Sunyaev Zel’dovich high resolution view of filamentary structures between galaxy clusters pairs

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‘Missing Baryons’

About half of the baryonic matter in the local Universe is not directly observable.

These ‘missing baryons’ could be in plasma outside galaxy clusters (Fukugita et al. 1998), a hypothesis confirmed by hydrodynamical simulations (Cen & Ostriker 1999).

~30% of baryons in the local Universe must reside in diffuse low density and hot (10^5 - 10^7 K) gas in the outskirts of galaxy clusters and along filaments connecting them into the so called cosmic web (Tuominen et al 2021).

Observing these ‘missing baryons is challenging’:

- Low gas density means faint X-ray emission ($L_X \sim n^2$)
- Low relativistic electrons number and weak magnetic fields makes radio observations very demanding

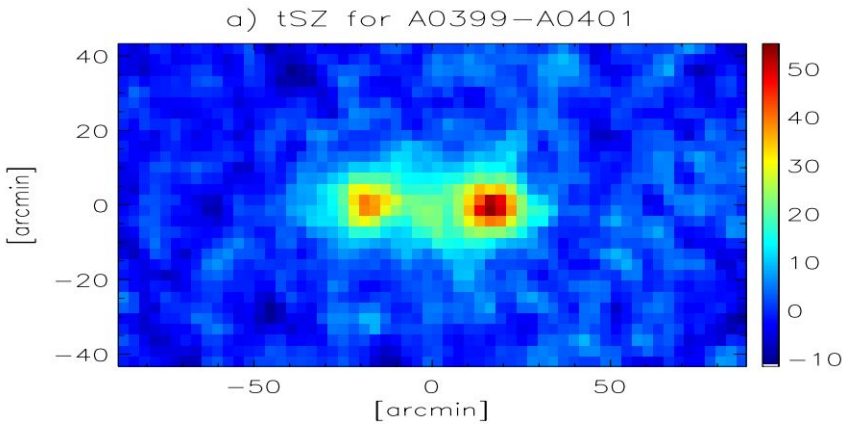
One way to detect these baryons is the Sunyaev-Zeldovich (SZ) effect: inverse Compton scattering of CMB photons with hot electrons in the intracluster medium. Thermal SZ amplitude is proportional to the Compton *y*-parameter:

$$y = \frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}}c^2} \int P_{\mathrm{e}}(r)dr = \frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}}c^2} \int n_{\mathrm{e}}(r)k_{\mathrm{B}}T_{\mathrm{e}}(r)dr$$

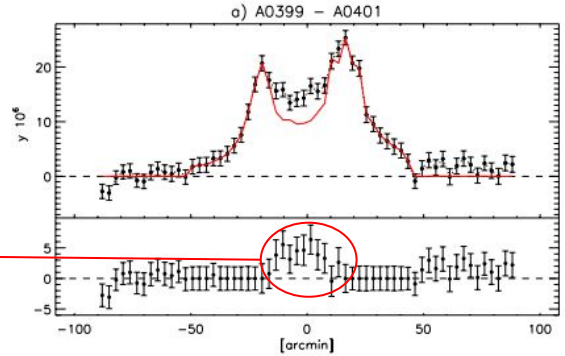
Low z cluster pairs can be perfect laboratories to observe these ‘missing baryons’ as filaments connecting them.

Abel 399-Abell 401 system (z~0.07)

Planck Collaboration et al. (2013)

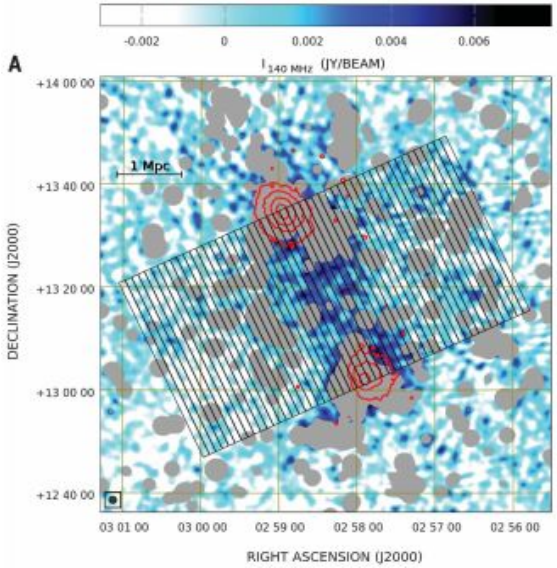


Planck *y*-map
7.18’ resolution



Excess after clusters removal
(only ~3 Planck beams)

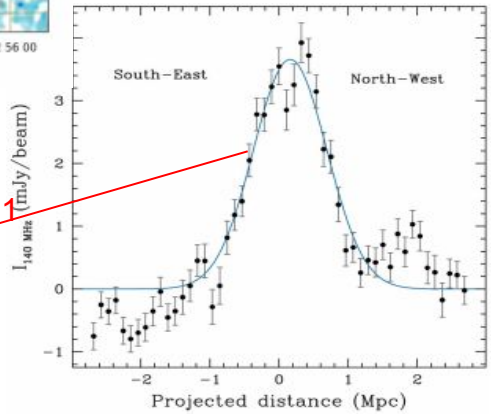
Govoni et al. (2019)



LOFAR 140 MHz
80’’ resolution

Radio ‘ridge’ between A399-401

$B < 1$ μG

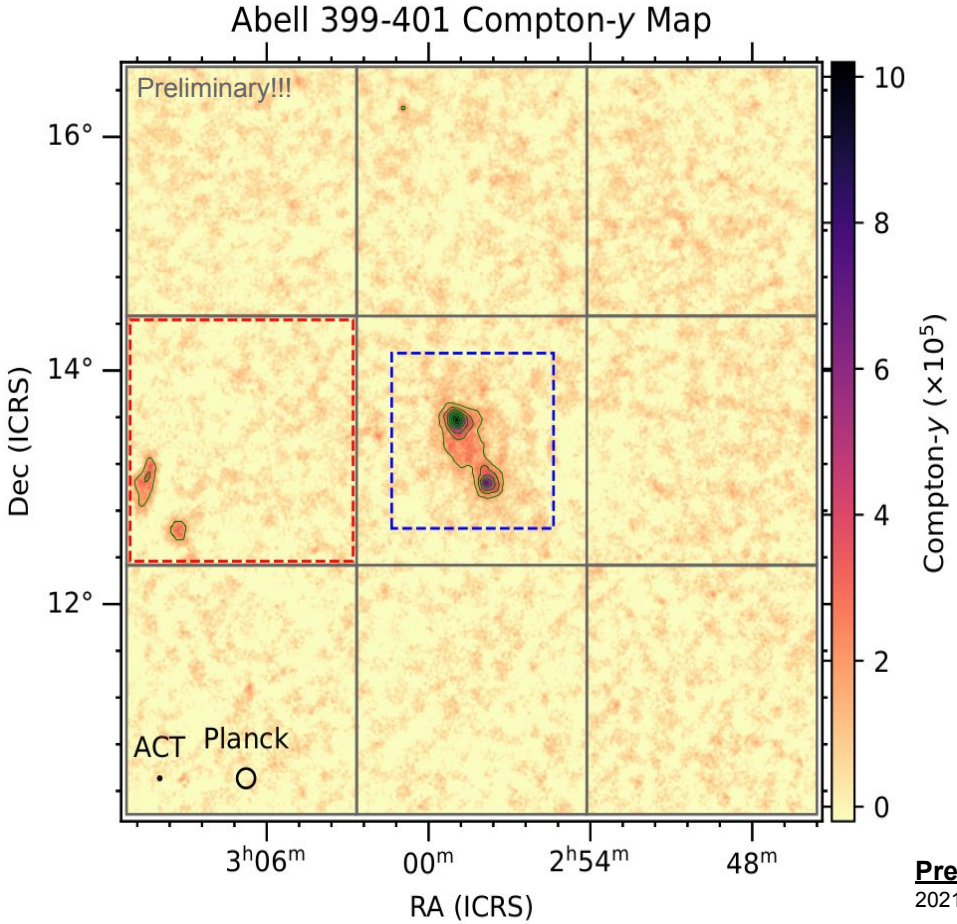


The Atacama Cosmology Telescope

- 6 m CMB telescope located at 5190 m altitude on the Chajnator plateau in the Atacama desert
- Observing since 2008
- High resolution (1-2 arcmin) temperature and polarization at: 98, 150 and 220 GHz
- 2 bands at 30 and 40 GHz added in 2020
- Together with SPT are the only high-resolution (~arcmin) CMB survey telescopes

Image credit: Debra Kellner

A399-401 ACT Compton-*y* map



- Using the 98, 150 and 220 GHz ACT + Planck maps (Madhavacheril et al. 2020)
- Main difference with respect to ACT DR5 (Naess et al 2020) is the inclusion of 2019 ACT data
- 1.65' angular resolution
- Zero-lag noise: $\sigma = 5.9 \times 10^{-6}$ y/pixels
- Green contours levels are 3, 5, 7, 9, 11, 13, and 15σ

- ❖ outer green boxes = Used to extract the Covariance Matrix (*M*)
- ❖ Dashed Red = Dust contaminated region, excluded to estimate *M*

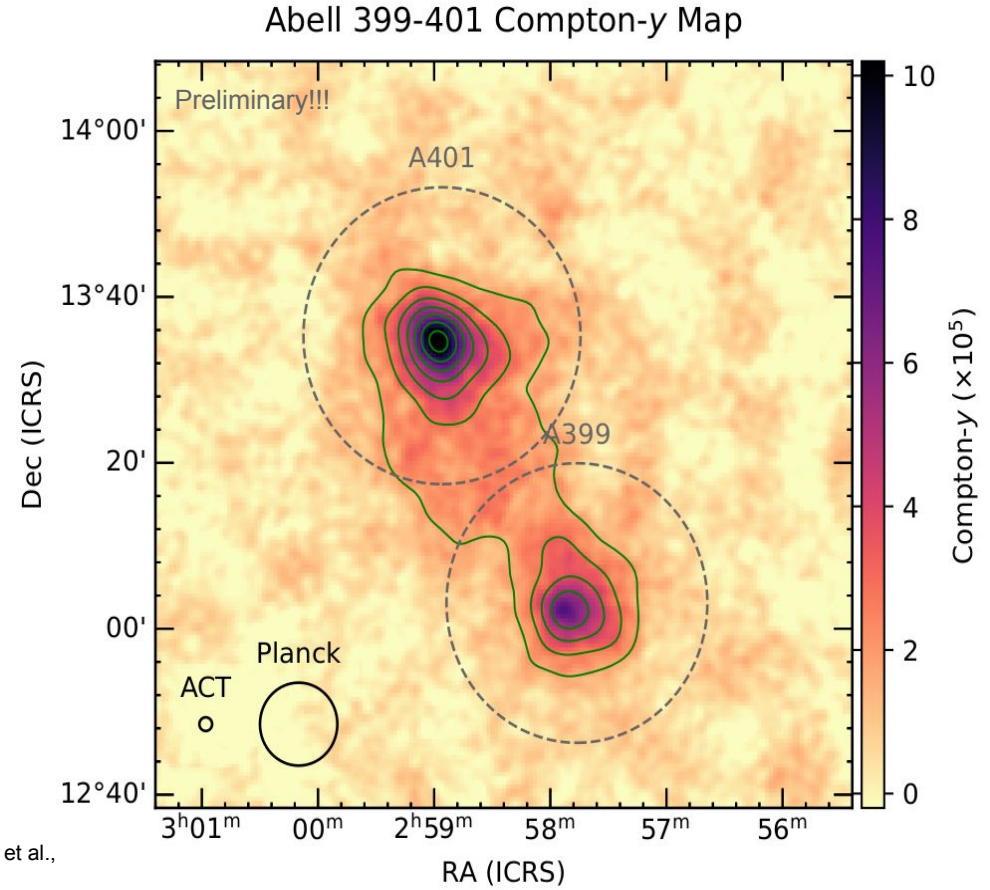
Preliminary!!! Hincks A.D., Radiconi F., Romero C., Madhavacheril M.S., Mroczkowski T., et al., 2021 (in prep.)

A399-401 ACT Compton-*y* map

ACT map zoom in (dashed blue region).

Contours levels are 3, 5, 7, 9, 11, 13, and 15σ

Dashed circles corresponding to their measured R_{500}



Preliminary!!! Hincks A.D., Radiconi F., Romero C., Madhavacheril M.S., Mroczkowski T., et al., 2021 (in prep.)

Fitted Models

We fitted four models with a MCMC algorithm (*emcee,* Foreman-Mackey et al. 2013):

1) 2 Elliptical β-profiles for A399 and A401
2) 3 Elliptical β-profiles for A399, A401 and the bridge region
3) 2 azimuthally-symmetric (Circular) β-profiles for A399 and A401 + mesa model for the bridge
4) 2 Elliptical β-profiles for A399 and A401 + mesa model for the bridge

Circular β-profiles (Cavaliere & Fusco-Femiano 1978)

$$P(r) = k_{\rm B} T_{\rm e} \frac{n_0}{[1+(\frac{r}{r_{\rm c}})^2]^{\frac{3}{2}\beta}}$$

β-profiles asphericity (Hughes& Birkinshaw 1998)

$$\frac{r}{r_{\rm c}} \longrightarrow \frac{\sqrt{x^2 + (y/R)^2}}{r_{\rm c}}$$

Mesa model

Ad hoc model to capture the apparent flatness of the inter-cluster excess (see previous slides) with minimal assumptions about its precise shape

$$g(l, w) = \frac{A_{\rm fil}}{1 + \left(\frac{l}{l_0}\right)^8 + \left(\frac{w}{w_0}\right)^8}$$

Preliminary!!! Hincks A.D., Radiconi F., Romero C., Madhavacheril M.S., Mroczkowski T., et al., 2021 (in prep.)

Fit Results

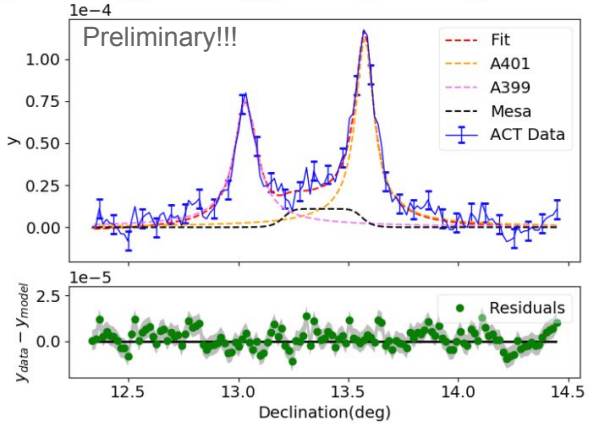
Preliminary!!!

Model	A399						
	A $(10^{-5}y)$	$\alpha(^\circ)$	$\delta(^\circ)$	β	r_c $(')$	θ $(^\circ)$	R
Ellip–β, no bridge	$8.2^{+0.6}_{-0.6}$	44.474 ± 0.003	13.030 ± 0.003	$0.74^{+0.08}_{-0.07}$	$2.7^{+0.6}_{-0.5}$	-53^{+18}_{-18}	$0.87^{+0.07}_{-0.07}$
3×Ellip–β	$7.9^{+0.6}_{-0.6}$	44.473 ± 0.004	13.030 ± 0.003	$0.84^{+0.13}_{-0.09}$	$3.1^{+0.8}_{-0.6}$	-47^{+27}_{-26}	$0.92^{+0.05}_{-0.07}$
Circ–β+mesa	$8.2^{+0.6}_{-0.6}$	44.473 ± 0.004	13.030 ± 0.003	$0.80^{+0.10}_{-0.08}$	$2.9^{+0.6}_{-0.5}$	N/A	1.0
Ellip–β+mesa	$8.1^{+0.6}_{-0.6}$	44.473 ± 0.004	13.030 ± 0.003	$0.81^{+0.11}_{-0.08}$	$3.0^{+0.7}_{-0.6}$	-47^{+27}_{-26}	$0.93^{+0.05}_{-0.07}$

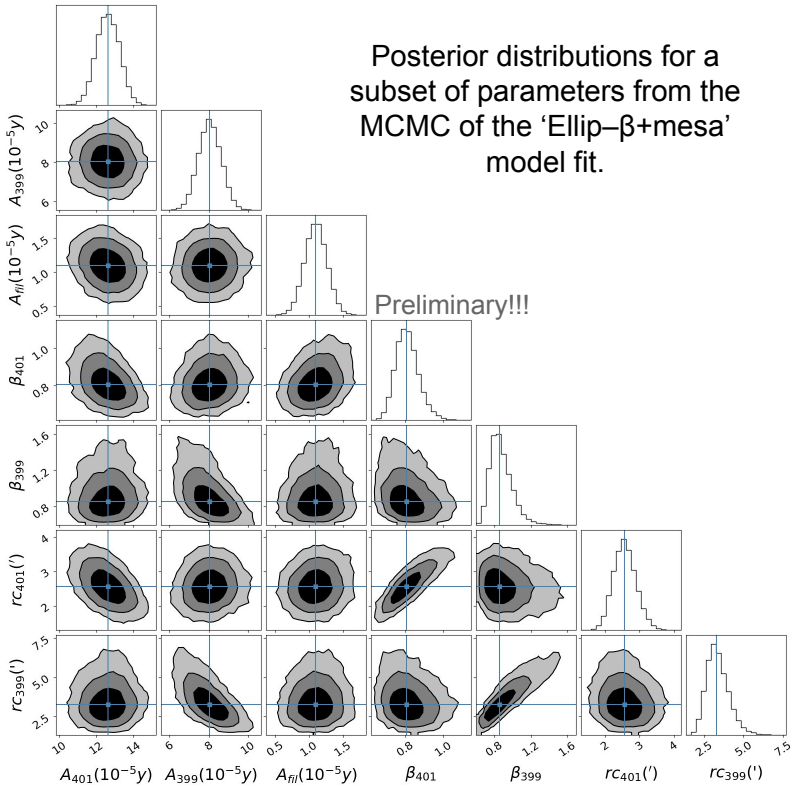
Model	A401						
	A $(10^{-5}y)$	$\alpha(^\circ)$	$\delta(^\circ)$	β	r_c $(')$	θ $(^\circ)$	R
Ellip–β, no bridge	$13.2^{+0.6}_{-0.6}$	44.750 ± 0.002	13.569 ± 0.002	$0.73^{+0.04}_{-0.04}$	$2.4^{+0.3}_{-0.3}$	-61^{+6}_{-6}	$0.77^{+0.05}_{-0.05}$
3×Ellip–β	$11.8^{+1.0}_{-1.0}$	44.750 ± 0.002	13.572 ± 0.002	$0.93^{+0.18}_{-0.10}$	$2.9^{+0.5}_{-0.4}$	-56^{+10}_{-9}	$0.83^{+0.06}_{-0.05}$
Circ–β+mesa	$12.7^{+0.6}_{-0.6}$	44.750 ± 0.002	13.572 ± 0.002	$0.83^{+0.06}_{-0.05}$	$2.4^{+0.3}_{-0.3}$	N/A	1.0
Ellip–β+mesa	$12.6^{+0.6}_{-0.6}$	44.751 ± 0.002	13.572 ± 0.002	$0.82^{+0.07}_{-0.06}$	$2.6^{+0.4}_{-0.3}$	-57^{+9}_{-8}	$0.82^{+0.06}_{-0.05}$

Model	Bridge							
	$A_{\rm fil}$ $(10^{-5}y)$	$\alpha(^\circ)$	$\delta(^\circ)$	l_0 $(')$	w_0 $(')$	r_c $(')$	θ $(^\circ)$	R
Ellip–β, no bridge	—	—	—	—	—	—	—	—
3×Ellip–β	$2.01^{+0.52}_{-0.41}$	$44.69^{+0.03}_{-0.03}$	$13.40^{+0.06}_{-0.05}$	—	—	$16.0^{+1.7}_{-2.4}$	fix	$0.80^{+0.13}_{-0.12}$
Circ–β+mesa	$1.20^{+0.17}_{-0.17}$	$44.67^{+0.01}_{-0.01}$	$13.35^{+0.02}_{-0.03}$	$11.7^{+1.4}_{-1.2}$	$10.6^{+1.0}_{-0.9}$	—	fix	—
Ellip–β+mesa	$1.10^{+0.17}_{-0.18}$	$44.68^{+0.02}_{-0.02}$	$13.37^{+0.02}_{-0.03}$	$12.3^{+1.7}_{-1.4}$	$10.8^{+1.1}_{-1.0}$	—	fix	—

1D profile of the best fit ‘Ellip–β+mesa’ model.



Posterior distributions for a subset of parameters from the MCMC of the ‘Ellip–β+mesa’ model fit.



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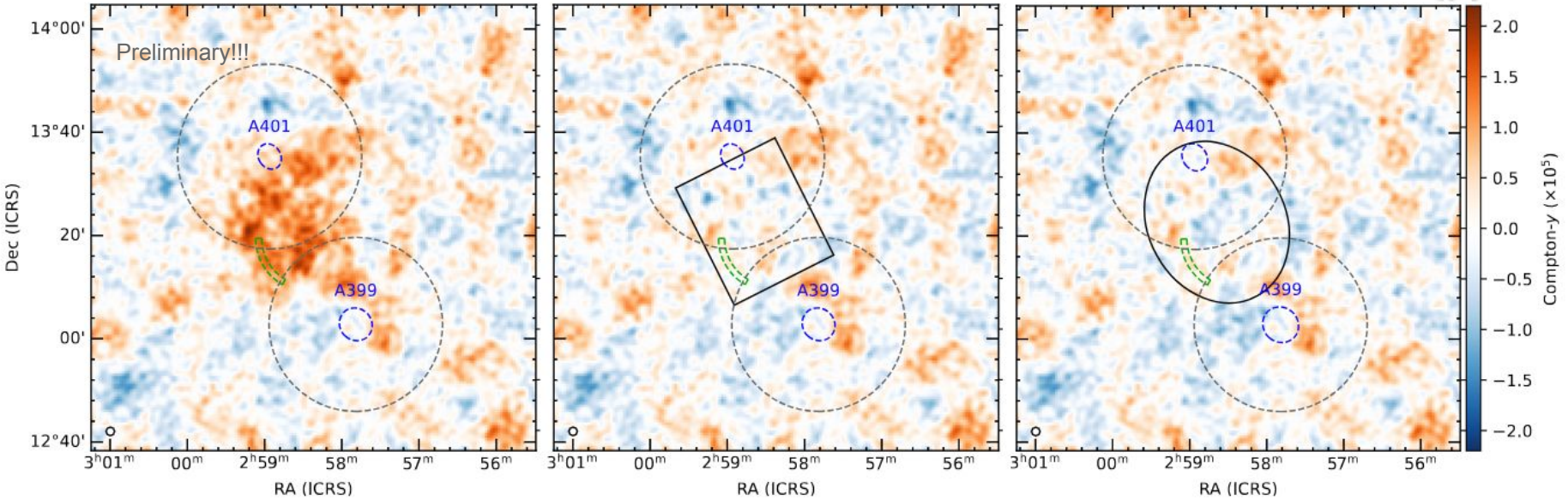
Residuals



2 Elliptical β-profiles | 2 Elliptical β-profiles + mesa | 3 Elliptical β-profiles

Green dashed region indicate the shock region identified in Akamatsu et al. (2017).

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Models comparison

Data	Model	P	Likelihood Ratio		AIC
			W	σ	w_i
ACT+*Planck*	Ellip–β , no bridge	17	—	—	4.3×10^{-8}
	3×Ellip–β	22	33.2	4.6	0.0047
	Circ–β+mesa	18	—	—	0.23
	Ellip–β+mesa	22	43.4	5.5	0.77
Planck only	Ellip–β, no bridge	17	—	—	0.0012
	Ellip–β+mesa	22	23.5	3.6	0.999

- P = Free Parameters
- Likelihood ratio $W = 2 \log \frac{\max \mathcal{L}_2}{\max \mathcal{L}_1}$ (only valid if Model 1 is and extension of Model 2)
- AIC = Akaike Information Criterion, w_i is the relative probability

Preliminary!!! Hincks A.D., Radiconi F., Romero C., Madhavacheril M.S., Mroczkowski T., et al., 2021 (in prep.)

Derived Quantities

From 2 Elliptical β-profiles + mesa best fit model we extracted:

- Mesa Compton integrated: $Y_{mesa} = (4.9\pm1.0)\times10^{-5}\mathrm{Mpc}^2$
- Mesa mass: $\mathbf{M_{mesa} = (3.3\pm0.7)\times10^{14}\,M_\odot}$ (gas + dark matter)
- Clusters masses:
  $\mathbf{M_{200,A399} = (18.1\pm2.2)\times10^{14}\,M_\odot}$ & $\mathbf{M_{200,A401} = (21.3\pm2.7)\times10^{14}\,M_\odot}$

$$M_{mesa}/(M_{200,A399} + M_{200,A401}) \simeq 8\%$$

- Mesa sizes (on the sky): $l_{fil}\times w_{fil} = 2.2\times1.9\ \mathrm{Mpc}^2$
- *y* at the Mesa center (Mesa + clusters halos): $y_{tot} = (2.8\pm0.3)\times10^{-5}$
- Assuming $kT_{fil} = 6.5$ keV (Akamatsu et al. 2017) and $y_{tot} = (8.0\pm1.0)\times(r_{fil}/\mathrm{Mpc})^{0.5}\times10^{-6}$

---> $\mathbf{r_{fil} = (12.1\pm3.9)\ Mpc}$ & $\mathbf{n_e = (0.88\pm0.24)\times10^{-4}\,cm^{-3}}$

Thickness along the l.o.s. r_{fil} >> l_{fil} & w_{fil}

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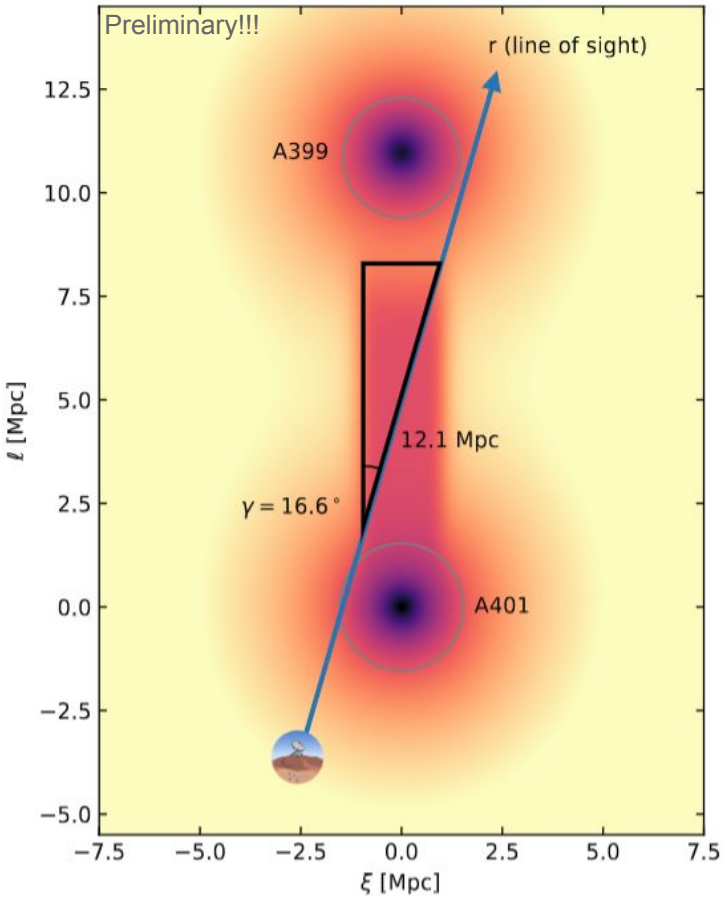
Toy Model



- Assuming a symmetric filament along the line connecting A399-401, so true thickness = w_{fil}
- Angle between l.o.s. and A399-401 axis (Mesa+cluster halos):
  $\gamma \propto \arcsin(w_{fil} / r_{fil}) = \mathbf{16.6^{+5.5}_{-3.8}\ deg}$
- A399-401 separation on the sky d_p = 3.2 Mpc
  ---> total separation $\mathbf{d_T = 12.1^{+3.4}_{-2.8}\ Mpc}$

Despite the highly idealized model we stress that combining *y* in the bridge and X-ray we find that A399-401 system has a significant component along the line of sight. Previous studies implicitly assume that the system lies almost entirely on the plane of the sky!!!!

Grey circles indicate:

$R_{500,A399} = (1.45 \pm 0.21)\,\text{Mpc}$ & $R_{500,A401} = (1.53 \pm 0.19)\,\text{Mpc} < \mathbf{d_T}$

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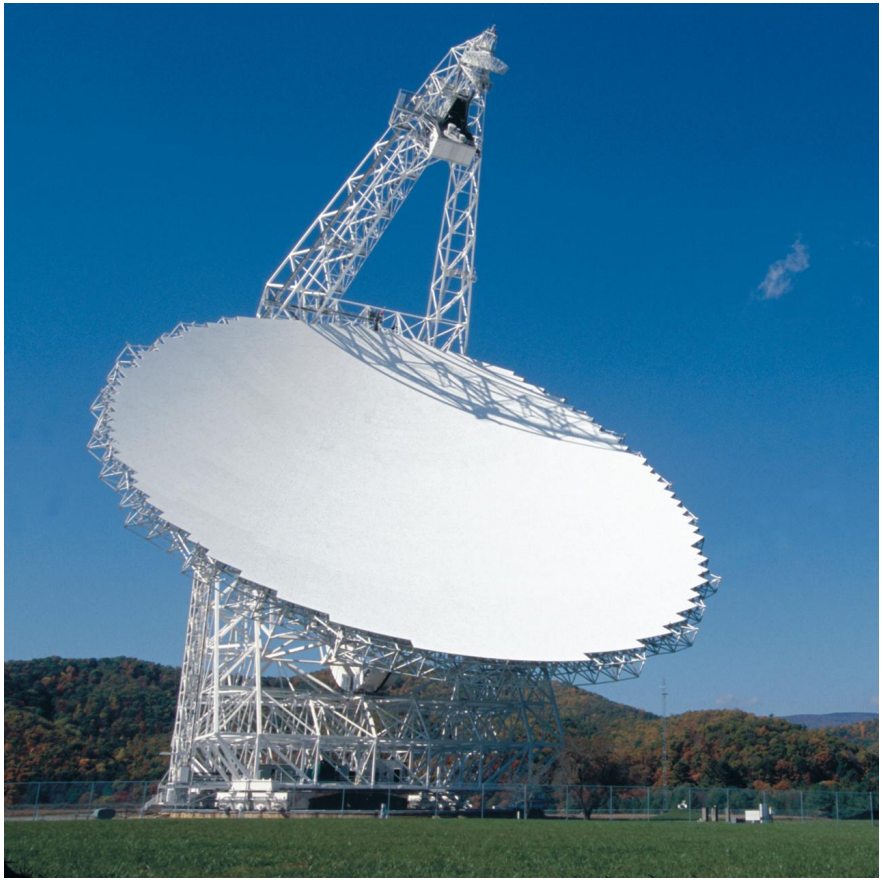
Mustang-2 @ Green Bank Telescope (GBT)

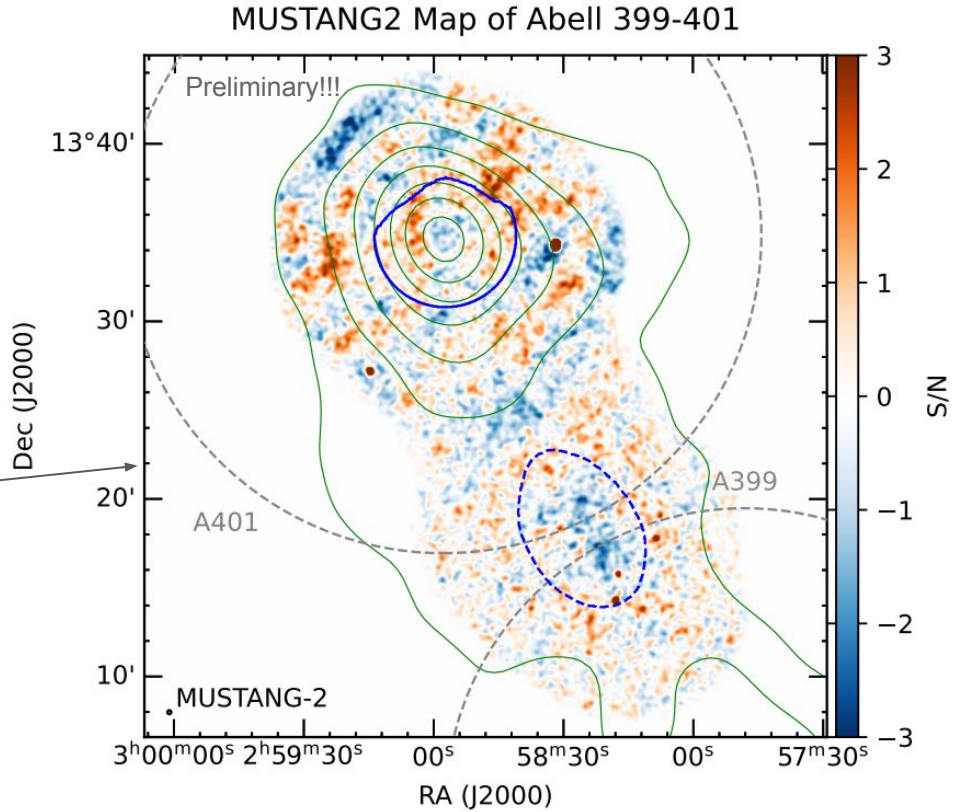


Credit: NRAO/AUI/NSF

- GBT primary mirror diameter: **100 m**
- GBT Frequency coverage: 100 MHz-100 GHz
- Protected by a 13000 km^2 Radio Quiet Zone
- GBT observational capabilities: Spectroscopy, Continuum, Pulsar, VLBI
- Mustang-2 (M2) is a 223-feedhorn bolometer camera operating @ 90GHz
- M2 Angular resolution: ~ 9''
- M2 FOV: ~ 4.25'
- Zenith opacity @ 90 GHz ~ 0.1; PWV $\lesssim$ 10 mm (https://www.gb.nrao.edu/mustang/wx.shtml)

Mustang-2 Data

- 66 hours of observing time. 44 h on source (P.I. E. Battistelli)
- We observed A401 and the intracluster(Mesa) region
- A399 has not been observed!!!!
- ‘Preliminary’ analysis using MIDAS (Romero et al. 2020) pipeline
- SNR map contains the scales from 12.7″< θ < 180″
- No imprints for large scale structures!!!



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Fluctuations

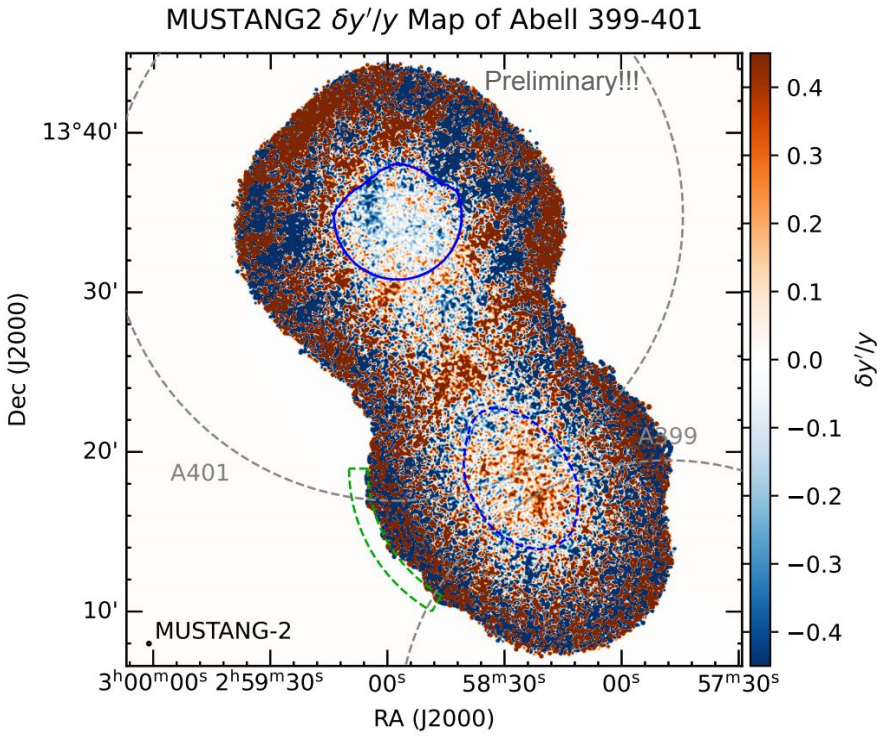
- We used the M2 map to study small-scale features in the intracluster (Mesa center) and A401 regions (blue lines).

- Map of δy′/ y using M2 map and ACT 2-Elliptical β-profiles + Mesa best fit model:
    - δy′ = y’ - y̲’
    - y’ = M2 Midas map
    - y̲’ = model filtered through the MUSTANG-2 pipeline
    - y = best-fit ‘Ellip–β+Mesa’ model

- Intracluster region (noise < 2.9 μK-arcmin) = 0.078 ± 0.015
- A401 (noise < 13.5 μK-arcmin) = 0.052 ± 0.022

Low level fluctuations in both regions!!

- A401 level suggest no major merger activity, but would allow for minor ongoing mergers
- Intracluster region ---> there are not strong theoretical expectations. The geometry of the system may erase fluctuations when projected on the sky??



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Conclusions

- Low z cluster pairs are the perfect science case to study the SZ signal from the hot gas in filamentary structures
- High angular resolution (~ arcmin) data play key role in studying systems properties
- By including ACT data, we increase the filament detection with respect to Planck only data
- A399-401 system has a significant component along the line of sight

Next

-- Hincks A.D. et al., 2021 (in prep.) will be soon be publicly available and submitted.

-- Shocks search adding new deep observations of A399-401 with ACT currently unprocessed (6x better resolution than Planck at same ν) and combining ACT with Mustang-2 data (~10'' resolution, 10-15 x better resolution than ACT at 98 and 150 GHz)

-- New ACT data of A399-401 + other cluster pairs stack ---> possible study of kSZ effect