THEORETICAL ASTROPHYSICS AND DATA ANALYSIS

Allocation: Director Discretionary/50 Knh
PI: Gilbert Holder[1]
Collaborators: Yuuki Omori[2], Yashar Hezavehe[3], Warren Morningstar[3], Neal Dalal[1], Joaquin Vieira[1], South Pole Telescope Collaboration

[1]University of Illinois at Urbana-Champaign
[2]McGill University
[3]Stanford University

EXECUTIVE SUMMARY

We have been investigating different avenues for mapping dark matter in the universe, on both the very largest scales (extending to the cosmological horizon) and the smallest scales (>1,000x smaller than the typical size of galaxies).

We have produced the highest-fidelity map of dark matter on cosmological scales using data from the South Pole Telescope, a 10-meter (m) telescope at the Geographic South Pole that is mapping the cosmic background microwave temperature and polarization fluctuations.

We have also started a search for clumps of dark matter on small scales in galaxies that are acting as gravitational lenses of background star-forming galaxies. We have previously detected one such clump in a galaxy and we are now extending this search to a larger sample of galaxies.

RESEARCH CHALLENGE

Roughly 80% of the mass in the universe is in the form of dark matter, which appears to be a particle beyond the standard model of particle physics. It barely (if at all) interacts with particles that we have measured in the lab, other than through gravity, which is how we infer the existence of dark matter. The problem is well-studied on scales of galaxies and clusters of galaxies; our work is searching for clues about its nature by looking on much larger and smaller scales.

If dark matter is not actually "matter" at all but is instead a first crack in the theory of general relativity, it could be expected that the very largest scales may show anomalous behavior, while interesting self-interactions or other possible properties of dark matter could be expected to affect how it clumps together on the smallest scales.

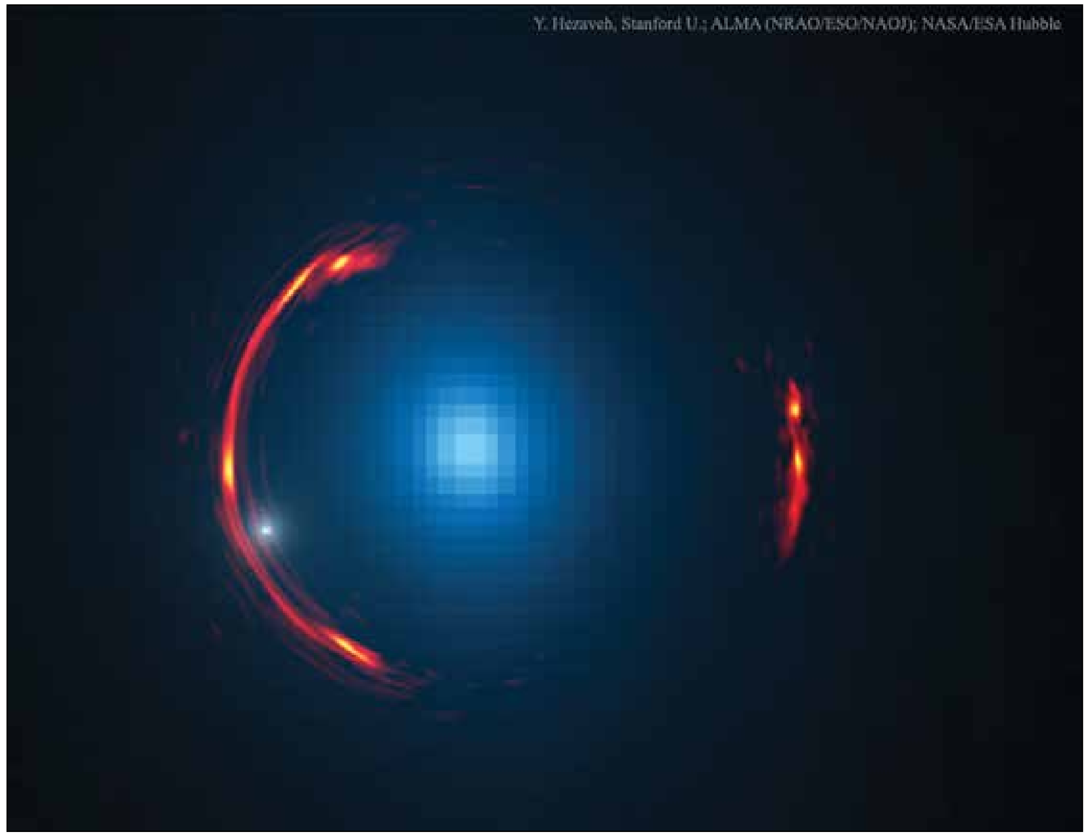

Figure 1: Strongly lensed distant star-forming galaxy SDP.81 as imaged by ALMA (red), with Hubble Space Telescope image of foreground lens galaxy (blue) in which dark matter is being studied at high resolution [2]. The white dot shows the size and location of the clump of dark matter that has been inferred using a maximum likelihood fit to the ALMA emission.

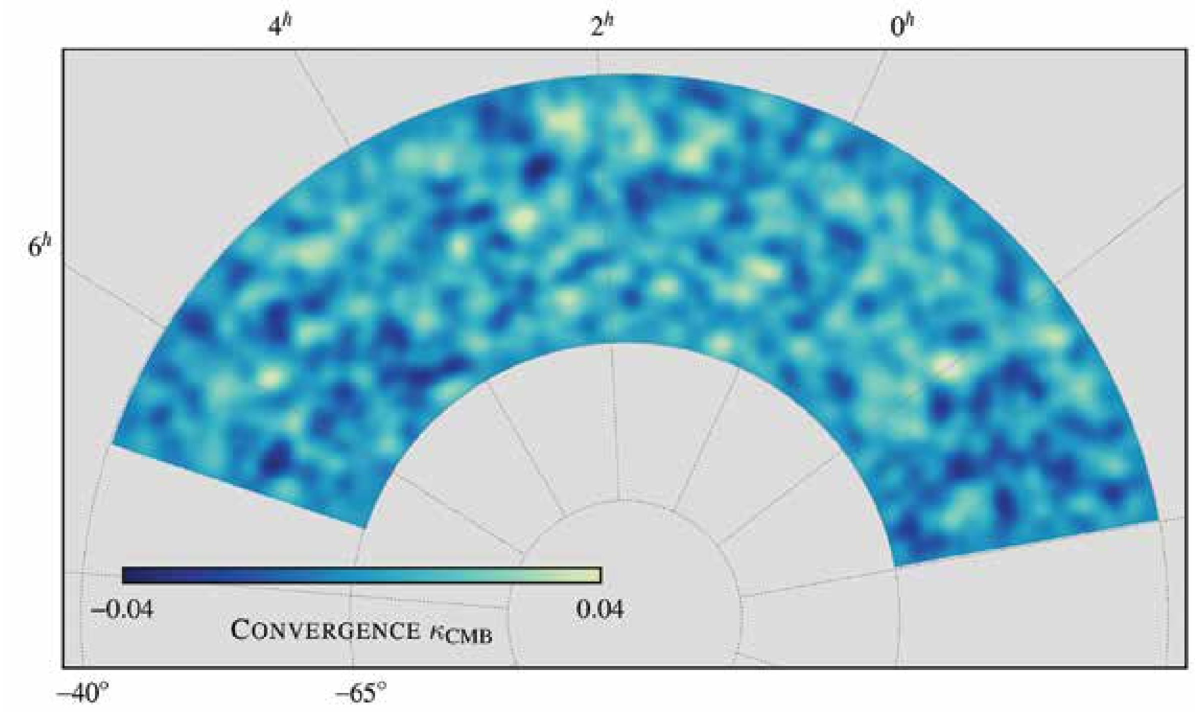

Figure 2: Map showing the integrated mass on the sky over 2,500 square degrees, obtained using intensity maps from the South Pole Telescope [1].

METHODS & CODES

We used the gravitational deflection of light to map out where the mass is in two different regimes, using either the cosmic microwave background fluctuations as the light source or star-forming galaxies observed at millimeter (mm)-wavelengths.

Using the cosmic microwave background, which is the most distant light we can measure in the universe, we make mass maps on extremely large scales by looking for subtle systematic correlations in the temperature and polarization fluctuations [1]. The South Pole Telescope, a 10-m mm-wave experiment at the Amundsen–Scott South Pole Station is mapping the cosmic microwave background at high resolution and sensitivity providing the experimental data for this work. Gravitational lensing changes the local statistical properties of the maps in a way that is sensitive to the local mass density, so we use custom-made second-order statistical estimators to make a map of the mass density.

Some distant star-forming galaxies are well-enough aligned with foreground galaxies that gravitational lensing can produce multiple images, which travel through different parts of the foreground galaxy. Small-scale structure from dark matter will be different for each of the images, allowing a search for small-scale features in the dark matter. We have developed a code to perform such a search, and successfully discovered substructure in a single galaxy [2] using data from the Atacama Large Millimeter Array, and we are now applying a similar analysis to new data on five more galaxies. The image used to discover the dark matter substructure in the first galaxy studied is shown in Fig. 1.

RESULTS & IMPACT

Using Blue Waters, we were able to run Monte Carlo simulations of the South Pole Telescope data analysis pipeline at a level that allowed us to make the map shown in Fig. 2: Over 2,500 square degrees, we have a map of how much mass there is at every point on the sky. "Lensing convergence" is a weighted average of the mass density along the line of sight to the source, and since the source (the cosmic microwave background) is at the edge of the observable universe, we get a complete census of the mass in the universe. This map is being used to compare with galaxy surveys to better understand the relationship between visible mass and dark matter. Going forward, the South Pole Telescope has a new camera that is roughly 10x faster at mapping the sky, which will enable both higher precision and higher resolution in this mass map within a year or two.

The search for small-scale substructure in the dark matter is ongoing. With the data currently being analyzed, we expect to be able to confirm or rule out dark matter candidates that have either a large thermal velocity ("warm dark matter") or dark matter composed of ultra-light particles that have a quantum mechanical fuzziness that extends to macroscopic scale ("fuzzy dark matter").

WHY BLUE WATERS

The combination of computing power and support staff for Blue Waters made this the premier option for performing this research.