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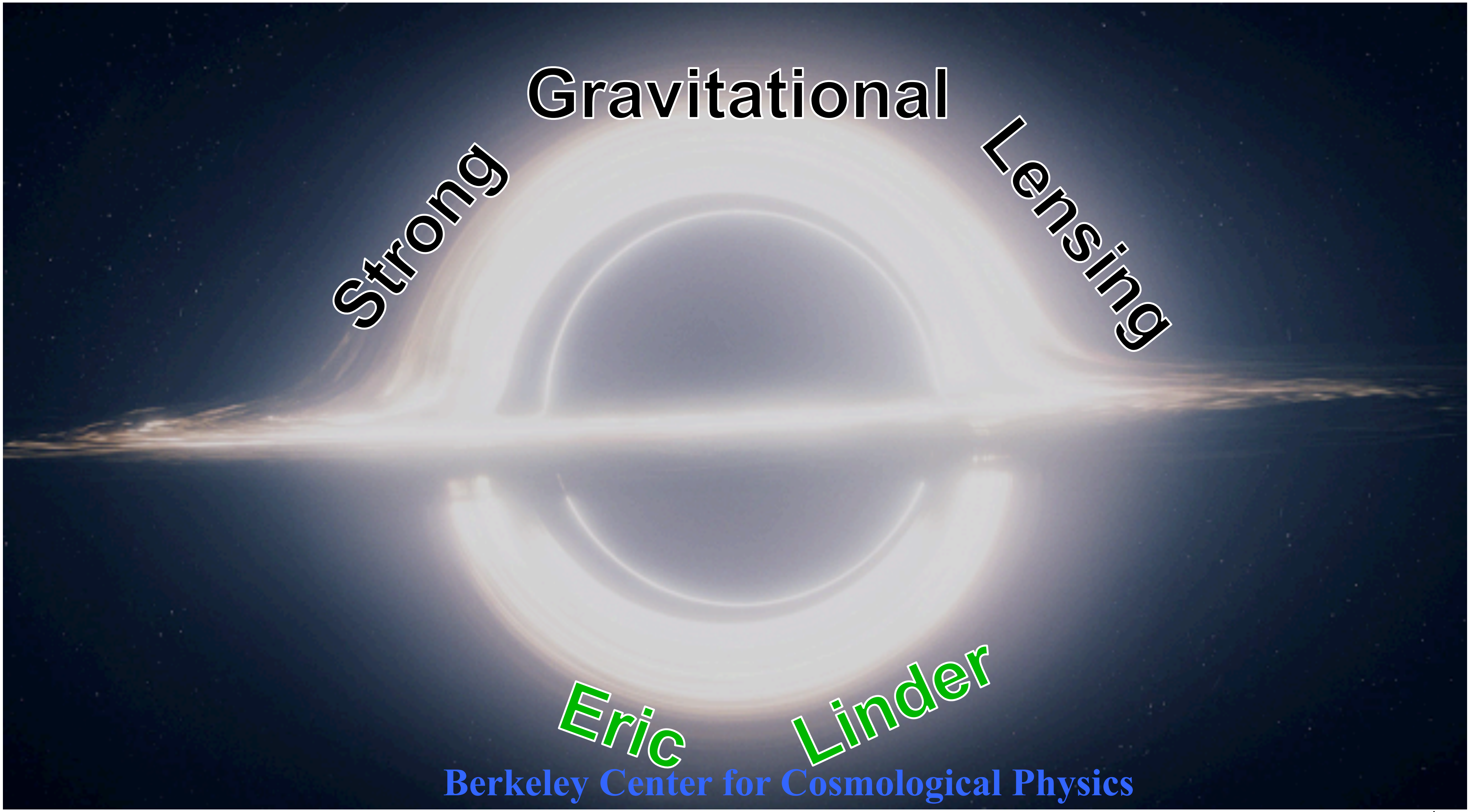
Reaching a Century: Classical and Modified General Relativity



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.

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.

Equivalence Principle

Einstein's Equivalence Principle:

Acceleration = Gravity = Curvature

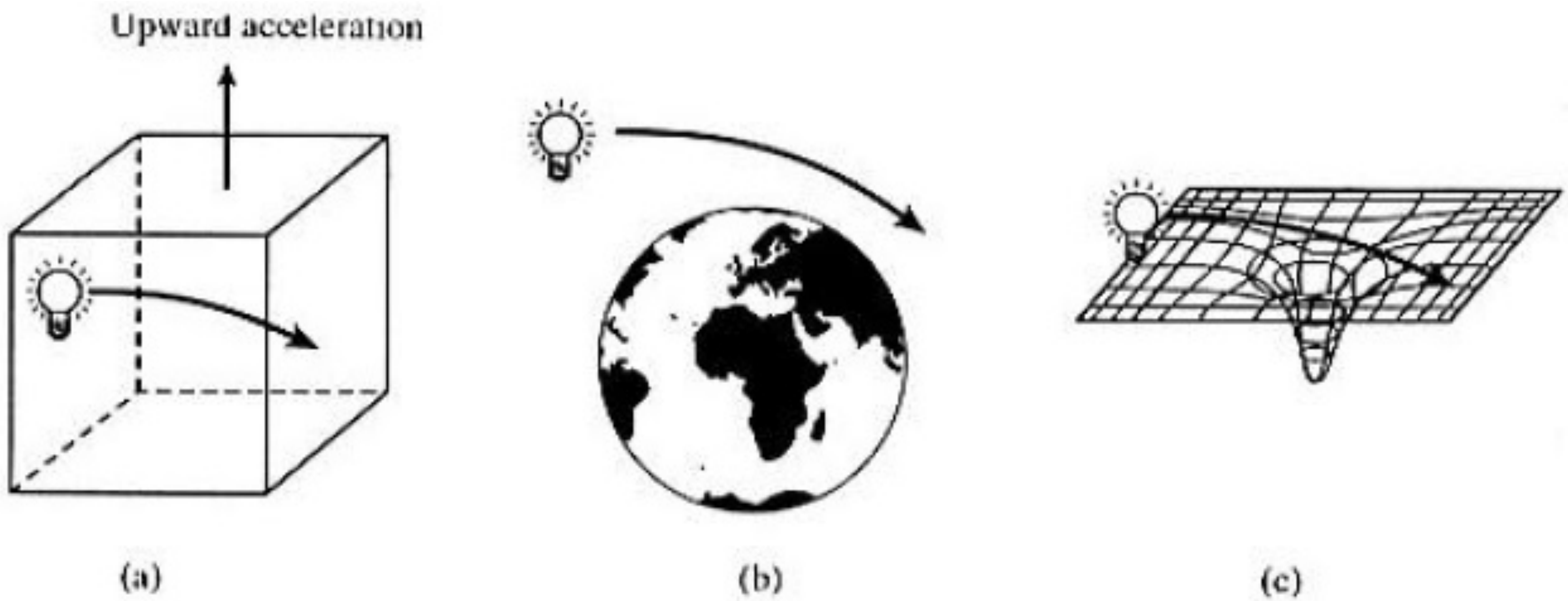

Figure 1.3 The motion of light equivalently interpreted as due to (a) acceleration in an elevator, (b) gravitational force of a mass, or (c) curvature of spacetime.

1st Test of General Relativity

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Einstein invented General Relativity with the measured precession of Mercury in mind.

The first testable prediction was of light bending – gravitational lensing – with value 2x Michell/Newton (today we would say the PPN parameter $\gamma=1$ not 0) because gravity bends light relative to the rulers (spacetime) plus spacetime bends also.

Light bending verified by Eddington 1919 solar eclipse expedition: Sun deflects by 1.75”.

But it took 16 more years (*pace* Chwolson) to develop strong gravitational lensing, i.e. that the light can bend along multiple paths to give multiple images.

Exercise

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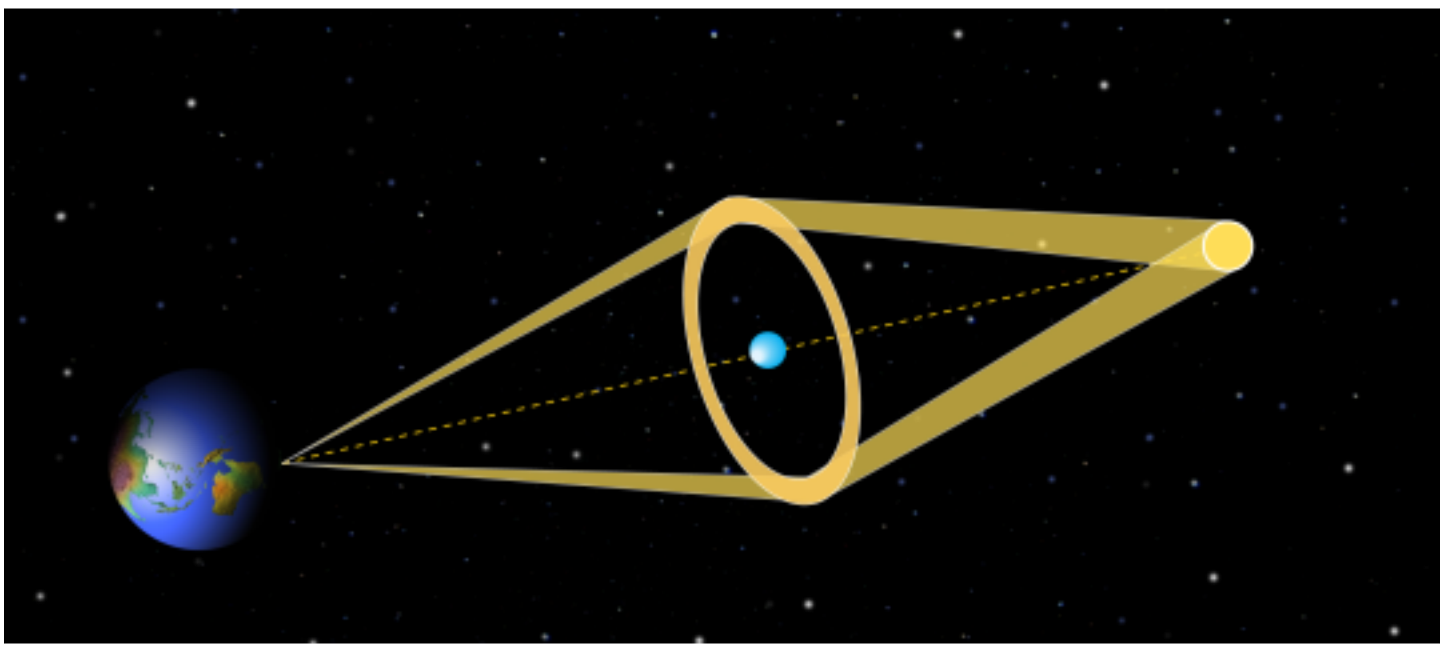
If you wanted to test GR during a solar eclipse by seeing multiple images, i.e. an Einstein ring, where would you need to be (in AU)?

Note 1 AU = 215 $R_{\odot}$.



Strong Gravitational Lensing

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Strong gravitational lensing:

Depends on the lens mass – so we can measure masses and mass distributions (MaCHOs, clusters)

Depends on the "focal length" – so we can measure cosmic distances.

Depends on theory of gravity – so we can test gravity (including in strong gravity regime?).

Magnifies (changes flux by changing sky area) – as a "gravitational telescope" so we can see very distant, faint objects or resolve AGN disks.

Strong / Weak / Micro

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Weak lensing is when a source gives a distorted image but not multiple images (shears a circle to an ellipse). Everything is weakly lensed at some level! (galaxies, CMB, 21 cm). Rule of thumb: WL good for mapping exterior regions (and total mass), SL good for internal structure.

Microlensing is when the multiple images are too close together to be resolved.

References:

Gravitational Lenses, Schneider, Ehlers, Falco (Springer-Verlag 1992)

Weak Gravitational Lensing and Its Cosmological Applications, Hoekstra & Jain, Ann. Rev. Nuc. Part. Sci 2008

Gravitational Lensing: Strong/Weak/Micro, Kochanek, Schneider, Wambsganss (Saas-Fee Lectures 2004)

Strong Lensing

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

New!

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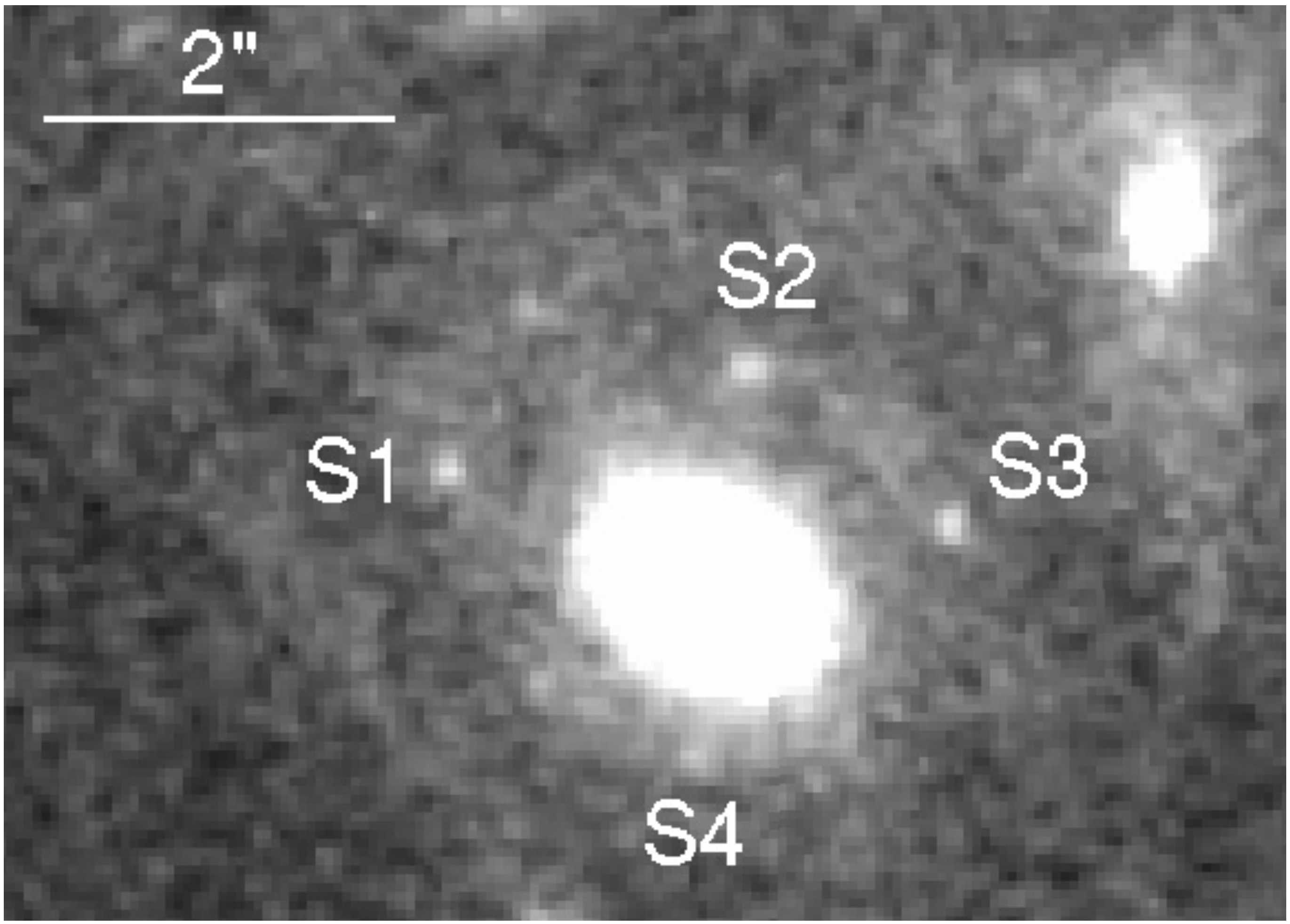
First multiply imaged supernova detected 1 week ago! Not just seeing a SN at z=1.49, but seeing it at 4 different times/phases, all at once! Kelly+, arXiv:1411.6009



Strong Lensing Time Delays

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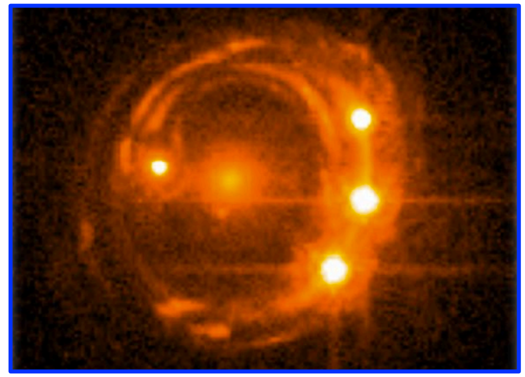
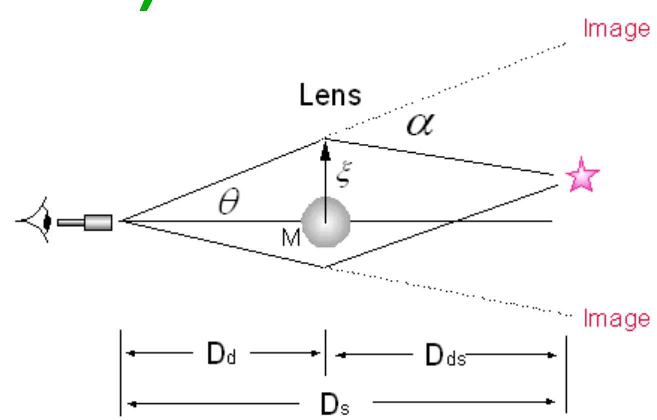
Strong gravitational lensing creates multiple images (light paths) of a source.



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

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



Hubble constant

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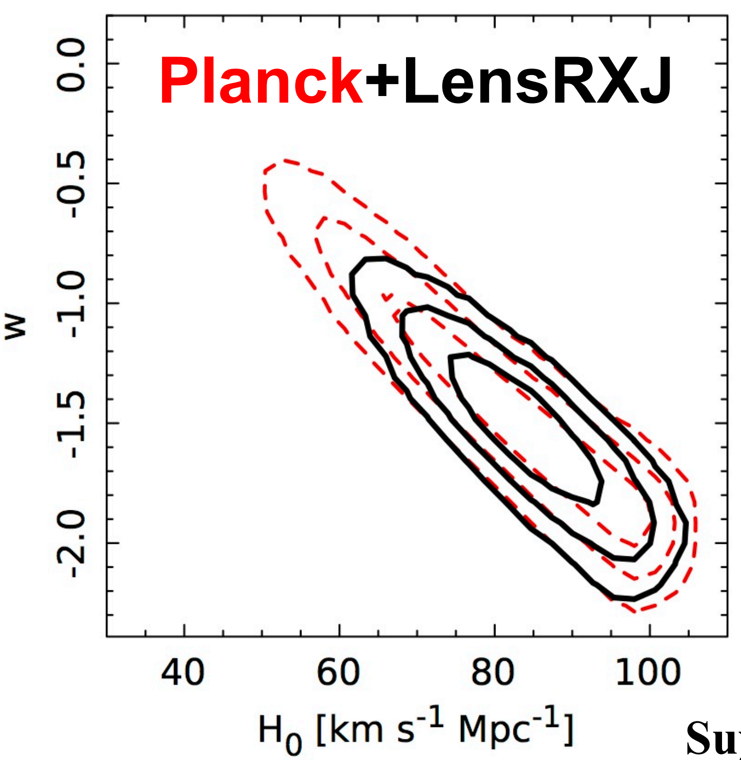
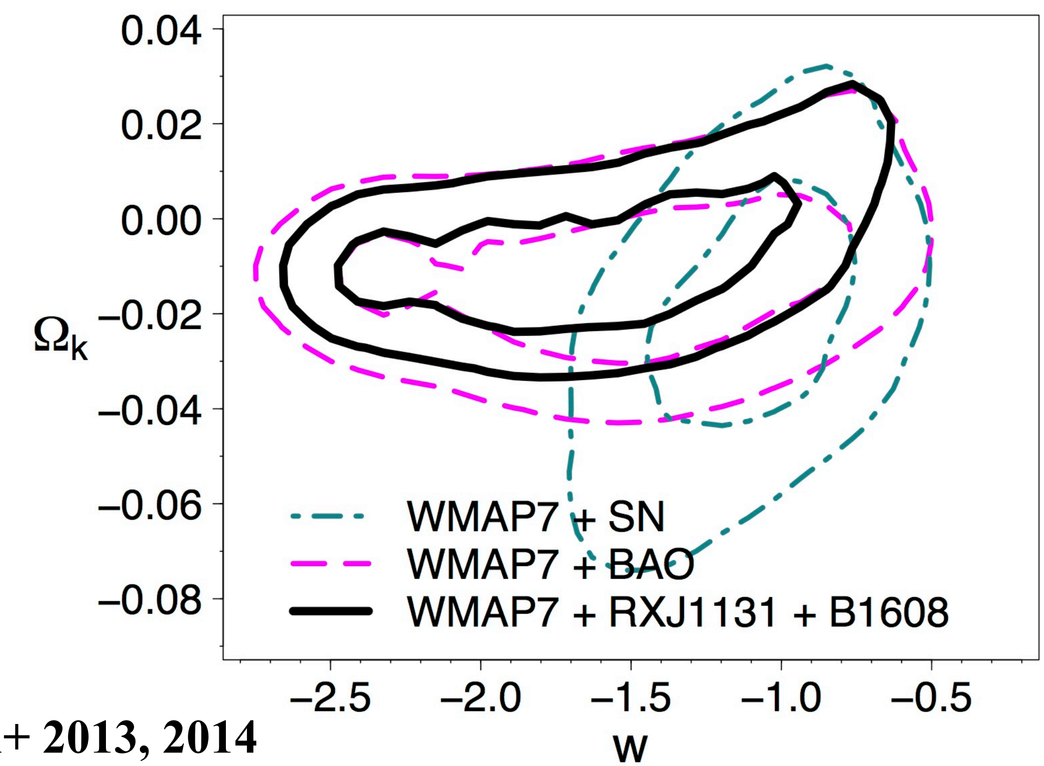
Since we observe a dimensional quantity, the time delay, we can measure the absolute distance, and hence the Hubble constant H_0. First proposed by Refsdal 1964, but just now becoming robust.

Even 1 or 2 good lenses are powerful!





Suyu+ 2013, 2014

Strong Lens Factories

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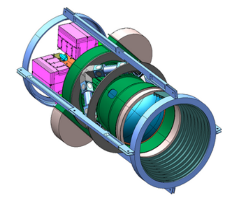
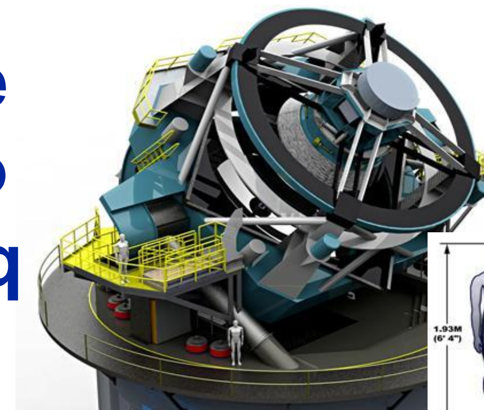
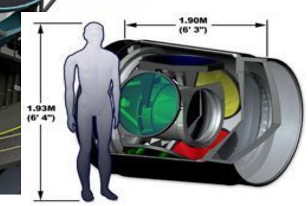


The Dark Energy Survey (**DES**) is underway at CTIO. It covers 5000 sq deg in 5 years.

Output: ~800 lensed AGN.





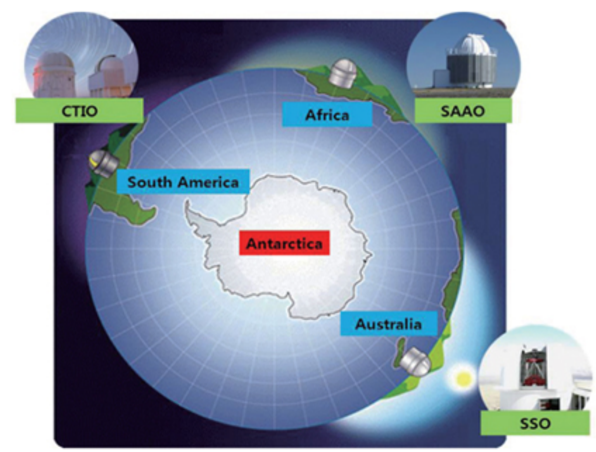
Large Synoptic Survey Telescope (**LSST**) will start in ~2020 at Cerro Pachon, Chile, covering 20,000 sq deg repeatedly in 10 years.

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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Best current distances are at 5% accuracy (16 systems known, 2 at 5%, +3 HST ongoing).

5 year aim: 25 systems with full follow-up (150 orbits Hubble Space Telescope). Long term: 1% distances.

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: GMT-AO; radio?).

Monitoring currently done with COSMOGRAIL network of 1.2-1.5m telescopes.

Time Delays + Supernovae

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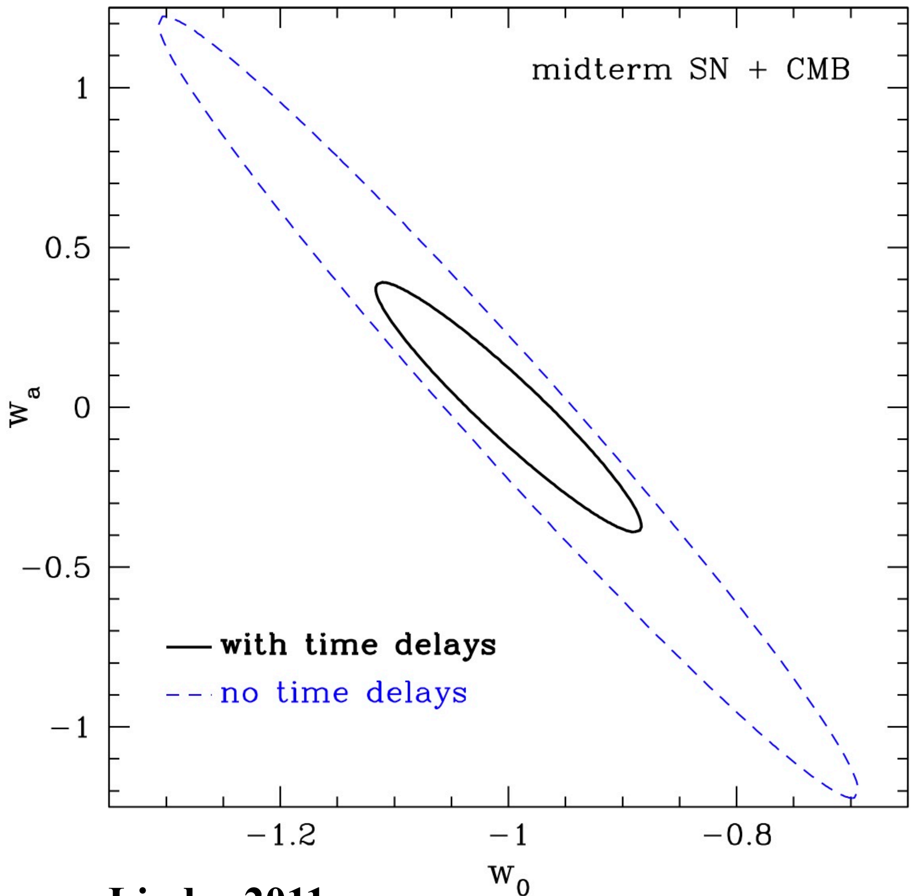
Lensing time delays give superb complementarity with SN distances plus CMB.



Linder 2011

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

5 year goal is to monitor 25-50 lens systems.

Ω_m to 0.0044
h to 0.7%
w_0 to 0.077
w_a to 0.26
immunizes vs curvature

Strong Lensing Cosmology

The Challenges:

Time delay estimation –

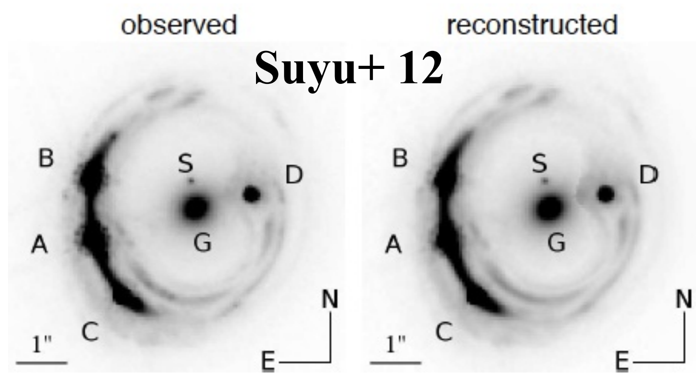
Time Delay Data Challenge: arXiv:1310.4830, 1409.1254

Blind analysis has achieved sub% accuracy

Lens modeling –

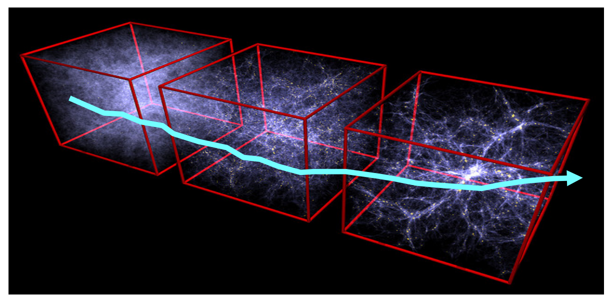
HST, Adaptive Optics

Strong advances



Line of sight mass –

Important role for simulations and xcorrs.



κ_{ext} from galaxy counts Greene+ 13 , all photometric info Collett+ 13, also see McCully, Keeton, Wong, Zabludoff 2014

Measuring Time Delays

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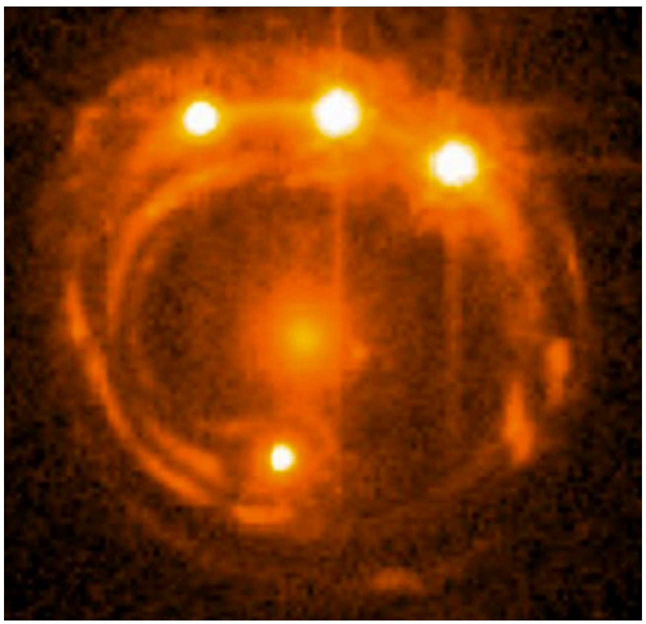
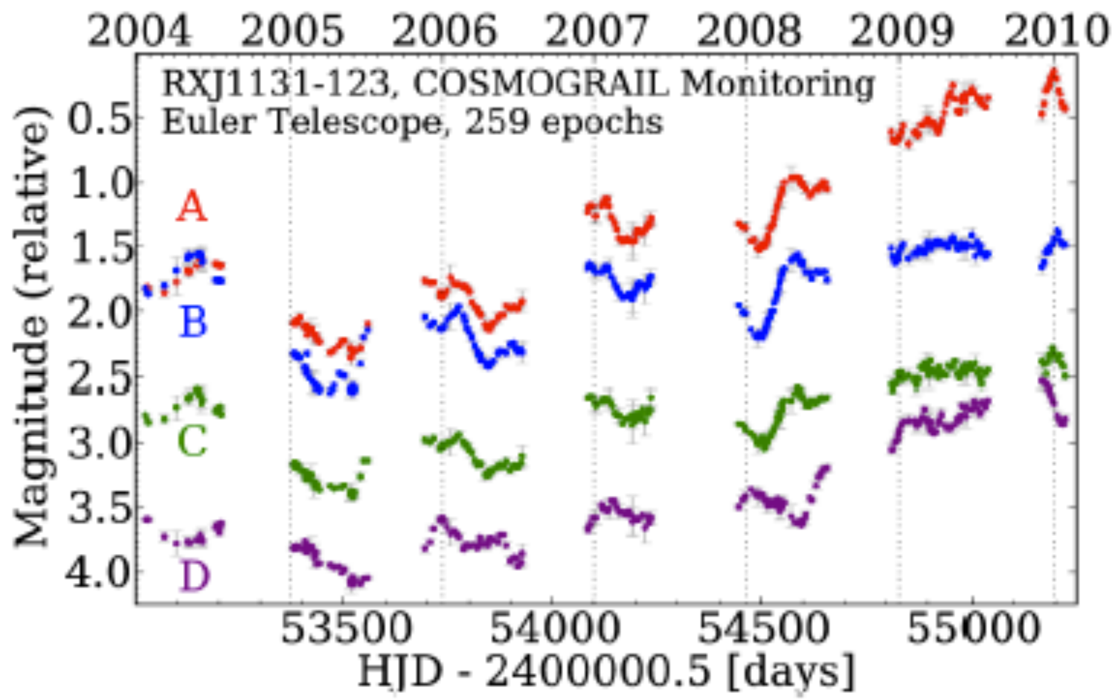
One of the challenges is measuring time delays between images in the presence of
1) noise, 2) gaps, 3) variability, 4) microlensing.





Time Delay Data Challenge

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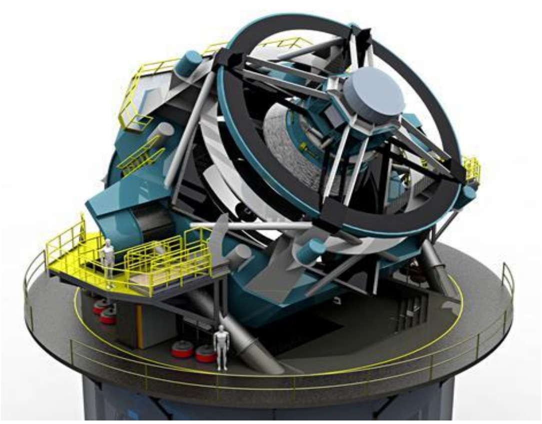
We use Gaussian Process statistics to find a family of light curves fitting the data, with correlations. Factor of 2 improvement over previous literature.

Real data: accurate and more precise than literature.

Kernel	Δt_{AB}	Δt_{AC}	Δt_{AD}	Δt_{BC}	Δt_{BD}	Δt_{CD}
HE 0435-1223 GP-DRW	-9.5 ± 0.3	-1.9 ± 0.4	-15.6 ± 0.3	8.1 ± 0.3	-6.0 ± 0.3	-13.6 ± 0.4
HE 0435-1223 Lit(1) [3]	-8.4 ± 2.1	-0.6 ± 2.3	-14.9 ± 2.1	7.8 ± 0.8	-6.5 ± 0.7	-14.3 ± 0.8
HE 0435-1223 Lit(2) [27]	-8.8 ± 2.4	-2.0 ± 2.7	-14.7 ± 2.0	6.8 ± 2.7	-5.9 ± 1.7	-12.7 ± 2.5

Hojjati, Kim, Linder 2013



Just finished participating in blinded Time Delay Data Challenge to reach next generation accuracy. Achieved 0.2% accuracy in TDC1!

Gaussian Process Fits

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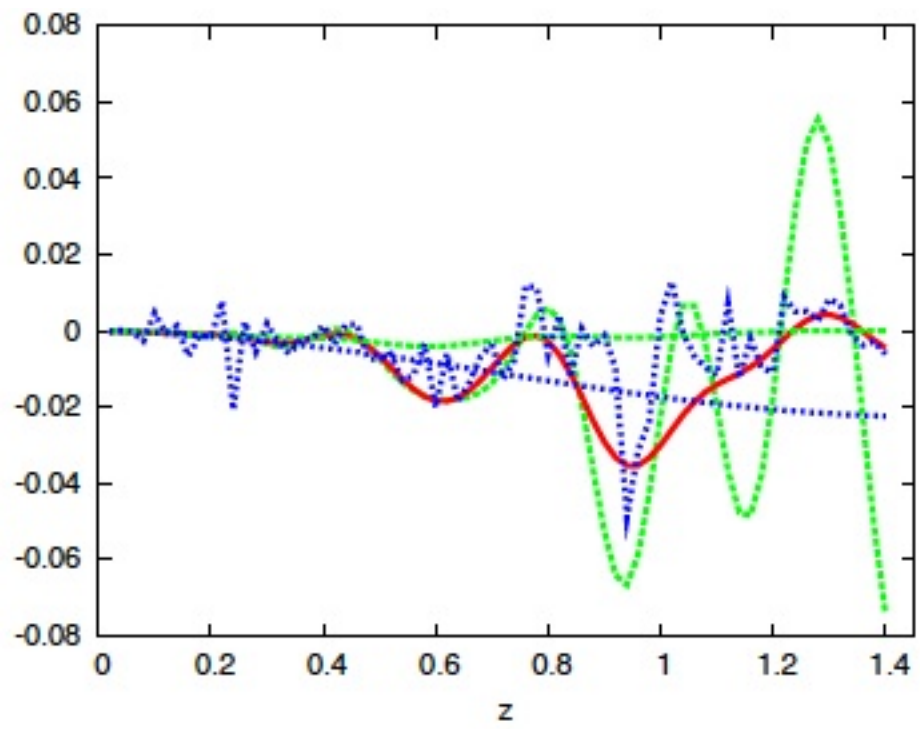
Gaussian Processes find a family of curves fitting the data; useful for regression of noisy, gappy data in a model independent manner, with clear error estimation.

The correlation function (kernel) determines the result and the hyperparameters give valuable information.

Red → green: change amplitude

Red → blue: change correlation length



Gaussian Process Fits

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$$2\ln\mathcal{L}(Y|\vec{\theta}) = -Y^T K^{-1} Y - \ln|K| - N_d \ln 2\pi$$

Gives best fit with least complexity. Hojjati & Linder 2014

Efficient, parallel code by Hojjati.

We crosscheck with two kernels, two minimizers and assess confidence with gold/silver/bronze (Lannister/Targaryen/Baratheon) classification.

Microlensing is fit simultaneously with the time delay and teaches us about dark matter substructure in the lens galaxy.

Strong lensing probes DE and DM (and H_0).

Time Delay Challenge

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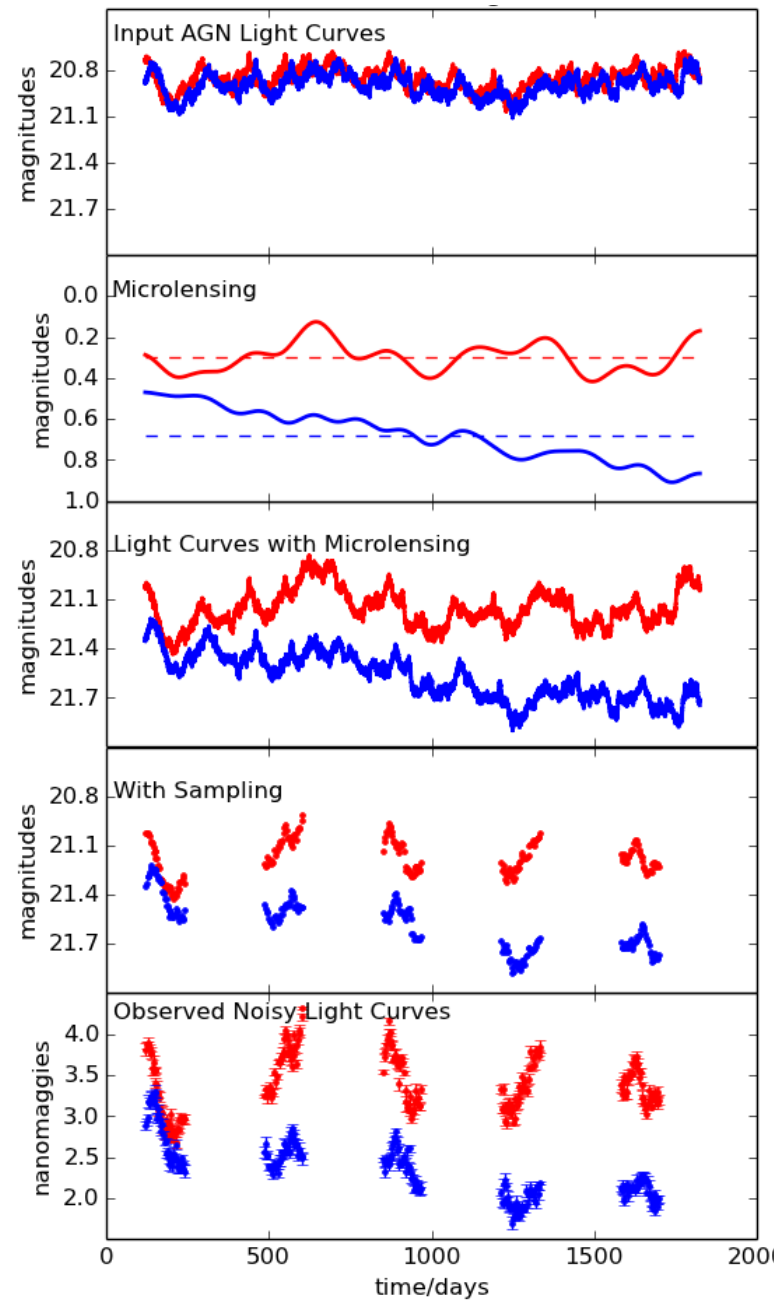
"Evil Team" (Liao, Dobler, Fassnacht, Marshall, Rumbaugh, Treu) **simulates AGN lightcurve, microlensing, obs/photo/sys noise, sampling.**

7 "Good Teams" passed TDC0 to enter TDC1.

10 different approaches ranging from fully automated to human-intensive.



arXiv:1409.1254

TDC 1

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TDC1 intended to inform cadence/survey trades. 5000 lightcurve pairs with "rungs" of different cadence/season/campaign length.

Rung	Mean Cadence (days)	Cadence Dispersion (days)	Season (months)	Campaign (years)	Length (epochs)
0	3.0	1.0	8.0	5	400
1	3.0	1.0	4.0	10	400
2	3.0	0.0	4.0	5	200
3	3.0	1.0	4.0	5	200
4	6.0	1.0	4.0	10	200

Results in brief:

**6 day cadence significantly weakens science.
Major effect just from number of epochs.
Short season reduces fit fraction.
Several methods (eye→automated) successful.**

Cosmology Requirements

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Precision can be traded against numbers.
More important is bias.

A systematic in time delay estimation propagates into the time delay distance and biases cosmological parameters.

If the systematics is redshift independent, this all goes into H_0. If redshift dependent (or in presence of other data/priors), it biases all parameters.

Estimate cosmology requirement on misestimation through Fisher bias formula.

$$\delta p_i = (F^{-1})_{ij} \sum_z \frac{\partial D_{\Delta t}}{\partial p_j} \frac{1}{\sigma^2(D_{\Delta t})} \Delta D_{\Delta t}$$

Knox, Scoccimarro, Dodelson 1998

Cosmology Requirements

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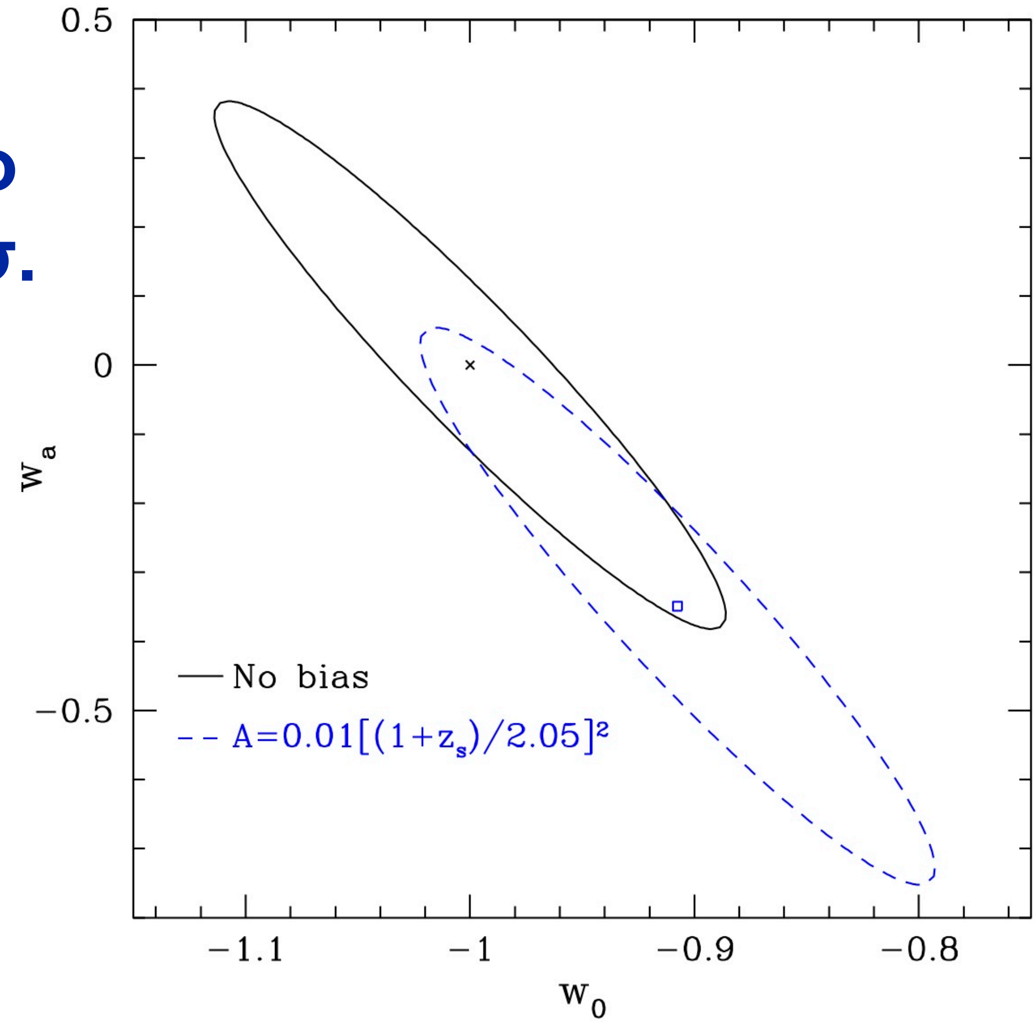
We want A= $\Delta D_{\Delta t}/D_{\Delta t}$ estimated accurately so parameters shift by <1σ.



Time delay estimation is only one of the uncertainties entering distance.

Final requirement:

A < 0.2%

Hojjati & Linder 2014

Gaussian Process Results

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Rung	f	χ^2	P	A
0	0.48	1.07	0.0578	-0.0005
1	0.36	1.11	0.0617	-0.0010
2	0.31	1.14	0.0854	-0.0000
3	0.29	1.67	0.0688	-0.0019
4	0.36	1.92	0.0909	-0.0036
Avg	0.36	1.36	0.0717	-0.0014
Avg[3d]	0.36	1.22	0.0669	-0.0008

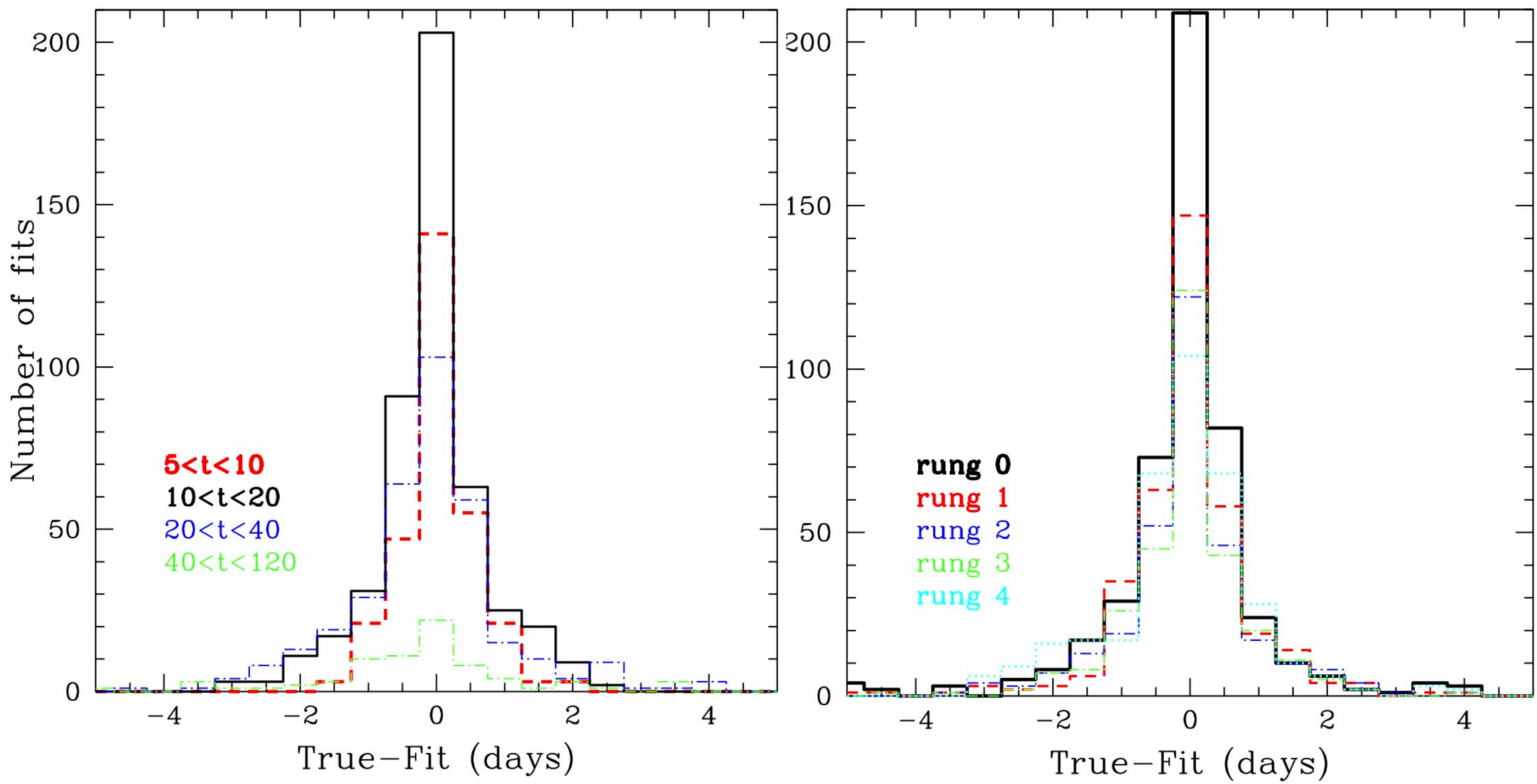
Hojjati & Linder 1408.5143

We optimized our pipeline for full automation and focused on accuracy.

Fulfilled next generation requirement A<0.2%!

Unbiased with respect to true time delay length, robust to variations in cadence (<6 days), survey.

Gaussian Process Results



Well peaked, symmetric distributions.

Time Delay Probe

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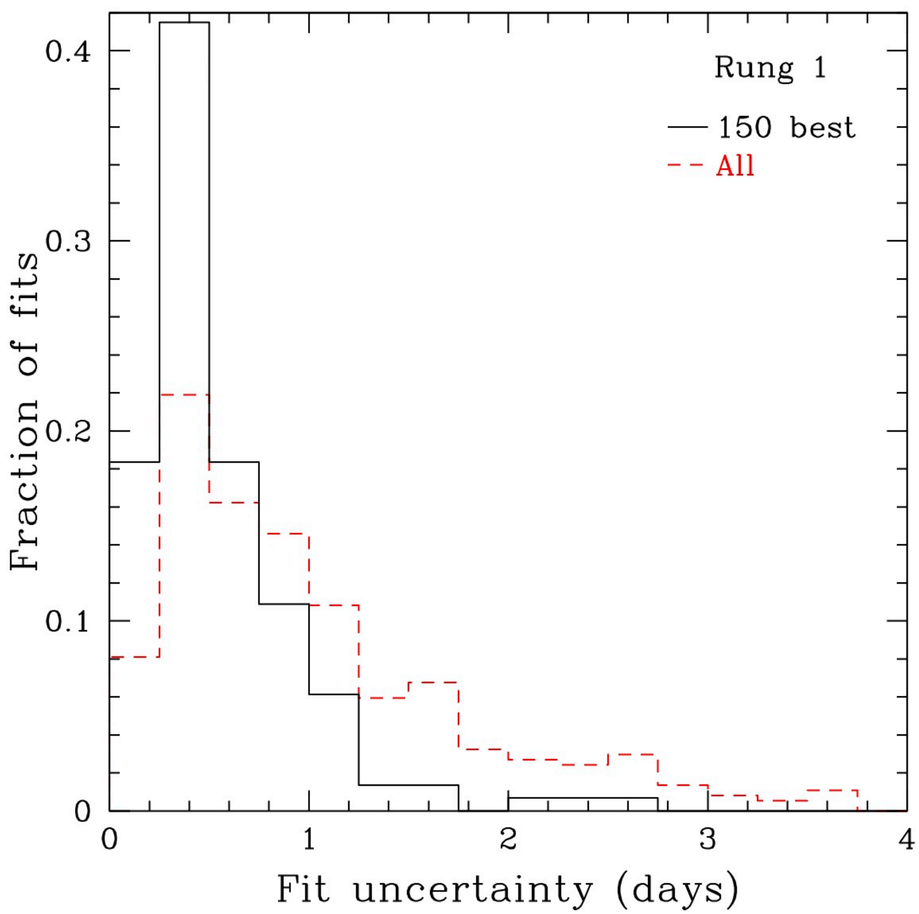
We can improve further by trading numbers for precision, e.g. take 150 most precisely measured systems. (Recall Linder 2011 found 150 systems gave excellent cosmological complementarity and h to 0.005.)



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.

Time Delay Distances

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Future work:

Study distribution of microlensing hyperparameters to learn about dark matter substructure.

New time delay fits given to Suyu for H_0 estimation (H0LiCoW). Recall Planck fills H_0 prior for wCDM, but H_0 to 7% when add 2 lenses (Suyu+ 2014).

Full covariance matrix for strong lensing distance probe, accounting for not just time delay estimation but mass along line of sight κ_{ext} (with simulations), lens mass profile γ, etc.

Test Gravity

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Test gravity in model independent way.

Gravity and growth: $\nabla^2\phi = 4\pi G\, a^2\, \delta\rho$

Gravity and acceleration: $-\vec{\nabla}\psi = \ddot{x}$

Are ϕ and ψ the same? (yes, in GR)

Tie to observations via modified Poisson equations:

$$\nabla^2(\phi + \psi) = 8\pi G_N\, a^2\, \delta\rho \times G_{\rm light}$$

$$\nabla^2\psi = 4\pi G_N\, a^2\, \delta\rho \times G_{\rm matter}$$

$G_{\rm light}$ tests how light responds to gravity: central to lensing and integrated Sachs-Wolfe.

cf Bertschinger & Zukin 2008

$G_{\rm matter}$ tests how matter responds to gravity: central to growth and velocities (γ is closely related).

Testing Gravity

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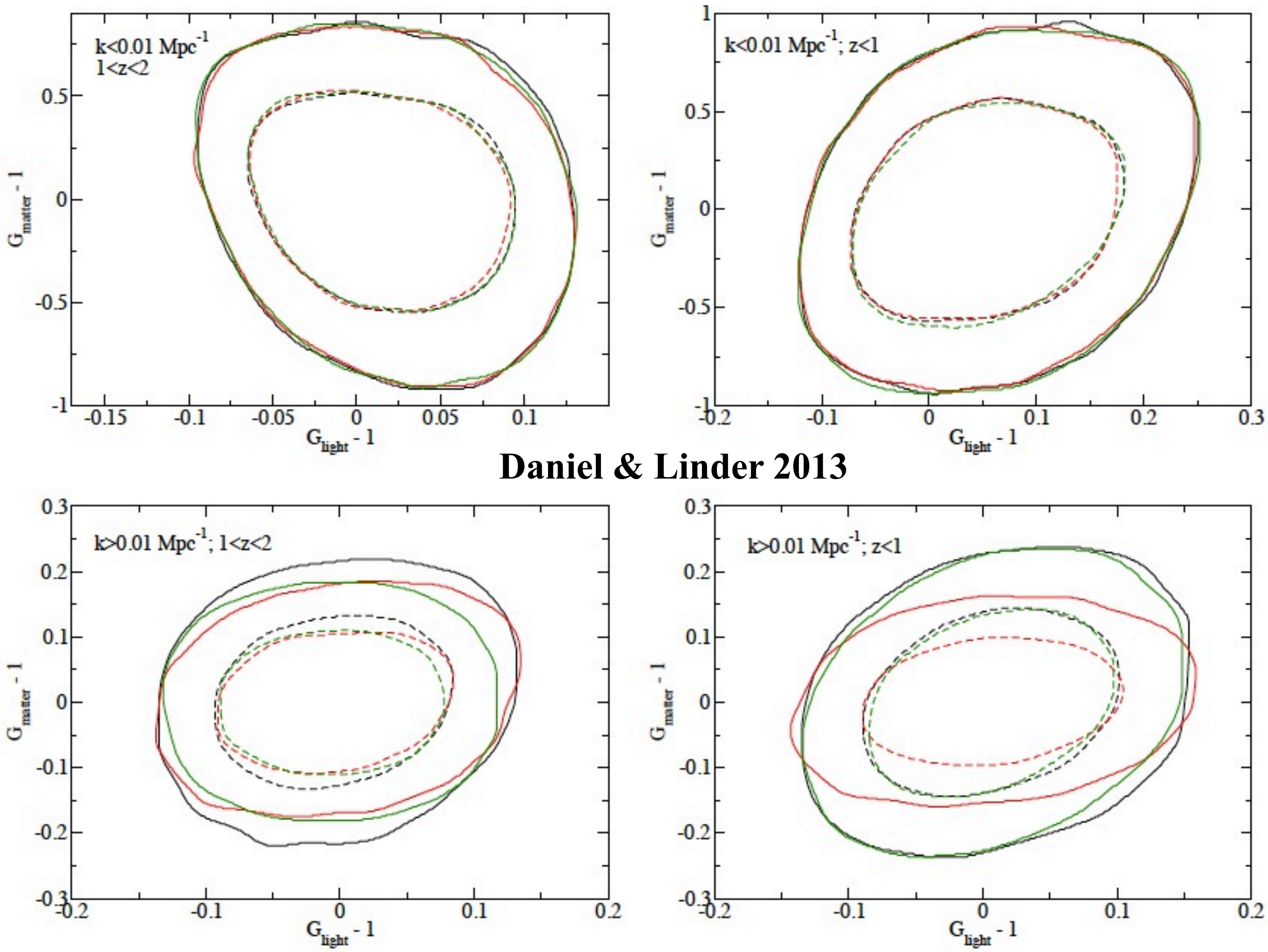
Model independent tests of gravity: two functions, at high/low z, high/low k (8 tests). Simultaneous fit for gravity, expansion (w_0, w_a), galaxy bias (27 bins).



Daniel & Linder 2013

DESI/Euclid +Planck

(even better with LSST WL)

Fit all

Fix to Λ

Fix to b~1/D

Strong Gravity

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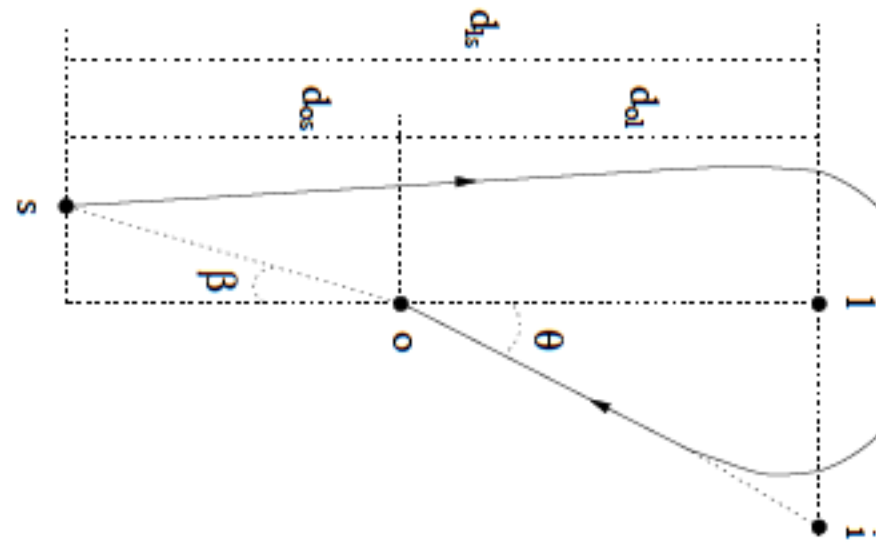
Retrolensing: Seeing yourself in the cosmos!, "Pi in the sky" Holz & Wheeler 2002



Probes down to 1.75 R_S – strong gravity regime.
Black hole early warning system: LSST could find 10 $M_\odot$ BH out to 1000 AU by looking for our Sun!

Strong Gravity

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Strong lensing images can also test the metric of a spinning black hole.

Strong lensing time delays of AGN may reveal inner structure – details of black hole accretion.

Accretion disk / tidal disruption will undergo Lense-Thirring precession, giving time variation signature (X-rays).

Event Horizon Telescope sub/mm VLBI – Mexico's GTM/LMT?

Summary & Future

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Strong lensing time delays give viable, strong new distance probe. Measures H_0, dark energy, dark matter substructure.

DES, LSST will find $10^{3\text{-}4}$ lens systems.

Time Delay Challenge shows accuracy at cosmological requirement A<0.2% can be met.

Hubble Frontier Fields: clusters as gravitational telescopes – galaxies to z>10, m<32.

Lensing also tests gravity – one potential or two?

Strong lensing may test strong gravity.
Good research projects!