Strong Gravitational Lensing with LSST and SNAP

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Overview

- Two complementary systems for extending the *current sample* by 2 orders of magnitude:
  a finder (LSST) and a resolver (SNAP)

- Quick introduction to the telescopes:
  system design, key numbers, current status

- 2 example science projects – with spin-offs – to illustrate the possibilities (i.e. not an exhaustive list!)

- Current efforts:
  precursor surveys (SDSS, SL2S, HAGGLeS...)
  experiment planning

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:

- **LSST - 2012?**
- **SNAP - 2013?**
- **SKA - 2015?**

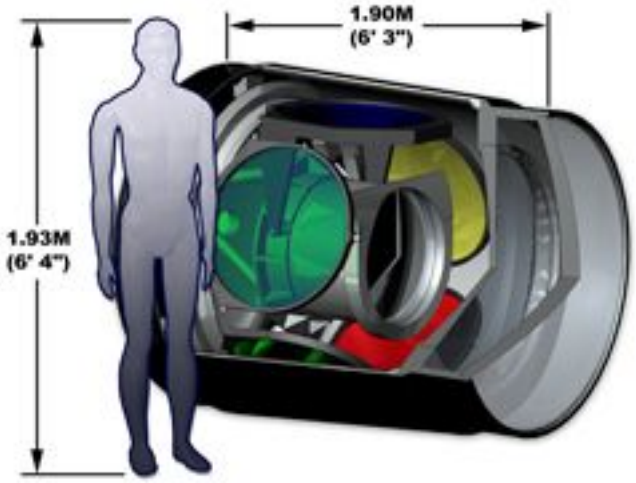
Just around the corner:

- **DES, PanSTARRS, E-VLA, E-Merlin, LOFAR, ... - 2007+**

Right here right now:

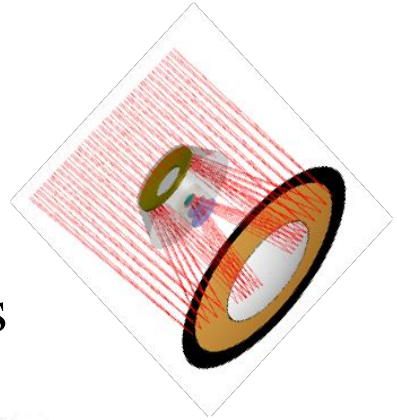
- **SDSS**
- **CFHTLS**
- **HST archive***

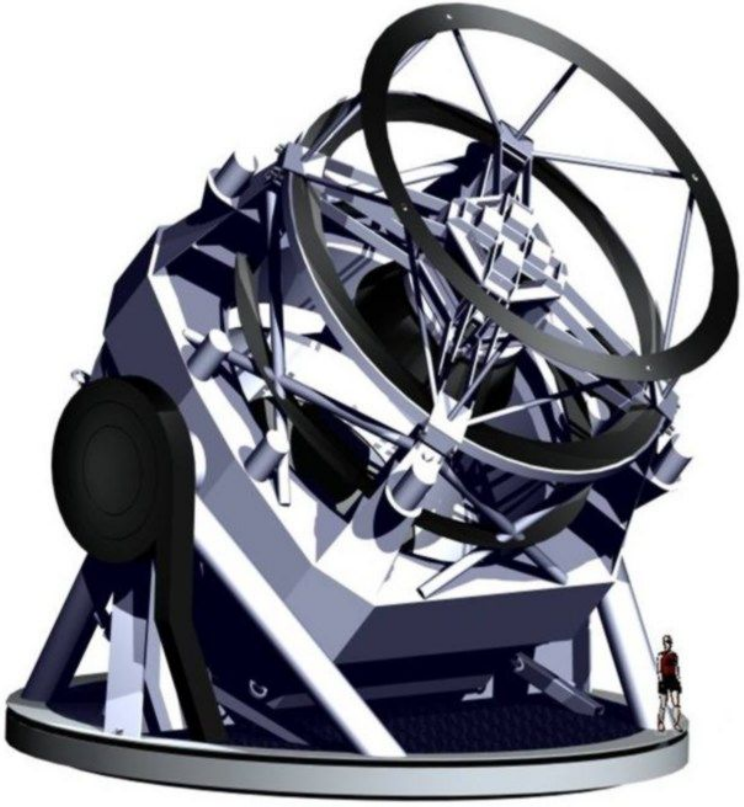
Strong lensing with LSST



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*** of the sky



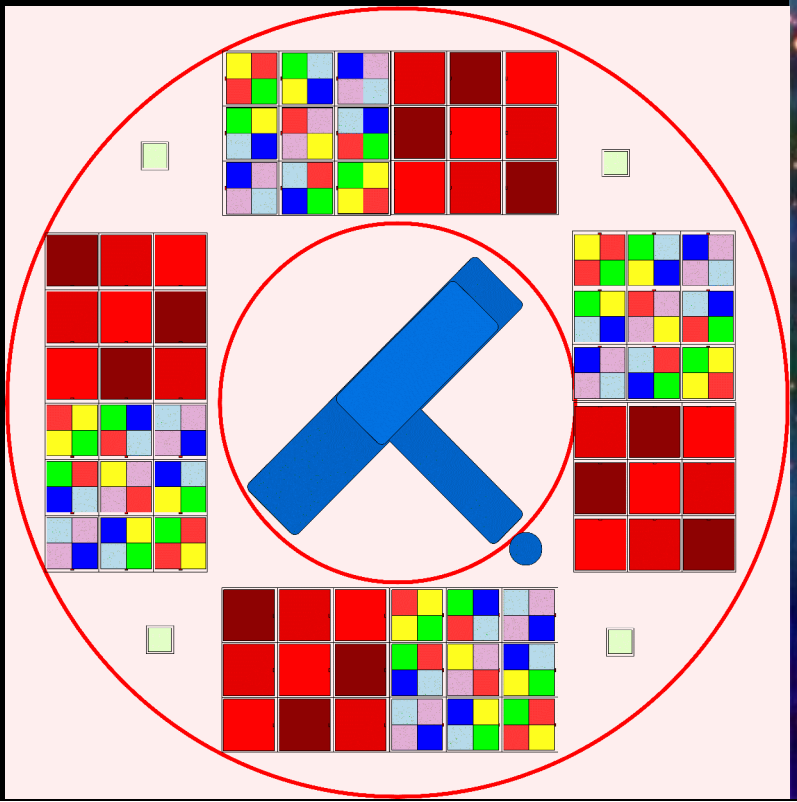


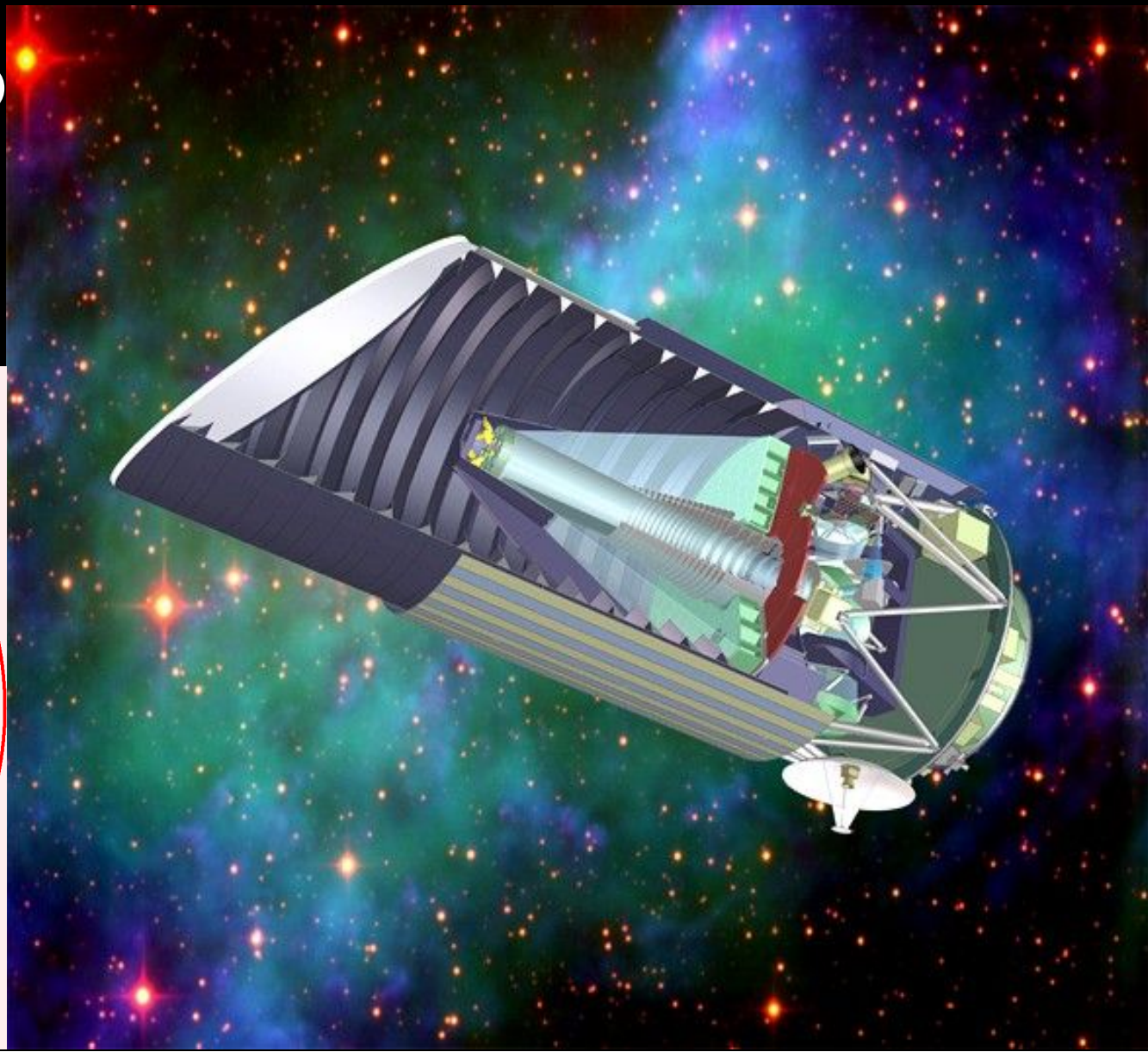
		Parameter	Required Value (units)	Goal Value (units)	Origin and Comments	Group 3 Supernovae	Group 4 Optical Transients	Group 5 NEA, Solar System	Group 6 Weak lensing	Group 7 Strong Lensing
1	a	Sky coverage	15,000 sq.deg for | Galactic Latitude| > 20o in less than 10 years	20,000 sq.deg for | Galactic 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

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:

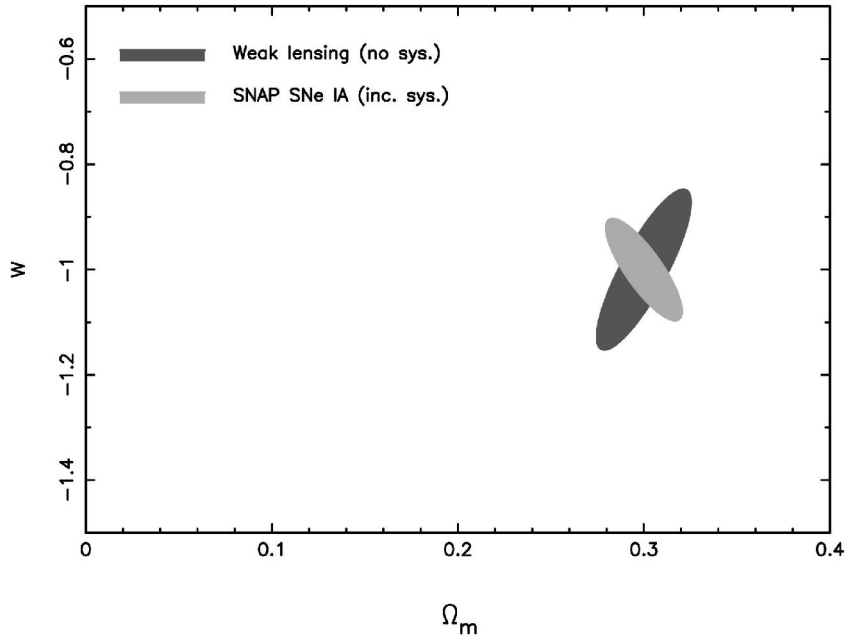
- 8 sq deg, I mag limit 30.3 (27.7 per visit), 4 day cadence
- Total observing time 22 months

"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...



Current status(1)

- LSST:

  In the process of applying for construction funds from NSF
  Site selected – Cerro Pachon, Chile
  Mirror is being cast this summer (takes 6 years!)
  Goal: first light December 2013, one year commissioning

- SNAP:

  Competing for JDEM this year, $600m cost cap met
  Part of Beyond Einstein program – more competition...
  NASA is not the only launcher!
  Could see first light as early as 2013...

Current status(2)

- Experiments are being planned now - for example:

  1) Hubble's constant* from strong gravitational lens time delays:
  finding lenses with LSST, measuring the delays, statistical analysis of the results, worrying about systematics

  2) Cosmography* and galaxy evolution with standard masses:
  finding lenses with SNAP, modeling the image separations, statistical analysis of the results, worrying about systematics

* Note: dark energy is a powerful driving force

- Making use of our experience with current data - for example:

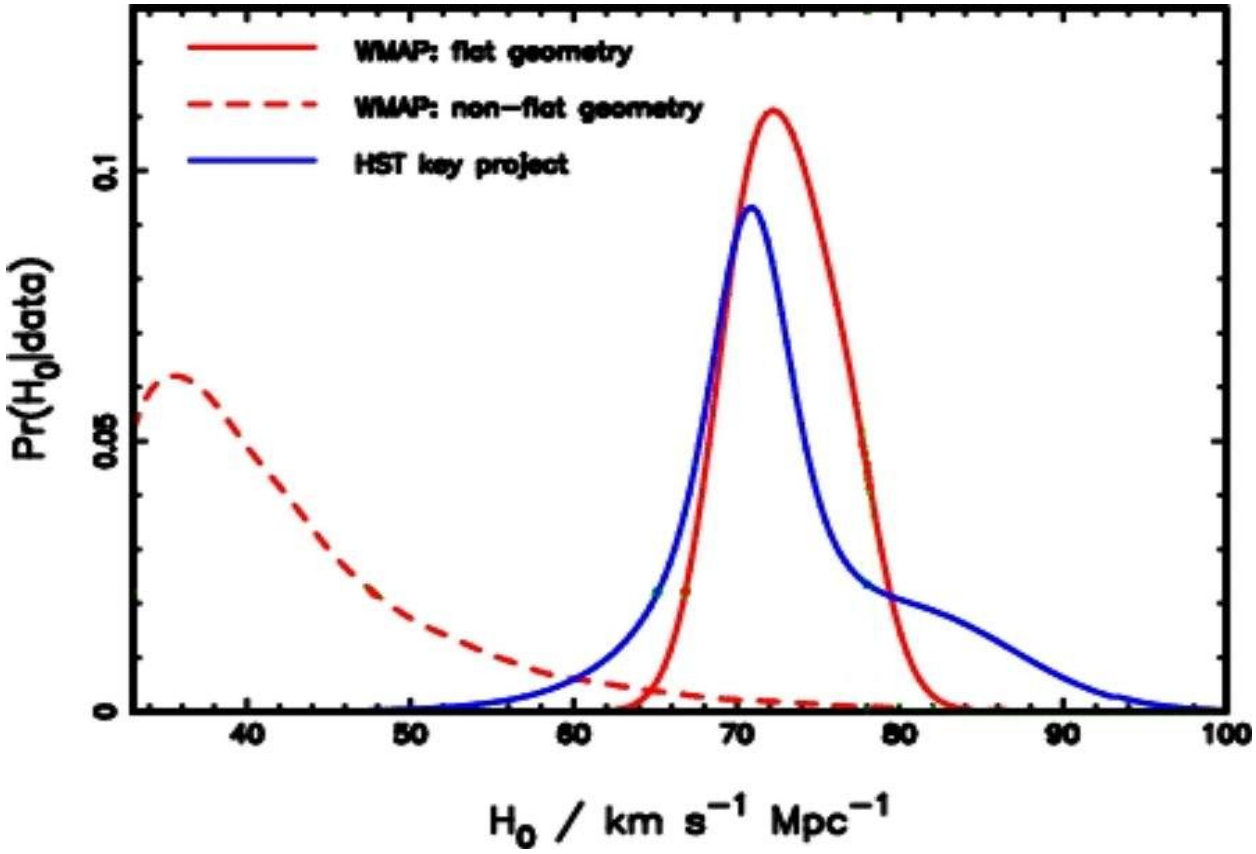
  The SDSS lensed quasar survey
  The HST Archive Galaxy-scale Gravitational Lens Search
  The Strong Lens Legacy Survey (CFHT-LS)

Science teams are undermanned –
watch out for opportunities!

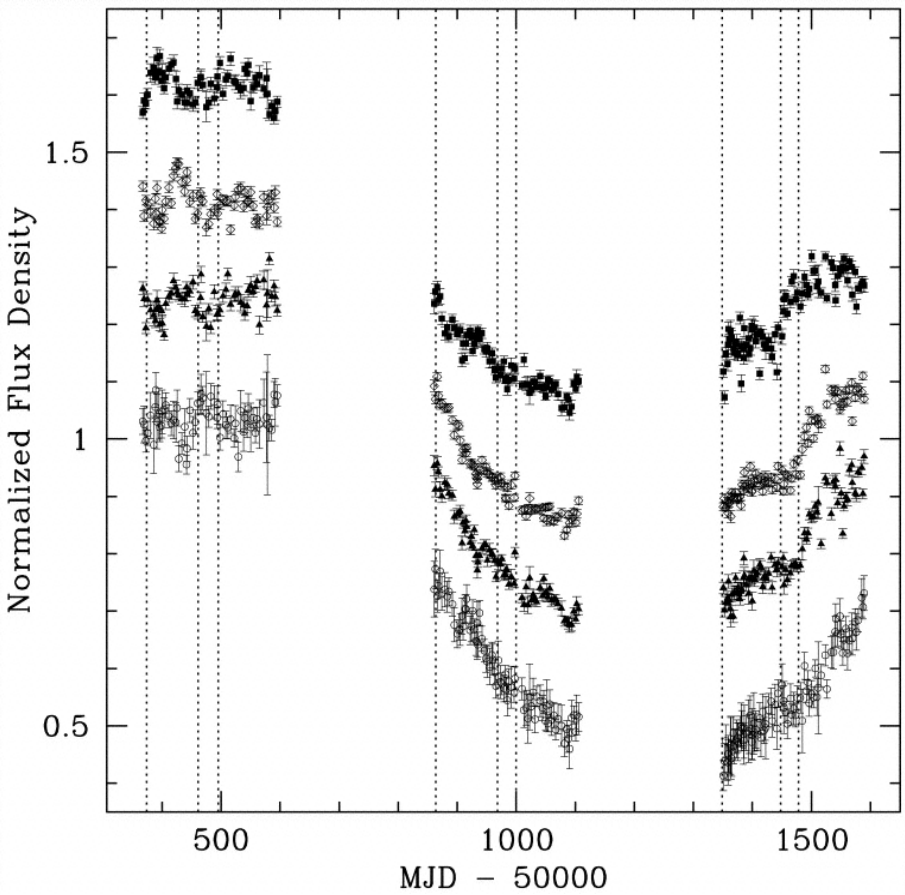
Hubble's constant from Strong Lensing

Gaining in support from the community...

- WMAP alone does not measure H0 unless a flat cosmology is enforced
- HST key project result is uncertain (systematics abound)
- Dataset combination inevitably contains degeneracies
- Independent probes are vital – to help break these degeneracies



Hubble's constant from one lens



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

B1608: (Suyu et al 2007, in prep)

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

5% precision on H_0 required:

- Photometry to 2% (VLA)
- 0.6% absolute flux calibration
- 3 observing seasons, each of 8 months
- 220 exposures over 3.5 years
- Some fortune with the variability

LSST numbers are similar

Hubble's constant from many lenses

New, forward-thinking approach (Oguri 2007):

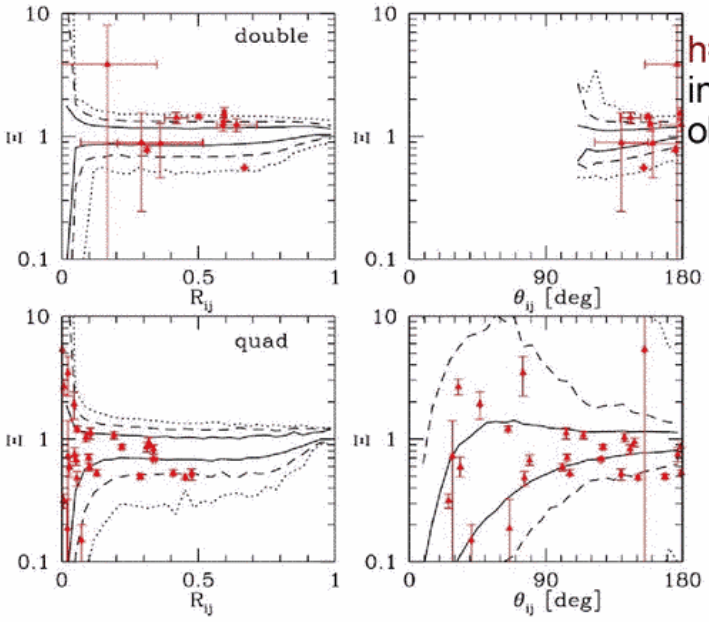
- Put all knowledge and beliefs about lens galaxy structure into a (prior) PDF, and use this to combine all available systems

A statistical approach

Strategy

1. Define a "reduced time delay" that can be a measure of how time delays differ from those in simple isothermal mass models Ξ
2. Characterize configuration of image pairs by using two dimensionless quantities R, θ
3. See reduced time delays for various lens potentials as a function of image configuration
4. Input a distribution of realistic lens potentials to derive a conditional PDF of time delays, p(delay|image config.)

p(Ξ|R) and p(Ξ|θ)



h=0.73 is assumed in computing Ξ for observed delays

Ξ_{obs} on average agree with the PDFs from sim

R and θ dependence also seen

p(Ξ|P) and p(Ξ|θ)

H_0 = 70 +/-6(stat) +/-8(sys) i.e. systematics-limited already

Large number statistics needed for "self-calibration:" can be investigated now

More information on environment?

Hubble's constant with LSST

Identify two possible sources for time-delay measurement – both affected by microlensing by stars in the lens galaxy:

- Quasars /AGN
  Variation is stochastic but persistent: the 10 years all count
  Photo-z of source highly uncertain
- Supernovae

Peak-fitting may give a more precise time delay – but variations in the microlensing due to changing source size is more of a worry. Photo-z tricky, but stacked image may show host galaxy

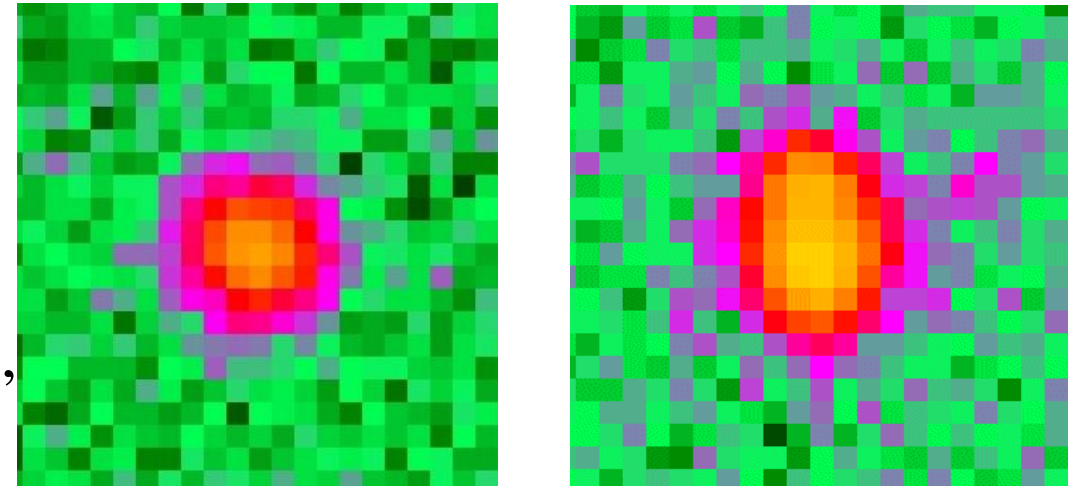
Both will be detected – and used!

Microlensing needs to be modeled too...
... as does the lens environment. Photo-zs? Weak lensing?

Finding lensed quasars: SDSS

Oguri et al (2006)

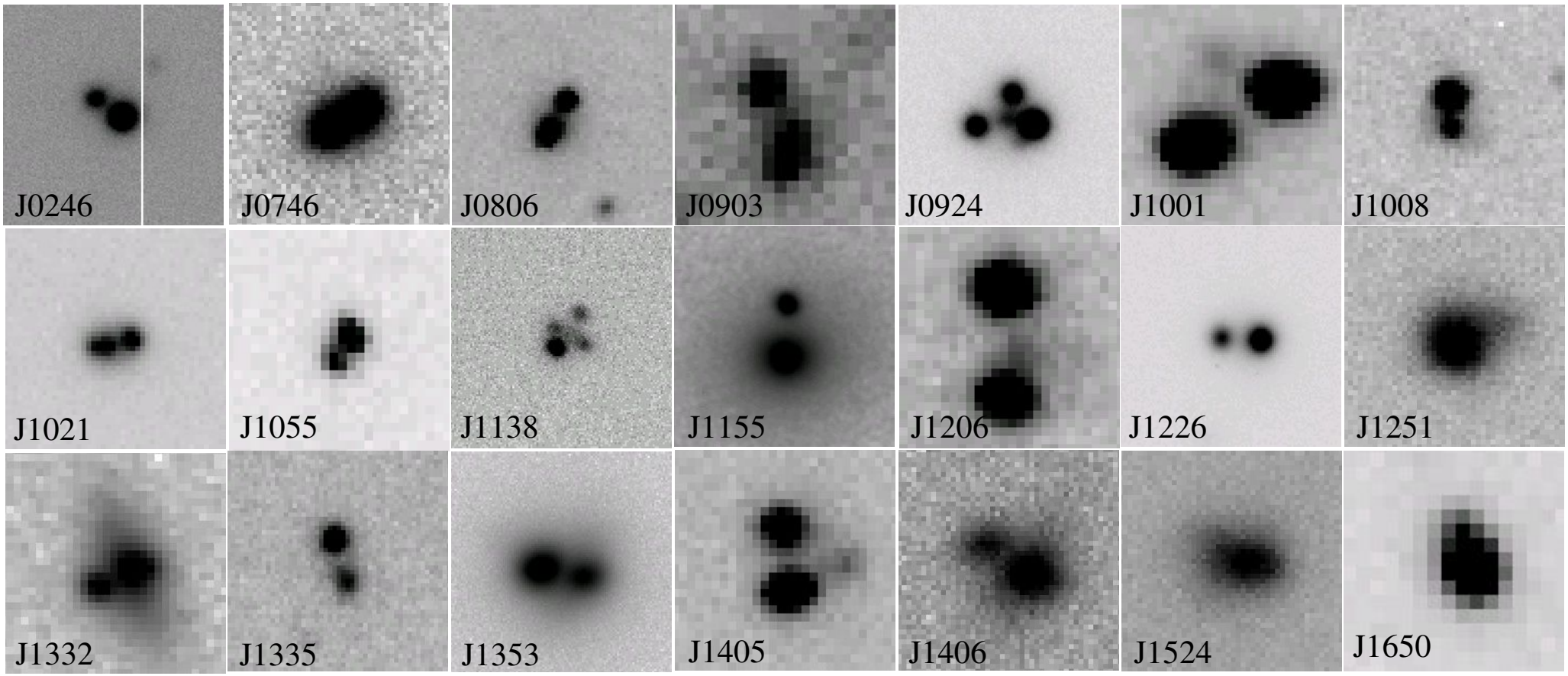
- From SDSS DR3, select
  22868 spectroscopic quasars,
  $0.6 < z < 2.2$
  $15.0 < i < 19.1$



normal *extended*

- 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, very few false positives

Finding lensed quasars: SDSS



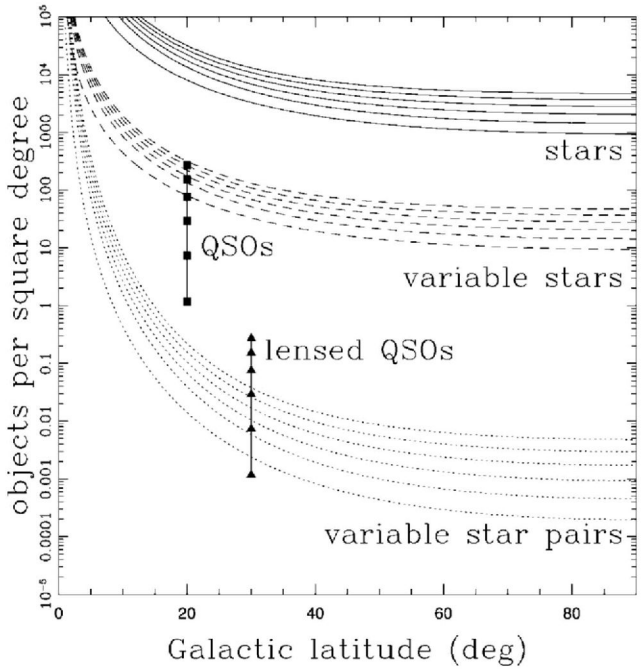
- Similar catalogue-level searching will be important in LSST era
- Spectroscopic follow-up problem is 100 times worse! Source plane redshifts are needed for Hubble constant measurement...

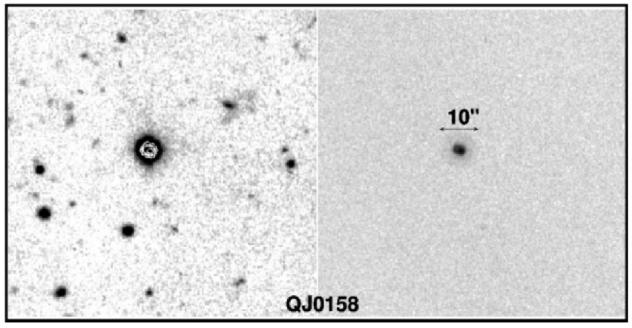
Are photo-z's good enough?

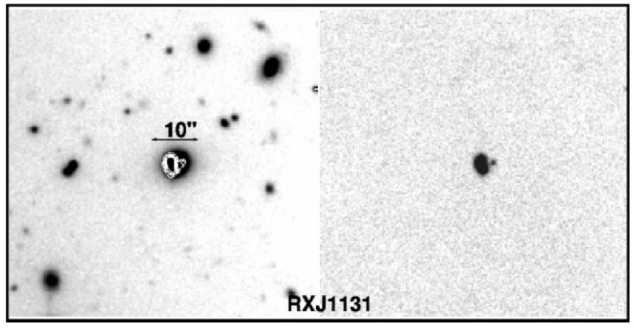
Finding lensed quasars: LSST

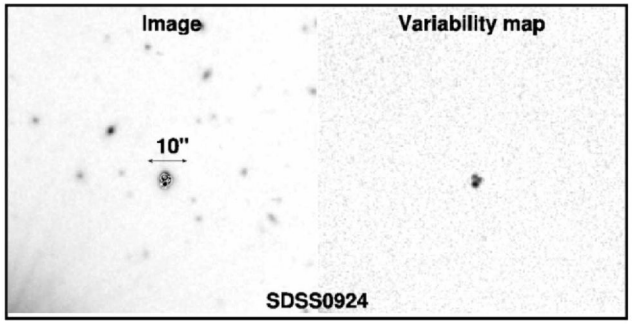
Select by variability (Pindor 2005, Kochanek et al 2006)

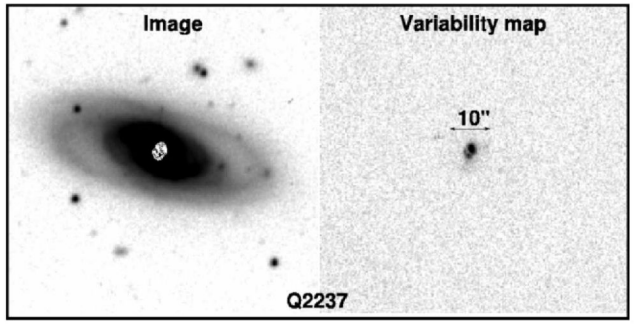
- Look for extended objects in difference images
- Color may help in classification
- Variable star pairs are biggest background
- Quads are almost impossible to mimic
- Needs simulating for LSST!



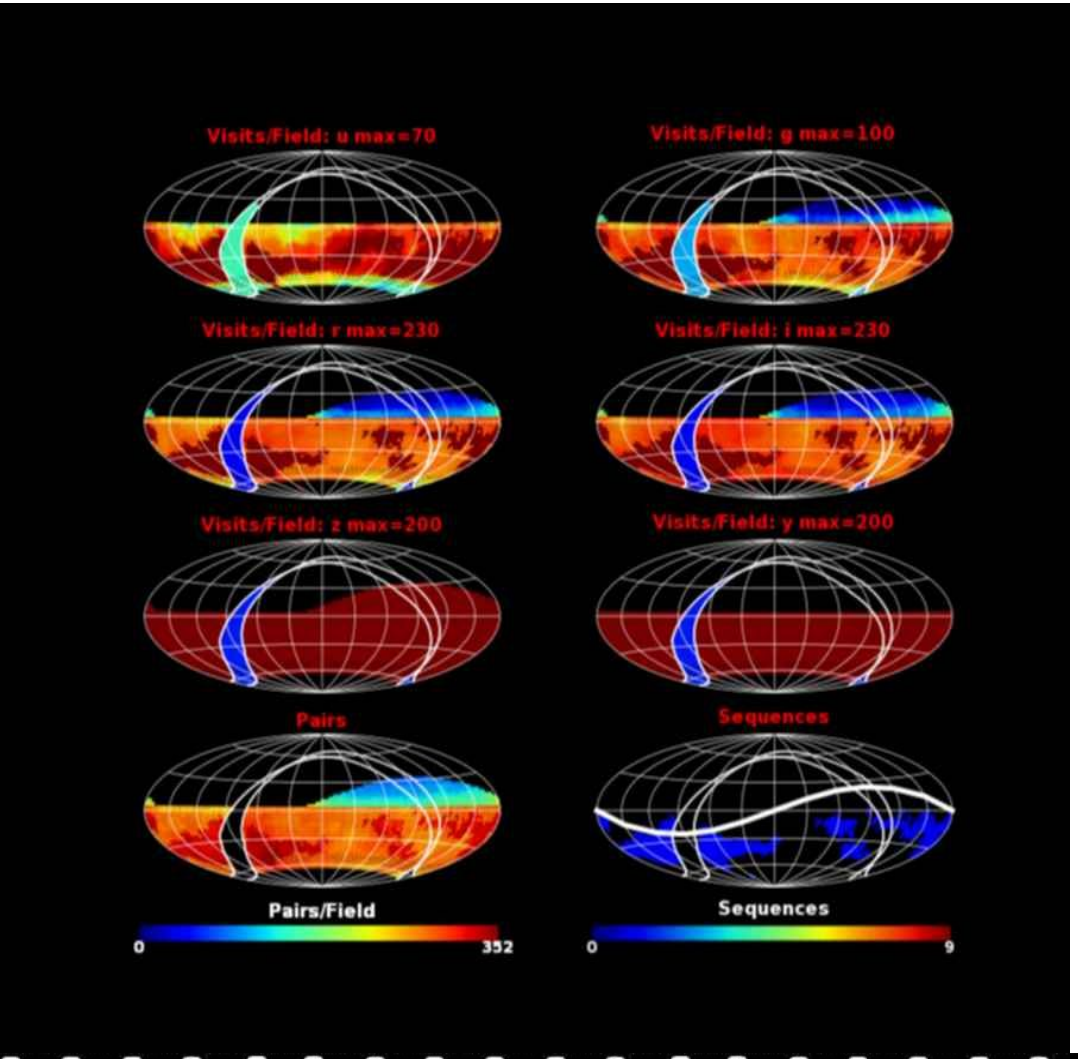






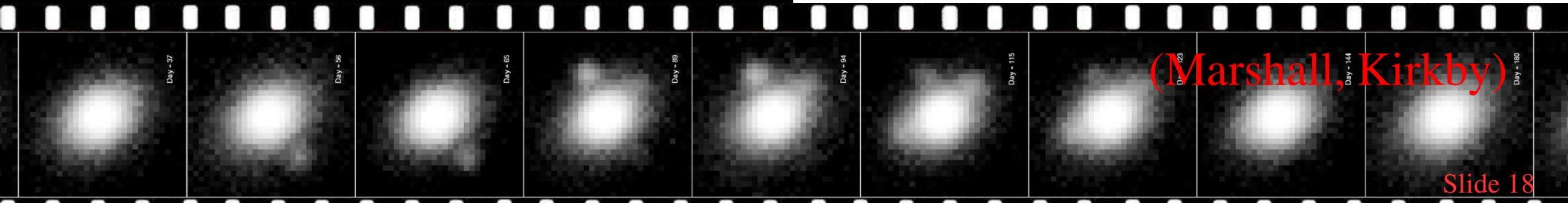


Time delays from Supernovae



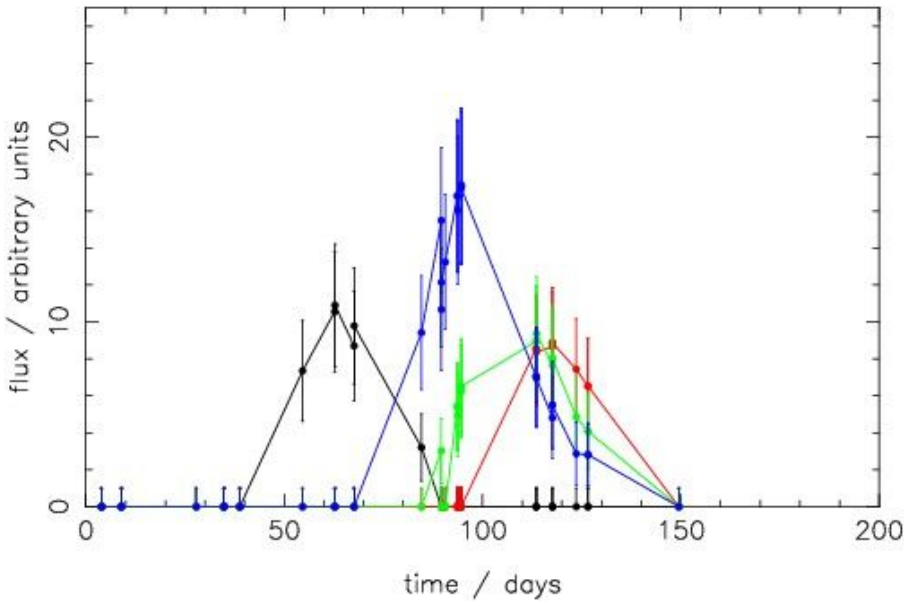
Derive time delay precision from image simulations:

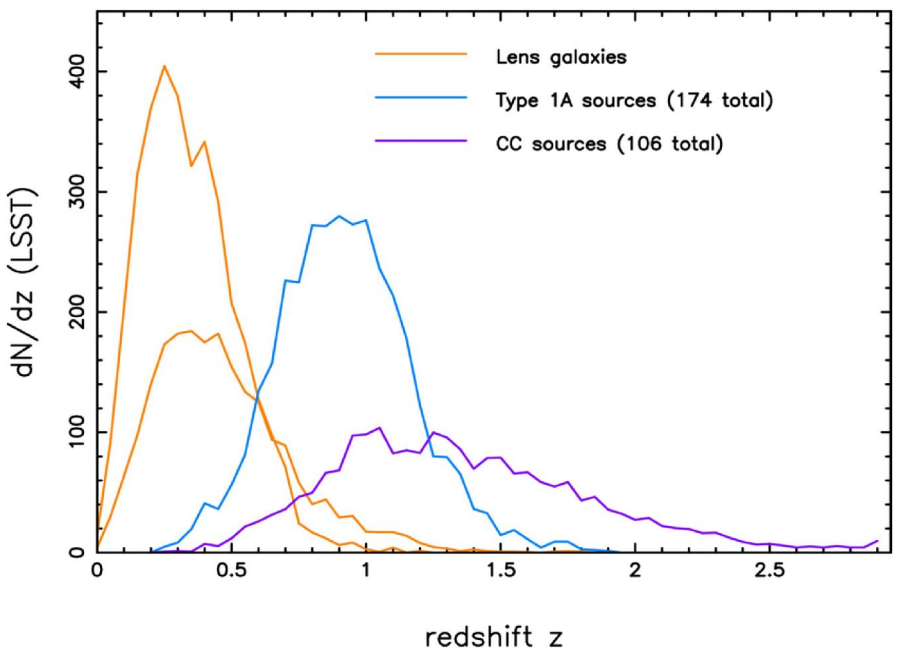
- Simulate lens, place in each of 2000 LSST fields
- Generate time sampling from LSST cadence simulator
- Simulate images with appropriate seeing, sky etc for each 30 second visit in each of 5 filters (grizY)
- Detect SN, measure fluxes, extract time delay from light curve



(Marshall, Kirkby)

Time delays from Supernovae





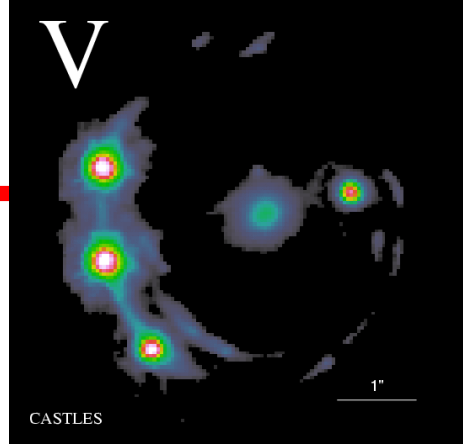
10% precision on time delays requires:

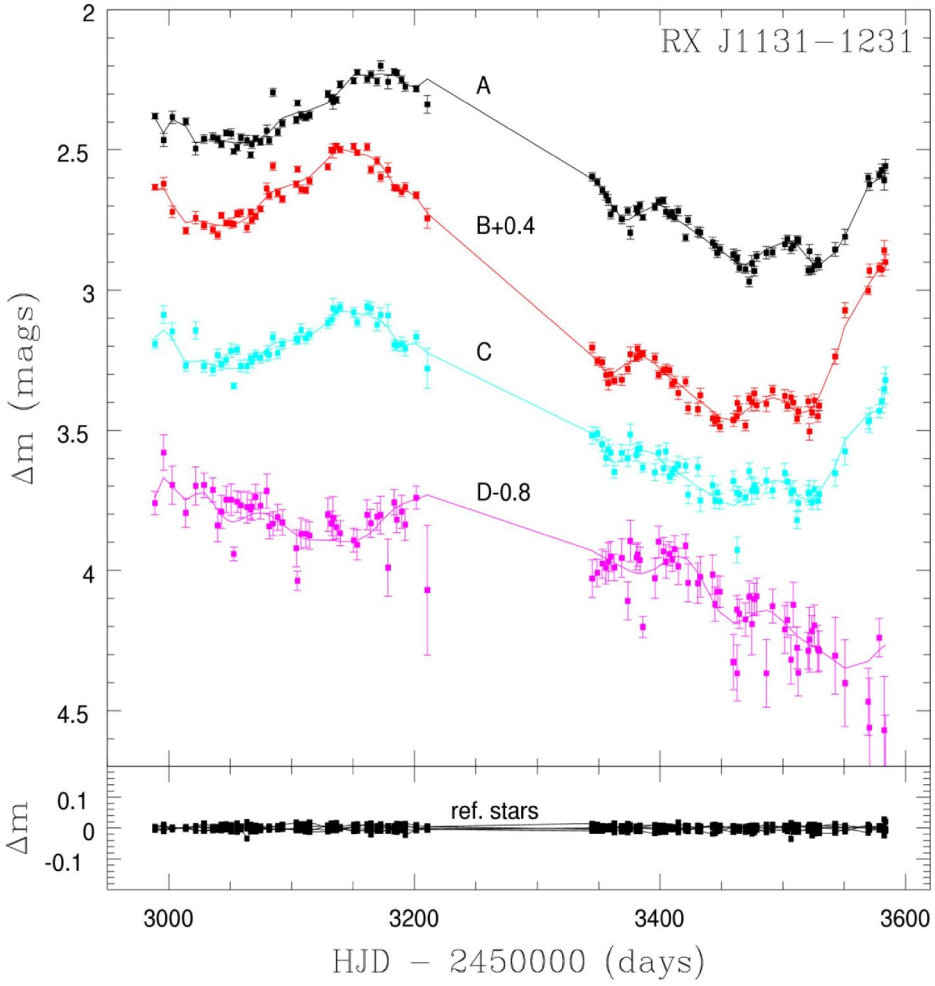
- peak observed magnitude of 23
- 50 visits over all 4 images
- regular sampling at 10-15 day cadence

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

- SN rates from Goobar et al: few hundred supernovae per sq degree per year, with redshift and observed magnitude distributions
- Expect a few hundred lensed supernovae (*with measurable time delays*)
- SN rates are uncertain but cadence factor might improve (by factor of 6 or so)
- Microlensing may limit time delay error to a few days (Keeton & Dobler 2006)...

Present-day optical monitoring





RXJ1131-12

(lensed quasar)

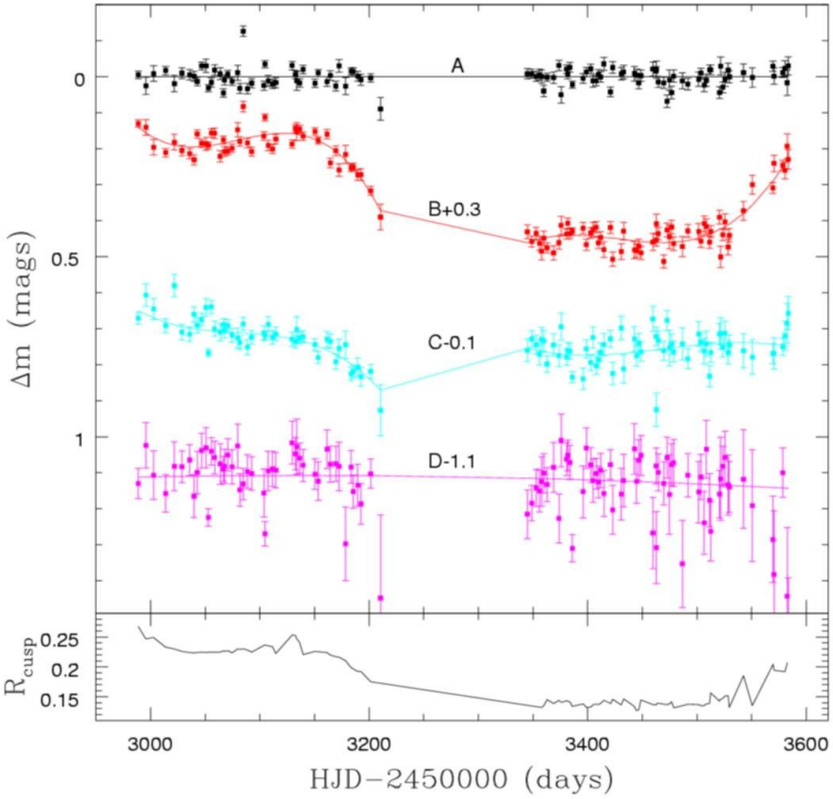
(Morgan, Falco et al 2006):
Time delay error ~ 2 days

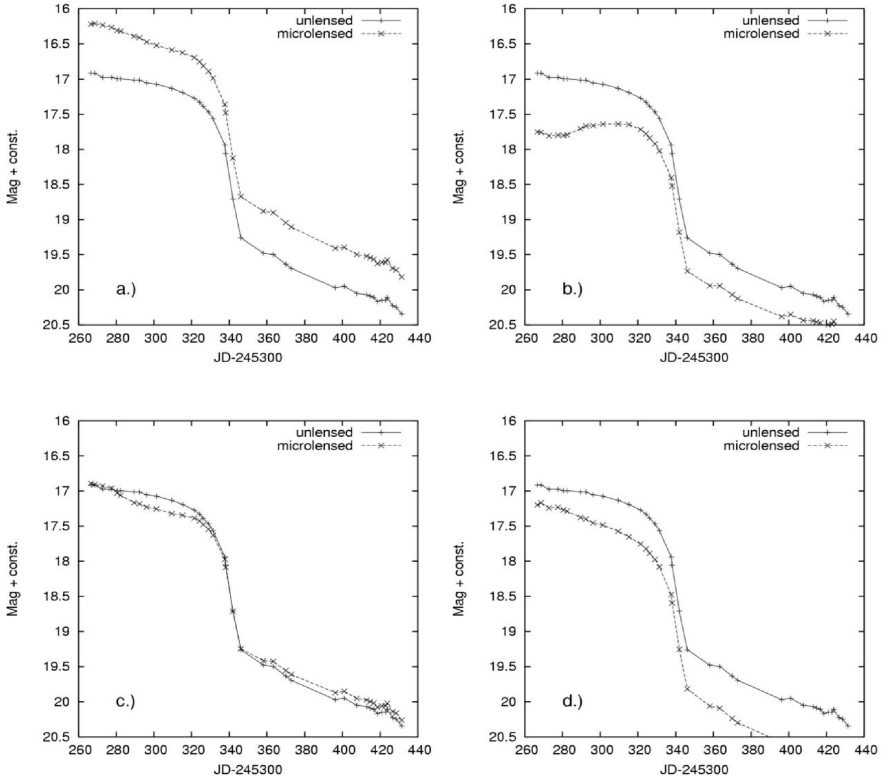
- 1-3" image separations,
  10,12,90 day time delays
- 4 telescopes, 1.3 – 3.5m class
- Photometry to 0.05mag
- 2 observing seasons, each of 7 months
- cadence ~ 5 days
- 101 epochs in total
- 0.7 mag variability

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

LSST numbers are similar
(except for the telescope bit)

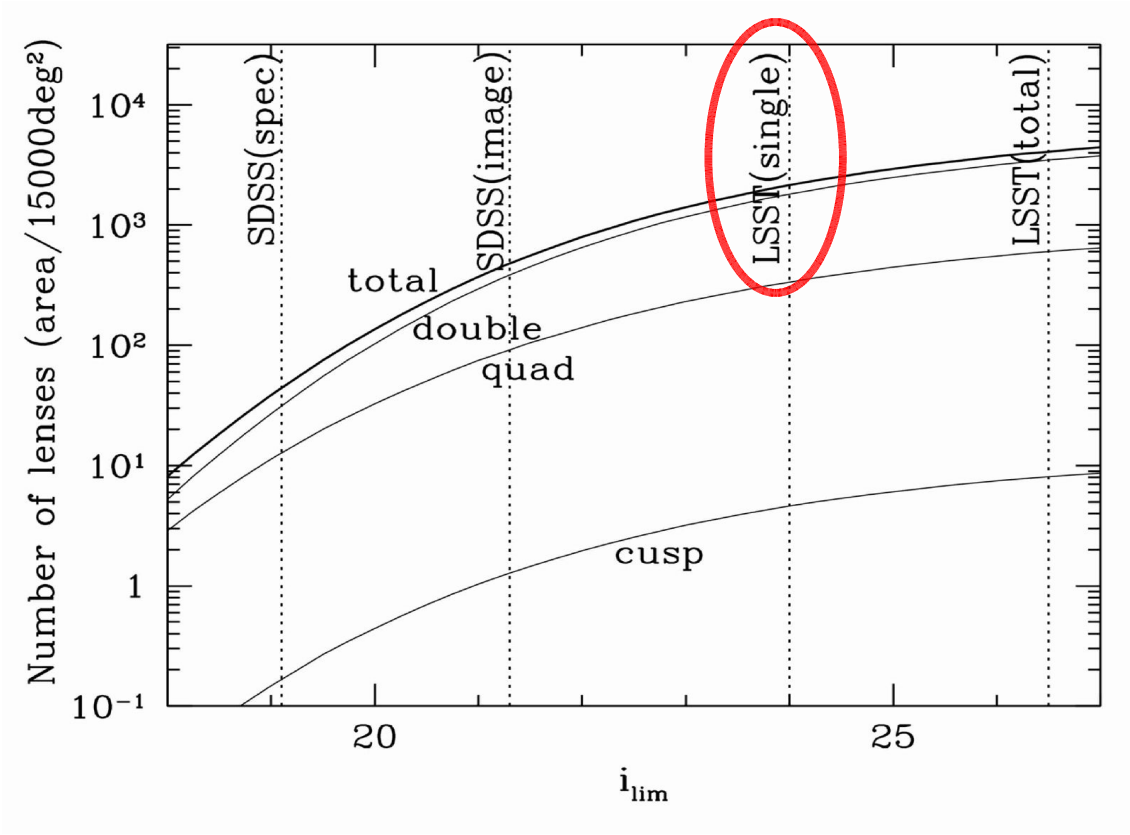
Microlensing





- Current lens monitoring studies show that microlensing can be modeled simultaneously – the variability is different for each image
- 90% supernovae are expected to be affected (Dobler & Keeton 2006)
- Some hope that this can be projected out too... but time delays to better than a few days accuracy will be difficult. Need large numbers for precision!

Time delays from quasars



NB. The LSST selection function favors doubles, which give a less model-dependent H0...

- Expect around 3000 lensed quasars with light curves: similar cadence factor to SN implies **500** with time delay precision < 10%
- This is difficult to quantify – but we are working on it...
- Numbers of useful lensed SN and lensed quasars should be comparable,
  ~1000 total is a *very conservative* estimate
- Available *precision* on H_0 would be ~10%/sqrt(1000) ~ **0.3%**

Conclusions

Gave *one example* of an LSST strong lensing project, to show that:

- Working with e.g. SDSS will give us the experience to deal with the LSST data as it arrives;
- The LSST project simulations are helping us plan the experiment, and get ready for the massive influx of data
- Very high precision will be available on H_0, but there is much to be done on understanding the systematics (some of which are astrophysical in nature...)
- "Rare" events (eg lensed SNe, as first detected with Pan-STARRS?!) get redefined with LSST!

Interesting and open questions:

Will microlensing prevent us breaking the model degeneracy using the standard candle nature of SN Ia in the modeling? Where are the source redshifts going to come from? Can we reliably select lenses by their variability? Which H_0 are we measuring anyway? And what about all the non-varying lenses out there?

SL2S: an LSST precursor survey

Cabanac et al 2006, astro-ph/0610362

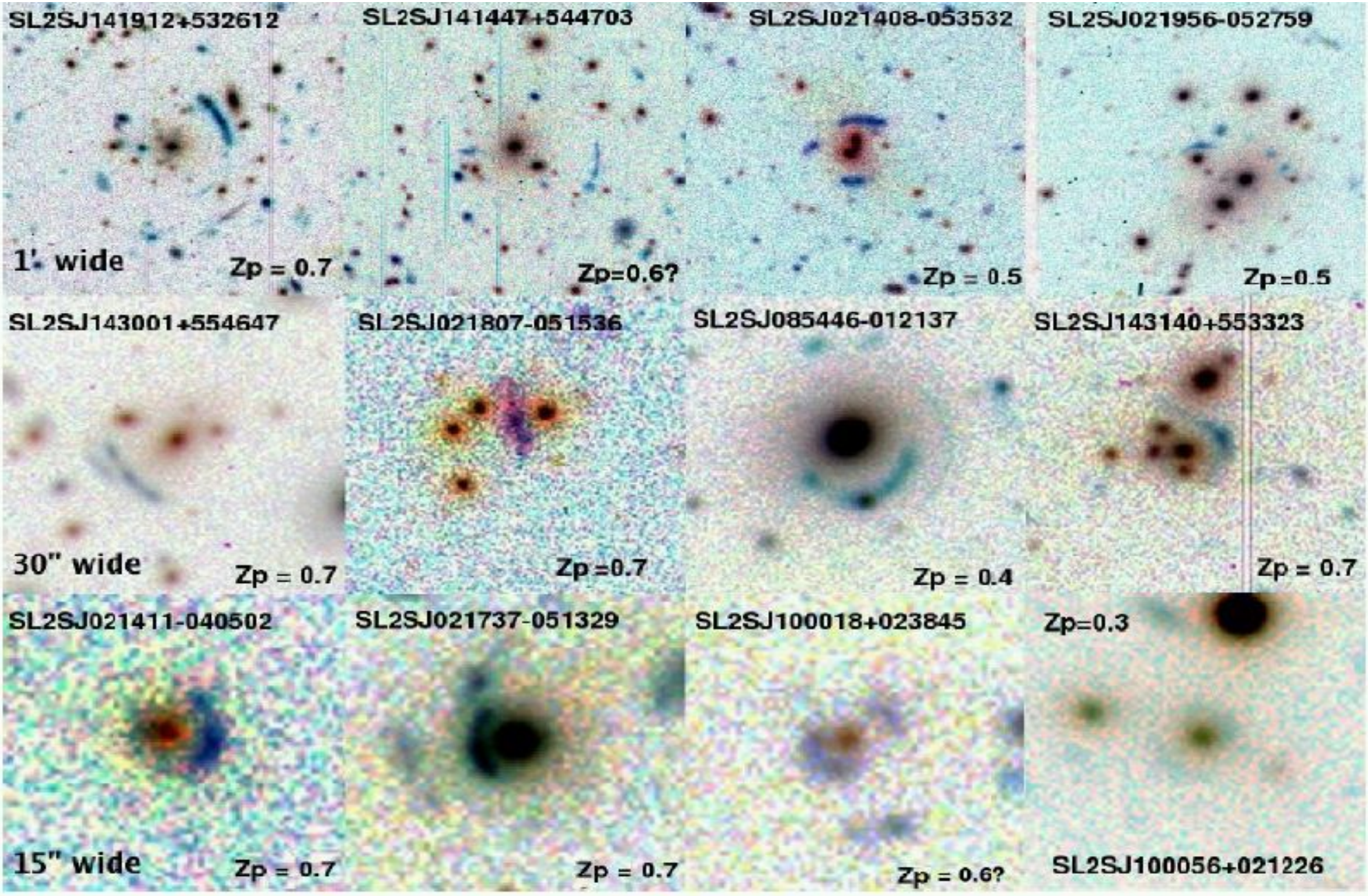
- CFHTLS to date:
  Wide: 28 sq degrees observed in (u')g'r'i'z' to i'<24.5
  Deep: 4 sq degrees to i'<25.8-26.3

- 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



SL2S: an LSST precursor survey

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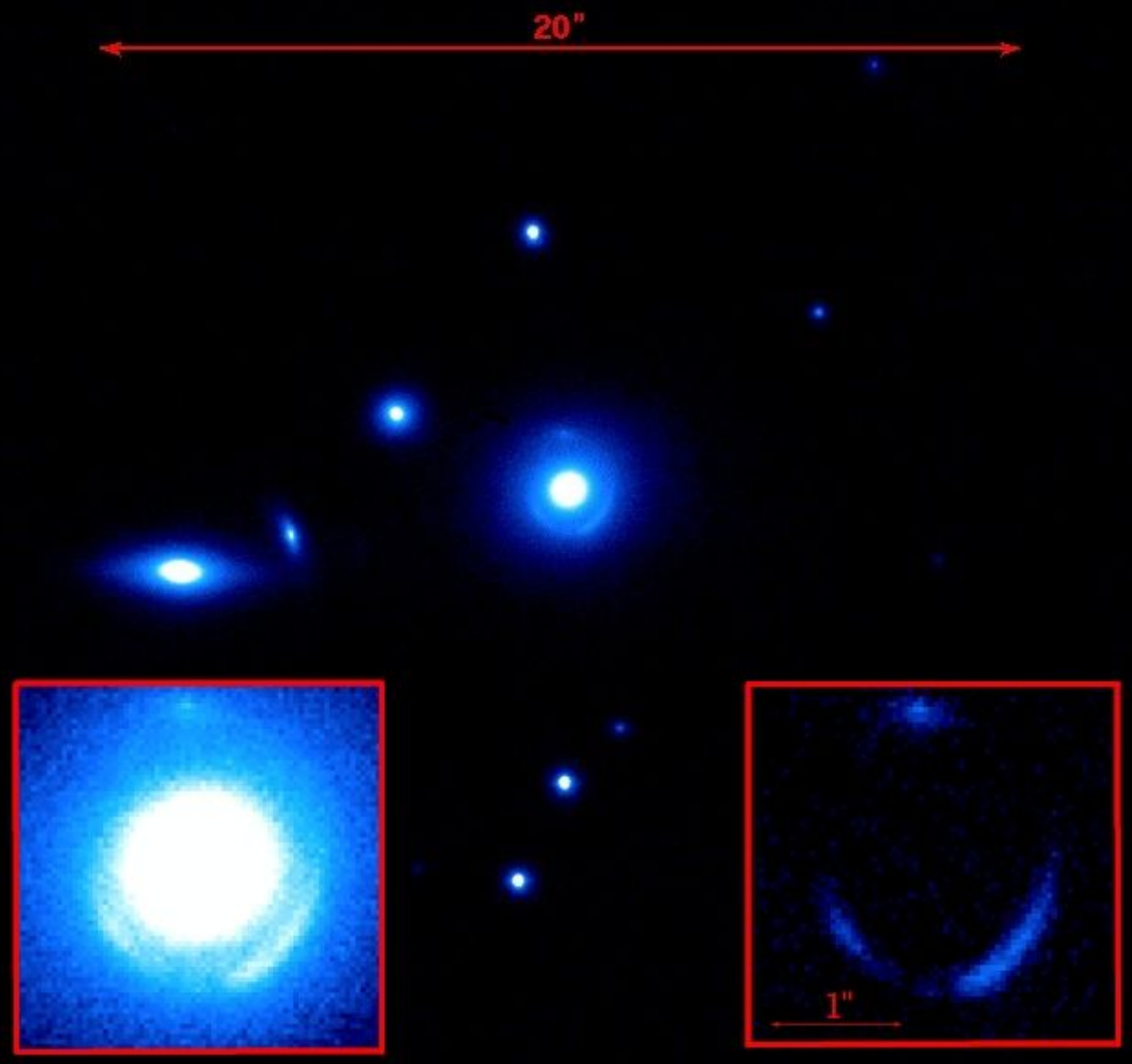
- CFHTLS to date:
  Wide: 28 sq degrees observed in (u')g'r'i'z' to i'<24.5
  Deep: 4 sq degrees to i'<25.8-26.3
  Best 20% of LSST 10 year survey is same depth as CFHT-LS Wide
- Filter images for arcs (Alard 2006), inspect elliptical galaxies for colour gradients and aligned blue residuals (Gavazzi et al 2006)

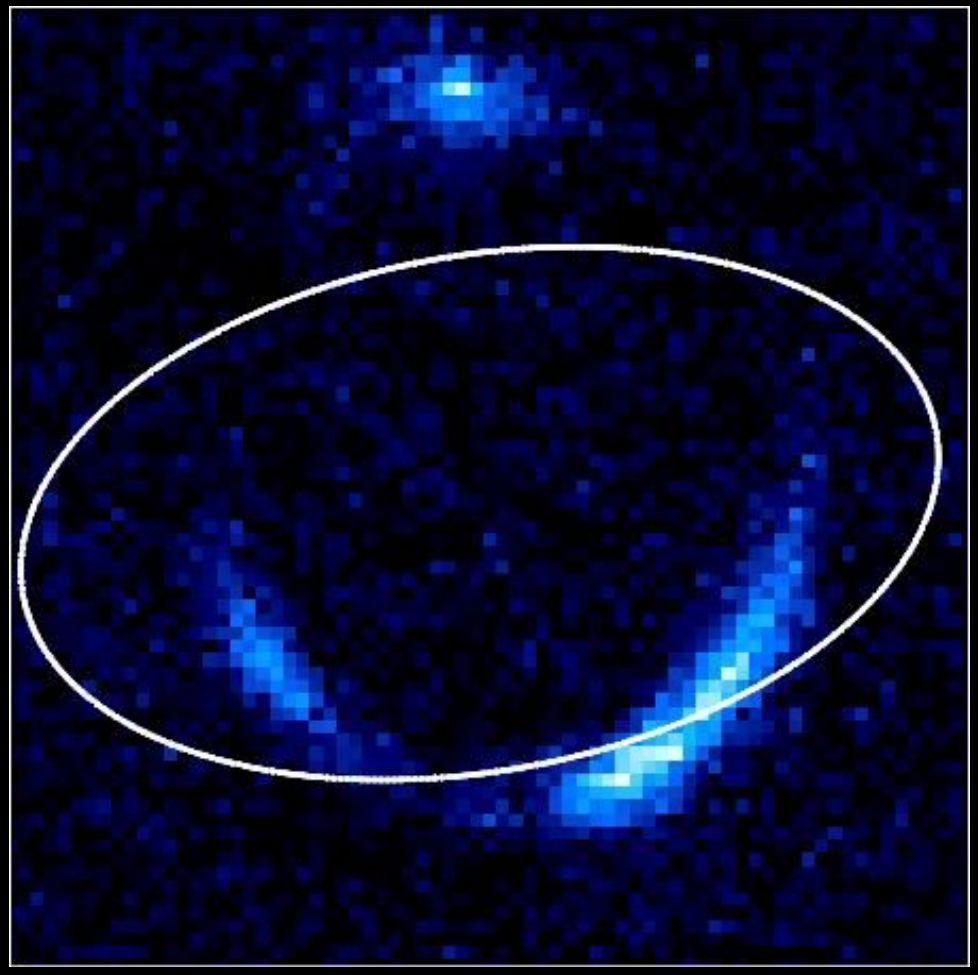
- 4 arcs (>7”), 22 rings (<3”), and 13 intermediate (3-7”) lenses – probing group-scale mass distributions
  LSST sample will be larger by a factor of 20000 / 32 = 600
- Following up with spectroscopy, JWST, LGS-AO...
  High resolution imaging, and spectroscopic, follow-up will still be important in the LSST era – for some of the science at least. This could be a bottleneck...

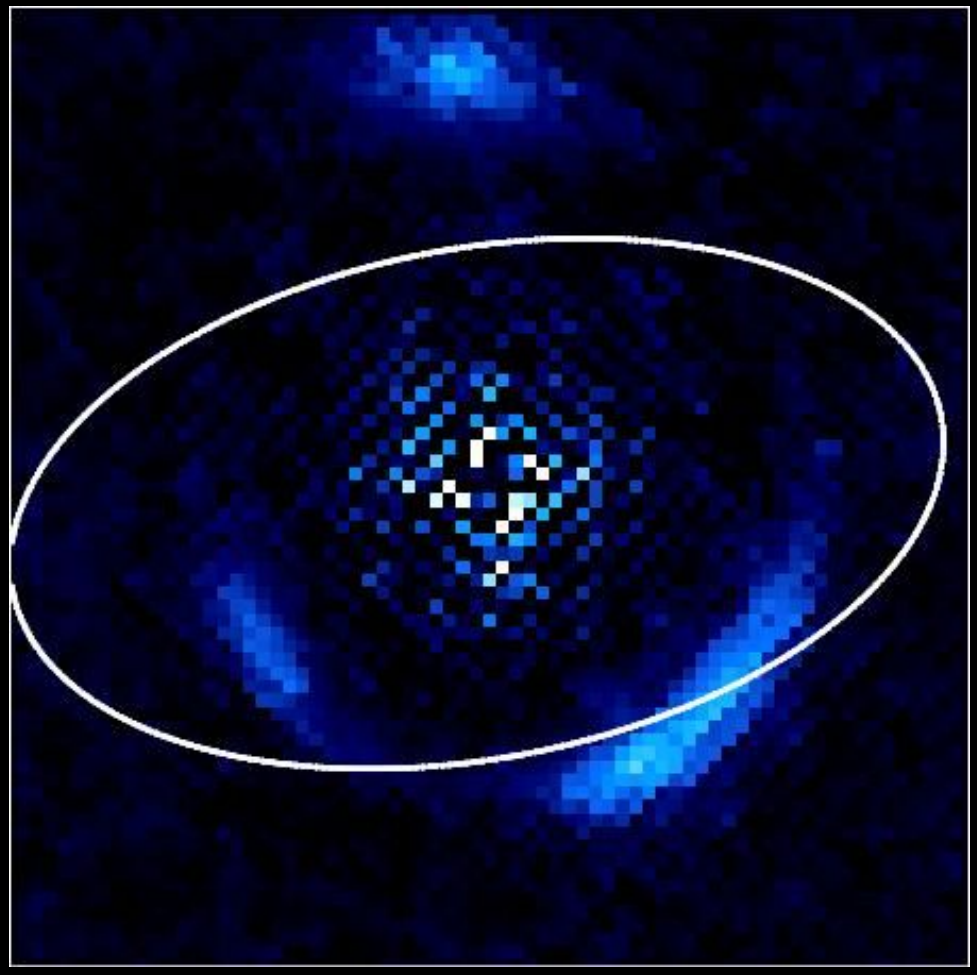
Keck NIRC2+LGSAO Kp-band image



- 60 minute exposure
- 40% of systems have suitable stars for tip-tilt correction
- Compare 60 mins Keck with 1 orbit HST nicmos, reconstruct source etc
- Marshall, Gavazzi et al 2007 ApJ submitted

Keck NIRC2+LGSAO vs. HST NICMOS





Lens image after subtraction of a smooth model for the lens galaxy light

HAGGLeS

Searching the entire HST imaging archive for typical lenses

- Exposure time > 2000s with ACS/WFC gets us 7 sq degrees
- 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

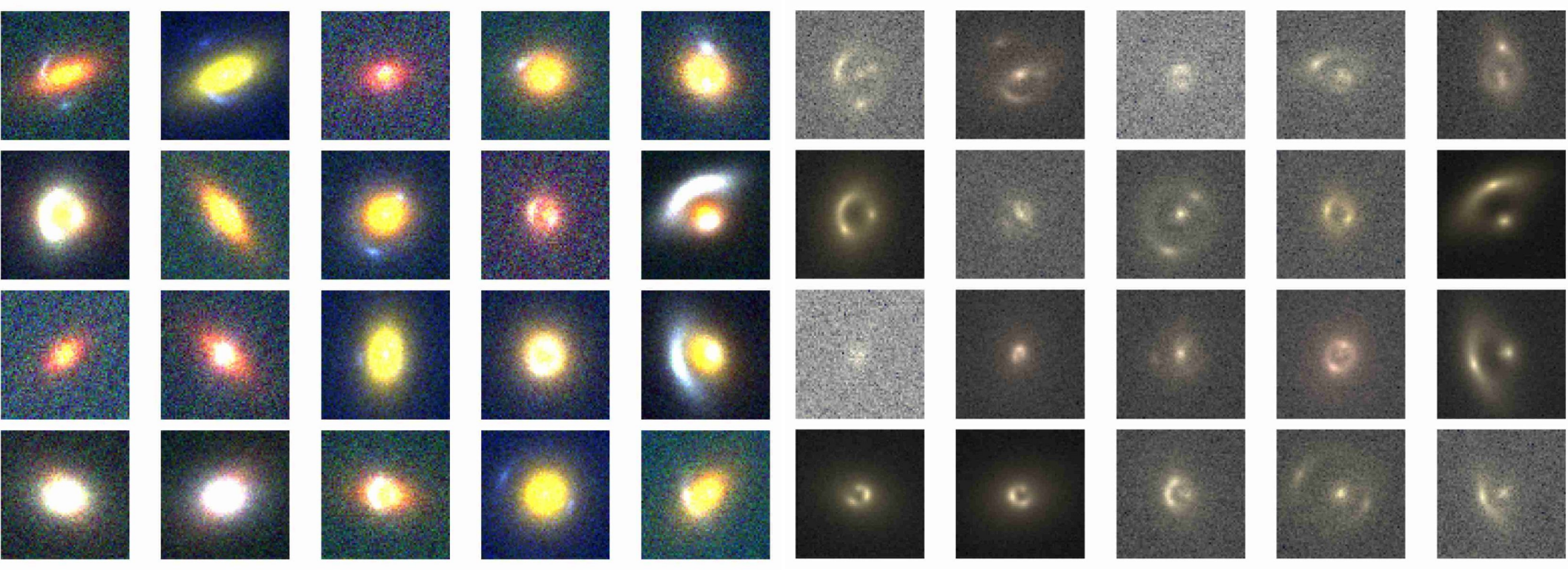
- **Prediction is c. 10 strong gravitational lenses per sq degree**

This is the only precursor dataset for SNAP –
see tomorrow's talk by Phil Marshall

The SNAP strong lens sample

Wide survey (1000 sq deg) should contain ~ ***20000 lenses***

- The vast majority are *red elliptical galaxies, lensing faint blue galaxies*
- The 9 filter photometry should permit photo-zs to 0.05 (for lenses) / 0.1 (for sources), and for a clean identification, component separation and classification of the lens:



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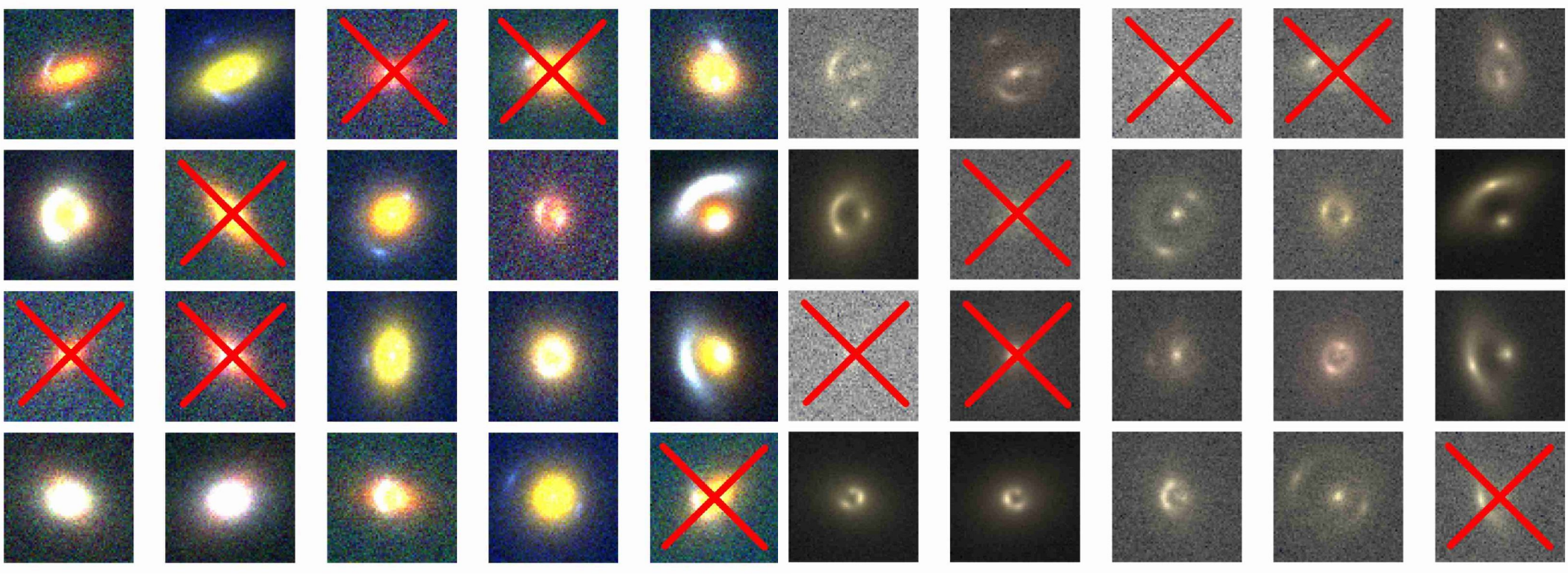
- The 9 filter photometry should permit photo-zs to 0.05 (for lenses) / 0.1 (for sources), and for a clean identification, component separation and classification of the lens:

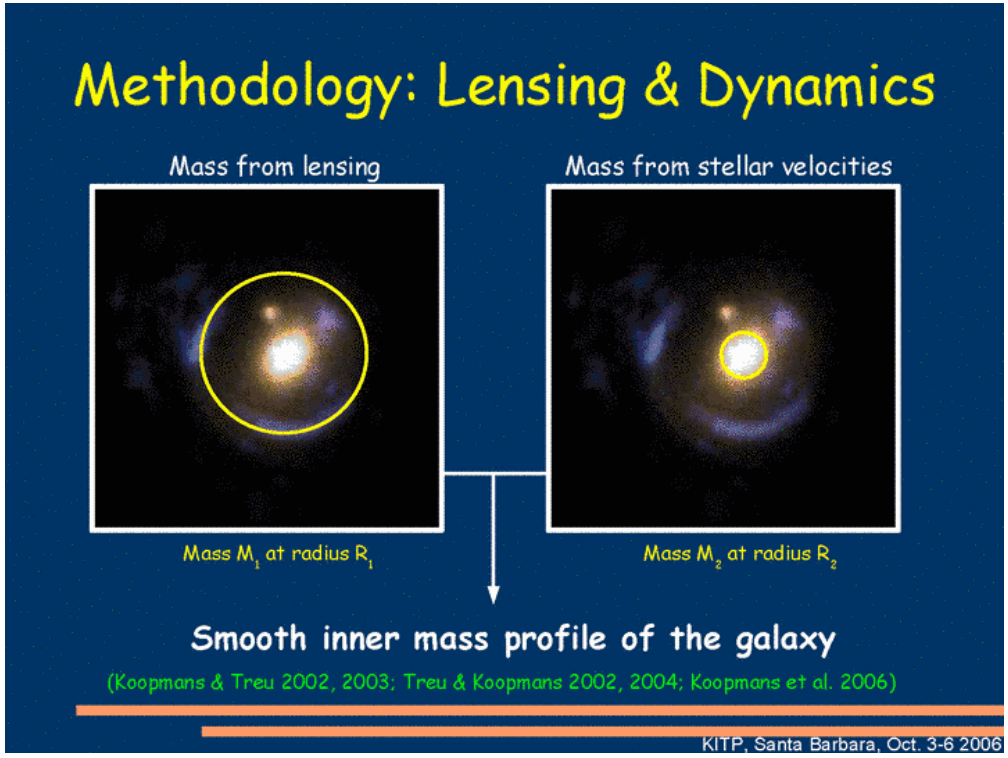


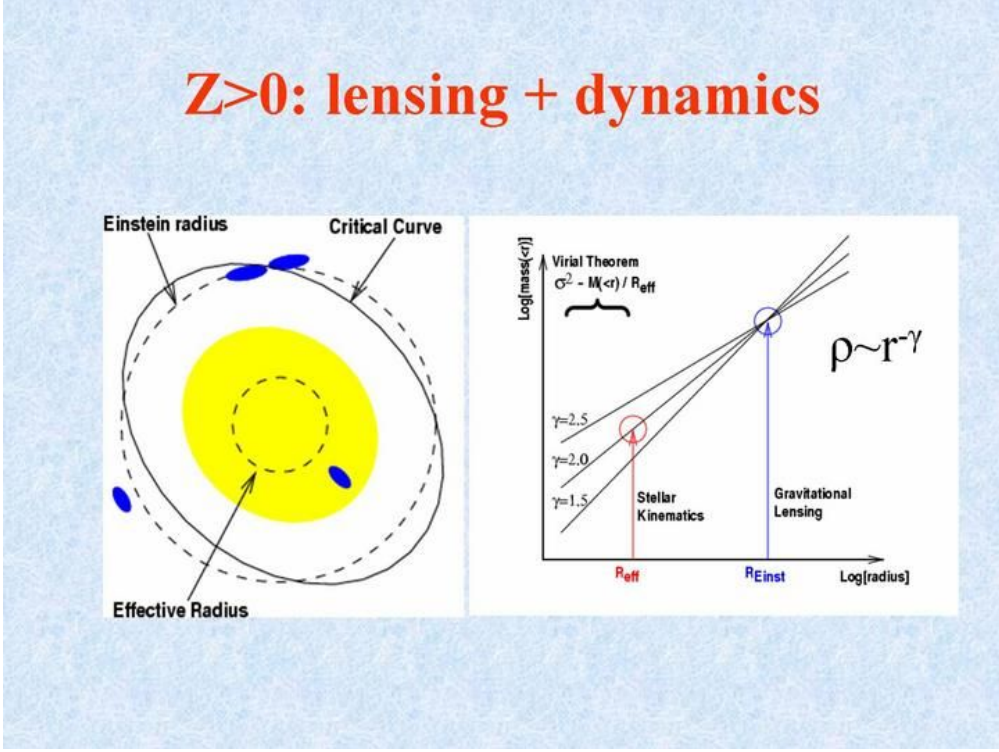
Slightly pessimistic cuts leave 12000 well-measured systems...

Elliptical lens galaxies

The SLACS and LSD (Koopmans & Treu 2002, 2004) lens galaxies appear to be ***standard masses***

- velocity dispersion ~ lensing SIS parameter
- total density profile power law slope ~ -2
- only weak trends with z, mass





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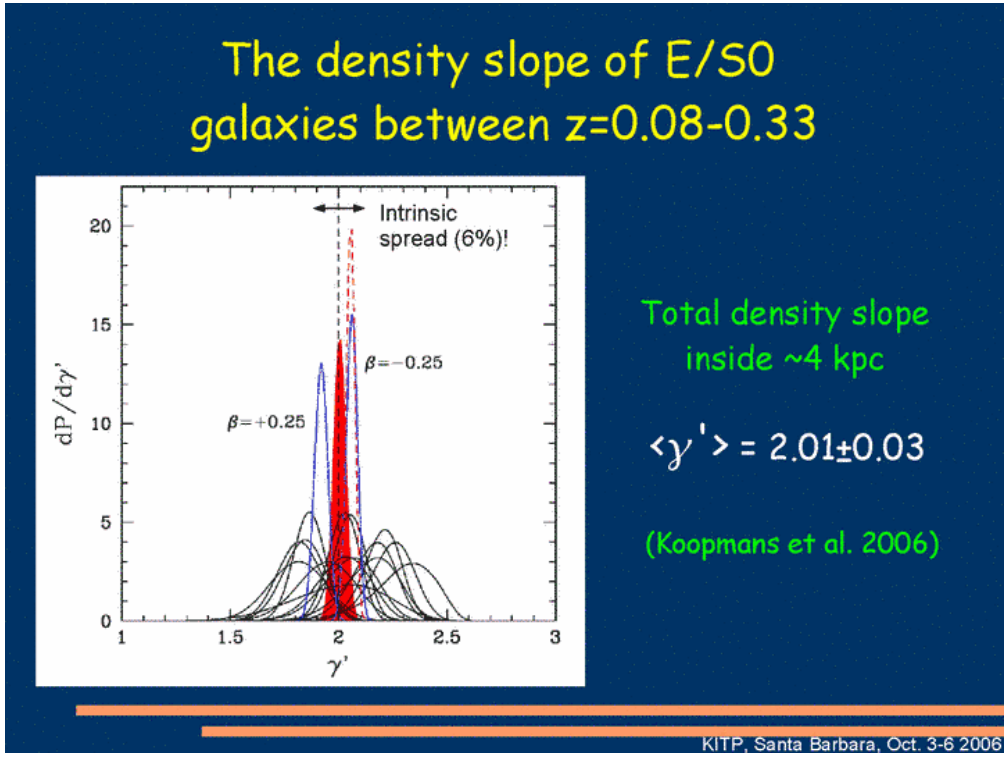
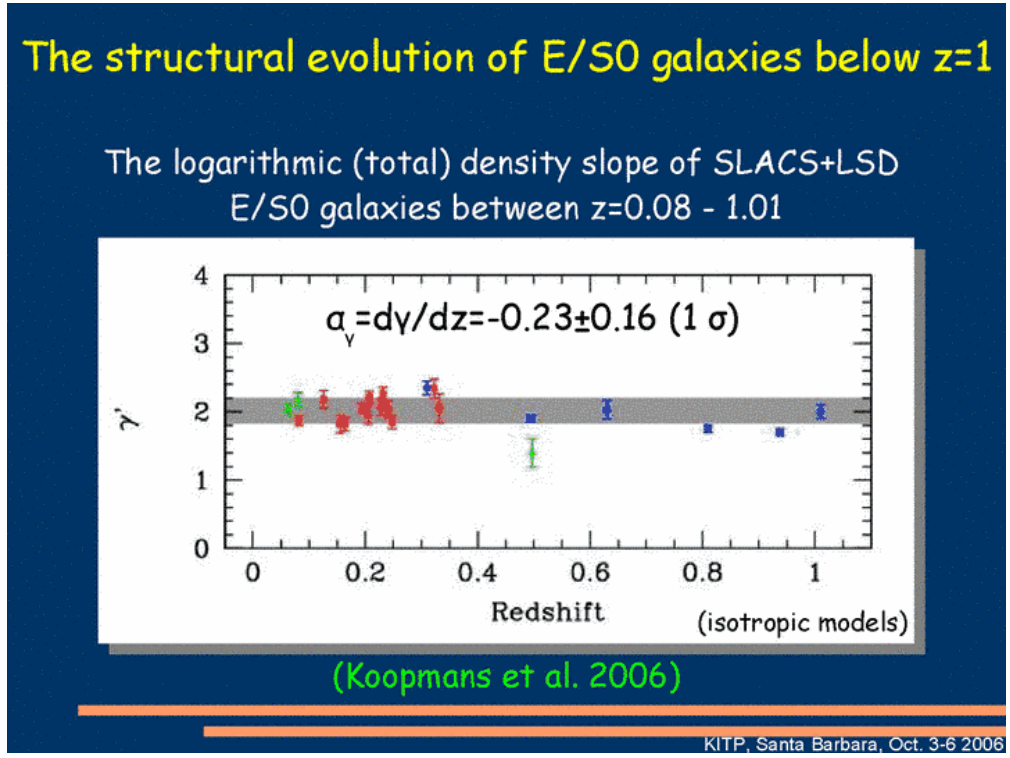


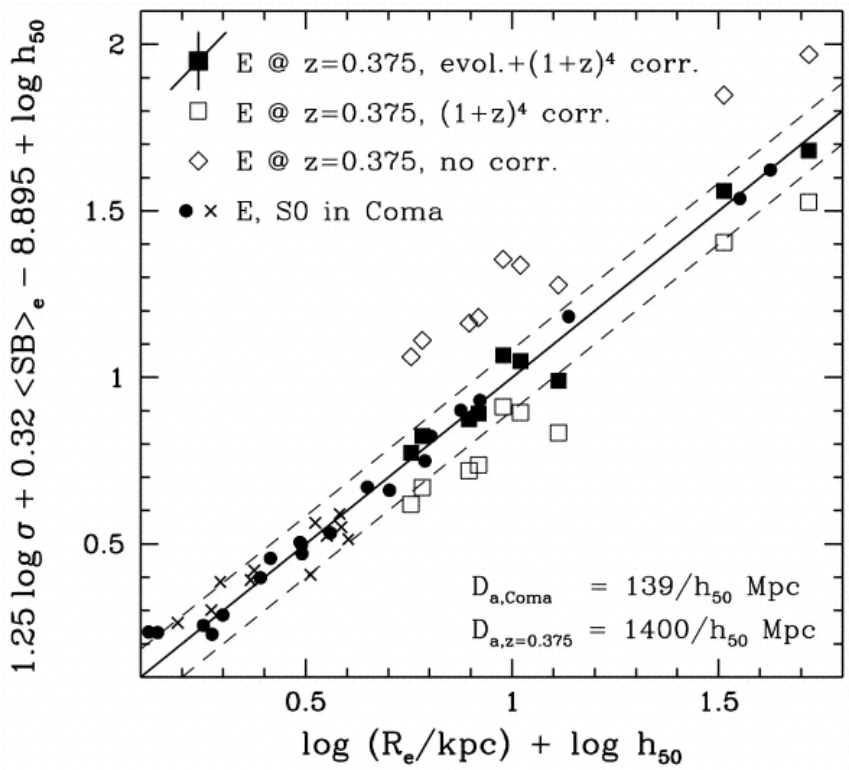


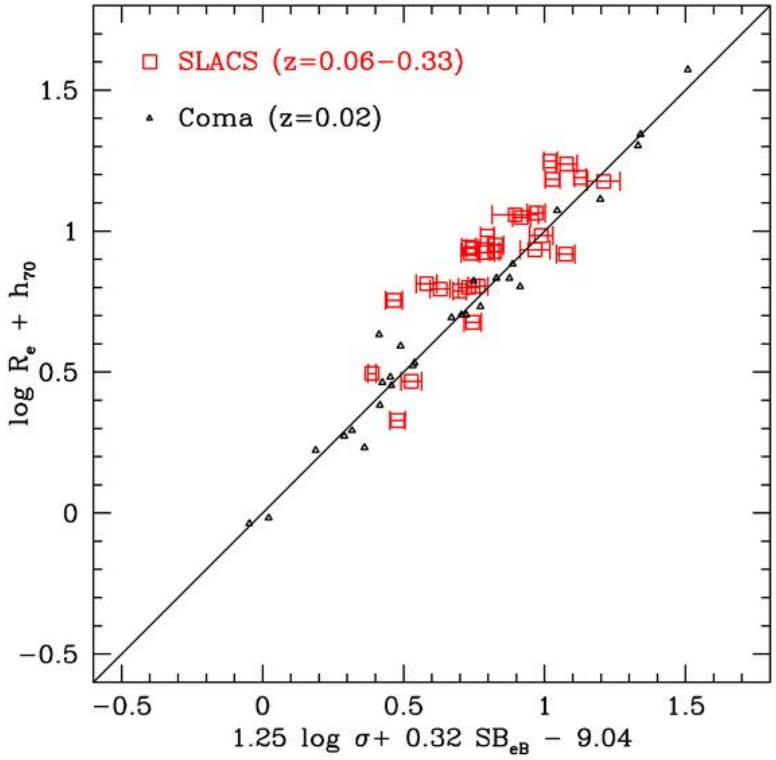
The Fundamental Plane

Standard mass ellipticals have been known about for some time:

$$\log(\sigma) = [\log(R_e) - \beta\, Sb_e + \gamma_{FP}] / \alpha$$

- In Coma, $\{\alpha,\beta,\gamma_{FP}\} = \{1.25, 0.32, 9.04\}$ (Bender et al 1998)
- SLACS lenses lie on same fundamental plane (Treu et al 2005)...



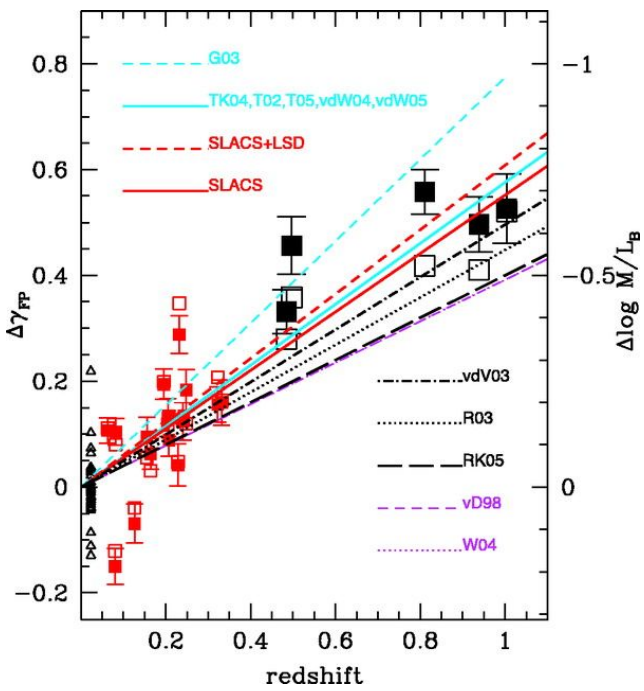


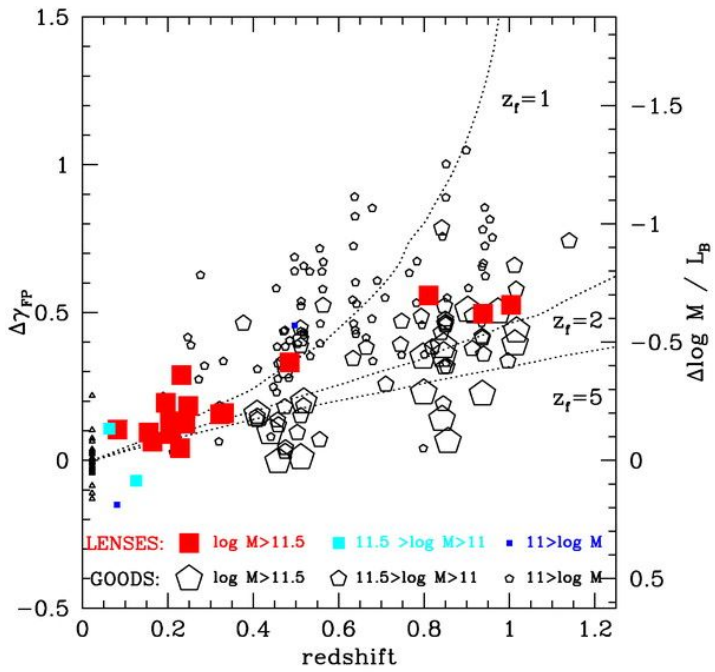
The Evolving Fundamental Plane

Ellipticals seem to be evolving passively:

$\log(\sigma) = [\log(R_e) - \beta\, SB_e + \gamma_{FP}] / \alpha$

- In Coma, $\{\alpha,\beta,\gamma_{FP}\} = \{1.25, 0.32, 9.04\}$ (Bender et al 1998)
- SLACS (and GOODS) ellipticals lie on same fundamental plane provided evolution is included: $SB_e = SB_e(z=0) - 1.8z$





Distance ratio cosmography

The geometry of elliptical galaxy strong lenses can constrain cosmological parameters, provided the lens mass distribution is understood:

- SLACS tells us that SIS is a good model
- FP studies show that dynamical masses can be obtained from photometry
- The assumptions linking the models seem robust

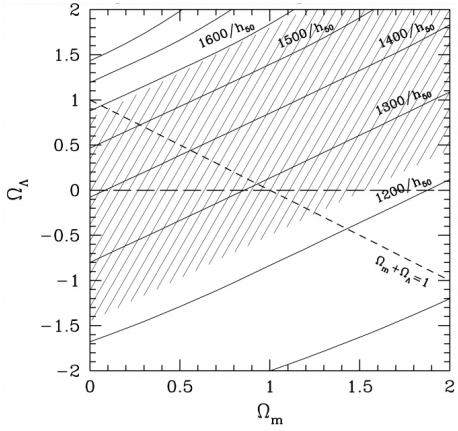
Image separations depend on mass and distances:

$$\Delta\theta = 8\pi\,(\sigma_{SIS}/c)^2\, D_{ds} / D_s$$

Velocity dispersion from FP has additional distance-dependence:

$$\sigma_{FP} \sim D_d^{(1/\alpha)}$$

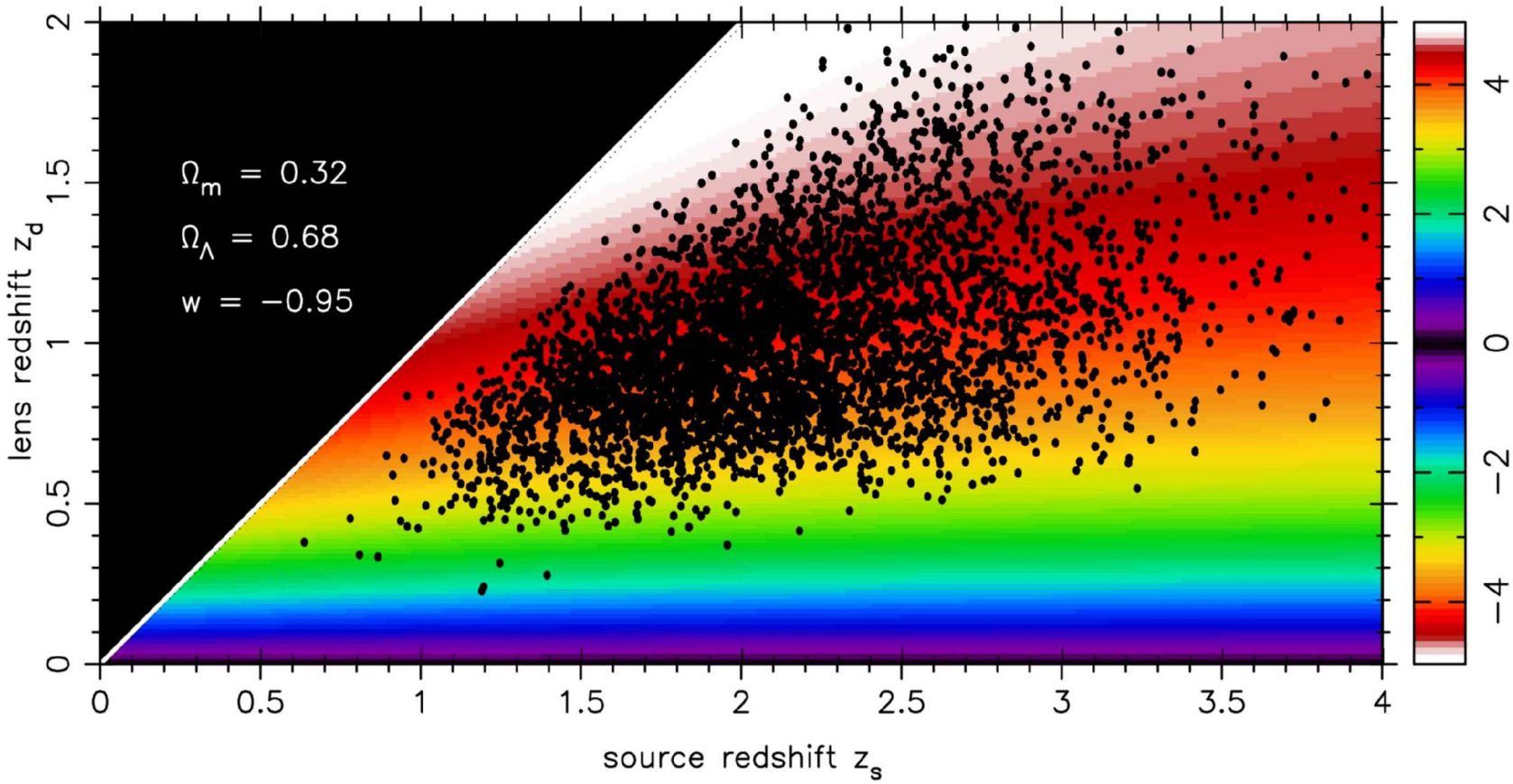
(This is how Bender et al tried to measure q_0)



Distance ratio cosmography

Each lens provides an estimate of $(D_{ds} / D_s)\, D_d^{(8/5)}$

Plot this on an "Einstein diagram:"

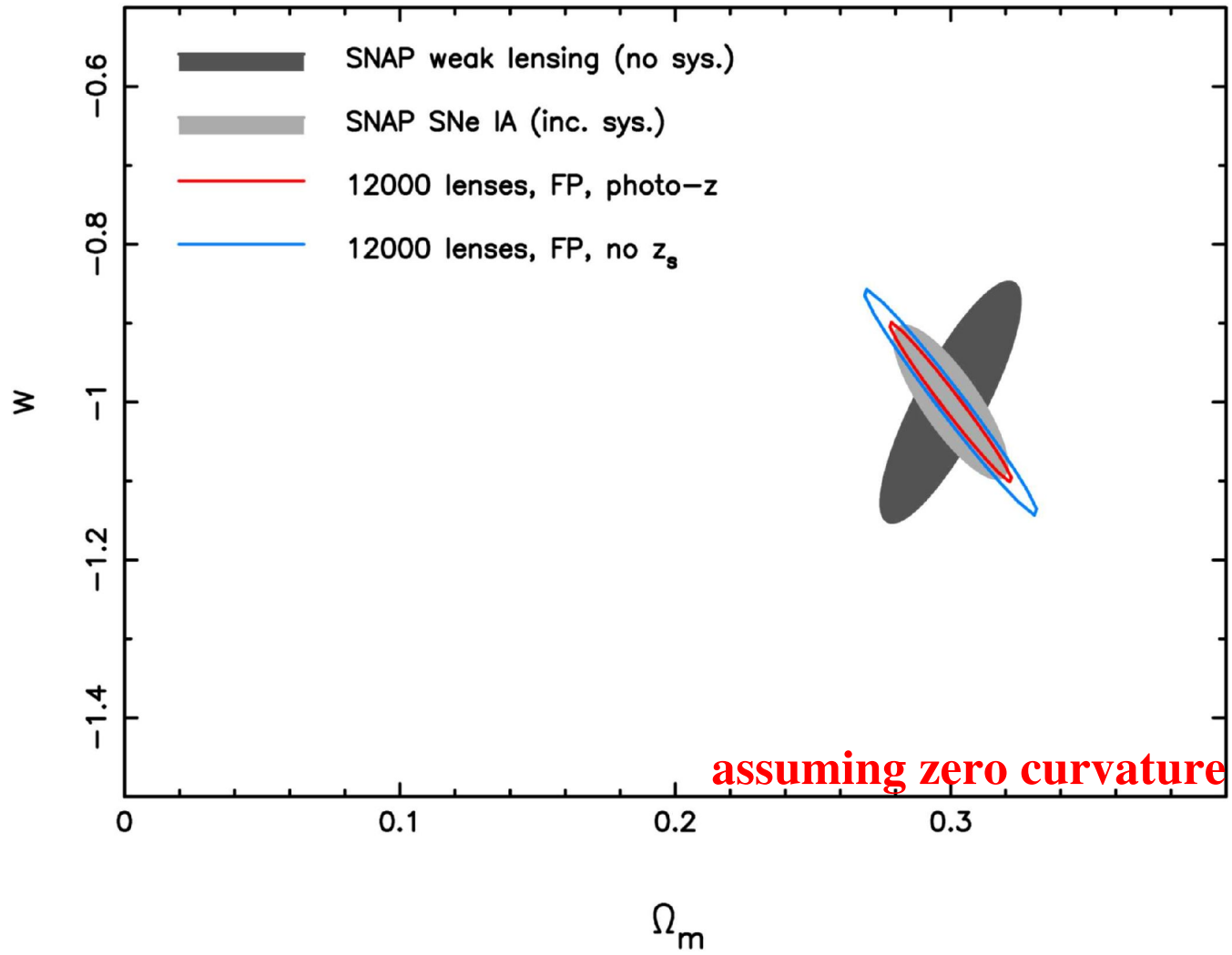


(Colour scale shows the surface of percentage difference from a reference [0.3,0.7,-1.0] cosmology)

Distance ratio cosmography

Inferring the parameters of the surface: Fisher matrix approach, assuming

- ¼ pixel accuracy on image separation
- 17% scatter in FP limiting the standard mass calibration



Distance ratio cosmography

Inferring the parameters of the surface: Fisher matrix approach, assuming

- ¼ pixel accuracy on image separation
- 17% scatter in FP limiting the standard mass calibration
- ***evolution of FP (in terms of lensing mass) is known exactly***

Previous slide showed high statistical power

Distance combination is clearly sensitive to lens galaxy evolution

Exciting probe of galaxy evolution!

Division of sample by type (E/S0)! Lens mass! Environment!

Fundamental plane studies like you've never seen them before!

To recover the cosmological sensitivity we need to either:

- Solve for galaxy mass/luminosity evolution simultaneously ("self-calibrating standard masses) – currently under study - or
- Acquire more information about the lens masses...

Spectroscopic follow-up

If dynamical masses are available (as with SLACS/LSD), each lens provides an estimate of (D_{ds} / D_s)

Possible spectroscopic follow-up:

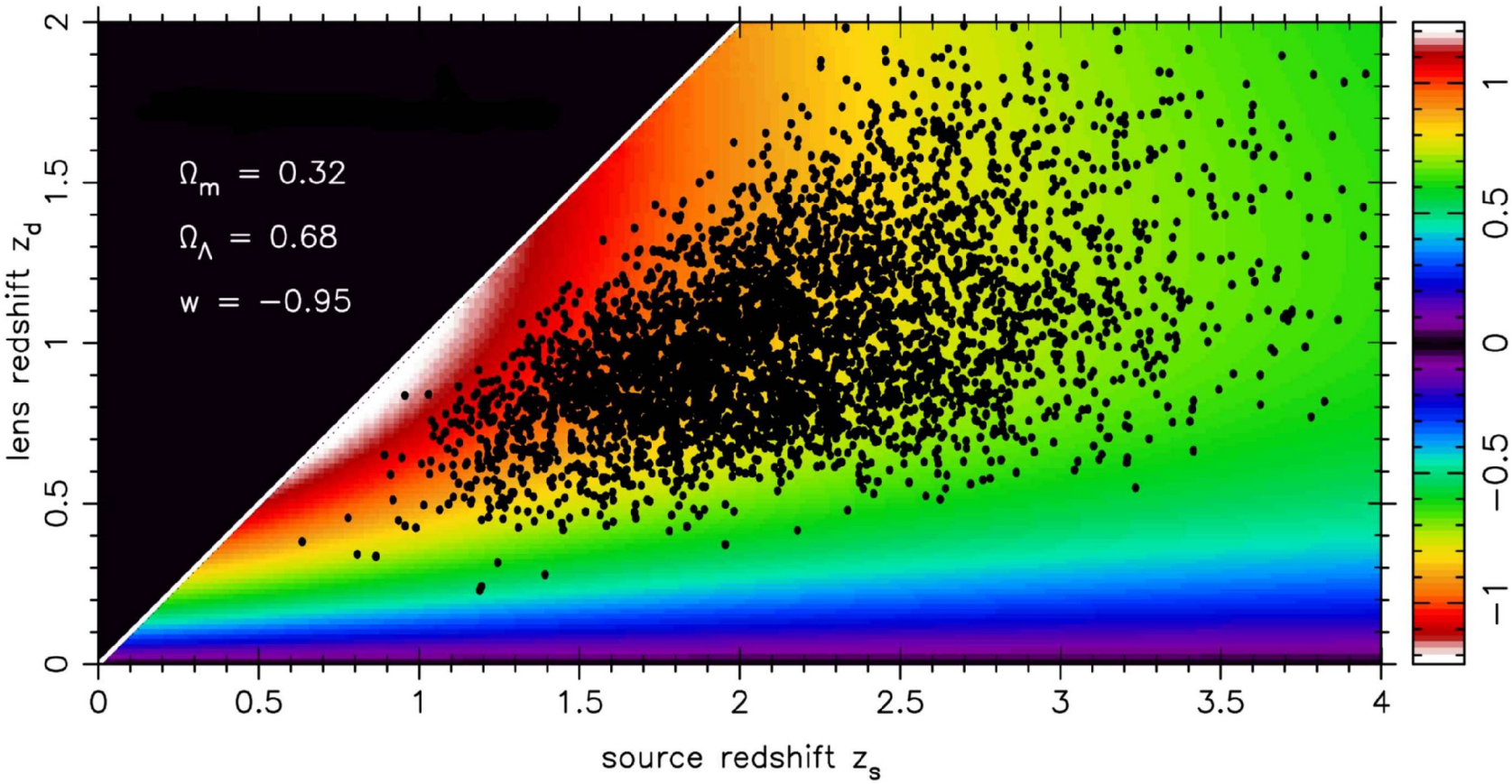
- need ~0.5 nights per system on an 8m-class telescope
- a 1.5 sq deg field multi-object spectrograph could do 15 lenses per shot
- 30 lenses per night, 1000 lenses in one month
- WFMOS would do exactly this (and probably more!) as part of its own LRG survey – *overlap between surveys is important*

Look at constraints from a random subsample, assuming

- lens and source redshifts to 0.001
- lens velocity dispersion to 10 km/s

Distance ratio cosmography

If dynamical masses are available (as with SLACS/LSD), each lens provides an estimate of (D_{ds}/D_s):

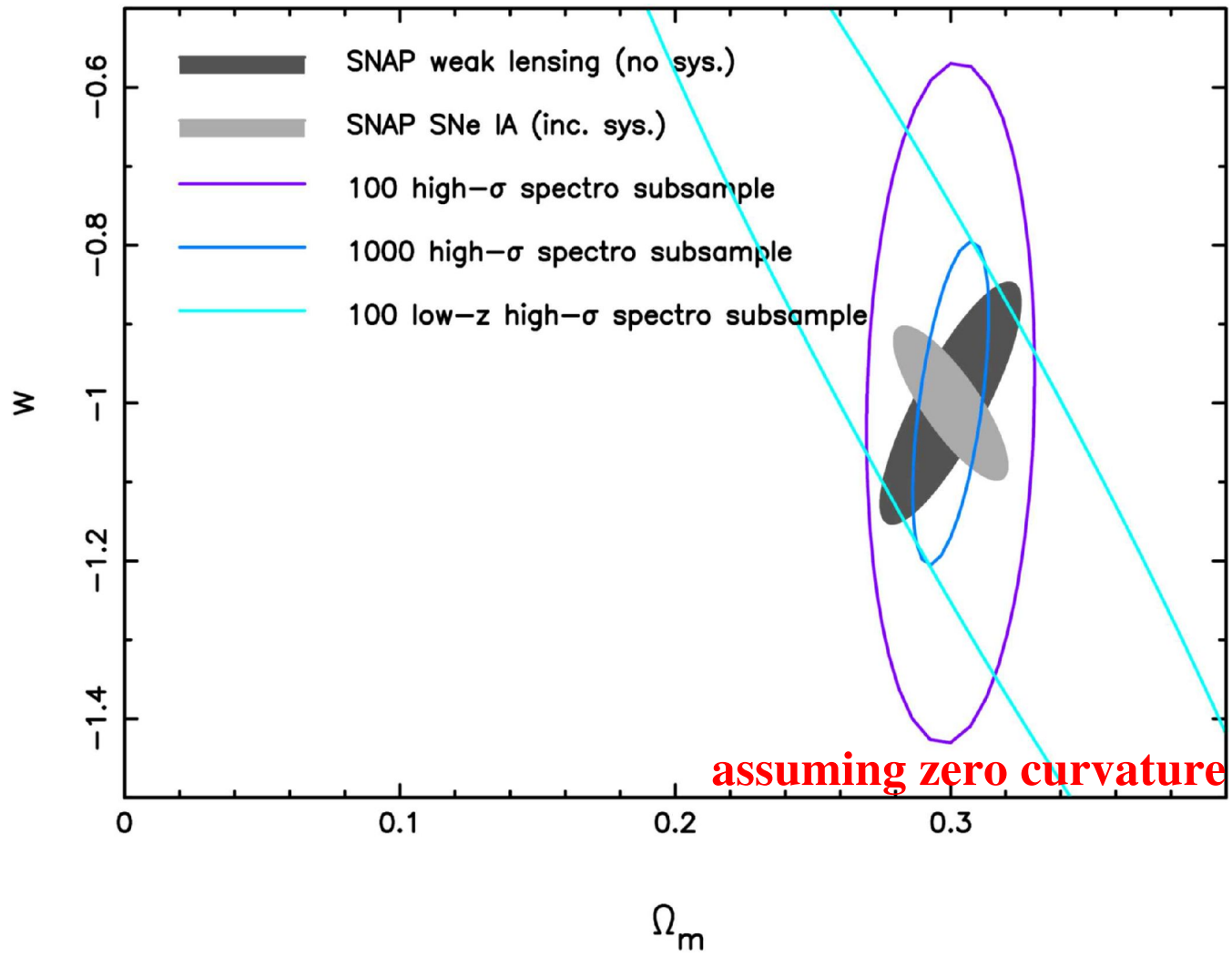


(Colour scale shows the surface of percentage difference from a reference [0.3,0.7,-1.0] cosmology)

Distance ratio cosmography

Inferring the parameters of the surface: Fisher matrix approach, assuming

- ¼ pixel accuracy on image separation
- velocity dispersions from follow-up spectroscopy



Conclusions

Gave *one example* of a SNAP strong lensing project, to show that:

- Working with e.g. the HST archive will give us the experience to deal with the SNAP data as it arrives;
- The SNAP project simulations are helping us plan the experiment, and get ready for the massive influx of data
- SLACS and fundamental plane studies should convince us that elliptical galaxies can be used as standard masses
- The ensemble generated by the SNAP survey provides remarkable statistical precision
- Whether the masses are self-calibrating is the current focus of research – in any case SNAP as a galaxy evolution probe is an exciting prospect

Interesting open questions:

Can we count on having a WF-MOS instrument to provide spectroscopic follow-up? Do we need it given the SNAP photometry? If we allow for scatter and evolution in the lens potential parameters, how much cosmographic information is left? What do we learn from the atypical lenses we will find? How will we find THEM?!

Closing remarks

LSST and SNAP will be observing in the post-Planck era – while independent cosmological probes are always valuable, we will probably learn much more about the mass properties of galaxies (and clusters!) from the strong lenses we find

Extensions of current projects to the extreme precision afforded by ~10^4 lenses are interesting – but surveys of this magnitude will find more exciting things than this!

Both datasets will be ENORMOUS and COMPLEX:

SNAP: 5Pb, 1.3 Terapixels

LSST: 15Pb per year for 10 years – and all public

They will require a LOT of manpower to analyse – keep it in mind

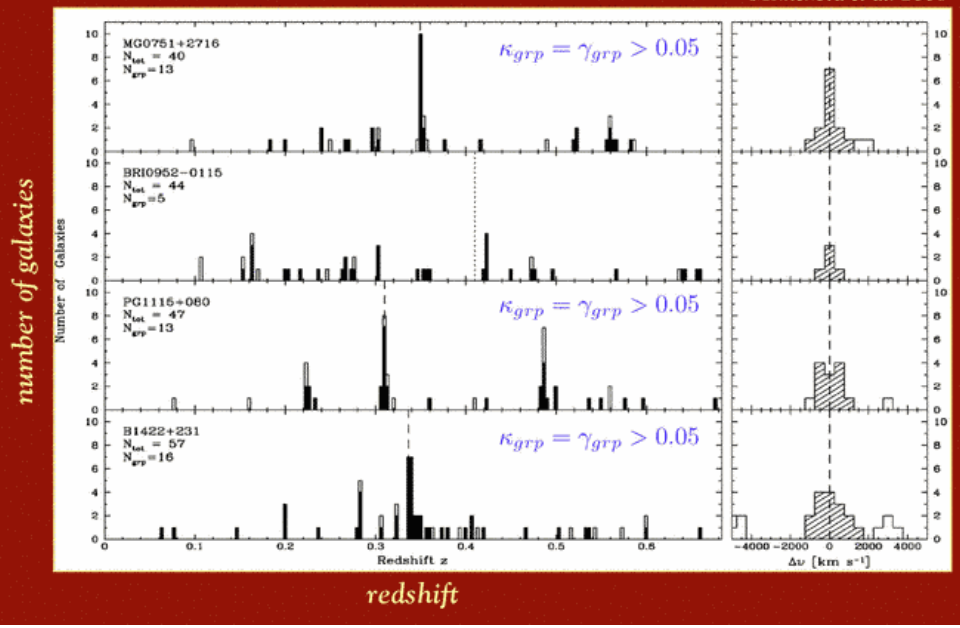
Spare slides

Observing the lens environment

- Spectroscopic surveys of getting us closer to modeling out the environment
- Photo-z for elliptical galaxies should be good enough – testable with current data!

Lens Environments: Results from Spectroscopy

Momcheva et al. 2006



Going for Gold

characterized lens environments, interlopers

most lenses in dense environments: *at least 6 of 8 (spectroscopy), 8 of 12 (photometry)*

>50% of environments affect lens potential

>50% have at least one superposed structure

>10% of los structures affect lens potential

exclude or account for lenses with complex environments and/or that lie in atypical beams

Momcheva, Zabludoff et al 2006 (KITP strong lensing meeting)

Hubble's constant from Strong Lensing

Gaining in support from the community

- WMAP alone does not measure H0 unless a flat cosmology is enforced
- HST key project result is uncertain (systematics abound)
- Independent probes are vital
- The accuracy on H0 may not be *very* different in ten years' time...?
- Two approaches:

- Model each lens in “excruciating detail,” and combine judiciously with other similarly well-studied systems (eg B1608 Fassnacht, Koopmans et al 2003)

- Put all knowledge and beliefs about lens galaxy structure into a (prior) PDF, and use this to combine all available systems (Oguri 2006)

Traditional (excruciating) approach taught us that:
1) It is not always easy to model the lens (and get sensible H0)
2) The environment plays a significant role
(we can only measure H0*[1-<κ>])

Hubble's constant from Strong Lensing

- Put all knowledge and beliefs about lens galaxy structure into a (prior) PDF, and use this to combine all available systems (Oguri 2006)
- Prior is not “fuzzy” - there's no self-calibration going on yet
- No testing of whether the PDF is an *adequate model* – the data may be flawed, or the model incomplete
- BUT:

(Controversial?) Conclusion

- 15 time delay quasars constrain H_0 to be:
  H_0=70±3 km/s/Mpc (68%)
- Or you can assume the Hubble constant to derive the nearly isothermal lens profile from observed delays (if you prefer...)
- Importance to construct clean statistical samples
  - future surveys like LSST will do a good job

Conclusion

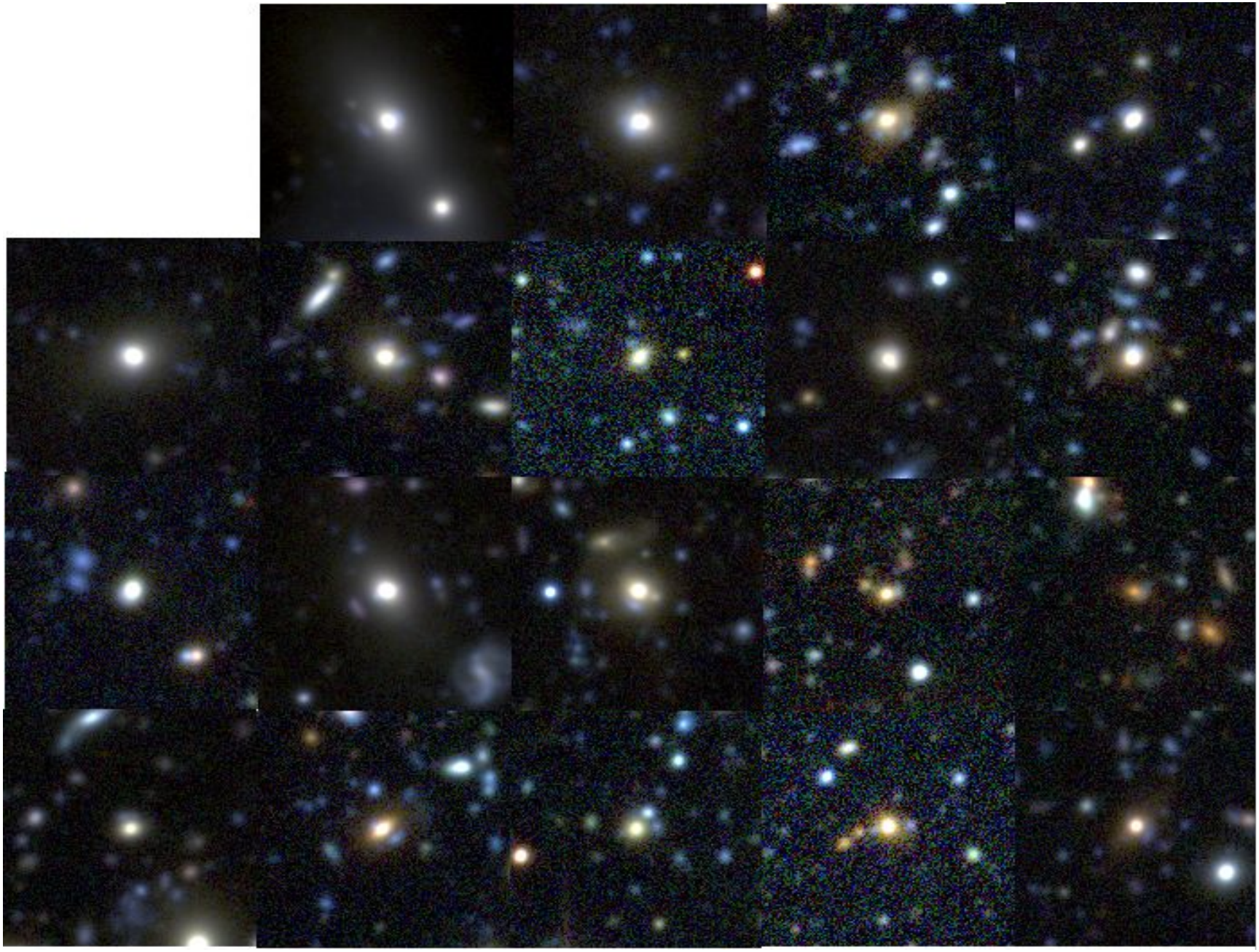
Using a new statistical approach we examined the dependence of time delays on various lens potentials as a function of image configuration

- Time delays are (statistically) less dependent on models
  ... if it is more asymmetric
  ... if it has larger opening angle
  ... if it is double rather than quad

Conclusion: Go ahead and monitor typical (“boring”) lenses!

LSST can provide environment, lens models and monitoring, and high statistical power to probe remaining systematics

SL2S: the Strong Lens Legacy Survey



LSST: Scaling up from SL2S

- 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

(i'=24.5 : i=25.4AB)

- LSST 10 year survey:
- 20000 sq degrees observed in (u)grizY to i<25.4AB

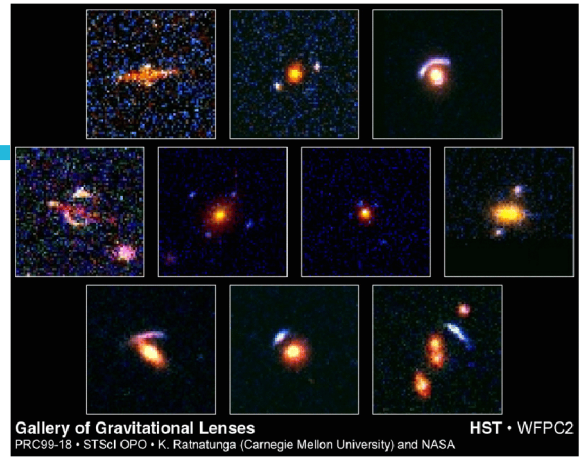
(the depth achieved when only keeping the best 20% of exposures)

Factor increase in numbers is ~600:

- 2400 arcs (>7”), 13200 rings (<3”), and 7800 intermediate (3-7”) lenses – probing group-scale mass distributions with large number statistics. Environmental science!

- Follow-up?

Surveying with HST



Previous galaxy-galaxy strong lens surveys:

- HST MDSS (Ratnatunga et al 1999)
  c. 0.17 sq degrees, to I=25
  10 candidates, 2 confirmed; prediction is 2

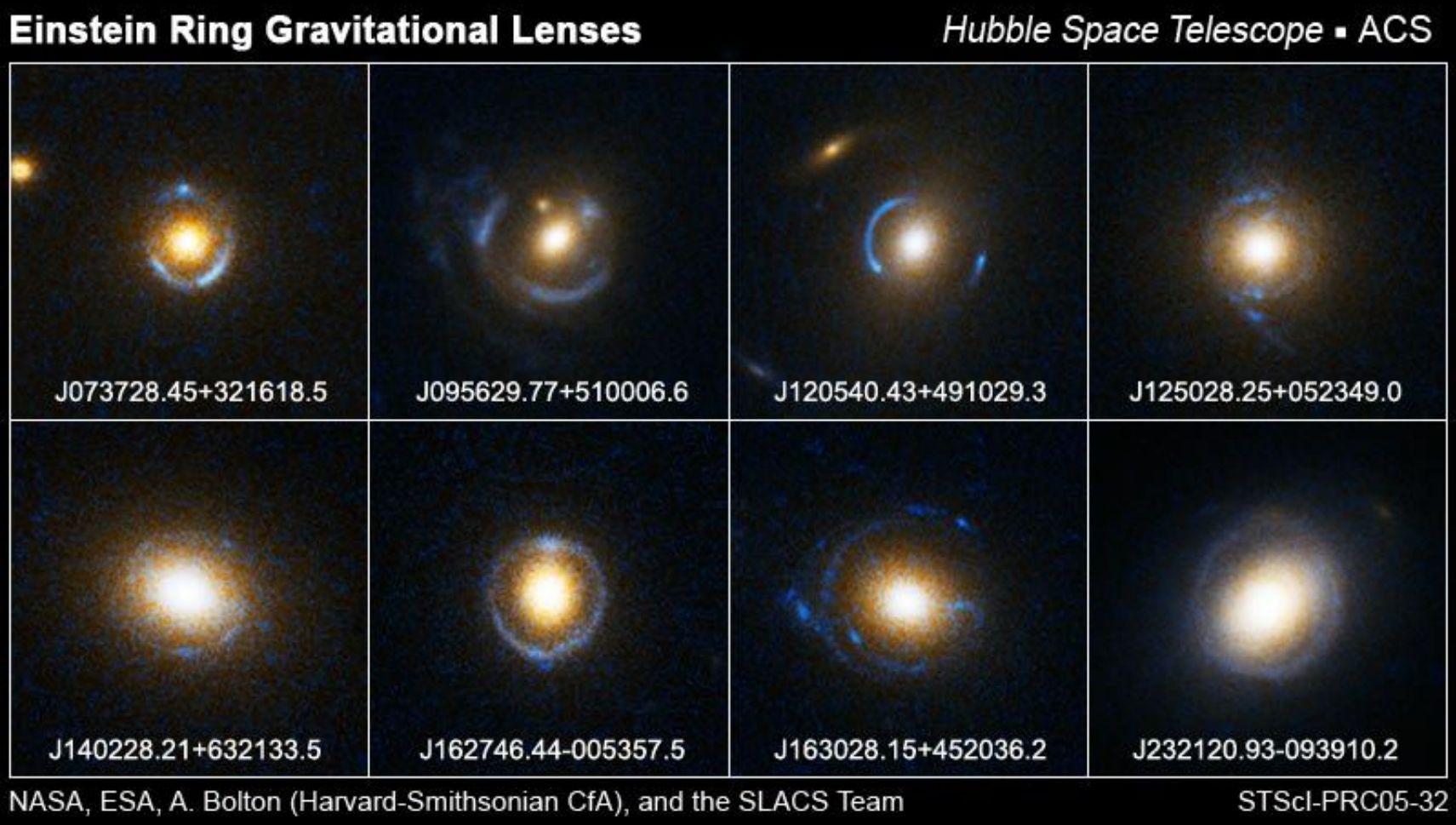
- GOODS (Fassnacht et al 2003) 320 sq arcmin, to c. SNAP depth
  48 candidates, 6 favourites: SNAP prediction to same magnitude is again 2 (one just outside field!)

- COSMOS, 2 sq degrees to I c. 26, two HST filters
  Prediction is c. 30 lenses, worth a look...

- SLACS, c. 100 good candidates selected from SDSS (5000 sq deg)

The SLACS survey

- Look for high redshift emission lines superimposed on SDSS elliptical galaxy spectra – candidate galaxy-galaxy lenses (Bolton et al 2005)
- Follow-up with HST to get convincing lens morphology
- Expected yield ~100 (from 5000 sq deg SDSS area)



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