GRAVITATIONAL LENSING

22 - STRONG LENSING MODELING & APPLICATIONS

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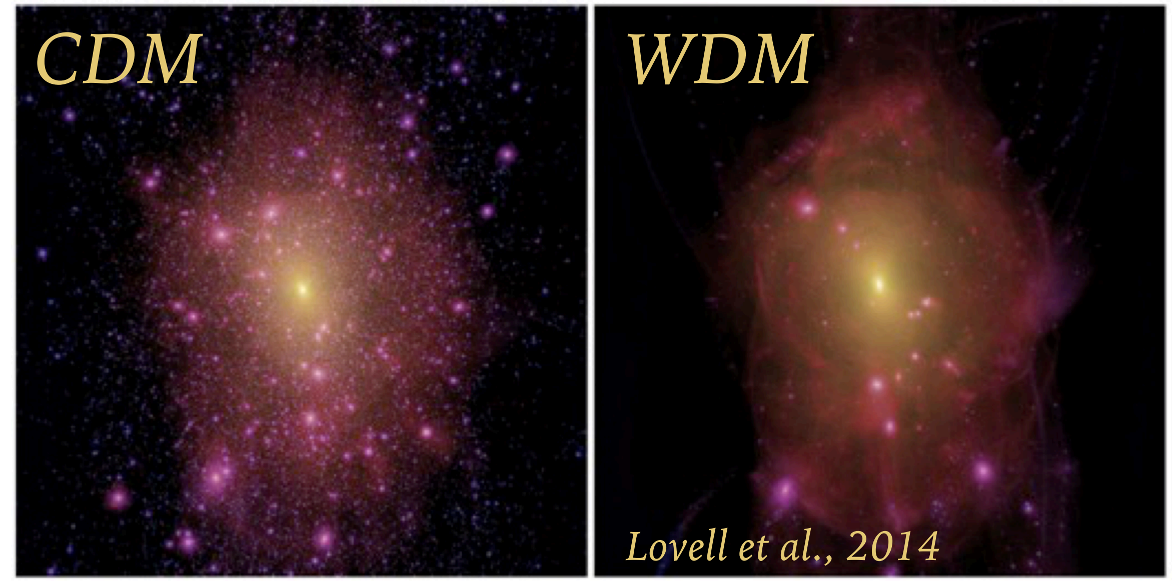
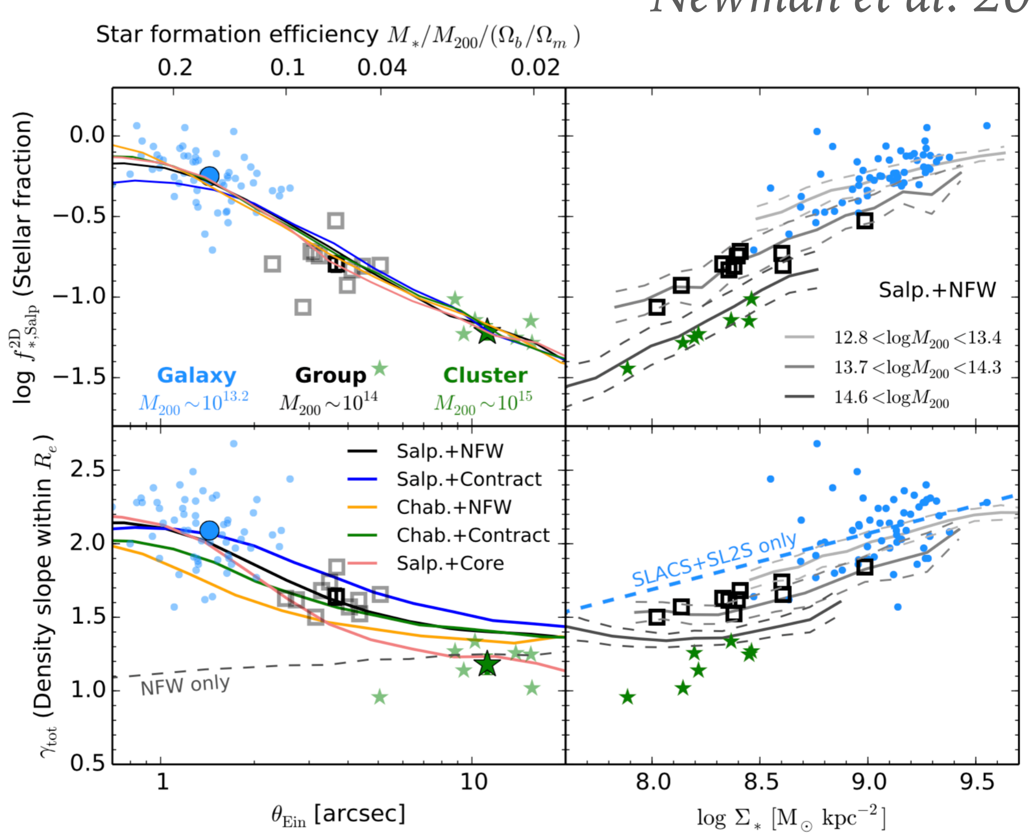
AA 2017-2018

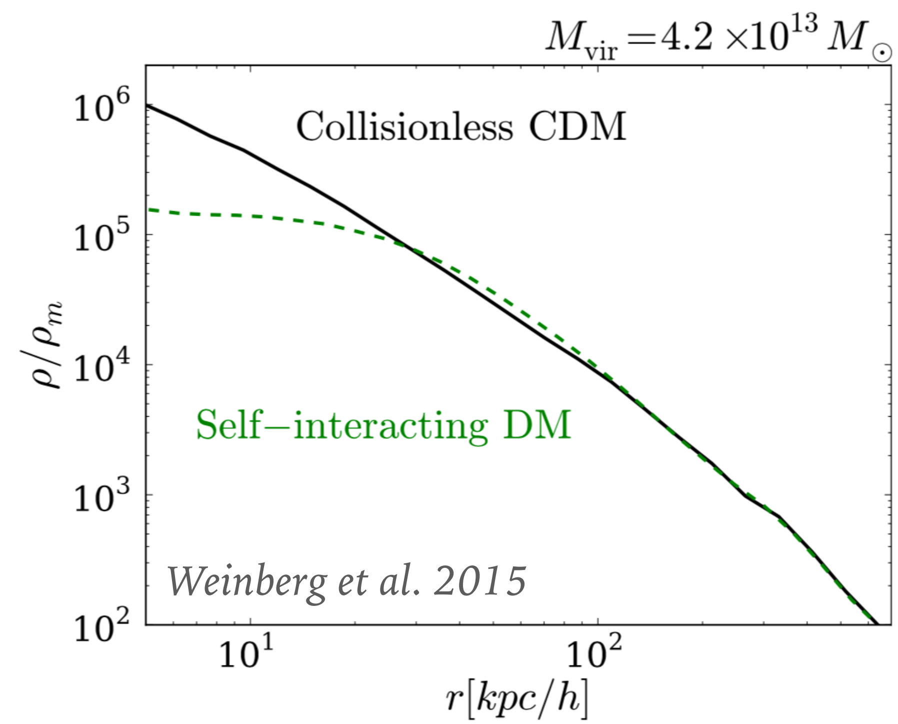
WHY TO LOOK INTO THE CORES OF GALAXIES AND CLUSTERS?

- **Nature of DM:** inner-slope of the density profiles, substructures, core shapes (CDM vs WDM, SIDM, etc)
- **Interplay between baryons and dark matter:** relative spatial distribution of DM and baryons; how baryons affect DM; how do galaxies form



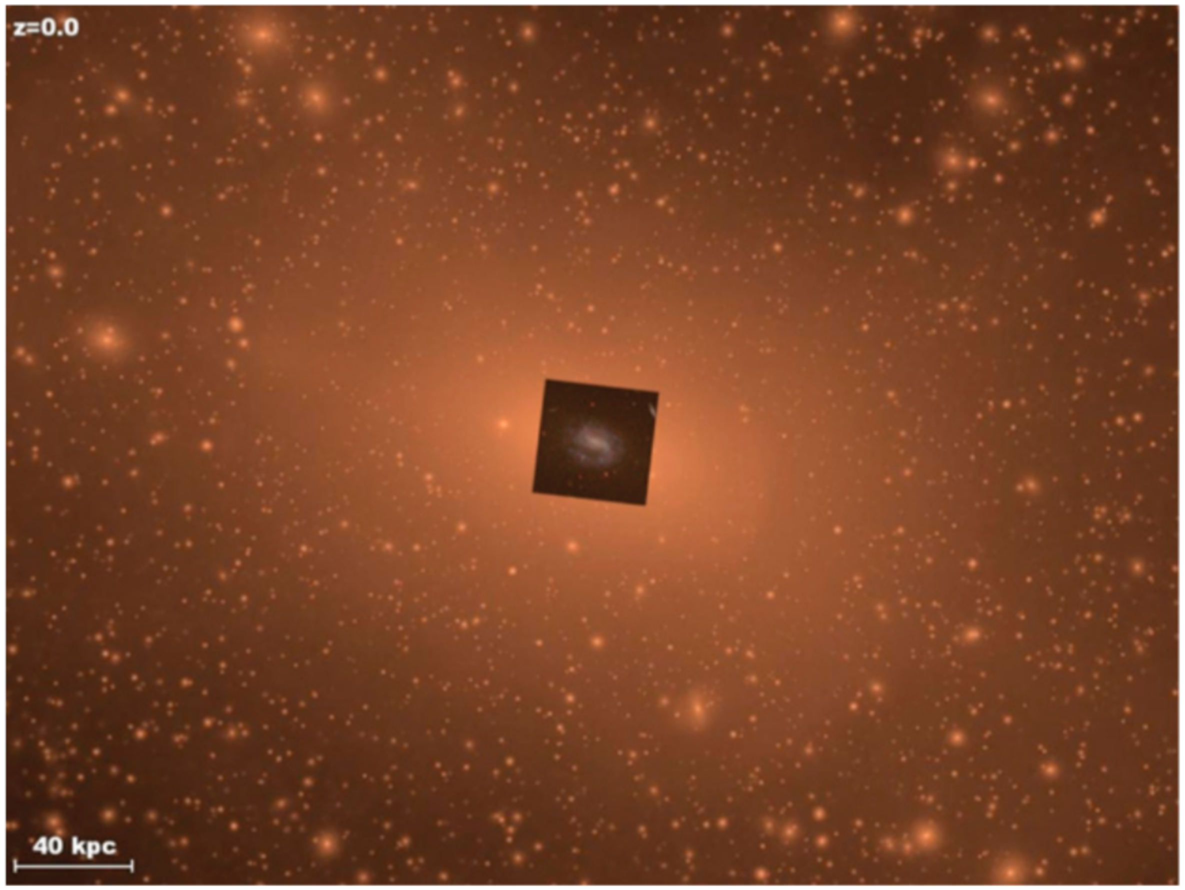
Newman et al. 2015

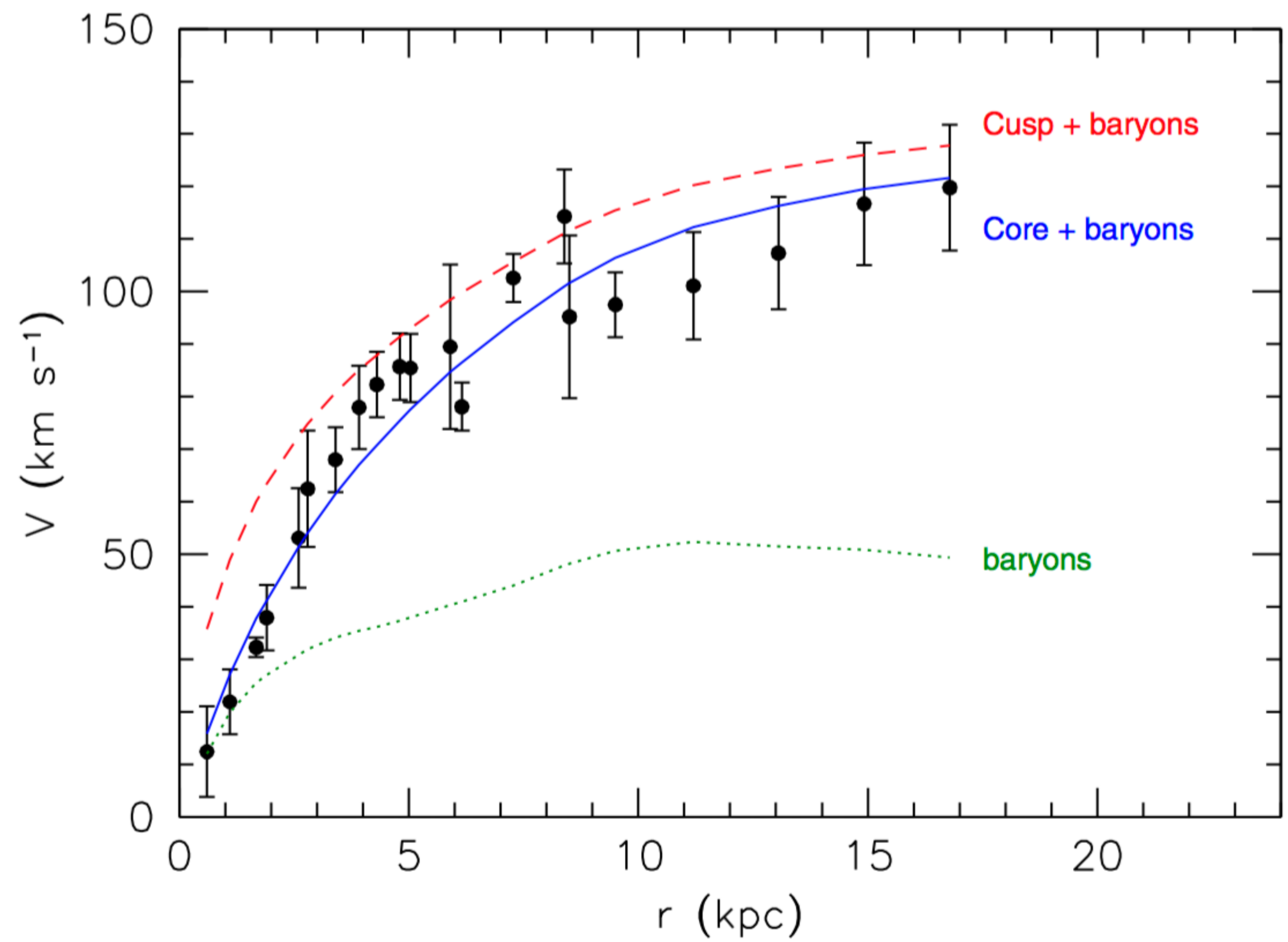




$$\textit{NFW} \qquad \rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

ARE DARK MATTER HALOS UNIVERSAL?

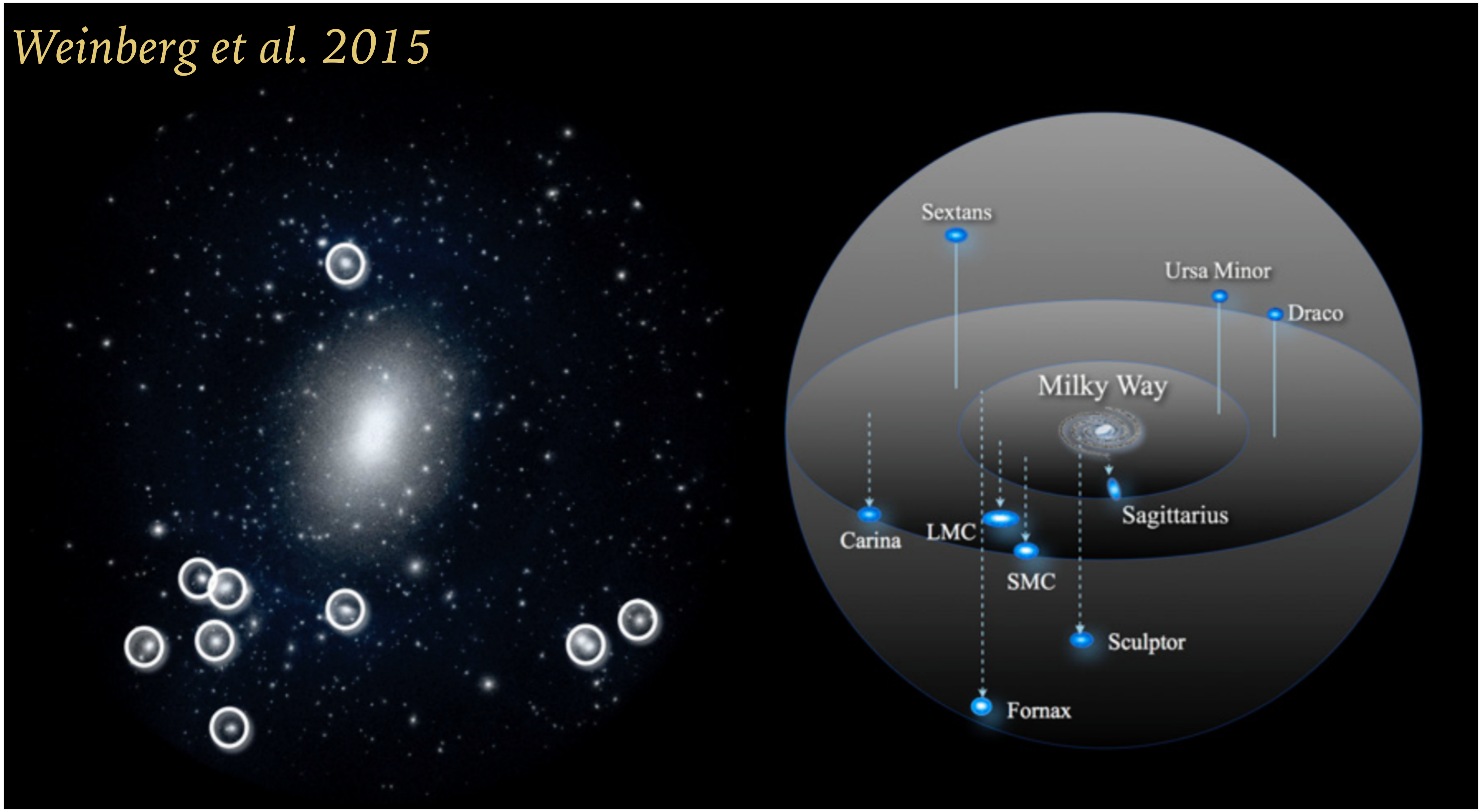




Weinberg et al. 2015

The cusp-core problem: *rotation curves of low-surface brightness galaxies (believed to be dark matter dominated) are inconsistent with cuspy dark-matter profiles (such as the NFW profiles). The circular velocity curve (dots with error-bars refer to the galaxy F568-3)*

SUBSTRUCTURES: THE MISSING SATELLITE AND “THE TOO BIG TO FAIL” PROBLEMS



The missing-satellite problem: *simulations show that CDM forms many more sub-halos than observed around the Milky-Way*

The too-big-to-fail problem: *the biggest sub-halos in simulations are too massive and dense to host the observed dwarf-satellites (x5 in mass)!*

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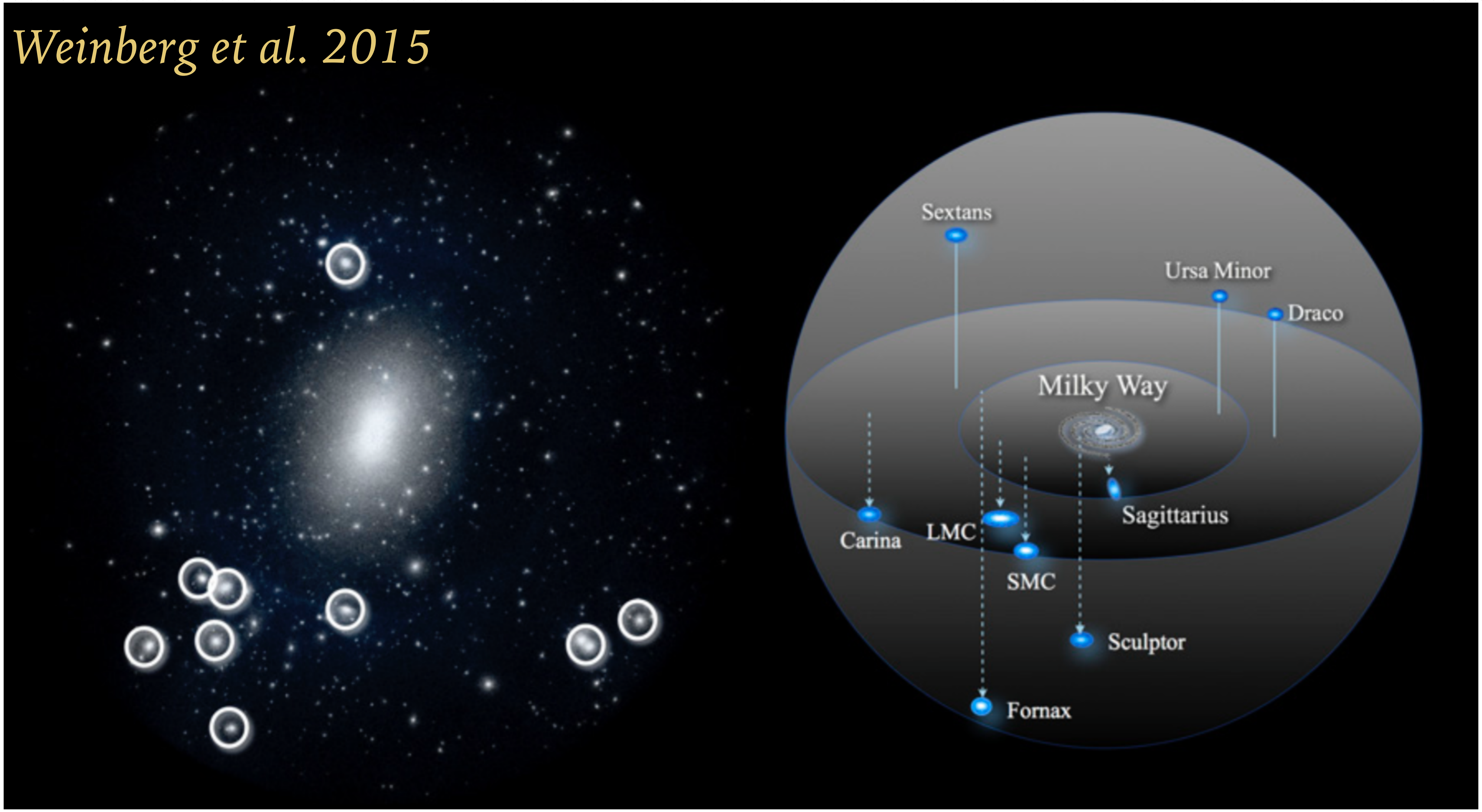

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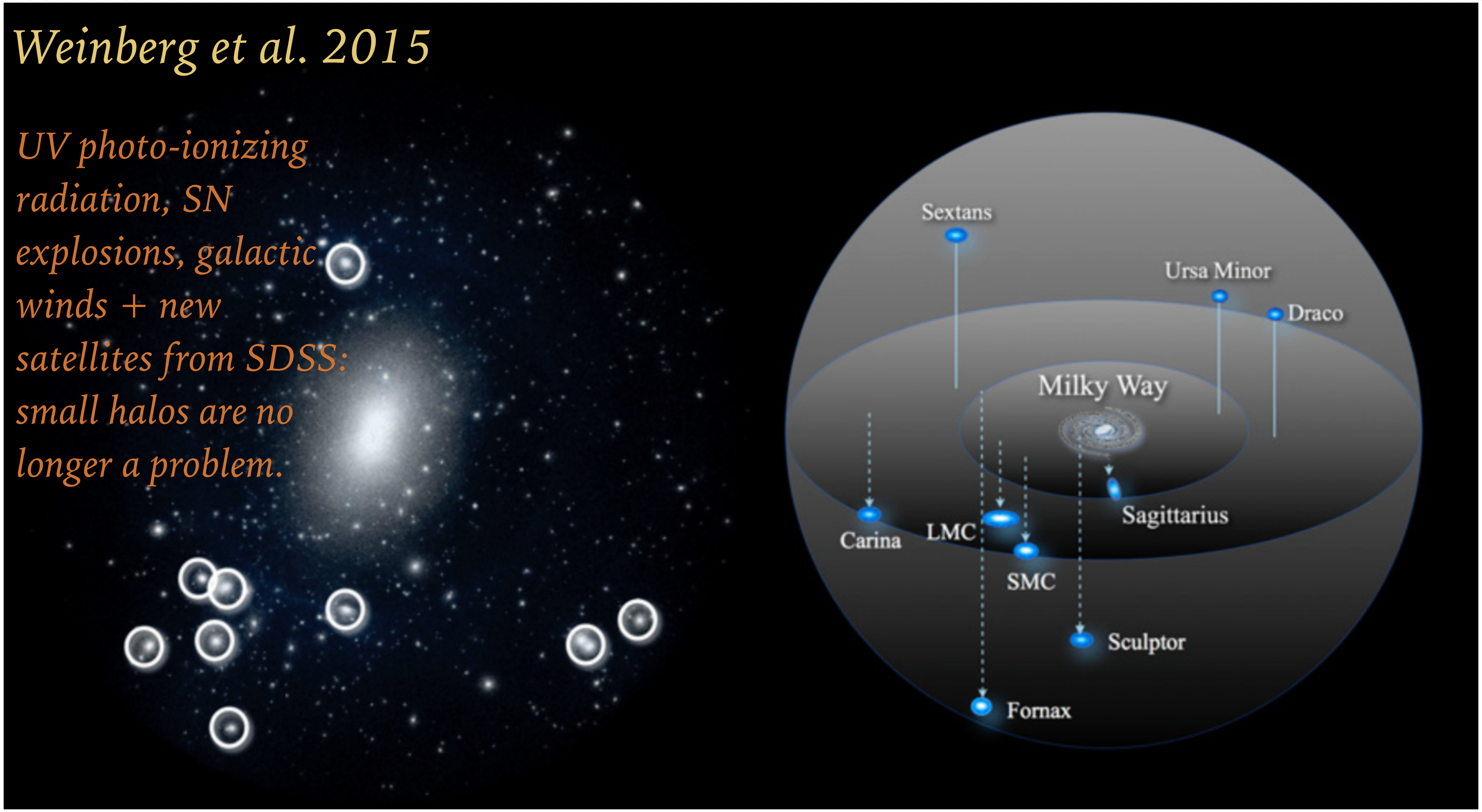

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SEMI-LINEAR INVERSION

(Warren & Dye, 2003; Dye & Warren, 2005; Suyu et al. 2006; Vegetti & Koopmans, 2009; Nightingale et al., 2017; Enia et al, 2018)

source pixel flux   *lensing*   *image pixel flux*   *error of pixel flux*

$$G = \chi^2_{im} = \sum_{j=1}^{J} \left[\frac{\sum_{i=1}^{I} s_i f_{ij} - d_j}{\sigma_j} \right]^2$$

$$\frac{\partial G}{\partial s_i} = 0 = \sum_{j=1}^{J} \left[\frac{2 f_{ij} (\sum_{k=1}^{I} s_k f_{kj} - d_j)}{\sigma_j^2} \right]$$

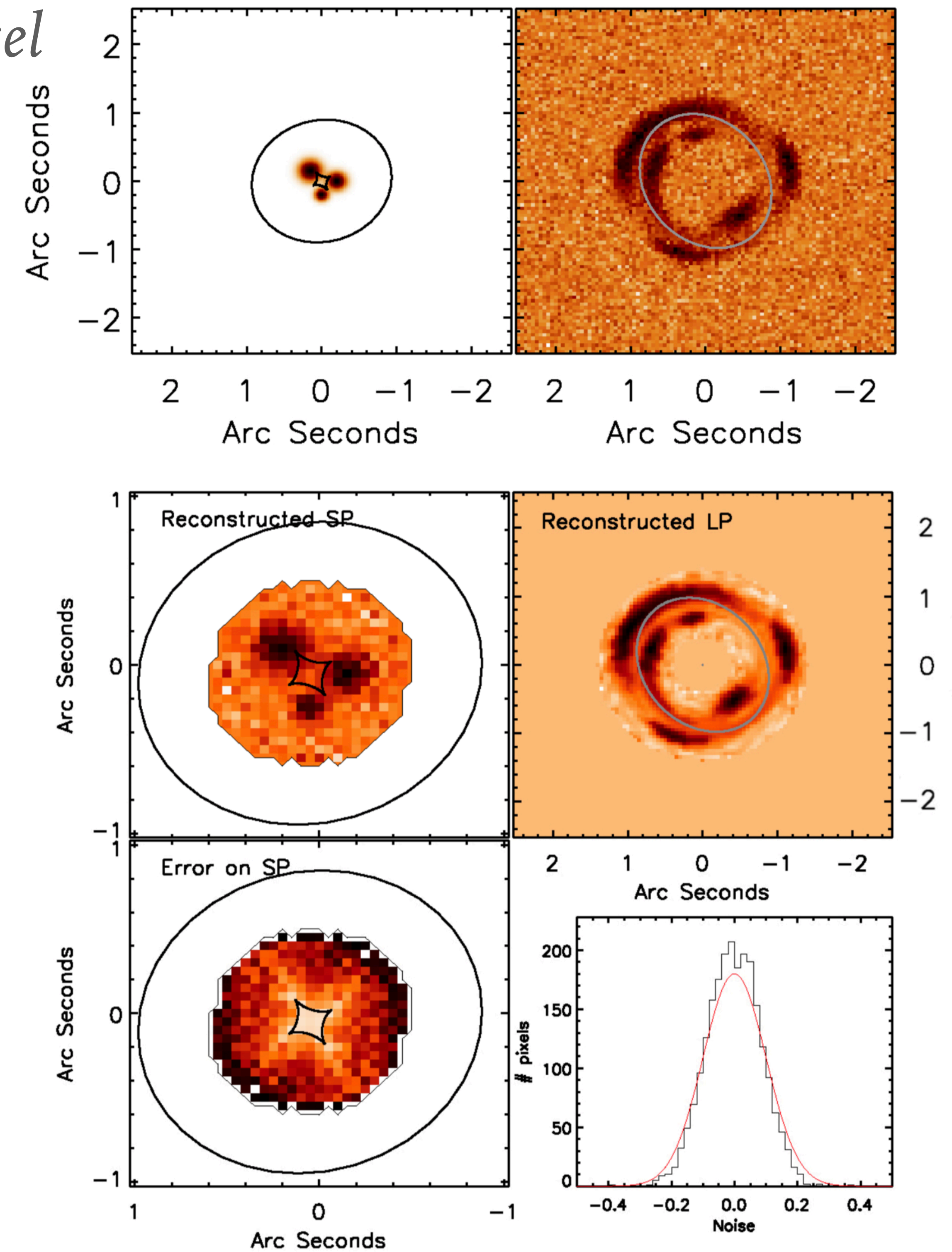
$$F_{ik} = \sum_{j=1}^{J} \frac{f_{ij} f_{kj}}{\sigma_j^2} \qquad D_i = \sum_{j=1}^{J} \frac{f_{ij} d_j}{\sigma_j^2} \qquad S_i = s_i$$

$$\mathbf{SF} - \mathbf{D} = 0 \qquad\qquad \mathbf{S} = \mathbf{F}^{-1}\mathbf{D}$$

In practice: need to add regularization term and account for blurring and noise.

Bayesian analysis to choose best lens and regularization parameters (Suyu et al. 2006)

A. Enia, Ph.D. thesis



OUTCOME

- model of the lens
- model of the source
- can be extended to *u,v* plane, i.e. to reconstruct lenses from interferometric data (e.g. sub-mm galaxies observed with ALMA or VLBI)
- promising for detecting small mass substructures (10^8-10^9 $M_\odot$; Vegetti et al. 2010, 2012; Hezaveh et al. 2016)
- first fit with smooth model, then add perturbations
- warning: difficult to disentangle substructure in the lenses or in the sources

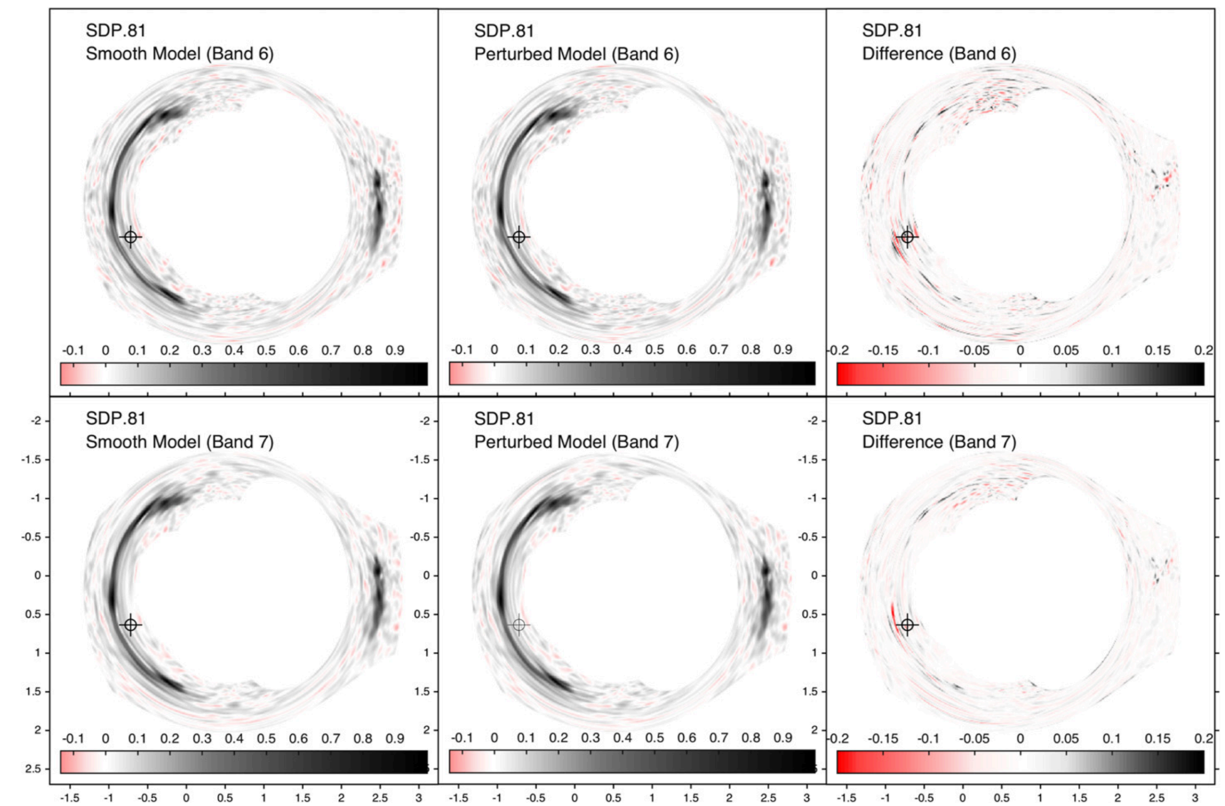
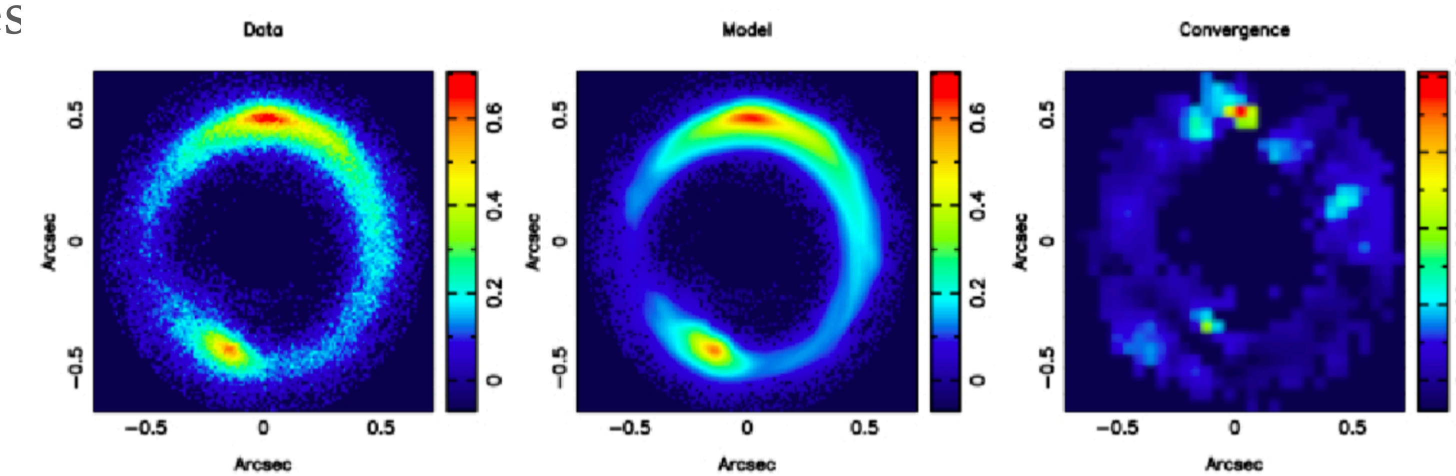
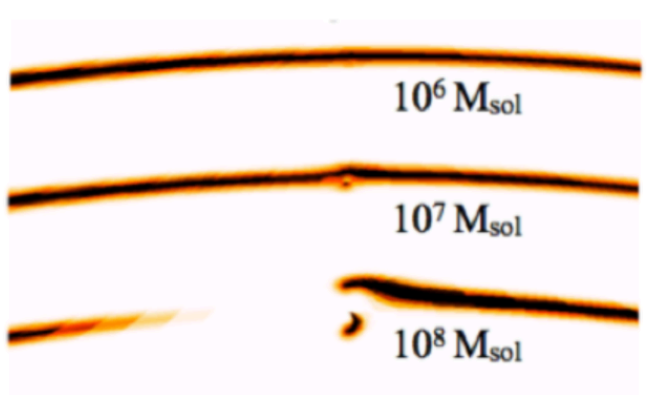


Figure 6. Top left: the sky emission model in band 6 for the best-fit smooth lens parameters for the SDP.81 data. Top middle: the same for the perturbed model. Top right: the difference between the two models. The bottom panels show the same for band 7. The bright feature in the difference plots is mainly caused by the astrometric anomaly of the arc. In each row, the images have been scaled to the peak flux of the smooth model.

Hezaveh et al. 2016

Vegetti et al. 2012





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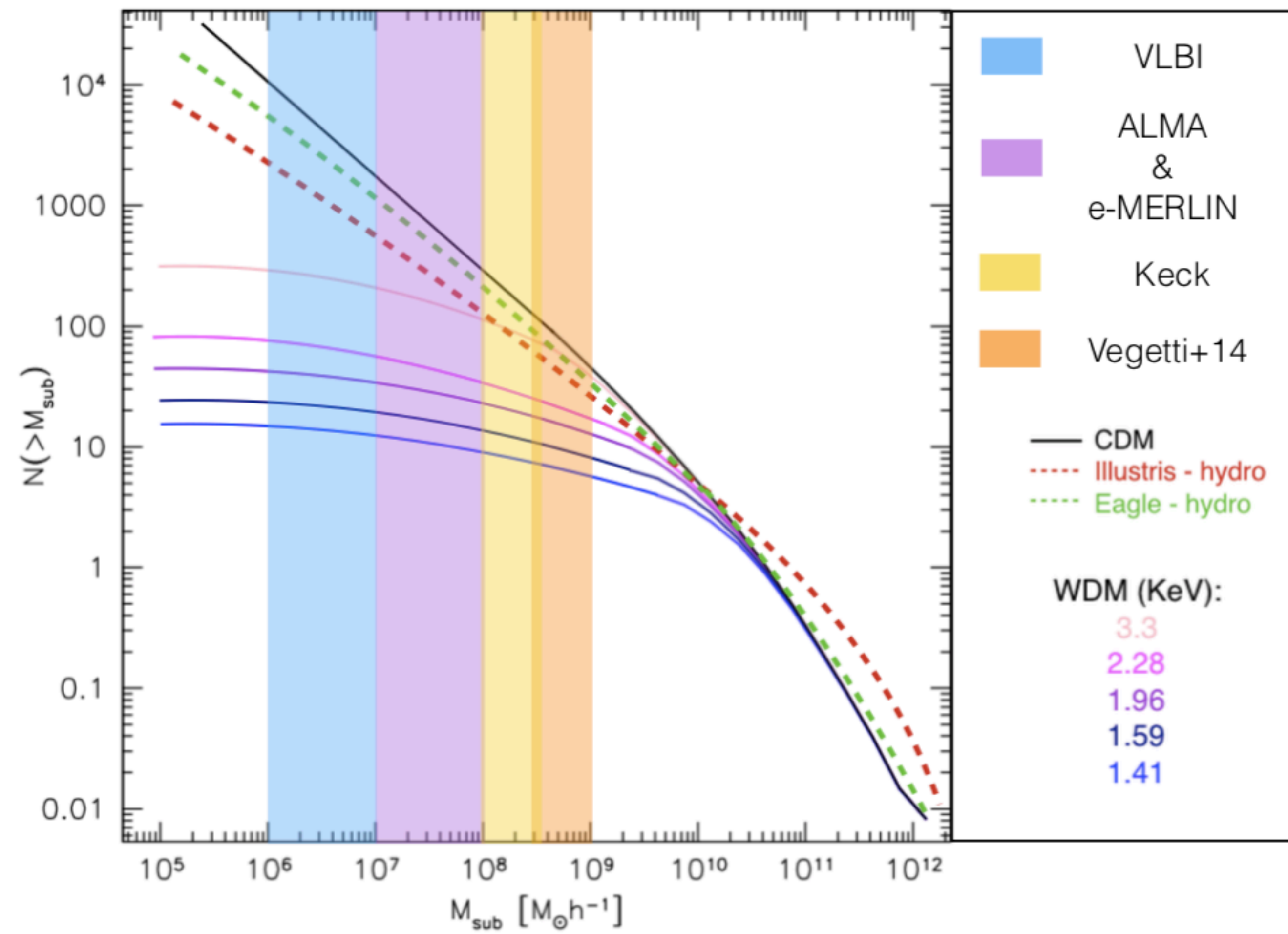

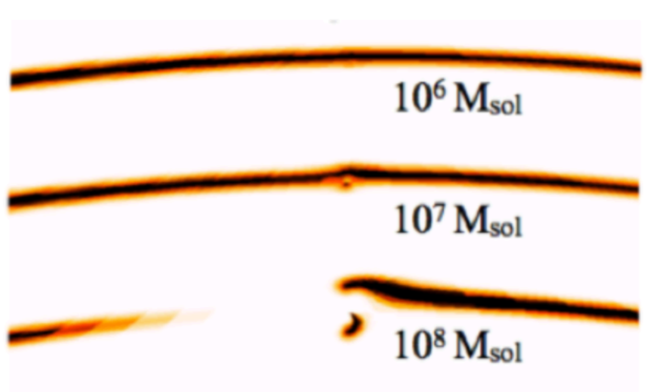

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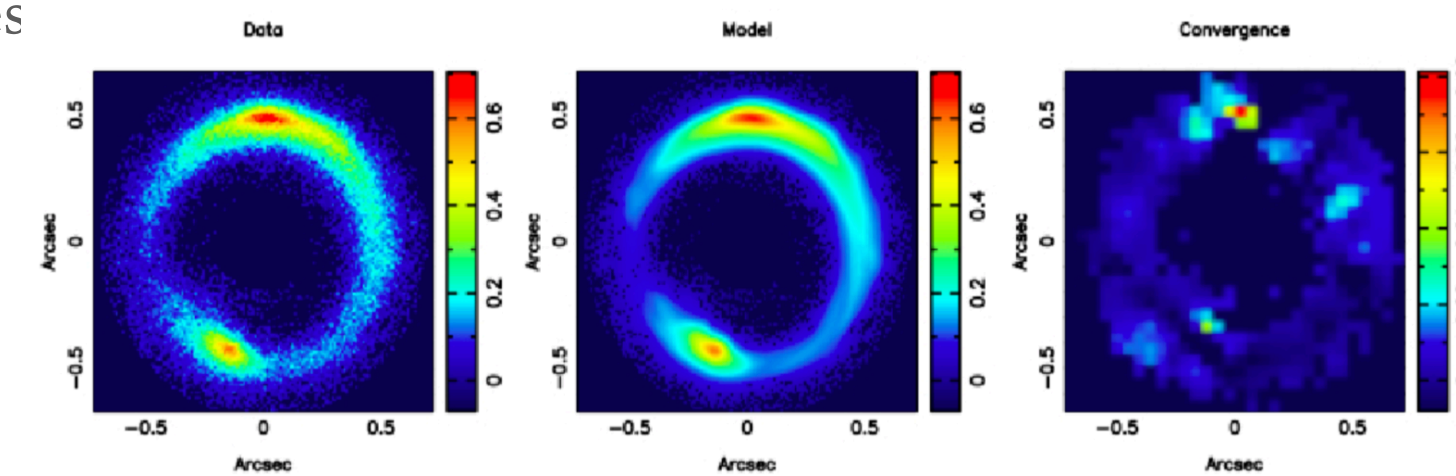
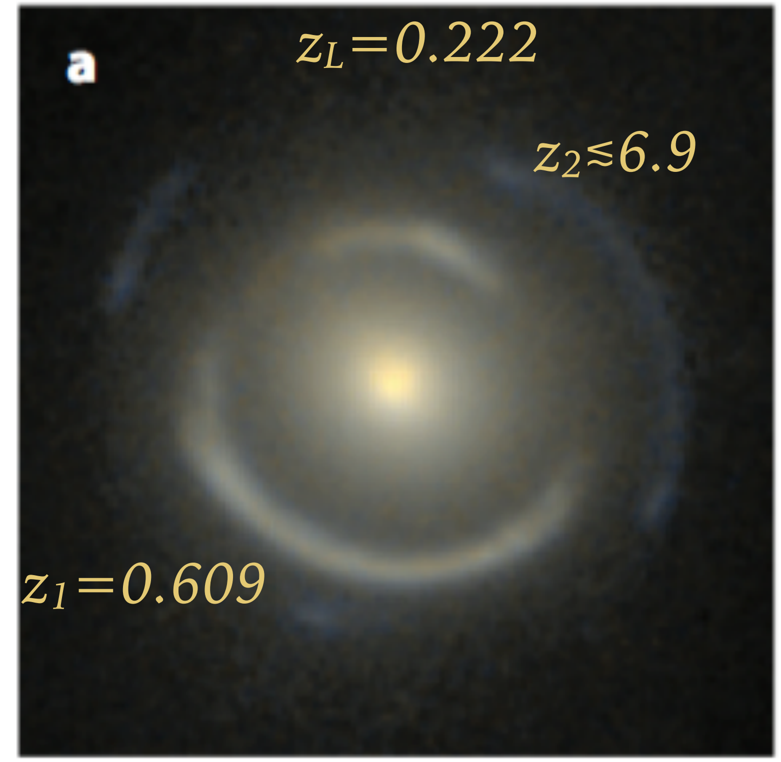
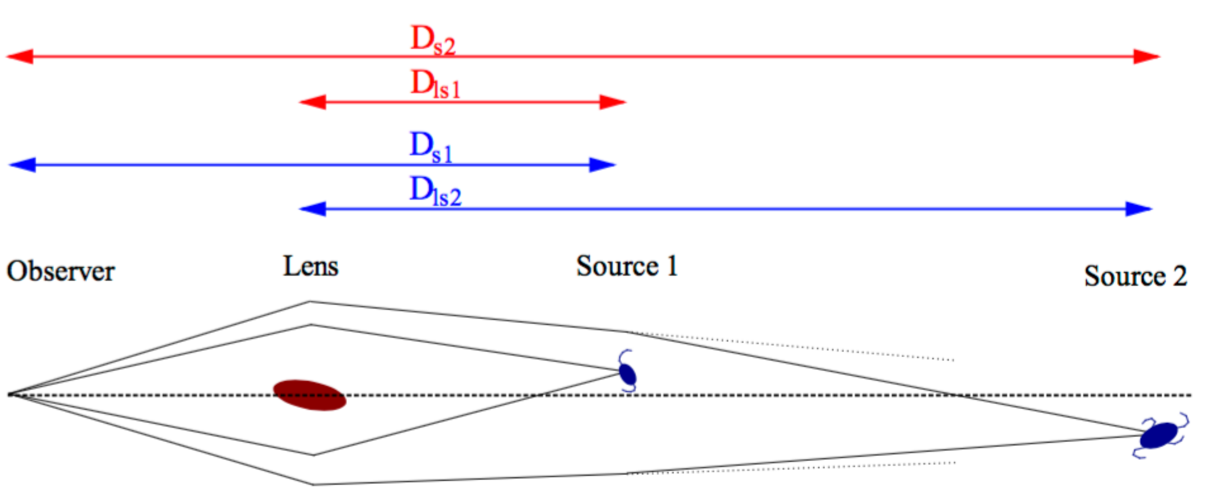


MASS DENSITY PROFILES

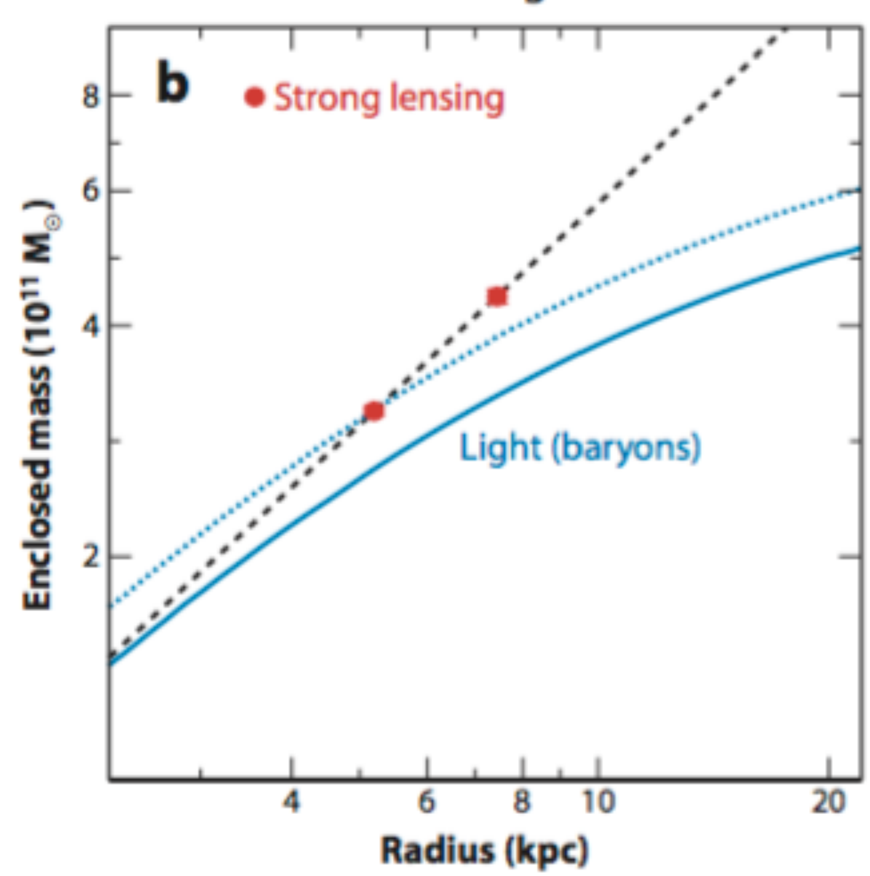
- “compound lenses” or “jackpot lenses” are special cases (Gavazzi et al. 2008)
- in such cases, two measurements of the mass at two different radii are possible, enabling the measurement of the slope of the mass profile
- the complication: it is a double lens!

SDSSJ0946 + 1006





Double Einstein ring J0946 + 1006

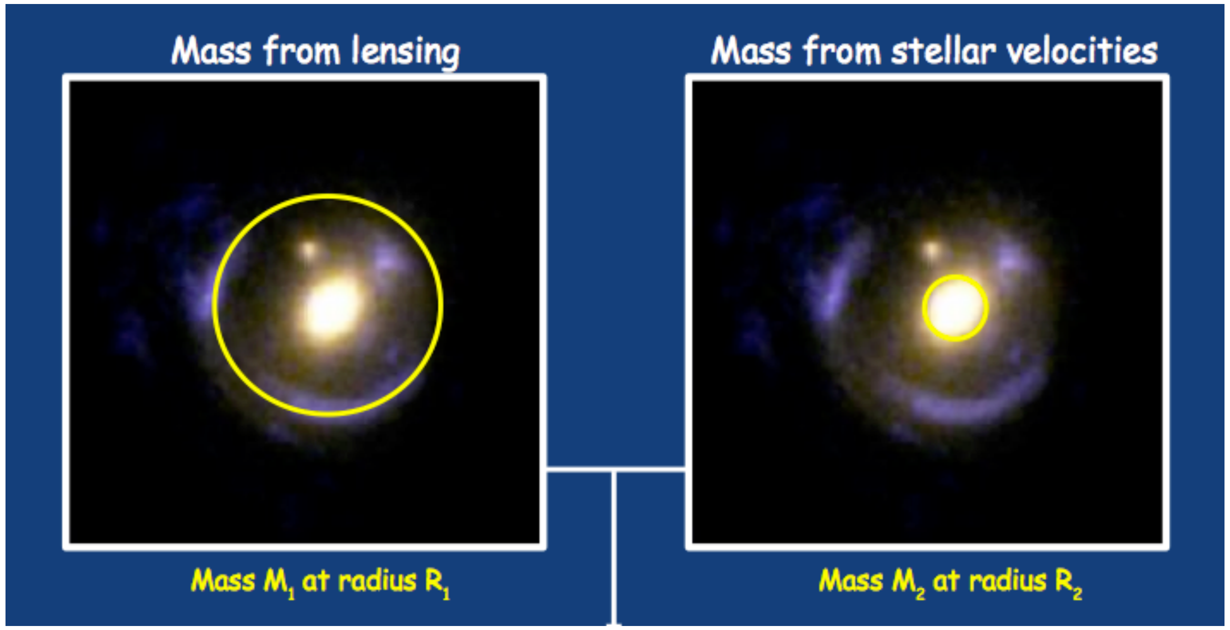


Collett et al. 2014

MASS DENSITY PROFILES

Koopmans & Treu 2002, Treu & Koopmans 2002, Koopmans et al. 2006, 2009, Sonnenfeld et al. 2013, Spiniello et al. 2015

- Generally, one single source, i.e. difficult to probe profile slopes with SL alone
- Since 2005 (LSD survey; Koopmans & Treu), SL and stellar kinematics have been used to probe the mass profiles of ETGs
- Results point into the direction that, at the scales probed by these two methods, the total mass profiles are nearly isothermal
- there seems to be very little evolution with redshift



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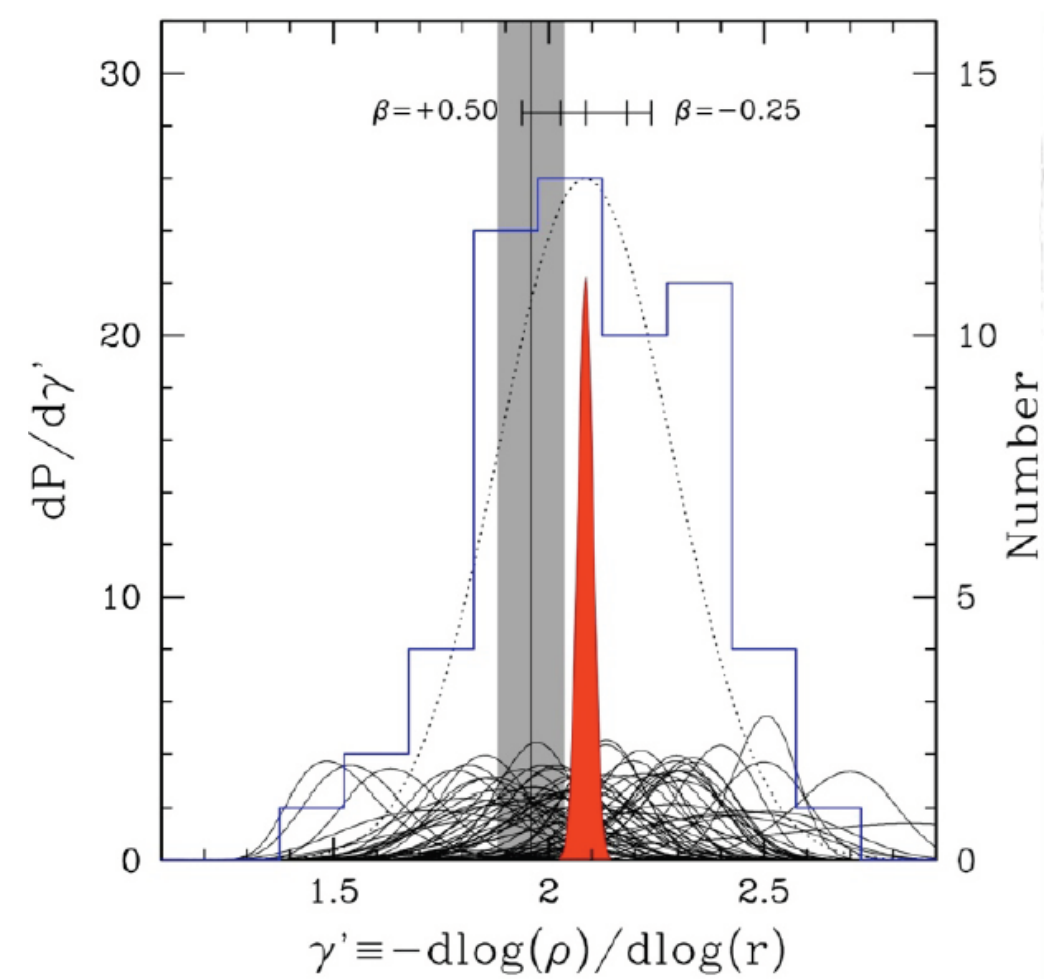

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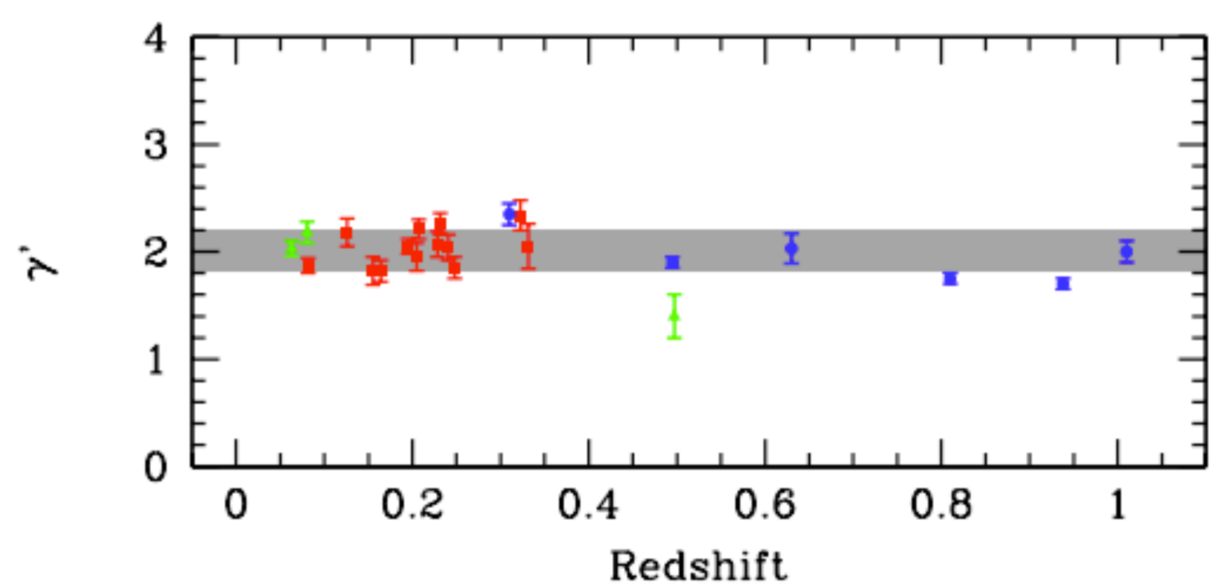

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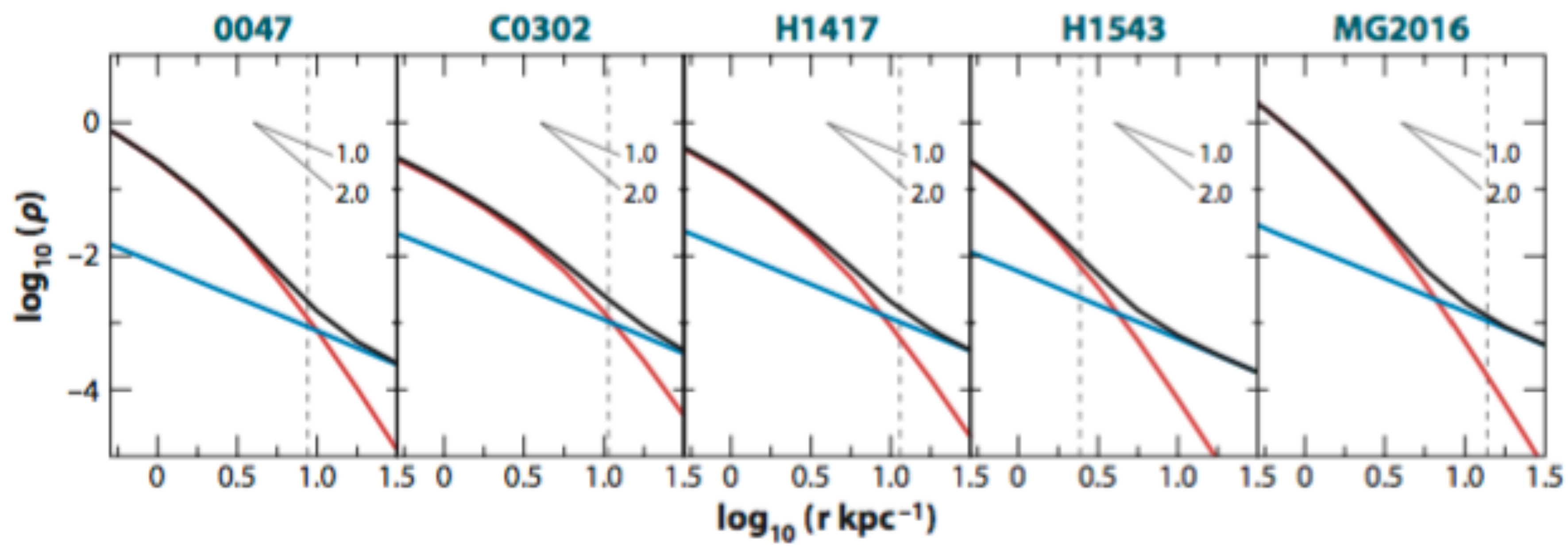
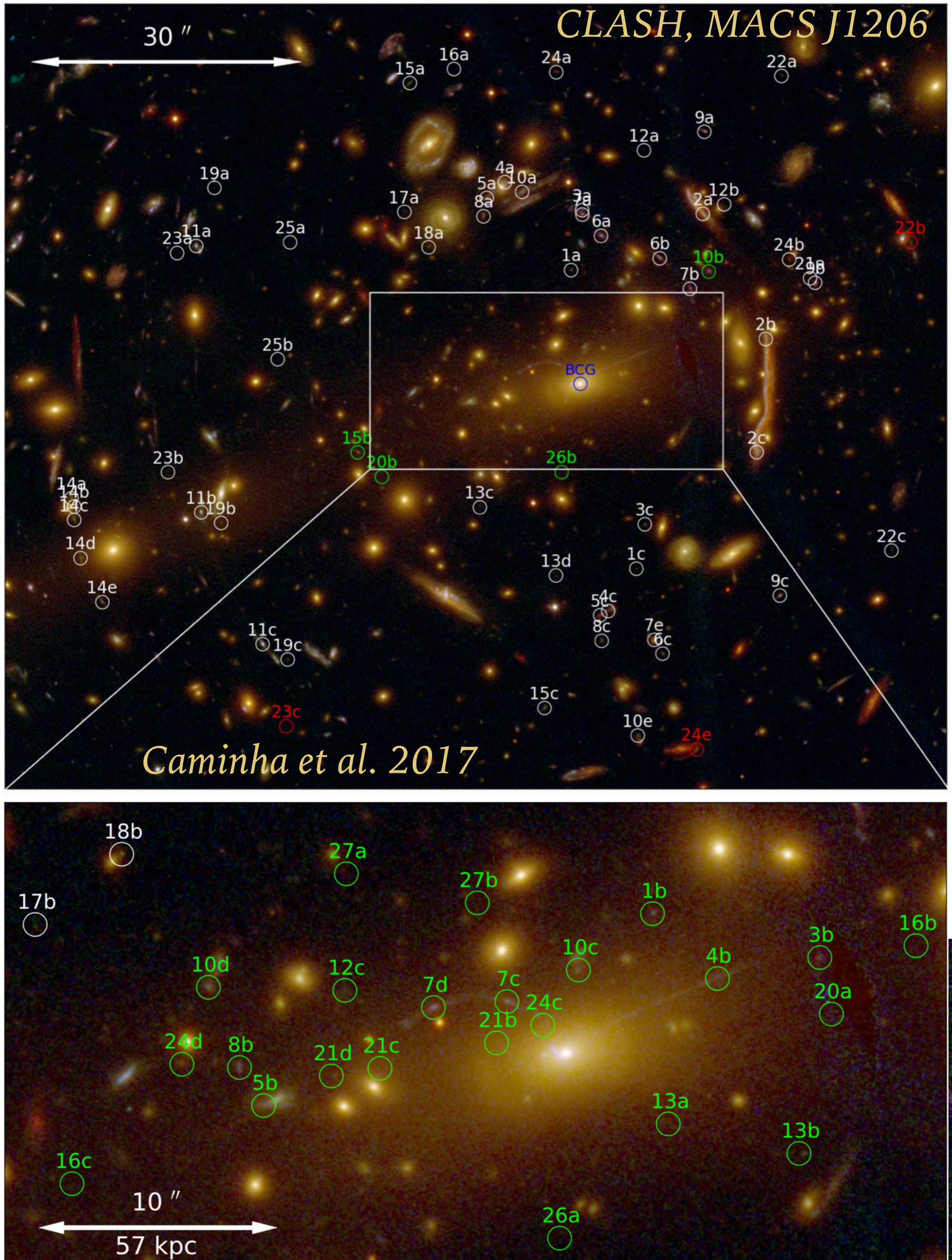


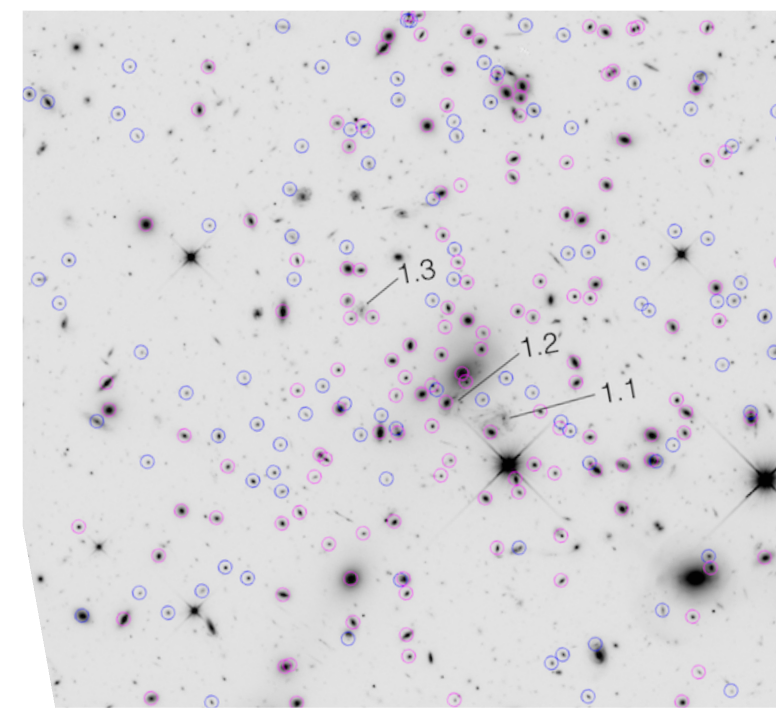
Difficult to say using SL by ETGs, because of the bulge-halo conspiracy…

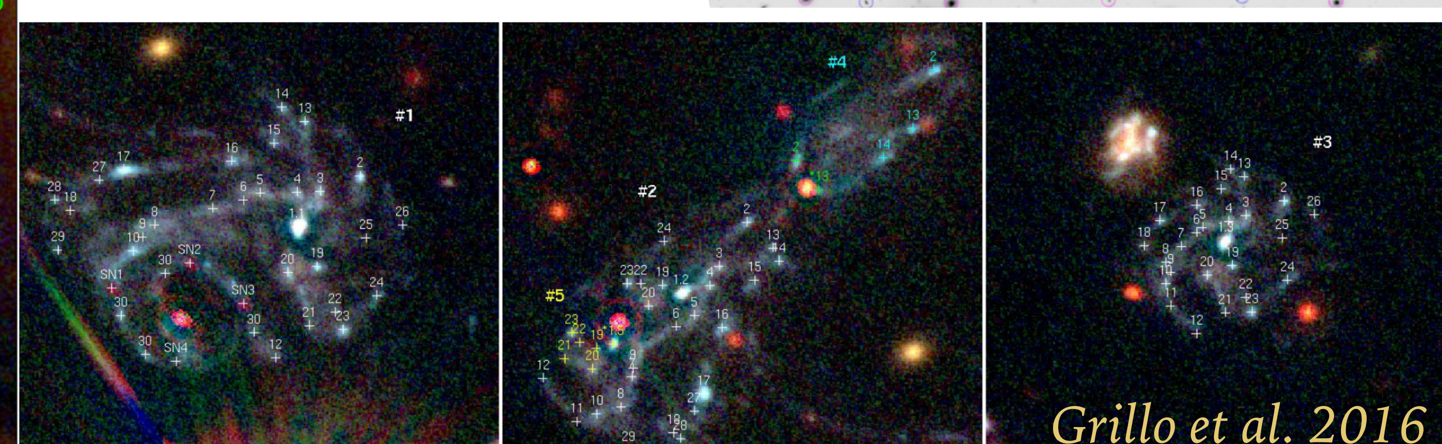
However, imposing the slope of the NFW profile, the assumption of a universal IMF to derive the stellar masses doesn't work (SLACS, Treu et al. 2010).

CLUSTER PARAMETRIC MODELS



- mostly positional constraints: several families of multiple images from sources covering a range of redshifts
- image deformation is sometimes usable





LENS OPTIMIZATION

- lensing likelihood:
- minimization of χ^2 to find the best $\mathbf{p}$ fitting the data
- iterate between image and source plane
- or optimization in the source plane
- Lenstool (Kneib et al. 1998; Jullo et al. 2010); GLAFIC (Kawamata et al. 2016)

Number of systems

$$\mathcal{L} = \Pr(D|\mathbf{p}) = \prod_{i=1}^{N} \frac{1}{\prod_{j=1}^{n_i} \sigma_{ij}\sqrt{2\pi}} \exp -\frac{\chi_i^2}{2}$$

Number of images

Contribution from single system

$$\chi_i^2 = \sum_{j=1}^{n_i} \frac{[\vec{\theta}^j_{obs} - \vec{\theta}^j_{\mathbf{p}}]^2}{\sigma_{ij}^2}$$

$$\vec{\beta}^j_{\mathbf{p}} = \vec{\theta}^j_{obs} - \vec{\alpha}(\vec{\theta}^j_{obs}, \mathbf{p})$$

$$\vec{\beta}^j_{\mathbf{p}} = \vec{\theta}^j_{\mathbf{p}} - \vec{\alpha}(\vec{\theta}^j_{\mathbf{p}}, \mathbf{p})$$

$$\chi_{S,i}^2 = \sum_{j=1}^{n_i} \frac{[\beta^j_{\mathbf{p}} - \langle\beta^j_{\mathbf{p}}\rangle]}{\mu_j^{-2}\sigma_{ij}^2}$$

SUBSTRUCTURES

- The complexity of cluster lenses is way larger than galaxy lenses.
- For example: asymmetric mass distributions, multiple halos, substructures. The number of free parameters can be very large.
- Some tricks can be used to reduce them. For example: cluster substructures, traced by galaxies, can be modeled with scaling relations linking their lensing properties to some observable (e.g. the luminosity)

$$\sigma = \sigma_\star \left(\frac{L}{L_\star}\right)^{1/4}$$

$$r_t = r_{t,\star} \left(\frac{L}{L_\star}\right)^{\eta}$$

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MODEL OF MACSJ1206 (CAMINHA ET AL. 2017)

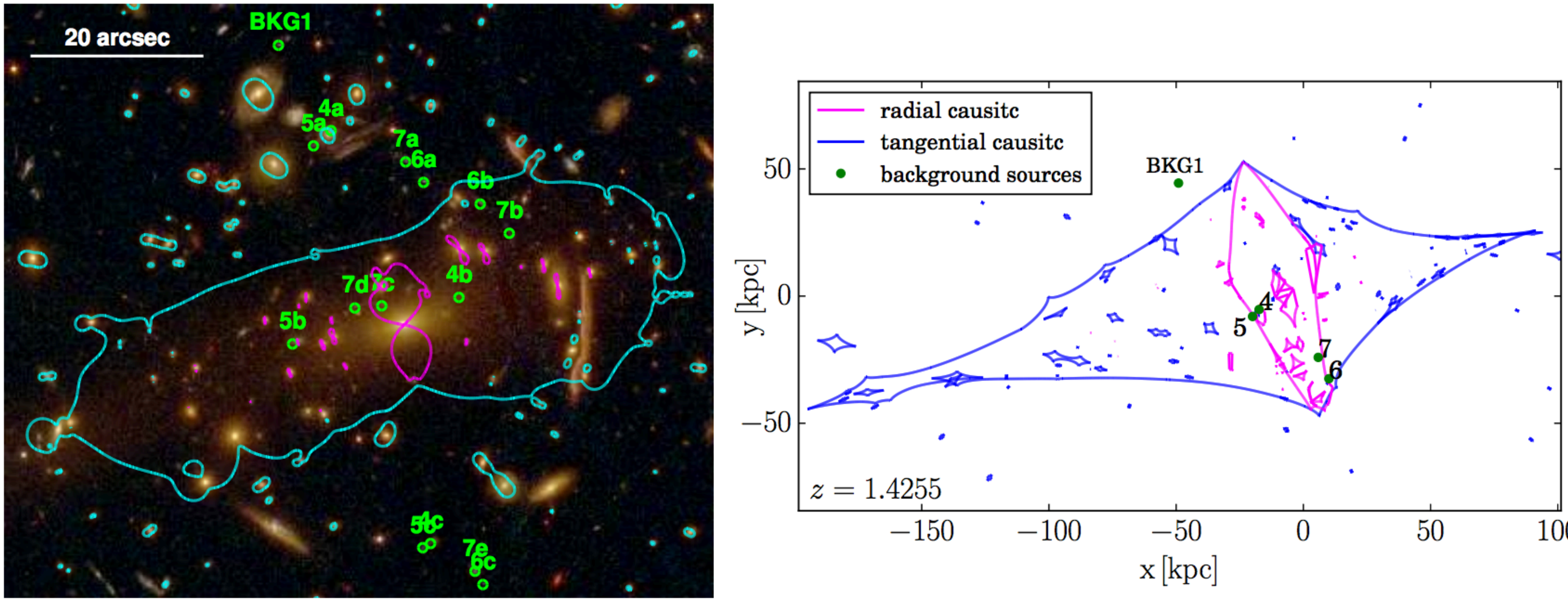


Fig. 6: Critical curves and caustics of the reference model P3ε for a source at z_{src} = 1.4255 (the mean redshift values of the sources). Left panel: Tangential (cyan) and radial (magenta) critical lines on the image plane. The green circles show the observed positions of the multiple images belonging to the four families within $\Delta z \leq 0.0011$. BKG1 is a background galaxy not multiply lensed by MACS 1206. Right panel: Tangential (cyan) and radial (magenta) caustics on the source plane, and the reconstructed positions of the background sources.

OUTCOME

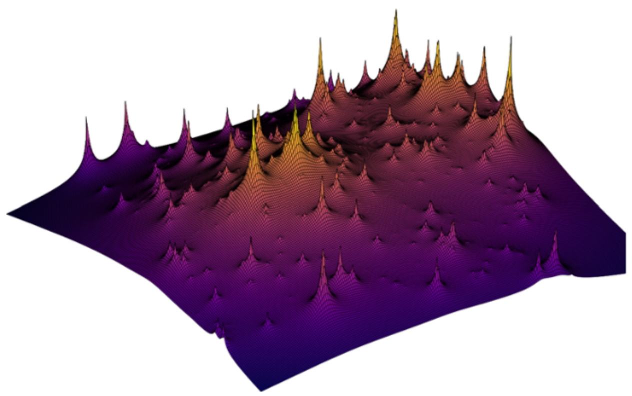


Figure 27. 3D visualization of the lensing-derived substructure distribution for Abell 2744.

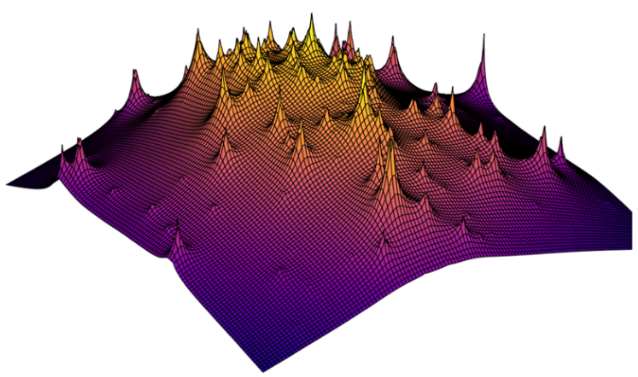


Figure 28. 3D visualization of the lensing-derived substructure distribution for MACSJ 0416.

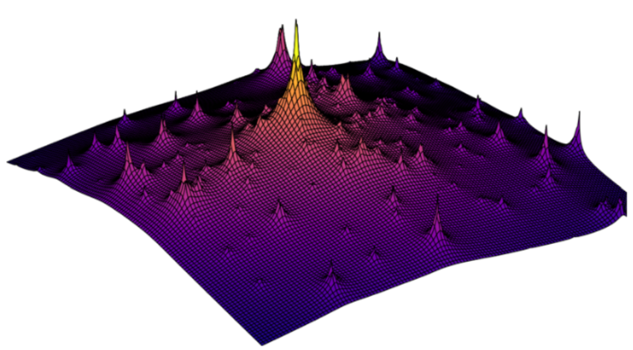
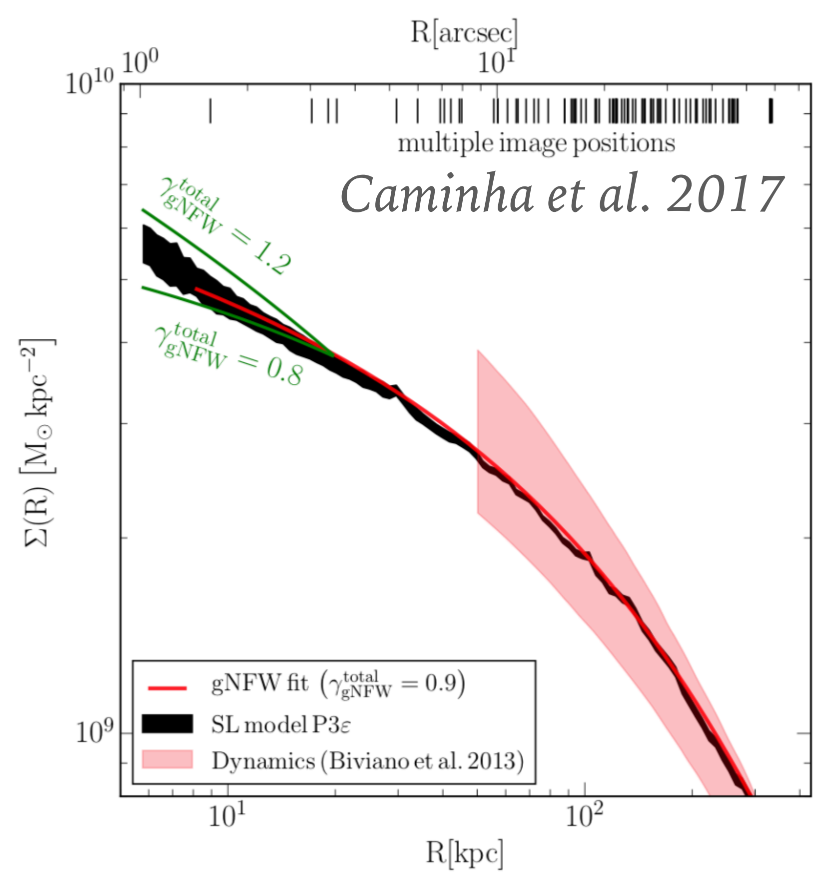


Figure 29. 3D visualization of the lensing-derived substructure distribution for MACSJ 1149.

Natarajan et al. 2017

- model parameters allow to reconstruct the lens projected mass distribution within the region probed by SL (Einstein radius)
- inner density profiles, substructure content
- some puzzling results, when comparing to predictions from CDM
- unfortunately: few lenses with very good data (deep HST imaging, many constraints)



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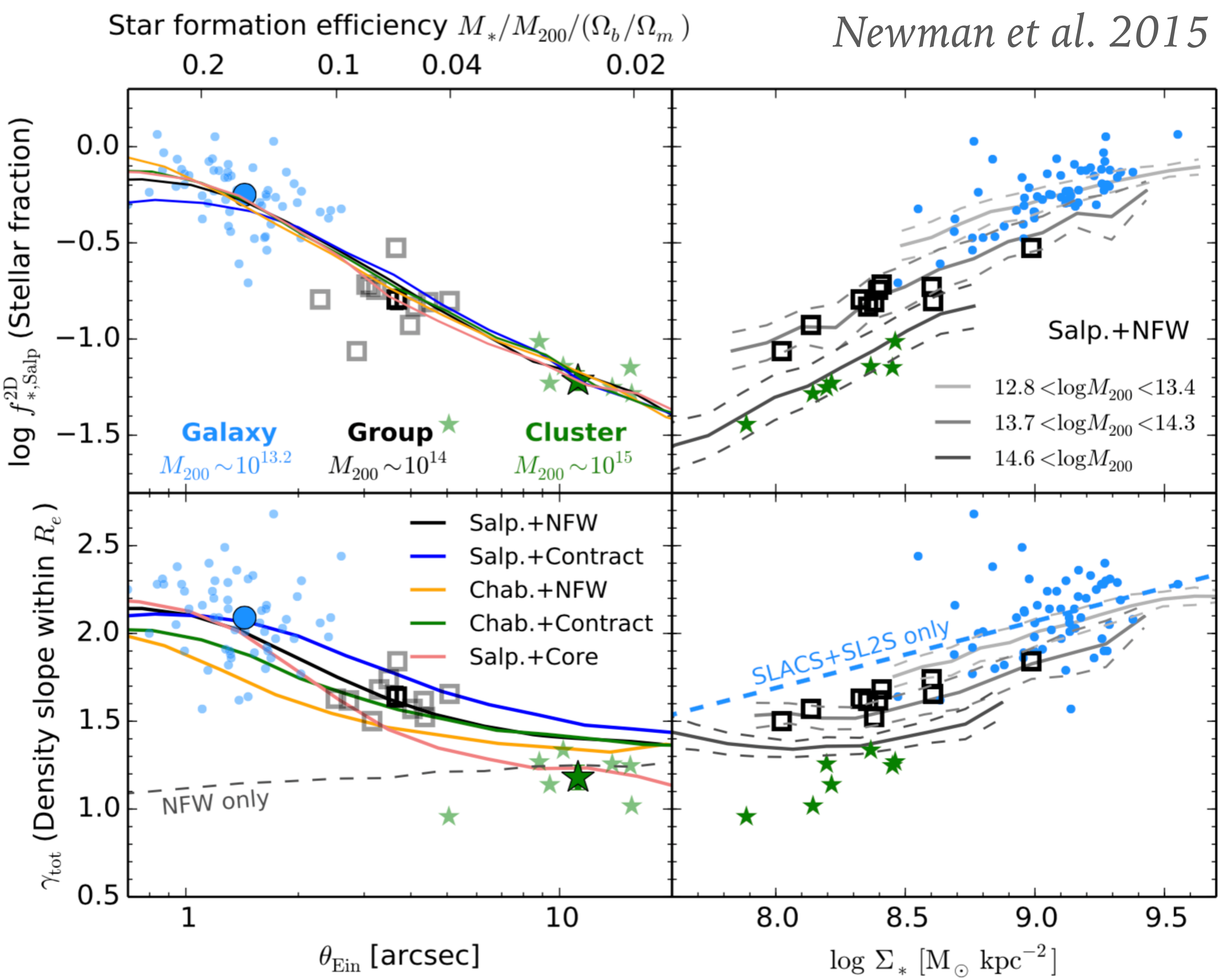

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