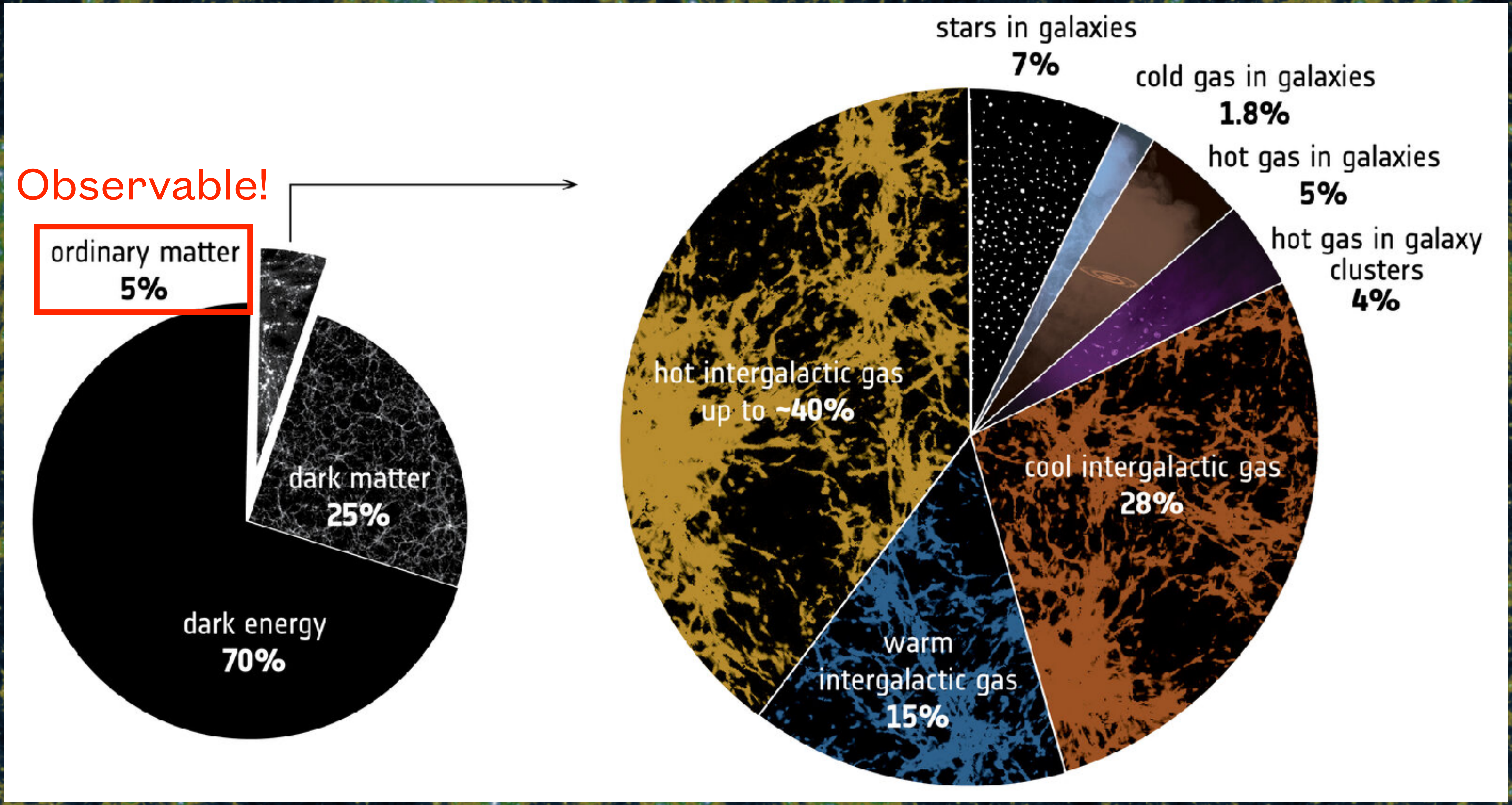
Horizon Run 5 Simulation - Formation of a Massive Cluster of Galaxies (https://www.youtube.com/watch?v=q8R3dfrq6_Y), Lee et al. (2021)

Structure of the Universe: Simulation (IllustrisTNG)



European Space Agency (https://www.esa.int/ESA_Multimedia/Images/2018/06/The_cosmic_budget_of_ordinary_matter)

Gas density + Stellar distributions

The IllustrisTNG Project (https://www.tng-project.org/explore/)

Structure of the Universe: Virgo Cluster

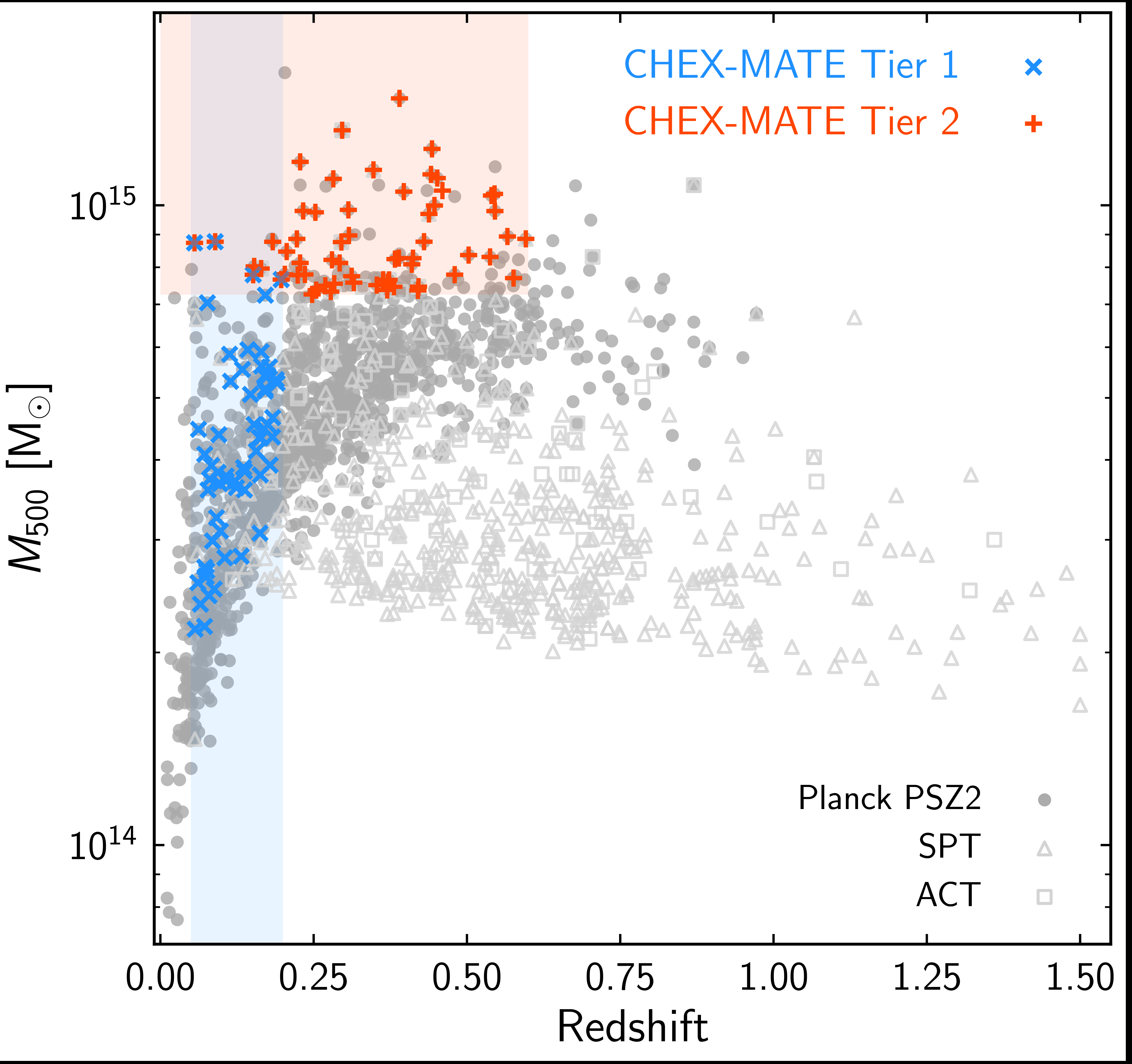

Circumgalactic/Intergalactic/Intracluster medium
Diffuse gas
Recycling gas
(Accretion: an acquisition of gas by the galaxy disk)
Accreting gas
15 kpc
Outflows
300 kpc
Tumlinson, Peeples, Werk (2017)
Supermassive black holes
M87
Rogelio Bernal Andreo
DeepSkyColors.com
Credit & Copyright: Rogelio Bernal Andreo (https://apod.nasa.gov/apod/ap150804.html)

CHEX-MATE: CLUster Multi-Probes in Three Dimensions (CLUMP-3D)

Credit: ESA/Euclid/Euclid Consortium/NASA,
image processing by J.-C. Cuillandre (CEA Paris-Saclay), G. Anselmi

CHEX-MATE

- CHEX-MATE: The Cluster HEritage project with *XMM-Newton* – Mass Assembly and Thermodynamics at the Endpoint of structure formation (CHEX-MATE Collaboration 2021)
  - 3 Msec XMM-Heritage program
  - Planck SZ selected 118 clusters
  - Tier-1: $z < 0.2$ and $\mathrm{dec} > 0$
    $$2 \times 10^{14}\mathrm{M}_\odot < M_{500} < 9 \times 10^{14}\mathrm{M}_\odot$$
    (volume-limited sample in the local universe)
  - Tier-2: $z < 0.6$ and $M_{500} > 7.25 \times 10^{14}\mathrm{M}_\odot$
    (sample of the most massive objects to have formed)



CHEX-MATE Collaboration (2021)

A&A 650, A104 (2021)
https://doi.org/10.1051/0004-6361/202039632

Astronomy & Astrophysics

The Cluster HEritage project with *XMM-Ne*
and Thermodynamics at the Endpoint o

A&A 672, A156 (2023)
https://doi.org/10.1051/0004-6361/202245012

CHEX-MATE: Pressure profiles of six galaxy clusters as seen by SPT and *Planck*

A&A 665, A117 (2022)
https://doi.org/10.1051/0004-6361/202243470

Astronomy & Astrophysics

CHEX-MATE: Morphological analysis of the sample

M. G. Campitiello[1,2], S. Ettori[1,3], L. Lovisari[1,4], I. Bartalucci[5], D. Eckert[6], E. Rasia[7,8], M. Rossetti[5], F. Gastaldello[5], G.W. Pratt[9], B. Maughan[10], E. Pointecouteau[11], M. Sereno[1,3], V. Biffi[12,13], S. Borgani[7,12,14,15], F. De Luca[16], M. De Petris[17], M. Gaspari[1,18], S. Ghizzardi[5], P. Mazzotta[16], and S. Molendi[5]

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Astronomy & Astrophysics

straining the origin of the scatter in galaxy
al X-ray surface brightness profiles

E. Rasia[2,3], G. W. Pratt[4], M. Arnaud[4], M. Rossetti[1], F. Gastaldello[1], D. Eckert[5],

A&A 679, A51 (2023)
https://doi.org/10.1051/0004-6361/202347234

Astronomy & Astrophysics

CHEX-MATE: A non-parametric deep lea
deproject and deconvolve galaxy cluster X-ra

A. Iqbal[1], G. W. Pratt[1], J. Bobin[2], M. Arnaud[1], E. Rasia[3,4], M. Rosset
H. Bourdin[6], F. De Luca[6], M. De Petris[7], M. Donahue[8], D. Eckert[9],
M. Gaspari[14], F. Gastaldello[5], R. Gavazzi[15,16], S. Ghizzardi[5], L
B. J. Maughan[19], E. Pointecouteau[20], and M. Se

Astronomy & Astrophysics manuscript no. 2Dmaps
November 7, 2023

CHEX-MATE: Characterization of the intra-cluster medium temperature distribution

L. Lovisari[1,2], S. Ettori[1,3], E. Rasia[4,5], M. Gaspari[6], H. Bourdin[7,8], M. G. Campitiello[1,9], M. Rossetti[10], I. Bartalucci[10], S. De Grandi[11], F. De Luca[7,8], M. De Petris[12], D. Eckert[13], W. Forman[2], F. Gastaldello[10], S. Ghizzardi[10], C. Jones[2], S. Kay[14], J. Kim[15], B. J. Maughan[16], P. Mazzotta[7], E. Pointecouteau[17], G. W. Pratt[18], J. Sayers[15], M. Sereno[1,3], M. Simonte[19], P. Tozzi[20]

CHEX-MATE: CLUMP-3D

Astronomy & Astrophysics manuscript no. aanda
July 12, 2023

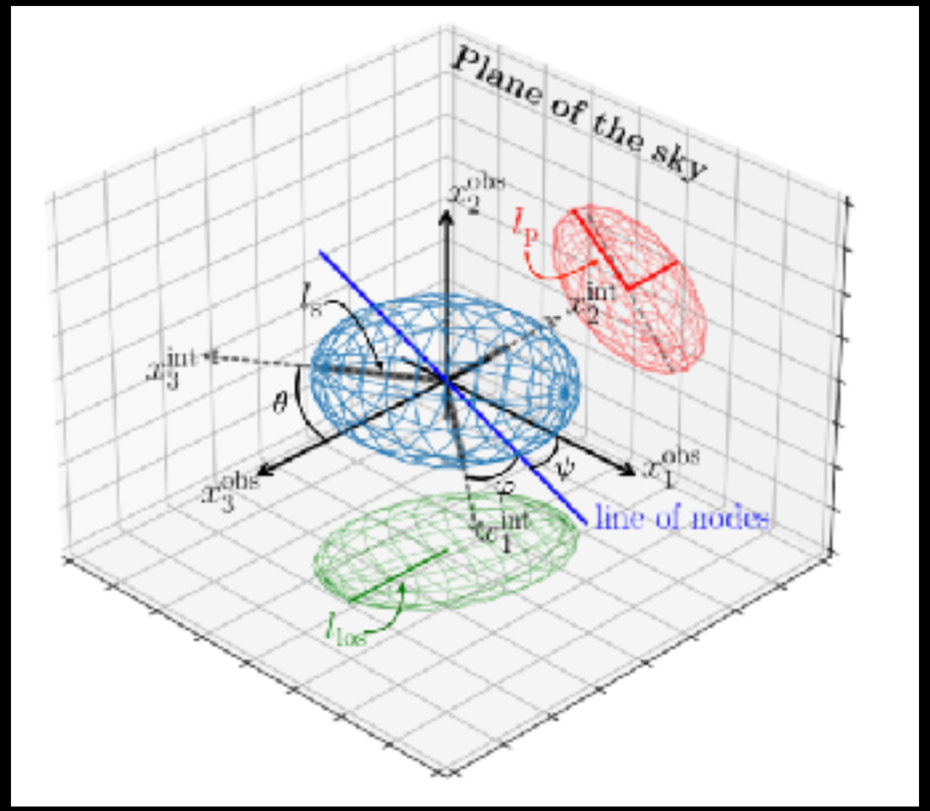
CHEX-MATE: CLUster Multi-Probes in Three Dimensions (CLUMP-3D)

I. Gas Analysis Method using X-ray and Sunyaev–Zel'dovich Effect Data

Junhan Kim[1], Jack Sayers[1], Mauro Sereno[2,3], Iacopo Bartalucci[4], Loris Chappuis[5], Sabrina De Grandi[6], Federico De Luca[7,8], Marco De Petris[9], Megan E. Donahue[10], Dominique Eckert[5], Stefano Ettori[2,3], Massimo Gaspari[11], Fabio Gastaldello[4], Raphael Gavazzi[12,13], Adriana Gavidia[1], Simona Ghizzardi[4], Asif Iqbal[14], Scott Kay[15], Lorenzo Lovisari[2], Ben J. Maughan[16], Pasquale Mazzotta[7,8], Nobuhiro Okabe[17,18,19], Etienne Pointecouteau[20], Gabriel W. Pratt[14], Mariachiara Rossetti[4], and Keiichi Umetsu[21]

(Affiliations can be found after the references)

Triaxial Analysis of Galaxy Clusters

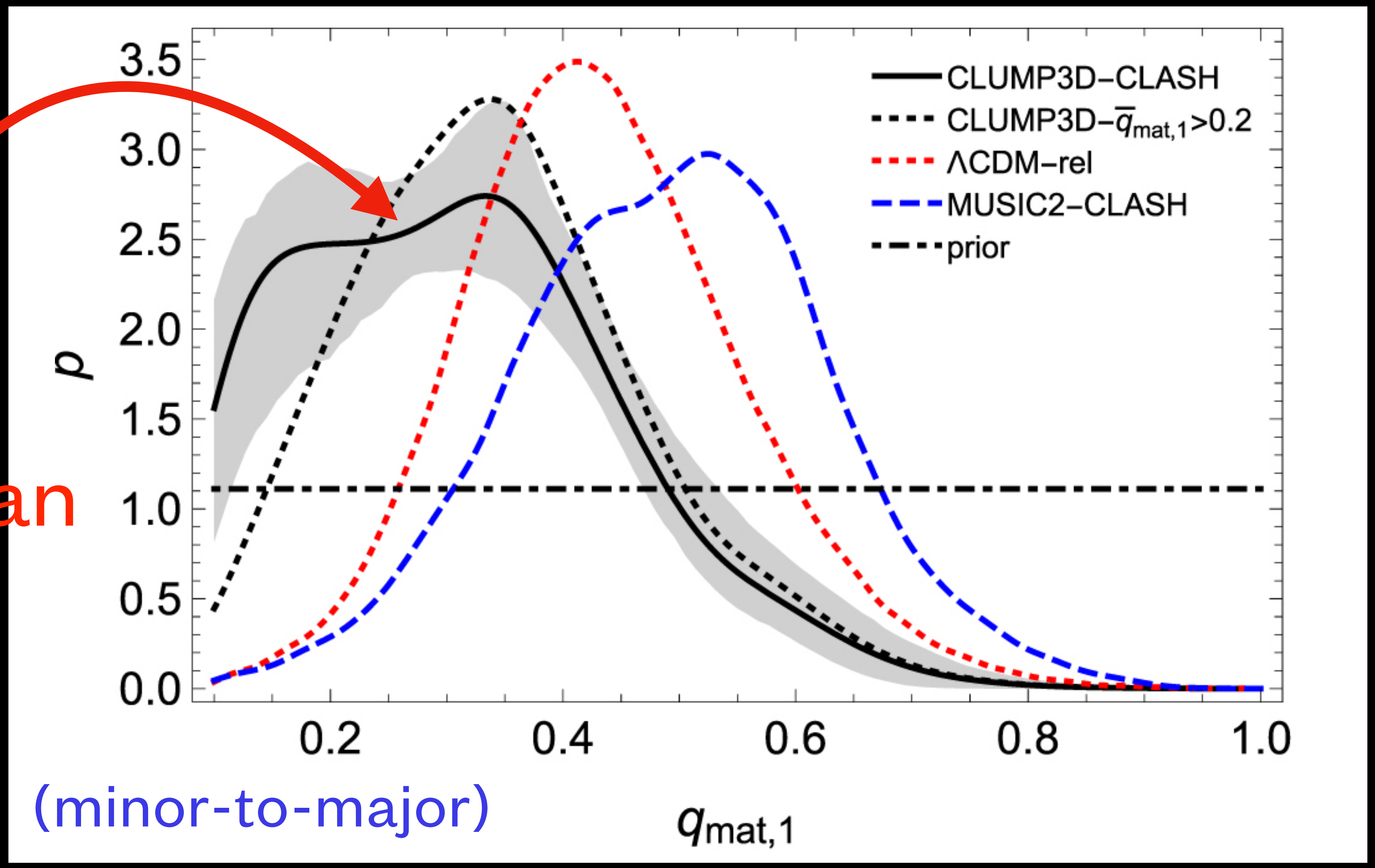


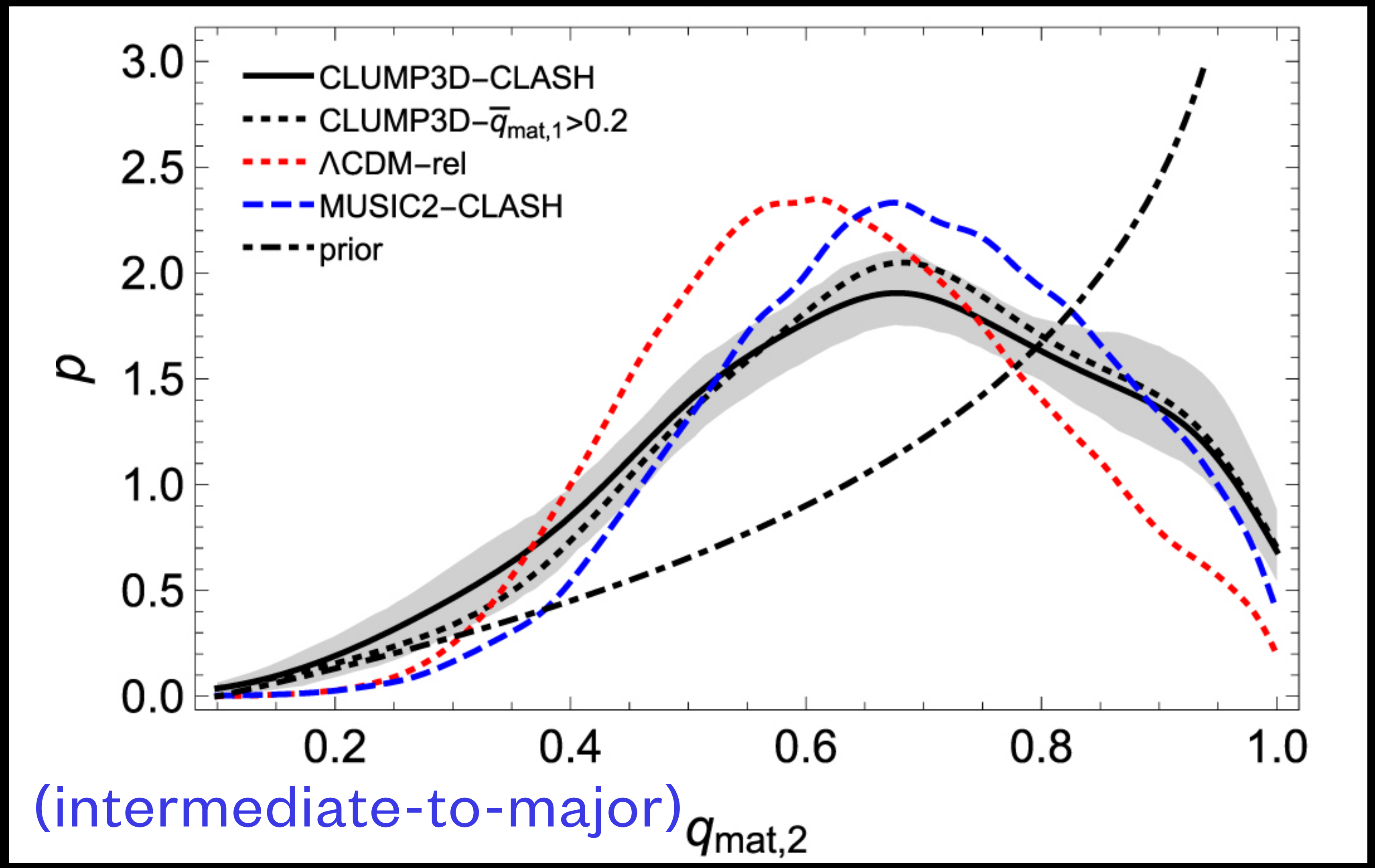
- Motivations
  - A better approximation of galaxy cluster than a spherical model.
    - Reduce the level of bias/scatter in derived parameters (e.g., Becker & Kravtsov 2011, Khatri & Gaspari 2016).
  - Correlation between shape parameters and halo properties (e.g., Ho et al. 2006; Lau et al. 2021; Stapelberg et al. 2022)
- Science goals
  - Galaxy Cluster Shape Measurements: **What is the distribution of three-dimensional shapes of galaxy clusters? (Cosmology)**
  - Non-Thermal Motions in the Intracluster Medium: **What is the level of non-thermal pressure support in the intracluster medium? (Astrophysics)**

Science Goal: Shape Measurements

- What is the distribution of three-dimensional shapes of galaxy clusters?
  - Cosmological models make strong predictions for the shape of DM halos (e.g., Yoshida et al. 2000)
  - CLASH results (Sereno et al. 2018) potentially suggest more extreme axial ratios compared to simulations.

smaller q than expected

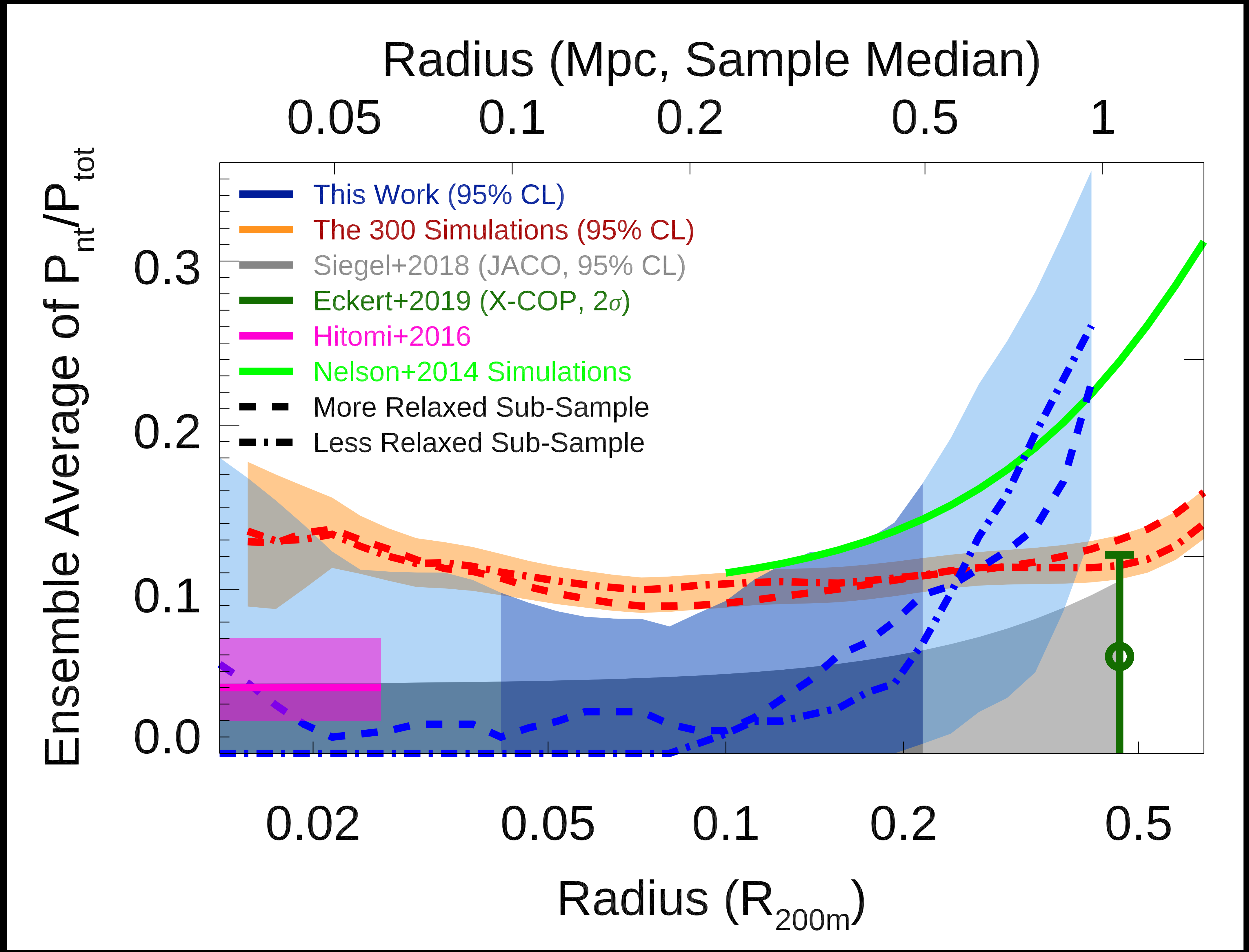




Sereno et al. (2018)

Science Goal: Non-thermal Pressure Profile

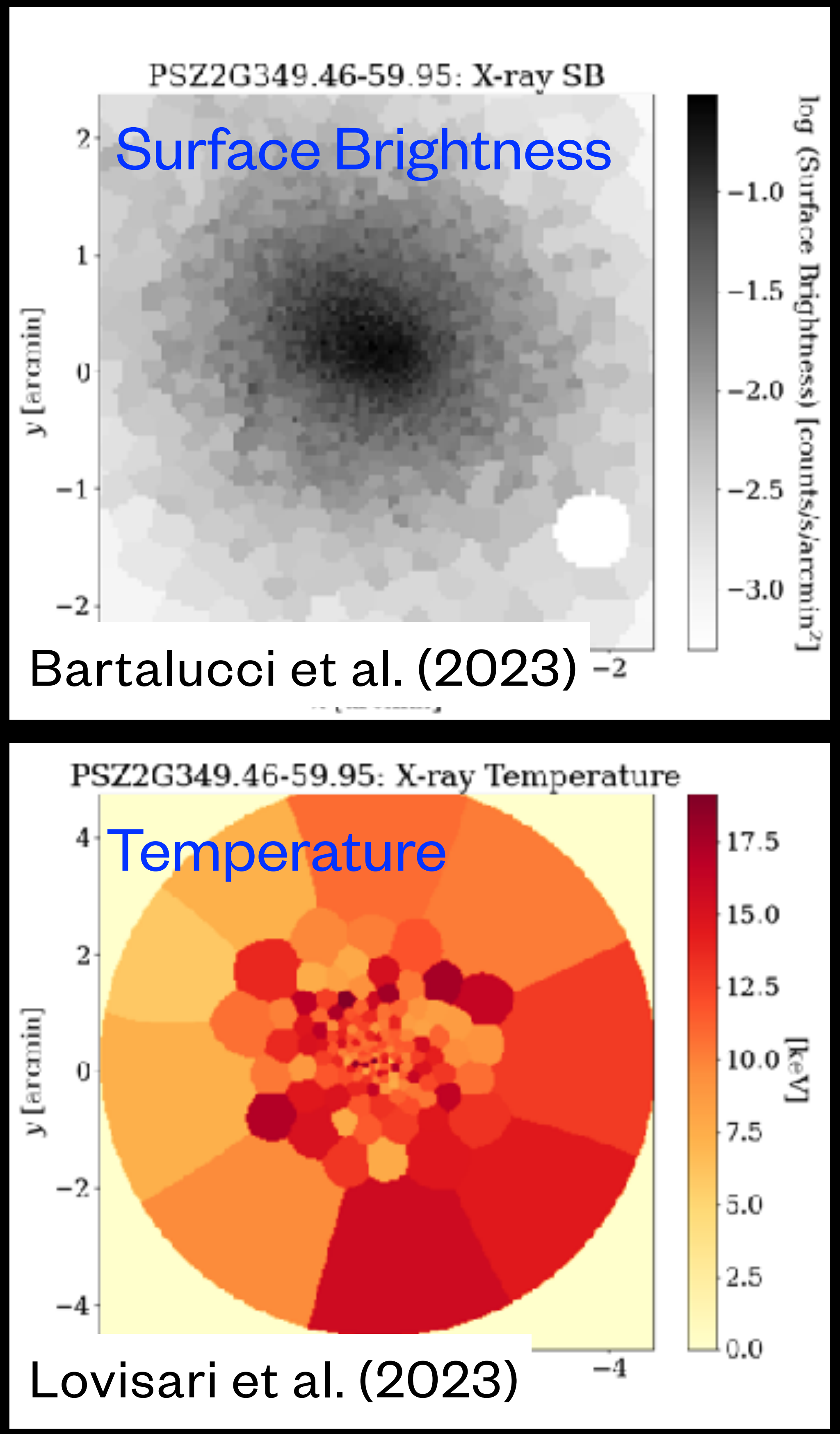
- What is the level of non-thermal pressure support in the ICM?
  - AGN outbursts inject significant energy into the ICM. Simulations predict that the thermalization of accreted material is inefficient.
  - CLASH analyses (Sayers et al. 2021) indicate that the non-thermal pressure profile is consistent with a broad range of simulations.
  - Outer regions of the ICM will be available given the XMM data available for CHEX-MATE.



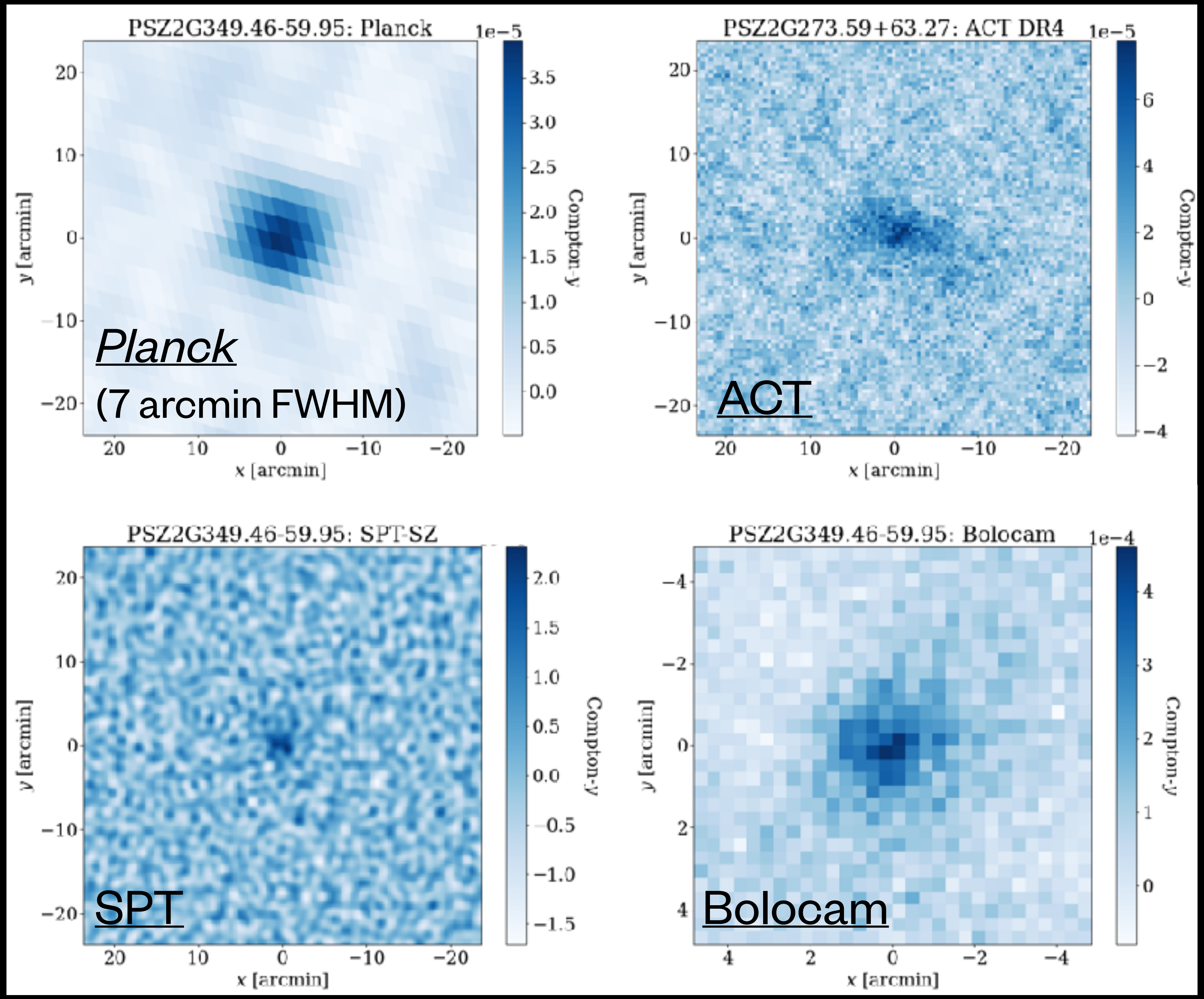
Sayers et al. (2021)

CHEX-MATE: Multiwavelength Dataset

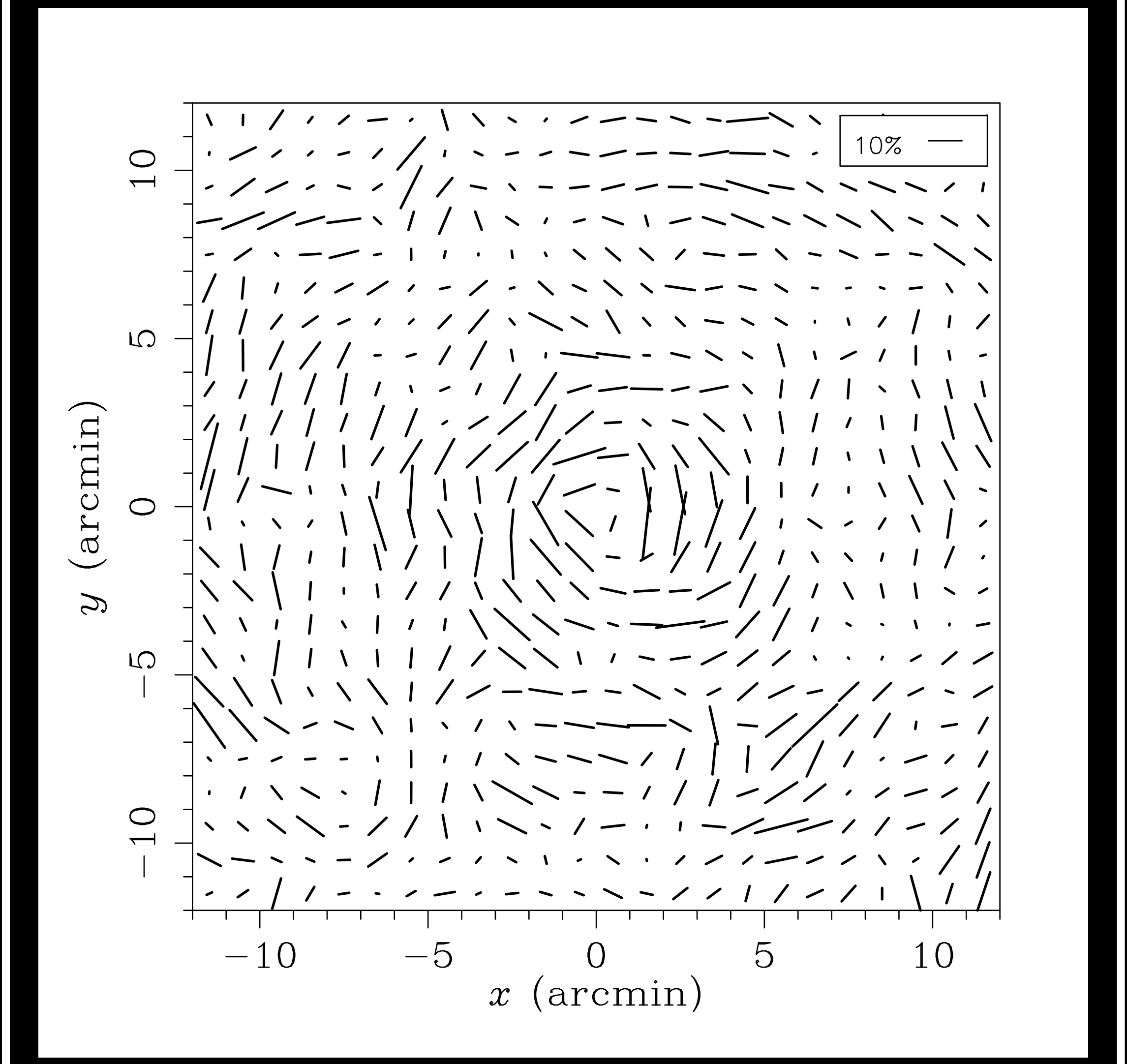
X-ray (*XMM*)



SZ (*Planck* & Ground-based)



Weak Lensing (Subaru)



(lensing data directly probe the total mass distribution)

Triaxial (Gas) Analysis: Formalism

- CLUster Multi-Probes in Three Dimensions (CLUMP-3D; Sereno et al. 2017, 2018; Chiu et al. 2018; Sayers et al. 2021): ICM profiles in 3D → Projected observables in 2D
- Model profiles
  - Electron density profile (Vikhlinin et al. 2006; Ettori et al. 2009)

$$n_e(\zeta) = n_0 \left(\frac{\zeta}{\zeta_c}\right)^{-\eta_e} \left[1 + \left(\frac{\zeta}{\zeta_c}\right)^2\right]^{-3\beta_e/2+\eta_e/2} \left[1 + \left(\frac{\zeta}{\zeta_t}\right)^3\right]^{-\gamma_e/3} \mathrm{cm}^{-3}$$

  - Gas pressure profile: gNFW (Nagai et al. 2007; Arnaud et al. 2010)

$$\frac{P(x)}{P_{500}} = \frac{P_0}{(c_{500}x)^{\gamma_p}[1 + (c_{500}x)^{\alpha_p}]^{(\beta_p-\gamma_p)/\alpha_p}}$$

- Observables: SZ, X-ray surface brightness, X-ray temperature

$$y \equiv \frac{\sigma_\mathrm{T} k_\mathrm{B}}{m_e c^2} \int_\parallel n_e T_e dl \qquad \mathrm{SB} = \frac{1}{4\pi(1+z)^3} \int_\parallel n_e^2 \Lambda_\mathrm{eff}(T_e, Z) dl \qquad T_\mathrm{sp} = \frac{\int W T_e dV}{\int W dV}\ \mathrm{keV}$$

Line-of-sight extent can be constrained!

Triaxial (Gas) Analysis: Formalism

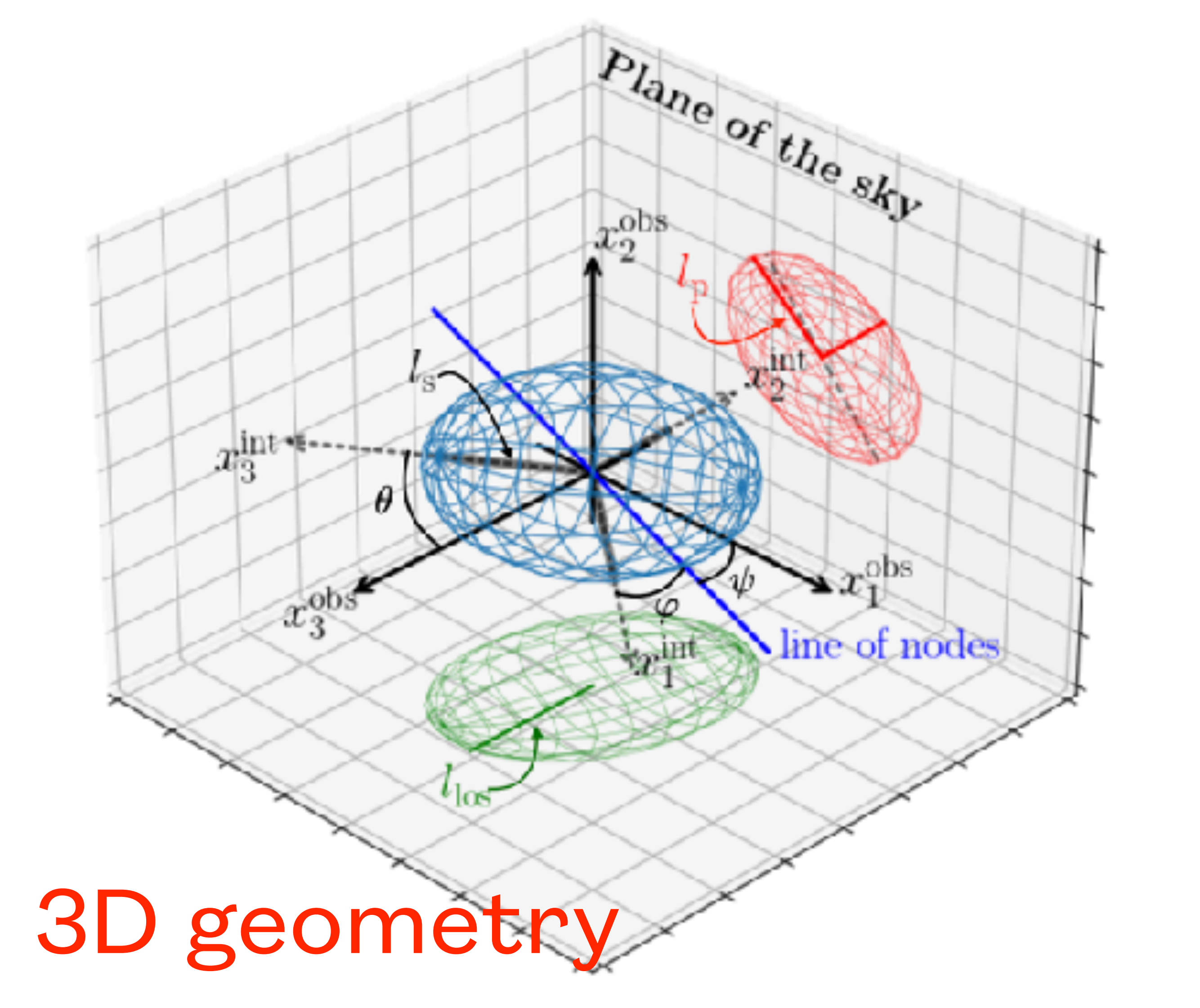
- Projection of the three-dimensional volume density onto the sky plane (Stark 1977; Sereno 2007; Sereno et al. 2010)

elongation parameter (geometry)

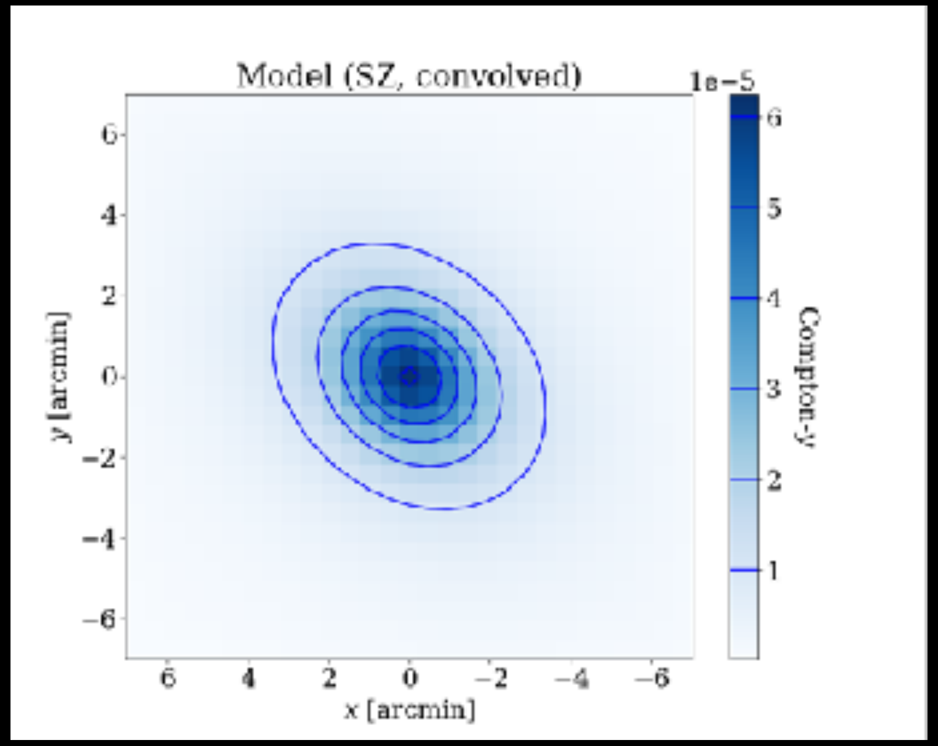
$$F_{\rm 2D}(x_\xi; l_{\rm p}, p_i) = 2 l_{\rm p} e_\parallel \int_{x_\xi}^{\infty} F_{\rm 3D}(x_\zeta; l_s, p_i) \frac{x_\zeta}{\sqrt{x_\zeta^2 - x_\xi^2}} dx_\zeta$$

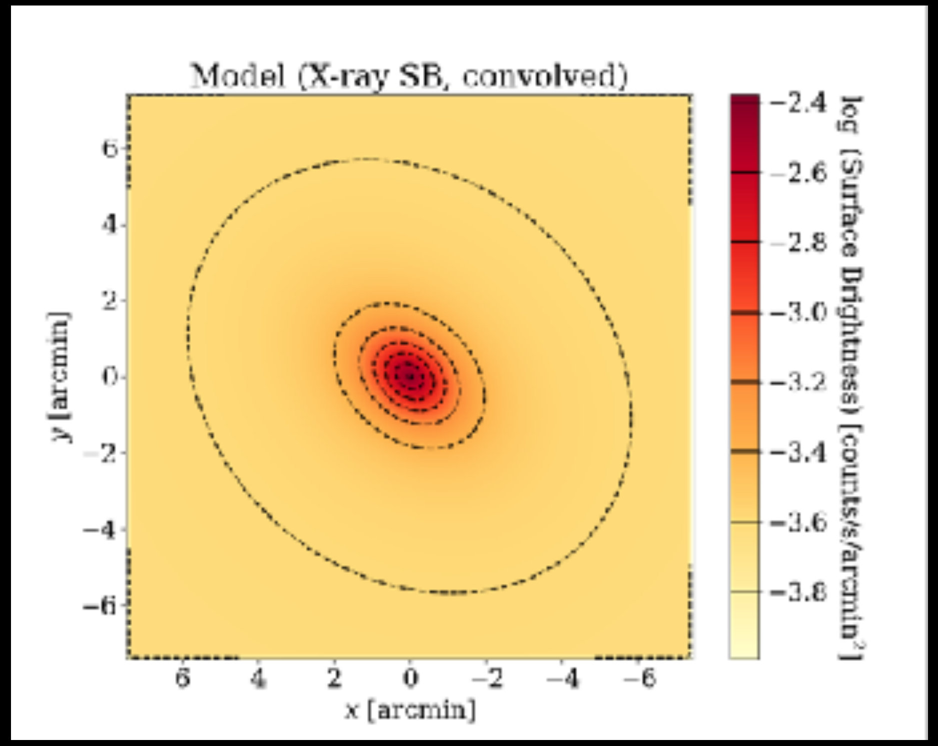
direct observables

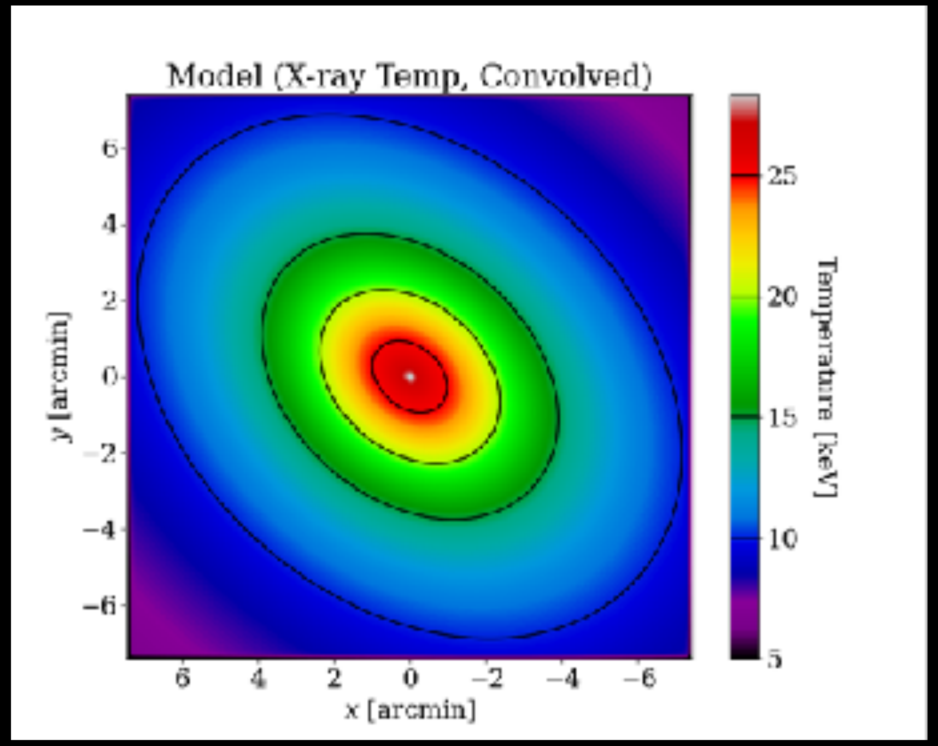
analytic profiles of the ICM model



Model profiles



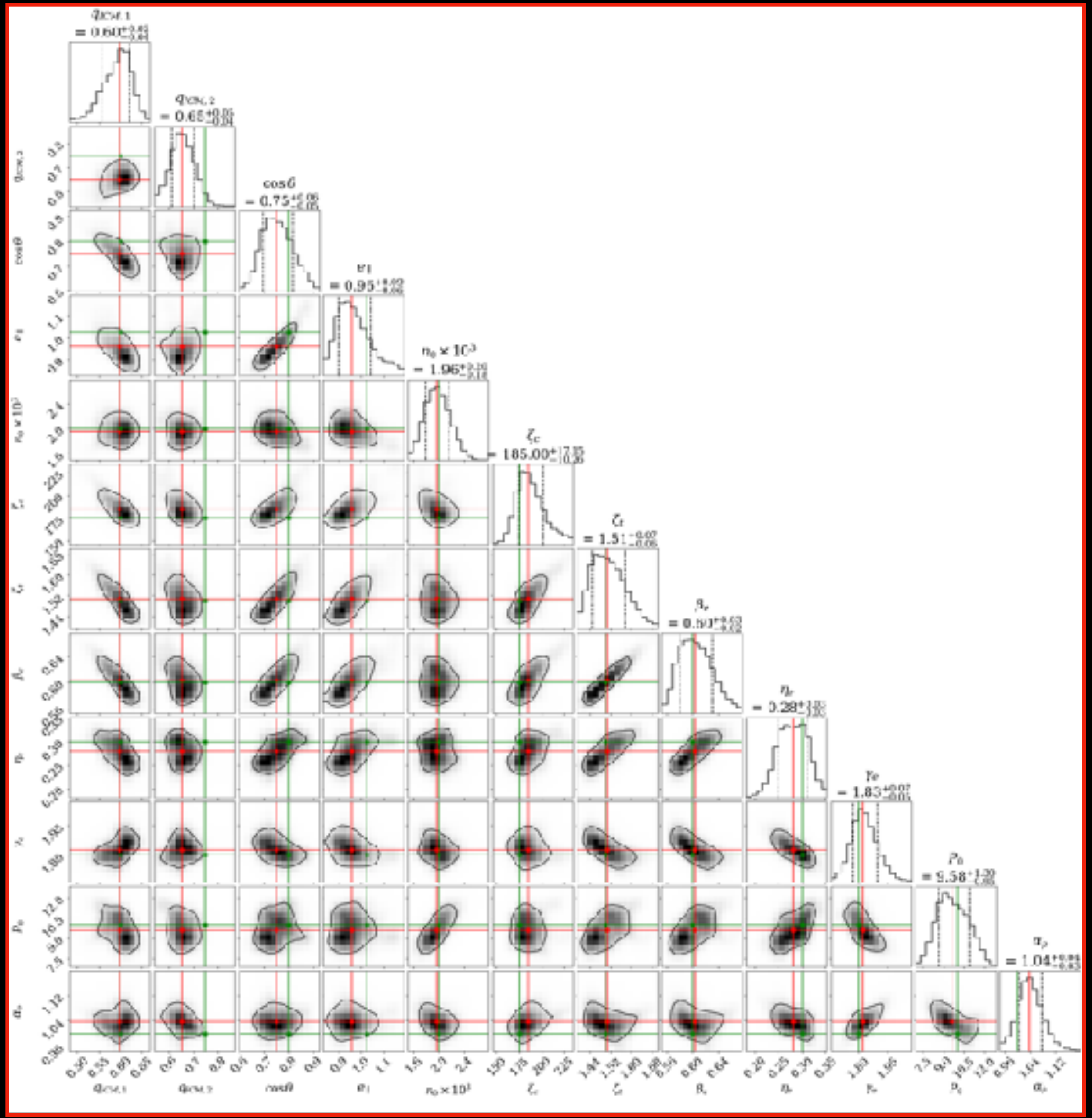




Triaxial (Gas) Analysis: Formalism

- Model fit: geometrical, electron density, gas pressure parameters (13 parameters)

Parameter	Units	Description	Default Prior
		Geometrical Parameters of a Triaxial Ellipsoid (Eqs. 1 and 4)	
$q_{\mathrm{ICM},1}$		Minor-to-major axial ratio of the ICM distribution	$\mathcal{U}(0, 1)$
$q_{\mathrm{ICM},2}$		Intermediate-to-major axial ratio of the ICM distribution	$\mathcal{U}(q_{\mathrm{ICM},1}, 1)$
$\cos\theta$		Cosine of the inclination angle of the ellipsoid major axis	$\mathcal{U}(0, 1)$
φ	deg	Second Euler angle	$\mathcal{U}\ (-\pi/2, \pi/2)$
ψ	deg	Third Euler angle	$\mathcal{U}\ (-\pi/2, \pi/2)$
		Electron Density Profile (Eq. 24)	
n_0	cm^{-3}	Central scale density of the distribution of electrons	$\mathcal{U}(10^{-6}, 10)$
ζ_c	kpc	Ellipsoidal core radius of the gas distribution	$\mathcal{U}(0, 10^3)$
ζ_t	Mpc	Ellipsoidal truncation radius of the gas distribution ($\zeta_t > \zeta_c$)	$\mathcal{U}\ (\zeta_c/10^3, 3)$
β_e		Slope of the gas distribution (in the intermediate region)	$\mathcal{U}(0, 3)$
η_e		Slope of the gas distribution (inner)	$\mathcal{U}(0, 1)$
γ_e		Slope of the gas distribution (outer)	$\mathcal{U}(0, 5)$
		Gas Pressure Profile (Eq. 15)	
P_0		Normalization for the gNFW pressure profile	$\mathcal{U}(0, 10^2)$
c_{500}		Pressure profile concentration ($r \sim r_s = R_{500}/c_{500}$)	$\delta(1.4)$
γ_p		Slope parameter for central region ($r \ll r_s$)	$\delta(0.3)$
α_p		Slope parameter for intermediate region ($r \sim r_s$)	$\mathcal{U}(0, 5)$
β_p		Slope parameter for outer region ($r \gg r_s$)	$\mathcal{U}(0, 15)^a$



PSZ2 G313.33+61.13 (Abell 1689)

- SZ (Planck: 7’ FWHM, ACT: 1.6’ FWHM) and X-ray (XMM) data from CHEX-MATE available for the triaxial analysis of the ICM distribution.
  - SZ: Planck (Planck Collaboration et al. 2016), ACT DR4 (Madhavacheril et al. 2020)
  - X-ray SB (Bartalucci et al. 2023): photon-count images in the [0.7-1.2] keV
  - X-ray temperature (Lovisari et al. 2023): spectroscopic fits in the [0.3-7] keV