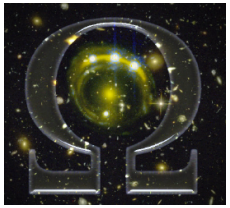

OMEGA-SALSO
Astrophysics

Jet Propulsion Laboratory
California Institute of Technology

Overview:

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With: The OMEGA Explorer Science Team, including (at JPL): Drs. Tim Goodsall, Varoujan Gorjian, Francis-Yan Cyr-Racine, Julian Merten

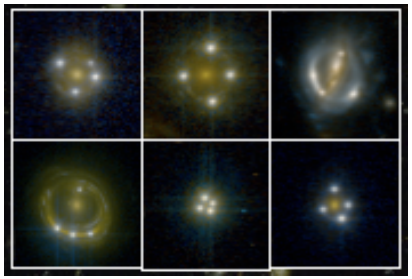
Scientific goals where new measurements or breakthroughs will be achieved:

- Dark matter particle thermal and interaction properties
- Dark matter and baryonic structure formation
- Detailed tomography of accreting supermassive black holes
- Maps of the innermost structure (and inner edge) of accretion disks
- Highly constrained stellar mass functions at cosmological distances
- Potentially statistical maps of large populations of cosmologically distant "nomad" planetary populations

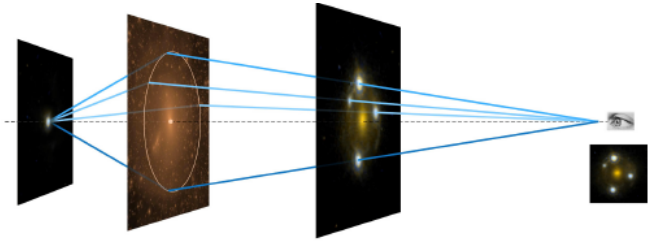
By the nature of the distance-range of the targets, each of these quantities will be mapped over several Gyr of cosmic time, enabling a unique view of their evolution, and opening a new extension beyond local-universe studies for comparisons against model expectations and predictions.

Graphics:

Gravitational lensing is a distorting, focusing, and magnifying phenomenon in nature. In the "strong" regime, multiple images can form, each with a different light-travel time to the observer.



Typical targets (as observed by Hubble): strong gravitational lenses, where foreground galaxies gravitationally create multiple images of distant Active Galactic Nuclei (QSOs).



Description:

- This is a time domain observatory capable of ~0.1 arcsec stability observations over ~600s, and efficiently re-targeting pre-determined sequences of ~1-200 objects with a variety of cadences and campaigns, tailored to their physical and time-variance properties.
- The targets are known and well-characterized strong gravitational lenses which feature multiple images of distant active galactic nuclei.
- Diffraction-limited observations at ~1um over ~600s and 0.4-2um span.
- The observations depend on ~1% reproducible precision spectro-photometry of ~0.4-2um, with a resolution of R~8000. An efficiently tiled or multi-plexed integral field unit spectrograph (IFS) achieves this.
- High-TRL observatory and mission design, except potentially the IFS:
    - An IFS with ~tens of arcsec^2 FOV can be achieved through an image slicer (c.f. the FINESSE Explorer), at high TRL.
    - A more attractive IFS design will allow for access to the full several arcmin FOV through MEMS or similar active re-direction.

Value to NASA:

Each of the scientific goals of this Observatory directly address driving science objectives of NASA, including the quest for determining "the origin, evolution, and fate of the Universe" and to "how planets, stars, galaxies, and cosmic structure come into being."

In addition to the primary goals driving the current concept, the instrumentation and time-domain focused mission implementation design of this Facility has a versatility that will enable new and unique insights into other fields of astrophysics, including in dynamical mapping of flare events in magnetic cataclysmic variables, and local-universe AGN reverberation mapping over several decades of black hole mass through extended mission observations. Targets of Opportunity such as nearby supernovae follow-up are enabled through Guest Observer channels.

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SALSO:
OBSERVATORY FOR MULTI-EPOCH GRAVITATIONAL LENS ASTROPHYSICS (OMEGA)

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Primary Concept Goal Category: Astrophysics.

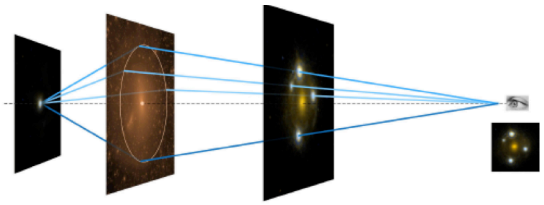

Figure 1. The geometry of a strong gravitational lens, with a source (left) being focused by a foreground galaxy (including the granular sub-structure of dark matter, depicted in the second panel from left), resulting in a multiply-imaged lens, as shown on the right.

Abbreviated Concept Summary: Through ~0.1arcsec resolution and percent level spectrophotometric time domain observations of certain classes of cosmologically distant strong gravitational lenses, it is possible to map multiple and overlapping sources of variability that reflect astrophysical properties in both the lensing galaxy and in the lensed sources. With the SALSO platform tailored to operate at optical and near-infrared wavelengths, and adapted to efficient acquisition of up to several sequential pre-selected targets per hour (even in LEO), a multi-year mission obtaining light curves with deliberately crafted cadences and observing campaigns for 1-200 targets will achieve several distinct scientific goals *simultaneously*, aspects of which cannot be approached through any other probe.

The targets are lenses where the foreground object is a massive galaxy, and the source being lensed is compact, such as an accreting supermassive black hole (Active Galactic Nuclei, AGN, or Quasi-Stellar Objects, QSOs). In these, the intrinsic angular scale of the QSO is as small as ~1micro-arcsec (with the size varying with wavelength because of the temperature and ionization structure of the disk and its environment). This roughly matches the gravitational lensing influence area of stars in the lensing galaxy, and is an important component to what will be probed through the SALSO-OMEGA observations. The QSO spectroscopic variations with time,

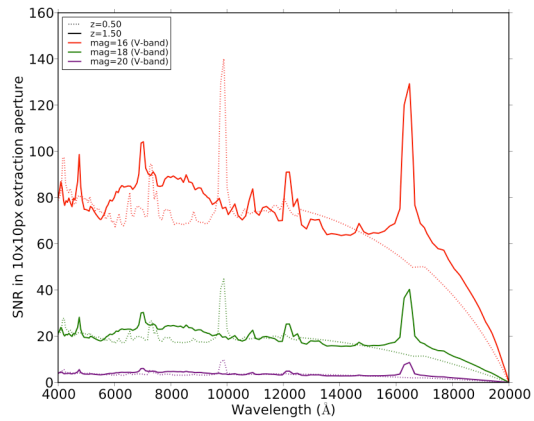

Figure 2. Signal to noise versus wavelength illustration for SALSO-OMEGA AGN targets at representative redshifts and apparent magnitudes.

which are magnified by a factor of up to ~10x by the lensing, can give tomographic maps of the QSO structure through reverberation mapping.

Goal of the Proposed Application: The OMEGA-SALSO Facility enables three major science areas: **1)** dark matter particle physics and associated astrophysics of structure formation, **2)** tomographic maps of the accretion disks and large scale environments of accreting super-massive black holes, and **3)** the instantaneous stellar mass distribution properties of stars, and potentially even of free-floating planets, in cosmologically distant galaxies. An important element to stress is that each of these is mapped over several billion years of cosmic time, by virtue of the range of redshifts of the targets.

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Benefits of the Application: The primary benefits of this application are scientific, with a technological implementation that strongly leverages recent experience with thermal, structural, and instrument design.

Top-level Description of the Design, Operation, and Results: A stable platform is important for the required pointing stability, at the level of ~0.1arcsec (or better) over at least ~10-minute integrations.

The spectroscopic resolution of R~8000 is driven by the need to kinematically resolve velocity structures within QSO emission lines. A basic exposure time calculator (ETC) has been built for simulating the observations from a diffraction-limited SALSO at 1um (and correspondingly stable platform), and an IFS. The ETC presently assumes a five-surface protected aluminum telescope and an instrument throughput of 70% from the combination of IFS reflections and dispersing elements. We have explored both a single-channel HgCdTe concept, and a two-channel

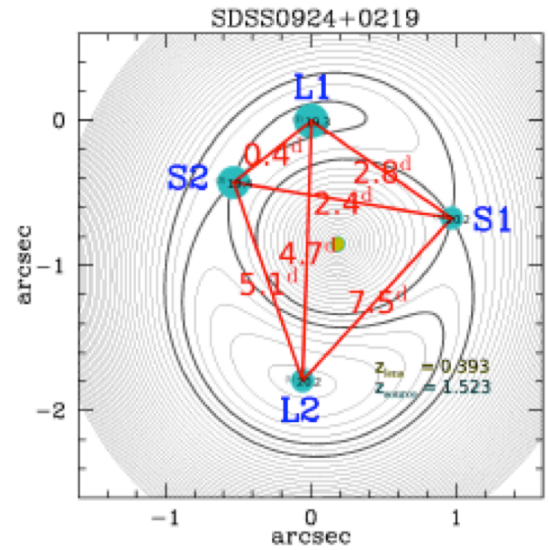

Figure 3 .The time delay surface of a lensed QSO, and the images that form.

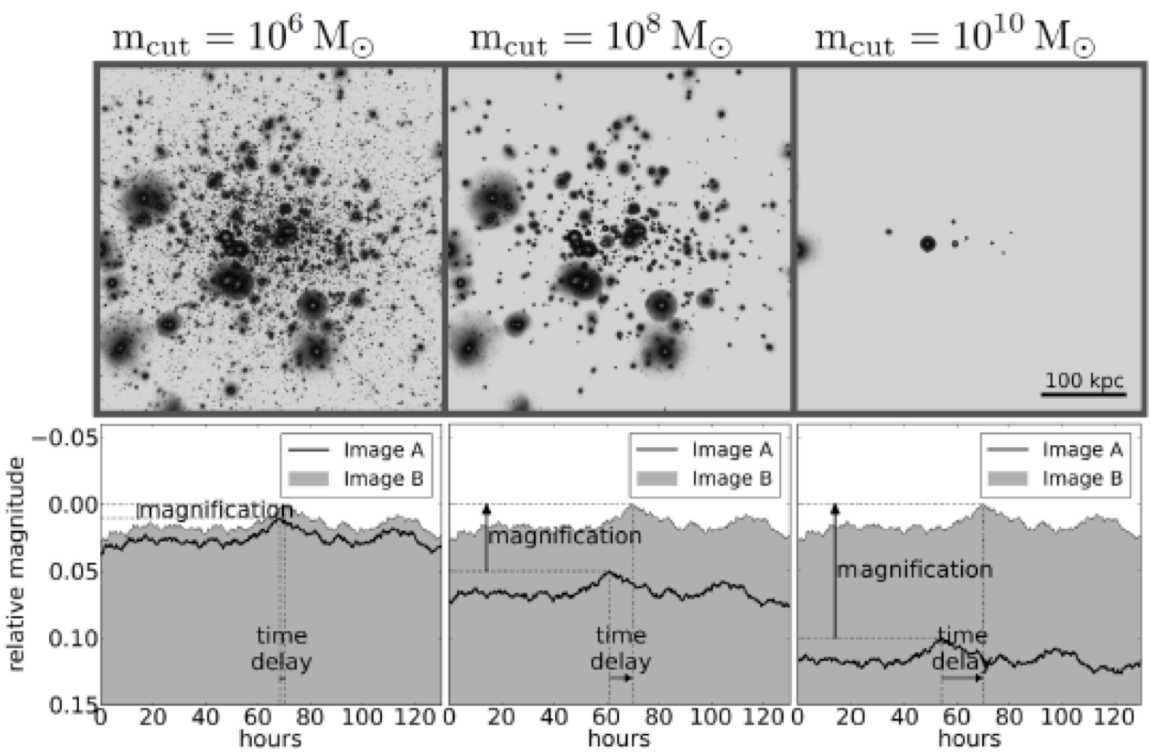

Figure 4. Top: dark matter substructure (only) from a galaxy simulation. The three columns show different levels of sub-structure, corresponding to different dark matter particle properties. Bottom: Simulated source light curves for two representative lens images that have been shifted to remove the effects of the smooth mass distribution. The differences between the curves correspond to typical magnification and time delay perturbations due to the substructure above. SALSO-OMEGA will measure these perturbations to high precision, towards characterizing the sub-structure level as a path to characterizing dark matter particle properties.

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system with an HgCdTe chip and a LBNL CCD. Figure 2 shows baseline results for the two-channel concept.

Goal 1) Dark matter physics. The path to dark matter physics is conceptually simple but subtle in implementation. As illustrated in Figure 4, details in the substructure properties of a galaxy can lead to different properties in the gravitationally lensed images of a QSO, which are encoded in large part in the time delays between the images. The observing campaigns can be designed to optimize this reconstruction. The modeling and related mathematical analysis will require Bayesian Inference techniques that are being developed now.

Goals 2 & 3) The Structure of Accreting Black Holes in AGN. We will characterize the structure of black hole accretion regions from the inner edge of the accretion disk through the Broad Line Region (BLR) out to the Narrow Line Region (NLR). We will study the accretion disk with microlensing, the BLR with reverberation mapping and the NLR with emission line images.

Microlensing and the Structure of the Accretion Disk: For the cases where there is an AGN that is being lensed by a foreground galaxy, the stars in the lensing galaxy will microlens the light from the accretion disk of the AGN. The Einstein radii of the stars in the host galaxy are very small and so they result in very small changes in the brightness of the background AGN, but the cumulative effect of all the stars provide detectable changes in the lensed images. There is a significant computational challenge of reconstructing the caustic pattern that is created by the stars in the lensing galaxy as they pass over the accretion disk, but the main barrier for this technique has been obtaining high quality/long duration data, which we can do with ease.

Reverberation Mapping and the BLR: Reverberation mapping of emission lines uses the lag between the brightening of the continuum emission of the accretion disk to the brightening of an emission line in the BLR, like H-alpha, to determine the distance of the BLR. Having both the distance of the BLR clouds and their velocities based on Doppler widths allows for a precise determination of the mass of the black hole.

With higher resolution spectra reverberation mapping of the accretion disk is possible. The broadness of a line like H-alpha arises from clouds moving at different velocities at different distances from the accretion disk. So when an increase in continuum light from the accretion disk hits different clouds that make up the broad line region the result is that the broad emission line changes its shape based on the various clouds brightening at differing distances from the accretion disk. Thus, a tomographic picture can be created based on which part of the broad spectral line brightens with respect to other parts of the emission line. This technique then creates a velocity-delay map, which allows us to infer the structure and velocity field of the BLR.

Spectroscopic Imaging and the NLR: The narrow line region spans from 10 to 100 pc and so is too large to be affected by microlensing or show reverberation. In fact it is so large that at the high resolution afforded by the 2.4m meter aperture, OMEGA should be able to obtain spatially resolved images. The extra magnification from the lens galaxy makes up for the greater distance. The critical emission lines to carry out all of the above AGN studies are well within the spectral range for OMEGA. The 0.4 to 2 mm region contains the broad H-alpha and beta lines and the narrow [OIII] lines as well as the CIV lines for sources from z = 0.5 to 1.5.

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