Made-to-Measure (M2M)
Dynamical modelling of external galaxies and the Milky Way

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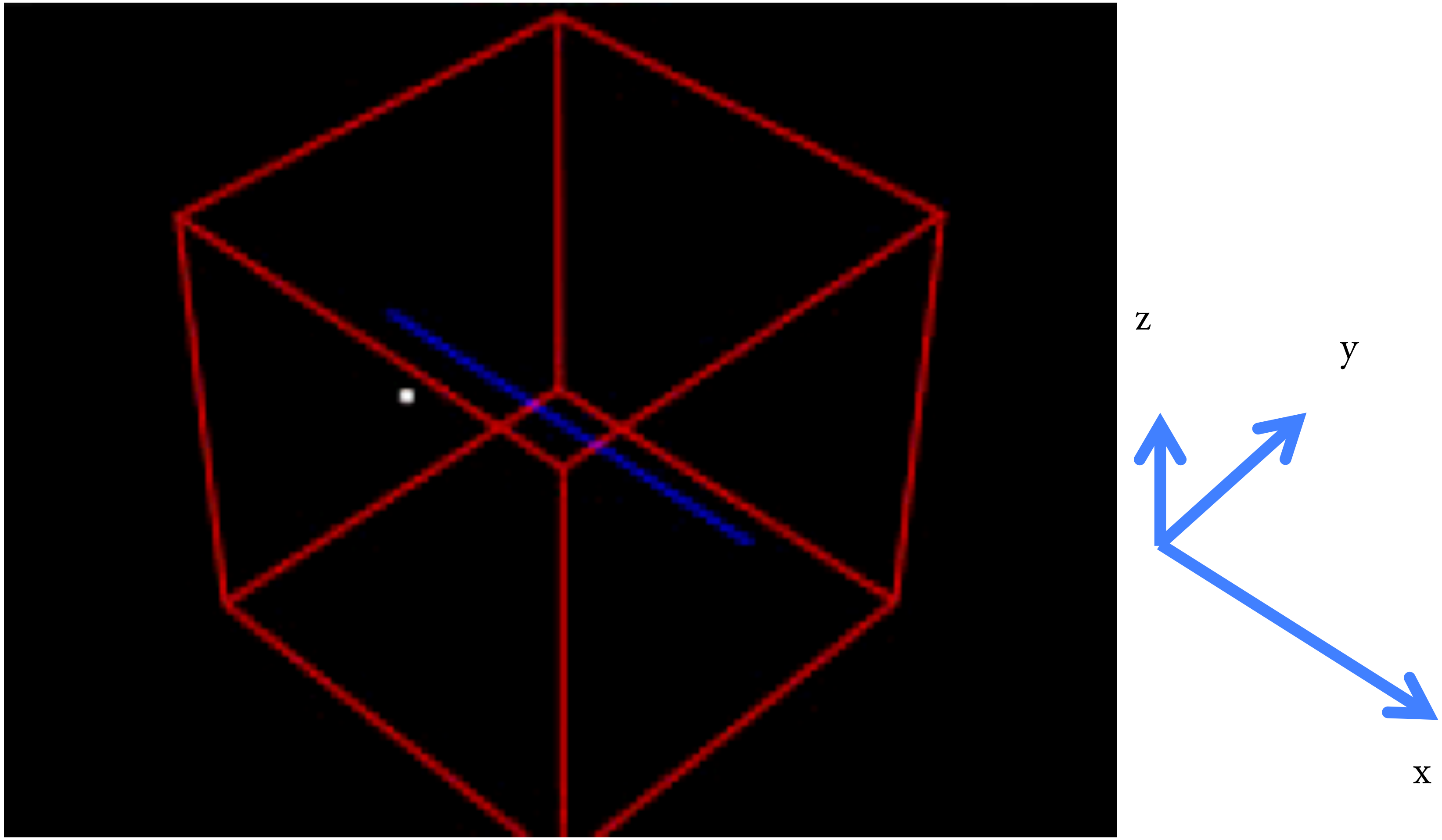
Motivation

- Important for
  - inferring mass (dark matter) distribution: shape, radial profiles, central supermassive black holes
  - establishing scaling relations, and finding clues for galaxy formation and evolution
- much better data becoming available
  - Milky Way: BRAVA, ARGOS, APOGEE, OGLE (proper motions), GAIA
  - External galaxies (IFUs): SAMI, MANGA
- Require better modeling techniques which will also guide observations

How to perform dynamical modelling?

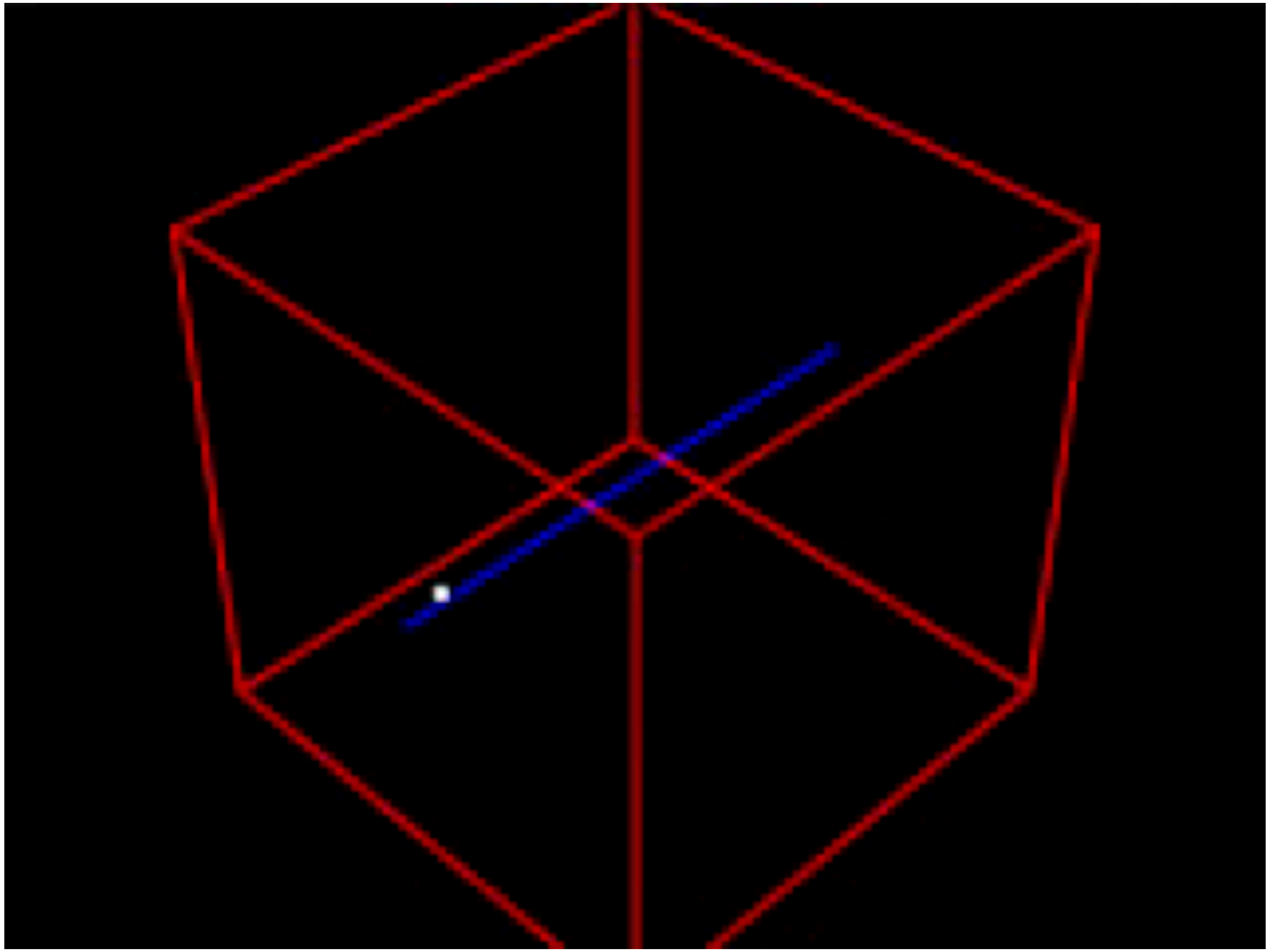
- Jeans equation
- Schwarzschild method: Orbit based method
- Made-to-Measure (M2M): Particle based method
- Torus Method
- In the last three methods, orbits play essential roles

Orbits in 3D triaxial potentials



- short-axis (z-) tube orbits (from Barnes)

Orbits in 3D triaxial potentials

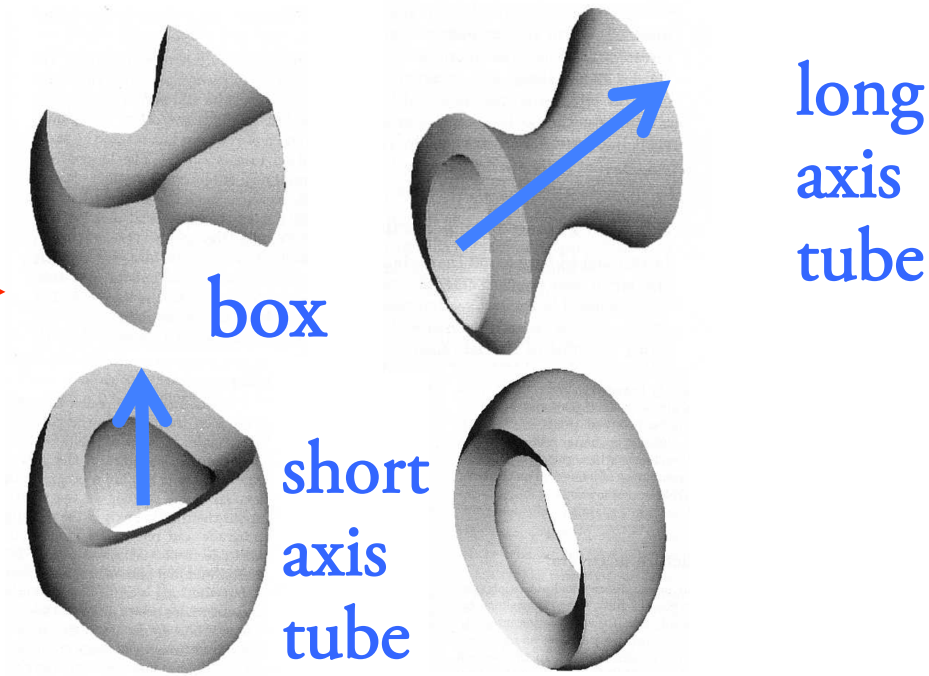


- box orbits (from Barnes)

Schwarzschild Method

$\rho_L \rightarrow \rho \rightarrow \phi$

orbits



+Chaotic orbits

- Schwarzschild (1979)
  - Orbit individual particles
  - End of run, use linear / quadratic programming to determine weights of different orbits
  - Well established (applications: black hole/galaxy masses)

[See Yougang Wang's talk tomorrow]

Made-to-Measure Method

(Syer & Tremaine 1996)

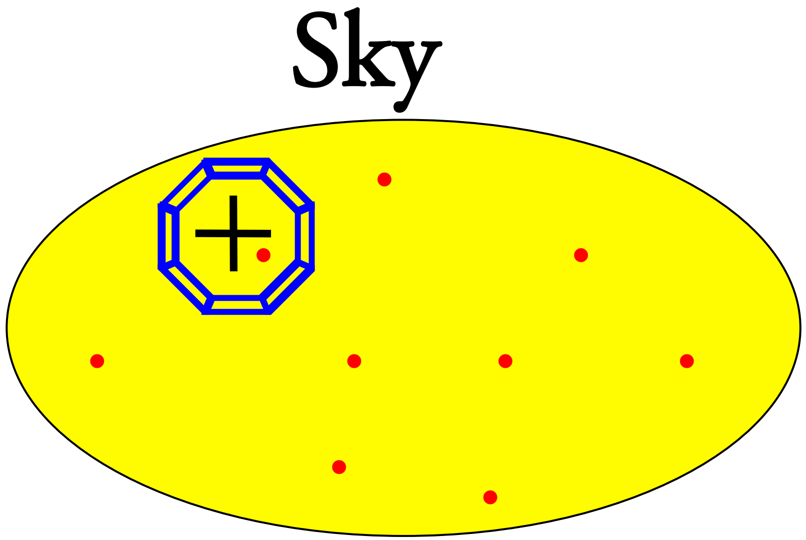
- Orbit system of particles
- Inflight weight adjustment to reproduce observations (not at the end)
- More flexibility than Schwarzschild's method
- Cross-checks on the Schwarzschild method: degeneracy?

Actual Observables

- Examples
  - Surface brightness
  - Mean line-of-sight (los) velocity
  - Los velocity dispersion
  - Los velocity distribution
    eg h3 (skewness), h4 (kurtosis)

- Also los velocities of individual stars, globular clusters

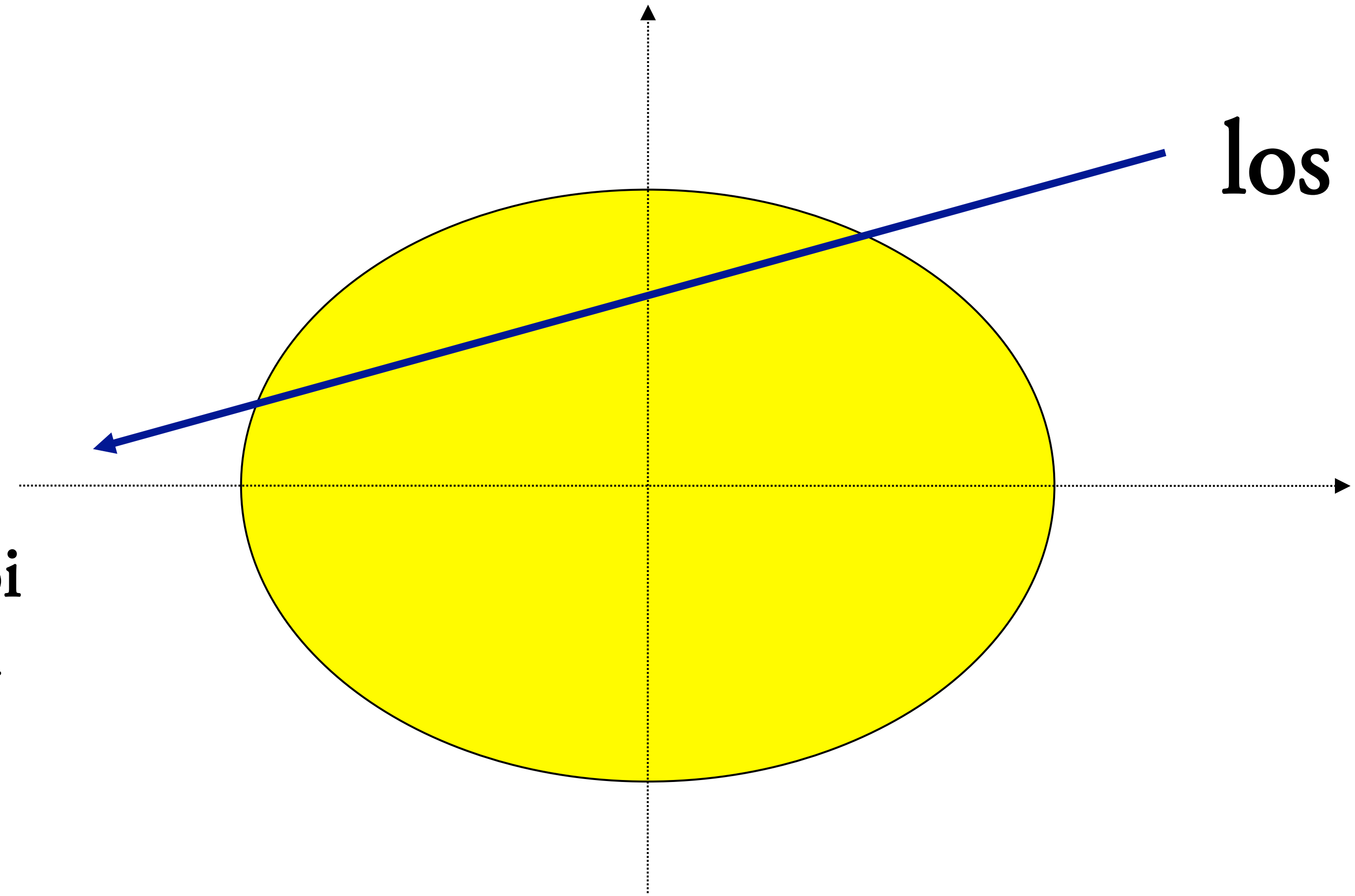
- Kinematics are luminosity weighted



In a given potential

- N (~10^6) particles are orbited
- Particle weights adjusted as a function of time

- **Regular**
  - Cartesian, polar, logarithmic in radius
- **Irregular**
  - e.g. from Voronoi binning of actual data



Model Observables

$$\bar{v}_{los,j} = \frac{\sum_i^N w_i v_{los,i} \delta_{ij}}{\sum_i^N w_i \delta_{ij}}$$

$$\bar{v}_{los,j} = \sum_i^N w_i \frac{v_{los,i}}{I_j A_j} \delta_{ij}$$

Position = j

Number of particles = N

Individual particle = i

$$y_j = \sum_i^N w_i K_{ji}$$

Kernel:

- Surface brightness
- Average velocity, dispersion, …

Weight Evolution

Weight evolution equation (Syer & Tremaine 96):

$$\frac{dw_i}{dt} \propto -\varepsilon w_i \left(\sum_j^J K_{ji} \Delta_j \right), \ \Delta_j = \frac{y_j - Y_j}{Y_j}, \ \varepsilon > 0$$

When the predicted y_j > observed Y_j, weight is reduced, and vice versa, until convergence is reached.

(Syer & Tremaine 96; Bissantz et al. 04; De Lorenzo 07, 08; Dehnen 09; Long & Mao 10; Morganti & Gerhard 2012)

Weight Evolution

$$F(w) = -\frac{1}{2}\chi^2 + \mu S + \frac{1}{\varepsilon}\frac{dS}{dt}$$

$$\chi^2 = \sum_k^K \lambda_k \chi_k^2 \qquad S = -\sum_i^N w_i \ln\left(\frac{w_i}{m_i}\right)$$

$$\frac{dw_i}{dt} = -\varepsilon w_i \left(\sum_k^K \lambda_k \sum_j^J \frac{K_{k,ji}}{\sigma_{k,j}} \Delta_{k,j} - \mu \frac{\partial S}{\partial w_i} \right)$$

Particle Initial Conditions

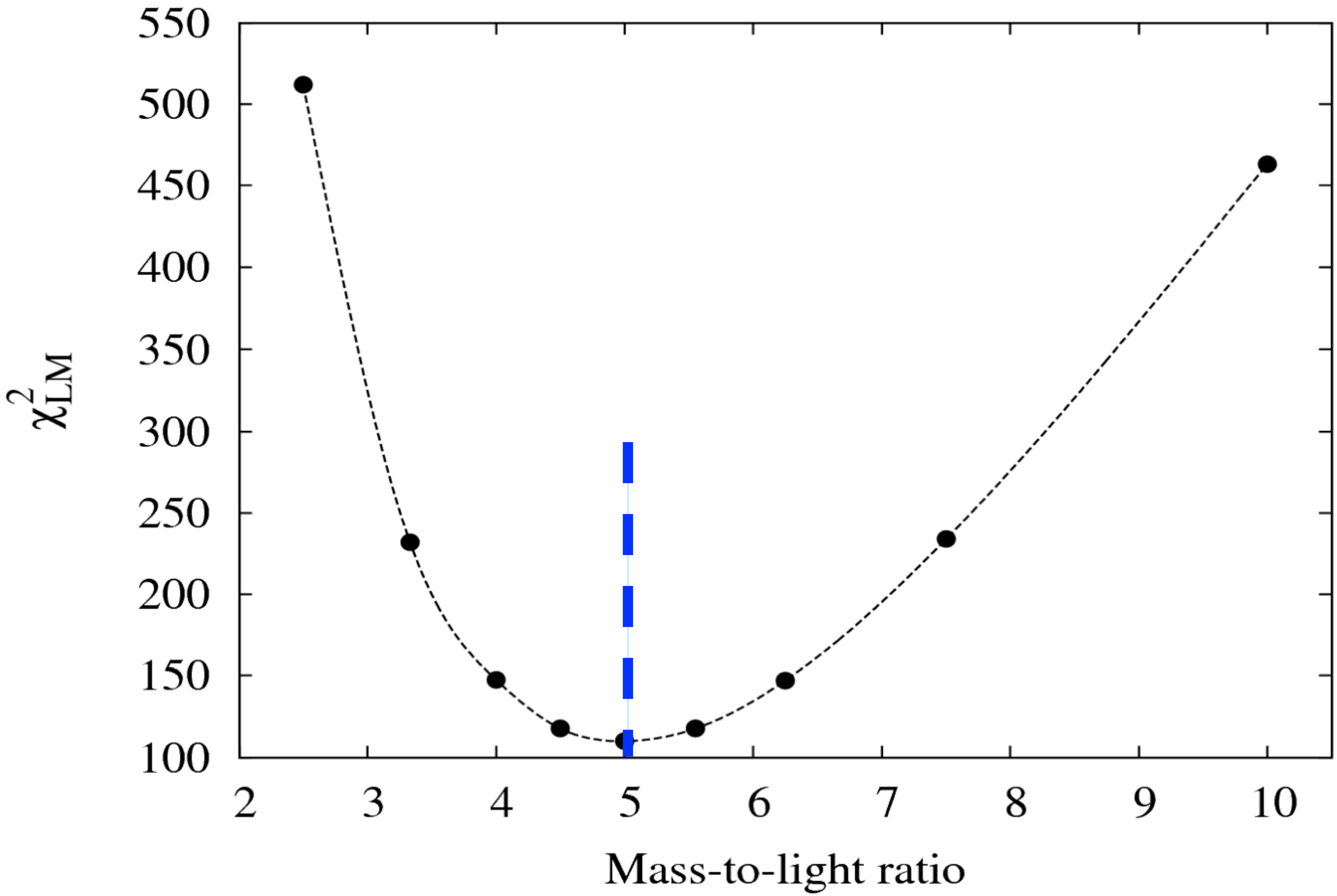
- Spatial coordinates match luminosity distribution

- Use (approximate) distribution function if available
- Sample integral space eg energy, angular momentum
- Velocity coordinates
  - Created using a given set of velocity dispersion functions eg from Jeans equations
  - Random

Mock Galaxy Model

- Plummer sphere $$\varphi(r) = -\frac{\mathrm{Y}}{\left(r^2+1\right)^{1/2}}$$
- Constructed mock data – surface brightness, los velocity dispersion, h4, isotropic dispersion
- Task:
  - use M2M to determine the mass-to-light ratio of the constructed data

M2M M/L = 4.97, Input: 5



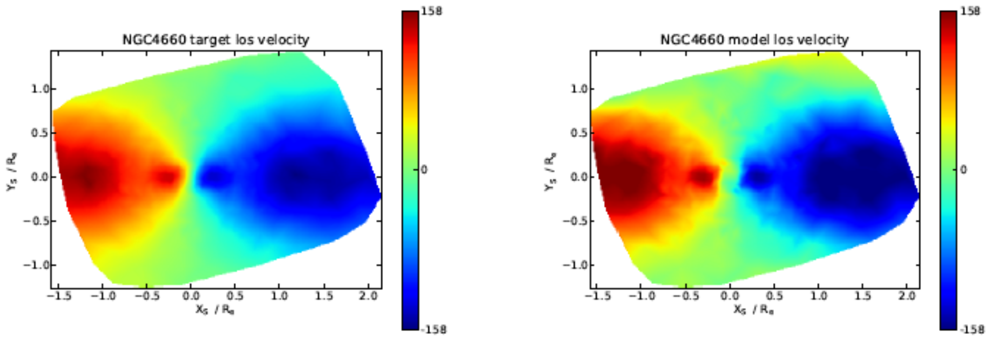
Long & Mao (2010)

Elliptical and Lenticular Galaxies

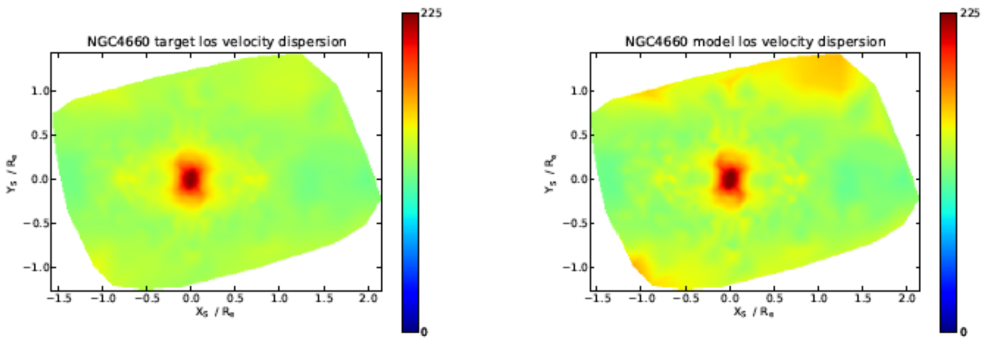
- Motivation
  - Compare M2M with Schwarzschild's method
- Based on Sauron data (Cappellari et al 2006)
  - 24 galaxies, fast / slow rotators, various kinematic features eg Kinematically Decoupled Cores (KDC), Counter Rotating Cores (CRC)
  - All have Sauron results
- M2M Implementation
  - MGE potential – interpolated acceleration tables
  - Voronoi binning – kdtree, nearest neighbour search
  - Rotation – set sign of v_theta appropriately

NGC 4660

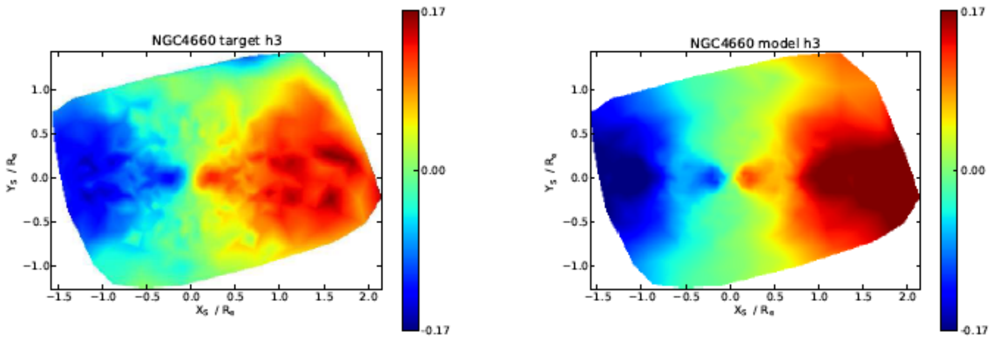
SB



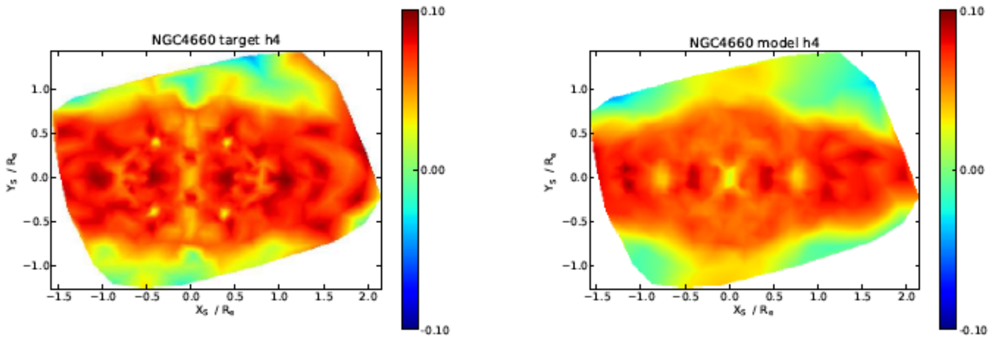
sigma



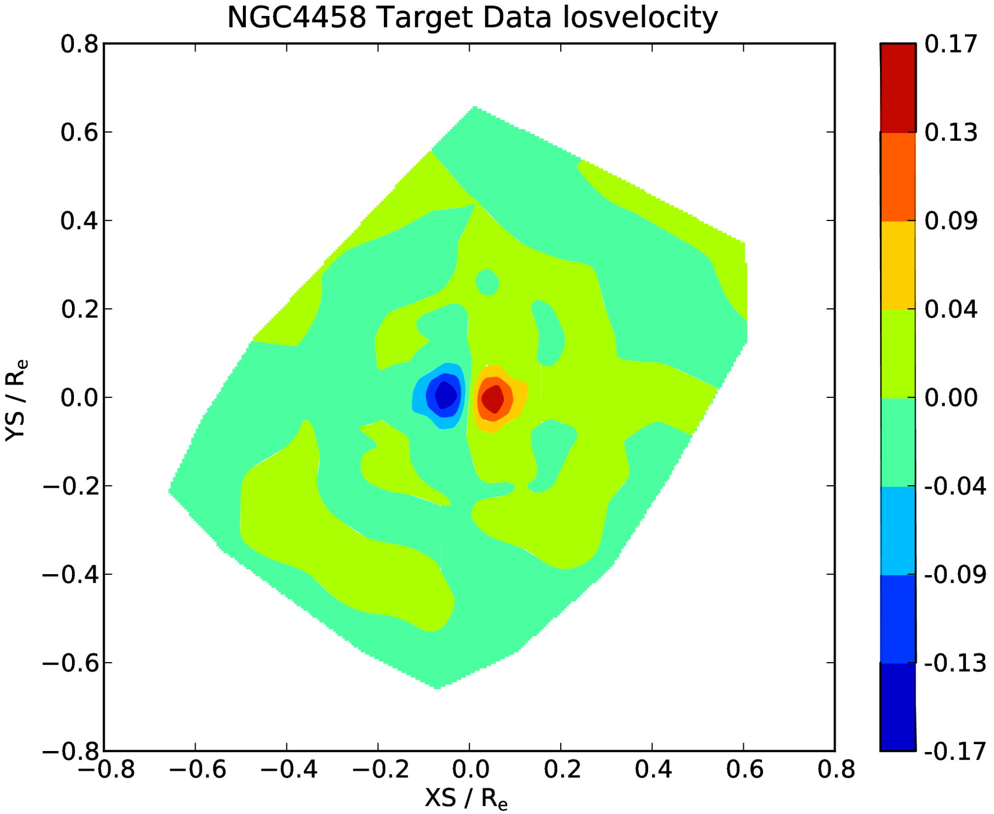
h3

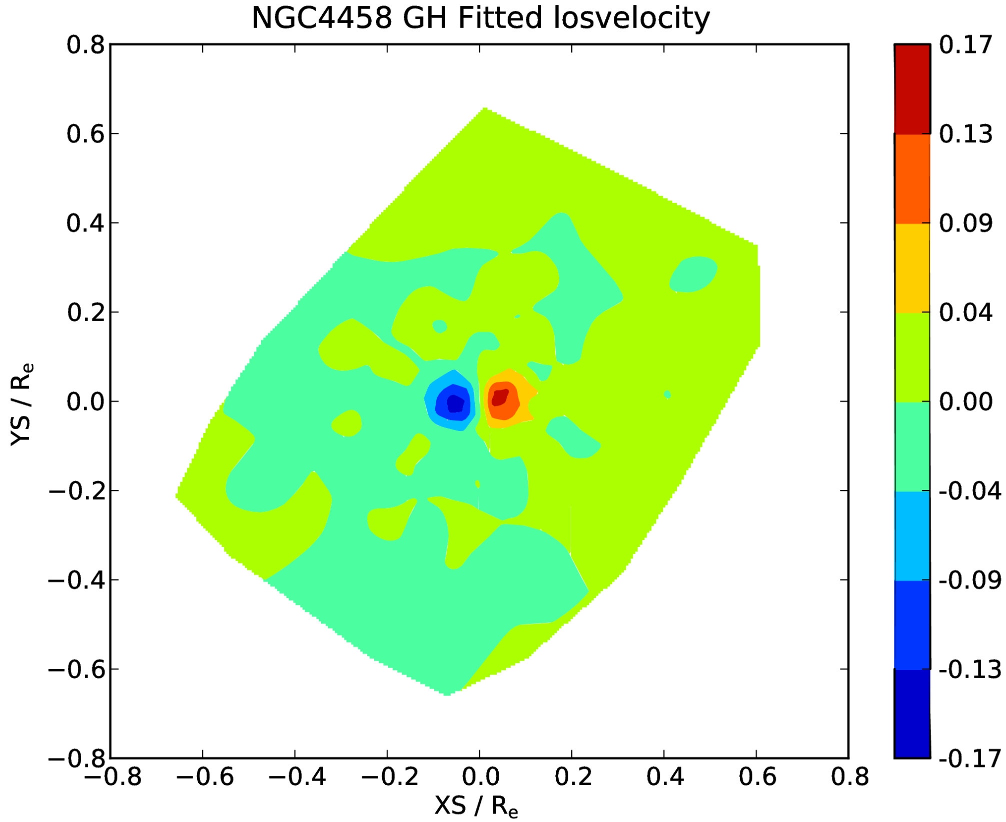


h4



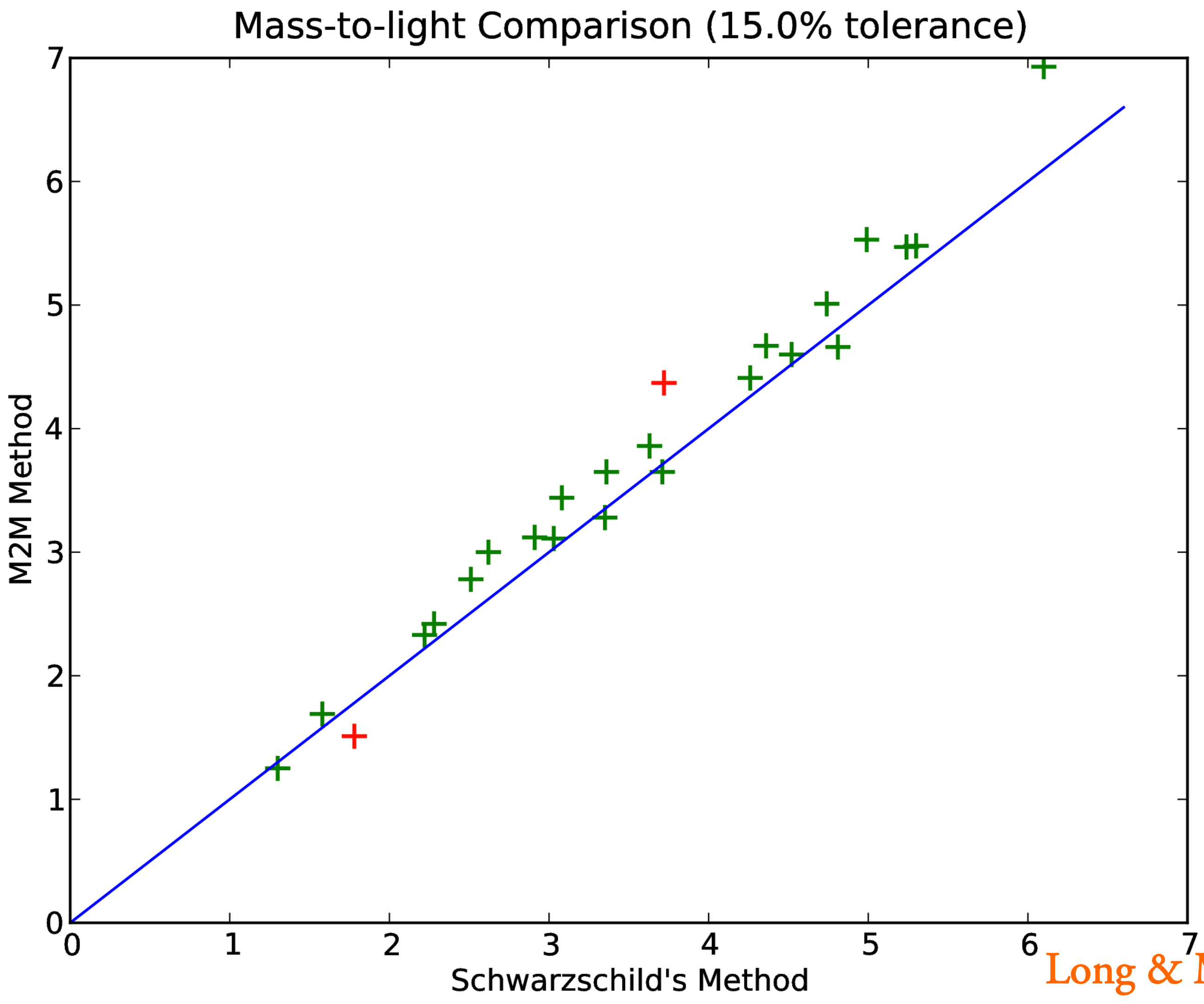
NGC 4458 - KDC





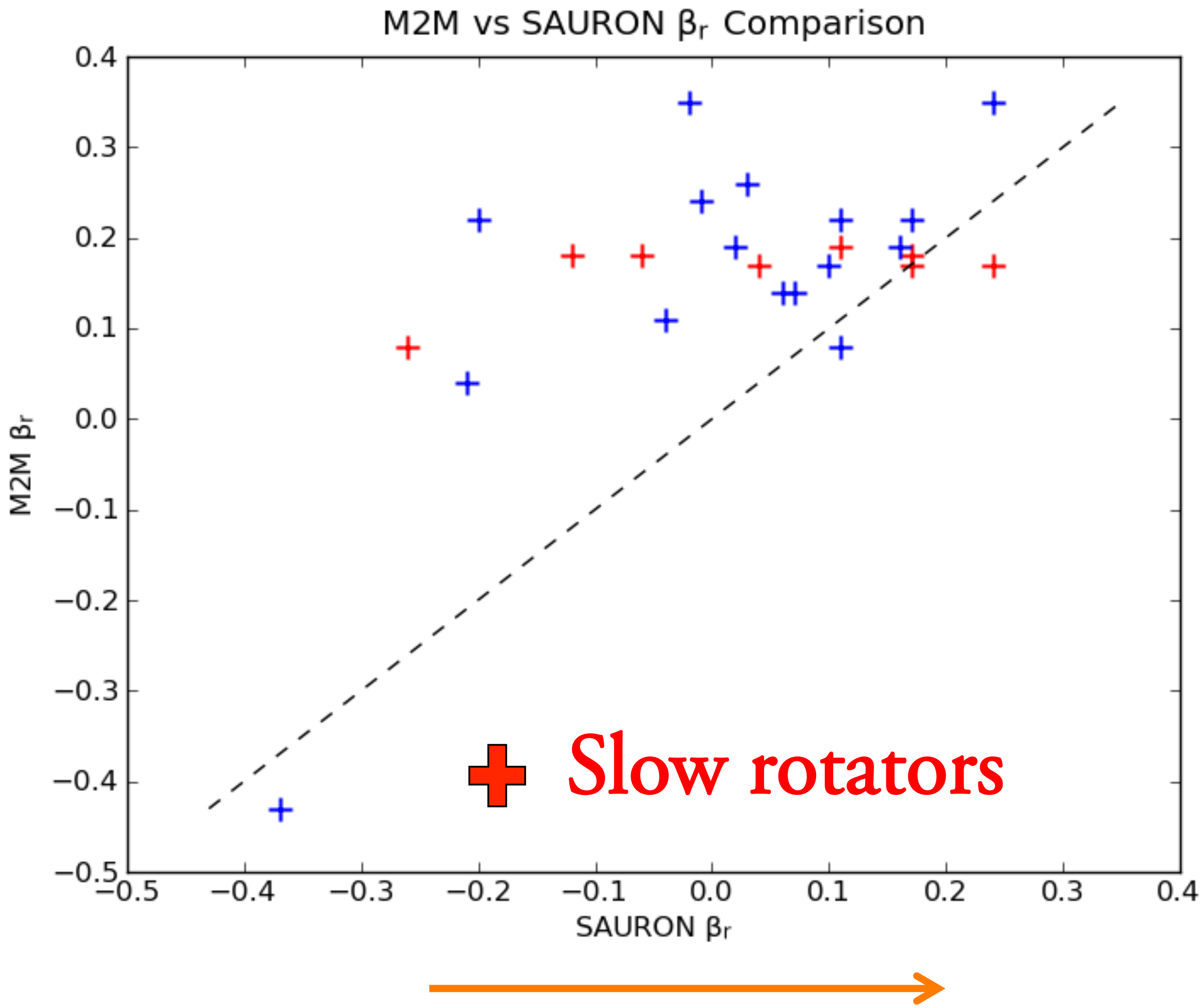
Can reproduce the kinematics well, e.g., Kinetically Decoupled Cores in NGC 4458

Mass-to-Light ratio: M2M vs. Schwarzschild



Long & Mao (2012)

Global anisotropy



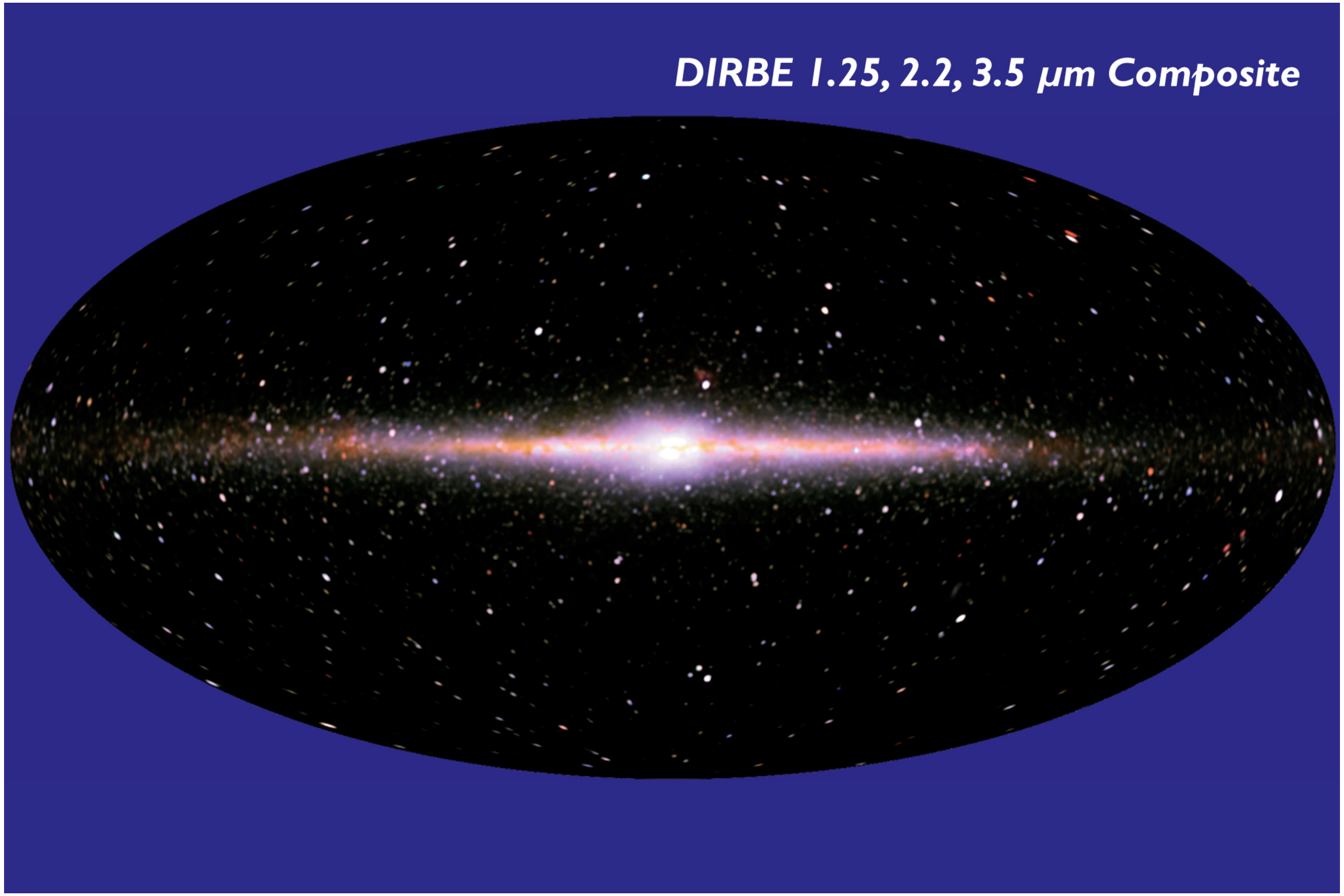
- M2M method more radially anisotropic
- Model not unique?

A larger value indicates more radial orbits

External galaxies: summary

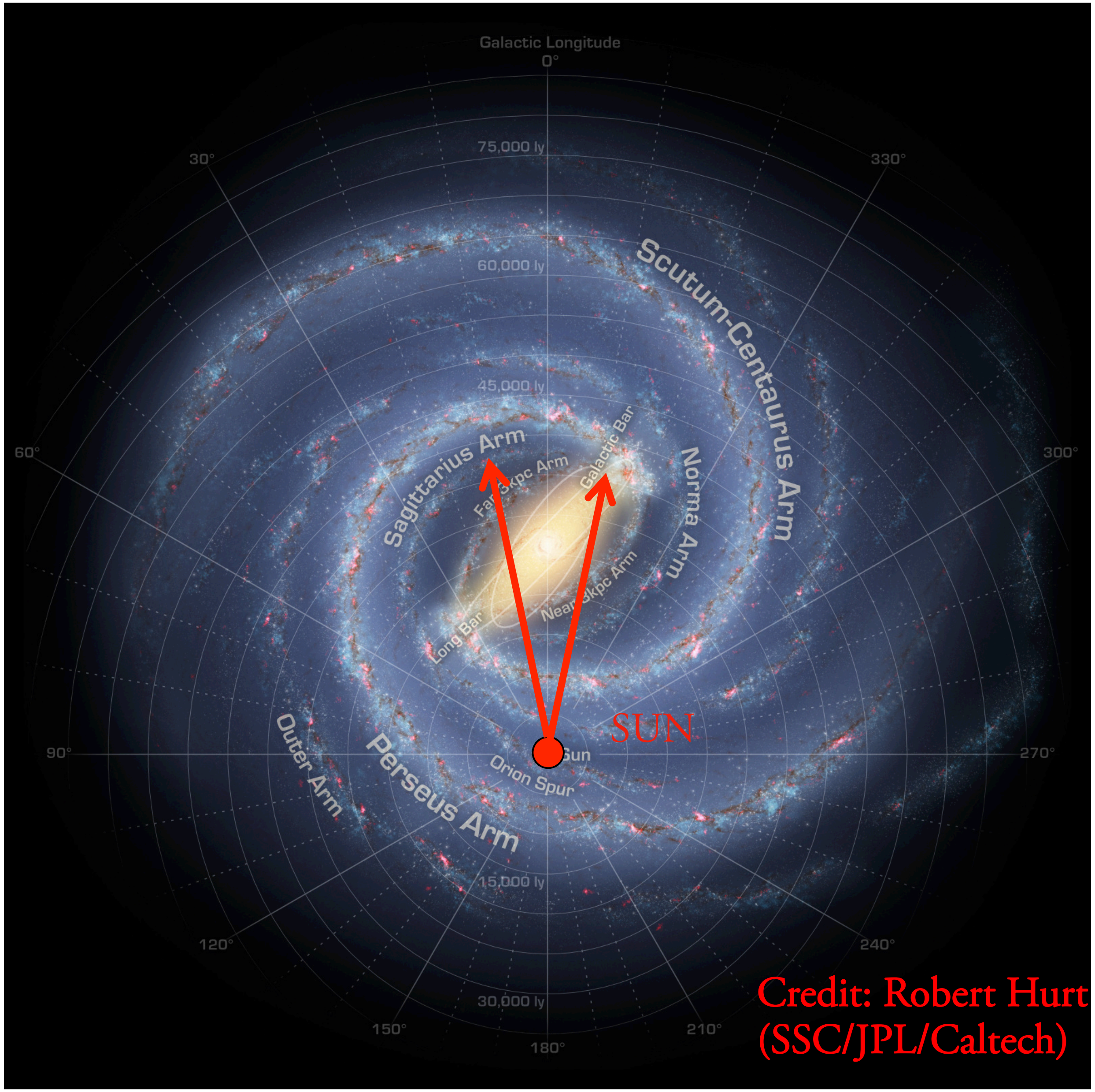
- Good agreement between M2M and Schwarzschild in terms of mass-to-light ratios
- M2M appears to have slight larger anisotropies
  - Model may not be unique
  - Require data at large radii (Morganti & Gerhard 2012)
- Comparison between different methods can be useful cross-checks

COBE Satellite View of the Milky Way



Light is asymmetric! MW is a barred SBc galaxy

Top-down view of the Galaxy



Why do we study the MW bar?

- Bar parameters are uncertain
- Provide clues for external barred galaxies: formation, evolution and dynamical processes

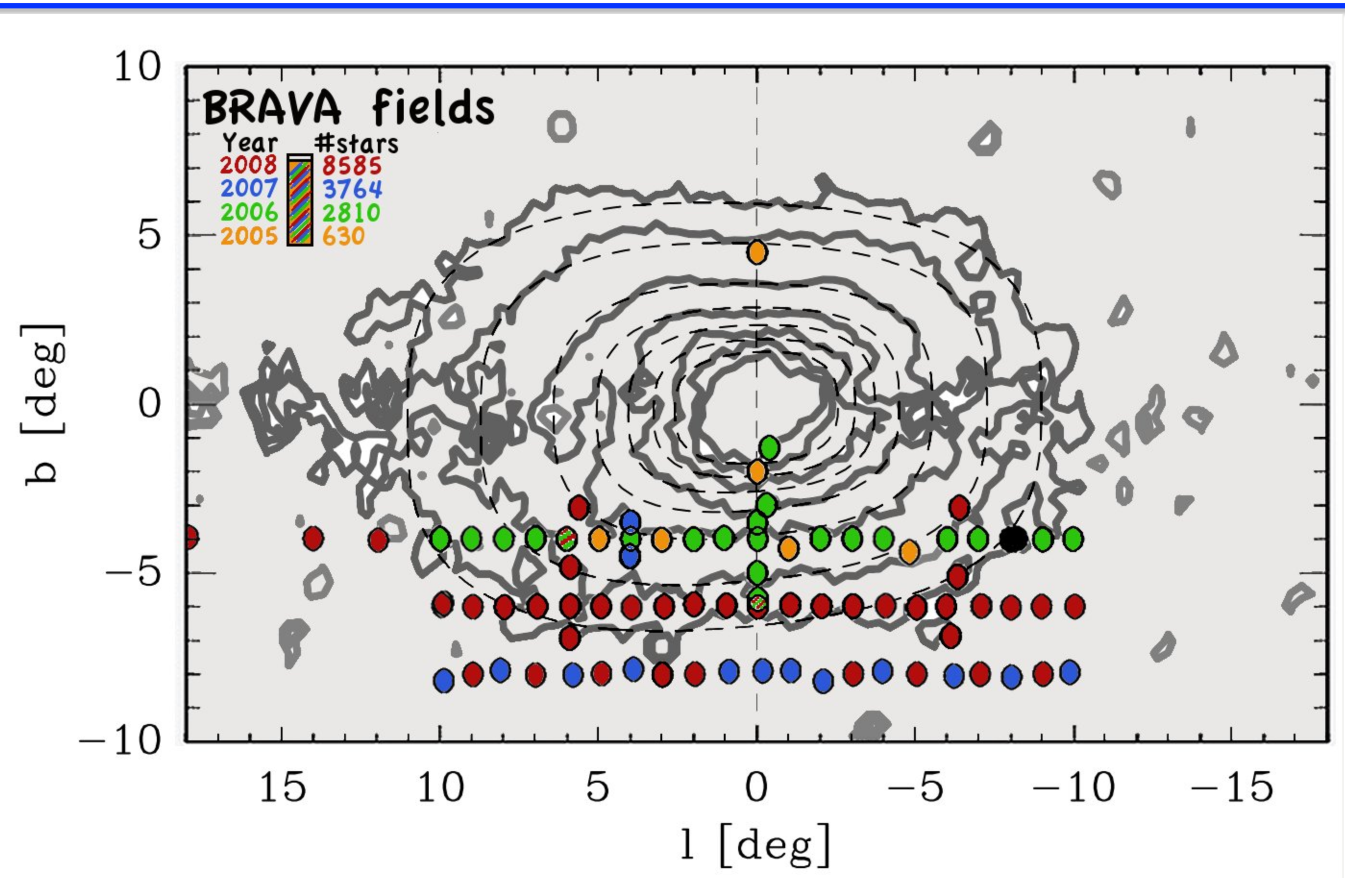
M2M modeling of MW

- Photometric data: Star counts (from OGLE) over large area

- Kinematic data
  - BRAVA
  - Proper motions from microlensing surveys

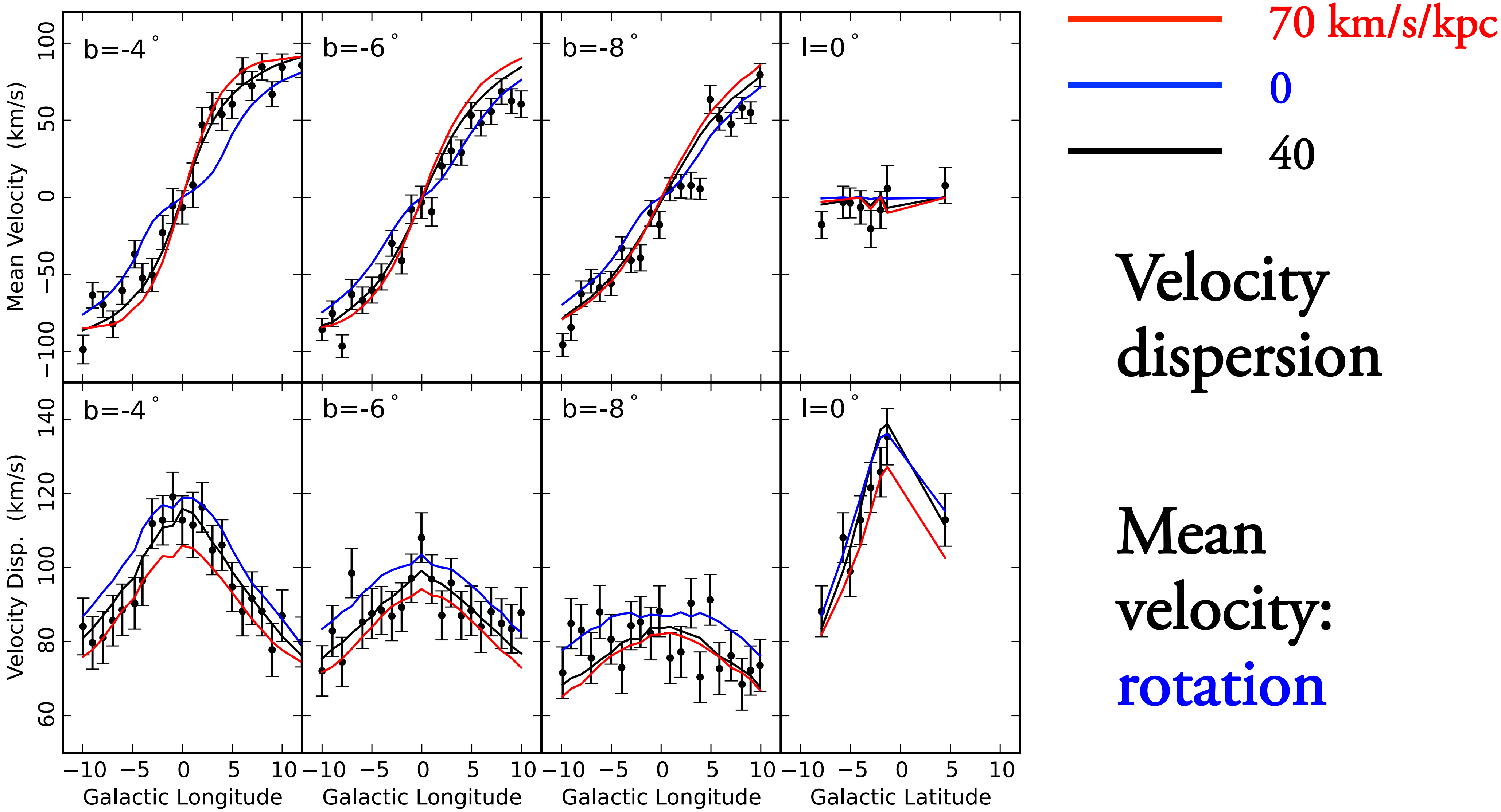
- Adjustment of M2M to the Milky Way
  - Takes into rotating frame kinematics
  - Non-parallel projection los to observers
  - First M2M + MW kinematic model
  - Initial conditions: Shen et al. (2010) numerical model

Radial velocity fields of BRAVA



- Radial velocities of 8500 red giants (Kunder et al. 2012)
- Velocity accuracy ~ 5 km/s

Reproducing BRAVA radial velocity

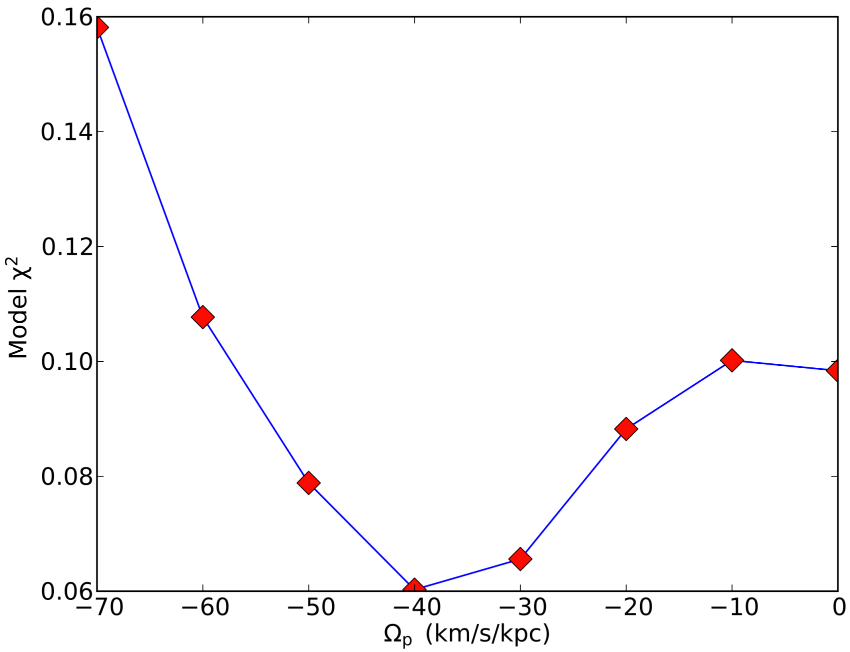


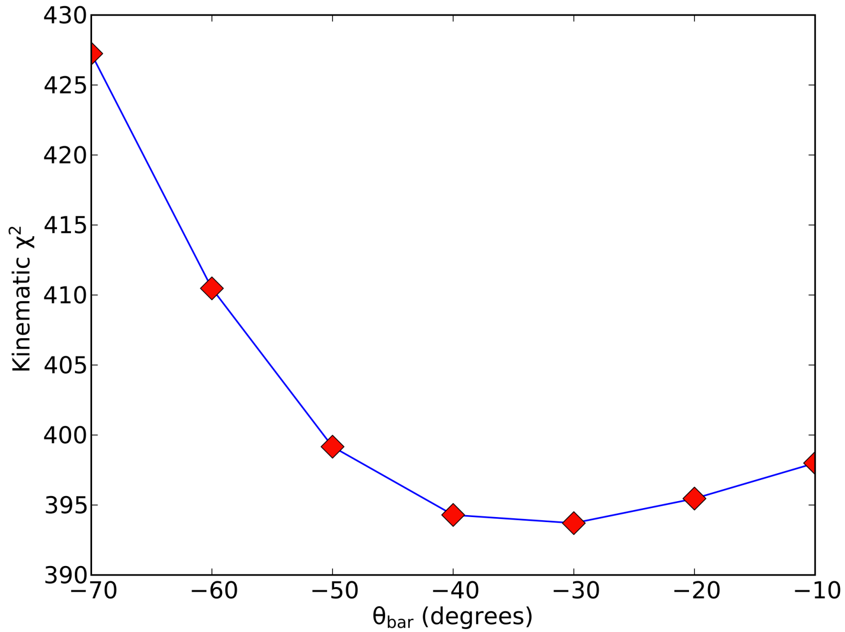
Velocity dispersion

Mean velocity: rotation

Long, Mao, Wang & Shen (2012)

Constraints on the Galactic bar parameters





Long, Mao, Wang & Shen (2012)

- Fit both surface brightness and BRAVA radial velocities
- Bar pattern speed: 40 km/s/kpc, angle: 30 degrees
  (consistent with Shen et al. 2010 & Weiner & Sellwood 1999)
- Not well constrained, need more data!

Summary & future outlook

- M2M has been applied successfully to both the MW and external galaxies

- More new data to come
  - APOGEE, ARGOS, GAIA for the Milky Way
  - E.g., SAMI/MANGA for external galaxies

- Much theoretical work yet to be done
  - Self-gravity, stability, degeneracy?
  - provide hints for how galaxies form and evolve