Modern advances in galactic astrophysics : from *scale-invariant dynamics* to a successful theory of galaxy formation and evolution

Lecture 2

Further on dynamical friction : evidence for merging galaxies.
Galaxy populations and correlations in their properties
21.12.2016

Selected Chapters on Astrophysics
Charles University, Praha,
December & January 2016/17

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Lecture 1 (14.12.16) **:**

The standard model of cosmology (SMoC) and the arguably greatest question of 20th/21st century physics **:** Do the postulated dark matter particles exist **?**

Lecture 2 (21.12.16) **:**

Further on dynamical friction **:** evidence for merging galaxies.
Galaxy populations and correlations in their properties

Lecture 3 (04.01.17) **:**

Structures on large scales and performance of the SMoC;
Correlations in the properties of galaxies I **:** Galaxies are simple systems.

Lecture 4 (11.01.17) **:**

Correlations in the properties of galaxies II.
Evidence for a new law of nature **:** space-time scale-invariant dynamics.
Some steps towards a deeper theoretical understanding.

Remember:

Chandrasekhar dynamical friction very efficient in capturing and decelerating passing galaxies ==> merging.

Position and motions of the observed satellite galaxies of the Milky Way difficult to understand if dark matter halos exist.

Assuming the SMoC to be valid: The *Dual Dwarf Galaxy Theorem* is falsified by observational data (no evidence for both dwarf types A&B) ==> SMoC ruled out as a viable model of the Universe.

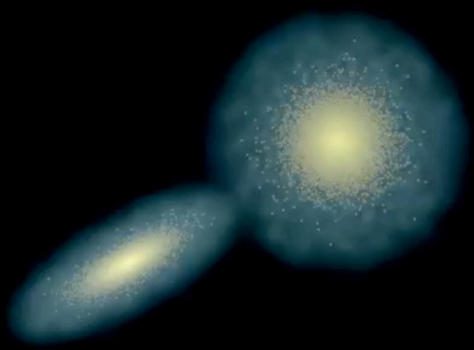
Tests of this conclusion via the arrangement of dwarf galaxy satellites : The Vast Polar Structure around the Milky Way is highly significant

Other disks of satellites (DoSs) exist (e.g. around Andromeda, M81, Cen A); DoSs appear to be the rule rather than the exception.

==> Consistent with Dual Dwarf Galaxy Theorem falsification !

Observed DoSs easily understandable as tidal-dwarf galaxy populations.

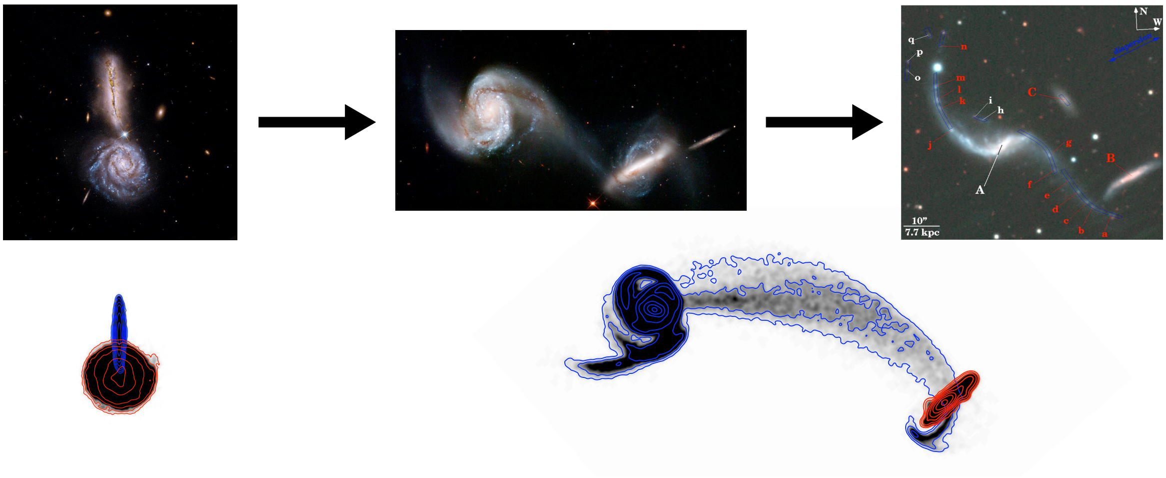
Relevance : The collision of two disks at high redshift



Wetzstein, Naab & Burkert 2007

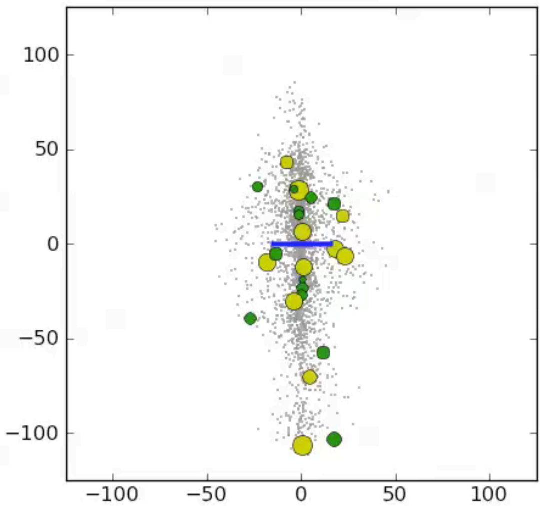
Phase-space-correlated tidal debris

Pawlowski et al. 2012



Fly-by encounter: e.g. Milky Way and Andromeda ? about 10-11 Gyr ago

Pawlowski et al. 2011



But : this is not possible in the SMoC because the MW and M31 would have merged within 1-2 Gyr.

See also Fouquet, Hammer et al. (2012) for another elegant explanation.

The disk-of-satellite arrangement thus strongly suggests that the satellite galaxies of the Milky Way and of Andromeda ought to be tidal dwarf galaxies.

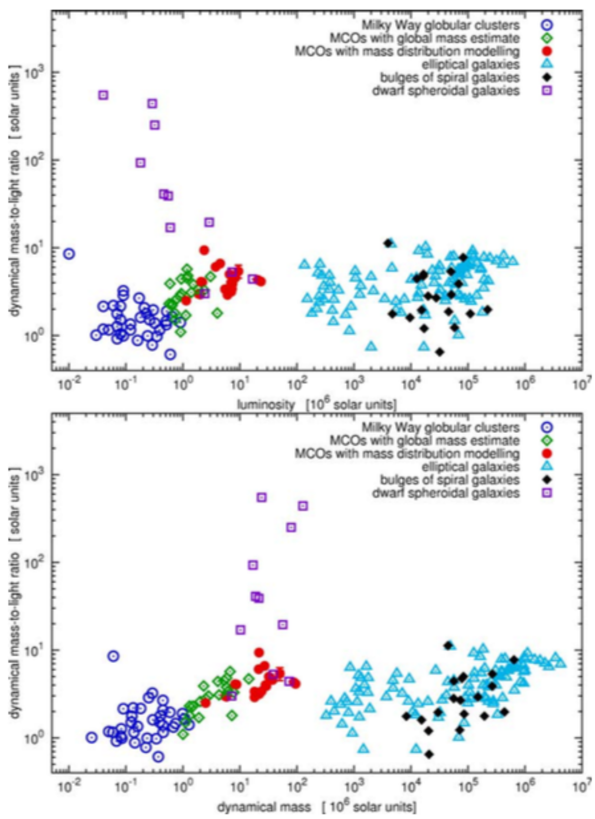
Also note that the satellite galaxies in the great plane of Andromeda and outside have indistinguishable internal properties.

Salomon, Ibata et al. 2015, MNRAS

. . . so the satellites should not contain dark matter .

. . . but :

Dabringhausen et al. (2008)



$$\left(\frac{M}{L}\right)_{\rm obs} = \frac{9}{2\,\pi\,G}\,\frac{\sigma_0^2}{\mu_0\,r_{\frac{1}{2}}}$$

$r_{1/2}$ is the half-light radius, i.e. the radius at which the central surface brightness, μ_0 , decreases to half its value, i.e by 0.75 mag/pc^2 .

Figure 5. Dynamical M/L_V ratio plotted against luminosity in the V band, L_V (upper panel), and mass, M (lower panel). The symbols are as in Fig. 2. The errors to the values of the MCOs are not much larger than the symbol size.

How can this discrepancy (disk-of-satellites vs dark matter content) be understood ?

A hint is given by possible tidal effects :

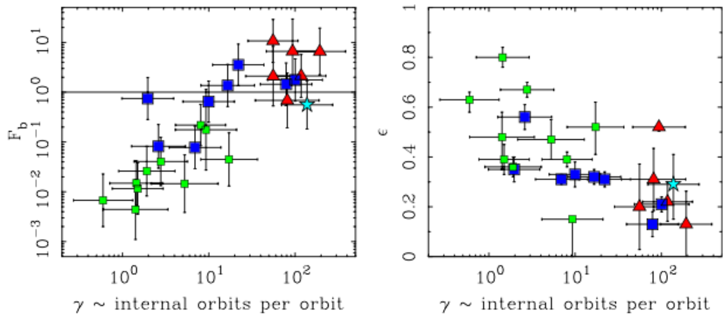
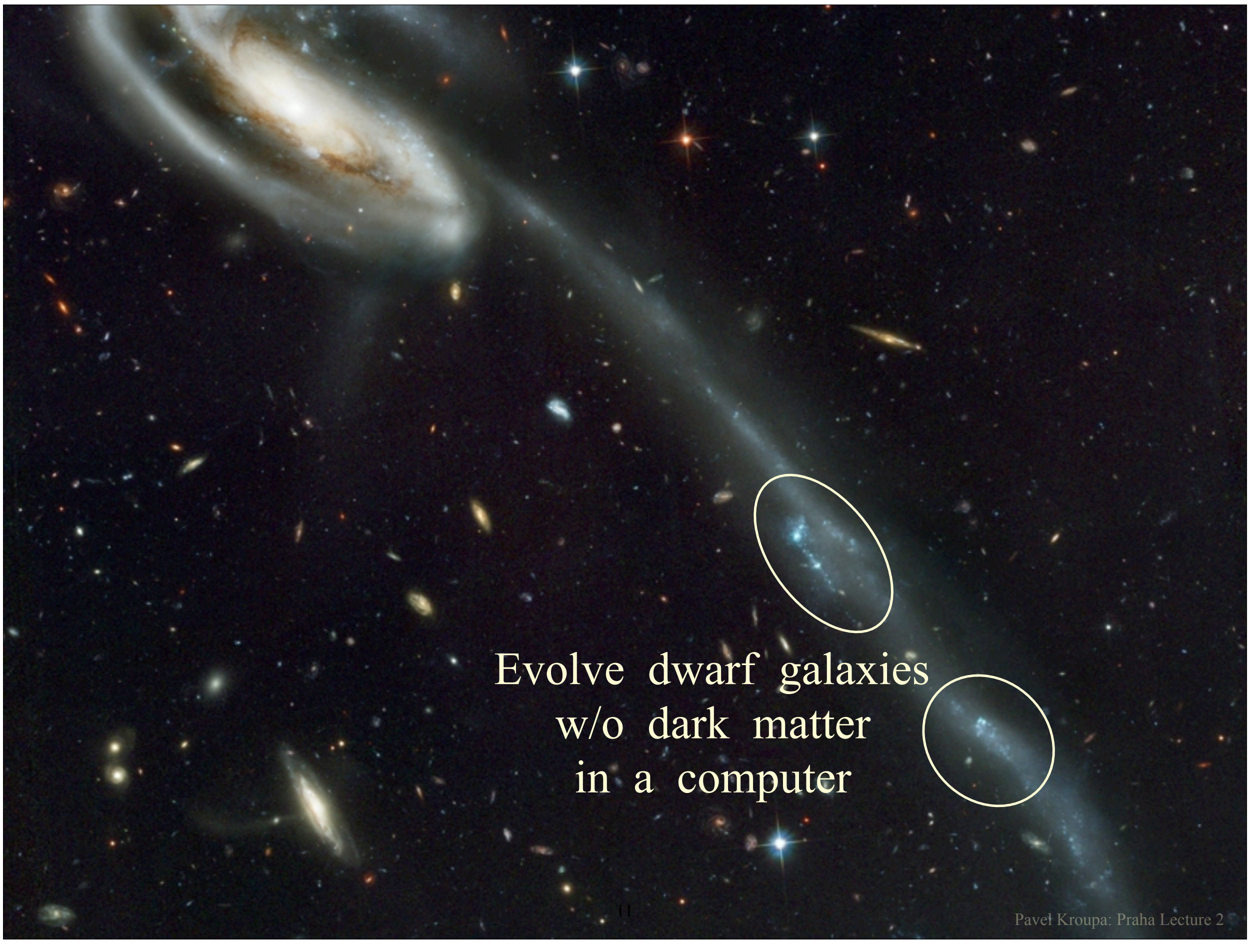
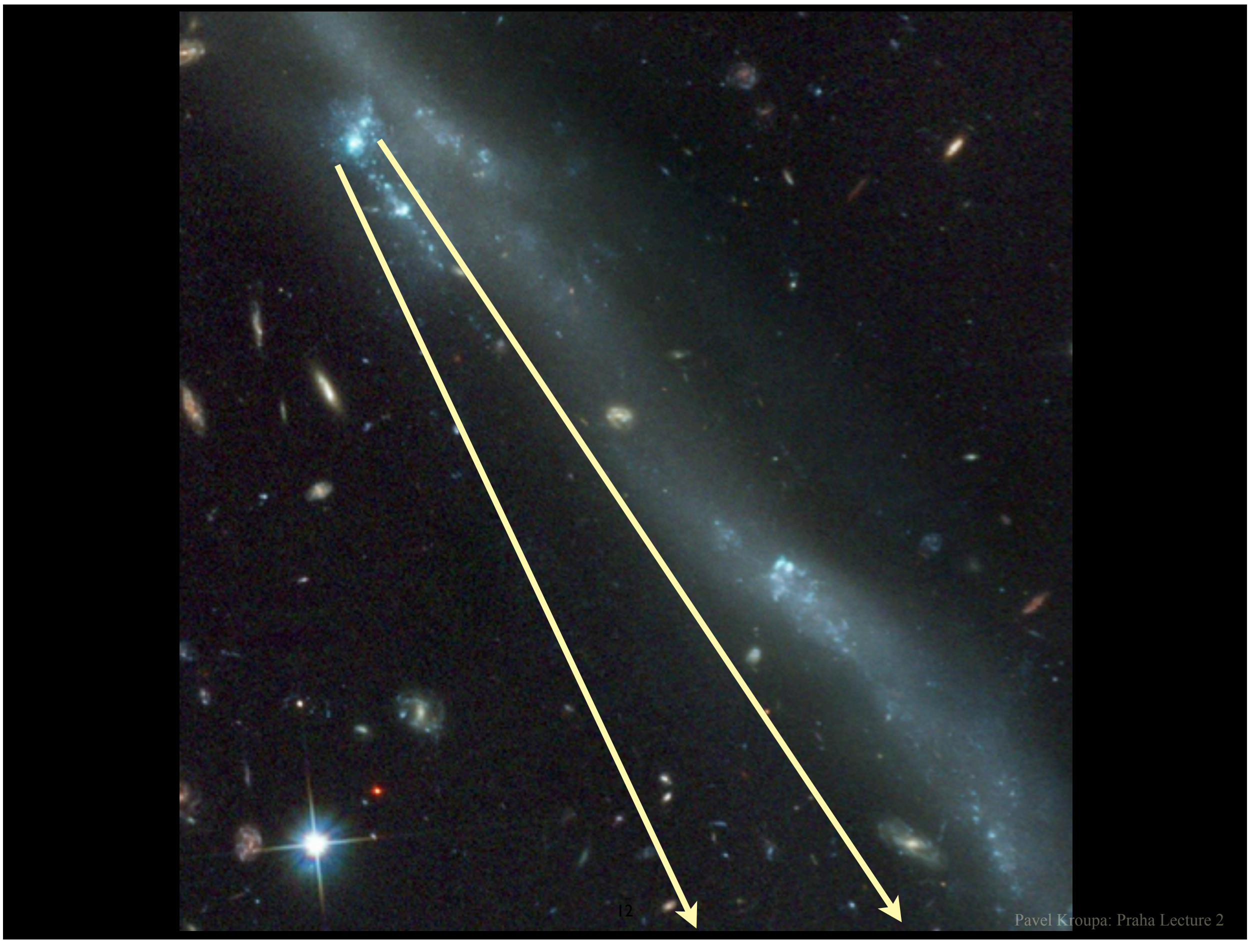


Figure 7. Residuals from the BTFR (left) and the ellipticities of dwarfs (right; symbols as per Figure 1) correlate with the number of orbits a star should complete within a dwarf for every orbit the dwarf completes about its host (Equation (6)). We expect pronounced non-adiabatic effects when $\gamma \lesssim 8$ (see the text). This corresponds approximately to where the discrepancy from the BTFR becomes significant, and to where dwarfs tend to become non-spherical.

McGaugh & Wolf (2010)

Evolution of TDGs


Evolve dwarf galaxies
w/o dark matter
in a computer
11
Pavel Kroupa: Praha Lecture 2


12
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Star-cluster complex
(cf *Tadpole*)

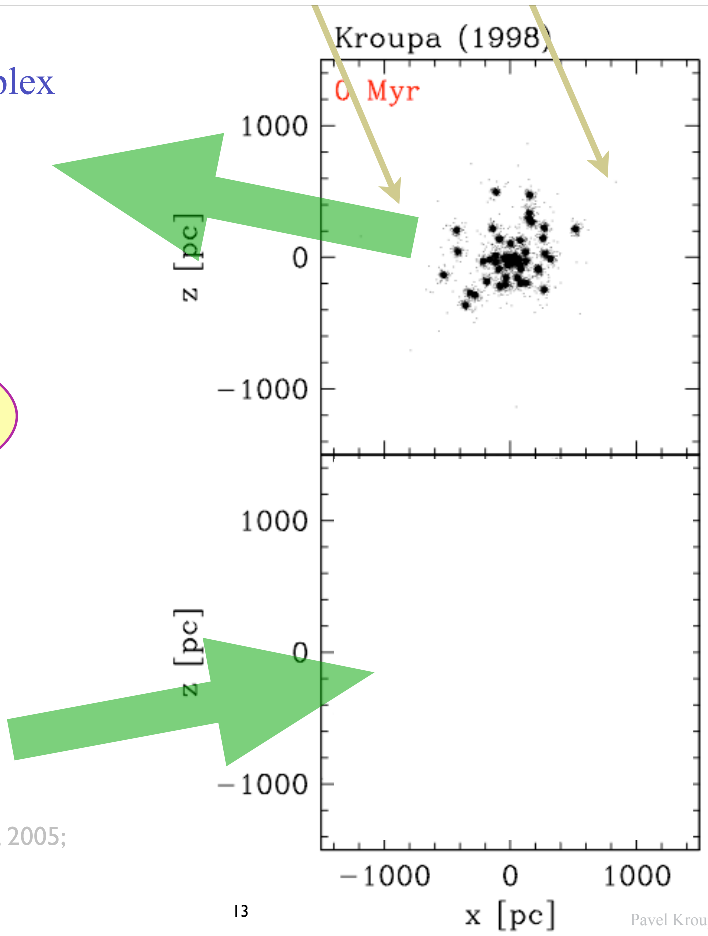
50 clusters
each $10^6\ M_\odot$

clusters as *fundamental galactic building blocks*

⇓

Spheroidal dwarf galaxy !

(Fellhauer et al. 2001, 2002a,b,c, 2005; Bekki et al. 2004)



Pavel Kroupa: Praha Lecture 2

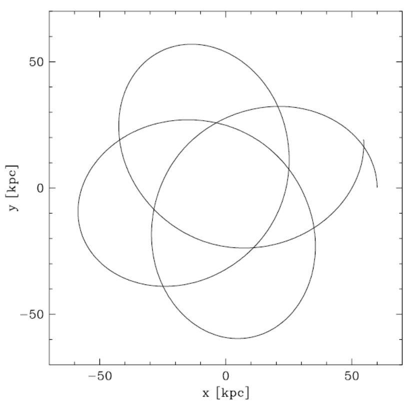
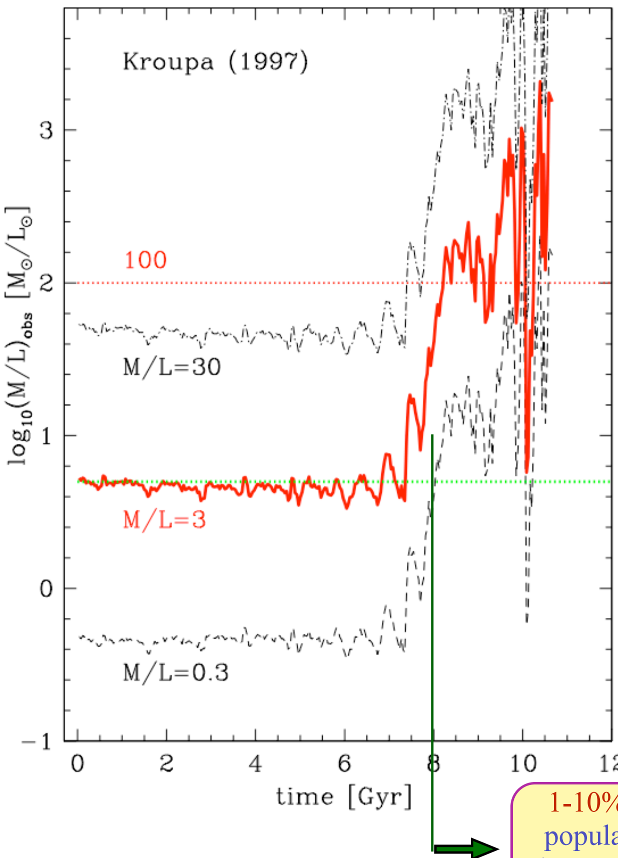


FIG. 3.—Orbital path of the satellite in simulations RS1-113 and Sat-M2.

$$\left(\frac{M}{L}\right)_{\rm obs} = \frac{9}{2\,\pi\,G}\,\frac{\sigma_0^2}{\mu_0\,r_{\frac{1}{2}}}$$

$r_{1/2}$ is the half-light radius, i.e. the radius at which the central surface brightness, μ_0, decreases to half its value, i.e by 0.75 mag/pc^2.



1-10% of population in remnant

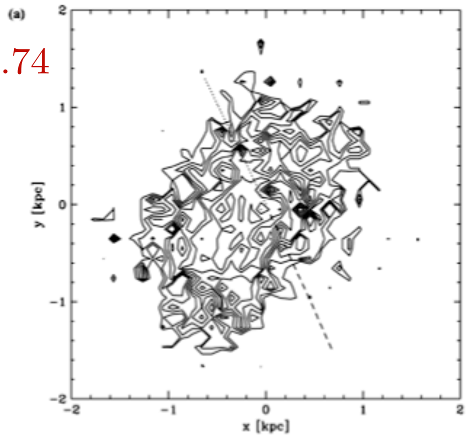
(Kroupa 1997)

The ***Remnants*** have a highly anisotropic $f(\mathbf{R}, V)$ and mass $\approx 10^5\ M_\odot$

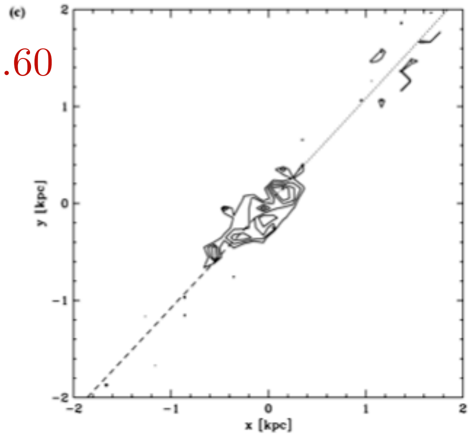
$R \approx$ few 100 pc

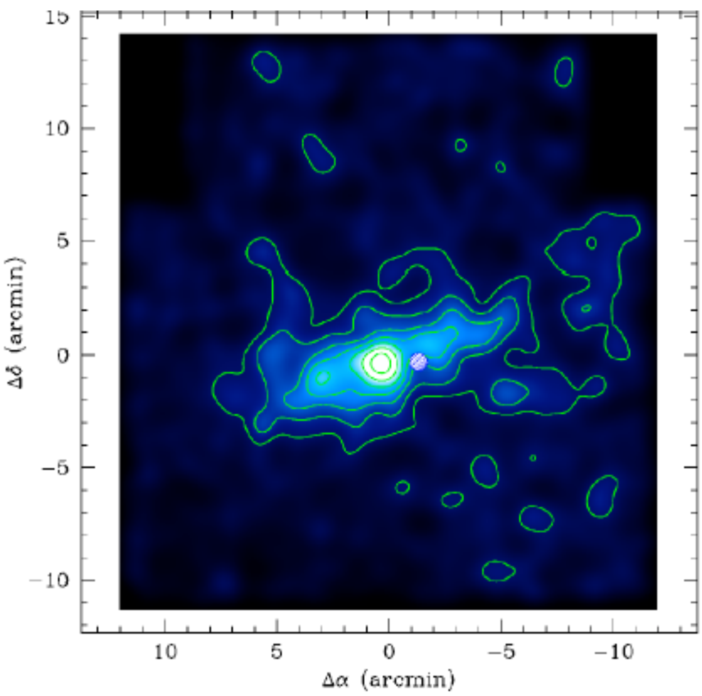
and $\left(\frac{M}{L}\right)_{\rm obs} \approx 10^{2-3}$!

$e = 0.74$



$e = 0.60$





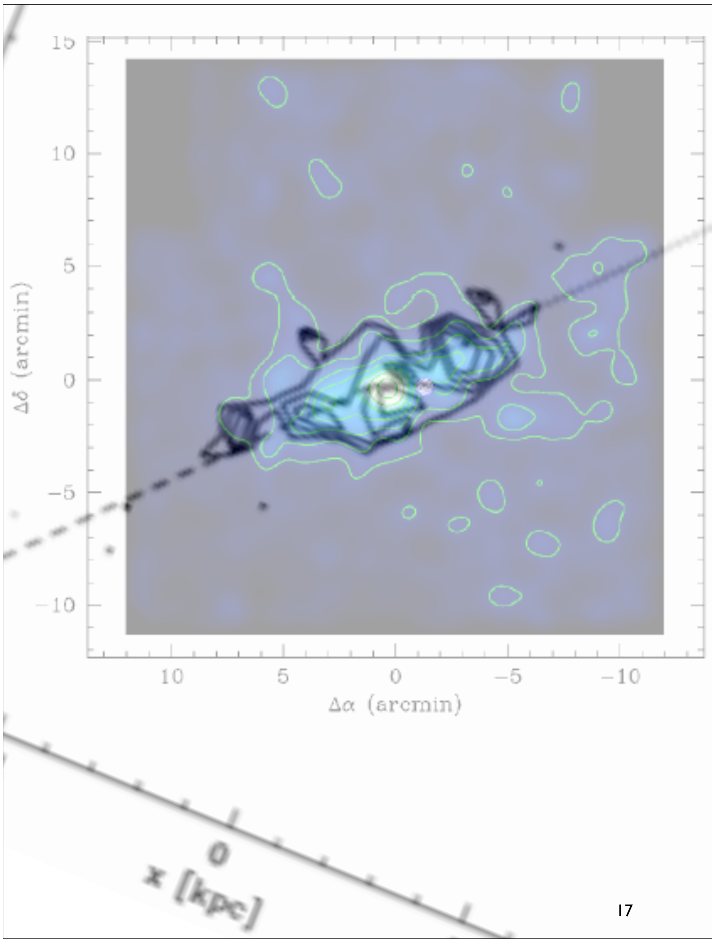
Hercules

D=130kpc

(Coleman et al. 2007)

Table 1
Properties of the Hercules dSph

Parameter	Value
R.A. (J2000)	16:31:02.0
Decl. (J2000)	12:47:29.6
$E(B-V)$ (mag)	0.055 ± 0.005^a
$(m-M)_0$ (mag)	20.6 ± 0.2
Distance (kpc)	132 ± 12
[Fe/H]	-2.1 ± 0.2
Age (Gyr)	13 ± 3
King r_h	$4.37' \pm 0.29'$ (168 ± 11 pc)
King r_c	$4.74' \pm 0.57'$ (182 ± 22 pc)
King r_t	$25.9' \pm 11.1'$ (994 ± 426 pc)
$c = \log(r_t/r_c)$	0.74 ± 0.25



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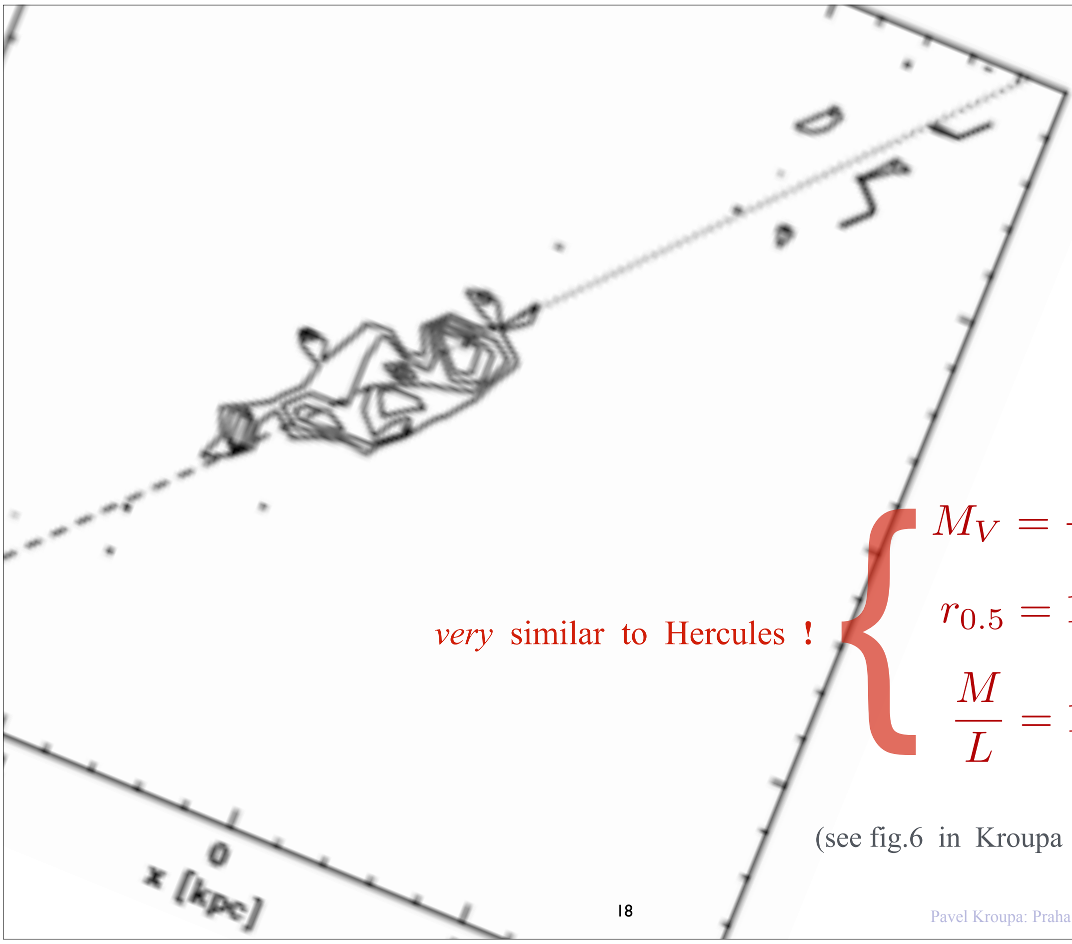

very similar to Hercules !

$$M_V = -9\,\mathrm{mag}$$

$$r_{0.5} = 180\,\mathrm{pc}$$

$$\frac{M}{L} = 10^{2.3}$$

(see fig.6 in Kroupa et al. 2010)

This is a

real prediction

10 years before

the discovery

of this

type of celestial object !

"Chemodynamical evolution of tidal dwarf galaxies – II. The long-term evolution and influence of a tidal field"

Ploeckinger et al. 2015, MNRAS

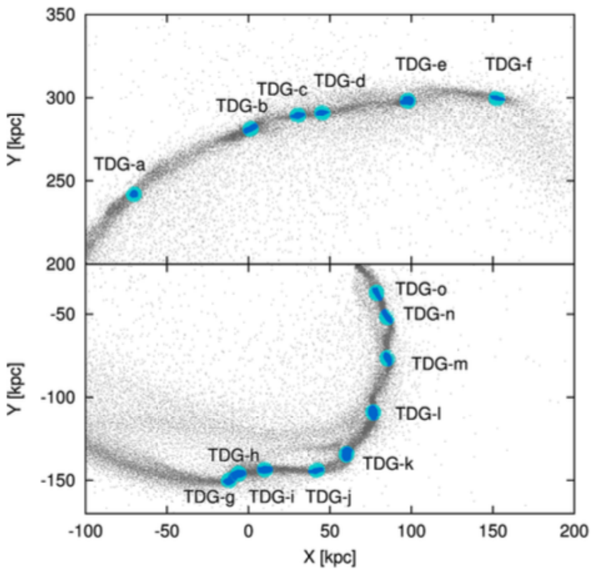

Figure A1. Simulation snapshot from Fouquet et al. (2012) at 1.5 Gyr after the first encounter of the interacting galaxies. The two panels show the two main tidal arms at this time. The grey dots indicate the positions of the tidal arm. For illustration, only every 10th SPH particle is plotted. The circles have a radius of $r_{TDG} = 5$ kpc and mark the positions of the identified proto-TDGs. The high-density ($\rho \geq 5 \times 10^{-26}$ g cm^{-3}) SPH particles within the proto-TDGs are highlighted within each circle.

"Chemodynamical evolution of tidal dwarf galaxies – II. The long-term evolution and influence of a tidal field"

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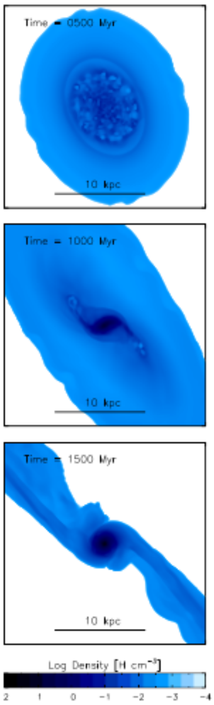

Figure 3. Gas distribution in the x–y plane and at $z = 0$ of TDG-p (columns 1 and 3), and TDG-r (columns 2 and 4) over time. Colour coded is the logarithmic hydrogen gas density.

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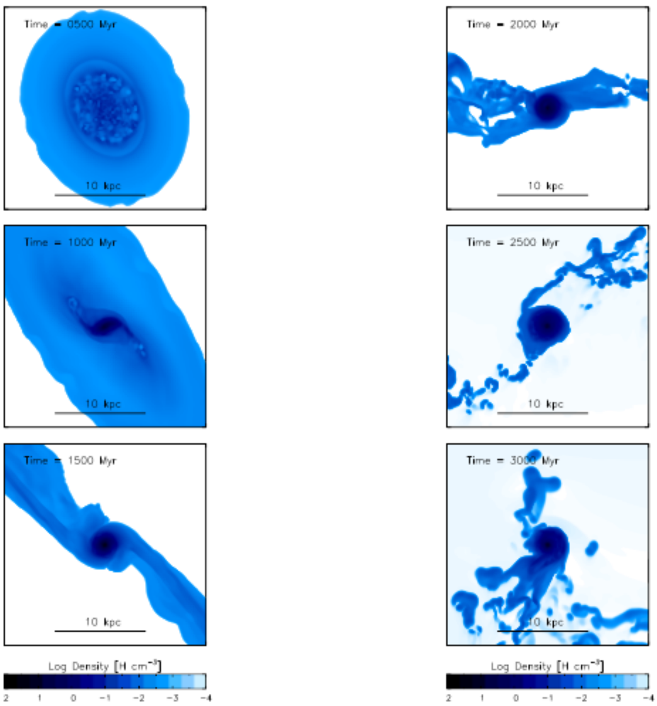

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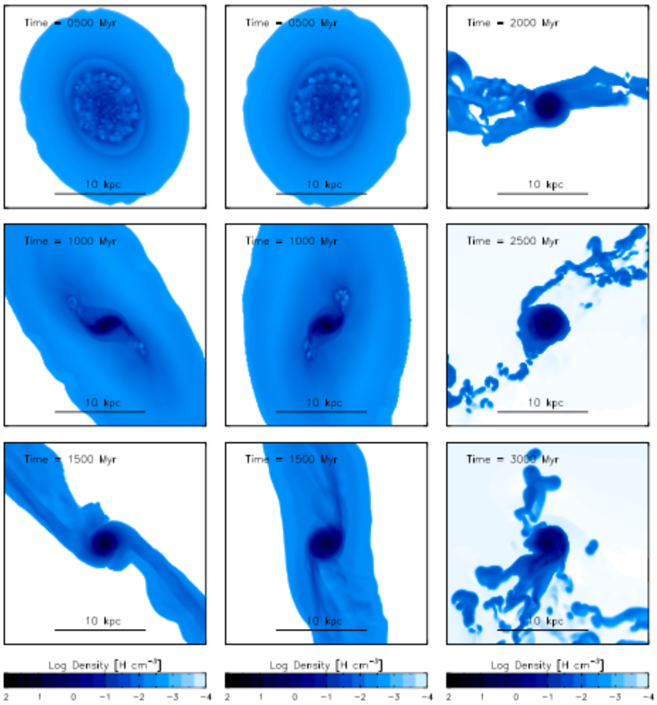

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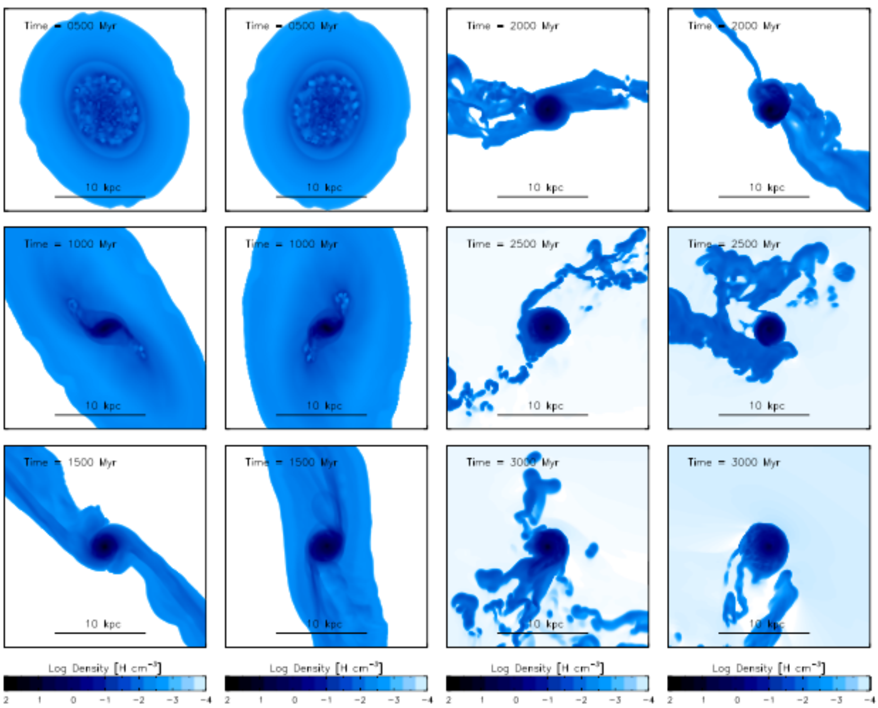

Table 1. Bound gas mass in 10^8 M$_\odot$ for the simulation runs TDG-p and TDG-r.

t (Gyr)	TDG-p	TDG-r
0.0	2.66	2.66
0.5	2.58	2.60
1.0	2.41	2.59
1.5	1.82	2.34
2.0	1.15	1.55
2.5	0.99	0.98
3.0	0.97	0.73

Table 2. Stellar mass in 10^6 M$_\odot$ throughout the simulation.

t (Gyr)	TDG-t	TDG-p	TDG-r
0.0	0	0	0
0.5	0.04	0.04	0.04
1.0	0.10	0.18	1.37
1.5	0.20	25.9	22.6
2.0	0.29	66.3	77.8
2.5	0.37	85.0	161.0
3.0	0.45	95.1	176.6

Figure 3. Gas distribution in the x–y plane and at $z = 0$ of TDG-p (columns 1 and 3), and TDG-r (columns 2 and 4) over time. Colour coded is the logarithmic hydrogen gas density.

Ploeckinger et al. 2015, MNRAS

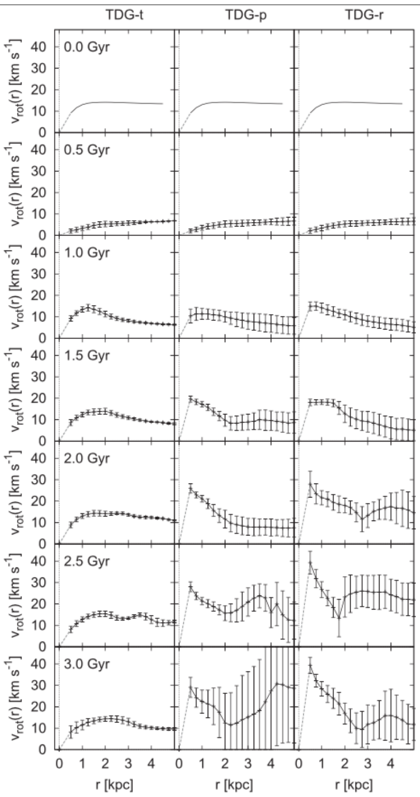

Figure 5. Rotation curves of the gaseous component of TDG-t (left-hand panels), TDG-p (middle panels), and TDG-r (right-hand panels). The absolute tangential velocities of all grid cells with densities $\rho > 10^{-26}\,\mathrm{g\,cm^{-3}}$ and within a vertical distance of $z = [-0.5, 0.5]$ kpc to the x–y plane are averaged in radial distance bins of 0.5 kpc. The 1σ deviation within the bins is indicated with error bars. The rotation curve for $r < 0.5$ kpc (dashed line) is not resolved in this sampling.

Ploeckinger et al. 2015, MNRAS

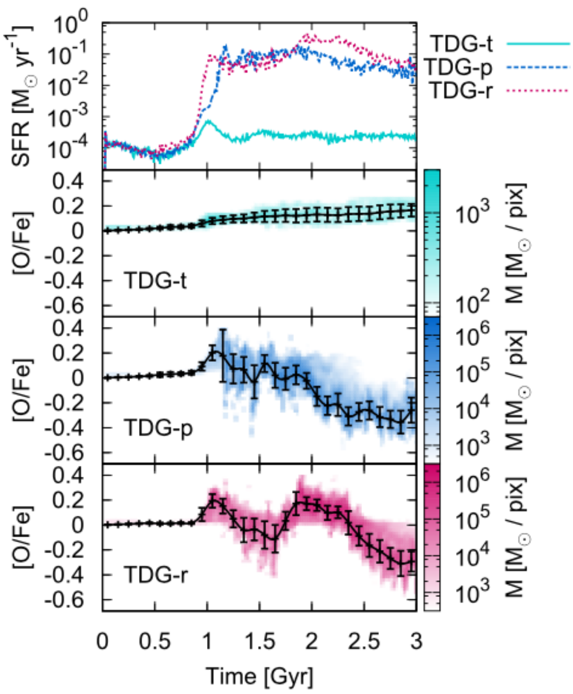

Figure 8. Top panel: SFRs for the simulation runs TDG-t (green, solid line), TDG-p (blue, dashed line), and TDG-r (red, dotted line). Bottom panels: evolution of chemical abundances of the star clusters in TDG-t, TDG-p, and TDG-r (second, third, and fourth panel) as a 2D histogram of [O/Fe] of each star cluster against its formation time in the simulation. The stellar mass in each pixel of $\Delta t = 25$ Myr $\times$ Δ[O/Fe] $= 0.025$ is colour coded. The data points show the mass-weighted, logarithmic average, and standard deviation error bars in time bins of 100 Myr. Note the different mass scale for TDG-t.

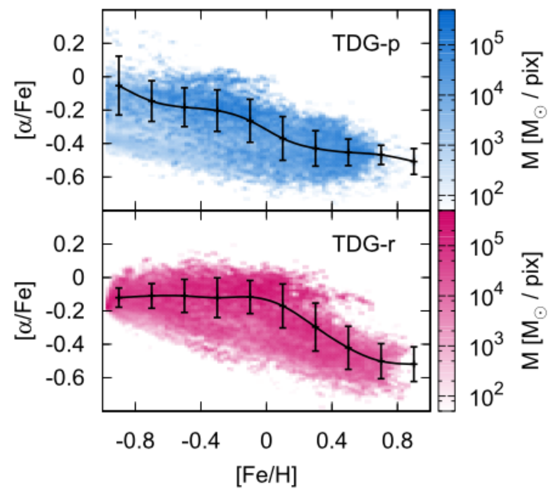

Figure 9. α element (O+Mg+Si+Ca) abundance ratios for TDG-p (top panel) and TDG-r (bottom panel) of all star clusters at the end of the simulation. The colour-scale represents the stellar mass in each pixel of Δ[Fe/H] $= 0.02 \times \Delta[\alpha$/Fe] $= 0.012$. The data points show the mass-weighted, logarithmic average, and standard deviation in bins of 0.2.

Ploeckinger et al. 2015, MNRAS

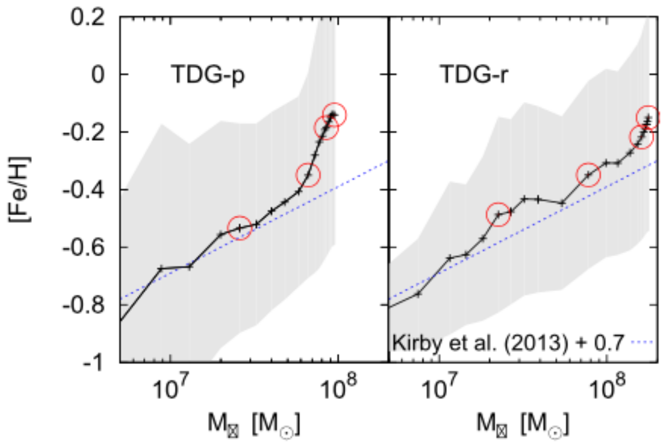

Figure 10. Iron enrichment of TDG-p (left-hand panel) and TDG-r (right-hand panel): for every 100 Myr, the mass-weighted average and standard deviation in [Fe/H] of all star clusters are calculated. The small crosses trace the evolution of the average [Fe/H] as the TDGs build up more stellar mass $M_{\star}$. The shaded area represents the 1σ region. The circles mark the position in this relation at 1.5, 2, 2.5, and 3 Gyr (from left to right). The dotted line is the *M*–*Z* relation (equation 12) from Kirby et al. (2013) increased by 0.7 dex (see text).

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The mass–metallicity relation of tidal dwarf galaxies

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We work in the framework of the IGIMF theory, according to which dwarf galaxies, characterized by small levels of star formation rates (SFRs), can produce only a small relative number of massive stars and, hence, the galaxy-wide IMF will be biased towards low-mass stars. In particular, we adopt the detailed IGIMF prescriptions of Weidner et al. (2013), which are able to reproduce a large range of observed galactic properties.

We assume the so-called simple model of chemical evolution: a one-zone model in which ejecta from dy- ing stars instantaneously mix with the surrounding gas. Moreover, the instantaneous recycling approximation is adopted,

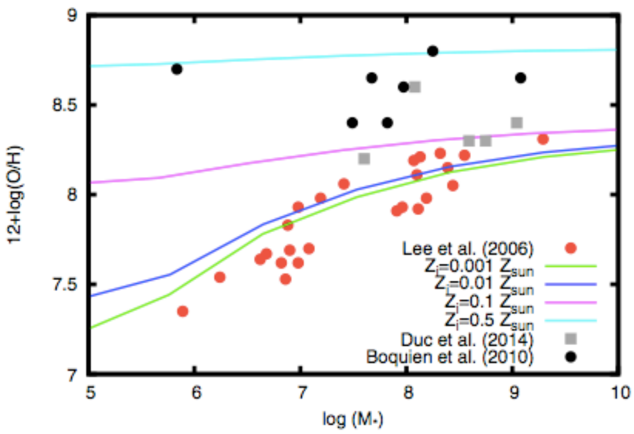


Figure 1. The MZ relation obtained by means of the simple model of chemical evolution within the IGIMF theory, with different values of the initial metallicity Z_i (see equation 1). Here, we compare the gas-phase abundance of the model galaxies with observations of dwarf galaxies in the Local Universe (from Lee et al. 2006; red circles) and of young TDGs (from Boquien et al. 2010 – black circles; Duc et al. 2014 – grey squares). Notice that the *x*-axis indicates the final stellar mass of the model galaxies, although the comparison focuses on gas-phase abundances. Notice also that the lower two curves ($Z_i = 10^{-3}$ and 10^{-2} $Z_{\odot}$) correspond to old TDGs and evolve for a longer time (see text for details).

Thus, all in all, the TDG-hypothesis for the origin of satellite galaxies is very promising. Repeated tidal shaping appears to be relevant for the observed dynamical M/L values, but it is not clear if this can account for the whole dark matter effect.

If all MW and Andromeda satellite galaxies are old TDGs then the "missing satellite problem" would become a "missing satellite disaster" - why **?**

The results above were obtained assuming Newtonian gravitation to be valid. Newtonian gravitation requires dark matter to account for structure formation and rotation curves.

So lets test this further **. . .**

Before proceeding : which type of galaxy at a mass scale above about 10^{10}Msun dominates the population of galaxies in the nearby (within about 8 Mpc) Universe **?**

This is strongly dependent on how galaxies form.

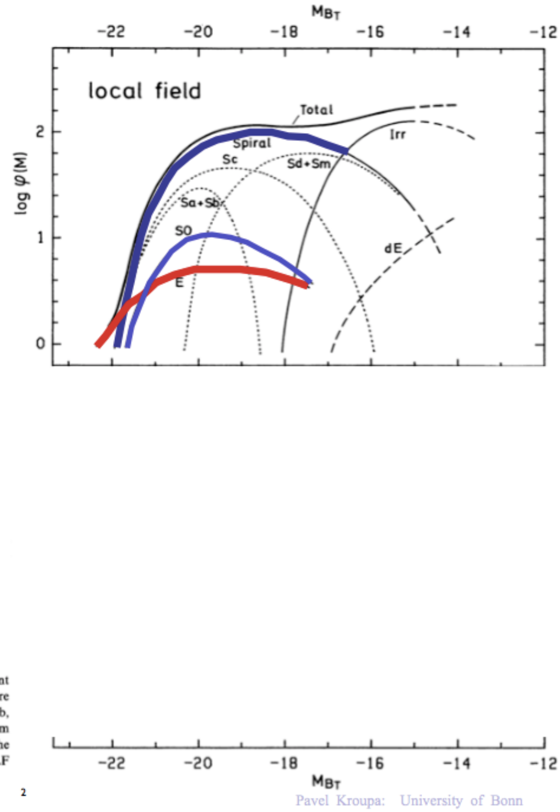
1. Collapse of a post-Big Bang gas cloud **?**

2. Through merging dark-matter halos **?**

According to the SMoC **:**

energy-content of Universe is approximately
25 % dark matter
5 % baryonic matter
70 % dark energy

The luminosity function of galaxies

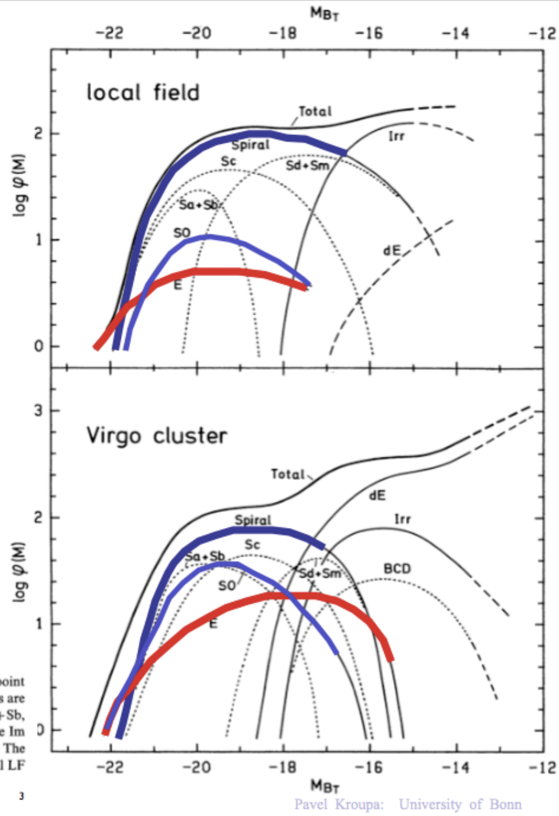


Binggeli et al. 1988

Figure 1 The LF of field galaxies (top) and Virgo cluster members (bottom). The zero point of log $\varphi(M)$ is arbitrary. The LFs for individual galaxy types are shown. Extrapolations are marked by dashed lines. In addition to the LF of all spirals, the LFs of the subtypes Sa+Sb, Sc, and Sd+Sm are also shown as dotted curves. The LF of Irr galaxies comprises the Im and BCD galaxies; in the case of the Virgo cluster, the BCDs are also shown separately. The classes dS0 and "dE or Im" are not illustrated. They are, however, included in the total LF over all types (heavy line).

The luminosity function of galaxies

Disk galaxies dominate overwhelmingly (>95%) above 10^{10} Msun



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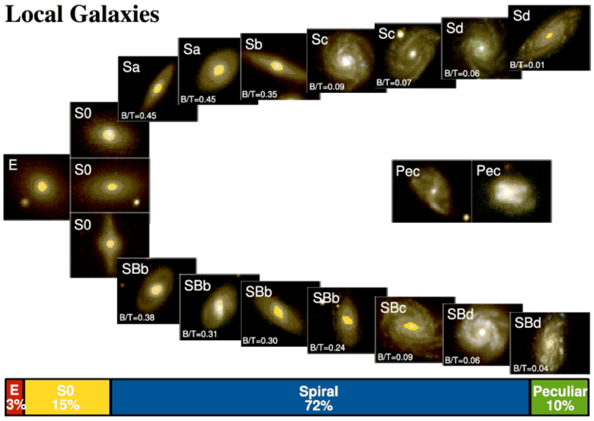
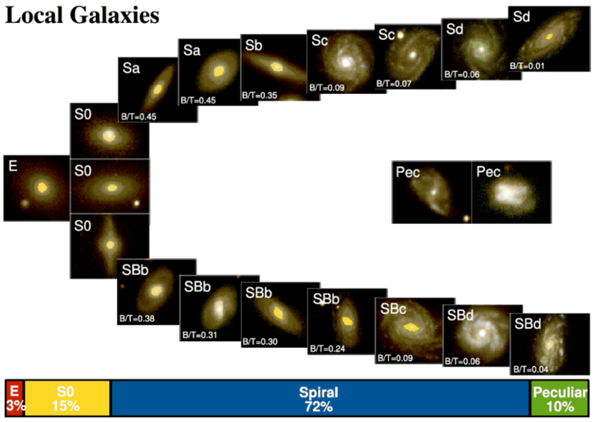


Ratio of E to other galaxies unchanging ?

Delgado-Serrano et al. (2010)

Galaxy mass in baryons
> 1.5x10^{10} Msun

6 Gyr ago



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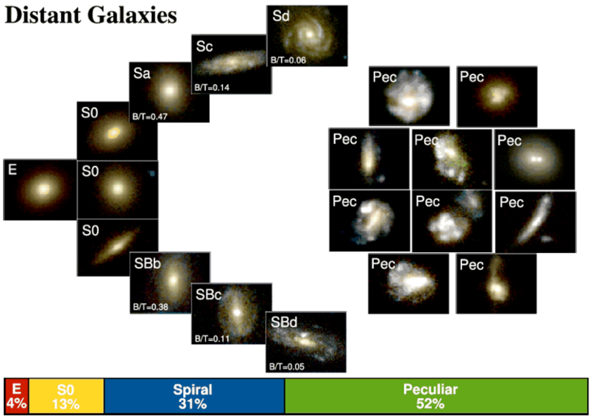


6 Gyr ago

Disk galaxies are thus by far the dominant population.

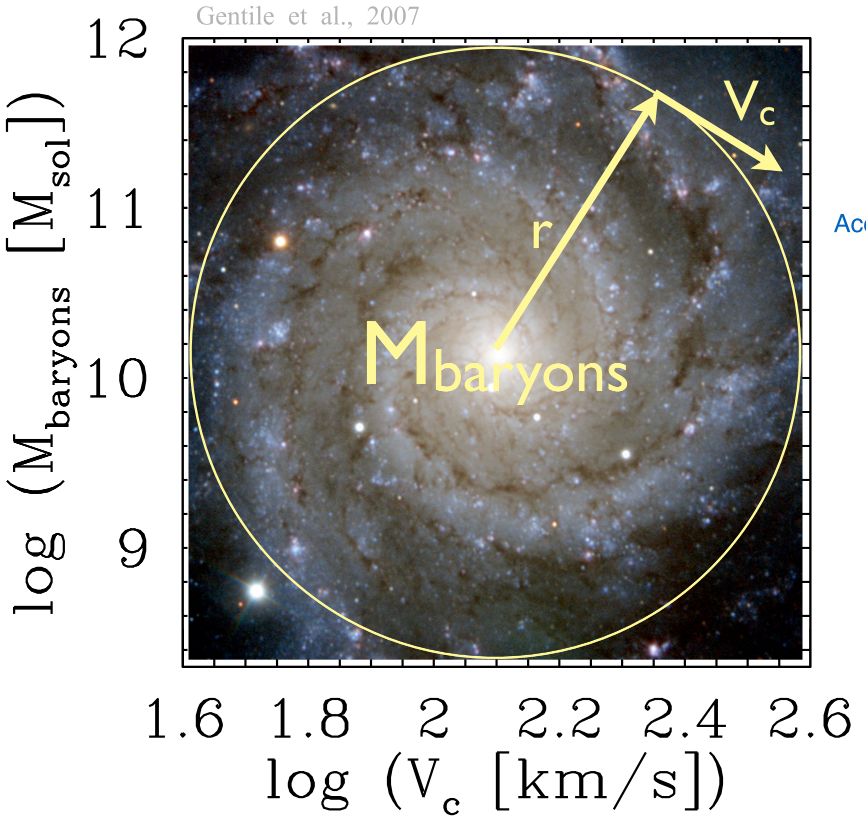
Ellipticals are the small exception -- cosmic accidents as it were.

What are the properties of disk galaxies ?
(we will return to this later again;
now still testing for the existence of dark matter halos).

Disc galaxies

Balance between
gravitation
and
centrifugal force

Disc galaxies



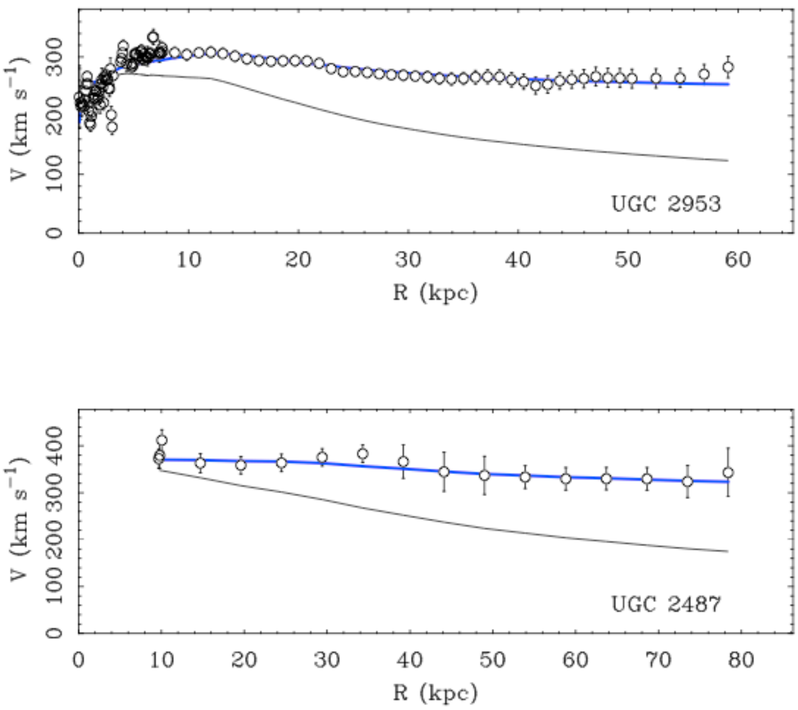
Balance between gravitation and centrifugal force

According to Newton :

$$g_{\rm N} = G\,\frac{M_{\rm baryons}}{r^2}$$

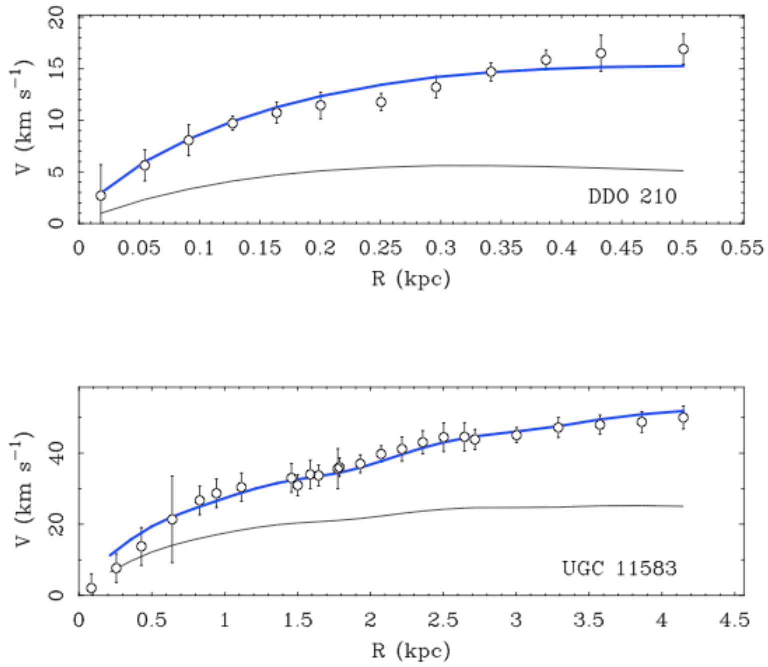
Measured :

$$g = \frac{V_{\rm c}^2}{r}$$



Famaey & McGaugh 2012

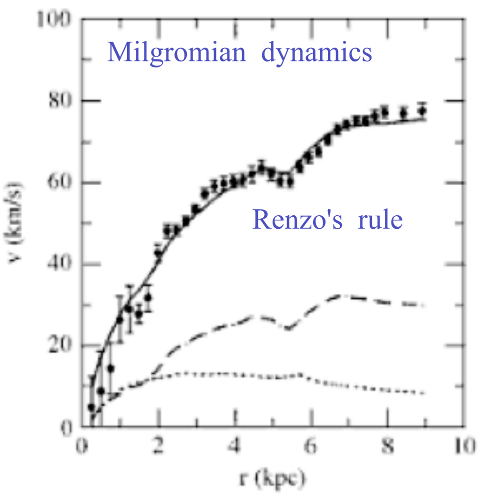
Figure 24: Examples of MOND fits (blue lines, using Eq. 53 with $\delta = 1$) to two massive galaxies [402]. With baryonic masses in excess of $10^{11}\,M_\odot$, these are among the most massive, rapidly rotating disk galaxies known. Stars dominate the mass, and Newtonian dynamics suffices to explain the innermost regions because of the high acceleration, but the mass discrepancy becomes apparent as the Keplerian decline (black lines) falls well below the data at the enormous radii spanned by these giant disks (the diameter of UGC 2487 spans half a million lightyears).



Famaey & McGaugh 2012

Figure 25: Examples of MOND fits (blue lines) to two dwarf galaxies [324]. The data for DDO 210 come from [29], and those for UGC 11583 (also known as KK98 250) are from [30] augmented with high resolution data from [281, 242]. The high gas content of these galaxies make them strong tests of MOND, as the one fit-parameter – the mass-to-light ratio of the stars – has only a minor impact on the fit. What is more, as they are deep in the MOND regime, the exact form of the interpolating function (Section 6.2) also has little impact on the fits, making them the cleanest tests of MOND, with essentially no wiggle room. Note that, with a mass of only a few million solar masses (comparable in mass to the largest globular clusters), the Local Group dwarf DDO 210 is the smallest galaxy known to show clear rotation ($V_f \sim 15$ km/s). It is the lowest point in Figure 3.

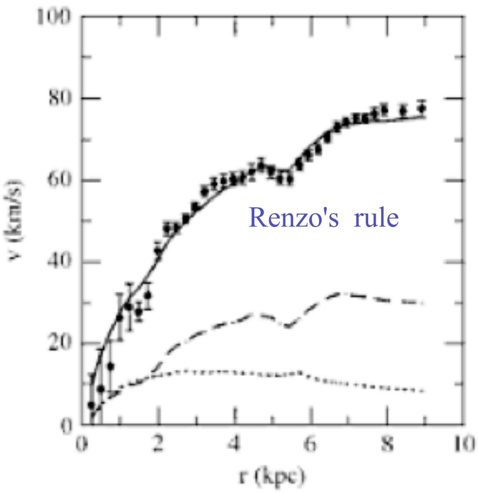
From Robert Sanders' Book on "*The Dark Matter Problem*", Cambridge University Press, 2010

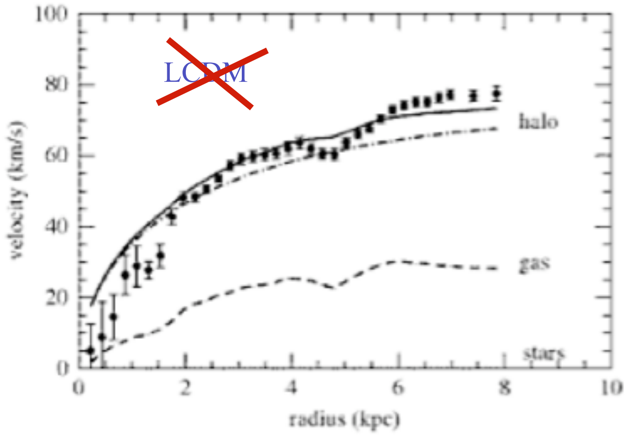


Gravitational force field must be sourced only by the baryons

Renzo's rule: wiggles in rotation curve correspond to structure in the density of observed matter (see Famaey & McGaugh 2012 review).

From Robert Sanders' Book on
"*The Dark Matter Problem*",
Cambridge University Press, 2010





This challenges the existence of dark matter halos.

Renzo's rule contradicts dark matter halos providing the potential.

Other problems due to dynamical friction :

Privon, Barnes et al. 2013

Dynamical Modeling with Identikit 7

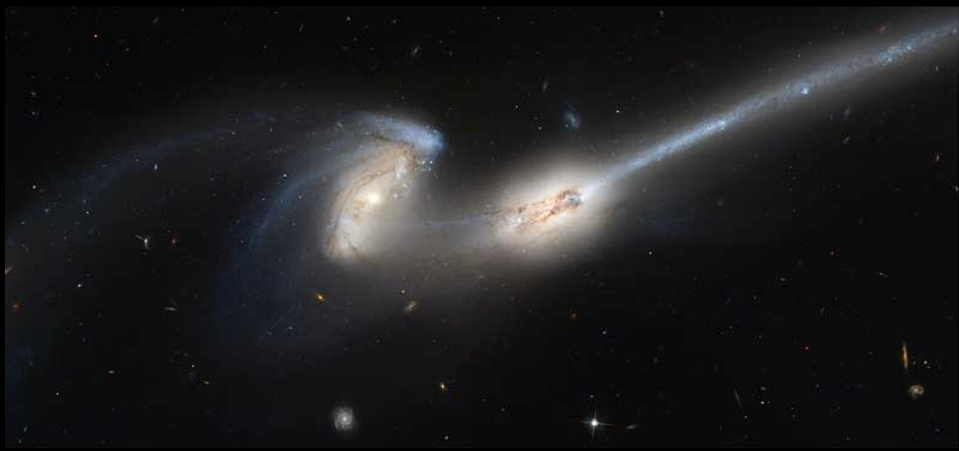
Table 2
Dynamical models derived from Identikit matching

System	e	p	μ	(i_1, ω_1)	(i_2, ω_2)	t	$(\theta_X, \theta_Y, \theta_Z)$	$\mathcal{L}$ (kpc)	$\mathcal{V}$ (km s^{-1})	M_{dyn} ($\times 10^{11}$ $M_\odot$)	t_{now} (Myr)	Δt_{merge} (Myr)
NGC 5257/8	1	0.625	1	(85°, 65°)	(15°, 340°)	3.38	(126°, -3°, 63°)	34	204	9	230	1200
The Mice	1	0.375	1	(15°, 325°)	(25°, 200°)	2.75	(78°, -44°, -130°)	39.5	165	6.6	175	775
Antennae	1	0.25	1	(65°, 345°)	(70°, 95°)	5.62	(-20°, 283°, -5°)	19.7	265	8	260	70
NGC 2623	1	0.125	1	(30°, 330°)	(25°, 110°)	5.88	(-30°, 15°, -50°)	6.9	123	0.6	220	-80

Note. — e – orbital eccentricity, p – pericentric separation (simulation units), μ – mass ratio, (i_1, ω_1) (i_2, ω_2) – disk orientations (see text for description), t - time of best match (simulation units, see text for description), $(\theta_X, \theta_Y, \theta_Z)$ – viewing angle relative to the orbit plane, $\mathcal{L}$ – length scaling factor, $\mathcal{V}$ – velocity scaling factor, M_{dyn} – estimate of the dynamical mass, t_{now} – time since first pericenter passage, Δt_{merge} – time until coalescence based on the assumed mass model.

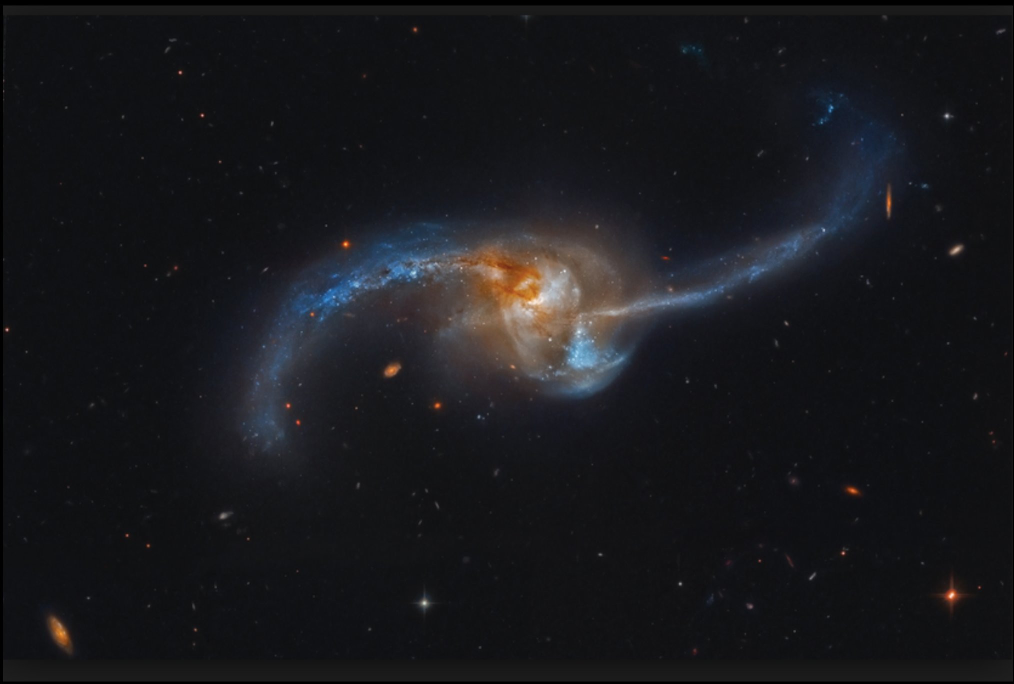
NGC 5257/8

The Mice



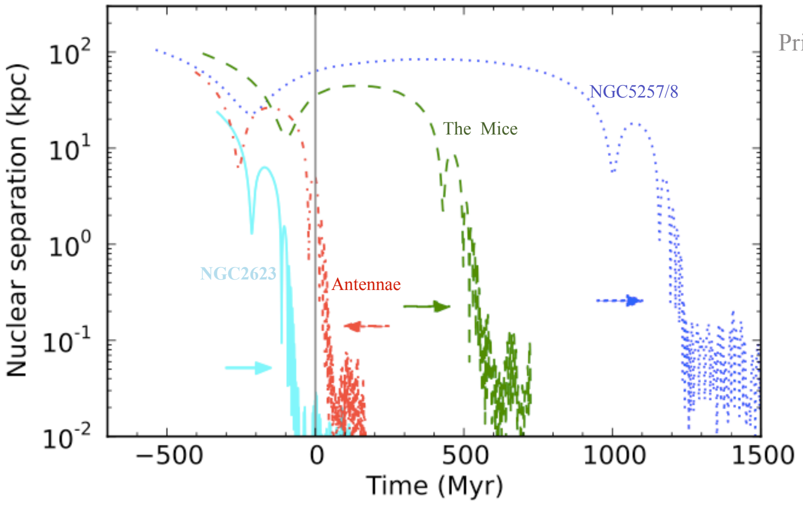
Antennae

NGC 2623



Dynamical friction : galaxy mergers - must be common

Galaxy encounters with mass ratio = 1 : mergers within 0.5-3 Gyr



Privon, Barnes et al. 2013

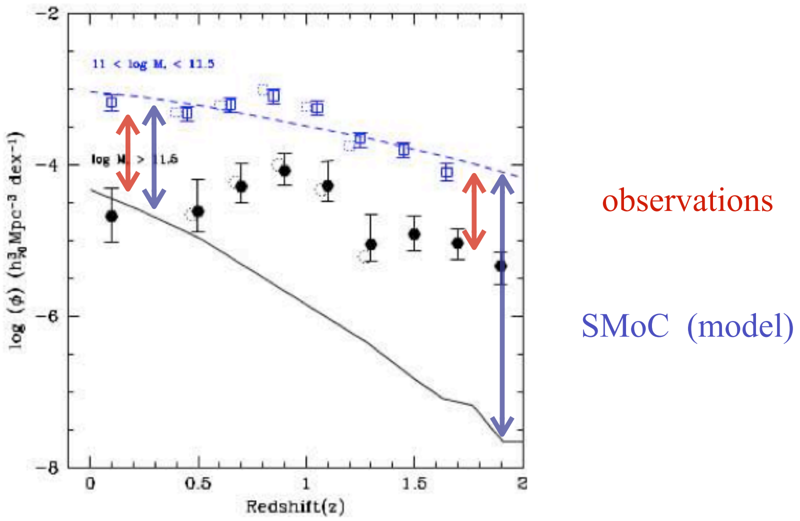
Figure 1. True nuclear separation as a function of time for NGC 5257/8 (dotted blue line), The Mice (dashed green), Antennae (dash-dot red), and NGC 2623 (solid cyan). Time of zero is the current viewing time (solid gray vertical line). The time since first passages for these systems is 175 − 260 Myr (cf. Table 2). Colored arrows mark the smoothing length in kpc for the corresponding system; this is effectively the spatial resolution of our simulations and the behavior of the curves on length scales smaller than the smoothing length is not reliable.

Barnes (1998) in "Dynamics of Galaxy Interactions" :

"Interacting galaxies are well-understood in terms of the effects of gravity on stars and dark matter."

***Ratio of massive to less-massive galaxies* does not evolve, in conflict with LCDM (SMoC) expectations**

Conselice 2012



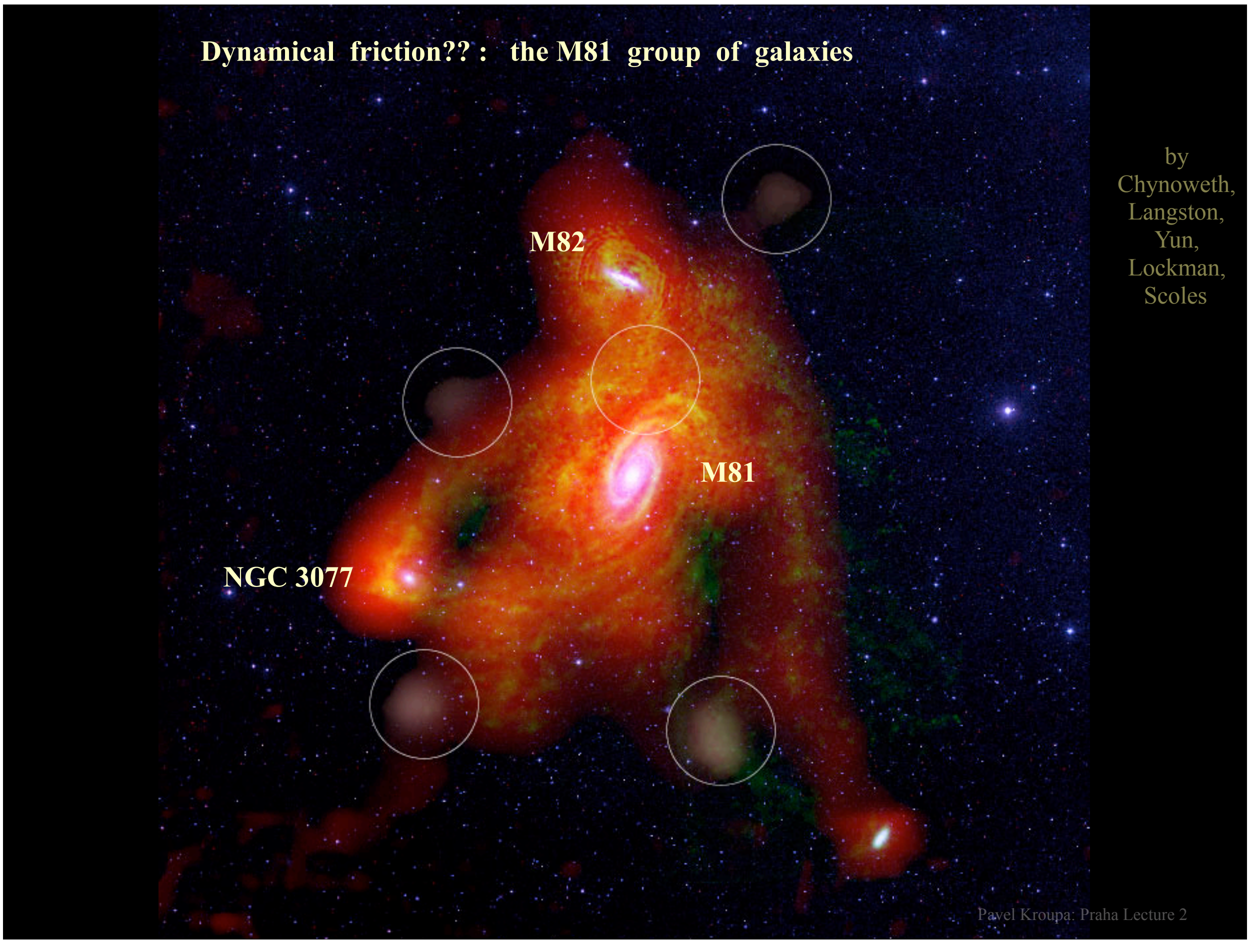
No evidence for growth of galaxies through mergers.

Thus : No increase in the number ratio of E galaxies to other galaxies, in contradiction with the expected increase through merging driven by dark matter halos in the SMoC.

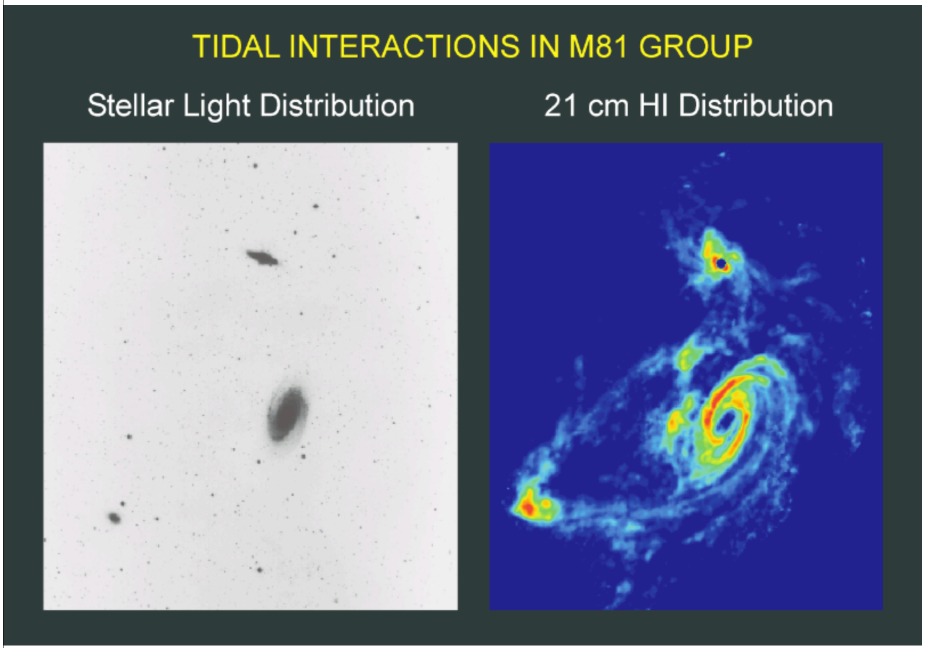
Merging not evident :

The M81 group of galaxies

- an analogue to the Local Group at 3.6 Mpc



Dynamical friction?? : the M81 group of galaxies



Last publications (conference proceedings only) :

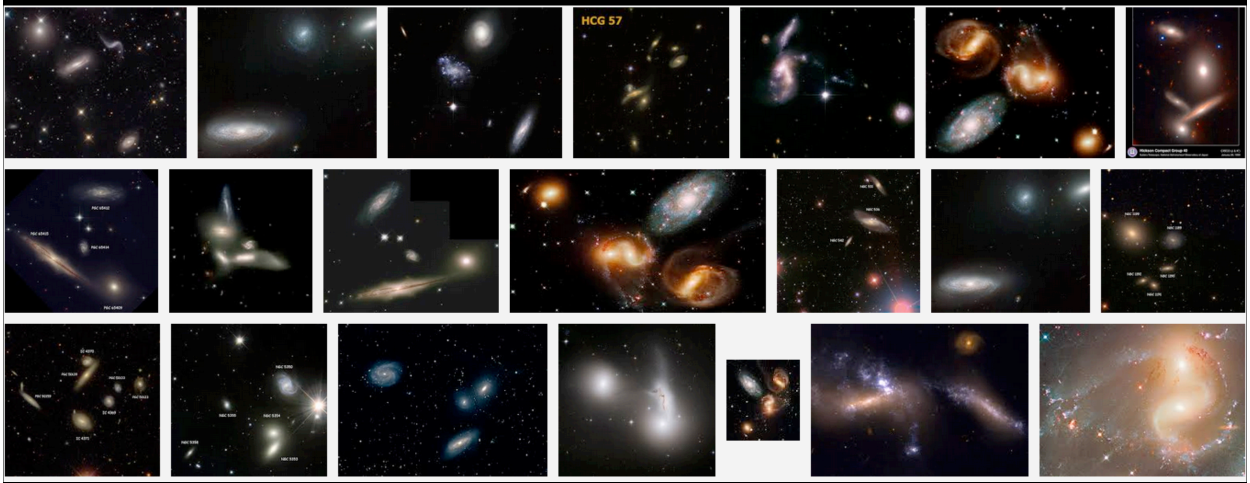
Yun 1999
=> no solutions with dark matter : system merges

Thomson, Laine & Turnbull 1999
=> no solutions with dark matter : system merges

AND, there are many other similar groups.

The *Hickson compact groups* are are particularly troubling for LCDM, because they all must have assembled during the past 1-3 Gyr with all members magically coming together for about one synchronised perigalactic passage, while the remnants (field E galaxies with low alpha element abundances from previously such formed groups) do not appear to exist in sufficient numbers.

silkscape.com



citing from COSMOS - The SAO Encyclopedia of Astronomy
on Hickson Compact groups:

> "The velocities measured for galaxies in compact groups are quite low (~200 km/s), making these environments highly conducive to interactions and mergers between galaxies.

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Instead, we find a significant number of compact groups in the nearby Universe, with well over 100 identified."

Sohn, Hwang, Geller et al. (2015, JKAS)

END of Lecture 2