Gravitational Lensing as a Sensitive Probe of Dark Sector Particles

D. Walker[a], L. Moustakas[b] and K. Sigurdson[c] for the OMEGA Collaboration

[a] *SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, U.S.A.,*
[b] *Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T, Canada,*
[c] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.*

Abstract:

In this worksheet, we overview the potential of the OMEGA Explorer Project to explore the particle nature of dark matter. We emphasize how the project can decisively search for hidden sector particles beyond the standard cold dark matter scenarios. Thus, along with the accelerator-based searches, this project provides a complementary probe of hidden sector particles [1].

1. The OMEGA Explorer Project

Determining the nature of dark matter is one of the outstanding problems in fundamental physics and astrophysics. Heroic efforts are underway attempting to produce a dark matter particle at the Large Hadron Collider, to detect dark matter through its rare but occasional recoil in a laboratory environment (e.g. the Xenon100 experiment), to observe dark matter through the radiation or particle products that are predicted to occur for some specific candidates (e.g. through gamma ray emission that the Fermi space telescope could have detected). Each of these approaches target dark matter on very local scales, cosmologically speaking, from the physical scale of a terrestial experiments through to galactic volumes. From the perspective of particle physics, each approach requires a significant (model-dependent) coupling between dark matter and Standard Model particles in order to observe a signal. Of course, dark matter is ***defined*** by large-scale gravitational effects on visible matter. OMEGA Explorer Project is designed to probe these gravitational effects in order to uncover the particle nature of dark matter. Importantly, the project can generate constraints on additional particles beyond cold dark matter in the hidden sector in a model independent way.

Dark matter, by far, is the dominant gravitational component in the universe. The specifics of its distribution on small and large (cosmological) scales in the universe depend on the properties of the dark matter particle itself, the specific ways with which it interacts with itself (and other hidden sector particles), and with the Standard Model particles with which we are familiar. In particular, measuring the statistics and properties of small (sub-galactic) scale dark matter halos is an astrophysical probe of dark matter with the potential to distinguish between several distinct classes of candidates with a variety of properties.

Astrophysical strong gravitational lensing systems, where a distant active galactic nucleus is multiply imaged into four images by a foreground massive galaxy, enables the possibility of measuring such substructures through their gravitational perturbation properties. This is complementary to all other probes, and working in tandem or independently of them, will provide new and potentially powerful information of the nature of dark matter and the composition of hidden sectors. Dark matter sub-galactic mass scales of one or two orders of magnitude below 10^6 solar masses ($M_\odot$) is possible through the tailored experimental design reflected in the OMEGA Explorer project, a dedicated space-based observatory that was proposed to NASA in 2011 [2]. This is a new discovery space that will produce fresh and possibly essential insights into dark matter properties. Developing detailed theoretical predictions for dark matter and hidden sector particle candidates is critical for quantifying the specific power of such an experiment.

2. Searching for New Physics Beyond Cold Dark Matter

Here we describe the connection between dark matter properties and the most dramatic consequences on the astrophysical scales on which their self-gravity will allow coherent structures to form. For simplicity focus on GeV dark matter. A sub-GeV dark photon is included which decays to the Standard Model soon after leaving thermal equilibrium with the Standard Model. We estimate the associated kinematic decoupling and the cutoff in the dark matter power spectrum. We finally show how OMEGA, along with constraints from accelerator based probes, can decisively constrain hidden sector particles.

It is well known the maximum dark matter clumping mass depends sensitively on the kinematic decoupling temperature [3, 4]

$$M_{\rm cut} \simeq 10^{-4}\Big(\frac{T_d}{10\ {\rm MeV}}\Big)^{-3} M_\odot \tag{1}$$

where $M_{\rm cut}$ is the cutoff in the dark matter power spectrum. This in turn sensitively depends on the dark matter particle physics as

$$T_d = \Big(\frac{M_\sigma^4\, M}{M_{\rm pl}}\Big)^{1/4} \tag{2}$$

where M is the mass of the dark matter. M_σ is the mass scale associated with the dark matter interaction cross section with the dark photons. For this example, we assume the dark photons are in thermal equilibrium with the Standard Model at the dark matter kinematic decoupling temperature. Assume the dark matter Compton scatters elastically with the dark photon and is parametrized by

$$\sigma \approx \frac{T^2}{M_\sigma^4}. \tag{3}$$

It is clear a larger dark photon-dark matter scattering cross section lowers $M_{\rm cut}$. For the masses listed in the first paragraph and for $M_\sigma \sim 1$ GeV, $M_{\rm cut} \sim 10^4$. We show this cutoff is within OMEGA's sensitivity in [1].

The constraint on $M_{\rm cut}$ is essentially a constraint on the coupling and mass of the hidden sector particles. Accelerator-based probes propose providing complementary constraints on the coupling and mass of hidden sector particles. We use both to place constraints on the mass and couplings of hidden sector particles [1].

3. Experimental Reach of the OMEGA Explorer

The OMEGA Explorer is a meter-class multi-wavelength imager, in low earth orbit, dedicated to tailored monitoring a sample of 24 strong gravitational lenses. These are lenses that have natural flux variations with time. By OMEGA's design to reach a photometric precision of $\sim 1\%$, it will be able to map these variations through hourly-cadenced monitoring of each lens, with campaigns that last several weeks each. Through these data, all of the fundamental properties of the gravitational lensing potential will be mapped well enough to potentially be sensitive to not only the overall mass structure of the lensing galaxy, but also of the gravitational perturbations due to the substructure within the lensing galaxy. The OMEGA science team has been developing realistic strong lensing simulations, and a Bayesian inference framework to evaluate the level of sensitivity to different substructure scenarios, which would arise from different dark matter particle fundamental properties. Based on preliminary work developed for the Explorer 2011 proposal, a clear cutoff in the existence of small scale structures below 10^6 solar masses is expected to be in relatively easy reach of OMEGA as currently designed. Based on the work done to date, considerably greater sensitivity is possible, and we are exploring how robust the constraints will be reaching to cutoff scales of 10^4 solar masses or lower.

4. Status and Future Plans

The OMEGA Explorer was proposed to NASA in 2011, and while not selected, was judged as a Category II mission, i.e. "selectable." The science team and associated close collaborators (including the first author of this report) are actively developing the strong lensing theory, and the particle physics theory, that will showcase the power of this experiment for making material advances of interest to the particle physics community. The work being completed now and in the near future will help bridge several fields of study from particle physics to astrophysics, and will open an as yet largely untapped area of quantitative dark matter studies. The practical future plans include a re-proposal of the OMEGA Explorer.

5. The OMEGA Collaboration

The OMEGA Science Team is an international collaboration that spans all of the key fields of physics and astrophysics that are involved in this multifaceted experiment.

Leonidas Moustakas, PI

Adam Amara	Andrew Benson	Misty Bentz

Adam Bolton	Misty Bentz	James Bullock
Remi Cabanac	Ed Cheng	Dan Coe
Art Congdon	Francis-Yan Cyr-Racine	Ben Dobke
Greg Dobler	Peter Eisenhardt	Richard Ellis
Ross Fadely	Chris Fassnacht	Sarah Gallagher
Raphael Gavazzi	Tim Goodsall	Varoujan Gorjian
Manoj Kaplinghat	Chuck Keeton	Jean-paul Kneib
Mike Kuhlen	Charles Lawrence	Harry Teplitz
Peter Eisenhardt	Phil Marshall	Tommaso Treu
Richard Ellis	Richard Massey	Joachim Wambsganss

References

[1] D. G. E. Walker, D. Finkbeiner, L. Moustakas and K. Sigurdson, *to appear.*

[2] L. AMoustakas, A. JBolton, J. TBooth, J. SBullock, E. Cheng, D. Coe, C. DFassnacht and V. Gorjian *et al.*, arXiv:0806.1884 [astro-ph].

[3] A. Loeb and M. Zaldarriaga, Phys. Rev. D **71**, 103520 (2005).

[4] E. Bertschinger, Phys. Rev. D **74**, 063509 (2006) [astro-ph/0607319].

[5] S. Profumo, K. Sigurdson and M. Kamionkowski, Phys. Rev. Lett. **97**, 031301 (2006).