Strong Lensing Distances:
A Different Lever

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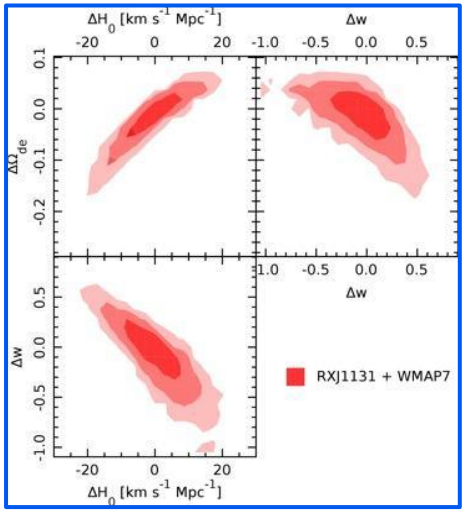
Cosmic Frontier Workshop at SLAC

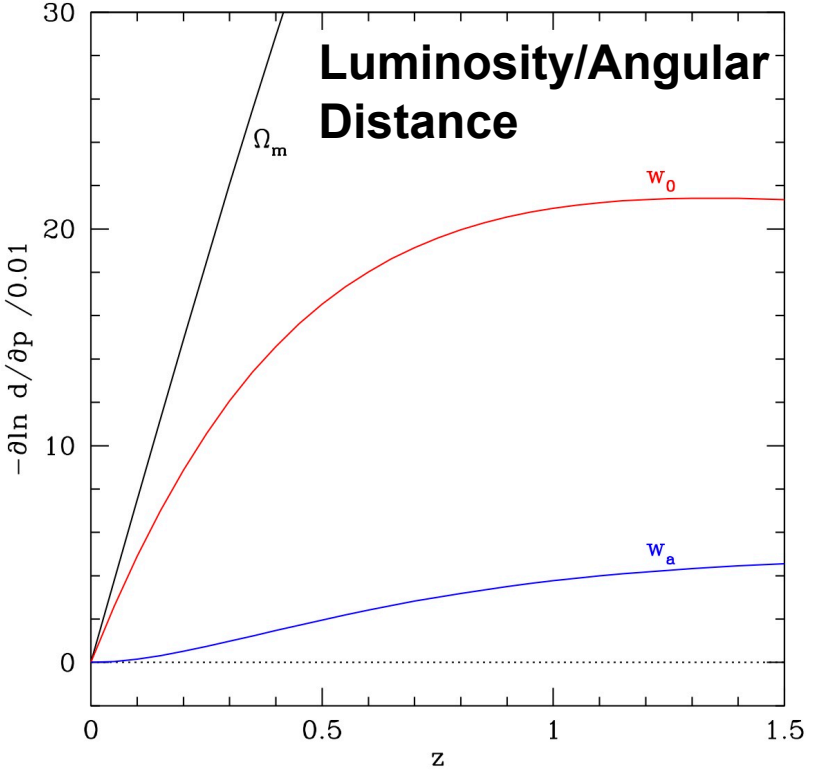


Overview

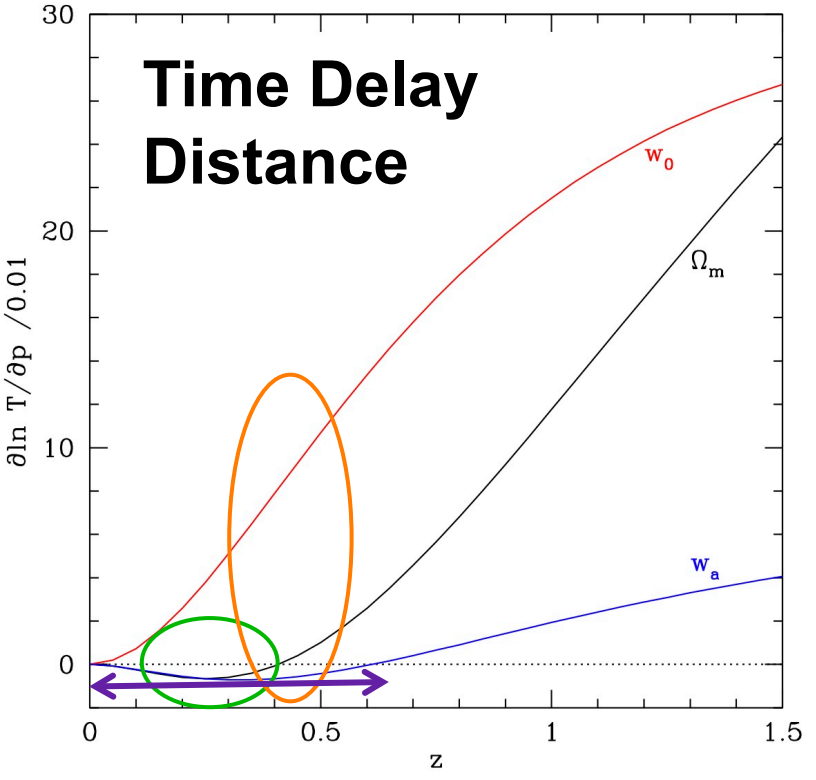
Why Strong Lensing?

Strong Lensing Time Delays

Strong gravitational lensing creates multiple images (light paths) of a source. Time delays between paths probe geometric path difference and lensing potential. Key parameter is distance ratio $T \equiv \frac{r_l r_s}{r_{ls}}$



Sensitivity



Strong theoretical complementarity Linder 2004, **Modeling advances** Oguri 2007, Suyu+ 2010, **Strong experimental complementarity** WMAP7: Komatsu+ 2011.

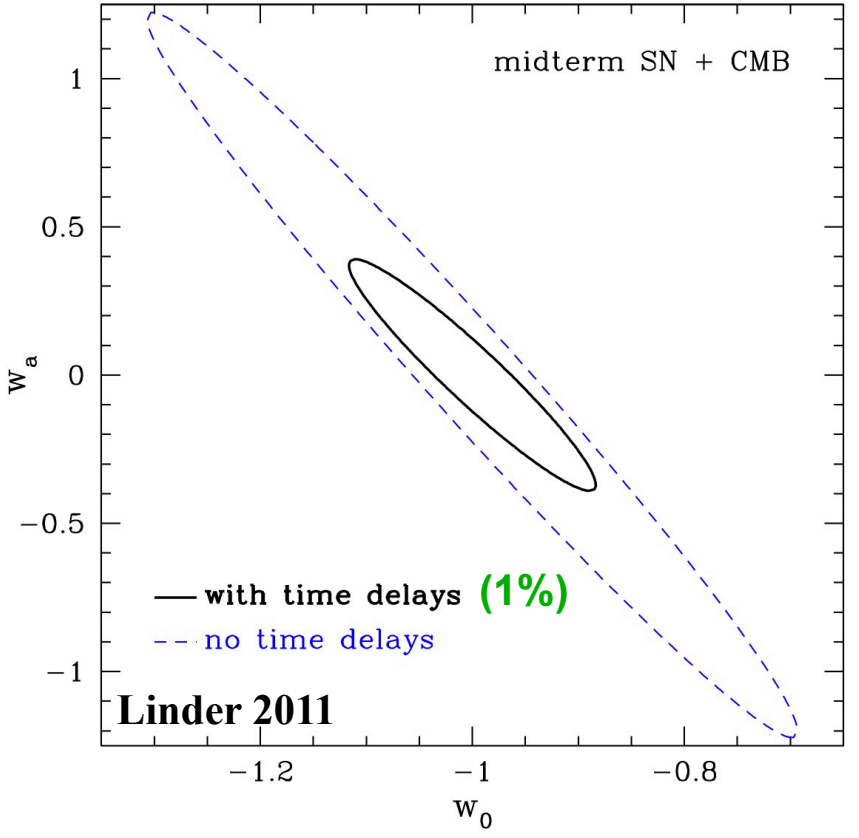
Time Delays + SN/BAO

Lensing time delays give superb complementarity with SN/BAO distances plus CMB.

For Stage III (Cosmology 2017), SL improves dark energy FOM by 30% (25 systems of 5% distances, 150 HST orbits).

SL+SN+CMB distances do 5x better on constraining DE in presence of curvature than SN+CMB alone.

SL with 1% systematics at z<0.6 improves SN+CMB FOM by 5x.



Strong Lensing Distance Surveys

Best current time delays at 5% accuracy (16 systems known, 2-5 at 5%). 5 year aim: 25 systems, 5% accuracy = 150 orbits HST. Long term: 1% distances.

Need 1) high resolution imaging for lens mapping and modeling, 2) high cadence imaging, 3) spectroscopy for redshift, lens velocity dispersion, 4) wide field of view for survey.

Synergy: HST/Keck/TMT+ LSST/WFIRST. SN survey included. Only low redshift $z<0.6$ needed for lenses.

Systematics control via image separations, anomalous flux ratios (probe DM substructure!). Need good mass modeling, computationally intensive. Recent advances in time delay extraction using advanced statistics (LSST Data Challenge).

Crosscorrelations with Other Probes

Time delays probe geometric path difference and lensing potential.

$$\Delta t(\vec{\theta},\vec{\beta}) = \frac{r_l r_s}{r_{ls}}(1+z_l)\,\phi(\vec{\theta},\vec{\beta})$$

Oguri 2007, Suyu+ 2009, Fadely+ 2010

geometric "focal length"

Fermat potential

$$\phi(\vec{\theta},\vec{\beta}) = \frac{(\vec{\theta}-\vec{\beta})^2}{2} - \psi(\vec{\theta})$$

geometric delay

lensing potential

$$\nabla^2\psi = 2\kappa$$

projected surface mass density

So potential crosscorrelation with other probes of mass, e.g. galaxy clustering, weak lensing, yielding enhanced calibration/constraints.

Also a dark matter substructure survey!

Dark Matter

See Moustakas talk in CF3 session at 1:30.

Strong lensing informs about

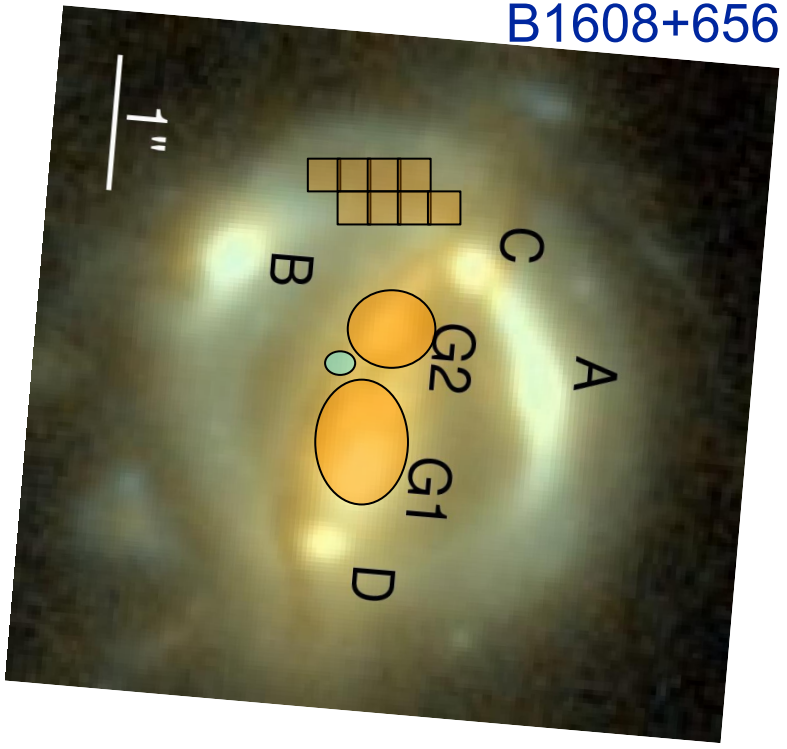
- **Dark matter substructure**
- **Particle nature – nonthermal, self interaction**
- **Dark Matter-SM interaction cross section**

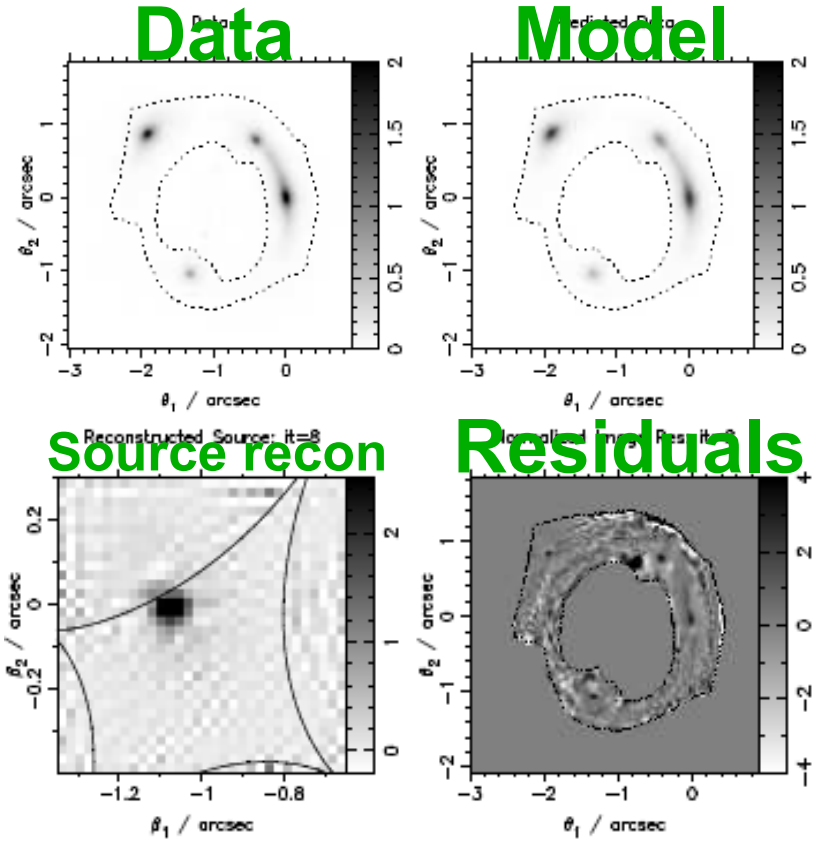
Lensing has achieved both statistical and individual subhalo detections.

Details and Current Status

Recent Advances

Gravitational Lens Systems





Relative time delays:

Δt_{AB} = 31.5 +2.0-1.0 days

Δt_{CB} = 36.0 ± 1.5 days

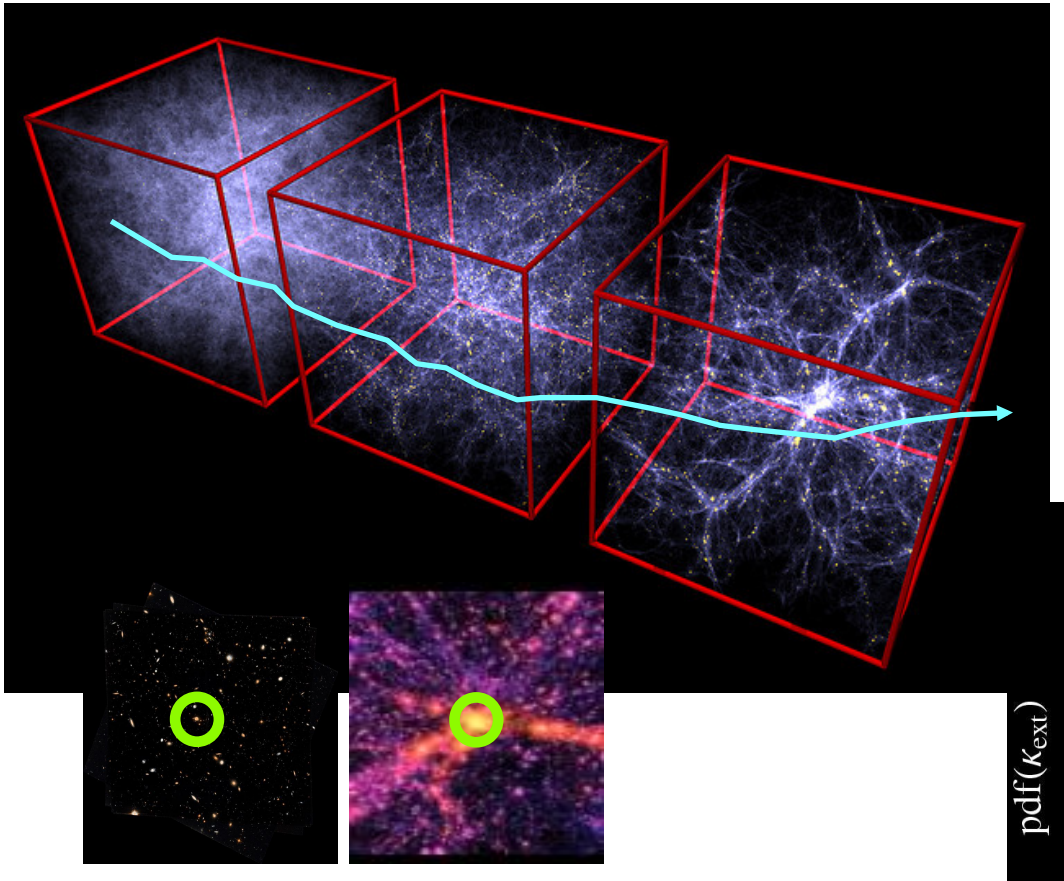
Δt_{DB} = 77.0 +2.0-1.0 days

Fassnacht et al. 1999, 2002

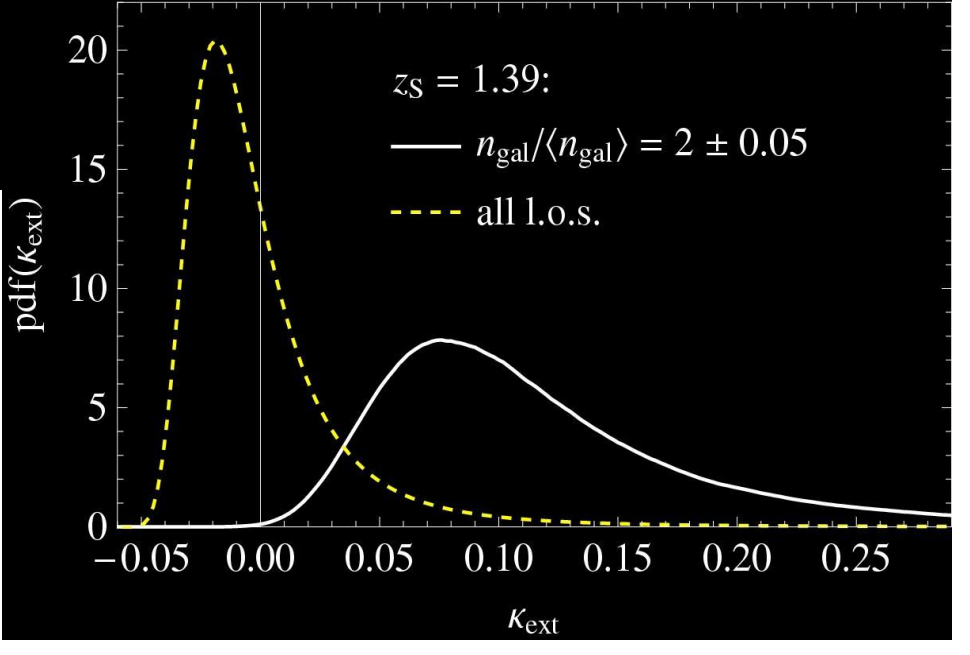
Mass model of G1 and G2 predicts HST/ACS image of Einstein Ring and G1 stellar velocity dispersion. **Suyu+ 2010**

Suyu 2012 extends to simpler, 2 image, wide separation systems, increasing number of cosmologically useful systems by ~6.

All the Mass that's Fit to Lens



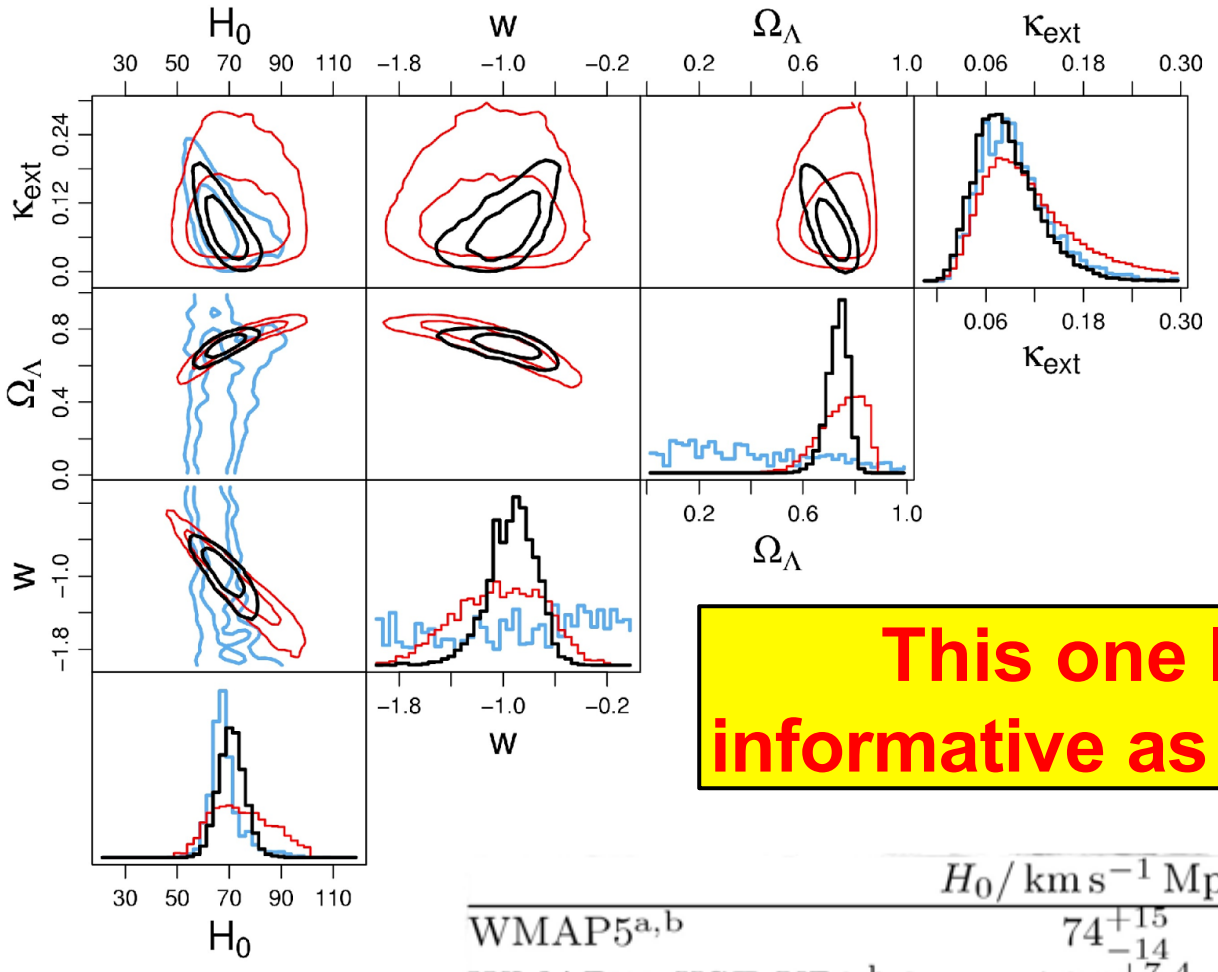
Weak lensing by line of sight structure: κ_{ext} external convergence both a nuisance and signal.



Important role for simulations and xcorrs.

κ_{ext} from lens-weighted galaxy counts Greene+ 13 , full 3D halo model mass recon using all photometric info Collett+ 13

Dark Energy Constraints



— WMAPw + B1608+656

— WMAPw

— UNIFORMw + B1608+656

(assuming flatness)

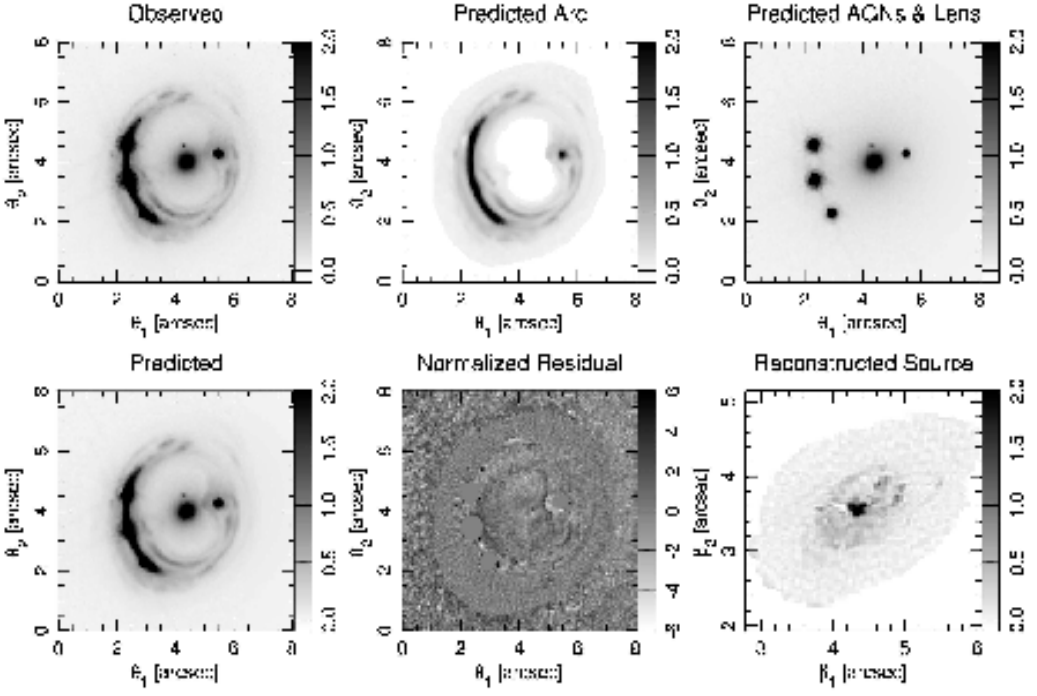
This one lens was as informative as SDSS+2DF BAO

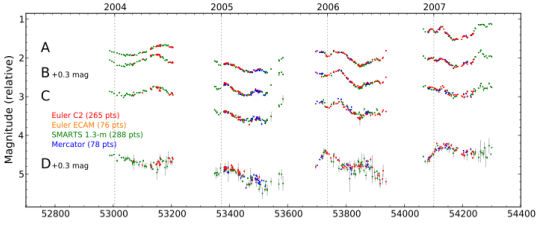
	H_0 / km s^{-1} Mpc^{-1}		w	
WMAP5[a,b]	74^{+15}_{-14}	20%	$-1.06^{+0.41}_{-0.42}$	42%
WMAP5+*HST* KP[a,b,c]	$72.1^{+7.4}_{-7.6}$	10%	$-1.01^{+0.23}_{-0.22}$	23%
WMAP5+SN[a,b,d]	$69.4^{+1.6}_{-1.7}$	2.3%	$-0.977^{+0.065}_{-0.064}$	6.5%
WMAP5+BAO[a,b,e]	$73.9^{+4.7}_{-4.8}$	6.6%	$-1.15^{+0.21}_{-0.22}$	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%

Also used in WMAP7 Komatsu+ 11

Accurate Cosmology?

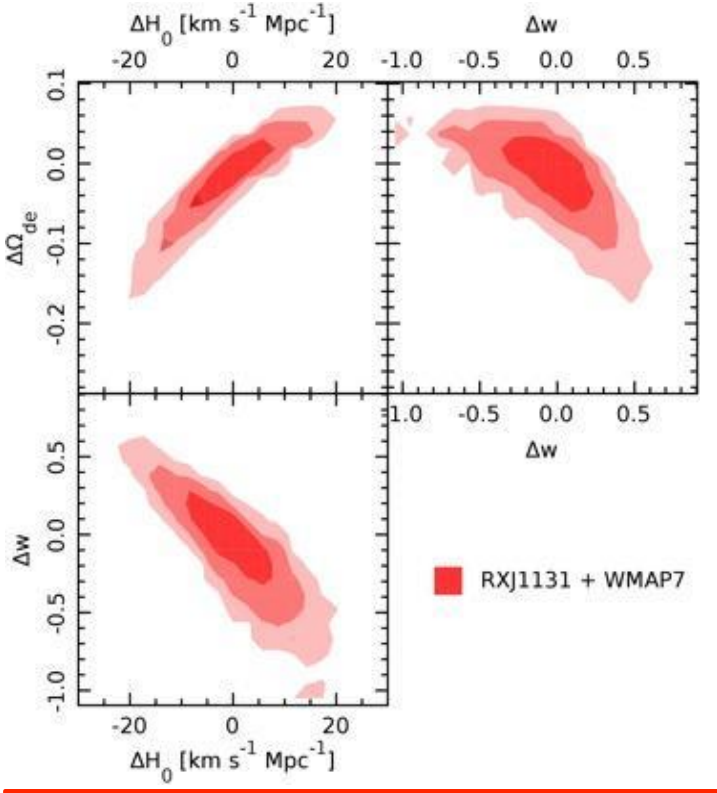
- Time delay distances provide an independent, complementary Dark Energy probe
- Large samples should enable high precision (cf SNe)
- Strong progress, also in systematics





RXJ1131

Suyu+ 2012

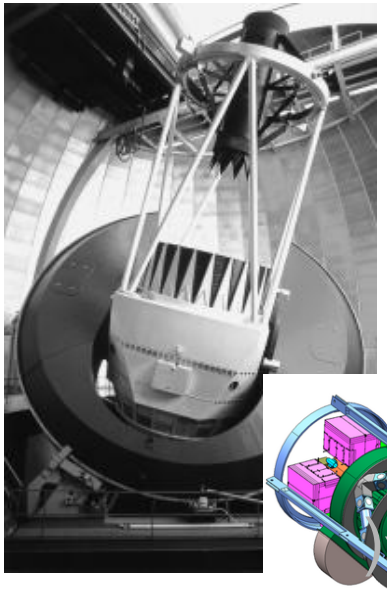


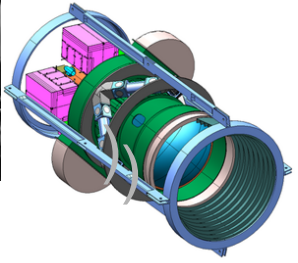
Blind cosmology analysis → H_0 to 6, w_0 to 0.19, Ω_{de} to 0.03

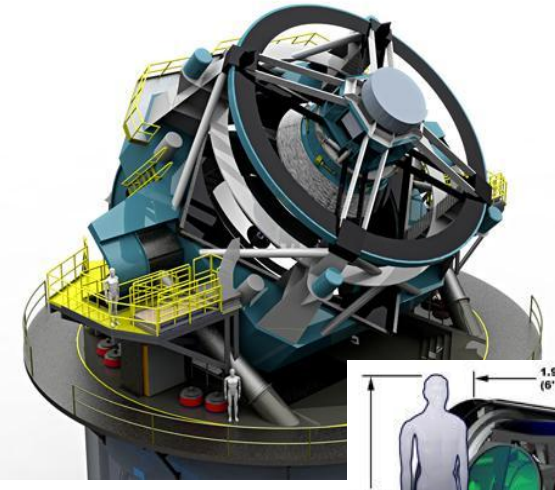
Future

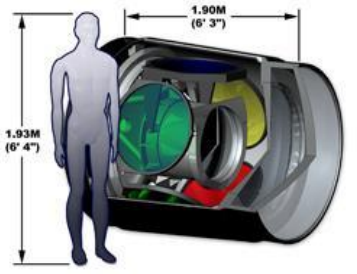
Plans and Prospects

Time-Variable Lens Factories



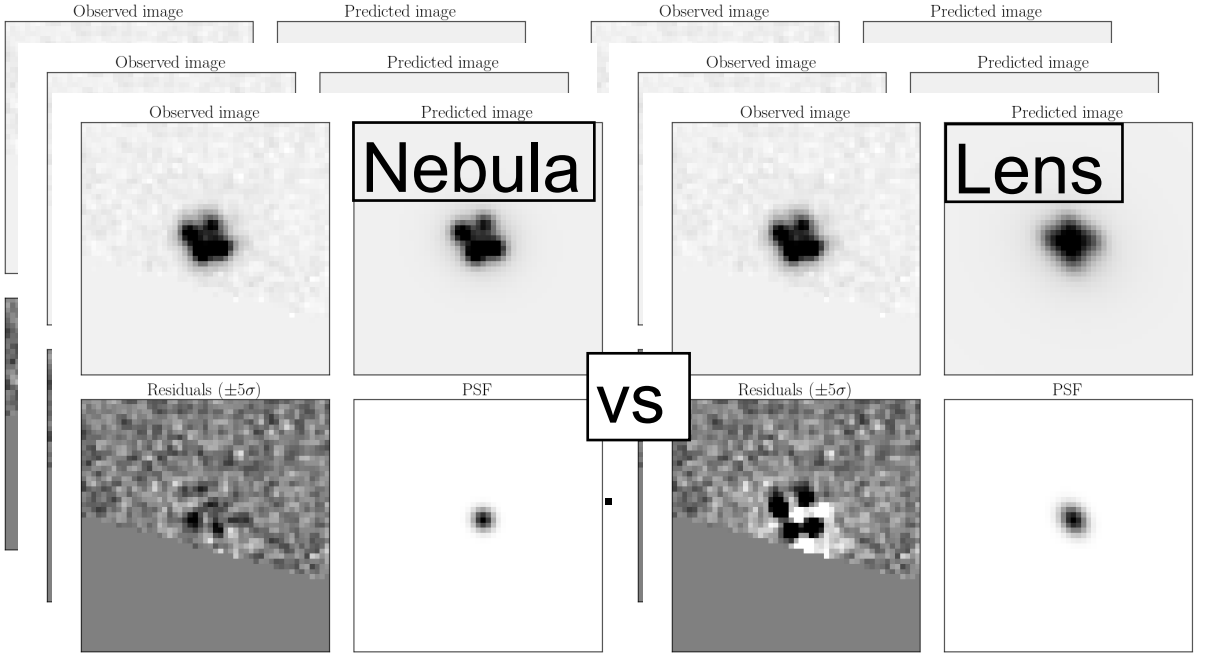






- **PS1 (2013): 30,000 sq deg, grizY, ~22 mag depth, IQ~1.0”,1000 lensed AGN?**
- **DES (2015): 5000 sq deg, grizy, ~24 mag depth, IQ~0.9”?, 1000+ lensed AGN**
- **LSST (2023): 20,000 sq deg, ugrizy, ~25 mag depth, IQ~0.7”, 8000 lensed AGN**

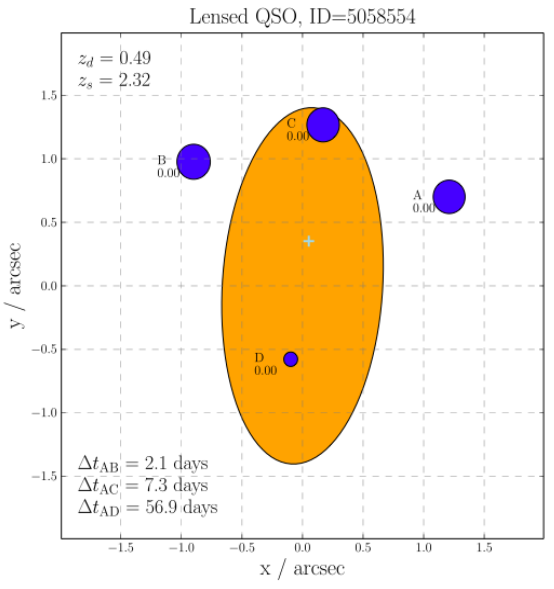
Automated Detection and Photometry

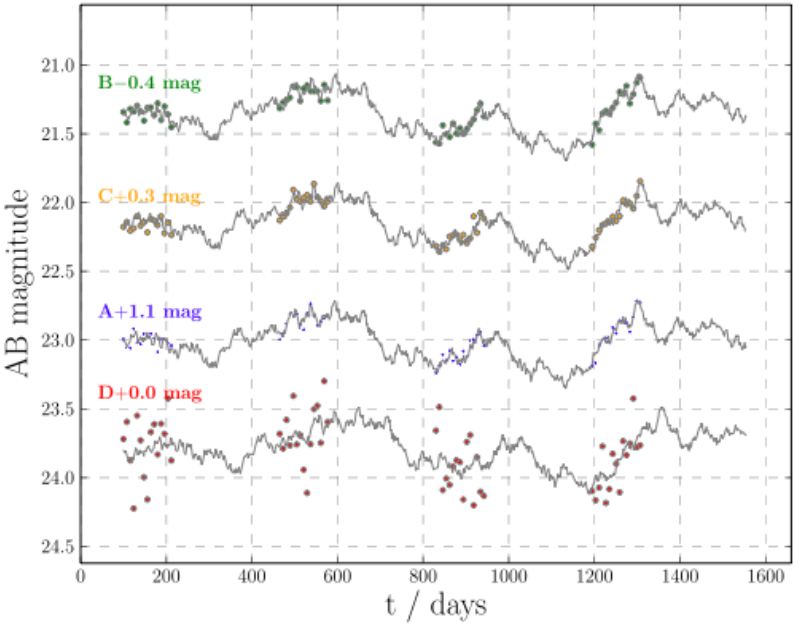


Marshall, Hogg & Lang, in prep

- **Gravitational lens candidacy requires a plausible model - made by the detection robot (Marshall et al 2009)**
- **Lens vs Nebula is a well-posed question, answered by Bayesian evidence ratio, or BIC**
- **"LensTractor" under development, initial application PS1**
- **Euclid catalogs will cut down LSST input target list**

Time Delay Measurement



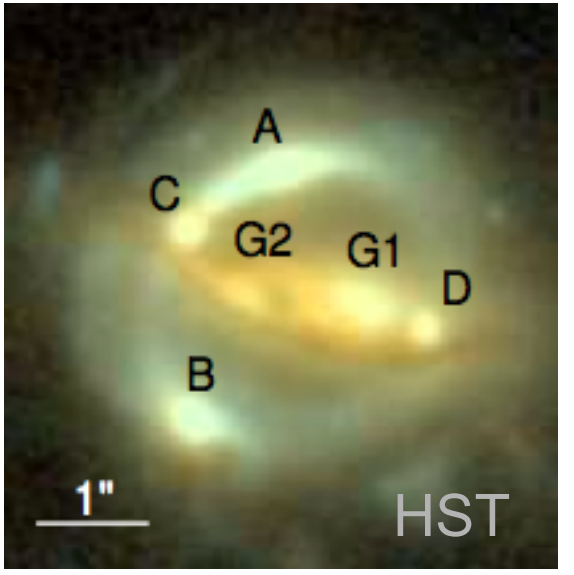


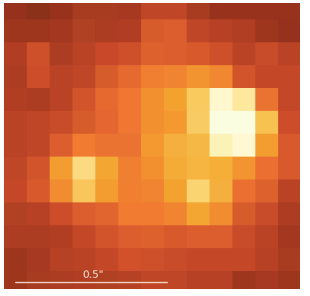
- **Monitoring with small telescope networks (COSMOGRAIL): aiming for 100 systems over next 8 years with STRIDES**
- **LSST will provide 10 year multi-filter lightcurves "for free" - optimize observing cadence for time delays?**
- **Optical lightcurves contain microlensing, which must be modeled as well: Gaussian Processes code Hojjati, Kim, Linder in prep; Time Delay Challenge™**

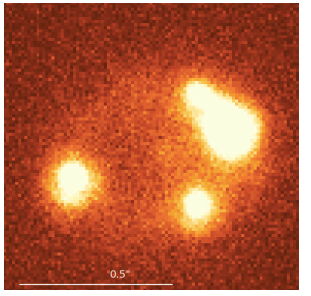
Following Up 1000 Lenses

Current facilities:

HST & Keck AO for imaging,
Keck & VLT for spectroscopy.
5-10 orbits, 1-2 hours per lens.
HST C20: 3 more systems observed







2025: IFU observations will be standard – redshifts, lens kinematics, 3D ring images all in one shot

How much telescope time for 1000 lenses?
Keck NGAO, TMT/E-ELT, JWST

Summary

Strong gravitational lensing time delay distances already being applied for dark energy cosmology.

Highly complementary for constraints.

Probes dark matter too.

Use spectro/imaging, crosscorrelations, simulations. Small + large telescopes.

Wide field surveys are lens finding factories.

Plus: lensed SN, double source-plane lenses