The mass and anisotropy profiles of nearby galaxy clusters from the projected phase-space density

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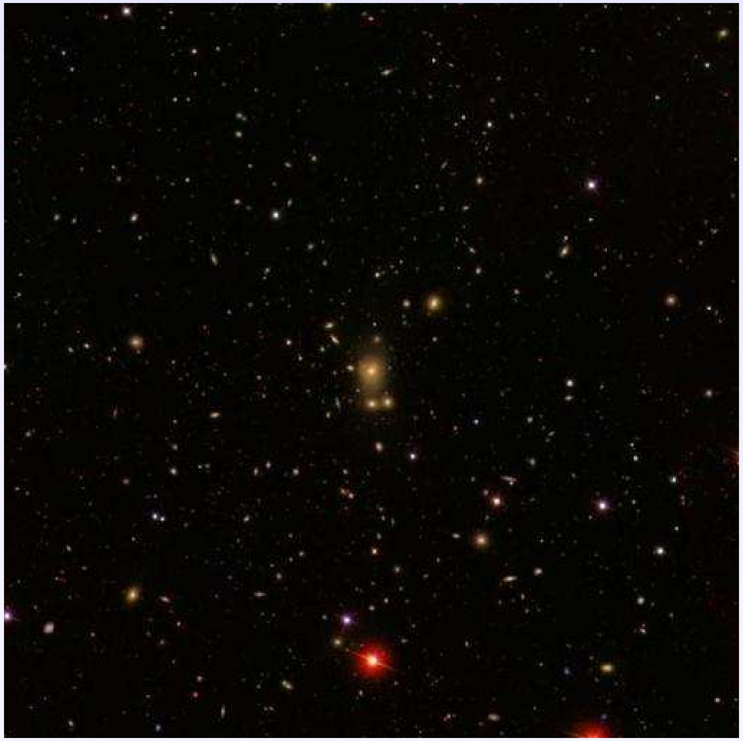
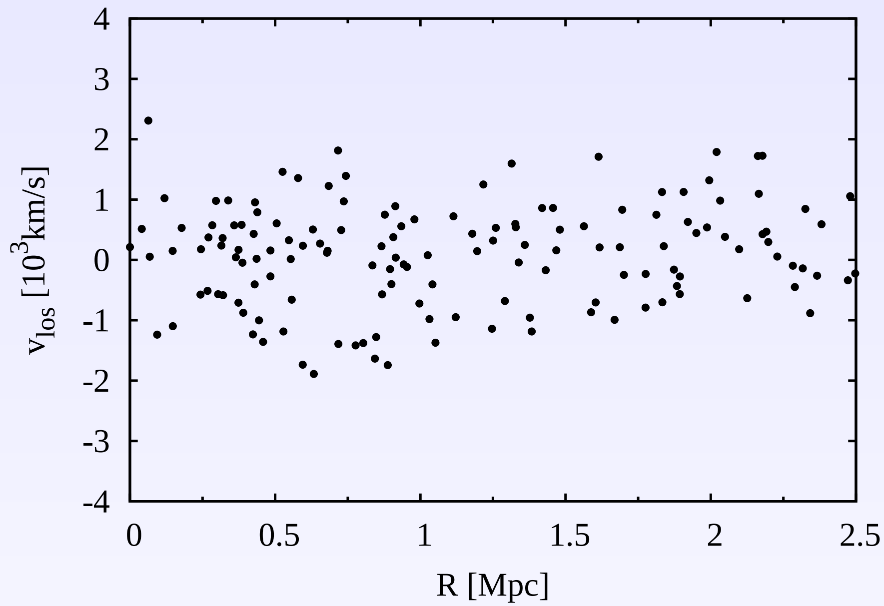
Outline

- Motivation
- DM density profile/anisotropy profile
- Model of the phase-space density: brief description
- Tests on mock kinematic data
- Application to nearby galaxy clusters
- Summary/Perspective for future

Motivation

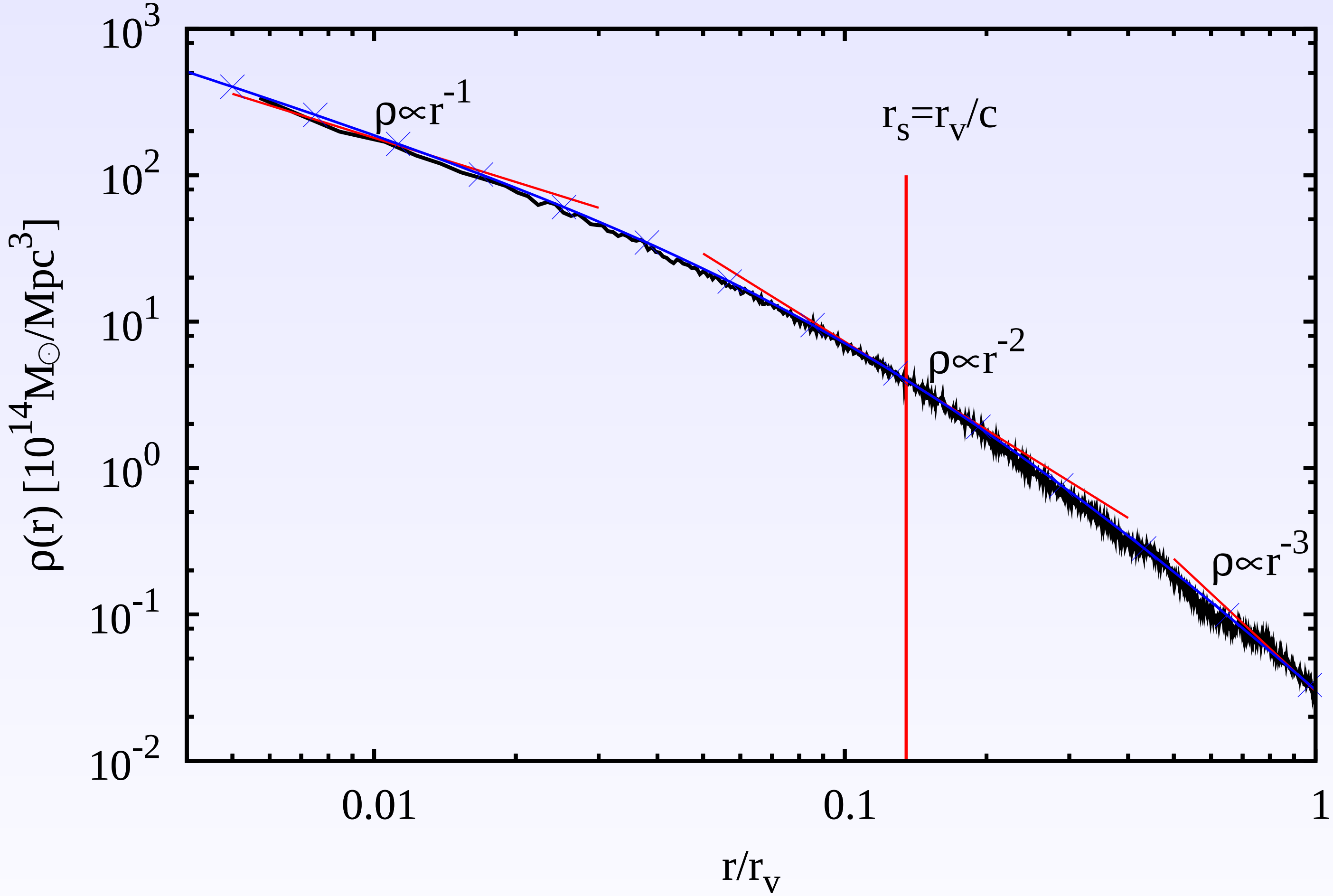




$$f_{los}(R, v_{los}) \rightarrow \rho_{DM}(r), \beta(r)$$

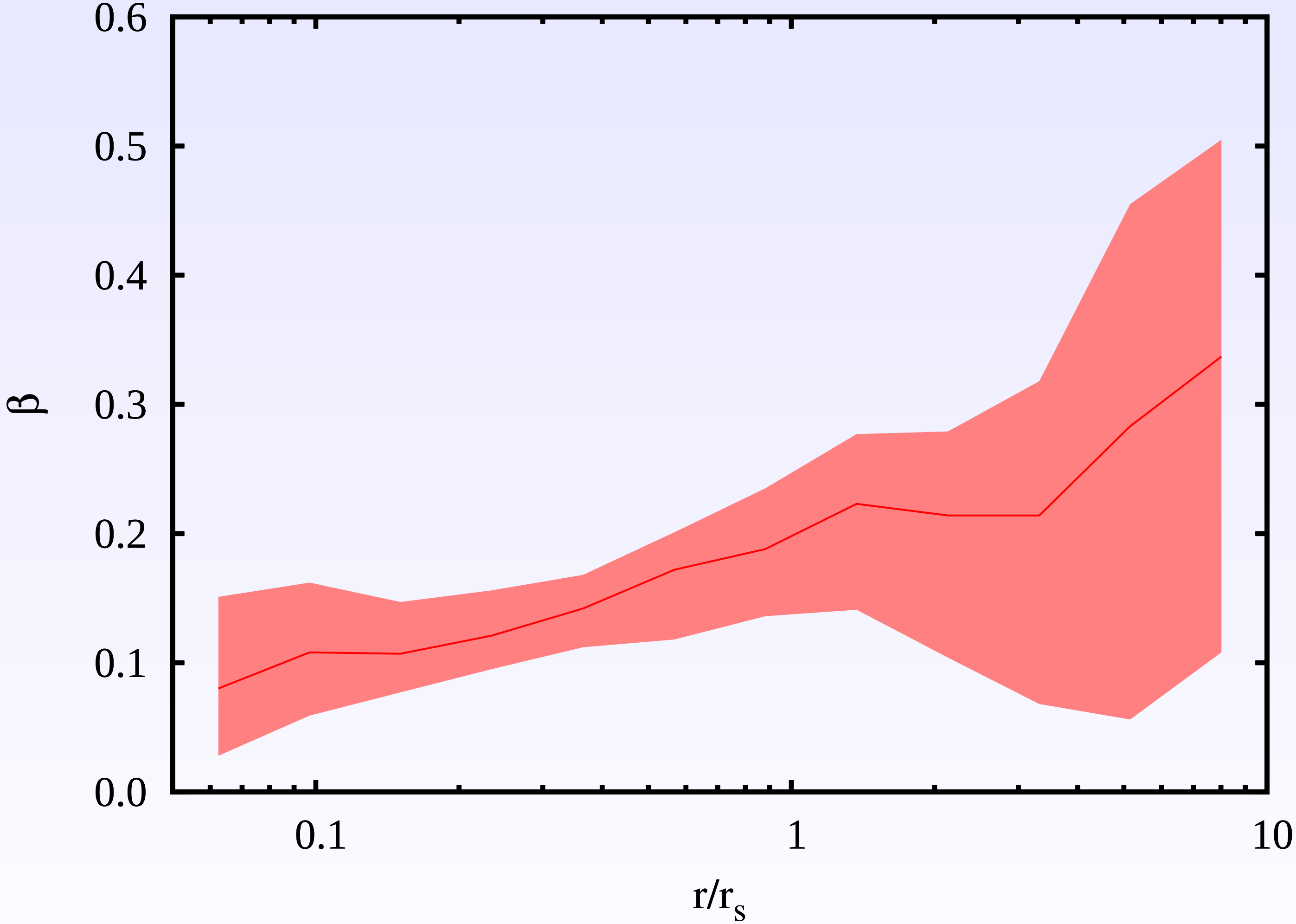
- no data binning
- breaking $M - \beta$ degeneracy

DM density profile



$$\rho_{NFW}(r) \propto \frac{1}{(r/r_s)(1+r/r_s)^2}$$

Anisotropy profile



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

Model of the phase-space density

$f(\mathbf{r}, \mathbf{v})$

- spherical symmetry: $f(\mathbf{r}, \mathbf{v}) = f(E, L)$
- 1st component: $\rho(r) \longrightarrow f(E, L)$
- 2nd component: $\beta(r) \longrightarrow f(E, L)$

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

- 1: radially-biased model
- 0: isotropic dispersion tensor
- $-\infty$: tangentially-biased model

History

- $\beta(r) = 0$

  Eddington (1916)

- $\beta(r) = \text{const.}$

  Hénon (1973)

- $\beta(r) = \frac{r^2}{r^2 + r_a^2}$

  Osipkov (1979), Merritt (1985)

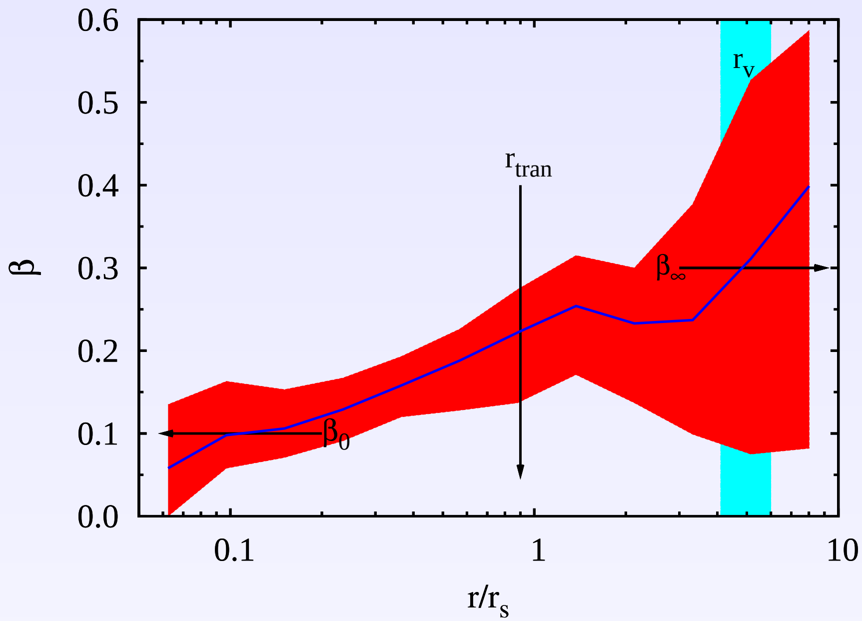
- $\beta(r) = \frac{r^2 - \alpha r_a^2}{r^2 + r_a^2}$

  Cuddeford (1991)

- $f(E, L) = f_E(E)(1 + L^2/(2L_0^2))^{-\beta_\infty}$

  Cuddeford & Louis (1995)

$f_L(L)$



Free parameters:

- $\beta_0 = \lim_{r \to 0} \beta(r)$
- $\beta_\infty = \lim_{r \to \infty} \beta(r)$
- $\beta(r_{tran}) \approx \frac{\beta_0 + \beta_\infty}{2}$

$$f_L(L) \propto \begin{cases} L^{-2\beta_0} & \text{for } L \ll L_0 \\ L^{-2\beta_\infty} & \text{for } L \gg L_0, \end{cases}$$

ansatz: $f_L(L) = \left(1 + \frac{L^2}{2{L_0}^2}\right)^{-\beta_\infty + \beta_0} L^{-2\beta_0}$

$f_E(E)$

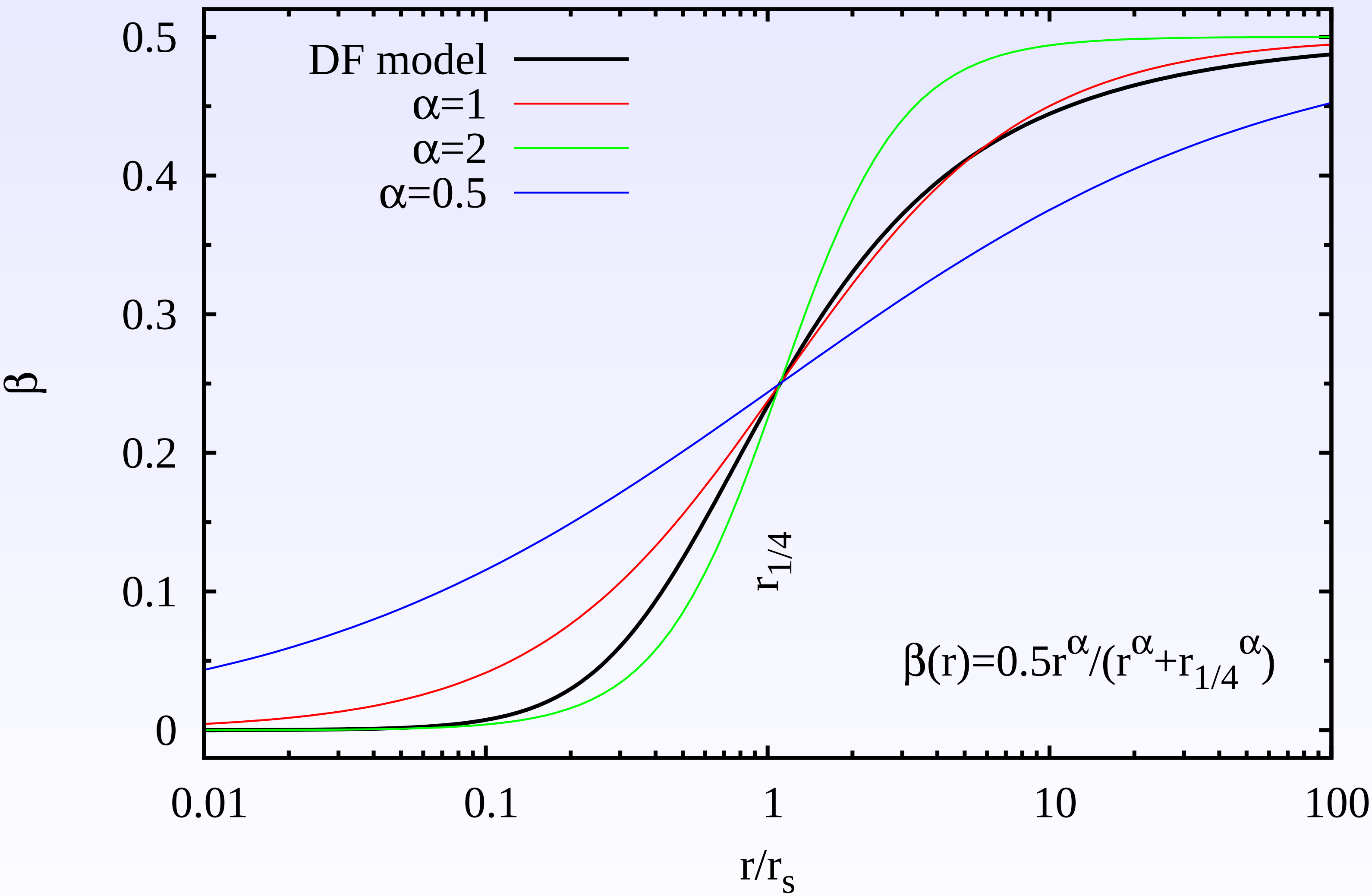
- $n_{gal}(r)$
- $\rho_{DM}(r) \rightarrow \Psi(r)$
  - $n_{gal}(r) \propto \rho_{DM}(r)$
  - $\rho_{DM} \propto \frac{1}{(r/r_s)(1+r/r_s)^2}$

$f_E(E)$

- $n_{gal}(r) = \int\int\int f_E(E) f_L(L) \mathrm{d}^3 v$
- $n_{gal}(r) = \int_0^{\Psi(r)} f_E(E) K(E, \Psi(r)) \mathrm{d}E$
- $n_{gal,i} = \sum_j K_{i,j} f_E(\Psi_j)$

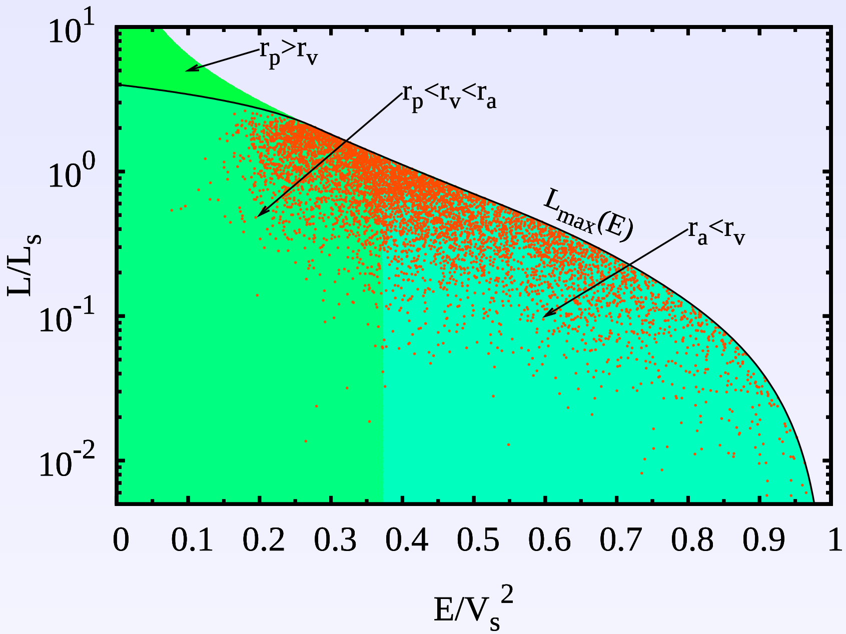
Wojtak et al. 2008

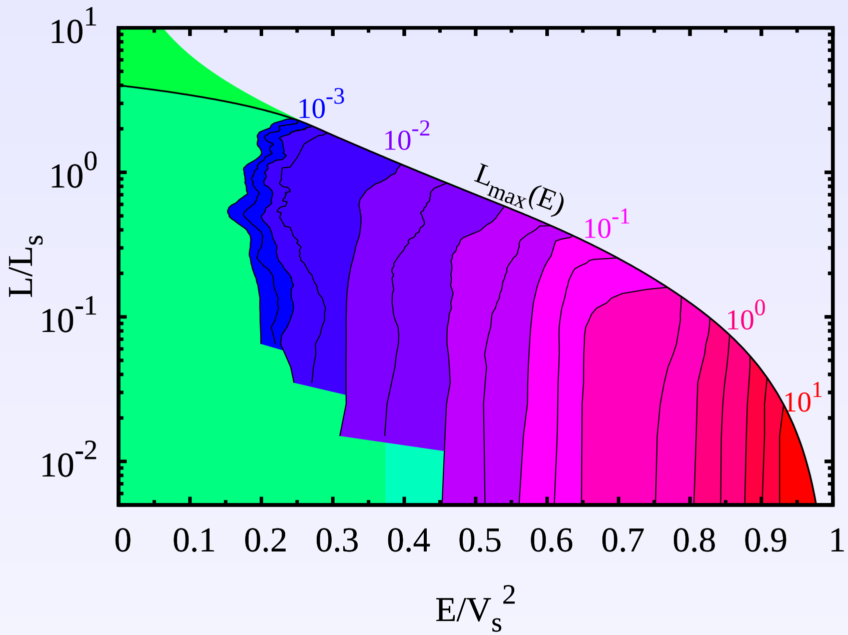
The shape of $\beta(r)$ profile



Comparison with the simulation

$f(E, L)$ from the simulation



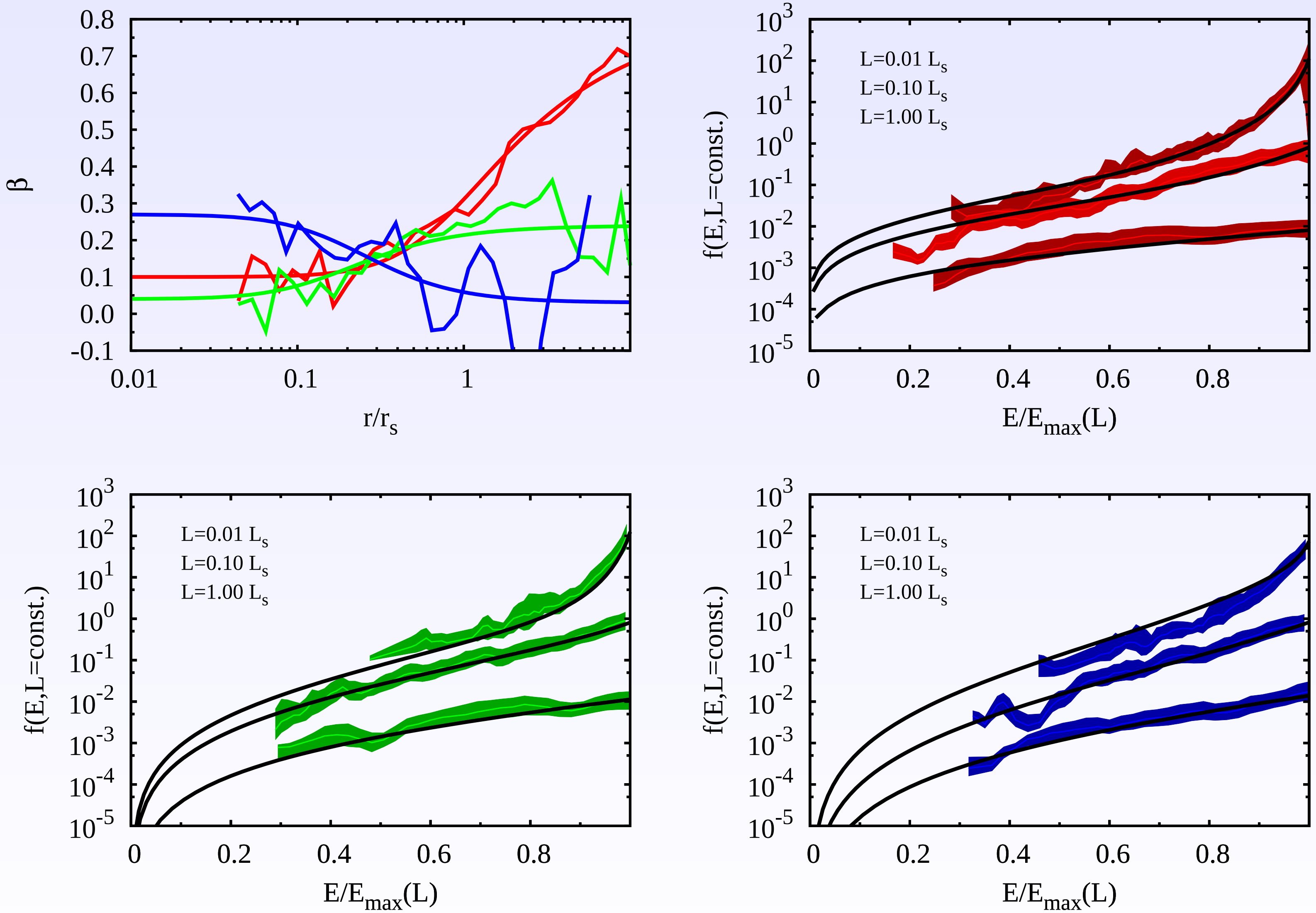


$$N(E, L) = \frac{d^2M}{dEdL}$$

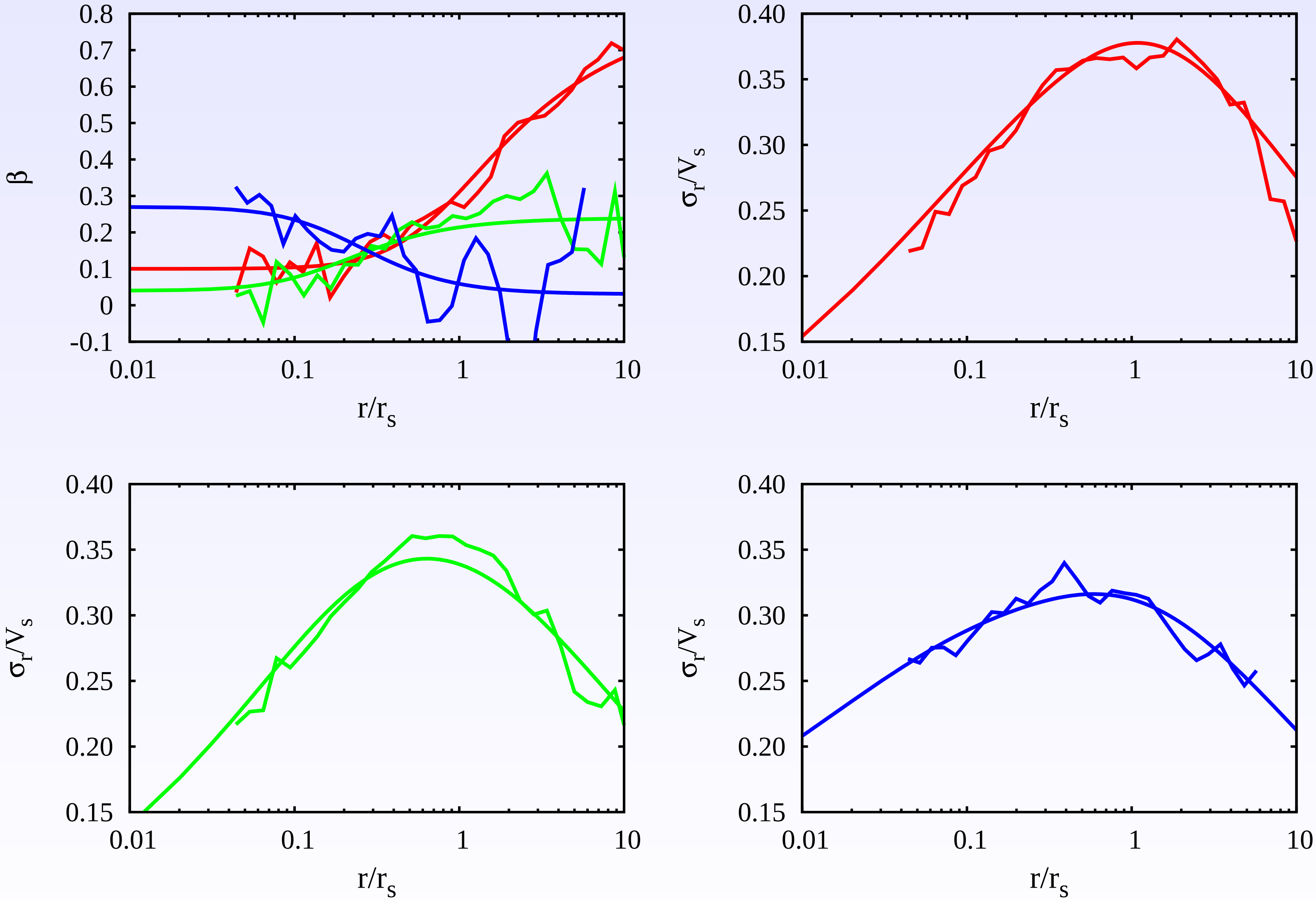
$$f(E, L) = \frac{N(E,L)}{g(E,L)}$$

- $g(E, L) = \int \delta(\frac{1}{2}v^2 - \Psi(r) - E)\delta(|\mathbf{r} \times \mathbf{v}| - L)\mathrm{d}^3r\mathrm{d}^3v$

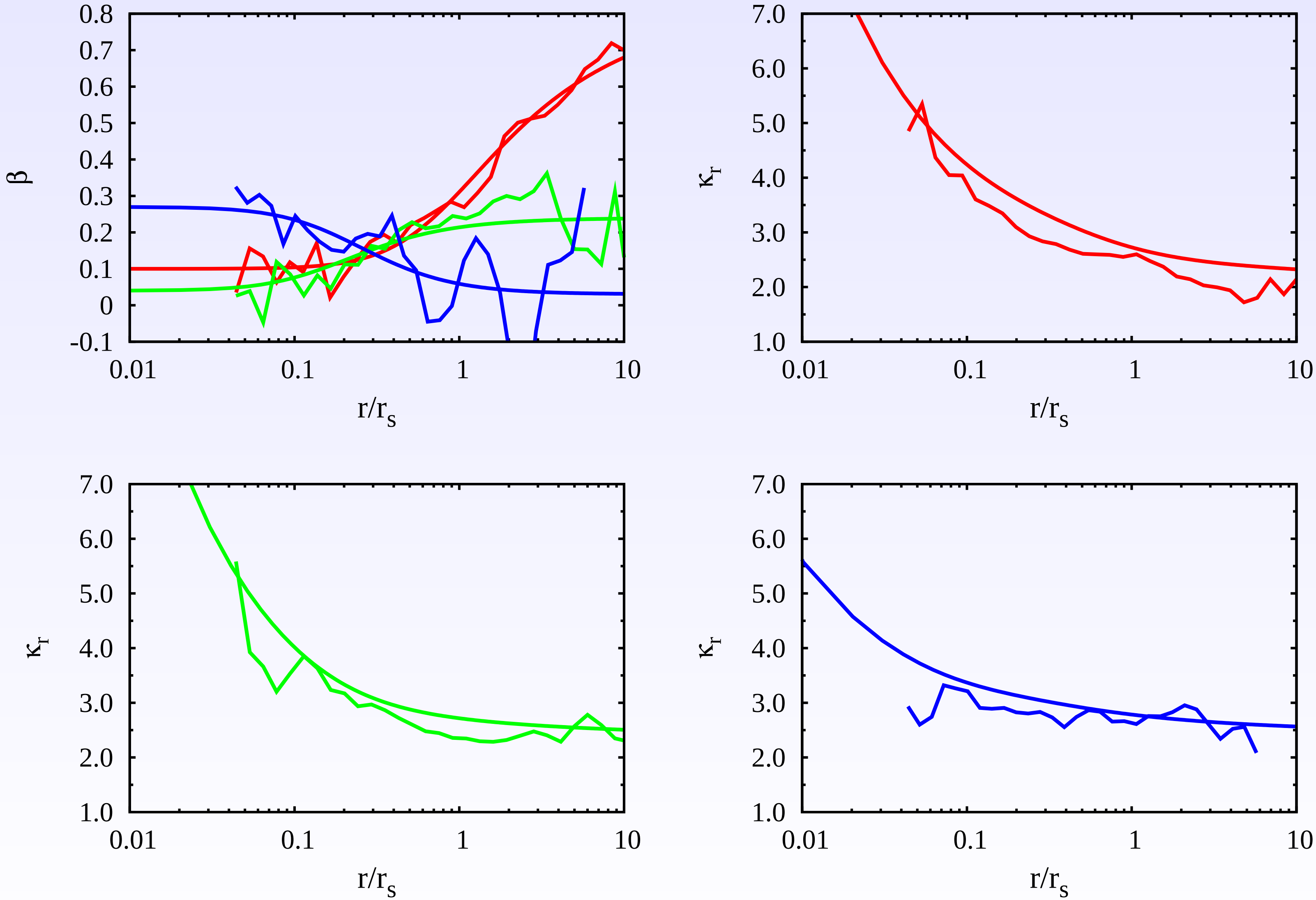
Comparison: $f(E, L)$



Comparison: $\sigma_r(r)$



Comparison: $\kappa_r = \langle v_r^4 \rangle / \sigma_r^4$

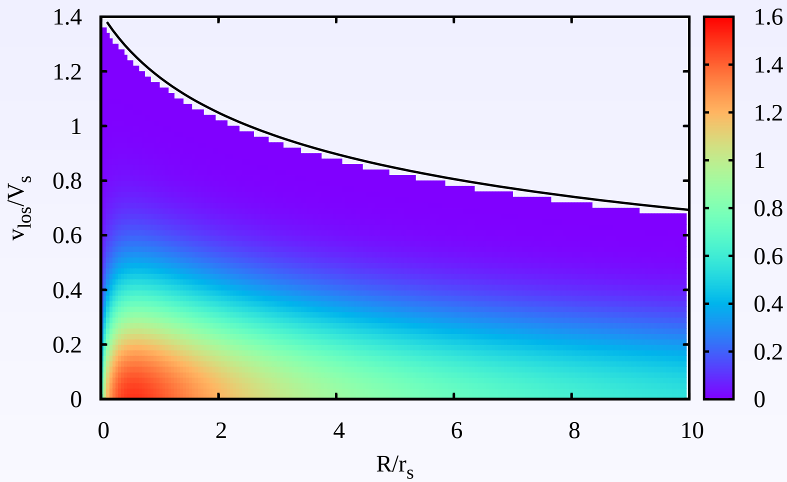


Projected phase-space density

Projected phase-space density

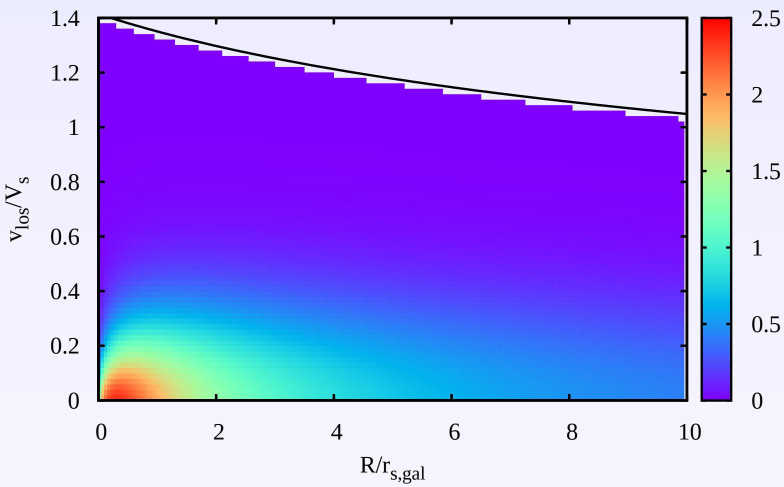
$$f_{los}(R, v_{los}) = 2\pi R \int_{-z_{max}}^{z_{max}} \mathrm{d}z \int \int_{E>0} \mathrm{d}v_R \mathrm{d}v_\phi f(\mathrm{r}, \mathrm{v})$$

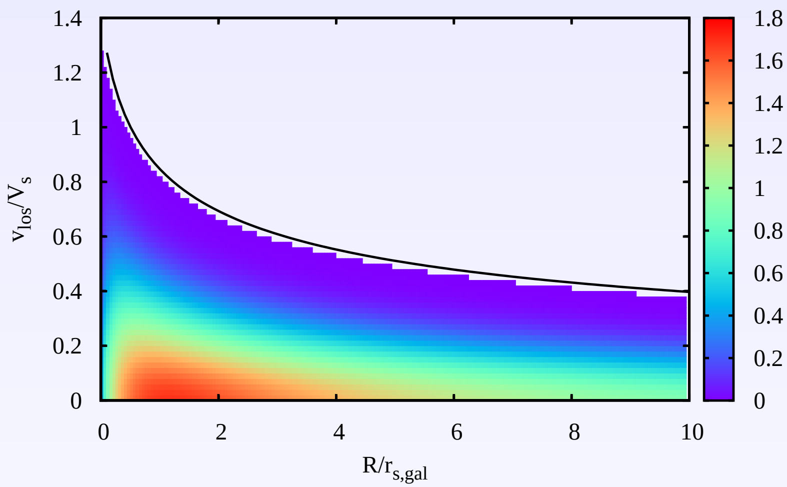
- $V_s \propto (GM_s/r_s)^{1/2}$
- r_s



Different $\rho_{DM}(r)$ and $n_{gal}(r)$

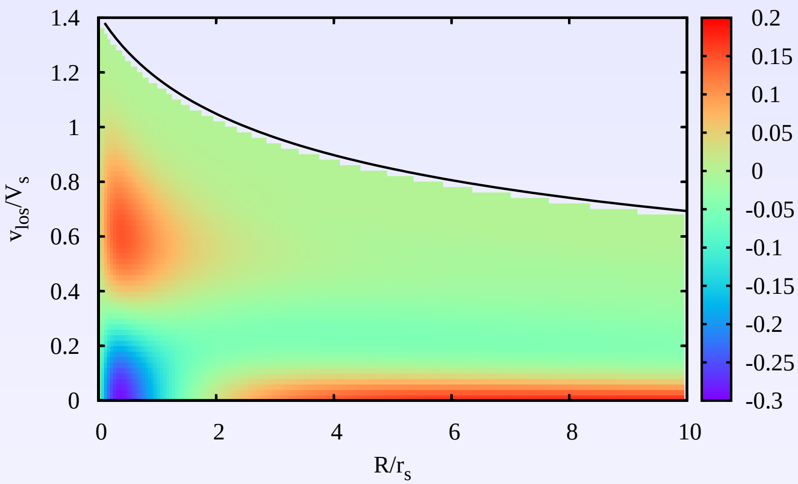
- $r_{s,DM}/r_{s,gal} = 5$
- $r_{s,DM}/r_{s,gal} = 1/5$

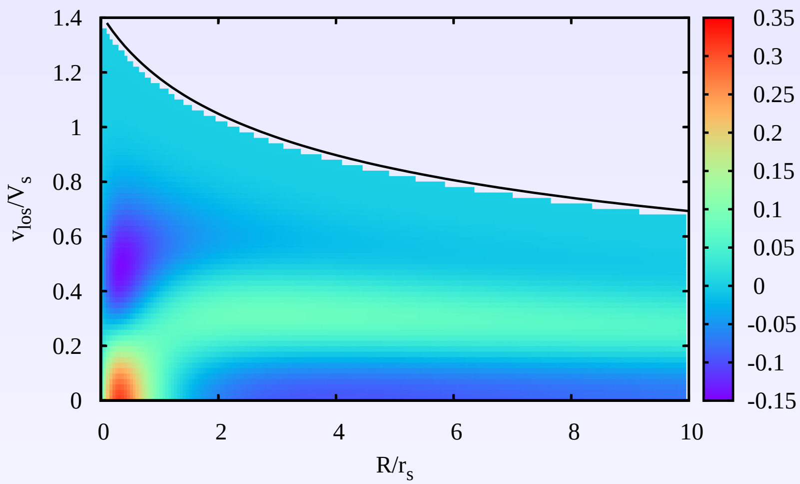




- $V_s \propto \sqrt{GM_{s,DM}/r_{s,DM}}$
- $r_{s,gal} \rightarrow \Sigma_{gal}(R)$
- $r_{s,DM} \rightarrow f_{los}(R, v_{los}) = \text{const.}$

$f_{los}(R, v_{los}) \leftrightarrow \beta_\infty$

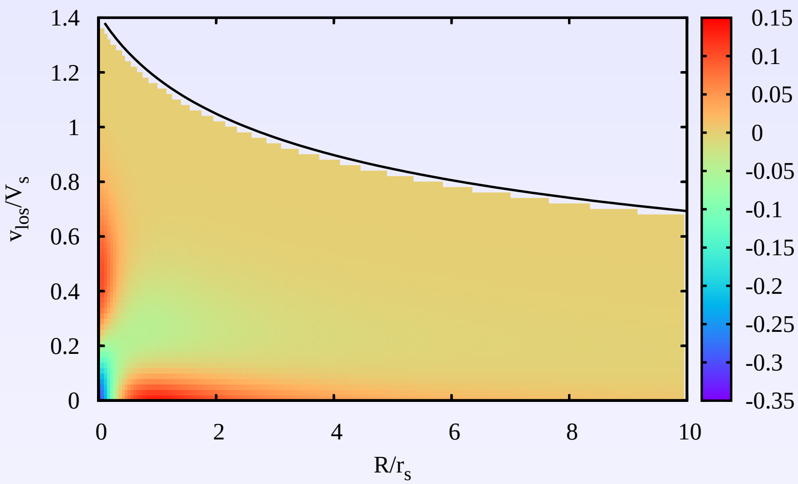


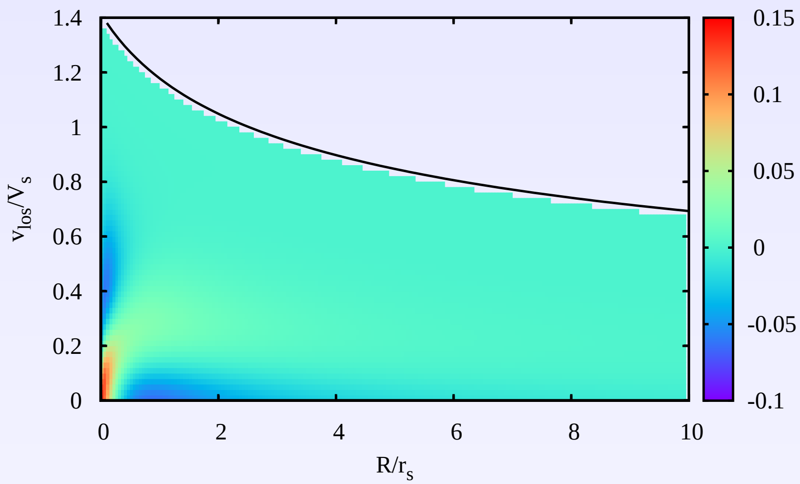


- $\beta_0 = 0$
- $\beta_\infty = 1$

- $\beta_0 = 0$
- $\beta_\infty = -2$

$f_{los}(R, v_{los}) \leftrightarrow \beta_0$





- $\beta_0 = 0.5$
- $\beta_\infty = 0$

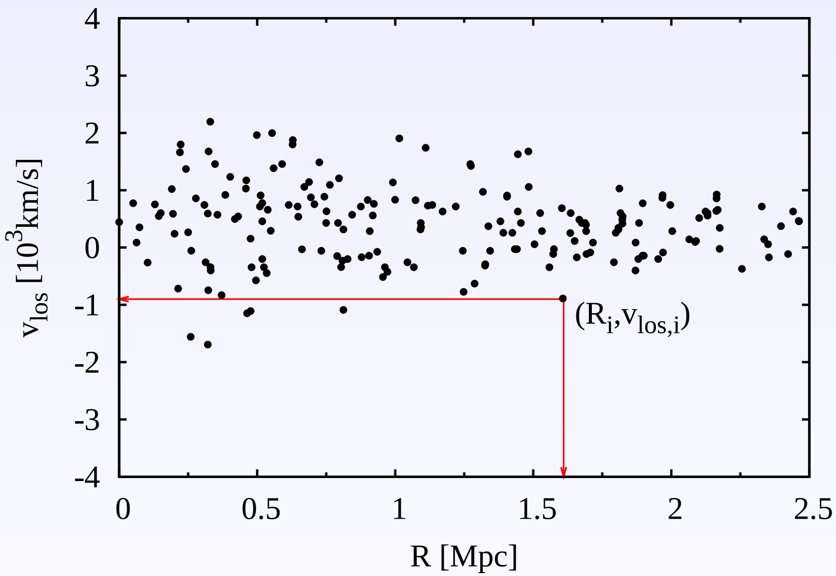
- $\beta_0 = -0.5$
- $\beta_\infty = 0$

Towards data analysis

Bayesian data analysis

$$f_{los}(R, v_{los}) = 2\pi R \int_{-z_{max}}^{z_{max}} \mathrm{d}z \int\int_{E>0} \mathrm{d}v_R \mathrm{d}v_\phi f(\mathrm{r}, \mathrm{v})$$

- $p_{post} \propto p_{prior} \mathcal{L}$



- $\mathcal{L} = \prod_{i=1}^{n} f_{los}(R_i, v_{los,i} | \{M_s, r_s, ...\})$

Parameters

- $n_{gal}(r) \propto \rho_{DM}(r)$
- $\rho_{DM}(r) \propto 1/((r/r_s)(1 + r/r_s)^2)$

Free parameters

- M_s and $r_s \longrightarrow M_v$ and c
- $\ln(1 - \beta_0)$ and $\ln(1 - \beta_\infty)$

Fixed parameter

- $L_0 = 0.198 L_s \longrightarrow r_{tran} \approx 1 r_s$

Test on mock kinematic data

Tests on simulated data

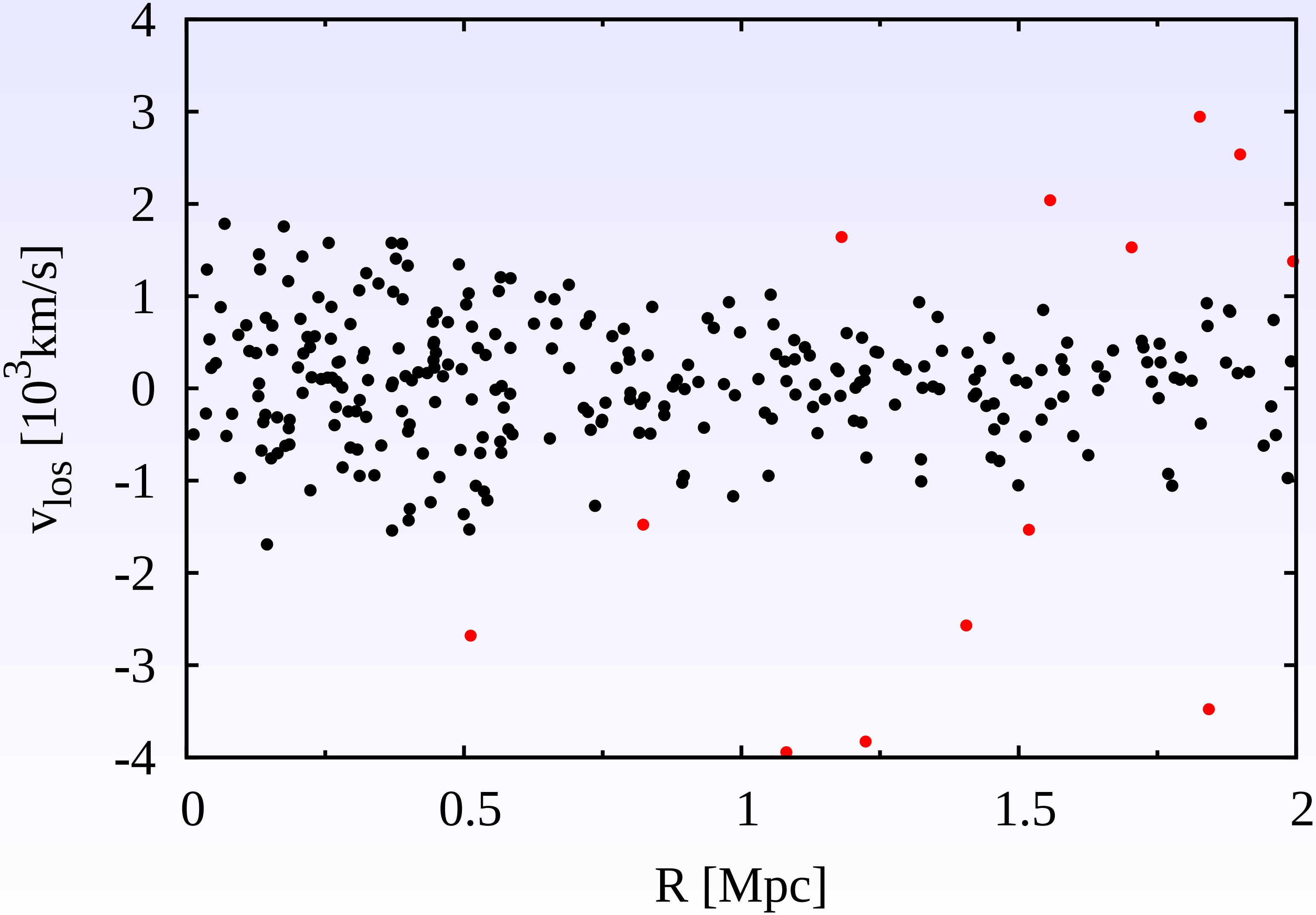
Motivation

- equilibrium
- finite size of the virial sphere
- infall zone
- substructures
- projection effects
- spherical symmetry

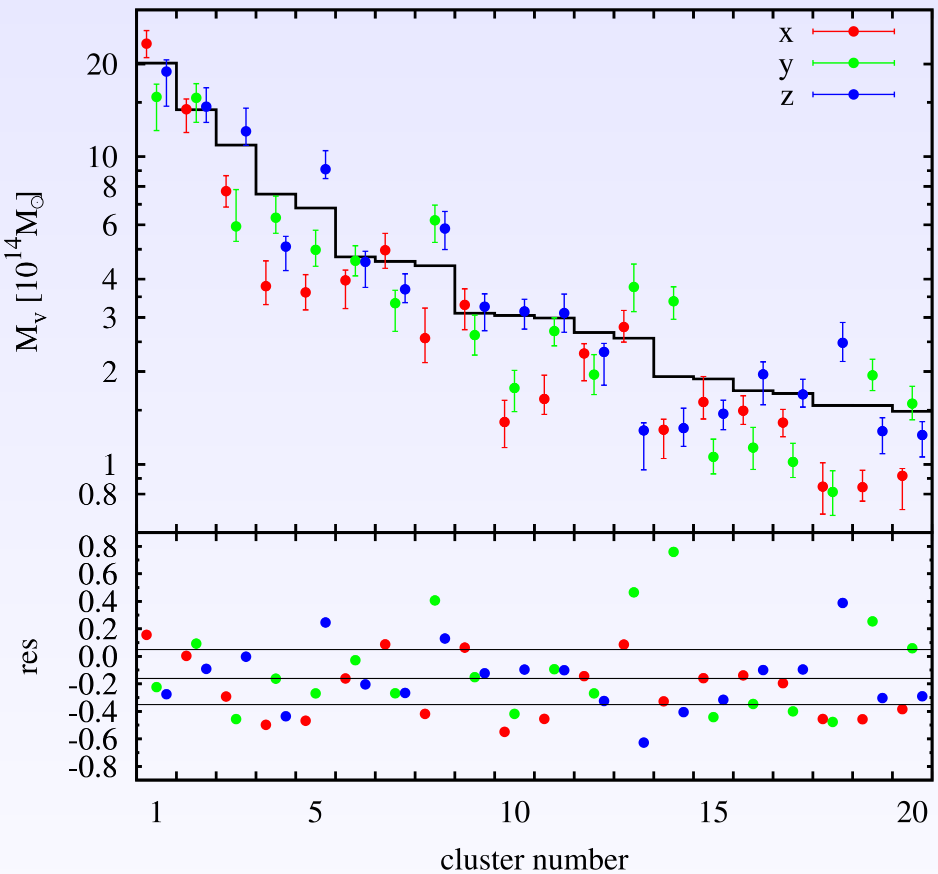
Mock kinematic data

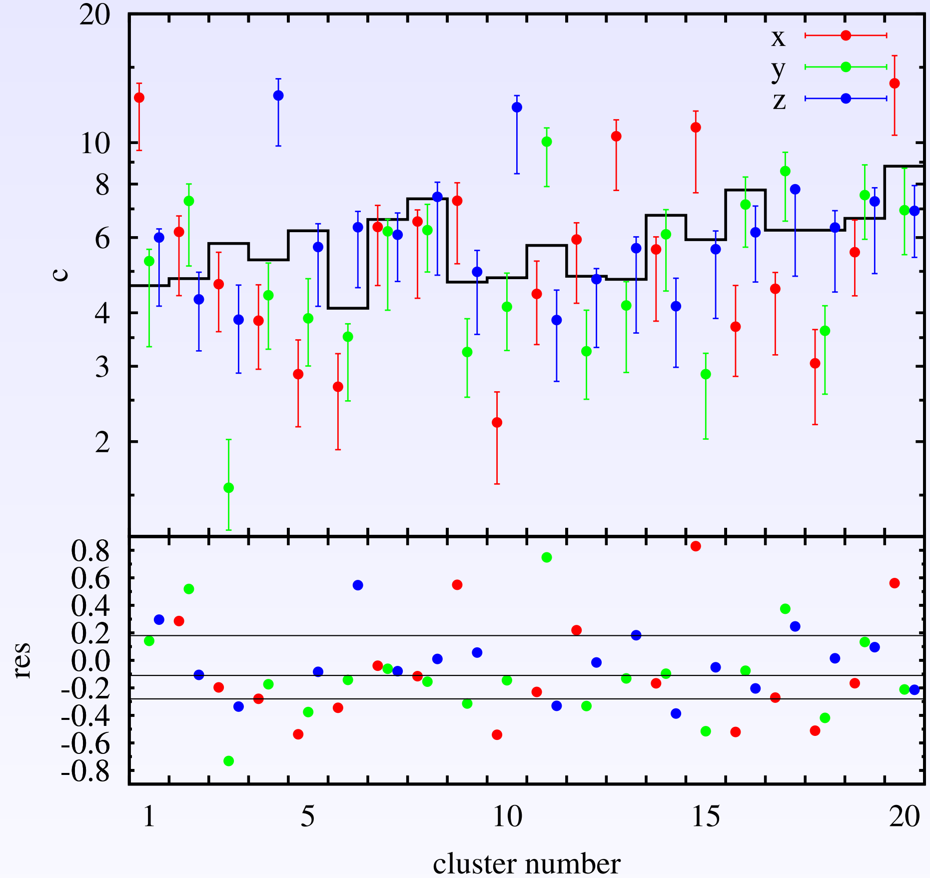
- relaxed haloes of the mass $10^{14} - 10^{15} M_\odot$
- tracer: particles
- 300 particles per “cluster”

Mock kinematic data

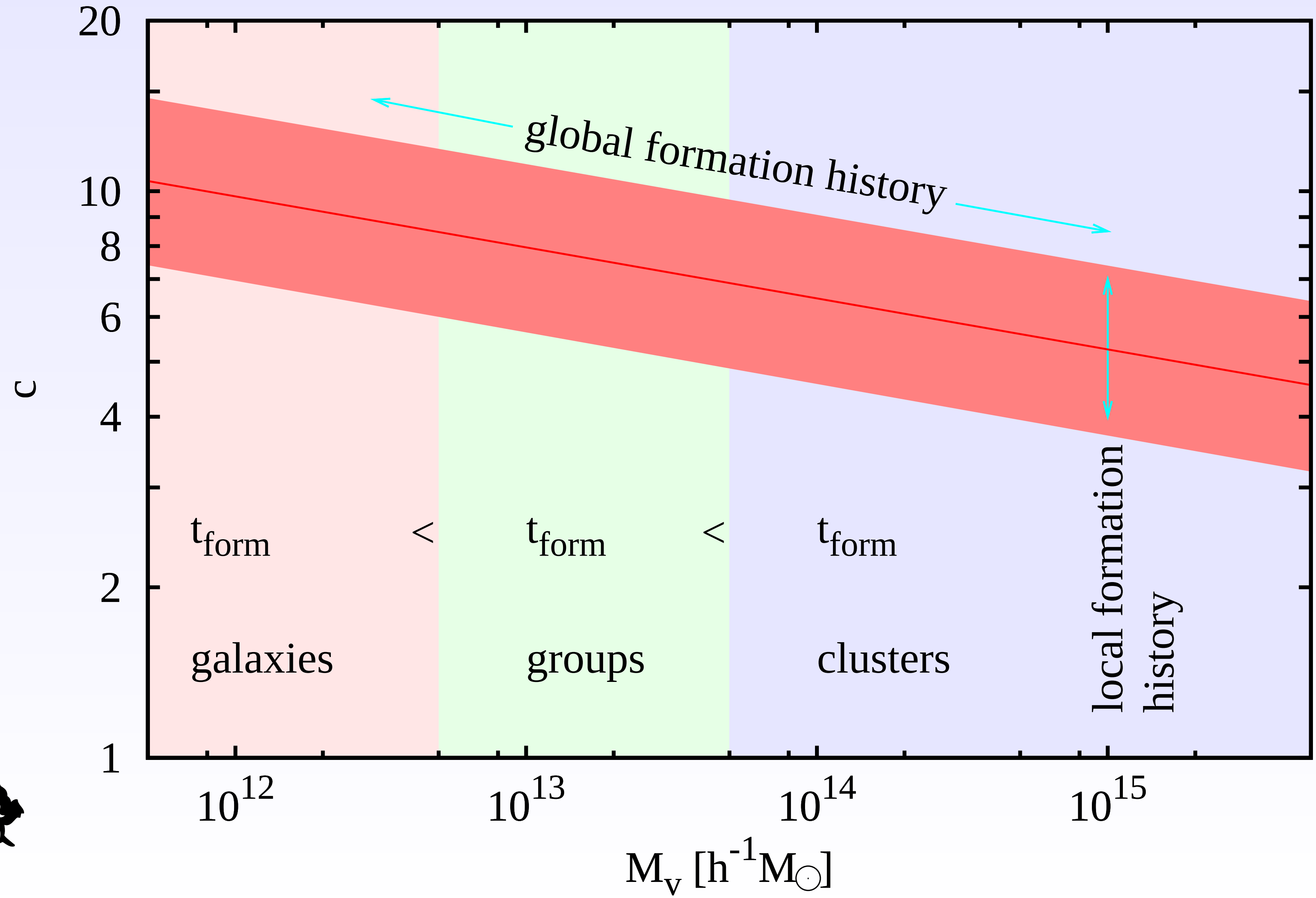


Constraints on M_v and c

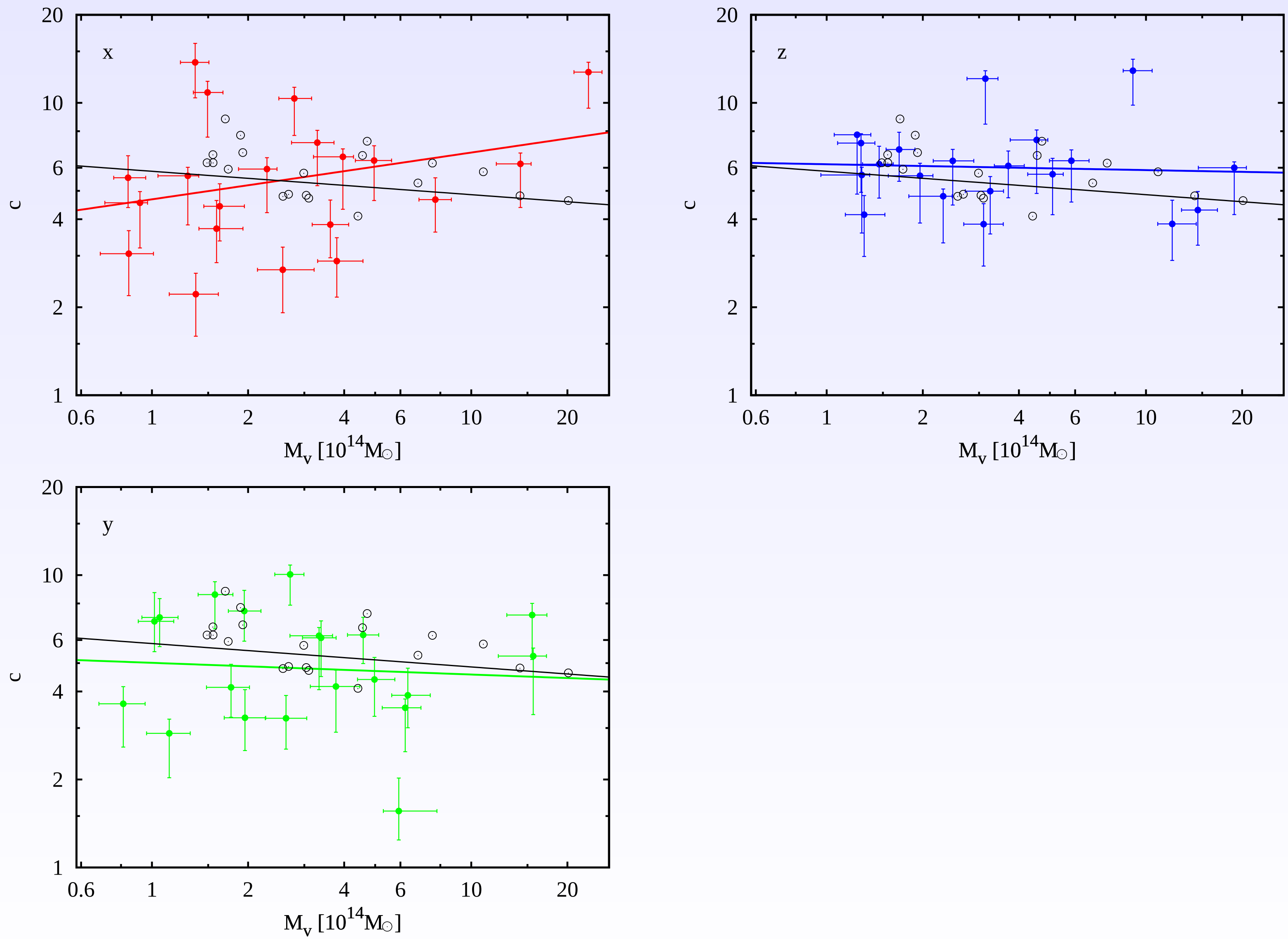




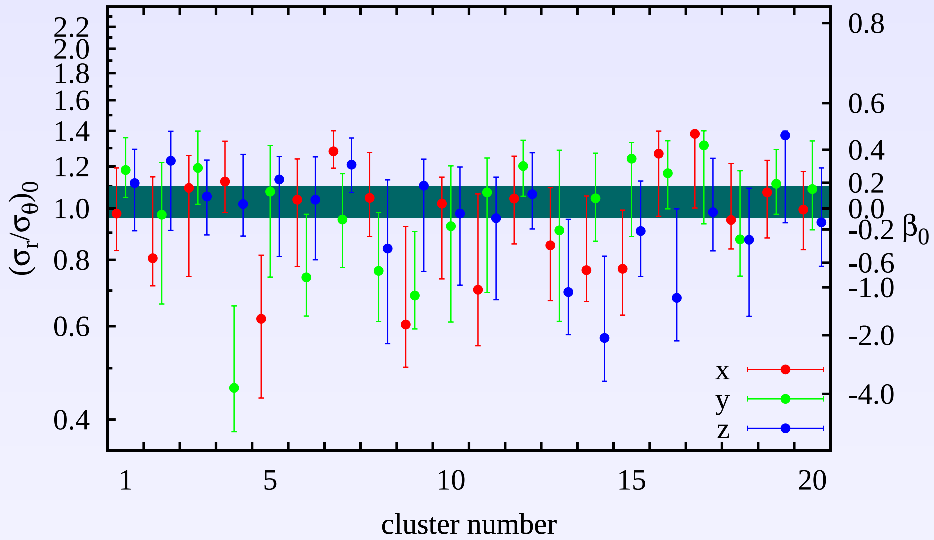
$c - M_v$ relation

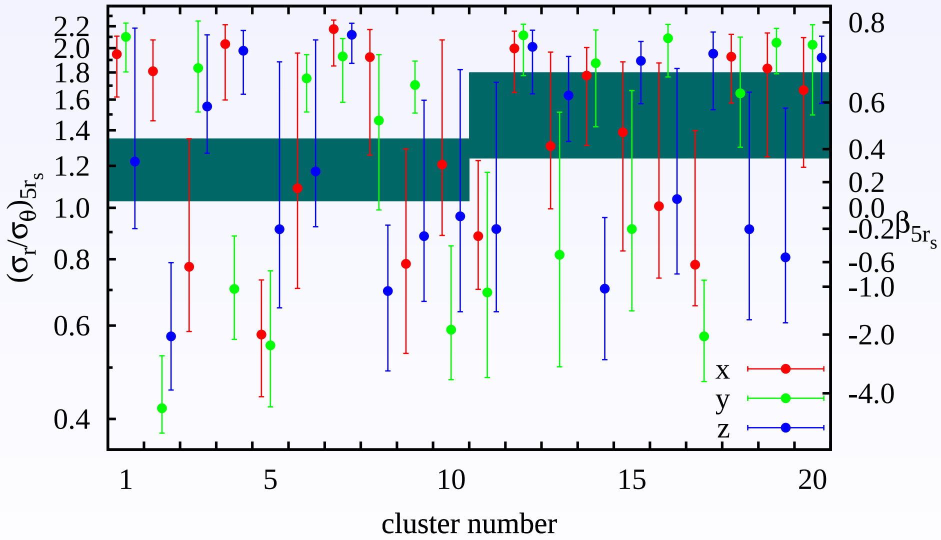


Recovering $c - M_v$ relation

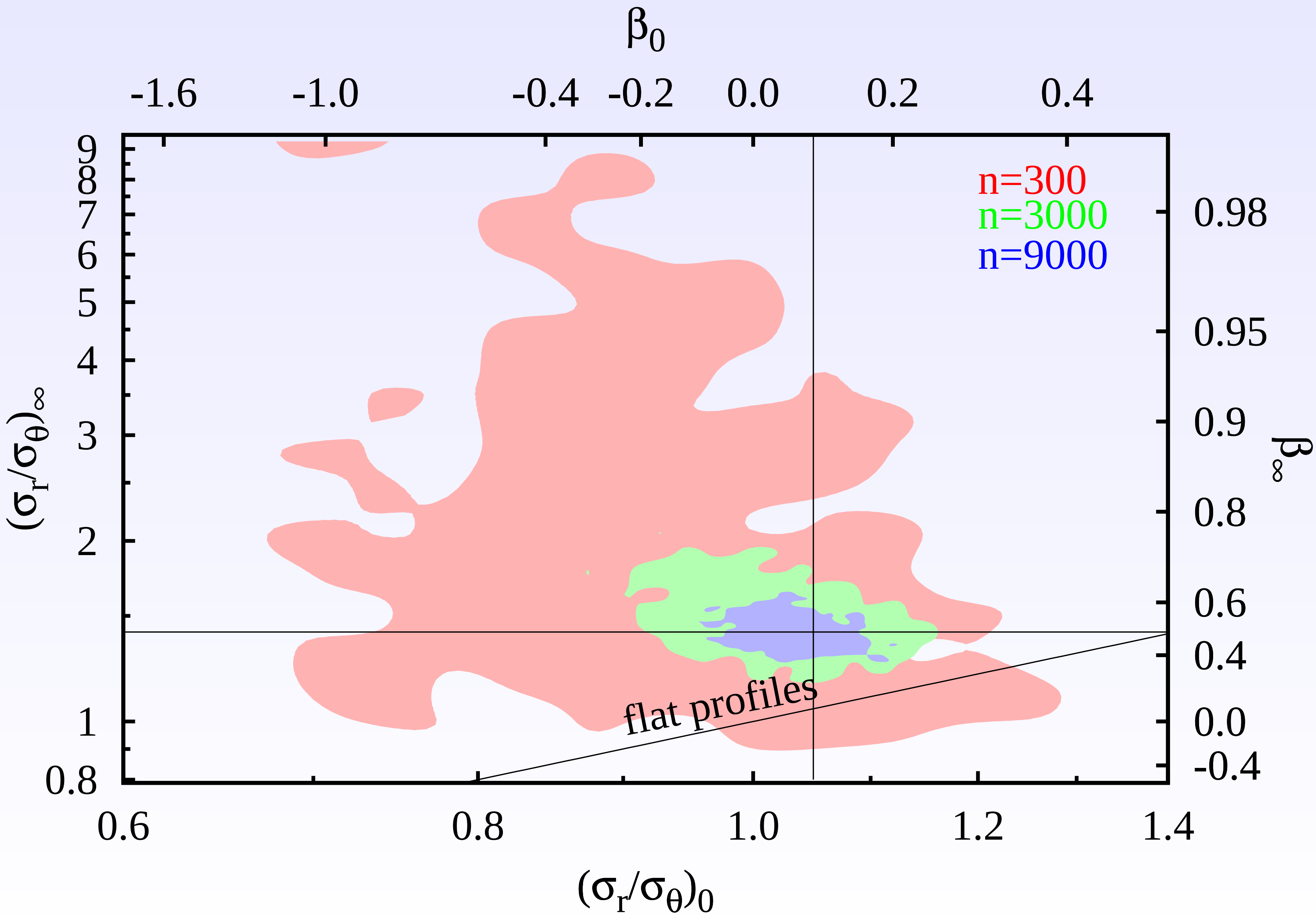


Constraints on β_0 and β_{5r_s}





β_0 and β_∞: need for more data points



β_0 and β_∞: hierarchical modelling

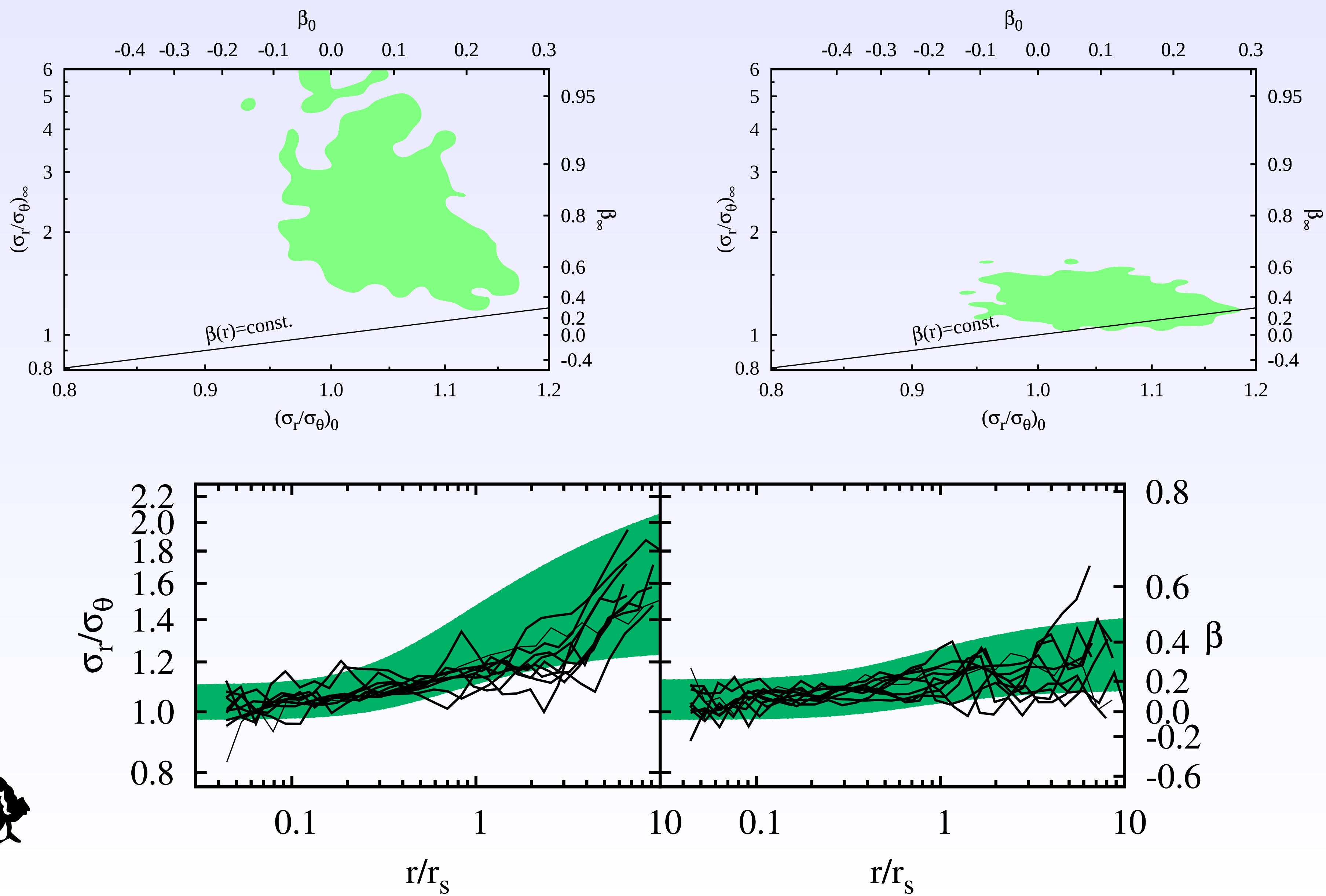
- cluster 1: $p_1(r_{s,1}, M_s)$
- cluster 2: $p_2(r_{s,2}, M_{s,2})$
- $\cdots$
- cluster N: $p_N(r_{s,N}, M_{s,N})$

$$p_{post}(\beta_0, \beta_\infty, r_{s,1}, M_{s,1}, \ldots) \propto p_{prior}\mathcal{L}$$

$$\mathcal{L} = \prod_{i=1}^{N} \prod_{j=1}^{n_i} f_{los}(R_{j,i}, v_{los,j,i} | \{\beta_0, \beta_\infty, r_{s,i}, M_{s,i}\})$$

$$p_{prior}(r_{s,1}, M_{s,1}, \ldots) = \prod_{i=1}^{N} p_i(r_{s,i}, M_{s,i})$$

Constraints on $\beta(r)$ from 10 clusters



Application to nearby galaxy clusters

Nearby ($z < 0.1$) galaxy clusters

Publically available database

- NASA/IPAC Extragalactic Database
- WINGS

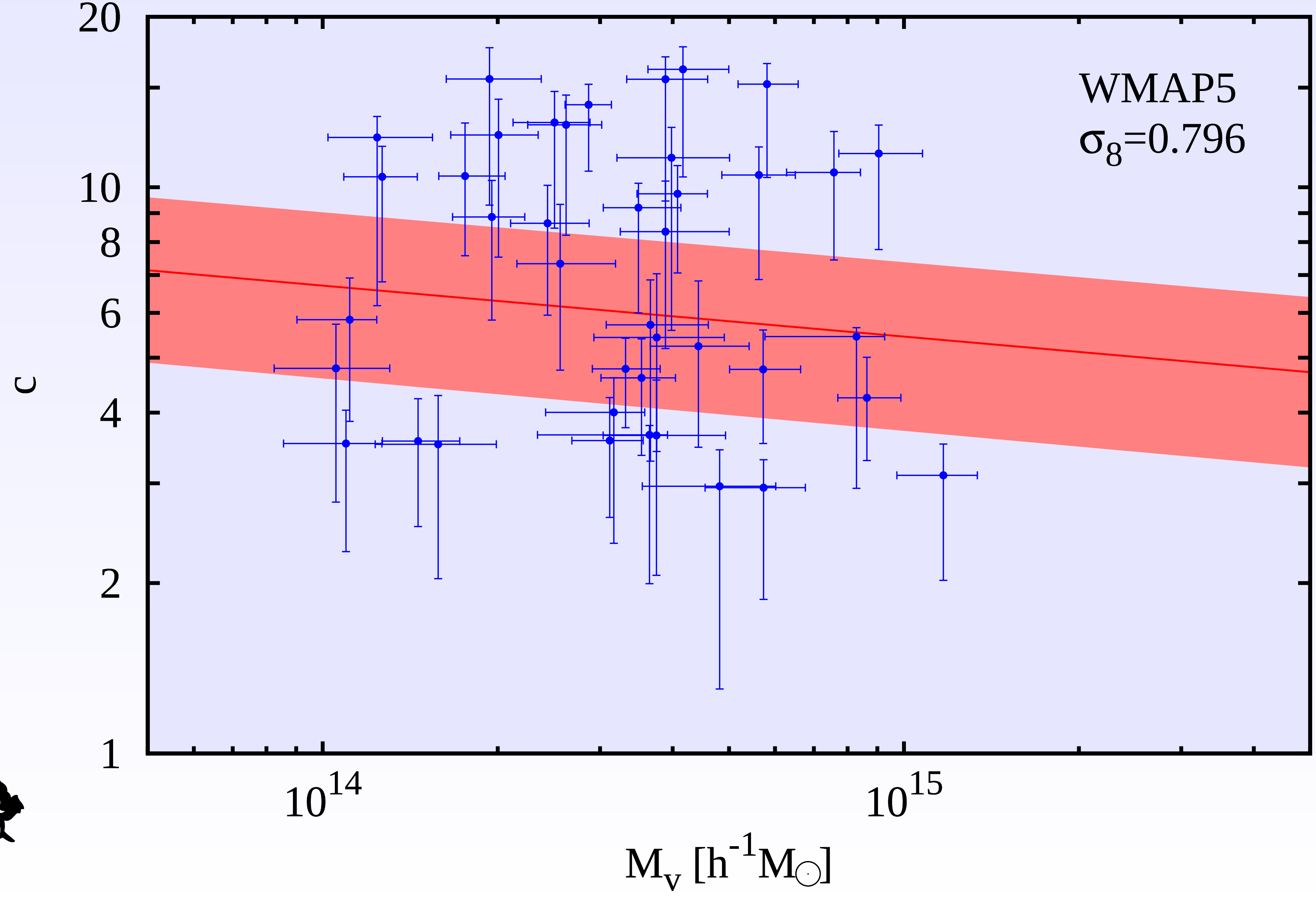
Cluster selection:

- symmetric X-ray image
- cool core
- regular velocity diagrams

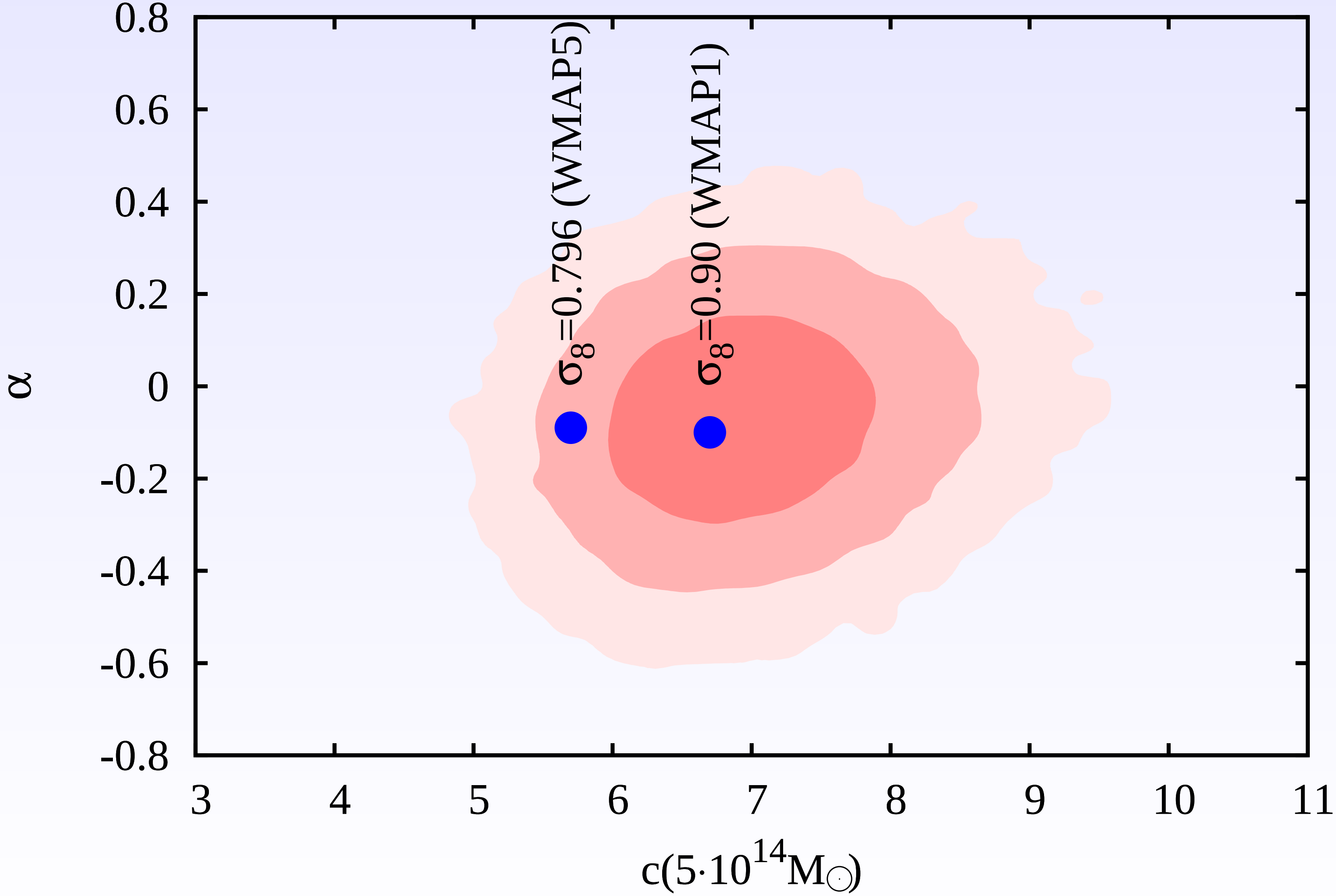
Final sample

- 41 clusters
- $100 - 200$ redshifts per cluster within $R < 2.5Mpc$

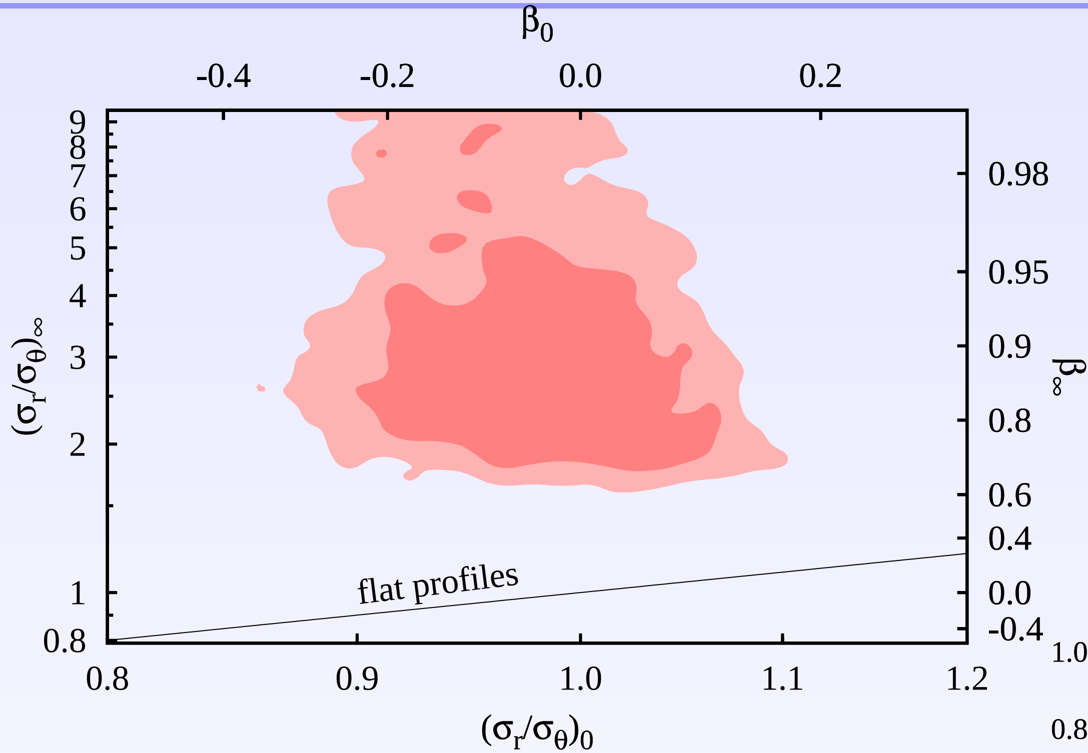
Constraints on $c - M_v$ relation



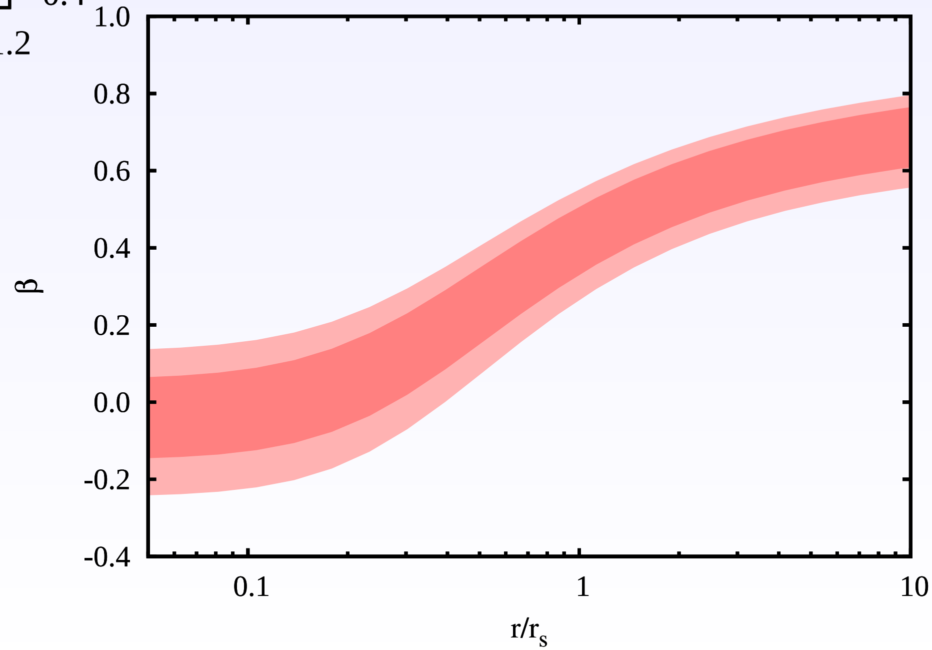
Slope and normalization of $c \propto M^{\alpha}$



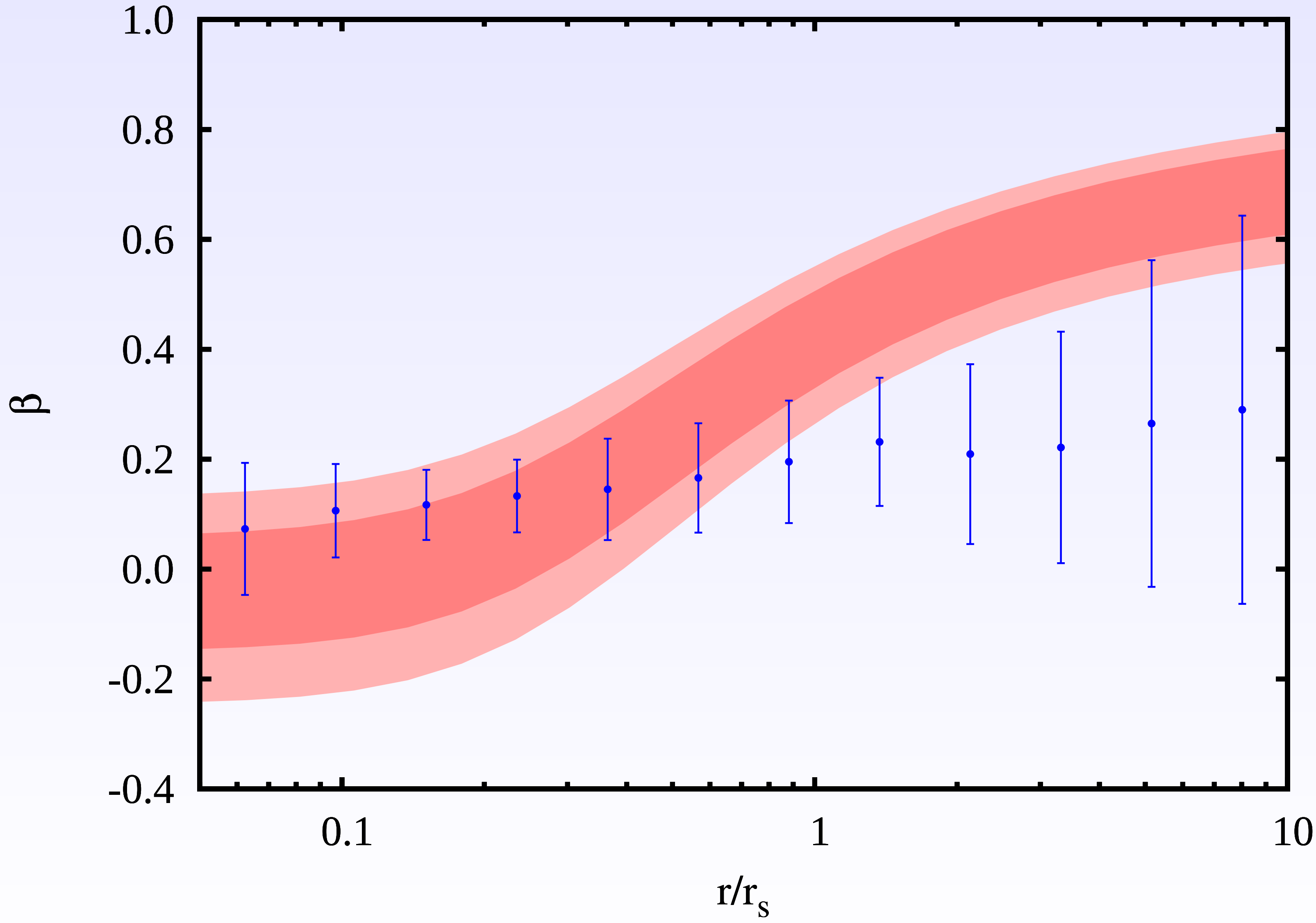
Constraints on the anisotropy profile



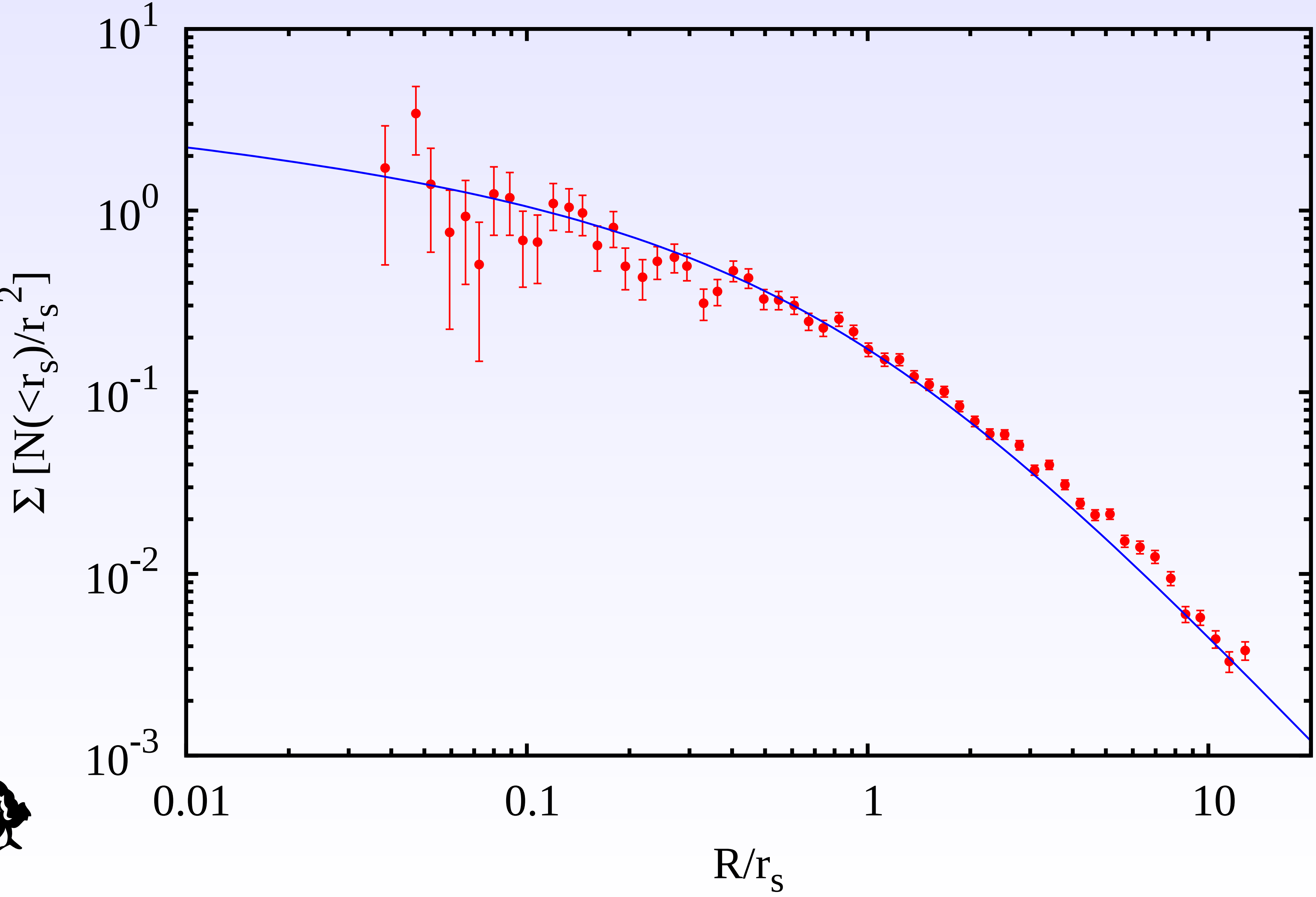
- 41 clusters
- 5707 redshifts



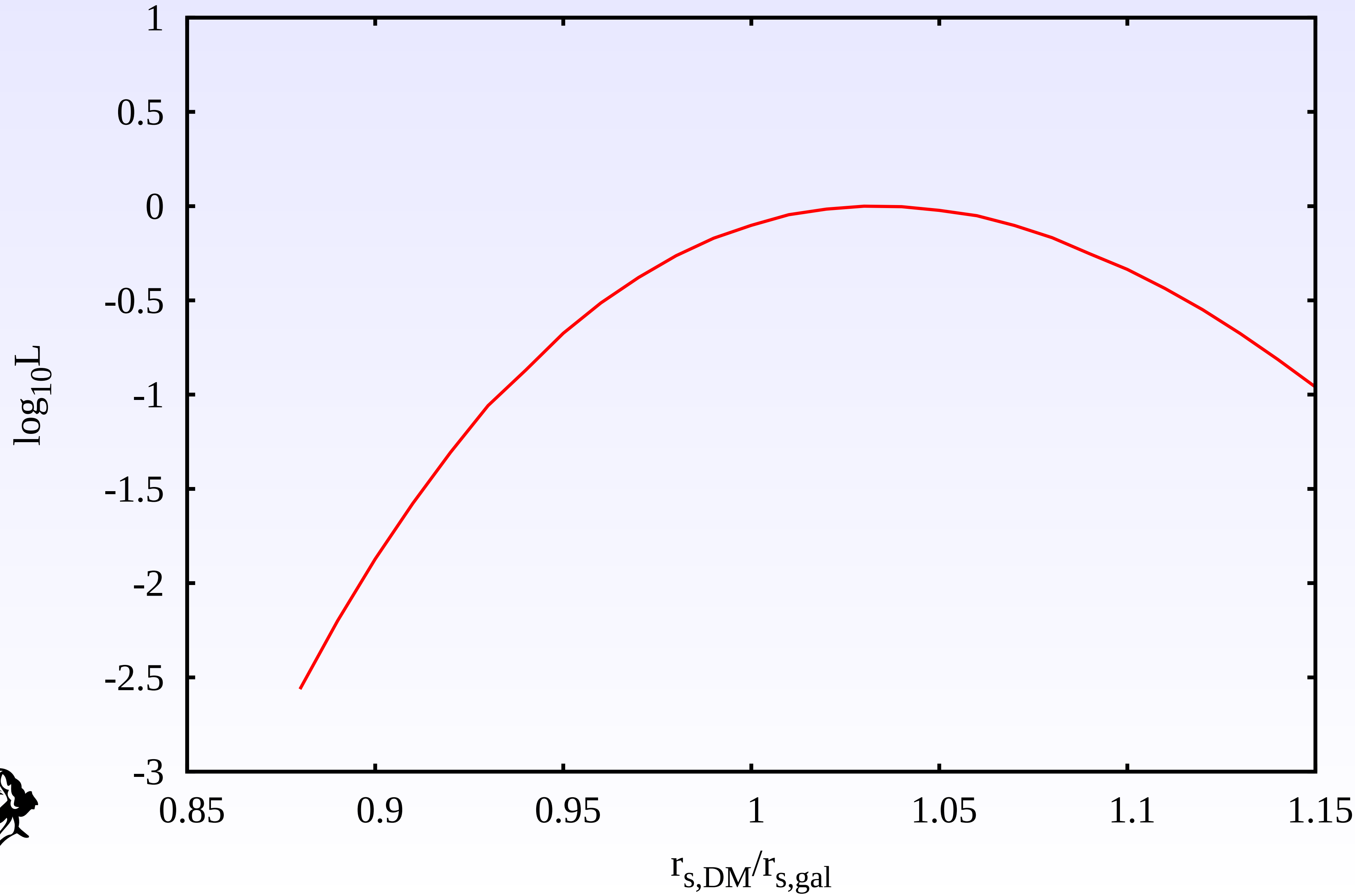
Comparison with the simulations



$n_{gal}(r) \propto \rho_{DM}(r)$?



$n_{gal}(r) \propto \rho_{DM}(r)$?



Summary

- model of distribution function
- tests on mock data
- application to nearby clusters
  - constraints on $c - M_v$ relation
  - $\beta_0 \approx 0$, $\beta(r_v) \approx 0.6$

Perspective for future

- SDSS satellites
- ellipticals
- groups