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

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Brief History of OLIMPO

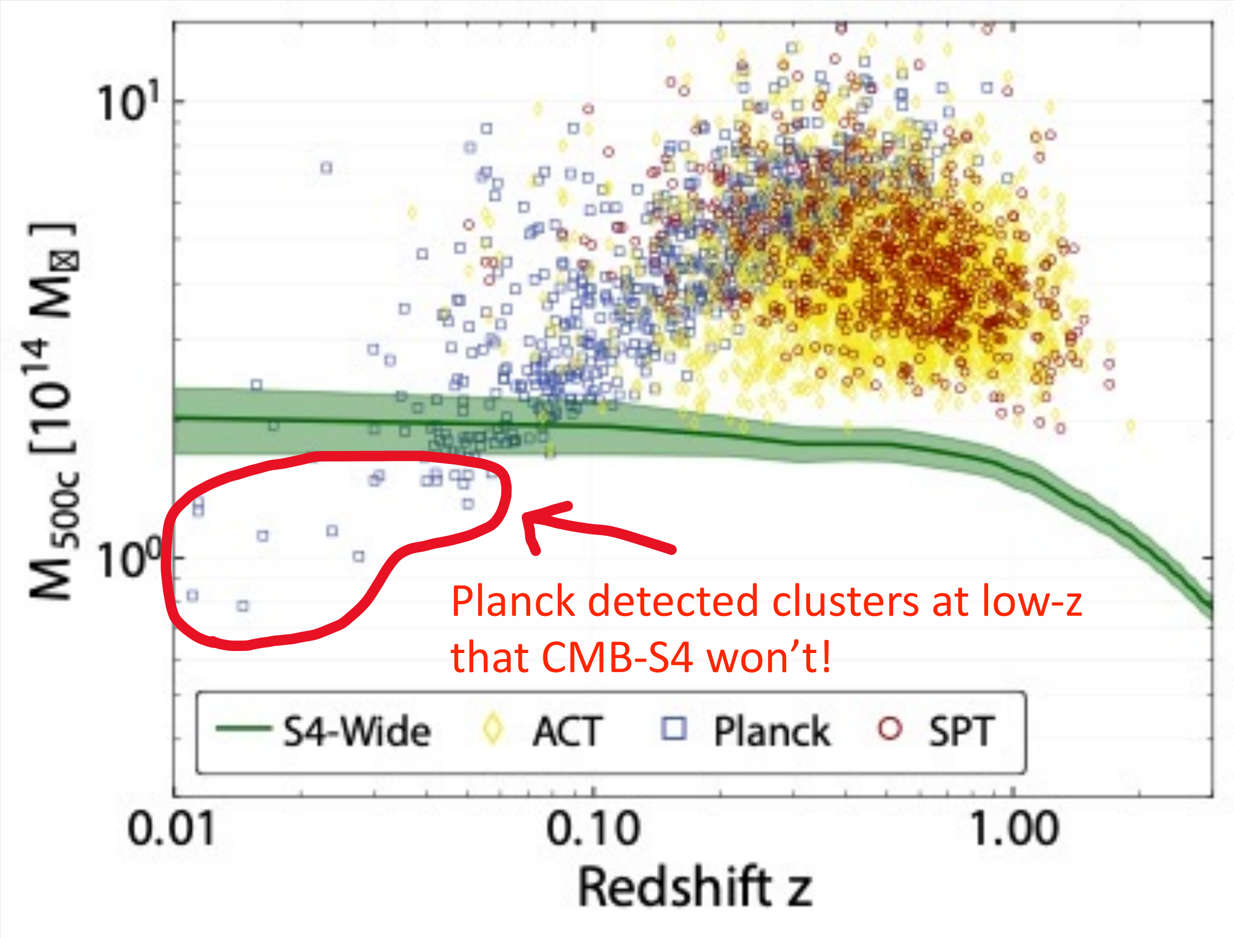
- Originally conceived and built by the group at Roma as a Balloon-Borne FTS with a 2.6 m primary and spectral coverage from 130-520 GHz in four separate bands (PI S. Masi)
- Horn-coupled Al KIDs on Si wafers
  - 19, 37, 23, and 41 detectors at 150, 250, 350, and 460 GHz
- Primary science goal of measuring the SZE spectrum in galaxy clusters to disentangle tSZE, kSZE, and rSZE
- Payload was launched from Svalbard in July, 2018
  - 5 day flight
  - A Telemetry issue prevented scientific observations
  - Cryogenic, Optical, and Detector noise performance all in good agreement with nominal expectations (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 w/ S. Hanany as PI

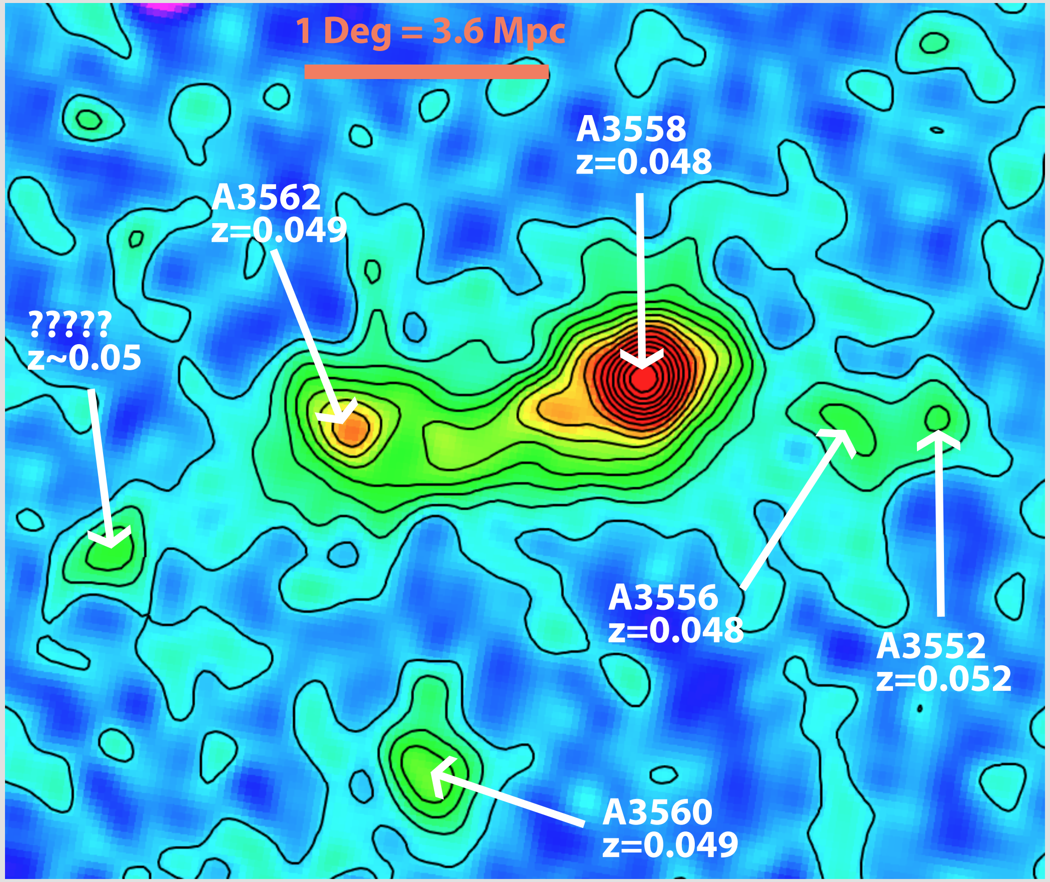
Why OLIMPO?

- Why SZE from a balloon with surveys from ACT, SPT, SO, CCAT (and CMB-S4 in the 2030s)
  - The atmosphere severely degrades SZE sensitivity on large angular scales
  - Studies of nearby objects, at z ~ 0.05, are not practical from the ground
- Why study obects at z ~ 0.05?
  - Best resolved, largest signal
  - They allow for the most detailed studies, requiring both SZE and X-ray (and radio), particularly for the diffuse gas in outskirts and filaments
  - Overlap with the best X-ray data from eROSITA and XRISM
- What are the detailed studies planned with OLIMPO?



OLIMPO Science Goals

- Probe the dynamics of LSS formation and evolution
  - Measure ICM gas dynamics from the core to the outer regions (kSZE + X-rays)
  - Probe gas kinetic energy, non-thermal pressure, energy cascade, energy dissipation and transport properties (tSZE/X-ray power spectrum + kSZE)
  - Connect kSZE and tSZE measurements 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)

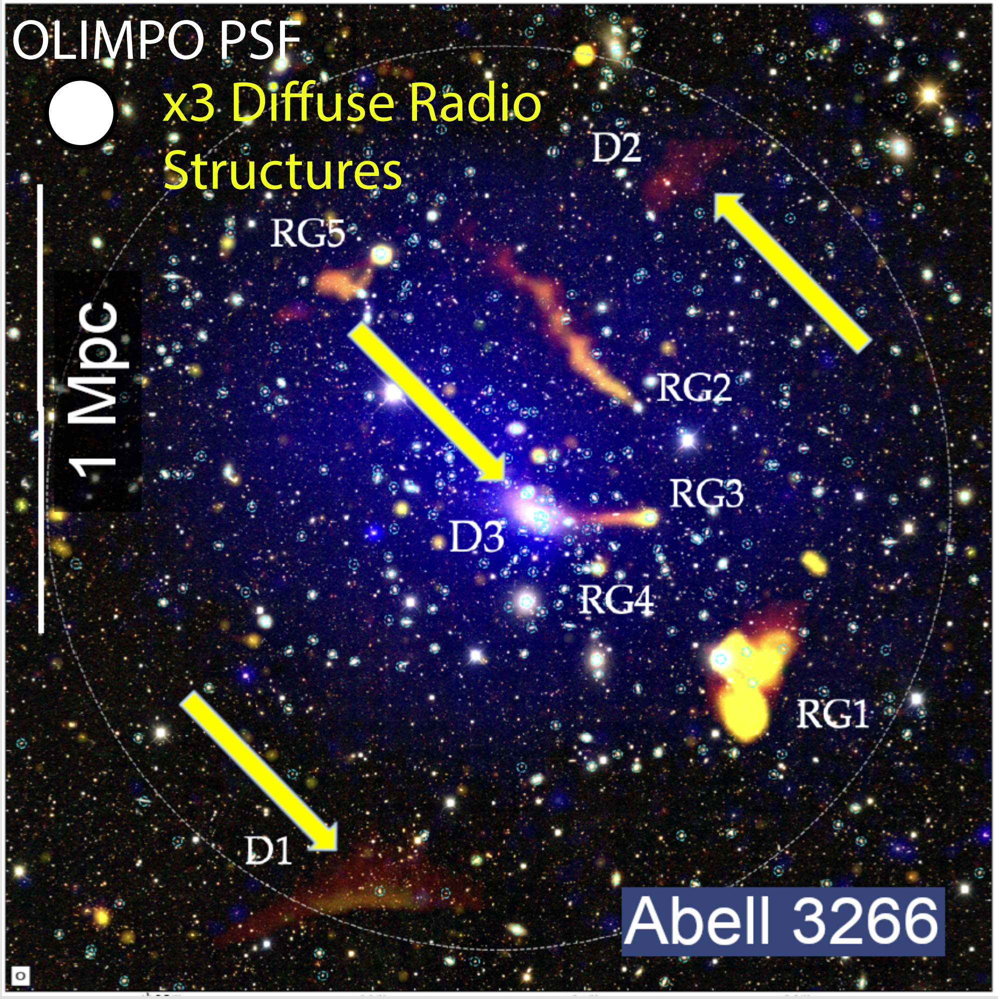


4° × 4° Planck image of filamentary structures

OLIMPO will provide images with two orders of magnitude lower noise and a factor of two better angular resolution

What Else is Required?

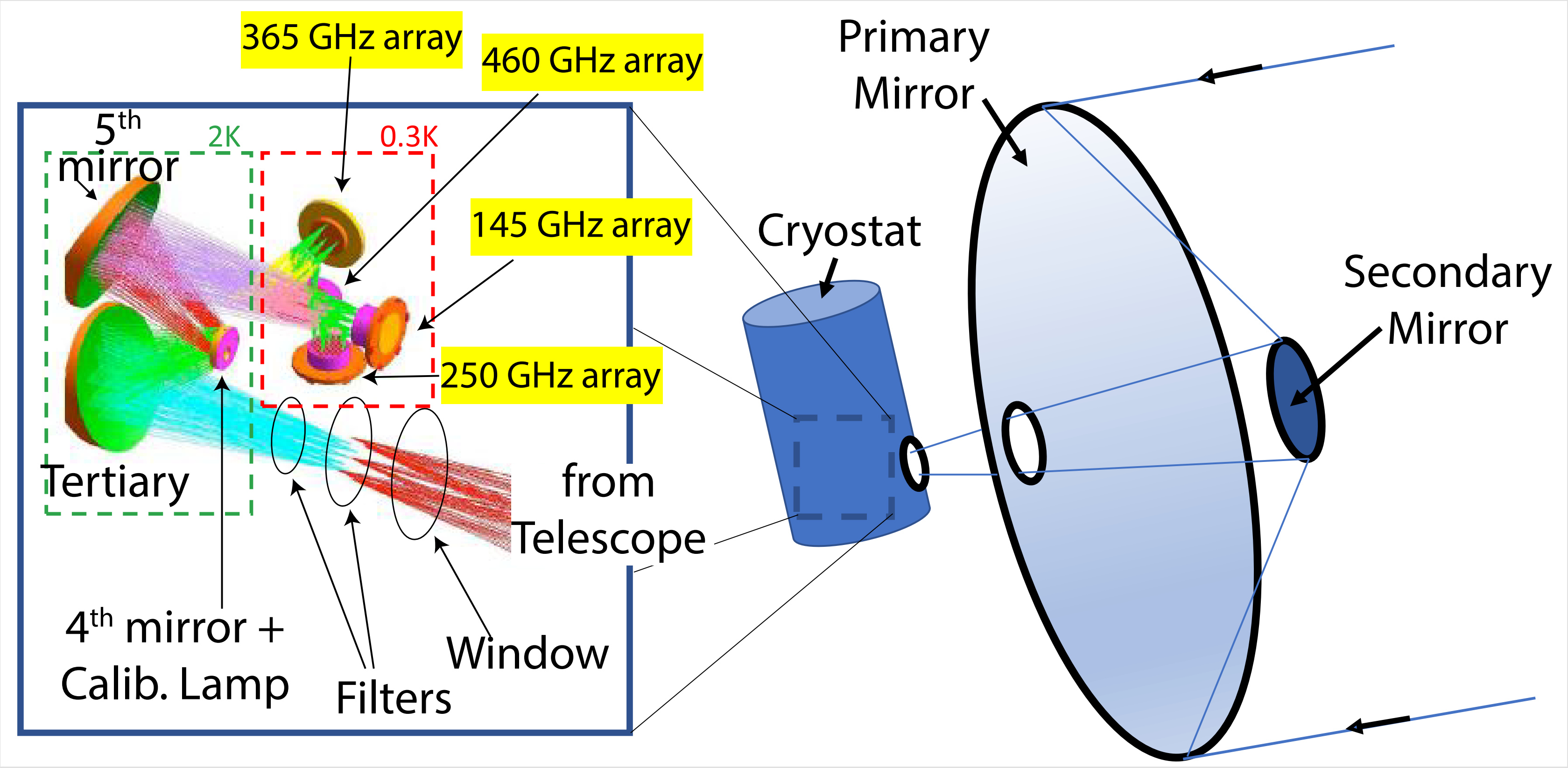
- Spectrally disentangling tSZE, kSZE, and rSZE is very difficult
  - X-rays break degeneracy
  - Need deep exposures on degree scales – eROSITA PV + eRASS (E. Bulbul)
- Deep radio observations to characterize halos and relics
  - MeerKAT and ASKAP (L. Rudnick)
- Detailed hydro-sims to interpret observational results
  - Combination of publicly available (IllustrisTNG, The300, Omega500) and custom runs within our team (C. Avestruz)
  - Generate mocks, analyzed identically to observed data, for comparison
  - Primary challenge is sufficient resolution in low density outskirts/filaments



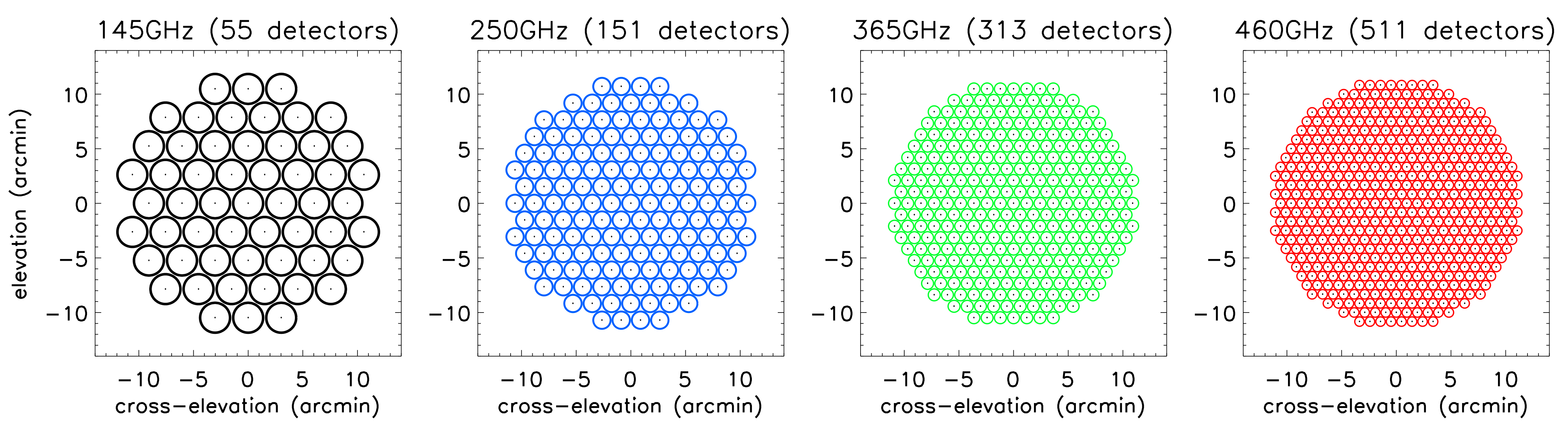
ASKAP (orange), XMM (blue), from Riseley+2022
Existing ASKAP data show x3 diffuse radio structures, including x2 Mach 2-3 shocks in the outskirts - modest detections in eROSITA PV

OLIMPO Instrument Details

- Cassegrain system with 2.6m 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

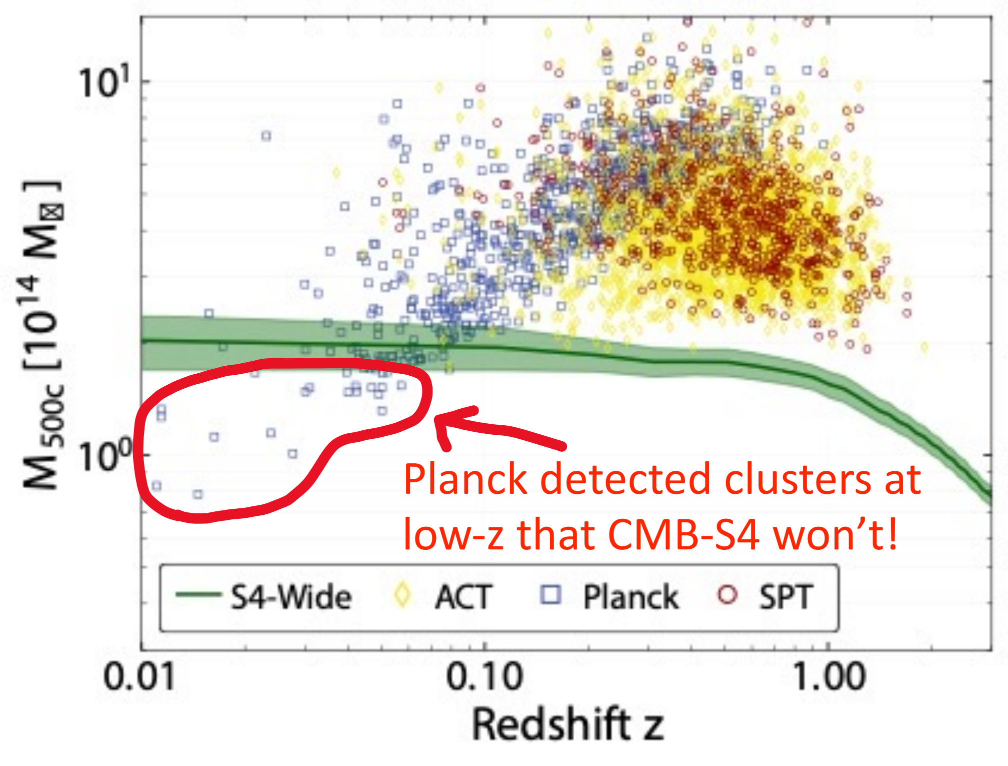


- Horn-coupled Al KIDs on Si
  - Same design as first flight
  - Hex-pack 1-fλ filling 24 arcmin co-aligned FOVs to efficiently map compact objects

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 Observations

- OLIMPO can make deep images
  - Two orders of magnitude deeper than Planck
  - An order of magnitude deeper than CCAT-P/CMB-S4 at high frequency
  - Similar depth 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	10 clusters + filaments
Planck [40]	33	47	150	3700	full sky
CCAT-P [28]	N/A	15 / 3.0	107 / 21	407 / 81	wide 20k deg^2 / deep 100 deg^2
CMB-S4 LAT [41]	2.0 / 1.0	5.7 / 3.5	N/A	N/A	wide 29k deg^2 / deep 1200 deg^2

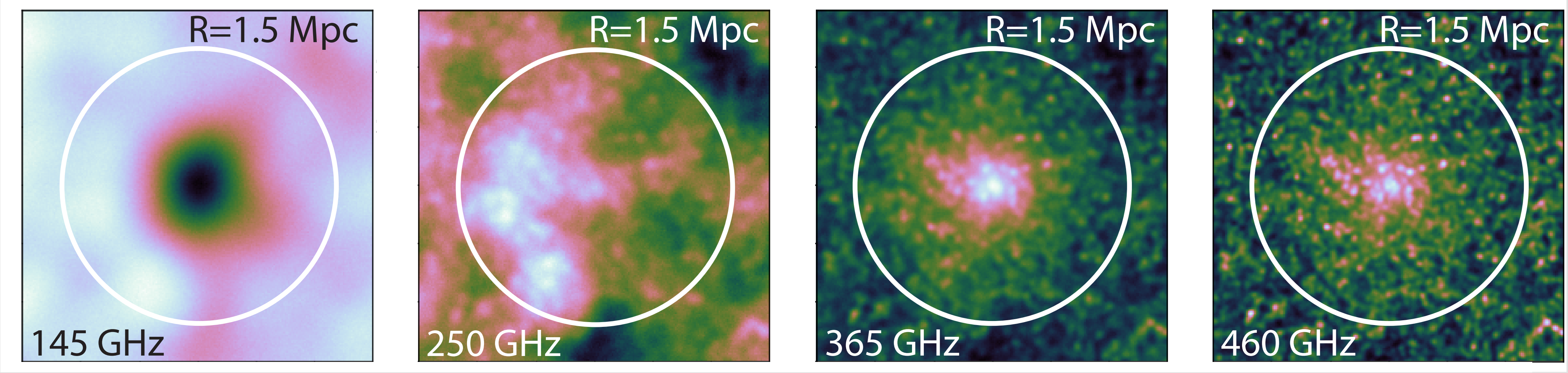
Planned OLIMPO Targets

- Six different fields, ten different clusters, three systems with bridges
  - All three of the eROSITA PV target fields
  - Plus three additional target fields identified from Planck

Group	Cluster	z	Map	Time (hrs)	*Planck* S/N	*eROSITA* cts	Notes
1	Abell 3391	0.05	$1.6^\circ \times 0.8^\circ$	100	17	1.74M	Bridge in *Planck*
	Abell 3395	0.05	$\mathrm{PA}^\dagger = 0^\circ$		14	1.25M	& *eROSITA* [37, 38, 88]
	Abell 3158	0.06	$0.8^\circ \varnothing^{\dagger\dagger}$	50	20	1.60M	disturbed [90, 91]
	Abell 3266	0.06	$0.8^\circ \varnothing$	50	41	2.47M	merger w/ 2 shocks [92]
2	Abell 3532	0.05	$2.2^\circ \times 1.0^\circ$	140	12	16.5k	A3532-A3530 bridge in
	Abell 3528	0.05	$\mathrm{PA} = 150^\circ$		11	24.4k	*Planck* & *eROSITA*;
	Abell 3530	0.05			5	33.0k	A3532-A3528 in *Planck*
	R J0812.5	0.06	$2.0^\circ \times 0.8^\circ$	120	11	18.7k	Possible bridge
	R J0820.9	0.06	$\mathrm{PA} = 80^\circ$		10	5.4k	in *Planck*
	Abell 0496	0.03	$1.3^\circ \varnothing$	130	12	97.6k	relaxed cool-core [93–95]

OLIMPO Observations

- We have built machinery to create mock OLIMPO observations (T. Macioce)
  - Including tSZE, kSZE, CMB, CIB, cluster-member galaxies
- See mock $1° \times 1°$ images below



eROSITA is Critical

- Combination of large FOV, raster scanning, and stable background allow for degree-scale measurements of ICM and WHIM
  - Not possible with Chandra/XMM
- ICM - OLIMPO alone cannot fully constrain τ_e, v_e, and T_e
  - eROSITA-measured T_e allows constraints on v_e
- WHIM – Te difficult to measure with eROSITA alone
  - OLIMPO tSZE + eROSITA SB measure n_e and T_e of WHIM

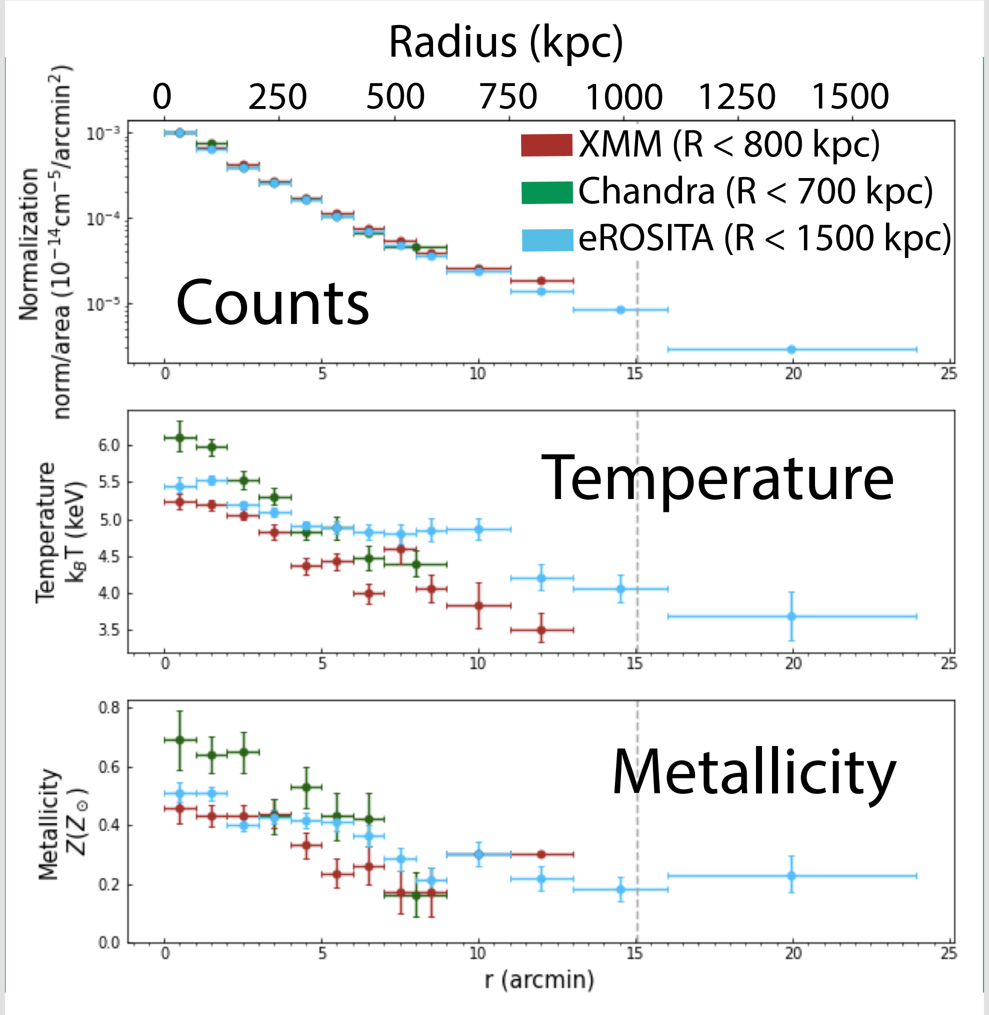


Figure from Whelan+2022
eROSITA ICM profiles for Abell 3158

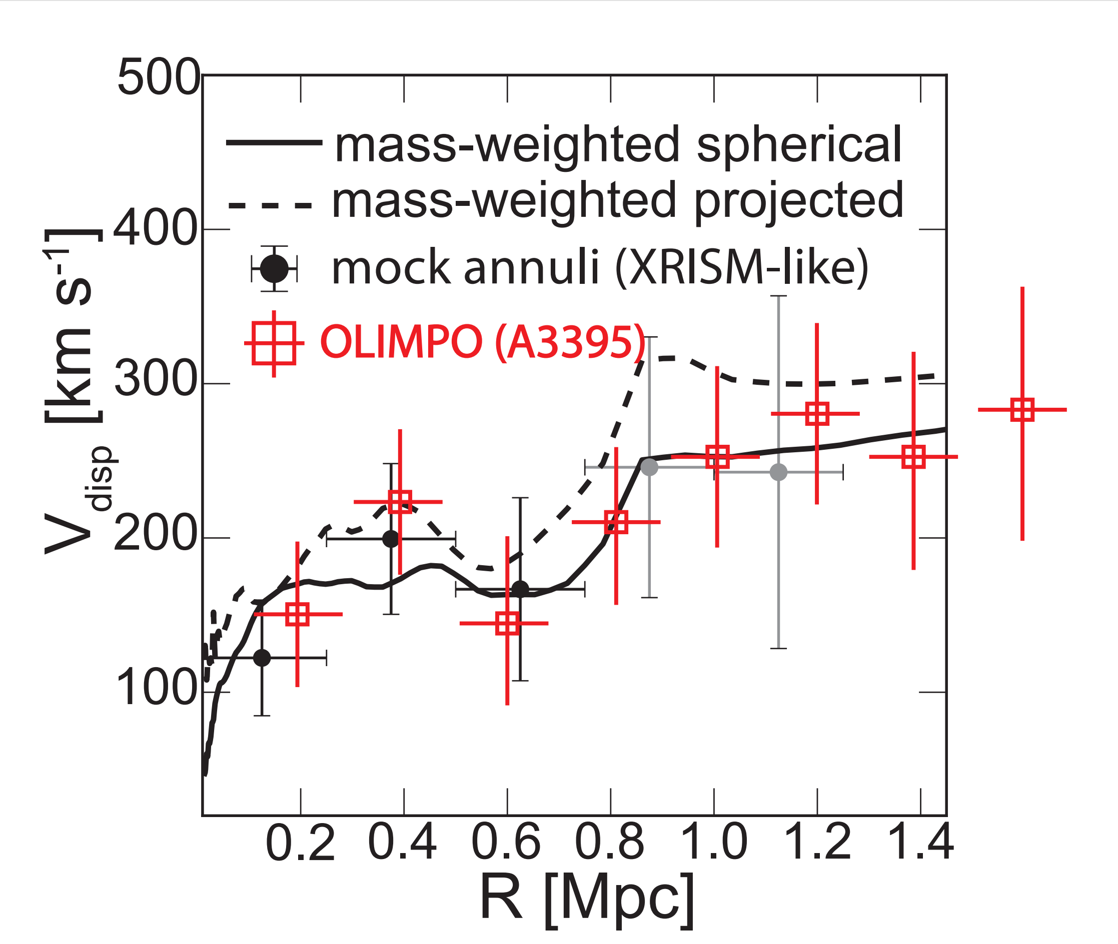
Projected OLIMPO Sensitivity

- Have used our mock observations and an analysis pipeline based on MCMC to project SZE constraints (E. Rapaport)
- Mocks include dominant contaminants, the CMB and the CIB
- Also include realistic prior on temperature from eROSITA
  - Typical tSZE S/N of ~100 in 200 kpc wide radial bins for clusters
  - Typical kSZE uncertainty corresponding to ~50 km/s in each radial bin
  - tSZE S/N of ~10 and velocity uncertainty of ~50 km/s per pixel in filaments

Cluster	Δpix Mpc	$0.4\leqslant R\leqslant 0.6$ Mpc tSZE S/N	$0.4\leqslant R\leqslant 0.6$ Mpc $\sigma(v_{\rm disp})$	$0.9\leqslant R\leqslant 1.1$ Mpc tSZE S/N	$0.9\leqslant R\leqslant 1.1$ Mpc $\sigma(v_{\rm disp})$	$1.4\leqslant R\leqslant 1.6$ Mpc tSZE S/N	$1.4\leqslant R\leqslant 1.6$ Mpc $\sigma(v_{\rm disp})$
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 Velocity Measurements

- OLIMPO will be able to measure ICM velocity dispersions to ±50-100 km/s in 200 kpc annuli out to at least 1.5 Mpc in radius
    - Not practical with XRISM, which *would require ≈1 Msec* to obtain similar constraints near 1 Mpc
- Typical S/N of 5 per cluster per radial bin
    - Directly measure non-thermal pressure
    - Differences towards/away from filaments

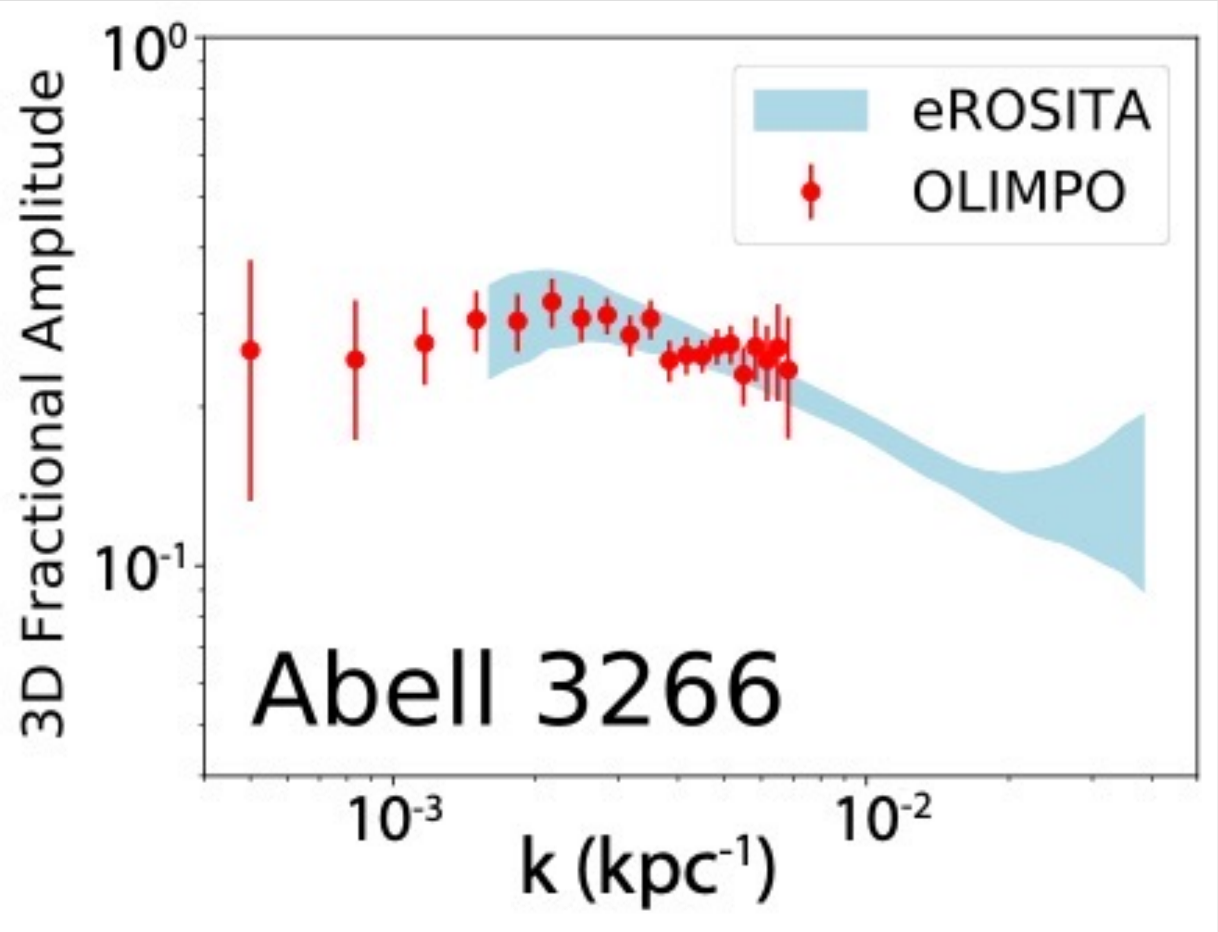


Adapted figure from Nagai+2013

OLIMPO will measure ICM velocity dispersion profiles from the central regions to at least 1.5 Mpc in radius

ICM Fluctuation Power Spectrum

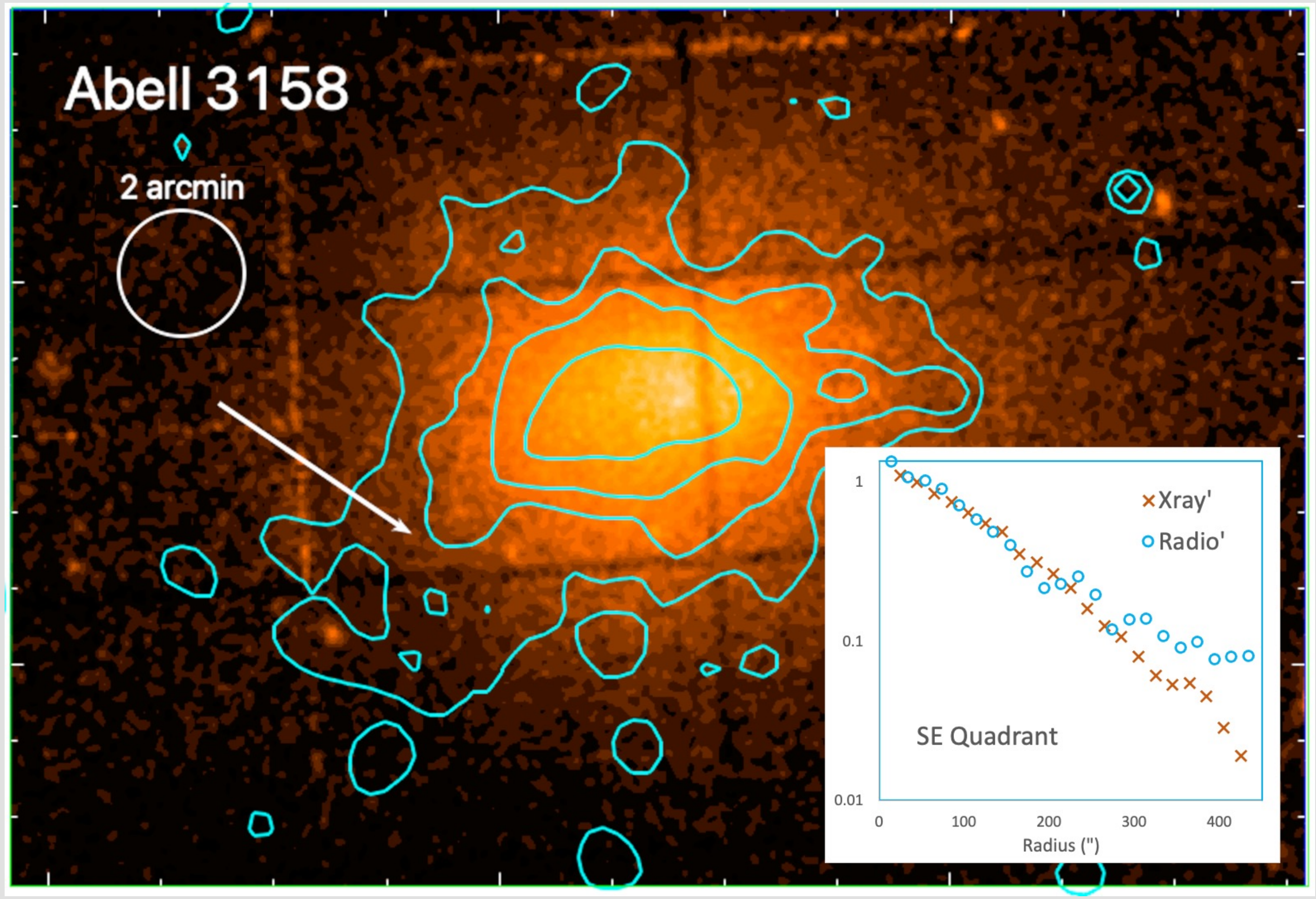
- OLIMPO will measure pressure fluctuations on scales from 0.2-2 Mpc
- eROSITA will measure X-ray SB fluctuations on scales from 0.05-0.5 Mpc
  - In combination we will probe almost *two orders of magnitude* in physical scale
  - Via simulations can connect to the underlying ICM turbulence



Expected results for Abell 3266
Blue represents actual measurement from eROSITA and red is the projection from mock a mock OLIMPO observation

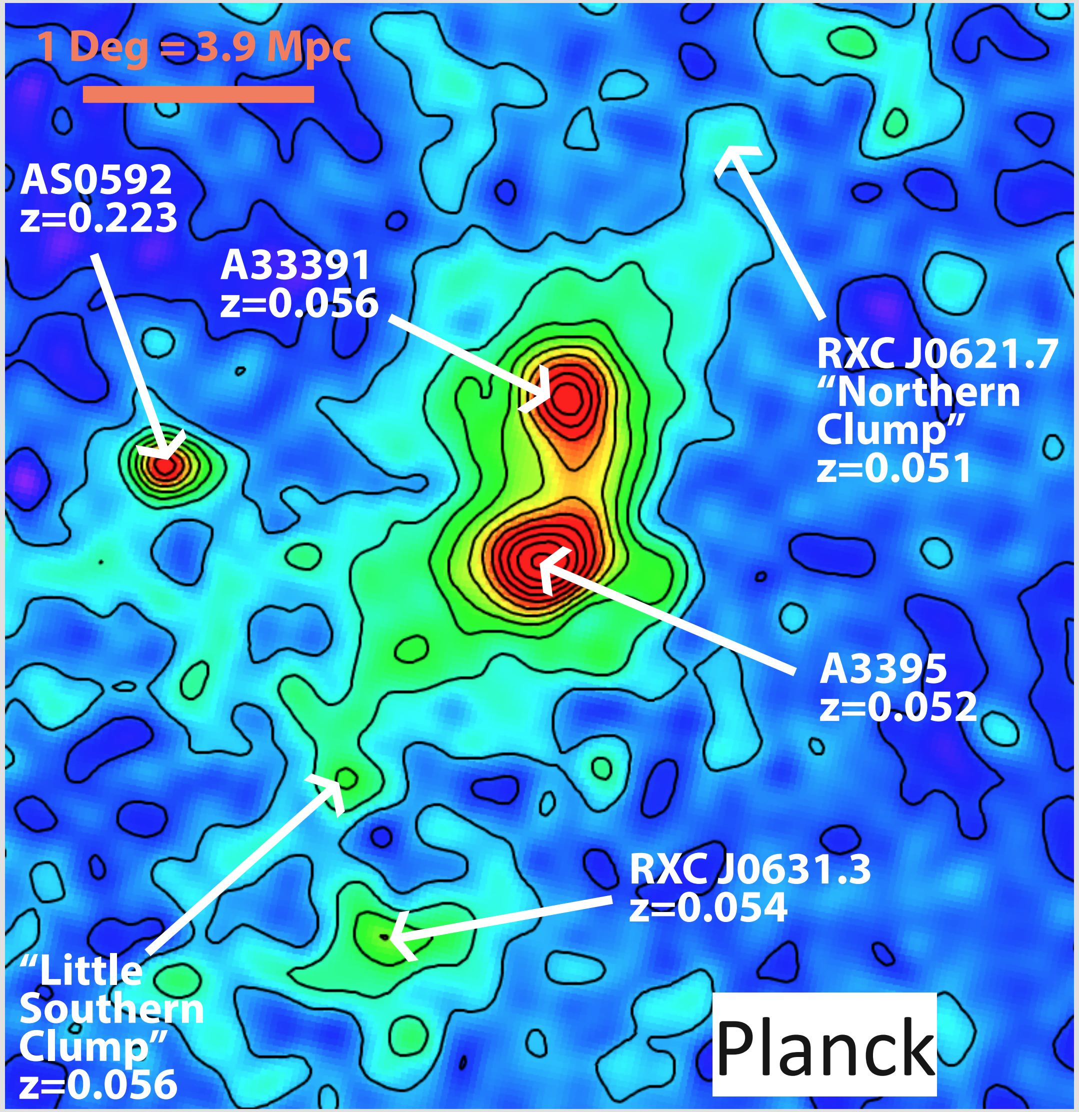
ICM and Relativistic Plasmas

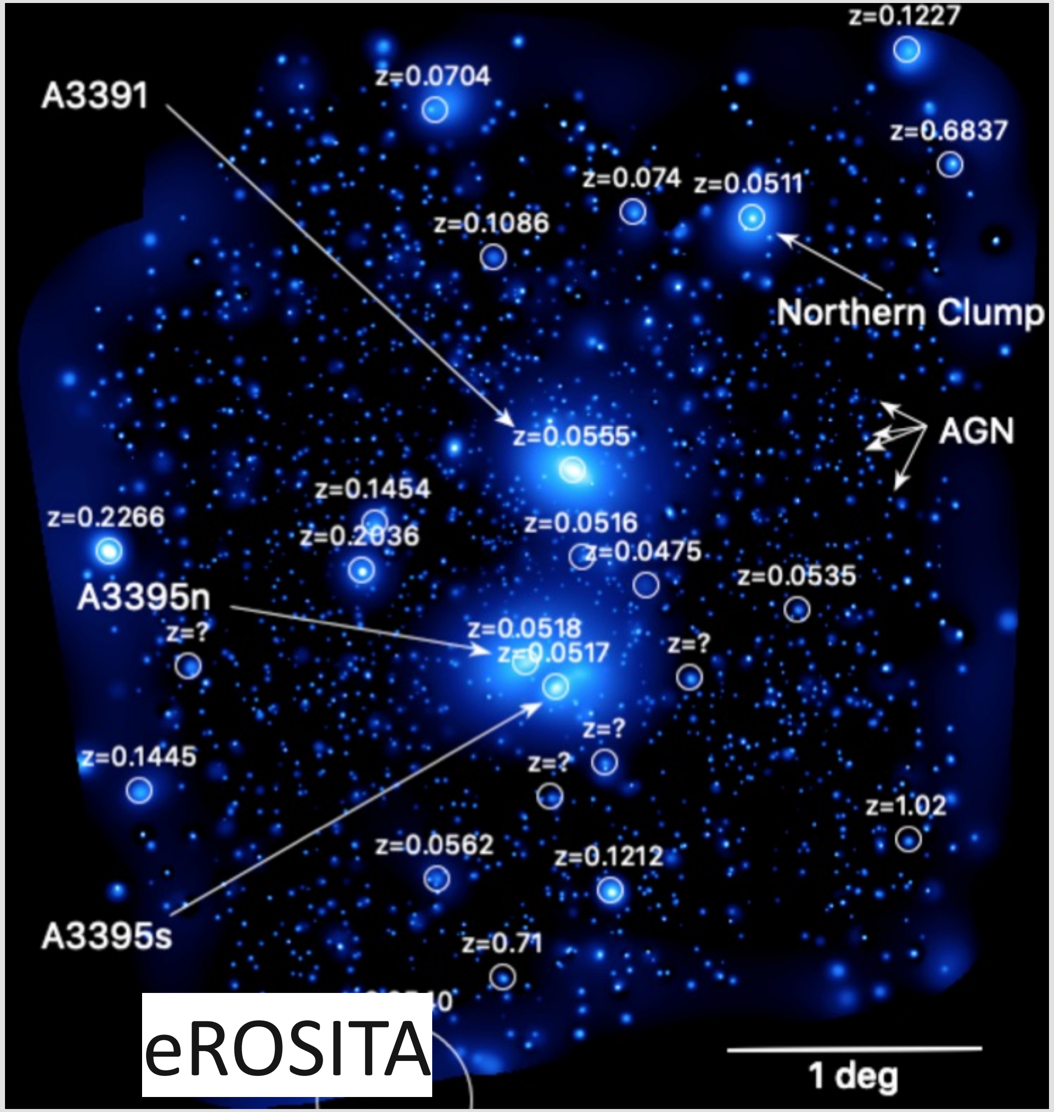
- Radio halos
  - We will be able to provide the *first direct observations* of turbulence thought to produce reacceleration
- Radio relics
  - Discrepancies between radio/X-ray Mach numbers
  - Most relics are at large radii – and thus difficult to study with X-rays
  - OLIMPO tSZE will measure ICM discontinuities associated with these relics



Meerkat radio contours overlaid on XMM X-ray image
There is a clear excess of radio emission in the SE, where we expect to see an enhanced kSZE signal with OLIMPO

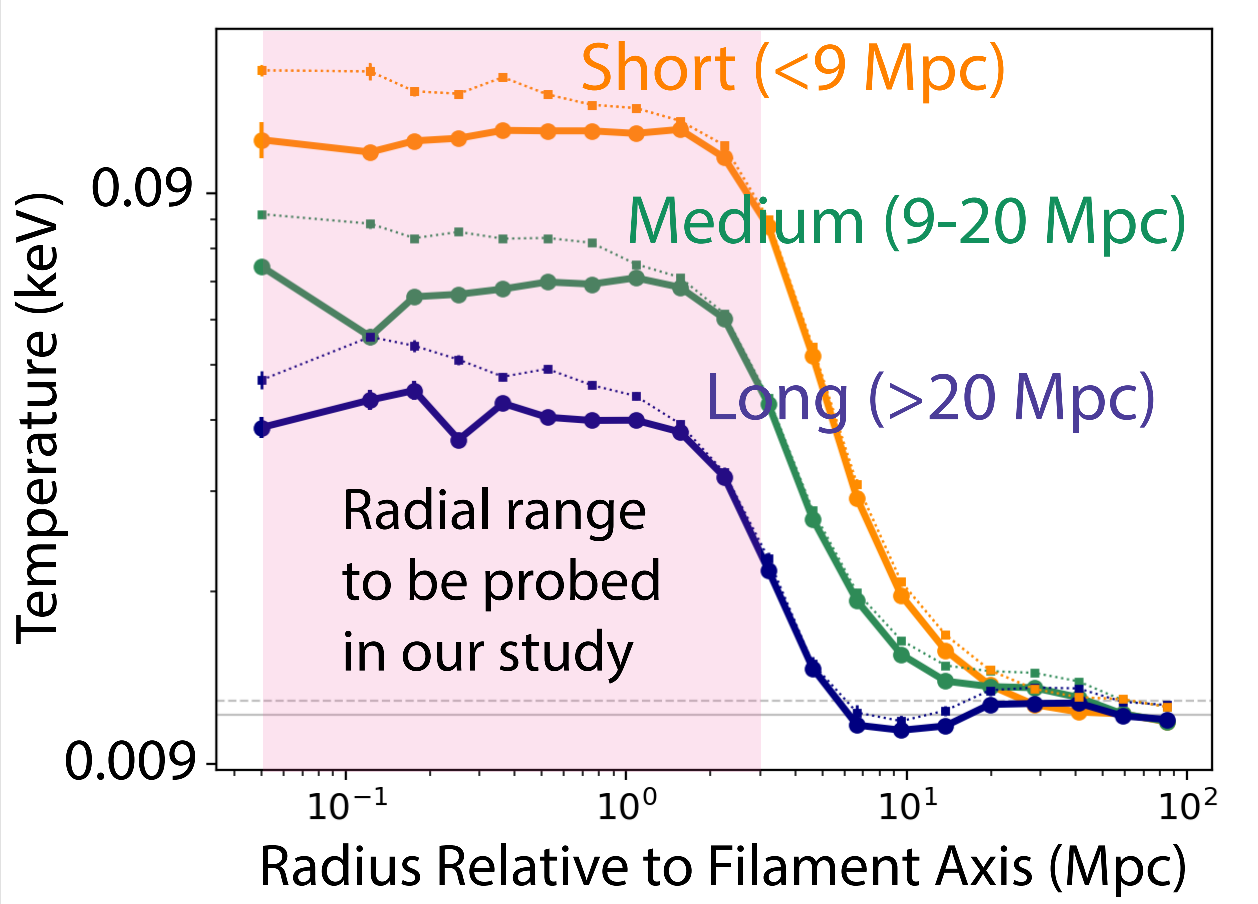
Characterizing the WHIM in Filaments





Characterizing the WHIM in Filaments

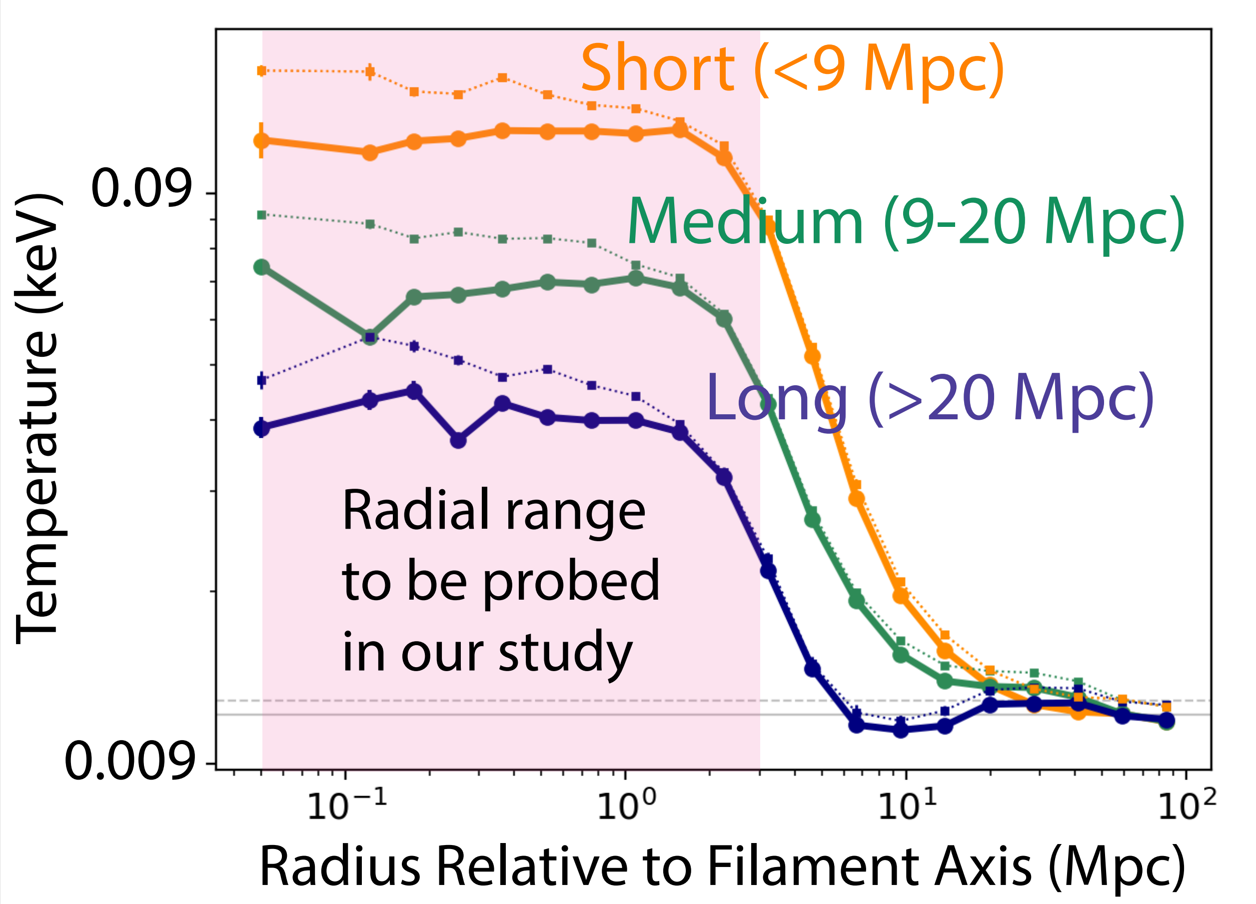
- Expected WHIM temperature in filaments is ~0.1 keV
  - It is very challenging to obtain spectroscopic constraints from eROSITA's 0.2—2.3 keV band
  - Handful of attempts with XMM/Chandra find much hotter ~1 keV gas in filaments (e.g., Eckert+2015, Alvarez+2018)
- Combining eROSITA SB with OLIMPO tSZE will robustly measure temperature
  - Most promising approach to constrain WHIM thermodynamics



Predicted Filament Temperatures from IllustrisTNG (Galarraga-Espinosa+2021)

Characterizing the WHIM in Filaments

- We can also measure gas velocity within filament
  - kSZE is brighter relative to tSZE at such cold temperatures
  - $\pm$50 km/s within 200 kpc pixels along filament to map out internal gas flow
- 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
  - Differentiate "Short", "Medium", and "Long"



Predicted Filament Temperatures from IllustrisTNG (Galarraga-Espinosa+2021)

Why OLIMPO?

- Unique science
  - Perform a detailed mapping of of the ICM velocity structure from the cluster center to regions dominated by accretion
  - Probe the connection between the ICM and the relativistic plasmas
  - Characterize the thermodynamics of WHIM gas in filaments (i.e., the “missing baryons”)
- SZE observations from above the atmosphere
  - Necessary to overlap with the best X-ray data available from eROSITA and XRISM 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