Future Strong Lens Surveys

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KITP, October 2006

Overview

- Science from very large samples of strong lenses
  (see also talks by everyone else)
- Future (within 10 years?) surveys
- The need for automation - recent successes from ongoing precursor work

Not included: clusters, intermediate surveys, history, much radio astronomy, spectroscopy...

Strong lensing science

Current sample: c. 200 lenses

We should aim to enlarge this by at least 2 orders of magnitude

An INCOMPLETE list of projects possible with ENORMOUS statistical samples:

- **Lens statistics**: galaxy mass profiles and their evolution with high precision, simultaneous inference of cosmological parameters?
- **Image separations**: galaxy mass profiles and their evolution with high precision, simultaneous inference of cosmological parameters?
- **Time delays**: lensed AGN, supernovae – simultaneous inference of H0, microlensing statsistics, lens environments, galaxy mass profiles etc etc
- **Sub-galaxy scale substructure**: anomalous magnification ratios (best in radio), extended source deformations
- **Redshift distribution** of the faintest galaxies
- **Rare events**: higher order catastrophes, lensed exotica...

Survey timescales

- **Daring to dream:**
  SKA - 2015?
  LSST - 2012?
  SNAP - 2013?
- Just Out of Reach:
  DES, PanSTARRS, E-VLA, E-Merlin, LOFAR, ... - 2007+
- **Right here right now:**
  SDSS
  CFHTLS
  HST archive

The Square Kilometre Array

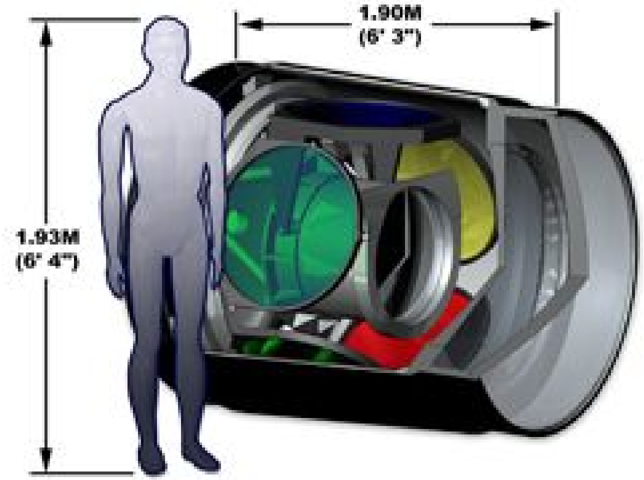
Proposed "RASKAL" survey (Koopmans et al):

- 20,000 square degrees to 3microJy at 0.01" resolution
- 1 billion sources (mostly starburst galaxies), so ~1million lenses (using CLASS optical depth)

- *In the future, gravitational lenses will not be rare events!*
- Large numbers of low mass lens galaxies: *lensing (and dynamics) with spirals, dwarfs*?
- *Source-targeted*: lens statistics are more robust
- Survey speed is vital – high sensitivity and large field of view allows *daily monitoring of all visible 1mJy sources*

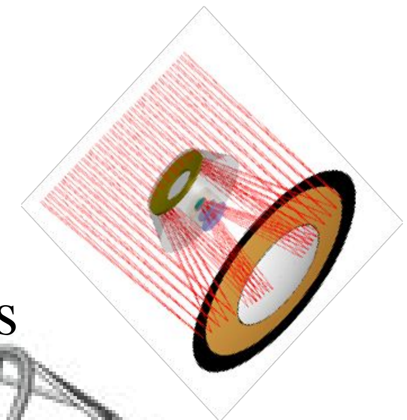
BUT radio work pre-SKA is unfortunately limited by TACs

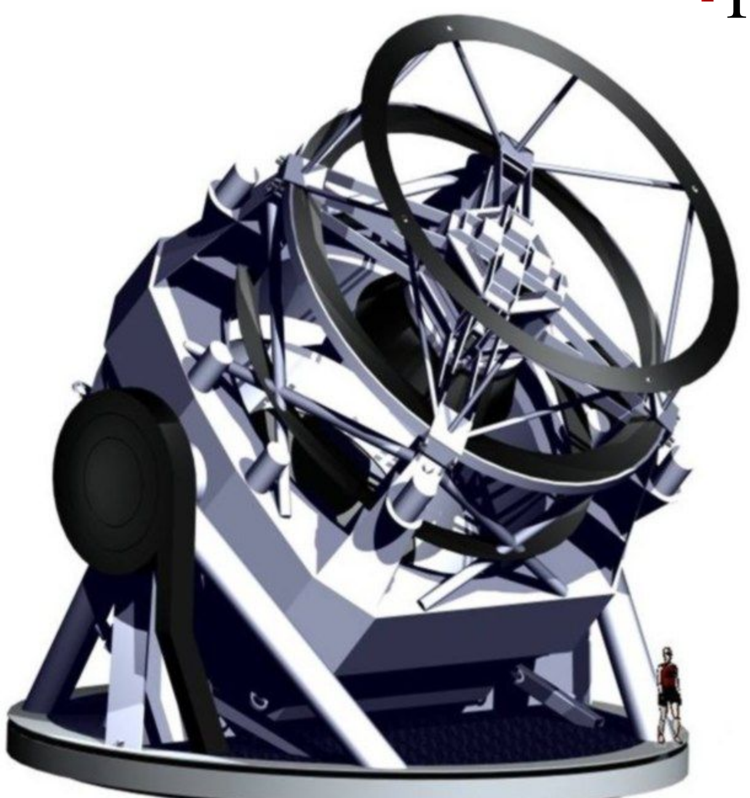
Strong lensing with LSST



High etendue survey telescope

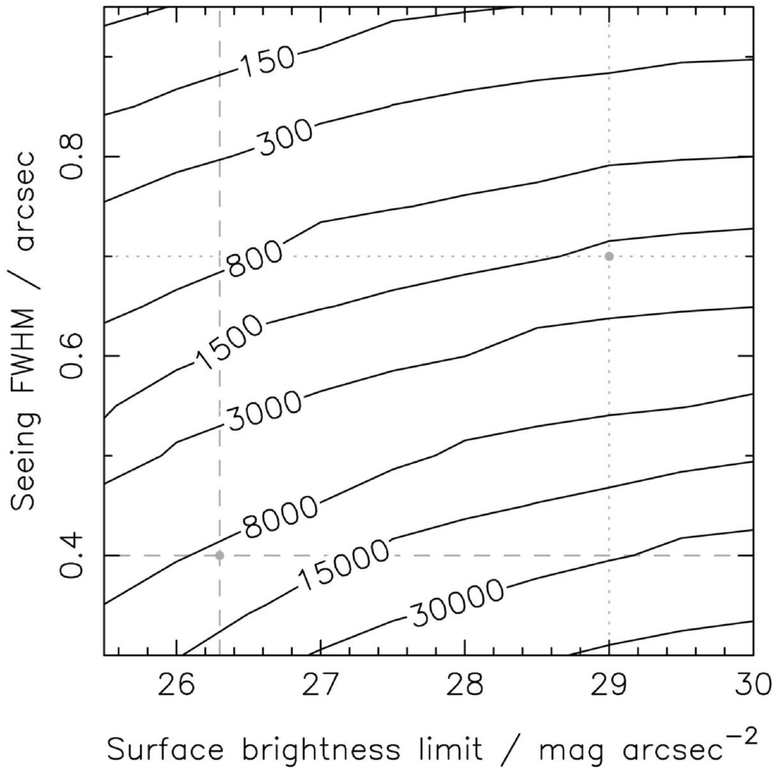
- 6m effective aperture
- 10 sq degree field
- 24.5 mag in 30 seconds
- Visible sky mapped in three nights
- Ten year movie

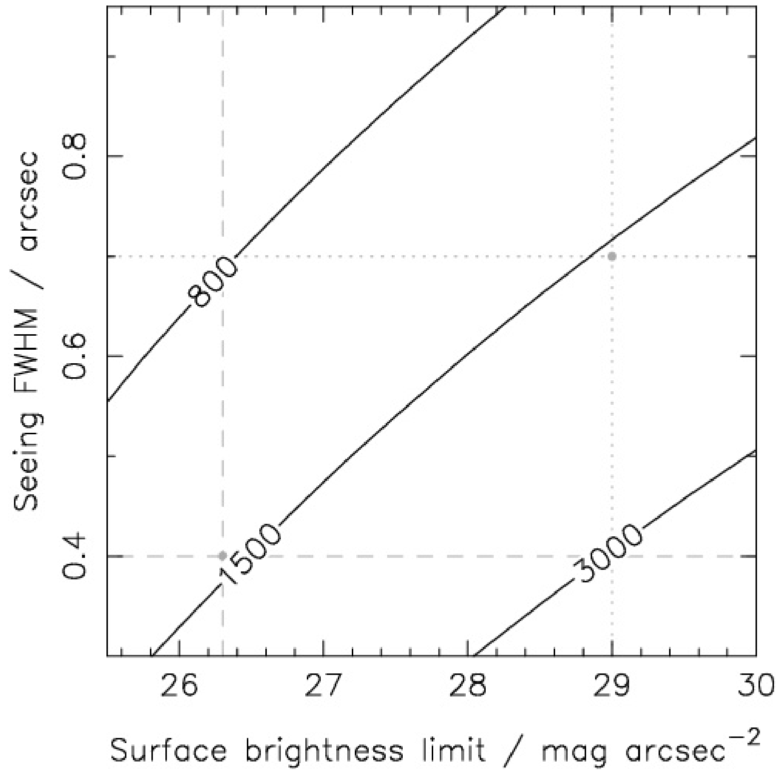




- **Just got $14 million from NSF for R&D**
- **First light in 2012?**

"Traditional" galaxy-scale lenses

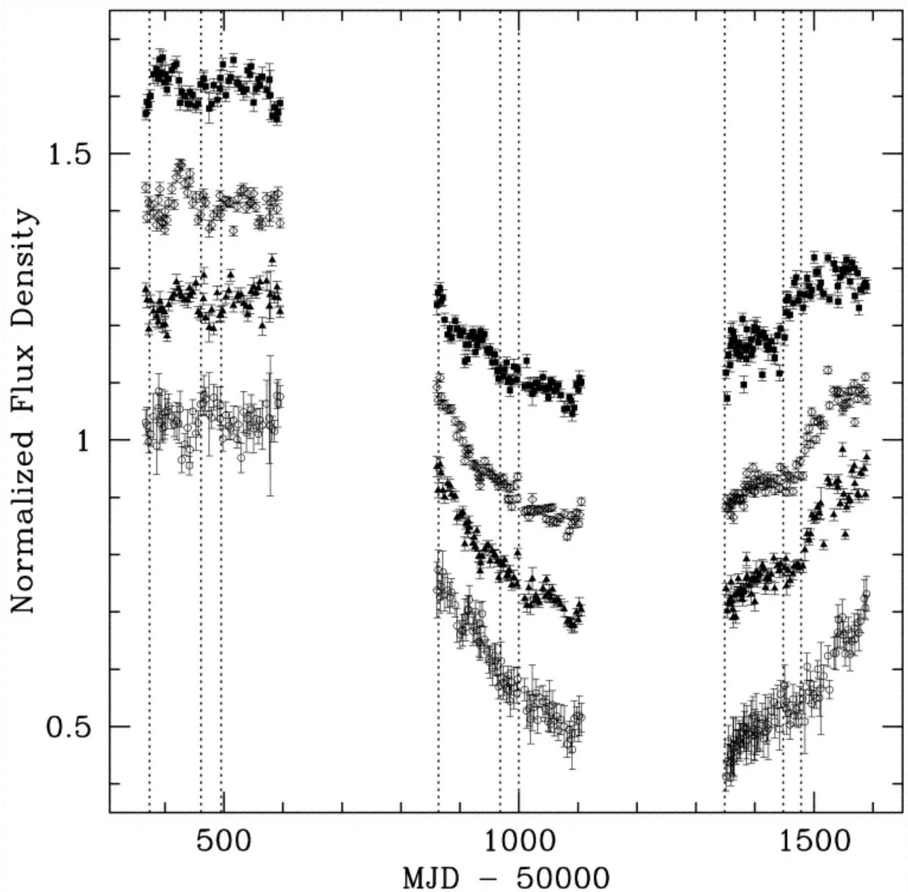




- Best seeing images contain majority of galaxy detections
- Very conservative estimates of detectability, 15000 sq degree survey
- At least 10,000 *detectable* lensed galaxies (all relatively wide separation),
- At least 1500 *detectable* lensed quasars – AGN likely more numerous still

Angular resolution is not LSST's strength...

LSST time delay measurement



B1608 (Fassnacht et al 2002):

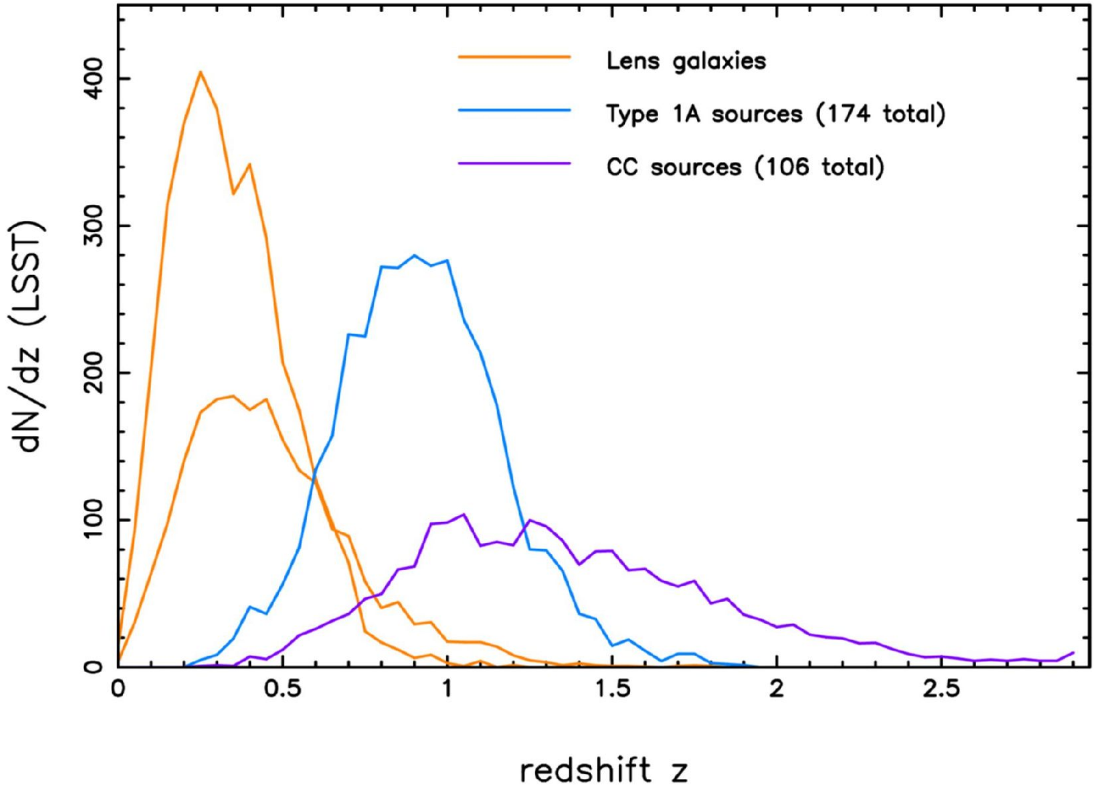
- 2” image separations, 30-80 day time delays

Few % precision on H_0 required:

- Photometry to 2% (VLA)
- 3 observing seasons, each of 8 months
- 220 exposures over 3.5 years
- Some fortune with the variability

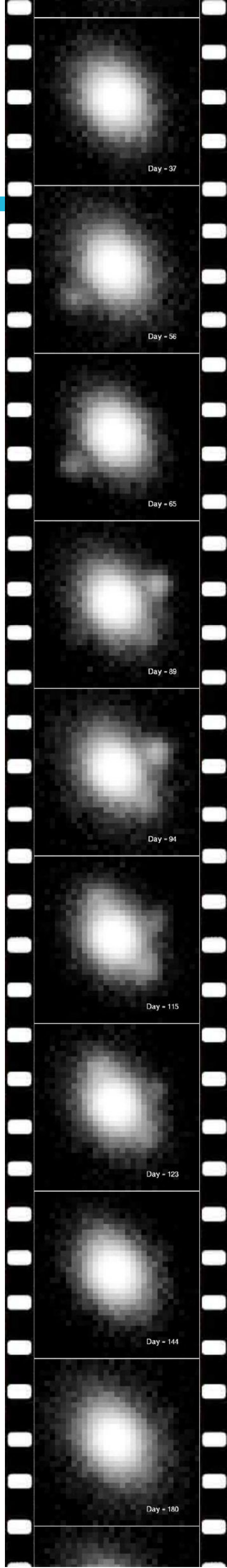
LSST numbers are very similar

Multiply-imaged supernovae



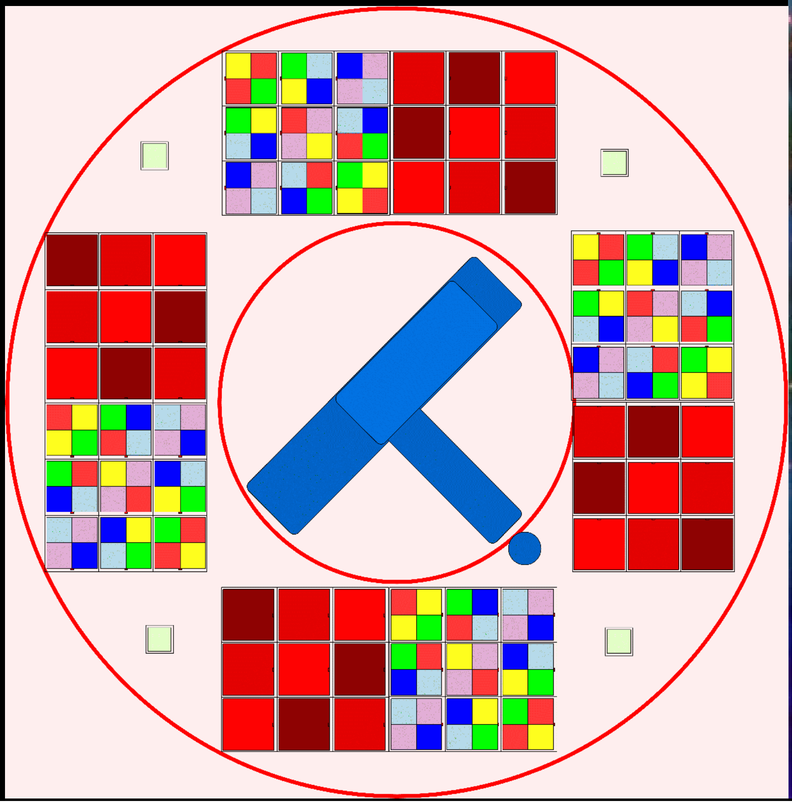
In a 10-year 20000 sq degree survey, “rare” objects get redefined!

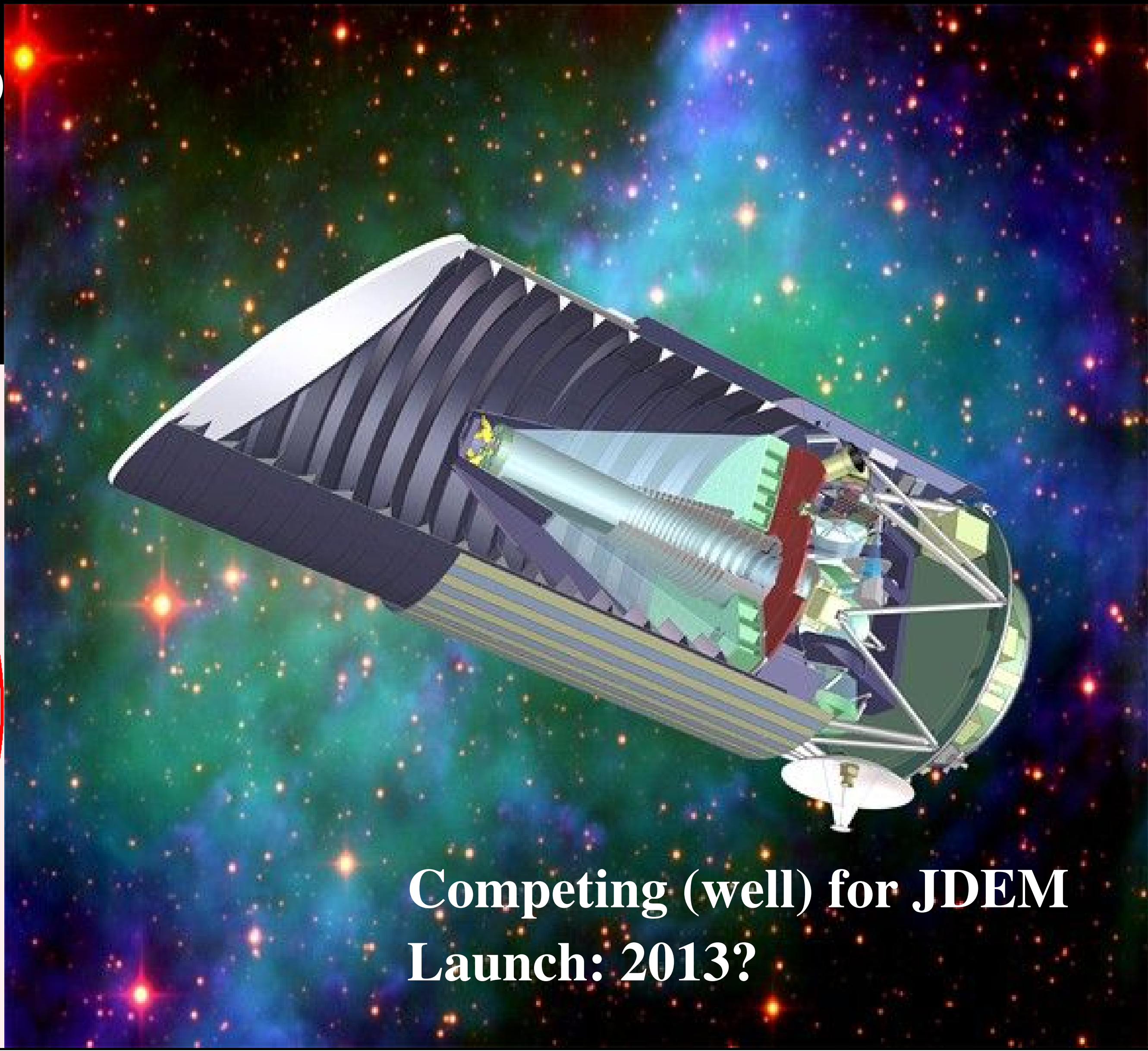
- SN rates from Goobar et al: few hundred supernovae per sq degree per year, redshift and observed magnitude distributions
- Expect a few hundred lensed supernovae (with measurable time delays) – this is again pessimistic – time delay and magnification likely limited by microlensing (e.g. Dobler & Keeton 2006)



SNAP

- 2m class telescope, 0.7 sq degree field of view
- IF Spectrograph for SNe
- 9 filters (350nm–1700nm)
- PSF 0.13 arcsec FWHM
- 0.1 arcsec pixels,
  HST-quality imaging





Planned SNAP surveys

"Deep" Type Ia SN survey:

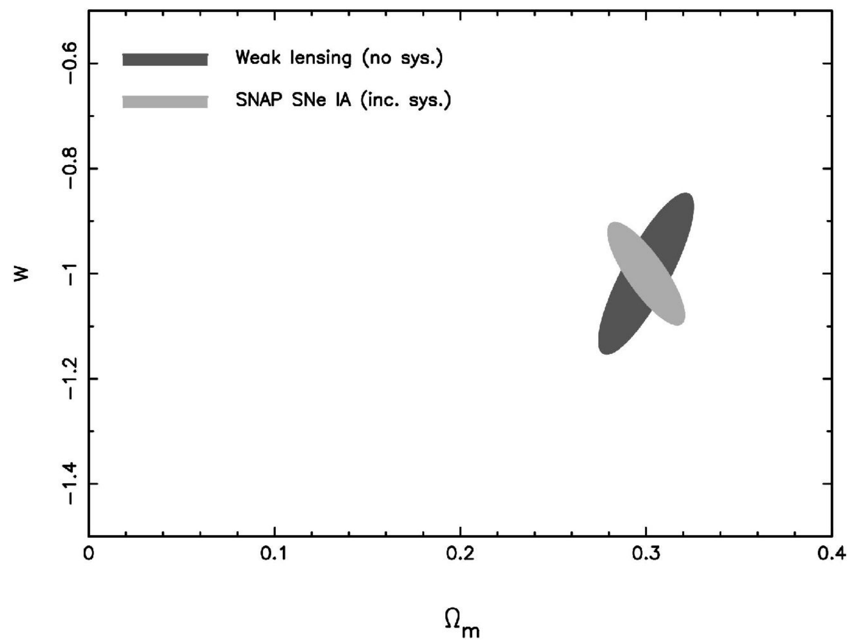
- 15 sq deg, I mag limit 30.3 (27.7 per visit), 4 day cadence
- Total observing time 32 months

"Wide" Weak lensing survey

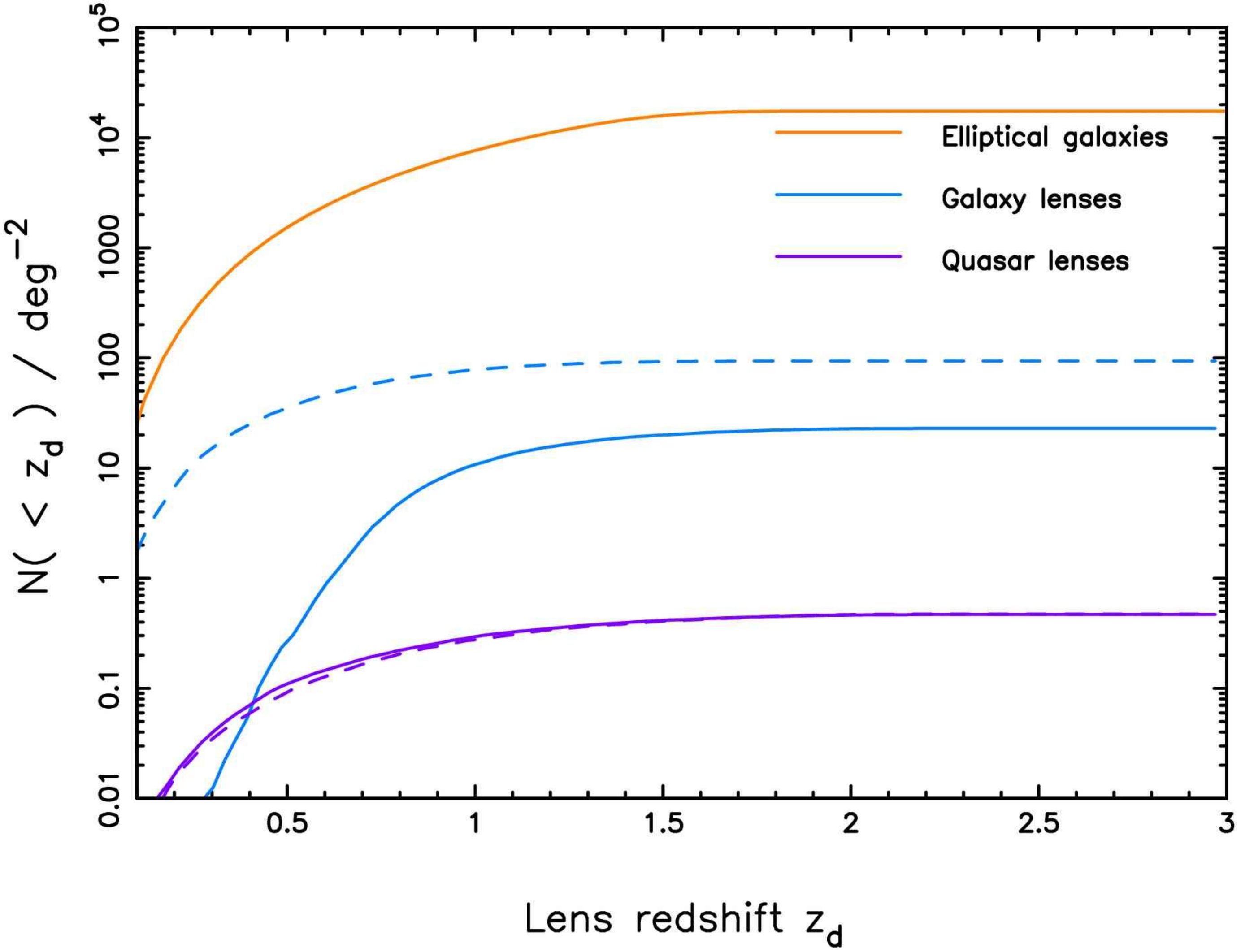
- 1000 sq deg, I mag limit 27.7, single epoch (6-way dither)
- Total observing time 16 months

"Panoramic" legacy survey

- 10000 sq deg, I mag limit 26.5
- Observing time 3 years
- Suggested use of community time...



Examining elliptical galaxies



1 in 40000 elliptical galaxies is lensing a quasar,

1 in 200 is lensing a normal galaxy

(but you may not be able to observe it)

Distance ratio cosmography

Can we extract cosmological parameters from 20,000 strong galaxy-galaxy lenses? Distance ratio is a weak function of cosmology

$$\theta_E = 4\pi \left(\frac{\sigma}{c}\right)^2 \frac{D_{ds}}{D_s}$$

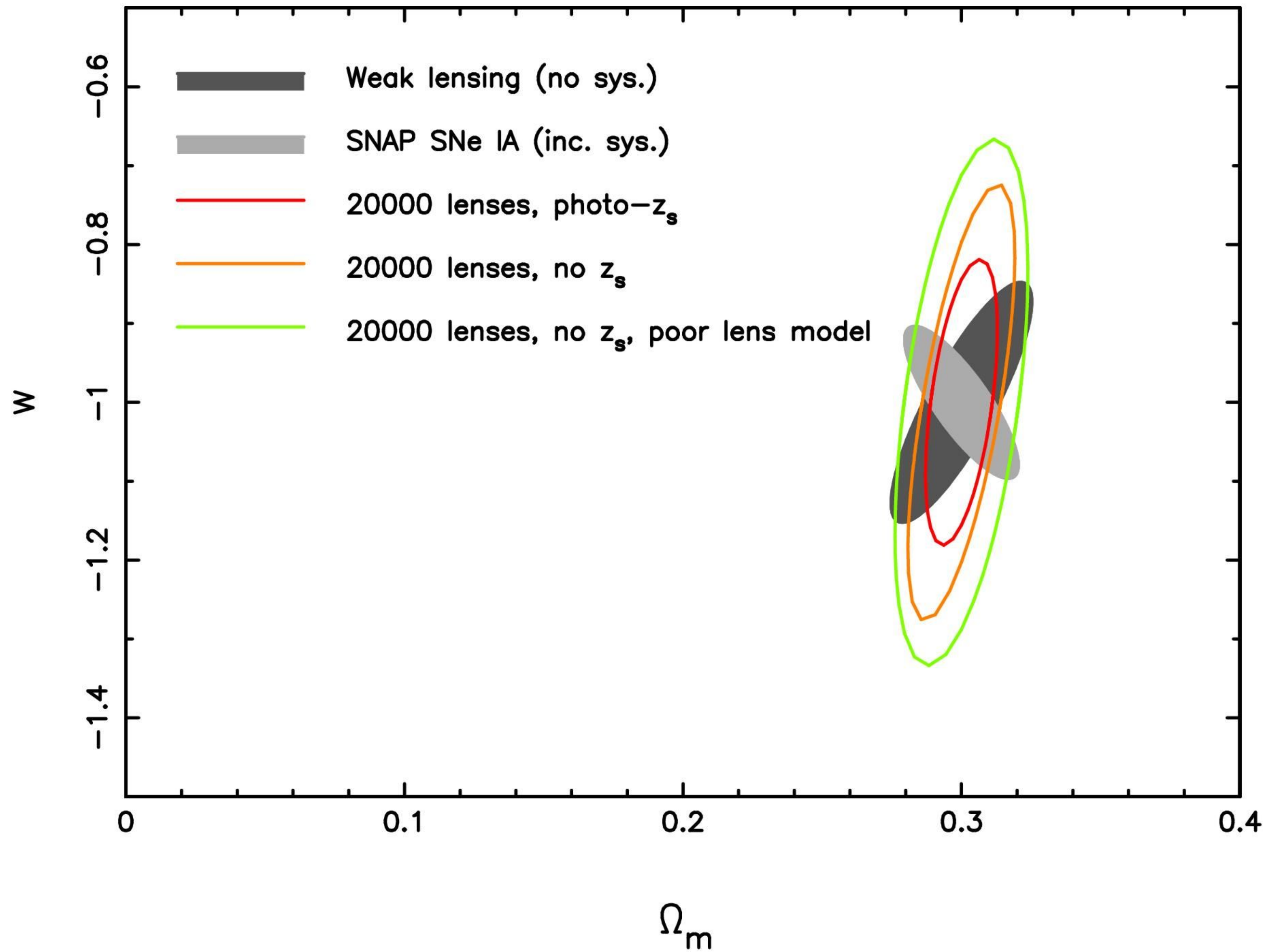
$$\frac{D_{ds}}{D_s} = 1 - \int_{z_d}^{z_s} H(z)^{-1} dz \Big/ \int_0^{z_s} H(z)^{-1} dz$$

Im et al (1997) attempted this with 7 MDSS lenses... Linder (2004) was optimistic (modulo systematics) but lacked realistic lens numbers.

Assume SIS model lenses, FP only for lens mass parameter, no evolution, no environments, SNAP photo-z's and image quality...

Keeton's talk (this conference): could use time delays to constrain mass model too – but have fewer systems.

Distance ratio cosmography



Precision **cosmology**

Systematic errors – galaxy properties

- Method hinges on relating lensing mass to some other mass indicator (velocity dispersion)
- Lenses are not well-modelled by just an SIS in general. Even if they were, FP gives estimate of velocity dispersion to just **16%, ~30 km/s** (Bernardi et al 2002)
- Evolution of FP is uncertain: there is (**at least**) an offset and scatter (**10%, ~20km/s**) in the relation between velocity dispersion and mass (Koopmans and Treu 2004, SLACS). This offset may be evolving. As will the distribution of profile slopes etc etc etc

- Correctly partitioning the information between nuisance and interesting parameters (astrophysics and cosmology?!) is a GENERAL PROBLEM facing future (and indeed current) surveyors (see Oguri 2006 astroph/0609694 for an interesting approach)

Preparing for the future

- Simultaneous inference of lens, source, environment and cosmological parameters is one thing we can practise in the next ten years

- Automating the detection of lenses is another

Moustakas et al (2006) searched 63 ACS fields by eye for elliptical galaxy lenses

Each field took about 15 minutes – that's 2.25 working weeks per square degree, or

45 Lexi-years to look at the SNAP wide survey

Better to have robots look at postage stamps

SL2S: the Strong Lens Legacy Survey

Cabanac et al 2006, out in ~weeks

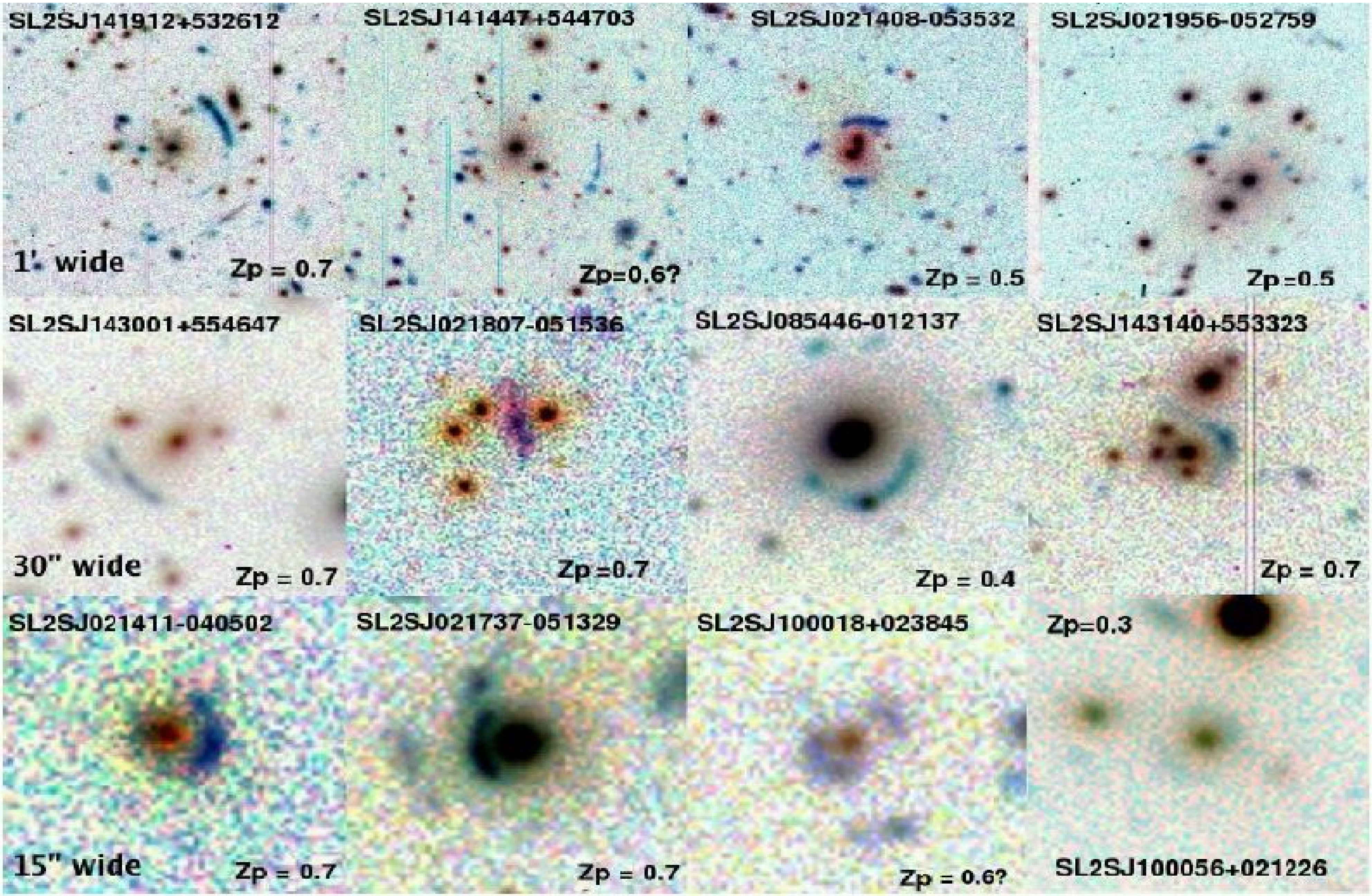
- CFHTLS to date:
  Wide: 28 sq degrees observed in (u')g'r'i'z' to i'<24.5
  Deep: 4 sq degrees to i'<25.8-26.3

- Filter images for arcs (Alard 2006), inspect elliptical galaxies for colour gradients and aligned blue residuals (Gavazzi et al 2006)

- 4 arcs (>7”), 22 rings (<3”), and 13 intermediate (3-7”) lenses – probing group-scale mass distributions

- Following up with spectroscopy, HST...

SL2S: the Strong Lens Legacy Survey



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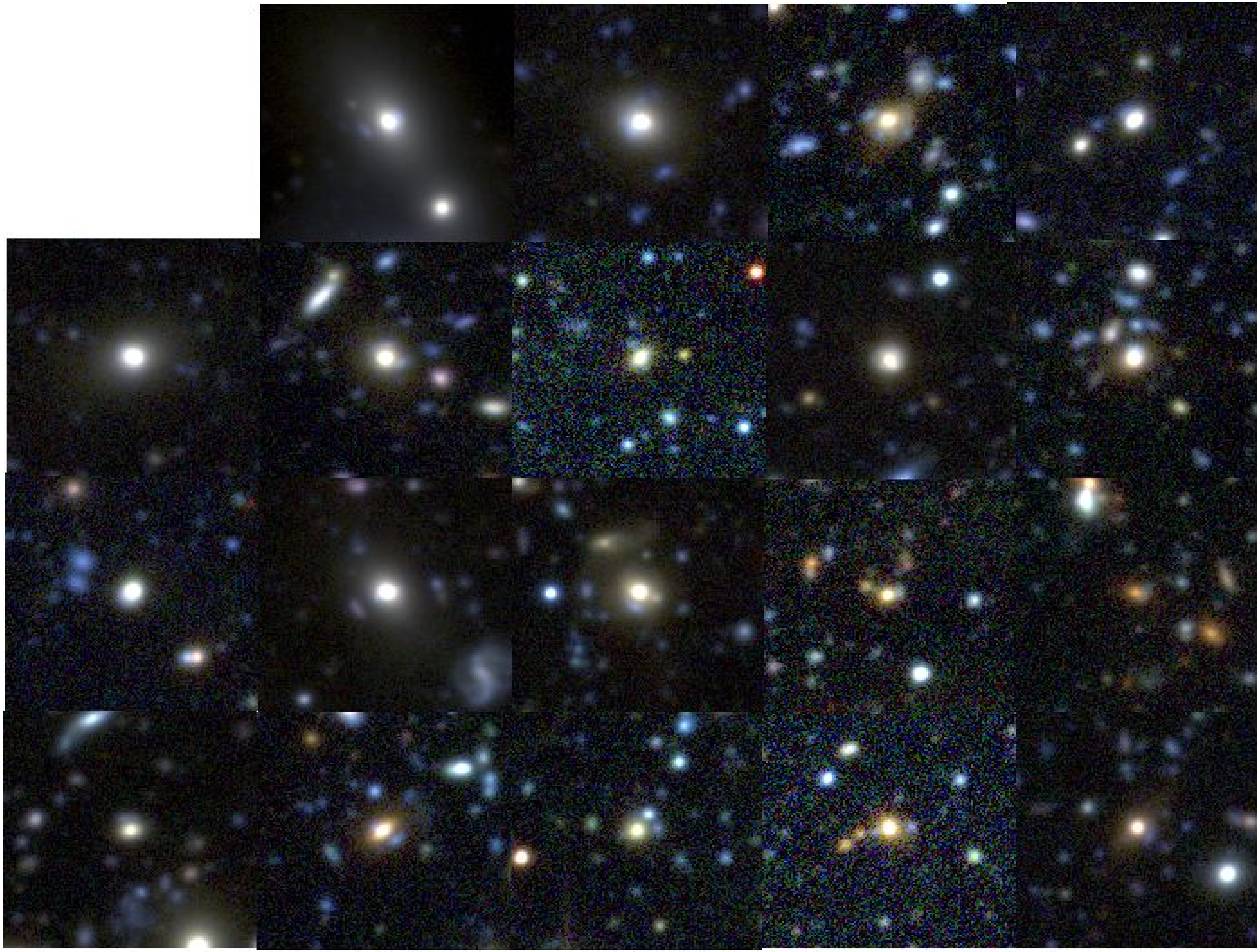
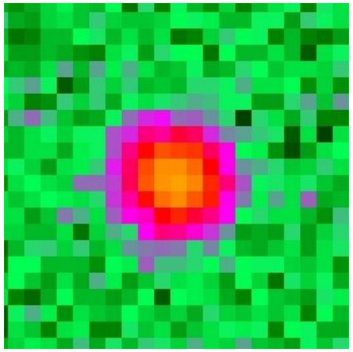
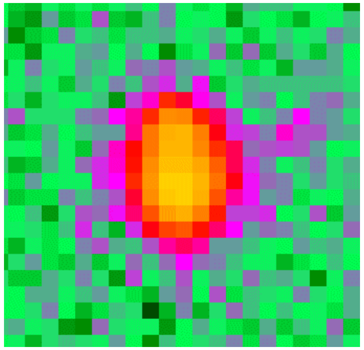


SDSS Lensed Quasar Search

Oguri et al 2006

- SDSS DR3:
  22868 spectroscopic quasars,
  0.6 < z < 2.2
  15.0 < i < 19.1



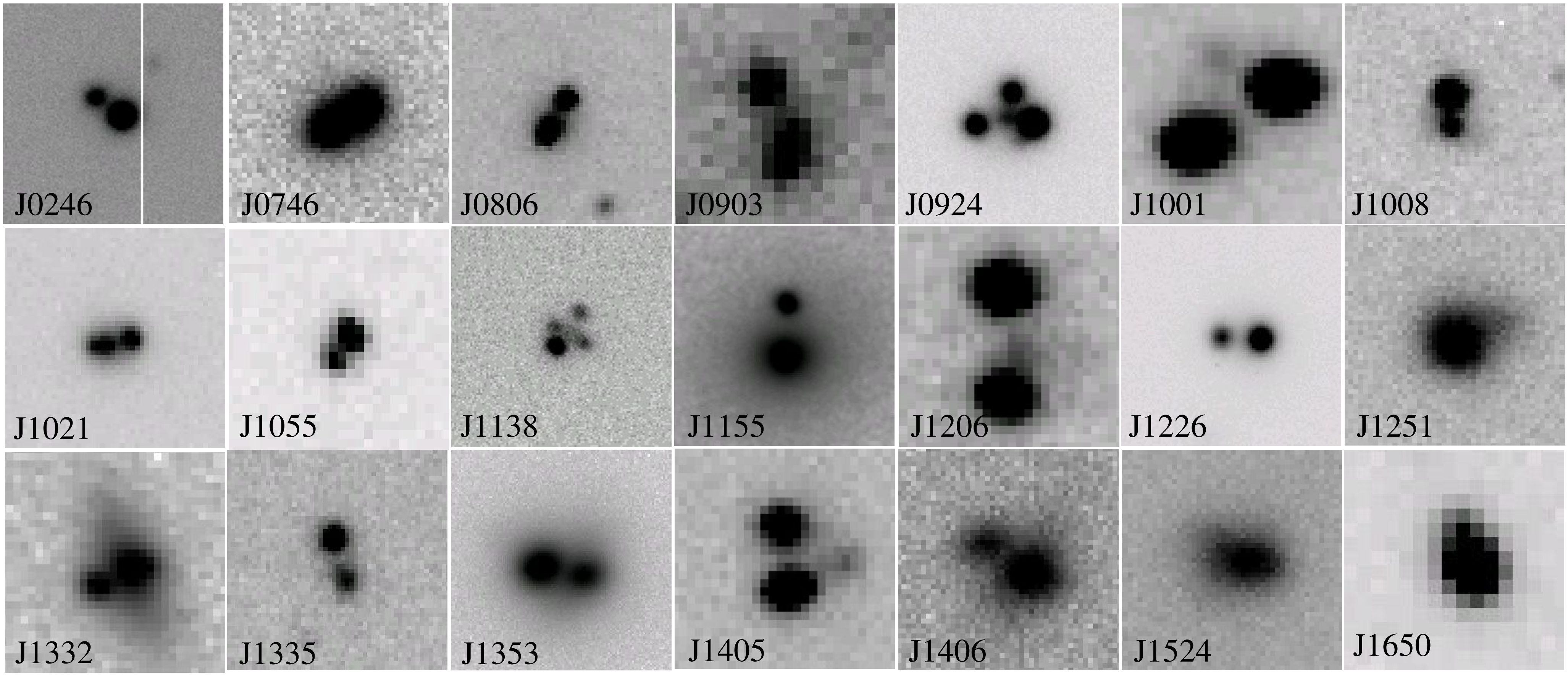


- Check SDSS imaging catalogues for "extended" flags
- Follow up with spectroscopy: accept candidates with matching image spectra and detected lens galaxy

- 21 small-separation candidates

- See poster by Masamune for more details, and for large separation lenses!

SDSS Lensed Quasar Search



Catalogue-level searching will be vital in LSST era
Spectroscopic follow-up problem is 100 times worse!

What about SNAP precursor data?

HAGGLeS

We are searching the entire HST imaging archive for lenses.

- Exposure time > 2000s gets us 7 sq degrees with ACS
- Insisting on 2 filters reduces this to 2.2 sq degrees
- Large surveys are only part of this: plenty of parallel fields, individual galaxies, clusters, GRBs etc etc totalling 1.2 sq degree

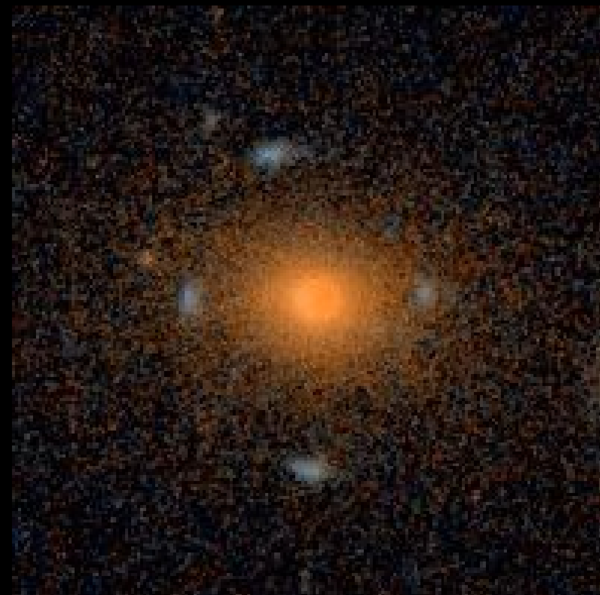
Prediction is 10 strong gravitational lenses per sq degree

- Some will already be known(!)
- Legacy will be access to archive in reduced form via postage stamp service, plus catalog of all galaxies observed by ACS
- *This is the only precursor dataset for SNAP*

`http://www.slac.stanford.edu/~pjm/HAGGLeS`

LEGS: A-list

HST1418+5236
“Dewdrop”

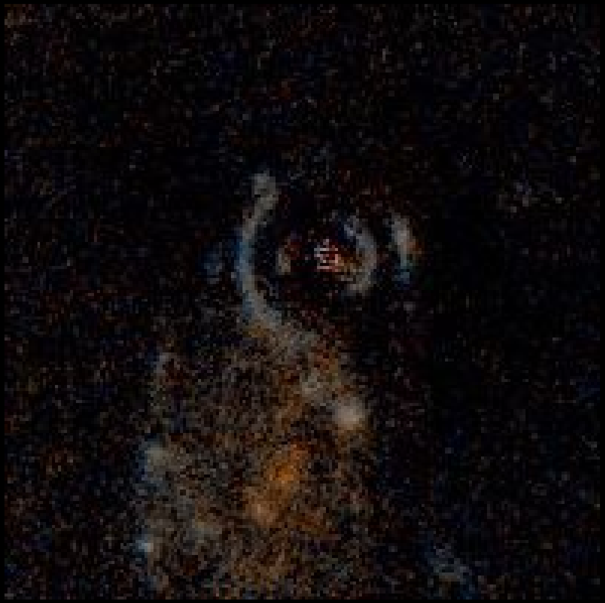


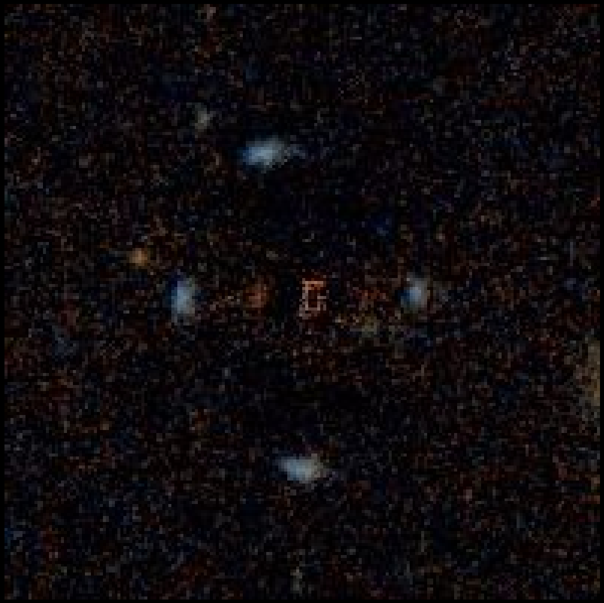
HST1417+5226
“Cross”

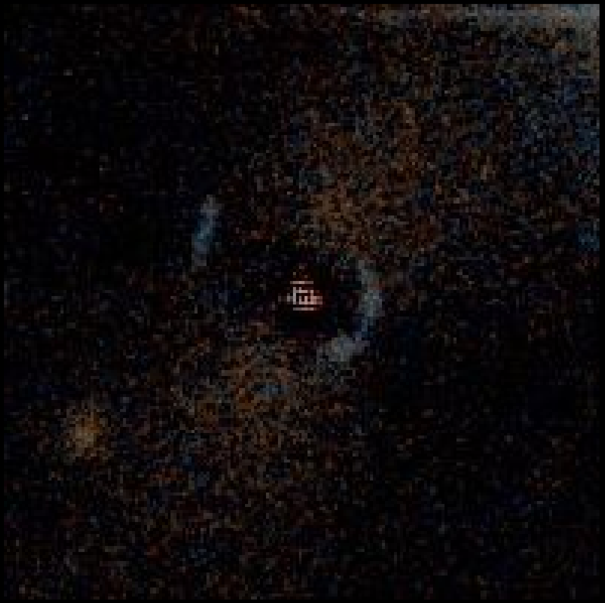
HST1418+5244
“Anchor”

Pilot project: Eyeball the Extended Groth Strip

LEGS: A-list







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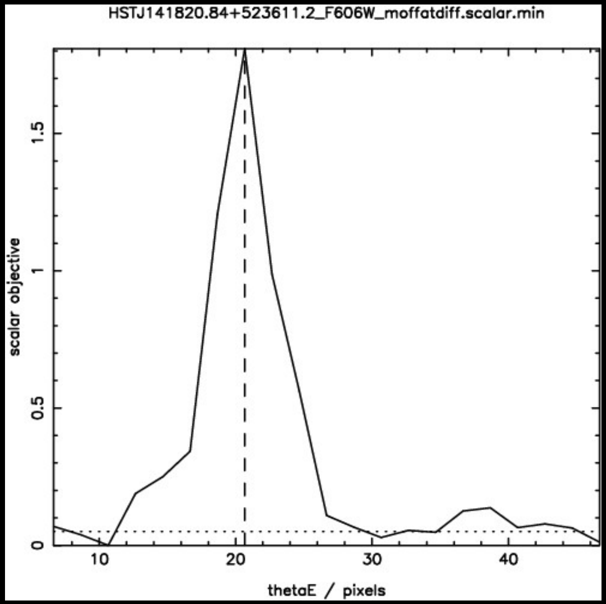

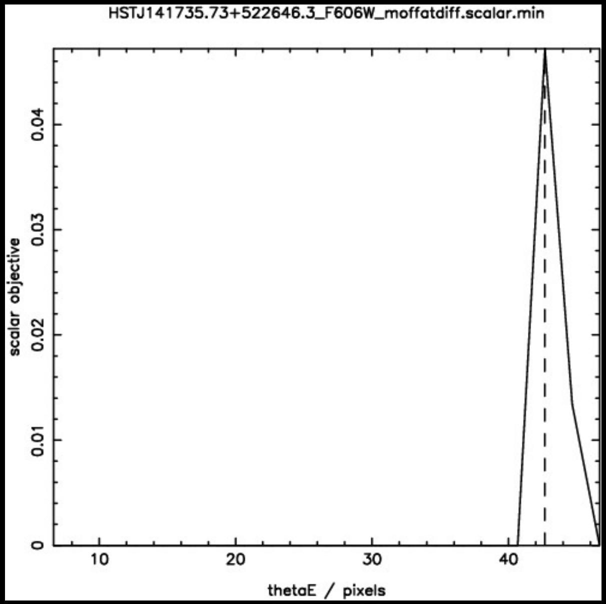

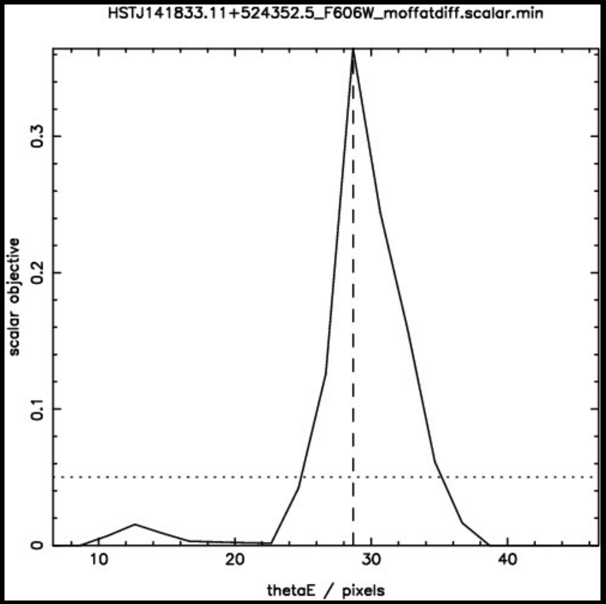

HST1418+5236 “Dewdrop”

HST1417+5226 “Cross”

HST1418+5244 “Anchor”

Model every bright extended object as a lens, and look for multiple bright pixels to be mapped to the source plane

Robotic lens searching - conclusion

All three robotic methods do the following:

- Remove the need for Lexi to look at large confusing images
- Convert man-hours to CPU-hours
- Reduce the number of candidates to be inspected to ~10-100 times the number of actual lenses
- Classification time becomes ~10 secs per candidate for ~100-1000 candidates per square degree, or

~10 Lexi-weeks to search the whole of the SNAP wide survey

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CONCLUSION:
Moustakas can do the job by himself

Conclusions

All strong lensing science projects benefit from larger samples

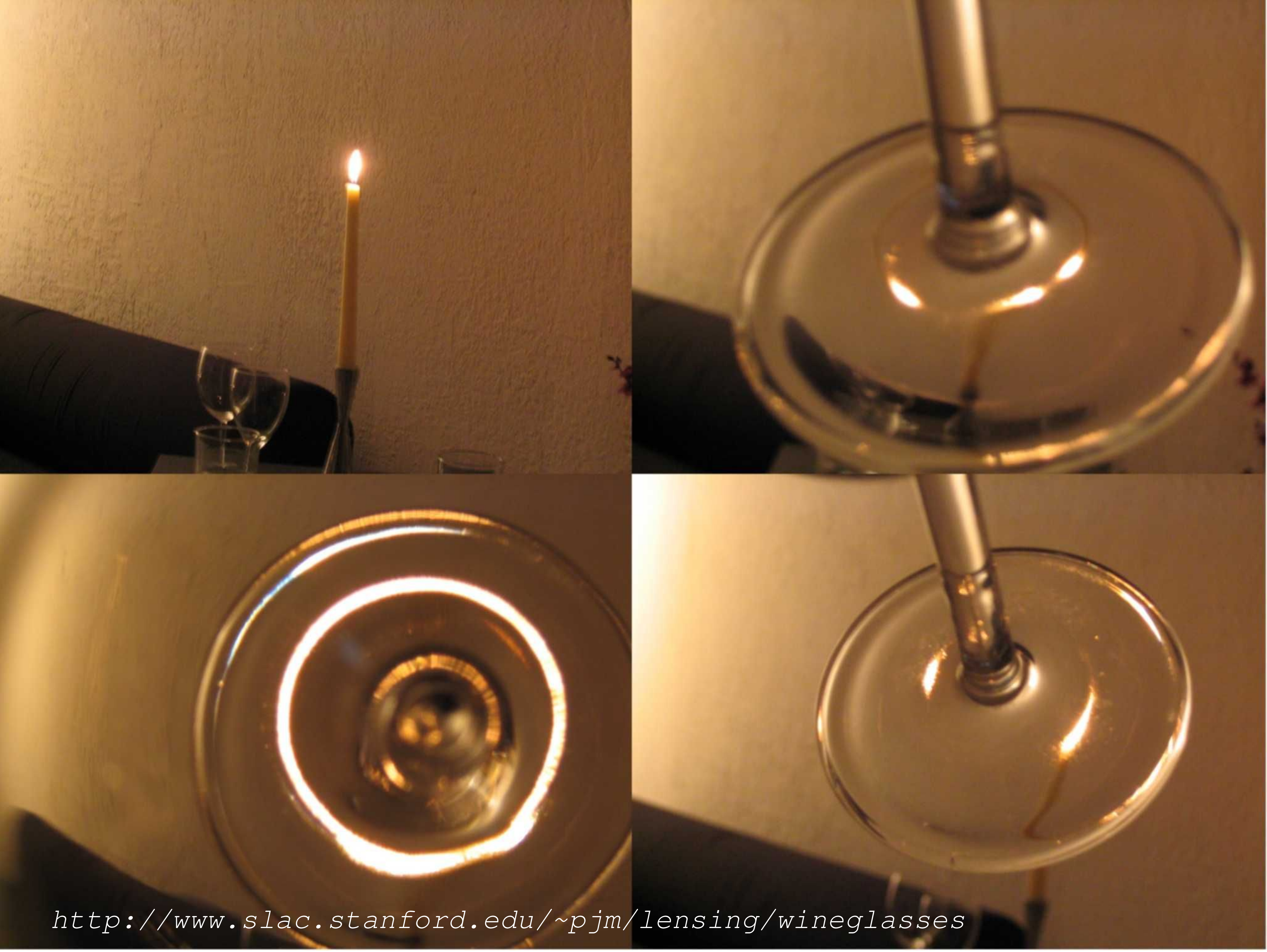
Future surveys (SNAP, LSST, SKA) will

- increase the number of known galaxy-scale lenses by > 100
- and make rare lenses commonplace

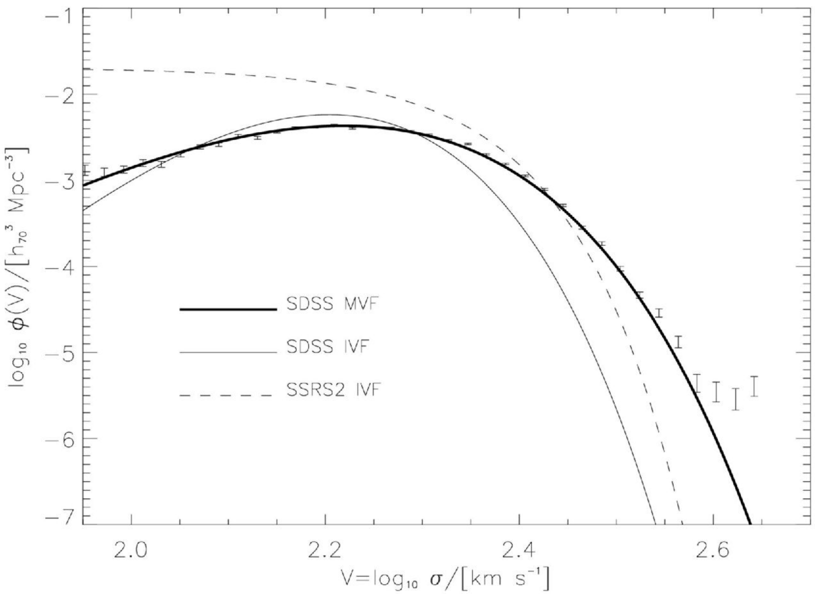
The data analysis, and statistics, become harder:

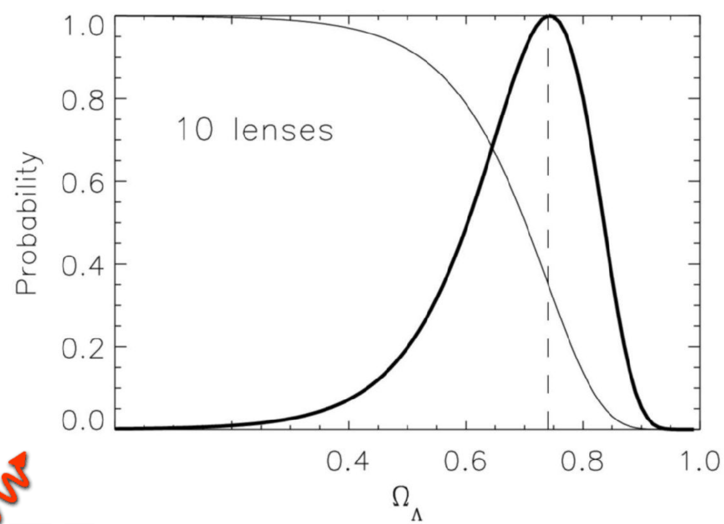
- Just finding lenses requires some level of automation – a start has been made in the HST archive, CFHTLS and SDSS surveys
- Accurate astrophysics and cosmology requires modelling systematics as well – probably with the same dataset
- Where is the follow-up going to come from?

Slide 28 for a 17 minute talk? Erm...


http://www.slac.stanford.edu/~pjm/lensing/wineglasses

Lens statistics





Mitchell et al 2004

If you:

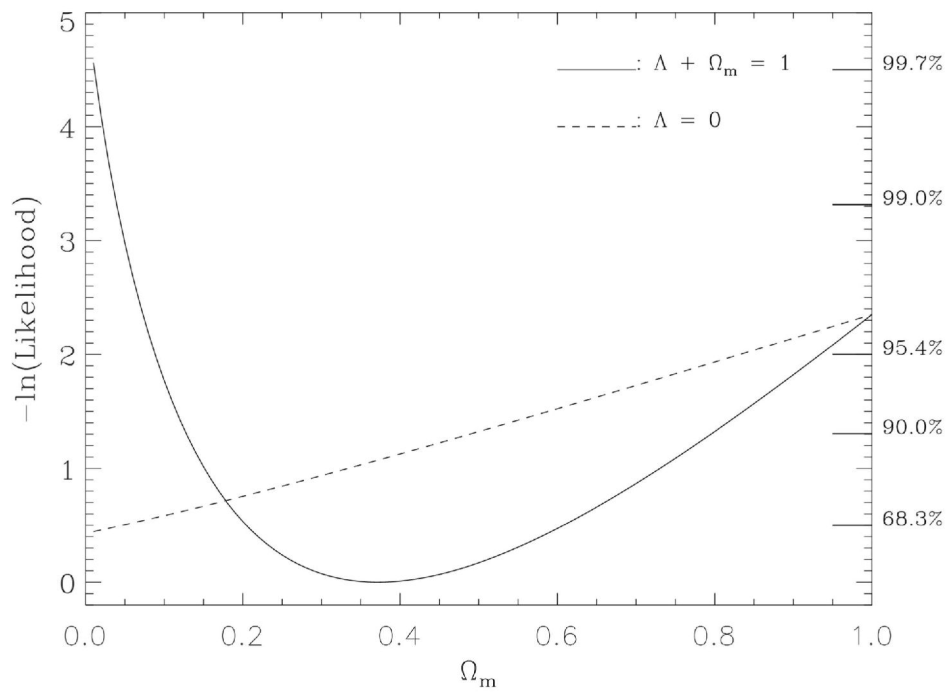
- know the number density of massive galaxies, and understand their mass distributions, and how they evolve, and you
- know the number density of source galaxies

then you:

- can predict the number of lenses, measure this, and deduce the volume containing the deflectors

- The volume is sensitive to dark energy...

Strong lens cosmography



- (Partial) degeneracy with evolution
- Need at least an enormous sample of lenses...

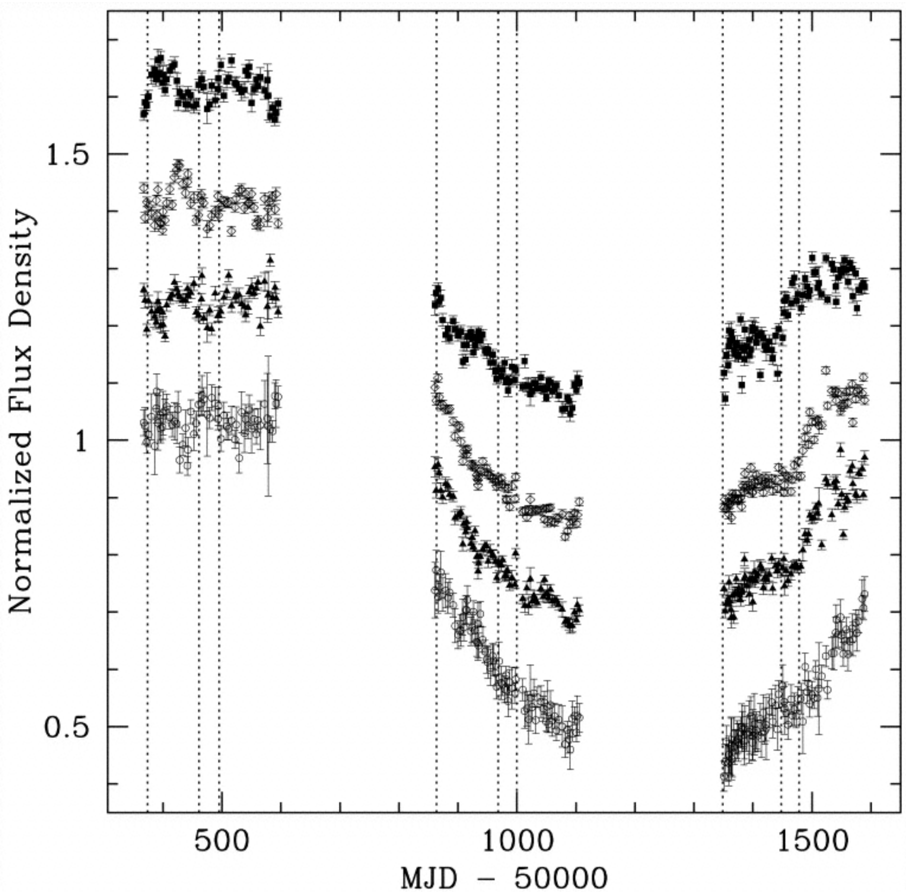
A weaker (but cleaner?) test:

- Model lenses
- Acquire independent mass estimate (eg stellar dynamics, Treu & Koopmans, or a low resolution alternative like the fundamental plane...)
- Require consistency by adjusting distance ratios

$$\theta_E = 4\pi \left(\frac{\sigma}{c}\right)^2 \frac{D_{ds}}{D_s}$$

$$\frac{D_{ds}}{D_s} = 1 - \int_{z_d}^{z_s} H(z)^{-1} dz / \int_0^{z_s} H(z)^{-1} dz$$

The Hubble constant



Independent of CMB, cepheids:

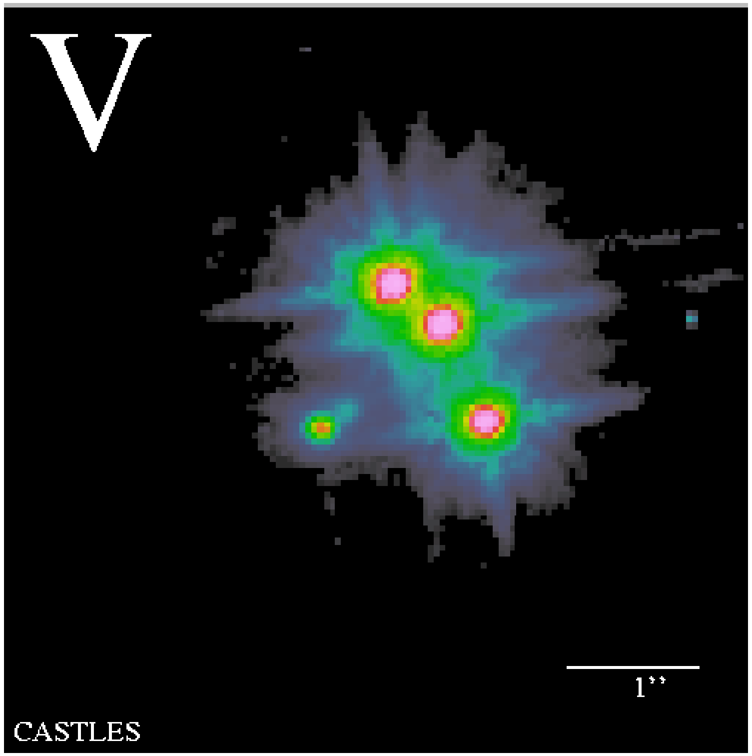
- Model lens image separations (arcsec) and predict time delays (days/h)
- Measure time delays (days)
- Infer environments, profiles, evolution at the same time...

$$c\Delta t = (1 + z_d)\frac{D_d D_s}{D_d s}\theta_E(\theta_2 - \theta_1)$$

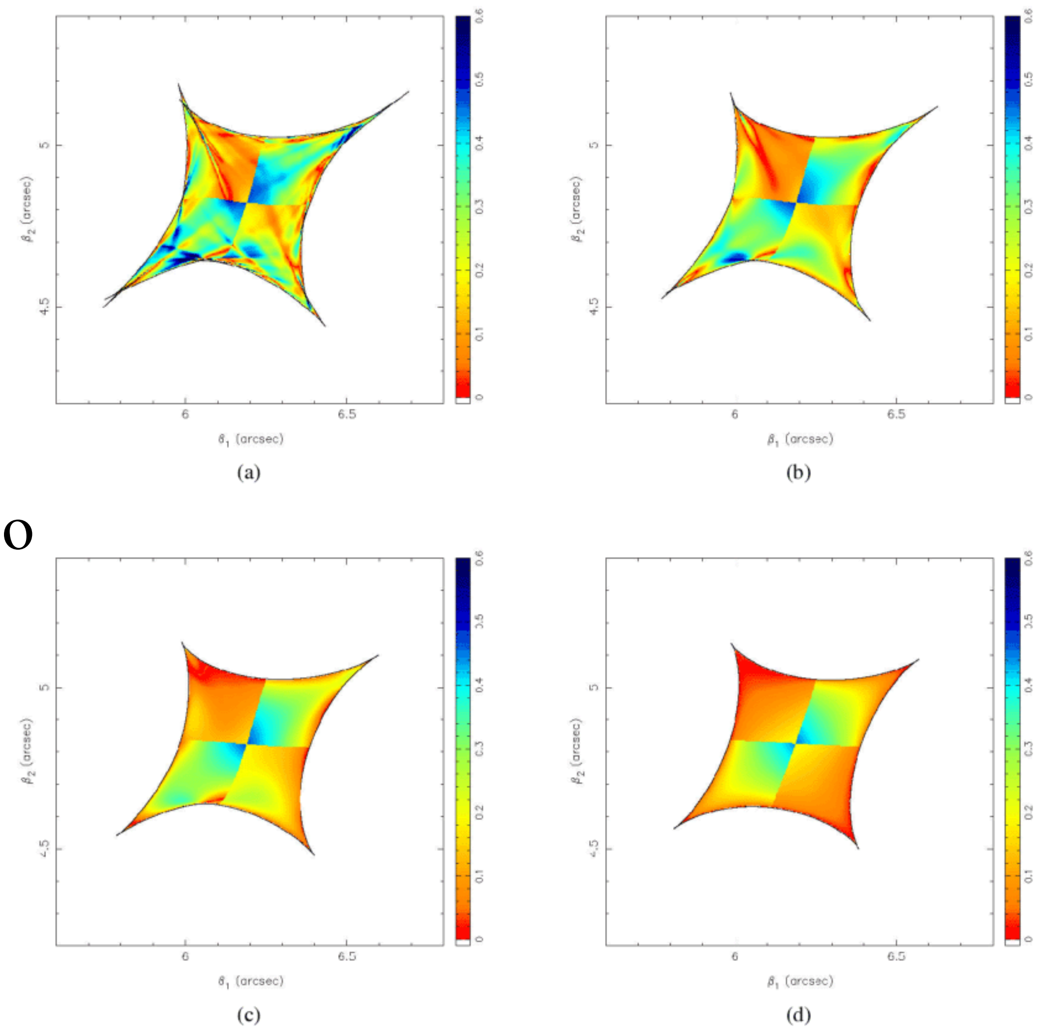
eg. B1608 (Fassnacht et al 2002):

- 2" image separation, 30-80 day time delays
- 220 exposures over 3.5 years
- 1% precision, accuracy?

Small-scale CDM substructure



- Additional (dark) substructure can explain anomalous flux ratios in multiple image systems (e.g. Bradac et al 2003)



- Radio is cleaner (smaller source so less microlensing)
- Large samples needed for statistical analysis of h.o.d.

Lens counting

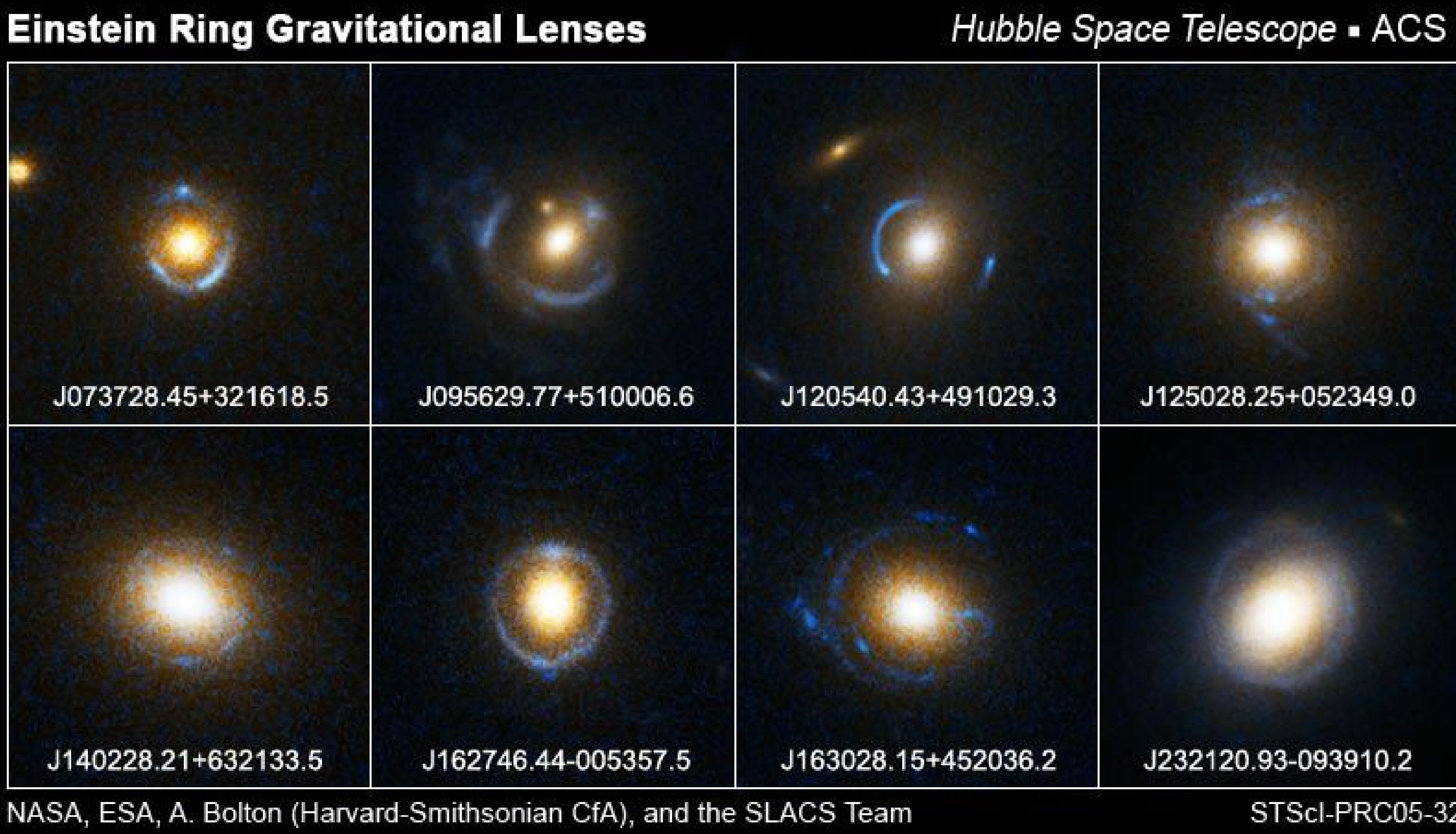
Integral over source number density, deflector number density, deflector cross-section, and selection function, best calculated by (Markov Chain) Monte Carlo methods

$$N_{\rm lens} = \int X \cdot \frac{d^2 N_d}{dz_d d\sigma_d} \cdot \frac{d^2 N_s}{dz_s dm_s}\, dz_d\, d\sigma_d\, dz_s\, dm_s$$

$$X(z_d, \sigma_d, z_s, m_s) = \int^{\beta_{\rm crit}} 2\pi S(\beta, \ldots)\, d\beta$$

- Take sources to be faint galaxies (as in weak lensing) or quasars; galaxies have disk+bulge profiles... quasars (2dF LF) are extrapolated to fainter than M=-22.5...
- Deflectors are elliptical galaxies (velocity dispersion function from SDSS), with assumed SIS mass profile
- Selection function: just geometry +magnification bias gives somewhat optimistic lens numbers, lens light can be important...

Strong gravitational lenses (11/05)



http://www.slacs.org

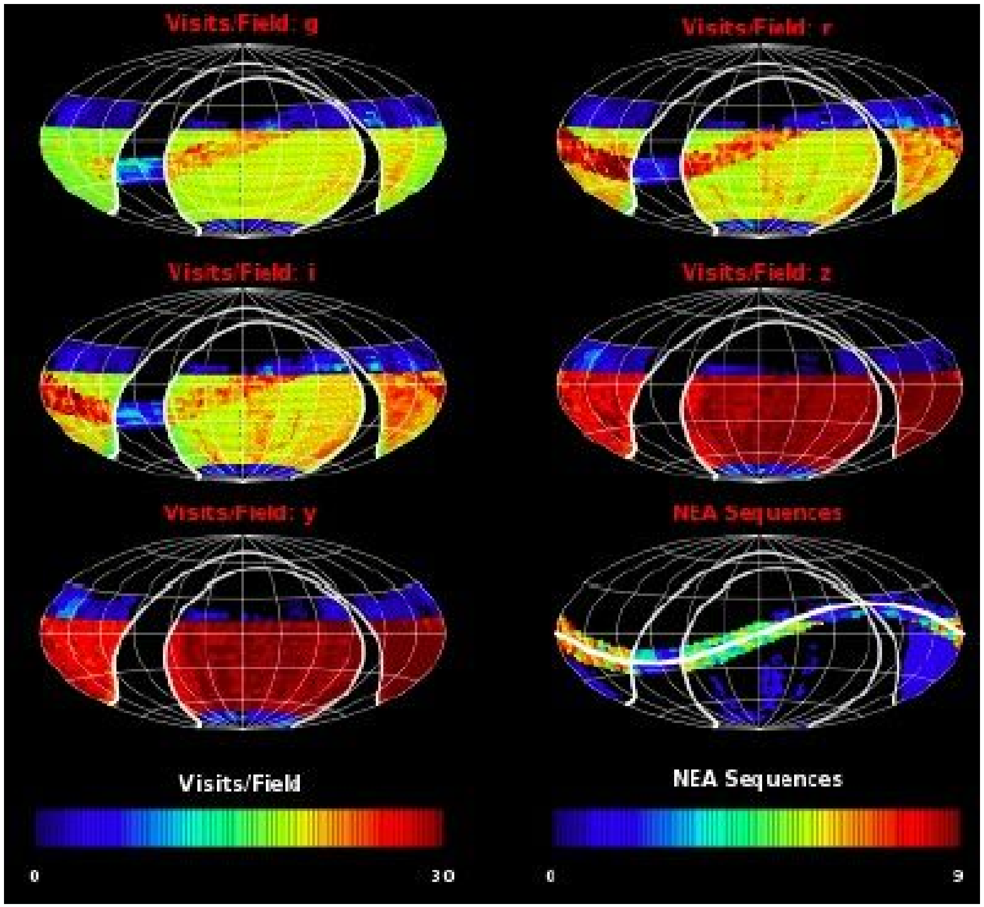
Selection functions

- Assume master catalogue generation unaffected by lensed images
- Match lens numbers calculation with visibility of lensed images in simulations – would trial lens system be selected as a candidate?
- Yes, if: image separation > 2 PSF widths, peak SB is detectable and > 10x lens light in optimal band (pessimistic?)

		Parameter	Required Value (units)	Goal Value (units)	Origin and Comments	Group 3 Supernovae	Group 4 Optical Transients	Group 5 NEA, Solar System	Group 6 Weak lensing	Group 7 Strong Lensing
1	a	Sky coverage	15,000 sq.deg for |Galactic Latitude| > 20o in less than 10 years	20,000 sq.deg for |Galactic Latitude| > 300 at zero Long., > 150 at 180 Long., in less than 10 years at airmass <1.5.	Dark Energy – Weak Lensing and Wide-Area Supernova Search	*			*	*
1	c	Sky coverage	500 sq.deg in >5 locations for |Galactic Latitude| > 20 deg	1000 sq.deg in > 10 locations for |Galactic Latitude| > 15 deg	Deep Supernova Search	*				
2	a	Total Filter complement	0.4-1.1 micron in 5 filters grizY	0.33-1.1 microns in 7 filters ubgrizY	5 filters required for accuracy in photometric redshifts. Y filter for extending accurate photo-z's to higher redshift.					
4	a	Number of visits in each filter over 10 years in each sky patch	150 in 5 filters	200 in 6 filters	Weak Lensing				*	
4	b	Number of visits in each filter over 10 years in each sky patch	230 in 4 filters	600 in 6 filters	Deep Supernova	*				
4	e	Number of visits in each filter over 10 years in each sky patch	500 in 1 filter	1000 in 2 filters	Transient lensing		*			
5	a	Depth and dynamic range of single exposure	17-24 AB mag, 10 σ	16-25 AB mag, 10 σ	Must be sky background noise limited.	*	*	*	*	*
6	a	Depth of final stacked image	29 mag/arcsec2, 10σ	29.5mag/arcsec2, 10σ	Weak lensing	*			*	*
7	a	Required image quality in each band per exposure	<0.8" FWHM	<0.6" FWHM	Weak Lensing – for shape measurement in r and i. Improvement in quadrupole moment to go as sqrt of number of exposures.	*	*	*	*	*

Notes: WL and SN surveys likely most useful, NEA stripe has useful cadence though. Cadences need clarifying for the dim. Assume mag limits correspond to 0.7" seeing

Multiply-imaged Supernovae

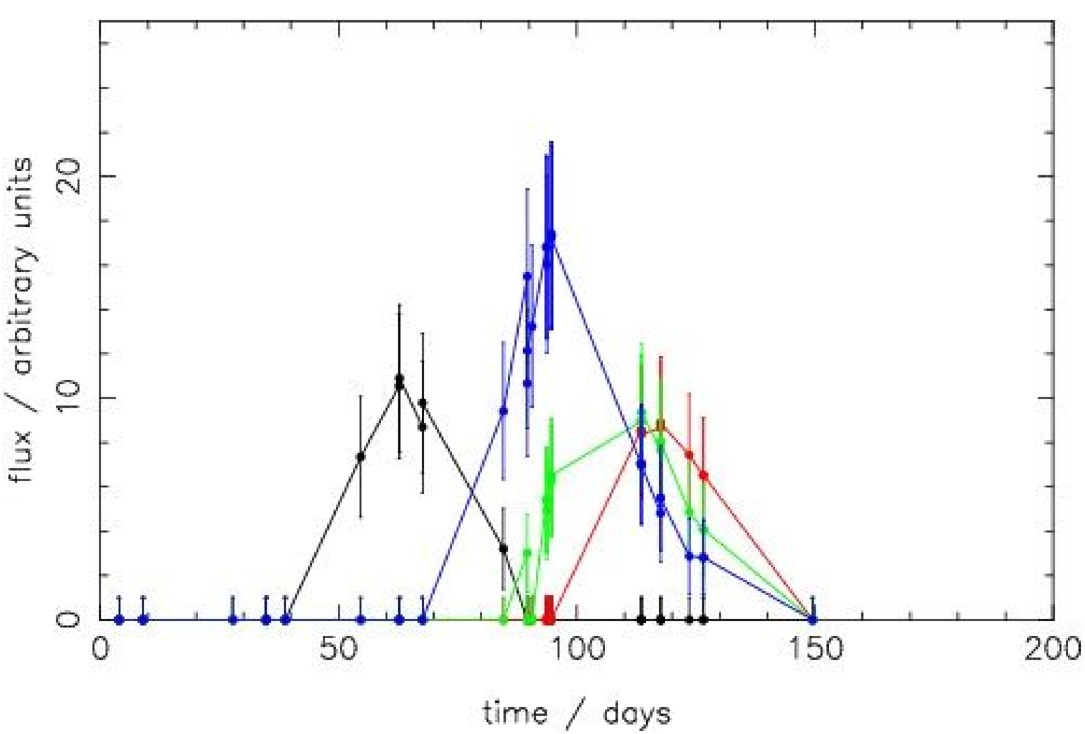


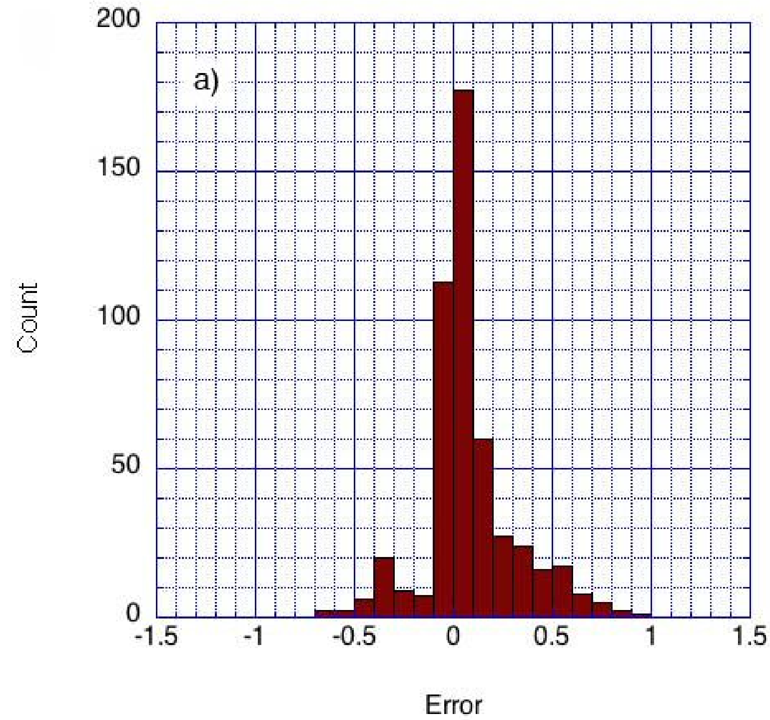
Derive time delay precision from image simulations (Kirkby)

- Simulate lens, place in each of 2000 LSST fields
- Generate time sampling from LSST cadence simulator
- Simulate images with appropriate seeing, sky etc for each 30 second visit in each of 5 filters (grizY)
- Detect SN, measure fluxes, extract time delay from light curve

KIPAC

LSST SN time delays





r filter gives best sampling - **10% precision on time delays requires:**

- peak observed magnitude of 23
- 50 visits over all 4 images
- regular sampling at 10-15 day cadence

About 15% of fields match these criteria, in WL-optimised schedule

KIPAC