N-body self-consistent stars-halo modelling of the Fornax dwarf galaxy

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Dwarf spheroidal galaxies (dSph) of the local group of galaxies

- The most dark matter dominated systems!

  Mass-to-light ratios about 10 to 1000.

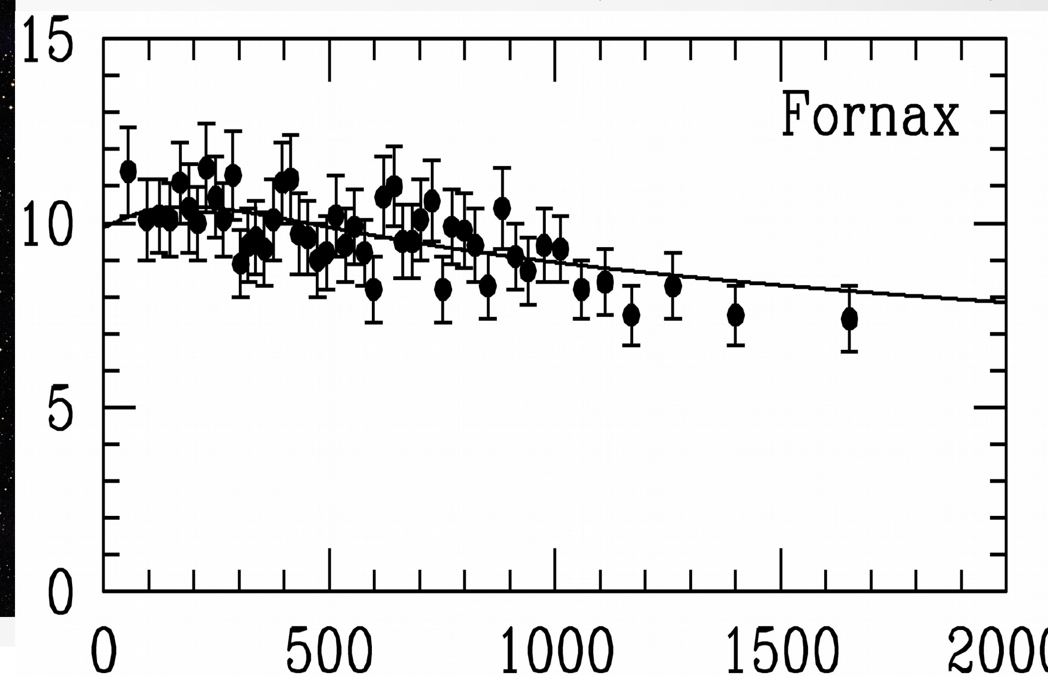
- Individual member stars can be resolved, their line-of-sight velocities can be measured. Kinematical data are more preciese than the optical ones.So, we have high-quality data for these galaxies.

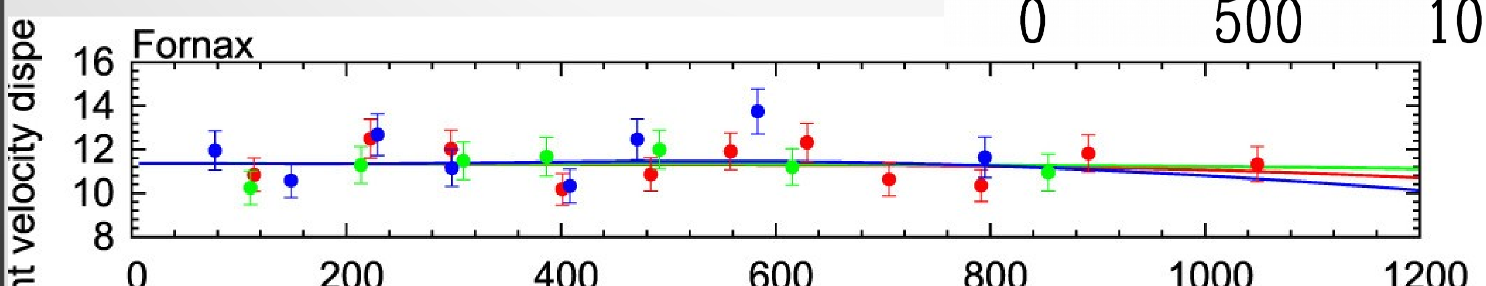
- K.Hayashi at al 2012, 2015, 2016, 2017

Fornax dwarf galaxy, ESO 356-4

Data by Walker et al. 2009

Modeled profile by
Salucci at al 2012, MNRAS 420, 3





Modeled profile by
Hayashi at al 2016
461, Issue 3, 21

N-body self-consistent modeling

- NEMO code mkkd95

  Kuijken, K., Dubinski. J., 1995, MNRAS, Vol. 277

  The code constructs a self-consistent model by the

  given parameters of the distribution function (DF) :

  about 10^6 particles or more, masses, coordinates, velocities
- AGAMA code

  Action-based galaxy modelling architecture

  Vasiliev E., 2018, MNRAS, p. 2556

  2500 orbits and 2.5*10^6 particles
- falcON Dehnen code:

  The code starts up evolution of models obtained by the above codes and estimates the stability parameter of them.
- Encreasing the number of particles to 10^7 don‘t change the results.

Two component NEMO models

- Stellar component (nemo bulge)

  Analytic axially-symmetric DF, following equipotentials, coinciding the King profile (1966) in the one-component case.

  $$\rho(R, \Psi)$$

- Axially-symmetric DM halo

  Lowered Evans model (Kuijken & Dubinski 1994)

  Evans model – analytic solution of the Jeans equations.

  Jeans equations follow from the collisionless Boltsman equation for statistical distritution of particles.

$$f_{[Lowered\ Evans]}(E, L_z) = \begin{cases} f_{Evans}(E, L_z), E < 0 \\ 0, E \geqslant 0 \end{cases}$$

DM nemo parameters

For the DM NEMO model we need 5 parameters:

- **q** – q, axial ratio, an optional flattening parameter for the potential ;
- **psi0** – Ψ_0, central potential;
- **v0** – $v_0 = \sqrt{2} * \sigma_0$ where σ_0 is the central velocity dispersion;
- **ra** – R_a, the radius at which the halo rotation curve, if continued at its $r = 0$ slope, would reach the value $\sqrt{2}\sigma_0$, a scaling radius for the halo;
- **rck2** – ${r_{ck}}^2 = \frac{{R_c}^2}{{R_K}^2}$ a core smoothing parameter – ratio of the core radius to the derived King radius at which the gravitational potential has risen by about $2{\sigma_0}^2$ over its central value, provided that the potential well depth is well above $2{\sigma_0}^2$.

NEMO mkkd95
Kuijken, K., Dubinski. J.,
1995, MNRAS, Vol. 277

Halo component

Stellar nemo parameters

mkkd95 stellar component

For the bulge NEMO model which stands for our visible part of the galaxy we need 3 parameters:

- **rhob** – ρ_b, central density;
- **psicut** – Ψ_c, bulge cut-off potential;
- **sigb** – σ_b, bulge central potential.

Hydrodynamic model of Hayashi et al (2015, 2016)

- Solving Jeans Equations for stellar component taking into account the anisotropy parameter in the field of DM (not self-consistent).

$$\beta_z = 1 - \frac{\overline{v_z^2}}{\overline{v_R^2}}$$

- Plummer profile for the stellar component:

$$\rho_{Plum}(R,z) = \frac{3M_p}{4\pi b_p^3}\left[1+\frac{m_p^2}{b_p^2}\right]^{-5/2}, m_p^2 = R^2 + \frac{z^2}{q^2},$$

$$q_{Fornax} = q_{ap}\sqrt{q_{ap}^2 - \cos^2 i}/\sin i, q_{ap} = 0.7$$

Zhao 1996 profile:

$$\rho(r) = \frac{C}{r^\gamma(1+r^{1/\alpha})^{(\beta-\gamma)\alpha}}$$

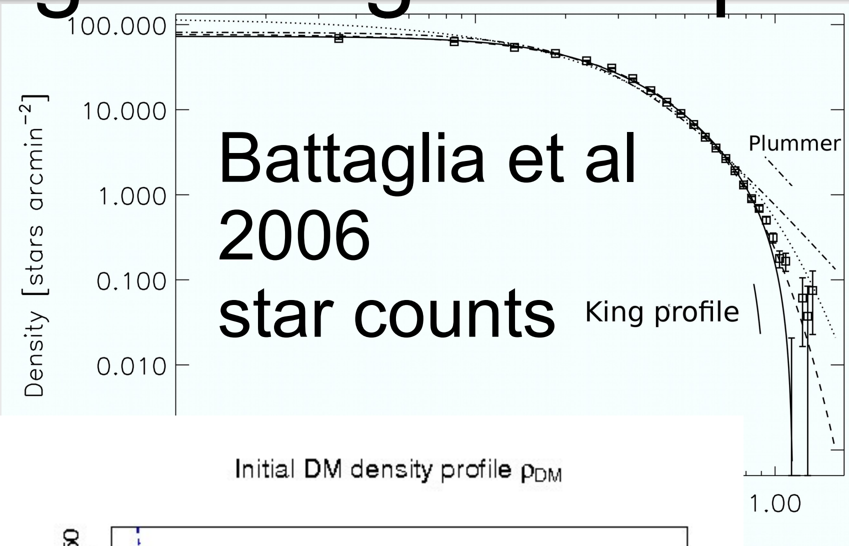
- DM profile:

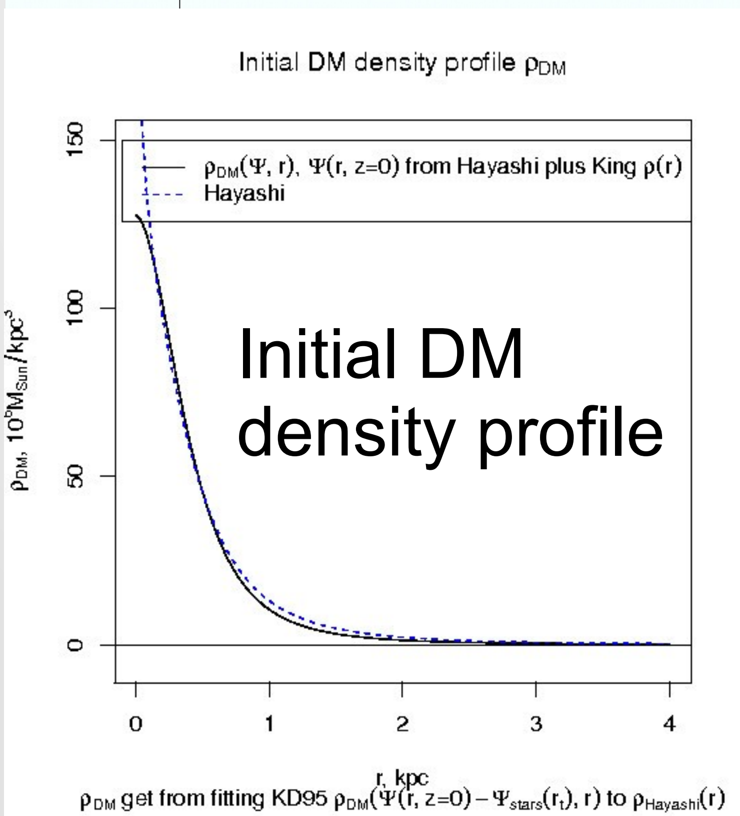
$$\rho_{DM}(R,z) = \rho_0\left(\frac{m}{b_{halo}}\right)^\alpha\left[1+\frac{m^2}{b_{halo}^2}\right]^{-(\alpha+3)/2}, m^2 = R^2 + \frac{z^2}{Q^2}, Q_{Fornax}$$

=1.11 - 2016

=0.38 - 2015

Using K.Hayashi resulting profiles for guessing nemo parameters





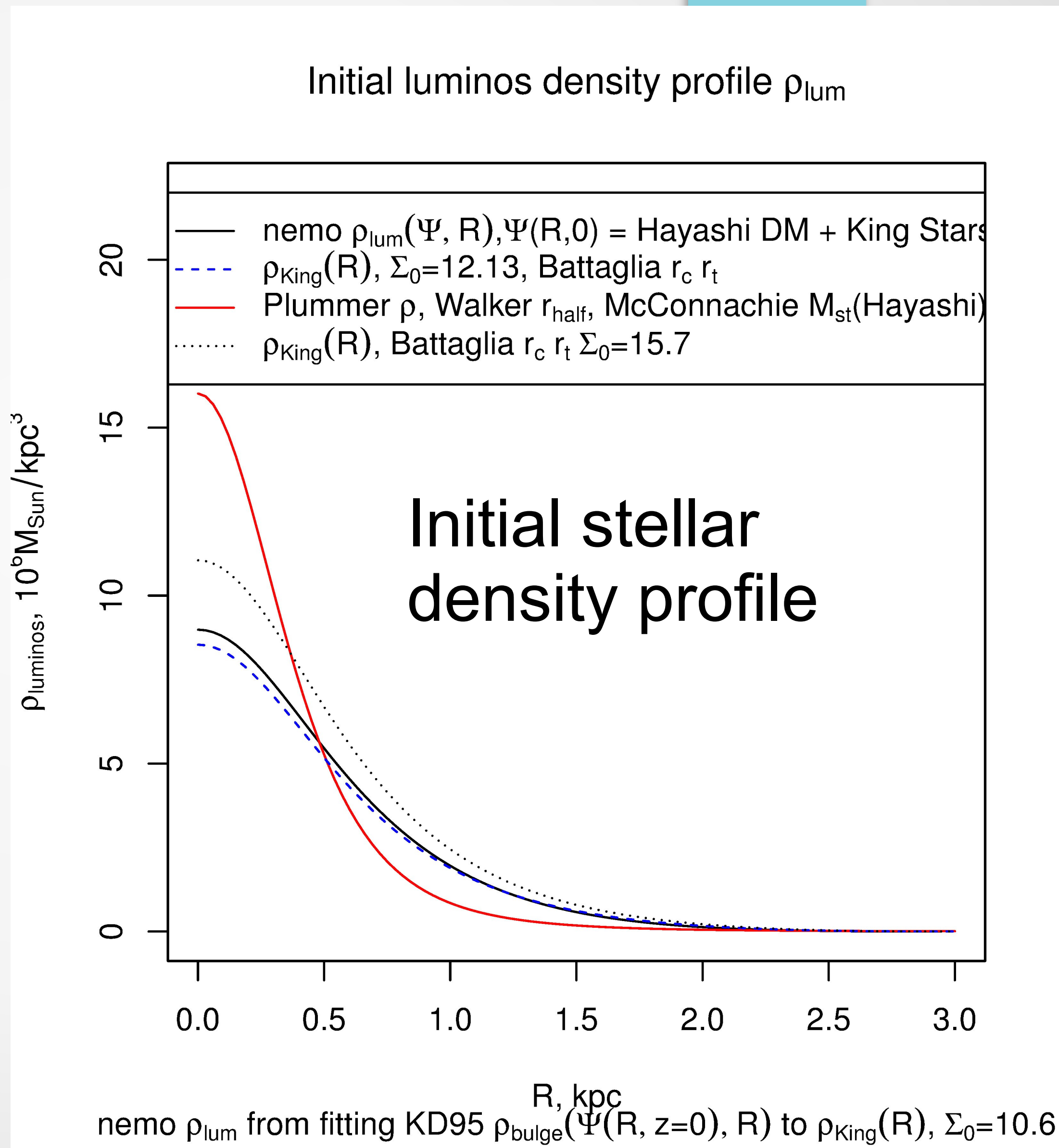
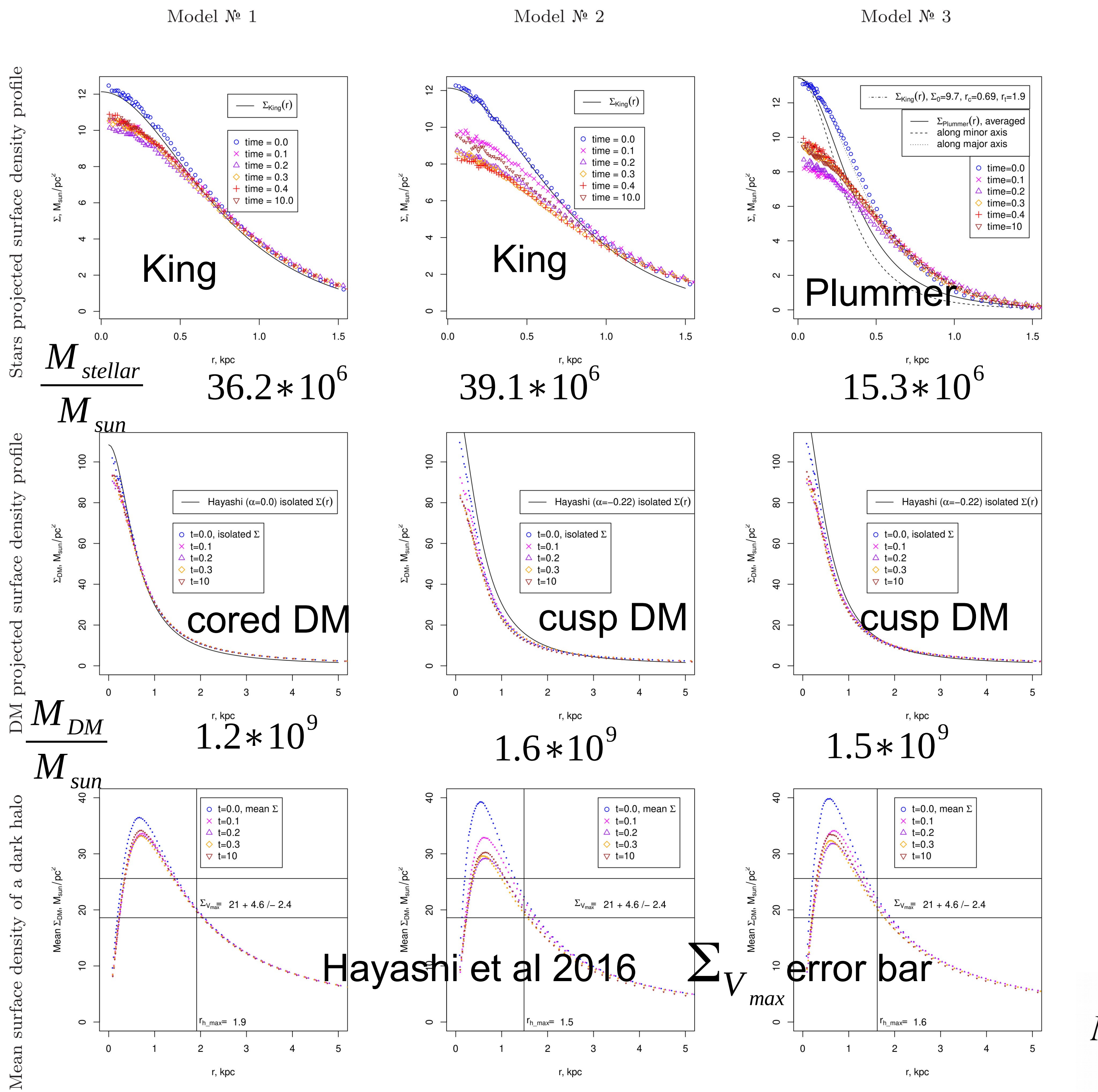


Figure 4. Surface density evolution of components for NEMO models



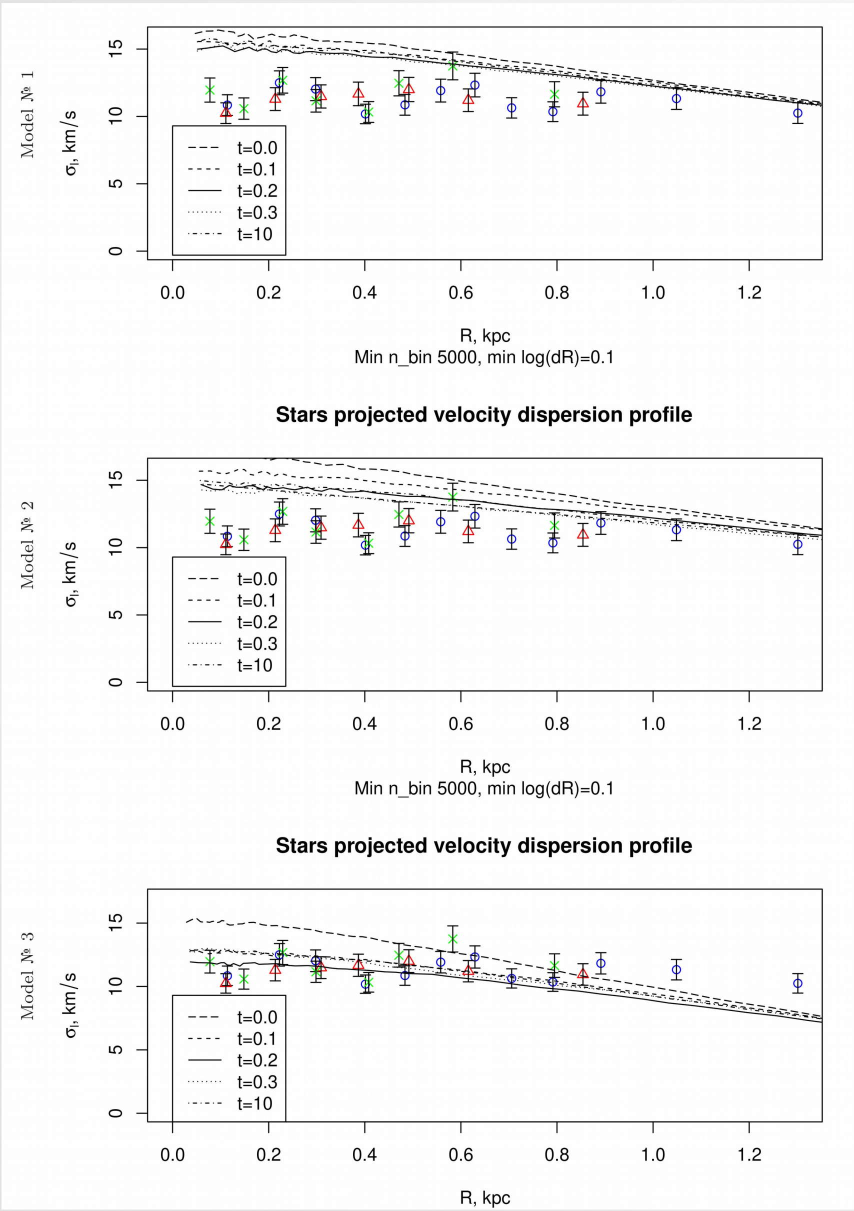
FalcON (Dehnen, 2002) evolution of the surface density profiles

Mean surface density of a dark halo within a radius of the maximum circular velocity

$$\Sigma_{\mathrm{V}_{\max}} = \frac{M(r_{\max})}{\pi r_{\max}^2},$$

$$M(r_{\max}) = \int_0^{r_{\max}} 4\pi\rho_{\mathrm{dm}}(r')r'^2 dr'$$

Velocity dispersion evolution for NEMO models



King stellar profile, cored DM profile

$$\overline{\chi^2} = 395$$

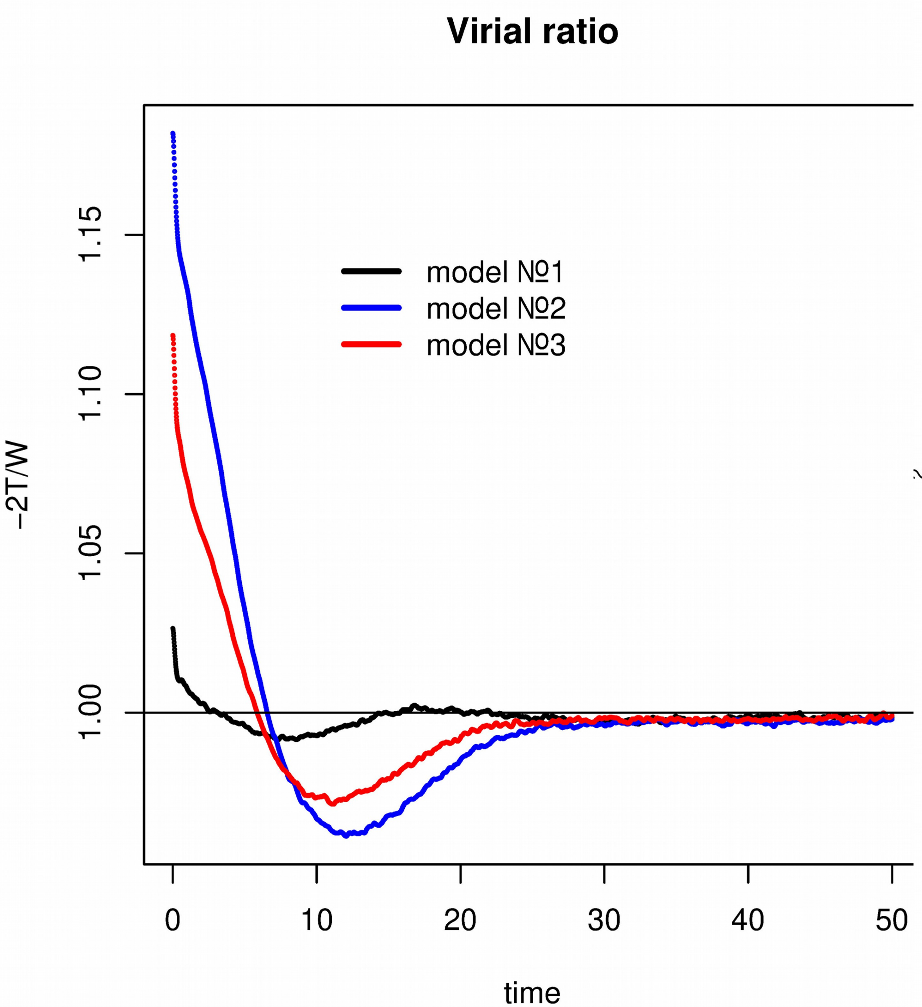
Drop of the King stellar profile, cored DM profile

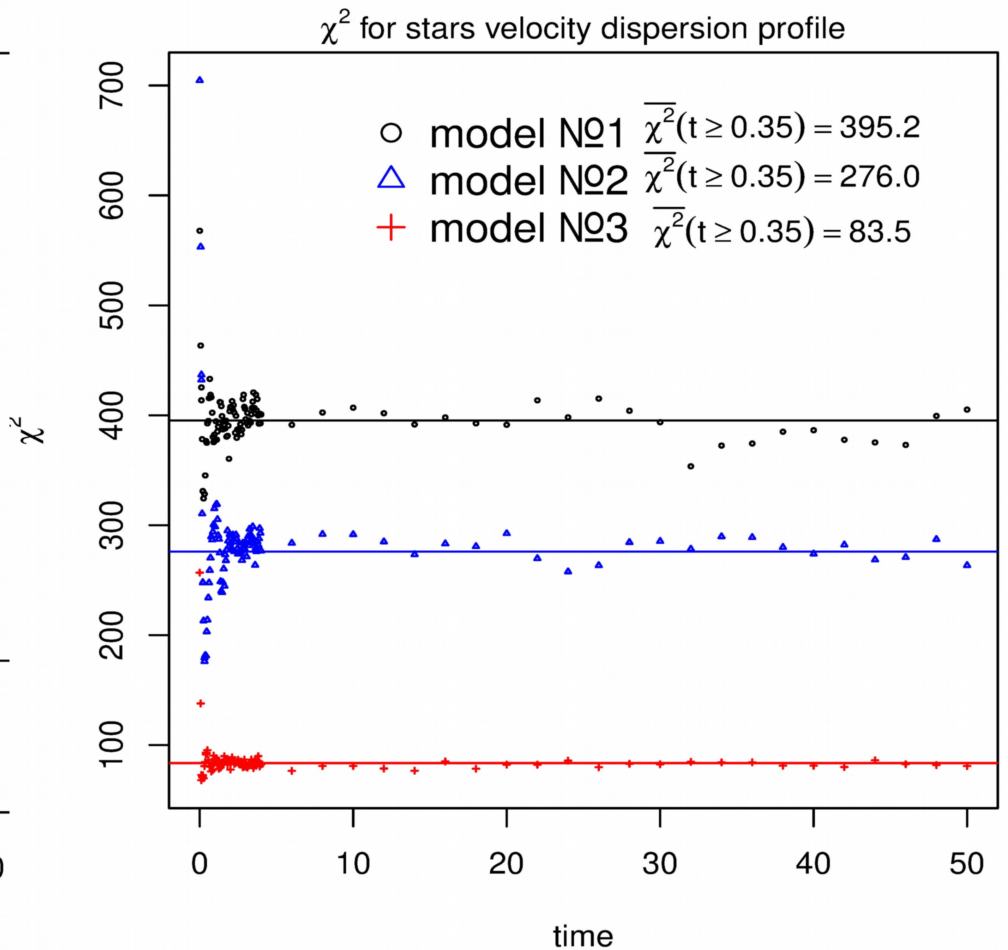
$$\overline{\chi^2} = 276$$

Drop of the Plummer stellar profile, cusp DM profile

$$\overline{\chi^2} = 83.5$$

Evolution of the virial ratio and χ^2 for NEMO models





T – kinetic energy of the system, W – potential energy

AGAMA: Action-based galaxy modelling architecture

NASA/ADS

AGAMA: action-based galaxy modelling architecture ()

Show affiliations

Vasiliev, Eugene

AGAMA is a publicly available software library for a broad range of applications in the field of stellar dynamics. It provides methods for computing the gravitational potential of arbitrary analytic density profiles or N-body models, orbit integration and analysis, transformations between position/velocity and action/angle variables, distribution functions expressed in terms of actions and their moments, and iterative construction of self-consistent multicomponent galaxy models. Applications include the inference about the structure of Milky Way or other galaxies from observations of stellar kinematics, preparation of equilibrium initial conditions for N-body simulations, and analysis of snapshots from simulations. The library is written in C++ , provides a PYTHON interface, and can be coupled to other stellar-dynamical software: AMUSE, GALPY, and NEMO. It is hosted at http://github.com/GalacticDynamics-Oxford/Agama.

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Bibcode:
2019MNRAS.482.1525V

Keywords:
methods: numerical; galaxies: kinematics and dynamics; Astrophysics - Astrophysics of Galaxies

AGAMA parameters

Zhao-like DM profile:

For the DM halo we use the Spheroid AGAMA component of the following form:

$$\rho(\bar{r}) = \rho_0 \left(\frac{\bar{r}}{a}\right)^{-\gamma} \left[1 + \left(\frac{\bar{r}}{a}\right)^{-\alpha}\right]^{\frac{\gamma-\beta}{\alpha}} \exp\left[-\left(\frac{\bar{r}}{r_{cut}}\right)^{\xi}\right],$$

$$\bar{r} = \sqrt{x^2 + (y/p)^2 + (z/q)^2} .$$

$$\begin{cases} \gamma_{AGAMA} = -\alpha_{Hayashi} , \\ \alpha_{AGAMA} = 2 , \\ \beta_{AGAMA} = 3 , \end{cases} \quad and \quad \begin{cases} \rho_0 = \rho_{0Hayashi} , \\ q = Q_{Hayashi} , \\ a = b_{\mathrm{halo}} , \\ p = 1.0 . \end{cases}$$

$$r_{cut} = 55, \ \xi = 2.5 .$$

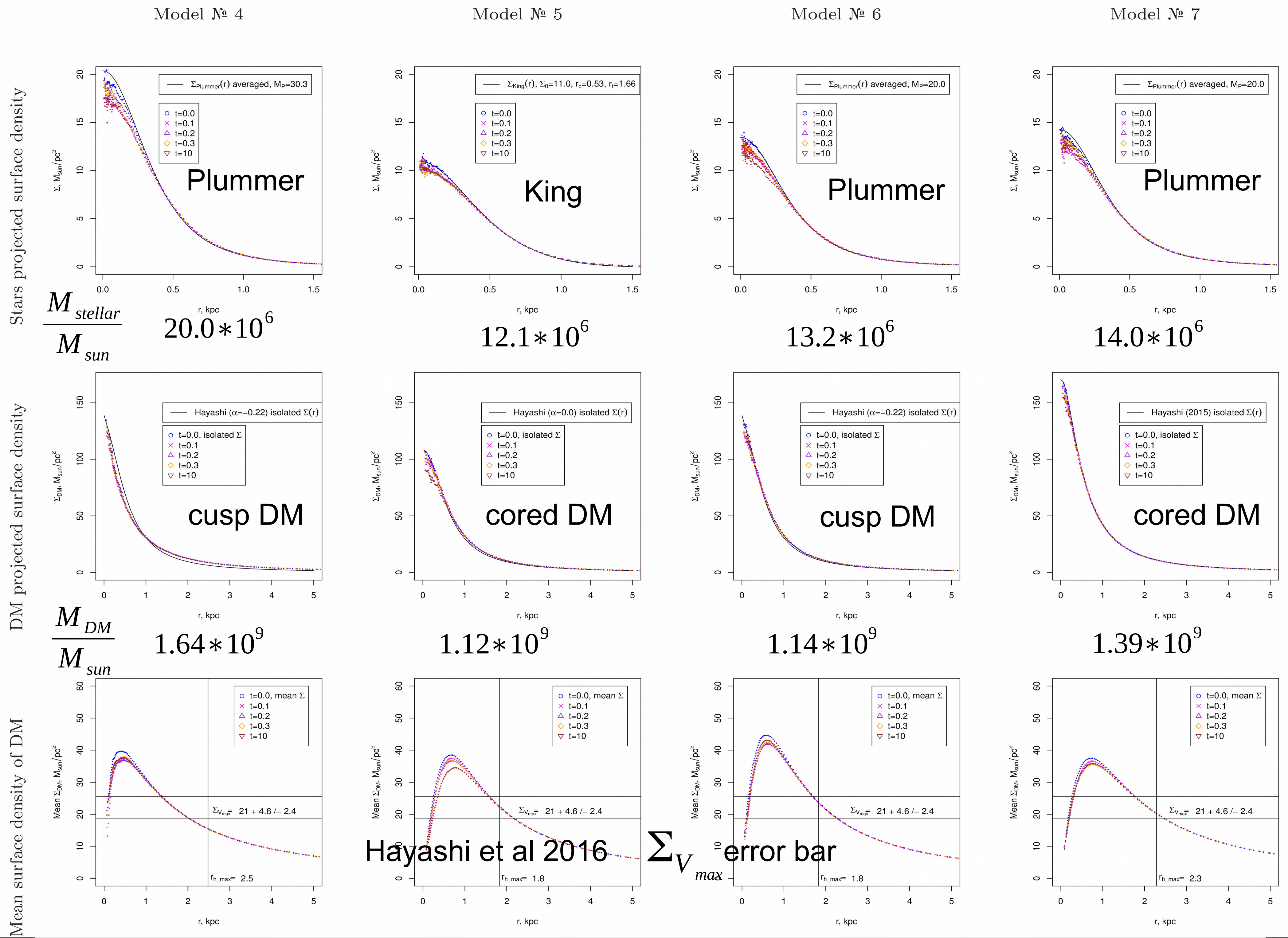
Two forms of stellar profile:

Plummer: mass, scaleRadius, axisRatioZ.

King: mass, W0, scaleRadius.

Kinematic constrains: beta, icbeta, ickappa

$$\beta_z = 1 - \frac{\overline{v_z^2}}{\overline{v_R^2}}$$



Model № 4
Model № 5
Model № 6
Model № 7
Stars projected surface density
DM projected surface density
Mean surface density of DM
Plummer
King
Plummer
Plummer
$\frac{M_{stellar}}{M_{sun}}$
$20.0*10^6$
$12.1*10^6$
$13.2*10^6$
$14.0*10^6$
cusp DM
cored DM
cusp DM
cored DM
$\frac{M_{DM}}{M_{sun}}$
$1.64*10^9$
$1.12*10^9$
$1.14*10^9$
$1.39*10^9$
Hayashi et al 2016
$\Sigma_{V_{max}}$ error bar
$\Sigma_{Plummer}$(r) averaged, M_P=30.3
Σ_{King}(r), Σ_0=11.0, r_c=0.53, r_t=1.66
$\Sigma_{Plummer}$(r) averaged, M_P=20.0
$\Sigma_{Plummer}$(r) averaged, M_P=20.0
Hayashi (α=−0.22) isolated Σ(r)
Hayashi (α=0.0) isolated Σ(r)
Hayashi (α=−0.22) isolated Σ(r)
Hayashi (2015) isolated Σ(r)
t=0.0
t=0.1
t=0.2
t=0.3
t=10
t=0.0, isolated Σ
t=0.0, mean Σ
$\Sigma_{V_{max}}$= 21 + 4.6 /− 2.4
r_{h_max}= 2.5
r_{h_max}= 1.8
r_{h_max}= 1.8
r_{h_max}= 2.3
Σ, M_{sun}/pc²
Σ_{DM}, M_{sun}/pc²
Mean Σ_{DM}, M_{sun}/pc²
r, kpc

Velocity dispersion evolution for AGAMA models

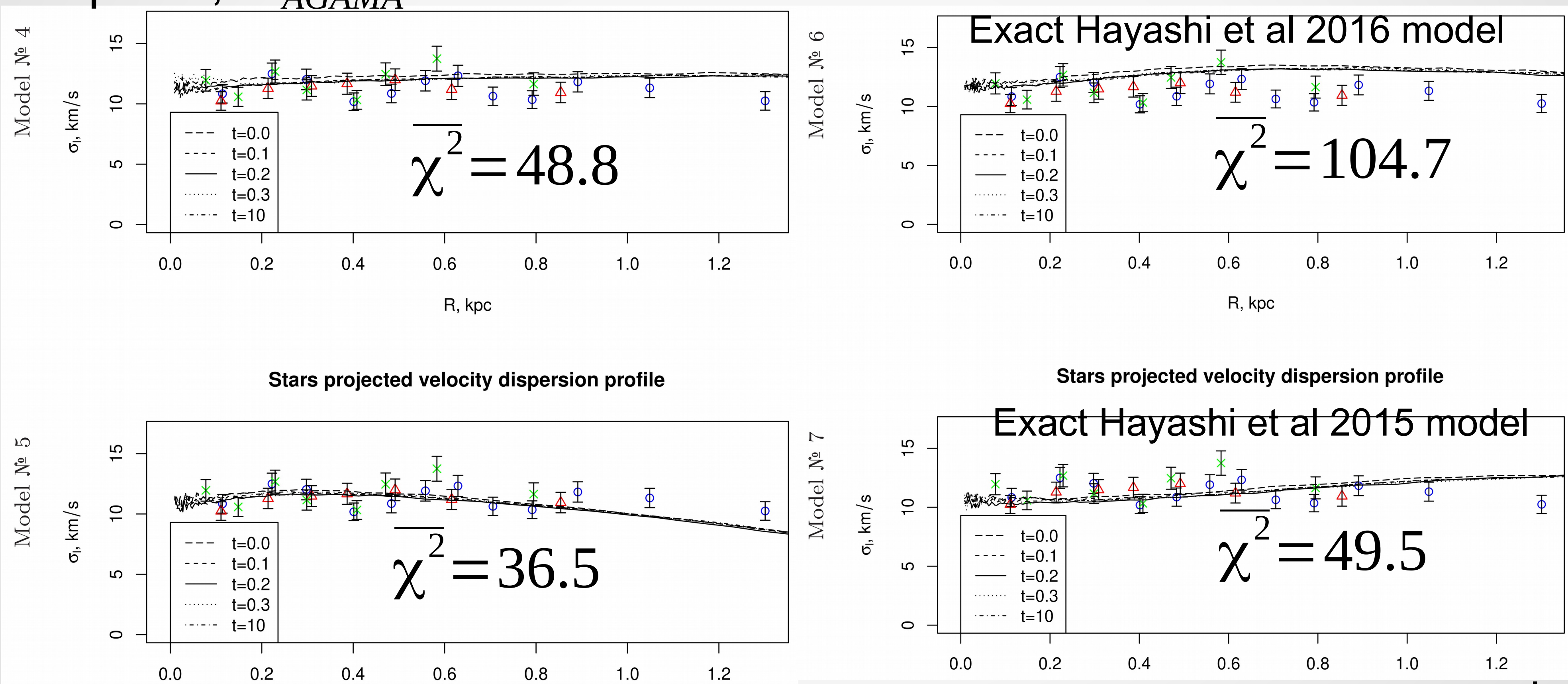
Plummer mass = 20.0, **beta** = -0.17

cusp DM, $\alpha_{AGAMA} = 1.0$

Plummer mass = 13.2,

icbeta= 0.47, **ickappa**= 1.0

cusp DM



King mass = 20.0, **beta** = -0.17

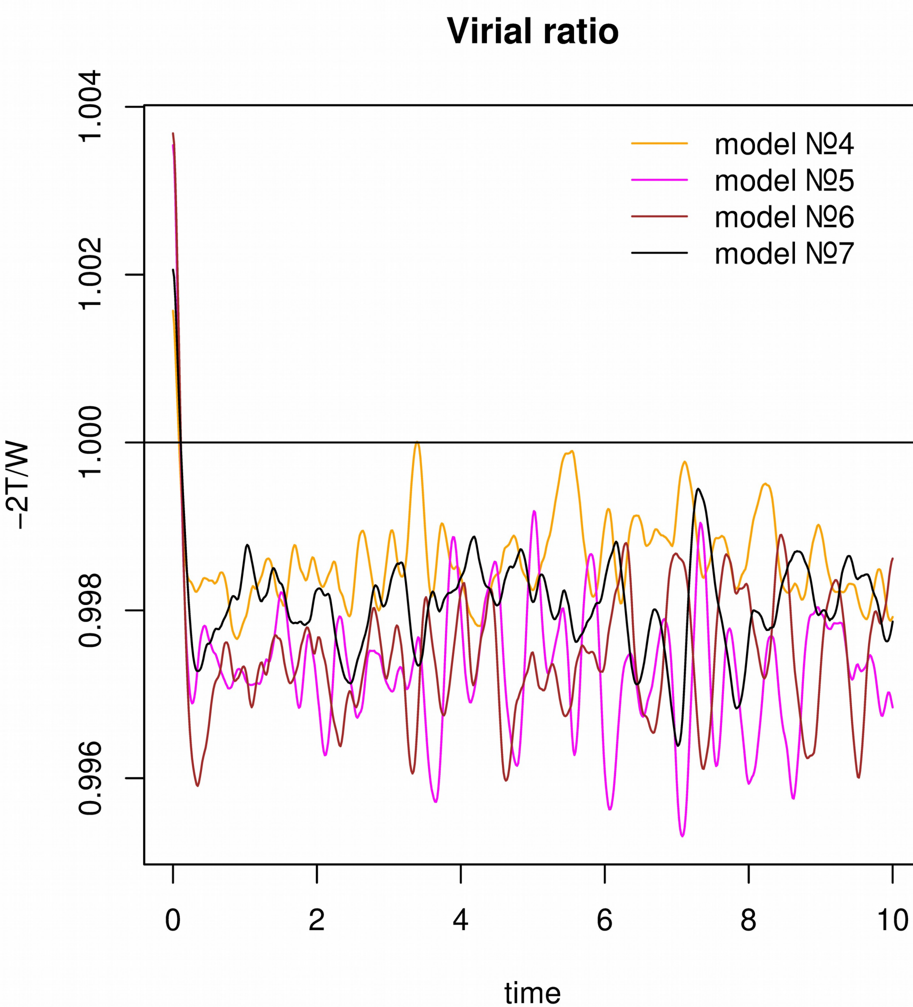
cored DM

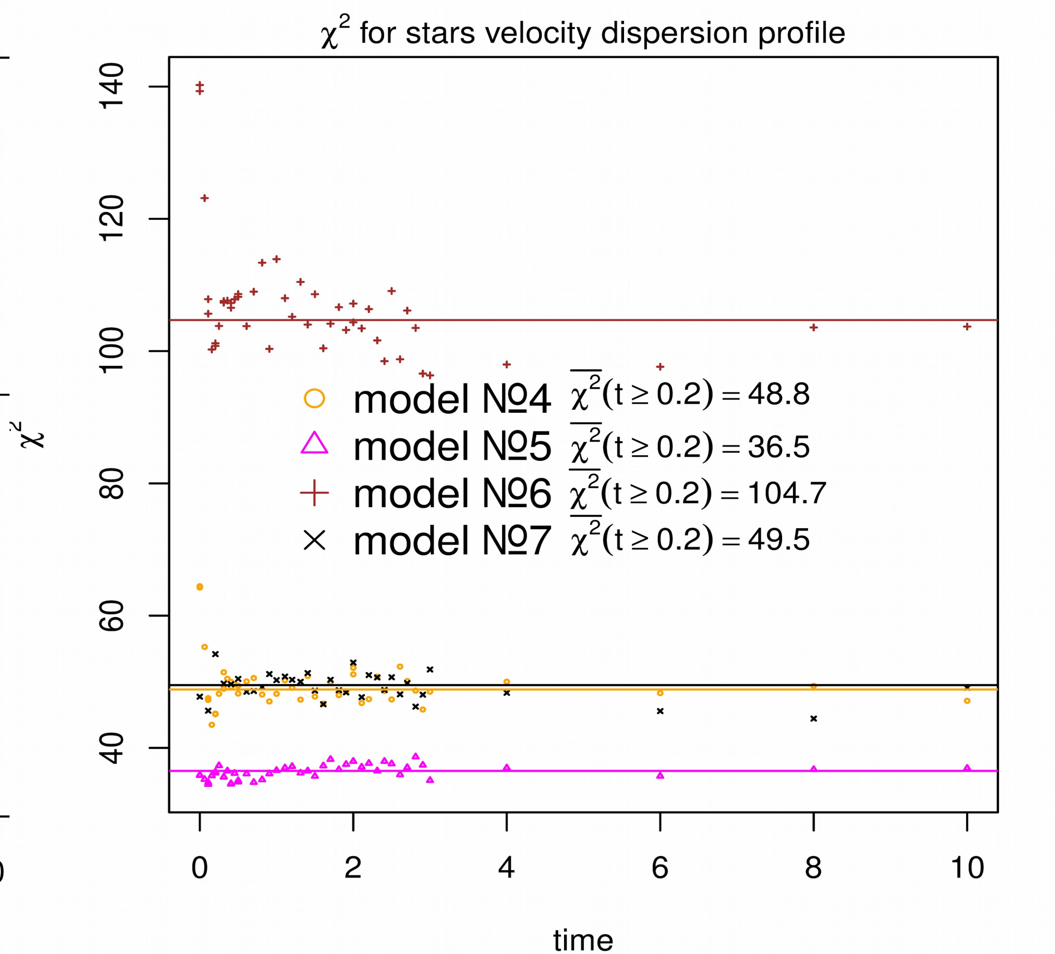
Plummer mass = 14.0,

icbeta= -0.17, **ickappa**= 1.0

cored oblate DM

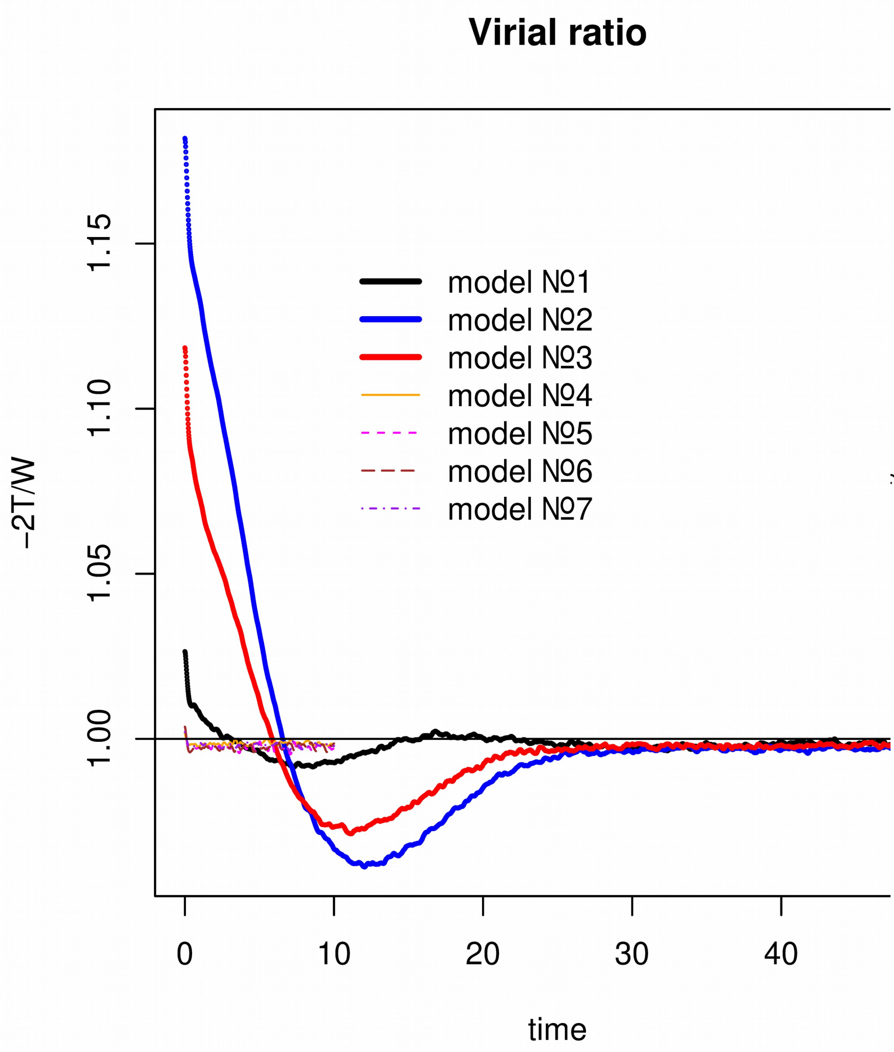
Evolution of the virial ratio and χ^2 for AGAMA models

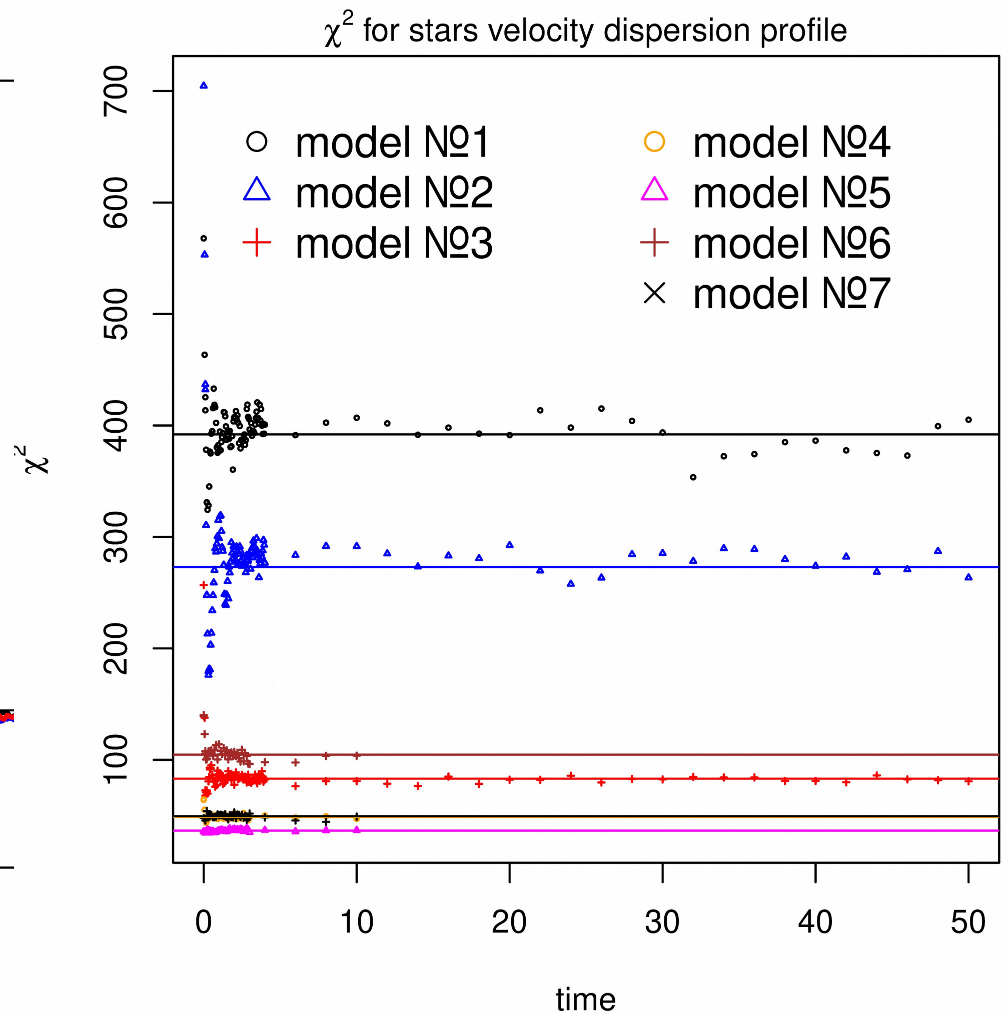




T – kinetic energy of the system, W – potential energy

NEMO vs AGAMA





Thank you for attention!