

## Gravitational Lensing with 30m class telescopes

Gravitational lensing is a physical phenomenon whose simplicity of measurement and interpretation provides exceptionally a powerful probe of the mass distribution and distance relations in the universe. The physics are minimal: gravitational fields of intervening objects bend light rays from cosmologically distant objects. The bending angles depend on the mass distribution along the line of sight and the cosmological distances between the source and the lenses. The observational effects are image distortions, multiple images in the case of strong lensing, relative image displacement, and magnification. The image distorting effects of the earth's atmosphere and aberrations in telescope optics can be corrected to the precision allowed by the density of unresolved point sources (stars) in the field. The correction techniques are now reaching levels such that a mean shear of about 0.2% can be reliably measured, given sufficient numbers of background source galaxies.

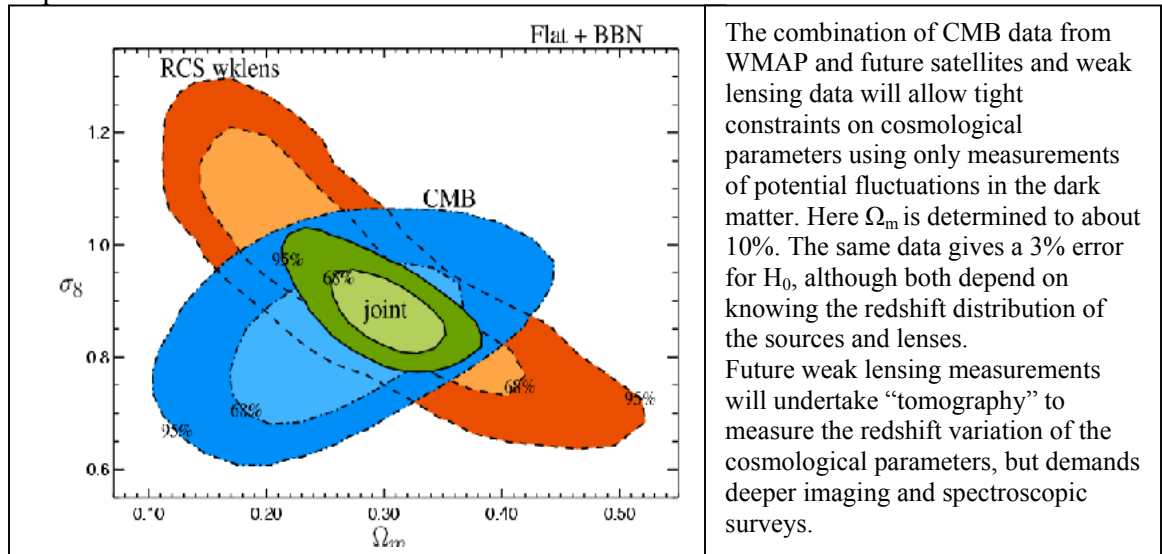
Thirty meter class telescopes offer the possibility of probing fainter sources, with much greater sky densities and likely having angular sizes so small that the resolving power of a large telescope will be required to resolve the faintest. The interpretation of lensing signals depends critically on knowing the source redshift distribution for which existing HST ACS images already require a 30m class telescope.

### Current Status of Gravitational Lensing

There is a natural division of lensing studies into weak and strong lensing. Weak lensing is the case when magnifications and individual image distortions are small, under, say 10%. Because galaxies are intrinsically elliptical measurements are made by averaging over hundreds or thousands of individual (PSF corrected) galaxies. Strong lensing distorts images into long arcs, often seen in rich clusters, and leads to multiple images. Both situations have a rich set of applications. Most measurements are currently done using conventional optical light where detector areas can be made large at reasonable cost. Consequently the median redshift of the source distribution remains under redshift one. Furthermore there is little incentive to go very faint, where the galaxies have angular sizes well below the sizes of the images in natural seeing PSF correction becomes less certain.

- Cosmic shear is the measurement of the variance of the mean shear in apertures as a function of their angular size. The shear variance is a measure of the mass power spectrum that is highly complementary to CMB measurements and in conjunction with the CMB is beginning to yield remarkably precise (~3-5%) measurements of various cosmological parameters, include the density parameter, the Hubble parameter, the normalization of the power spectrum. An important next step in this field is to undertake "tomography" where low-precision redshift techniques (often photometric) are used to separate source and lens galaxies to measure the evolution of mass structure and implement distance ratio tests for cosmology.

- Dark matter-luminous matter cross-correlations measure the mass density profiles of clusters, groups and individual galaxies. These are now competitive with dynamical and X-ray plasma techniques in estimating statistical masses but are not yet useful on a case by case basis due to limited background behind anything other than a large cluster.
- Dark matter mapping in the field is still in its infancy. The signals in the field are quite weak and one wants to map the distribution of dark matter filaments which will appear on scales of about ten arc-minutes at intermediate redshift. A much higher density of sources and extension to higher redshifts is required.



- Strong lensing leads to large magnifications that act as “gravitational telescopes”. Spectra of lensed galaxies have produced many of the brightest known galaxies out to redshift five.



An ACS/HST image of Abell 1689, showing a small section of the image. Hundreds of arcs are visible over the entire image allowing detailed mapping of the cluster mass potential and cosmological model. This image is nearly at the depth of the Hubble Deep field and will require an ELT with near diffraction limited images to acquire spectra and better images of the arcs. Gravitational magnification preserves surface brightness but stretches the image to boost the total brightness. It seems probably that the first detections of high sky density exotic sources such as globular cluster in formation and first light sources may well first be made through gravitational lenses.

- Multiple image lenses of variable sources can be used to measure the Hubble parameter in a “single step”. The complication is to know the lensing potential well enough to separate it from the cosmology. However, this field is rapidly developing the required precision based on the simplicity of the measurement.

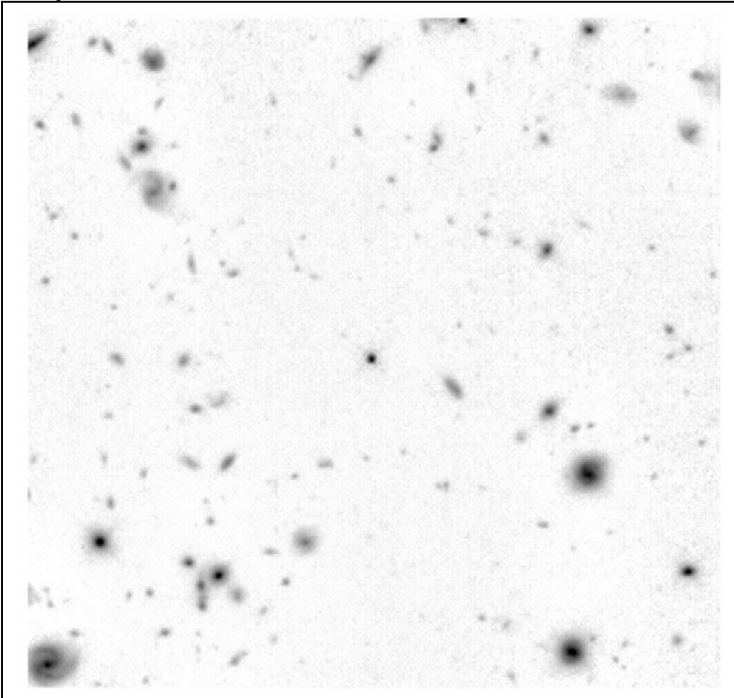
## The role of a 30m class telescope

The development of 30m class telescopes will open several fundamental new measurement opportunities, including:

- spectroscopy to determine redshifts of faint source galaxies,
- spectroscopy to determine redshifts of faint lenses, and,
- imaging of small ( $\ll 0.1''$ ) background galaxies.

Some of the deepest available images are the NICMOS HDF observations which cover about 50 arc-seconds in the HDF. The sky density of galaxies at  $m_{AB}=28$  mag is about  $0.5 \times 10^6$  galaxies per square degree, or, about one per 5 arc-seconds, on the average. At this flux level it is important to bear in mind the surface brightness limits of the 1.6 micron NICMOS data as well. Where the counts go at fainter levels is a little hard to say, and these data have the usual concerns about fluctuations in very small fields. The  $\log N$ - $m$  relation has a slope of about 0.1-0.15, although it is expected that new populations such as young globular clusters could come in around  $m_{AB}=30$  mag to increase the numbers. At the 1 nJy level,  $m_{AB}=31.4$  mag, we can expect several million per square degree, or about one per square arc-second, which will open new opportunities in lensing

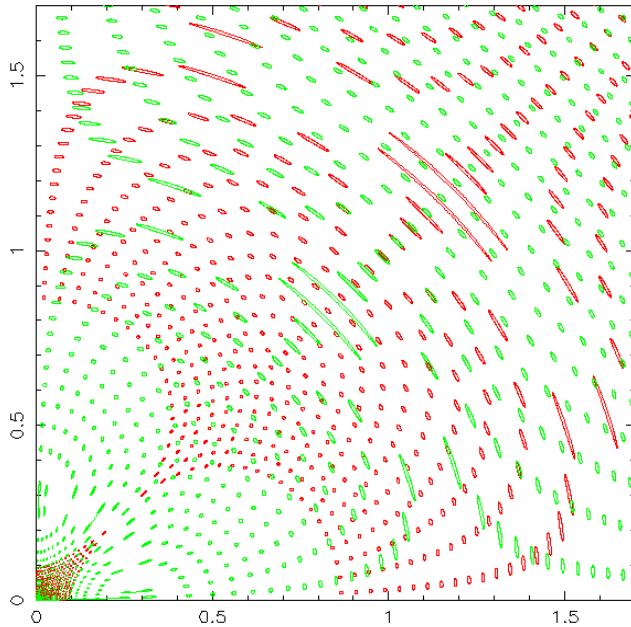
analysis.



The NICMOS HDF at 1.6 microns. The region shown is about  $50''$  on a side. The faintest galaxies are near  $m_{AB} = 27$  mag with a sky density of about  $0.3 \times 10^6$  per square degree. JWST will be able to obtain much deeper images for which the 30m will obtain spectra, and potentially better resolved images in the J and H bands. A 10x higher sky density and the accompanying redshifts will be invaluable for lensing.

The angular resolution of a 30m will allow a significant step beyond JWST to probe to yet higher sky densities of background objects to make new measurements.

1. The source density will be so large that it can be split into various source and lens planes which will enable the construction of dark matter maps, roughly to overdensities of a few times the mean density so that filaments and other weakly nonlinear structures predicted by CDM theory will be made “visible”.
2. For a fixed lens plane using several different source planes will allow the dependence of lensing on redshift to be examined. This will become a fairly powerful statistical test for the evolution of the cosmological constant.
3. Strong lensing in clusters will have sufficient numbers of background galaxies that background galaxies at different redshifts will appear within a few arcseconds of each other but with significantly different shear and magnification. This will allow significant progress in breaking the degeneracy between the details of the shape of the cluster potential and cosmology.



The figure shows strong lensing of sources at redshifts of approximately 1 (green) and 2 (red) for a cluster at redshift 0.5 in a flat,  $\Omega_m=0.3$  universe. If the critical line is at  $11''$  at redshift 1.0 then it is at about  $17''$  at redshift 1.3. With a sky density of over a million sources per square degree there are several arcs near each other allowing the cosmology-cluster lens degeneracy to be partially broken. Mapping with small scale structure in lenses is an important test of small scale nonlinear CDM theory.

### *Observing programs*

Lensing observations generally require multiple measures of the gravitational field. In strong lensing, the shear is sufficiently great that it overwhelms the intrinsic shape of the galaxy. The canonical Einstein radius for a  $1000 \text{ km s}^{-1}$  cluster is 15 arc-seconds. Therefore a field of one arc-minute or more would take in most of the strong lensed background. The most challenging aspect would be to obtain spectra at  $m_{AB} \sim 31$  mag. If all objects have Lyman alpha it would be possible to do this in about 10-100 hours, depending on details of redshift and line intensity. Absorption line spectra will be possible but will be in the 300 hour category for unmagnified sources. For a field of view of at least one arc-minute, with 5 mas pixels, it should be possible to provide a sample of around one thousand spectra at the nano-Jansky level, depending on a myriad of instrument specification details. A single cluster then will require two months of dark nights and a comprehensive program of sensibly combined field and cluster observations.

For weak lensing, to map filaments for instance, a region of 20 co-moving Mpc subtends about one degree at redshift of 0.5. The width of a filament would be of order a Mpc, depending on how low in over-density one wanted to go. The high sky density for imaging could be obtained by JWST, but the spectroscopy of a sample of faint background to give  $n(z)$  and faint galaxies that might trace the structure would require a 30m telescope. The background redshift distribution in principle only needs to be done once, and can be applied in many other places on the sky.

These two programs together will consume one to two years of telescope time. Of course the data will serve many different purposes and do not need to be done within a single program of observations. Given that we have no secure knowledge of the source counts

or the source properties at these very faint fluxes this program will necessarily be best approached on the usual step-wise basis, which clearly must start with deep imaging.

## **Complementing other New Telescopes**

The primary natural complement to the 30m is JWST which will excel at imaging in the infrared. The 30m will use spectral resolutions of more than a thousand to obtain redshifts of the background. For point-like objects (proto-globular clusters, first light) the resolving power of the 30m will be a powerful complement to JWST imaging.

ALMA will be able to do Sunyaev-Zel'dovich maps of clusters. The SZ effect measures the line of sight pressure integral through the cluster. Under the hydrostatic equilibrium assumption this will provide an important complementary insight into the cluster. ALMA's ~15 arc-second field will generally require mosaics to cover an appreciable cluster area. Future X-ray telescopes will also provide high resolution temperature and density maps which will allow us to substantially decode clusters.

LISA, the space-borne gravity wave detector system, will be able to detect exotic gravitational phenomena, such as white dwarf binary in-spiral, nearby one hundred solar mass black hole mergers, and super-massive black hole mergers out to redshift of about 100 where cosmology will play a role. The large detection distance is because the signals depend on the angular diameter distance, which do not vary much beyond redshift two. The most dramatic signals will likely be caught in near real time and the more massive events have the benefit of being relatively slower, giving LISA time to orbit the sun and give us its positional accuracy of a few degrees. Clearly preliminary imaging, probably a combination of optical and radio, will be essential to locate unusual sources. However, a 30m will be an invaluable complement to understanding the astrophysics of these dramatic events.