Cosmology with double-source-plane lenses

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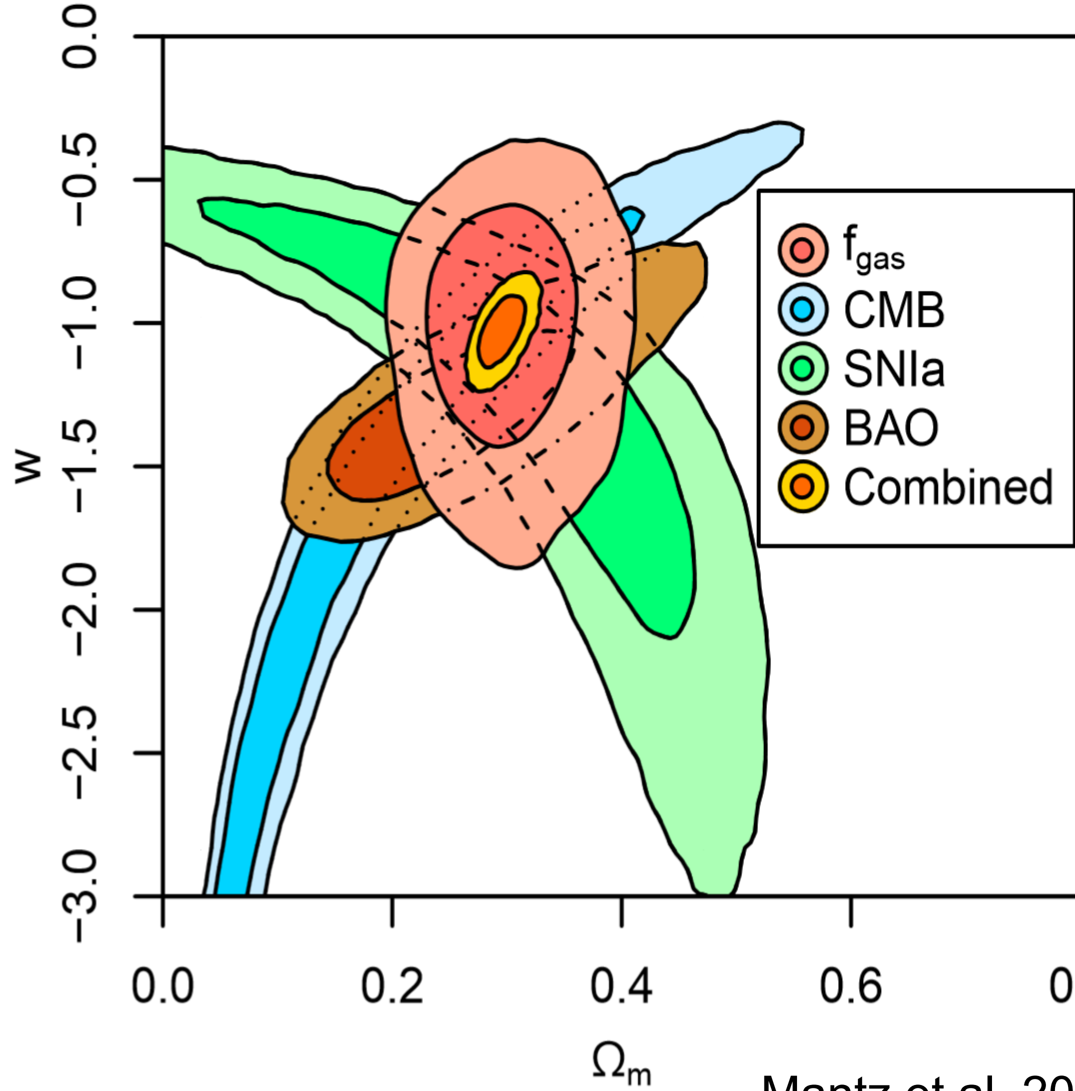
T. E. Collett & M. W. Auger (2014).
Cosmological constraints from the double source plane lens SDSSJ0946+1006. *arXiv:1403.5278*

Few Probes of Dark Energy

Precise measurements

Systematics important



Mantz et al. 2014

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

Uncertainty in the mass model makes cosmography hard

Hubble constant

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

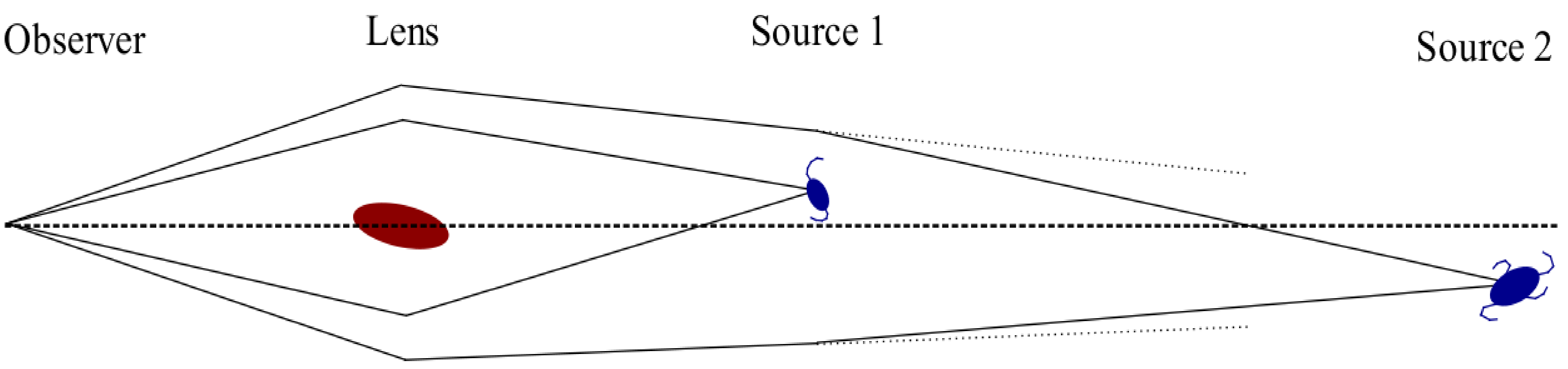
+ can add a term for spatial curvature

Matter Density

Dark Energy Equation of State

Double source plane strong lensing

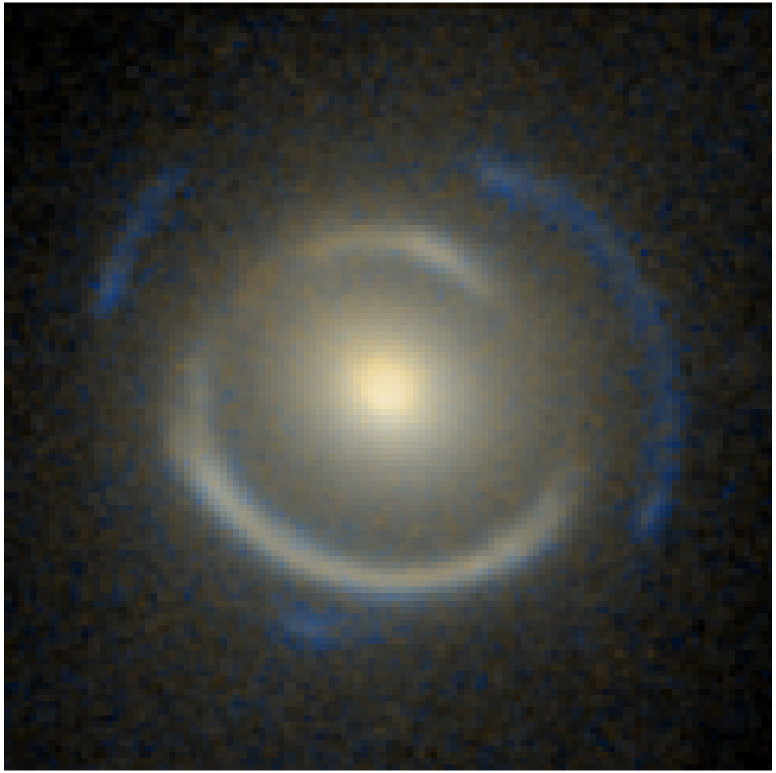
A gravitational lens system with two background sources, each at a different redshift.



RARE

The observable:

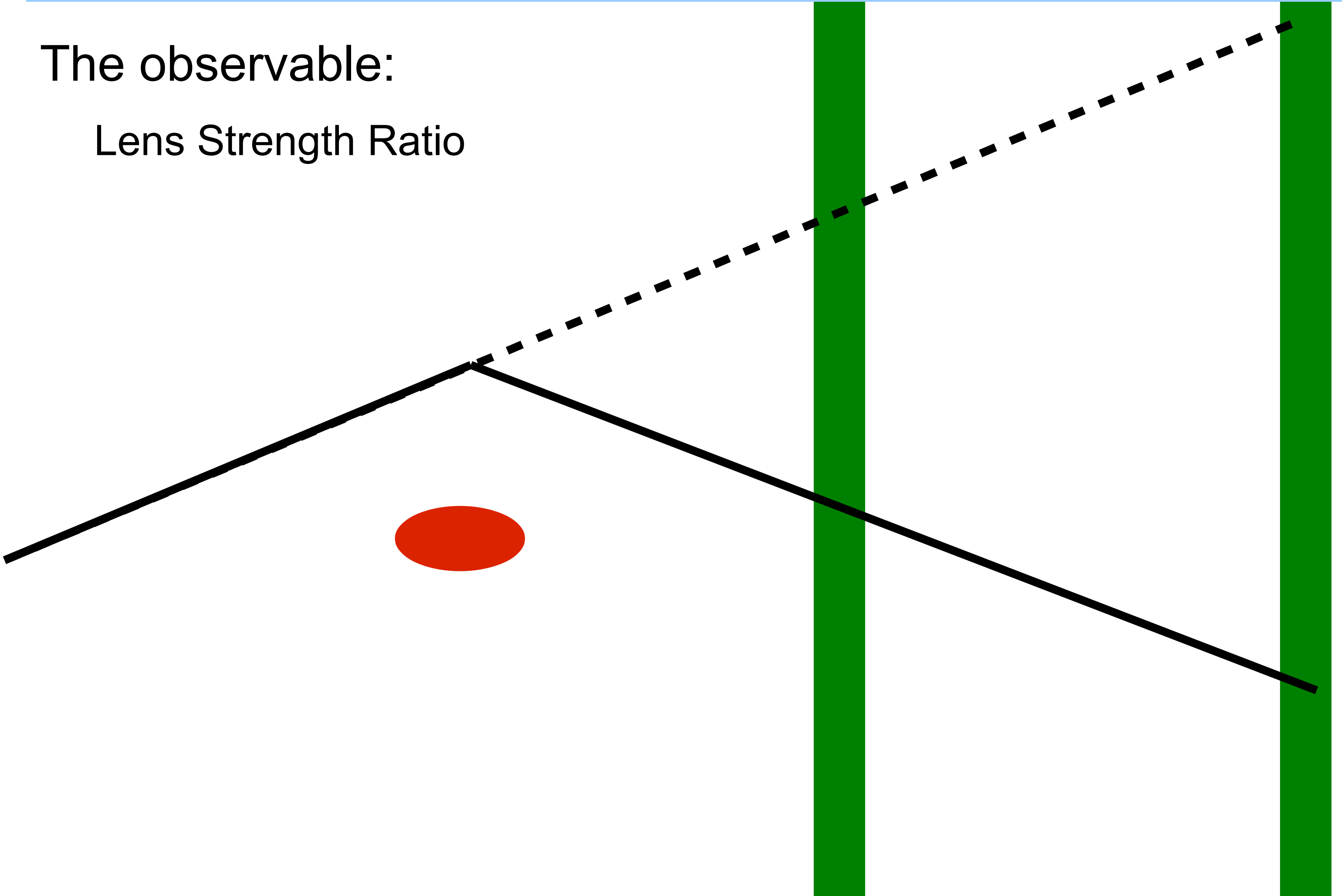
Lens Strength Ratio



Approximately the ratio of Einstein radii

The observable:

Lens Strength Ratio



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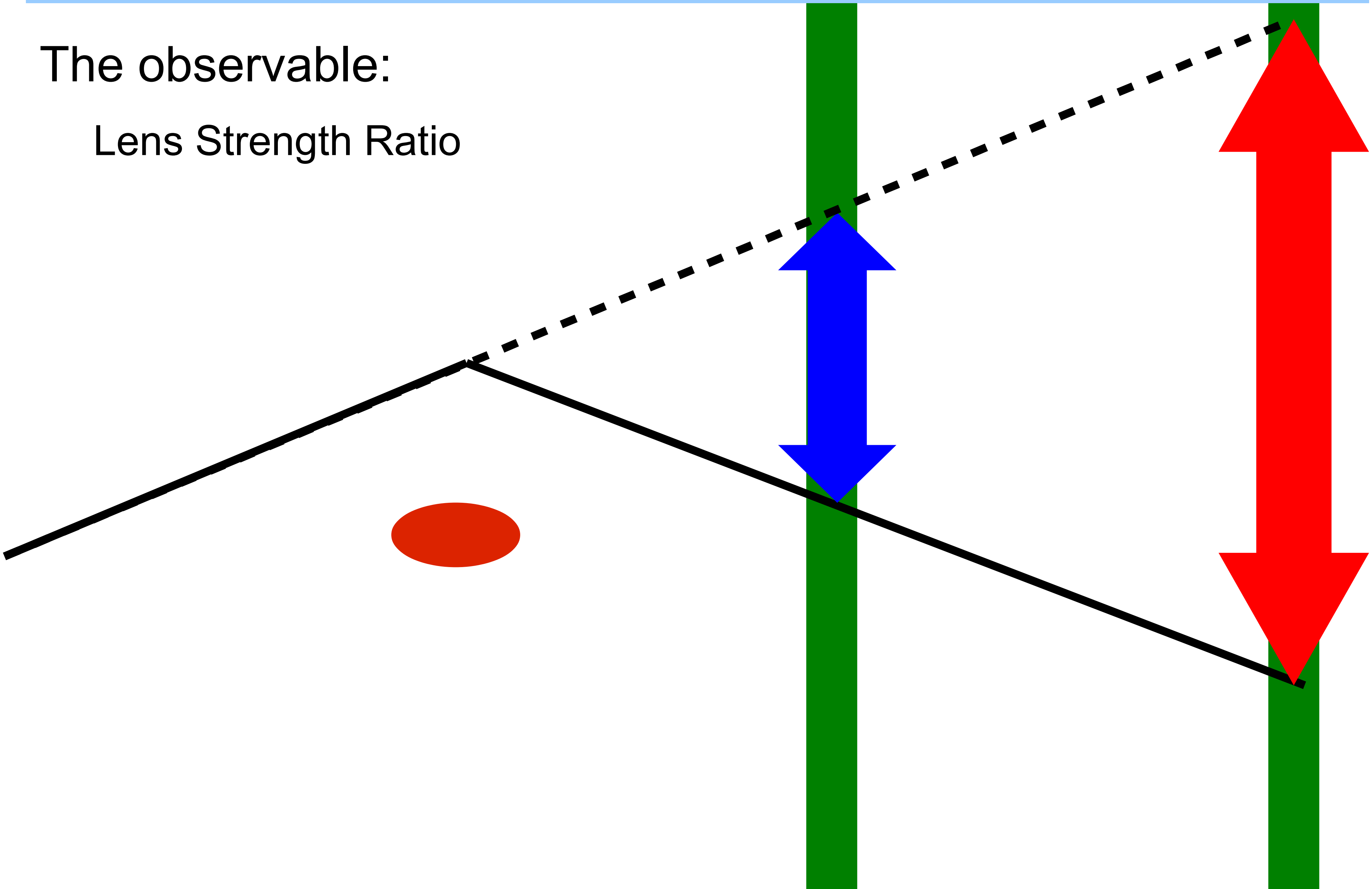
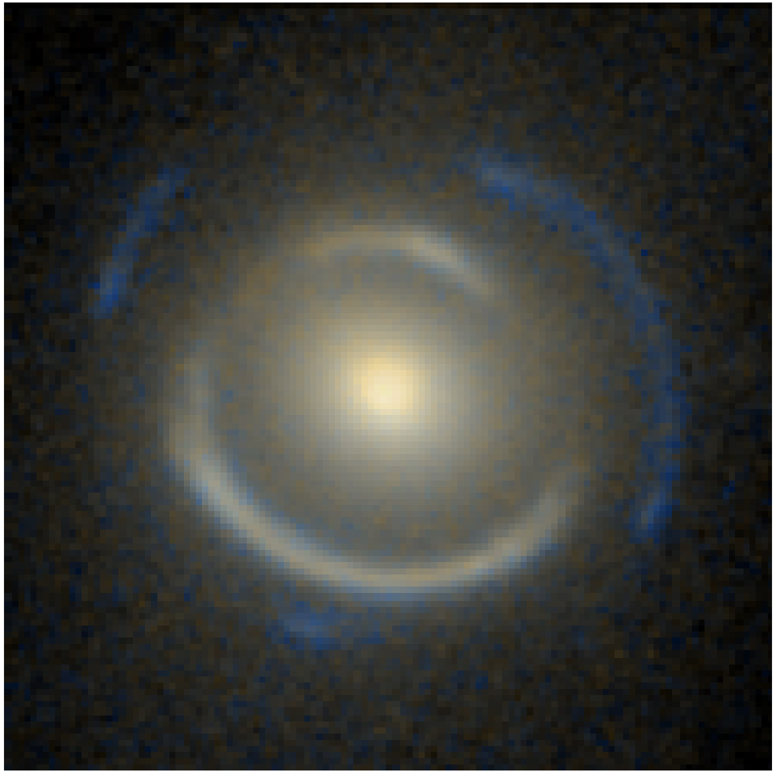
Lens Strength Ratio

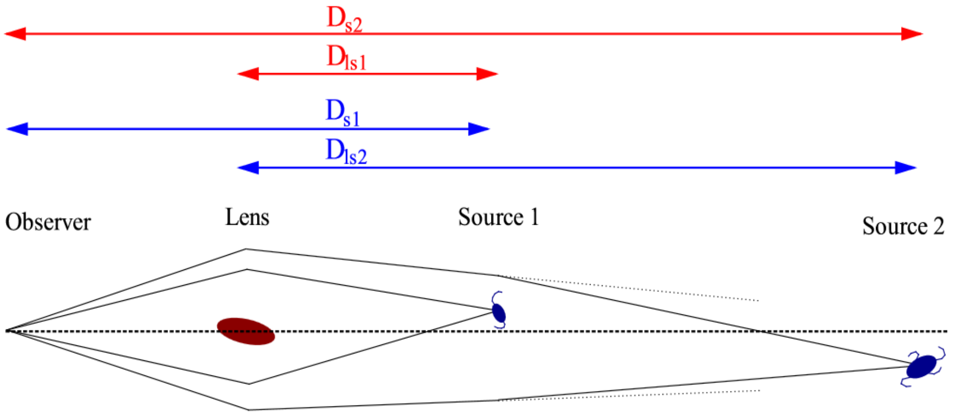


The observable:

Lens Strength Ratio

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



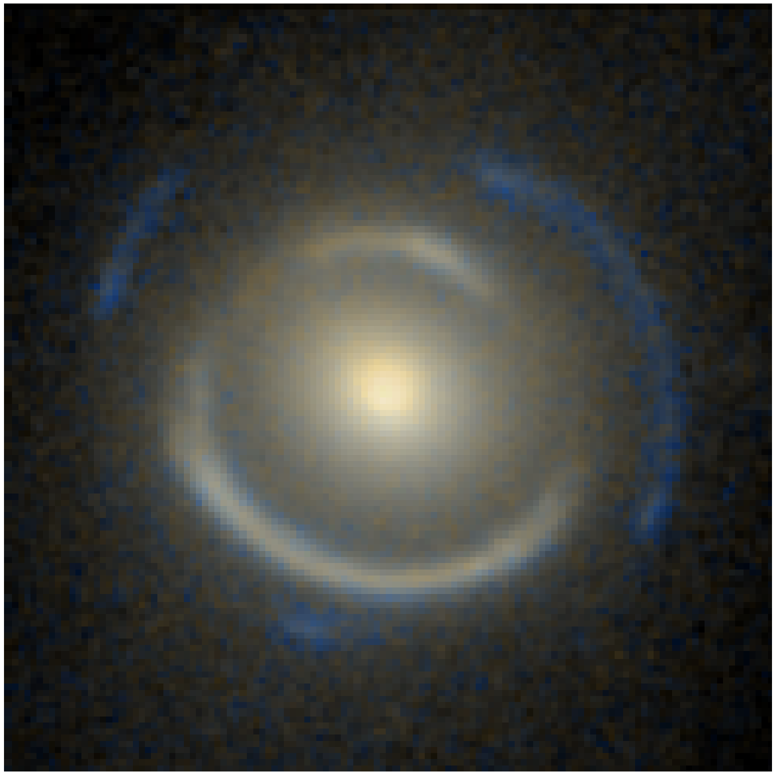


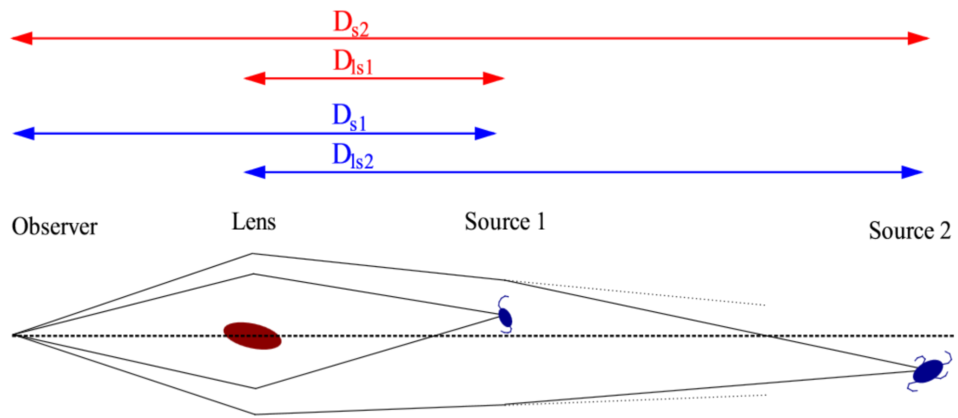
The observable:

Lens Strength Ratio

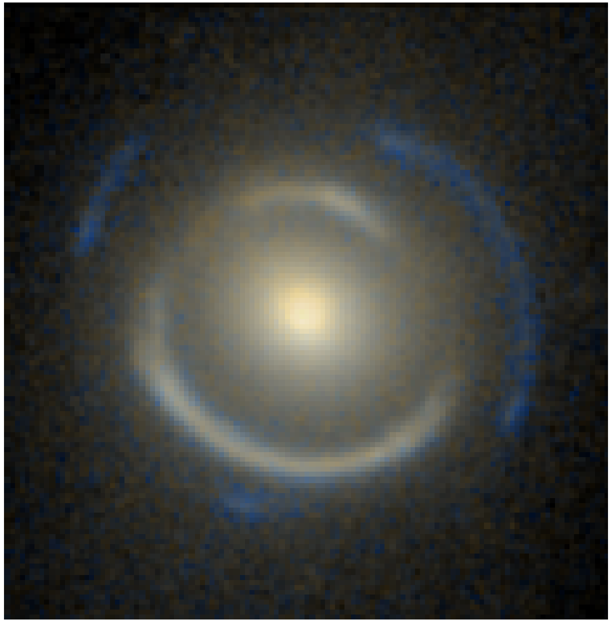
$$\beta = \frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}}$$

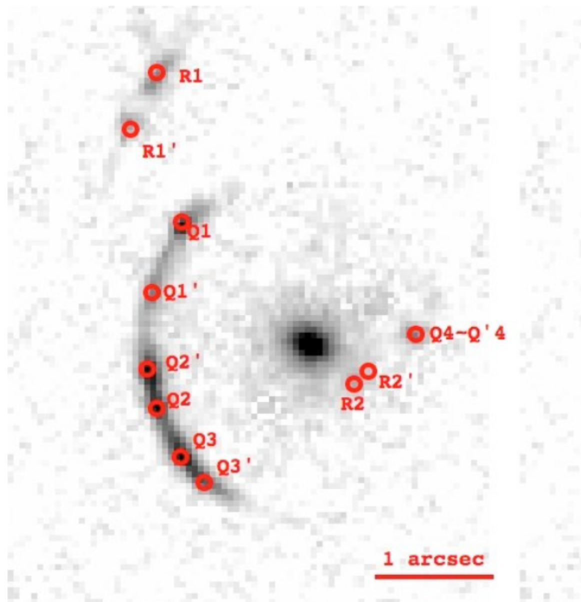
No dependence on the Hubble constant!

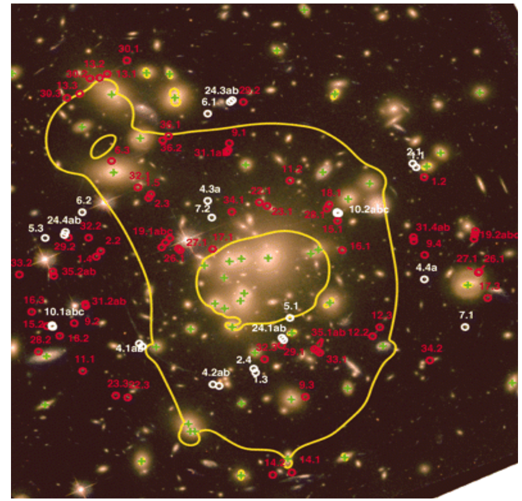


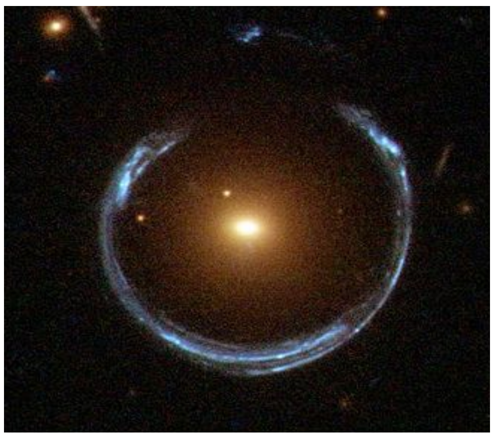


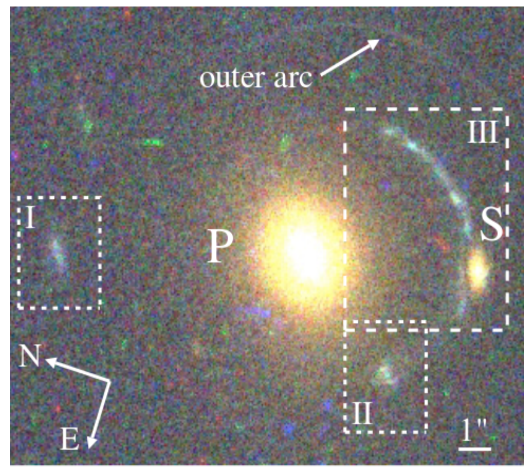
Double source plane strong lensing











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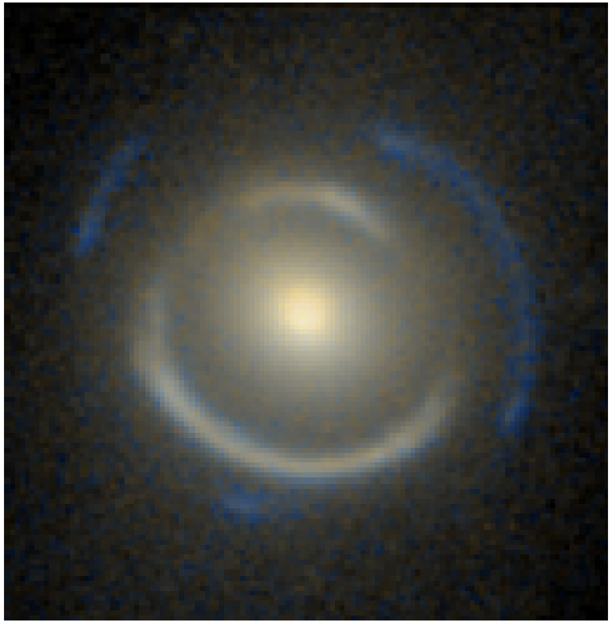
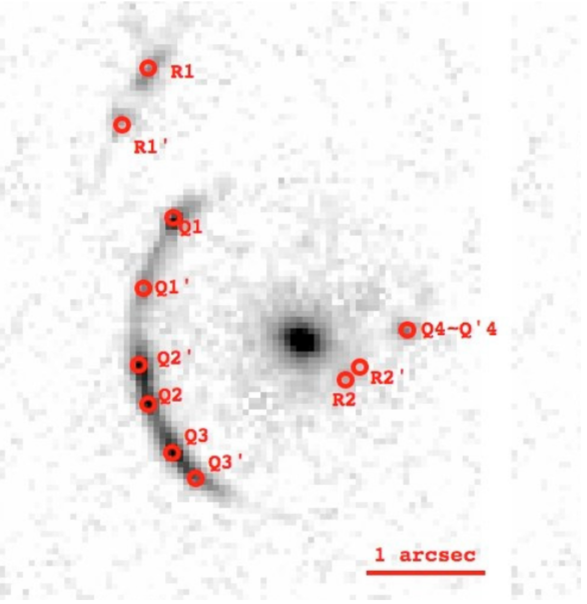
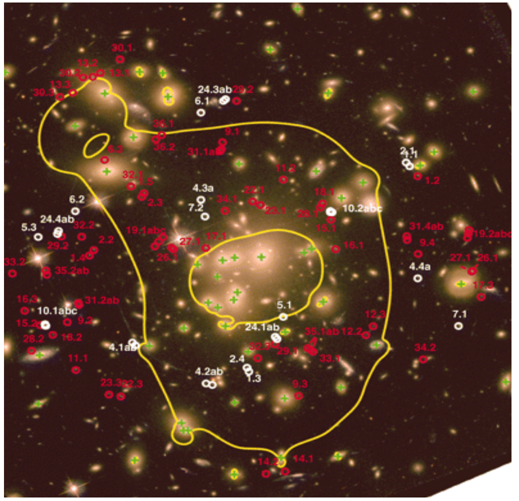
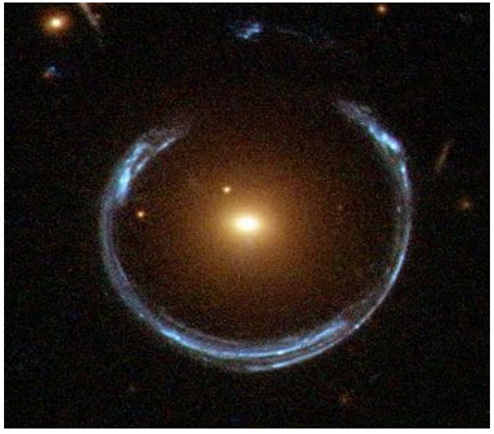


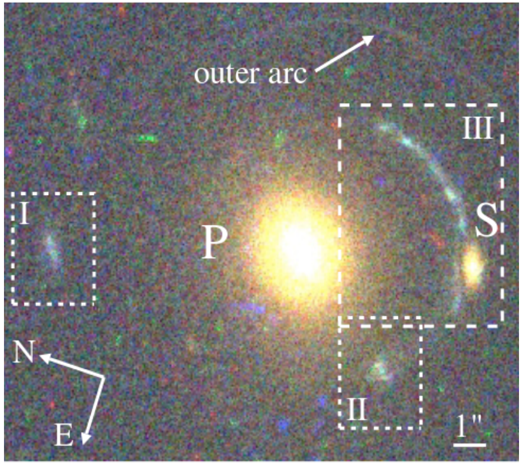






Cross section scales rapidly with mass

$$\sigma \sim M^4$$



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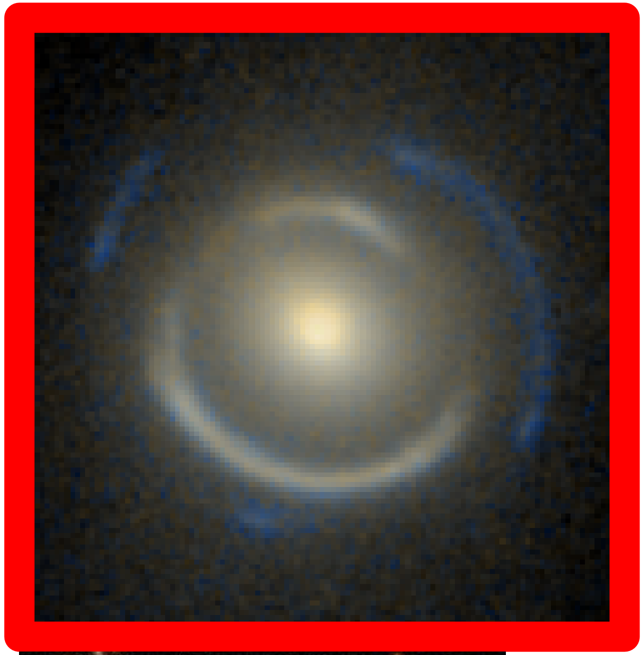

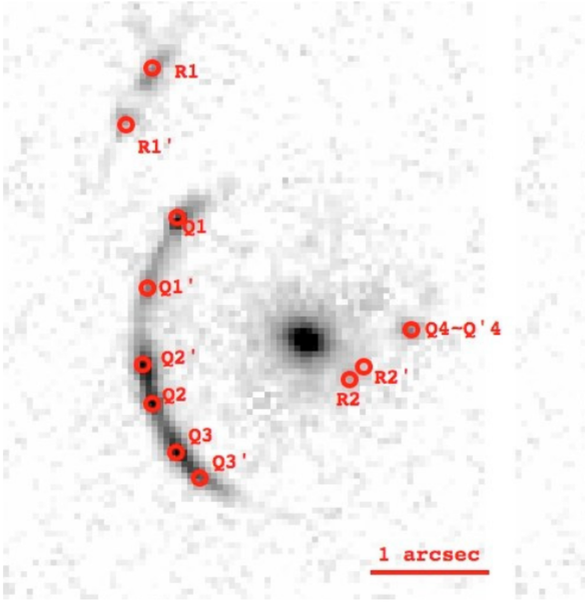

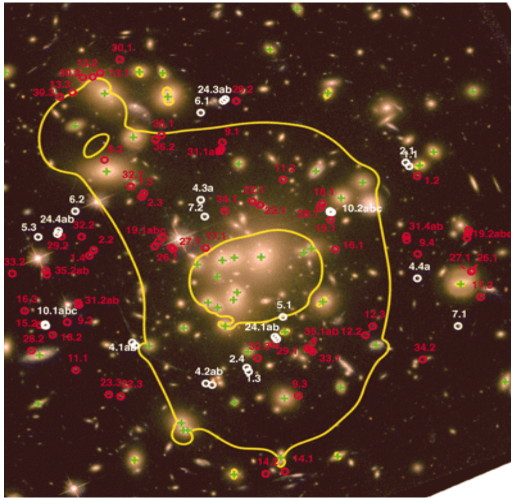

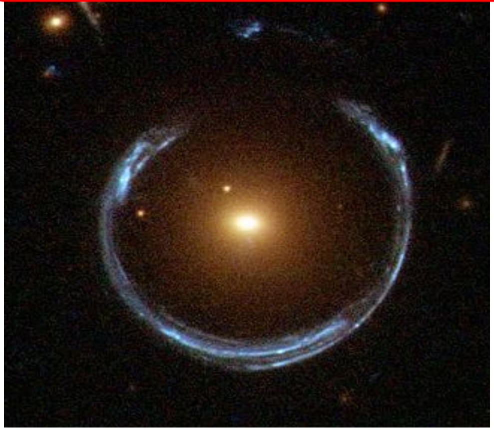

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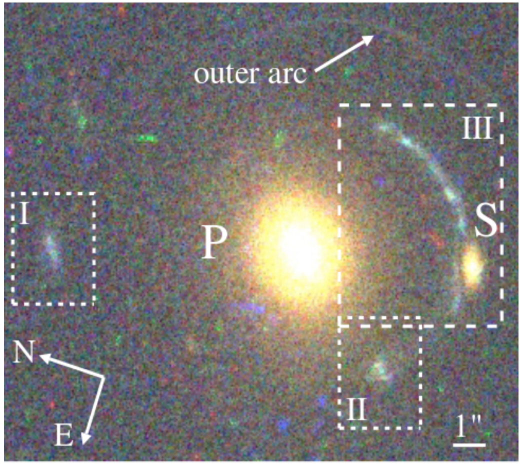
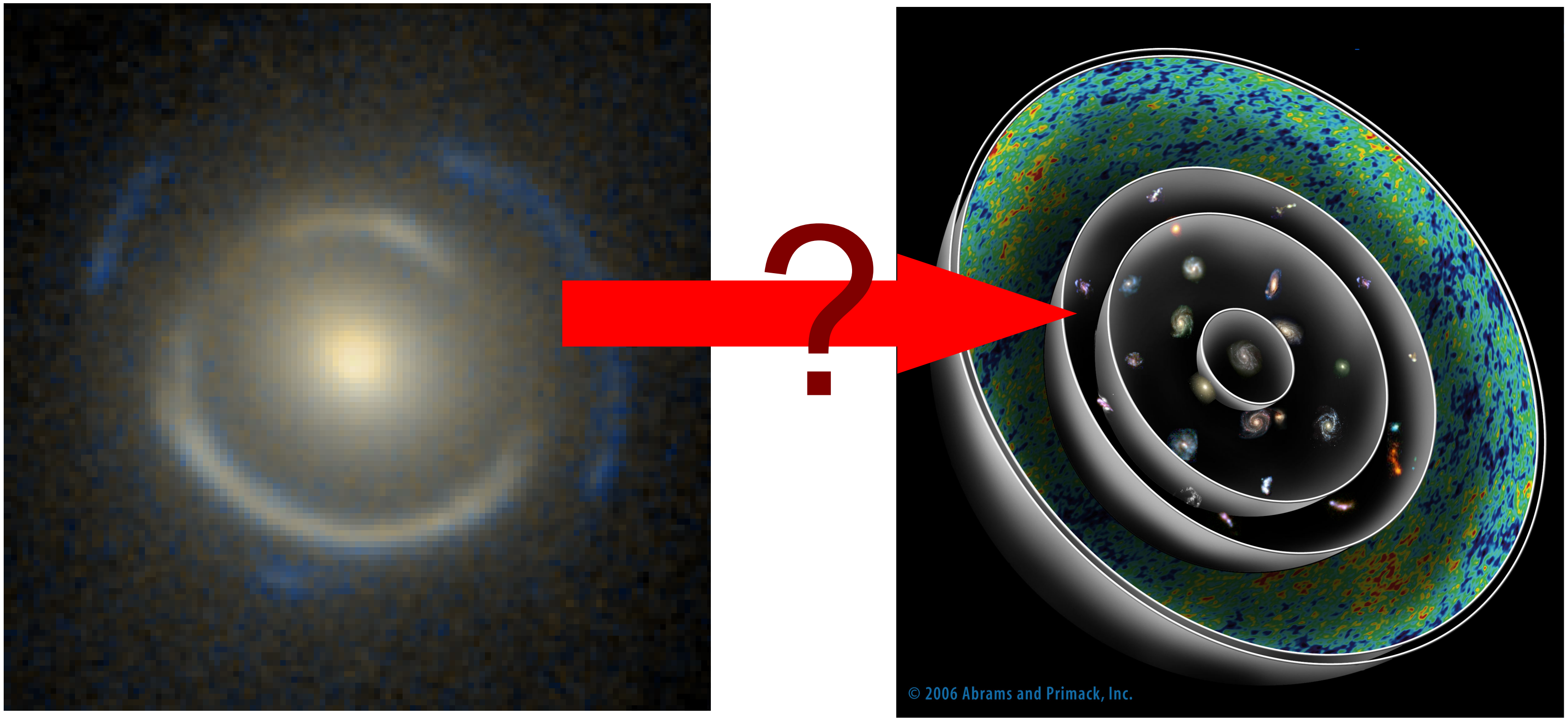
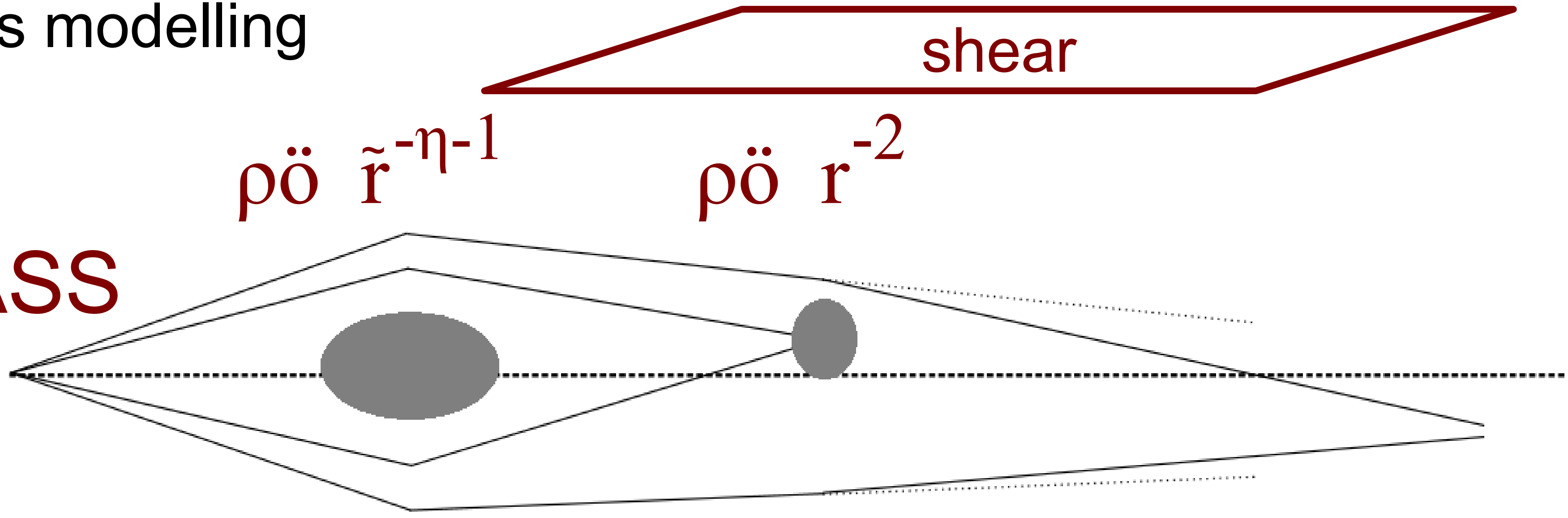


What do we need to do?

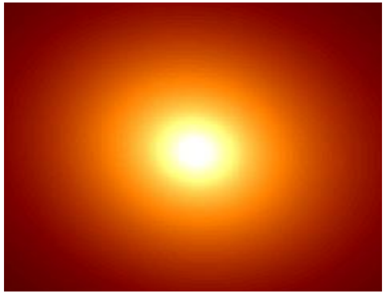


Lens modelling

MASS



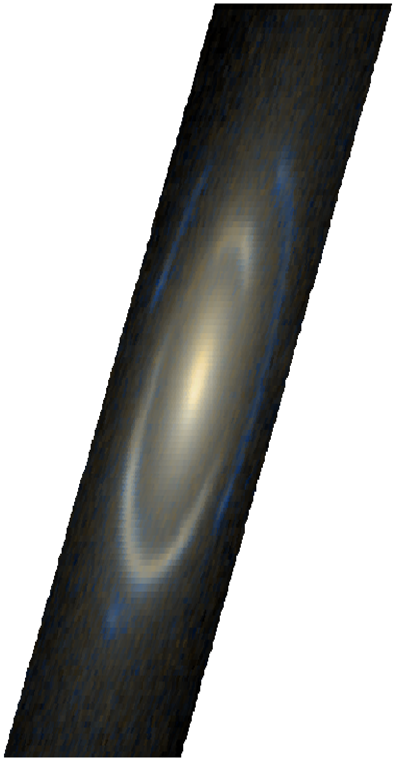
LIGHT

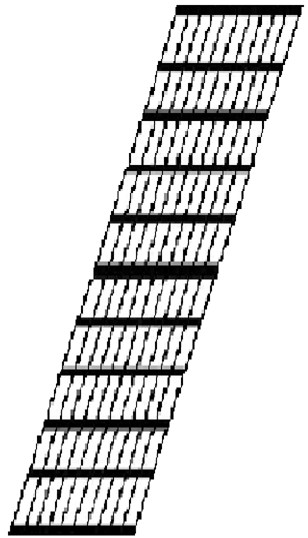


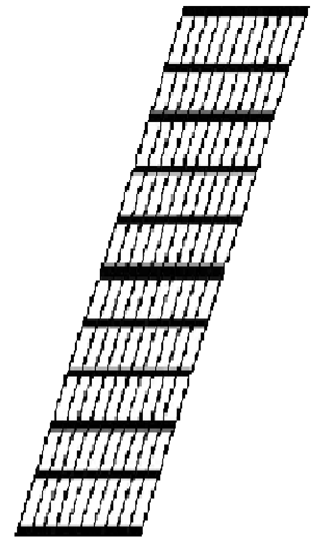
Sersic

Regularized, Pixellated Sources

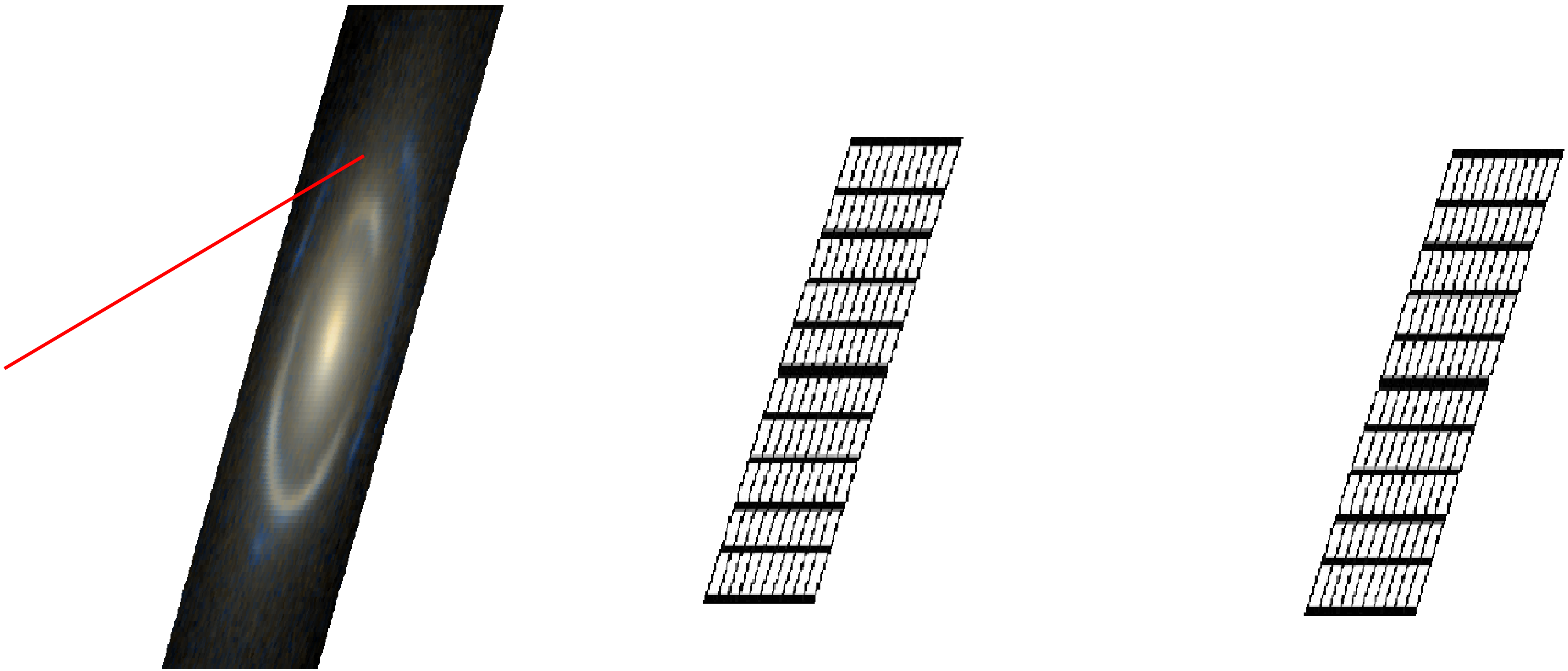
Lens modelling



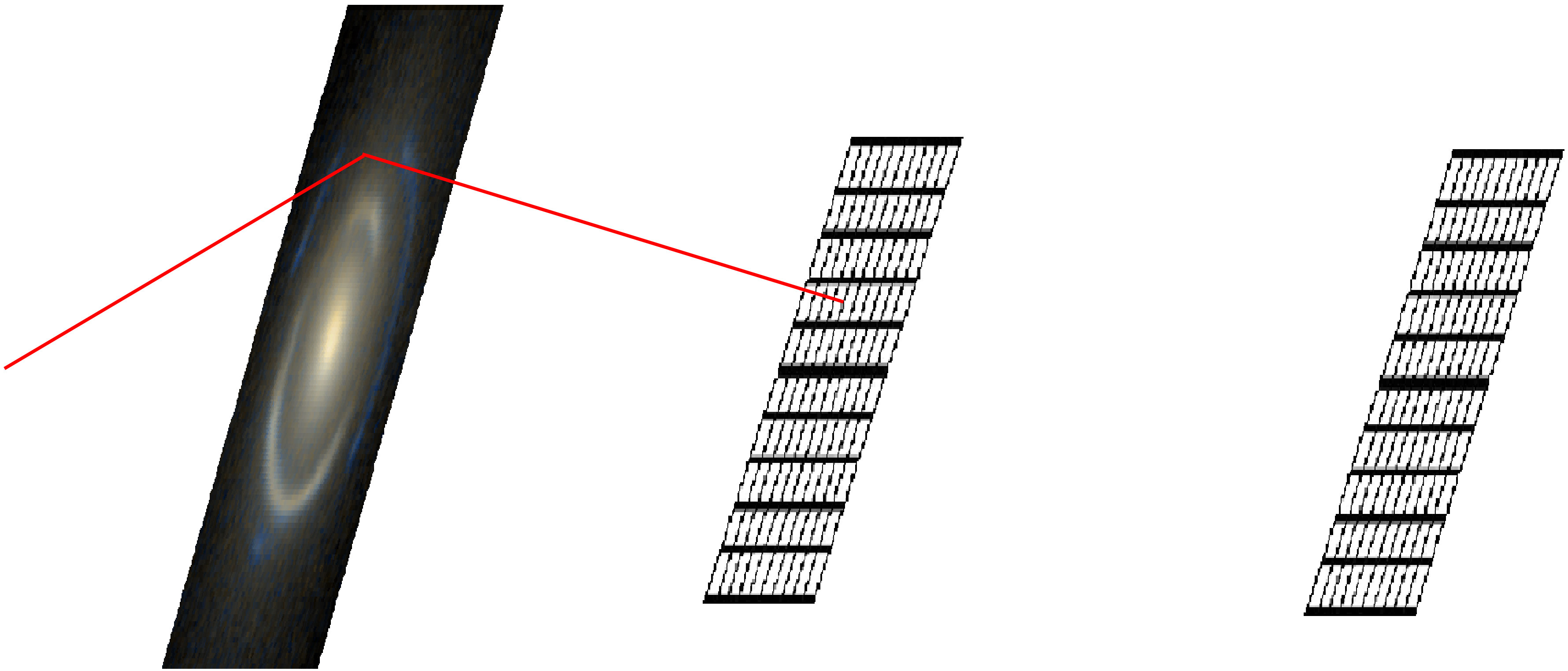




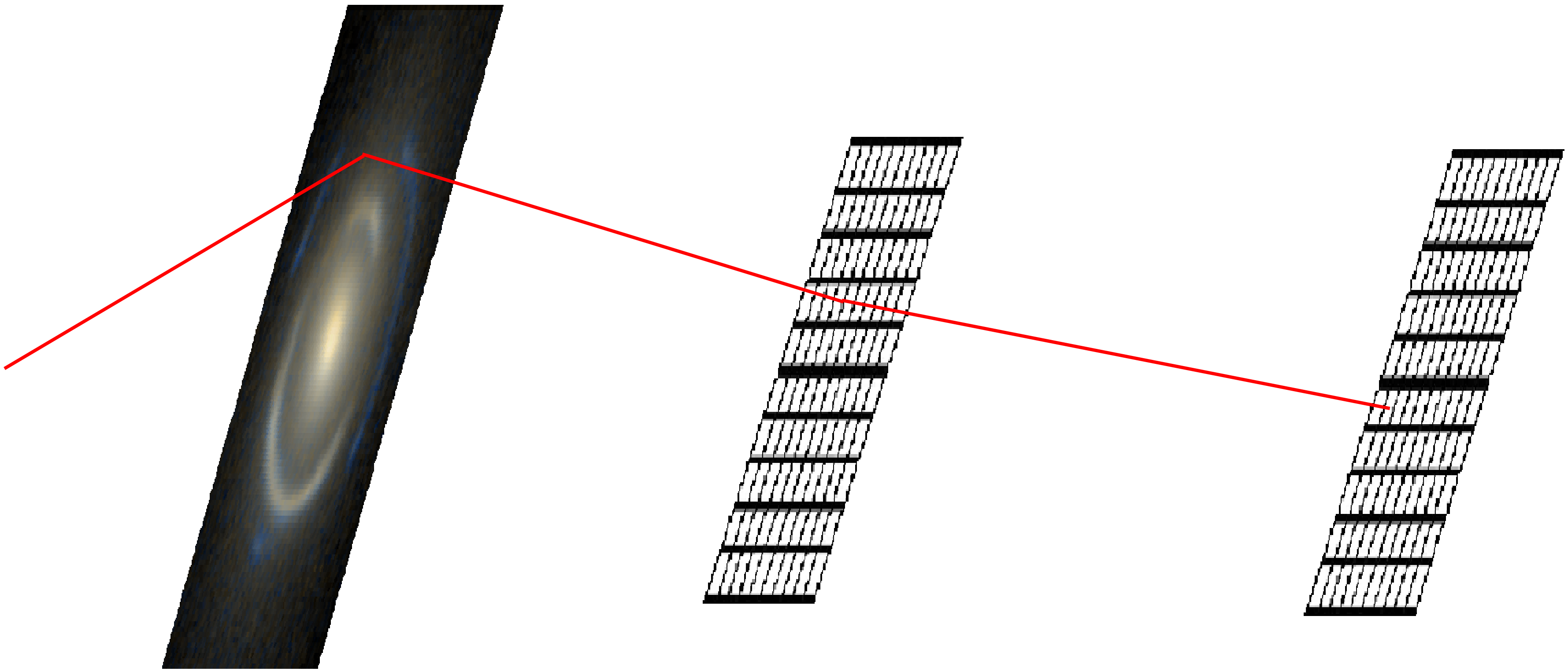
Lens modelling



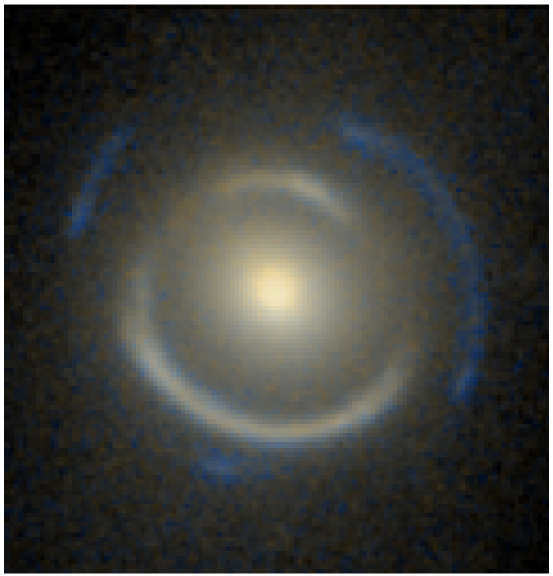
Lens modelling



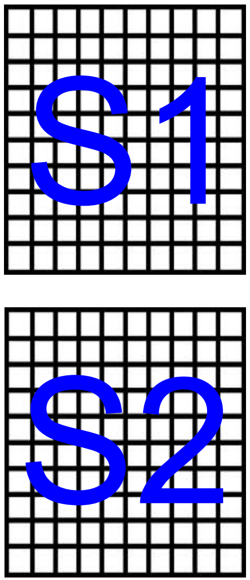
Lens modelling



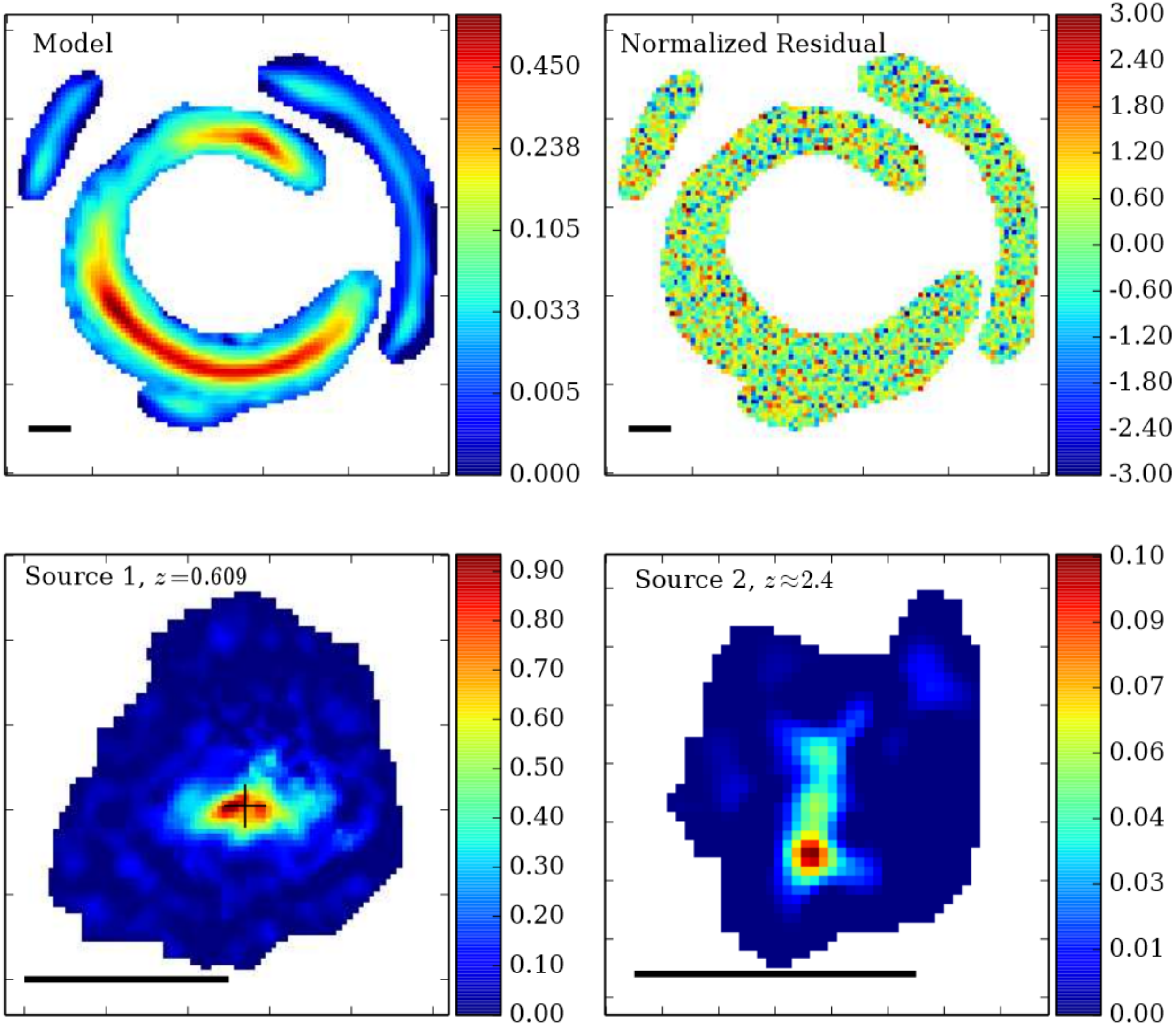
Lens modelling



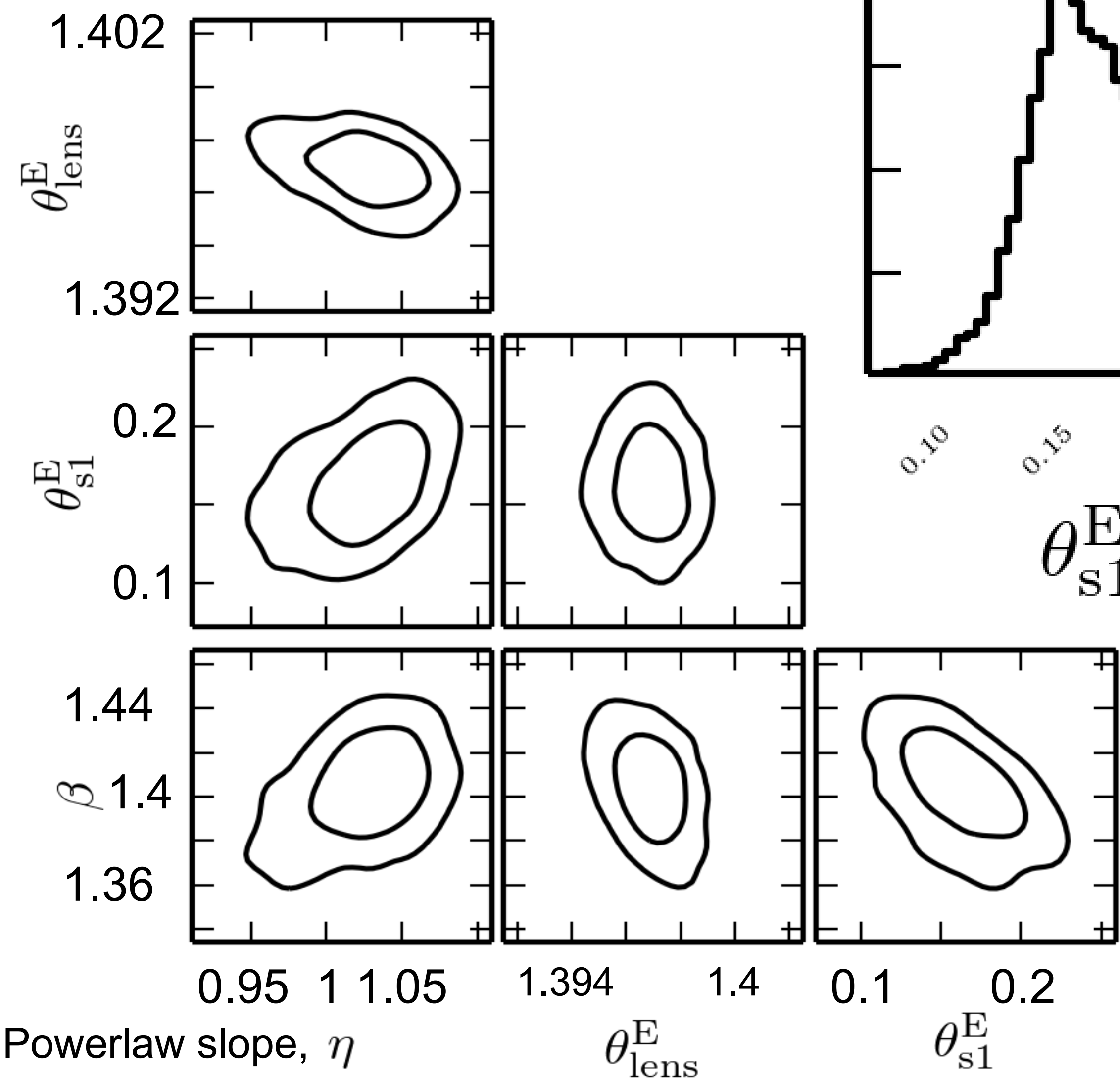
$$= \left(M \right)$$

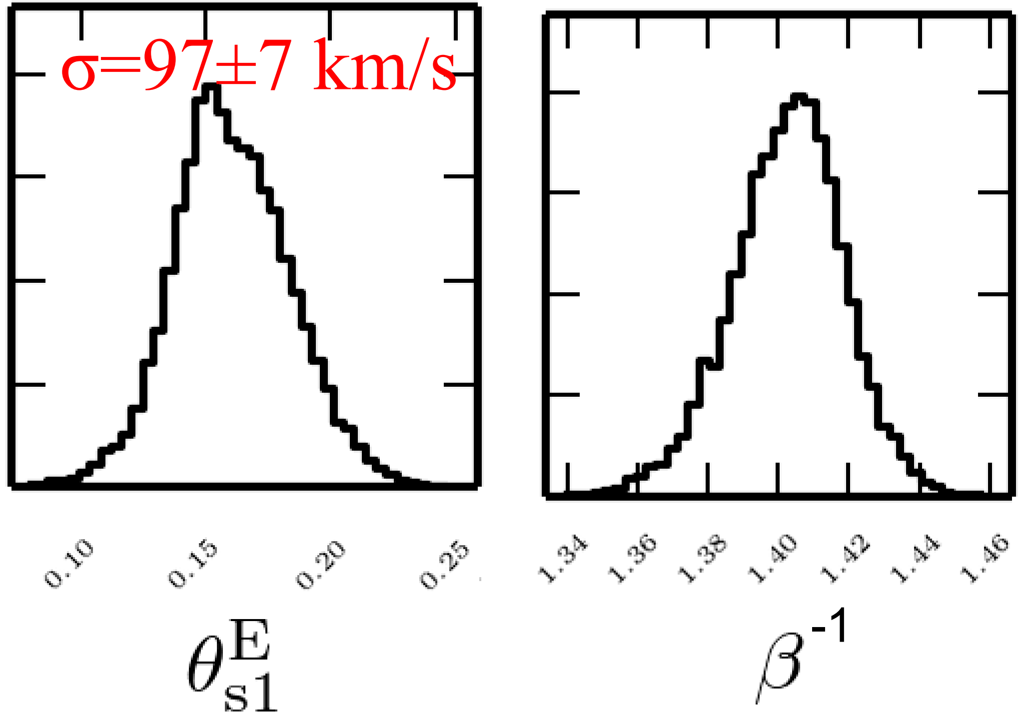


Modelling J0946



Modelling J0946

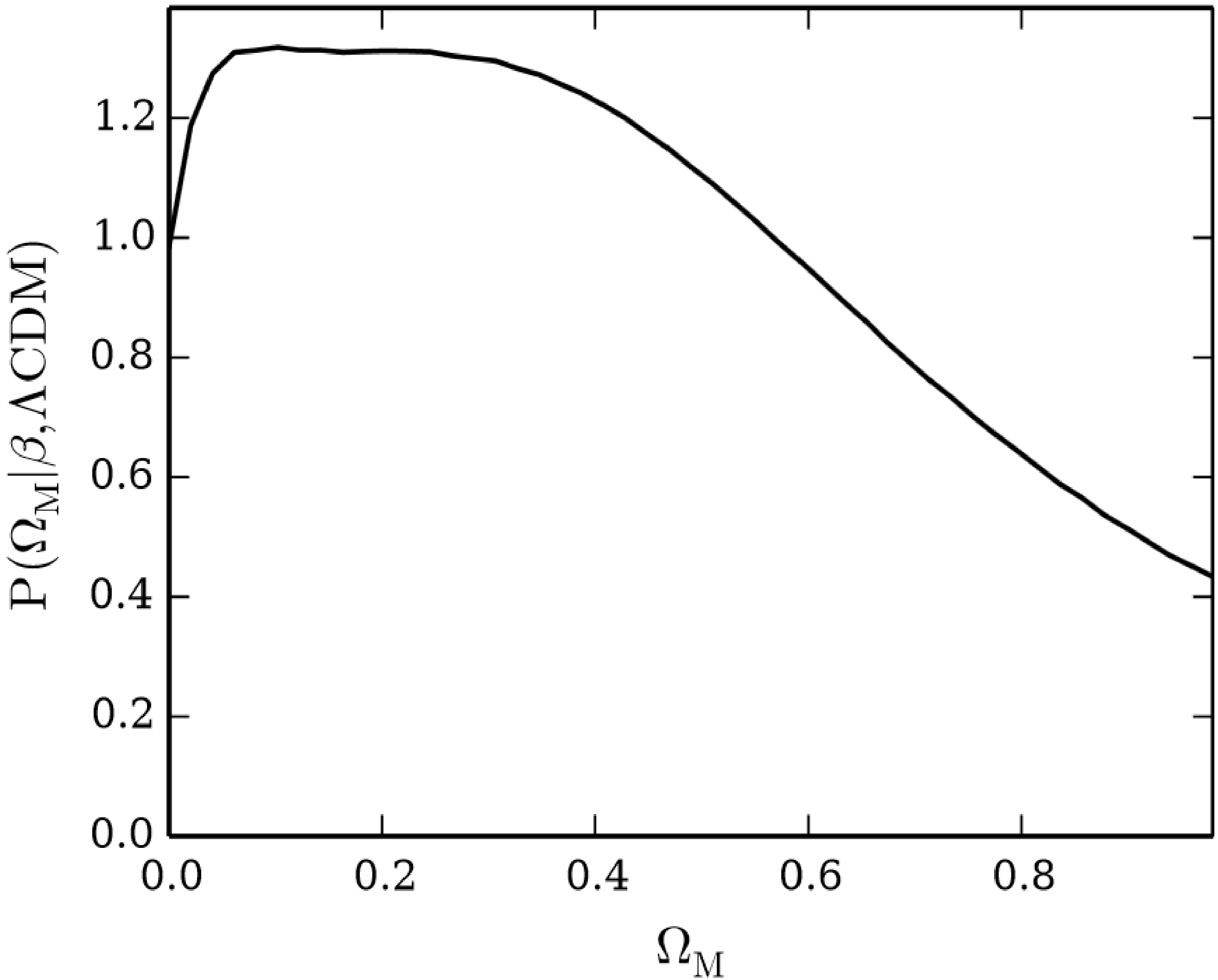




$$\beta = \frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}}$$

$$\beta^{-1} = 1.404 \pm 0.016$$

Constraining Cosmology.



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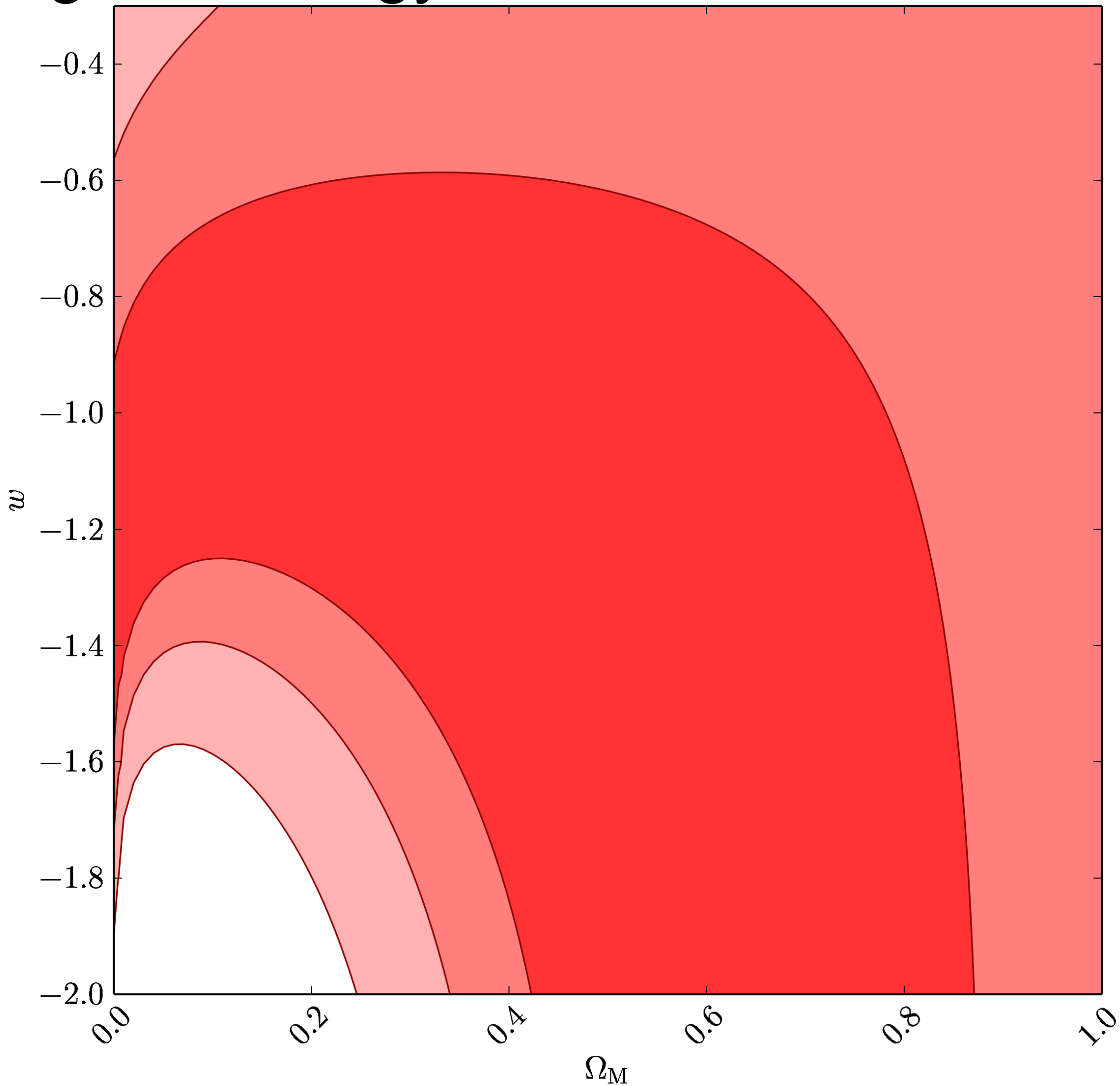

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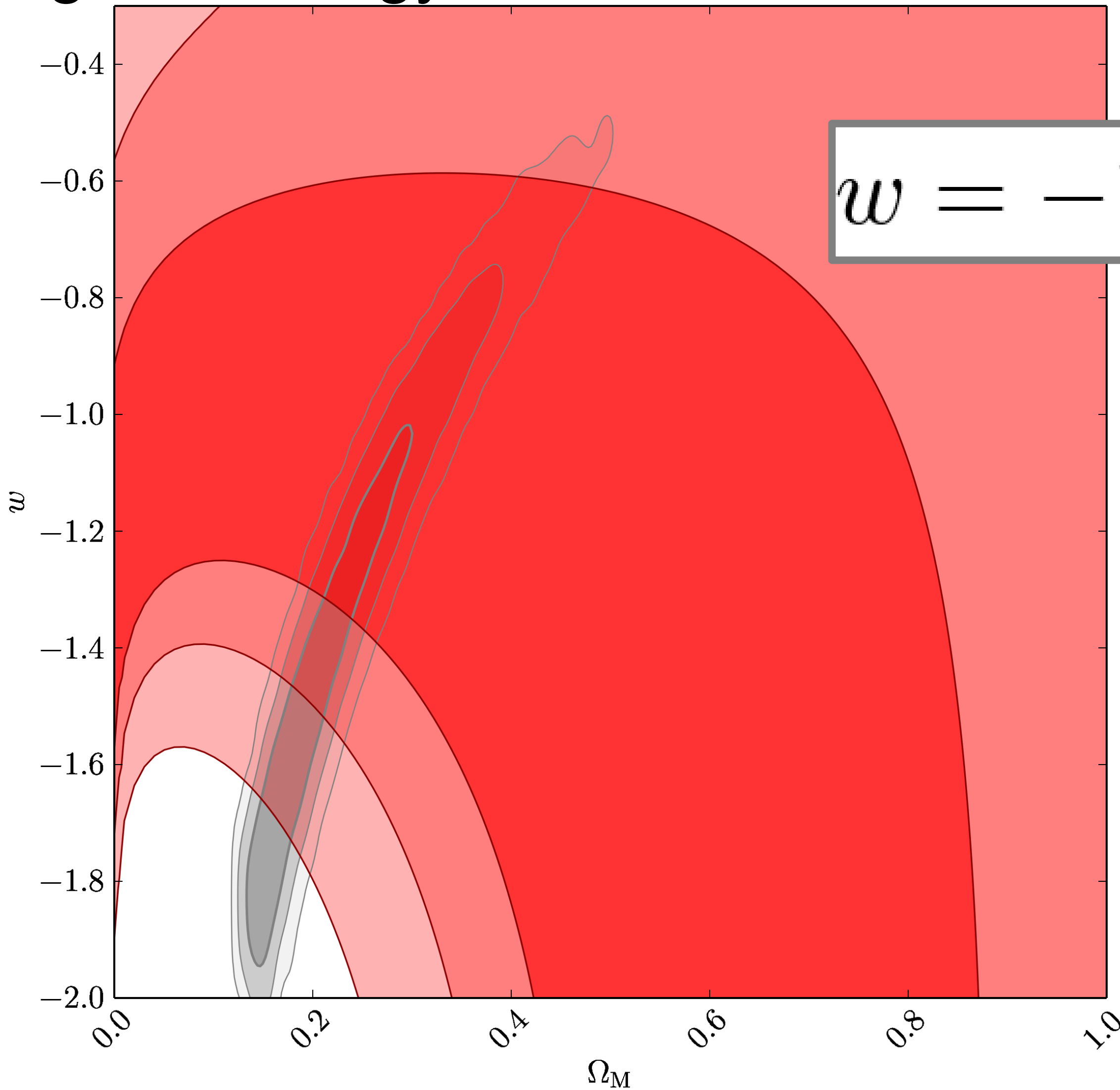
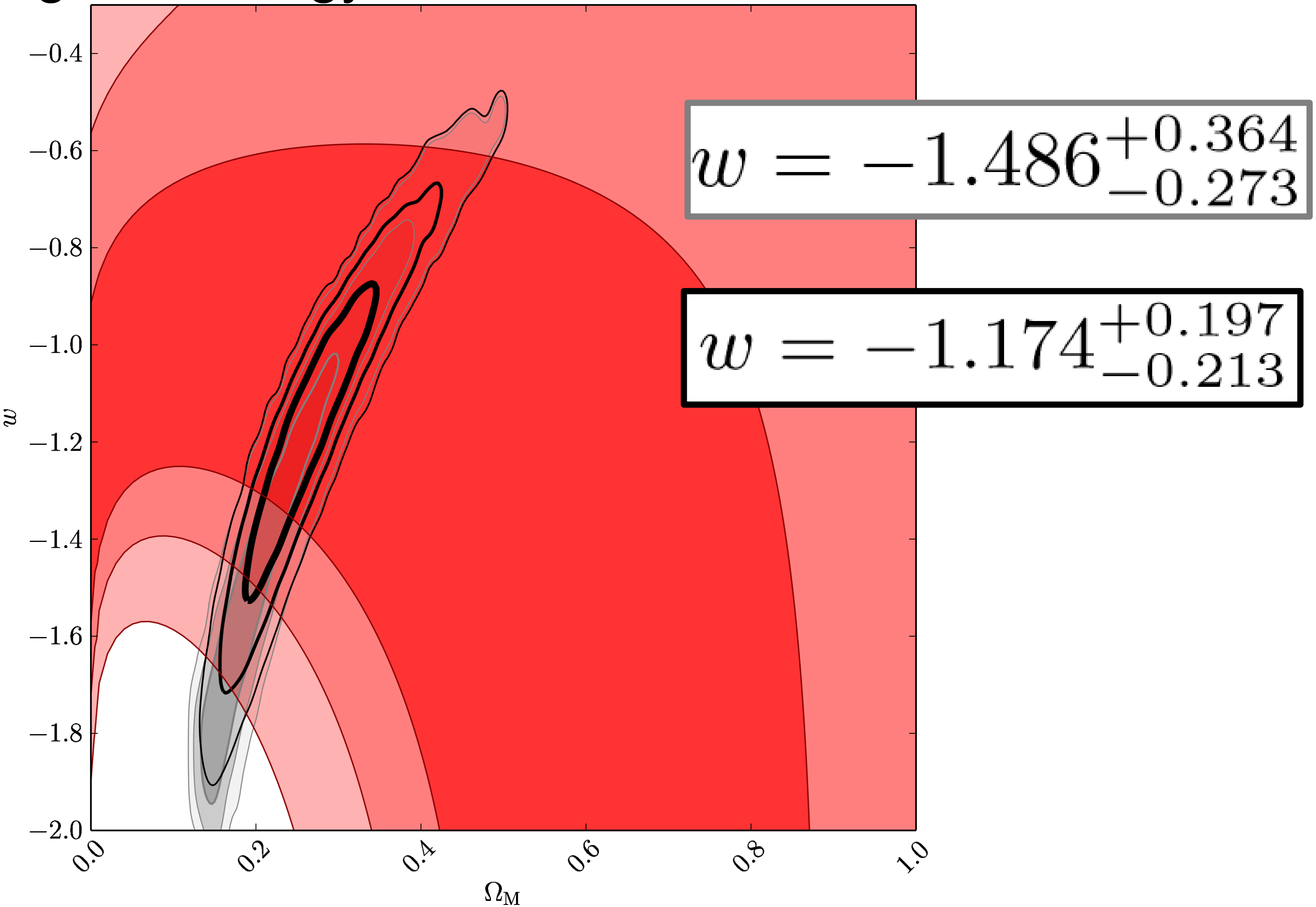
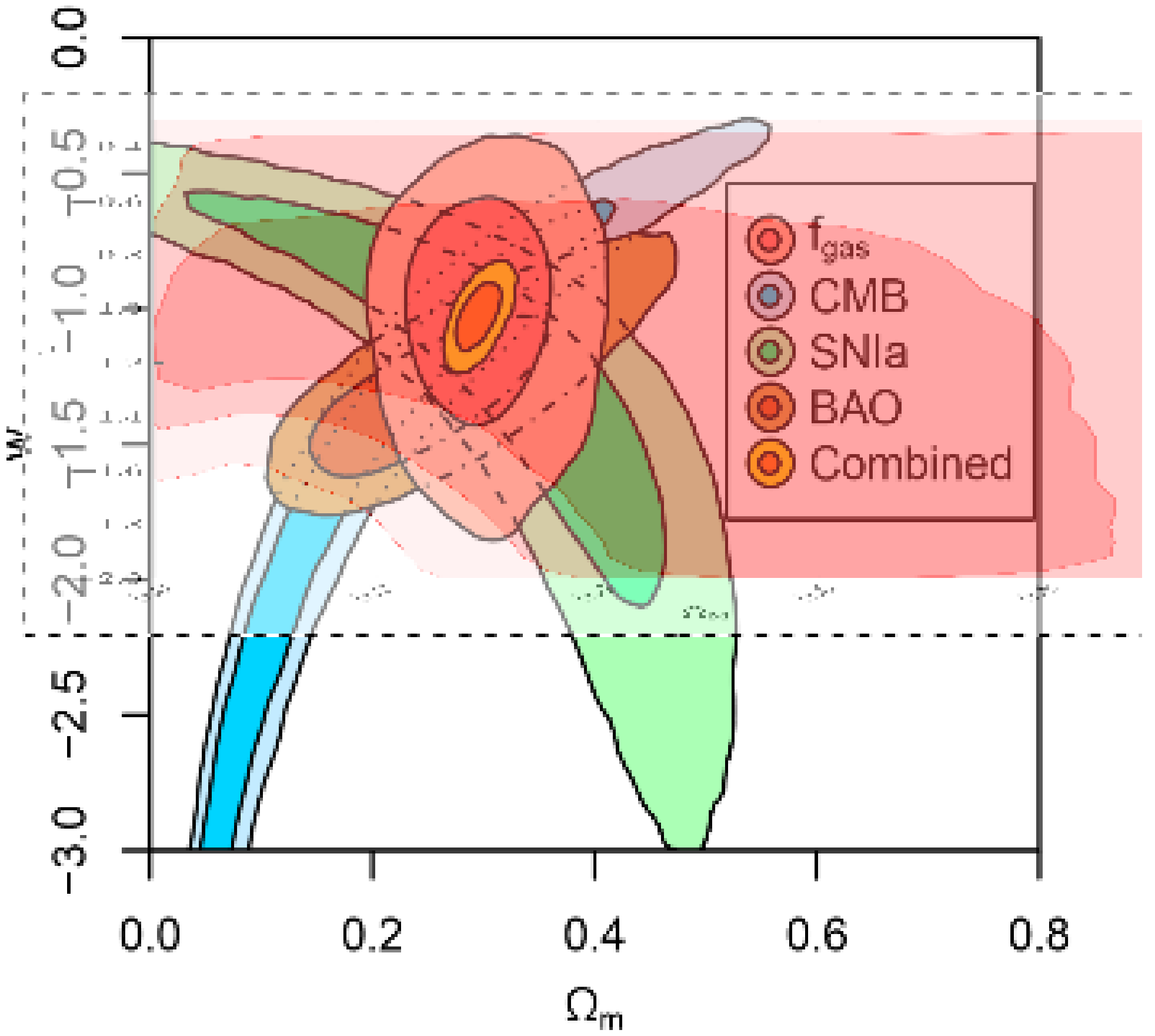


$$w = -1.486^{+0.364}_{-0.273}$$

Constraining Cosmology.



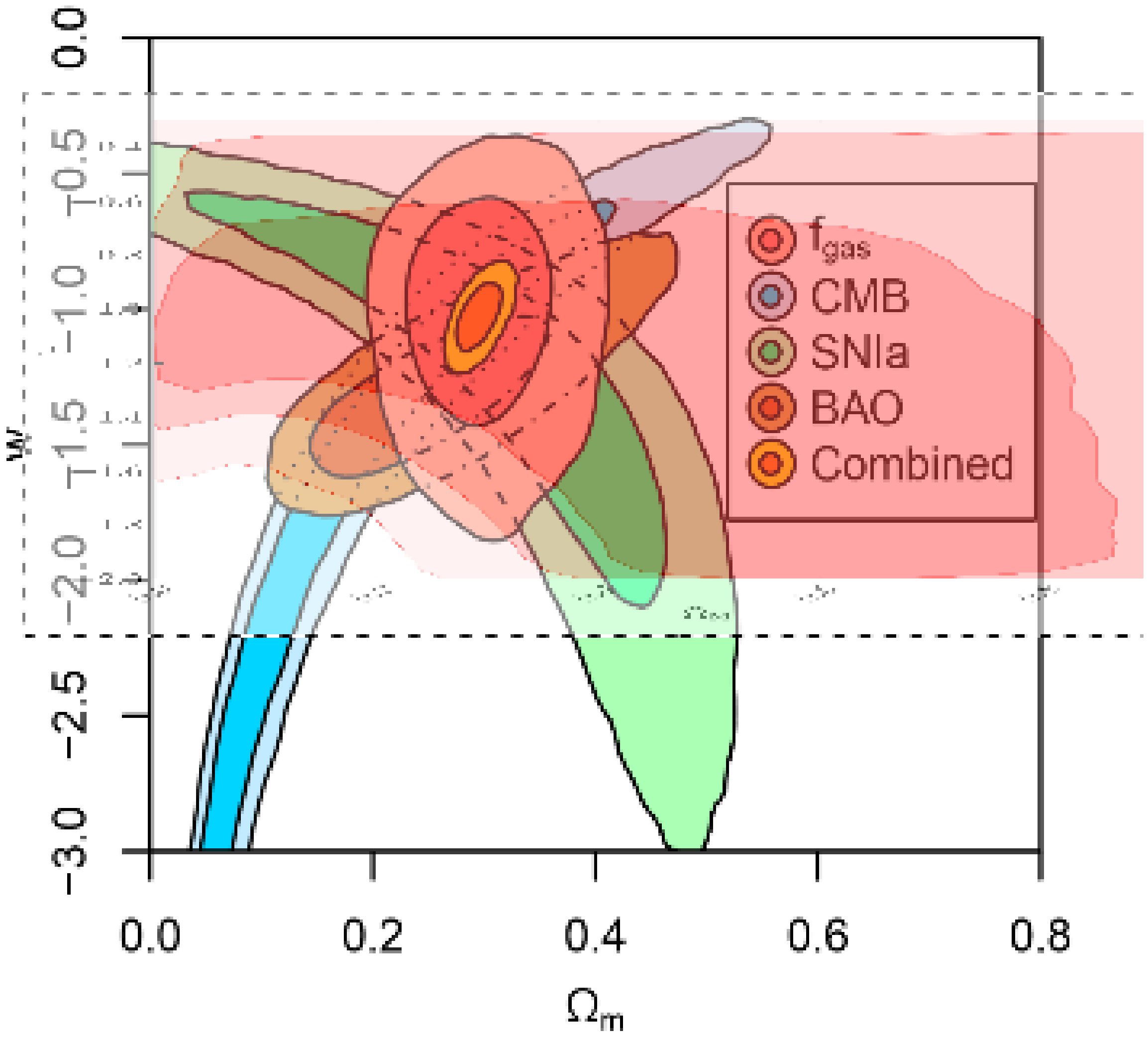
Constraining Cosmology.



Constraining Cosmology.

J0946 + WMAP prior

$$w = -0.99^{+0.27}_{-0.25}$$



Constraining Cosmology.

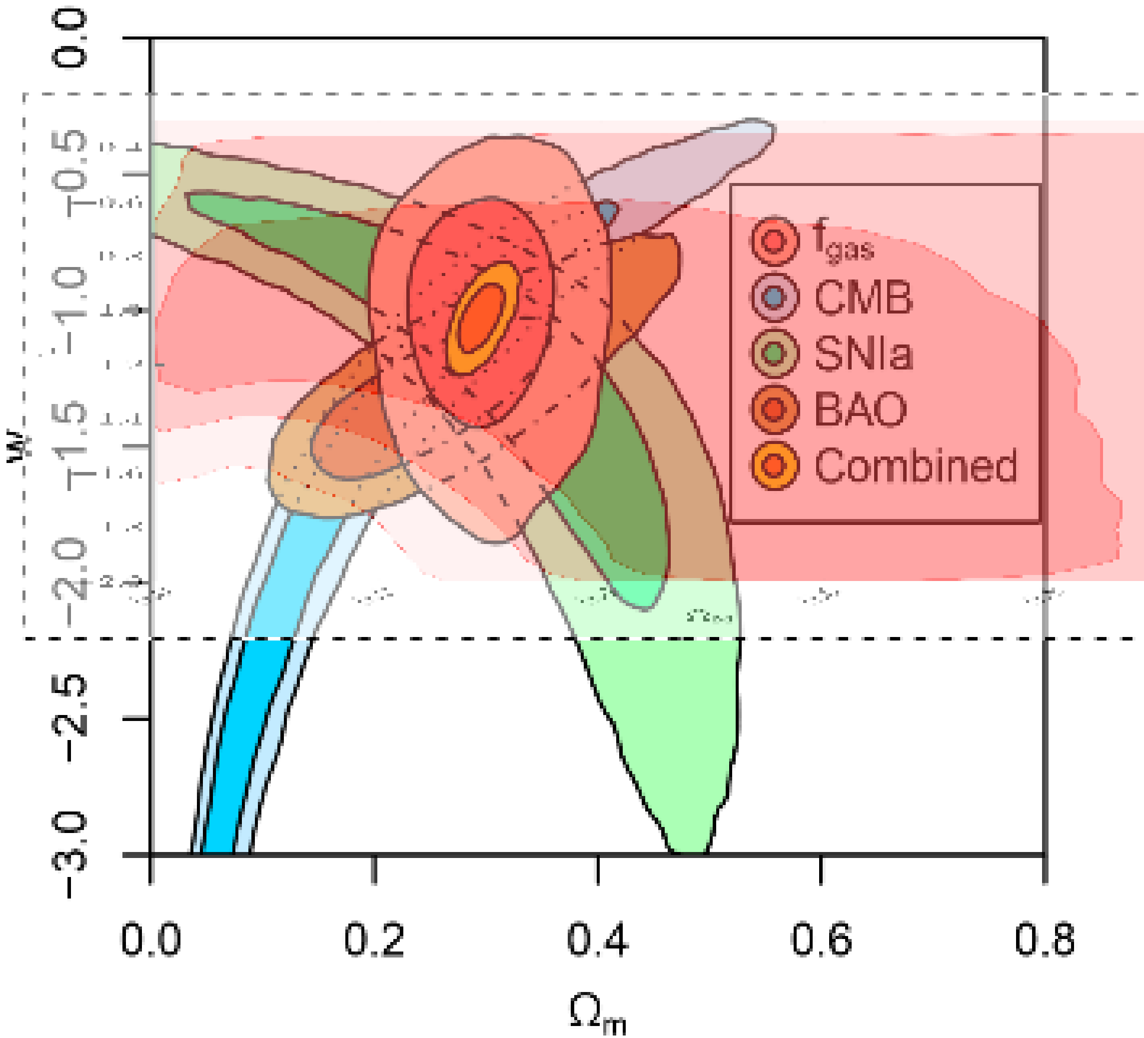
J0946 + WMAP prior

$$w = -0.99^{+0.27}_{-0.25}$$

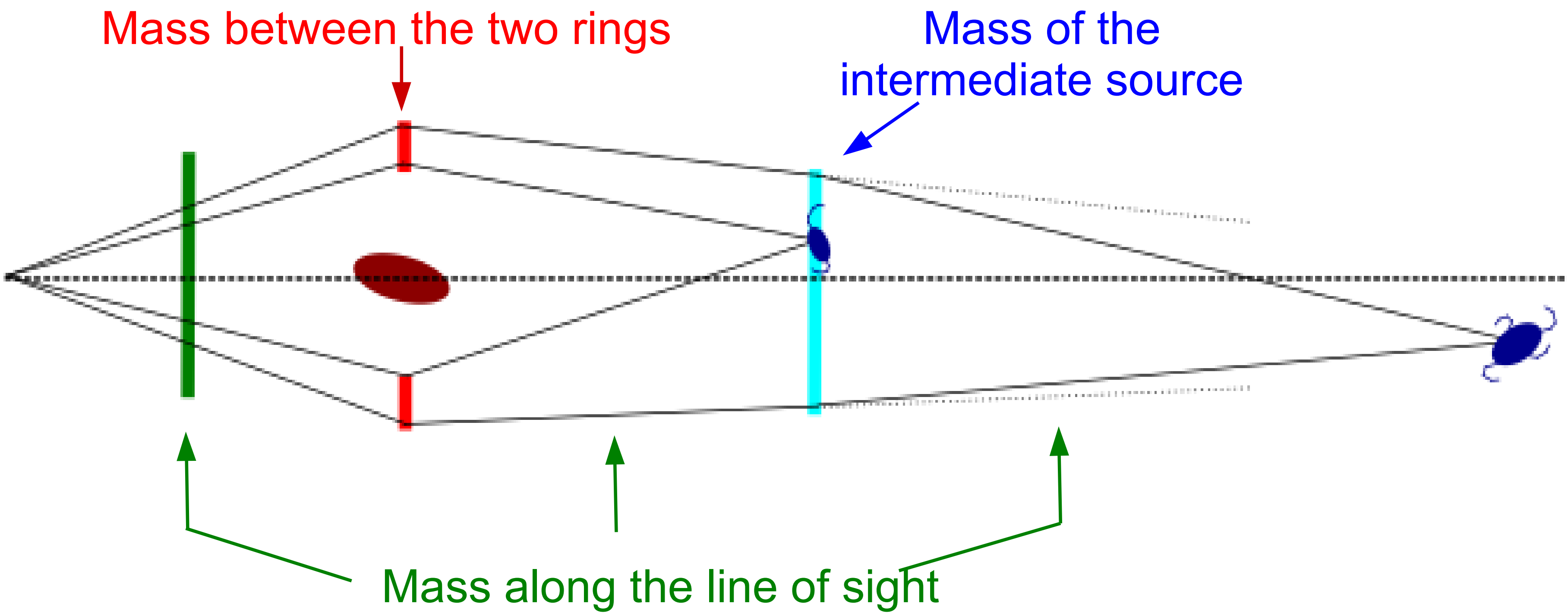
C. Heymans et al.

$-1.05^{+0.33}_{-0.34}$ CFHTLenS + WMAP7

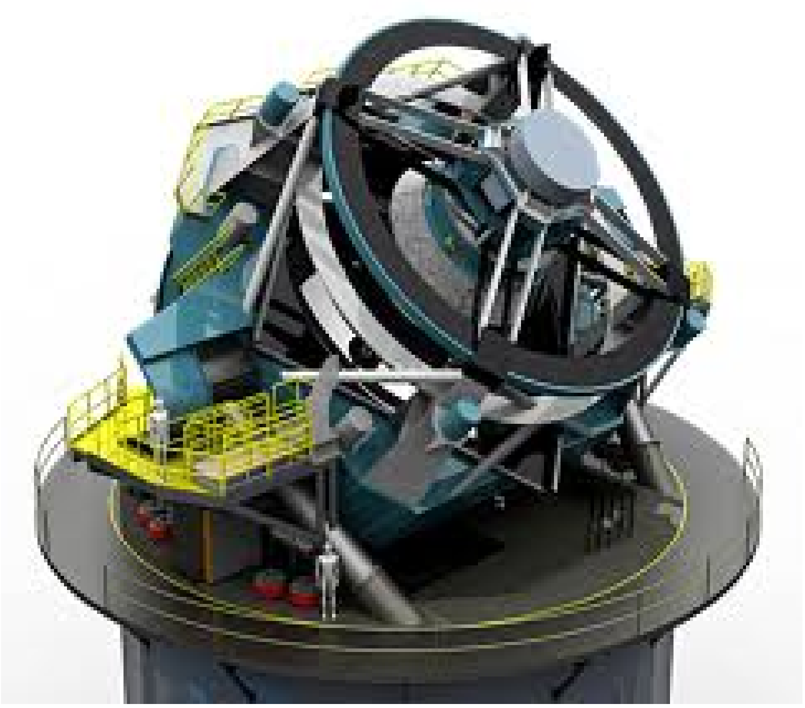
(2013, 68% CLs)

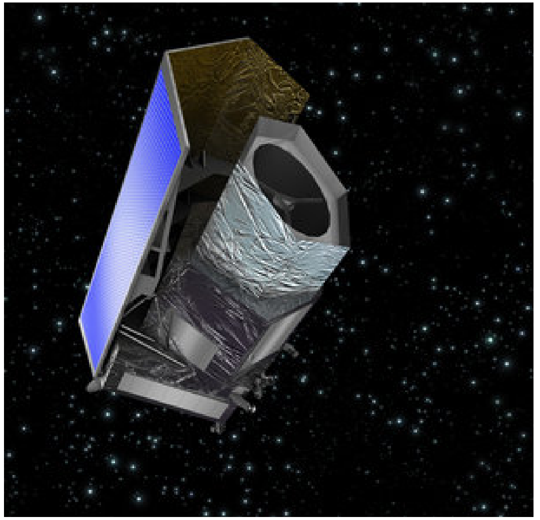


Systematics

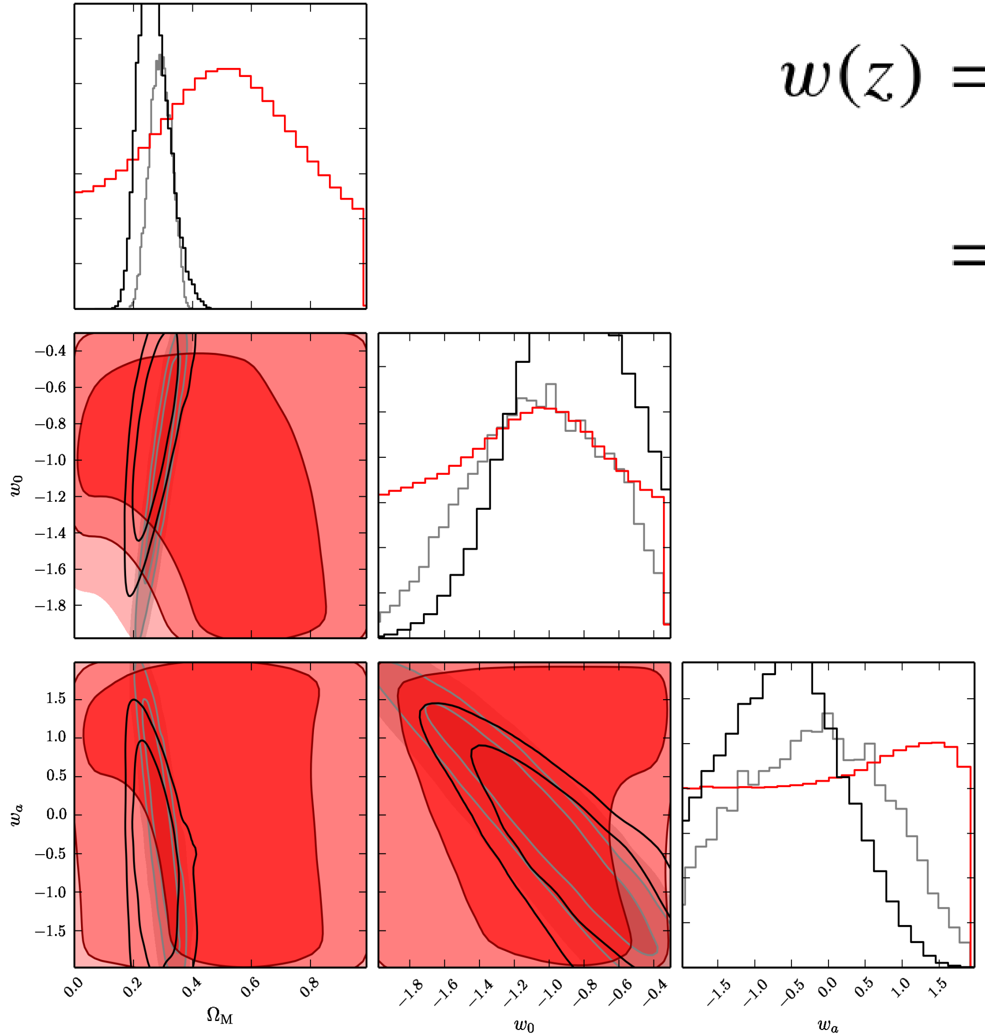


The Future





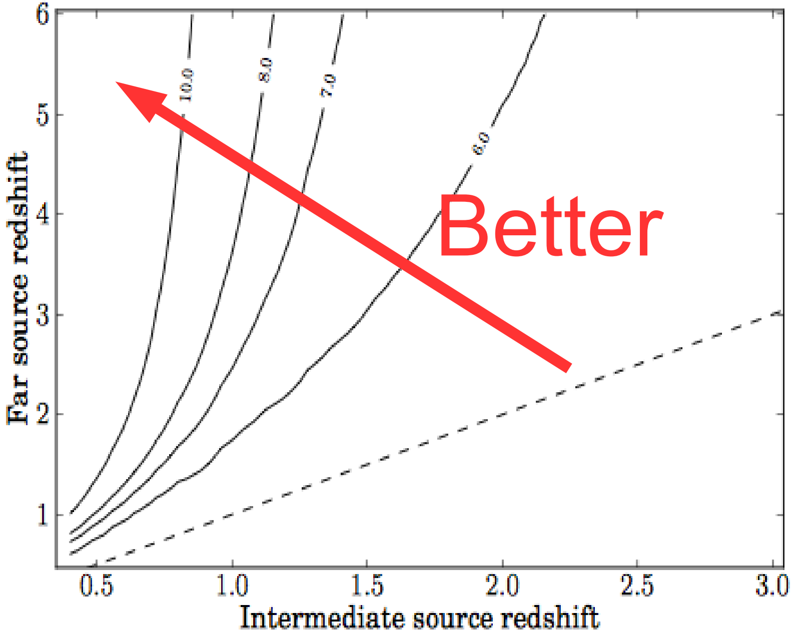
Evolving Dark Energy

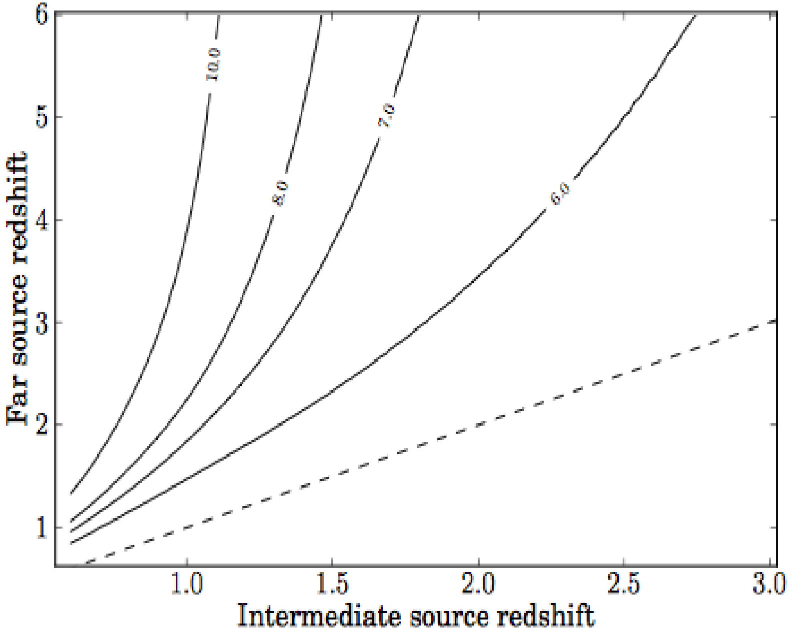


$$w(z) = w_0 + w_a(1 - a)$$
$$= w_0 + w_a\left(\frac{z}{1+z}\right)$$

The Future

FoM~1/(A95) : Bigger is better



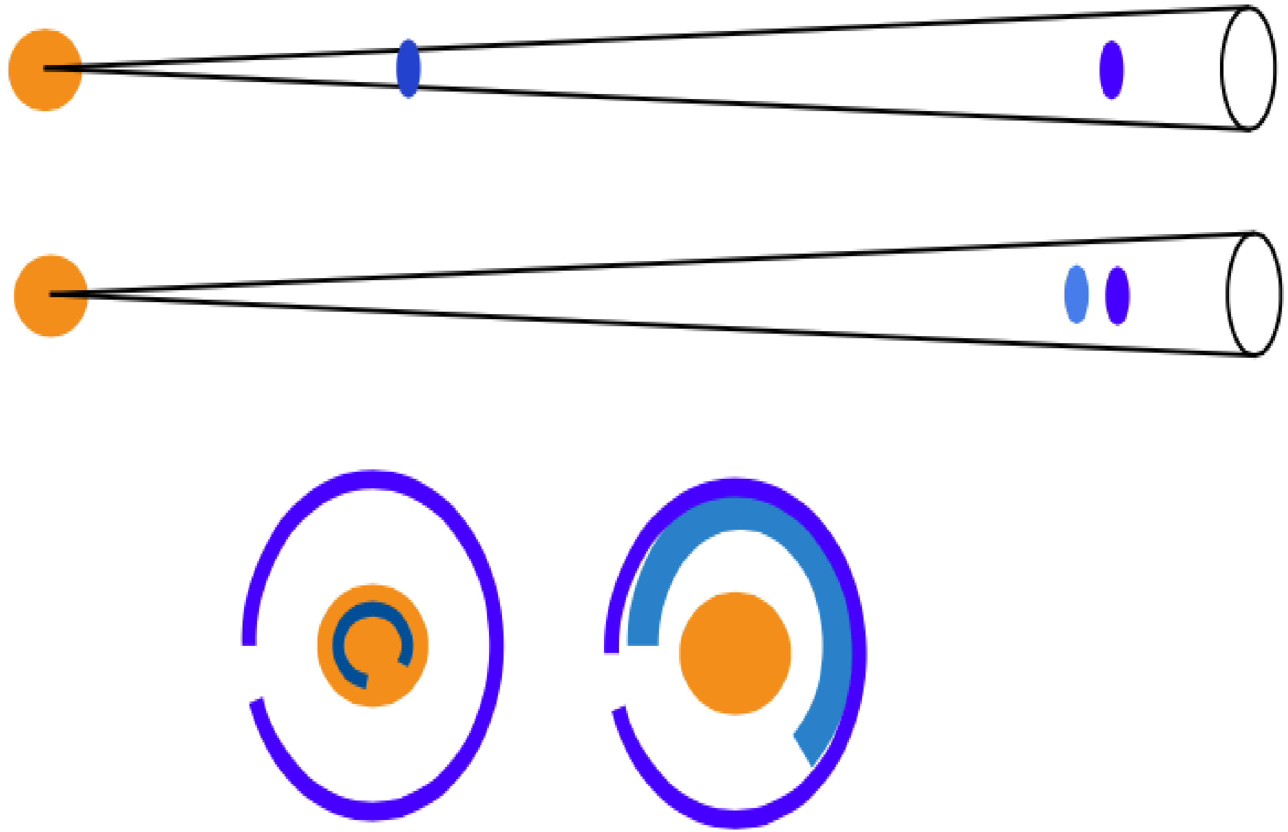


Z_l=0.35

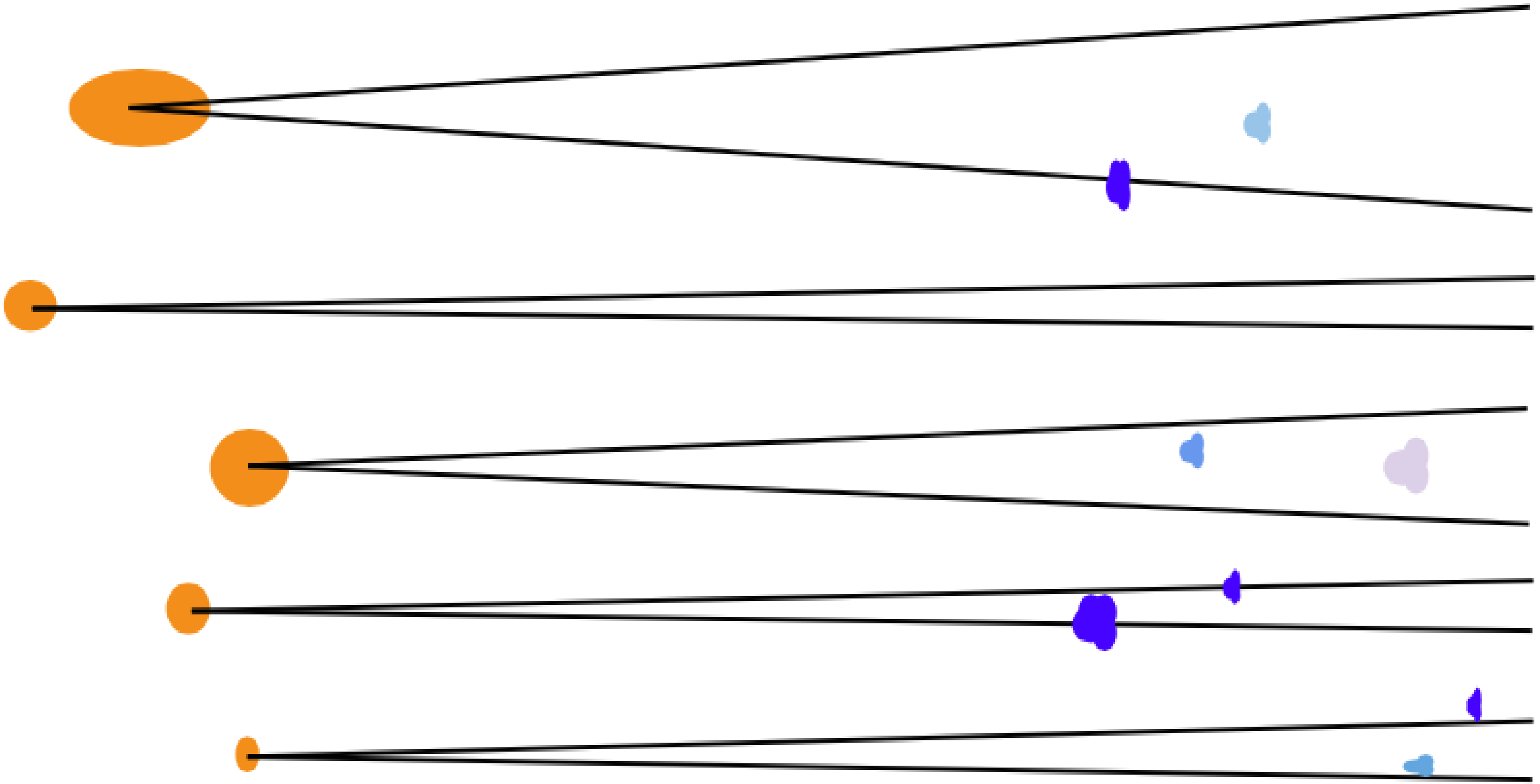
Z_l=0.55

1% measurement of beta
CMB prior

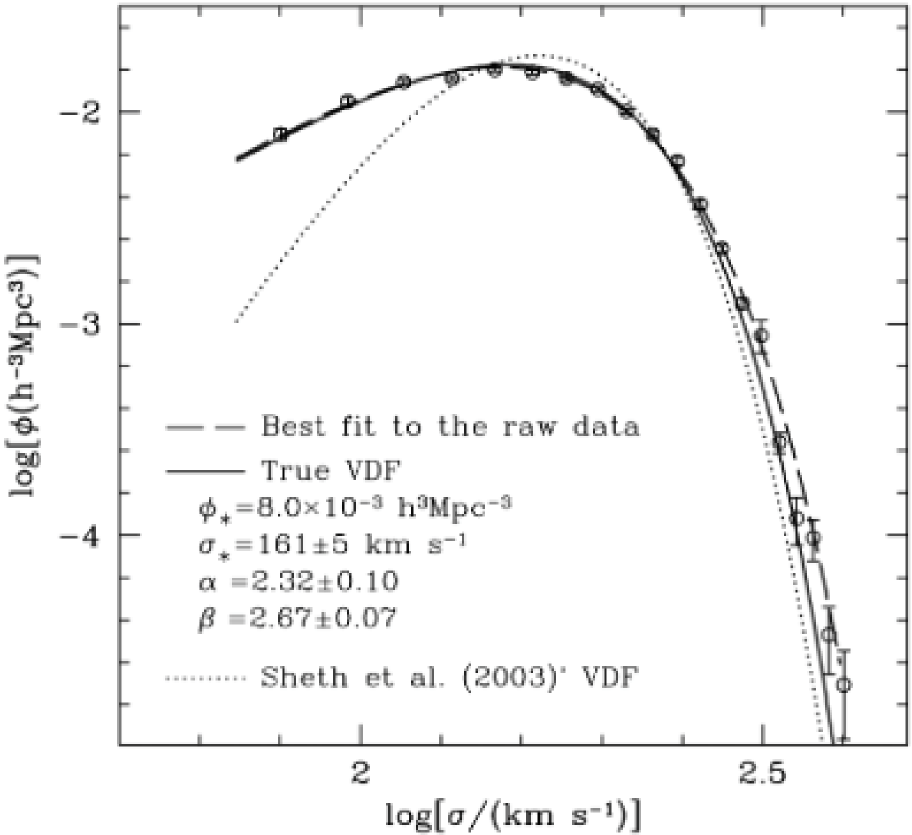
The Future



Lens Population Forecasting



Lens Population Forecasting



Choi, Park & Vogeley 2007

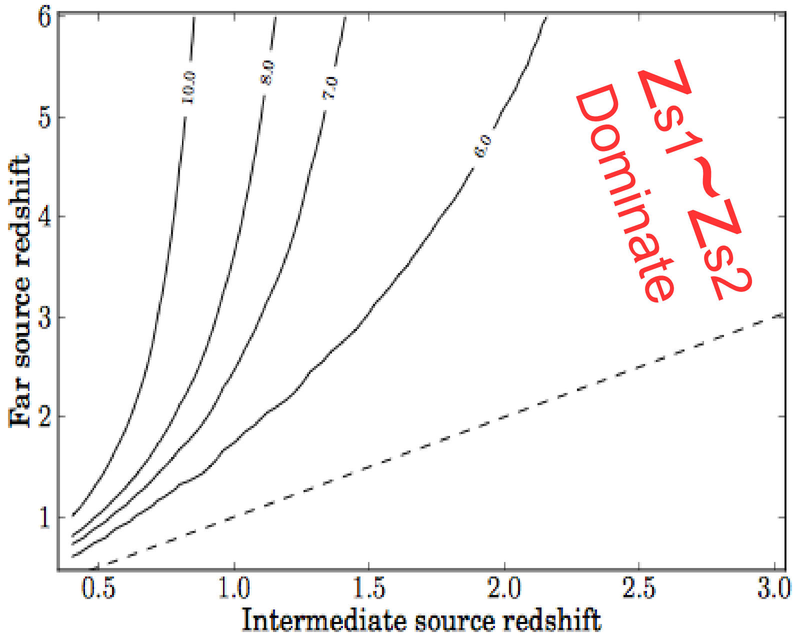
Deflectors:
SDSS

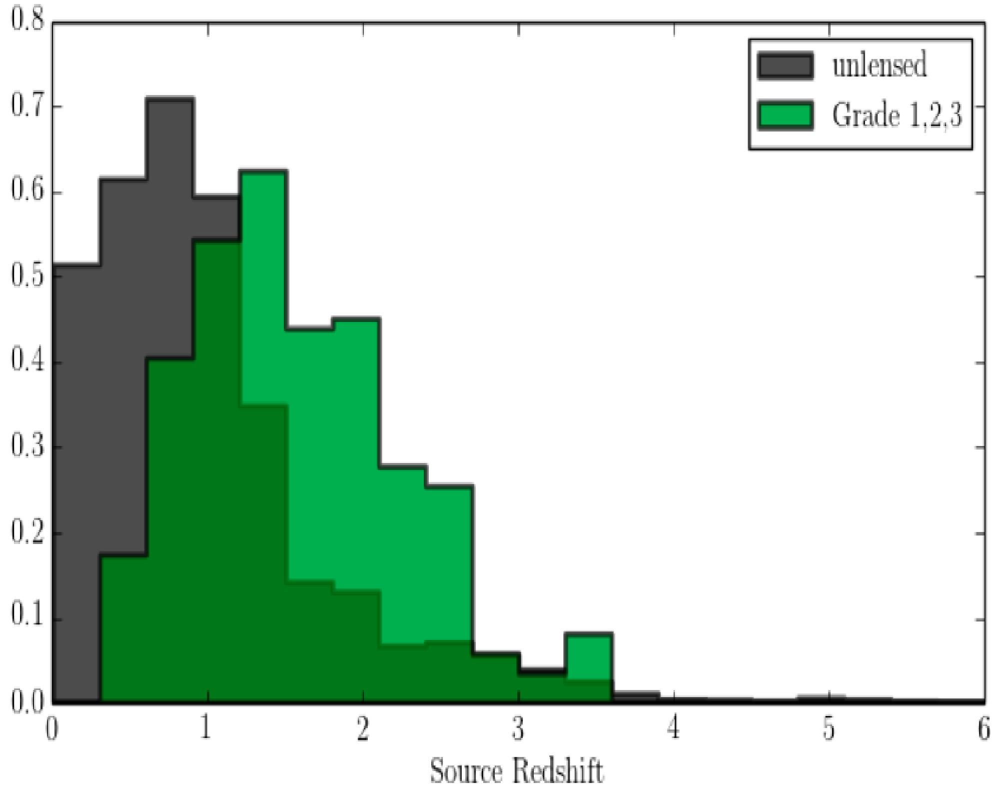
P(*griz*,z,r,σ,q)

Sources:
Cosmos

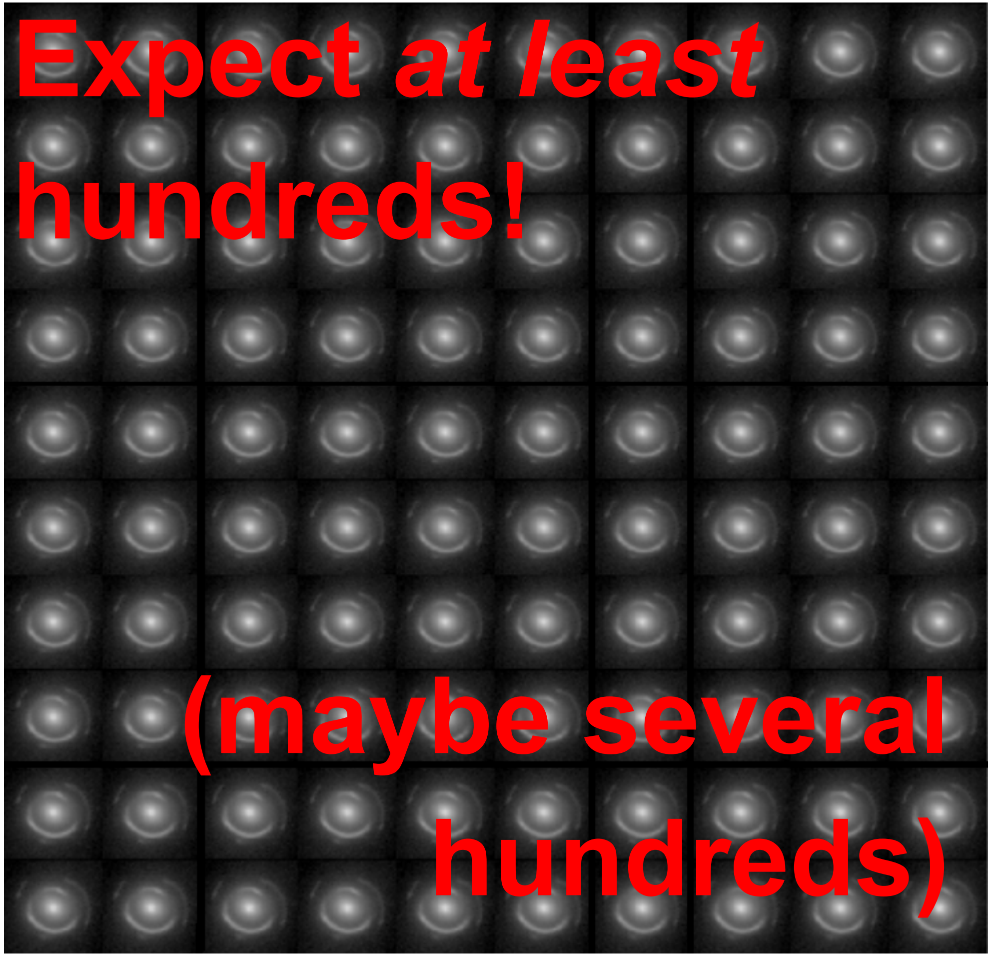
P(*griz*,z,r)

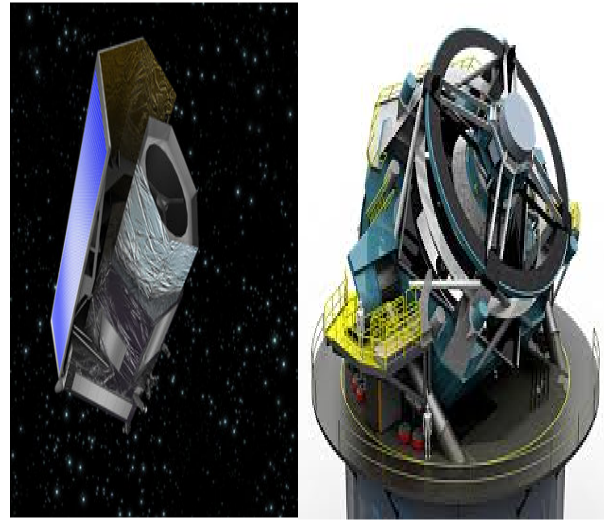
The Future


10.0
8.0
7.0
6.0
Zs1~Zs2
Dominate
Far source redshift
Intermediate source redshift
0.5
1.0
1.5
2.0
2.5
3.0
1
2
3
4
5
6


unlensed
Grade 1,2,3
Source Redshift
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
1
2
3
4
5
6

Euclid

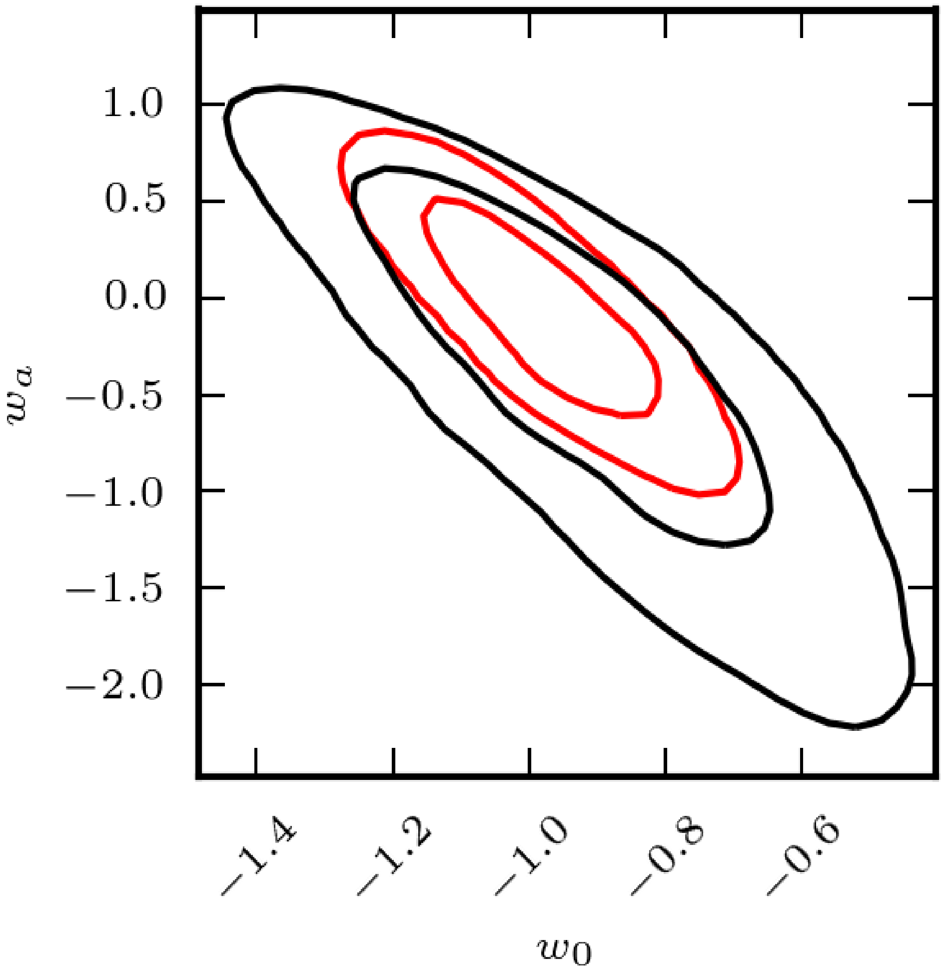




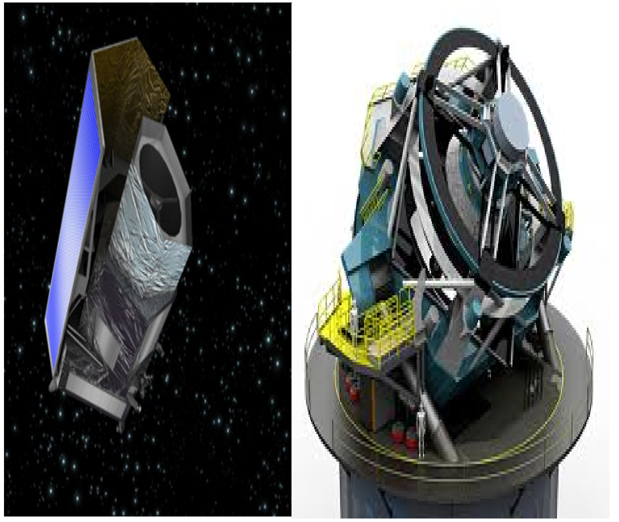
~10^5 galaxy scale strong lenses (based on COSMOS)

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

Euclid



Collett+ in prep.



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

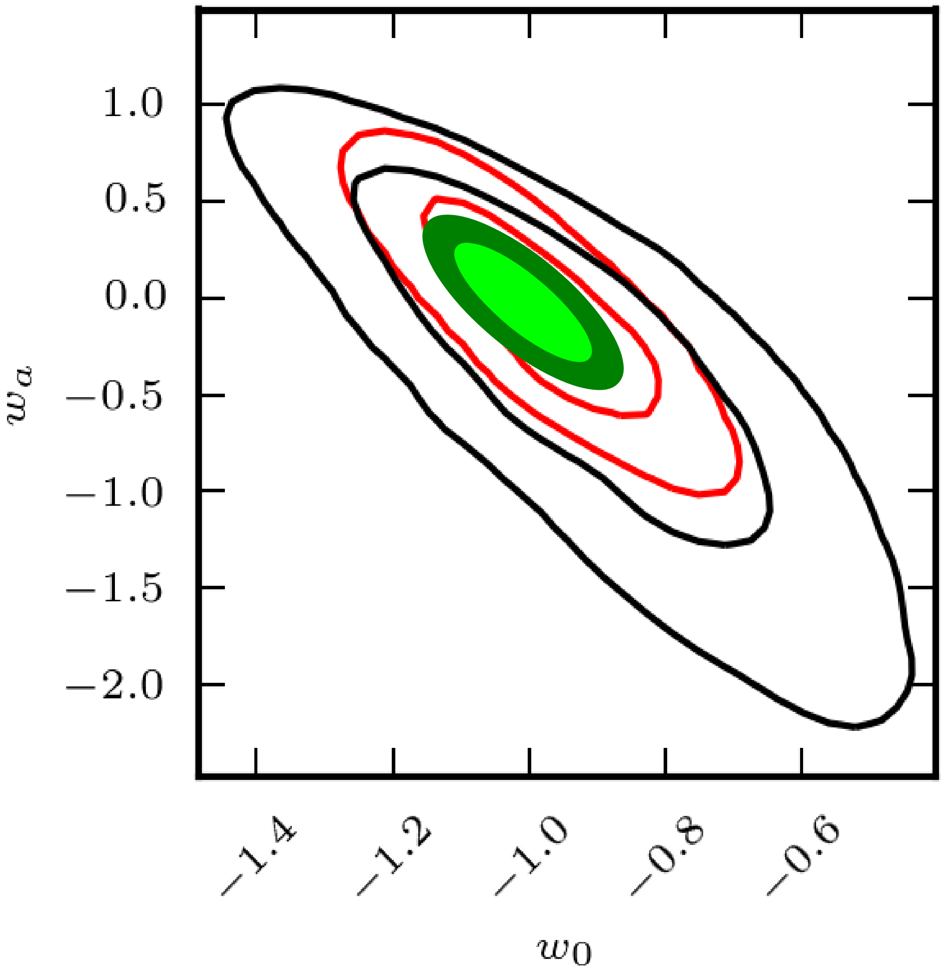
Red: 100 lenses, $\Omega_k \neq 0$

FoM = 38

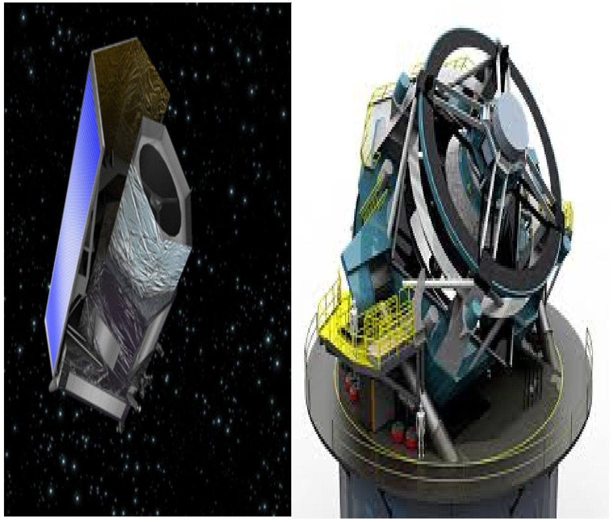
$\sigma(\Omega_k) = 0.005$

(includes Planck prior)

Euclid



Collett+ in prep.



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

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

FoM = 38

$\sigma(\Omega_k) = 0.005$

(includes Planck prior)

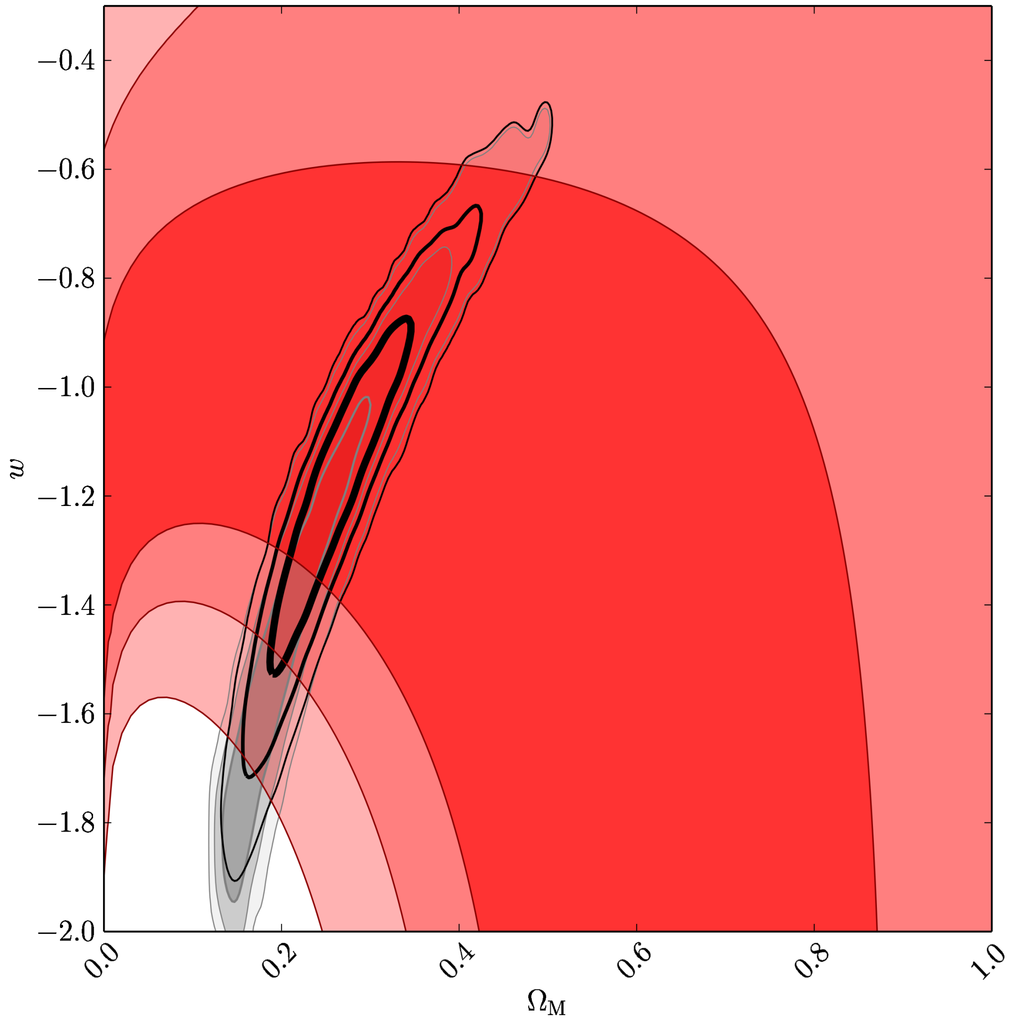
Summary

$$w = -1.174^{+0.197}_{-0.213}$$

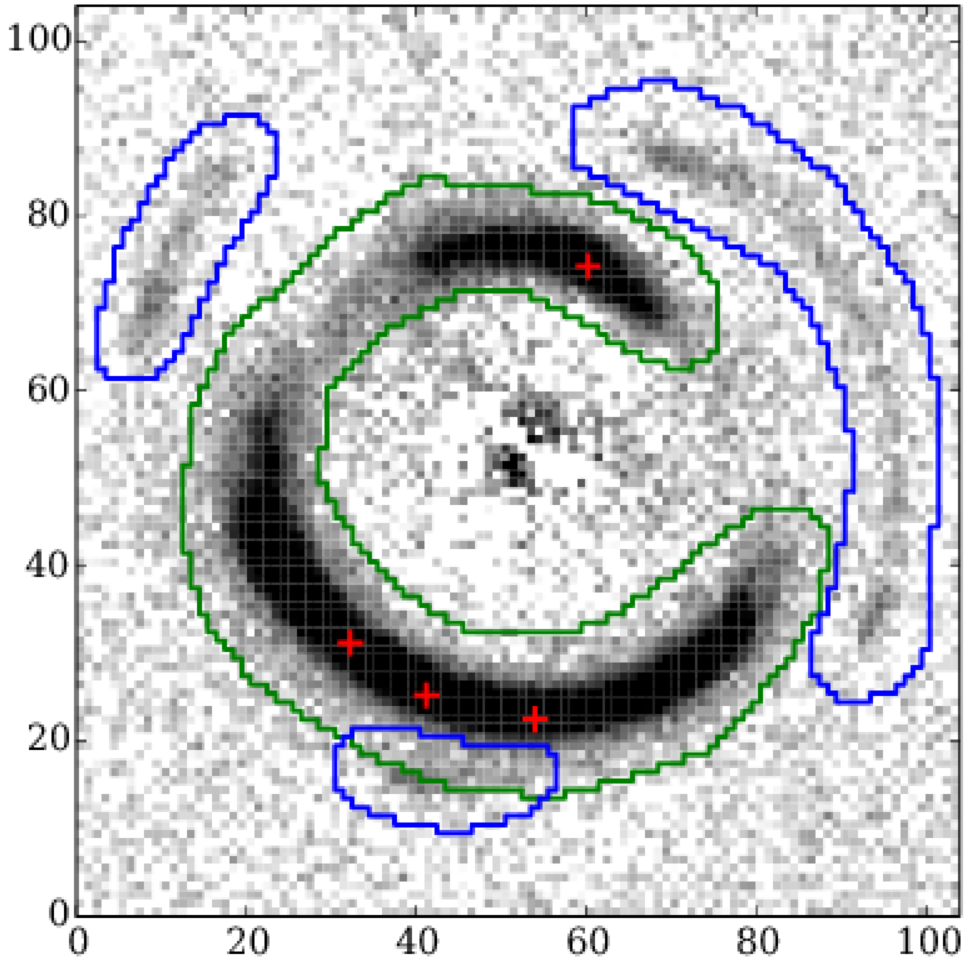
Independent systematic errors

Independent of Hubble constant

DPLSs will be competitive and complementary cosmological probes in the Euclid/LSST/SKA era



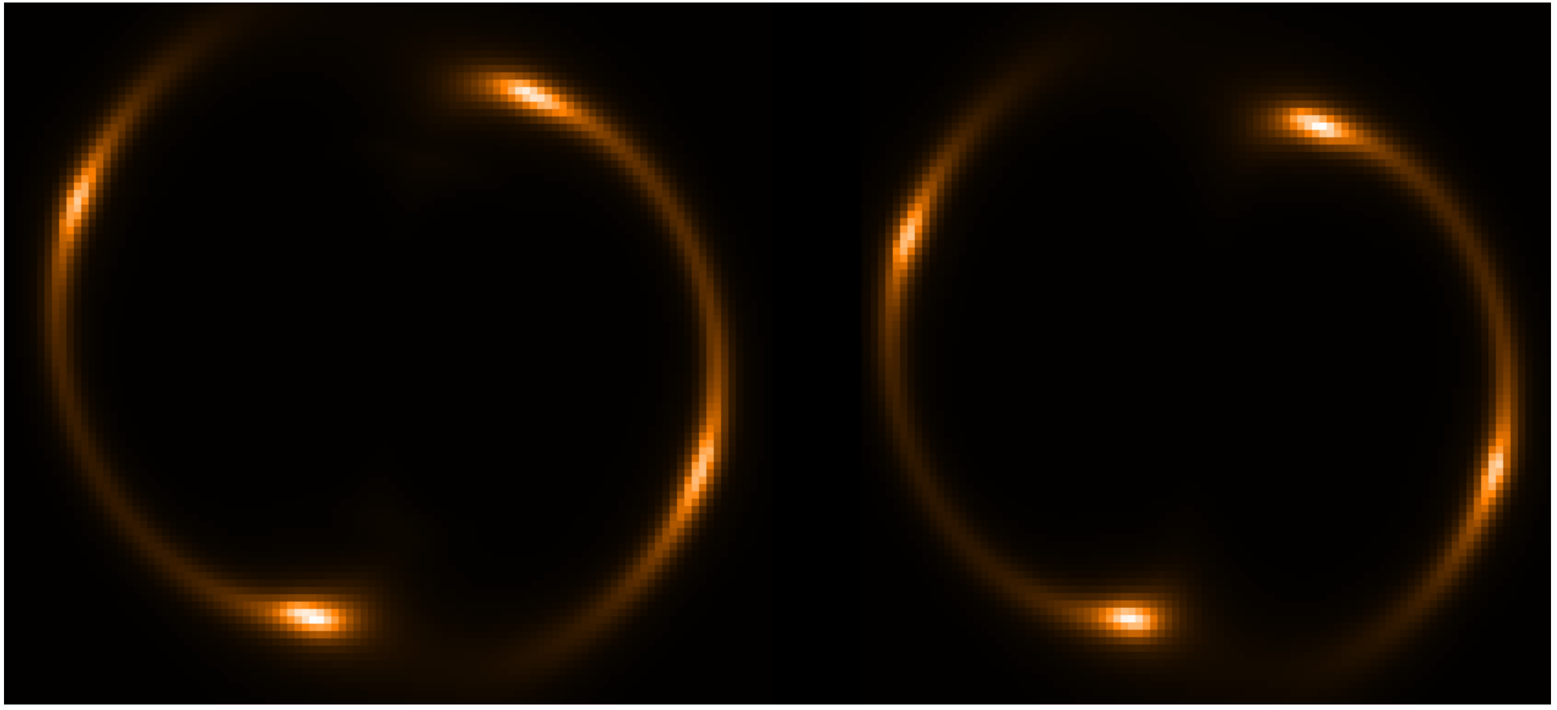
Idealizations



- Pre-subtract galaxy
- Source flux only in masked region
- Deterministic location of first source mass
- Curvature regularized sources
- Simple Mass models
- No line of sight lensing

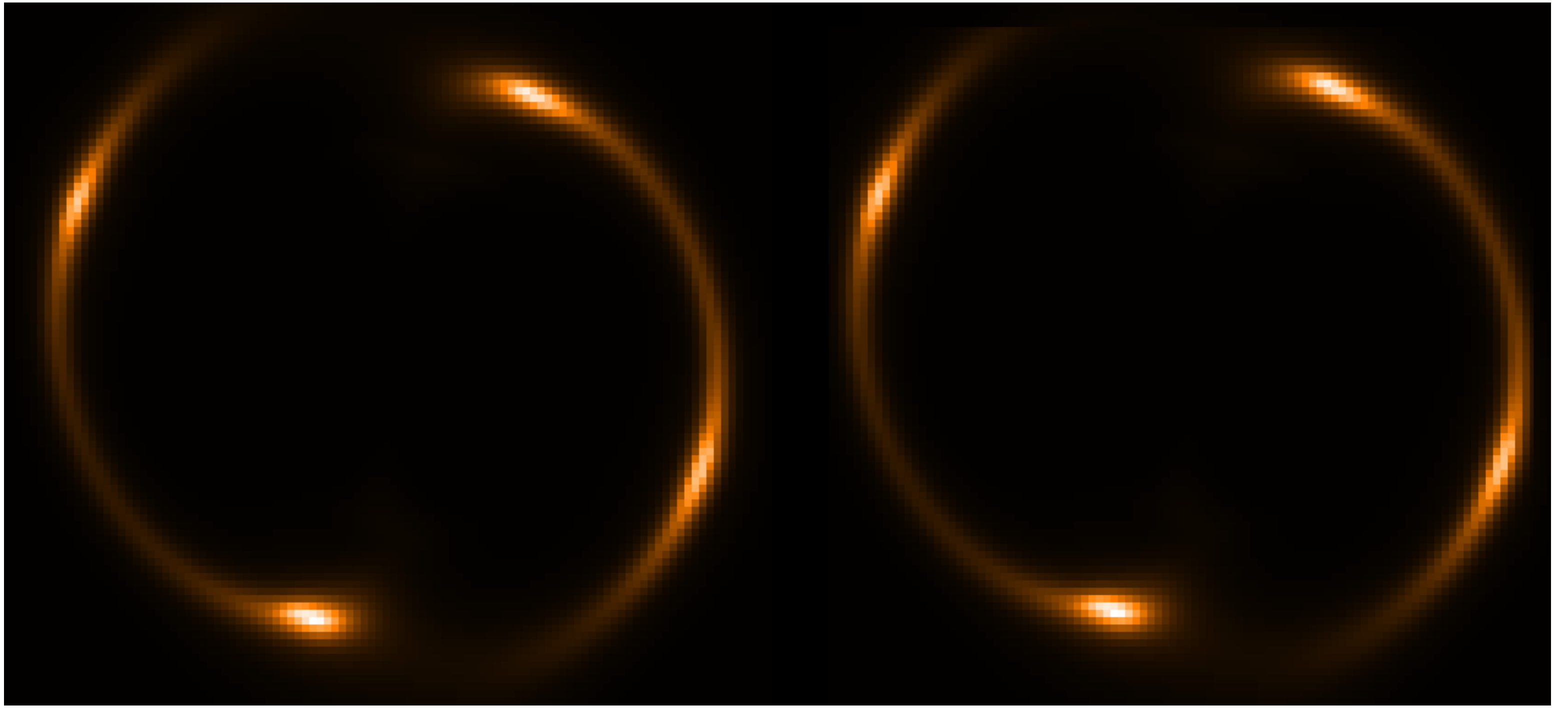
Intermediate source: θ_E=0.16”

$\sigma_v \approx 100$ kms^{-1}

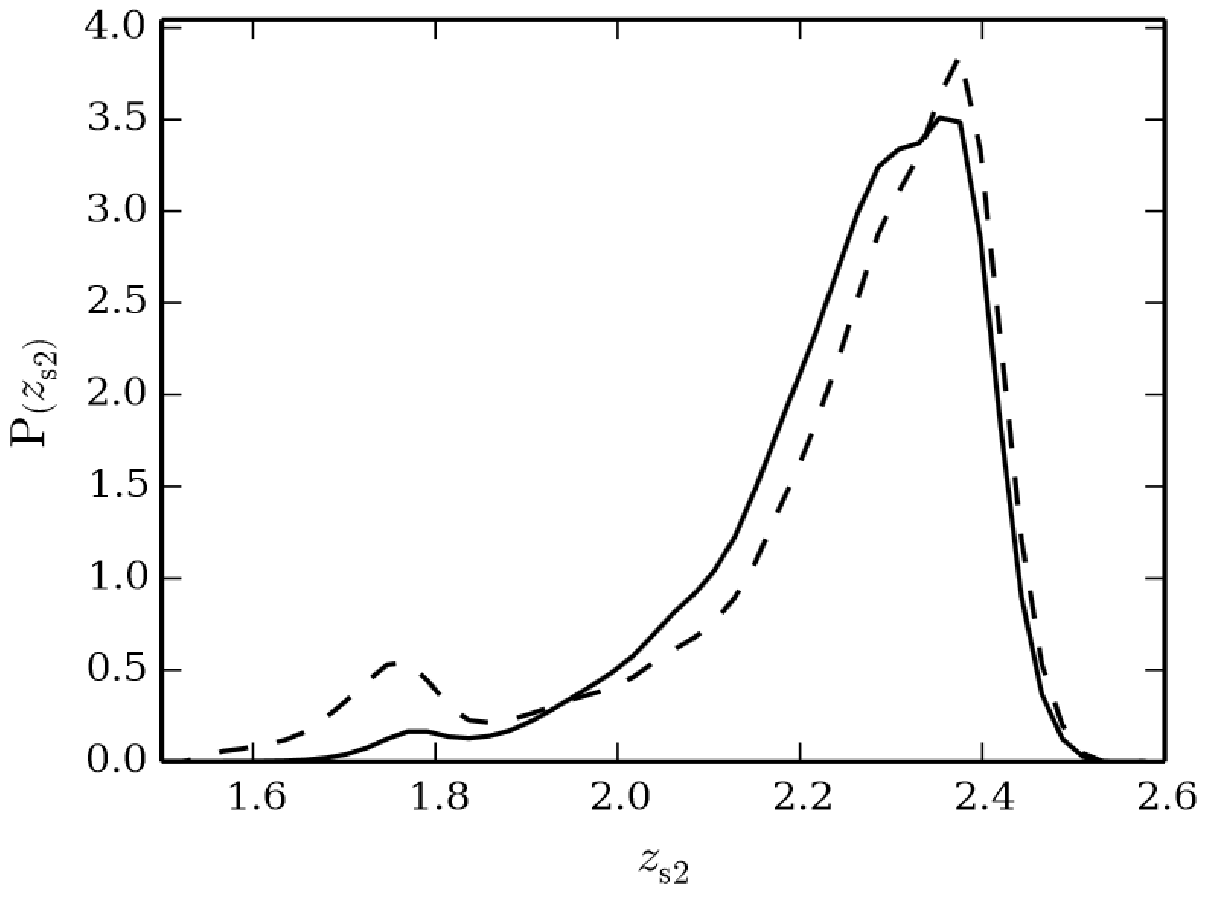


Intermediate source: θ_E=0.16"

$\sigma_v \approx 100$ kms^{-1}



Second Source Redshift



Exotic lenses with Euclid/LSST

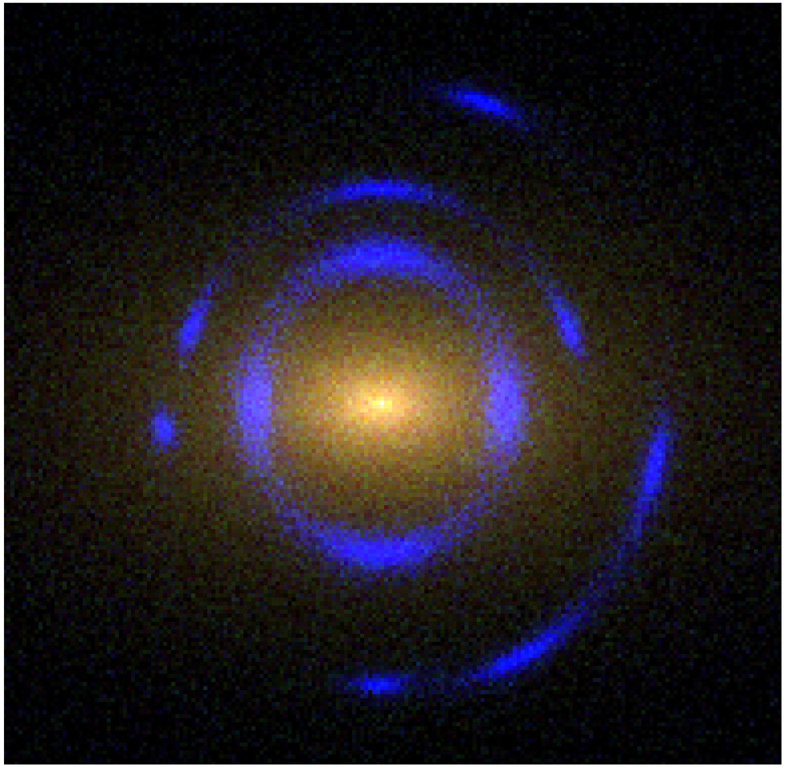
~ 40 lensed type Ia Sne

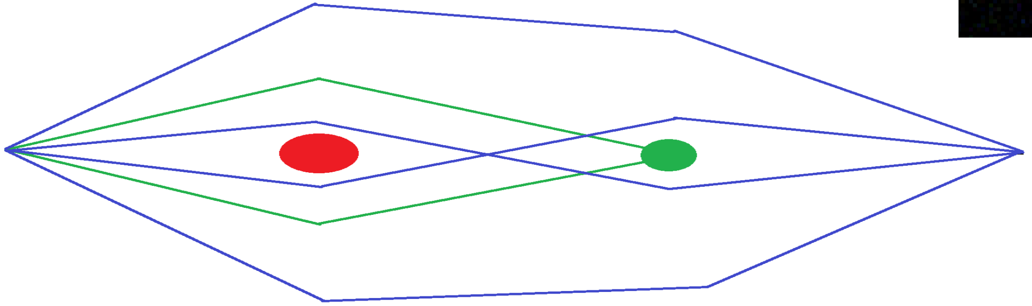
~ 30 DSPLs where one is an AGN

~ Triple source plane lenses?

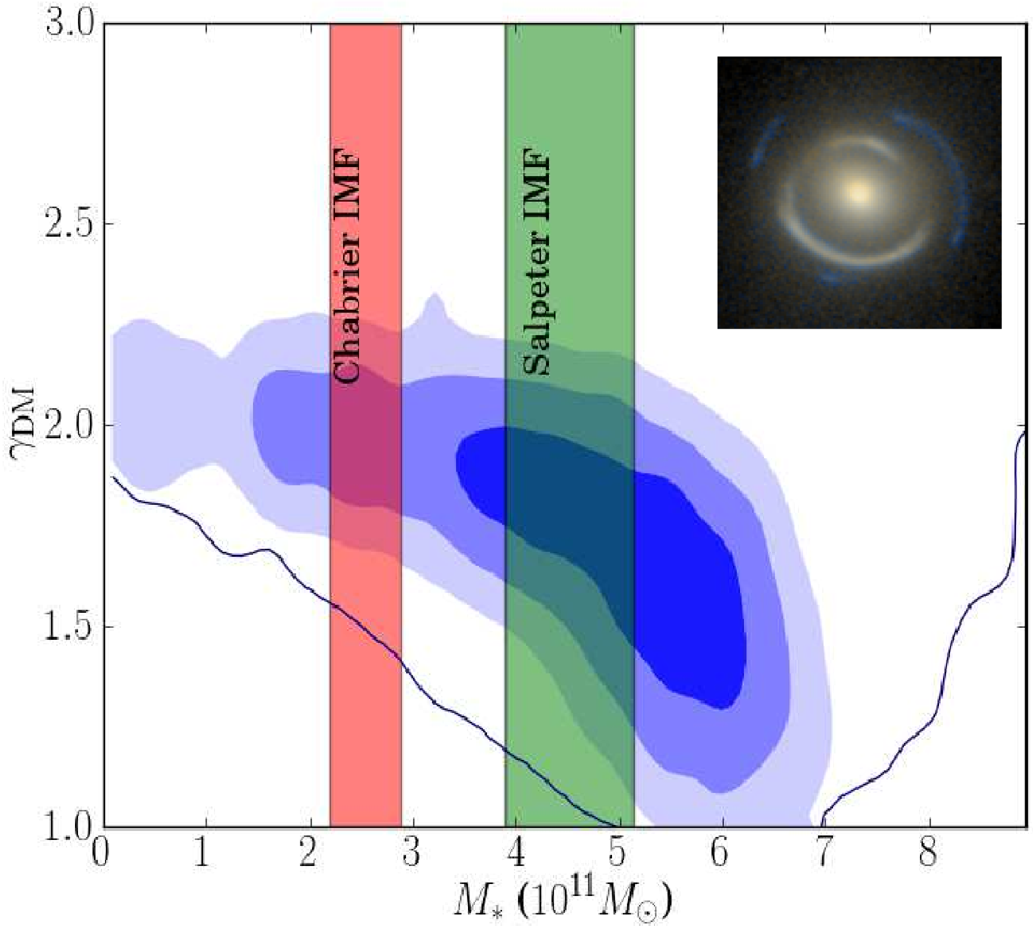
~ Double time-delay systems?

*These numbers have big error-bars!





Three rings from two sources?



(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

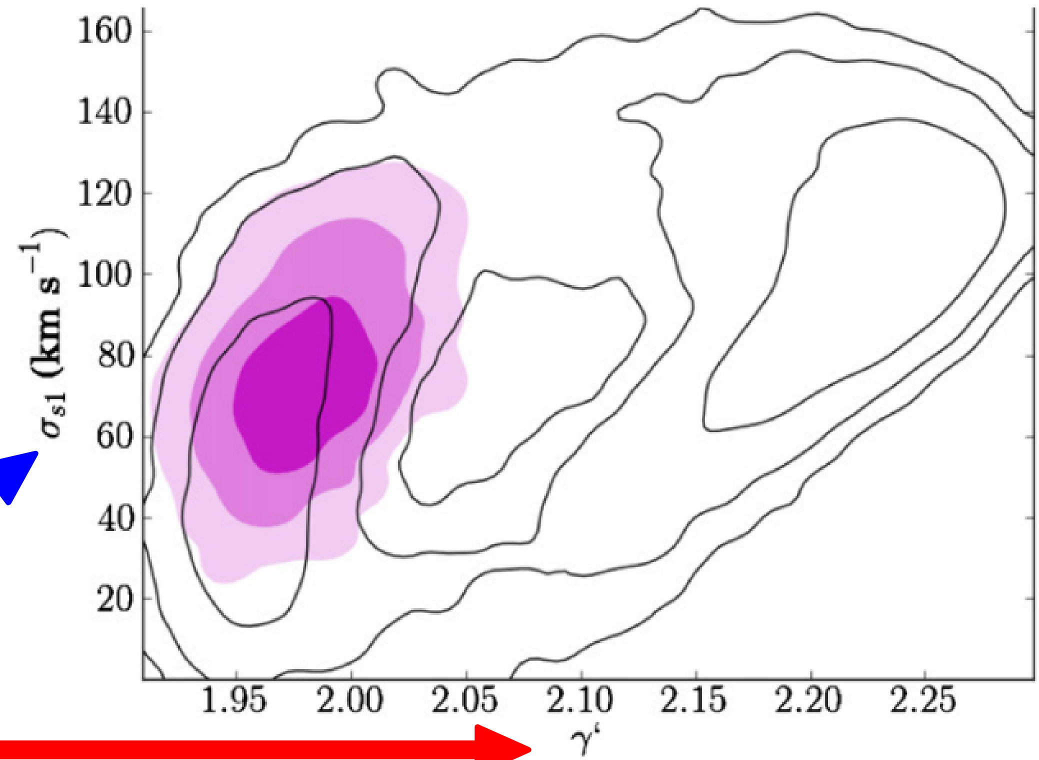
Perturbations by the intermediate source

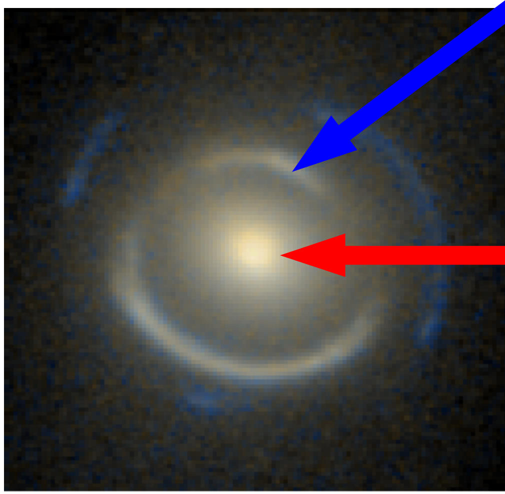
If completely neglected:

LMC: ~1% systematic error on β

MW: ~10% systematic error on β

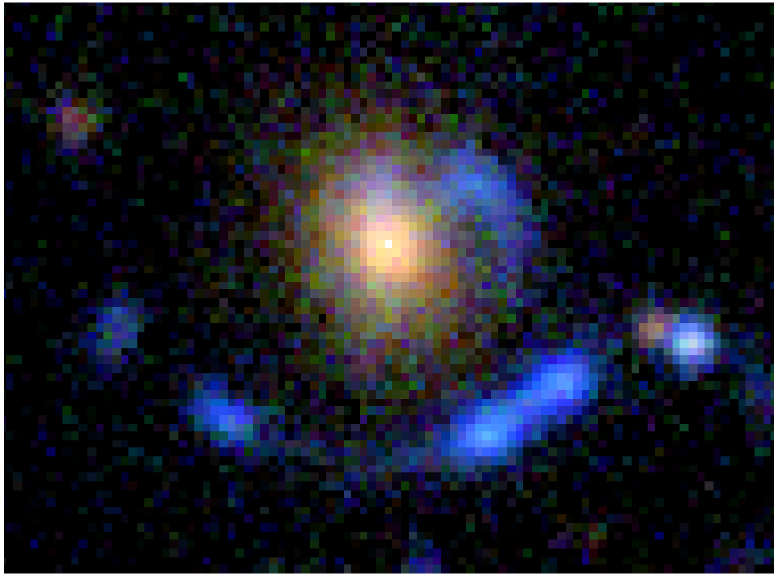
Effect is detectable: include in the lens model.





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

Finding more systems

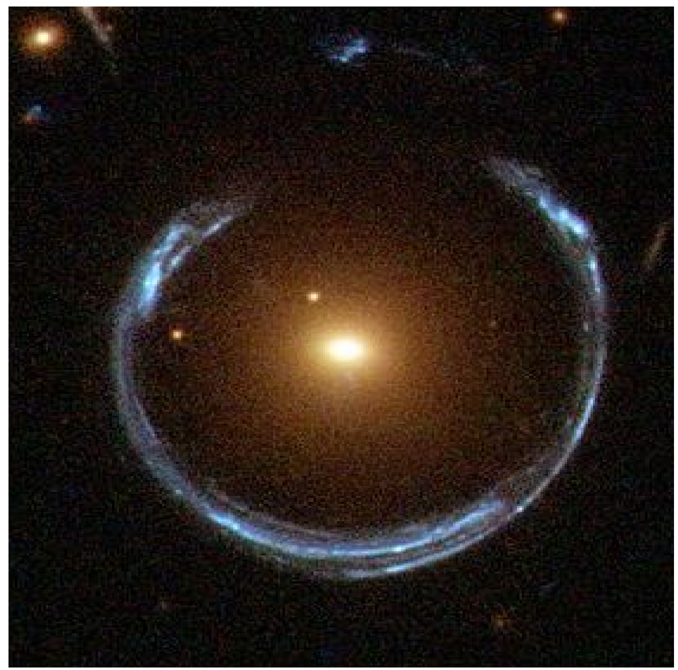


- Piggy-back on deep, large area surveys
- Target known lenses
- Target the most massive galaxies

THE DARK ENERGY SURVEY

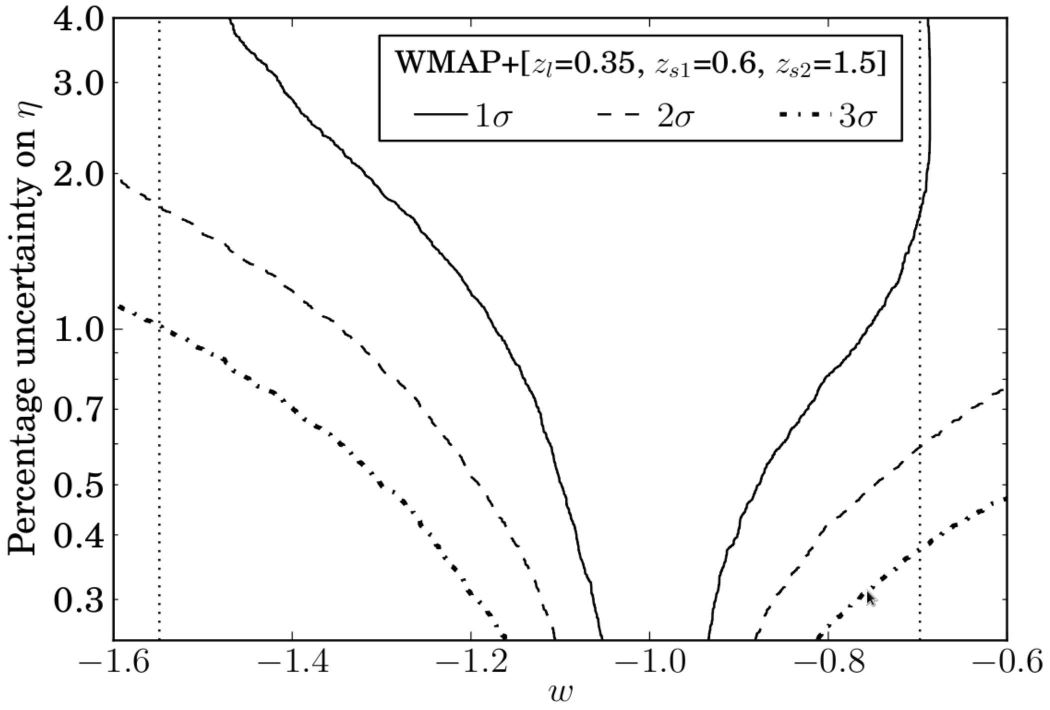
MegaPrime CFH MegaCam Legacy Survey

CFHTLS



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
3. Line of sight lensing may be significant



Constraints with 6 systems.

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

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

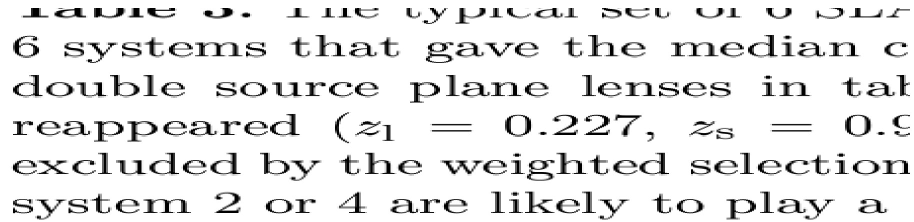
<u>WMAP+</u>

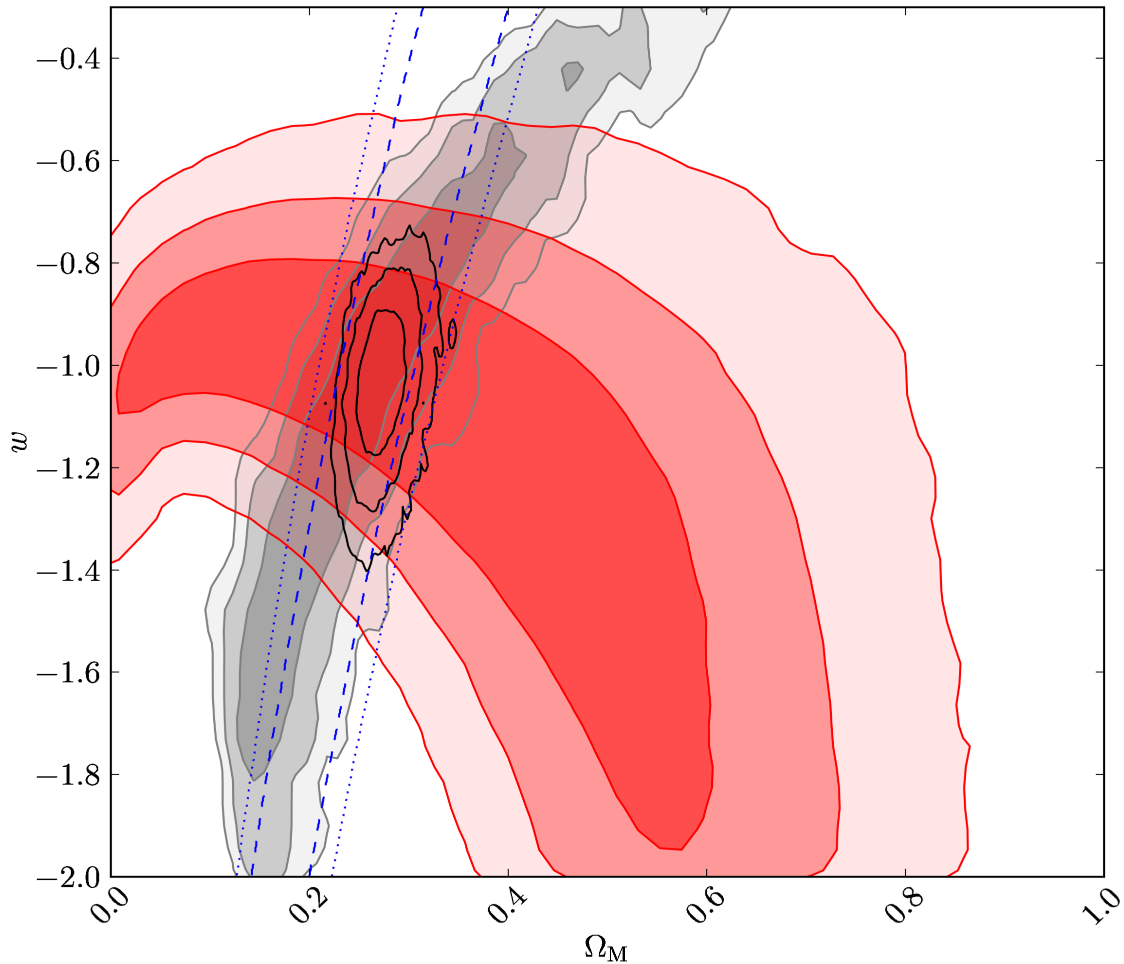
1 system $w_{DE} = -0.99 \pm 0.27$

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

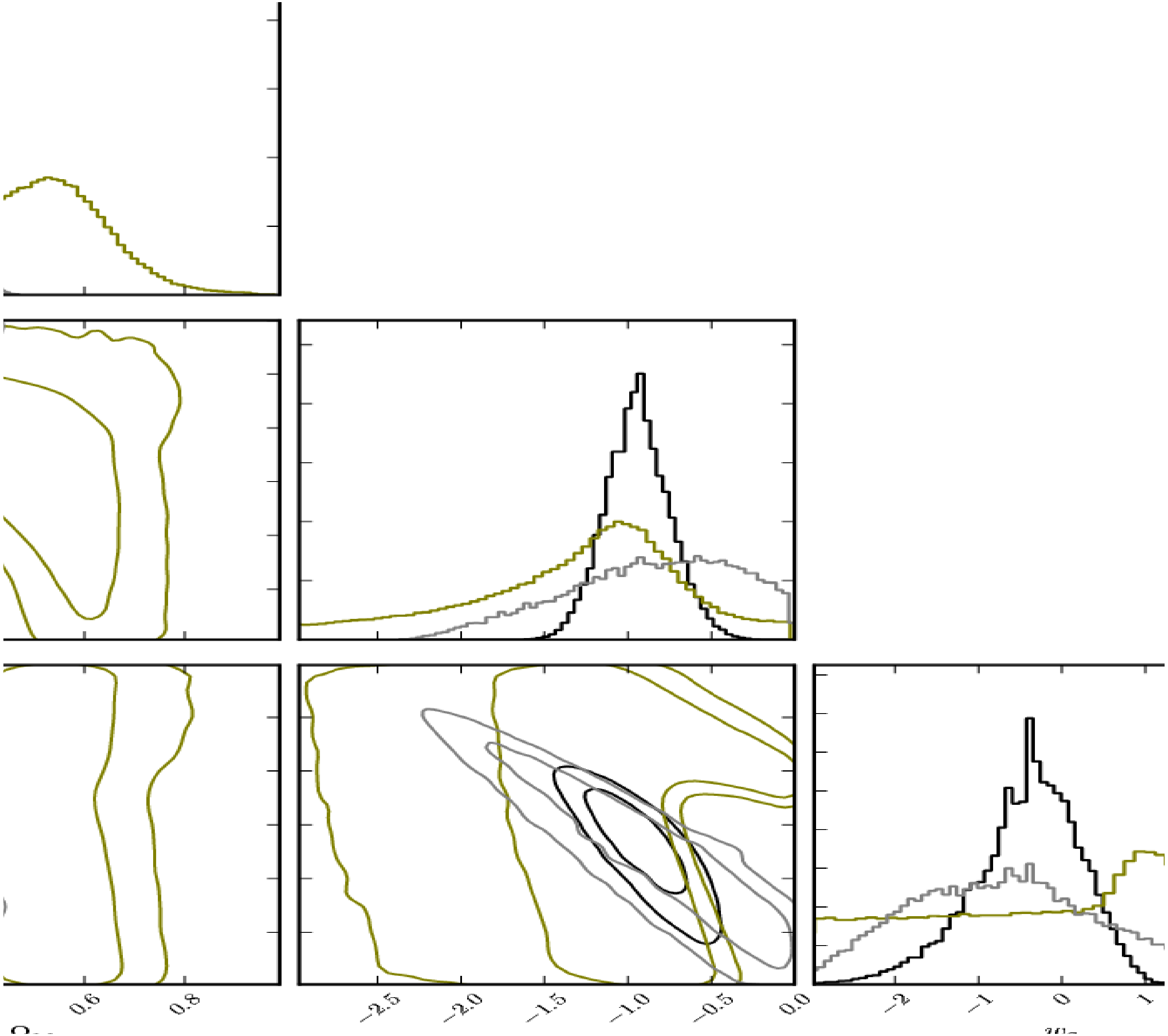
<u>WMAP+BAO+Time Delay+</u>

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

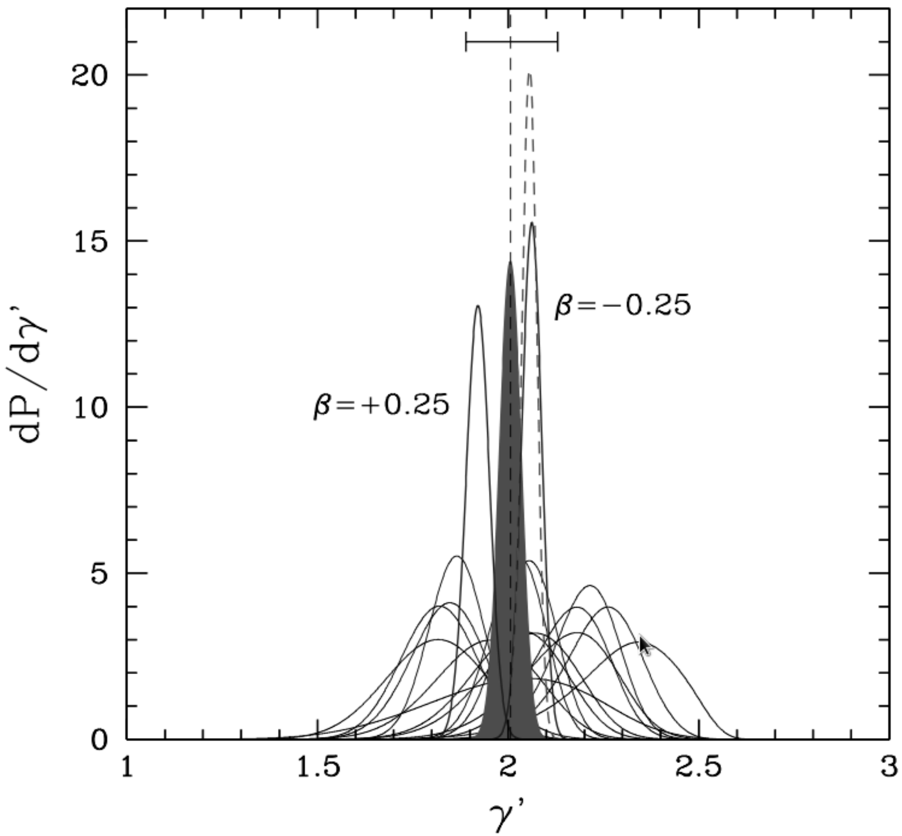

6 systems that gave the median c
double source plane lenses in tal
reappeared (z_l = 0.227, z_s = 0.9
excluded by the weighted selection
system 2 or 4 are likely to play a



Planck+6



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)