Searching Hidden Dark Core in Abell 520 with JWST

Scientific Category: High-redshift Galaxies and the Distant Universe
Scientific Keywords: Cosmology, Dark matter distribution
Instruments: NIRCAM
Proposal Size: Very Small
Exclusive Access Period: 12 months
Allocation Information (in hours):
Science Time: 13.5
Charged Time: 17.3

Abstract

The Abell 520 galaxy cluster has been the subject of debate due to its unusual mass distribution, particularly the presence of a dark core that does not coincide with the distribution of visible galaxies or gas. This has sparked a theoretical exploration into the properties of dark matter, including the possibility of dark matter self-interactions. The unresolved nature of Abell 520's mass distribution remains a key challenge, with current findings suggesting that further investigations are needed to conclusively understand the role of dark matter in the cluster's formation and dynamics. The weak-lensing data, combined with new methods and higher-resolution observations, are critical for advancing our understanding of dark matter's fundamental properties. This proposal requests observing time with the James Webb Space Telescope (JWST) to conduct a weak-lensing study of the galaxy cluster Abell 520, which has previously shown intriguing evidence of a "dark core" in its mass distribution. The improved data will enable us to probe the nature of dark matter, particularly by placing tighter constraints on the self-interaction cross-section of dark matter. In addition to mass reconstruction, the JWST data will support complementary studies such as high-resolution imaging for strong-lensing analysis, photometric redshift catalog creation, and time-domain observations of variable sources. These efforts will enhance our understanding of the dark matter distribution in Abell 520 and potentially provide insights into the fundamental properties of dark matter.

Target Summary:

Target	RA	Dec
ACO-520	04 54 10.1000	+02 55 38.00

Observing Summary:

Target	Observing Template	Flags	Allocation *
ACO-520	NIRCam Imaging *F277W, F090W, F356W, F150W, F444W, F200W*		48,450 / 61,950

* Science duration / charged duration (sec)

Total Prime Science Time in Hours:	13.5
Total Charged Time in Hours:	17.3

Observing Description

We propose using the imaging mode of the NIRCam instrument, which contains two 2.2’ x 2.2’ fields, namely module A and module B, separated by 44” covering 9.7 arcminute square in total. Since the cluster extends beyond the footprint of a single pointing, we will use a mosaic pattern to cover the full region of interest. In addition, we will adopt a standard dither pattern to improve sampling and mitigate under-sampling issues.

Investigators:

Investigators and Team Expertise are included in this preview for your team to review. These will not appear in the version of the proposal given to the TAC, to allow for a dual anonymous review.

Role		Investigator	Institution	Country
PI	&	Mr. Shurui Lin	University of Illinois Urbana-Champaign	USA/IL

Number of investigators: 1
& Contacts: 1

Team Expertise:

PI Lin is an expert in weak lensing, photometry data analysis and machine learning.

Scientific Justification (required for all)

1 Background

Galaxy clusters are immense structures composed of hundreds to thousands of galaxies, vast reservoirs of hot, X-ray-emitting gas, and a dominant halo of dark matter. Their enormous gravitational potential, which far exceeds what would be expected from visible, baryonic matter alone, has made them critical laboratories for probing the nature of dark matter. Early studies of galaxy clusters, such as those by Zwicky [15], revealed discrepancies between the observed motions of galaxies and the gravitational pull inferred from visible matter, sparking nearly a century of debate and investigation. Over time, several explanations were proposed, ranging from the presence of a yet-undetected "dark matter" component [13], to modifications of Newtonian gravity [2], and even new particle dynamical responses [12].

Gravitational lensing refers to the phenomenon where a massive object bends the light around it, resulting in magnification and distortion of the observed images. In the context of massive, extended structures like galaxy clusters, this phenomenon manifests as the weak-lensing (WL) effect, where background galaxies acquire small but systematic shape distortions (shear) due to the cluster's gravitational field [1]. By statistically analyzing the ellipticities of a large number of lensed galaxies, one can infer the shear map induced by the cluster. From this map, it is then possible to reconstruct the underlying mass distribution of the cluster, revealing not only the visible matter—such as galaxies and hot intracluster gas—but also the otherwise undetectable dark matter component [7].

A decisive breakthrough came with [3] on the Bullet Cluster (1E 0657-558), which provided one of the most compelling and direct pieces of evidence for the existence of dark matter. By weak-lensing, they precisely measured the mass distribution without relying on assumptions about the underlying gravitational theory. Their reconstruction of the gravitational potential revealed a mass profile that does not align with the hot plasma—the cluster's dominant baryonic component—traced by X-ray observations. Instead, the bulk of the cluster's mass was spatially offset from the gas, closely following the distribution of collisionless galaxies. This offset cannot be explained by a modified gravity theory and thus serves as a smoking gun evidence of dark matter.

Following the Bullet Cluster discovery, even more intriguing evidence emerged from the rich galaxy cluster Abell 520, with the image from Canada France Hawaii Telescope (CFHT). Observations revealed not only a clear offset between the mass distribution and the hot gas, but also the presence of a massive "dark core" in the reconstructed mass map [11]. Unlike the Bullet Cluster, where the dark matter distribution followed the galaxies, Abell 520's dark core coincided with the X-ray peak yet contained few or no galaxies, posing a significant challenge to the traditional collisionless Cold Dark Matter (CDM) paradigm. Such configuration, where mass is concentrated in a region with little galaxies, may hint at dark matter self-interactions. By the interactions, dark matter particles could scatter off each other, potentially creating mass concentrations that are decoupled from visible matter [10]. As a result, Abell 520's "dark core" serves as a beacon for alternative theoretical frameworks like Self-Interacting Dark Matter (SIDM), thereby offering a unique opportunity to probe the particle physics underlying the dark matter sector.

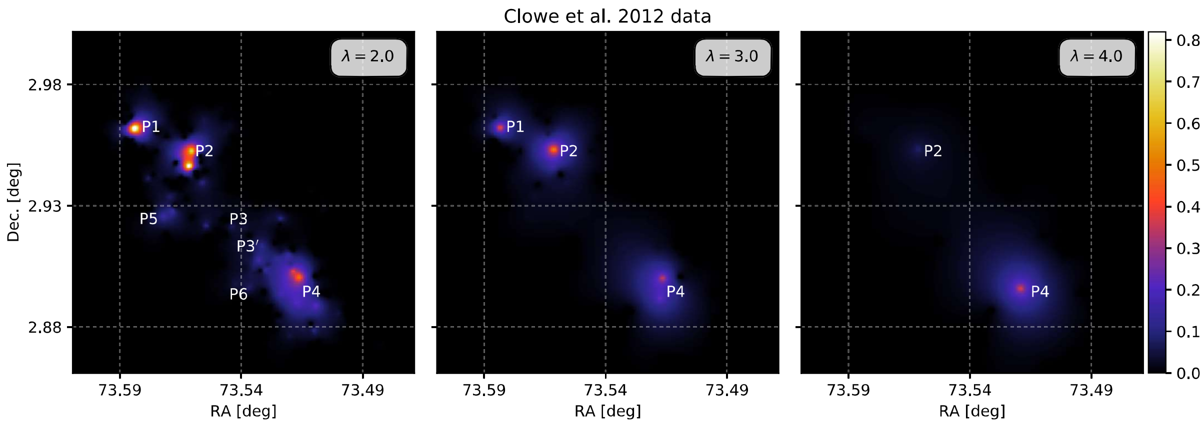

Figure 1: Figure from [14]. Surface mass reconstructions from [4] data for regularization parameters $\lambda = 2.0$, 3.0, and 4.0, where the colorbar is showing the surface mass. Labels P1–P6 indicate the approximate locations of the relevant structures reported in [4] and [8]. From left to right, one can see that noise and low-amplitude features are better suppressed with increasing λ. The presence of a dark core at P3 claimed by [8] is visible in the $\lambda = 2.0$ map, but not in the $\lambda =$ 3.0,4.0 maps.

Subsequent observations of Abell 520 using more refined weak-lensing techniques with the Hubble Space Telescope (HST) continued to fuel debate over the nature of its mass distribution. Initially, a high-resolution analysis revealed a "dark core" detected at more than 10σ significance [9], prompting theoretical work that used this result to place stringent lower limits on the self-interaction cross-section of dark matter, thus opening the door to Self-Interacting Dark Matter (SIDM) models [8]. However, a competing study, employing an alternative shape catalog also derived from HST data, failed to reproduce the dark core signal, effectively challenging the earlier findings and injecting fresh uncertainty into the interpretation [4]. An even more recent analysis that combined both shape catalogs ultimately supported the presence of a dark core, while at a much lower significance level, thereby underscoring the inherent difficulties in weak-lensing mass reconstruction and leaving the true nature of Abell 520's mass distribution—and its implications for dark matter physics—an ongoing puzzle [14].

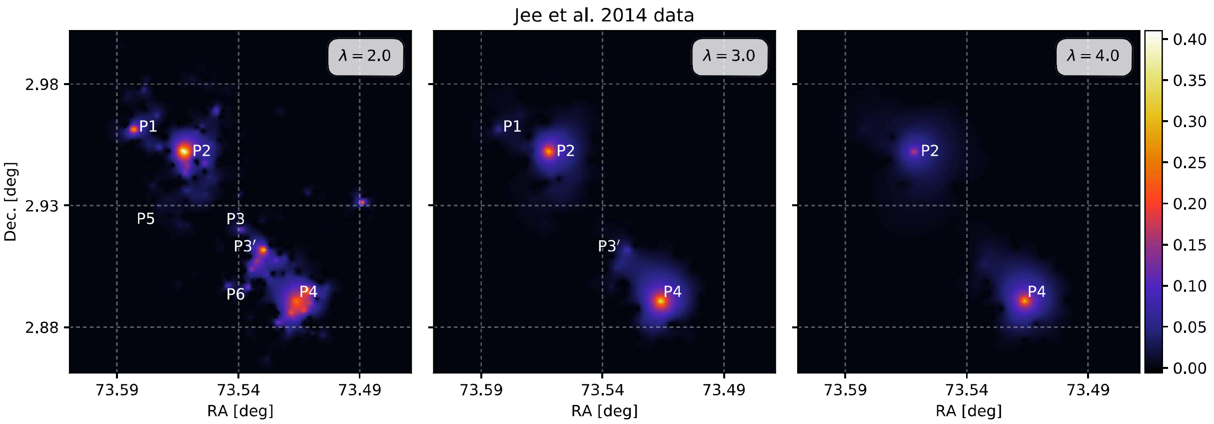

Figure 2: Figure from [14]. Surface mass reconstructions from [8] data for regularization parameters $\lambda = 2.0$, 3.0, and 4.0, where the colorbar is showing the surface mass. Labels P1–P6 are the same as in Figure 1. The mass maps agree well with the [4] data overall, but there are important differences. In particular, the P5 structure seen in [4] is missing here, while the dark core at P3more prominent.

2 This Proposal

For this proposal, we request JWST observing time for Abell 520 with NIRcam. Based on JWST's superior sensitivity and resolution, we expect to reach a background galaxy density of approximately 200 galaxies arcmin^{-2} [5, 6], nearly twice that achieved by previous HST observations [8]. This boost in background source density will significantly improve the signal-to-noise ratio of our weak-lensing measurements—on a per-pixel basis, the increase will be at least a factor of $\sqrt{2}$. Such an enhancement not only provides a more robust test of the existence of the "dark core" in Abell 520, but also enables a higher-resolution mass reconstruction that can reveal subtle substructures previously undetectable at lower source densities. By correlating these refined mass maps with X-ray gas distributions and galaxy mass data, we will be able to trace the mass assembly history and internal dynamics of the cluster with unprecedented clarity.

Based on the advantages mentioned above, we come up with the following primary science:

1. Reconstructing the weak-lensing mass map of Abell 520 using the JWST-based shape catalog. 2. Investigating the enhanced mass map for previously undetected substructures.

Beyond this, the improved weak-lensing constraints will have direct implications for dark matter physics. By providing a more accurate mass profile and quantifying the degree of core formation, the new JWST data will allow us to place tighter constraints on the SIDM cross-section. Ultimately, such insights can help determine whether dark matter is truly "dark" and collisionless.

3 Legacy Value

In addition to the weak-lensing mass reconstruction, the near-infrared (NIR) photometry obtained from JWST offers a suite of complementary science opportunities. (1), high-resolution imaging near the cluster's overdensity peak will enable strong-lensing analyses, providing an independent mass measurement that can be directly compared to the weak-lensing results for consistency checks. (2), precise NIR photometry across a wide redshift range will support the construction of robust photometric redshift catalogs, thereby informing studies of galaxy evolution, star formation histories, and the growth of cosmic structures in the early universe. (3), the use of multiple exposures taken at different times—originally intended for dithering and improved image quality—can serve as time-domain observations, enabling the search for variable sources such as active galactic nuclei, supernovae, or gravitationally lensed transients. Collectively, these secondary projects extend the impact of our JWST observations well beyond mass mapping, offering fresh insights into both the cluster environment and the broader cosmic ecosystem.

Technical Justification (required for GO, DD and Survey only)

Instrument selection: Weak gravitational lensing demands both high-quality images and multiband photometry for photometric redshift estimation. Therefore, we propose to use the NIRCam instrument with three short-wavelength filters (F090W, F150W, and F200W) and three long-wavelength filters (F227W, F365W, and F444W). We use F200W to proceed with galaxy shape measurement because of the best sampling rate of the images in terms of the ratio between PSF size and pixel size.

Observing mode: We use the imaging mode of the NIRCam instrument, which contains two 2.2' x 2.2' fields, namely module A and module B, separated by 44" covering 9.7 arcminute square in total. Since the cluster extends beyond the footprint of a single pointing, we will use a mosaic pattern to cover the full region of interest. In addition, we will adopt a standard dither pattern to improve sampling and mitigate under-sampling issues.

Exposure time calculation: Using the JWST Exposure Time Calculator (ETC), we estimate that 8074.05 seconds per filter with 10 groups per integration and 4 dither times in a DEEP8 readout pattern. This exposure time can achieve a 5σ detection of a point source at 29.5 mag in the F200W filter. In total, 13.45 hours are required to observe the target region. The number density of galaxies will be more than 200 per arcminute square, which is roughly twice as much as HST observation with similar exposure time.

Target selection: Abell 520 is a well-known, massive, merging galaxy cluster located at the intersection of three filamentary structures. Previous weak-lensing studies have revealed a "dark core" that lacks a sufficient baryonic counterpart, making it an ideal target for probing dark matter properties. With a redshift of z$\sim$0.2 and an elongated structure spanning up to 25", the cluster is well-suited for a single JWST visit.

References can be listed at the end of the proposal and do not count towards page limits. (This text can be deleted).

References

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