Large Synoptic Survey Telescope

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Accurate Cosmography with LSST Time Delay Lenses

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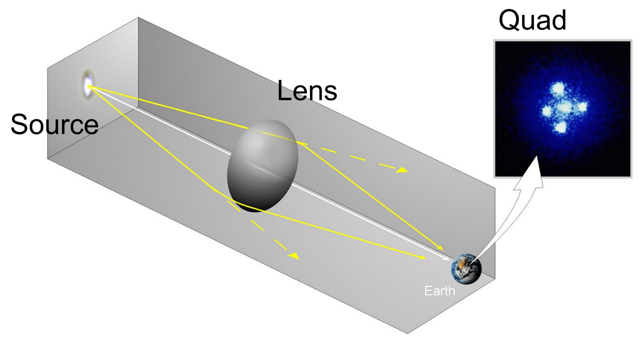
LSST will discover several thousand lensed quasars and supernovae, and provide high signal-to-noise ratio, well-sampled lightcurves for each. We explore the potential of the expected sample of well-measured 4-image (quad) lens systems for constraining cosmological parameters, when followed-up spectroscopically, via measurements of the "time delay distance" to each one. Based on recent experience with individual lenses studied in great detail with the VLA, Keck and HST, we make plausible assumptions about our likely knowledge of the lens model and lens environment to quantify the largest sources of systematic error, and use simulations of LSST lightcurves to estimate the expected time delay precision. We find that the resulting constraints on the parameters of the Dark Energy equation of state are competitive with and complementary to those from other LSST cosmological probes.

Measuring distance with gravitational lenses

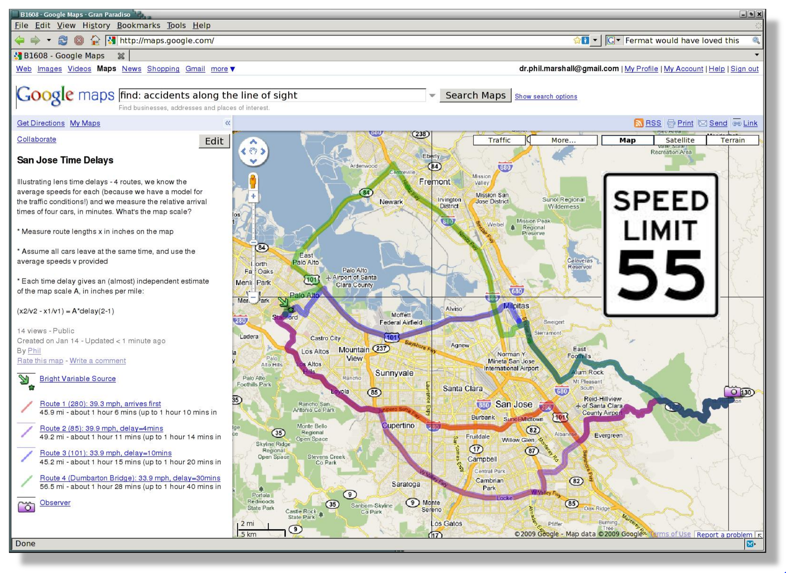


Photon arrival time is just **D / c'** where **D is the time delay distance**, a combination of distances to and between the lens and source - and depends on cosmological parameters.

$$t = \frac{1}{c}\,\frac{D_{\rm d}D_{\rm s}}{D_{\rm ds}}(1+z_{\rm d})\left[\frac{1}{2}(\theta-\beta)^2-\psi(\theta)\right]$$

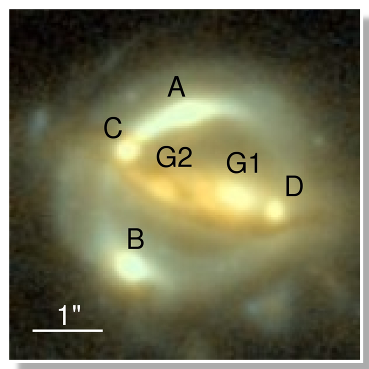
The ***effective speed c'*** varies with gravitational potential and image position - which together determine the refractive index of the lens at each image.

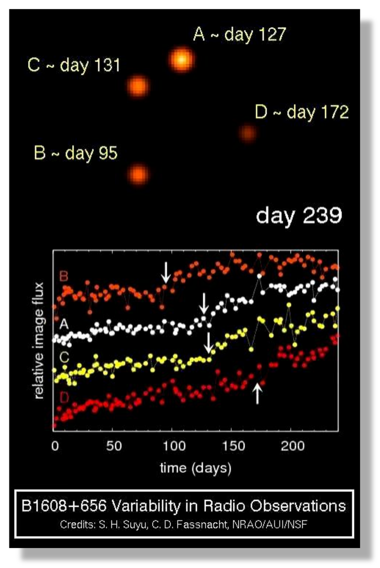
Measure **differences in signal arrival time,** model the lens potential to get **c'** for each image, and invert to get **distance D.**



If you know the average speeds and relative arrival times of 4 cars that set off at the same time, you can work out the scale on the map.

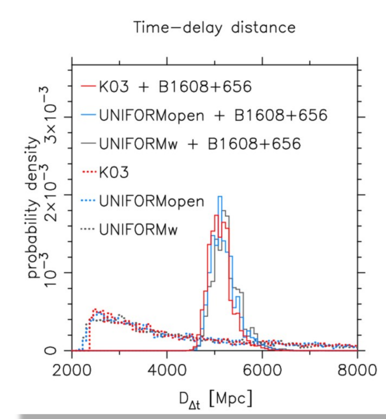
Measuring the B1608+656 distance to 5% accuracy





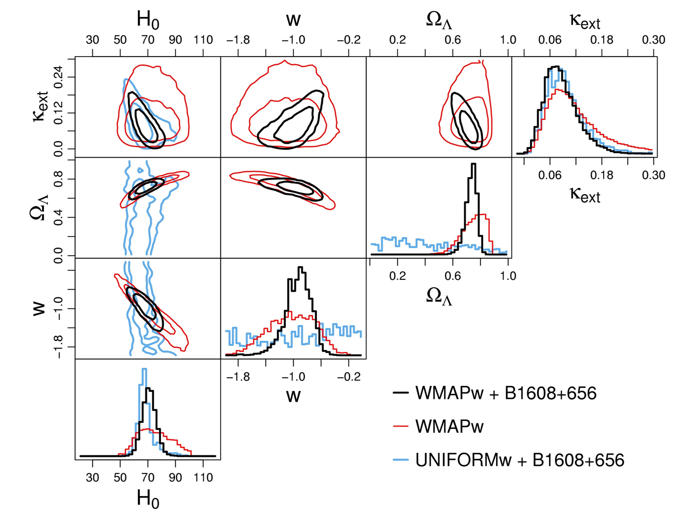
B1608+656 Variability in Radio Observations
Credits: S. H. Suyu, C. D. Fassnacht, NRAO/AUI/NSF

B1608+656 is a radio-selected quad lens system. The source is a variable radio AGN: its time delays were measured to 2-5% (Fassnacht et al 2002, left) in 3 x 8 month seasons of VLA monitoring, at 3-day cadence.



Deep HST/ACS imaging (left) and Keck spectroscopy were used by Suyu et al (2010) to model the lens potential in some detail. They found the potential to be smooth at the 2% level, indicating that it is well-described by a simple two-component mass model, with power law density profile. The stellar velocity dispersion provides a strong constraint on the profile index - as does the deep HST imaging of the Einstein Ring.

The dominant systematic error is due to mass along the line of sight. This "external convergence" is accounted for by folding in a broad PDF generated by sampling the Millennium Simulation and selecting sightlines that are, like B1608's, twice over-dense in galaxy number counts.



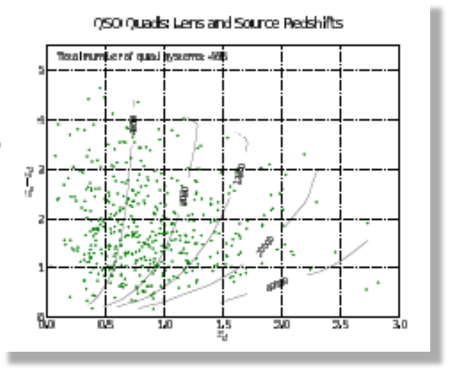
The resulting distance measurement for B1608+656 is independent of cosmological model (upper right) and accurate to 5%. Suyu et al then infer a Hubble constant of 70 ± 7%, and a (constant) Dark Energy equation of state w of -0.94 ± 18%, assuming a flat Universe (right).

	$H_0/\,{\rm km\,s^{-1}\,Mpc^{-1}}$		w	
WMAP5[a,b]	74^{+15}_{-14}	20%	$-1.06^{+0.41}_{-0.42}$	42%
WMAP5+*HST* KP[a,b,c]	$72.1^{+7.4}_{-7.6}$	10%	$-1.01^{+0.23}_{-0.22}$	23%
WMAP5+SN[a,b,d]	$69.4^{+1.6}_{-1.7}$	2.3%	$-0.977^{+0.065}_{-0.064}$	6.5%
WMAP5+BAO[a,b,e]	$73.9^{+4.7}_{-4.8}$	6.6%	$-1.15^{+0.21}_{-0.22}$	22%
WMAP5+Riess[f]	74.2 ± 3.6^{g}	5.0%	-1.12 ± 0.12	12%
WMAP5+B1608	$69.7^{+4.9}_{-5.0}$	6.9%	$-0.94^{+0.17}_{-0.19}$	18%

B1608, a single gravitational lens, is more informative than the HST Key Project, and comparable to all the current SDSS+2DF BAO data.

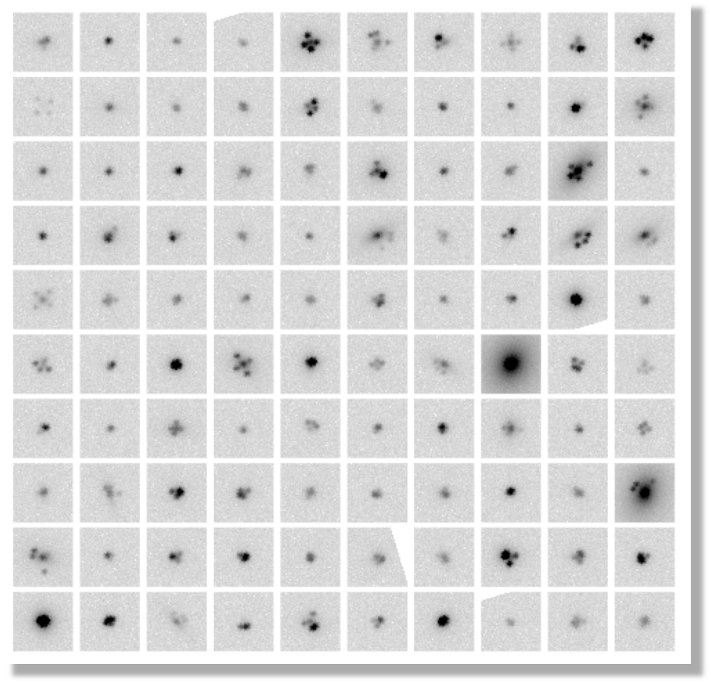
A mock LSST quad lens sample

LSST will discover several thousand galaxy-scale time delay lens systems. Requiring the third-brightest image to be detected at 10-sigma in a single exposure taken in median conditions, Oguri & Marshall (2010) estimate that **the number of "well-measured" quad lens systems should be around 500 (including both quasar and supernova sources)**. Their predicted redshifts and time delay distances are shown on the right.

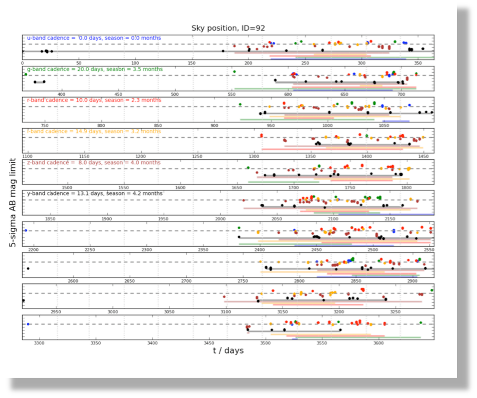


We show here simulated 6" cutout images of the mock LSST quadruply imaged quasars (see also the poster by Jernigan et al).

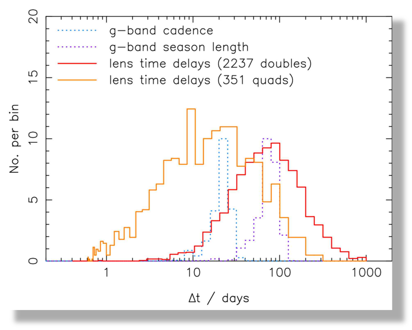
The lensed images are typically well-resolved in the best seeing images; the narrower-separation lenses will appear as objects with variable, extended morphology (e.g. Kochanek et al 2006).



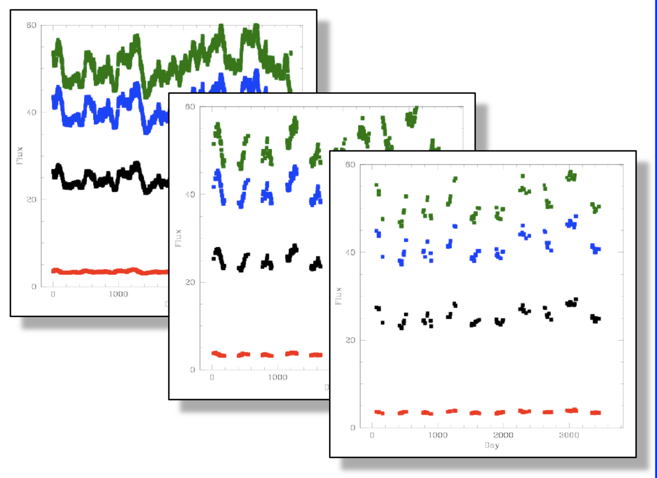
Simulated LSST AGN lightcurves



Run 1.29 of the LSST Operations Simulator was used to explore the lightcurve sampling rate for the quad sample. Seasons are typically 3-5 months long (depending on filter), while the median cadence is around 20 days (or 4 days when combining all filters, left).

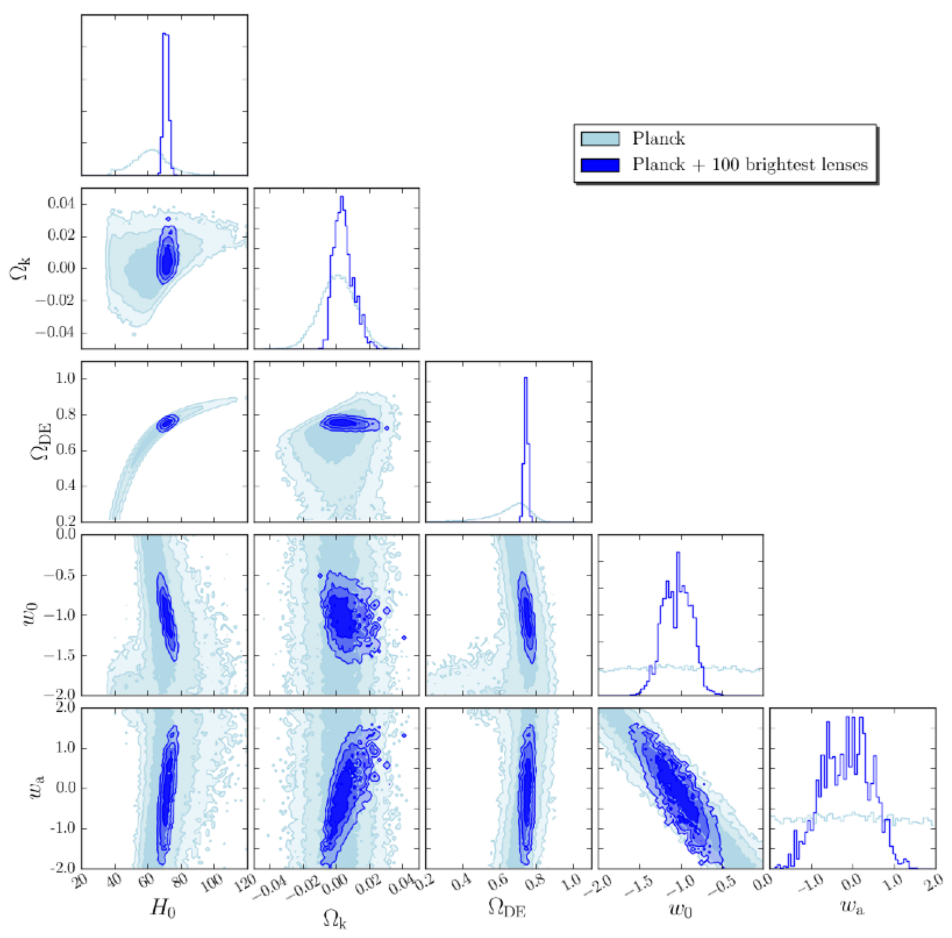


Approximately 1 in 4 quad time delays are both covered (shorter than the median season length) and well-sampled (longer than the median cadence), suggesting that **additional monitoring may be required to measure the shorter time delays.**



Experiments with mock lightcurves generated with plausibly-varying (damped random walk) model AGN sources suggest that **several-day precision should be possible,** for the long delays. We are investigating improvements from combining the light curves obtained in all filters.

Cosmography forecast from 100 LSST time-delay quads



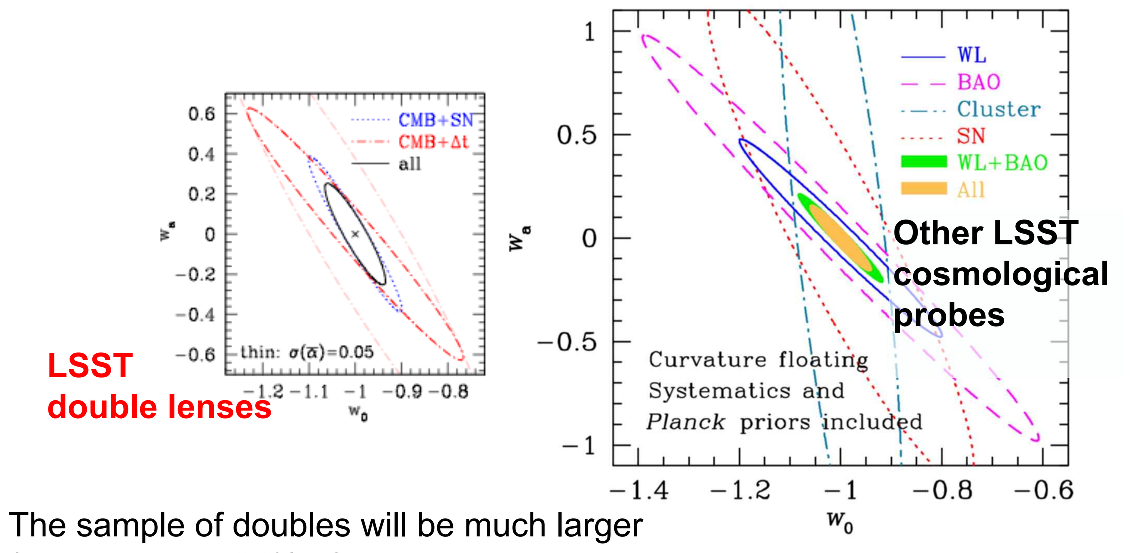
We selected the 100 systems with the brightest lens galaxies, and assumed the time delay distance to each was measured to 5%. This requires a level of follow-up comparable to that devoted to B1608 - the LSST survey data will constrain the external convergence. The resulting cosmological parameter constraints are predicted in the figure to the left.

Where Suyu et al combined B1608 with WMAP5, we importance-sample the anticipated Planck prior PDF. We do not assume a spatially flat cosmology, and we allow the Dark Energy equation of state parameter to evolve linearly with scale factor (with coefficient w_a).

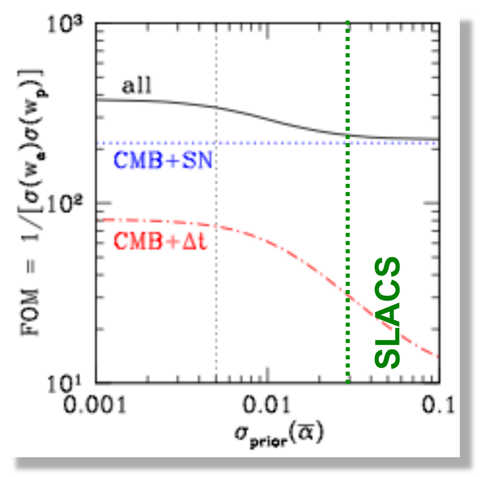
We predict the following parameter uncertainties (68% confidence):

$H_0 \pm 2\%$ $W_k \pm 0.01$ $W_{DE} \pm 0.02$
$w_0 \pm 0.2$ $w_a \pm 0.7$

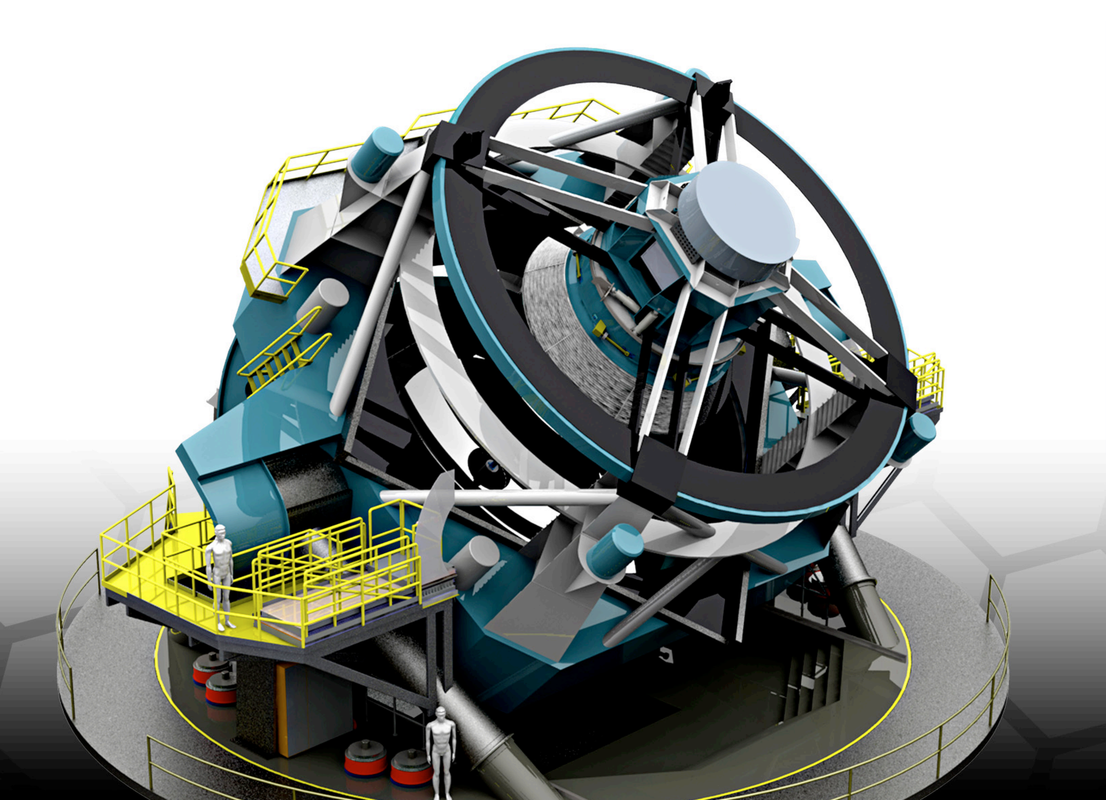
Cosmography forecast from 1500 LSST time-delay doubles



The sample of doubles will be much larger (they make up 86% of the mock lens catalog). Oguri & Marshall (2010) computed cosmographic constraints assuming spectroscopic redshifts but no detailed modeling, and found that **1500 double-image time delay lenses can provide similar precision on w_0 and w_a**



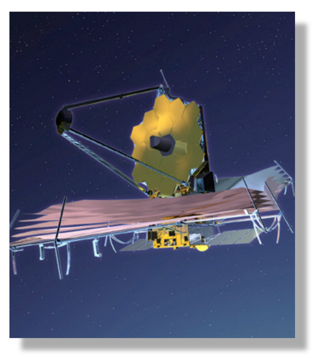
However, to reach this precision, the mean effective slope of the lens mass profile must be known to ± 0.01: current lens samples provide this to just ± 0.03.



The problem of follow-up

Measuring time delay distance to 5% requires:
- Spectroscopic redshifts of lens and source, lens galaxy velocity dispersions
- High resolution, high signal/noise imaging for ring modeling
- Time delays measured to better than 5%

A sample of 100 quads would require, over 10 years:
- 60 nights spectroscopy time on 10m telescopes, fewer with a GSMT
- ~300 hours JWST or ground-based LGSAO imaging
- Several thousand epochs of flexible optical or radio monitoring



References

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