021

# DM and Gaseous Boundaries

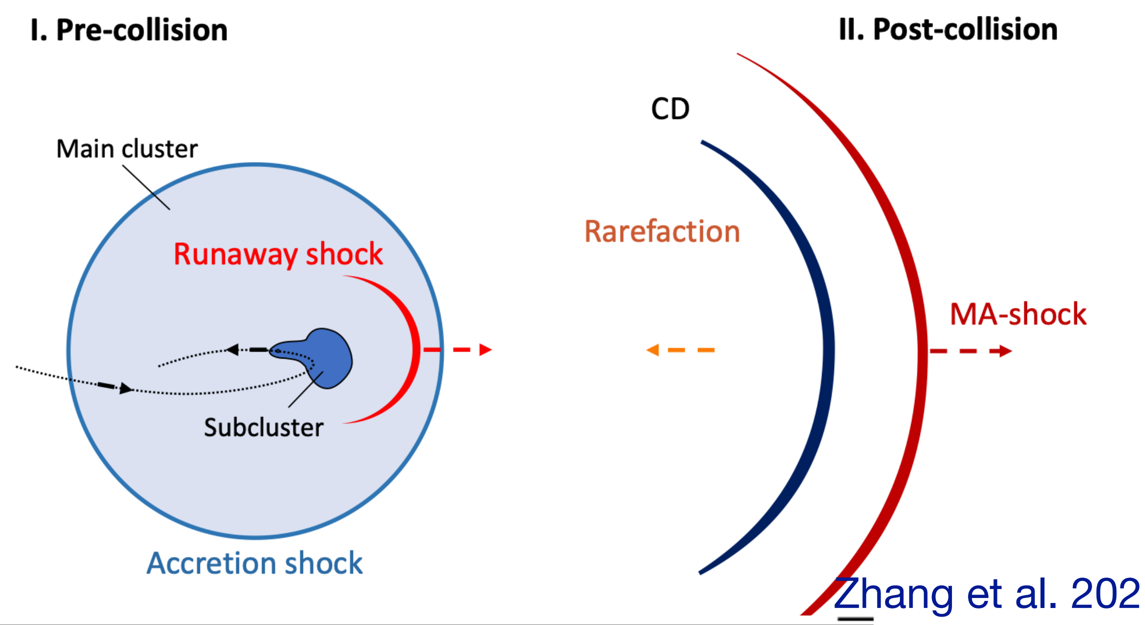


Zhang et al. 2021

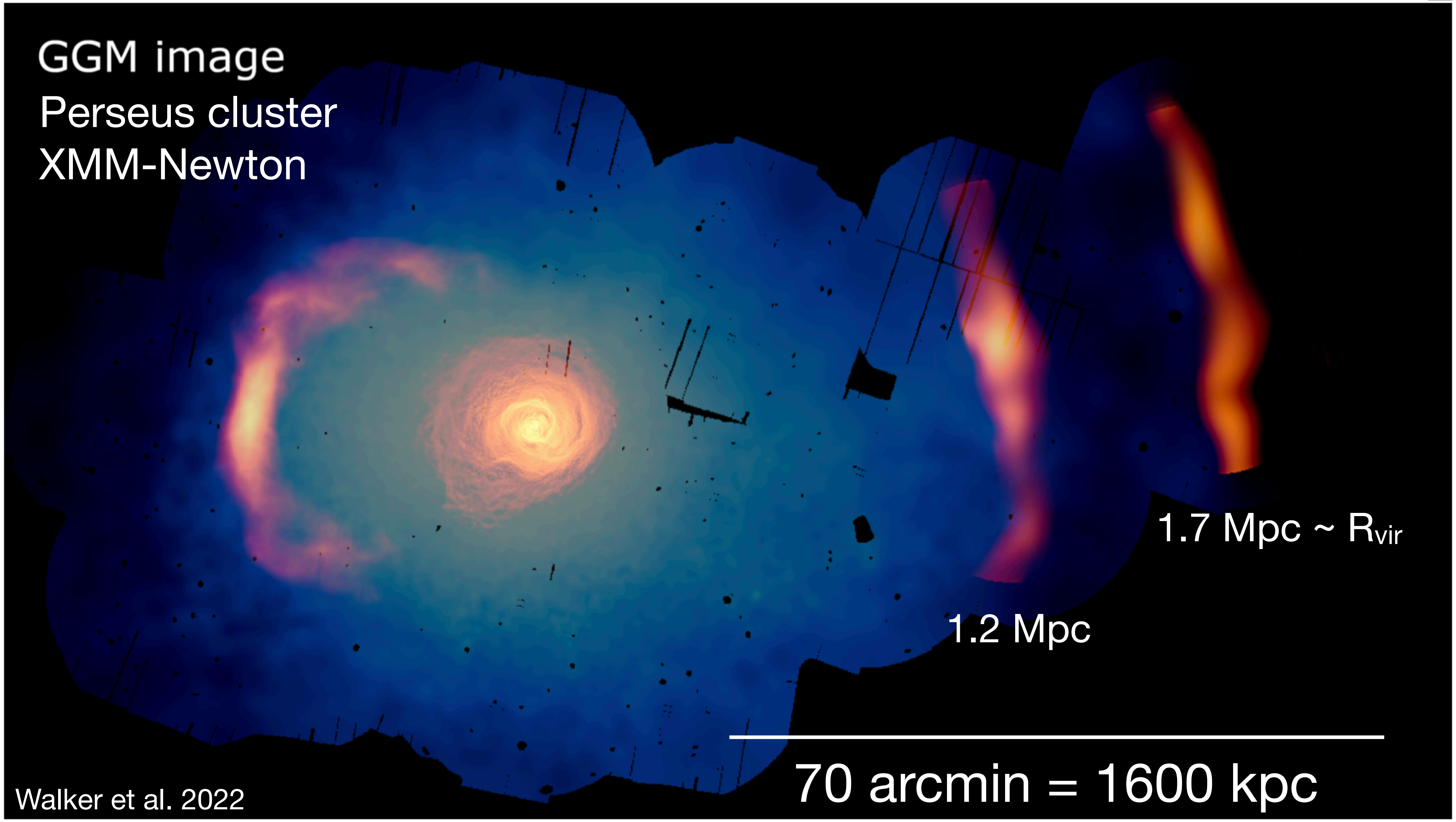

Aung et al. 2020

- Cosmological predictions predict an offset between DM and gaseous boundaries ~ $R_{gas}$ ~ 1.89 $R_{sp}$
- Slow smooth accretion rate + mergers can naturally explain this difference

# Hints of Merging Shocks

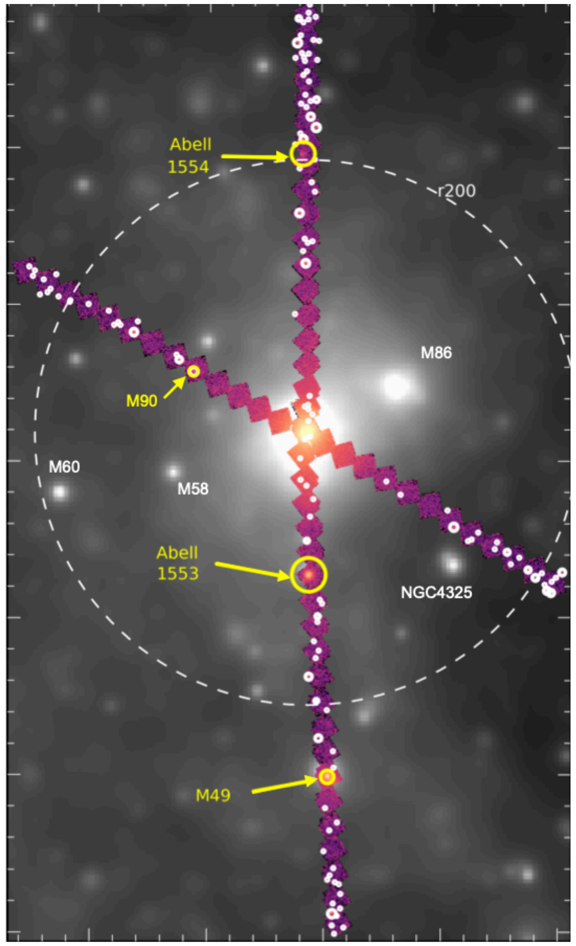


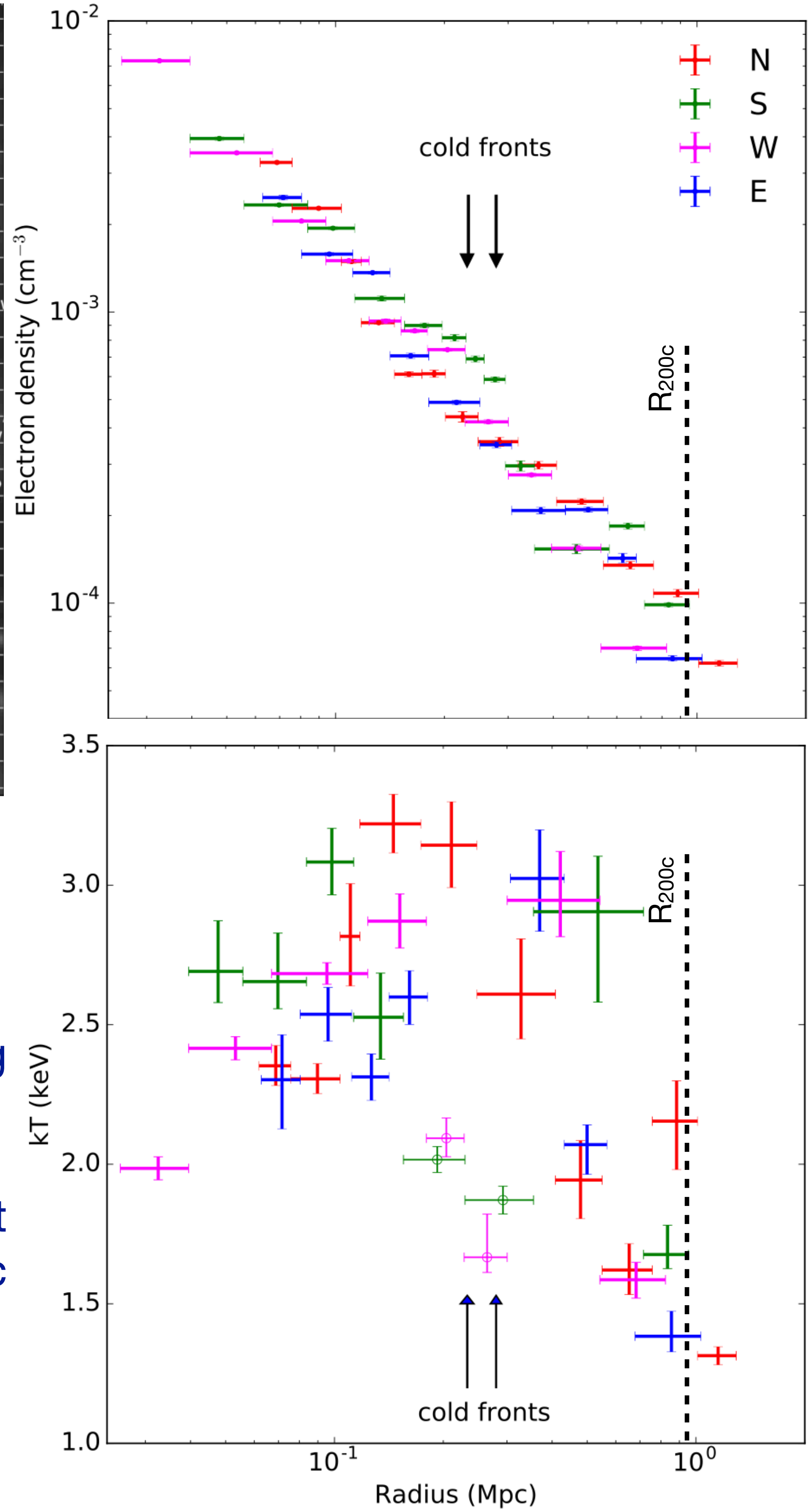

Zhang et al. 2021




- Two discontinuities detected at large radii in the Perseus cluster
- “Sloshing cold fronts” or collisions between the accretion and runaway shock?

# Cluster Outskirts ($R_{vir}$, $R_{200c}$)



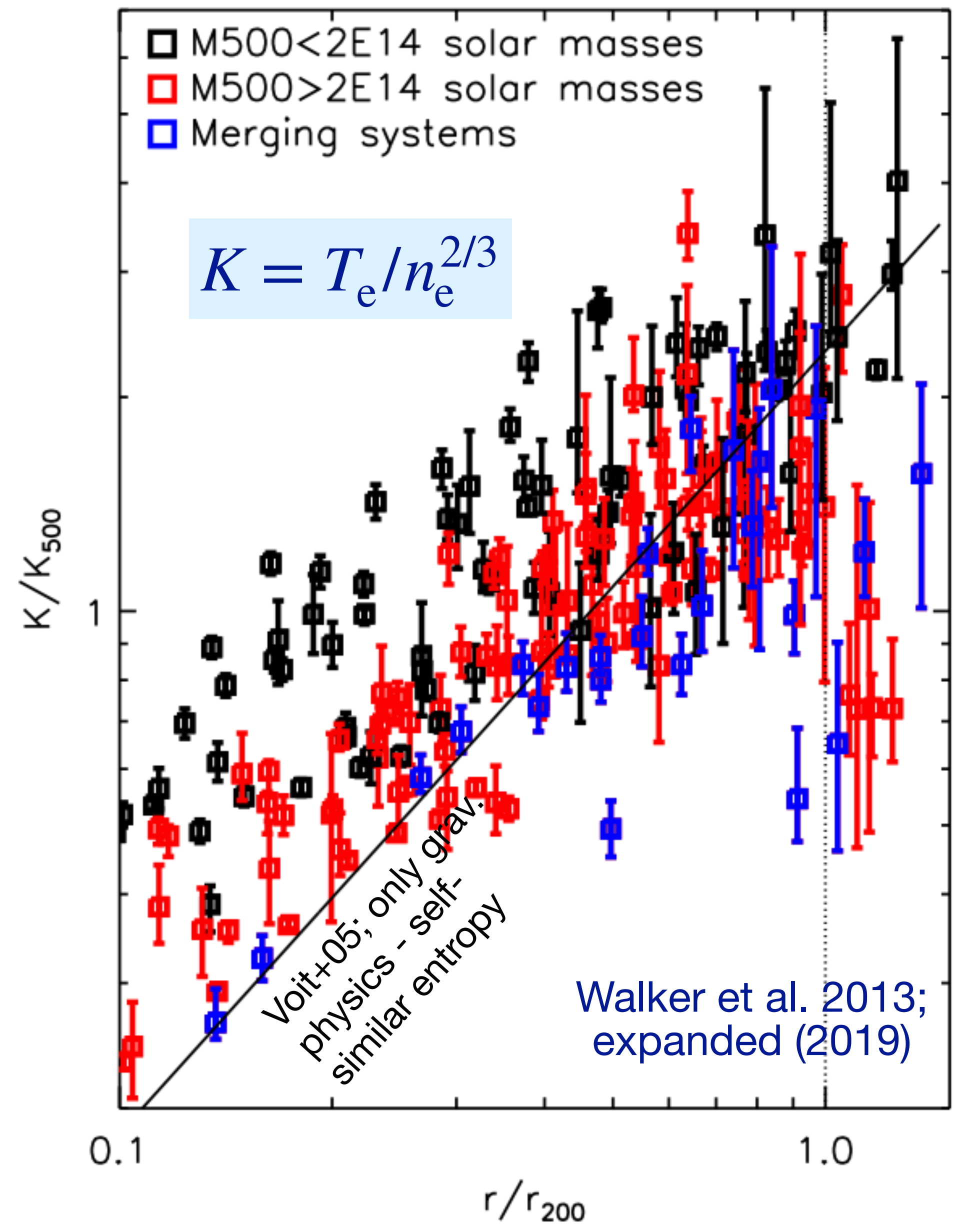




**Witnessing the growth of the nearest cluster:**

- large-scale sloshing pattern (two new CFs)
- two high-T regions at 1 Mpc (S) and 605 kpc (W), likely shocks

Simionescu et al. 2017

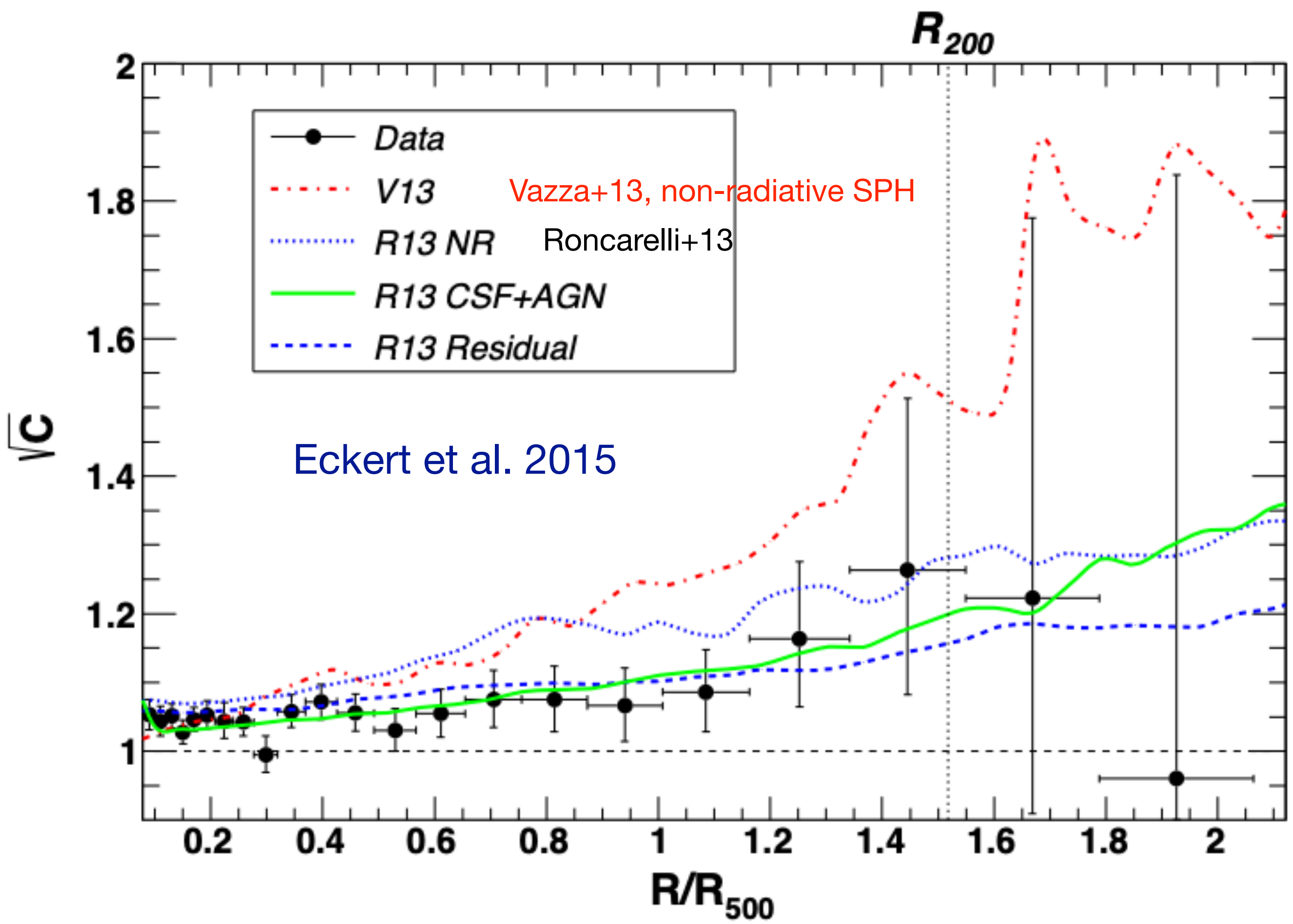
**Sample of Suzaku measurements**

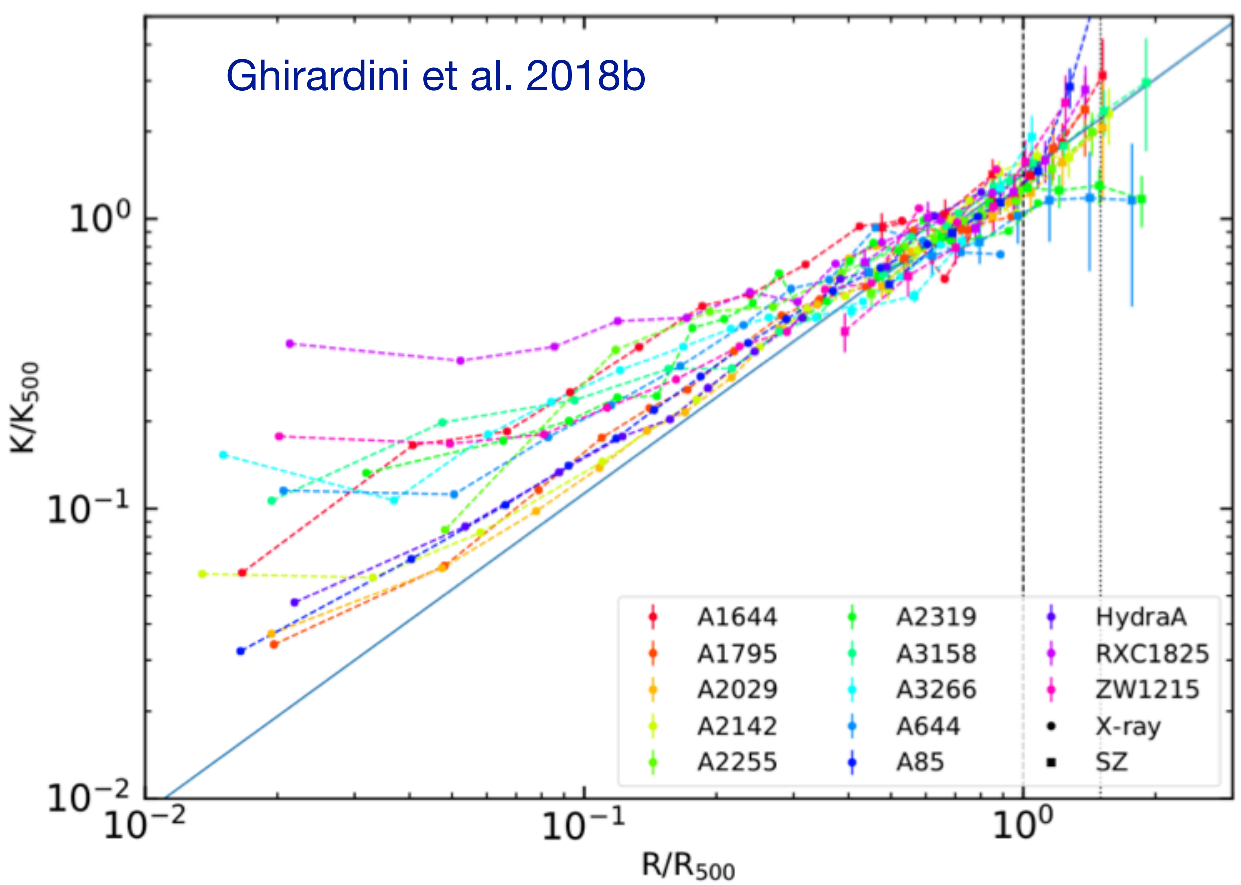



- Entropy tends to be below (consistent with) the baseline prediction in massive (low-mass) systems
- Entropy excess at small radii is much more pronounced in low-mass systems —> stronger impact of AGN feedback

# Clumping: $C = \langle \rho_{gas}^2 \rangle / \langle \rho_{gas} \rangle^2$

X-ray emission $\propto \rho_{gas}^2$ —> unresolved dense clumps will increase the observed X-ray luminosity and bias gas density by a factor of $\sqrt{C}$



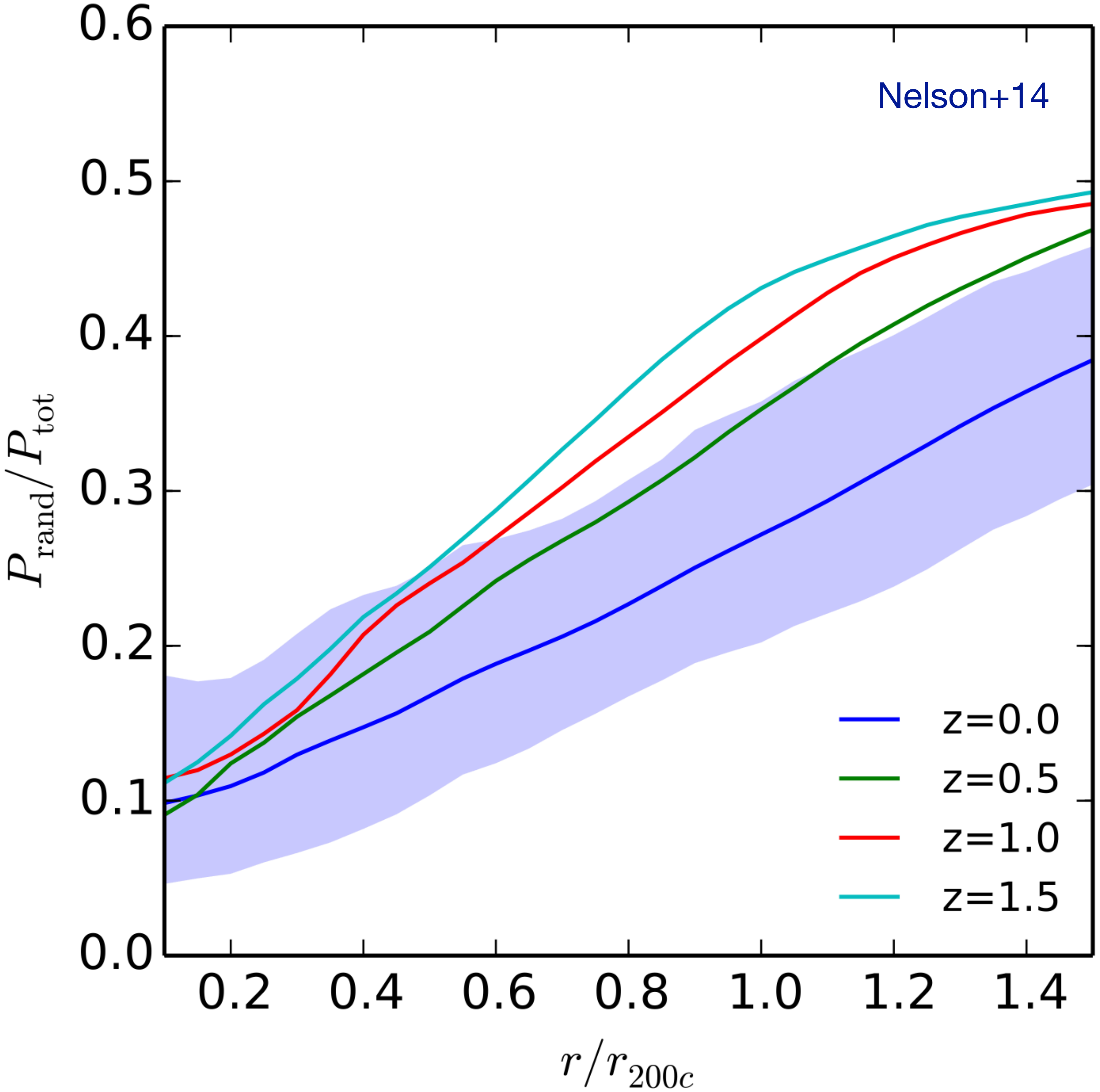

- Clumping factors by comparing the median and mean X-ray SB of ROSAT clusters + predictions of numerical simulations

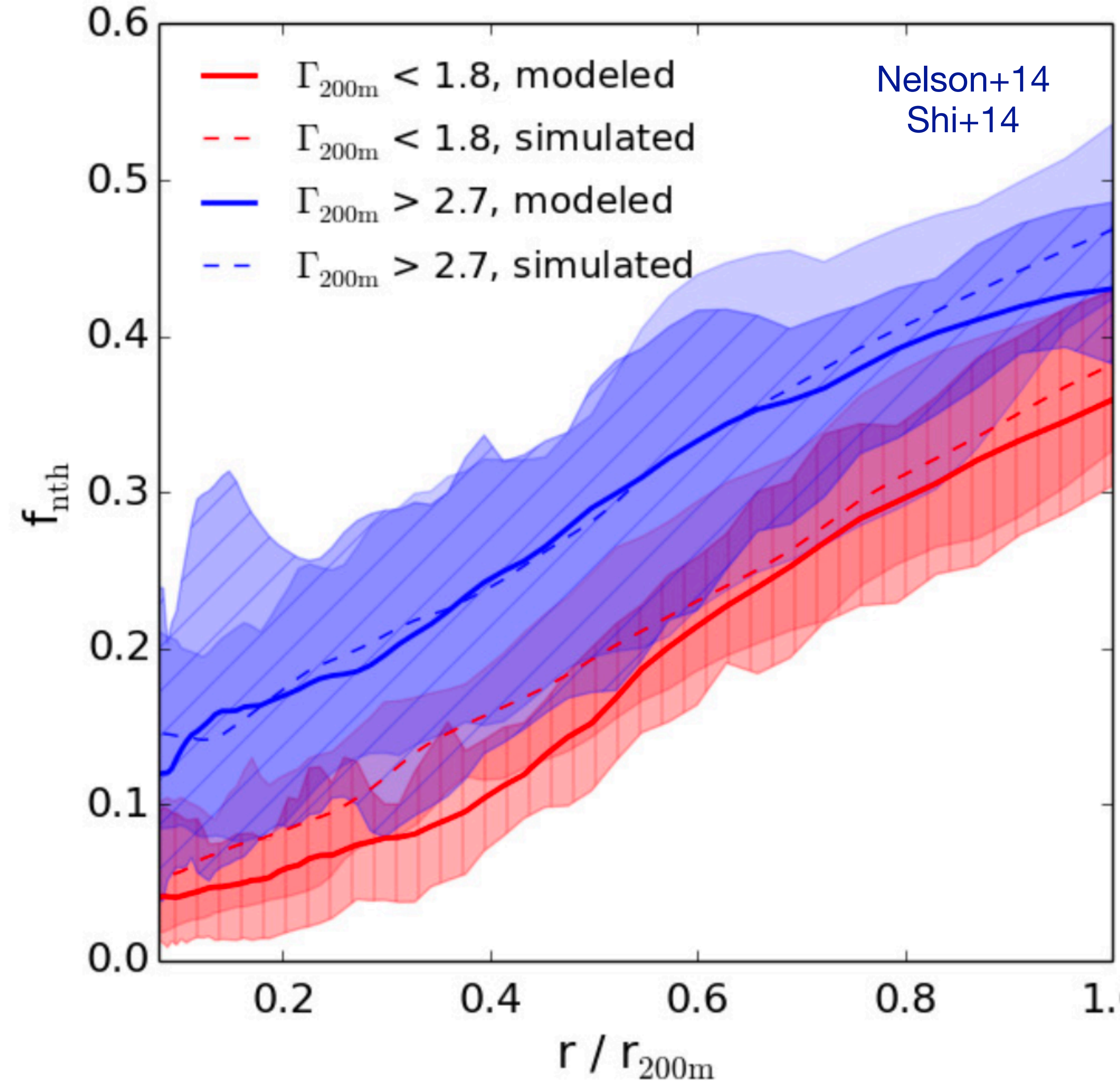
- Based on X-COP (XMM+Planck) sample: when clumping is taken into account, entropy is in better agreement with the baseline entropy profile

# Non-Thermal Pressure

**Hydrostatic equilibrium:** $$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM_{\rm total}(r)}{r^2}$$

$$P = P_{\rm ther} + P_{\rm turb} + P_{\rm CR} + P_{\rm m.f.}$$

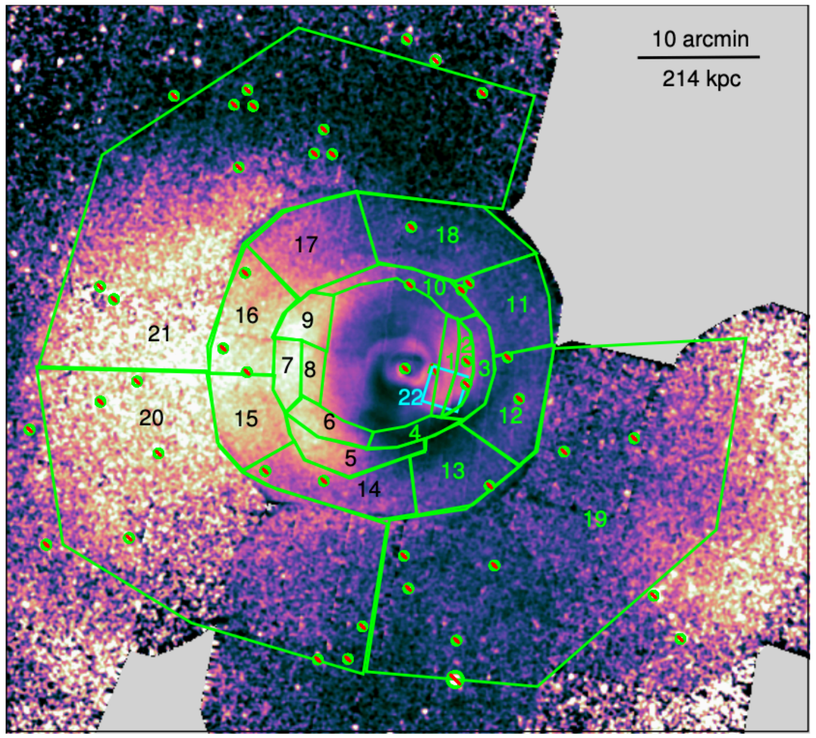


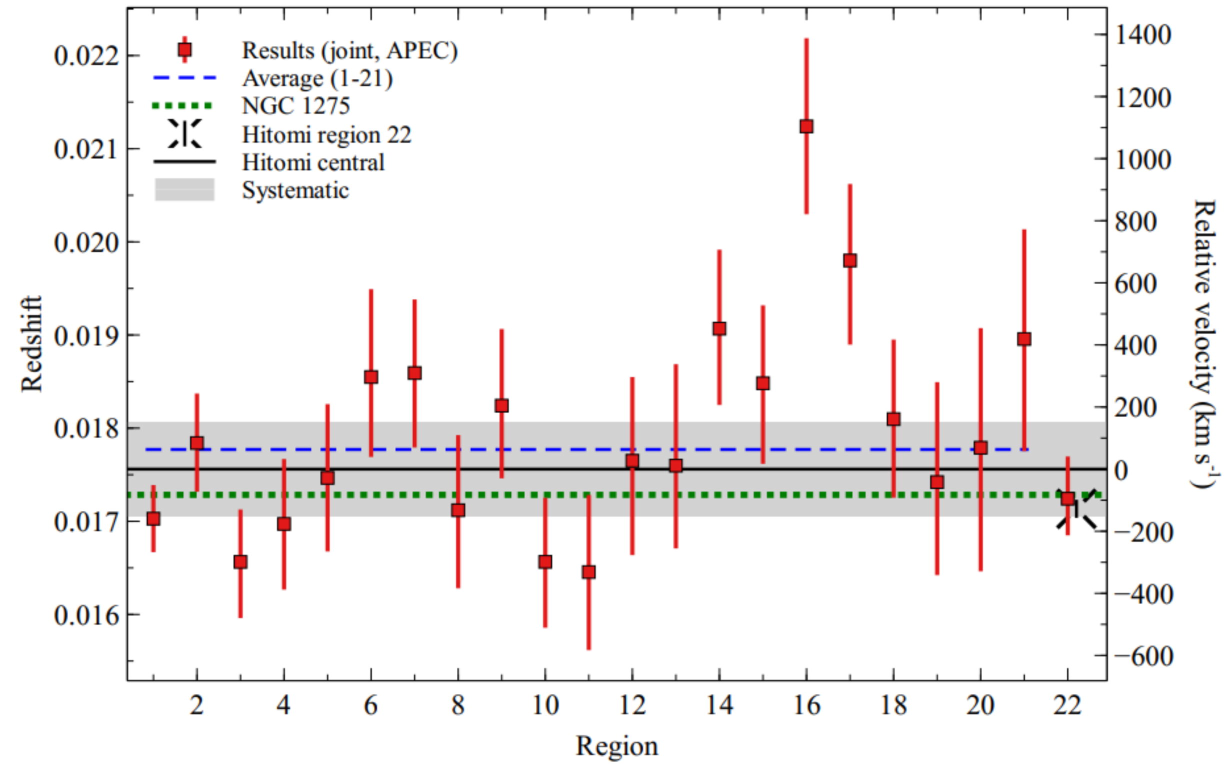



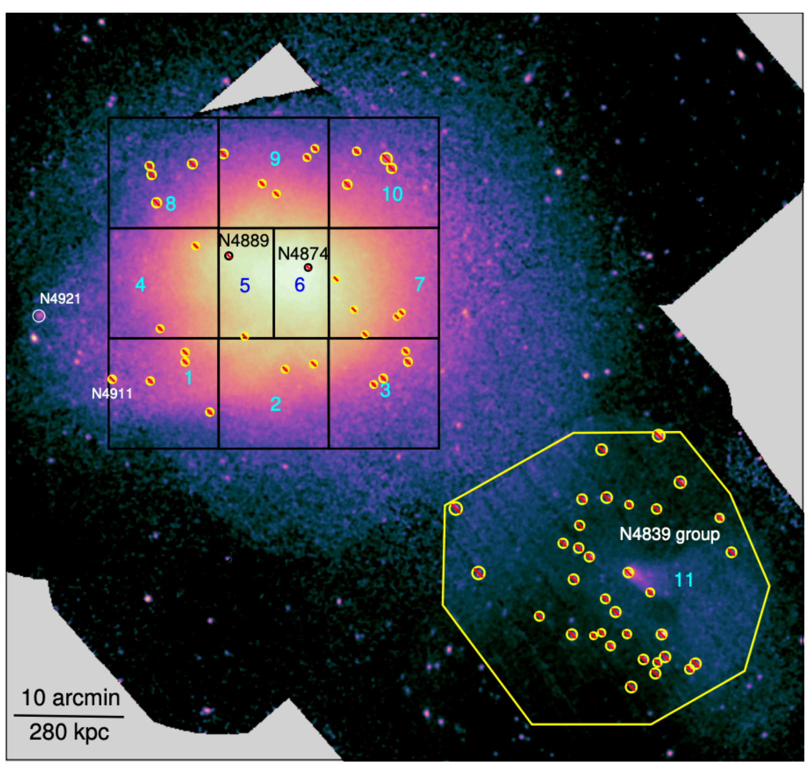

Lau et al. 2009; Vazza et al. 2009; Battaglia et al. 2012, Rasia et al. 2006; Nagai et al. 2007; Nelson et al. 2012, 2014a; Shi et al. 2016, etc.

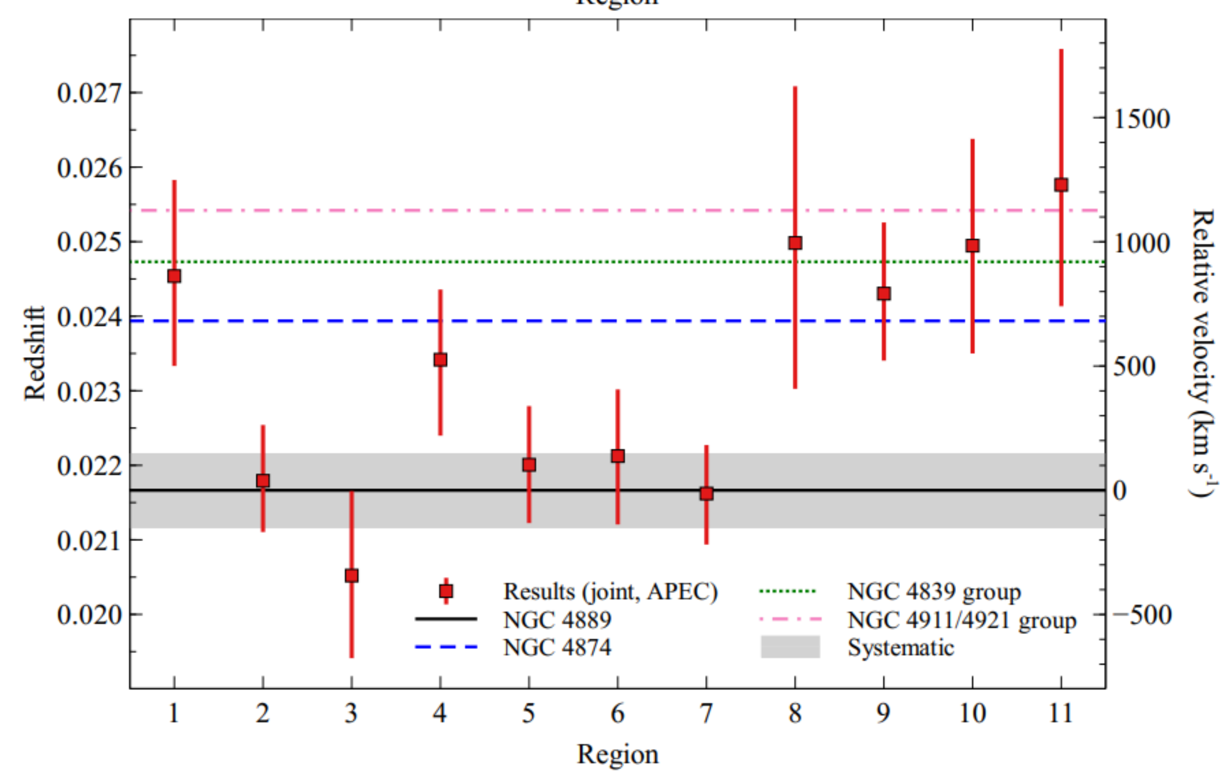
# Direct Measurements of Bulk Velocities

EPIC-pn detector on XMM-Newton + a new technique to calibrate the energy scale
nominal calibration accuracy: 550 km/s
new energy scale of the detector: 150 km/s




Sanders et al. 19; see also Gatuzz19, 22

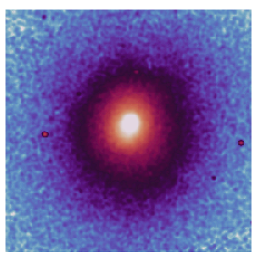
# Velocity Power Spectra from X-ray Surface Brightness Fluctuations

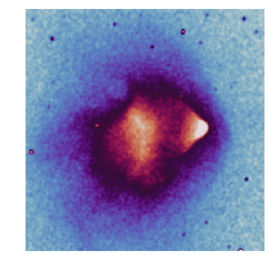
$$\frac{\delta\rho}{\rho} = \eta \frac{V}{c_s}; \quad \eta \sim 1 \pm 0.2$$ for clusters in various dynamical states

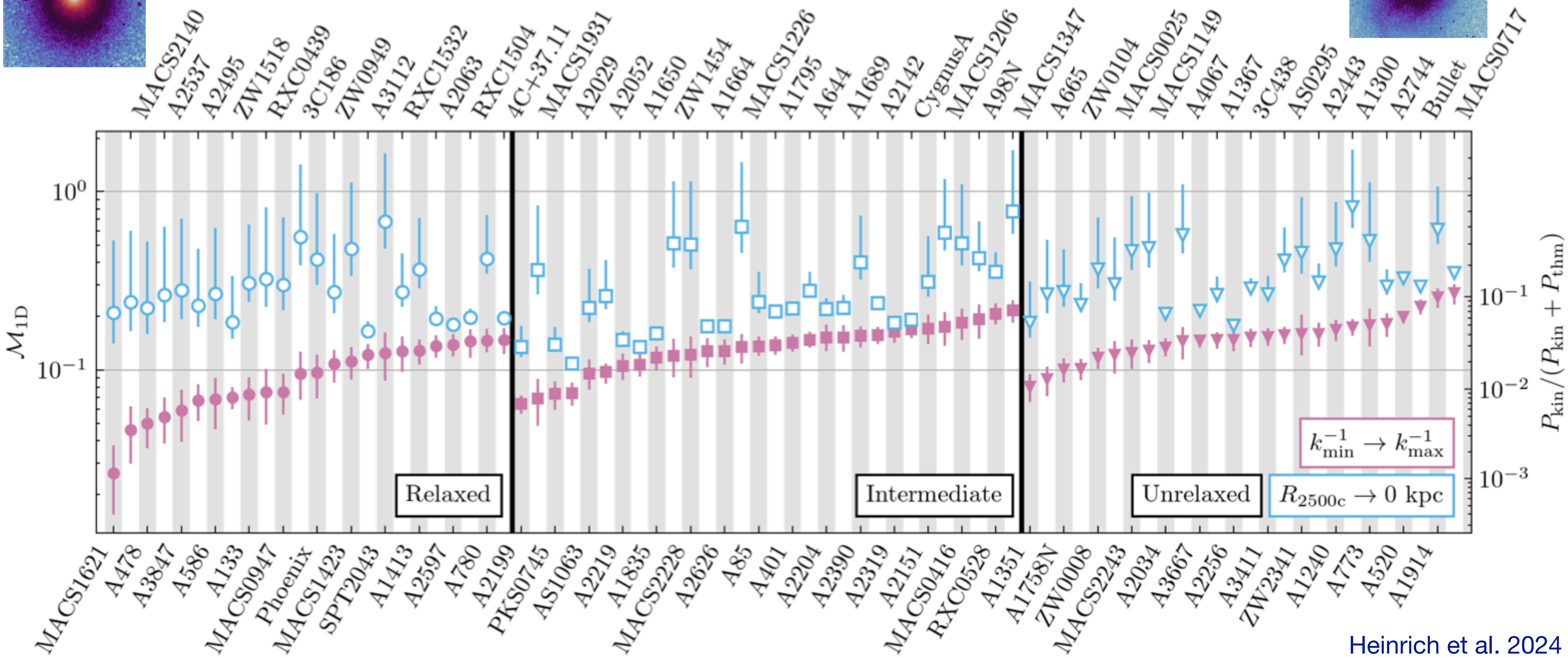
Zhuravleva et al. 2023

Based on a sample of ~ 80 clusters

Analyzed regions: from center (excluding cool core) to $R_{2500}$

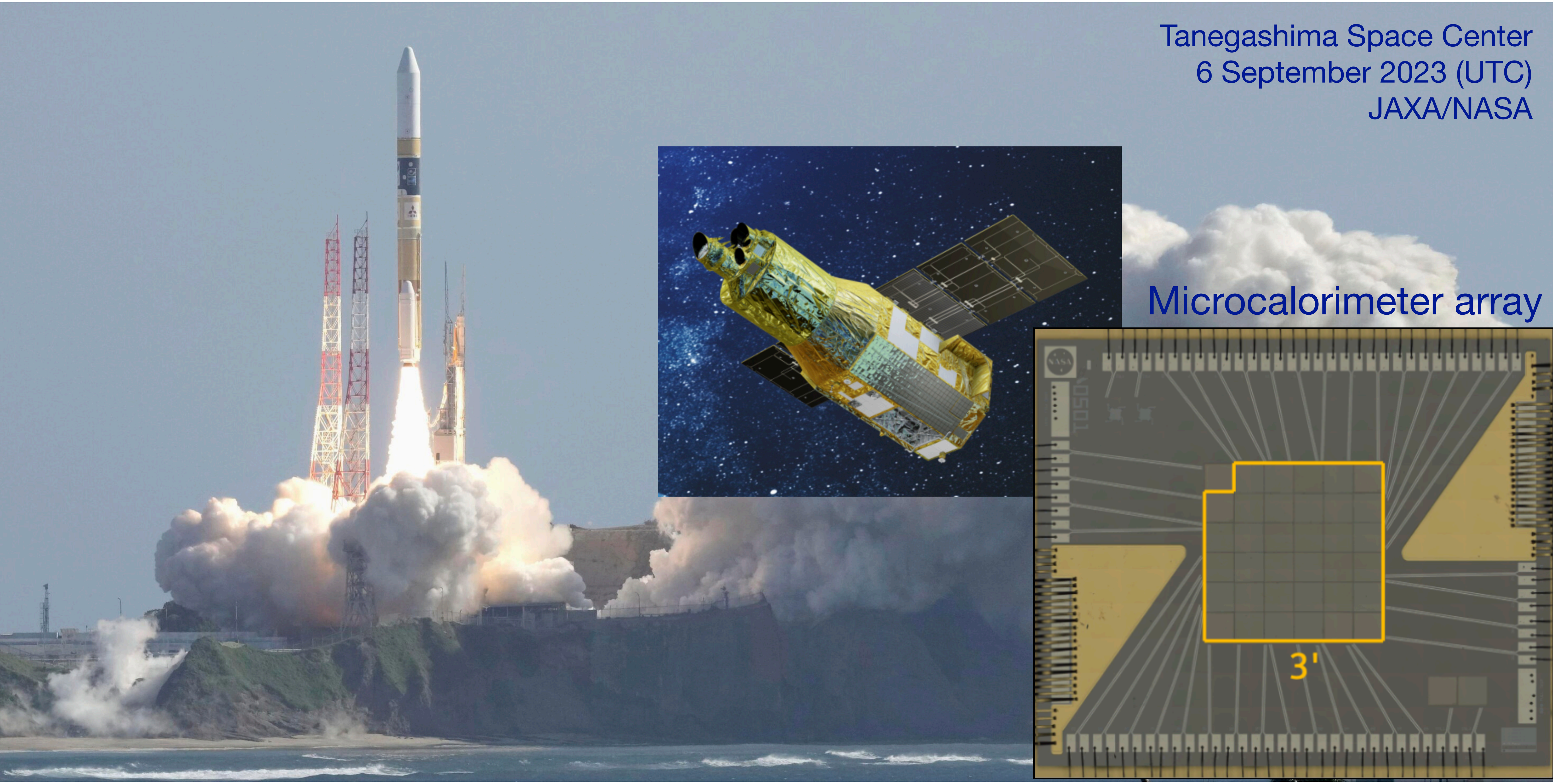







Heinrich et al. 2024

# X-ray Imaging and Spectroscopy Mission




- Non-dispersive spectrometer
- In-flight spectral resolution 4.5 eV
- 1.3’ angular resolution
- 2-17 keV energy band

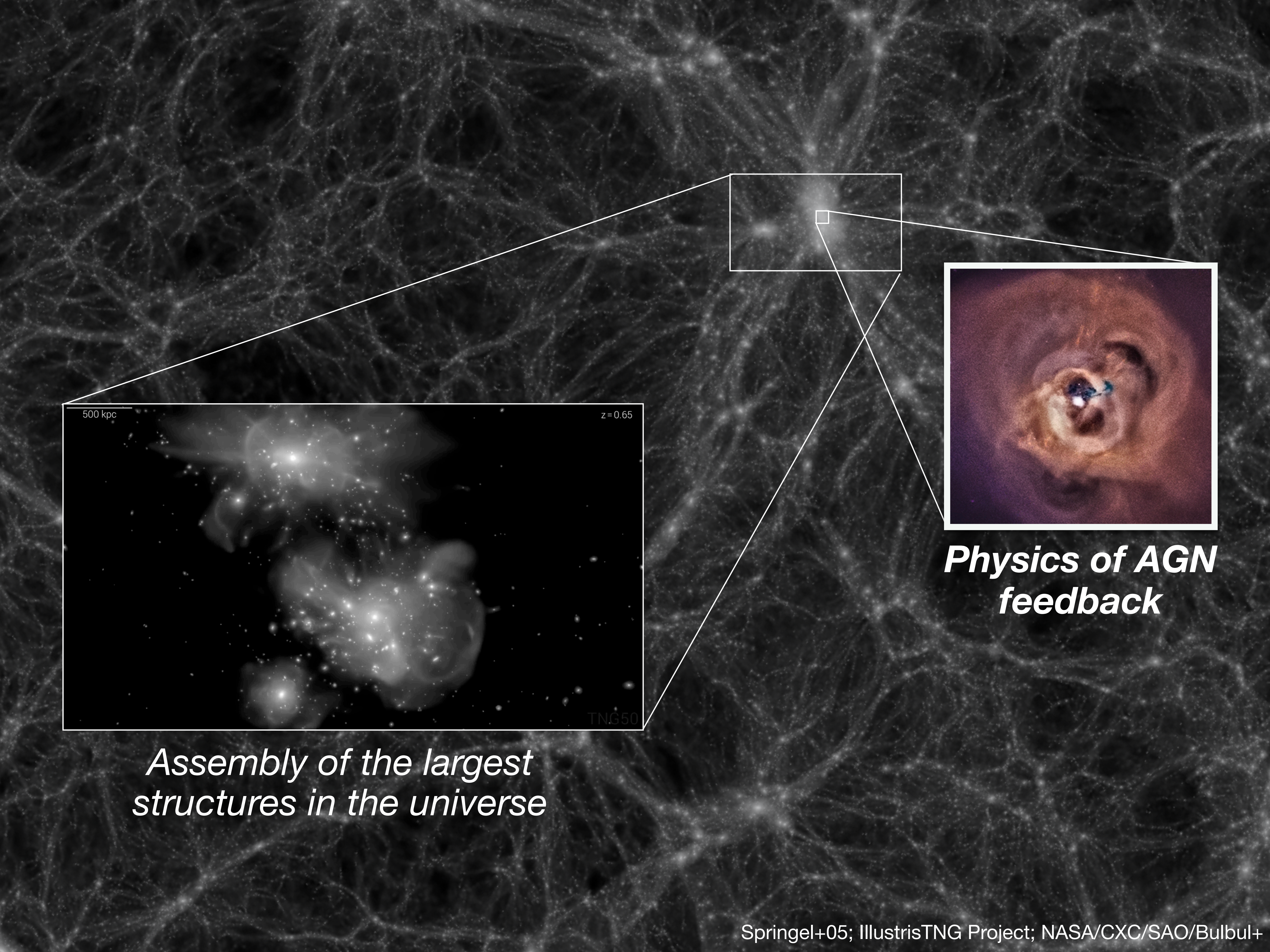
XRISM collaboration

# Important Disclaimer

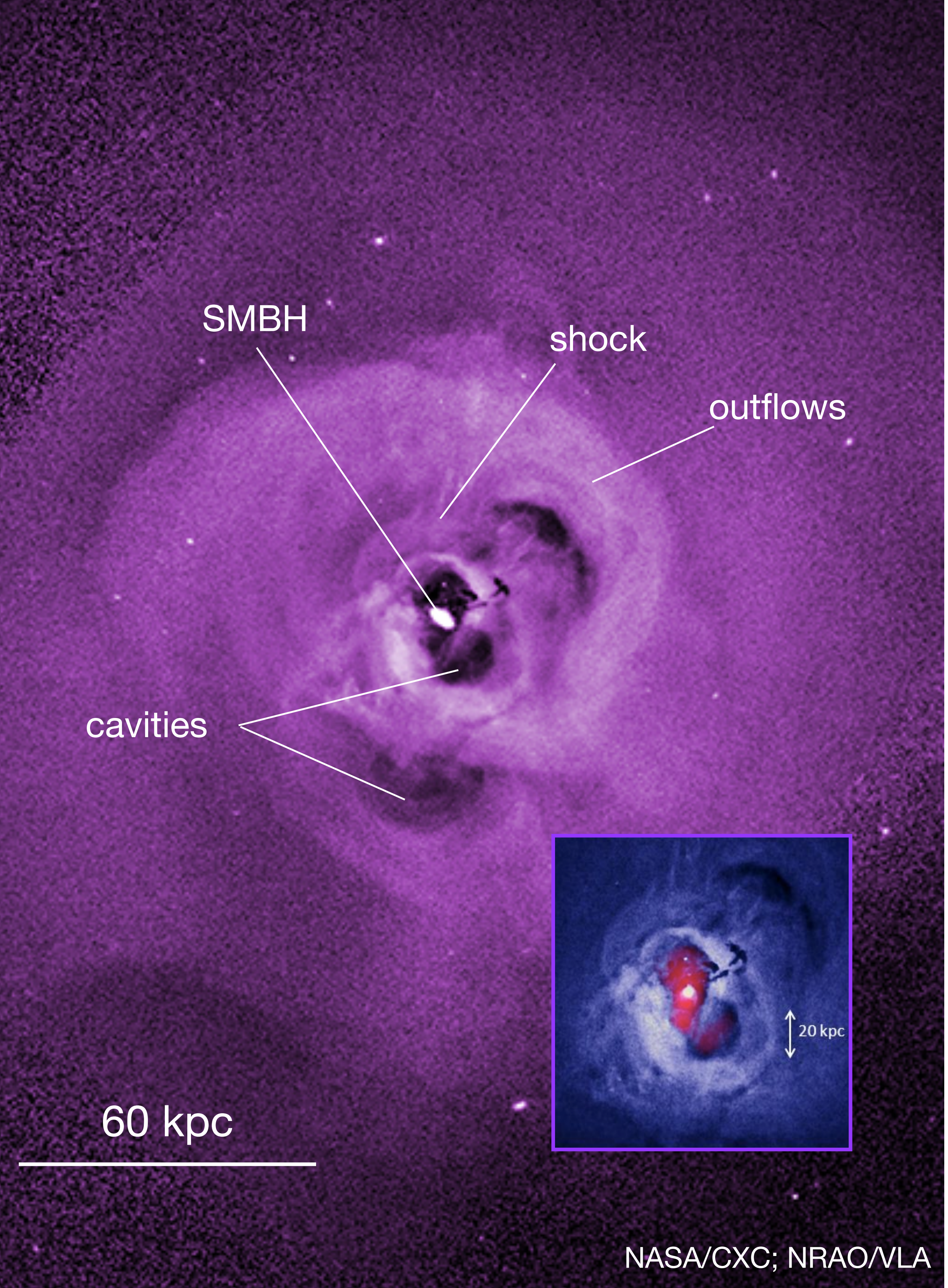
- XRISM is the result of a decade-long effort of hundreds of scientists and engineers at JAXA, NASA, ESA and many academic institutions and industries all over the world
- As a reward for their effort, the members of the XRISM Science Team have exclusive access to the data of the Performance Verification
- The results I will show have been obtained on **proprietary data**
- The Agencies and the Japanese Government attribute the uttermost importance to the respect of the confidential nature of these results
- On their behalf, **I am asking the audience – in the room and on-line - not to disseminate any of these results** via social media or other means. **Please, do not take pictures or screenshots**

On behalf of XRISM collaboration

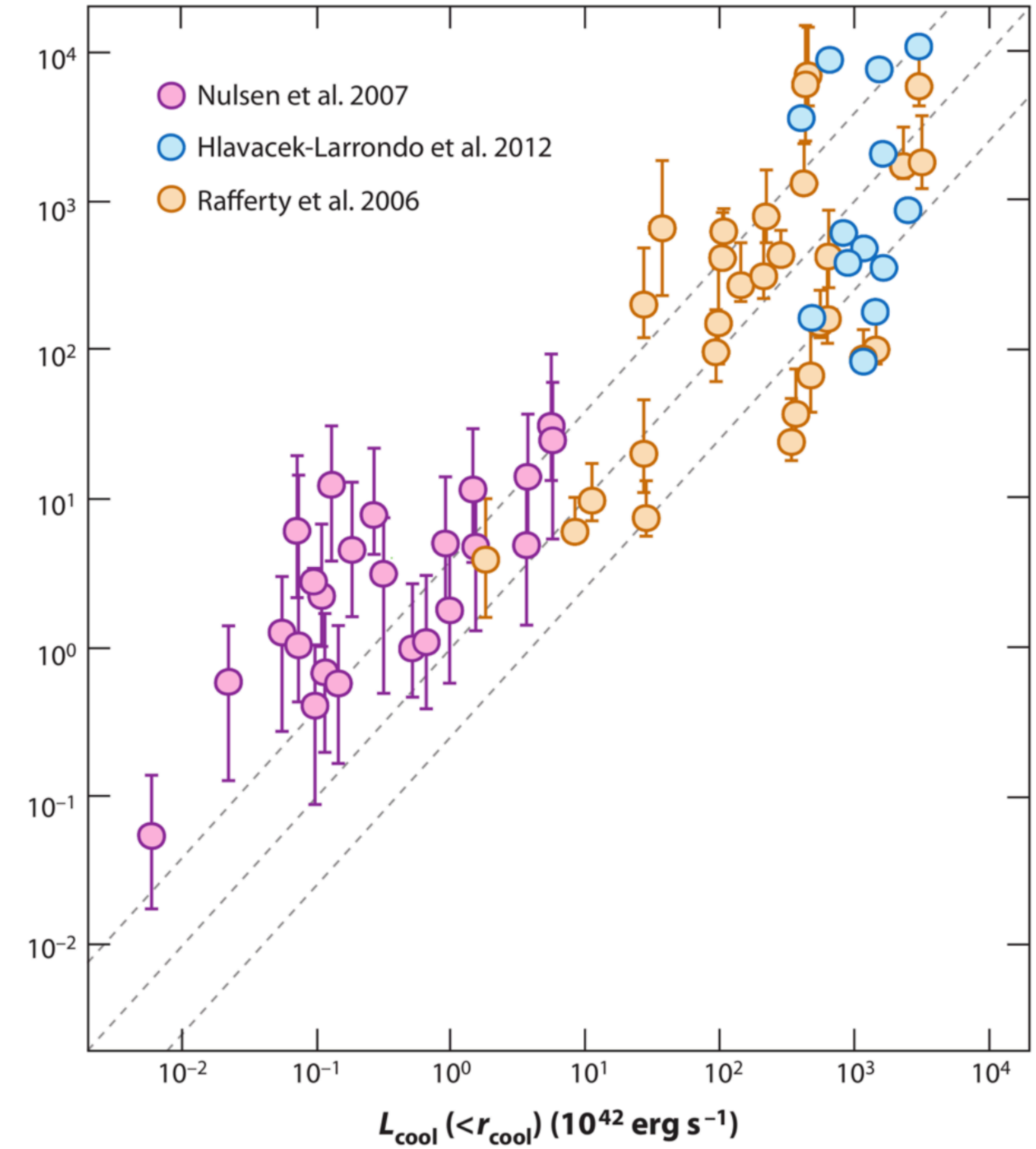
# Coma Cluster: a Merger


500 kpc
z = 0.65
TNG50
Physics of AGN feedback
Assembly of the largest structures in the universe
Springel+05; IllustrisTNG Project; NASA/CXC/SAO/Bulbul+

# Perseus cluster



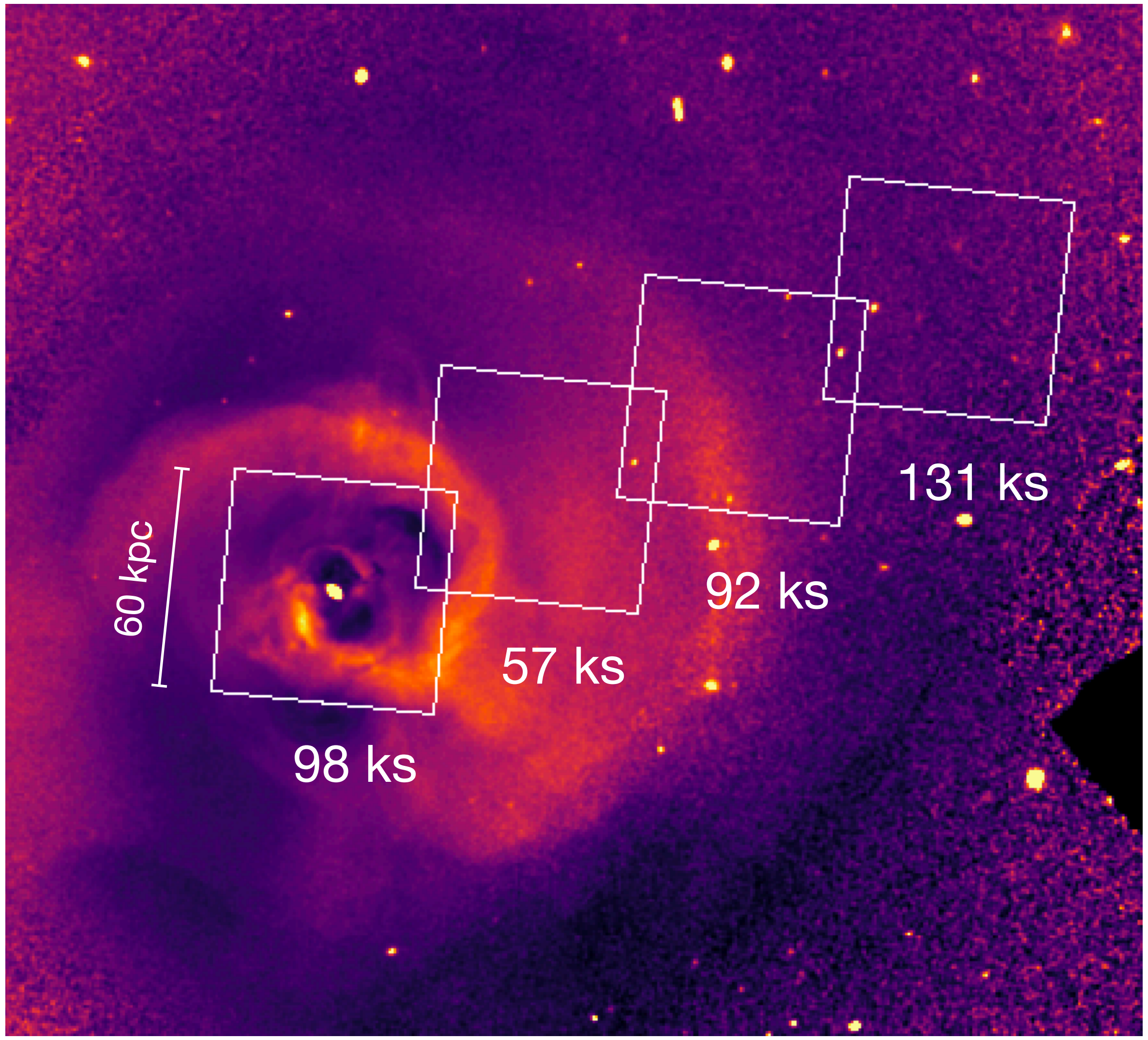

mechanical power in bubbles




energy loss by X-ray radiation

Churazov+00, McNamara+00, Fabian+03,12, Sanders+07, Birzan+12, Hlavacek-Larrondo+13, etc.

# Perseus Cluster:
# Feedback vs. Mergers (Sloshing)




XRISM collaboration/Perseus team

# Takeaway points

## *Exciting times for cluster physics*

- Interacting runaway and accretion shocks is essential part of cluster outskirts; merger-accelerated shocks
- The DM and gaseous boundaries offset could be explained with smooth background accretion + cluster mergers
- X-ray observations discover new discontinuities in cluster outskirts supporting this picture
- Gas entropy in cluster outskirts: probe of non-gravitational physics, gas clumping, non-thermal pressure
- Gas kinematics is a new reliable observable: XMM-Newton (bulk motions), Chandra (fluctuations), XRISM
- New era of high-resolution X-ray spectroscopy, first maps of gas kinematics