Tony Mroczkowski
European Southern Observatory (ESO)

2022-November-09

The AtLAST project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951815

Observations of the SZ effect in the *Athena* Era

The thermal Sunyaev-Zeldovich Effect

thermal SZ

Arises because of thermal motion of (non-relativistic) electrons

$$\delta i_{\text{tsz}} \propto \frac{x^4 e^x}{(e^x-1)^2}\left[x\frac{e^x+1}{e^x-1}-4\right]\int n_e T_e \,\mathrm{d}l$$

$$x = h\nu / k_b T_{\text{cmb}}$$

- distinctive spectral signature
- redshift-independent surface brightness

Measure of the line-of-sight integral of electron thermal **pressure**

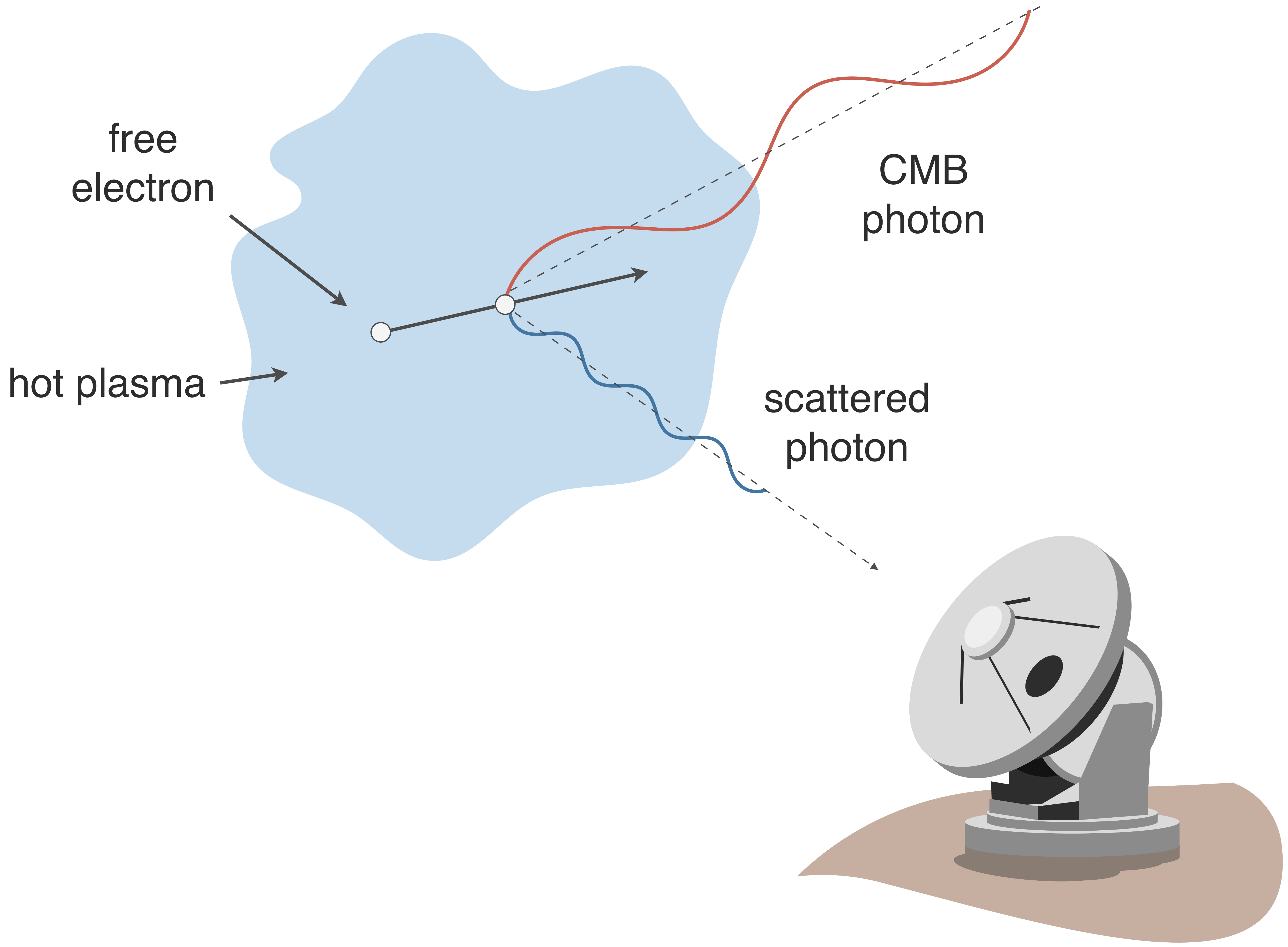


Image is courtesy of Luca Di Mascolo

The kinetic Sunyaev-Zeldovich Effect

kinetic SZ

Doppler effect due to bulk motion of clusters relative to CMB rest frame

$$\delta i_{\mathrm{ksz}} \propto \frac{x^4 e^x}{(e^x - 1)^2} \int n_{\mathrm{e}} v_{\mathrm{e}} \, \mathrm{d}l$$

- redshift-independent surface brightness
- T_{CMB} blackbody spectrum
- independent of Hubble flow

Traces line-of-sight **peculiar velocity (momentum)** of electron distribution

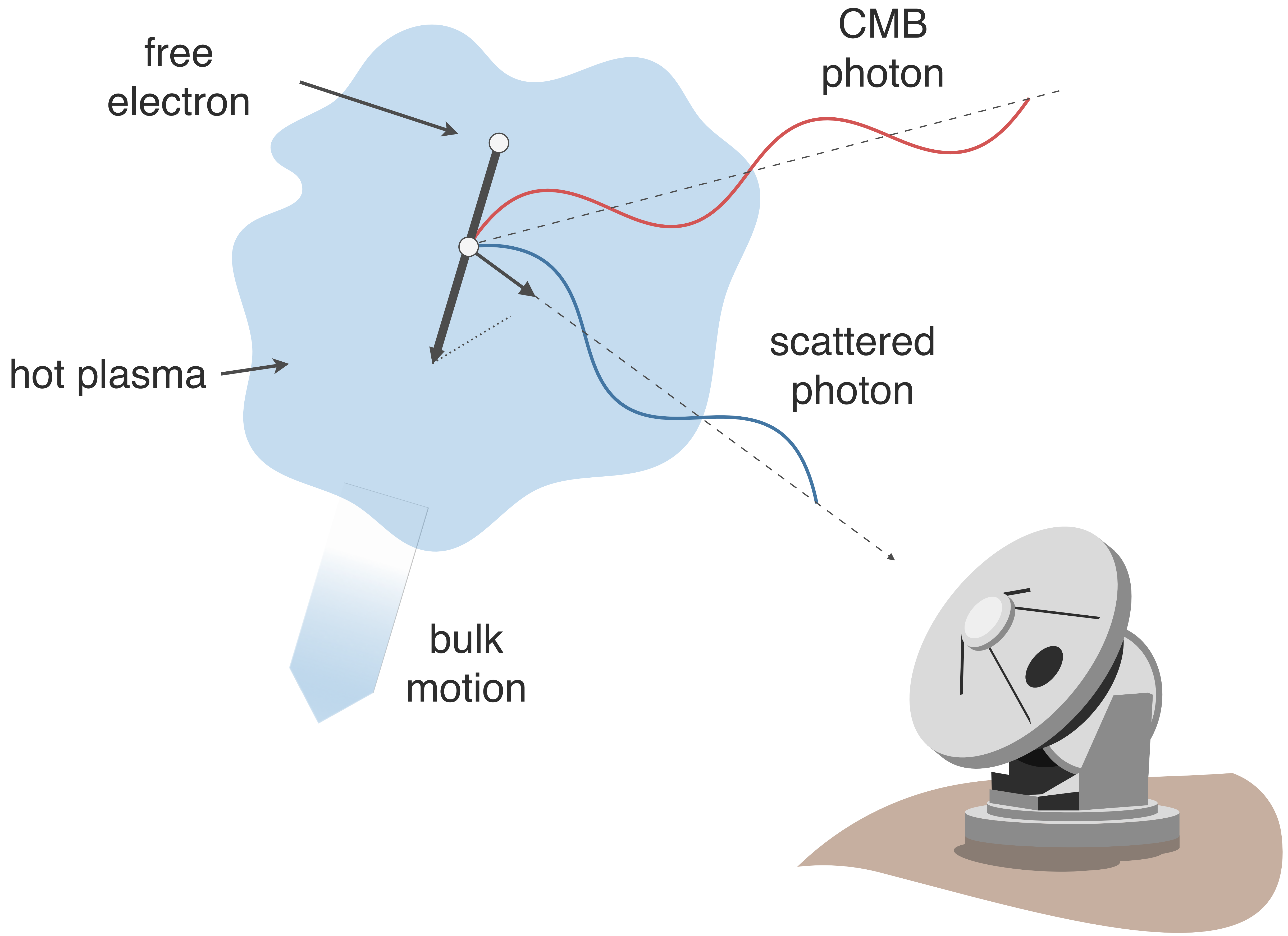
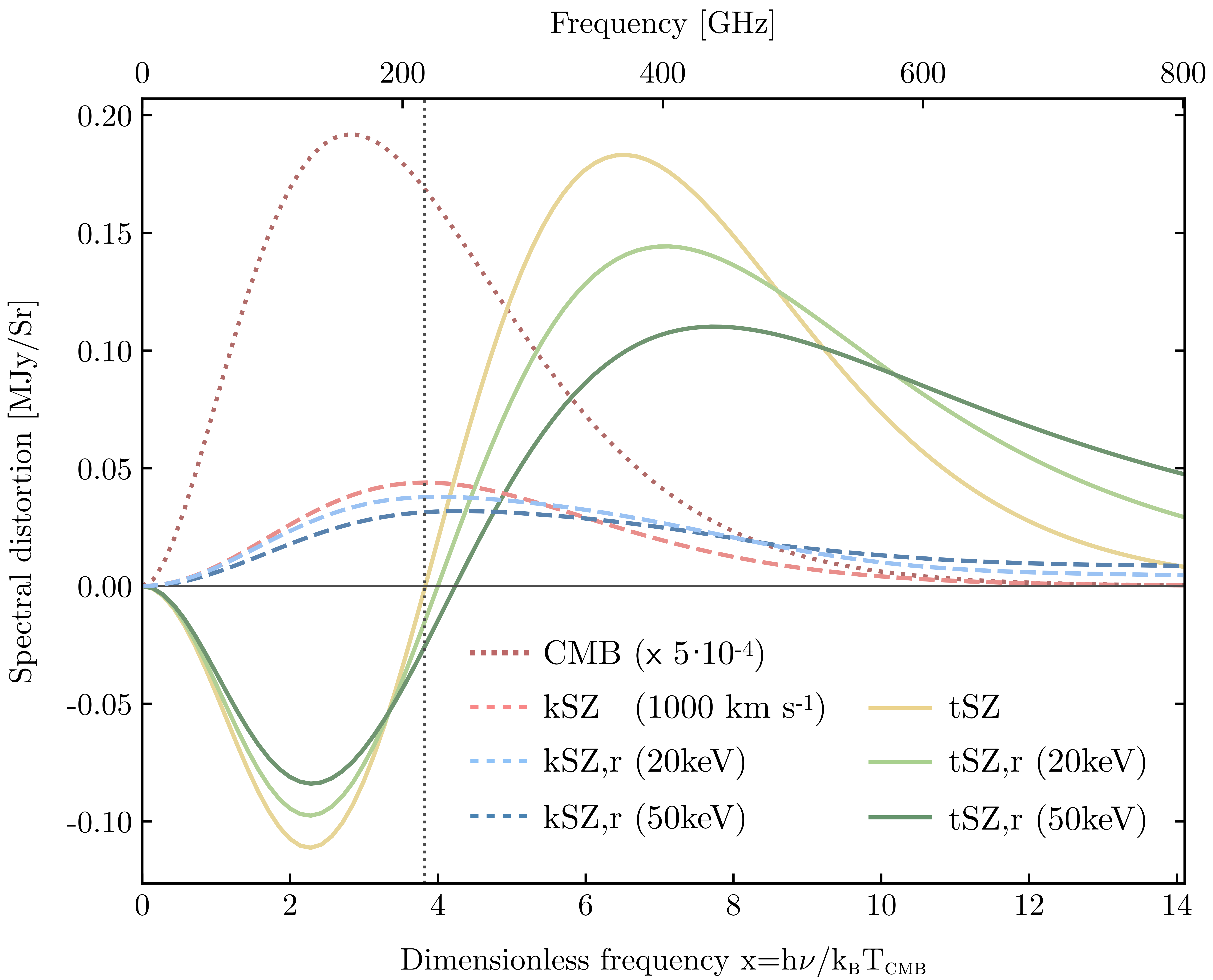


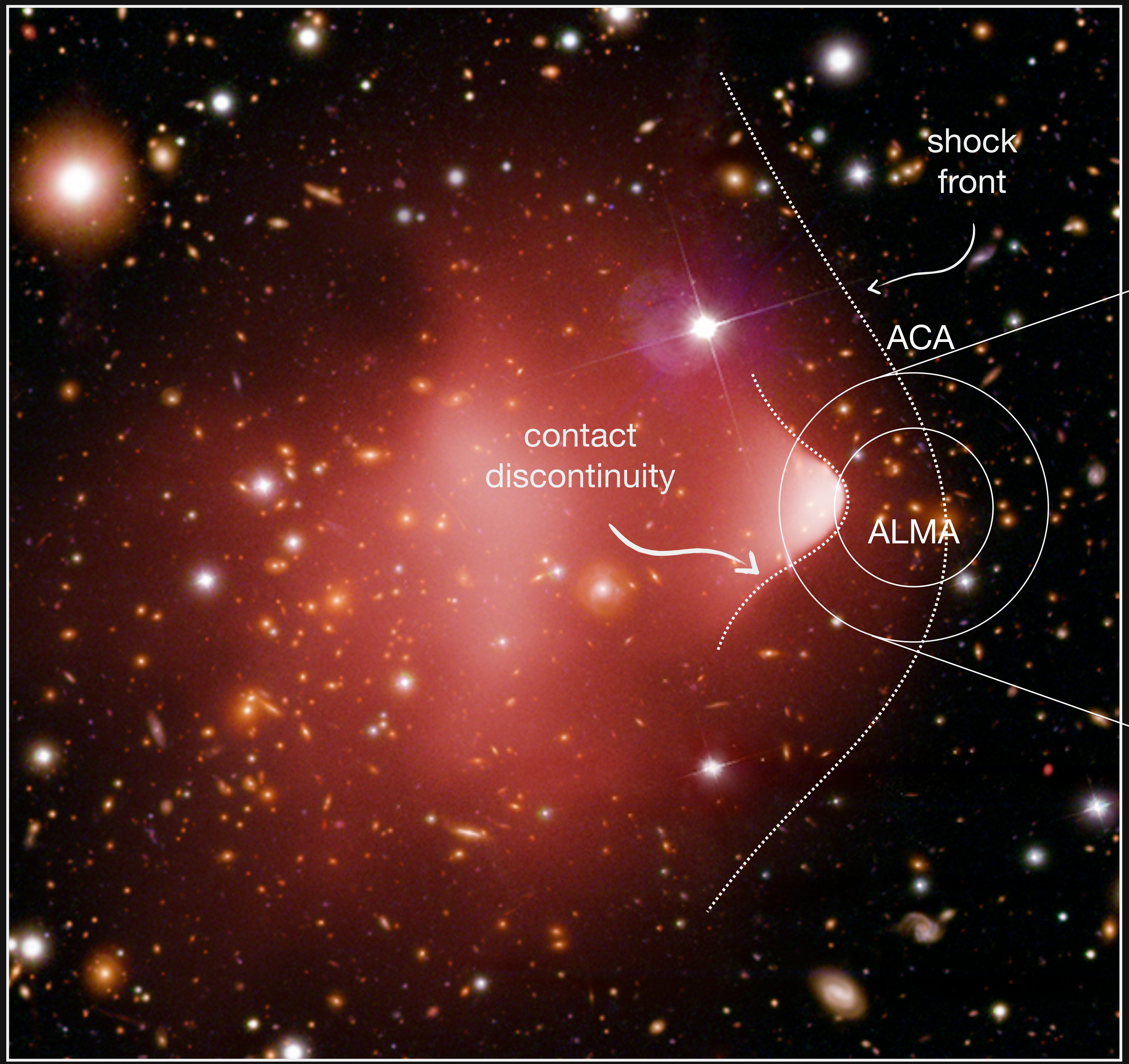
Image is courtesy of Luca Di Mascolo

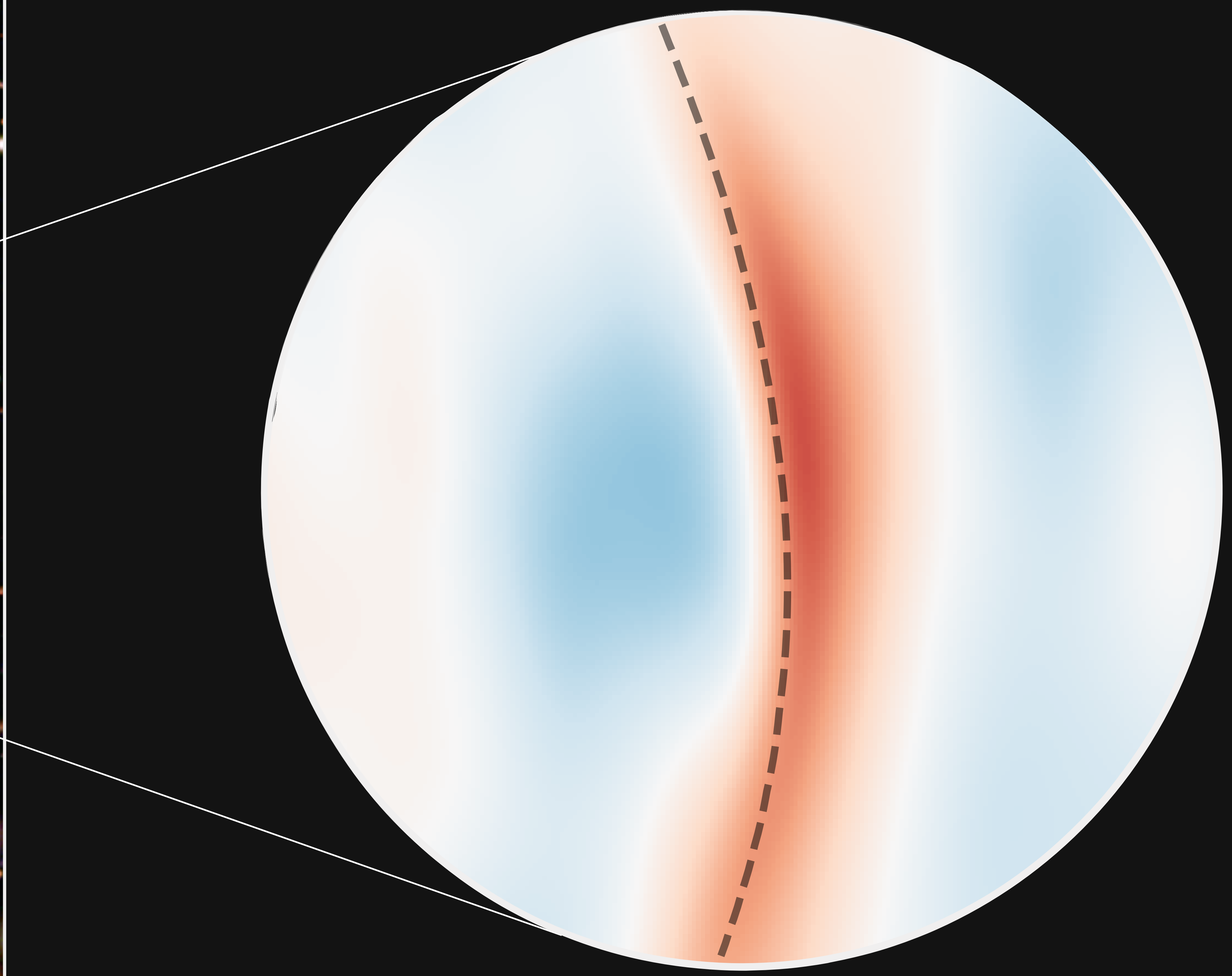
Overall tSZ and kSZ distortions



ALMA

The Bullet cluster

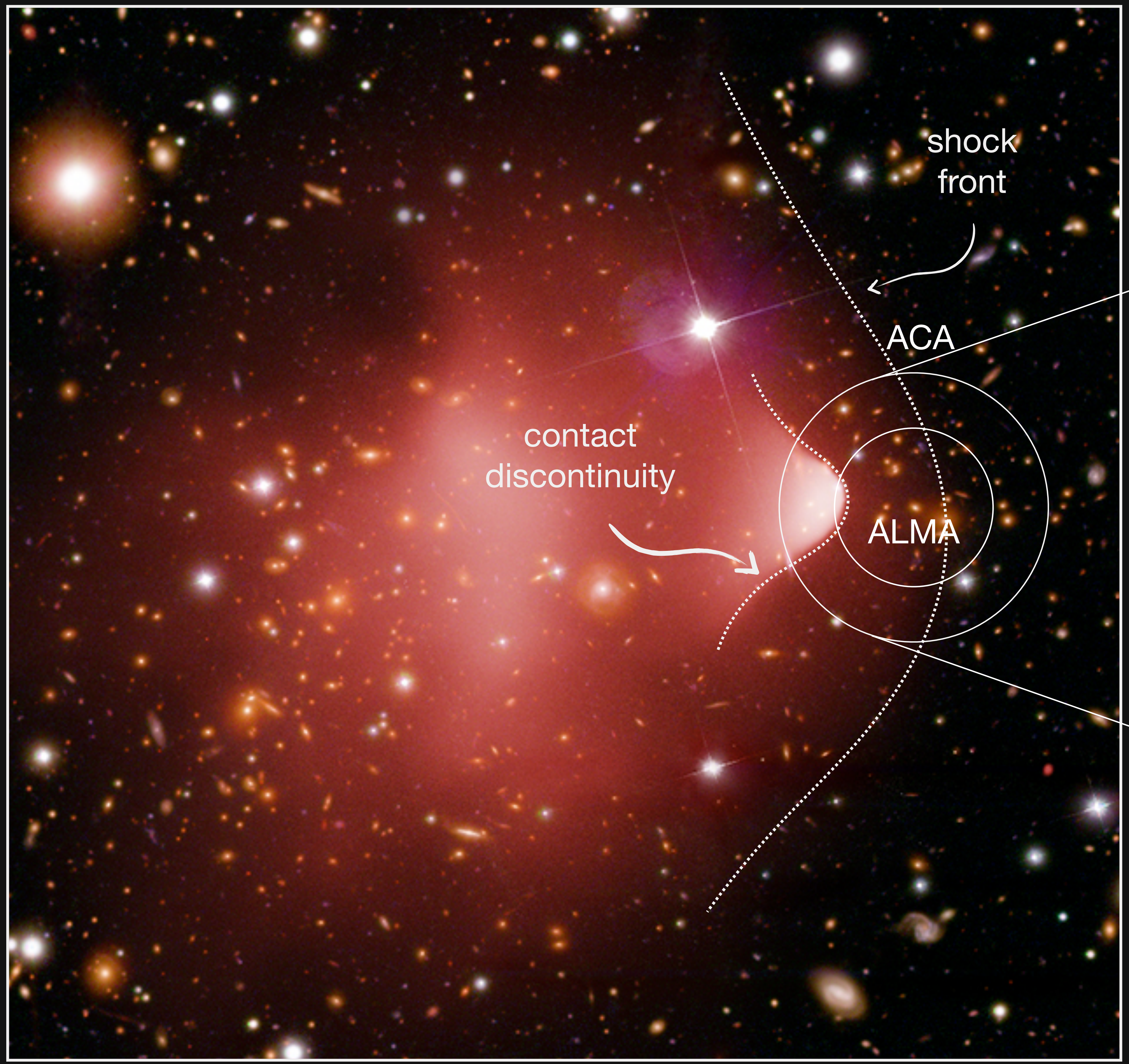


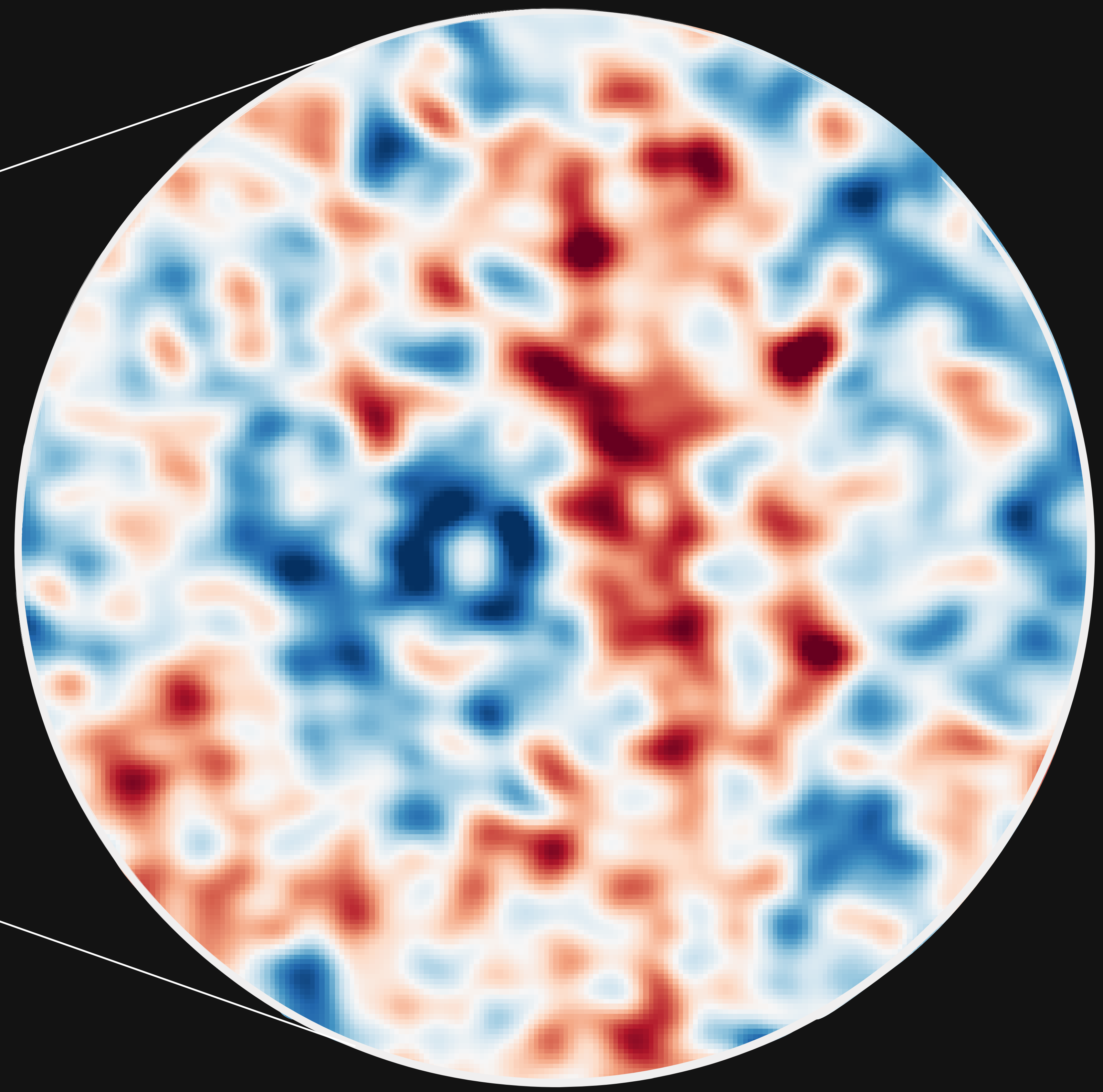


ALMA Band 3 Model

Di Mascolo, Mroczkowski, et al., 2019, A&A, 628, A100

The Bullet cluster





ALMA Band 3 Data

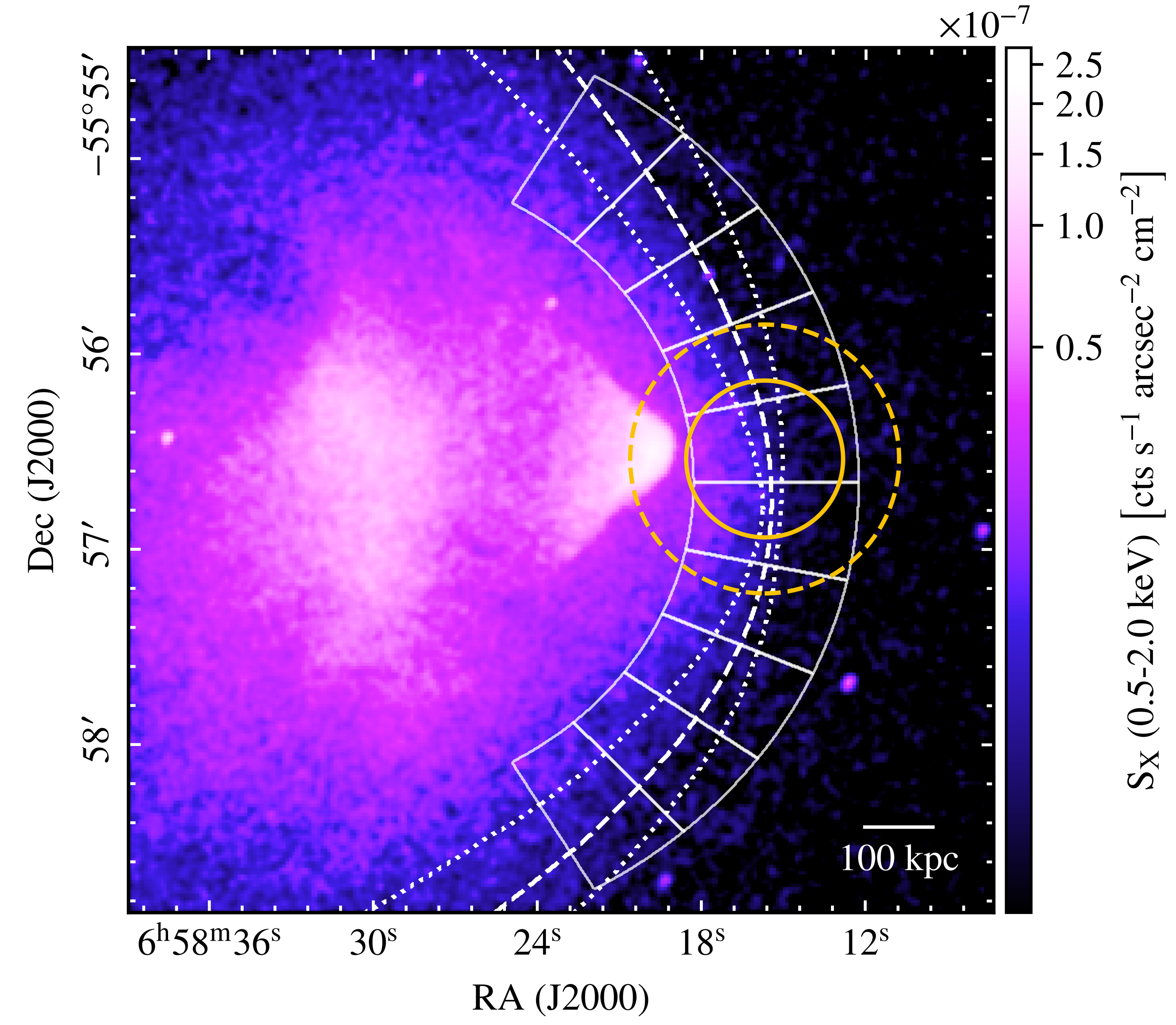
Di Mascolo, Mroczkowski, et al., 2019, A&A, 628, A100

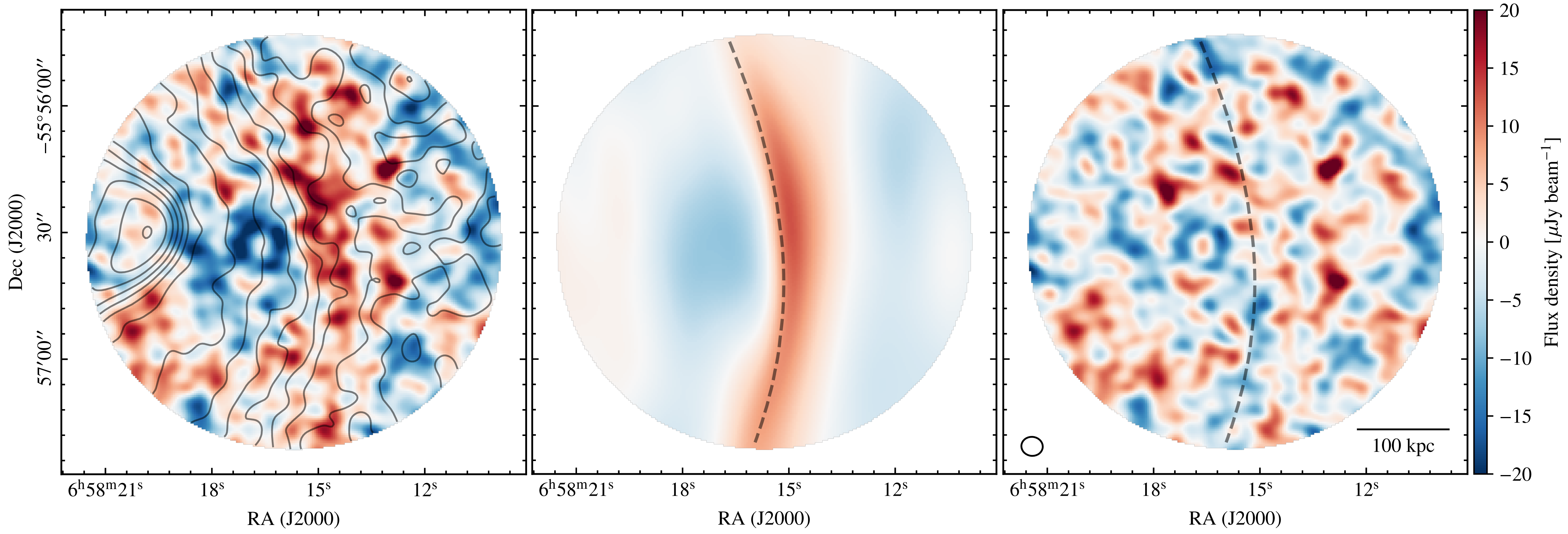
ALMA SZ observations of the Bullet

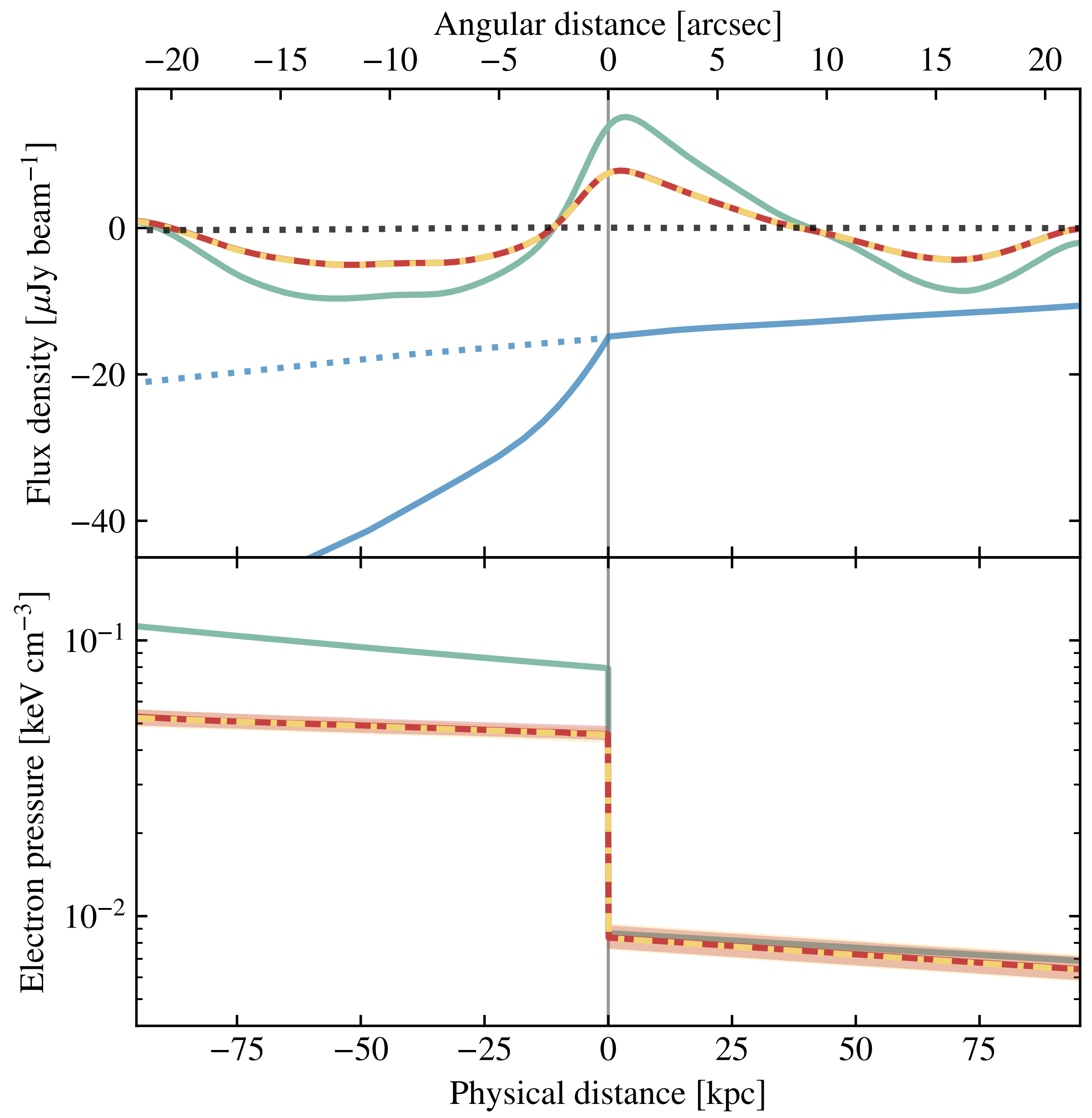
- We obtained ALMA & ACA Band 3 data (11 and 21 ksec) *way back* in Cycle 2 to probe the shock in the Bullet cluster. We have now deeper and more extended observations with the ACA.

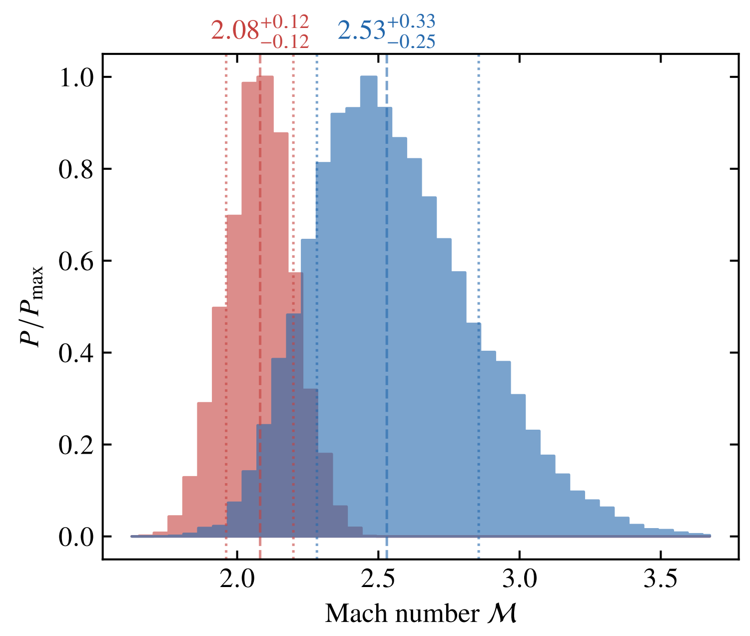
- While merger velocities provide tests of cosmology, we used these observations for constraints on the electron-ion equilibration time. We find *the electron-ion equilibration is more naturally explained by adiabatic processes* (for comparison, see also Russell et al. 2022 results on A2246).

- For ALMA, the big challenge is interferometric filtering and the lack of information on scales >1.7'. See Di Mascolo et al. 2019, A&A, 628, A100.





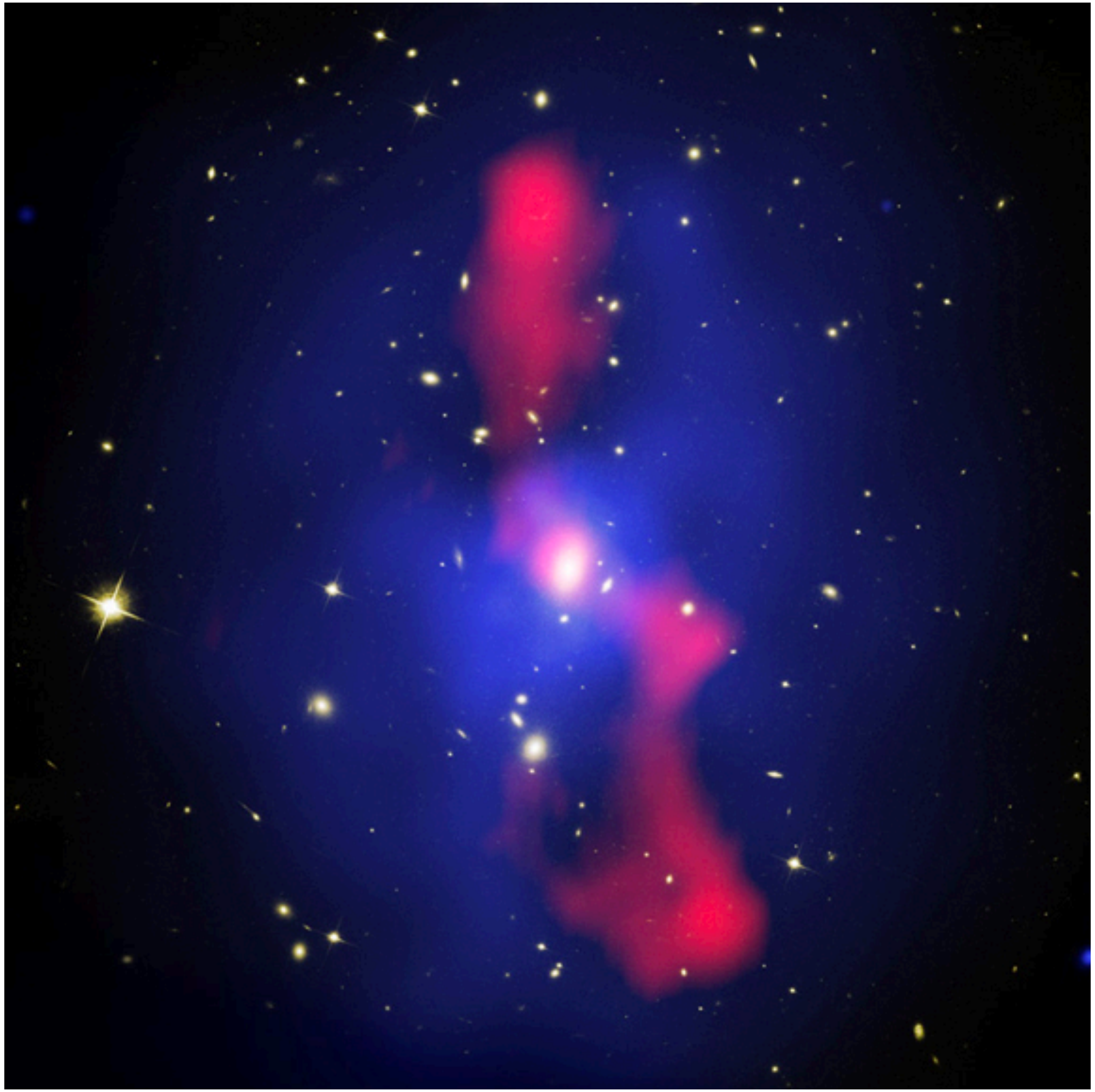




MS0735.6+7421

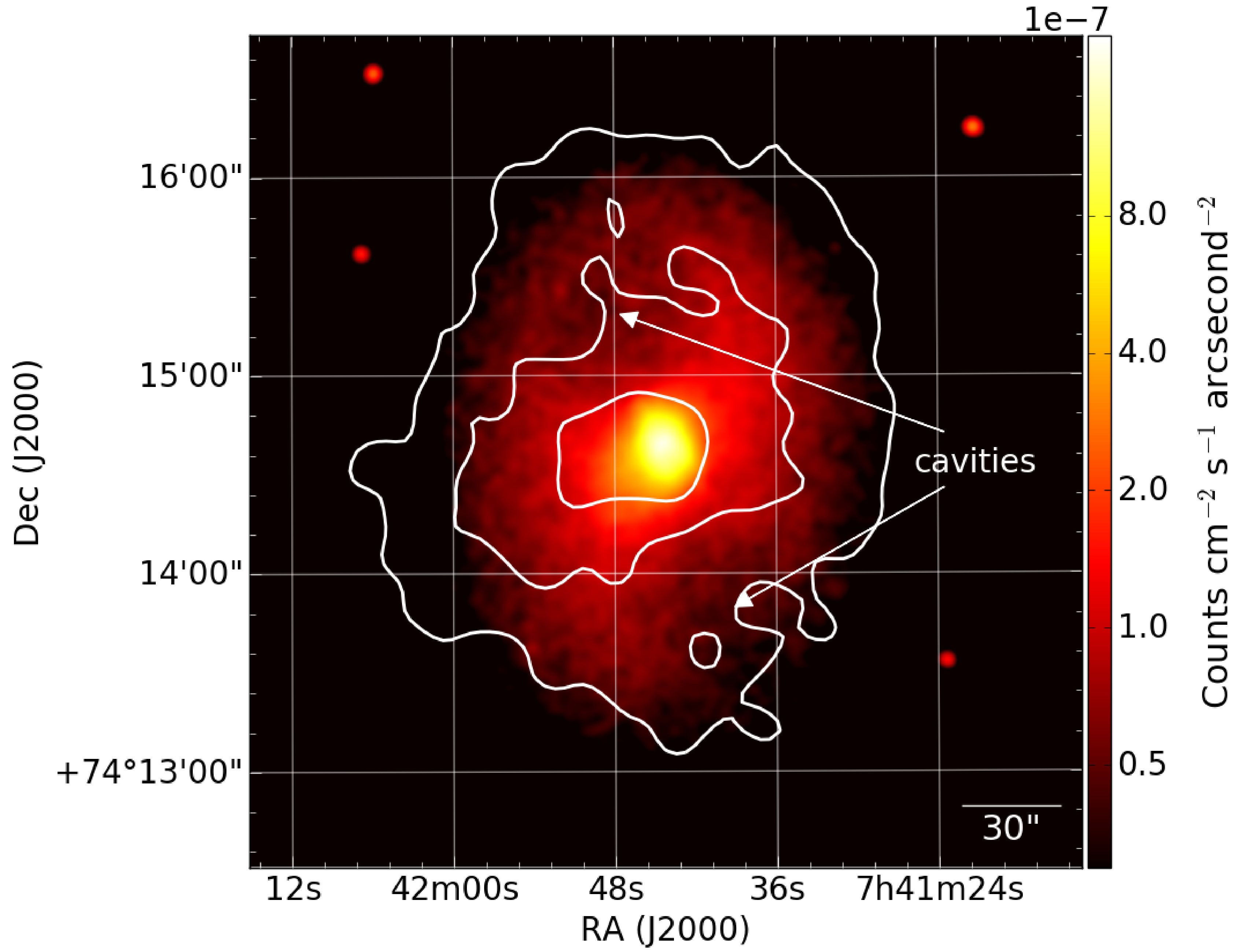
AGN bubbles/cavities

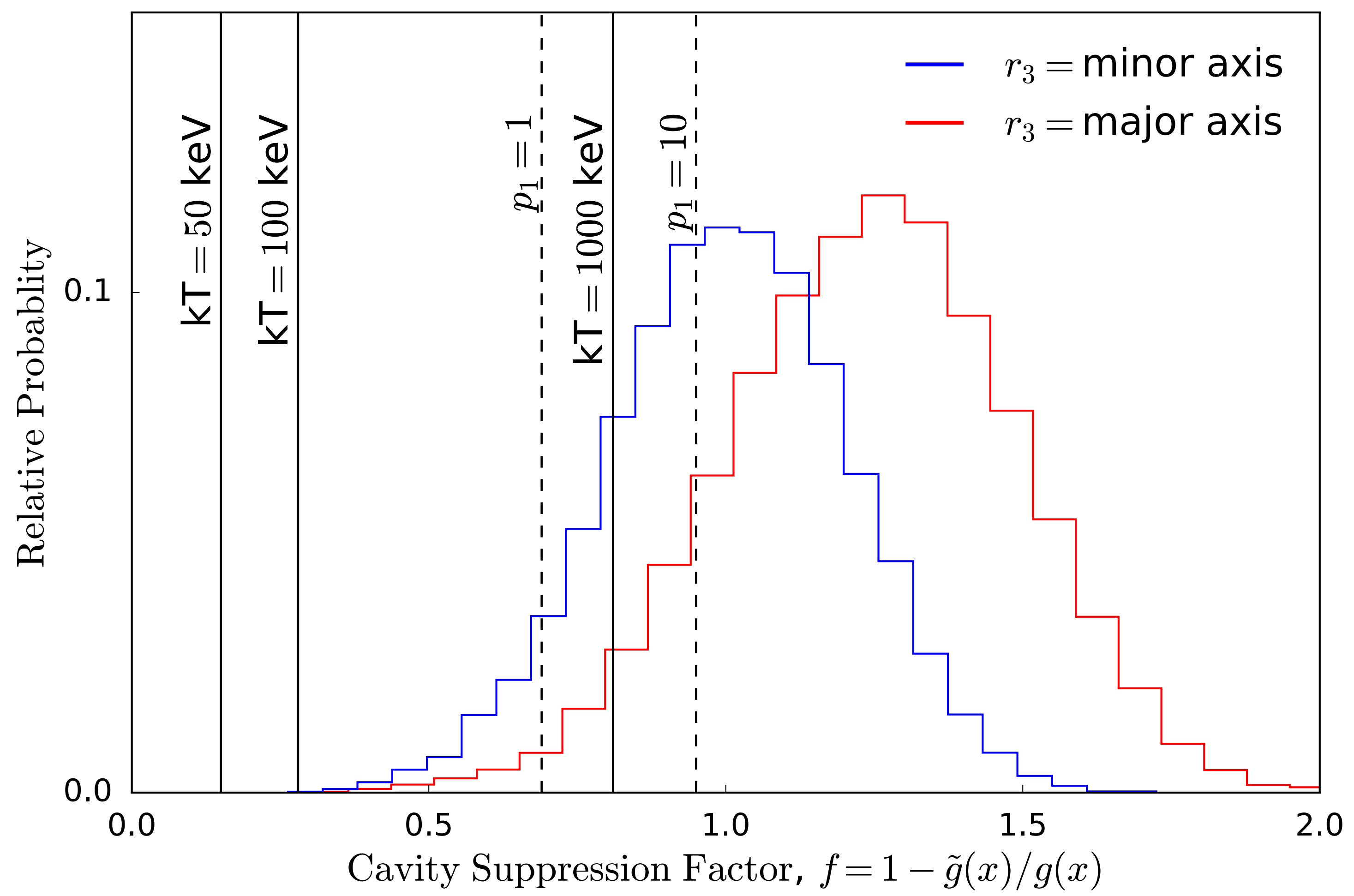
- 2nd most energetic AGN-driven X-ray cavities (or radio bubbles) known
- Blue is Chandra X-ray; Red is VLA radio.
- Figure is from https://chandra.harvard.edu/photo/2006/ms0735/
- see also the recent LOFAR imaging from Bégin et al. and deeper Chandra observations in Vantyghem et al. 2014

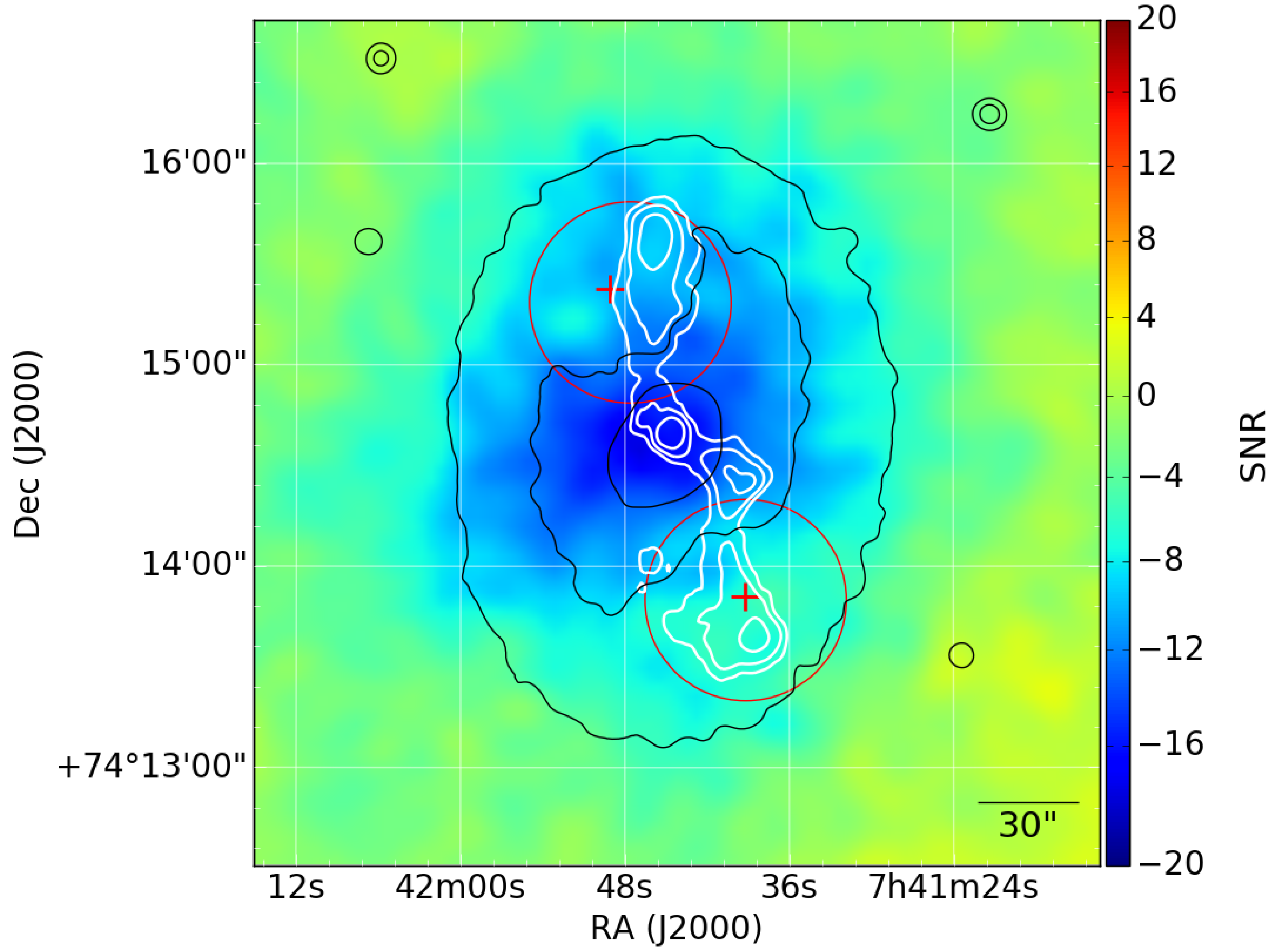


MS0735.6+7421

- These figures are from Abdulla et al. 2019, showing the constraints from CARMA 30 GHz data
- These first SZ constraints came from CARMA 30 GHz measurements, modeled using the X-ray model fit in Vantyghem et al. 2014.



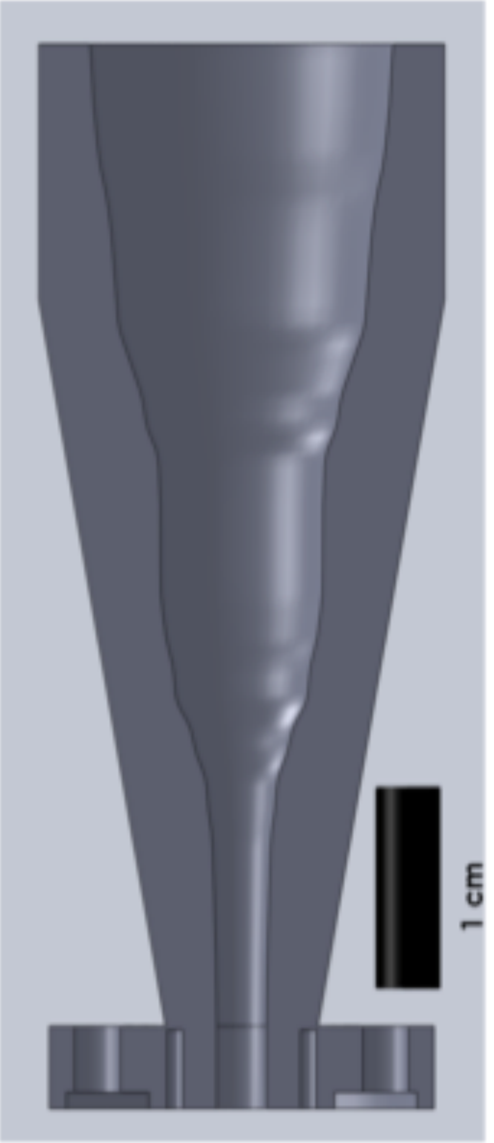


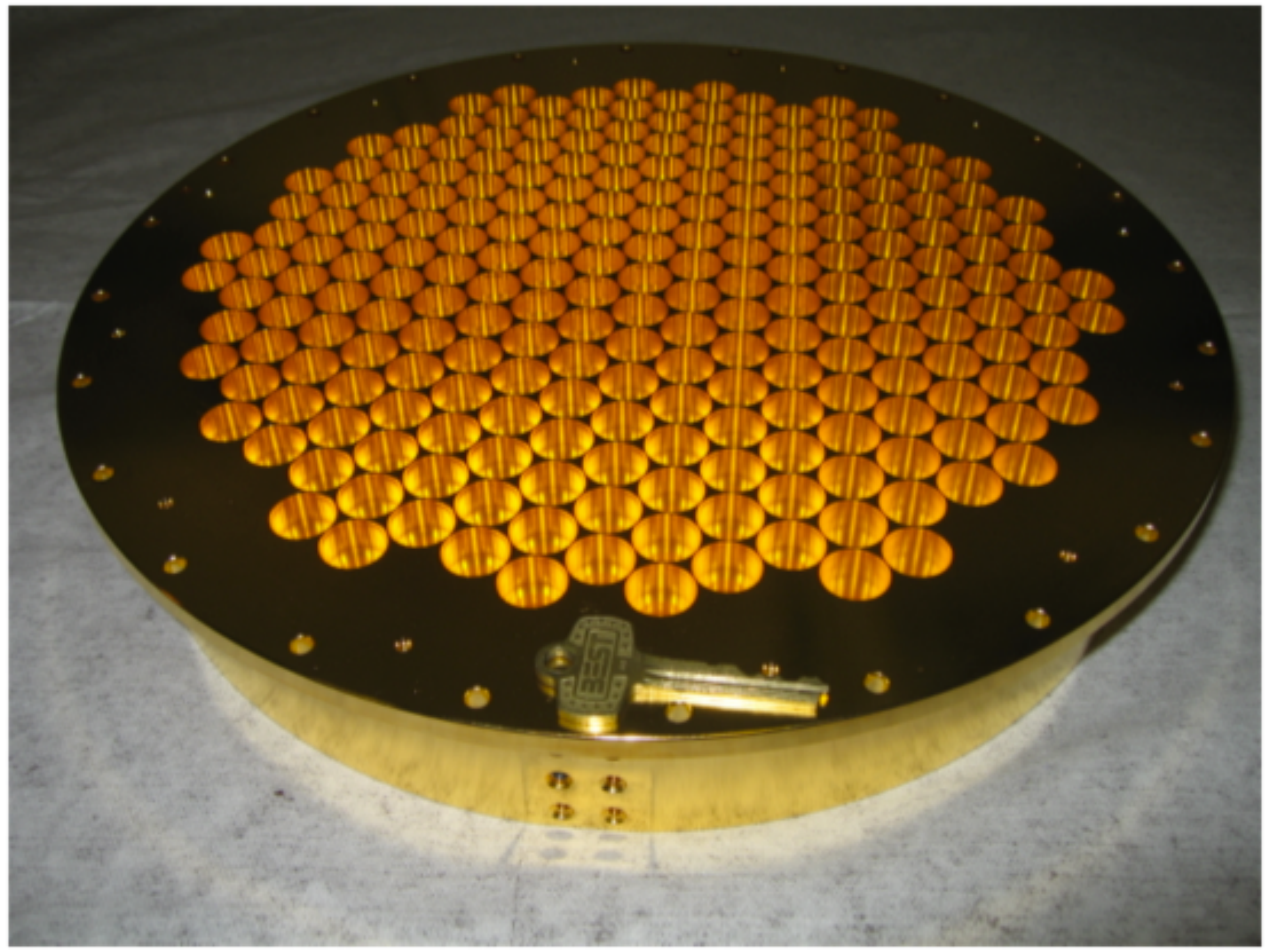


Green Bank Telescope

100-meter GBT

- The GBT is the largest fully steerable structure on land (148 meters tall, only 16% less than Sagrada Familia).
- MUSTANG-2 is a 223-element bolometer array on the GBT.
- MUSTANG-2 operates in a single band around 90 GHz (continuum only, covering W-band from 75-110 GHz).
- Features a 9" FWHM resolution (i.e. comparable to Athena, XMM, and eROSITA).
- 4.3' instantaneous field of view (FoV).



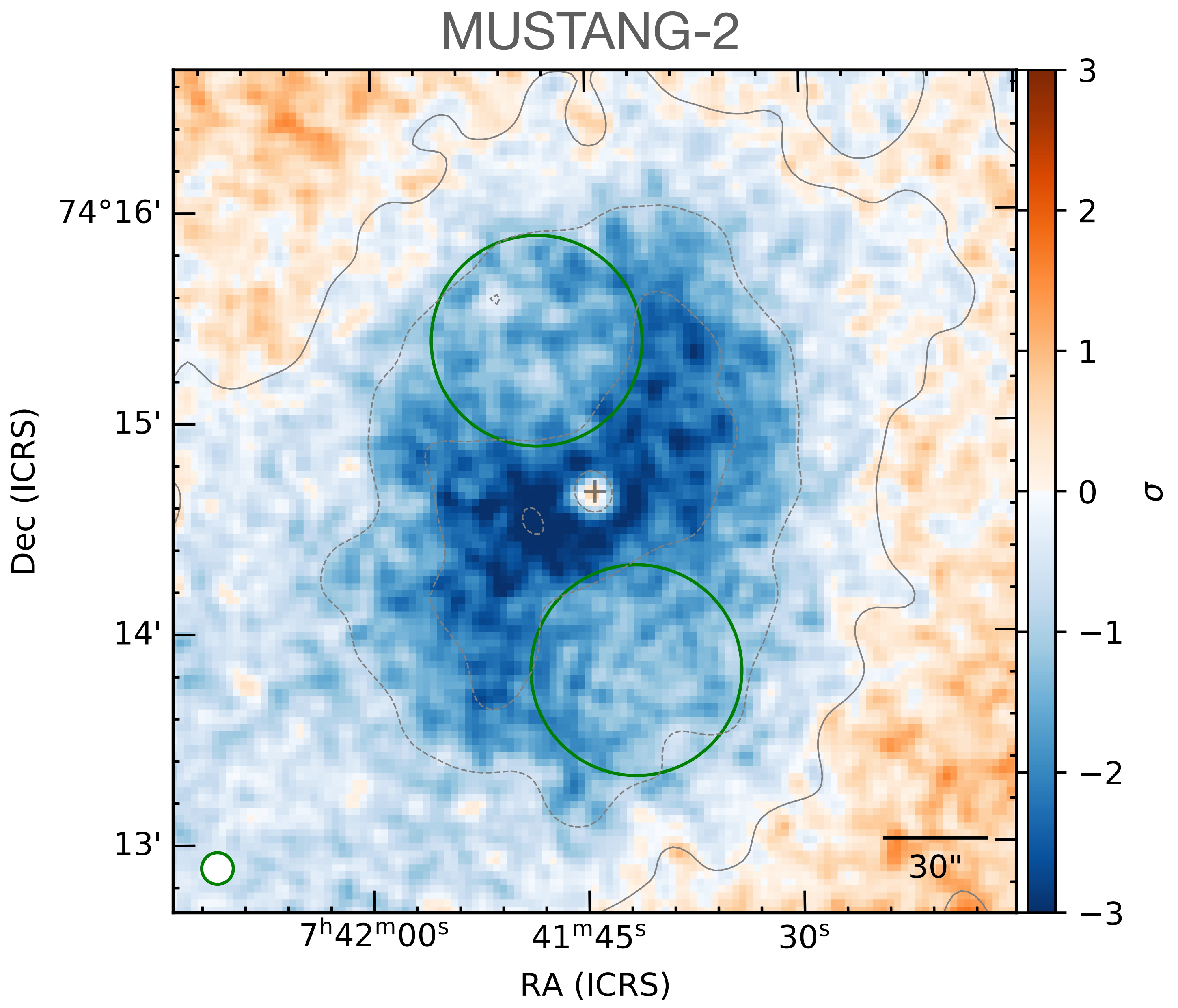


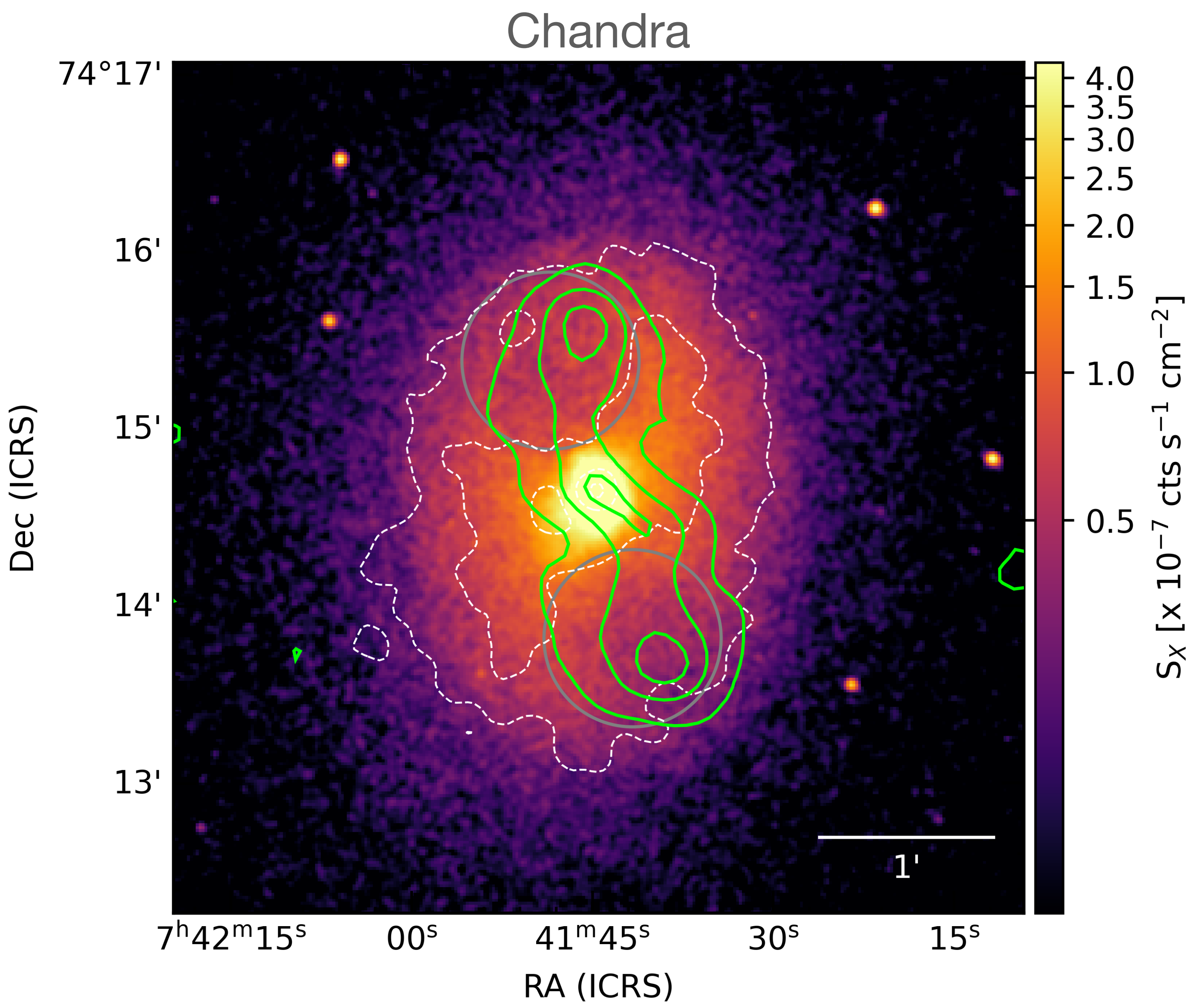
MUSTANG-2

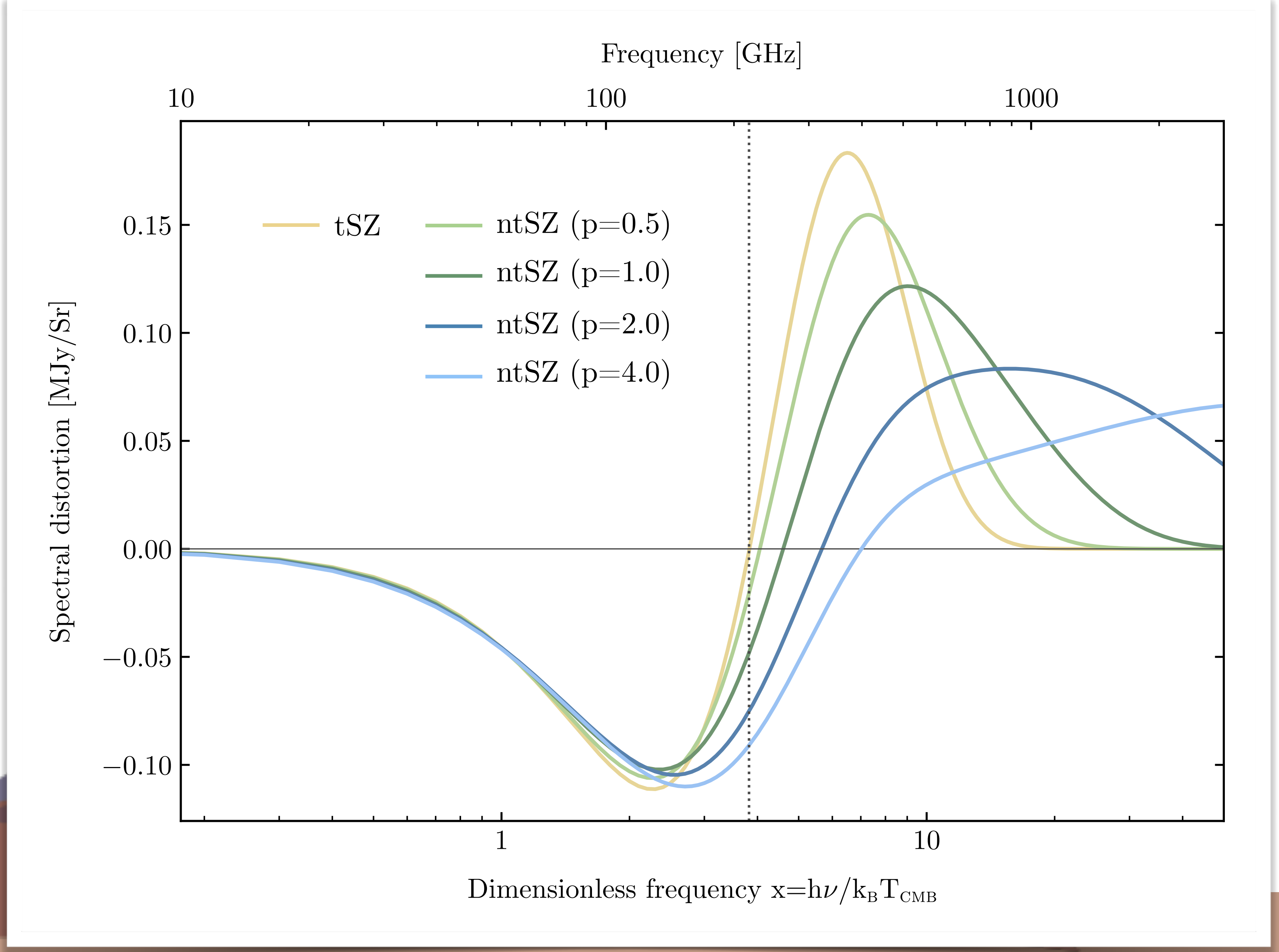
90 GHz SZ imaging at 9” resolution

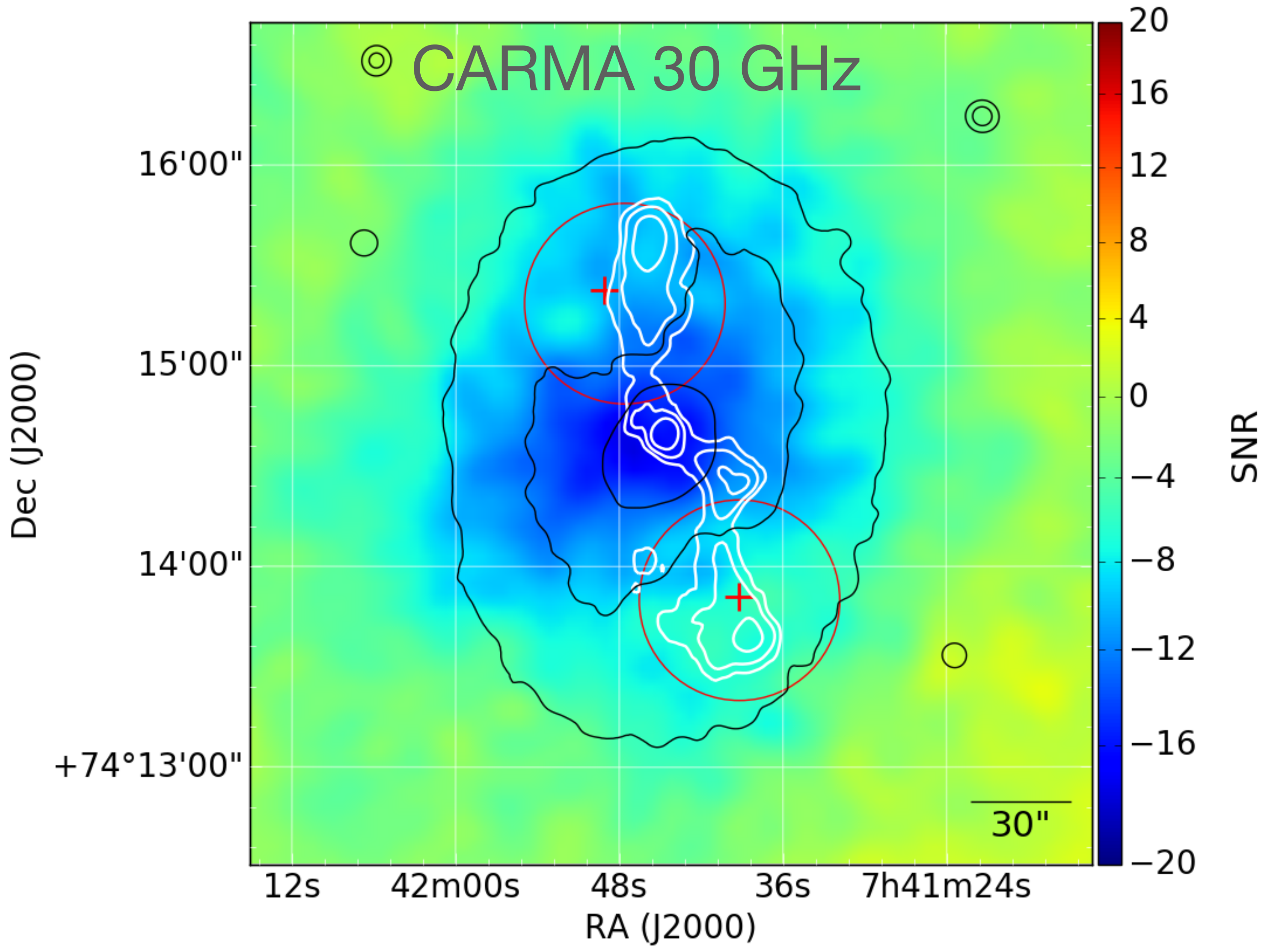
- Our observations of MS 0735 (upper panel), in Orlowski-Scherer et al (*accepted, in press*). *Chandra* X-ray image is shown in the lower right panel (with the MUSTANG-2 contours). CARMA (Abdulla et al. 2019) is below for comparison.

- Since the novel physics is in the SZ increment (> 220 GHz; see below, left), we really want to reliably probe high frequencies (~400-500 GHz) at high angular resolution and sensitivity. This will require new facilities such as AtLAST (atlast-telescope.org)



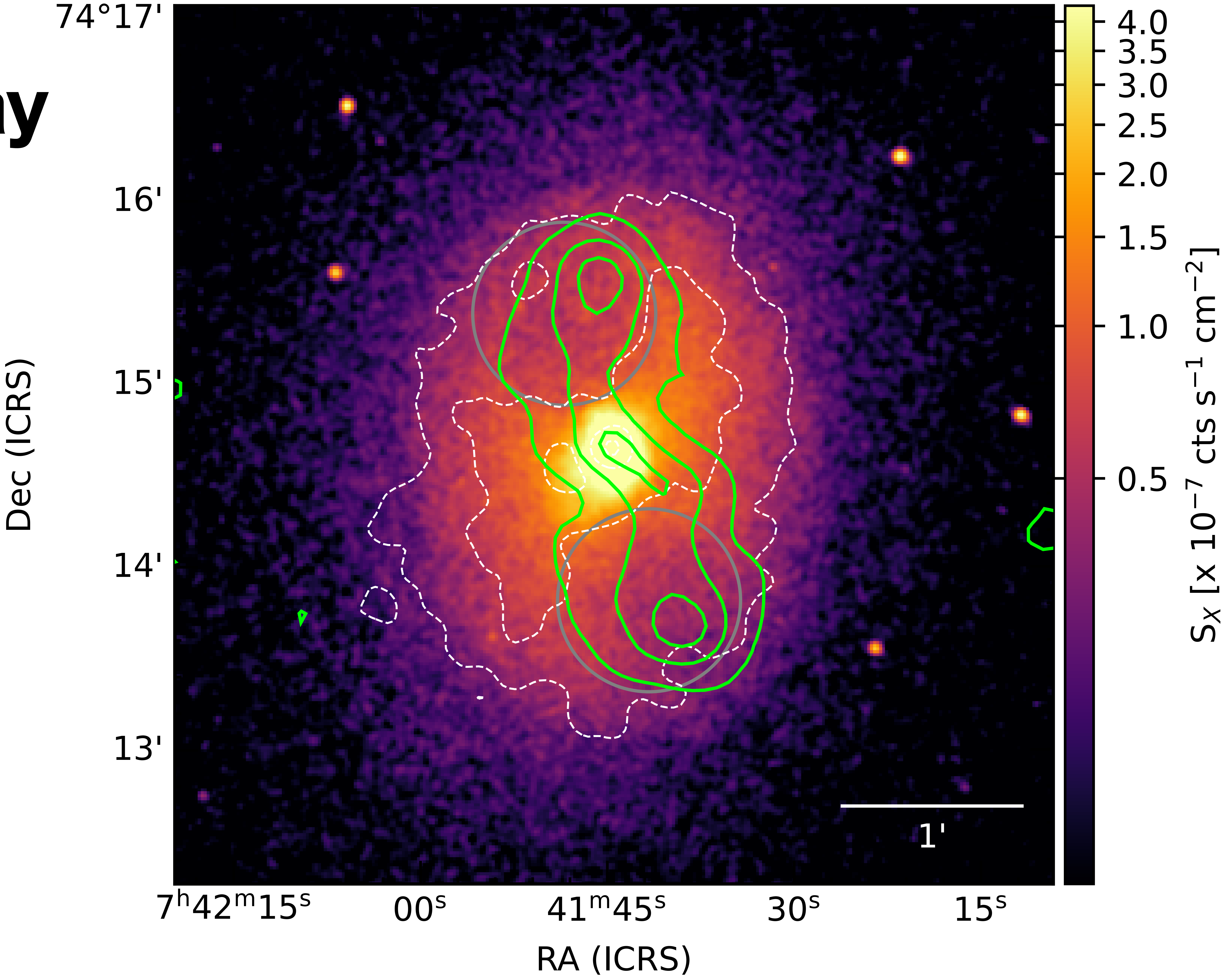


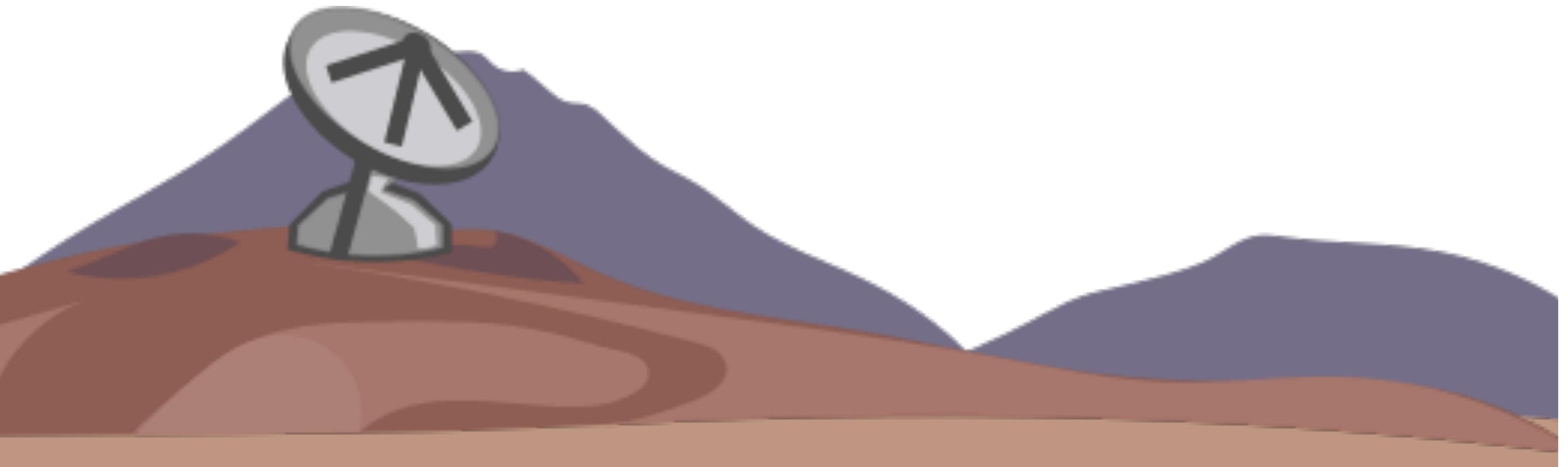




Chandra X-ray

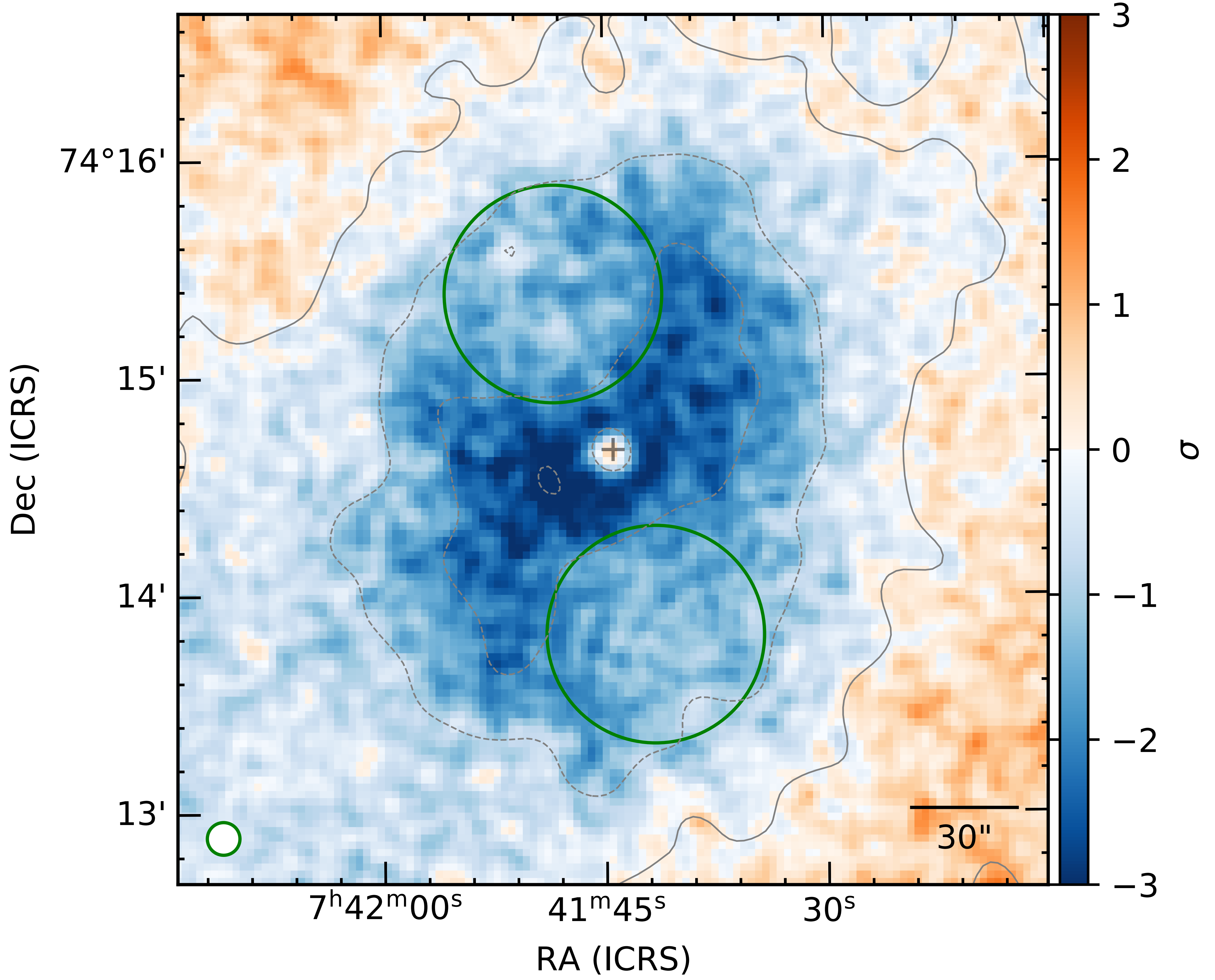
- 500 ksec (~6 days) of *Chandra* observations on source
- MUSTANG-2 90 GHz SZ contours in white dashed lines
- VLITE 330 MHz radio overlaid in green
- X-ray priors were essential for this analysis.
- See Orlowski-Scherer et al. 2022 (in press)





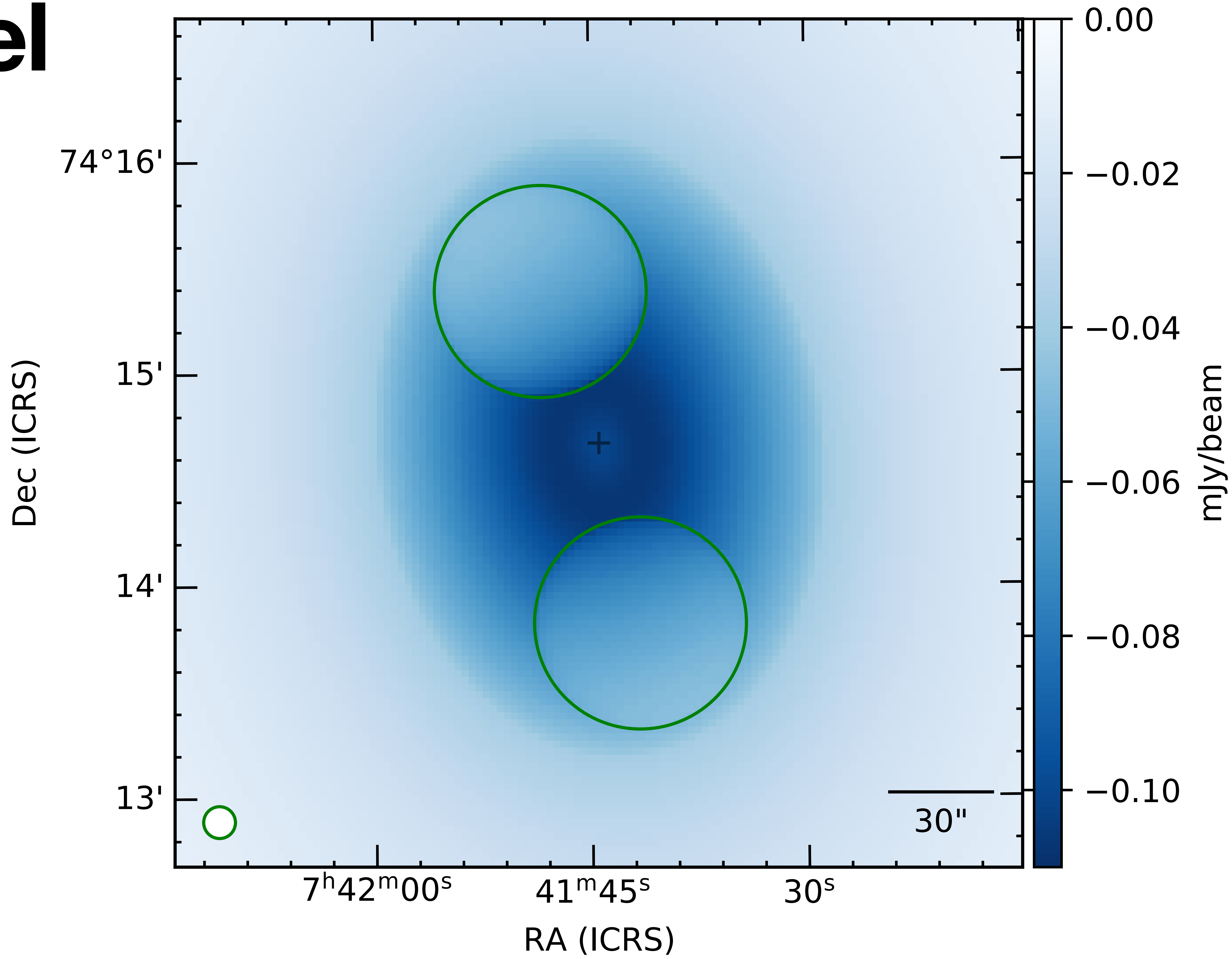
SZ observation

- ~50 ksec (~14 hours) of MUSTANG-2 data
- green circles denote cavities
- much of the SZ structure correlates with X-ray features, lending credibility to both
- See Orlowski-Scherer et al. 2022 (in press)



best-fit SZ model

- green circles denote cavities
- cocoon shock (M~1.0-1.8) improves significance of SZ model fit.
- See Orlowski-Scherer et al. 2022 (in press)



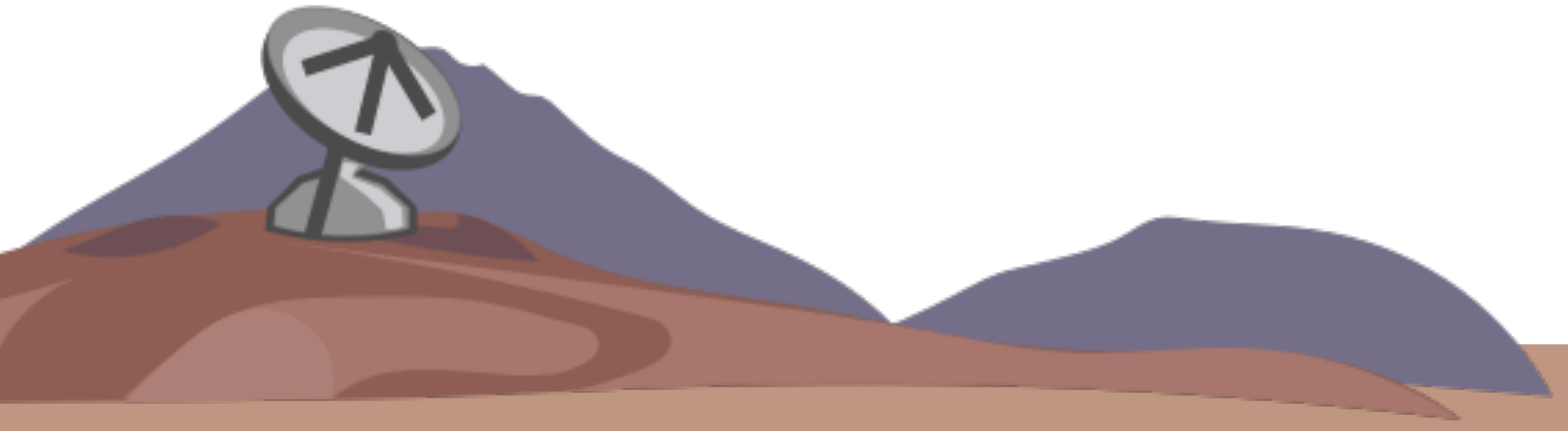
SZ instruments on the 100-m GBT

overview of W-band (75-110 GHz) continuum arrays on the GBT

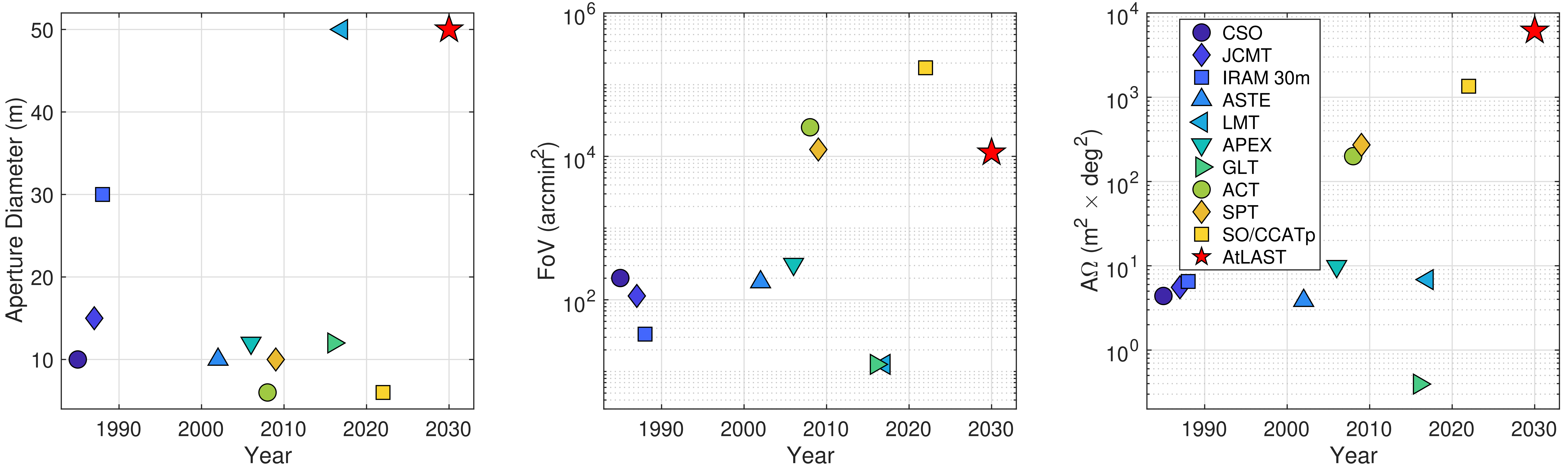
- MUSTANG (1) was the Multiplexed SQUID/TES Array at Ninety GHz.
- MUSTANG-2 is the current generation successor to MUSTANG
- Next-generation W-band imager for the GBT will use Kinetic Inductance Detectors (KIDs) and a readout similar to that on FYST/CCAT-p.
- As the technology advances rapidly, it is easy to foresee a much larger SZ machine: *the Atacama Large Aperture Submm Telescope (AtLAST)*

instrument:	**MUSTANG**	**MUSTANG-2**	**next-gen**
technology	SQUID/TES with time domain readout	SQUID/TES with microwave MUX	Kinetic Inductance Detectors (KIDs)
number of detectors	64 total, 65% yield	223 total, 85% yield	~10k, >95% yield
instantaneous FoV	42"	4.3'	~8.2'
relative mapping speed*	1	14	280
year commissioned	2009	2017	2024-2025 expected

*Note: the mapping speed improvement is only for the instrument. The surface quality of the GBT also improved >4x since the start of MUSTANG.



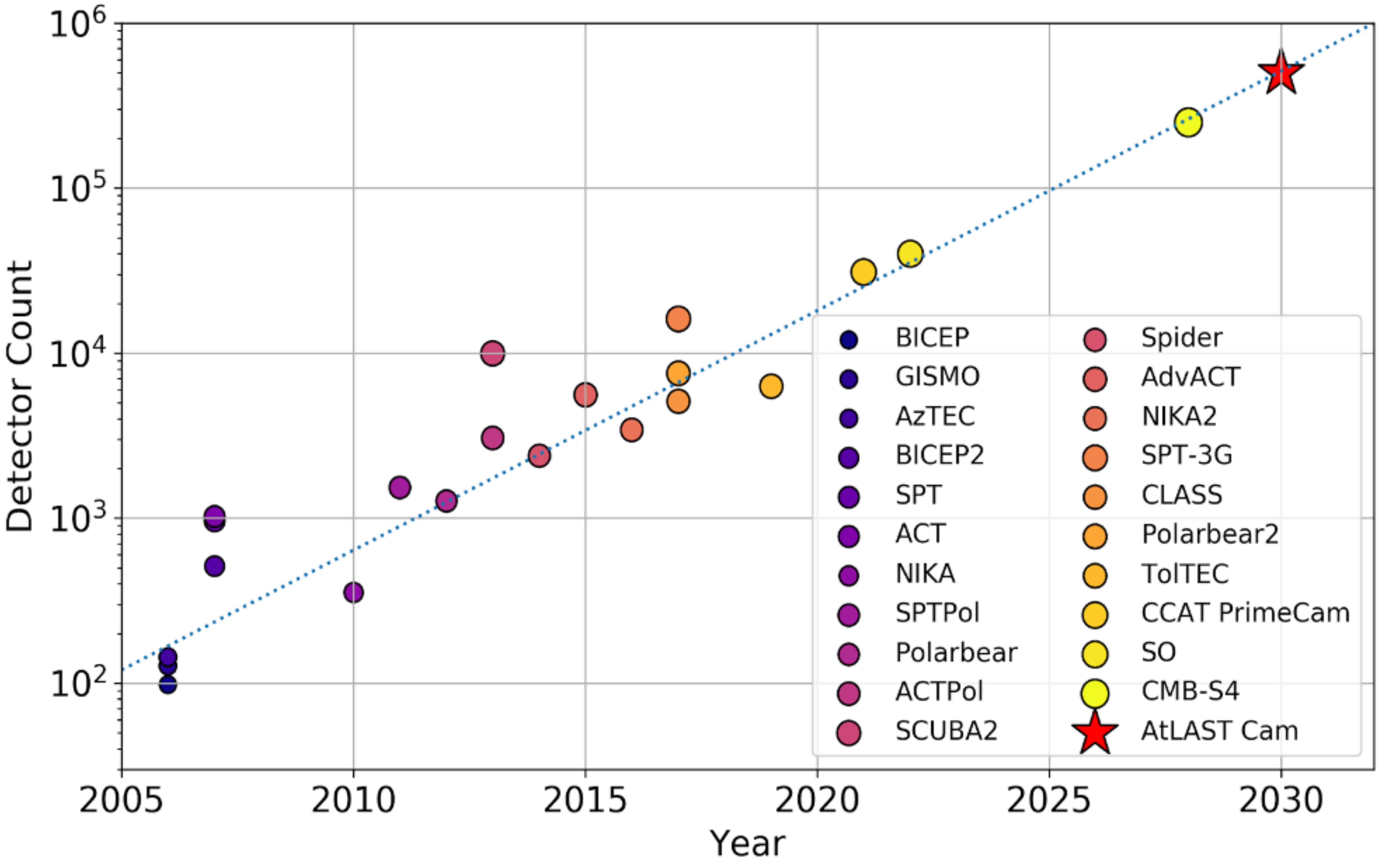
What is AtLAST?



- AtLAST will be a **50-meter** telescope with a 2 degree Field of View (FoV), covering all of the ALMA frequencies (35-950 GHz).
- Plots are: Aperture size, Instantaneous FoV, and Throughput (collecting area x FoV).
- The future of mm/submm is high throughput (AΩ): *many beams → low confusion limit, deeper maps, higher cadence on sky*

How do we populate the focal plane?

- Answer: Time is on our side (though we also need to develop new instrumentation)
- The number of detectors in instruments leading the field grows by a factor of 10 every ~7 years, so we expect to be in the megapixel regime by the end of this decade.
- Over the ~30 year lifetime of AtLAST, this could reach >10 gigapixels.



Conclusions

SZ going into the 2030's

- 6-meter SZ survey instruments like Simons Observatory and CMB-S4 will be commence this decade and likely continue into the next, though their arcminute resolutions sometimes leave much to be desired.
- A handful of pathfinding instruments (e.g. ALMA, ACA, MUSTANG-2, NIKA2) are yielding high resolution observations on a few select fields of a few square arcminutes in size. *Soon: TolTEC, MISTRAL, a successor to MUSTANG-2, ALMA Bands 1 & 2, and SKA.*
- A large aperture, high throughput mm/submm telescope like AtLAST is imminently feasible, surveying areas of the sky >500 times larger than current subarcminute resolution SZ instrumentation.
- A funded design study (https://cordis.europa.eu/project/id/951815) for AtLAST is ongoing. Once funded for construction, AtLAST will be commissioning within 5 years.
- Now is the time to build a strong SZ science case to complement *Athena*!