Dark Cosmology Centre

Niels Bohr Institutet

The dark and luminous mass structure of early-type lens galaxies

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"Galaxies and Cosmology in Light of Strong Lensing", Kavli IPMU, 19 November 2014

Elliptical Galaxy ESO 325-G004 in the Abell Cluster S0740

Hubble Heritage

EARLY-TYPE GALAXIES

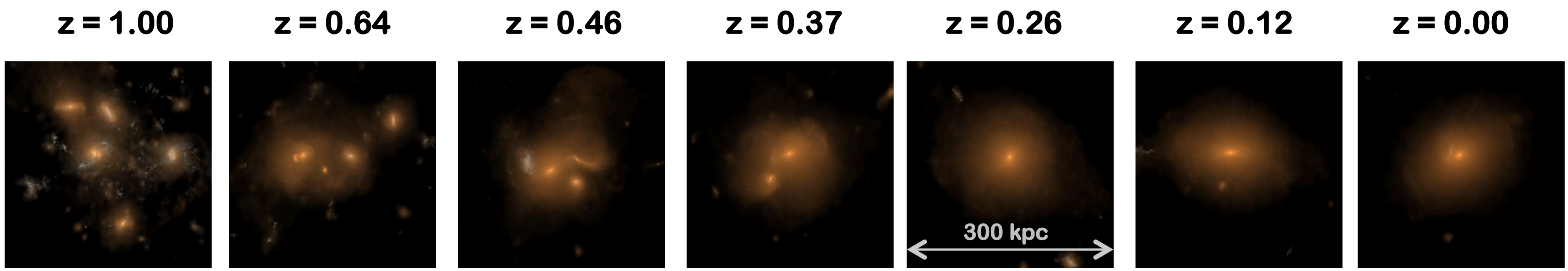
SIMPLE SYSTEMS?

- Red and dead
- Pressure supported systems
- Smooth and homogeneous appearance
- Regularity, scaling relations

OPEN QUESTIONS

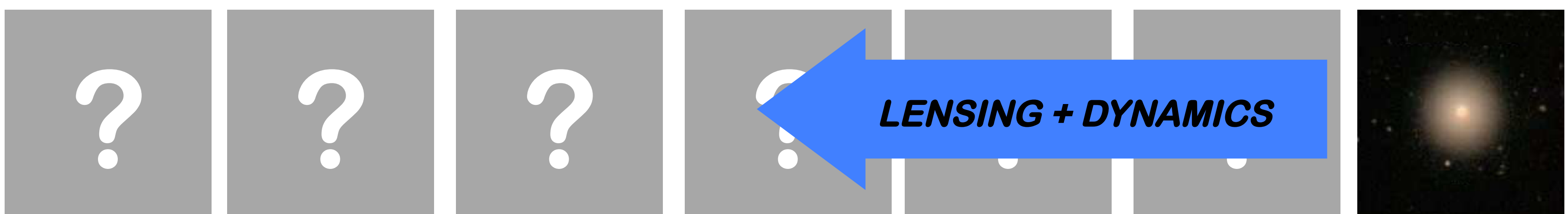
- Internal structure
  - Mass distribution
  - Orbital structure
  - Dark matter fraction
  - Shape of dark matter halo
- Formation and evolution
  - How does the structure change with time, and how does this compare with simulations?

Probing Galaxy Formation and Evolution



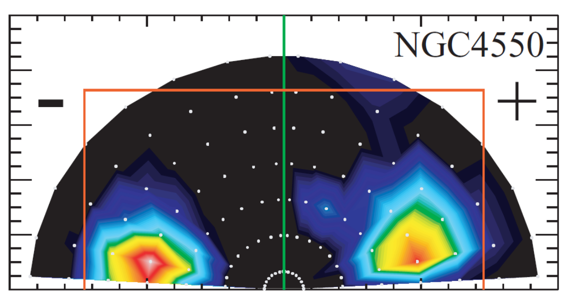
SIMULATIONS

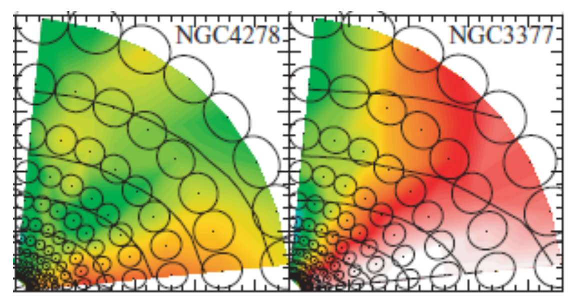
Illustris Collaboration (Vogelsberger et al. 2014)
formation of a massive ETG: log M_*=11.8



OBSERVATIONS

detailed orbital structure
from dynamical models
(Cappellari et al. 2007)

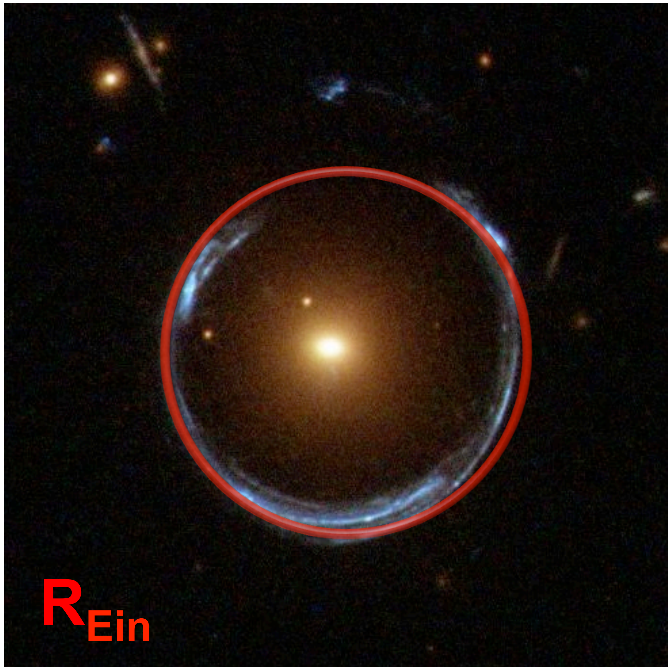




dynamical structure

Combining Lensing & Dynamics:

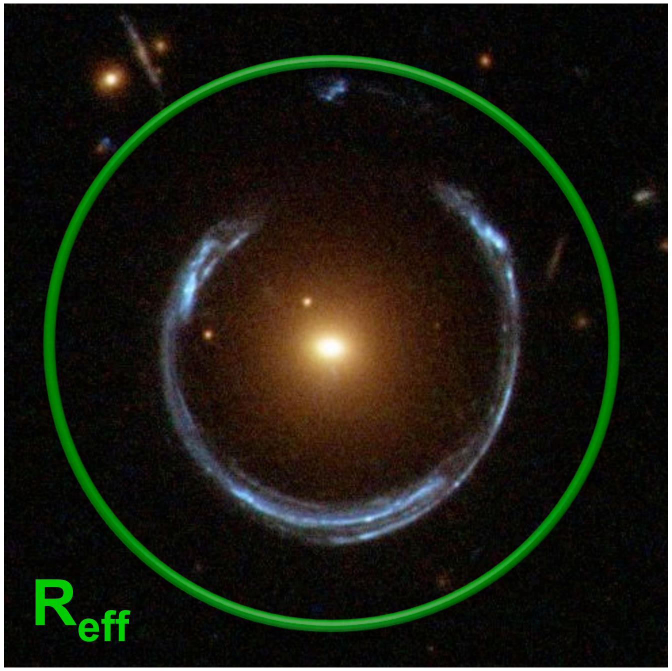
GRAVITATIONAL LENSING



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)

- 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** (MB+ 2011)
  - 1 system: **Keck** long-slit spectra (MB+ 2012)
  - 13 systems: X-Shooter spectra (in progress)

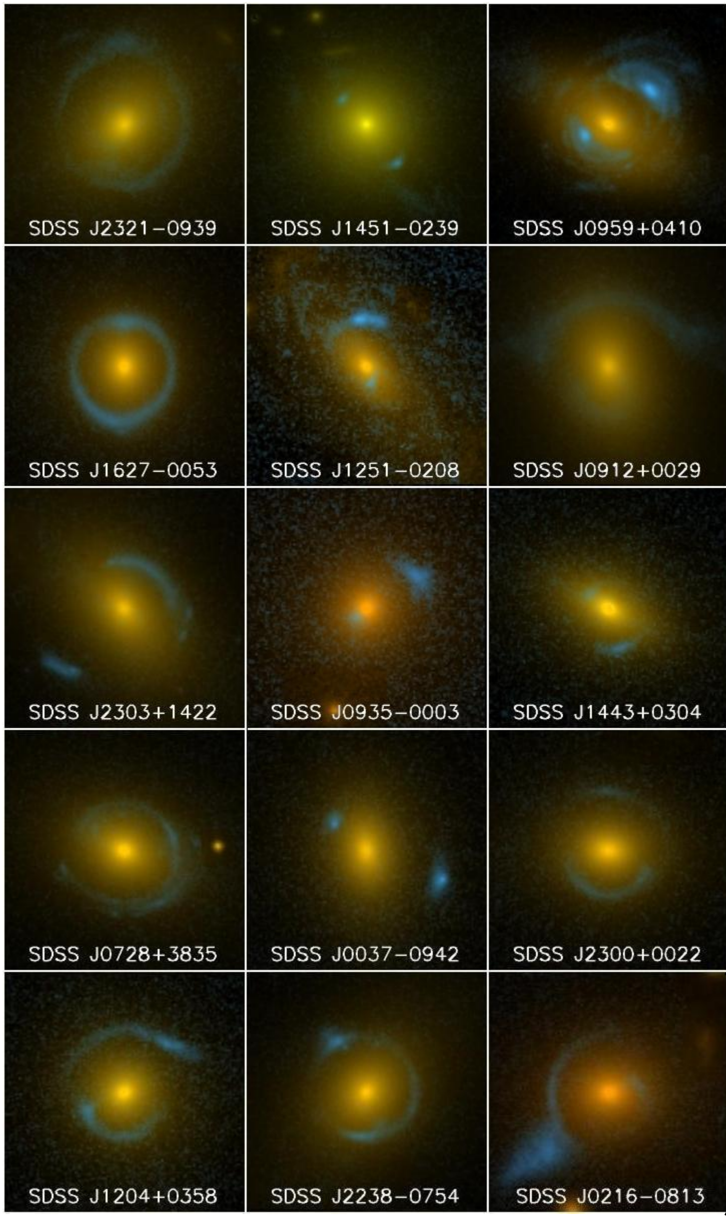
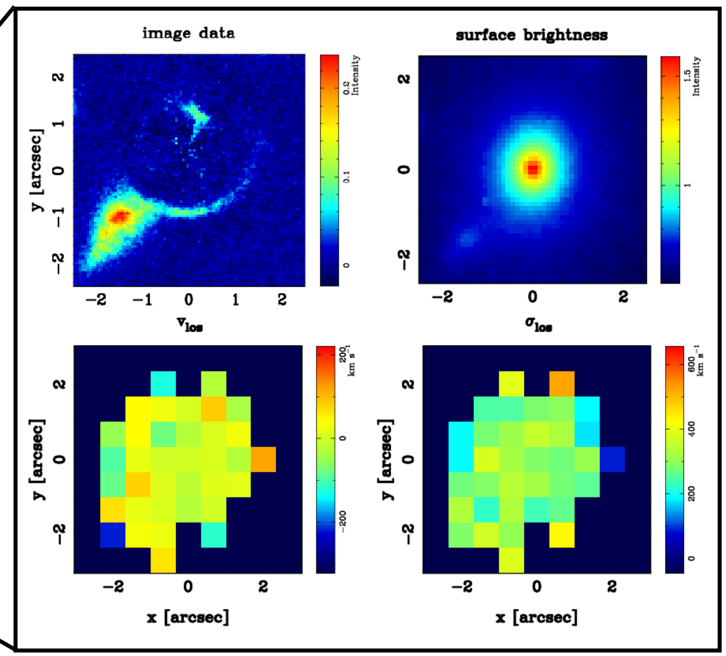
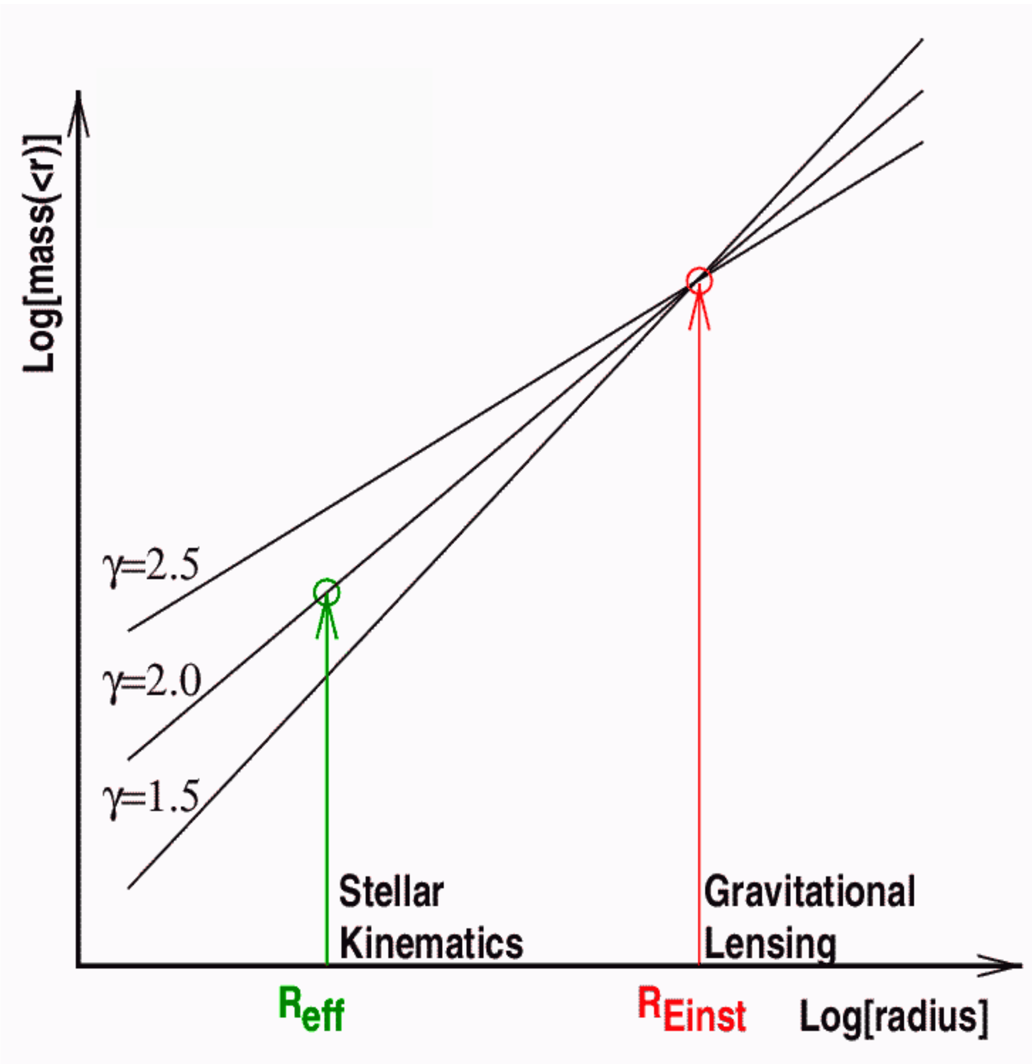


Image credit: SLACS team
see Bolton et al. (2008), Koopmans et al. (2009)



Robust SLACS analysis:
Lensing + Dynamics as independent problems

e.g. Treu & Koopmans 04
Koopmans et al. 06



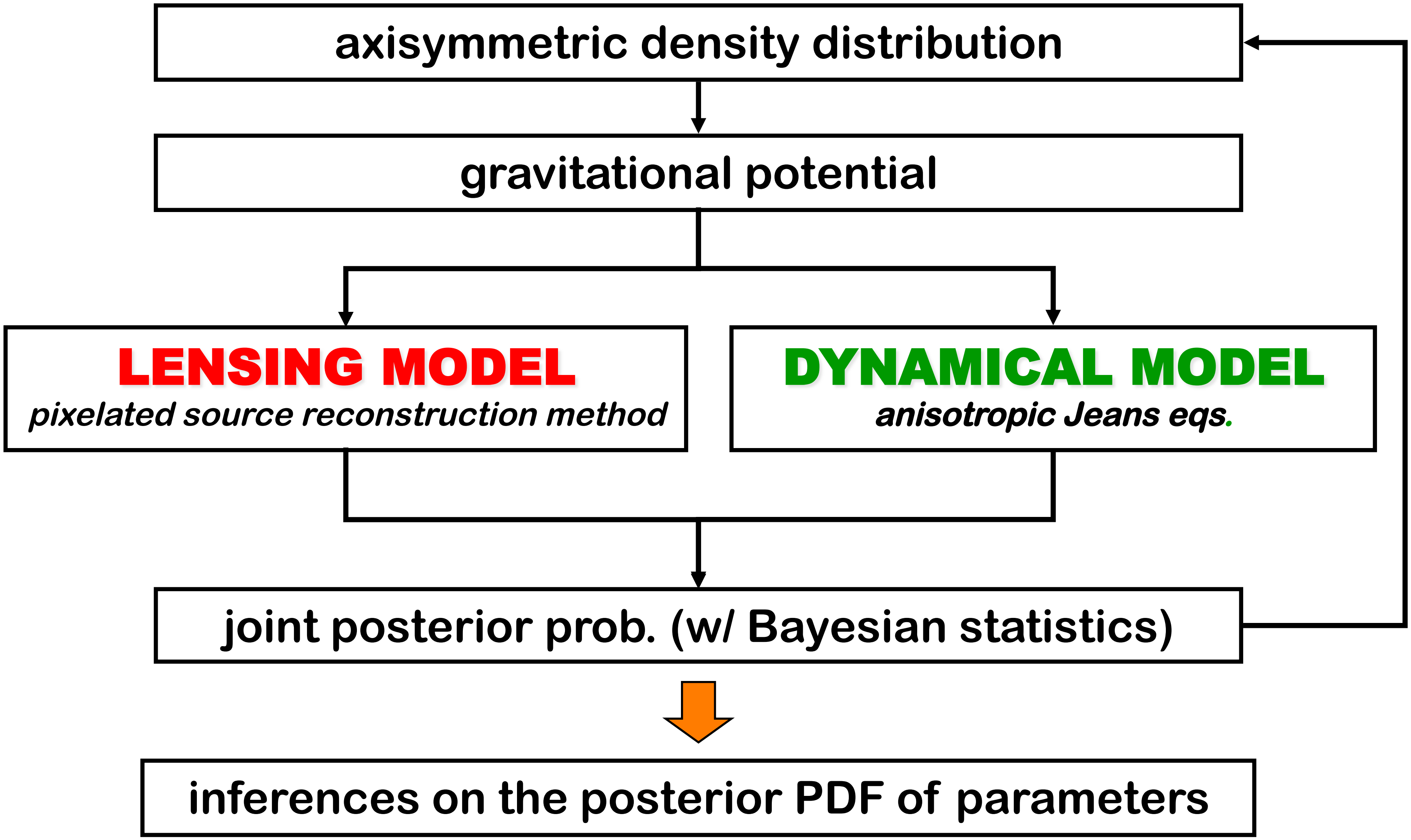
LENSING

- SIE model
- $M(R < R_{Einst})$ imposed as a constraint for the dynamical models

DYNAMICS

- power-law total density profile $\rho_{tot}(r) \propto r^{-\gamma}$
- spherical Jeans eqs.
- stellar anisotropy: constant β_r
- data: 3'' aperture average σ

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**

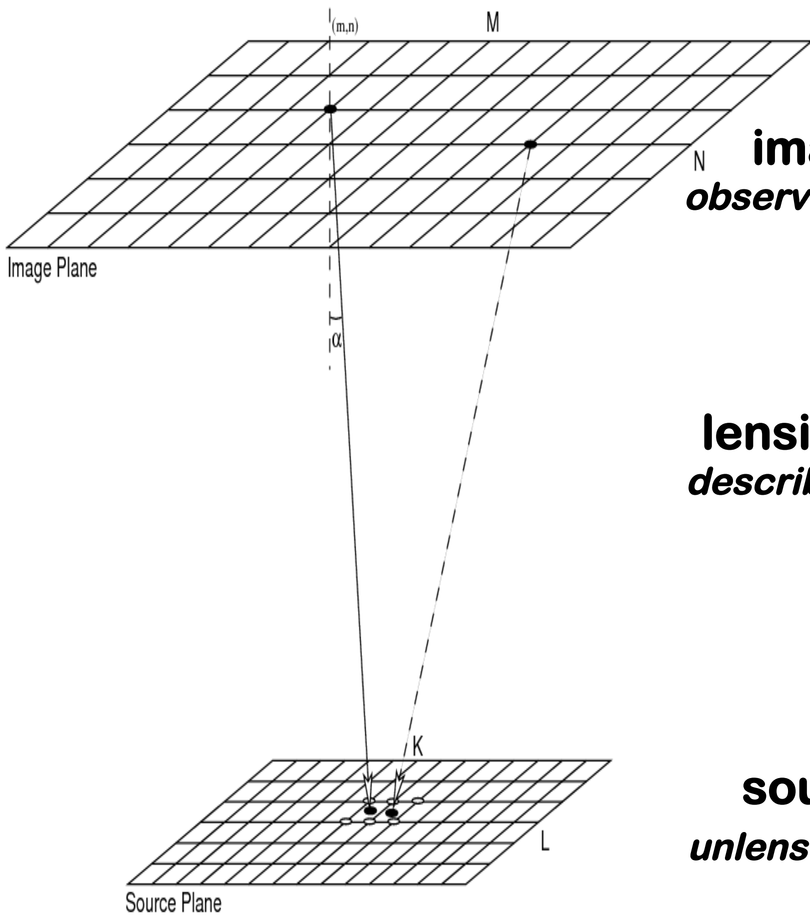
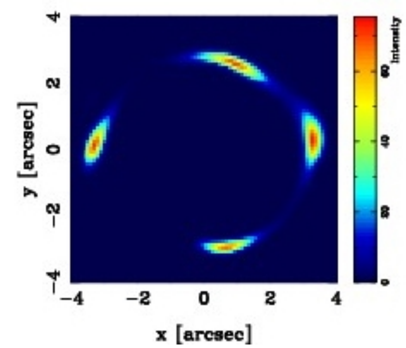
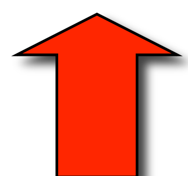


image plane
observed lensed image



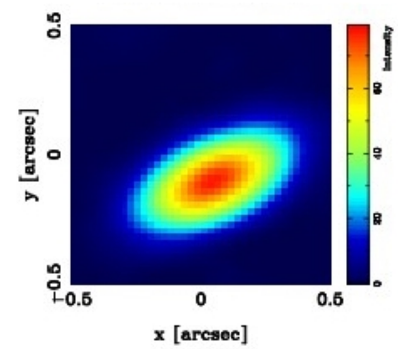
d

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}

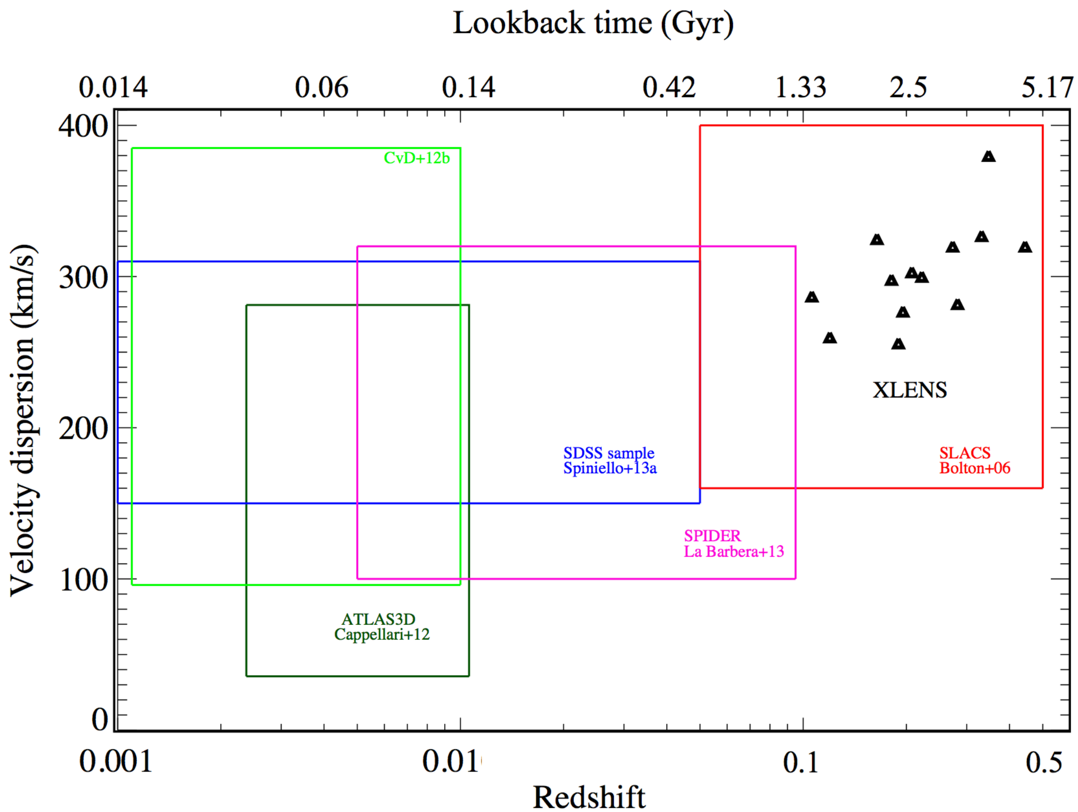
Dynamical Model

- **Anisotropic Jeans equations** (Cappellari 2008)
  - Free parameter [#6]: meridional plane orbital anisotropy ratio $b = \sigma_R^2/\sigma_z^2$

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. 2012, 2013)

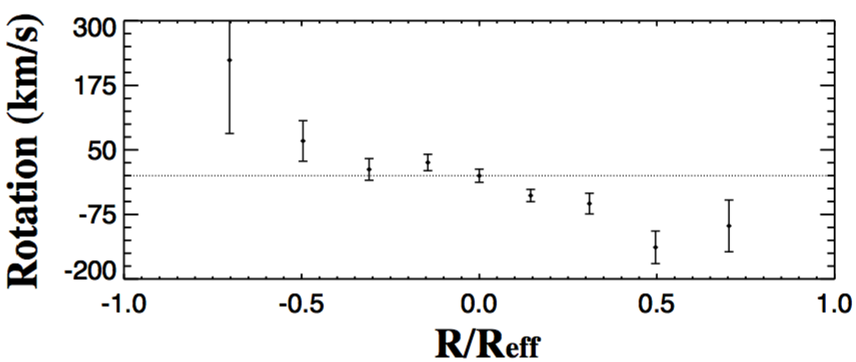


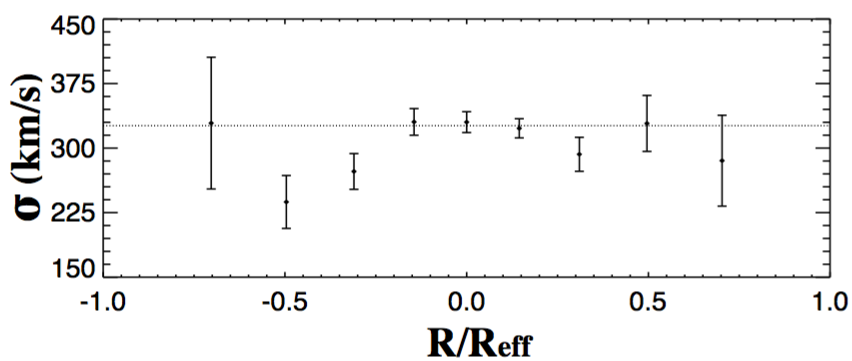
Spiniello et al., in prep.

XLENS: SLACS ellipticals + X-Shooter

X-Shooter Lens Survey (XLENS)

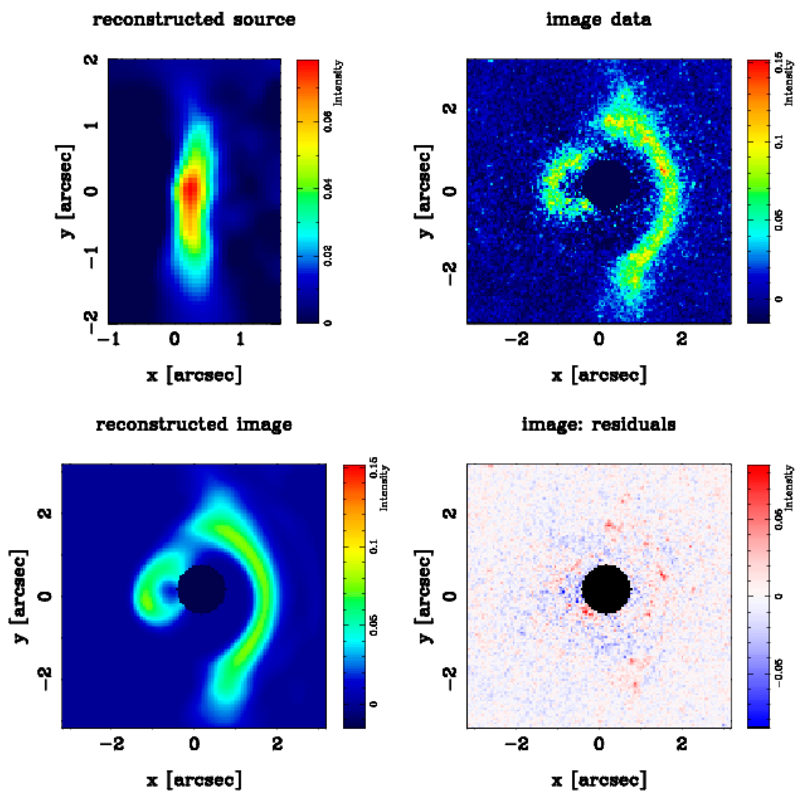
- We can investigate the 3D mass structure of individual massive ETGs.
- We infer stellar masses from two independent methods:
  - joint self-consistent lensing + dynamics analysis
  - spectroscopic stellar pop. study
- Inferences on the properties of the stellar initial mass function (IMF): slope and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



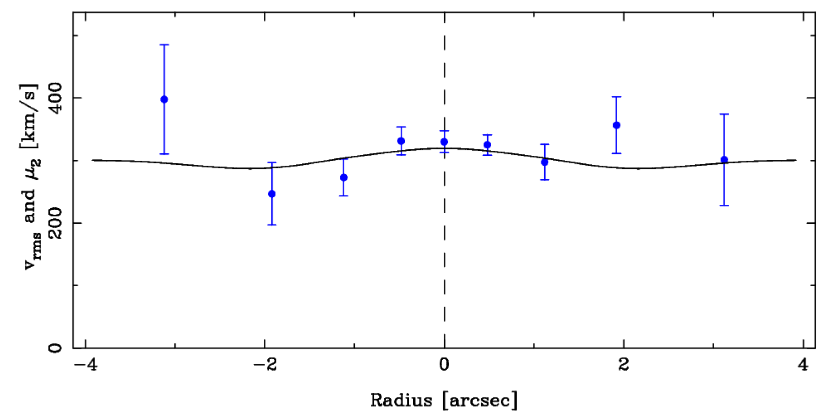


Combined analysis of lens ETG J0912

GRAVITATIONAL LENSING

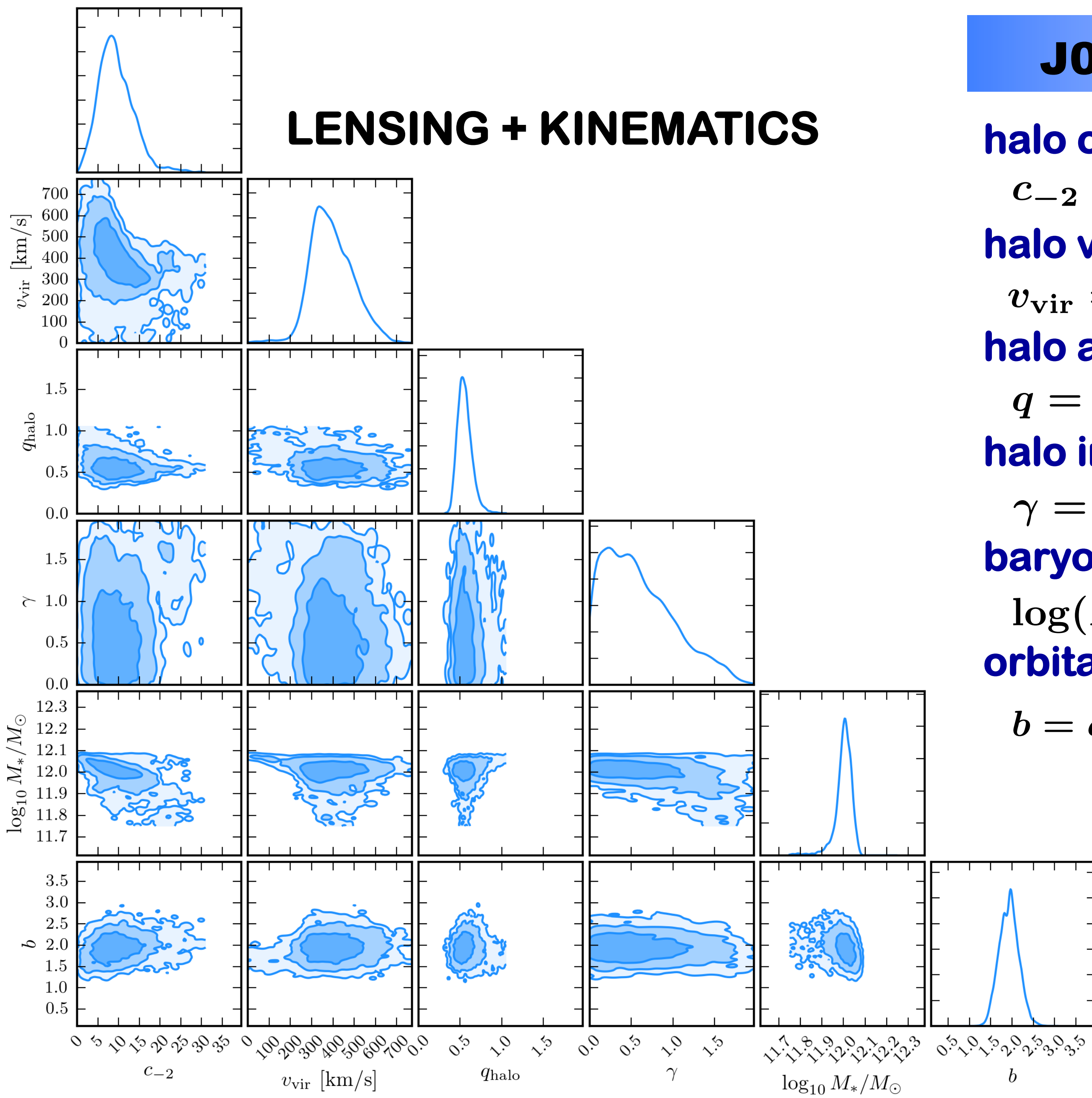


STELLAR KINEMATICS



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_e



J0912: inferences

halo concentration:

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

halo virial velocity:

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

halo axial ratio:

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

halo inner slope:

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

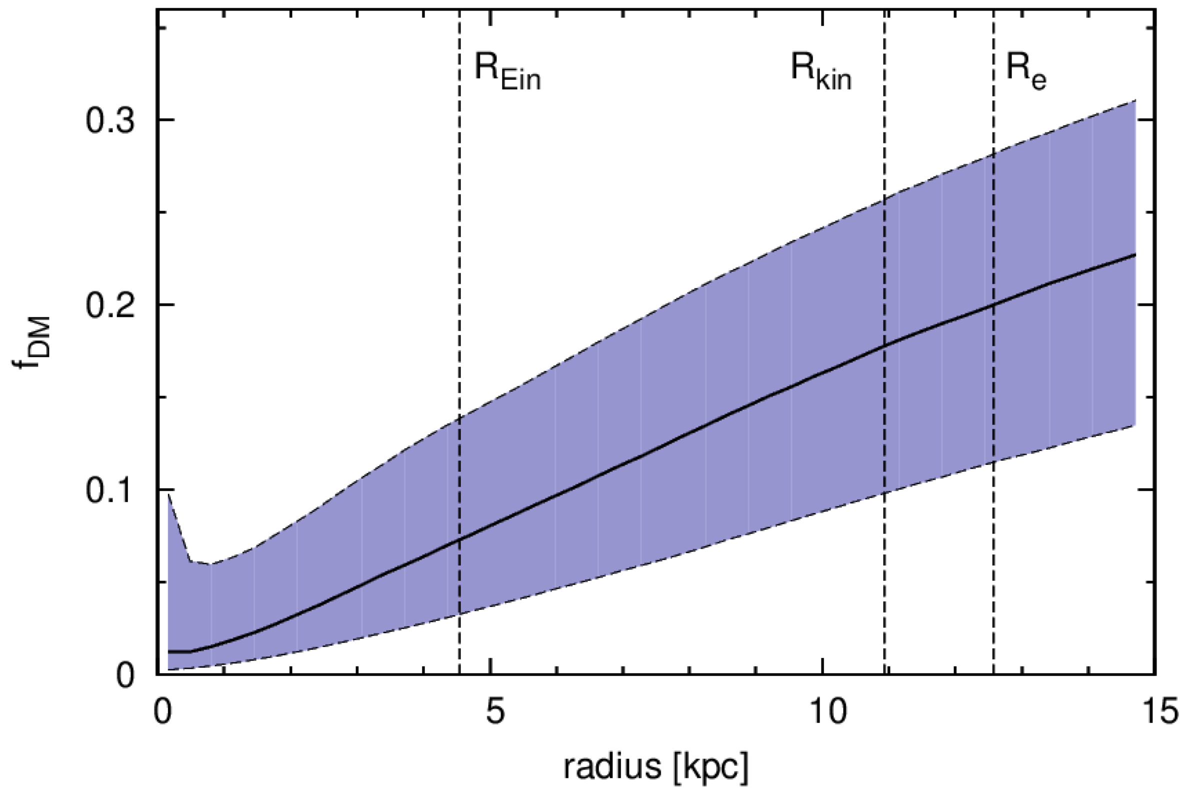
baryonic mass:

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

orbital anisotropy par.:

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

J0912: dark matter fraction profile

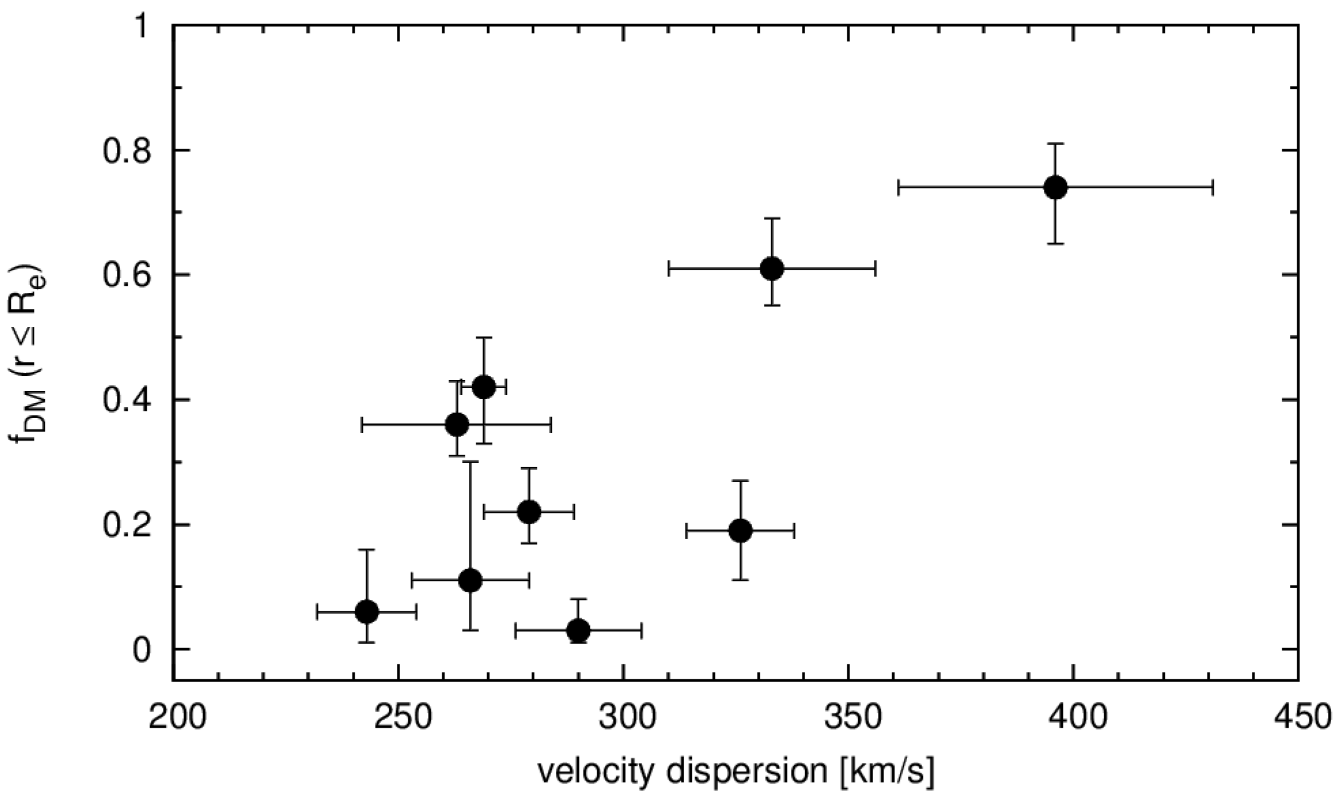


- We can investigate the f_{DM} radial profile within the galaxy inner regions (~ 1 R_e) probed by data-sets
- inner regions dominated by baryonic matter for this system

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

XLENS sample: dark matter fraction

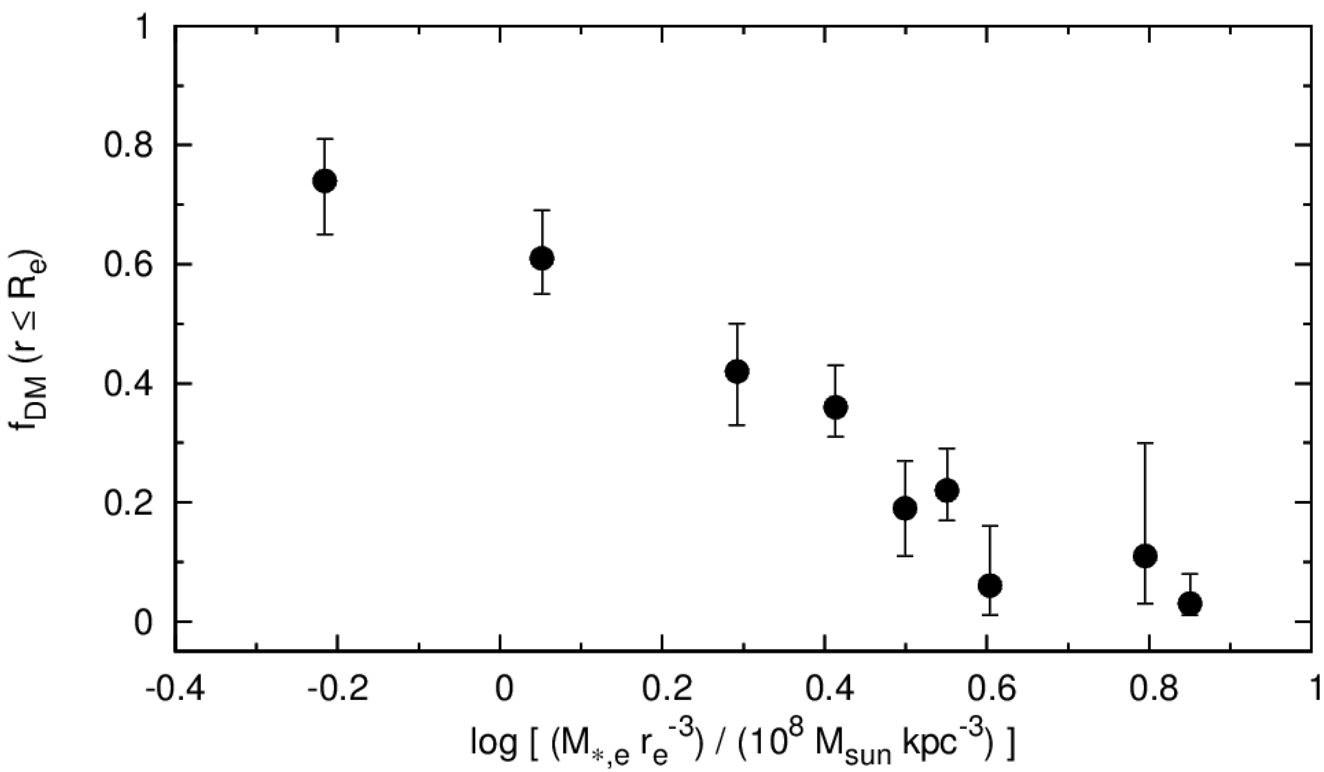
- dark matter contribution within $r = R_e$
- f_{DM} about 10 – 40% with scatter except for the two most massive galaxies (beyond $\sigma \sim 350$ km/s)
- J0935: $f_{DM} \sim 74\%$ and J0216: $f_{DM} \sim 60\%$
  dark matter dominated within $r = R_e$



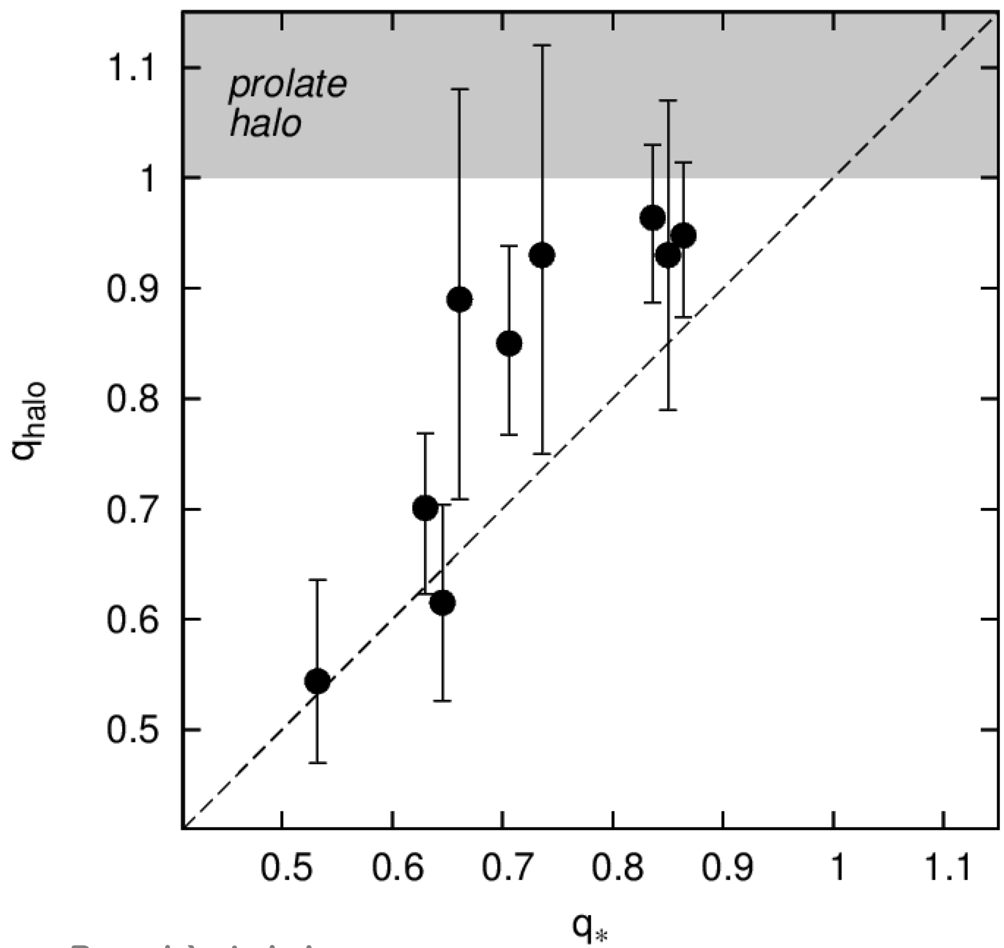
Barnabè et al., in prep.

XLENS sample: dark matter fraction

- the dark matter fraction f_{DM} ($\leq R_e$) is higher in galaxies with lower stellar mass density $\rho_* \propto M_e/r_e^3$ (cf. Sonnenfeld et al. 2014)
- J0935 and J0216 have significantly lower ρ_* than the remaining (less massive) systems



XLENS sample: dark halo flattening

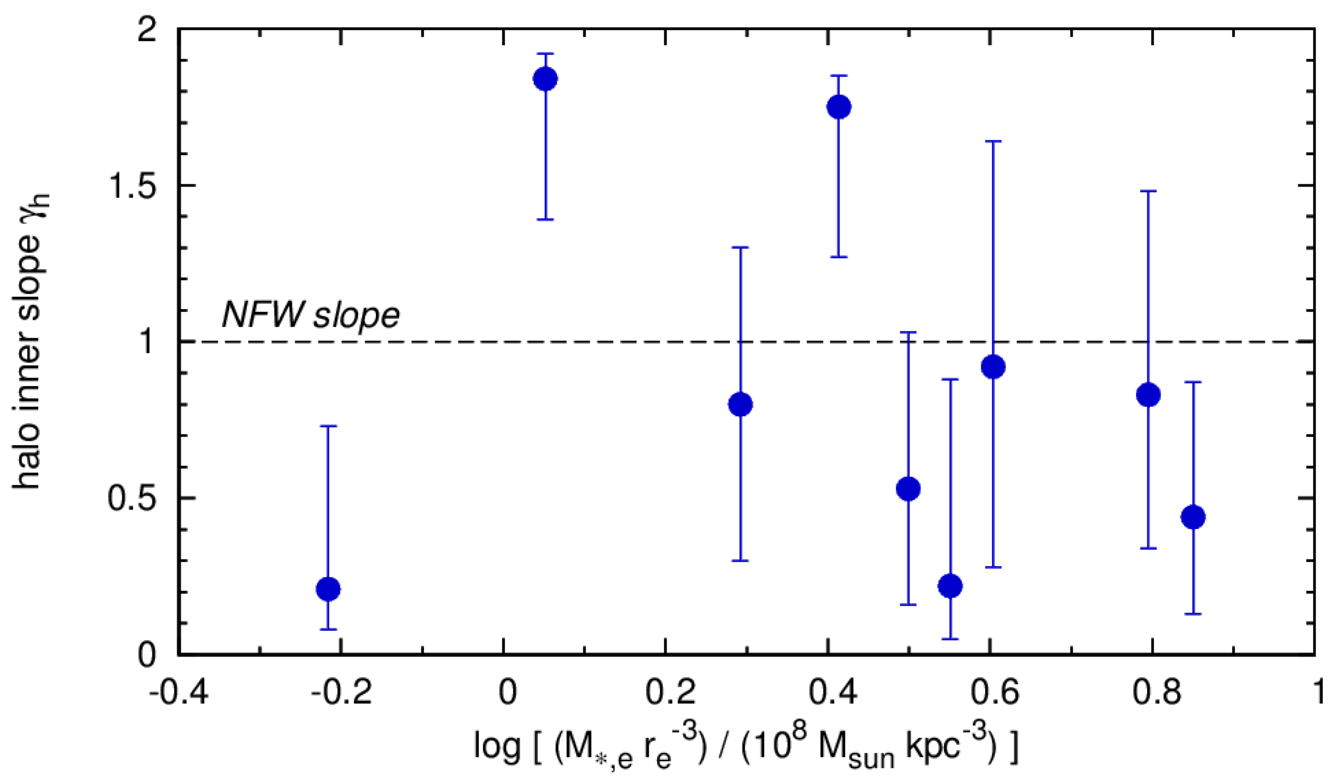


Barnabè et al., in prep.

- DM axial ratio similar to stellar axial ratio
- halo usually (slightly) rounder than the stellar component
- mildly prolate haloes are possible

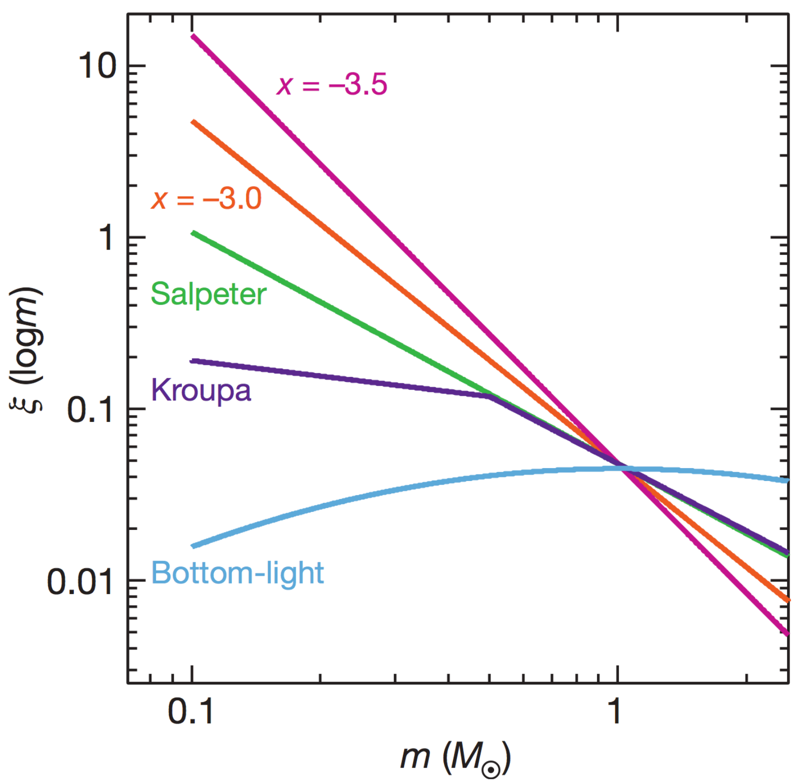
XLENS sample: inner slope

- **halo inner slope largely unconstrained with the current data-set**
- **most systems are shallow or consistent with NFW, only two galaxies are clearly steeper**



The stellar initial mass function of ETGs

van Dokkum & Conroy (2010)

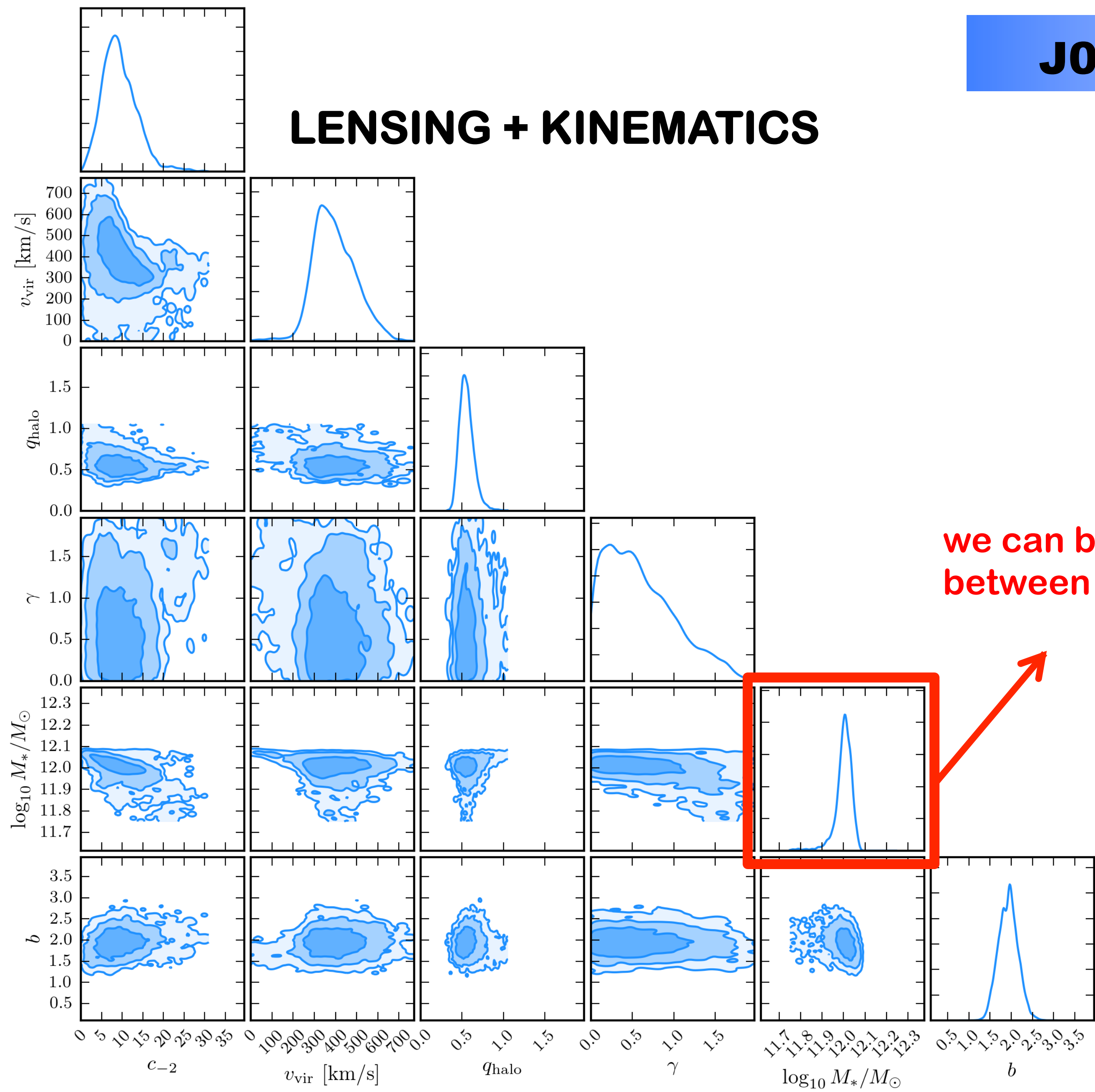


$$\zeta(m) = \frac{dN}{dm} \propto m^x$$

- stellar IMF describes the distribution of stellar masses when the population is formed
- critical to understand almost every aspect of galaxy evolution
- Milky Way: stellar IMF found to be well described by a **Chabrier or Kroupa profile**
- Milky Way: IMF is the same across different environments: "universality"
- **IMF found to be steeper than Chabrier in massive ellipticals** (e.g. Treu et al. 2010, van Dokkum & Conroy 2010, Cappellari et al. 2012, etc.)
- Is the IMF universal?

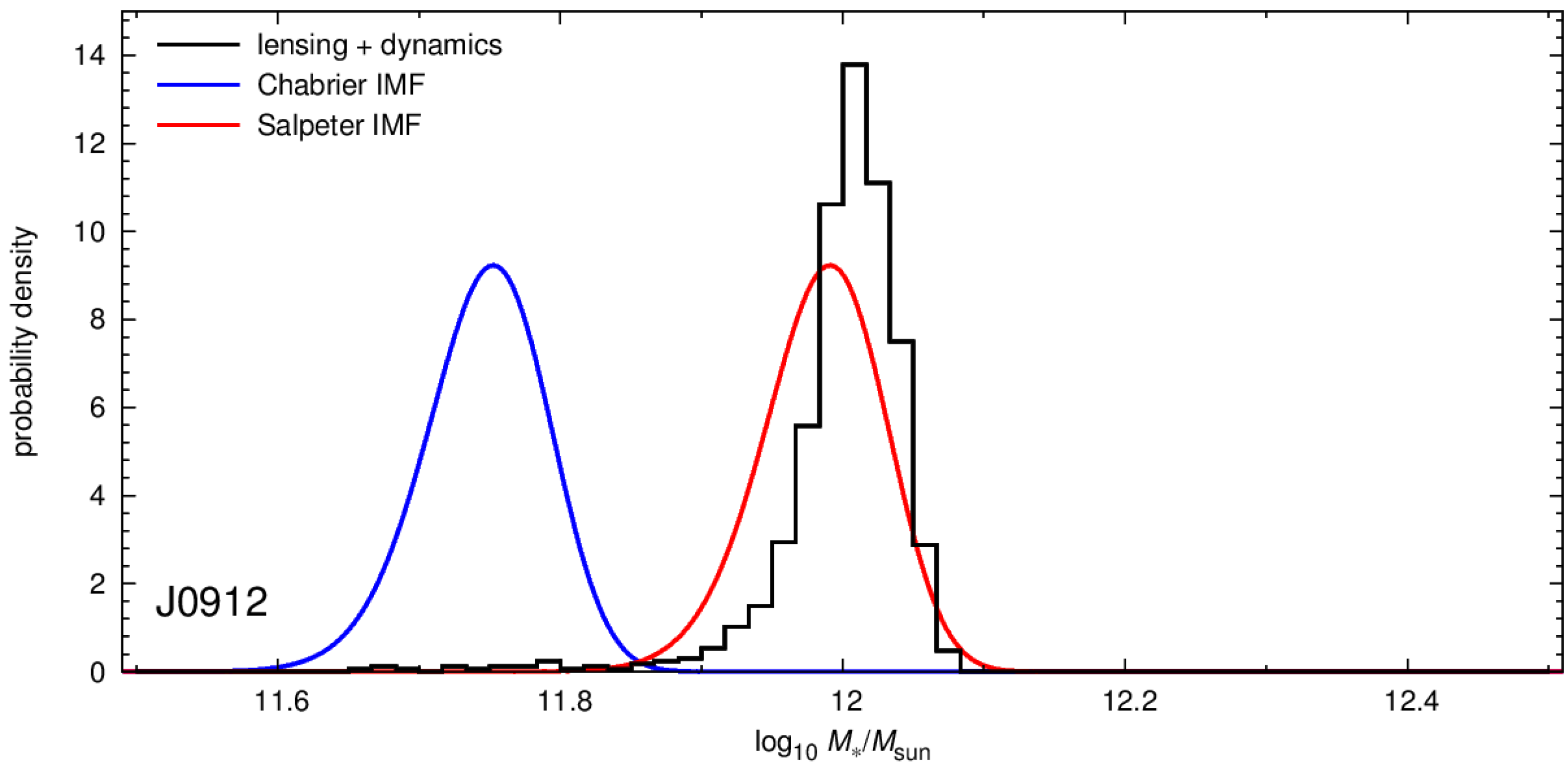
J0912: inferences

LENSING + KINEMATICS



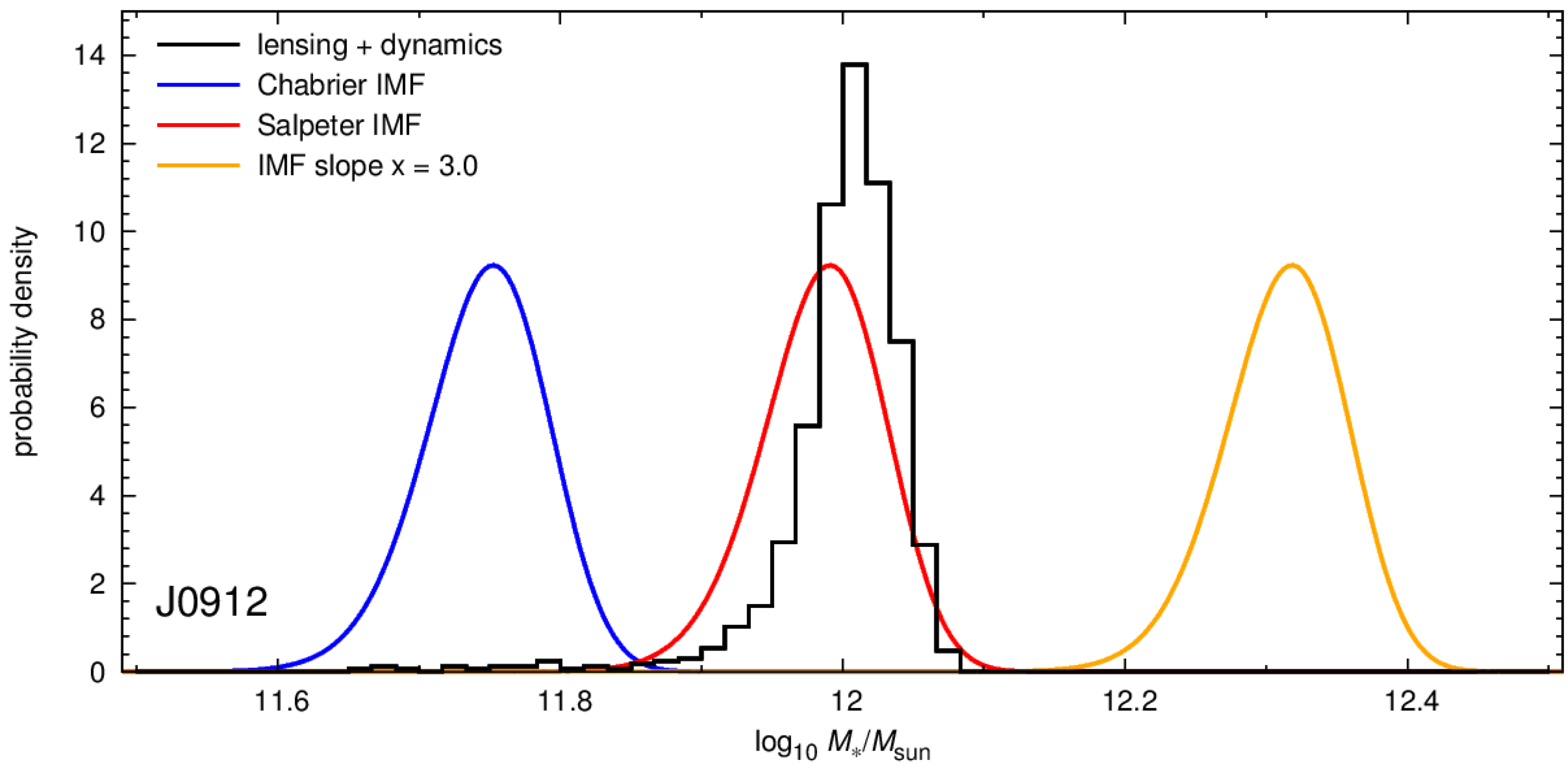
we can break the degeneracy between IMF and dark matter

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 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, Cappellari et al. 2013)

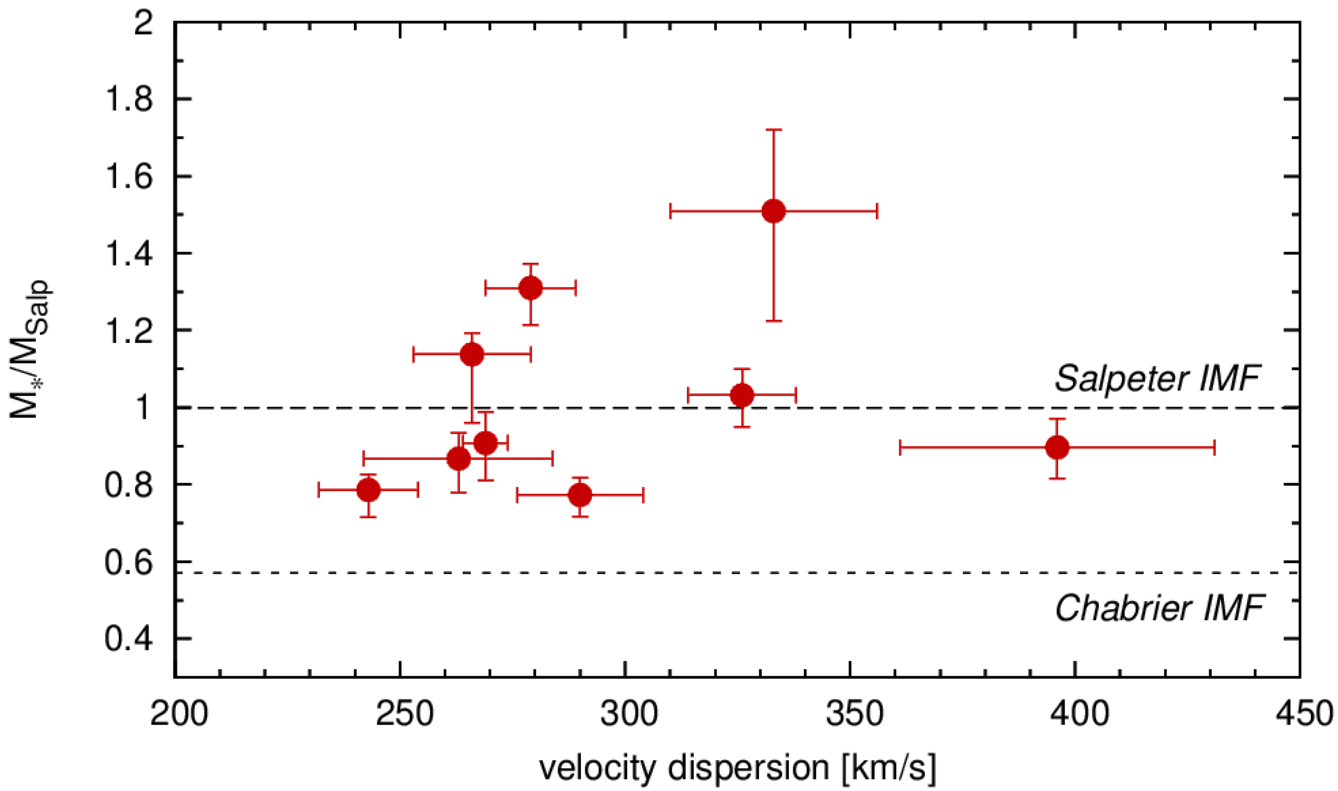
IMF inferences: super-Salpeter IMF ruled out



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

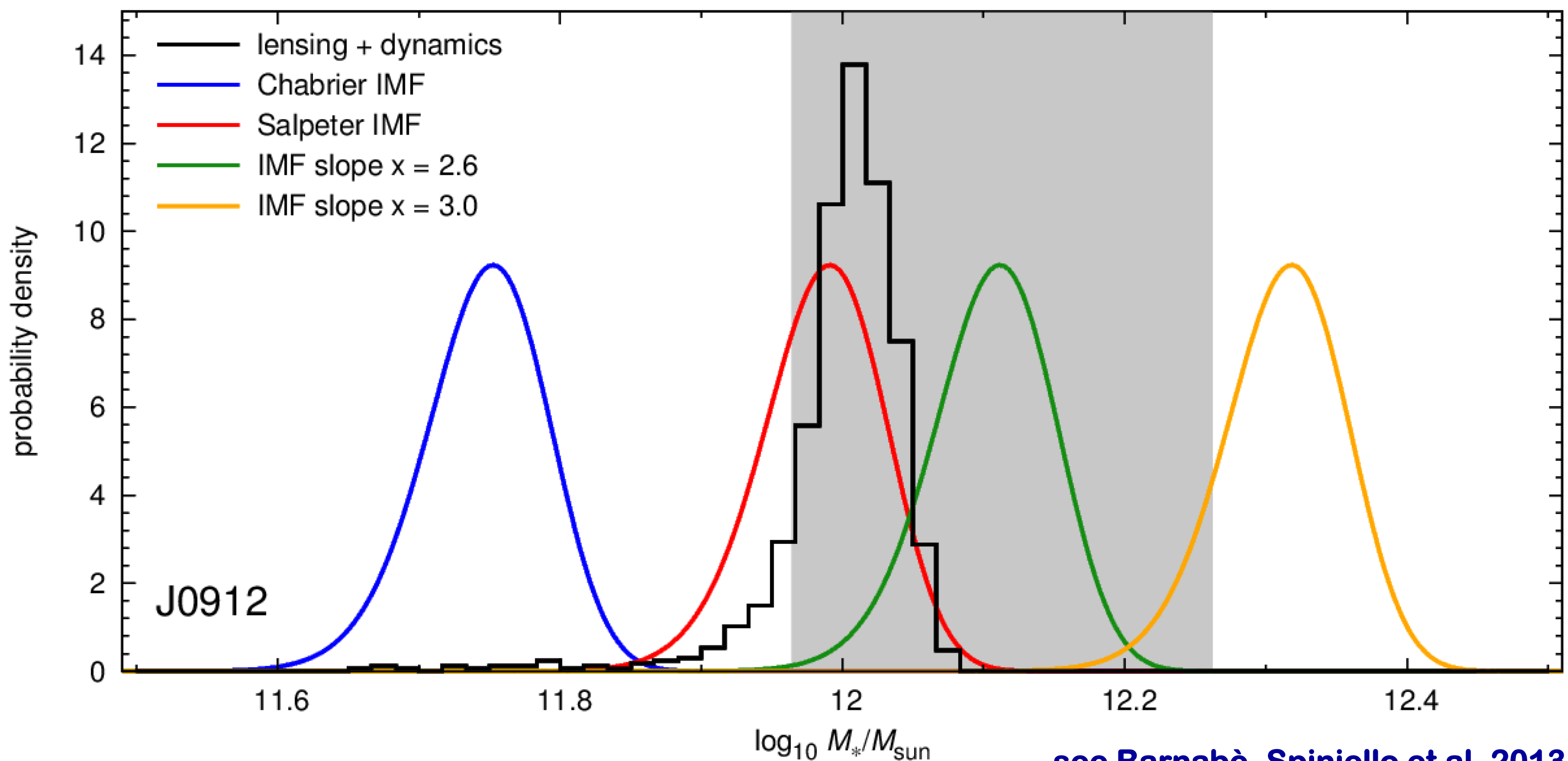
XLENS sample: IMF inferences

- IMF steeper than Chabrier
- Salpeter-type IMF (slope x ~ 2.35) for most systems
- no clear trend with velocity dispersion



Barnabè et al., in prep.

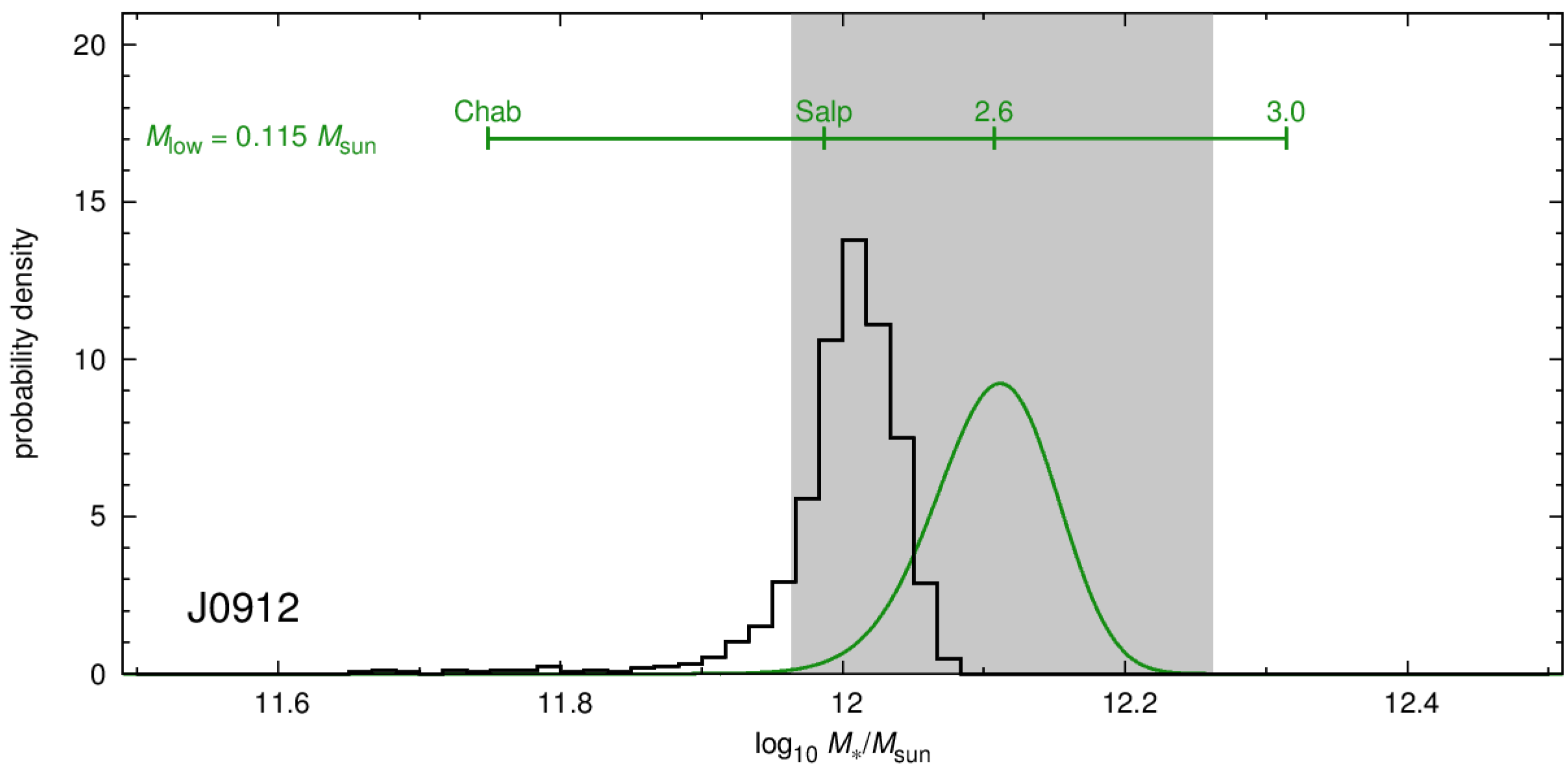
Comparing two independent methods
lensing+dynamics and SSP analysis



see Barnabè, Spiniello et al. 2013

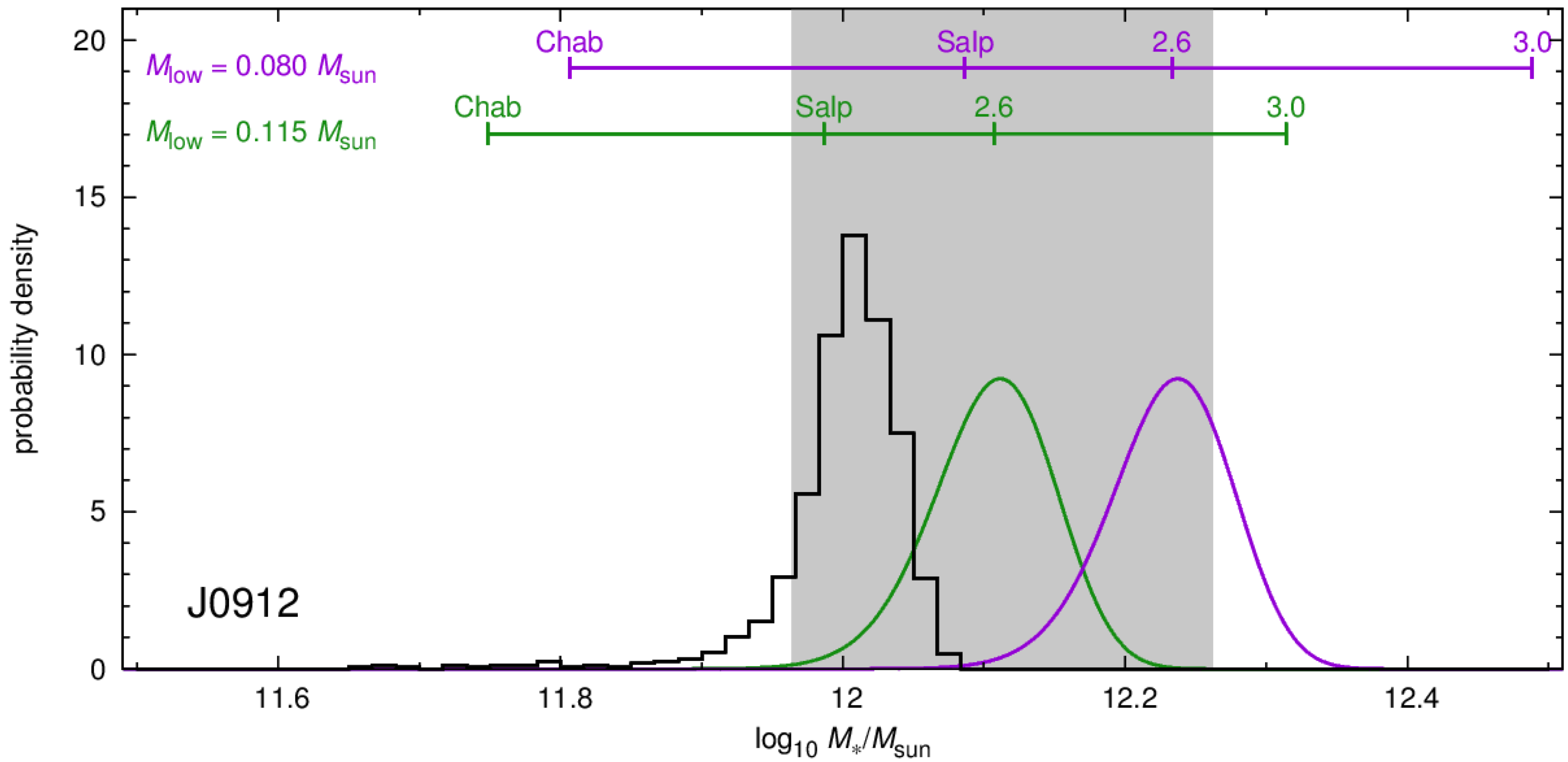
- **The stellar masses inferred from the spectroscopic single stellar population (SSP) analysis of optical line-strength indices (see Spiniello et al. 2013) is consistent with the *independent* inferences from the combined L+D study (which makes no assumptions on the IMF)**
- **IMF slope derived from spectroscopic SSP analysis: x = 2.60 ± 0.30**

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
- Low-mass stars with $M < 0.15\ M_{sun}$ have little effect on spectral lines but can contribute significantly to the total stellar mass
- Values from M_{low} = 0.08 to 0.15 are used in SP evolution codes

IMF inferences: constraints on M_{low}



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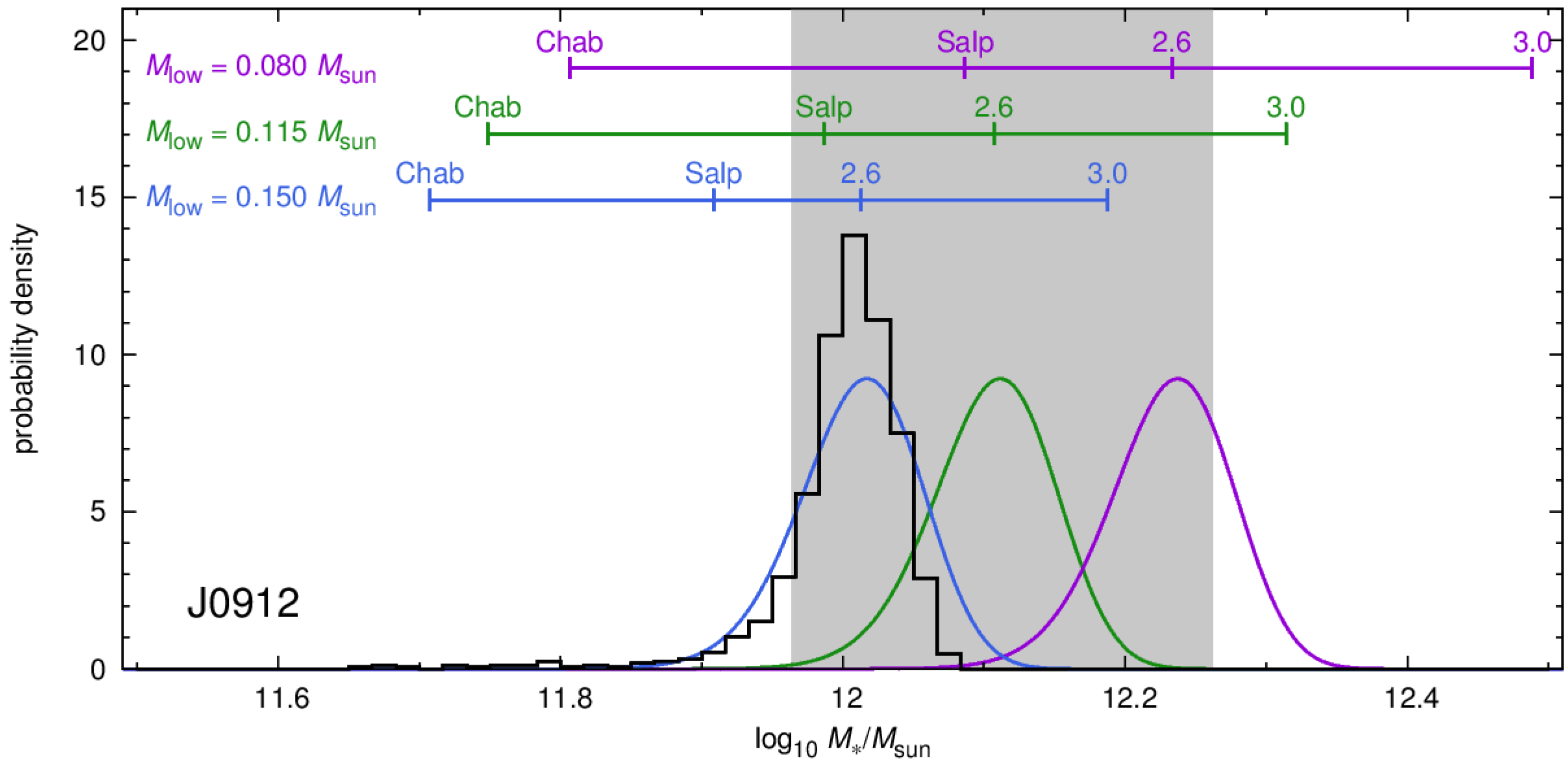

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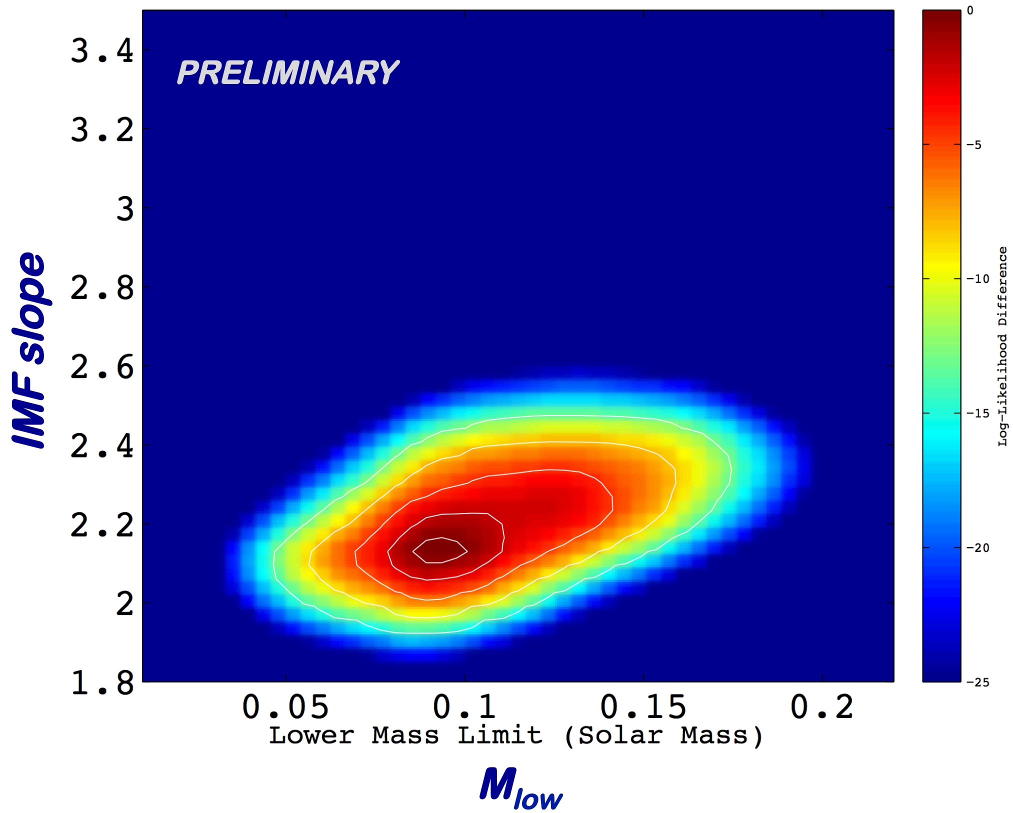
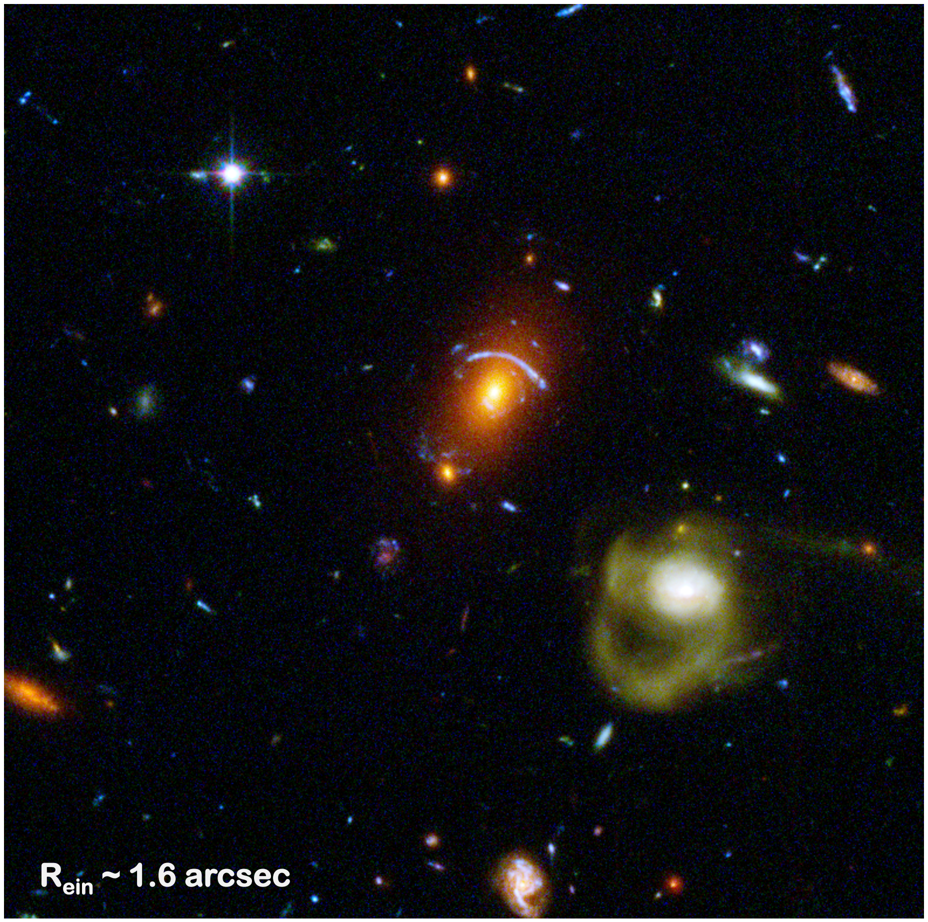
joint inference on IMF slope and M_{low}



- We combine the results of the L+D and SSP analyses for six galaxies to derive the joint inference on slope and low-mass cut-off limit
- IMF slope: $x = 2.15 \pm 0.06$
- Low-mass cut-off: $M_{low} = 0.10 \pm 0.01\ M_{sun}$

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, Chiara Spiniello, Oliver Czoske and Lise Christensen

Conclusions

❑ Mass structure of ETGs:

- 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 (within 1 R_e): around 10-40% for typical ETGs, except for the most massive ellipticals which are DM dominated ($f_{DM} \geq 60\%$).
- We can study dark halo properties within ETGs inner regions: slope, flattening (rounder than q_*), trend with stellar mass density.

❑ Initial mass function of ETGs:

- Lensing + dynamics can break the degeneracy between f_{DM} and IMF
- IMF of massive ellipticals is steeper than Chabrier, with significant scatter; most systems have IMFs close to Salpeter.
- Independent methods (combined lensing & dynamics; spectroscopic SSP analysis) give consistent inferences on the stellar masses
- First constraints on the low-mass cut-off of the initial mass function