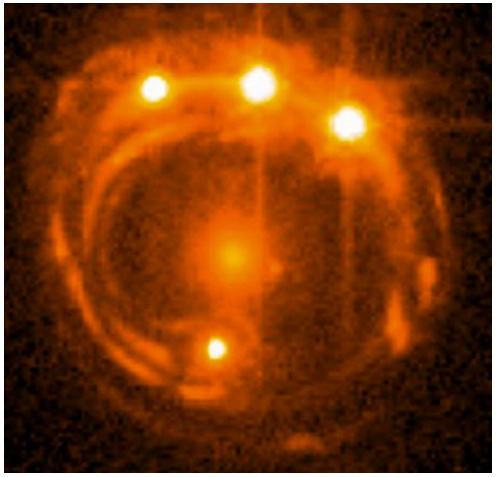
Strong Lensing

Cosmology, Data Challenges, and Followup

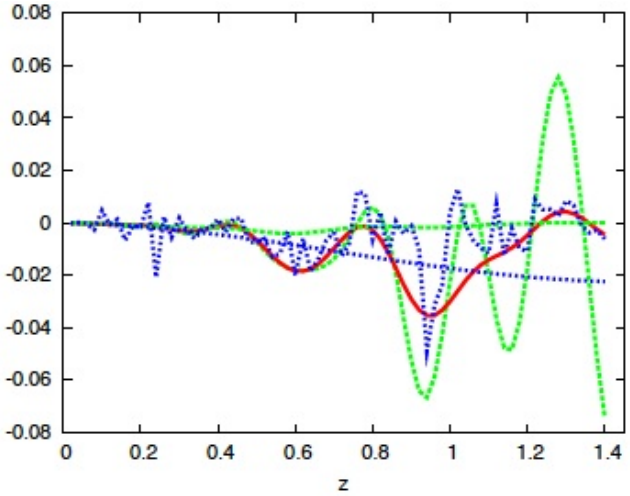
Eric Linder

26 April 2016



Berkeley Center for Cosmological Physics

Leadership Scientist, KASI



Strong Lensing

Strong lensing is visible to the eye, in highly elongated arcs and multiple images.

Light Deflection

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That gravity bends light may seem a modern idea, but it was predicted by Michell 1783, along with black holes. "The first to apply statistics to the study of the cosmos."

Michell had in 1750 found that magnetism obeys an inverse square law. In 1760 he predicted seismic waves and tsunamis.

He invented the torsion balance for measuring G, used by Cavendish in 1798.

Attempted to measure solar radiation pressure but "the needle melted".

Considered measuring gravitational redshift but not technically practical.

Strong Lensing Time Delays

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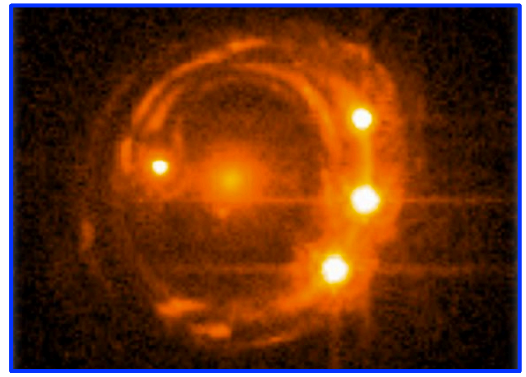
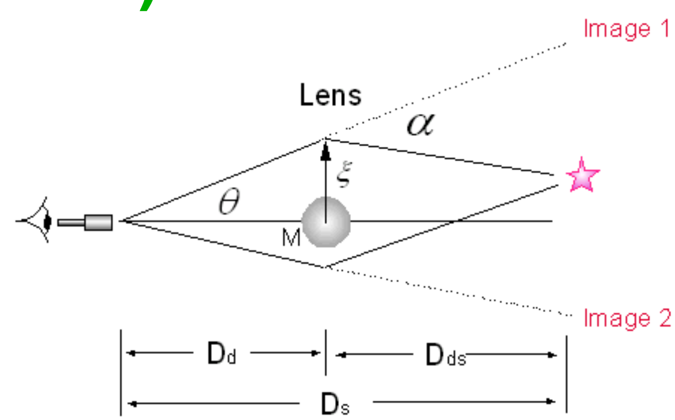
Strong gravitational lensing creates multiple images (light paths) of a source.



When the source is variable (quasar / AGN), we can measure the time delays between the images. This probes the geometric path difference (cosmology) and the lensing potential (dark matter).

Key parameter is a distance ratio, the time delay distance

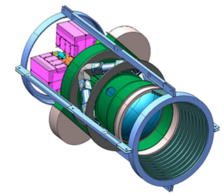
$$D_{\Delta t} \equiv \frac{d_l d_s}{d_{ls}}(1+z_l)$$



Strong Lens Factories

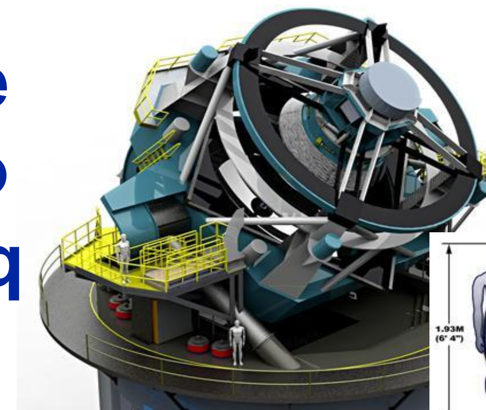
The Dark Energy Survey (DES) is underway at CTIO. It covers 5000 sq deg in 5 years.

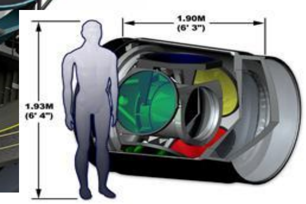
Output: ~800 lensed AGN.



Large Synoptic Survey Telescope (LSST) will start in ~2022 at Cerro Pachon, Chile, covering 20,000 sq deg repeatedly in 10 years.

Output: ~8000 lensed AGN.

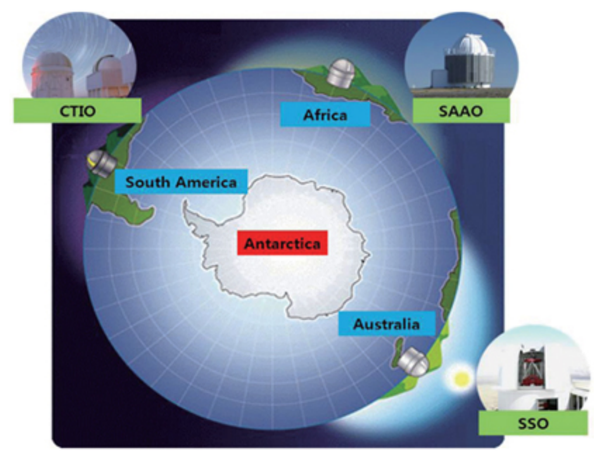




Monitoring: KMTNet
(Korea Microlensing Telescope Network)

Three 1.6m telescopes

Three 340 Mpixel cameras with 4 deg^2 fields



Strong Lensing Distance Surveys

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1) **Find** the lenses with wide field survey
   – Dark Energy Survey in south (future: LSST).

2) **Monitor** with high cadence imaging
   – DES

3) **Follow up** with spectroscopy for redshift and lens velocity dispersion, and high resolution imaging for lens modeling
   – HST (future: DESI? GMT-AO?).

Monitoring currently done with COSMOGRAIL network of 1.2-1.5m telescopes. Future: KMTNet?

Time Delays + Supernovae

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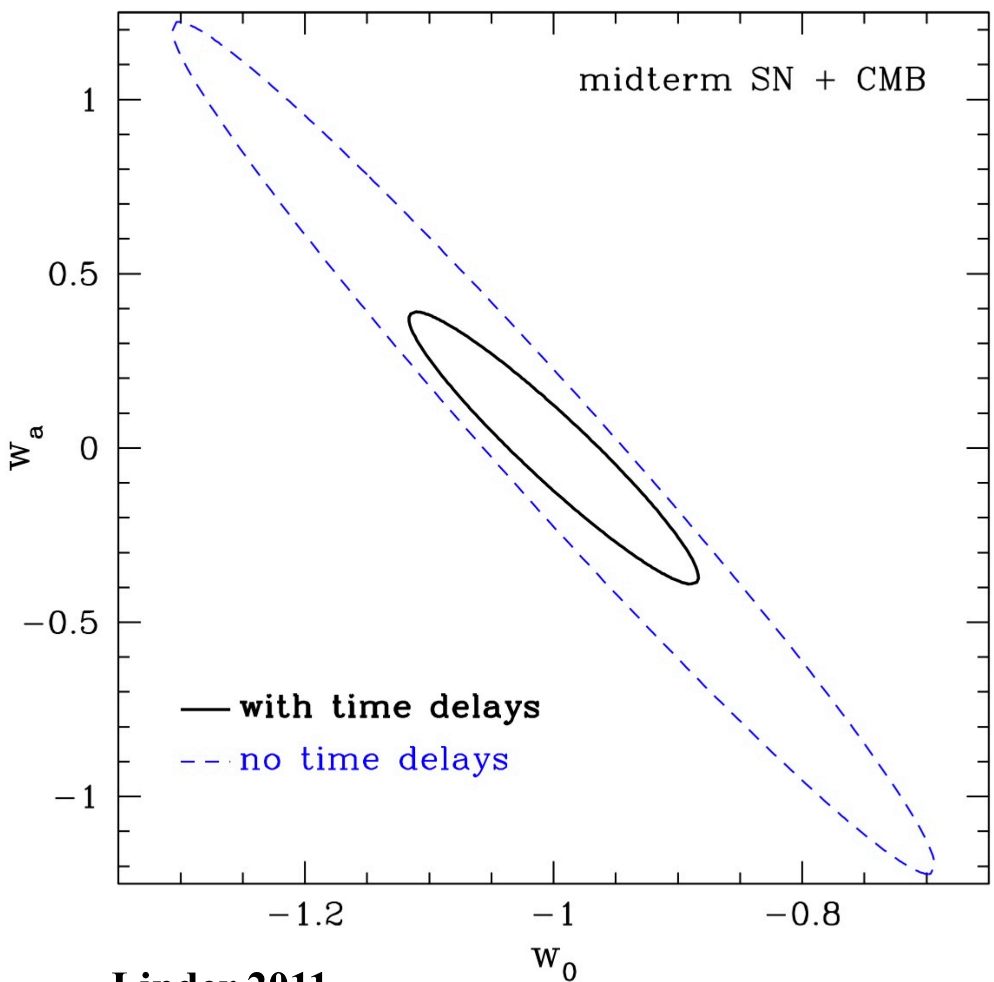
Lensing time delays give superb complementarity with SN distances plus CMB.

Linder 2004



Linder 2011

With 150 well-measured time delays, we get a factor of 5x improvement in dark energy constraints.

Ω_m to 0.0044

h to 0.7%

w_0 to 0.077

w_a to 0.26

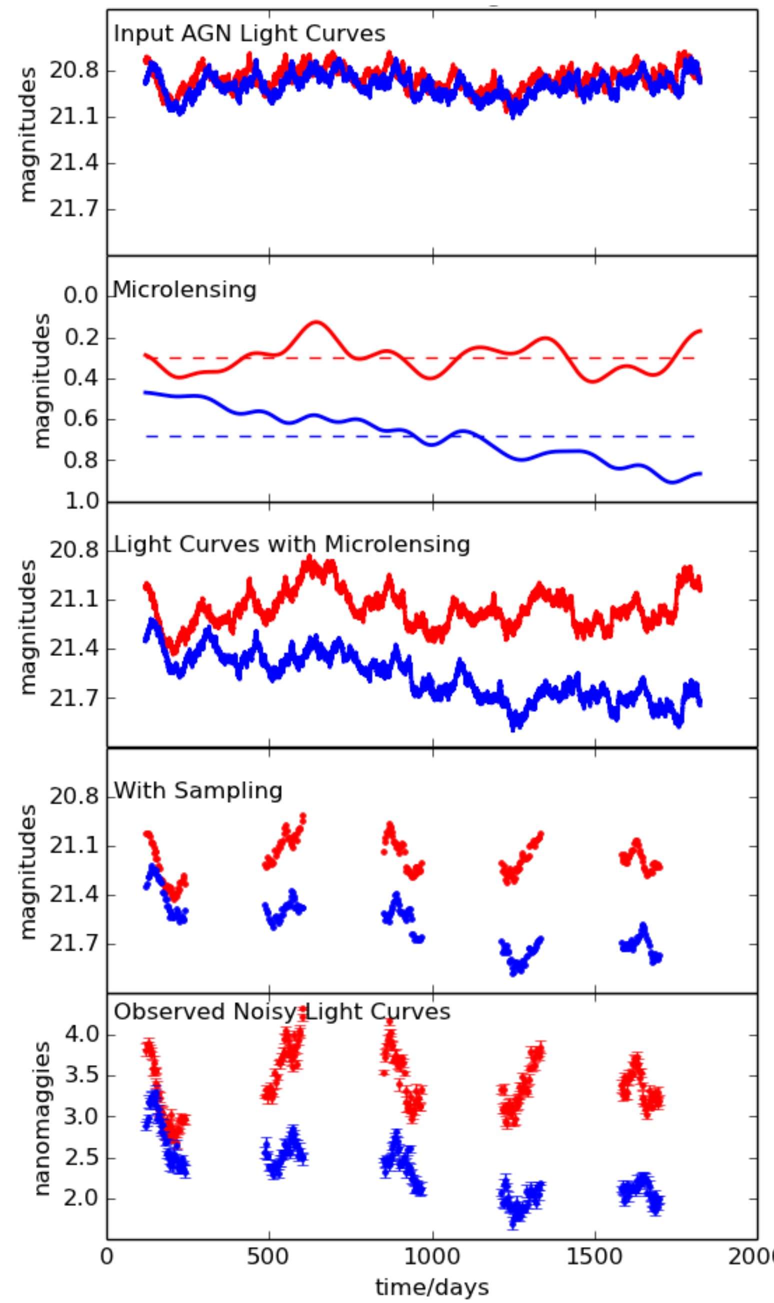
immunizes vs curvature

Time Delay Challenge

One of the challenges is measuring time delays between images in the presence of 1) noise, 2) gaps, 3) variability, 4) microlensing.

Blind data competition
Time Delay Challenge
TDC0, TDC1 ApJ 2015a, 2015b

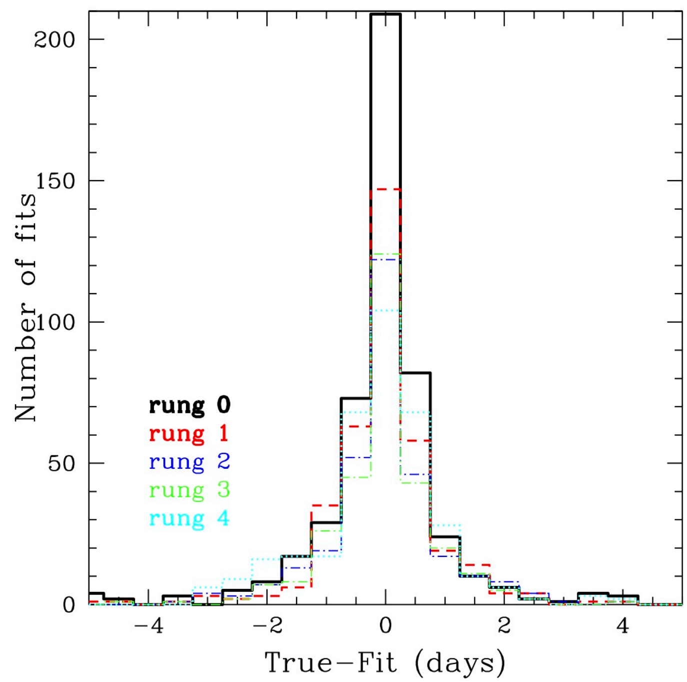
Cosmology requirement on bias $t_{fit}-t_{true}$:
A<0.2% Hojjati & Linder 2014



Theory, Computation, and Statistics

Challenging problem in advanced statistics and computation. Hojjati-Linder team uses Gaussian Processes for crosscorrelation Hojjati, Kim, Linder 2013; Hojjati & Linder 2014. **Success!** Bias in fit A=0.08% (0.02% optimized).

Microlensing is fit simultaneously with the time delay (probe of dark matter substructure in the lens galaxy).



~5 teams with various statistical methods successful (including Aghamousa & Shafieloo 2015)

Time Delay Probe

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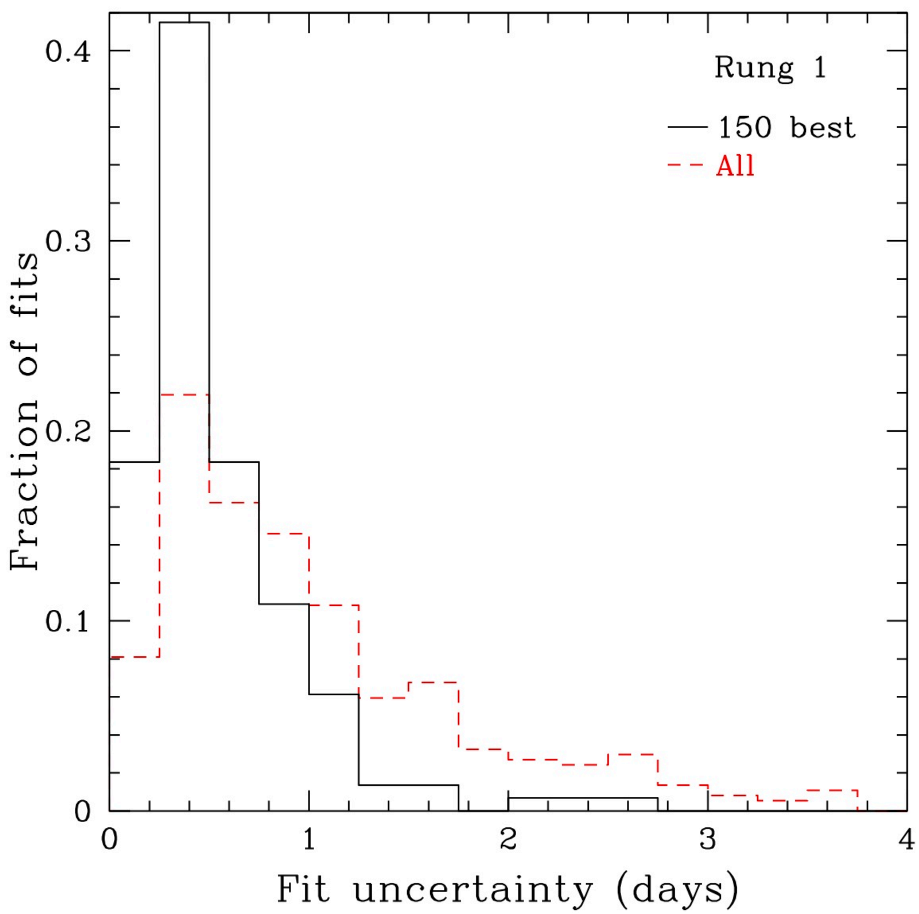
We can improve further by trading numbers for precision, e.g. take 150 most precisely measured systems. (Recall Linder 2011 found 150 systems gave excellent cosmological complementarity and h to 0.005.)



Average	P	A
All rungs	0.027	-0.0011
3 day cadence	0.025	-0.0002

Fewer, more precise systems also reduces follow-up requirements on spectroscopy and high resolution imaging.

Resident Evil 2: TDC 2

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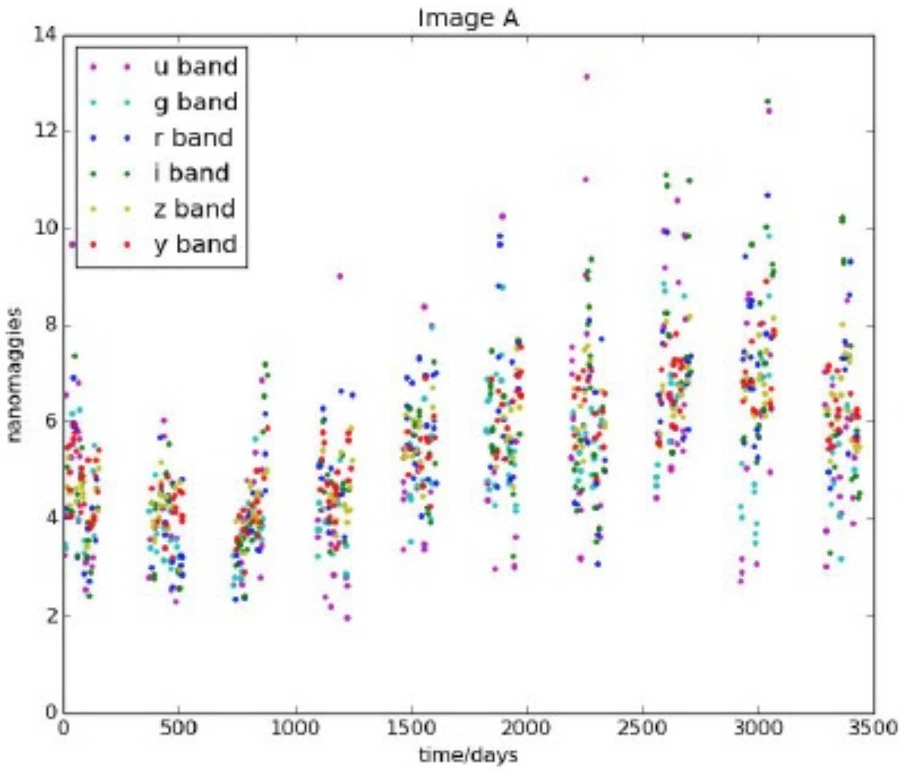
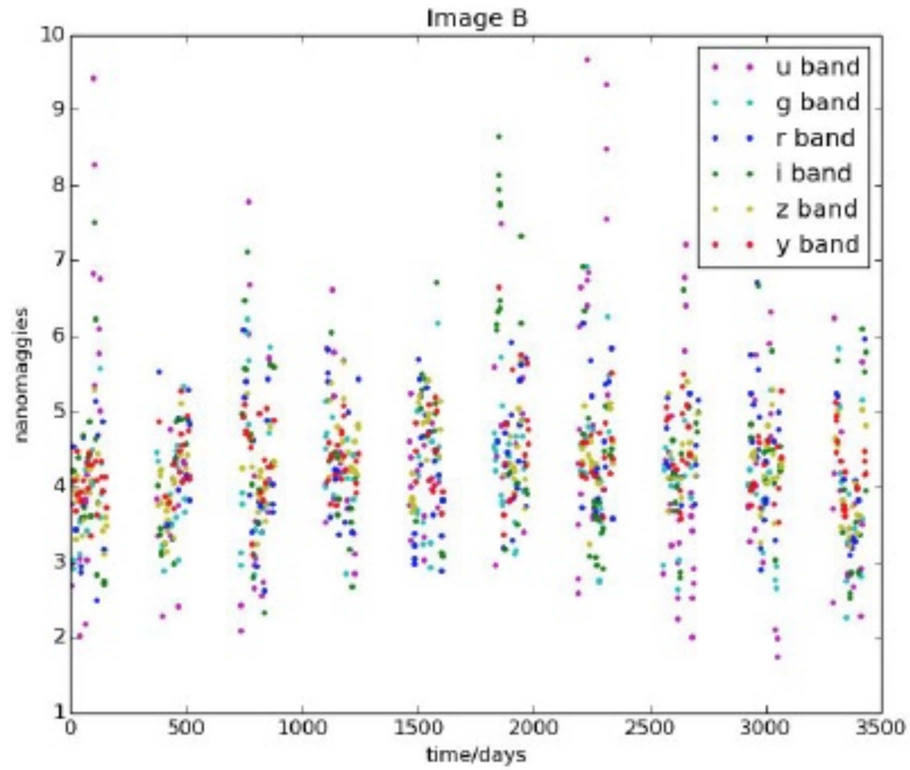
Time Delay Challenge 2 – even more evil (realism) to assess impact of multifilter cadence, and optimize.





- **AGN color variability**
- **Chromatic microlensing**
- **LSST OpSim model and feedback**

Evil Overlords: Phil Marshall, Kai Liao, Scott Daniel...

Coming in May!

Survey Followup Optimization

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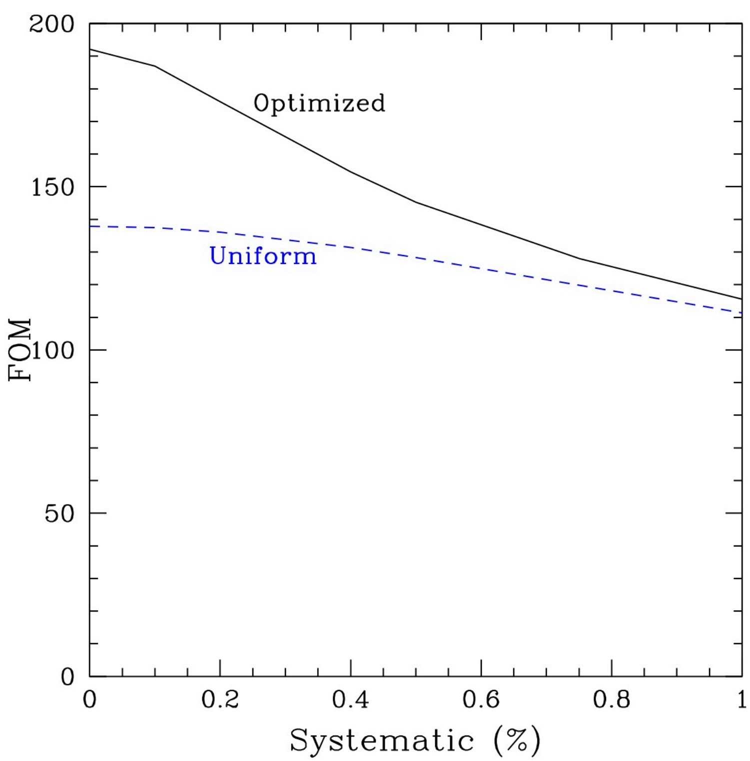
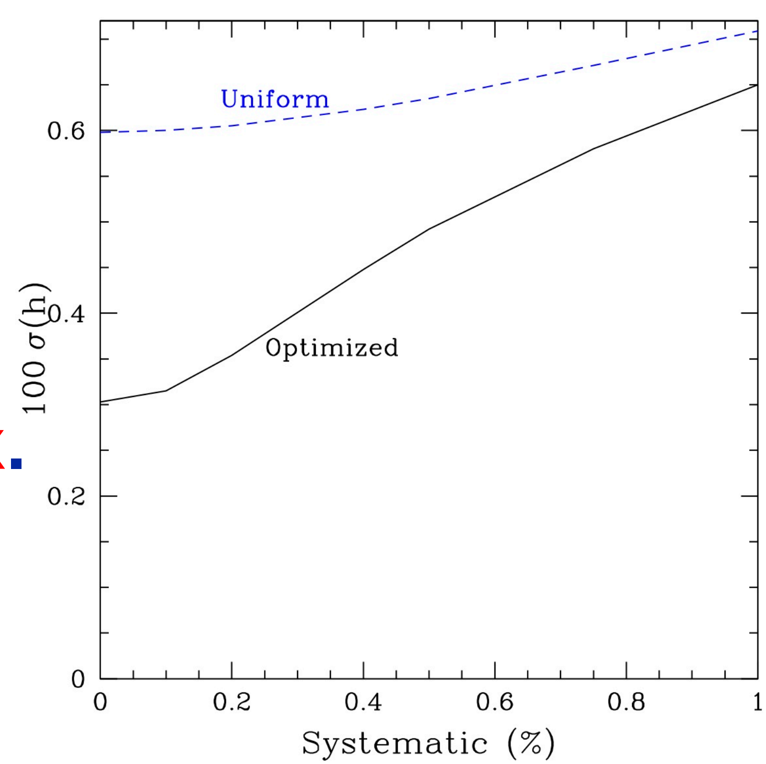
Wide field imaging surveys can't do it all. Need spectroscopy for lens galaxy profile modeling.

Must optimize cosmology leverage under fixed resource (spectroscopy time) constraints.

Fast, efficient optimization code Linder 2015.



Improve DE FOM by 40%, $\sigma(H_0)$ by 2x.



Sculpting Cosmology

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Fast, efficient optimization code: Merit vs cost

1) Where's the **leverage**? Starting from input distribution, subtract one system at each z and compute

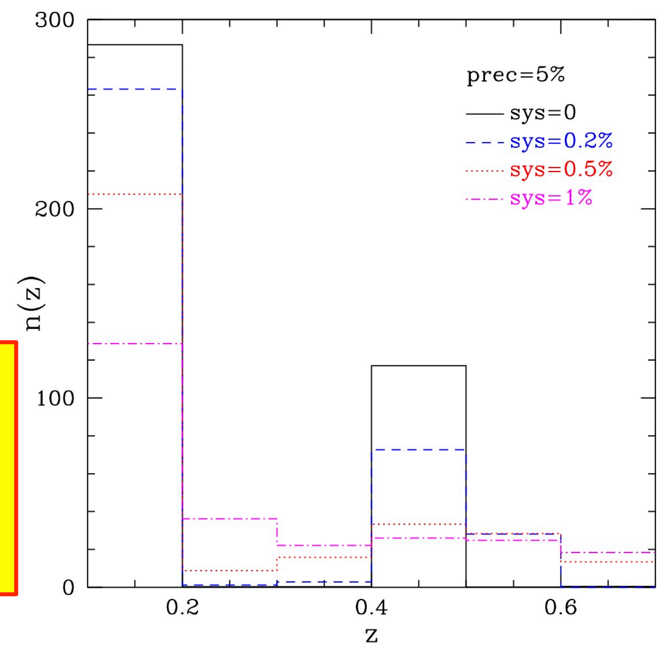
$$\dot{\rm FOM}_i = \frac{{\rm FOM(perturbed)} - {\rm FOM}}{\Delta t_i}$$

where Δt_i is the cost (time) at z_i.

2) **Reallocate** 1 from lowest leverage z_{sub} to others as

$$\Delta n_j = \Delta n_{\rm sub} \left(\frac{1+z_{\rm sub}}{1+z_j}\right)^8 \frac{\dot{\rm FOM}_j}{\sum_{k\neq{\rm sub}} \dot{\rm FOM}_k}$$

3) Compute new FOM and **iterate** to convergence.



Low redshift valuable, z_{lens}>0.5 not.

Double Source Plane Lensing

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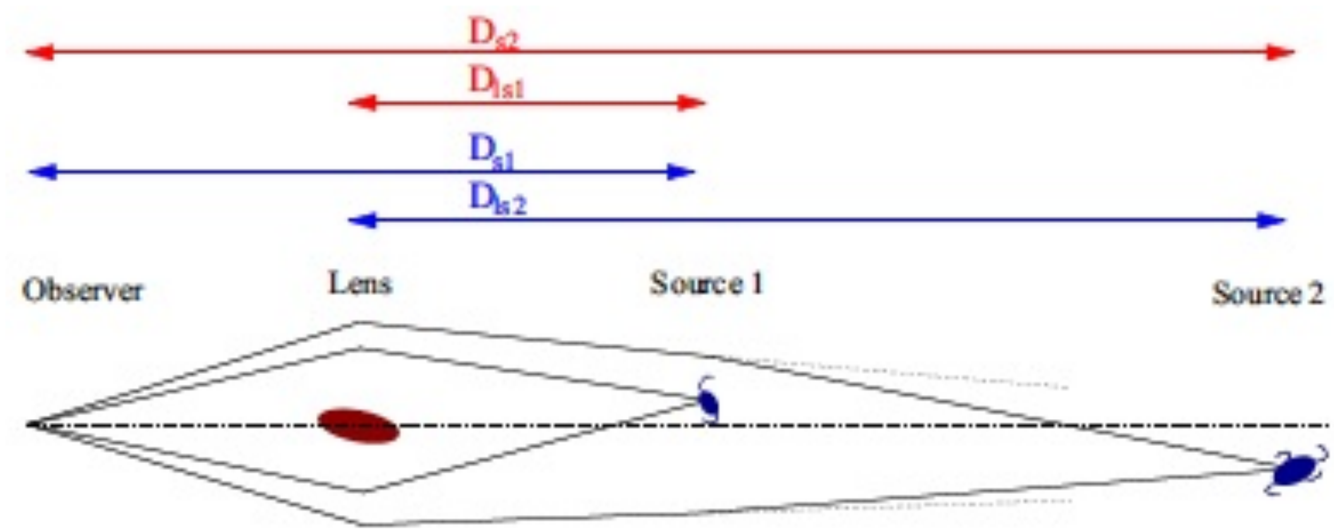

- **Possible new geometric probe.**
- **Ratio of Einstein radii ~ ratio of image separations.**

$$\frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}} \equiv \beta$$

- **Lens model ~cancels out.**
- **Independent of H_0.**

Collett+ 2012, Collett & Auger 2014

Double Source Plane Lensing

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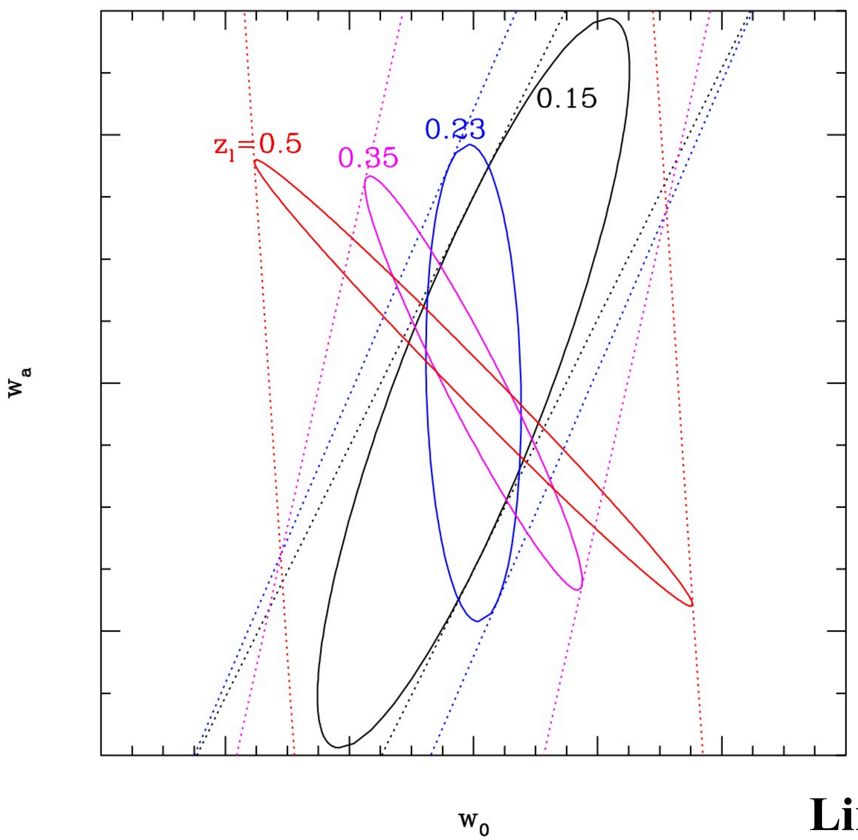
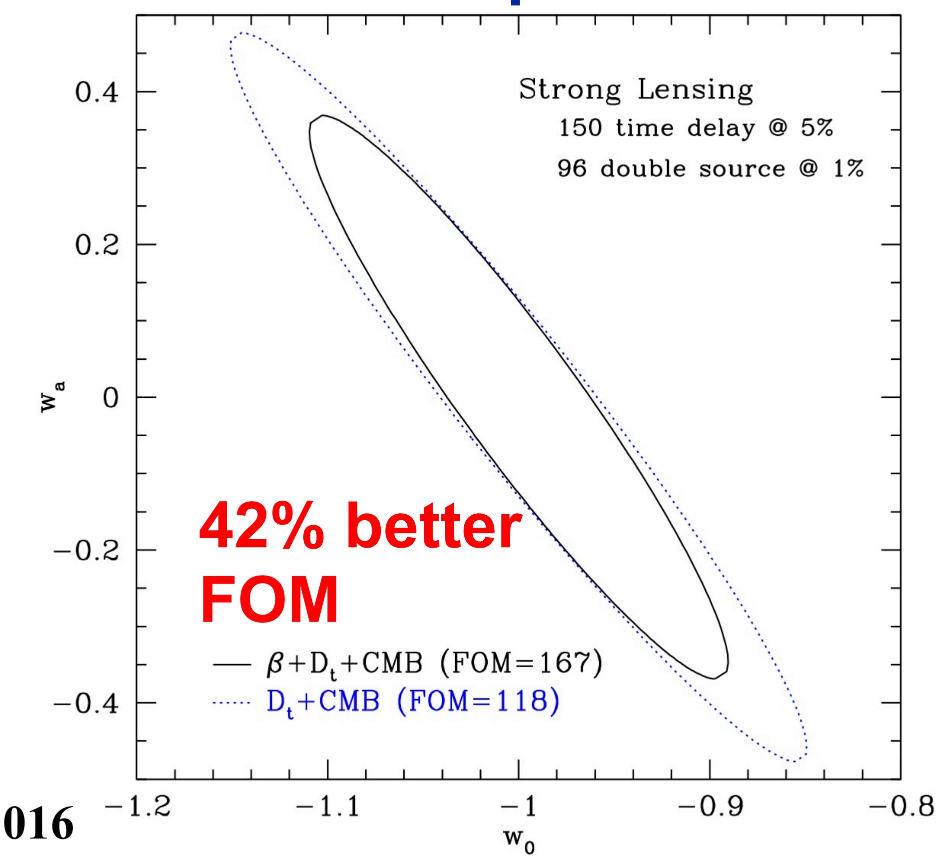
Weak cosmology probe by itself, but has good complementarity – opposite orientation of w_0-w_a!

Low redshift lenses have power.

Lots of work still to do, but strong lensing (time delays plus double sources) could be a good crosscheck probe.





Linder 2016

Summary & Future

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Strong lensing time delays give viable, strong new distance probe. DES, LSST will find $10^{3\text{-}4}$ lens systems.

Time Delay Challenge shows accuracy at cosmological requirement A<0.2% can be met. TDC2 bringing new levels of evil/realism – advanced statistics can inform survey strategy.

Followup optimization under constrained resources. Maximizing LSST + other facilities.

Double source plane lensing – a **new probe** with good complementarity.

What else can Future Sky Surveys and Big Data do in the time domain with clever statistical tools?

Panel Discussion on Time Domain

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Similarity/diversity of statistical techniques for cosmology/ microlensing/exoplanet surveys. E.g. *How to best handle inter-year missing observations (big gaps in time-series)?*

Complementarity of facilities for time domain science, e.g. wide surveys, long term monitoring, spectroscopic followup. E.g. *Who does spectroscopic follow-up of transients discovered by LSST?*

Big data future challenges and machine learning. E.g. *How to best match colors when observations in different filters are not simultaneous? Role of data challenges?*

Speculations on time domain discovery space - time scales, transients, multimessenger. E.g. *How do we do transient classification? Diversity of machine learning techniques?*