THE 11TH KIAS WORKSHOP ON COSMOLOGY AND STRUCTURE FORMATION
10/31/2024

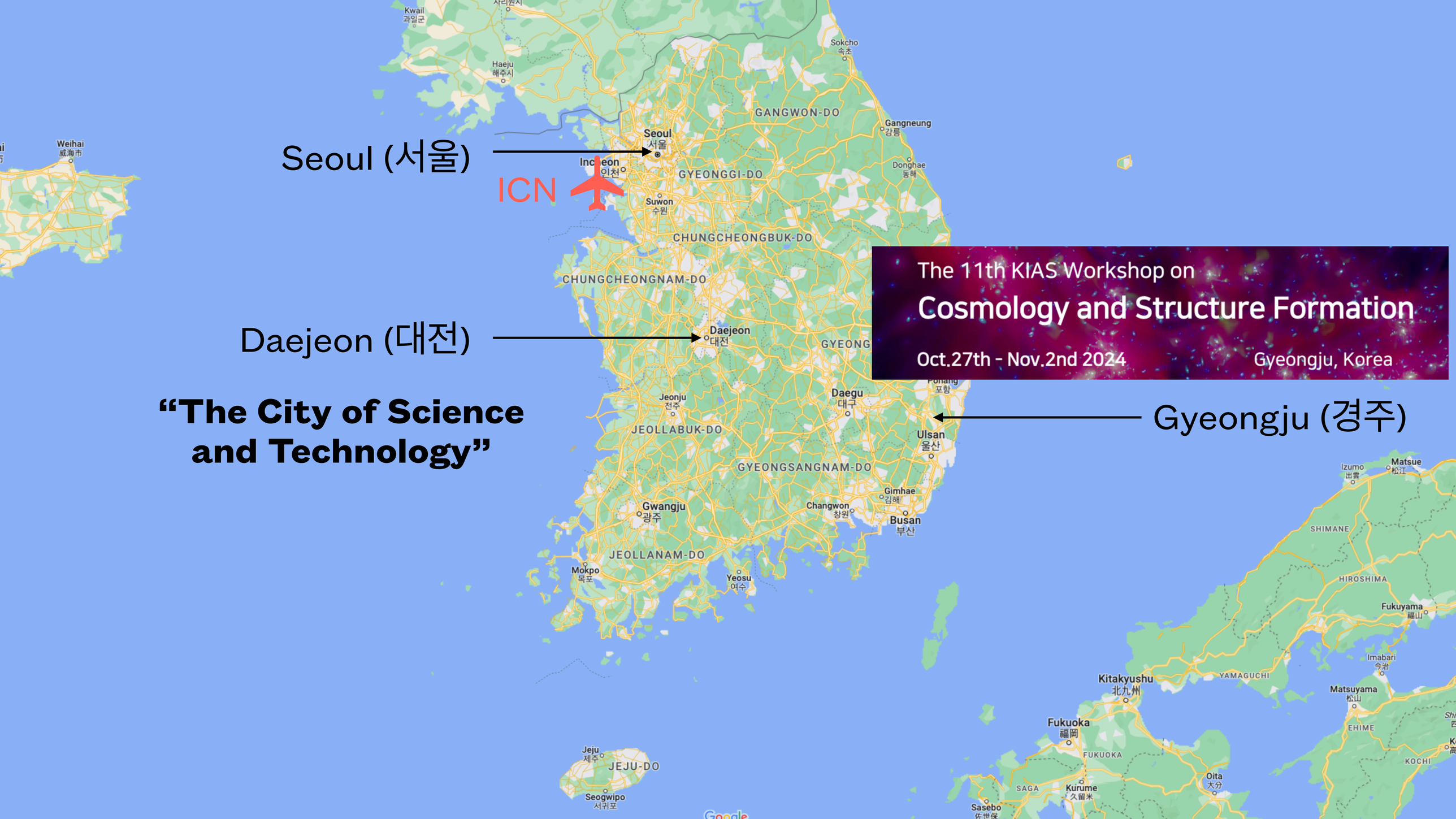
CHEX-MATE: CLUster Multi-Probes in Three Dimensions (CLUMP-3D)

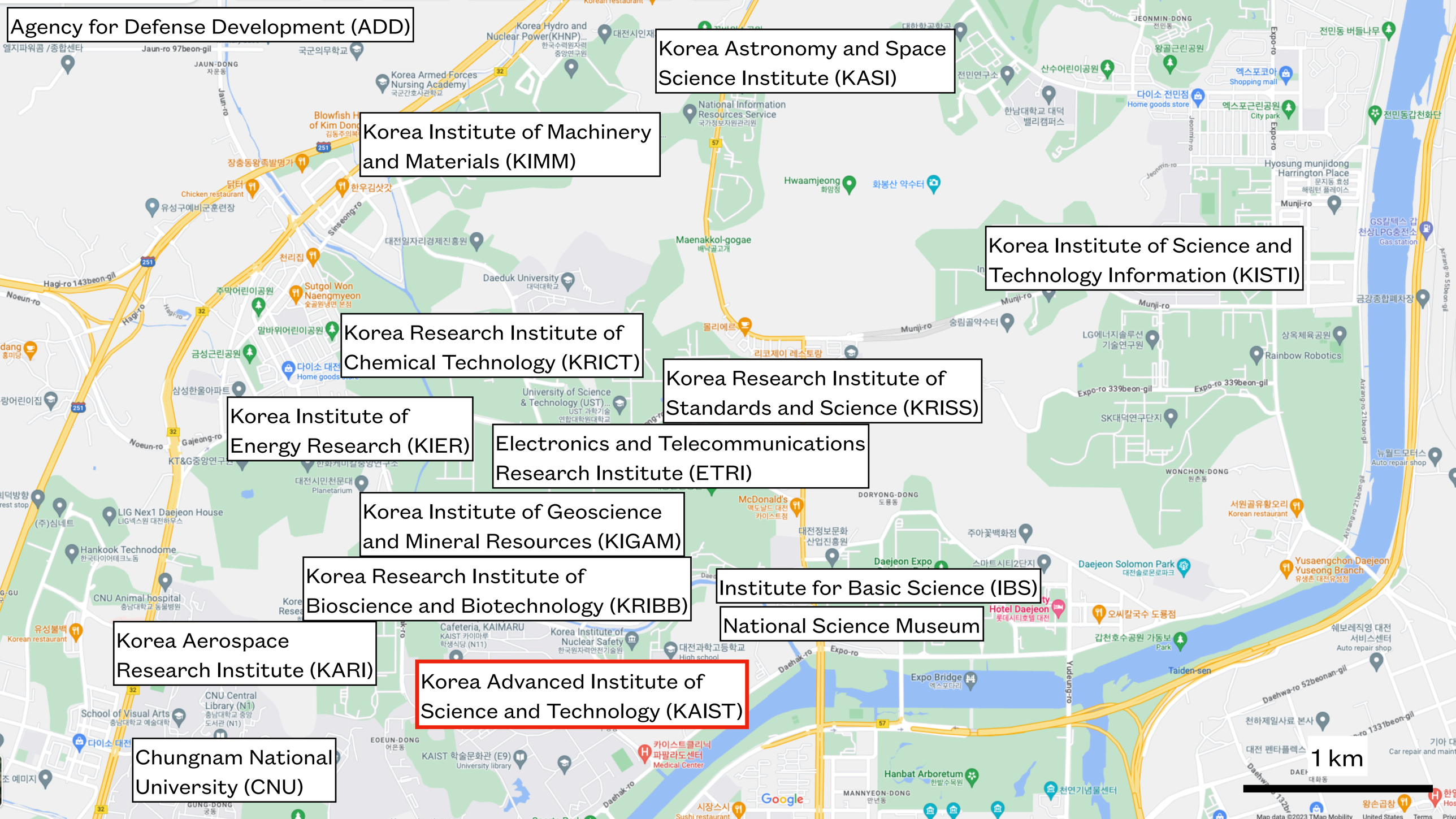
Junhan Kim 김준한

Department of Physics
Korea Advanced Institute of Science and Technology (KAIST)
(junhan@kaist.ac.kr)

+ Jack Sayers, Adriana Gavidia, Harshda Saxena (Caltech),
Mauro Sereno (INAF, INFN Bologna), Keiichi Umetsu (ASIAA),
Aron Lee (KAIST), and CHEX-MATE Collaboration

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


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"The City of Science and Technology"
The 11th KIAS Workshop on
Cosmology and Structure Formation
Oct.27th - Nov.2nd 2024
Gyeongju, Korea
Gyeongju (경주)
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Korea Research Institute of Bioscience and Biotechnology (KRIBB)
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Korea Advanced Institute of Science and Technology (KAIST)
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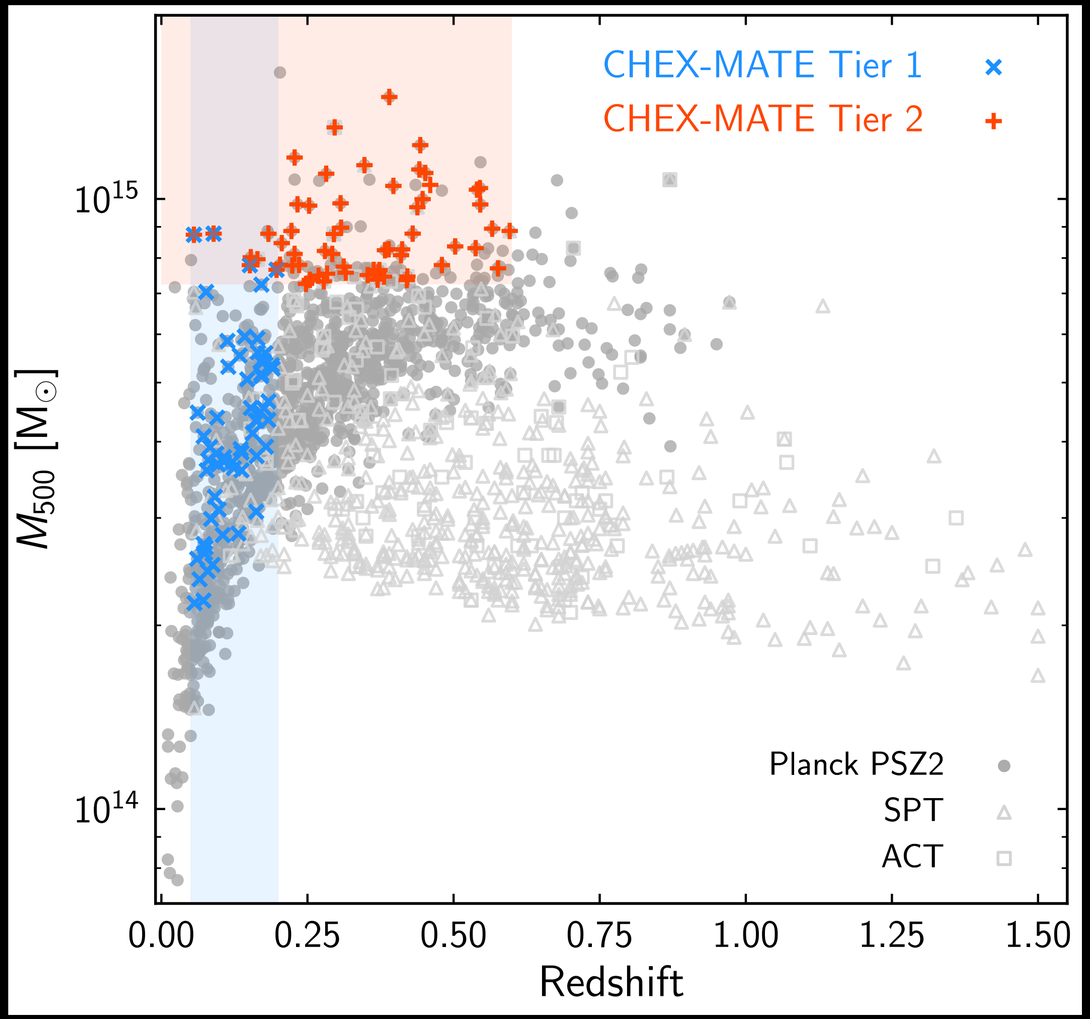
CHEX-MATE

- 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)
  - http://xmm-heritage.oas.inaf.it/



CHEX-MATE Collaboration (2021)

- CHEX-MATE Collaboration (2021). **The Cluster HEritage project with XMM-Newton: Mass Assembly and Thermodynamics at the Endpoint of structure formation (CHEX-MATE). Programme Overview**, A&A, 650, A104
- Campitiello, M. G., et al. (2022). **CHEX-MATE: Morphological analysis of the sample**, A&A, 665, A117
- Oppizzi, F., et al. (2023). **CHEX-MATE: Pressure profiles of six galaxy clusters as seen by SPT and Planck**, A&A, 672, A156
- Bartalucci, I., et al. (2023). **CHEX-MATE: Constraining the origin of the scatter in galaxy cluster radial X-ray surface brightness profiles**, A&A, 674, A179
- Bourdin, H., et al. (2023). **CHEX-MATE: X-ray absorption and molecular content of the interstellar medium toward galaxy clusters**, A&A, 678, A181
- Iqbal, A., et al. (2023). **CHEX-MATE: A non-parametric deep learning technique to deproject and deconvolve galaxy cluster X-ray temperature profiles**, A&A, 679, A51
- Lovisari, L., et al. (2024). **CHEX-MATE: Characterization of the intra-cluster medium temperature distribution**, A&A, 682, A45
- Balboni, M., et al. (2024). **CHEX-MATE: A LOFAR pilot X-ray - radio study on five radio halo clusters**, A&A, 686, A5
- Rossetti, M., et al. (2024). **CHEX-MATE: Robust reconstruction of temperature profiles in galaxy clusters with XMM-Newton**, A&A, 686, A68
- Dupourqué, S., et al. (2024). **CHEX-MATE: Turbulence in the intra-cluster medium from X-ray surface brightness fluctuations**, A&A, 687, A58

CHEX-MATE: CLUMP-3D

A&A, 686, A97 (2024)
https://doi.org/10.1051/0004-6361/202347399
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Astronomy & Astrophysics

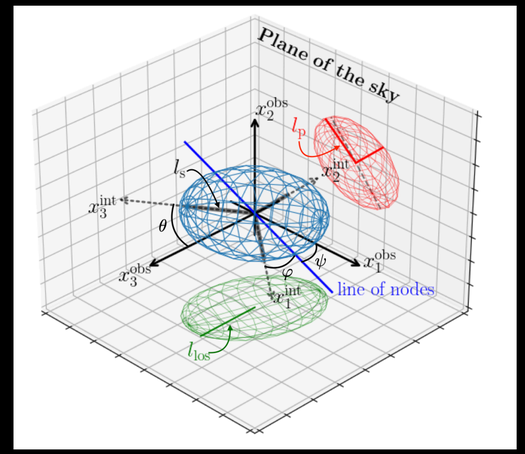
CHEX-MATE: CLUster Multi-Probes in Three Dimensions (CLUMP-3D)

I. Gas analysis method using X-ray and Sunyaev–Zel'dovich effect data

Junhan Kim[1,2], Jack Sayers[1], Mauro Sereno[3,4], Iacopo Bartalucci[5], Loris Chappuis[6], Sabrina De Grandi[7], Federico De Luca[8,9], Marco De Petris[10], Megan E. Donahue[11], Dominique Eckert[6], Stefano Ettori[3,4], Massimo Gaspari[24,12], Fabio Gastaldello[5], Raphael Gavazzi[13,14], Adriana Gavidia[1], Simona Ghizzardi[5], Asif Iqbal[15], Scott T. Kay[16], Lorenzo Lovisari[5,17], Ben J. Maughan[18], Pasquale Mazzotta[8,9], Nobuhiro Okabe[19,20,21], Etienne Pointecouteau[22], Gabriel W. Pratt[15], Mariachiara Rossetti[5], and Keiichi Umetsu[23]

Kim et al. (2024)

Triaxial Analysis of Galaxy Clusters

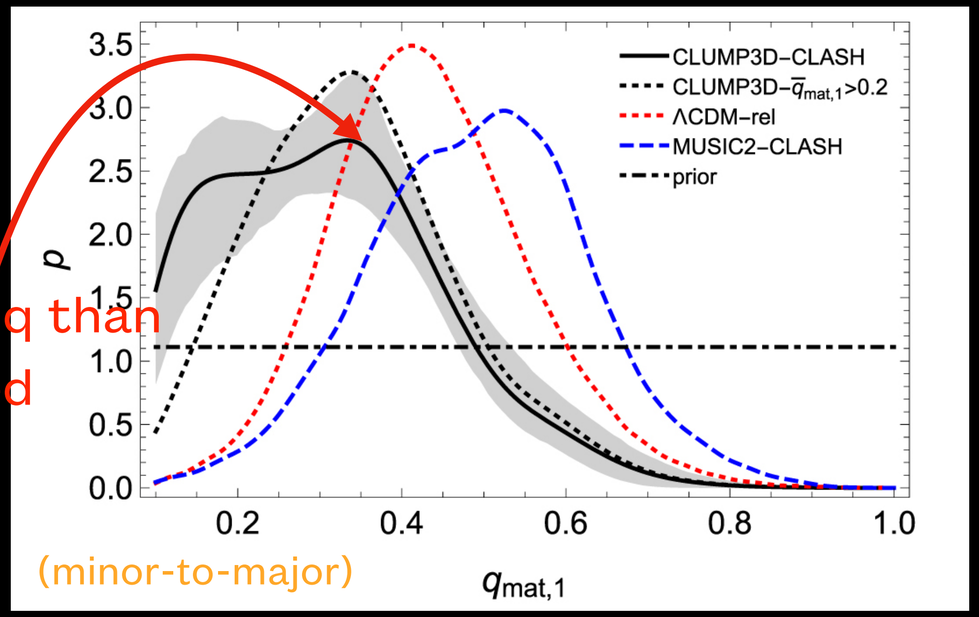


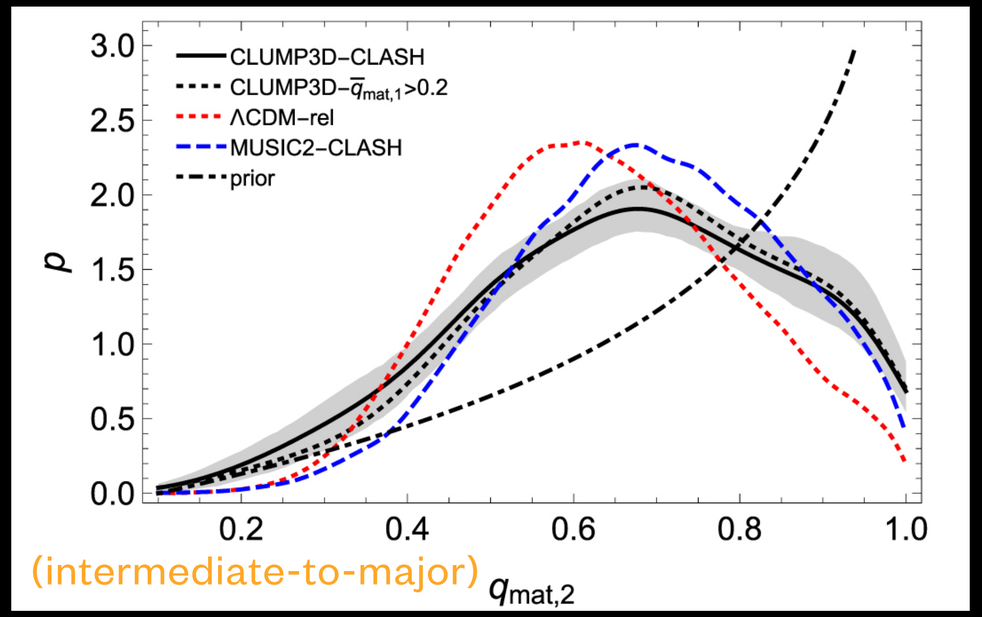
- Motivations
  - Better approximation of galaxy cluster than a spherical model.
    - Reduce the level of bias/scatter in derived parameters (e.g., Becker & Kravtsov 2011, Khatri & Gaspari 2016).
  - Correlation between shape parameters of the DM halo and its properties & formation history (e.g., Ho 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

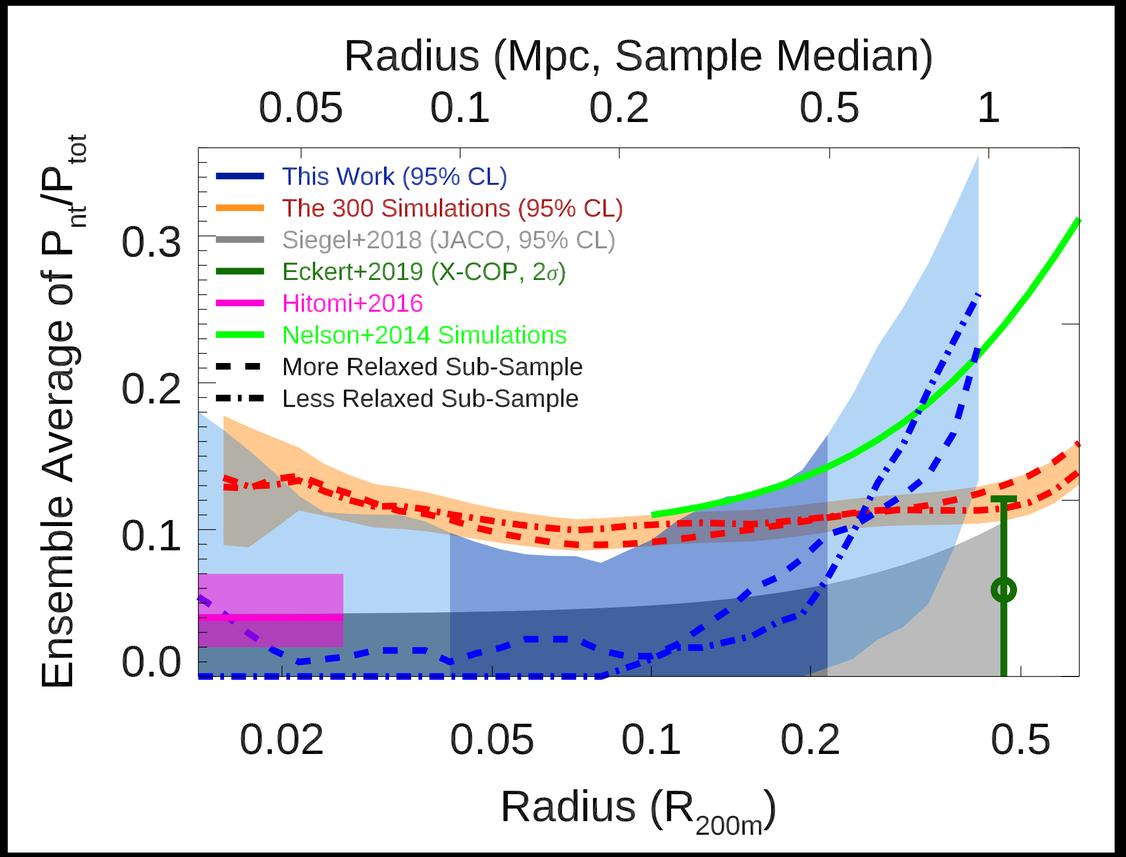




Sereno et al. (2018)

Science Goal: Non-thermal Pressure Profile

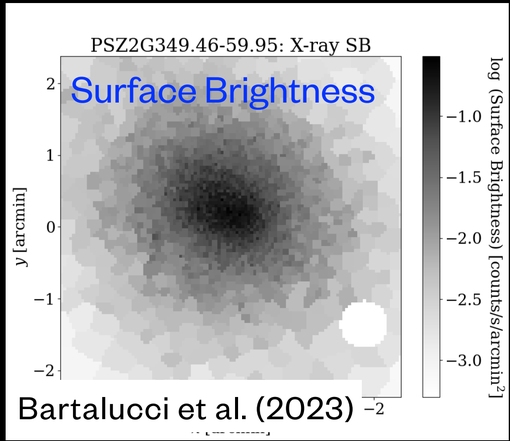
- What is the level of non-thermal pressure support in the ICM?
  - AGN outbursts inject significant energy into the ICM. Simulations predict that the thermalization of accreted material is inefficient.
  - CLASH analyses (Sayers et al. 2021) indicate that the non-thermal pressure profile is consistent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



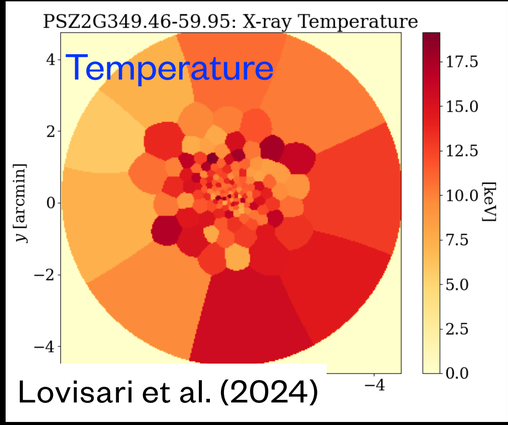
Sayers et al. (2021)

CHEX-MATE: Multiwavelength Dataset

X-ray (*XMM*)

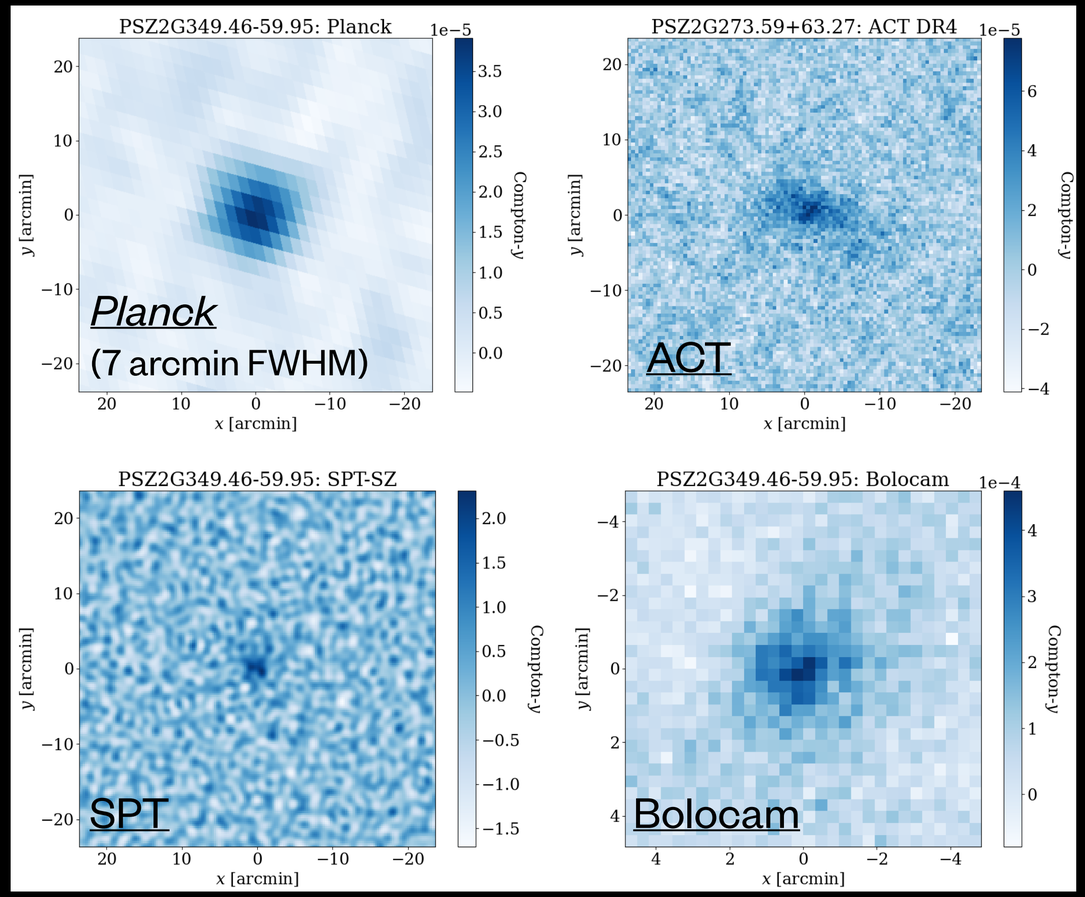


Bartalucci et al. (2023)

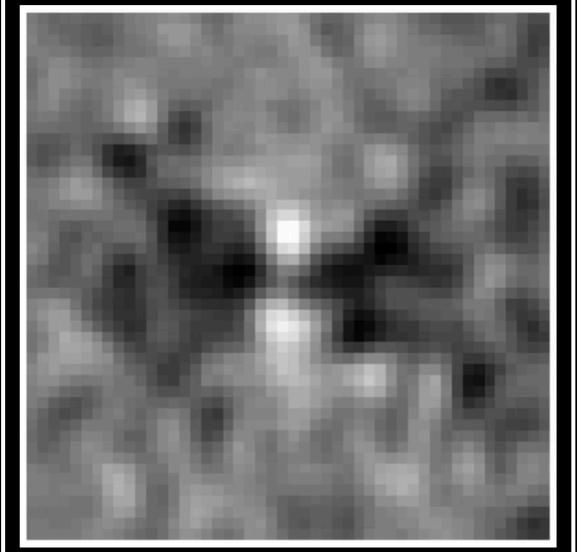


Lovisari et al. (2024)

SZ (*Planck* & Ground-based)



Weak Lensing (Subaru HSC)



(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

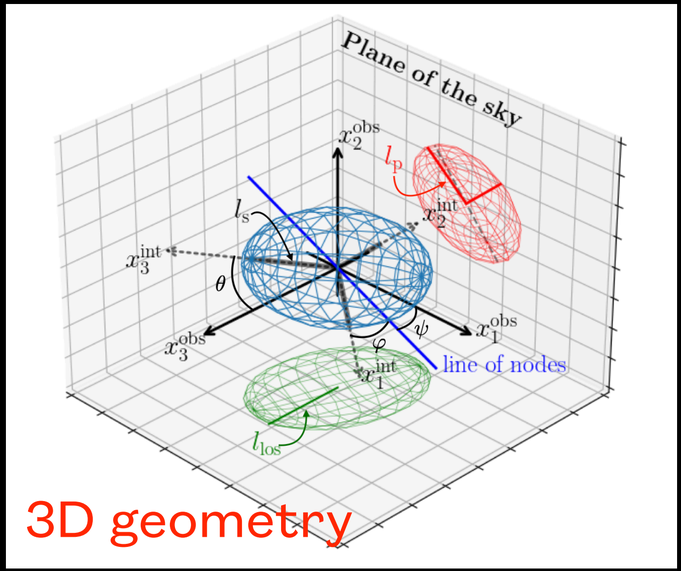
- Projection of the three-dimensional volume density onto the sky plane (Stark 1977; Sereno 2007; Sereno et al. 2010)

elongation parameter (geometry)

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

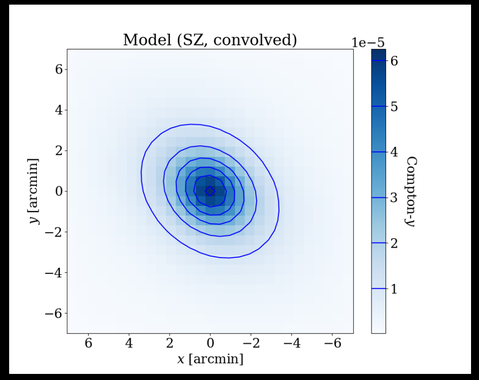
direct observables

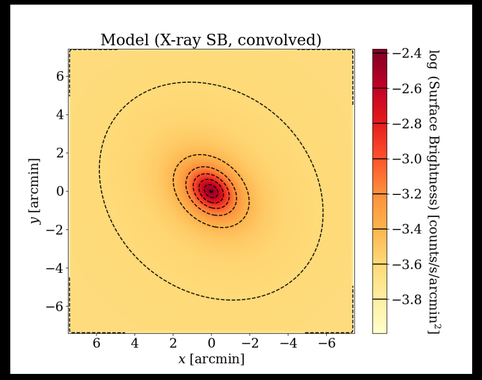
analytic profiles of the ICM model

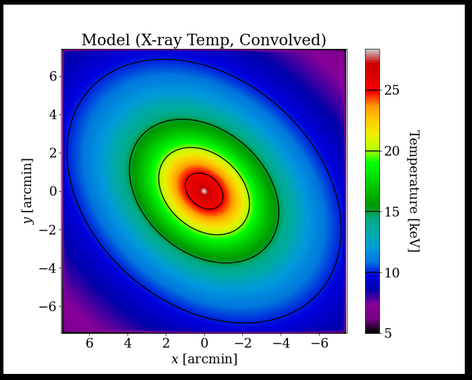


3D geometry

Model profiles





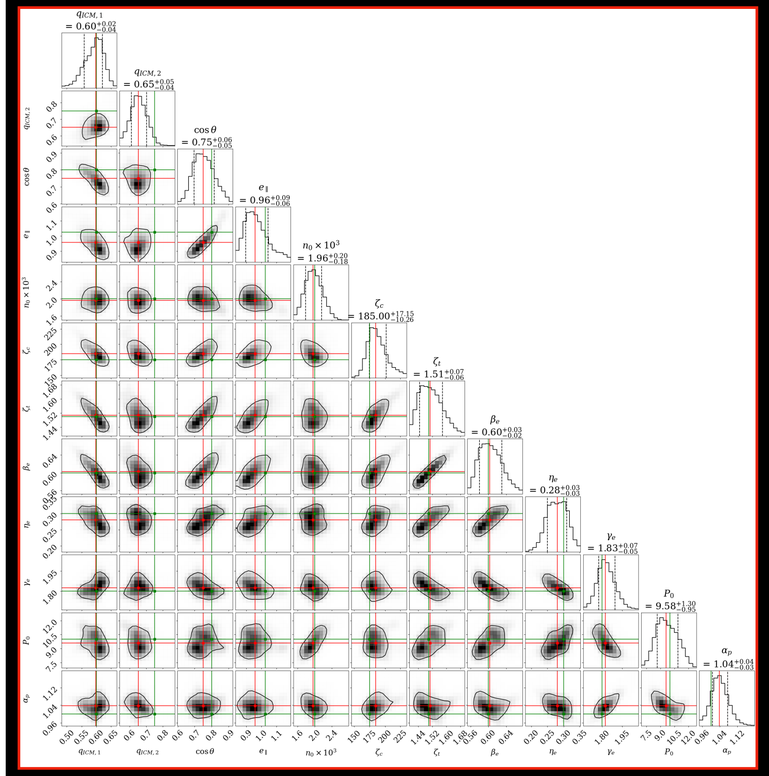


2D observables

Triaxial (Gas) Analysis: Formalism

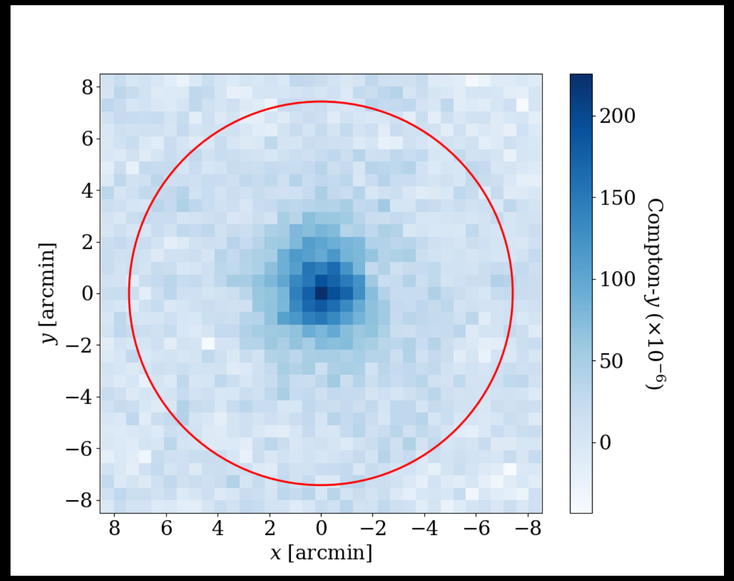
- Model fit: geometrical, electron density, gas pressure parameters (13 parameters)

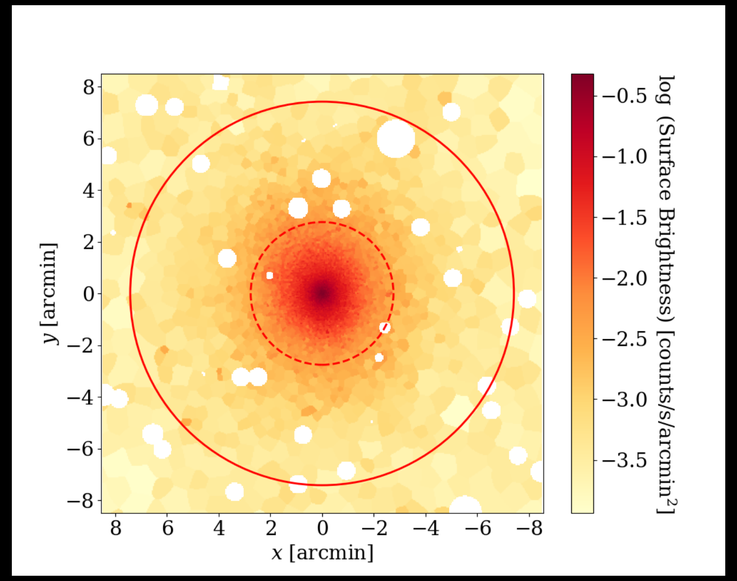
Parameter	Units	Description	Default Prior
		Geometrical Parameters of a Triaxial Ellipsoid (Eqs. 1 and 4)	
$q_{\rm ICM,1}$		Minor-to-major axial ratio of the ICM distribution	$\mathcal{U}(0,1)$
$q_{\rm ICM,2}$		Intermediate-to-major axial ratio of the ICM distribution	$\mathcal{U}(q_{\rm ICM,1},1)$
$\cos\theta$		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	$\rm cm^{-3}$	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 ($r \sim r_{\rm s} = R_{500}/c_{500}$)	$\delta(1.4)$
γ_p		Slope parameter for central region ($r \ll r_{\rm s}$)	$\delta(0.3)$
α_p		Slope parameter for intermediate region ($r \sim r_{\rm s}$)	$\mathcal{U}(0,5)$
β_p		Slope parameter for outer region ($r \gg r_{\rm s}$)	$\mathcal{U}(0,15)^a$

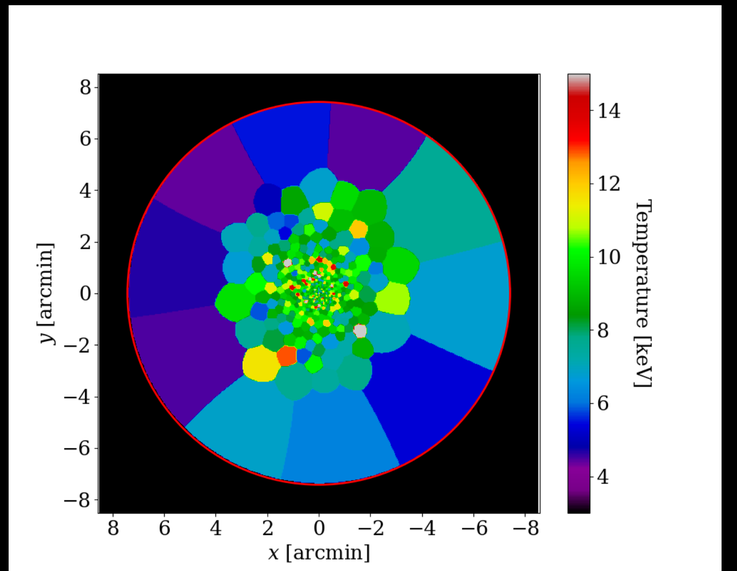


PSZ2 G313.33+61.13 (Abell 1689)

- CHEX-MATE Tier-2 cluster; z = 0.183, (Planck SZ estimated) $M_{500} = 8.77 \times 10^{14}\, M_{\odot}$
- 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



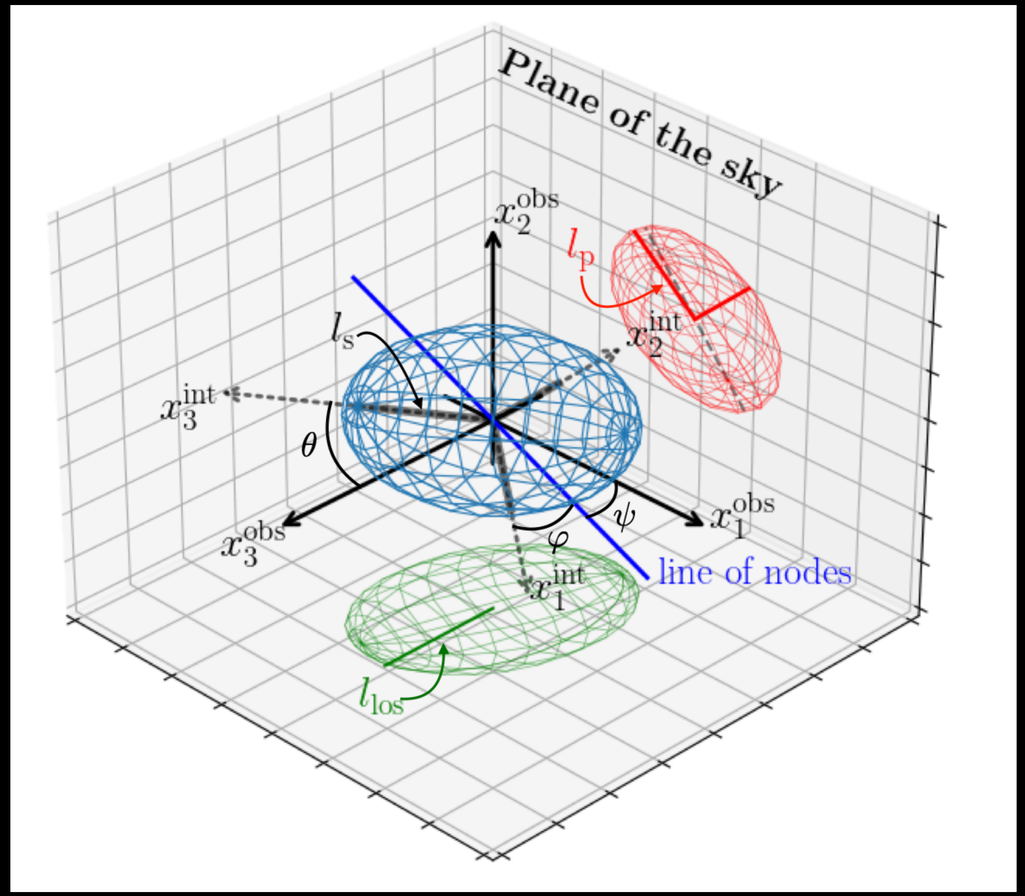




PSZ2 G313.33+61.13 (Abell 1689): Model Fit

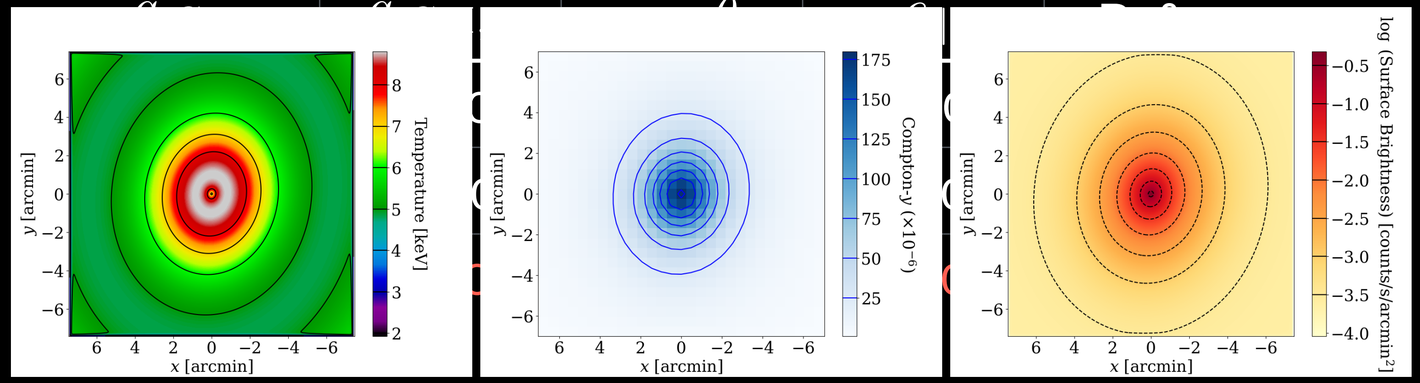
- The analysis effectively constrains the model geometry at the few percent level.
- Compared to the similar gas-only analysis using X-ray and SZ data presented in Sereno et al. (2012), the axial ratios and elongation parameters in our study demonstrate a substantial improvement, with uncertainties an order of magnitude lower.

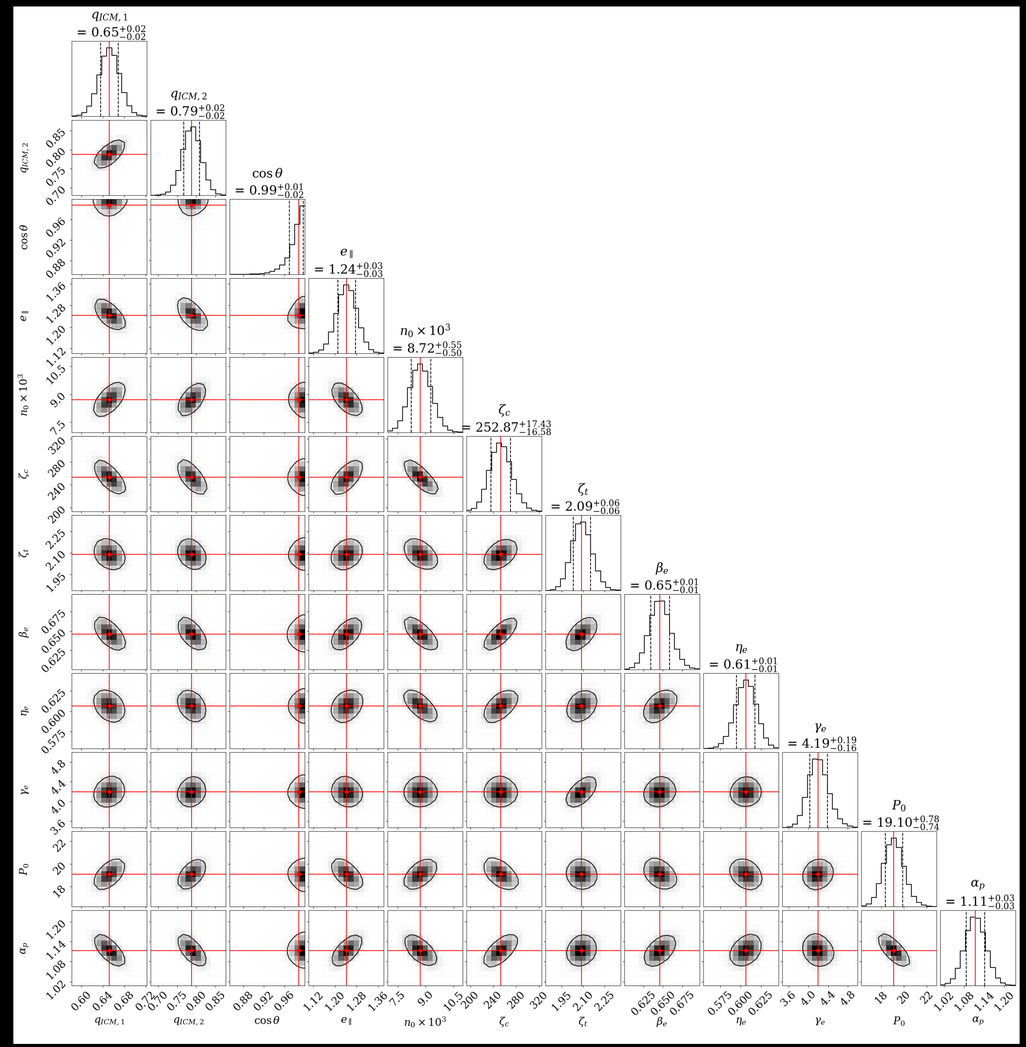
$q_{\mathrm{ICM},1}$	$q_{\mathrm{ICM},2}$	$\cos\theta$	$e_{\parallel}$	Reference
0.70 ± 0.15	0.81 ± 0.16	0.70 ± 0.29	1.68 ± 0.53	Sereno et al. (2012)
0.63 ± 0.14	0.70 ± 0.16	0.93 ± 0.06	1.16 ± 0.10	Umetsu et al. (2015)
0.65 ± 0.02	0.79 ± 0.02	≥ 0.96	1.24 ± 0.03	This work



PSZ2 G313.33+61.13 (Abell 1689): Model Fit

- The analysis effectively constrains the model geometry at the few percent level.
- Compared to the similar gas-only analysis using X-ray and SZ data presented in Sereno et al. (2012), the axial ratios and elongation parameters in our study demonstrate a substantial improvement, with uncertainties an order of magnitude lower.





Non-Thermal Pressure Calculation

From Kim et al 2024:

Can calculate elliptical gas pressure profile:

$$\rho_{gas} = \mu_e m_p n_e$$

Can calculate elliptical gas density profile:

$$P_{th} = P_e \frac{\mu_e}{\mu}$$

From addition of WL analysis:

Can calculate gravitational potential on triaxial ellipsoid.

Assume generalized HSE

$$\nabla P_{\rm tot} = -\rho_{\rm gas} \nabla \Phi,$$

Due to elliptical symmetry, this reduces to:

$$\frac{dP_{tot}}{d\zeta} = -\rho_{gas} \frac{d\Phi}{d\zeta}$$

Undo this to get total pressure needed to offset gravity

Non-thermal pressure:

Spherically average the total pressure and thermal pressure, then:

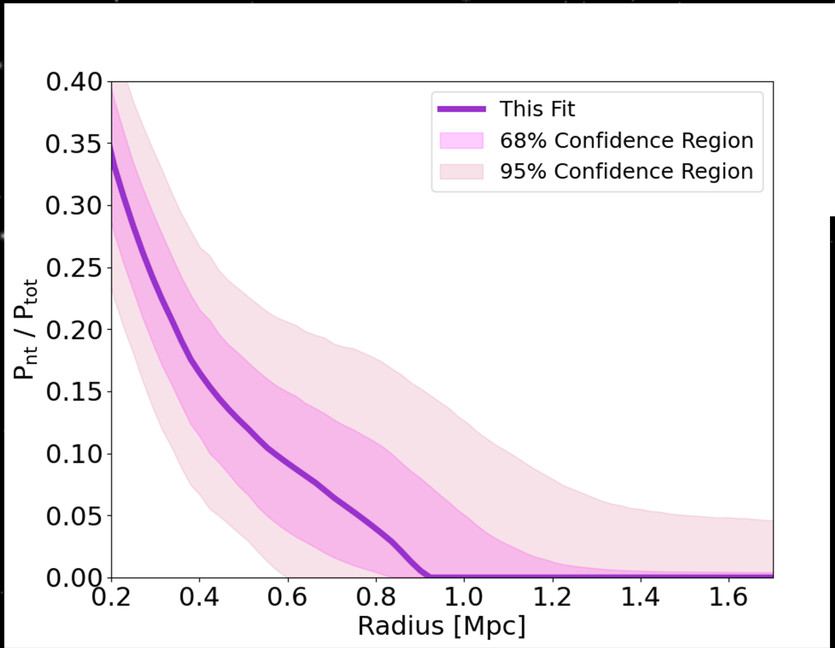
$$P_{nt} = P_{tot} - P_{th}$$



Slide: Adriana Gavidia (Ph.D. Student, Caltech)

CHEX-MATE: CLUMP-3D II. *Combined Gas Dark Matter Analysis from X-ray, SZE, and Weak Lensing*

Non-Thermal Pressure Fraction for A1689

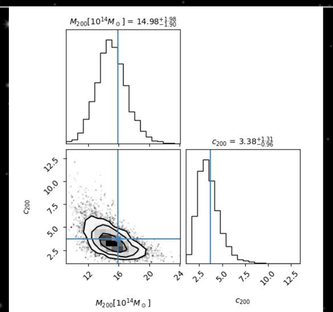


- Computation time to determine P_{nt} is significant

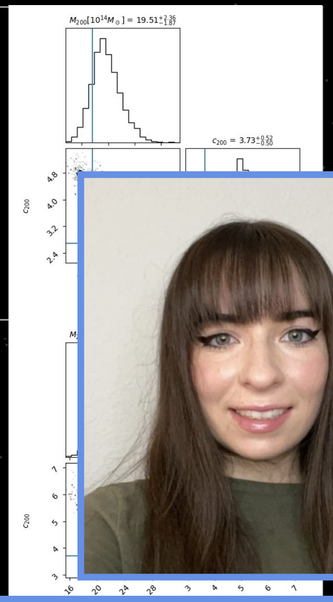
WL Analysis: Consistency Checks

Note: Expected values for these clusters are from Umetsu+2016 where shear AND magnification data were used

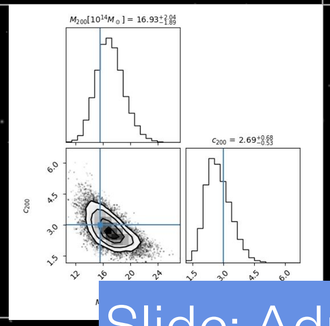
MACS J1206



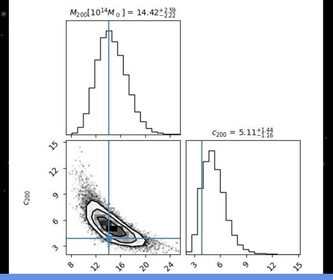
A209



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Slide: Adriana Gavidia (Ph.D. Student, Caltech)

CHEX-MATE: CLUMP-3D III. *The Triaxial Geometry of an SZE-Selected Sample*

Research Goal

- Aim to answer -
  - Does survey selection based on observables like SZ effect result in a biased detection population of 3D triaxiality and orientation?
  - If yes, does this lead to a WL mass bias?

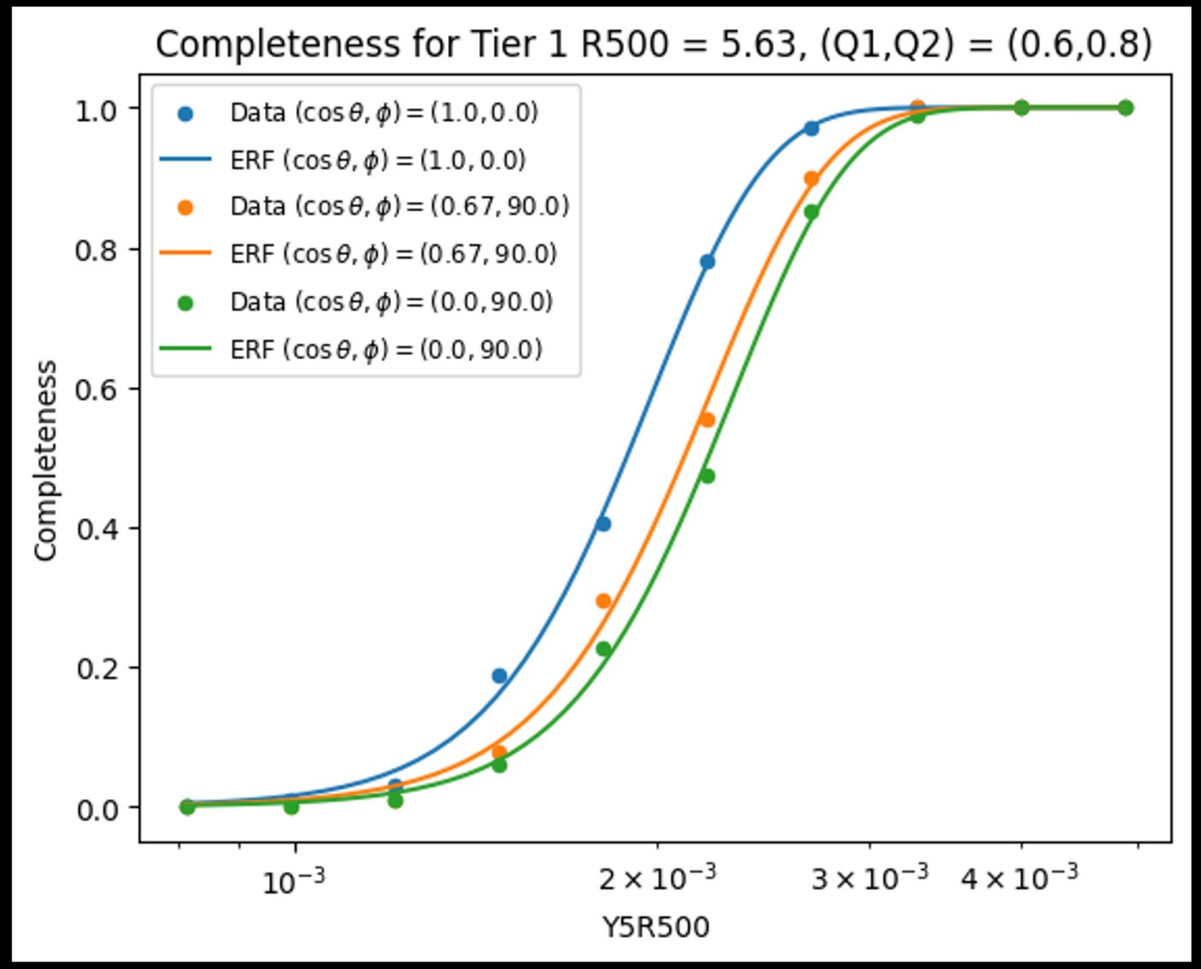
- Use the CHEX-MATE sample of clusters -
  - Set of 118 volume and mass limited clusters from XMM-Newton
  - Have uniform and high-quality multi-wavelength data to fit for and quantify the 3D orientation



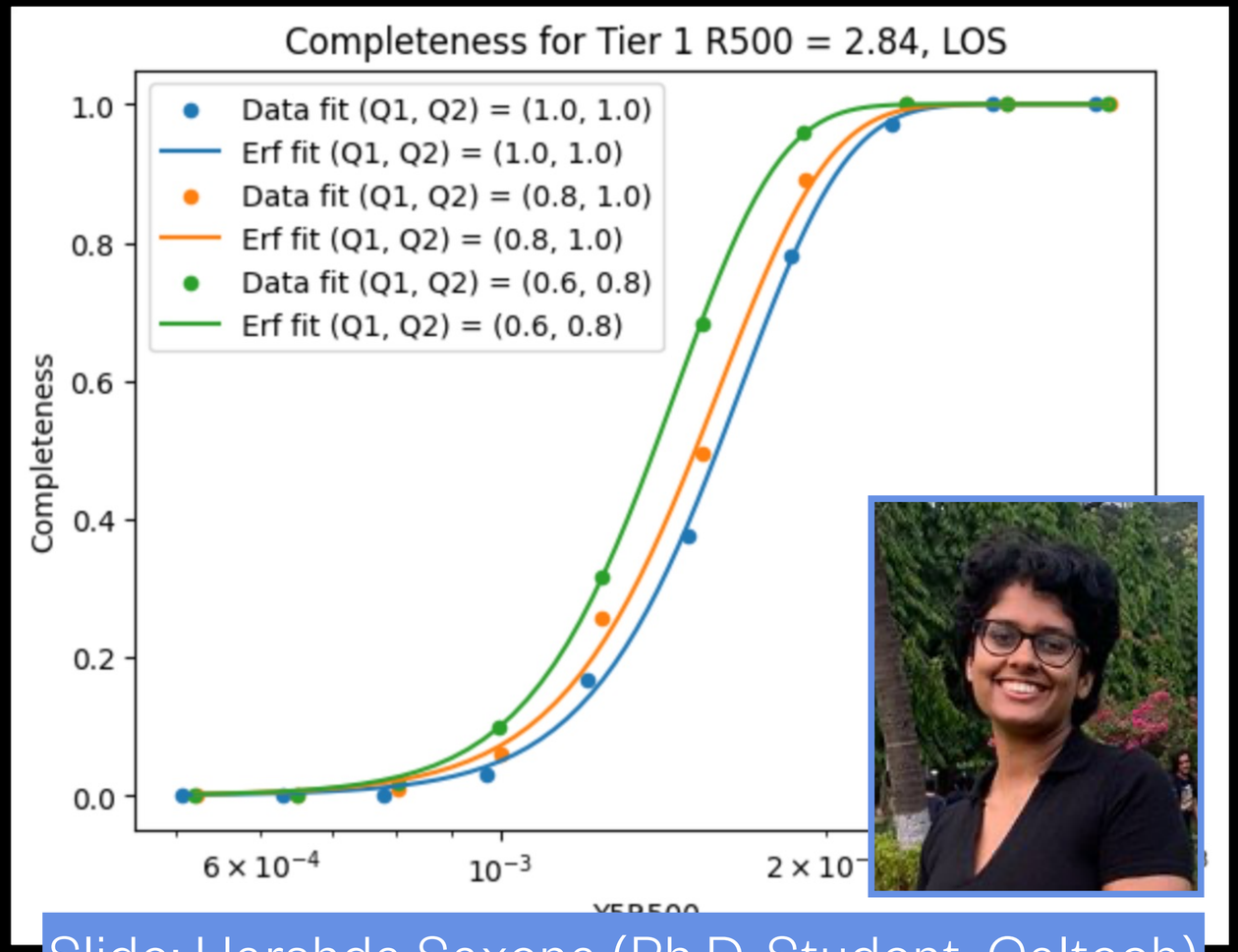
Slide: Harshda Saxena (Ph.D. Student, Caltech)

Triaxial Cluster completeness - contd.

Clusters along LOS have a higher probability of being detected



More Triaxial clusters along LOS have higher probability of being detected

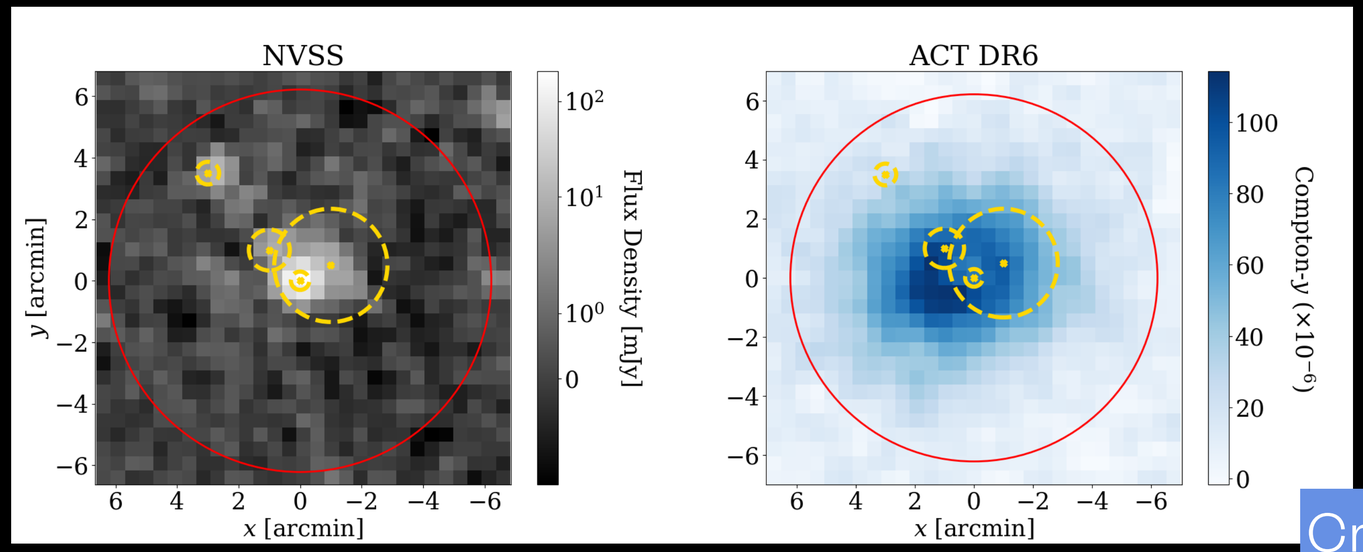


Slide: Harshda Saxena (Ph.D. Student, Caltech)

CLUMP-3D: Improved Triaxial Analysis

CHEX-MATE: CLUMP-3D V. *Gas Axial Ratios and Orientations for the DR1 Sample*

- Study the distribution of ICM axial ratios & orientations for the DR1 sample
- Determine which of those objects can be modeled through a direct comparison with mock observations (The 300, Gianfagna et al. 2023): The impact of deviations from triaxial symmetry due to, e.g., sub-structures or mergers.
- Identify radio/dusty sources using external catalogs (e.g., NVSS 1.4 GHz).





Credit: Aron Lee (MS Student, KAIST)

Summary: CHEX-MATE CLUMP-3D

- CHEX-MATE Program: 3 Msec XMM Heritage program to study 118 clusters (clean, well-characterized selection with a large sample size)
- CLUMP-3D triaxial analysis of the sample using multiwavelength (X-ray, SZ, and lensing) dataset: We will (1) test ΛCDM predictions of cluster shapes and (2) probe the thermalization efficiency of newly accreted cluster material.
- Triaxial analysis of the ICM using X-ray + SZ effect maps (Kim et al. 2024).
  - We presented the forward modeling formalism and improved the multi-probe analysis.
  - We applied the triaxial analysis to reconstruct the gas shape of PSZ2 G313.33+61.13 (Abell 1689). The analysis effectively constrains the model geometry.
- Stay tuned for the upcoming results toward the full triaxial analysis of the CHEX-MATE clusters!