# *Discrete axisymmetric Jeans modeling of Local Group dSphs and M15*


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# *Outline*

- Why Jeans modeling, why discrete
- Modeling of LG dSphs
  - Clipping interlopers
  - Splitting populations
- M15
- Conclusions

# *Motivation*

- High-quality kinematic data now available
- Newly developed fast methods for solving the Jeans equations without assumption of spherical symmetry
  - LG dSphs are not spherical
  - Are there any biases in the mass determinations?
- Can we fit non-parametric models without assumption cusp/core?
- Preparation for discrete Schwarzschild modeling

# *Axisymmetric jeans modeling (JAM)*

- Jeans equations assuming axial symmetry:

$$\frac{\nu\overline{v_R^2} - \nu\overline{v_\phi^2}}{R} + \frac{\partial(\nu\overline{v_R^2})}{\partial R} + \frac{\partial(\nu\overline{v_R v_z})}{\partial z} = -\nu\frac{\partial\Phi}{\partial R}$$

$$\nu\overline{v_k v_j} \equiv \int v_k v_j f \, \mathrm{d}^3 \boldsymbol{v}.$$

$$\frac{\nu\overline{v_R v_z}}{R} + \frac{\partial(\nu\overline{v_z^2})}{\partial z} + \frac{\partial(\nu\overline{v_R v_z})}{\partial R} = -\nu\frac{\partial\Phi}{\partial z},$$

- Assume velocity ellipsoid aligned with the coordinate system and flattening for the velocity ellipsoid:

$$\beta_z(R, z) \equiv 1 - \frac{\overline{v_z^2}}{\overline{v_R^2}}$$

Cappellari 2008

# Discrete modeling

- Jeans model predicts second moment of the velocity
- Discrete modeling – no loss of spatial and velocity resolution
- Assume absence of all streaming motions
- Approximate likelihood by Gaussian

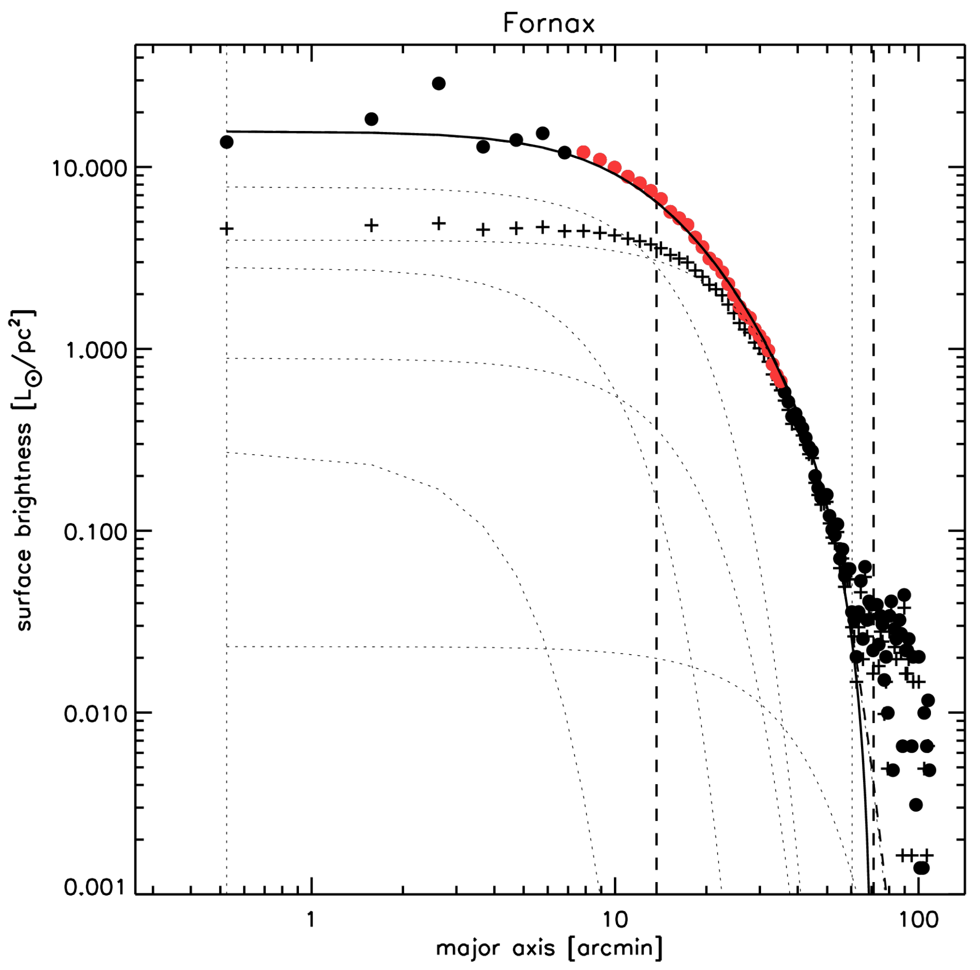
$$\mathcal{L}(\langle v_{\rm los}^2\rangle \,|v_{\rm obs}, \sigma_v) = \frac{1}{\sqrt{2\pi\left(\langle v_{\rm los}^2 + \sigma_v^2\rangle\right)}} \exp\left(-\frac{v_{\rm obs}^2}{2\left(\langle v_{\rm los}^2\rangle + \sigma_v^2\right)}\right)$$

- As test for using histograms in Schwarzschild modeling

# Discrete modeling

MGE expansion based on King models from Irwin & Hatzidimitriou (1995)

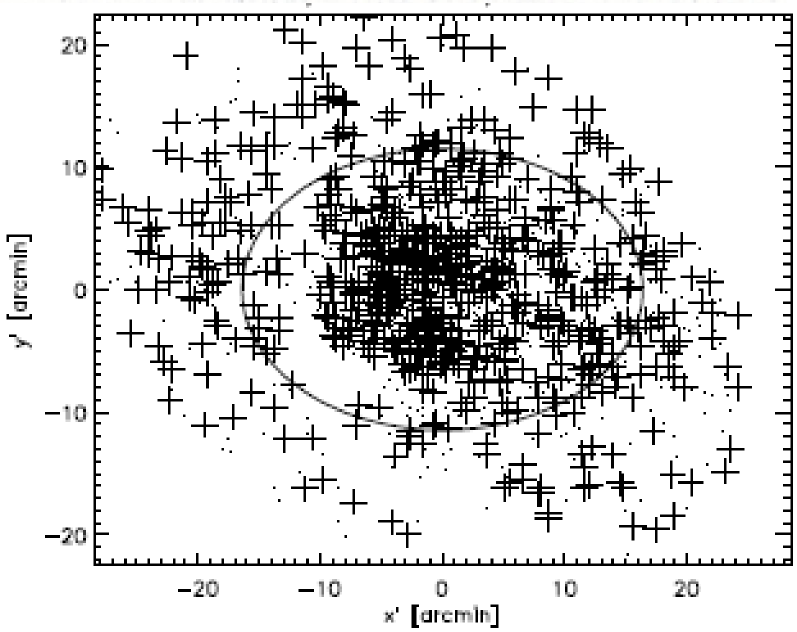
Density by varying MGE components



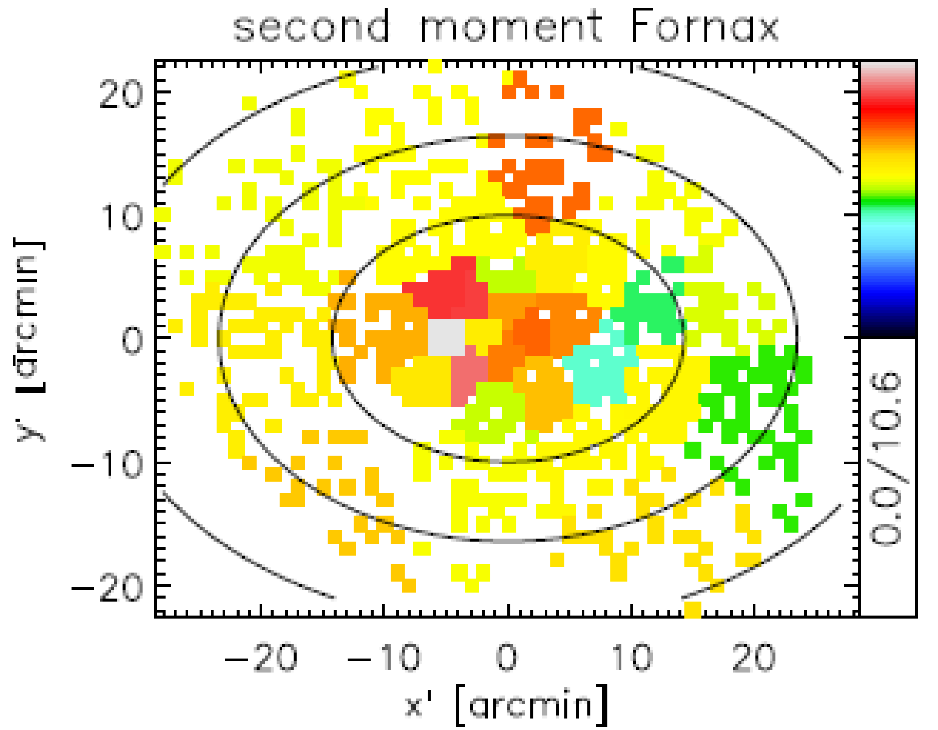
# *Discrete modeling*

Data from Walker et al., clipped at 99% membership probability

737 velocities




32 bins

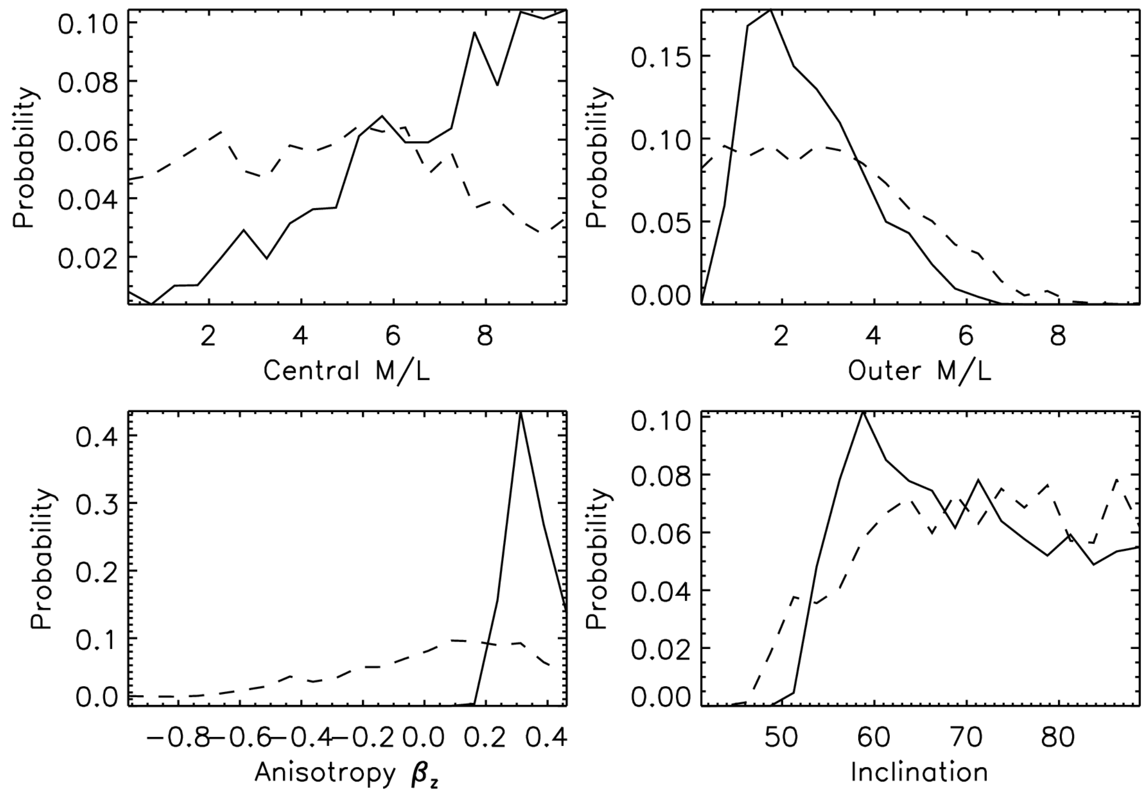


# Discrete modeling

Dashed line = binned data

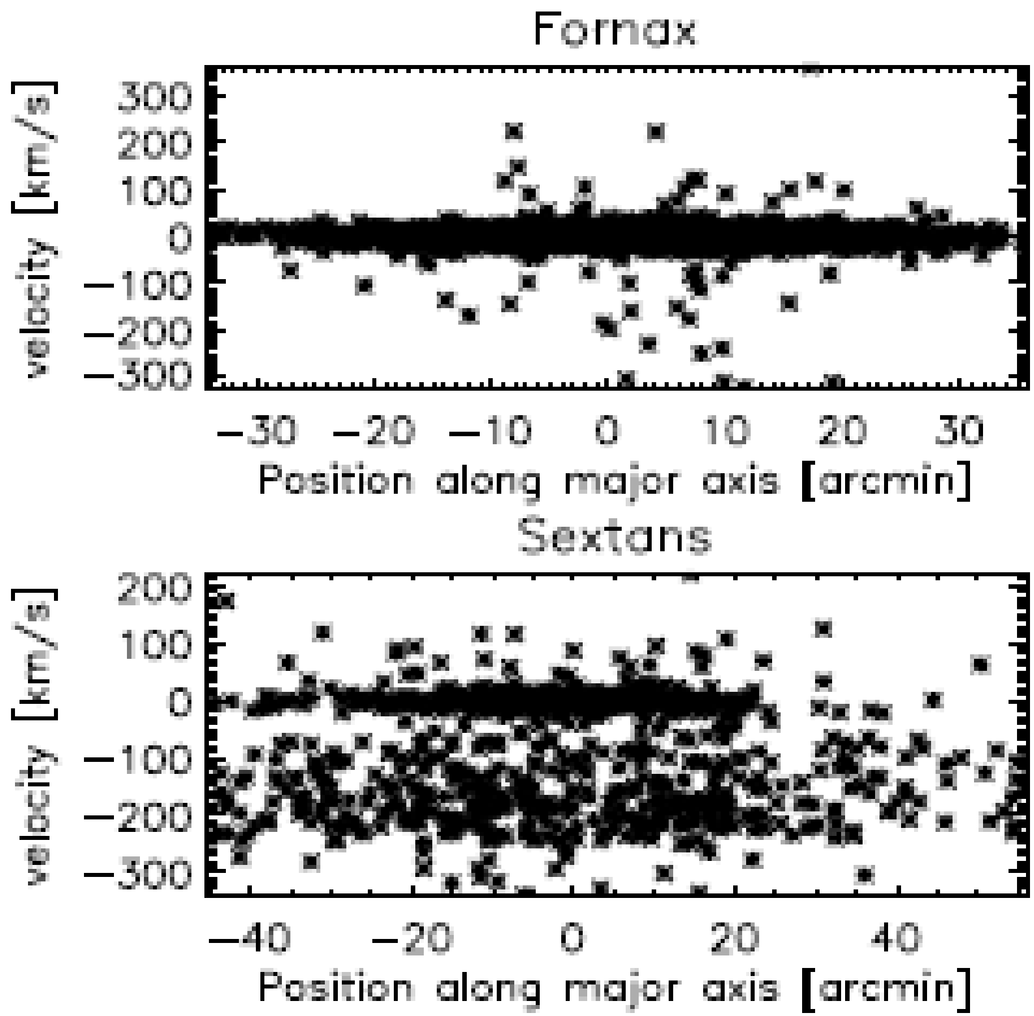
Solid line = unbinned data

Fornax



# *Dealing with interlopers*

- Where to clip?




Walker+08

# *Dealing with interlopers*

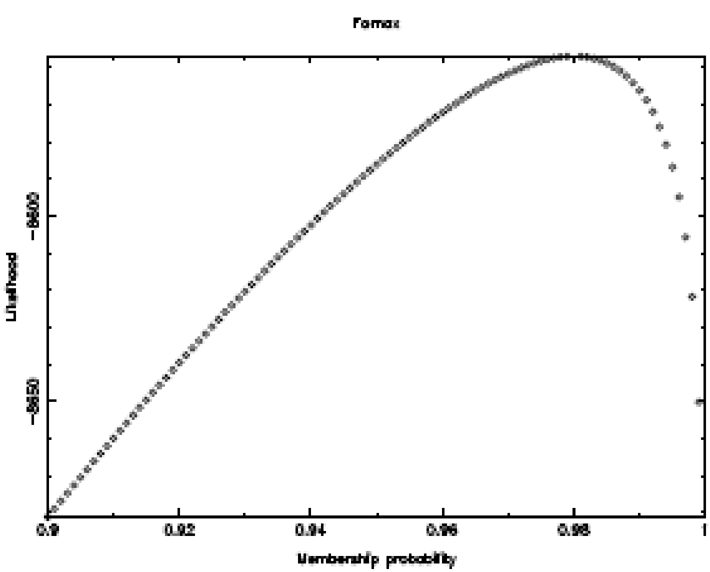
- Likelihood: $$\begin{aligned}\mathcal{L} &= p(\{v_i\}_{i=1}^{N}|\{b_i\}_{i=1}^{N}, \mathrm{dSph\ model, MW\ model}) \\ &= \prod_{i=1}^{N} p(v_i|\mathrm{dSph\ model})^{b_i} \cdot p(v_i|\mathrm{MW\ model})^{1-b_i}\end{aligned}$$

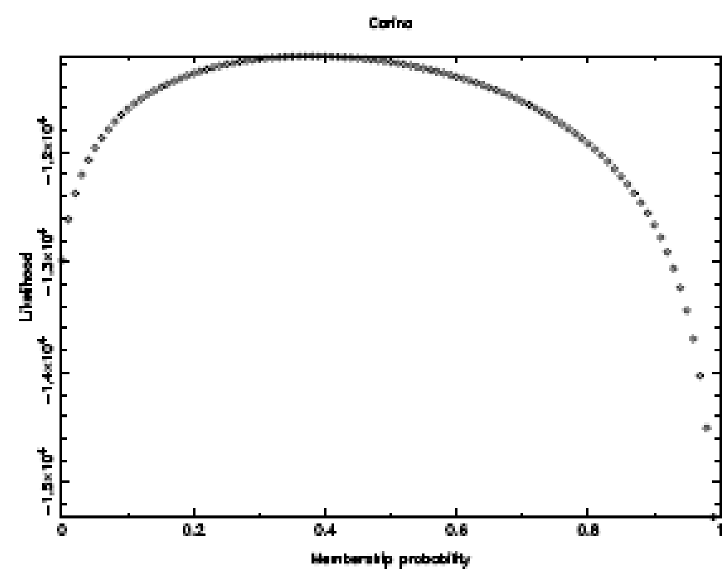
  Prior: $$p(\{b_i\}_{i=1}^{N}|P_{m_i}) = \prod_{i=1}^{N} P_{m_i}^{b_i} \cdot (1 - P_{m_i})^{1-b_i}$$

- Need good model for the Milky Way foreground (selection function)

# *Dealing with interlopers*

- $$p(v_i|\text{MW model}) = \frac{1}{2v_{\max}}$$

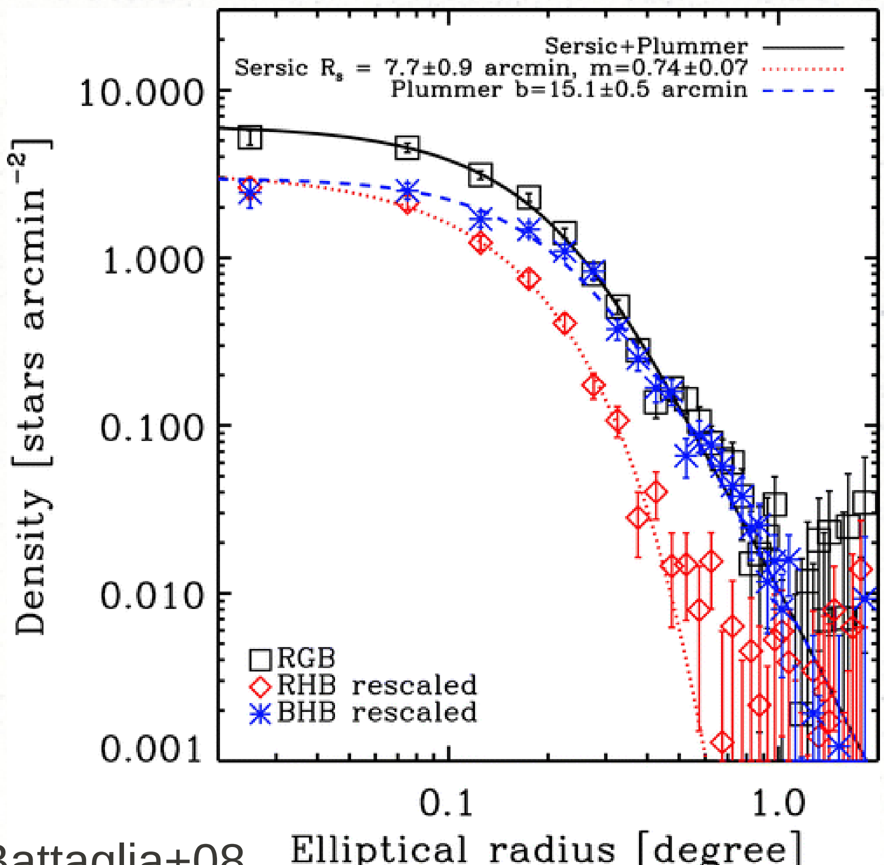



Fornax

Carina

# *Chemical tagging*

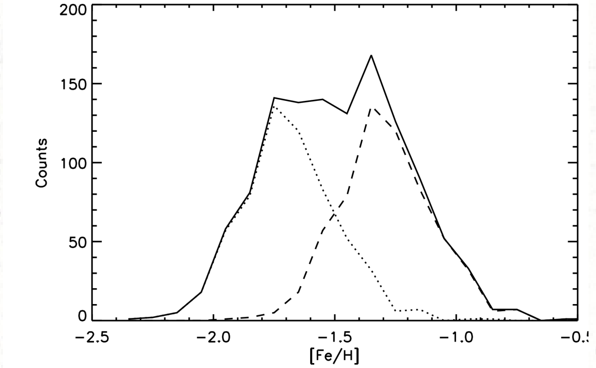



Battaglia+08

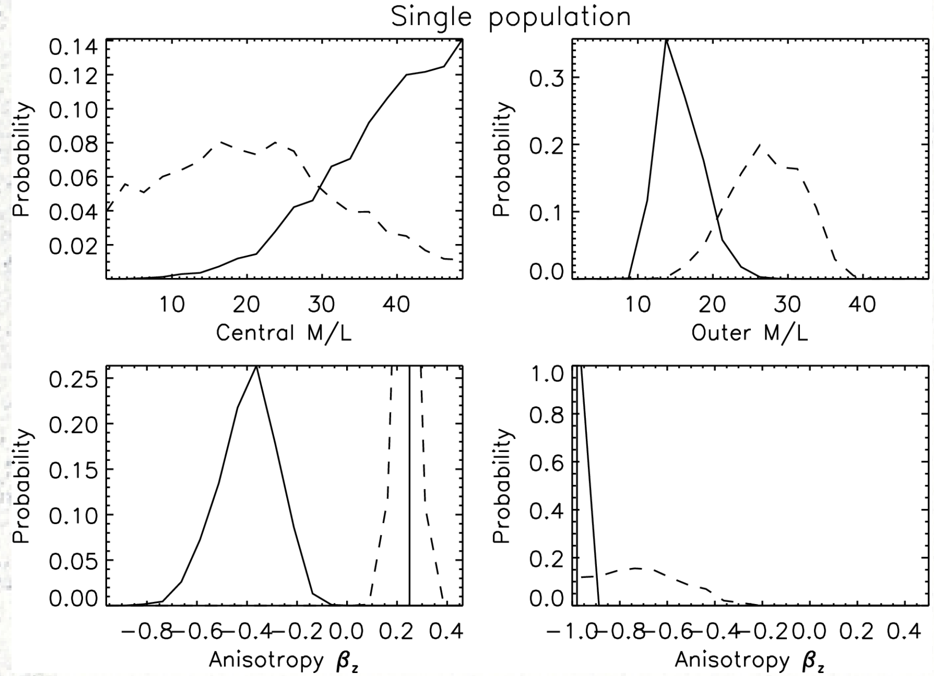
- Battaglia et al. split the metal poor/rich sample with hard cut: can we improve on this by using probabilities
- For Jeans modelling, luminosity profile of the two populations is essential

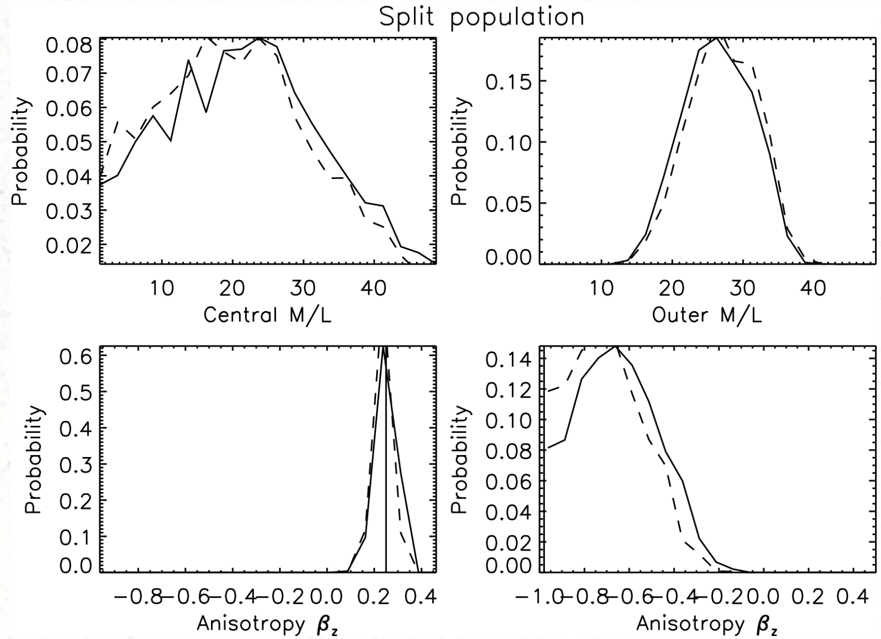
# *Chemical tagging*

- Hard cut in metallicity did not work for real data of sculptor, neither did metallicity distributions




- Seems to work for mock data



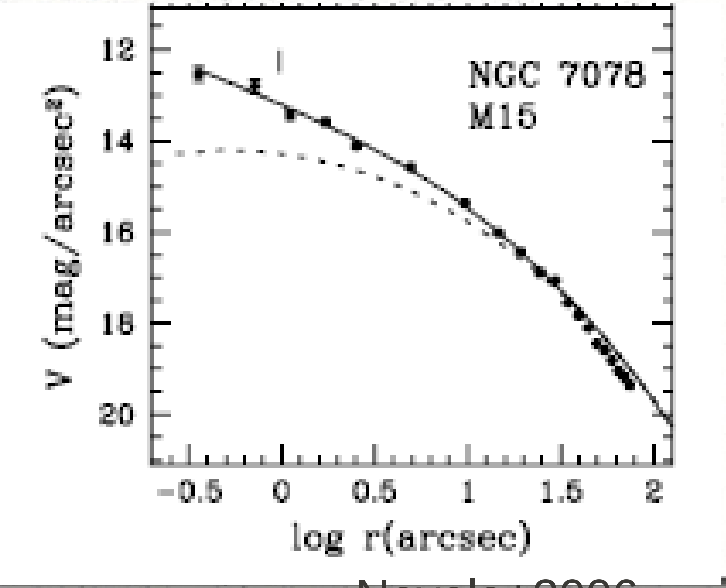



# *Summary*

- Chemical tagging and metallicity distributions seem to work, but require more work

# *M15*

- M15 prototypical core-collapse globular cluster
- M/L profile should vary as function of radius
- Presence of IMBH?

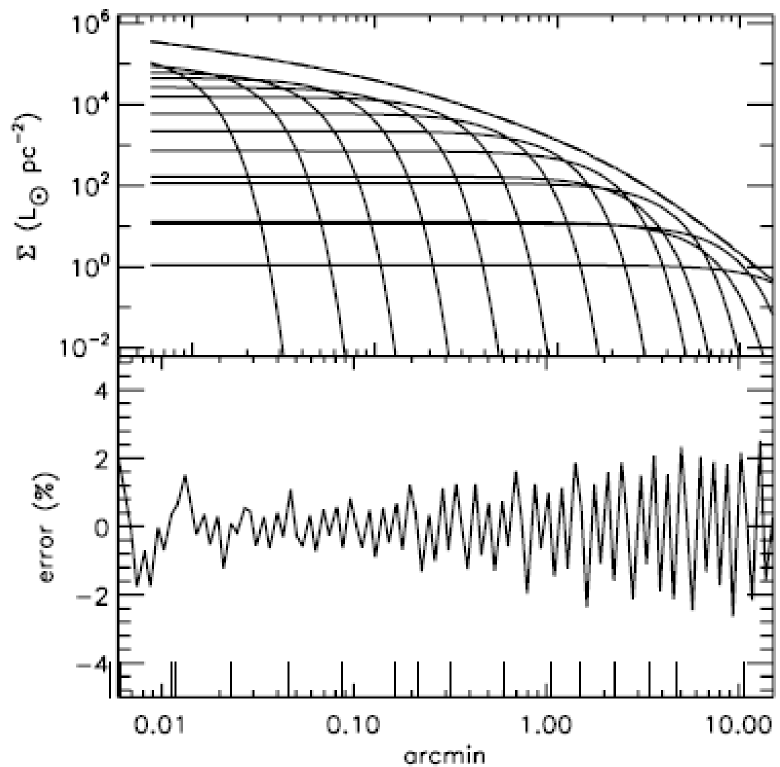



Noyola+2006

# M15: data

- Re-analyze publicly available data:
  - Line-of-sight velocity data from Gebhardt et al. (1995), vd Marel (2002)

    (1546+64 stars)
  - Proper motions from McNamara (2003) (703 stars mainly in centre)
  - Luminosity profile (Noyola & Gebhardt, 2006; vd Bosch, 2006)



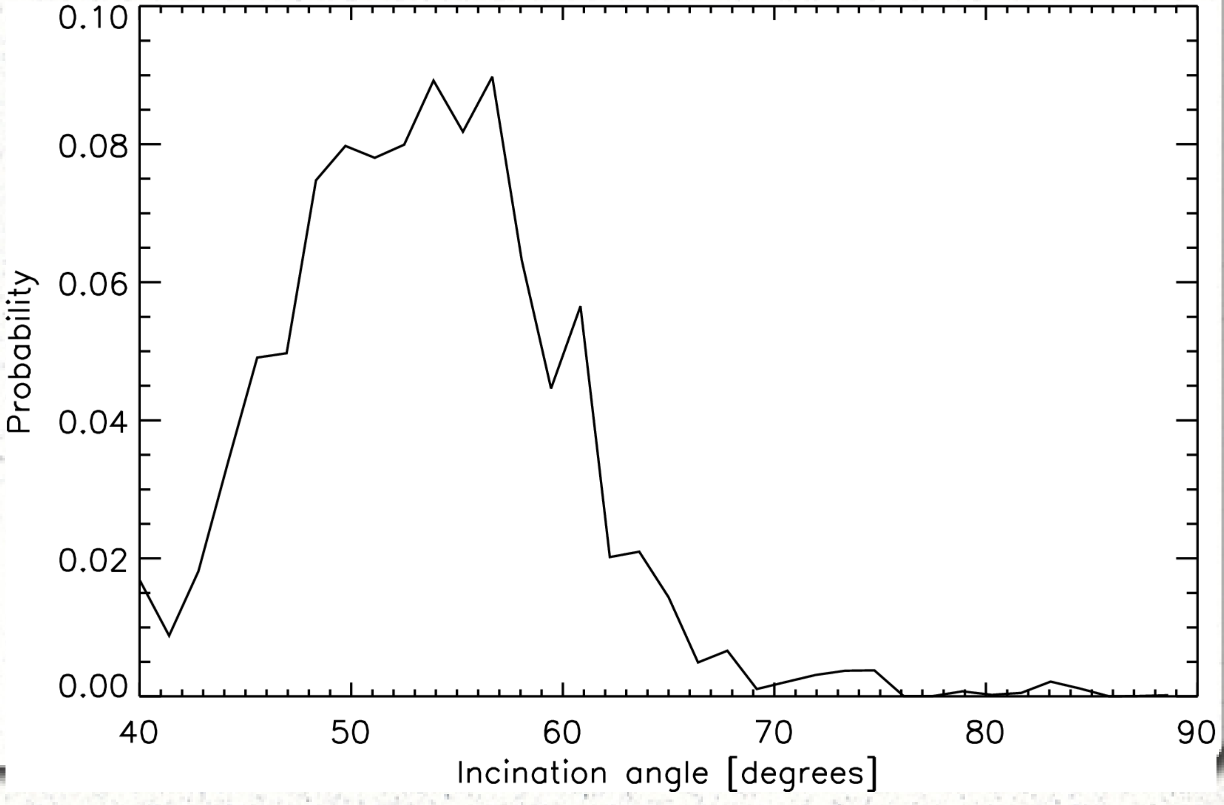

Van den Bosch+06

# *Assumptions*

- M/L 'non-parametric': leave first 3 gaussians + $6^{th}$ + $10^{th}$ gaussian free, interpolate M/L for gaussians in between
- Anisotropy parametrized by Osipkov-Merritt-like profile: may be negative
- Inclination between 40 and 90 degrees
- Black hole mass between 0-4000 solar mass

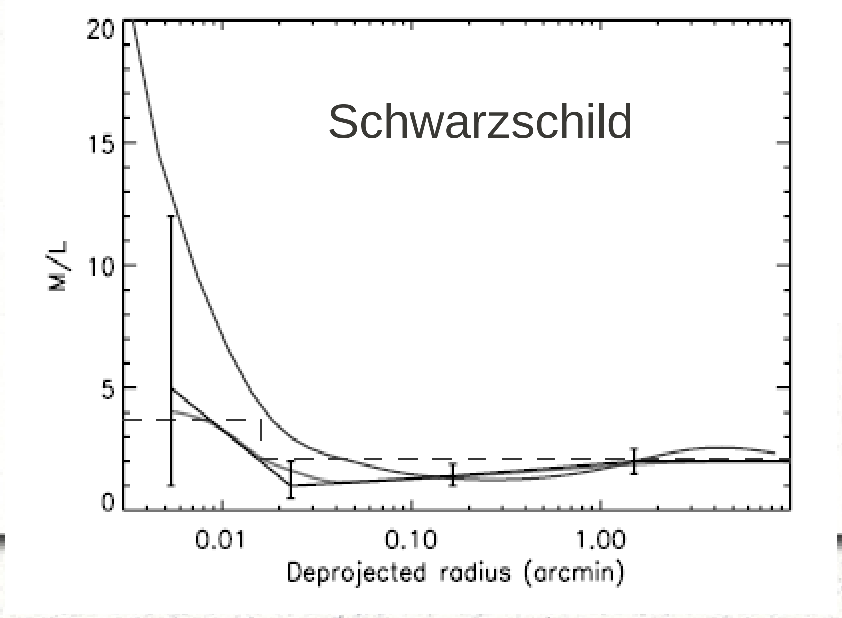
# *M15: Inclination*

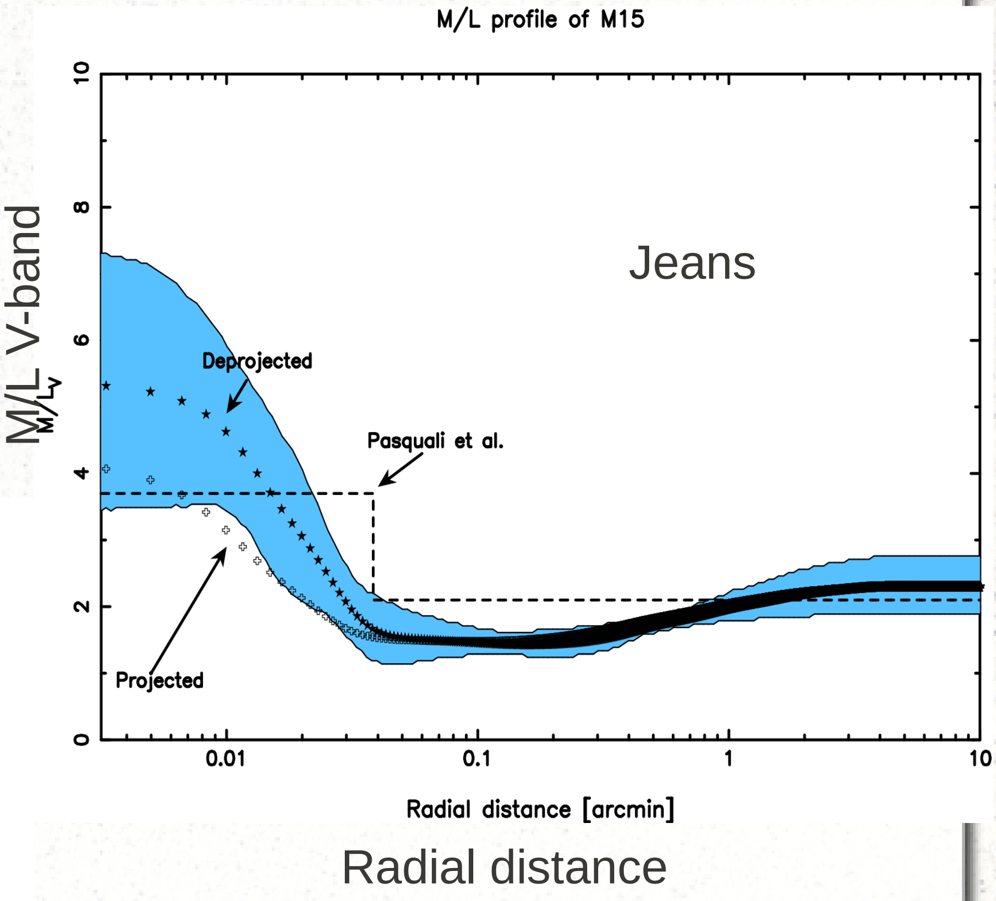
- Slightly lower, though completely consistent with vdB06: 59±12



# M15: M/L

- M/L increases toward outer parts: mass segregation
- Steep rise in inner parts: stellar remnants? Or black hole?
- Excellent comparison with previous determinations of M/L profiles



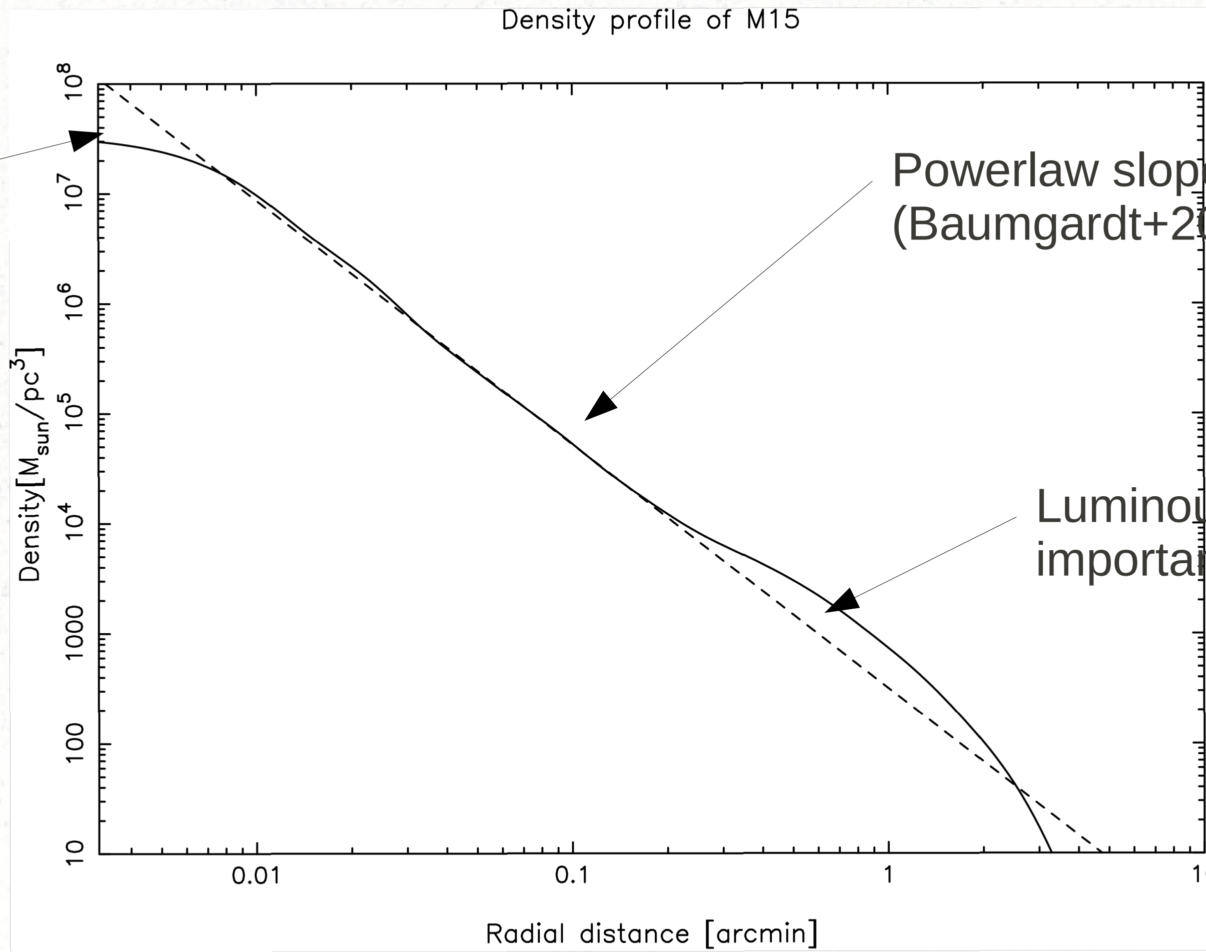
# M15: IMBH?

| Data | BH mass | $\beta_z$ | Free gaussians | $\theta$ | Notes |
|---|---|---|---|---|---|
| (2) | (3) | (4) | (5) | (6) | |
| vlos | $2321 \pm 1091$ | 0. | 4 | 60. | |
| vlos | $2411 \pm 1066$ | free | 5 | 60. | |
| proper | $1315 \pm 1015$ | 0. | 5 | 60. | |
| proper | $2098 \pm 1245$ | 0. | 5 | 60. | Fitted dynamical center |
| proper+vlos | $2034 \pm 1080$ | free | 5 | free. | |

- With this MGE expansion always additional black hole required

# M15: IMBH?

Missing mass compensated for by IMBH?




Powerlaw slope -2.22 (Baumgardt+2003)

Luminous mass important

# *Summary*

- No evidence for IMBH in M15

# *What's next?*

- Schwarzschild modeling with discrete tracers?

- Different solutions of the Jeans Equation:
  - Maybe a more 'physical solution' however, very difficult to calculate
  - Still DF maybe non-existent

# *Conclusions*

- Dynamical modelling with discrete kinematic tracers looks promising
- Although significantly higher central density, no evidence for IMBH in M15
- It is possible to use different kinematic populations to constrain the potential: still lot of work to do