First ALMA Detection of a Galaxy Cluster Merger Shock

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We report on the first ALMA measurement of a galaxy cluster merger shock, observed at the location of a radio relic in the famous El Gordo galaxy cluster at redshift $z \sim 0.9$. Located at about half the current age of the Universe, this is also the most distant example of a directly measured astrophysical shock. ALMA Band 3 was utilised to measure the Sunyaev–Zel'dovich (SZ) effect signature that confirms a small-scale change in pressure as expected from the passage of a shock in the intracluster medium. The results support a previous radio-based estimate of the shock Mach number and display similarities, and also some mild tensions, with the X-ray based results. Most importantly, these results show the potential of ALMA to detect galaxy cluster shocks, observations that will advance our knowledge of cluster formation, non-thermal particle acceleration and amplification of magnetic fields across the entire observable Universe where such relic shocks can be found.

Scientific context

Shock phenomena are ubiquitous in astrophysics, from the Earth's bow shock in the solar wind to supernova remnants and accretion shocks in the jets of active galactic nuclei (AGN). They signify supersonic gas motions. The largest coherent shock structures known form in and around clusters of galaxies and can be up to megaparsecs in length. One expected example of such a large-scale shock is the accretion shock that occurs at the outer boundary of a galaxy cluster where the denser intracluster gas meets the infalling inter-galactic medium; however, such shocks have not yet been observed directly. Another type of cluster shock is the merger shock, occurring when galaxy clusters collide at supersonic speeds, generating low-Mach-number shocks in the hot intracluster plasma. Studies of merger shocks are important because they provide an understanding of the heating processes in the intracluster medium, point to cluster merger dynamics, including infall velocities, and provide insight into the production mechanism of high-energy cosmic ray particles at the shock fronts.

The observation and modelling of galaxy cluster merger shocks became possible during the last two decades thanks to the superb capabilities of the X-ray spectral/imaging instruments on-board the Chandra and X-ray Multi-Mirror (XMM) Newton satellites. However, it is also possible to detect these shocks in the millimetre/submillimetre (mm/sub-mm) wavebands, by means of the so-called Sunyaev–Zel'dovich (SZ) effect. This is a small modification in the spectral intensity of the Cosmic Microwave Background (CMB) radiation in the direction of galaxy clusters.

The SZ effect is proportional to the line-of-sight integral of the thermal gas pressure, and hence is an ideal tool for measuring the pressure variation created by the passage of a shock. Another very attractive property of the SZ effect is that its surface brightness is independent of redshift, because it depicts a spectral distortion of the CMB as a result of scattering. This makes the SZ effect suitable for measuring structures in the cluster pressure distribution out to very high redshifts. With the fully operational Atacama Large Millimeter/submillimeter Array (ALMA), the mm/sub-mm astronomy community now has a tool to study cluster merger shocks that is as powerful as the X-ray instruments, and a method that is also far more efficient at high redshifts.

One problem with ALMA is its small field-of-view: even in the lowest frequency band currently available (84–116 GHz) the field-of-view is only about one arcminute, while most galaxy clusters are several times larger than that. This makes it difficult to survey a large number of galaxy clusters as far as their outer radii to search for the merger shocks, where a shock front might be observable under favourable projection angles. In this regard a promising approach is to observe galaxy cluster radio relics. Like all other astrophysical shocks, cluster merger shocks accelerate particles and accelerated electrons gyrating in the shock-boosted magnetic field produce megaparsec-long synchrotron emissions, known as radio relics. The connection between cluster merger shocks and the radio relic signals has been established in numerous theoretical works as well as X-ray observations in the low-redshift Universe (see, for example, Skillman et al., 2013; Vazza et al., 2015; Akamatsu & Kawahara, 2013).

We initiated the study of relic shocks in the SZ effect using low-resolution Planck data for the very nearby Coma cluster (Erler et al., 2015), but ALMA has the capacity to truly open up this research frontier, particularly for the great many radio relics expected to be discovered in the southern sky by the Square Kilometre Array (SKA) Pathfinder surveys. This brief article gives a summary of the very first ALMA observation of a cluster merger shock, in the famous $z = 0.87$ cluster ACT-CL J0102-4915 (commonly known as "El Gordo"; see Menanteau et al., 2012) and discusses the future outlook for such measurements. More details on these results can be found in Basu et al. (2016).

ALMA observations of El Gordo

The prominent NW radio relic of the El Gordo cluster was observed with the ALMA main array in December 2015, and also with the ALMA Compact Array (ACA) between January and September 2016. Here we present images and analysis results from the main array data (12-metre diameter dishes) only. The total duration of the observations was 5.2 hr (3 hr on-source time after calibration), which represents a modest amount of telescope time compared to the typically > 100 hours that X-ray telescopes spend on high-z clusters. The ALMA observations were made with thirty-five antennas and reached a root mean square (RMS) noise of 6 μJy/beam at the centre of a CLEAN image (with a synthesised beam size of 3.6 × 2.7 arcseconds), or equivalently, an RMS brightness sensitivity of about 0.1 mK.

Figure 1 shows some of the multi-wavelength data that are available for the El Gordo cluster and puts our ALMA observation in perspective. The background is a colour composite image made of multiple pointings from the Spitzer Infra-Red Array Camera (IRAC) at 3.6 μm, showing the concentration of red galaxies in this distant cluster. The purple contours are derived from a Chandra soft-band (0.5–2 keV) X-ray brightness image and the green contours come from a low-frequency (2.1 GHz) radio observation made with the Australia Telescope Compact Array (ATCA). The opposing pairs of diffuse, extended radio emission can be seen clearly, indicating a merger that happened roughly in the plane of the sky. The most prominent of these radio relics is the NW one, roughly 0.7 Mpc long, which we observed with ALMA in Band 3 (the ALMA primary beam is shown by the white circle). The observed intensity distribution after image deconvolution (the dirty image) is shown as a zoomed-out inset, where a ripple-like signal with peak amplitude of roughly 20 μJy/beam can be identified.

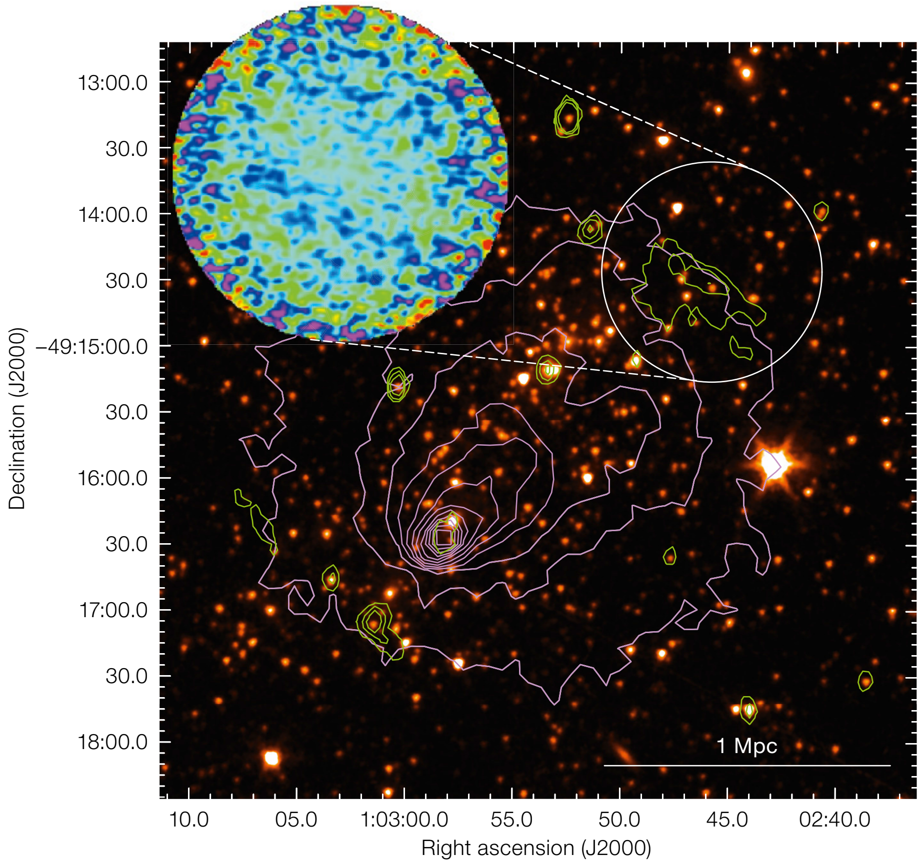


Figure 1. A panchromatic view of the El Gordo cluster and its NW radio relic. The background image is a mosaic from multiple Spitzer/IRAC pointings at 3.6 μm, overlayed with X-ray brightness contours from Chandra data (purple) and 2.1 GHz radio contours from ATCA data (green). The white circle marks the region imaged by ALMA and the zoomed-out inset shows a deconvolved image.

The origin of the faint, ripple-like signal, signifying a shock as seen by ALMA in the SZ effect, is explained in Figure 2. The pressure boost associated with a shock in the intracluster medium creates a step-function-like change in the Comptonisation profile after projection along the line of sight. This is measured as a temperature or flux decrement with respect to the background CMB signal at 100 GHz (Band 3). Since this local pressure boost scales roughly as the shock Mach number squared (typical Mach numbers for cluster merger shocks are ~ 2–4), the change in the SZ signal is non-negligible and ALMA, as the world's most sensitive mm/sub-mm interferometer, can easily detect such signal variations.

However, owing to the incomplete data coverage in the visibility plane (*uv* plane), a direct deconvolution to the image plane generates a ripple-like pattern. This is known as a dirty image and is shown in the right panels of Figure 2 for two mock ALMA observations: one for a realistic noise level comparable to that in our data (peak signal-to-noise in the image is roughly two) and one for data with five times better signal-to-noise. The ripple-like pattern is more evident in the second case whereas in our actual data it is mostly obscured by noise. The extended, cluster-wide SZ signal is practically invisible owing to a lack of sufficiently short baselines in the current interferometric observation.

Using standard synthesis imaging techniques, such dirty images are further processed with methods like CLEAN to approximate the actual intensity distribution on the sky. However, in the case of our weak and diffuse signal, with both positive and negative amplitudes, a blind application of CLEAN does not produce any significant improvements. On the other hand, selecting specific regions to perform the CLEANing operation can cause significant biases in the location and amplitude of the shock jump that we are trying to measure. Hence we developed a method to fit the cluster shock models directly to the data from the interferometer in the visibility plane that bypasses all these imaging steps. The ALMA images shown here are only for illustration; the actual results are based on this *uv*-fitting technique which is novel for ALMA data analysis and particularly suitable for modelling the extended SZ signal in galaxy clusters. The selection of the best-fit model (with the associated uncertainties) is carried out using a Bayesian Monte Carlo Markov Chain (MCMC) method that was implemented using the CASA software and is readily adaptable for combining results from multi-wavelength data.

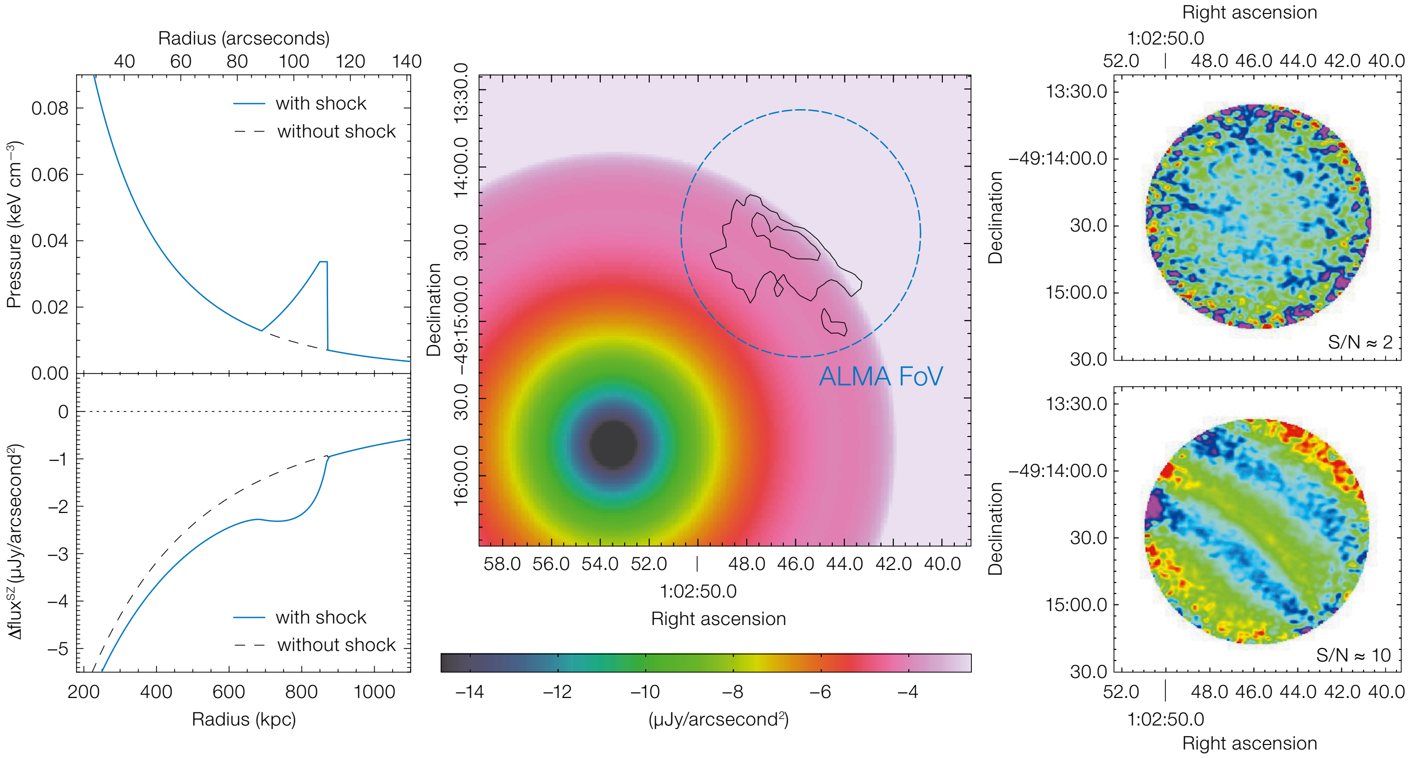


Figure 2. ALMA imaging of a cluster merger shock, illustrated by simulations. The shock-boosted pressure creates a step-function-like change in the SZ flux decrement, shown in the left panels. In the centre a mock SZ image made from this pressure model with the actual relic contours is shown. The ALMA field-of-view (FoV) is shown by the blue circle. On the right are two simulated ALMA observations with different signal-to-noise levels. In reality, we do not use such images but rather fit our shock model directly to the ALMA visibility data.

Shock profile and Mach number

A panchromatic view of El Gordo's NW relic shock is shown in Figure 3. This Figure presents for the first time a consistent picture of the non-thermal (radio synchrotron) and thermal (X-ray emission and SZ effect) signal variations across a cluster merger shock. The top panel is the 2.1 GHz radio profile (Lindner et al., 2014) which was fitted with a phenomenological synchrotron emissivity model. The two middle panels depict the Chandra X-ray temperature and brightness profile measurements. Owing to the high redshift of this cluster, most of the outer X-ray profile lies below the instrumental and astrophysical photon background (denoted by the blue dotted line in the third panel) and hence there are only marginal constraints on the gas temperature from the pre-shock region. In the bottom panel the SZ flux modulations at 100 GHz as observed by ALMA are shown. The green lines show the respective best-fit theoretical models and the red dot-dashed lines are the observed profiles after beam smoothing (radio) or image deconvolution (SZ).

The Chandra brightness data provide a clear measurement of a profile discontinuity that is indicative of a shock. However, such brightness edges can in principle also occur from large-scale contact discontinuities in galaxy clusters, commonly known as cold fronts. Since the X-ray temperature measurements are inconclusive, the cold front scenario can be ruled out using the ALMA SZ data. Indeed, our ALMA data analysis by itself provides support for the existence of a shock at more than the 98 % confidence level. The vertical grey line running through the four panels in Figure 3 is the best-fit shock location from the ALMA data and is fully consistent with the radial shock profiles we derived individually from the radio and X-ray data sets. The accuracy of the determination of the shock location by ALMA is comparable to that from the Chandra X-ray measurement and is better than the best radio data currently available.

We can model the shock Mach number independently, either from the ALMA SZ or the Chandra X-ray brightness measurements, and a comparison between these two is shown in Figure 4. The main Figure presents the joint posterior probabilities for the shock Mach numbers and the pre-shock gas pressure values, where the latter is also denoted as a function of the total cluster mass (assuming a specific intracluster pressure model). While the current ALMA data are very good at detecting the small-scale variations in the pressure profile, they cannot constrain the overall normalisation of that pressure owing to a lack of complementary short-spacing or single-dish data. This creates a strong anti-correlation between the Mach number and the upstream pressure estimates (seen from the green contours). The SZ modelling by itself points towards a weak shock, with the peak probability for the shock Mach number around $M \sim 1.5$. The X-ray brightness modelling, on the other hand, suggests a stronger shock, with $M \gtrsim 3$. When the results from the X-ray analysis are used as a prior in the SZ shock modelling, we get an intermediate value which is shown by the yellow contours in the main panel. The inset Figure shows the marginalised probability distributions

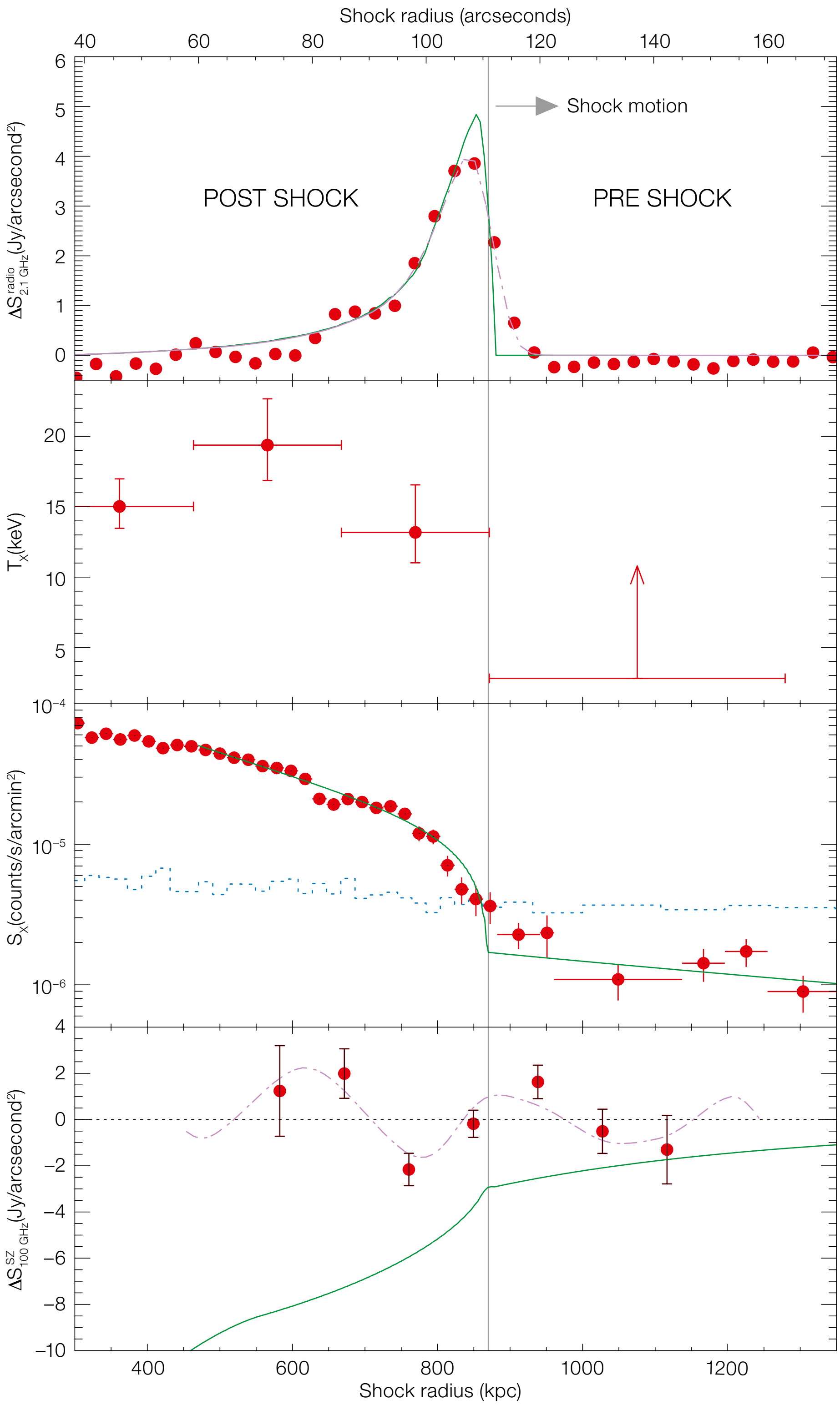


Figure 3. The profile of the NW shock in the El Gordo cluster across three wavebands. From top: radio synchrotron emission from the relic at 2.1 GHz; X-ray temperature estimates from Chandra data; X-ray surface brightness in the soft band (0.5–2 keV); and the SZ effect measurement from the 100 GHz ALMA observation. The vertical line at 870 kpc is the shock boundery, as determined from the SZ data.

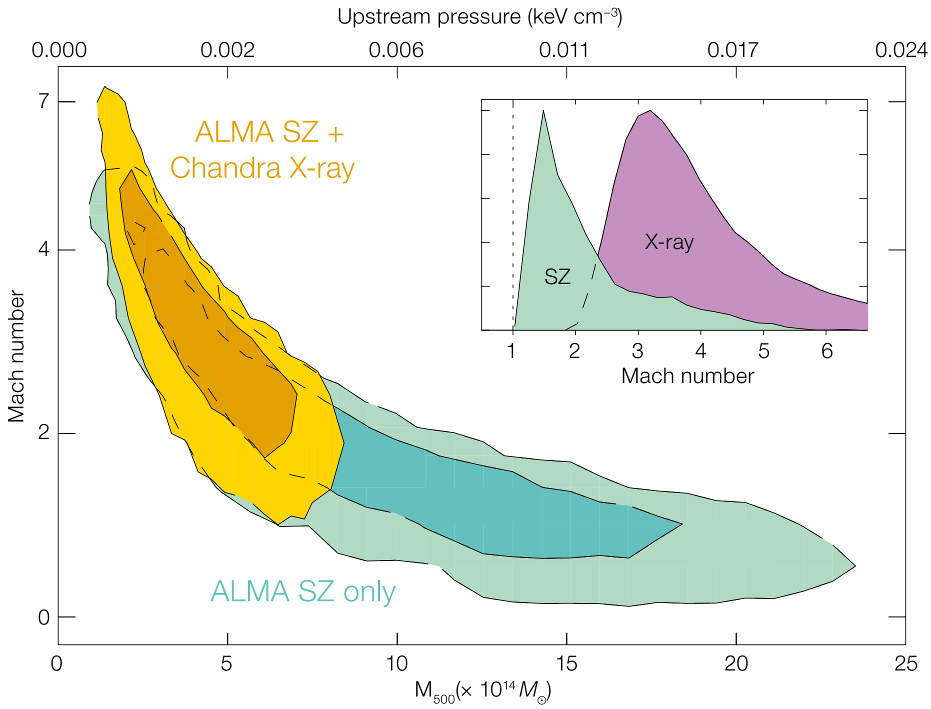
of only the Mach number values derived from the SZ and X-ray modelling independently.

The combined SZ/X-ray peak likelihood for the Mach number is $M \sim 2.5$ and this is fully consistent with a previous estimate made from the synchrotron spectral slope at the leading edge of the relic (Lindner et al., 2014). While this can be used as a justification for the standard diffusive shock acceleration paradigm (DSA; Blandford & Eichler, 1987), at least for this high-z radio relic, the mild tension between the SZ and X-ray best-fit estimates could also point to more interesting physics that might be happening at the shock front. This could be, for example, a non-equilibrium between the electron and ion temperatures or a boost in the observed X-ray brightness jump due to an inverse-Compton component. The slight mismatch could also be indicative of the different systematic dependences of the SZ and X-ray signals on the assumed shock geometry. These possibilities are currently under investigation and such joint analyses of SZ and X-ray signals suggest a promising future path for modelling the astrophysics of cluster merger shocks and their connection to the growth of cosmic structures.

Future outlook

We have described the ALMA SZ measurement of a galaxy cluster merger shock at the location of a radio relic. The cluster target is the famous El Gordo, which was detected from the Atacama Cosmology Telescope (ACT) cluster survey via the SZ effect and is likely the most massive high redshift cluster above $z > 0.5$. This object also hosts the highest-redshift radio relics (and radio halo) known to date. The detection of a merger shock at the location of one of these relics is therefore a clear demonstration of the advantages of using the SZ effect to detect high-z shock features. The multi-wavelength analysis method employed in our work also provides an example of how to systematically probe the non-thermal and thermal radiation associated with a cluster merger shock, and possibly detect new physical effects that cannot be disentangled from the data at any single waveband.

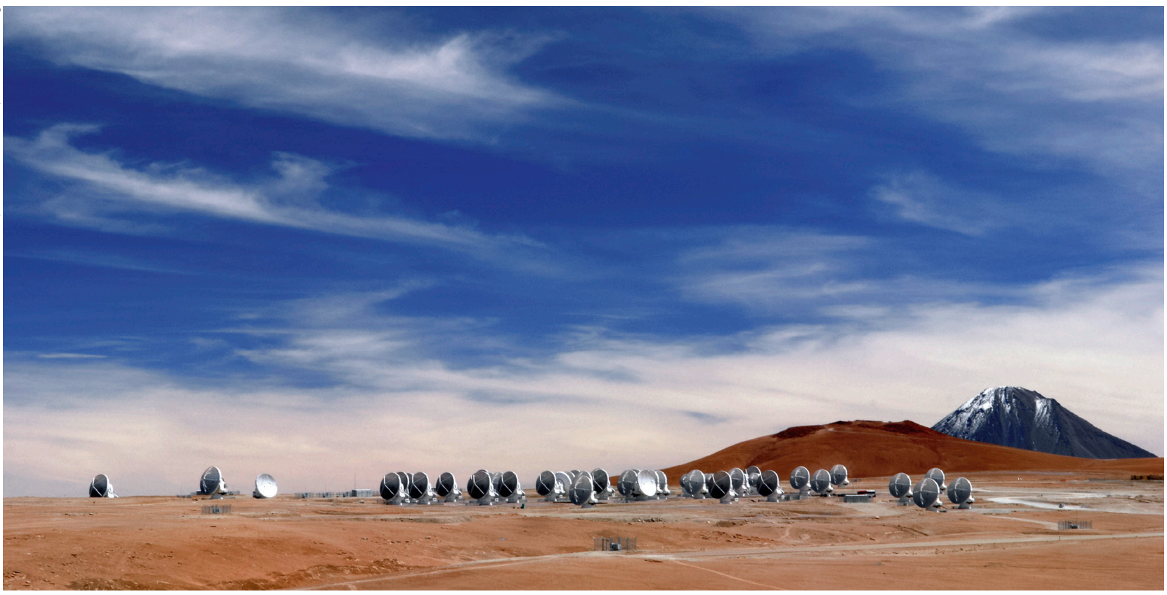
Figure 4. Joint constraints on the shock Mach number and the pre-shock pressure. Green contours are the result of ALMA SZ modelling only, whereas the yellow ones result from using an additional X-ray prior. Darker and lighter colours mark the 68 % and 95 % credibility regions. In the inset are shown the probability distributions for the Mach number as obtained from fitting the SZ and X-ray data.



The ALMA results outlined here are the product of only a moderate amount of observing time (3 hours on-source) and are a clear demonstration of the power of ALMA to study galaxy cluster substructures in the SZ effect. The precision of the current results has been limited by a lack of constraints on the overall normalisation of the SZ signal, but it can be improved by using data from the ALMA Compact Array or single-dish instruments. Even though SZ measurements alone cannot provide a full thermodynamical description of the intracluster medium, as is generally possible from the analysis of X-ray spectral/imaging data, for the purpose of modelling shock Mach numbers the SZ effect is sufficient. In this regard ALMA provides an excellent tool to complement the X-ray shock measurements of many low- and intermediate-redshift objects and to find shock signatures for the first time in many high-redshift ones. Another promising method would be to combine ALMA SZ data with short-duration X-ray observations, where the latter provide estimates for the gas density but not necessarily the temperature, in order to study features present in the intracluster medium through a joint SZ/X-ray analysis. Being the most sensitive sub-arcminute resolution SZ instrument currently available, and also the only one in the southern hemisphere, ALMA is uniquely positioned to make many such observations in the near future.

References

Akamatsu, H. & Kawahara, H. 2013, PASJ, 65, 16
Basu, K. et al. 2016, ApJ, 829, L23
Blandford, R. & Eichler, D. 1987, PhR, 154, 1
Erler, J. et al. 2015, MNRAS, 447, 2497
Lindner, R. R. et al. 2014, ApJ, 786, 49
Menanteau, F. et al. 2012, ApJ, 748, 7
Skillman, S. W. et al. 2013, ApJ, 765, 21
Vazza, F. et al. 2015, A&A, 580, A119



The Atacama Large Millimeter/submillimeter Array on the Chajnantor plateau.