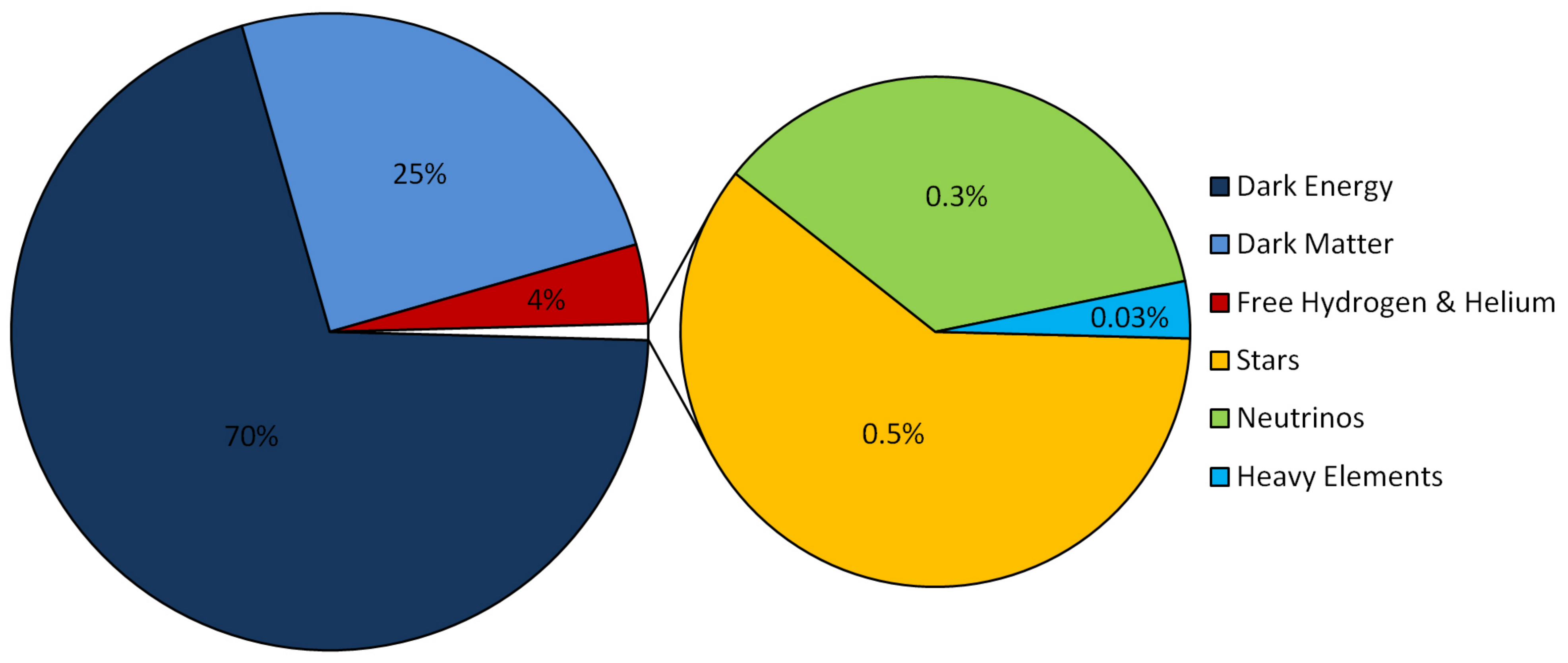
N-body self-consistent stars-halo modeling of the Fornax dwarf galaxy

Shchelkanova G.A., ITEP, Moscow; NSU, Novosibirsk

Cosmological Composition



The history of DM

- Fritz Zwicky, 1933. Coma cluster

  Dynamical mass of the cluster 400 times outweighs stellar mass.

  (By contemporary estimation about 50.)

- F.Zwicky, V.Zvorykin, 1937

  Gravitational lensing.

- H.W. Babcock, 1939, Rotation curve of M31

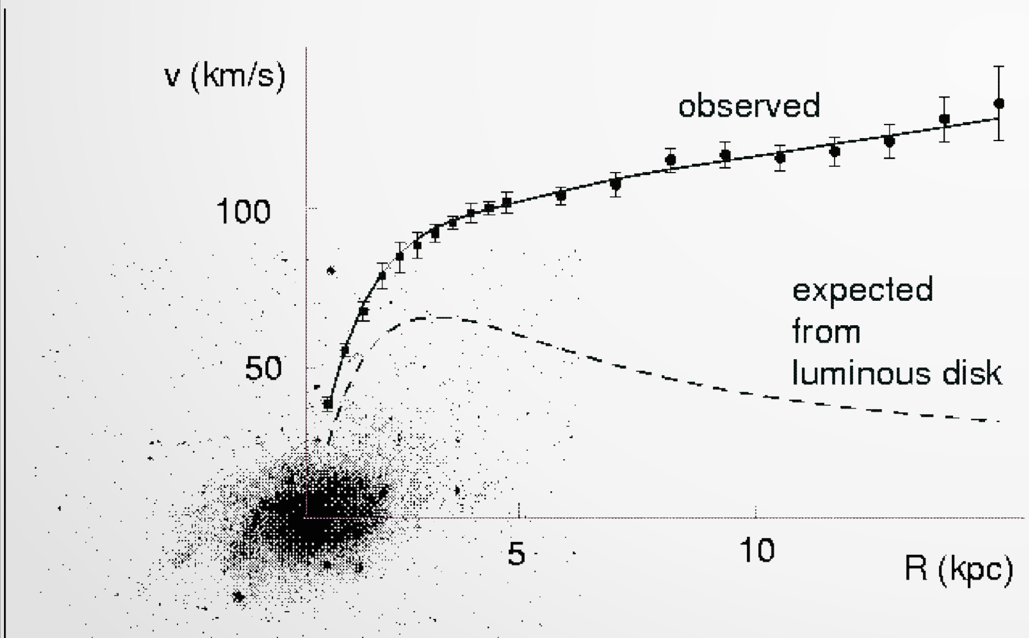
  Rotation curve grows while the surface density falls.

The mass of galaxy cluster and rotation curves.

- Velocity dispersion of galaxies in the cluster :

$$u^2 \sim \frac{GM}{R} \sim G \rho R^2$$

- Rotation curves:



M33 rotation curve

$$v^2 = \frac{GM}{R}$$

$$M = M_{tot} \Rightarrow v^2 \sim \frac{1}{R}$$

Revision of the topic in the 70-th

- Radioastronomical observations: G.A. Seielstad and J. B. Whiteoak, 1965*; B.A. Vorontsov-Veljaminov, 1969*

  Rotation curves over the optical radius.

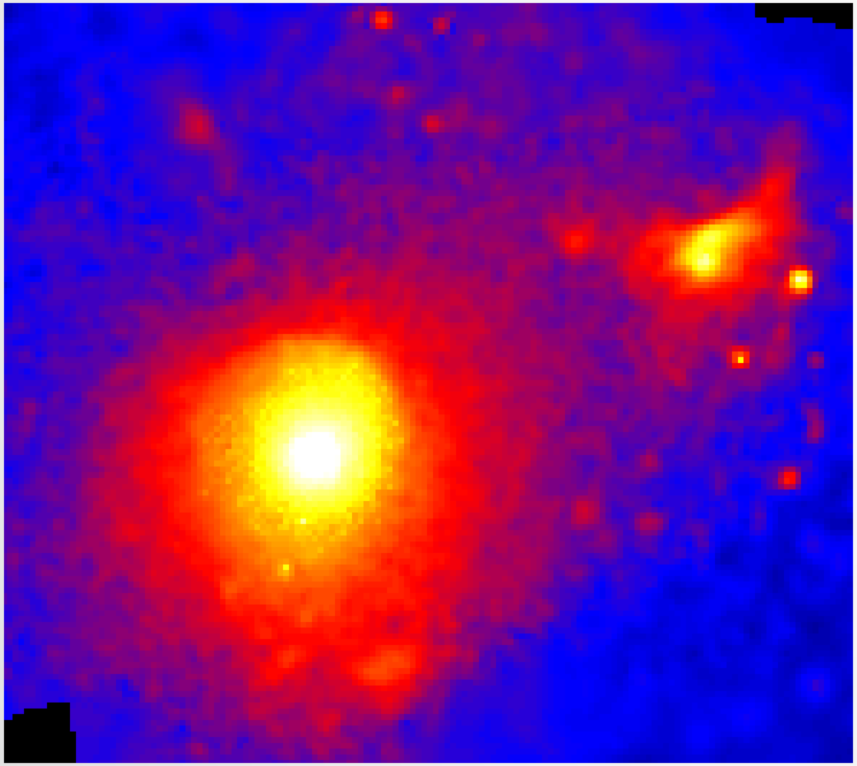
- *J. Einasto, A. Kaasik, E. Saar, 1974;*
- *J. P. Ostriker, P. J. E. Peebles, A. Yahil, 1974*

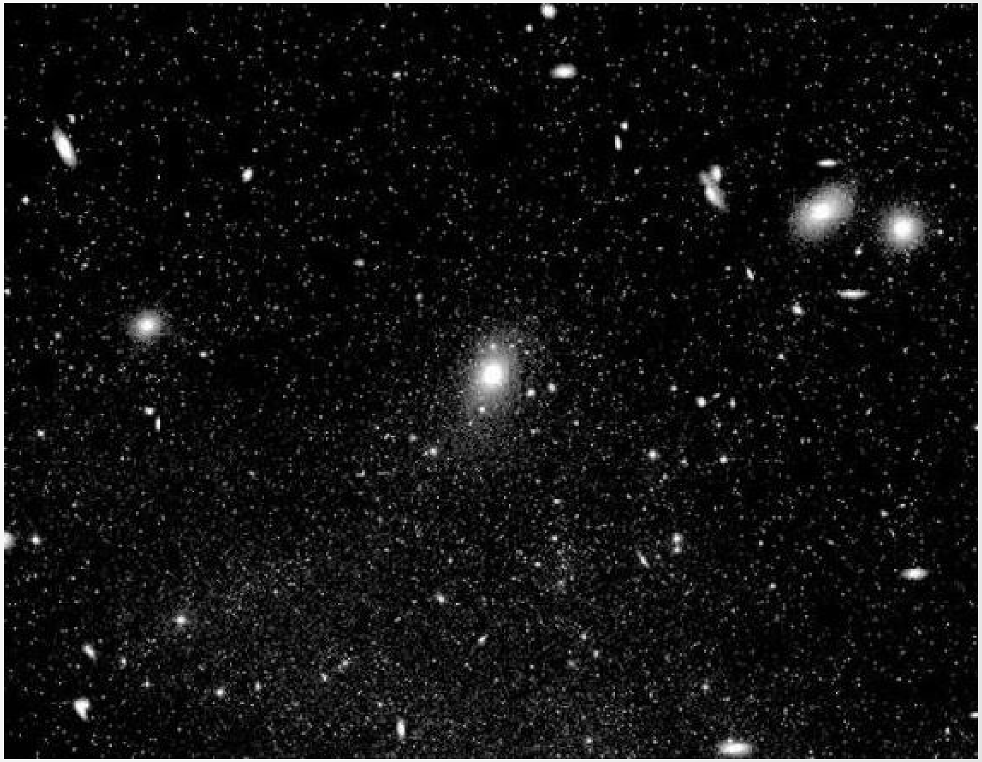
  The size and mass of galaxies and the mass of the Universe.

  Estimation of the mass of a galaxy by the dynamics of the satellite galaxies.

X-ray emitting hot gas of the clusters of galaxies

$$RT \sim \frac{GM}{R}$$



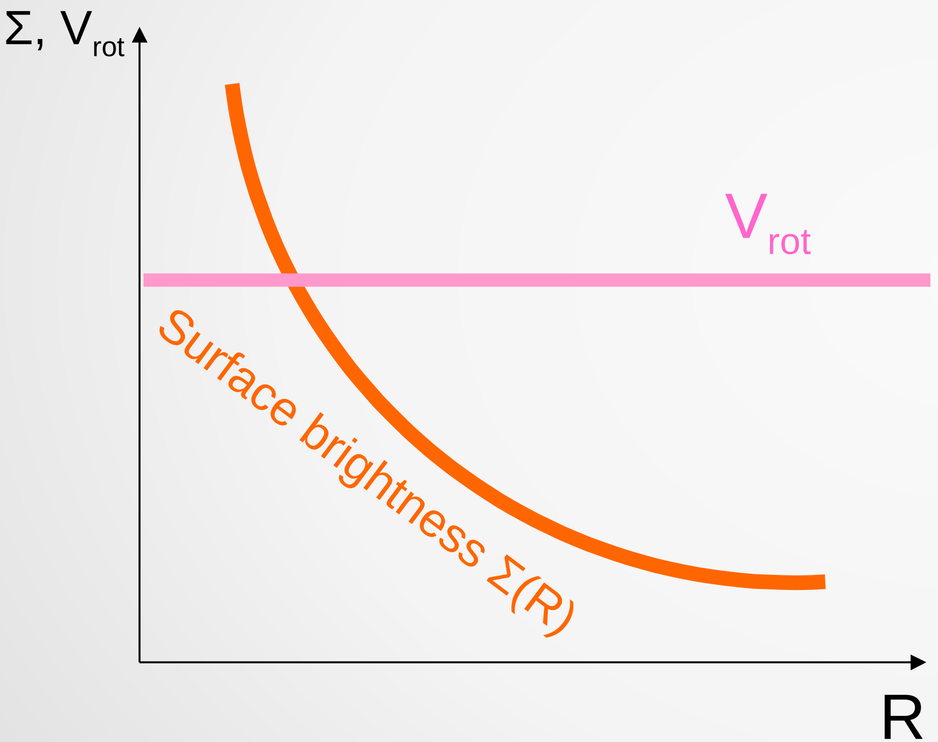


X-ray Virgo cluster image is on the left part of the screen and visual image on the right part.

Plain rotation curves without DM

- Mestel disk

$$\Sigma(R) \sim \frac{\Sigma_0 R_0}{R}$$



$$V_{rot}^2 = 2\pi G \Sigma_0 R_0$$

Cosmological arguments

- Anisotropy of the cosmic microwave background radiation (CMB)

  (forseen by G.Gamov, noticed in 1941, discovered in 1965):

  for z ~ 10^3 the anisotropy ~ 10^(-5)

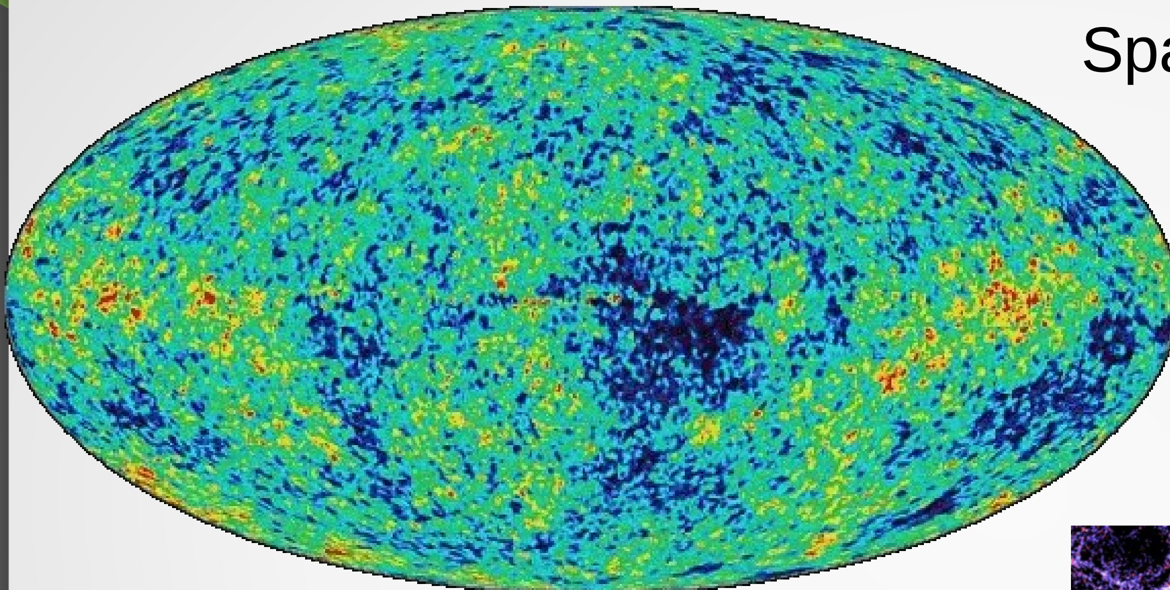
  for z ~ 1 the anisotropy should be ~1%, but it‘s wrong

- Large scale structure of the Universe (1990th): superclusters and filaments. But even with proposed DM componetn this structures could‘t be formed on such a scales (30-200Mpc).

- Discovery of the accelerating expansion of the Universe from SN Ia observations.

  Saul Perlmutter,Brian P. Schmidt, Adam G. Riess, 1998

Anisotropy of the CMB and Large-scale structure of the Universe



Space-based radiotelescopes:

RELIKT-1 (SU, 1983—1984)

COBE (USA, 1989—1996)

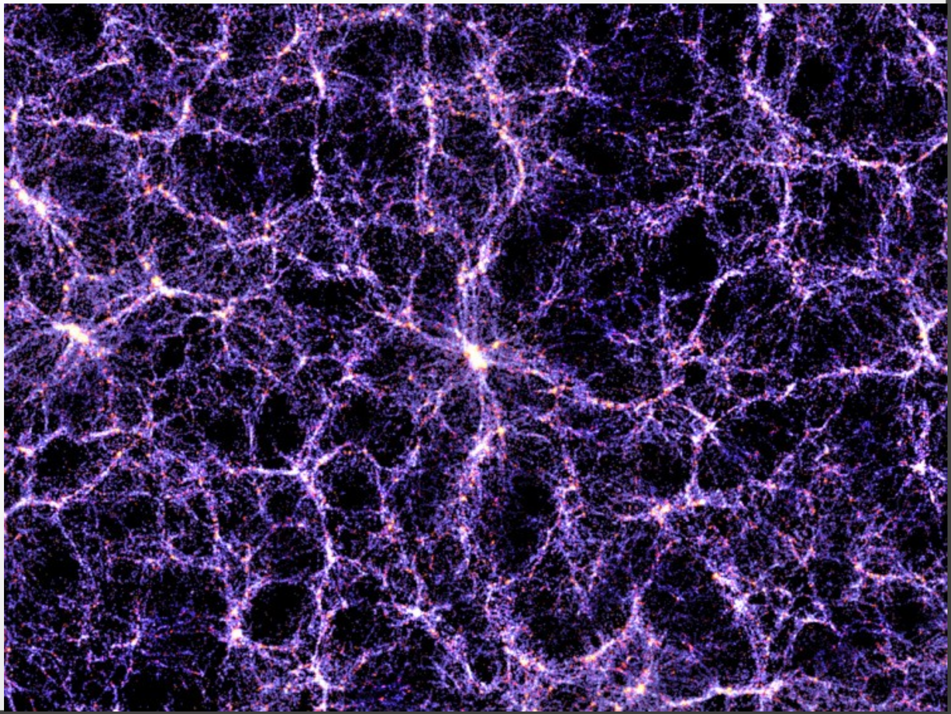
WMAP (USA, 2001—2009)

Planck (EU, 2009—2010)

Modeling of the large-scale structure of the Universe:

stars
galaxies
galaxy groups
galaxy clusters
superclusters
walls and filaments

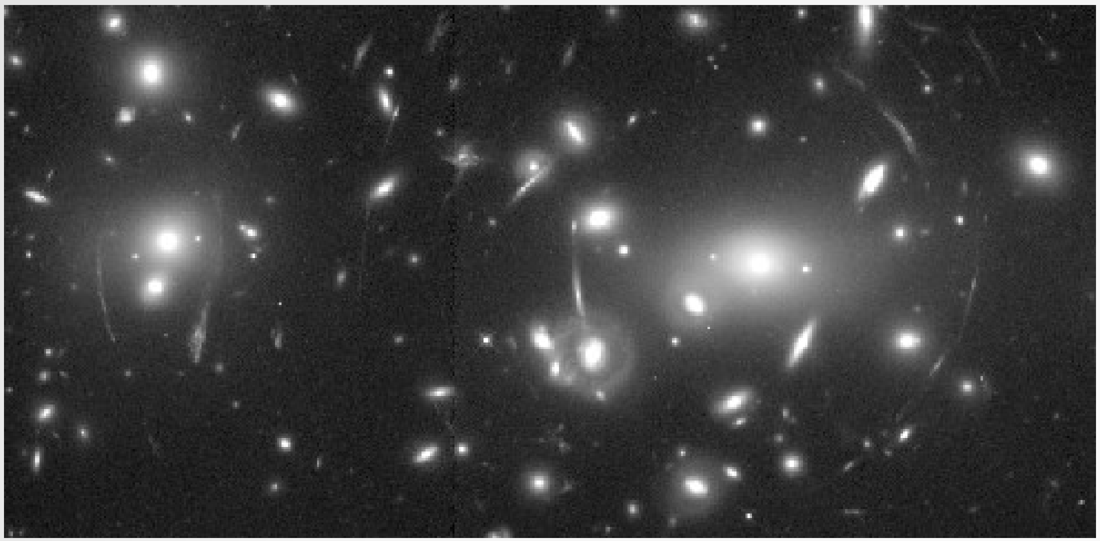
VOIDS
between



Arguments for DM

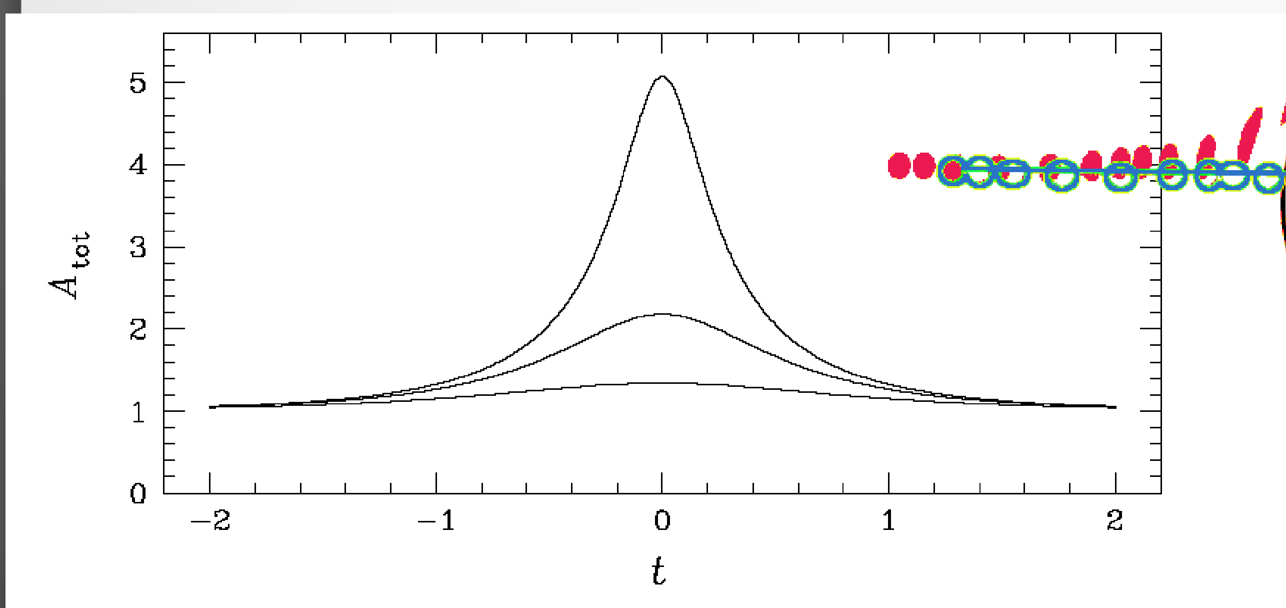
- Strong gravitational lensing: Einstein rings, circular arcs and multiple images of background objects in the field of the invisible mass.
- Weak gravitational lensing: small distortion of the background objects in the field of the invisible mass.
- Microlensing: transient luminosity increasing of the background object while the invisible mass of the Galaxy halo crossing line of sight.

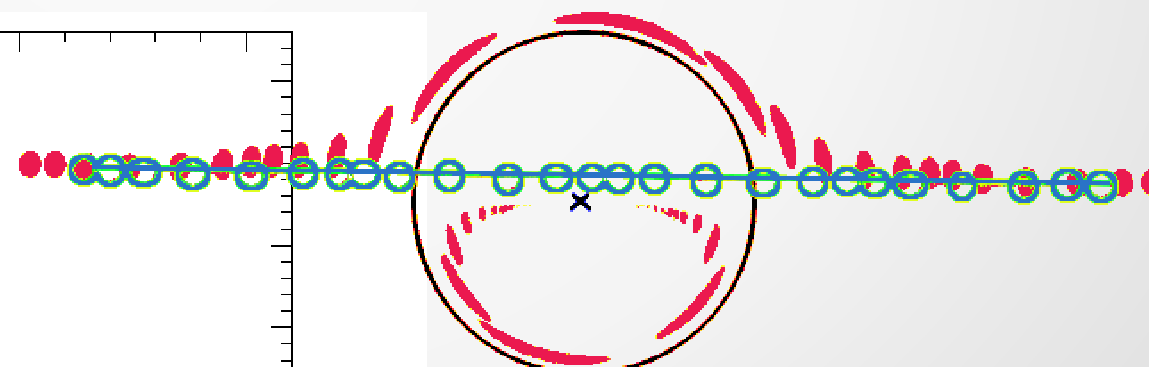
Lensing and microlensing events



Einstein rings,
circular arcs.

Moveing of *the stellar image* in
the black hole field.





Proposals about the distribution of DM in galaxies

Burkert

$$\rho_B(R)=\frac{\rho_0 r_h^3}{(R+r_h)(R^2+r_h^2)}$$

Moore

$$\rho_M(R)=\frac{\rho_0 r_h^3}{R^{1.5}(R^{1.5}+r_h^{1.5})}$$

Navarro
Frenk
White

$$\rho(R)=\frac{\rho_0 r_h^3}{R(R+r_h)^2}$$

Profiles with variably exponented radius: R^α

singular $\alpha<0$

core-profiles $\alpha=0$

MOND – modified Newton dynamics

Modifired Gravity

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

- The most dark matter dominated systems!

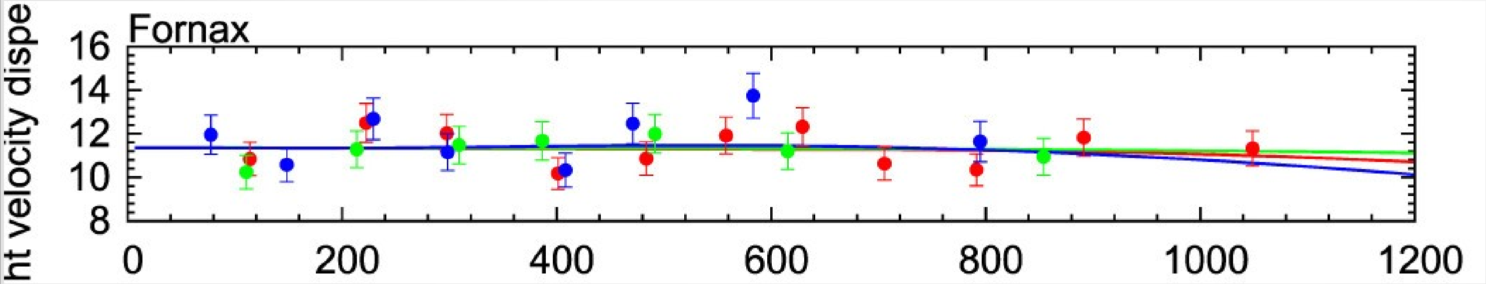
  Mass-to-light ratios about 10 to 1000.

- Individual member stars can be resolved, their line-of-sight velocities can be measured. So, we have high-quality data for these galaxies.

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

Fornax dwarf galaxy

K.Hayashi at al 2016



Velocity dispersion profile

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) :

  10^6 particles, masses, coordinates, velocities

- falcON Dehnen code:

  The code starts up evolution of the model obtained by mkkd95 and than we can see estimate stability of the mkkd95 model.

Two component model

- Stellar component (nemo bulge)

  Analytic axially-symmetric DF, following equipotentials, close to the King profile (1966).

  $\rho(R, \Psi)$

- 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.

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

Hydrodynamic K.Hayashi model

- Solving Jeans Equations for setllar component taking into account the anisortopy 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:

$$\rho_{Plum}(R,z) = \frac{3M_p}{4\pi b_p^3}\left[1 + \frac{m_p^2}{b_p^2}\right]^{-5/2}, m_p^2 = R^2 + \frac{z^2}{q^2}, q_{Fornax} \sim 0.7$$

- DM profile:

$$\rho_{DM}(R,z) = \rho_0 \left(\frac{m}{b_{halo}}\right)^{\alpha} \left[1 + \frac{m^2}{b_{halo}^2}\right]^{-(\alpha+3)/2}, m^2 = R^2 + \frac{z^2}{Q^2}, Q_{Fornax} = 1.1$$

Using K.Hayashi resulting profiles for guessing nemo parameters

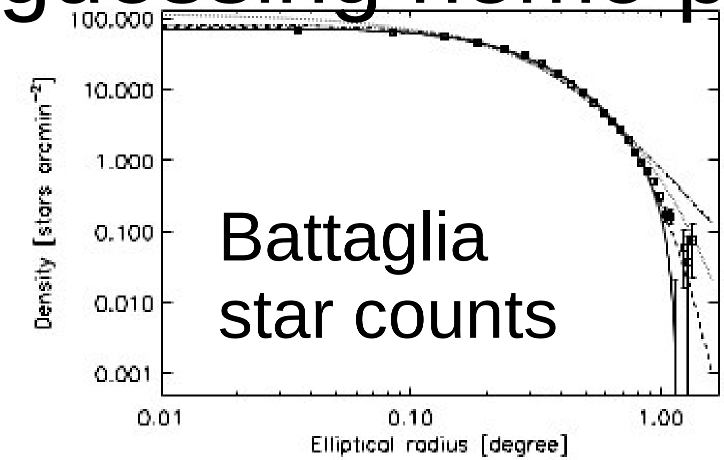


Fig. 3.
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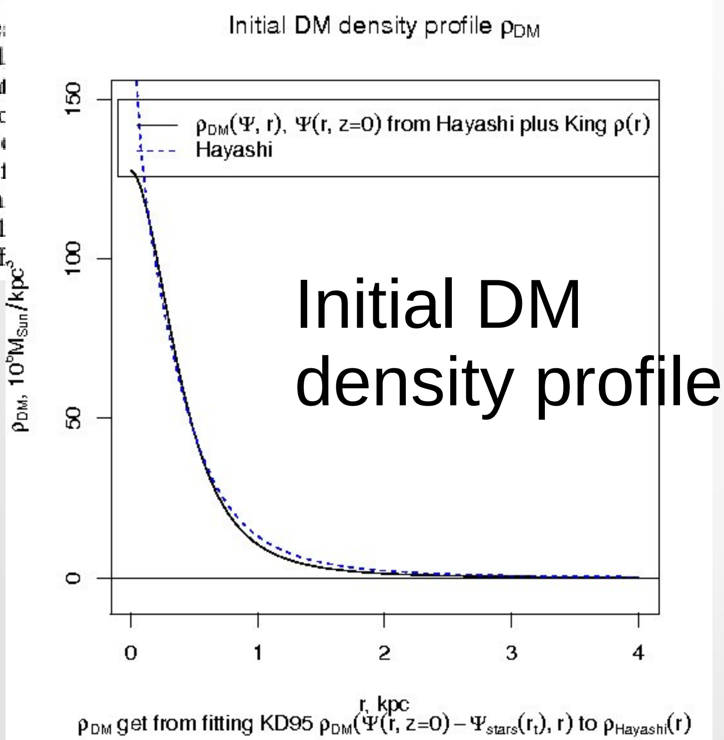
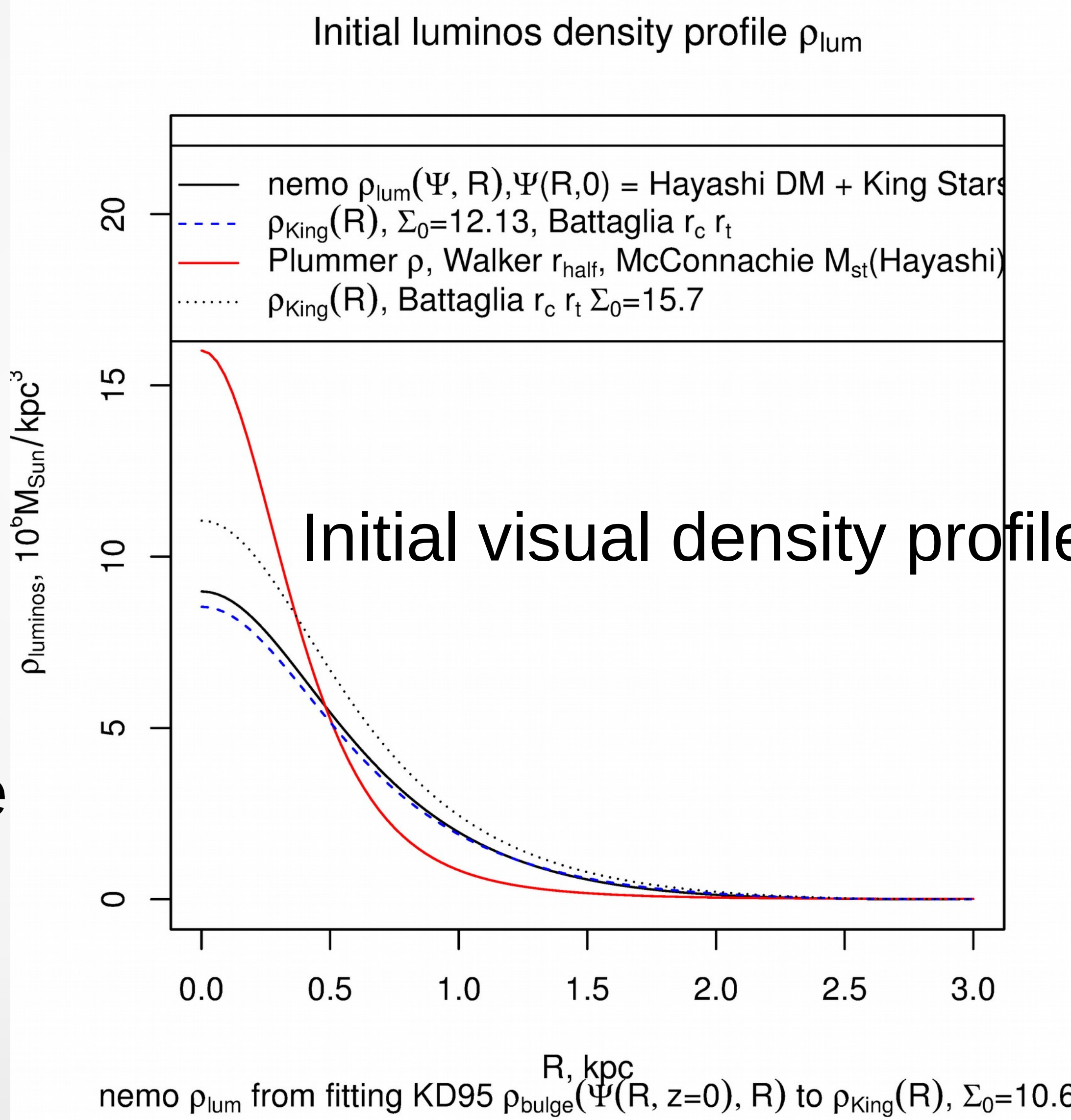




Received models

- Model 1: $\alpha = 0$

  Initial visual profile – central surface density lower, than Battaglia,but the same radiuses.

  Virial theorem violation: -2T/W = 2.6%

  M_dyn/M_stars = 34.5

- Model 2: alpha=-0.22

  Initial visual profile – same as model 1

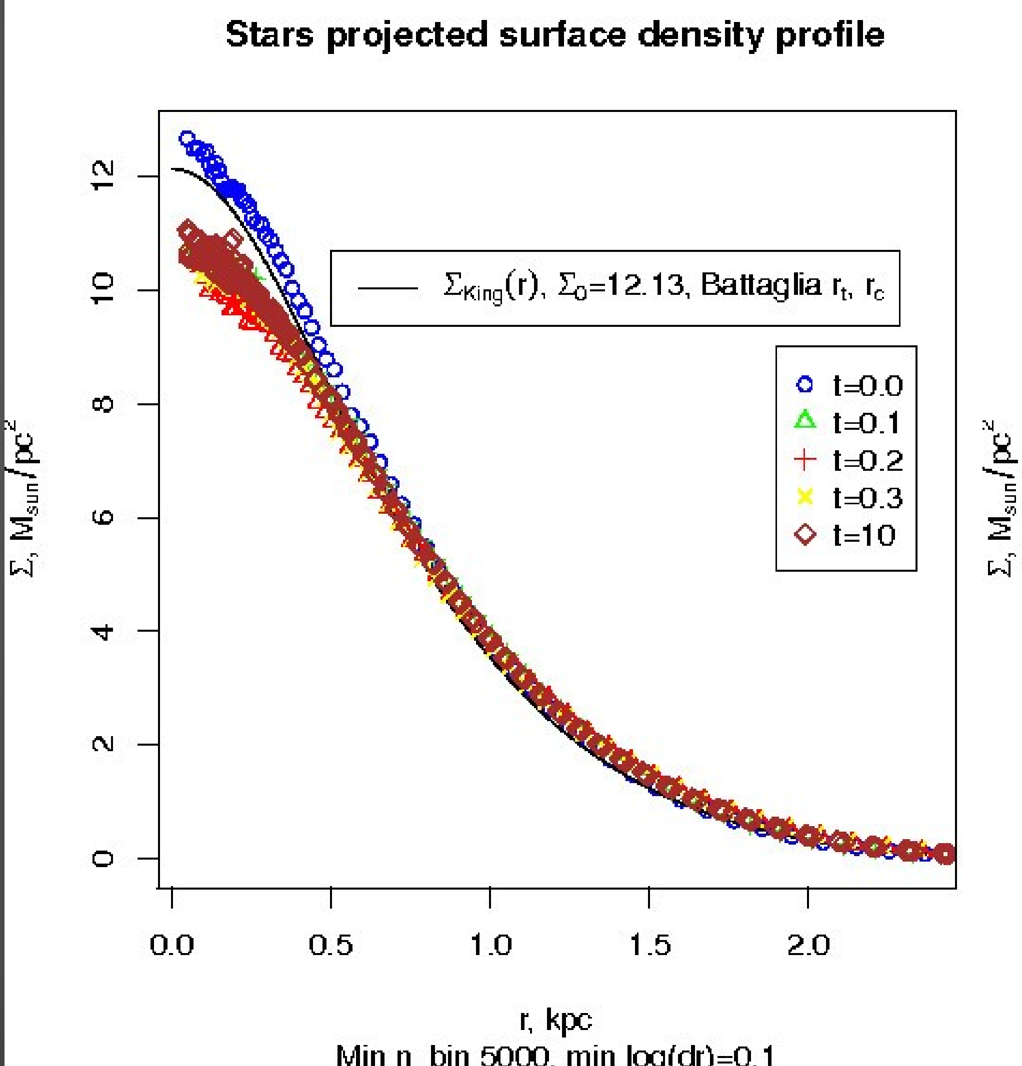
  Virial theorem violation: -2T/W = 18%

  M_dyn/M_stars = 43.0

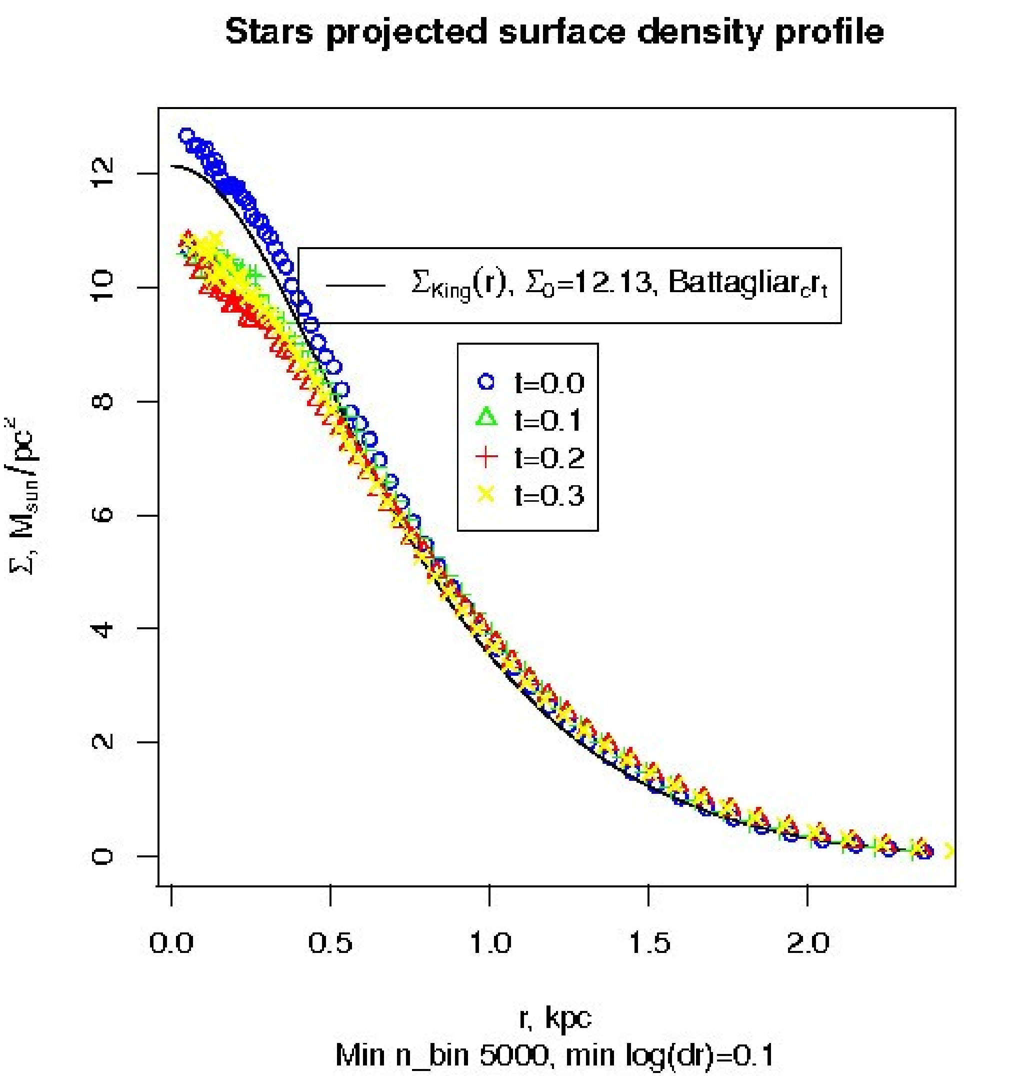
  Both models are rather stable during the evolution.

Model stars surface density

Model 1

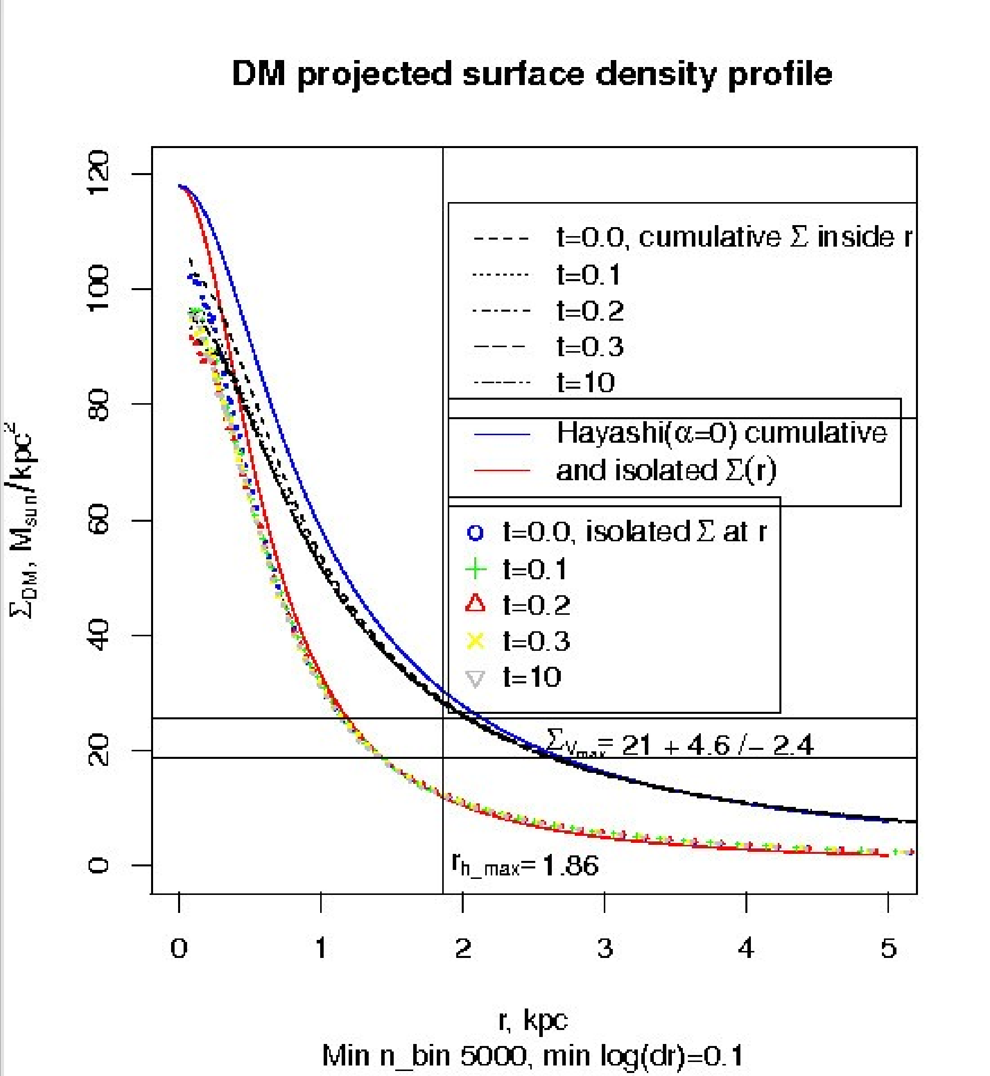


Model 2

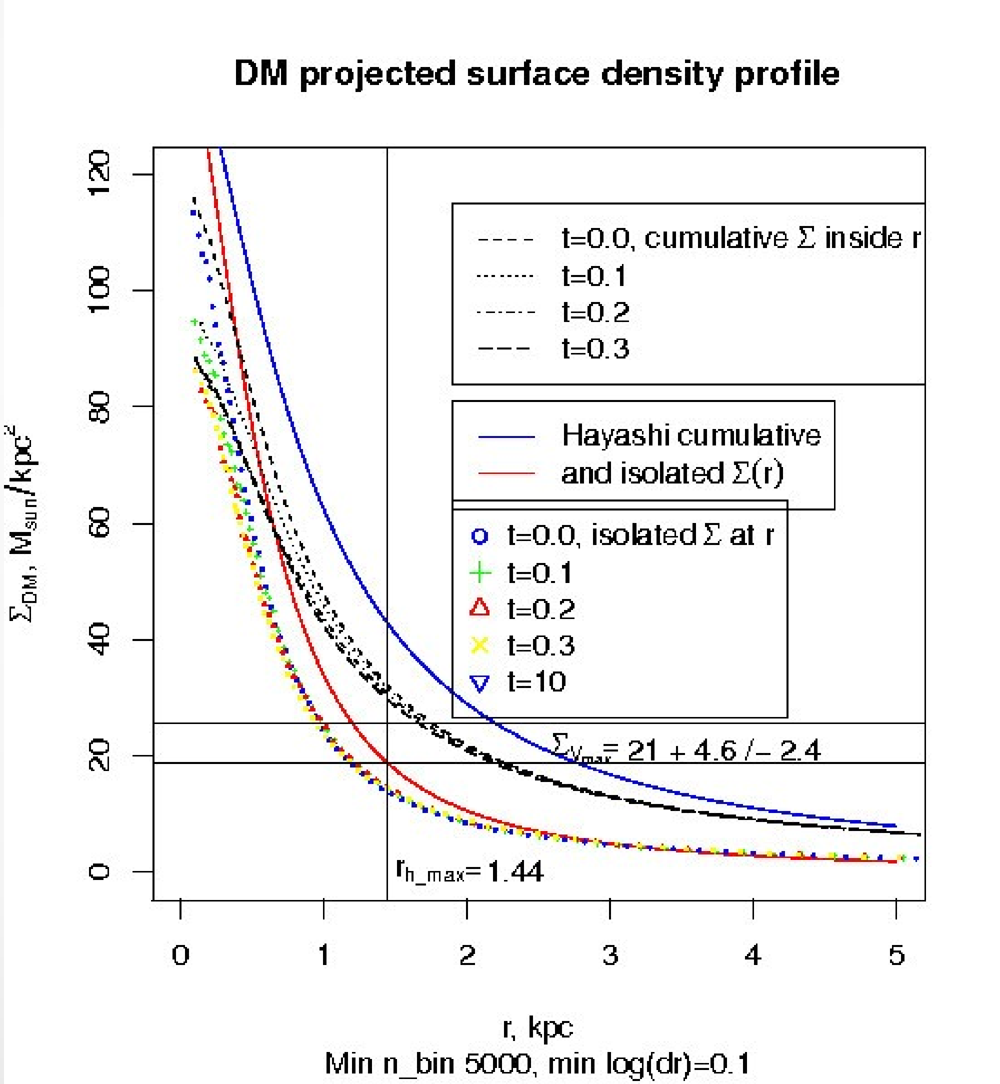


Model DM surface density

Model 1



Model 2



Comparison to Hayashi

2. Dark Halo Surface Density within a Radius of Maximum Circular Velocity

In this work, we adopt the mean surface density of a dark halo defined by HC15a to compare this density estimate from observational data with those from pure N-body simulations. Given any of the parameters of a dark halo (e.g., scale length, scale density, and any slopes of dark matter density profiles), this surface density within a radius of the maximum circular velocity, $V_{\rm max}$, is given as

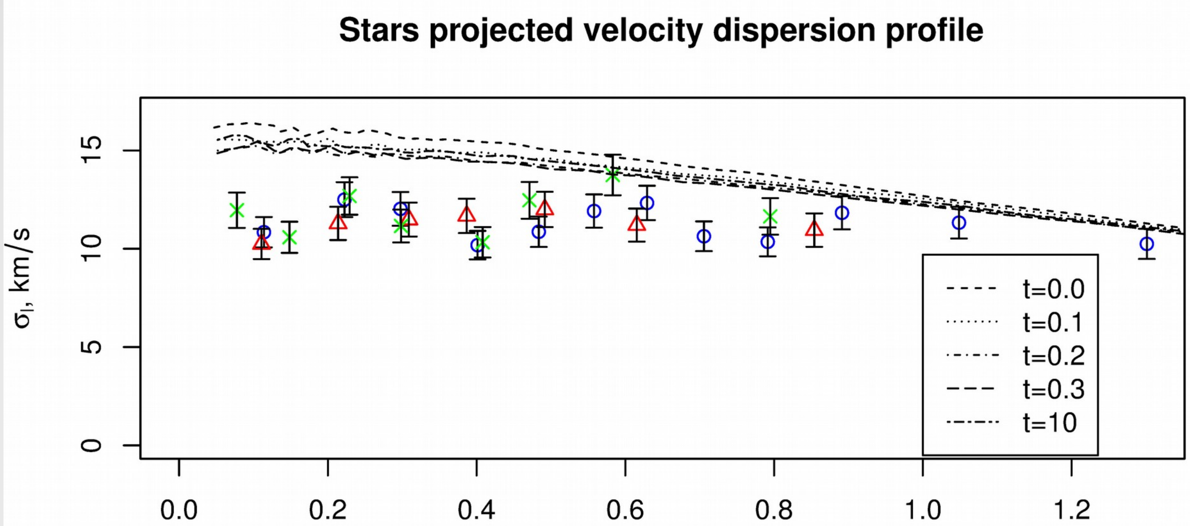
$$\Sigma_{\rm V_{max}} = \frac{M(r_{\rm max})}{\pi r_{\rm max}^2}, \quad (1)$$

where $r_{\rm max}$ denotes a radius of maximum circular velocity of a dark halo, and its enclosed mass within $r_{\rm max}$ is given as

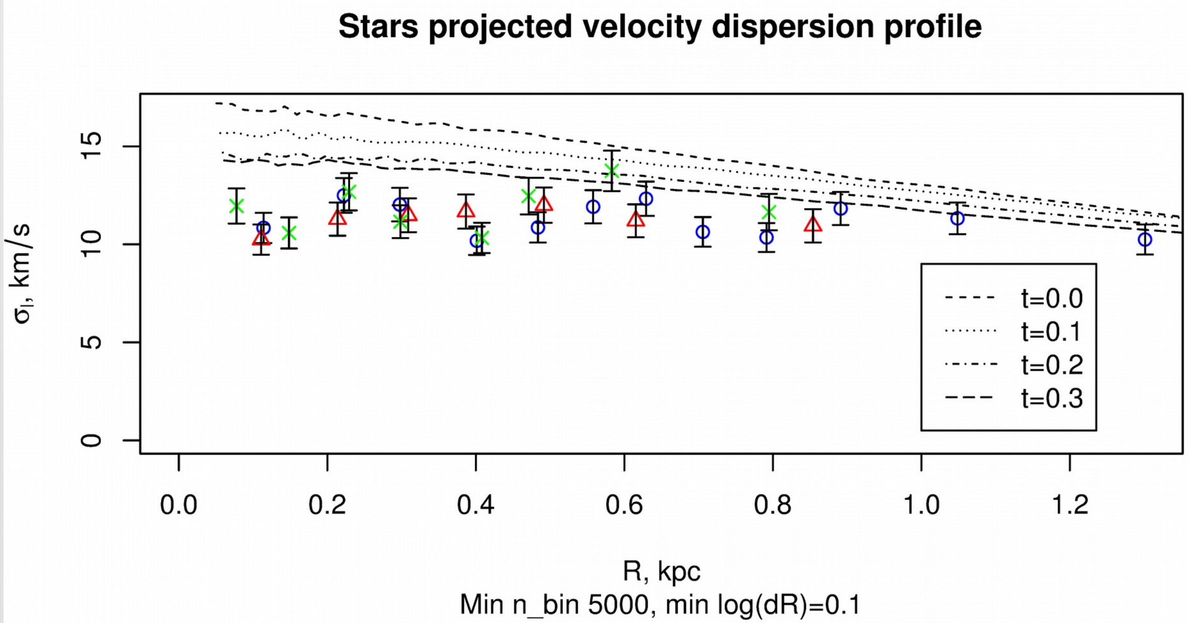
$$M(r_{\rm max}) = \int_0^{r_{\rm max}} 4\pi \rho_{\rm dm}(r') r'^2 dr' \quad (2)$$

where $\rho_{\rm dm}$ denotes a dark matter density profile. Under the axisymmetric assumptions, the variables of the spherical radius, r', are changed to those of the elliptical radius, m', and then

Comparison to observed velocity dispersions



Model 1



Model 2

Reasons of discrepancies

Jeans equations with anisotropy parameter:

$$\overline{v_z^2} = \frac{1}{\nu\,(R,\, z)} \int_z^{\infty} \nu \frac{\partial \Phi}{\partial z} dz, \qquad (1)$$

$$\overline{v_\phi^2} = \frac{1}{1 - \beta_z} \left[\overline{v_z^2} + \frac{R}{\nu} \frac{\partial \left(\nu \overline{v_z^2} \right)}{\partial R} \right] + R \frac{\partial \Phi}{\partial R}, \qquad (2)$$

AGAMA: Action-based galaxy modelling architecture

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AGAMA: Action-based galaxy modelling architecture

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23 February 2018

ABSTRACT

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; 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; 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.

1 INTRODUCTION

Galaxy models are vital for understanding their structure and evolution. The rapid increase in quantity and quality of observational data, both for Milky Way and external galaxies, calls for similar advances in modelling techniques. One of the most powerful approaches describes the stars and other mass components by distribution functions (DF) in the space of integrals of motion. For several reasons discussed later in the paper, actions are the most appropriate choice for these integrals of motion. A DF provides a complete description of the system, and various other properties (density, velocity distributions, etc.) can be computed from a DF in a given potential. A flexible representation of the gravitational potential is also a necessity. A dynamically self-consistent model of a stellar system implies certain relations between the potential and the DF; depending on the scientific context, this may or may not be required.

This paper presents a software framework for galaxy

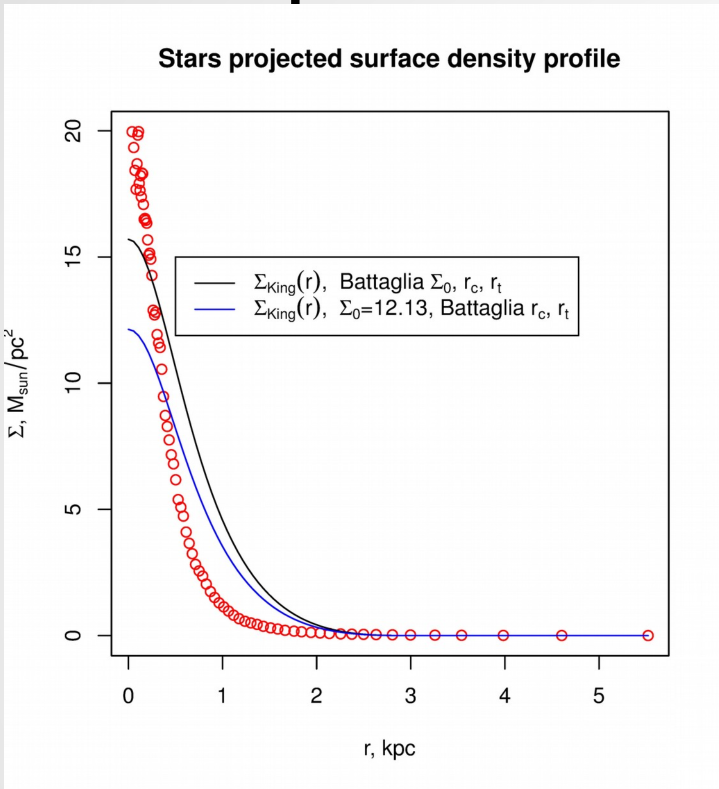
tion/angle variables, in particular, a new implementation of the Stäckel fudge (Section 3).

- Several types of DFs expressed in terms of actions (including a new class of disc DF), and associated routines for computing DF moments and creating an N-body representation of a DF in a given potential (Section 4).
- The framework for iterative construction of self-consistent galaxy models (Section 5).

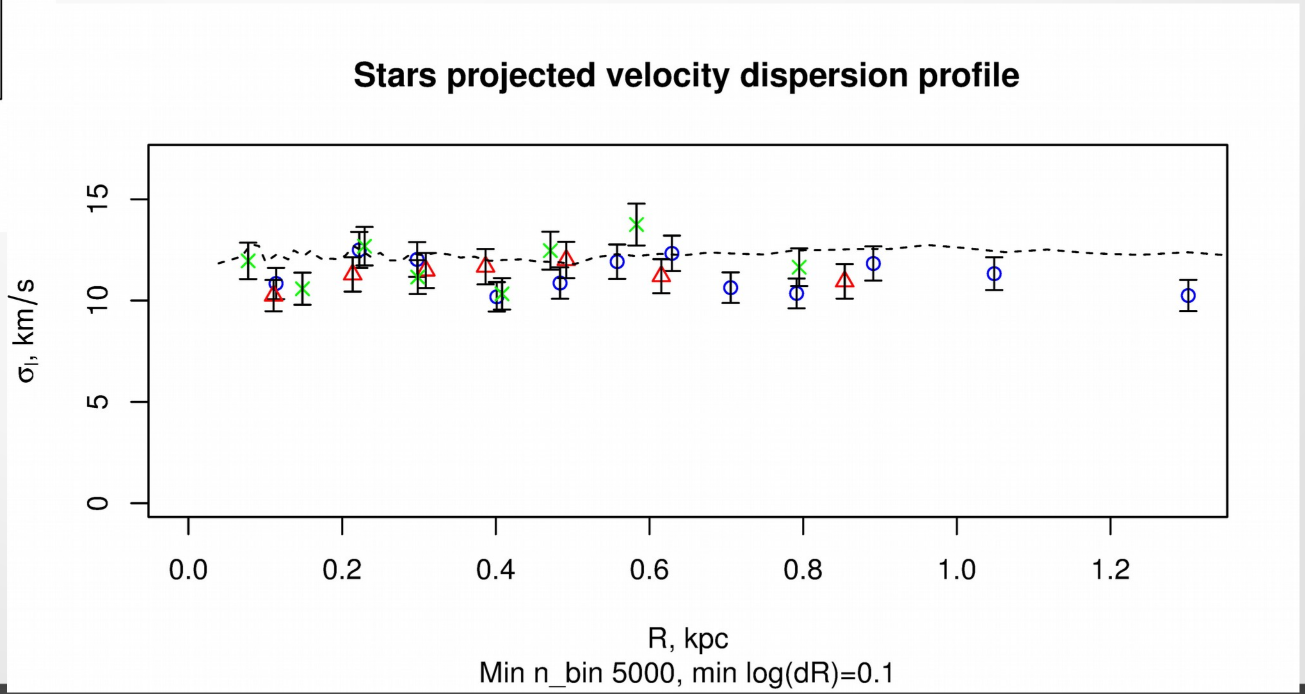
We illustrate some of the possible applications and compare Agama to other similar software projects in Section 6.

The Agama library is written primarily in C++ to achieve maximum efficiency, and has a Python interface offering greater flexibility for practical work. It is distributed with many example programs both in C++ and Python, illustrating various aspects of its use (we present a few short Python listings in the paper). It also includes several other stellar-dynamical software projects: an updated version of the Monte Carlo simulation code Raga (Vasiliev 2015),

AGAMA modeling with Plumer initial profile



Deviation from the best-fit observed surface density profile
but excellent ageement
with the velocity dispersion profile.



Thank you for attention!