Dark Cosmology Centre

Niels Bohr Institutet

Dissecting the 3D structure of galaxies with gravitational lensing and stellar dynamics

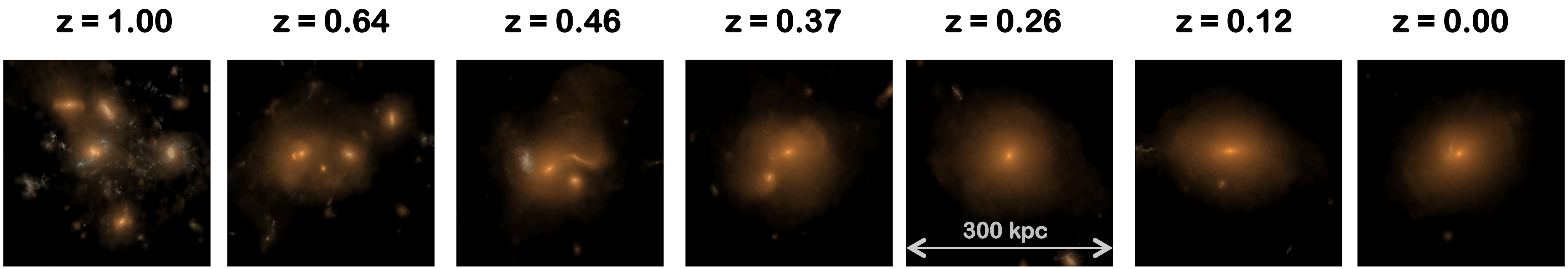
Matteo Barnabè

Dark Cosmology Center & Niels Bohr International Academy

Copenhagen University

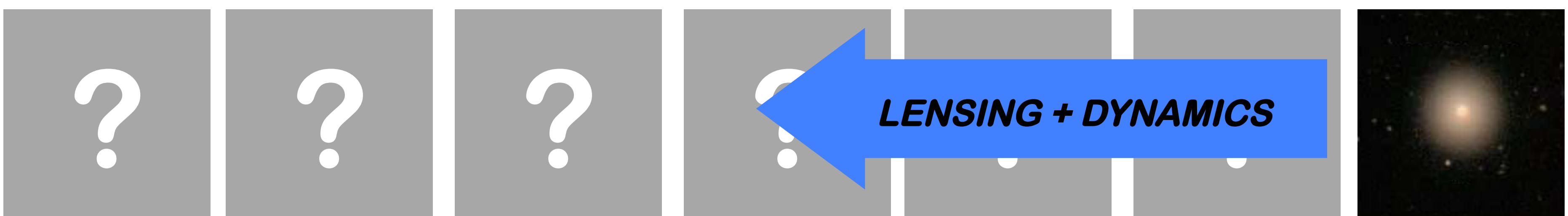
In collaboration with: ***Oliver Czoske (IfA Vienna), Chiara Spiniello (MPA Garching), Léon Koopmans (Kapteyn), Scott Trager (Kapteyn), Tommaso Treu (UCSB), Aaron Dutton (MPIA Heidelberg), Matt Auger (IoA, Cambridge), Brendon Brewer (Auckland)***

Probing Galaxy Formation and Evolution



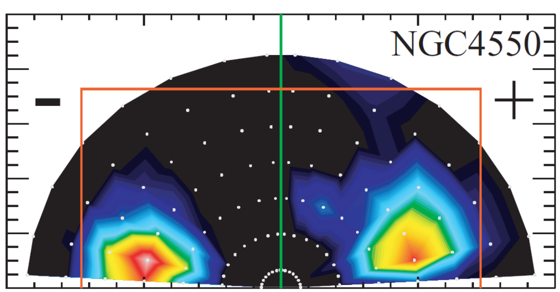
SIMULATIONS

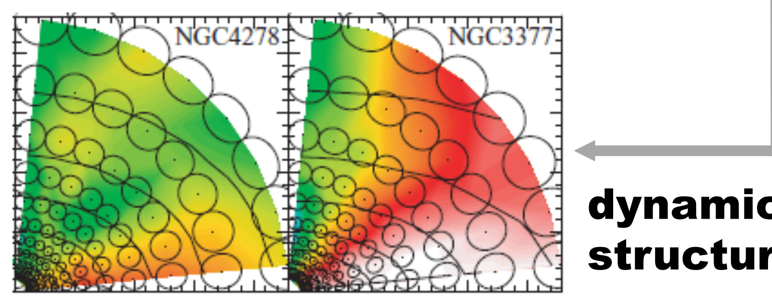
Illustris Collaboration (Vogelsberger et al. 2014)
formation of a massive ETG: log M_*=11.8



OBSERVATIONS

detailed orbital structure
of SAURON galaxies
(Cappellari et al. 2007)

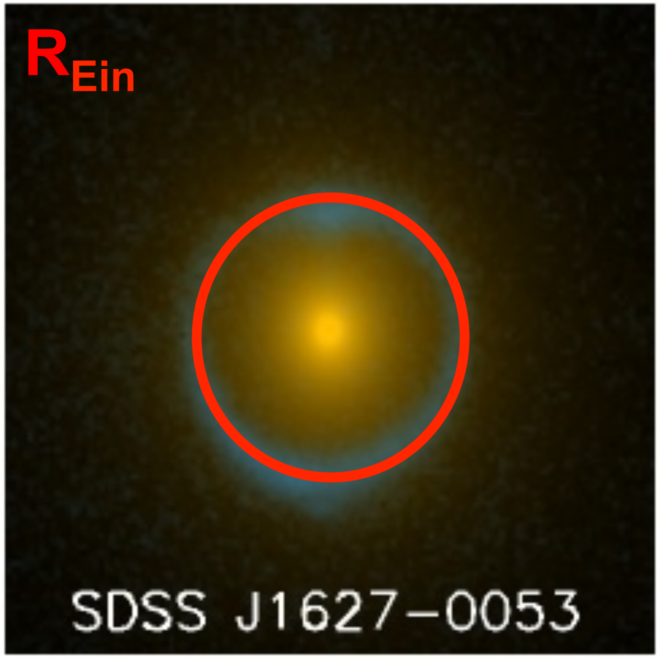




dynamical structure

Combining Lensing & Dynamics:

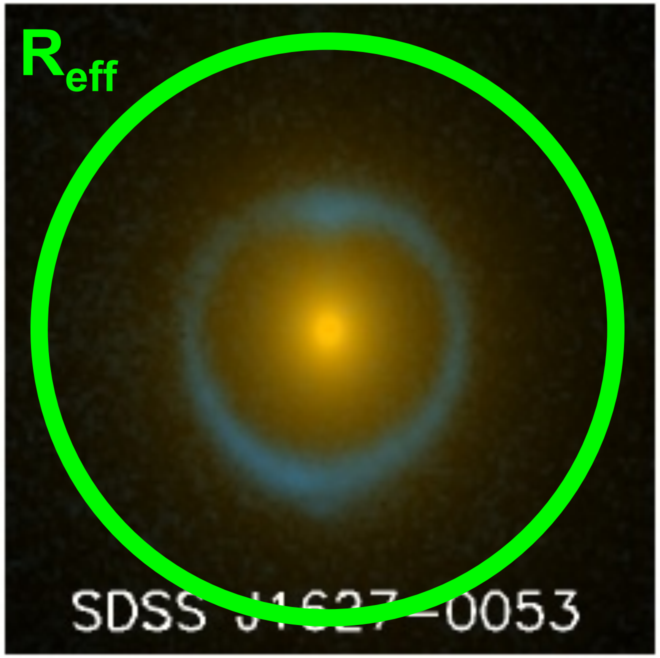
GRAVITATIONAL LENSING



Accurate determination of total mass inside Einstein radius (projected along R_{Ein} cylinder)

+

STELLAR DYNAMICS



Information on 3D mass profile within the region probed by kinematic observations

Sloan Lens ACS Survey (SLACS)

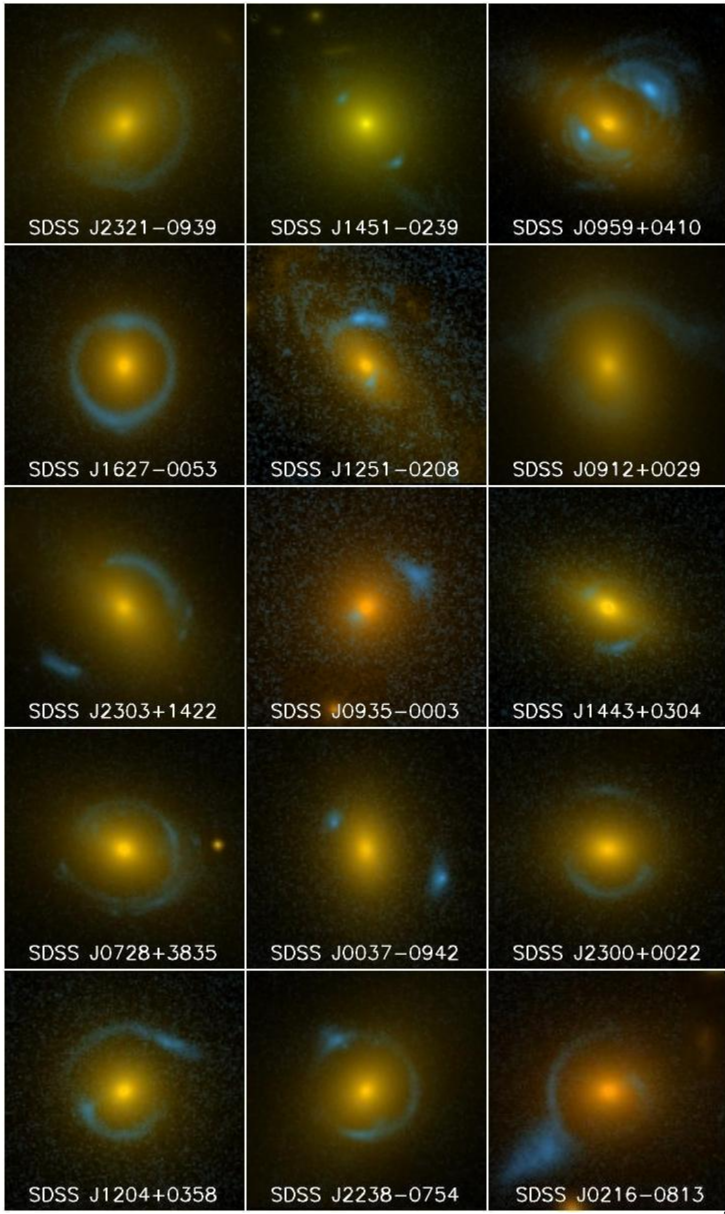
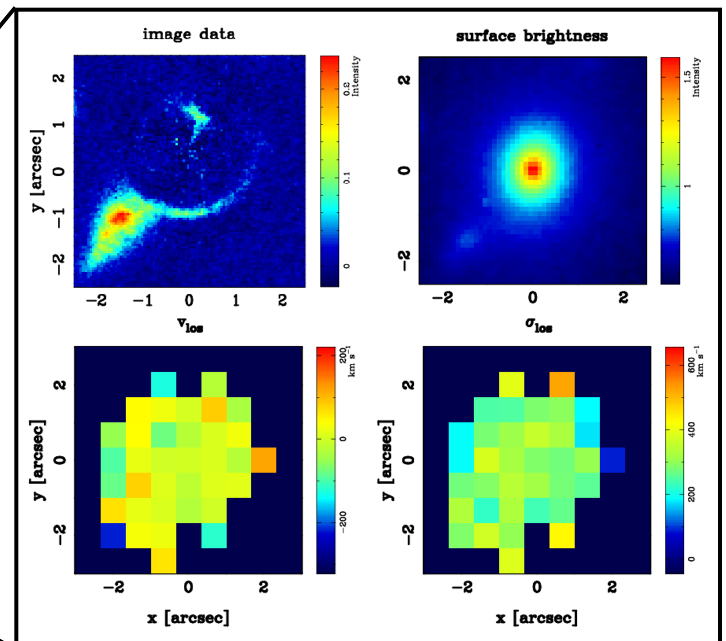
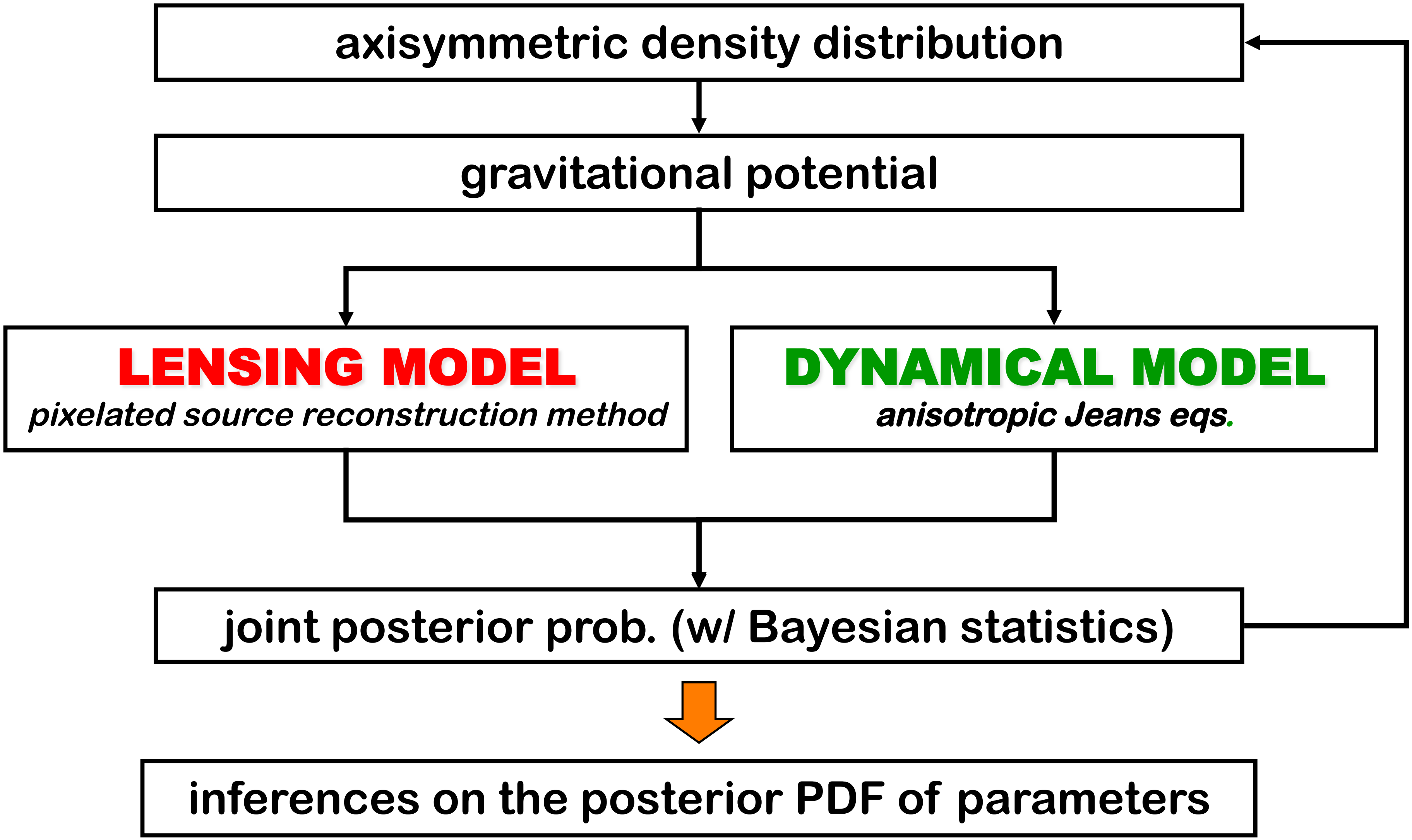


Image credit: SLACS team
see Bolton et al. (2008), Koopmans et al. (2009)

- Spectroscopic lens-selected survey: candidates selected from SDSS database
- HST follow-up to confirm candidates
- ~100 lens galaxies at z = 0.08 – 0.51
- High-res multi-band imaging with HST
- follow-up spectroscopic observations:
  - 16 systems: **VLT VIMOS IFU** (Barnabè et al 2011, Czoske et al. 2012)
  - 1 system: **Keck** long-slit spectra (MB+ 2012)
  - 13 systems: X-Shooter spectra (in progress)



CAULDRON:
COMBINED LENSING AND DYNAMICS ANALYSIS



Barnabè & Koopmans 2007, Barnabè et al. 2012

Lensed Image Reconstruction

- Pixelated source reconstruction method
  (cf. Warren & Dye 2003, Koopmans 2005)
- Includes regularization, PSF blurring, oversampling
- Expressed formally as a **linear inversion problem: L s = d**

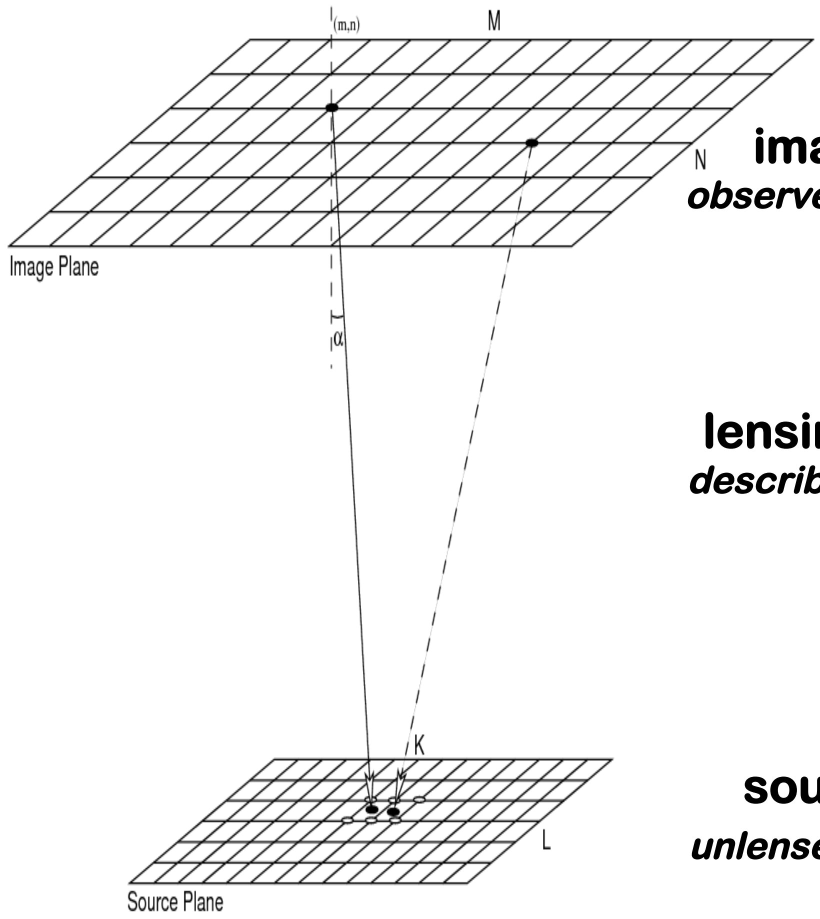
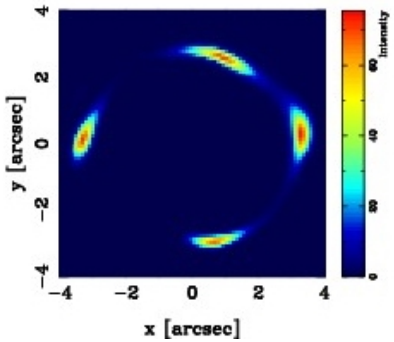
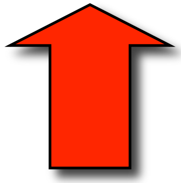


image plane
observed lensed image



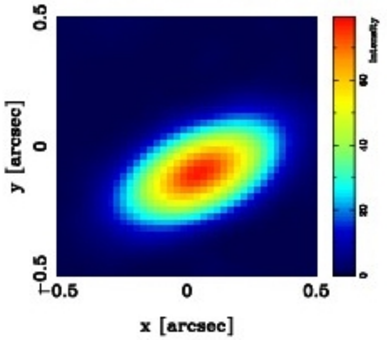
d

lensing operator
describes the mapping



L(Φ)

source plane
unlensed source object



s

Mass Model

- **Dark matter halo:** axisymmetric generalized NFW density profile:

$$\rho_{\rm DM}(m) = \frac{\delta_c\, \rho_{\rm crit}}{(m/r_{\rm s})^{\gamma}\,(1 + m/r_{\rm s})^{3-\gamma}}$$

$$m^2 \equiv R^2 + \frac{z^2}{{q_{\rm h}}^2} \qquad \delta_c = \frac{200}{3}\,\frac{c^3}{\zeta(c,\gamma,1)}$$

  - Free parameters [#1-4]: inner slope γ, three-dimensional axial ratio q_h, concentration c_{-2}, virial velocity v_{vir}

- **Luminous mass distribution:** *multi-Gaussian expansion* (MGE) technique (Emsellem et al. 1999, Cappellari 2002) to SB profile.
  - Luminous mass distribution is self-gravitating, *not just a tracer*
  - Free parameter [#5]: baryonic mass M_{bar}

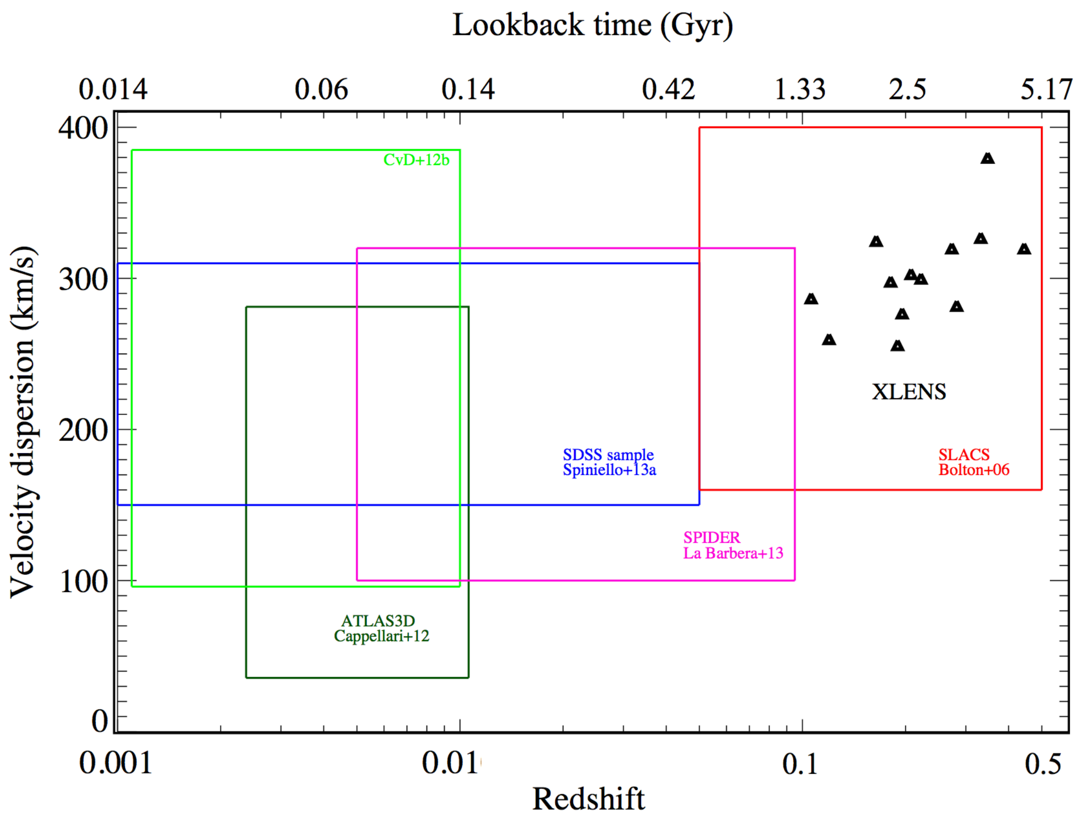
Dynamical Model

- **Anisotropic Jeans equations** (Cappellari 2008)
  - Free parameter [#6]: meridional plane orbital anisotropy ratio b

XLENS: SLACS ellipticals + X-Shooter

X-Shooter Lens Survey (XLENS)

- Ongoing study of 13 massive ETGs probing redshift range z ~ 0.10 to 0.45
- SLACS early-type lenses: HST multi-band imaging of the lens structure
- High signal-to-noise X-Shooter spectroscopic observations: stellar kinematics and spectroscopic SSP analysis of optical line-strength indices (see Spiniello et al. 2011, 2012)

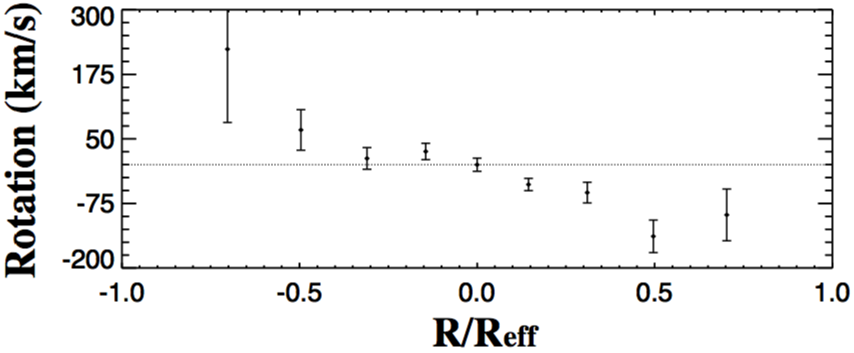


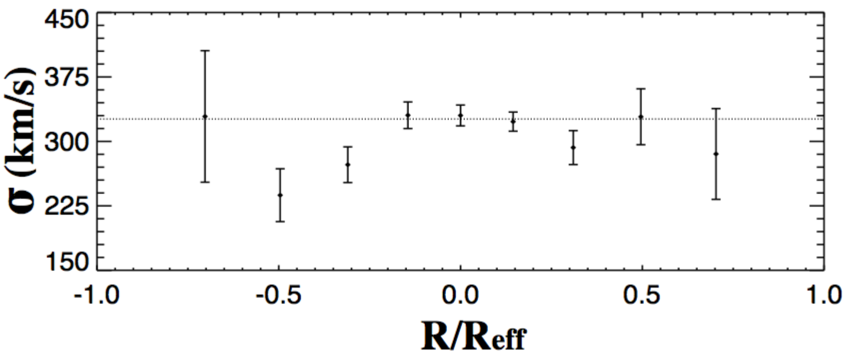
Spiniello et al., in prep.

XLENS: SLACS ellipticals + X-Shooter

X-Shooter Lens Survey (XLENS)

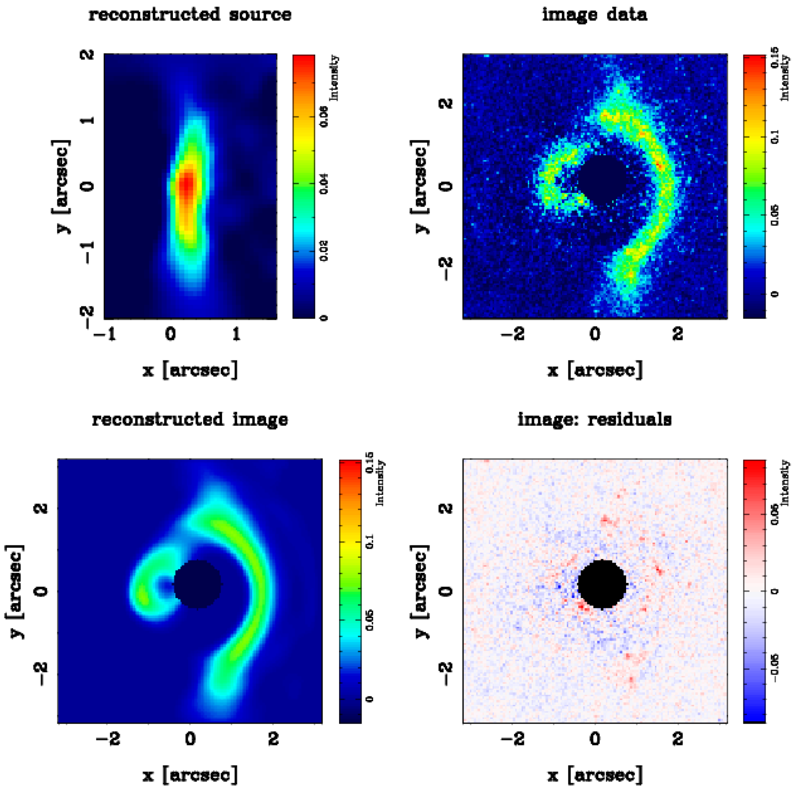
- We can investigate the 3D mass structure of individual massive ETGs.
- We infer stellar masses from two independent methods:
  - joint self-consistent lensing + dynamics analysis
  - spectroscopic SSP study
- Inferences on the properties of the stellar initial mass function (IMF): slope and low-mass cut-off.



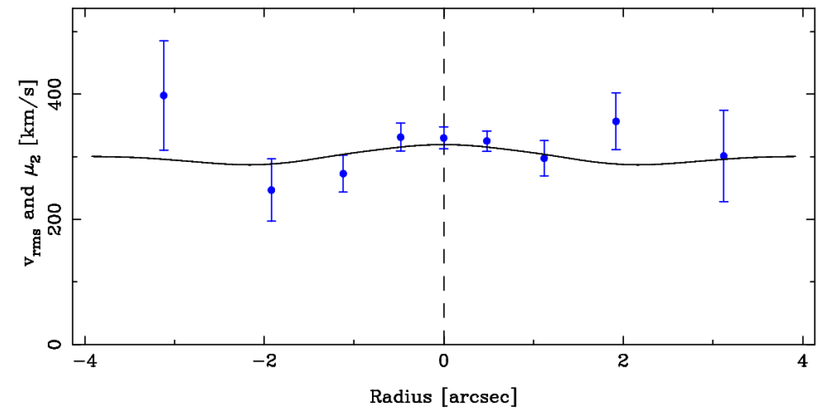


Combined analysis of lens ETG J0912

GRAVITATIONAL LENSING



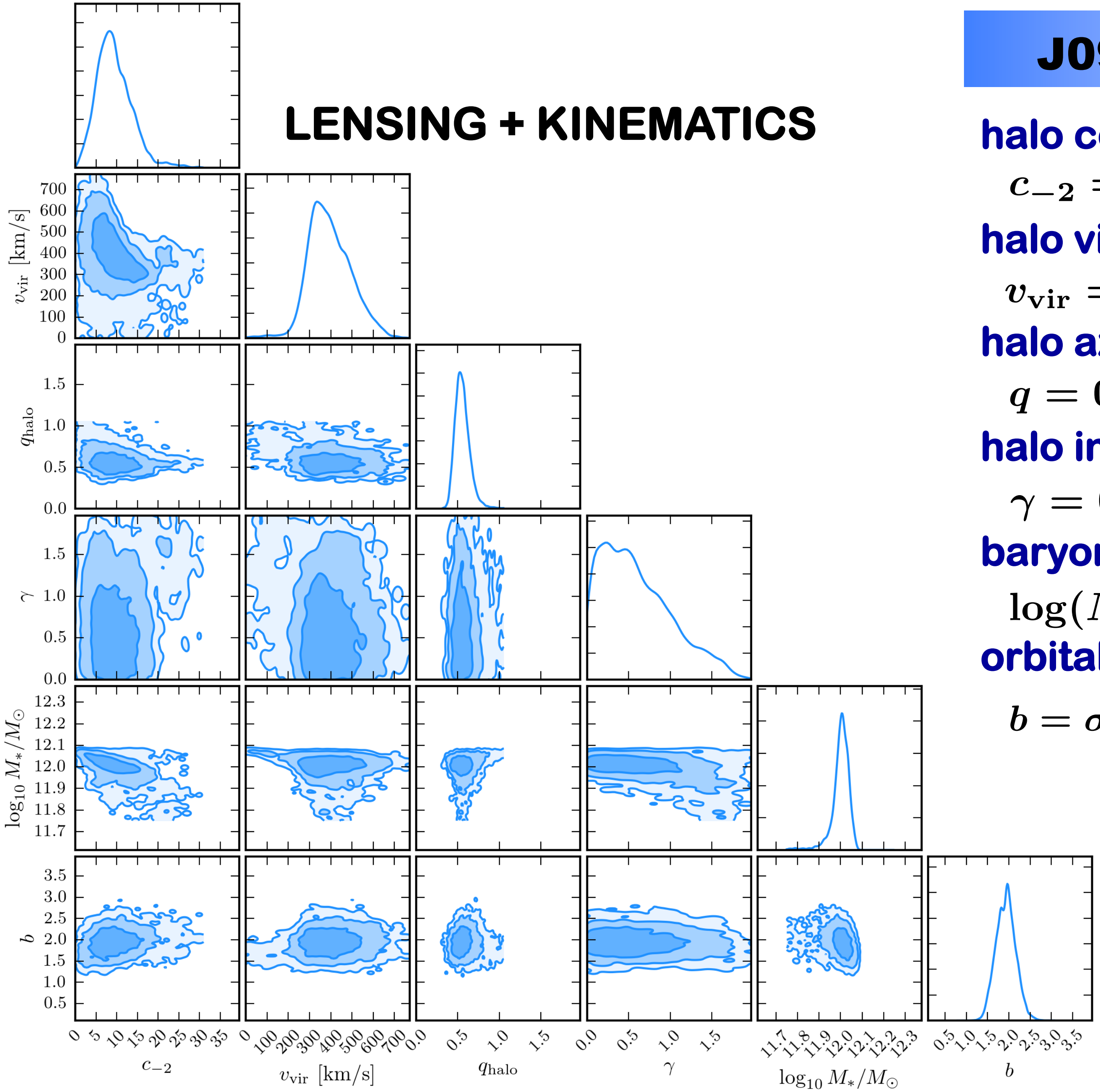
STELLAR KINEMATICS



J0912: massive ETG (velocity dispersion $\sigma \sim 330$ km/s) at z = 0.164

Kinematic data-set obtained with VLT X-Shooter, extends to ~ 1 R_{eff}

DM fraction (within 1 R_{eff}) ~ 0.20±0.08



LENSING + KINEMATICS

J0912: inferences

halo concentration:

$$c_{-2} = 9.1^{+4.5}_{-3.5}$$

halo virial velocity:

$$v_{\rm vir} = 385^{+115}_{-83}\ \text{km/s}$$

halo axial ratio:

$$q = 0.54^{+0.09}_{-0.07}$$

halo inner slope:

$$\gamma = 0.53^{+0.50}_{-0.37}$$

baryonic mass:

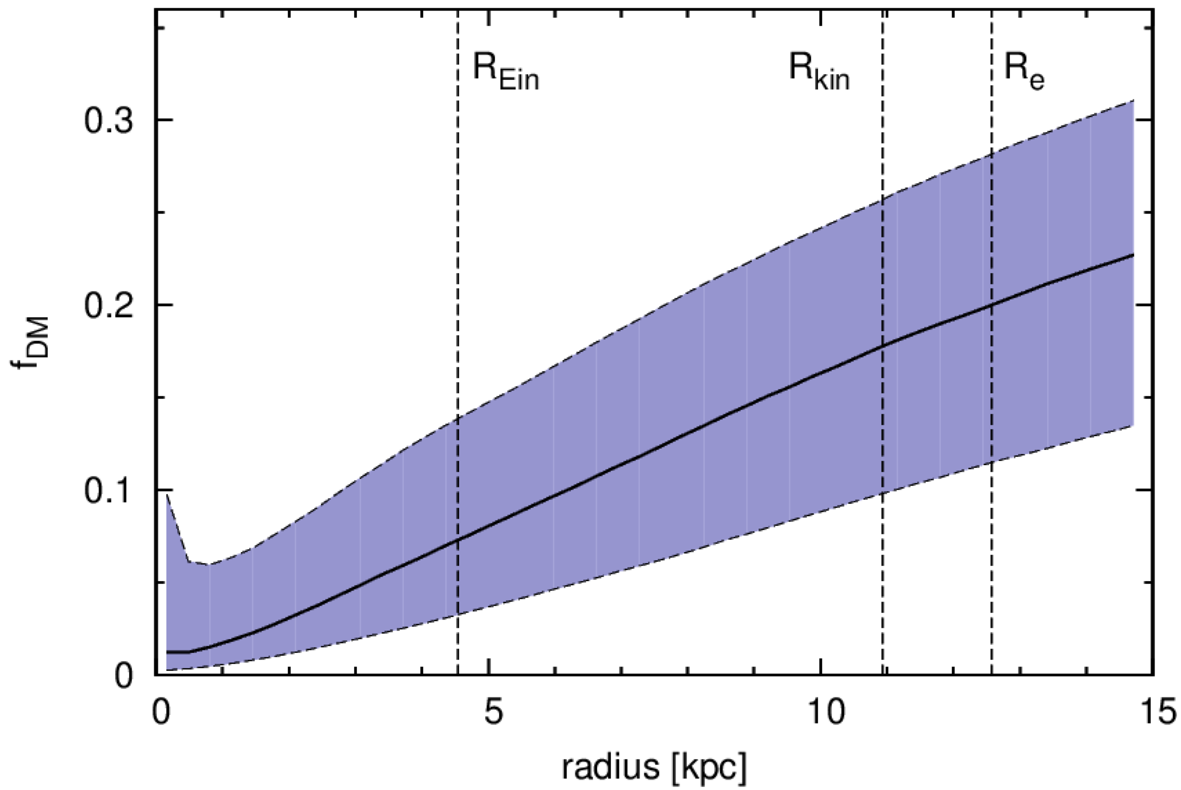
$$\log(M_\star/M_\odot) = 12.01^{+0.03}_{-0.03}$$

orbital anisotropy par.:

$$b = \sigma_R^2/\sigma_z^2 = 1.94^{+0.21}_{-0.24}$$

Barnabè et al., in prep.

J0912: dark matter fraction profile

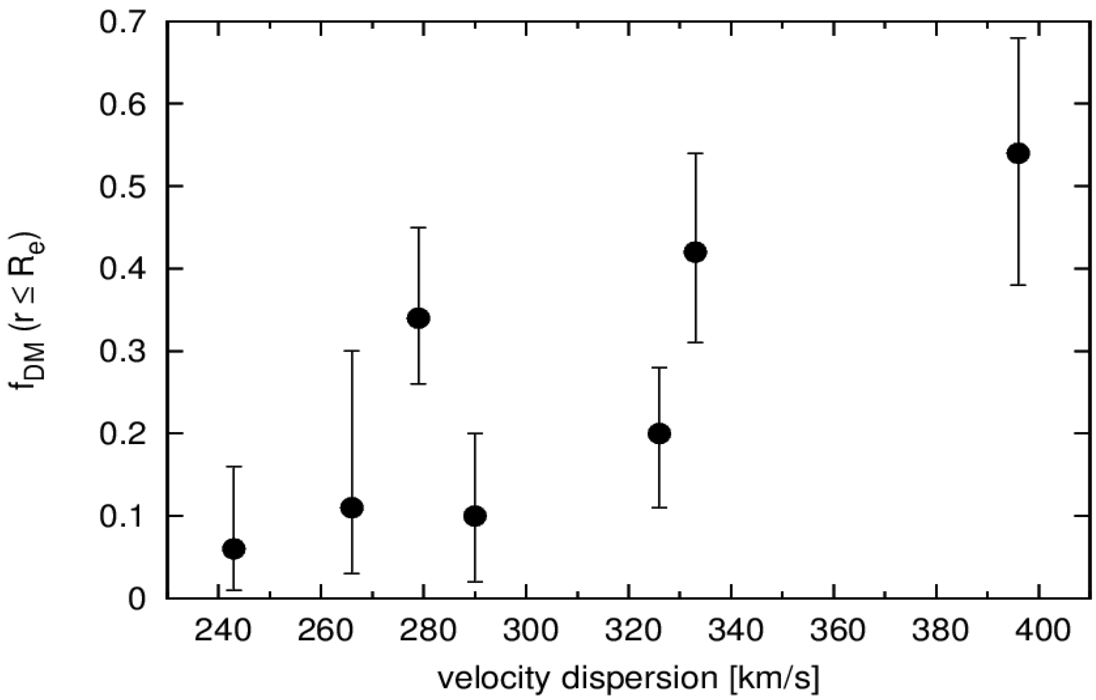


- We can investigate the radial f_{DM} profile within the galaxy inner regions (~ 1 R_{eff})
- inner regions dominated by baryonic matter

$$f_{\rm DM}(r \leq Re) = 0.20^{+0.08}_{-0.09}$$

dark matter fraction for the XLENS sample

- Preliminary result based on 7 analyzed galaxies
- dark matter contribution within r = Re
- f_{DM} about 10 – 40% except for most massive galaxy
- J0935 (most massive galaxy) has f_{DM}(r<Re) ~ 55%
- IMF: Salpeter or slightly steeper



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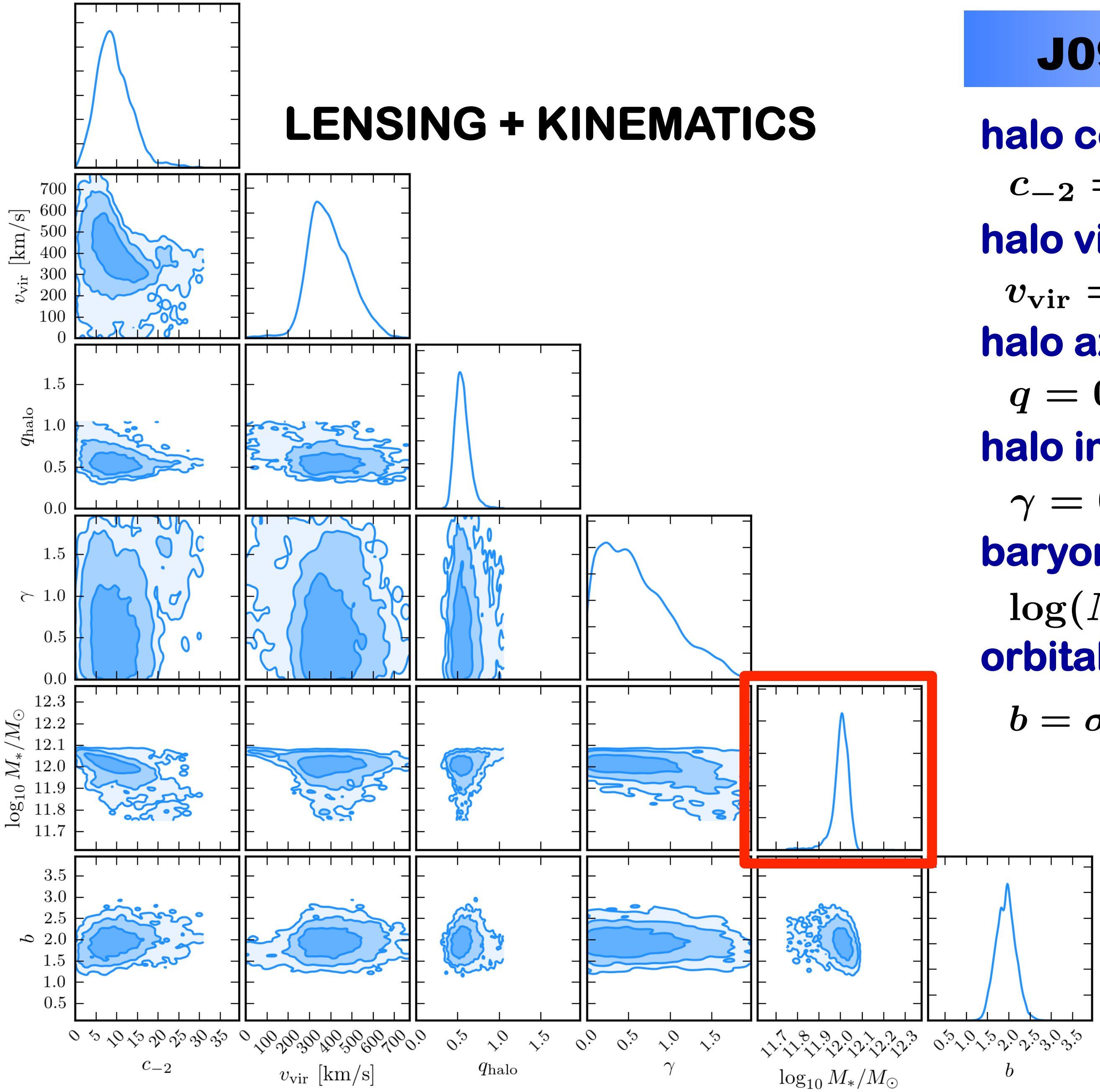

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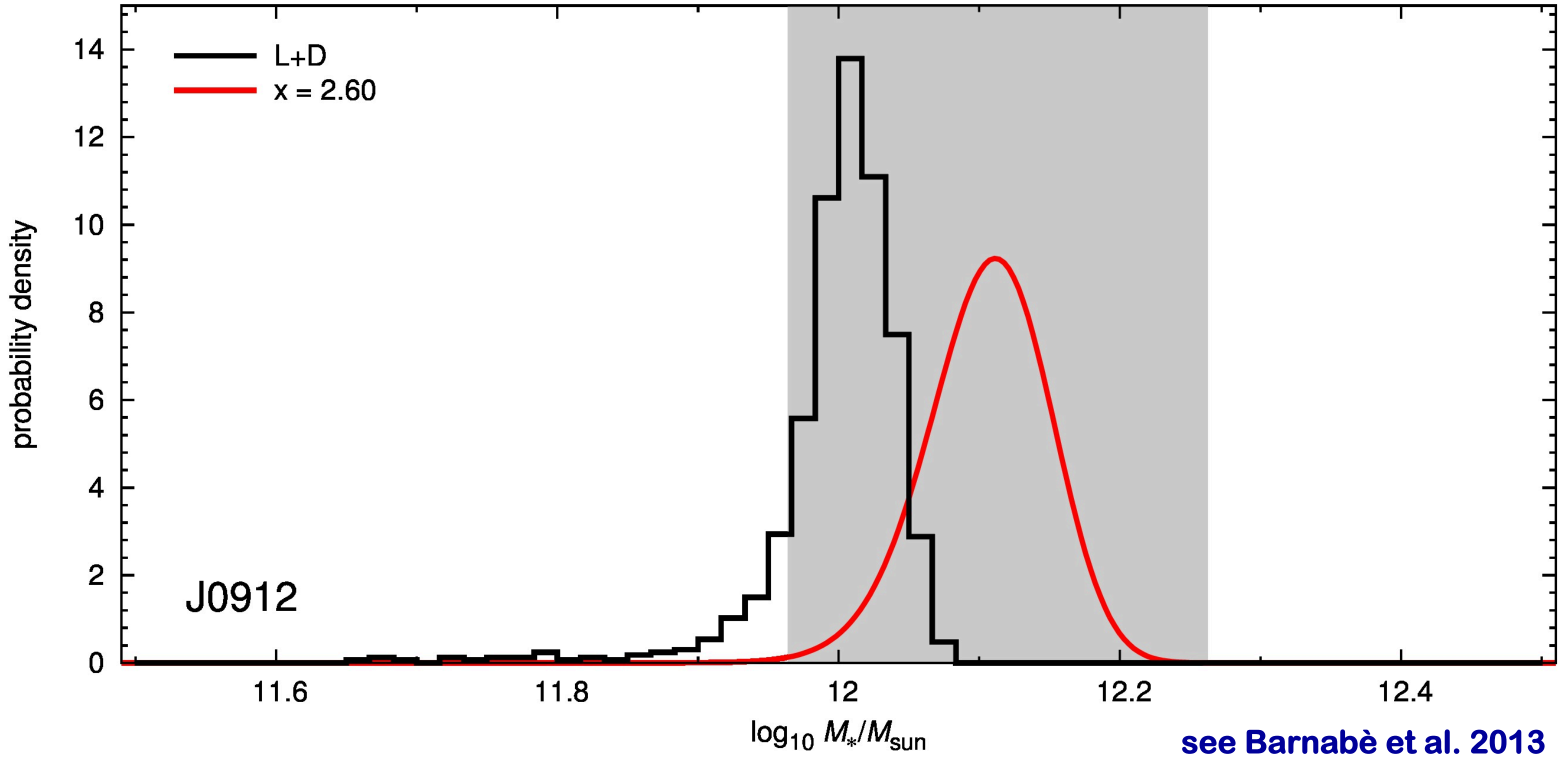
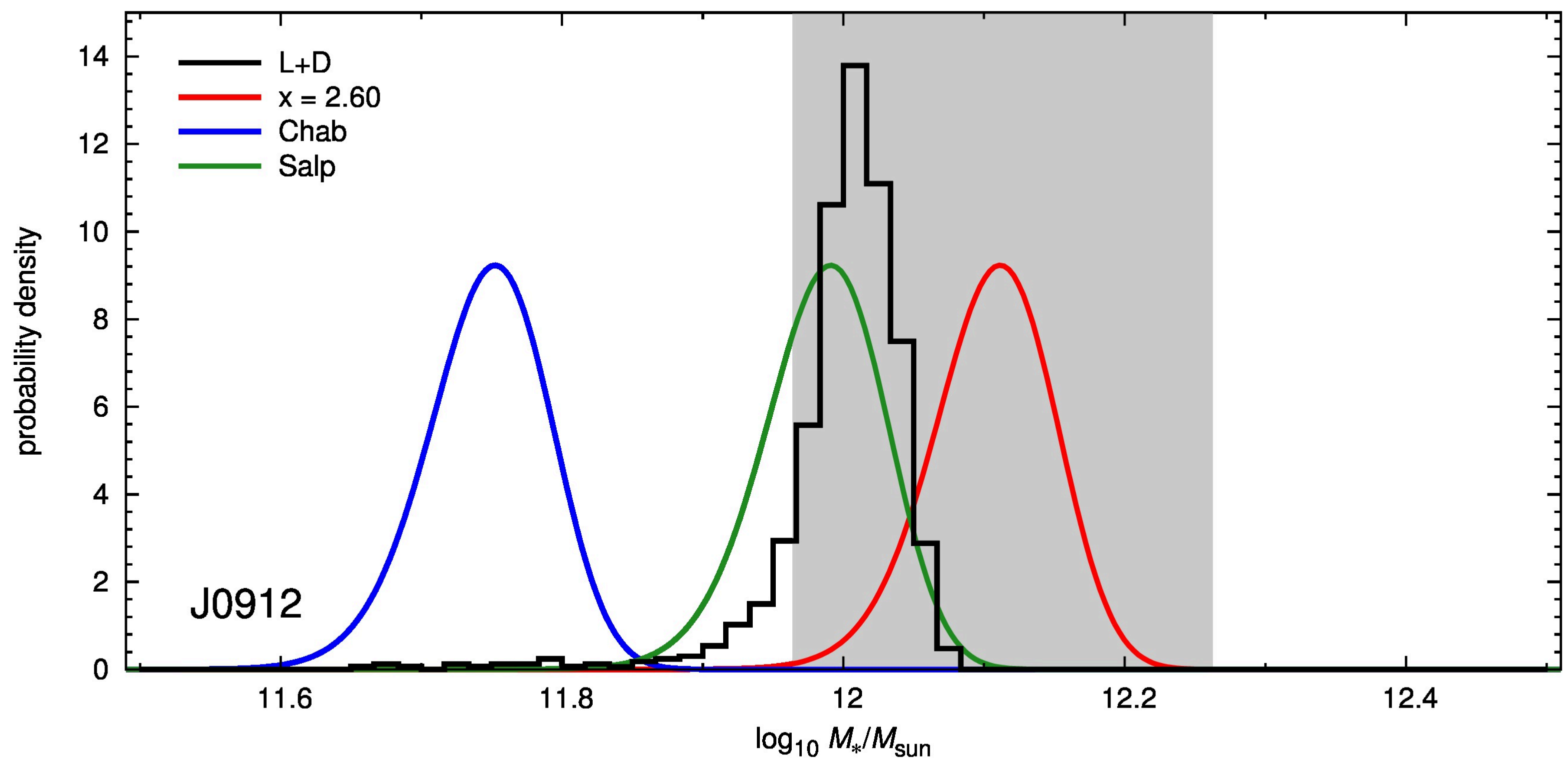
Comparing two independent methods
lensing+dynamics and SSP analysis



see Barnabè et al. 2013

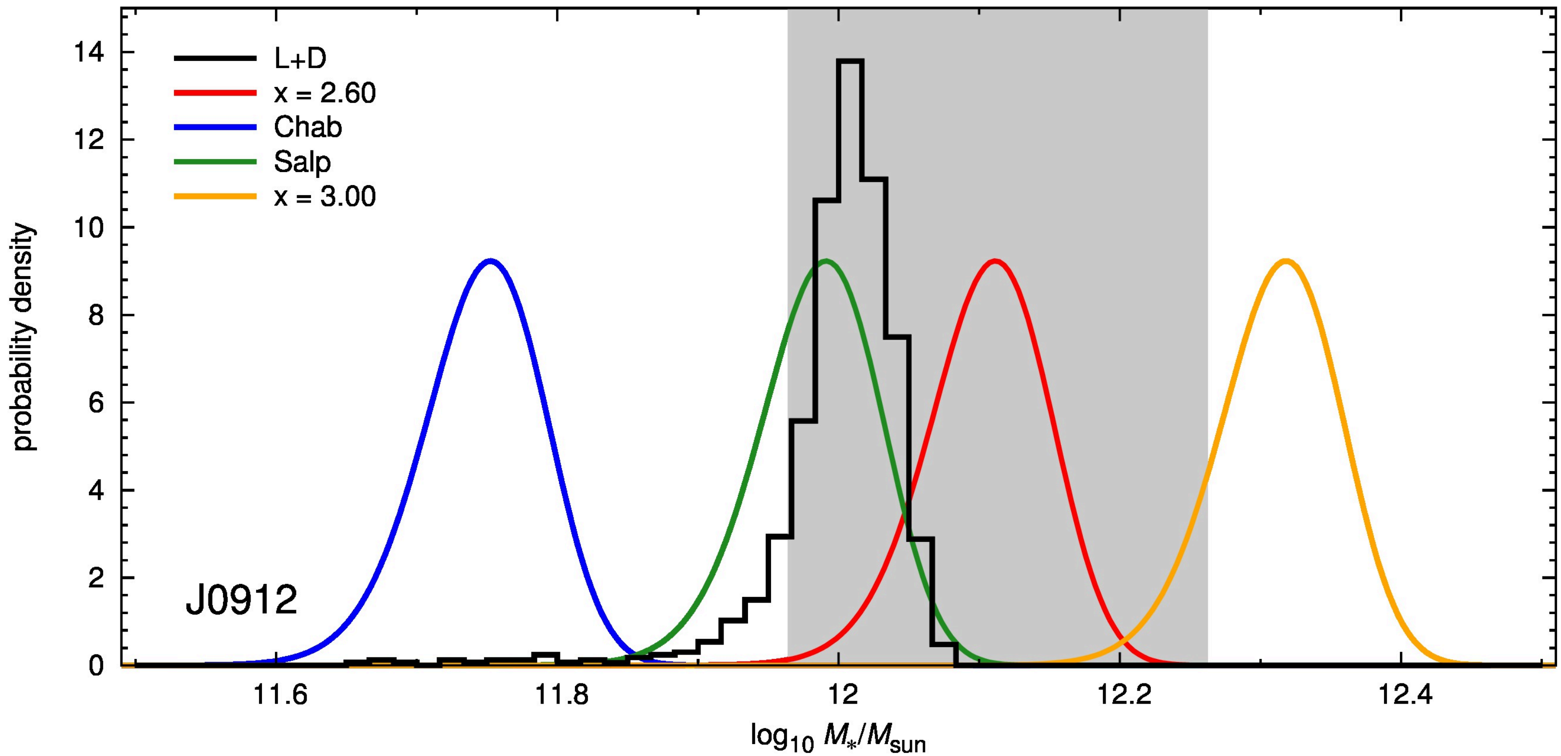
- The stellar masses inferred from the spectroscopic single stellar population (SSP) analysis of optical line-strength indices is fully consistent with the *independent* inferences from the combined lensing and dynamics study (which makes no assumptions on the IMF)
- IMF slope derived from spectroscopic SSP analysis: $x = 2.60 \pm 0.30$

IMF inferences: Salpeter is favored



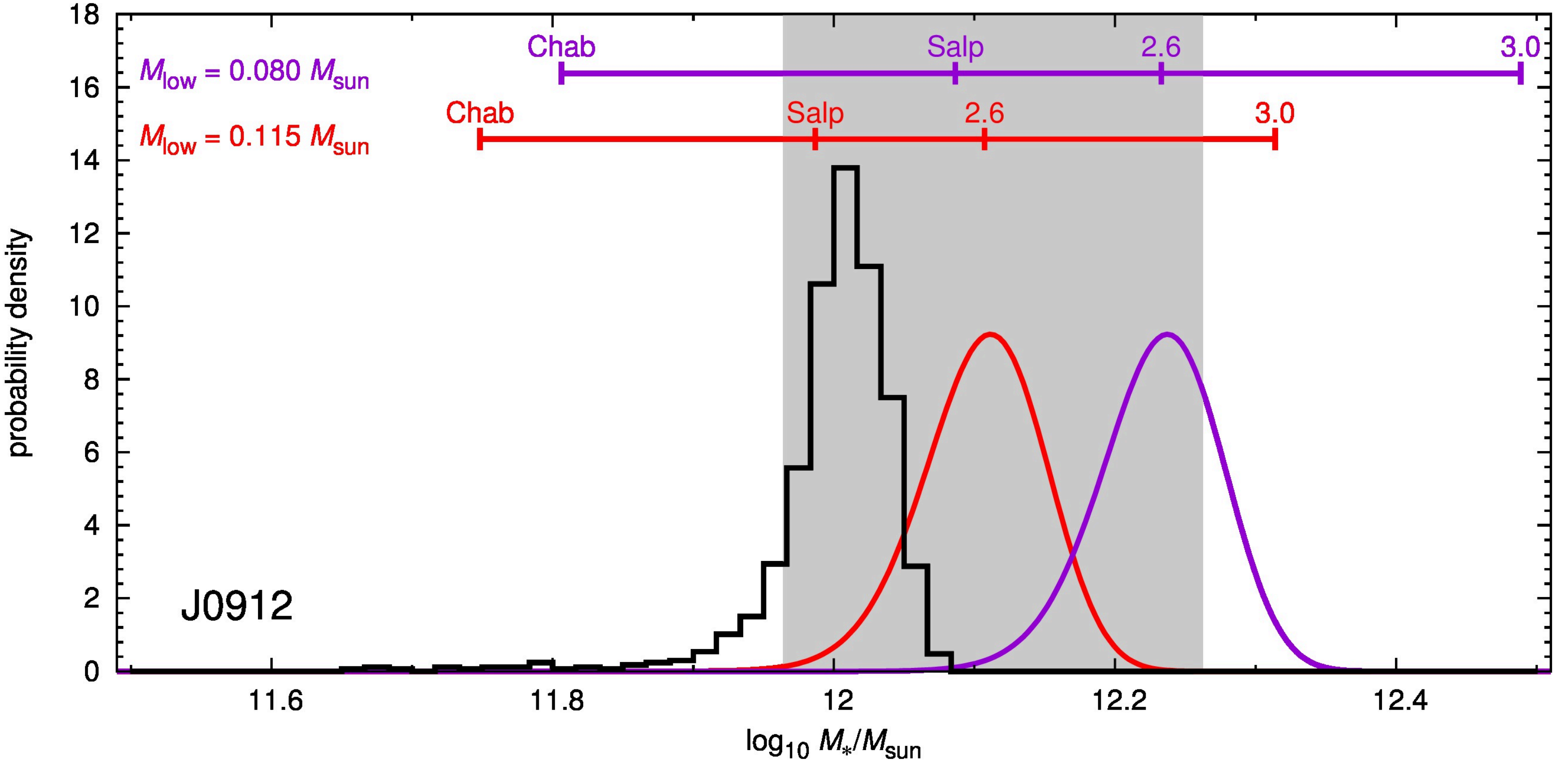
- Salpeter IMF (x = 2.35) is favored over a Chabrier IMF, which is ruled out with 99% probability (Bayes factor *B* = 67)
- Salpeter is perfectly consistent with the inferences from L+D
- In agreement with the results of state-of-the-art stellar population synthesis analysis (e.g. Conroy & van Dokkum 2012)

IMF inferences: super-Salpeter IMF ruled out



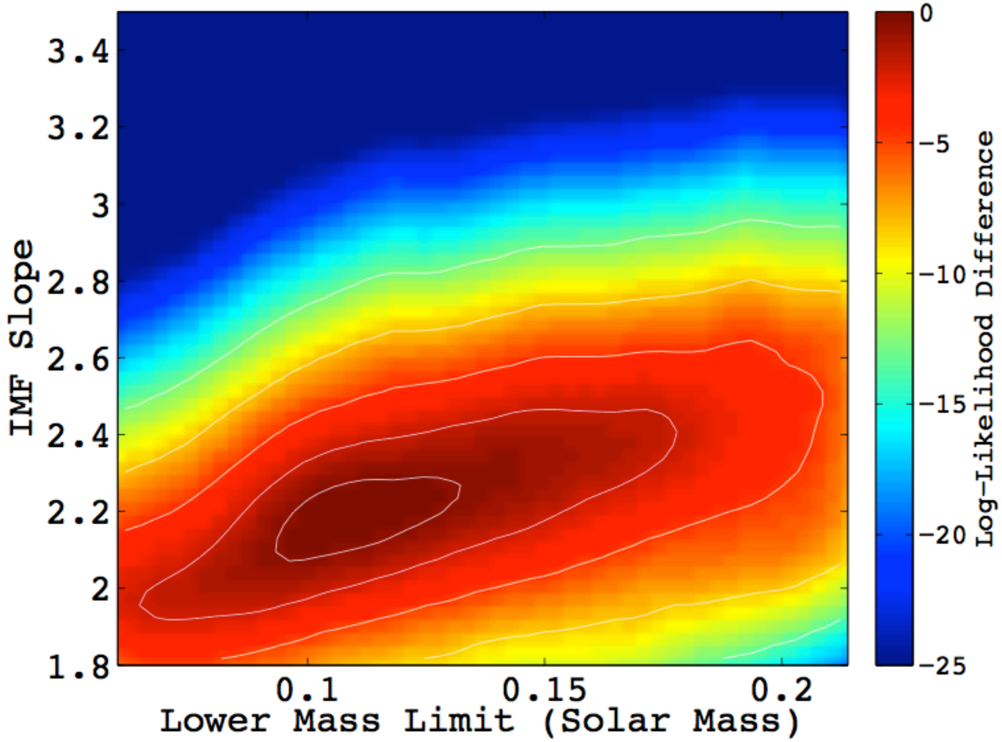
- IMFs significantly steeper than Salpeter ("bottom-heavy", $x \geq 3.0$) are ruled out with decisive evidence for this system: Bayes factor $B > 1000$
- Super-Salpeter IMFs with $x \approx 3.0 – 3.5$ have been suggested (see e.g. Ferreras et al. 2013) for massive ellipticals

IMF inferences: constraints on M_{low}



- We can constrain for the first time the low-mass cut-off M_{low} for the IMF
- M_{low} is crucial when determining the stellar mass-to-light ratio from stellar population evolutionary codes
- $M_{low} = 0.08\ M_{sun}$ (corresponding to the hydrogen burning limit) is ruled out with decisive evidence (99.7% probability) wrt the standard DSEP-adopted value $M_{low} = 0.115\ M_{sun}$ (for *MAP* slope $x = 2.60$)

joint inference on IMF slope and M_{low}

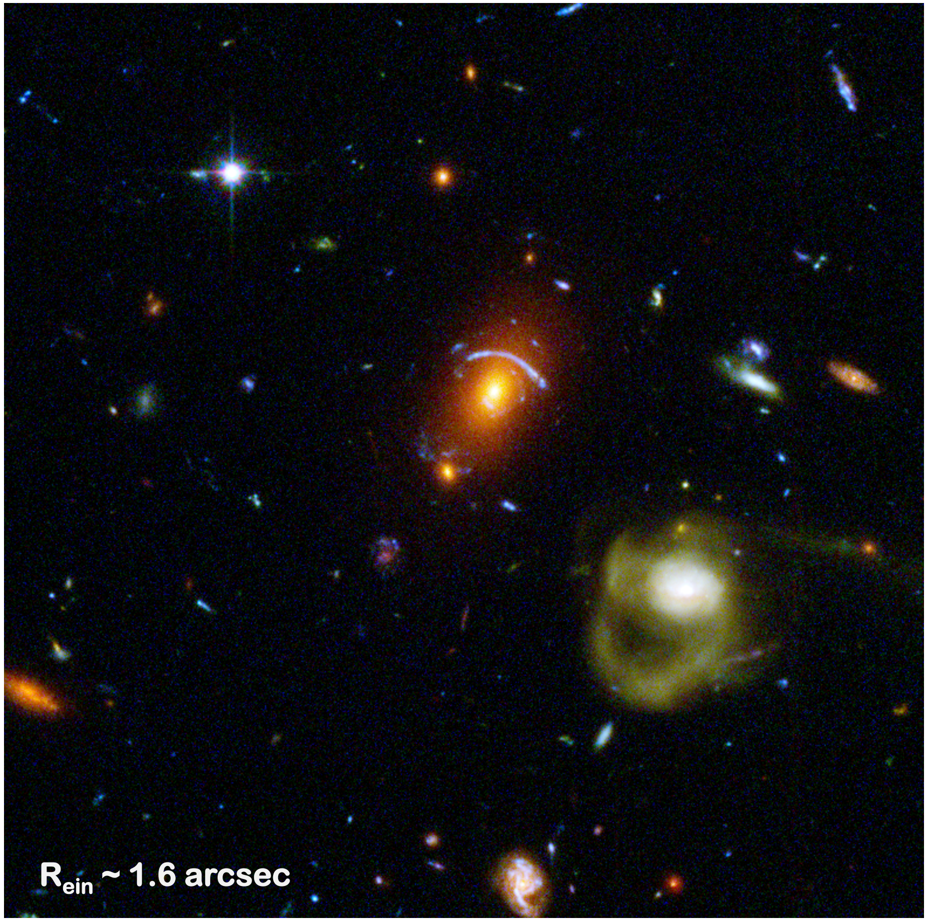


Barnabè et al. 2013

- We combine the results of the L+D and SSP analyses of two galaxies (J0912 and J0936) to derive the joint inference on slope and low-mass limit
- IMF slope: $x = 2.21 \pm 0.14$ (consistent with Salpeter)
- Low-mass cut-off: $M_{low} = 0.12 \pm 0.03\ M_{sun}$

Typical values of M_{low}/M_{sun} used in stellar pop. evolutionary codes: 0.08 (Conroy & van Dokkum 2012); 0.10 (Bruzual & Charlot 2003, Vazdekis et al. 2012); 0.115 (DSEP, Chaboyer et al. 2001); 0.15 (models based on Padova 2000 isochrones)

a faraway massive lens ETG...



- A massive lens elliptical at z = 0.62 (lookback time ~ 6 Gyr)
- HST image + VLT-VIMOS integral-field spectroscopy (30 OBs)
- The most distant system known to date for which a combined in-depth lensing + dynamics analysis has ever been attempted
- preliminary σ ~ 265 km/s
- more coming soon…

in collaboration with Claudio Grillo, Oliver Czoske, Chiara Spiniello and Lise Christensen

Conclusions

- The combination of gravitational lensing with high-res spatially resolved kinematics allows us to investigate the dark and luminous structure of massive ellipticals beyond the local Universe ($z > 0.1$)
- dark matter fraction around 10-40% within 1 R_{eff}, except for most massive ellipticals (f_{DM} already $\geq$ 50% within effective radius)
- Independent methods (combined lensing + dynamics; spectroscopic SSP analysis) give fully consistent inferences on the stellar masses
- Inferred best-fit IMF slopes from SSP modeling: $x = 2.10 \pm 0.15$ for J0936 (σ = 250 km/s) and $x = 2.60 \pm 0.30$ for J0912 (σ = 330 km/s)
- Results on the IMF of the two studied systems:
  - Salpeter IMF is favored
  - Chabrier IMF ruled out with prob > 95%
  - Super-Salpeter IMFs ruled out with decisive evidence
- First constraints on low-mass limit for the IMF