Galaxy Structure & Evolution

with Strong Lensing & Galaxy Dynamics

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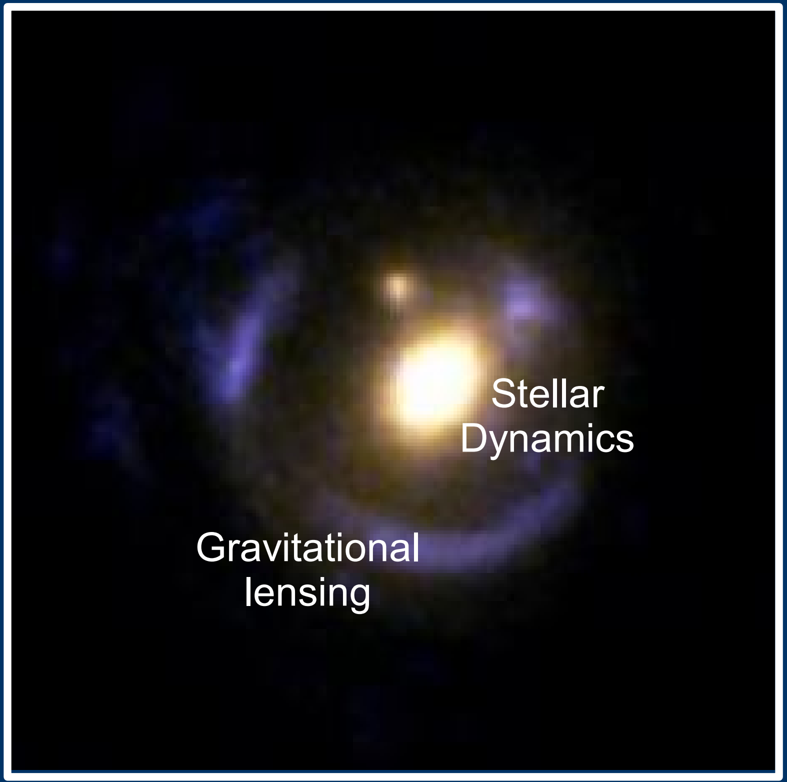

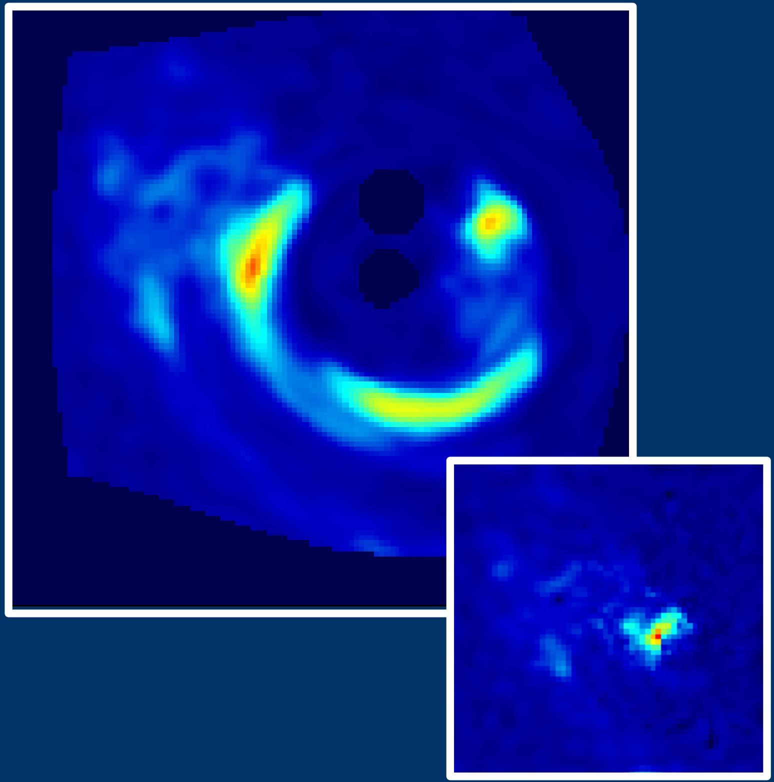

Collaborators

Tommaso Treu	(UCSB)	LSD + SLACS Survey
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Raphael Gavazzi	(UCSB)	

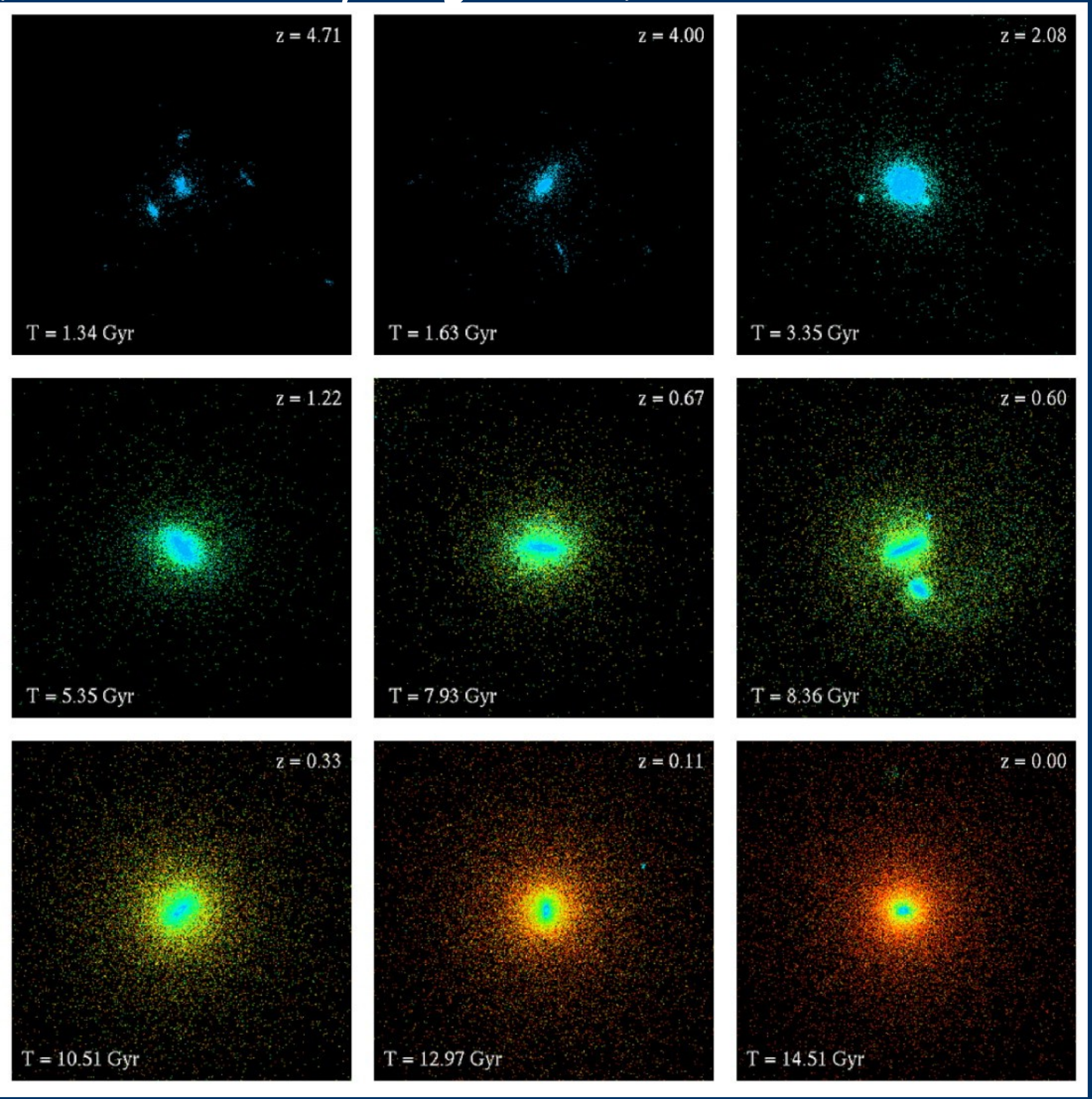
Why Measure the Mass Structure of (E/S0) Galaxies?

(1) Galaxy formation models predict distinct DM density profiles (e.g. NFW97, Moore et al. 98)
(2) DM density profiles are modified by collisional and/or gravitational processes of baryons & stars.
(3) Hierarchical models also predict abundant DM mass substructure, which is not (yet) found.

The Stellar & DM density profiles and their evolution a direct measure of the (hierarchical) galaxy formation process, in particular for early-type galaxies (i.e. merger remnants)

E/S0 Galaxy Structure & Formation

(blue to red is young to old) Meza et al. 2003



Only several "self-consistent" simulations have been done.

(1) Galaxies can contract with time: radial density profile changes

(2) Galaxies shapes can change with time.

(3) Galaxies grow more massive with time.

(4) Substructure evolves.

Methods to study the Mass Structure and Formation of Galaxies

Method	Region	Range z
Strong Lensing	Inner	z~0.01-1
Stellar Dynamics	Inner	z<0.1
GC/PN Dynamics	Inner/Outer	z<0.01
HI/gas tracers	Inner/Outer	z<0.2
X-ray Haloes	Outer	z<0.1
Weak Lensing	Outer	z~0.3-1

Gravitational Lensing:

Why use GLs to probe galaxy structure & evolution?

(1) Gravitational lens systems are found from z~0 to z~1

(2) They are probes of the inner regions (<15 kpc) of galaxies where DM & baryons interact.

(3) Their physics is based only on gravity.

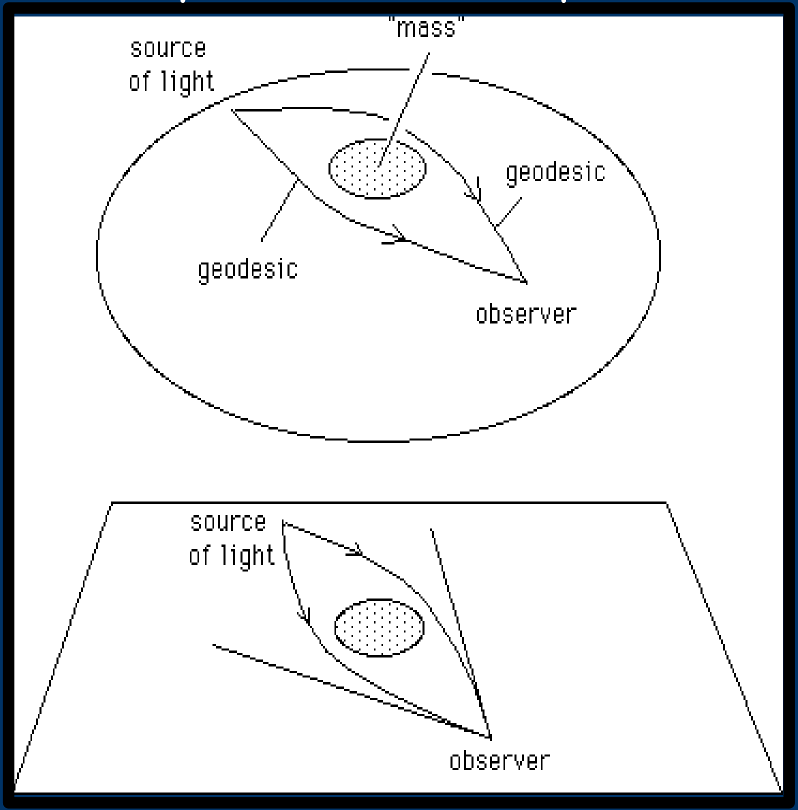
(4) The lens structure is determined from the lensed images, hence the latter's S/N is more important than that of the lens galaxy.

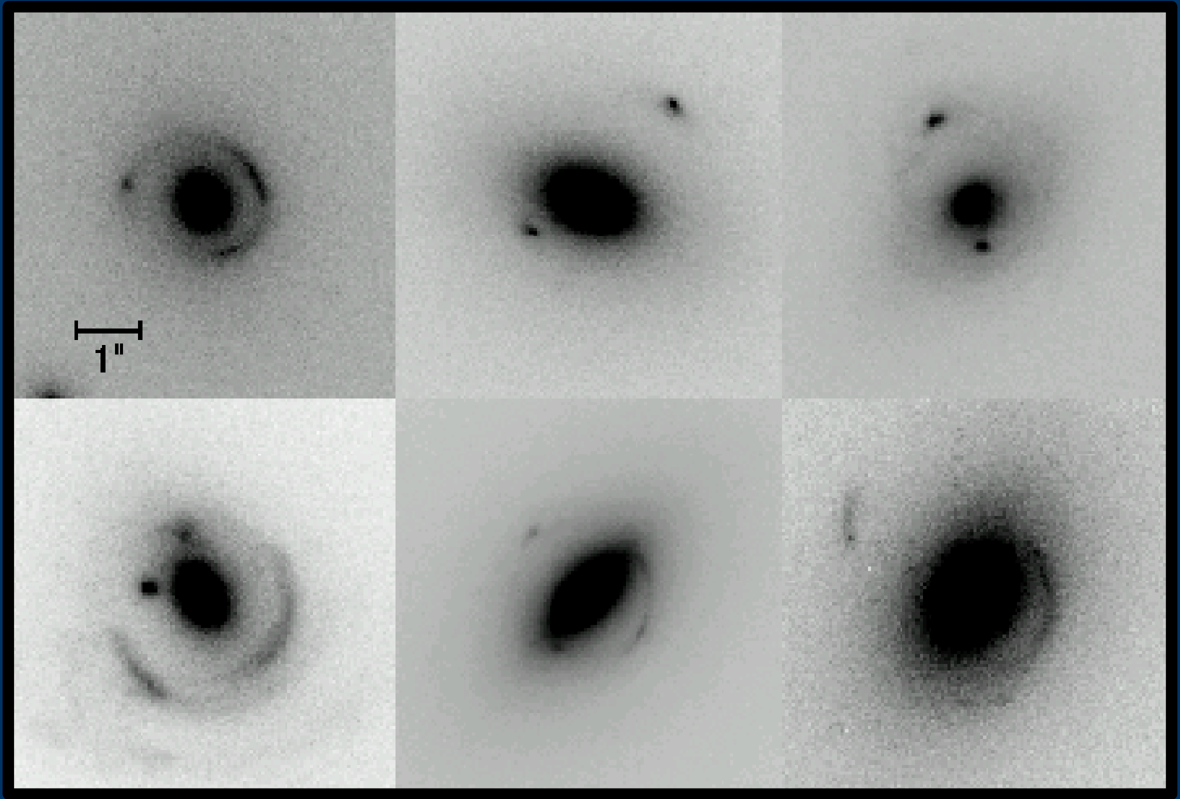
(5) Lensing is independent from the nature and state of the lensing mass (e.g. warm/cold, (non)equilibrium).

(6) GLs are often mass selected and their mass can be determined to a few percent accuracy

Methodology: Gravitational lensing

Galaxy mass distorts space → Multiple images form of a background object





Reconstruct galaxy mass ← Extract information from the multiple images

Mass-Model Degeneracies

Gravitational Lensing: mass-sheet degeneracy

Lensing observables (except time-delays for known H_0) are invariant under a 'global' transformation of the lens surface mass density

$$\kappa \Leftrightarrow (1-\kappa_c)\kappa + \kappa_c$$

Also leads to an "local" degeneracy of the mass slope.

Stellar Dynamics: mass-anisotropy degeneracy

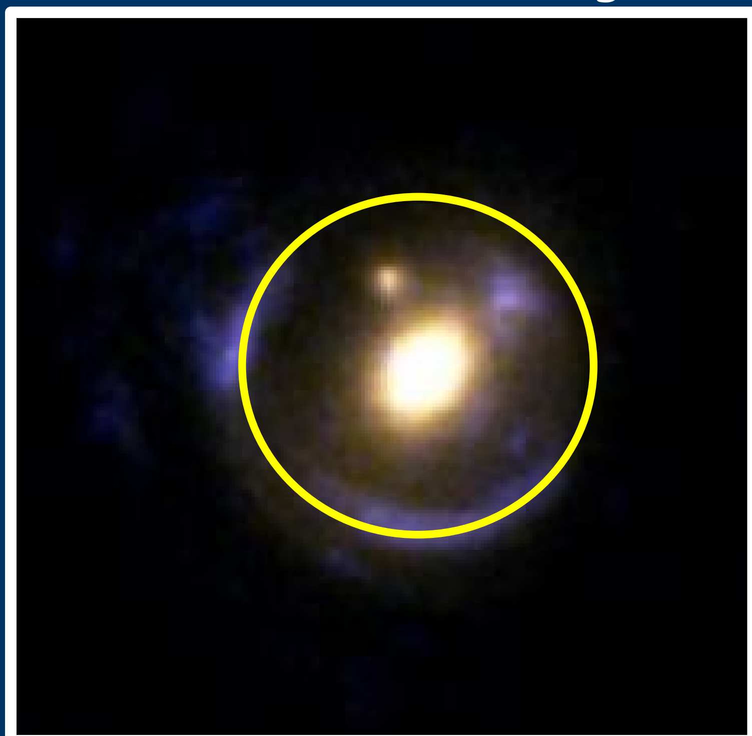
The kinematic profile can be nearly invariant between changes in mass profile and anisotropy of the stellar velocity ellipsoid. [Can be "broken" with LOSVD profile (e.g. h_3, h_4), but high S/N is required.]

Why Combine Galaxy Dynamics & Strong Lensing?

- Degeneracies are nearly orthogonal.
- Both methods are only based on gravity (ie few "gastrophysical" assumptions).
- Most lens galaxies are bright E/S0 galaxies that can be studied to z~1.
- Individual systems can be studied (in contrast to e.g. weak lensing).

Methodology: Lensing & Dynamics

Mass from lensing



Mass M_1 at radius R_1

Mass from stellar velocities

Mass M_2 at radius R_2

Smooth inner mass profile of the galaxy

(Koopmans & Treu 2002, 2003; Treu & Koopmans 2002, 2004; Koopmans et al. 2006)

Methodology: Lensing & Dynamics

Velocity dispersion inside an apperture:

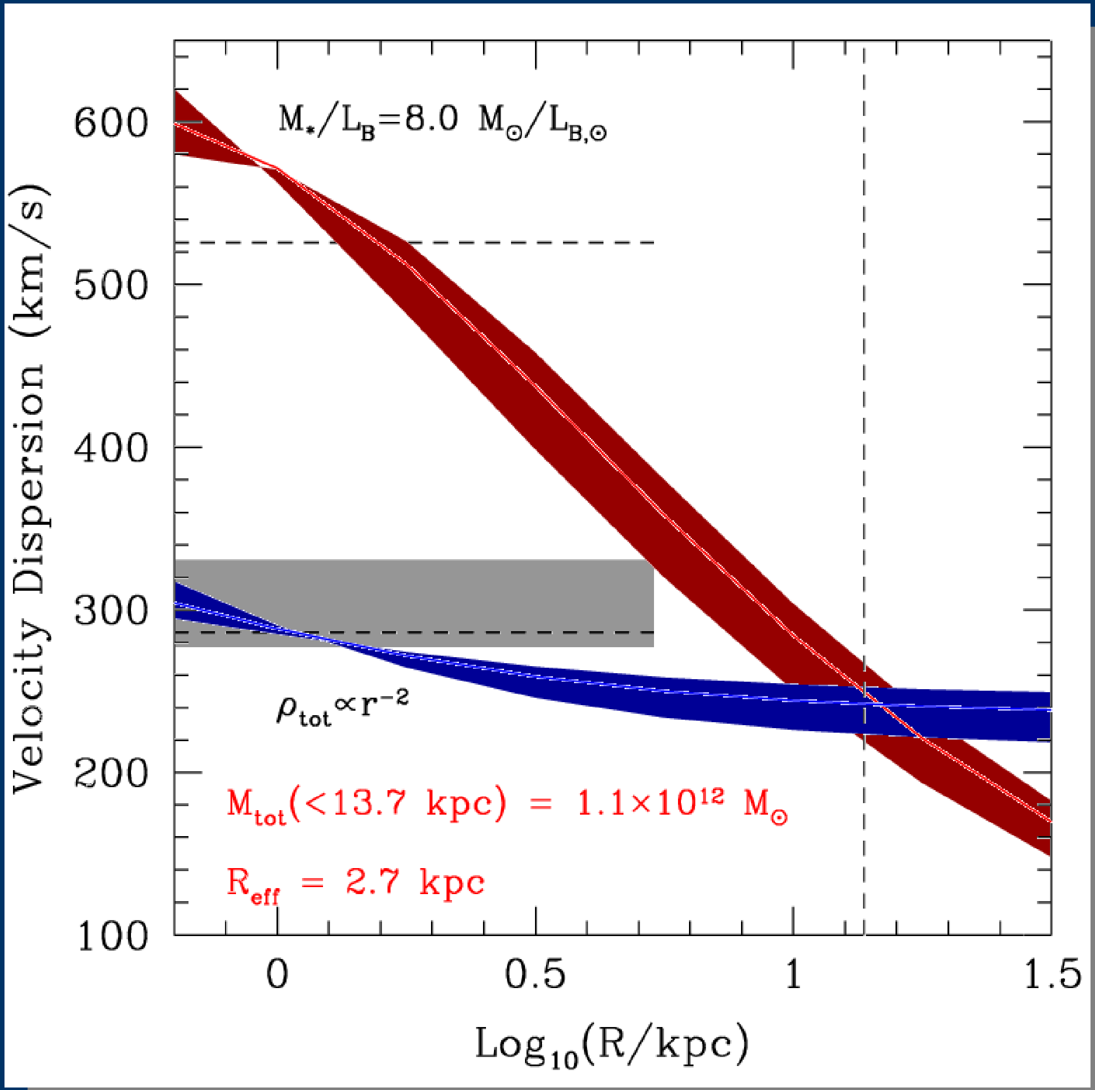
$$\langle v_{||}^2 \rangle (\leq R_{\rm A}) = \frac{1}{\pi} \left[\frac{G M_{\rm E}}{R_{\rm E}} \right] f(\gamma', \delta, \beta) \times \left(\frac{R_{\rm A}}{R_{\rm E}} \right)^{2-\gamma'}$$

Accuracy on log. density slope:

$$\left\langle \delta_{\gamma'}^2 \right\rangle = \alpha_g^{-2} \left\{ \left\langle \delta_{M_{\rm E}}^2 \right\rangle + 4 \left\langle \delta_{\sigma_{||}}^2 \right\rangle \right\}$$

(Koopmans 2005)

Methodology: Lensing & Dynamics



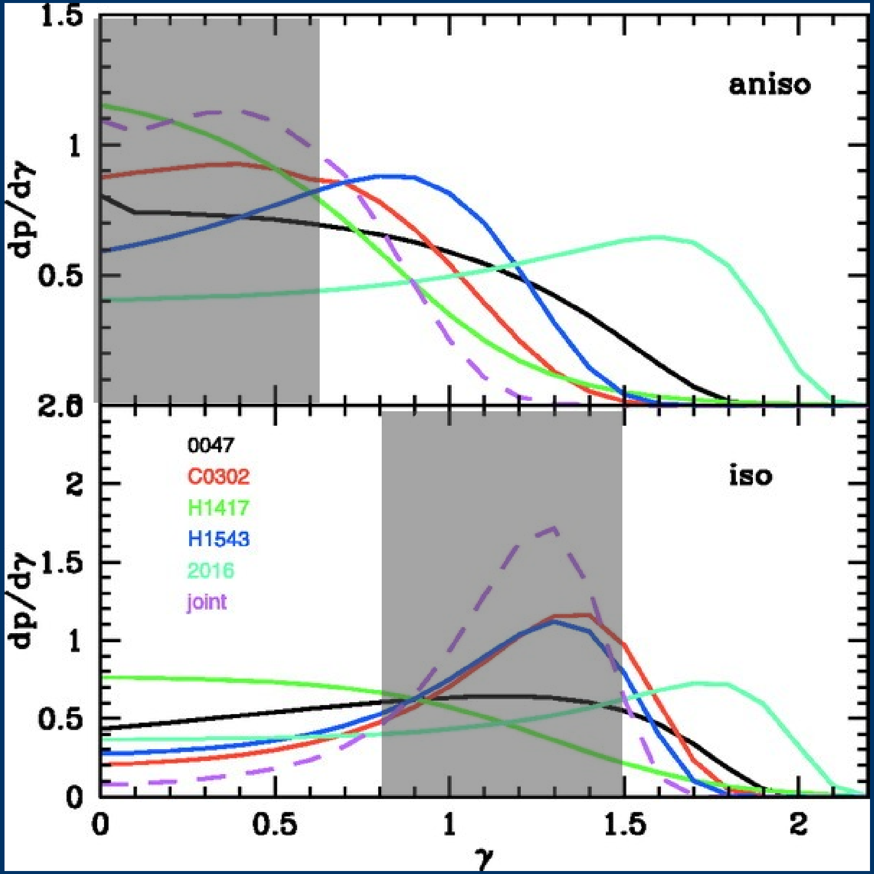
MG2016+112 (z_{lens}=1.01)

- Constant M/L models fail dramatically to match the observed velocity dispersion.
- An isothermal density profile for stars+DM fits the vel. dispersion within the errors.

(e.g. Koopmans & Treu 2002; Treu & Koopmans 2002)

Separating Stellar and Dark Matter

LSD Survey



Two component mass models:

» Isotropic models ($R_i=\infty$):

$\langle \gamma_{DM} \rangle = 1.3^{+0.2}_{-0.4}$ (68% CL)

» Anisotropic models ($R_i=R_{eff}$):

$\langle \gamma_{DM} \rangle < 0.6$ (68% CL)

(e.g. Koopmans & Treu 2003; Treu & Koopmans 2004)

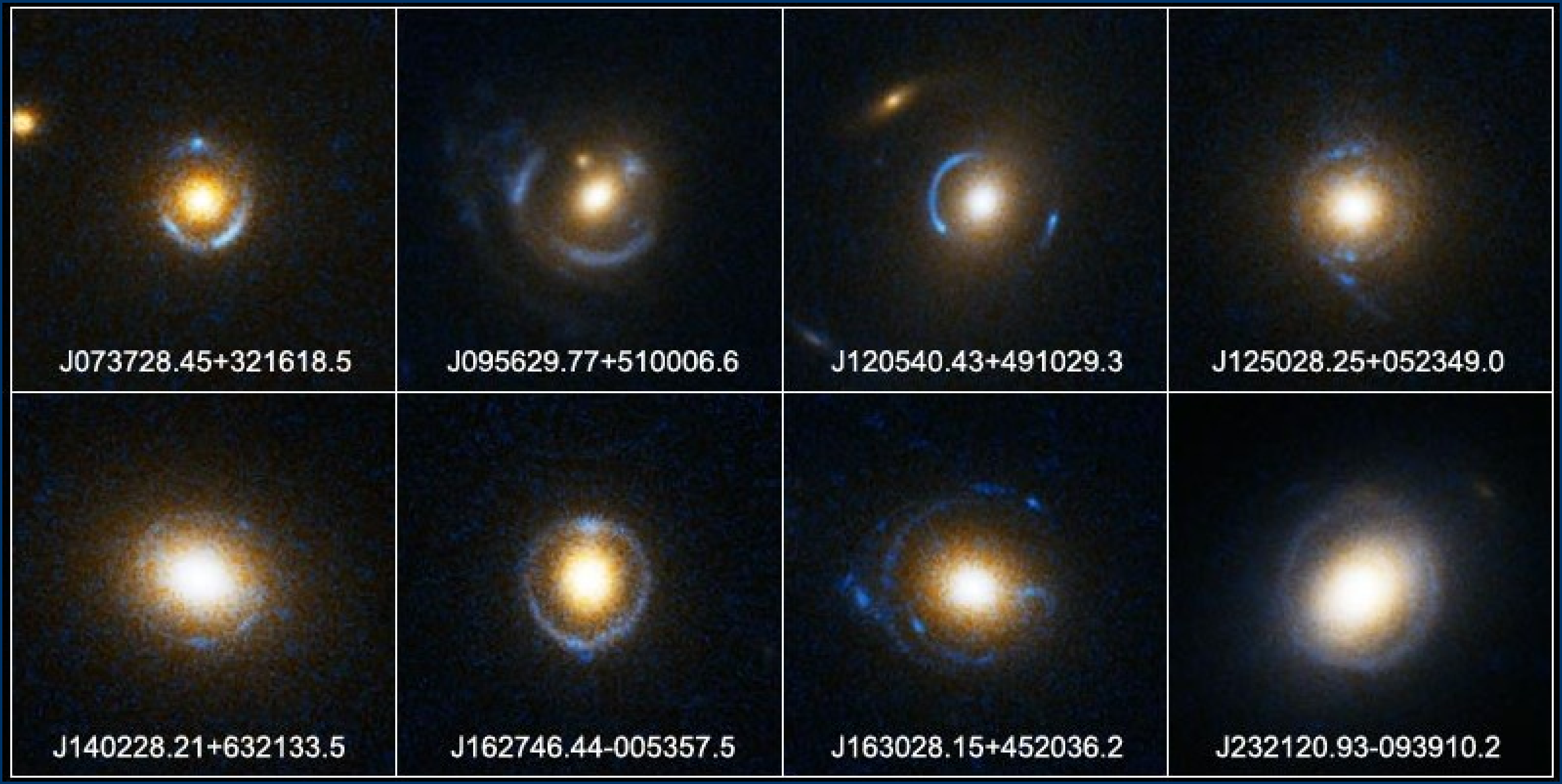
SLACS Survey

HST Snapshot Survey of spectroscopically selected lens-candidates from the SDSS. (Bolton et al. 2004, 2005, 2006)

SELECTION OF LENS CANDIDATES:

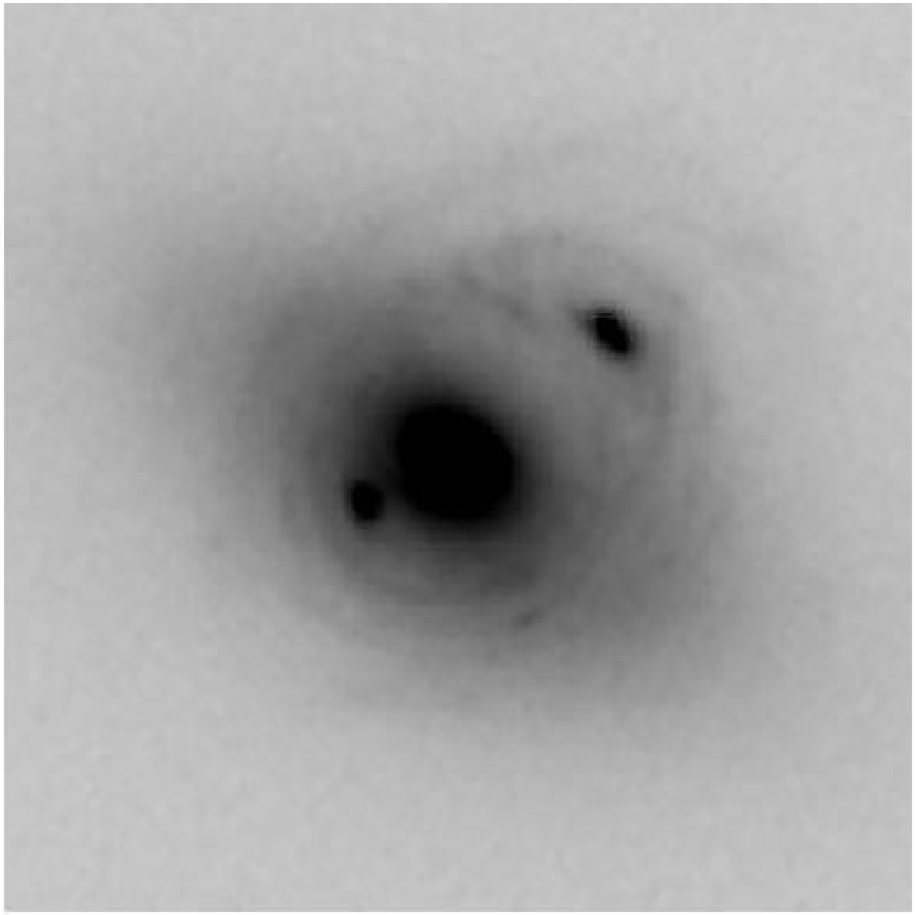
- 150,000 Luminous Red +MAIN Galaxies from SDSS (e.g. Eisenstein et al. 2004)
- Each galaxy has a SDSS spectrum → redshifts & velocity dispersion
- Some spectra show higher-z emission lines.
  At least 3 emission lines including OII-$\lambda\lambda$3728 ? → **New lens?**
- HST-ACS 7-min snapshots in F435W and F814W/1 orbit GO in F814W.

SLACS Survey: Einstein Rings & Arcs

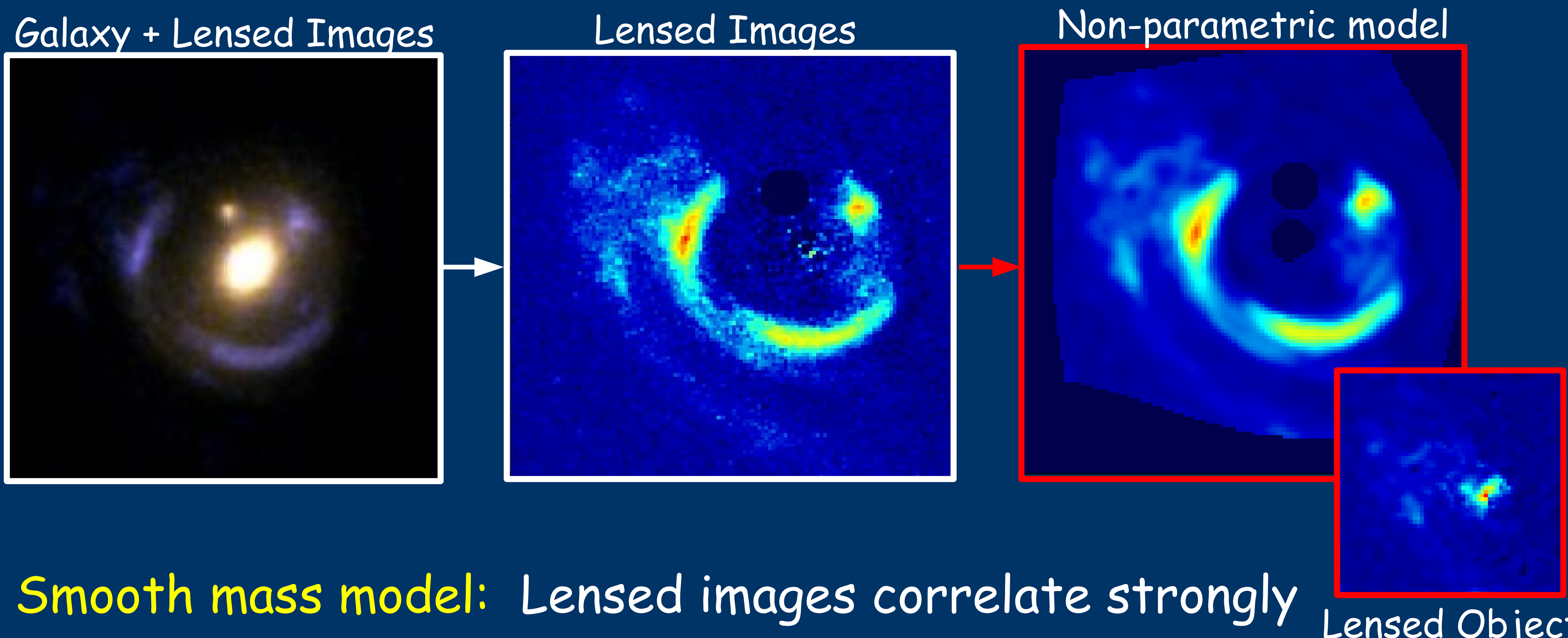


(Bolton et al. 2005/6; Treu et al. 2006; Koopmans et al. 2006)

The "ultimate" system for non-parametric lensing?



Methodology: Non-parametric lensing



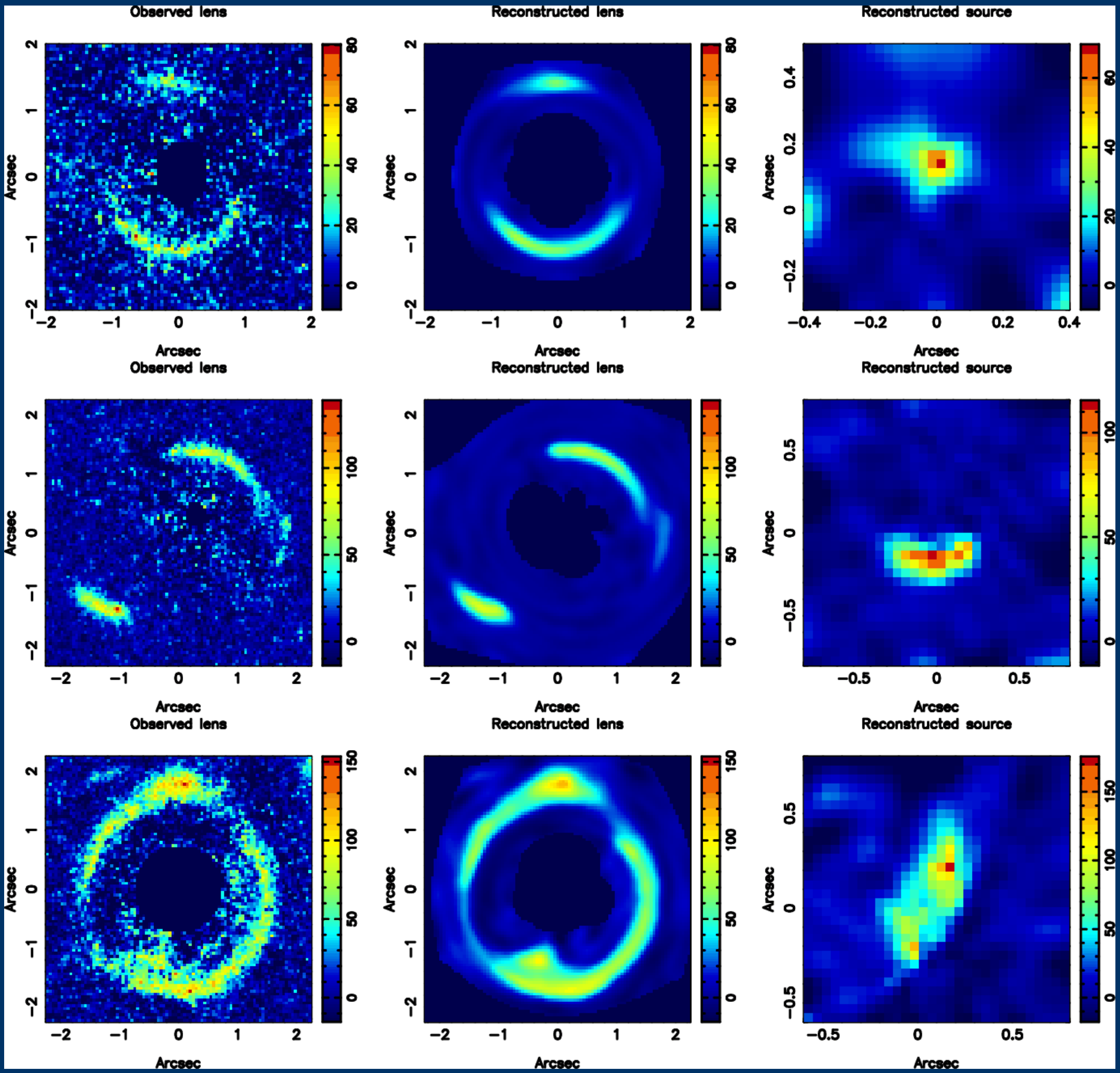
Smooth mass model: Lensed images correlate strongly

Clumpy mass model: Lensed images correlate less.

Exploit this to detect (DM) clumps

(e.g. Warren & Dye 2003, Koopmans & Treu 2004, Koopmans 2005, Suyu & Blandford 2006a&b)

Non-parametric source reconstructions

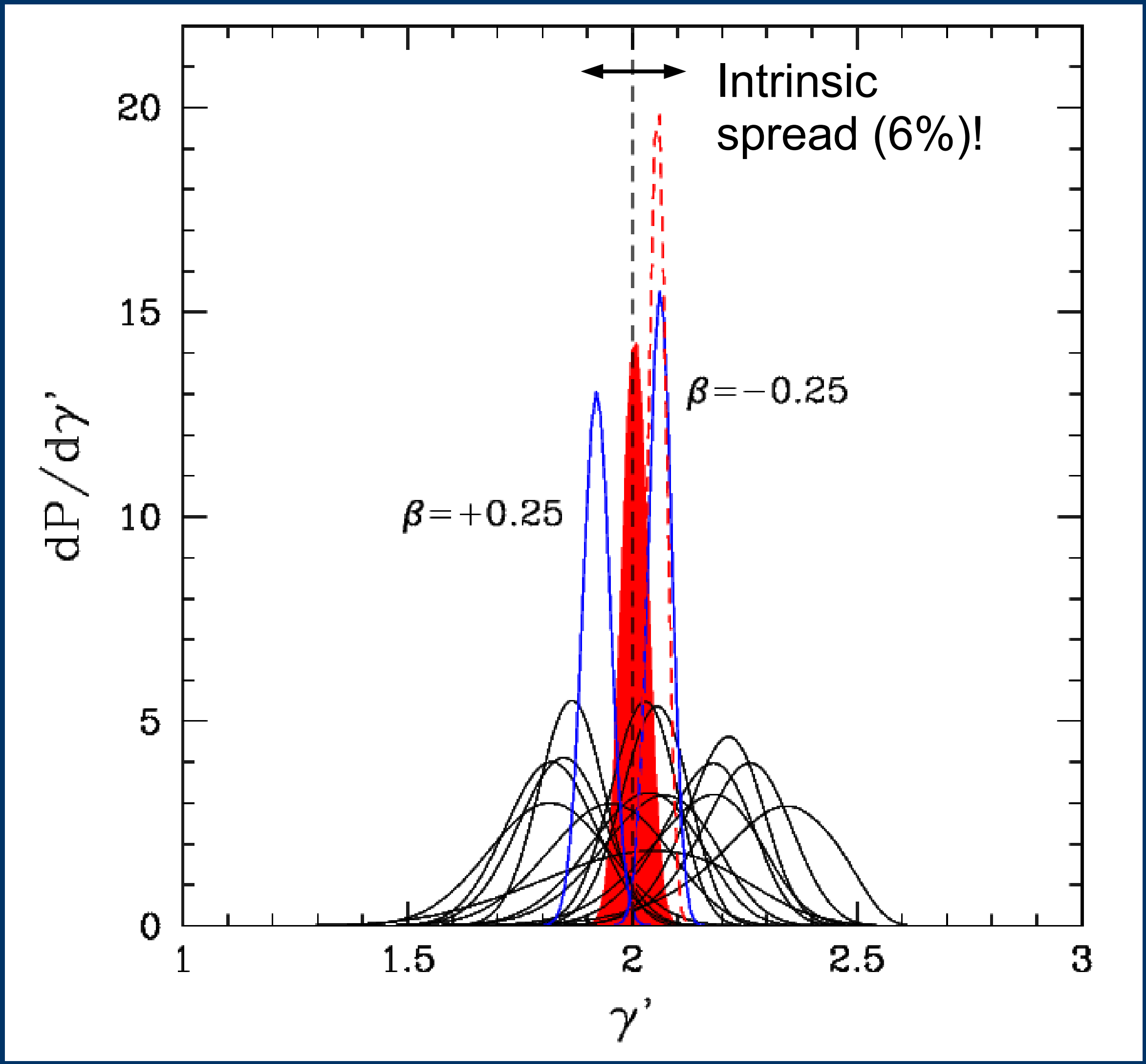


(Koopmans 2005; Koopmans et al. 2006)

Very accurate mass measurement and shape & orientation of the total mass ditribution in the inner 5-10 kpc

Combined with the galaxy dispersion from the SDSS & HST images of the lens galaxies, we can measure the total density slope (γ)

The density slope of E/S0 galaxies between z=0.08-0.33



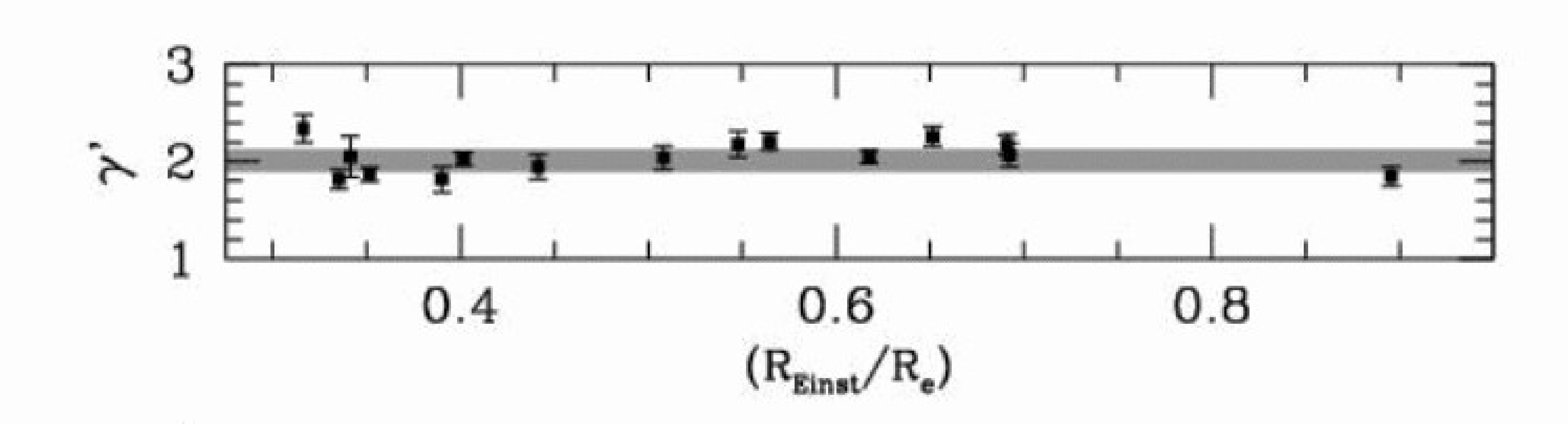
Total density slope inside ~4 kpc

$\langle \gamma' \rangle = 2.01 \pm 0.03$

(Koopmans et al. 2006)

The density slope of E/S0 galaxies between z=0.08-0.33

The log. power-law slope does not vary over 0.3 – 0.9 R_{eff}

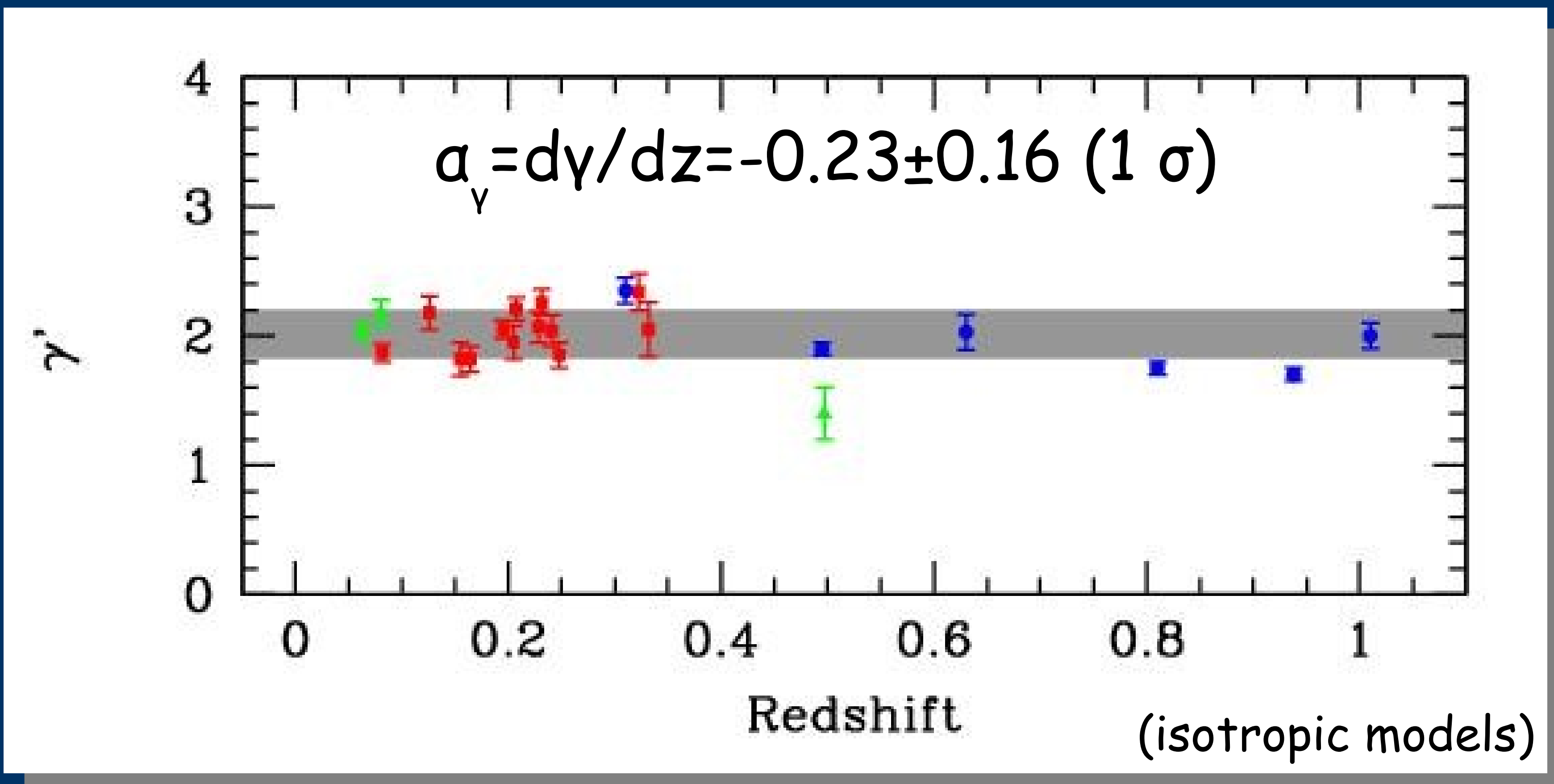


This suggest, although not proves, that a power-law provides an excellent description of E/S0 density profiles inside their effective radius

(Koopmans et al. 2006)

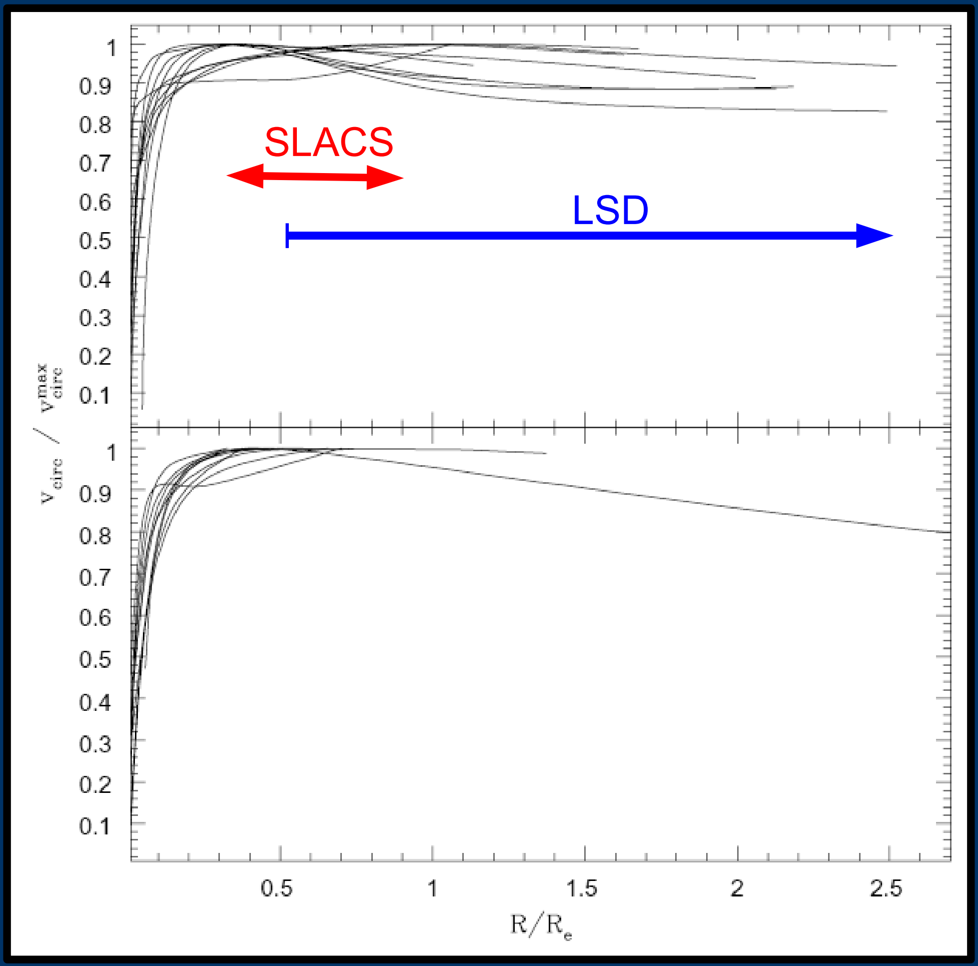
The structural evolution of E/S0 galaxies below z=1

The logarithmic (total) density slope of SLACS+LSD E/S0 galaxies between z=0.08 - 1.01



(Koopmans et al. 2006)

The structural evolution of E/S0 galaxies below z=1



Gerhard et al. (2001)

(1) The combined LSD+SLACS results show no/marginal evidence for evolution in the log. density slope.

(2) Spread (6%) is similar to z=0 ellipticals (~10%).

(3) Radial ranged covered similar to z=0 ellipticals (0.3-5 R_{eff}).

What does this mean for galaxy formation?

Since (1) Collisionless mergers conserve the inner density-cusp slope (e.g. Wechsler et al. 2002; Dehen 2005) and E/S0 galaxies are dominated by collisional matter.

(2) Collisionless mergers do NOT result in isothermal density profiles (e.g. NFW, Moore)

Then The (mass-dominant) gas-poor progenitors of E/S0s must have formed an isothermal density core through collisional processes at z>>1, which was subsequenctly conserved in the hierarchical merging.

Hence microphysics (e.g. gas/star-formation) must know about macrophysics (gravity) to conspire to an isothermal baryonic+DM density profile in E/S0s out to at least $5R_{eff}$!

Forthcoming & Future Work

Observational:

- Continued SNAP+GO observations with HST to discover more lenses (80-100).
- Deep V, I & H-band observations with HST-ACS of extended arc/ring systems.
- VLT Large Program with VIMOS-IFU for 2D kinematics of 17 SLACS systems.
- Keck long-slit follow-up for kinematics of northern targets.
- Gemini/Magellan follow-up of sources.
- Ground-based wide-field imaging

Forthcoming & Future Work

Theoretical:

- Self-consistent lensing & dynamics. (Barnabè & Koopmans, 2006, in prep.; PhD of Matteo Barnabè).

  >> Source Σ & DF, $f(E,L_z)$ are grid-based

- Non-parameteric source & potential reconstruction. (Koopmans 2005; Suyu et al. 2006; PhD of Simona Vegetti)

  >> Source Σ & Ψ are grid-based

SELF-CONSISTENT LENSING AND DYNAMICS (PhD: Matteo Barnabè)

Axisymmetric density distribution: $\rho(\mathbf{R,z})$

Gravitational potential: $\Phi(\mathbf{R,z,\eta_k})$

LENSED IMAGE REC.

DYNAMICAL MODEL

linear optimization

Maximize the evidence

Bayesian method for model comparison which embodies the "Occam's Razor" (MacKay '92)

Vary η_k: non-linear parameters

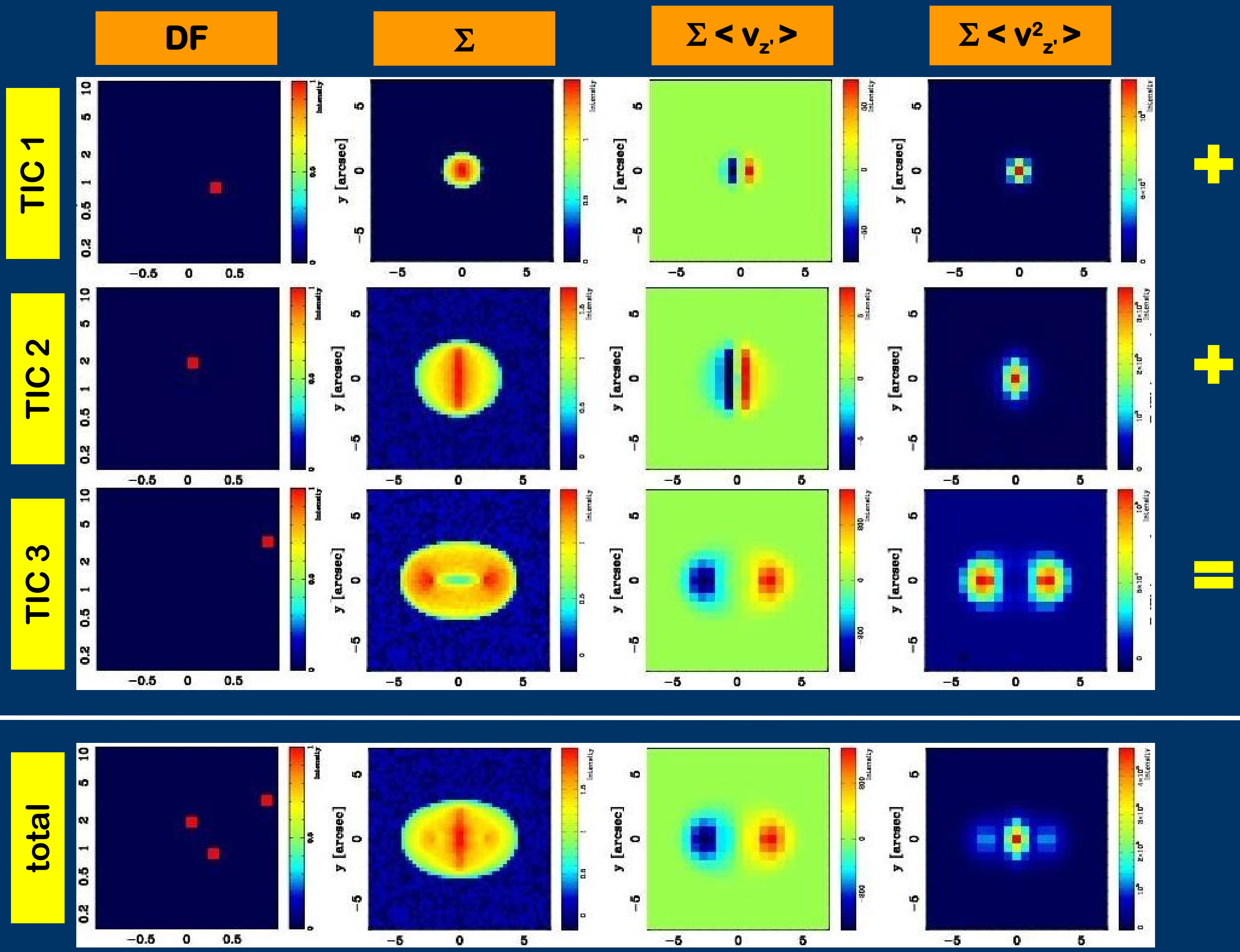
when converges

Best values for the non-linear parameters η_k

source reconstruction

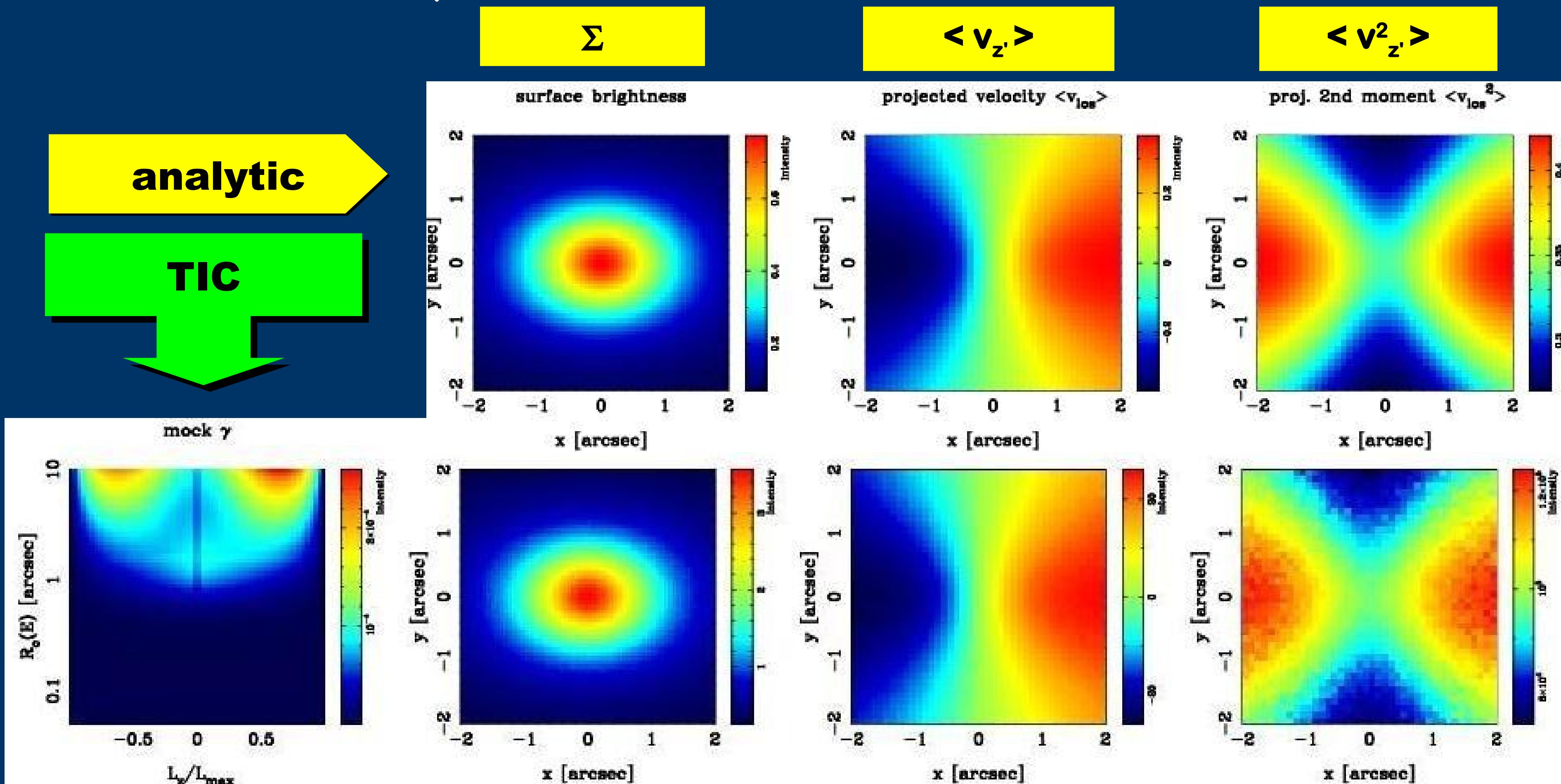
DF reconstruction

TICs superposition



TIC method vs analytic case: comparison

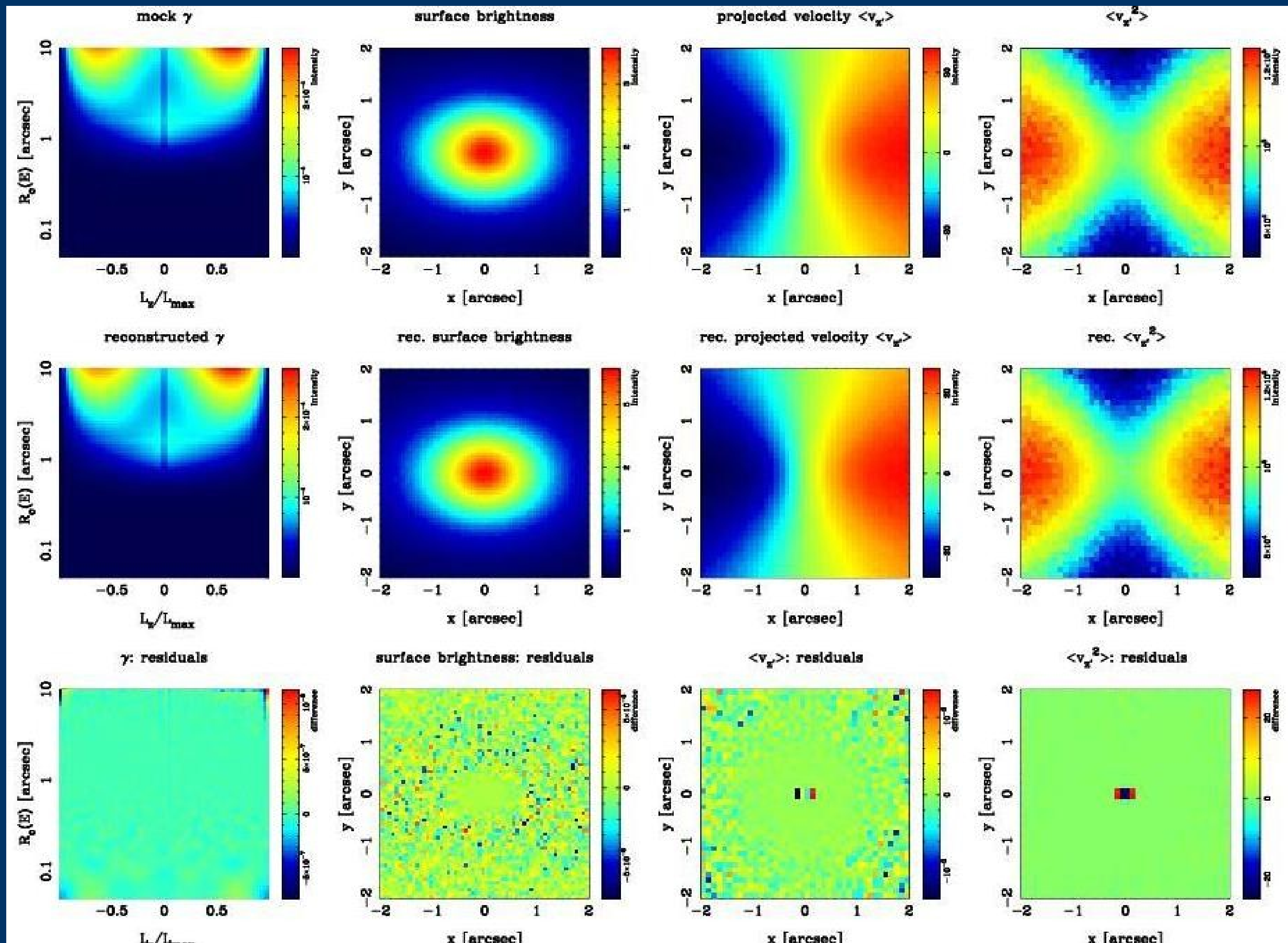
Evans (1994) power-law models provide a fully analytic test case
ρ, Φ, the DF, the surface brightness and the projected velocity moments are all analytic



Dynamical Model = DF reconstruction

$\propto$ DF | Σ | $< v_{z'} >$ | $< v^2_{z'} >$

mock | reconstructed | residuals



Summary/Conclusions

- Strong gravitational lenses + stellar dynamics provide a powerful probe into the inner (<15 kpc) structure of (mostly E/S0) galaxies to z=1, where baryons and DM interact.

- The density profile of E/S0 galaxies are isothermal with a logarithmic density slope of 2.0 and a scatter of at most 6% in the most massive galaxies. This is similar to E/S0 and spiral galaxies at low z.

- The ensemble average density slope of E/S0s does not significant evolve at z<1 !