Dynamical models of dwarf spheroidal galaxies: application to Fornax

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Summary

Introductions:

- Dwarf spheroidal galaxies (dSphs)
- Dynamical modeling methods
- Action-based distribution functions (DFs)

Application to the Fornax dSph:

- The samples
- Best model: a cored dark halo
- Results

Conclusions

Dwarf Spheroidal Galaxies

Fornax

Sculptor

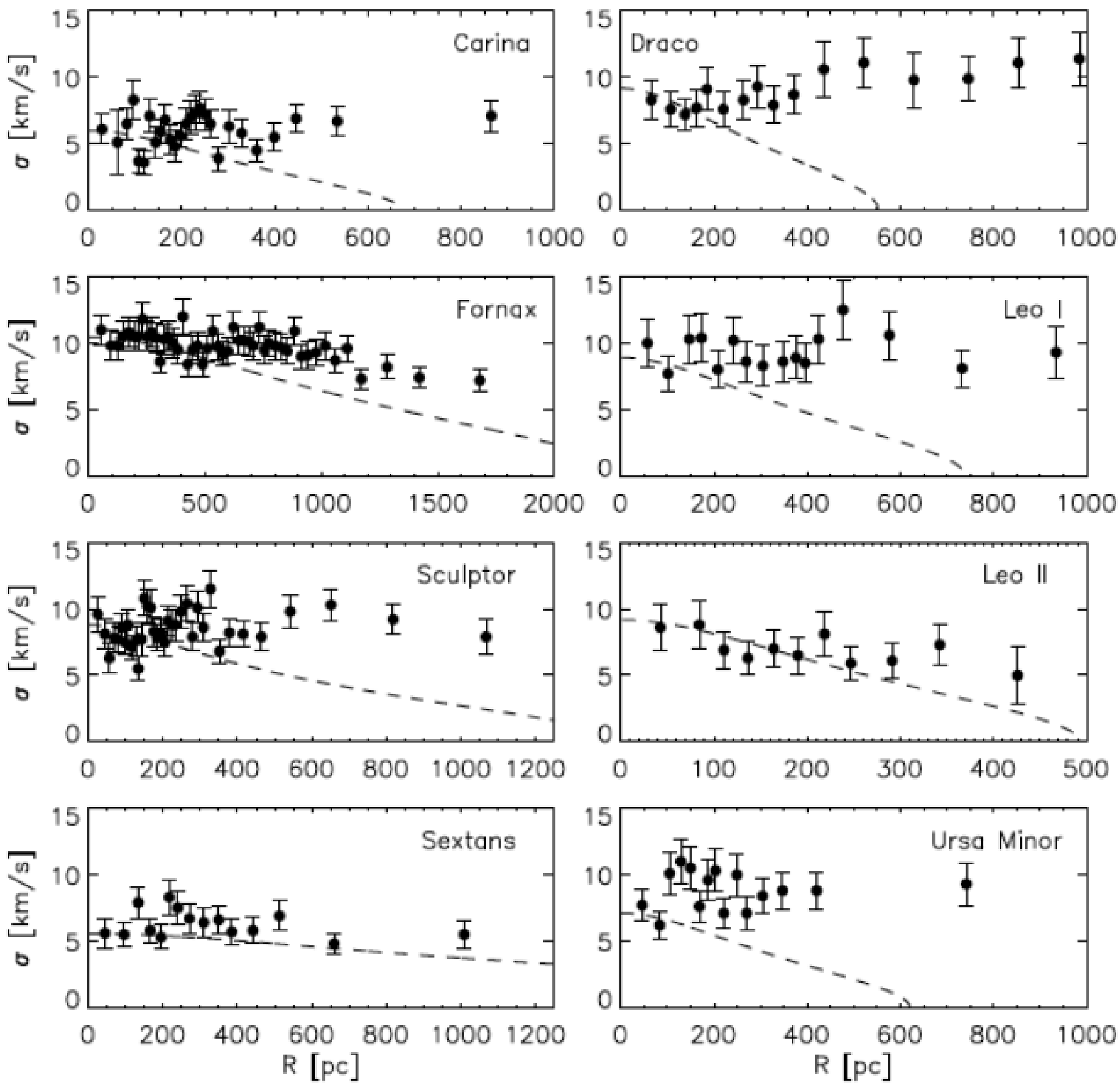
credits: ESO/Digitized Sky Survey 2

Dwarf spheroidal galaxies (dSphs):

- Nearby systems (resolved sellar pop.s)
- Pressure supported, flattened
- Dark-matter dominated (equilibrium ?)

References:
Battaglia et al. (2013), Irwin & Hatzidimitriou (1995), Aaronson (1983)

Dwarf Spheroidal Galaxies



Perfect laboratories to:

- probe ΛCDM cosmology on the smallest scales
- study dark-matter properties in a convenient environment
- search for dark-matter indirect detection

References:
Battaglia et al. (2013), Irwin & Hatzidimitriou (1995), Walker et al. (2009)

Mass modeling methods

	Jeans	Schwarzschild	DF
Analytical DF?			
Computational cheap?			
Physical model?			

Distribution Function (DF)
= probability at any given
point of the phase-space

$$f = f(\boldsymbol{x}, \boldsymbol{v})$$

What's needed:

- Steady-state
- Equilibrium (no tides, no recent interactions)
- CBE satiesfied

Mass modeling methods

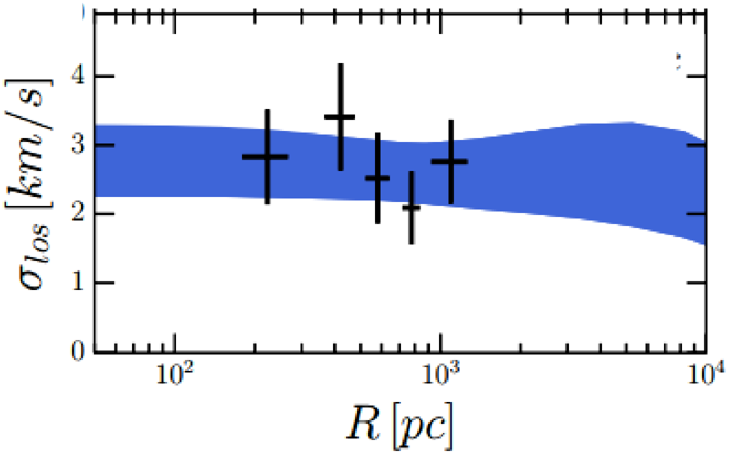
	Jeans	Schwarzschild	DF
Analytical DF?	✗		
Computational cheap?	✓		
Physical model?	✗		

Jeans Analysis

$\Sigma(R)$

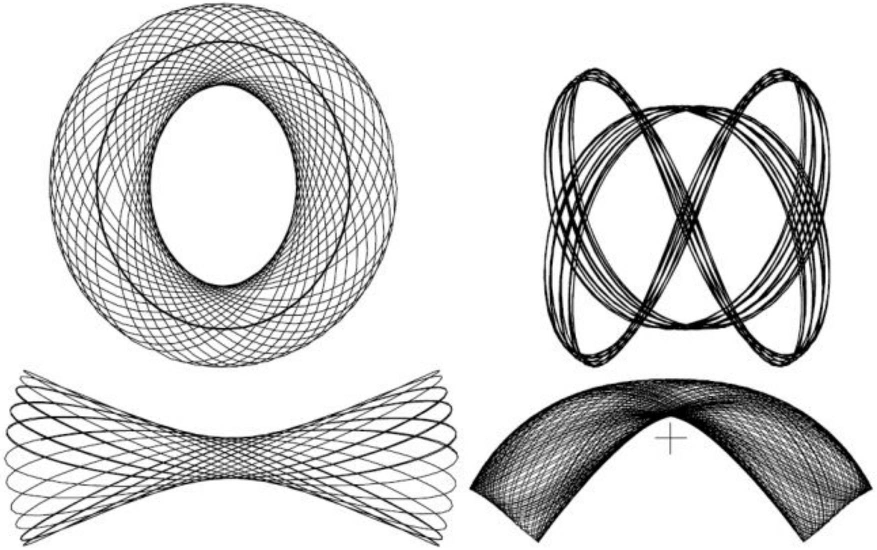
Φ Assume a reasonable fit to the light profile, a potential and an anisotropy distribution $\beta(r)$

Integrate Jeans Equations



Mass modeling methods

	Jeans	Schwarzschild	DF
Analytical DF?	✗	✗	
Computational cheap?	✓	✗	
Physical model?	✗	✓	



Schwarzschild techniques:

Libraries of numerical orbits are weighted to get a good match with Observed data

Mass modeling methods

	Jeans	Schwarzschild	DF
Analytical DF?	✗	✗	✓
Computational cheap?	✓	✗	✓
Physical model?	✗	✓	✓

DF based methods:

Assume an analytic expression for the DF

$$f(E) \quad f(E, L_z) \quad f(\boldsymbol{J})$$

Compute all the relevant model properties

$$\rho(\boldsymbol{x}) \quad \wp(\boldsymbol{x}_\perp, v_{\rm los})$$

Get physically consistent models

DF depending on actions

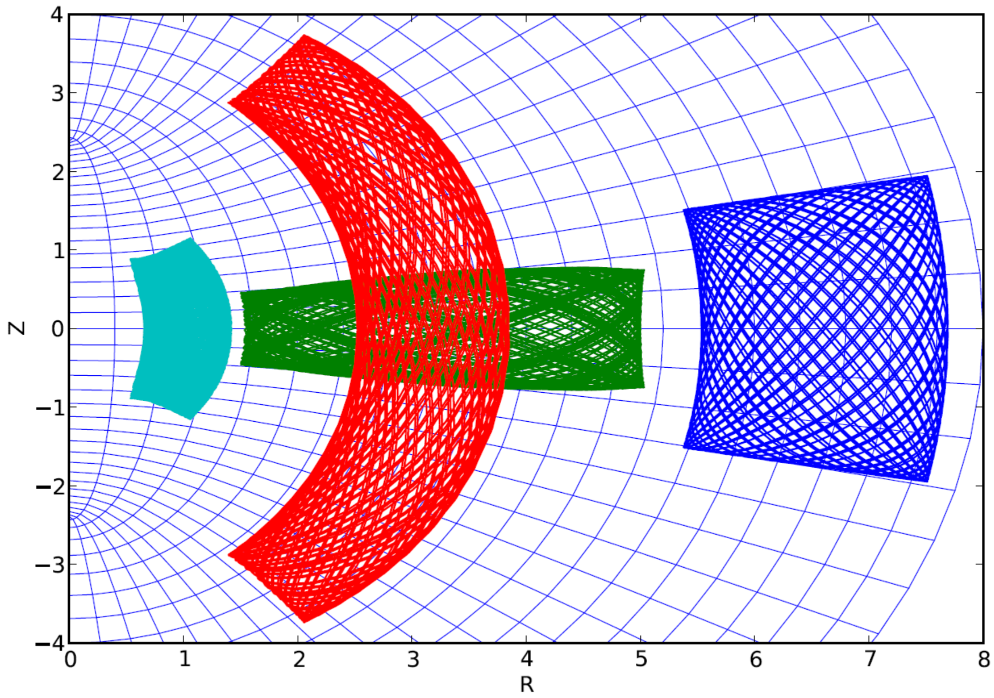
Life-changing questions.

How to write any reasonable DF?

$$f = f(\boldsymbol{x}, \boldsymbol{v})$$

Jeans Theorems!

Adopt integrals of motion as argument of the DF



- Which integrals?

  The actions

  $$(J_r, J_\phi, J_z)$$

- and why?

  Flattening

  Rotation

  Multi-component systems

Model set-up and comparison to data

Setting the models: Assume **separate DFs** for stars and dark-matter

Spherical models

$$f_{\rm tot}(\boldsymbol{J}) = f_\star(\boldsymbol{J}) + f_{\rm dm}(\boldsymbol{J})$$

$$(\rho_\star, \Phi_\star) \quad (\rho_{\rm dm}, \Phi_{\rm dm})$$

and find the self-consistent pairs

Integrate for

$$\wp_\star(\boldsymbol{x}_\perp, v_{\rm los}) = \frac{\int {\rm d}^2 \boldsymbol{v}_\perp \, {\rm d} x_\parallel \, f(\boldsymbol{J})}{\Sigma_\star(x_\parallel)}$$

Model line-of-sight velocity distribution (**LOSVD**)

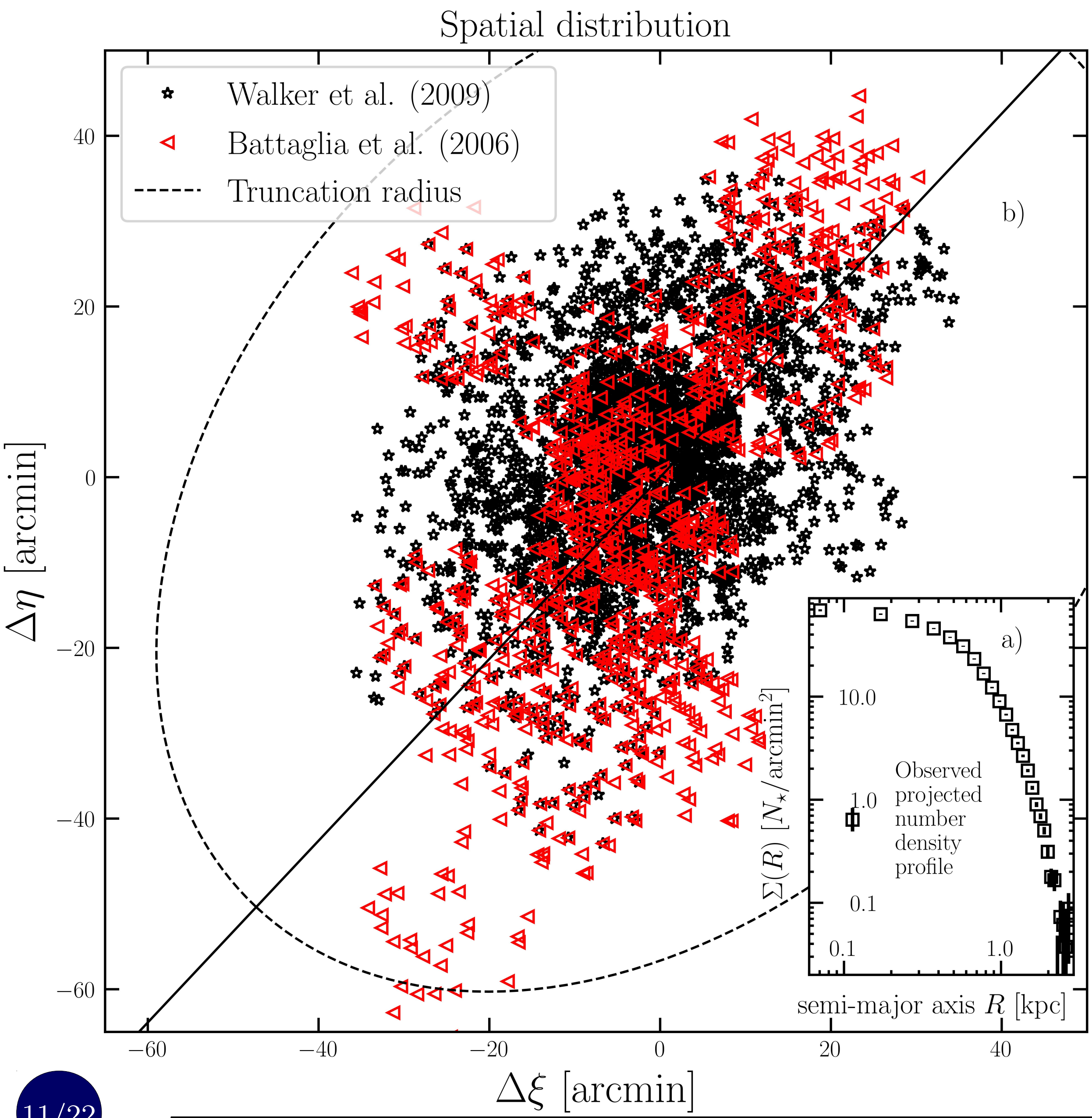
- star-by-star analysis (no use of binned data)
- physical LOSVD

$$n_\star(\boldsymbol{x}_\perp) = \frac{\int {\rm d}^3 \boldsymbol{v} {\rm d} x_\parallel \, f(\boldsymbol{J})}{\rho_\star(\boldsymbol{x})}$$

Model projected density

+ Add a model for MW foreground contamination

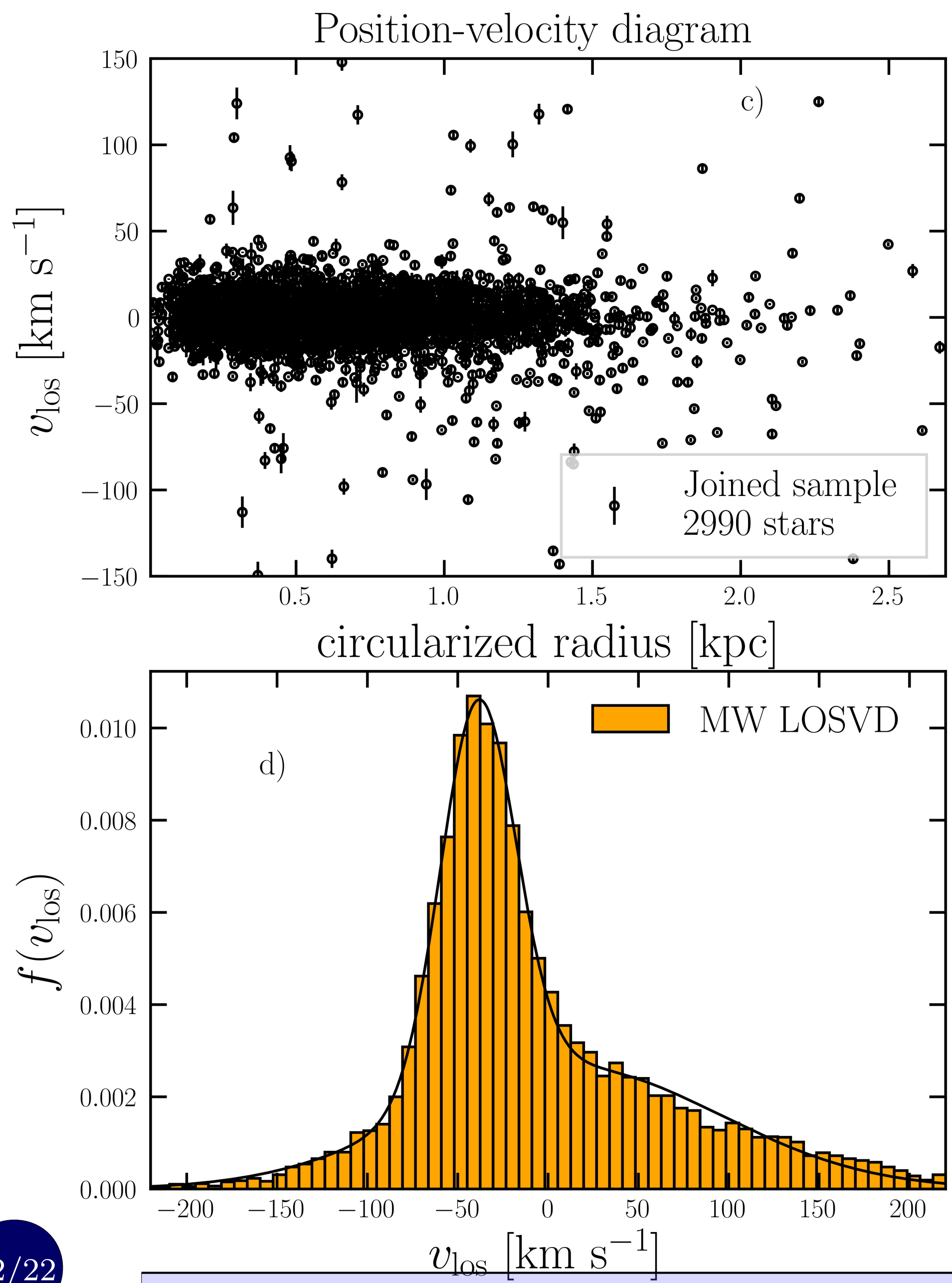
Fornax samples



Data sets:

- **Photometric sample** Projected stellar number density profile (Battaglia et al. 2006)
- **Kinematic sample** measures of star velocities along line-of-sight (Battaglia et al. 2006, Walker et al. 2009)
- **Milky Way LOSVD model** (Robin et al. 2004)

Fornax samples



Kinematic Sample

- Joined sample of Battaglia et al. 2006 and Walker et al. 2009
- Cross-matched
- Corrected for system velocity, extent of Fornax on the plane of the sky
- Binaries accounted

Fornax: a cored dark halo

$$f_{\rm tot}(\boldsymbol{J}) = f_{\star}(\boldsymbol{J}) + f_{\rm dm}(\boldsymbol{J})$$

Stars DF $f_{\star}(\boldsymbol{J})$ **:** designed to reproduce **anisotropic** stellar components, with **truncation** of adjustable steepness in the outer parts and **cored** in inner parts (Pascale et al. 2018b)

DM DF $f_{\rm dm}(\boldsymbol{J})$ **:** designed to reproduce **NFW-like** models with the optional presence of a **core of variable size** in the inner parts of the density distribution (Posti et al. 2015, Cole & Binney 2017)

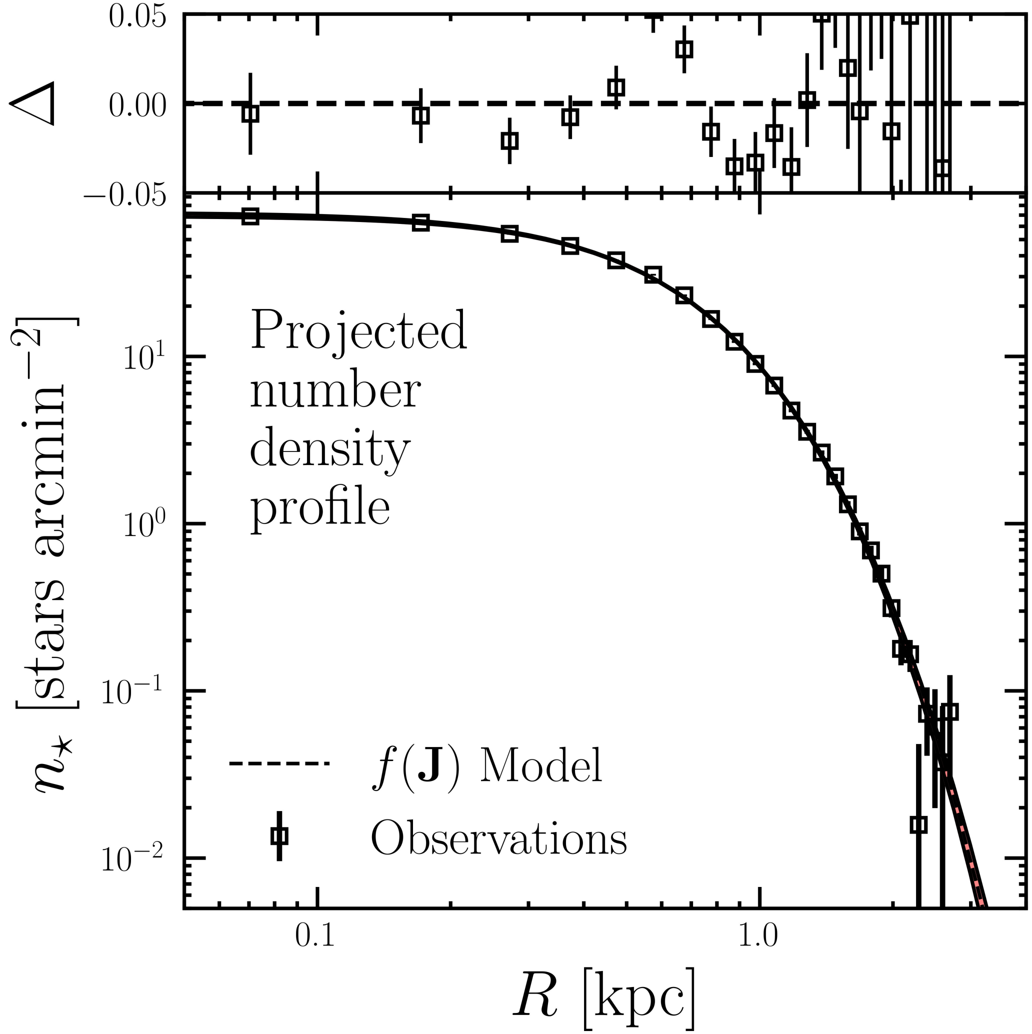
Family	$r_{\rm c}$/[kpc]	(Probability)
MFL	–	4.7×10^{-41}
NFW halo	–	3.4×10^{-31}
Cored halo 1	0.34	1.2×10^{-8}
Cored halo 2	0.87	0.52
Cored halo 3	1.03	1

Five scenarios (families) have been considered:

- 3 cored halo families
- NFW family
- Mass-follows-light family

Best Model: Cored halo

Fornax: a cored dark halo



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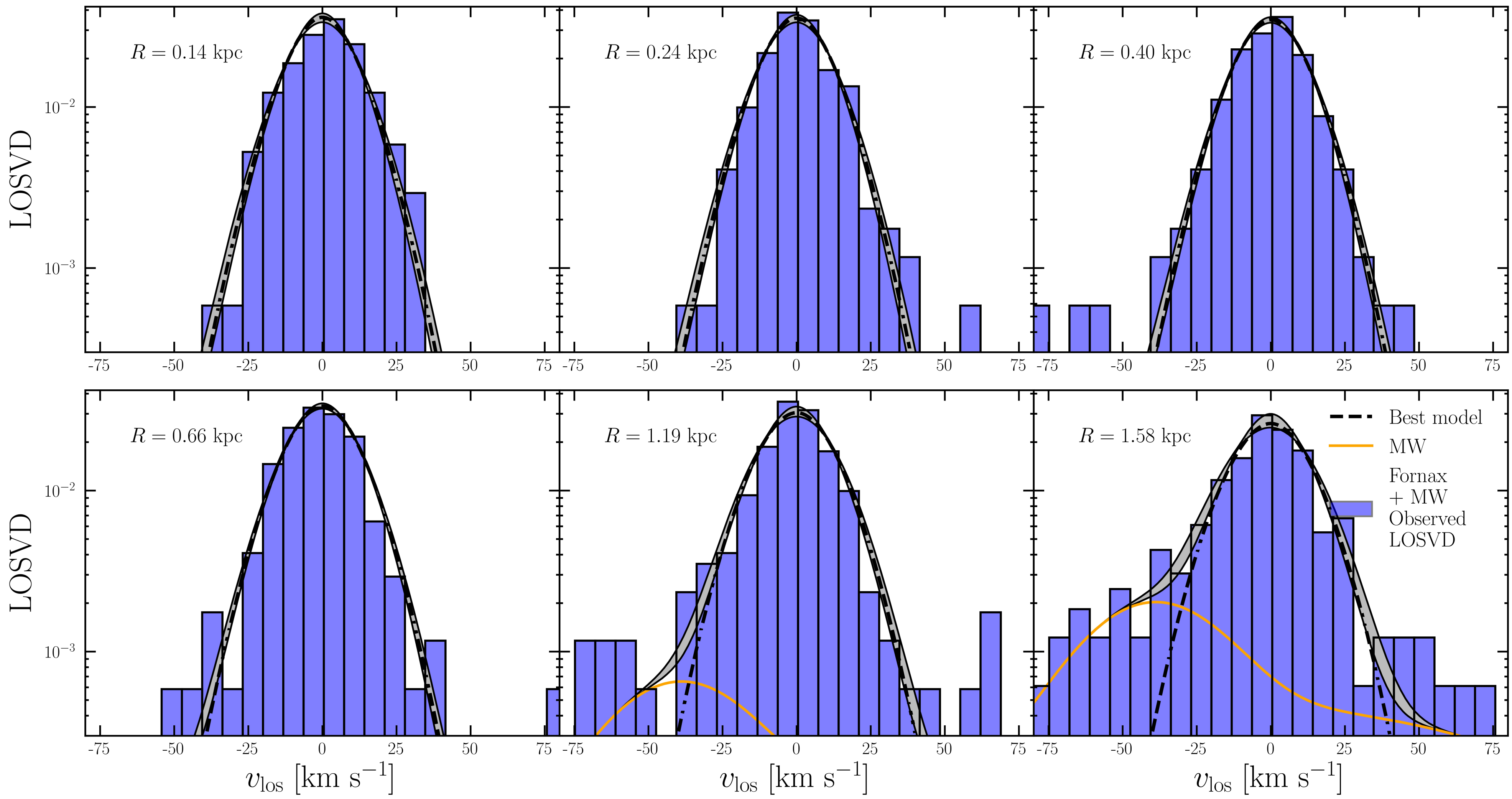
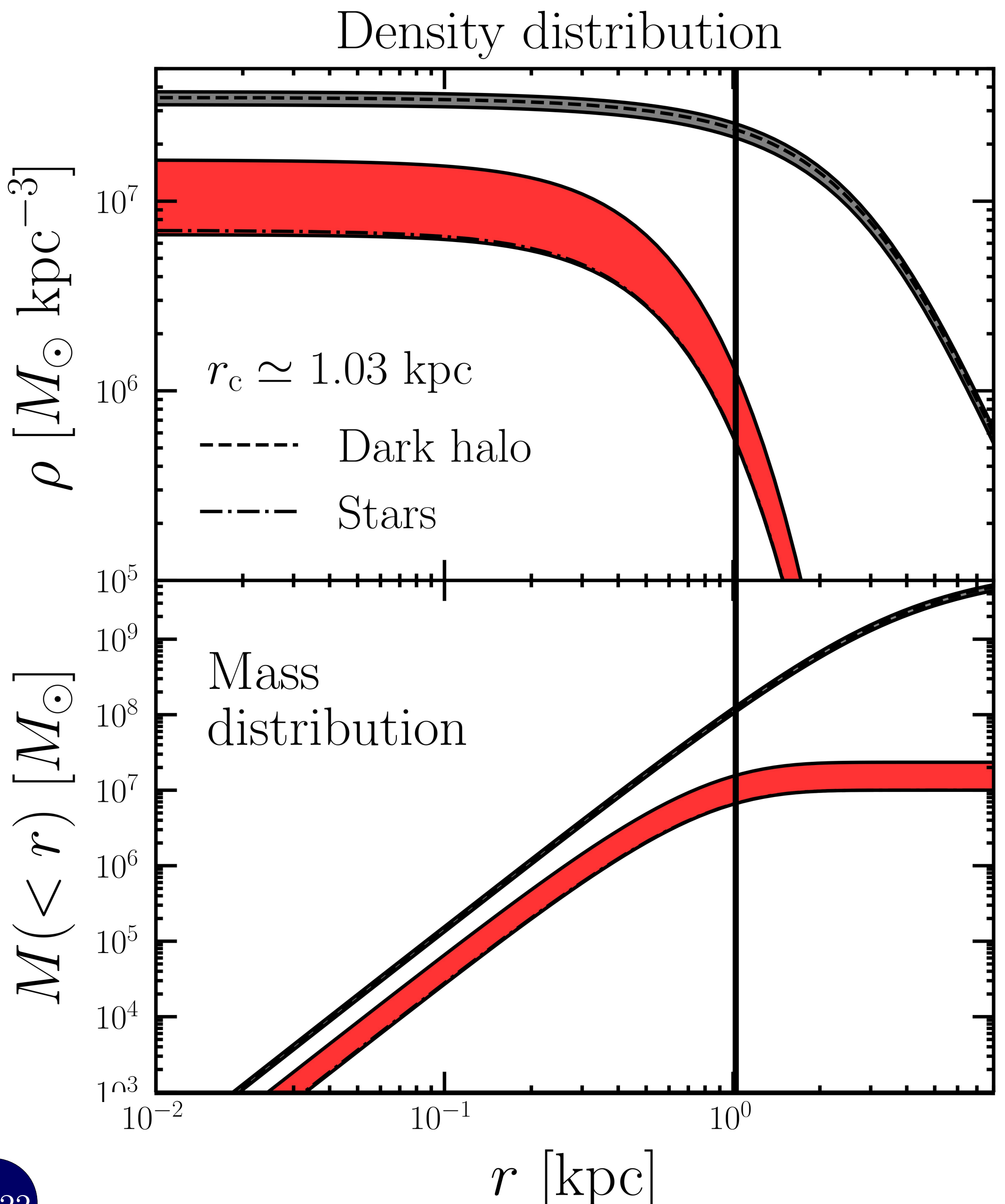
Fornax: a cored dark halo

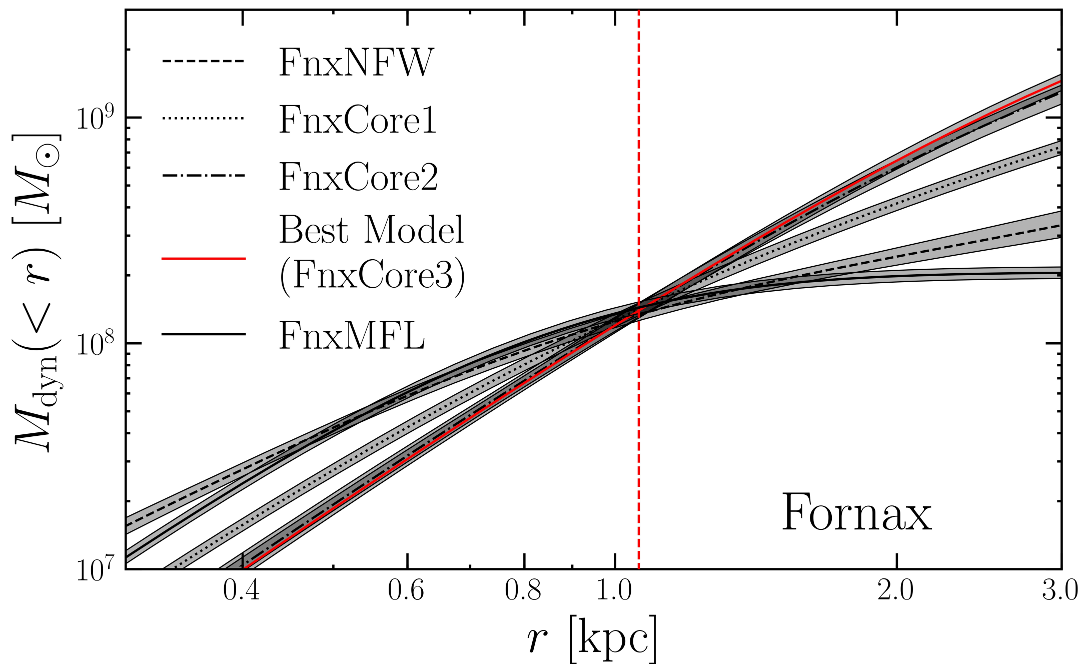


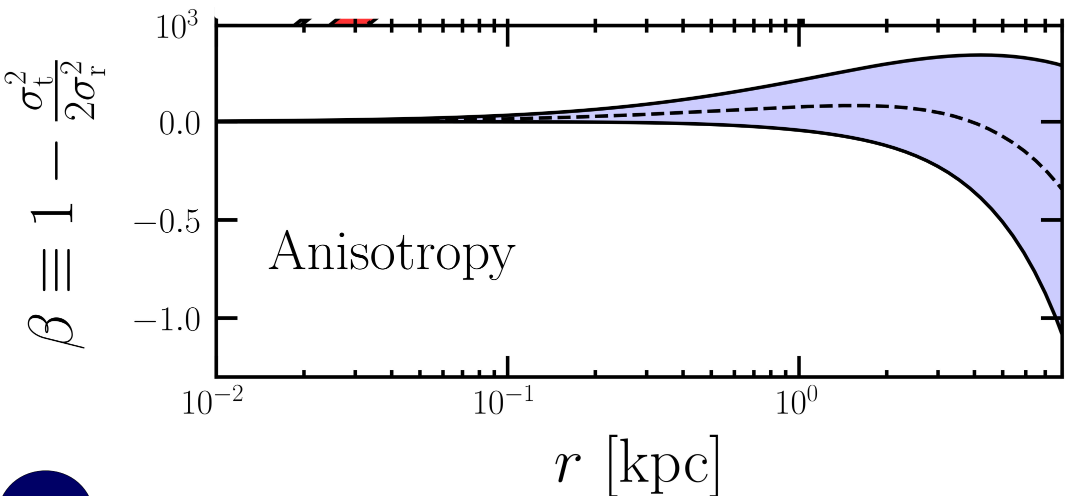
Fornax: Results



- Dark matter dominates over stars over the full radial extent of Fornax
- Largest core among the family explored. Further investigations show that $r_{c,dm} \leqslant 4\,\mathrm{kpc}$
- NFW and MFL hypothesis rejected with high statistical significance

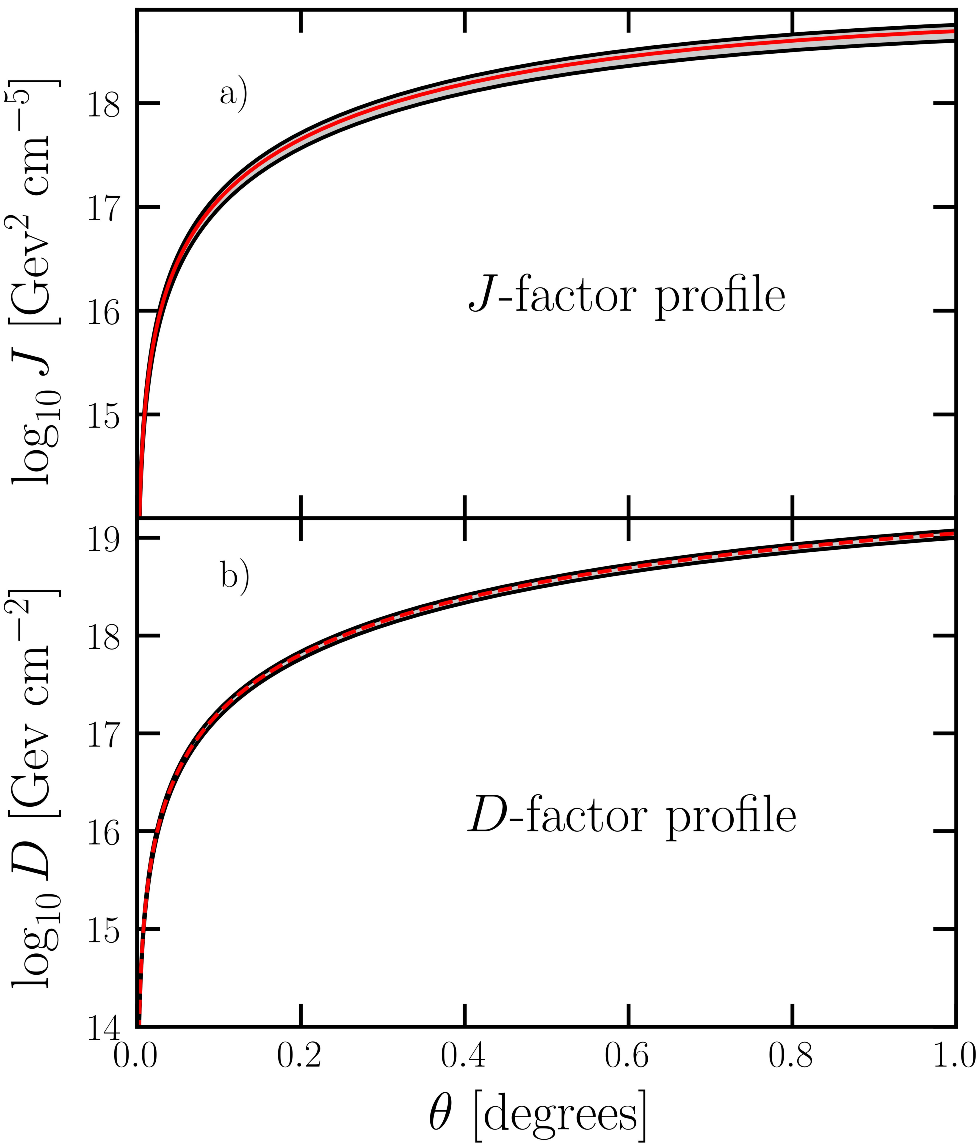
Fornax: Results





- Dark matter dominates over stars over the full radial extent of Fornax
- Largest core among the possible models explored
- NFW and MFL hypothesis rejected with high statistical significance
- Anisotropy independent mass estimate $M_{\rm dyn}(r \simeq 1.7\, R_{\rm e}) \simeq 1.38 \times 10^8\, M_\odot$
- Isotropic velocity distribution

Fornax: indirect detection



Perfect targets for dark matter **indirect detection**

***J*-factor**: proportional to the γ-ray flux due to annihilation

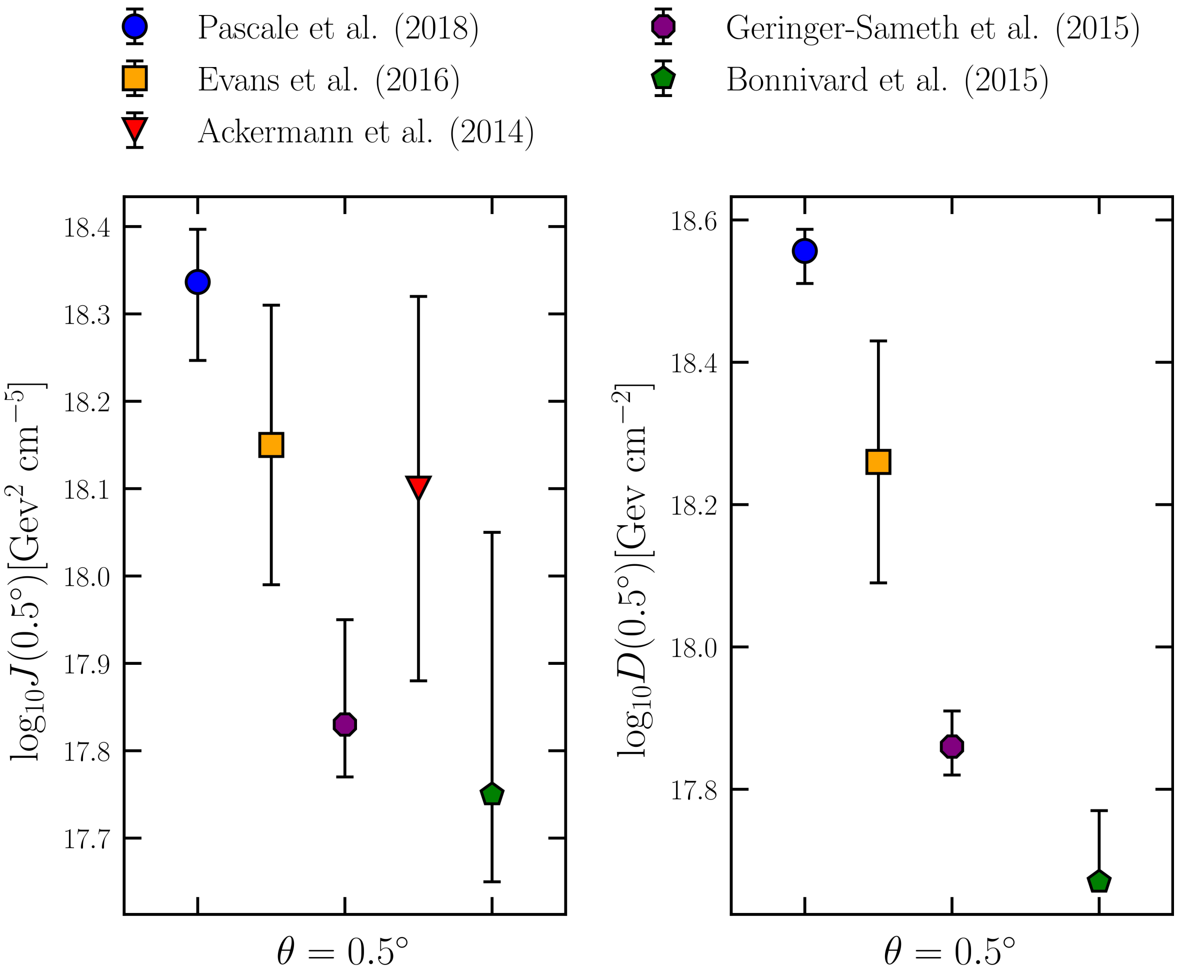
$$J(\theta)=\frac{2\pi}{d^2}\int_{-\infty}^{+\infty}\mathrm{d}z\int_0^{\theta d}\rho_{\rm dm}^2\,R\,\mathrm{d}R$$

***D*-factor**: proportional to the γ-ray flux due to decay

$$D(\theta)=\frac{2\pi}{d^2}\int_{-\infty}^{+\infty}\mathrm{d}z\int_0^{\theta d}\rho_{\rm dm}\,R\,\mathrm{d}R$$

The higher the better!

Fornax: indirect detection



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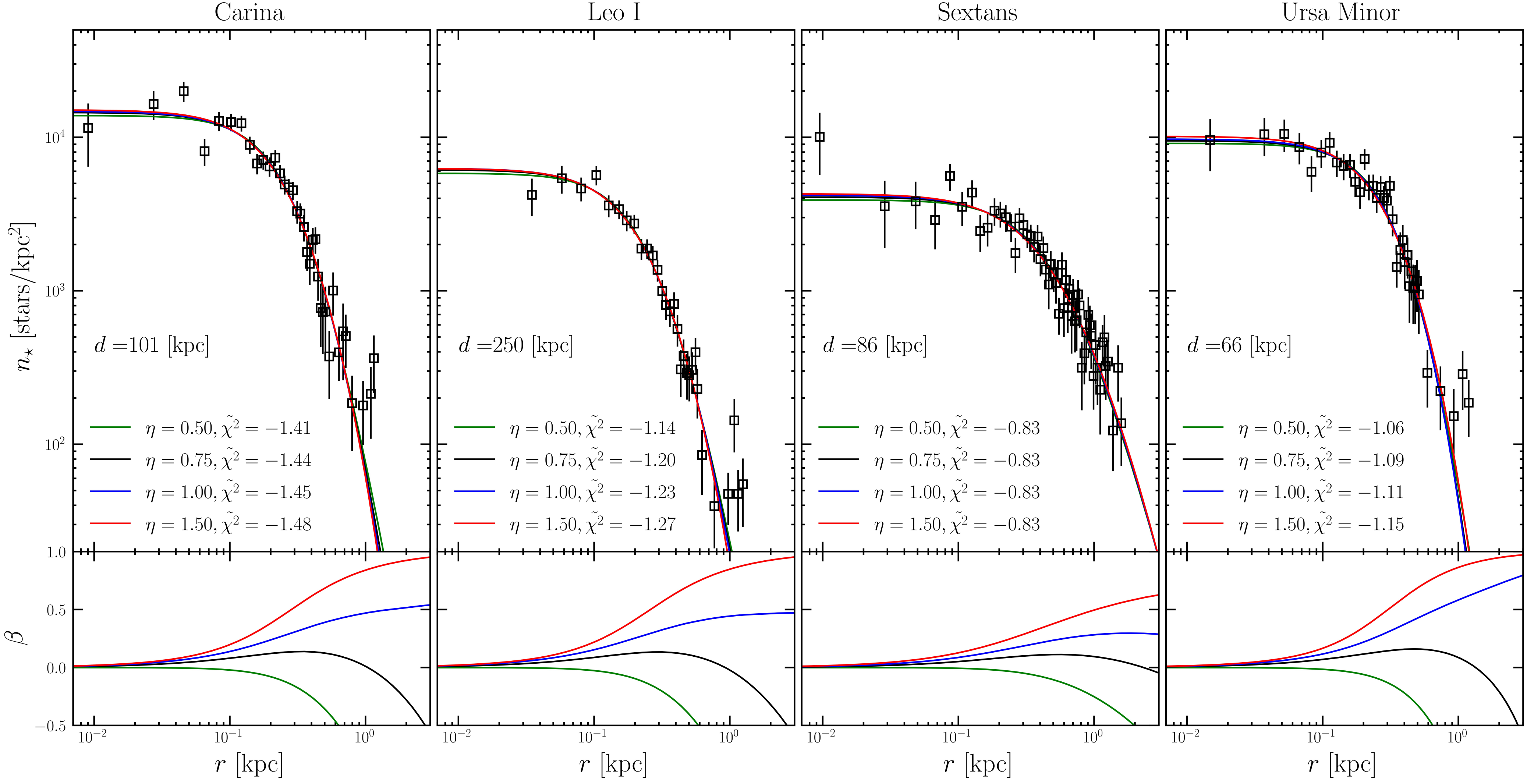
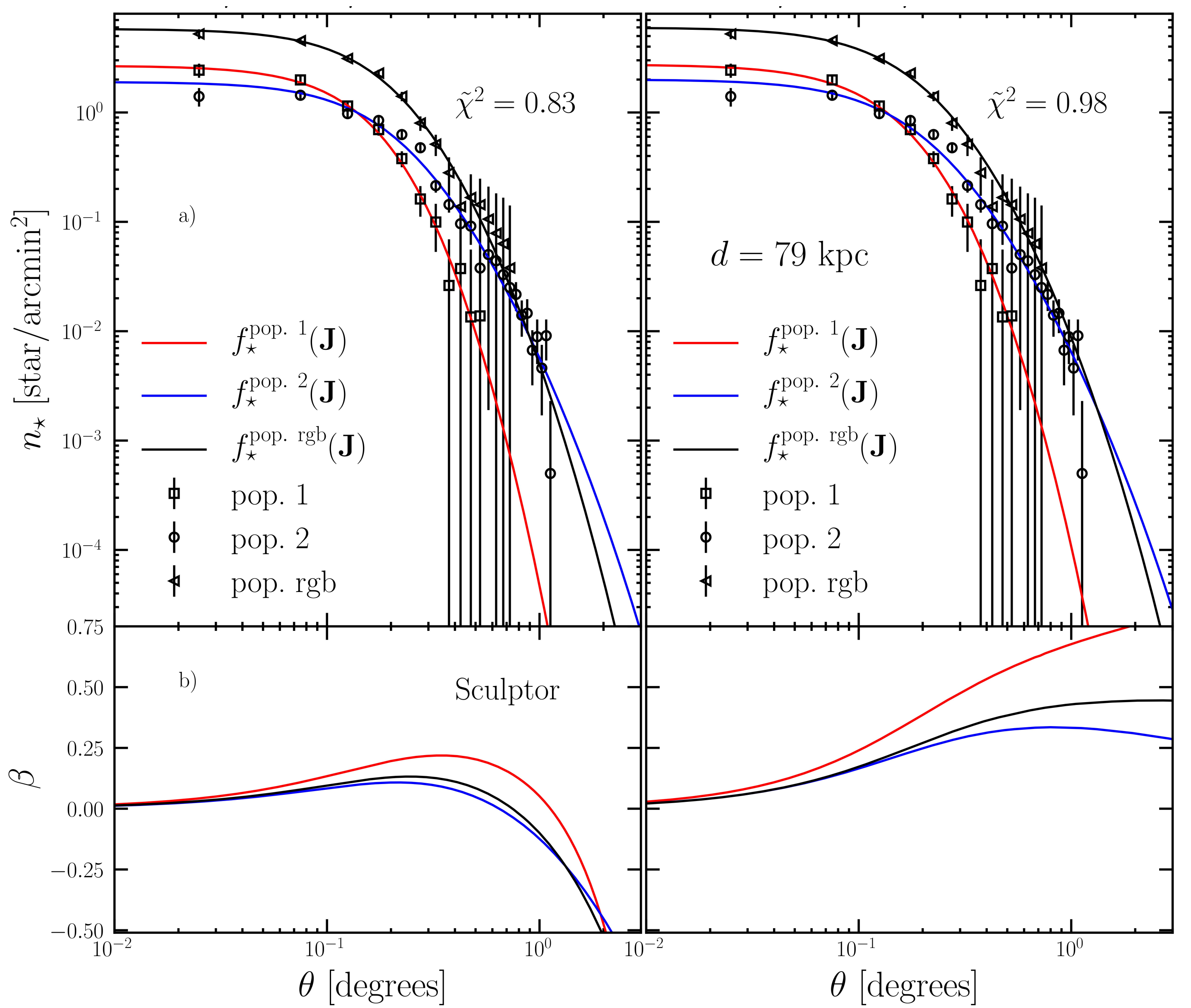
Not so much a bad candidate!

Space for other dSphs?



Space for other dSphs?



Positive in testing other dSphs

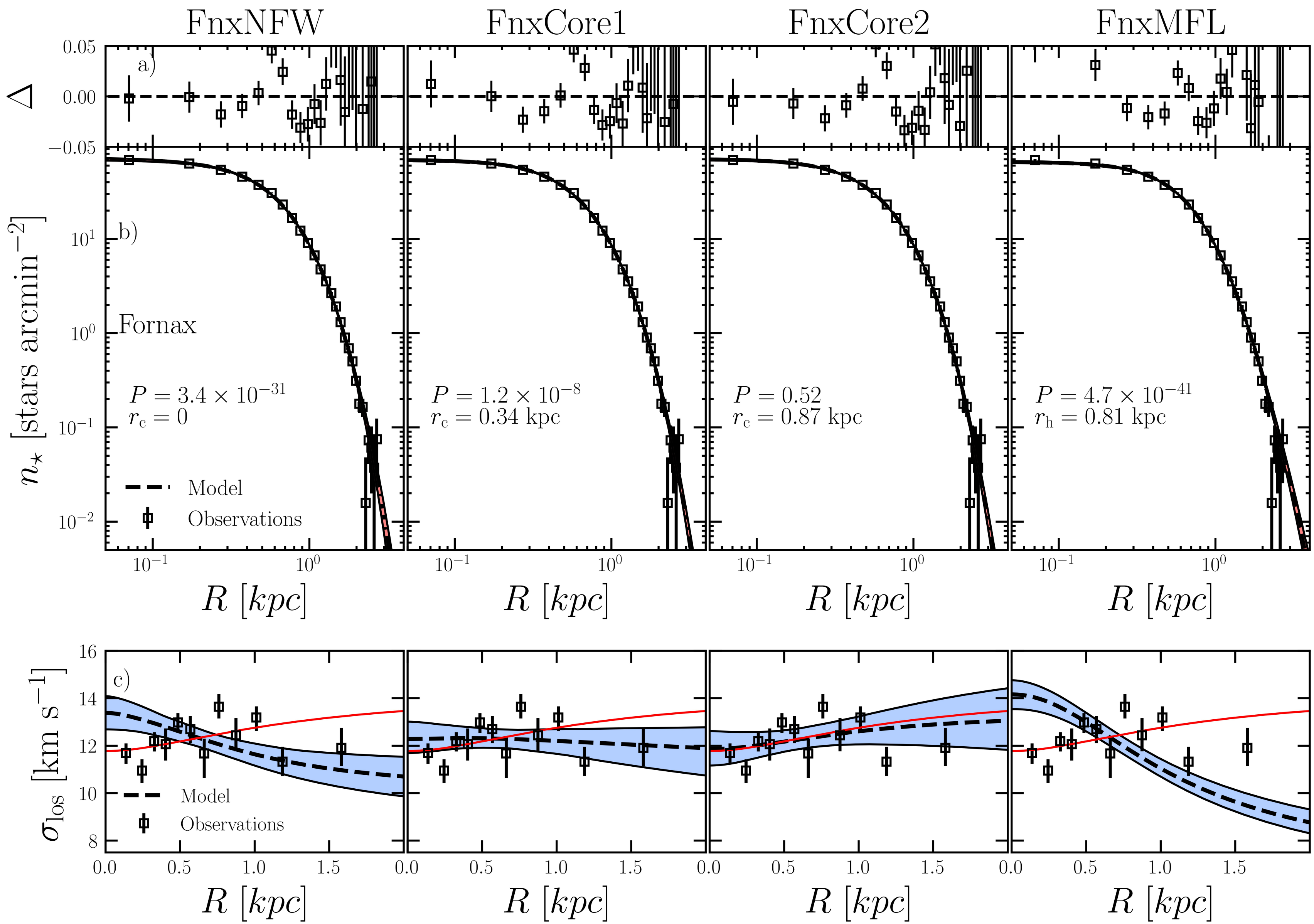
Appealing in the multicomponent modeling when separate stellar components are available (Pascale 2018b, in prep)

Conclusions

- First dynamical models based on DF of the Fornax dSph.
- Improved data-model comparison, accounting for:
  - Individual stars basis (no binning)
  - Physical LOSVD
  - MW contaminants
- Best model: cored dark-matter halo, isotropic stellar distribution
- Accurate measurements of J-D factors
- Test to other dSphs, ok

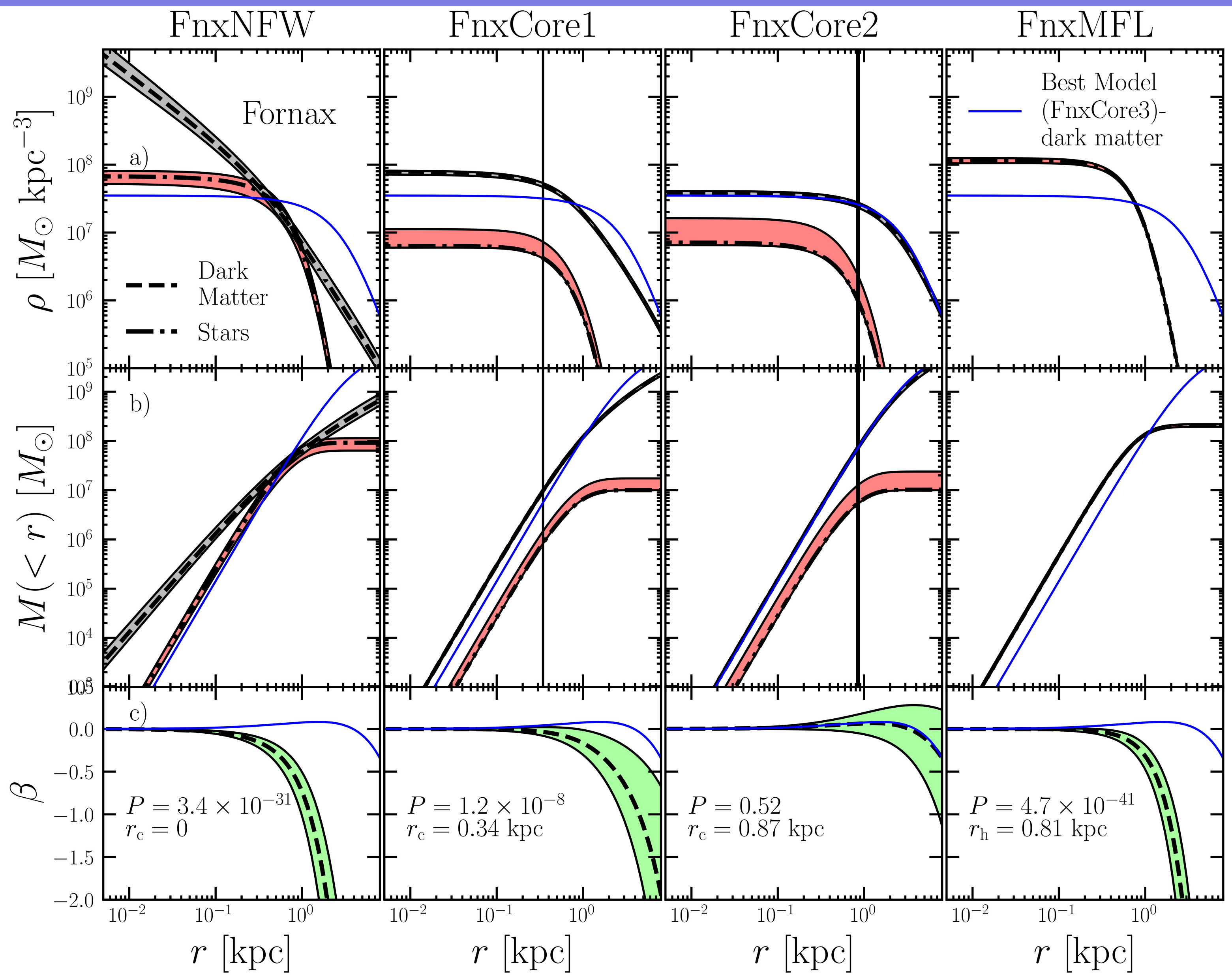
Auxiliary Slides

Performances of other models



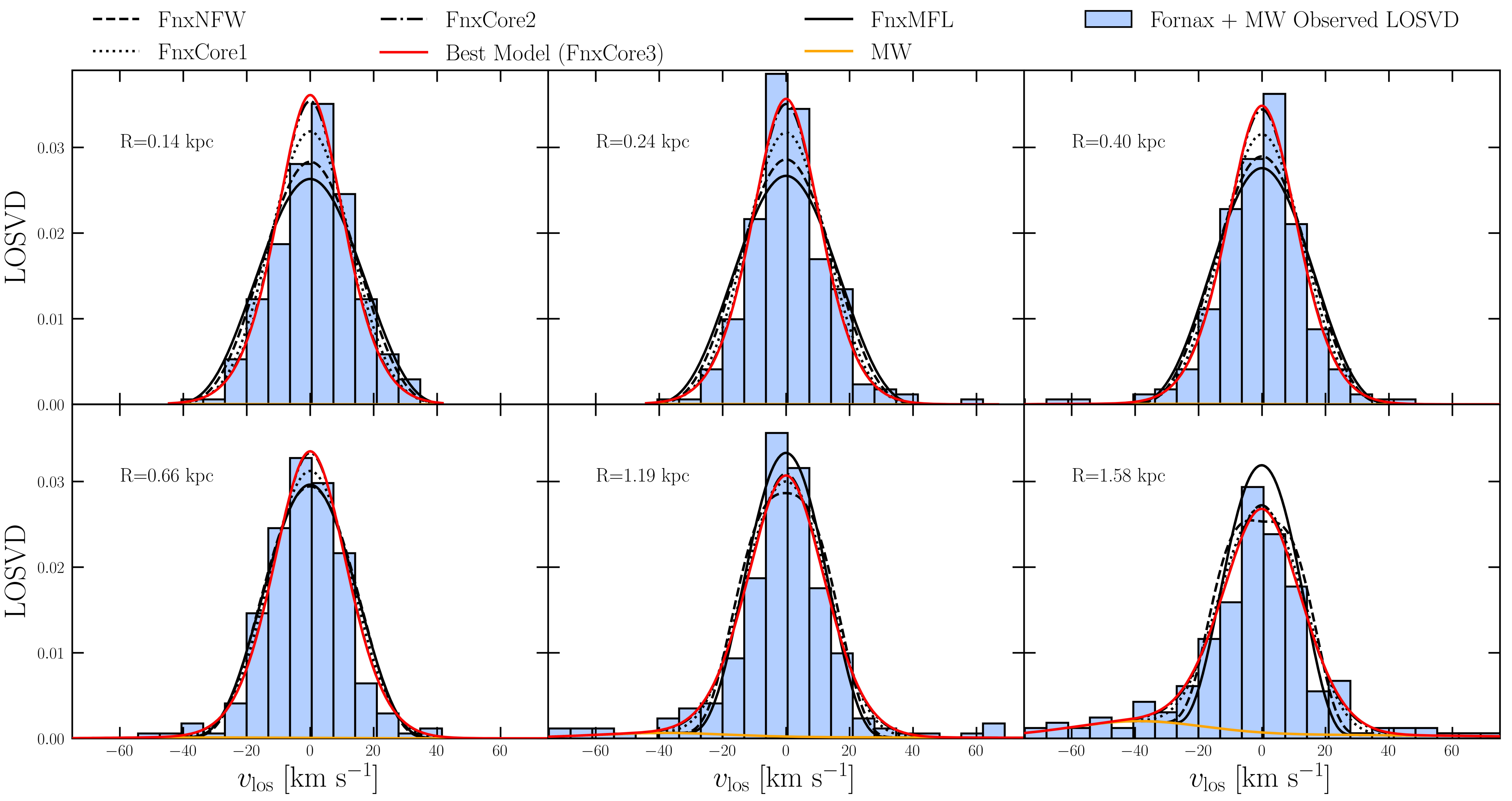
A1/A3

Performances of other models

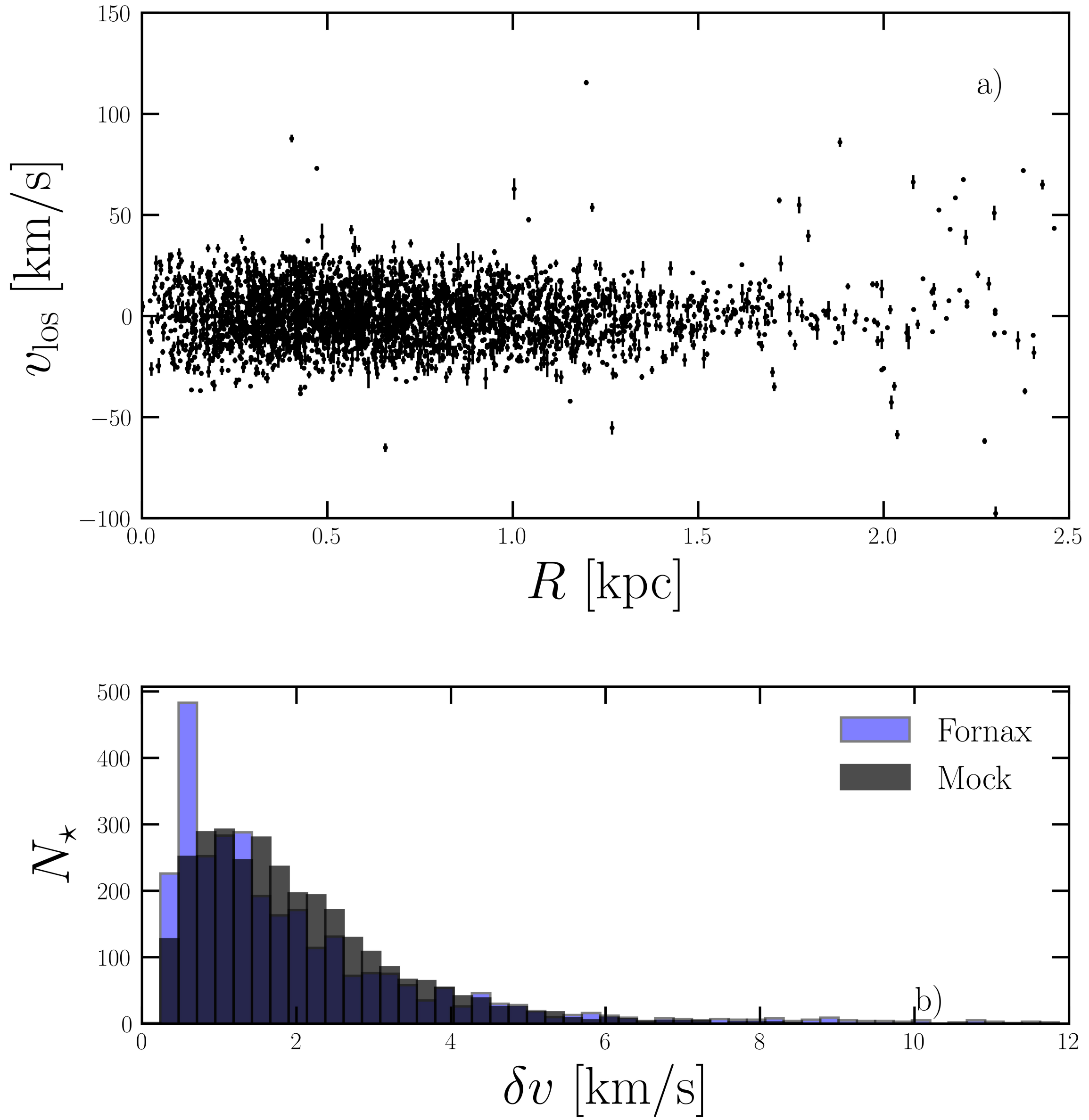


A2/A3

Performances of other models



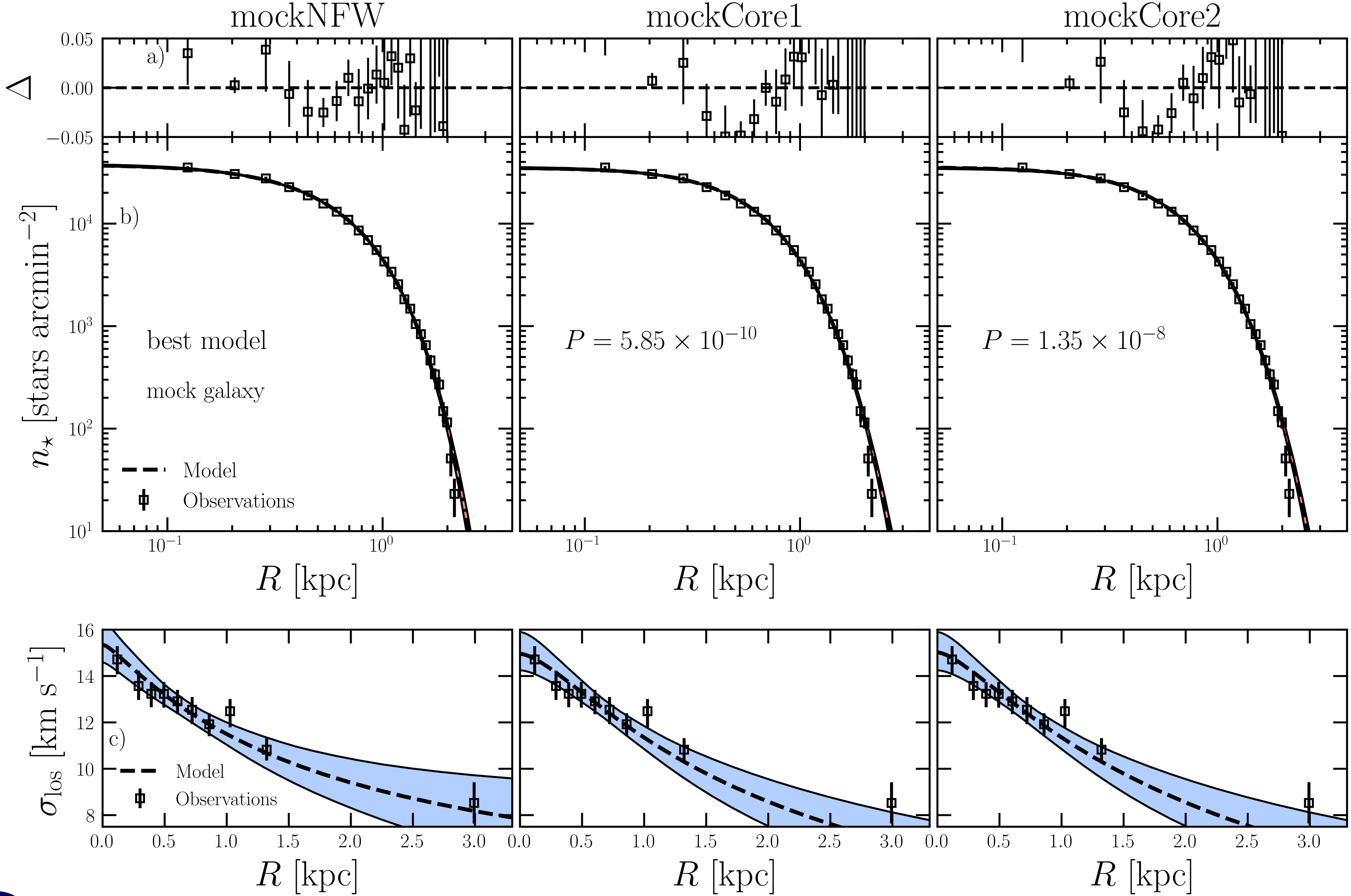
Mock test: samples



Application to **mock galaxy:**

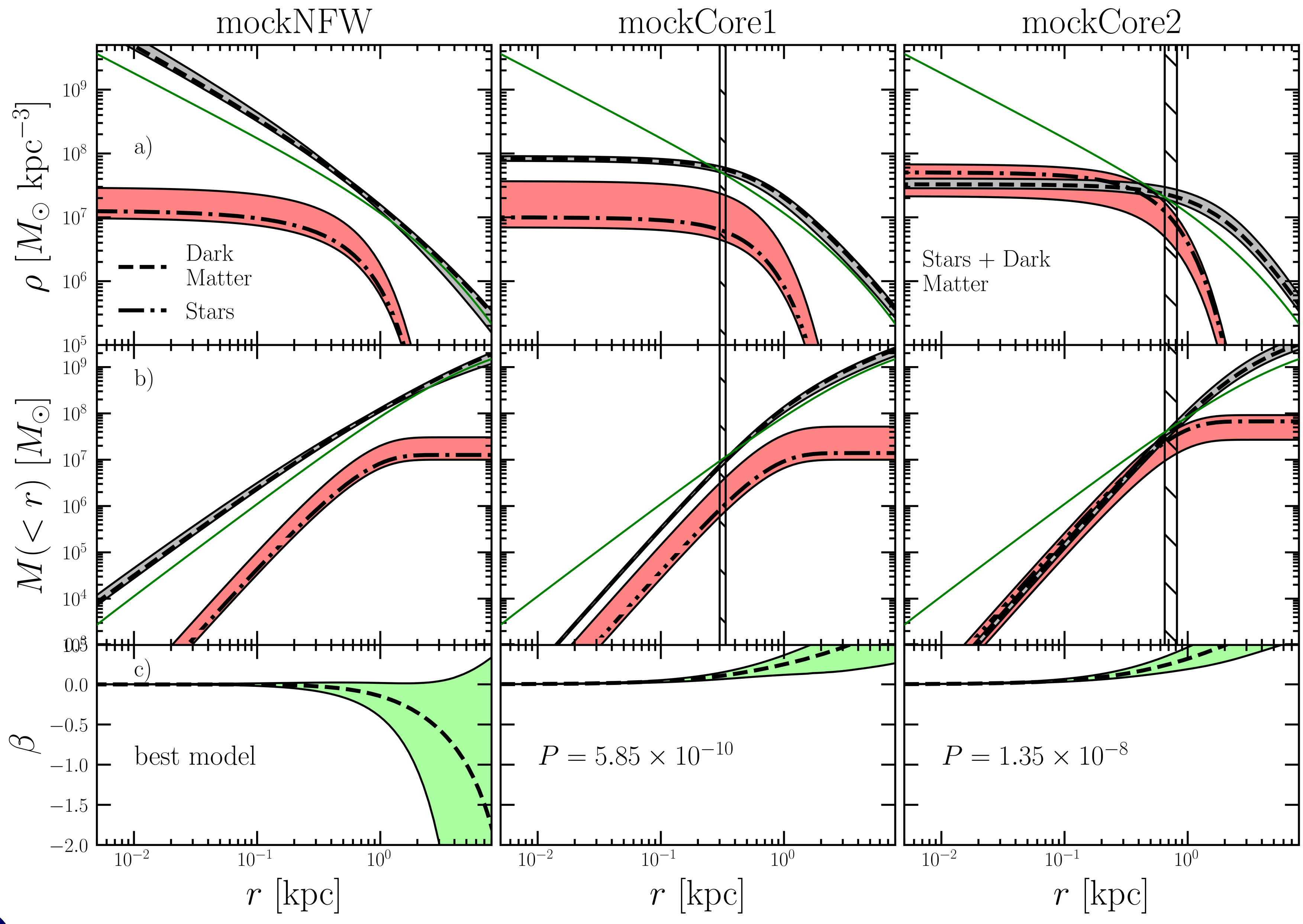
- Stellar component embedded in a dominant **NFW** halo
- **Isotropic** stellar velocity distribution
- Photometric and kinematic samples similar to the Fornax samples

Mock test: results



B2/B3

Mock test: results



DF for dSphs and GCs

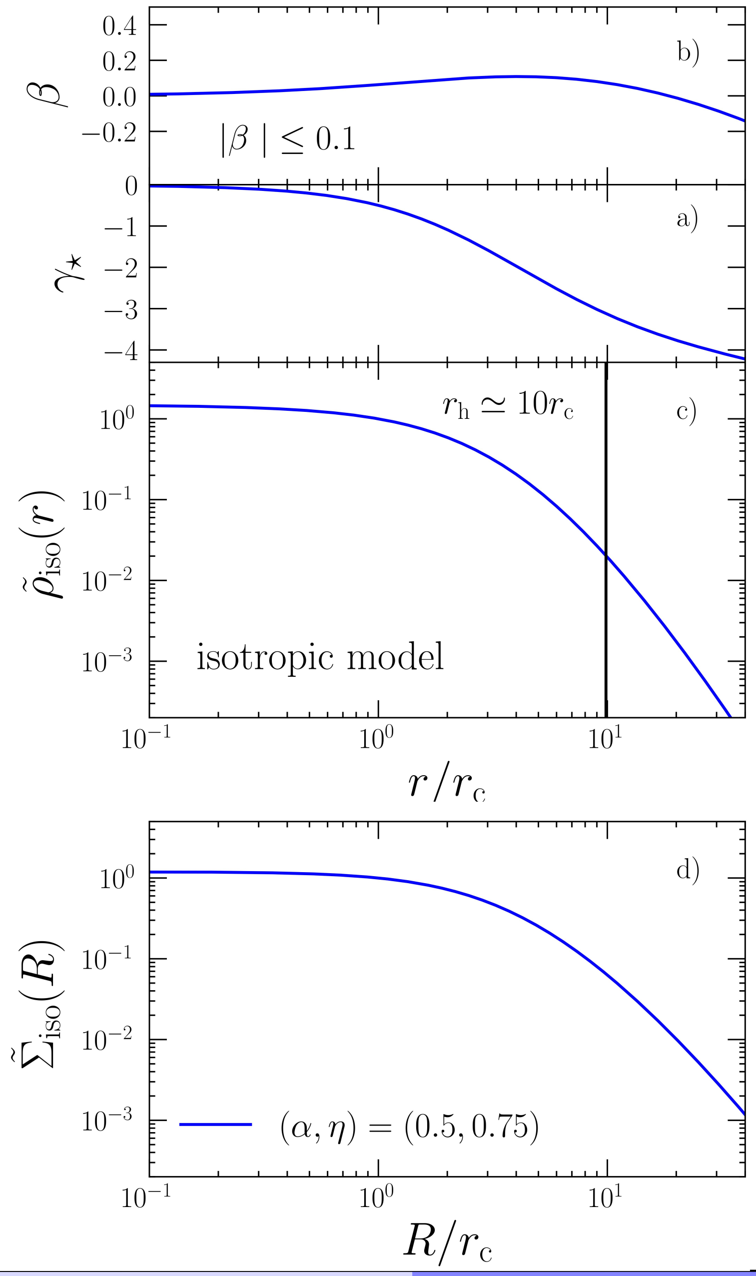
$$M_\star f_\star(\boldsymbol{J}) = M_\star f_0 \exp\left[-\left(\frac{k(\boldsymbol{J})}{J_{0,\star}}\right)^\alpha\right]$$

$$k(\boldsymbol{J}) = J_r + \eta\left(|J_\phi| + J_z\right) = J_r + \eta L$$

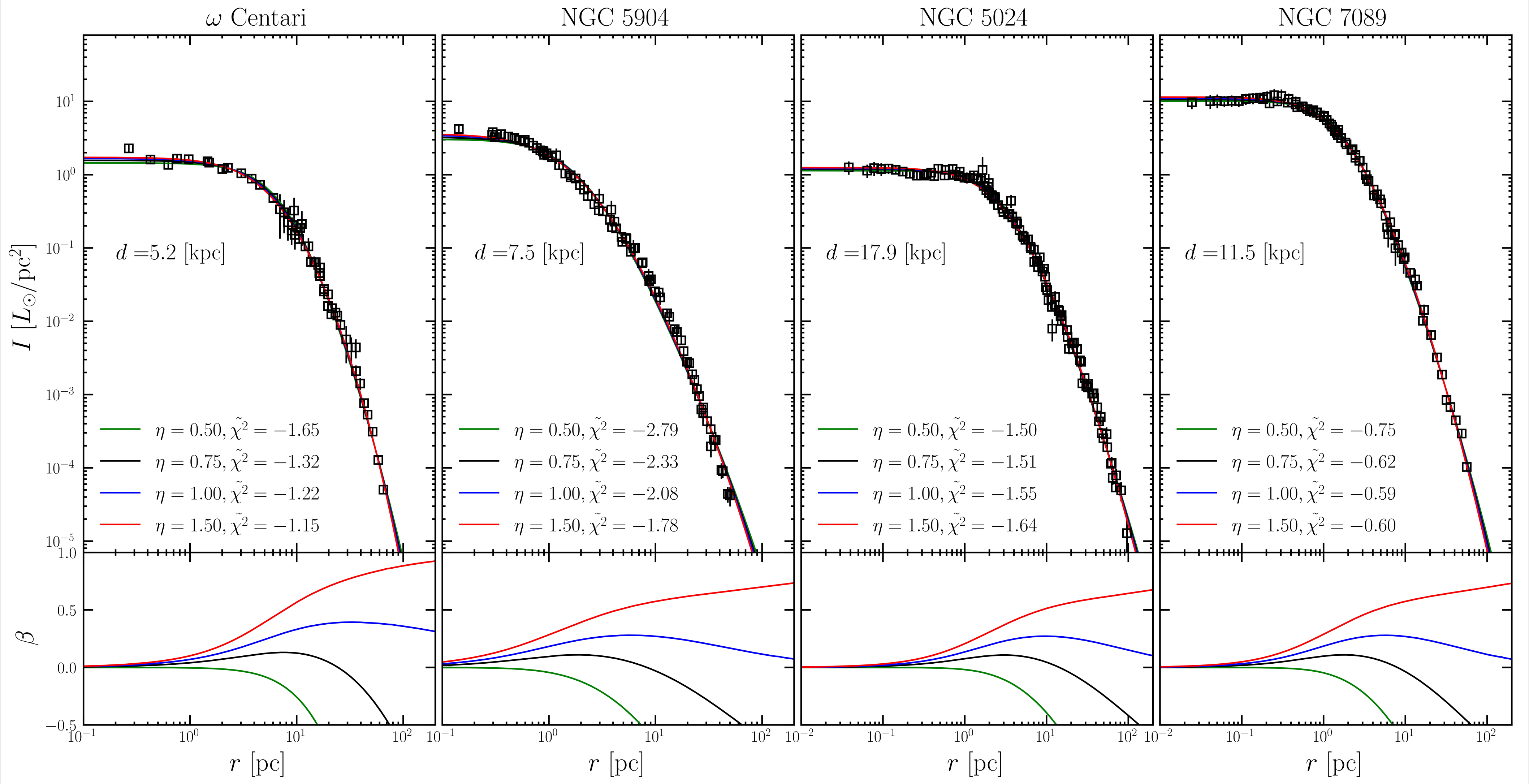
$$f_0 = \frac{\eta^2 \alpha}{(2\pi J_{0,\star})^3 \Gamma(3/\alpha)}$$

Free parameters:

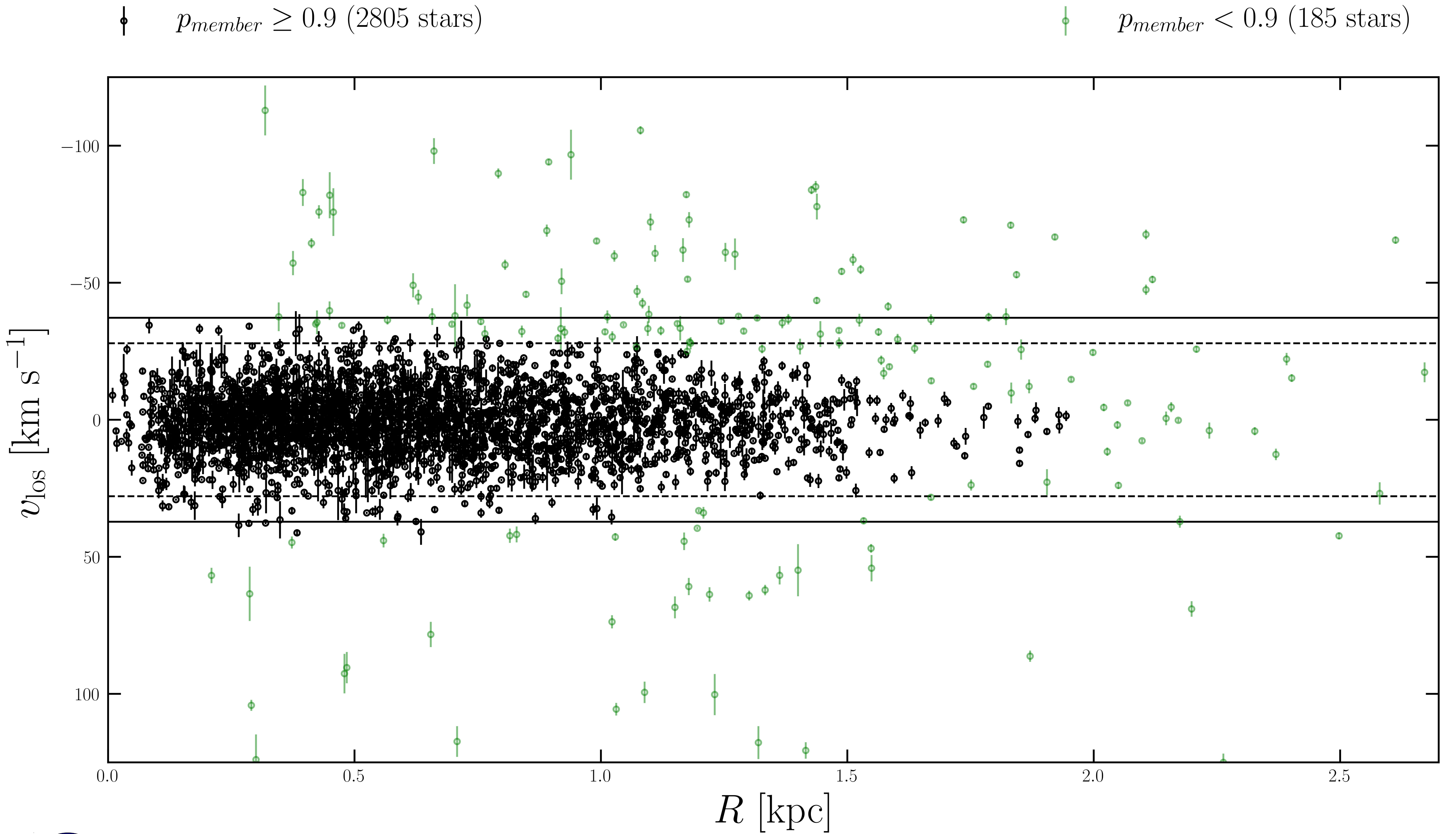
- (α, η) : dimensionless parameters regulating the structural and kinematic model properties
- $M_\star$: total mass
- $J_{0,\star}$: action scale



DF for dSphs and GCs

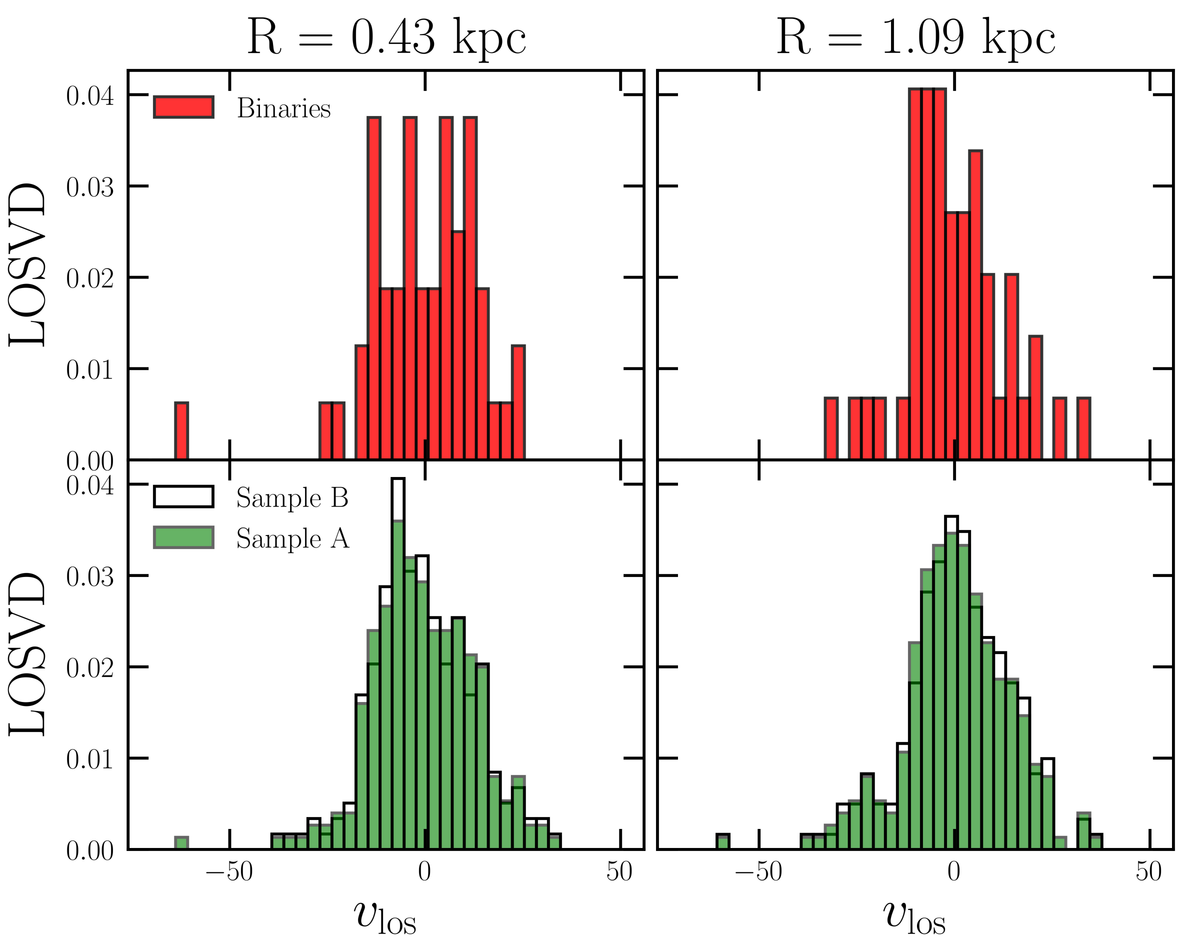


About the best model



D1/D2

About the best model



Sample A: whole cross-matched stars

Sample B: cross-matched stars without binaries

LOSVDs computed in two radial bins (inner and outer Fornax)

Bins have approximately the same number of stars

Flattened models