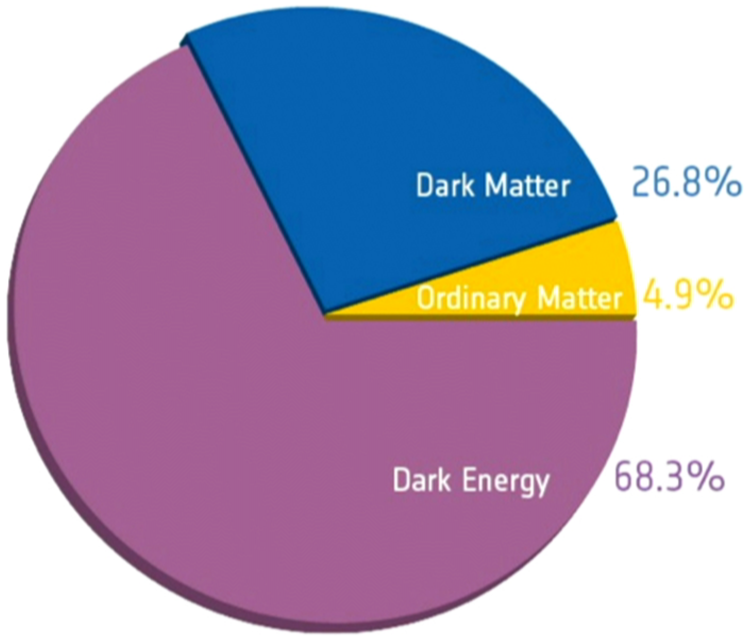
Title: Measuring the cosmological parameters with strong gravitational lensing

Date: May 17, 2016 11:00 AM

URL: http://pirsa.org/16050006

Abstract: <p>We are currently in an era of precision cosmology, but is it an era of accurate cosmology? By measuring cosmological parameters with many independent probes we can convince ourselves that our measurements of the parameters are indeed correct. Thanks to recent progress, strong gravitational lensing is now a powerful probe of cosmology. In this talk I'll report on a measurement of H0 at 5% precision using two strongly lensed quasars and a 20% measurement on the equation of state of dark energy using a double source plane lens. I'll also present new results from a z=1 strong lensing cluster where the dark matter profile deviates significantly from the NFW profile that is predicted by cold dark matter simulations, but it is consistent with simulations of self-interacting dark matter. I'll finish by discussing how upcoming wide area surveys can provide hundreds of exotic strong lenses that can be used for precise and accurate cosmology over the next decade.</p>

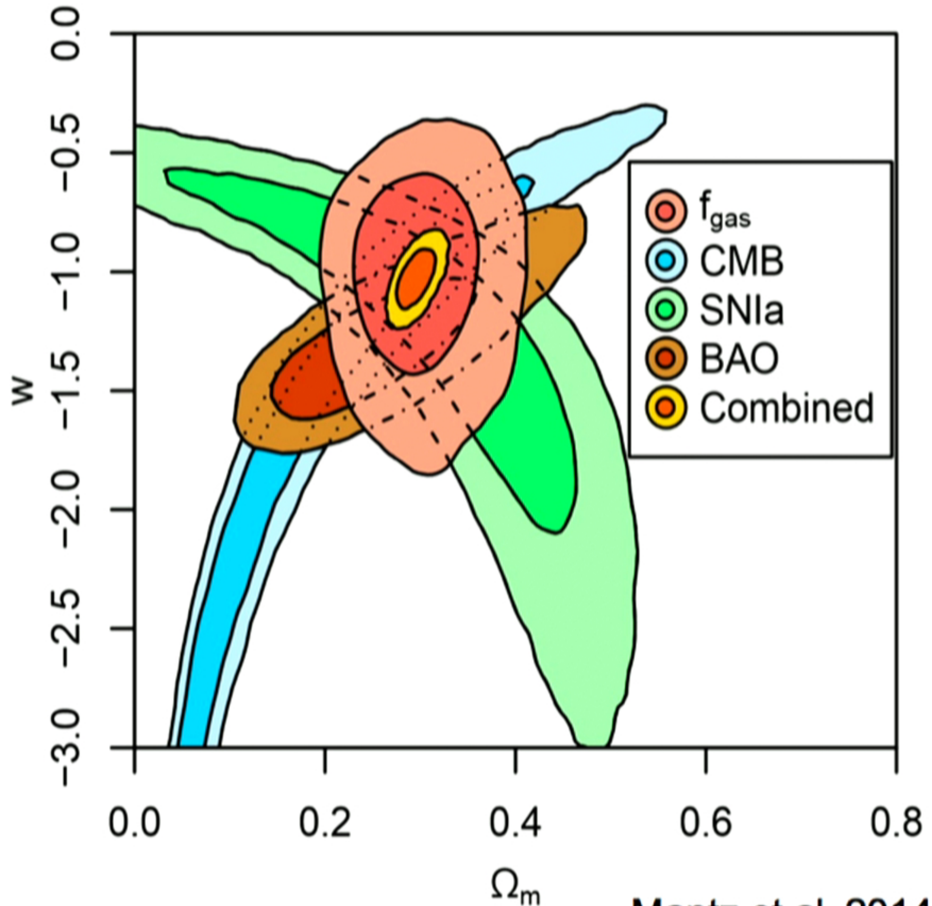
Today's concordance model: ΛCDM



Few Probes of Dark Energy

Precise measurements

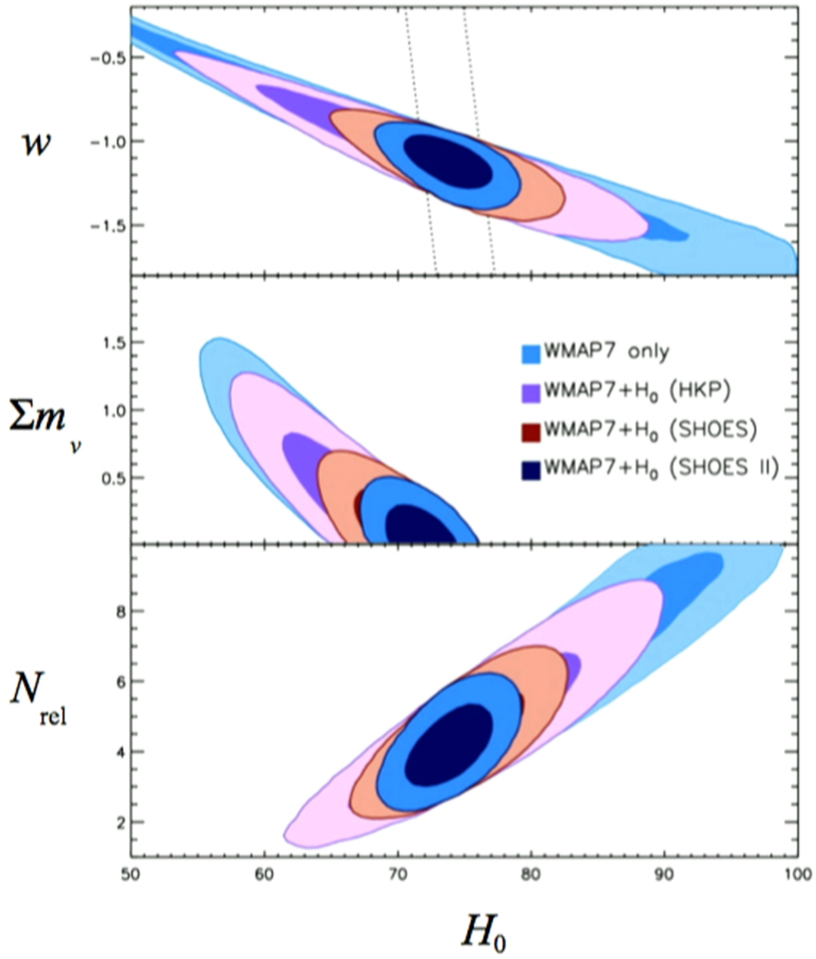
Systematics important



Mantz et al. 2014

Probing Cosmological Parameters with Strong Lenses

Thomas Collett



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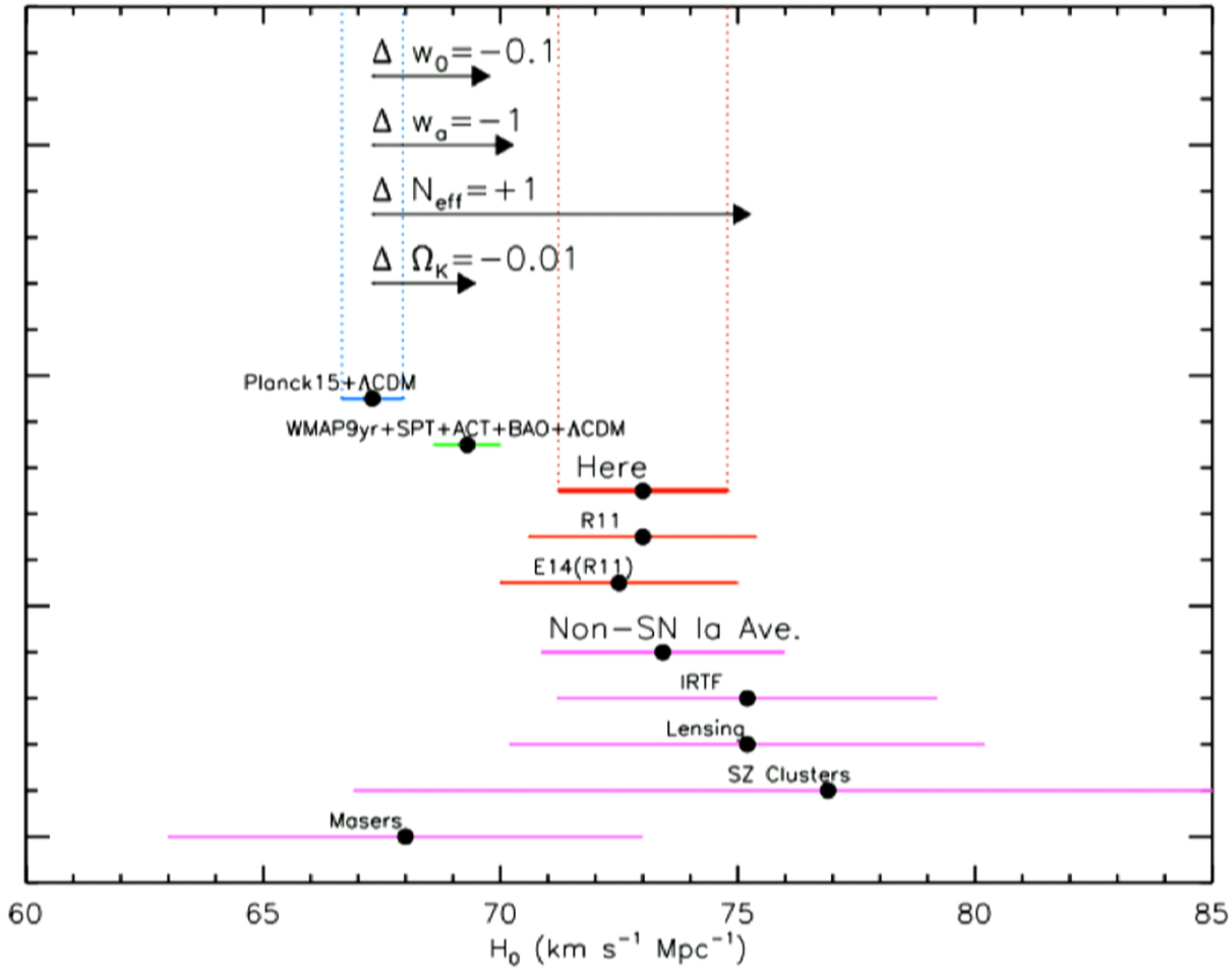
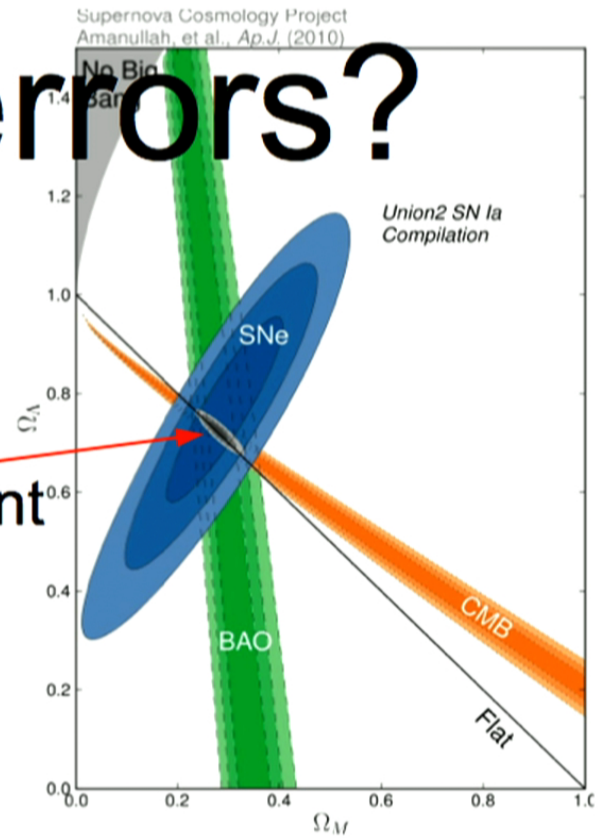


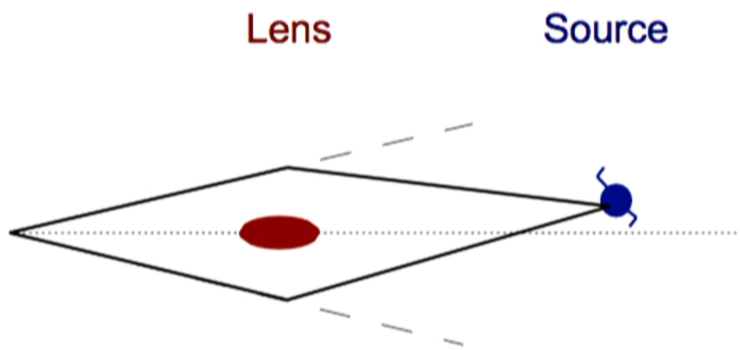
Reiss+ , 2016

New physics? or systematic errors?



All 3 probes are consistent

Strong lensing is an optical bench



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

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

Probing Cosmological Parameters with Strong Lenses
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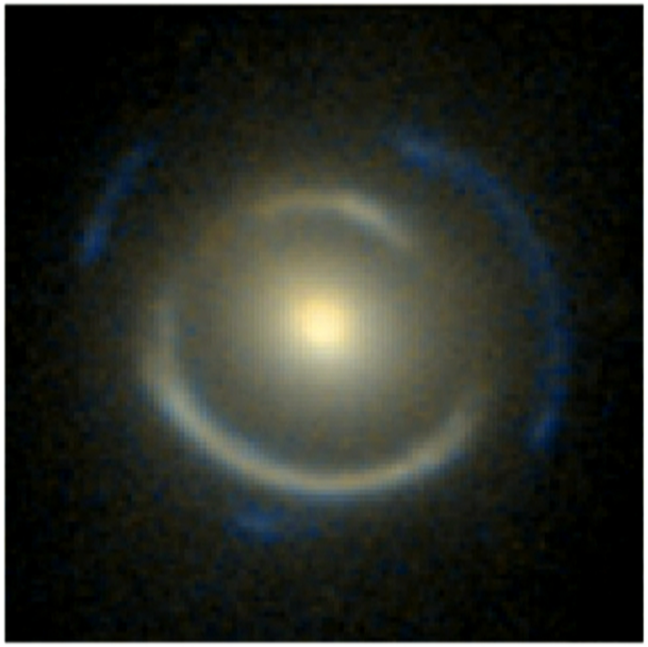
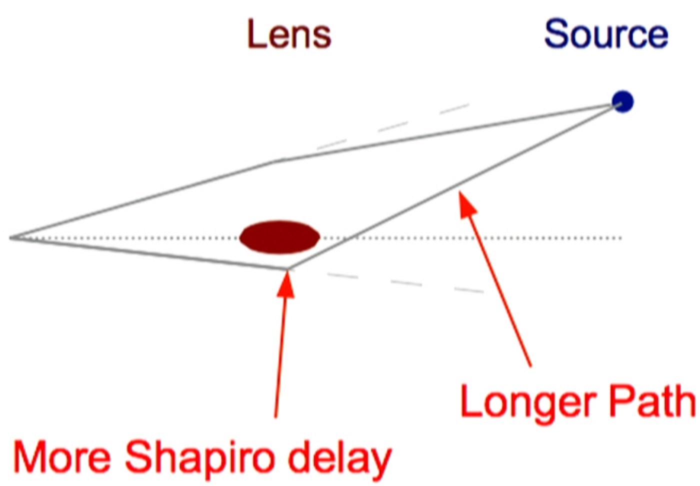
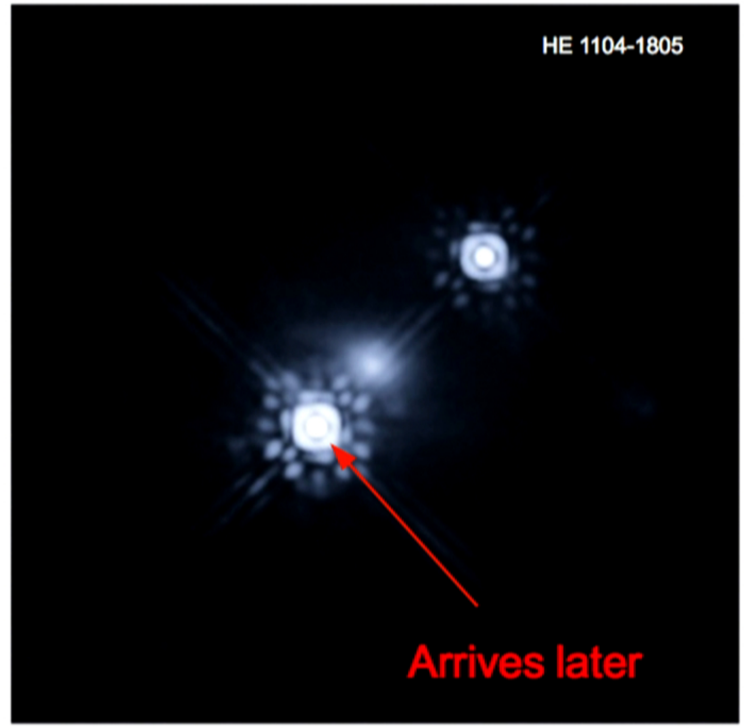


Strong lensing time delays



$$\Delta t \propto D_{\Delta t} = (1+z_1)\,(D_1 D_s)/D_{1s}$$



Most sensitive to the Hubble constant.

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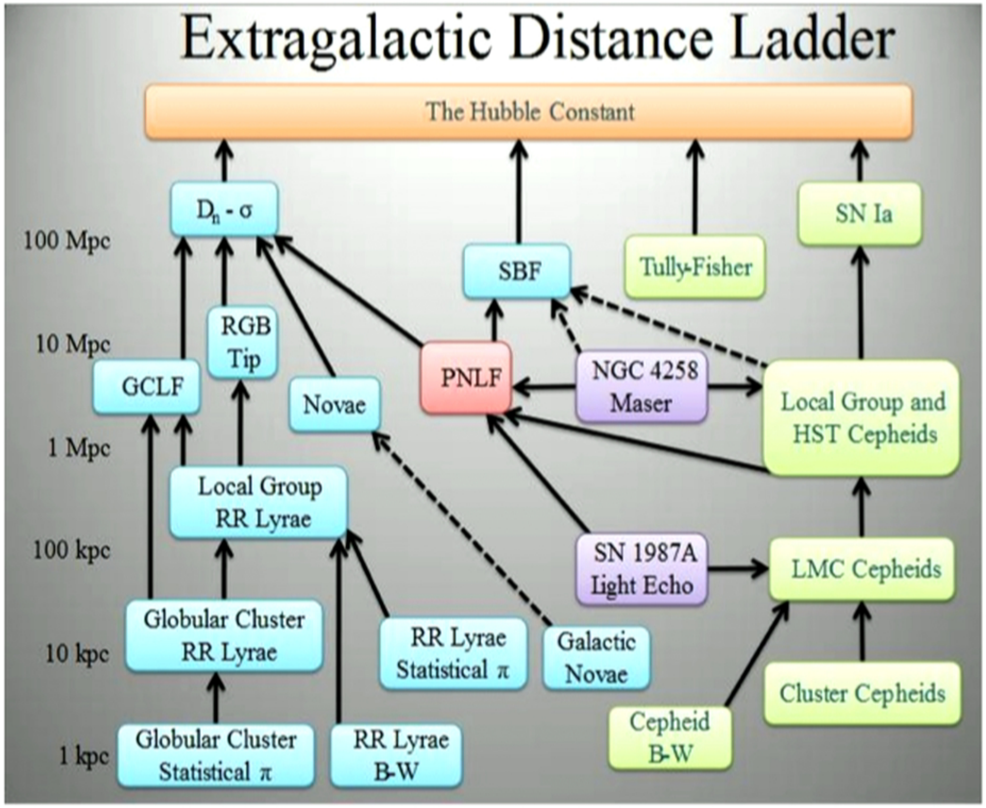
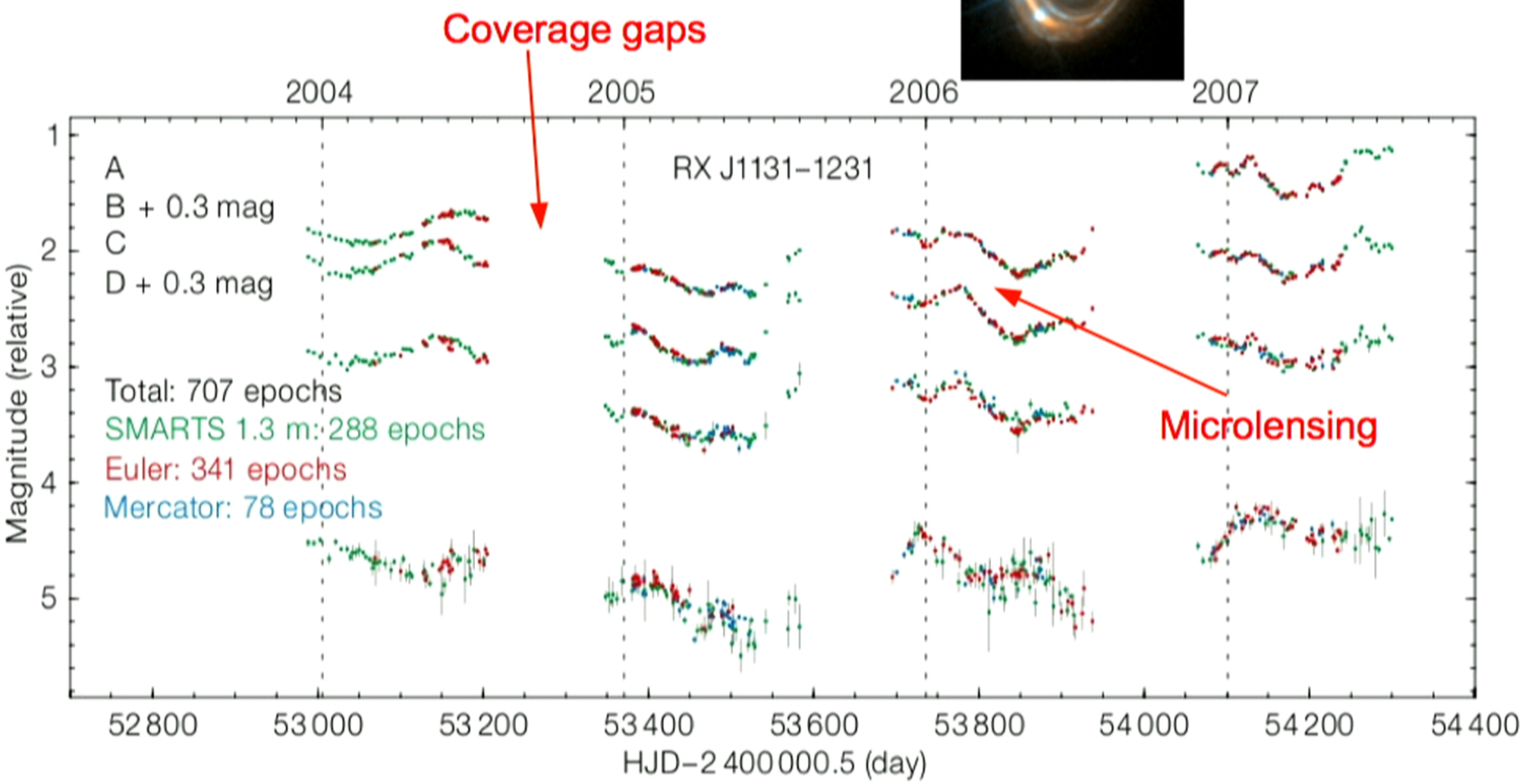
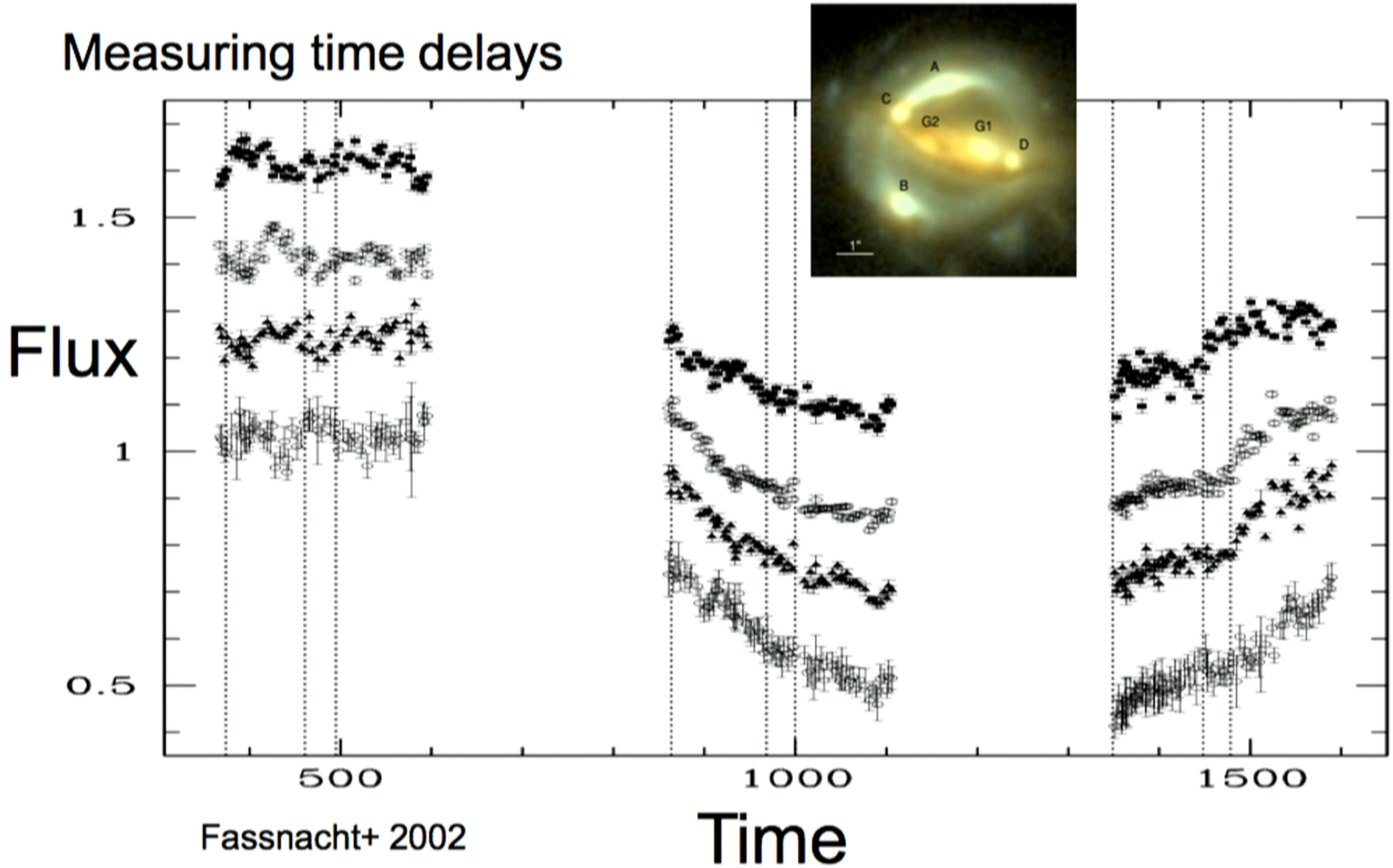


Measuring time delays



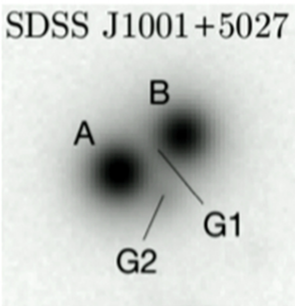
Tewes+ 2012

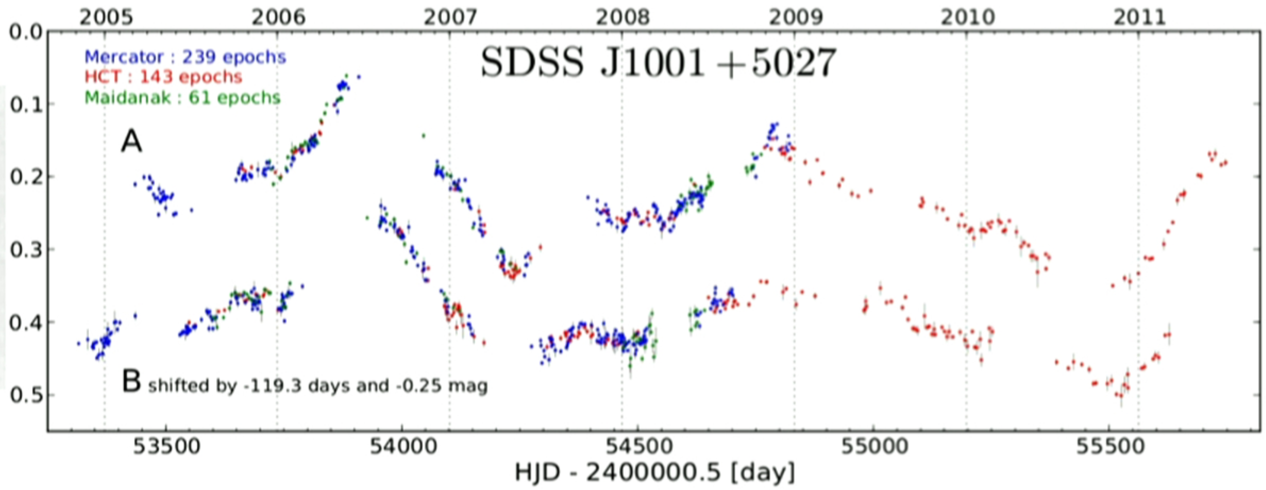
Measuring time delays

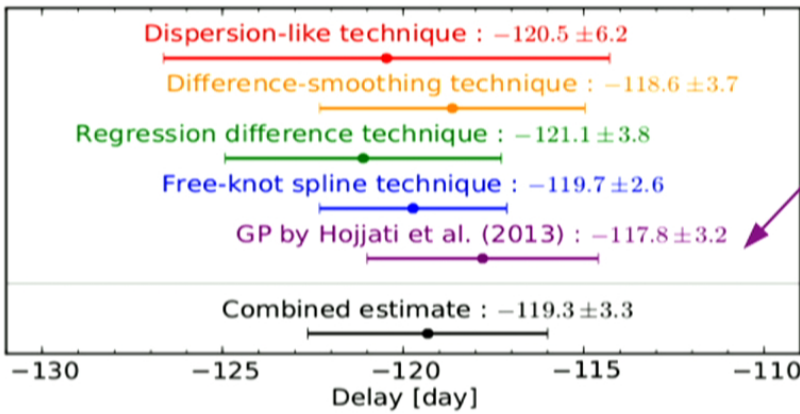


Fassnacht+ 2002

Cosmograil





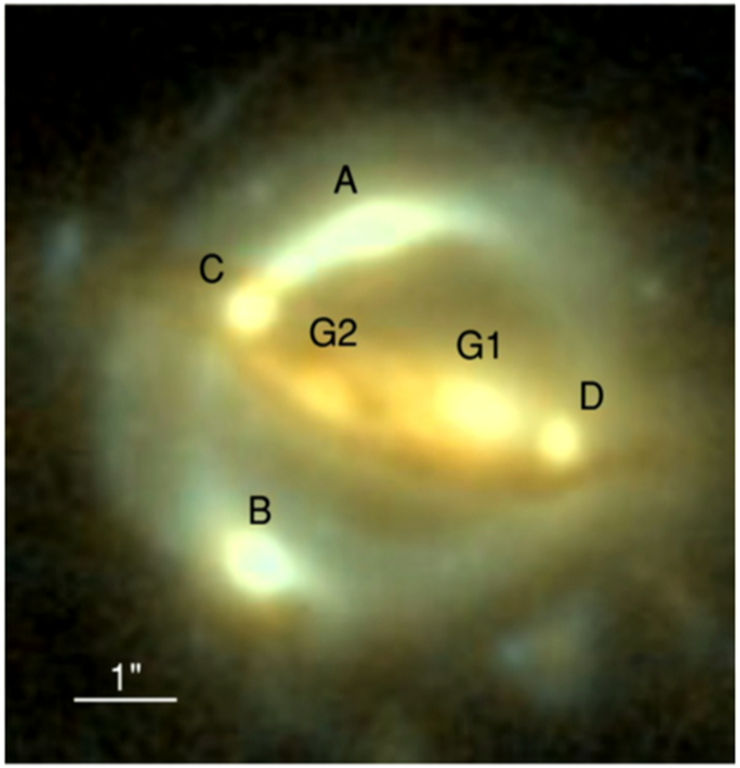


Blind, independent team and different method get the same result

Accurate time delays at +/- 3 day precision

Rathna Kumar+ 2013

Modelling the lenses



B1608

RXJ1131

Modelling the lenses

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

What's the constant of proportionality?

- Location of the images
- Gravitational potential

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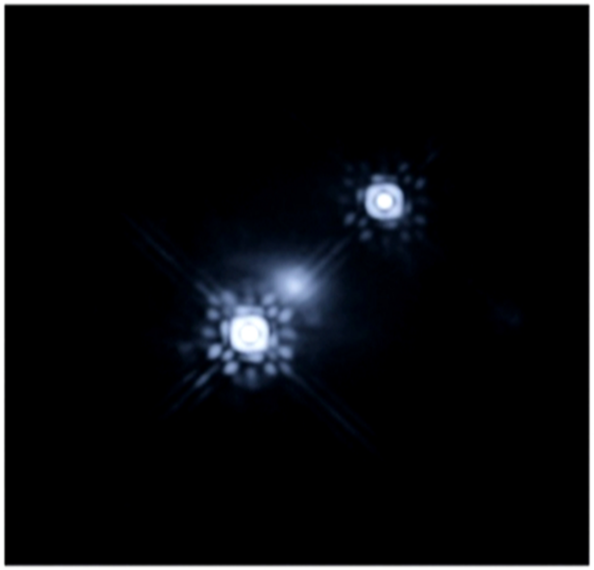
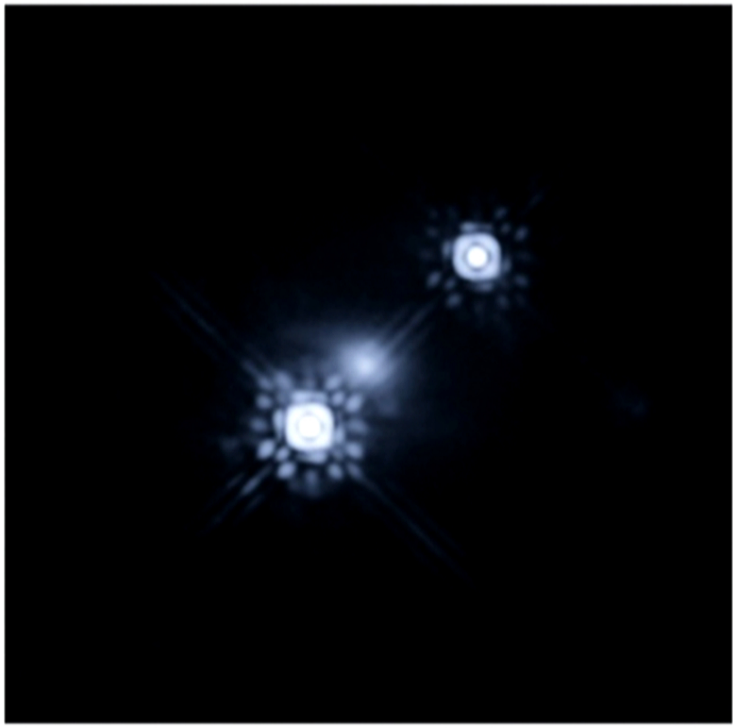


$$c\Delta t = D_{\Delta t}\left(\tfrac{1}{2}(\theta_1 - \beta)^2 - \tfrac{1}{2}(\theta_2 - \beta)^2 - \psi(\theta_1) + \psi(\theta_2) \right)$$

Constraining the steepness of the potential

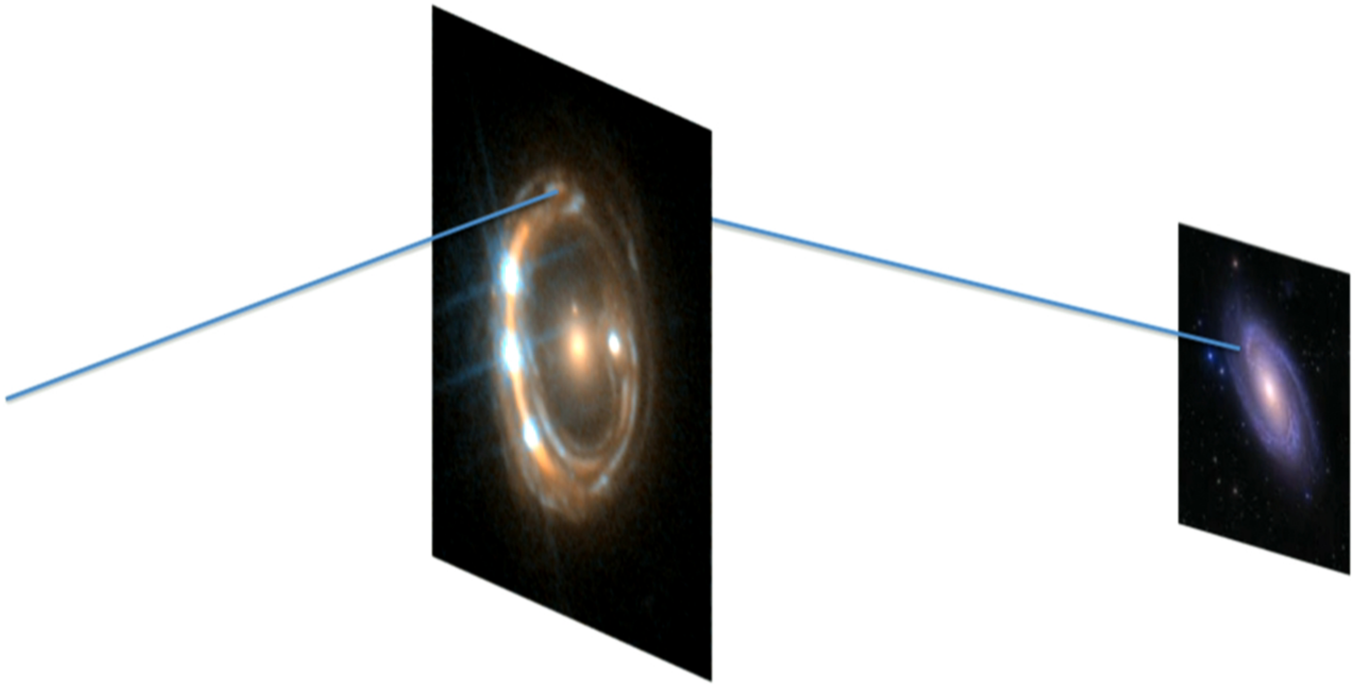


Not enough information

Constraining the steepness of the potential

Lots of information

Lens Modelling

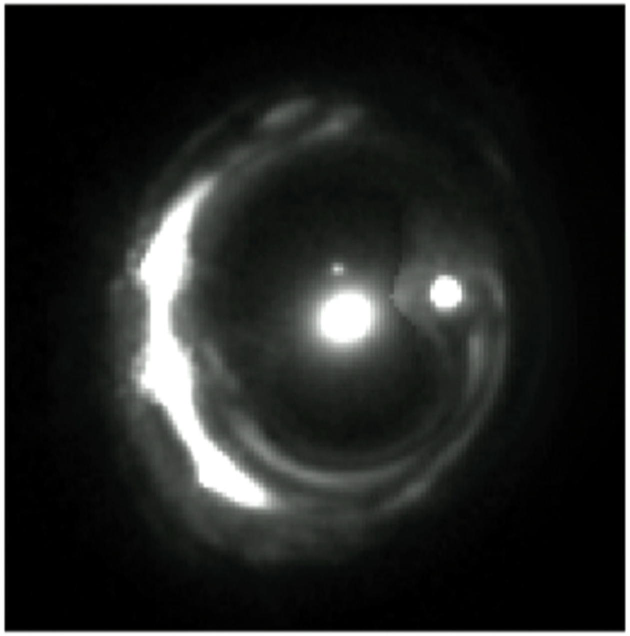


Lens Modelling

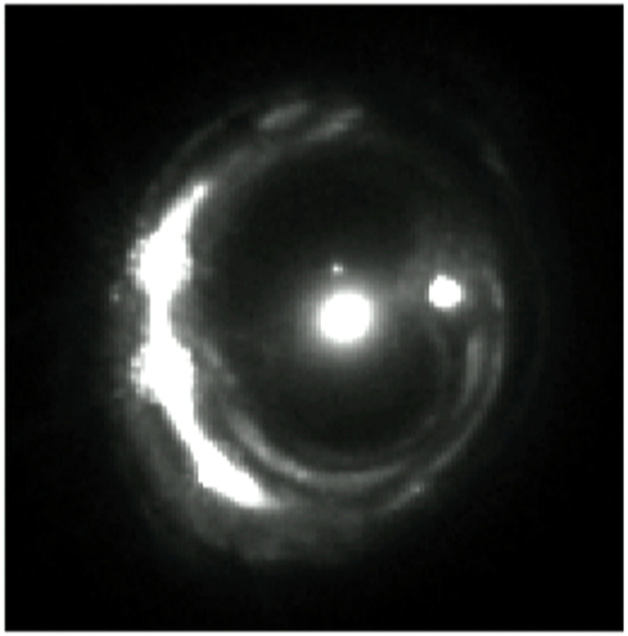
$$= (\mathrm{M})^{\mathrm{SOURCE}}$$

Then sample the mass + source model

Constraining the steepness of the potential

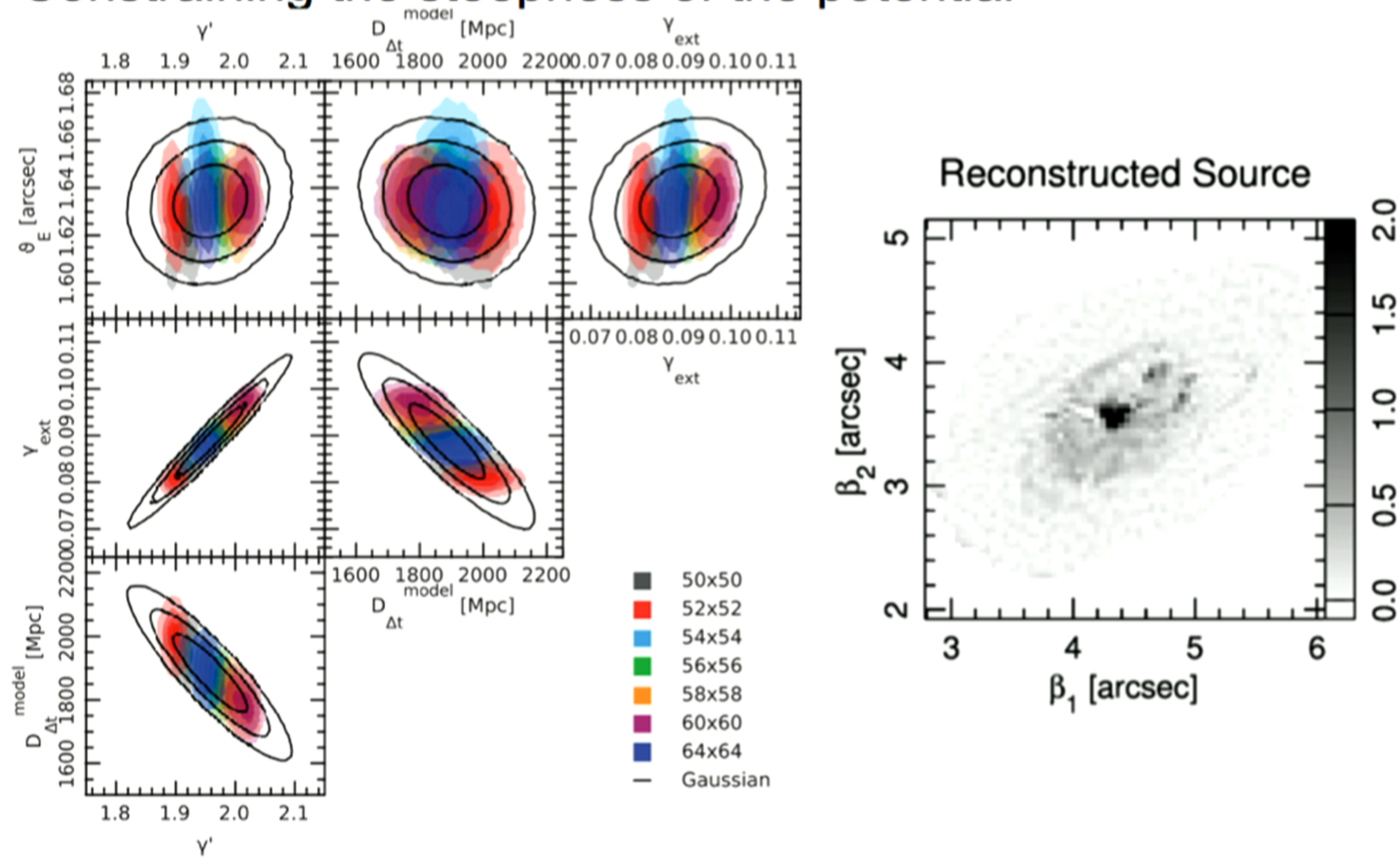


(Most probable) Model

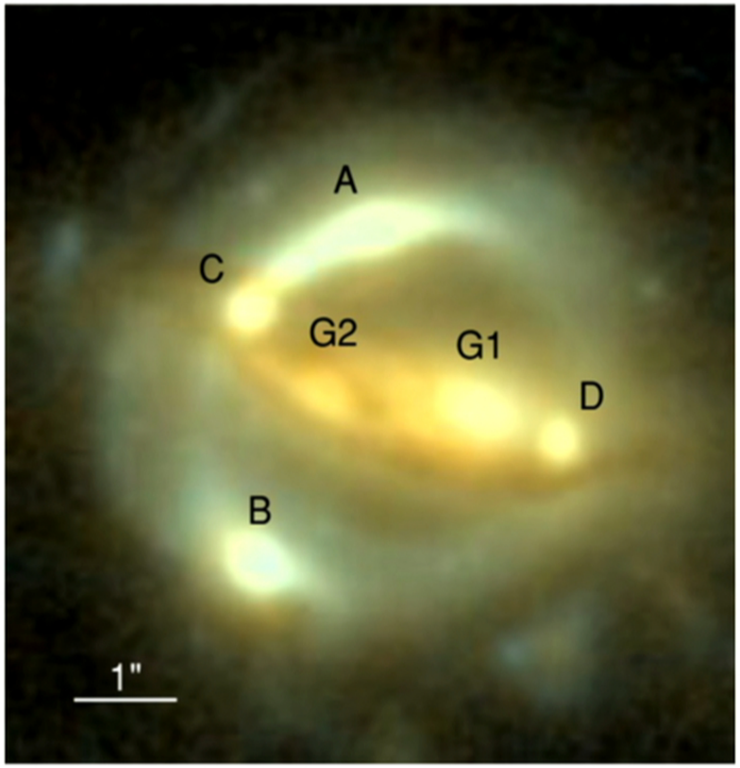


Data (F814W)

Constraining the steepness of the potential



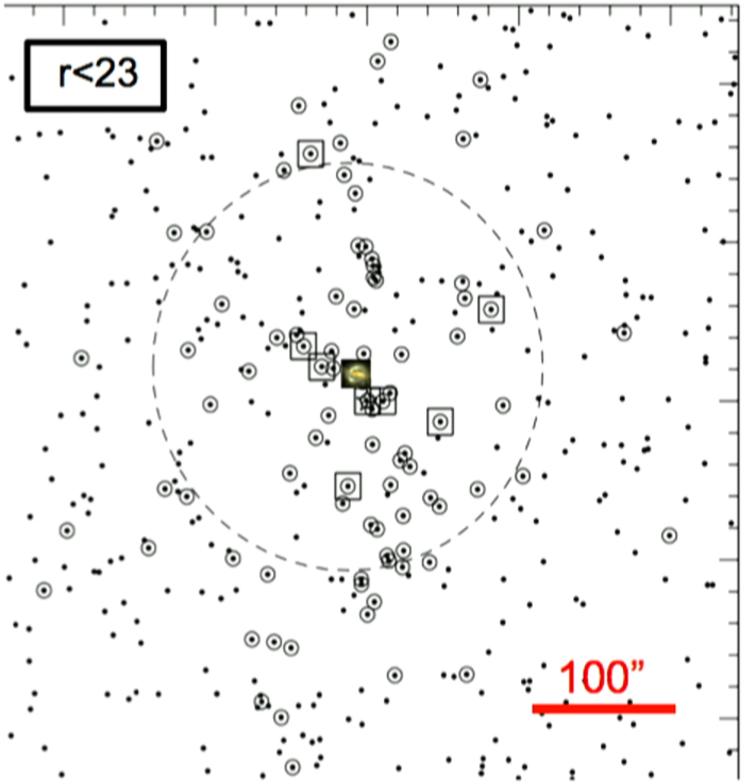
This is NOT the correct context of a strong lens:



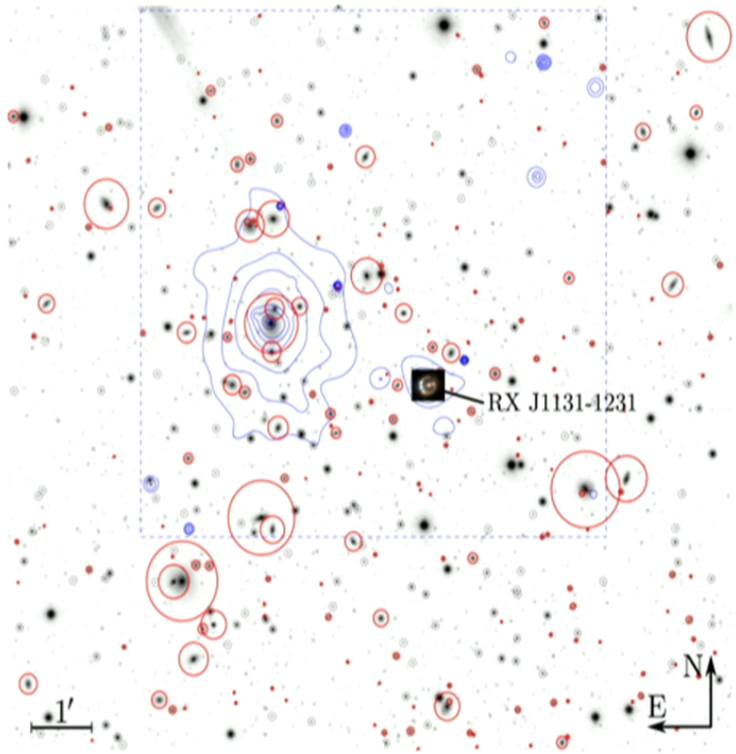
B1608

RXJ1131

This is the correct context of a strong lens:



B1608

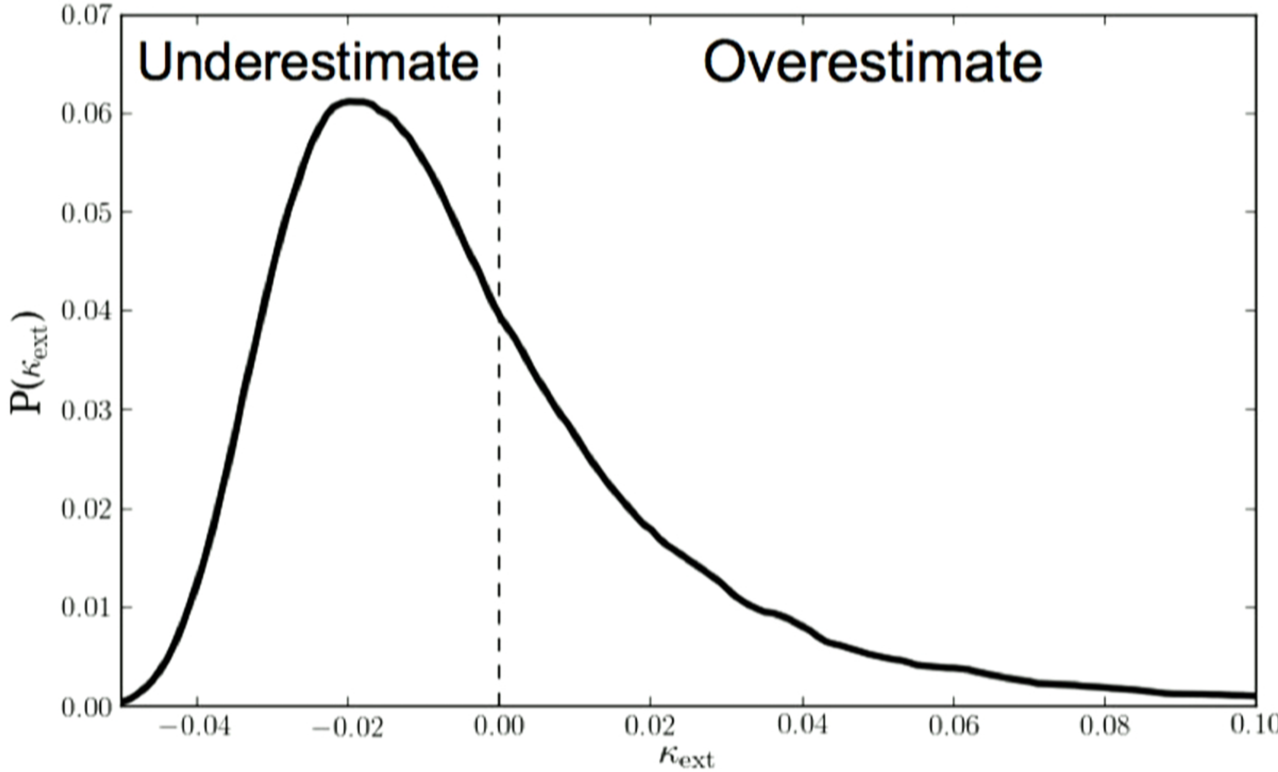


RXJ1131

Probing Cosmological Parameters with Strong Lenses — Thomas Collett

The Mass Sheet Degeneracy

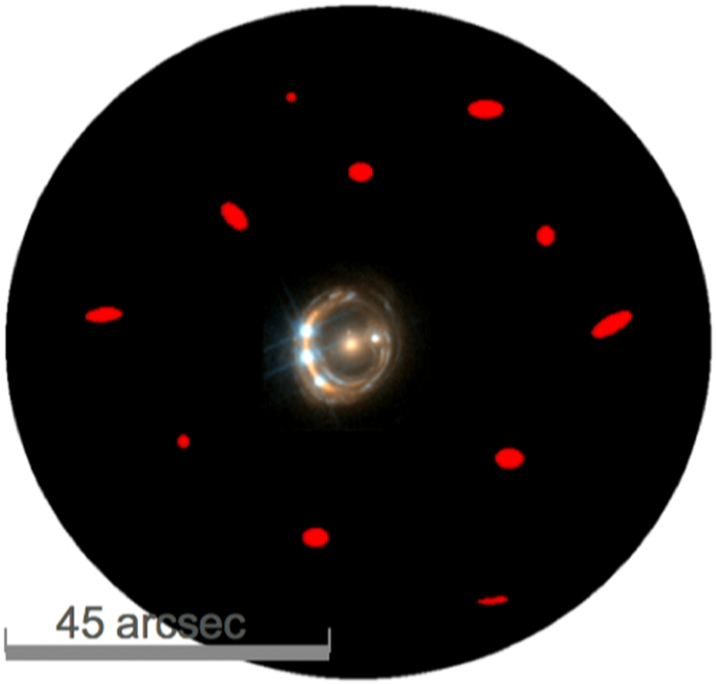
$$H_0 \sim H_0^{\text{homogeneous}} \times (1-\kappa_{ext})$$

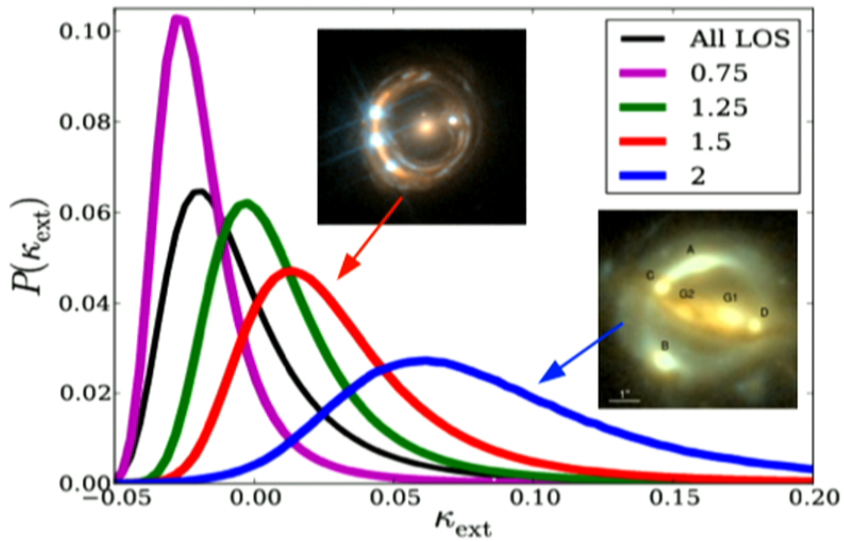


Hilbert+ 2010

Ray tracing through the Millennium Simulation

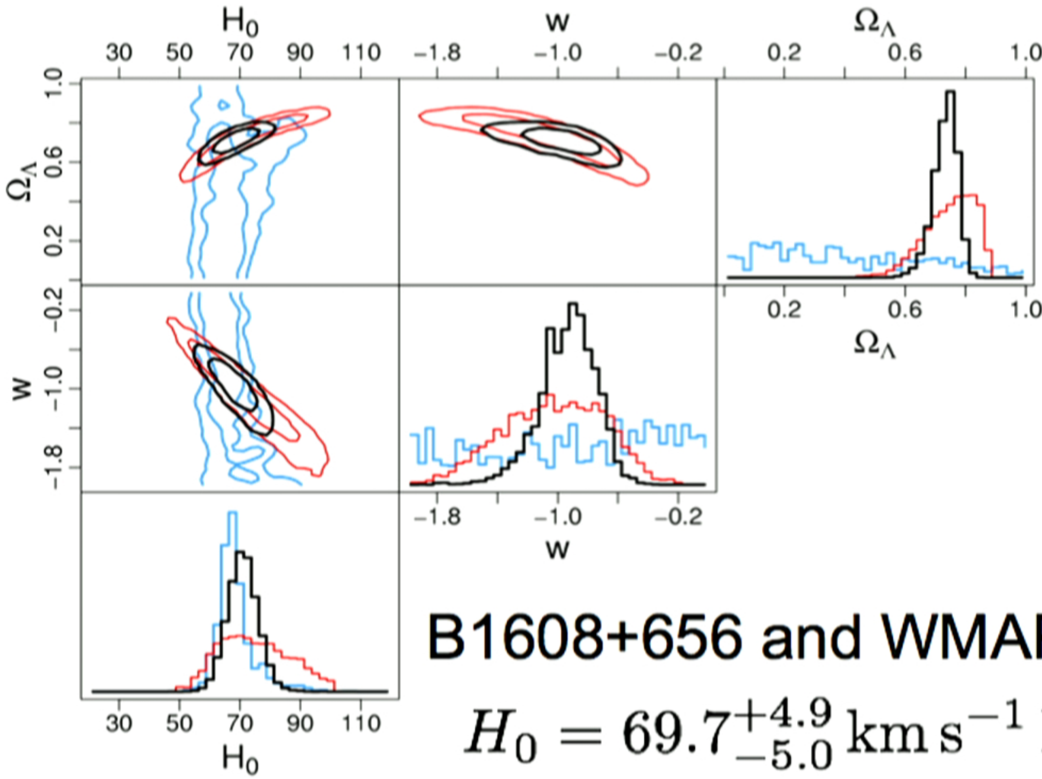
The Mass Sheet Degeneracy

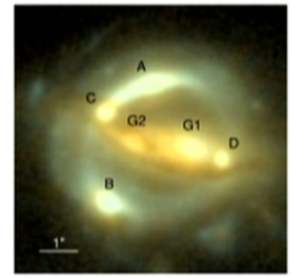




Greene+ 2013

Cosmological results



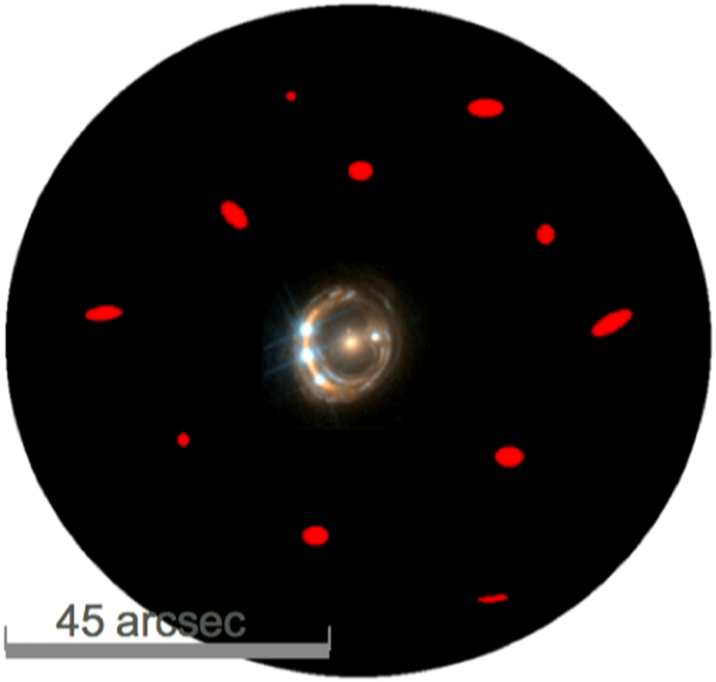


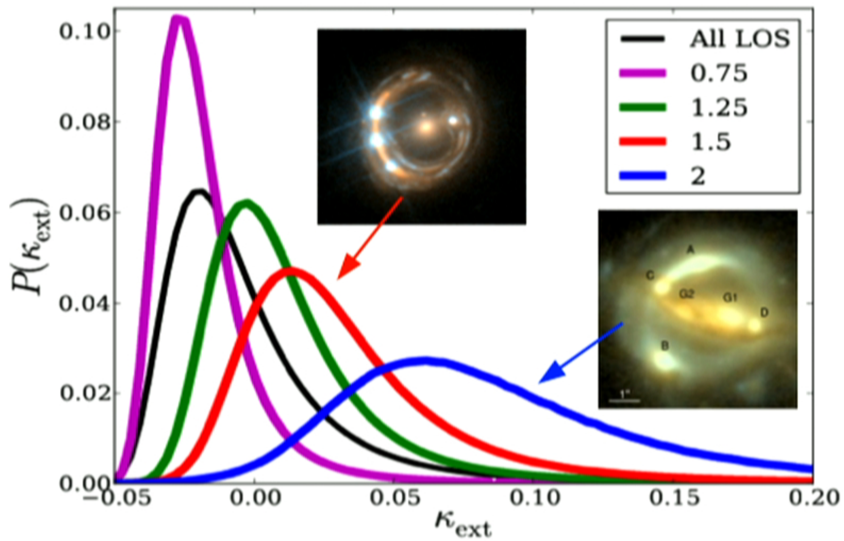
B1608+656 and WMAP5:

$$H_0 = 69.7^{+4.9}_{-5.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$w = -0.94^{+0.17}_{-0.19}$$

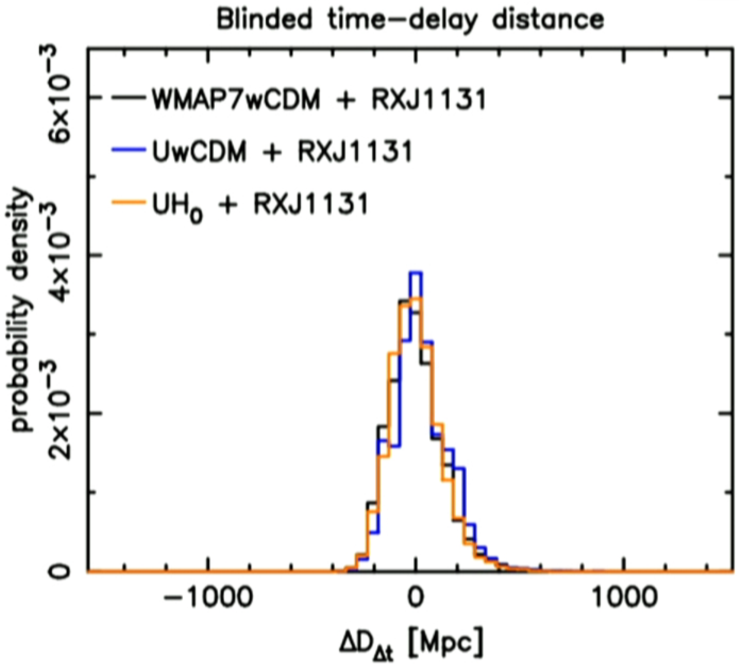
The Mass Sheet Degeneracy

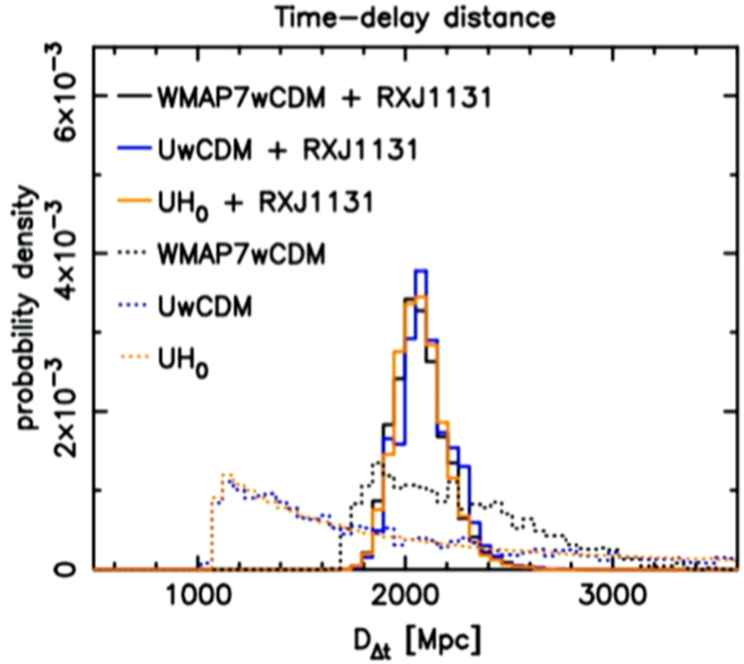




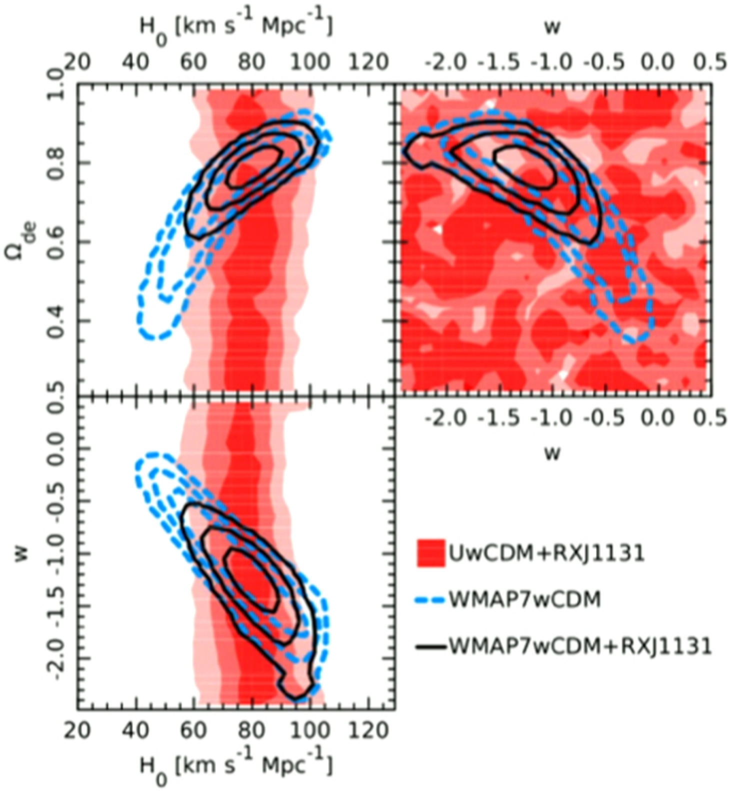
Greene+ 2013

Cosmological results



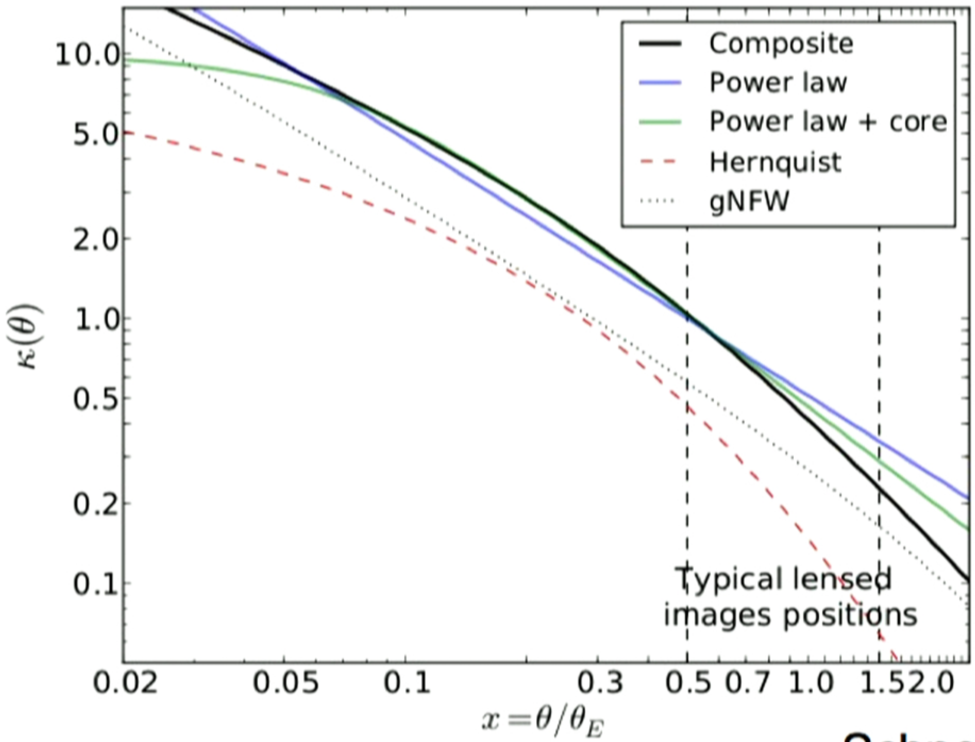


Cosmological results



$$H_0 = 79 \pm 5$$

Revisiting the lens profile:

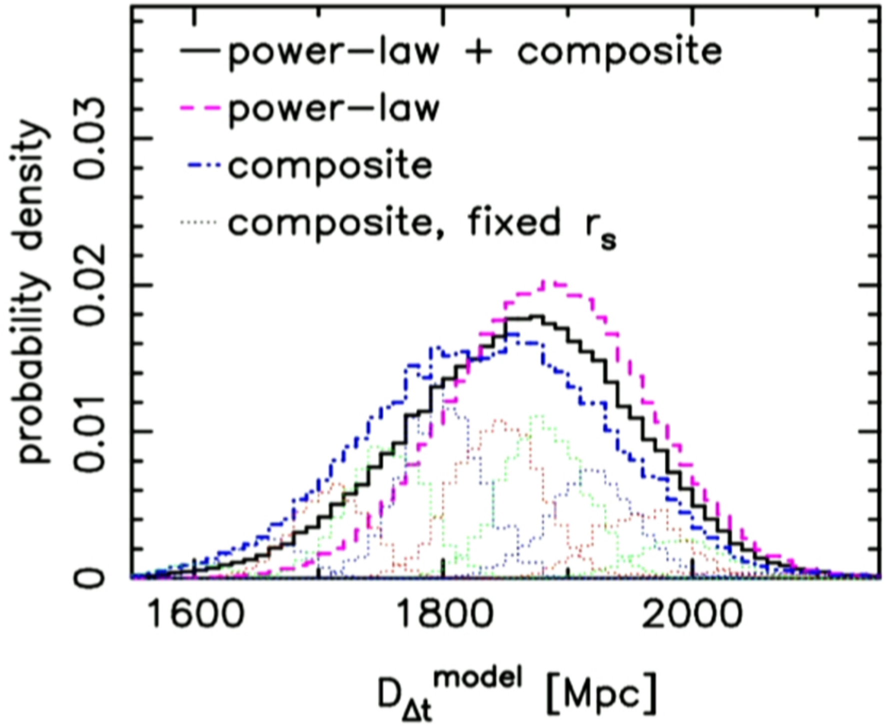


Model choice could bias H_0 by 20%!

(A little bit alarmist)

Schneider & Sluse, 2013

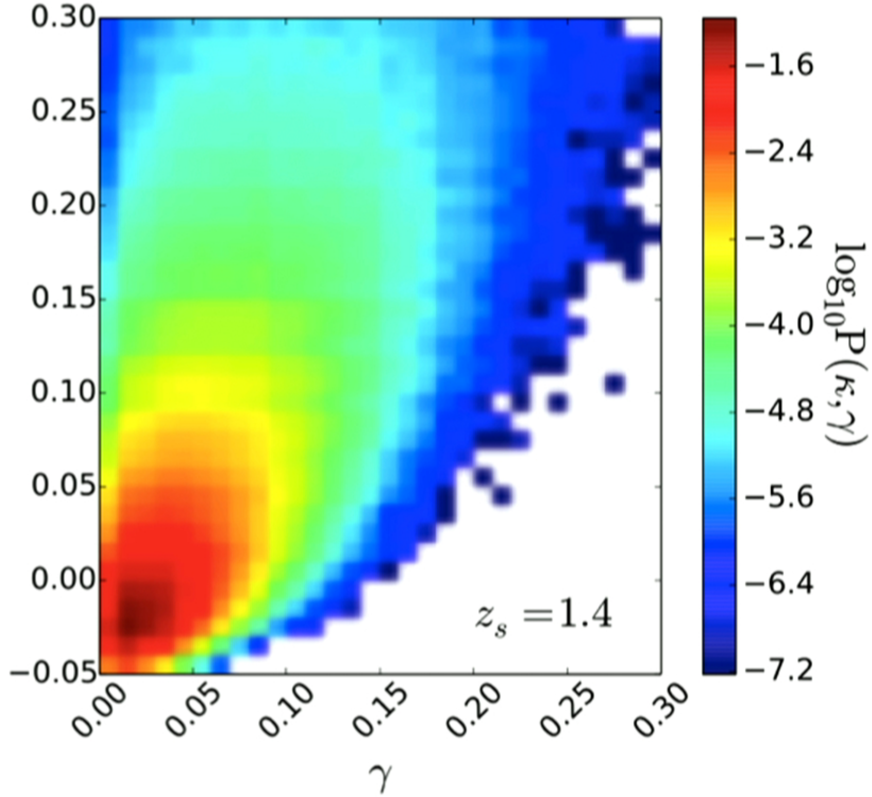
Revisiting the lens profile:



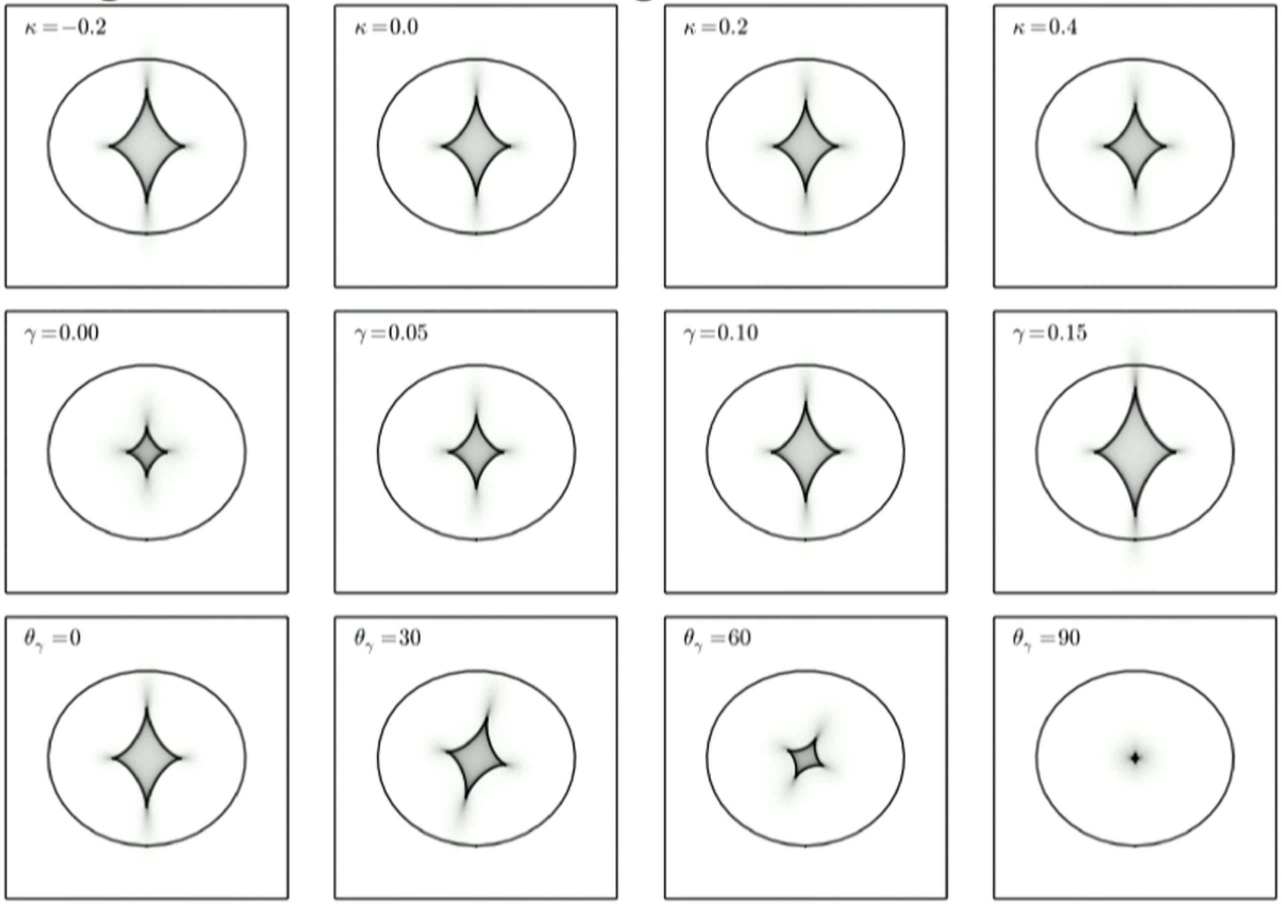
Revisiting the external convergence:

Overestimate H_0

Underestimate H_0



Revisiting the external convergence:



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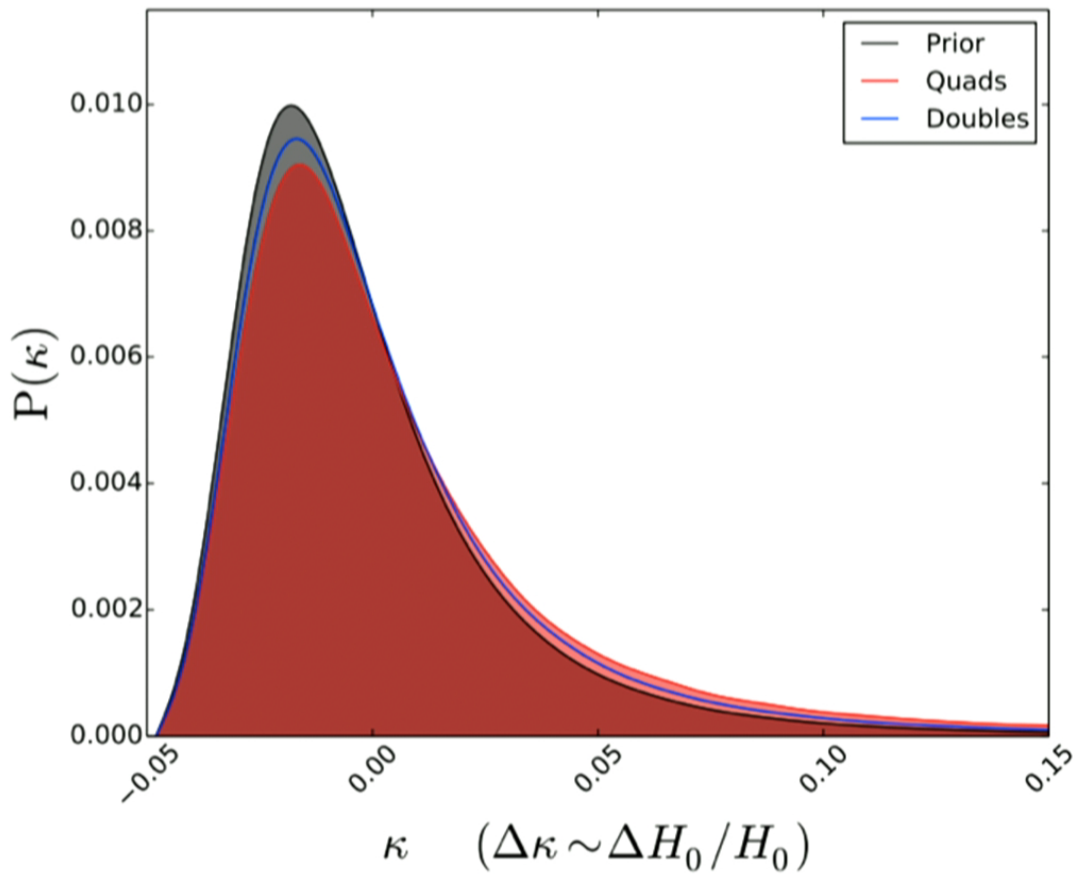

Probing Cosmological Parameters with Strong Lenses

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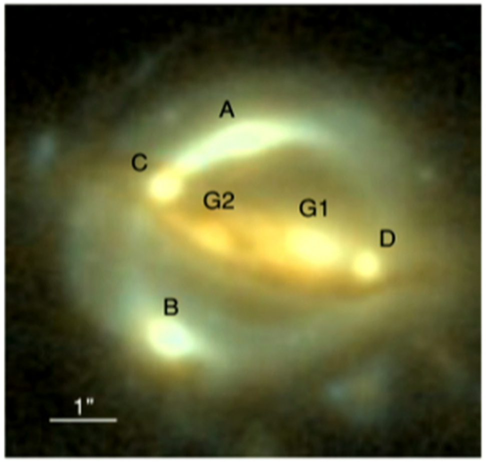
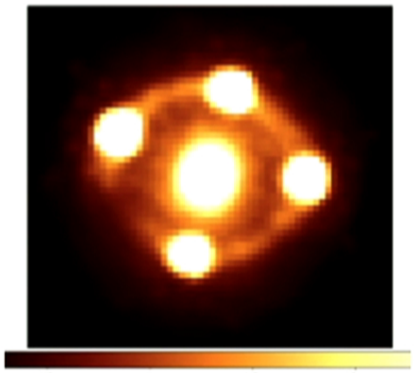
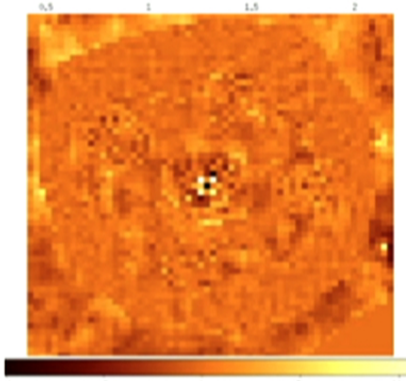


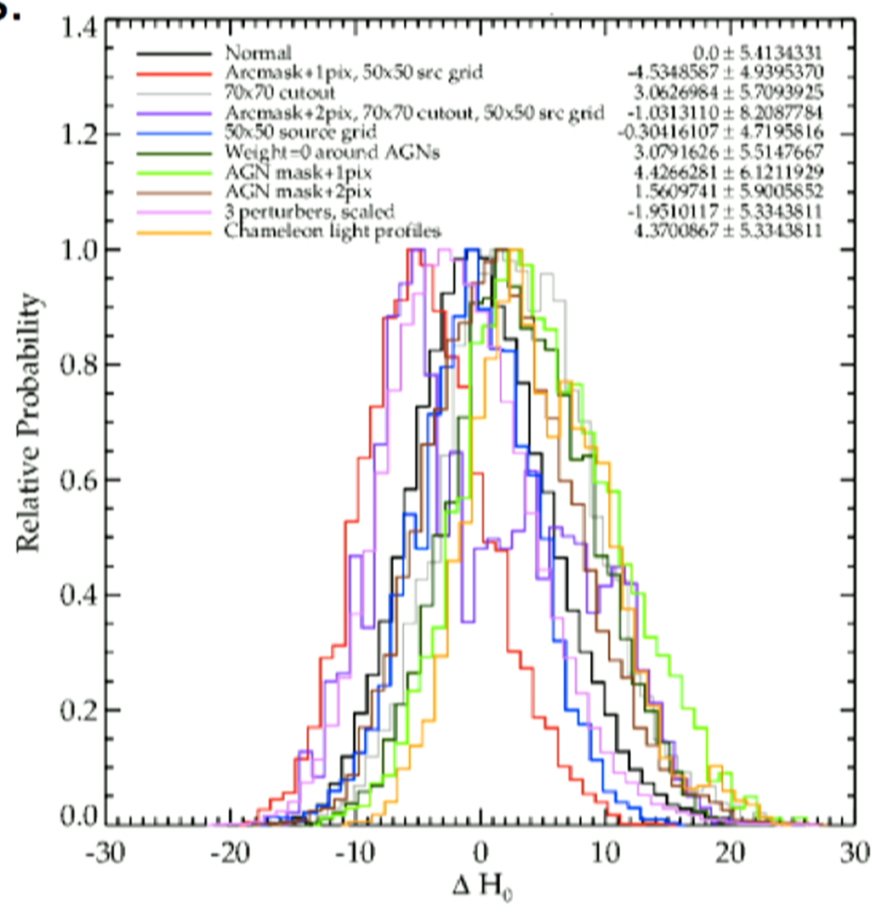
Cosmology	Parameter	Marginalized Value (68% CI)	Precision
wCDM	H_0	$75.2^{+4.4}_{-4.2}$	5.7%
	$\Omega_{\rm de}$	$0.76^{+0.02}_{-0.03}$	2.5%
	w	$-1.14^{+0.17}_{-0.20}$	18%
oΛCDM	H_0	$73.1^{+2.4}_{-3.6}$	4.0%
	Ω_Λ	$0.75^{+0.01}_{-0.02}$	1.9%
	$\Omega_{\rm k}$	$0.003^{+0.005}_{-0.006}$	0.6%

The future for time delays.

Right now (HST cycle 20)

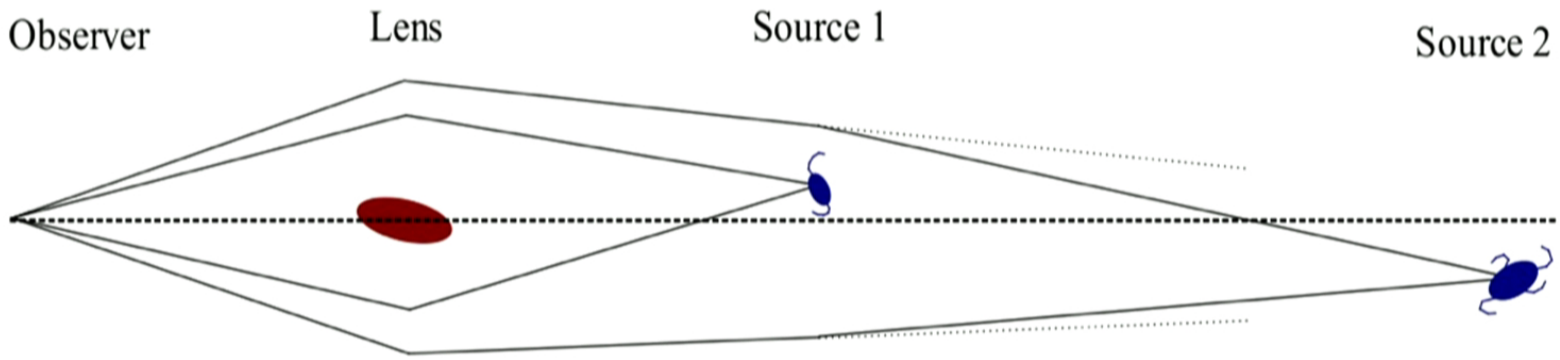






Double source plane strong lensing

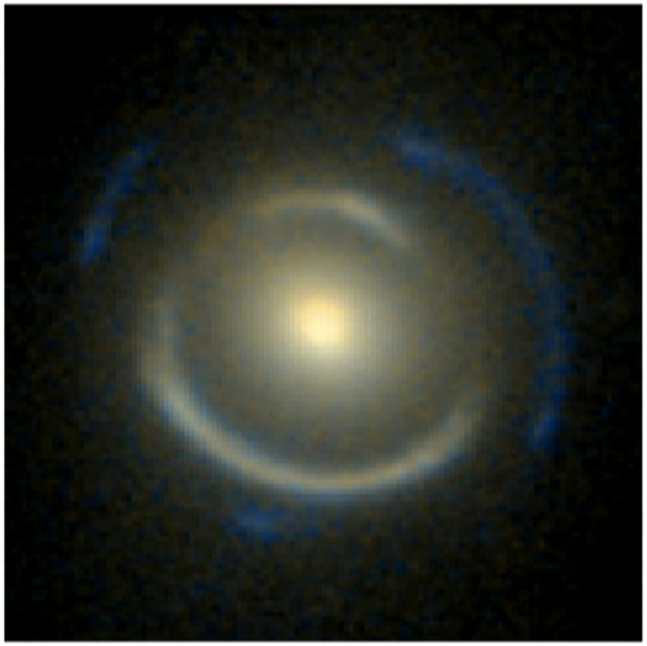
A gravitational lens system with two background sources, each at a different redshift.



RARE

The observable:

Lens Strength Ratio

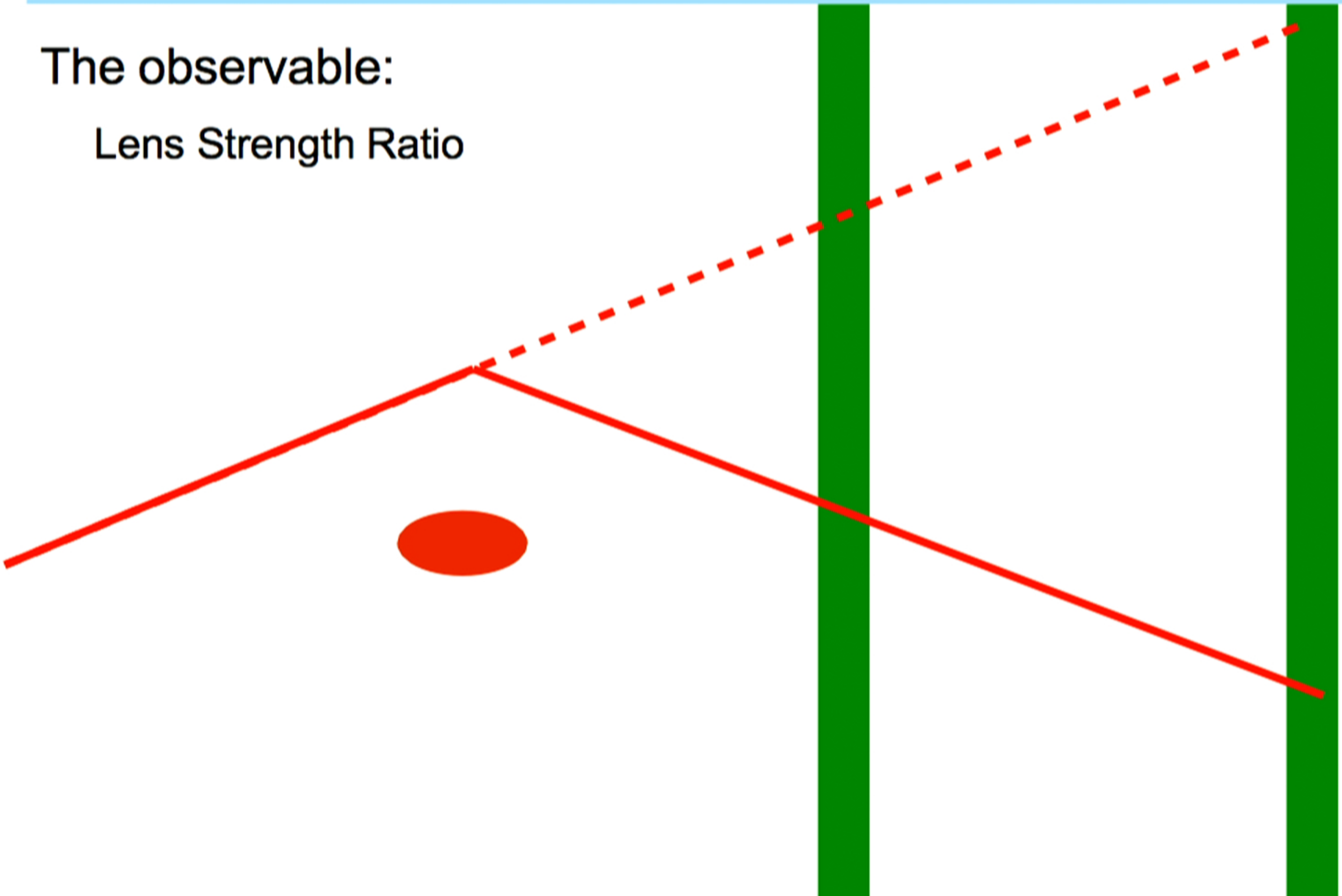


Approximately the ratio of Einstein radii

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

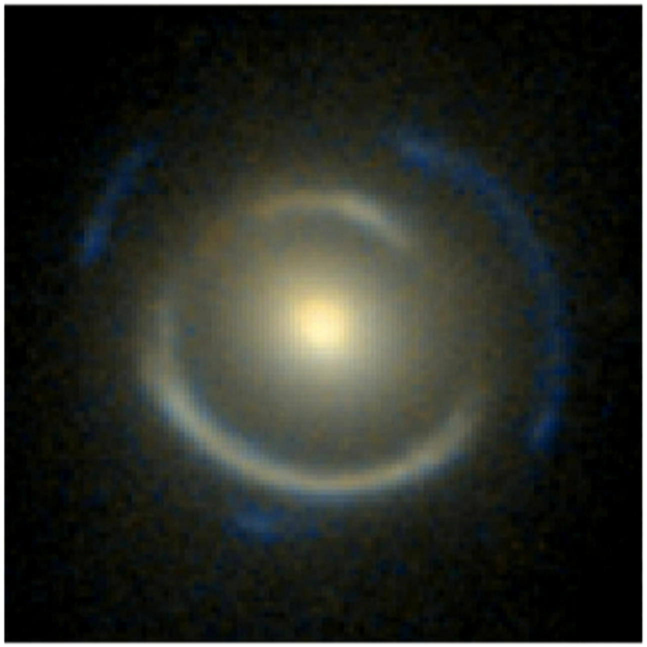
The observable:

Lens Strength Ratio



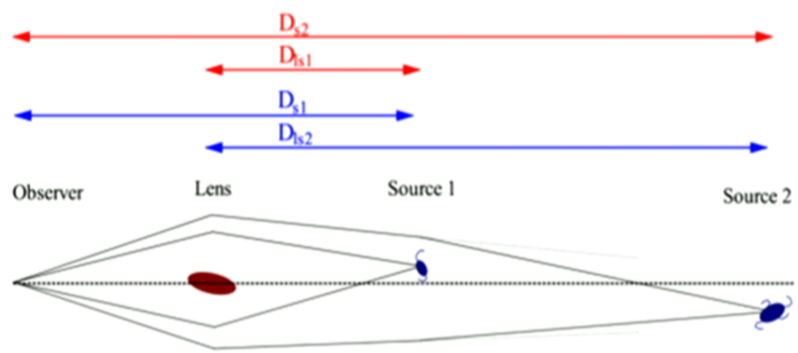
The observable:

Lens Strength Ratio



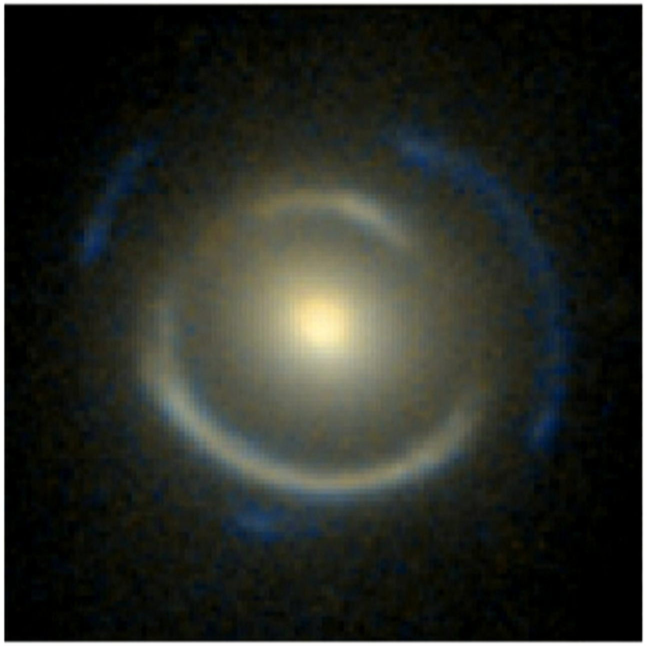
$$\beta = \frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}}$$

No dependence on the Hubble constant!



The observable:

Lens Strength Ratio



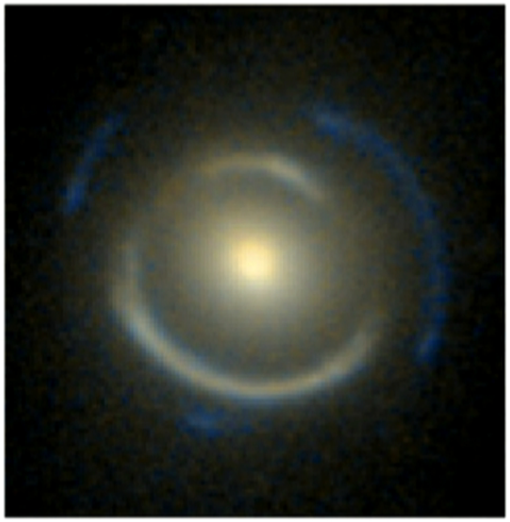
$$\beta = \frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}}$$

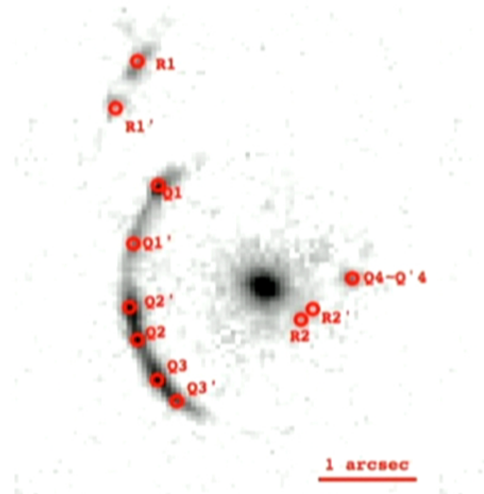
No dependence on the Hubble constant!

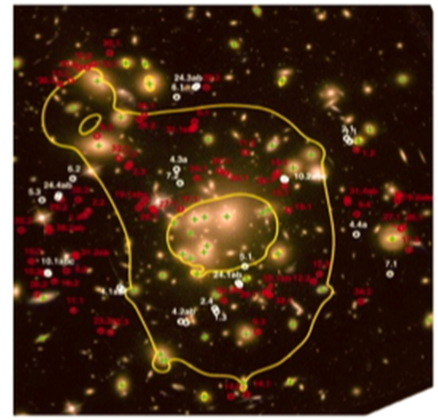
Easier than time-delay lensing

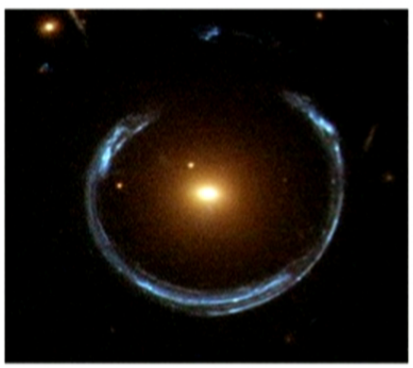
(No monitoring, line-of-sight partly cancels)

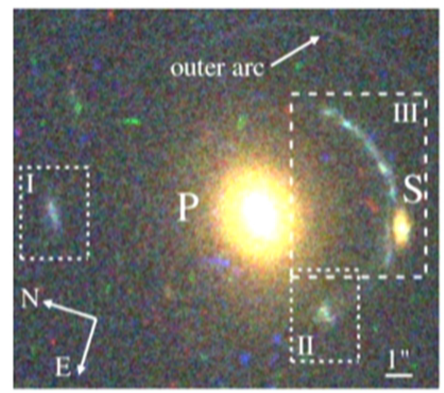
Double source plane strong lensing



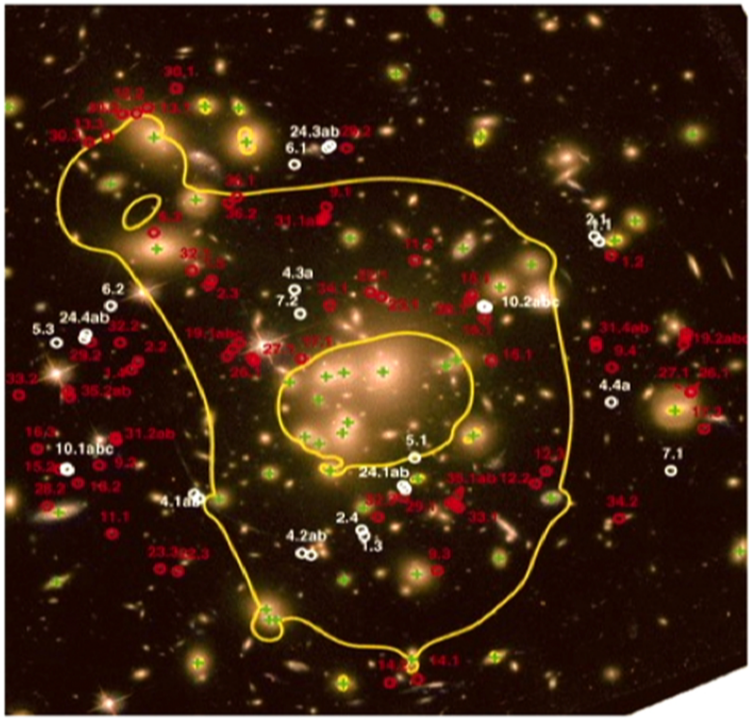








Jullo et al. (2010) Results:

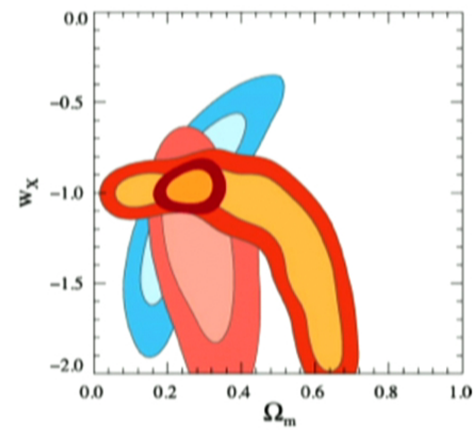


$$\Omega_M = 0.25 \pm 0.05,\ w_{DE} = -0.97 \pm 0.07$$

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

The mass is *very* complicated

- Hard to control systematics



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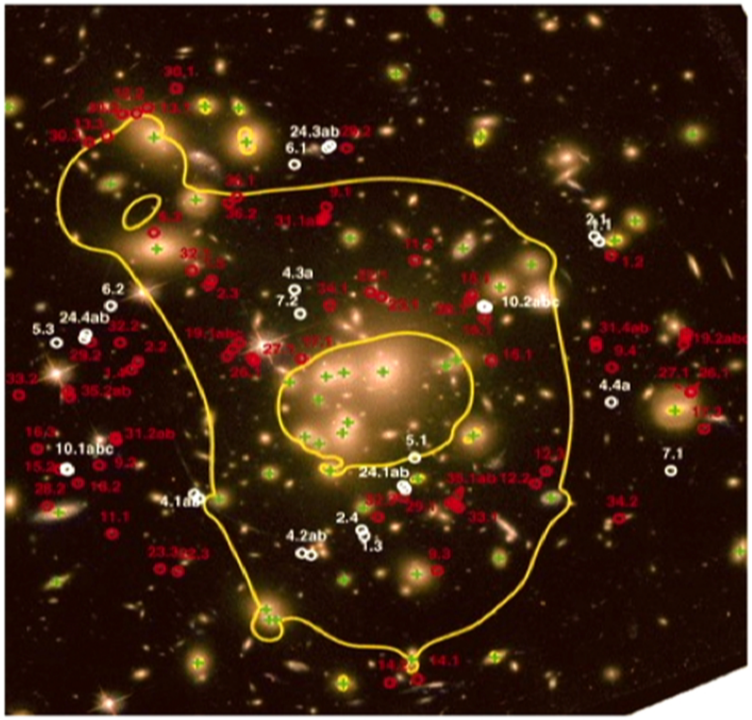
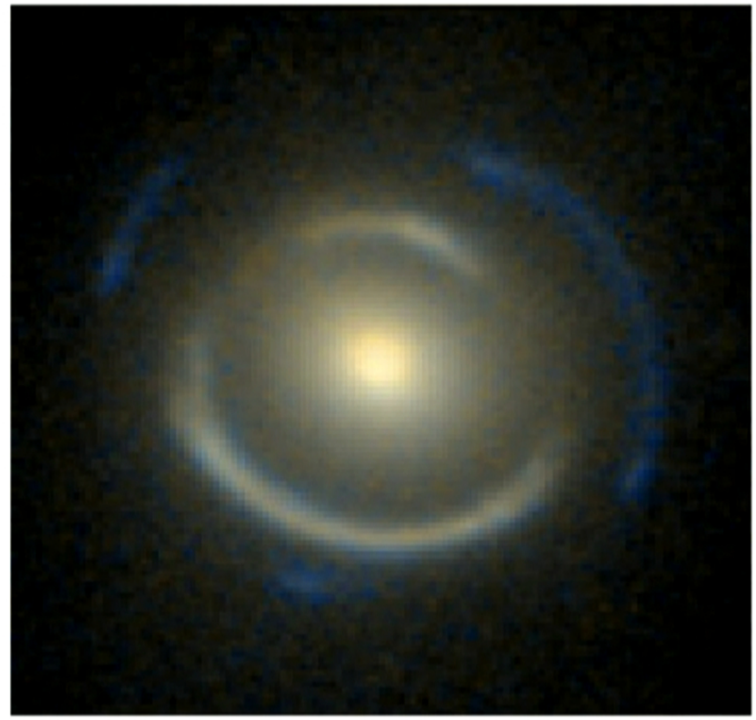
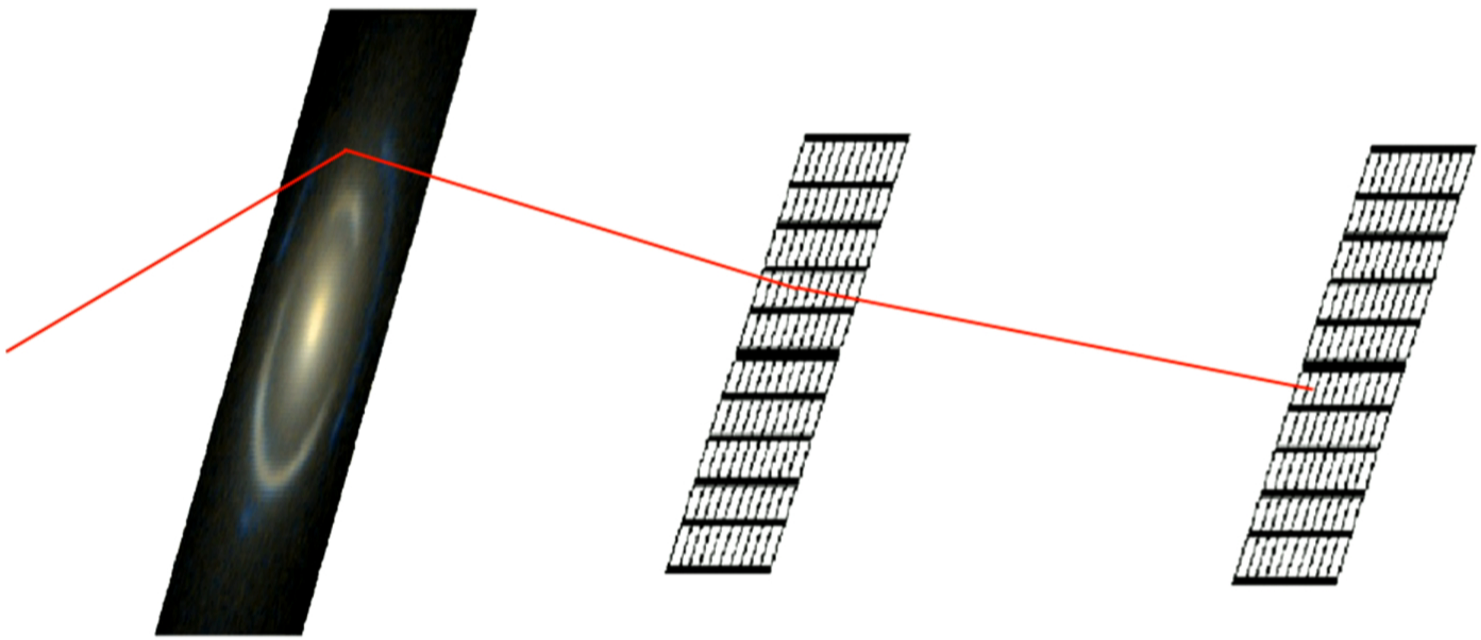
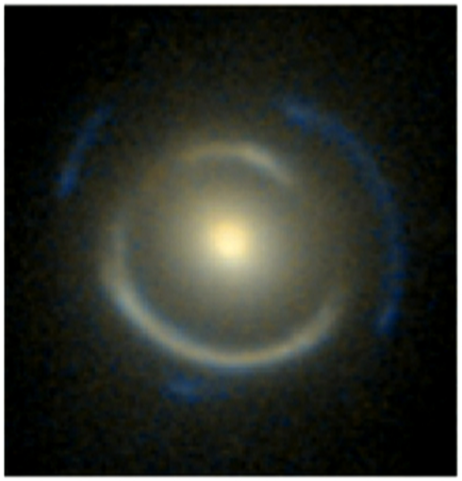




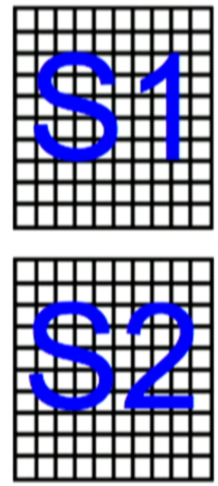
Lens modelling



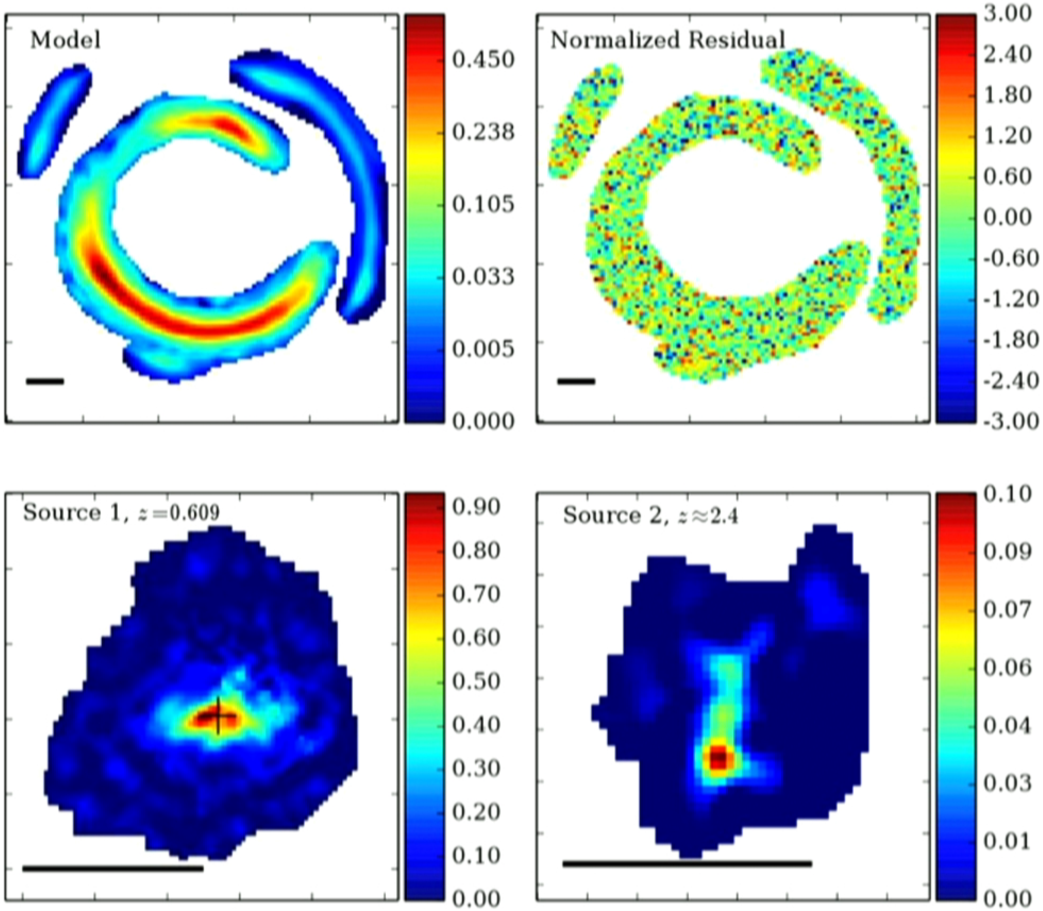
Lens modelling



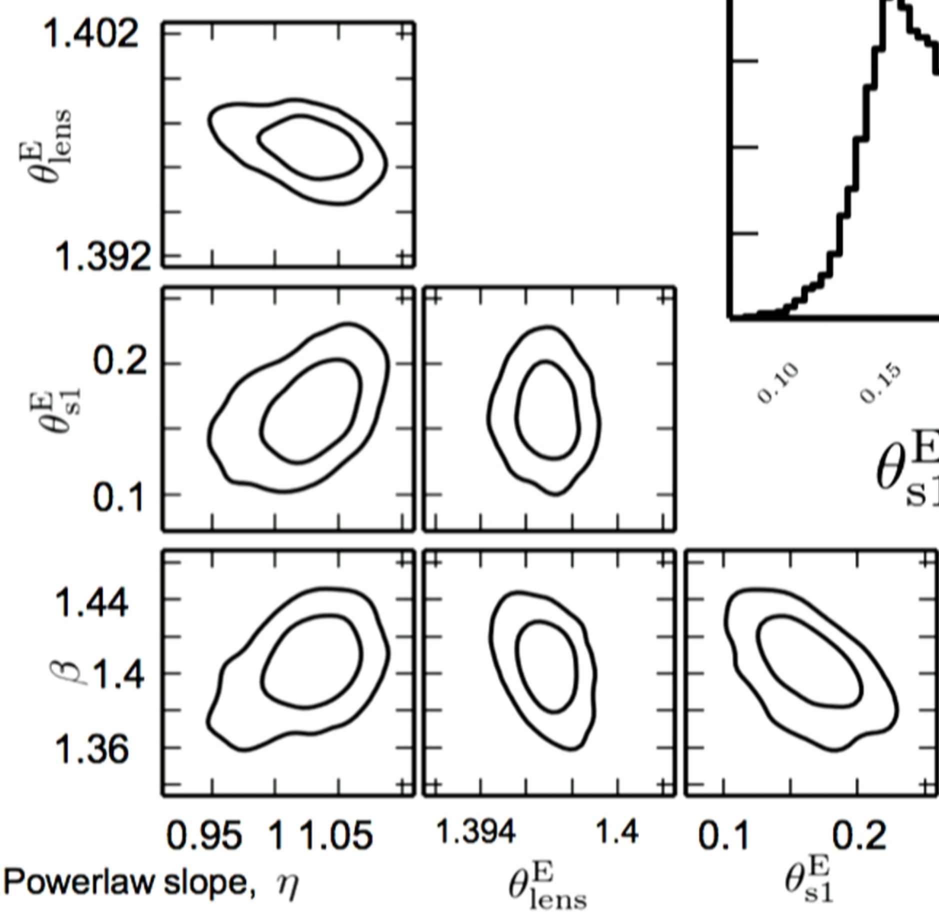
$$= \left(M \right)$$

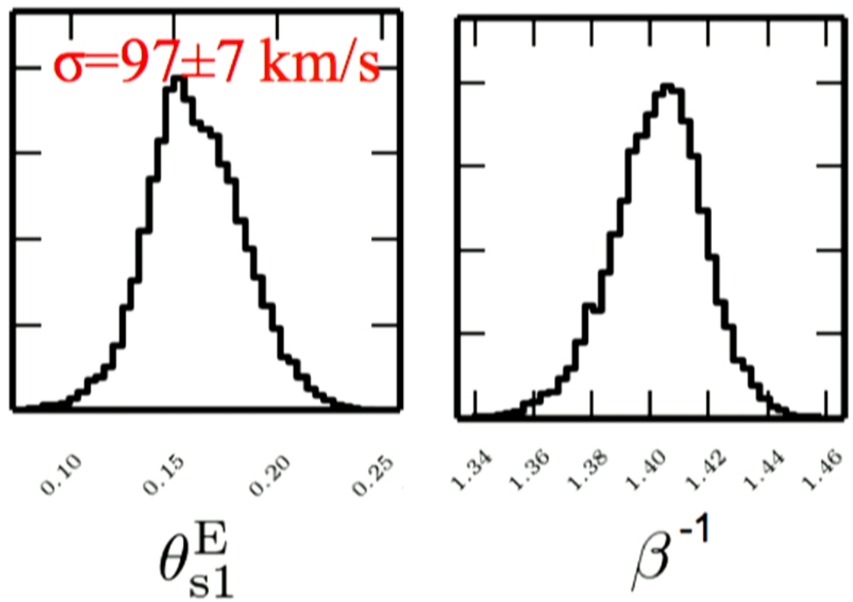


Modelling J0946



Modelling J0946

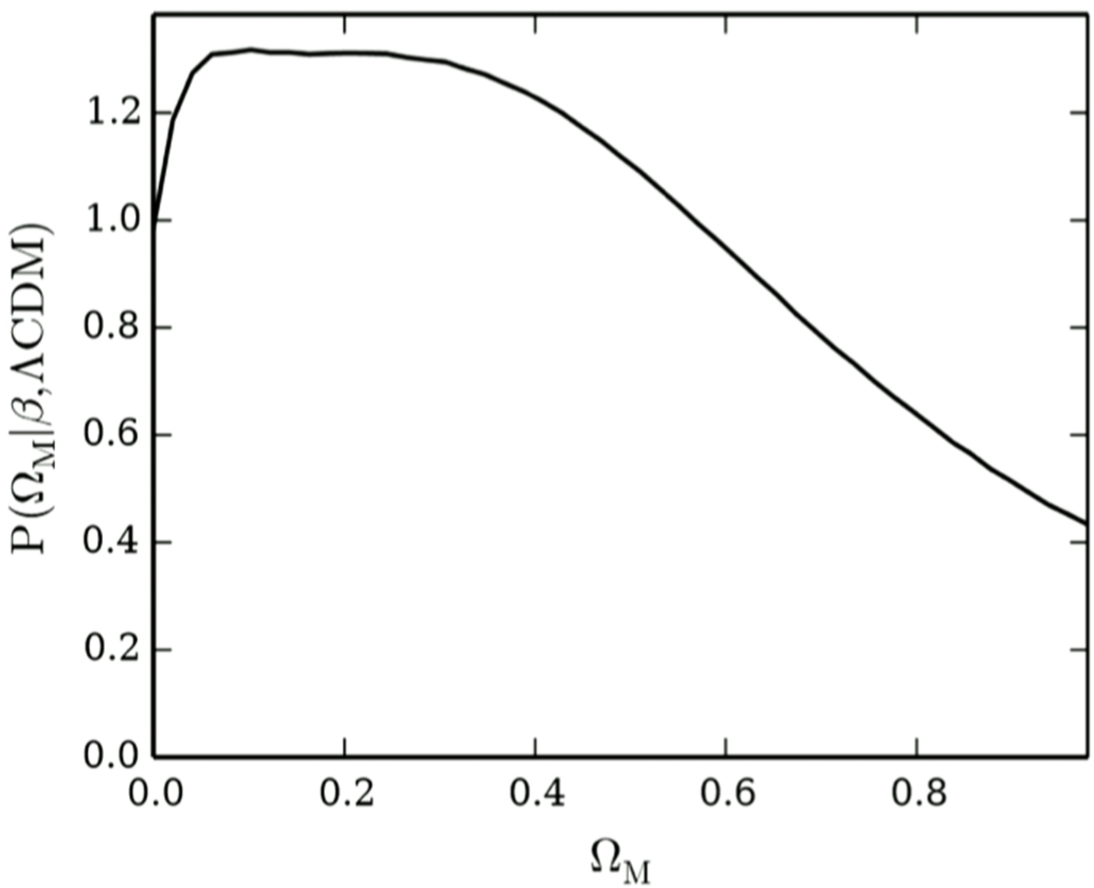




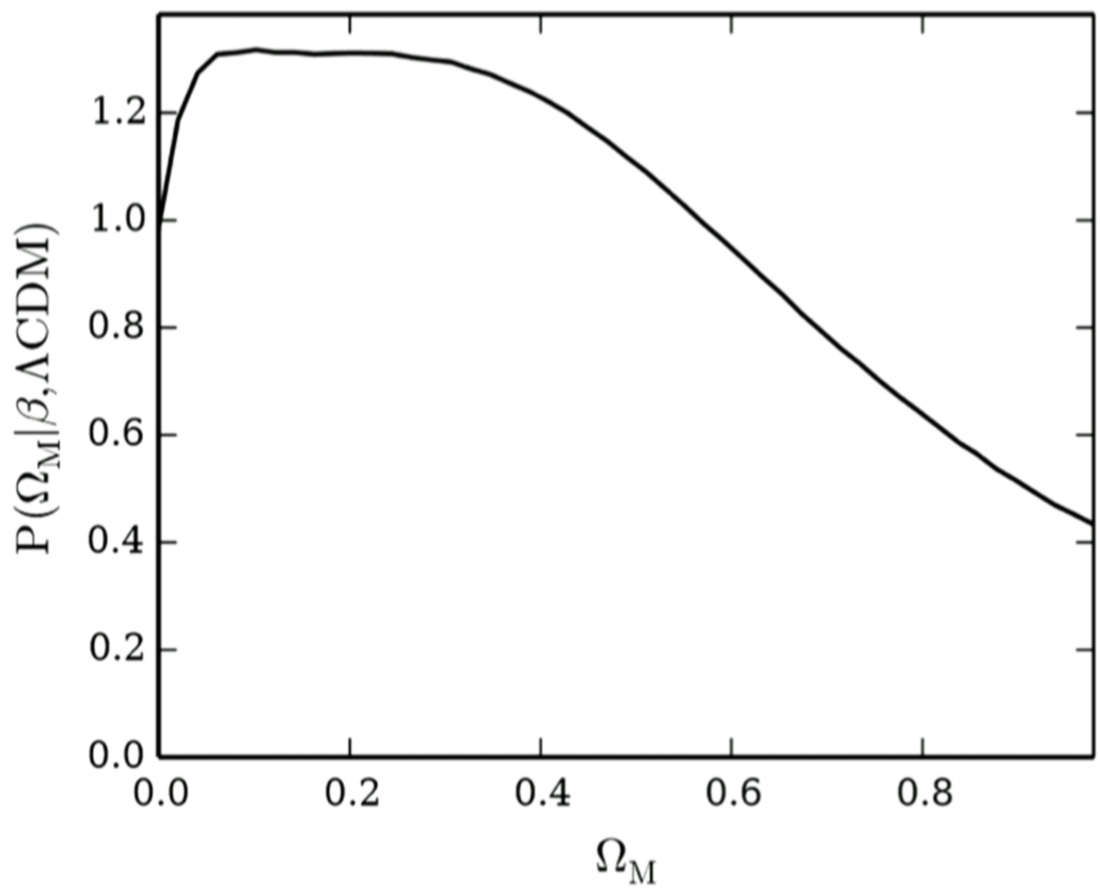
$$\beta = \frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}}$$

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

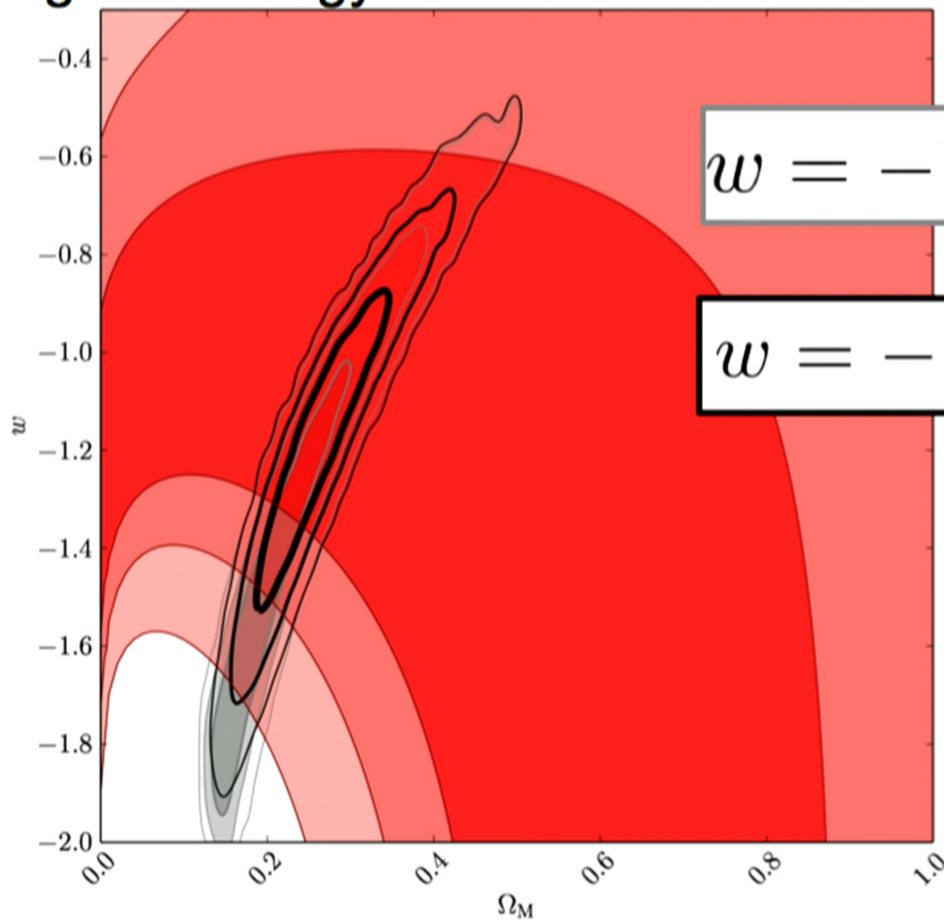
Constraining Cosmology.



Constraining Cosmology.



Constraining Cosmology.



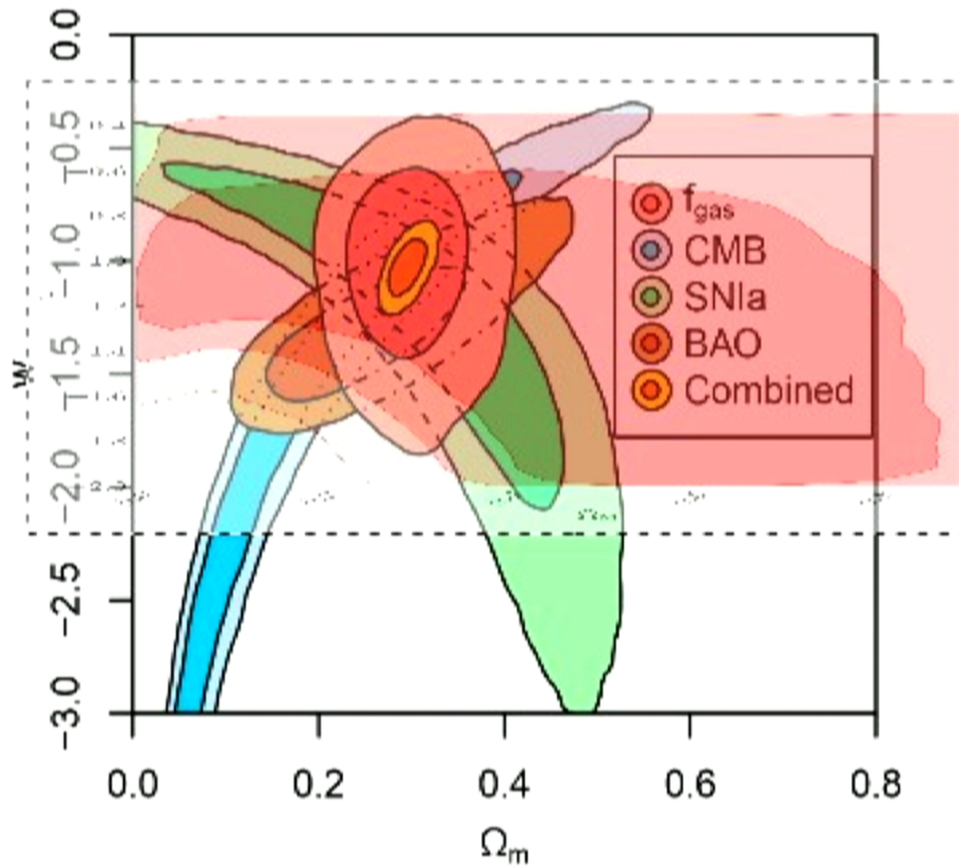
$$w = -1.486^{+0.364}_{-0.273}$$

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

Constraining Cosmology.

J0946 + WMAP prior

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



C. Heymans et al.

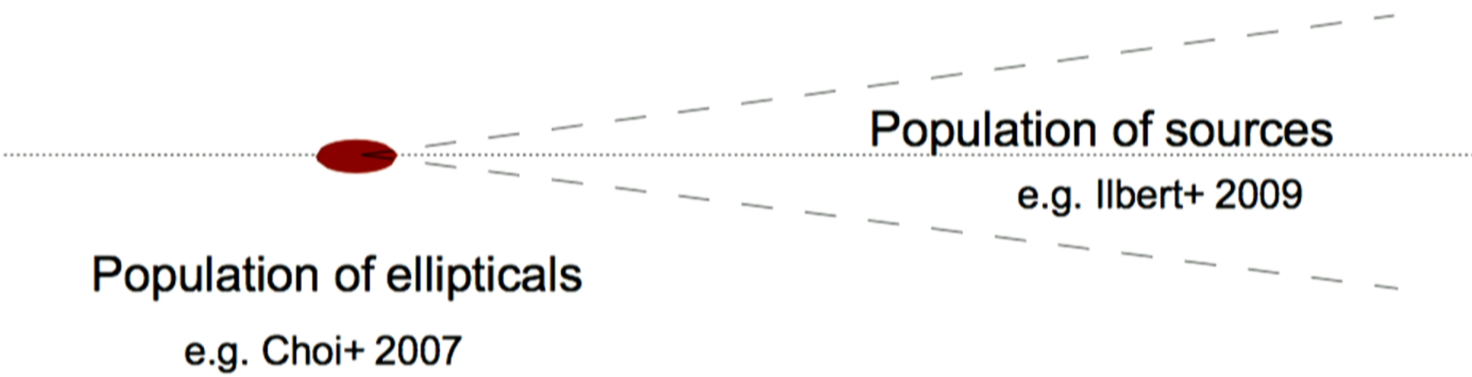
$-1.05^{+0.33}_{-0.34}$ CFHTLenS + WMAP7

(2013, 68% CLs)

Forecasting the rate of strong lensing

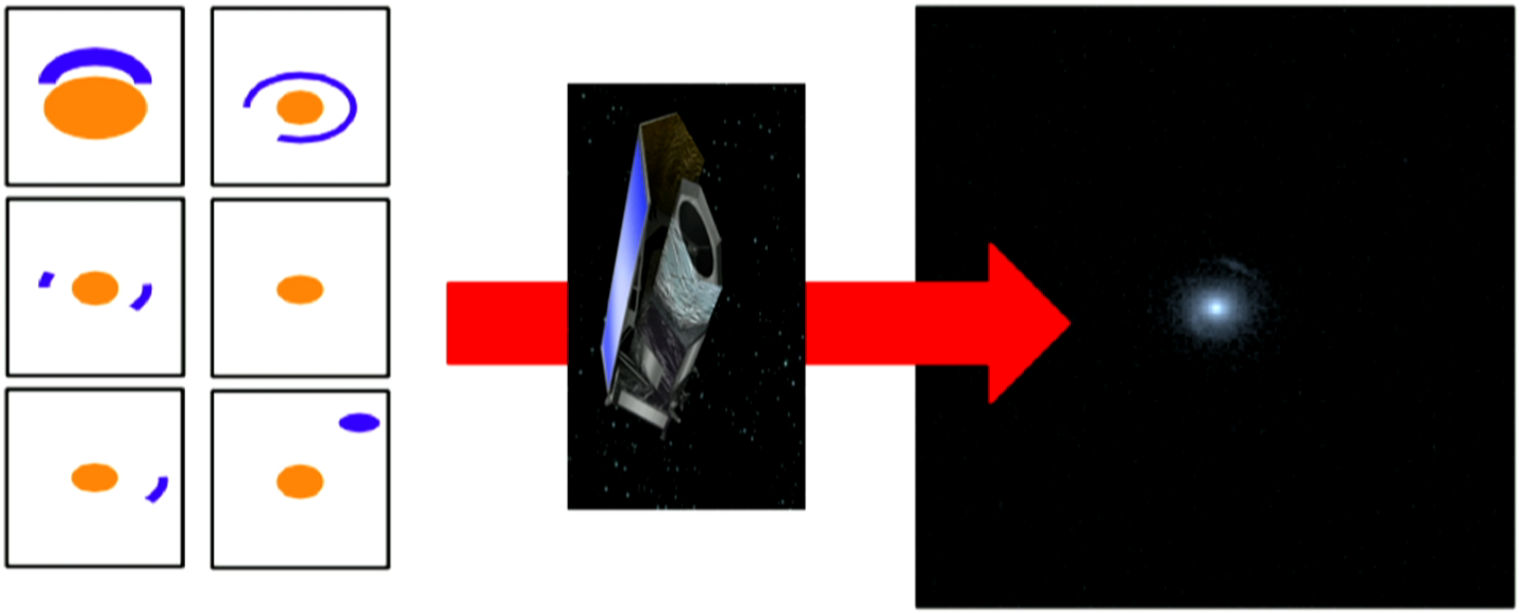
Lenses are close to Isothermal

- Constant *physical* deflection angle

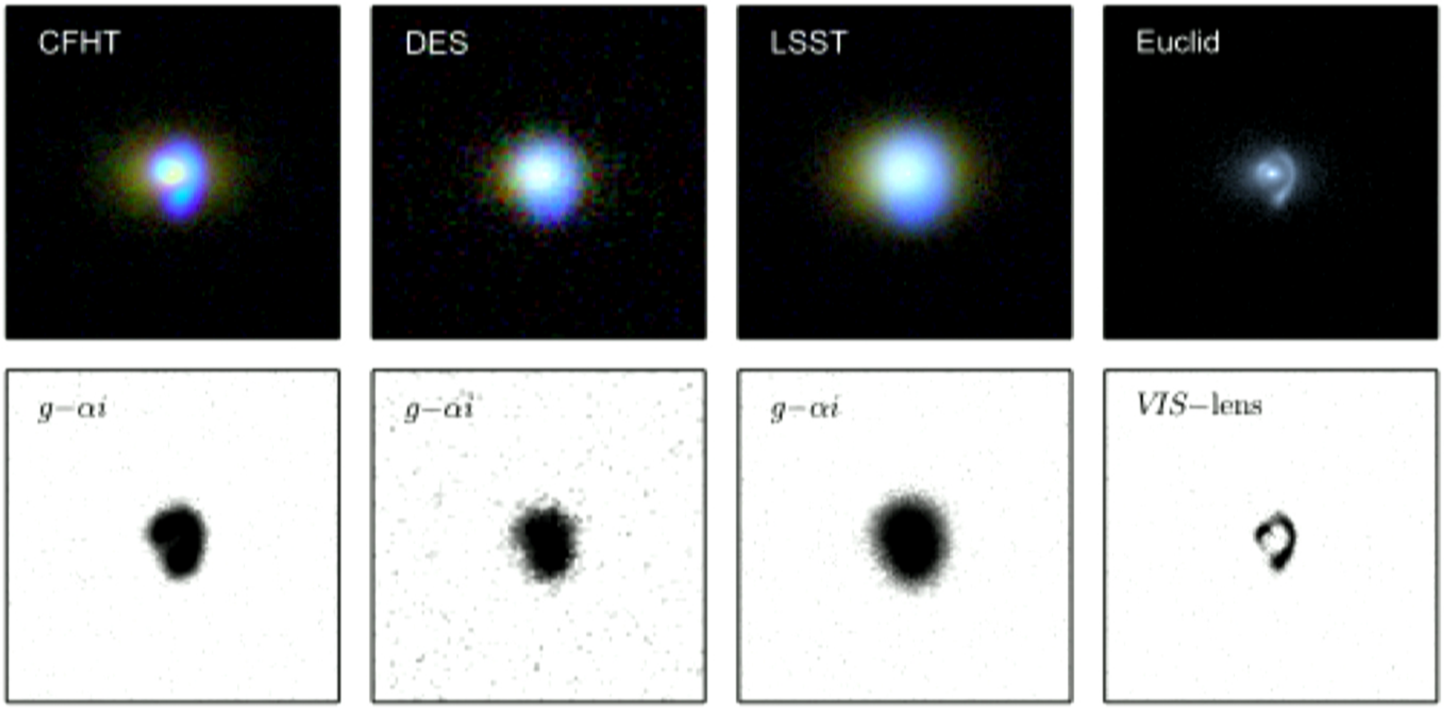


Detectability is harder to forecast

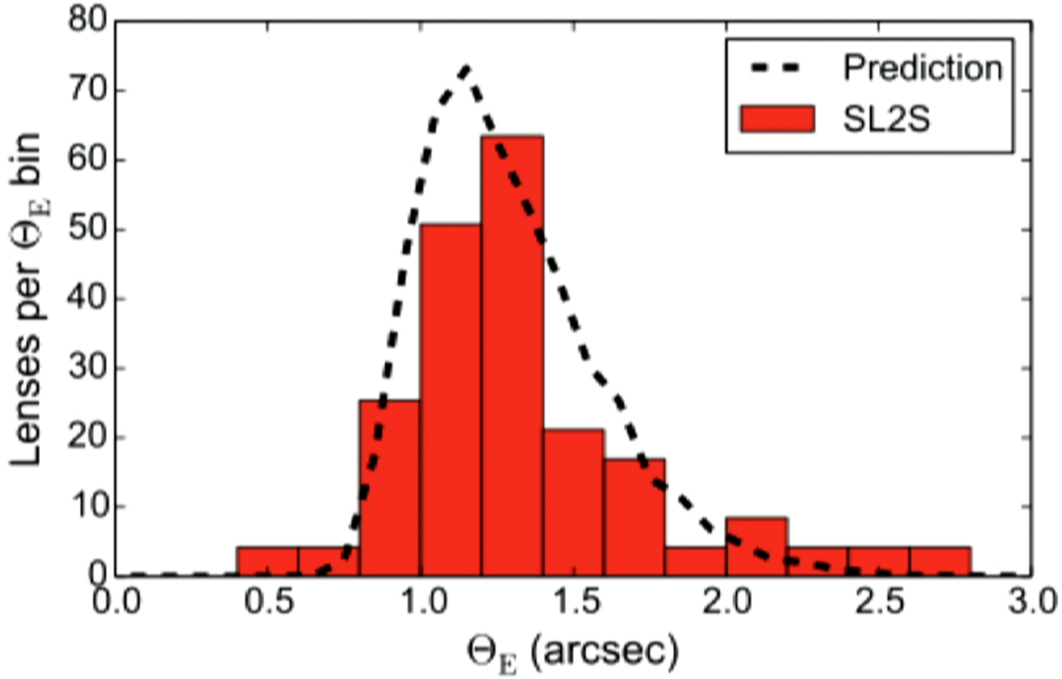
Lens Population Forecasting

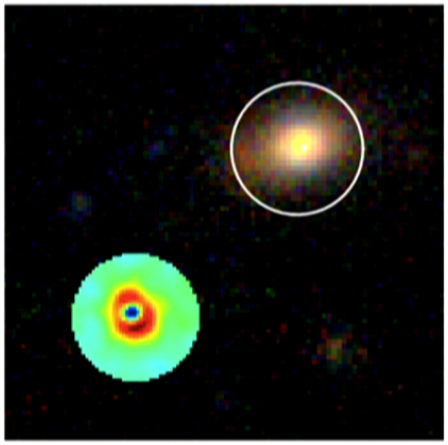


Lens Population Forecasting

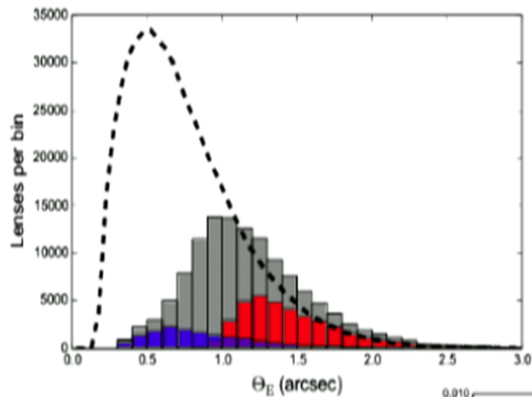


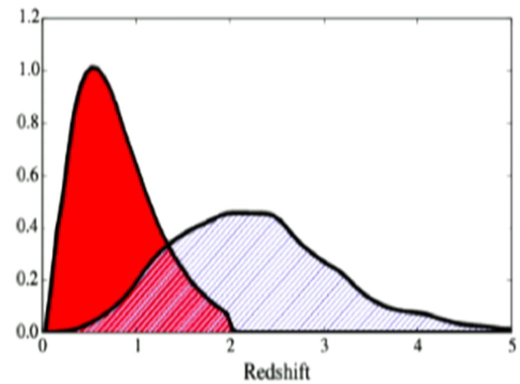
Lens Population Forecasting

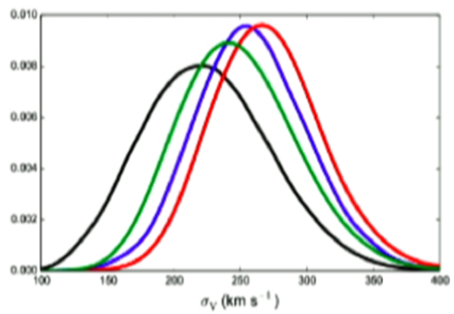




Lens Population Forecasting



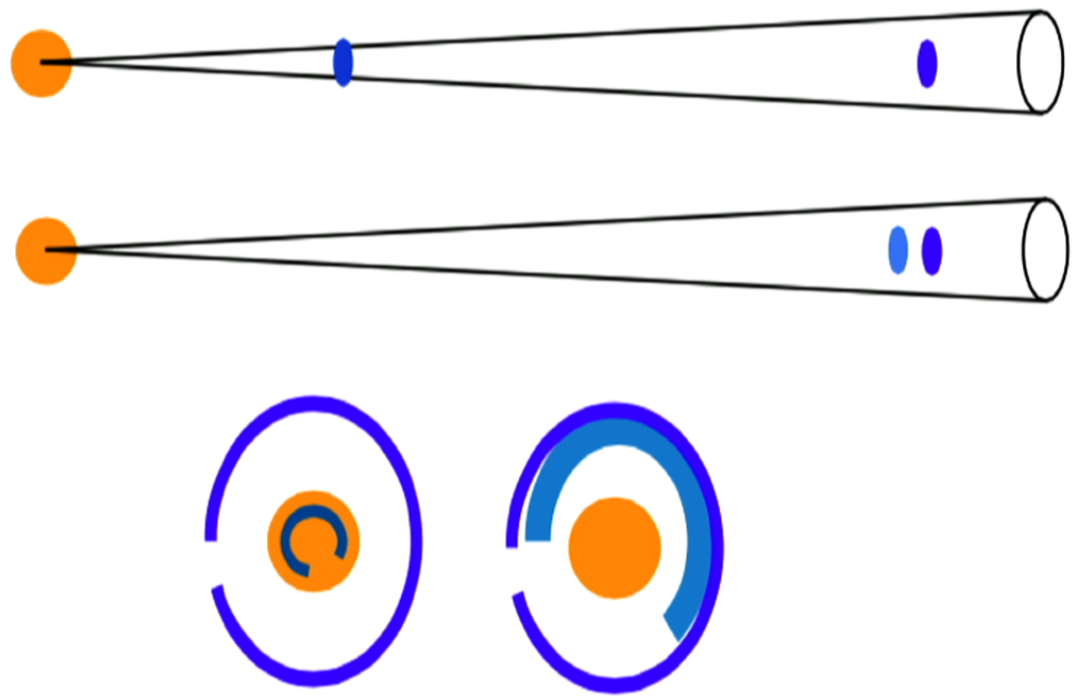




Optimistic:
DES: 2400
LSST: 120000
Euclid: 170000

Current*:
DES: 800
LSST: 62000
Euclid: 0*

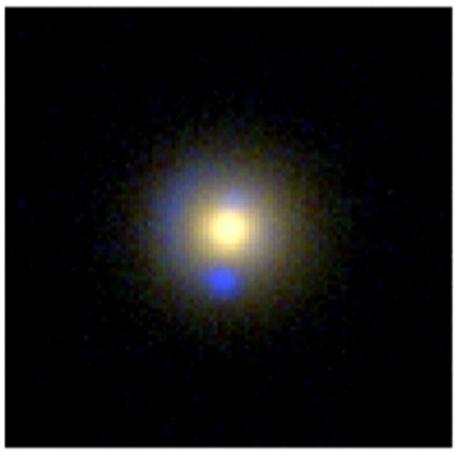
Predictions for double plane lenses

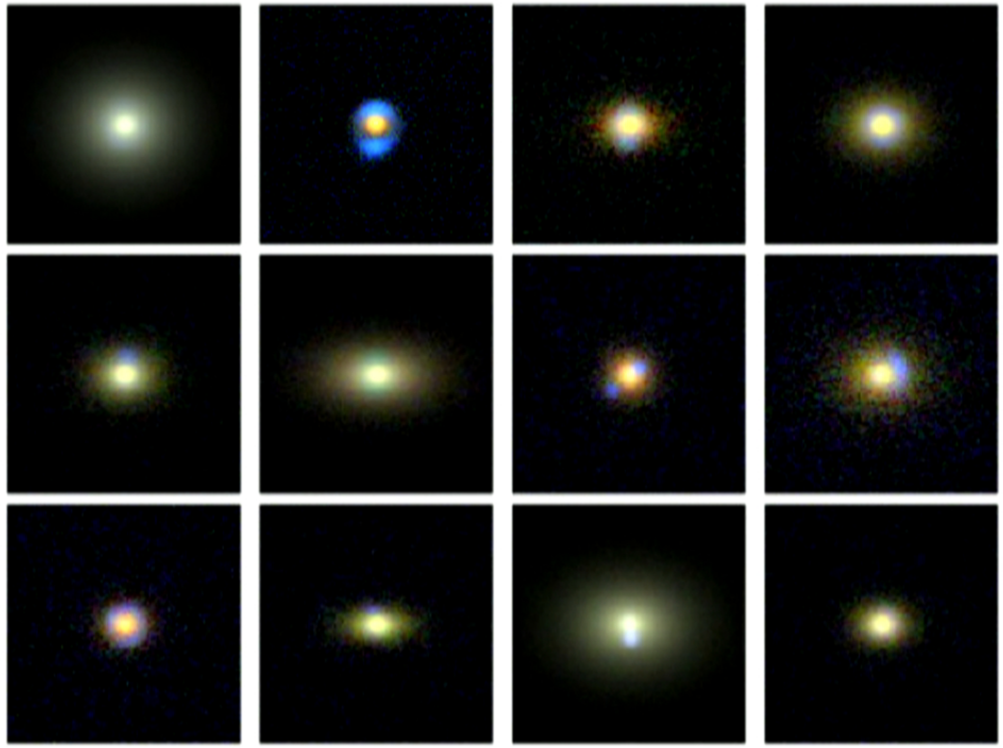


Forecasting the rate of DSPLs

DES+HSC

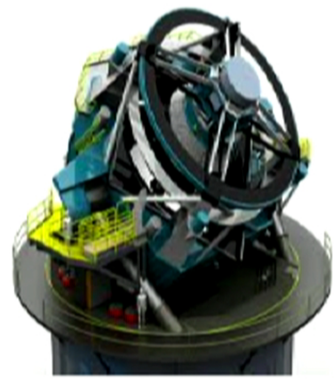
~10





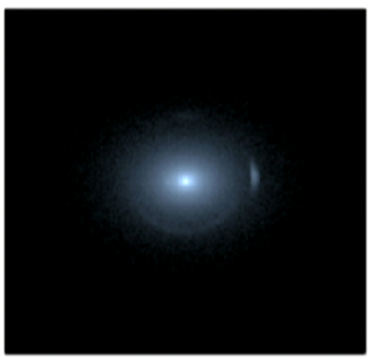
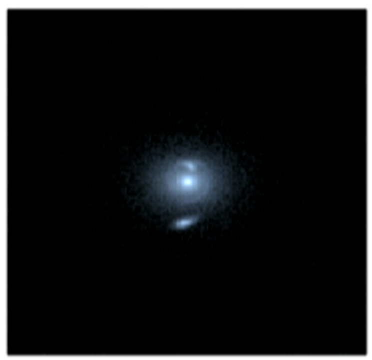
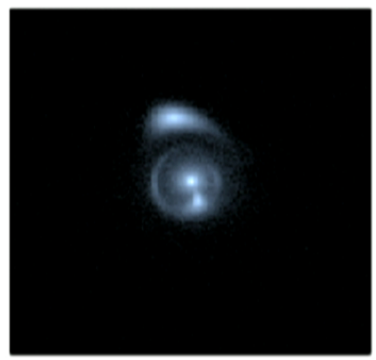
Lens Population Forecasting



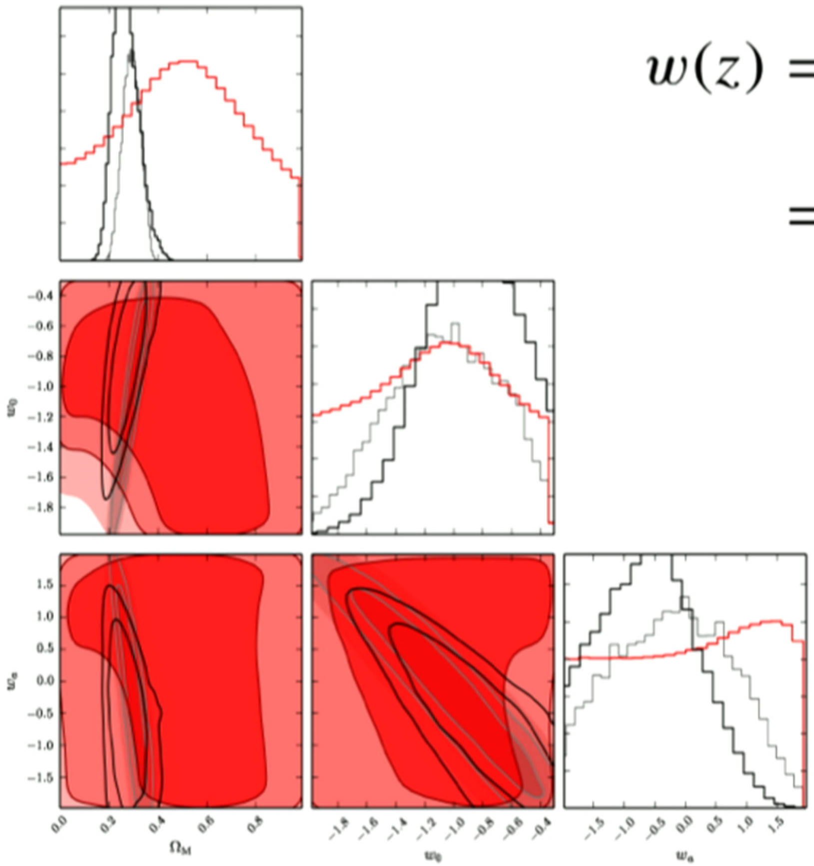


120

best single exposure

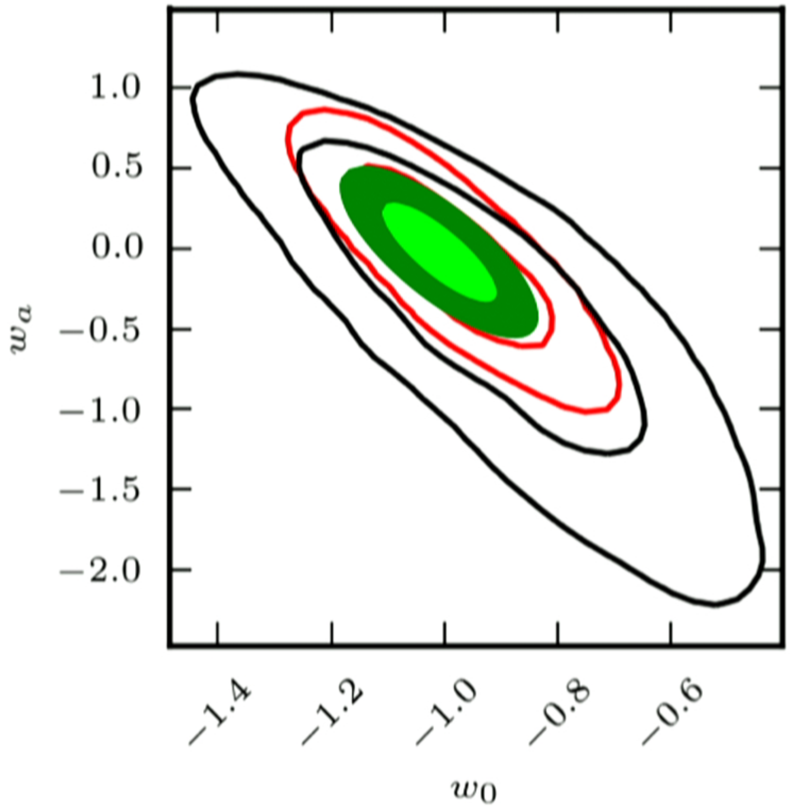





Evolving Dark Energy

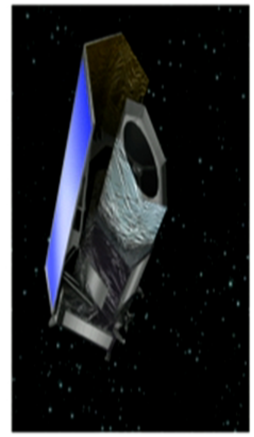


$$w(z) = w_0 + w_a(1 - a)$$
$$= w_0 + w_a\left(\frac{z}{1+z}\right)$$

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)

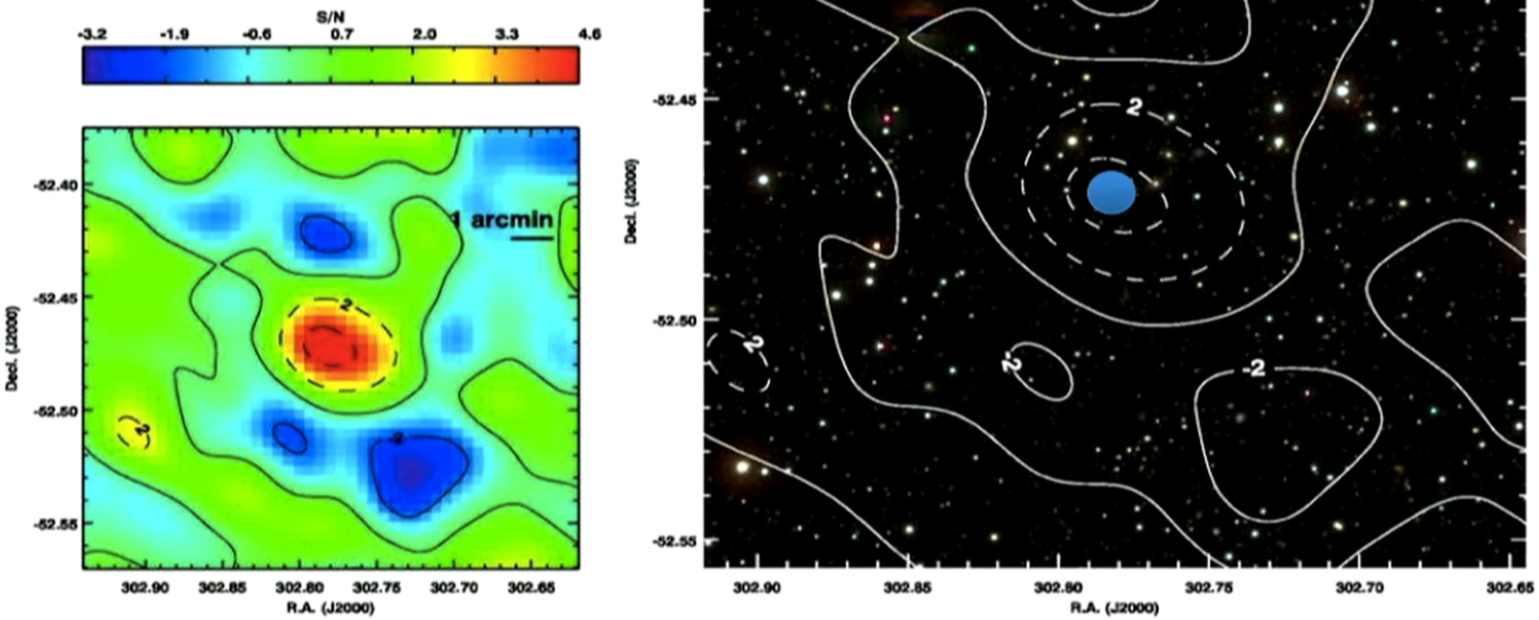
The Central Dark Matter Profile of a z~1 lensing cluster

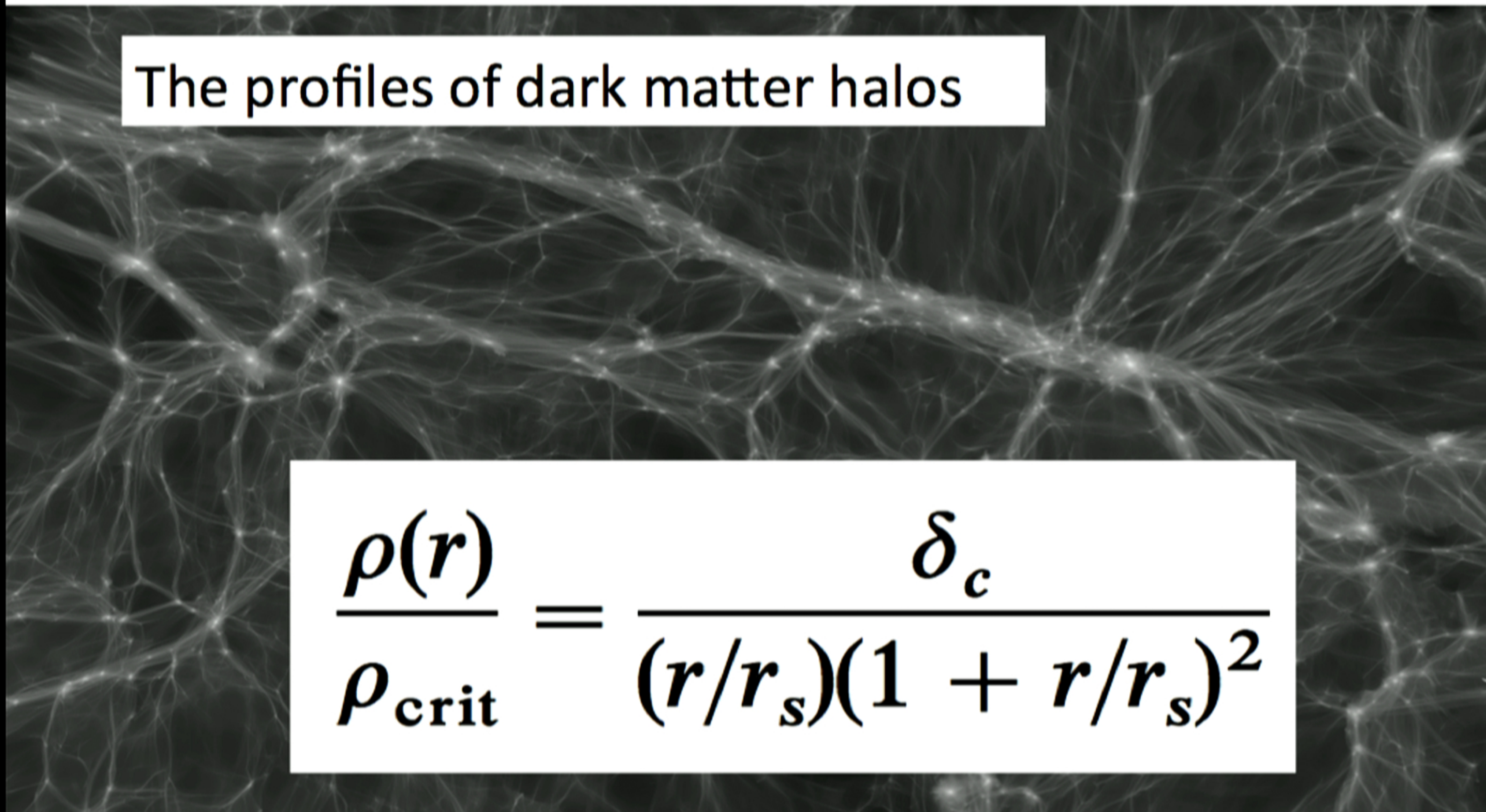
YOU DIDN'T HEAR ANY OF THIS!

SPT SZ Mass: $M_{500} = 2.2 \pm 0.9 \times 10^{14}\ M_{\odot}$

Lensing Mass: $M_E = 10^{13.95 \pm 0.05}\ M_{\odot}$

Bleem et al 2015

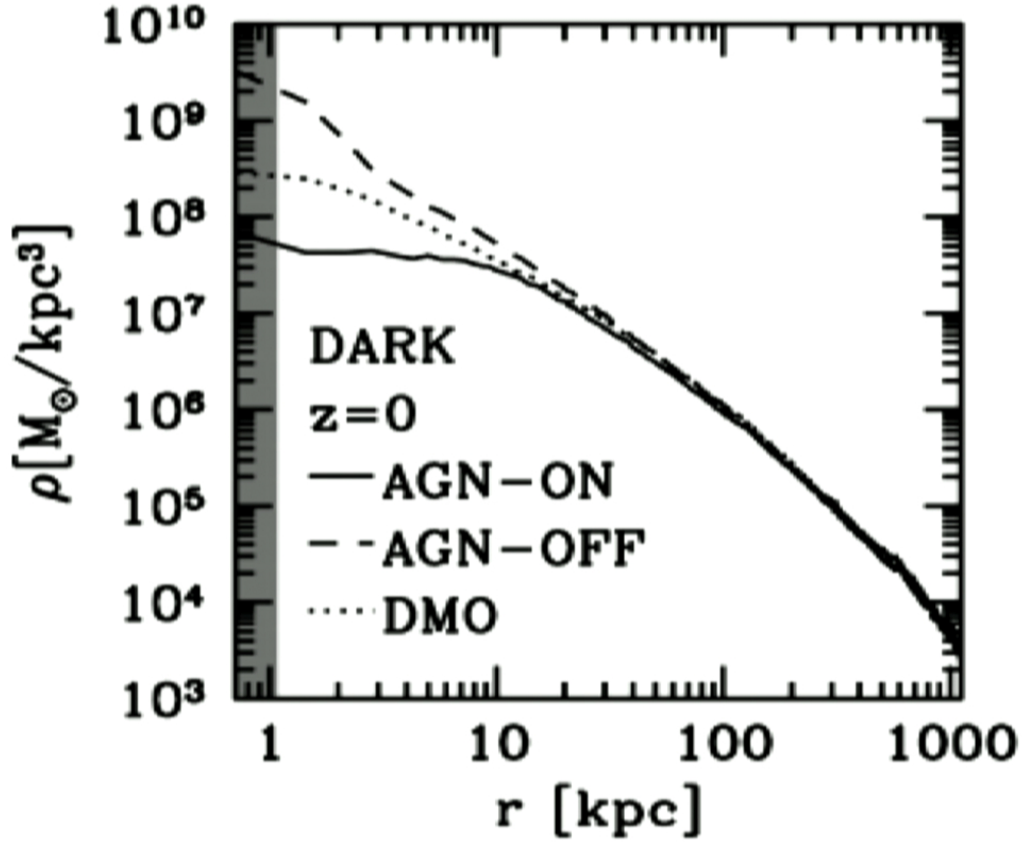




The profiles of dark matter halos

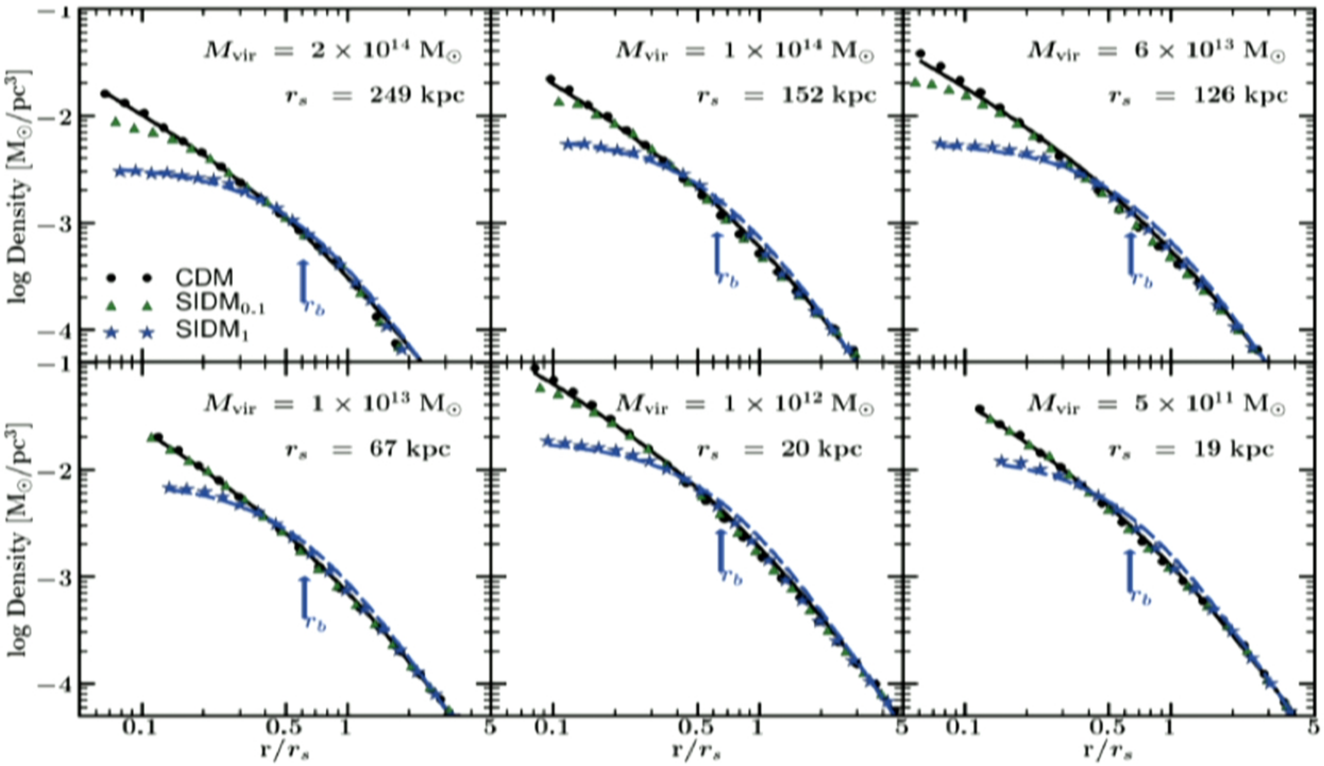
$$\frac{\rho(r)}{\rho_{\mathrm{crit}}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

Baryons complicate the picture



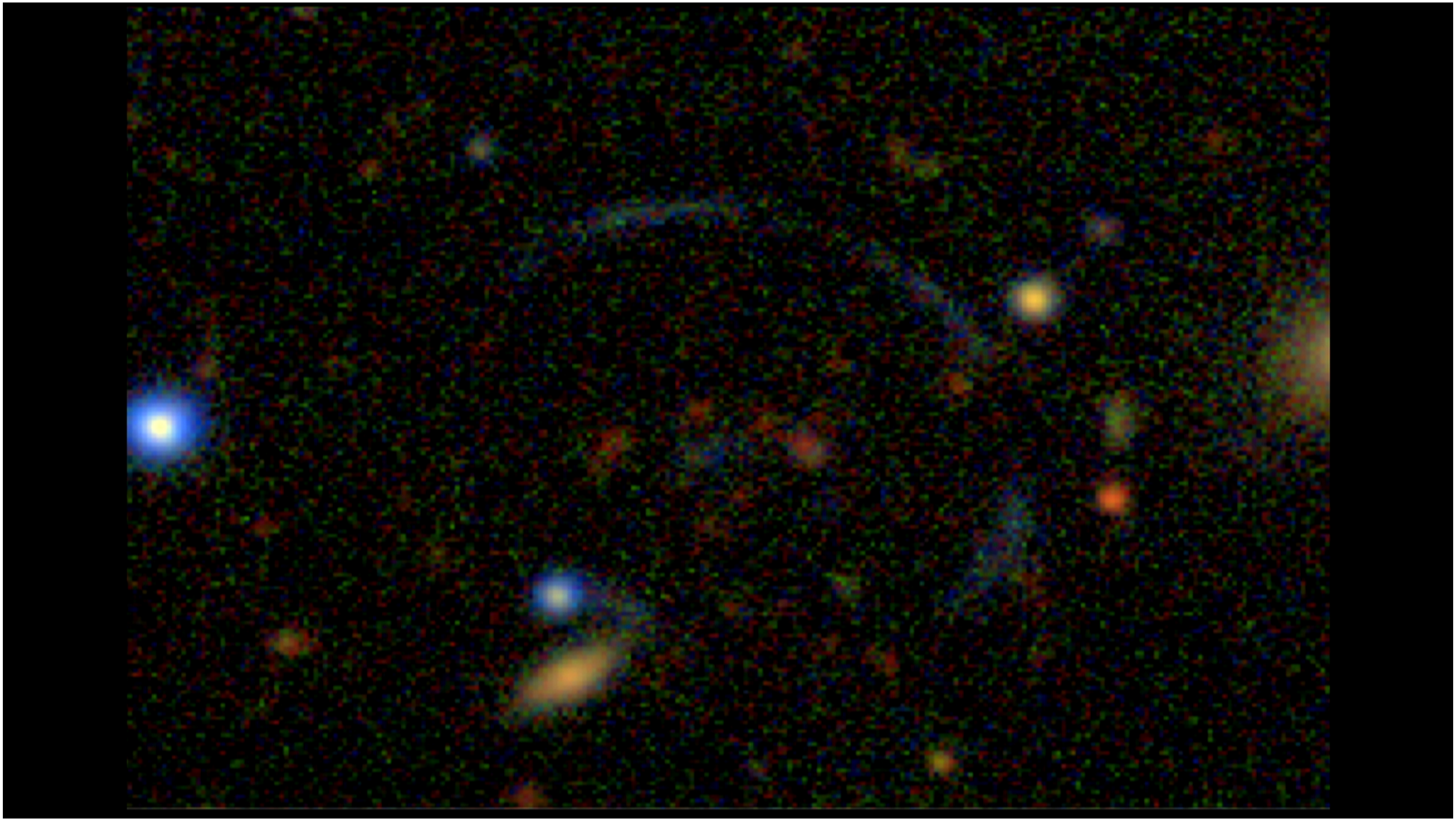
Martizzi et al 2012

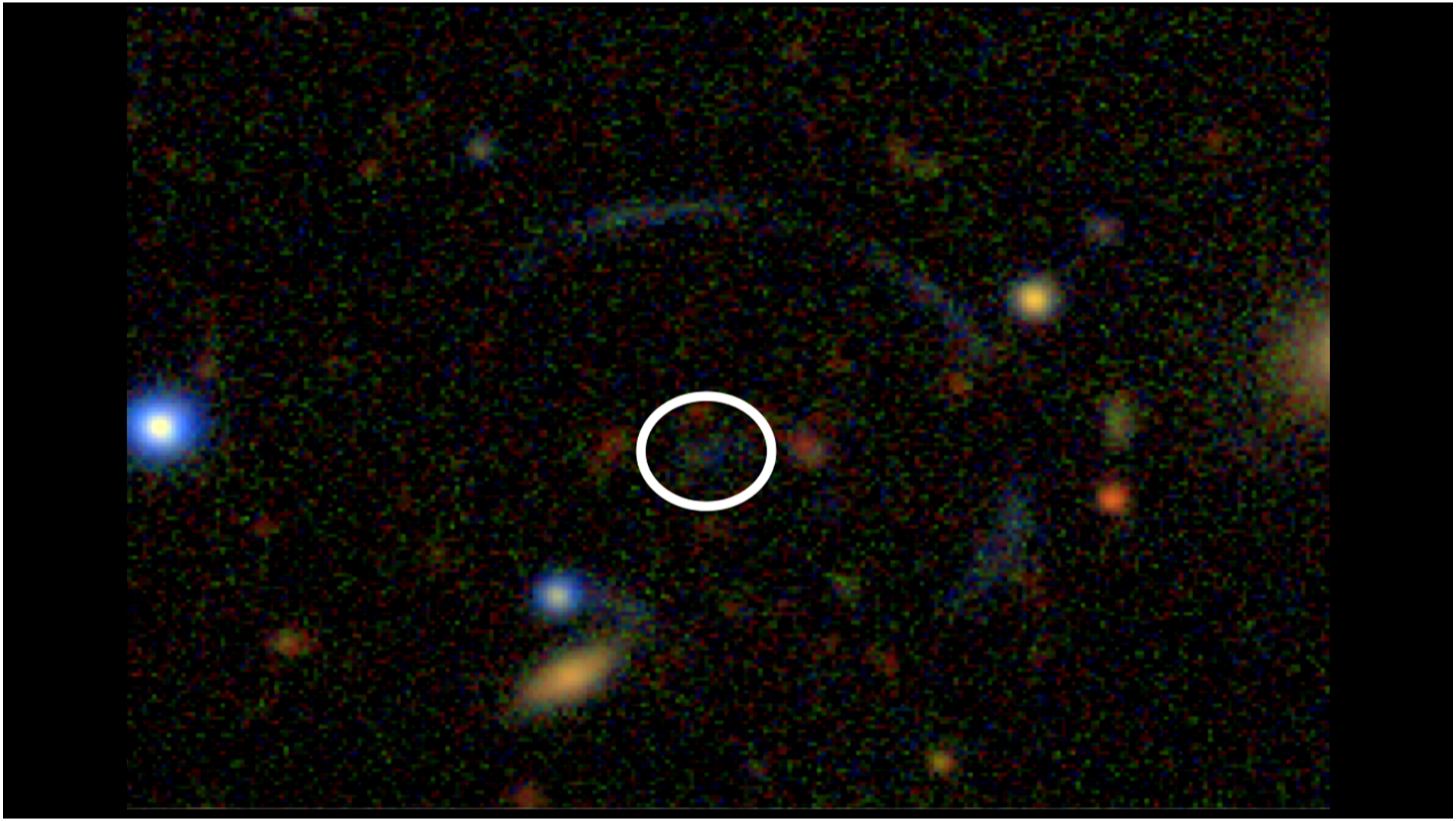
Self interacting Dark Matter



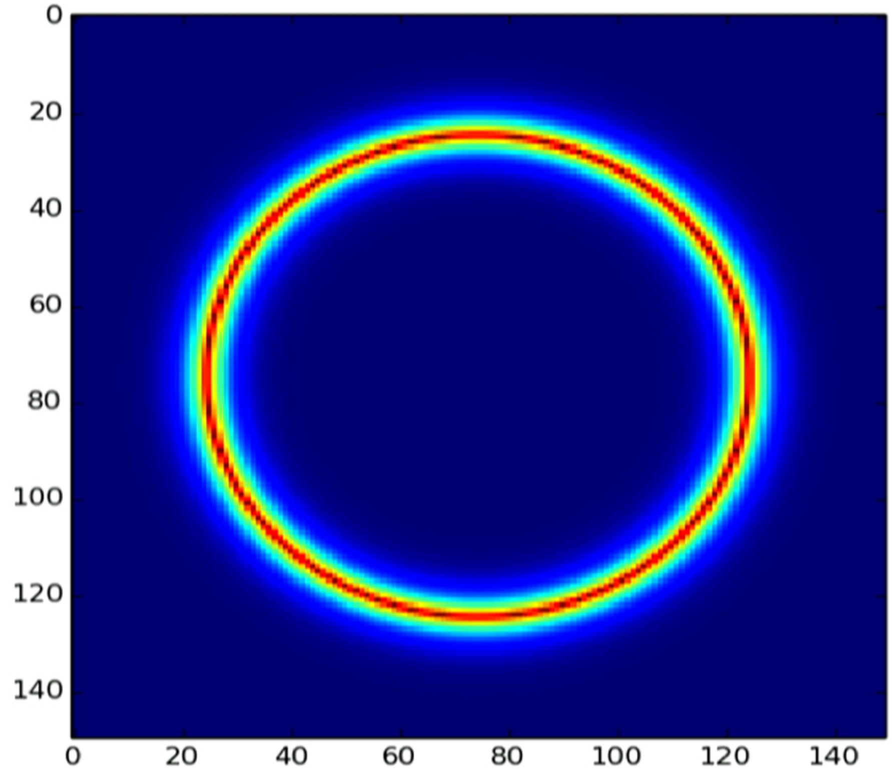
With self-interactions turned on, halo central densities decrease, forming cored density profiles.

Rocha et al 2012





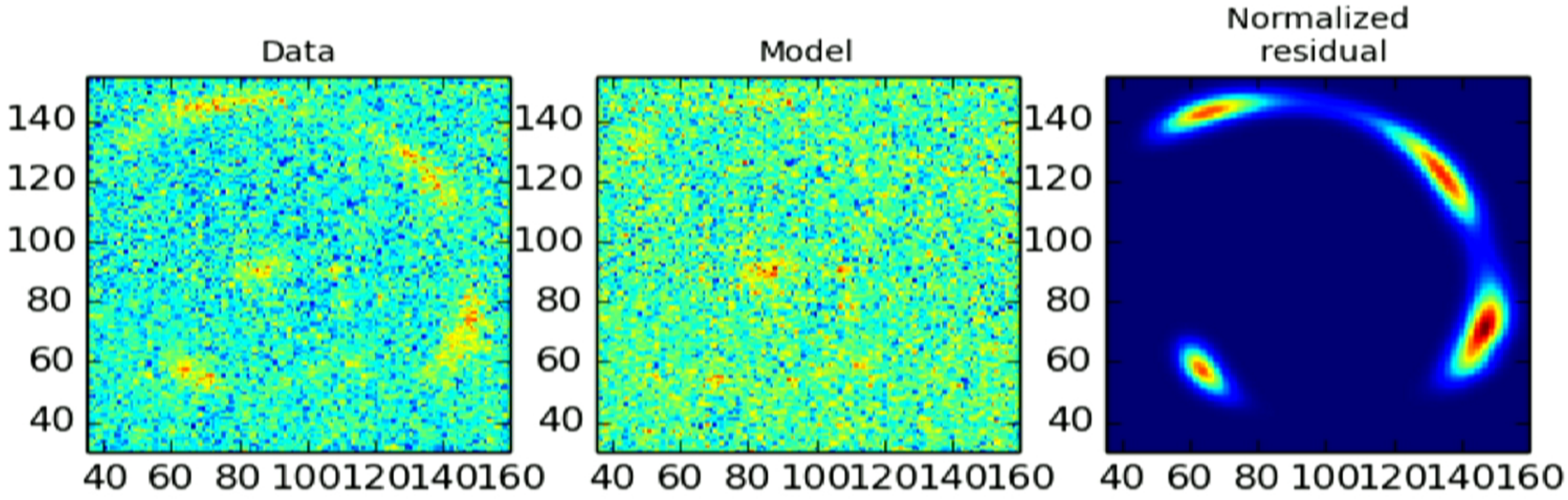
Isothermal lens: $\rho \sim r^{-2}$



Powerlaw Profile

$\rho \sim r^{-n}$

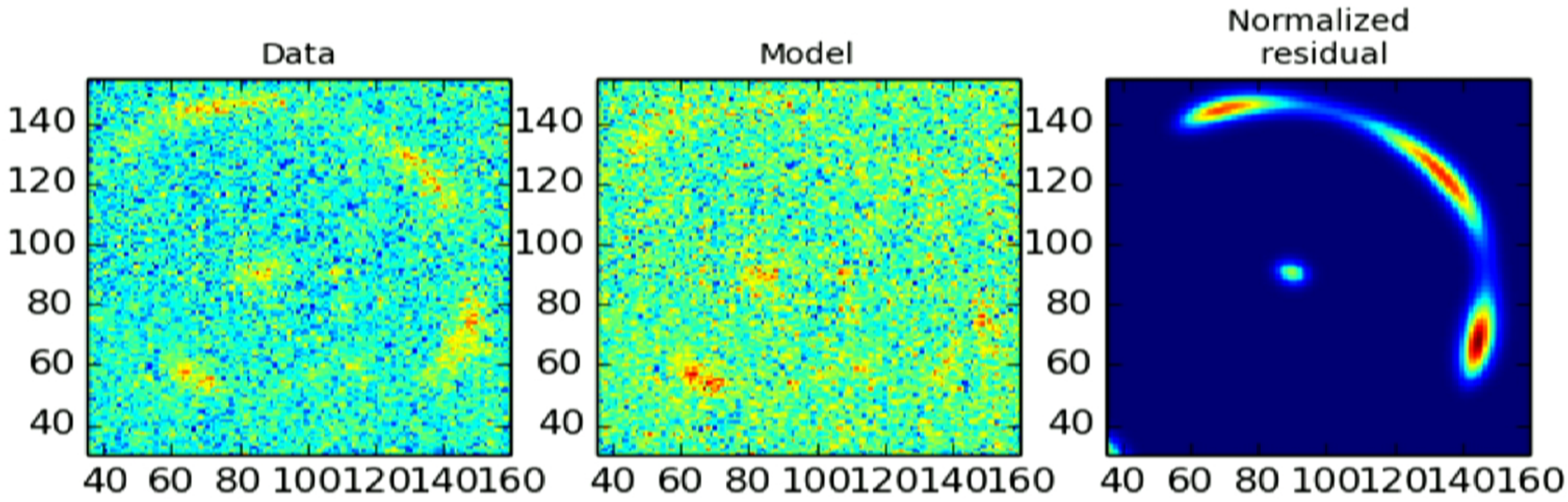
Plus flattening, and galaxies as isothermal clumps

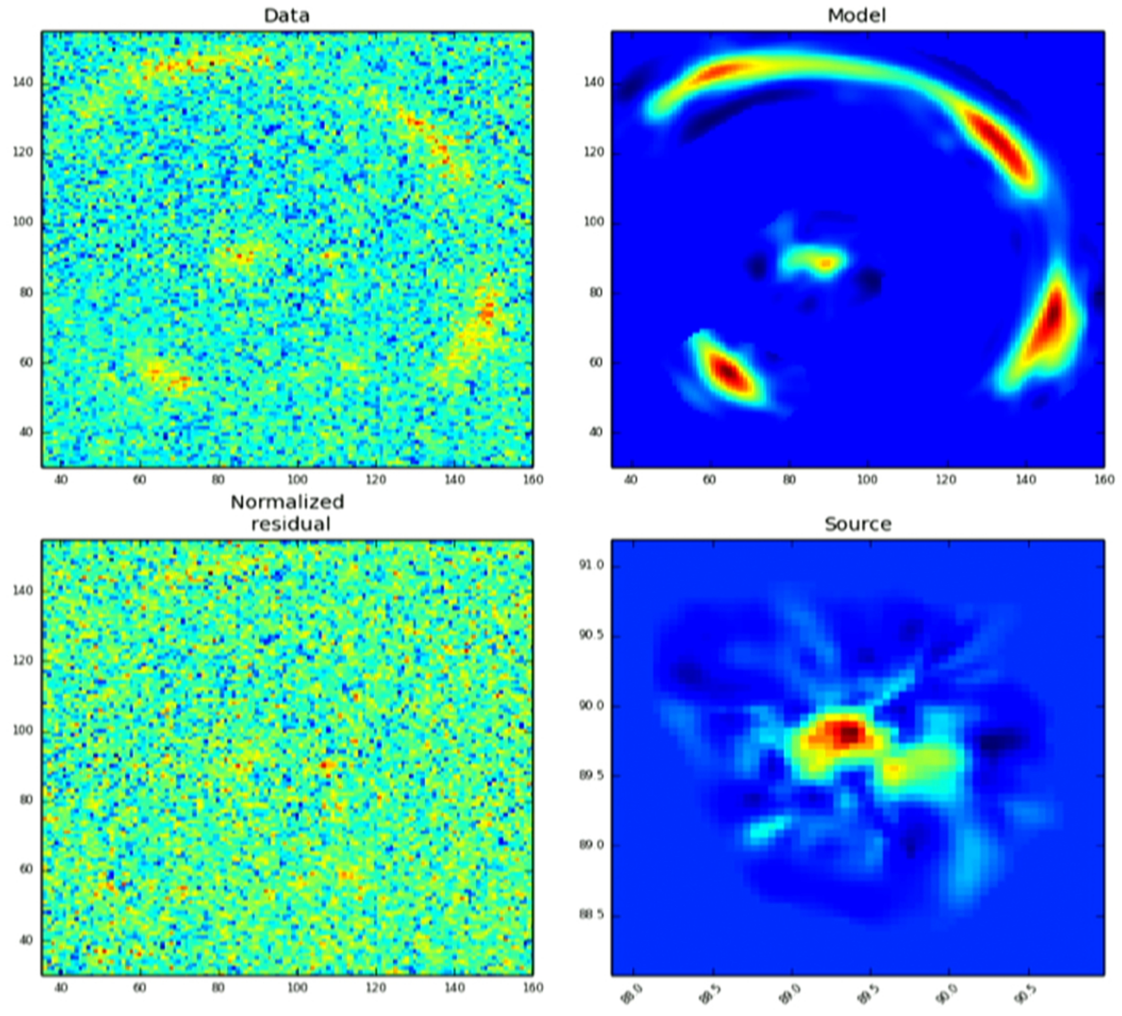


gNFW Profile

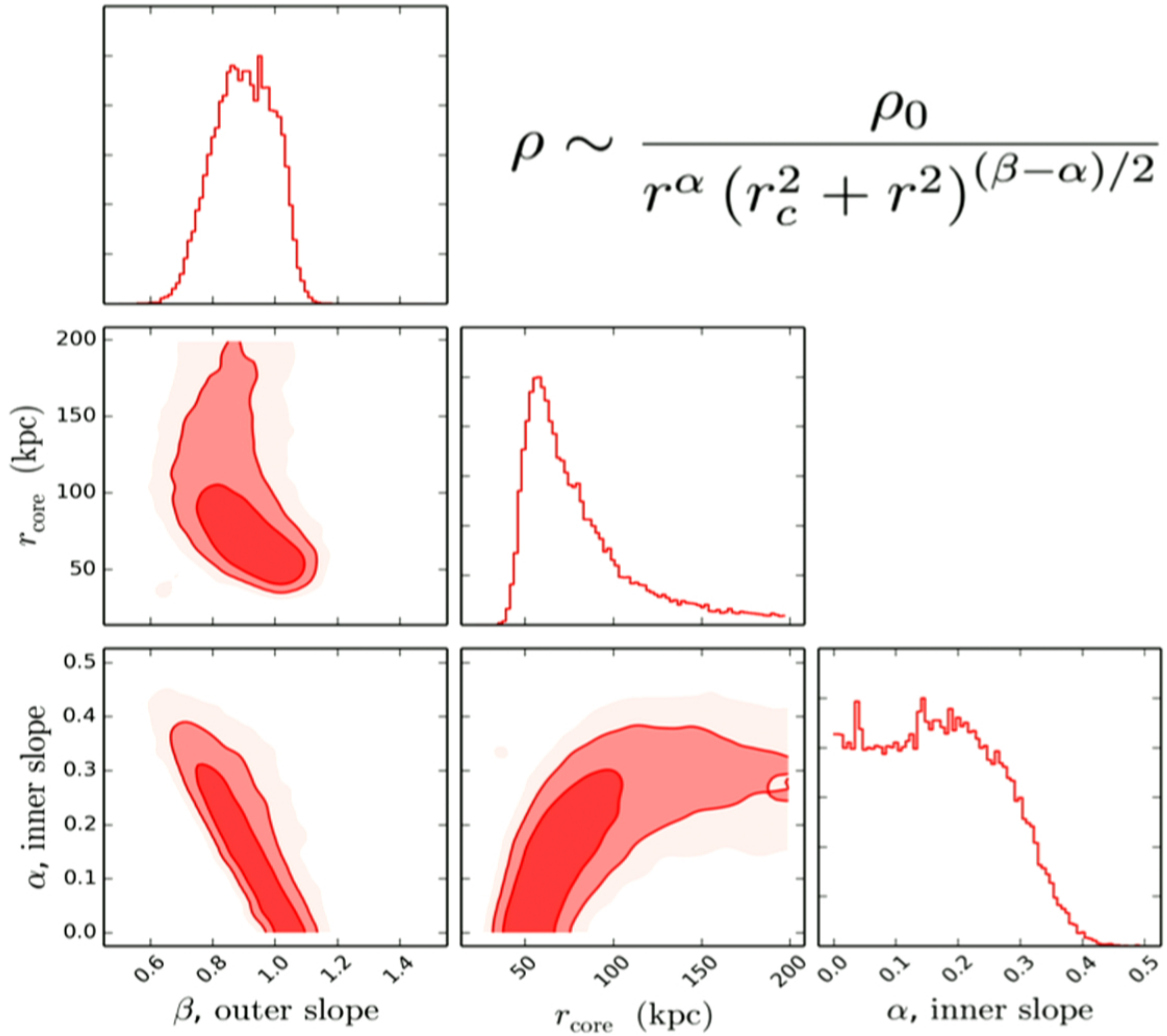
$$\rho(r) = \frac{\delta_c \rho_{\rm crit}}{(r/r_s)^{\alpha}[1 + (r/r_s)]^{3-\alpha}}$$

Plus flattening, and galaxies as isothermal clumps

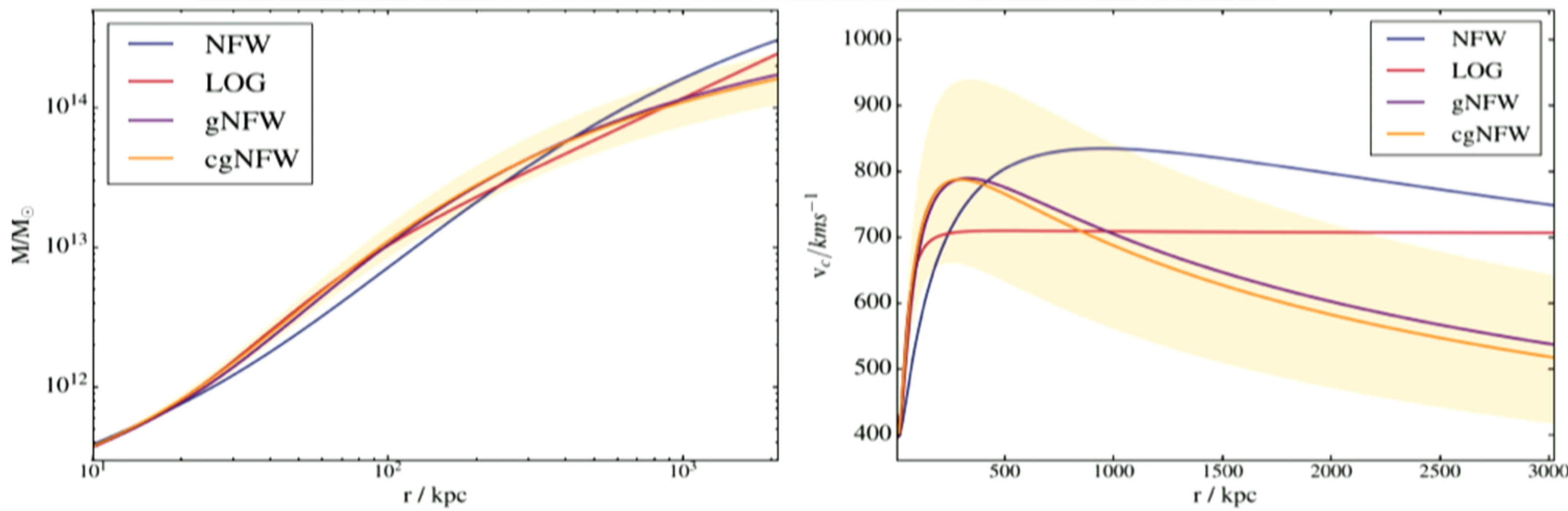



Data
Model
Normalized residual
Source

$$\rho \sim \frac{\rho_0}{r^\alpha \left(r_c^2 + r^2\right)^{(\beta-\alpha)/2}}$$

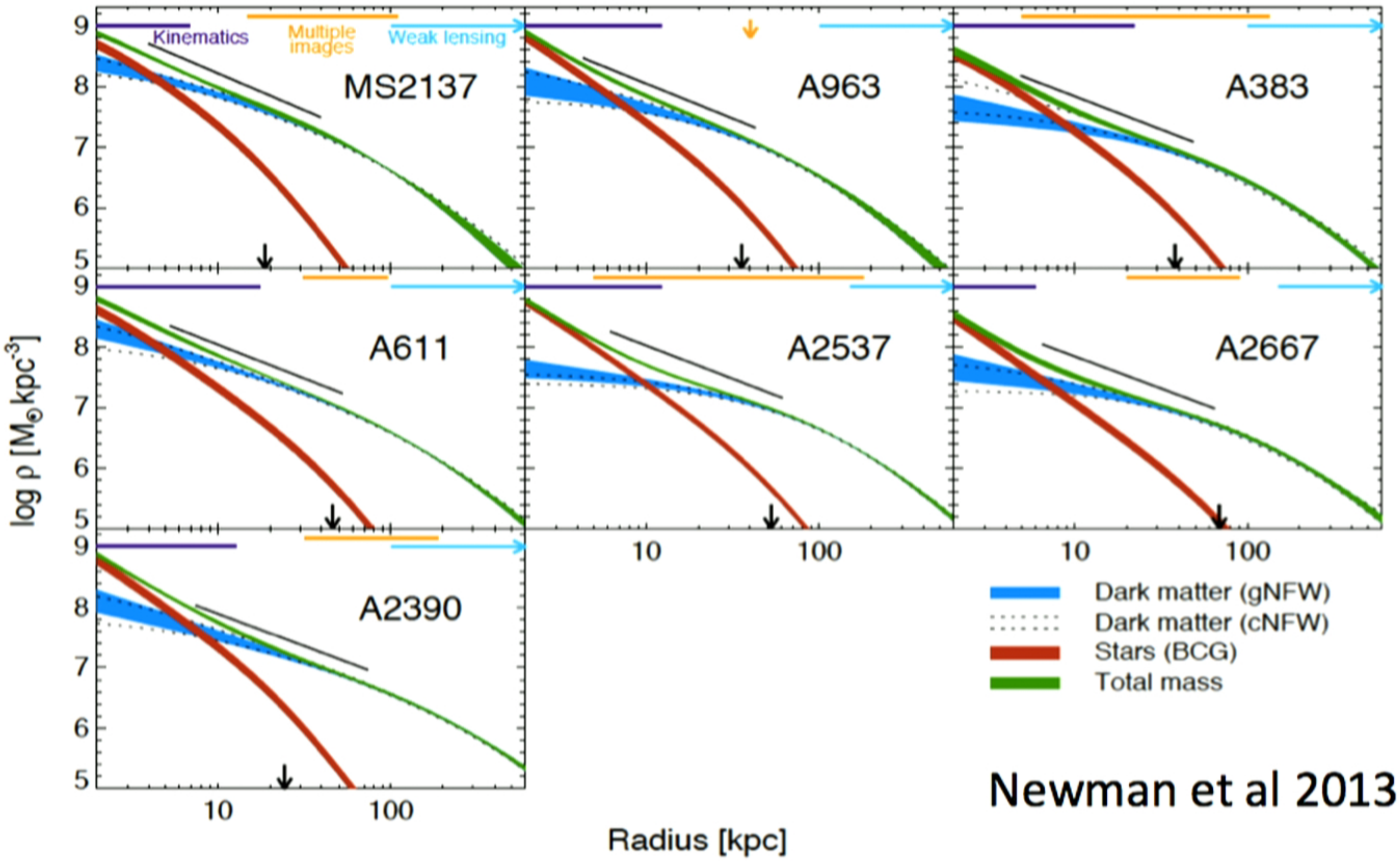


Constraints at z=0

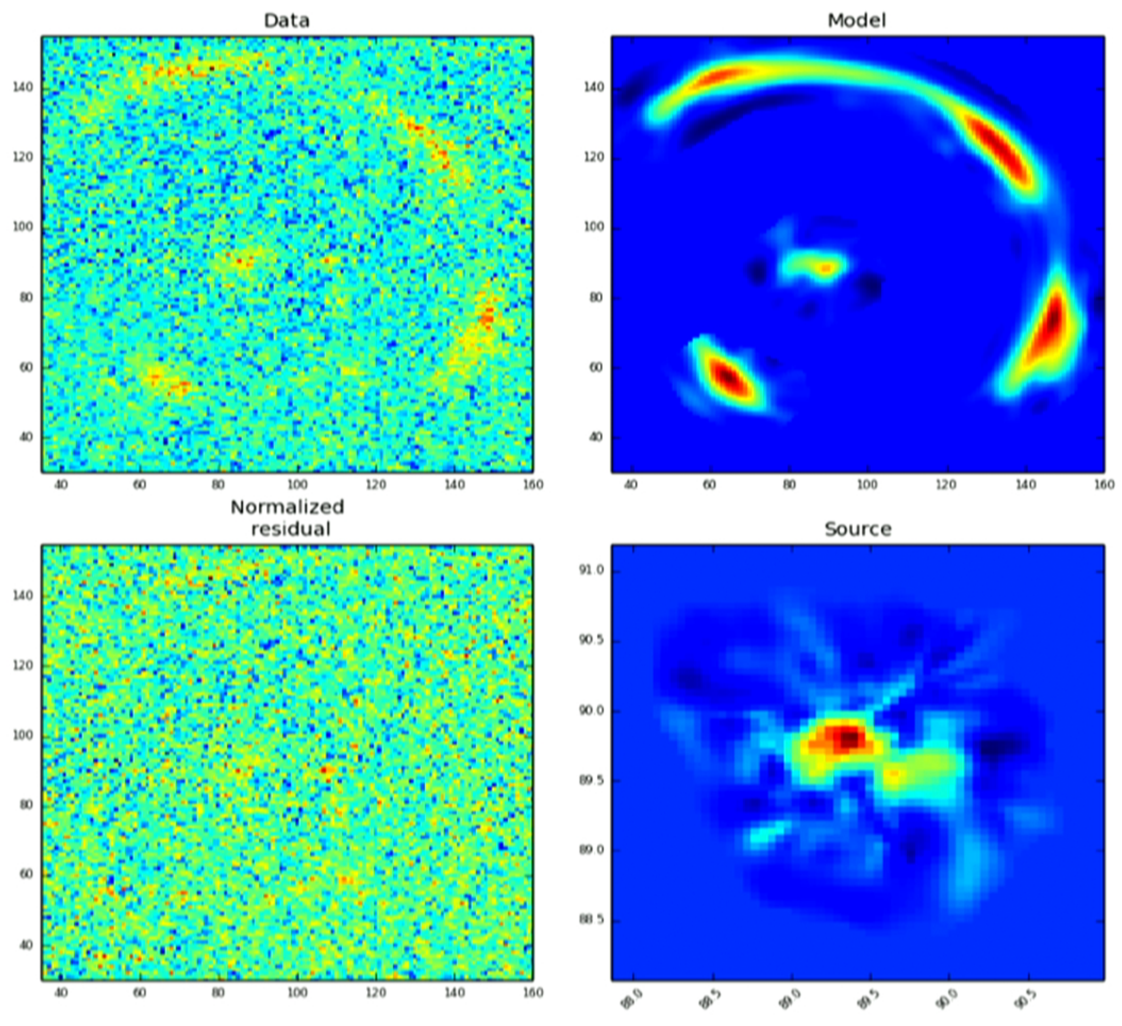


Oldham & Auger 2016

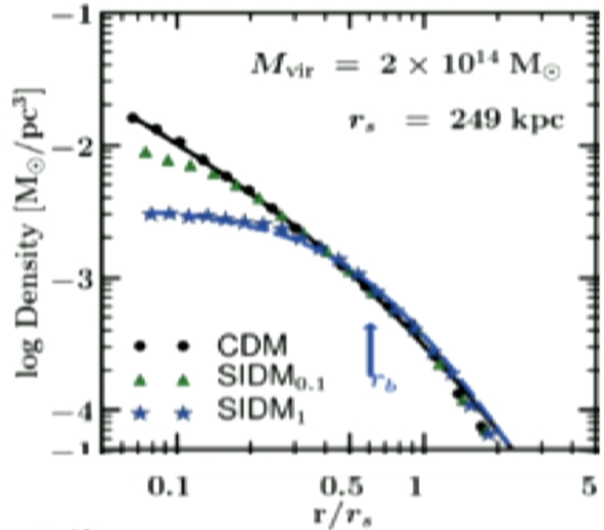
Throwing everything at 7 z~0.2 clusters

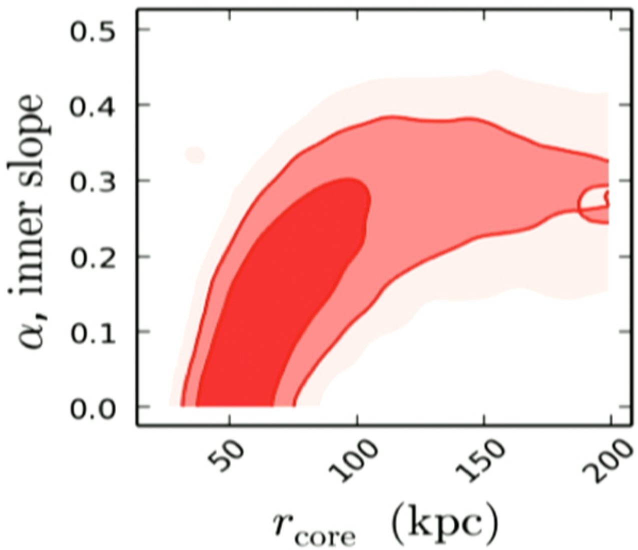


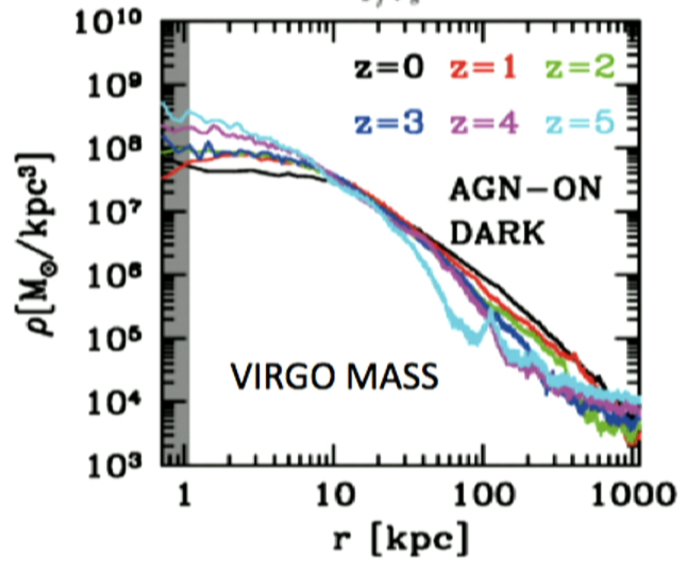
Newman et al 2013


Data
Model
Normalized residual
Source

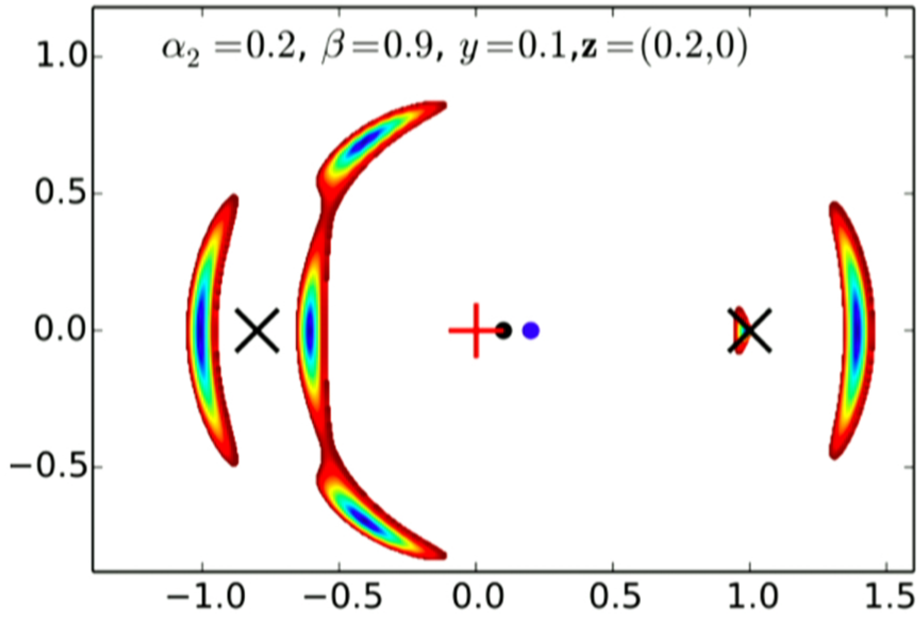
- First measurement of inner DM profile at z=1
- This DM halo is much shallower than NFW
- Core is huge (> 35 kpc)





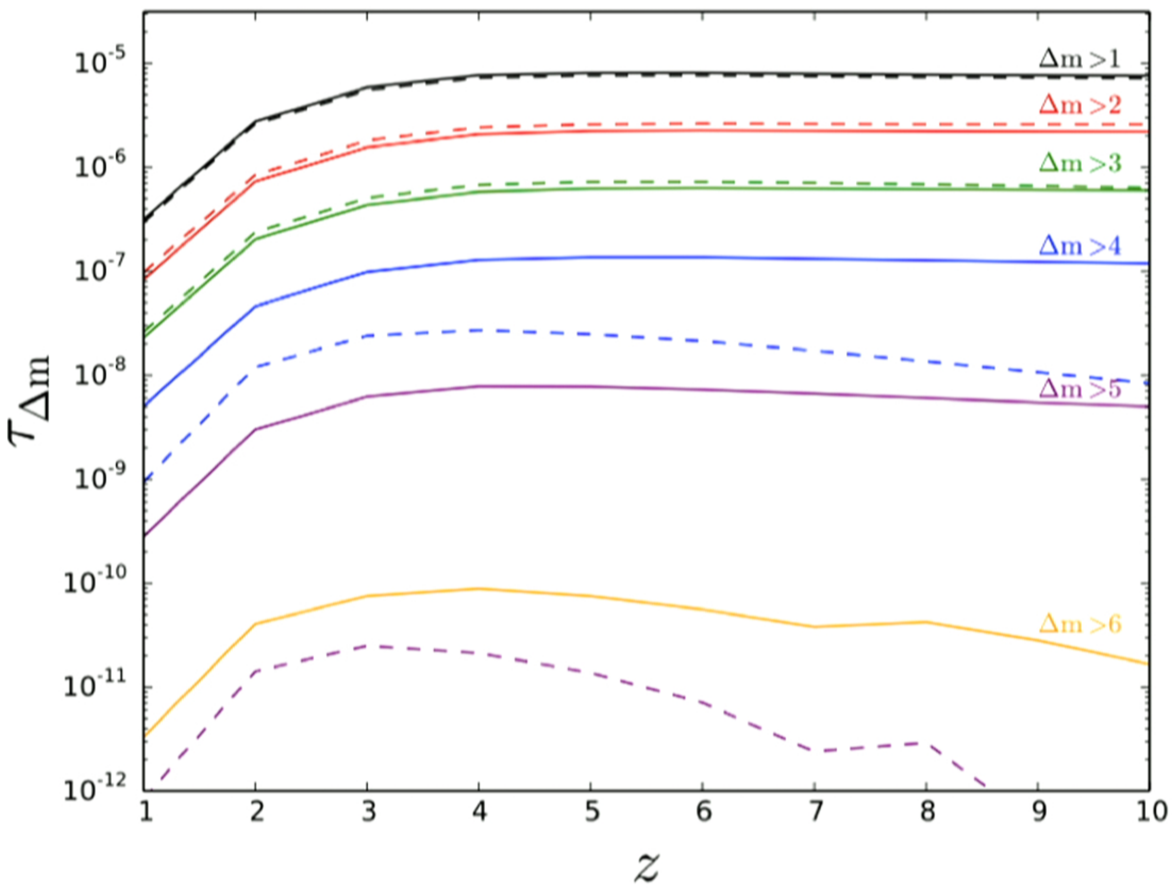


Einstein Zig-Zags



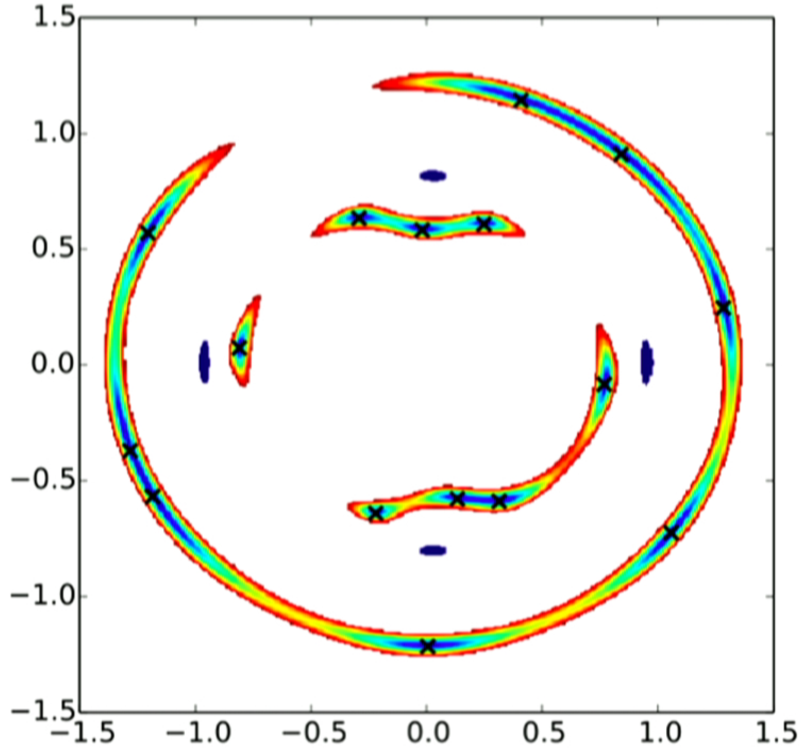
Cosmology with DSPLs

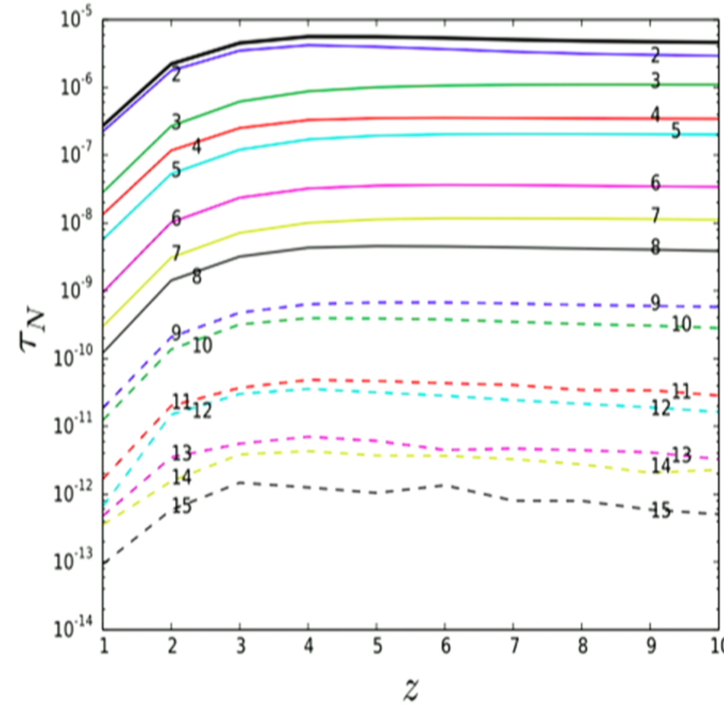
Thomas Collett



Cosmology with DSPLs

Thomas Collett





Summary

Strong lensing provides powerful complementary constraints on the dark Universe

The future holds hundreds of DSPLs and thousands of time-delay lenses.

Systematics are independent (but need controlling!)