

# Thirty Meter Telescopes and Gravitational Lensing

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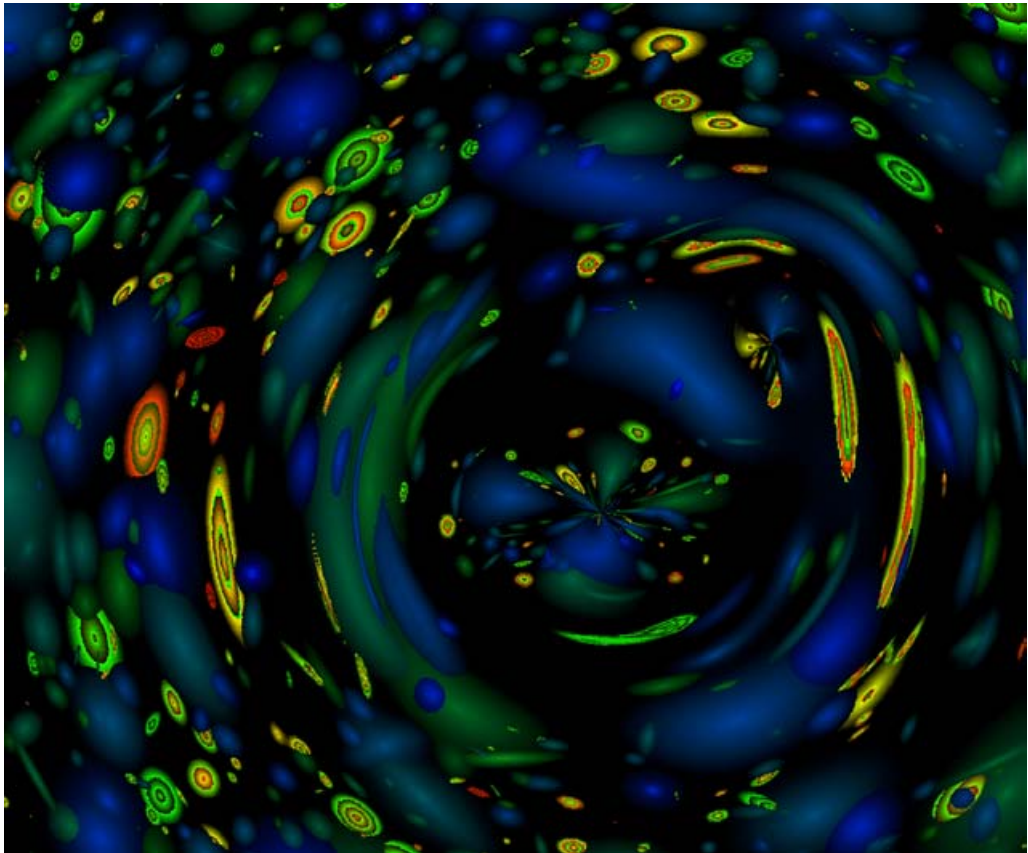
**Abstract.** Diffraction limited 30m class telescopes will play an important role in gravitational lensing studies, coming online in approximately 2015. As imaging telescopes they will complement the  $\sim 6\text{m}$  JWST, probing to smaller angular scales in greatly magnified objects near critical lines and for measuring shear of objects below the JWST angular scale, such as luminous super-star clusters at high redshift. The high source density will allow more detailed mass mapping in the weak lensing regime and will be useful in breaking the cosmology-lens potential degeneracy in strong lensing. As multi-object spectrographs 30m telescopes should provide spectra over the entire optical and near infrared spectrum region. The statistical distribution of redshifts needed to invert projected shear measurements and calibration of photometric redshifts for “tomography” will be available to flux levels around 5-10 nano-Jansky (approx  $29.5 m_{AB}$ ). However, a one nJy object is expected to require  $\sim 500$  hours to acquire a redshift, which is most of the dark time in an observing season. Accordingly “gravitational telescopes” will be an important tool for probing the very faint high redshift universe, magnifying a few square arc-seconds at a time by factors of 10-1000.

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## 1. Introduction

The science cases for 30 meter class telescopes emphasize that there are important problems of faint objects, small galaxies at high redshift, star formation and planet formation where we need to have diffraction limited imaging and spectrographs and increased spectrographic capabilities in the near-infrared, without giving up the undoubted benefits of the optical part of the spectrum. The new capabilities will have important benefits for the study of gravitational lensing to probe problems in cosmology, galaxy formation and the distribution of lensing mass. In particular, the capabilities of examining smaller, fainter source populations will allow a much higher sky density of background sources to be used, allowing more precise mass mapping and providing sufficient redundancy that the mass-cosmology degeneracy can be resolved.

The performance of a 30m telescope will be considered for its utility with lensing problems. In the case of weak lensing, images useful for shear analysis and photometric redshifts are already available from HST well beyond the limit of calibrated (photometric) redshift distributions. The image/spectra mismatch will widen with the arrival of JWST if only 10m class telescopes are available. The  $D^4$  advantage of a diffraction limited telescope provides nearly two orders of magnitude gain at 30m. For strong lensing, the imaging capabilities of a 30m telescope will allow the smallest angular scales to be resolved which will preserve regions of very high magnification. To obtain even an  $R=2000$  spectrum for sources fainter than about five nJy will likely be routine through the study of sources that are magnified by a factor of ten or more in a strong lens. Of course this approach requires that the source population be sufficiently numerous, more than about  $10^5$  per square degree, that there will be substantial numbers.



**Figure 1.** A simulation of a  $40 \times 32''$  piece of sky with galaxies visible to redshift fifteen (the skymaker simulator from Terapix with a speculative luminosity and mass evolution!) visible through a  $800 \text{ km s}^{-1}$  elliptical lens with an offset  $300 \text{ km s}^{-1}$  lens. The colors reflect the redshift, blue at zero, yellow at  $z = 6$  and red at  $z = 15$ . The intensity scale is logarithmic. In a region of say  $10 \times 10$  arcsec, there are dozens of objects, spanning a wide range of redshifts hence have significantly different shear and magnification near the same image plane location.

Adaptive optics is not without its limitations. The PSF has a diffraction limited core plus a “halo” with the characteristics of the natural seeing PSF. To a first approximation the light in the diffraction core is given by  $S$ , the Strehl ratio. For isolated sources this means that performance scales as  $S^2 D^4$ , where  $D$  is the aperture of the telescope. However, for high surface brightness backgrounds and crowded regions the performance can scale as  $S^4 D^4$ , placing a high premium on a high quality Strehl in the AO system.

## 2. Weak lensing analysis and 30m telescopes

Hubble Space Telescope imaging in the Ultra Deep Field can reach to  $m_{AB} = 28.5$  to  $29.0$  mag Beckwith *et al.* (2003). The  $\sim 6\text{m}$  aperture of JWST will make these depths routine, particularly at wavelengths beyond 1 micron, which will allow much larger sky areas to be acquired (although still at considerable expense) as is required for many aspects of lensing analysis. Although photometric redshifts are a powerful tool to determine redshifts to the precision required for statistical inversion of lensing measurements (such as cosmic shear or higher moment measurements) they are secured on the basis of a spectroscopic calibration of the redshifts. The “Generic GSMT” exposure time calculator

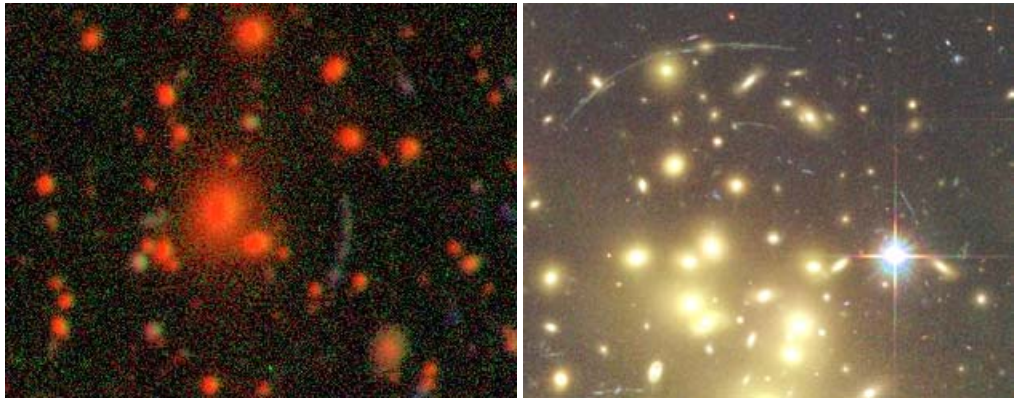
(<http://www.noao.edu/noao/staff/brooke/gsm/>) finds that it takes about  $7.8 \times 10^5$  seconds (about 43 dark nights of 5 hours) to obtain a  $s/n = 5$  continuum spectrum at  $1.6\mu$  with a 30m telescope and an R=2000 spectrograph operating near the diffraction limit ( $0.03 \times 0.15''$  slit) with a Strehl-throughput product of 0.3. Although this is a very expensive observation, it is comparably costly in the limited-lifetime JWST mission time (see exposure times at <http://www.stsci.edu/jwst/science/jms/reports.html>). The TMT project plans to be able to acquire spectra to this depth over a field of about 5 arcminutes, which will in principle allow hundreds of spectra to be obtained at the same time.

Thirty meter class telescopes are unlikely to be very useful for any wide area imaging work, although it is not specifically precluded. Large areas of natural seeing imaging are best done on smaller aperture telescopes. Space-based telescopes will provide enviable PSF stability over relatively large fields. However, for targeted observations the TMT will have high quality AO imaging capabilities at the diffraction limit over a field of about one arcminute and sampling of a few milli-arcseconds. This will be of interest for targeted studies on the scales of individual galaxy halos, for which 100 kpc subtends about a 20 arcsecond circle at redshift one. At a source density of  $10^6$  per square degree there will be approximately one hundred field galaxies per halo, of which at least half will be background for lens galaxies at redshift one. There is also the prospect that components of background galaxies, such as the nuclear bulge and compact HII regions will make suitable sources for statistical shear measurements. In principle these measurements could be of interest for galaxy size halos over approximately redshift 0.5 to 5, becoming too large at low redshift and too few bright background objects at high redshift.

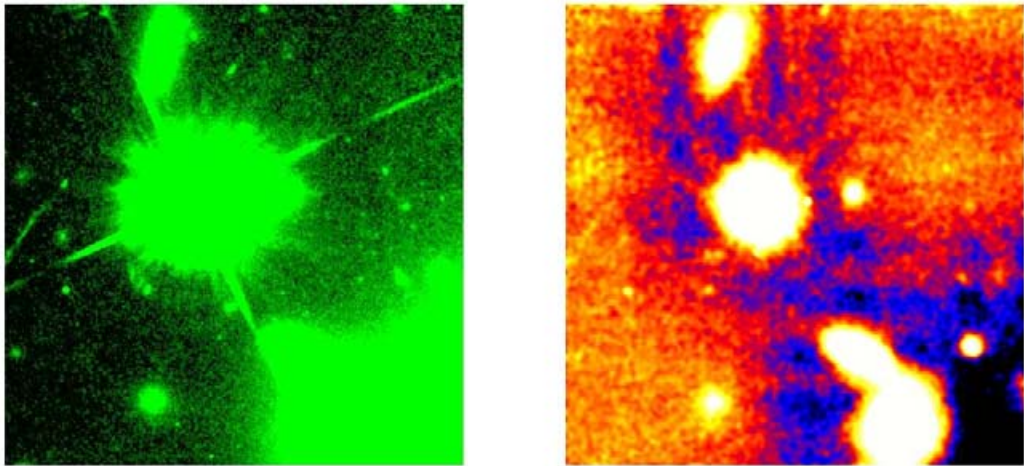
### 3. Strong Lensing

Strong gravitational lensing studies will be revolutionized on 30m class telescopes. The detection of lensing events is strongly dependent on the telescope aperture and angular resolution. First, the probability of lensing increases in direct proportion to the density of background galaxies that a telescope can comfortably reach. Second, the telescope must be able to resolve the arc, otherwise it dilutes the high surface brightness of very small or unresolved regions, such as super-star clusters and nuclear bulges at high redshift. Four meter class telescopes at good sites (and in space!) opened up gravitational lensing because they were the first to have sub-arcsecond images and the aperture to comfortably reach sources densities of about  $10^4$  per square degree. At sky densities approaching  $10^6$  degree<sup>-2</sup> the faint background galaxies are near (or below) the angular resolution of the Hubble Space telescope in the optical bands. Such images are well matched to the angular resolution in the K band available from JWST and AO-equipped ground-based telescopes.

A ground-based 30m class telescope with AO should reveal many hundreds and possibly thousands of arcs in galaxy clusters (see Fig 1), and should make multiple images a much more common phenomena for individual galaxies. In galaxy clusters an important consequence is that within a region of say  $10 \times 10$  arcseconds there will be several background galaxies with varying shear, depending on their redshift and precise position relative to the caustic surfaces. This opens up the opportunity of locally breaking the degeneracy between the gradient of the lensing potential and the cosmology if redshifts are available for all the sources as well as the lens. In the case of smooth lenses with simple elliptical asymmetry this would be a simple and powerful tool. However, in the presence of irregularities in the cluster potential, such as the visible galaxies and remnant (dark matter) tidal tails, statistical averaging will be required to derive high precision cosmological information. However, since the measurements are primarily geometrical,



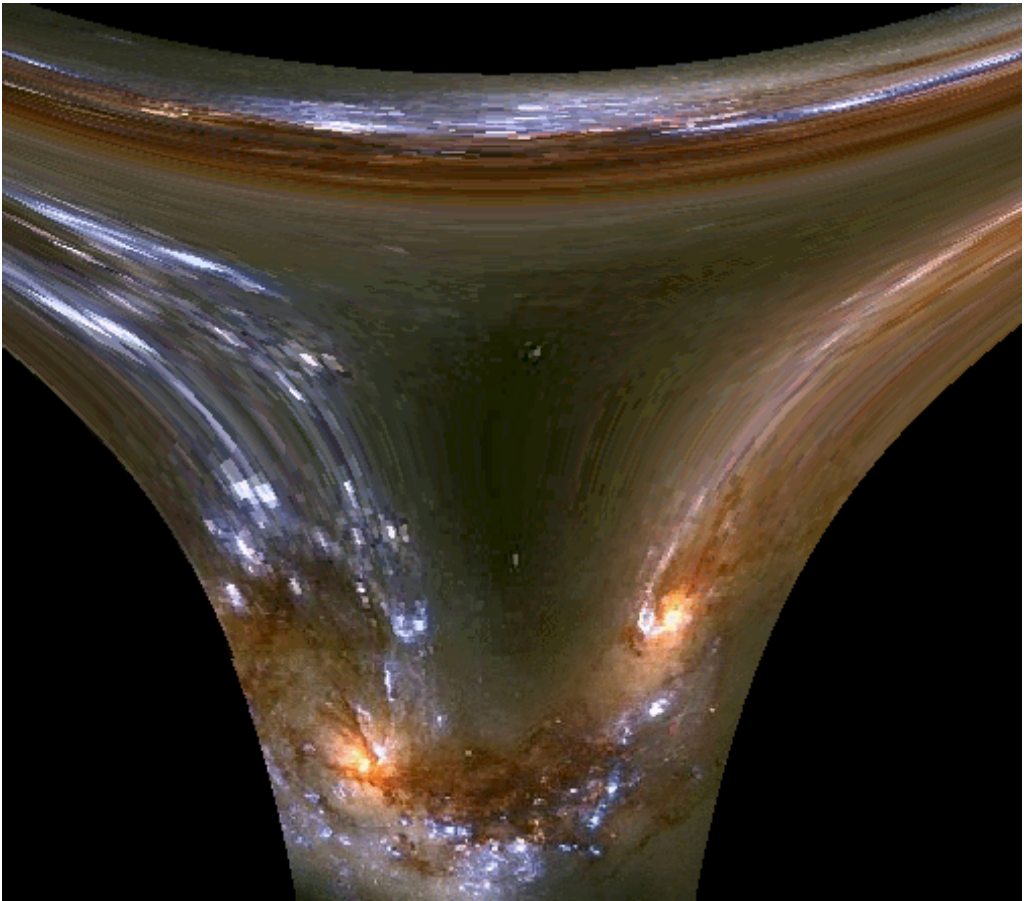
**Figure 2.** Left: a discovery image of a gravitational arc from the CFHT Legacy survey. Right: Part of the spectacular Hubble ACS image of Abell 1689, emphasizing the importance of having near diffraction limited performance to avoid diluting unresolved high surface brightness features. The image size ratio between these two images, about a factor of 7, is roughly the improvement that a 30m will give in the near-IR, with spectroscopy likely being one of the main uses. The bright star in the lower right of the HST image is the guide star at the center of Figure 3.



**Figure 3.** The region of the bright star ( $m_V \simeq 13$  mag) in A1689. Left: the ACS image i band image. The field is  $16''$  on a side. Precisely the same area done with the Gemini Altair adaptive optics system in the K band in a 3 hour image. The limiting magnitude is  $K_{AB} \simeq 26$ . The PSF core is about 0.08 arcseconds in both images. The faint arc to the left of the guide star is detected in K. Most of the faint galaxies are also visible in K light. MCAO systems on 8m telescopes will enlarge the field of view and provide a more uniform PSF. However, these images already show the limitations of 8m class telescope AO for strong lensing studies. The  $D^4$  gain, along with increased field, on an 30m will be transformative.

position and shape of very high precision and the “noise” is of astrophysical interest as well, the 30m telescopes will open a new domain of investigation. Moreover, since the probability of lensing is linear in the density of background sources, every galaxy cluster will exhibit at least a few arcs. For a 10:1 arc the source plane area magnified is about one tenth the radius of the critical line in the cluster, typically 15 arcsec. Therefore the magnified area is about 5 sq arcseconds. But, with several thousand massive clusters, the total area magnified becomes large enough to create a very useful sample.





**Figure 4.** The Antennae galaxies scaled to redshift three and placed across the critical line of a  $800 \text{ km s}^{-1}$  galaxy cluster. The field of view is 3 arcseconds. The super-star clusters are not resolved in this image, The SSCs near the critical line will be magnified by factors around one hundred.

#### 4. Gravitational Telescopes

It is clear that routinely reaching to nano-Jansky flux levels for high redshift galaxies and “first light” objects is just within the reach of JWST and TMT. A single very massive “first star” is likely to appear at about  $m_{AB} \simeq 35$  or so at redshift 15, however a super star cluster may consist of some dozen or so of these stars and much of the light may emerge from an HII region near the resolution limit of a 30m. Young star clusters in galaxies like the Antennae (see Figure 4) that are near cluster critical lines will be massively amplified. Given that 2-8m routinely find factors of ten, the superior PSF of a 30m should frequently (the numbers are roughly inversely proportional to the amplification) find magnifications of a factor of a hundred. The resulting five magnitude brightness boost, as well as the one-dimensional increase in linear scale will be important to allow the study of a representative sample of very faint, very high redshift sources. Almost all of this work will be in the JHK bands, where one can work between the emission lines of the sky spectrum to take advantage of the relatively dark sky in between.

## 5. Project status

The combination of scientific importance and technical excitement has led to several projects to advance 20-30m class projects, and larger. One example is the Thirty Meter Telescope Project (TMT), a partnership of Caltech, the University of California, AURA and ACURA (Canada). At the time of writing the TMT project plans to go to cost review (i.e. a technically and financially complete project) in mid-2006. There is about 40 FTE of activity in TMT at present which will rapidly rise over the next few months in order to meet this milestone and continue on schedule to construction.

## 6. Conclusions

Thirty meter class telescopes will be important partners for gravitational lensing studies. They will primarily provide the spectroscopic redshifts to calibrate photometric redshifts of deep imaging surveys. A 30m will also be useful for deep imaging studies on the scales of individual galaxy halos, over the redshift of 0.5 to 5 range. Strong lensing will be one of the few ways to obtain spectra of objects below a few nano-Jansky (unlensed) level at levels where the spectra can be adequately dispersed for astrophysical study. Diffraction limited spectroscopy using a 30m is particularly well suited to this exciting area of study.

## Acknowledgements

Support for the Canadian Large Optical Telescope work comes from NSERC, NRC and the Canada Foundation for Innovation. The A1689 AO image is a collaboration amongst Tim Davidge, Stephen Gwyn, Luc Simard and RGC using Gemini. Thanks to members of the Canadian LOT SAC, the TMT SAC, the GSMT Science Working Group, and the European ELT Science Working Group for lively ongoing discussions.

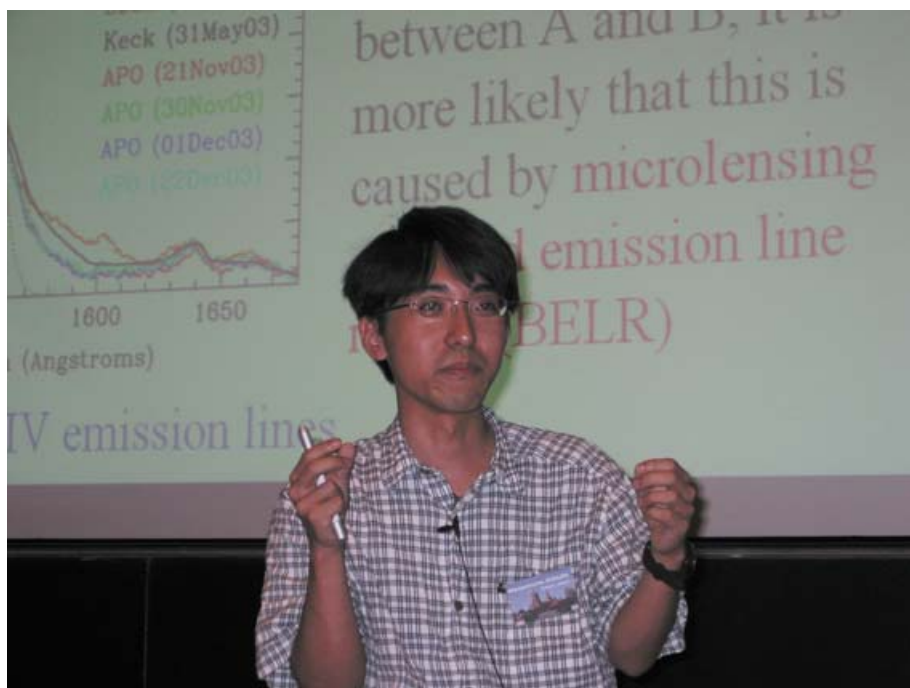
## References

Beckwith, S. V. W., *et al.* 2003, American Astronomical Society Meeting, 202 (see also <http://www.stsci.edu/hst/udf>)

## Discussion

DANIELLE ALLOIN: What is the cost estimate for instrumentation for a 30m telescope?

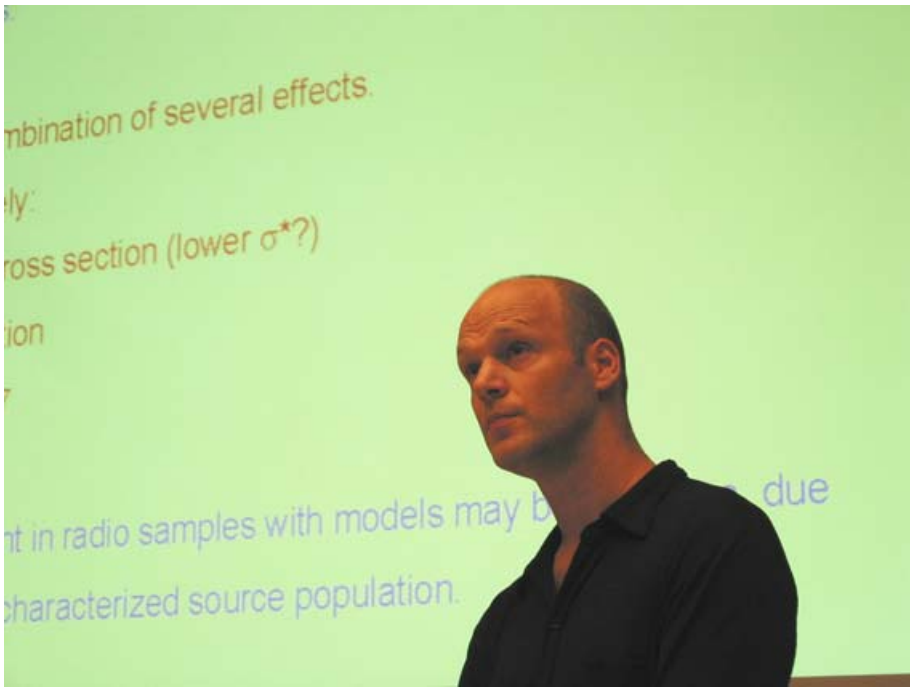
CARLBERG: The currently available cost studies were done at the conceptual design stage. The total cost of a 30m is estimated as \$700-800M US dollars, which includes a contingency of nearly \$100M. The estimated "first light" instrumentation budget is \$80M, with a separate budget of approximately \$150M for adaptive optics. It is currently planned that there will be three first light instruments built within this budget. A PDR level cost review should be available in mid-2006 from TMT.



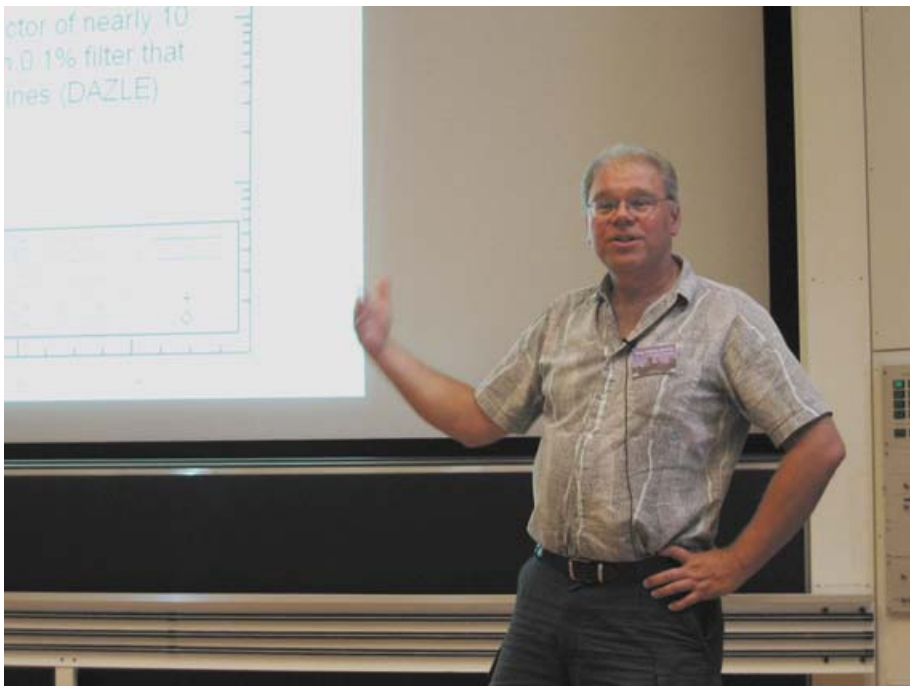
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