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:

\[
y = \frac{\sigma_T}{m_e c^2} \int P_e(r) dr = \frac{\sigma_T}{m_e c^2} \int n_e(r) k_B T_e(r) dr
\]

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

Govoni et al. (2019)

LOFAR 140 MHz
80’’ resolution

Radio 'ridge' between A399-401

Excess after clusters removal
(only ~3 Planck beams)

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
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 15$\sigma$

- 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.)
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)

β-profiles asphericity (Hughes & Birkinshaw 1998)

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

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

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

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

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

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

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

<table>
<thead>
<tr>
<th>Data</th>
<th>Model</th>
<th>$P$</th>
<th>Likelihood Ratio</th>
<th>AIC</th>
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<tbody>
<tr>
<td>ACT+Planck</td>
<td>Ellip–β, no bridge</td>
<td>17</td>
<td>—</td>
<td>$4.3 \times 10^{-8}$</td>
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<td>Ellip–β+mesa</td>
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<td>23.5</td>
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</table>

- **$P$ = Free Parameters**

- **Likelihood ratio** \[ W = 2 \log \frac{\text{max } \mathcal{L}_2}{\text{max } \mathcal{L}_1} \] (only valid if Model 1 is an extension of Model 2)

- **AIC = Akaike Information Criterion**, $w_i$ is the relative probability

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

From 2 Elliptical $\beta$-profiles + mesa best fit model we extracted:

- Mesa Compton integrated: $Y_{\text{mesa}} = (4.9\pm1.0) \times 10^{-5} \text{Mpc}^2$

- Mesa mass: $M_{\text{mesa}} = (3.3\pm0.7) \times 10^{14} \text{M}_\odot$ (gas + dark matter)

- Clusters masses:
  
  $M_{200,\text{A399}} = (18.1\pm2.2) \times 10^{14} \text{M}_\odot \quad \& \quad M_{200,\text{A401}} = (21.3\pm2.7) \times 10^{14} \text{M}_\odot$

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

- Mesa sizes (on the sky): $l_{\text{fil}} \times w_{\text{fil}} = 2.2 \times 1.9 \text{Mpc}^2$

- $y$ at the Mesa center (Mesa + clusters halos): $y_{\text{tot}} = (2.8\pm0.3) \times 10^{-5}$

- Assuming $kT_{\text{fil}} = 6.5 \text{ keV}$ ([Akamatsu et al. 2017](#)) and $y_{\text{tot}} = (8.0\pm1.0) \times (r_{\text{fil}} / \text{Mpc})^{0.5} \times 10^{-6}$

  $r_{\text{fil}} = (12.1\pm3.9) \text{ Mpc} \quad \& \quad n_e = (0.88\pm0.24) \times 10^{-4} \text{ cm}^{-3}$

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

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Preliminary!!! Hincks A.D., Radiconi F., Romero C., Madhavacheril M.S., Mroczkowski T., et al., 2021 (in prep.)
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):
  \[ \gamma \propto \arcsin\left(\frac{w_{fil}}{r_{fil}}\right) = 16.6^{+5.5}_{-3.8} \text{ deg} \]

- A399-401 separation on the sky $d_p = 3.2$ Mpc
  \[ \rightarrow \text{ total separation } d_T = 12.1^{+3.4}_{-2.8} \text{ Mpc} \]

Despite the highly idealized model we stress that combining $\gamma$ 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:

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

Preliminary!!! Hincks A.D., Radiconi F., Romero C., Madhavacheril M.S., Mroczkowski T., et al., 2021 (in prep.)
Mustang-2 @ Green Bank Telescope (GBT)

- GBT primary mirror diameter: **100 m**
- GBT Frequency coverage: 100 MHz-100 GHz
- Protected by a 13,000 km² 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 \leq 10 mm ([https://www.gb.nrao.edu/mustang/wx.shtml](https://www.gb.nrao.edu/mustang/wx.shtml))

Credit: NRAO/AUI/NSF
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 $12.7'' < \theta < 180''$
- No imprints for large scale structures!!!

Preliminary!!! Hincks A.D., Radiconi F., Romero C., Madhavacheril M.S., Mroczkowski T., et al., 2021 (in prep.)
We used the M2 map to study small-scale features in the intracluster (Mesa center) and A401 regions (blue lines).

Map of $\delta y'/y$ using M2 map and ACT 2-Elliptical $\beta$-profiles + Mesa best fit model:

- $\delta y' = y' - y'$
- $y' = $M2 Midas map
- $y' = $model filtered through the MUSTANG-2 pipeline
- $y = $best-fit 'Ellip–$\beta$+Mesa’ model

Intracluster region (noise < 2.9 $\mu$K-arcmin) = $0.078 \pm 0.015$

A401 (noise < 13.5 $\mu$K-arcmin) = $0.052 \pm 0.022$

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??

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