Joint Gravitational Lensing and Stellar Dynamics Analysis of Early-Type Galaxies

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What is the mass structure of the early-type galaxies and *how* does it evolve with time?

- Understanding internal structure of early-type galaxies (e.g. shape of dark matter halos and correlation with total mass)
- Understanding formation and evolution of early-type galaxies
- Test validity of ΛCDM scenario of hierarchical formation on small (non-linear) scales

Methods to measure the density profiles of distant (z > 0.1) galaxies

GRAVITATIONAL LENSING

BUT... LIMITATIONS

- Difficult to separate luminous and dark matter components
- Mass-sheet degeneracy: lensing observables (except time-delays) are invariant under a transformation of the lens surface density: $\kappa_0 \leftrightarrow (1 - \kappa_{sh})\,\kappa_0 + \kappa_{sh}$

STELLAR DYNAMICS

BUT... LIMITATIONS

- Scarcity of dynamical tracers at large radii
- Mass-anisotropy degeneracy: The kinematic profile can be nearly invariant between changes in mass profile and anisotropy of the stellar velocity dispersion tensor.

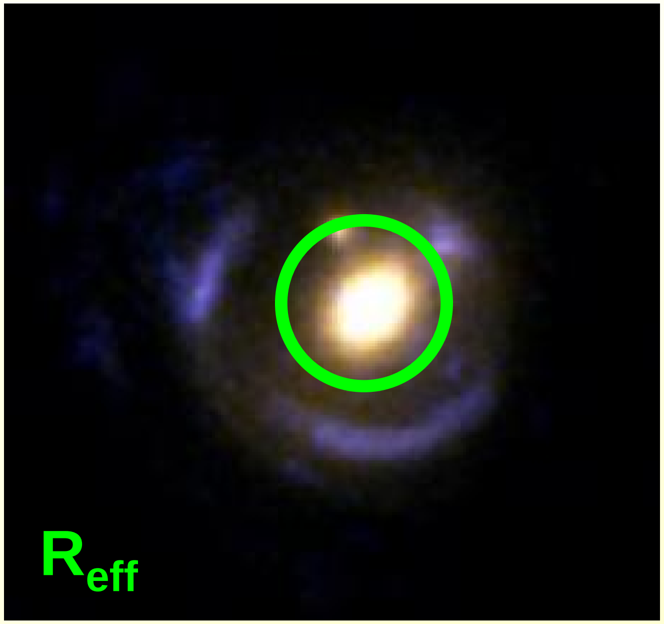
Breaking the degeneracies...

Joint and self-consistent analysis:

GRAVITATIONAL LENSING

+

STELLAR DYNAMICS

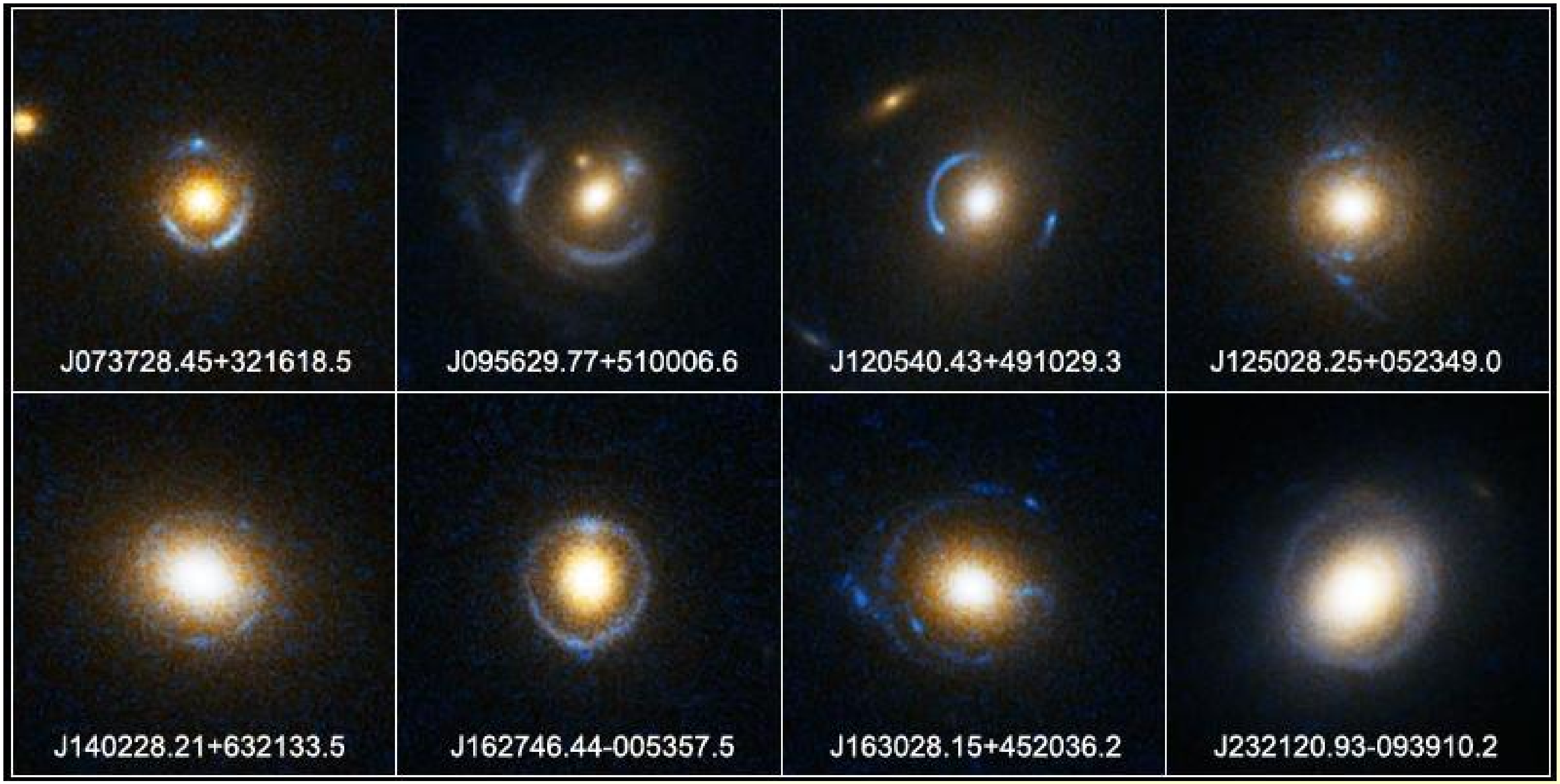


Accurate and (nearly) model independent determination of mass inside Einstein radius

Determination of the mass inside the effective radius (= inner regions)

THE DATA: searching for early-type lens galaxies

LSD and SLACS surveys



Credit: Bolton & the SLACS team

DATA:

- Lensed image
- Galaxy: surface brightness, velocity, velocity dispersion

LENSING

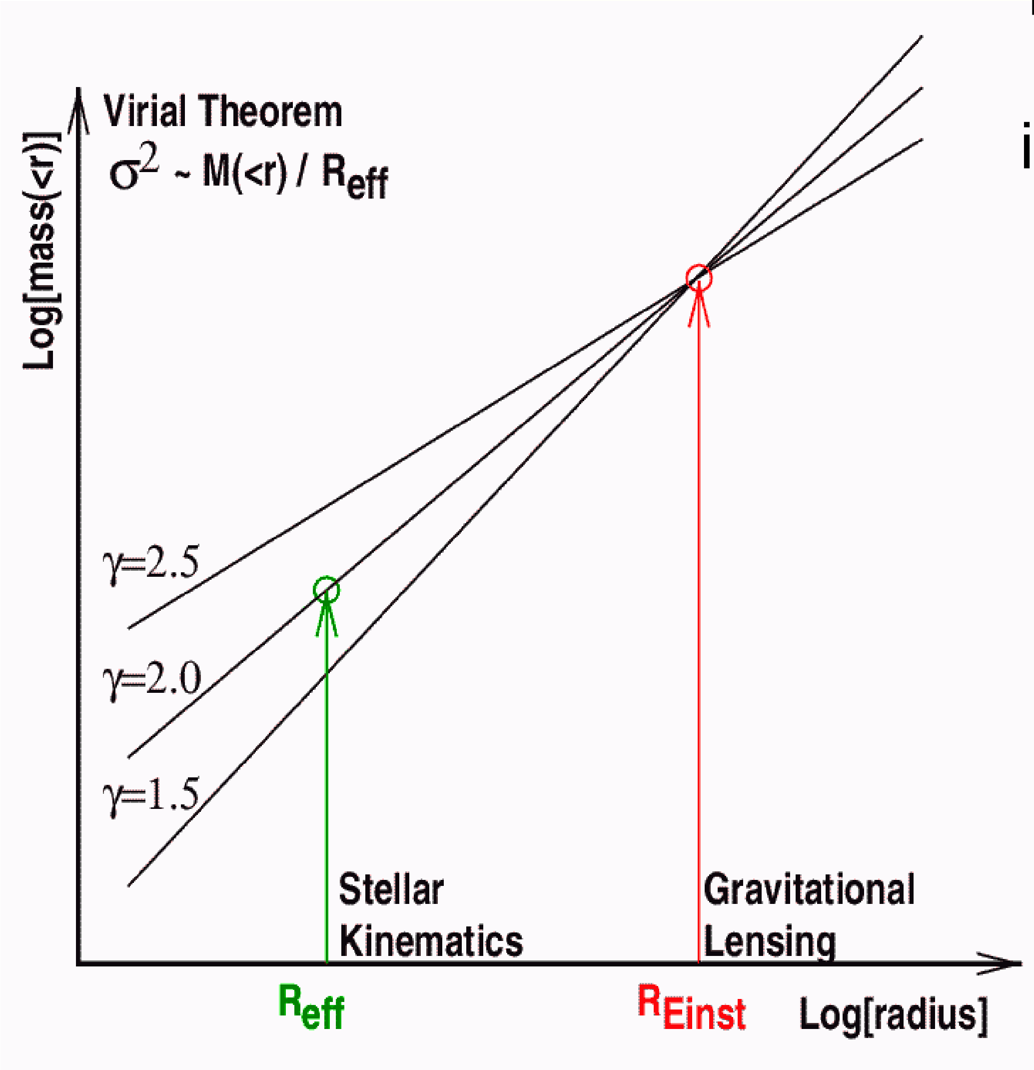
- About 40 E/S0 lens galaxies from LSD and SLACS surveys (and more to come)
  - HST snapshots: images in B and I bands

KINEMATICS

- Luminosity weighted velocity dispersion inside an aperture of 3’’ (from SDSS)
- 2-dim integrated field spectroscopy (with VLT-VIMOS)
- Longslit spectra along major and minor axes (with Keck)

First order analysis of the SLACS sample

Koopmans & Treu ‘03, ‘04, Koopmans et al ‘06



Lensing and Dynamics treated as independent problems:

LENSING: SIE model, $M(R < R_{Einst})$ imposed as a constrain for the dynamical models

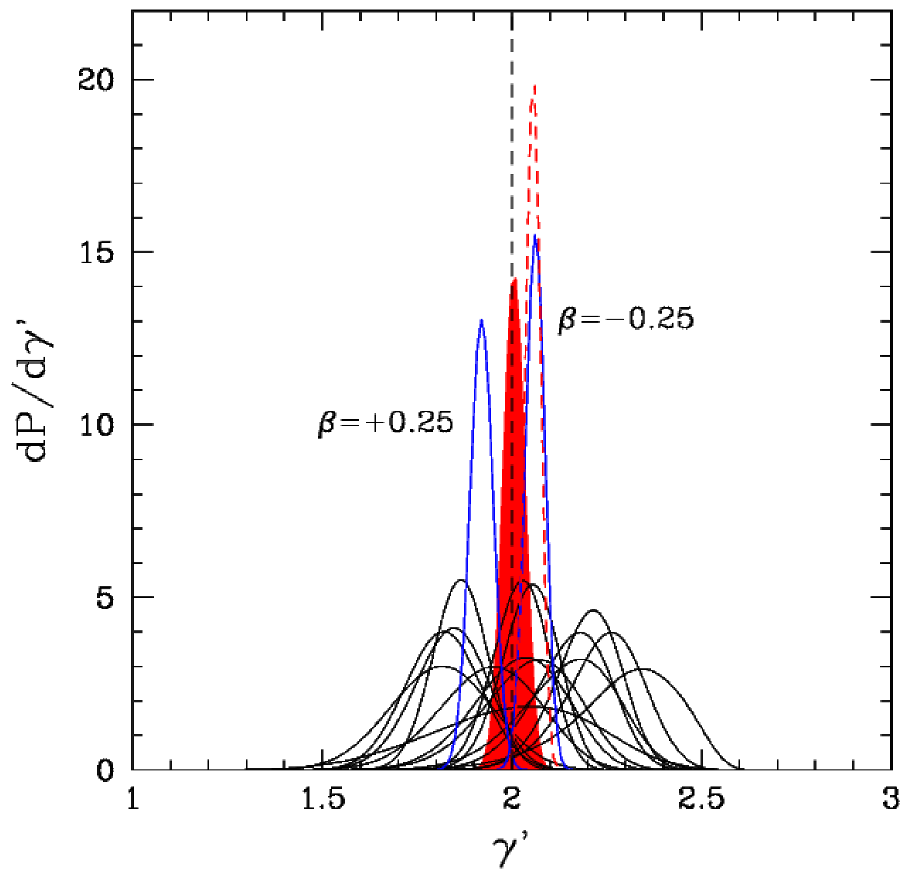
DYNAMICS: spherical Jeans Equations with OM anisotropy

$$\rho_{tot}(r) = \rho_0(r/r_0)^{-\gamma}$$

Highlights of results with this approach

Koopmans et al 2006

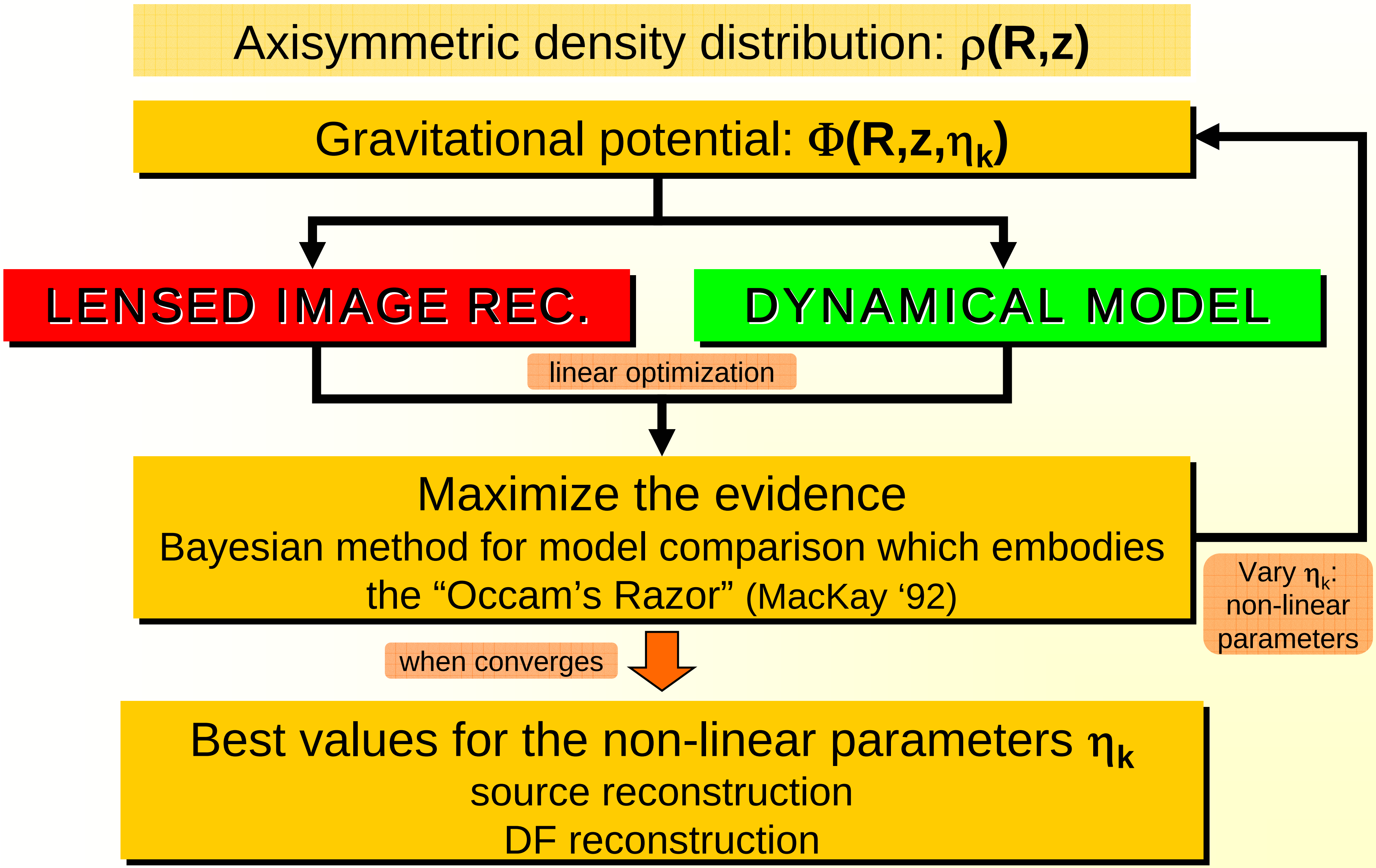
- Total density slope of E/S0 galaxies (inside ~4 kpc) between z = 0.08 - 0.33 is
  $\langle\gamma\rangle = 2.01 \pm 0.03$
  Intrinsic spread: only 6%
- No significant evolution of the total density slope for the range z = 0.08 – 1.01



NEED FOR A FULLY SELF-CONSISTENT APPROACH

- More rigorous approach: self-consistency
- Modeling: spherical → axisymmetric
- Provides more detailed information about the typology of the POTENTIAL of the lens E/S0 galaxy and the POTENTIAL PARAMETERS (then: POTENTIAL → DENSITY)
- Provides information about the dynamical structure (i.e. DISTRIBUTION FUNCTION) of the lens galaxy

A SELF-CONSISTENT METHOD FOR JOINT LENSING AND DYNAMICS ANALYSIS



strength of this method: lensing and dynamics can be expressed as formally analogous problems:

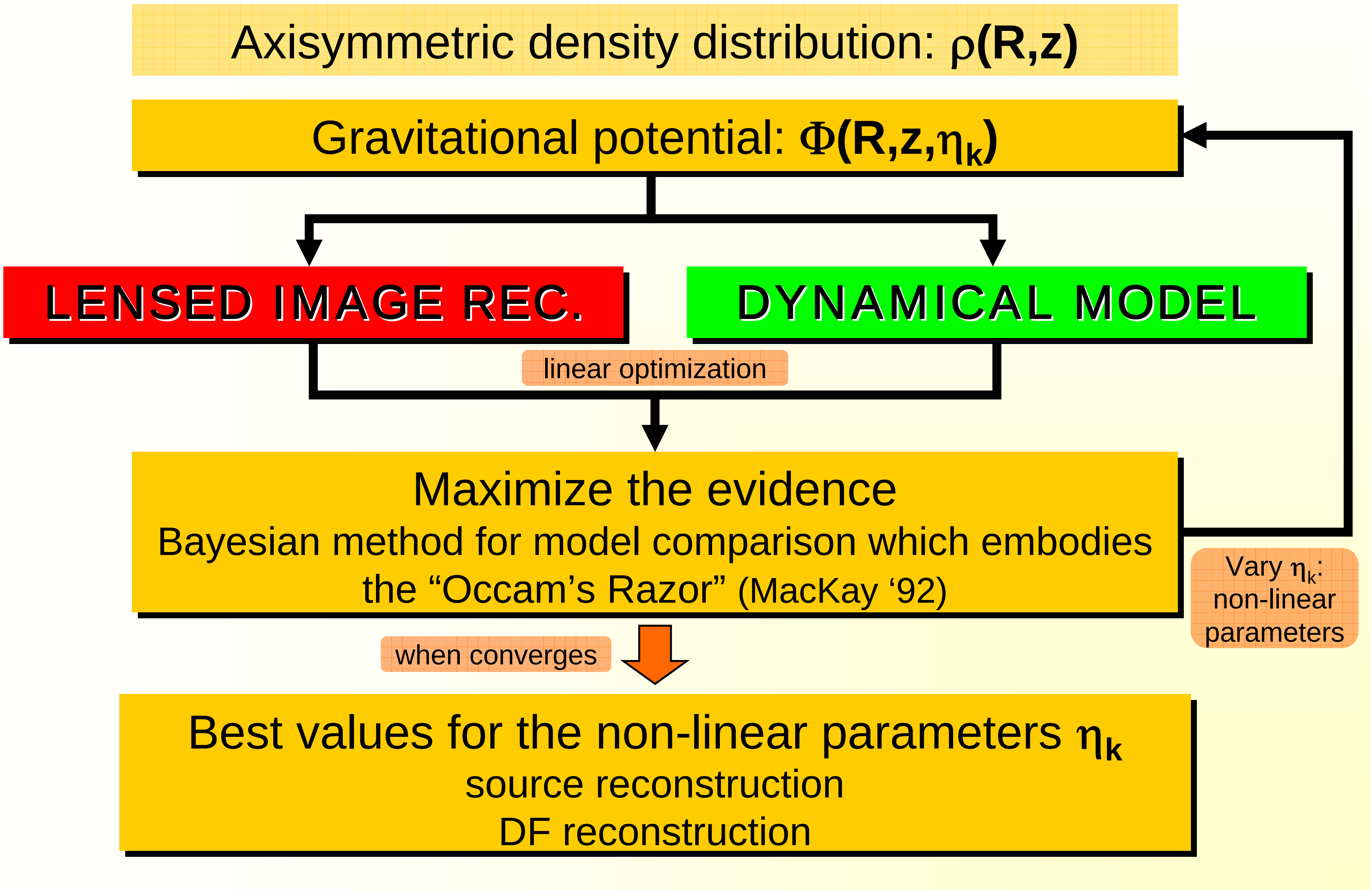
L s = d [ill-conditioned linear systems]

linear optimization:

- Ill-conditioned problem: L s = d
  L = linear operator, s = solution, d = data/constraints
- Choose a suitable regularization operator H
- Minimize the penalty function:
  $P = ||Ls - d||^2 + \lambda||Hs||^2 = \chi^2 + \text{regularization}$
- Best solution s obtained solving the set of linear equations:
  $(L^T L + \lambda H^T H)s = L^T d$

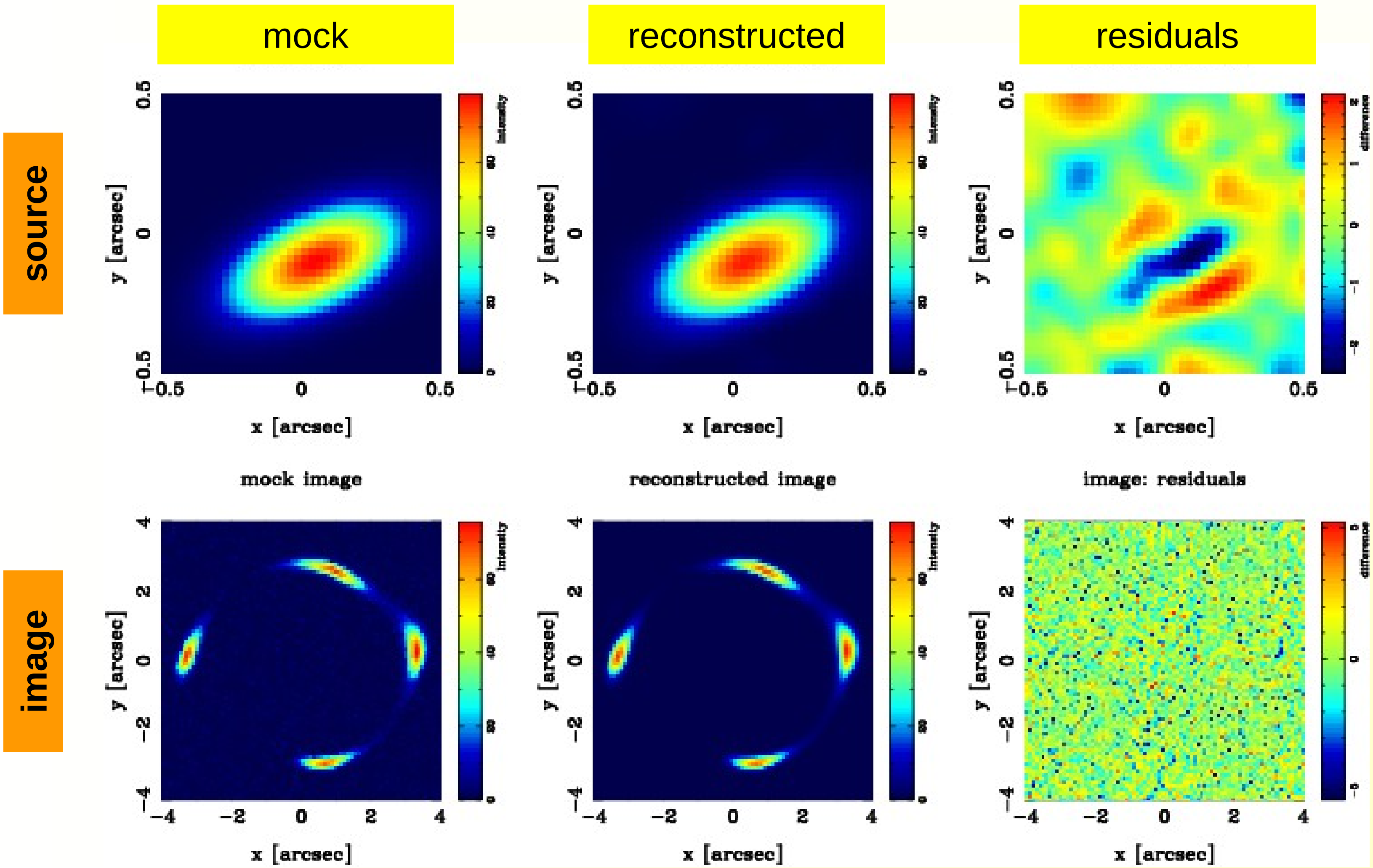
limited memory BFGS (**Broyden-Fletcher-Goldfarb-Shanno) method** with boundaries → positive (i.e. physical) solutions for source and DF reconstructions

A SELF-CONSISTENT METHOD FOR JOINT LENSING AND DYNAMICS ANALYSIS



Lensed Image Reconstruction

- Non parametric source reconstruction method (Warren & Dye 2003, Koopmans 2005); includes regularization



Lensing and Dynamics as linear problems: $L\ s = d$

	LENSING	DYNAMICS
L	Lensing operator	
s	reconstructed source	
d	obs. lensed image	

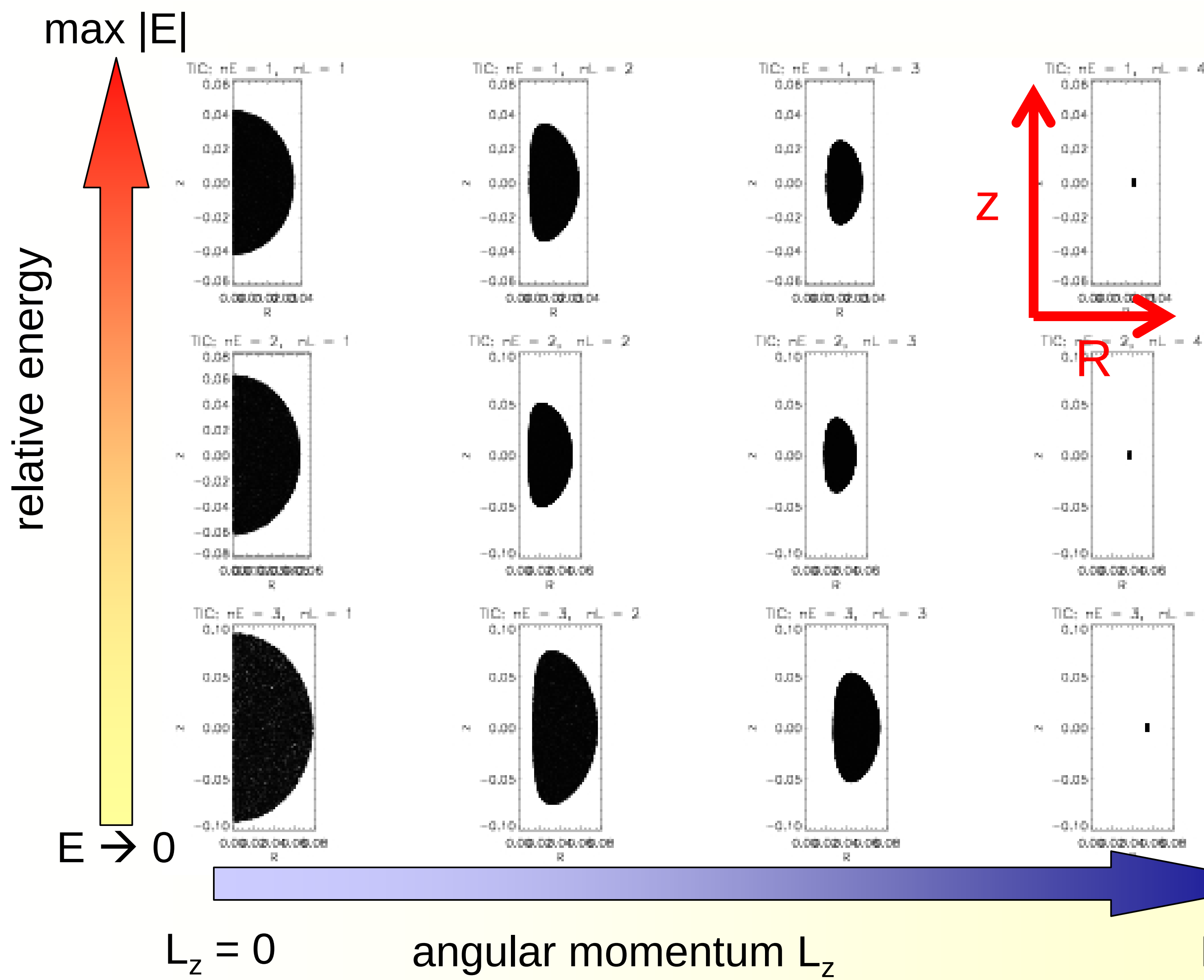
Dynamical Model

- TWO INTEGRAL SCHWARZSCHILD METHOD (Verolme & de Zeeuw 2002) extended and sped up through a novel Monte Carlo approach
- Building blocks: not orbits, but δ distribution functions (TICs), completely specified by energy E_j and angular momentum $L_{z,j}$
- The (unprojected) density and velocity moments of a TIC are analytical and easy to calculate
- Any axisymmetric density distribution can be described as a superposition of TICs

j-th TIC (Two Integral Component)

$$f_j = \begin{cases} \mathbf{C}\ \delta(E - E_j)\ \delta(L_z - L_{z,j}) & \text{inside ZVC} \\ 0 & \text{outside ZVC} \end{cases}$$

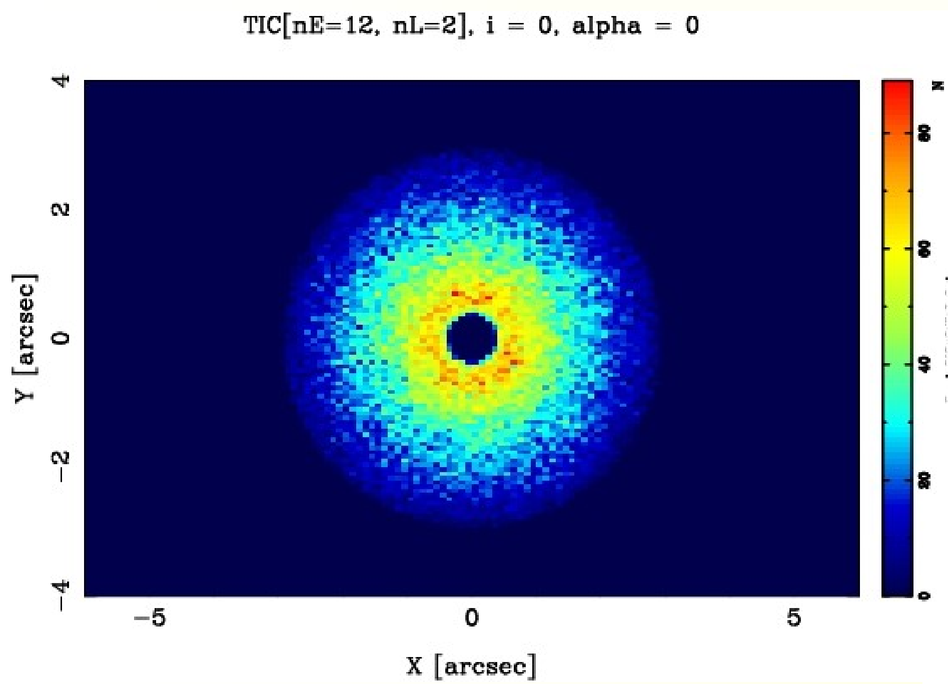
TIC: Two Integral Components



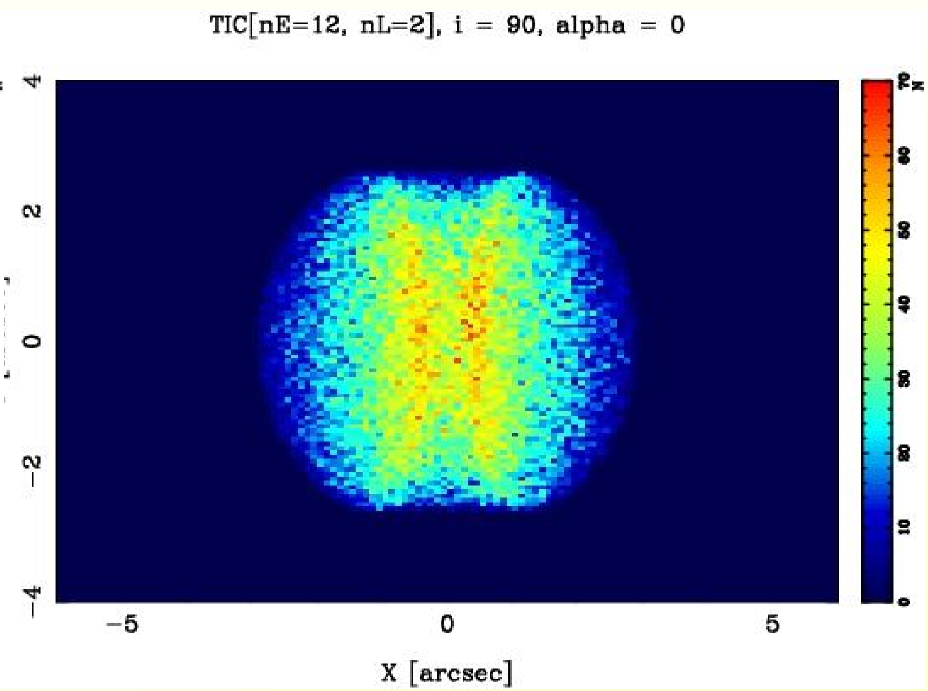
Each choice of (E, L_z) defines a TIC and, with Φ, its associated ZVC (= zero velocity curve) in the meridional plane

TIC: Two Integral Components

= Dirac-delta distribution functions

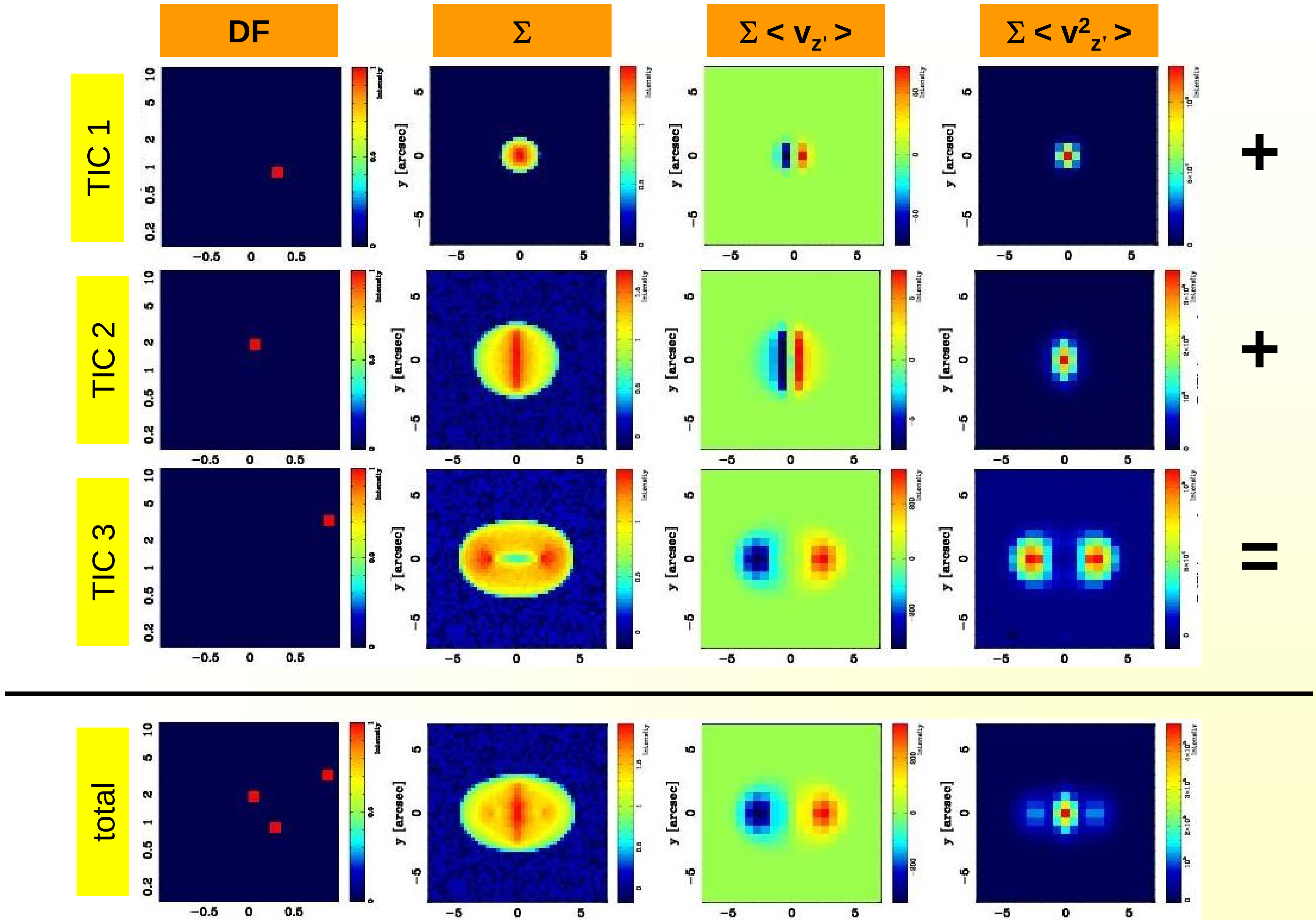


density distribution projected **face-on**



density distribution projected **edge-on**

TICs superposition

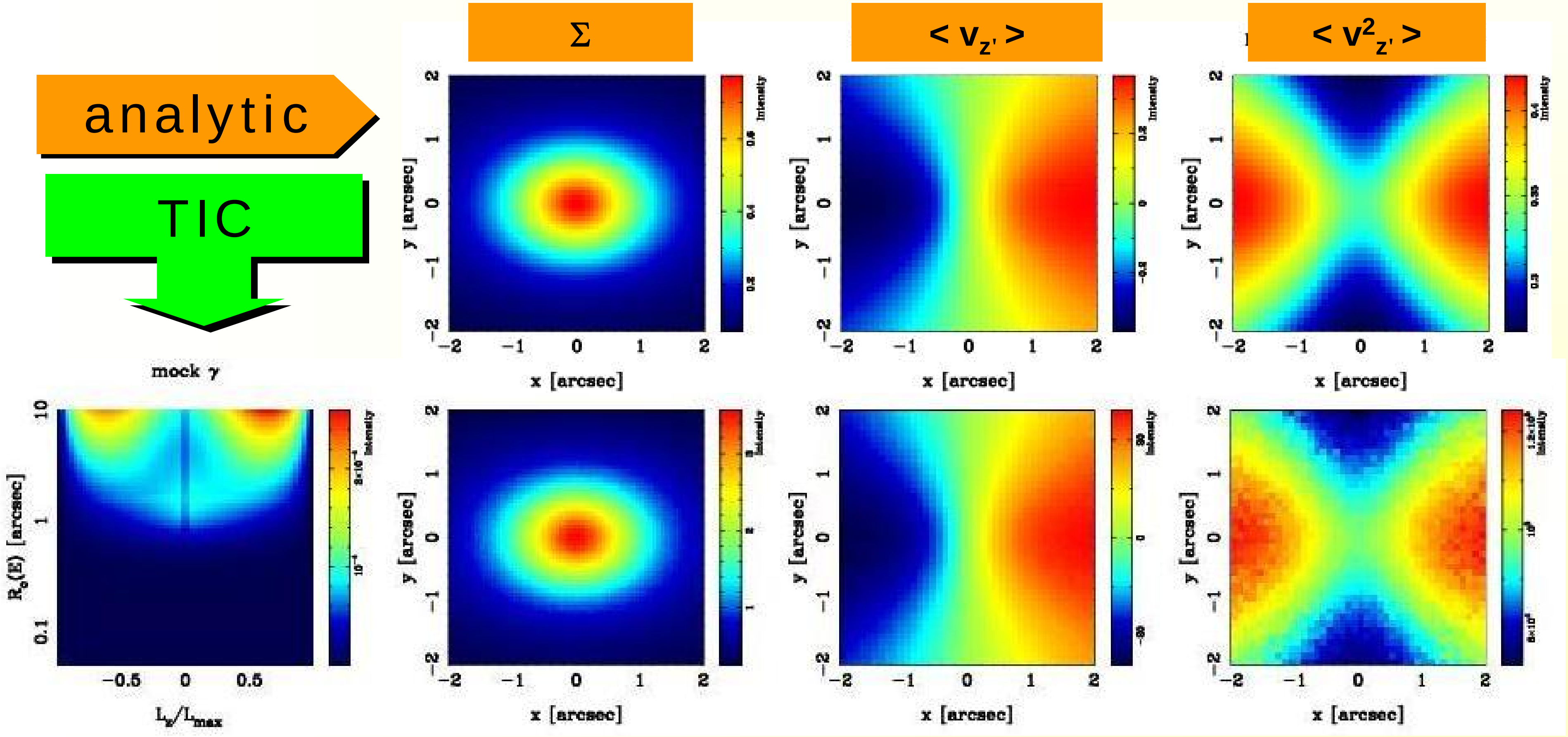


Lensing and Dynamics as linear problems: L s = d

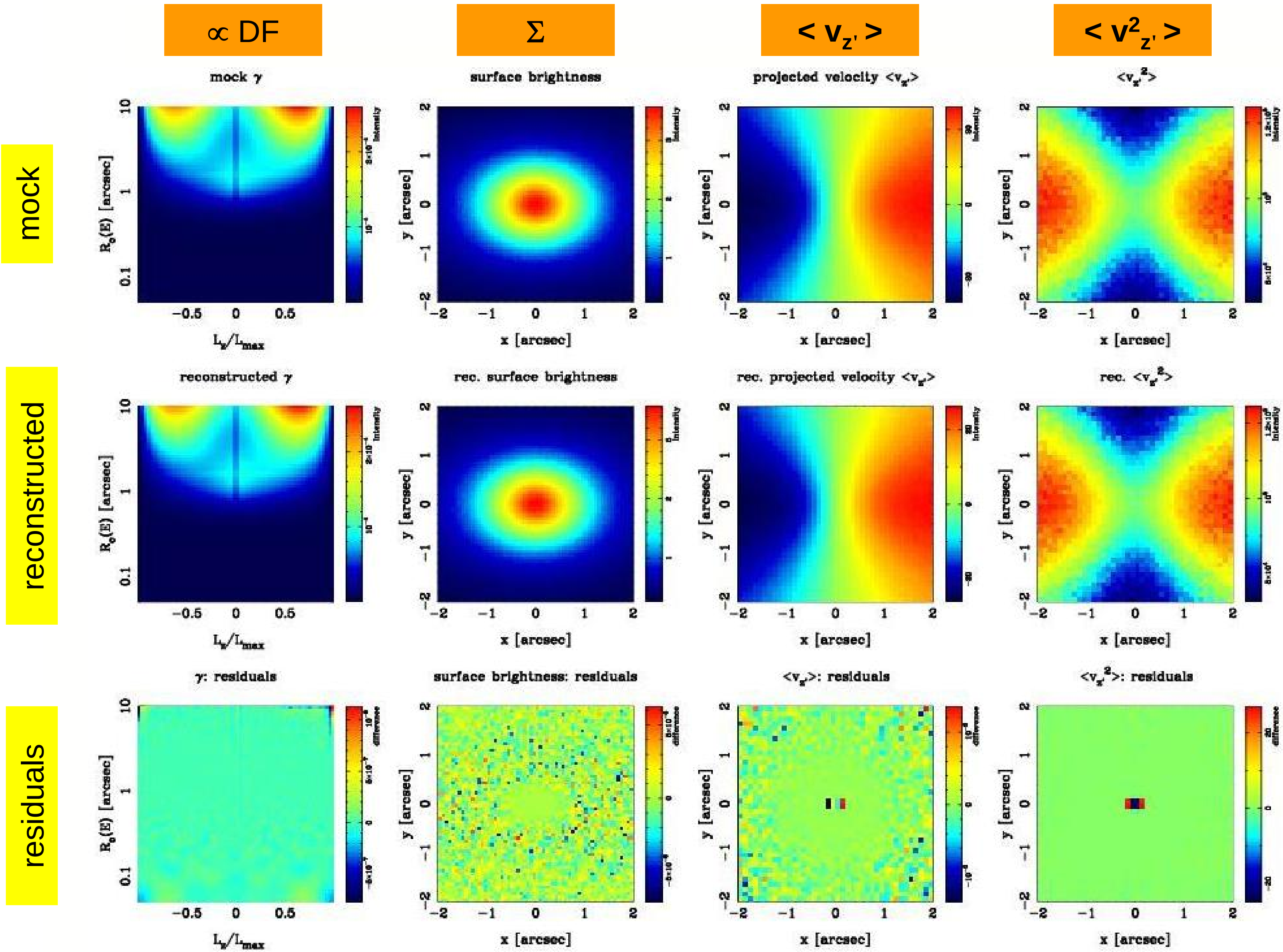
	LENSING	DYNAMICS
L	Lensing operator	"Dynamics operator" i.e. matrix storing the TICs as columns
s	reconstructed source	(weighted) distribution function
d	lensed image	Surface brightness, projected v_{los}, projected σ_{los}

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



NON-LINEAR OPTIMIZATION

- Iterative steps: vary the non-linear parameters η_k of the potential (or density)
- We need an objective criterion to determine which is the "best model"

general problem → MODEL COMPARISON

solution → EVIDENCE MAXIMIZATION

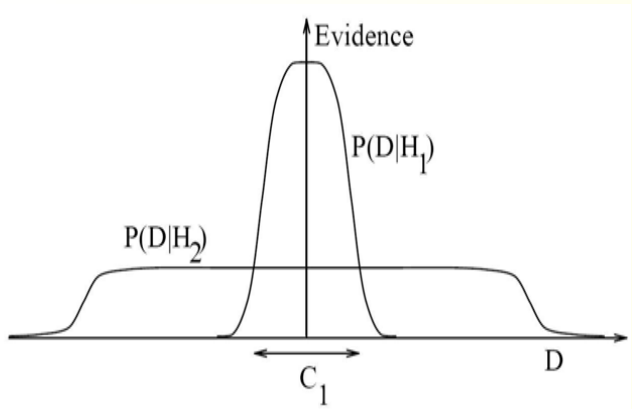
Evidence = merit function in the bayesian framework (the evidence represents the plausibility of a model, given a dataset)

Evidence method for model-comparison

(MacKay 92, 95, 98; Suyu et al 06)

- Evidence = merit function in the bayesian framework (generalization of maximum likelihood)
- Extremely powerful and versatile
- MODEL COMPARISON (no general method exists for solving this problem in "orthodox" statistics)
- Automatically embodies the OCCAM'S RAZOR

Occam's Razor



Penalize unnecessary complex models, avoiding over-parametrization

Inference framework in practice

(MacKay '98, Suyu et al 2006)

Level 1

model fitting

$$P(s|d,\lambda,M,H) = \frac{P(d|s,M) \times P(s|\lambda,H)}{P(d|\lambda,M,H)}$$

likelihood; prior; evidence; Posterior probability

Level 2

find best hyperparameters

$$P(\lambda|d,M,H) = \frac{P(d|\lambda,M,H) \times P(\lambda)}{P(d|M,H)}$$

Level 3

model comparison

$$P(M|d,H) \propto P(d|M,H) \times P(M)$$

Project is ongoing...

CODE & ANALYSIS

- Code core: completed
- Currently: testing on mock systems
- Next future: apply to the observational data (reduced data will soon be available)

OBSERVATIONS

- 17 full datasets
- Deeper HST imaging
- Search for new lenses
- Stellar kinematics data (VLT and Keck)

Aim: Deep HST imaging + extended kinematics for ~30 systems

Final Goal: obtain mass density profiles for a good sample of early-type galaxies up to $z \approx 1$ and compare with numerical simulations