OLIMPO: a Balloon-Borne SZE Imager to Probe ICM Dynamics and the WHIM

Jack Sayers (Caltech), on behalf of the OLIMPO team

Camille Avestruz (Michigan), Elia Stefano Battistelli (Roma), Akos Bogdan (SAO), Andrea Botteno (INAF), Esra Bulbul (MPE), Federico Cacciotti (Roma), Fabio Columbro (Roma), Alessandro Coppolecchia (Roma), Scott Cray (Minnesota), Giuseppe D'Alessandro (Roma), Paolo de Bernardis (Roma), Marco De Petris (Roma), Shaul Hanany (Minnesota), Luca Lamagna (Roma), Erwin Lau (SAO), Silvia Masi (Roma), Allesandro Paiella (Roma), Francesco Piacentini (Roma), Eitan Rapaport (Caltech), Larry Rudnick (Minnesota), Harshda Saxena (Caltech), Rito Basu Thakur (Caltech), Irina Zhuravleva (Chicago), John ZuHone (SAO)

Brief History of OLIMPO

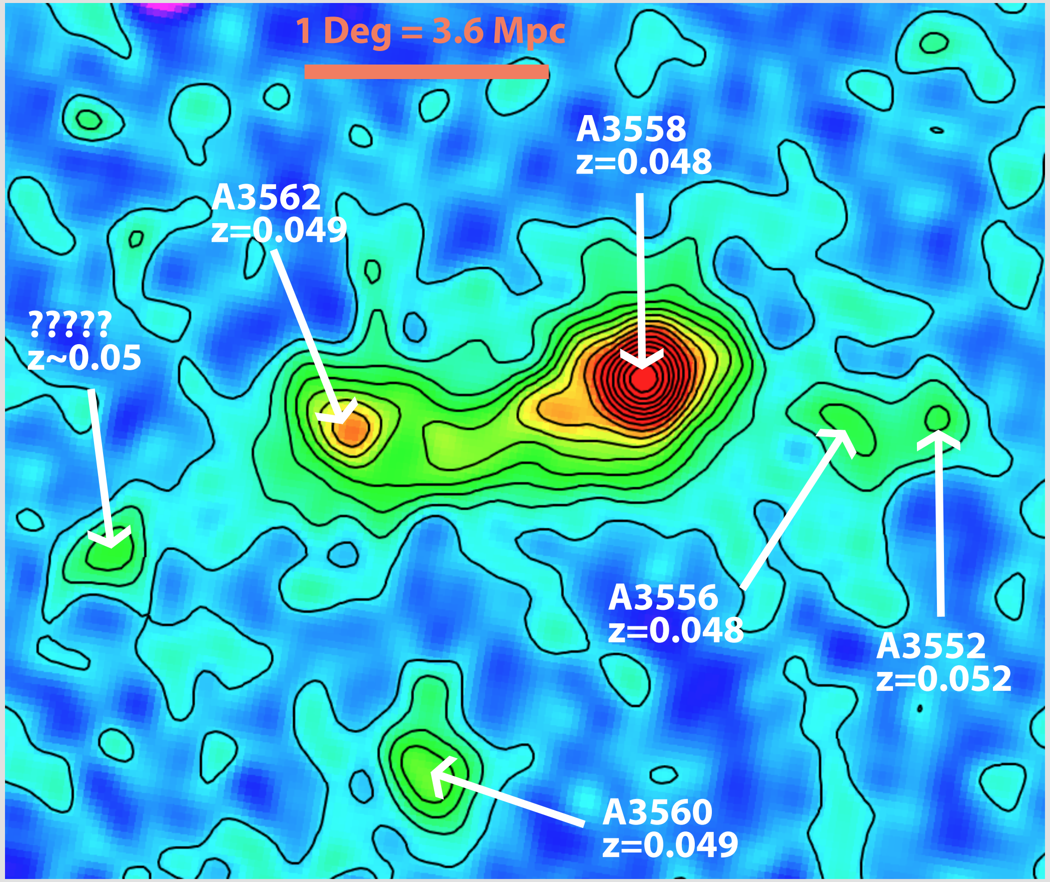
- Originally a Balloon-Borne FTS at 130-520 GHz (PI S. Masi)
- 2.6 m primary mirror (arcminute resolution)
- Horn-coupled Al KIDs on Si wafers
    - 19, 37, 23, and 41 detectors at 150, 250, 350, and 460 GHz
- Designed for SZE science
- Payload launched from Svalbard in July, 2018
    - 5 day flight
    - A Telemetry issue prevented scientific observations
    - Cryogenic, Optical, and Detector noise performance was excellent
        - Coppolechia+2020, Masi+2019, Paiella+2019

Planned Future for OLIMPO

- We aim to build on the *proven* elements of the OLIMPO instrument
  - Cryogenic system
  - Optical design
  - KID geometry
  - General gondola architecture
- While making *substantive* improvements
  - New telemetry, power, motors
  - An order of magnitude more KIDs
  - Remove the FTS – use as photometer
- To enable *novel* studies of ICM physics and WHIM via an Antarctic flight
  - NASA/APRA concept

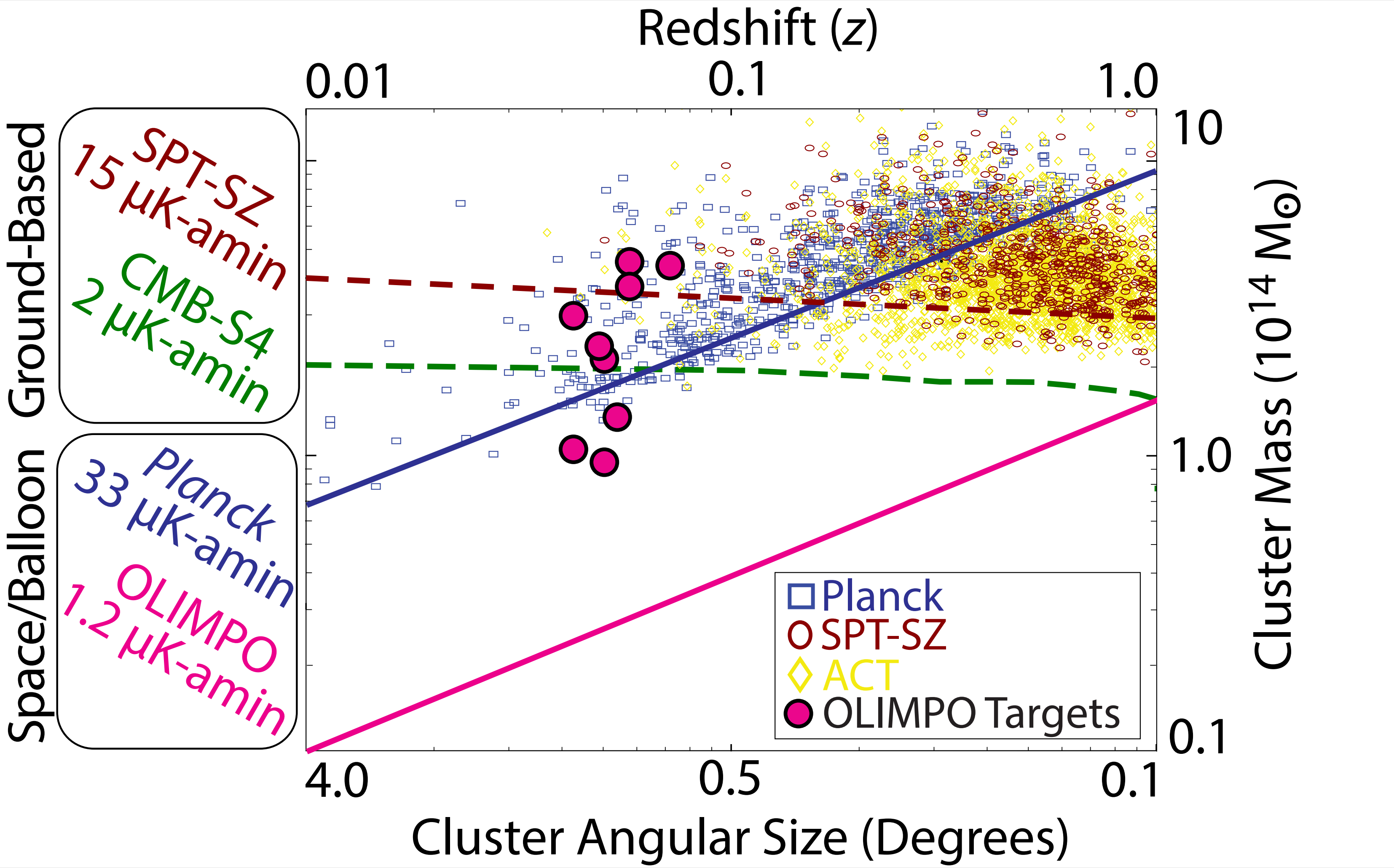
OLIMPO Science Goals

- Probe the dynamics of LSS formation and evolution in clusters
  - High S/N mapping of the ICM velocity structure in the accretion-dominated outskirts with the kSZE
  - Probe gas kinetic energy, non-thermal pressure, energy cascade, energy dissipation and transport properties
  - Connect ICM velocity structure with radio features (halos, relics)
- Characterize the “missing baryons” in filamentary WHIM gas
  - Measure the spatial distribution of temperature, density, and velocity within filaments (tSZE + kSZE + X-rays)



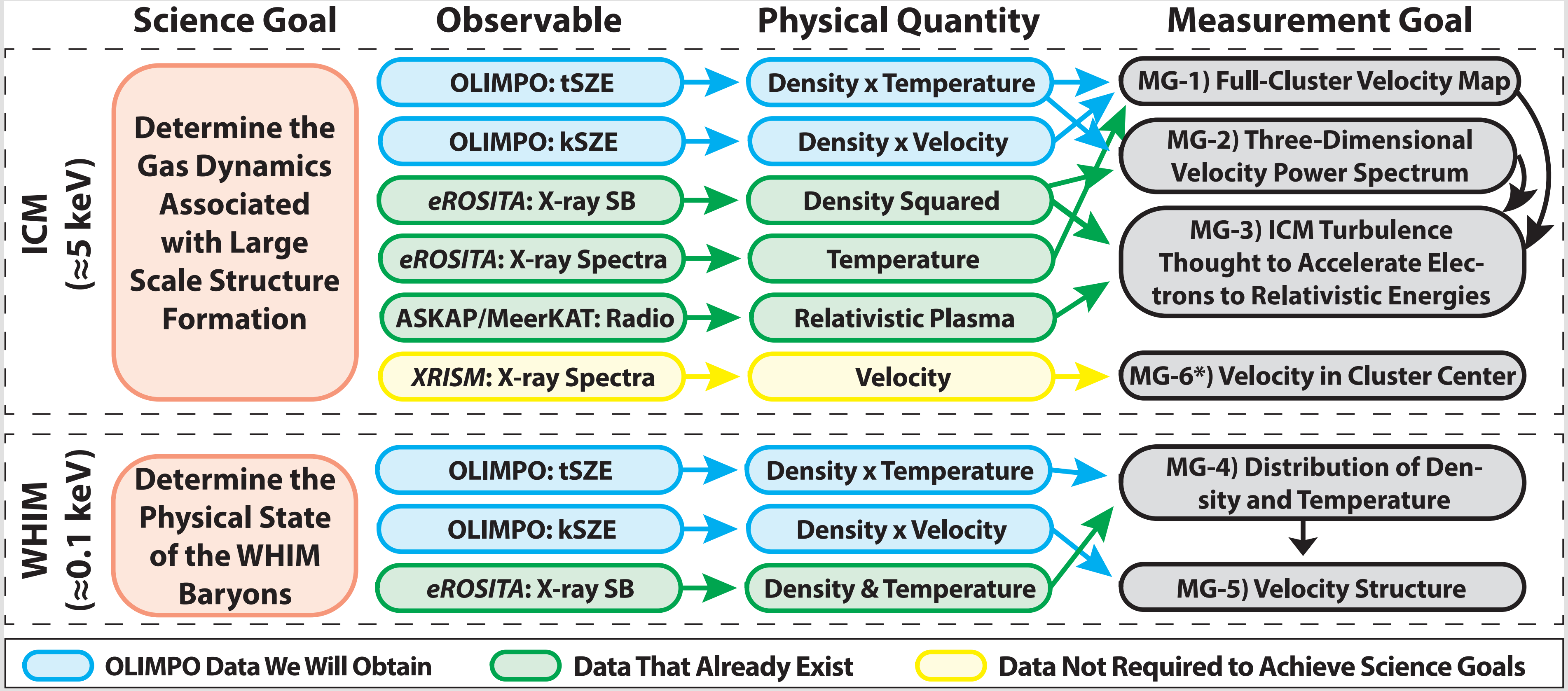
4° × 4° Planck image of filamentary structures
OLIMPO will provide images with two orders of magnitude lower noise and a factor of two better angular resolution

- Science requires *extremely deep* observations of the *brightest possible* objects
  - Low-z clusters and filaments
  - Also have best possible X-ray and radio data
- Not viable from the ground
  - Atmosphere severely degrades sensitivity on multi-degree angular scales



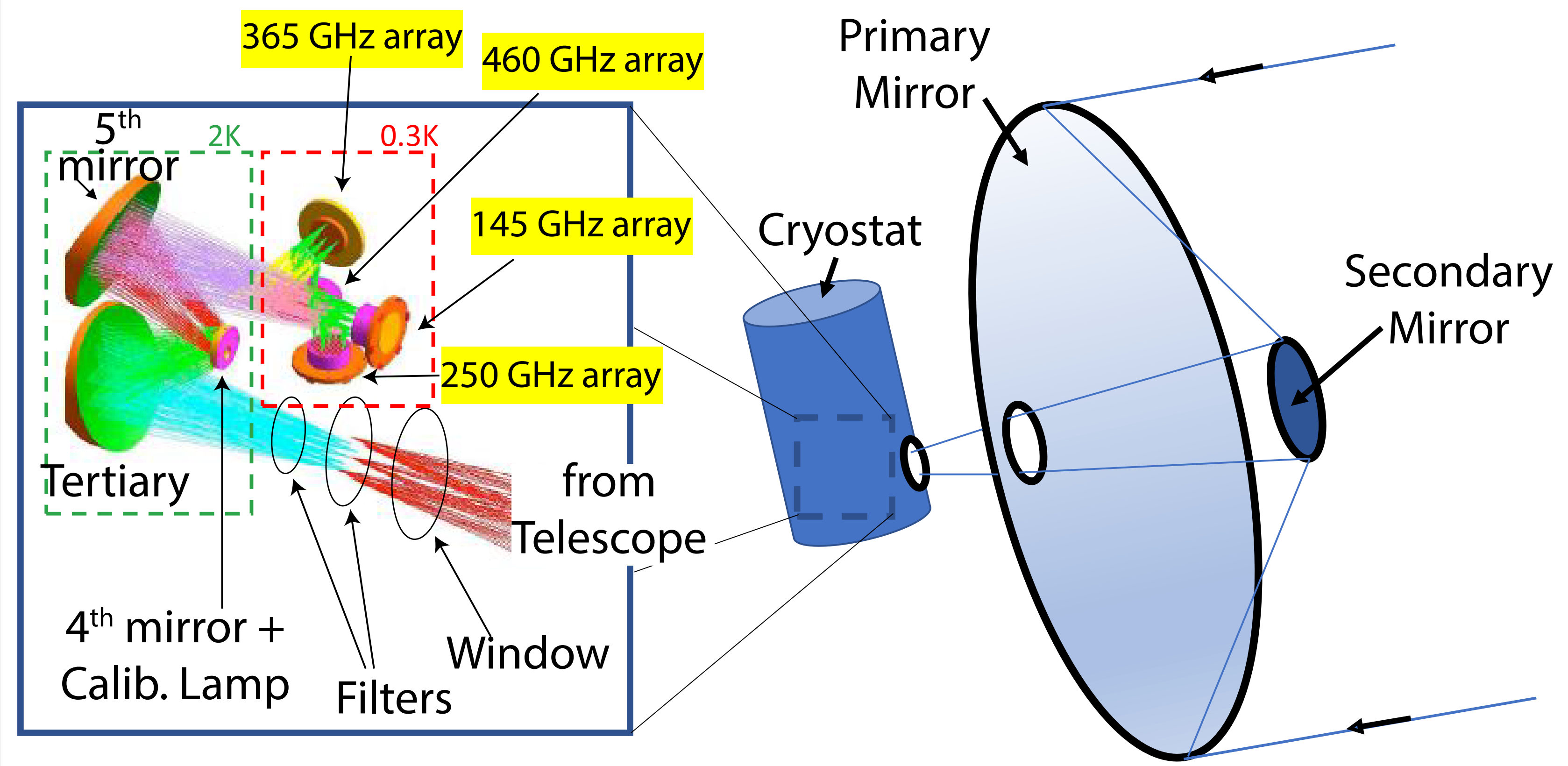
What Else is Required?

- Need X-rays to disentangle tSZE, kSZE, and rSZE (highly degenerate SZE spectra)
  - Deep exposures on degree scales – eROSITA PV (E. Bulbul)
- Deep radio observations to characterize halos and relics (A. Botteon, L. Rudnick)
- Detailed hydro-sims to interpret results (C. Avestruz, E. Lau, J. ZuHone)

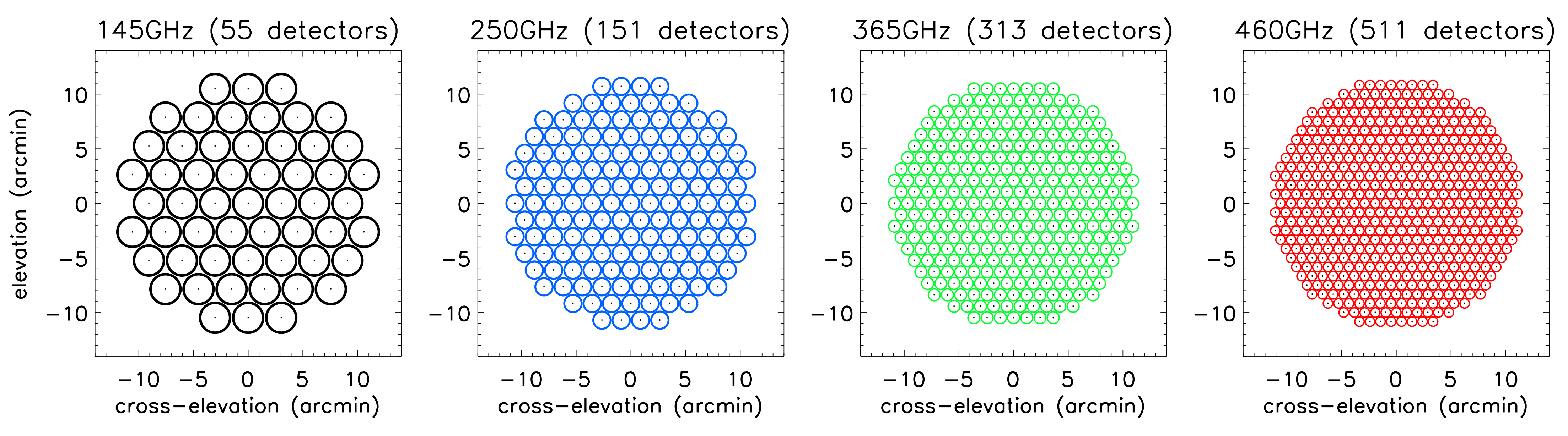


OLIMPO Instrument Details

- Cassegrain system with 2.6 m primary mirror
  - PSF FWHM of 3.3’, 1.9’, 1.3’, and 1.0’ at 145, 250, 365, and 460 GHz (2-4 times better than Planck)
- Cold reflective optics w/ aperture stop
- Dichroics to separate bands
- No FTS!
- Flight-proven components



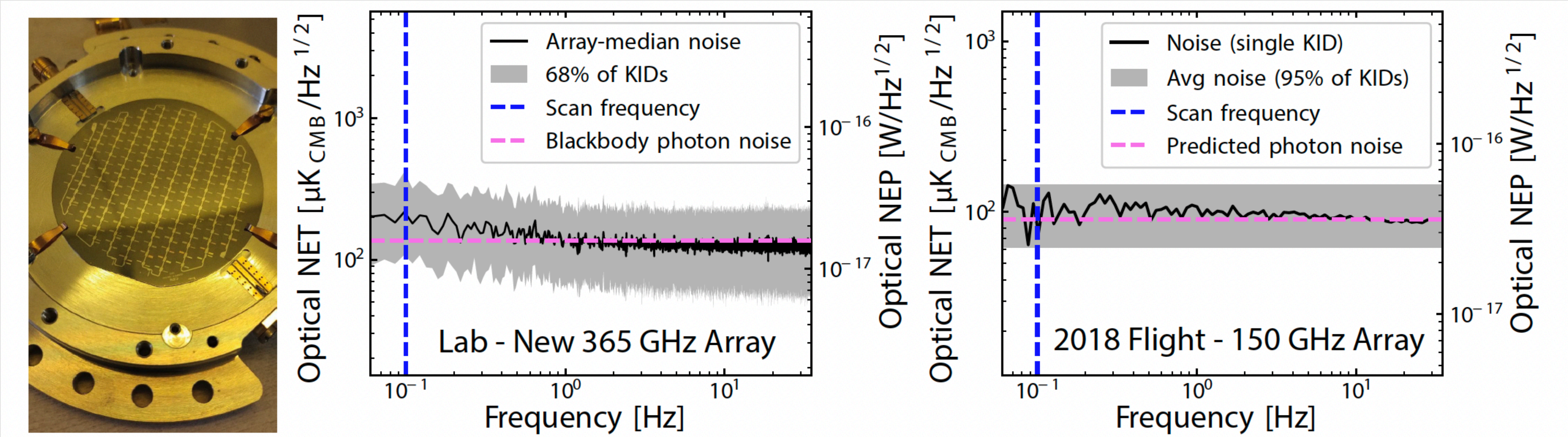
OLIMPO Instrument Details



- Horn-coupled Al KIDs on Si
  - Same design as first flight
  - Hex-pack 1-fλ filling 24 arcmin co-aligned FOVs to efficiently map compact objects

Band (GHz)	145	250	365	460	Total
Number of detectors	55	151	313	511	1030
FWHM (arcmin)	3.3	1.9	1.3	1.0	-
Detector NEP ($\times 10^{18}$ W/$\sqrt{\text{Hz}}$)	9.4	11	7.0	7.2	-
Detector NET^a ($\times 10^6$ K$\sqrt{\text{s}}$)	58	70	255	834	-
Array NET^a ($\times 10^6$ K$\sqrt{\text{s}}$)	8	6	15	39	4.6

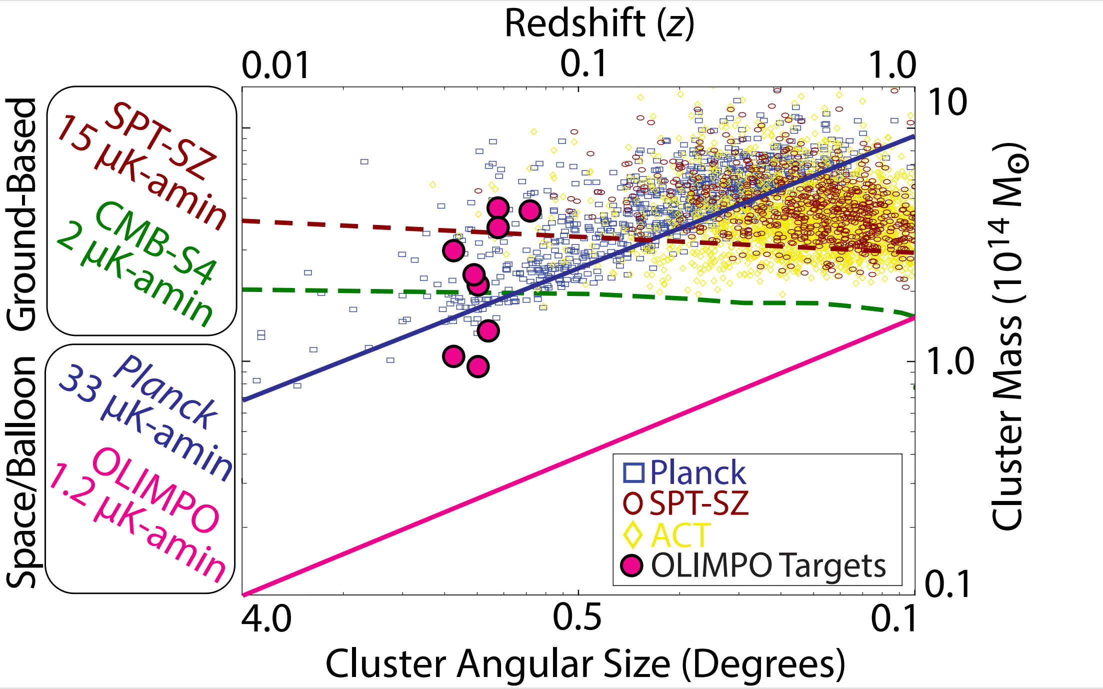
OLIMPO Detector Readiness



- We have fabricated and tested a full-scale 365 GHz array with 313 KIDs (Cacciotti+ 2024)
  - 85% detector yield (meeting flight specification)
  - Photon-noise limited above the planned scan frequency

OLIMPO Observations

- OLIMPO can make *very deep* pointed observations
  - $10^{2\text{-}3}$ times deeper than *Planck*
  - 10 times deeper than CCAT-P and CMB-S4 at high frequency
  - Similar to CMB-S4 at 150 GHz, but without the atmosphere

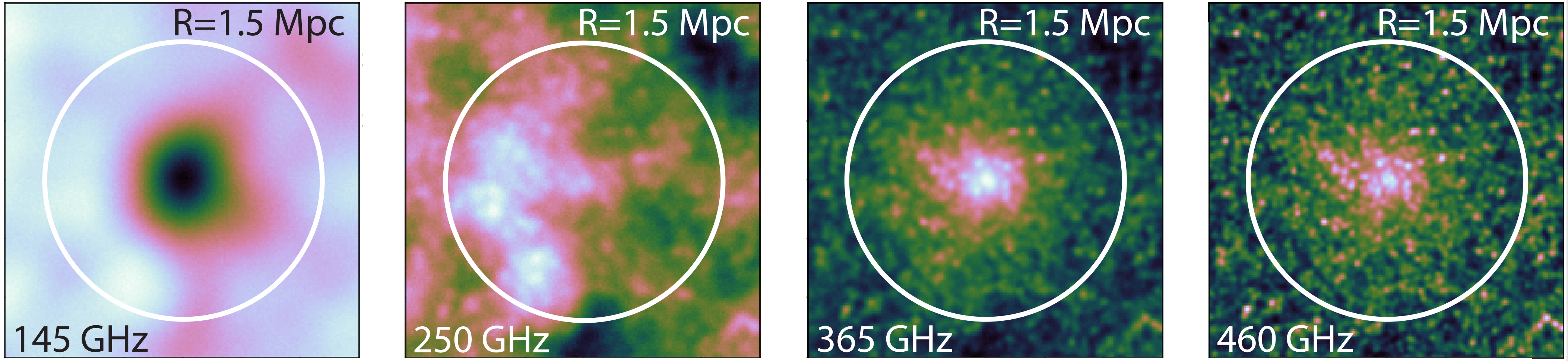


Map Noise (μK_{CMB}–arcmin)

Instrument	Frequency Band (GHz) 145	250	365	460	Notes
OLIMPO	1.2	0.9	2.3	5.8	9 clusters + 4 laments
Planck [34]	33	47	150	3700	full sky
CCAT-P [35]	N/A	15 / 3.0	107 / 21	407 / 81	wide 20k deg^2 / deep 100 deg^2
CMB-S4 LAT [36]	2.0 / 1.0	5.7 / 3.5	N/A	N/A	wide 29k deg^2 / deep 1200 deg^2

OLIMPO Sensitivity Projections

- We have created realistic mock OLIMPO observations (T. Macioce)
  - Including tSZE, kSZE, CMB, CIB, cluster-member galaxies



Cluster	Δpix Mpc	0.4⩽R⩽0.6 Mpc tSZE S/N	0.4⩽R⩽0.6 Mpc $\sigma(v_{disp})$	0.9⩽R⩽1.1 Mpc tSZE S/N	0.9⩽R⩽1.1 Mpc $\sigma(v_{disp})$	1.4⩽R⩽1.6 Mpc tSZE S/N	1.4⩽R⩽1.6 Mpc $\sigma(v_{disp})$
Abell 3395	0.20	145	45 km/s	115	60 km/s	80	80 km/s
Abell 3266	0.23	260	15 km/s	125	50 km/s	50	140 km/s
A3391–A3395	0.20	tSZE S/N = 20 and $\sigma(v)$ = 45 km/s per pixel along bridge axial center					
A3530–A3528	0.20	tSZE S/N = 10 and $\sigma(v)$ = 95 km/s per pixel along bridge axial center					

Direct ICM Velocities

- OLIMPO will probe velocity structure in the accretion-dominated zone at large radii
  - Not viable with *XRISM*

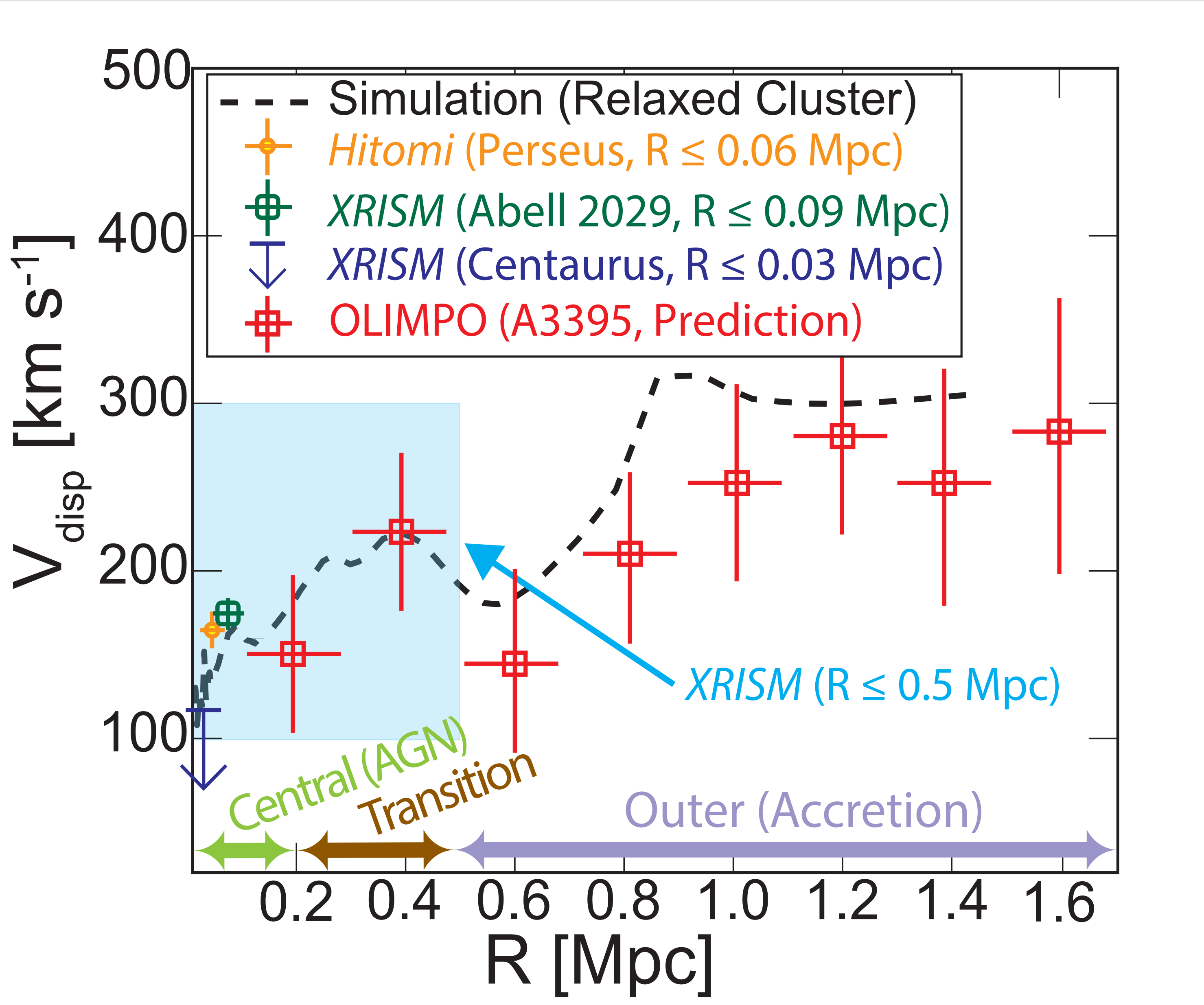
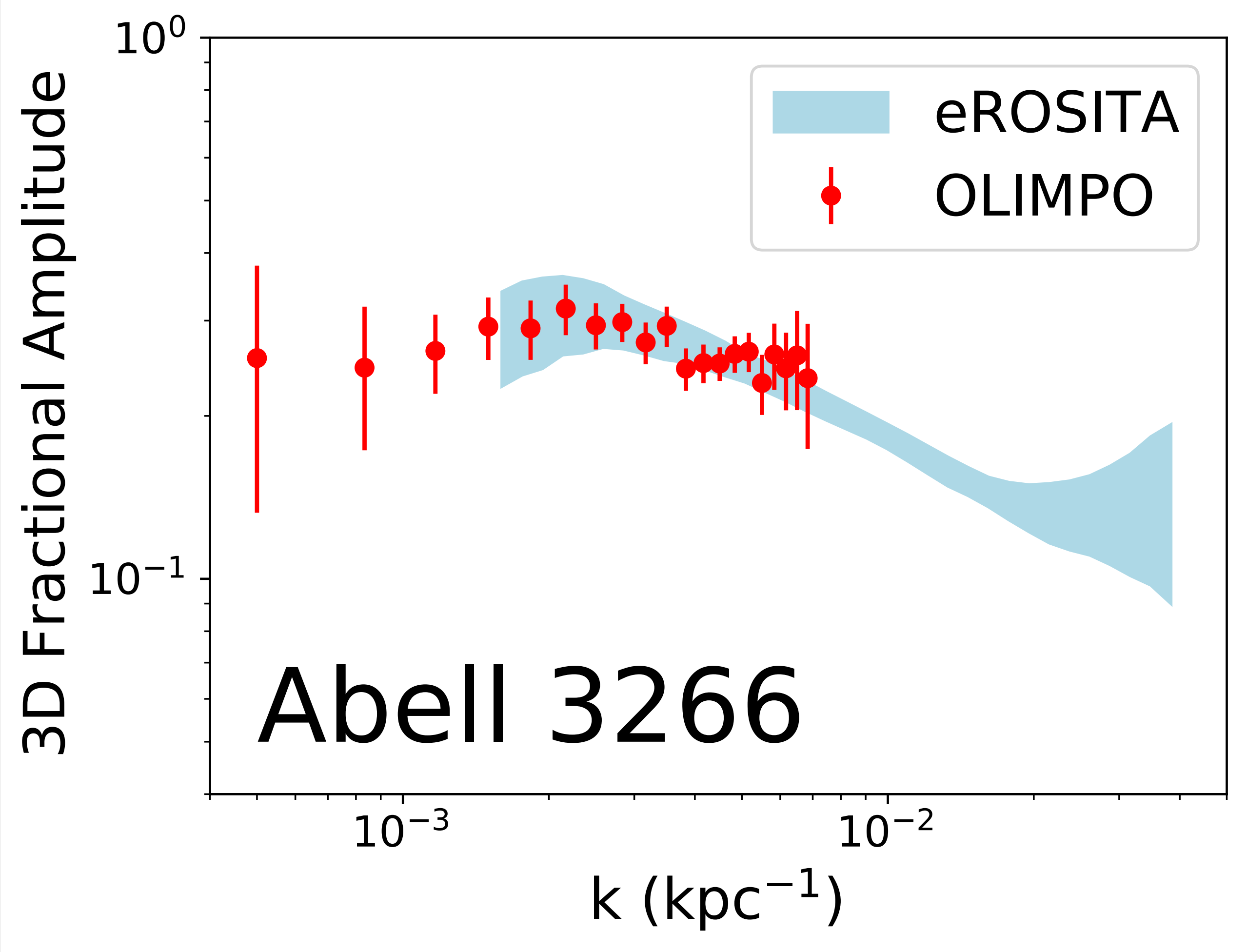


Fig. adapted from Nagai+2013

OLIMPO will measure ICM velocity dispersion profiles to at least 1.5 Mpc in radius

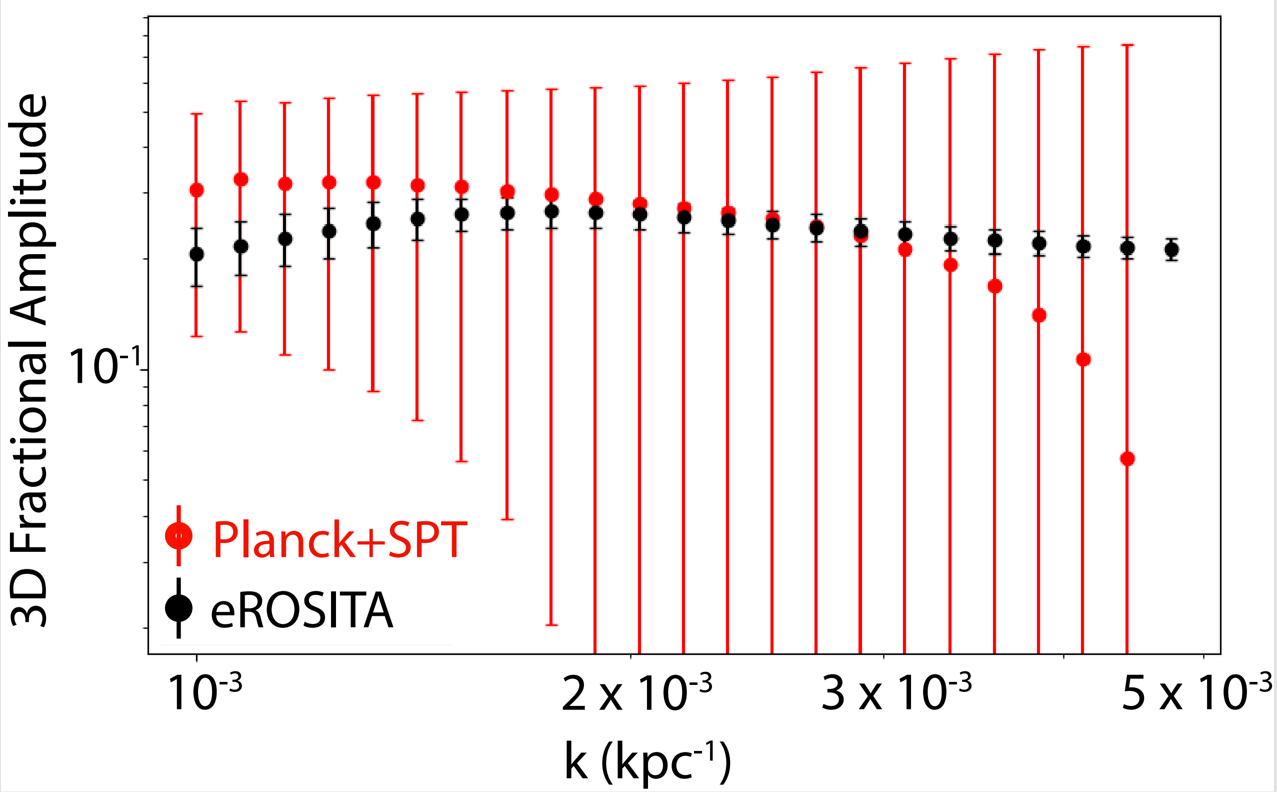
ICM Fluctuation Power Spectrum

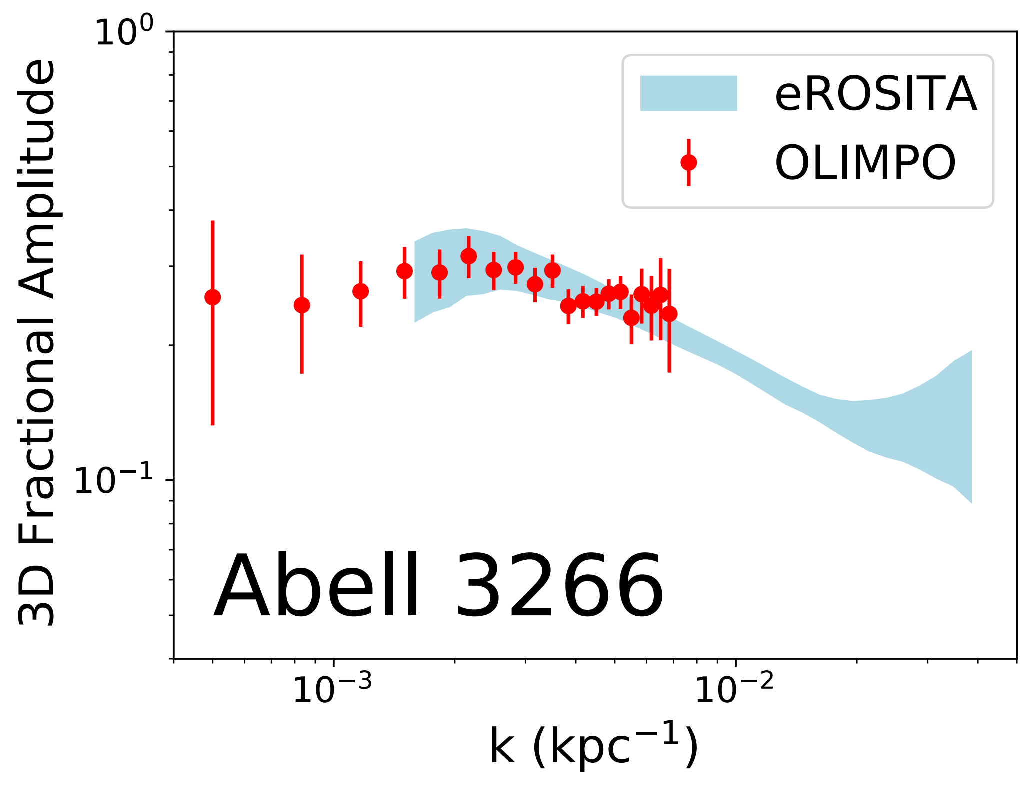
- In combination with *eROSITA* we will probe almost *two orders of magnitude* in physical scale
- Connect to underlying ICM turbulence via simulations
- Ratio of SZE/X-ray yields thermodynamic state
  - Gentle (isobaric)
  - Vigorous (adiabatic)



Expected results for Abell 3266

Blue represents actual measurement from eROSITA and red is the projection from a mock OLIMPO observation

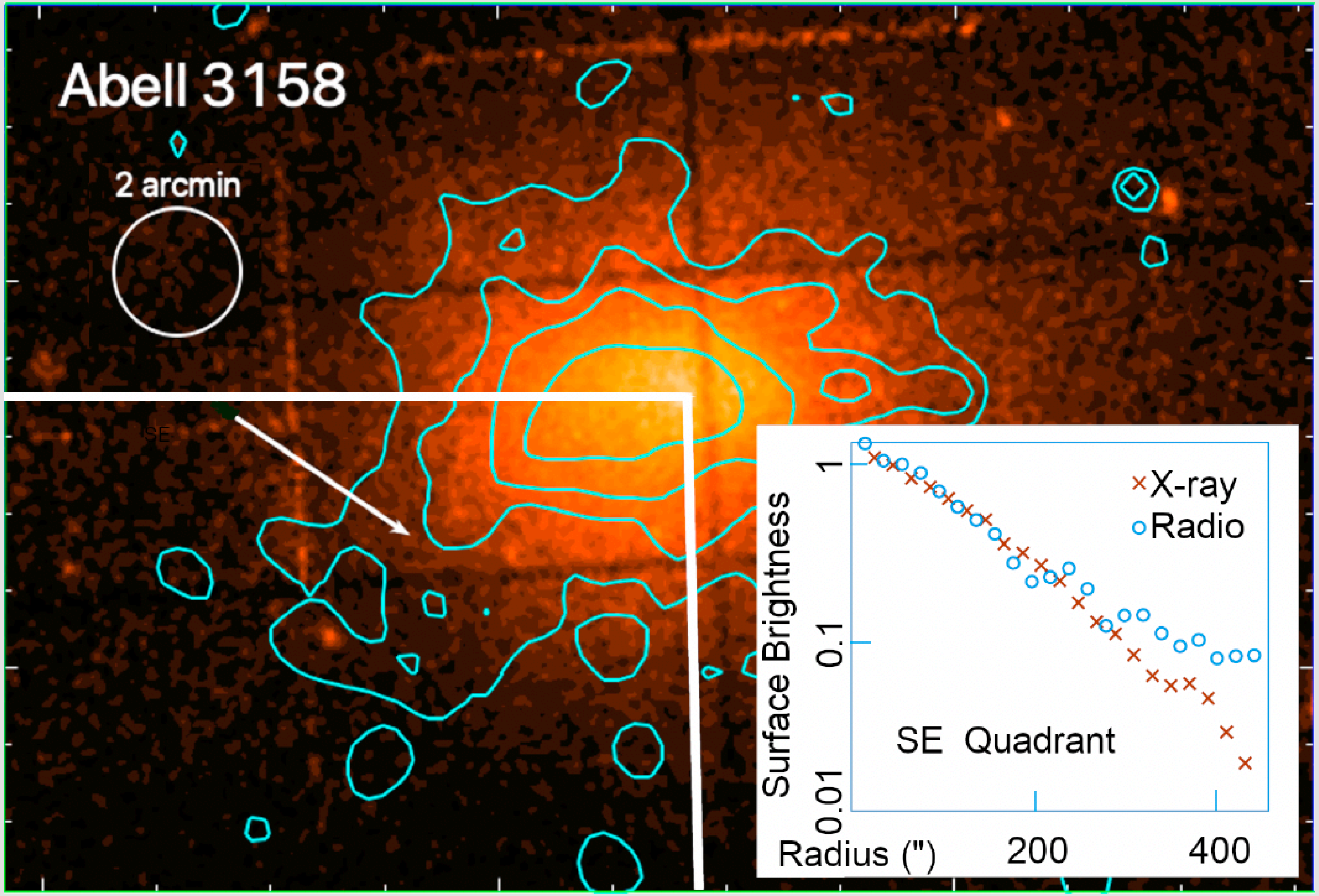




- We are now finalizing an analysis utilizing the best currently available SZE data from Planck+SPT (H. Saxena + A. Heinrich)
  - Results coming soon!
- OLIMPO will provide a factor of ~20 improvement!

ICM and Relativistic Plasmas

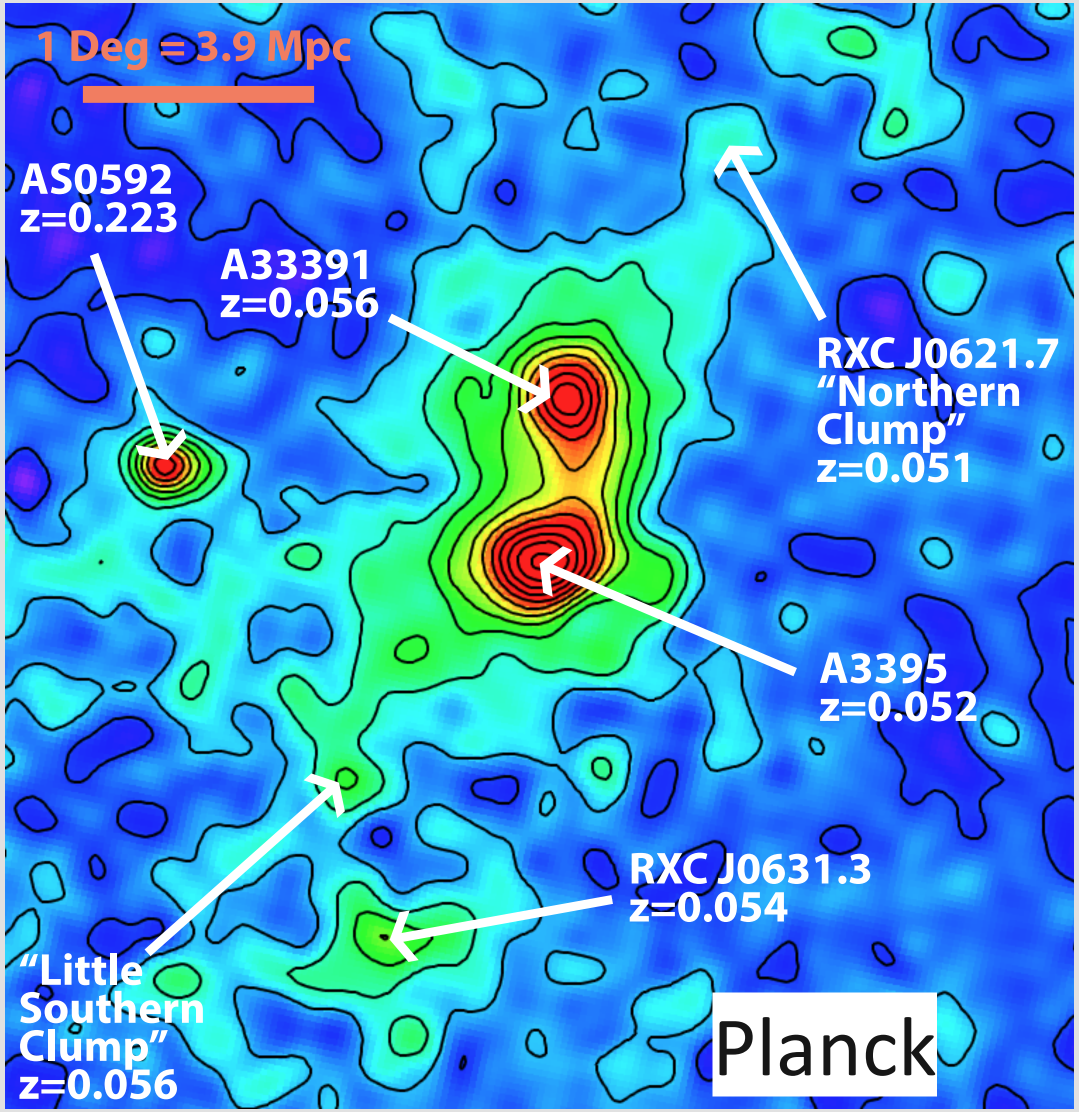
- Radio halos: kSZE will provide *direct observations* of turbulence thought to produce reacceleration

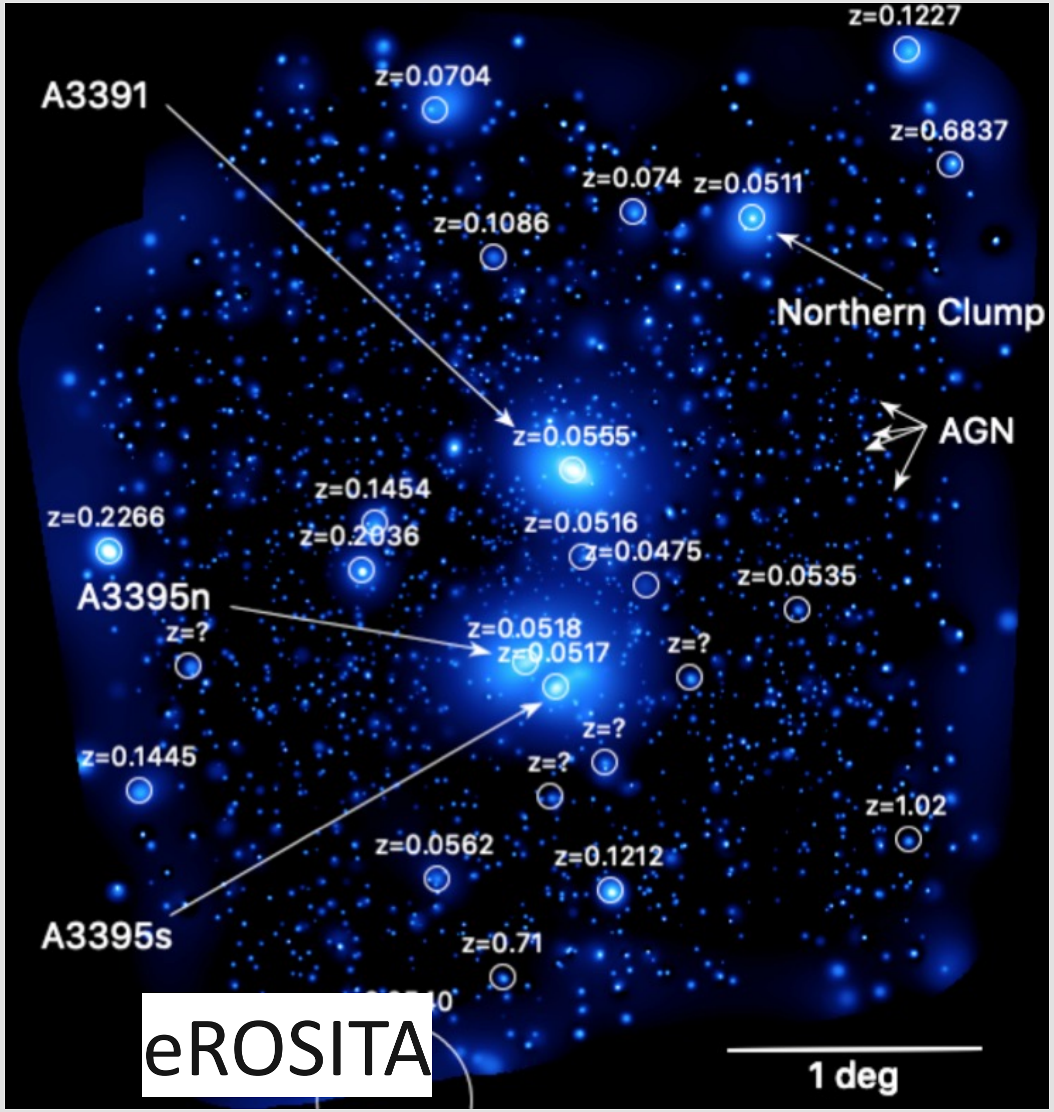


Meerkat radio contours overlaid on XMM X-ray image

Clear radio excess in the SE, expect an enhanced kSZE signal with OLIMPO

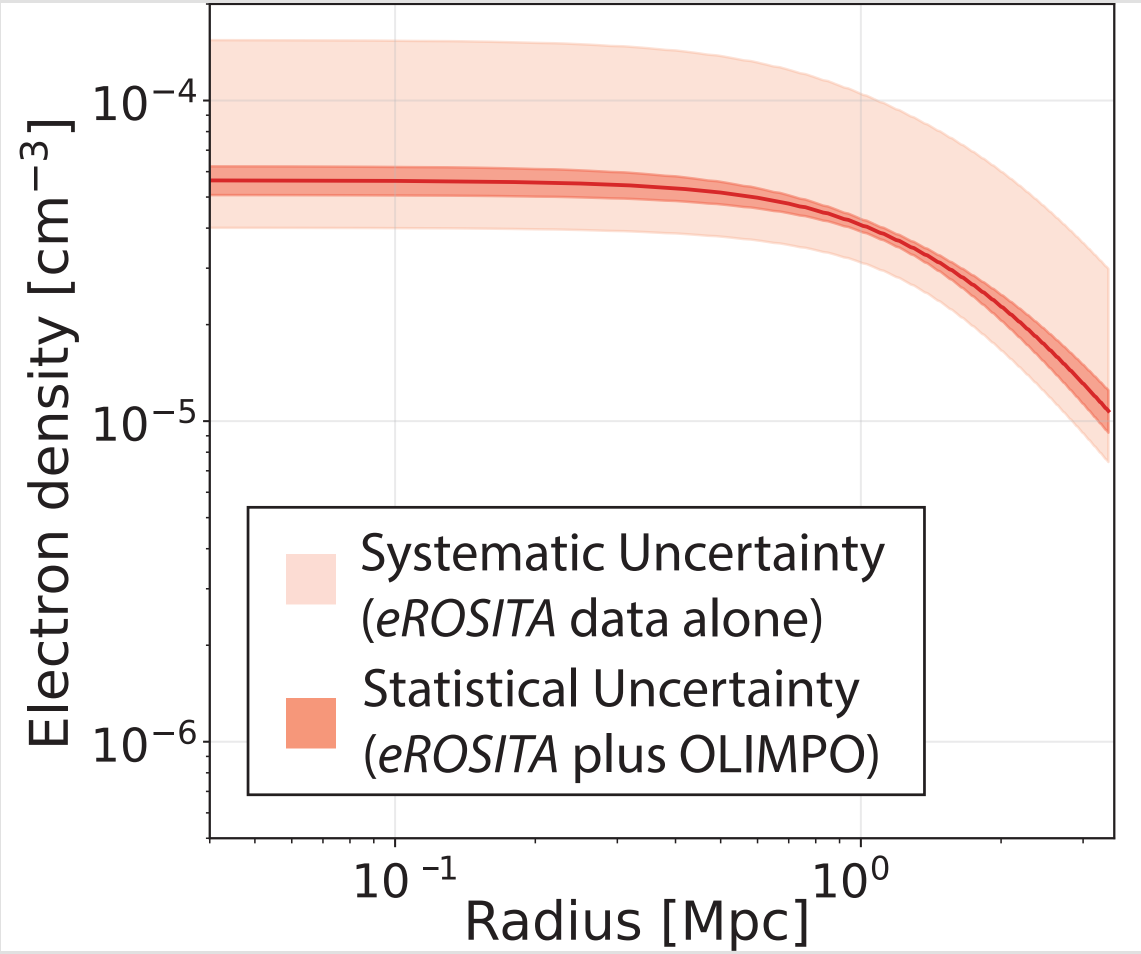
Characterizing the WHIM in Filaments





Characterizing the WHIM in Filaments

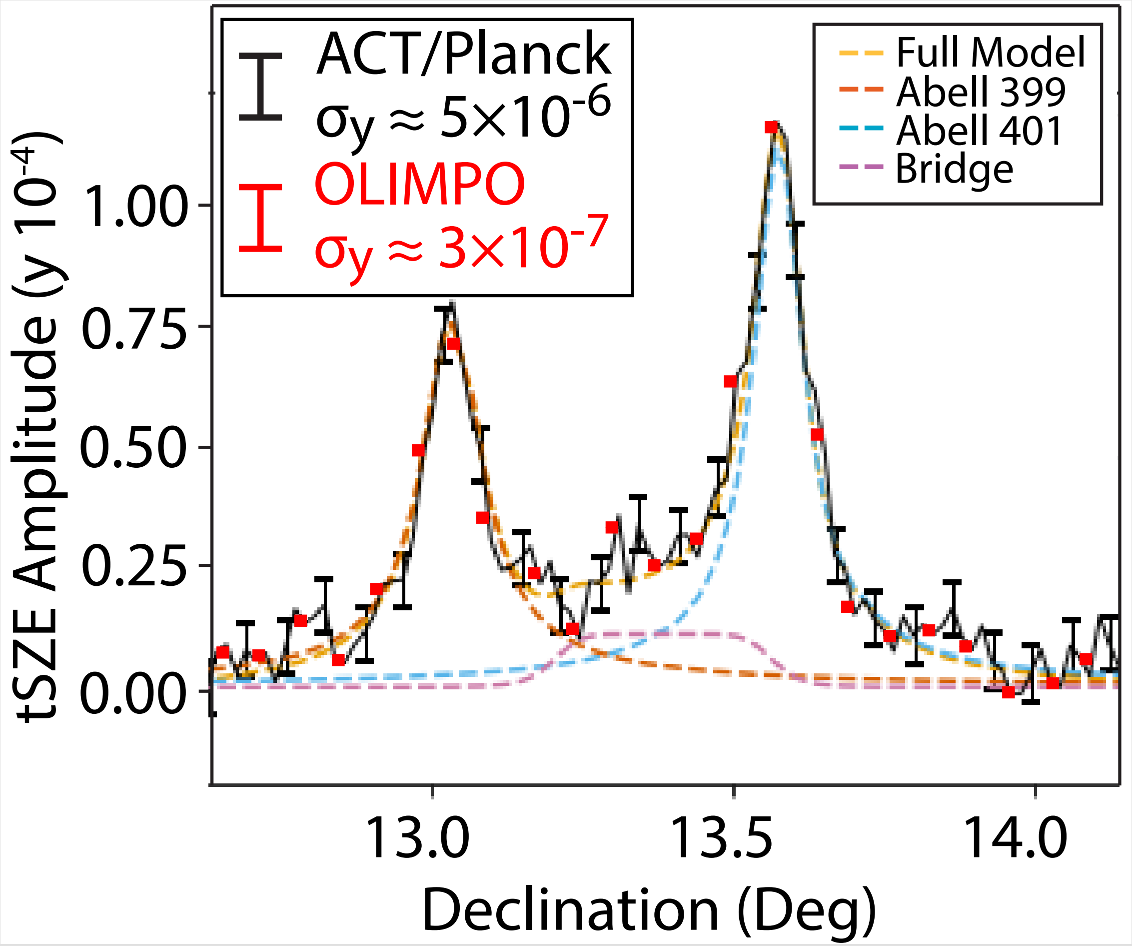
- Expected WHIM temperature in filaments is ∼0.1 keV
  - Very challenging to obtain spectroscopic constraints from eROSITA's 0.2—2.3 keV band
  - Generally find much hotter ∼1 keV gas (see also *XMM*/*Chandra*)
- Combining *eROSITA* SB with OLIMPO tSZE will robustly measure temperature
  - Most promising approach to constrain WHIM thermodynamics
  - See poster by Delaney White!



eROSITA X-ray analysis of a filament
Limited by large systematic uncertainties from spectroscopic measurements (adapted from Dietl+2024)

Characterizing the WHIM in Filaments

- We can also measure gas velocity within filament
  - kSZE is brighter than tSZE at such cold temperatures
  - Measure predicted 100 km/s spin dipole about filament axis to $\pm$10-20 km/s per filament
- And we can measure the absolute velocity of the clusters connected at each end of the filament
  - Disentangle distance/redshift degeneracy to measure LOS extent of filament to $\pm$1 Mpc



Comparison of OLIMPO with current state of the art from ACT/Planck (adapted from Hincks+ 2022)

Why OLIMPO?

- Unique science
  - Perform a detailed mapping of of the ICM velocity structure in outer regions dominated by accretion
  - Probe the connection between the ICM and the relativistic plasmas
  - Characterize the thermodynamics of WHIM gas in filaments
- SZE observations from above the atmosphere
  - Necessary for detailed single-object studies
  - Overlap with best X-ray data available from eROSITA at $z \sim 0.05$
- Also leveraging the best radio data from MeerKAT, ASKAP
- Detailed comparisons with simulations to extract the science
- Based on hardware that largely exists and has been flight tested