Title: Where the hot universe meets the energetic universe

Speakers: Sanskriti Das

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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Abstract:

The hot circumgalactic medium (CGM), a reservoir of missing baryons, metals, and energy, plays a key role in our understanding of galaxy evolution. However, extraordinary observational challenges make the hot CGM one of the least understood components of galaxies. Studying the hot CGM was not the objective of current X-ray or mm facilities during the
design phase. However, as an excellent byproduct, observing the hot CGM has emerged as a promising field over the last two decades, coming at the forefront of priority science goals for the current and upcoming decades. I will discuss three snippets of our recent efforts to detect and characterize the hot CGM: 1) X-raying the Milky Way: Investigating thermal, chemical, and kinematic anomalies; 2) Is CGM detectable? Conducting deep searches in individual external galaxies using X-ray; and 3) Test for self-similarity: stacking many galaxies in mm (Sunyaev-Zeldovich Effect). I will highlight how our findings provide insights into the impact of galactic feedback on the hot CGM, establish our confidence in leveraging current telescopes to inform theoretical simulations, and set a benchmark for designing experiments with next-generation X-ray and mm facilities.

~~Where the hot universe meets the energetic universe~~

Hot circumgalactic medium (CGM) observations

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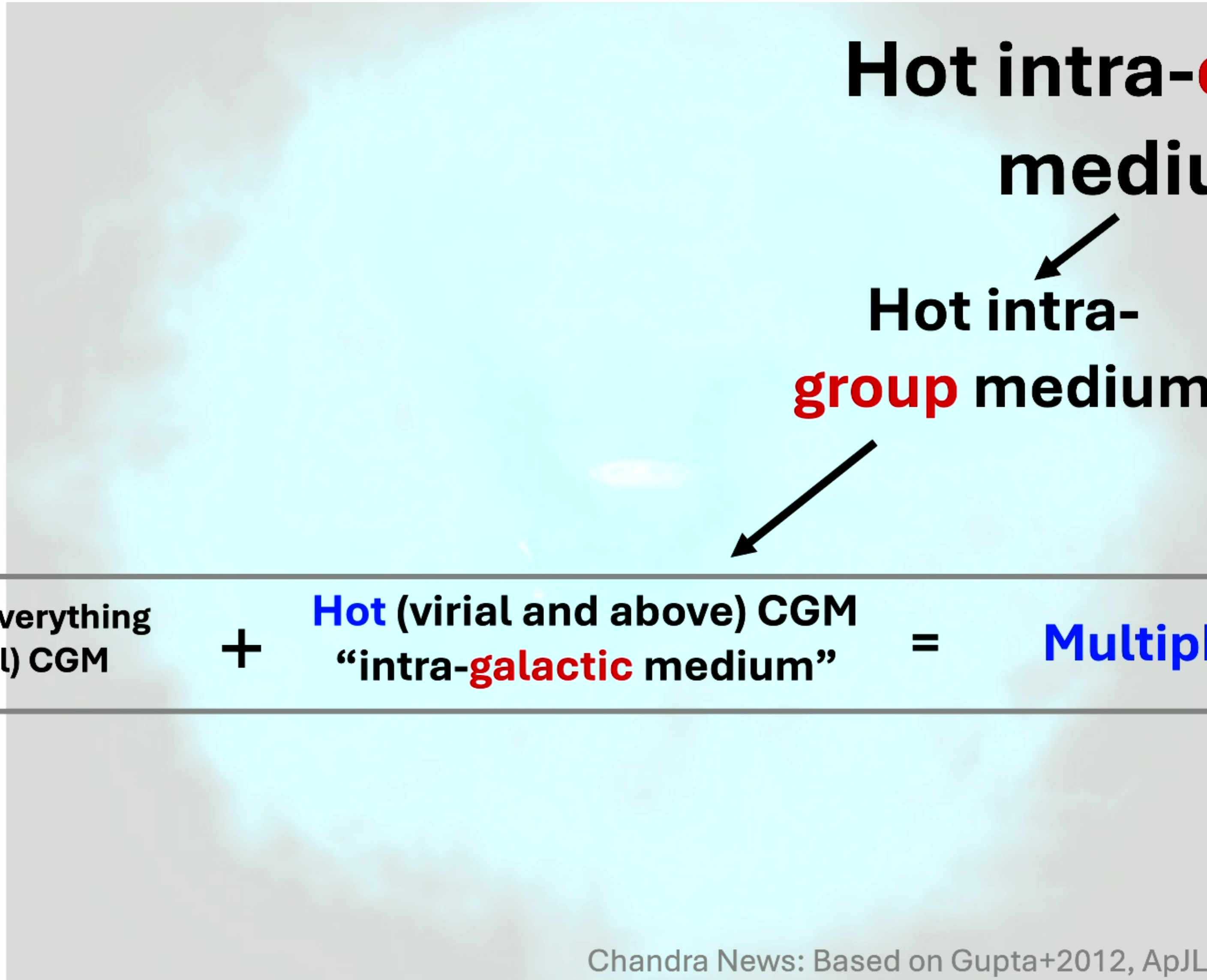
Hot intra-cluster medium

↓

Hot intra-group medium

↓

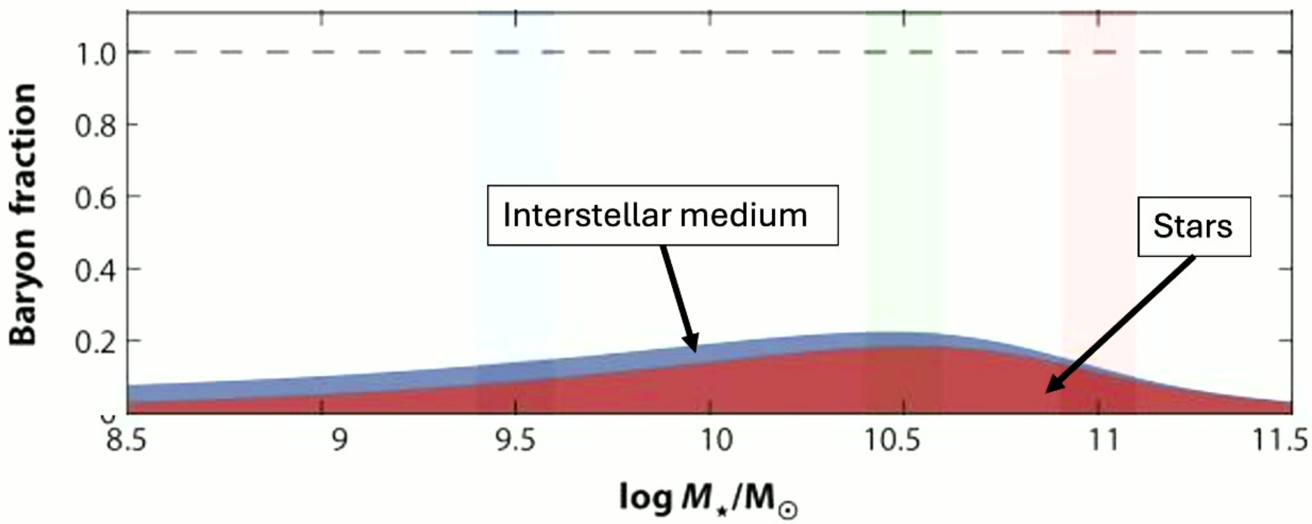
Not-so-hot (everything below virial) CGM	+	**Hot** (virial and above) CGM “intra-galactic medium”	=	**Multiphase CGM**



Chandra News: Based on Gupta+2012, ApJL

Why is studying the hot CGM important?

1. Missing ***galactic*** **baryons** problem: do all galaxies retain rest of their allotted baryons in the CGM?



$$\text{Baryon fraction} = \left(\frac{\text{Mass of baryons}}{\text{Mass of baryons} + \text{dark} - \text{matter}}\right)/f_{b,cosmo}$$

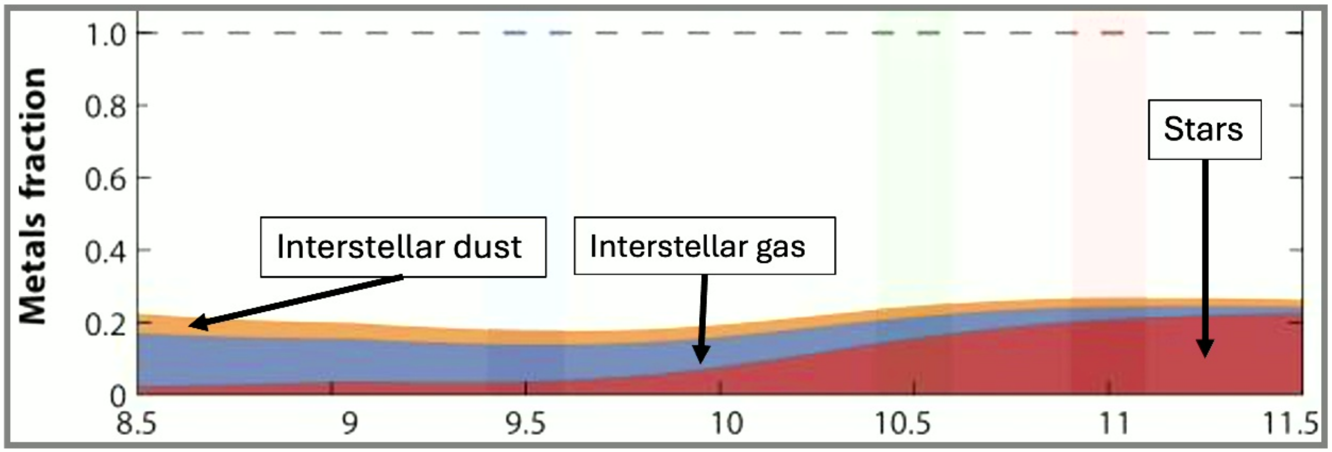
Tumlinson+17, ARA&A (Also see: Putman+2012, Mathur+2022)

Why is studying the hot CGM important?

2. Missing **metals** problem: do all galaxies retain rest of their produced metals in the CGM?

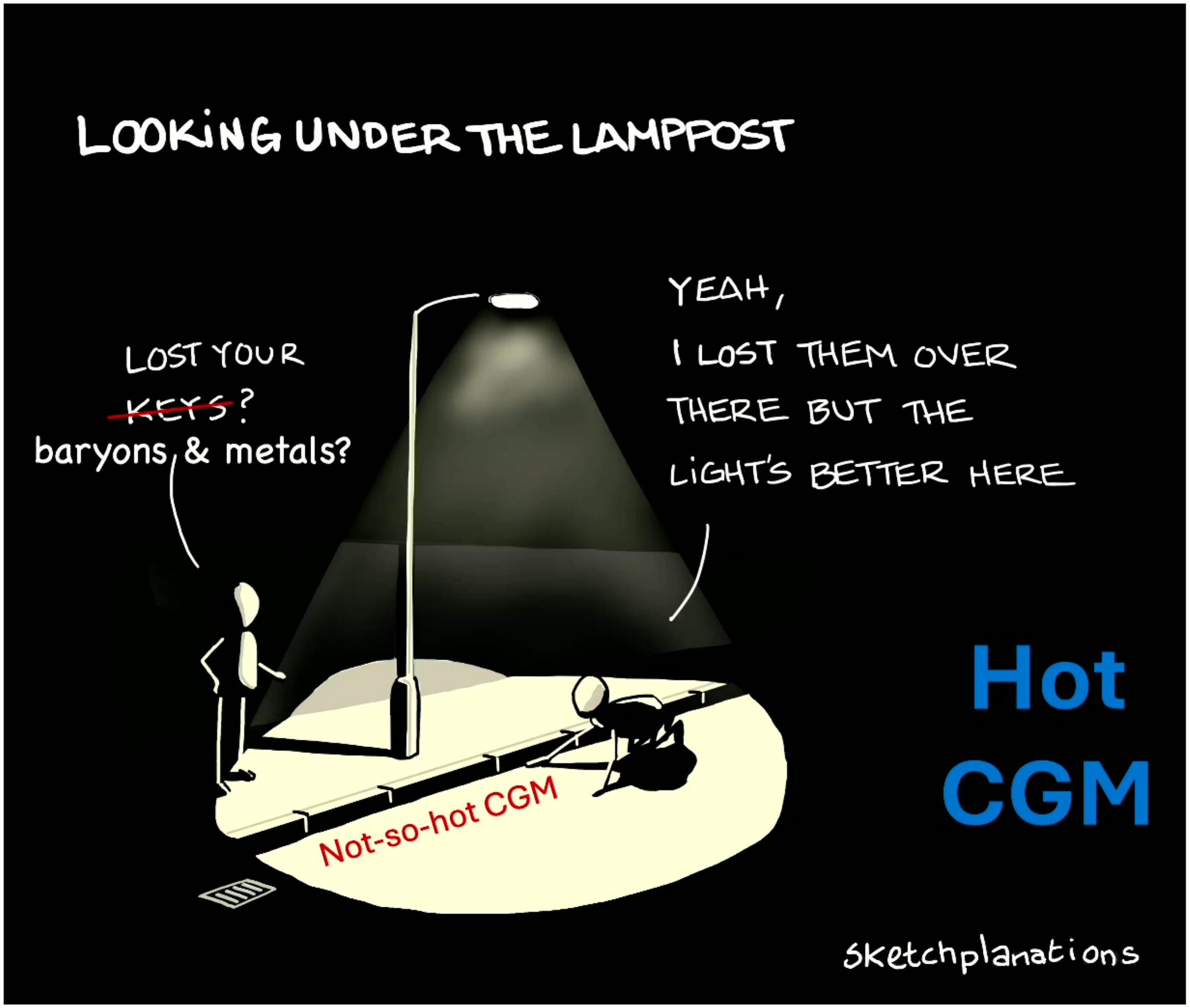
3. Missing **feedback** problem. Where does the energy from galactic winds go?

$$\text{Metals fraction} = \frac{\text{Mass of observed metals}}{\text{Mass of expected metals}}$$



Tumlinson+17, ARA&A (Also see: Putman+2012, Mathur+2022) $\log M_\star/M_\odot$

4

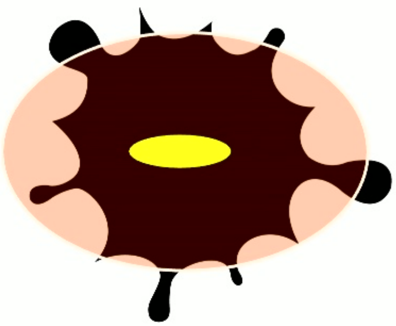

LOOKING UNDER THE LAMPPOST
LOST YOUR
KEYS?
baryons, & metals?
YEAH,
I LOST THEM OVER
THERE BUT THE
LIGHT'S BETTER HERE
Not-so-hot CGM
Hot
CGM
sketchplanations

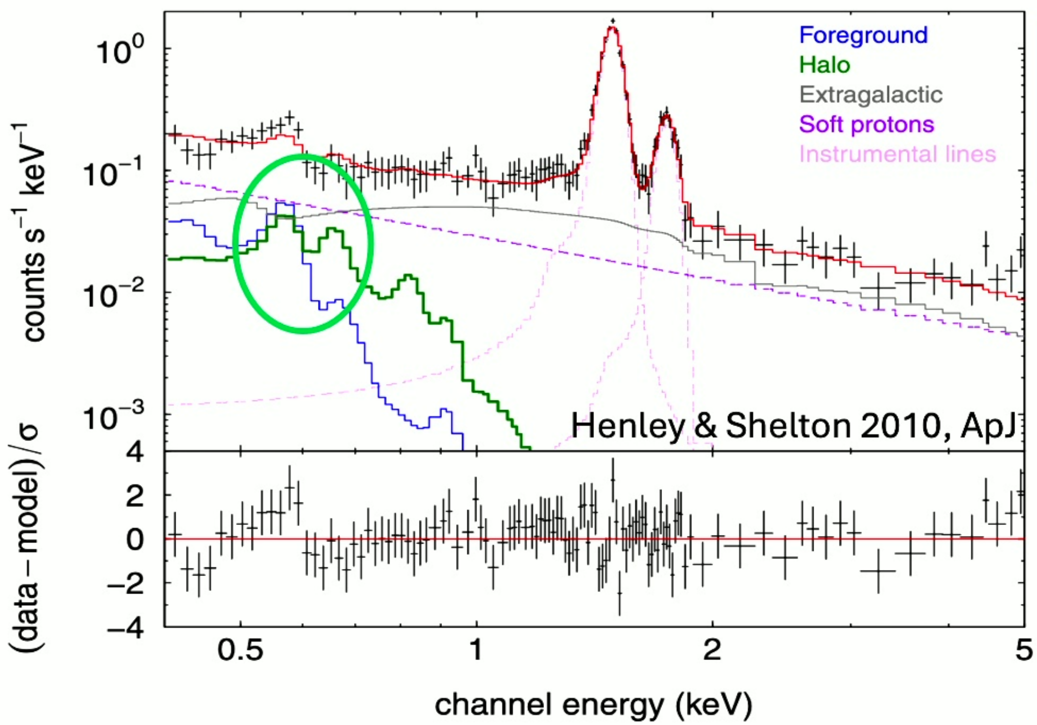
1. **Milky Way**
2. External **individual** galaxies
3. External **stacked** galaxies

Prediction of a hot Galactic halo/CGM (Spitzer 1956)

First detection, and separation from the ISM with **ROSAT** (Snowden+1995, Kuntz+2000)

Constraint on **temperature:** $\frac{I_{OVIII}}{I_{OVII}} \rightarrow$ $\mathbf{T_{emission}}$ and emission measure **EM** $= \int n_e n_H dr_{\parallel}$





X-ray emission from the hot CGM: ≈10% free-free + ≈90% highly ionized metals

Summary (until ~2020):

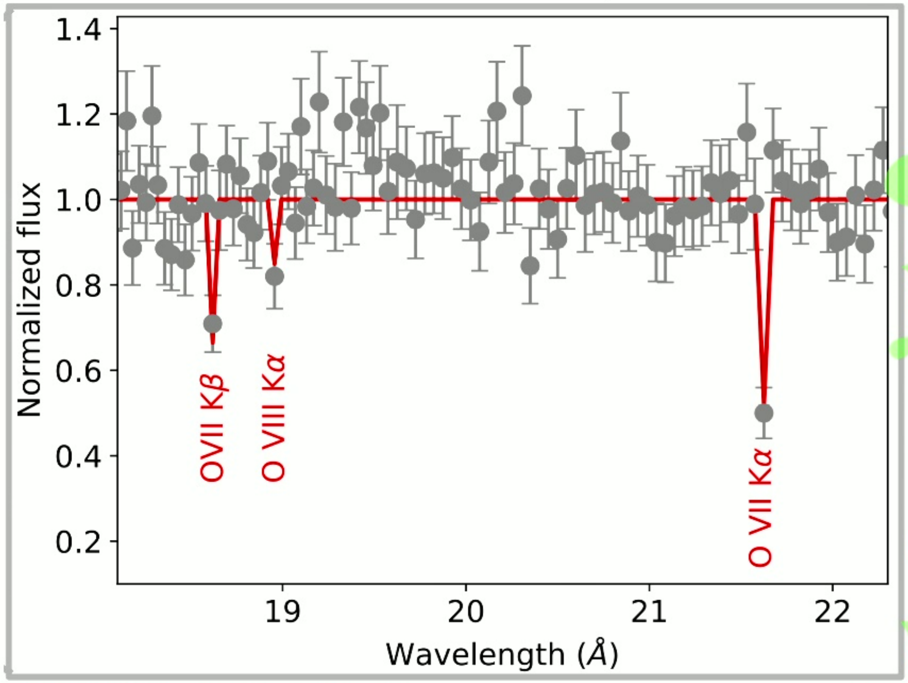
1. $T_{emission}$ ≈ constant at $10^{6.3}$ K across the sky
2. **EM varies by ≈an order-of-magnitude** without any correlation with (l,b)

Also see: Gupta+2009, Yoshino+2009, Nakashima+2018 (**Suzaku**); Henley+2013, 2015 (**XMM**); Kaaret+2020 (**HaloSat**)

$$N_{OVII} = \int n_H dr_{\parallel} \, A_{O/H} f_{OVII}$$

$$\frac{N_{OVIII}}{N_{OVII}} \rightarrow T_{absorption}$$

X-ray absorption from the hot CGM: highly ionized metals

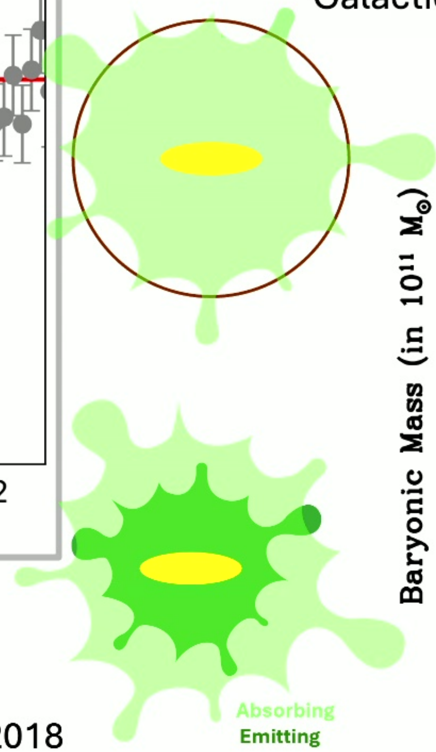


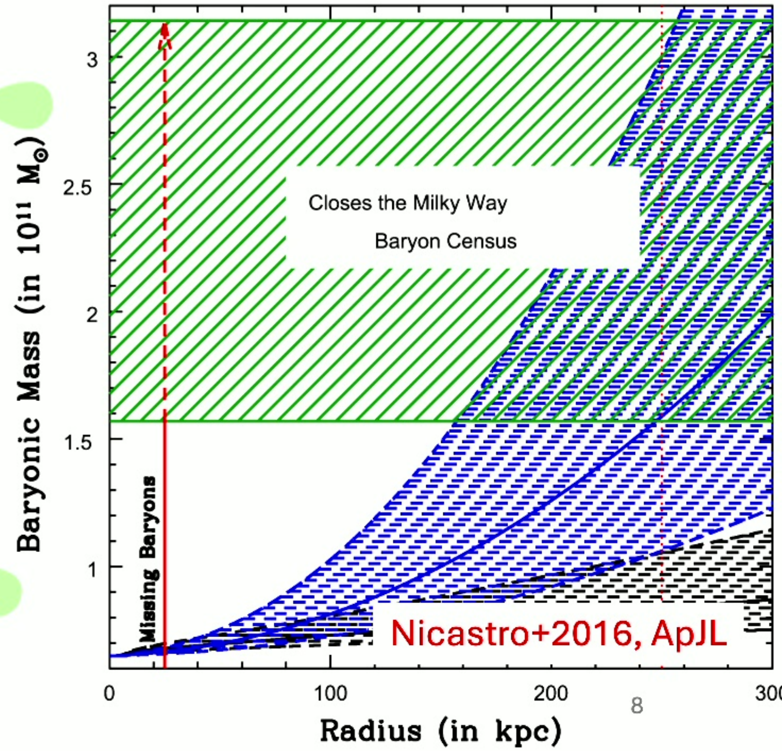
Das 2024, ApJL, 963, 48

Also see: Nicastro+2002; Williams+2005; Gupta+2012, Gupta+2015; Gupta+2017; Gatuzz+2018

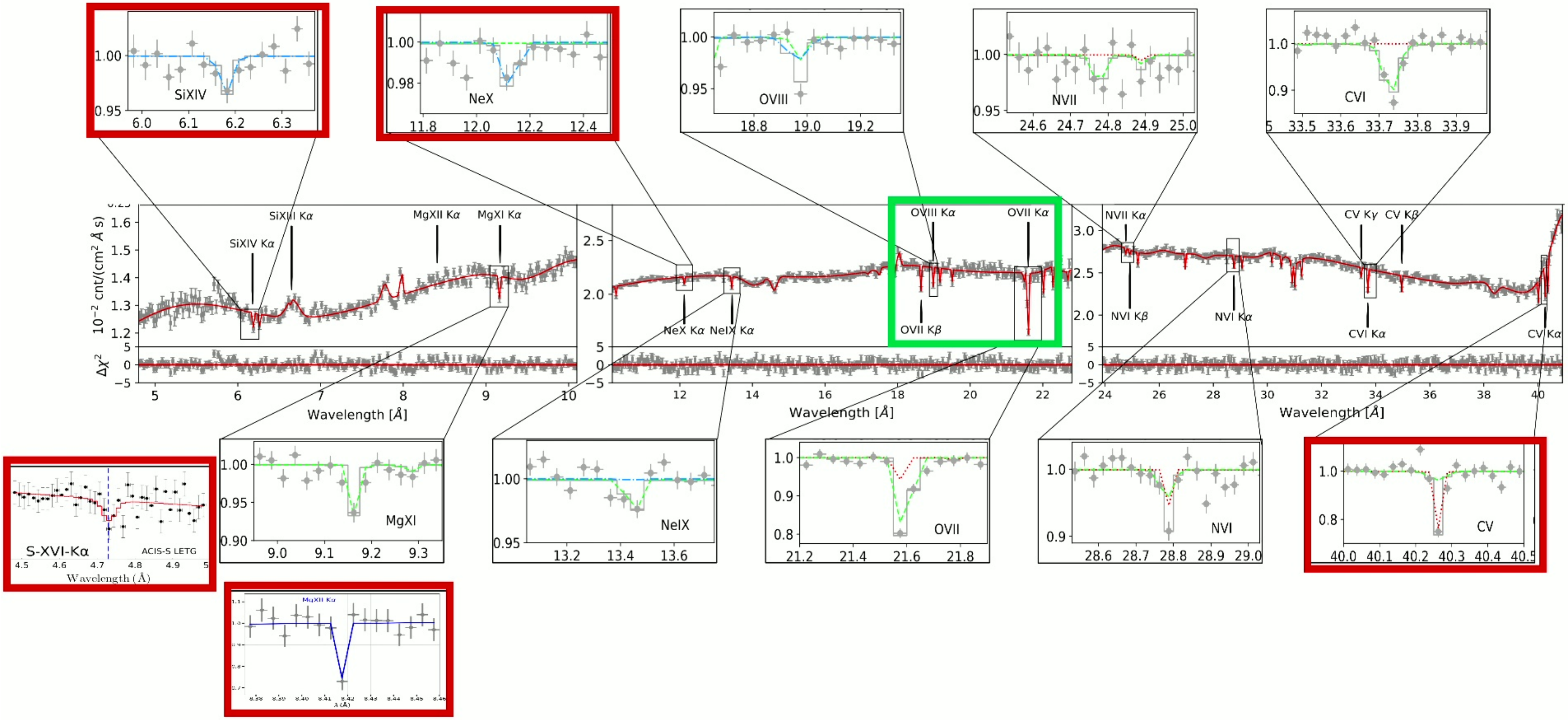
Summary (until ~2020):

1. $T_{absorption} = T_{emission} \approx 10^{6.3}$ K
2. **N_{OVII} varies by ≈an order-of-magnitude** without any correlation with (l,b)
3. Path length >200 kpc [emission meets absorption]
4. Hot CGM mass (0.3 Z_{sun}) ≈10^{11} M_{sun}; closes the Galactic baryon census





We probe He-like ions and H-like ions of C, N, O, Ne, Mg, Si, and S with XMM/Chandra grating



1. Das et al. 2019a, ApJL, 882, 23; 2. Das et al. 2021, ApJ, 918, 83; 3. Lara-DI et al. 2023, ApJ, 946, 55; 4. McClain et al., 2024, MNRAS, 527, 5093; 5. Lara-DI et al. 2024, MNRAS, 531, 3034; **6. Singh, Das & Mathur 2025 (to be submitted soon)**

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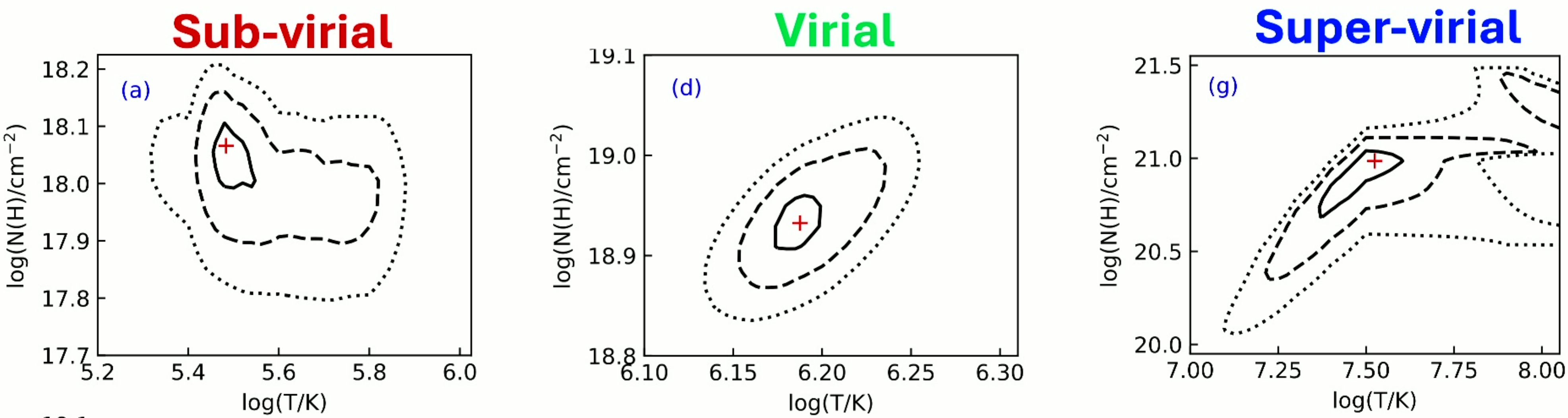
Hybrid-ionization modeling reveals

1. A $10^{7.5}$ K **super-virial** phase coexists with the 10^{6} K **virial** phase and the $10^{5.5}$ K **sub-virial** phase

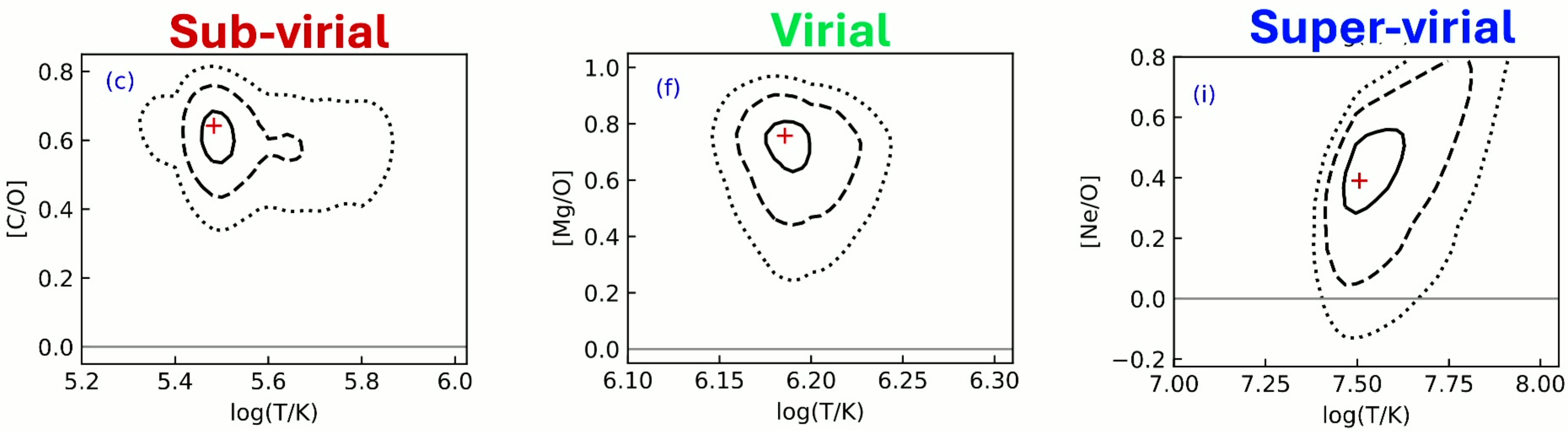


C V, N VI, O VII | **C VI, N VII, O VII, OVIII, Ne IX, Mg XI** | **OVIII, Ne X, Mg XII, Si XIV, S VI**

- A metal ion could be distributed across more than one phase
- Different ions of the same metal might not originate in the same phase

1. Das et al. 2019a, ApJL, 882, 23; 2. Das et al. 2021, ApJ, 918, 83; 3. Lara-DI et al. 2023, ApJ, 946, 55; 4. McClain et al., 2024, MNRAS, 527, 5093; 5. Lara-DI et al. 2024, MNRAS, 531, 3034; **6. Singh, Das & Mathur 2025 (to be submitted soon)**

Hybrid-ionization modeling reveals
2. **Non-solar** chemical composition of C, N, O, Ne, Mg, Si, and S in all three phases



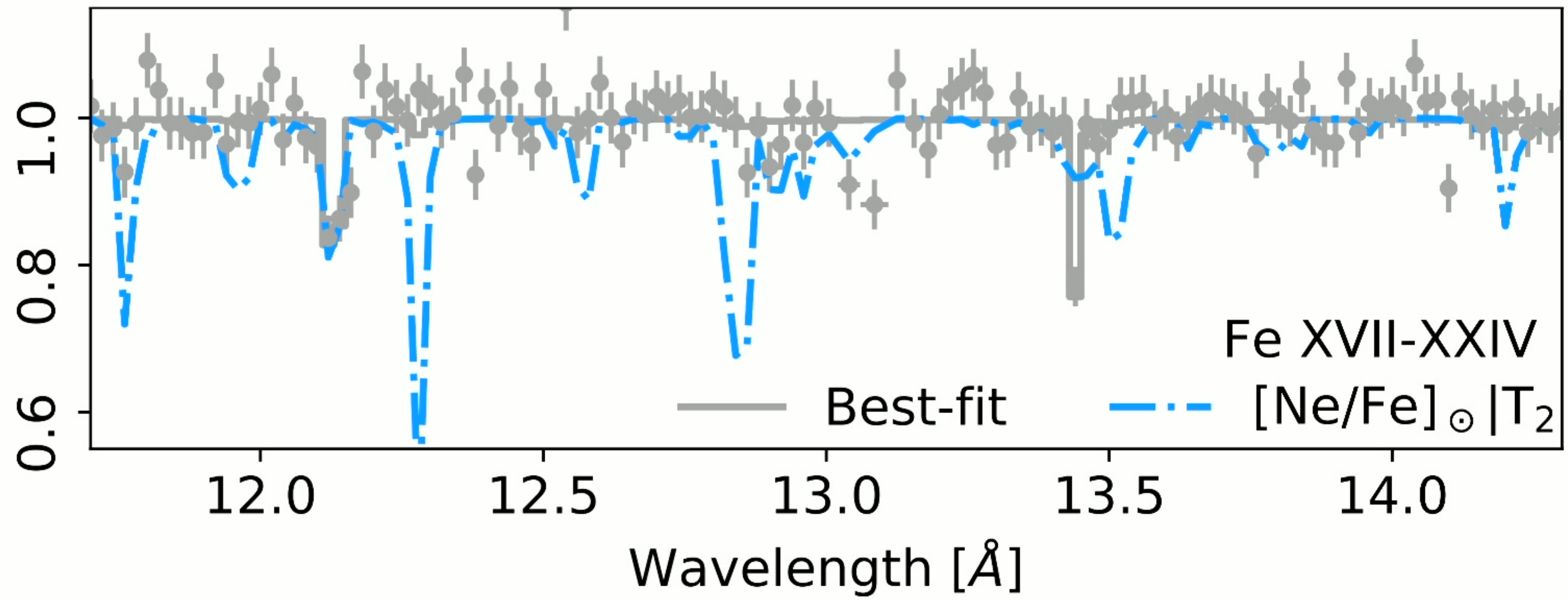
Abundance ratio of the same two metals are

- Different in different phases
- Different toward different sightlines in the same phase

1. Das et al. 2019a, ApJL, 882, 23; 2. Das et al. 2021, ApJ, 918, 83; 3. Lara-DI et al. 2023, ApJ, 946, 55; 4. McClain et al., 2024, MNRAS, 527, 5093; 5. Lara-DI et al. 2024, MNRAS, 531, 3034; **6. Singh, Das & Mathur 2025 (to be submitted soon)**

Hybrid-ionization modeling reveals

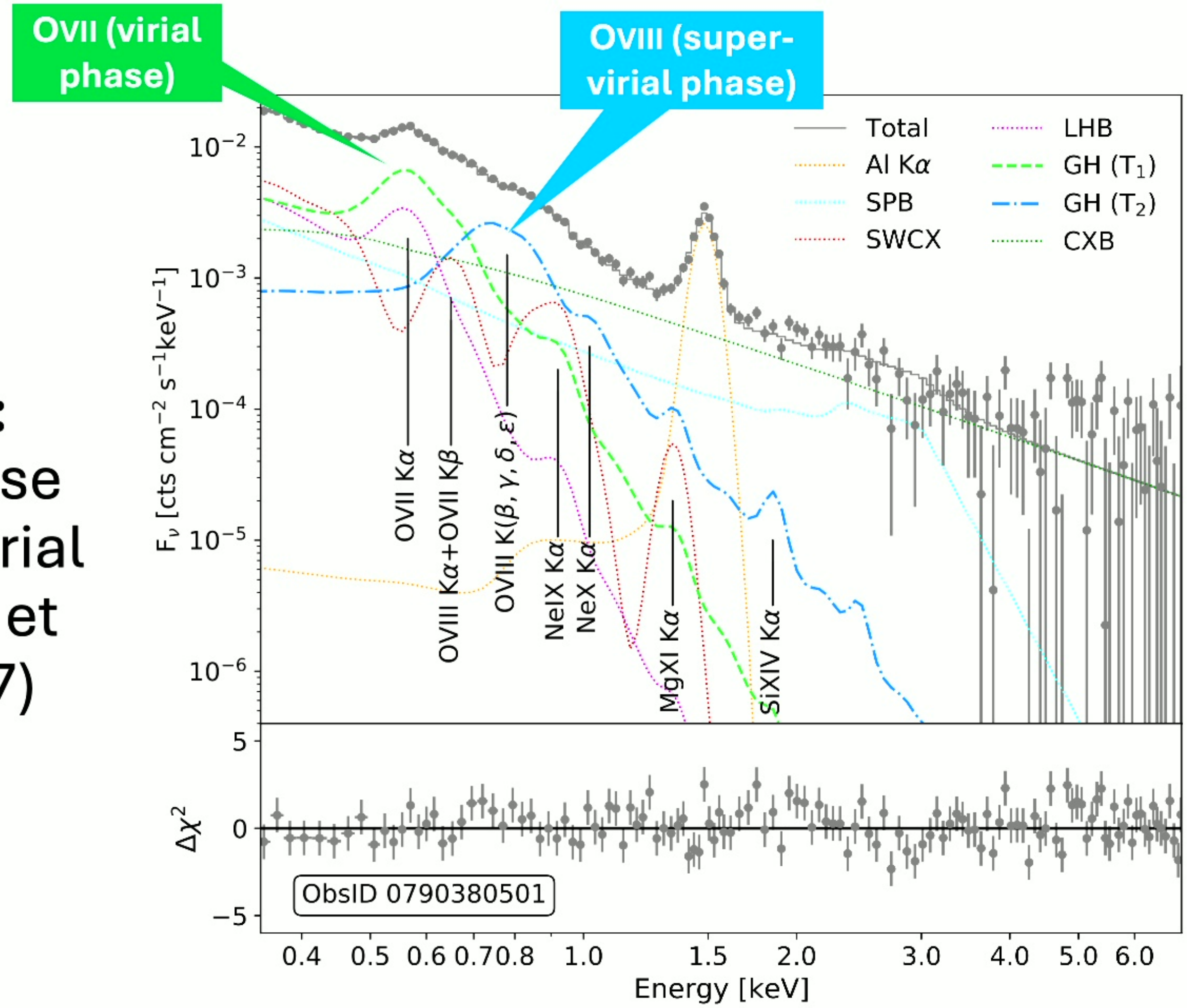
3. **Super-solar α/Fe**



None of these three results were predicted in theories

1. Das et al. 2019a, ApJL, 882, 23; 2. Das et al. 2021, ApJ, 918, 83; 3. Lara-DI et al. 2023, ApJ, 946, 55; 4. McClain et al., 2024, MNRAS, 527, 5093; 5. Lara-DI et al. 2024, MNRAS, 531, 3034; **6. Singh, Das & Mathur 2025 (to be submitted soon)**

Discovery with XMM:
≈$10^{6.8}$ K super-virial phase coexists with the 10^6 K virial phase in emission (Das et al. 2019c, ApJ, 887, 257)



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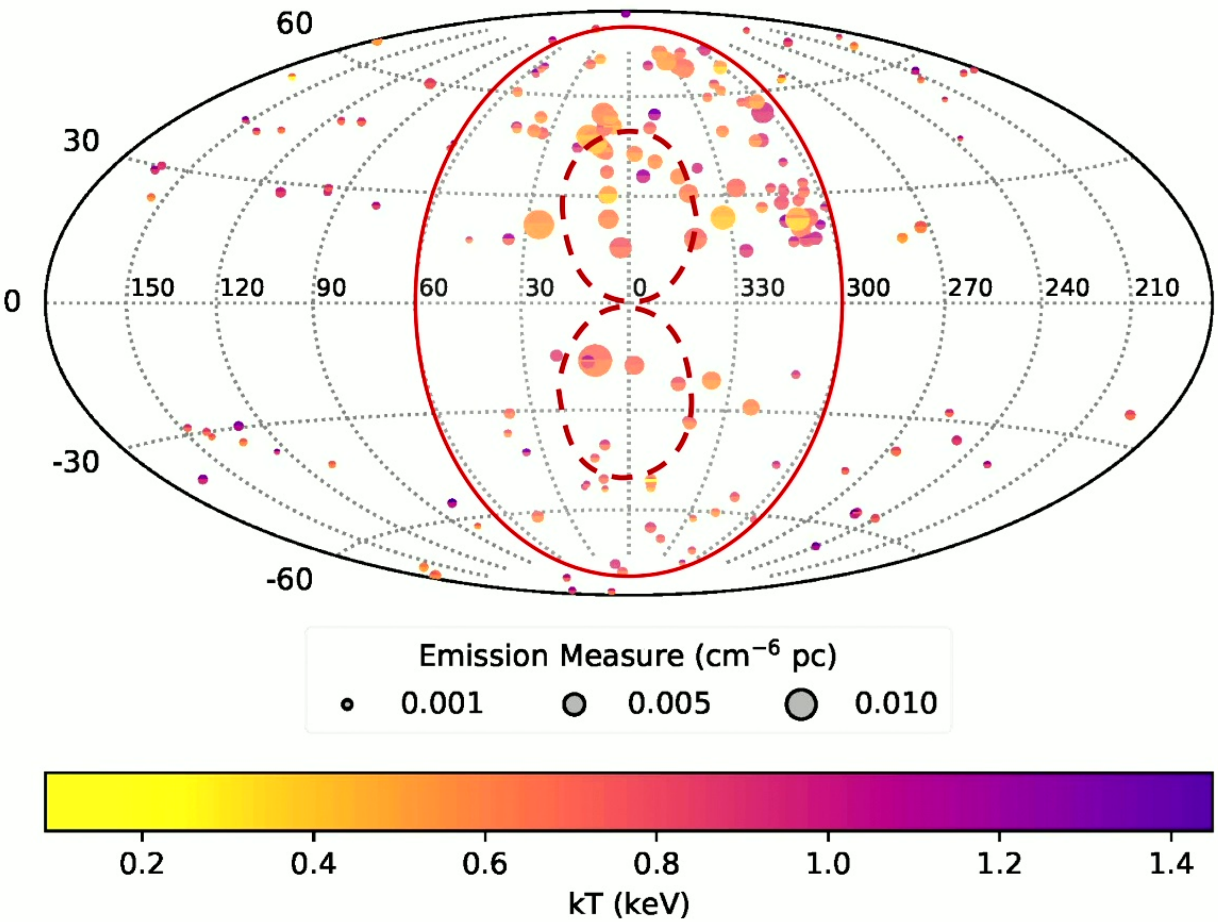
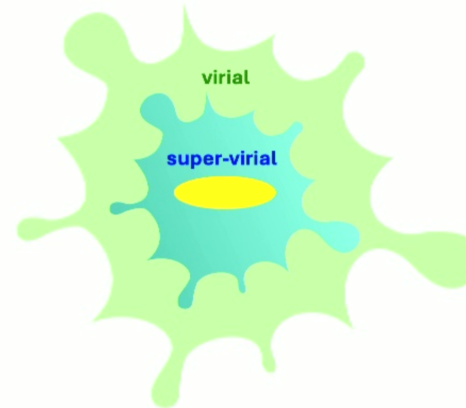


Gupta+23, Nature Astronomy



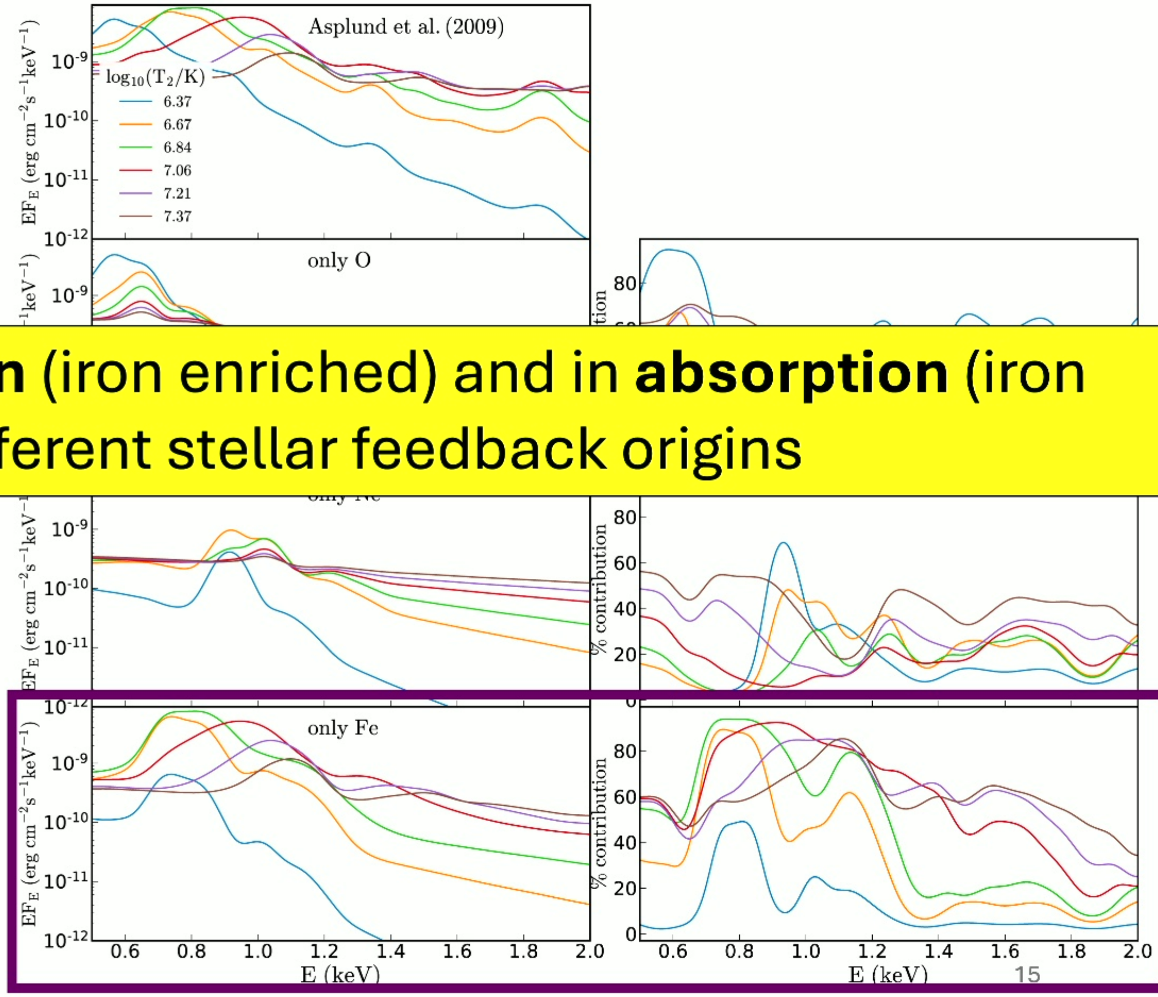
Follow-up with Suzaku, HaloSat, and eROSITA (Gupta+2021, Bluem+2022, Gupta+2023, Ponti+2023): 60% of the sky shows a super-virial phase coexisting with the virial phase.

$T_{super\text{-}virial} \approx 0.4\text{-}1.4 \times 10^7$ K;
$EM_{super\text{-}virial}/EM_{virial} \approx 0.1$

Chemical tagging:

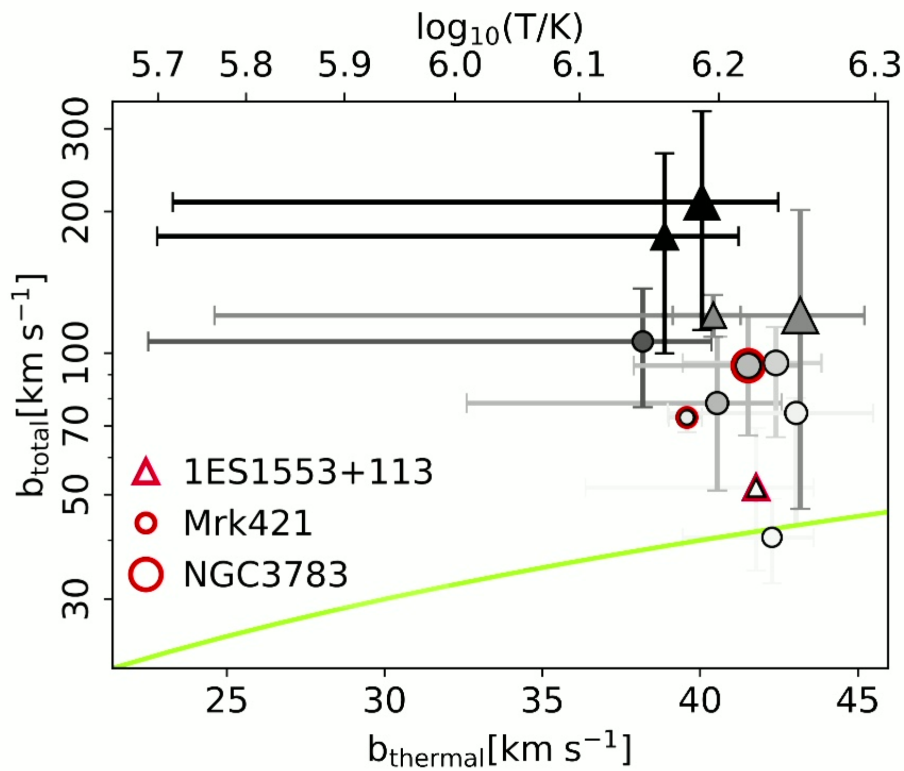
Super-virial gas in emission (iron enriched) and in absorption (iron lacking) have different stellar feedback origins

(Bhattacharyya, Das et al. 2023, ApJ)



Non-thermal broadening of OVII absorption lines

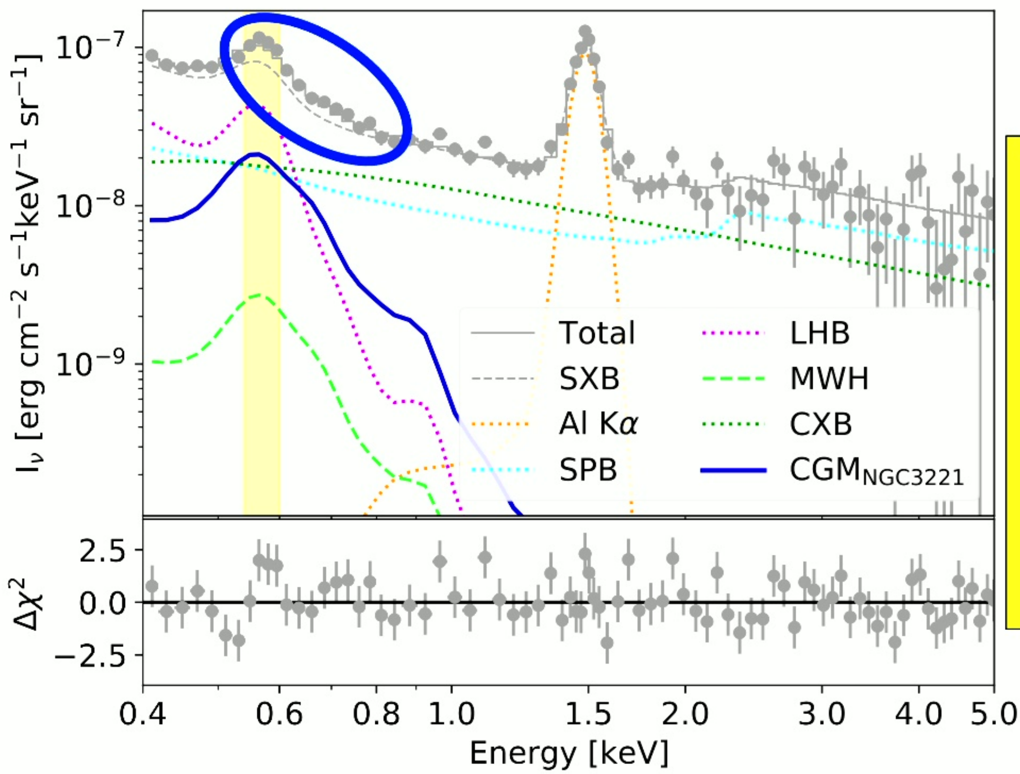
$$\langle v_T \rangle = 40 \text{ km s}^{-1}$$
$$\langle v_{nT} \rangle = 50 - 70 \text{ km s}^{-1}$$



Das 2024, ApJL, 963, 48

Hot CGM of external galaxies: X-ray emission

30-200 kpc spectrum of NGC 3221 ($M_* \approx 9 \times 10^{10}\ M_{sun}$), z=0.014



The detected CGM

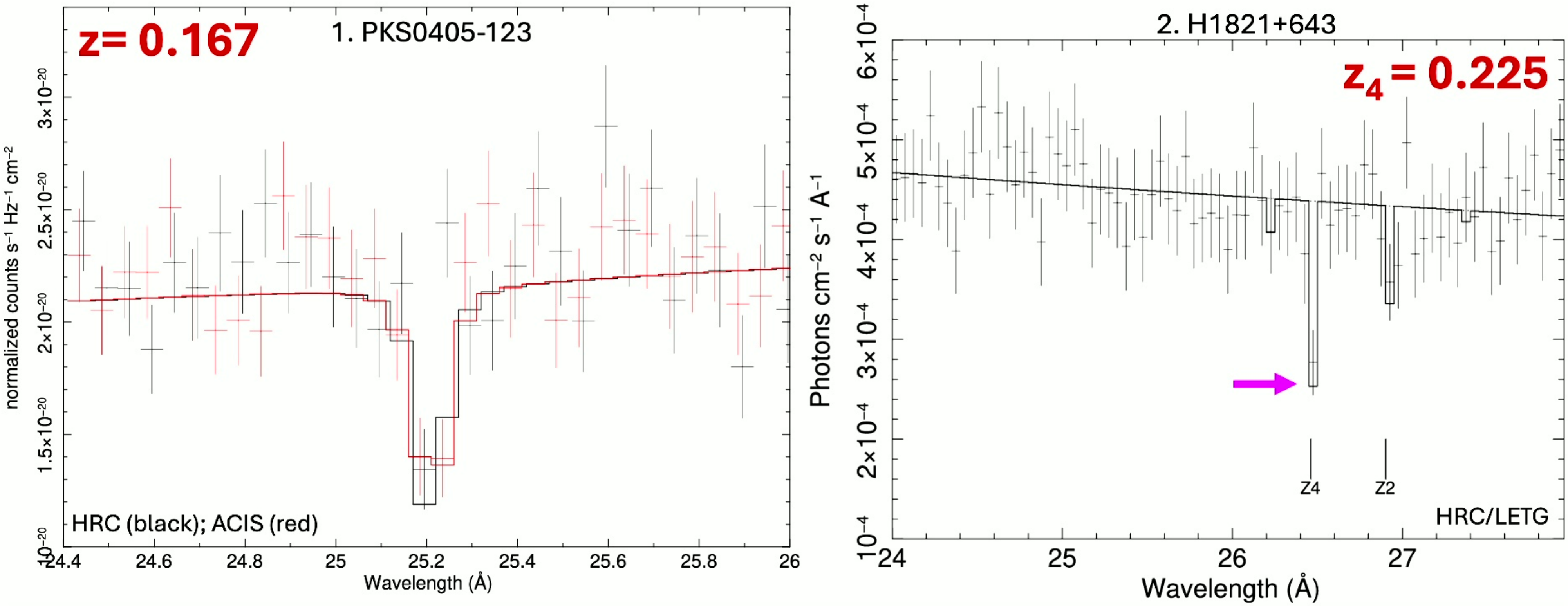
- is hot at $T \approx 10^{6.4}$ K $\approx T_{200c}$
- is sufficiently massive to account for the missing *galactic* baryons (at 0.1-0.3 Z_{sun})
- is the **first and only** (so far) external individual galaxy with such detection
- Want to see more such study? Ask the TAC ☺☺

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

See also: Tullmann+2006, Yamasaki+2009, Bogdan+2015 [non-detections]; Anderson+2016, Bogdan+2017, Li+2017 [detection of inner CGM]

Hot CGM of external galaxies: X-ray absorption

Look for O VII absorption at the same redshift as the "unusually broad" O VI absorption toward the same QSO

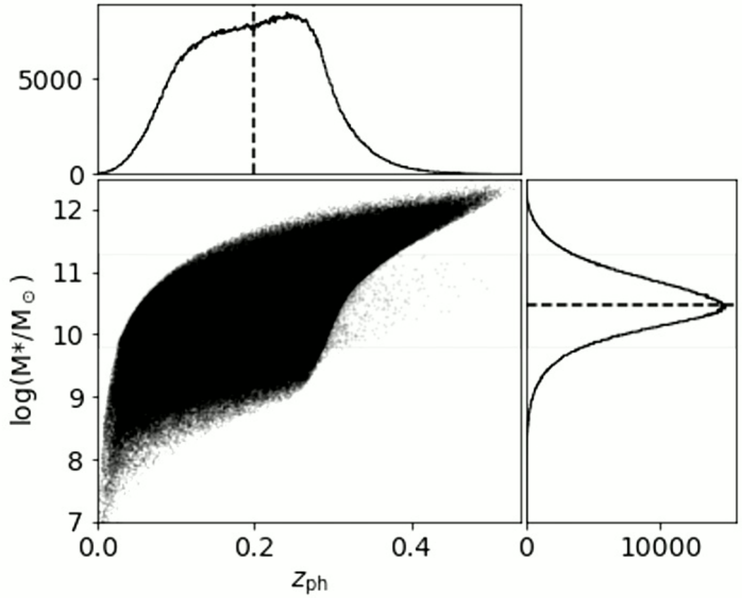


These are the **first 2 and only 2** (so far) external individual galaxies with such detections

1. Mathur et al. 2021, ApJ, 908, 69; 2. Mathur et al. 2023, MNRAS L, 525, 11

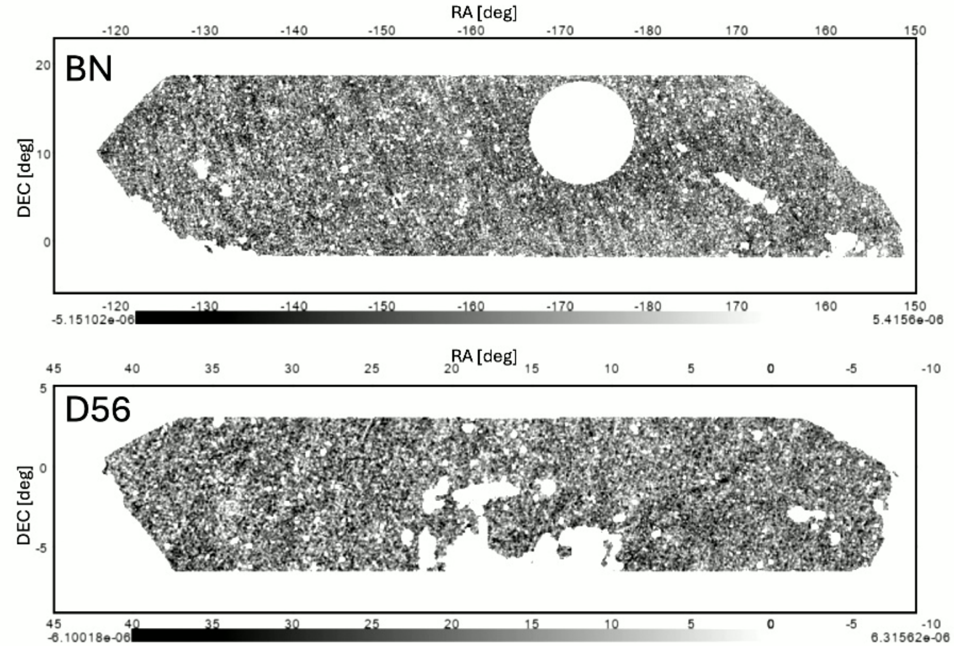
Hot CGM of external galaxies: tSZ effect

WISExSuperCosmos galaxy catalog (Bilicki+2016)



X

ACT + Planck Compton-*y* map (Madhavacheril+2020)

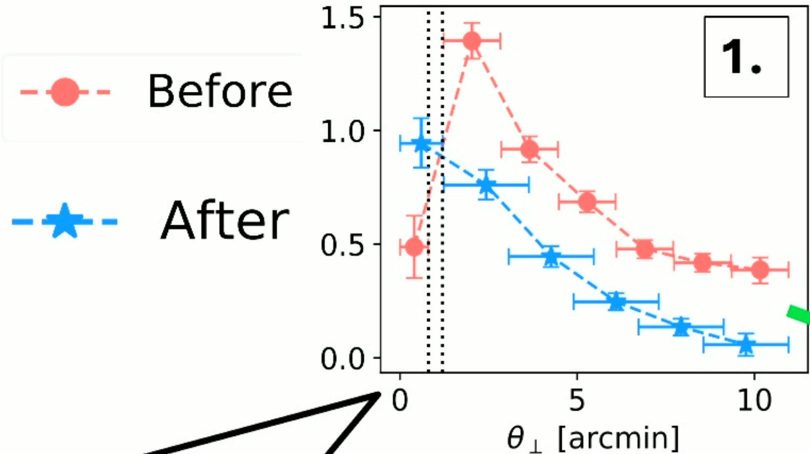


1. 0.63 million z ≈ 0-0.3 $M_*=10^{9.8\text{-}11.3}\,M_{sun}$ galaxies
2. Only **field** galaxies (to avoid intra cluster medium)
3. **Exclude** radio-loud and/or IR-bright **AGN**

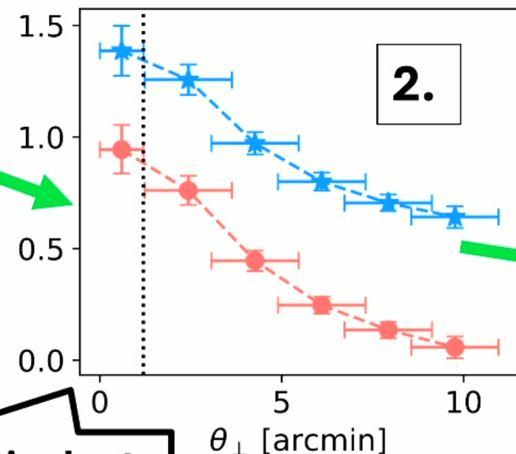
1. Correct for **cosmic dust (CIB)**
2. Remove regions of high **Galactic dust** extinction
3. Mask **galaxy clusters**
4. Mask **radio** sources

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

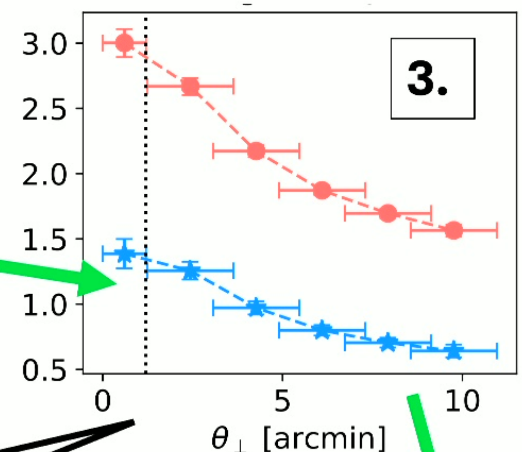
Preparing the y-map for stacking



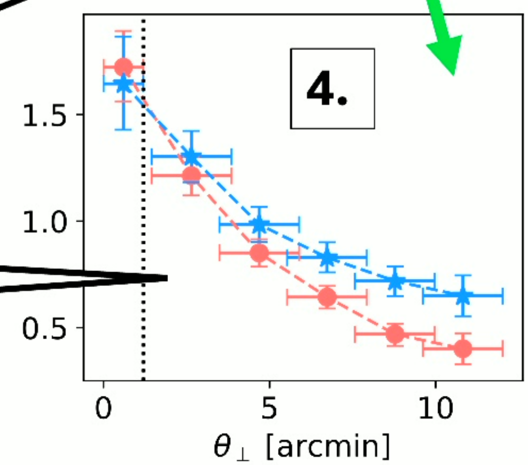
1. Correct for the **Cosmic Infrared Background**



2. Correct for **Galactic dust**



3. Mask R_{200} regions around **galaxy clusters**



4. Mask affected regions around point **radio sources**

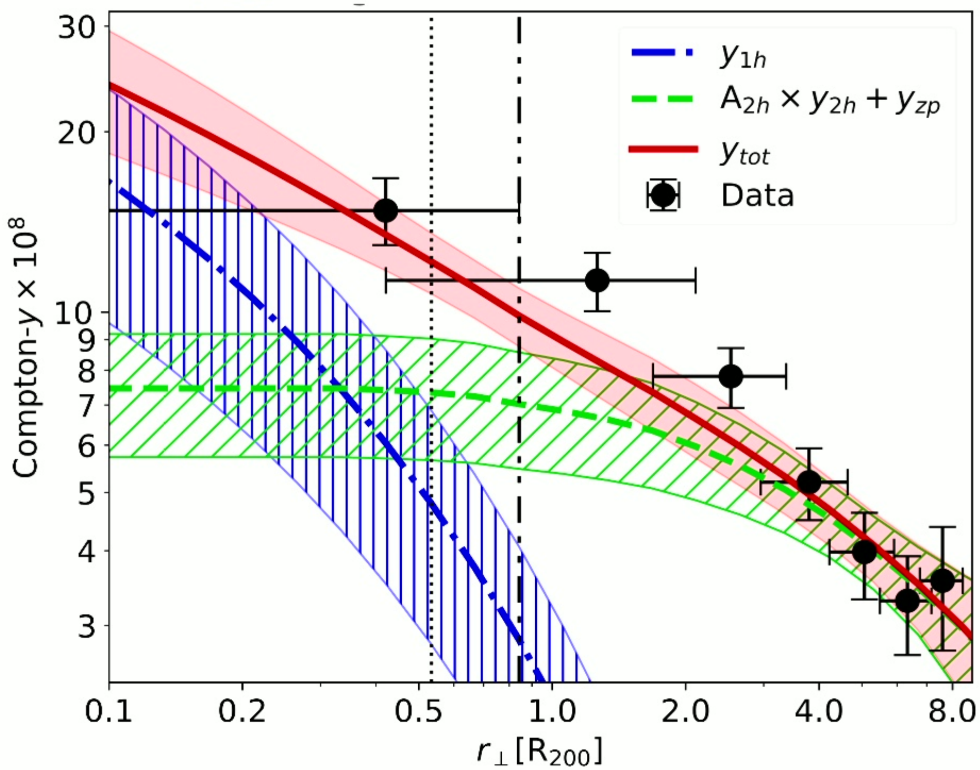
- Stack at a fixed fraction of virial radius up to $\mathbf{8R_{200}}$ (instead of fixed angular size)

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

Cross-correlation with 0.63 million WISExSuperCosmos galaxies

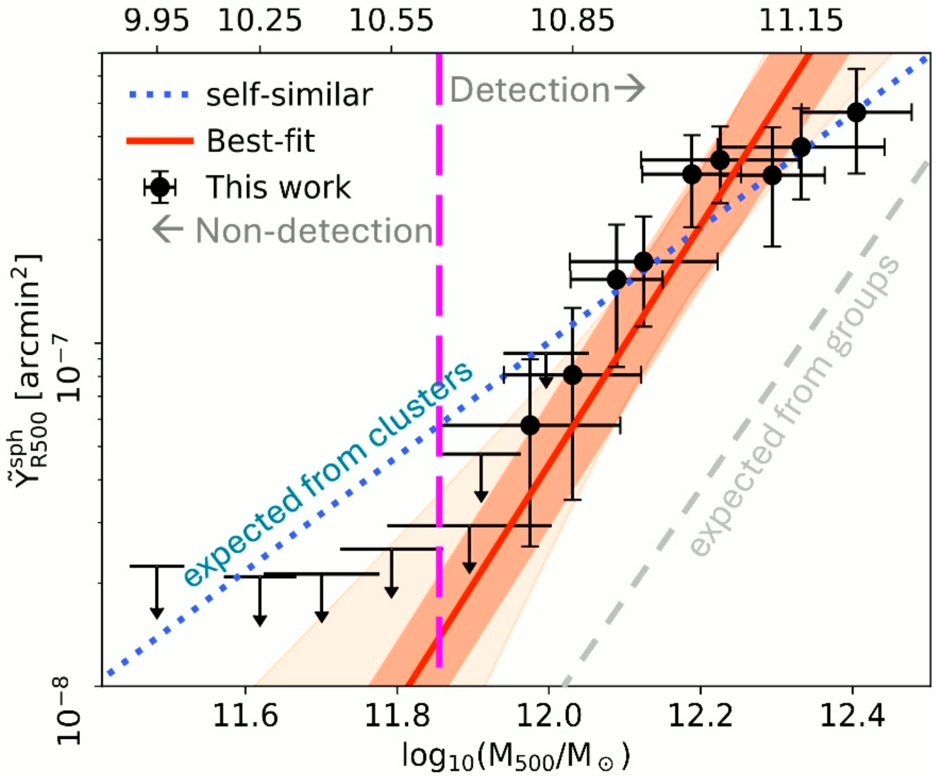
$y_{tot} = y_{1h} + A_{2h}y_{2h} + y_{zp}$

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



Thermal energy:

$$\tilde{Y}^{sph}_{R500}(M_{500}) \propto \int_0^{R_{500}} P_e(r|M_{500},z)4\pi r^2 dr$$

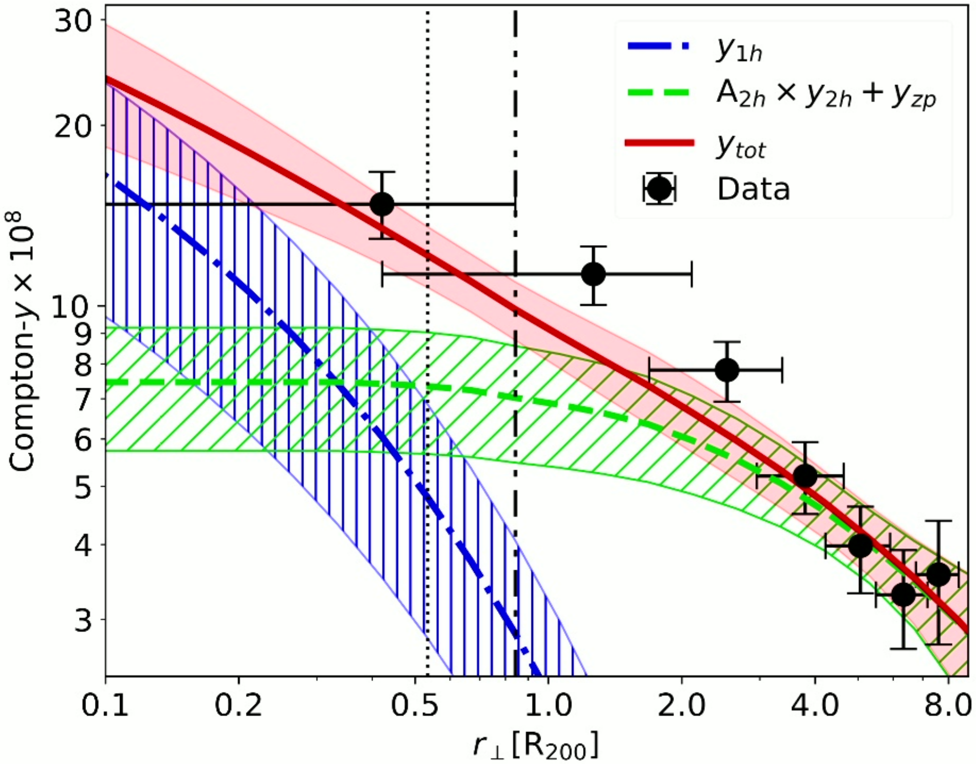


Das, Chiang & Mathur, 2023, ApJ, 951, 125

Cross-correlation with 0.63 million WISExSuperCosmos galaxies

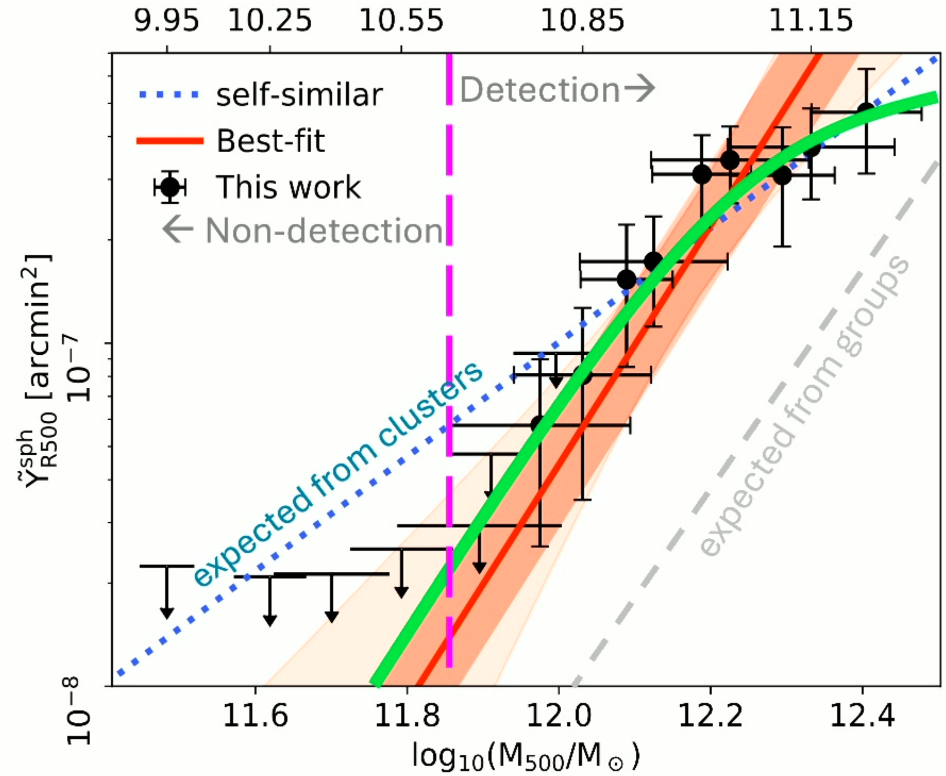
$$y_{tot} = y_{1h} + A_{2h}y_{2h} + y_{zp}$$

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



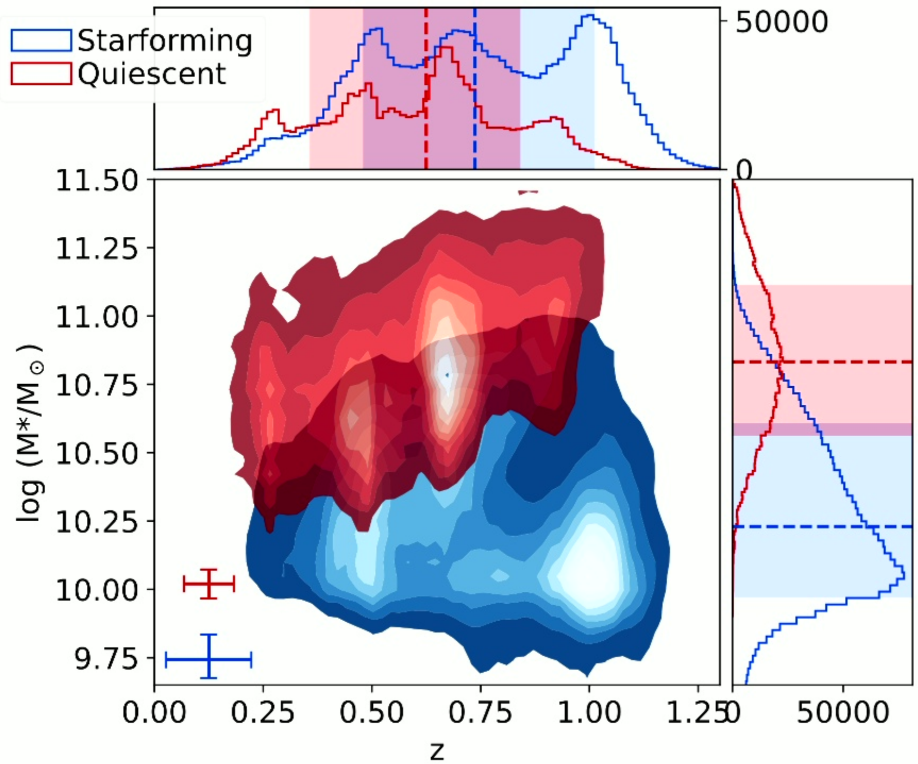
Thermal energy:

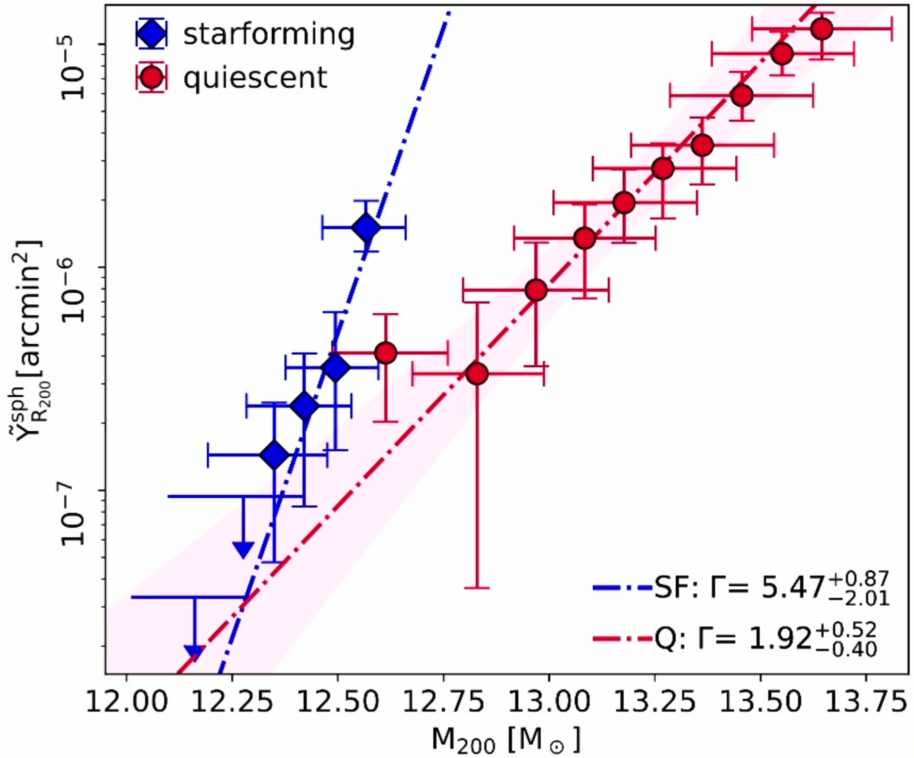
$$\tilde{Y}^{sph}_{R500}(M_{500}) \propto \int_0^{R_{500}} P_e(r|M_{500},z)4\pi r^2 dr$$



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

Cross-correlation with 2.5 million WISExDESI galaxies (0.7 million quiescent and 1.8 million star-forming)



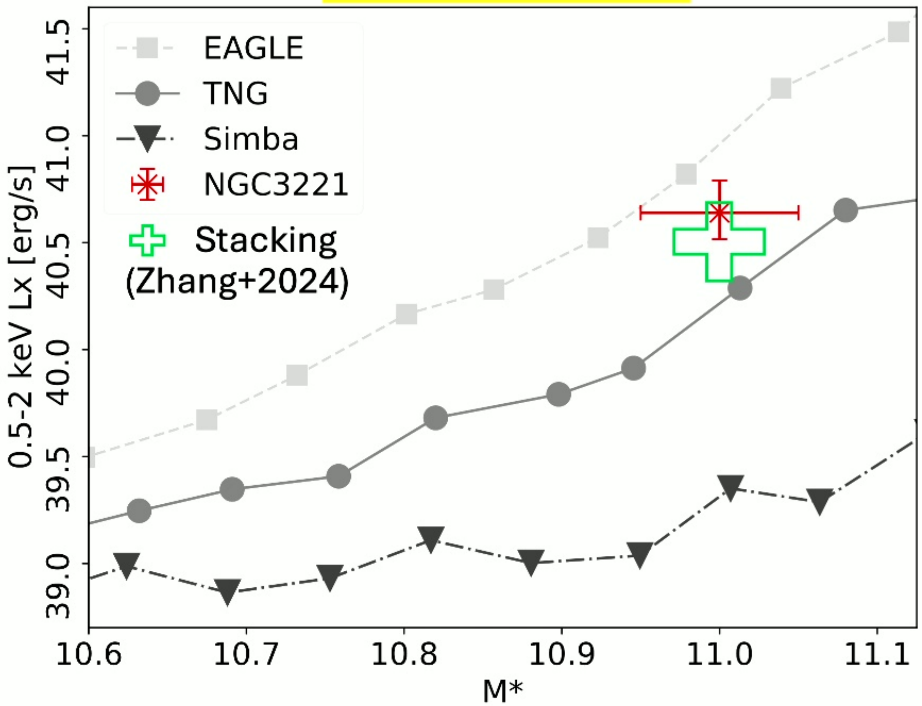


Das, Truong, Chiang & Mathur 2025

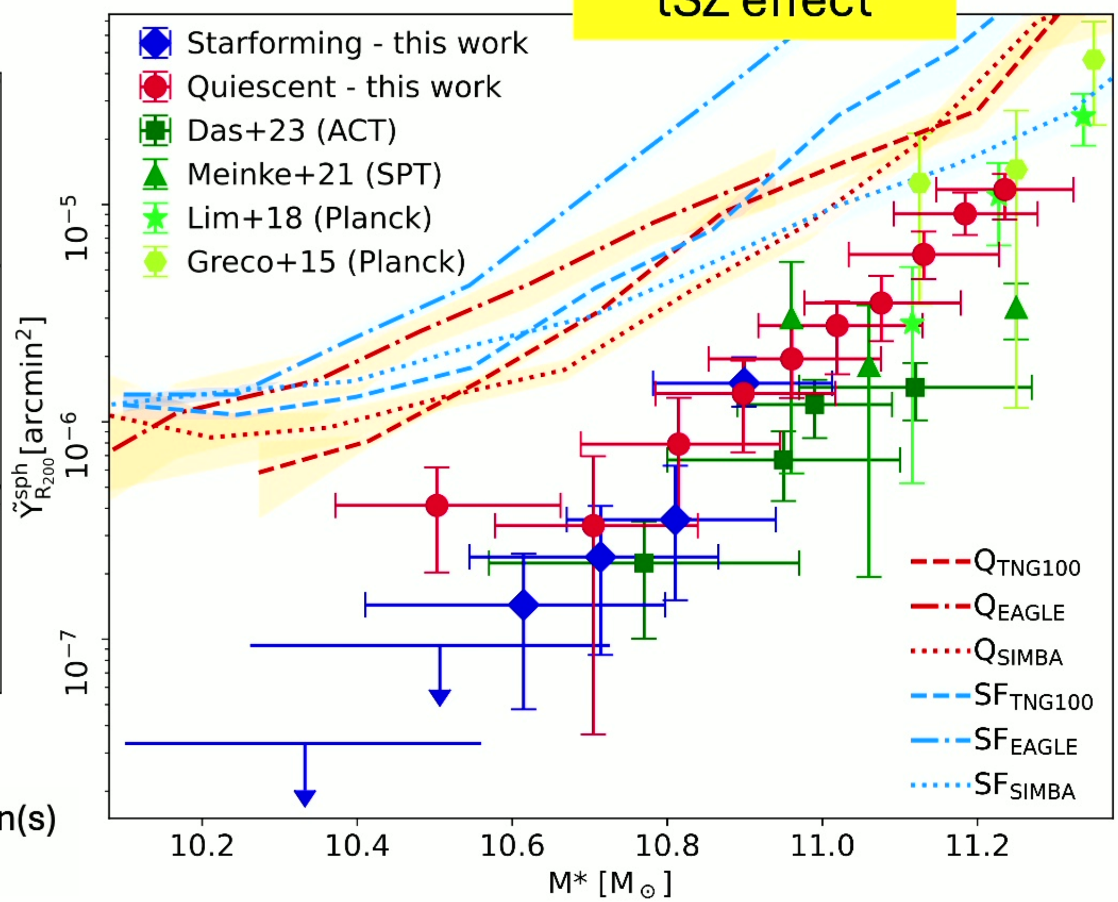
Quiescent galaxies follow self-similarity of thermal energy; Star-forming galaxies do not

How well are simulations doing?

X-ray emission



tSZ effect



Please send predictions from your favorite simulation(s) to compare with our X-ray and tSZ results!

Summary

1. Hot CGM of the **Milky Way** has anomalous thermal, chemical, and kinematic properties
2. X-ray emission from the hot CGM of external individual spiral galaxies
   a) is detectable
   b) is extended out to >150 kpc (0.7 R_{200})

   We should utilize CCDs of XMM/XRISM for CGM science in X-ray emission
3. X-ray absorption by the hot CGM of external individual galaxies
   a) is detectable
   b) is extended out to >100 kpc

   We should utilize gratings of XMM/Chandra for CGM science in X-ray absorption
4. tSZ effect from the hot CGM of stacked galaxies
   a) is detectable
   b) does not indicate a flatter pressure profile
   c) does not follow the Y-M trends of galaxy clusters or massive groups
   d) is different for quiescent and star-forming galaxies

   mm telescopes with <1' angular resolution is crucial for CGM science in tSZ

Questions?

Also, I will start applying for faculty positions from this fall