Multi-wavelength observations of the hot CGM

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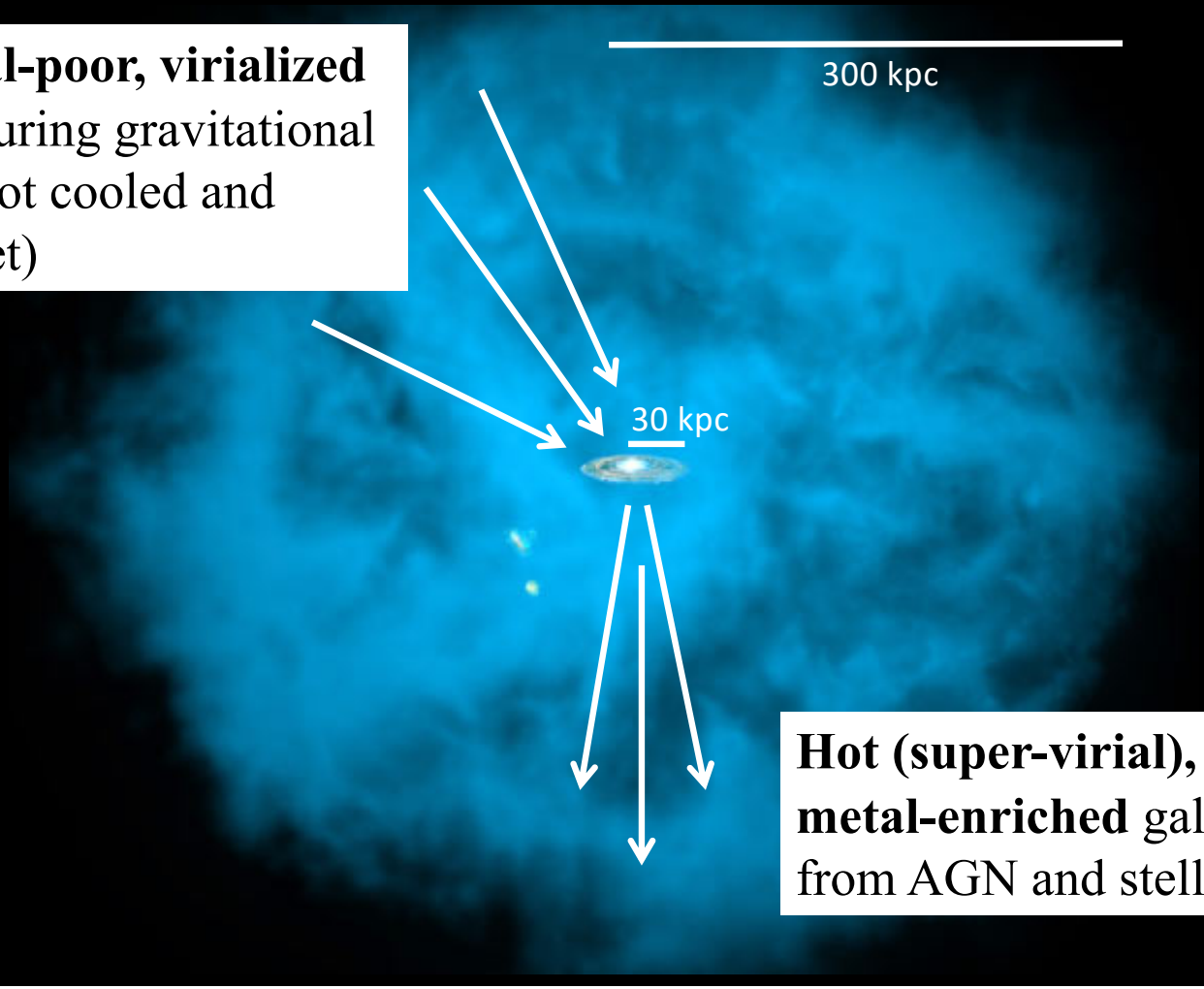
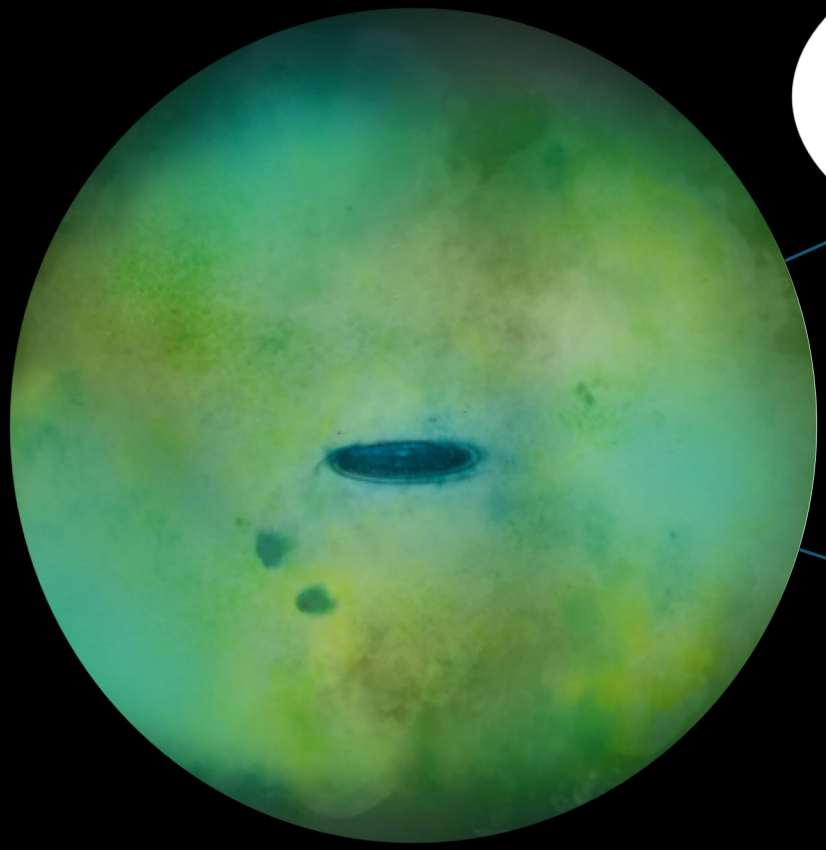
Circumgalactic medium (CGM): the active mediator between intergalactic and interstellar medium

Low-density, metal-poor, virialized shock-heated gas during gravitational collapse (that has not cooled and fallen to the disk yet)



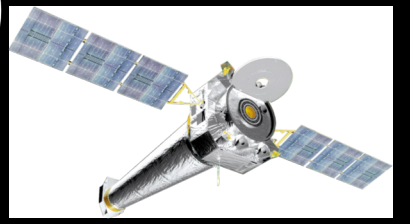
Hot (super-virial), denser, metal-enriched galactic outflow from AGN and stellar feedback

Gupta+2012, ApJL;
Chandra News



Das+2019, ApJL (ESA News)

Individual external galaxy in X-ray emission spectroscopy



Stacked galaxies in mm (Sunyaev Zeldovich Effect)

CGM of individual external galaxies

1. Signal detection is extremely **sensitive to** how we deal with the **background that dominates** the total emission
2. Target selection is crucial – in terms of a) intrinsic properties, b) environmental properties and c) 3-D sky position

Our target – NGC 3221

[40 ks XMM and 120 ks Suzaku data]

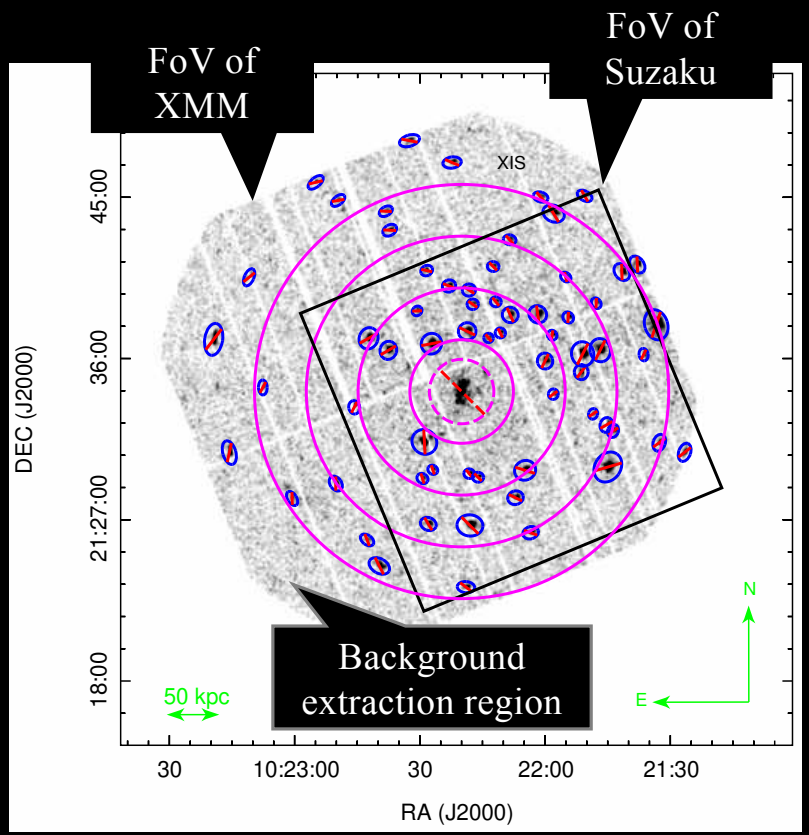
M_{200} = **3x10^{12}** M_{sun} (R_{200} ≈275 kpc)

SFR = **9.9 M_{sun} yr^{-1}**

Not an AGN

Field galaxy

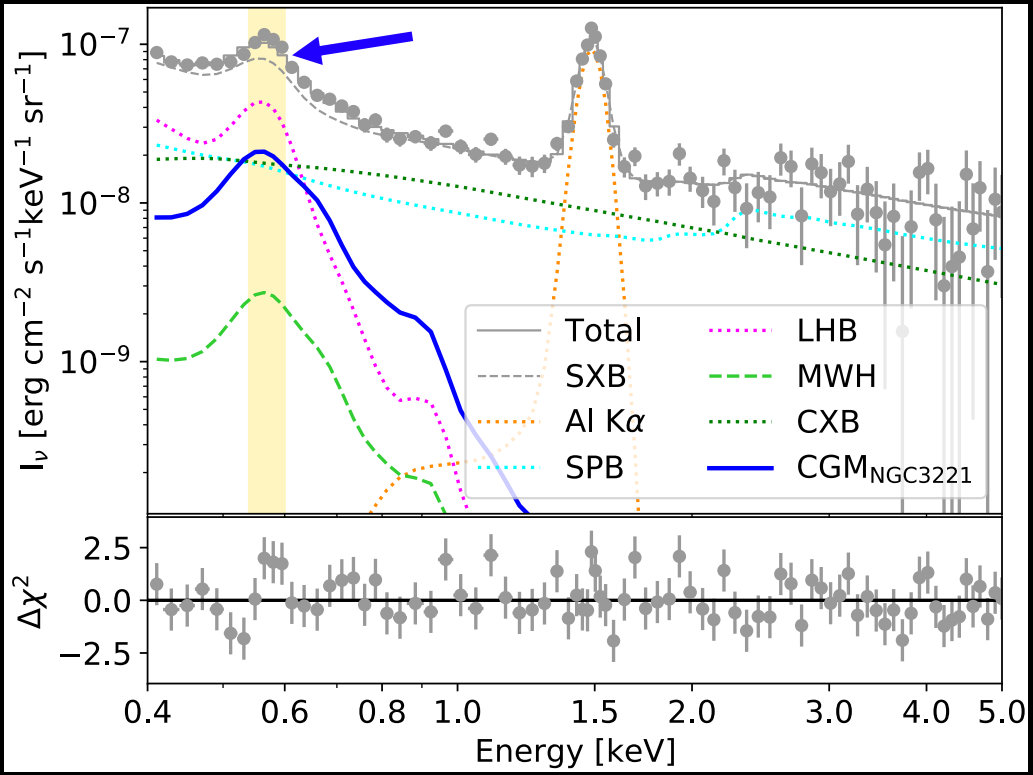
$l = 214^{o}$, $b = 56^{o}$; $z = 0.0134$



Das et al. 2019b, ApJ, 885, 108 (Suzaku); Das et al. 2020a, ApJ, 897, 63 (XMM)

CGM of individual external galaxies

Advanced spectroscopy – *simultaneous and conditional fitting* of the "on-source" and "background" spectra from the same data instead of *subtracting* the background



Independently detected with

- Suzaku (**3.6σ**) out to 150 kpc ≈ 0.55 R_{200}

and with

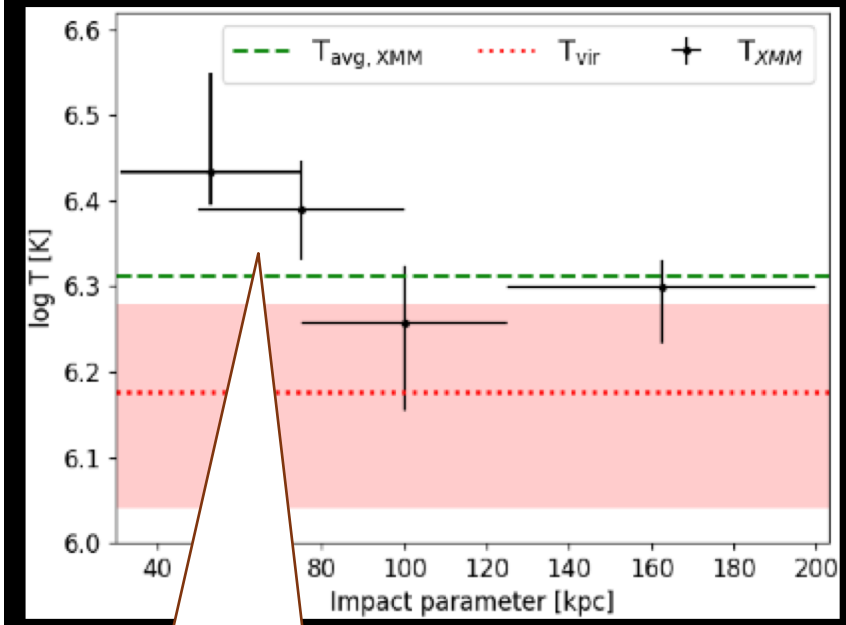
- XMM-Newton (**4.0σ**) out to 200 kpc ≈ 0.75 R_{200}

with background extracted from 0.75-0.9 R_{200}

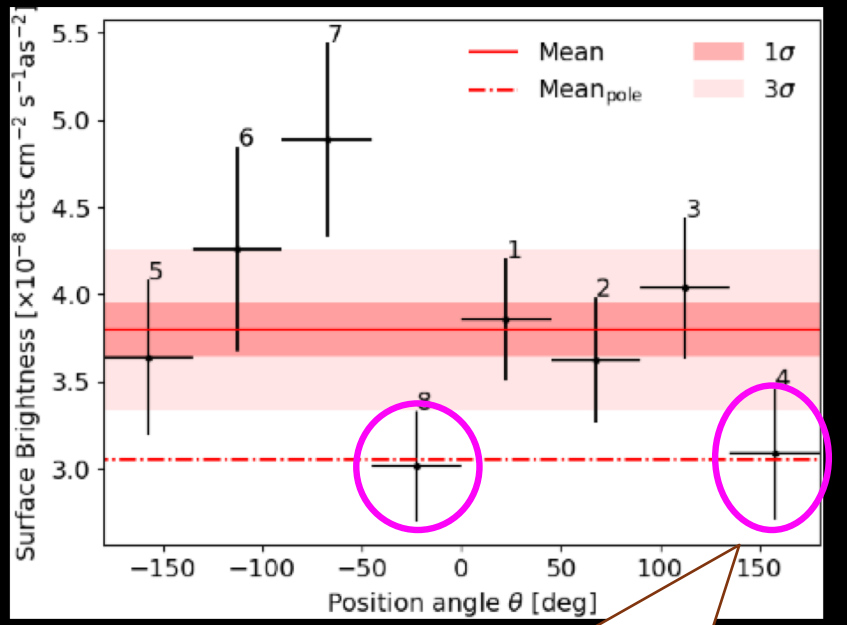
This is the **first and only external spiral galaxy** with such a detection so far

Das et al. 2019b, ApJ, 885, 108 (Suzaku); Das et al. 2020a, ApJ, 897, 63 (XMM)

CGM of individual external galaxies



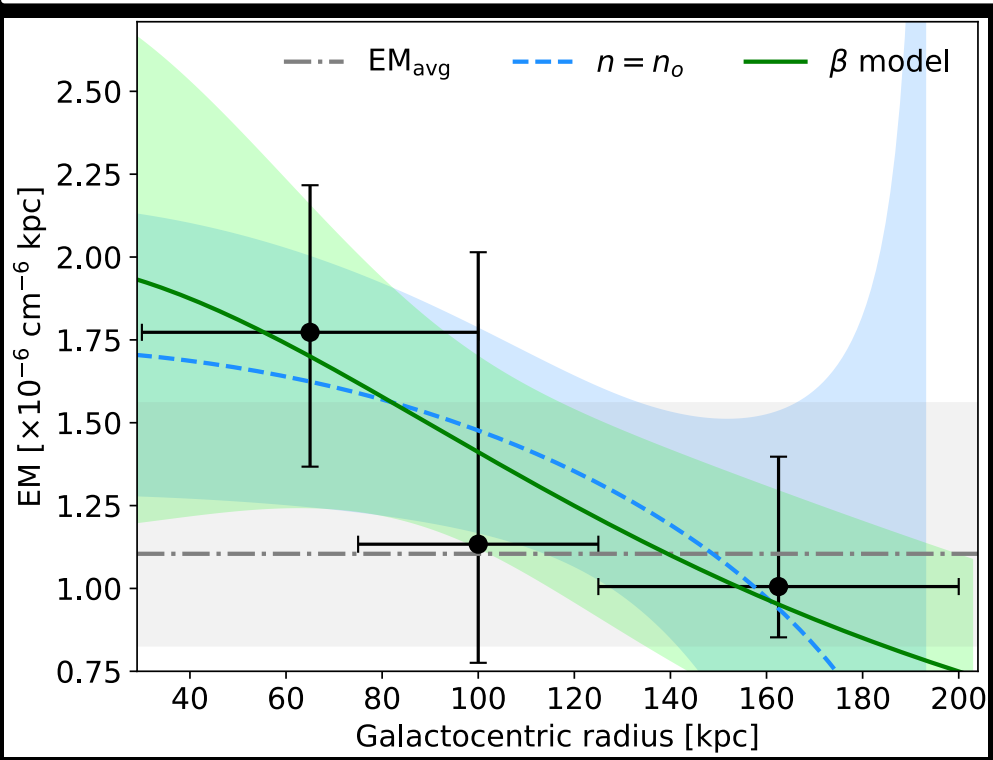
Increasing temperature within 100 kpc. **Thermal feedback?**



Deficit in 0.5-2 keV surface brightness along the minor axis within 100 kpc. **Cavity?**

Das et al. 2019b, ApJ, 885, 108 (Suzaku); Das et al. 2020a, ApJ, 897, 63 (XMM)

CGM of individual external galaxies

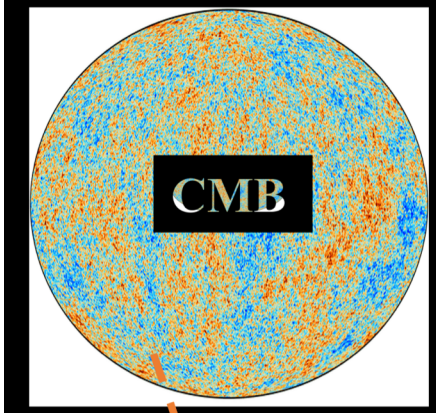


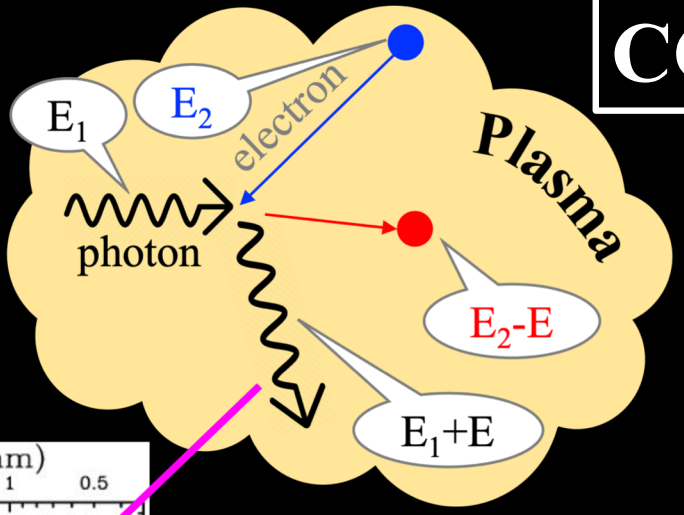
- $n_o \approx 10^{-4}$ cm^{-3} and $r_c = \mathbf{155 \pm 46}$ kpc $\equiv 0.6 \pm 0.2$ R_{200} for $\beta = 0.5$
- $M_{CGM} = \mathbf{10 \pm 2 \times 10^{10}}$ M_{sun} for 0.3 Z_{sun}
- $f_{baryon} = \mathbf{0.11 \pm 0.05}$ for 0.3 Zsun

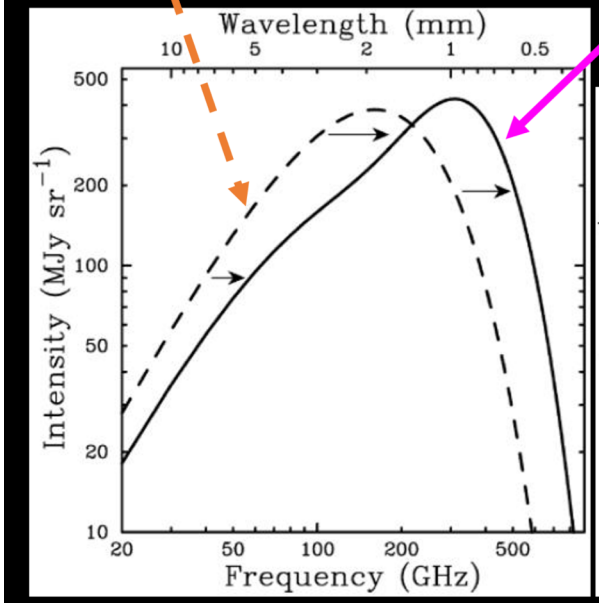
We have got **450 ks of new XMM/EPIC data** of NGC3221 that would provide more precise measurements. Stay tuned!

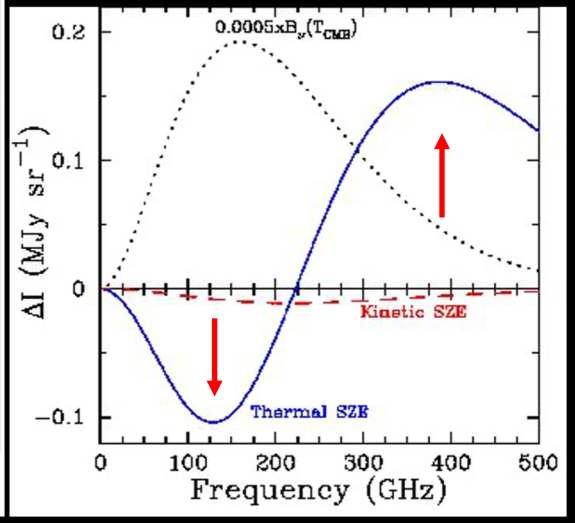
Das et al. 2019b, ApJ, 885, 108 (Suzaku); Das et al. 2020a, ApJ, 897, 63 (XMM)

CGM of stacked galaxies







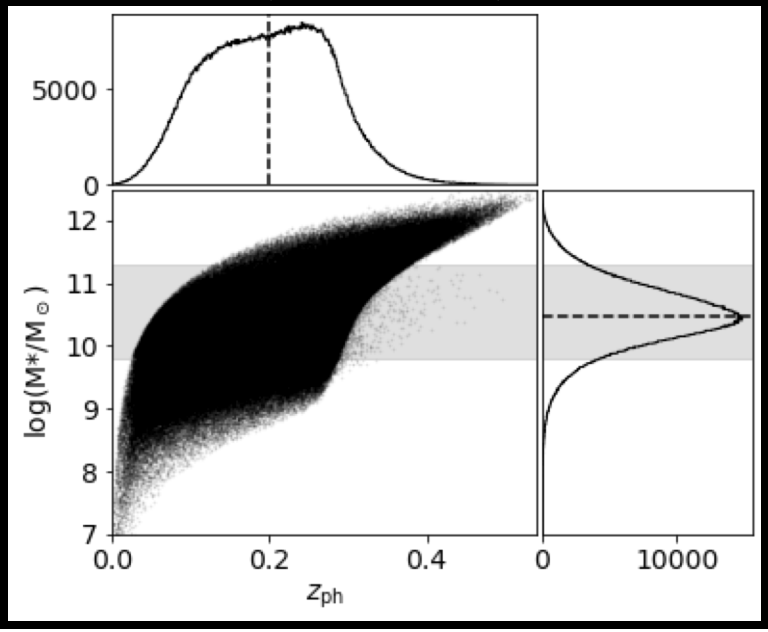


- Thermal Sunyaev-Zel'dovich (tSZ) Effect is characterized by the Compton-y parameter: $\boldsymbol{y = (\sigma_T / m_e c^2) \int P_e dl}$
- A measure of thermal energy [$\propto \int P_e dV$]
- Probe the ionized intervening medium

Sunyaev & Zel'dovich 1969, Nature, 223, 721

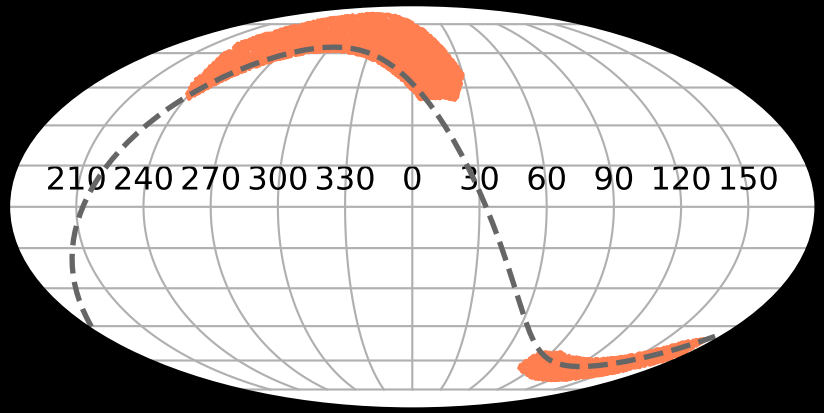
CGM of stacked galaxies

WISExSuperCosmos galaxy catalog (Bilicki+2016)



X

Atacama Cosmology Telescope +Planck Compton-*y* map (Madhavacheril+2020)



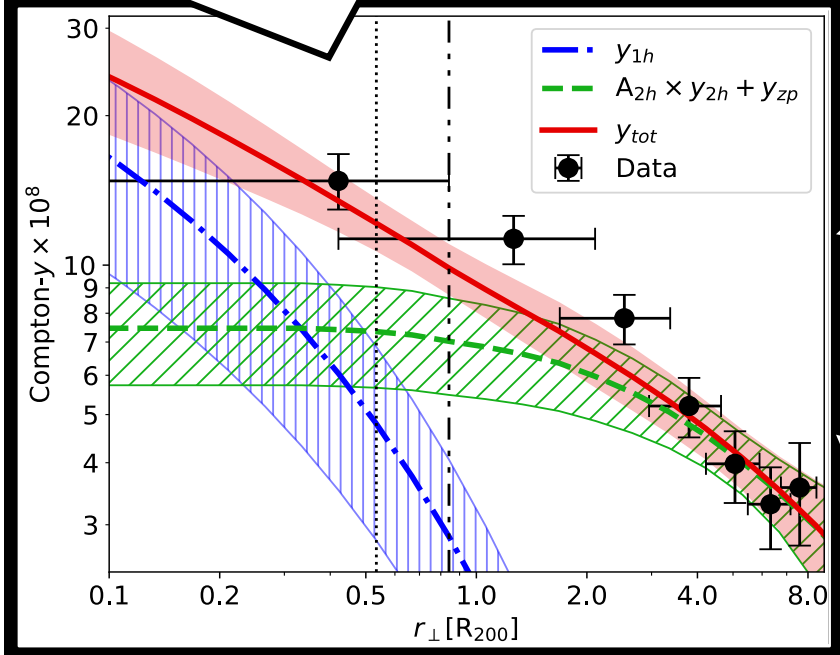
1. 0.63 million $z<0.3$ $M_*=10^{9.8\text{-}11.3}$ M_{sun} galaxies; 2. Only **field** galaxies

3. **Exclude radio** galaxies and galaxies with **W1-W2>0.8**

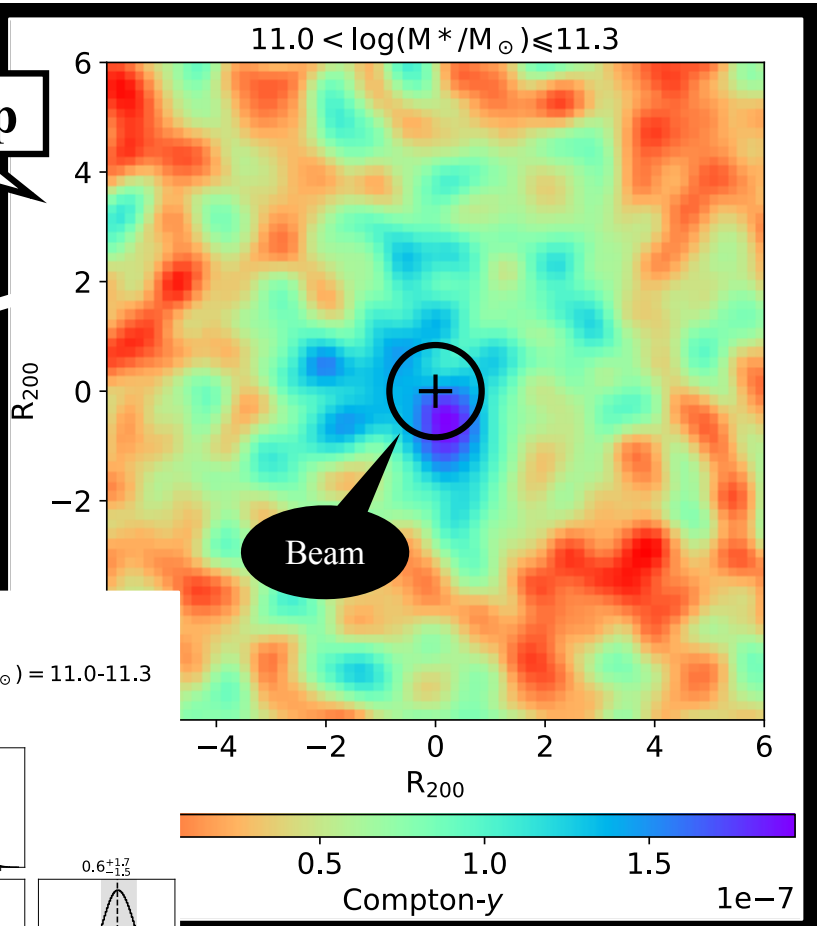
Das, Chiang & Mathur, 2023, ApJ, 951, 125

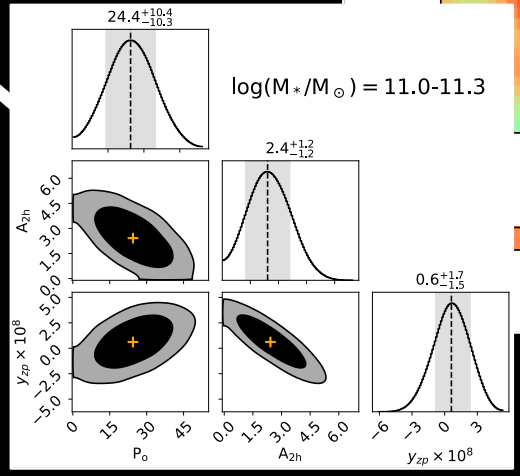
Differential profile

$$y(R) = \bar{y}(R - \Delta R \leq r_\perp < R + \Delta R)$$



Stacked y-map





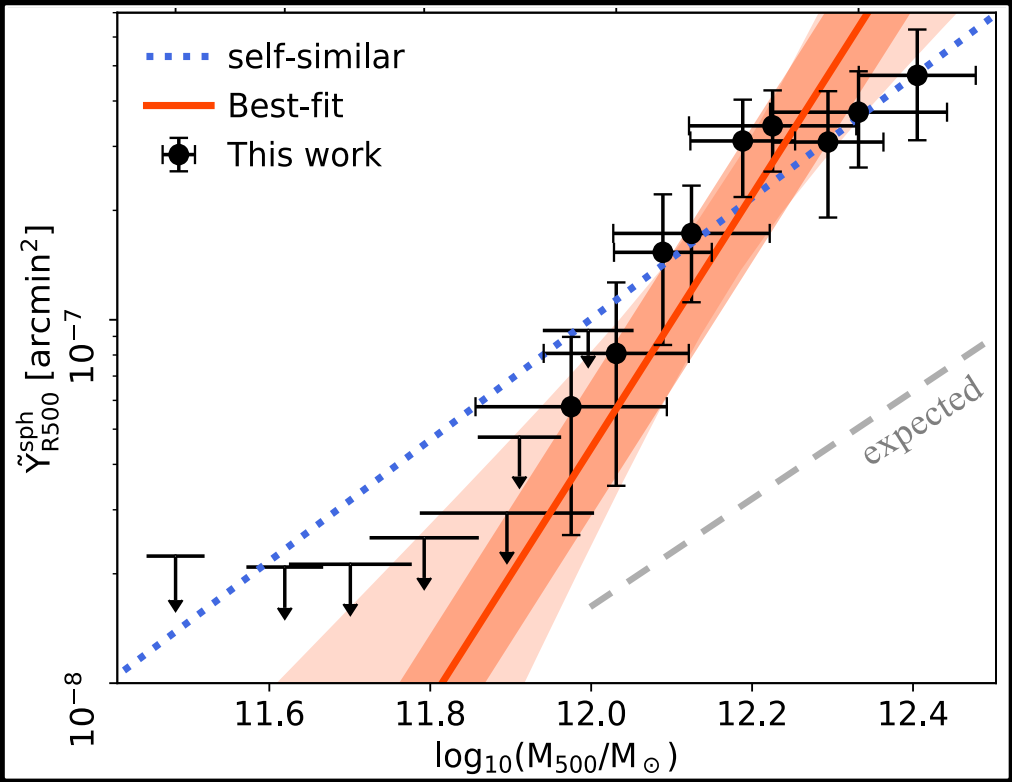
$$y_{tot} = y_{1h} + A_{2h} y_{2h} + y_{zp}$$

$$y_{1h} = \mathrm{P_e}(r \,|\mathrm{M}_{500}, z) \circledast \mathrm{beam}_{\mathrm{ACT}}$$

Das, Chiang & Mathur, 2023, ApJ, 951, 125

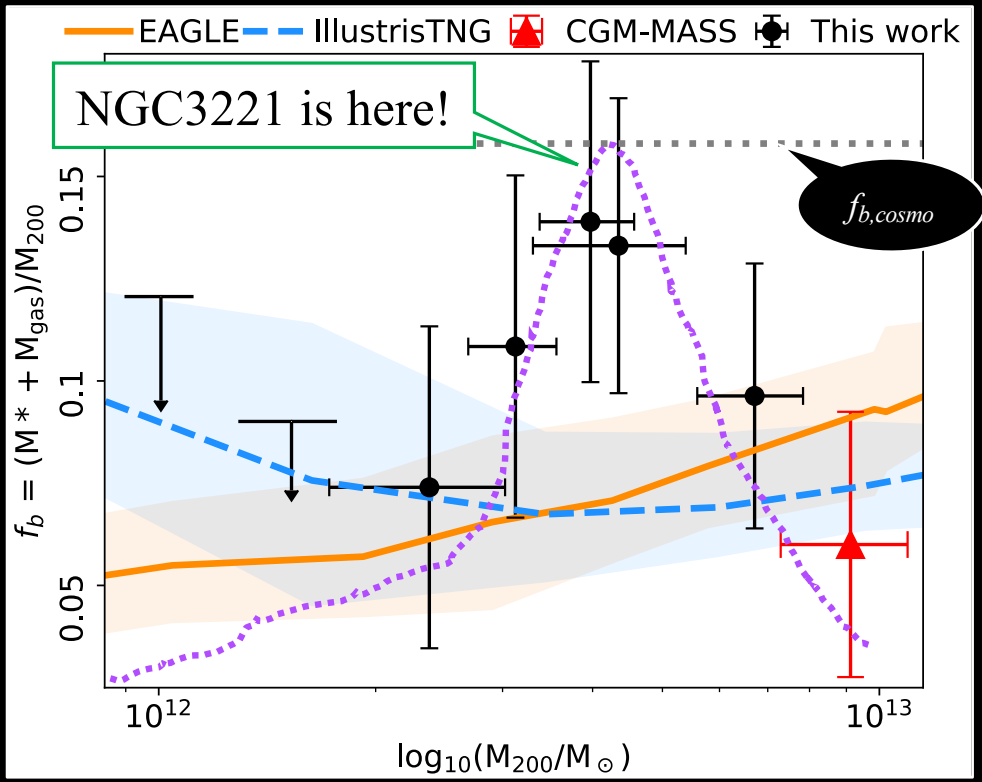
P_e from Arnaud+2010; 2-halo term from Vikram+2017

Thermal energy



Individual galaxies **don't** follow self-similar relation in terms of slope & normalization

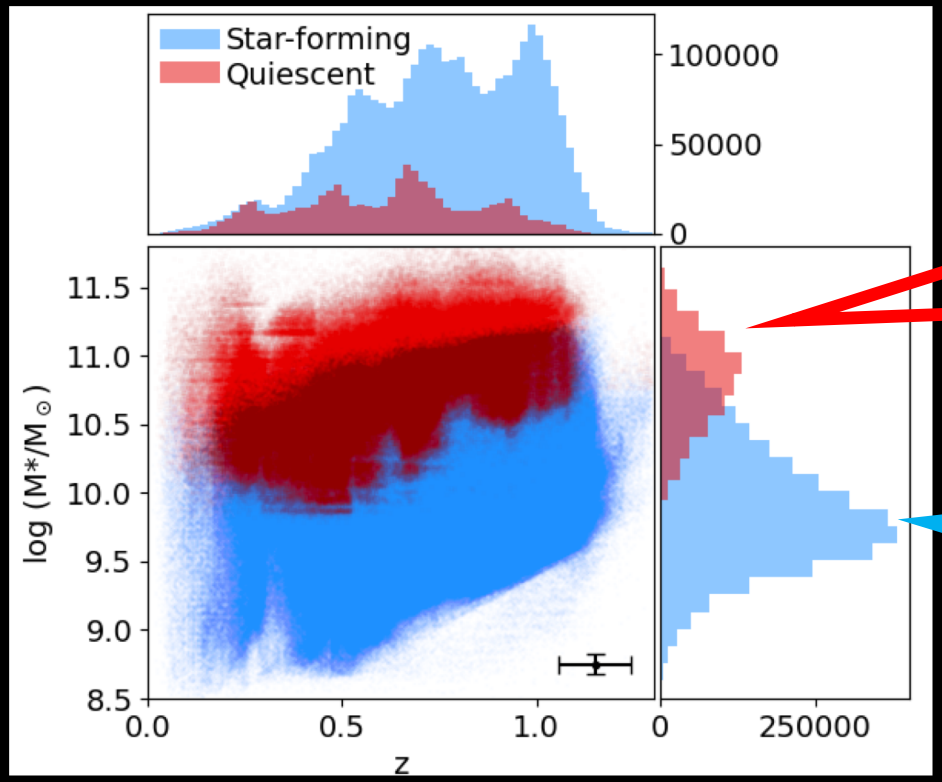
Baryon fraction

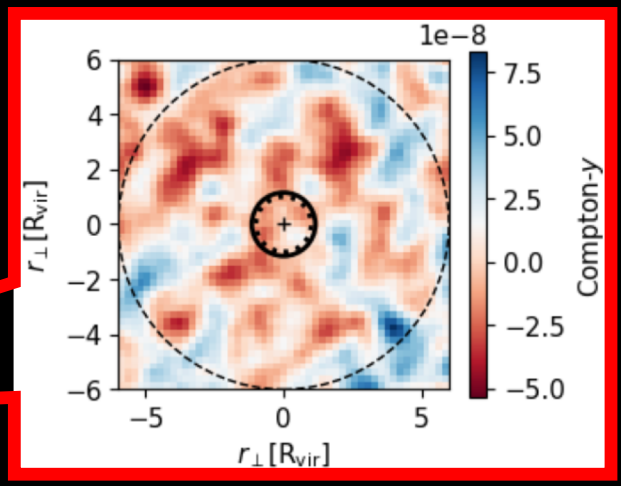


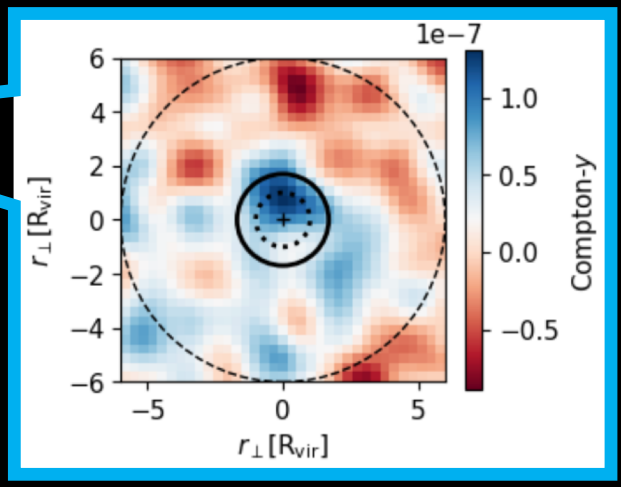
Baryon fraction could vary with mass in a non-monotonic way

Das, Chiang & Mathur, 2023, ApJ, 951, 125

Thermal pressure in the CGM of **star forming** and **quiescent** WISExDESI galaxies







Das et al. 2024c (in prep.)

Summary

1. **Detecting the CGM of individual external galaxies in X-ray emission is extremely challenging but doable** with existing telescopes. It helps us distinguishing among conflicting feedback prescriptions.
2. The CGM of external galaxies in **SZ effect suggests unexpected trend in thermal energy and baryon fraction** that we have yet to understand

Thank you for listening! Questions?