# Dynamical models of dwarf spheroidal galaxies


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Small Galaxies, Cosmic Questions - 30/07/19

# Dwarf spheroidal galaxies

Fornax

Sculptor

credits: ESO/Digitized Sky Survey 2

- Pressure supported, flattened
- Dark-matter dominated
- Probe $\Lambda$CDM cosmology on the smallest scales
- Study dark-matter properties in a convenient environment
- Search for dark-matter indirect detection

# Dynamical models based on DFs

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

A DF describes the probability of finding a star at a given volume of the phase space

Any DF:

- Satisfies the CBE (Collisionless Boltzmann Equation) $\frac{Df}{Dt} = 0$
- Is physical (Non-negative function)

Powerful tools of the interpretation of observations because they predict the outcome of any observations

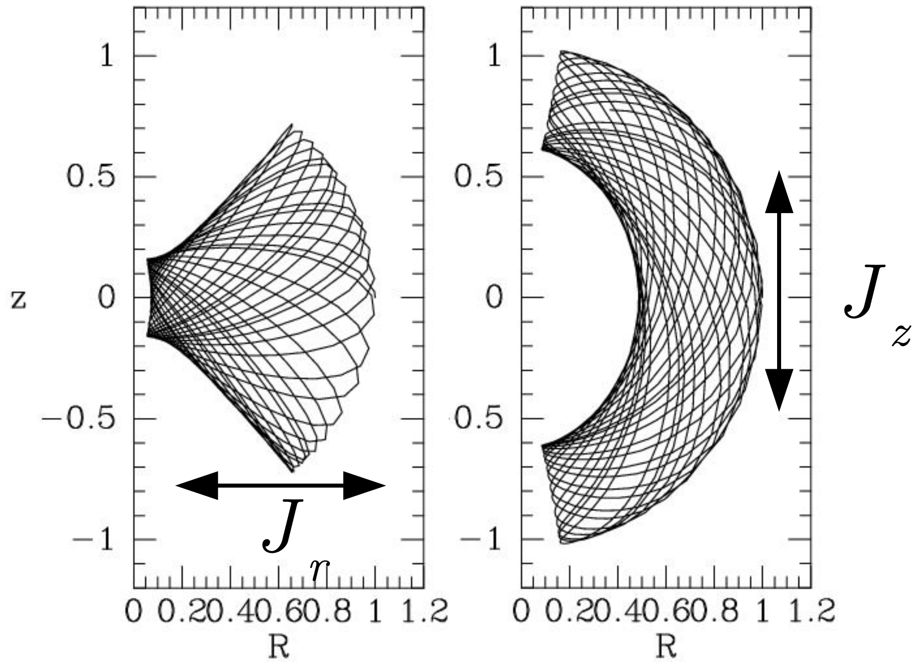
*Jeans Theorems*

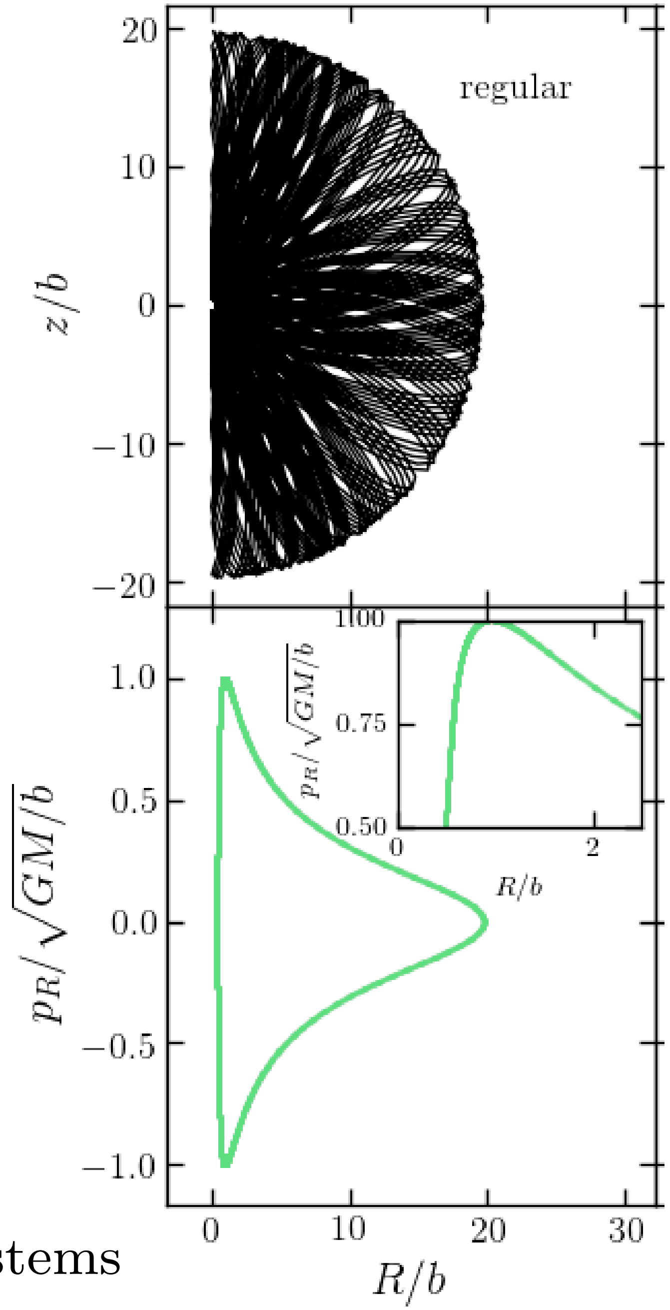
Adopt integrals of motion as argument of the DF

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

# Action based-DFs

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




Which integrals?

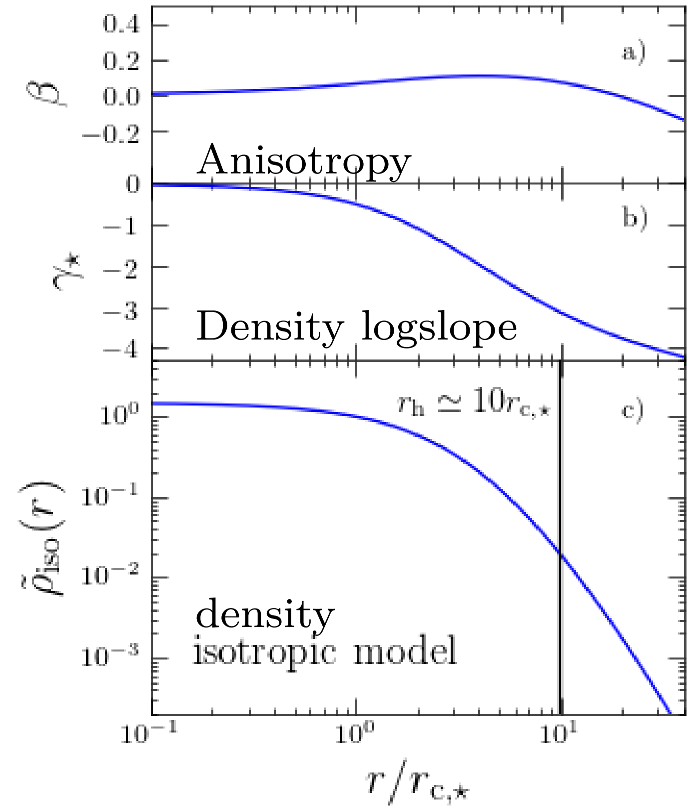
The actions

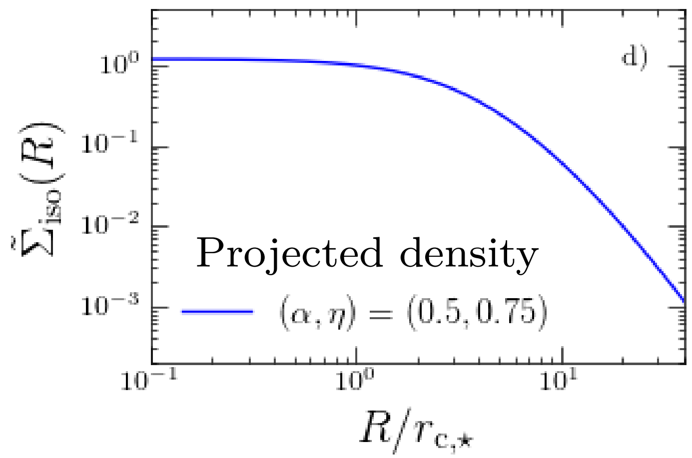
$$(J_r, J_\phi, J_z)$$

why?

- Flattening
- Rotation
- Multi-component systems

# The distribution function




Pascale R., Binney J., Nipoti C., Posti L., 2019, MNRAS

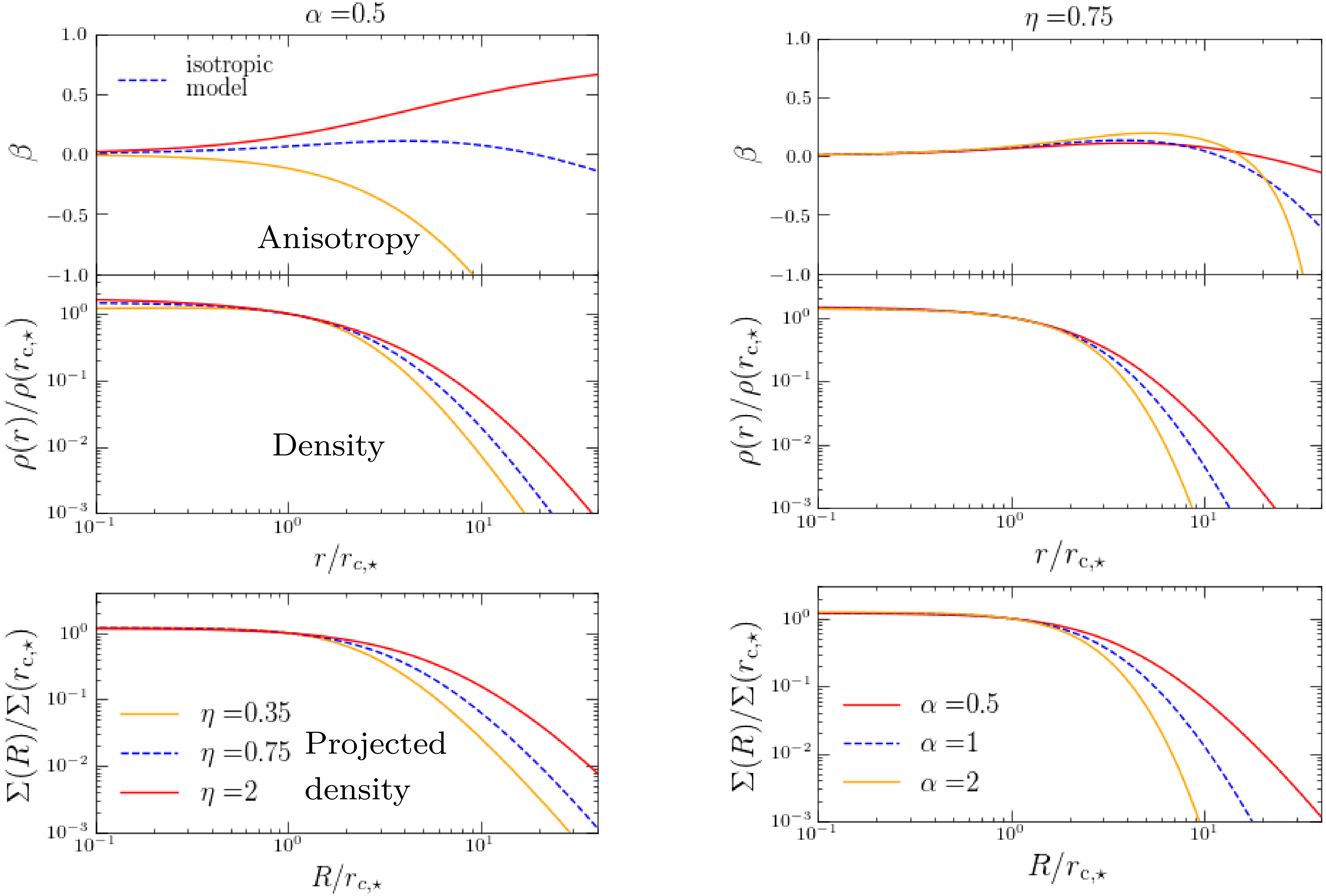
$$f_\star(\mathbf{J}) = M_\star f_0 \exp\left[-\left(\frac{k(\mathbf{J})}{J_\star}\right)^\alpha\right]$$

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

Free parameters:

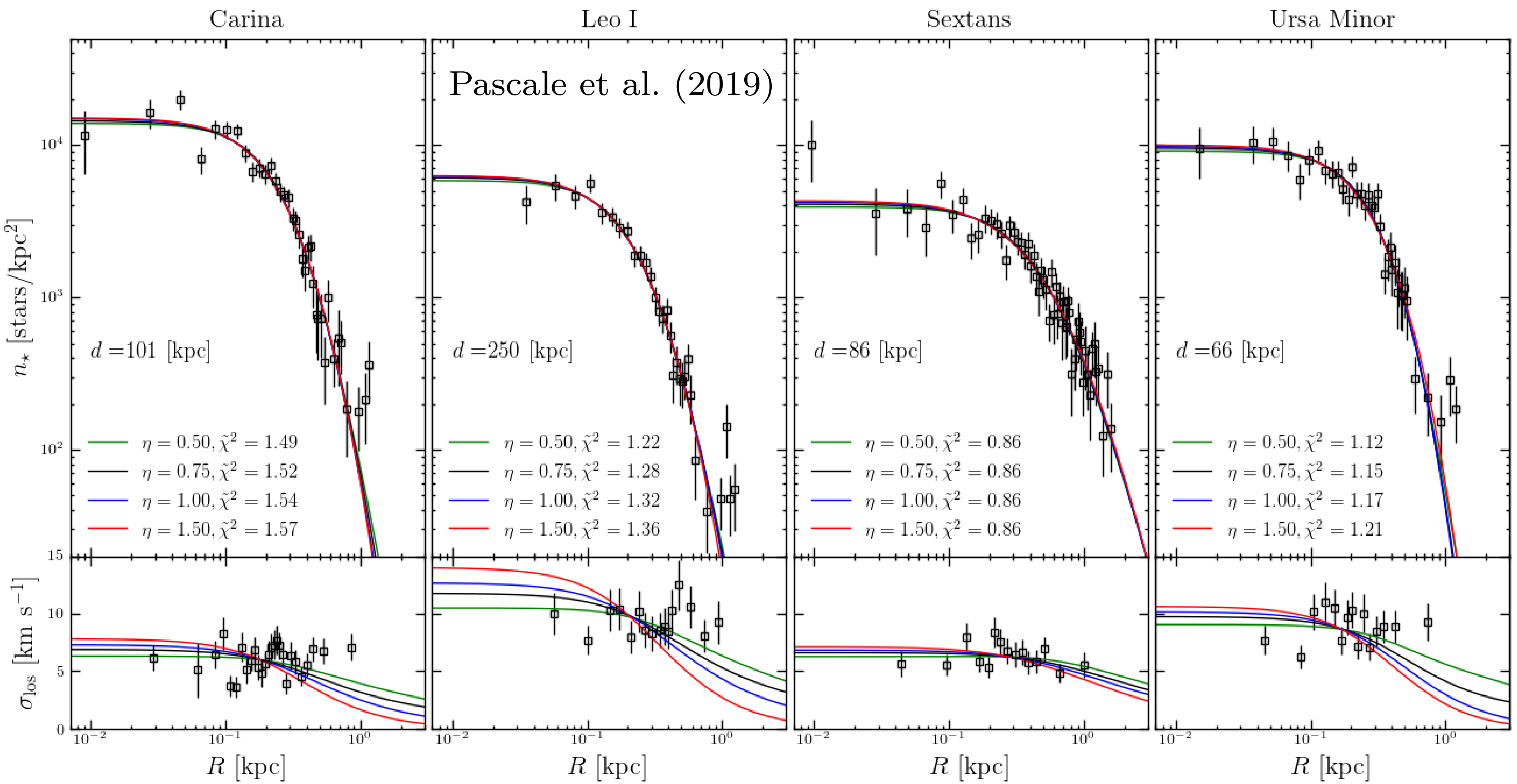
- Dimensional parameters $(M_\star, J_\star)$
- Dimensionless parameters $(\alpha, \eta)$

# The free parameters



# Test cases: dwarf spheroidal galaxies



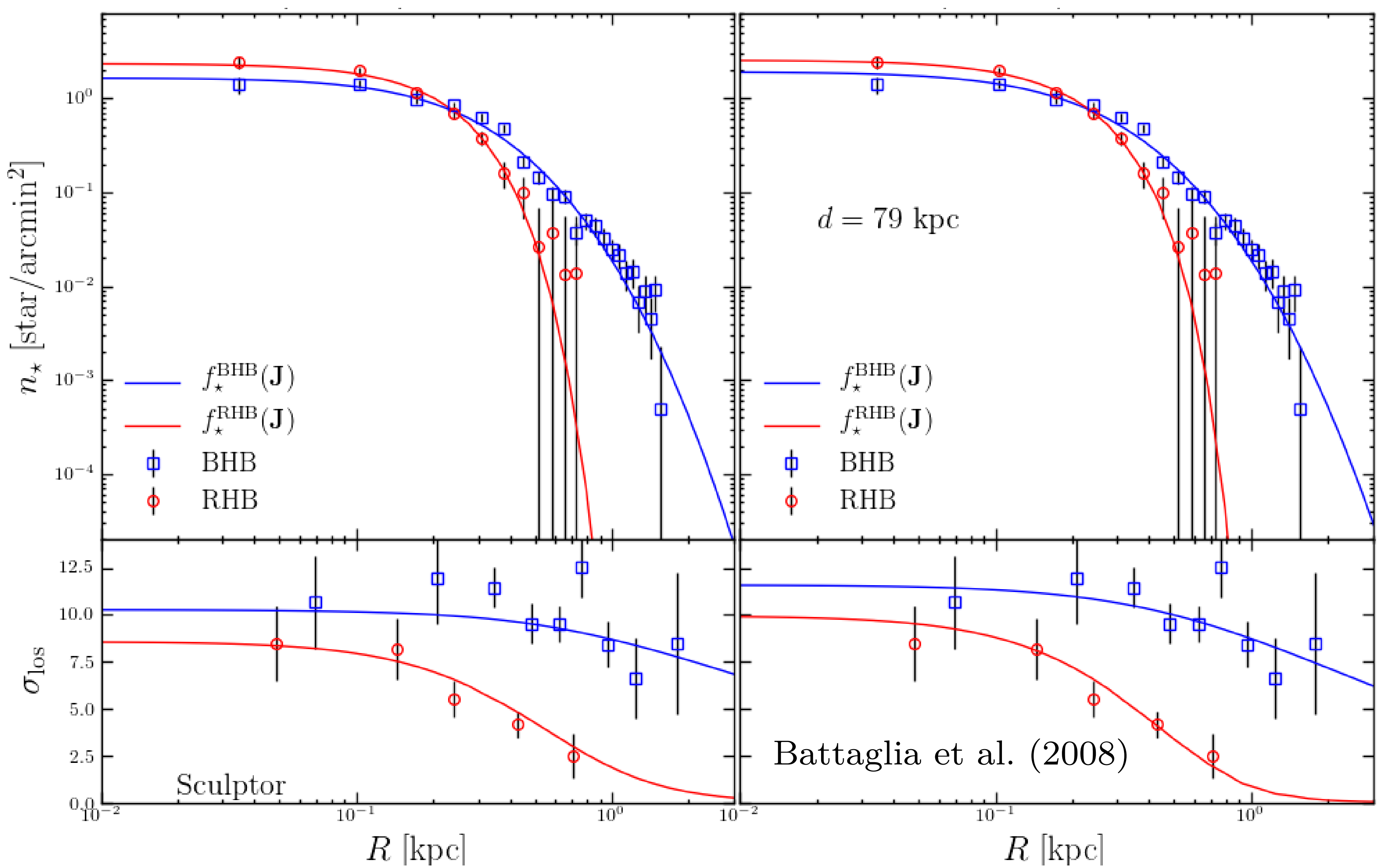



Irwin & Hatzidimitriou (1995)
Mateo et al. (1998)
Walker et al. (2007)

# Test cases: multi-component Sculptor

Iorio et al. (2019)

$$f_{\rm tot}(\boldsymbol{J}) = f_{\rm BHB}(\boldsymbol{J}) + f_{\rm RHB}(\boldsymbol{J}) + f_{\rm DM}(\boldsymbol{J})$$



# Application to Fornax



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

**Stars DF** $f_\star(\boldsymbol{J})$ **:** reproduces cored, **anisotropic** stellar components, with **truncation** of adjustable steepness

**DM DF** $f_{\rm dm}(\boldsymbol{J})$ **:** reproduces **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)

Pascale et al. (2018), MNRAS, 480, 927
Pascale et al. (2019a),

Battaglia et al. (2015)

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

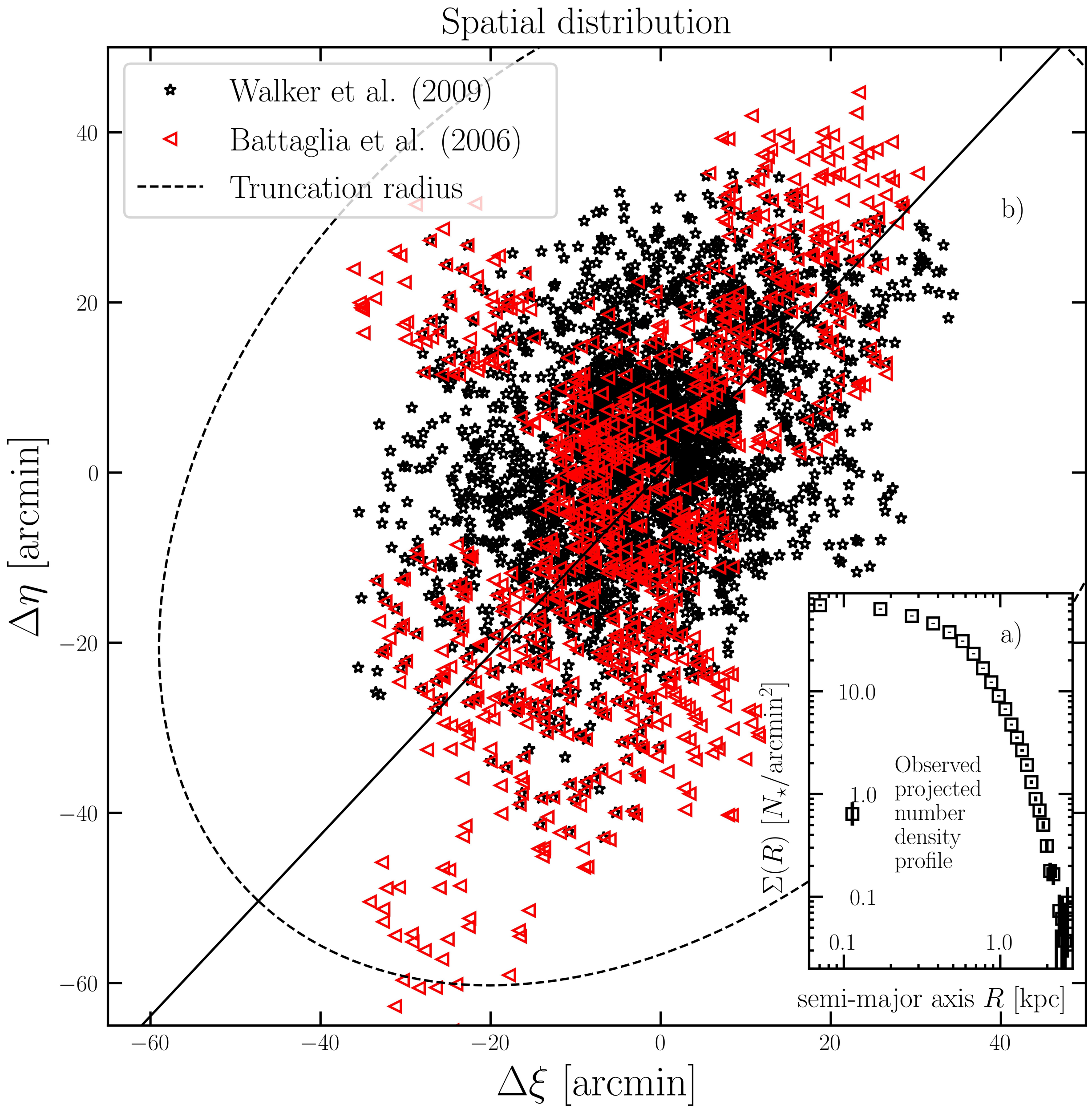
Five scenarios:

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

**Best Model: Cored halo**

# Application to Fornax

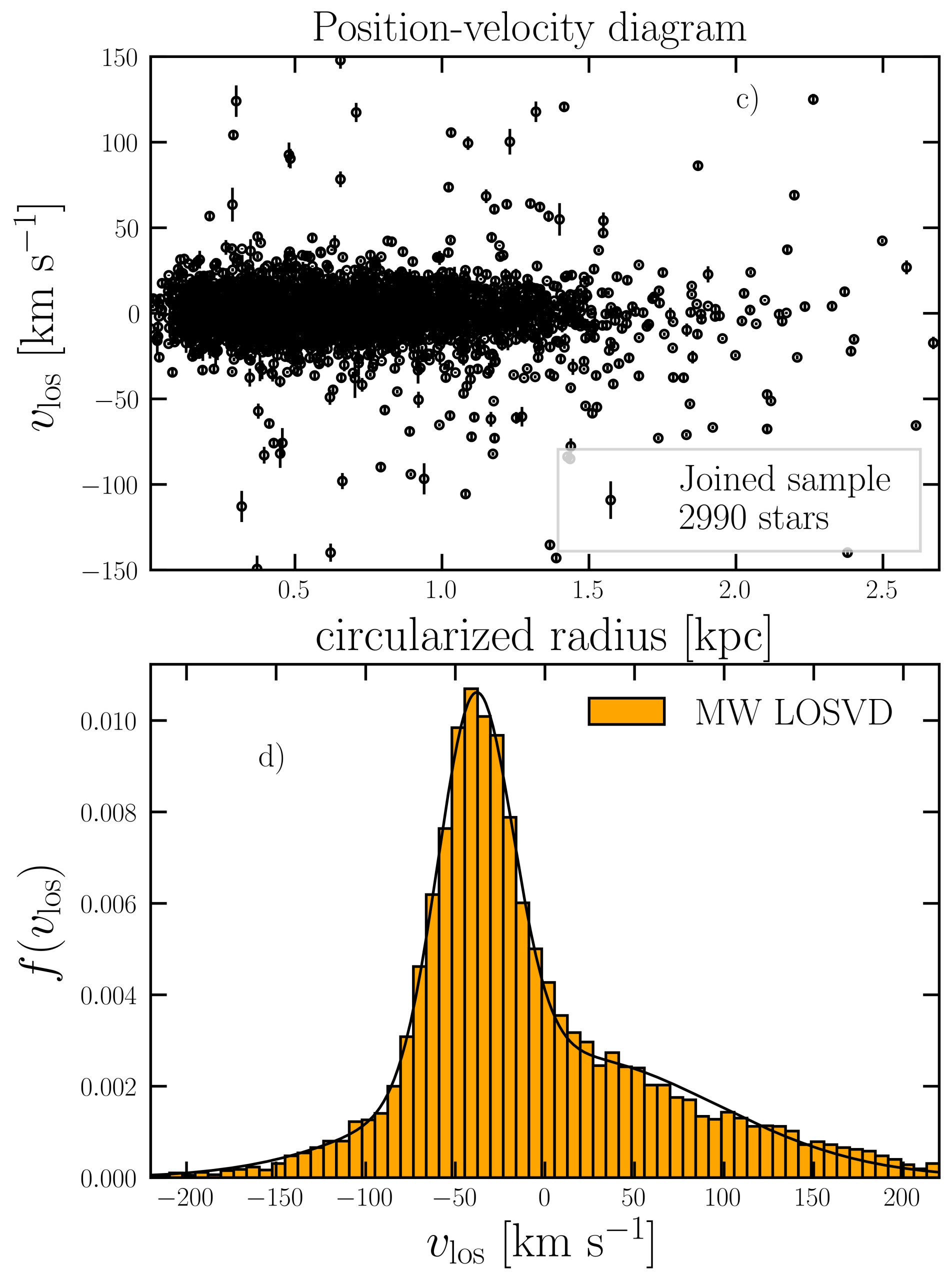





- **Photometric sample** Projected stellar number density profile (Battaglia et al. 2006)
- **Kinematic sample** measures of star velocities along line-of-sight (Battaglia et al. 2006, Walker et al. 2009)
- **Milky Way LOSVD model** (Robin et al. 2004)

# Application to Fornax



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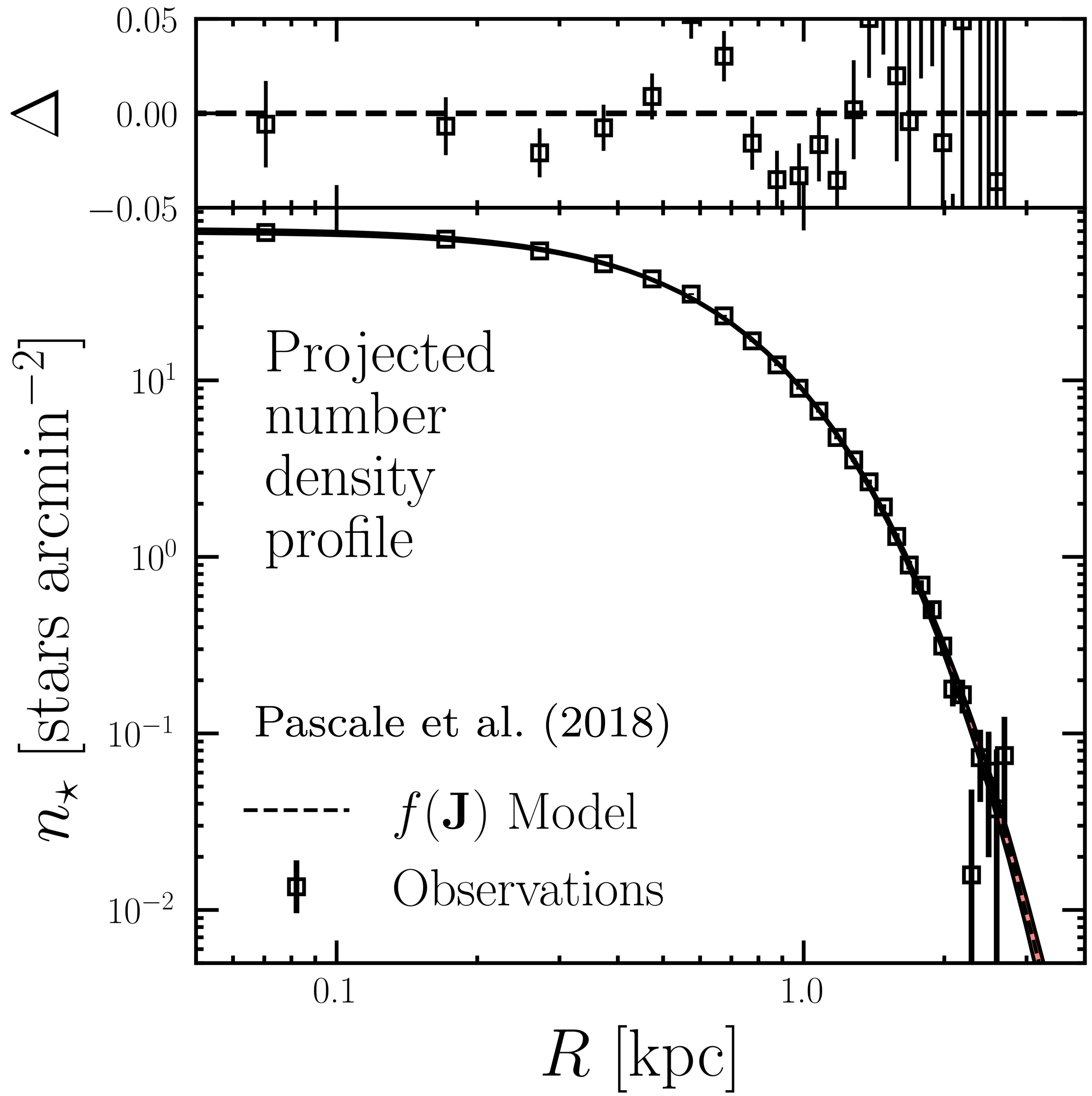
# Application to Fornax






- Fit between the model and observed projected number density profiles

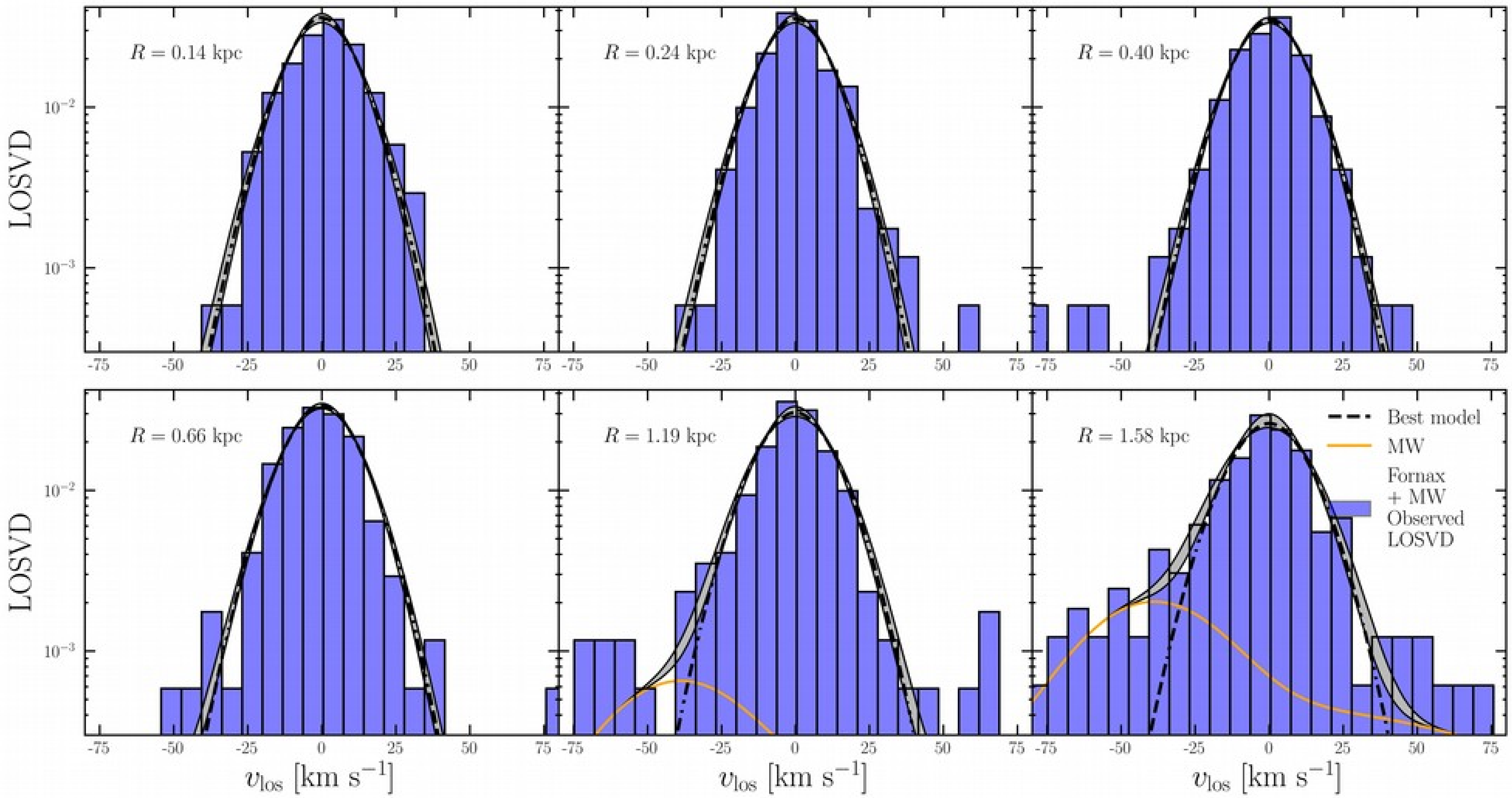
$$n_\star(\boldsymbol{x}_\perp) = \frac{\int \mathrm{d}^3 \boldsymbol{v} \, \mathrm{d} x_\parallel \, f(\boldsymbol{J})}{\rho_\star(\boldsymbol{x})}$$

- Individual stars are fitted through the model line-of-sight velocity distribution (LOSVD)

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

# Application to Fornax

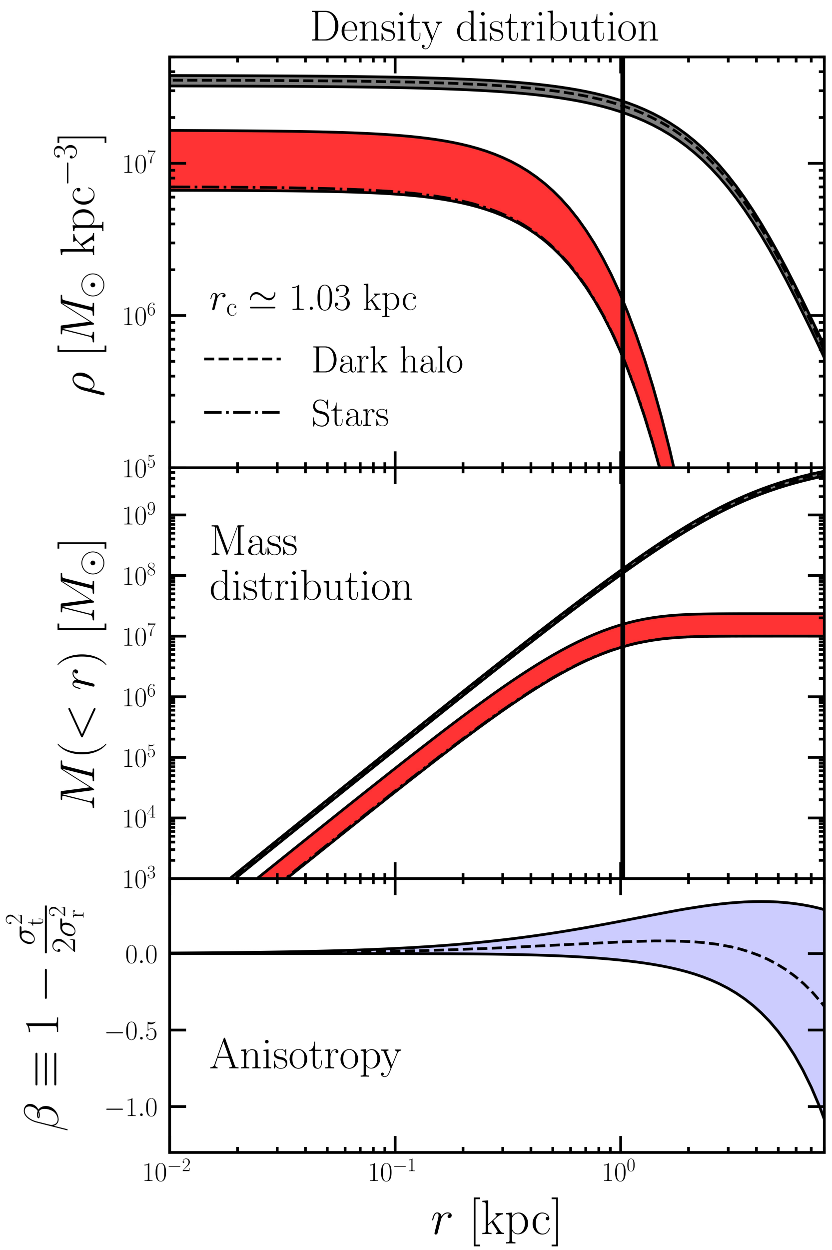





Pascale et al. (2018)

# Application to Fornax





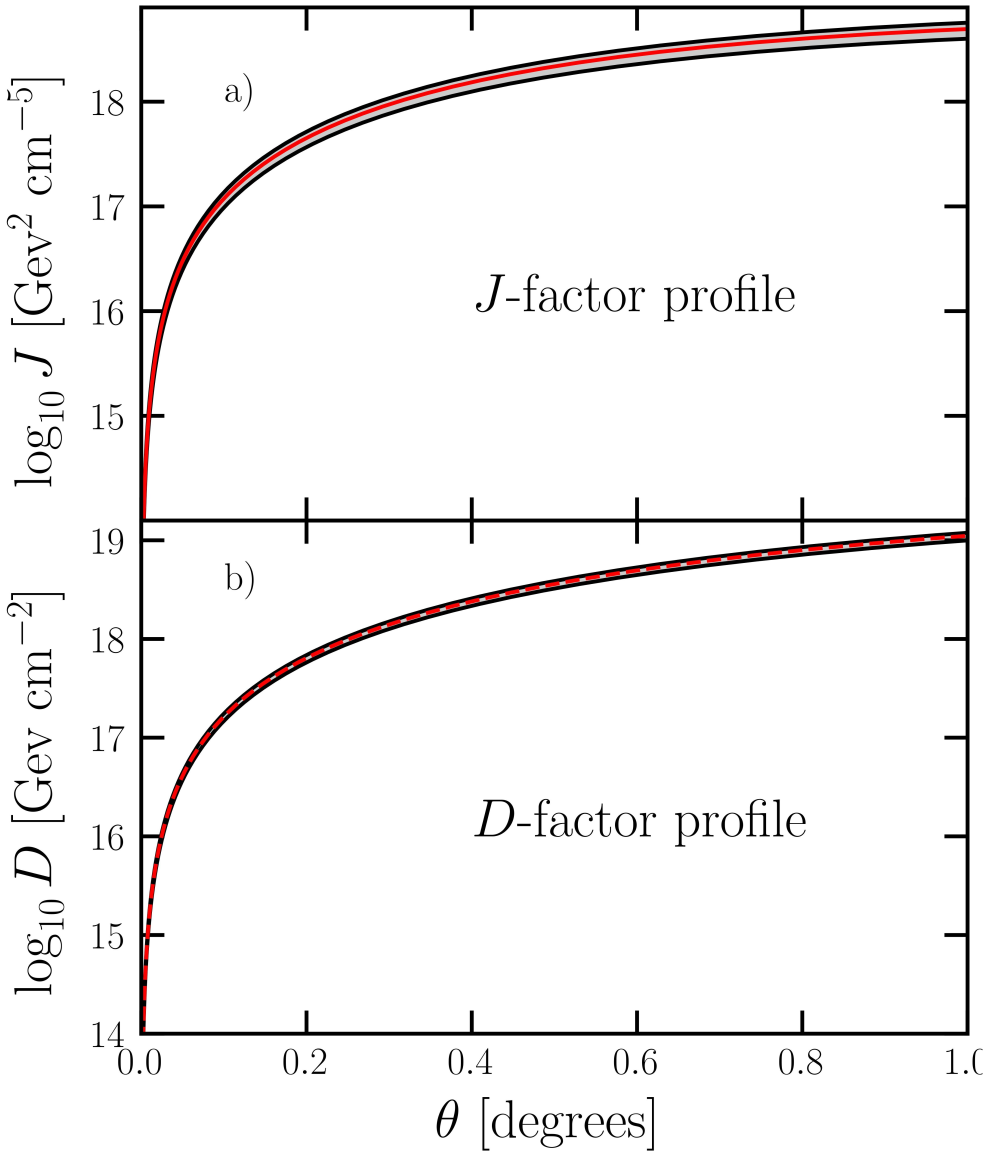

- Almost isotropic velocity distribution
- Cored dark matter halo, $r_c \sim 1$ kpc
- Dark matter dominated galaxy with

$$\frac{M_{\mathrm{dm}}}{M_\star} \simeq 144$$

Pascale et al. (2018)

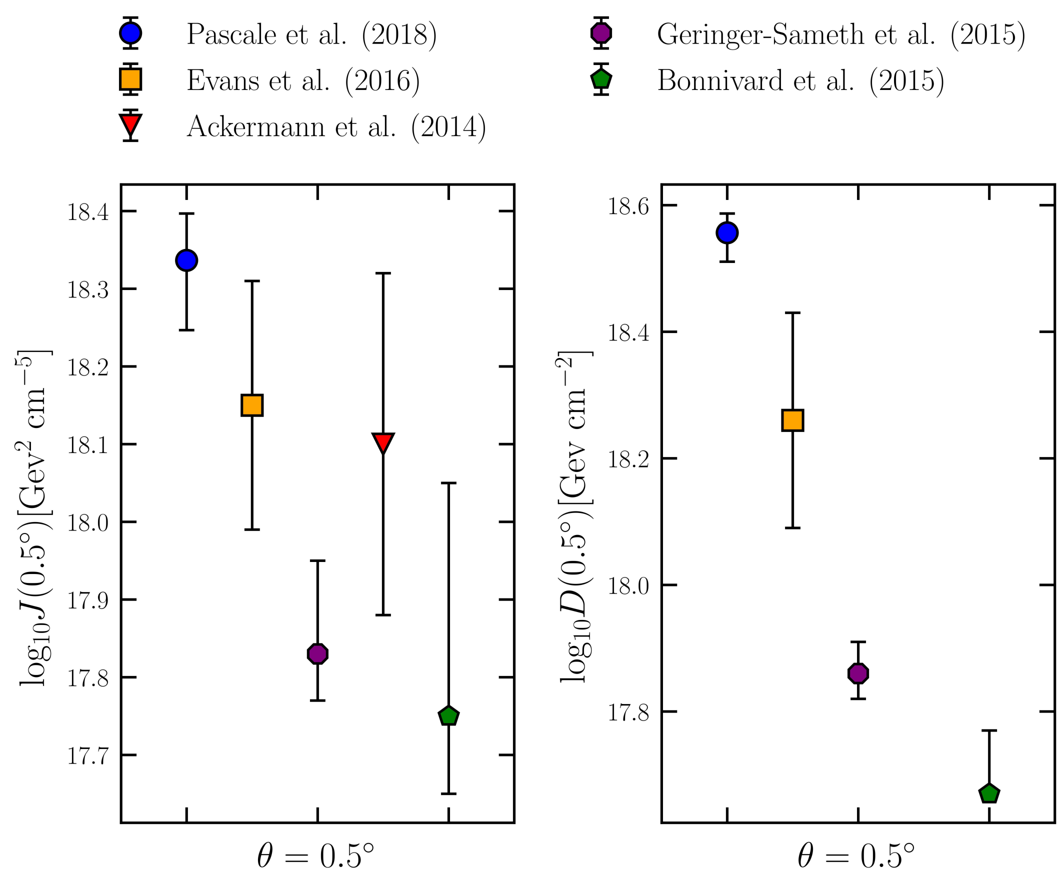
# Application to Fornax





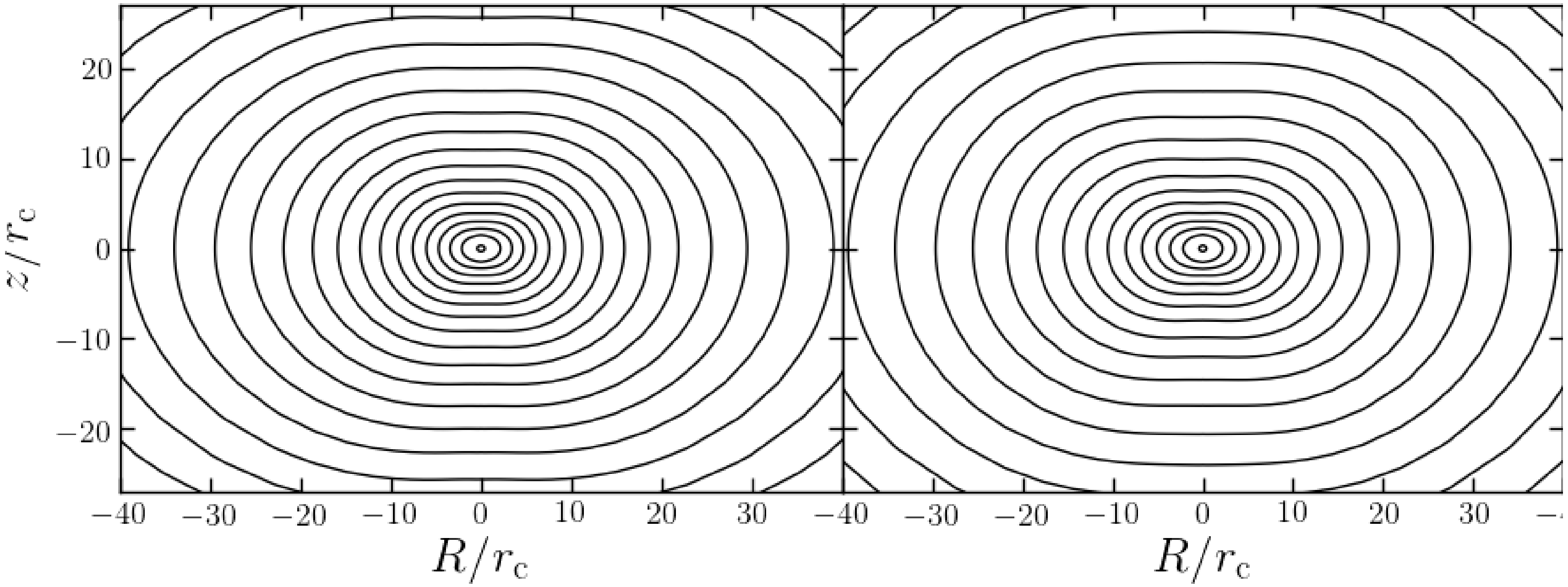

Pascale et al. (2018)

Indirect search for dark matter: The annihilation ***J*-factor** and the decay ***D*-factor**

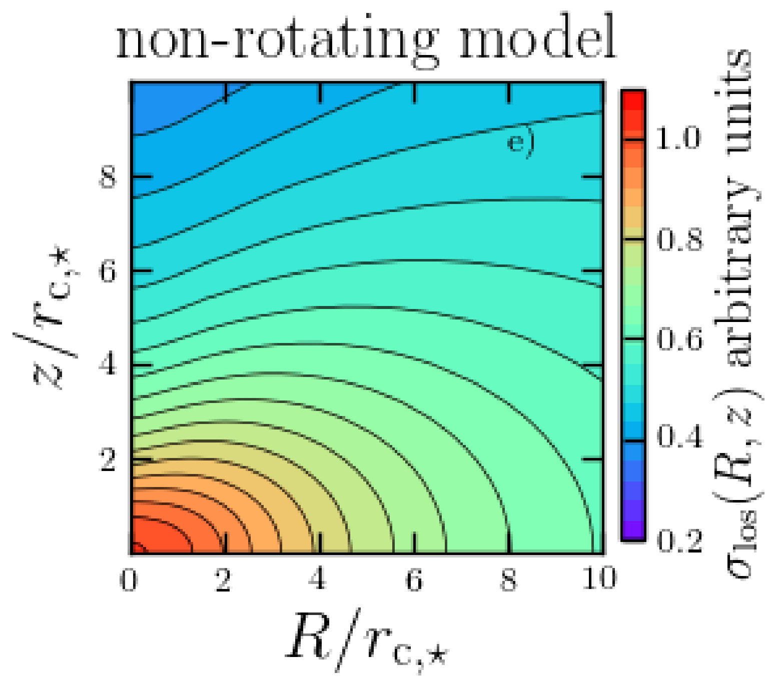


# Flattened models






Pascale et al. (2019b), submitted to MNRAS, arXiv:1907.09526




Extension from spherical to flattened components. Axis ratios up to ~ 0.6

# Summary and Conclusions



- New distribution function to model dSphs:
  Few free parameters and great flexibility

- Multi-component modeling and flattening easily manageable with action-based DFs

- Positive on dSphs: two-component test models of several dSphs and multi-component models of Sculptor

- Application to Fornax:
  - Best model: cored halo
  - Isotropic stellar velocity distribution

- Application to flattened components


Pascale R., Posti L., Nipoti C., Binney J., 2018, MNRAS, 480, 927

Pascale R., Binney J., Nipoti C., Posti L., 2019a, 488, 2423

Pascale R., Binney J., Nipoti C. 2019b, submitted to MNRAS, arXiv:1907.09526