Snowmass2021 - Letter of Interest

Roman Space Telescope Strong Lensing Probes of Dark Matter Substructure

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: *Nancy Grace Roman Space Telescope*, formerly known as the *Wide Field Infrared Survey Telescope*, is scheduled to launch in the mid-2020's and will provide a multi-band, high-resolution view of the cosmos. Equipped with a mirror the size of *Hubble Space Telescope* and a $0.3\ \mathrm{deg}^2$ infrared-sensitive camera $\sim 100\times$ larger than *Hubble/Wide Field Camera 3*, *Roman* will efficiently and sensitively map large areas of the sky with $\sim 0.1''$ resolution. This resolution will enable the discovery of ~ 1000 gravitationally-lensed quasars, which in turn provide detailed constraints on the properties of dark matter substructures. We review the promise of *Roman* for achieving dark matter constraints through strong lensing, both as stand-alone lensing experiment and in collaboration with other facilities.

Nancy Grace Roman Space Telescope (*Roman*) is a 2.4m space telescope scheduled to be launched in the mid-2020's by the United States National Aeronautics and Space Administration (NASA)[1;2]. Formerly known as the *Wide Field Infrared Survey Telescope*, *Roman* will undertake an ambitious set of mission surveys including a large area cosmology survey ($\sim 2000\ \mathrm{deg}^2$) with multiband imaging ($H \sim 26.7$AB flux limit) and slitless grism spectroscopy ($\sim 10^{-16}\ \mathrm{erg\ s^{-1}\ cm^{-2}}$ line sensitivity at $\lambda \sim 1.5\mu$m).

While the cosmology mission surveys are designed to constrain structure formation and the expansion history through weak lensing and baryon acoustic oscillations, *Roman* can test our picture for small-scale dark matter structure formation more directly through gravitational lensing. The cold dark matter plus cosmological constant (ΛCDM) paradigm forms one of the pillars of our models for the origin and evolution of cosmic structures. While remarkably successful at matching observations on large scales, there have been persistent observational challenges to the cold, collisionless dark matter expectations on dwarf-galaxy scales. These "small-scale controversies" may simply stem from a poor understanding of the baryonic processes involved in galaxy formation, or indicate more complex dark sector physics[3].

Detailed testing of the standard paradigm on small scales remains one of the most pressing issues in cosmology. Numerical simulations in ΛCDM predict a rich spectrum of substructure in galaxy halos. Small fluctuations in the galaxy-scale lensing potential caused by these substructures should result in measurable "flux anomalies" in the magnifications of quadruply-lensed quasar images[4]. While discrepancies between the observed flux ratios and those predicted by a smooth lens model may have been found in quasar lenses[5–7], the small size of current samples limits our understanding (~ 56 quad lenses[8], even fewer with high-resolution imaging). According to predictions of the occurrence of multiply-imaged strong-lensed quasars in wide-area surveys[9], the *Roman* cosmology survey will revolutionize this field by increasing the sample of quad lenses by more than $20\times$ to ~ 1000 objects.

The ability to use strong-lensed quasars as probes of the small-scale structure of dark matter halos can be powerful for constraining the nature of dark matter itself. The quasar strong-lensing method is potentially sensitive to the presence of any dark matter component that may suppress small-scale power. Subhalos in the host galaxy lens and in structures along the line of sight[10] affect the image positions and flux ratios. By modeling how the mass function of subhalos, which is directly controlled by the small-scale power spectrum, influences the lensing signal, the presence of a warm dark matter component can be constrained. For instance, Gilman et al. 2020[11] used space-based imaging[12] of only 8 multiply-lensed quasars to place 95% confidence limits of $m_{DM} > 5.2$ keV assuming thermal relics. With increased samples of dozens of quad-image strong lenses with high-resolution imaging, constraints can be achieved[13] on sterile neutrino dark matter models with masses $m_{DM} \sim 7$keV required to explain the 3.5keV line seen in *XMM-Newton* and *Chandra* x-ray data[14–16].

Over the last decade, methods have been developed to use extended lensed sources, in addition to the point-like AGN, to identify substructures through distortions of lensed images. Extended sources are imaged into arcs and rings that probe a larger volume in the lens halo, increasing the number of subhalos that can be sensed. They also can be drawn from larger populations of background sources, typical galaxies rather than bright AGN. Vegetti & Koopman (2009)[17] described a method for identifying substructures with high-resolution optical/IR imaging of extended galaxies, with Vegetti et al. (2012)[18] reporting a detection of a dark substructure in a gravitational lens at $z = 0.9$. In related work, Hezaveh et al. (2013, 2016a)[19;20] described the use of (sub-)millimeter spectral lines from dusty lensed galaxies to search for subhalos in the lenses. The wide survey area of the *Roman* cosmology survey, along with its combination of multi-band imaging and spectroscopy, will provide many avenues for identifying large samples of lensed galaxies for such substructure searches. By combining space-based and ground-based surveys[21–23], *Roman* can contribute by extending strong-lensing probes of dark matter to halo inner density profile slope measurements[24–26], group-to-cluster scale lenses[27], and statistical measures of the matter power spectrum[28].

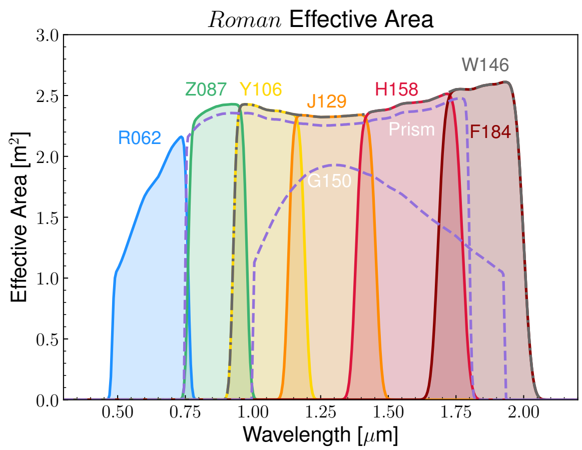

Figure 1: Effective area of *Roman* in its multiband photometric and grism spectroscopic bands as a function of wavelength (updated from Akeson et al. 2019[2]). Shown are the $R062$ (blue), $Z087$ (green), $Y106$ (yellow), $J129$ (orange), $H158$ (red), $F184$ (crimson), and $W146$ (gray dot-dashed) photometric filters, and the G150 and Prism spectroscopic filters (purple dashed). The high-resolution multiband imaging and slitless spectroscopy will enable *Roman* to constrain substructure in individual lenses and thereby provide information on the nature of dark matter.

While *Roman* covers smaller areas than either *Euclid* from space or *Vera Rubin Observatory* from the ground, the potency of *Roman* to provide improved constraints on the small-scale matter power spectrum through lensing is significantly enhanced by its high-resolution, ultradeep, space-based, multiband imaging and grism spectroscopy. The *Roman* cosmology survey is expected to have Y, J, and H filter images, along with additional coverage in the $F184$ filter that extends to $\lambda \approx 2\mu$m. The high-resolution imagery will help combat potential systematic issues with interpreting flux anomalies in the presence of baryonic structures like disks[29], and help resolve uncertainties about the potential impact of central baryonic components on the survivability and presence of dark substructure[25;30;31]. This array of near-infrared filters will reduce the effect of dust attenuation from the lensing galaxies on the source images, improving the sensitivity to multiply imaged lenses. With the high spatial resolution of the grism spectroscopy, *Roman* gains a complementary probe using the flux ratio of strong quasar lines such as OIII to constrain substructure[32;33].

Using *Roman*, astronomers will explore the substructure science achievable from the mission cosmology surveys and various general observer and archival research programs. NASA has fully committed to open science with *Roman*, with the mission data products released publicly without a proprietary period. Community science efforts, like the Space Warps-HSC effort at the Zooniverse project[34], will be able to involve the public in the discovery of multiply-lensed quasars in the *Roman* data. A host of machine-learning-based methods for the discovery of strong-lensed systems have already been developed[35–38], providing broad opportunity for automated identification of quad-lens quasars and multiply-lensed galaxies in the *Roman* surveys.

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