H_0 from lensed quasars using difference-smoothing & PixeLens

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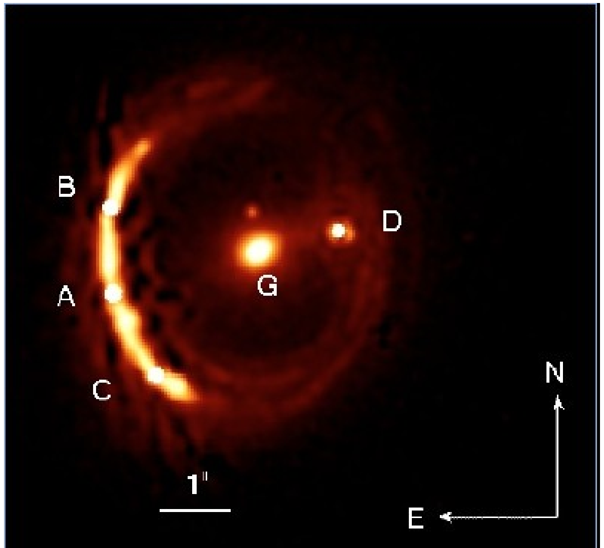
Outline

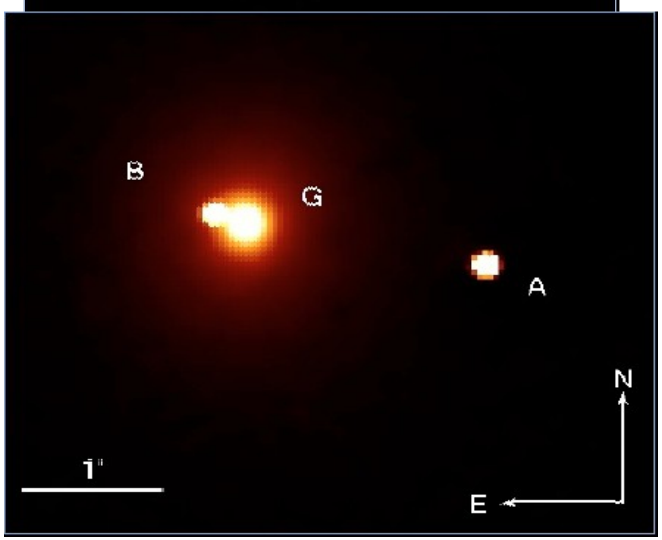
- H_0 through strong gravitational lensing
- Time delay measurement using difference-smoothing technique
- Lens modelling using PixeLens to infer H_0
- Lessons from Strong Lens Time Delay Challenge
- Work in progress

H_0, the Hubble constant at the present epoch

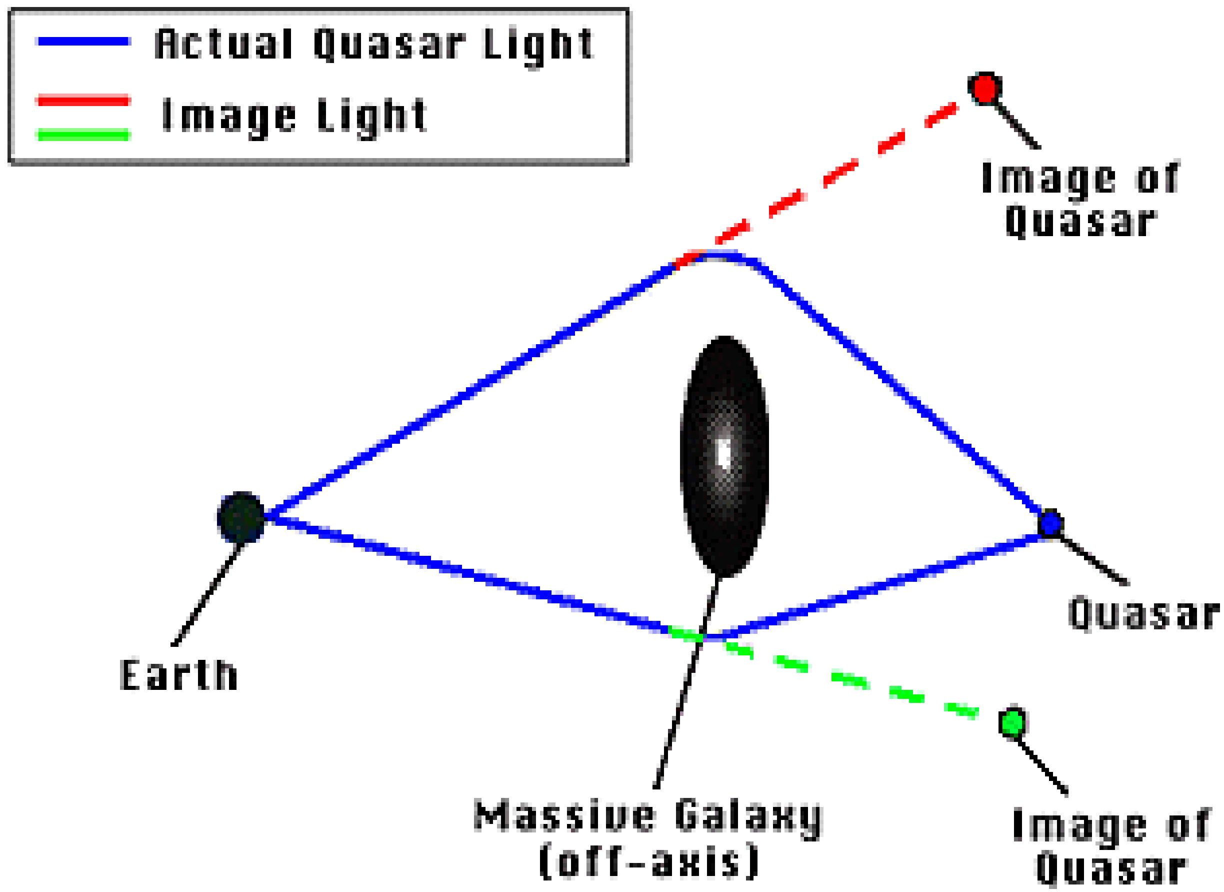
- H_0 is the current expansion rate of the universe
- An important cosmological parameter
- All extragalactic distances depend on its value
- Some estimates: (1) 72 ± 8 km/s/Mpc (Freedman et al. 2001, ApJ, 553, 47) (2) 73.8 ± 2.4 km/s/Mpc (Riess et al. 2011, 730, 119) (3) 67.3 ± 1.2 km/s/Mpc (Planck collaboration 2014, A&A, 571, 16)
- Multiple approaches to measure H_0 are needed to understand the unknown systematic errors in each method

Strong gravitational lensing





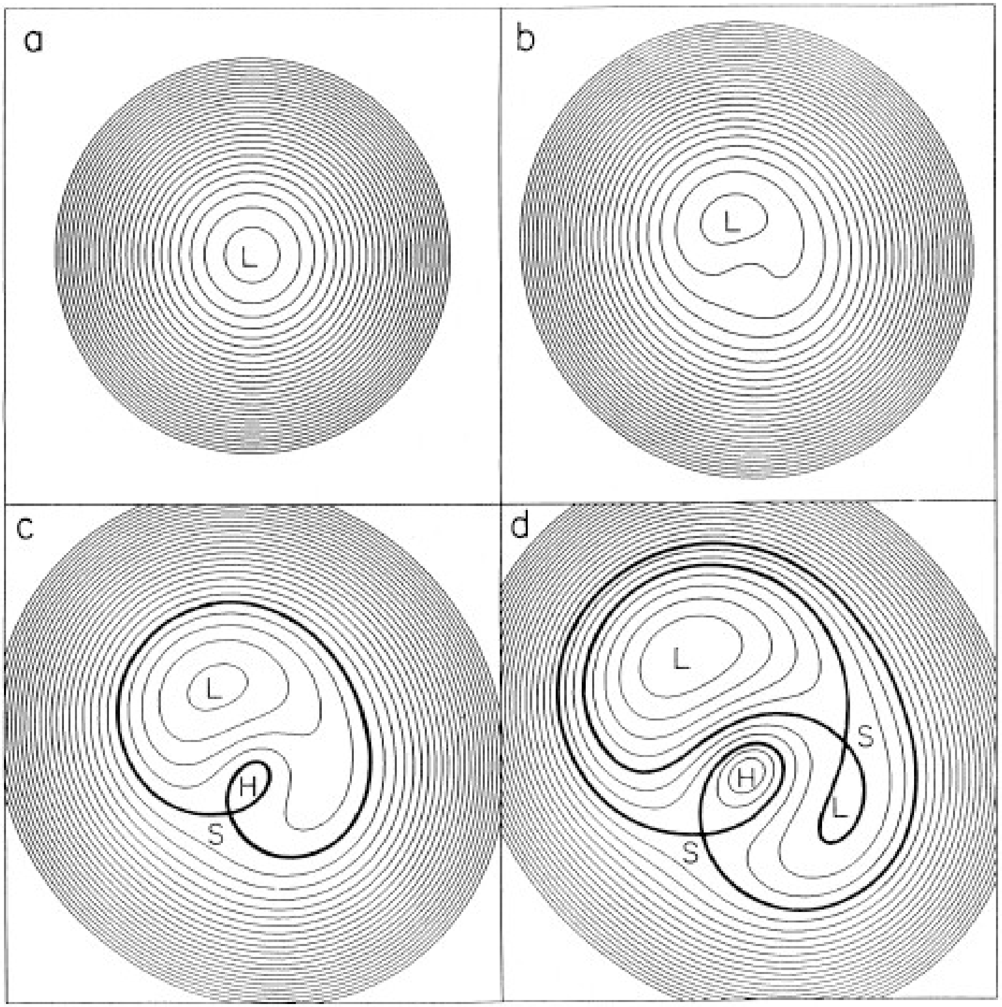
Chantry et al. 2010



http://imagine.gsfc.nasa.gov/

Arrival time surface

- Light from background source gets delayed due to geometrical differences in the path and also due to gravitational time dilation
- Images form at the extrema of the arrival time surface (Fermat's principle)



www.astro.phys.ethz.ch/~jread/Lectures/PixeLens/pixelens.pdf

The time-delay method

- By measuring the time delay between the images of a variable background source and modelling the mass distribution in the lensing galaxy, it is possible to determine H_0 (Refsdal 1964, MNRAS, 128, 307)
- Advantages: (1) Based on well-established physics of GR (2) Allows one-step distance determination (3) Time delays primarily depend on H_0 and less sensitive to other cosmological parameters
- Caveats: (1) Requires several years of regular telescope monitoring to pin down the time delay (2) Several degeneracies associated with modelling the mass distribution in the lensing galaxy/cluster

Difference-smoothing technique

- Measurement of time delay between a pair of light curves is highly non-trivial for several reasons – irregular sampling, seasonal gaps, extrinsic variations
- Difference-smoothing is based on minimizing the mismatch between the difference light curve with a smoothed version of it (Rathna Kumar et al. 2013, A&A, 557, 44)
- Two free parameters: (1) Decorrelation length (2) Smoothing time scale
- Uncertainty of time delay in Rathna Kumar et al. (2013) estimated using simulated light curves from PyCS (Tewes, Courbin & Meylan 2013, A&A, 553, 120)

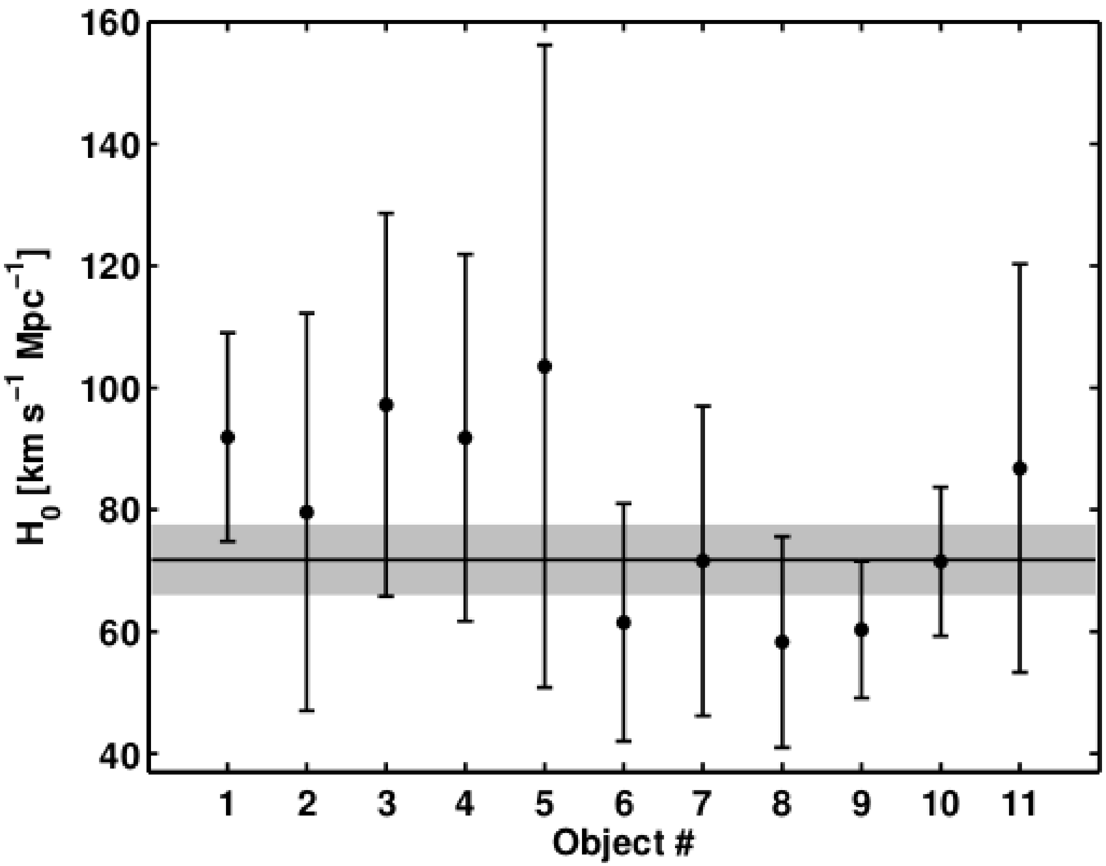
Homogeneous analysis of publicly available light curves

- In Rathna Kumar, Stalin & Prabhu (2014, submitted to A&A, arXiv:1404.2920) we introduced a recipe for tuning the free parameters and simulating light curves for uncertainty estimation
- Some important features in simulating light curves: (1) Residual extrinsic variability included (2) Delays around the measured delay also simulated (3) Uncertainty updated iteratively until the range of simulated delays is atleast as wide as the 2-sigma confidence interval implied by the unceratainty
- Homogeneously applying the procedure to the publicly available light curves of 24 lensed quasars with reported delays in the literature, we identified 18 systems in which atleast one time delay (between images adjacent to each other in terms of arrival-time order) could be measured to better than 33.3% precision

Lens modelling using PixeLens to find H_0

- PixeLens (Saha & Williams 2004, AJ, 127, 2604) builds an ensemble of pixellated lens models compatible with the input data
- Essential data: Redshifts of source and lens, astrometry of quasar images w.r.t the center of the main lensing galaxy, arrival-time order of images, known time delays (between images adjacent to each other in terms of arrival-time order)
- Modelling 11 lenses, we found $H_0 = 71.8 \pm 5.8$ km/s/Mpc
- Effect of external shear included through maximum-likelihood analysis
- Uncertainty of time delays propagated through addition of fractional uncertainties in quadrature

(1) HE 0435-1223, (2) RX J0911.4+0551, (3) Q0957+561, (4) SDSS J1004+4112, (5) HE 1104-1805, (6) PG 1115+080, (7) RX J1131-1231, (8) SBS 1520+530, (9) CLASS B1608+656, (10) WFI J2033-4723 and (11) HE 2149-2745



Lessons from Strong Lens Time Delay Challenge

- The same approach used in Rathna Kumar, Stalin & Prabhu (2014, submitted to A&A, arXiv:1404.2920) was also followed for TDC1 (Liao et al. 2014, submitted to ApJ, arXiv:1409.1254)
- The purpose of the challenge was to blindly test the current capabilities of the community for measuring time delays from lensed quasar light curves synthesised to mimic what can be expected from LSST
- Results for our team were unsatisfactory. Most notable reasons: (1) Outliers at 3-sigma level (2) Tendency to over-estimate uncertainty for poorly sampled light curves

Refining our approach to measure delays

- It is now possible to critically evaluate any given recipe for measuring delays thanks to TDC1 light curves and truth-files
- Optimum choice of free parameters found to be crucial for accurate time delay measurement
- A crucial correction: Decorrelation length = Mean sampling with 3-sigma rejection & Residual extrinsic variability adjusted to 2-sigma level of noise
- Possible remaining problem: (Error overestimation persists?) The recipe for noise rescaling needs to be critically assessed

Remaining work

- Refining our curve-shifting approach to a satisfactory level of accuracy and precision using a large sample of TDC1 light curves
- Update our homogeneous analysis of publicly available lensed quasar light curves
- In H_0 estimation, propagate uncertainties in time delays and external convergence following a Monte Carlo approach
- Implement these changes in Rathna Kumar, Stalin & Prabhu (2014, submitted to A&A, arXiv:1404.2920), which is still under revision