# OLIMPO (+eROSITA ~~and XRISM~~) Science Drivers, Feasibility, and Budget Constraints

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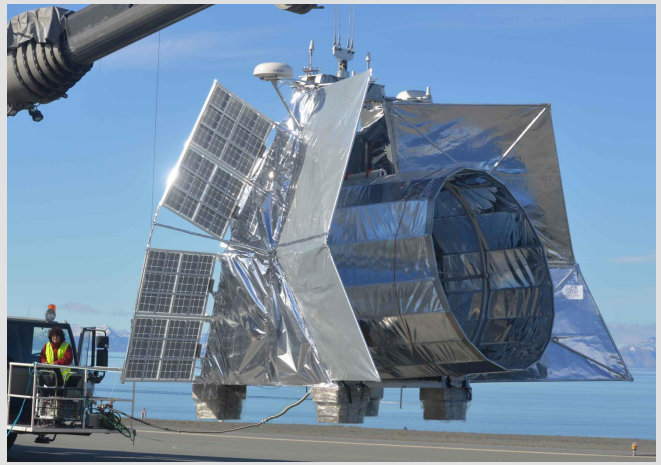
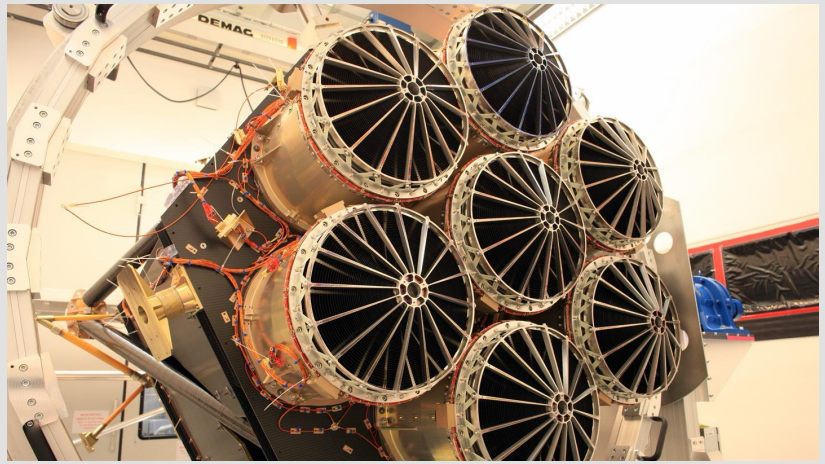
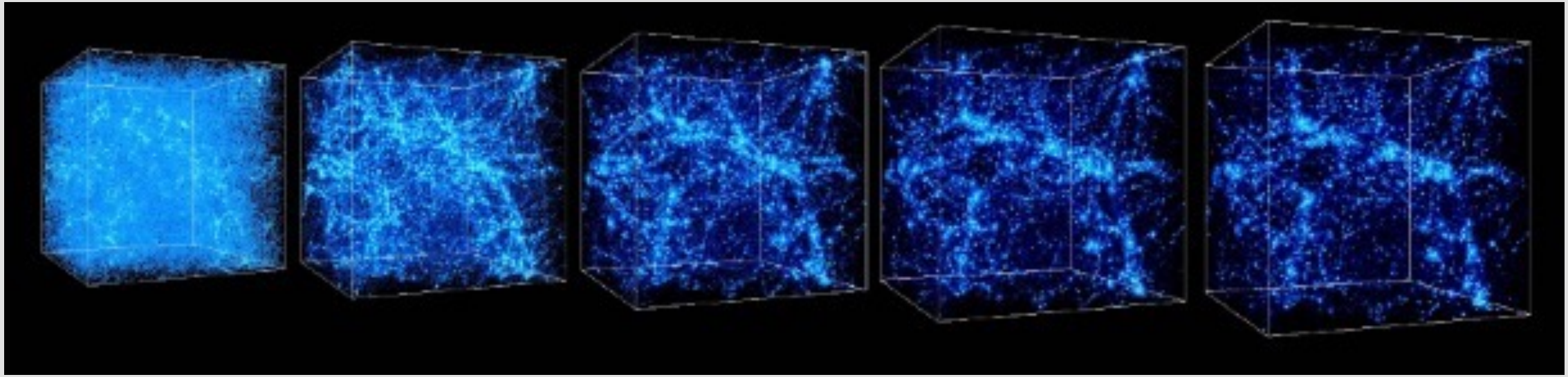




# What are the Science Questions We Want to Answer?

- How do the largest structures (galaxy clusters) in our Universe form?
- What are the physical properties and distribution of the warm-hot intergalactic medium (WHIM) that comprises half of the total baryons in the Universe?



# What Observations are Needed to Answer these Questions?

- Structure growth occurs in the outer regions of galaxy clusters where new material is accreting
  - The gas density in these regions is very low, and so the signal is extremely dim and diffuse
- The WHIM exists within the filaments of the cosmic web
  - The gas density in these regions is very low, and so the signal is extremely dim and diffuse

# What Observations are Needed to Answer these Questions?

- To detect dim and diffuse signals, it is necessary to observe objects as close to us as possible (low-$z$) since they will be the brightest
- Because galaxy clusters and filaments are large in size (a few Mpc), these nearby objects subtend large angles (a few degrees)
- We thus need instruments with large fields of view
  - While mosaicing images from smaller fields is possible, this is generally very difficult or impossible when looking for diffuse signals much larger in size than the individual mosaics

# What Quantities Do We Need to Measure?

- Structure growth involves the conversion of coherent infall gas velocities to thermalized (random) motions
  - We thus need to probe the velocity structure of the gas
  - Existing measurements already establish the distribution and thermal state of the gas within galaxy clusters (including the outskirts)
- Roughly half the baryons are known to exist in filaments as WHIM
  - We have little to no knowledge of the distribution or thermal state of this gas
  - We also have no knowledge of its velocity structure

# What Quantities Do We Need to Measure?

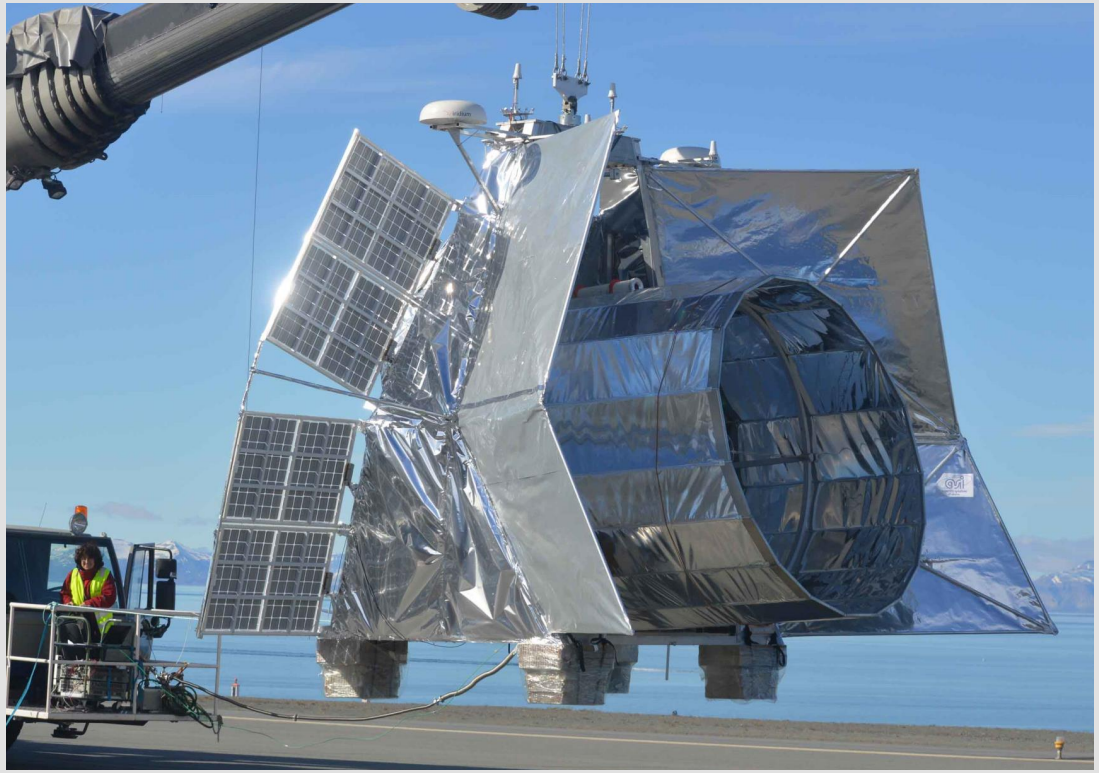
- Gas velocities in cluster outskirts
  - X-ray spectroscopy to measure emission line shifts and broadening
    - Not viable until (at least) the late 2030s via *NewAthena*
  - Viable *now* via kinematic SZ observations (Doppler shift of CMB) and fluctuations in the thermal SZ effect
    - Both require very deep multi-band SZ data with fidelity to degree angular scales
      - Not possible from the ground due to atmospheric fluctuations on similar scales
    - Can be achieved from above the atmosphere in a balloon
    - X-ray surface brightness also needed to break degeneracies
      - *eROSITA* has already delivered such data
- We need a sensitive multi-band SZ balloon to complement *eROSITA*!

# What Quantities Do We Need to Measure?

- WHIM thermodynamics and velocity structure
  - Can be done with very deep X-ray observations
    - Again, will not be viable before *NewAthena*
  - *eROSITA* has sufficient soft-band sensitivity to detect the low energy photons
    - But band limitations make it difficult/impossible to probe temperature
    - It also lacks the spectral resolution (and sensitivity) to measure velocities
  - Combining eROSITA with deep thermal SZ effect data does yield temperature
  - Associated kinematic SZ effect also probes velocity structure
- The *eROSITA* data already exist
- We need a sensitive multi-band SZ balloon to complement *eROSITA*!

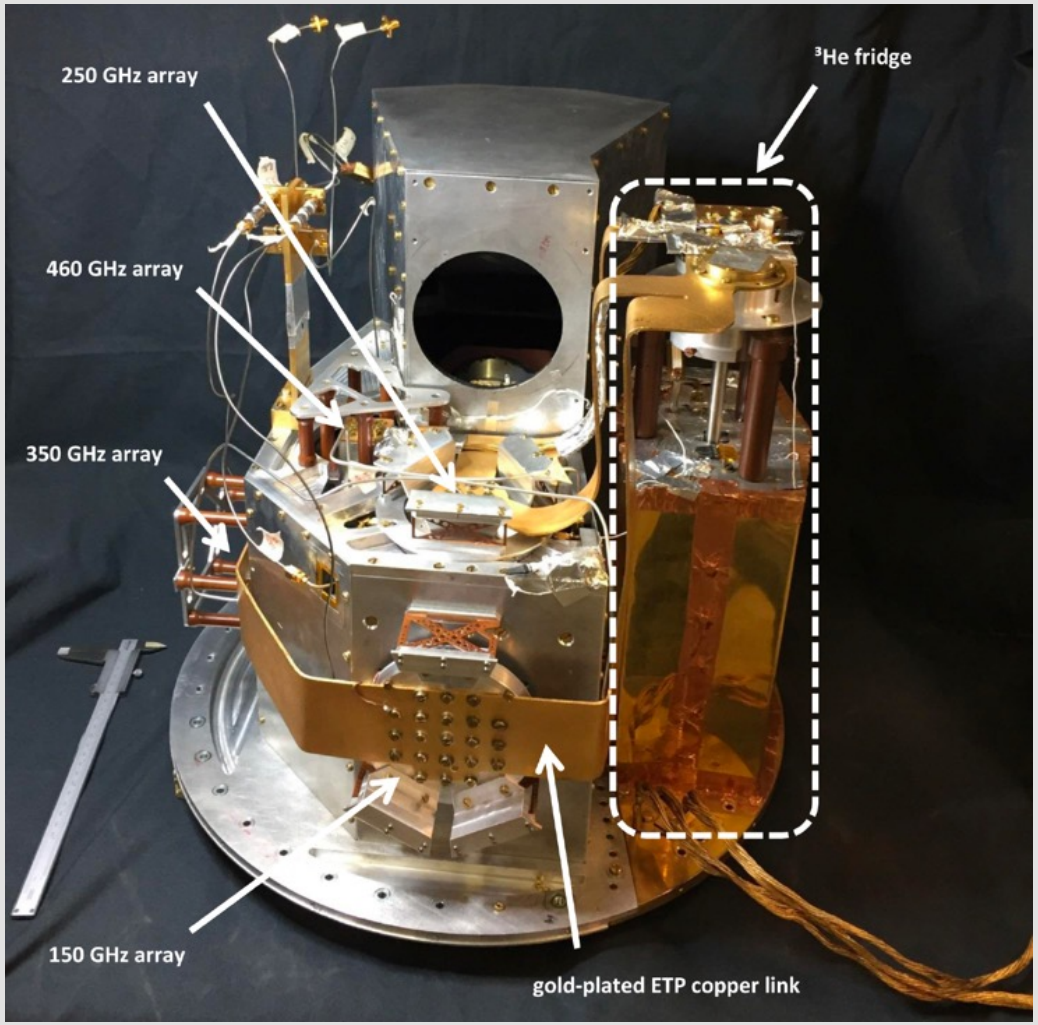
# What is the Best Path to Flying an SZ Balloon?

- In the USA, this is done via the NASA/APRA program
- Typical budget is $6-10M
- Given our science requirements, it would be difficult (impossible?) to do this starting from zero
- The Italian Space Agency recently flew the OLIMPO SZ balloon…



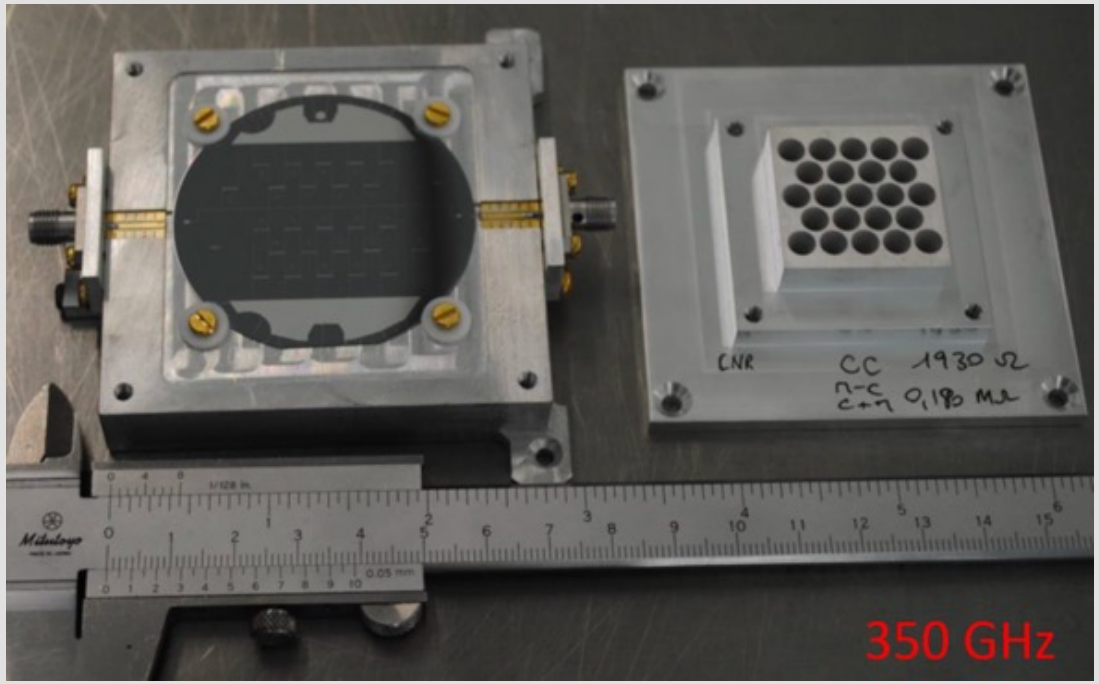
# The Original OLIMPO Concept – the Good

- OLIMPO was built for four-band operation at 150, 250, 350, and 460 GHz
  - Perfect for our SZ observations
- The primary mirror is 2.6 m in diameter
  - Provides 200 kpc resolution of nearby structures at $z \sim 0.05$, sufficient for our science
- The cryogenic system provides 25 days of operation
  - Sufficient to obtain the deep observations we require

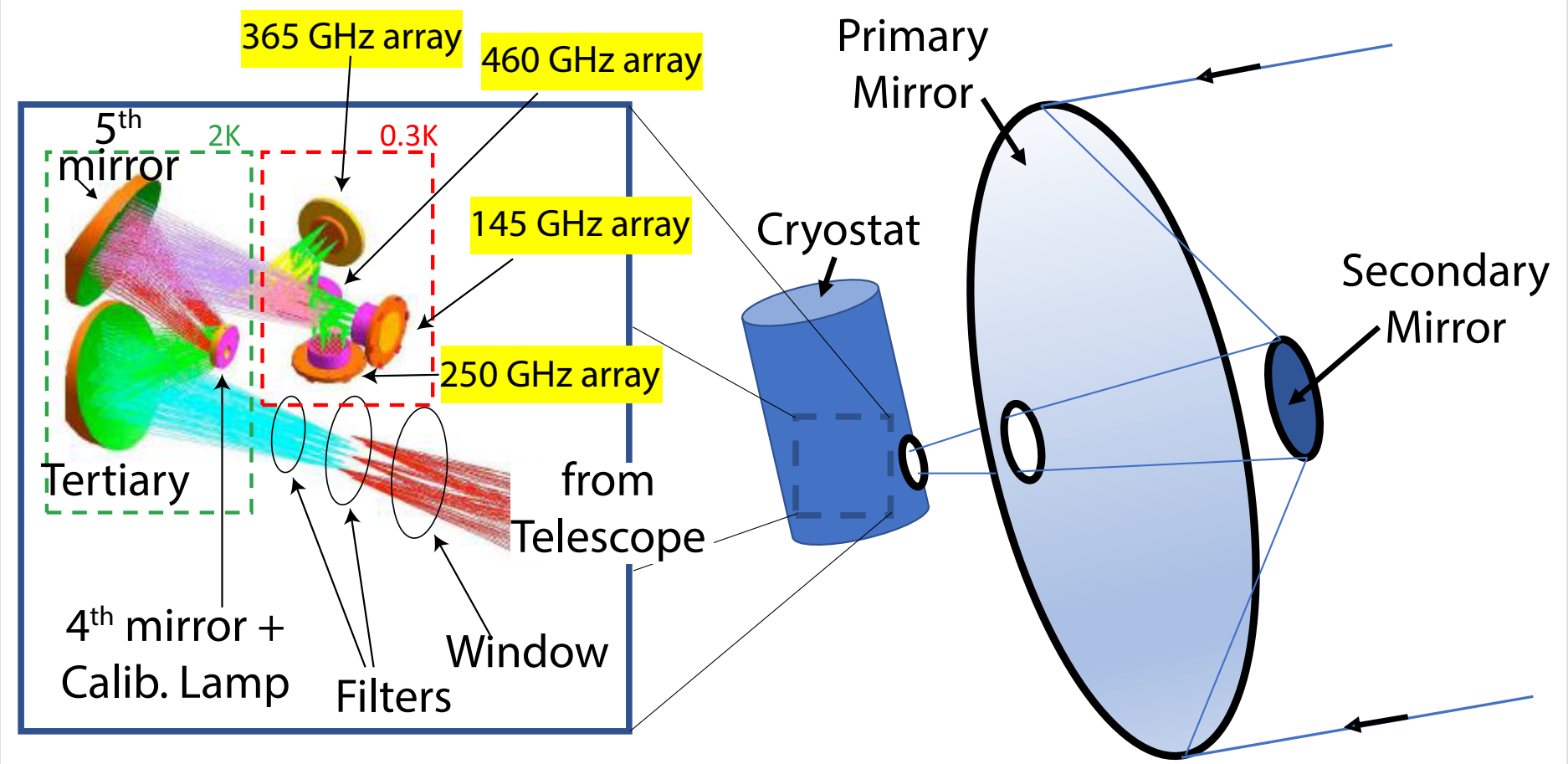


# The Original OLIMPO Concept – to Improve

- Total detector count is 120 (approximately 30 per band)
  - Insufficient sensitivity
  - We can upgrade to fill the field of view with 1030 total detectors
- Existing instrument has an FTS for medium resolution spectroscopy
  - Limits the field of view and reduces sensitivity
  - Not needed for our science, and so will be removed
- Readout upgrade using modern electronics to accommodate the increase in detectors
- Improve telemetry and motion control

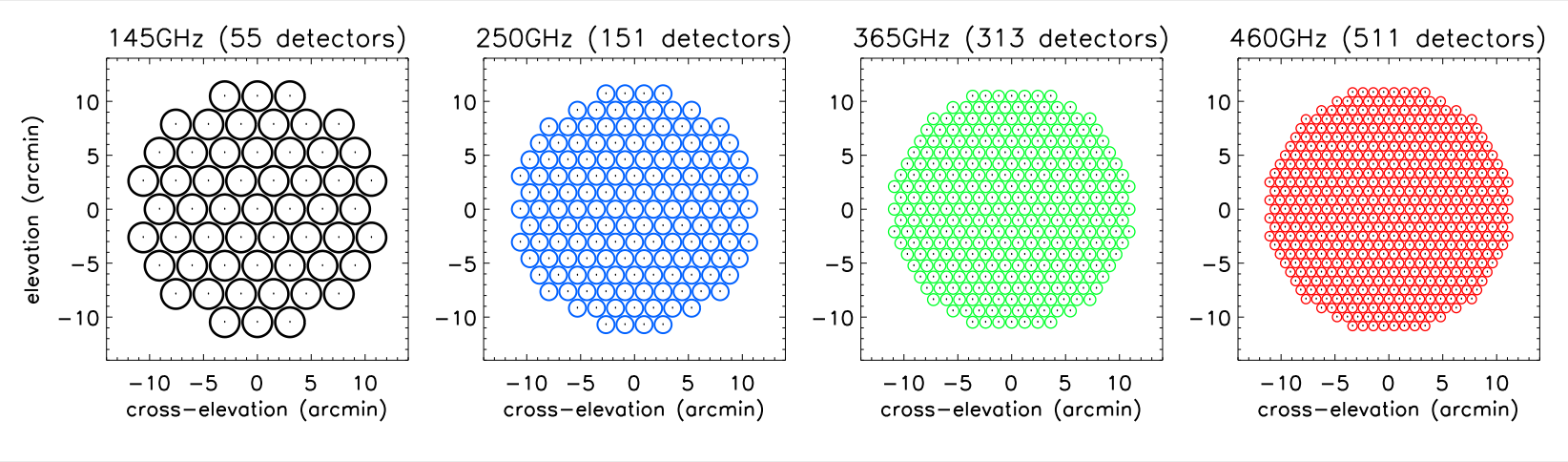


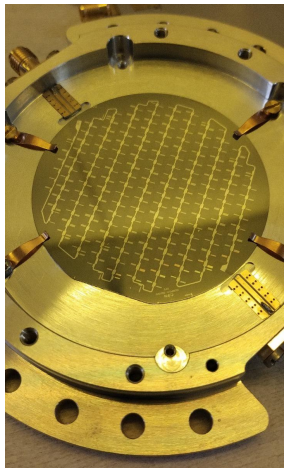
# New OLIMPO Optical Design

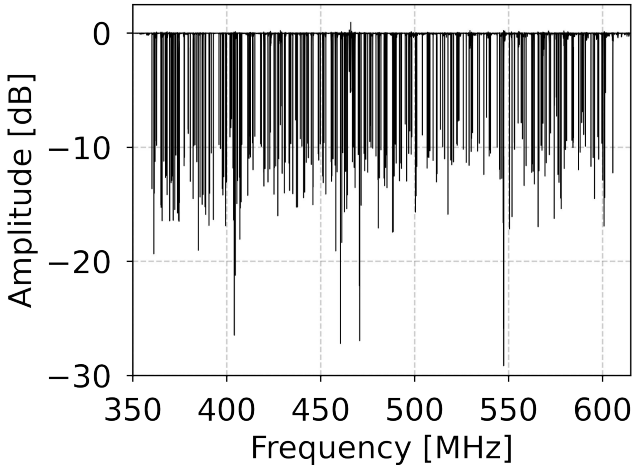


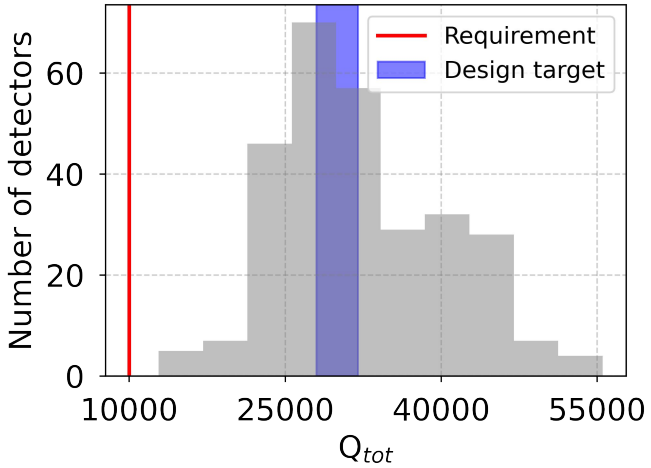
# Will Our Upgrades Allow For the Science?

- We can completely fill the available 24 arcmin field of view with detectors in all four bands
- A 350 GHz test array has already been fabricated and verified



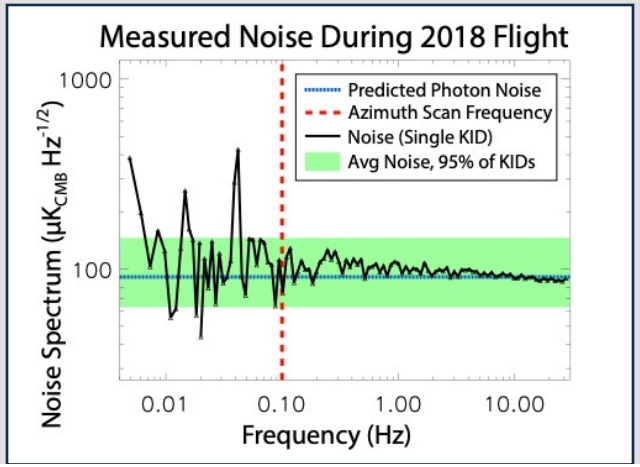





# How Sensitive Will the New OLIMPO Be?

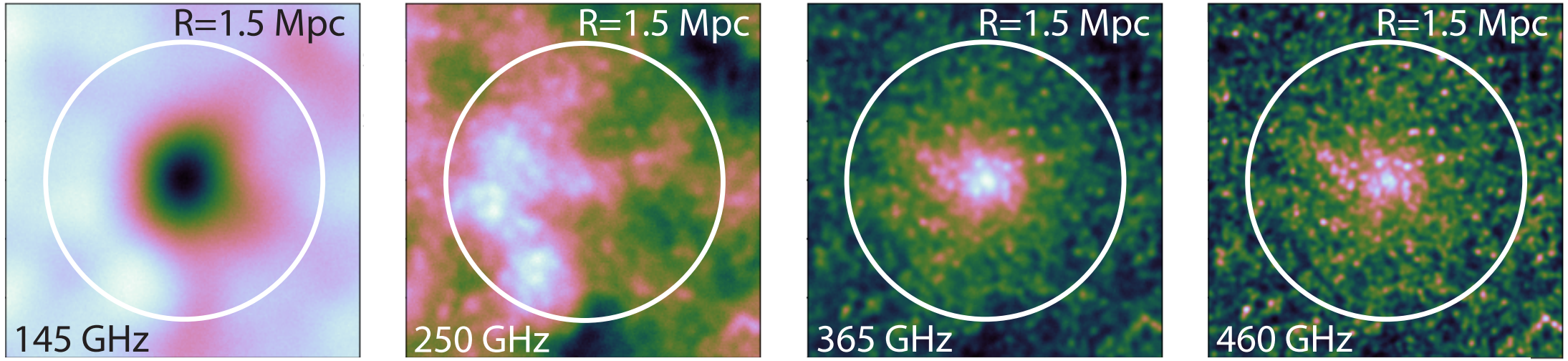
- From the measured performance of OLIMPO's prior flight, along with our optical model for the new design, we can project the sensitivity




| 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 $\text{NET}_{\text{CMB}}$ ($\times 10^{6}$ K$\sqrt{\text{s}}$) | 58 | 70 | 255 | 834 | - |
| Array $\text{NET}_{\text{CMB}}$ ($\times 10^{6}$ K$\sqrt{\text{s}}$) | 8 | 6 | 15 | 39 | 4.6 |

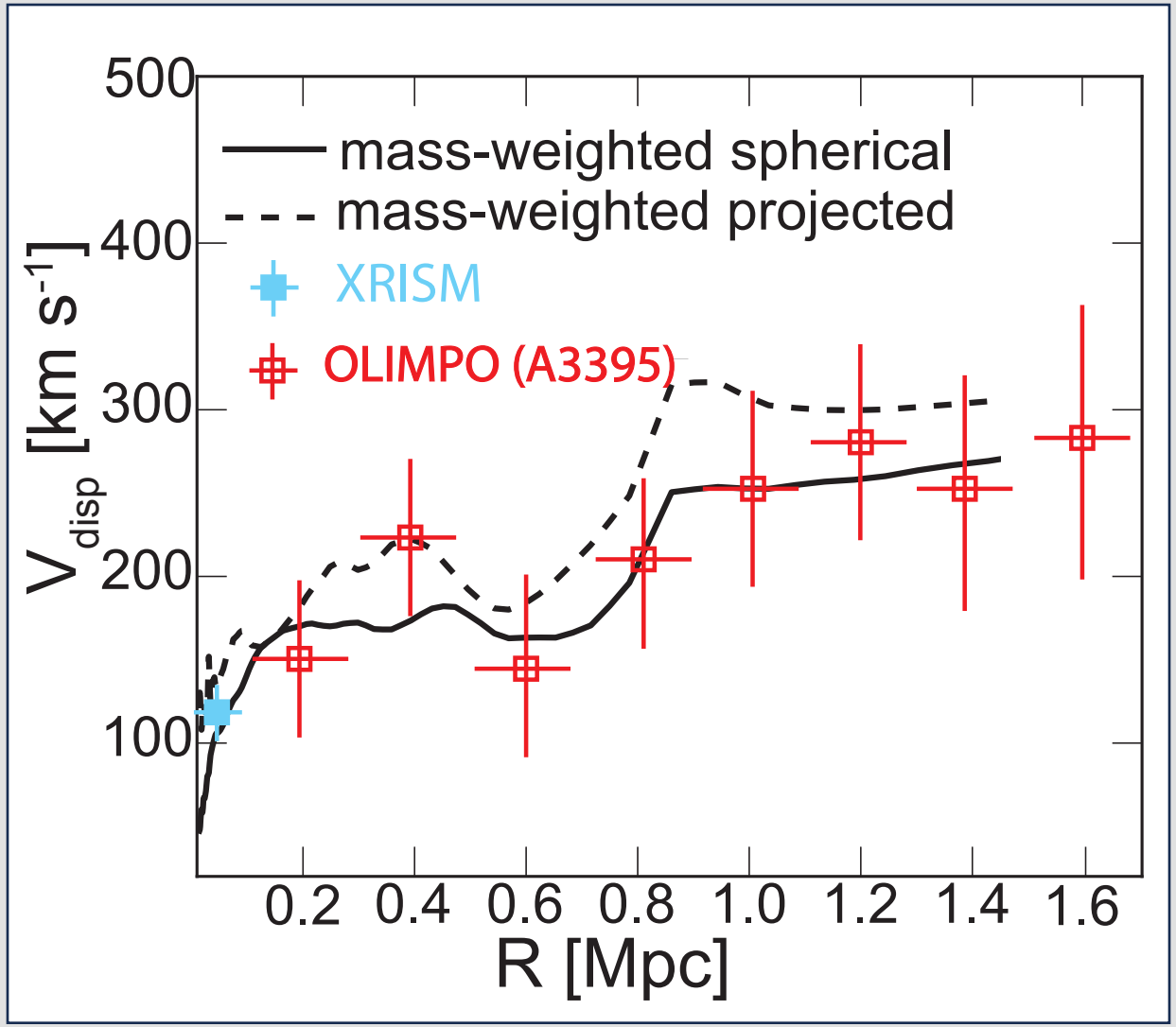
# Is This Sensitivity Sufficient For Our Science?

- Using the predicted sensitivity, along with our planned flight duration, we can create mock observations of galaxy clusters (and filaments)
- These need to include instrument noise and all relevant astrophysical contaminants
- The mocks can be analyzed to derive constraints on gas properties



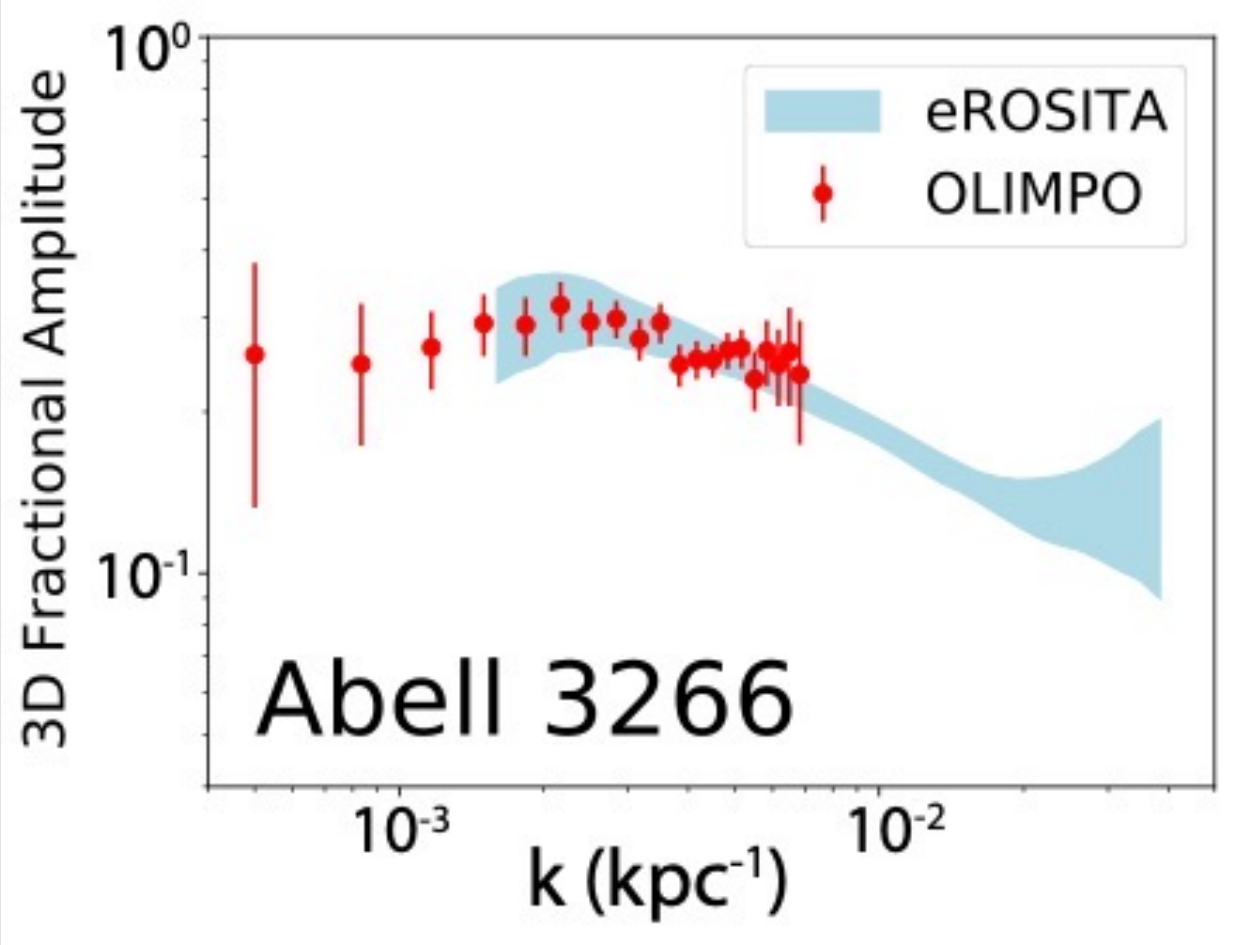
# Direct Velocity Measurements Via Kinematic SZ Effect

- What is the expected velocity structure?
  - Simulations suggest motions on the order of 300 km/s (or higher)
- We thus need to obtain a precision of approximately 100 km/s
  - Our mock observations suggest this will be the case



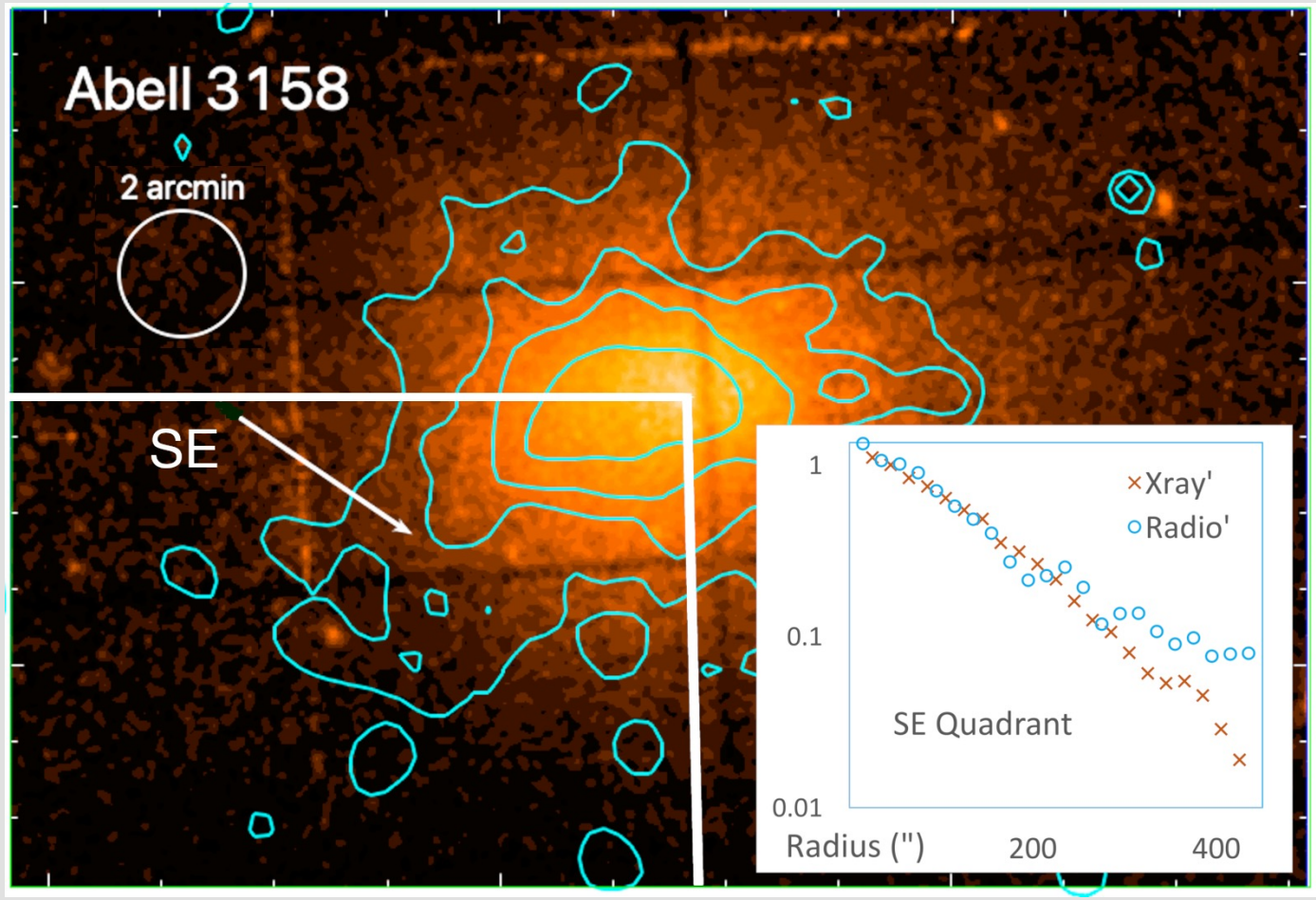
# Velocity Structure Via SZ (and X-ray) Fluctuations

- What is the expected fluctuation power spectrum?
  - At small scales (large k) it should have approximately a Kolmogorov-Taylor shape
  - Dissipation scale at ~100 kpc (beyond what we can probe)
  - A turnover at small k (~1 Mpc) corresponding to injection scale
  - Peak fractional amplitude of order 0.1
- We expect to measure these features at high significance



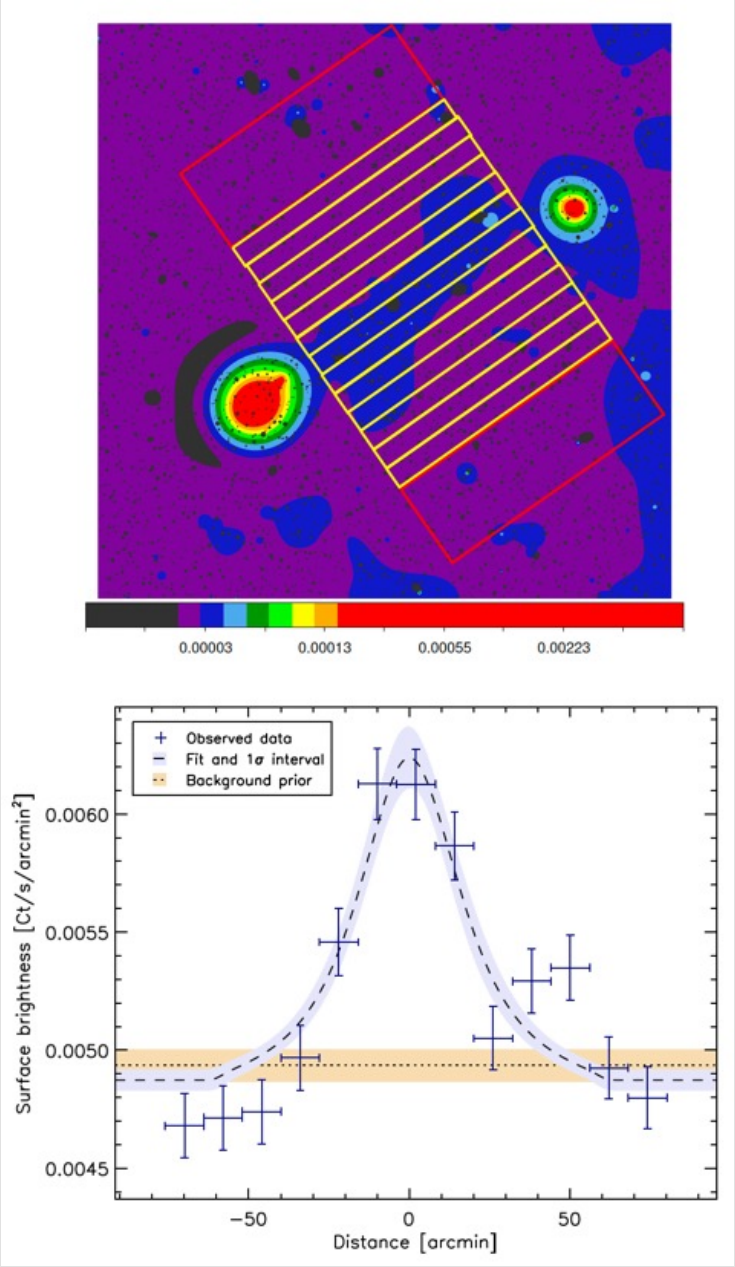
# Other Velocity Probes

- Diffuse radio emission is thought to trace relativistic particles
- Most likely process is re-acceleration via gas turbulence
- Excess radio emission should thus correlate with enhanced gas velocities
- We will be able to directly test this paradigm for the first time!

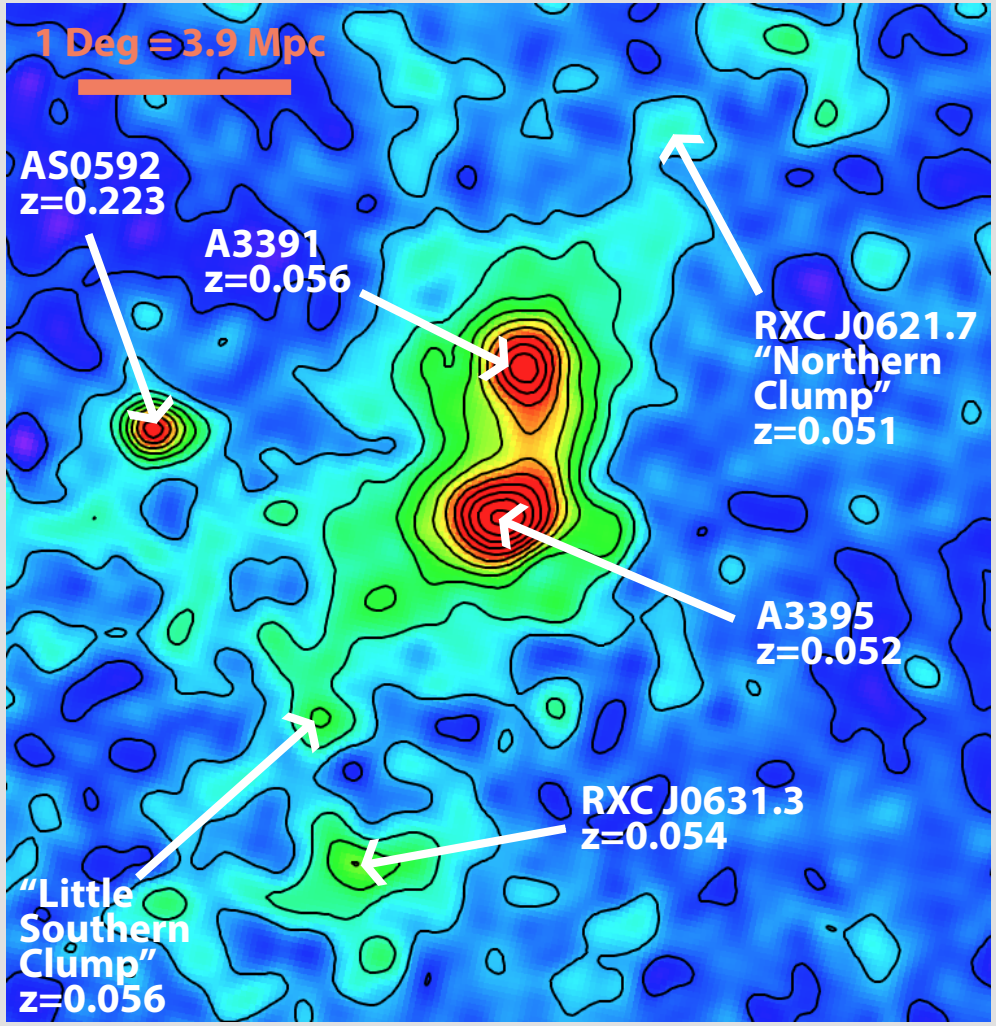


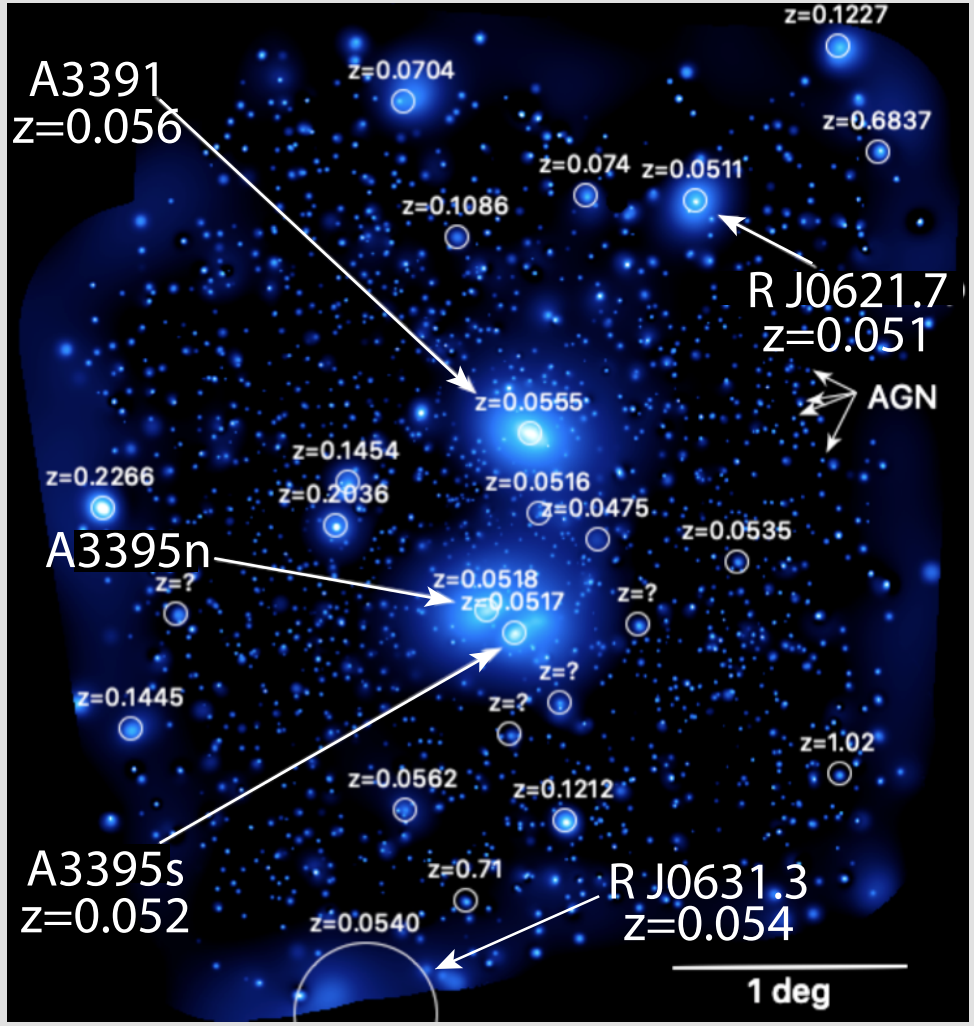
# WHIM Gas in Filaments

- eROSITA has demonstrated that it can detect the warm-hot gas in filaments
  - But temperature (and velocity) measurements remain elusive
- With OLIMPO we can detect the thermal SZ with a signal-to-noise of 20 per 200 kpc-sized pixel
  - Combined with eROSITA, we can measure temperature out to an axial radius of 1 Mpc
- Filaments are predicted to have a coherent axial rotation of 100 km/s
  - OLIMPO can measure such rotations to a precision of 20 km/s per filament



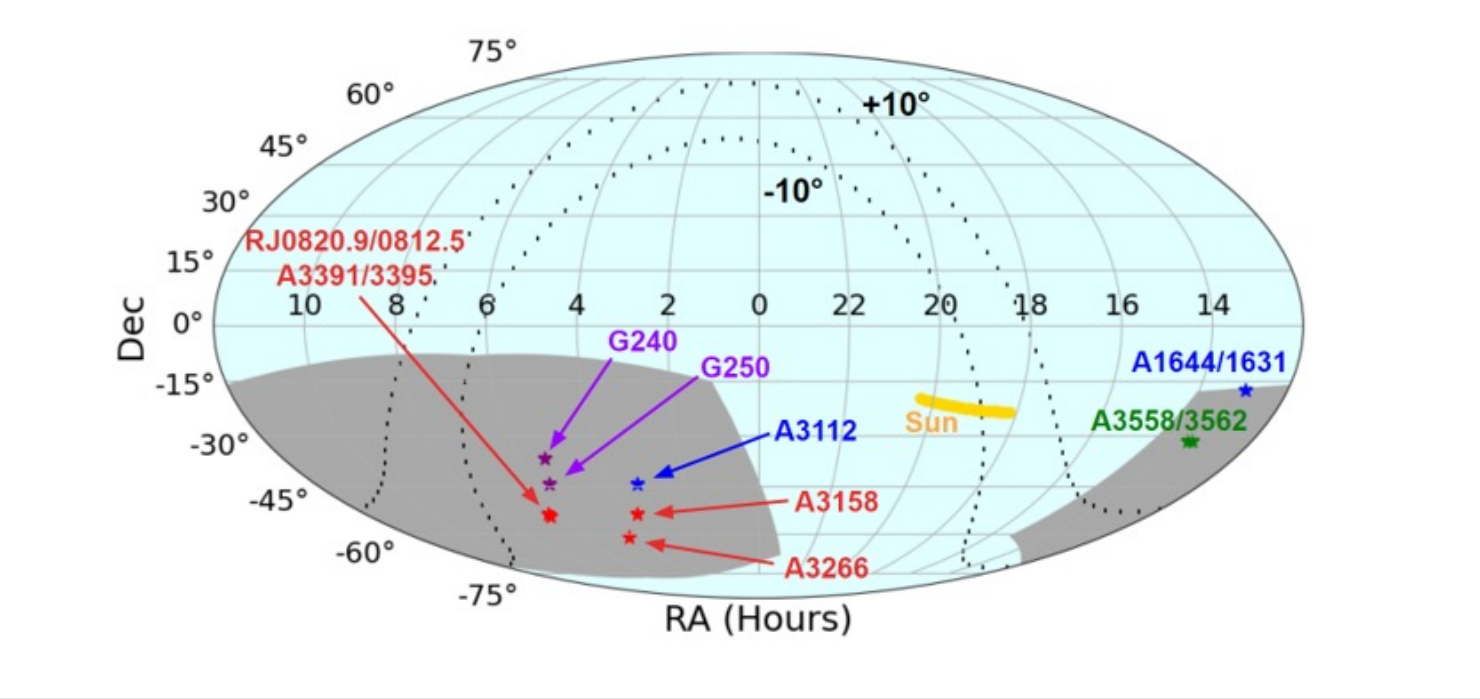
# WHIM Gas in Filaments (*Planck* and *eROSITA*)



# Can OLIMPO Observe Viable Targets?

- OLIMPO can only fly from Antarctica, and so it can only access a small portion of the sky
- This overlaps with the Western Galactic hemisphere (where *eROSITA* data are available)
- There are 9 clusters and 4 filaments with good *eROSITA* data available
  - Sufficient to completely fill a 25 day flight



# OLIMPO Targets

| Grp | Cluster | $z$ | Map† | Time (hrs) | *eROSITA* Cts ICM | *eROSITA* Cts Bridge | Cluster Properties | Bridge (Mpc) |
|---|---|---|---|---|---|---|---|---|
| 1 | R J0621.7 | 0.05 | $1.4^\circ \times 1.2^\circ$ | 95 | 250k†† | 2.3k | Weak Cool-Core [37] | 2.8 |
| | Abell 3391 | 0.05 | $1.4^\circ \times 1.2^\circ$ | 95 | 1.74M | 14.4k | Disturbed [37] | 1.1 |
| | Abell 3395 | 0.05 | $1.4^\circ \times 1.2^\circ$ | 95 | 1.25M | 3.3k | Merging Binary [37] | 5.1 |
| | R J0631.3 | 0.05 | | | 71k†† | | Shock w/ Relic [100] | |
| | Abell 3158 | 0.06 | $0.8^\circ \varnothing$ | 50 | 1.60M | N/A | Disturbed [101, 102] | N/A |
| | Abell 3266 | 0.06 | $0.8^\circ \varnothing$ | 50 | 2.47M | N/A | Merger, 2 Shocks [79] | N/A |
| 2 | Abell 1644 | 0.05 | $2.8^\circ \times 0.8^\circ$ | 95† | 240k†† | 740 | Sloshing Core [103] | 5.9 |
| | Abell 1631 | 0.05 | | | 140k†† | | Very Low X-Ray SB [104] | |
| | Abell 3112 | 0.07 | $0.8^\circ \varnothing$ | 50 | 3.8M†† | N/A | Cool-Core [105] | N/A |

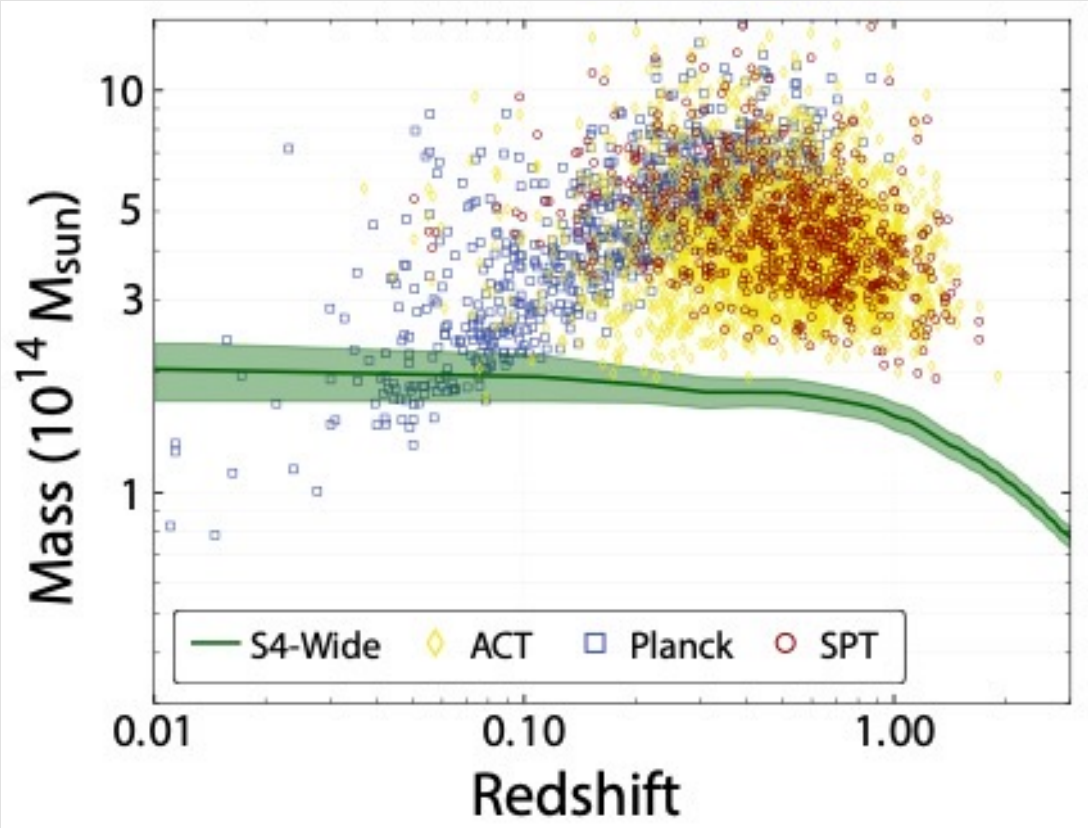
# Are We Confident the Science Goals Cannot Be Achieved With Existing Facilities?

- As a first check, let's compare raw sensitivity with other relevant past and planned facilities
- Existing *Planck* data are 2-3 orders of magnitude less sensitive
- A future combination of CCAT-P and CMB-S4 is close….

| Map Noise ($\mu K_{CMB}$–arcmin) | | | | | |
|---|---|---|---|---|---|
| Instrument | Frequency Band (GHz) | | | | Notes |
| | 145 | 250 | 365 | 460 | |
| OLIMPO | 1.2 | 0.9 | 2.3 | 5.8 | 9 clusters + 4 filaments |
| *Planck* [39] | 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 [40] | 2.0 / 1.0 | 5.7 / 3.5 | N/A | N/A | wide 29k $deg^2$ / deep 1200 $deg^2$ |

# But CCAT-P and CMB-S4 Operate From the Ground (Through the Atmosphere)

- Even though CMB-S4 is two orders of magnitude more sensitive than *Planck*, *Planck* is better able to detect clusters at $z \leq 0.05$
- This is because these clusters span degree scales, where atmospheric fluctuations are severe
- Thus, even with sensitivity comparable to OLIMPO, CCAT-P and CMB-S4 cannot achieve our science goals



# Can We Complete OLIMPO Within the Allowable Budget for NASA/APRA?

- We have now established that by upgrading OLIMPO, in combination with *eROSITA*, we can achieve unique science to better understand large-scale structure growth and the WHIM
- This science cannot be obtained with any other existing or planned facilities
  - At least until the late 2030s with *NewAthena*
- But, how much will it cost?

# What is OLIMPO's Budget?

- New hardware is needed
  - Readout electronics, drive motors, telemetry system, etc.
- New detector arrays are needed
  - Will be provided by Italian partners (i.e., free to NASA/APRA)
- By far, the biggest costs are associated with labor
  - Person effort is needed to design, test, and integrate all of the new instrument components
  - Person effort is needed to fly the balloon (including target planning)
  - Person effort is needed to analyze the SZ data (calibration, etc.)
  - Person effort is needed to reduce X-ray and radio data
  - Person effort is needed to combine the SZ, X-ray, and radio data in order to obtain constraints on the gas properties
  - Person effort is needed to produce numerical simulations of the gas to test for systematics in our analysis and to assist with interpretation

# Is OLIMPO Viable?

- Because we are leveraging so much existing hardware, along with Italian contributions (upgraded detectors), we are able to fit our ambitious science program within a viable NASA/APRA budget
- Without these “free” contributions, compromises would be needed
  - Reduced instrument capabilities?
  - A less thorough scientific analysis?
  - A combination of both?
- Is OLIMPO “ideal”
  - No…
  - The likely first upgrade path would be a larger primary mirror
    - Not only could we resolve smaller gas structures
    - But we could also better remove astrophysical contamination to obtain better sensitivity limits
    - On a balloon, total mass is highly constrained, and so the $D^{2.6}$ scaling is difficult to overcome
- This is usually the regime where any realistic instrument concept ends up
  - Not “ideal”, but capable of delivering new and interesting science that cannot otherwise be achieved