



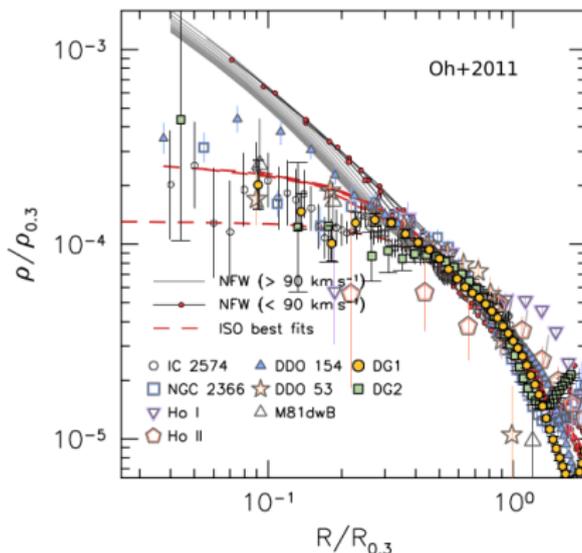
# Probing Dark Matter in Dwarf Galaxies with Non-Parametric Mass Models

Pascal S.P. Steger

ETH Zurich

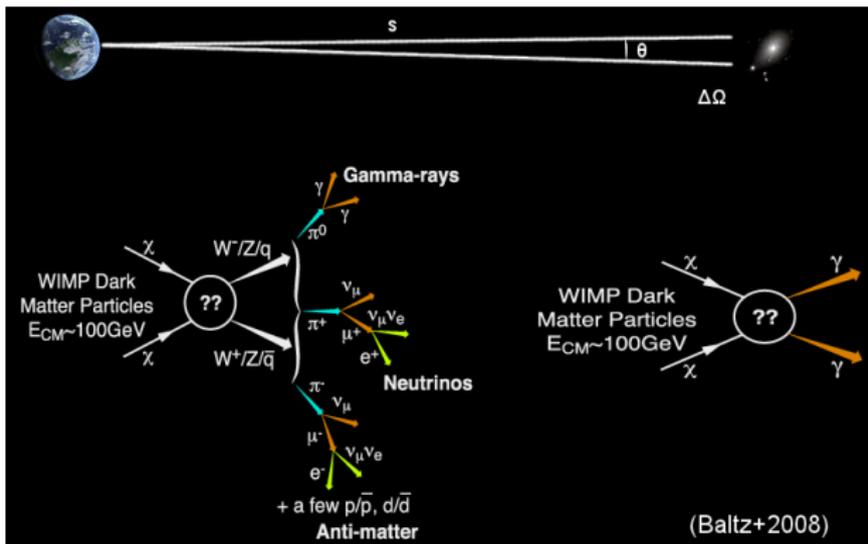
# Why Yet Another Mass Modelling Scheme?

Cusp/Core Problem:



- SIDM? Baryons? Others?
- If baryons responsible for a cusp-core transformation, expect core to shrink with decreasing  $M_*$

# Why Yet Another Mass Modelling Scheme?



$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{8\pi} \frac{\langle\sigma v\rangle}{m_{DM}^2} \frac{dN_\gamma}{dE_\gamma} \times J(\Delta\Omega)\Delta\Omega$$

$$J(\Delta\Omega) = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{LOS} ds \rho^2(r(s))$$

# Why Yet Another Mass Modelling Scheme?

Study	Method	Central Slope
Battaglia 2008	pop splitting	core (low sign.)
Walker, Penarrubia 2011	pop splitting	core (high sign.)
Amorisco, Evans 2012	pop spl.; dist. func	core (high sign.)
Breddels et al. 2011	Schwarzschild	cannot tell
Richardson, Fairbairn 2014	new virial method	cusp
Strigari 2014	pop spl.; dist. func	cusp

Table : Observations: Cusps or Cores?

# New Modelling Technique

Our goals:

- 1 assume non-parametric form for density  $\rho(r)$
- 2 use multiple stellar tracer populations split by e.g. Fe/H

# Jeans Modelling

- Stars obey collisionless Boltzmann equation

$$0 = \frac{\partial f}{\partial t} + \vec{\nabla}_x f \cdot \vec{v} - \vec{\nabla}_v f \cdot \vec{\nabla}_x \Phi$$

- assuming spherical symmetry and steady-state: Jeans eq.

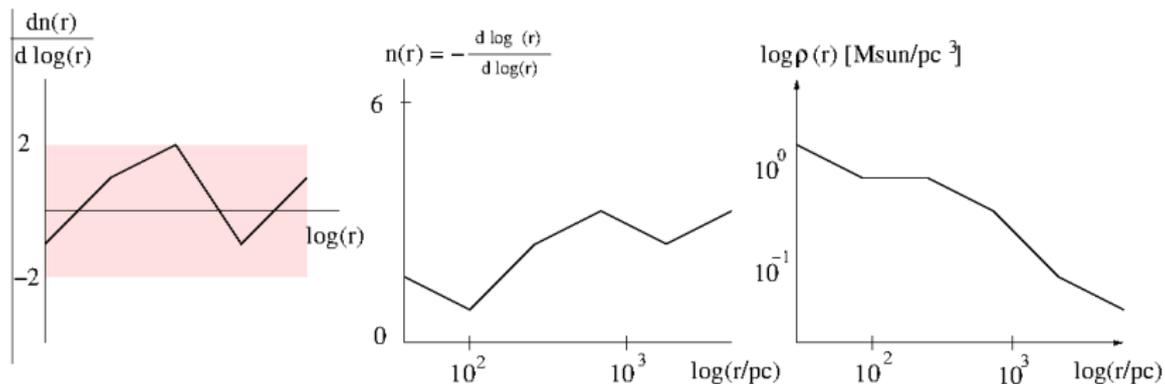
$$\frac{d(\nu\sigma_r^2)}{dr} + \frac{2\beta(r)}{r}\nu\sigma_r^2 + \nu\frac{GM(<r)}{r^2} = 0; \quad \beta(r) = 1 - \frac{\sigma_t^2(r)}{\sigma_r^2(r)}$$

- degeneracy between mass  $M(<r)$  and velocity anisotropy  $\beta(r)$
- attempted break by using multiple tracer populations with  $\beta_1 \neq \beta_2$ , but inside the same  $M(r)$  (Walker, Penarrubia 2011)

# Non-Parametric Jeans Modelling

$$\rho(r) = Ar^{-n(r)}, \quad n(r) = -\frac{d \log \rho(r)}{d \log r}$$

$$\rho(r) = \rho_{1/2} \cdot \exp \left[ - \int_{\log r_{1/2}}^{\log r} n(s) ds \right]$$

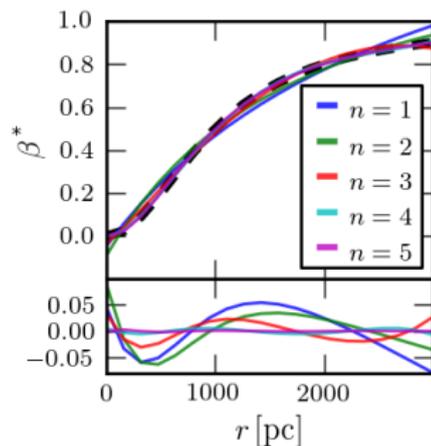


# Non-Parametric Jeans Modelling

$$-\infty < \beta(r) \leq 1 \quad \rightarrow \quad -1 \leq \beta^*(r) \leq 1$$

$$\beta^* = \frac{\sigma_r^2 - \sigma_t^2}{\sigma_r^2 + \sigma_t^2} = \frac{\beta}{2 - \beta},$$

$$\beta^*(r) = \sum_{j=0}^{N_\beta} \beta_j \cdot \left( \frac{r_j}{r_{\max}} \right)^j$$



# Non-Parametric Jeans Modelling

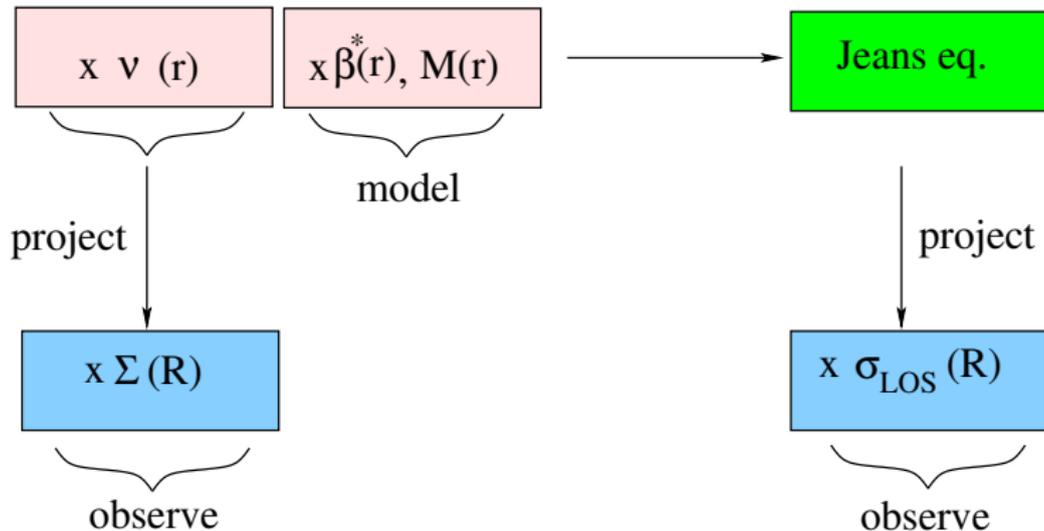
Numbers of Parameters for  $x$  populations:

$$\begin{aligned}\beta^* &\rightarrow 4 \cdot x \\ \nu &\rightarrow (N_{\text{bin}} + 3) \cdot x \\ M(r) &\rightarrow N_{\text{bin}} + 3\end{aligned}$$

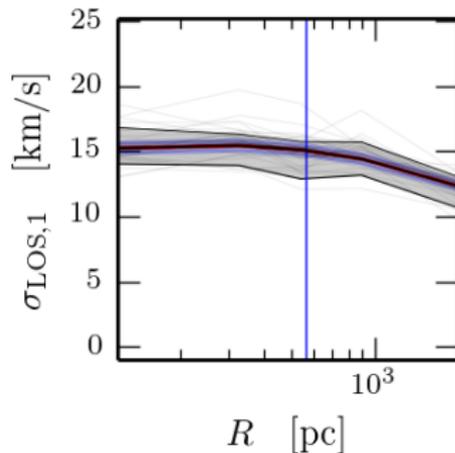
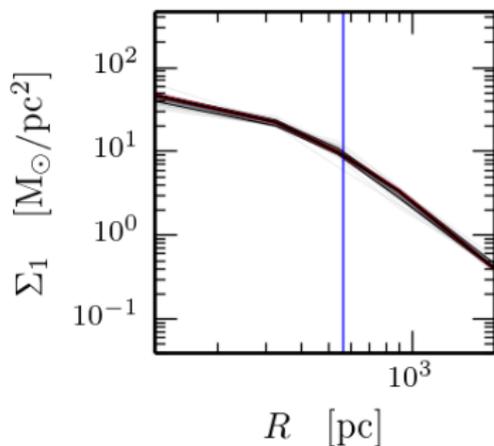
Example:  $N_{\text{bin}} = 7, x = 2$  gives 38 parameters.

Need to sample the whole parameter space  $\rightarrow$  MultiNest (Feroz+2009, Feroz+2013)

# General Procedure



# Goodness of Fit



$$\chi^2 = \sum_{i=1}^N \chi_{\Sigma,i}^2 + \chi_{\sigma,i}^2 \quad (1)$$

$$\chi_{\Sigma,i}^2 = \sum_{j=1}^{N_{\text{bin}}} \left( \frac{\Sigma_{\text{data},i}(r_j) - \Sigma_{\text{model},i}(r_j)}{\varepsilon_{\Sigma}(r_j)} \right)^2, \quad (2)$$

# Mock Data

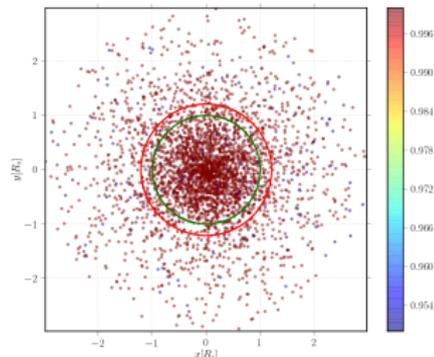
$$\rho_{DM} = \rho_0 \left( \frac{r}{r_{DM}} \right)^{-\gamma_{DM}} \left[ 1 + \left( \frac{r}{r_{DM}} \right)^{\alpha_{DM}} \right]^{(\gamma_{DM} - \beta_{DM}) / \alpha_{DM}}$$

$$\nu_*(r) = \nu_0 \left( \frac{r}{r_*} \right)^{-\gamma_*} \left[ 1 + \left( \frac{r}{r_*} \right)^{\alpha_*} \right]^{(\gamma_* - \beta_*) / \alpha_*}$$

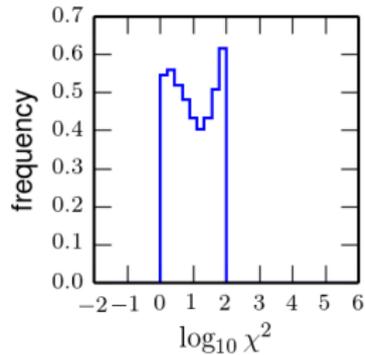
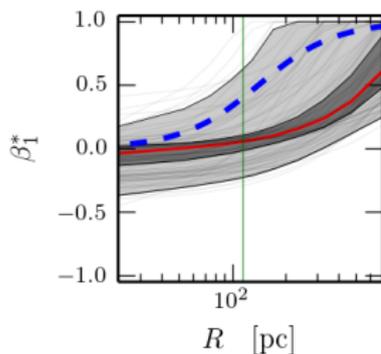
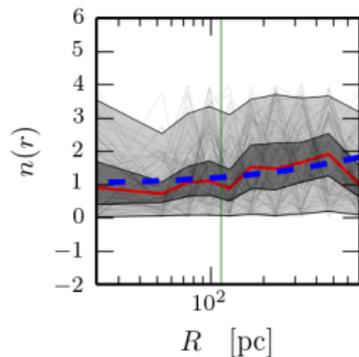
$$\beta(r) = 1 - \frac{\sigma_\theta^2}{\sigma_r^2} = \frac{r^2}{r^2 + r_a^2}$$

c.f. Walker&Penarrubia 2011;  
Gaia Challenge:

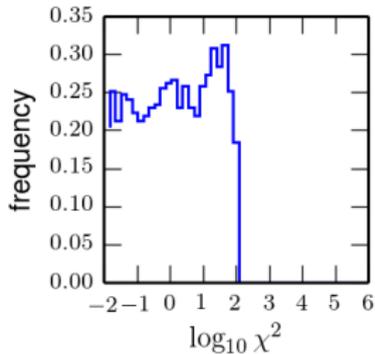
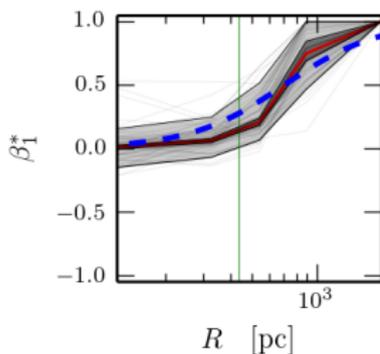
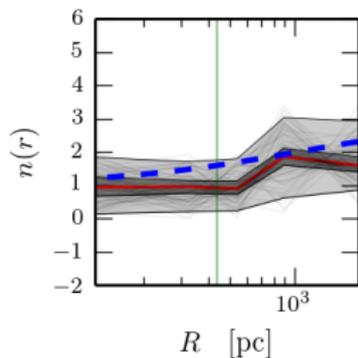
<http://astrowiki.ph.surrey.ac.uk/dokuwiki/doku.php?id=tests:sphtri>



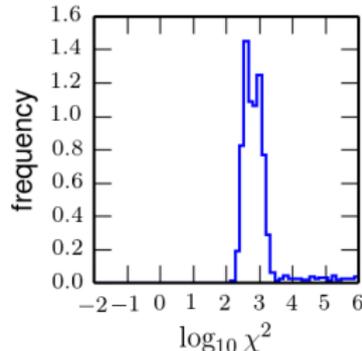
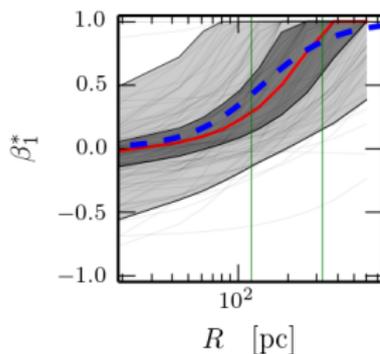
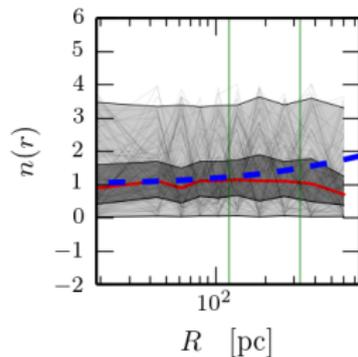
## Cusp 1 Population No Prior



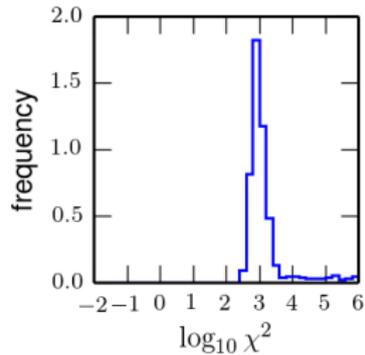
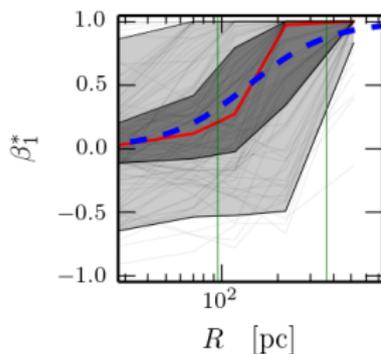
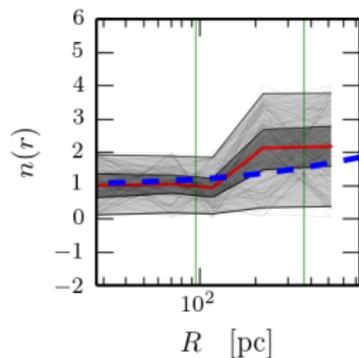
# Cusp 1 Population $n(r)$ , $n'(r)$ Priors



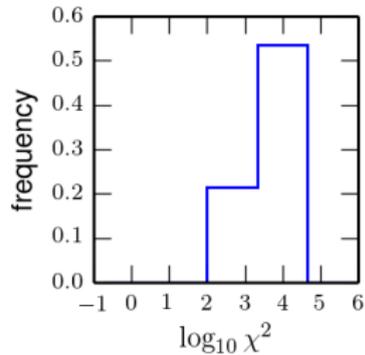
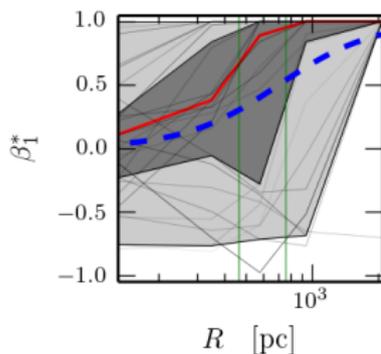
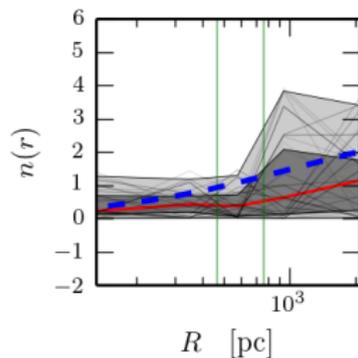
# Cusp 2 Populations, No Prior



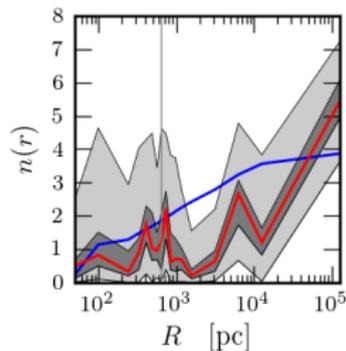
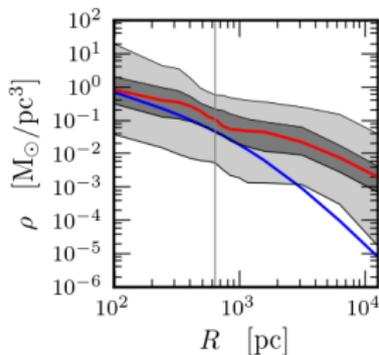
# Cusp 2 Populations, $n(r)$ Priors



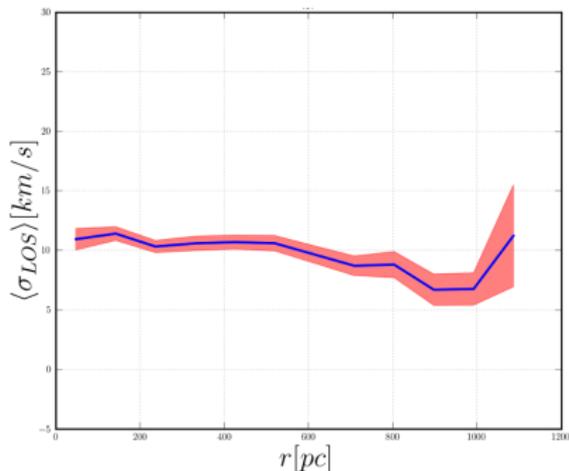
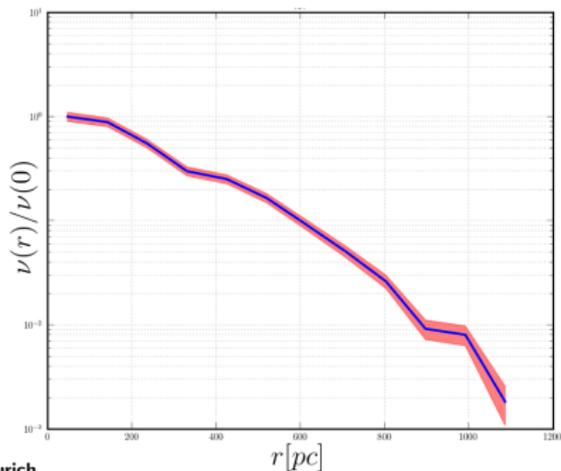
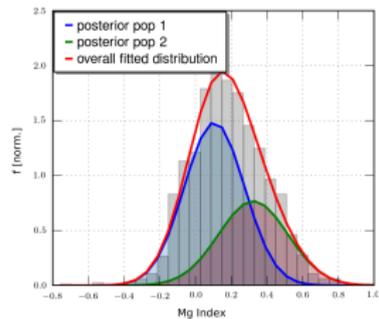
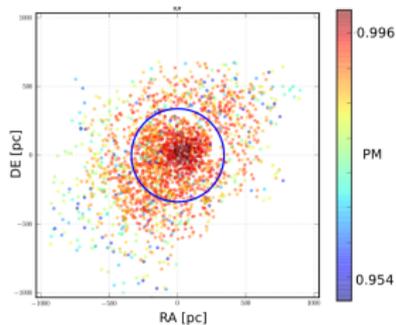
# Core 2 Populations, $n(r)$ Priors



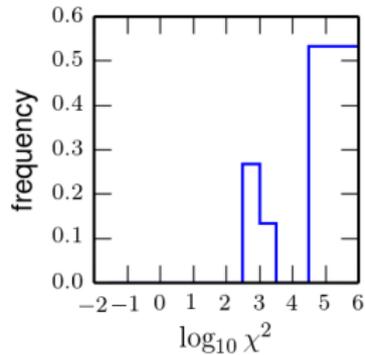
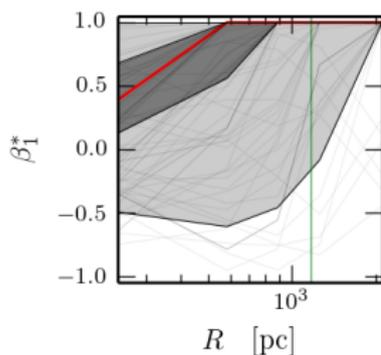
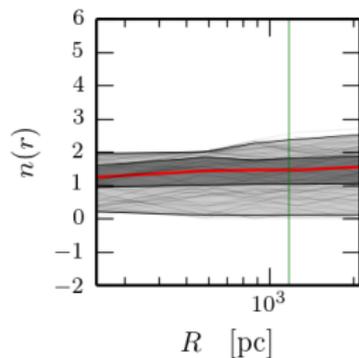
# Triaxial 1 Population, No $n(r)$ Priors



## Fornax



# Fornax 1 Pop, $n(r)$ Priors - Preliminary



# Summary

- New Modelling Technique with Minimal Assumptions
- Multiple Populations → break  $M(r), \beta(r)$  degeneracy
- Need priors on  $n(r)$  and  $n'(r)$
- → can reproduce cusps and cores on nearly  $2\sigma$
- Triaxial with bias at high radius, but smaller than other errors.
- Preliminary results for Fornax exclude a perfect core at about  $2\sigma$ .
- Other dwarf spheroidals are being analyzed.

# Computation of Velocity Dispersions

$$\sigma_r^2(R) = \frac{1}{\nu(R)} B(R) \int_R^\infty \frac{GM(r) \nu \sigma_r^2}{r^2} \tilde{B}(R) dr,$$

$$B(R) = \exp \left[ -2 \int_{r_{\min}}^R \frac{\beta(s)}{s} ds \right], \quad \tilde{B}(R) = \exp \left[ 2 \int_{r_{\min}}^R \frac{\beta(s)}{s} ds \right]$$

$$\sigma_{\text{LOS}}^2(R) = \frac{2}{\Sigma(R)} \int_R^\infty \left[ 1 - \beta \frac{R^2}{r^2} \right] \frac{\nu(r) \sigma_r^2(r) r}{\sqrt{r^2 - R^2}} dr$$

# Hernquist Model - Integration Check

- check of the integration routine
- using polynomial interpolation
- good fit of  $\sigma_{LOS}$  even at high radii

