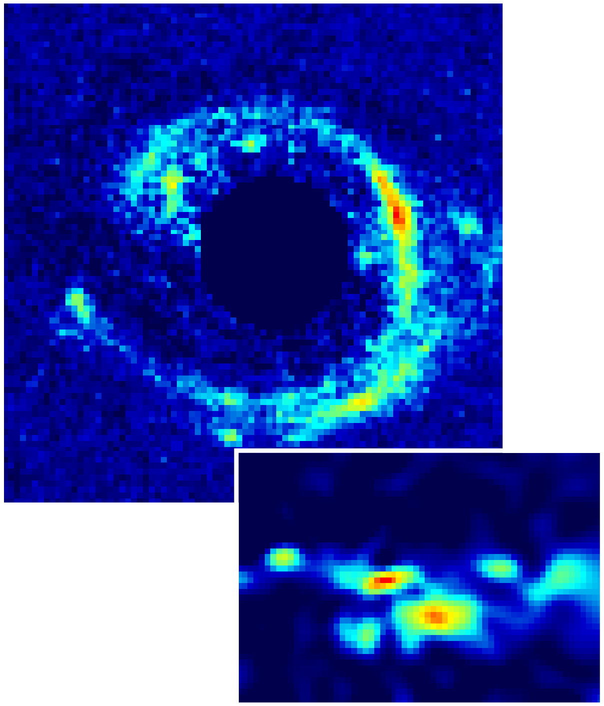
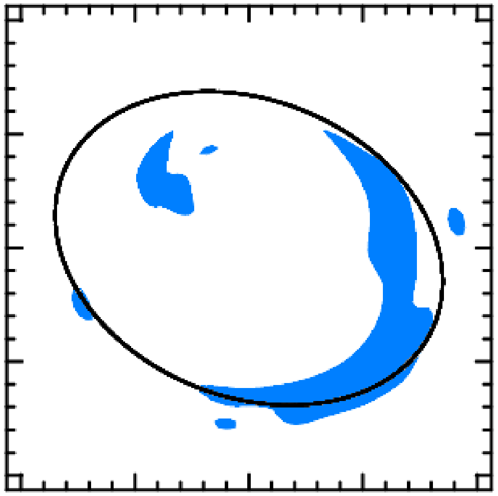
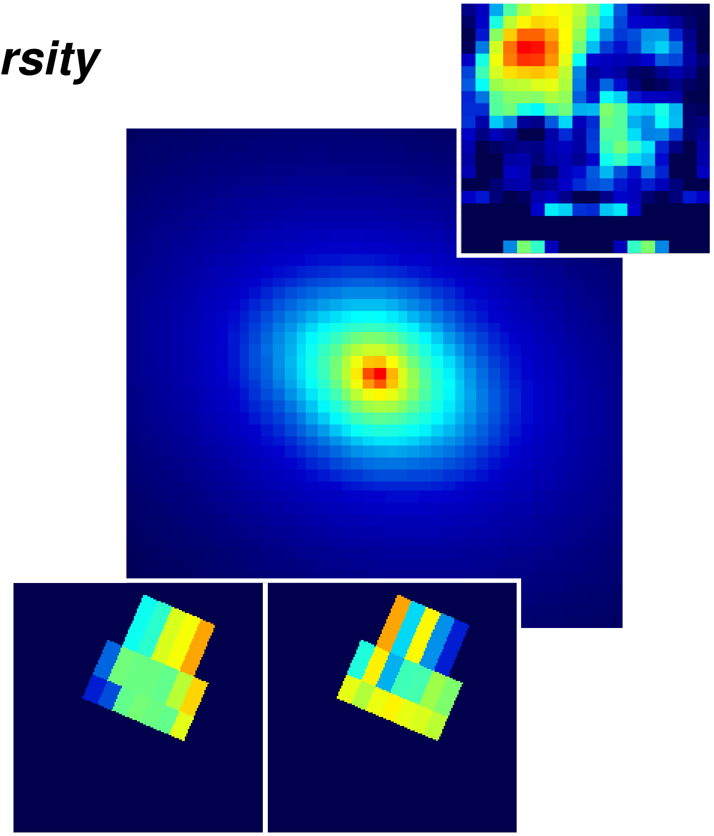
CAULDRON: dynamics meets gravitational lensing

Matteo Barnabè

KIPAC/SLAC, Stanford University





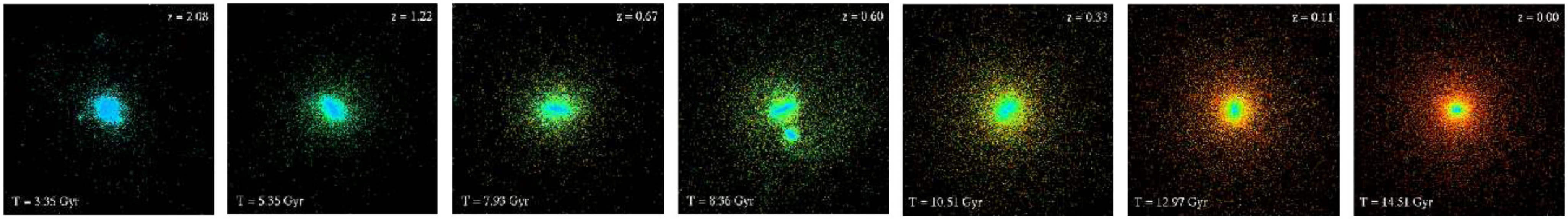


Collaborators: Léon Koopmans (Kapteyn), Oliver Czoske (Vienna), Tommaso Treu (UCSB),
Aaron Dutton (MPIA), Matt Auger (Cambridge), Phil Marshall (Oxford), Brendon Brewer (UCSB), Adam Bolton (Utah)

"Dynamics meets kinematic tracers" **– Schloss Ringberg, 11 April 2012**

Probing Galaxy Formation and Evolution

z = 2.08 z = 1.22 z = 0.67 z = 0.60 z = 0.33 z = 0.11 z = 0.00



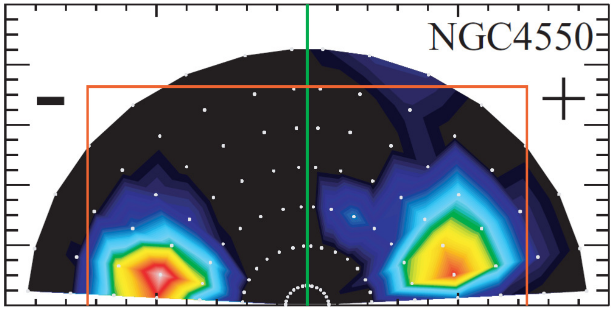
SIMULATIONS

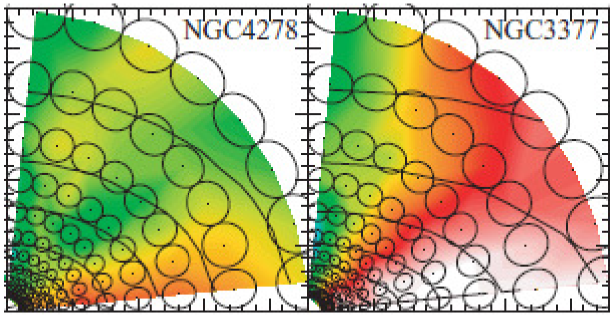
Meza et al. (2003): includes DM, stars and gas; star particles colored according to age

? ? ? ?

LENSING + DYNAMICS

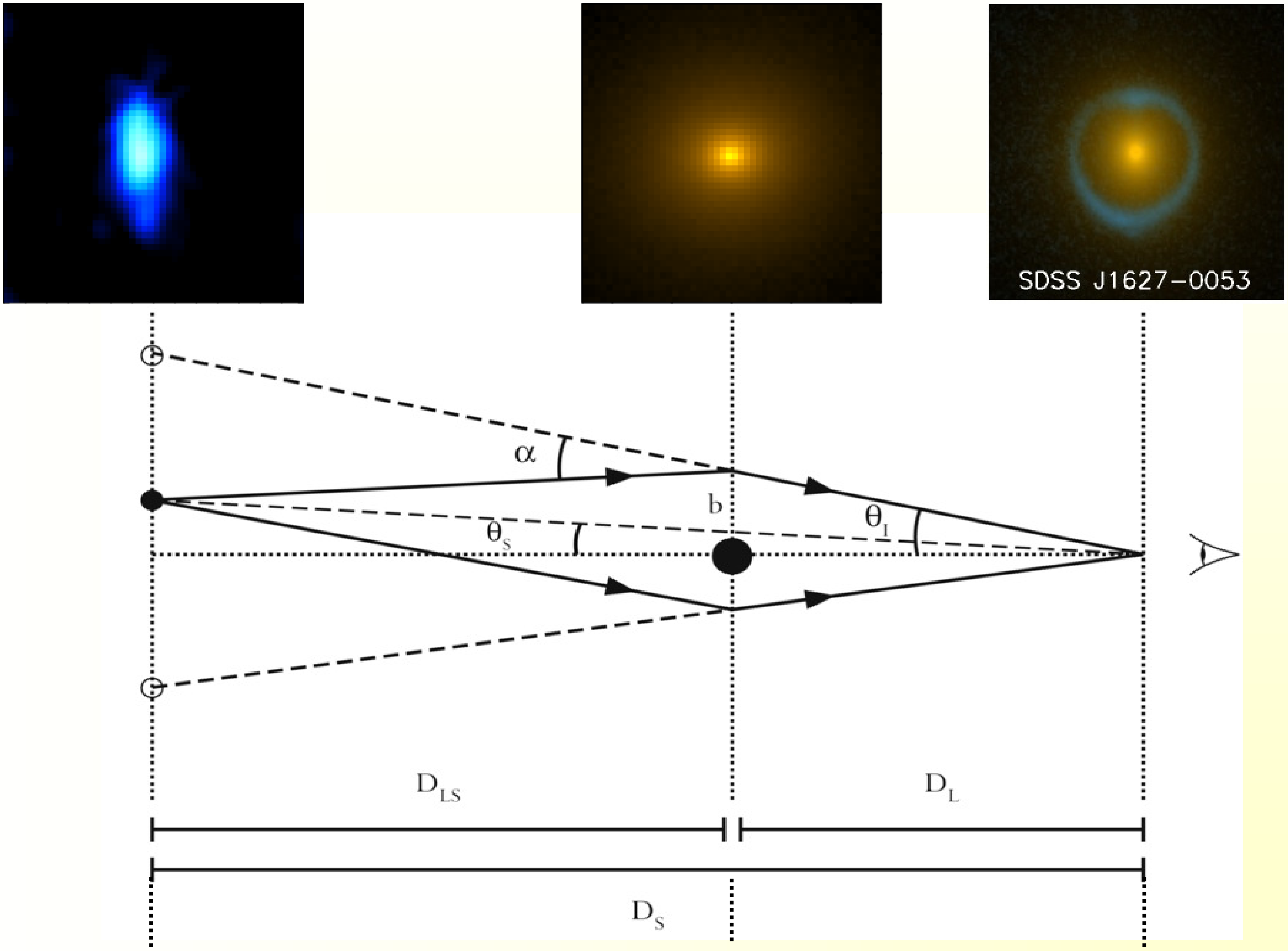
OBSERVATIONS





dynamical structure

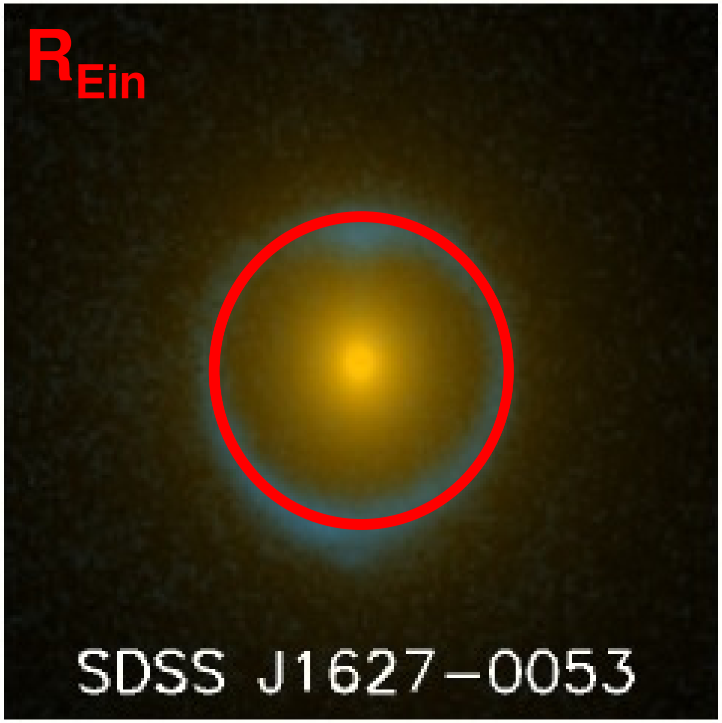
Gravitational Lensing



Source plane **Lens plane** **Observer plane**

Combining Lensing & Dynamics:

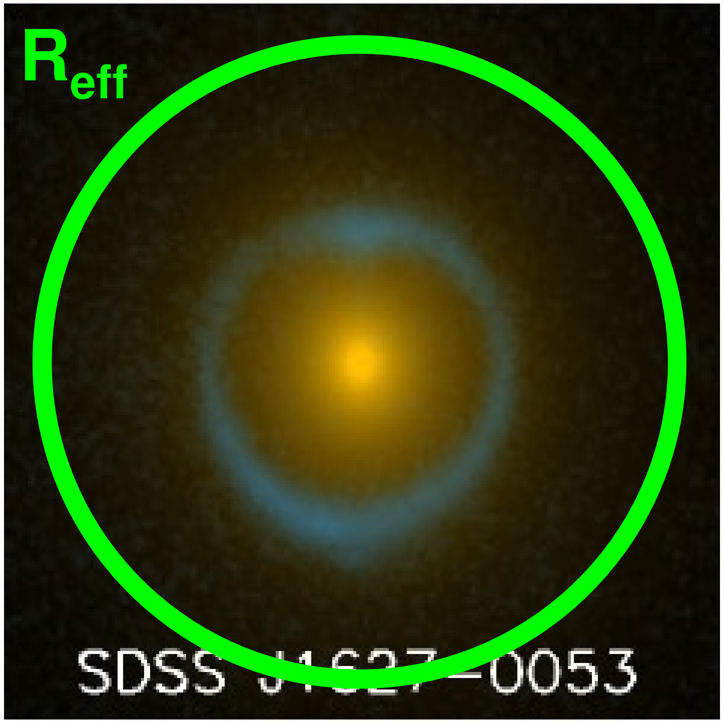
GRAVITATIONAL LENSING



Accurate and (nearly) model independent determination of mass inside Einstein radius

+

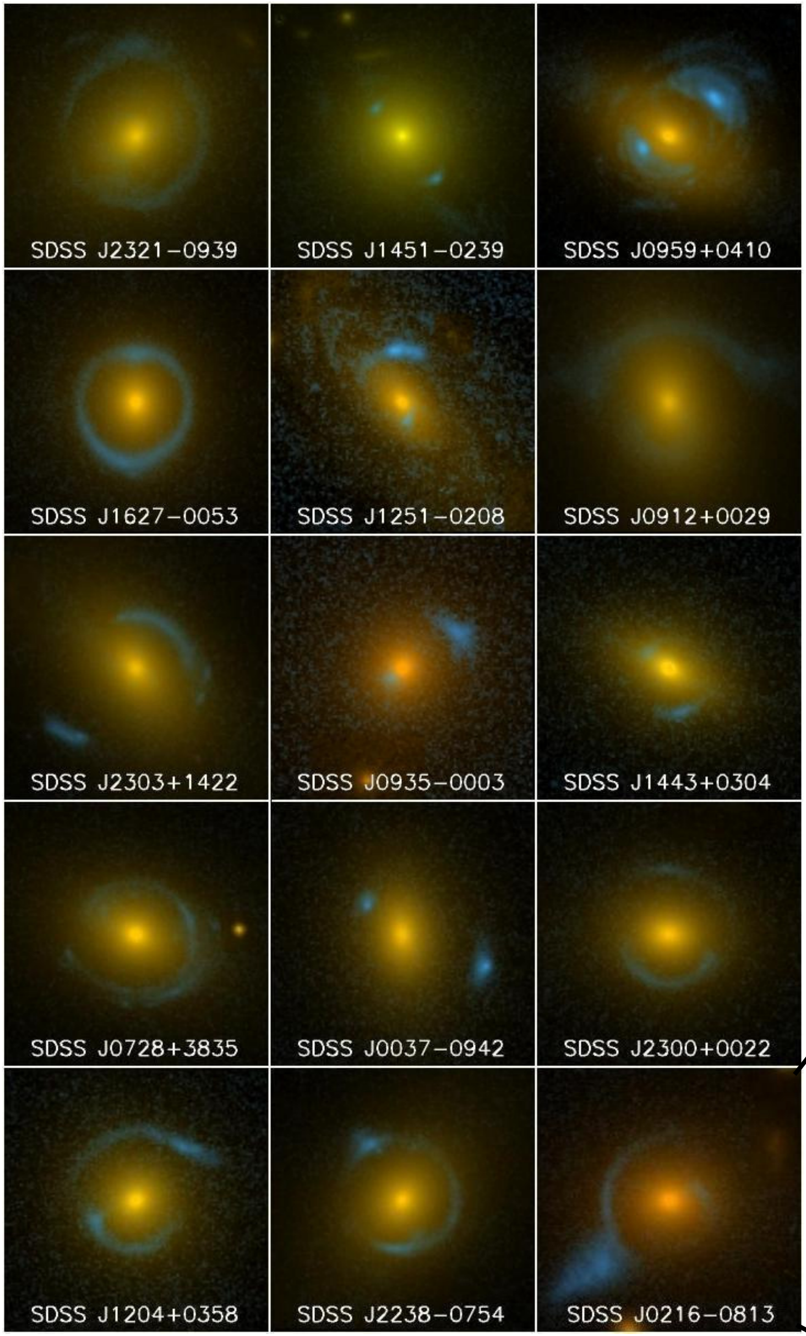
STELLAR DYNAMICS



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 imaging with HST ACS (F814W)
- follow-up spectroscopic observations:
    - 16 systems: **VLT** VIMOS IFU
    - 1 system: **Keck** long-slit spectra



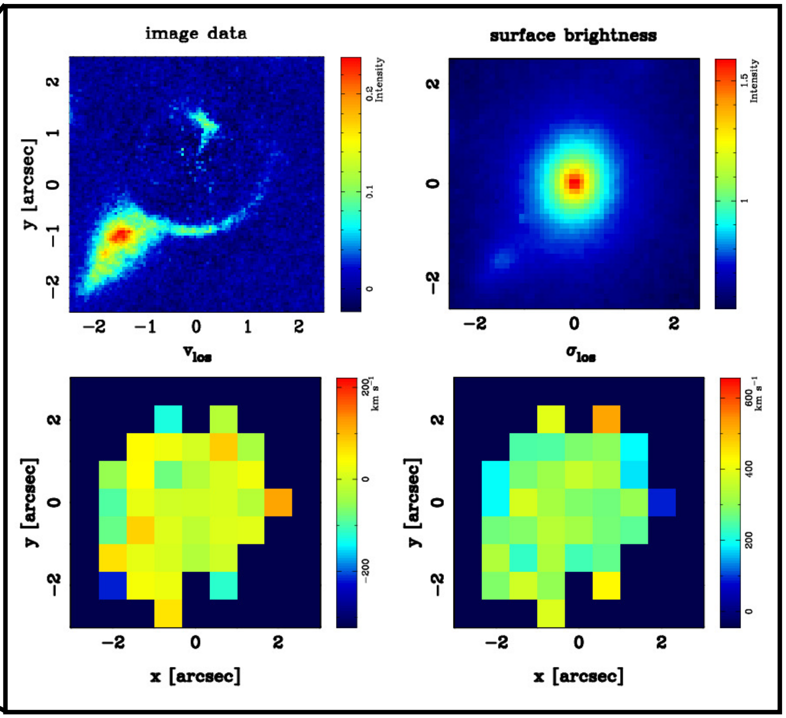
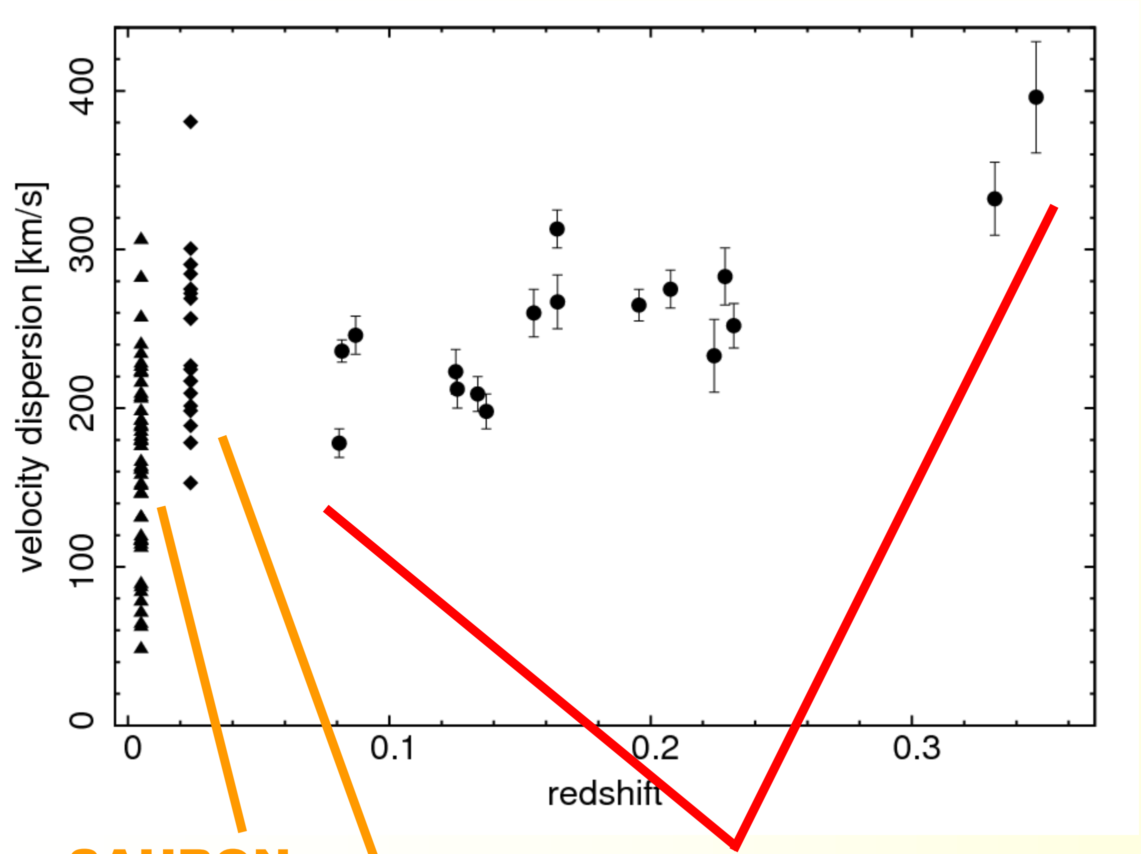


Image credit: Adam Bolton & the SLACS team
Bolton et al. (2008), Koopmans et al. (2009)

Studying early-type galaxies beyond the local Universe

SLACS complements local E/S0 studies



SAURON

Coma survey

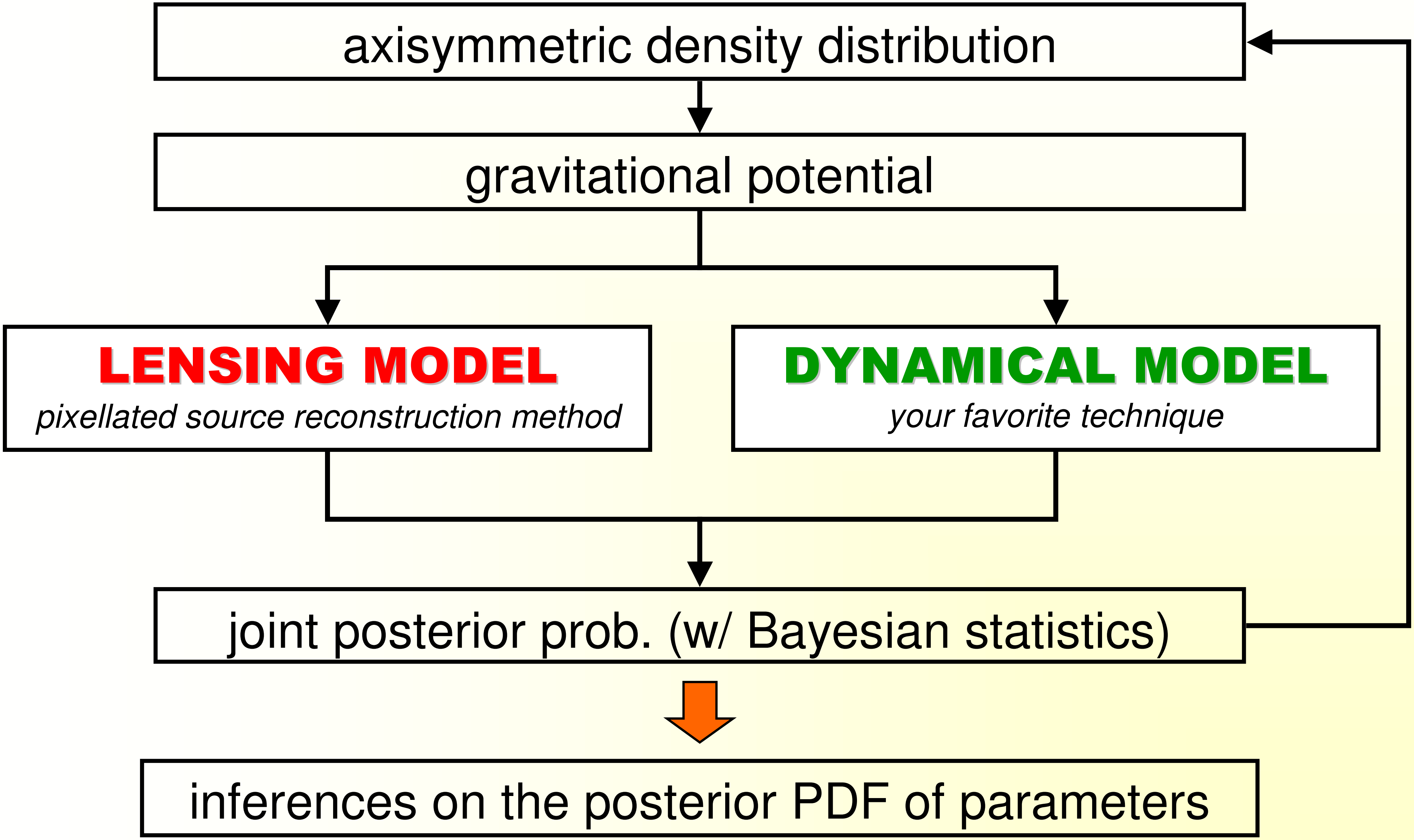
SLACS (VIMOS)

▲ Galaxies observed within the SAURON Survey
(de Zeeuw et al. ‘02, Cappellari et al. ‘07)

◆ Coma cluster ellipticals
(Thomas et al. ‘07)

● SLACS systems with available VLT VIMOS integral field spectroscopic observations

CAULDRON:
COMBINED LENSING AND DYNAMICS ANALYSIS



axisymmetric density distribution

gravitational potential

LENSING MODEL

pixellated source reconstruction method

DYNAMICAL MODEL

your favorite technique

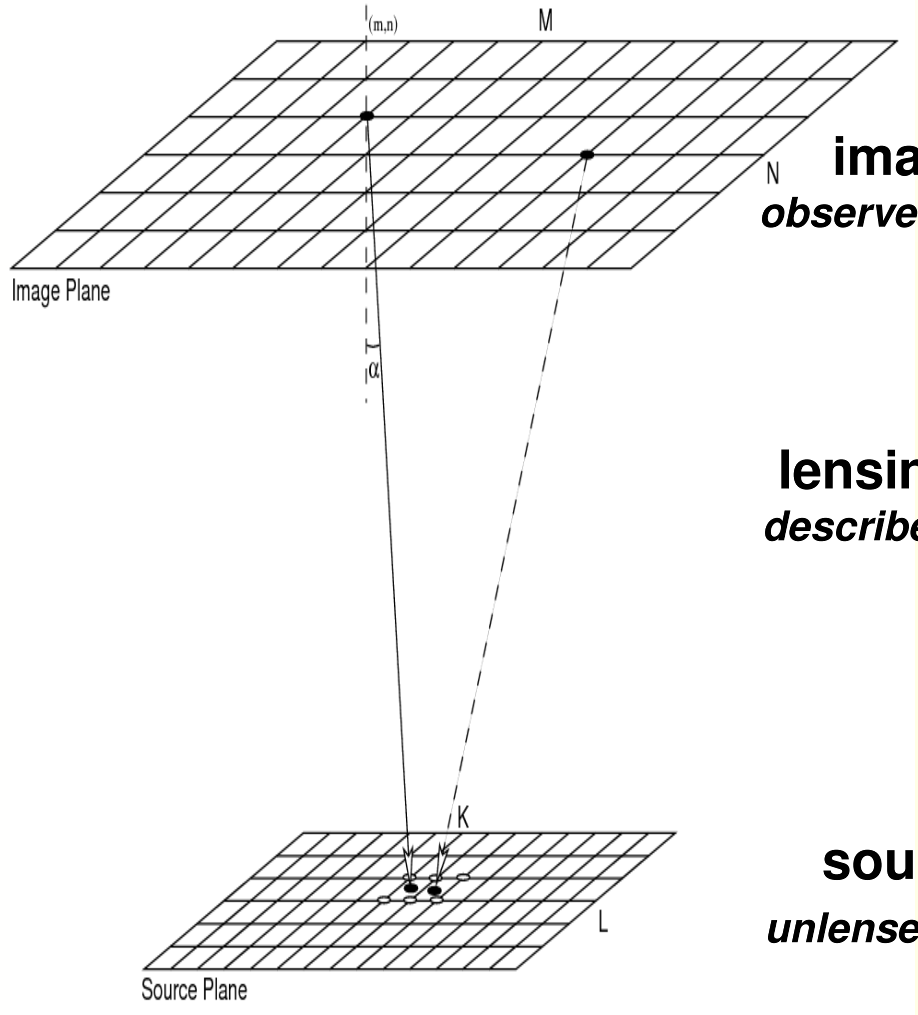
joint posterior prob. (w/ Bayesian statistics)

inferences on the posterior PDF of parameters

Barnabè & Koopmans 2007, Barnabè et al. 2012

Lensed Image Reconstruction

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



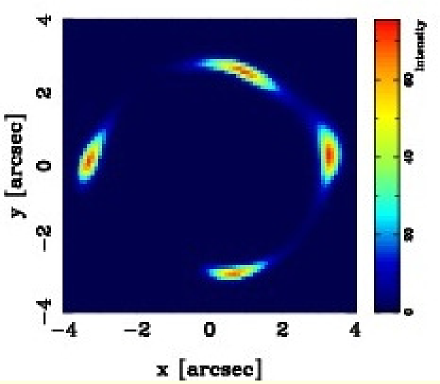


image plane

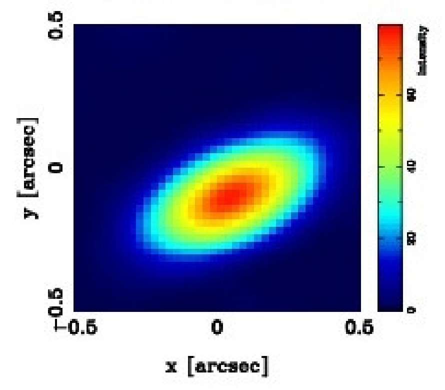
observed lensed image

d

lensing operator

describes the mapping

L(Φ)

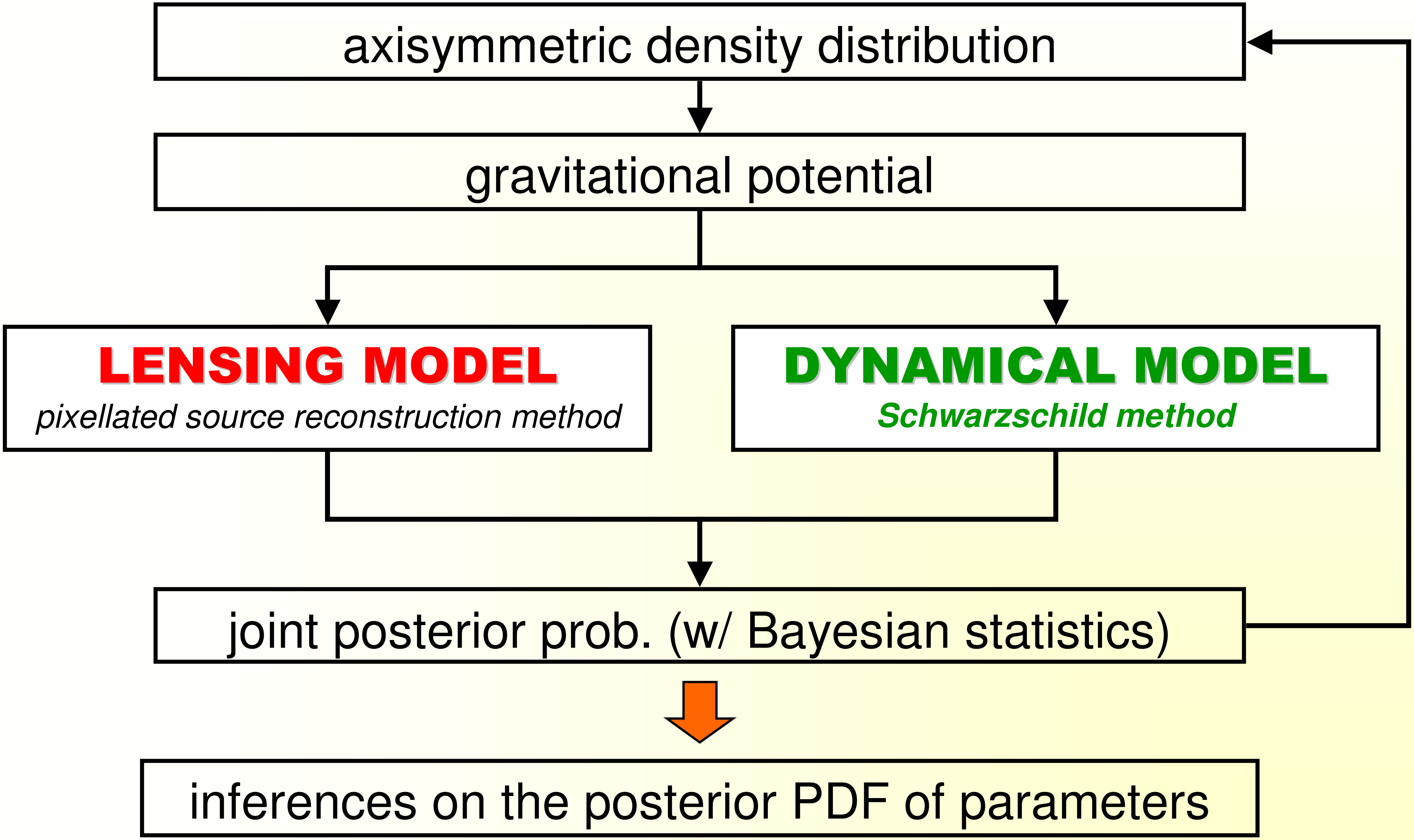


source plane

unlensed source object

s

CAULDRON:
COMBINED LENSING AND DYNAMICS ANALYSIS



axisymmetric density distribution

gravitational potential

LENSING MODEL

pixellated source reconstruction method

DYNAMICAL MODEL

Schwarzschild method

joint posterior prob. (w/ Bayesian statistics)

inferences on the posterior PDF of parameters

Barnabè & Koopmans 2007, Barnabè et al. 2012

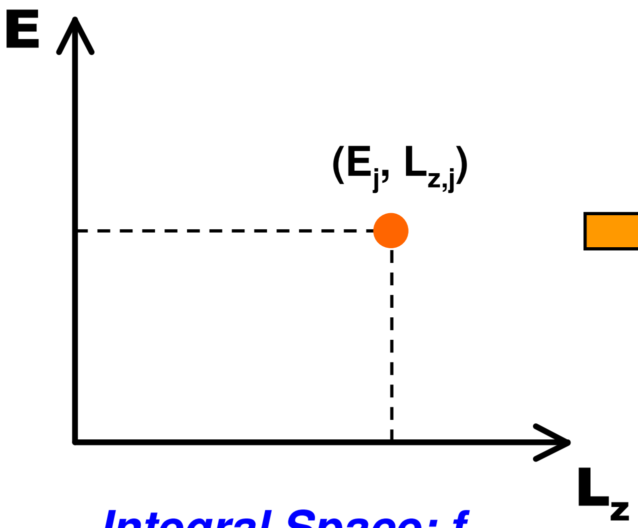
A Very Fast Orbit-Superposition Method: TICs

Cretton 1999, Verolme & de Zeeuw 2002, Barnabè & Koopmans 2007

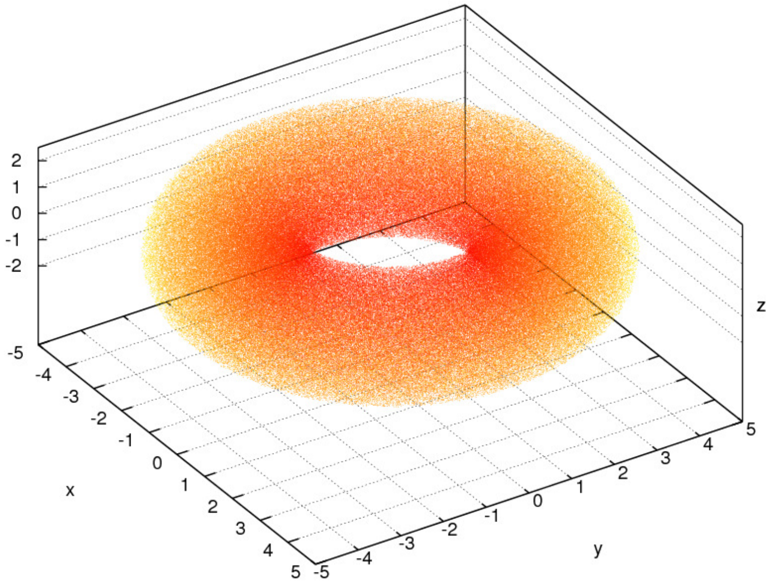
- **Two-Integral Schwarzschild Method** (Cretton et al. 1999, Verolme & de Zeeuw 2002) extended and sped up through Monte Carlo approach: one full dynamical model in ~ 10-30 sec.
- **Building blocks**: two-integral components (**TICs**): elementary stellar systems derived from a Dirac-δ DF, completely specified by energy **E_j** and angular momentum **$L_{z,j}$**

$$f_j(E_j, L_{z,j}) = \begin{cases} \dfrac{C_j}{2}\,\delta(E - E_j)\,\delta(L_z - L_{z,j}) & \\ 0 & \textbf{outside the ZVC} \end{cases}$$

- The (unprojected) density and velocity moments of a TIC are analytical and fast to calculate.

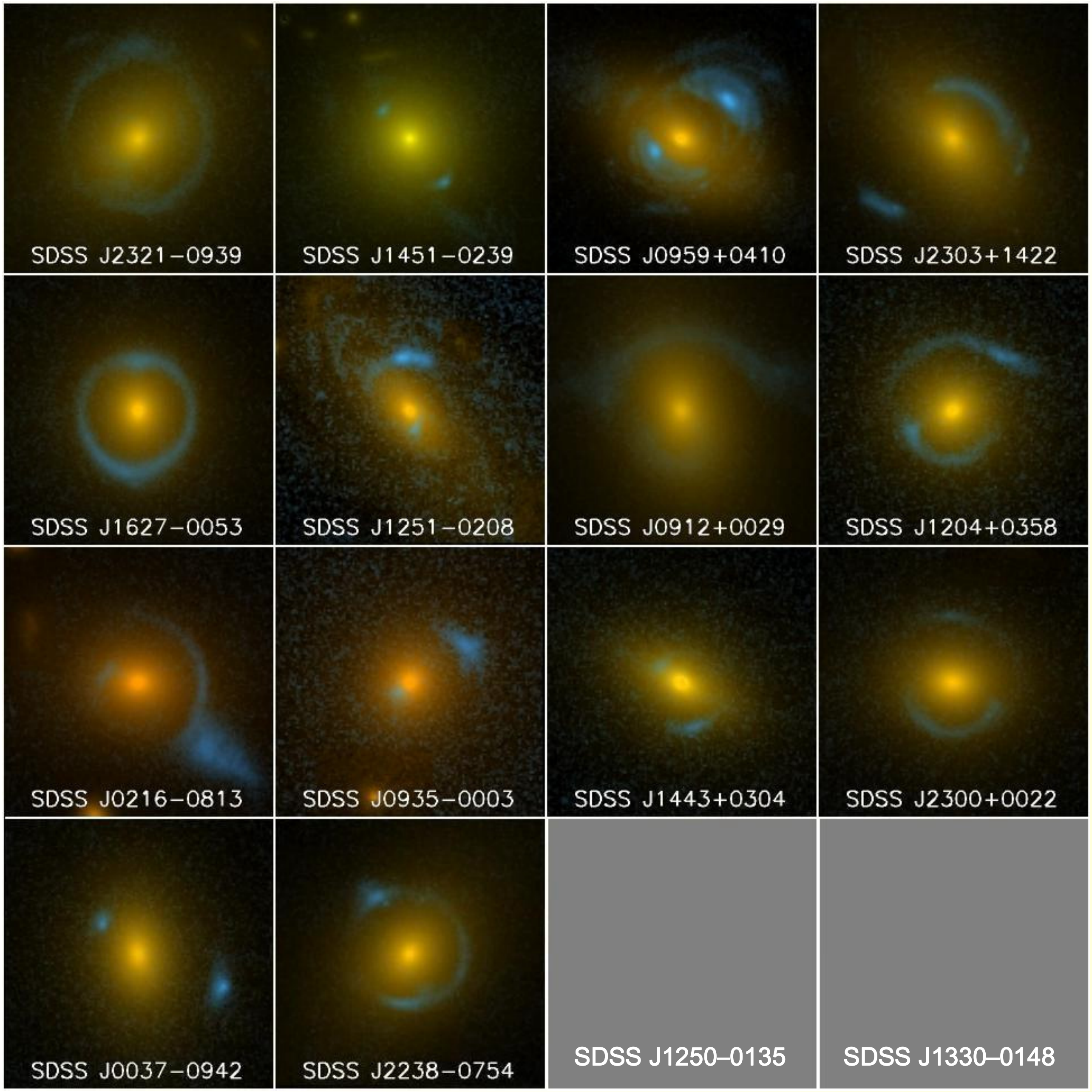


Integral Space: f_j



j-th TIC: 3D density distribution

Combined L+D analysis of 16 early-type galaxies beyond the local Universe



total mass density profile:

axisymmetric
power-law model

$$\rho(m) = \frac{\rho_0}{m^{\gamma}} \ ,$$

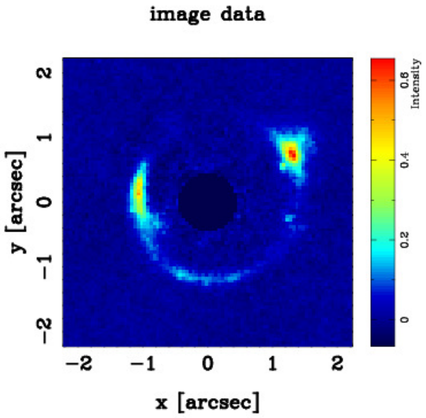
$$m^2 = R^2 + z^2/q^2$$

Analysis:
Barnabè et al. (2009, 2011)

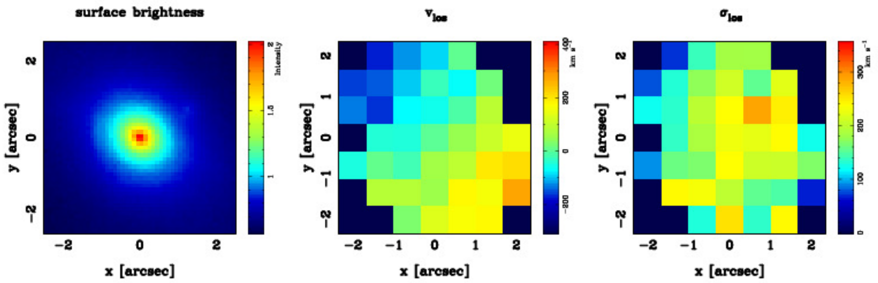
SDSS J2238

Data set:
(Czoske et al. 2012)

GRAVITATIONAL LENSING



STELLAR DYNAMICS



z_{src} = 0.712
z_{lens} = 0.137
σ_{SDSS} = 198 km/s

R_{Einst} = 3.1 kpc
R_{eff} = 5.6 kpc

BEST MODEL

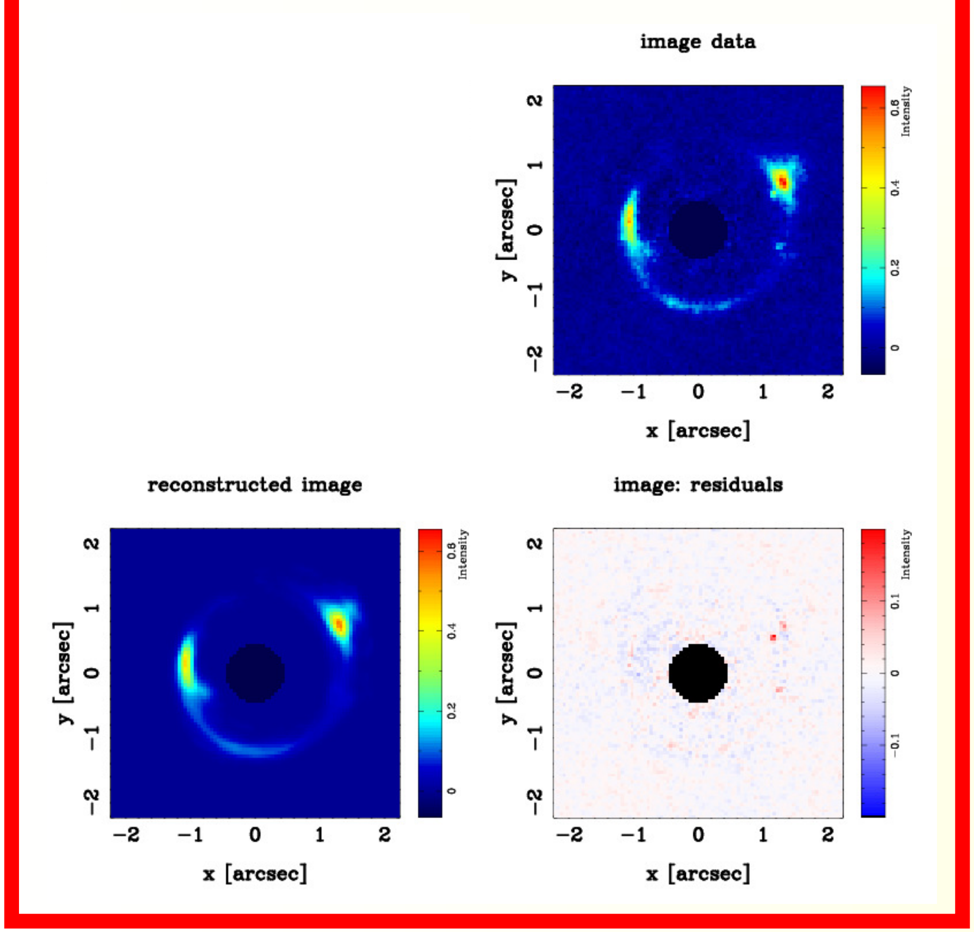
incl = 80°
α_0 = 0.36
γ = 2.09
q = 0.78

Analysis:
Barnabè et al. (2009, 2011)

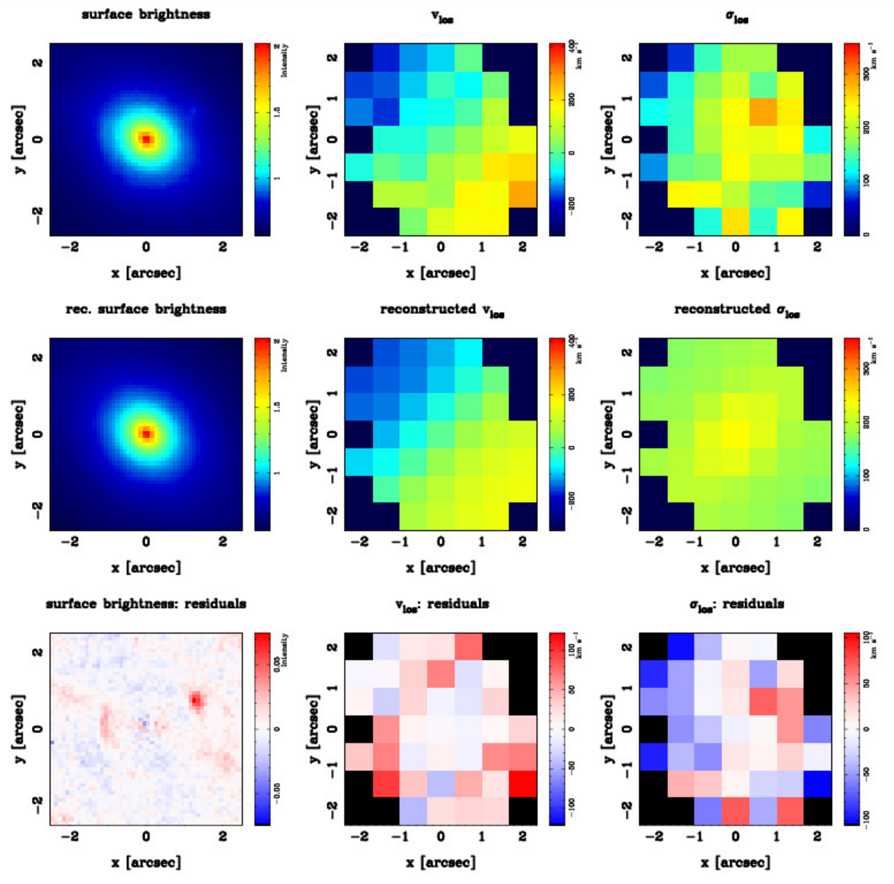
SDSS J2238

Data set:
(Czoske et al. 2012)

GRAVITATIONAL LENSING



STELLAR DYNAMICS



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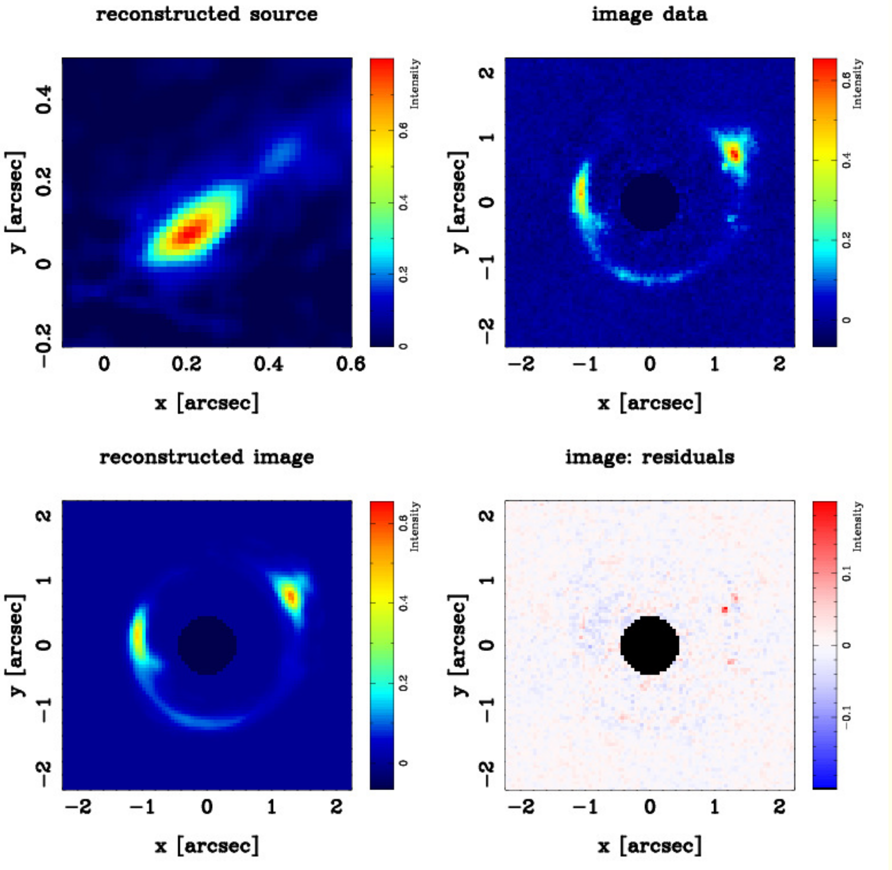
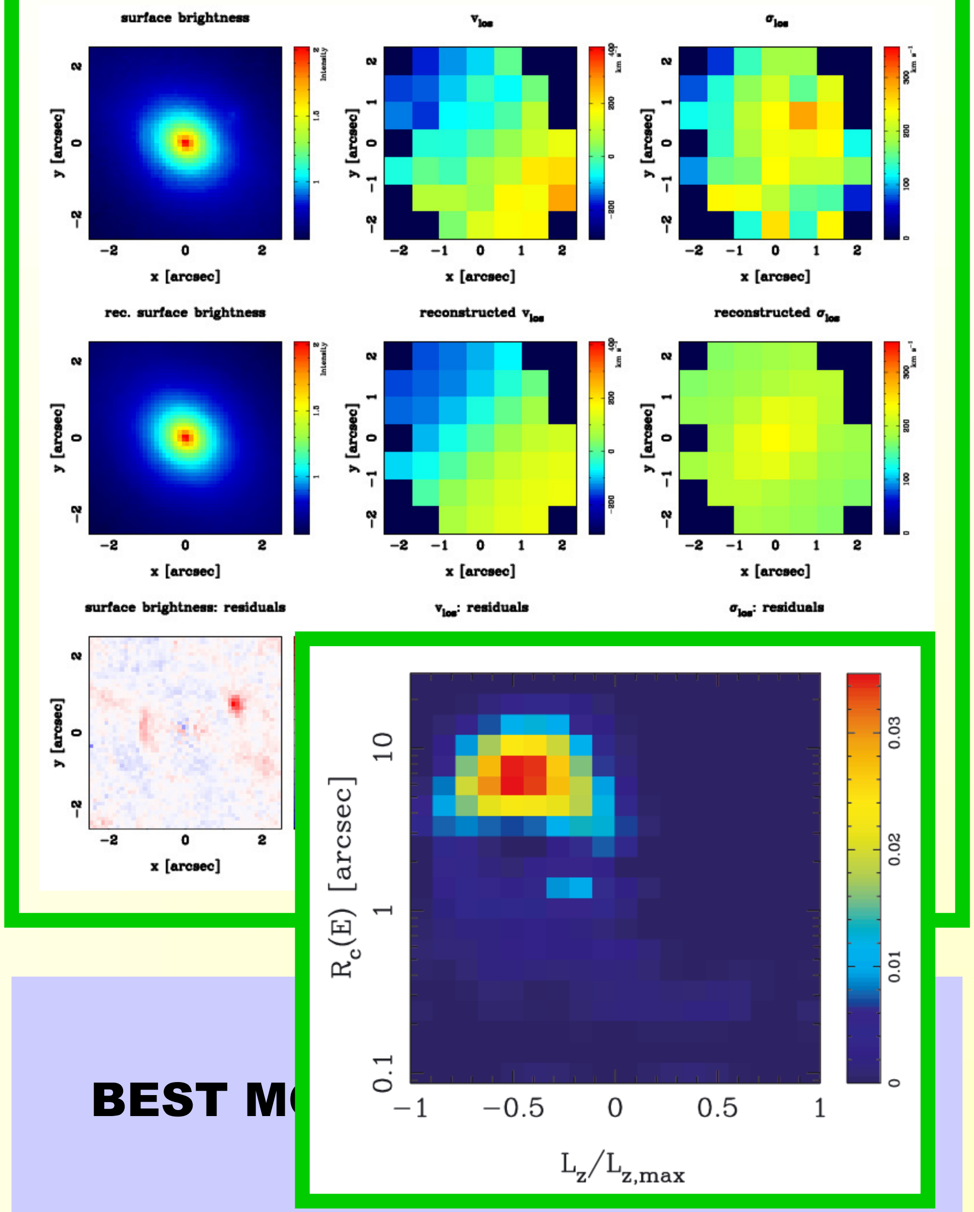


STELLAR DYNAMICS

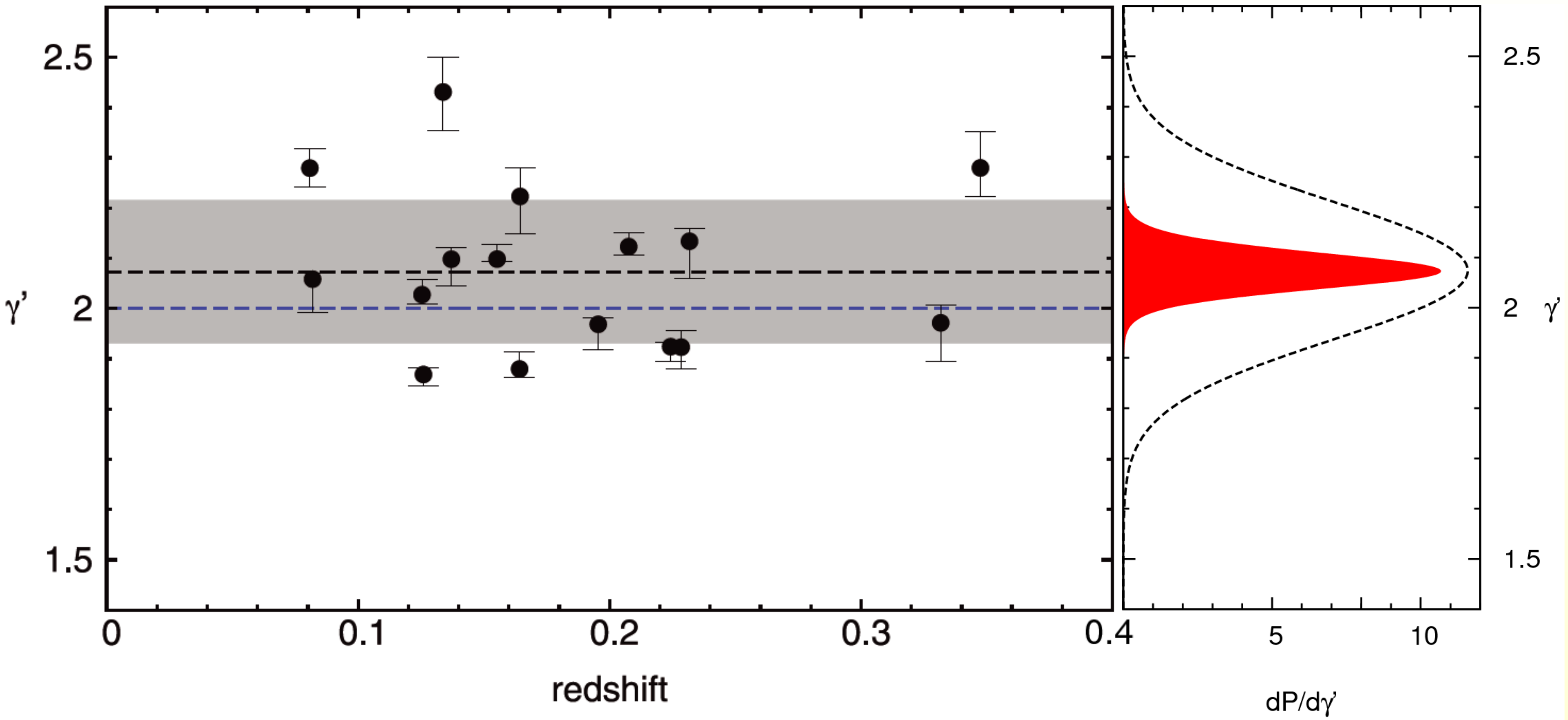


z_{src} = 0.712
z_{lens} = 0.137
σ_{SDSS} = 198 km/s

R_{Einst} = 3.1 kpc
R_{eff} = 5.6 kpc

BEST MO

Results: Slope

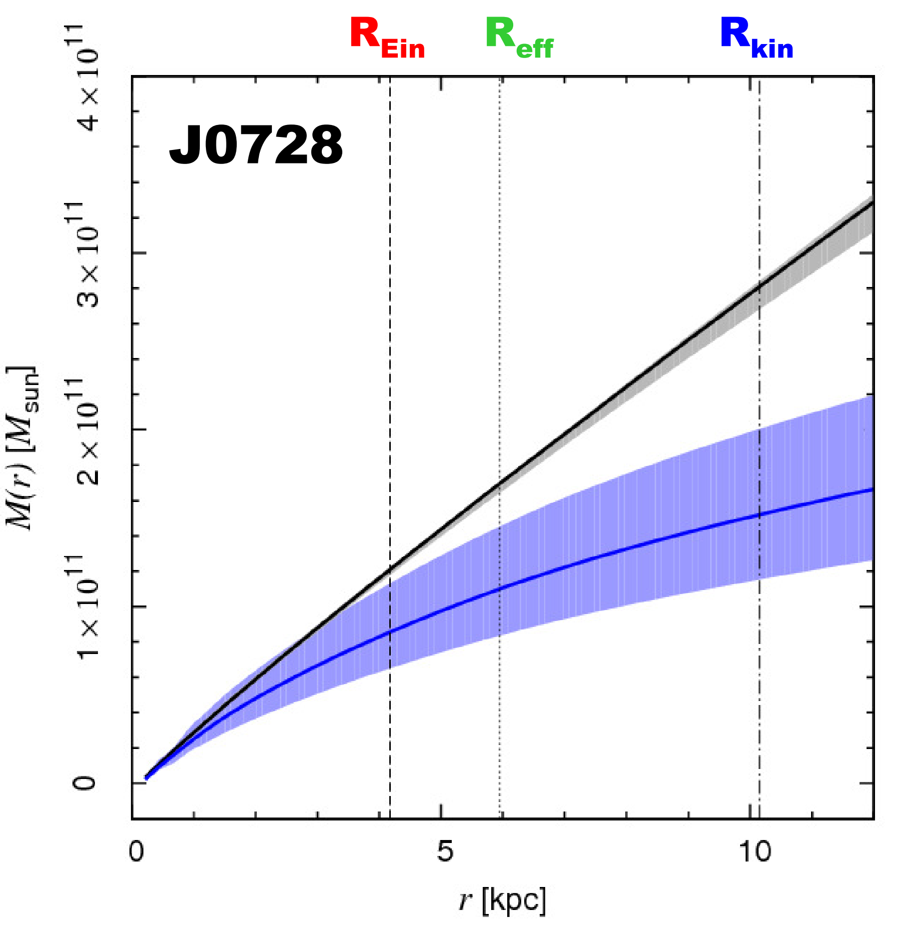


DENSITY PROFILE OF THE ENSEMBLE

- Total density profile is close to isothermal: $<\gamma> = 2.07$
- No evolution ($z = 0.08 – 0.35$)
- Intrinsic spread of about 7 %
- No corr. with q, R_{Einst}/R_{eff}, σ_{SDSS}

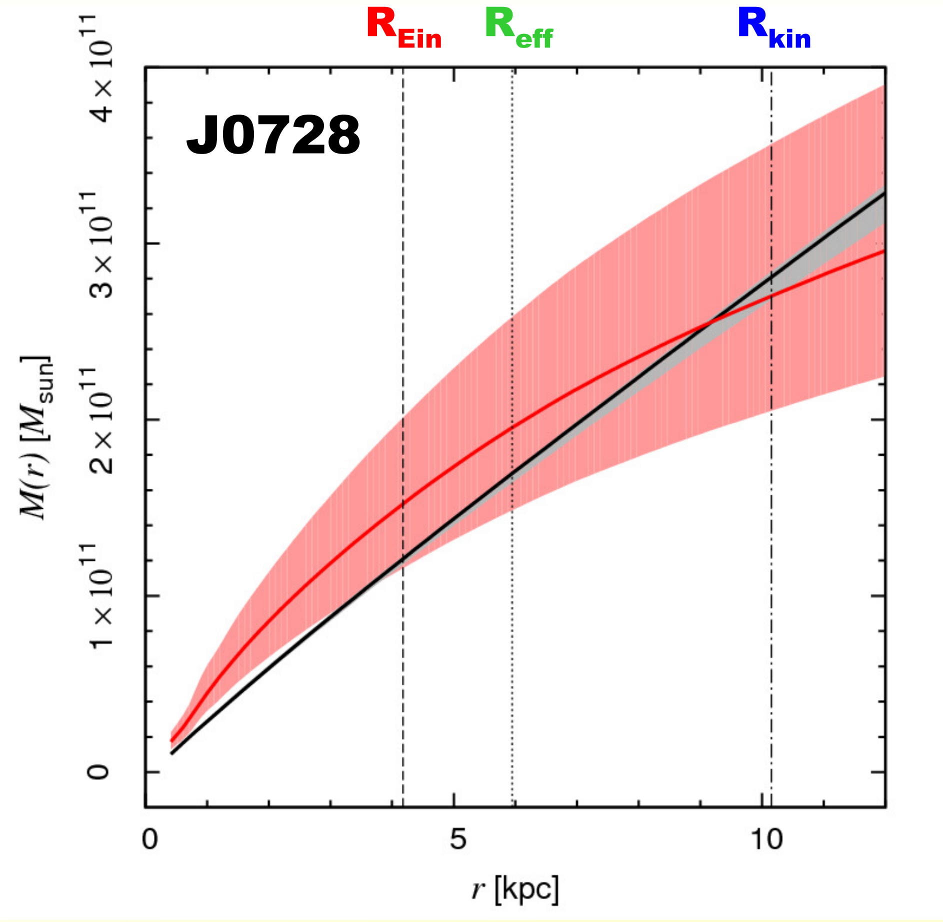
Dark and luminous mass profile

Luminous mass from stellar population analysis



M* for **Chabrier** IMF

log[M_{Chab}/M_{sun}] = 11.44 ± 0.12

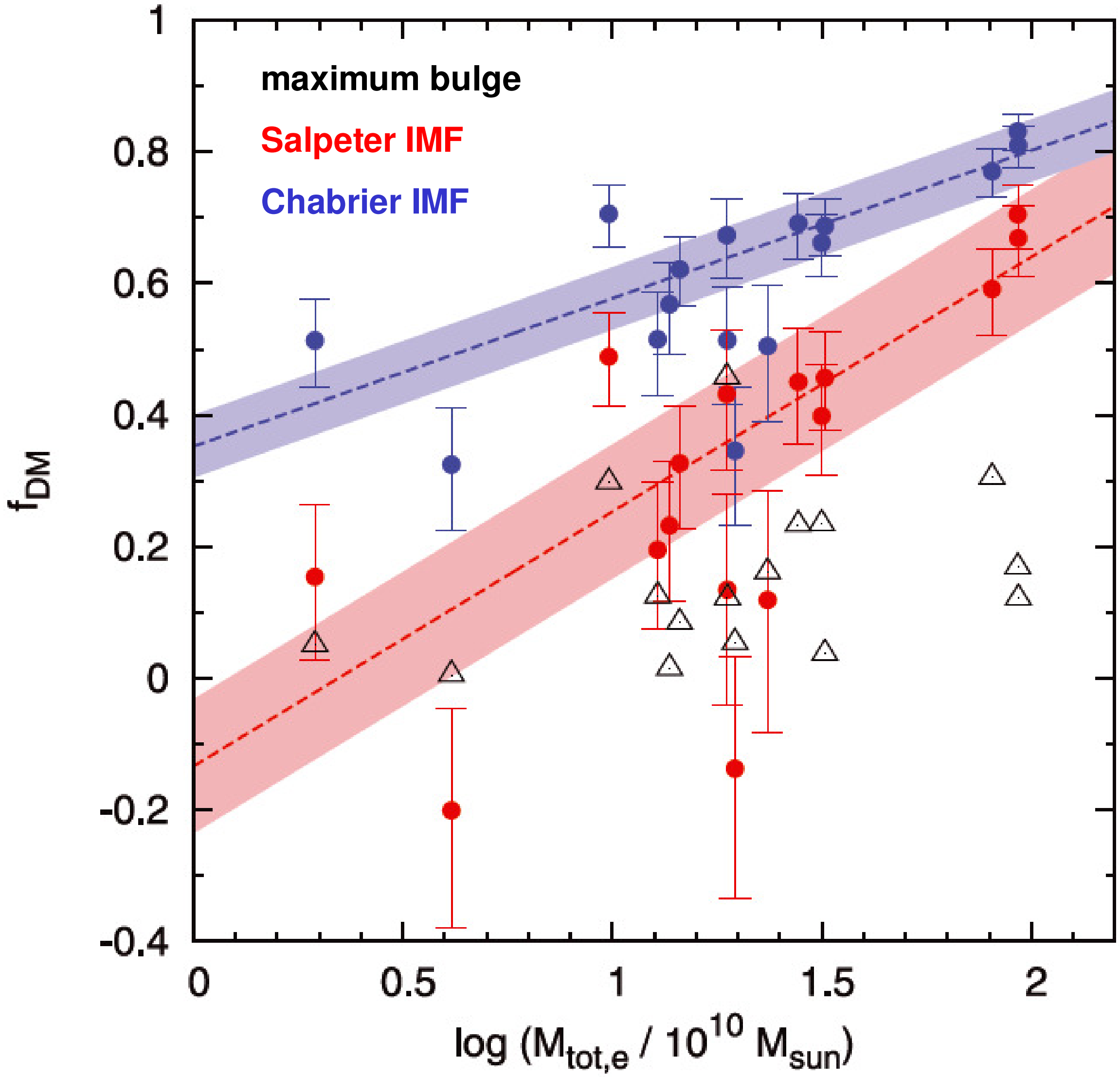


M* for **Salpeter** IMF

log[M_{Salt}/M_{sun}] = 11.69 ± 0.12

- *Stellar mass estimates from Auger et al. (2009) stellar pop. analysis using HST multi-band imaging data*

Dark Matter Fraction



Barnabè et al. (2011)

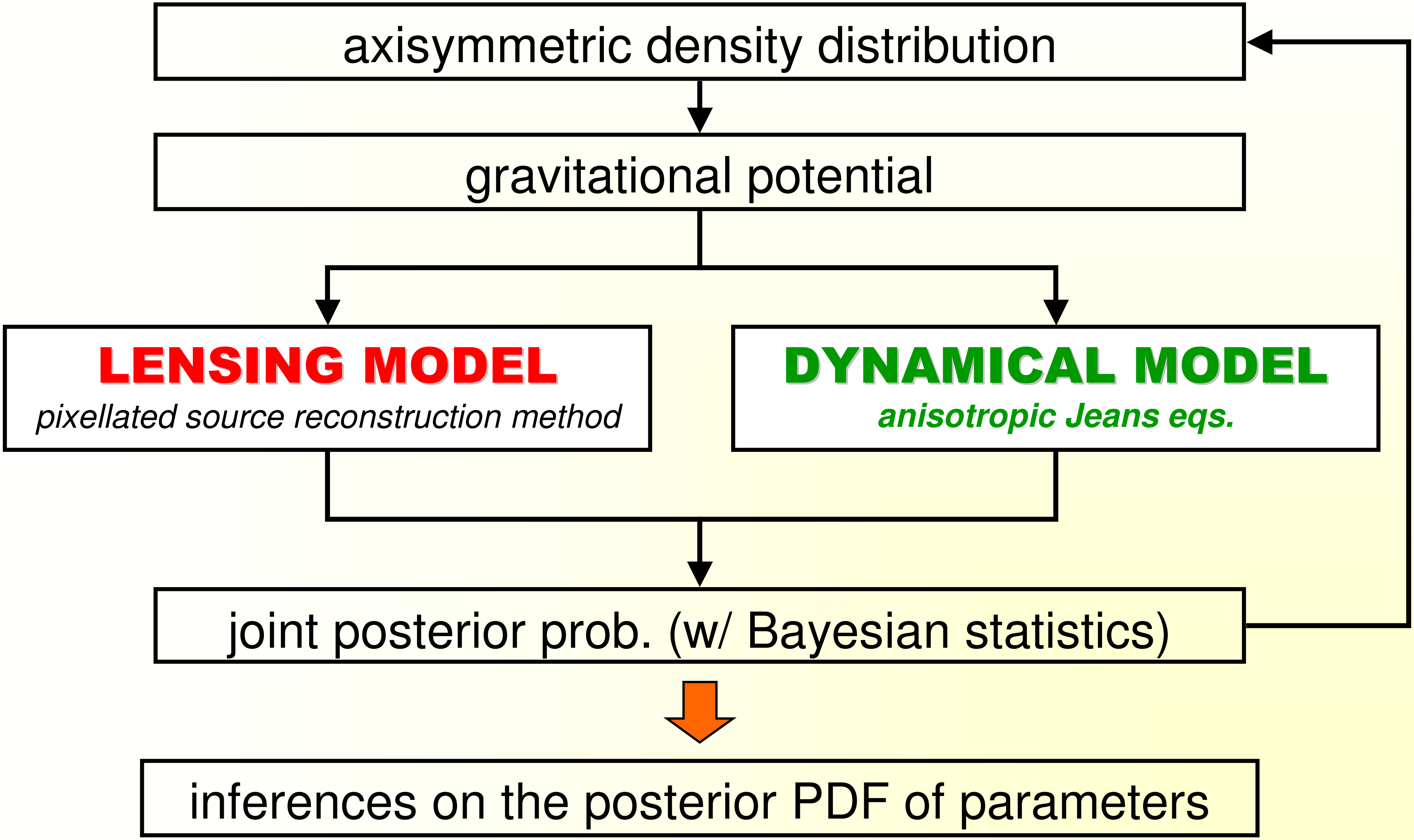
DM fraction lower limit:
0% to 40% within R_{eff}

Salpeter: $<f_{DM}> = 0.31$
Chabrier: $<f_{DM}> = 0.61$

Chabrier or Salpeter IMFs: **more massive systems contain more DM**, and are DM-dominated already in the inner regions

Chabrier produces high DM fractions: cf. Weijmans et al. (2009), Grillo et al. (2010)

CAULDRON:
COMBINED LENSING AND DYNAMICS ANALYSIS



axisymmetric density distribution

gravitational potential

LENSING MODEL

pixellated source reconstruction method

DYNAMICAL MODEL

anisotropic Jeans eqs.

joint posterior prob. (w/ Bayesian statistics)

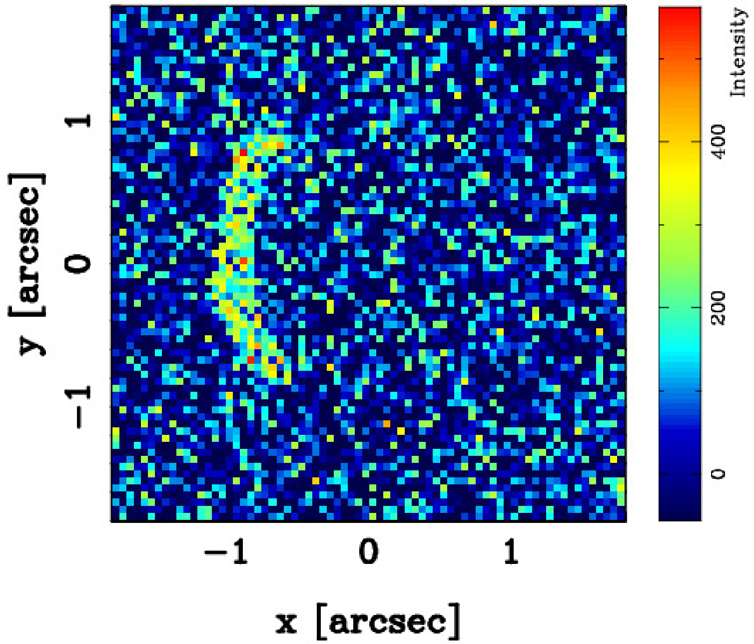
inferences on the posterior PDF of parameters

Barnabè & Koopmans 2007, Barnabè et al. 2012

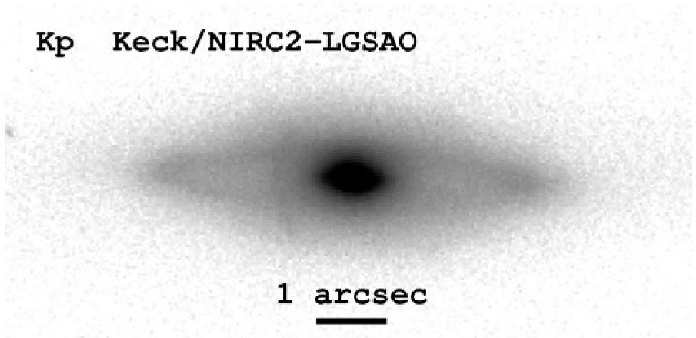
J2141: Dissecting a Spiral Lens Galaxy

Dutton et al. (2011), Barnabè et al. (2012)

LENSED IMAGE



SURFACE BRIGHTNESS

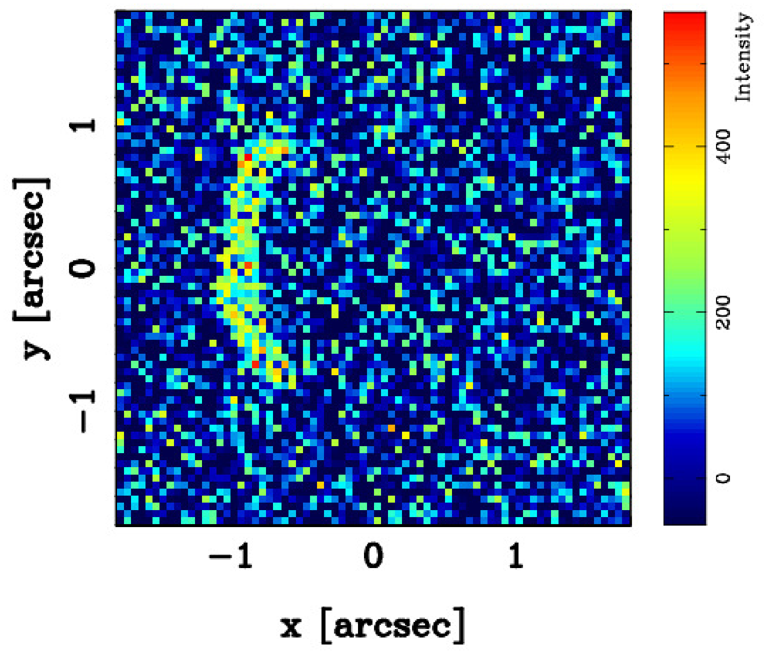


$z_{\mathrm{lens}} = 0.138$

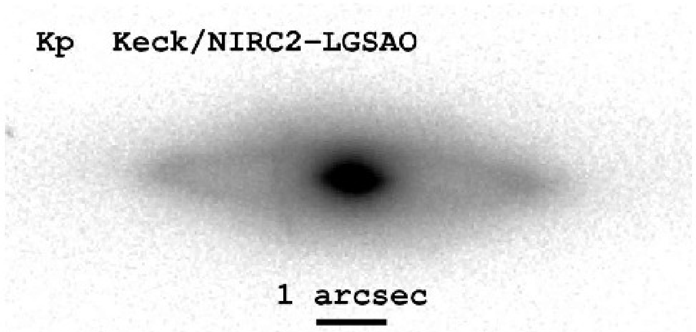
J2141: Dissecting a Spiral Lens Galaxy

Dutton et al. (2011), Barnabè et al. (2012)

LENSED IMAGE

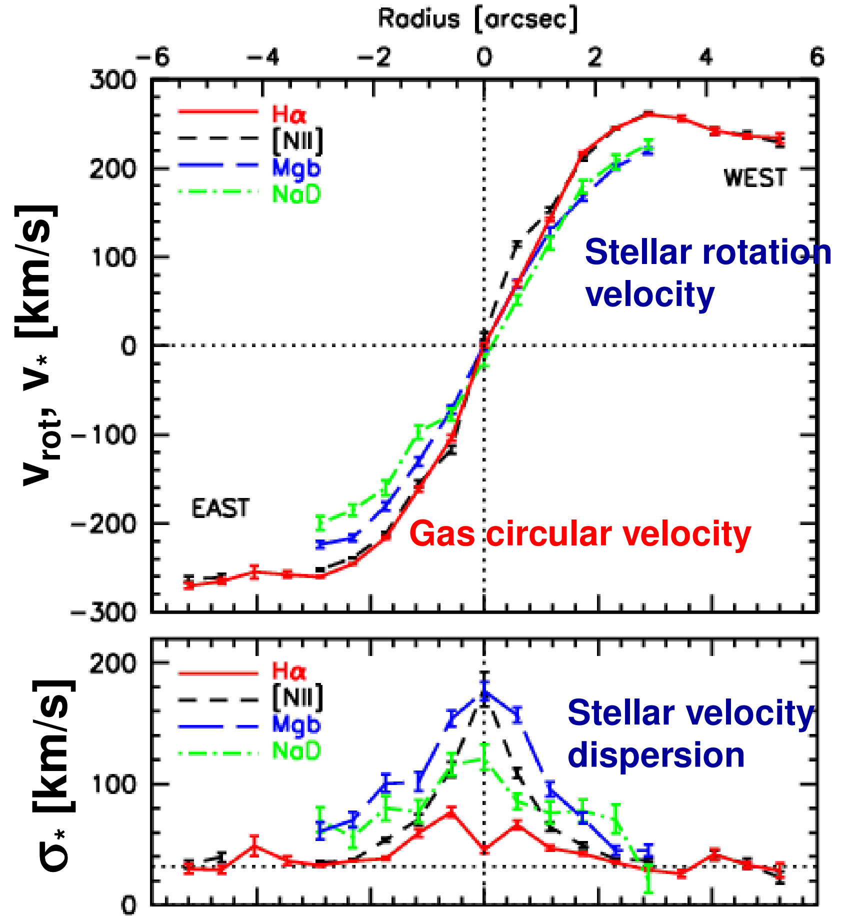


SURFACE BRIGHTNESS



z_{lens} = 0.138

KINEMATICS



Stellar rotation velocity

Gas circular velocity

Stellar velocity dispersion

Disk dominated, very inclined: *i* = 78 deg

Self-consistent analysis by combining gravitational lensing, gas rotation curve and stellar kinematics simultaneously

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}

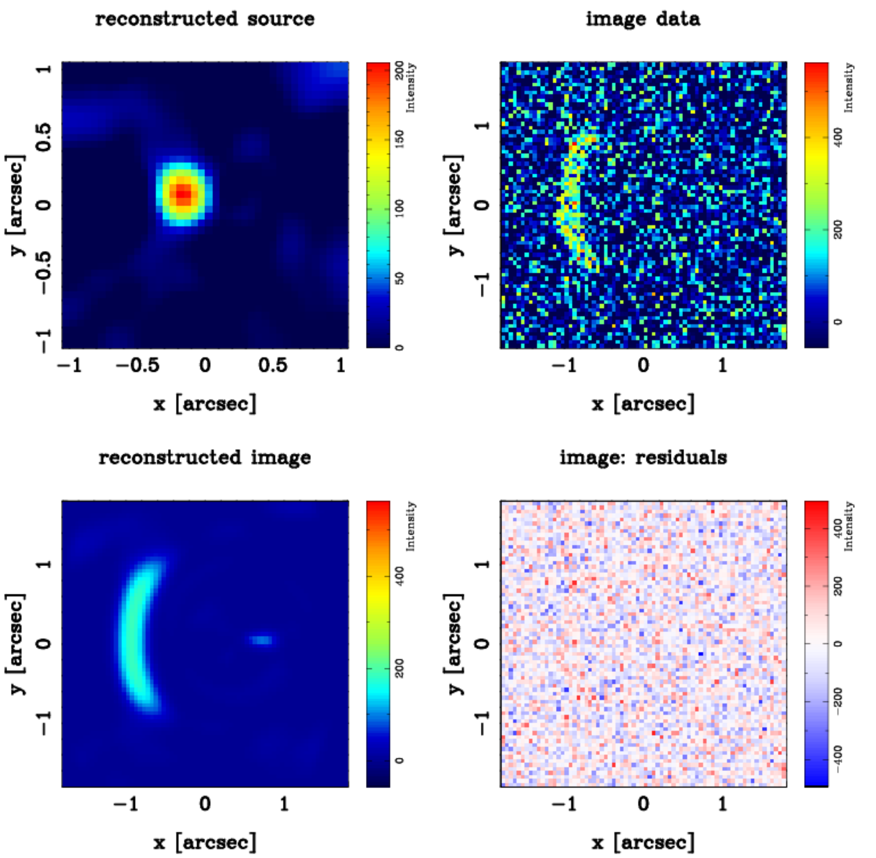
- **Luminous mass distribution:** *multi-Gaussian expansion* (MGE) technique (Emsellem et al. 1999, Cappellari 2002) to K’-band image.
  - Luminous mass distribution is self-gravitating, *not just a tracer*
  - Free parameter [#5]: baryonic mass M_{bar}

dynamical model

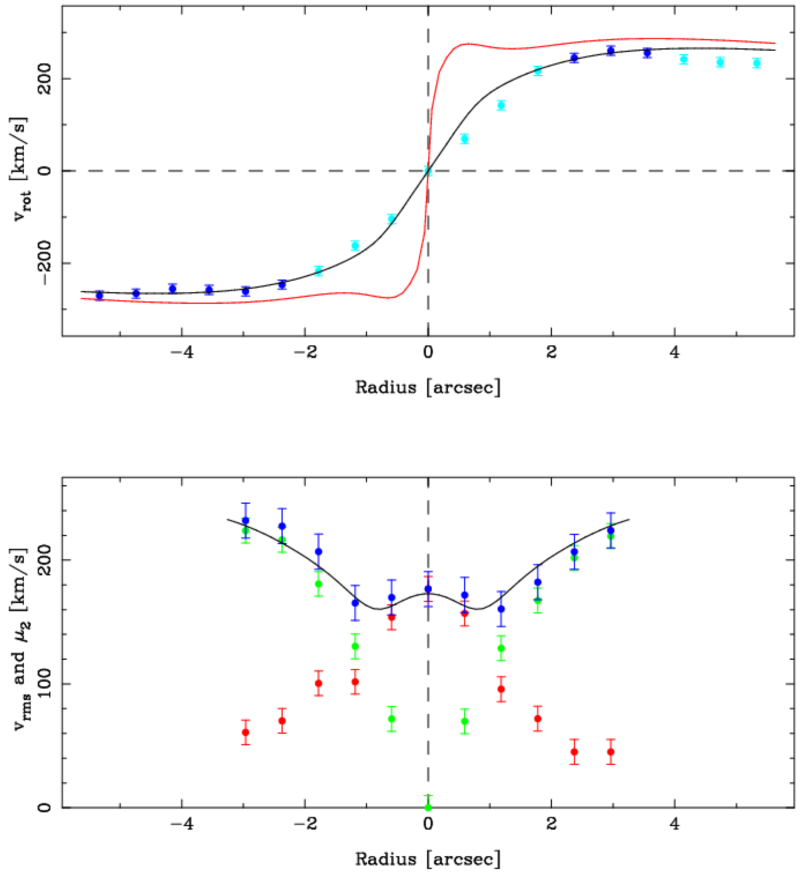
- **Anisotropic Jeans equations** (Cappellari 2008)
  - Free parameter [#6]: meridional plane orbital anisotropy ratio b

Reconstructed Observables

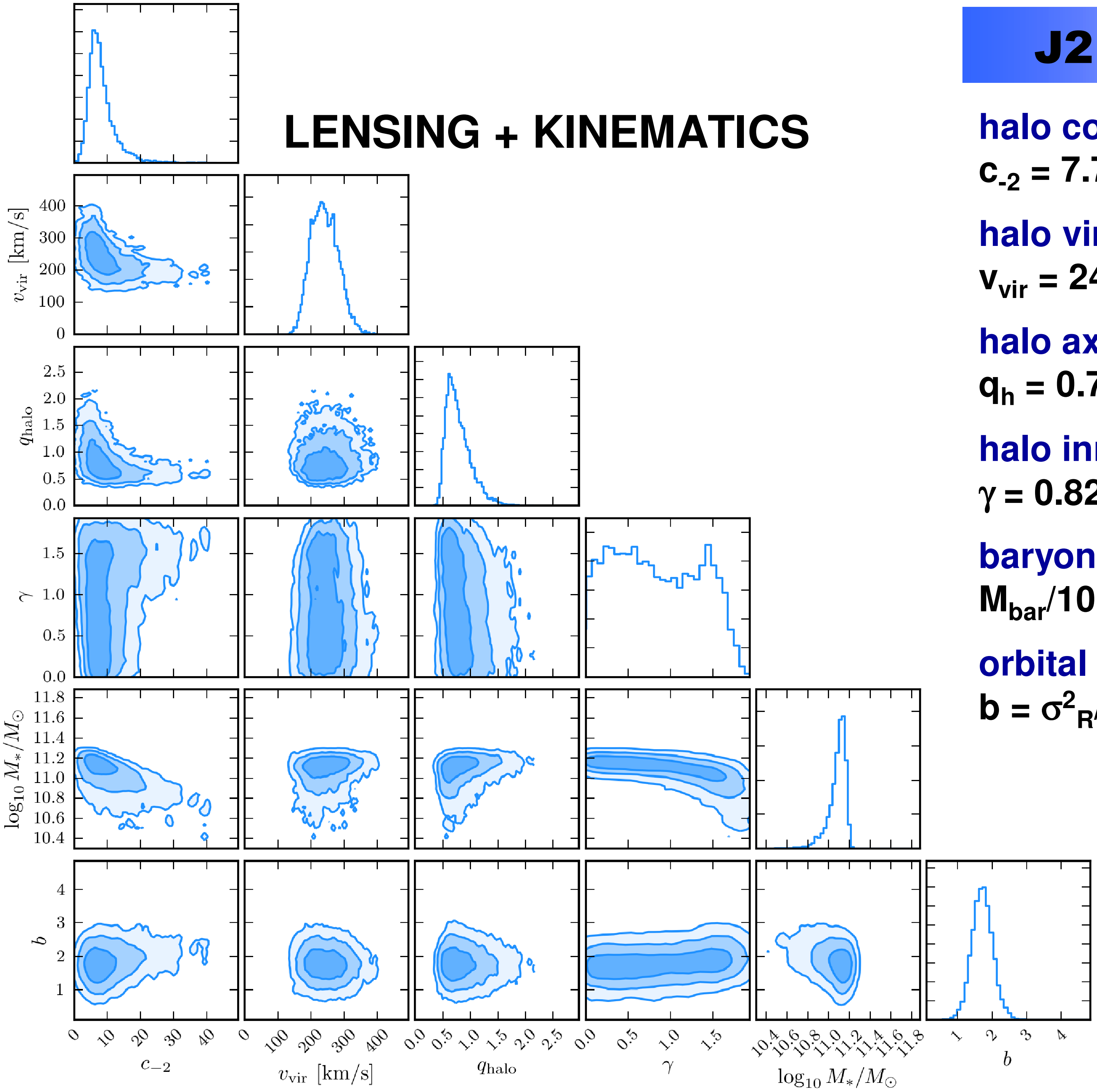
GRAVITATIONAL LENSING



GAS & STELLAR KINEMATICS



J2141: inferences



LENSING + KINEMATICS

halo concentration:

$c_{-2} = 7.7^{+4.2}_{-2.5}$

halo virial velocity:

$v_{\rm vir} = 242^{+44}_{-39}$ km/s

halo axial ratio:

$q_h = 0.75^{+0.27}_{-0.16}$

halo inner slope:

$\gamma = 0.82^{+0.65}_{-0.54}$

baryonic mass:

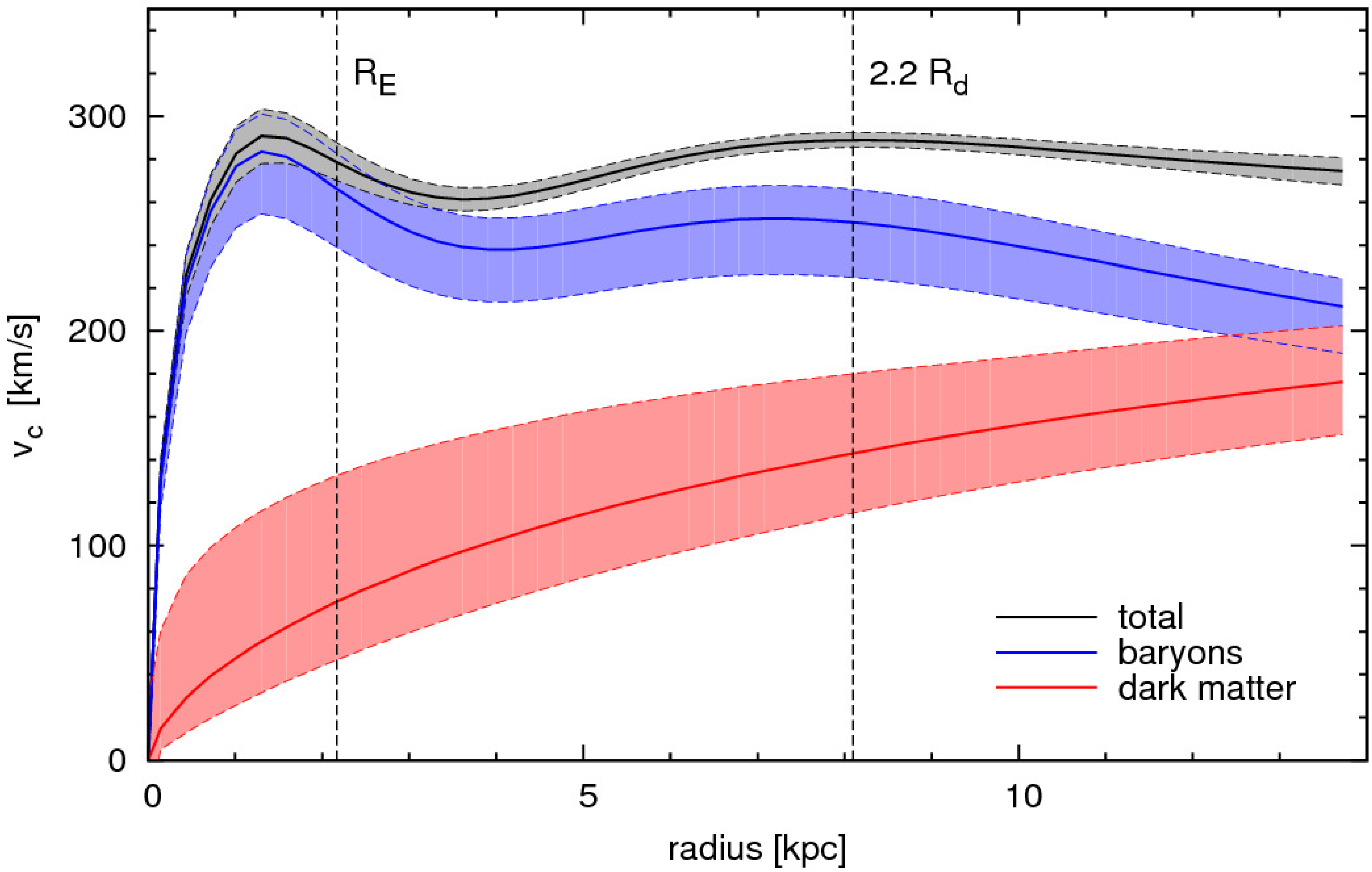
$M_{\rm bar}/10^{11} M_{\rm sun} = 1.32^{+0.16}_{-0.25}$

orbital anisotropy parameter:

$b = \sigma^2_R/\sigma^2_z = 1.77^{+0.30}_{-0.29}$

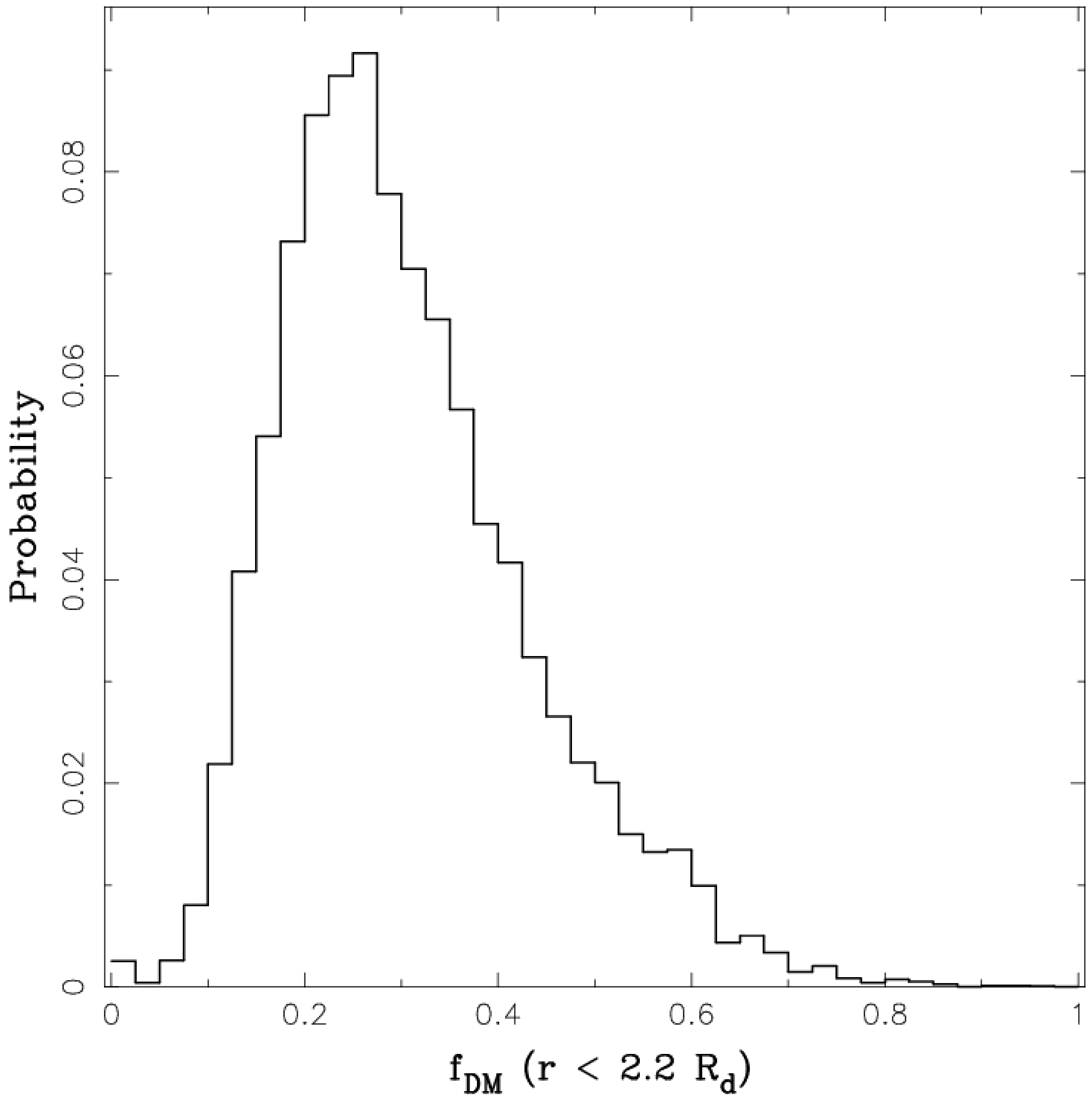
Barnabè et al. 2012

Results: baryons and dark matter



- We can test the “maximum disk hypothesis”: the **disk is maximal** $v_{bar}(2.2\ R_d)/v_{tot}(2.2\ R_d) = 0.87^{+0.05}_{-0.07}$
- Baryons are the dominant component within the disk galaxy inner regions
- DiskMass project (Berhsady et al. 2011) finds that nearby disk galaxies are *submaximal* (different method, probes different regions)

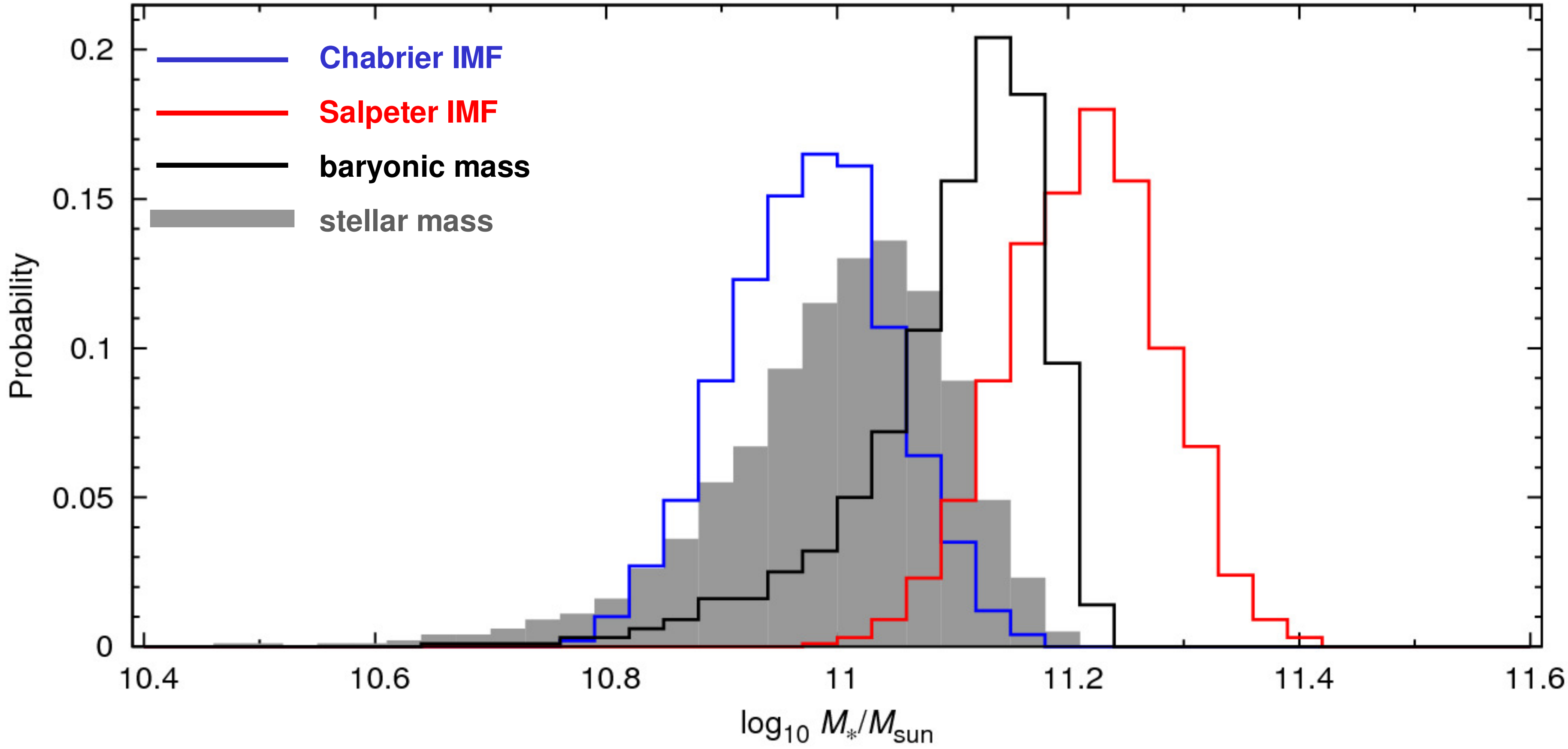
Results: baryons and dark matter



Dark matter fraction enclosed within the spherical radius r = 2.2 disk scale lengths, inferred from combined lensing + dynamics analysis

- **$f_{DM} = 0.28^{+0.15}_{-0.10}$**
- Dark matter dominated models ($f_{DM} > 0.5$) are possible but disfavored (prob < 10%)
- Models without dark matter ($f_{DM} < 0.05$) are ruled out at > 3σ level

Results: initial mass function



- Total baryonic mass well constrained from the analysis: $\log(M_{bar}/M_{sun}) = 11.12^{+0.05}_{-0.09}$
- Contribution from cold gas: 20 +/- 10 % of the total baryonic mass
- **Chabrier IMF is preferred**: Bayes factor = 5.7 (substantial evidence)
- General picture: fast-rotating low-mass galaxies have Chabrier IMF, slow-rotating massive ellipticals have Salpeter IMF?
  (cf. Auger et al. 2010, van Dokkum and Conroy 2010, Cappellari et al. 2012)

Conclusions: Combining Lensing & Dynamics

- Self-consistent, computationally efficient method: allows us to “dissect” both early- and late-type lens galaxies beyond the local Universe
- Bayesian framework: rigorously derive uncertainties
- Full use of the available data sets (lensed images, surface brightness, kinematics)
- Lensing + Dynamics: overcome individual limitations of these methods
- Joint Lensing & Dynamics:
  powerful instrument: most detailed analysis to date of the density profile, mass budget and structural properties of a sample of distant galaxies ($z > 0.1$)