Constraining Dark Energy with Double Source Plane Strong Lenses

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With:
Matt Auger, Vasily Belokurov,
Phil Marshall and others

ArXiv:1203.2758, ArXiv:1303.6564
and unpublished work

Strong lensing is an optical bench

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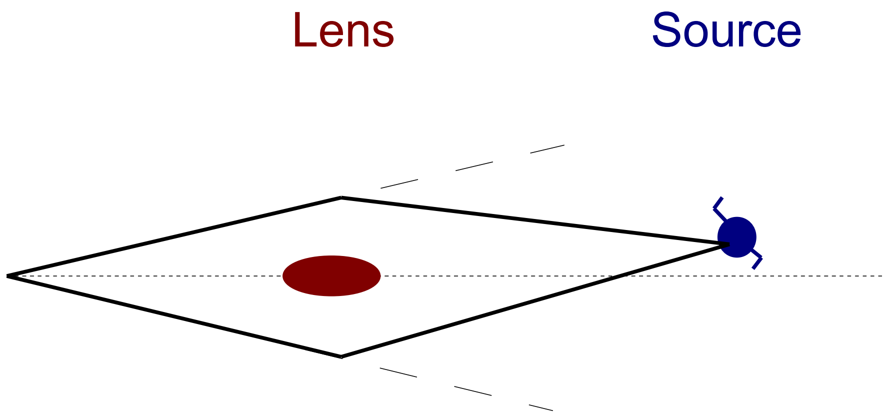

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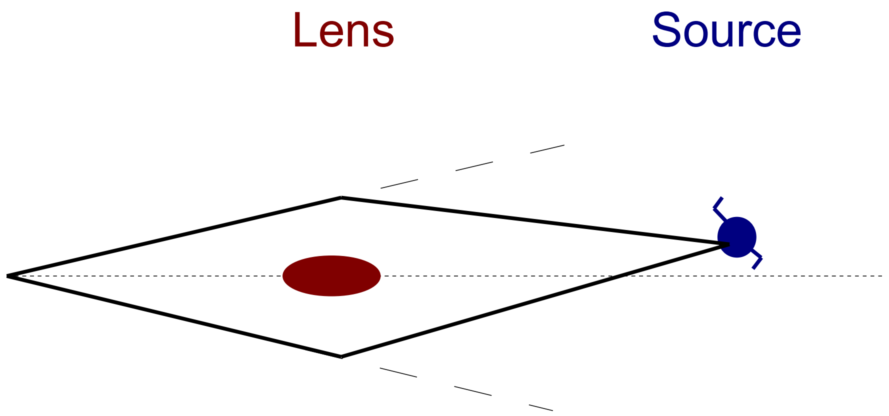

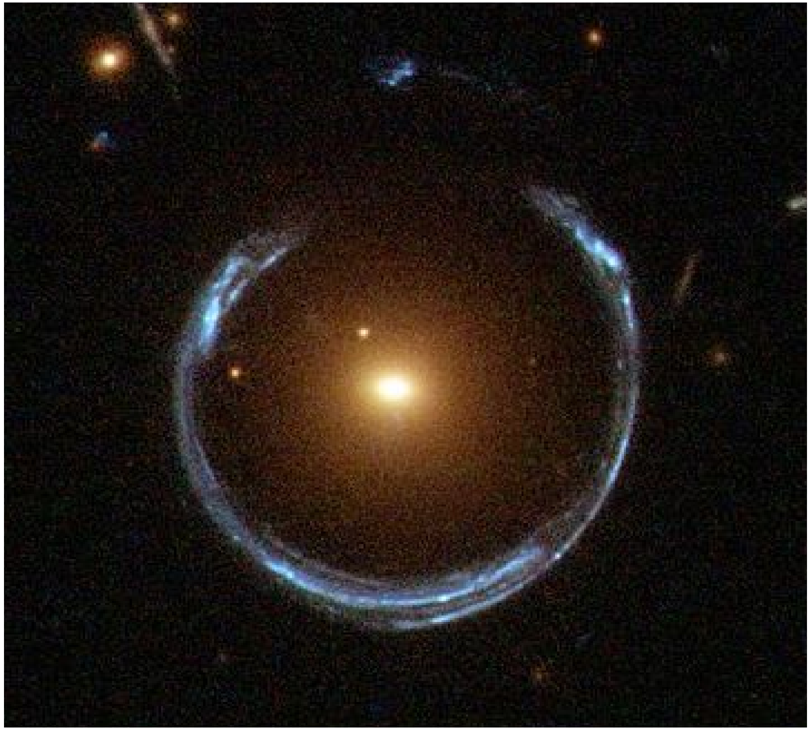

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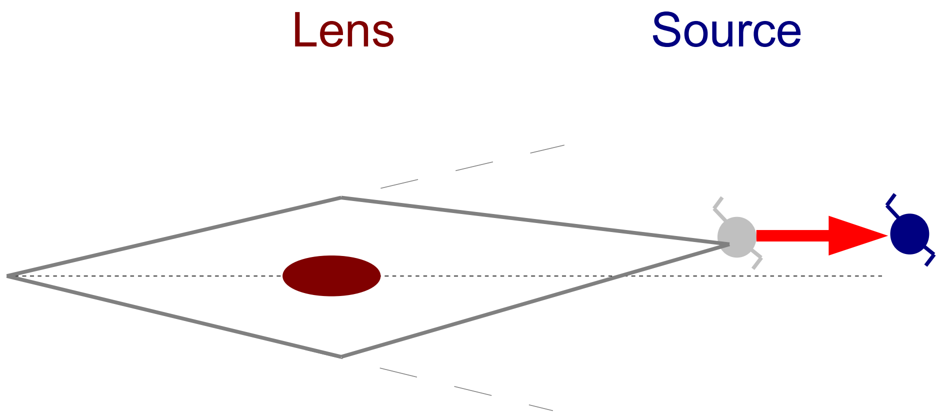

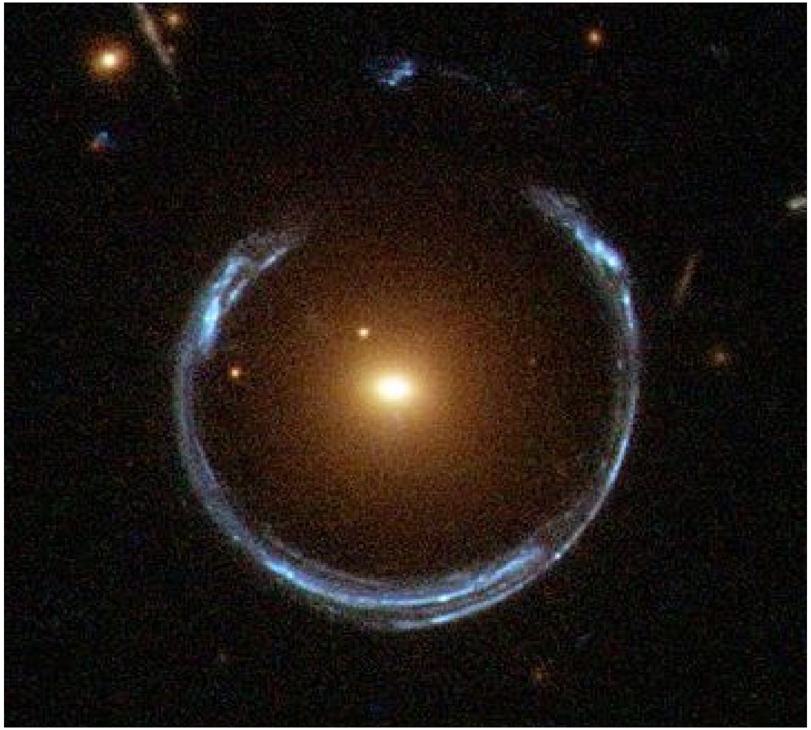

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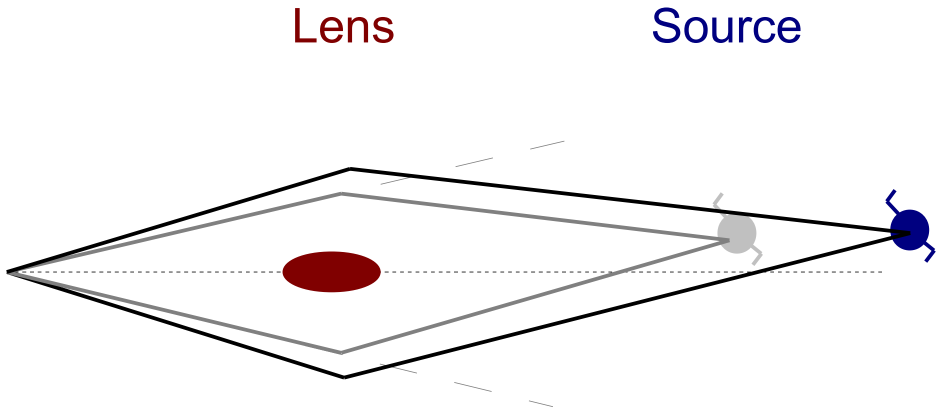

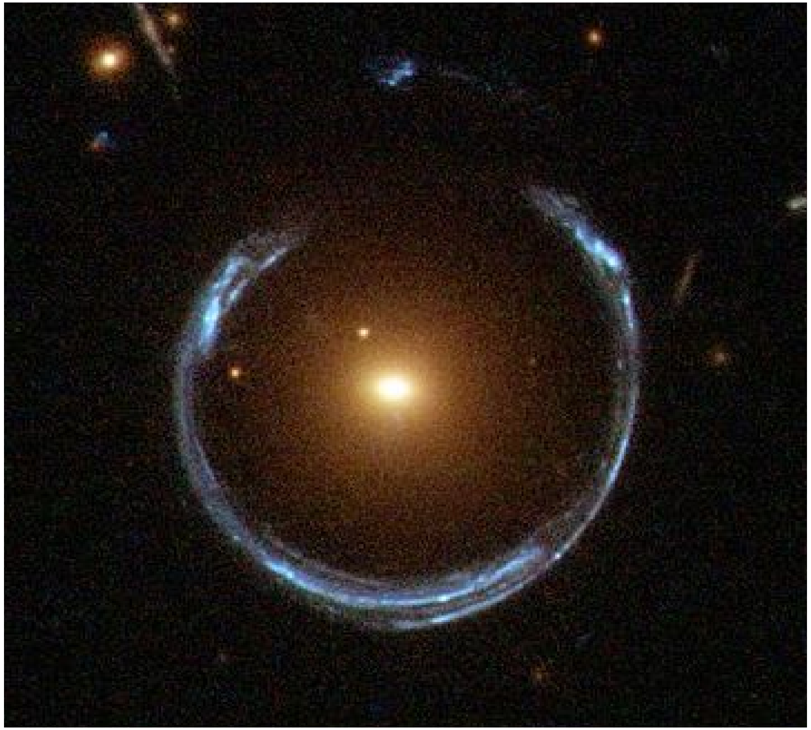

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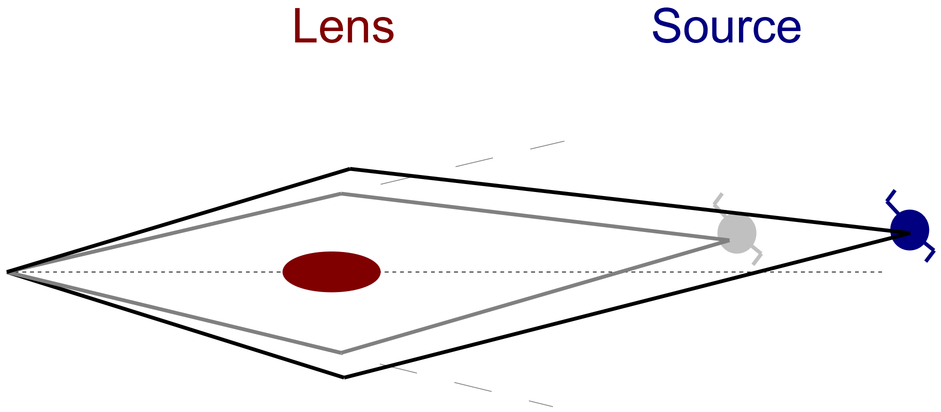

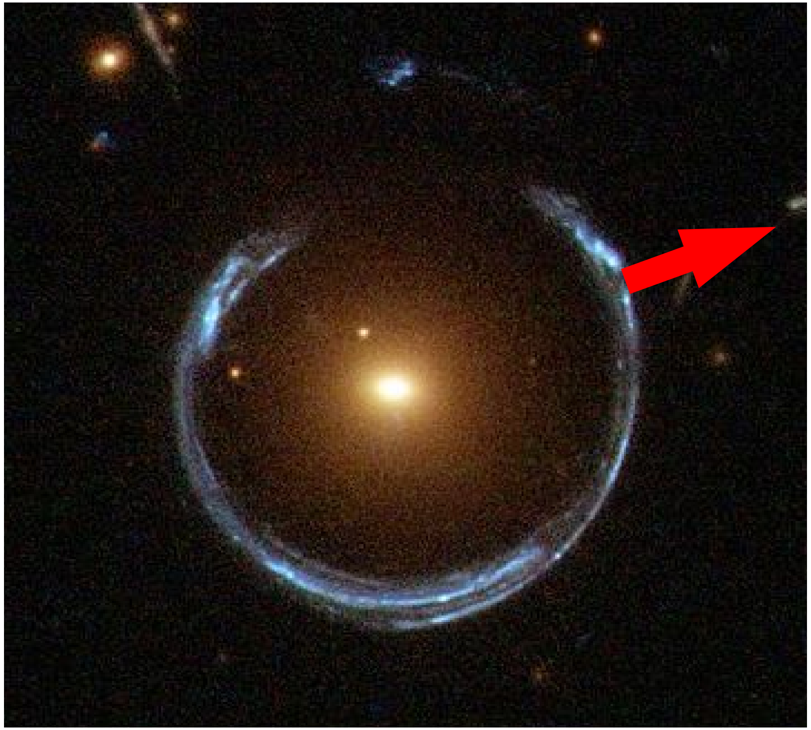

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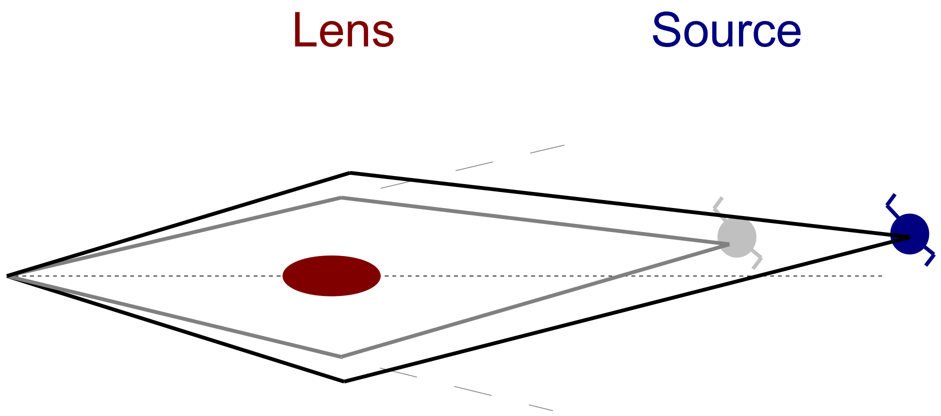


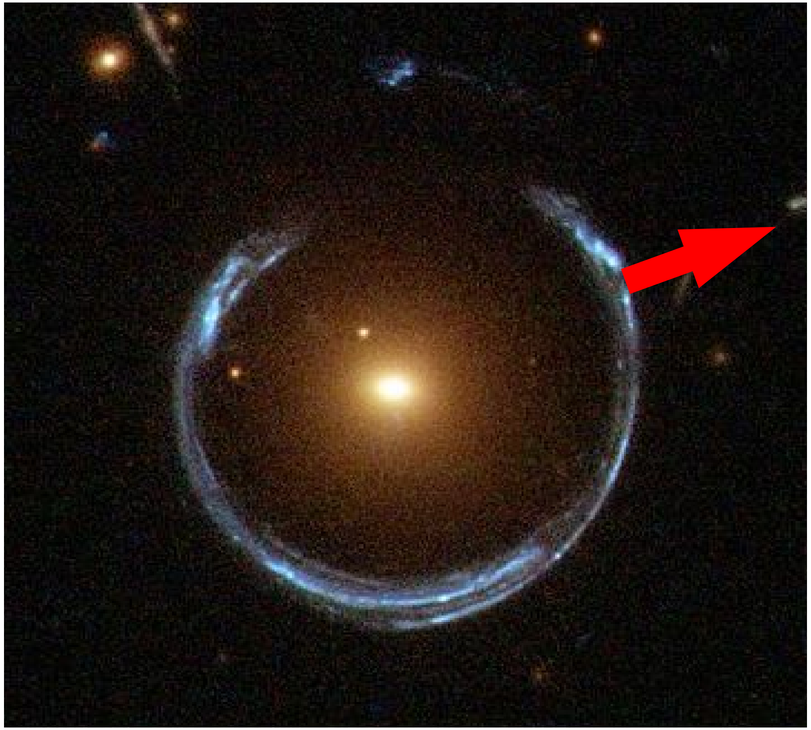
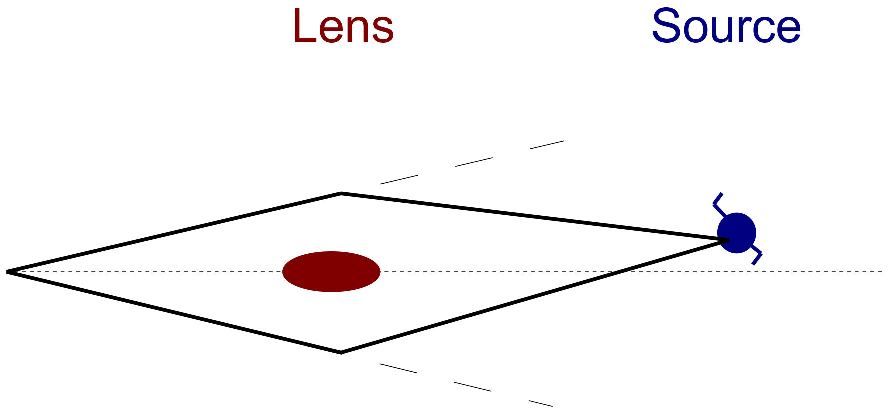
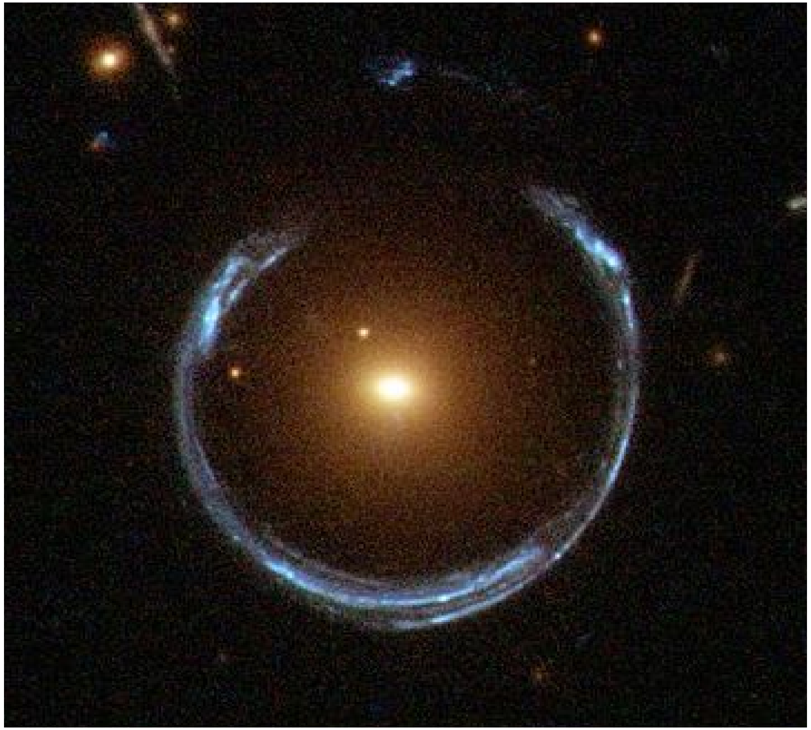


Image configurations depend on the distances

Strong lensing is an optical bench





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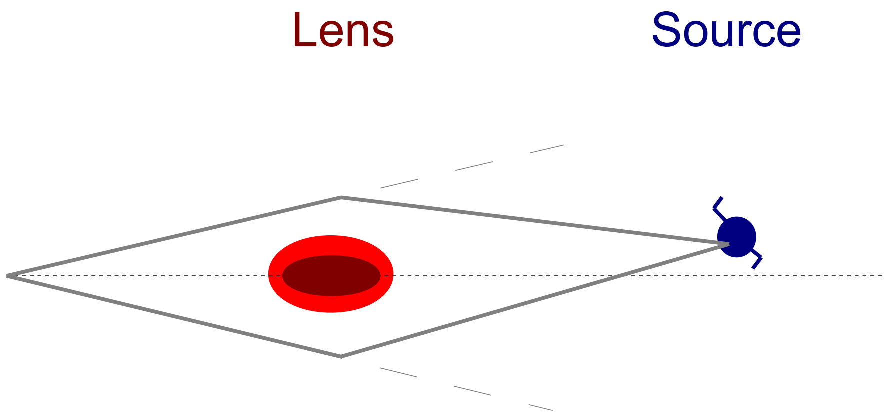

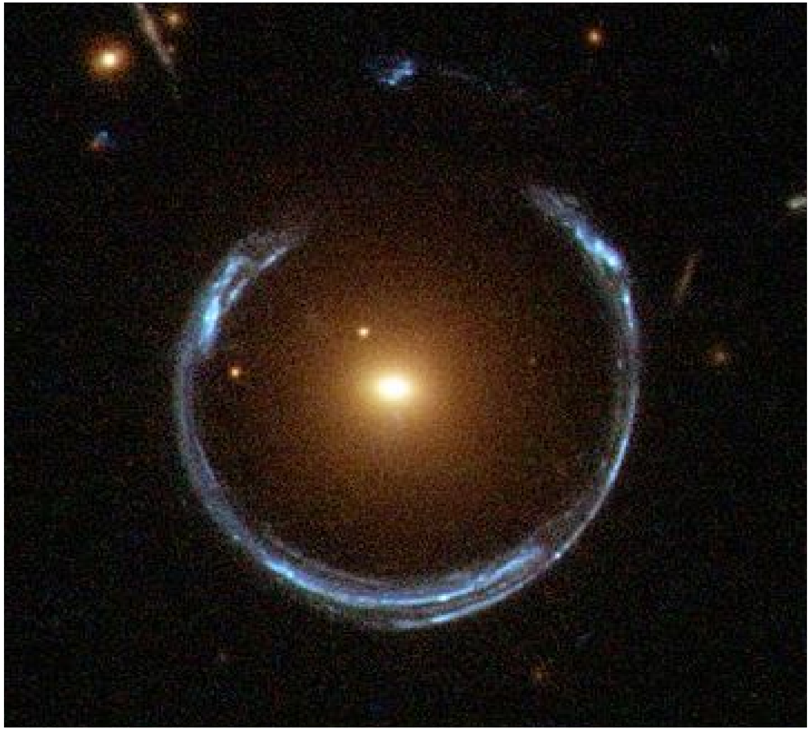

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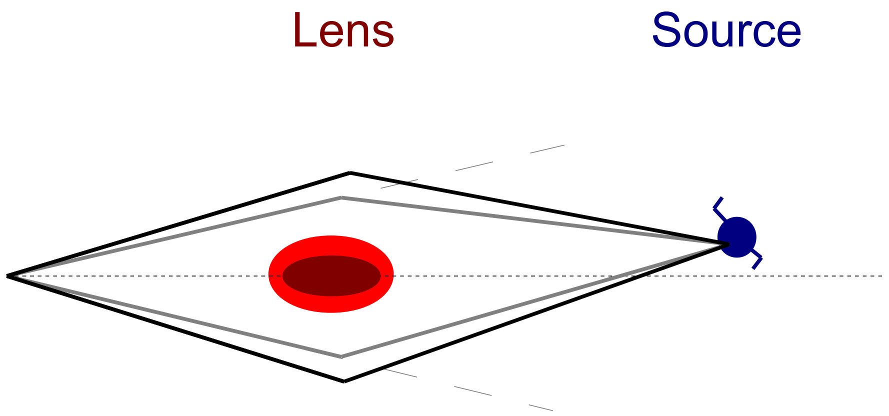

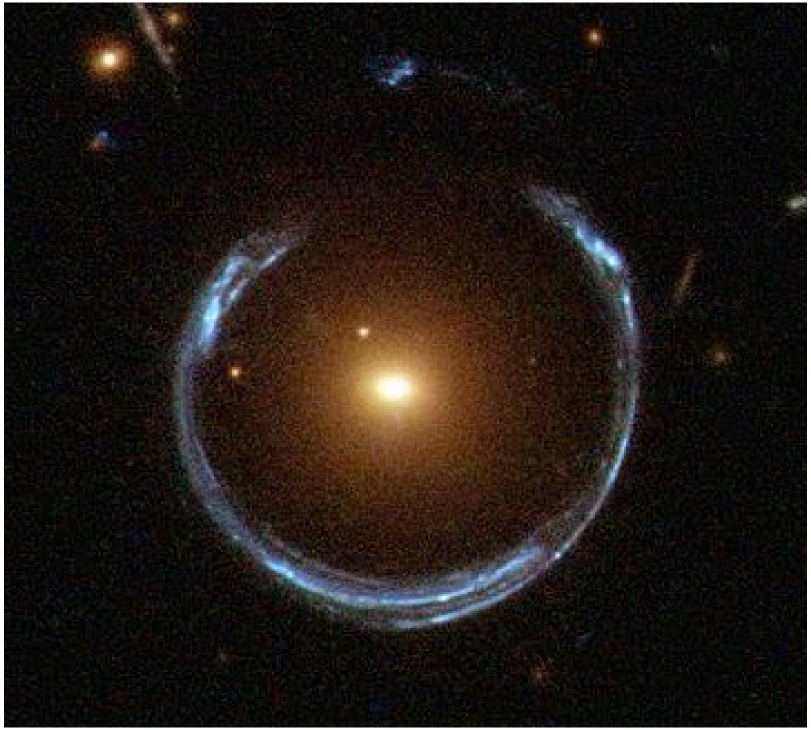

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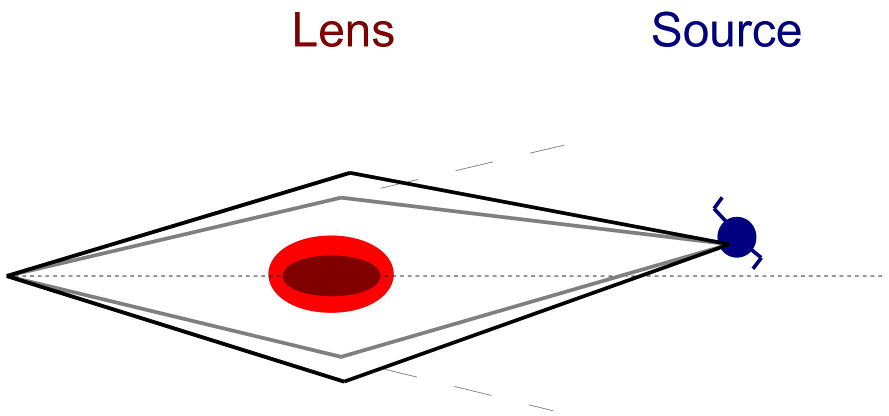

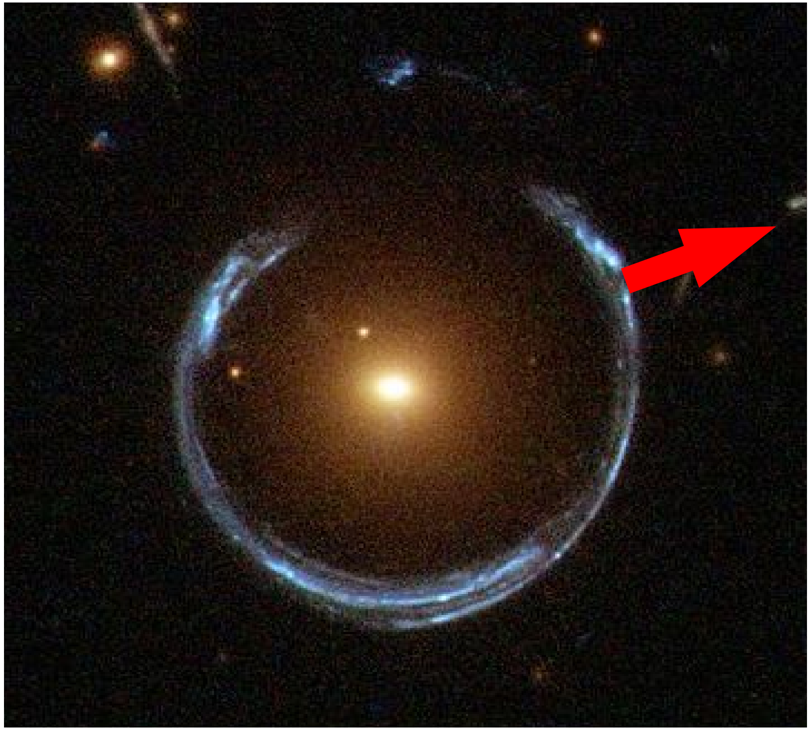

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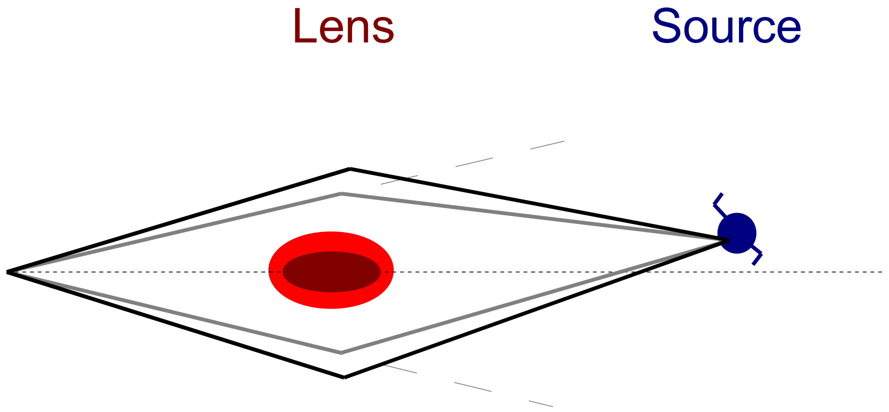


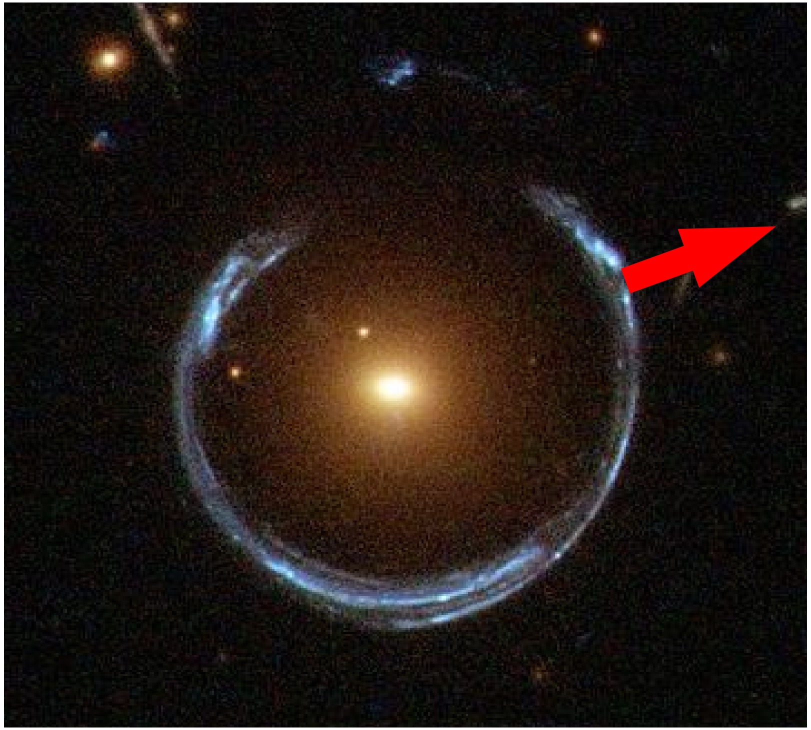


Image configurations depend on the lensing mass.

$$\theta_{\rm E} = \sqrt{\frac{GM(\theta_{\rm E})}{c^2}\frac{D_{\rm ls}}{D_{\rm ol}D_{\rm os}}}$$

Uncertainty in the mass model makes cosmography hard

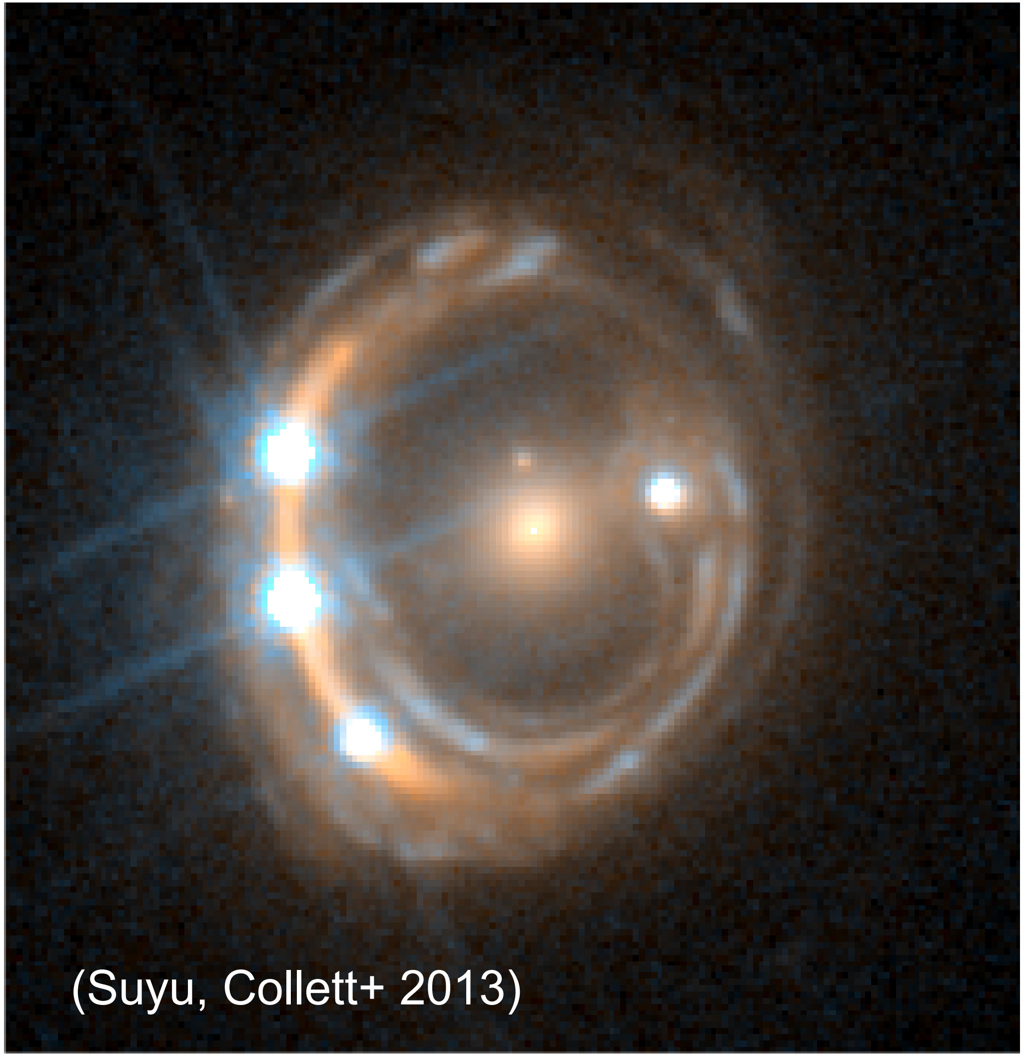
Hubble constant

$$D_{\rm ij} = \frac{c/H_0}{(1+z_{\rm j})}\int_{z_{\rm i}}^{z_{\rm j}} \frac{{\rm d}z}{\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w)}}$$

+ can add a term for spatial curvature

Matter Density

Dark Energy
Equation of State

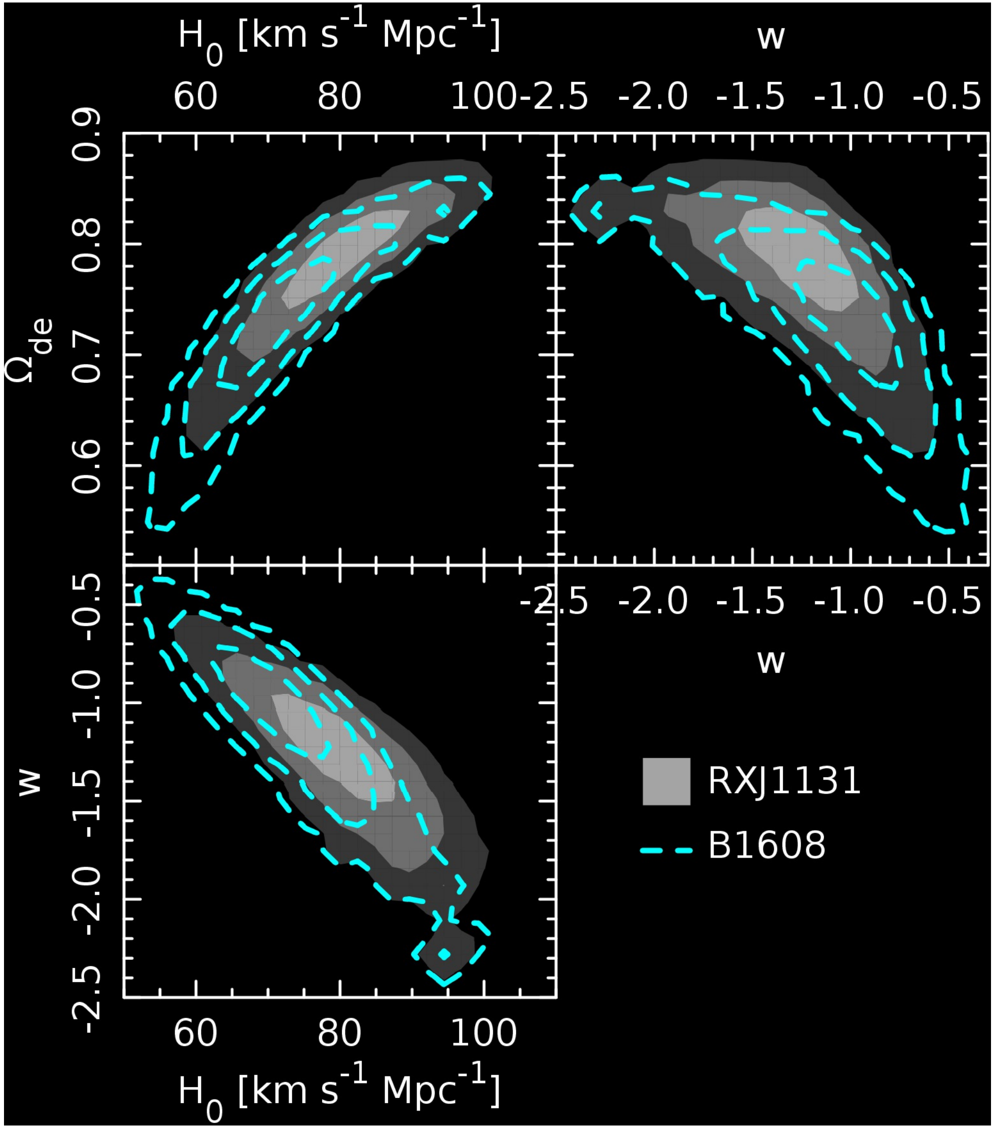

(Suyu, Collett+ 2013)

Time Delays:

Different images:
- ➔ Different path lengths
- ➔ Different Shapiro delays

$$\Delta t \propto D_{\Delta t} = (1+z_l)\,(D_l\, D_s)/D_{ls}$$

Need to get mass model right!



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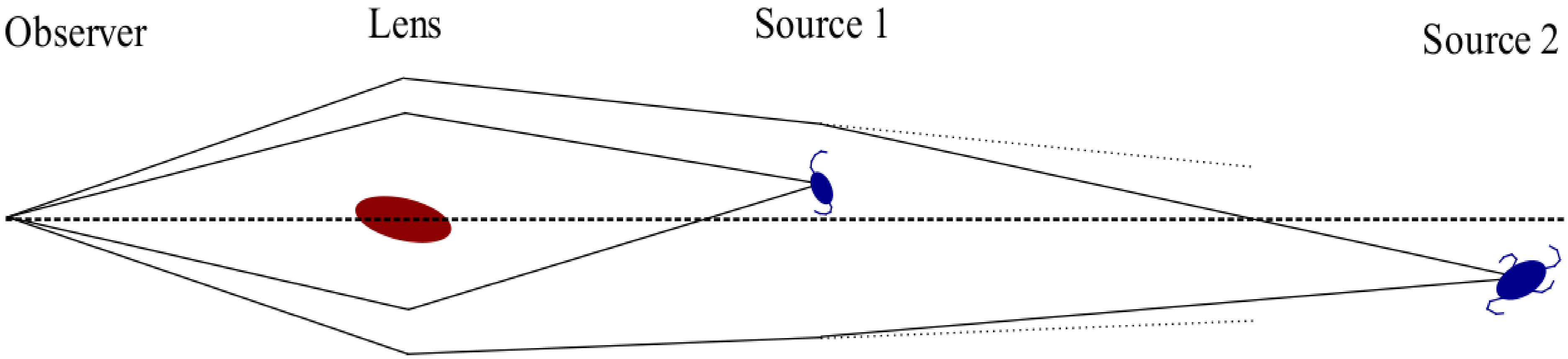
A gravitational lens system with two background sources, each at a different redshift.



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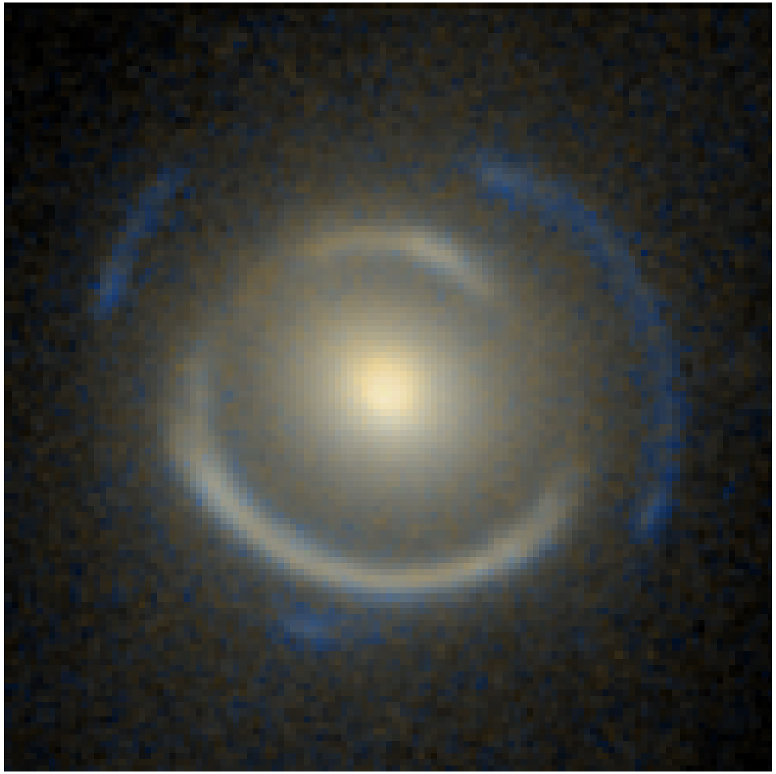

SLACS
J0946+1006

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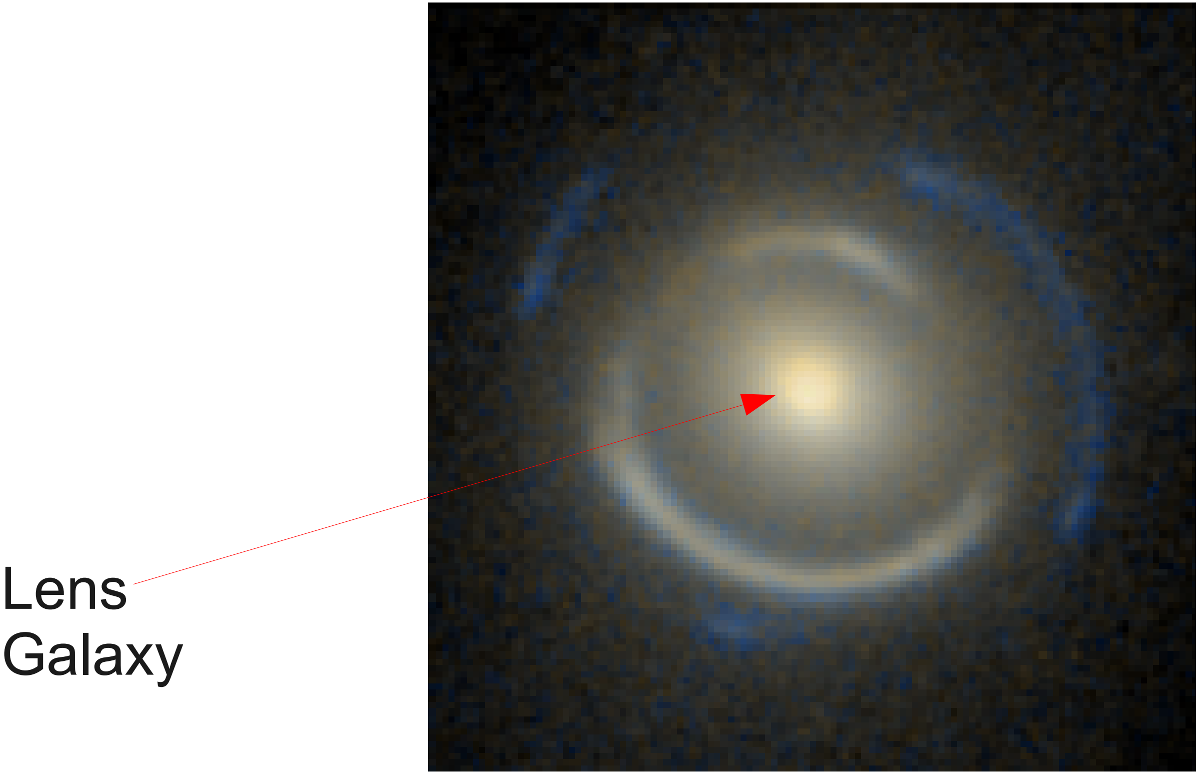

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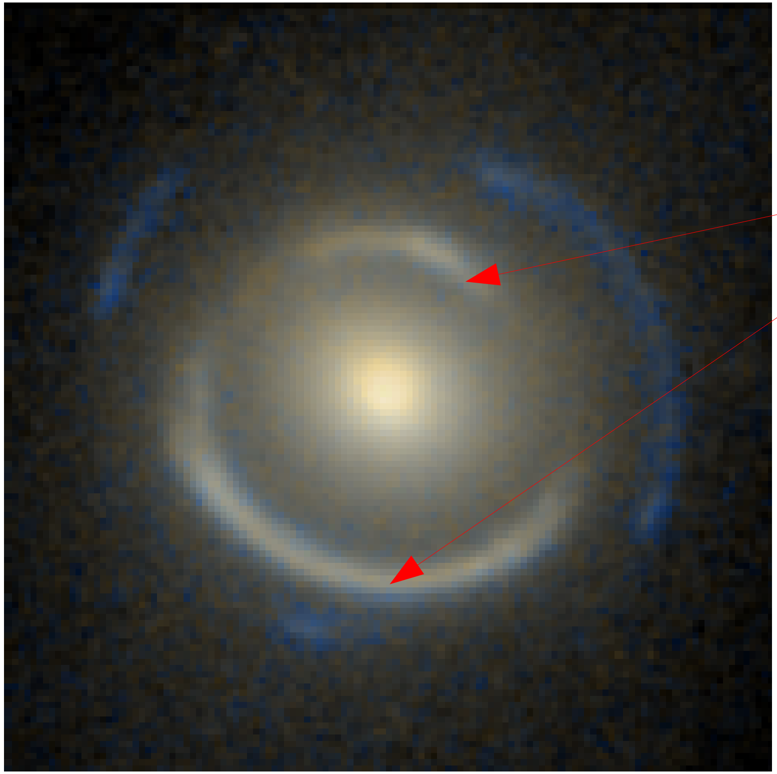

Images of the intermediate source

SLACS J0946+1006

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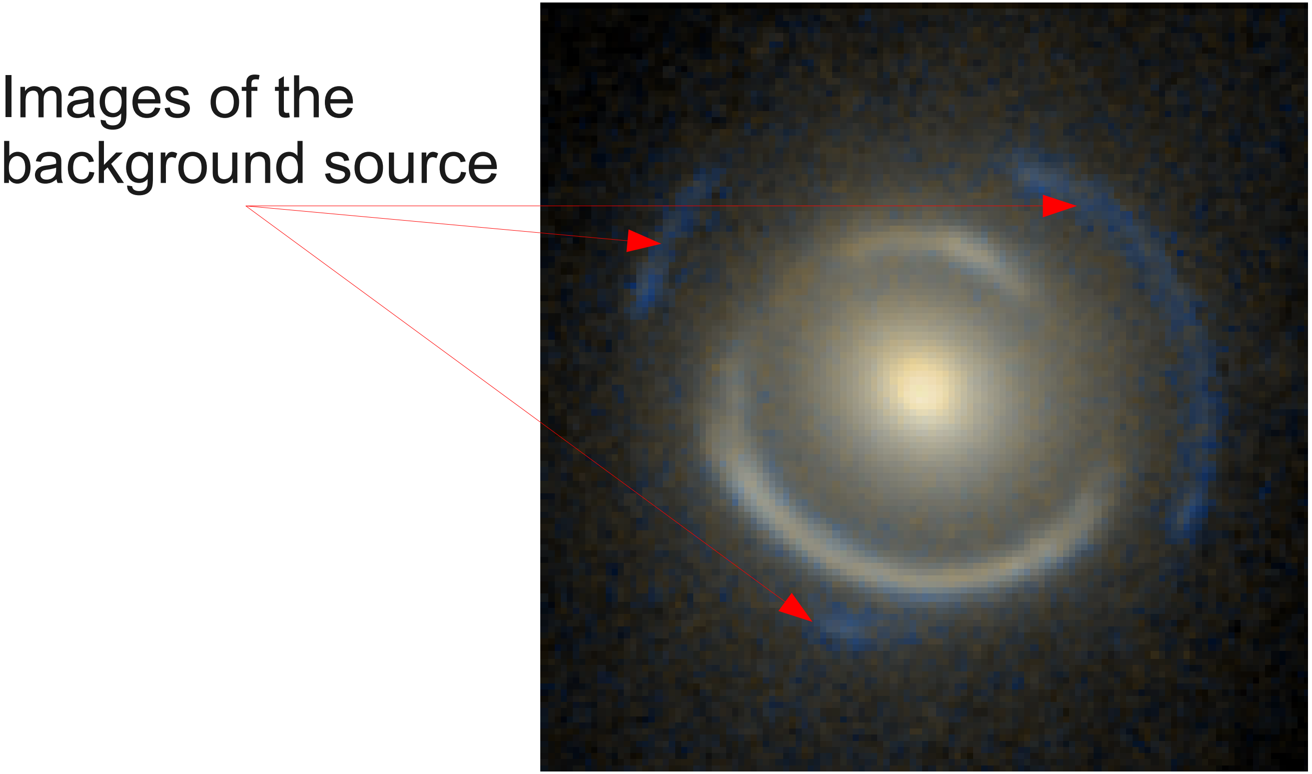
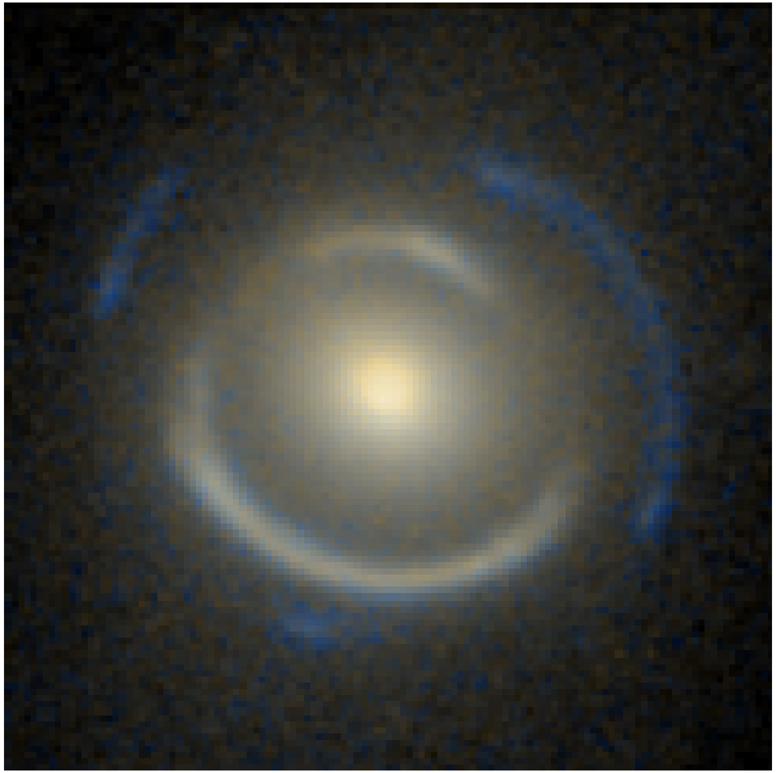


SLACS
J0946+1006

The observable:

The Ratio of Einstein Radii.



$$\eta = \frac{\theta_{\mathrm{E},1}}{\theta_{\mathrm{E},2}}$$

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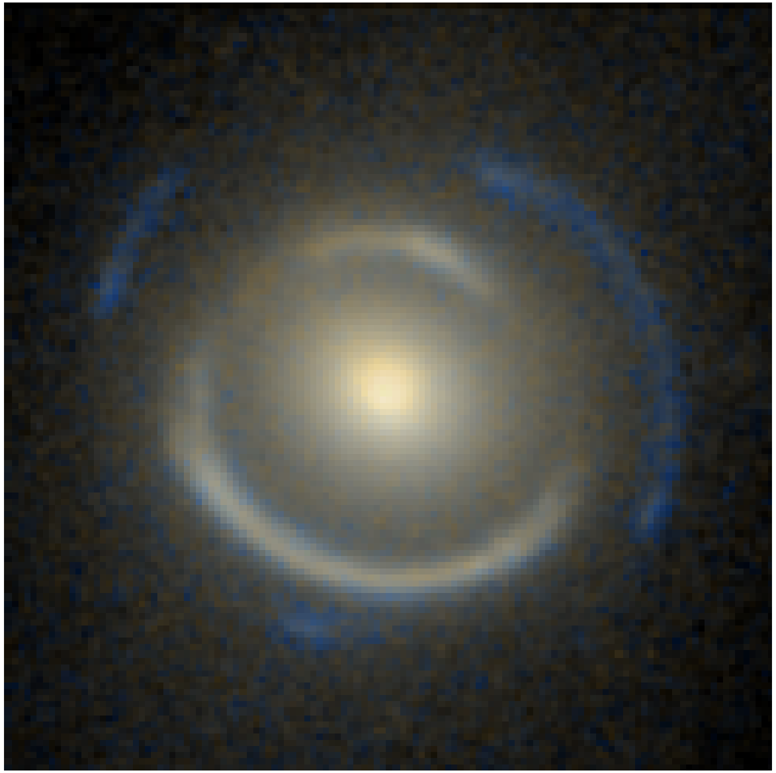

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$$\theta_{\mathrm{E}}^{\mathrm{SIS}} = 4\pi \frac{\sigma_V^2}{c^2} \frac{D_{\mathrm{ls}}}{D_{\mathrm{s}}}$$

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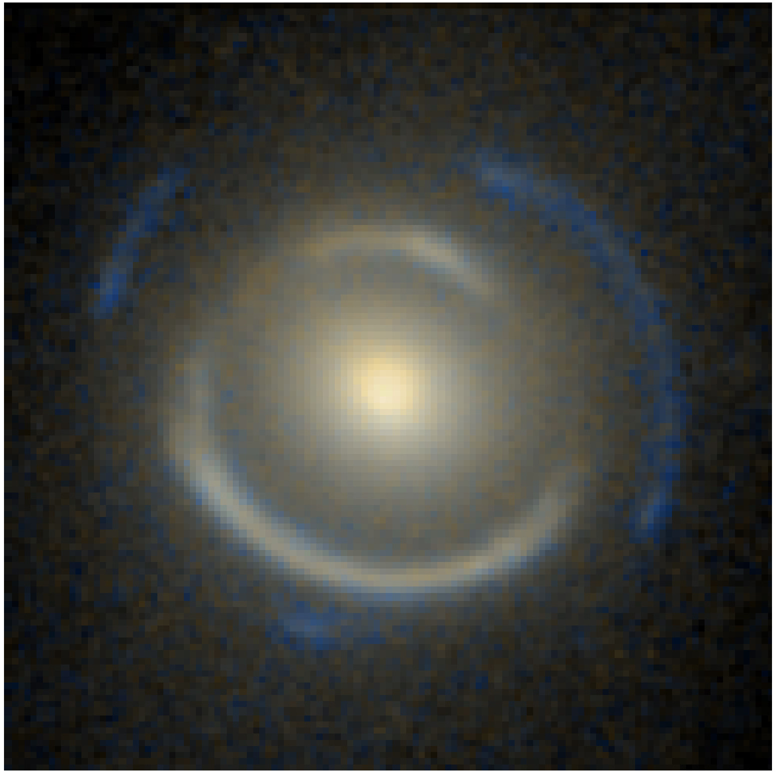

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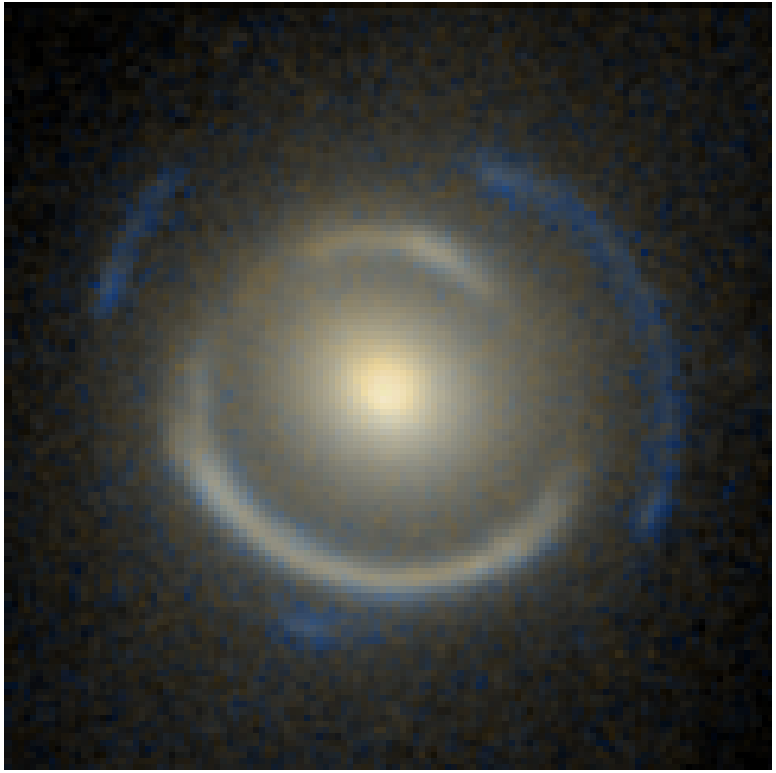

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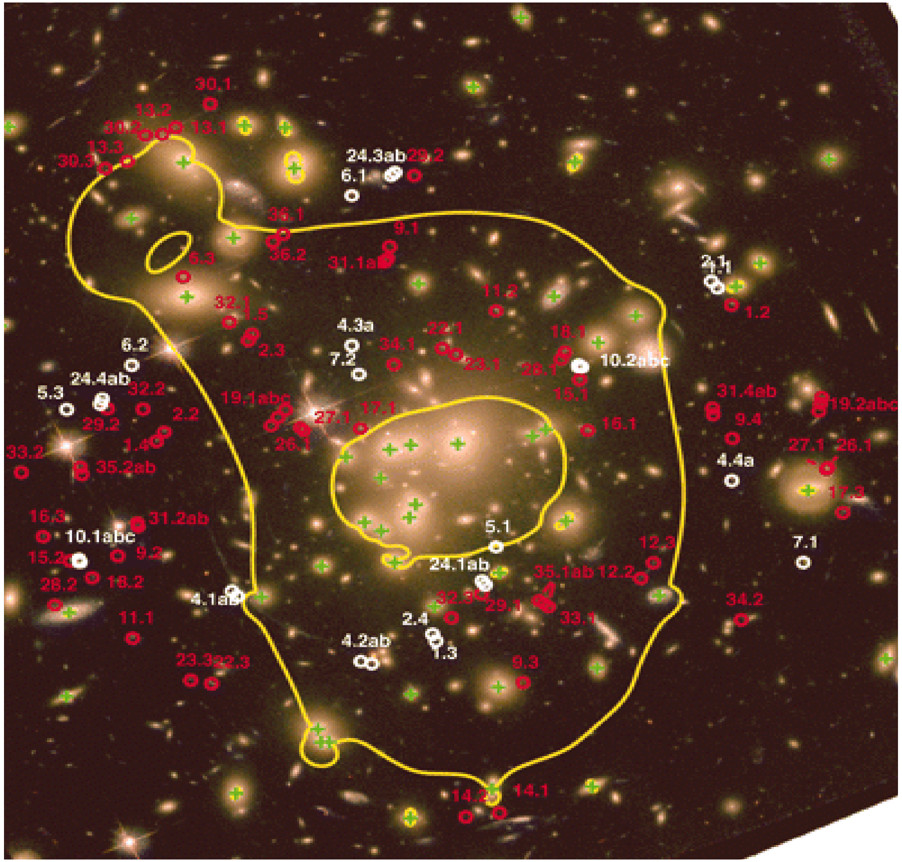
No dependence on the Hubble constant!

Jullo et al. (2010) Results:



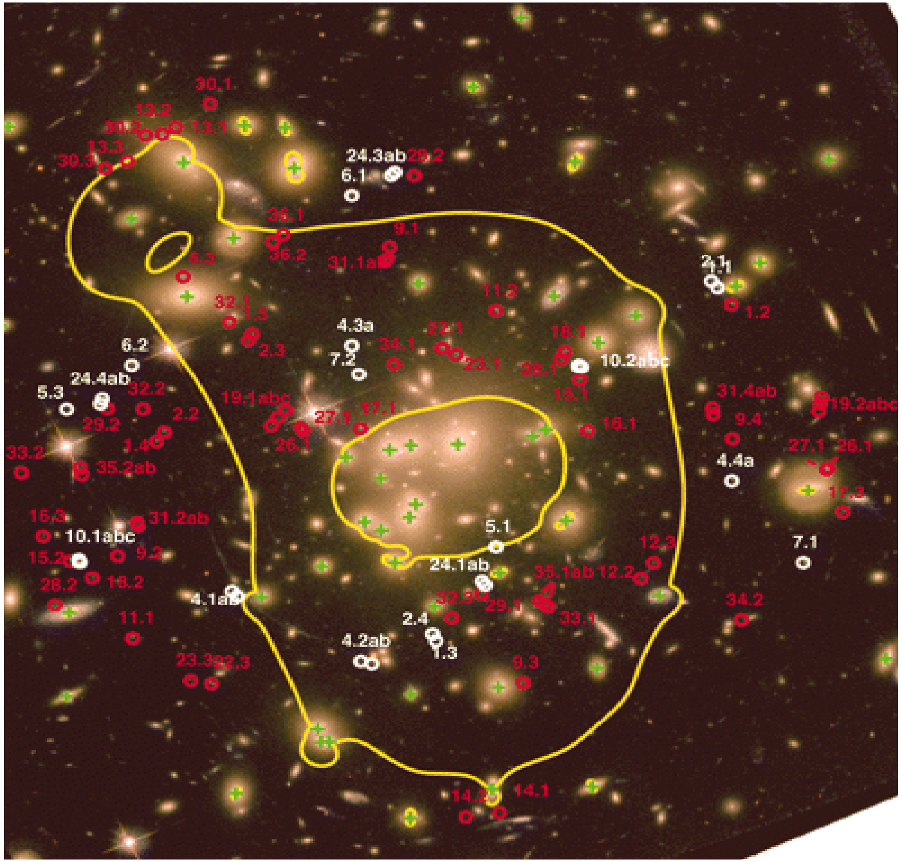
$\Omega_M = 0.25 \pm 0.05,\ w_{DE} = -0.97 \pm 0.07$

(Abel 1689 + WMAP5 + X-ray cluster constraints)

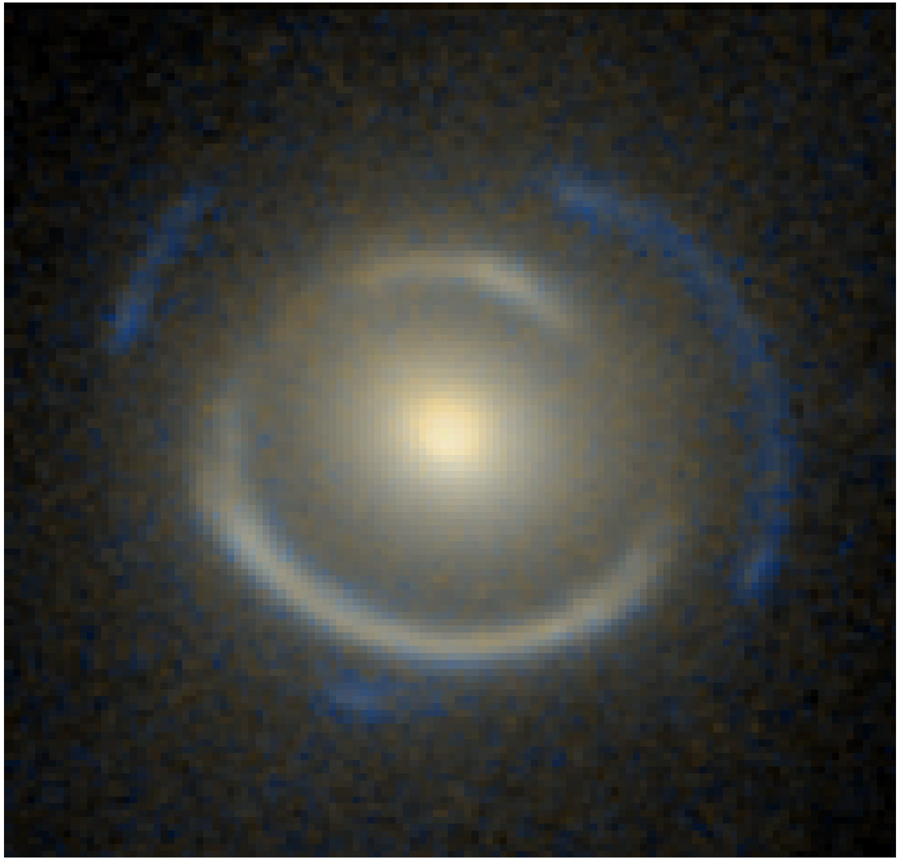
The mass is *very* complicated

- Hard to control systematics

Jullo et al. (2010) Results:



BAD

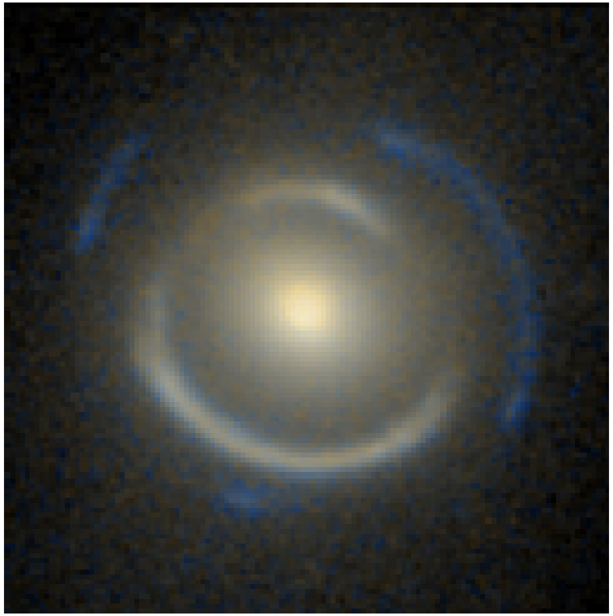


GOOD

Constraining Cosmology.

Preliminary models of J0946 suggest statistical uncertainty of ~1% on the ratio of Einstein Radii.

Uncertainty is dominated by the lens' mass density slope

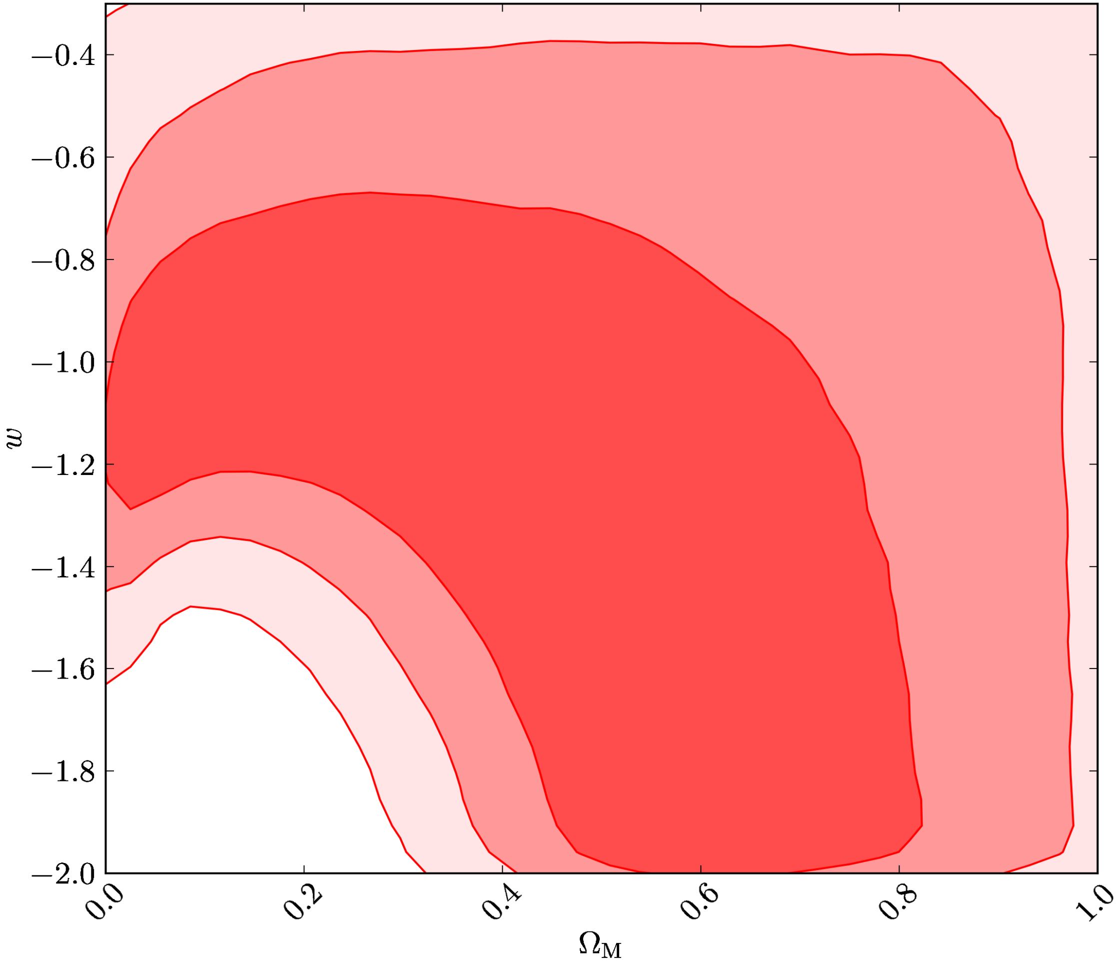


Constraining Cosmology.

z_l = 0.35

z_{s1} = 0.6

z_{s2} = 1.5



Collett+ 2012

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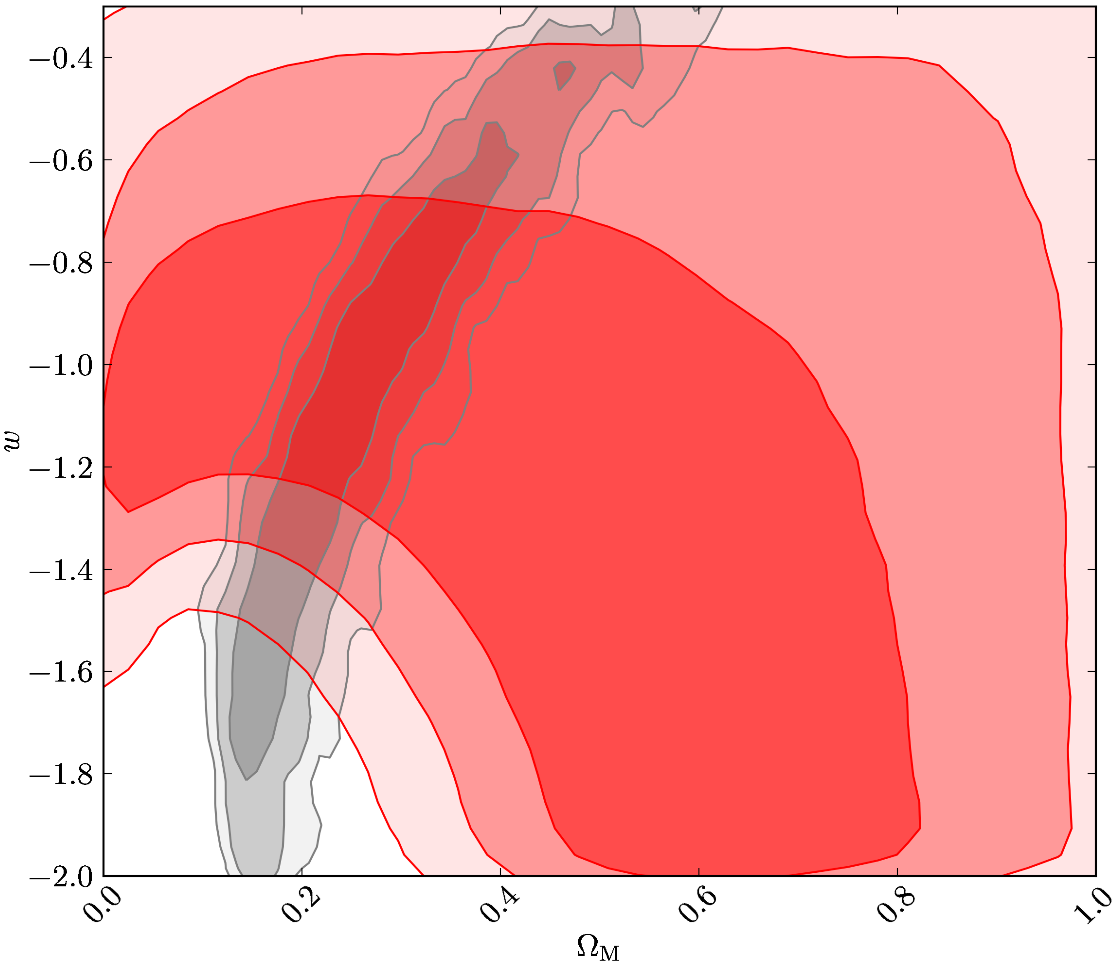
WMAP



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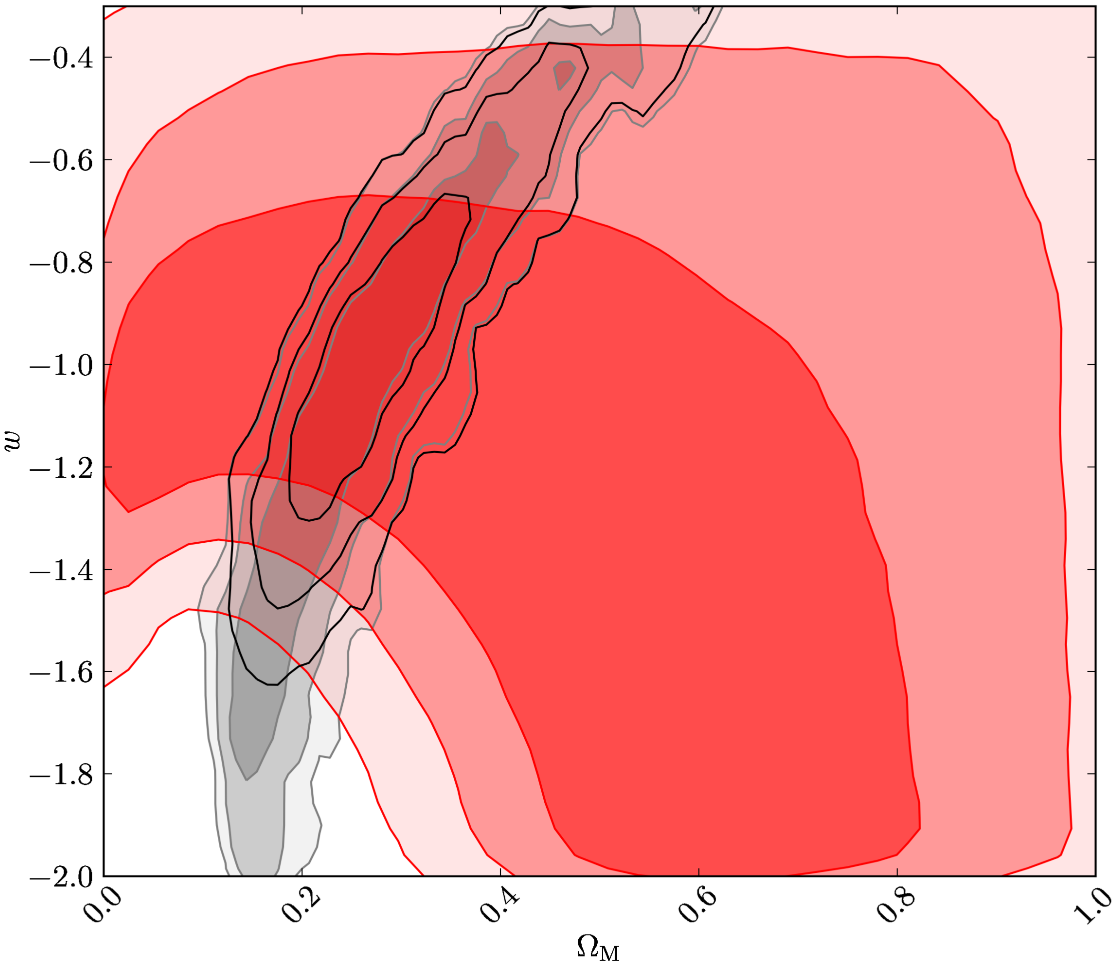
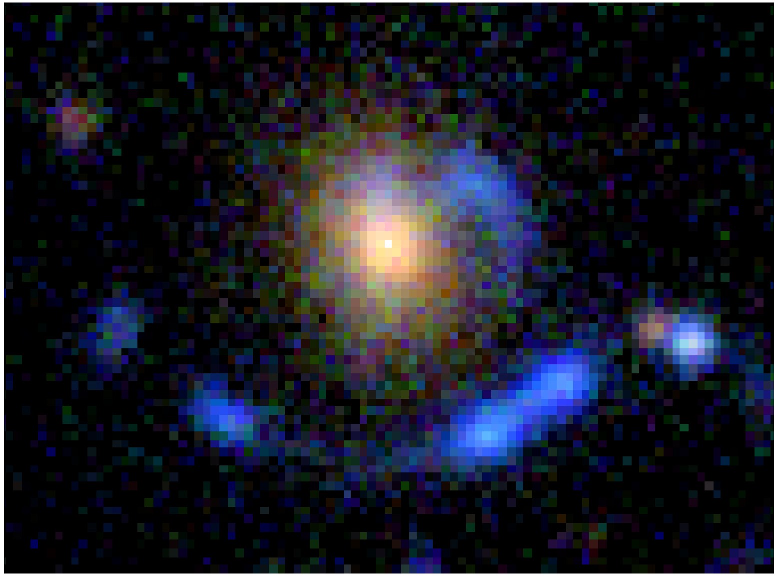
Combination



Collett+ 2012

Finding more systems



THE DARK ENERGY SURVEY

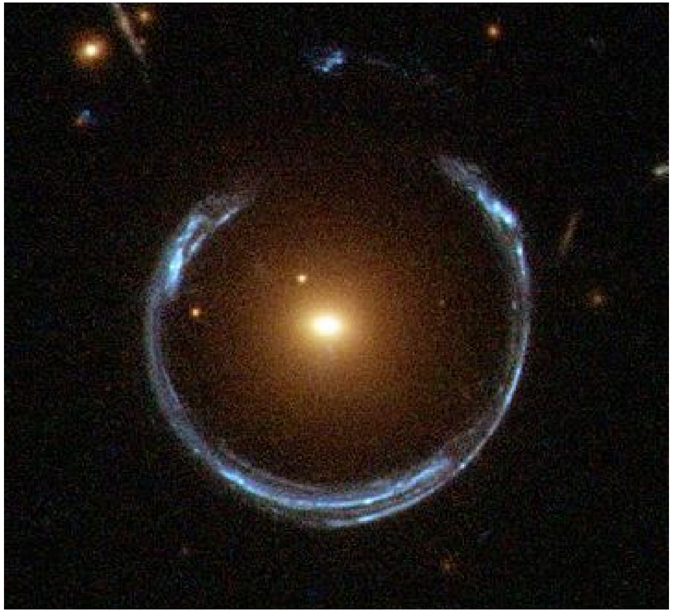
MegaPrime CFH MegaCam Legacy Survey CFHTLS

Pan-STARRS PS1 Science Consortium

Piggy-back on deep, large area surveys

Target known lenses

Target the most massive galaxies



Constraints with 6 systems.

Forecast the distribution of lens and source redshifts

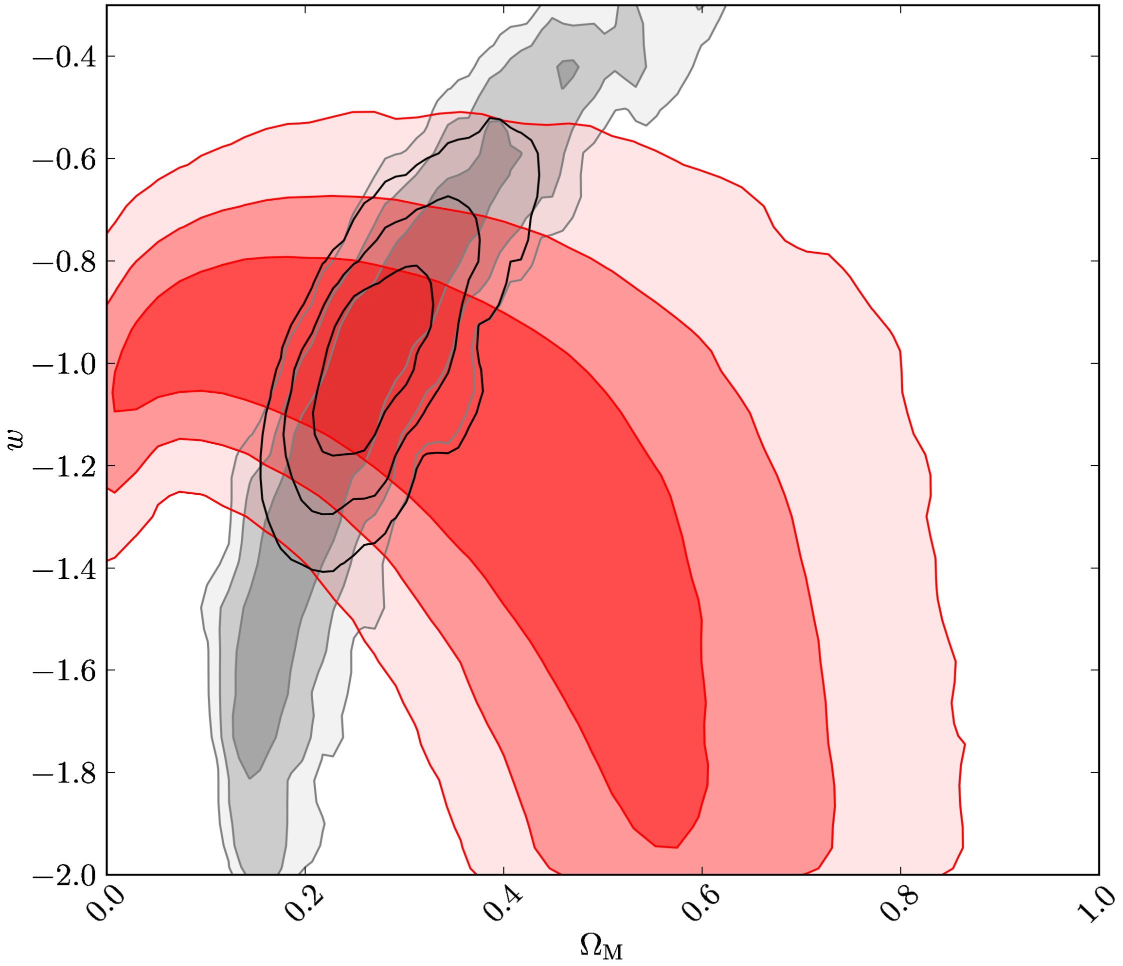
WMAP+6 systems is ~2.5 times better than WMAP+1.

WMAP+

1 system $w_{\mathrm{DE}} = -0.99 \pm 0.27$

6 systems $w_{\mathrm{DE}} = -1.01 \pm 0.11$

Collett+ 2012



Beyond *w*CDM

Evolving models of dark energy:

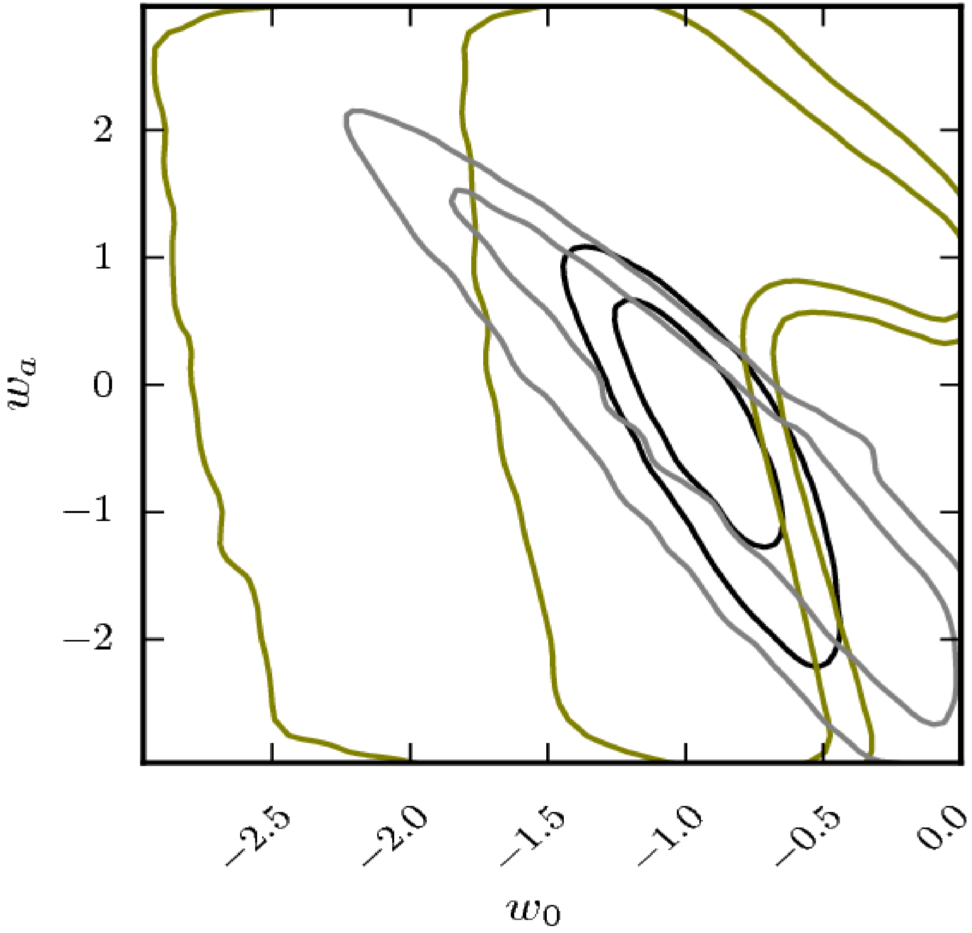
$$w(z) \;=\; w_0 + w_a(1-a)$$

Olive: 6 double source plane lenses

Grey: Planck (Forecast, including polarization and weak lensing constraints)

Black: combination

Collett+ 2012



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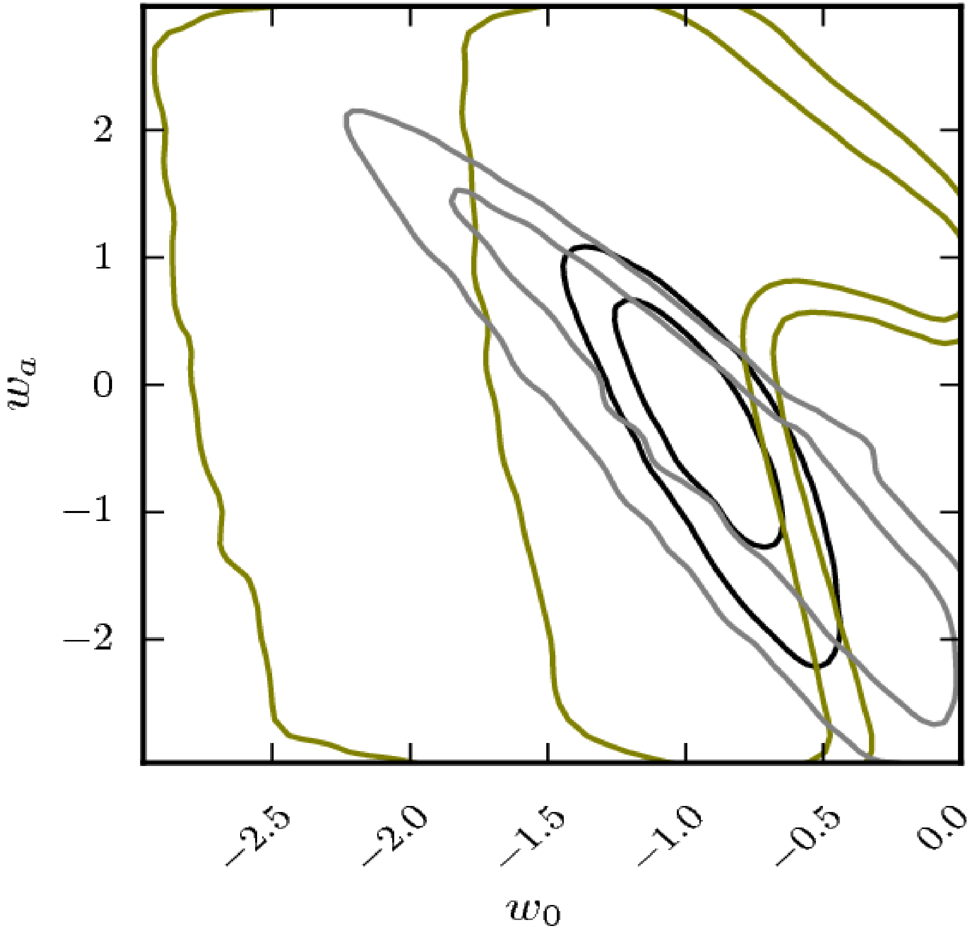
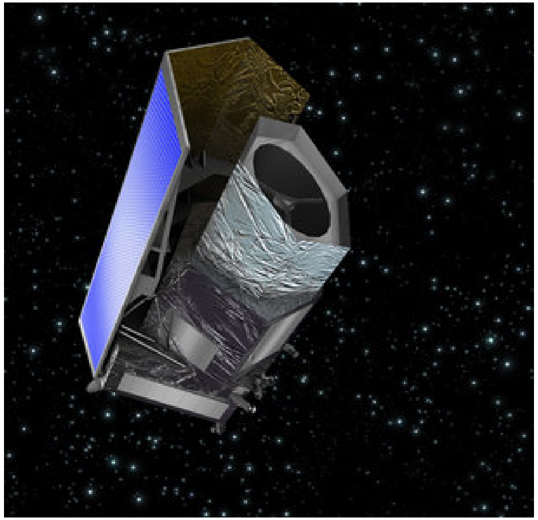
$$\mathrm{FoM} = 6.17\pi/A_{95} = 14.2$$

WMAP plus Union SNe → 15 (Mortonson+2010)

Collett+ 2012



Euclid



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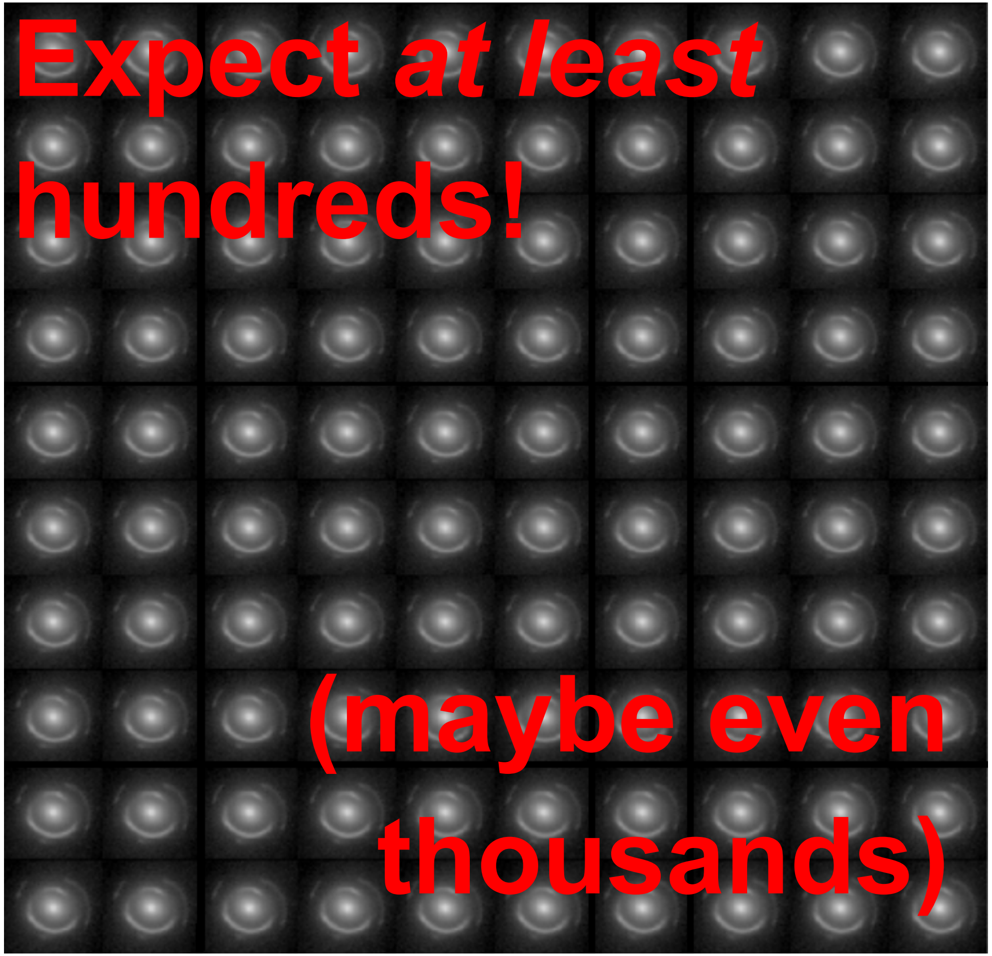
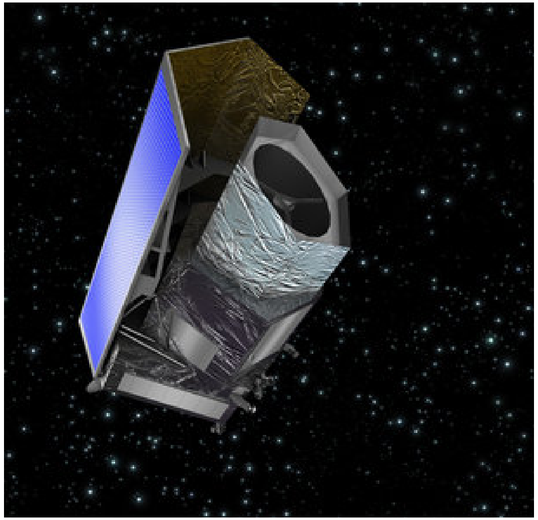


Expect *at least* hundreds!

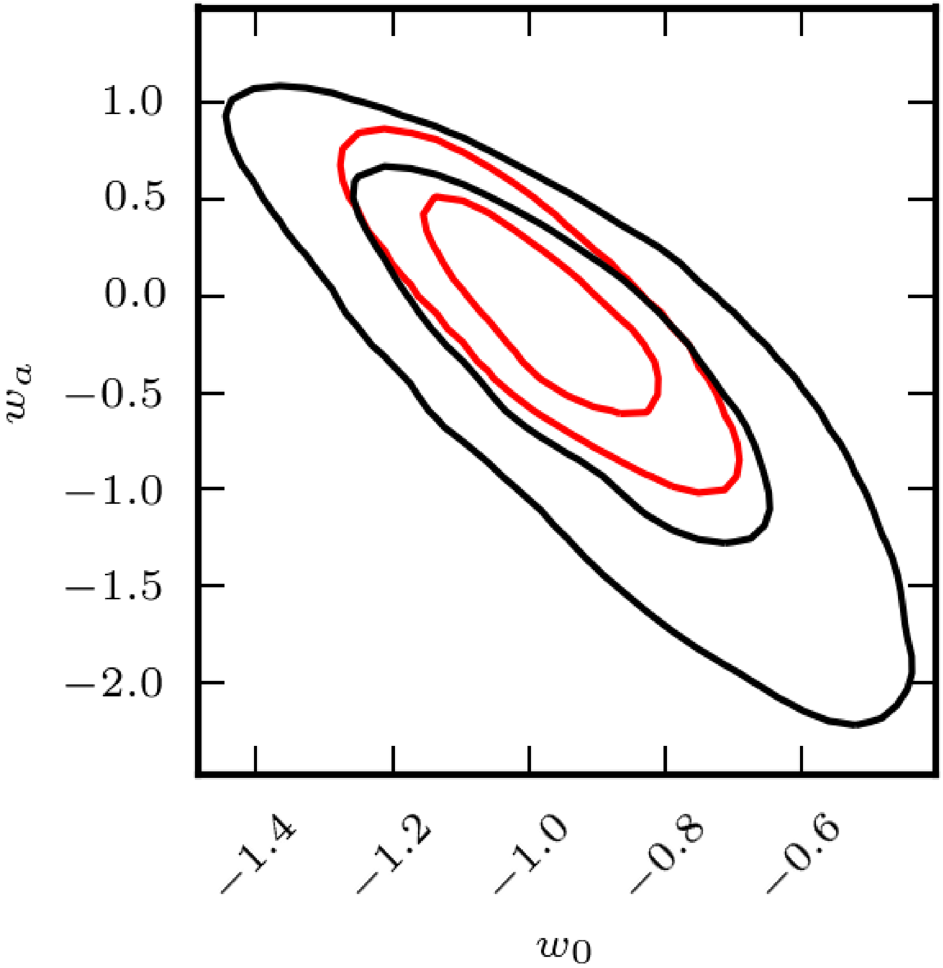
(maybe even thousands)



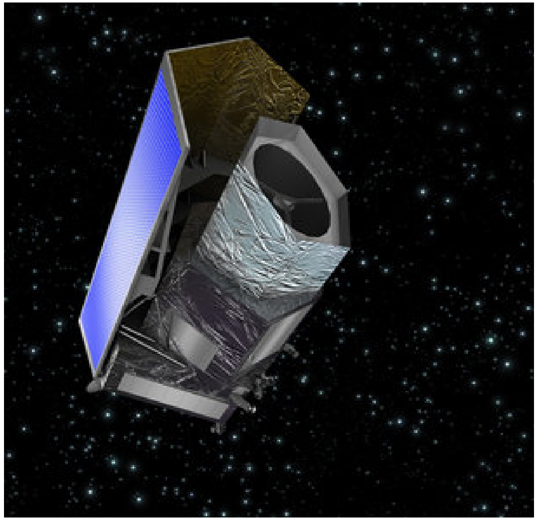
~10^5 galaxy scale strong lenses (based on COSMOS)

1 in 40-80 galaxy scale lenses will be doubles (Gavazzi+ 2008)

Euclid



Collett+ in prep.



Black: 6 lenses, $\Omega_k = 0$

FoM = 14.2

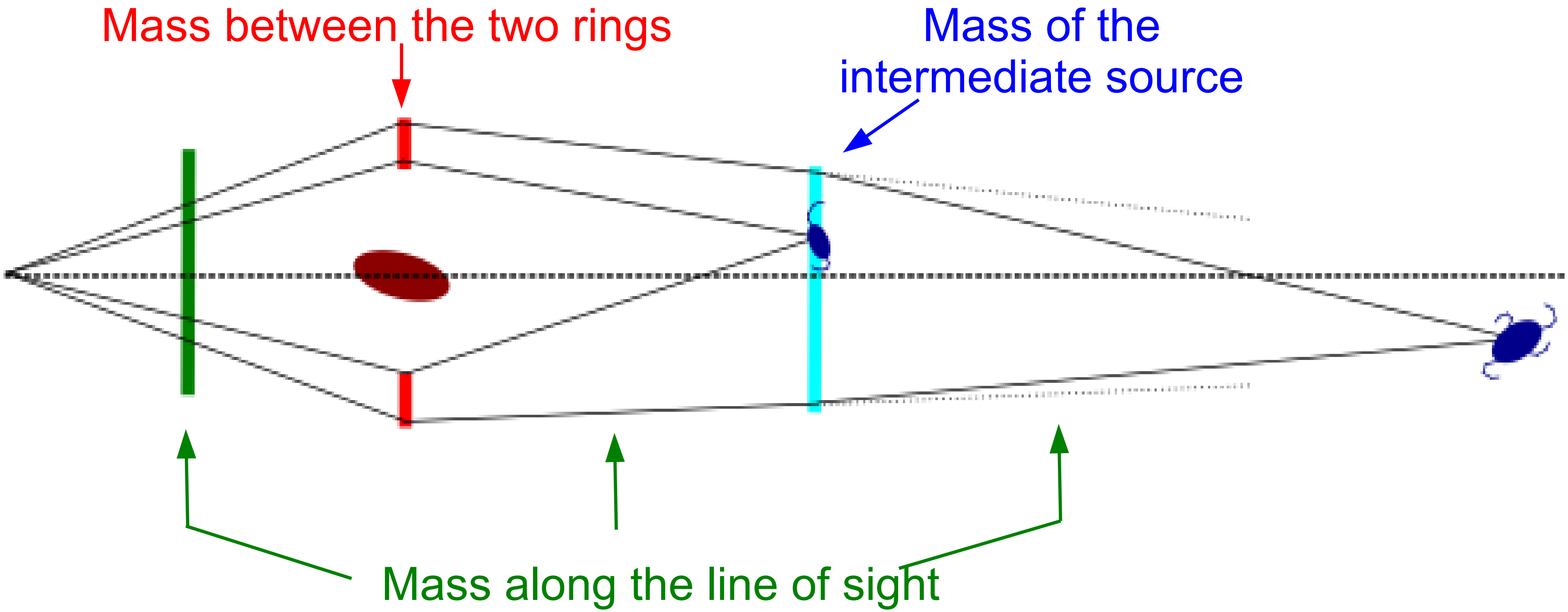
Red: 100 lenses, $\Omega_k \neq 0$

FoM = 38

Systematics

A.K.A. Learning cool stuff about mass in the universe

Systematics



Mass between the two rings

Mass of the intermediate source

Mass along the line of sight

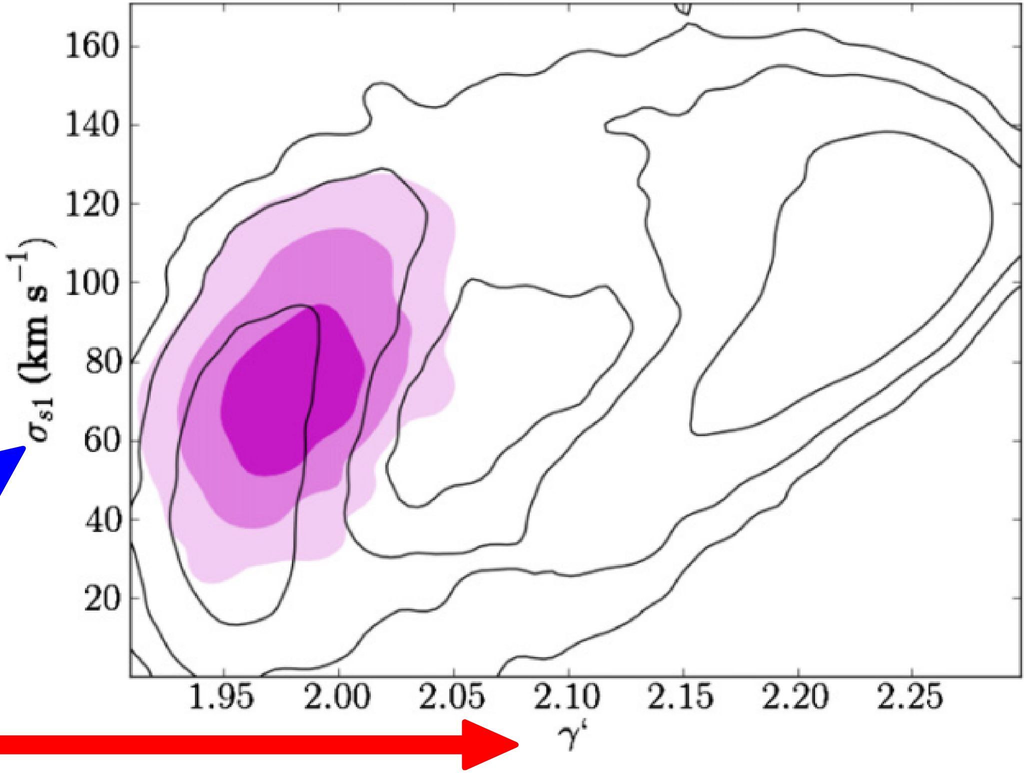
Perturbations by the intermediate source

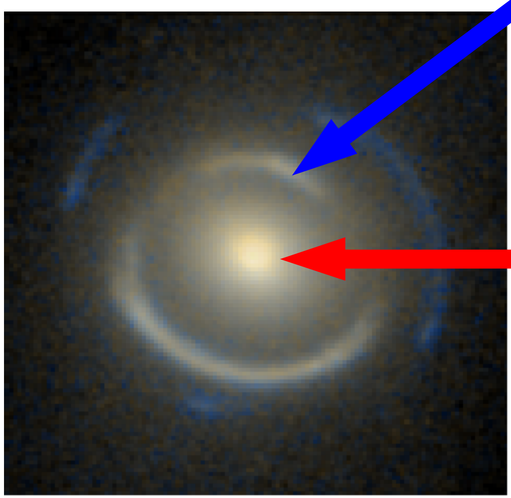
If completely neglected:

LMC: ~1% systematic error on η

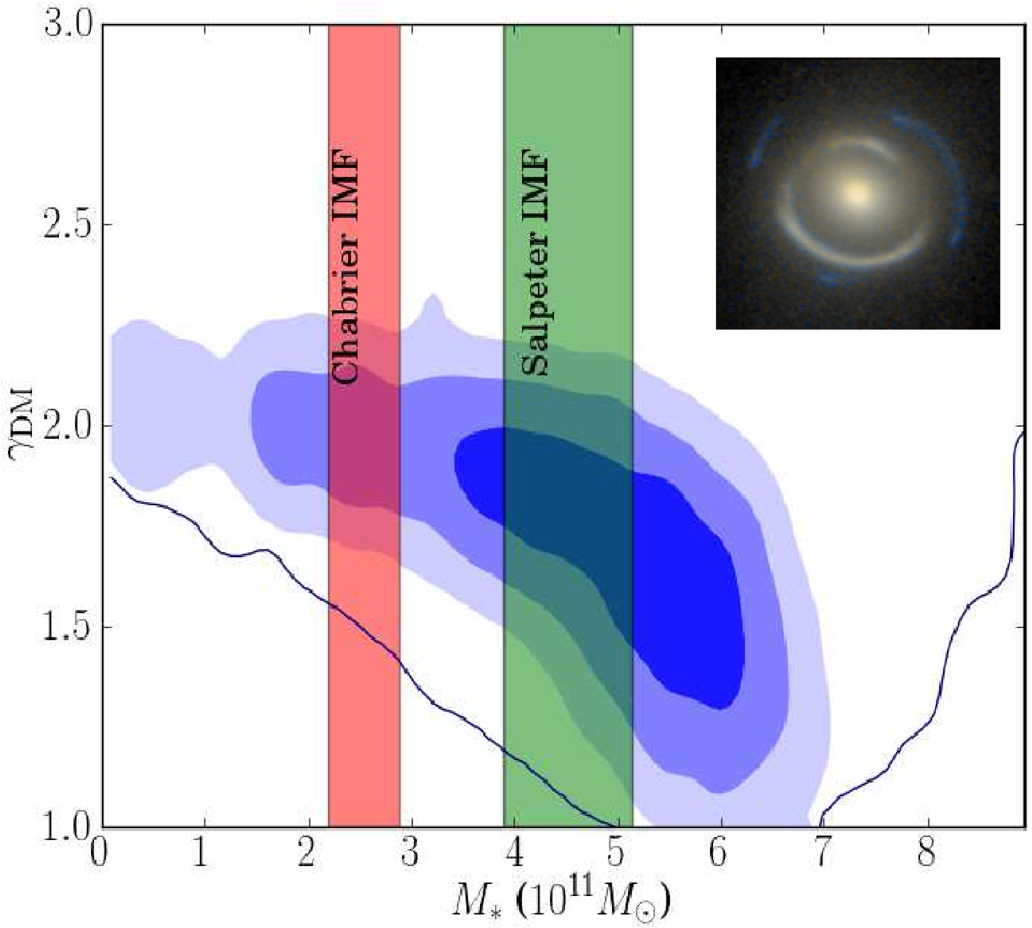
MW: ~10% systematic error on η

Effect is detectable: include in the lens model.





(Sonnenfeld+ 2012, Fixed cosmology, photometric z_{s2})



(Sonnenfeld+ 2012)

Profile of the Lens

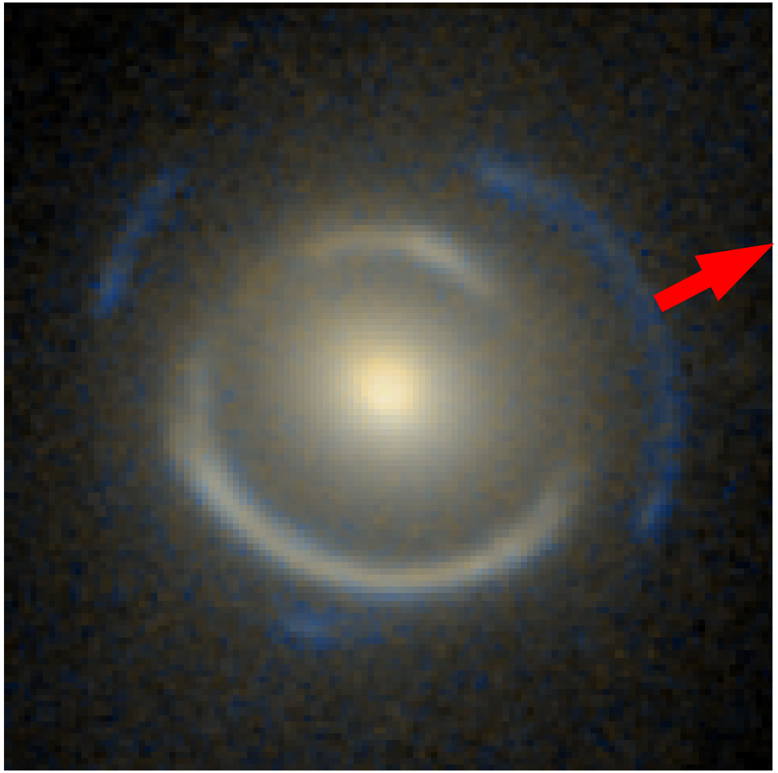
Strong constraints on the mass profile

- ➔ $\gamma_{TOT} = 1.98 \pm 0.02 \pm 0.01$

  OR
- ➔ $\gamma_{DM} = 1.7 \pm 0.2$

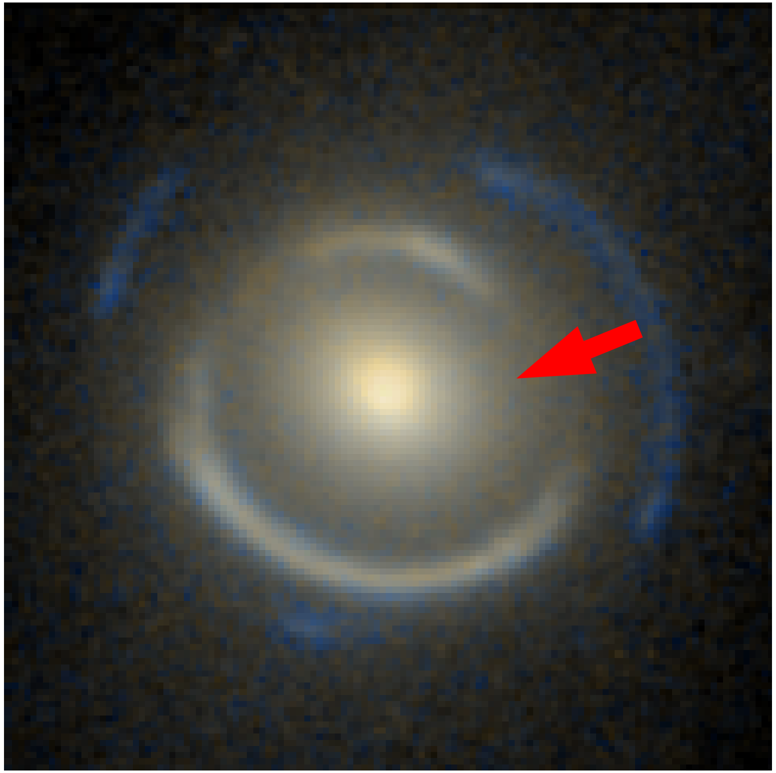
Using dynamics and both Einstein radii

The Mass Sheet Degeneracy



Overdense dark matter halos cause convergence of rays

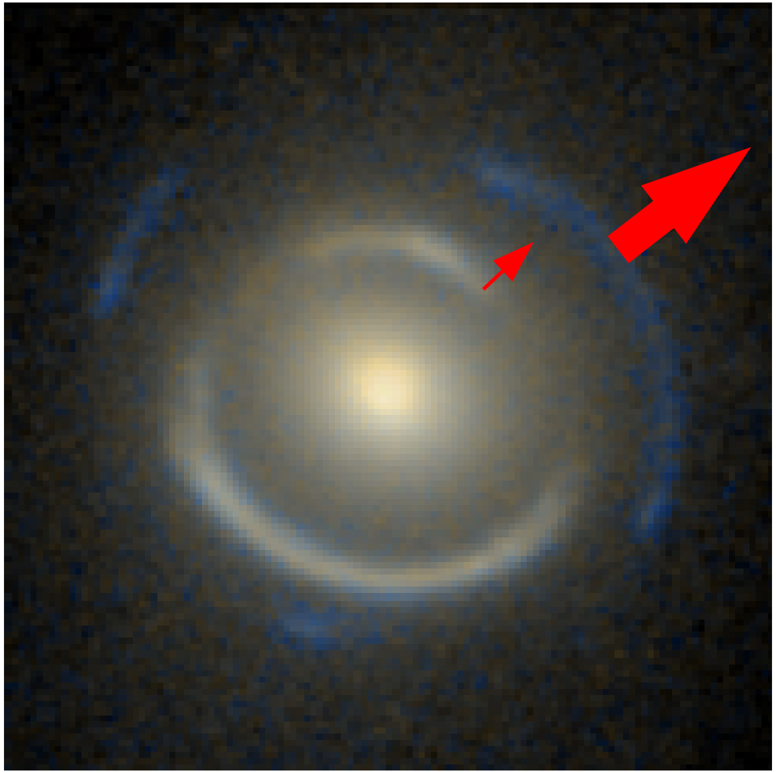
The Mass Sheet Degeneracy



Overdense dark matter halos cause convergence of rays

Underdense voids cause divergence of rays

The Mass Sheet Degeneracy



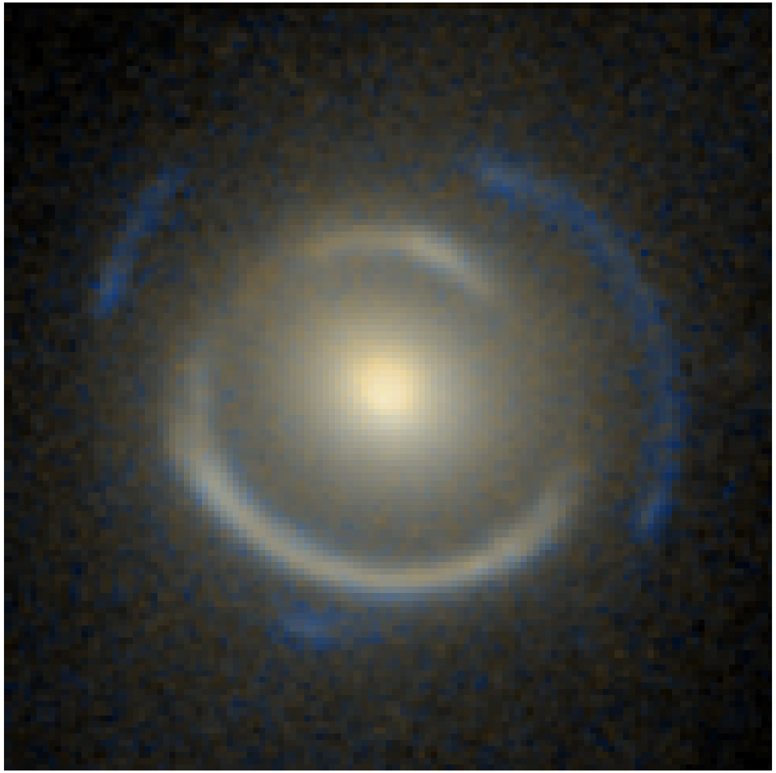
Effect depends on the distance of the source – slightly perturbs the inferred cosmology

Convergence proportional to surface mass density

$$\kappa = (4\pi G D_{ls} D_l / c^2 D_s)\ \Sigma$$

~~The Mass Sheet Degeneracy~~

Magnification-Absolute magnitude degeneracy

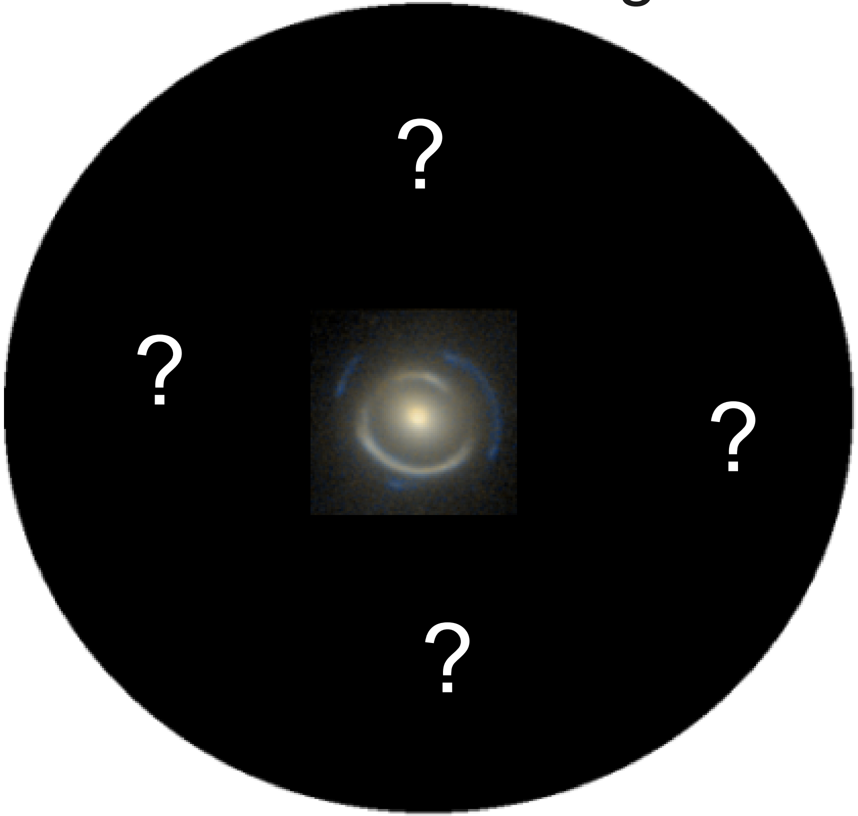


Directly relevant to

- High-z SNe
- GRBs
- High redshift luminosity functions

EVERYTHING IS WEAKLY LENSED

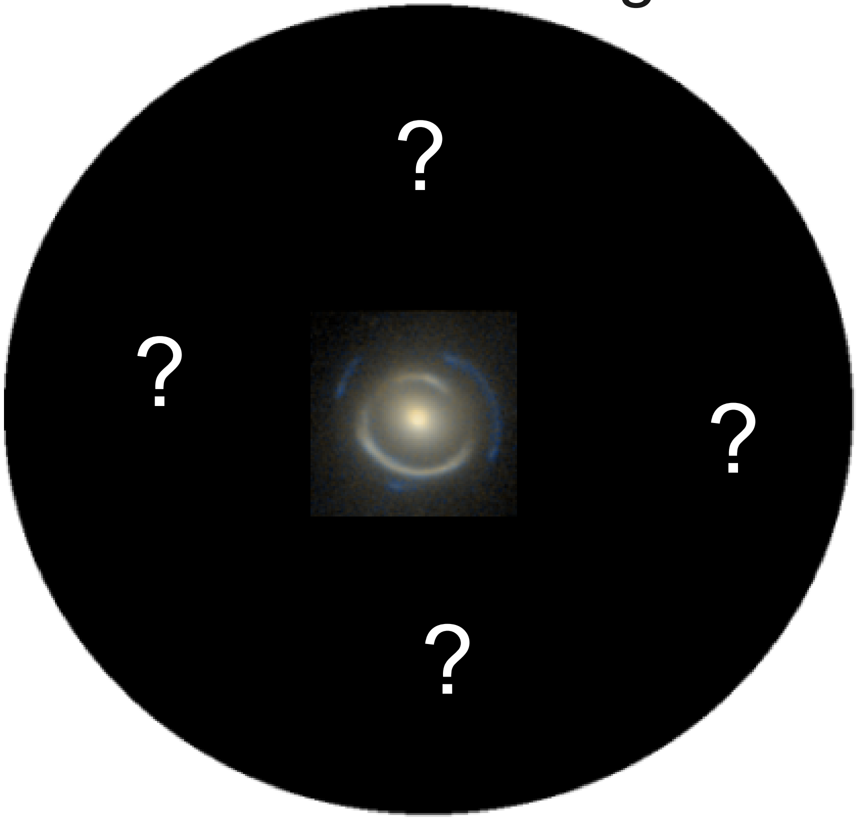
The Mass Sheet Degeneracy

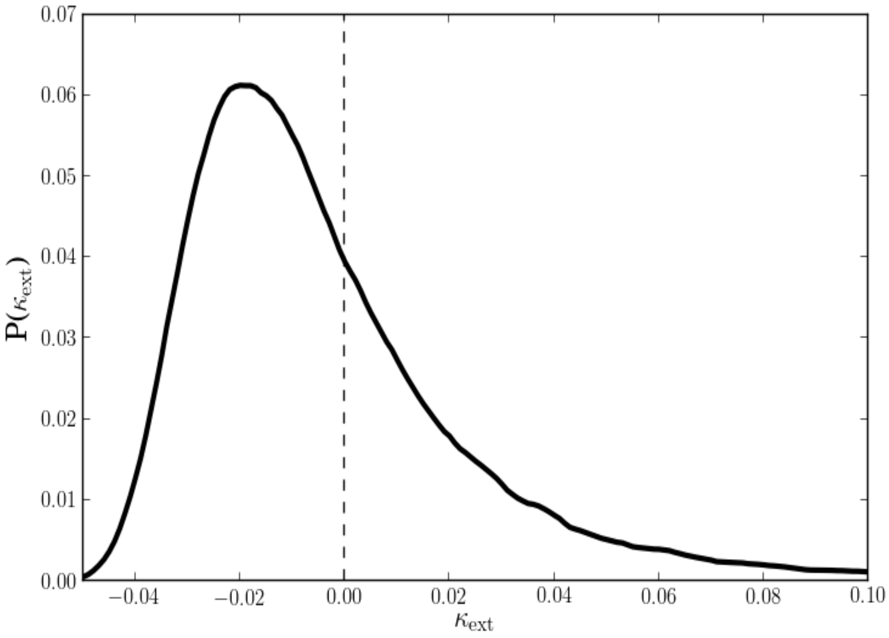


0.01 change in κ approximately:

0.5% in ratio of Einstein radii, 1% in time-delay distance,
2% in magnification of an unlensed source

The Mass Sheet Degeneracy





Hilbert+ 2010

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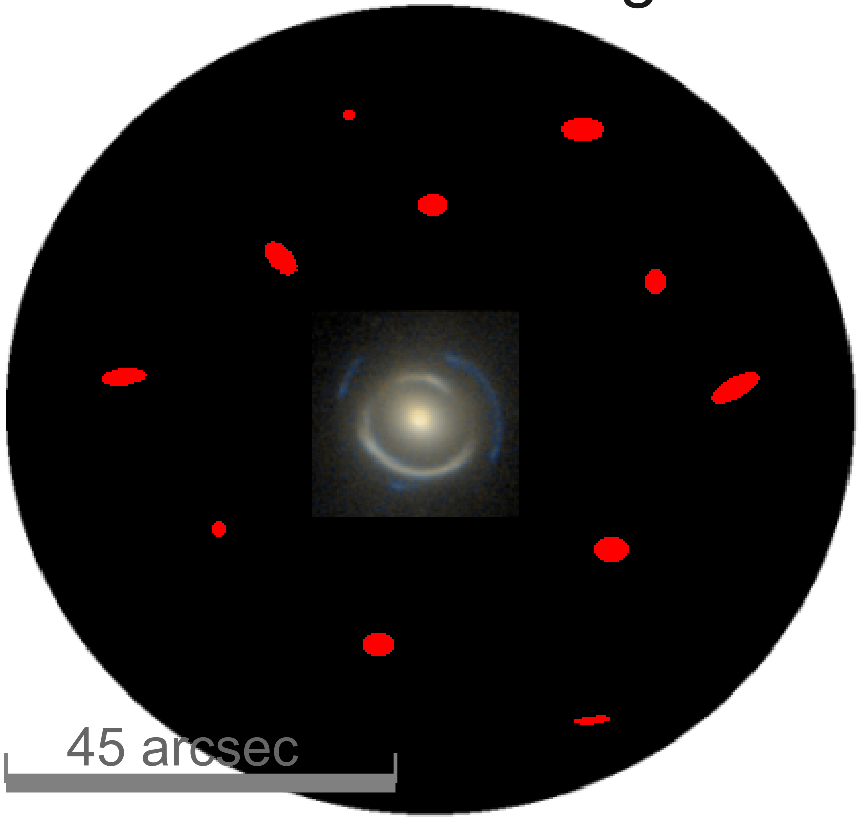
The Mass Sheet Degeneracy



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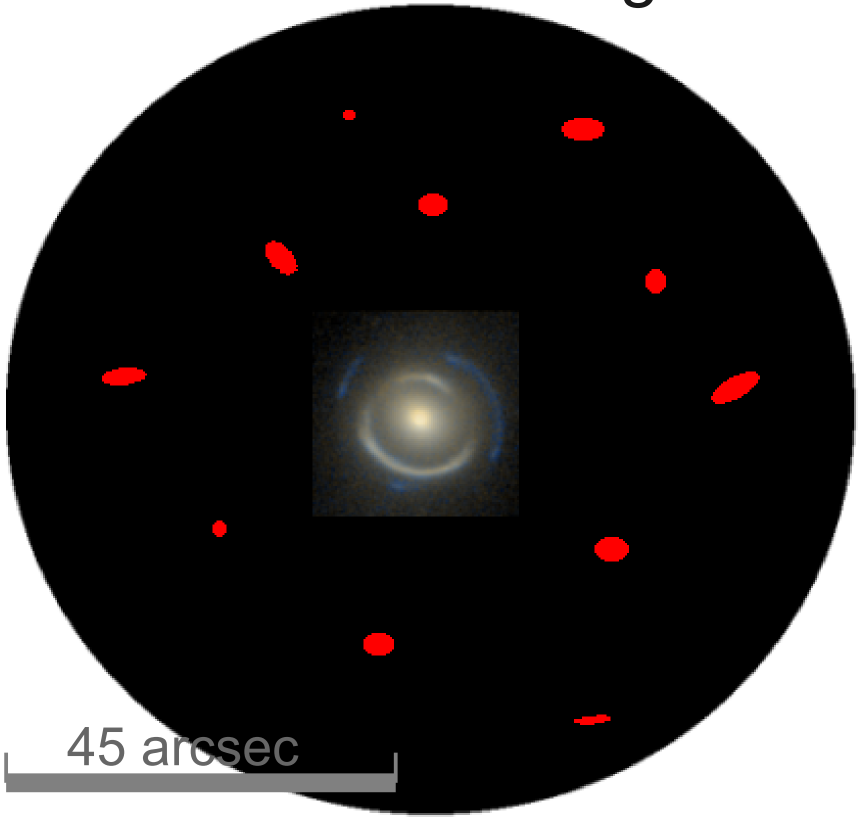

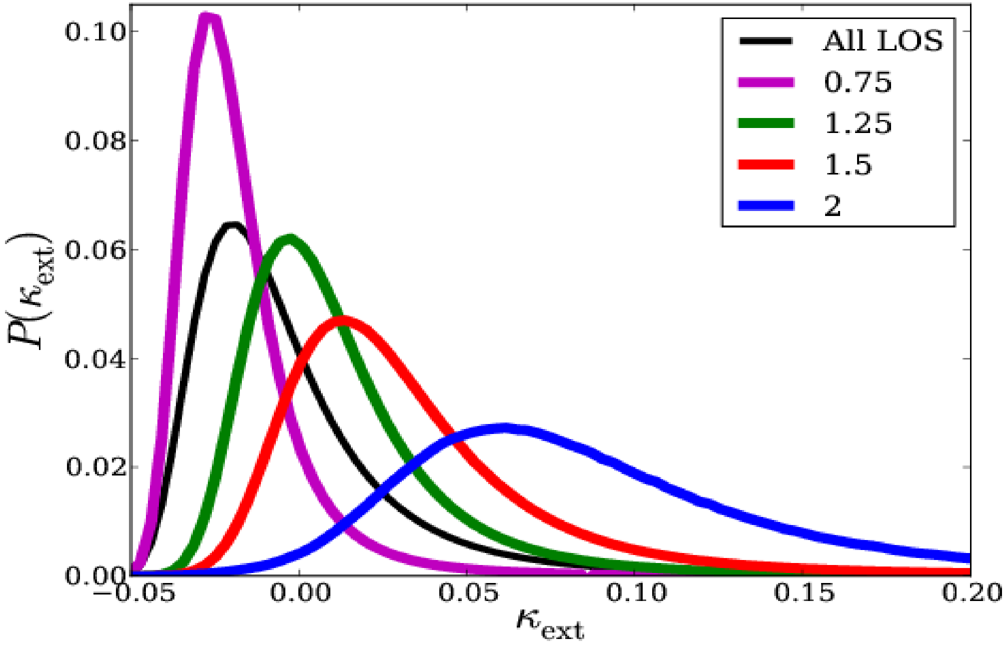

Greene, Collett+ 2013

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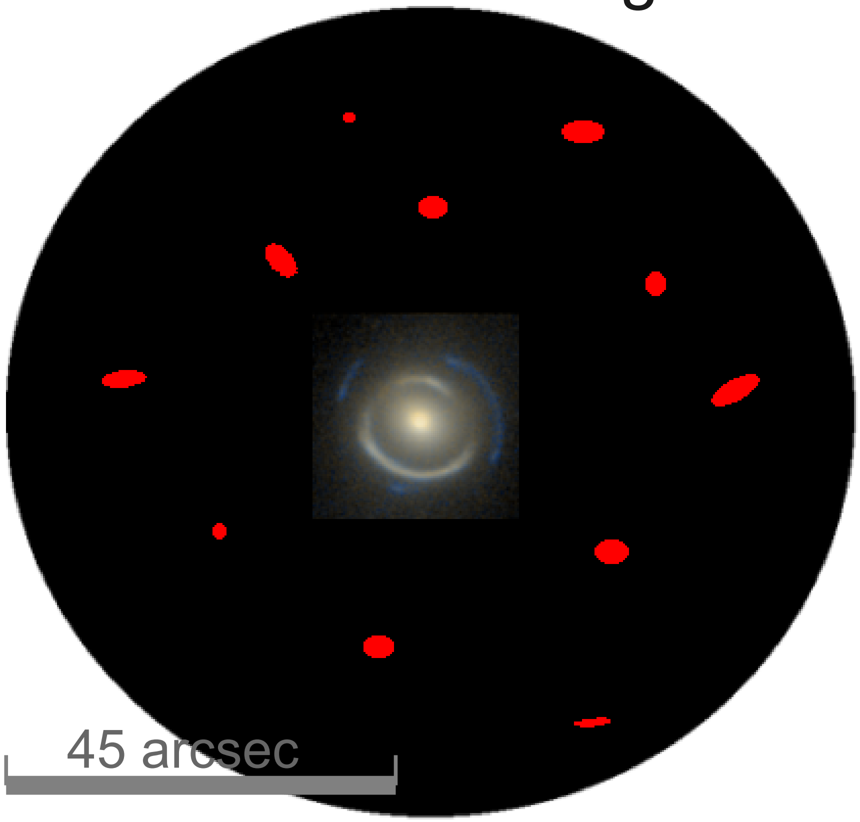
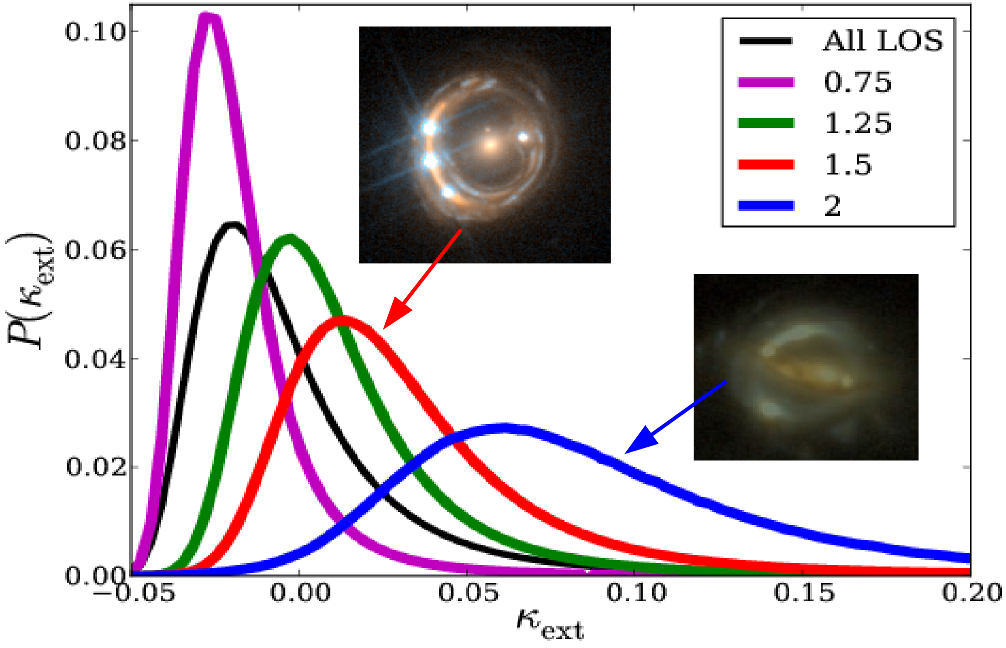
The Mass Sheet Degeneracy





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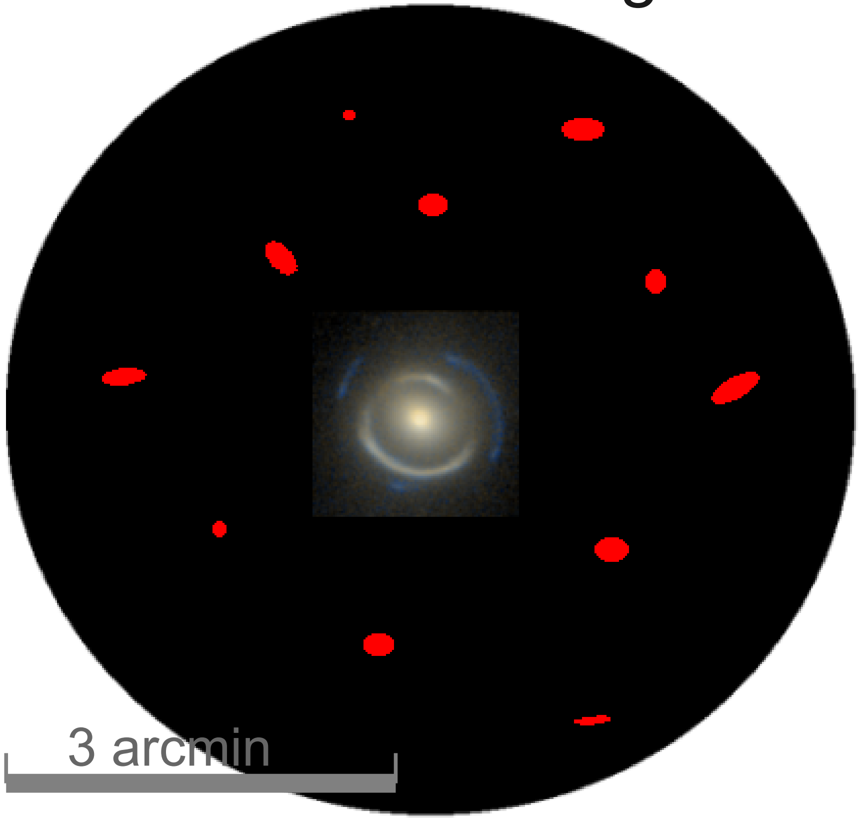

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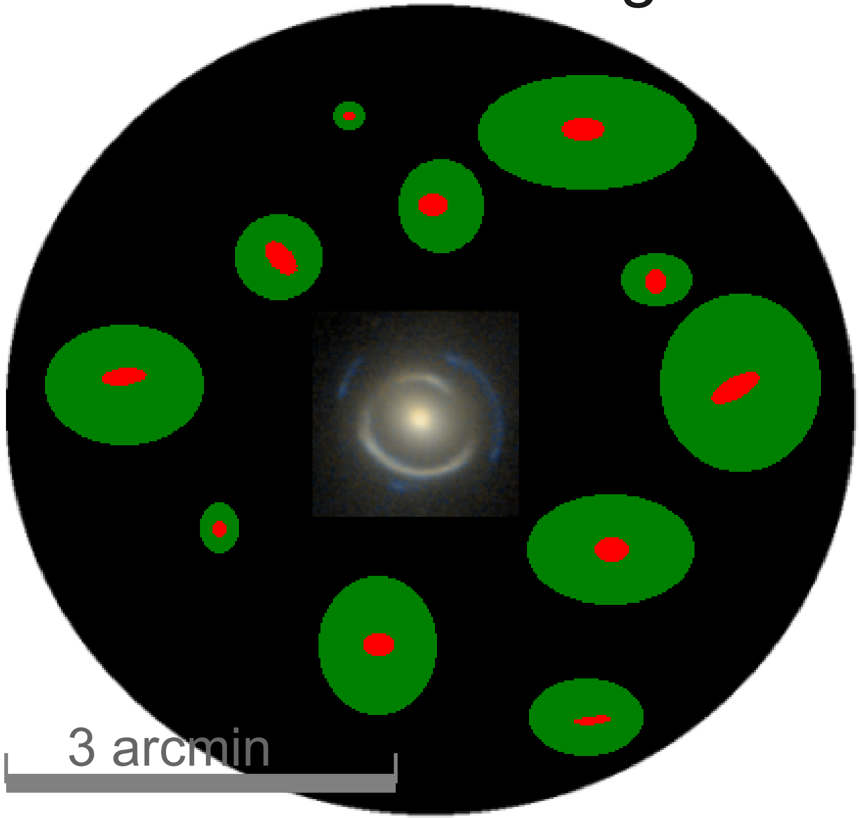

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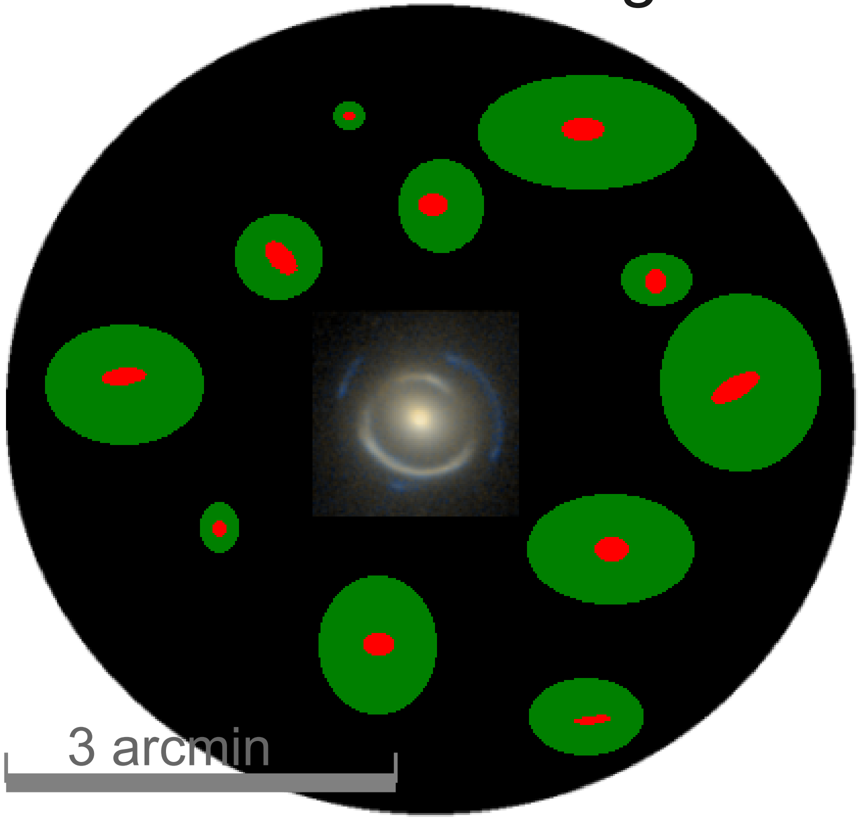
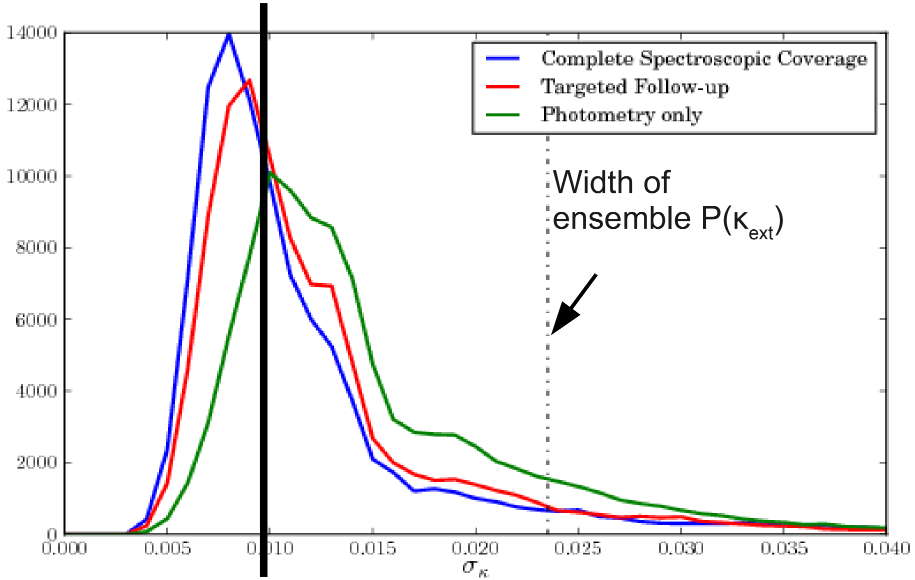


Collett+ 2013



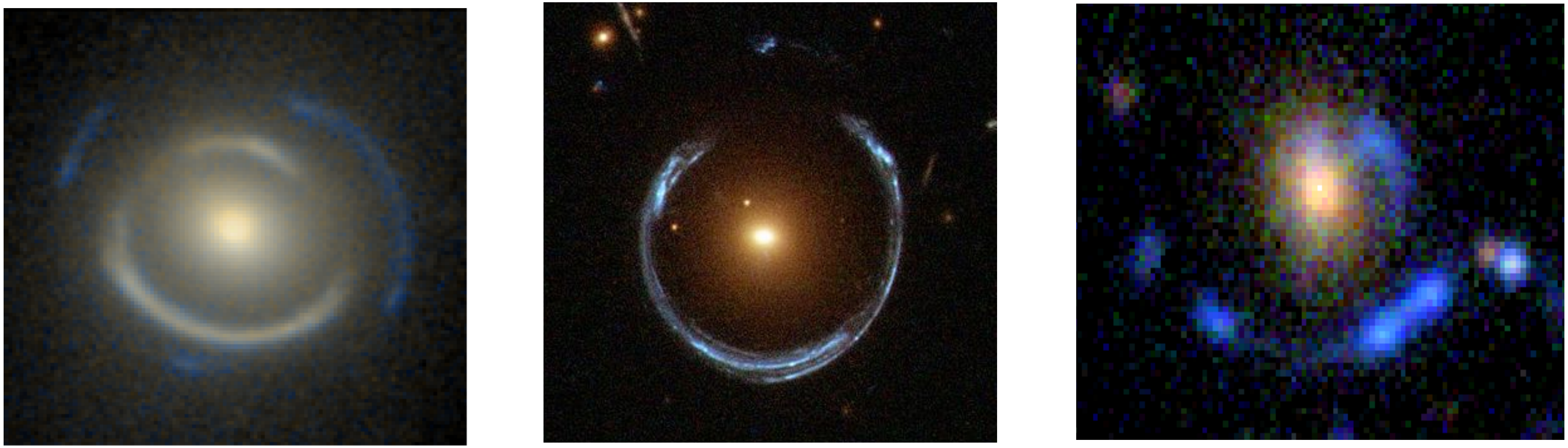
0.01 precision on κ.
Unbiased*

0.01 change in κ approximately:

0.5% in ratio of Einstein radii, 1% in time-delay distance,
2% in magnification of an unlensed source

Summary

- Strong lensing provides powerful complementary constraints on cosmological parameters
- I'm working hard to make sure the systematics are under control!



Thanks to

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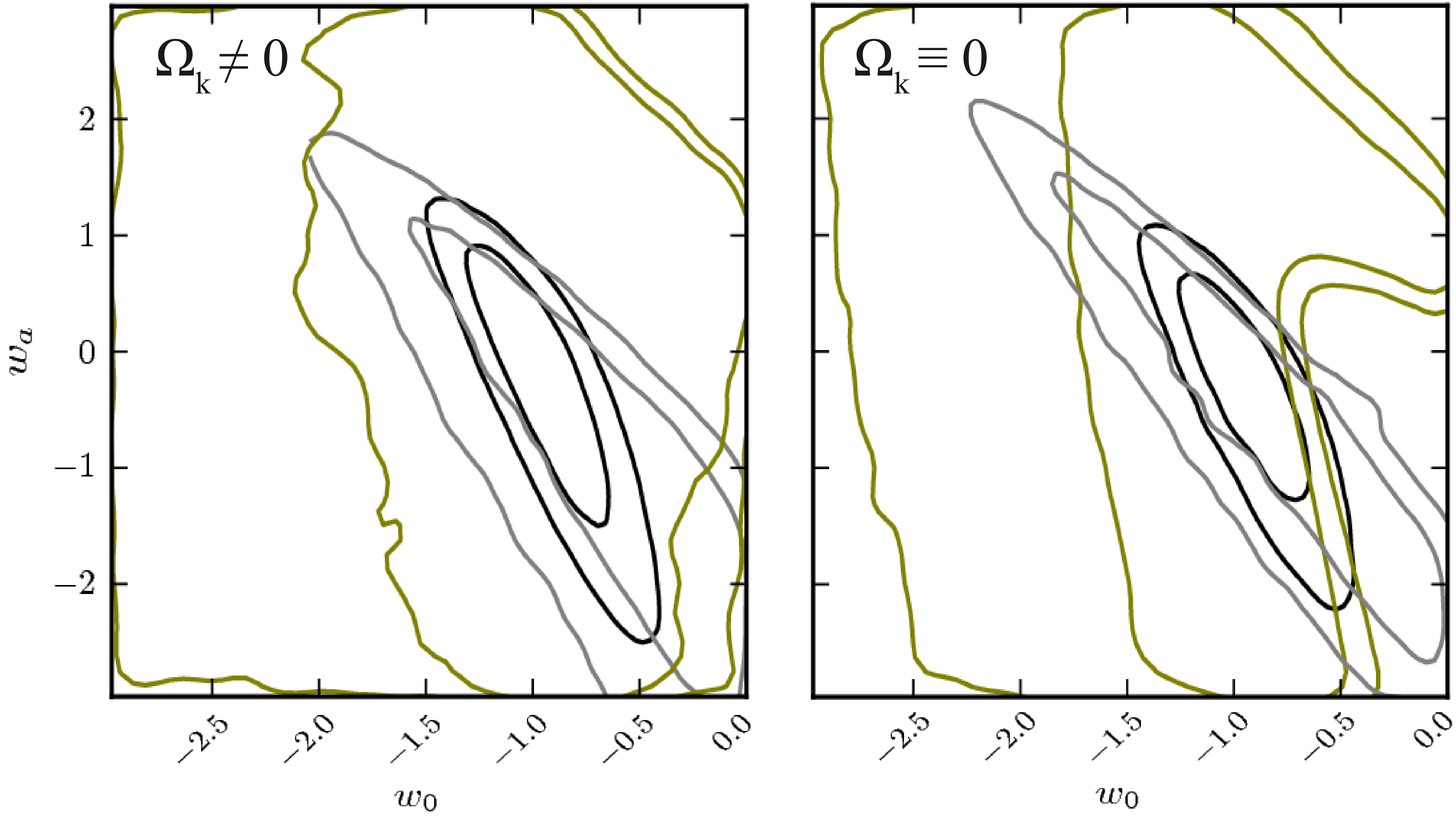
for sponsoring my attendance

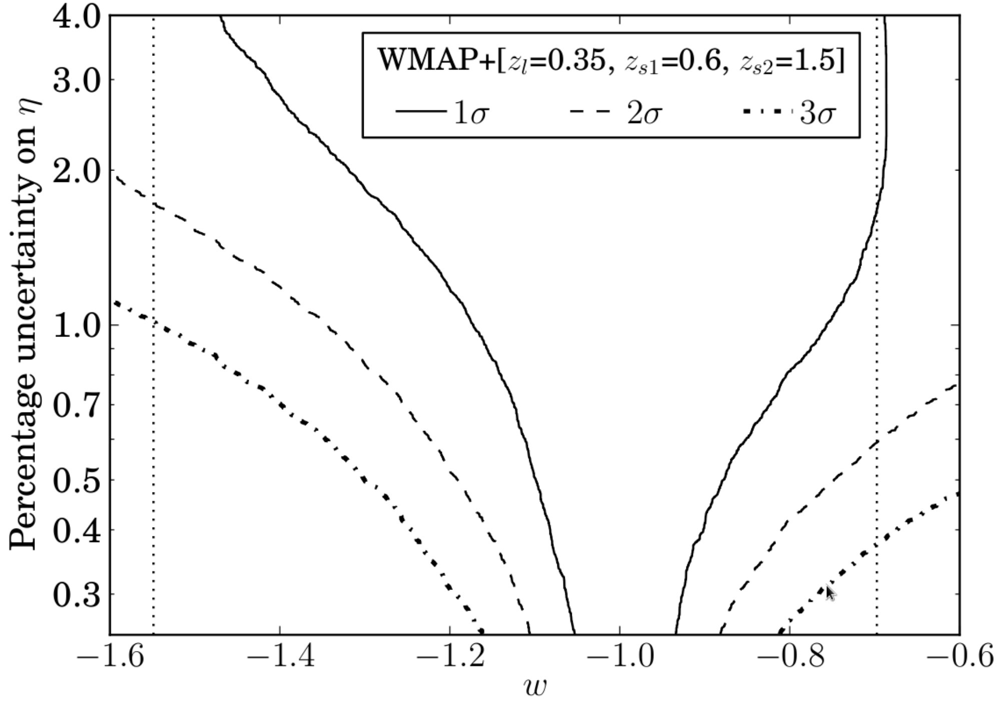
Spare Slides

What about the assumption of flatness?



What if we can't measure the ratio of Einstein radii to 1%?

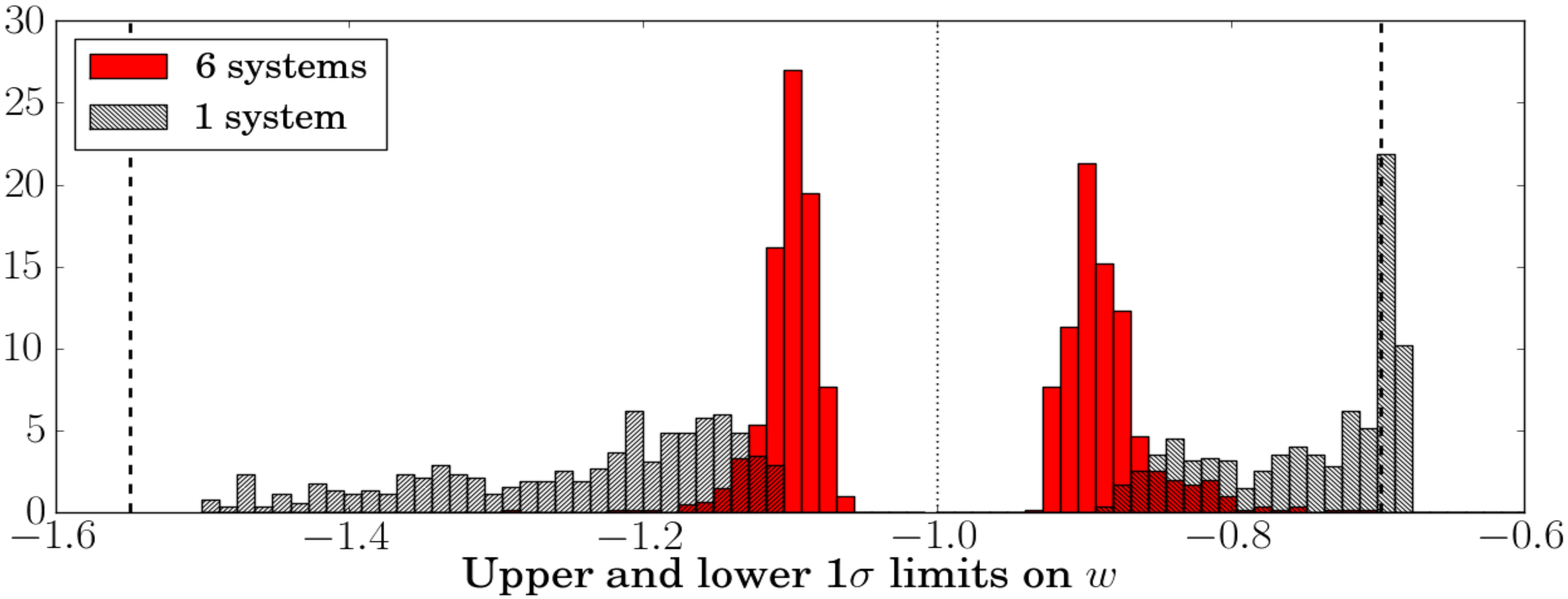
1. Compound lensing – the intermediate source has mass
2. The lens is an astrophysical object – they aren't perfectly isothermal or perfectly spherical



Cosmology with a population of systems.

SLACS:
1.1mm, S > 1 mJy → ~1.5 double source plane systems (1.5 in 78)
1.1mm, S > 0.3 mJy → ~3 double source plane systems (3 in 78)

But can be more efficient if you focus only on the most massive lenses.



Constraints with 6 systems.

System	1	2	3	4	5	6
z_l	0.440	0.227	0.195	0.227	0.194	0.111
z_{s1}	1.192	0.783	0.632	0.931	0.446	0.316
z_{s2}	3.859	0.931	2.724	1.766	2.058	0.463

Pick the set of systems that provided the median constraints on w.

WMAP+6 systems is ~2.5 times better than WMAP+1.

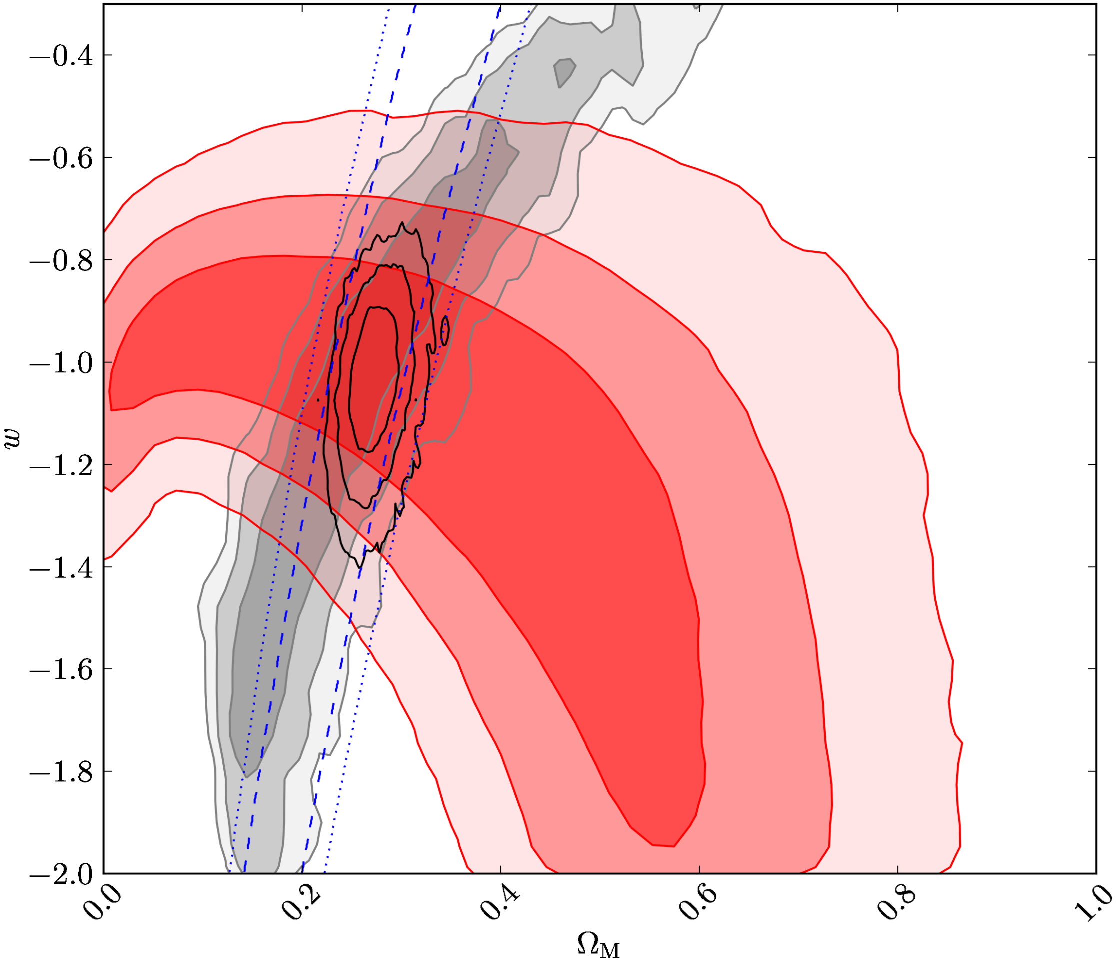
<u>WMAP+</u>

1 system $w_{\mathrm{DE}} = -0.99 \pm 0.27$

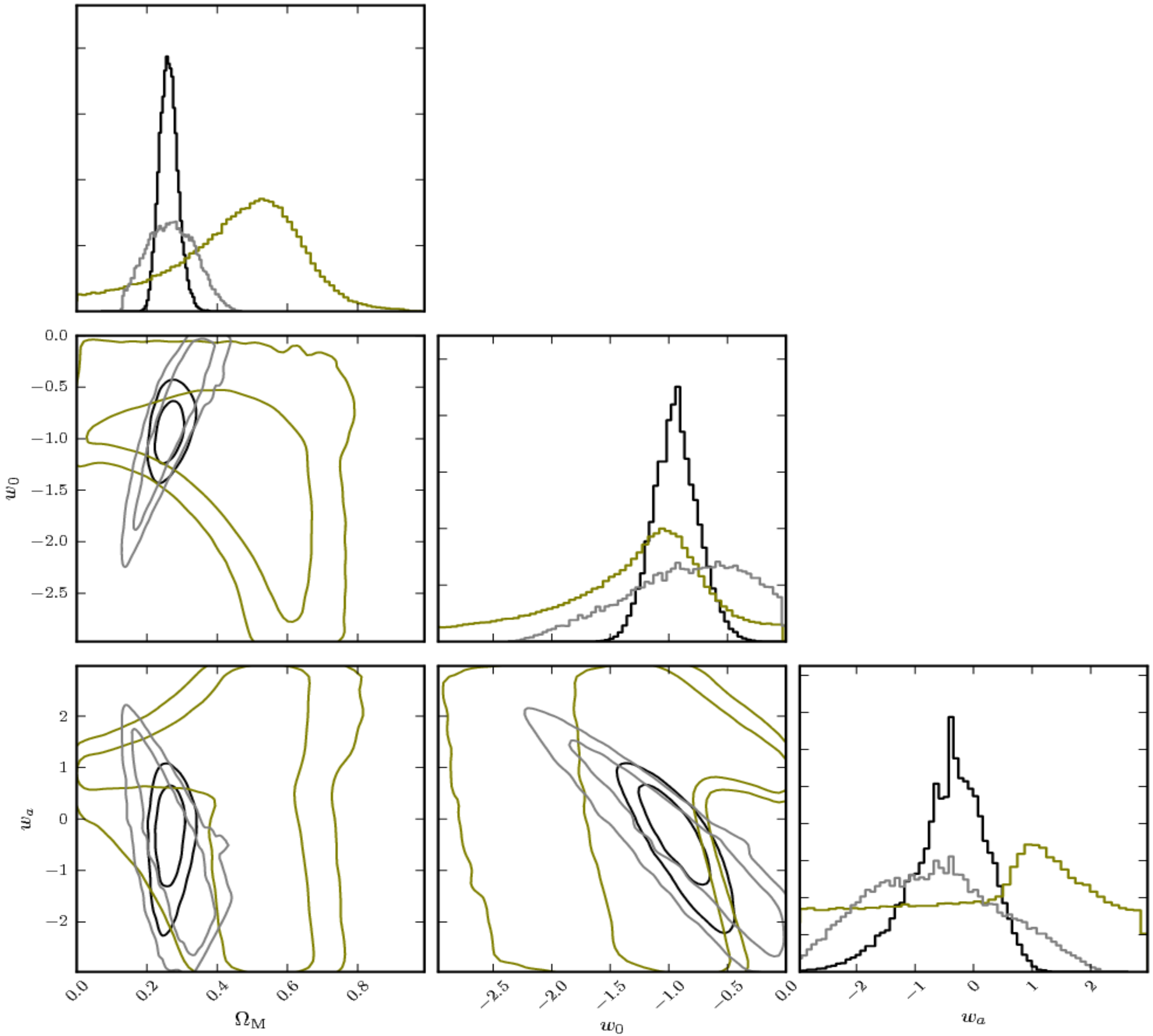
6 systems $w_{\mathrm{DE}} = -1.01 \pm 0.11$

<u>WMAP+BAO+Time Delay+</u>

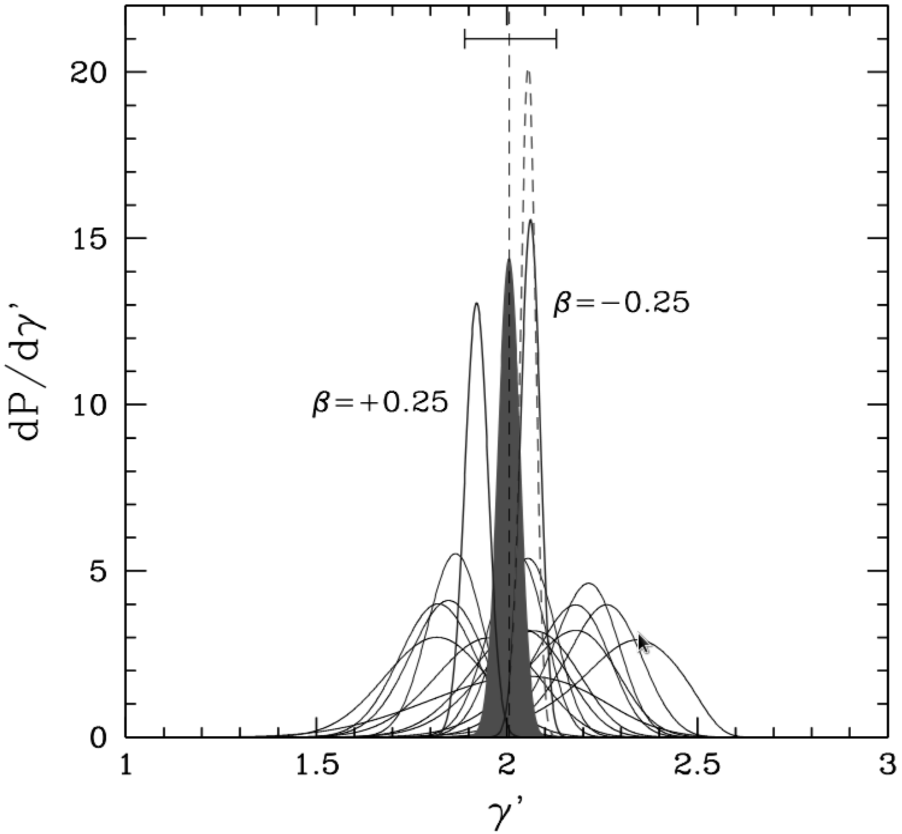
6 systems $w_{\mathrm{DE}} = -1.04 \pm 0.09$



Planck+6


0.0
−0.5
−1.0
−1.5
−2.0
−2.5
w_0
2
1
0
−1
−2
w_a
0.0
0.2
0.4
0.6
0.8
$\Omega_{\rm M}$
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
w_0
−2
−1
0
1
2
w_a

Probing the mass profile of galaxies



Combine Einstein Radius with stellar dynamics

Fit a power-law:

$$\rho = \rho_0 r^{-\gamma'}$$

Lenses are approximately isothermal ($\gamma'=2$).

(Koopmans+ 2006)

$\gamma' = 2.078 \pm 0.027$ with an intrinsic scatter of 0.16 ± 0.02

(Auger+ 2010)