H0licow: Cosmology from Strong Gravitational lensing

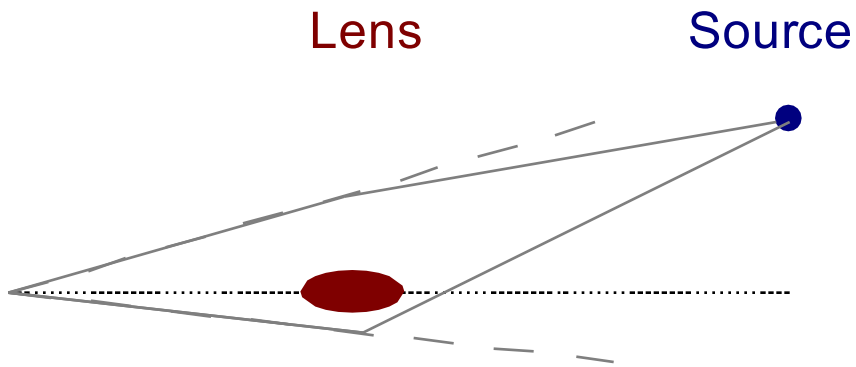
Thomas Collett
On behalf of the H0licow collaboration

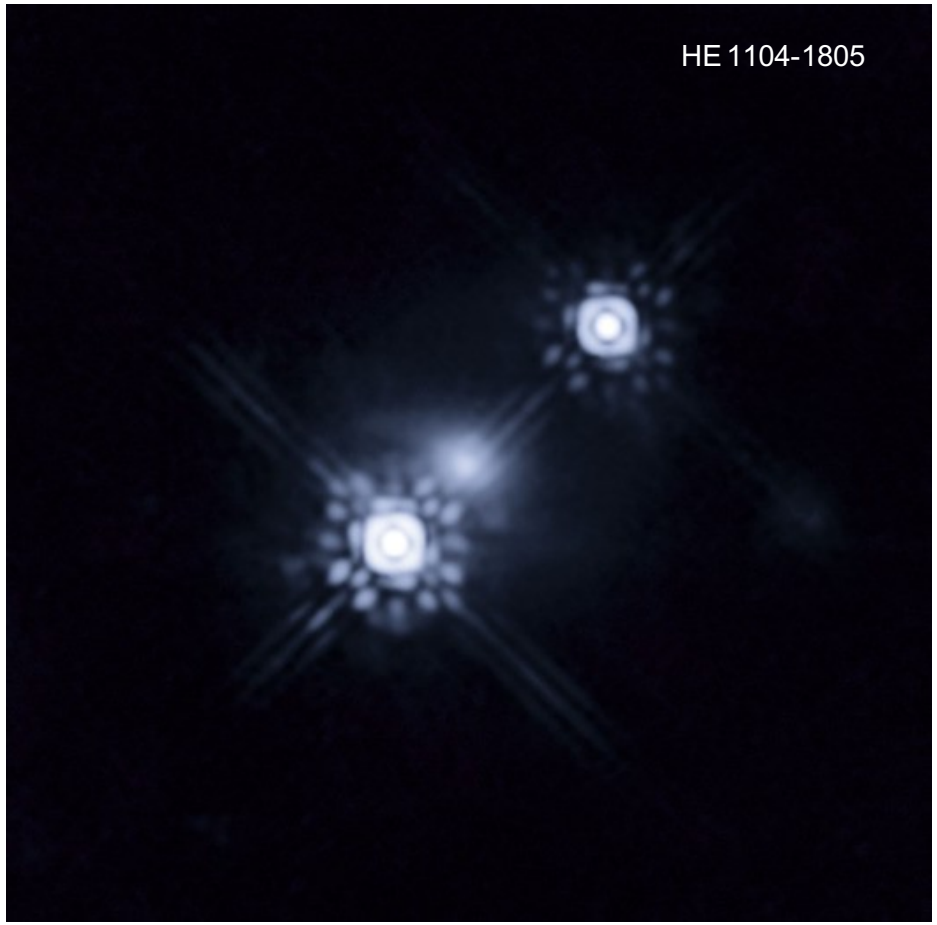
H0LiCOW: H_0 Lenses in COSMOGRAIL's Wellspring

→ Establish time-delay gravitational lenses as one of the best cosmological probes

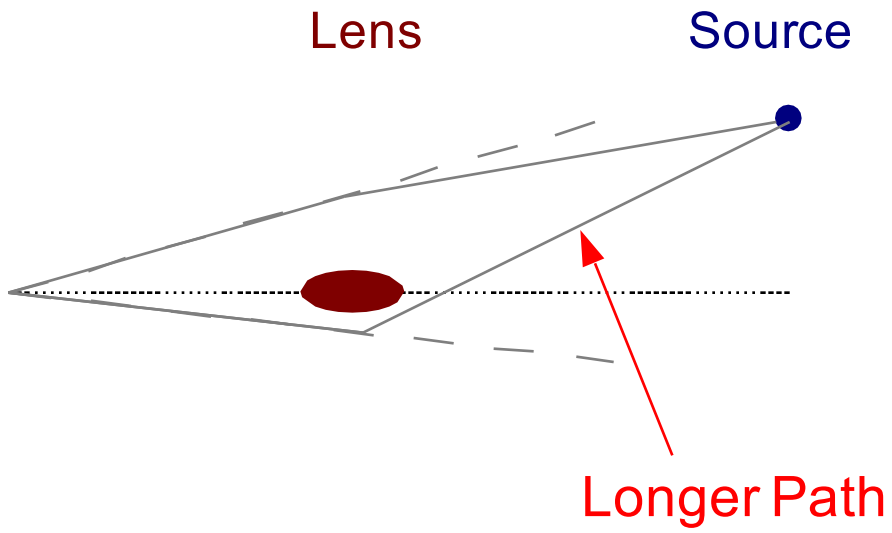
$$\theta_{\mathrm{E}} = \sqrt{\frac{GM(\theta_{\mathrm{E}})}{c^2}\frac{D_{\mathrm{ls}}}{D_{\mathrm{ol}}D_{\mathrm{os}}}}$$

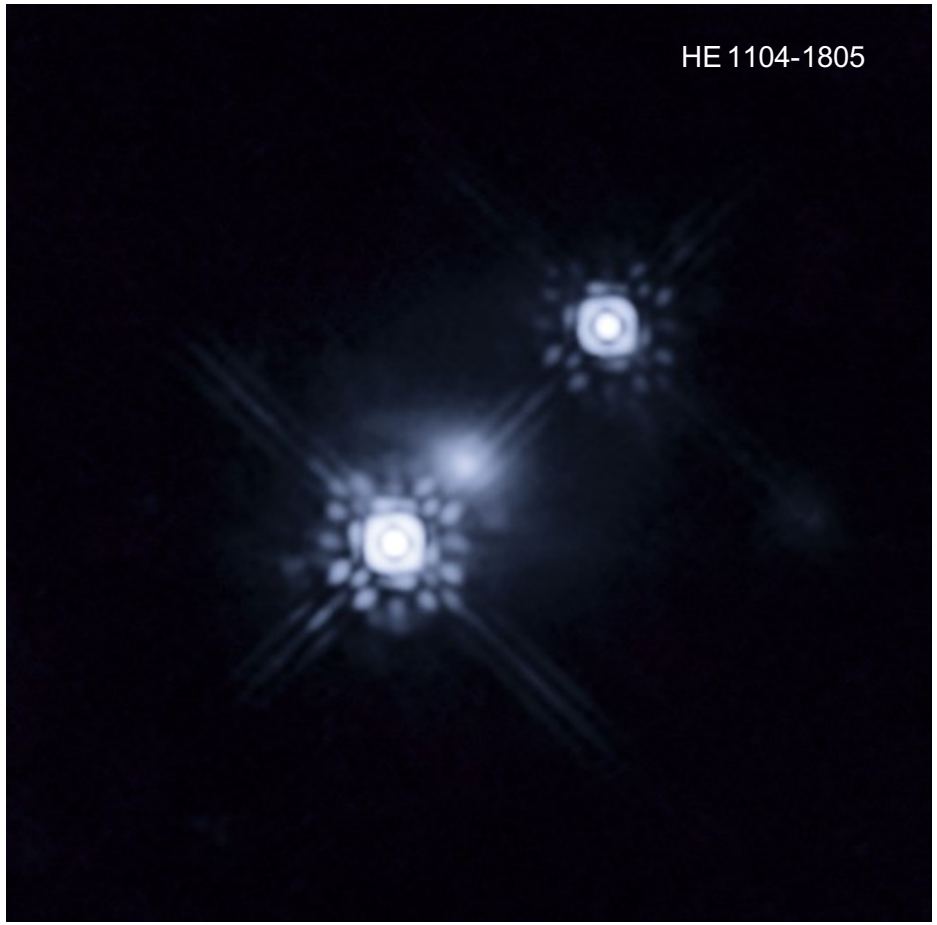
Strong lensing time delays



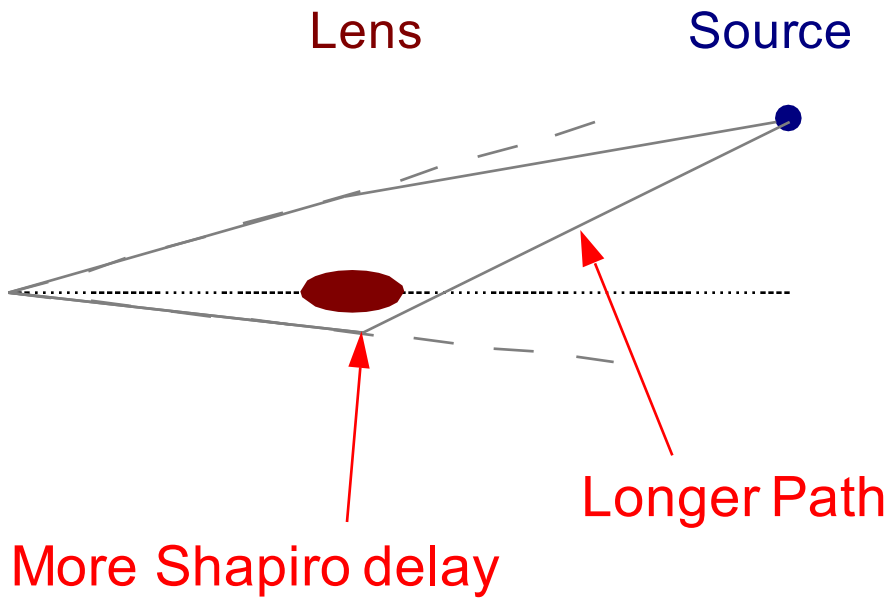


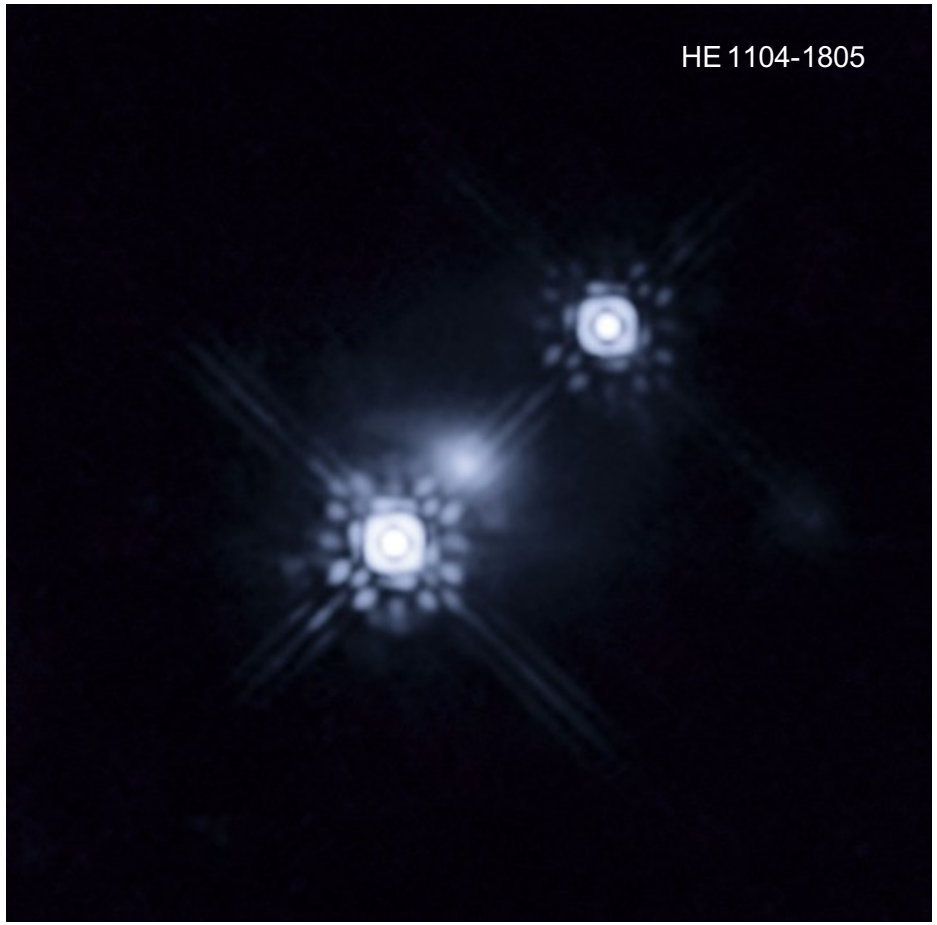
Strong lensing time delays



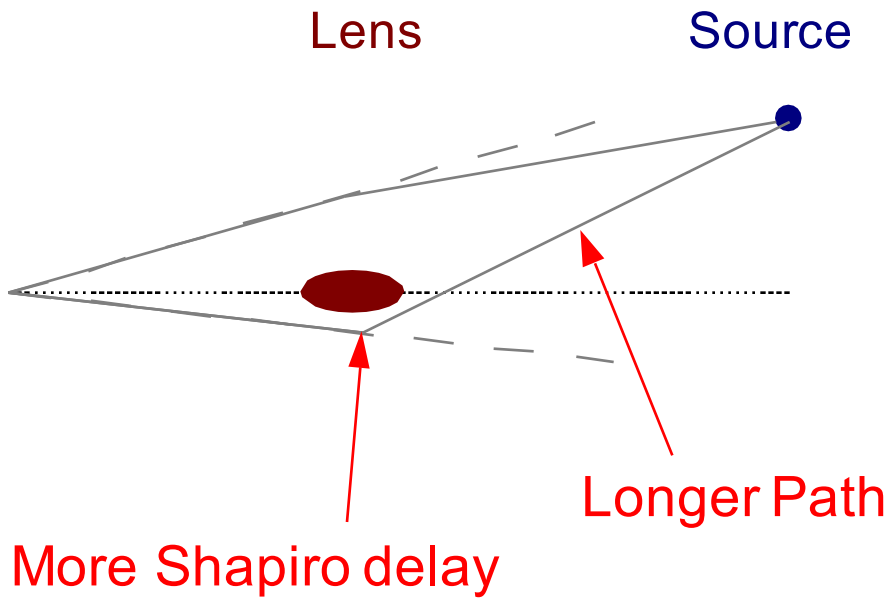


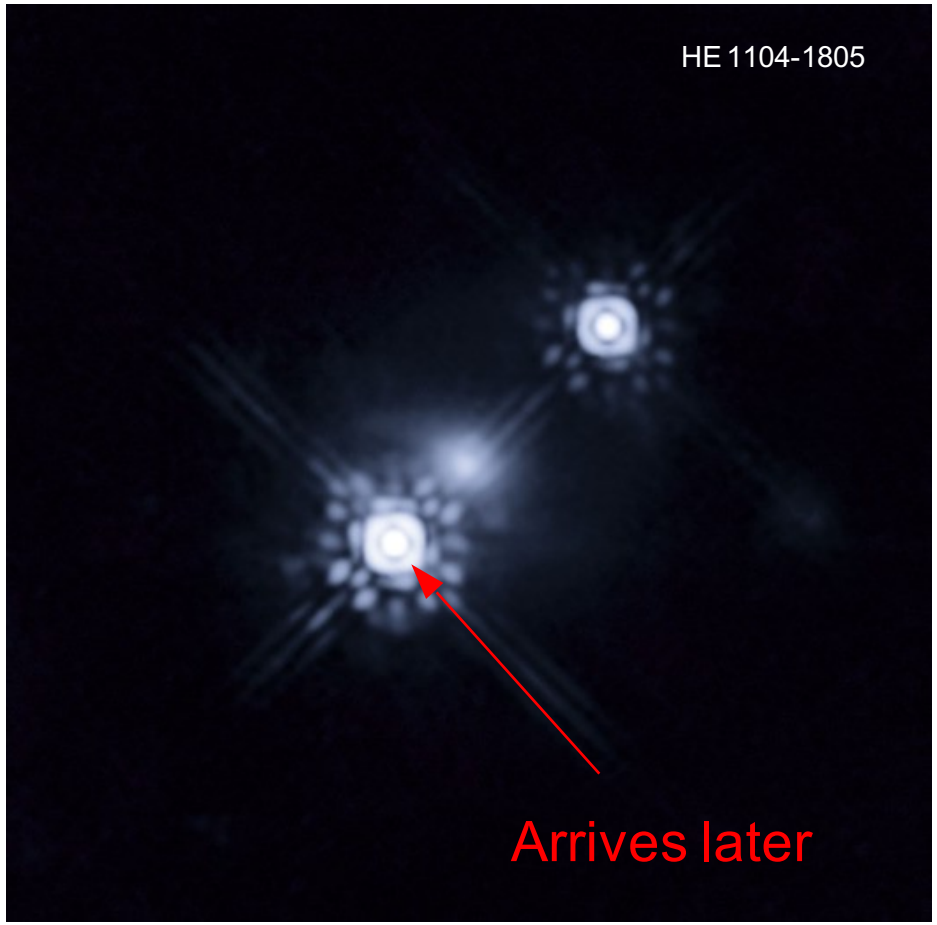
Strong lensing time delays



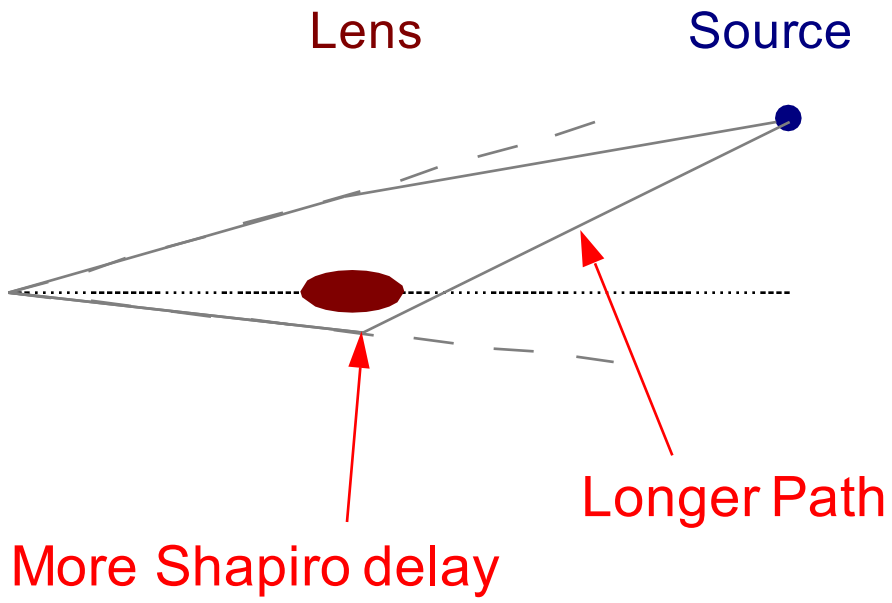


Strong lensing time delays

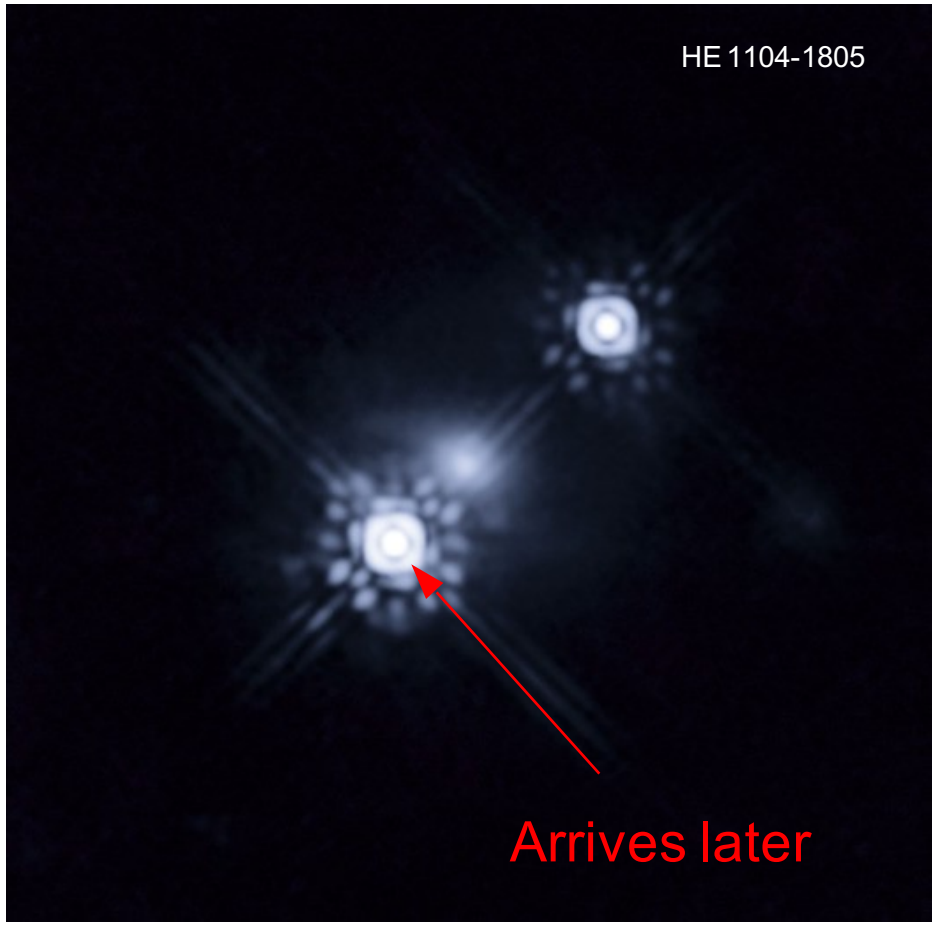




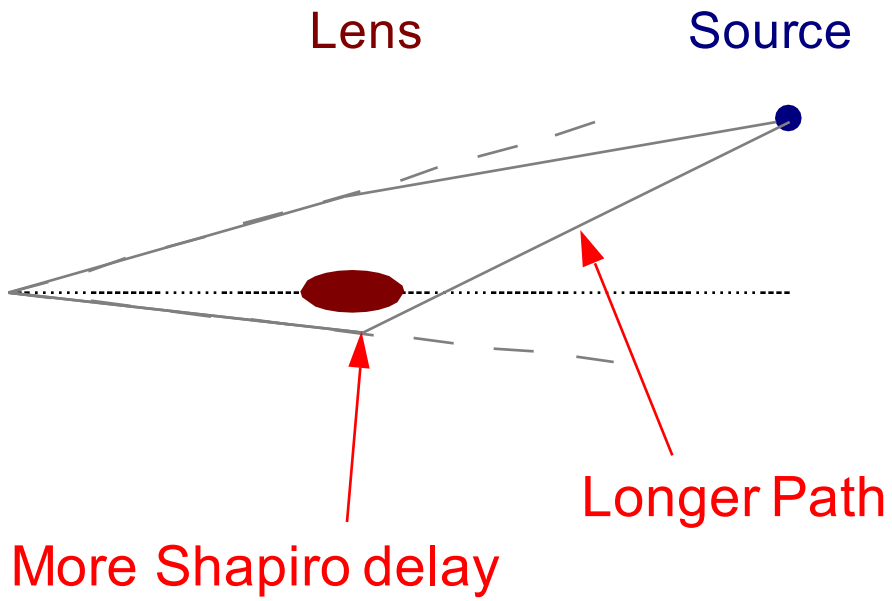
Strong lensing time delays

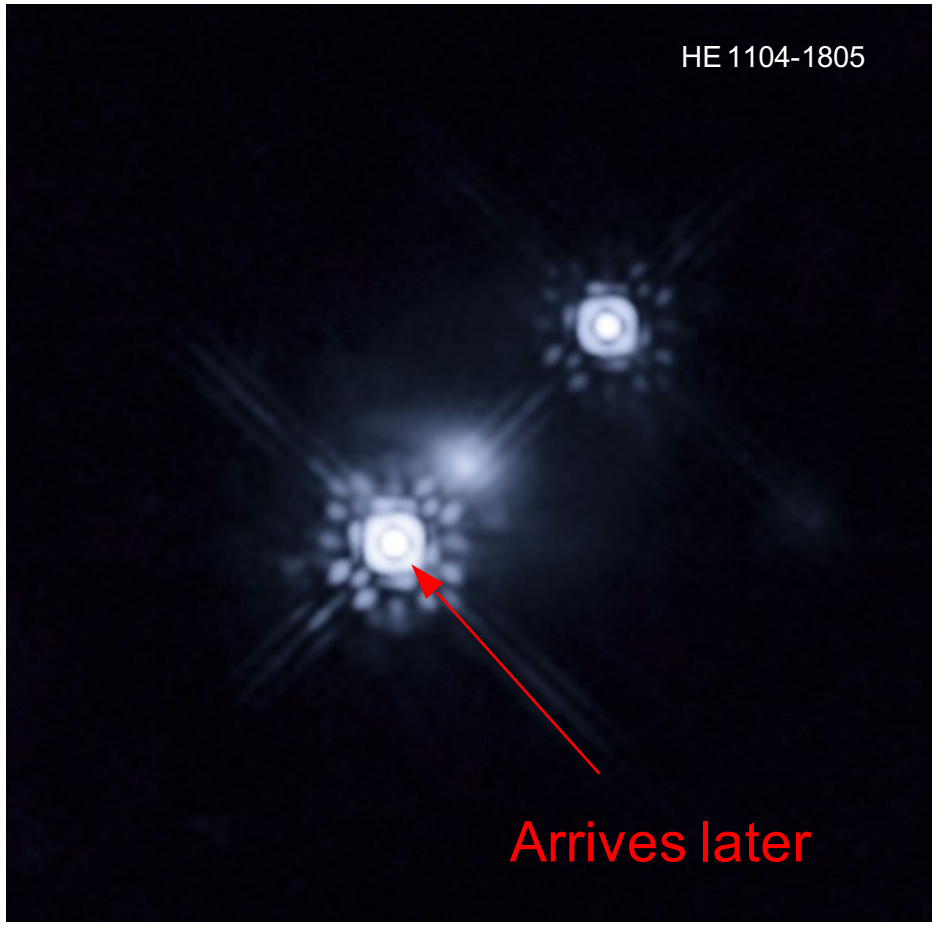


$$\Delta t \quad \propto \quad D_{\Delta t} = (1+z_l)\ (D_l D_s)/D_{ls}$$



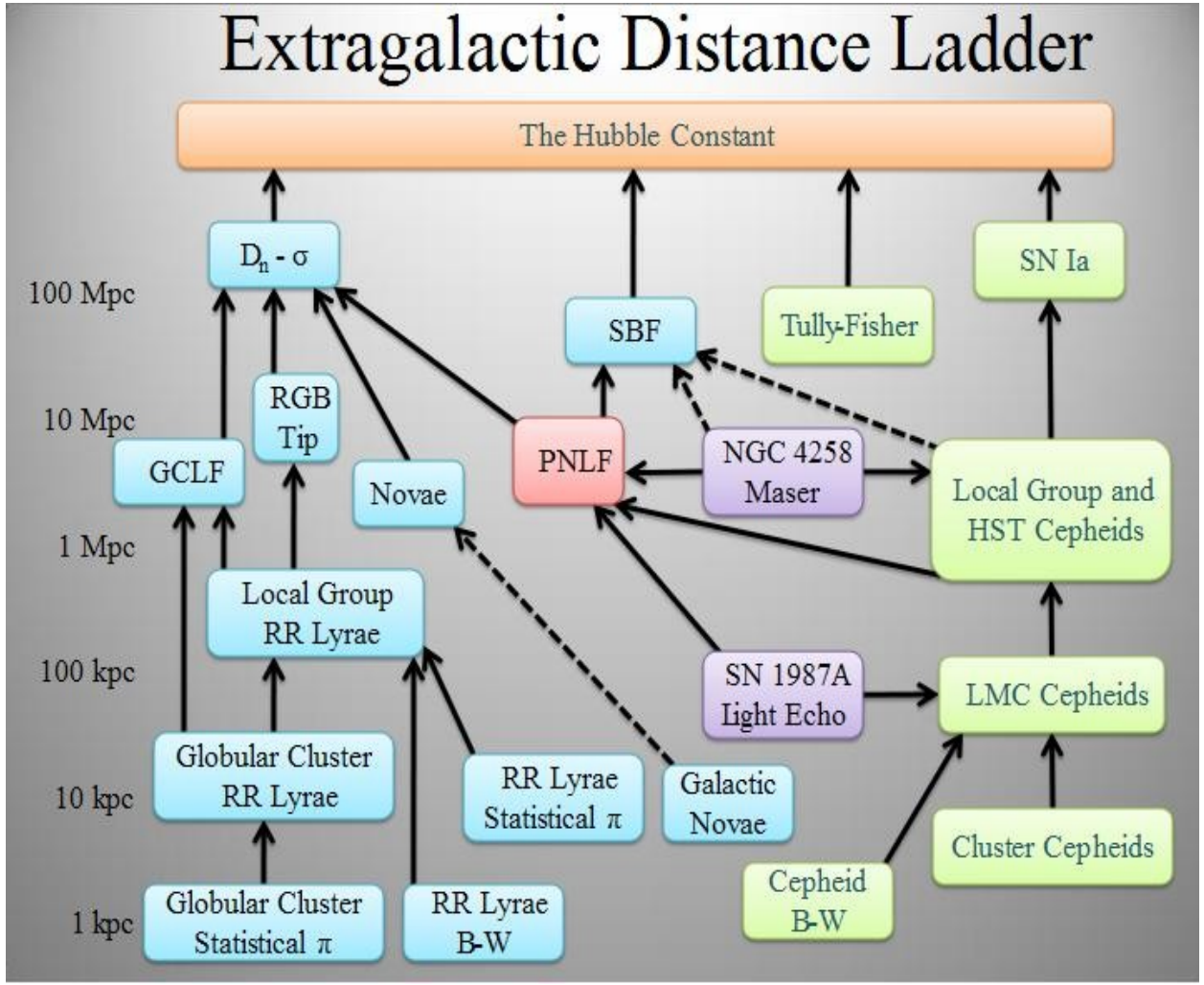
Strong lensing time delays

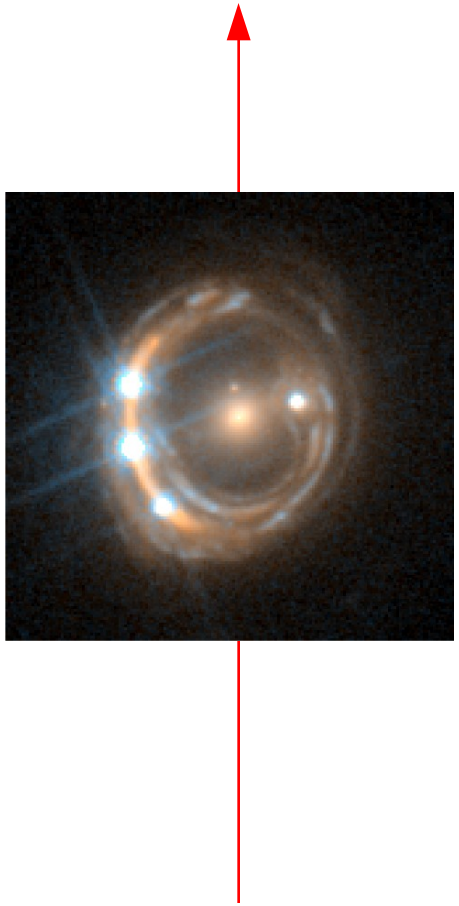




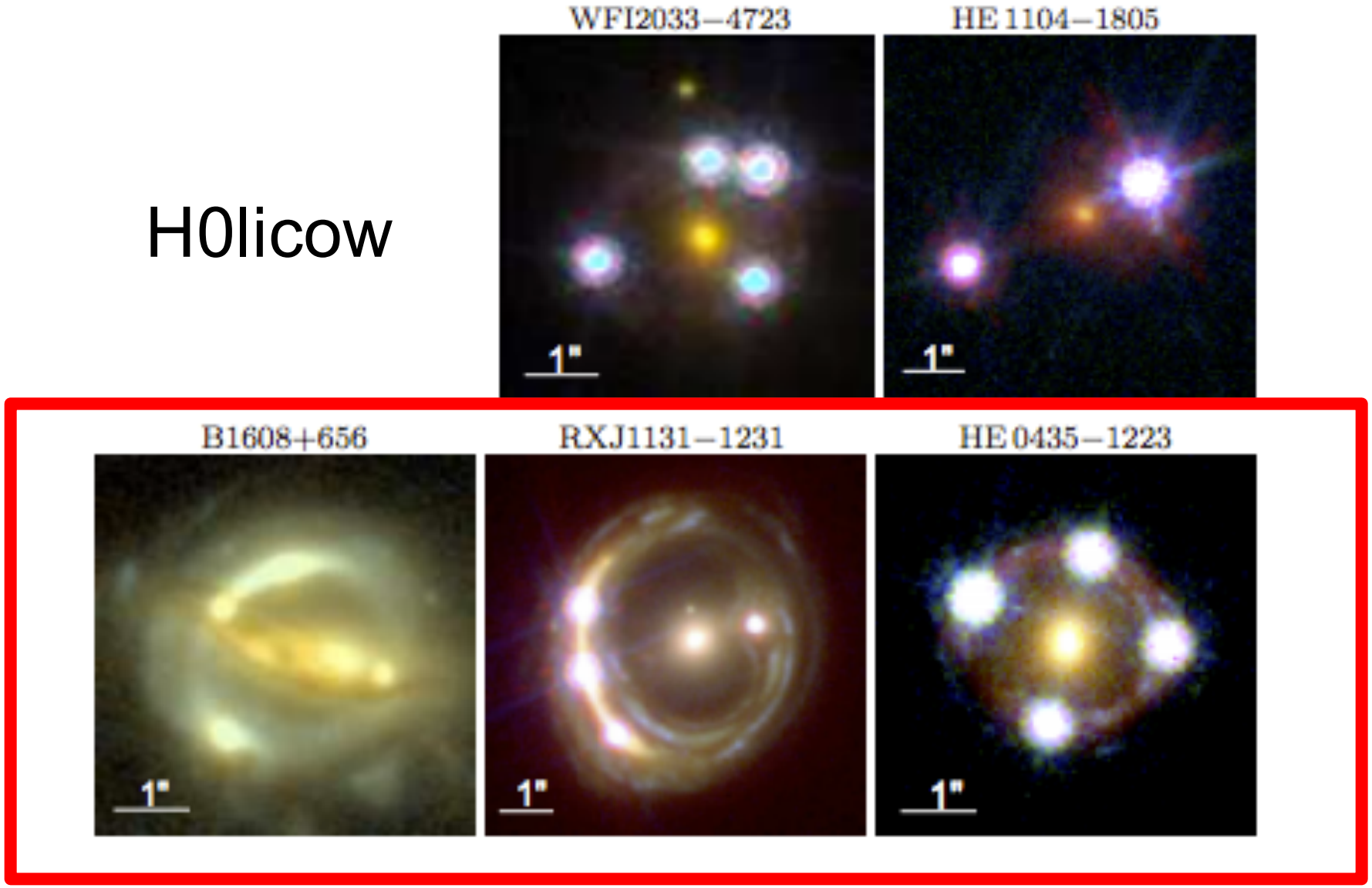
$$\Delta t \quad \propto \quad D_{\Delta t} = (1+z_l)\ (D_l\, D_s\,)/\,D_{ls}$$

Most sensitive to the Hubble constant.


Extragalactic Distance Ladder
The Hubble Constant
100 Mpc
10 Mpc
1 Mpc
100 kpc
10 kpc
1 kpc
D_n - σ
SBF
Tully-Fisher
SN Ia
RGB Tip
GCLF
Novae
PNLF
NGC 4258 Maser
Local Group and HST Cepheids
Local Group RR Lyrae
SN 1987A Light Echo
LMC Cepheids
Globular Cluster RR Lyrae
RR Lyrae Statistical π
Galactic Novae
Cluster Cepheids
Cepheid B-W
Globular Cluster Statistical π
RR Lyrae B-W

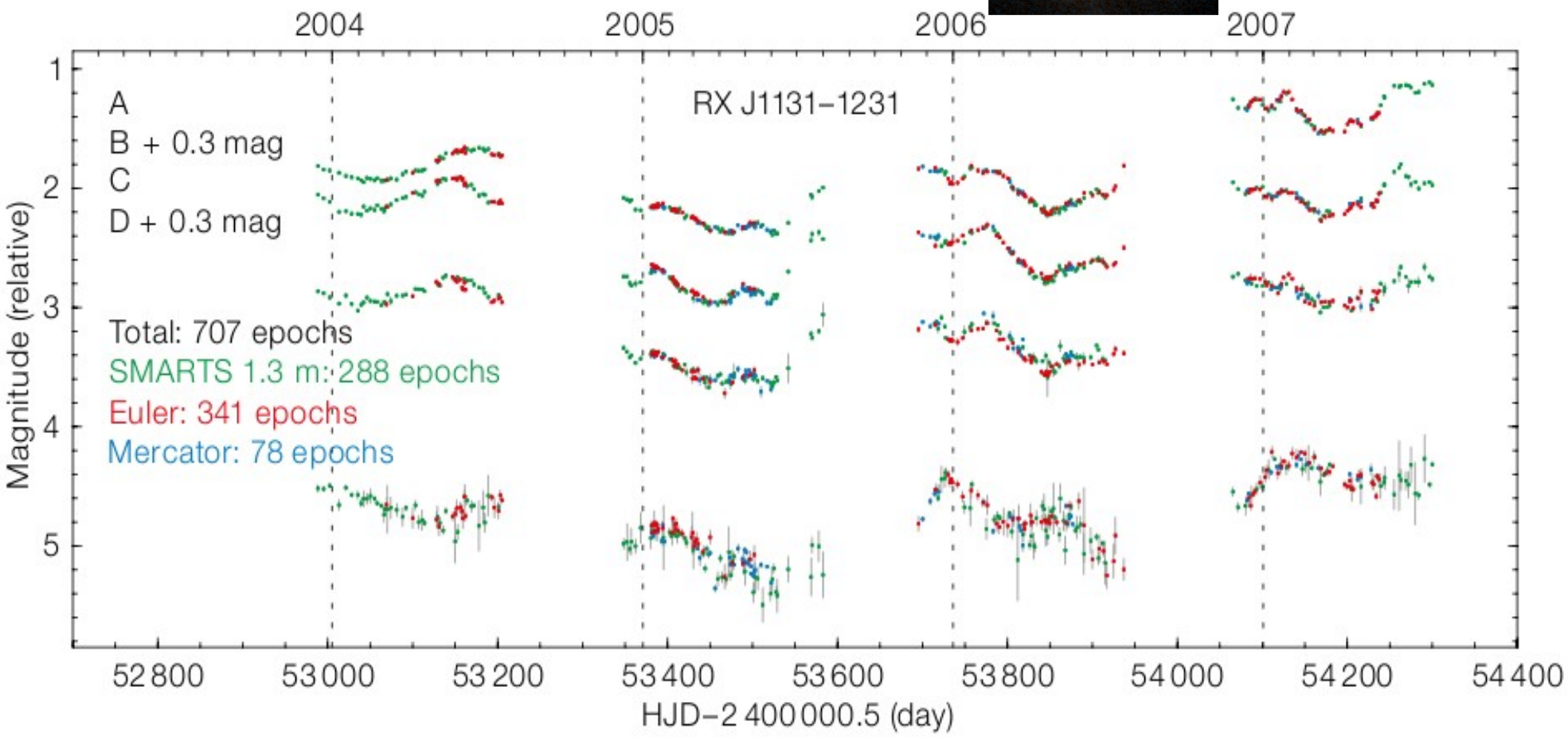


H0licow



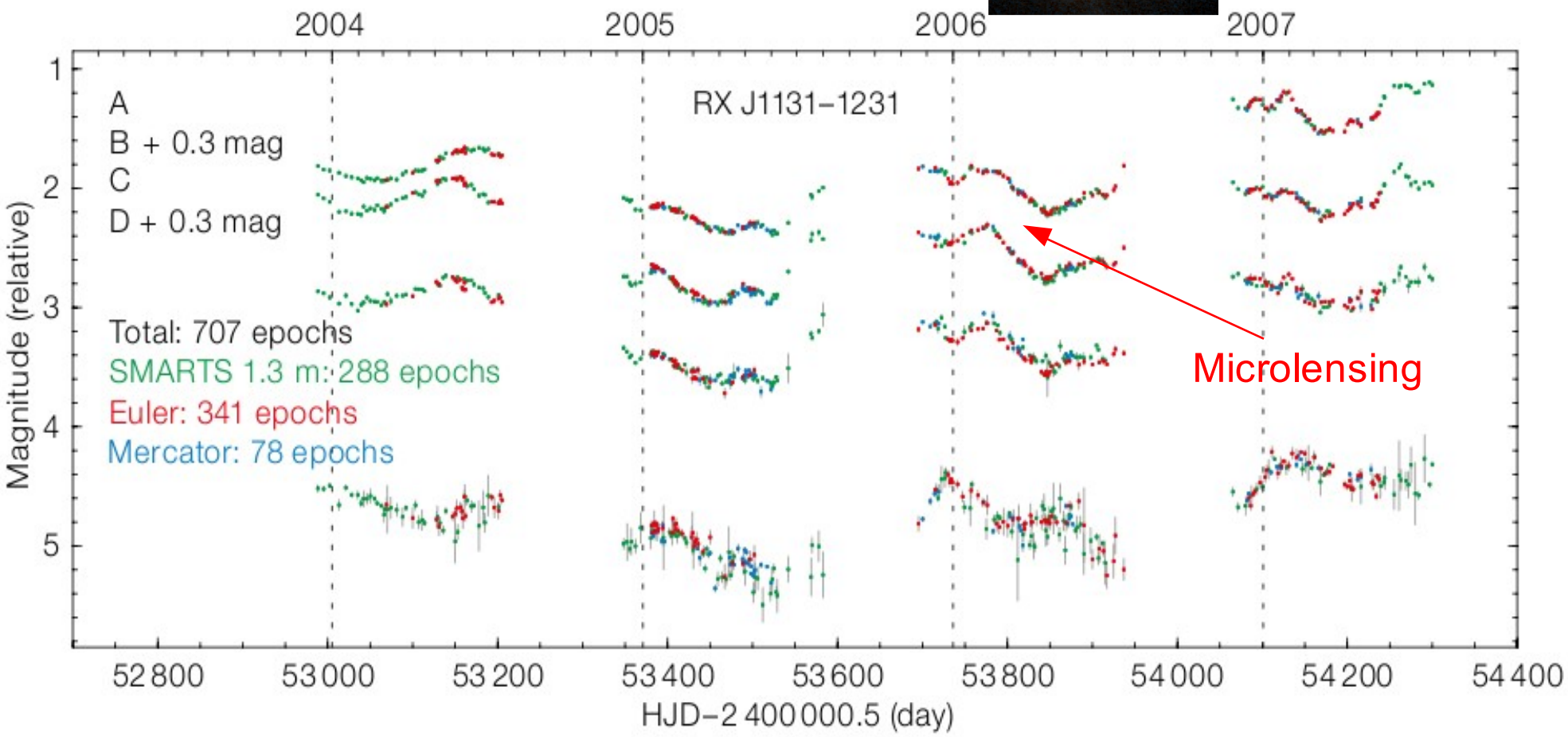
Suyu et al 2017

Measuring time delays



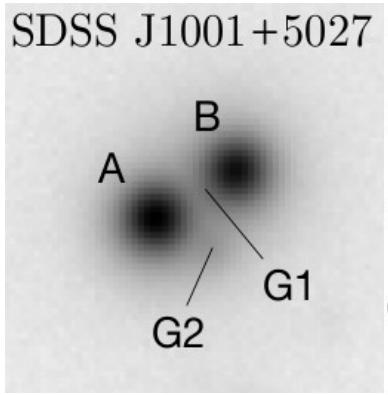
Tewes+ 2012

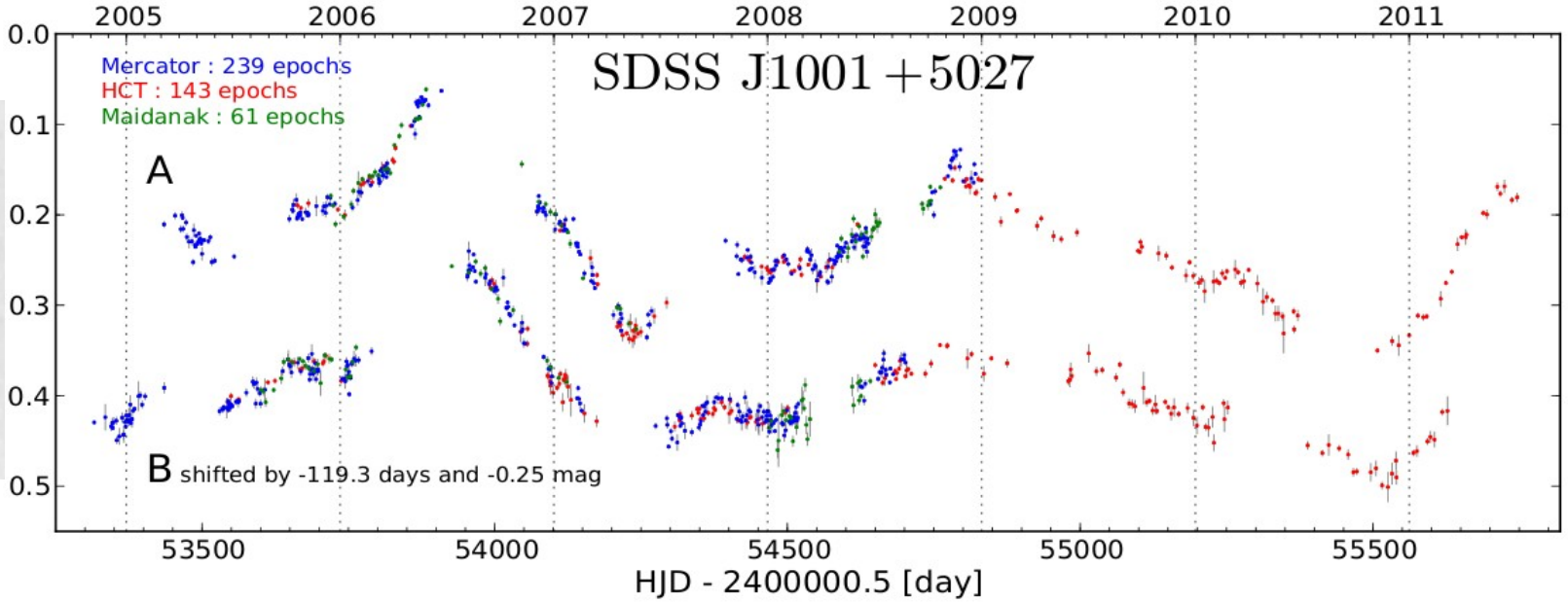
Measuring time delays

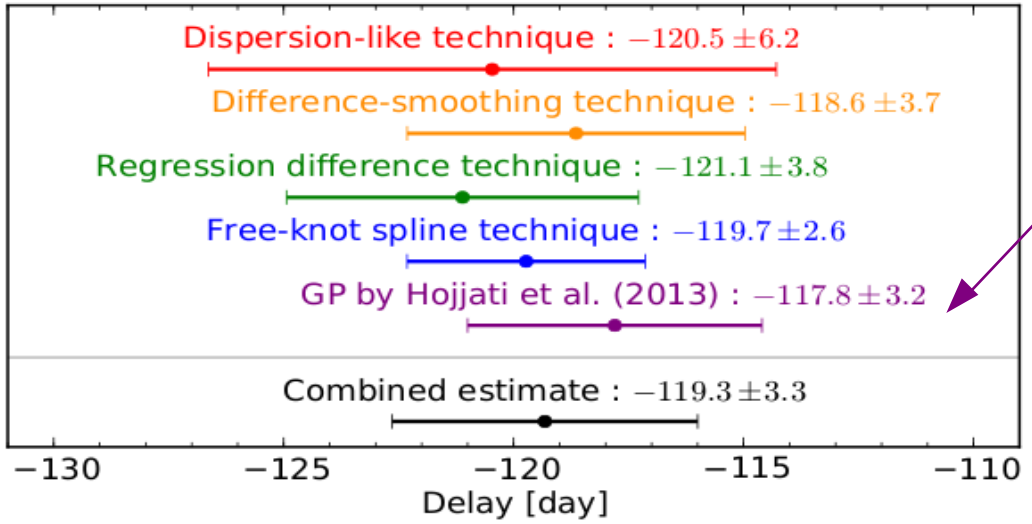


Tewes+ 2012

Cosmograil







Blind, independent team and different method get the same result

Accurate time delays at +/- 3 day precision

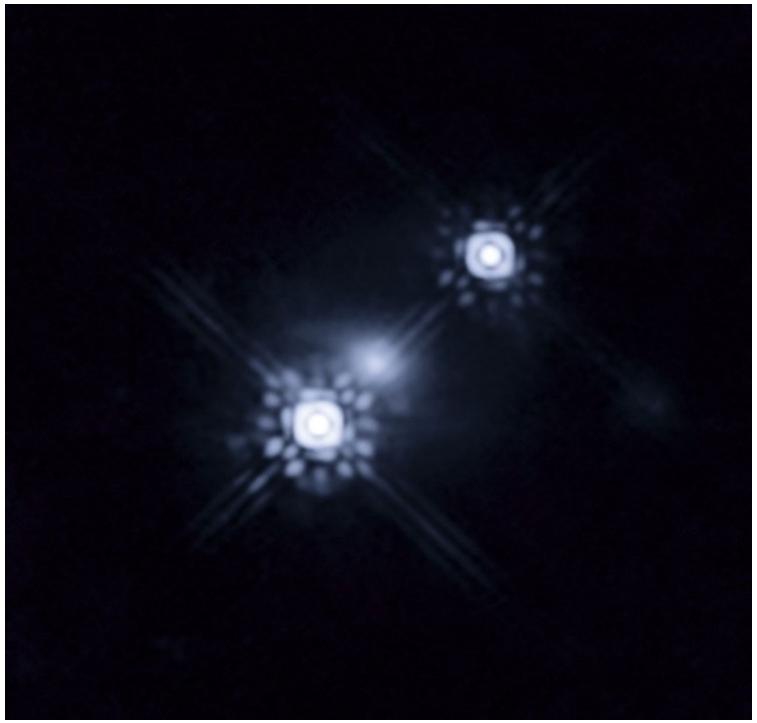
Rathna Kumar+ 2013

Modelling the lenses

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

What's the constant of proportionality?

- Location of the images
- Gravitational potential



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

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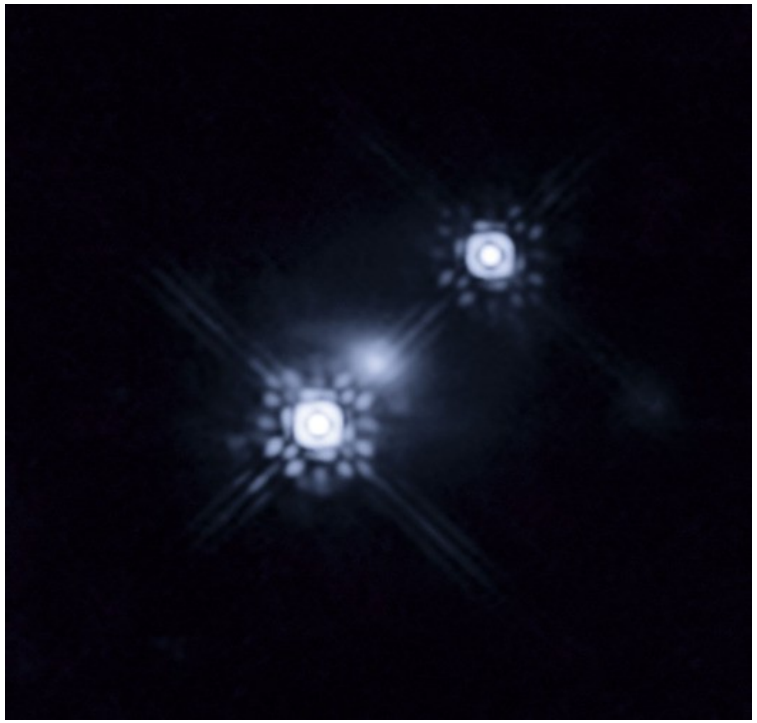
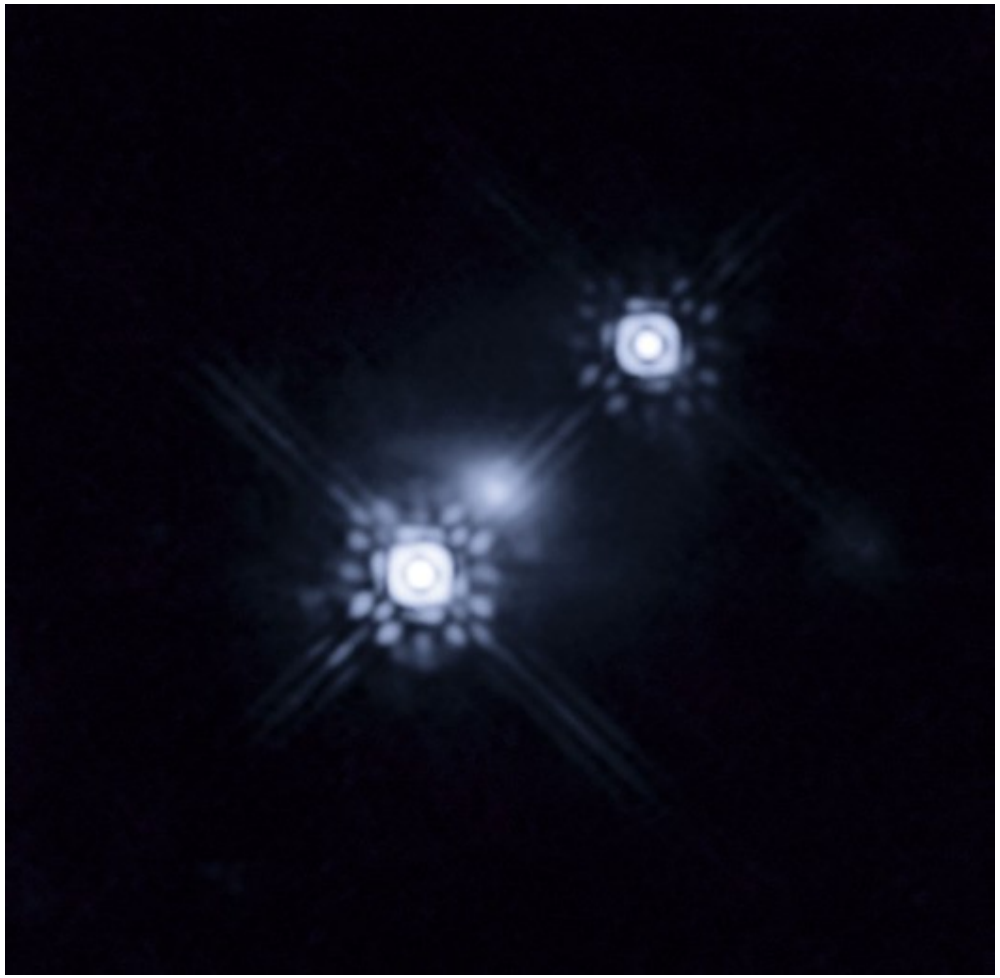
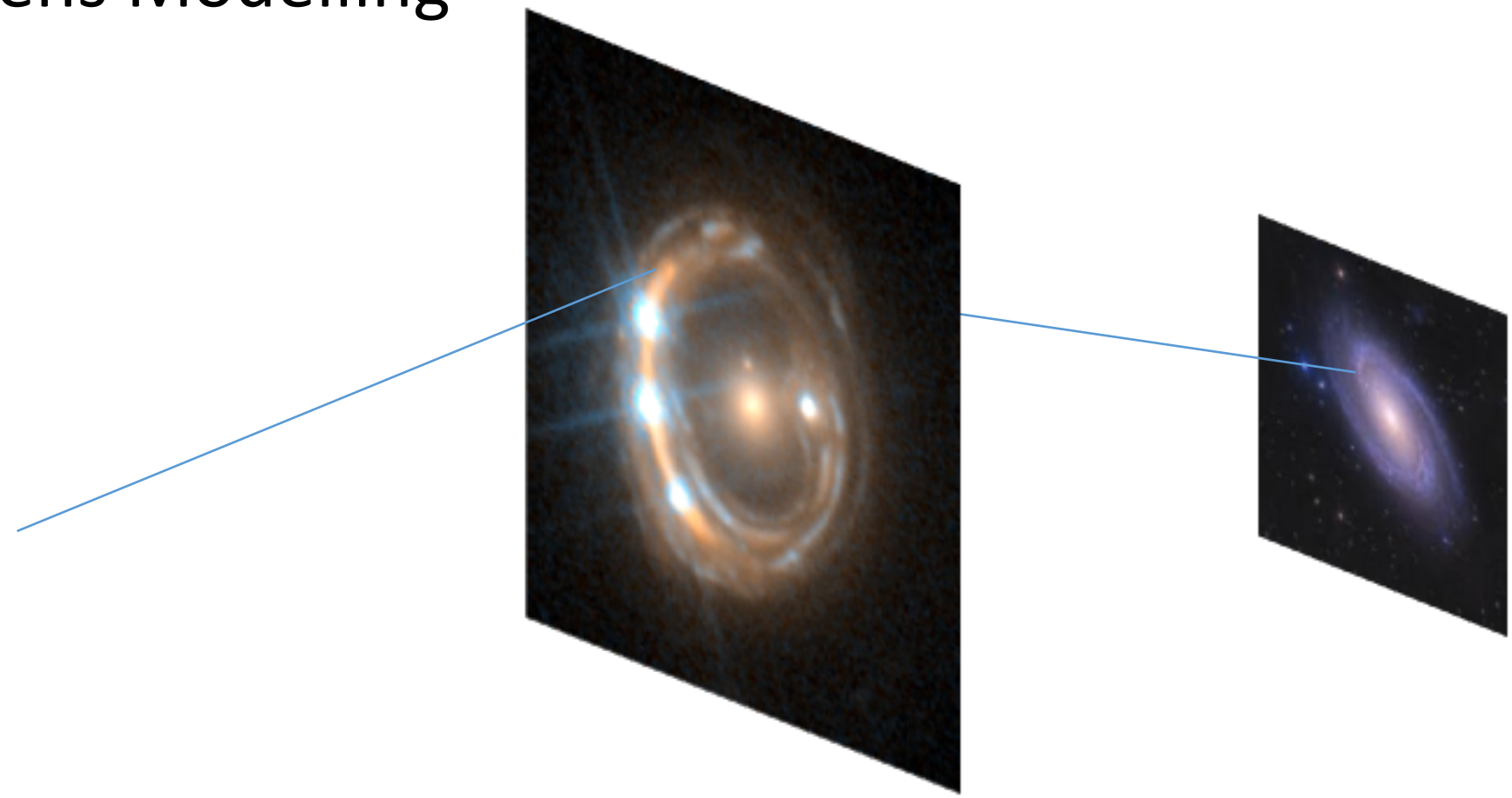


How is the mass distributed in the lens?

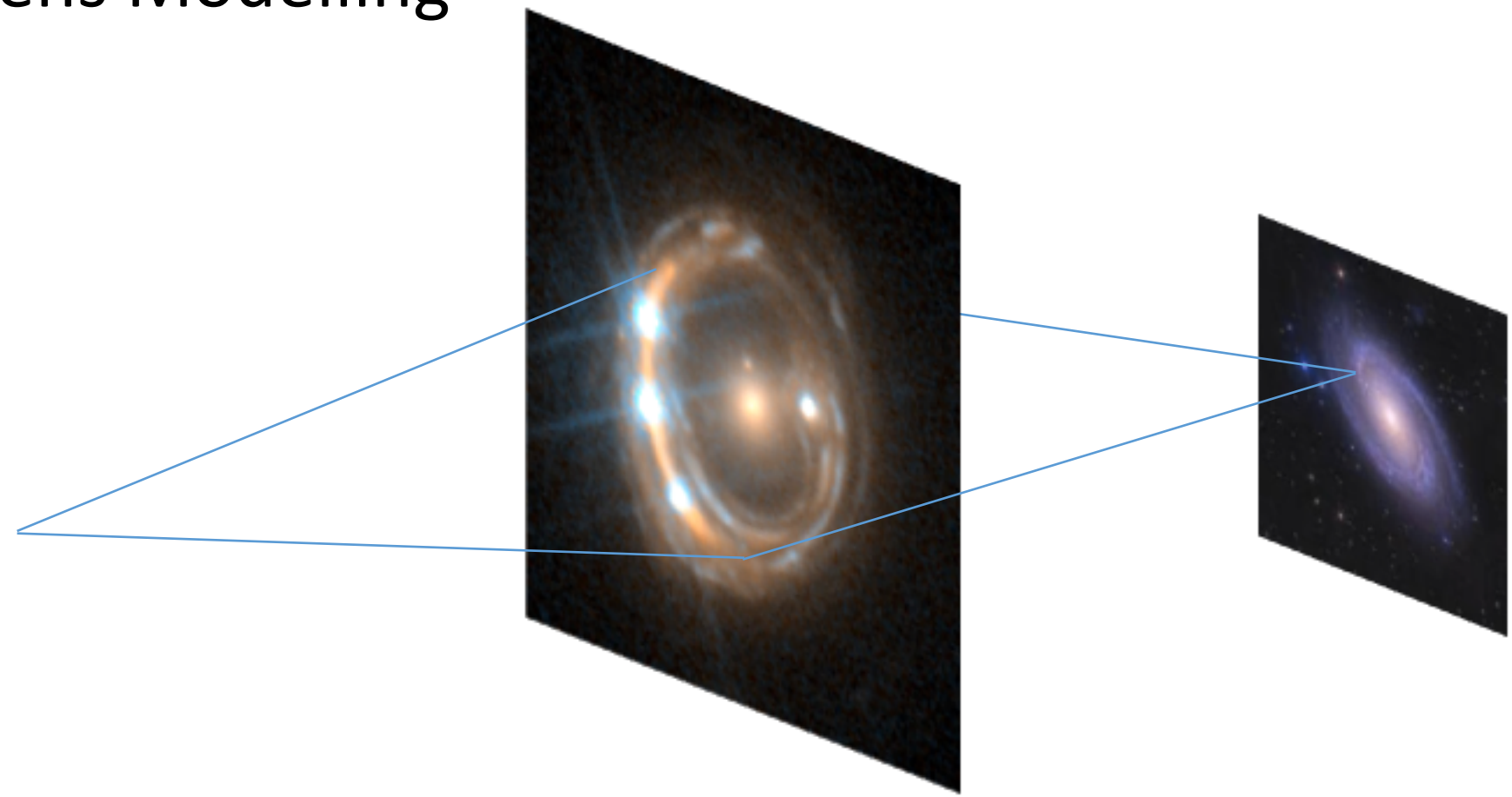
$$c\Delta t \quad = D_{\Delta t} (\tfrac{1}{2}(\theta_1 - \beta)^2 \ - \ \tfrac{1}{2}(\theta_2 - \beta)^2 \ - \ \psi(\theta_1) + \psi(\theta_2))$$



Lens Modelling



Lens Modelling

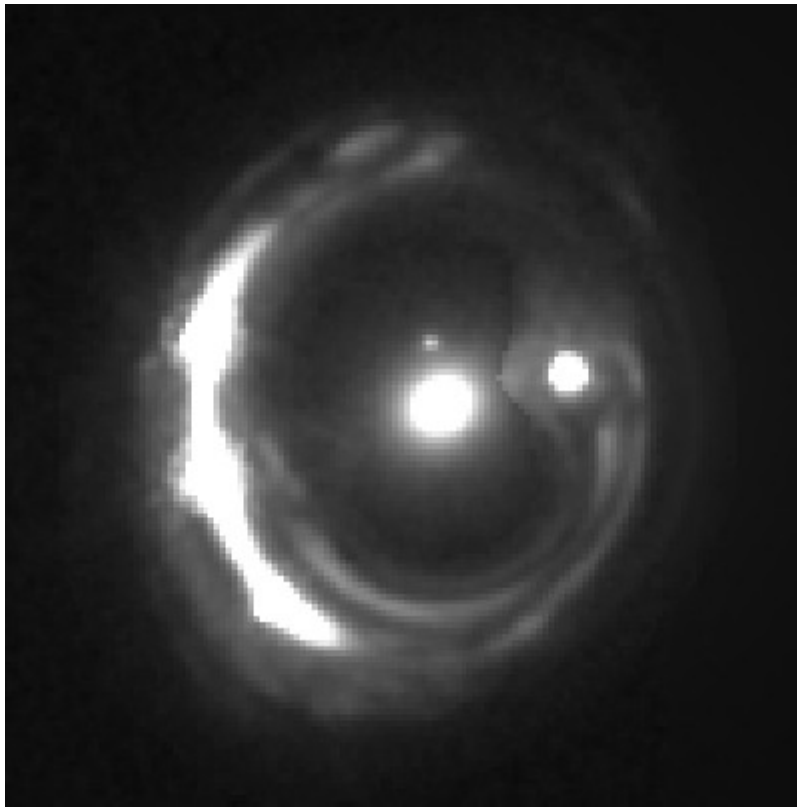


Lens Modelling

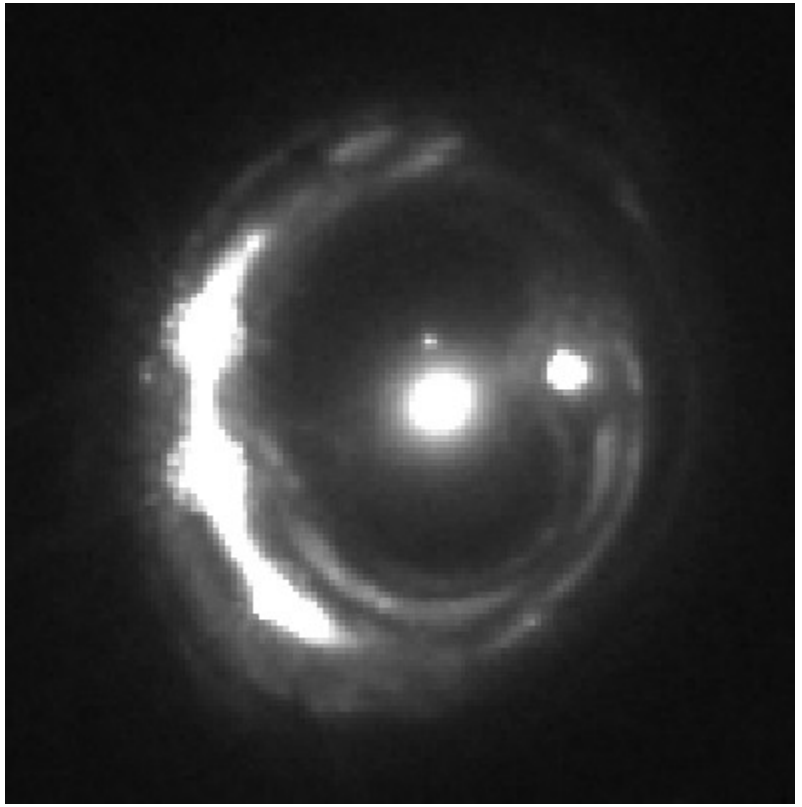
$$= \left(M \right)_{SOURCE}$$

Then sample the mass + source model

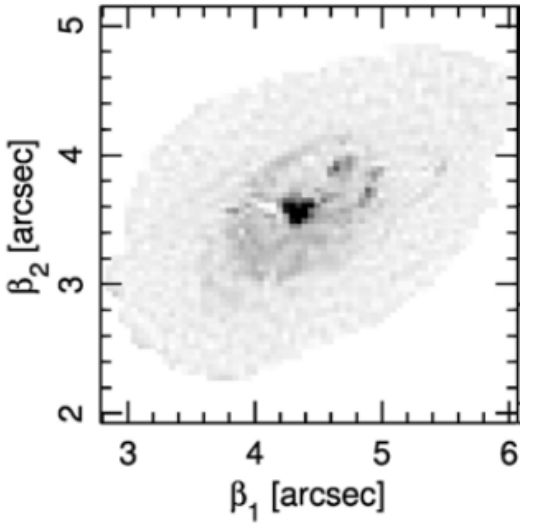
Constraining the steepness of the potential



(Most probable) Model

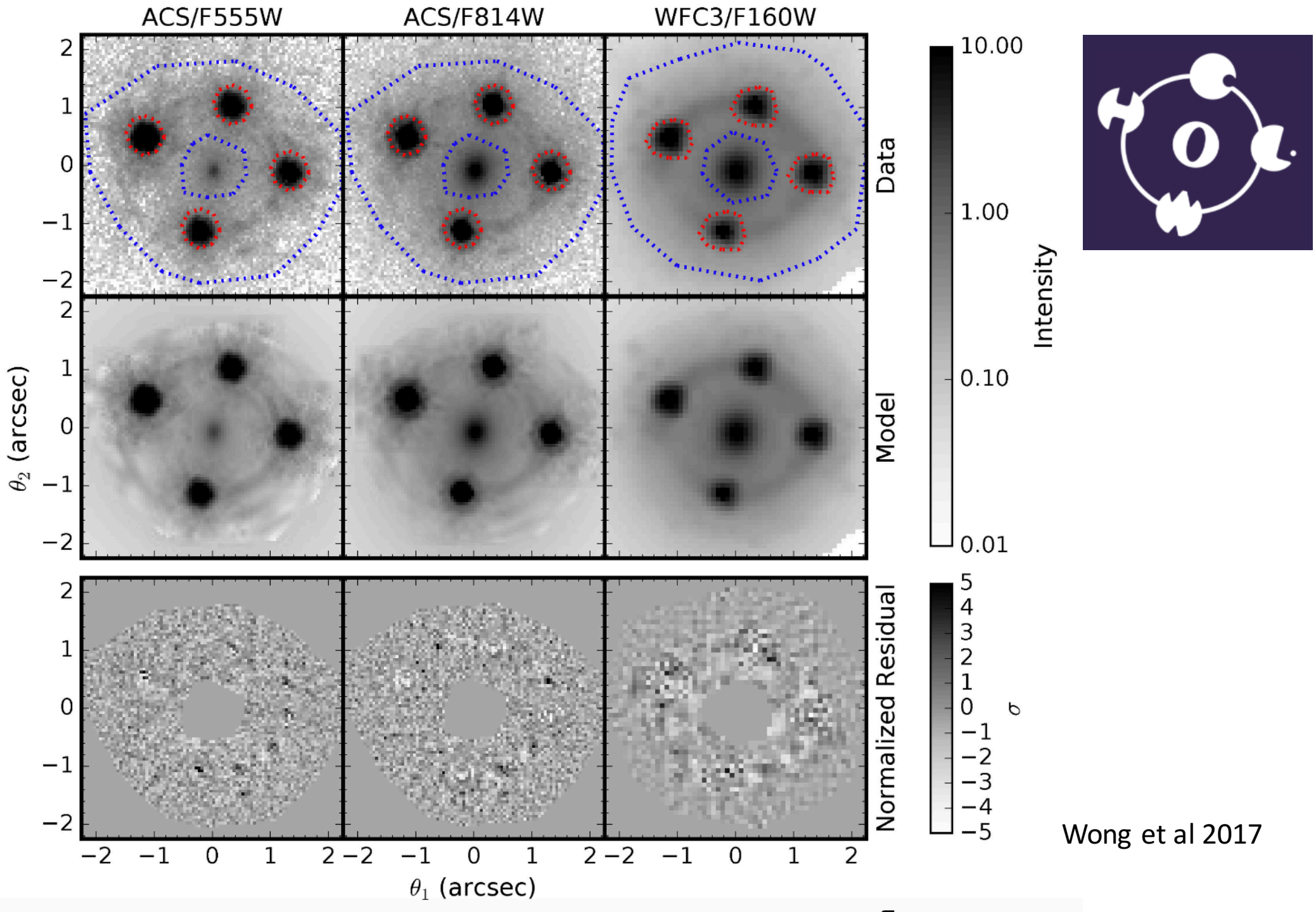


Data (F814W)



Unlensed source

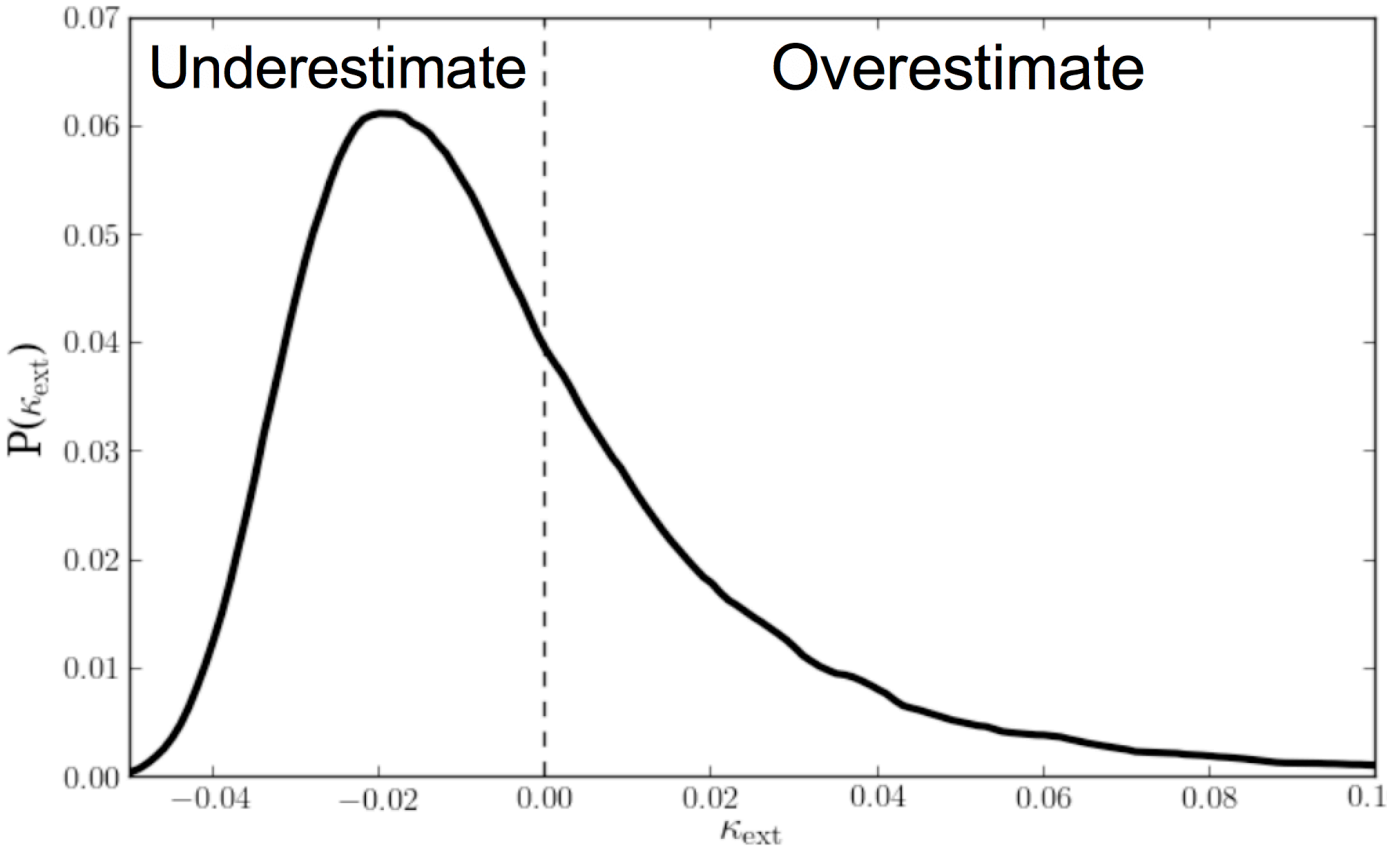
Suyu et al 2013



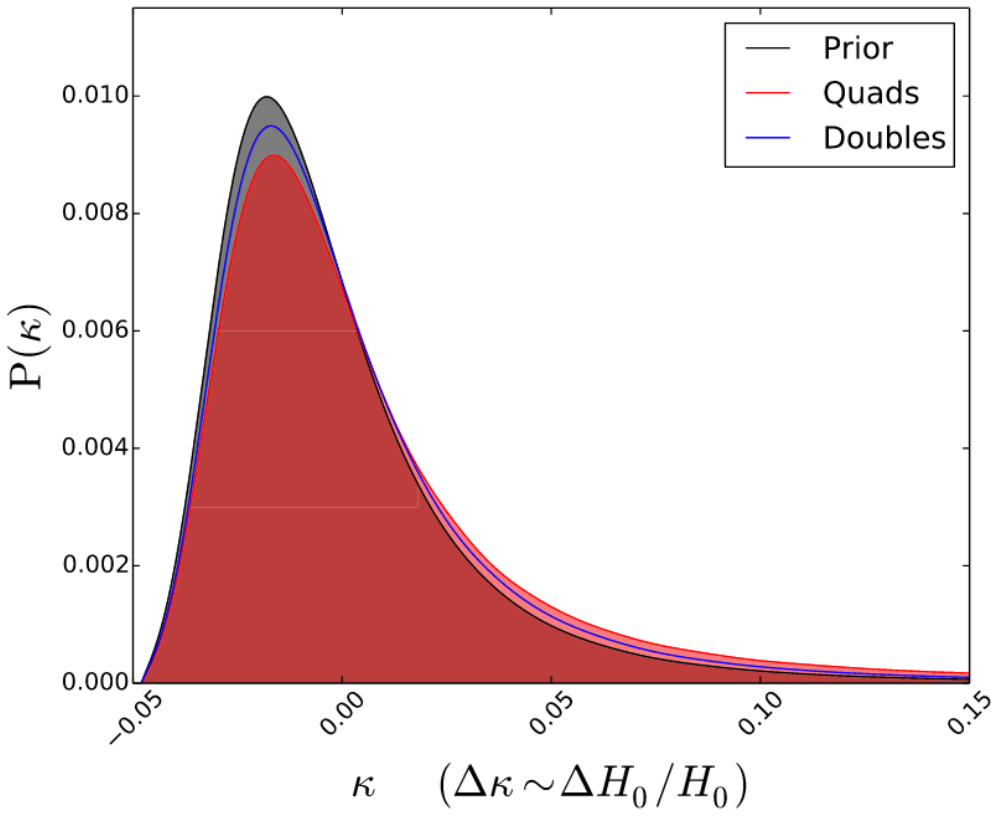
Wong et al 2017

The Line-of-Sight

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



Hilbert+ 2010

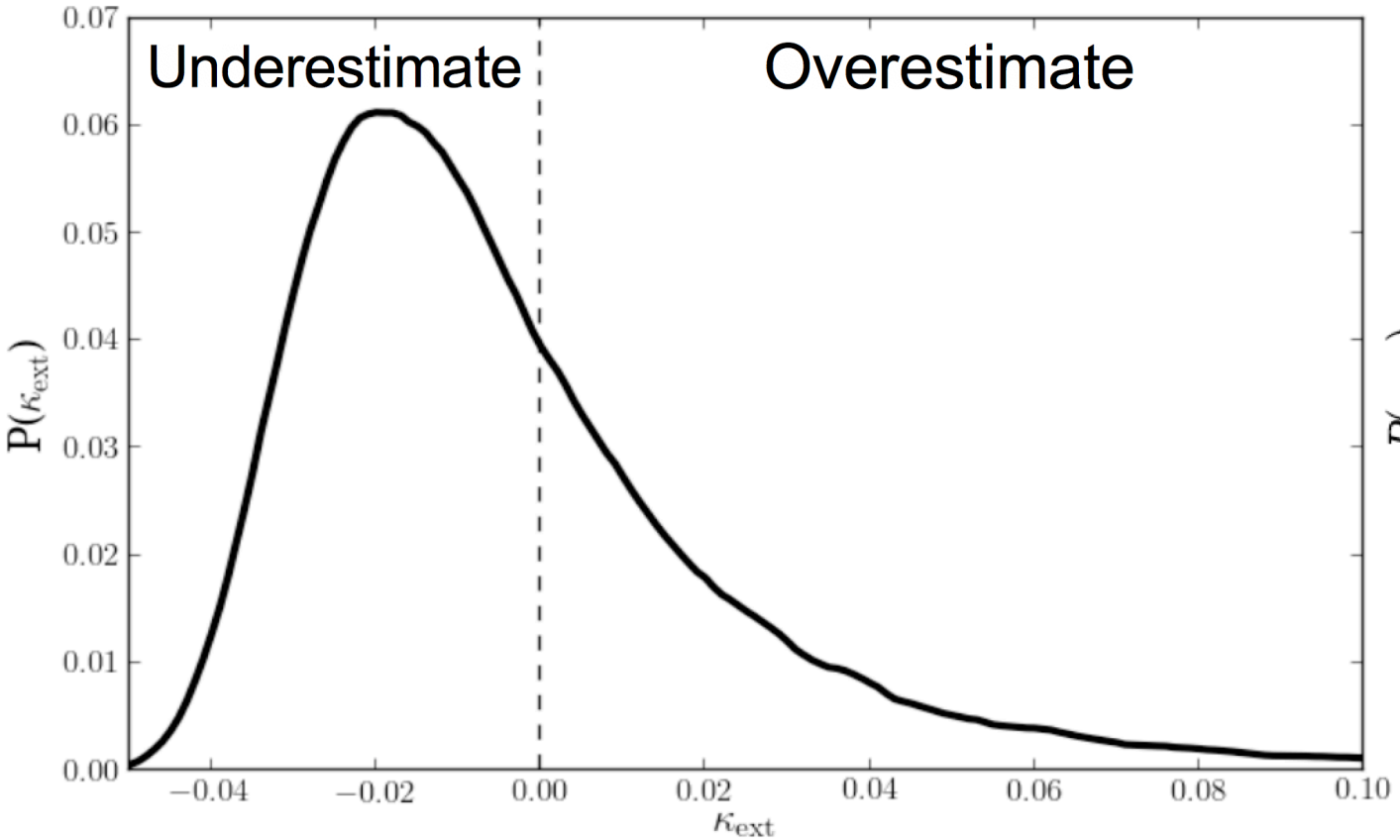


Collett & Cunnington 2016

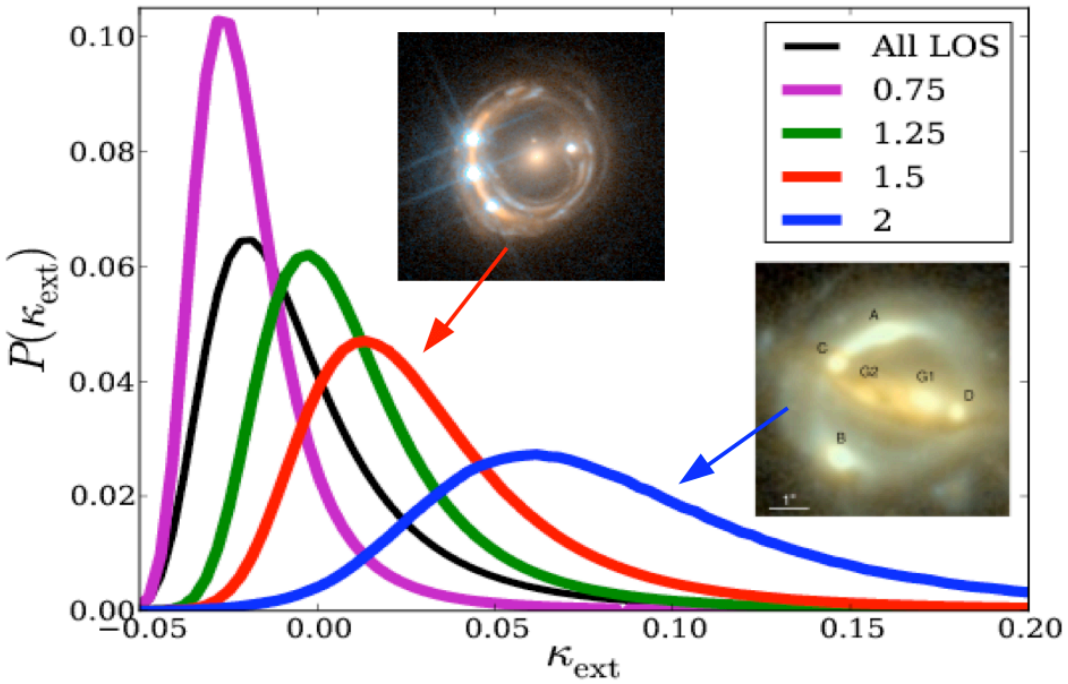
Ray tracing through the Millennium Simulation

The Line-of-Sight

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



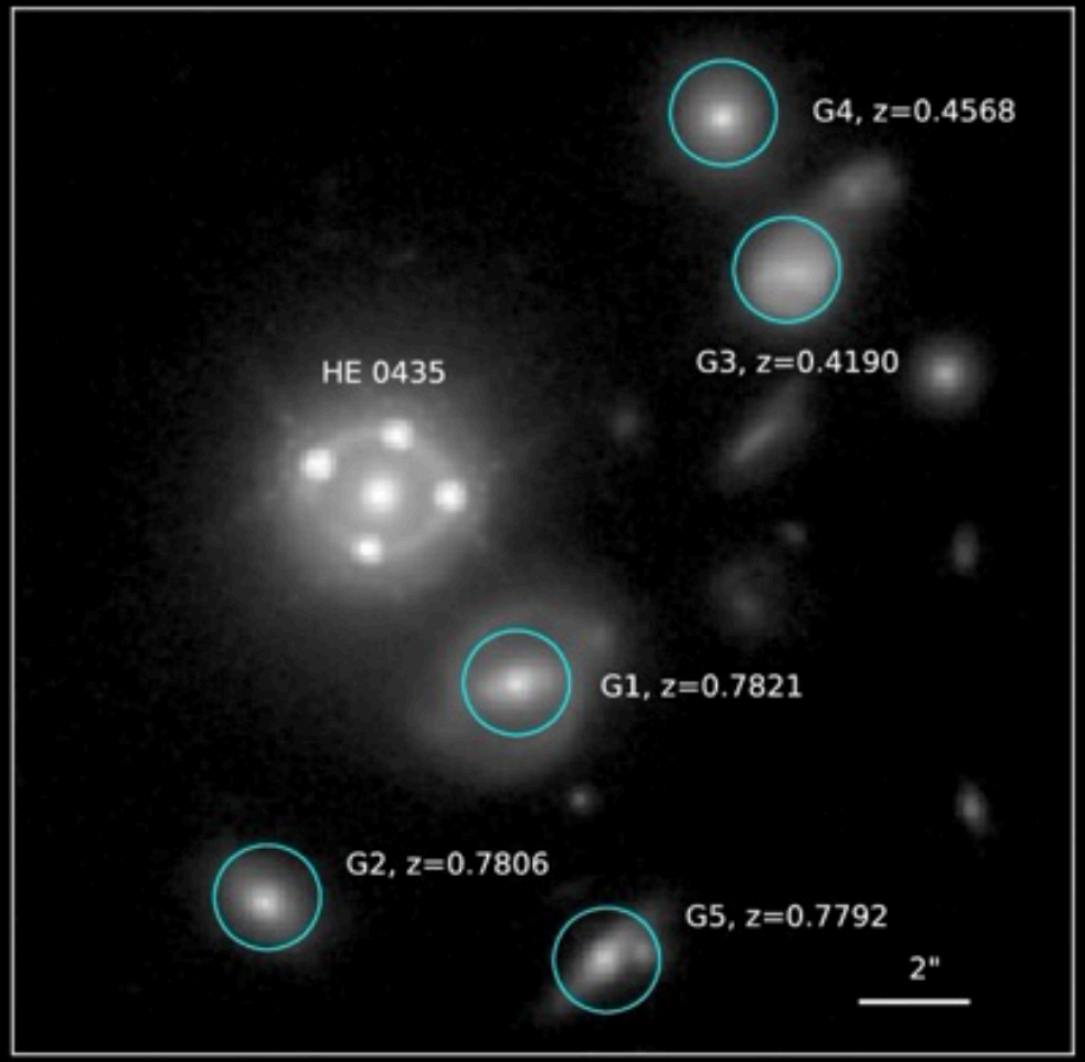
Hilbert+ 2010



Ray tracing through the Millennium Simulation

Lens environment

Spectroscopic campaign of HE0435-1223 field

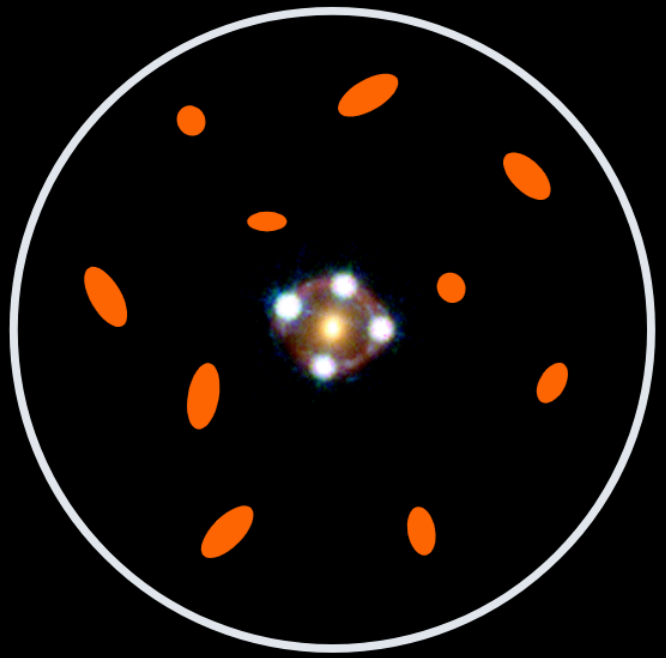


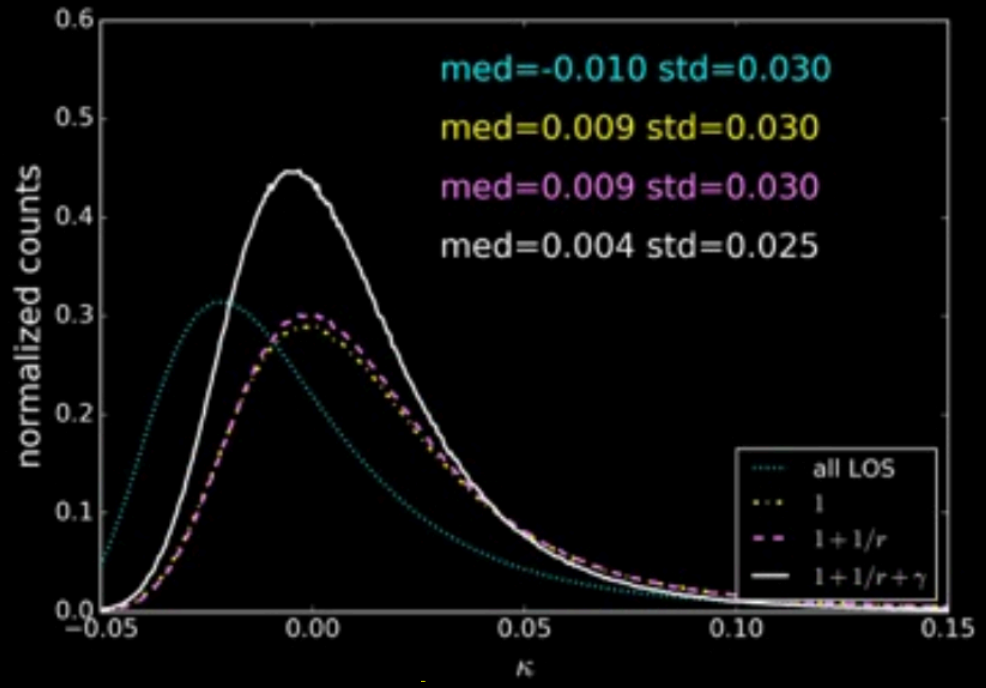
- 100 spec-z within 3' from strong lens
- identified 9 group candidates
- spec-z of galaxies within 12" measured, important for lens mass model
- negligible flexion shift [McCully et al. 2016]: most galaxies and groups can be treated as external shear field [Sluse, Sonnenfeld, Rumbaugh et al. arxiv:1607.00382]

Sluse et al 2017
Rusu et al 2017

Lens environment

- wide-field multi-band imaging to quantify κ_{ext}
- weighted number counts + Millennium Simulation
  [Fassnacht et al. 2011; Hilbert et al. 2007, 2009; Suyu et al. 2010, 2013, Greene et al. 2013]
- thorough investigation of weighting schemes with CFHTLenS as control field, get κ_{ext} distribution with uncertainty σ_κ=0.025
  [Rusu, Fassnacht, Sluse et al. arxiv:1607.01047]





Sluse et al 2017
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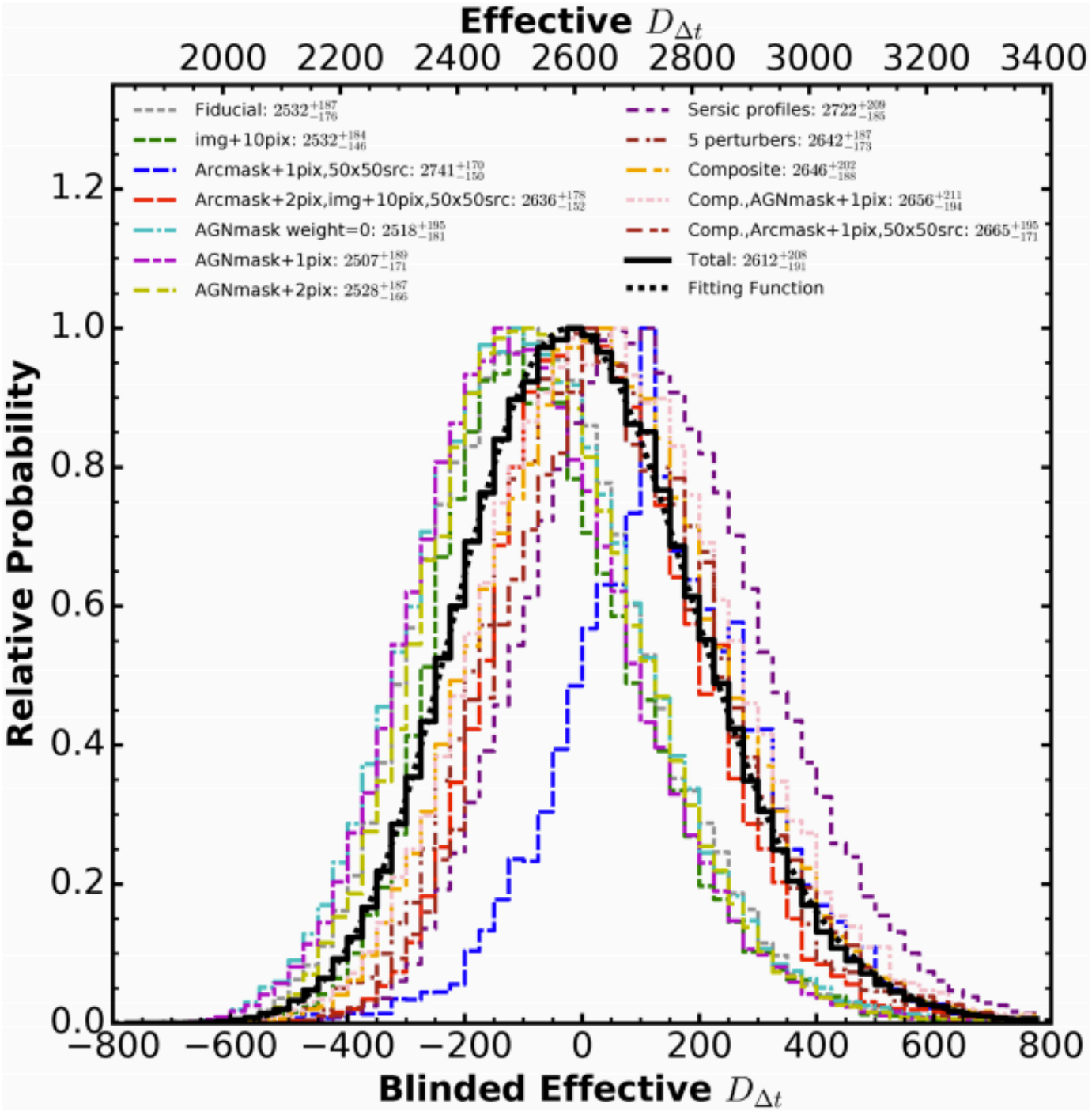
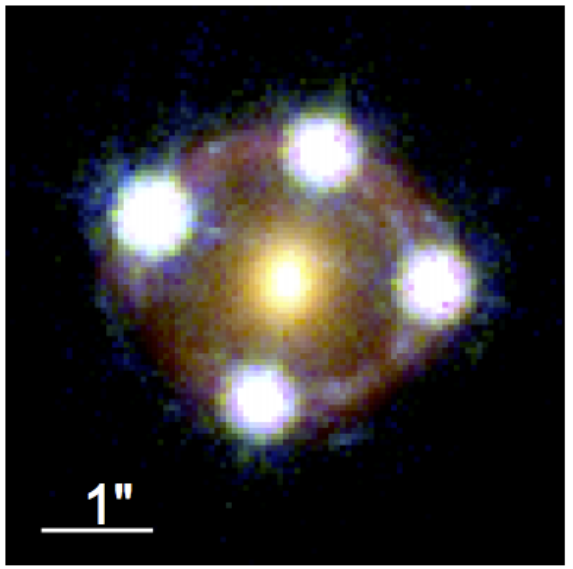
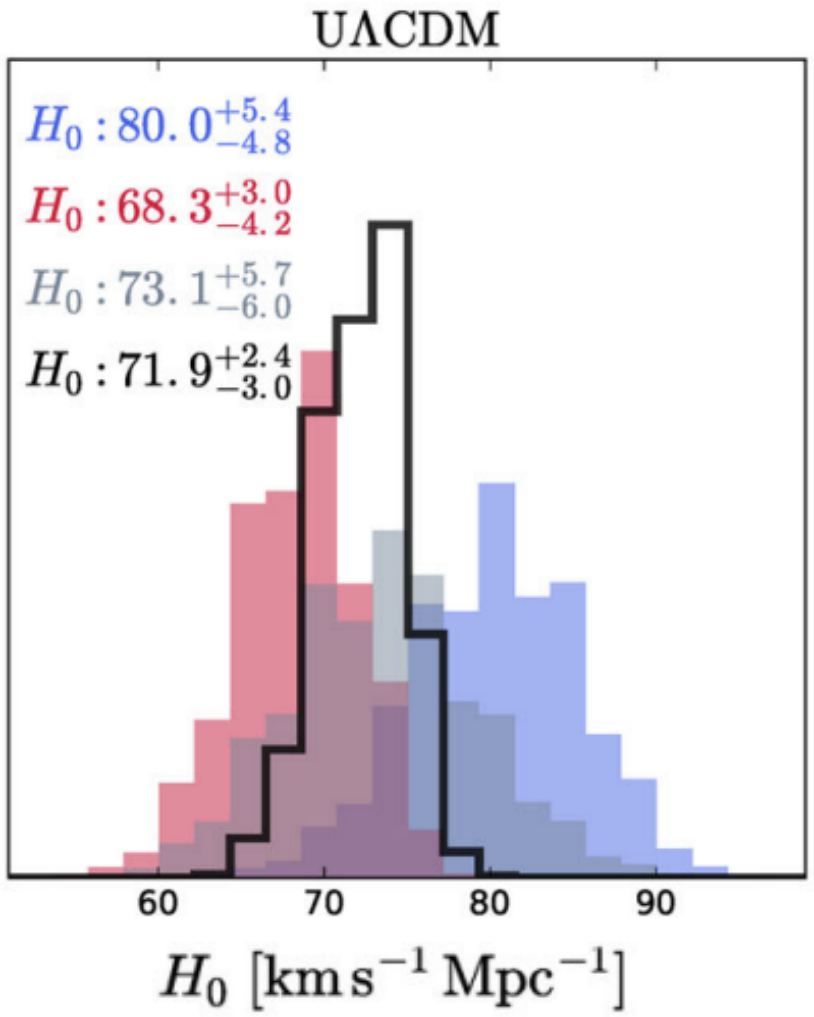
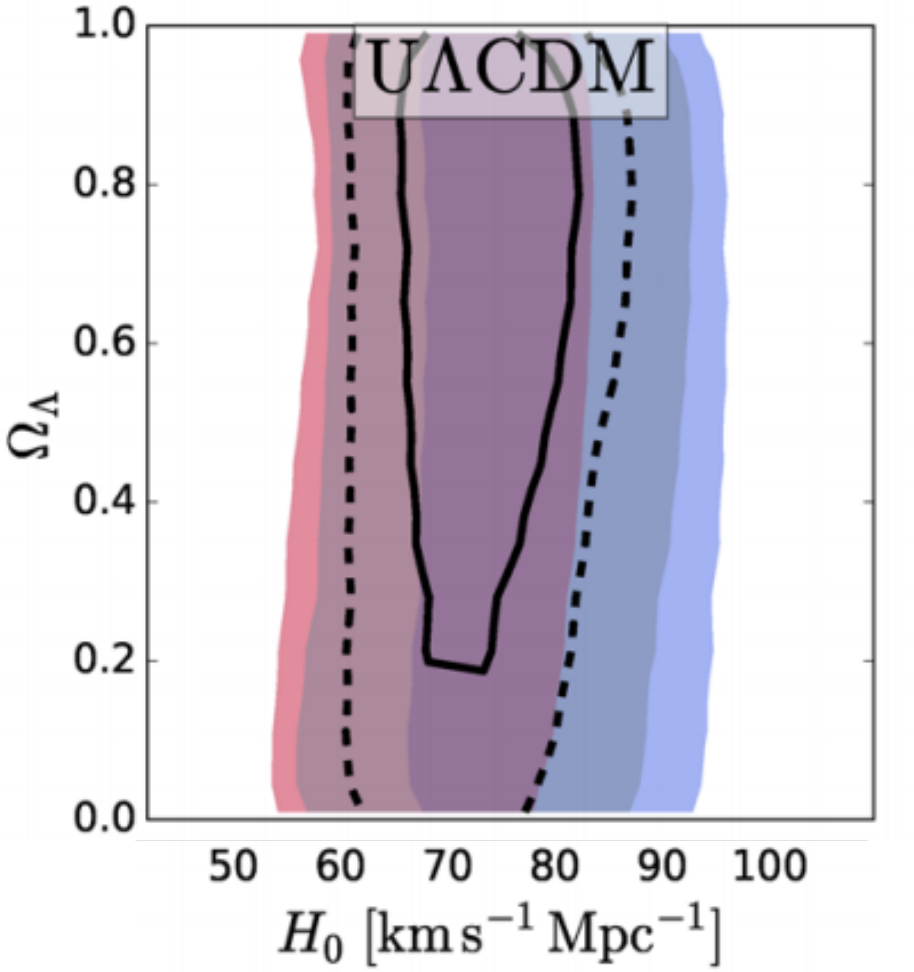


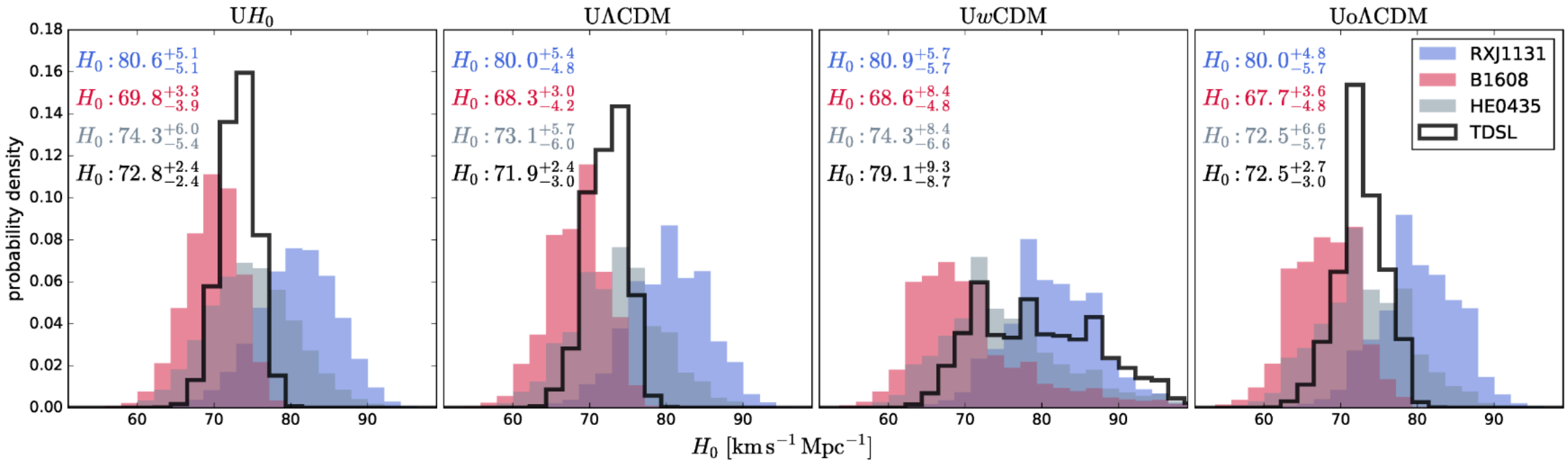


Wong et al 2017





Bonvin et al 2017



Flat ΛCDM cosmology
$\Omega_m = 1 - \Omega_\Lambda = 0.32$
H_0 uniform in [0, 150]

Flat ΛCDM cosmology
$\Omega_m = 1 - \Omega_\Lambda$
H_0 uniform in [0, 150]
Ω_m uniform in [0, 1]

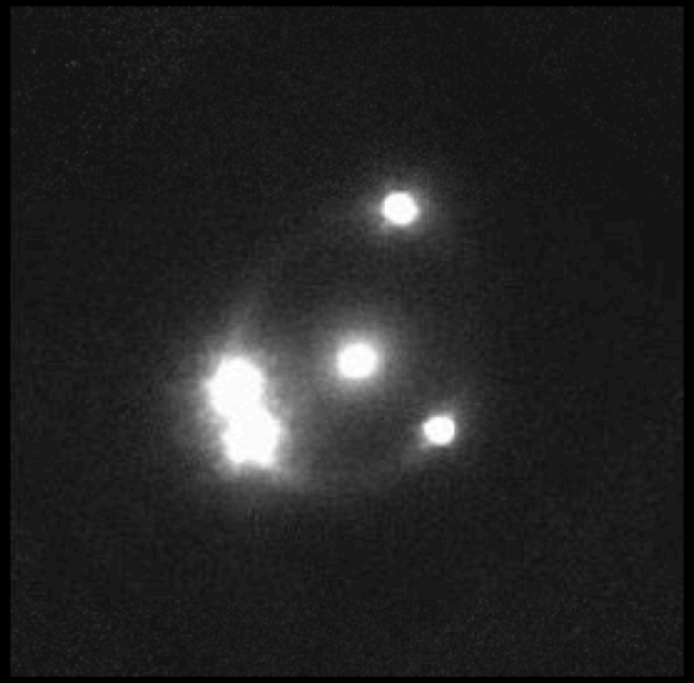
Flat wCDM cosmology
H_0 uniform in [0, 150]
Ω_{de} uniform in [0, 1]
w uniform in [−2.5, 0.5]

Non-flat ΛCDM cosmology
$\Omega_m = 1 - \Omega_\Lambda - \Omega_k > 0$
H_0 uniform in [0, 150]
Ω_Λ uniform in [0, 1]
Ω_k uniform in [−0.5, 0.5]

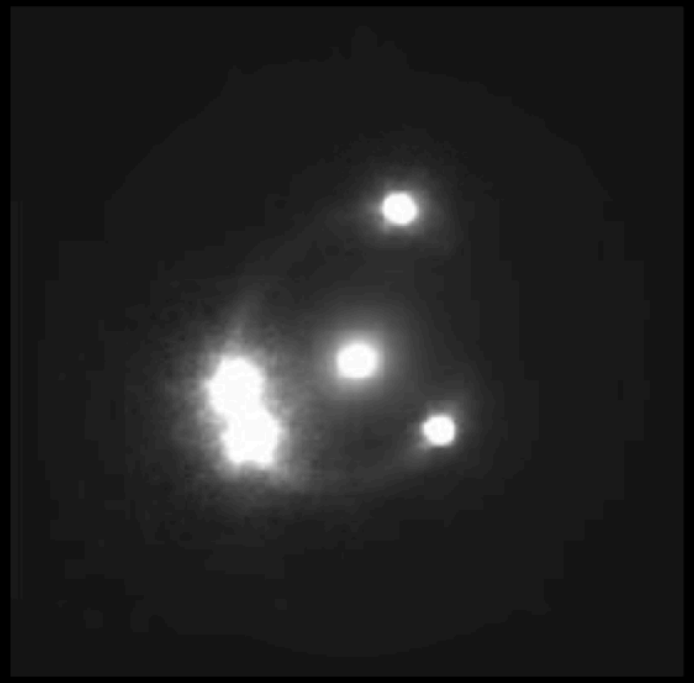
UH0	UΛCDM		UwCDM			UoΛCDM		
H_0	H_0	Ω_Λ	H_0	Ω_{de}	w	H_0	Ω_Λ	Ω_k
$72.8^{+2.4}_{-2.4}$	$71.9^{+2.4}_{-3.0}$	$0.62^{+0.24}_{-0.35}$	$79.1^{+9.3}_{-8.7}$	$0.72^{+0.19}_{-0.34}$	$-1.79^{+0.94}_{-0.49}$	$72.5^{+2.7}_{-3.0}$	$0.51^{+0.28}_{-0.30}$	$0.1^{+0.3}_{-0.3}$

Bonvin et al 2017

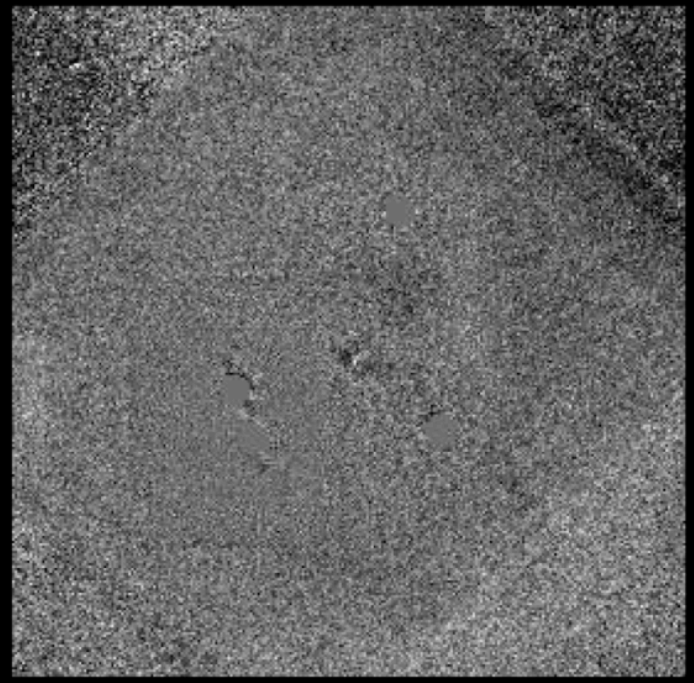
data



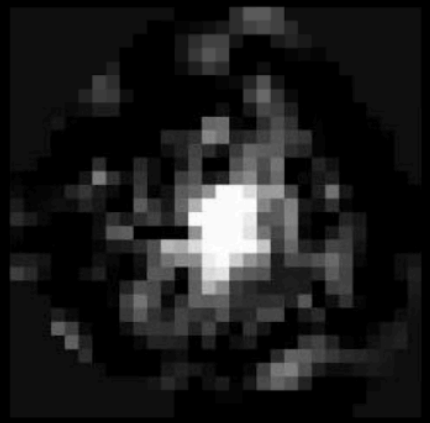
model



Normalized residuals

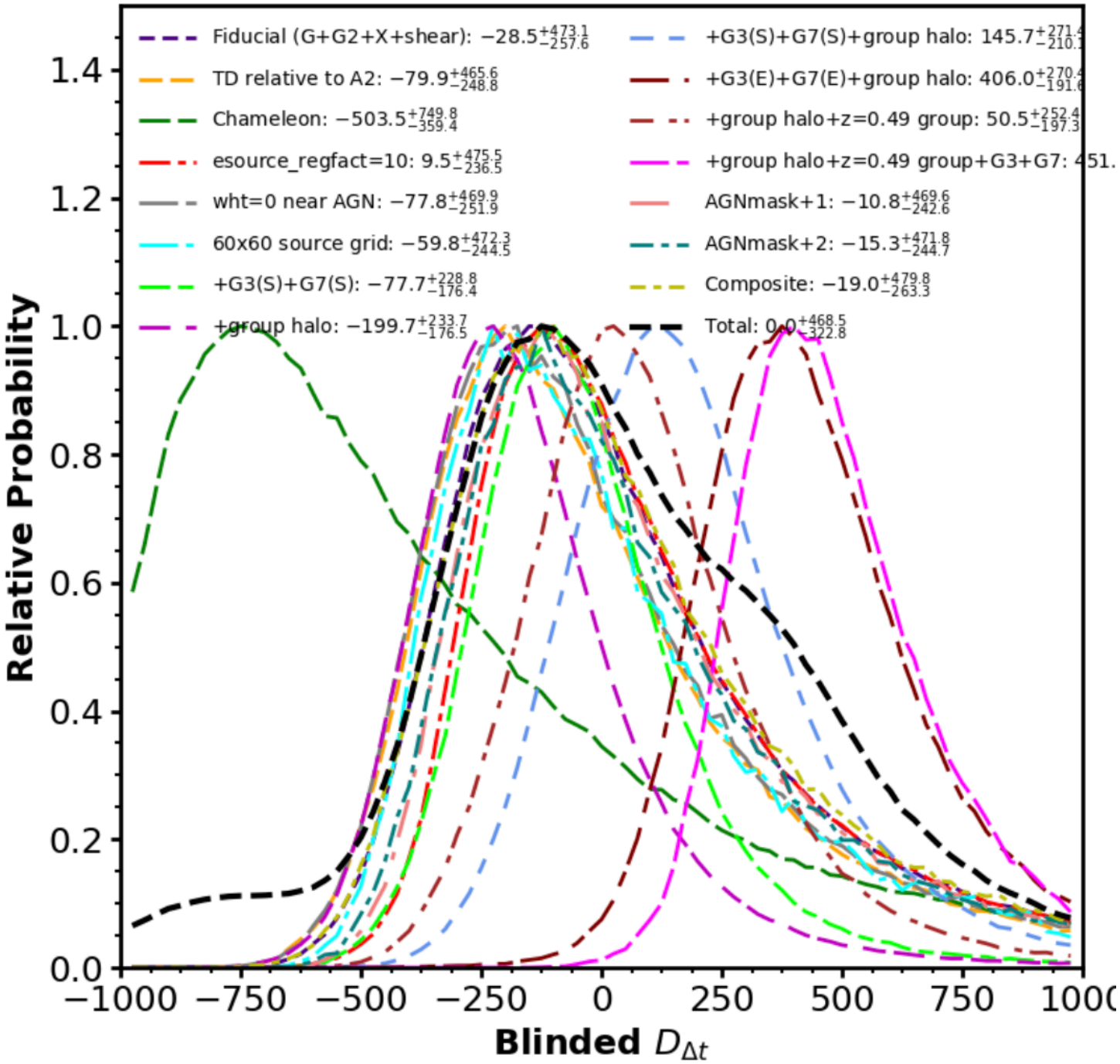


Reconstructed source

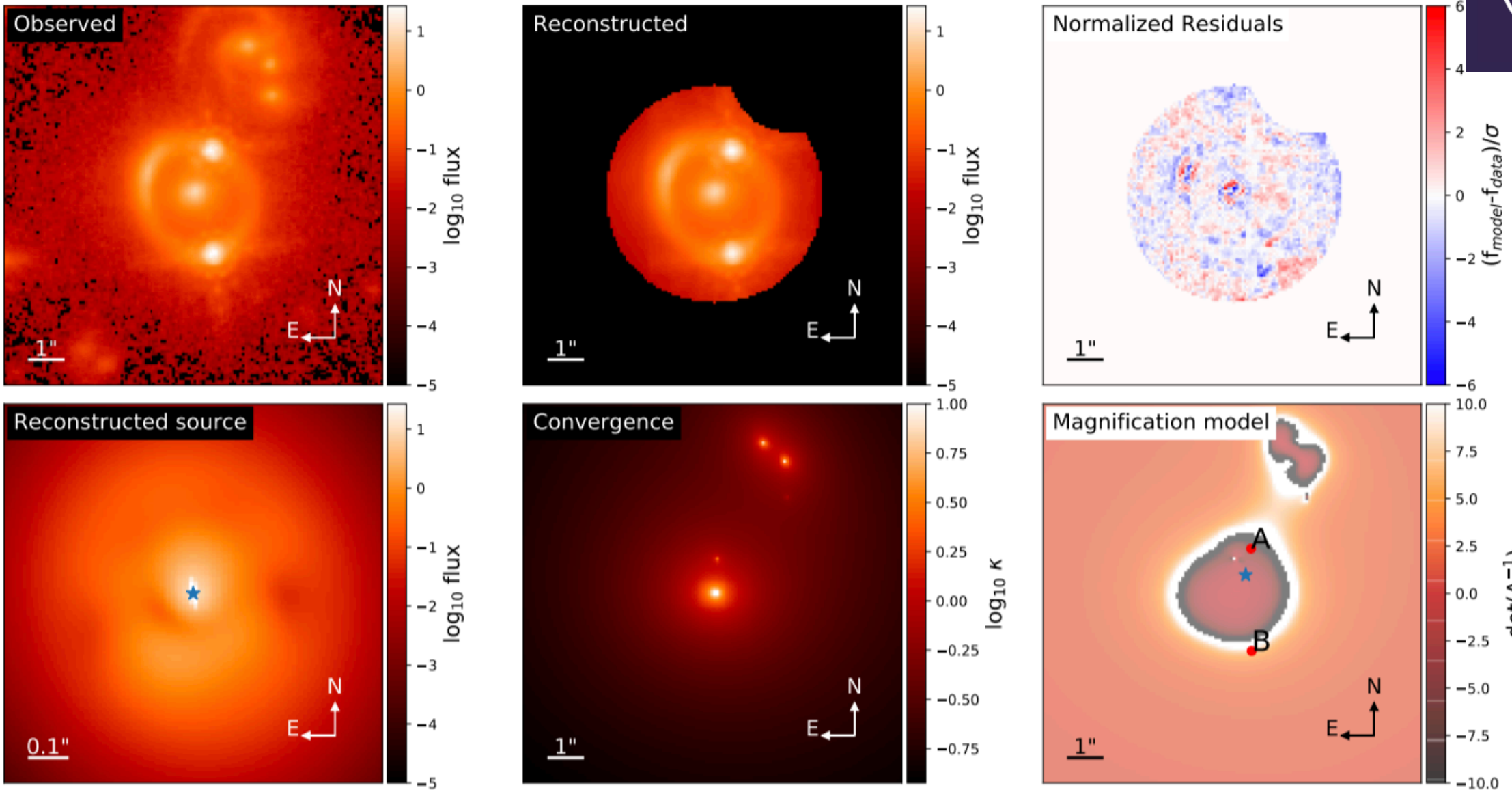


AO modeling

Chen et al. in prep.



Wong et al in prep

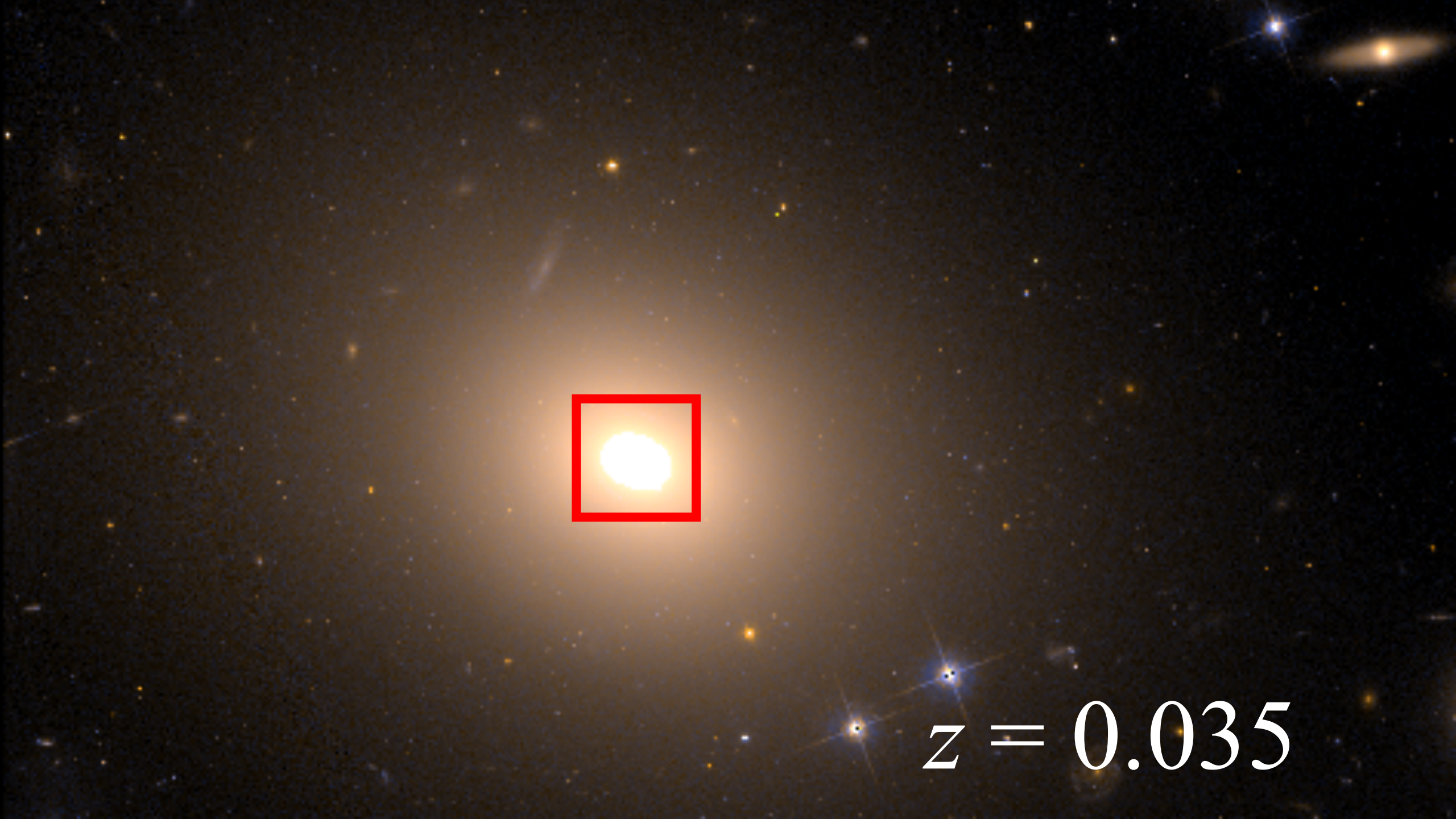


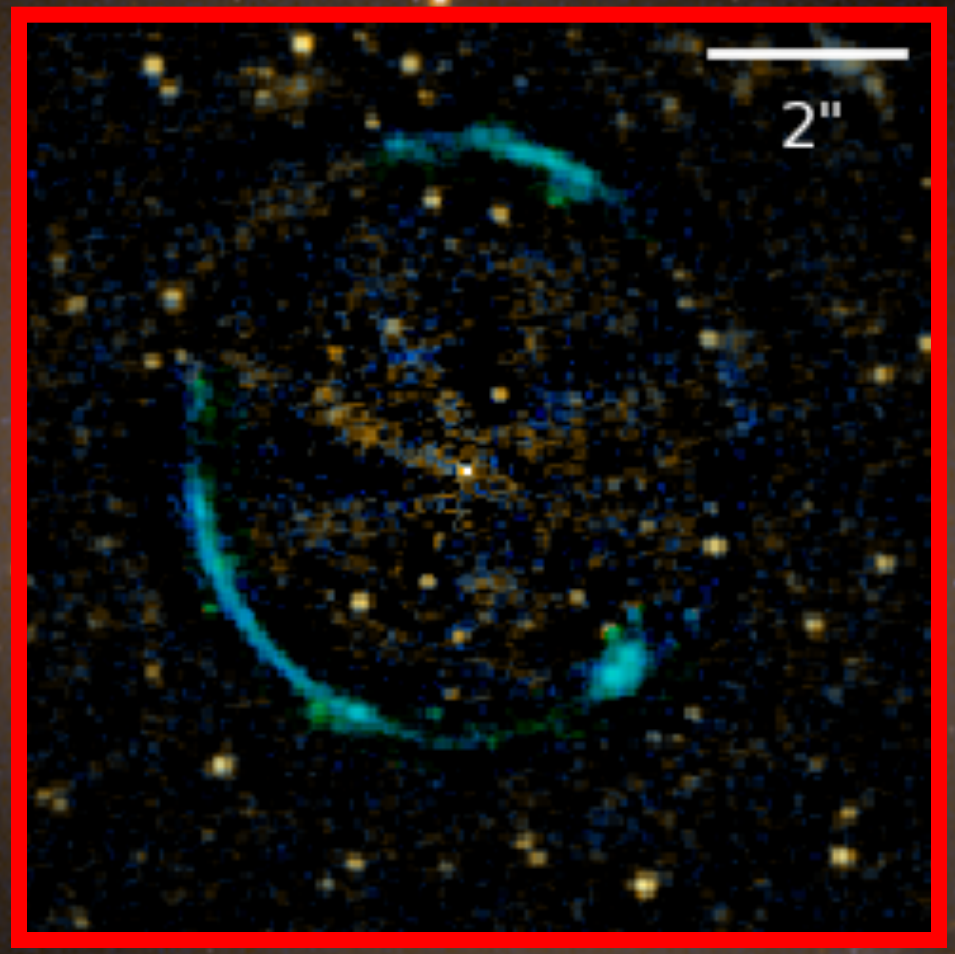
Birrer et al in prep

Beyond time-delays

Low redshift lenses

$z = 0.035$


$z = 0.035$



$z = 0.035$

Data from Collett et al, 2018.

EMBARGOED until 2nd June 2018

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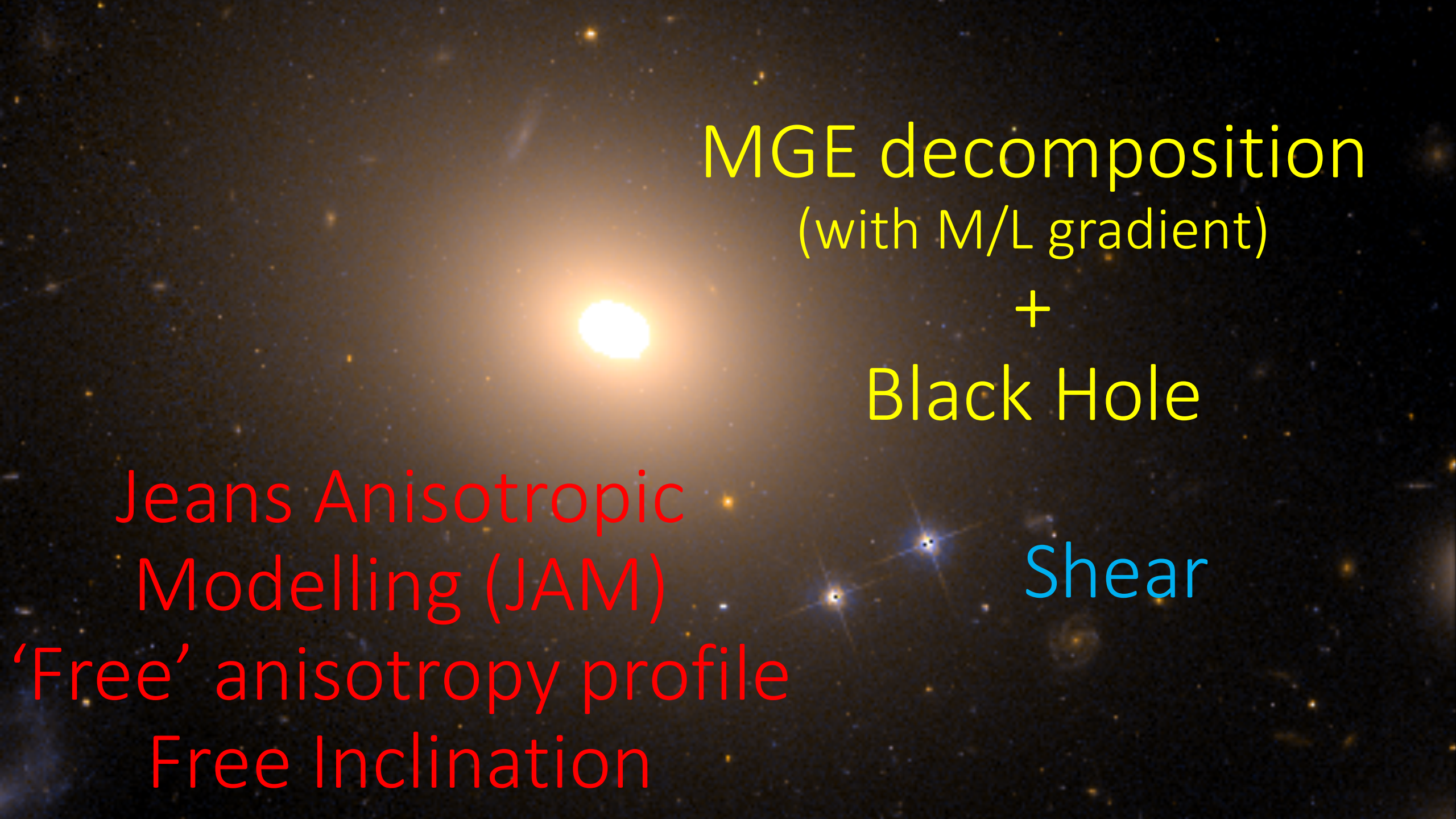
MGE decomposition
(with M/L gradient)
+
Black Hole
Jeans Anisotropic
Modelling (JAM)
‘Free’ anisotropy profile
Free Inclination
Shear

Lens model from Collett et al, 2018.

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Kinematic model from Collett et al, 2018.

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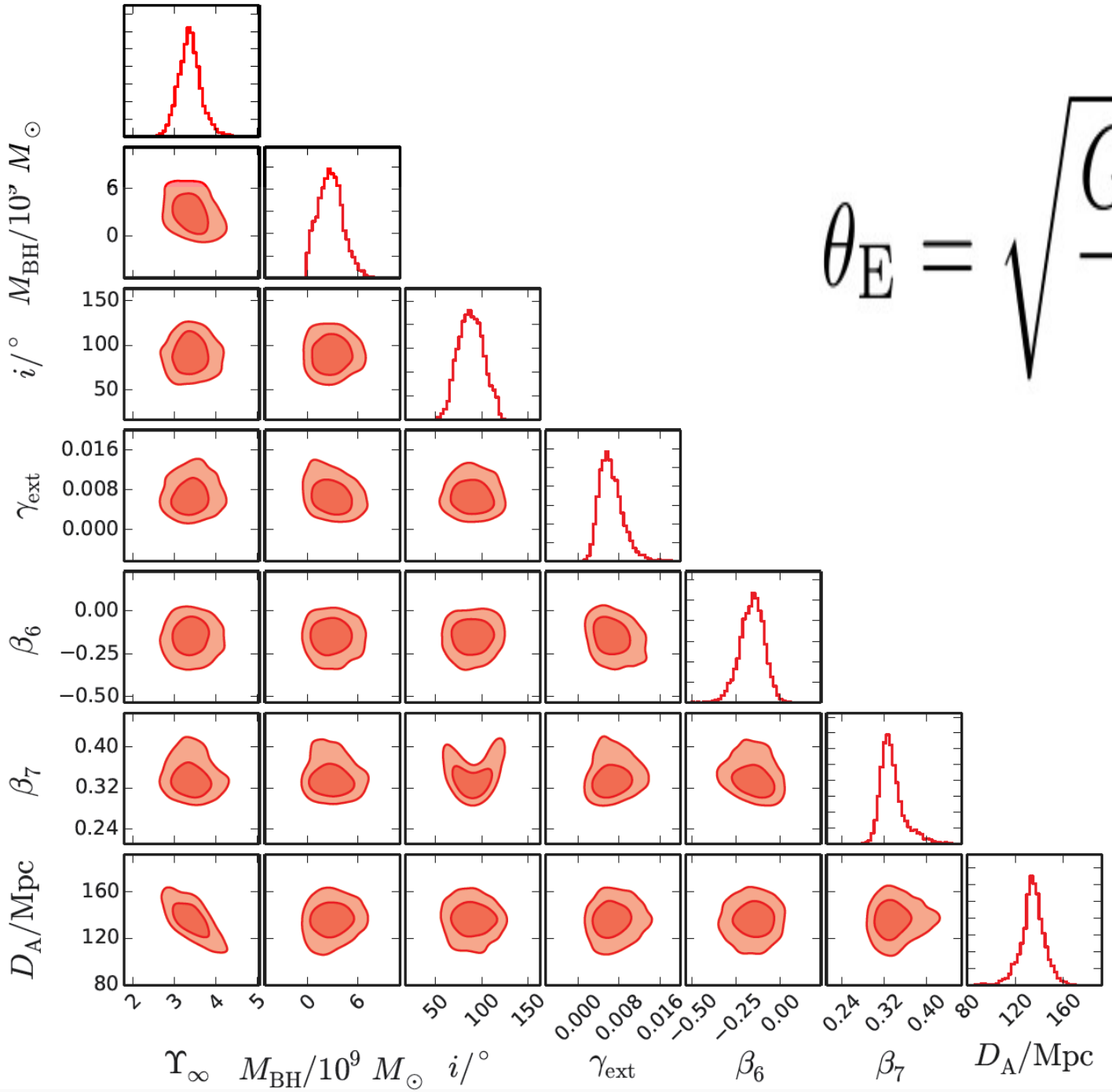
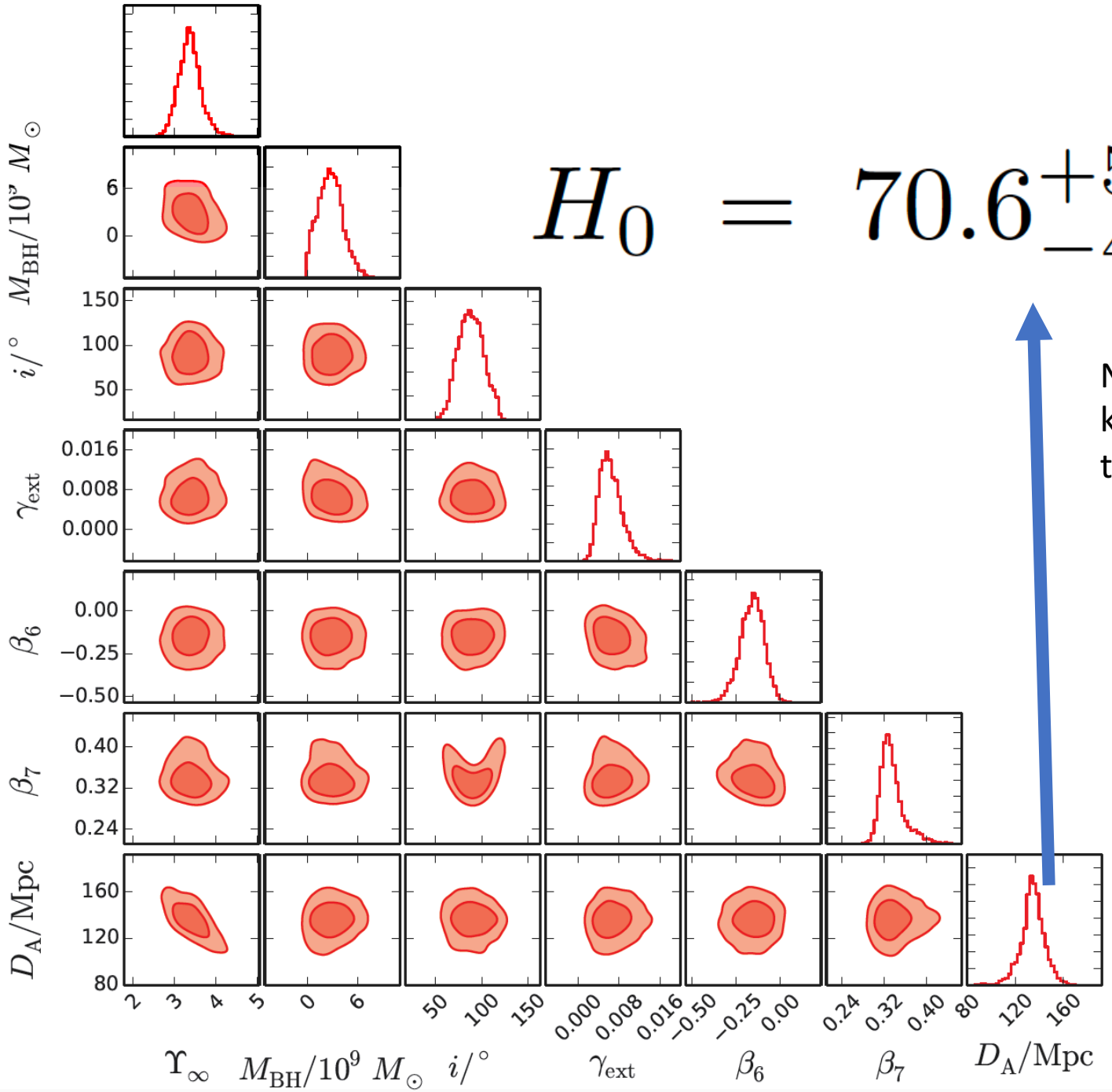


$$\theta_{\rm E} = \sqrt{\frac{GM(\theta_{\rm E})}{c^2}\frac{D_{\rm ls}}{D_{\rm ol}D_{\rm os}}}$$

Collett et al, submitted

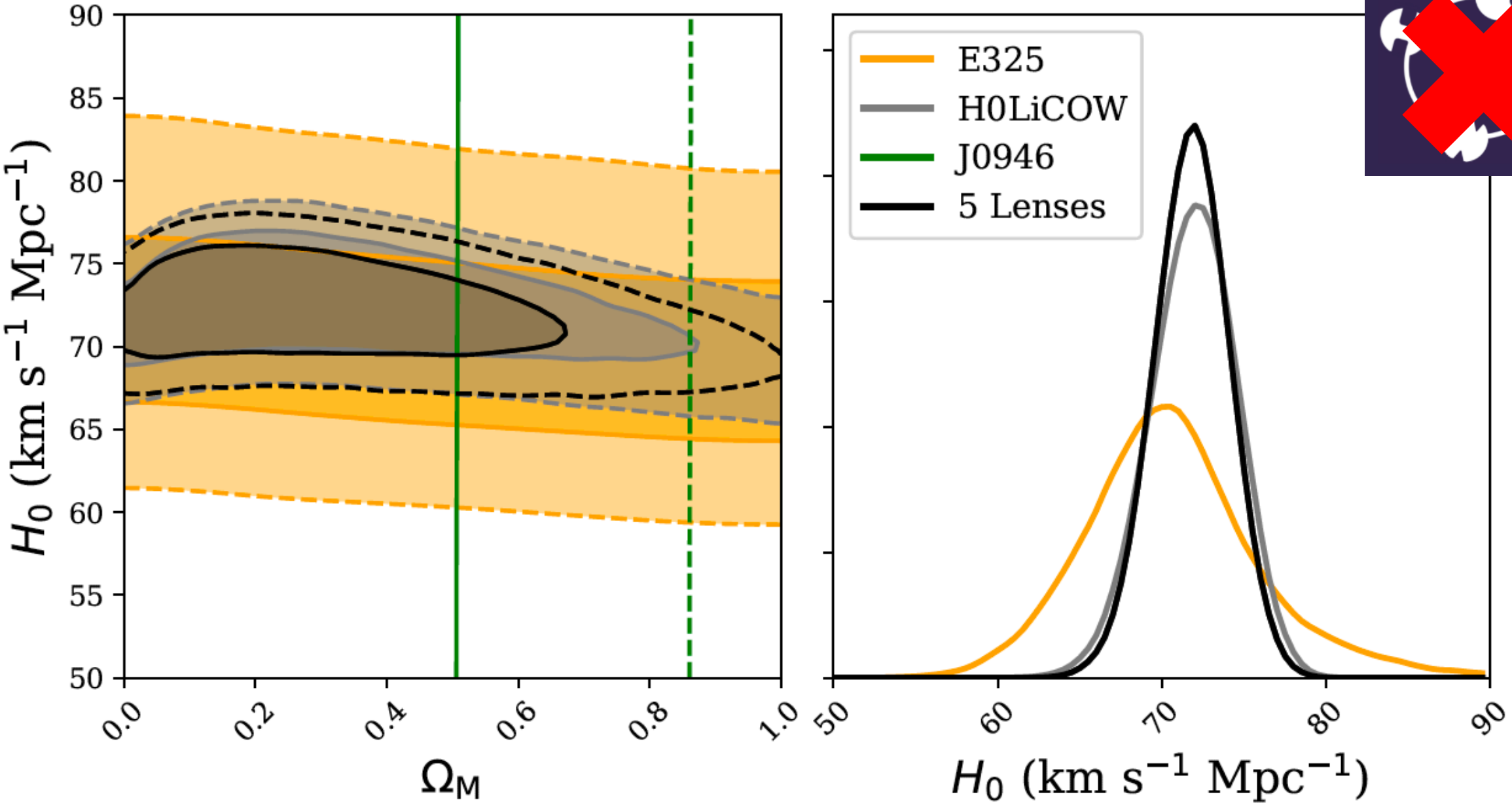


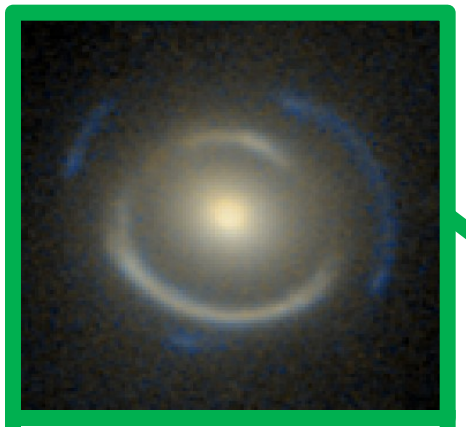
$$H_0 = 70.6^{+5.3}_{-4.7}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

NB/ includes uncertainty due to measuring kinematics -> this measurement is close to the systematic floor :-(

Collett et al, submitted

$$H_0 = 72.1 \pm 2.2\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

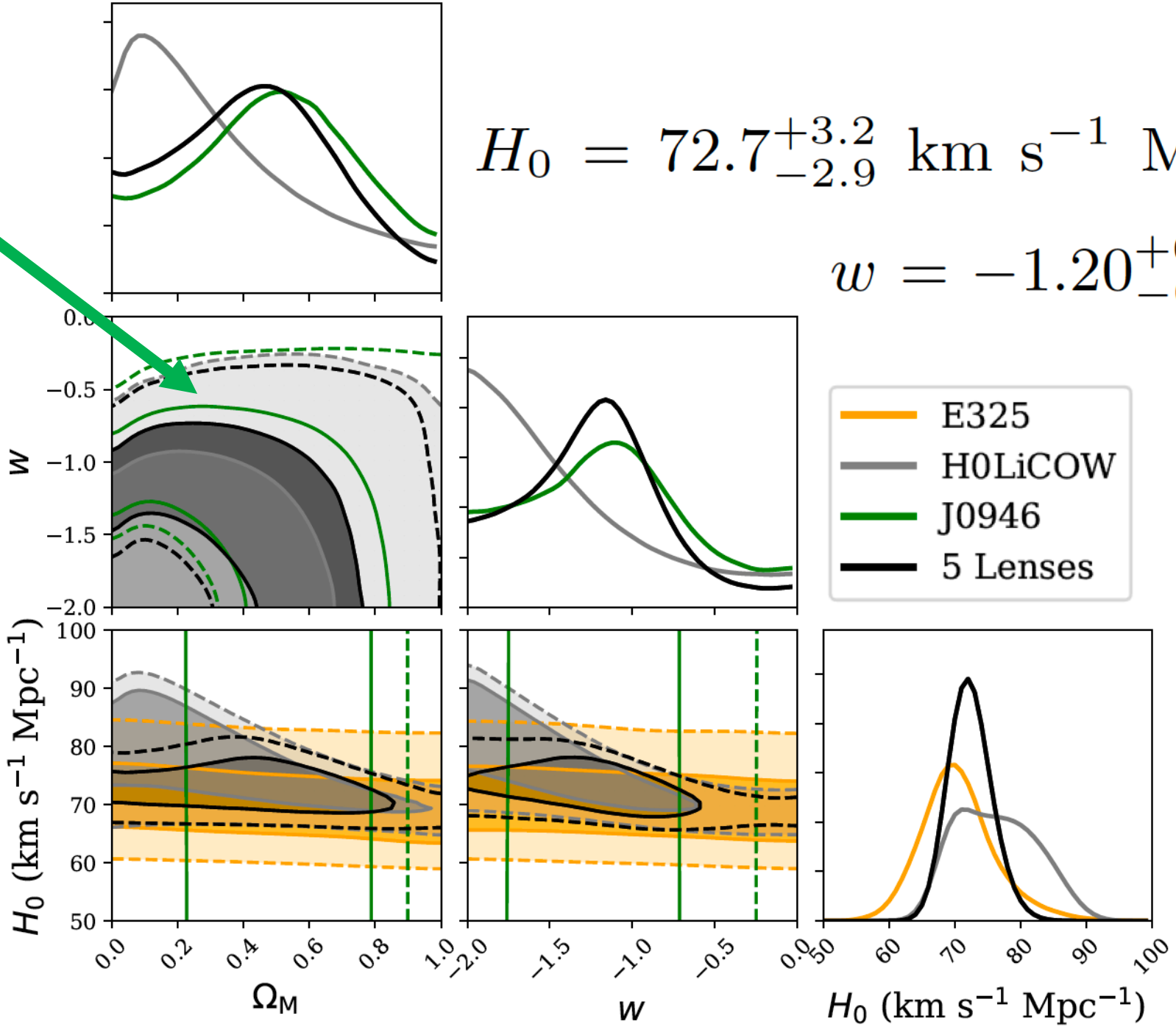




$$\beta = \frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}}$$

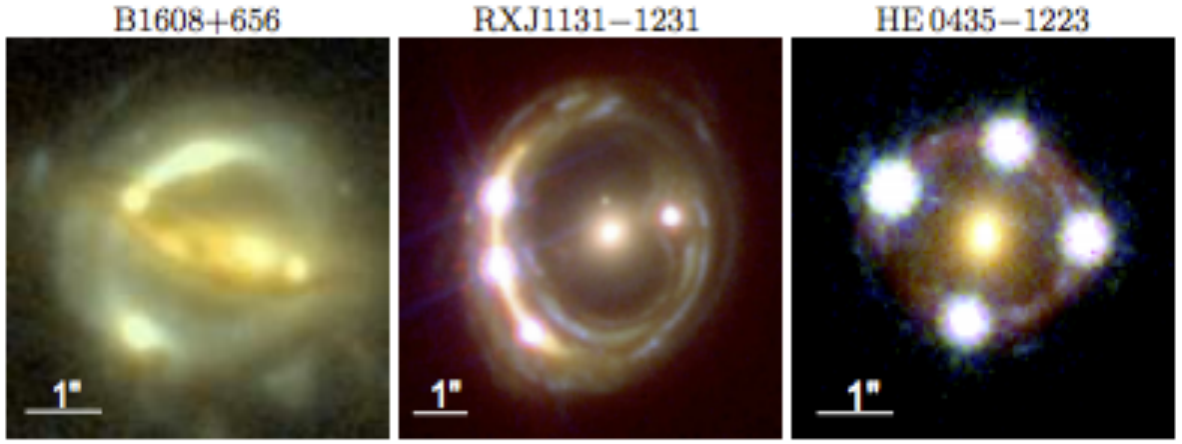
$$H_0 = 72.7^{+3.2}_{-2.9}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

$$w = -1.20^{+0.39}_{-0.46}$$

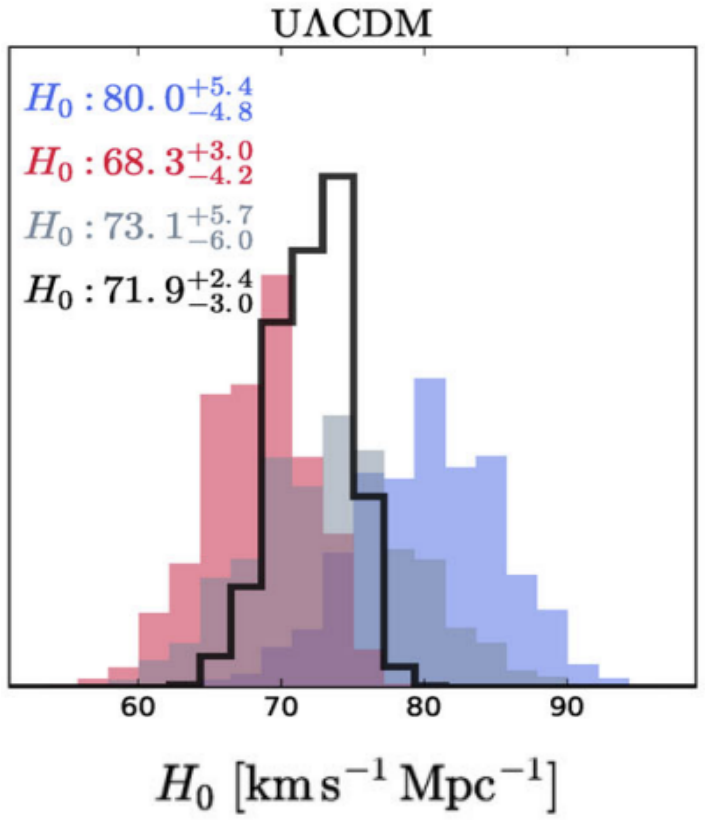


$o w_0 w_a$CDM

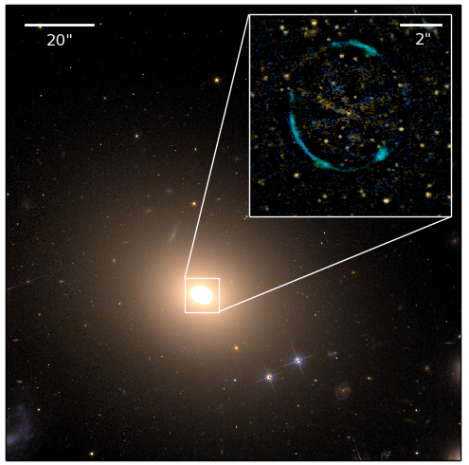
$72.7^{+3.3}_{-2.9}$

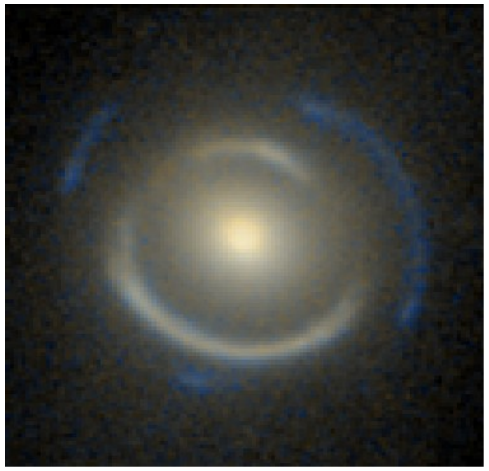


$$H_0 = 71.9^{+2.4}_{-3.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

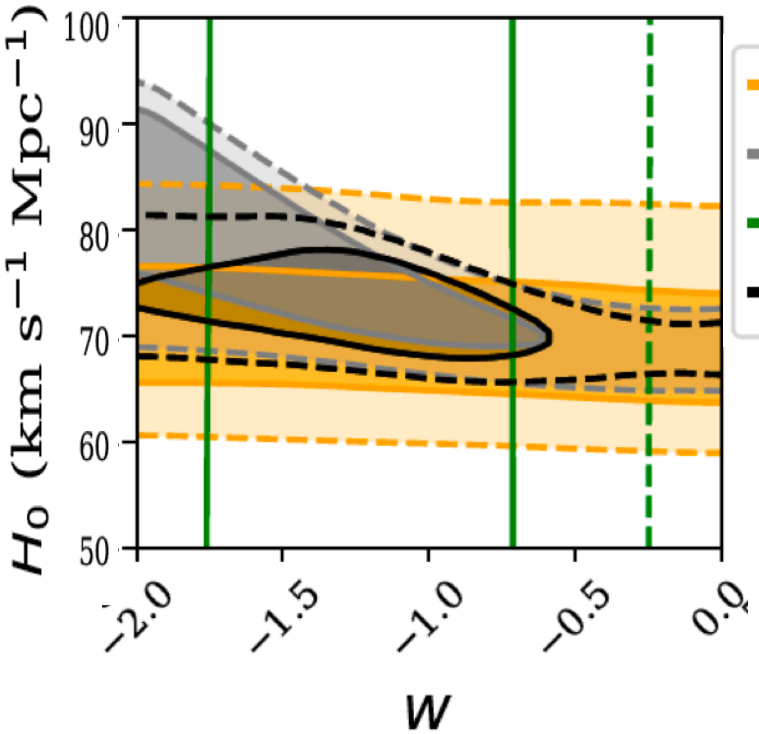


Bonvin et al 2017





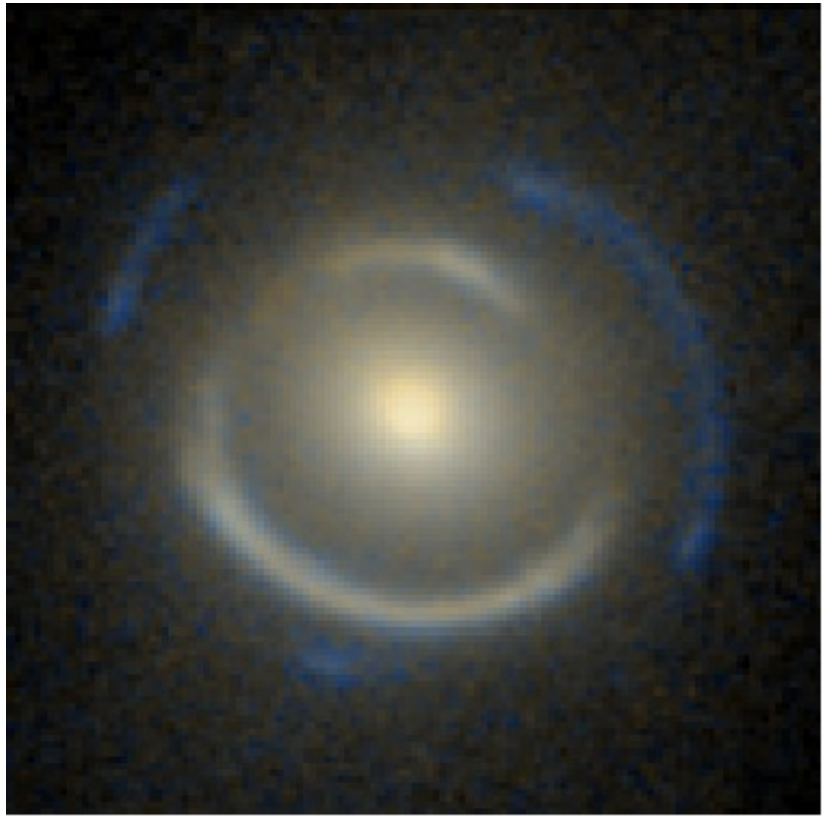
$$H_0 = 72.1 \pm 2.2\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$



Collett et al, submitted

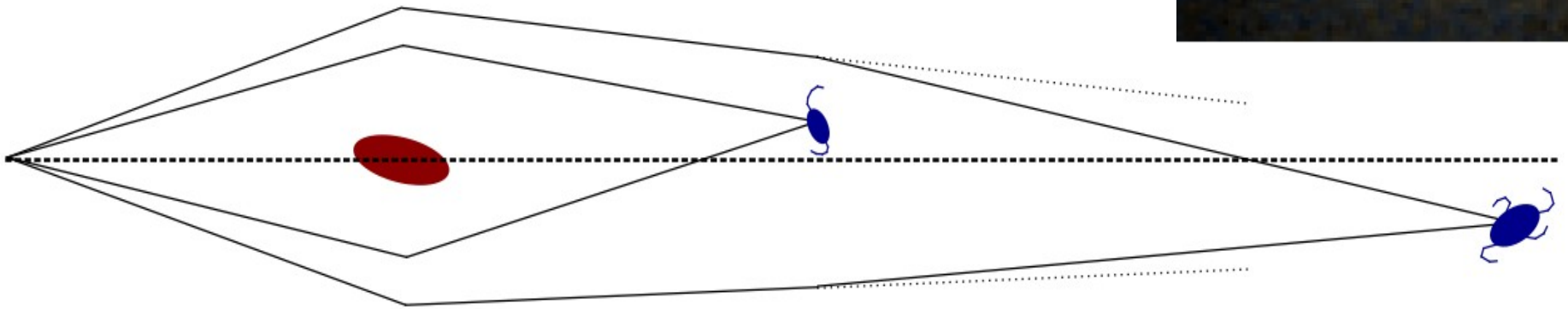
Extra slides

Beyond time-delays

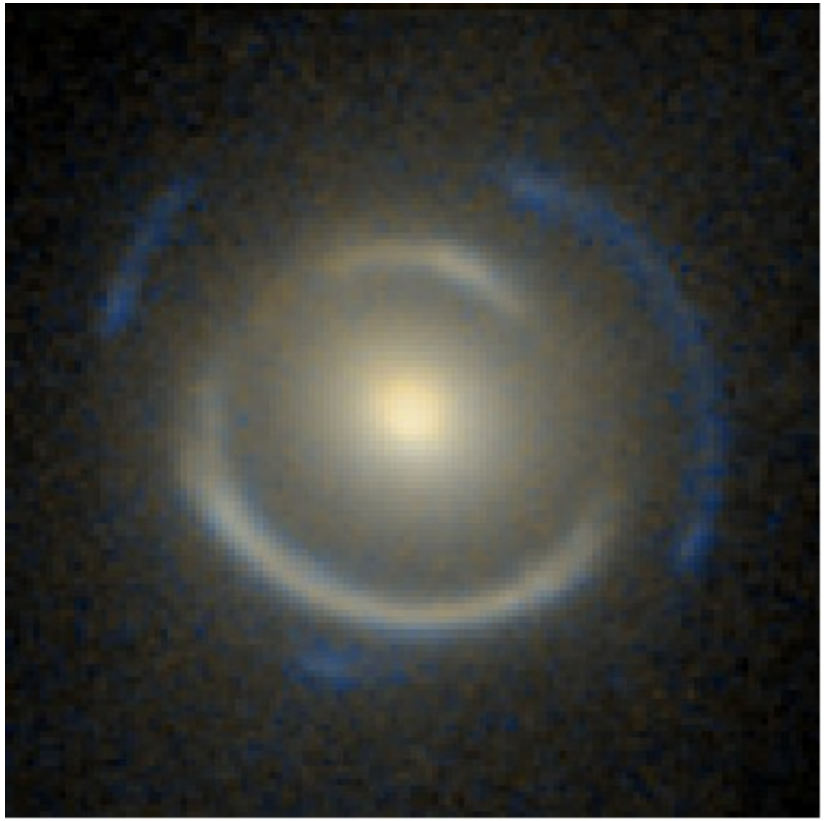


Double source plane strong lensing

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

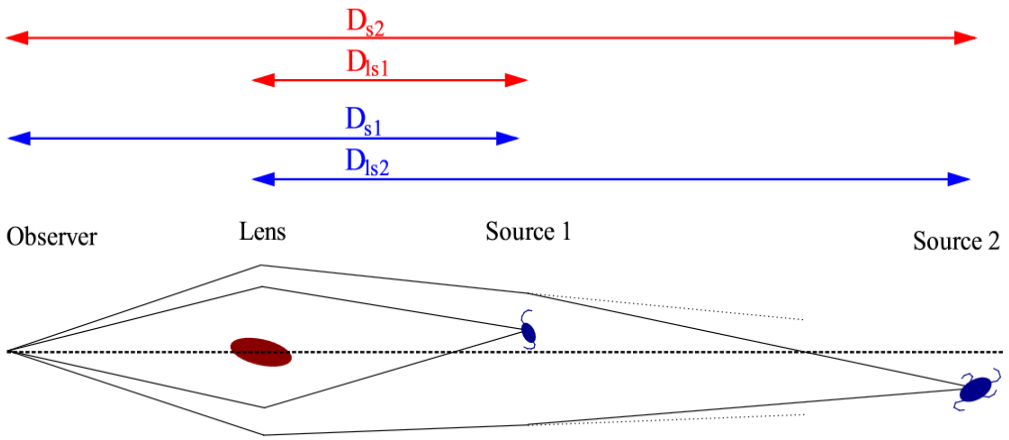


New observable:
Ratio of Einstein radii

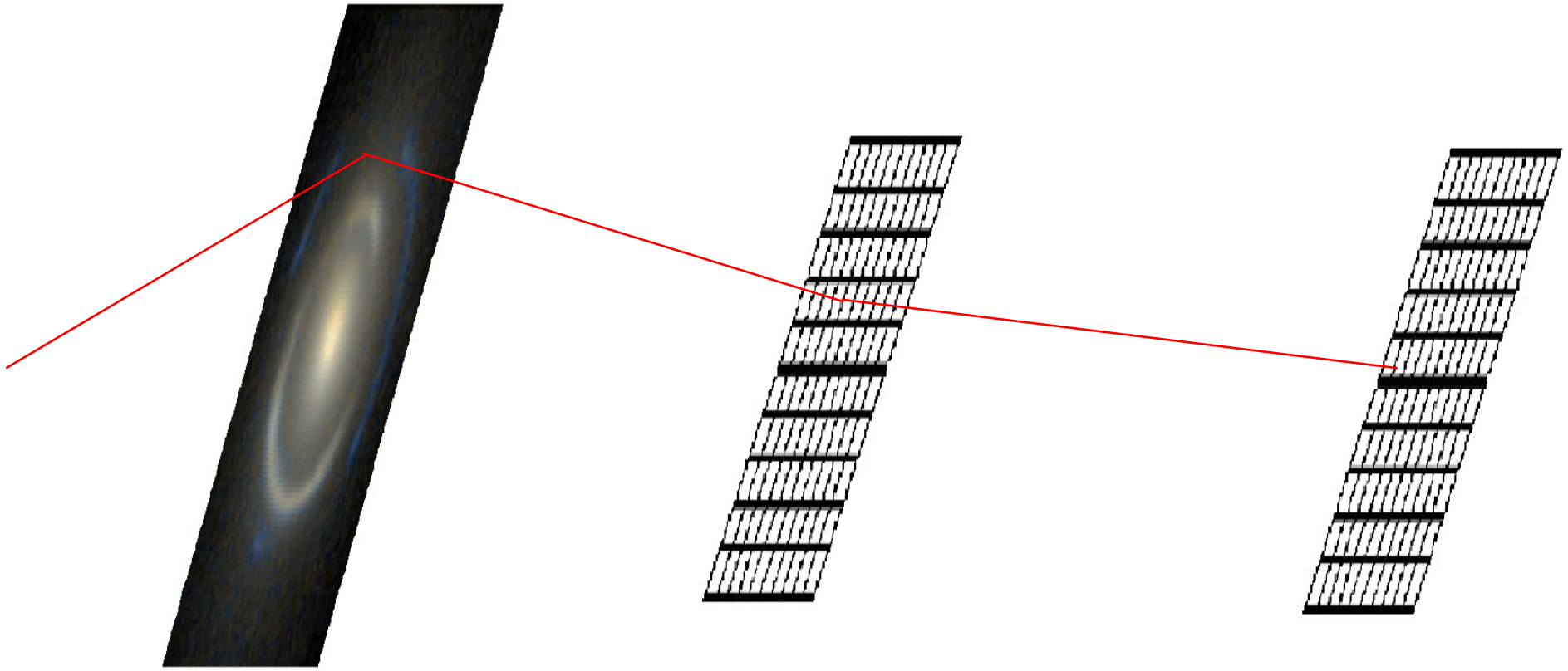


$$\beta = \frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}}$$

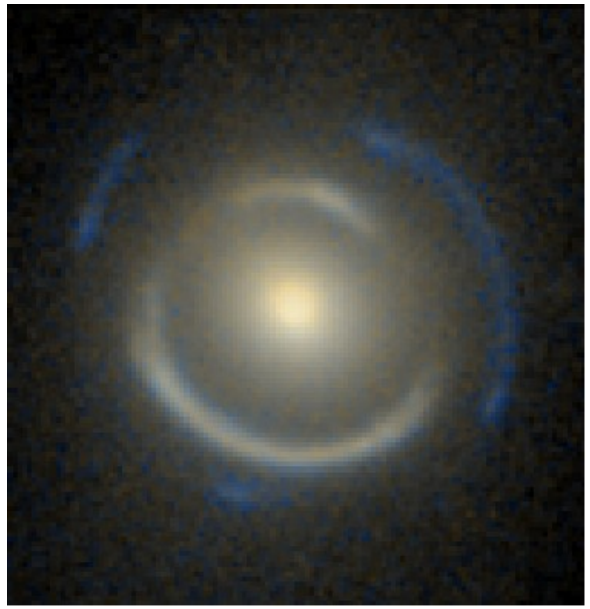
No dependence on the Hubble constant!



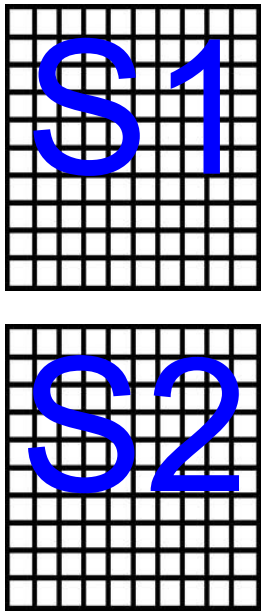
Lens modelling



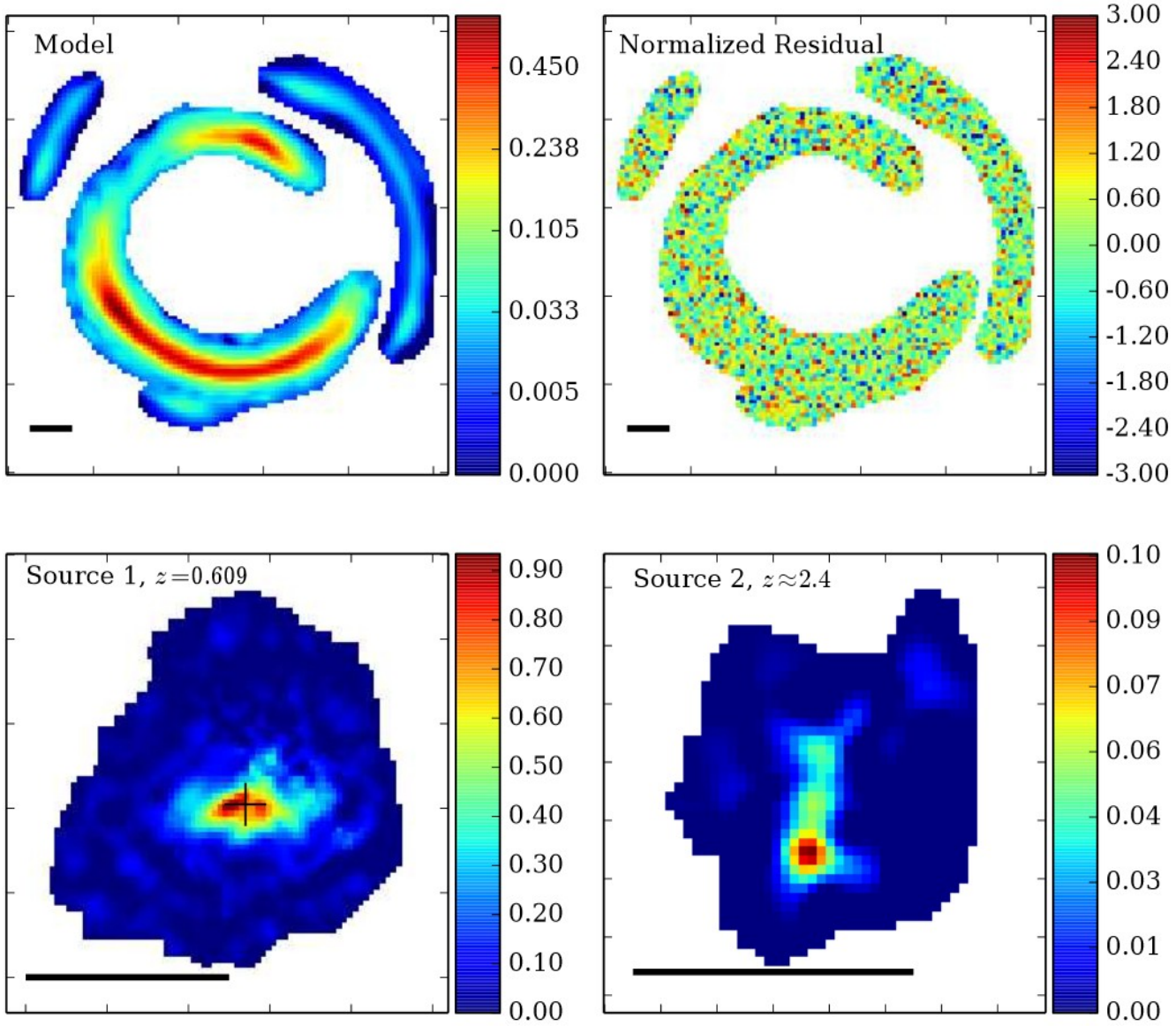
Lens modelling



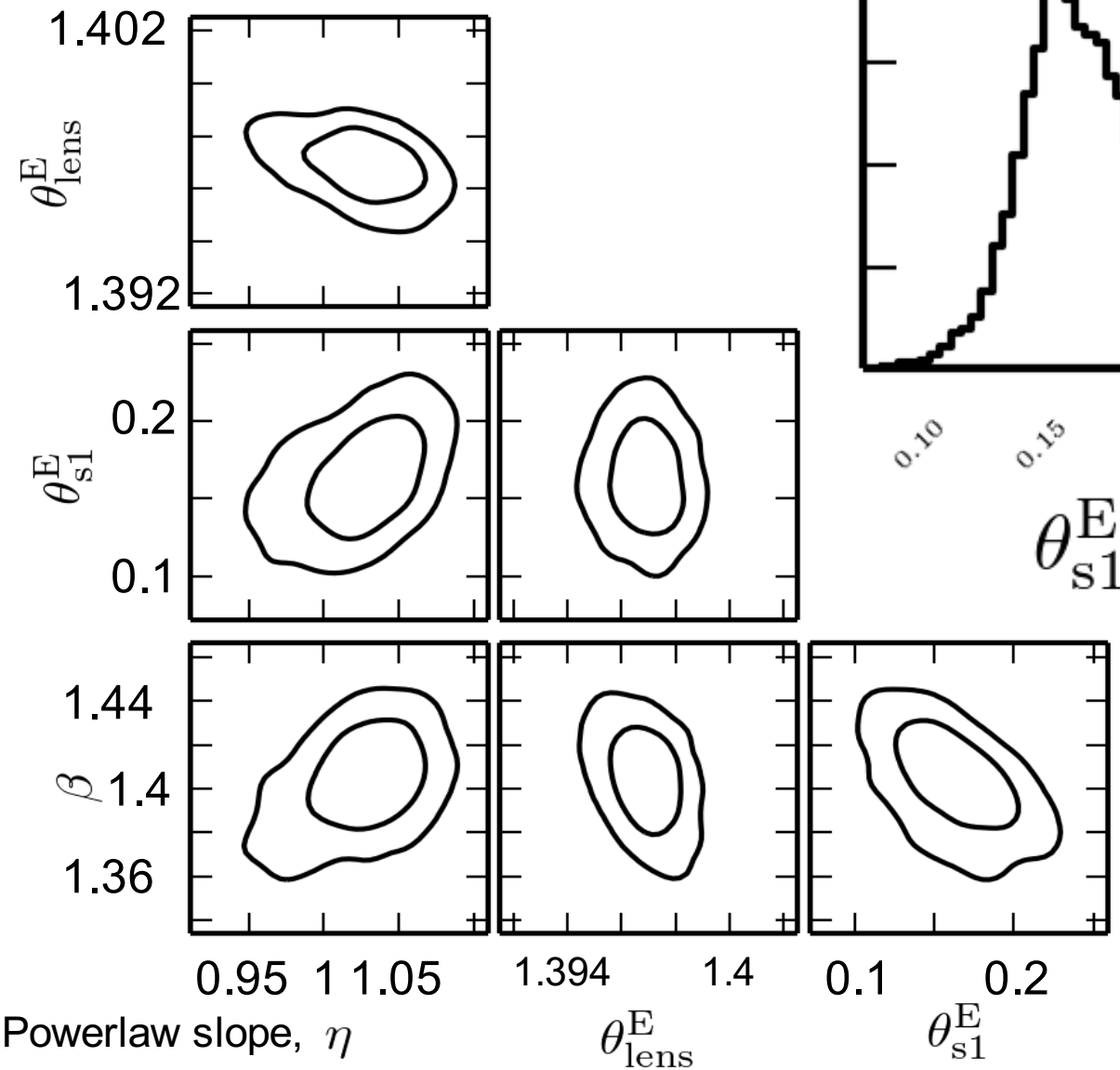
$$= \left(M \right)$$

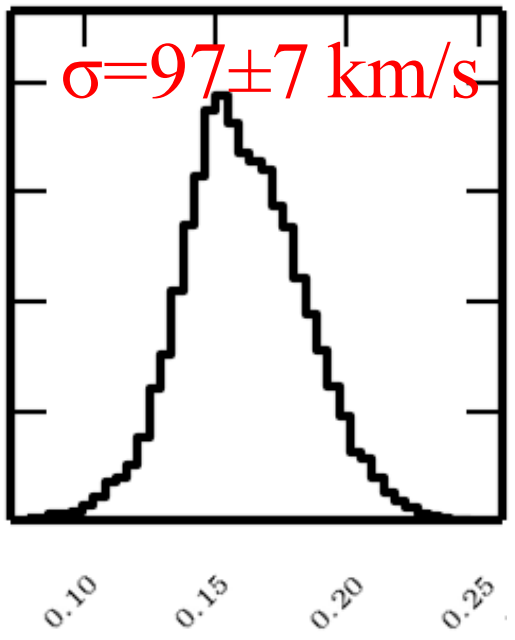


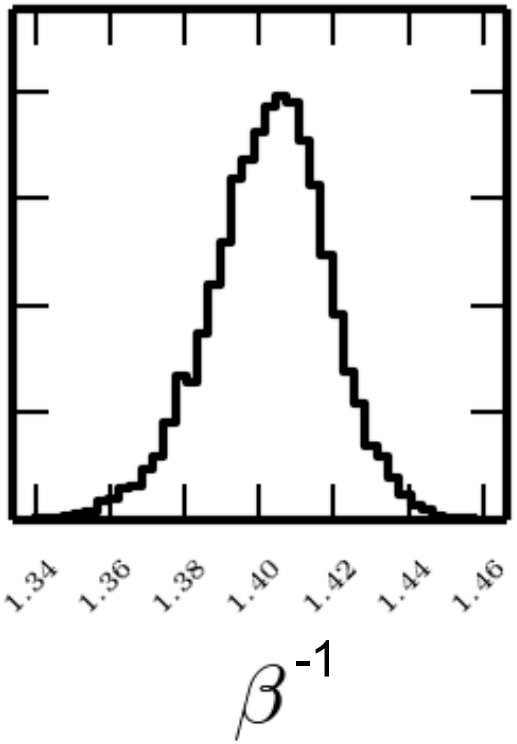
Modelling J0946



Modelling J0946



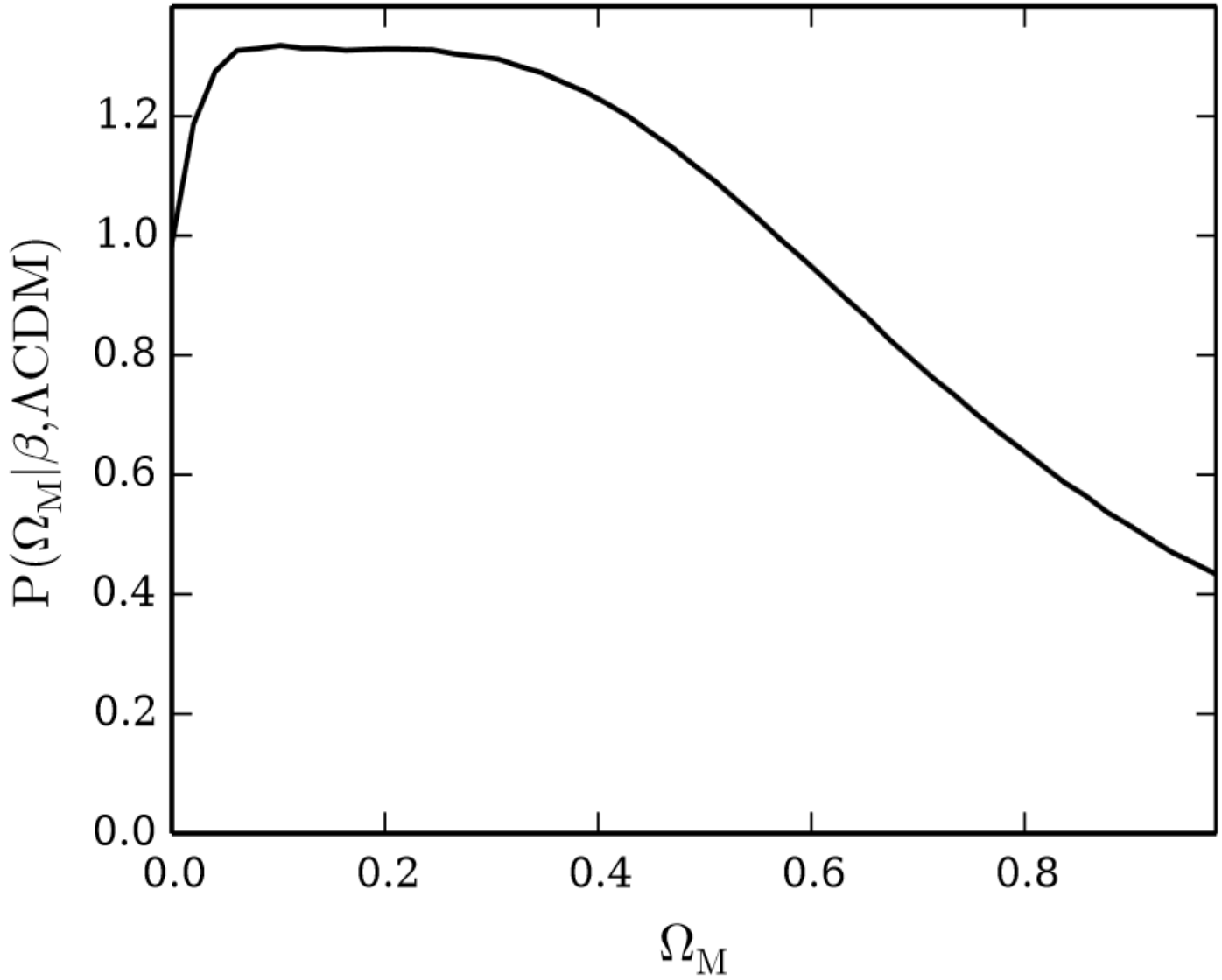




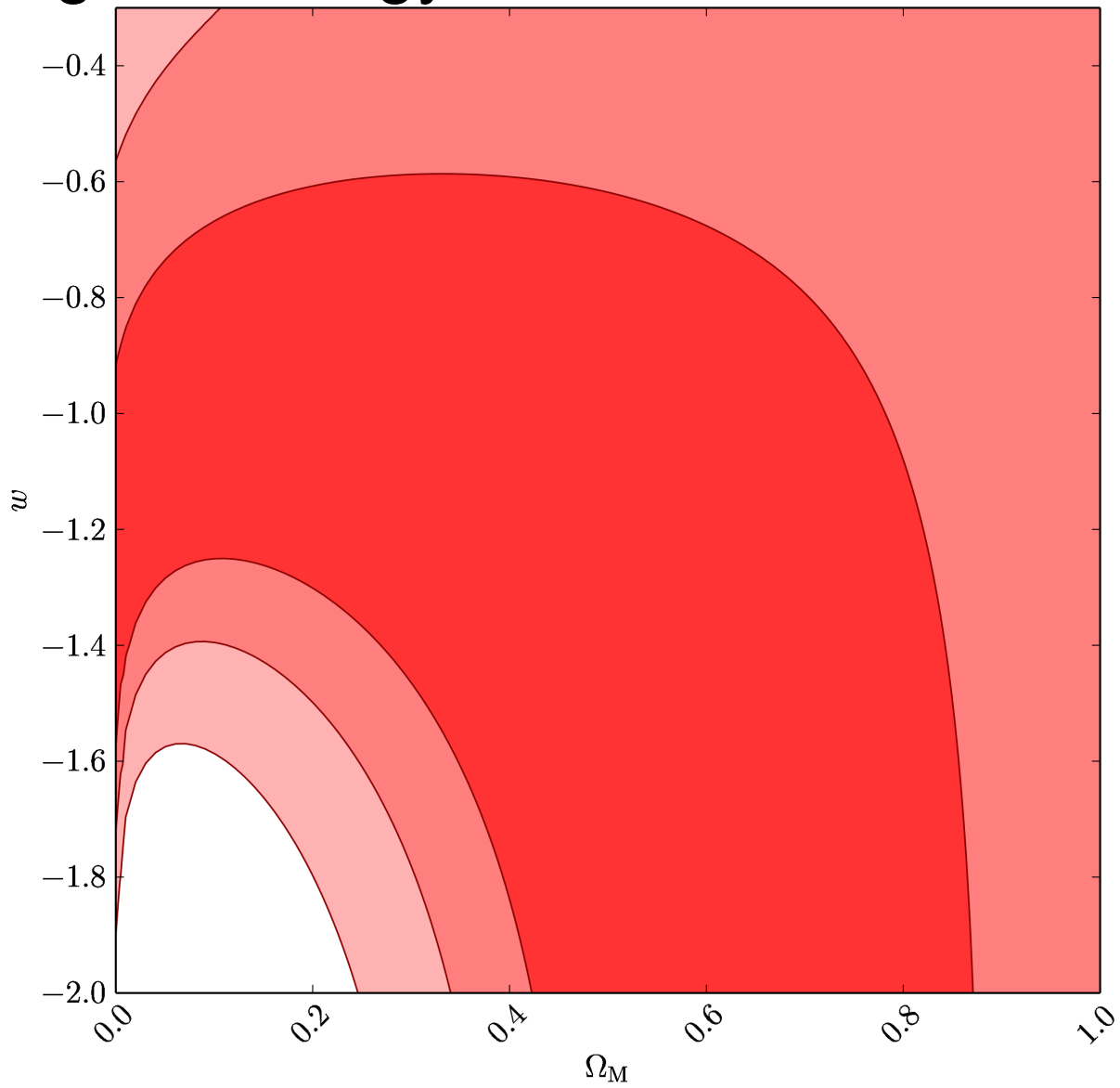
$$\beta = \frac{D_{ls1} D_{s2}}{D_{s1} D_{ls2}}$$

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

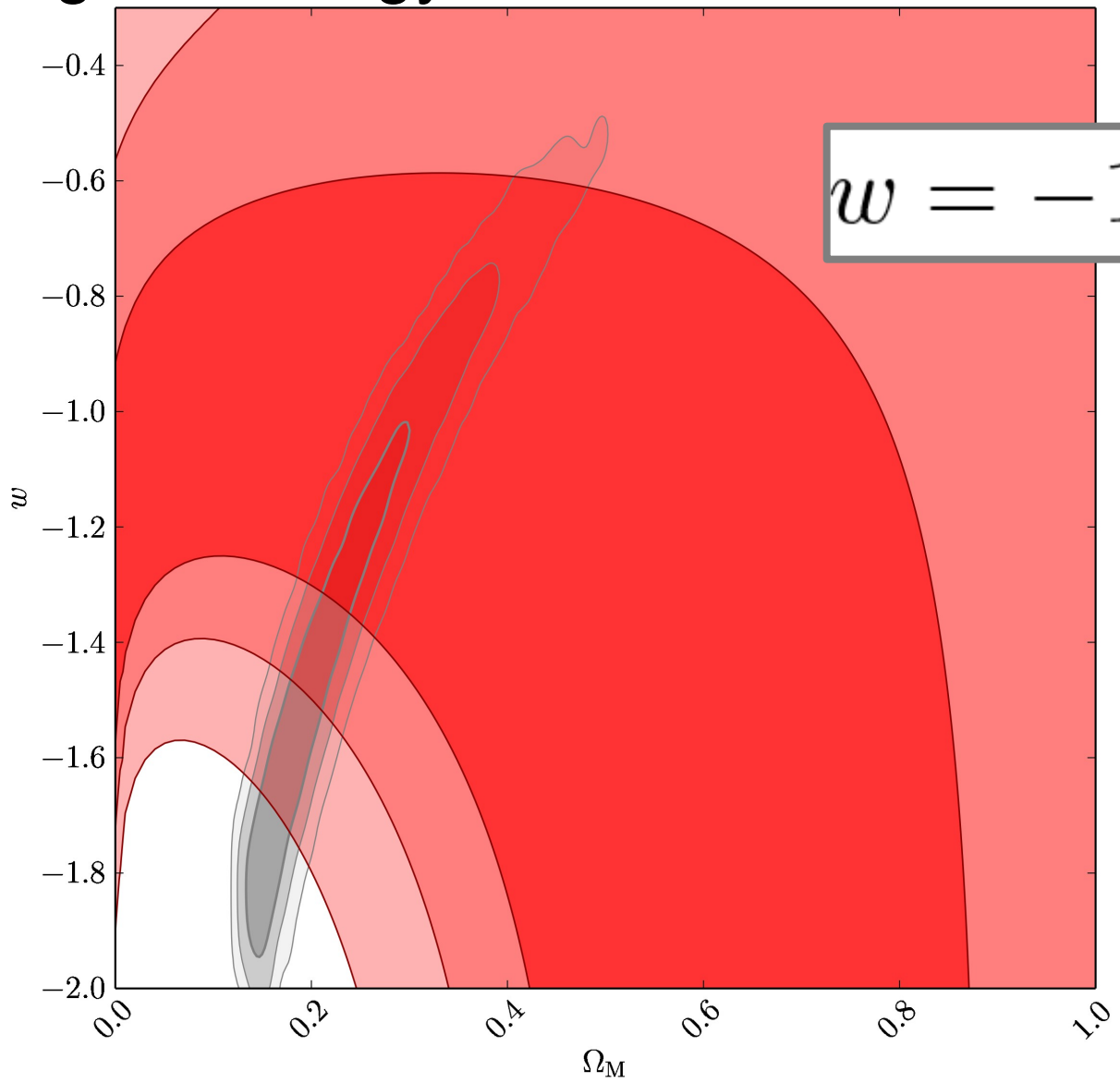
Constraining Cosmology.



Constraining Cosmology.

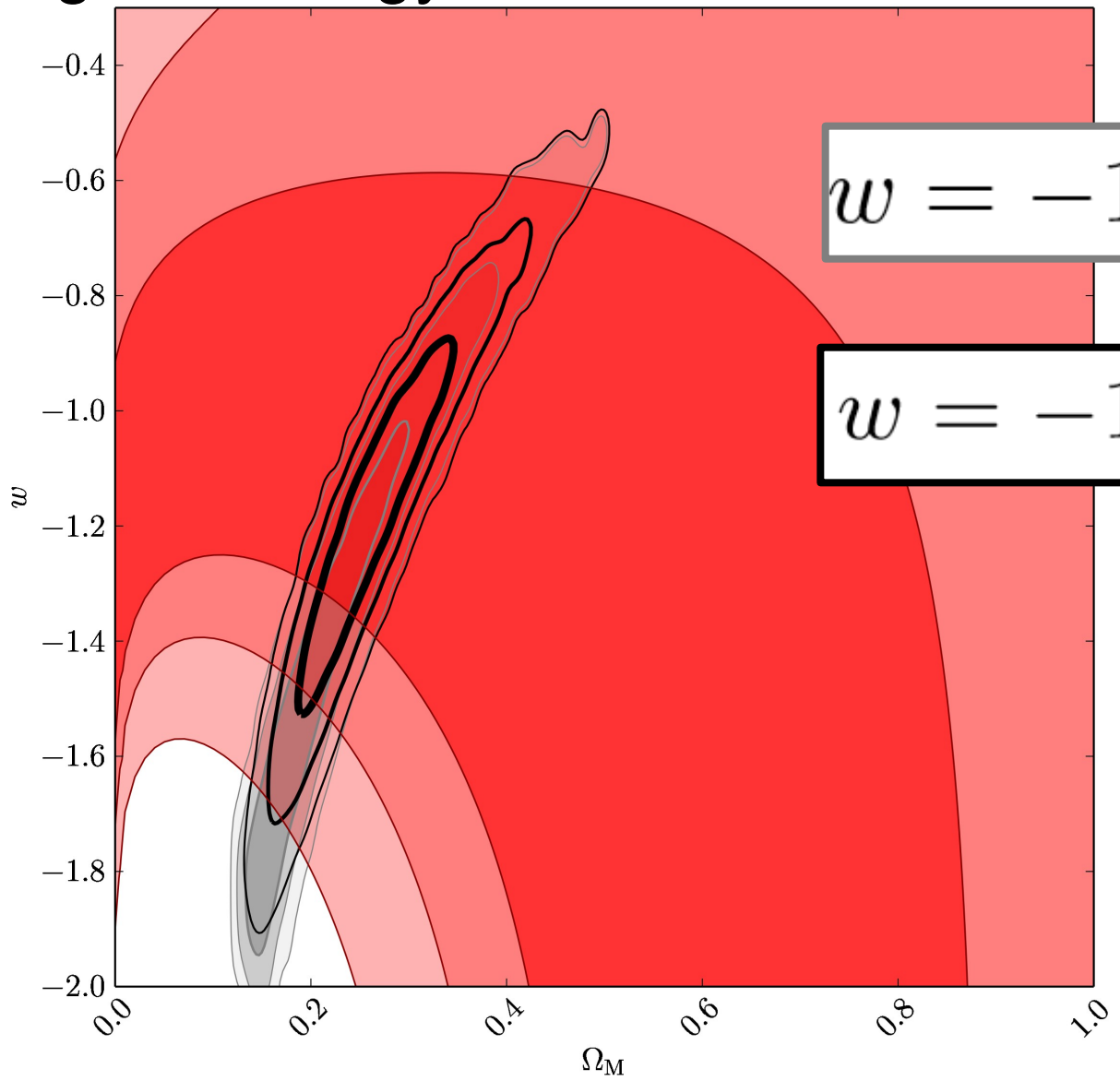


Constraining Cosmology.



$$w = -1.48\ ^{+0.36}_{-0.27}$$

Constraining Cosmology.



$$w = -1.48\ ^{+0.36}_{-0.27}$$

$$w = -1.17\ ^{+0.19}_{-0.21}$$