Made-to-measure/N-body methods

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Outline

- *M2M/Nbody methods.*
- *M2M applications.*
- *M2M applied to barred galaxies.*
- *M2M/NMAGIC applied to the MW.*

Dynamical models

The Goal: recover the phase space DF of stars in galaxies (total Φ, DM, BHs, orbit structure, formation history...

Several techniques:

- *Fit parametrized DFs to match observations*

  Dejonghe 84, Gerhard 91, Dehnen & Gerhard 93, Kronawitter+00

- *Find solutions to Jeans equations that reproduce obsevations*

  Binney & Mamon 82, Binney 90, van der Marel & van Dokkum 07, Cappellari+08

- *Schwarzschild orbits superposition method*

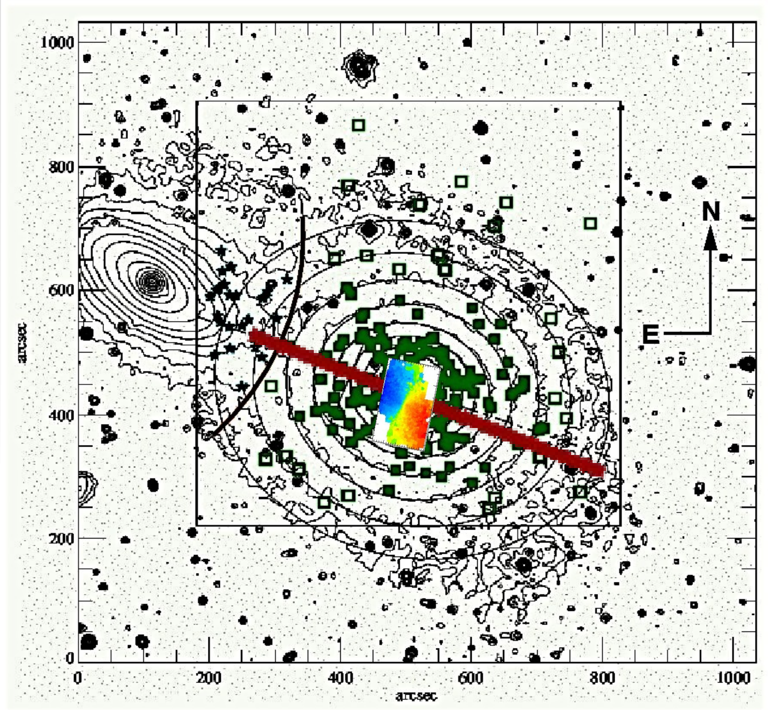
  Schwarschild 79, Gebhardt+ 03, Thomas+05, van den Bosch+08

- *M2M particle methods.*

  Syer & Tremaine 96, Bissantz+04, de Lorenzi+07, Rodionov+09, Dehnen 09, Long & Mao 10

M2M methods: the data

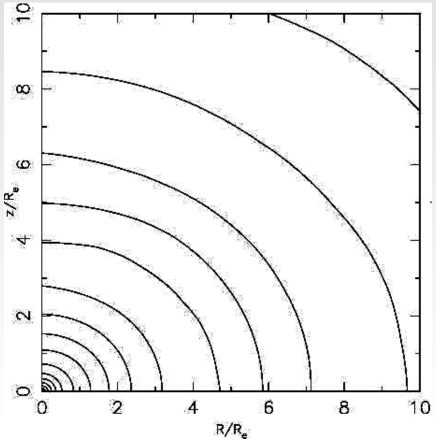
Take a galaxy



NGC 3379, de Lorenzi+ 09

Photometric observables

Surface brightness and luminosity density

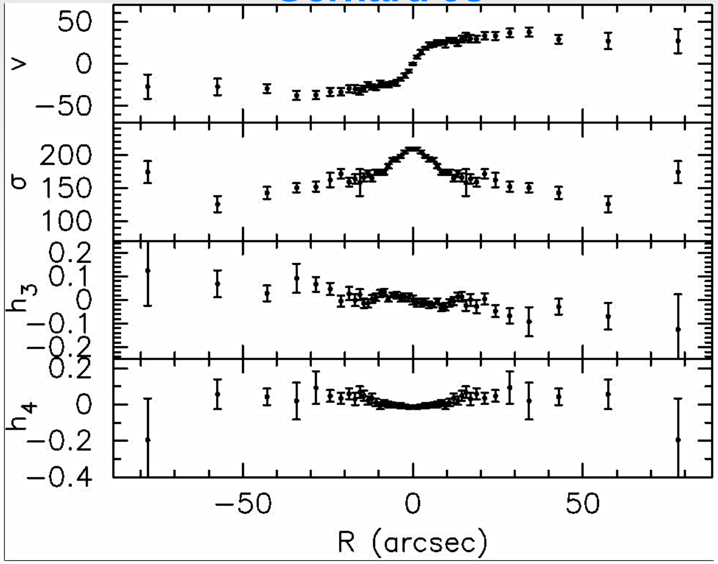


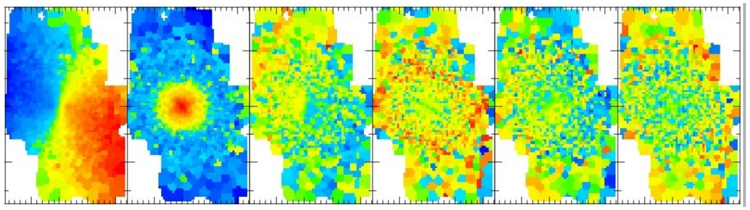
(axisymmetric deprojection, e.g. Magorrian 99)

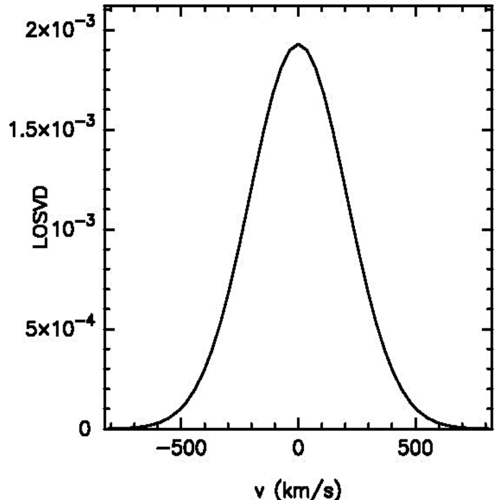
Kinematic observables

Luminosity weighted Gauss-Hermite moments of the LOSVD

e.g. van der Marel & Franx 93, Gerhard 93







PNe data (trace the light!) either binned or as discrete radial velocities

M2M methods: the N-body model.

- Set up an initial N-body model
- Evolve it self-consistently and/or add external potential
- Adapt particle weights/probabilities maximizing

$$F = -\frac{1}{2}\chi^2 + \mu S$$

Regularization term (entropy)

Typical chi^2

$$\chi^2 = \sum_j \Delta_j^2$$

Difference between model and target for j-observable

$$\Delta_j = \frac{y_j - Y_j}{\sigma(Y_j)}$$

Error for each observable (de Lorenzi+07)

FORCE OF CHANGE

$$\frac{\mathrm{d}w_i}{\mathrm{d}t} = \varepsilon w_i(t) \left(\mu \frac{\partial S}{\partial w_i} - \sum_j \frac{K_j\left[\mathbf{z}_i(t)\right]}{\sigma(Y_j)} \Delta_j(t) \right)$$

Temporal Smoothing

Global Weight entropy Regularization (GWR)

- The problem is generally ill-conditioned (many more orbits than observational constraints) large freedom in the weight adaption

- Need for regularization

$$F = -\frac{1}{2}\chi^2 + \mu S$$

Regularization term (entropy)

Entropy regularization

$$S = -\sum_i w_i \log \frac{w_i}{\hat{w}_i}$$

→ GWR scheme: limited amount of allowed smoothing (**bias towards ICs, stronger where data constraints weaker**)

↓ **Undersmoothed models**

$$\hat{w}_i = \frac{1}{N}$$

... same as initial particle weights. Prevent arbitrary weight changes!

New smoothing, the **Moving Prior Regularization (MPR, Morganti & Gerhard 2012)**:

- Grid particles in (E,x), x=L/Lc (phase-space)
- Prior = average weight in cell
- Smooth the grid of priors
- Use new priors in a weight entropy

Allows higher μ ⇒ Smoother models

M2M methods: Different Implementations

Dehnen 2009

- Normalization of weights
- Integration time depending on dynamical time.
- Different temporal smoothing

Long & Mao 2010

- Weight convergence criterion
- B-contrained model
- Temporal smoothing

De Lorenzi, Debattista, Gerhard & Sambhus, 2007, de Lorenzi +2008

$$F = -\frac{1}{2}\chi^2 + \mathcal{L} + \mu S$$

likelihood of PNe

Regularization term (entropy)

M2M methods: NMAGIC discrete velocities

Measure the likelihood of a sample of discrete velocities v_j at positions $\mathbf{R}_j = (x_j, y_j)$ on the sky by

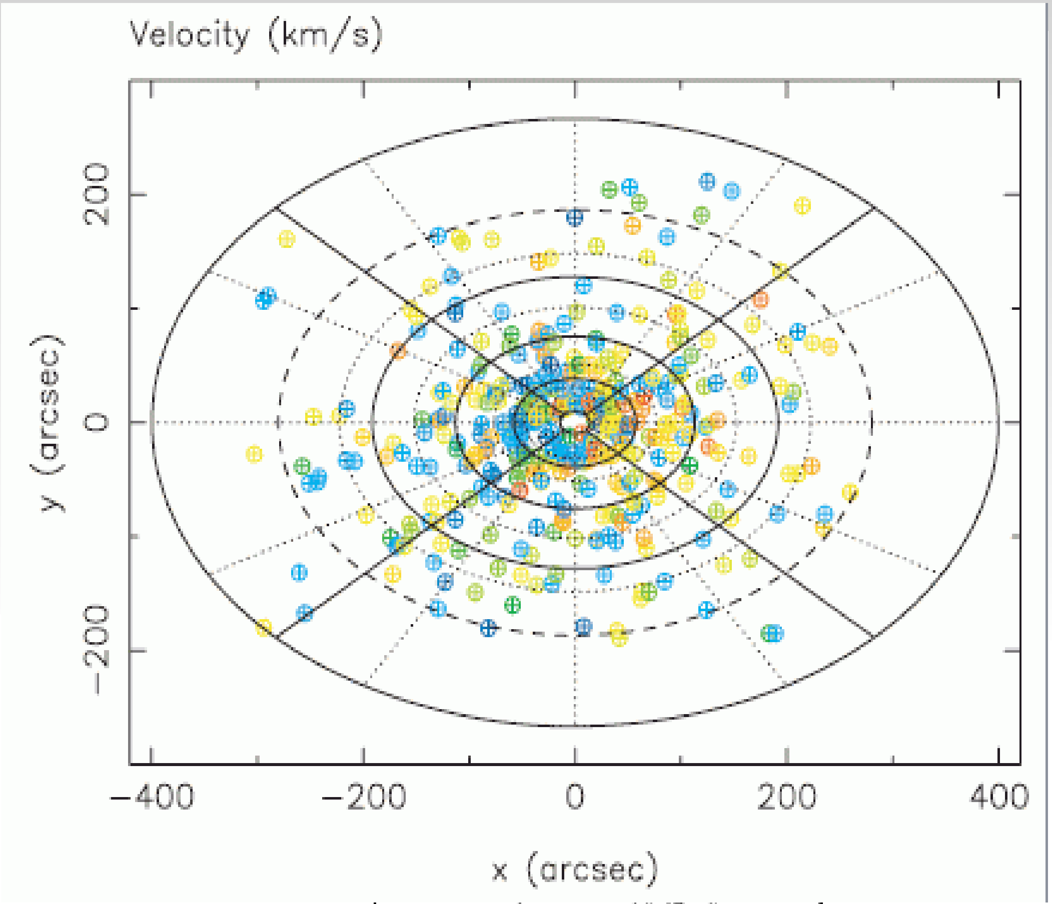
$$\mathcal{L} = \sum_j \ln \mathcal{L}_j; \tag{1}$$

$$\mathcal{L}_j(v_j, \mathbf{R}_j) = \frac{1}{\sqrt{2\pi}} \int \frac{\mathrm{d}L}{\mathrm{d}v_z}(v_z, \mathbf{R}_j) e^{-(v_j - v_z)^2/2\sigma_j^2} \mathrm{d}v_z, \tag{2}$$

is the likelihood function for a single star (Romanowsky & Kochanek 2001), σ_j is the error in its velocity, and $\mathrm{d}L/\mathrm{d}v_z$ is the LOSVD with line-of-sight along the z-axis.

Add equation (1) to the merit function F:

$$F = -\frac{1}{2}\chi^2 + \mathcal{L} + \mu S$$



Additional contribution to the force of change

$$\frac{\mathrm{d}w_i}{\mathrm{d}t} = \varepsilon w_i \sum_j \delta_{ji} \left(\frac{1}{\sqrt{2\pi}} \frac{e^{-(v_j - v_{z,i})^2/2\sigma_j^2}}{\widehat{\mathcal{L}}_j} - \frac{1}{l_j} \right), \tag{4}$$

$$\widehat{\mathcal{L}}_j = \frac{1}{\sqrt{2\pi}} \sum_i \delta_{ji} w_i e^{-(v_j - v_{z,i})^2/2\sigma_j^2}, \tag{5}$$

$$l_j = \sum_i \delta_{ji} w_i. \tag{6}$$

De Lorenzi et al. 2008

M2M/NMAGIC: Efficient M/L Estimation

Consider χ^2 as functions of mass-to-light ratio Υ, which converts model units (MU) to physical units (PU):

$$\chi^2 = \sum_j \Delta_j(\Upsilon)^2. \quad (1)$$

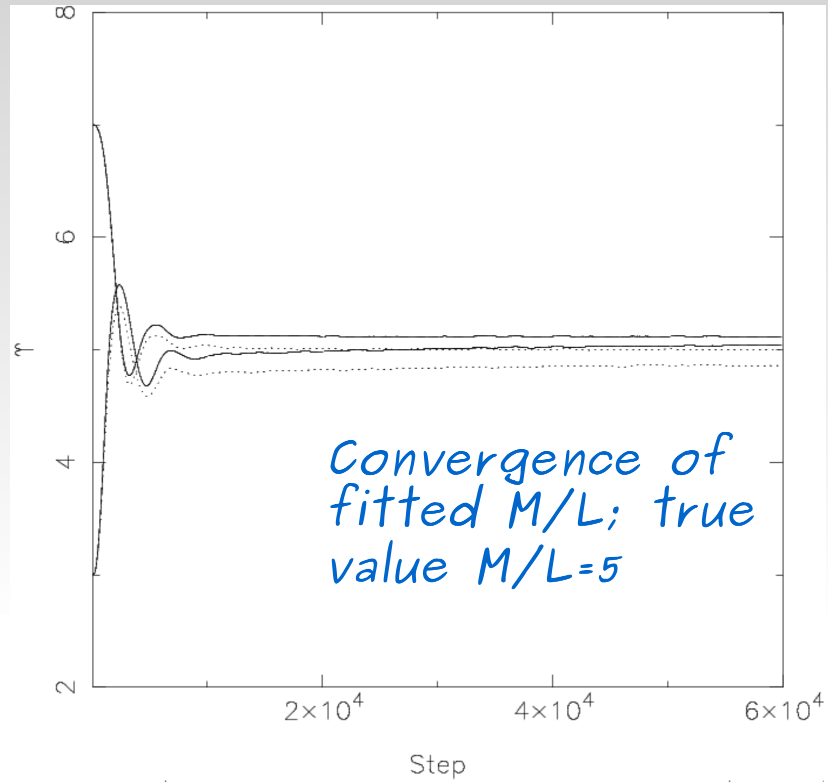
Define a force-of-change (FOC) for the mass-to-light ratio Υ

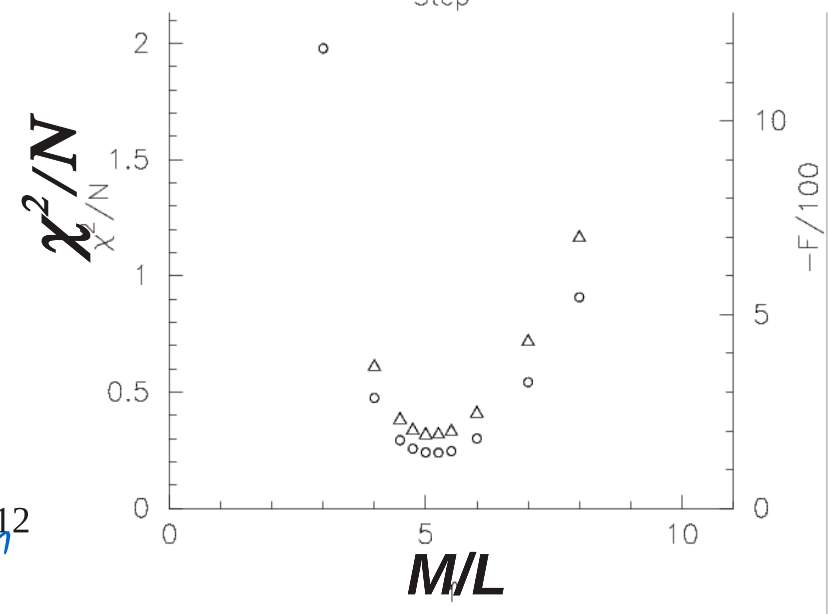
$$\frac{d\Upsilon}{dt} = -\eta\Upsilon \frac{\partial\chi^2}{\partial\Upsilon} = -\eta\Upsilon \sum_j 2\Delta_j(\Upsilon) \frac{\partial\Delta_j(\Upsilon)}{\partial\Upsilon}, \quad (2)$$

$$\frac{1}{2}\frac{\partial\chi^2}{\partial\Upsilon} = \sum_j \frac{\Delta_j(\Upsilon)}{\sigma(B_{n,p})} \frac{\partial b_{n,p}}{\partial\Upsilon}, \quad j = \{n, p\} \quad (3)$$

where $B_{n,p}$ is the target observable and $\sigma(B_{n,p})$ its error. E.g., use luminosity-weighted Gauss-Hermite moments, and $\partial v_{z,i}/\partial\Upsilon = v_{z,i}/2\Upsilon$ for $v_{z,i}$ given in physical units.

Scheme can be understood as a gradient search along the $\chi^2(\Upsilon)$ curve when simultaneously the particle model is fitted to the observational constraints.





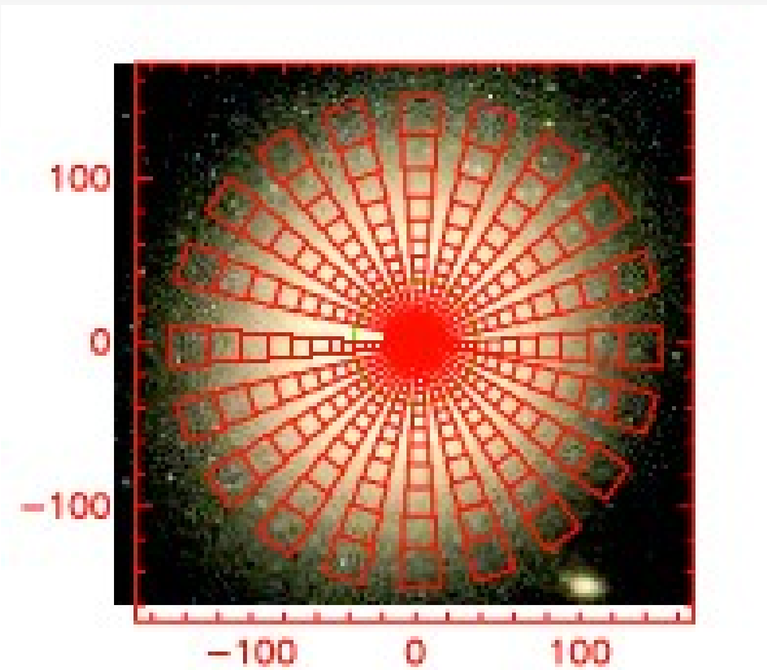
χ^2 of models with different M/L

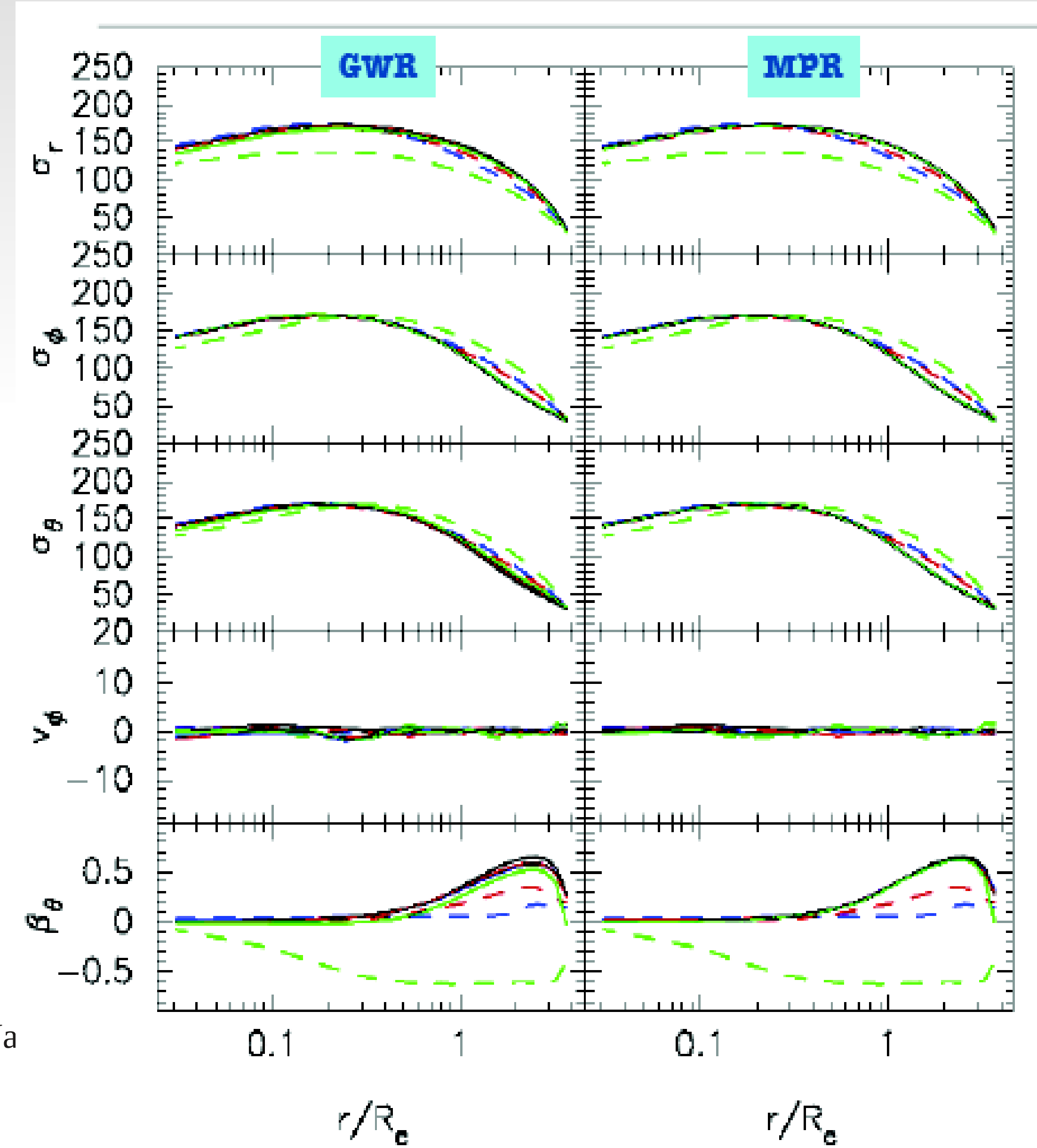
De Lorenzi et al. 2008

Recovering the unique solution

In theory, in the spherical non rotating case, if the potential is known a unique inversion of the data exists (Dejonghe & Merritt 92).

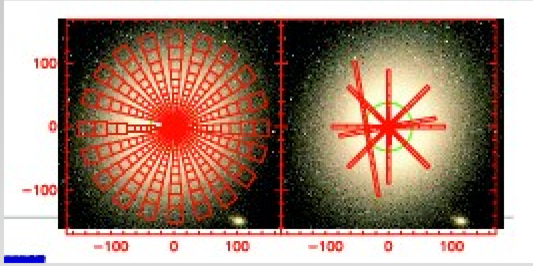
Target models are constructed with both idealized and realistic data.



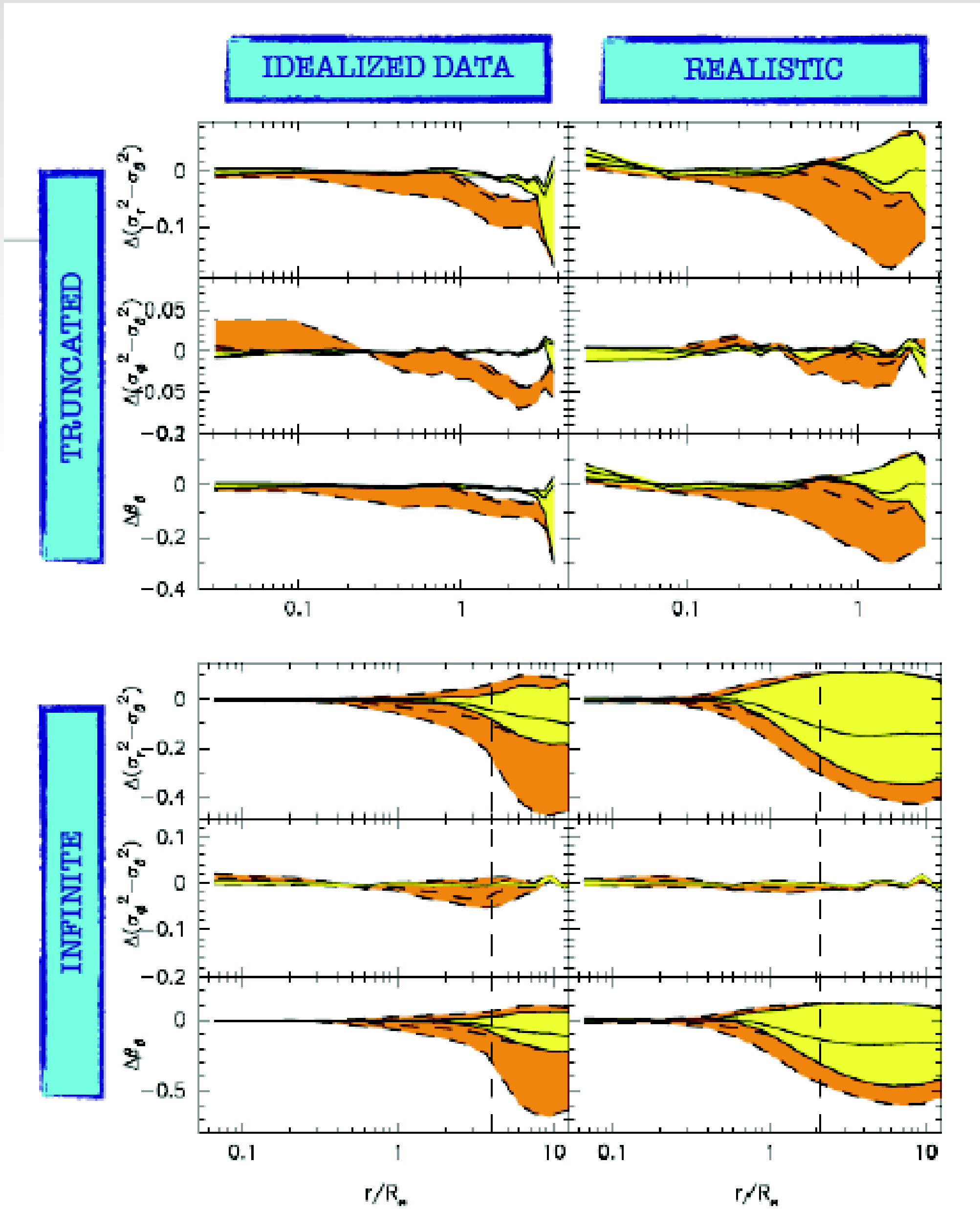


Martinez-Va

Morganti & Gerhard 2012



Recovering the unique solution



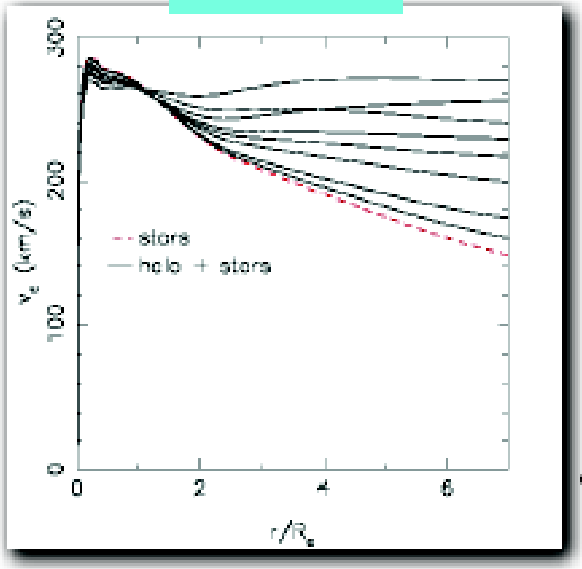
- For a truncated spherical target galaxy with idealized data, NMAGIC models show that the target can be recovered accurately and independent on the initial particle model, specially for the MPR.
- Lack or poor quality of the data introduce degeneracies in the dynamical modelling results, and a dependence on the initial particle model.
- The reliability of the models is limited to those regions in which good observational data exist.

Morganti & Gerhard 2012

Applications of M2M/NMAGIC:
Halos of Intermediate Luminosity Ellipticals

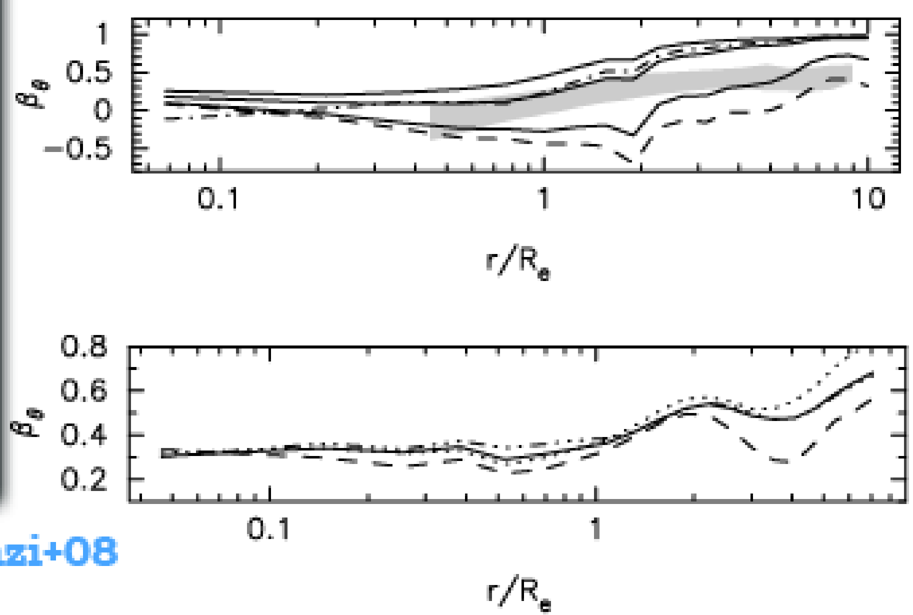
A range of potentials and anisotropy profiles are consistent with photometric and kinematic data

NGC 4697

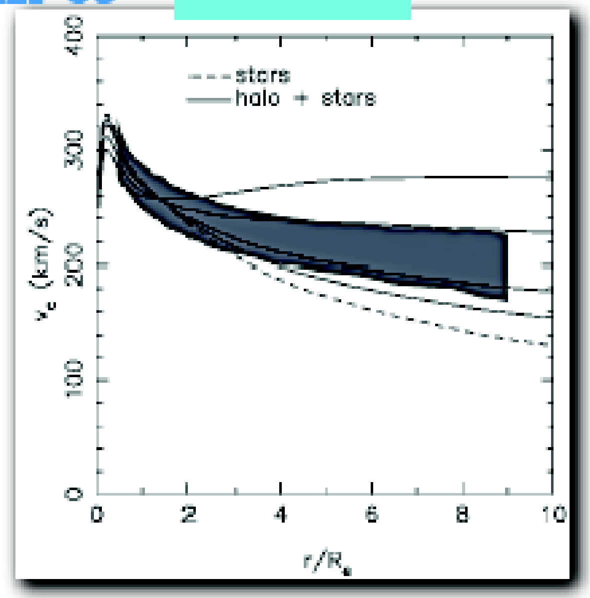


de Lorenzi+08

de Lorenzi+09



NGC 3379



No higher order moments of LOSVD for PNe → Mass-anisotropy degeneracy

M2M: Applications.

Milky Way (Bissantz et al. 2004, Rattenbury et al. 2007)

- Self consistent numerical simulation
- OGLE proper motion data
- Rough agreement with observations.
- The model seems more anisotropic than the data
- Variation field-to-field in proper motion dispersions.

Draco (Long & Mao 2010):

- 159 line-of-sight stellar velocities with errors
- Isotropic velocity dispersion model
- 539±136MSun/LSun

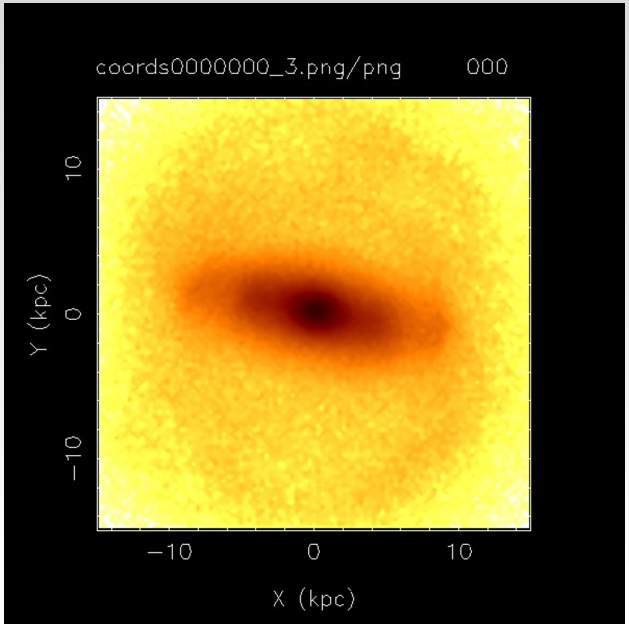
Elliptical and lenticular galaxies (Long & Mao 2012):

- 24 elliptical and lenticular galaxies. SAURON data
- (M/L)M2M~(M/L)Sch
- Fewer of the M2M-models tangentially anisotropic by comparison with their SAURON Schwarzschild counterparts.

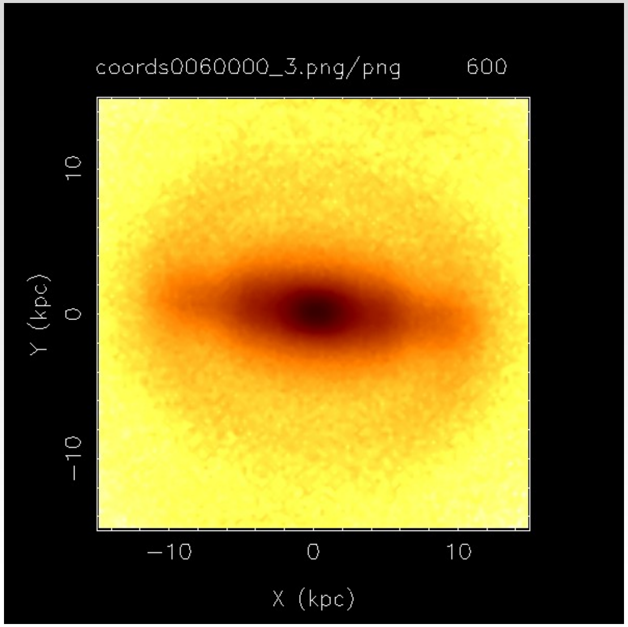
M2M/NMAGIC model of barred galaxies

Initial Model

Target Model

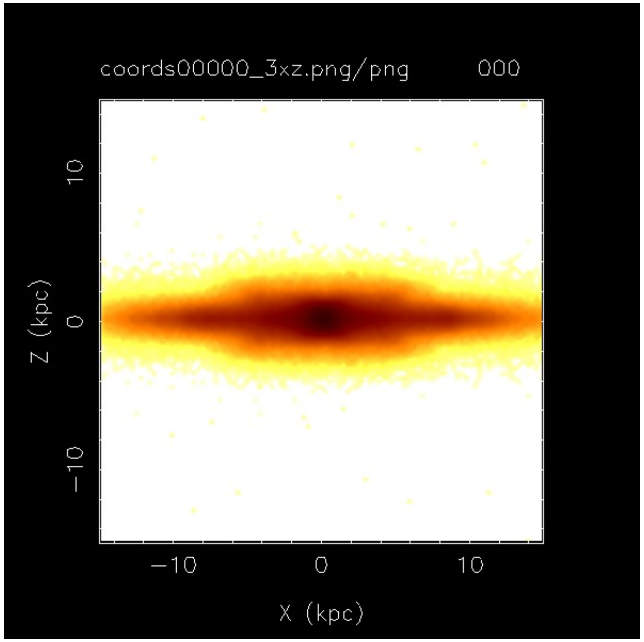


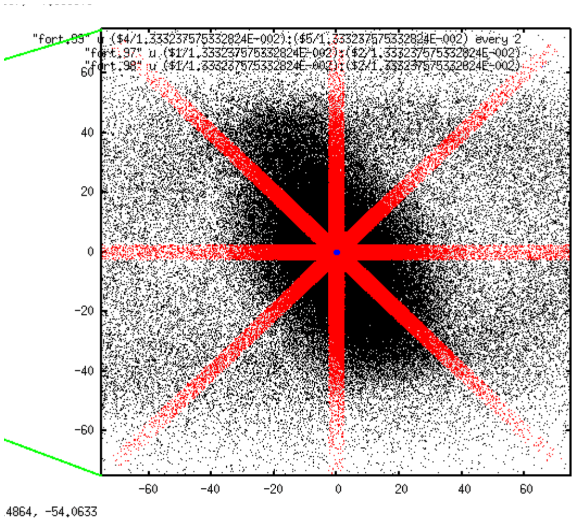
Observables

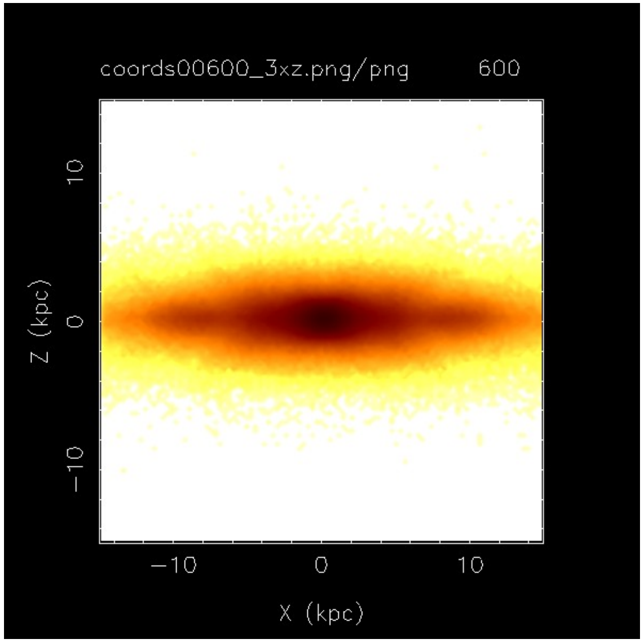


ALMs

Slits



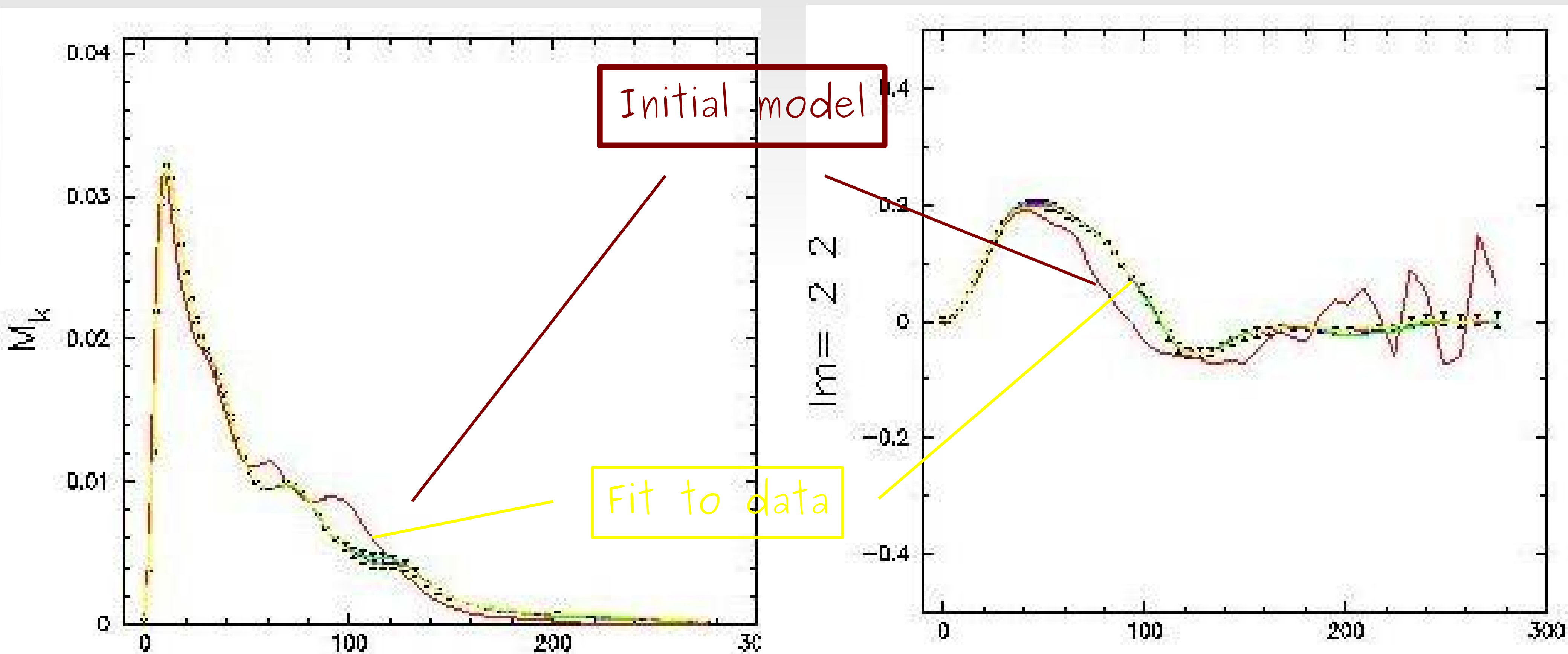




From model to model: Light

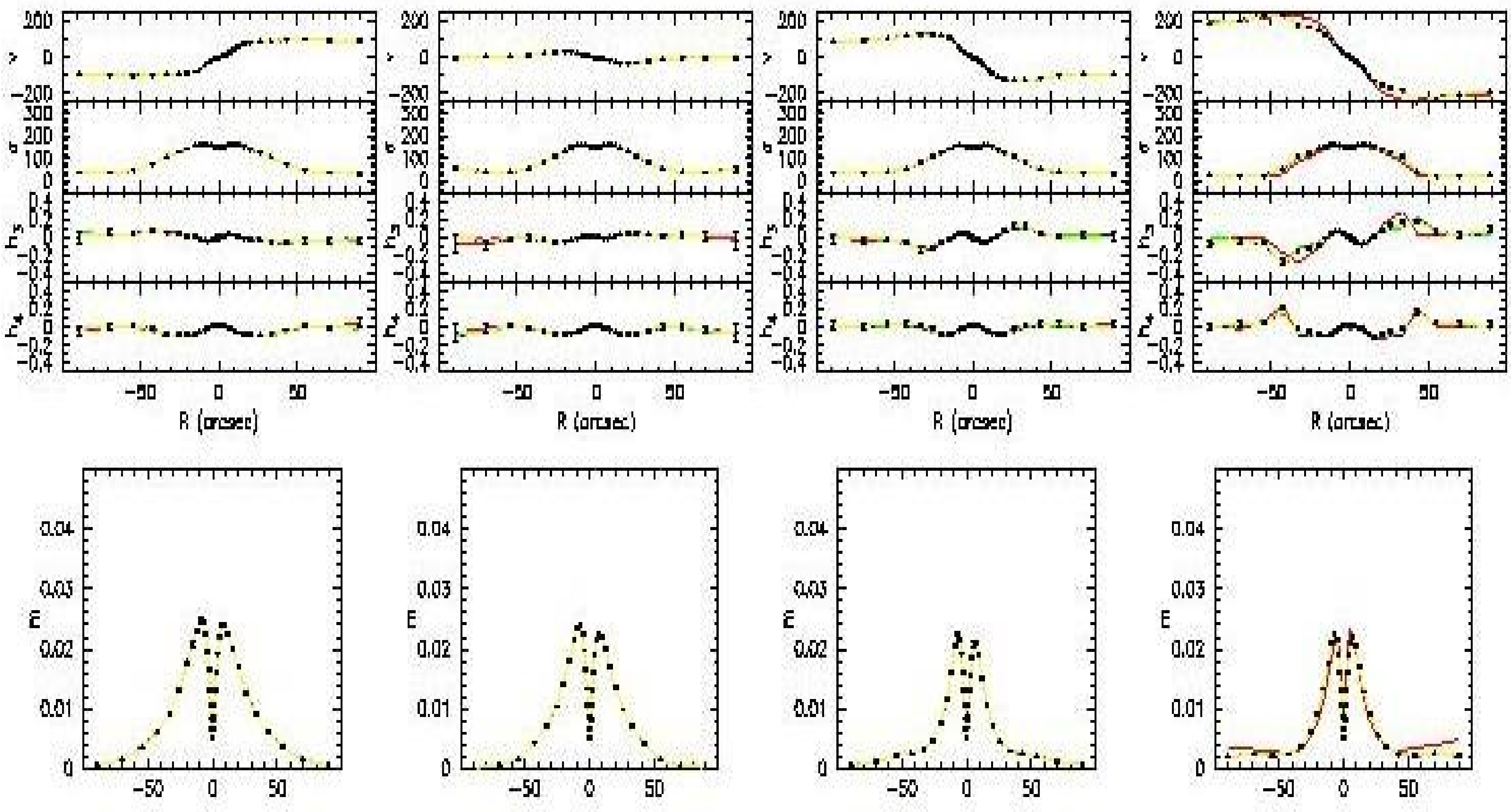
Mass distribution in spherical shells

Mode 2, equivalent to bar strength

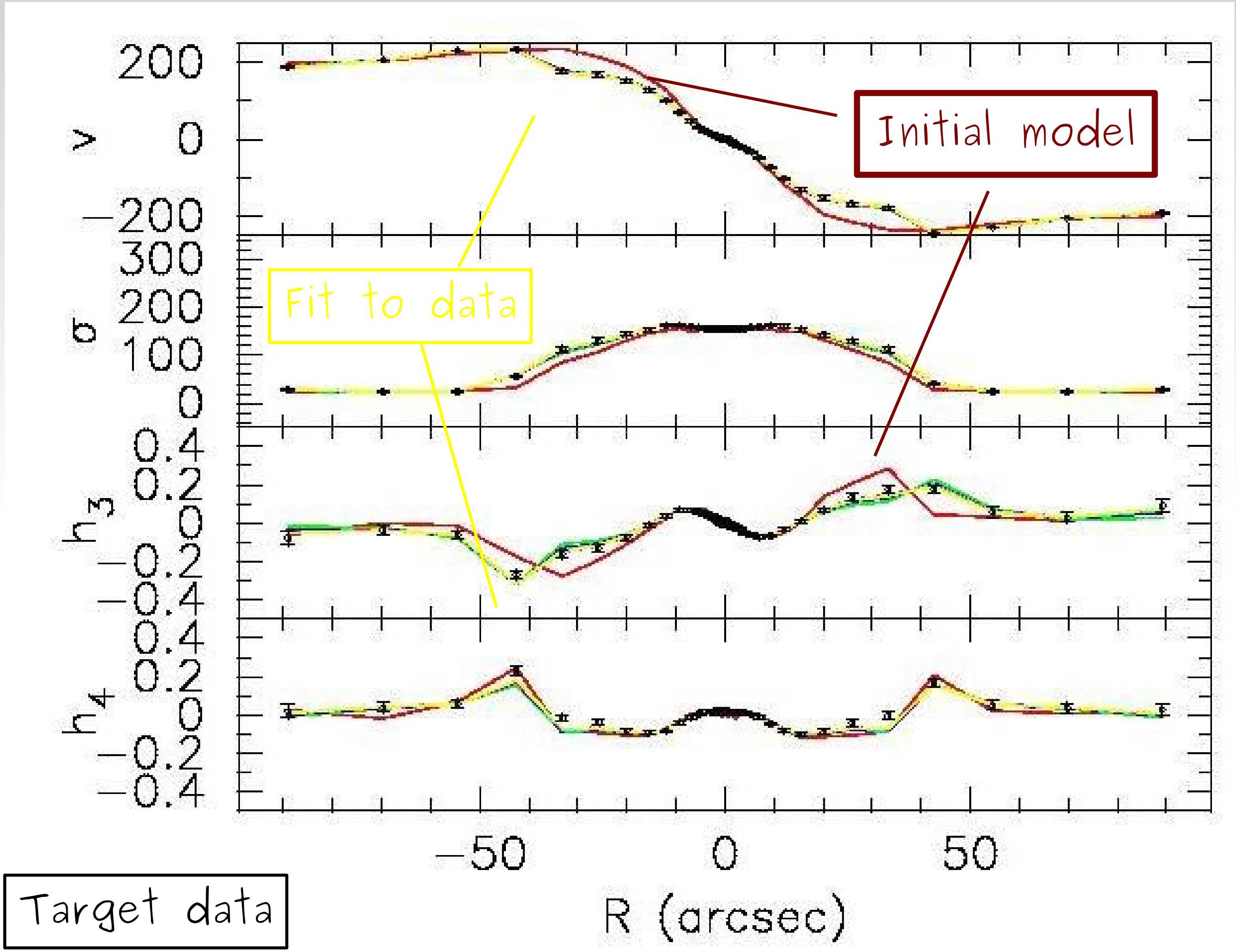


Target data

From model to model: Slit kinematics

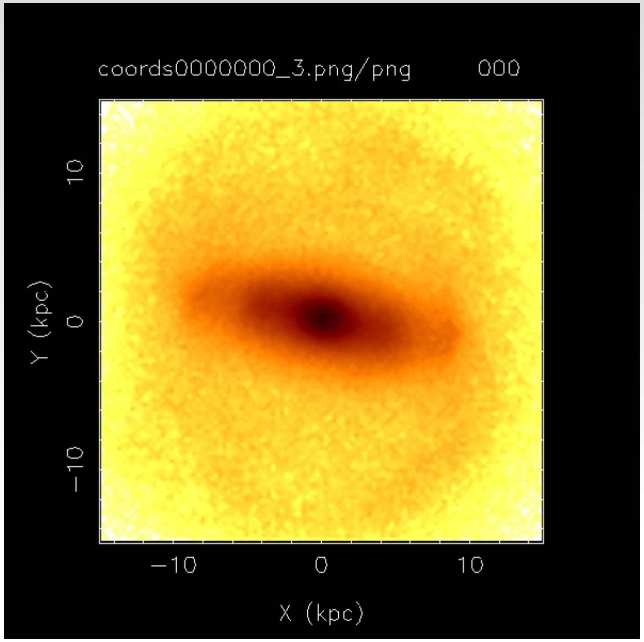


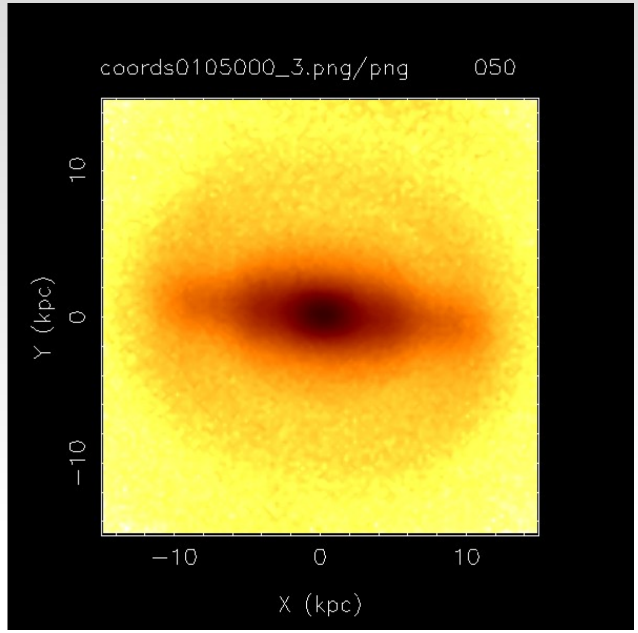
From model to model: Slit kinematics

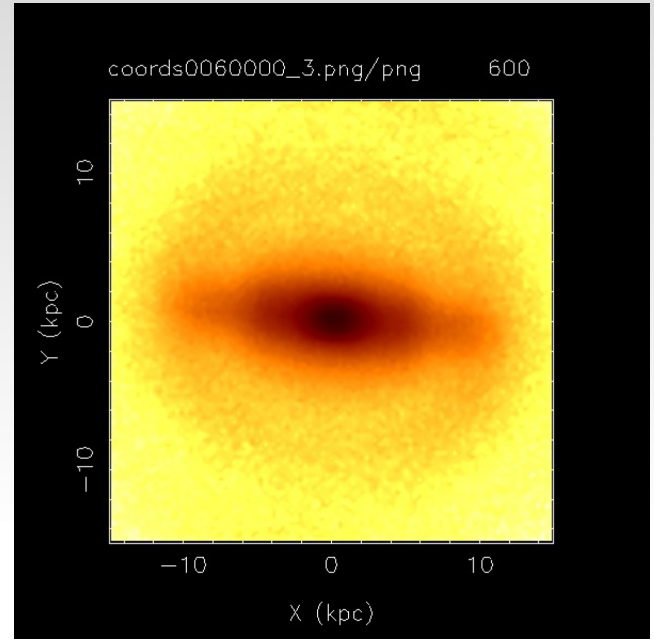


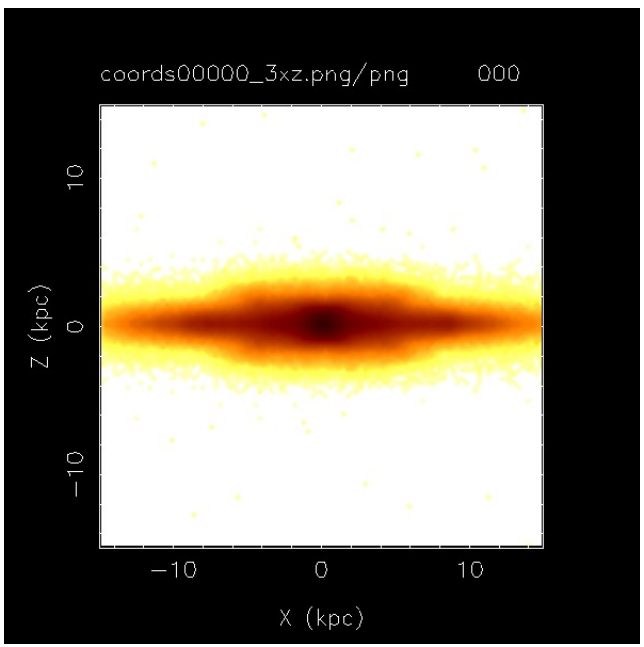
From model to model

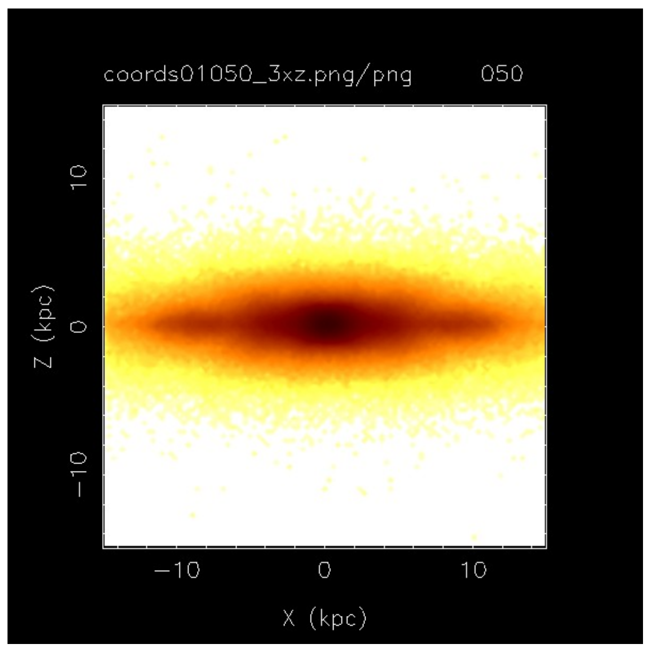
Initial Model	Final Model	Target Model

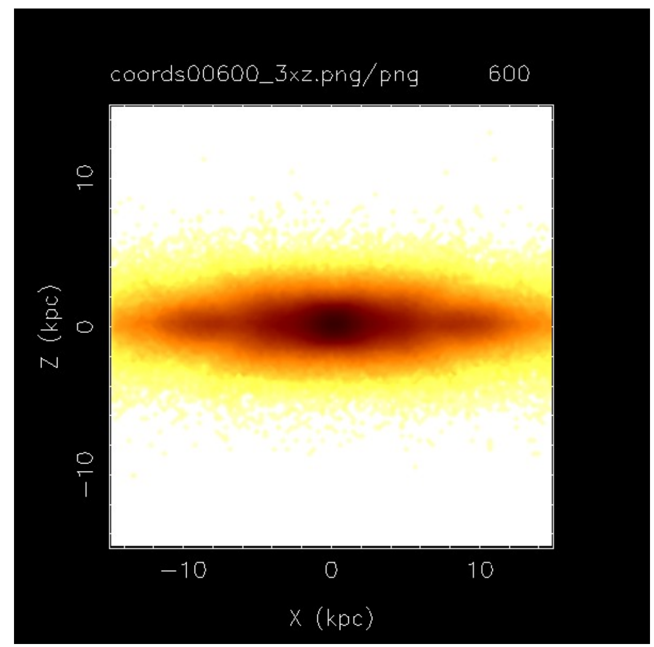










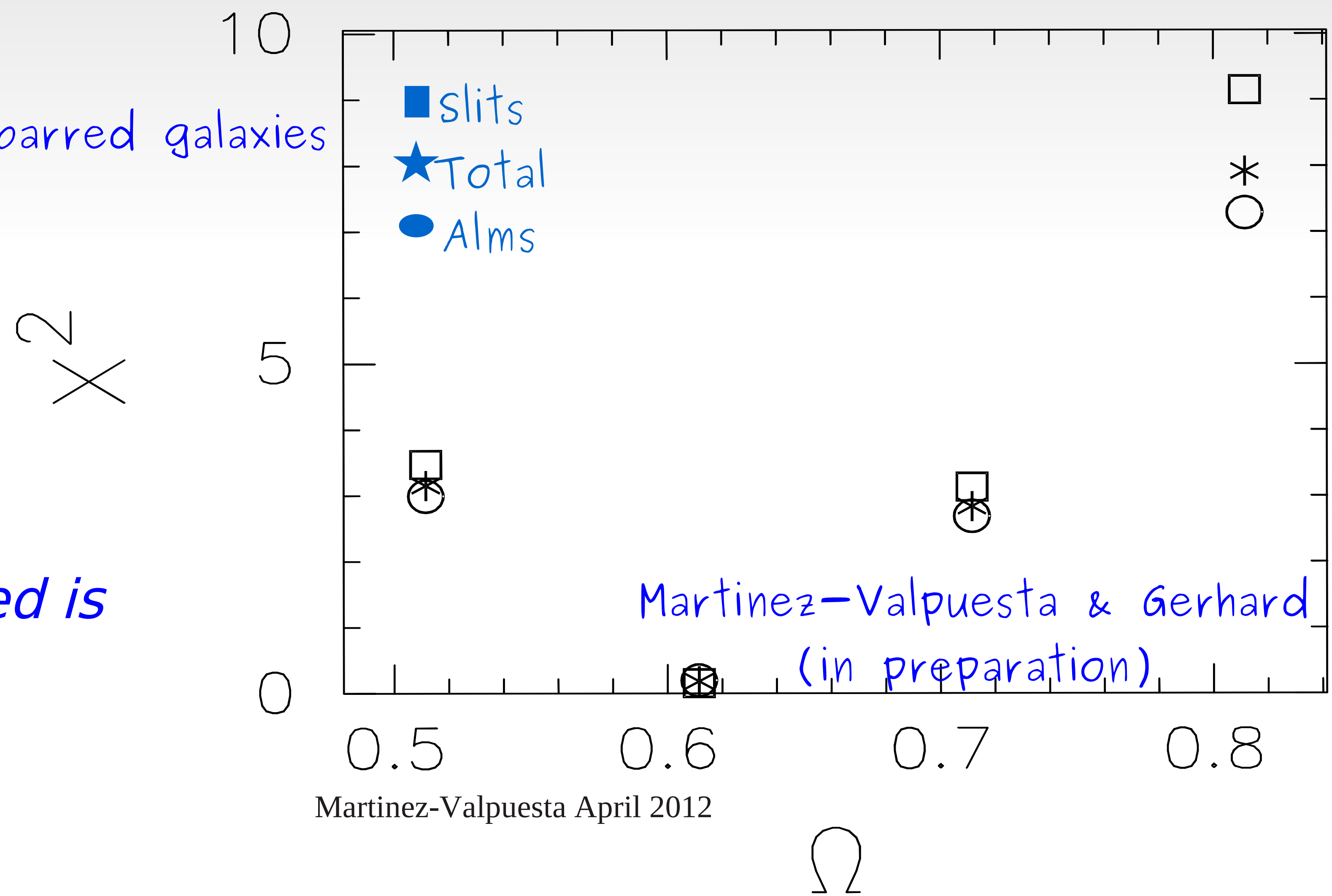


Applying NMAGIC to find the pattern speed of bars

The pattern speed of observed bars has been an issue for long time.

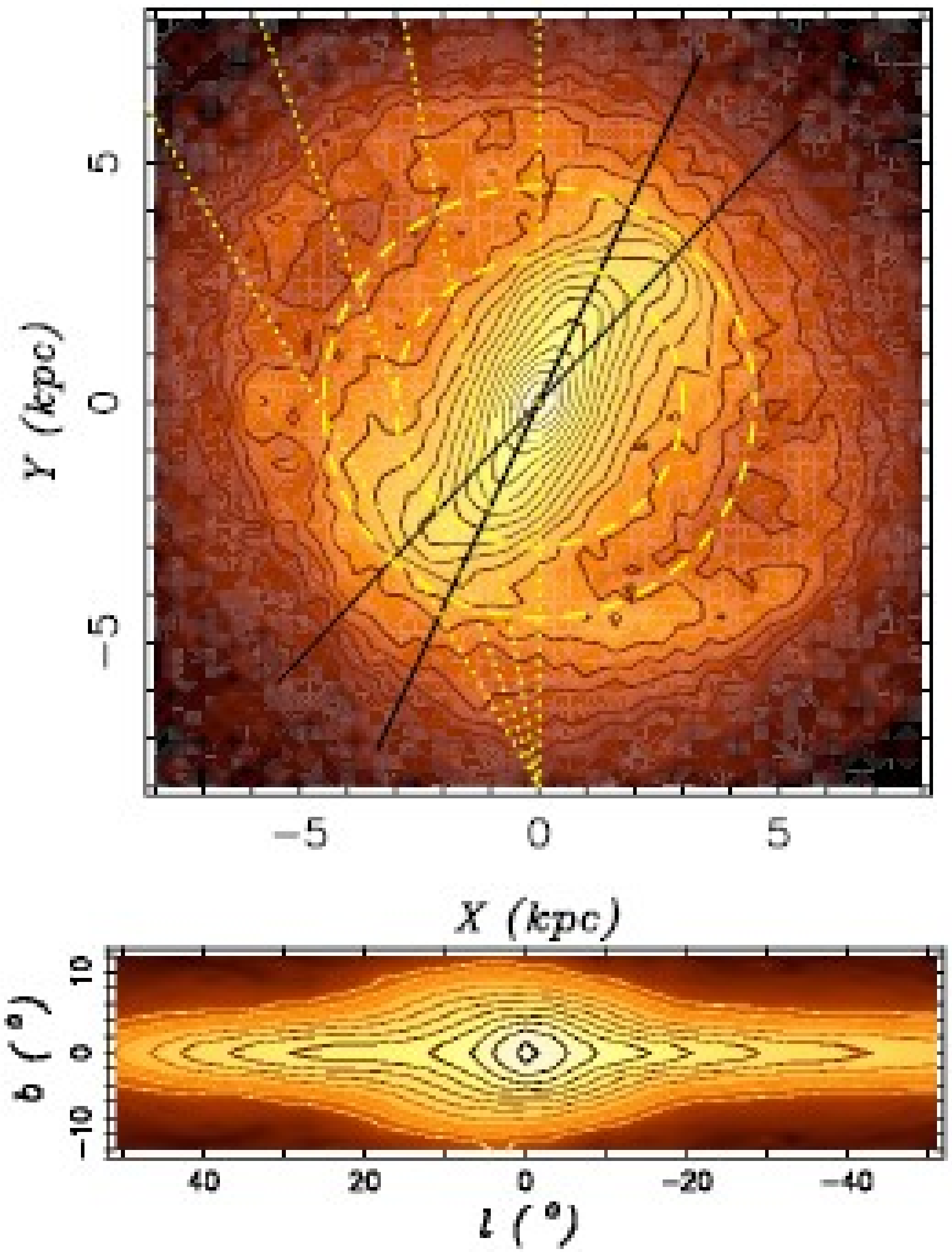
There are two main ways: resonances and Tremaine-Weinberg

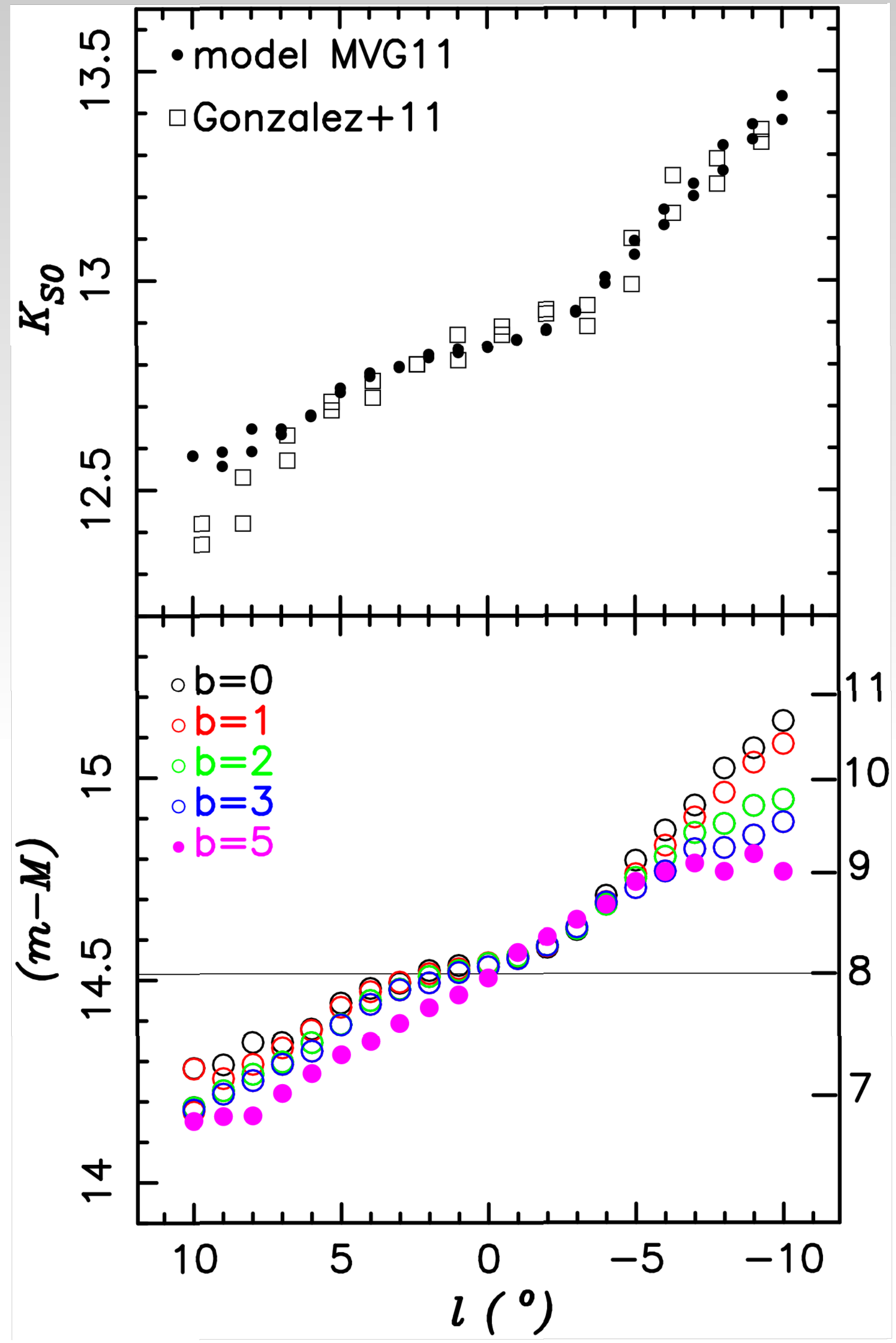
NMAGIC fit to barred galaxies



Our target pattern speed is 0.61.

A dynamical model for the MW



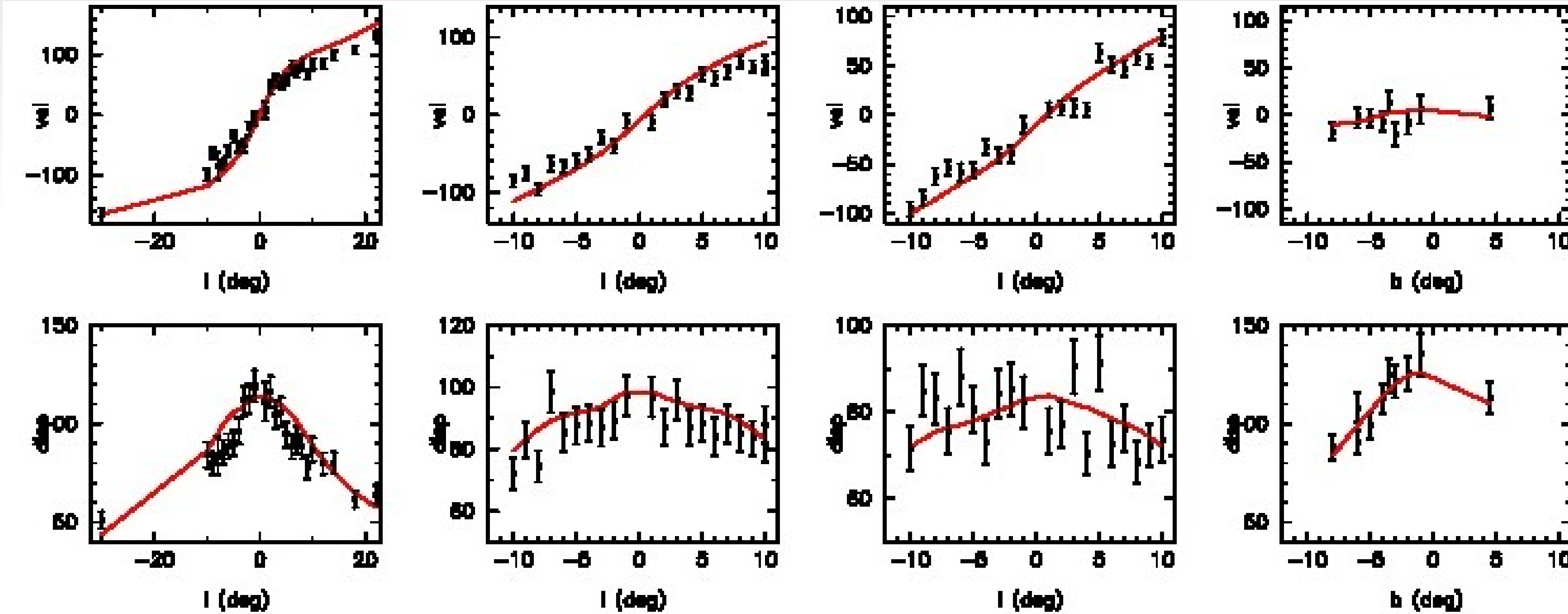


Martinez-Valpuesta & Gerhard, 2011, ApJ Letters, 734,20

Gerhard & Martinez-Valpuesta 2012, ApJ Letters, 744,8

Model describes structure of bulge well. Next question is whether also the kinematics can be understood...

b=-4 b=-6 b=-8 Minor axis

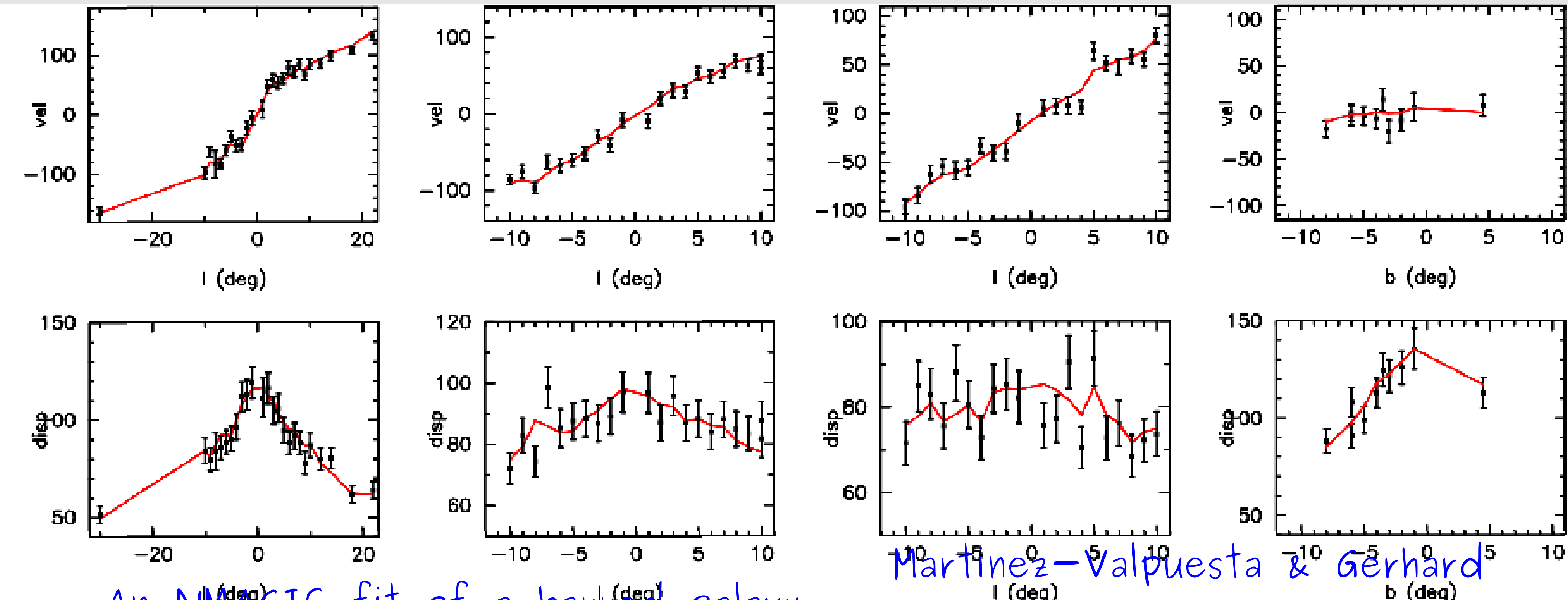


Data points from the **BRAVA** survey Kunder et al. (2012)

NMAGIC starting with the previous model, fits and reproduces the kinematics of the Milky Way.

48CPUS~2.2hours

b=-4 b=-6 b=-8 Minor axis



An NMAGIC fit of a barred galaxy simulation MV&G+2011 to BRAVA data

Martinez-Valpuesta & Gerhard (in preparation)

Data points from the **BRAVA** survey Kunder et al. (2012)

The resulting model is slightly more boxy. Work in progress

Summary

- M2M/NBODY methods are a powerful tool to obtain dynamical models from complex data.
- Some degeneracy still remains when the data are incomplete.
- MPR entropy smoothing helps to obtain unbiased smooth models.
- M2M can be applied to ellipticals and barred galaxies.
- M2M/NMAGIC can be applied to discrete kinematic tracers.
- M2M/NMAGIC can be used to get an accurate dynamical model for our Milky Way.