Utilizing Fast Radio Bursts to Trace Intercluster Filaments and Constrain the Hubble Constant and Cosmic Curvature in a ΛCDM Universe

Joey Huang, Krrish Kainth, Aly Nathoo, Aryan Yenni

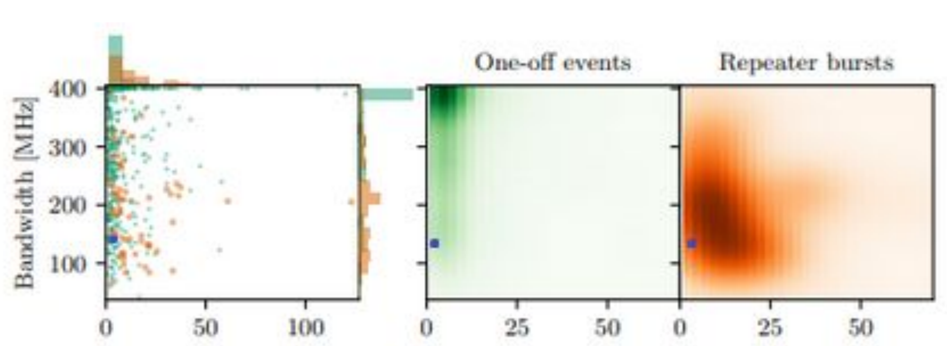
Computer Science and Engineering

ABSTRACT

Fast radio bursts (FRBs) are brief, low-frequency radio pulses that originate billions of light years away from Earth. The free electron content along the line of sight causes the burst to be smeared out in time. The amount of smearing (quantified by the dispersion measure) allows FRBs to effectively map the distribution of matter in the Universe, specifically in the warm–hot intergalactic medium (WHIM), a proposed solution to the missing baryon problem. As the WHIM is normally not visible to telescopes due to its composition of ionized hydrogen, FRBs provide a unique opportunity to probe the structure of the Universe. By observing the relationship between galaxy clusters documented by the Abell catalogue and FRBs documented by the Canadian Hydrogen Intensity Mapping Experiment (CHIME), astronomers can learn details about the regions of the Universe that the bursts pass through. This paper presents a large-scale search on the relationship between the filaments of galaxy clusters and FRBs. We detect a curvature in the dispersion measure stack and trace out the large-scale structure in the universe. To further strengthen the signal, we stacked data from CHIME and the Abell catalogue. Finally, we examine the possible candidates for a gravitationally lensed FRB. As the time delay between the images of lensed FRBs can be measured to extremely high precision, we present the results of a search for strongly-lensed FRBs, which can be used to constrain the Hubble constant and cosmic curvature of the Universe.

INTRODUCTION

Fast radio bursts (FRBs) are transient, low frequency radio pulses that originate from other galaxies. Although their root source remains uncertain, FRBs have observable properties that help probe the distribution of matter in the universe. Specifically, these radio pulses are smeared through time due to scattering interactions with the matter, especially electrons, they pass through. This lengthening is quantified by the dispersion measure and can be attributed to the charged particles of the Milky Way, an FRB's host galaxy, and the intergalactic medium. Given the significant amount of baryonic matter that likely constitutes the warm-hot intergalactic medium (WHIM) and the non-uniform density of this matter, differences in the dispersion measures of FRBs can theoretically indicate the locations of overdensities. This includes filaments of faint matter that stretch between clusters of galaxies. Moreover, identifying FRBs that are gravitationally lensed can provide insights into the expansion rate of the universe. In a gravitationally lensed system, a massive body causes an object in the background to appear at multiple points in the sky by bending light that the object emits in different directions towards the observer. Since FRBs are transient events, the different images of a lensed FRB would appear at slightly different times depending on the path the light took per image. This arrival time difference can be used to estimate the Hubble constant.



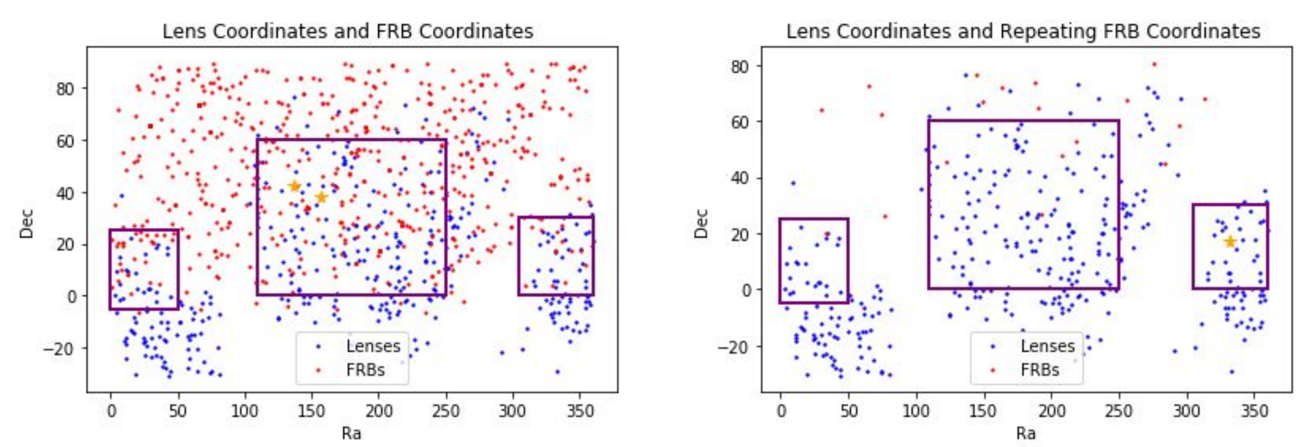
One-off versus repeater fast radio bursts (2106.04356)

The blue dot represents one Lens Repeating FRB candidate with a Bandwidth of 143 MHz and a Duration of 1.5 ms

METHODOLOGY

Search for a Lensed FRB System

- Holismokes Paper II Table: 358 Lens Galaxies in the entire Northern extragalactic sky. Focused on massive luminous red galaxies as lenses producing an Einstein Radii > 1.5"
- Chime FRB Catalog 1: 599 FRBs (including repeats) across the Northern Hemisphere, as detected by CHIME. For each FRB, the redshift was determined based on the excess DM using the Macquart Relation (the host galaxy DM contribution was assumed to be 145 pc/cm^3).



Gravitationally Lensed FRBs are fast radio bursts that have been lensed by intervening galaxies. Lensing is when matter concentrations distort and magnify light from behind while being in the same line of sight. In order to identify a lensed FRB, many attributes need to be evaluated. First of all, we need to find an FRB that is "overlapping" or very close to a lensed system.

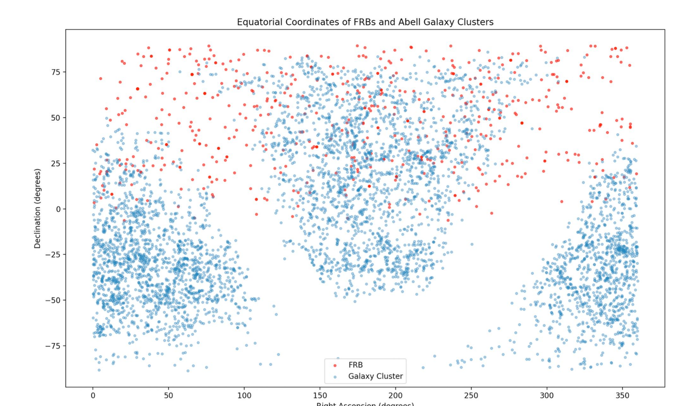
Locations in the night sky are expressed with coordinates known as Right Ascension (RA) and Declination (DEC). The FRB and Lens Catalogs contained values for these two attributes which allowed us to find proximate candidates.

Given that universe is a 3D spherical shape, RA and DEC could be better represented in three-dimensional cartesian coordinates allowing for a better representation of distances between points and more consideration of all data. Our first step was to mathematically convert the coordinates of the FRB and Lens to allow for further investigation.

Using the converted coordinates, a function was used to find FRBs and Lenses close enough to each other within a certain tolerance. The distance between an FRB and a Lens was found using the Clairaut's relation and a tolerance distance between points of 0.01 yielded 3 potentially lensed FRBs approximately 0.7 RA and DEC degrees from each corresponding lens.

Imaging the Cosmic Web

- Abell Galaxy Cluster Catalogue: 5250 galaxy clusters located throughout the sky, most with redshifts between 0 and 0.2



First, pairs of galaxy clusters within 17 h_{70}^{-1} Mpc of each other were found based on their xyz coordinates, as calculated from their RA, DEC, and redshifts. Converting the line of sight from Earth and the neighboring galaxy clusters into vectors ∈ R^n, each each cluster pair and FRB whose line of sight with Earth was closer to the line segment between the clusters and than behind the pair (based on the lower bounds of their 95% confidence redshift intervals) were recorded. Filaments having a length of less than 17 h_{70}^{-1} Mpc were rejected because of the difficulty distinguishing these filaments from pockets of gas between merging clusters.

Afterwards, we determined the xy coordinates of each FRB relative to its cluster pair (positioned at (±1,0)) from the perspective of Earth). For a given group, we calculated the xyz coordinates of the two galaxy clusters and the FRB on the unit sphere centered about Earth. Distance was found using the Haversine formula. Then, the centroid of the triangle formed by the three points was used to define the perspective plane. Projecting the three points onto a Gaussian surface and applying coordinate transformations yielded the desired relative position of the FRB.

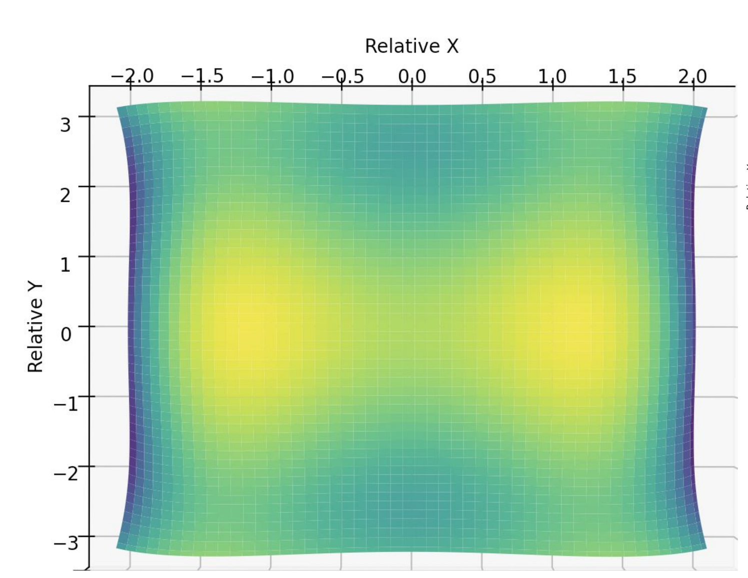
Subsequently, the relative positions and DMs were plotted. A regression model of the form $DM = A + Bx^2 + Cy^2 + Dx^2y^2 + Ex^2y^4 + Fx^4 + Gy^4 + Hx^4y^4$ was fit to the data. To test the significance of this model, the process of finding nearby FRBs, determining the relative coordinates of the FRBs, and producing a filament regression model was repeated for the same galaxy cluster pairs and 359 mock FRB catalogues, each with RA values of 1° to 359° higher than the actual angles. The values of the coefficients from these mock tests were plotted in histograms and in a corner plot, with the coefficients from the actual model indicated as lines. Furthermore, the 359 values per coefficient were averaged and the model corresponding to the resulting mean parameters was visualized. The filament model was also graphed for random RA modifications and selected RA modifications (90°, 180°, 270°).

RESULTS

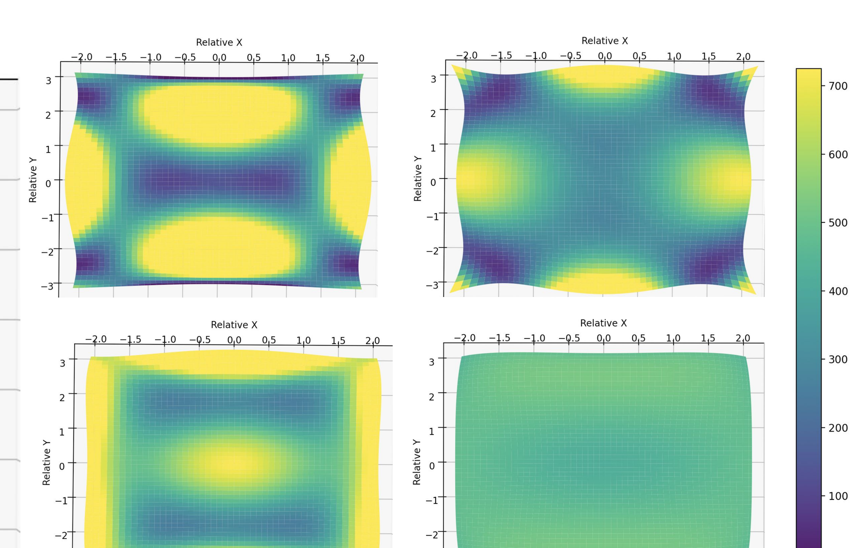
Gravitationally Lensed FRB Candidates

Lens	RA (J2000)	DEC (J2000)	Redshift	FRB	RA (J2000)	DEC (J2000)	Dispersion Measure	Estimated Redshift
PS1J1028+3820	157.045826	37.66	0.35	FRB20181128B	157.2	38.28	454.5	0.456142
PS1J0907+4233	136.866648	41.4494	0.495	FRB20191229A	137.2	42.0	955.9	0.899324
PS1j2208+1712	332.10415	16.78916	0.4682	FRB20190117A	331.7	17.4	393.1	0.378953

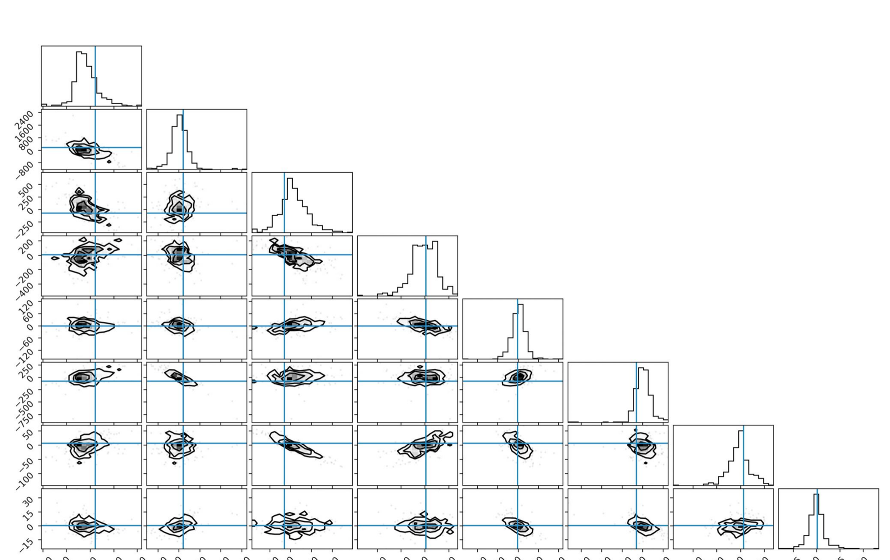
Candidates are denoted in graphs above by orange stars



Filament model for the actual (unrotated) FRB catalogue. The mean absolute error is 205.2 pc/cm^3.



Filament models for the FRB catalogue rotated (in RA) by 90° (top left), 180° (top right), and 270° (bottom left), and the average filament model of all 359 rotated catalogues (bottom right) (which has a mean absolute error of 257.0 pc/cm^3).



Corner plot of the 8 filament model coefficients for the 359 rotated FRB catalogues, with the coefficients for the actual (unrotated) catalogue model represented by the blue lines.

CONCLUSION

Search for a Lensed FRB System

As mentioned before, many specific requirements need to be met in order to identify a lensed FRB. The three FRB candidates that we found were the the most adjacent to a lens system in the two catalogs. One requirement for a lensed FRB is for the radio burst to be behind the lens galaxy, far enough to not be within the lens system itself. We can identify how far an object is from Earth using redshift, a measure of the stretch of a wavelength with larger values meaning further distances. Notingly, the redshift of an FRB is just a rough estimate based on the dispersion measure. Of the three candidates, two have redshifts where the FRB is behind the lens, with one having the FRB at a further distance from the lens demonstrating that it isn't part of the lens system. As mentioned, the FRB redshift to Dispersion Measure estimate isn't perfect, and therefore this doesn't necessarily eliminate the other contenders.

Another interesting attribute to recognize is whether or not the FRB is repeating. A lensed FRB may appear to be repeating and therefore be identified as a repeating FRB when it actually is a single burst that has been lensed making it seem repetitive. One candidate was a repeating burst which makes it preferential in our analysis despite it having a redshift placing it in front of the lens. If the repeating FRB has the attributes of a single burst, it could likely be a lensed FRB.

Our final analysis involved finding the chance coincidence probability of various portions where data points matched up. This would portray the likelihood of finding a candidate in a portion of the sky. The coincidence probability is found by taking a certain area of data, we used the purple rectangles shown in the graphs on the left and applied this formula: (# of FRB/ Area) * (# of lens/ Area) * (Area) * (Tolerance Area)

Chance Coincidence Probability

Rectangle	All FRB Coincidence Probability	Repeating FRB Coincidence Probabilty
Left	1.117	0.0399
Center	2.507	0.0721
Right	0.665	0.0392

This shows the probability of finding a lensed system solely due to chance. An estimated 4.289 candidates was calculated involving all FRBs, but only 0.1512 candidates were found to be repeating. The likelihood of finding a perfectly lensed fast radio burst that is repeating is quite unlikely but is shown to be possible.

Imaging the Cosmic Web:

The filament model coefficients corresponding to the actual FRB data are not noticeable outliers in the distribution of coefficient values for the 359 mock catalogues. However, the true coefficients produce a filament model that resembles the structure of straight filaments between relatively close clusters. Moreover, this actual model is visually dissimilar from the models of selected catalogue rotations and of the average of all the rotations, which do not align with the expected shapes of intercluster filaments and their impact on the DMs of FRBs. Therefore, the dispersion measure stack for the true FRB data hints at the presence of filaments between galaxy clusters, as predicted theoretically and supported by optical analyses. Improvements to this study, including the optimization of the cluster pair-FRB distance parameters, more accurate FRB redshift and host galaxy DM contribution estimates, careful selection of the mathematical filament model, and consideration of different filament types, can strengthen the signal. Additionally, the detection of more FRBs in the future will increase the data available for such an investigation, yielding more definite results. Overall, these findings suggest that FRBs have promise for detecting filaments and other regions of relatively high (or low) density baryonic matter via their dispersion measures, serving as valuable tools for determining the mass structure of the universe.

ACKNOWLEDGEMENTS

We would like to thank our advisor, Calvin Leung, for guiding us through this research endeavor. We also appreciate the Aspiring Scholars Directed Research Program (ASDRP) for providing us with the platform to conduct this research.