The Future of Strong Gravitational Lensing

Texas Symposium, Geneva
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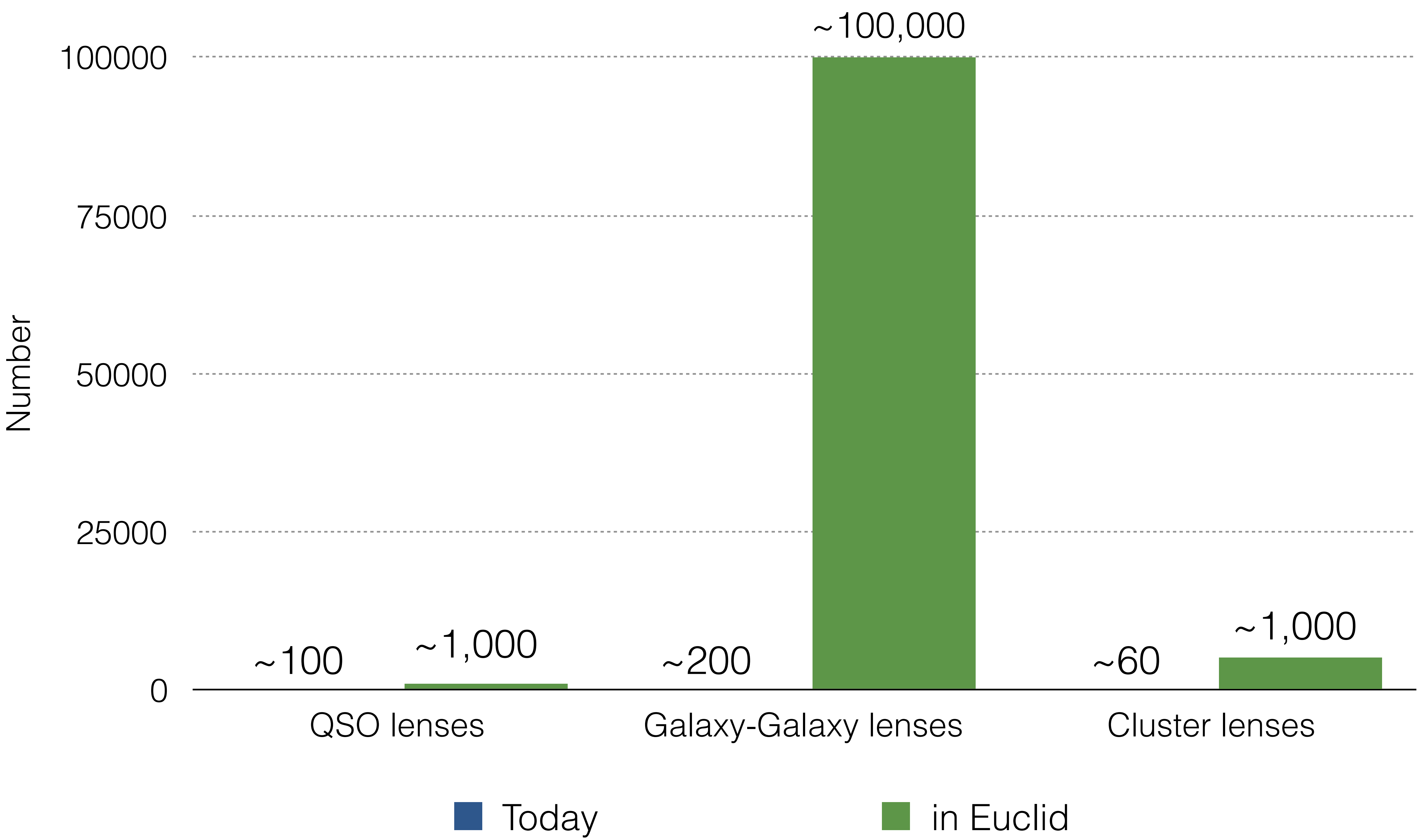
Numbers of known strong lenses



Future Data Sets : KIDS, DES, Pan-Starrs, LSST, Euclid

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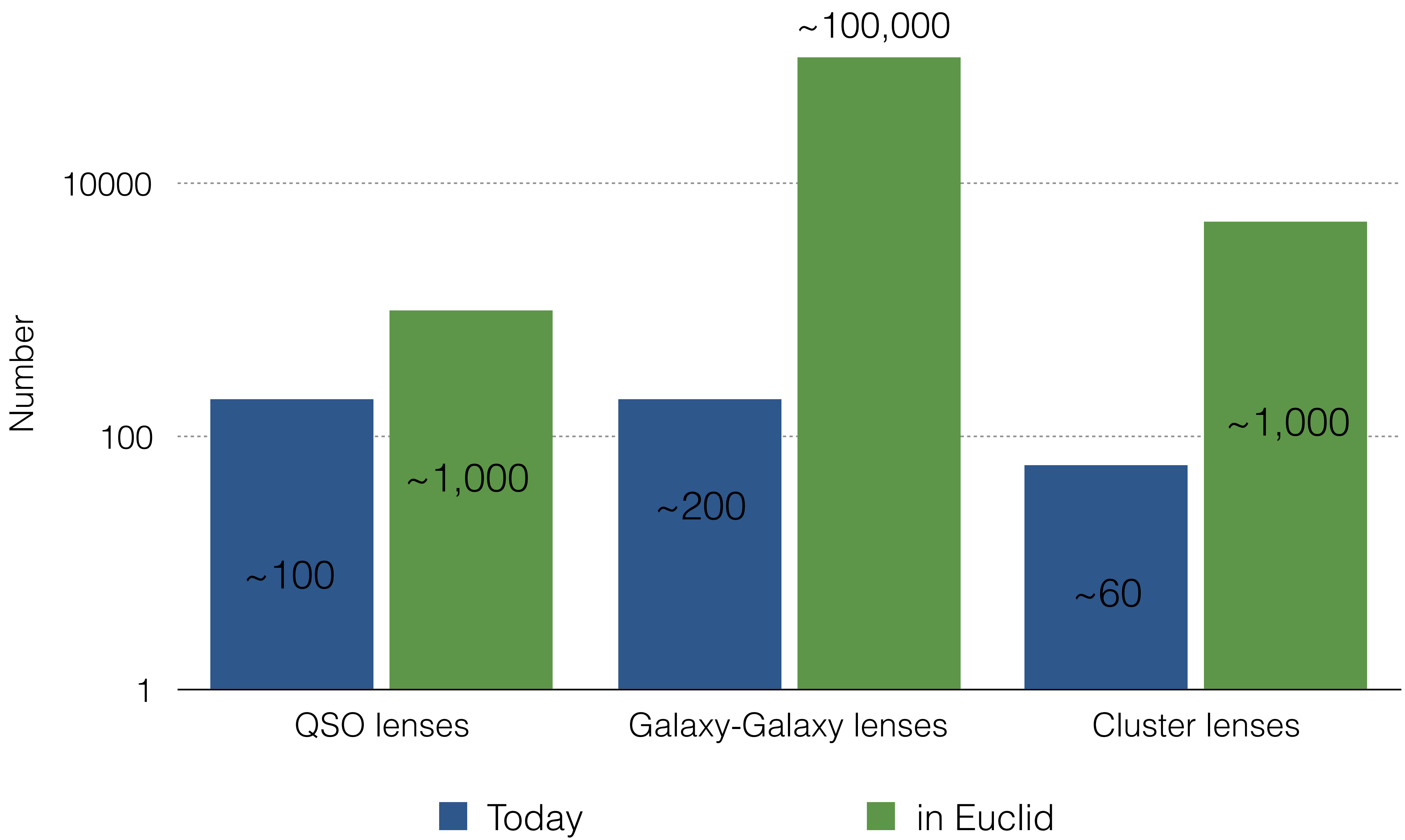
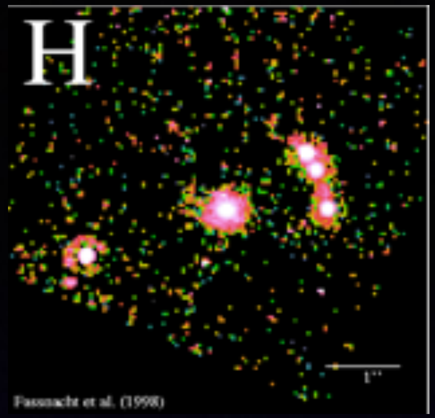
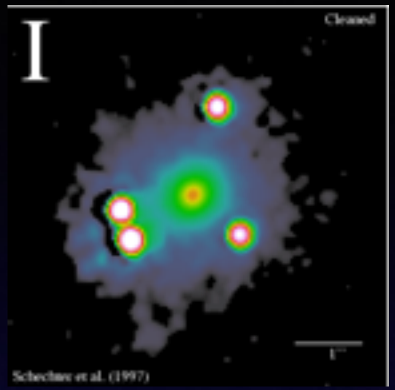


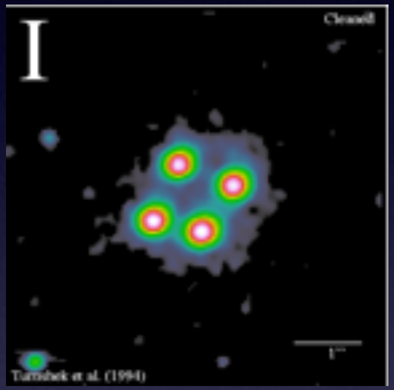
Future Data Sets : KIDS, DES, Pan-Starrs, LSST, Euclid

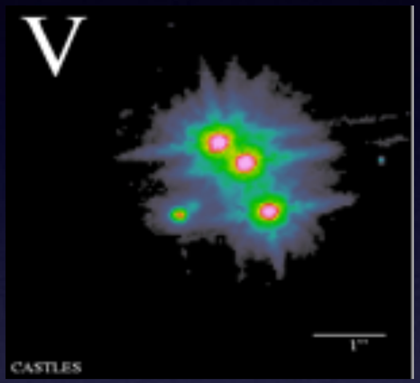
Galaxy Scale Strong Lenses

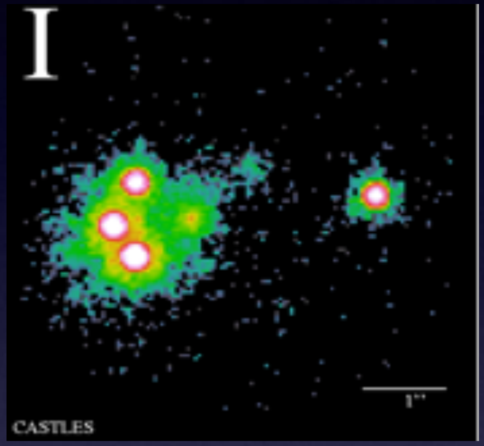


Galaxy - QSO Lenses

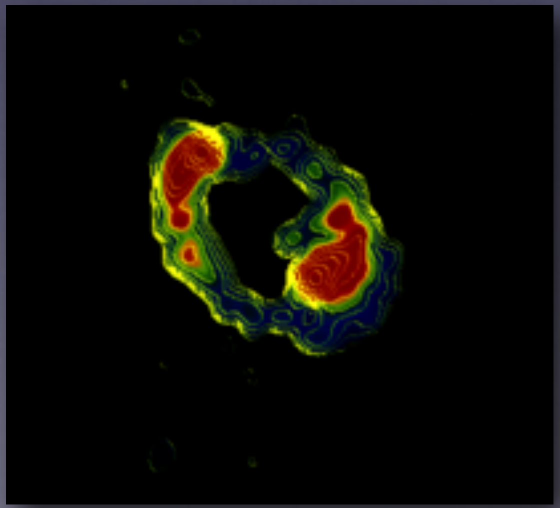


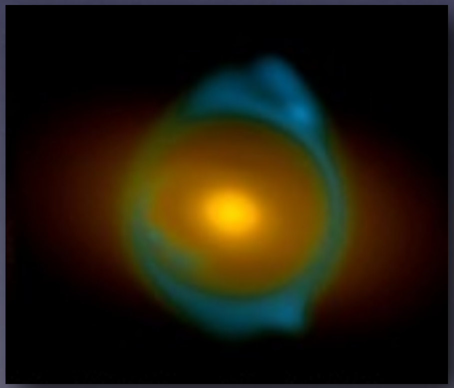






Galaxy - Galaxy Lenses





Uses for strong lenses

- Cosmological parameters

- Distribution of mass or theory of gravity in the lenses

- Find and study high redshift sources

Cosmology and Lens Density

θ_{E} angular Einstein radius

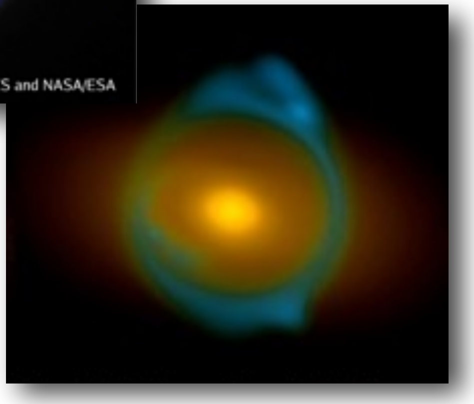
$$\pi\theta_{\mathrm{E}}^2 = \frac{M(\theta_{\mathrm{E}})}{\sigma_{\mathrm{crit}}}$$ area within Einstein radius

$M(\theta_{\mathrm{E}})$ mass within Einstein radius

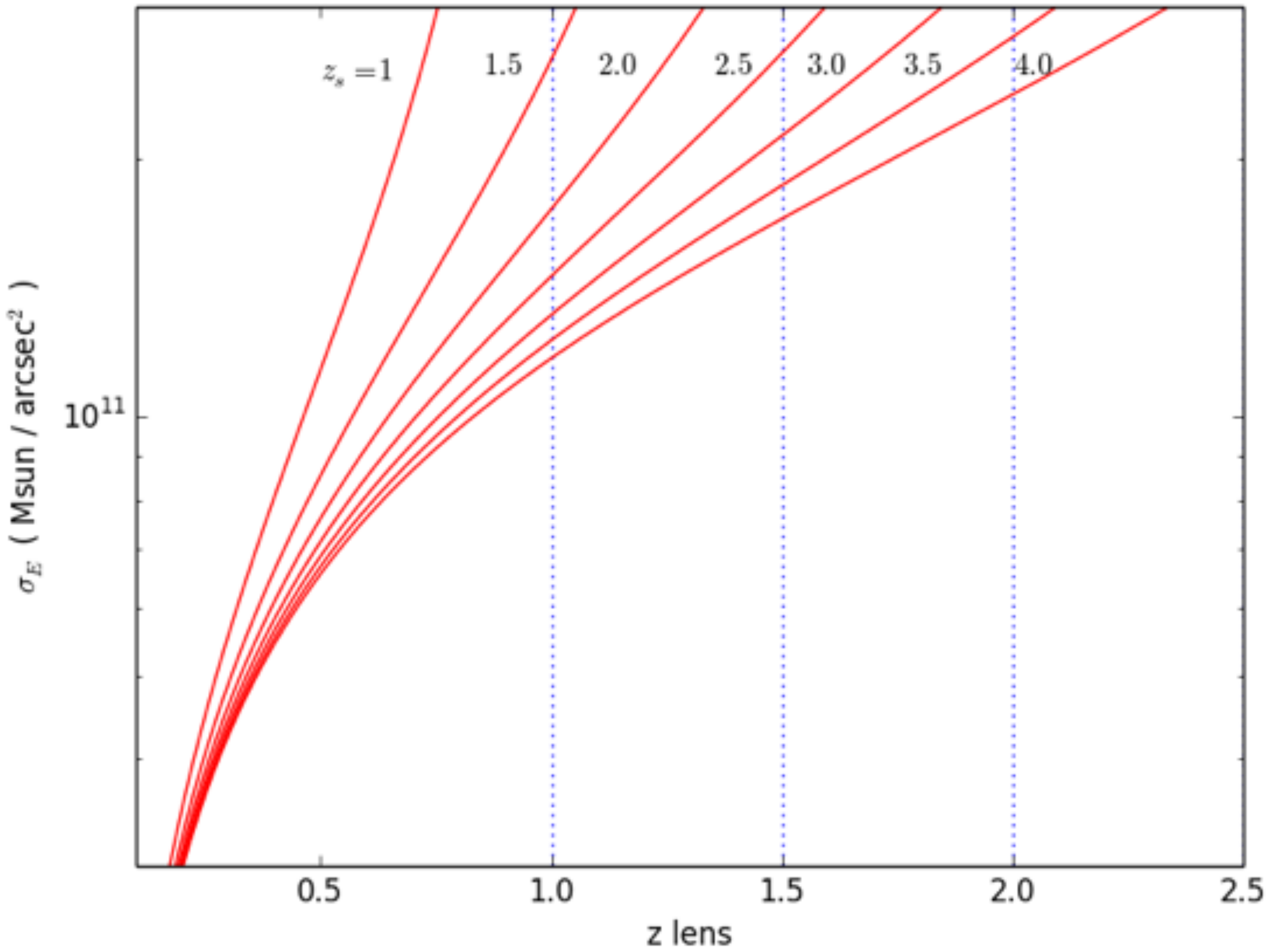
$$\sigma_{\mathrm{crit}} = \frac{c^2}{4\pi G}\frac{D_l D_s}{D_{ls}} = \Sigma_{\mathrm{crit}} D_l^2$$ critical density

Cosmology and Lens Density

$$\sigma_{\rm crit}(z_s, z_l) = \frac{M(\theta_{\rm E})}{\pi\theta_{\rm E}^2}$$



critical density as a function of lens redshifts

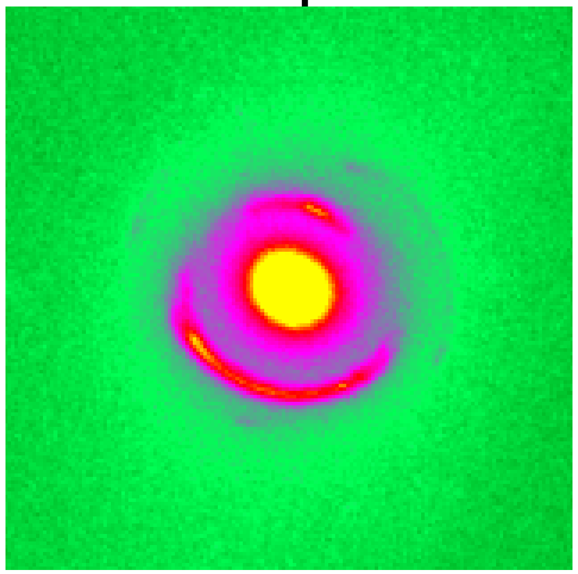


Need to know the mass to get the cosmology or vice versa.

$$M(\theta_{\rm E}) = \pi\theta_{\rm E}^2\sigma_{\rm crit}(z_s, z_l)$$

Cosmology and Lens Density

The Jackpot Lens



Gavazzi et al. 2008

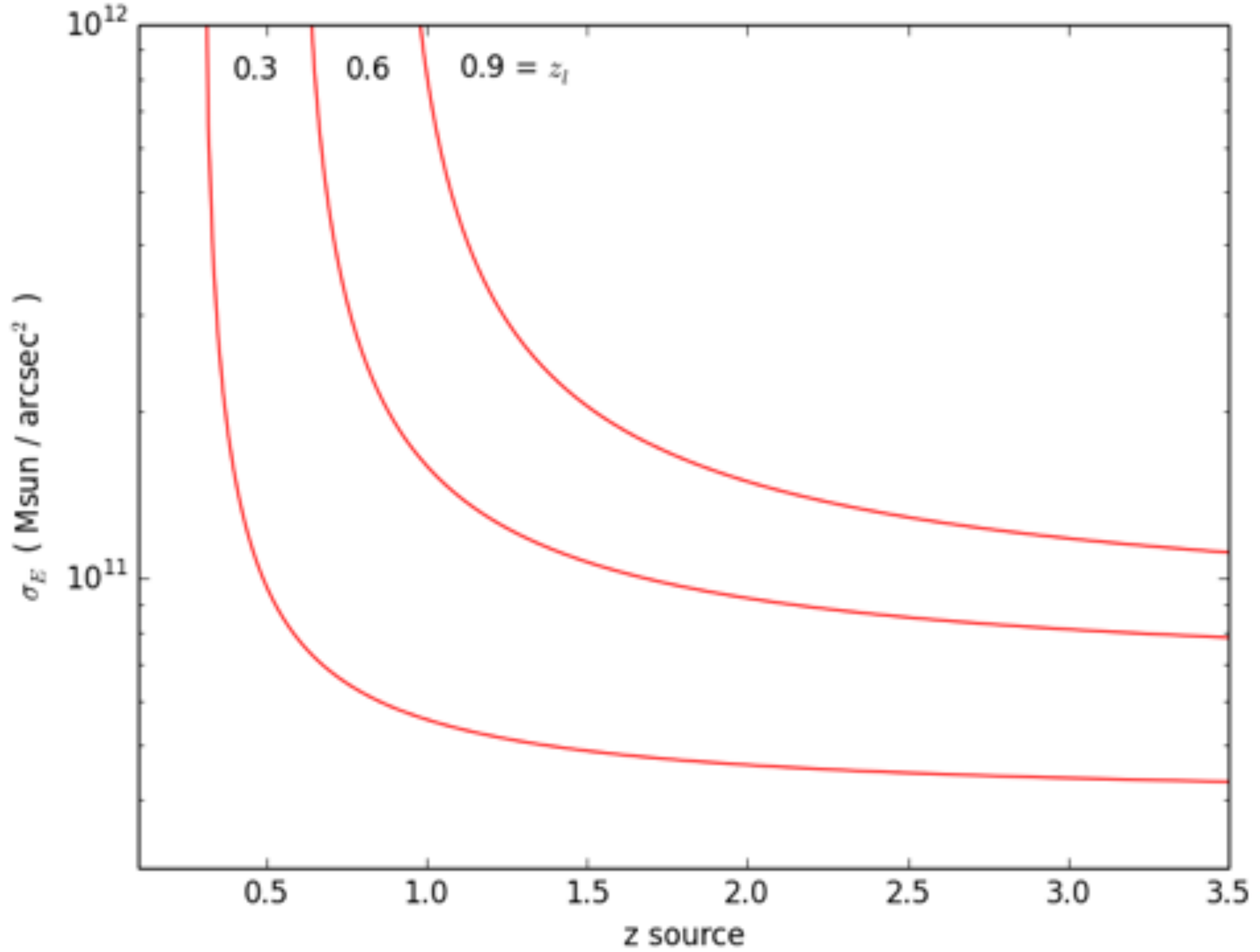
$$z_{\text{lens}} = 0.222$$

$$z_{\text{source 1}} = 0.609$$

$$z_{\text{source 2}} = 3.1^{+2.0}_{-1.0}$$

$$\frac{\sigma_{\text{crit}}(z_s, z_l)}{\sigma_{\text{crit}}(z'_s, z'_l)} = \frac{M(\theta_{\text{E}})}{M(\theta'_{\text{E}})} \left(\frac{\theta'_{\text{E}}}{\theta_{\text{E}}}\right)^2$$

critical density as a function of source redshifts



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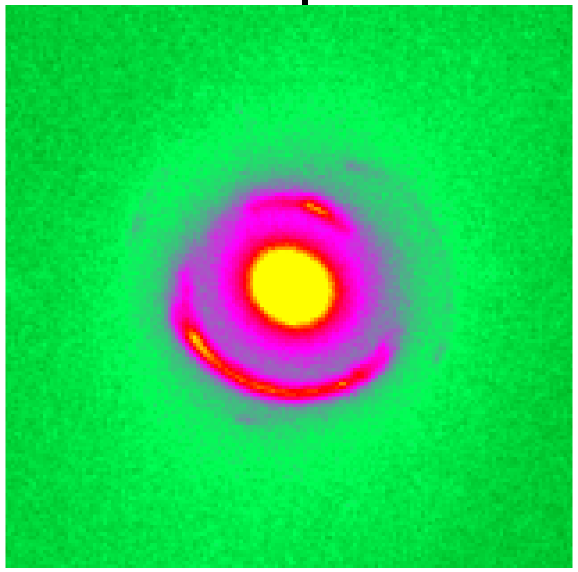

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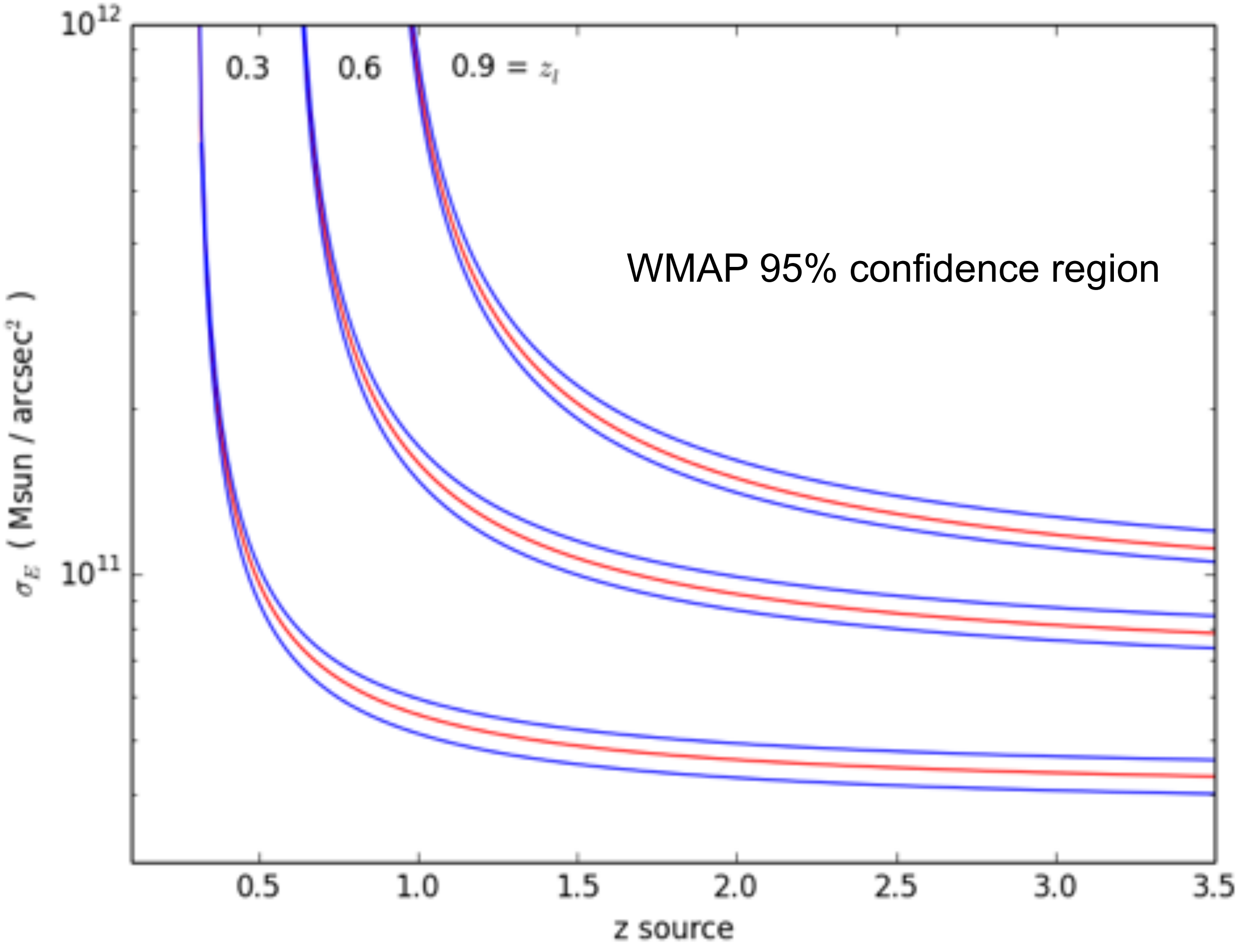

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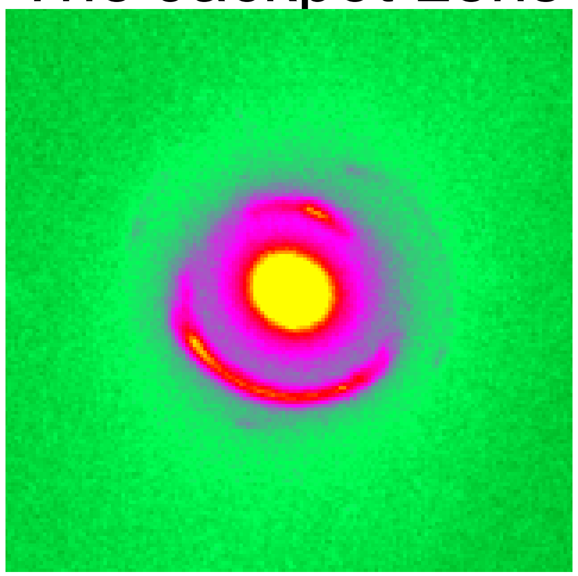
The Jackpot Lens



Gavazzi et al. 2008

$$z_{\rm lens} = 0.222$$

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Collett & Auger 2014

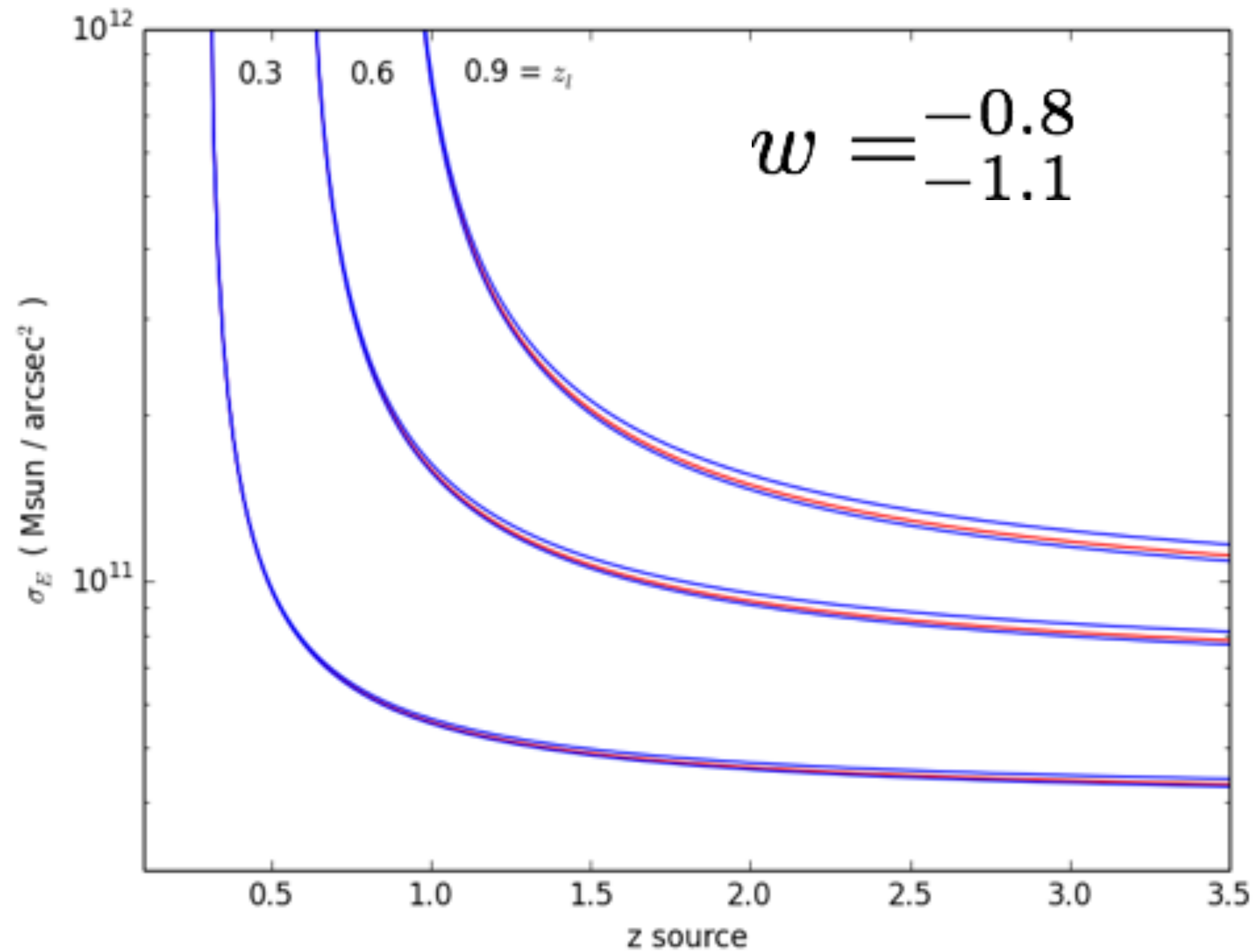
$\Omega_m = 0.33^{+0.33}_{-0.26}$ alone

$w = -1.17^{+0.20}_{-0.21}$ with Planck

assuming isothermal profile

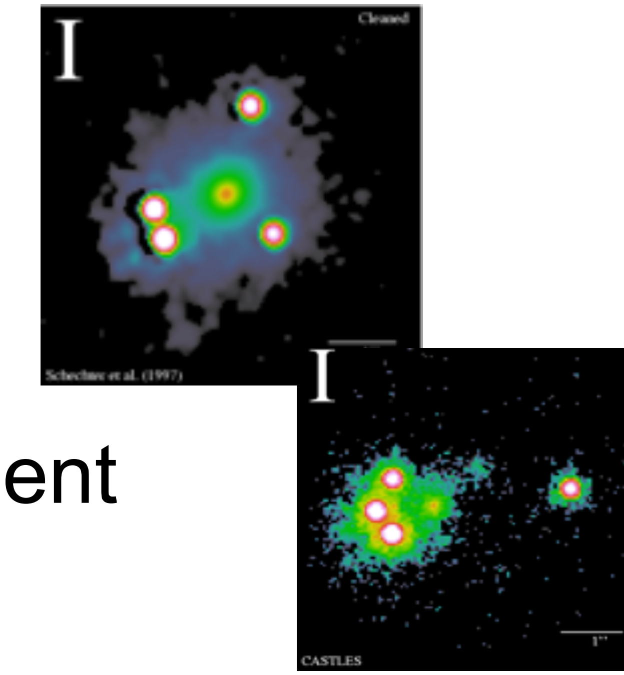
$$\frac{\sigma_{\rm crit}(z_s, z_l)}{\sigma_{\rm crit}(z'_s, z'_l)} = \frac{M(\theta_{\rm E})}{M(\theta'_{\rm E})} \left(\frac{\theta'_{\rm E}}{\theta_{\rm E}}\right)^2$$

critical density as a function of source redshifts



$$M(\theta_{\rm E}) - M(\theta'_{\rm E}) = \pi\left(\theta_{\rm E}^2 \sigma_{\rm crit}(z_s, z_l) - \theta'^2_{\rm E}\sigma_{\rm crit}(z'_s, z'_l)\right)$$

Cosmology and Lens Density



Time-delays of lensed quasars

Long term monitoring

Careful modelling of lens and environment that does involve assumptions

Suyu, et al. 2010 $H_o = 70.6 \pm 3.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Fassnacht et al. 2002

WMAP + $H_o = 69.7^{+4.9}_{-5.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$ prior

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

COSMOGRAIL - global lens monitoring program

Lens Statistics - number counts of lenses as a function of z

Careful calibration of lens finding efficiency and bias

Susceptible to radial profile degeneracy

Strong Lens Finding

In the past this has been done by eye or with spectroscopic methods

Need automated methods to address large imaging survey data sets and with quantifiable detection efficiency.

PCA lens subtraction
Arc finders
Pattern recognition using neural nets
vector machines, deep learning
Color template subtraction
Crowd Sourcing - *Spacewarps*
Direct lens modelling of all candidates

Joseph, et al. 2014
Paraficz, et al, submitted
Maturi et al. 2015

More, A. et al 2015

Strong Lens Simulations

Large scale simulations of strong lenses

~ 1 million images of galaxy-galaxy lenses

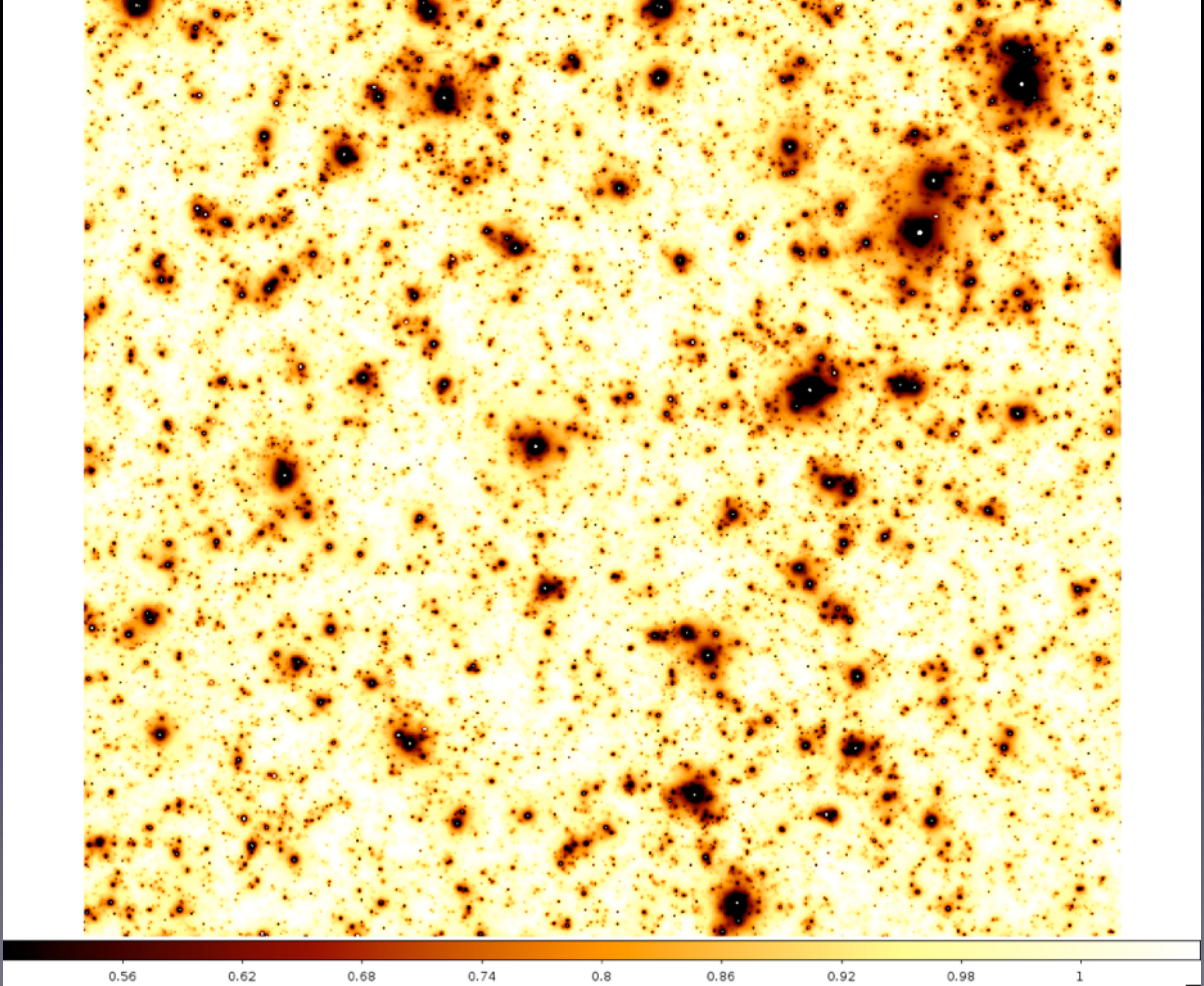
multiple colors

realistic noise & psf that match survey

realistic source & lens surface brightness

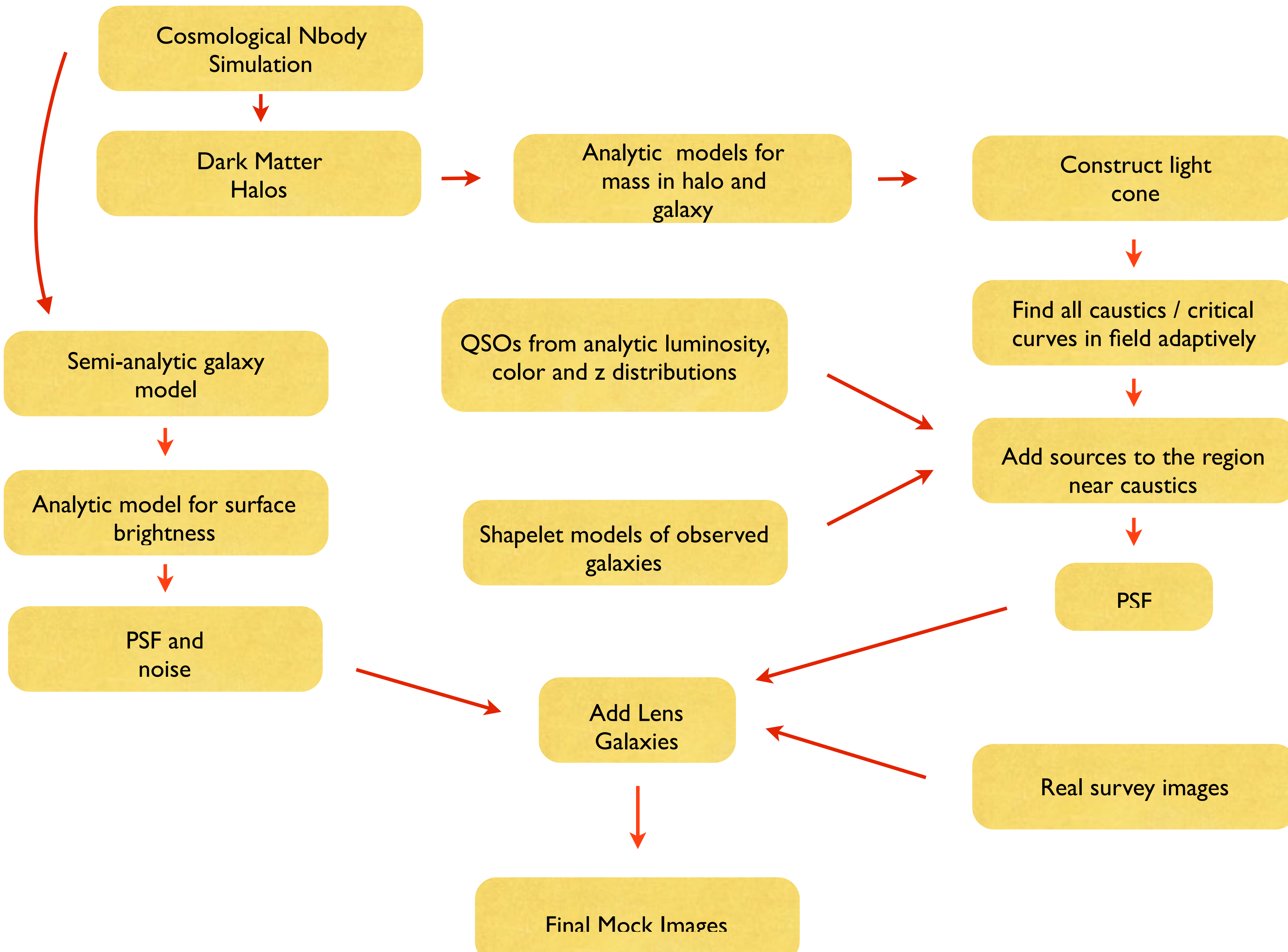
realistic environment, full ray-tracing through light-cone

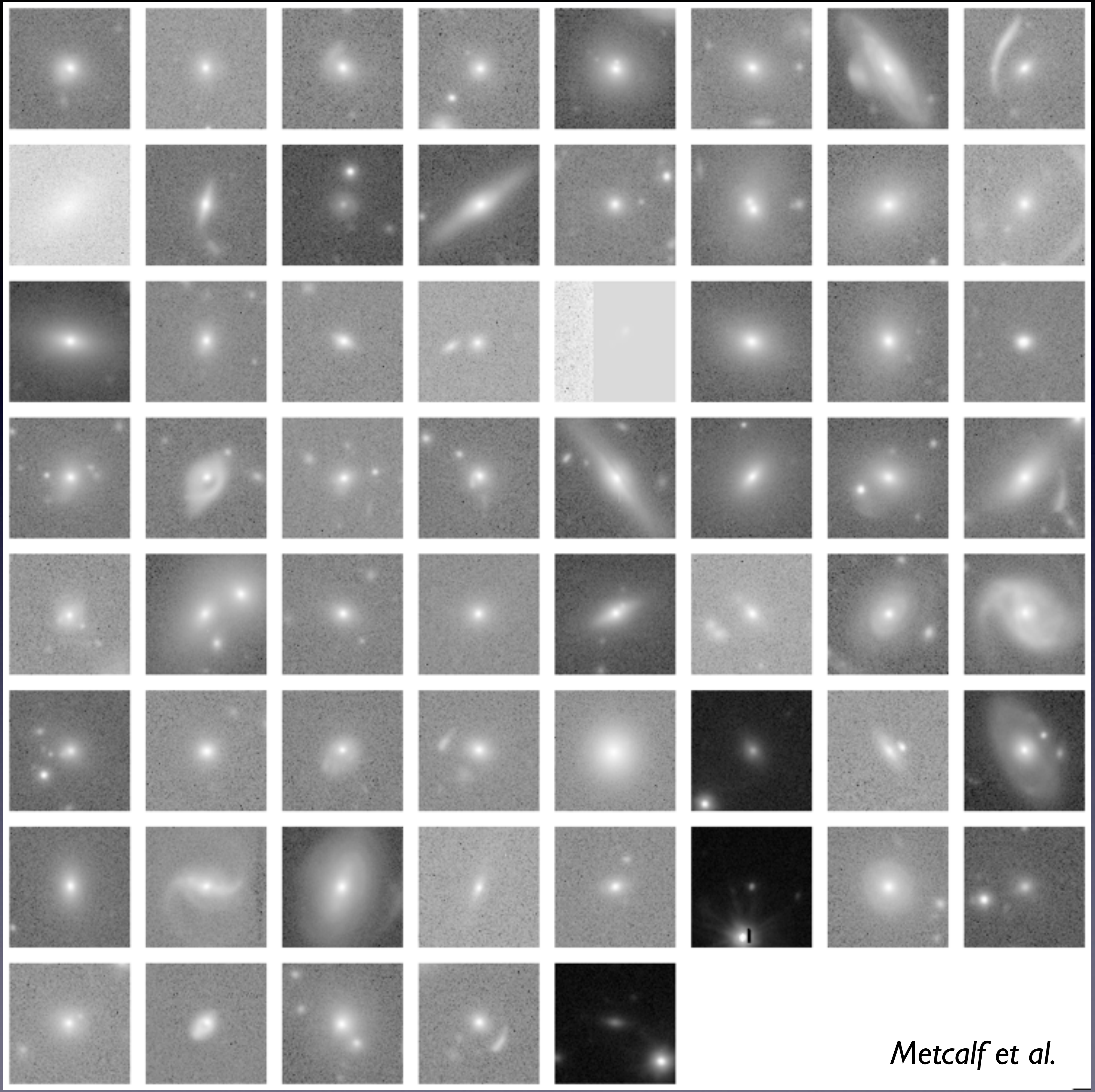
Available through the Bologna Lens Factory along with weak lensing and cluster lensing simulations

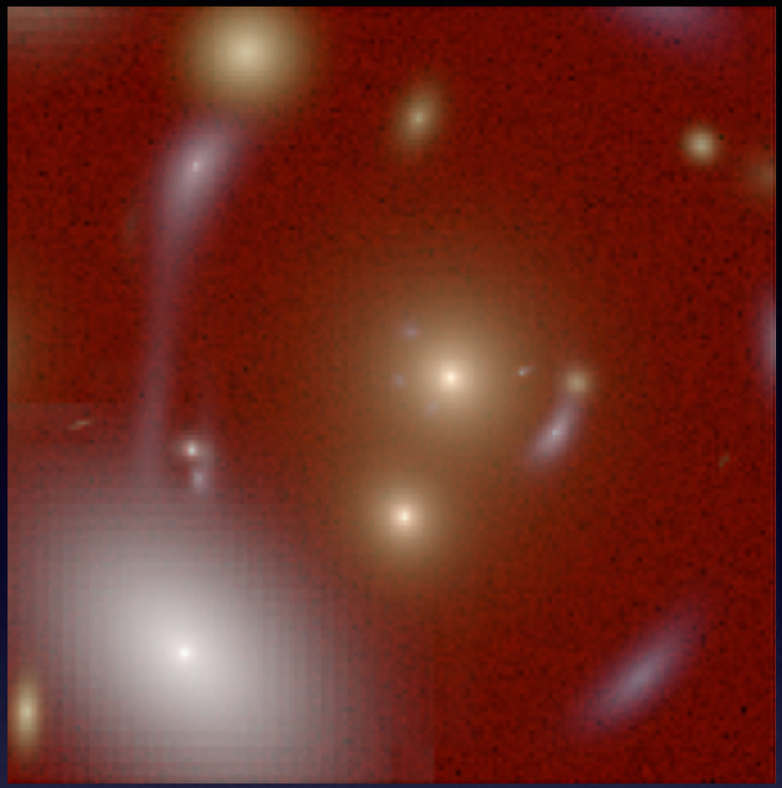


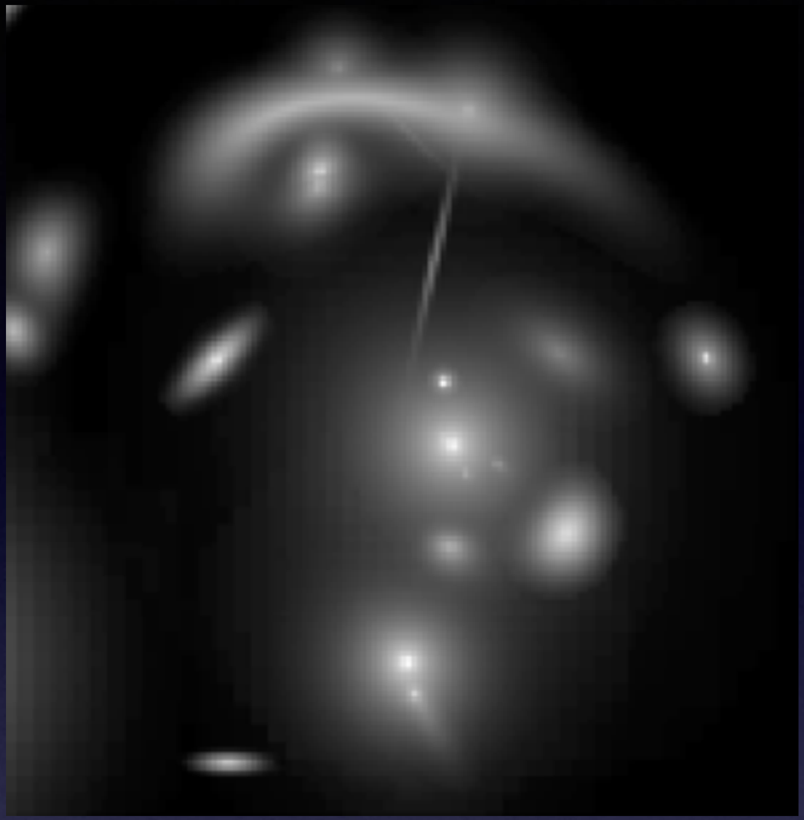
0.56
0.62
0.68
0.74
0.8
0.86
0.92
0.98
1

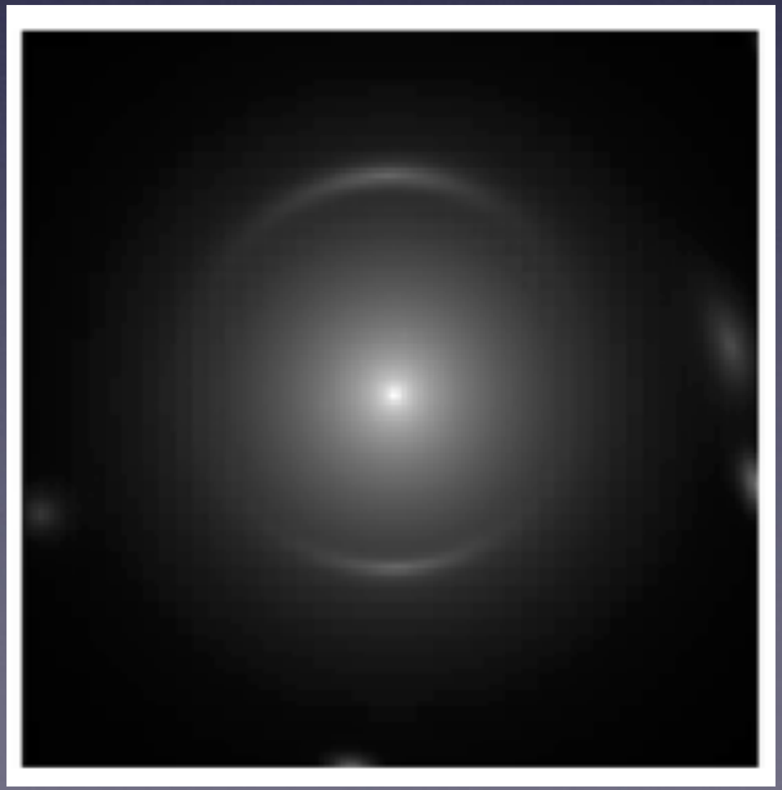
Galaxy-Galaxy Lens Simulations

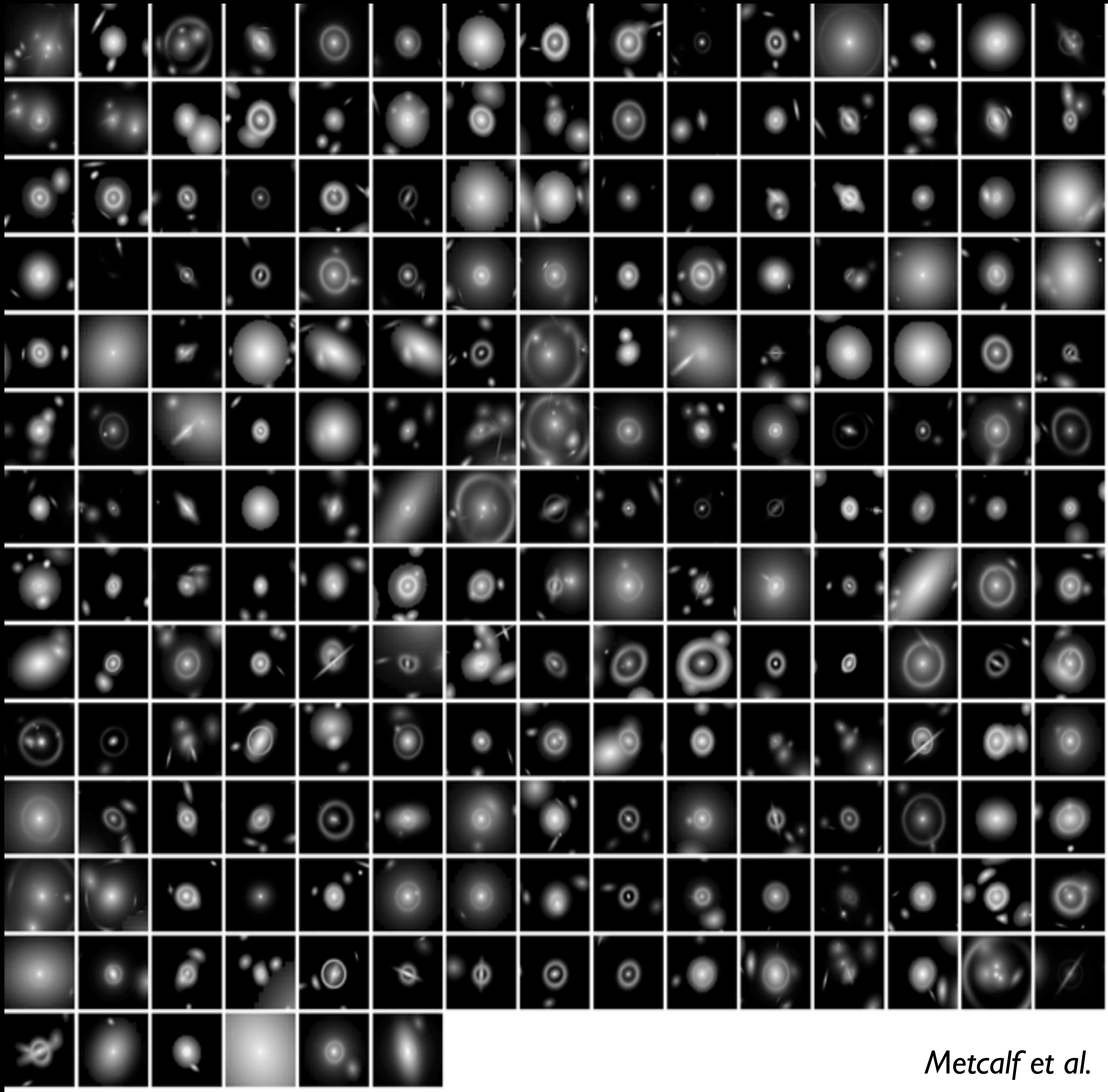



Metcalf et al.









Metcalf et al.

Strong Lens Modelling

Conjugate Point Methods	Forward Reconstruction Methods	Backward Reconstruction or Lens Inversion Methods
Points on the image that are identified as from the some source component are mapped back to the source plane and the distance between them is used as a penalty function.	Make a lens and source model. Trace back all images to the source plane and integrate the pixels to find an image that is compared on the image plane.	Make a lens model. Use lens model to project the image back onto the source plane. Impose a smoothness prior on the source to favour one model over another.
Computationally fast and easy	Computationally slower with large number of model parameters.	Computationally faster than the forward method, but implementations are not that fast.
Does not use all the data. Not always applicable with sooth source images.	Uses all the data and has good statistical foundation	Uses all the data, but is not complete statistically justified.
Used for QSO and all strong cluster lens analyses	Limited by large number of degrees of freedom	Uses in high resolution HST data with Einstein rings.

The LENSED lens modelling code

Tessore, N., Bellagamba, F., RBM, 2015, arXiv:1505.07674.

General purpose lens modelling code

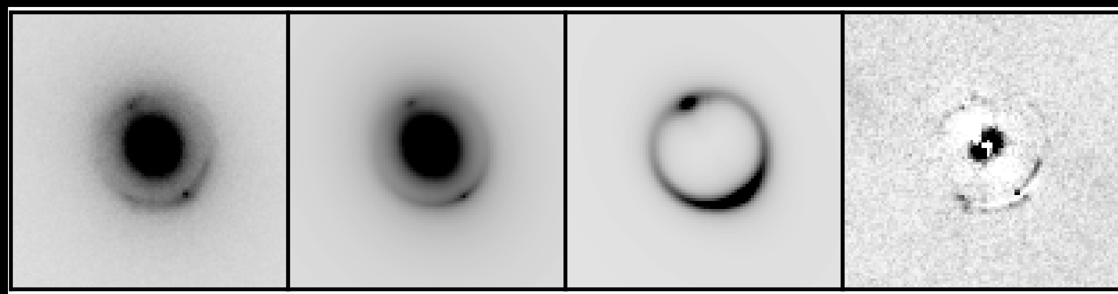
Massively parallel GPU accelerated
- > 1,000,000 rays/sec
- ~ 1,000 source & lens models / sec

Full evidence calculation using nested sampling, MultiNest

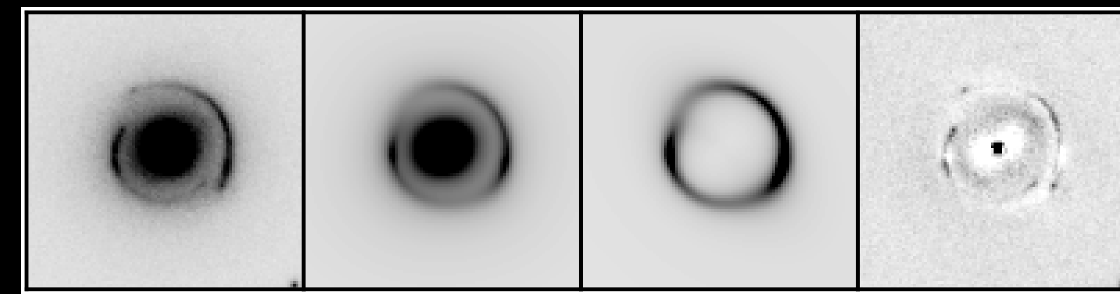
Easy to use

Easy to extend - adding source or lens models is very easy

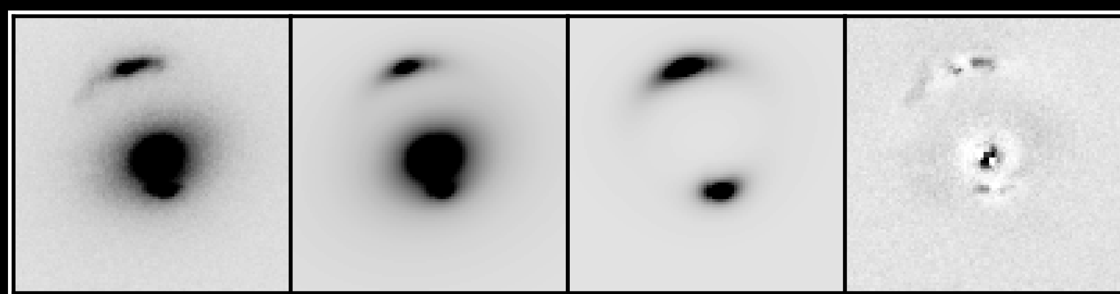
publicly available at http://glenco.github.io/lensed/



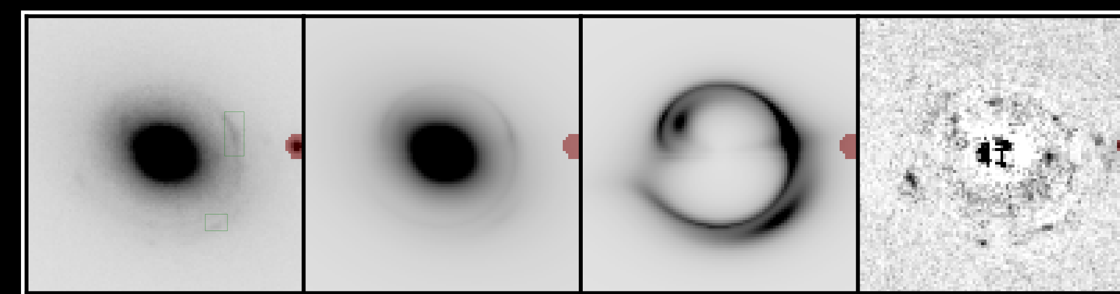
SDSS J0029-0055



SDSS J0252+0039

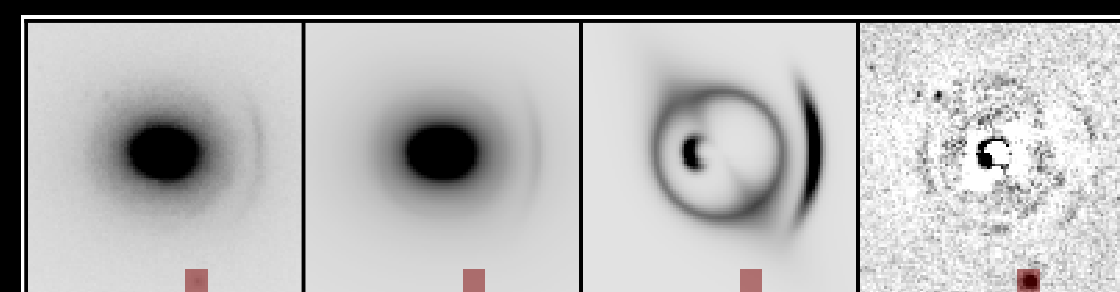


SDSS J0330-0020

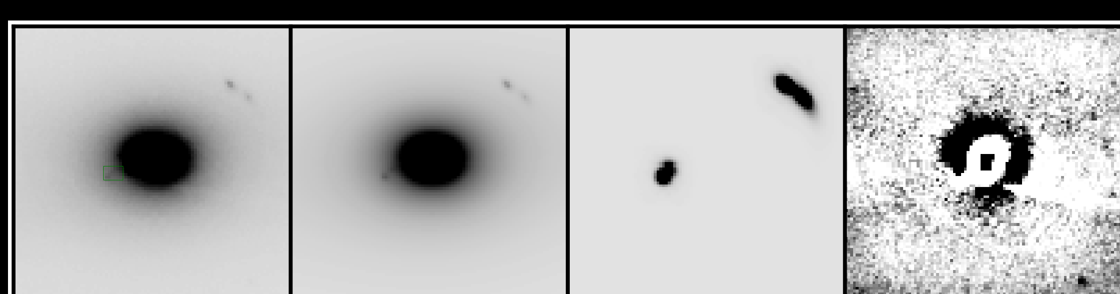


SDSS J0728+3835

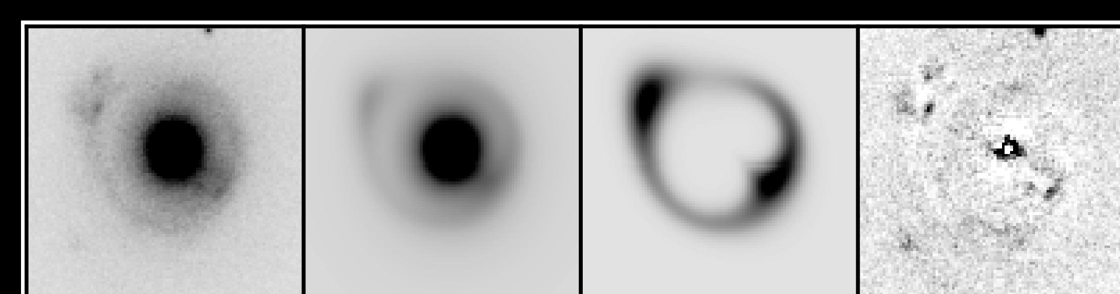
SDSS J0808+4706



SDSS J0822+2652



SDSS J0841+3824



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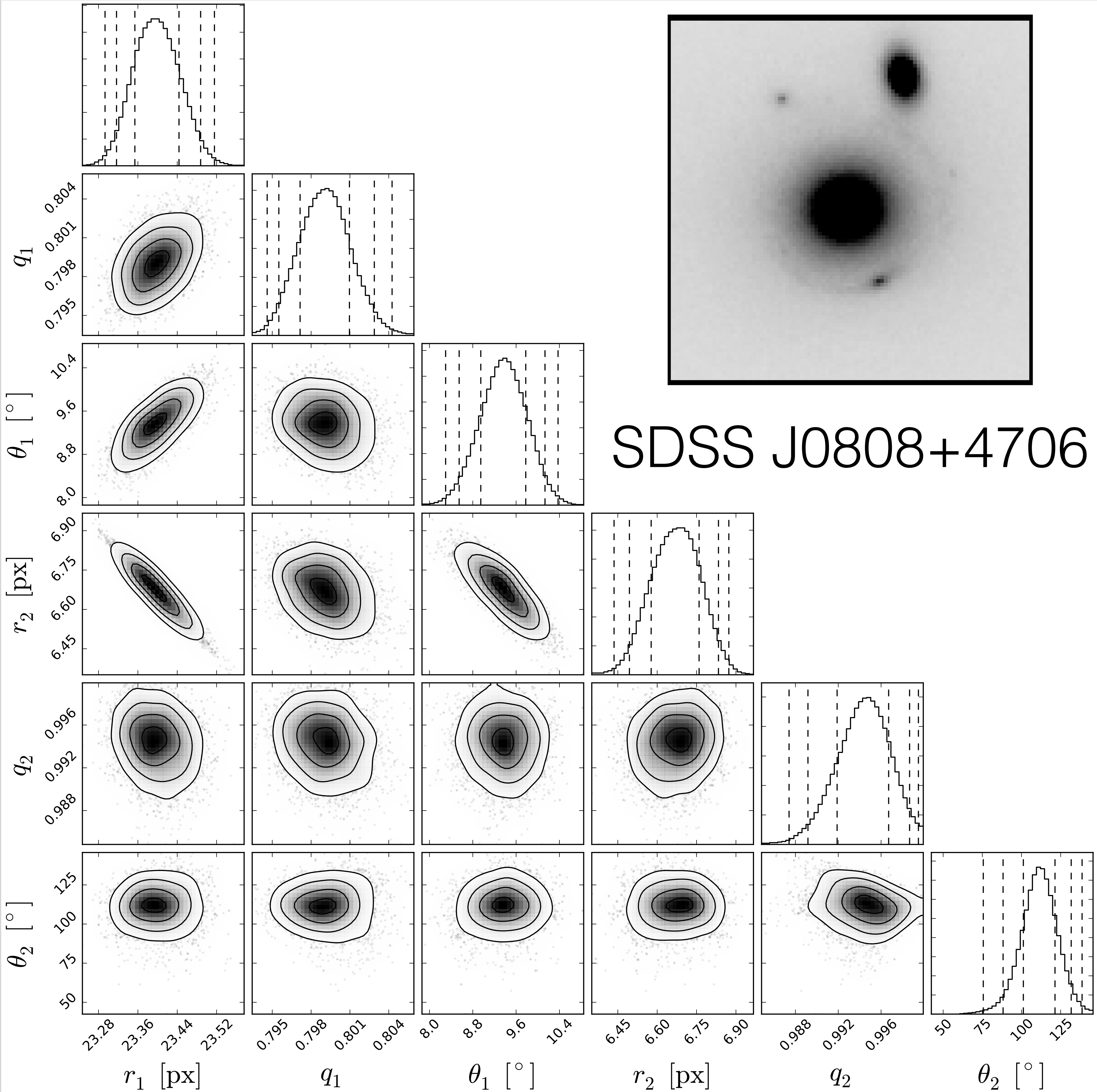
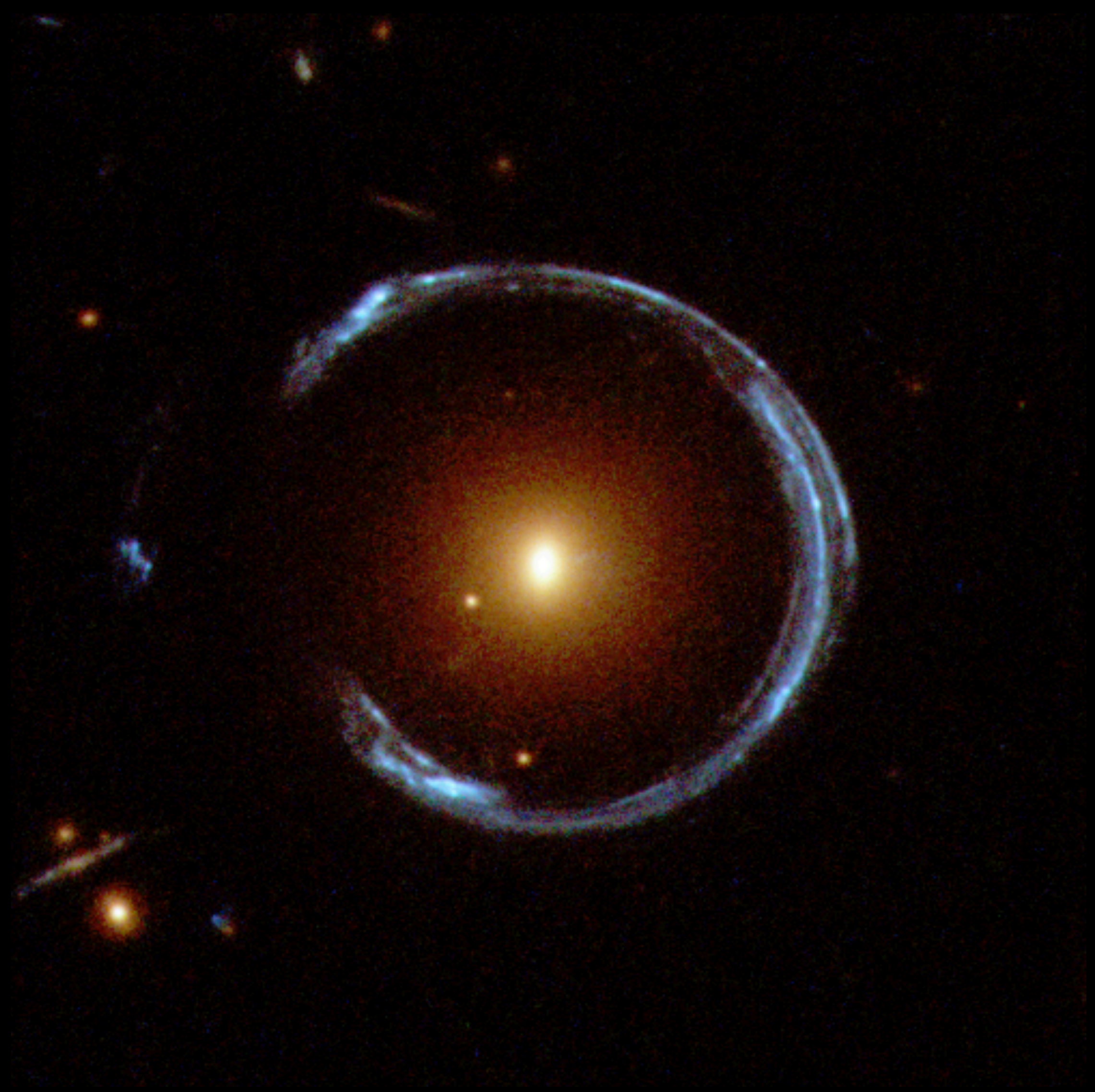


SDSS J0808+4706
q_1
0.804
0.801
0.798
0.795
θ_1 [°]
10.4
9.6
8.8
8.0
r_2 [px]
6.90
6.75
6.60
6.45
q_2
0.996
0.992
0.988
θ_2 [°]
125
100
75
50
23.28
23.36
23.44
23.52
r_1 [px]
0.795
0.798
0.801
0.804
q_1
8.0
8.8
9.6
10.4
θ_1 [°]
6.45
6.60
6.75
6.90
r_2 [px]
0.988
0.992
0.996
q_2
50
75
100
125
θ_2 [°]

Cosmic Horseshoe

SDSS J1148+1930

- discovered in SDSS data by Belokurov et al. (2007)
- lens at $z = 0.444$ very well aligned with $z = 2.381$ source
- spectroscopy suggested a very large velocity dispersion $\sigma_v = 430 \pm 50$ km/s
- might be one of the most massive galaxies observed
- lensing analysis of *INT* data by Dye et al. (2008)

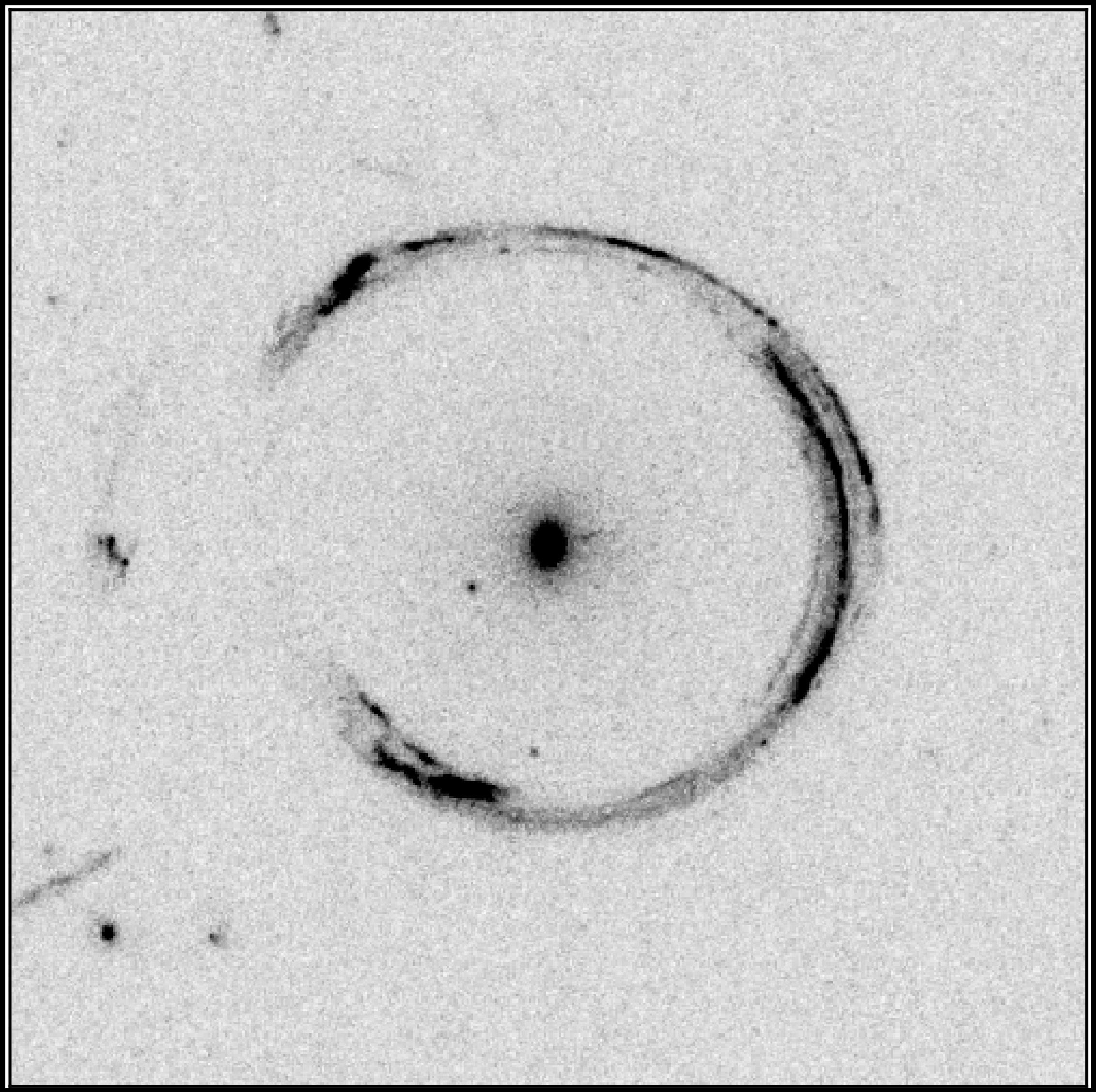


Tessore, Bellagamba & RBM

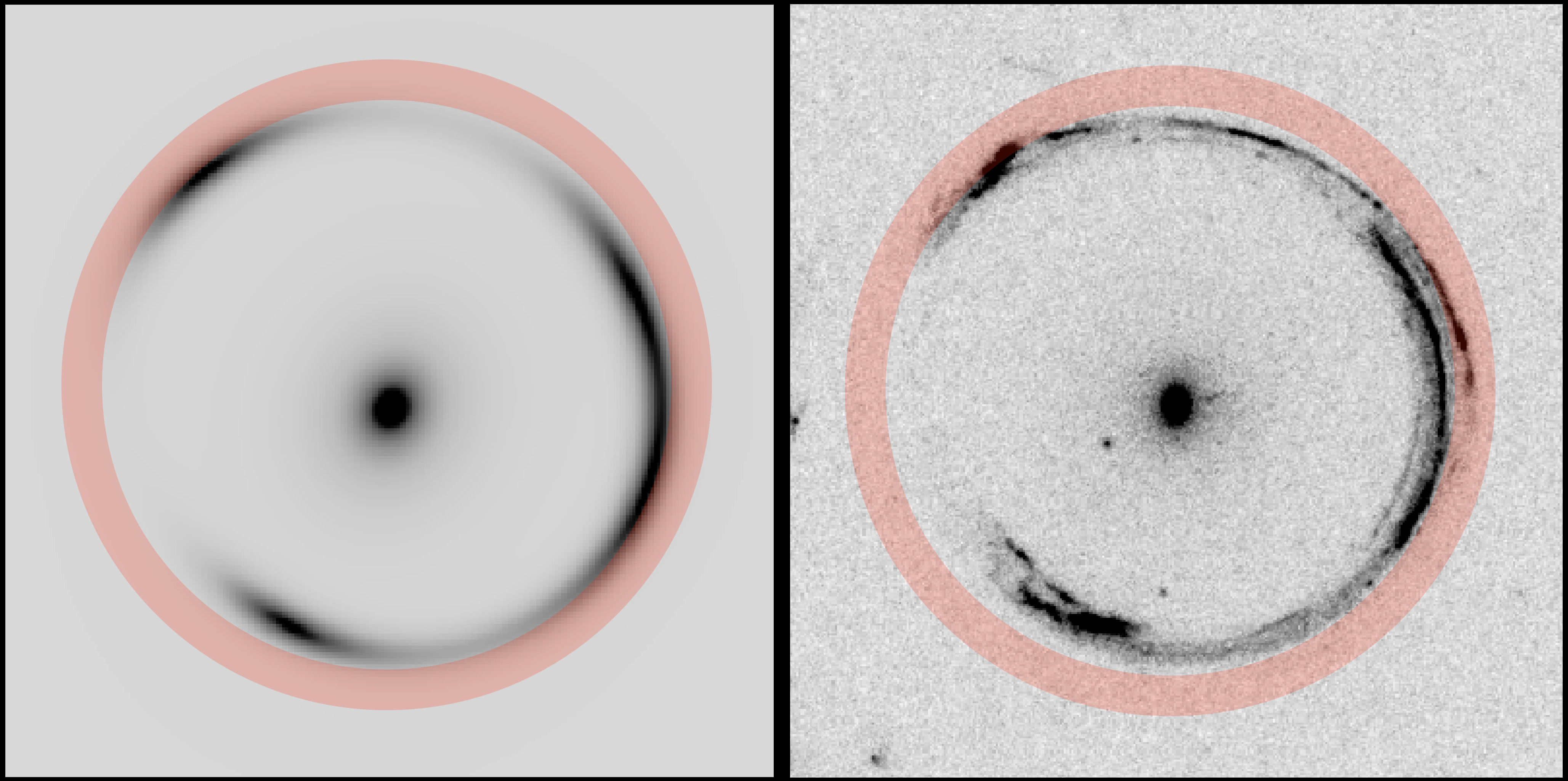
Tessore, Bellagamba & RBM

Cosmic Horseshoe

- apparently rediscovered by Diehl et al. (2009)
- follow-up observation by *HST* under proposal 11602 (2009)
- public data from *HST* in the *F475W*, *F606W*, *F814W* bands
- to date there is **no lensing analysis** of the *HST* data
- basis for reconstruction: *F475W* image



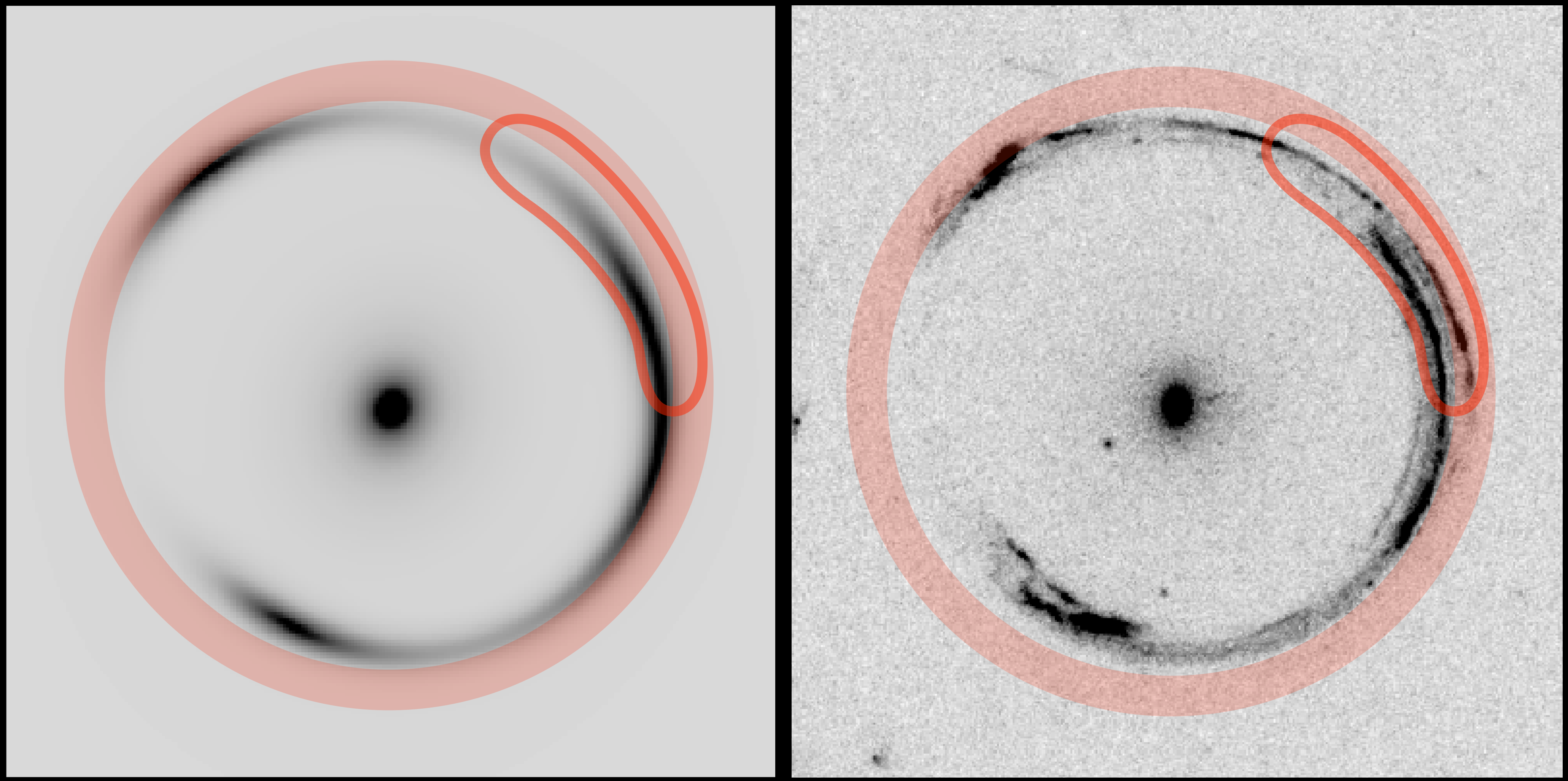
Tessore, Bellagamba & RBM



Cosmic Horseshoe

SIE, 1 Sérsic source

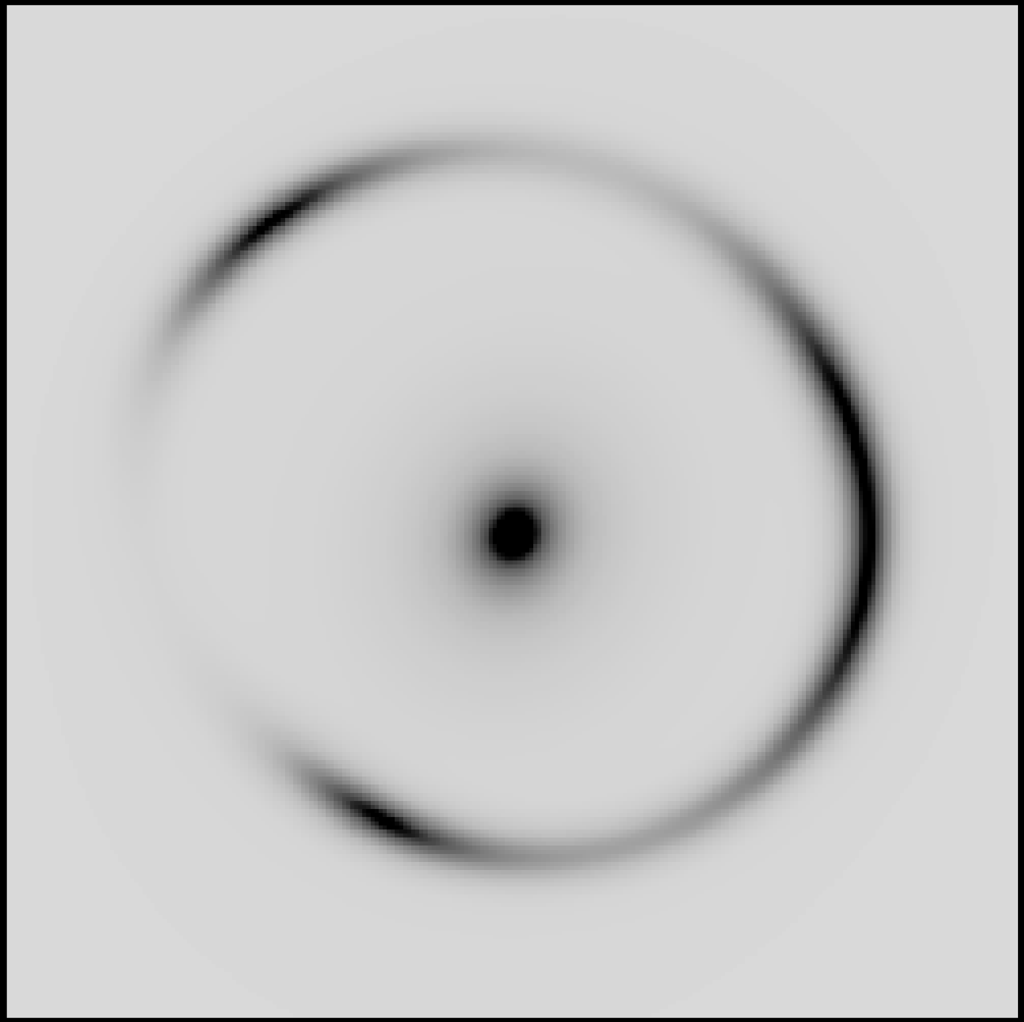
Tessore, Bellagamba & RBM

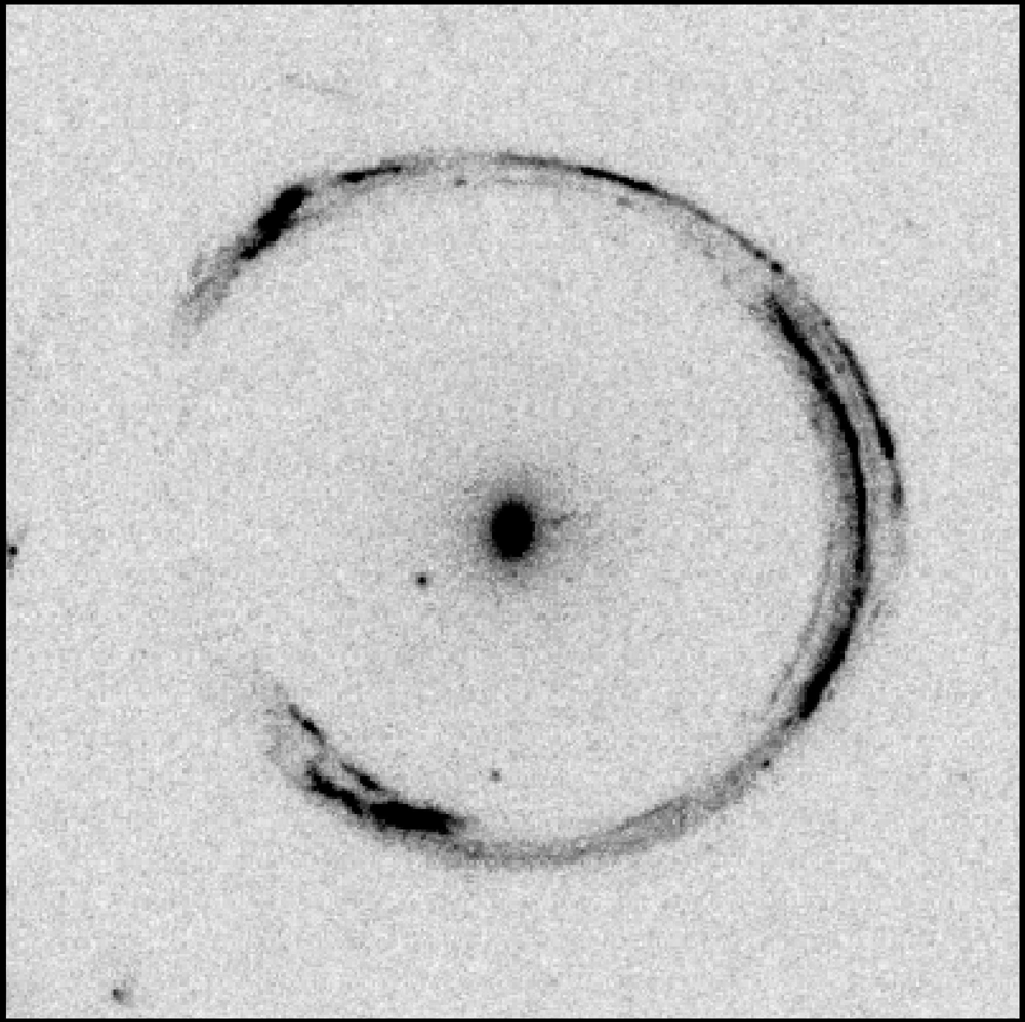


Cosmic Horseshoe

SIE + external shear, 1 Sérsic source

Tessore, Bellagamba & RBM





Cosmic Horseshoe

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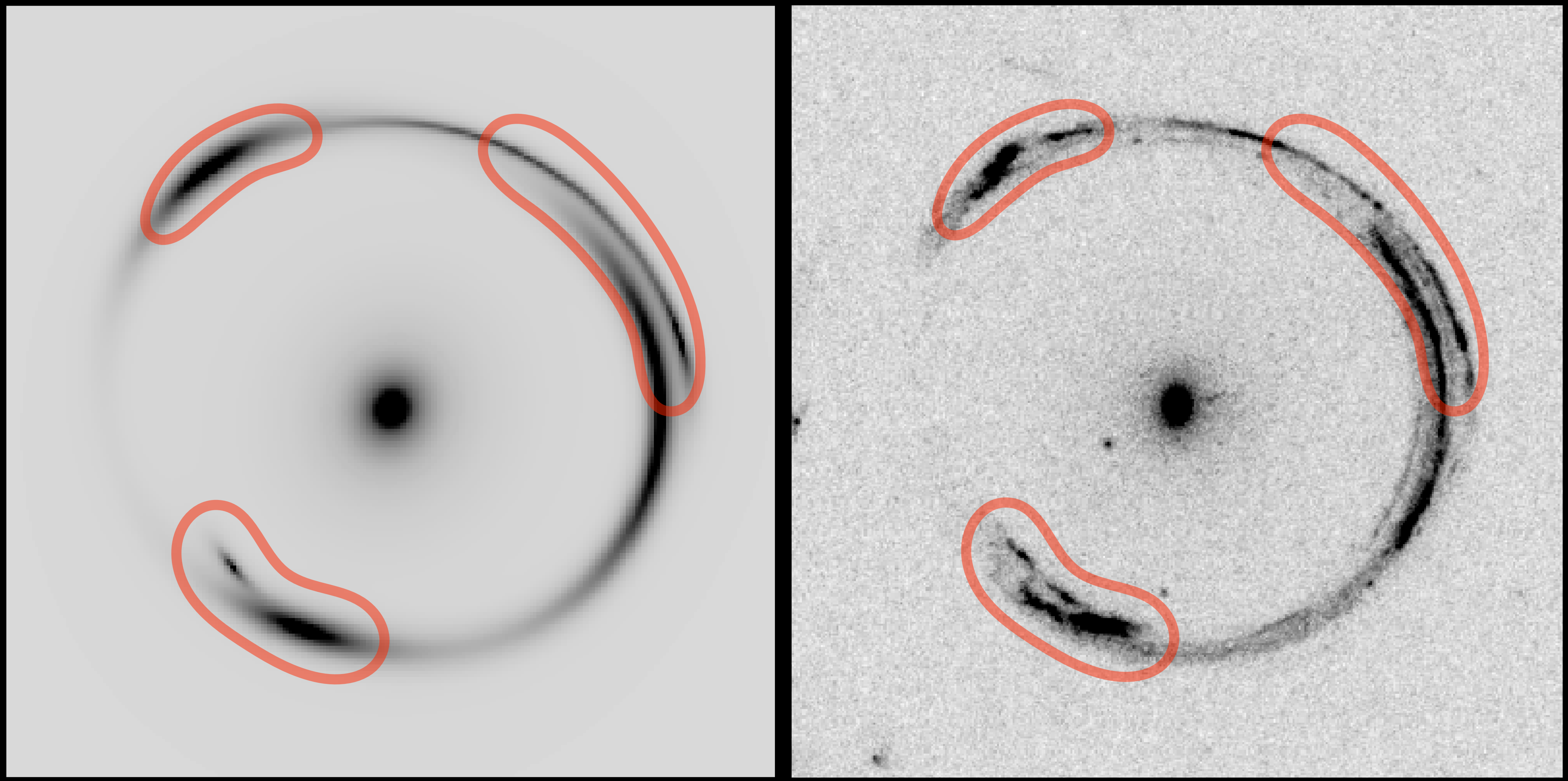
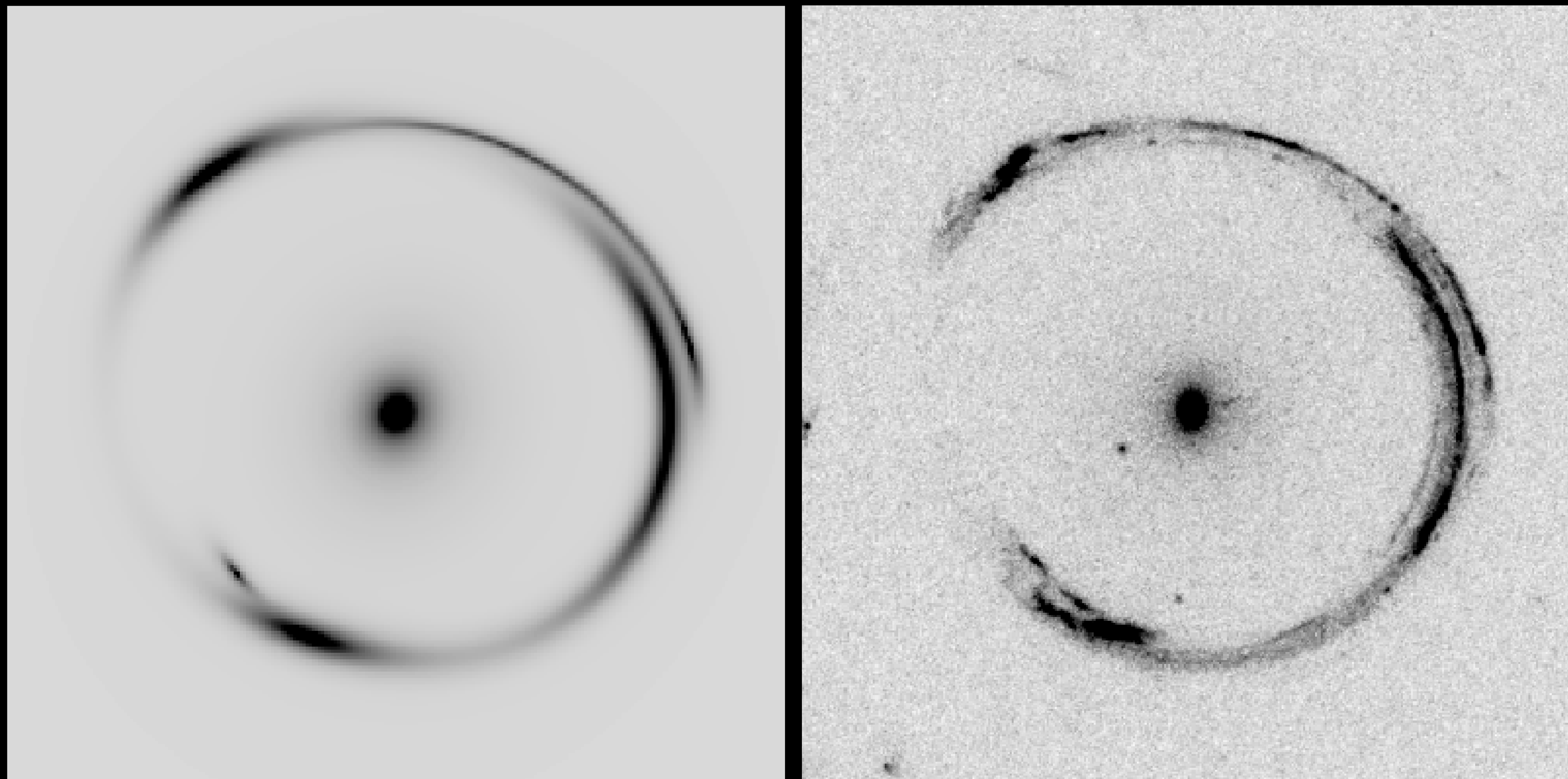
Tessore, Bellagamba & RBM



Cosmic Horseshoe

SIE + external shear, 2 Sérsic sources

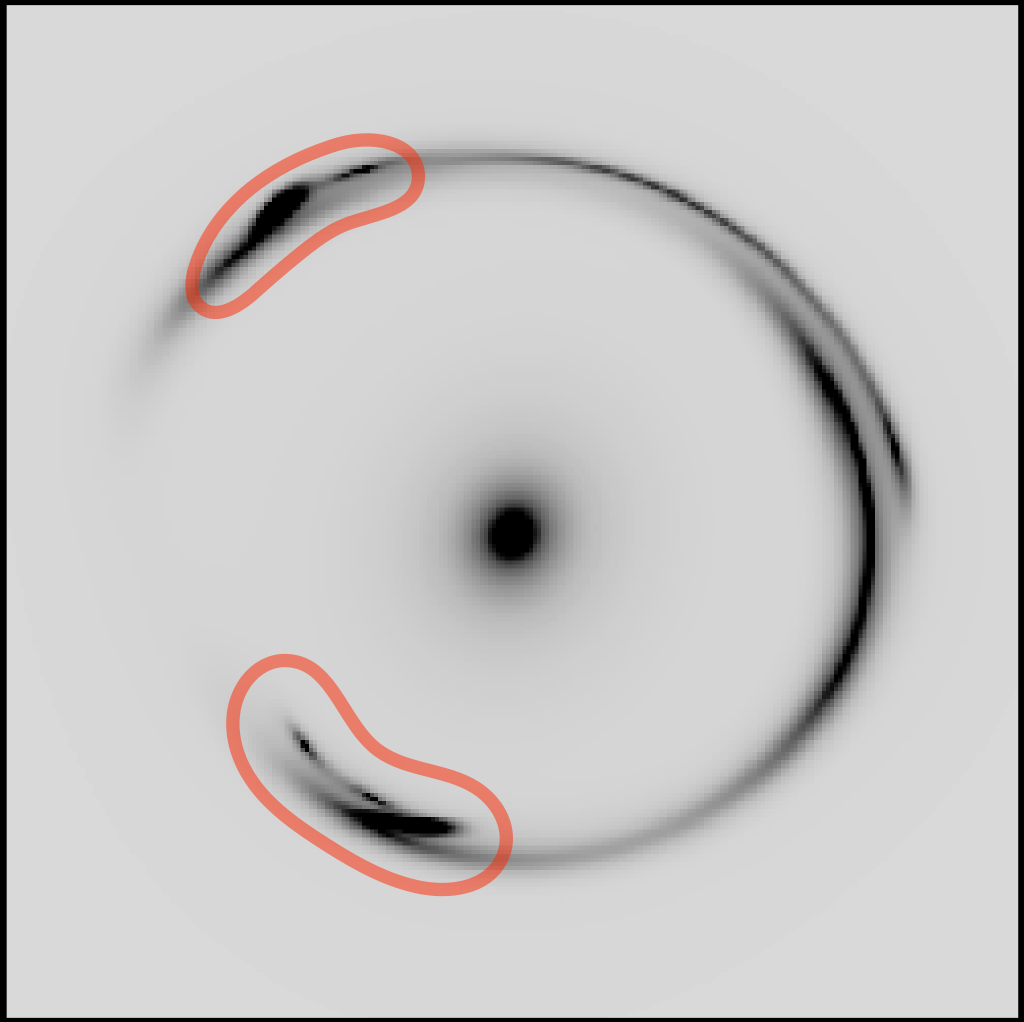
Tessore, Bellagamba & RBM

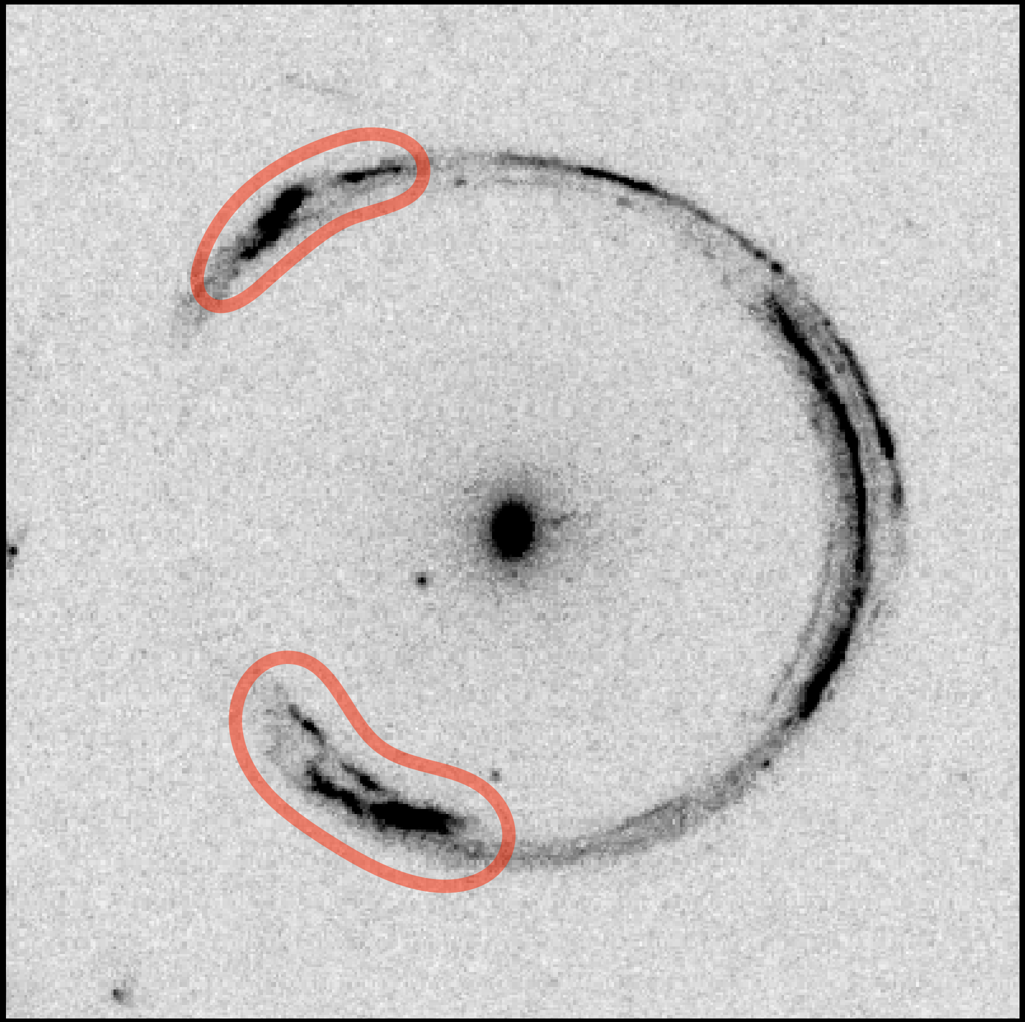


Cosmic Horseshoe

SIE + external shear, 2 Sérsic sources

Tessore, Bellagamba & RBM

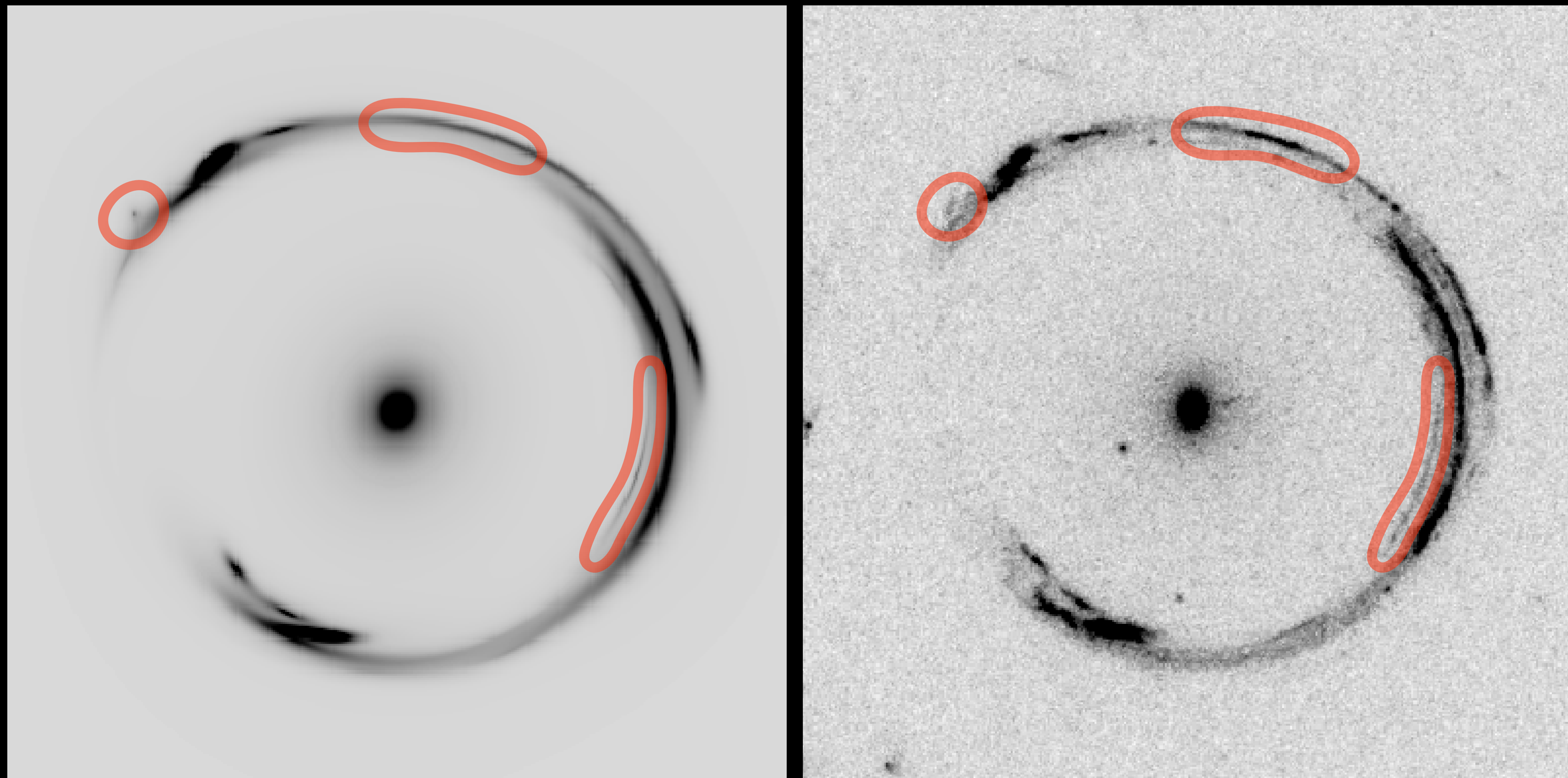




Cosmic Horseshoe

SIE + external shear, 4 Sérsic sources

Tessore, Bellagamba & RBM



Cosmic Horseshoe

elliptical power law (Tessore & Metcalf 2015) + external shear, 6 Sérsic sources

all principal features of the image are reconstructed

Conclusions

- Future surveys will increase the number of known strong lenses by orders of magnitude.

- These lenses will tell us many things about the distribution of matter around galaxies, groups and clusters - small scale structure, separation between dark matter and baryons or possible deviations from GR.

- They will tell us something about cosmology, but it will always be limited by modelling systematics and assumptions about the lenses' mass distribution.

- New tools are being developed to find and analyse strong lenses on a much larger scale.