GALAXIES
Lecture 7-8

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Plan

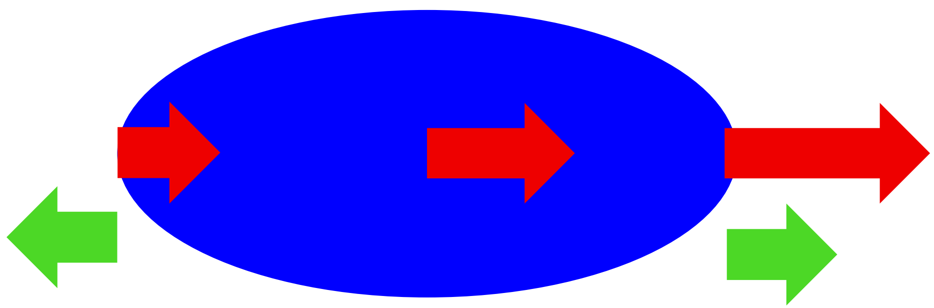
1. Structure of galaxies: haloes and disks, circular velocities, NFW profile, exponential disk, Sersic profile
2. The Milky Way and galaxies of the Local Group
3. Orbits of stars in different potentials
4. Distribution functions, Jeans modeling, orbit-superposition models
5. Bars in galaxies: formation, evolution, orbital structure, dependence on environment
6. Spiral structure: geometry of spiral arms, formation scenarios
7. Interactions: tidal evolution and mergers, properties of merger remnants
8. Galaxy formation in cosmological context, cold and hot dark matter scenarios, top hat model, problems of theory on small scales

Tidal effects in galaxies

- Tidal forces play an important role in the formation and evolution of galaxies
- They seem to be the main process behind the transformation of spirals into ellipticals
- The can explain the origin of the morphology-density relation
- Tidal forces contribute to the formation of bars and spiral arms
- Tidal arms and streams are important probes of galactic potential

Tidal force

- The tidal force is the secondary effect of the force of gravity
- The force arises due to the difference in the gravitational forces acting on different parts of an extended body



- The force acting on the body will be

$$F \sim 1/(r \pm \Delta r)^2 \sim 1/r^2 \pm 2\Delta r/r^3 + \ldots$$

Static tidal field

- A satellite travels on a circular orbit in the gravitational field of a much larger spherical host system
- In the frame rotating with the satellite the external tidal field is stationary
- This simple configuration provides a first approximation to the description of various systems: a moon orbiting a planet, a planet orbiting a star, binary stars, globular clusters and dwarf galaxies near the Milky Way

Restricted three-body problem

- The host and satellite systems are point masses M and m, traveling at separation R_0 on a circular orbit around their mutual center of mass
- The restricted three-body problem is to find the trajectory of a massless test particle that orbits in the combined gravitational field of these two masses
- Solutions of this problem provide an approximation to the motion of stars in the outer parts of a satellite stellar system

The Jacobi integral

- The two masses orbit their common center of mass with angular speed

$$\Omega = \sqrt{\frac{G(M+m)}{R_0^3}}.$$

- The gravitational field is stationary in a coordinate system centered on the center of mass that rotates at this speed, with

$$\mathbf{x}_m = [MR_0/(M+m), 0, 0]$$

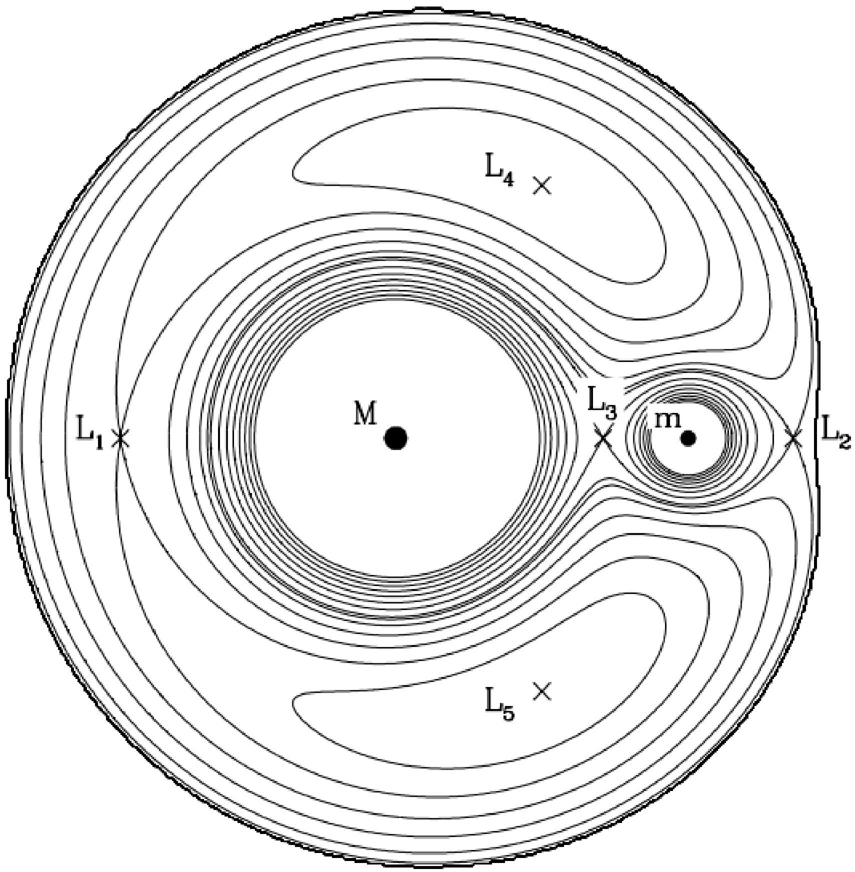
and

$$\mathbf{x}_M = [-mR_0/(M+m), 0, 0]$$

- On any orbit in such a system the Jacobi integral is conserved

$$E_J = \tfrac{1}{2}v^2 + \Phi(\mathbf{x}) - \tfrac{1}{2}|\boldsymbol{\Omega} \times \mathbf{x}|^2$$
$$= \tfrac{1}{2}v^2 + \Phi_{\rm eff}(\mathbf{x})$$

The effective potential



contours of constant
effective potential

- The extrema of effective potential are the Lagrange points:

  L_1, L_2 L_3 (saddle points)

  L_4, L_5 (maxima)

- Surfaces with $\Phi_{\text{eff}}(\mathbf{x}) = E_{\text{J}}$ are called zero-velocity surfaces
- The last closed zero-velocity surface around one body is called its tidal or Roche surface

The tidal radius

- We identify the outermost radius of orbits bound to mass m as the distance r_J between m and L_3
- At L_3 the effective potential has a saddle point so

$$\left(\frac{\partial \Phi_{\text{eff}}}{\partial x}\right)_{(x_m - r_J, 0, 0)} = 0$$

- For point masses the effective potential is

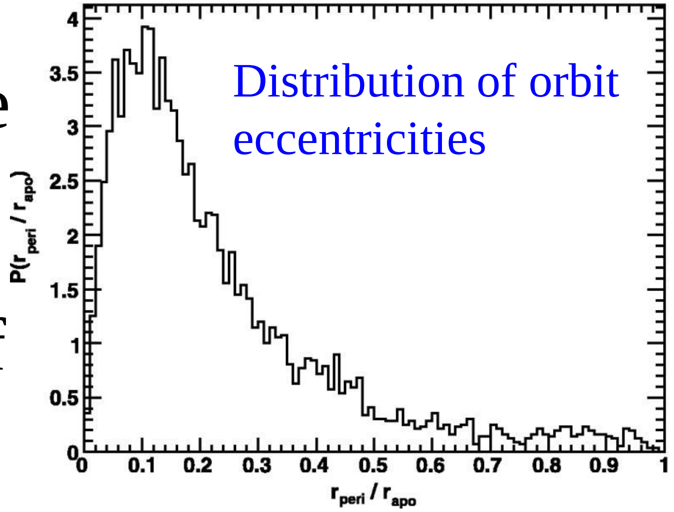
$$\Phi_{\text{eff}}(\mathbf{x}) = -G\left[\frac{M}{|\mathbf{x}-\mathbf{x}_M|} + \frac{m}{|\mathbf{x}-\mathbf{x}_m|} + \frac{M+m}{2R_0^3}(x^2+y^2)\right]$$

- In the limit of small m<<M we get the Jacobi radius

$$r_J = \left(\frac{m}{3M}\right)^{1/3} R_0$$

Difficulties

- In most applications, the satellite system is not on a circular orbit, there is no reference frame in which the potential experienced by a test particle is stationary and no analog of the Jacobi integral exists
- In many cases, the satellite orbits within the body of the host system, so the point-mass approximation is not accurate



King's tidal radius

- King (1962) argued that the tidal radius can be approximated as a radius where the acceleration on the third body vanishes, which leads to the expression

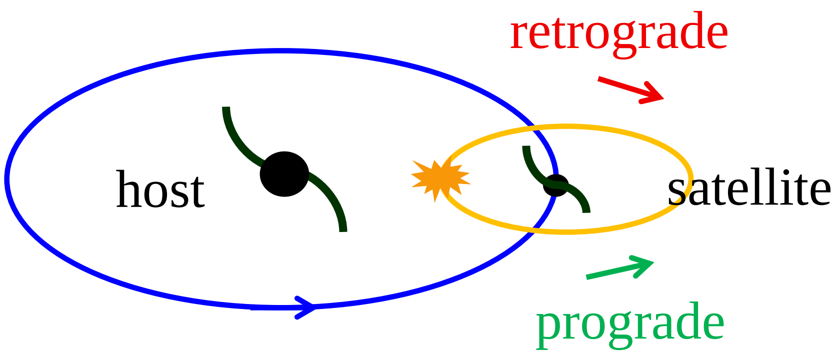
$$R_{\rm t} = r_{\rm peri} \left[\frac{M_{\rm s}}{M_{\rm g}(3+e)} \right]^{1/3}$$

with

$$e = (r_{\rm apo} - r_{\rm peri})/(r_{\rm apo} + r_{\rm peri})$$

- The idea was that once the satellite is trimmed to the tidal radius at the pericenter, it will retain this shape of the density profile also in the other parts of the orbit
- This motivated the use of King profiles in globular clusters and dwarf galaxies

Dependence on orbit



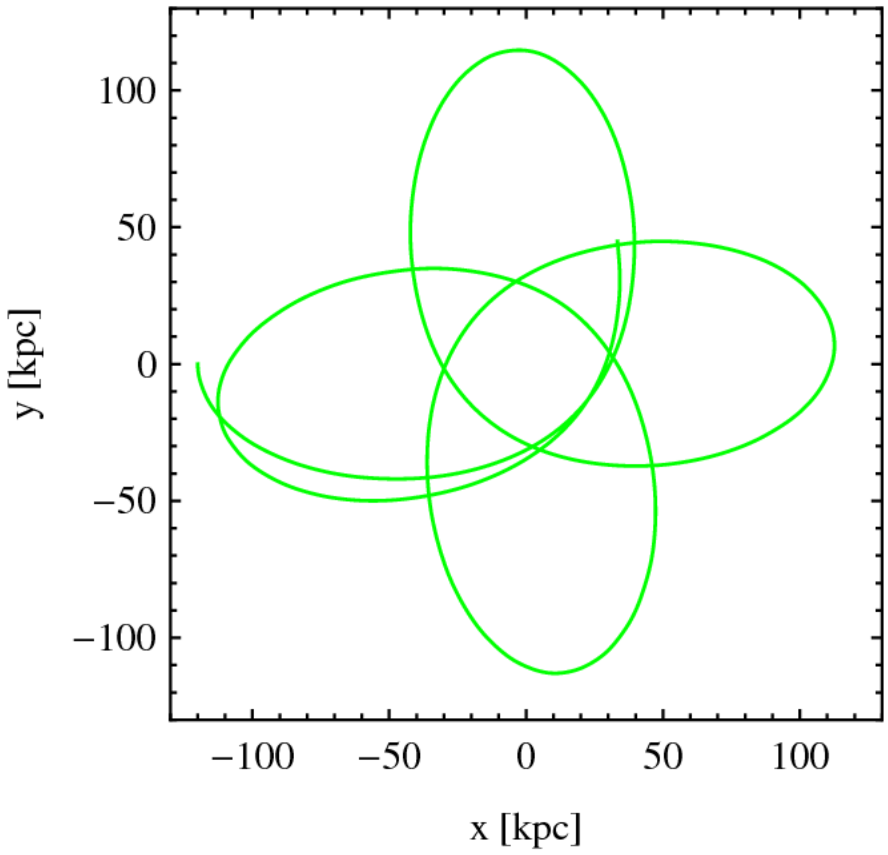
Read et al. 2006
Gajda & Łokas 2016

- It turns out that the size of the tidal radius depends not only on the shape of the orbit but also on the direction of motion of the satellite
- The tidal radius is different for pro- and retrograde orbits
- The tidal radius is larger for retrograde orbits

Tidal stripping vs stirring

- Tidal stripping and tidal stirring are two different processes originating from tidal interaction
- Both describe what happens to the satellite galaxy, not the host
- Tidal stripping refers to the mass loss, both in the stellar and dark matter component
- Tidal stirring concerns the evolution of the inner structure and kinematics of the galaxy
- Both processes occur simultaneously while the small galaxy orbits around its host

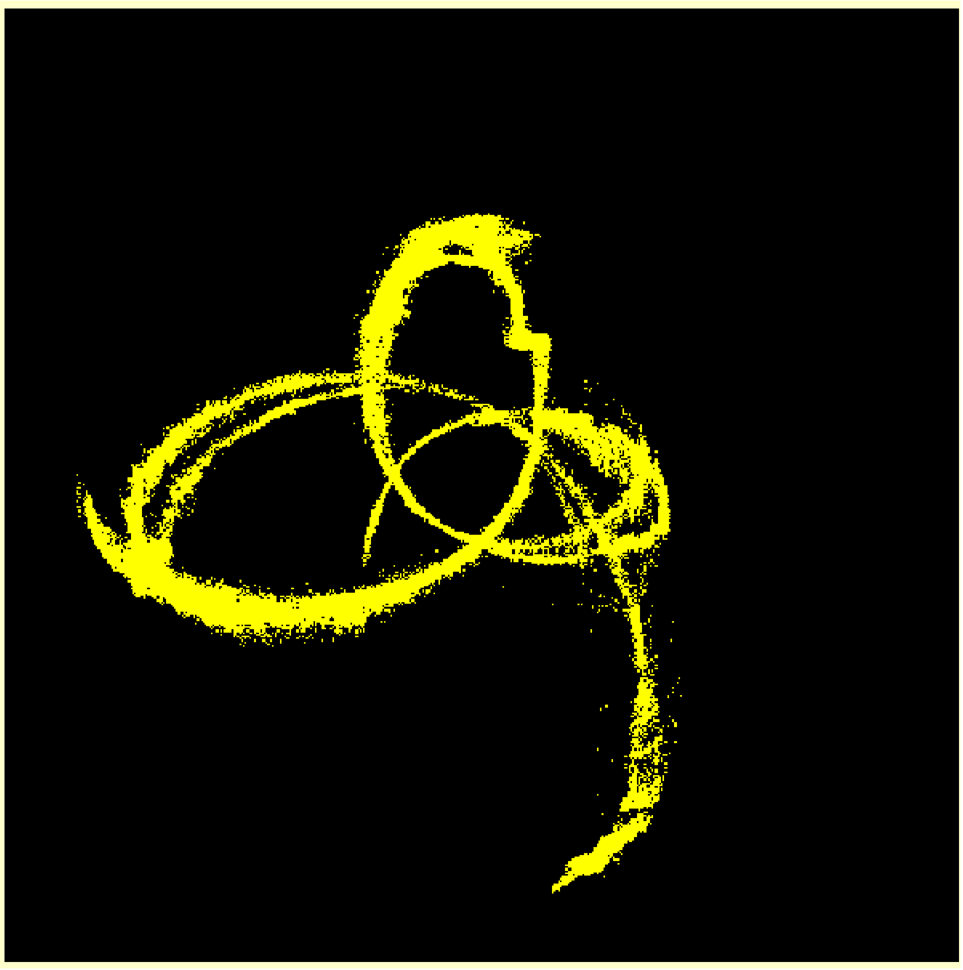
Tidal evolution: example



- A dwarf galaxy of mass $10^9\ M_\odot$ is placed on a typical orbit around the Milky Way-sized host
- The dwarf is composed of a stellar disk of mass 2 x $10^7\ M_\odot$ embedded in a standard NFW dark matter halo
- Its evolution is followed for 10 Gyr

Łokas et al. 2014a

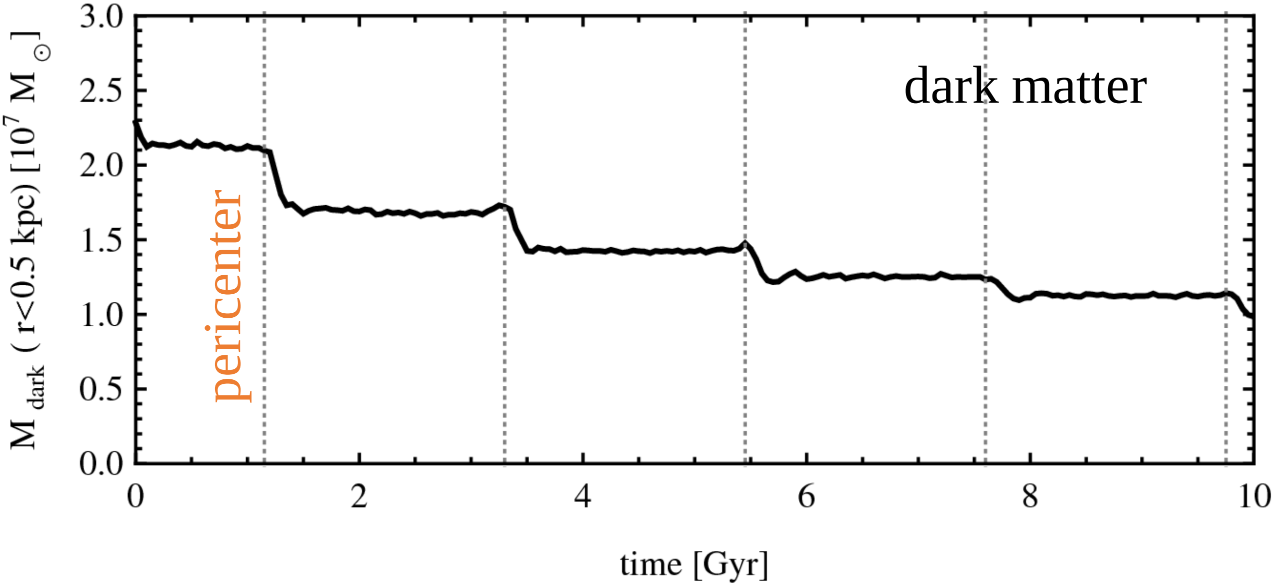
Tidal stirring

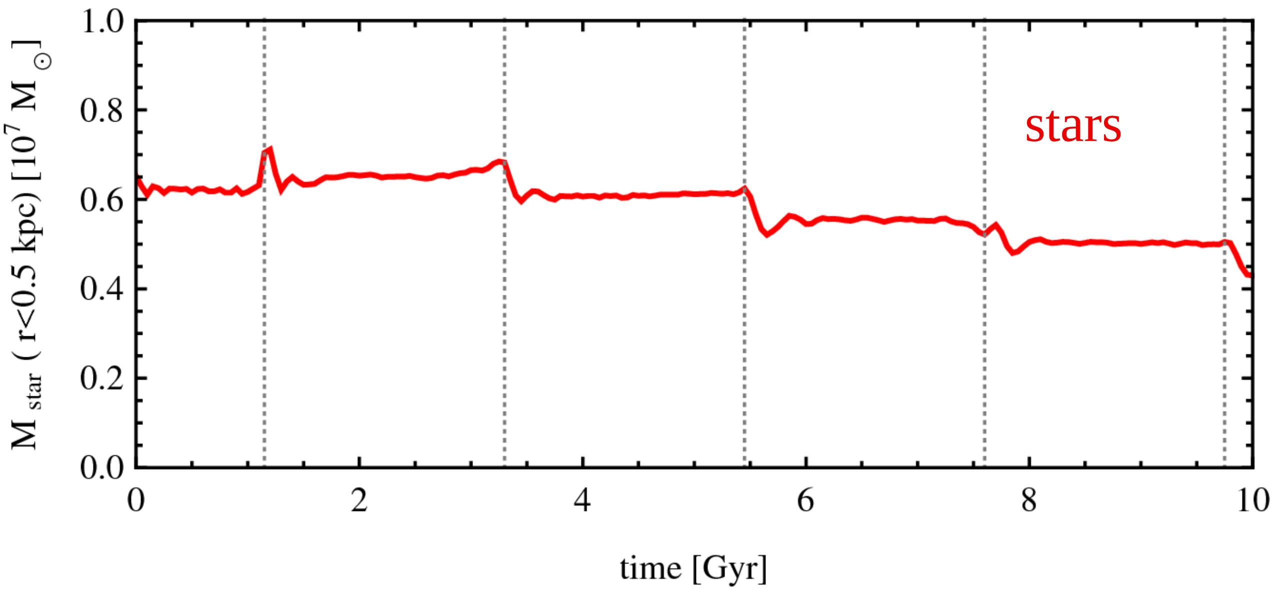


Effects of tidal stirring:

- Mass loss
- Morphological transformation
- Rotation changed to random motions

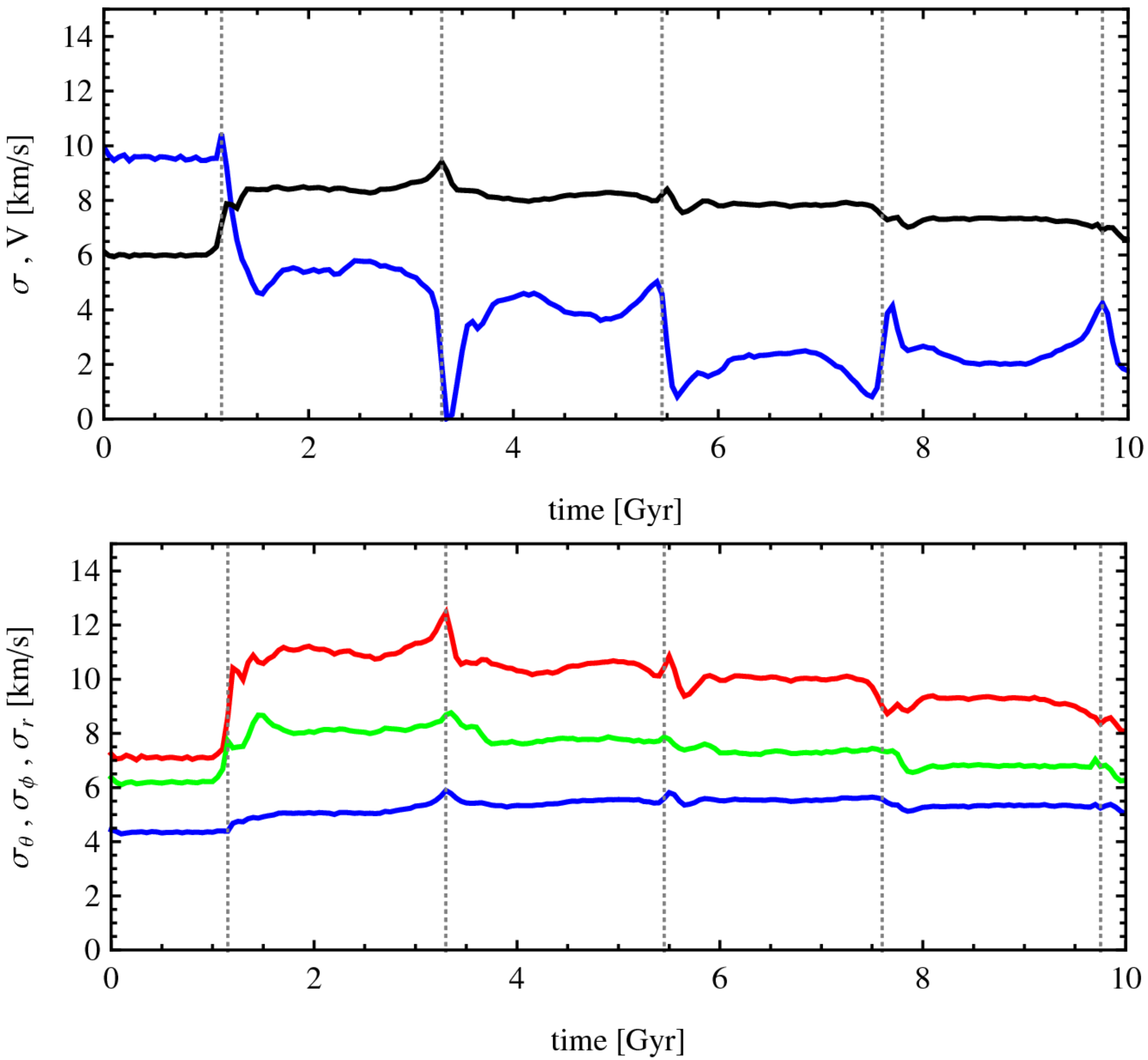
Mass loss





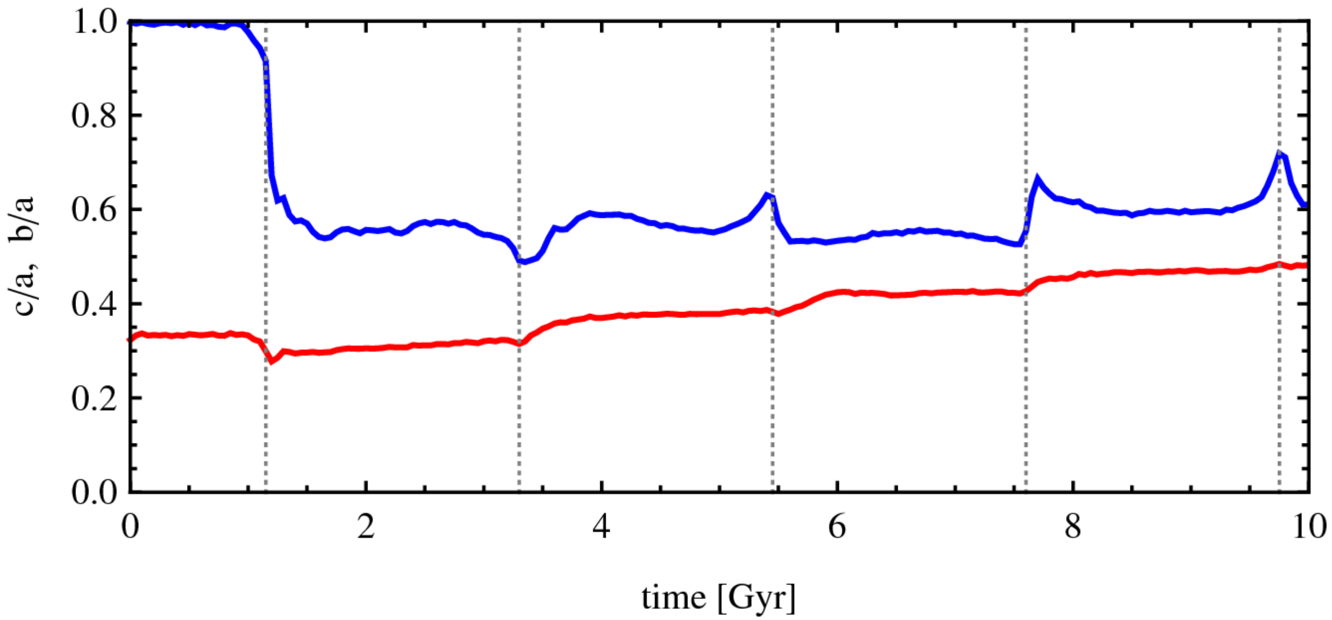
- Mass loss is similar in stars and dark matter, except at first pericenter
- Mass loss is strongest at pericenter passages

Kinematics

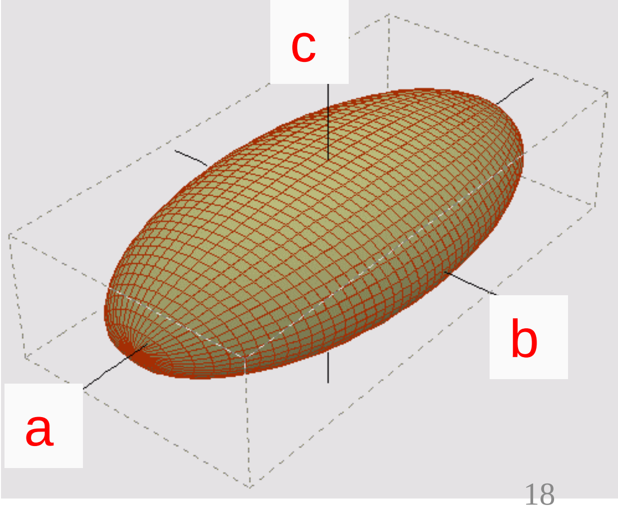


- Rotation is diminished
- Velocity dispersion increases
- Radial motions increase most

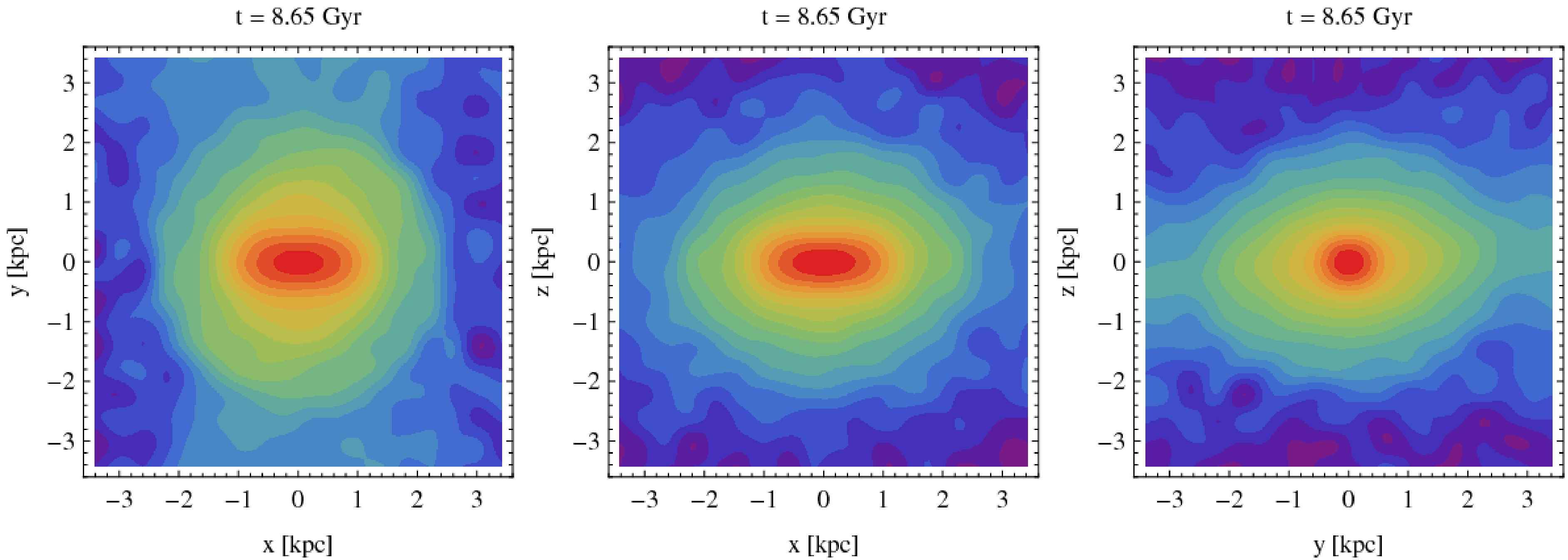
Evolution of shape



At first pericenter passage the initial disk transforms into a triaxial shape

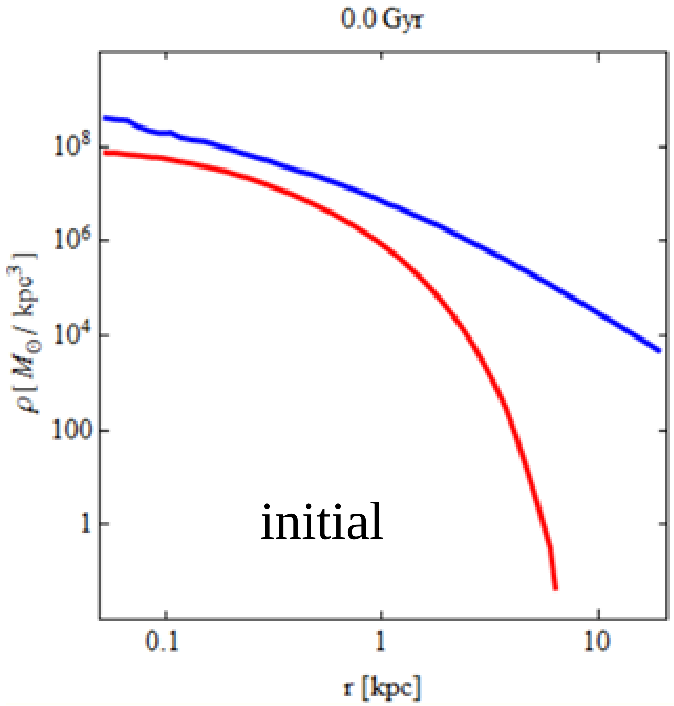


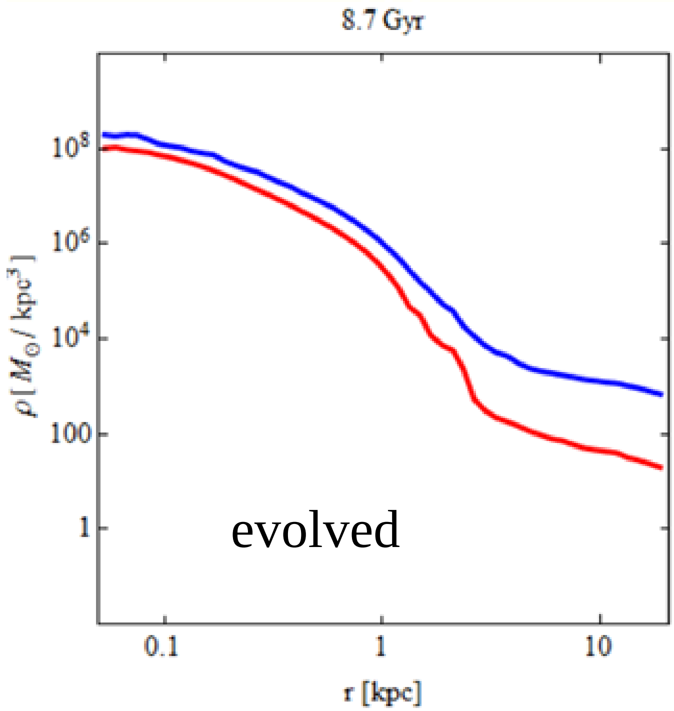
Surface density maps



Example of the evolved product of tidal stirring viewed along the three major axes of the stellar component

Density profiles



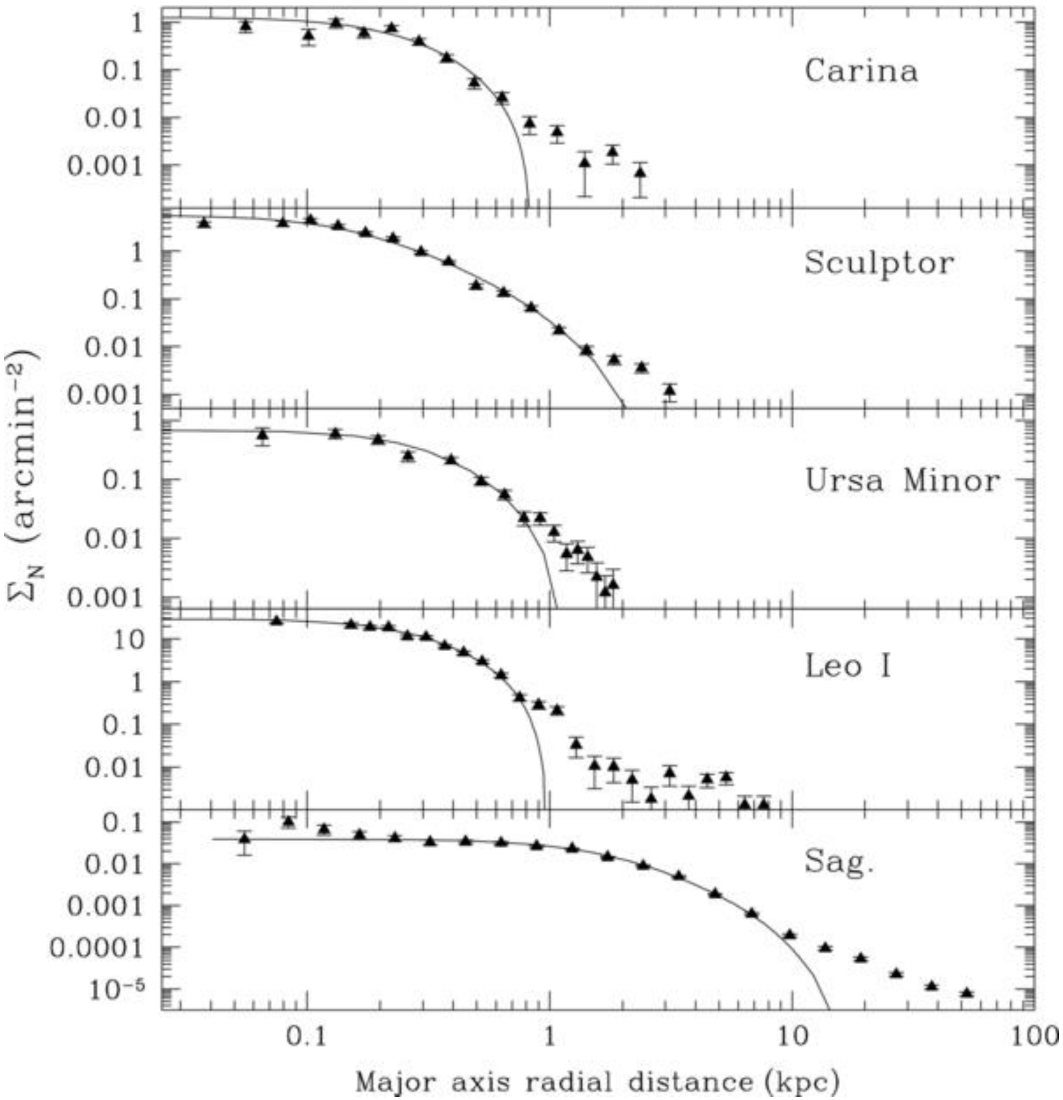


- The outer part of the dark halo is stripped very quickly
- At the end of the evolution dark matter follows stars

dark matter

stars

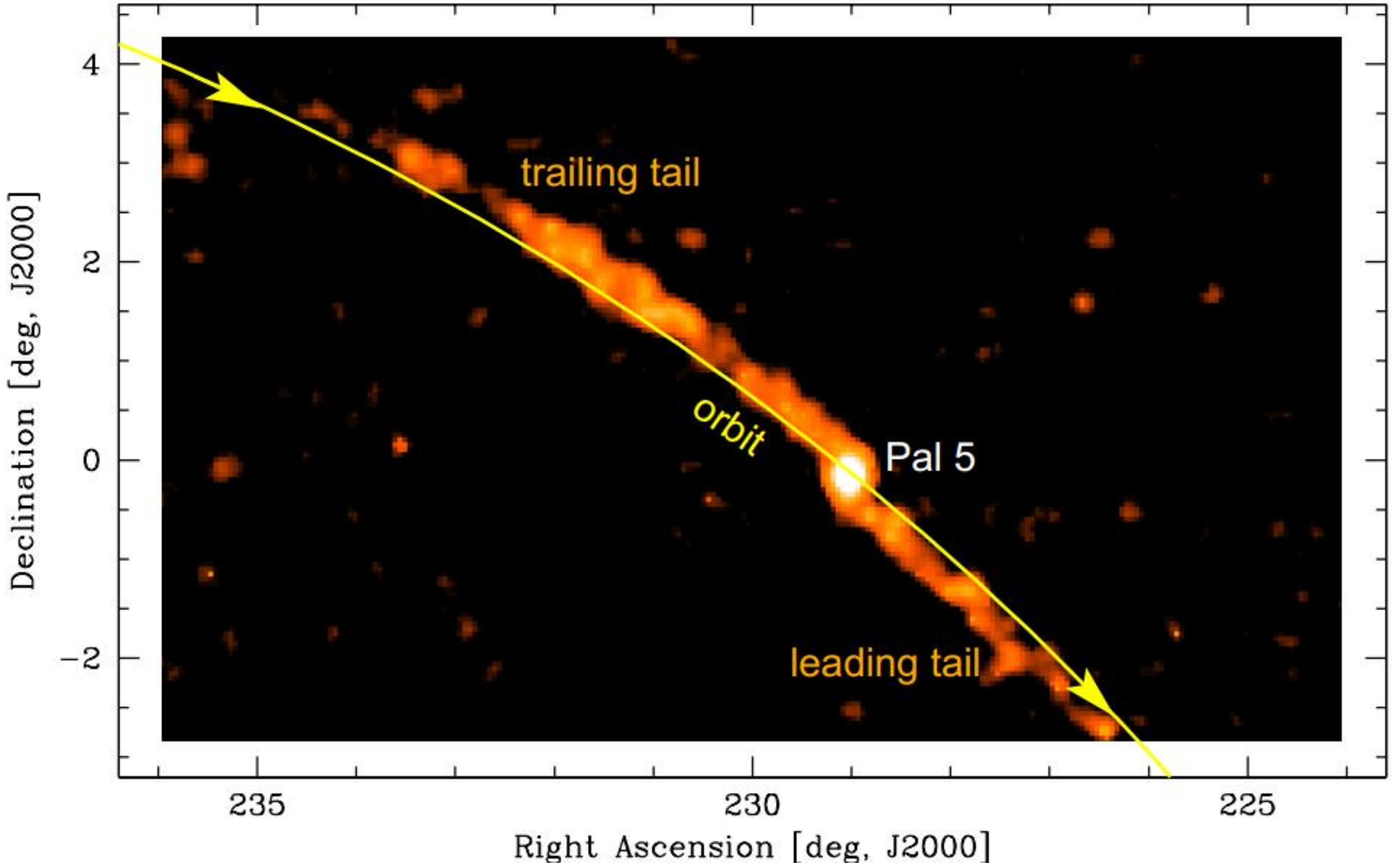
Tidal tails



- Evidence for tidal tails exists for many dwarfs
- Tidal tails can contaminate kinematic samples and lead to mass overestimates
- They can be used to probe the host potential

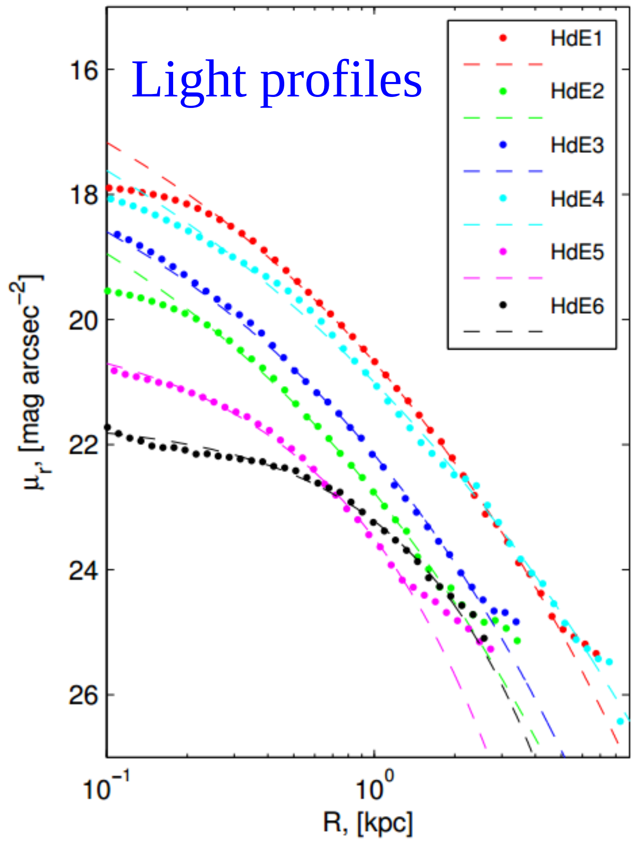
Frinchaboy et al. 2012

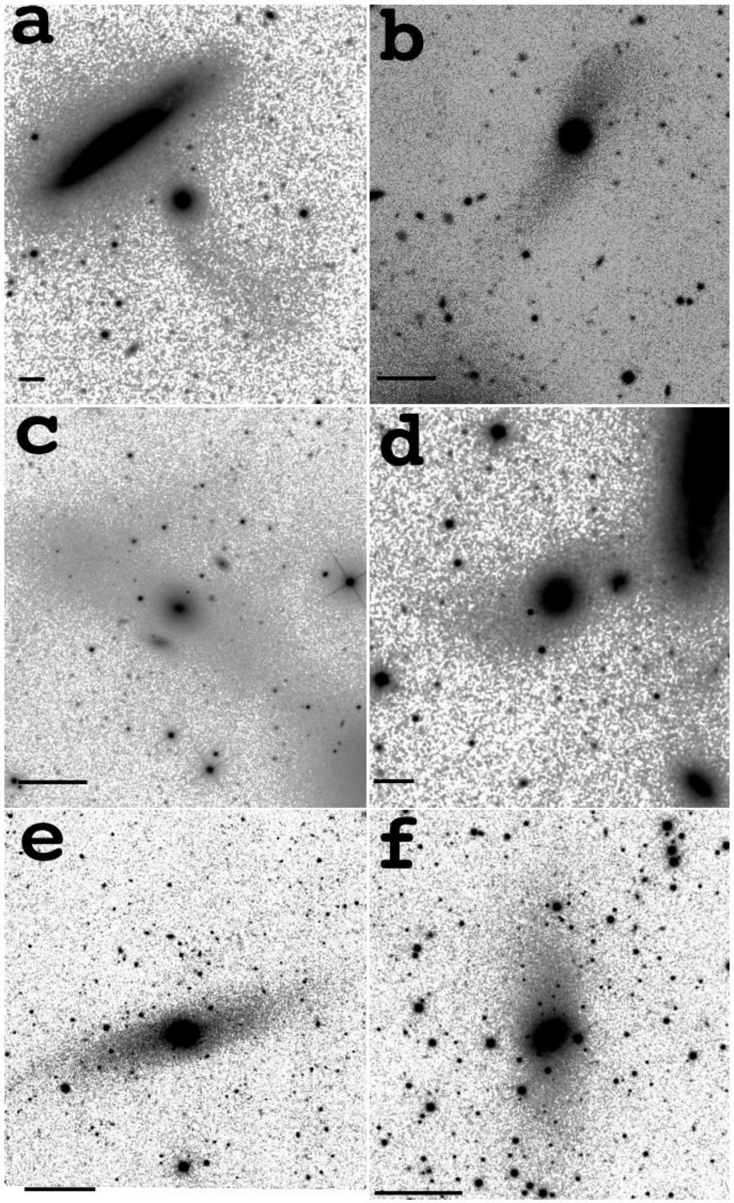
Examples of tidal tails



Globular cluster Palomar 5

Examples of tidal tails

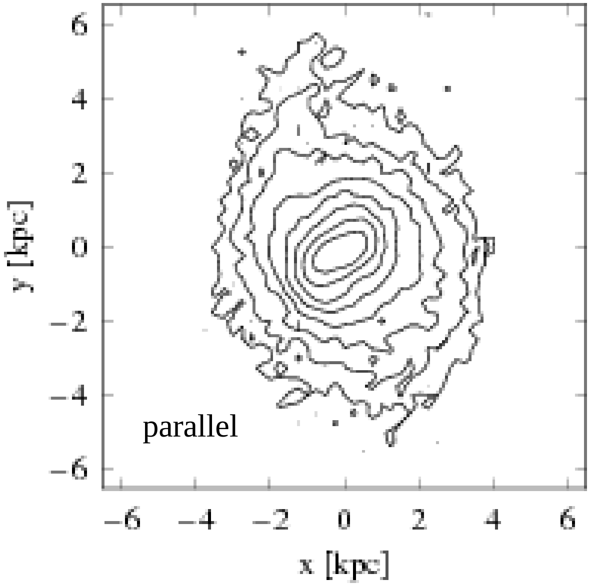


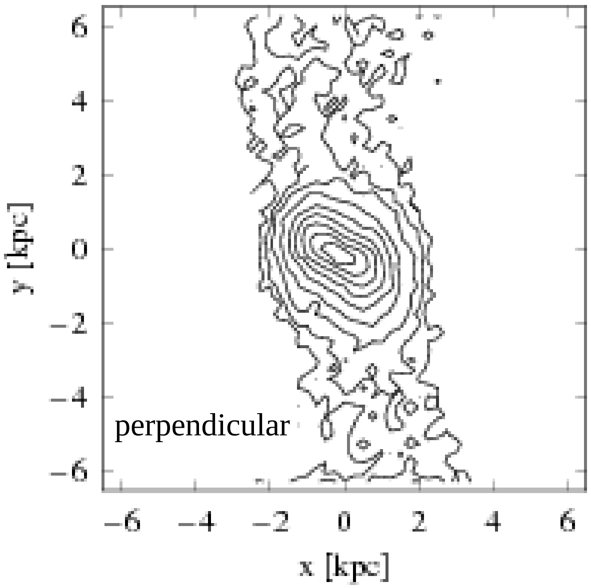


Tidal tails around dwarf elliptical galaxies in nearby groups identified in SDSS

Paudel & Ree 2014

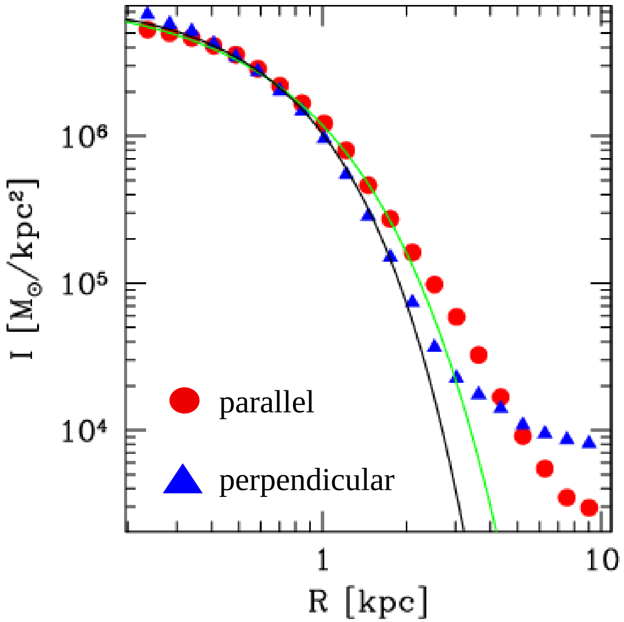
Observational effects of tails



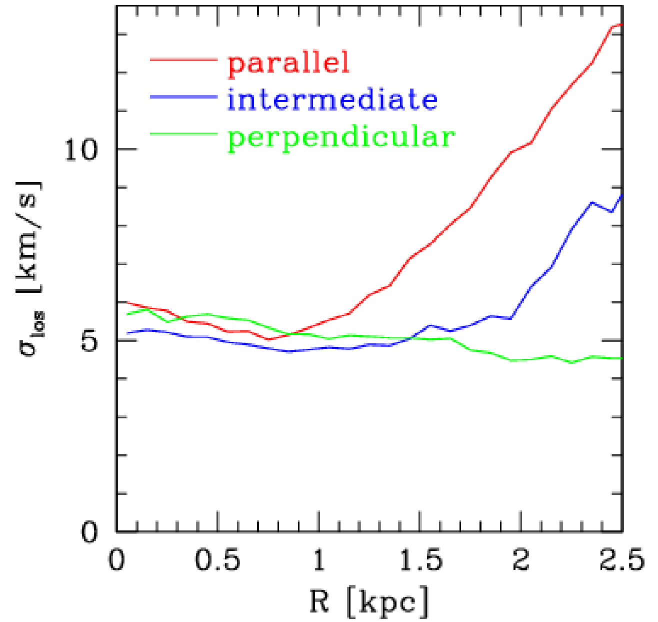


Measured properties of dwarfs will depend on the direction of observations

Klimentowski et al. 2007



Surface densiy profile



Velocity dispersion

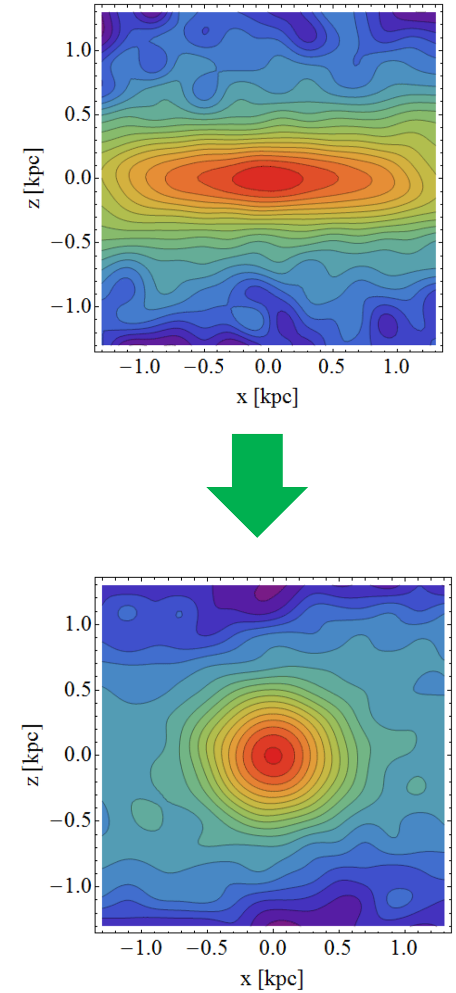
Tidal stirring scenario

- All dwarf galaxies were initially disks embedded in dark matter haloes
- In the vicinity of a big galaxy they are strongly affected by tidal forces
- Tidal forces cause strong mass loss and the formation of tidal tails
- The evolution involves morphological transformation, from a disk to a bar and then a spheroid
- Streaming motions of stars change to random motions

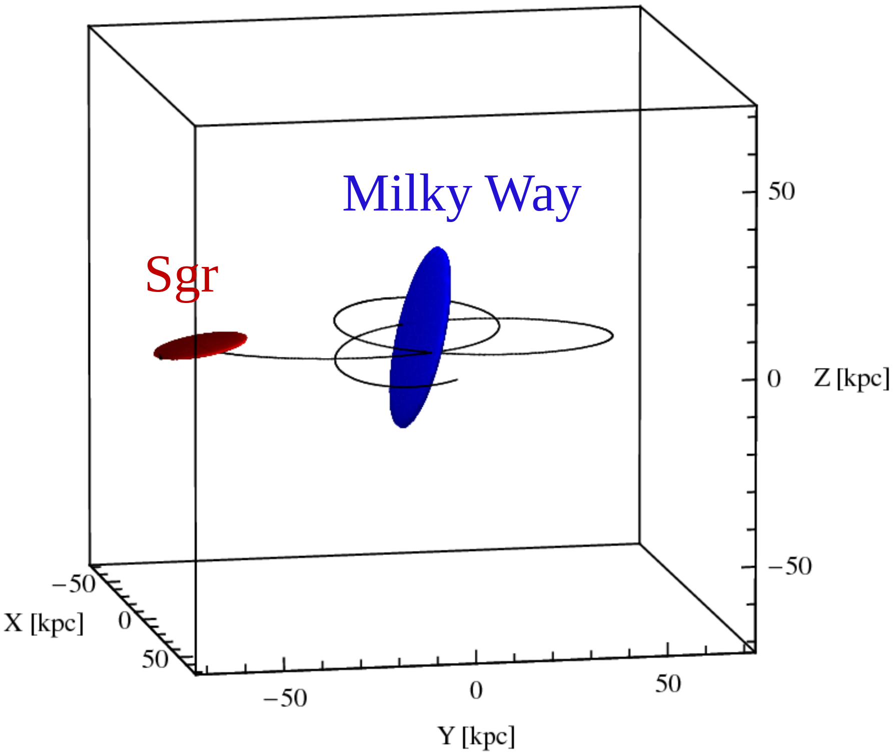
Mayer et al. 2001, 2006, Kazantzidis et al. 2011

Origin of dSph galaxies

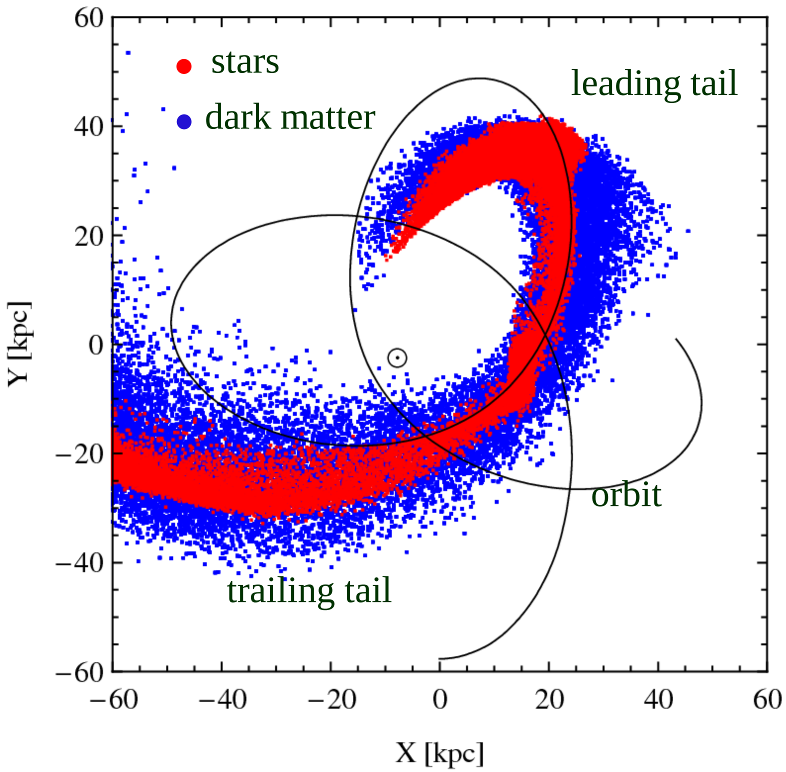
- The tidal stirring model provides a scenario for the formation of dSph galaxies (elliptical and non-rotating) from dIrr progenitors (disky and rotating)
- It also explains the morphology-density relation: dSph galaxies are found closer to the big galaxies, while dIrrs occupy isolated regions at the outskirts of the LG



Simulation of Sgr



initial configuration

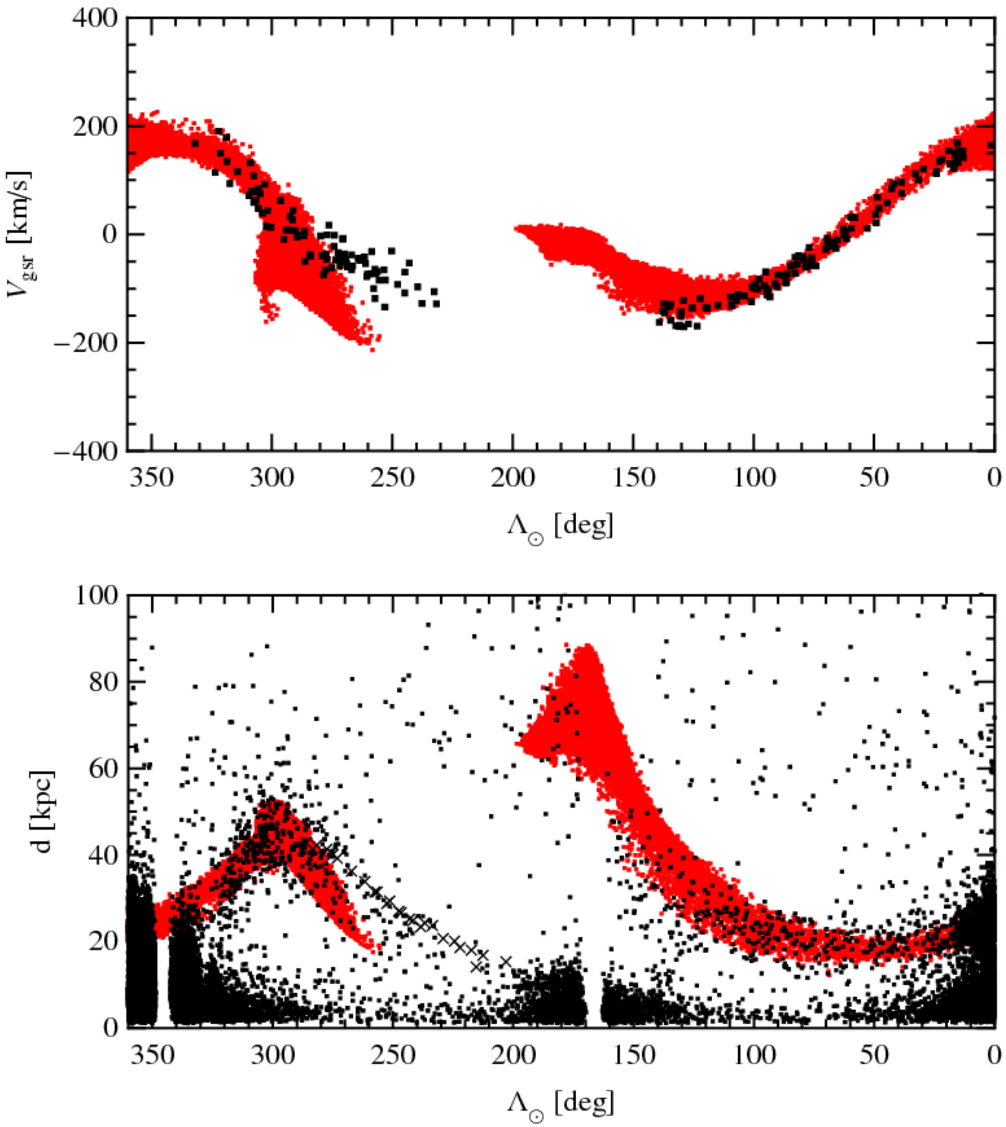


after 1.3 Gyr

Dwarf galaxy with initial mass of 1.6 x 10^{10} $M_{\odot}$, composed of a disk and dark halo, evolving on a tight, prograde orbit (apo/peri=58/17 kpc) around the Milky Way; after 1.3 Gyr has just passed the second pericenter

Łokas et al. 2010

Tidal debris



The velocities and distances of stars in the tails are reproduced reasonably well, although there is space for improvement (non-spherical halo?)

simulation

real data

Galaxy interactions

- Encounters and mergers of galaxies play a central role in their evolution, and in fact galaxies are formed by the mergers of smaller galaxies
- Even apparently isolated galaxies are surrounded by much larger dark halos whose outermost parts are linked to the halos of neighboring galaxies
- Gas, stars, and dark matter are being accreted onto galaxies up to the present time

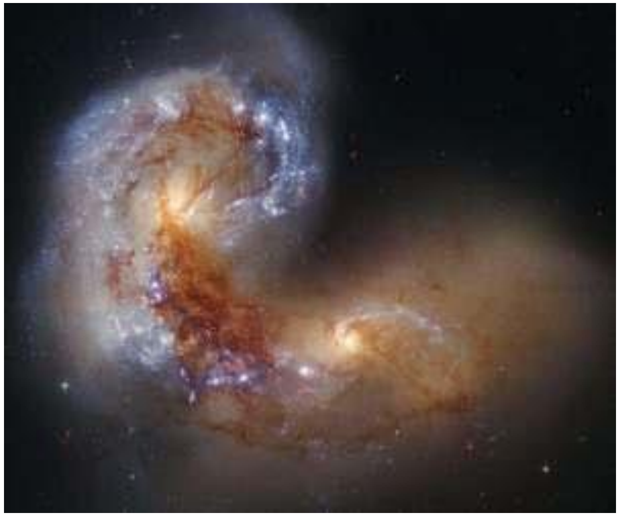
Galaxies are not island universes

Evidence for mergers

Observational evidence for mergers includes:

- peculiar galaxies
- grand-design spirals
- ring galaxies
- shells
- starburst galaxies

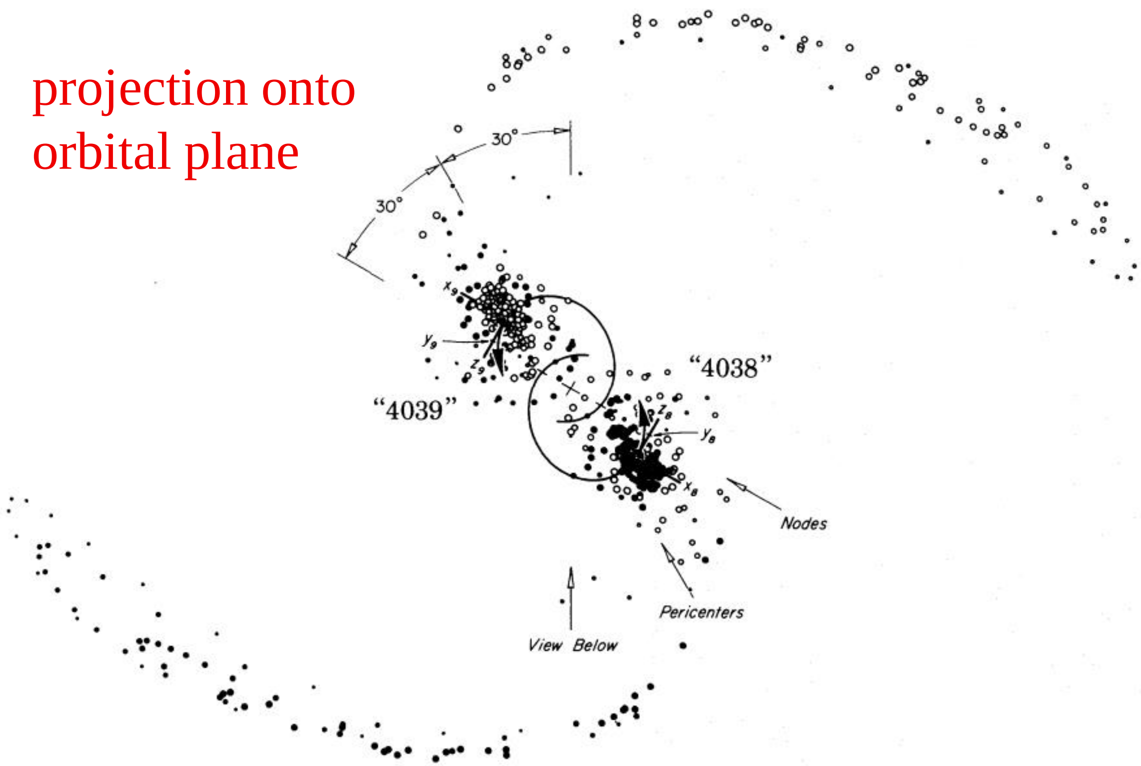
Antennae



NGC 4038/4039, the tidal tails span ~100 kpc, the narrowness of the tails indicates that they come from a cold stellar system (with low velocity dispersion) rather than a hot one

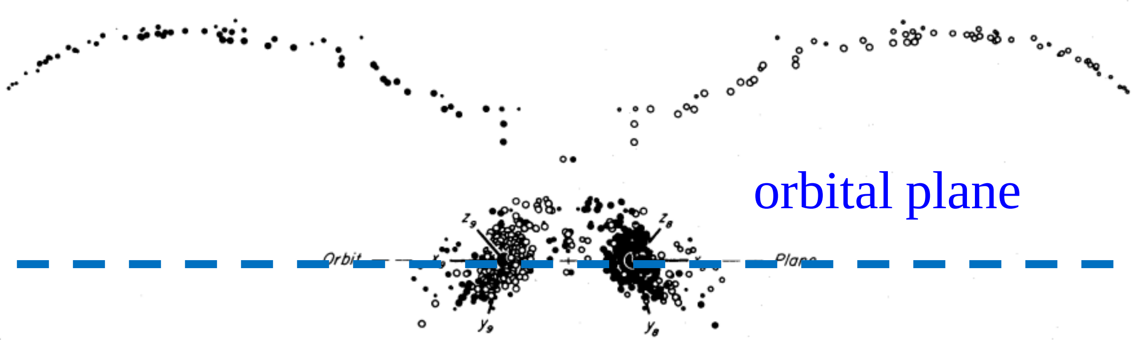
Are Antennae a merger?

projection onto orbital plane



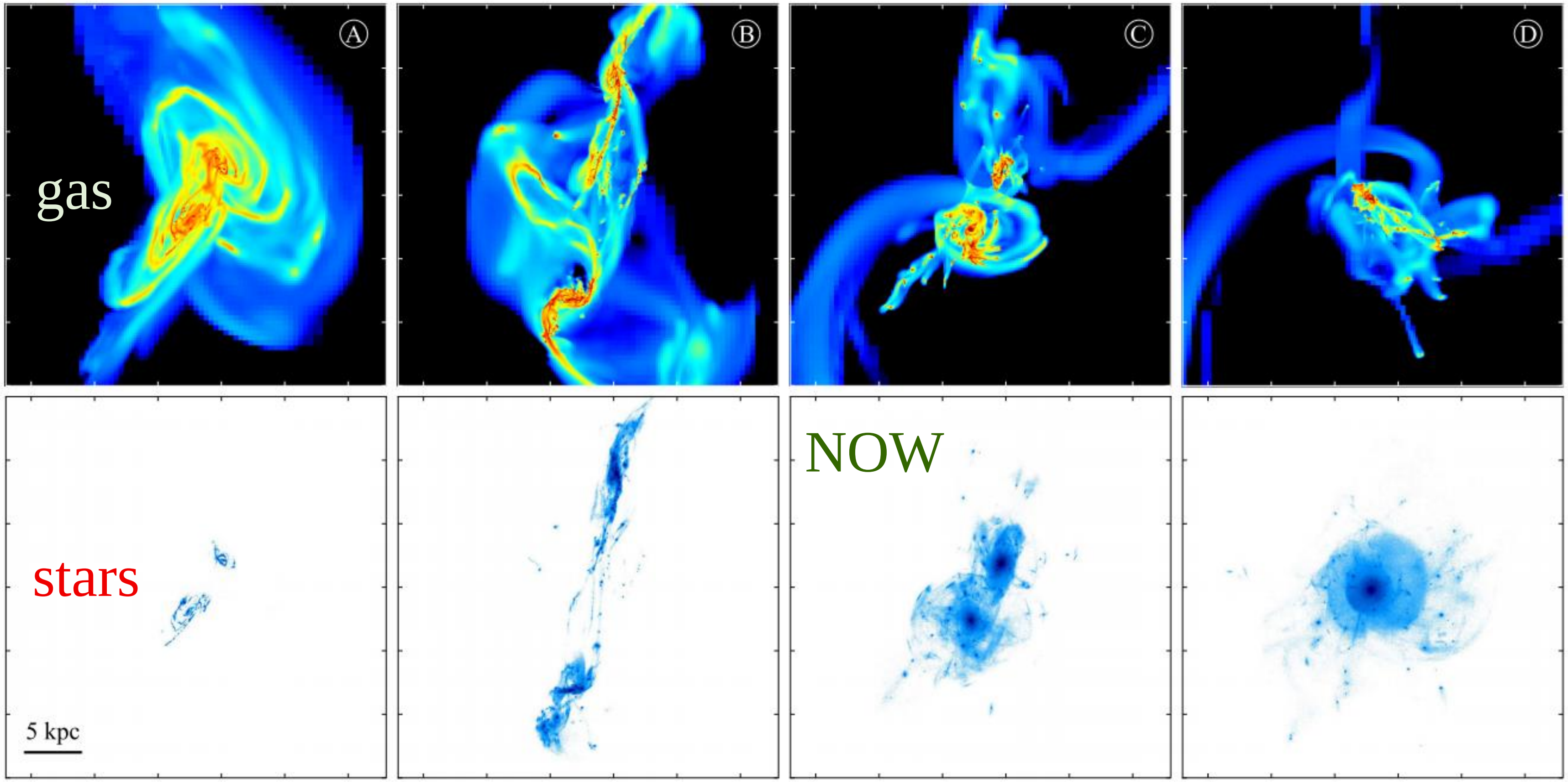
The first rough model of the interaction of two disky galaxies

Toomre & Toomre (1972)



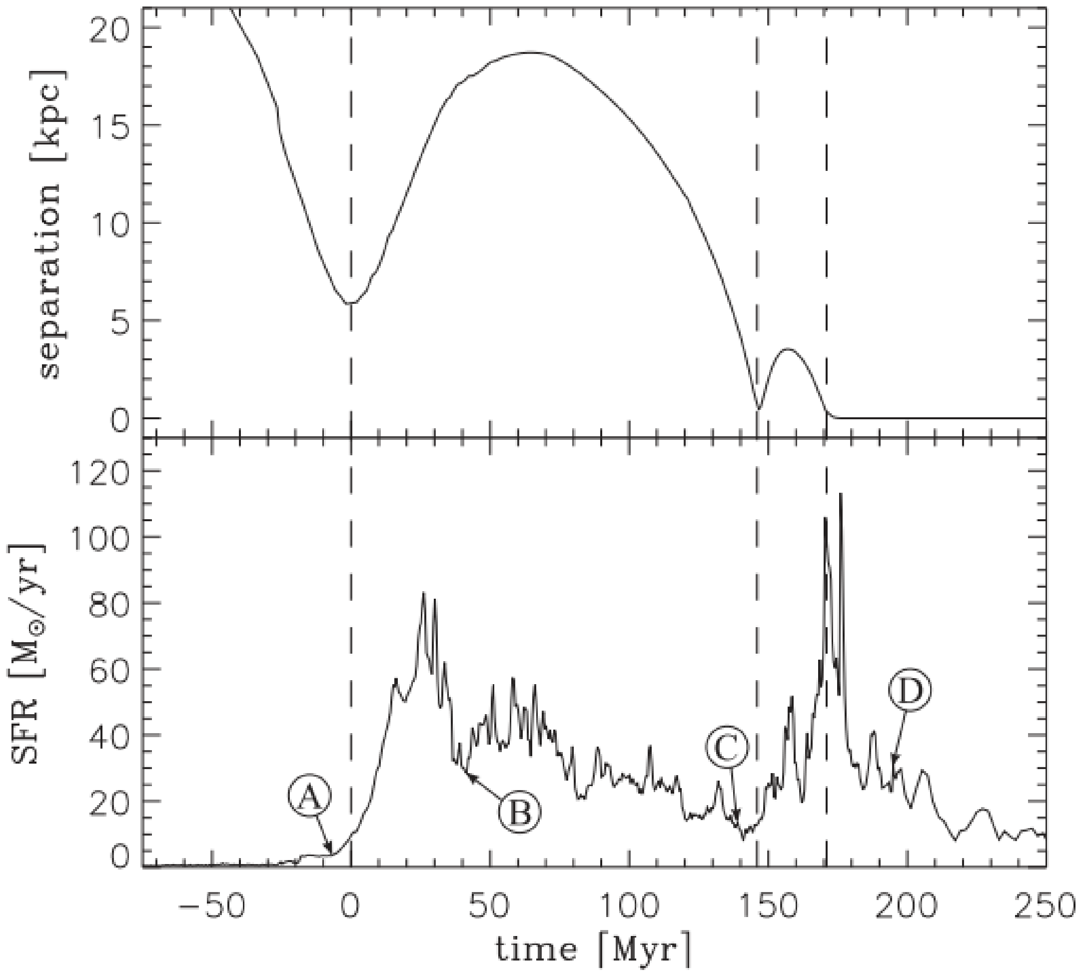
orbital plane

Newer simulations



New simulations including full dynamics and the gas component show that mergers are efficient triggers of star formation

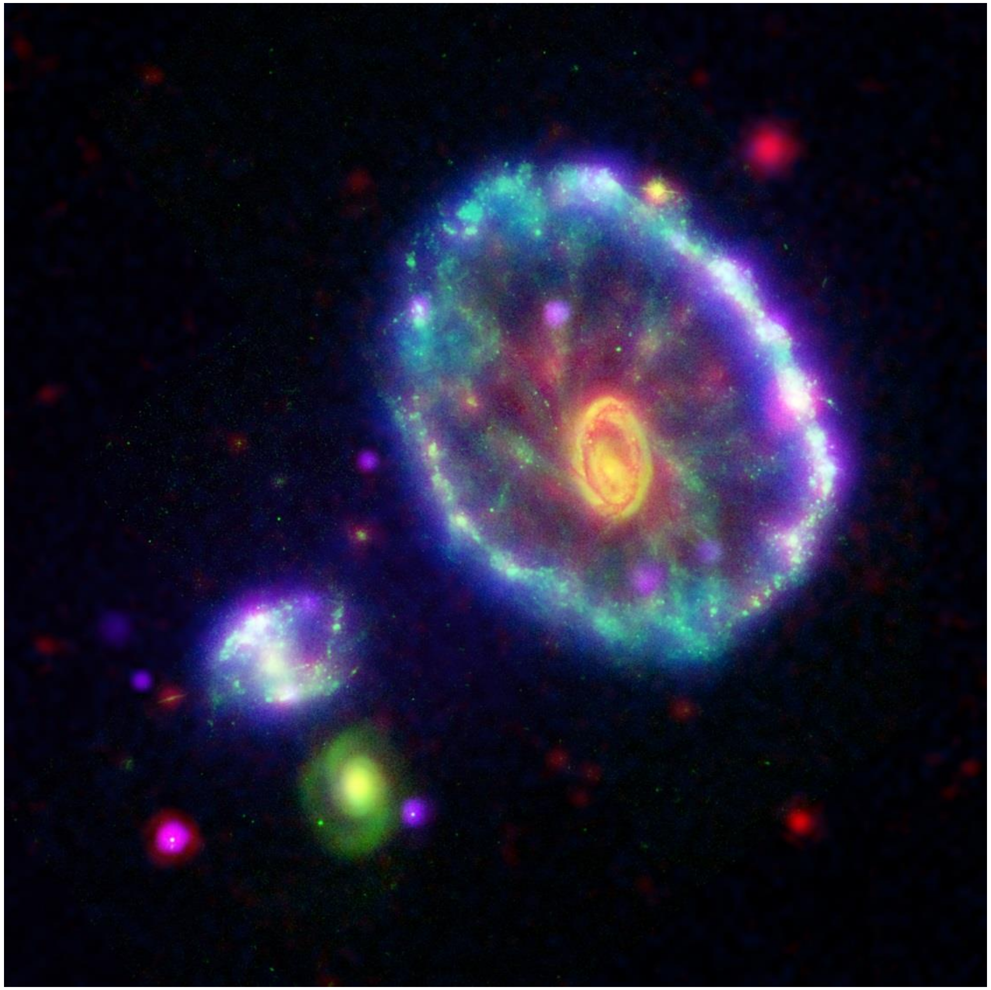
Star formation rate



Star formation starts right after the first pericenter passage and will have a peak when the galaxies merge completely

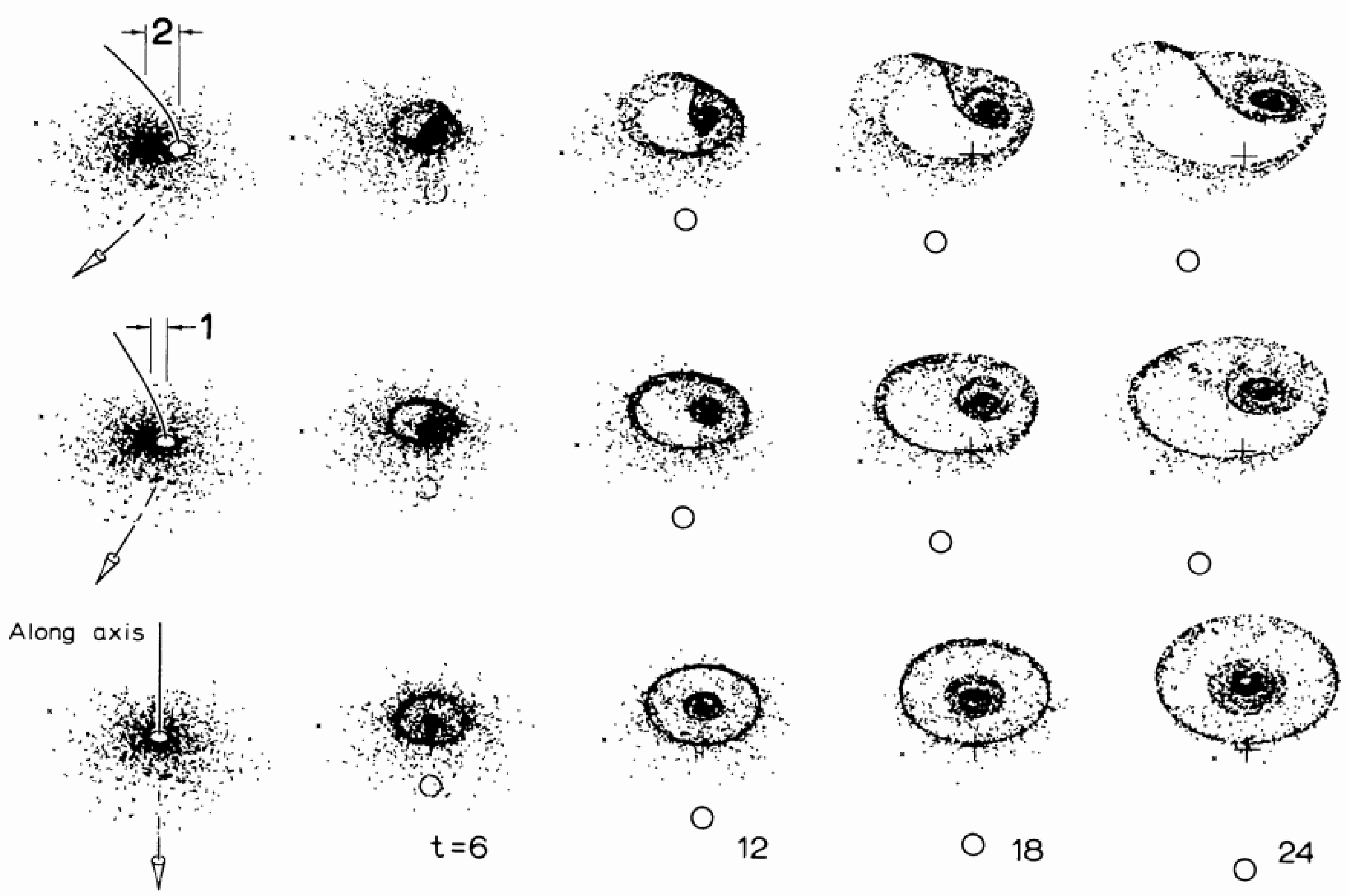
Renaud et al. 2015

Cartwheel galaxy



The best-known example of a small class of ring galaxies, at a large distance of 150 Mpc, probably formed by a head-on collision with a smaller system

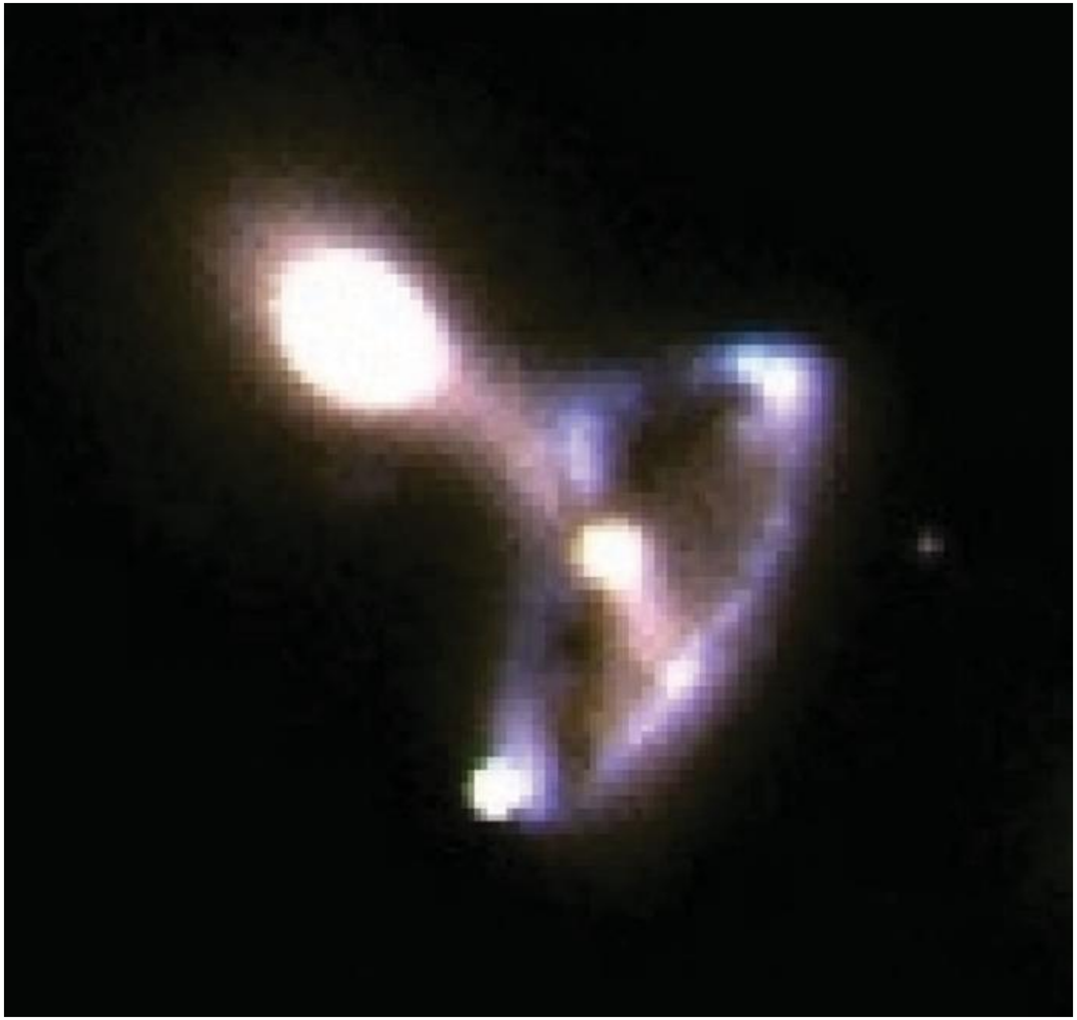
Formation of ring galaxies



Off-center collisions lead to asymmetries in the ring

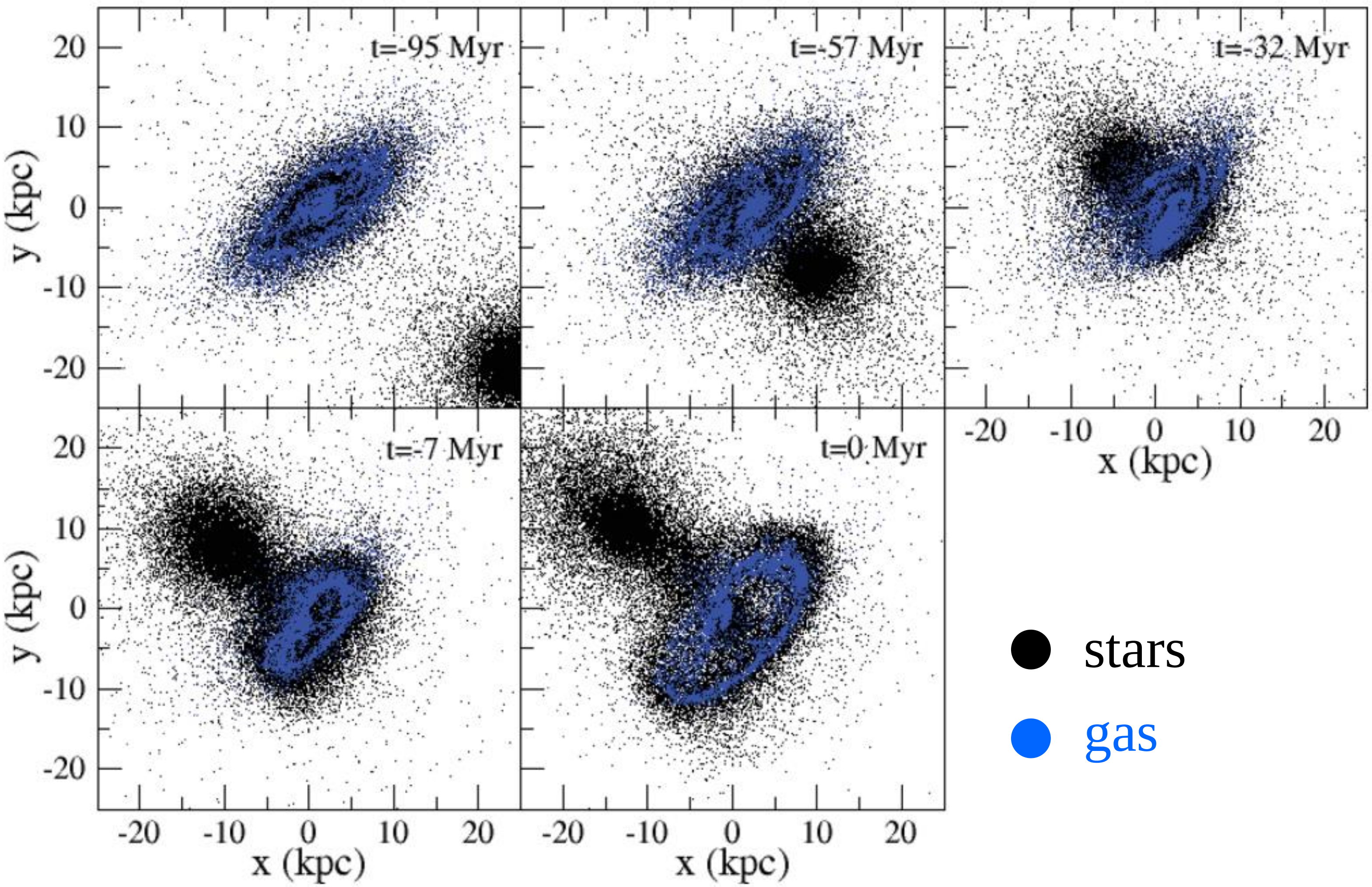
Toomre 1978

Auriga's Wheel



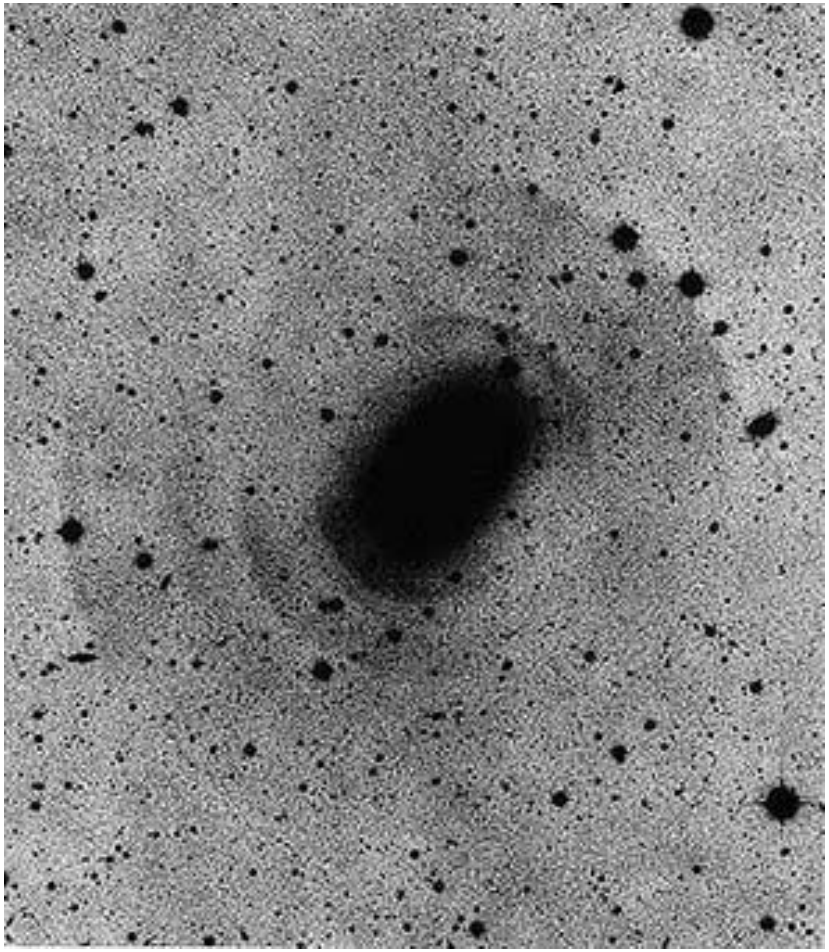
One of the most distant ring galaxies known, at 460 Mpc, discovered in 2011

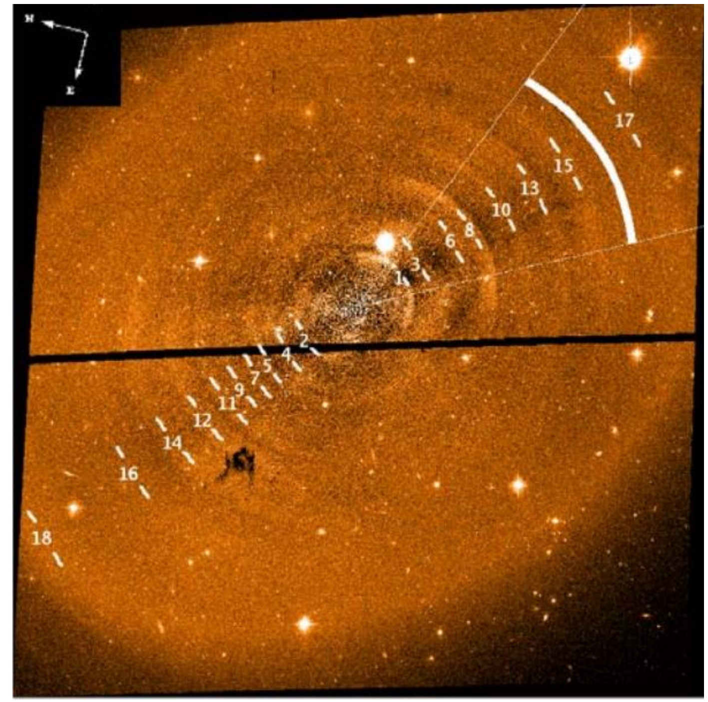
Model of Auriga's Wheel



Smith et al. 2012

NGC 3923



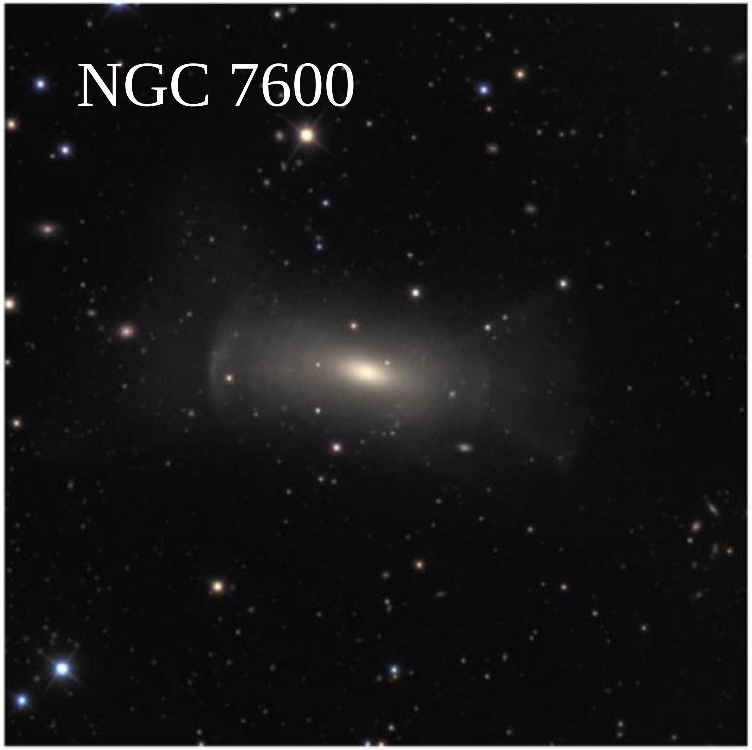


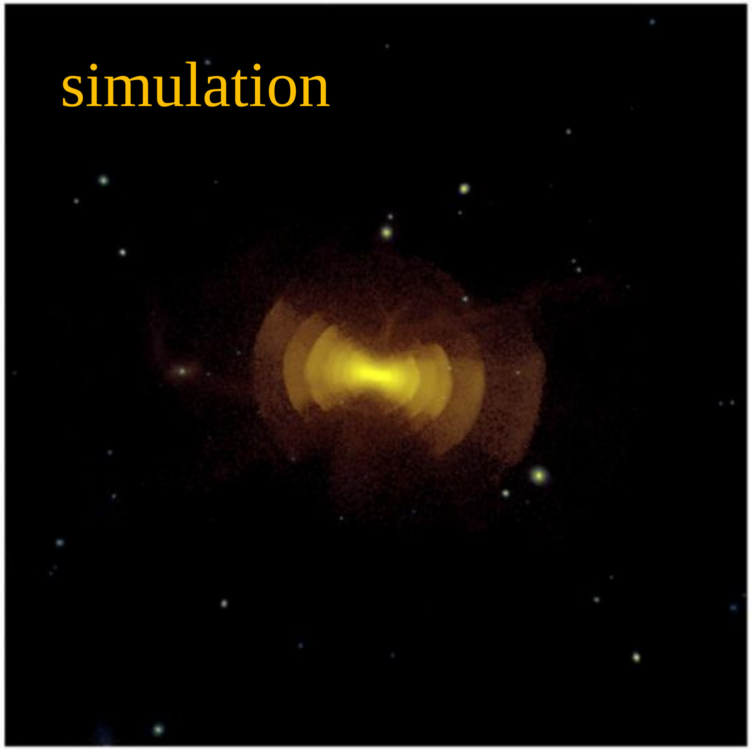
Residual image

Sikkema et al. 2007

Elliptical galaxy (E4) with a collection of shells

Shells in simulations

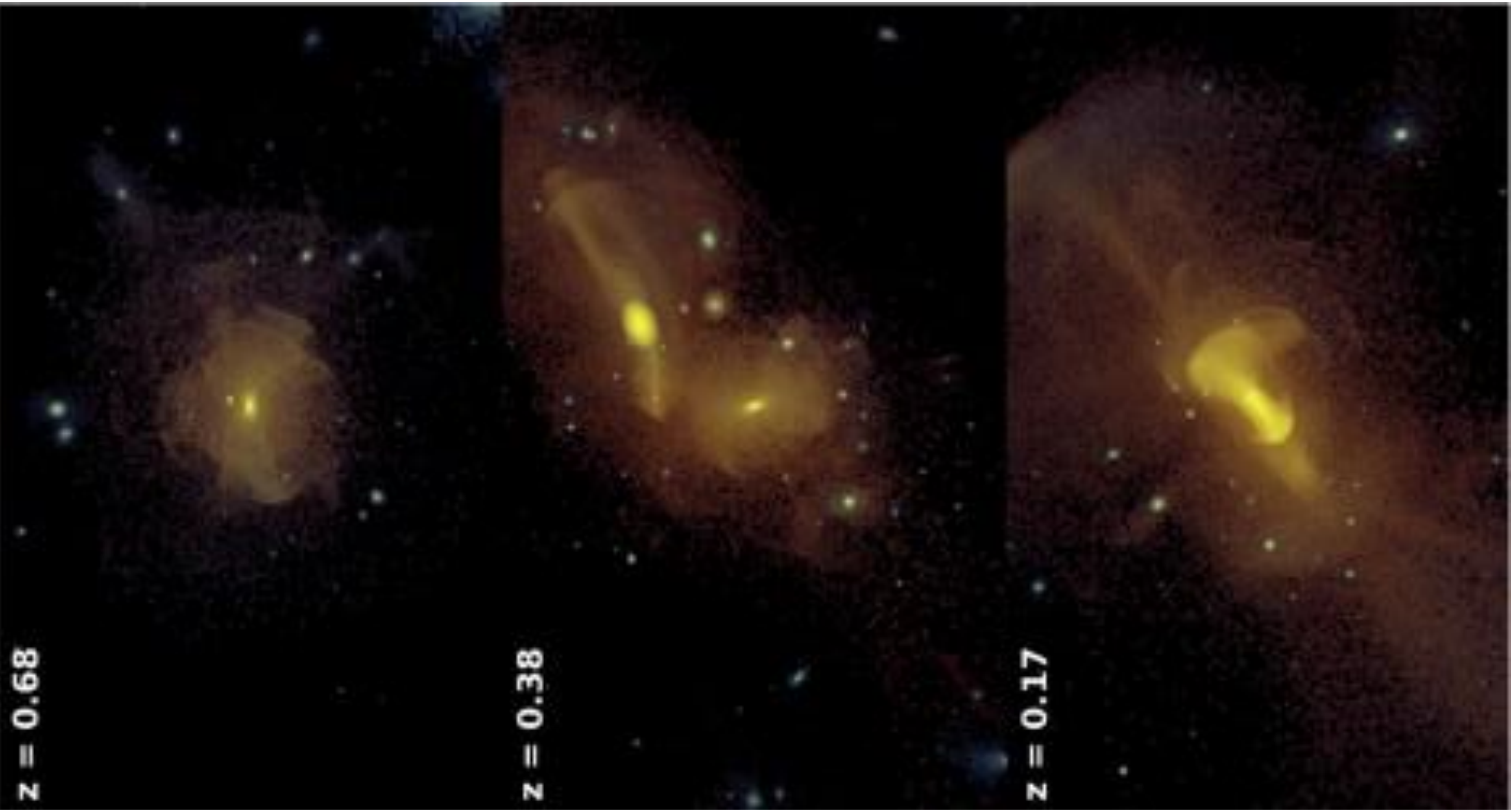




Cooper et al. 2011

Shells are formed by radial mergers with smaller satellites, here 3:1 merger in cosmological simulation with a result remarkably similar to NGC 7600

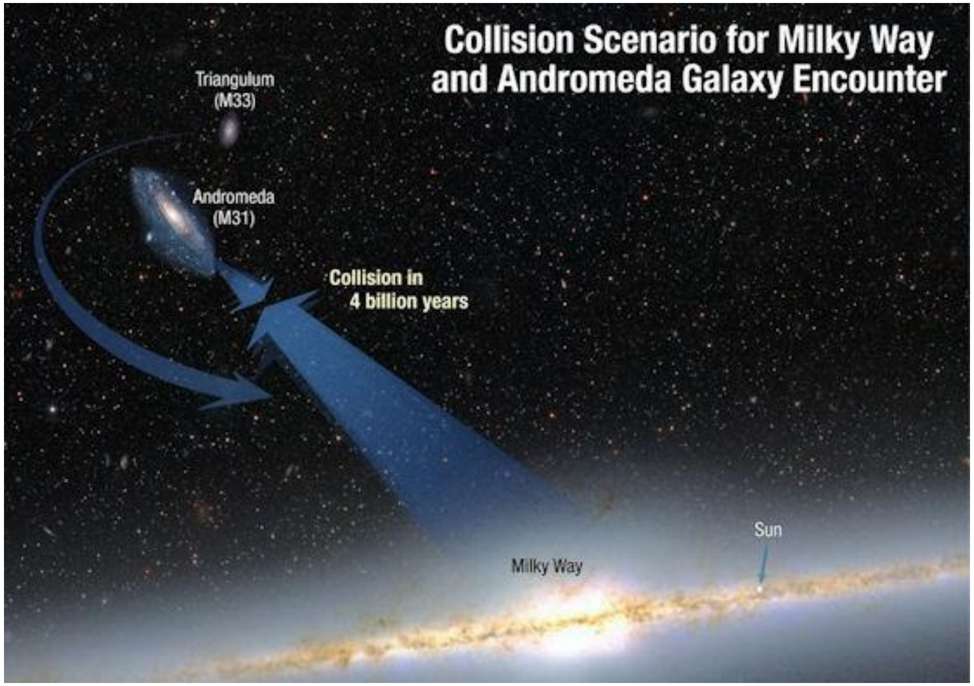
Shells in simulations



MW-M31 collision

- Radial and proper motion measurements in M31 show that the velocity of Andromeda with respect to the center of the Milky Way is:

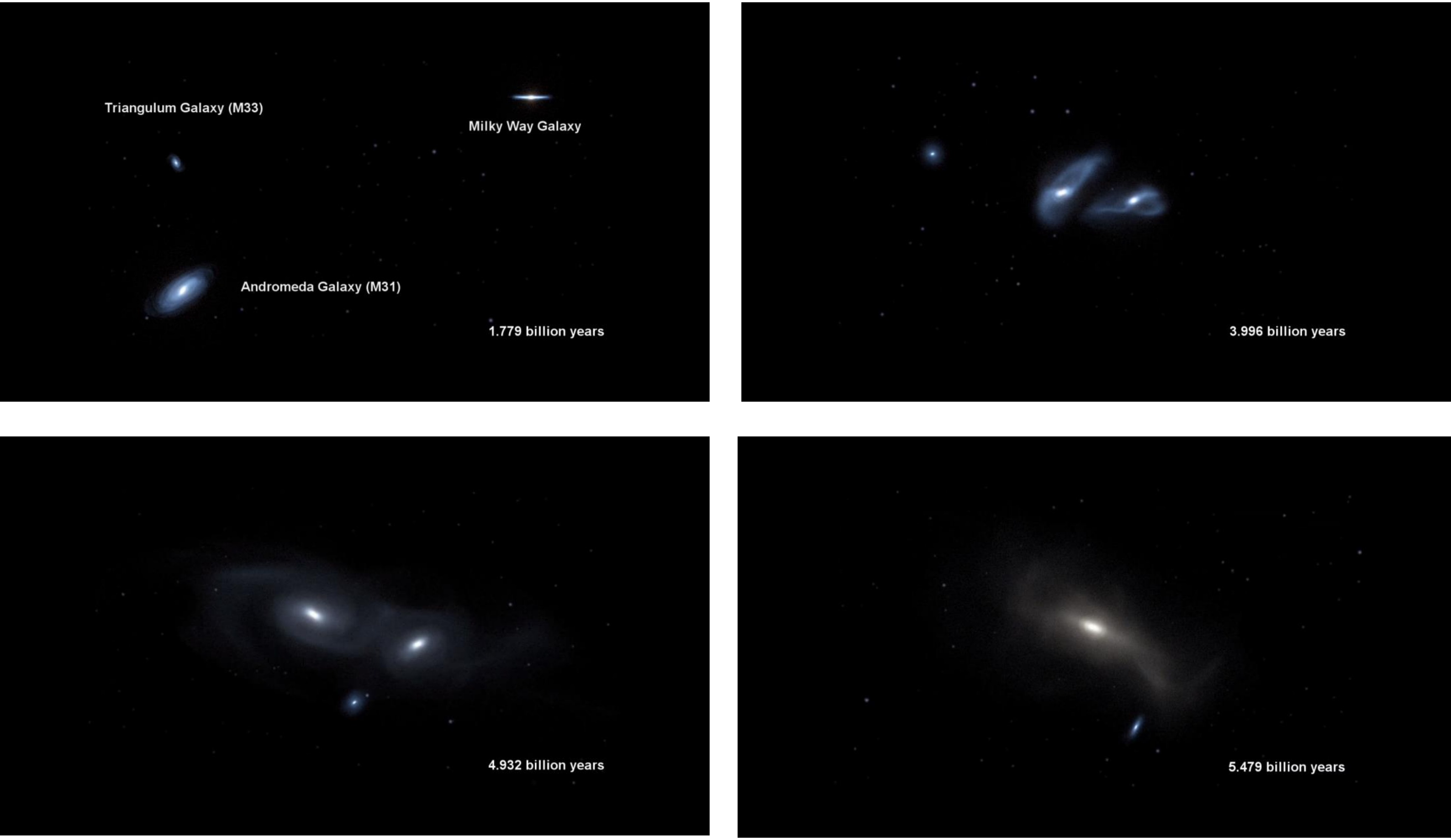
V_{rad} = -109.3 km/s
V_{tan} = 17.0 km/s



- This means that MW and M31 are going to collide forming a giant elliptical galaxy

van der Marel et al. 2012

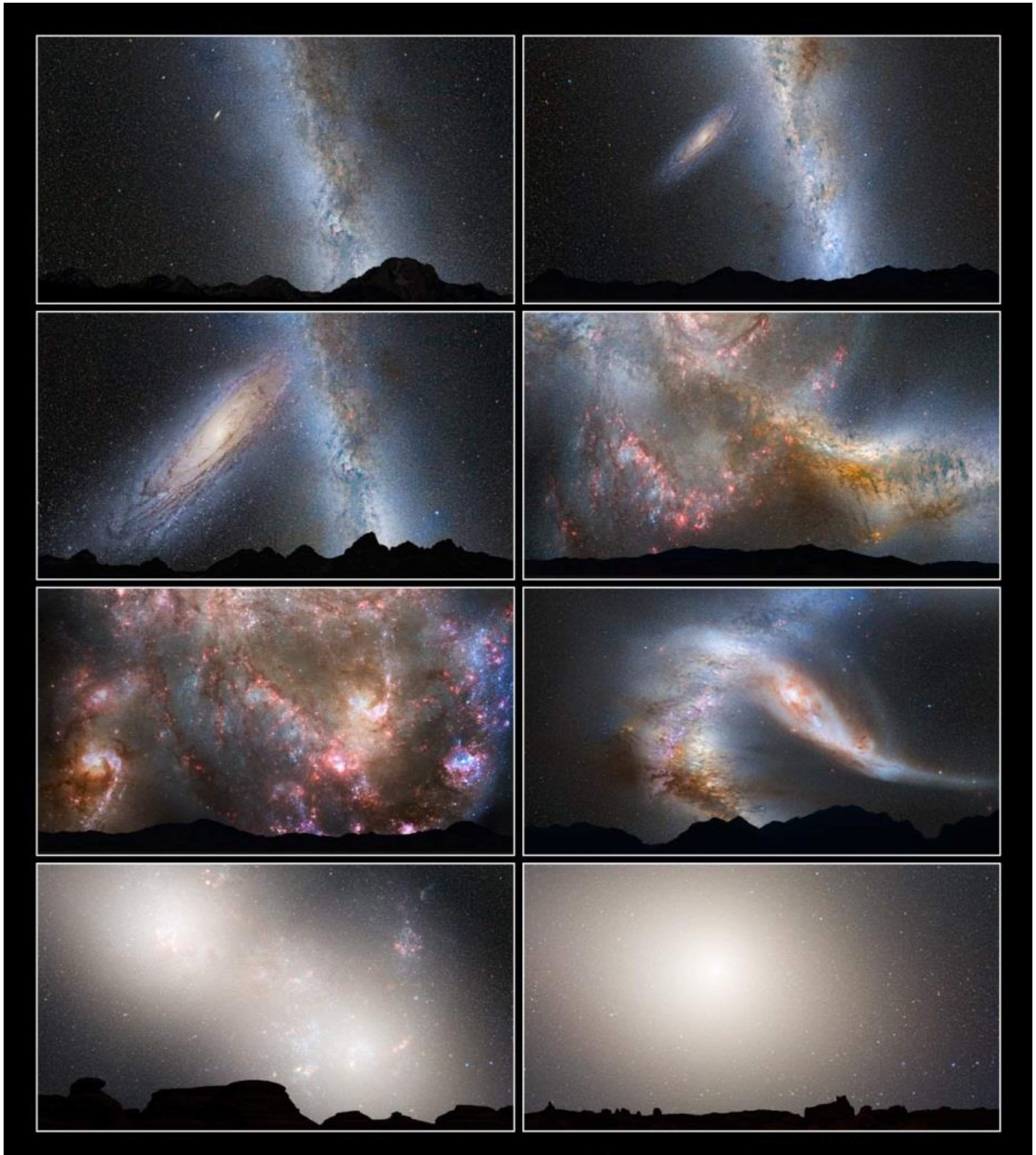
MW-M31 collision



The sequence of events

Now

in 2 Gyr



in 3.75 Gyr

in 3.85 Gyr

in 3.9 Gyr

in 4 Gyr

in 5.1 Gyr

in 7 Gyr

Possible scenario

- In this particular scenario Milky Way and Andromeda will finally merge in

  t = 5.86 (+1.61/-0.72) Gyr

  forming a giant elliptical galaxy
- The first pericenter will occur at

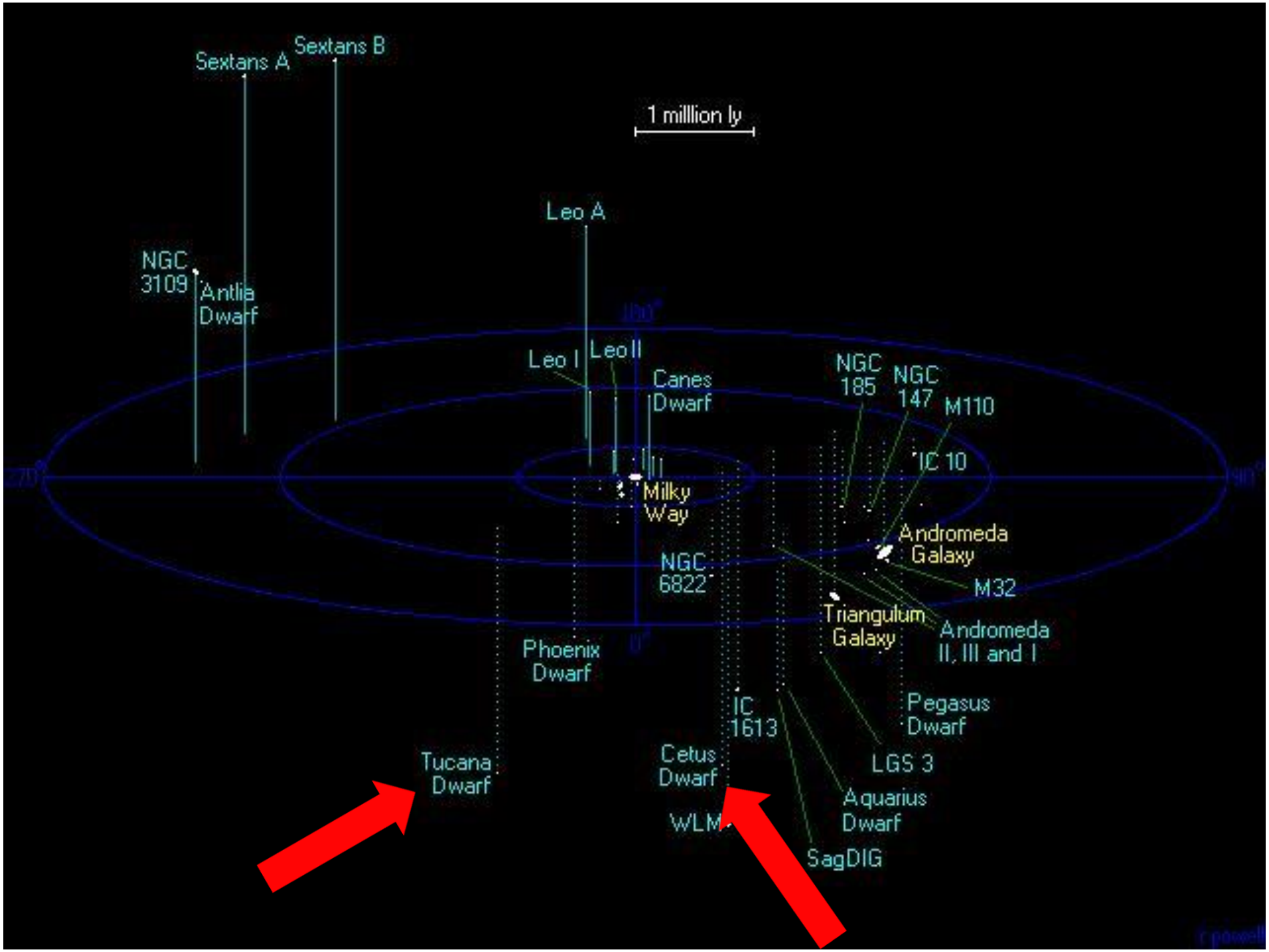
  t = 3.87 (+0.42/-0.32) Gyr

  r = 31.0 (+38.0/-19.8) kpc
- Most probably M31 and MW will merge first and M33 will remain on orbit around them
- There is a small probability of 7% that M33 will be ejected out of the Local Group

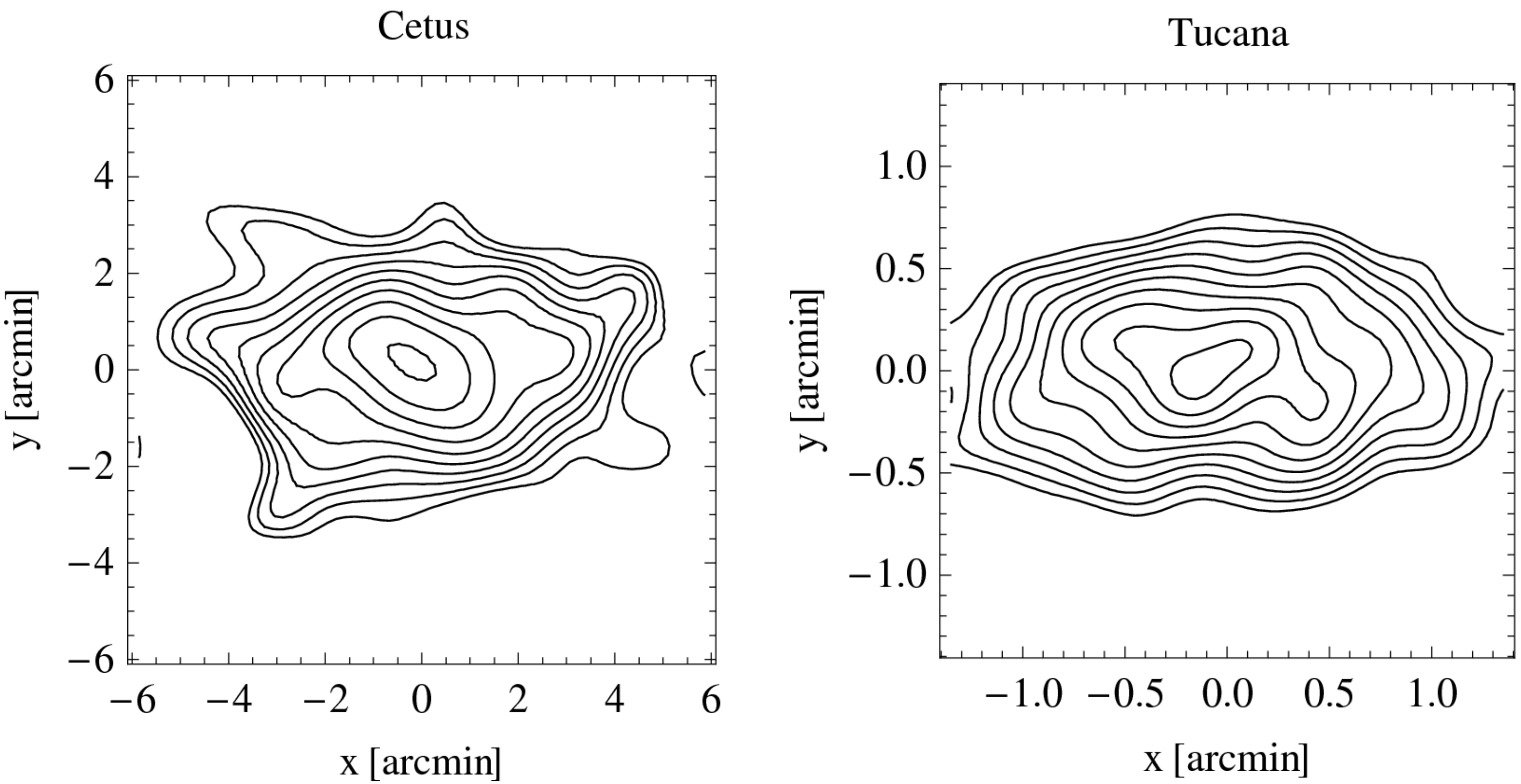
Mergers between dwarfs

- Mergers between dwarf galaxies are believed to be rare because once accreted the satellites move with large relative velocities
- However, if they do happen mergers could lead to the formation of dSph galaxies out of disks
- This hypothesis is supported by the fact that the tidal stirring scenario is ineffective for orbits of pericеters larger than ~50 kpc while a few dSph galaxies are found at ~800 kpc
- Evidence for past mergers in the form of shells exists for a few dwarfs

The Local Group

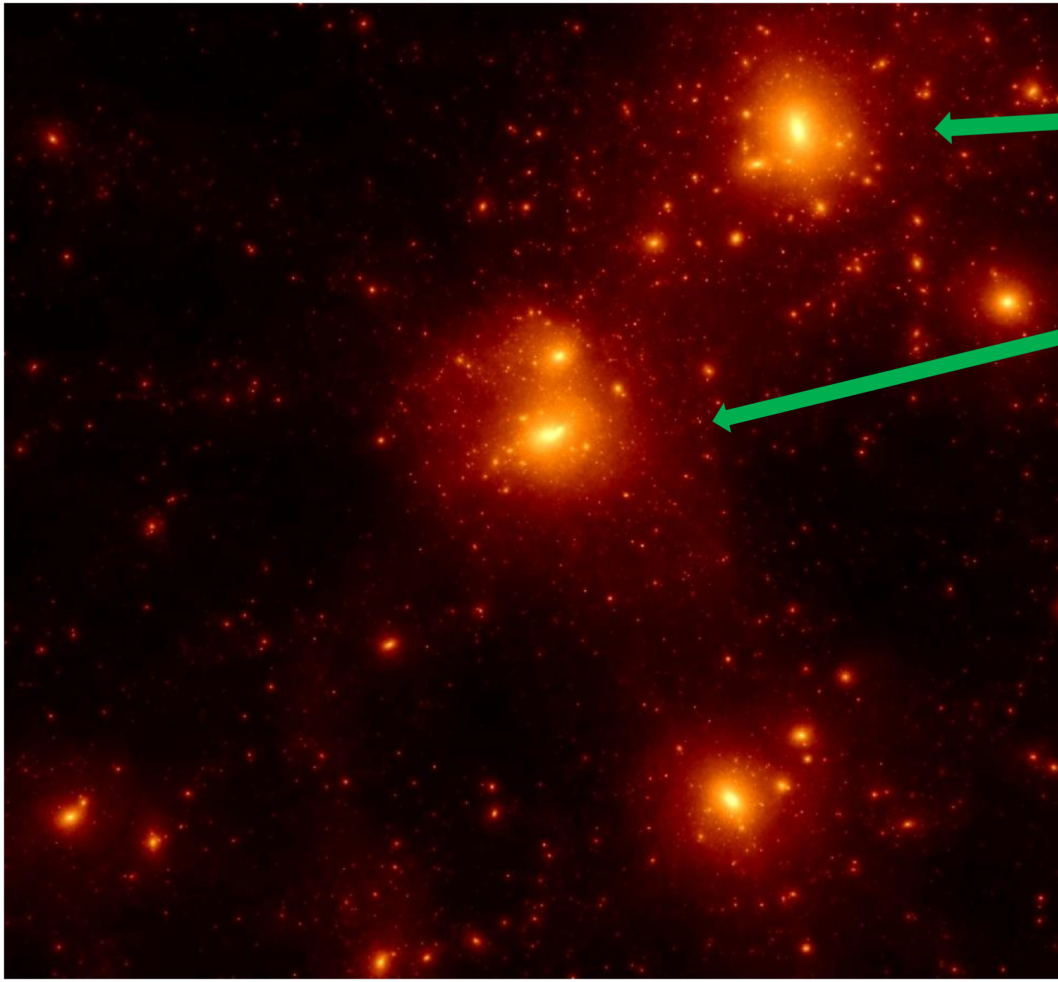


Cetus and Tucana



Cetus and Tucana are typical dSph galaxies although located at ~800 kpc from the main galaxies

Simulation of the Local Group



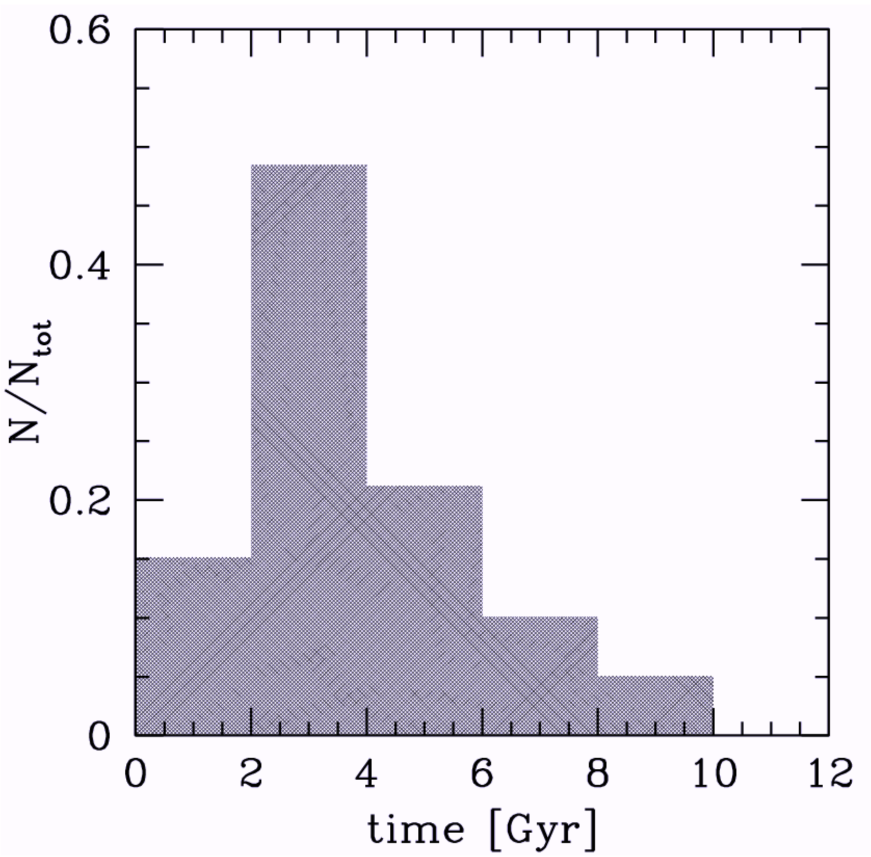
Milky Way

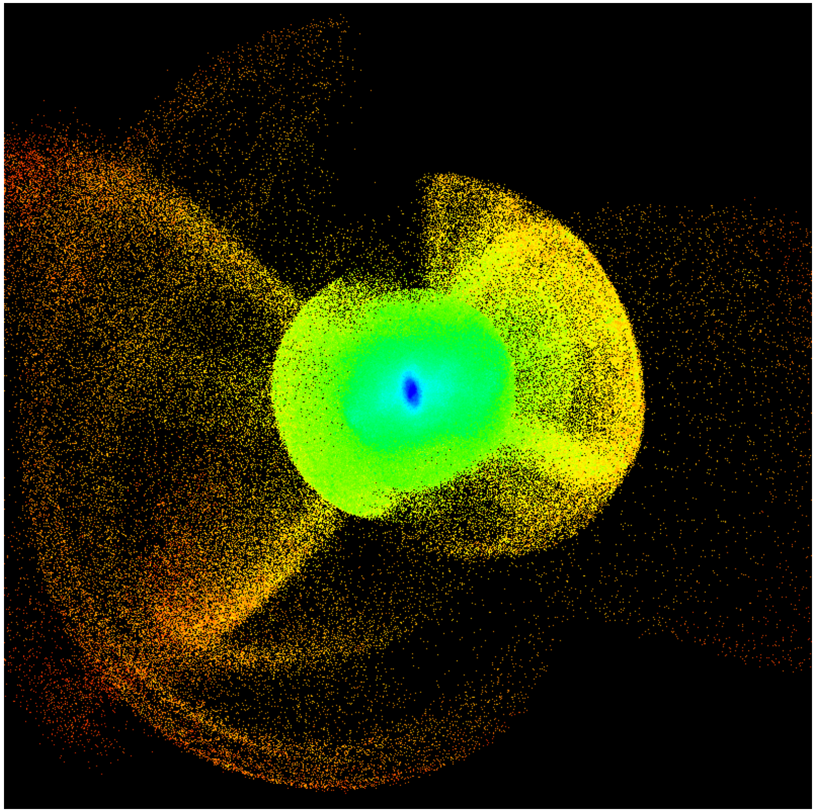
Andromeda

Mergers between subhaloes, satellites of MW and M31, can be studied using such simulations

http://www.clues-project.org/

Mergers between satellites

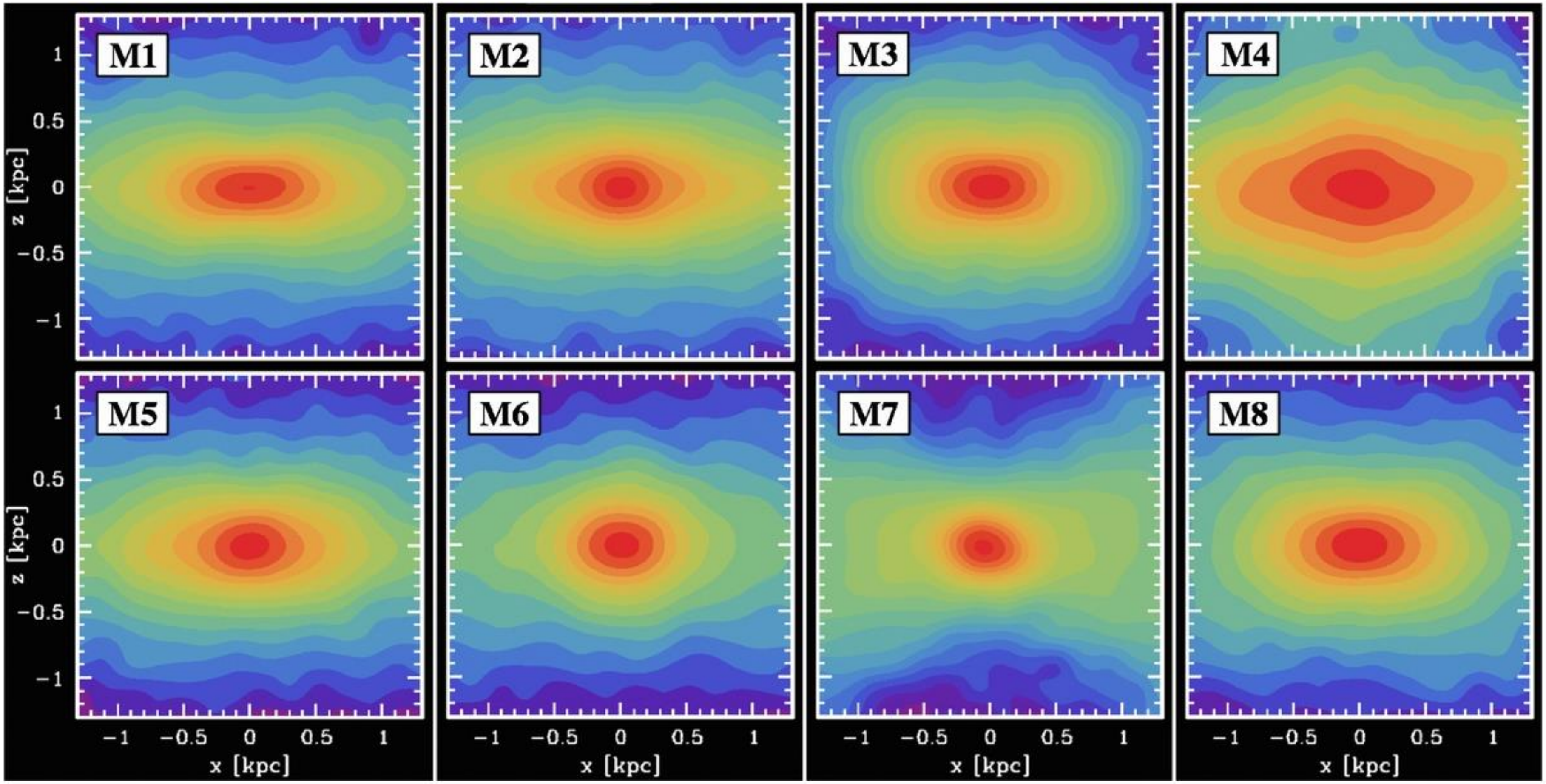




Klimentowski et al. 2010

Although mergers are rare, they do happen, mostly early on in the evolution, more than 7 Gyr ago

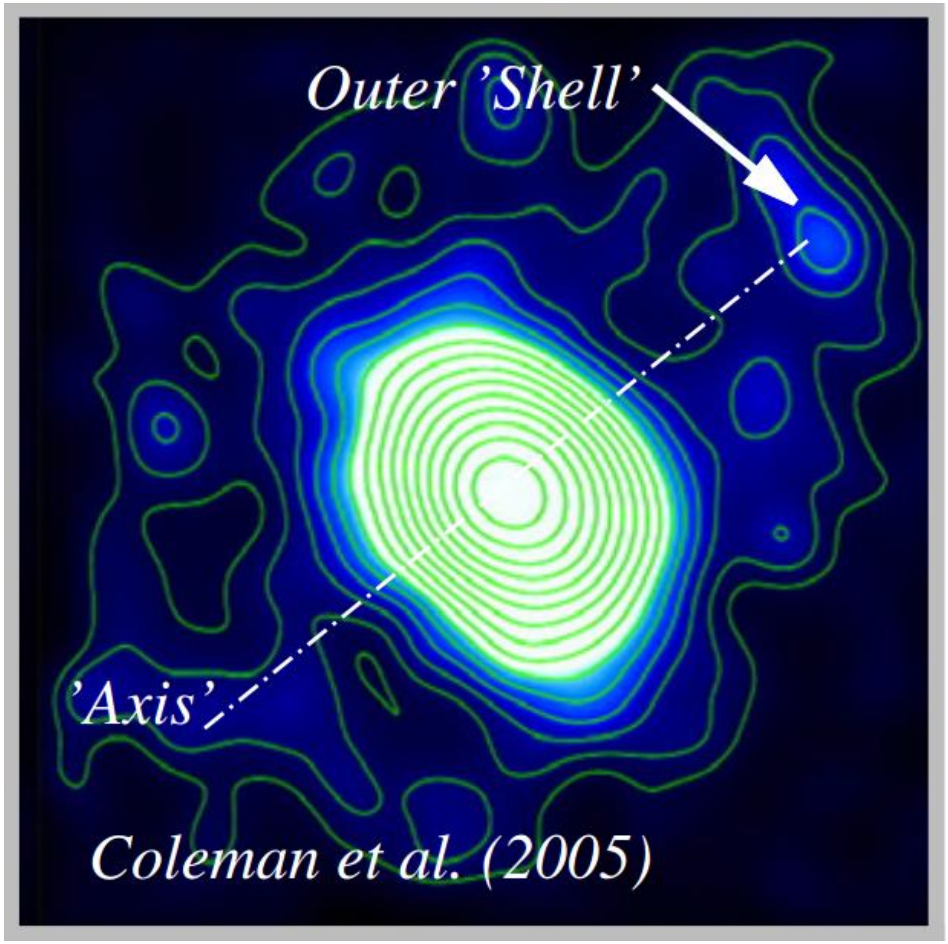
Merger products



Kazantzidis et al. 2011

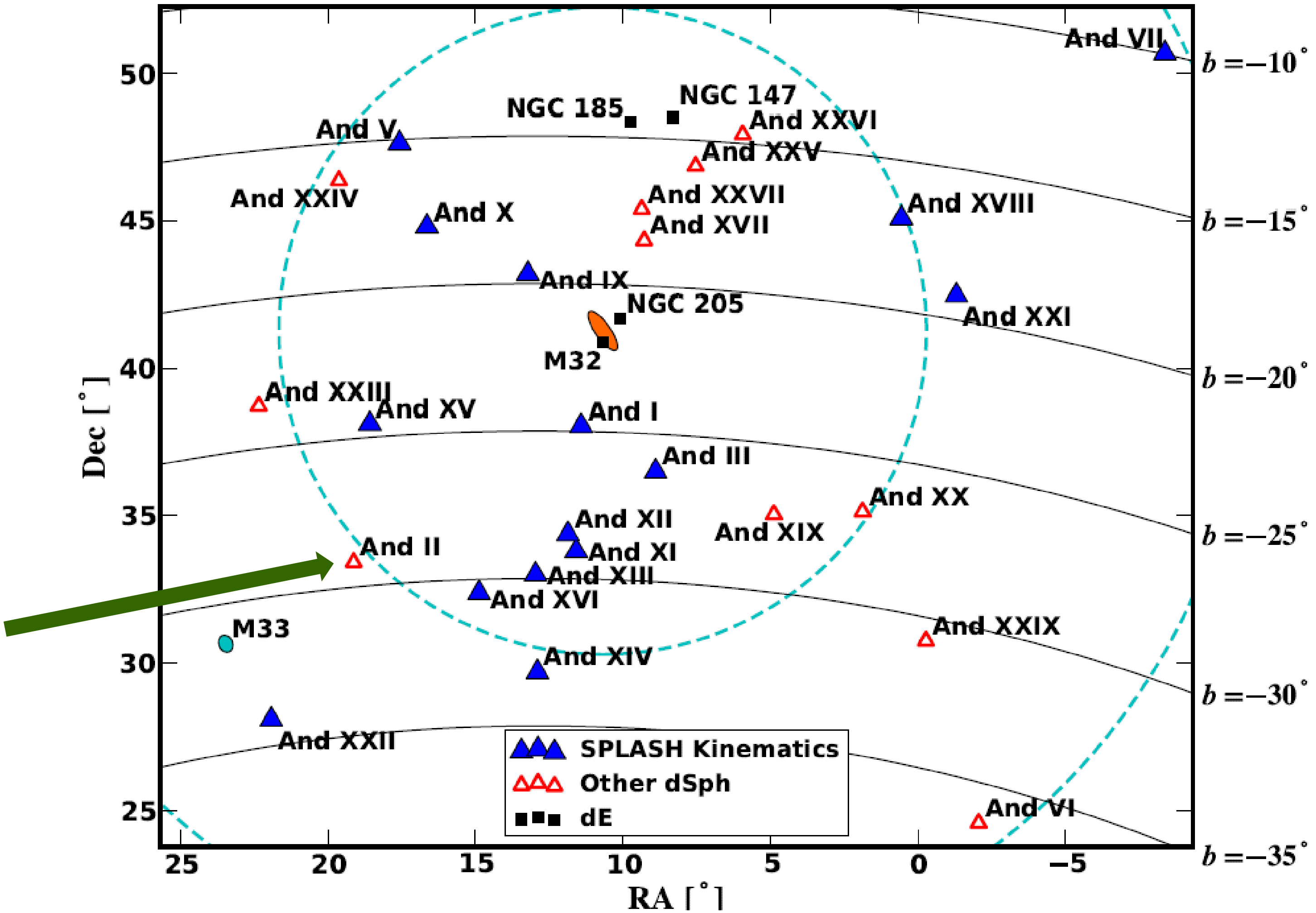
- After 10 Gyr of evolution
- Most non-spherical appearance (view along y axis)

Fornax as merger remnant



- Stellar overdensities in the form of at least two shells have been observed in the outskirts of Fornax
- Such shells can be produced by a merger with a smaller object on radial orbit

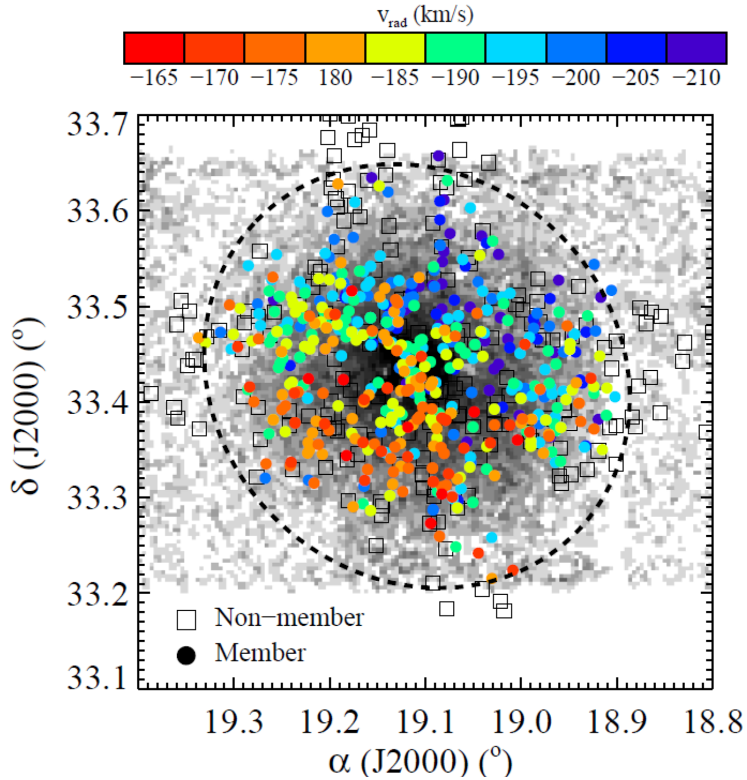
Andromeda's dwarfs



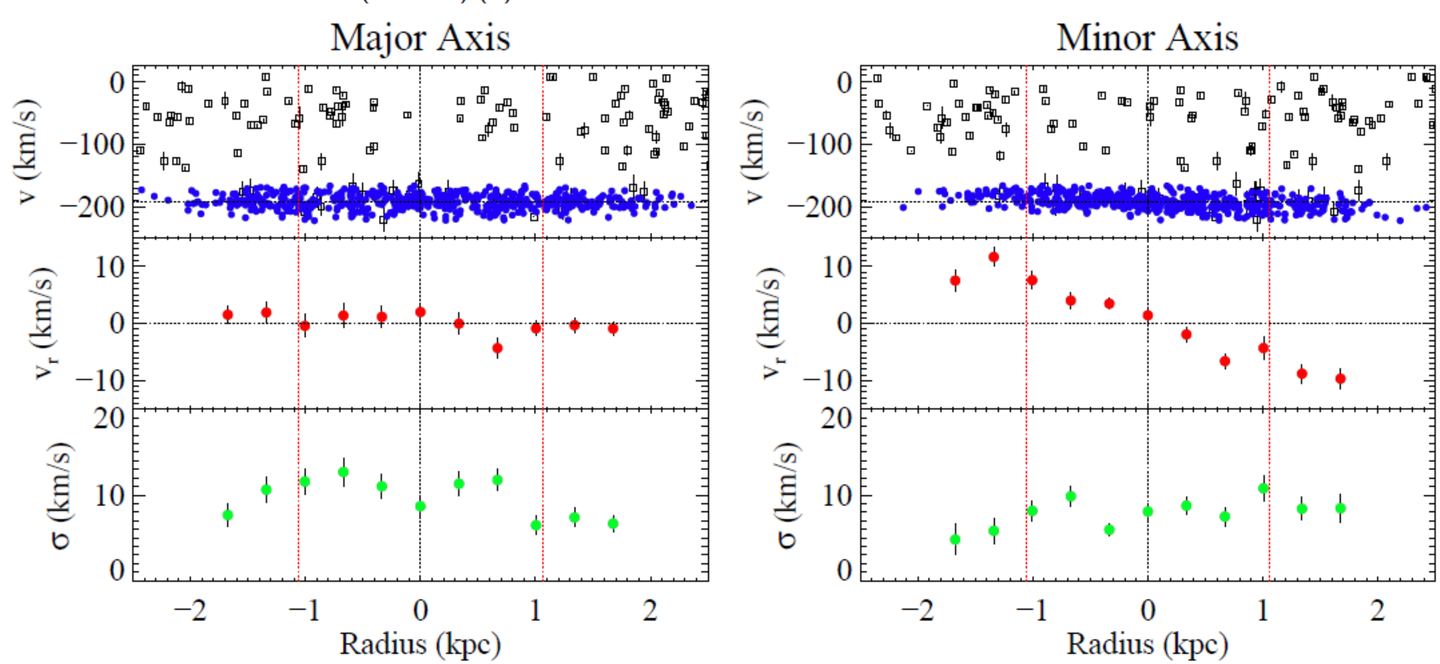
SPLASH = Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo

Tollerud et al. 2012

Prolate rotation in And II

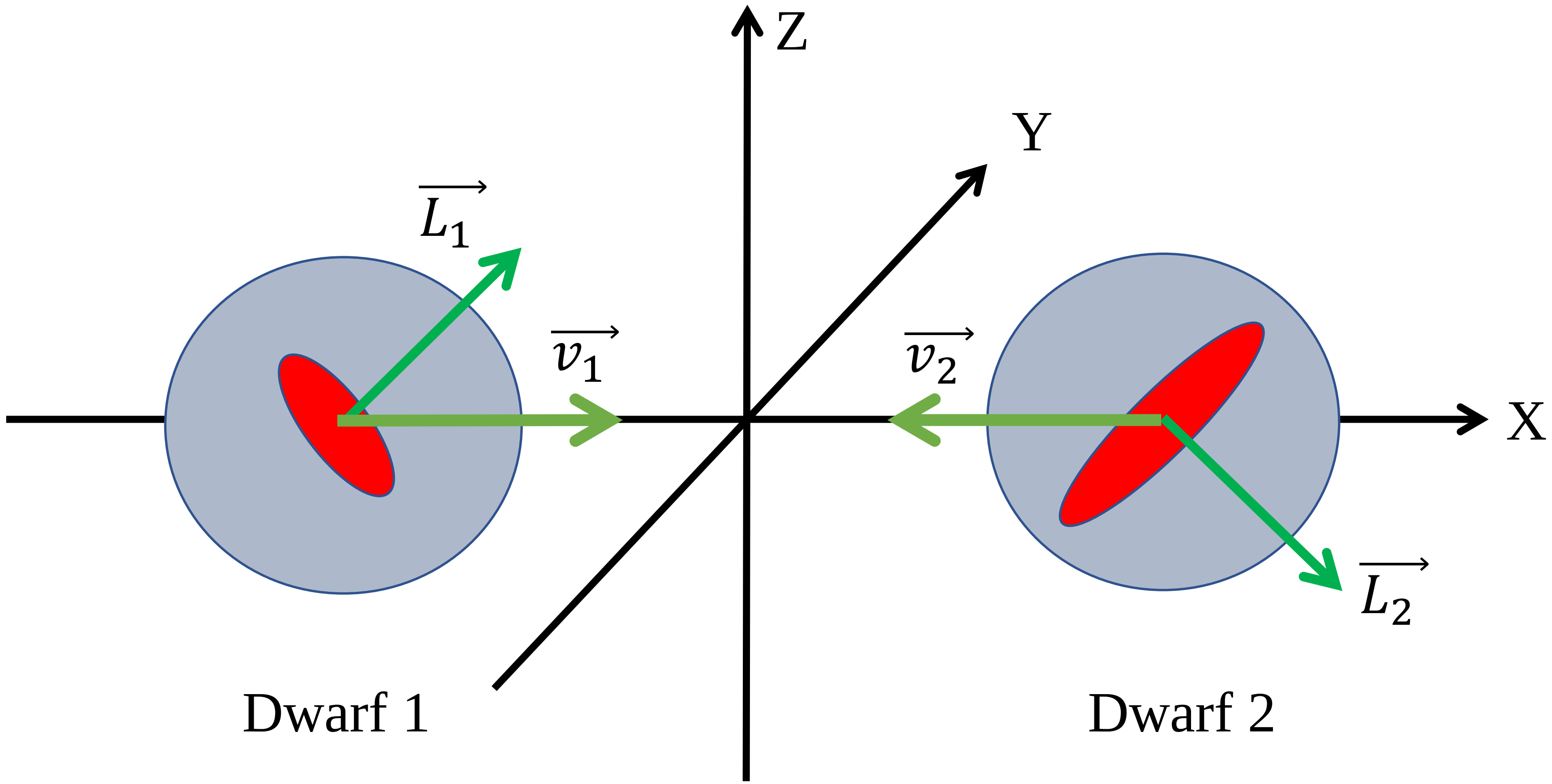


- Kinematics from 531 RGB stars
- First dwarf galaxy to show prolate rotation

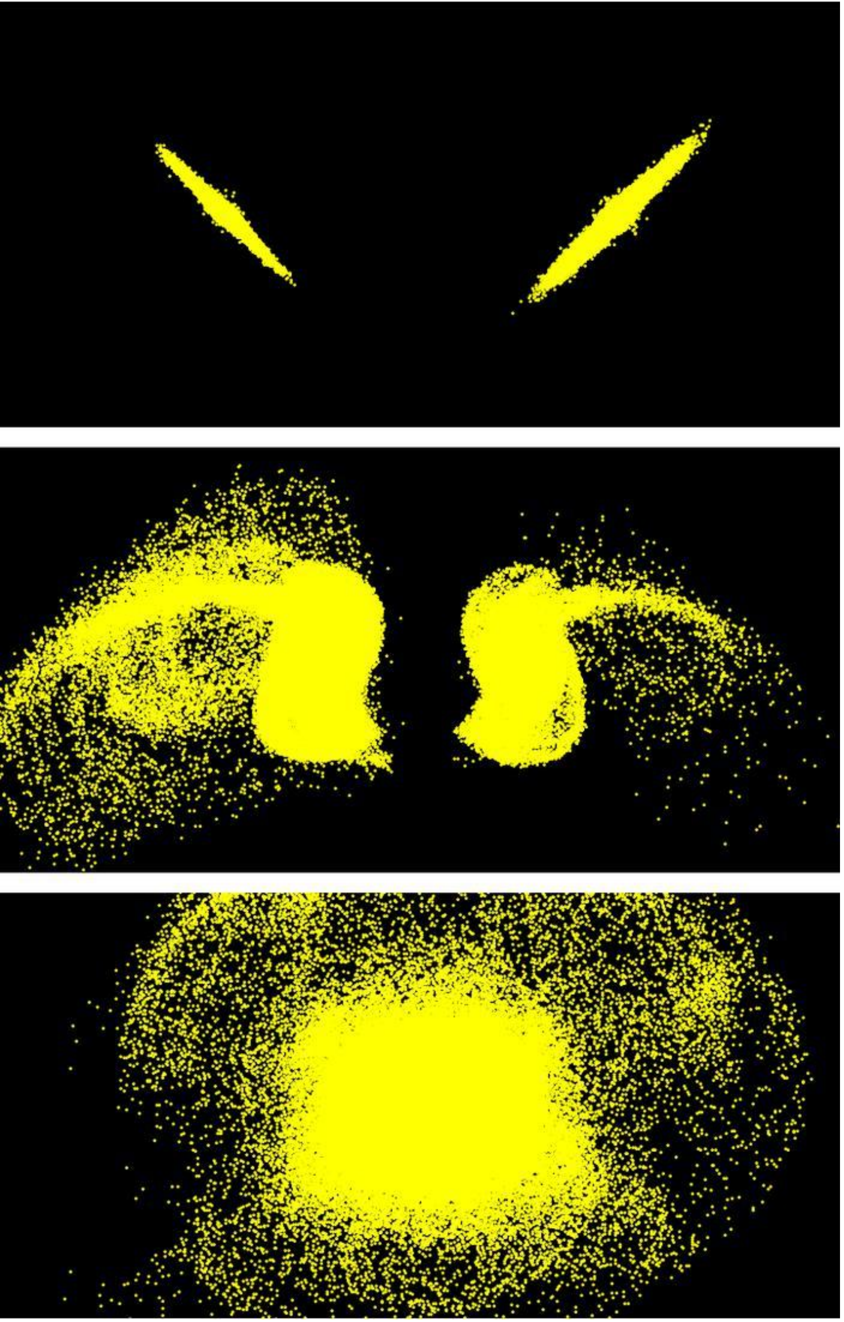


Ho et al. 2012

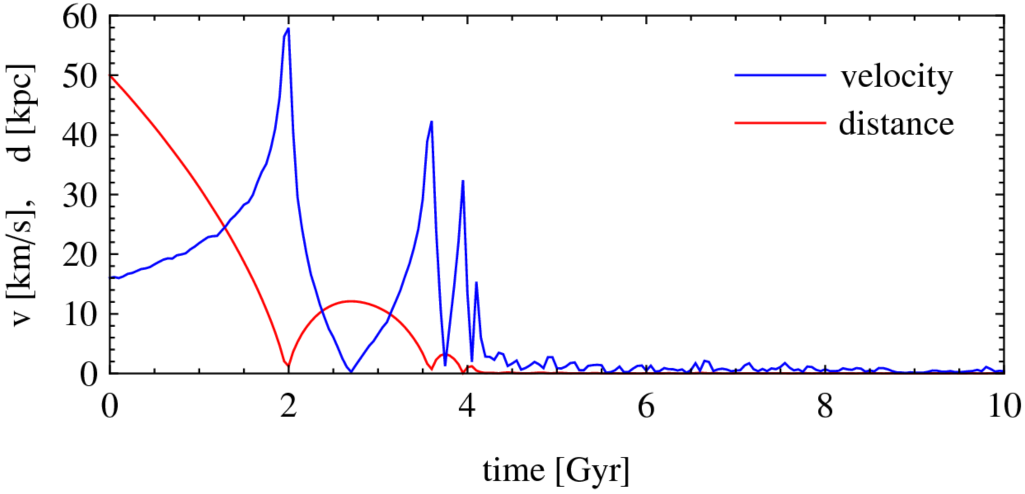
Initial conditions for merger



- Merger between very similar dwarf galaxies
- Only the disk scale-lengths are different



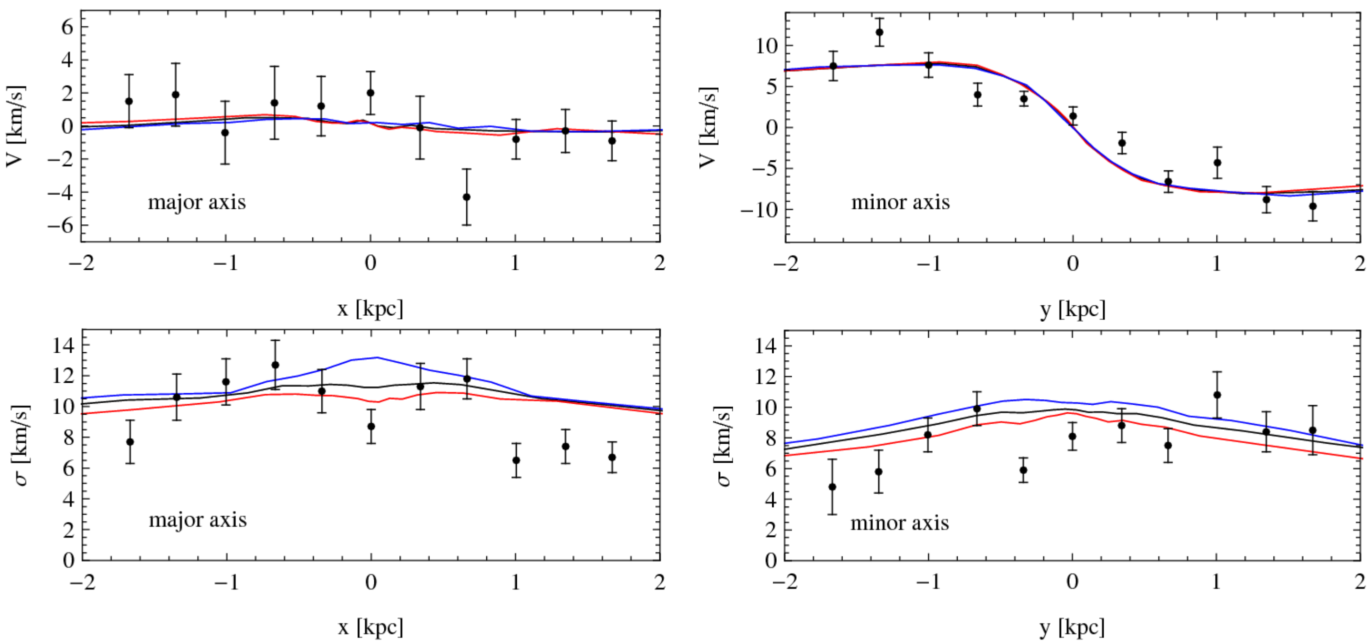
Evolution

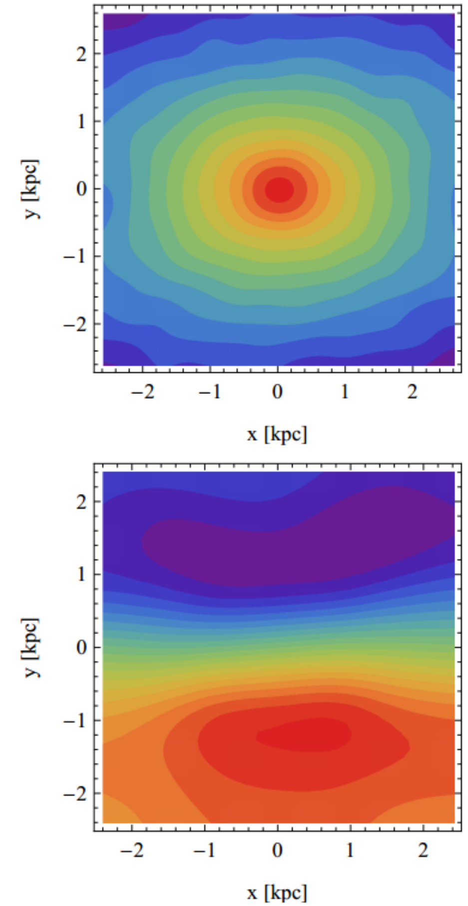


- First fly-by is after 2 Gyr
- The dwarfs merge completely after about 4 Gyr

Łokas et al. 2014b

Comparison with data

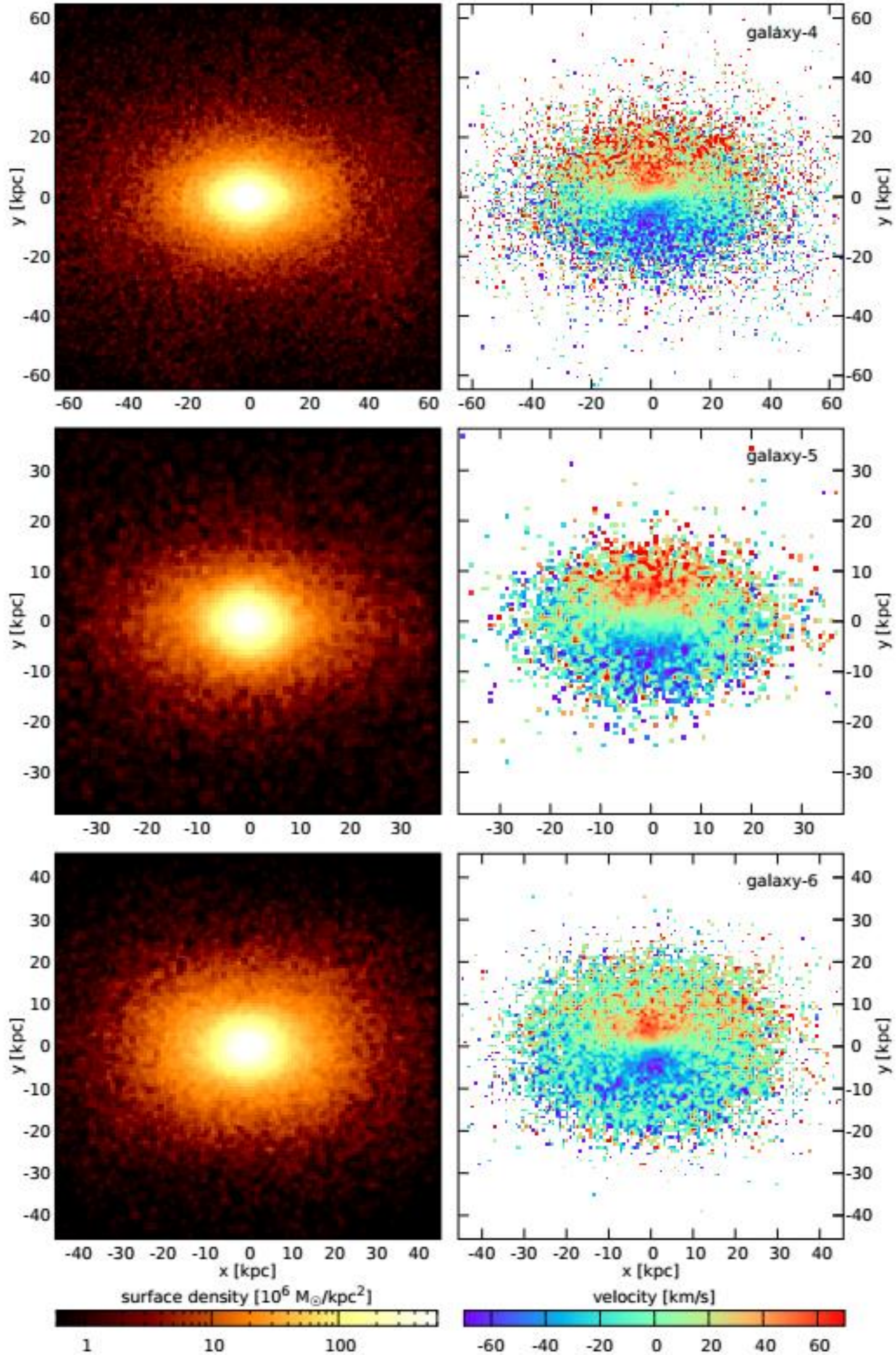




- Significant rotation is only along the minor axis
- Kinematics of both components is very similar

Łokas et al. 2014b

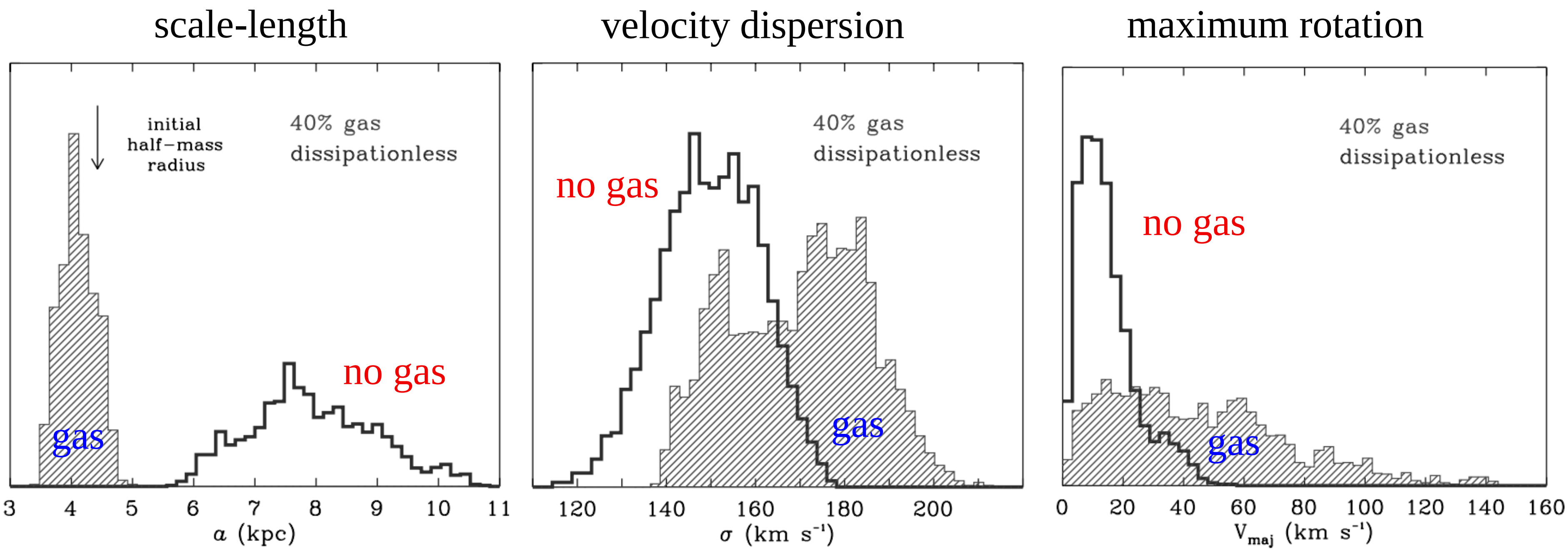
Galaxies with prolate rotation from Illustris



- Almost 60 objects with prolate rotation were identified among 7000 massive galaxies
- All were formed by radial mergers of gas-poor galaxies

Ebrova & Łokas 2017

Properties of merger remnants



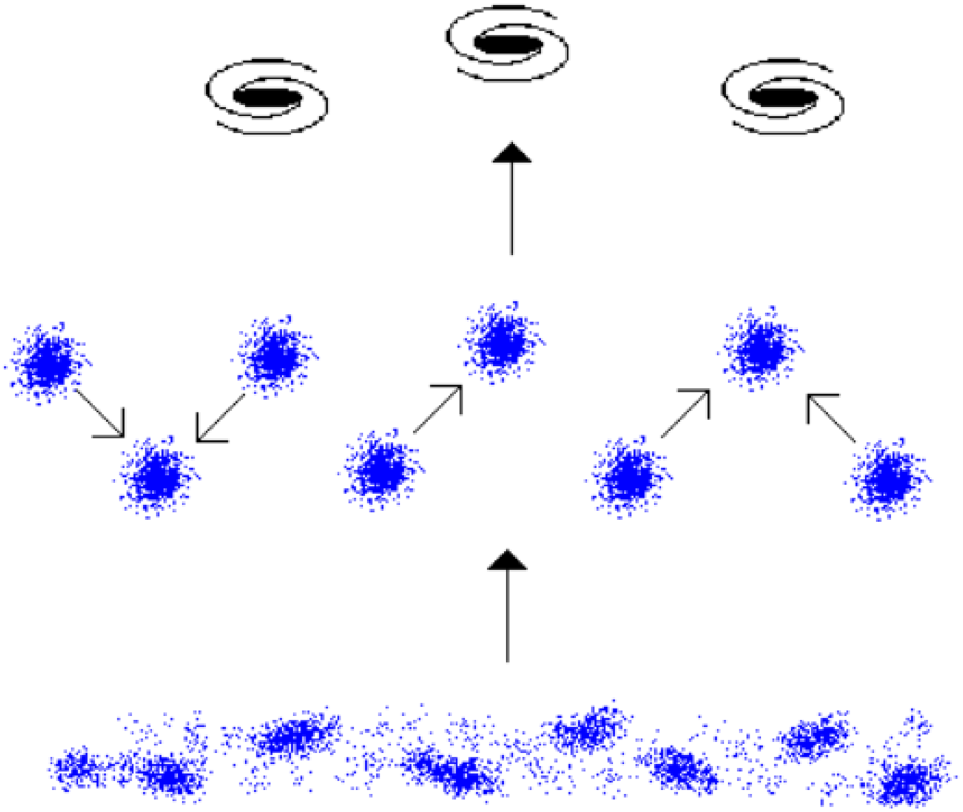
Properties differ significantly depending on gas content: remnants of dissipational mergers are smaller, rounder, have a larger central velocity dispersion and show significant rotation compared to remnants of dissipationless mergers

Cox et al. 2006

Scenarios of evolution

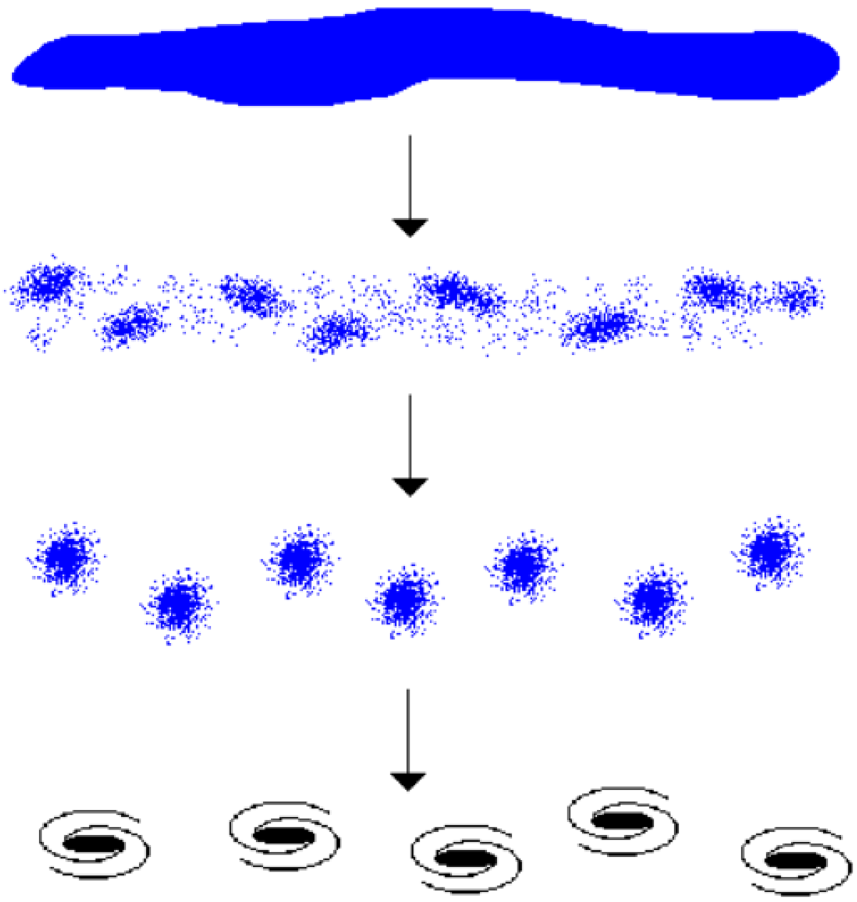
- Depending on the properties of dark matter, the structure will form in a different way
- In general, two main flavours of dark matter were considered: cold dark matter and hot dark matter
- Cold dark matter may be composed of slow particles like WIMPs (weakly interacting massive particles)
- Hot dark matter is composed of fast-moving particles with the main candidate in the form of neutrinos

Bottom-up galaxy formation



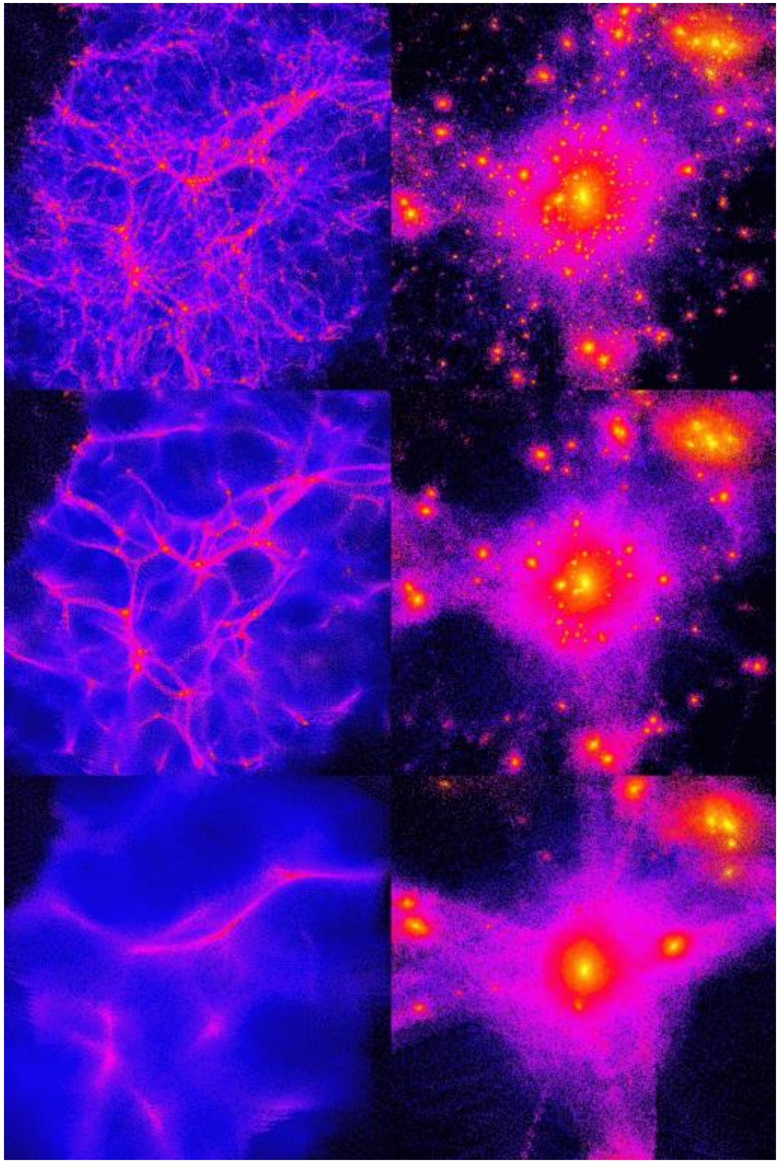
With cold dark matter structure forms so that small objects collapse first and then merge to form bigger structures

Top-down galaxy formation



With hot dark matter structure forms so that largest structures collapse first and then fragment to form smaller structures

Structure formation



cold dark matter

(a lot of substructure forms)

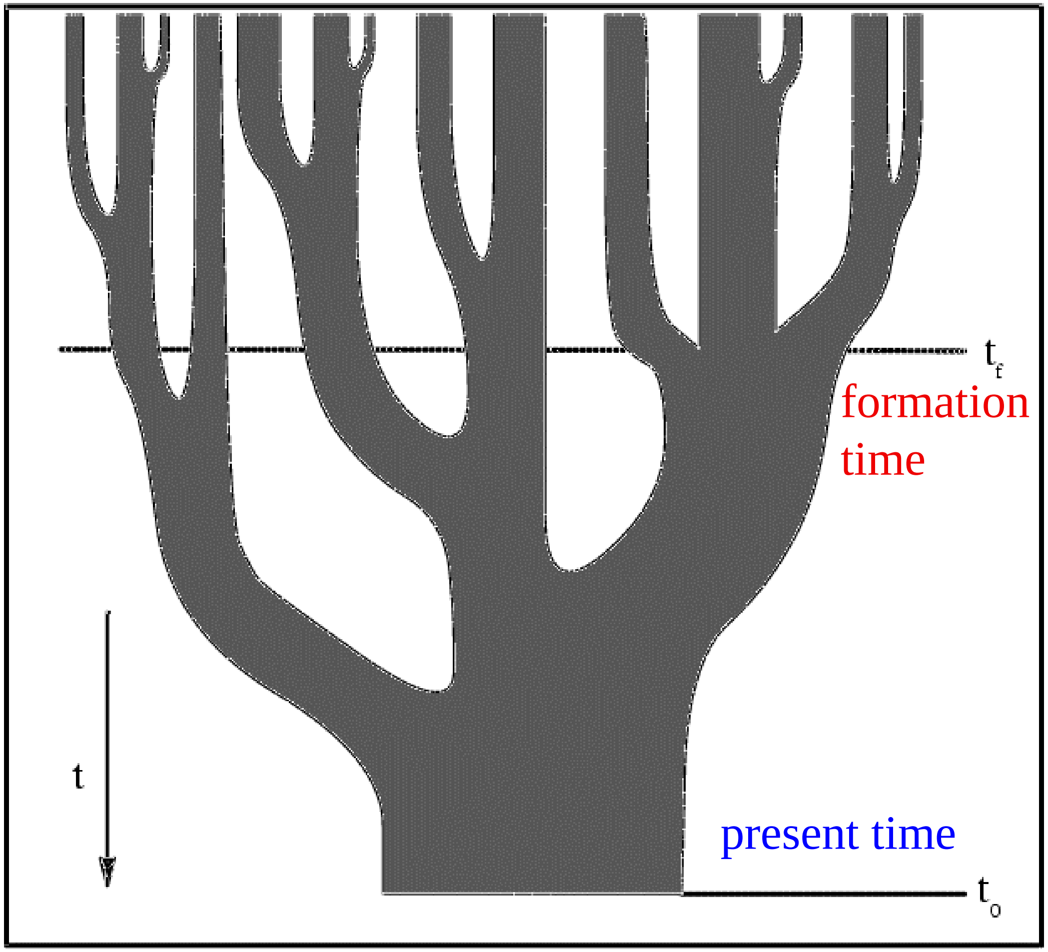
warm dark matter

(smallest haloes disappear)

hot dark matter

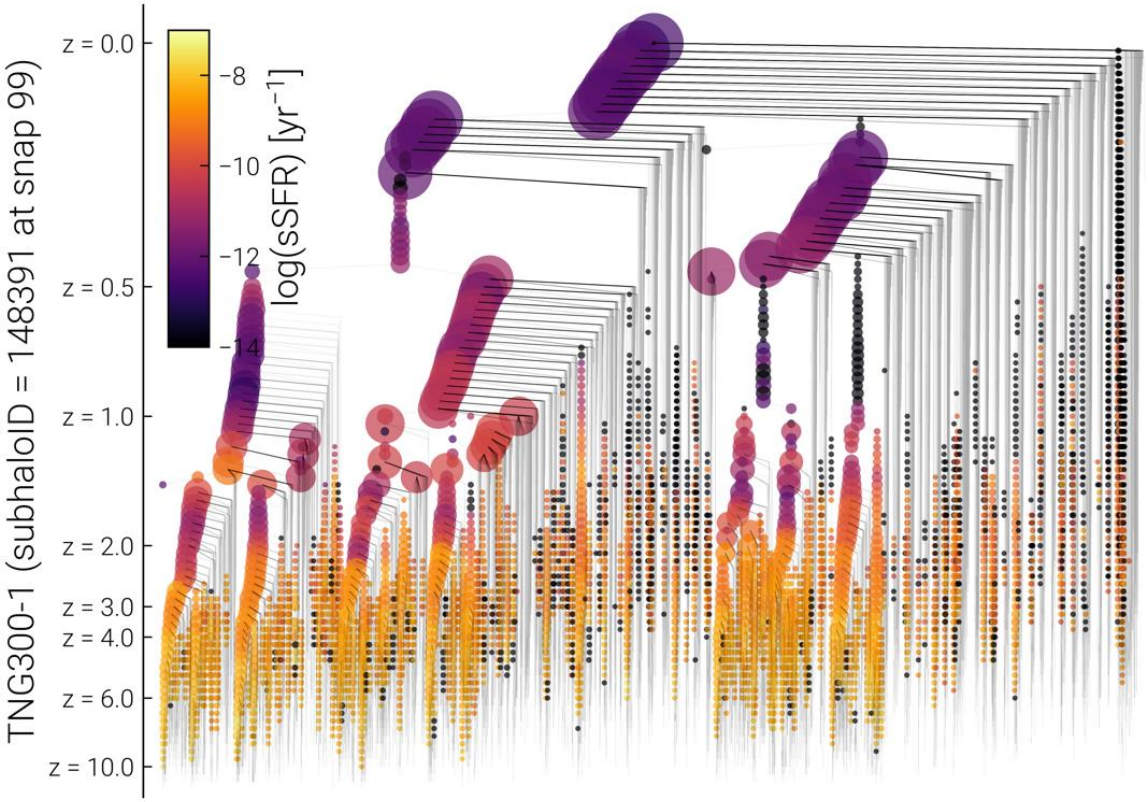
(no structure at small scales)

Merger trees



- Haloes grow by a series of mergers of smaller parent haloes
- The formation time of a halo is when a parent containing half of the mass of the final halo is first created

Example of merger tree



- Example of merger tree for a massive central galaxy of a cluster from IllustrisTNG simulations
- The galaxy forms via multiple mergers of smaller objects

https://www.tng-project.org

Strongly non-linear evolution

- When the density contrast $\delta = (\rho-\rho_b)/\rho_b$ in a given region is low, linear and perturbation theory can be applied
- Once it grows above unity, $\delta>1$, the linear regime and the perturbative expansion break down
- We then need to apply different approximations
- One of such approaches is the so-called spherical collapse or spherical top-hat model
- In this model we follow the evolution of a single, spherical region of uniform density in an otherwise unperturbed Universe

Evolution of the overdensity

- The region initially, at time t_i contains within the radius r_i the mass

$$M_i(r_i) = \frac{4\pi}{3}\rho_{b,i} r_i^3 (1+\Delta_i)$$

- The evolution is described by the equation (for a model without the cosmological constant)

$$\frac{d^2 r}{dt^2} = -\frac{GM}{r^2} \qquad \Rightarrow \qquad \frac{1}{2}\left(\frac{dr}{dt}\right)^2 - \frac{GM}{r} = E$$

- In the case with the cosmological constant

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 - \frac{GM}{r} - \frac{H^2 \lambda r^2}{2} = E$$

Condition for collapse

- For the perturbation to collapse we need it to be gravitationally bound, so $E < 0$
- The energy is the sum of the kinetic and potential energy at the initial time

$$E = \frac{\dot{r}^2}{2} - \frac{GM}{r} = \frac{H_i^{\,2} r_i^{\,2}}{2} - \frac{4}{3}\pi G \rho_b(t_i) r_i^{\,2}(1+\Delta_i) = \frac{H_i^{\,2} r_i^{\,2} \Omega_i}{2}\left[\Omega_i^{\,-1} - (1+\Delta_i)\right]$$

- The condition $E < 0$ thus means

$$\Delta_i > \Delta_{i,\,cr} = 1/\,\Omega_i - 1$$

- Therefore in the flat or closed Universe every overdense region ($\Delta_i > 0$) will eventually collapse

The maximum radius

- If $E < 0$ at some point the region will stop expanding and will start to collapse
- At the time of maximum expansion $dr/dt = 0$ and the energy is

$$E = -\frac{GM}{r_{ta}} = -\frac{r_i}{r_{ta}} \frac{H_i^2 r_i^2 \Omega_i}{2}(1+\Delta_i)$$

$$\frac{r_{ta}}{r_i} = \frac{1+\Delta_i}{\Delta_i - (\Omega_i^{-1} - 1)}$$

where r_{ta} is the turnaround radius

- Depending on the initial overdensity the region will reach a different turnaround radius

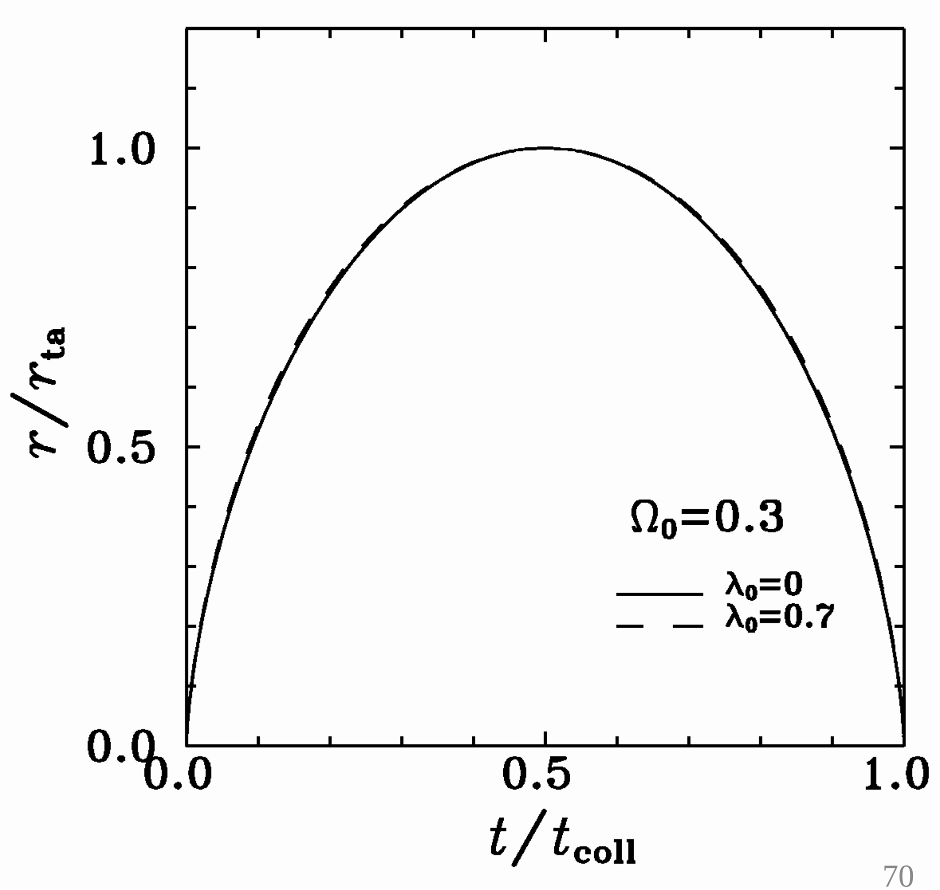
Solutions

In the case without the cosmological constant we can find an analytic solution in the form of the cycloid

$$\frac{r}{r_{ta}} = \frac{1}{2}(1 - \cos\theta)$$

$$\frac{t}{t_{ta}} = \frac{1}{2\pi}(\theta - \sin\theta)$$

$$0 \le \theta \le 2\pi$$



Comparison with linear evolution

- The evolution of the perturbation is best described by the changes in the density contrast which for $\Omega=1$ is

$$\delta = \frac{9}{2}\frac{(\theta - \sin\theta)^2}{(1-\cos\theta)^3} - 1$$

- On the other hand, the linear theory predicts

$$\delta_L = \frac{3}{5}\left(\frac{3}{4}\right)^{2/3}(\theta - \sin\theta)^{2/3}$$

- Comparing the predictions:

θ	δ_L	δ
$2\pi/3$	0.57	1.01
π	1.06	4.6
2π	1.69	∞

Characteristic densities

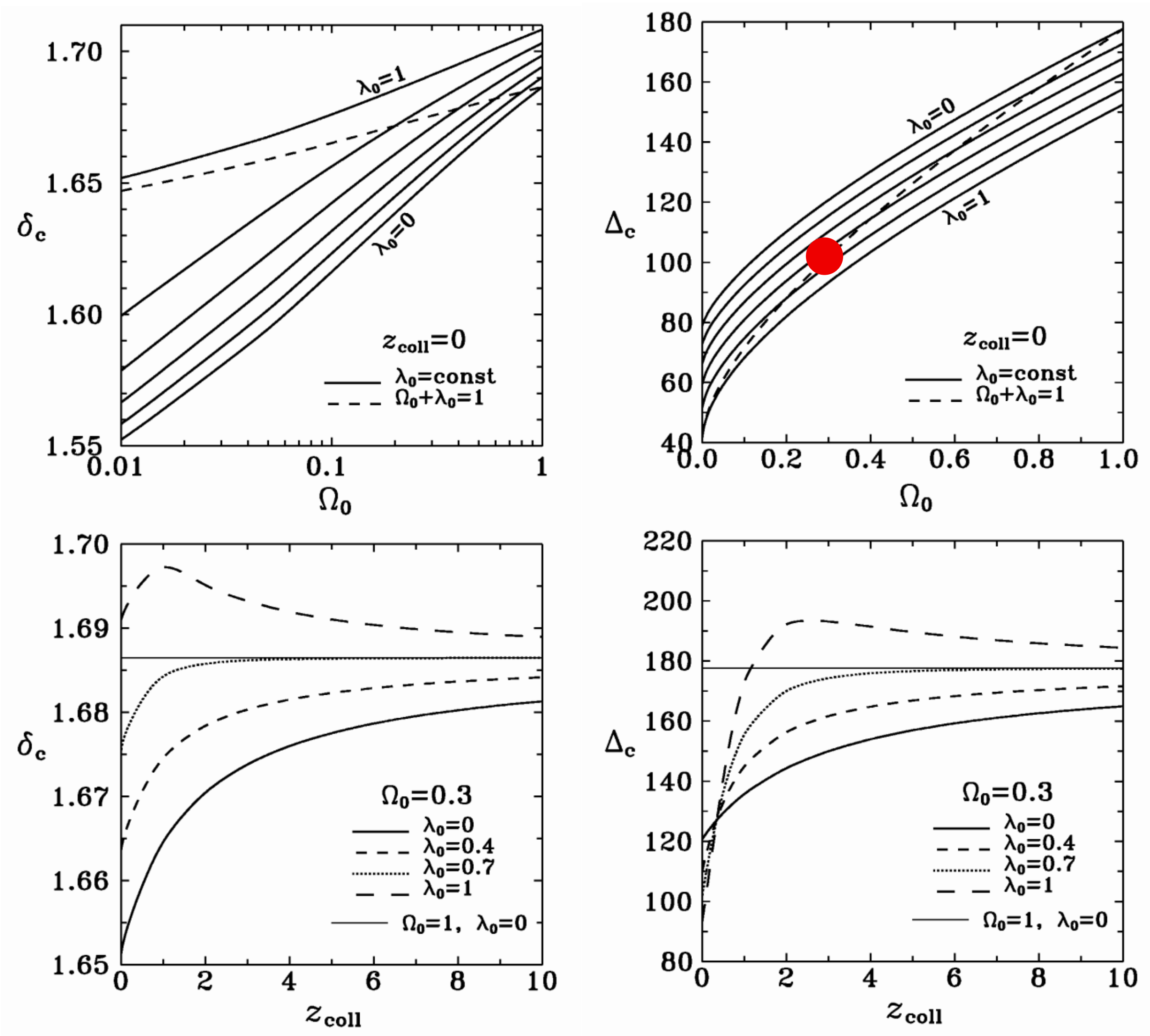
- At the time of collapse ($t=t_{coll}$, $\theta=2\pi$) for $\Omega=1$ the density contrast predicted by the linear theory is $\delta_c = 1.69$
- The nonlinear density contrast approaches infinity but earlier the cycloid model breaks down and the region virializes
- According to the virial theorem, the relation between the kinetic and potential energy is then

$$2E_k / |E_p| = 1 \quad \Rightarrow \quad r_{coll} = r_{ta} / 2$$

for a uniform sphere

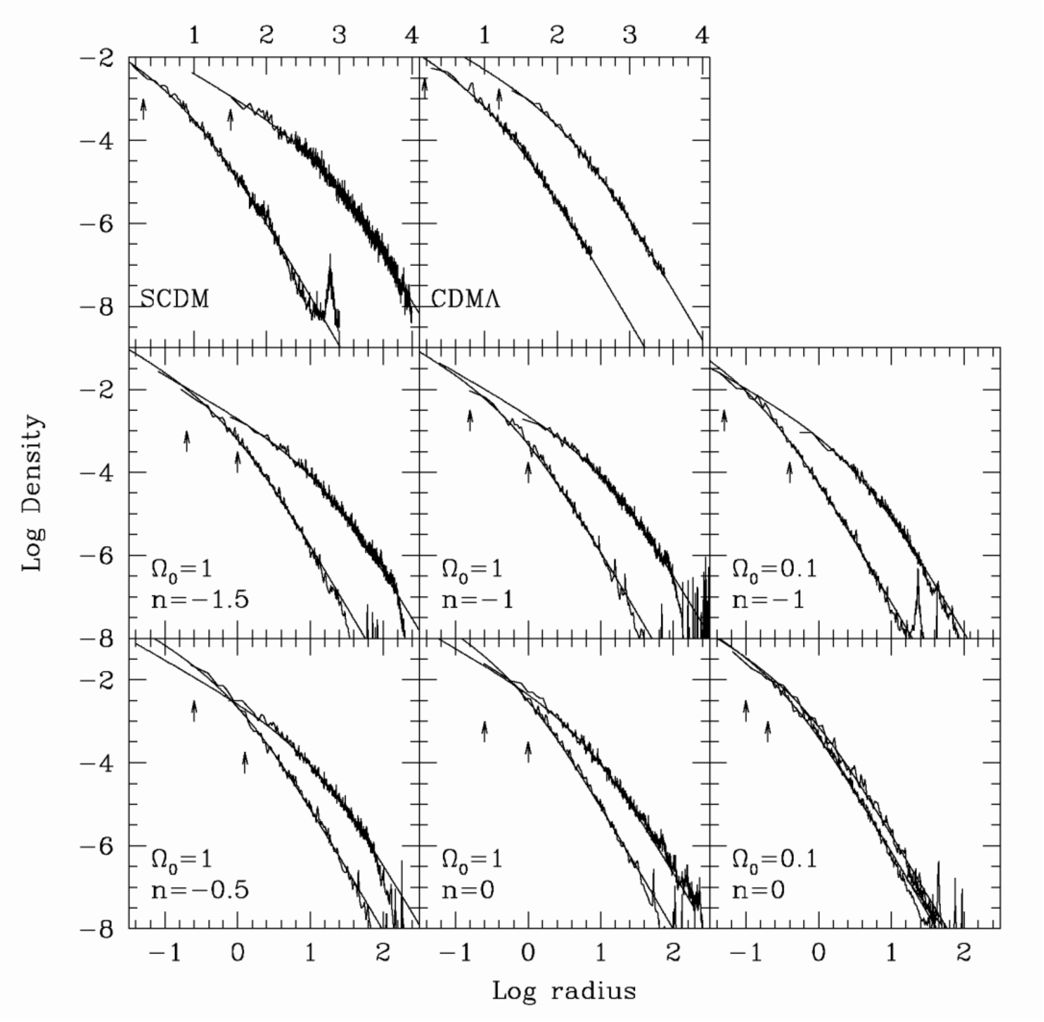
- And we get $\Delta_c = \rho_{vir} / \rho_{crit} = 18\,\pi^2 = 178$ for the real density with respect to the critical density

δ_c i Δ_c depend on cosmology



$\Delta_c = \rho_{vir} / \rho_{crit} = 102$ for the standard ΛCDM model

Density profiles of DM haloes



The universal profile of DM haloes (NFW)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_{char}}{(r/r_s)(1+r/r_s)^2}$$

is valid up to the virial radius defined by the virial overdensity

$r_s = r_v / c$ – scale radius

r_v – virial radius

c – concentration

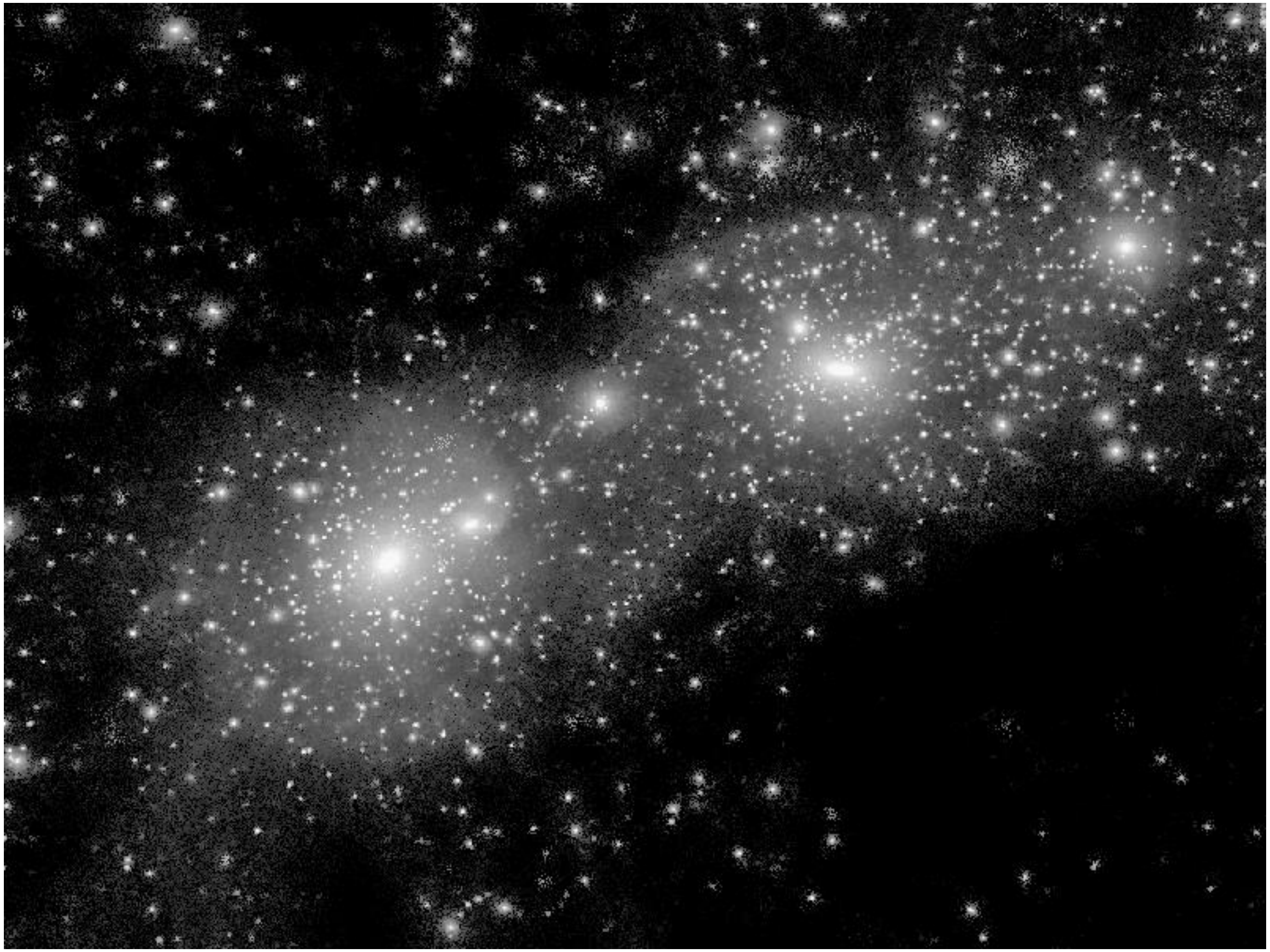
The ΛCDM paradigm

- Our universe started about 13.8 Gyr in a big bang
- It is composed of 4% baryons, 27% cold dark matter and 70% the cosmological constant
- Its geometry is flat
- The large-scale structure of the universe originates from small fluctuations formed in the era of inflation
- The structure formed „bottom up” – from small to large scales with smaller objects forming first and merging to produce bigger ones
- Dark matter halos formed earlier and then accreted baryons to form galaxies

Famous problems of ΛCDM

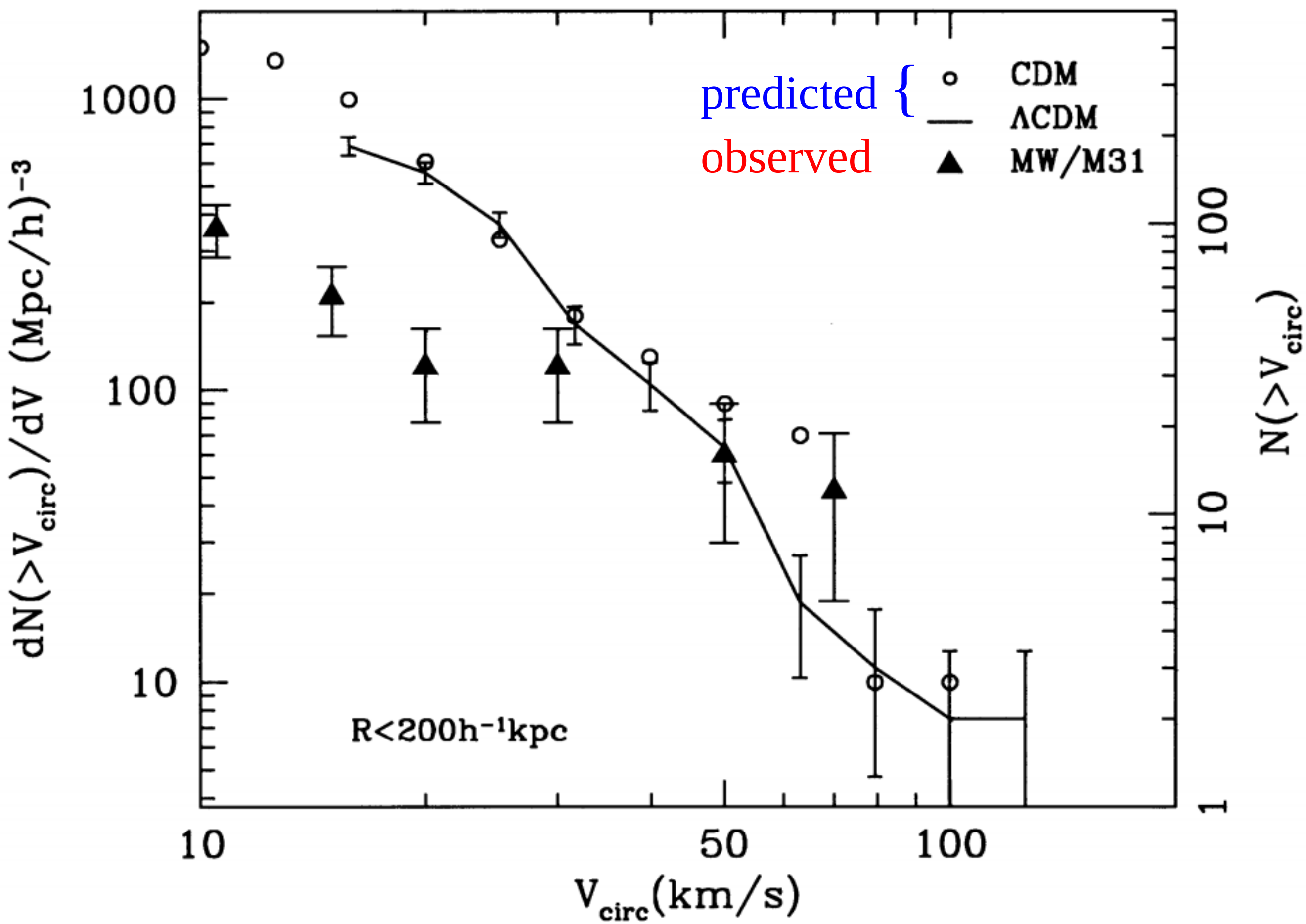
- The problem of missing satellites
- The cusp/core problem

Problem of missing satellites



Klypin et al. 1999, Moore et al. 1999

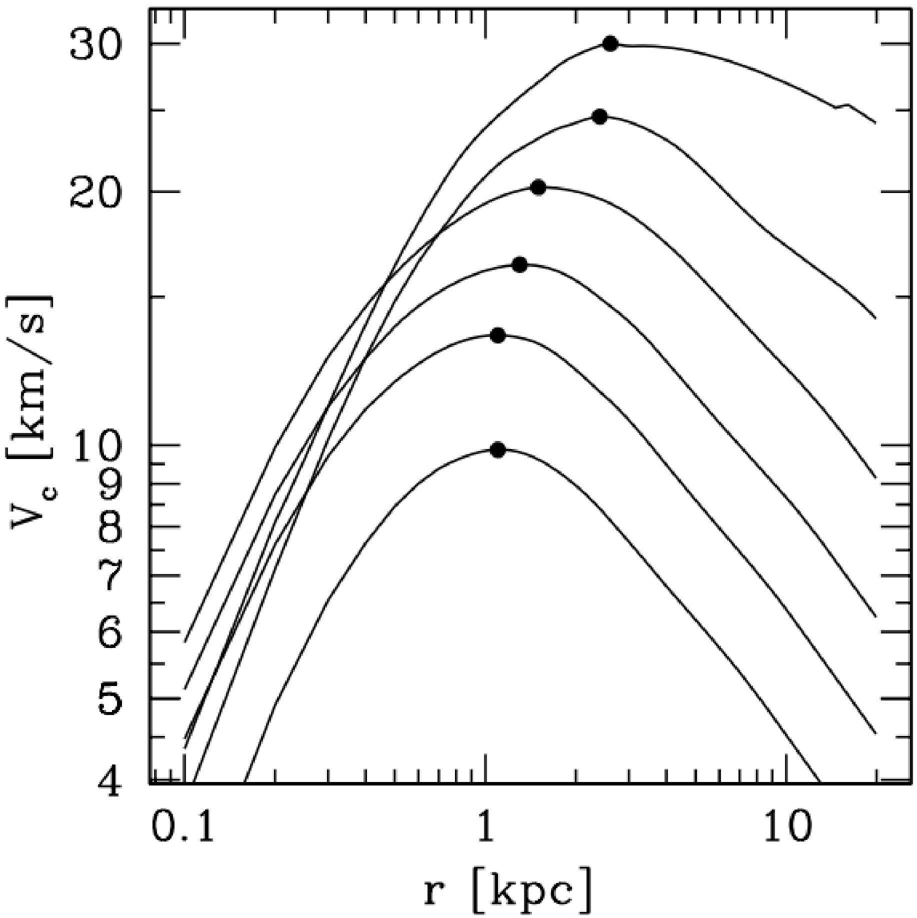
Mass function of satellites



The number of satellites predicted by ΛCDM simulations is much smaller than observed

Klypin et al. 1999

Circular velocity of haloes



The maximum value of the circular velocity profile of a halo is a robust measure of the halo mass often used in studies based on simulations

$V_c = [G\ M(r)/r]^{1/2}$

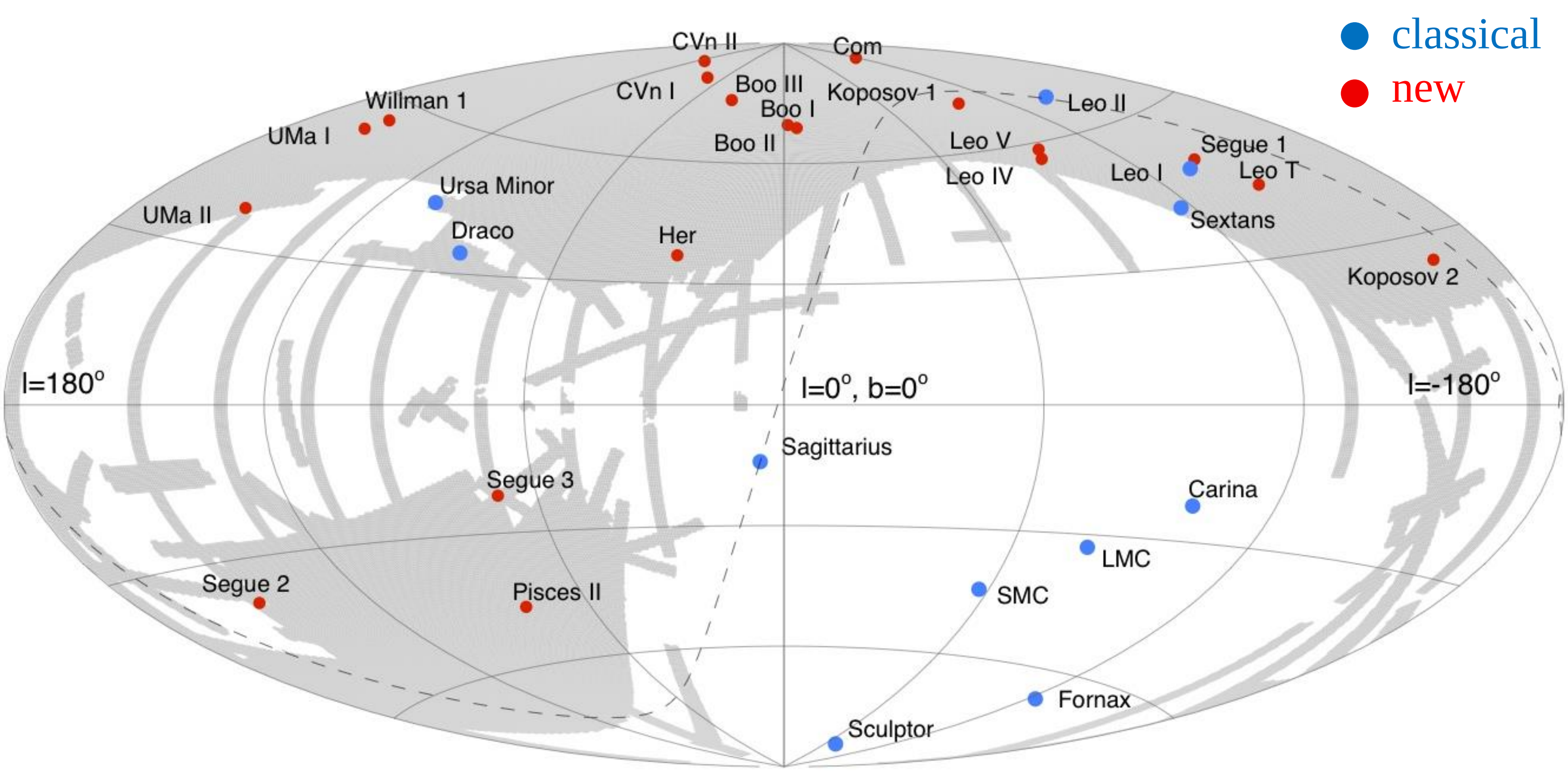
$M \sim V_{max}^{3.5}$

Klimentowski et al. 2009

Solutions to MSP

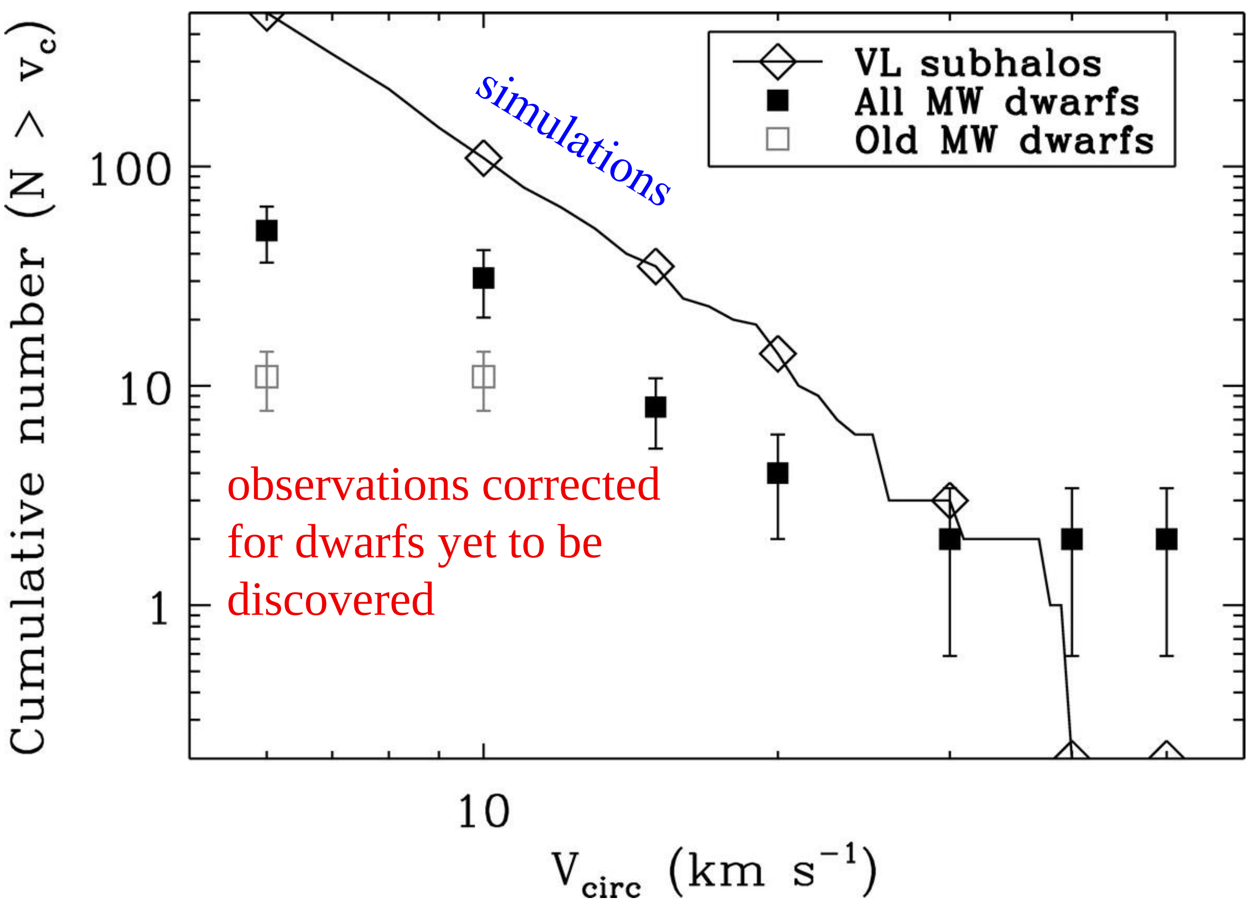
- The missing dwarf galaxies remain to be discovered
- Dwarfs inhabit only the most massive subhaloes or most massive when accreted or formed at the earliest times
- Baryon physics affects the distribution of dark matter in dwarfs and makes them less bound and subject to disruption

New dwarfs discovered



Ultra-faint dwarfs were discovered in SDSS significantly increasing the number of known satellites of the Milky Way

Including new dwarfs



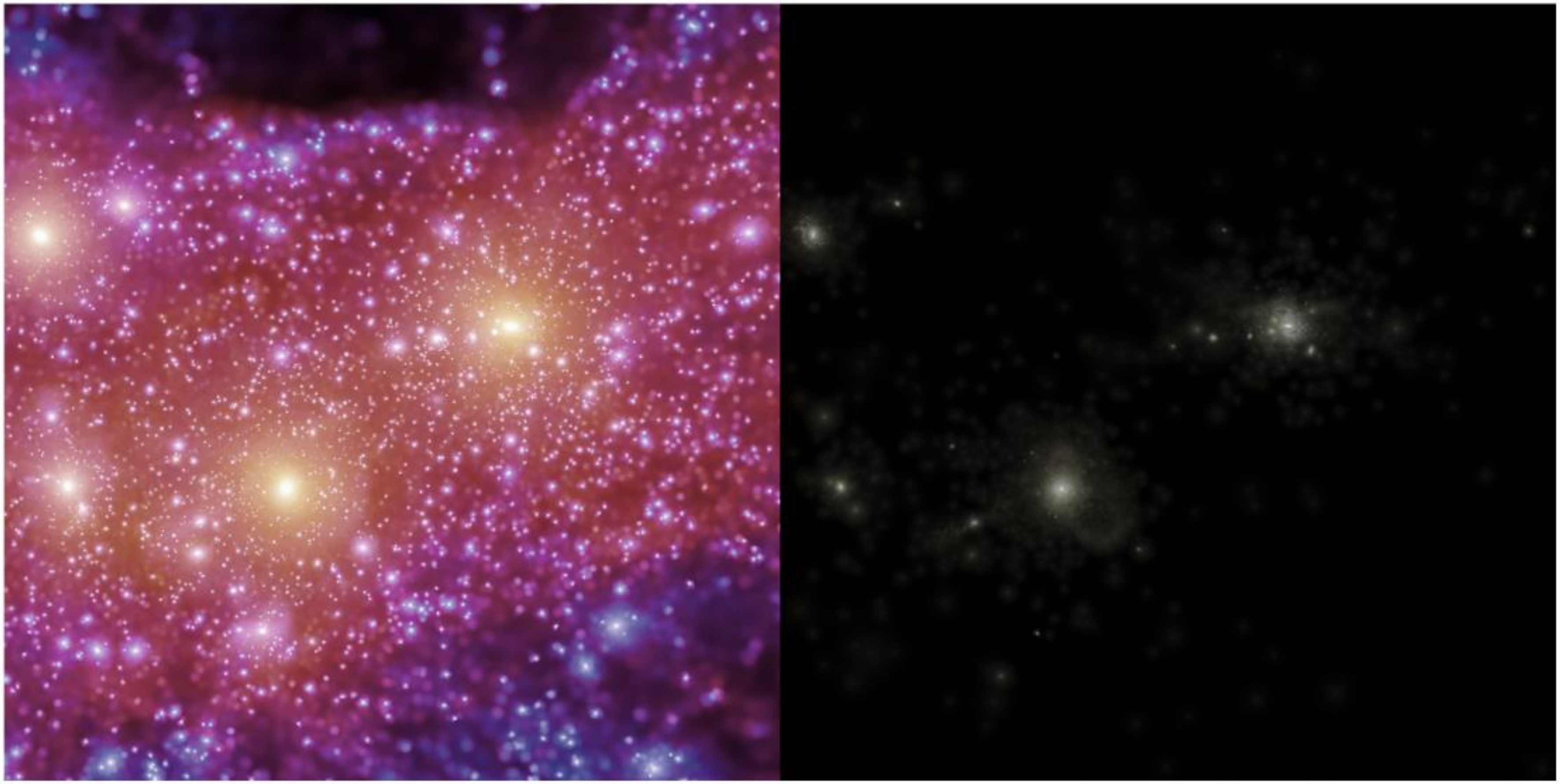
Taking into account the new dwarfs partially solves the problem of missing satellites, but not fully

Simon & Geha 2007

Biased galaxy formation

dark matter

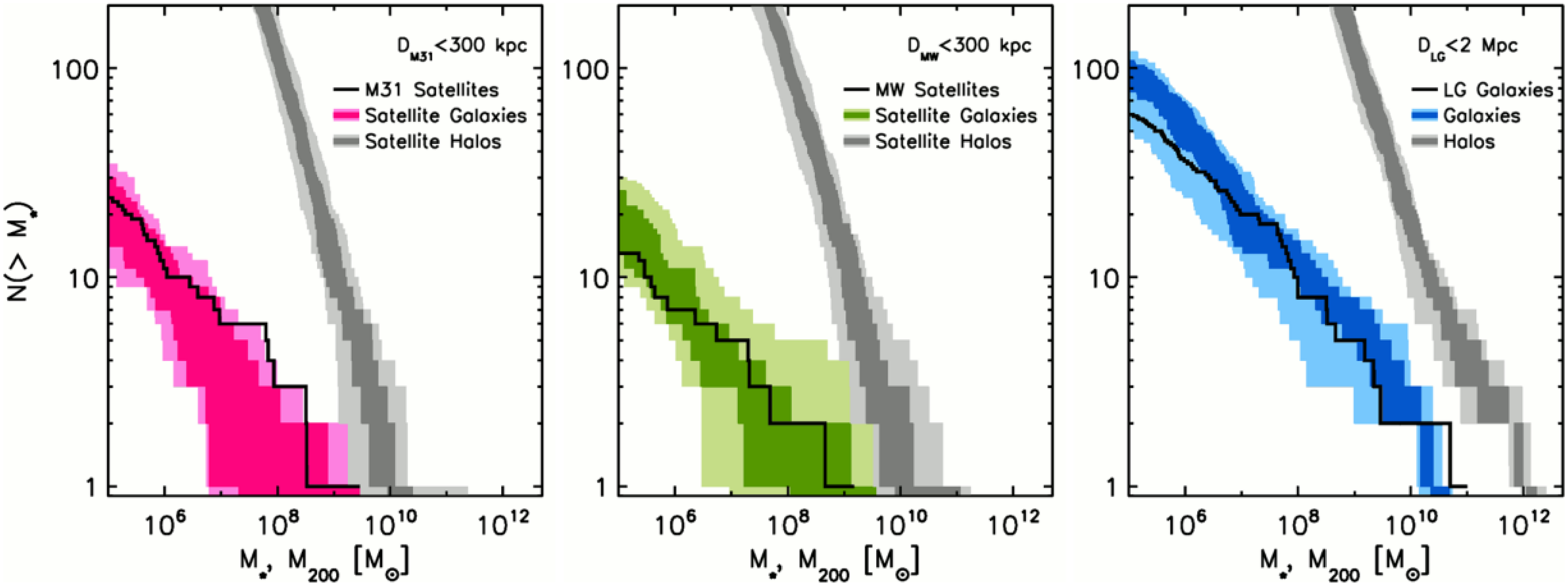
stars



2 Mpc

Galaxies form only in most massive haloes

Mass functions of galaxies

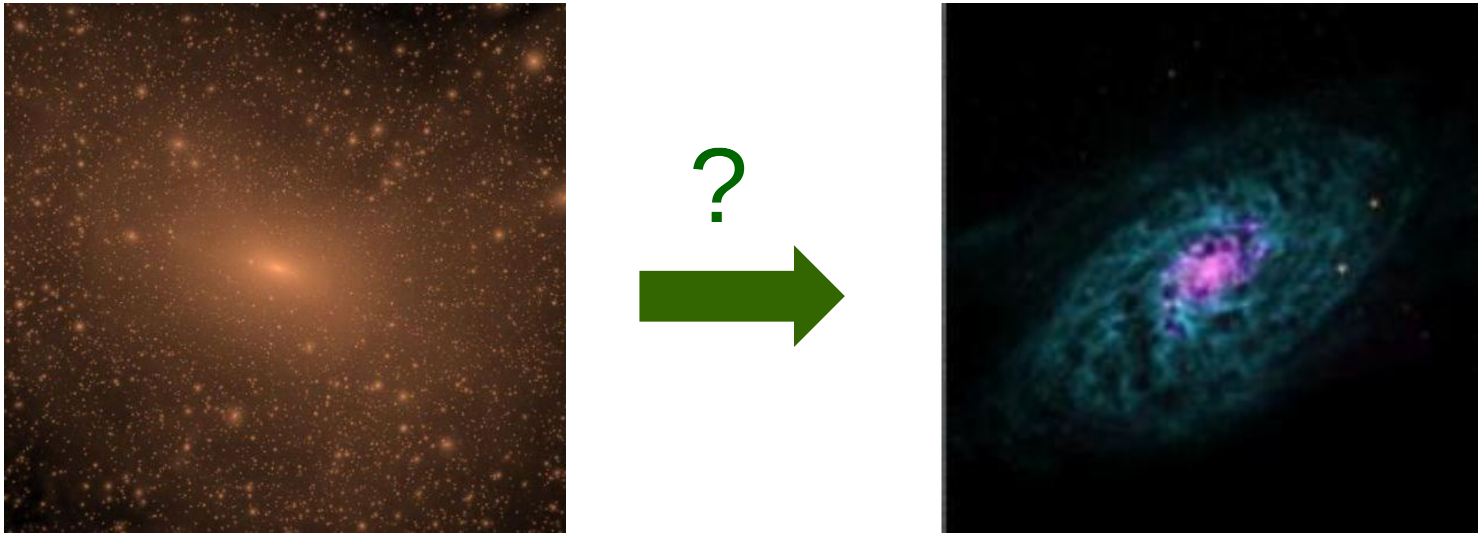


Sawala et al. 2016

Predicted galaxy mass functions agree with observations for stellar masses $M_* > 10^5\ M_\odot$

The cusp/core problem

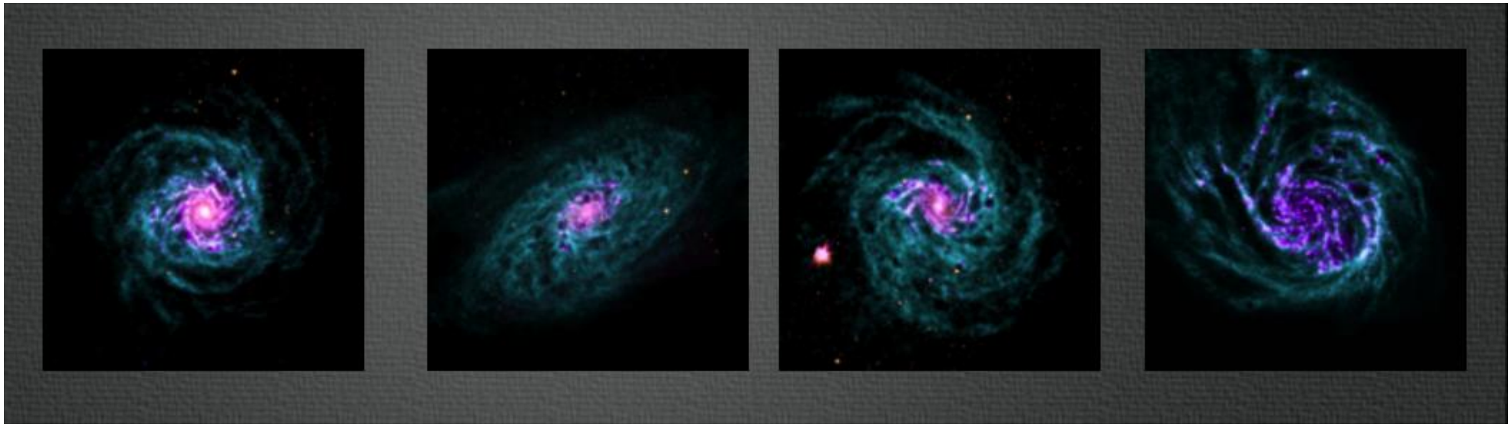
- Pure dark matter simulations predict cuspy density profiles in the inner parts
- Observations suggest that dark matter profiles of LSB galaxies have cores
- The problem usually concerns dwarf galaxies



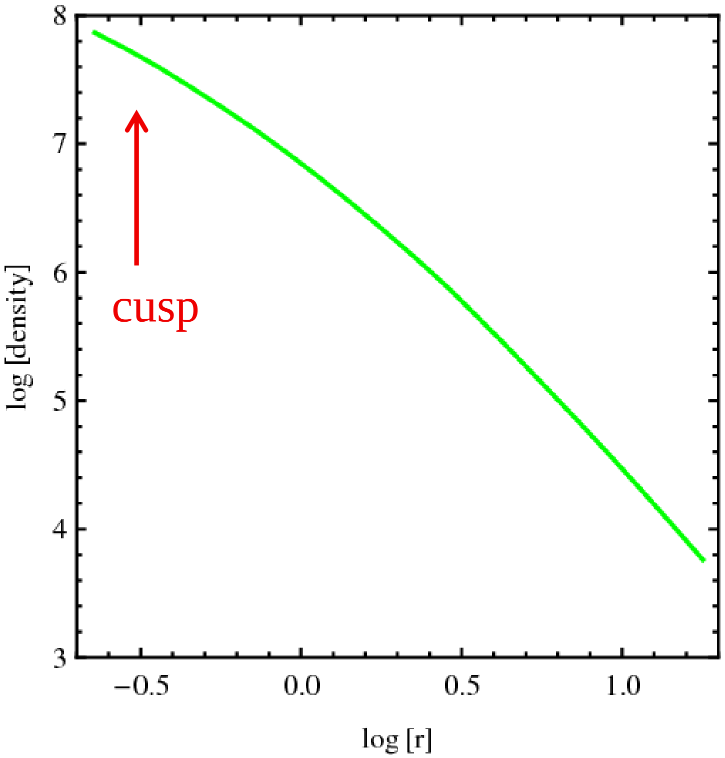
DM halo galaxy

Why dwarf galaxies?

- Dwarf galaxies provide good opportunity for measuring dark matter distribution in their centers
- They have simple dynamical structure (no bulges)
- They are characterized by low baryon fractions so baryons contribute less to the dynamics
- Dark matter dominates even in the center in contrast to normal galaxies



Cuspy profiles



Navarro, Frenk & White 1997

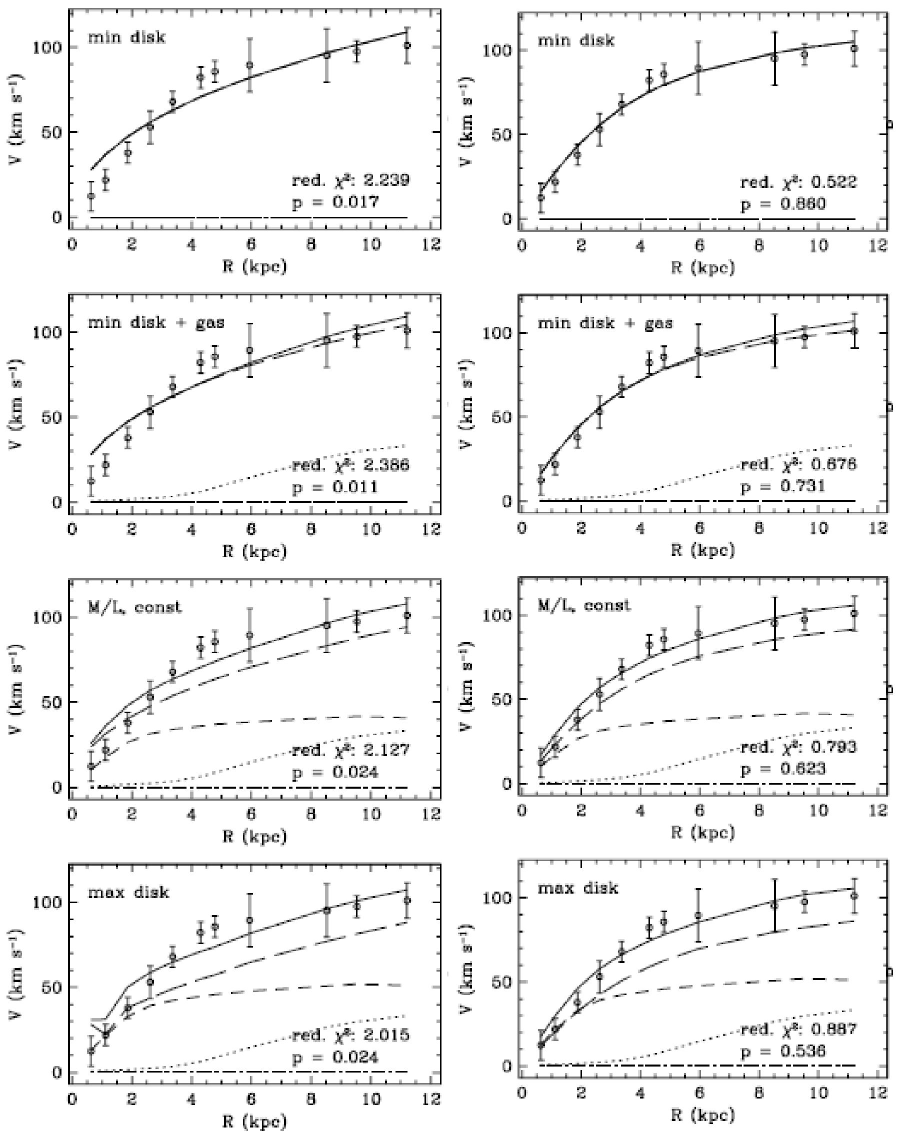
The NFW dark matter profile

$\rho \sim (r/r_s)^{-1} (1+r/r_s)^{-2}$

describes well the density distribution of dark matter in halos of different masses formed in pure dark matter simulations

Is it preserved in real galaxies?

Observations



NFW core

Rotation curves of dwarf galaxies seem to be better fitted by dark matter profiles with cores for different galaxies, observation type etc.

galaxy F568-3

de Blok, McGaugh & Rubin 2001

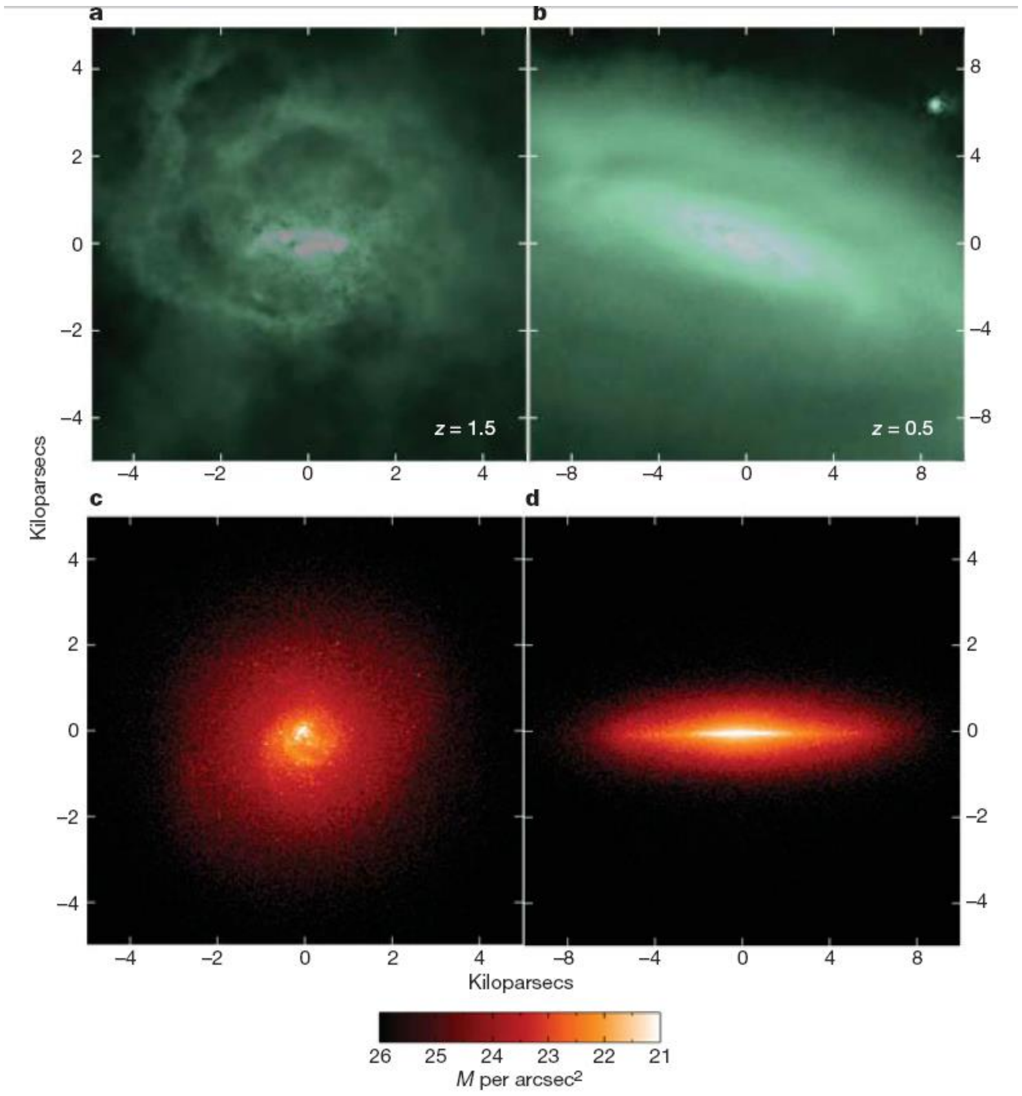
Proposed solutions

- Cusps are there but we are unable to detect them due to observational uncertainties: beam smearing, center offset, non-circular motions, triaxial halos
- Cusps are changed into cores due to a number of baryon physics effects: changes of potential caused by starburst-driven outflows, SN-driven bulk motions of the gas, dynamical friction acting on gas clumps, transfer of angular momentum from baryons to dark matter
- Cusps do not form because dark matter has different properties, e.g. is self-interacting

Improved models

- High resolution N-body + hydro simulations of the formation of dwarf galaxies in the ΛCDM context (halos for resimulation selected from low-resolution large-scale simulation)
- Include baryonic processes: gas cooling, star formation, cosmic UV background heating, gas outflows driven by supernovae
- Critical improvement: individual star-forming regions of mass $10^5\ M_\odot$ are resolved and only high density gas clouds are allowed to form stars
- A dwarf galaxy of mass $\sim 10^{10}\ M_\odot$, a cored DM profile and no bulge is formed

The dwarf galaxy

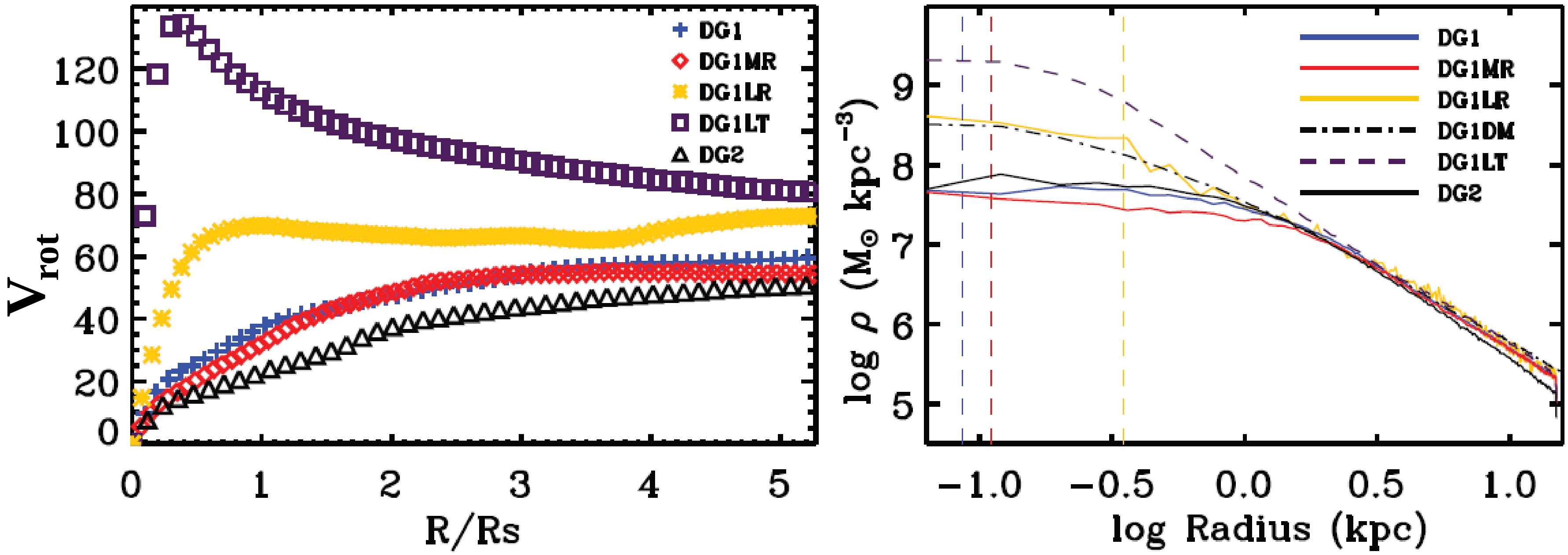


Density distribution of the gas at different redshifts (4.3 and 8.6 Gyr after Big Bang)

Distribution of light in the infrared band at z=0

Governato et al. 2010

Rotation curves and DM profiles



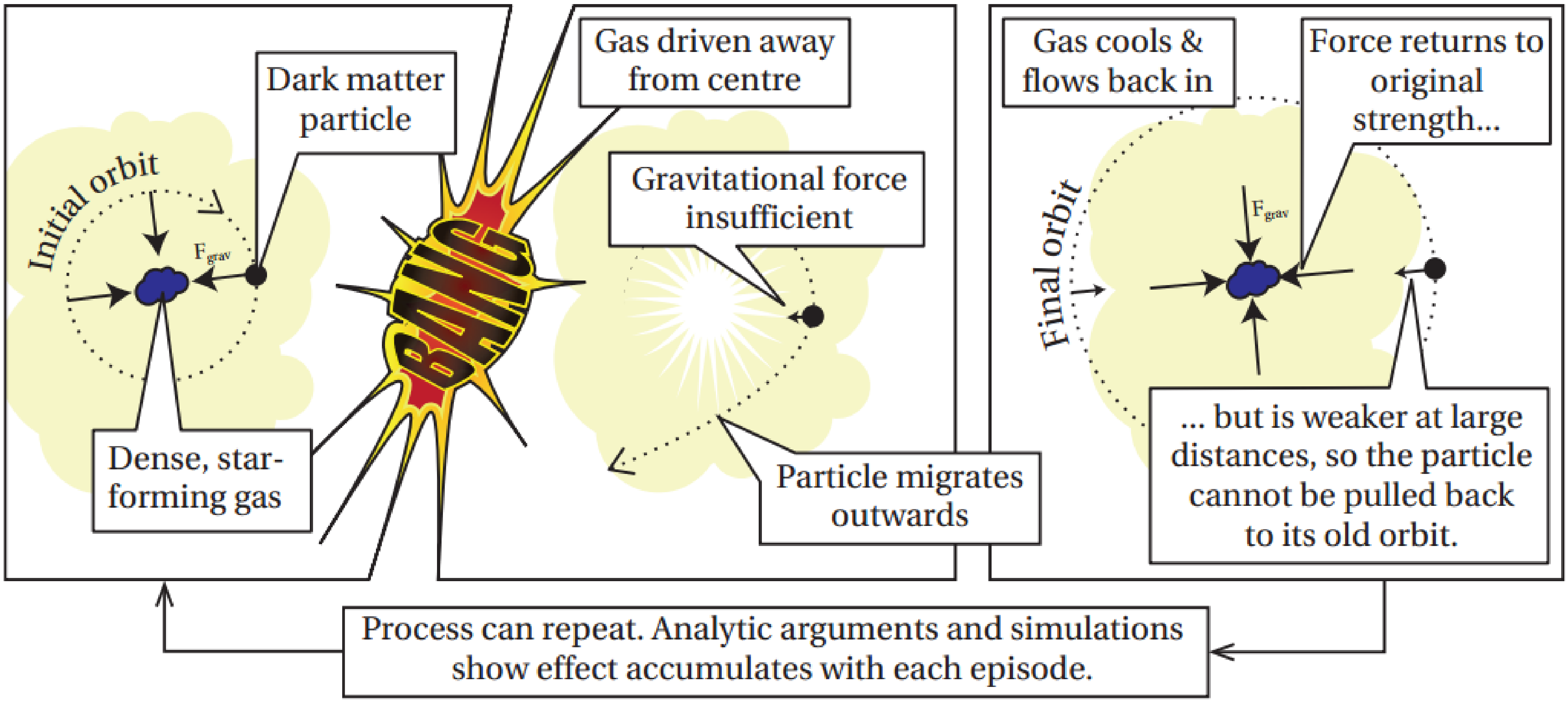
DG1, DG2 – two different realisations of dwarf galaxies

DG1MR, DG1LR – medium and low resolution

DG1DM – DM only

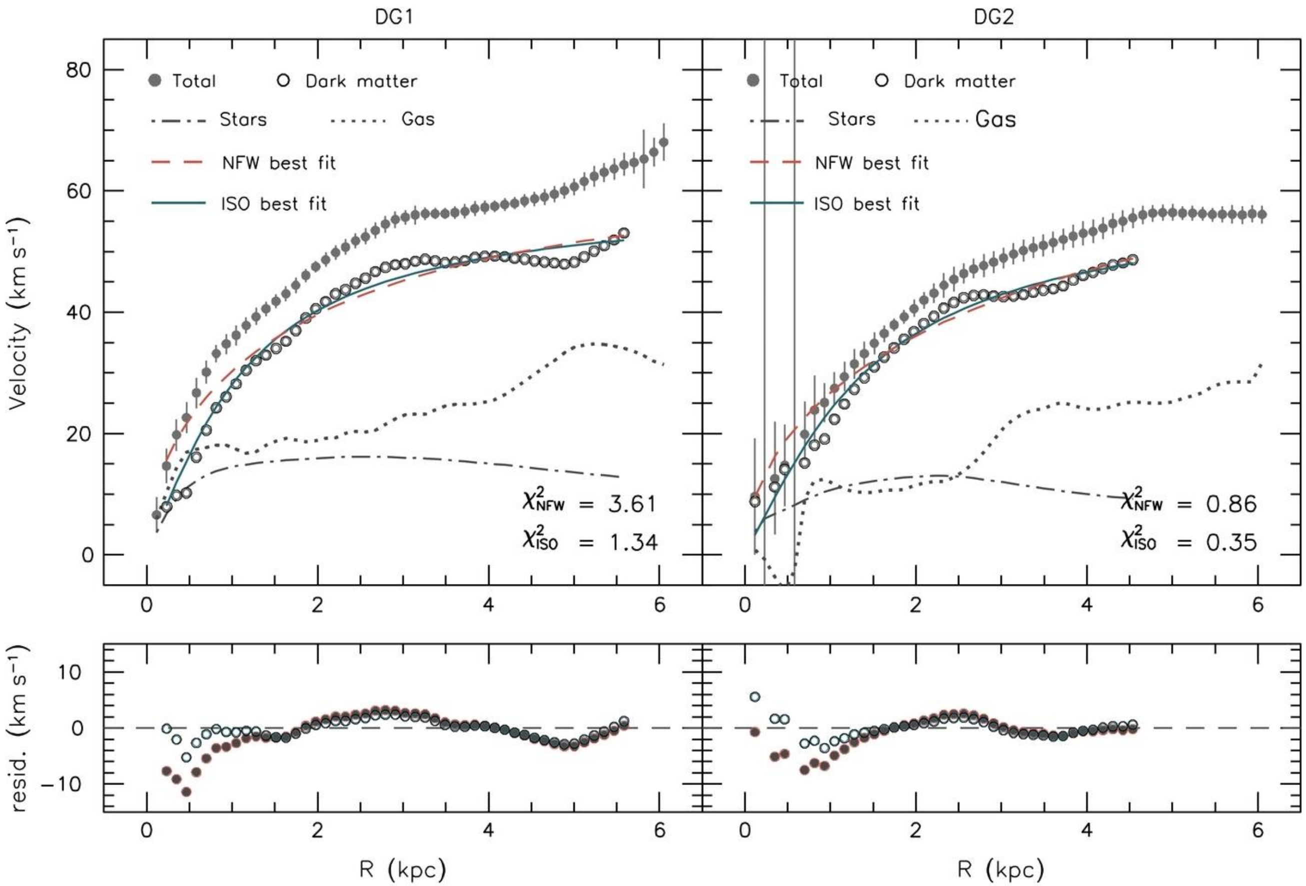
DG1LT – low threshold for star formation (no outflows)

Interpretation



Outflows of gas are identified as the main mechanism altering the distribution of dark matter: they change the central potential causing the halo to expand and form a core

Analysis of simulated dwarfs



Analysis performed as on real observations: cores are detected so observational effects are under control

Oh et al. 2011

The THINGS survey

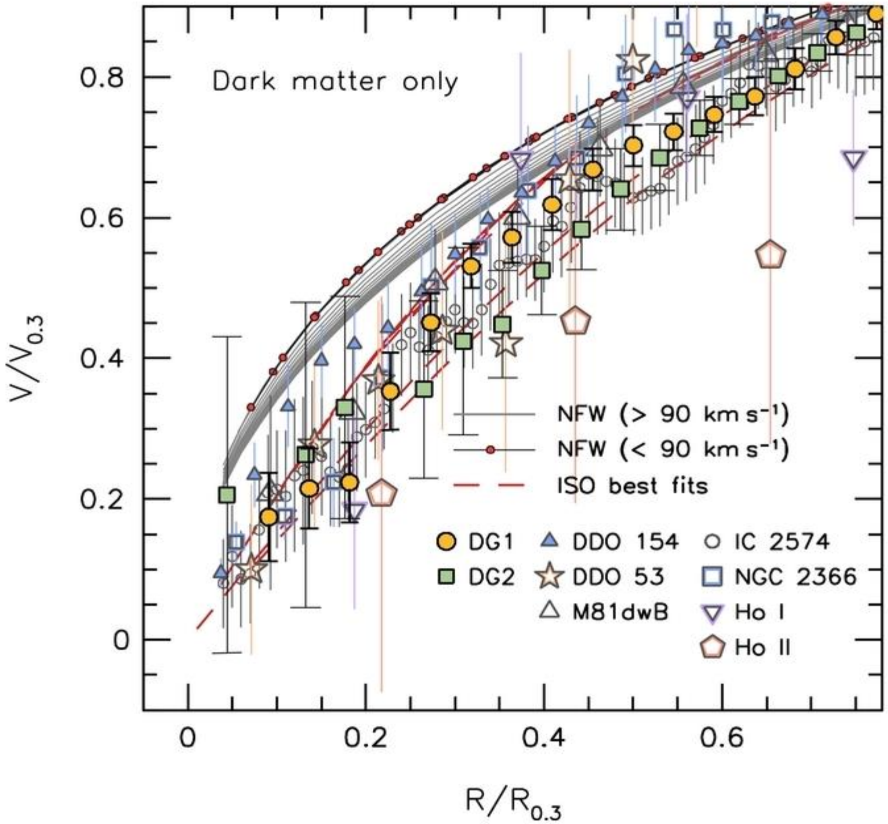
- The HI Nearby Galaxy Survey (THINGS) is a large program undertaken by NRAO Very Large Array (VLA)
- Observations of nearby galaxies in 21 cm HI line with 7 arcsec angular resolution and 5 km/s velocity resolution
- The goal was to investigate galaxy morphology, star formation and mass distribution
- A sample of 34 objects at distances 3-15 Mpc

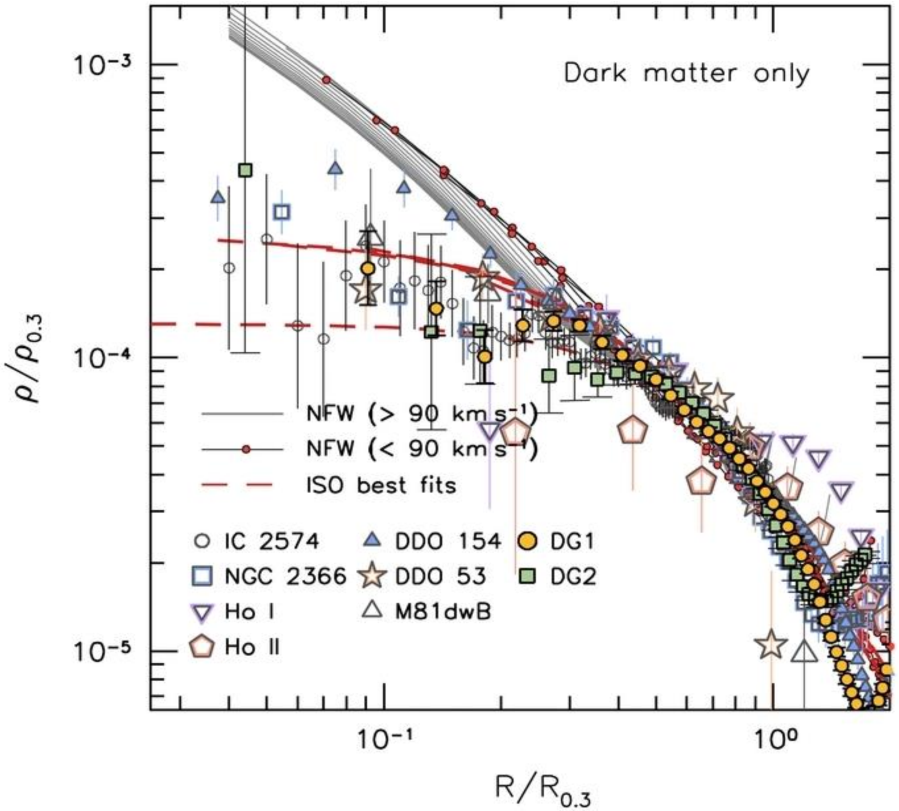
The THINGS survey

NGC 628
NGC 925
NGC 1569
NGC 2366
NGC 2403
Holmberg II
M81 dwarf A
DDO 53
NGC 2841
NGC 2903
Holmberg I
NGC 2976
NGC 3031
NGC 3077
M81 dwarf B
NGC 3184
NGC 3198
IC 2574
NGC 3351
NGC 3521
NGC 3621
NGC 3627
NGC 4214
NGC 4449
NGC 4736
DDO 154
NGC 4826
NGC 5055
NGC 5194
NGC 5236
NGC 5457
NGC 6946
NGC 7331
NGC 7793

DM in THINGS galaxies

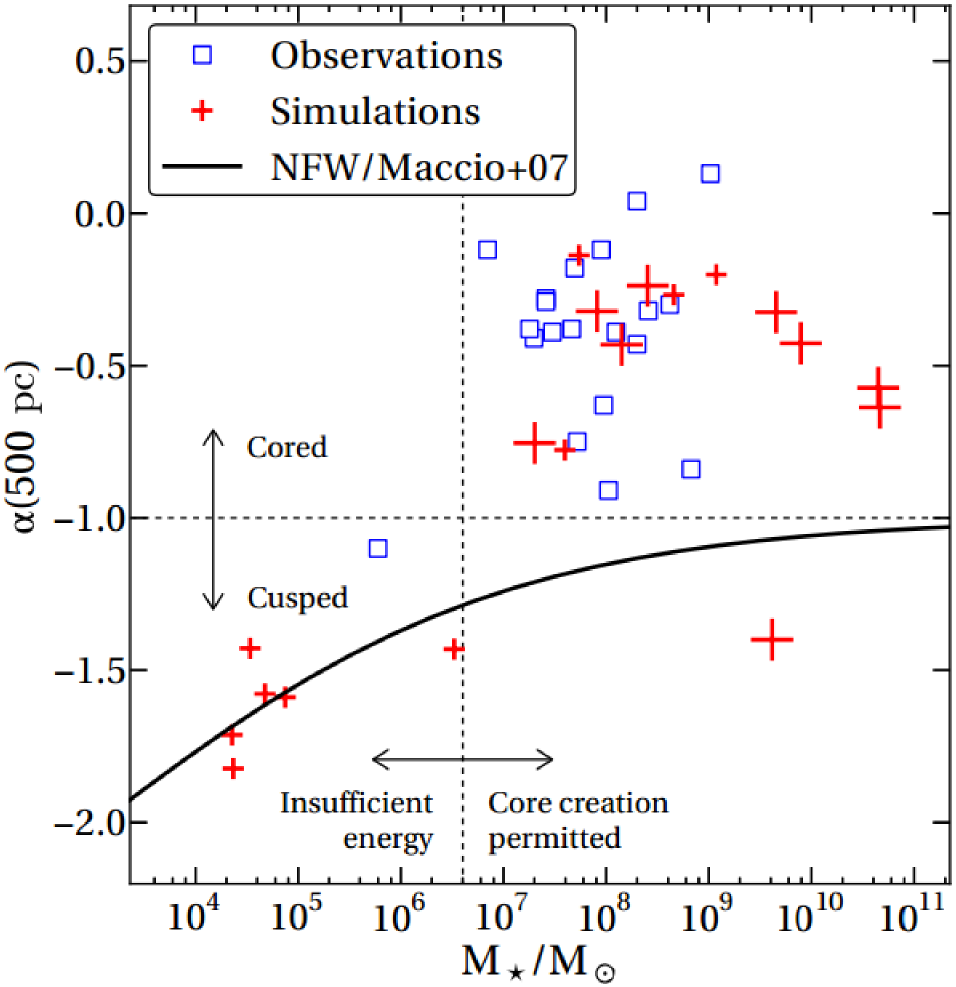
Oh et al. 2011





Circular velocity profiles of THINGS galaxies are better fitted by cored profiles than NFW

Not always cores



- Formation of the core requires enough baryons
- For small stellar components the feedback is not strong enough and the galaxies retain cusps

Governato et al. 2012, Pontzen & Goevernato 2014

Are the problems related?

- The cusp/core problem appears to be solved by proper treatment of star formation processes
- New simulations are able to reproduce dwarf galaxies with cored DM profiles
- The cored DM profiles have implications for the missing satellites problem: dwarfs with cores are easier to destroy by tidal forces

Solving the problems

- The problems reported as fatal for ΛCDM arise when observations are confronted with predictions from dark matter only simulations under the assumption that baryonic processes are unimportant
- The distribution of light is not a precise tracer of dark matter and simple models for populating dark matter structures with galaxies do not capture the complexity of galaxy formation physics
- Full hydrodynamic simulations have previously focussed on individual galaxies ignoring the LG environment and have not yet been able to reproduce the LG dwarf galaxy population