# Snowmass2021 - Letter of Interest

# *Strong Lensing Probes of Dark Matter*

**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]*
■ (TF08) BSM Model Building
■ (TF09) Astro-particle physics & cosmology
■ (CompF2) Theoretical Calculations and Simulation

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**Abstract:** Strong gravitational lensing provides a unique probe of dark matter structure at the smallest cosmological scales, and thus constrains the particle nature of dark matter itself. By coupling directly to gravity, lensing circumvents luminous tracers of the underlying dark matter, and it is sensitive to mass scales below those of typical dwarf galaxies. Should dark matter continue to evade direct detection, gravitational probes such as lensing will provide the only means with which to probe its particle nature, such as the mass, self-interaction strength, non-gravitational interactions with the Standard Model, and compact object abundances. Exploiting the full power of lensing to constrain the nature of dark matter requires a sufficiently large and well-characterised sample of lenses, exquisite data and sophisticated analysis tools. While a large sample of lenses is being assembled by current and upcoming surveys (such as Rubin, Roman, Euclid observatories), sufficiently sensitive data can only be obtained with the resolution and collecting area of large ground based facilities with adaptive optics, such as extremely large telescopes (ELTs), or the James Webb Space Telescope (JWST). It is key to continue to support the development of adaptive optics from the ground for high resolution imaging and spectroscopy and to support cross-disciplinary, collaborative efforts to unite dark matter analysis with particle theory and experiment.

**Background:** As the particle physics community seeks to diversify the experimental effort to search for dark matter, it is important to remember that astrophysical observations provide robust, empirical measurement of fundamental dark matter properties. In the coming decade, astrophysical observations will guide other experimental efforts, while simultaneously probing unique regions of dark matter parameter space. In this Letter of Interest we emphasise and promote strong gravitational lensing as a dark matter experiment. Strong lensing is a purely gravitational phenomenon, which probes mass concentrations independent of their baryonic content on sub-galactic scales, including in mass regimes where halos contain few to no stars [1–4]. The detection and quantification of halo structure down to halo mass $\mathrm{M_h} \sim 10^7 M_\odot$ provides a stringent test of different dark matter models that makes unique predictions for the abundance and density profiles of halos in this regime. Examples of these models include warm dark matter (WDM), self-interacting dark matter (SIDM), primordial black holes (PBH), and fuzzy dark matter (FDM). While some dark matter models change primarily the abundance of structure, other models result in imprints on the density structure of halos. Strong lensing is sensitive to both effects at low mass. Strong lensing observables are sensitive to both subhalos associated with the host dark matter halo of the main deflector, and field halos along the entire the line of sight from the source to the observer[5–7]. The latter population is unaffected by tidal forces from a host halo, making line-of-sight halos pristine laboratories for probing dark matter physics through structure formation.

**Recent progress:** Analyses of resolved distortions in extended Einstein rings have resulted in the detection of substructure with inferred lensing masses of $M_{\rm lens} \approx 10^{8-9} M_\odot$ with the Hubble Space Telescope, Keck adaptive optics (AO), and ALMA interferometric data[8–13]. The sensitivity of a lensing detection is limited by the angular resolution of the data, and by the structure of the lensed source. Additional challenges arise in the modelling process as a result of the complexity of the data set, uncertainties in telescope and instrument response, and degeneracies in the lens model and source structure. Very Long Baseline Array (VLBA) radio observations have the capacity to probe structure power at the $10^7 M_\odot$ scale, albeit for a very small sample of lens systems, and require analysis pipelines that can cope with the large data volume per observational target.

The magnification ratios between adjacent images of multiply-imaged quasars provide an alternate means of probing substructure. Initial studies showed that these data are consistent with CDM at scales of $\gtrsim 10^9$ $\mathrm{M_\odot}$ [3;14]. Recent progress with newly gathered data and a re-analysis of previously existing data resulted in tighter constraints demonstrating consistency with CDM to scales of $\gtrsim 10^8$ $\mathrm{M_\odot}$ [15;16]. The latest constraints correspond to a free-streaming length scale of $\sim 10\mathrm{kpc}$, or an equivalent thermal relic particle mass of $m_{\rm th} > 5$ keV, ruling out warmer mass functions at 2 sigma confidence. A similar study constraining the mass-concentration relation of dark matter halos at $\sim 10^9$ $\mathrm{M_\odot}$ [17] showed consistency with CDM predictions, and the extrapolation of N-body simulation results to the scales probed by lensing.

The magnification of lensed images depends on the size of the background source, and thus the interpretation of these data depends on the size of the emitting source region (radio vs narrow-line emission region) and on the smooth component of the lens model with respect to which anomalies can be identified. Over-simplified lens models [18] can bias the expected flux ratios, and baryonic structures such as prominent disks can affect the interpretation of anomalous structures in both real lenses [19–21] and simulated ones [22].

**The way forward - opportunities and challenges:** Deviations from CDM predictions at mass scales of $10^7 M_\odot$, where galaxy formation models have minimal impact on the structure and abundance of dark matter halos, would require physics beyond $\Lambda$CDMwith a particle physics model of dark matter. Conclusive results at the $10^7 M_\odot$ scale will require an expanded sample size of suitable lens systems, and improved data quality. The Rubin and Roman Observatories will yield up to 10,000 gravitational lenses, including several hundred quadruply-imaged quasars. The order of magnitude expansion of the current strong lens sample size forms the basis upon which strong gravitational lensing probes of dark matter and dark energy will operate in the next decade. However, this sample of lenses will not translate into constraints on dark matter at the $10^7 M_\odot$ level on its own; sufficiently precise and sensitive follow-up efforts must be undertaken for a targeted subsample. Further, for a decisive measurement to determine the physical nature of dark matter, multiple independent approaches with statistical significance and rigorous tests of systematics and assumptions are required.

Existing adaptive-optics supported ground and space-based facilities and with the near-term advances in all-sky access of adaptive optics, such as the commissioning KAPA instrument[23] , paired with the emerging sample of gravitational lenses, have the spatial resolution necessary for precise determination of the mass function and structure of halos in the range $10^{8-10} M_\odot$ with gravitational imaging. Gravitational imaging sensitivity will significantly benefit from the improved imaging resolution afforded by next-generation telescopes. For constraints from unresolved image flux ratios, predictions for required numbers of lenses and flux measurement precision are provided by Gilman et al. (2019)[7]. The expected number of quadruply-lensed quasars on the sky is sufficient to meet the requirements to measure the mass structure at $\sim 10^7$ M$_\odot$, but the constraining power of a fixed sample size depends strongly on the measurement precision of the flux ratios. Current state of the art measurements presented by Nierenberg et al. (2020)[24] achieve 5-6 $\%$ precision. Considering that most of the quadruply-lensed quasars to be added to the existing sample will be fainter, enhanced observational capabilities will ensure that lensing reaches the $10^7 M_\odot$ target threshold.

The James Webb Space Telescope (JWST) will enable precise spectroscopic measurement of narrow line and dusty-tori flux ratios, but may not have the capacity to do so for a required sample of $\sim 100$ quadruply-lensed quasars. In addition, uncertainties in the emitting source structure affect the interpretation of the flux ratios and thus provide a systematic floor unless resolved measurements of a subset of quasars can be achieved. The collecting area of the next generation of ground based extremely large telescopes (ELTs; US-ELTP for the US) with adaptive optics will make it possible to precisely measure flux ratios for a sufficiently large sample and allow a statistically precise inference of the structure at $\sim 10^7$ M$_\odot$. In addition, when the adaptive optics performance on ELTs becomes near diffraction limited, the currently unresolved narrow line emission regions become resolved and assumption on the source morphology can be replaced by direct empirical evidence.

In addition to the required data to perform the dark matter experiment with strong lensing, ongoing developments in the data analysis techniques encompassing image simulation, signal extraction and statistical inference tools, including the use of machine learning approaches, need to be pursued to cope with the expected data sets. Furthermore, accurate predictions of the gravitational and non-gravitational imprints on the structure formation process at the probed mass resolution require advanced computational approaches. Furthermore, translating observations into constraints on dark-matter particle properties requires a dedicated simulation effort, which includes creating many realizations of lens systems with full baryonic and dark-matter physics.

In conclusion, exploiting the full power of lensing to constrain the nature of dark matter requires both exquisite data and sophisticated analysis tools. While the latter are being developed on precursor datasets, the former can only be obtained with the resolution and collecting area of extremely large telescopes (ELTs). The analysis of the proposed data will require continued support for the development of methods, computational techniques and resources, as well as a robust interface between strong lensing predictions and cosmological numerical simulations of different dark matter theories.

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