How the Local Group data constrain the existence of dark matter I

LCDM, Modified Gravity or new Dark Matter models?

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Universite Pierre a Marie Curie, Paris

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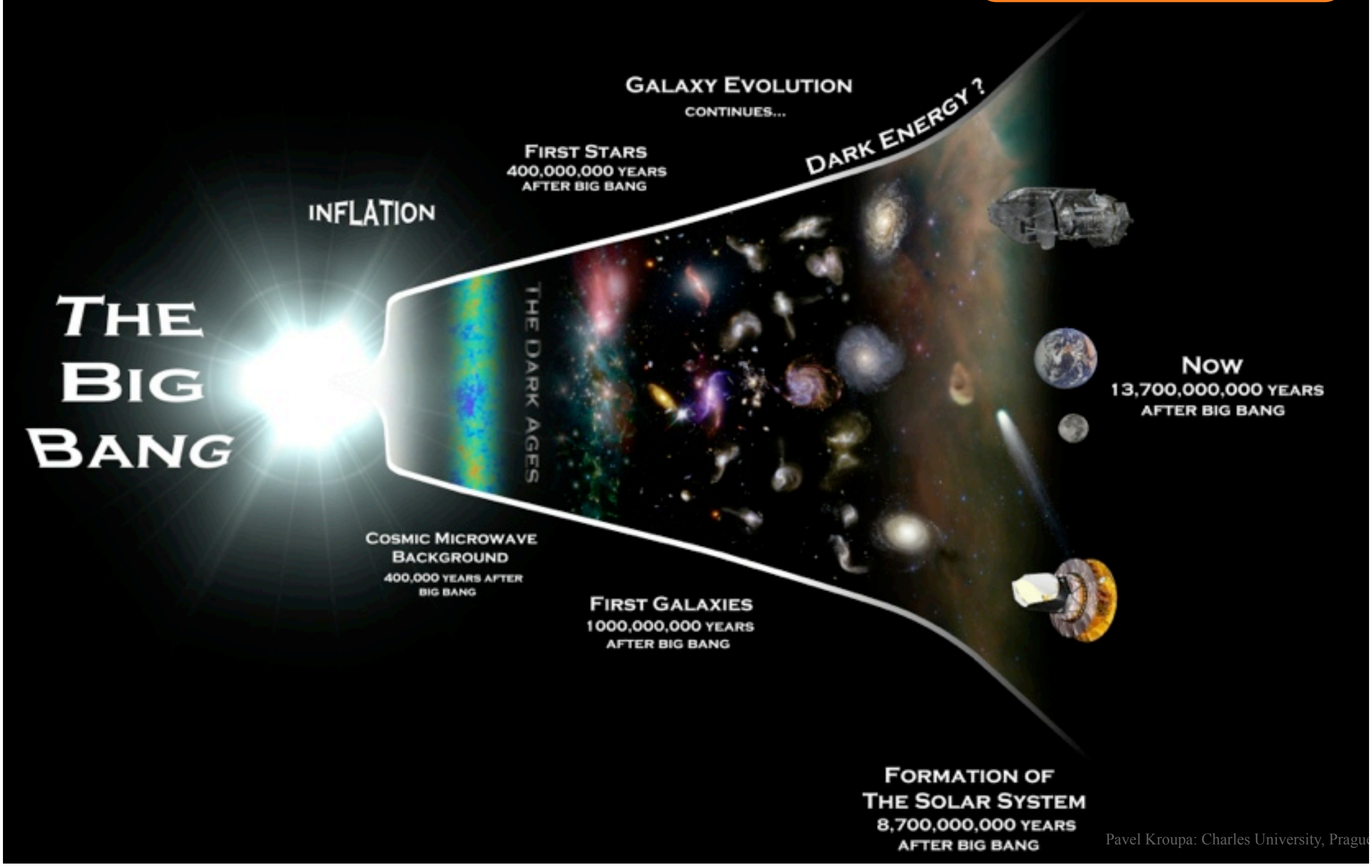
The Standard Modell of Cosmology (SMoC) :
1. Einstein is valid
2. All matter created at Big Bang

⇒ dark matter + dark energy needed

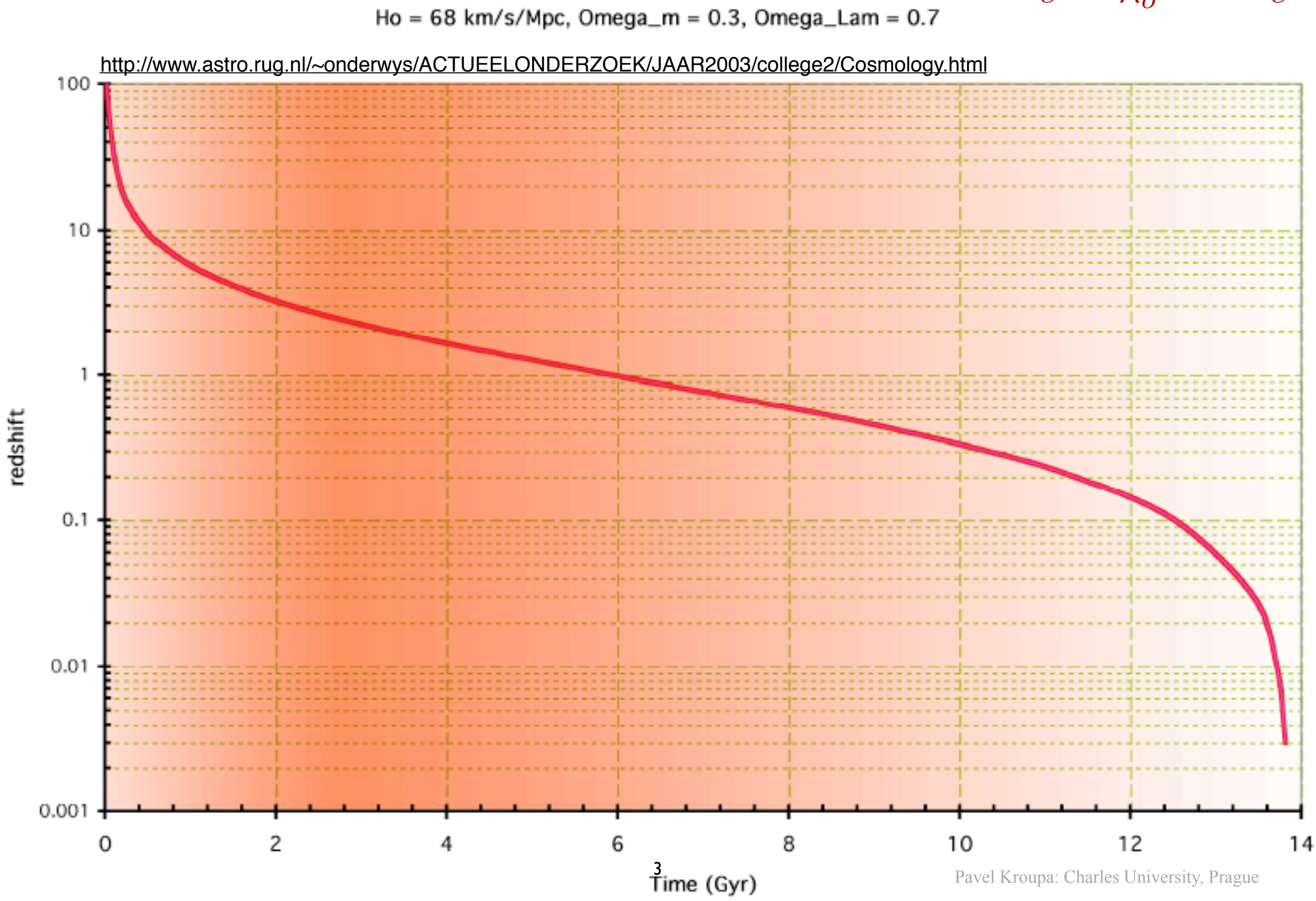


Pavel Kroupa: Charles University, Prague

The redshift - time relation

depends on the cosmological model, e.g.:

$$z = \frac{v}{c} = \frac{\delta\lambda}{\lambda_o} = H_o \frac{d}{c}$$



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Cosmological structure formation

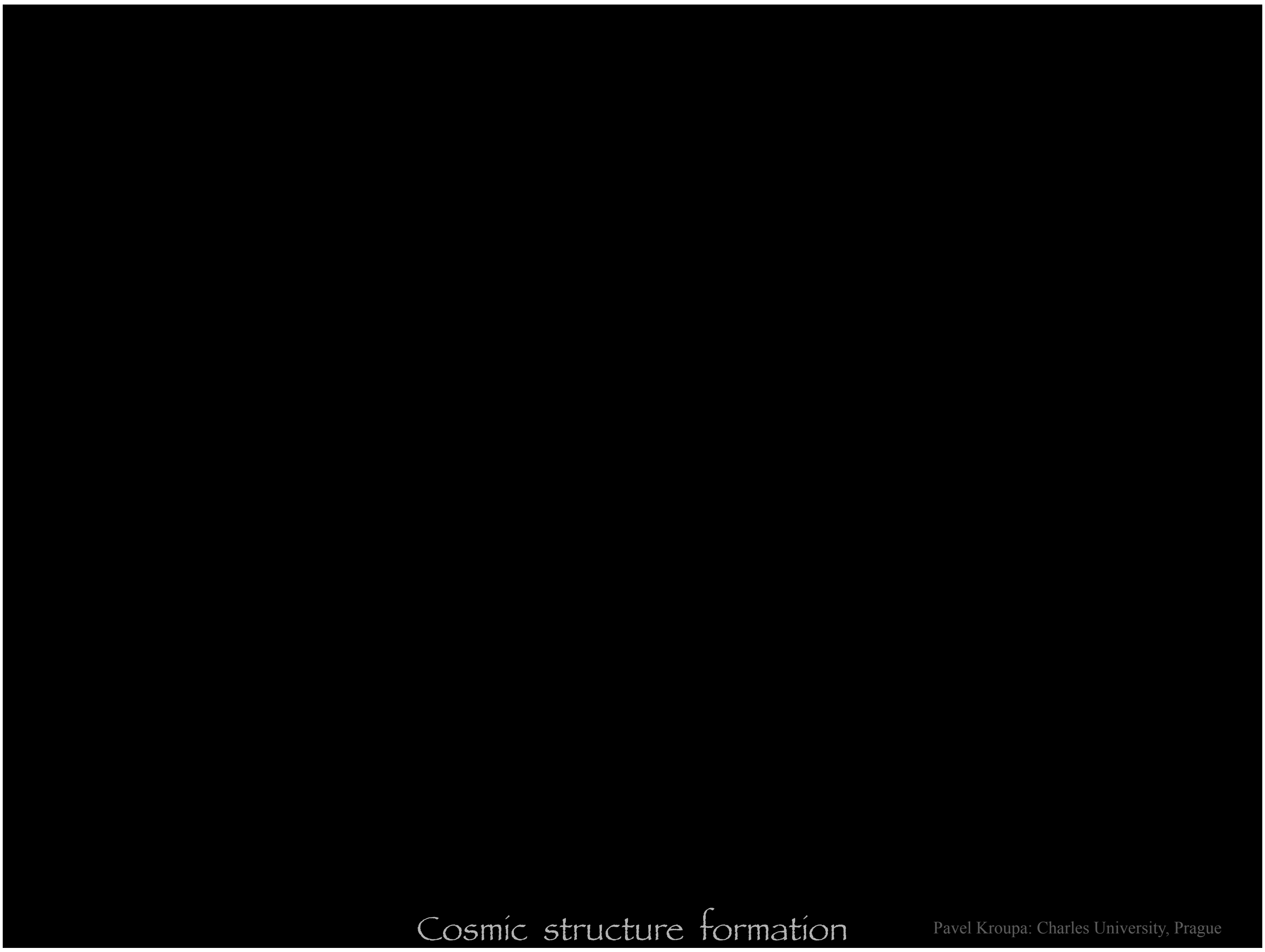
Movie by John Dubinski and Kameel Farah (CITA)
of structure formation.

(http://www.cita.utoronto.ca/~dubinski/nbody/)

Cosmic Cruise (1:55)

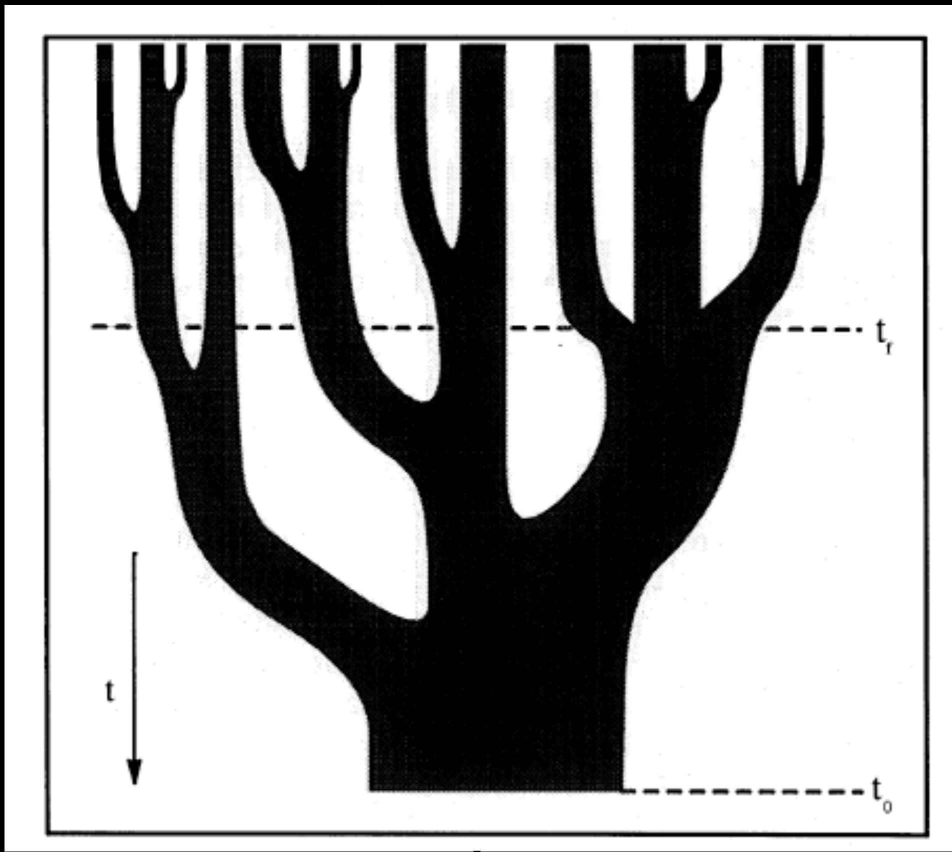
About 14 billion years ago, the universe began in a Big Bang. In one single instant, all matter and energy were created. Rapid expansion caused the matter to cool and change into atoms and also the mysterious dark matter. At first, the dark matter was spread out evenly but faint echoes of the seething quantum foam that existed at the instant of creation remained like random ripples on the surface of a frozen pond. Gravity took hold of these noisy echoes and caused them to collapse into halos of dark matter that became the seeds of the galaxies.

In this animation, we fly straight through a 130 million particle simulation of dark matter travelling hundreds of millions light years over 14 billion years. We illuminate the dark matter particles so that we can watch the formation of the cosmic web - the foundation of all structure in the prevailing model of cosmology. At the start, the regular grid of particles reflects the featureless nature of the universe at the beginning. As the flight continues, we witness the formation of the first structures through the collapse of density fluctuations. These merge with other structures and grow into the dark halos of sizes varying from galaxies to galaxy clusters.



Structures form according to the cosmological merger tree

Lacey & Cole (1993)



the beginning Big Bang

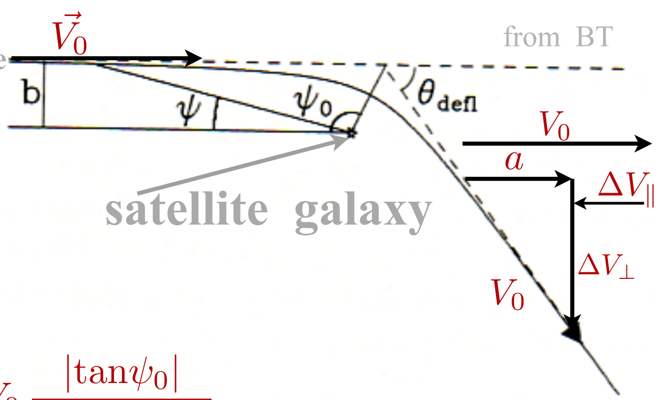
low-mass DM halos form first and coalesce to larger structures

today

Why do the galaxies merge so profusely ?

A direct test for the existence of dark matter particles :

Dynamical Friction



Conservation of energy implies that the relative speed before and after the encounter is equal to V_0.

$$|\Delta \vec{V}_\perp| = V_0 \sin\theta_{\rm defl} = V_0\,|\sin 2\,\psi_0| = 2\,V_0\,\frac{|\tan\psi_0|}{1+\tan^2\psi_0}$$

$$= \frac{2\,b\,V_0^3}{G\,(M+m)}\left[1+\frac{b^2\,V_0^4}{G^2\,(M+m)^2}\right]^{-1}$$

$$|\Delta \vec{V}_{||}| = V_0 - a = V_0\,(1-\cos\theta_{\rm defl}) = V_0\,(1+\cos 2\psi_0) = 2\,V_0\,\frac{1}{1+\tan^2\psi_0}$$

$$= 2\,V_0\,\left[1+\frac{b^2\,V_0^4}{G^2\,(M+m)^2}\right]^{-1}$$

Note that $\Delta\vec{V}_{||}$ points opposite to $\vec{V}_0$.

Visualisation

(integrate over all satellite--DM-particle encounters)

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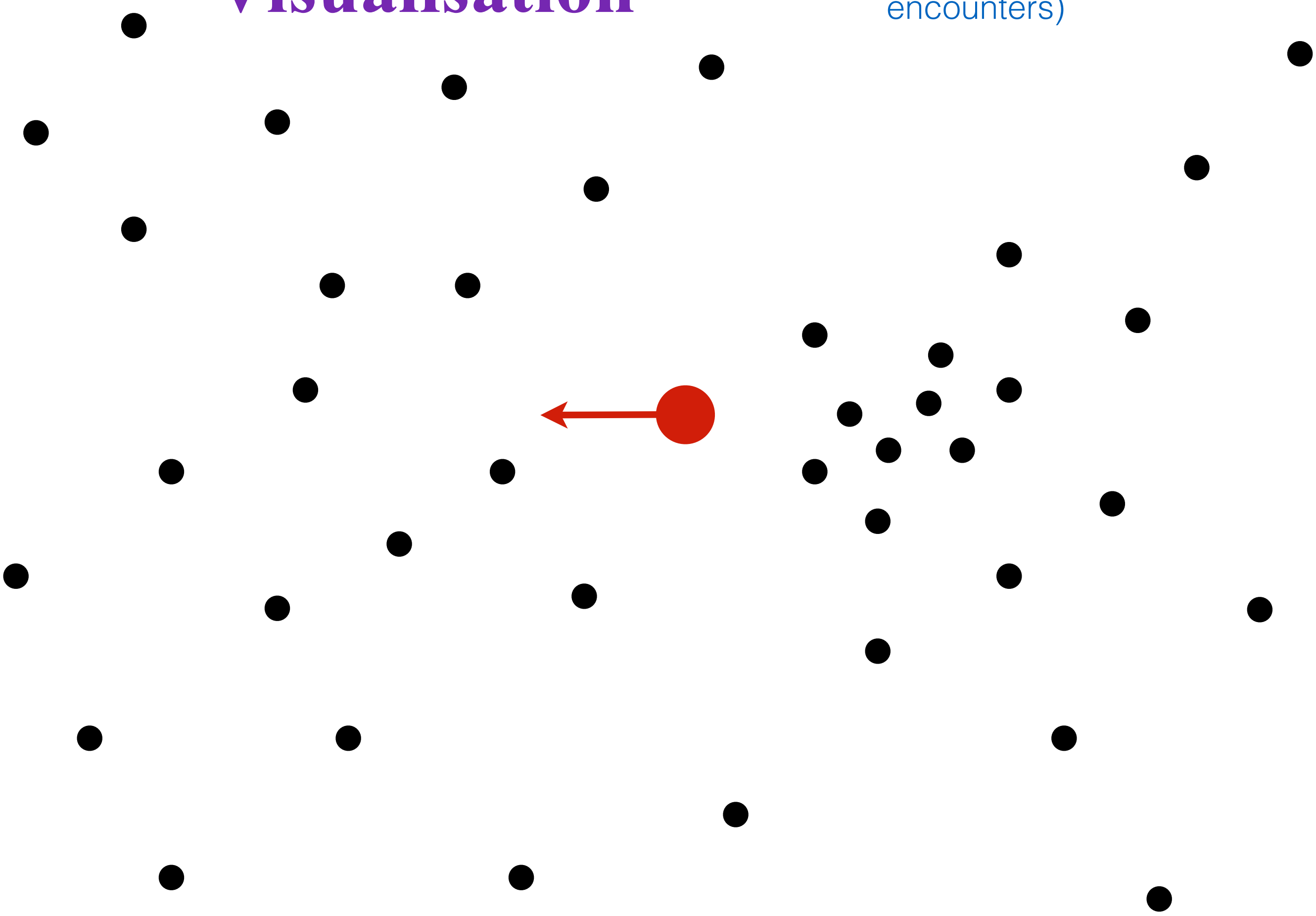

$$\frac{d\vec{v}_M}{dt} = -\frac{4\,\pi \ln\Lambda\, G^2\,(M+m)\,\rho_0\,m}{v_M^3}\left[\mathrm{erf}(X) - \frac{2\,X}{\sqrt{\pi}}\,e^{-X^2}\right]\,\vec{v}_M$$

where $X \equiv \frac{v_M}{\sqrt{2}\,\sigma}$

Chandrasekhar dynamical friction

Note : the deceleration is proportional to the mass-density of the field particles.

it is proportional to M (for $M \gg m$); the drag force is thus proportional to M^2.

The formula above has been derived by assuming the background field density to be homogeneous and infinite. Numerical simulations show, however, that the formula works well for satellites orbiting in large galaxies ($M_{\rm sat} \ll M_{\rm host}$ and $R_{\rm sat} \ll R_{\rm host}$).

The Coulomb parameter is somewhat arbitrary through uncertain minimum and and maximum encounter distances.

$$\frac{d\vec{v}_M}{dt} = -\frac{4\,\pi \ln\Lambda\, G^2\,(M+m)\,\rho_0\,m}{v_M^3}\left[\mathrm{erf}(X) - \frac{2\,X}{\sqrt{\pi}}\,e^{-X^2}\right]\,\vec{v}_M$$

When M is on a *circular orbit* within the host, $v_M = v_c(r)$, then dynamical friction exerts a torque,

$$\vec{T} = \vec{r} \times \vec{F}_{\rm DF} = \frac{d\vec{L}}{dt} \qquad \text{where} \qquad \vec{F}_{\rm DF} = M\,\frac{d\vec{v}_M}{dt}$$

$$\vec{L} = M\,\vec{v}_c(r) \times \vec{r}, \qquad |\,|L| = M\,v_c\,r$$

$$\frac{dL}{dt} = r\,F_{\rm DF}(r) = r\,\left[F_{\rm DF}(r)\right]$$

$$= r\left[M\,\frac{dv_M}{dt}\right]$$

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$$= r\left[M\,\frac{dv_M(r)}{dt}\right]$$
$$= M\left(v_c + r\,\frac{\partial v_c}{\partial r}\right)\frac{dr}{dt}$$

$$\frac{dL}{dt} = \frac{d}{dt}\left(M\,v_c\,r\right)$$

$$M\left(v_c(r) + r\,\frac{\partial v_c(r)}{\partial r}\right)\frac{dr}{dt} = M\,r\,\frac{dv_M}{dt}$$

Assume $v_c(r) \approx$ constant

$\sigma(r) \equiv \sigma_{\rm 1D}(r) \approx$ constant

(good assumption for an isothermal dark-matter halo assuming it is made of particles)

and that $\rho(r) = \dfrac{v_c^2}{4\,\pi\,G\,r^2}$ (= "singular isothermal sphere")

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(good assumption for an isothermal dark-matter halo)

and that $\rho(r) = \dfrac{v_c^2}{4\,\pi\,G\,r^2}$ (= "singular isothermal sphere")

with $v_c = \sqrt{2}\,\sigma_{\rm 1D} =$ constant

dynamical friction formula from above (evaluate erf(X) from tables)

$$r\,\frac{dr}{dt} = -0.524\,\ln\Lambda\,\frac{G\,M}{\sigma}$$

$$\int_{r_i}^{0} r\,dr = -0.524\,\ln\Lambda\,\frac{G\,M}{\sigma}\int_0^{t_{\rm msgr}} dt$$

$$t_{\rm msgr} = \frac{0.95}{G \ln\Lambda} \frac{r_i^2}{M} \sigma$$

This is approximately the time which a satellite galaxy with mass M (baryonic + dark matter halo !) needs to spiral to the centre of the host halo starting at initial radius r_i

Dark matter halo properties :
Maccio et al. 2007, 2008
Bullock et al. 2001;
see Kroupa et al. 2010
for formulae

$G = 0.0045 \text{ pc}^3 \, M_\odot^{-1} \, \text{Myr}^{-2}$

$\ln\Lambda \approx 3$

Binney & Tremaine (1987, p. 427)

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t_{msgr} [Myr]	M [M_{sun}]	r_i [kpc]	σ [pc/Myr]
		200	200
		50	100

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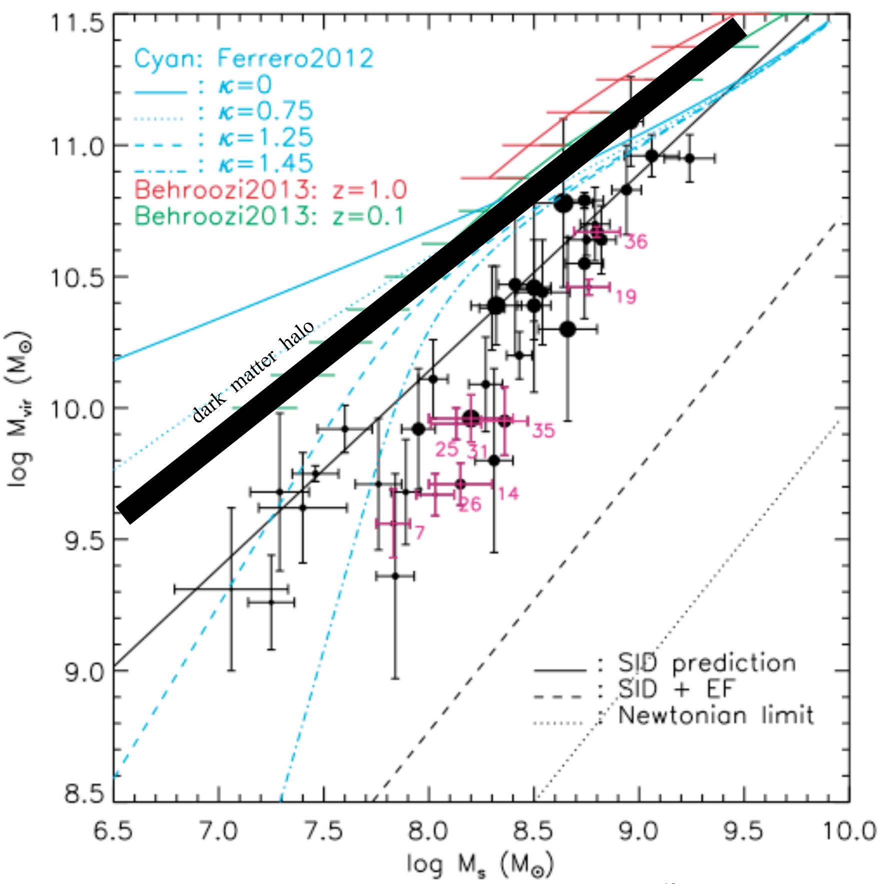
Each baryonic galaxy has a pre-infall DM halo mass :



Wu & Kroupa 2015, MNRAS

E.g. a 10^8 Msun pre-infall satellite ought to have had a DM halo mass $> 10^{10}$ Msun such that its orbital decay time would be short.

Simulations with stellar feedback, star formation and gas dynamics

Sales, Navarro et al. 2017, MNRAS, "The low-mass end of the baryonic Tully–Fisher relation" (EAGLE simulation)

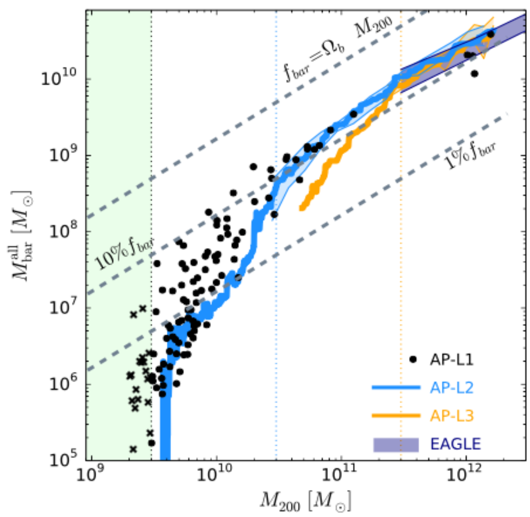


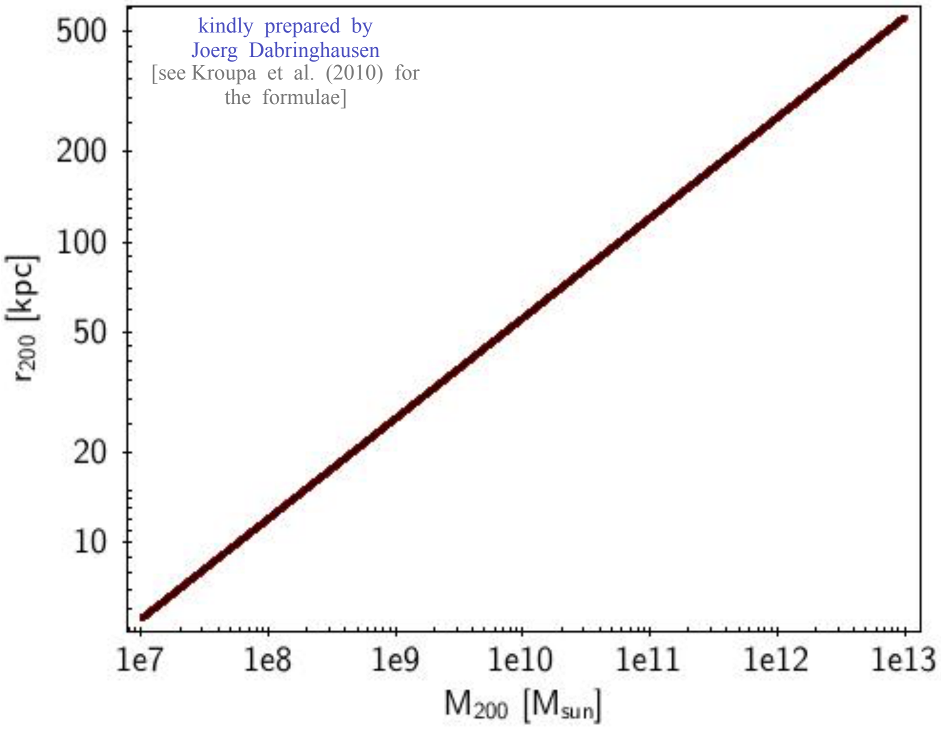
Figure 1. Left: galaxy baryonic mass ($M_{\rm bar}^{\rm all} = M_{\rm gas}^{\rm all} + M_{\rm str}$) versus virial mass ($M_{200}$) in our simulated galaxy sample. Shaded regions indicate the interquartile baryonic mass range at given M_{200} and highlight the virial mass range over which the simulation results are insensitive of resolution. Vertical dotted lines indicate the minimum converged virial mass for each resolution level. Thick lines of matching colour indicate the median trend for each simulation set, as specified in the legend, and extend to virial masses below the minimum needed for convergence. Dashed grey lines indicate various fractions of all baryons within the virial radius. Note the steep decline in 'galaxy formation efficiency' with decreasing virial mass. Dark filled circles indicate the results of individual AP-L1 galaxies. A light green shaded region highlights non-converged systems in our highest resolution runs. Crosses are used to indicate galaxies in haloes considered 'not converged' numerically. Right: stellar half-mass radius, $r_{\rm h}^{\rm str}$, as a function of virial mass for simulated galaxies. Symbols, shading, and colour coding are as in the left-hand panel. Limited resolution sets a minimum size for galaxies in poorly resolved haloes. The same minimum mass needed to ensure convergence in baryonic mass seems enough to ensure convergence in galaxy size, except, perhaps, for AP-L1, for which we adopt a minimum converged virial mass of 6×10^9 M$_\odot$. The values adopted for the minimum virial mass are listed in Table 1.

E.g. a 10^8 Msun pre-infall satellite ought to have had a DM halo mass $>$ 10^{10} Msun such that its orbital decay time would be short.

see also Matthee, Schaye et al., 2017, MNRAS, "The origin of scatter in the stellar mass-halo mass relation of central galaxies in the EAGLE simulation"
http://adsabs.harvard.edu/abs/2017MNRAS.465.2381M

A pre-infall (z=0) DM halo has a virialised radius :

Within r_{200} is the mass M_{200} and a density 200 times larger than the critical cosmological density; r_{200} is approximately the virialised radius.



DM halos are, in a sense, like spider's webs : once two DM halos approach within the sum of their radii they begin to merge, if their relative velocity is comparable to the velocity dispersion of the larger halo.

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This is approximately the time which a satellite galaxy with mass M (baryonic + dark matter halo !) needs to spiral to the centre of the host halo starting at initial radius r_i

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t_{msgr} [Myr]	M [M_{sun}]	r_i [kpc]	σ [pc/Myr]
$10^{7.75}$	10^7	200	200
$10^{6.25}$	10^7	50	100

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$10^{6.75}$	10^8	200	200
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$10^{5.25}$	10^8	50	100
$10^{5.75}$	10^9	200	200
$10^{4.25} \approx$ 10 Gyr	10^9	50	100
$10^{4.75} \approx$ 10 Gyr	10^{10}	200	200
$10^{3.25} \approx$ 1 Gyr	10^{10}	50	100
$10^{3.75} \approx$ 1 Gyr	10^{11}	200	200
$10^{2.75} \approx$ 0.1 Gyr	10^{12}	200	200

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$\ln\Lambda \approx 3$

Binney & Tremaine (1987, p. 427)

Are these analytical estimates

realistic ?

Perform numerical simulations ...

Privon, Barnes et al. 2013

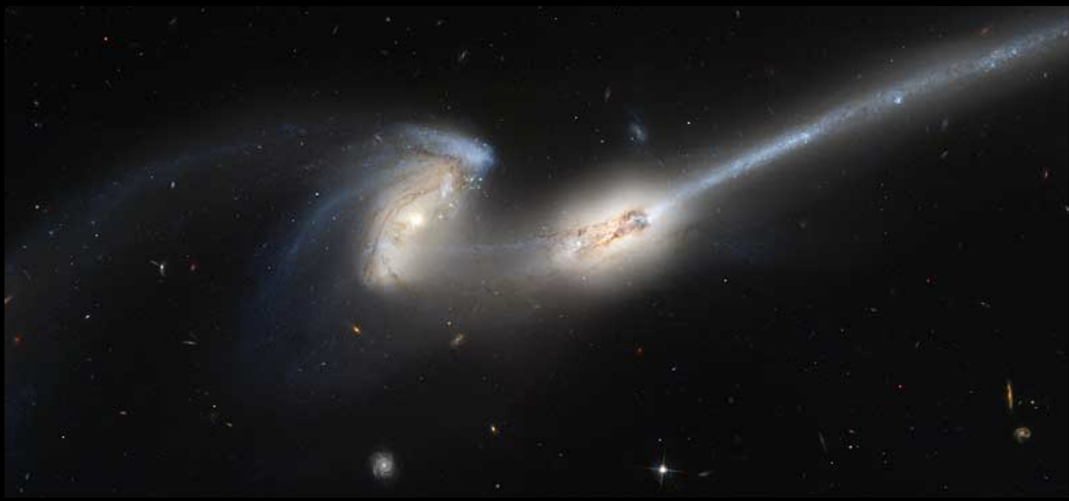
Table 2
Dynamical models derived from Identikit matching

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.

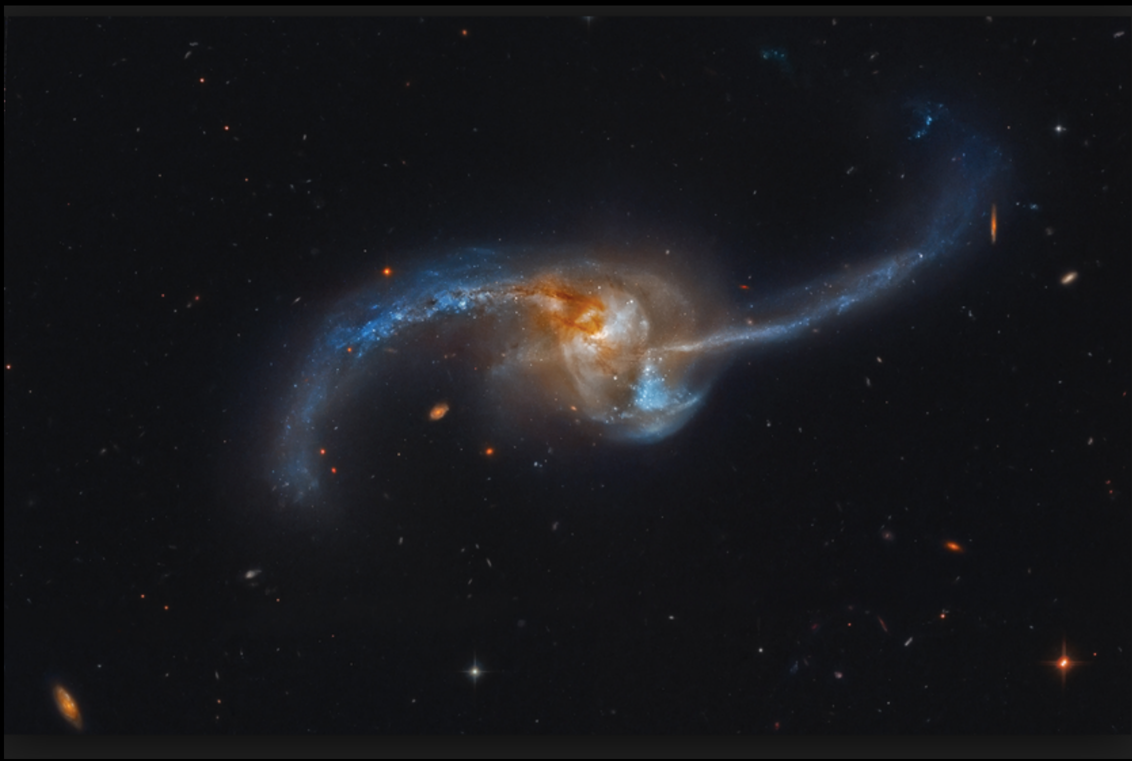
NGC 5257/8

The Mice



Antennae

NGC 2623



Pavel Kroupa: Praha Lecture 2

Privon, Barnes et al. 2013

Dynamical Modeling with Identikit 7

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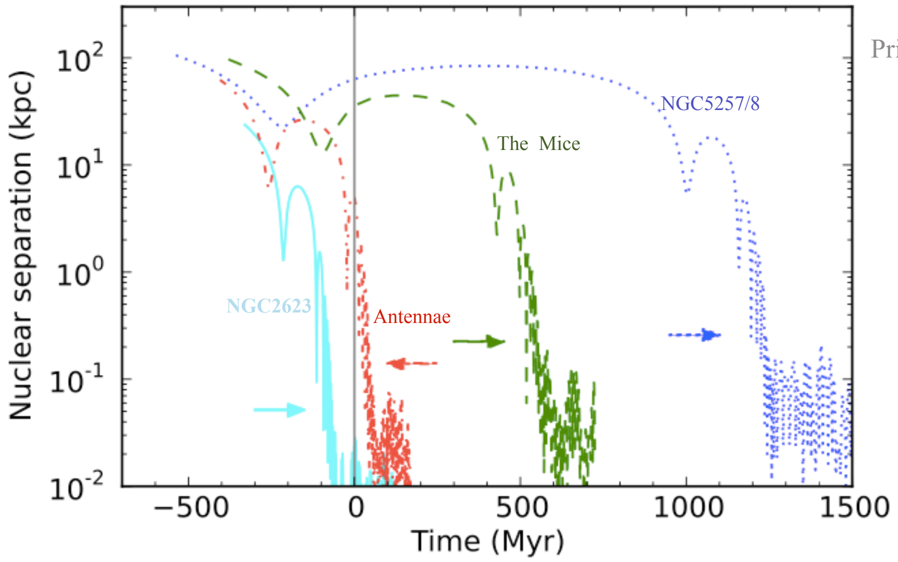
Dynamical friction : galaxy mergers - must be common

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."

Are these analytical estimates

realistic ?

... yes !

Test dynamical friction on the satellite galaxies of the Milky Way ...

Mon. Not. R. Astron. Soc. **416,** 1401–1409 (2011) doi:10.1111/j.1365-2966.2011.19138.x

Using dwarf satellite proper motions to determine their origin

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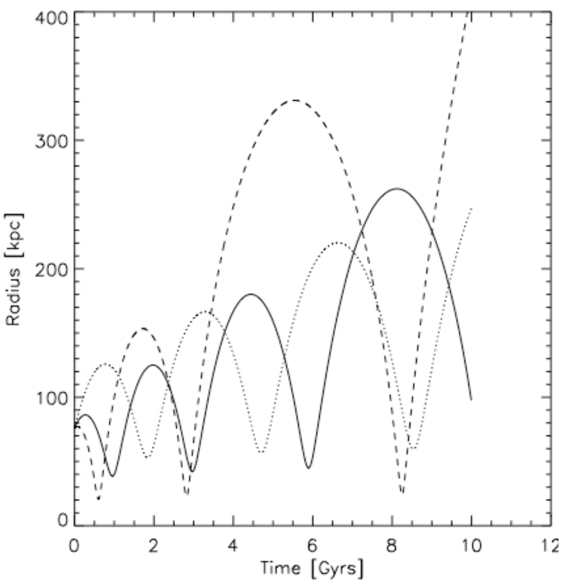
ABSTRACT

The highly organized distribution of satellite galaxies surrounding the Milky Way is a serious challenge to the concordance cosmological model. Perhaps the only remaining solution, in this framework, is that the dwarf satellite galaxies fall into the Milky Way's potential along one or two filaments, which may or may not plausibly reproduce the observed distribution. Here we test this scenario by making use of the proper motions of the Fornax, Sculptor, Ursa Minor and Carina dwarf spheroidals, and trace their orbits back through several variations of the Milky Way's potential and account for dynamical friction. The key parameters are the proper motions and total masses of the dwarf galaxies. Using a simple model, we find no tenable set of parameters that can allow Fornax to be consistent with filamentary infall, mainly because the 1σ error on its proper motion is relatively small. The other three must walk a tightrope between requiring a small pericentre (less than 20 kpc) to lose enough orbital energy to dynamical friction and avoiding being tidally disrupted. We then employed a more realistic model with host halo mass accretion and found that the four dwarf galaxies must have fallen in at least 5 Gyr ago. This time-interval is longer than organized distribution is expected to last before being erased by the randomization of the satellite orbits.

Table 2. Galactocentric distances and velocities of the dSphs. For Fornax, Sculptor and Ursa Minor, our V_{x_0} corresponds to Piatek et al. (2003, 2005, 2006, 2007a) V_r and our V_{y_0} to their V_t. For Carina, the proper motion comes directly from Pasetto et al. (2011). Distances come from Mateo (1998).

dSph	r_0 (kpc)	V_{x_0} (km s^{-1})	V_{y_0} (km s^{-1})
Fornax	138 ± 8	-31.8 ± 1.7	196 ± 29
Sculptor	87 ± 4	79 ± 6	198 ± 50
Ursa Minor	76 ± 4	-75 ± 44	144 ± 50
Carina	101 ± 5	113 ± 52	46 ± 54



Angus et al. 2011

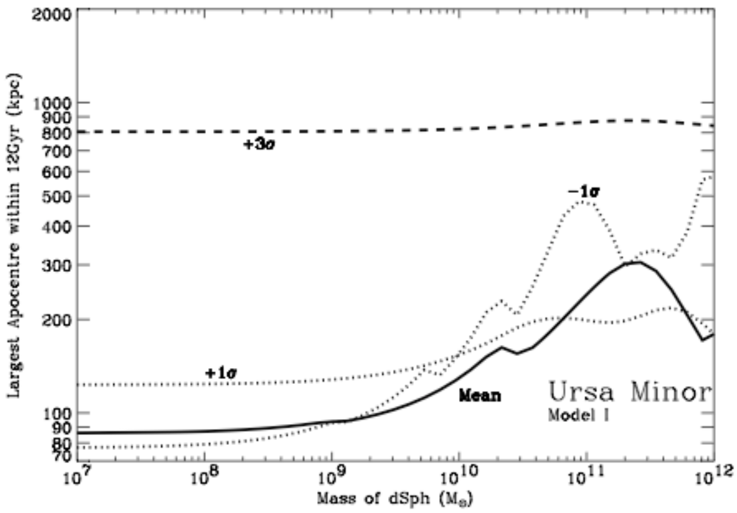


Figure 2. Here we show sample orbits for the Ursa Minor dSph (using a $5 \times 10^{10}\,M_\odot$ mass and Galactic model I) to demonstrate how the orbital apocentre decays with time due to DF. The different lines are for different values of the observed proper motion. The solid line is the mean, the dotted line is found by adding the 1σ error in parallel to the mean and the dashed line is found by adding the 1σ error antiparallel.

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Accepted 2011 May 25. Received 2011 May 25; in original form 2010 September 14

Table 2. Galactocentric distances and velocities of the dSphs. For Fornax, Sculptor and Ursa Minor, our V_{x_0} corresponds to Piatek et al. (2003, 2005, 2006, 2007a) V_r and our V_{y_0} to their V_t. For Carina, the proper motion comes directly from Pasetto et al. (2011). Distances come from Mateo (1998).

dSph	r_0 (kpc)	V_{x_0} (km s^{-1})	V_{y_0} (km s^{-1})
Fornax	138 ± 8	-31.8 ± 1.7	196 ± 29
Sculptor	87 ± 4	79 ± 6	198 ± 50
Ursa Minor	76 ± 4	-75 ± 44	144 ± 50
Carina	101 ± 5	113 ± 52	46 ± 54

ABSTRACT

The highly organized distribution of satellite galaxies surrounding the Milky Way is a serious challenge to the concordance cosmological model. Perhaps the only remaining solution, in this framework, is that the dwarf satellite galaxies fall into the Milky Way's potential along one or two filaments, which may or may not plausibly reproduce the observed distribution. Here we test this scenario by making use of the proper motions of the Fornax, Sculptor, Ursa Minor and Carina dwarf spheroidals, and trace their orbits back through several variations of the Milky Way's potential and account for dynamical friction. The key parameters are the proper motions and total masses of the dwarf galaxies. Using a simple model, we find no tenable set of parameters that can allow Fornax to be consistent with filamentary infall, mainly because the 1σ error on its proper motion is relatively small. The other three must walk a tightrope between requiring a small pericentre (less than 20 kpc) to lose enough orbital energy to dynamical friction and avoiding being tidally disrupted. We then employed a more realistic model with host halo mass accretion and found that the four dwarf galaxies must have fallen in at least 5 Gyr ago. This time-interval is longer than organized distribution is expected to last before being erased by the randomization of the satellite orbits.

Therefore . . .

The present-day motions and distances of MW satellites preclude them to have fallen-in from a filament if they have dark-matter halos.

→ tension with dark-matter hypothesis

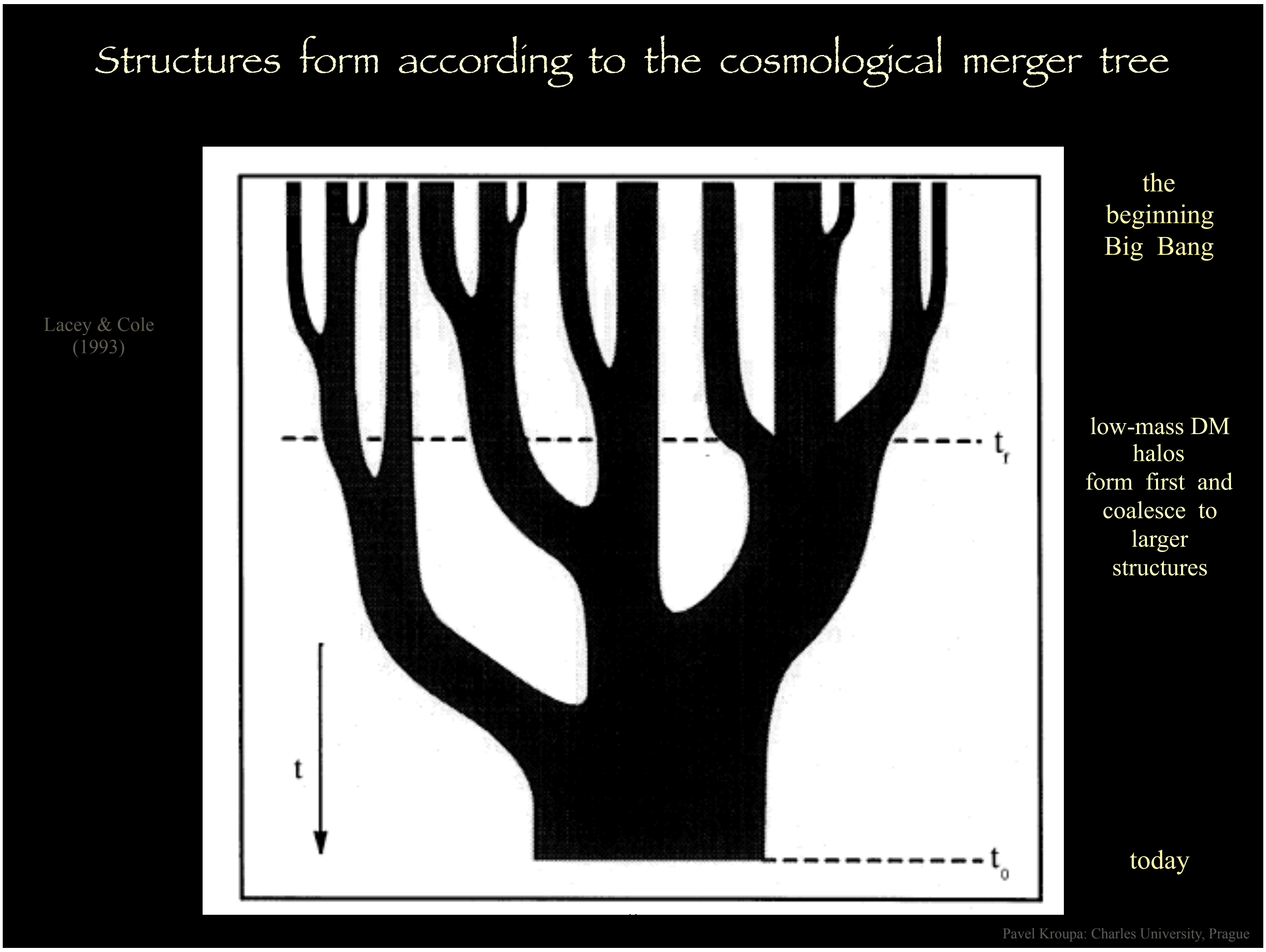
Therefore . . .

The present-day motions and distances of MW satellites preclude them to have fallen-in from a filament if they have dark-matter halos.

We will return to the distribution of satellite galaxies later.

Is there independent evidence for this ?

The standard model of cosmology (SMoC) predicts that each and every galaxy has a history of mergers.



Is there independent evidence for this ?

The standard model of cosmology (SMoC) predicts that each and every galaxy has a history of mergers.

The mergers are random, i.e. every galaxy has a different merger history !

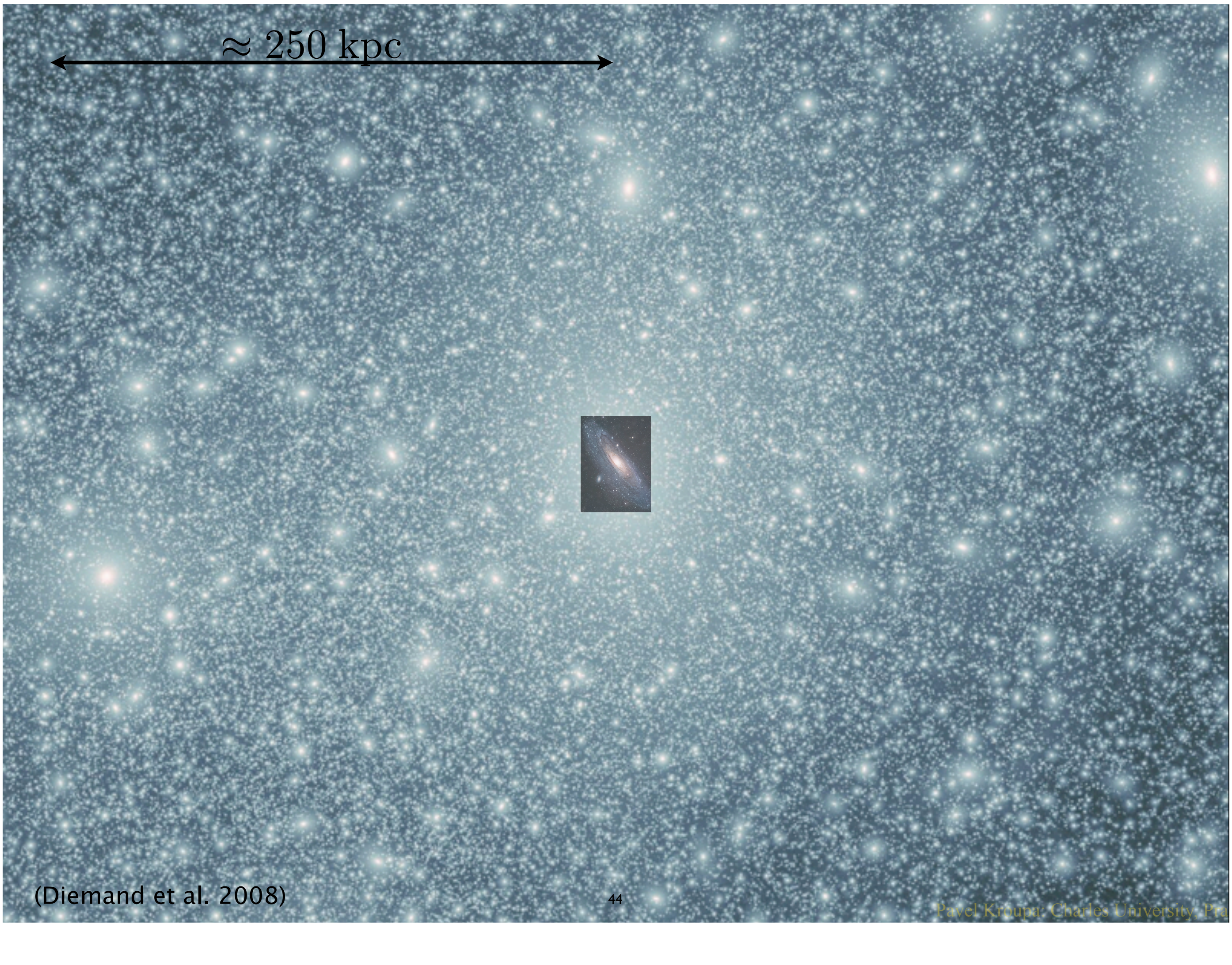
This has a number of important consequences :

Consequences of random mergers :

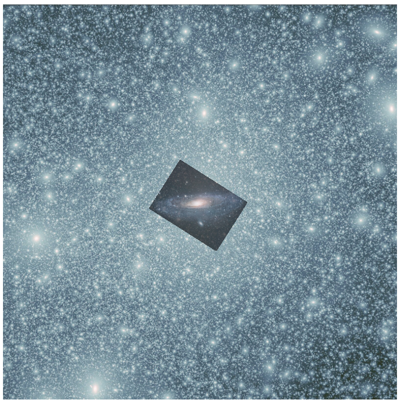
I. Phase-space distribution of satellite galaxies.

Satellite galaxies populate not-yet merged sub-halos (in the SMoC) **!**

These are spheroidally distributed, a largely pressure-supported 3D population around any large galaxy.



(Diemand et al. 2008)



(Kroupa et al. 2005; Pawlowski, Pflamm-Altenburg & Kroupa 2012, Ibata et al. 2013
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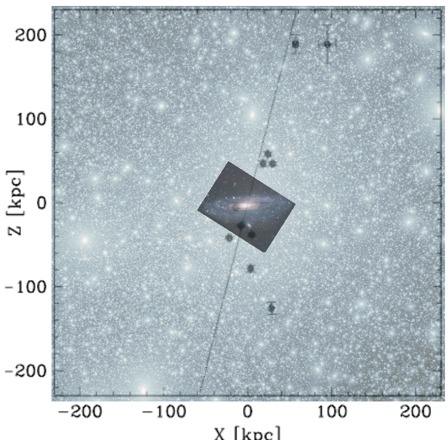

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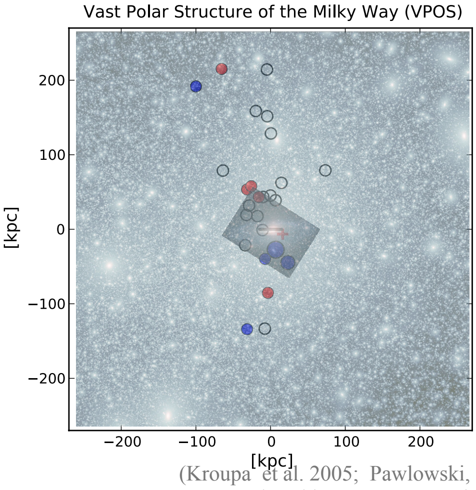

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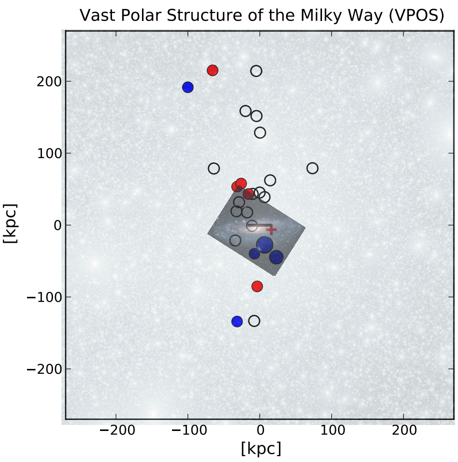

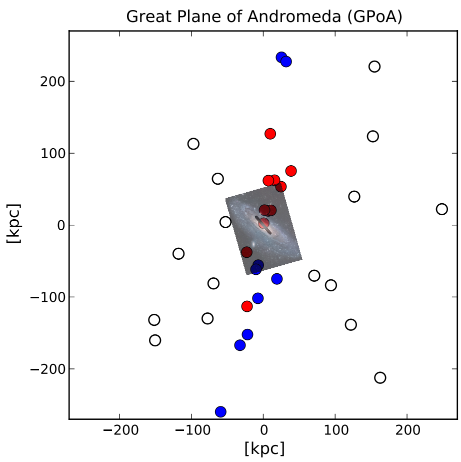

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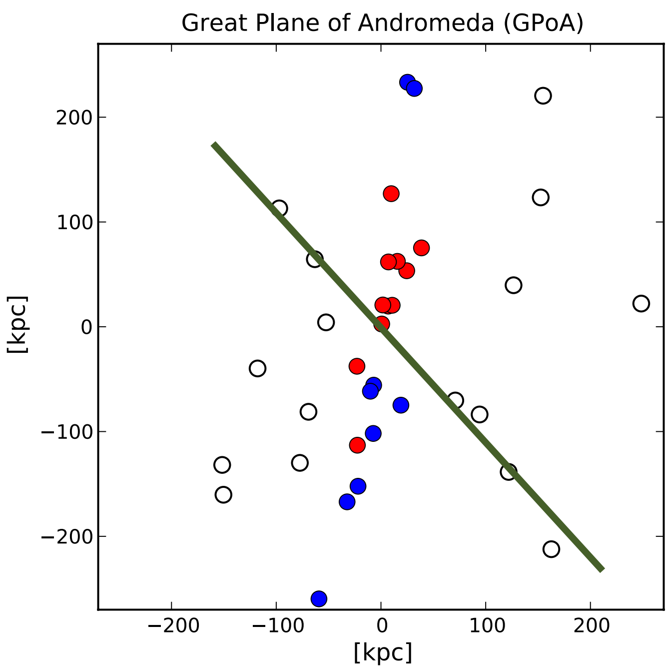
Our neighbour: the Andromeda galaxy

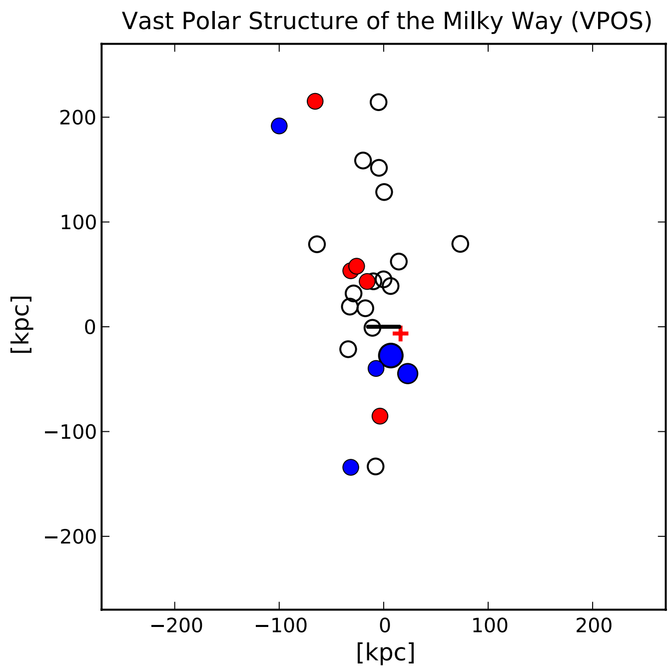
Pavel Kroupa: Charles University, Prague

Andromeda



Ibata et al. 2013, 2014

Milky Way



Pawlowski & Kroupa 2013

Milky Way

Is the VPOS or DoS or plane of satellites significant ?

MNRAS 456, 448–458 (2016) doi:10.1093/mnras/stv2

The alignment of SDSS satellites with the VPOS: effects of the survey footprint shape

Marcel S. Pawlowski★
Department of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA

In answering a question posed by the French royal astronomical society, Bernoulli (1735) was one of the first to apply probability theory to astronomy. He set out to determine whether the alignment of the then known six planets and their orbits in the Solar system along a common ecliptic plane could arise by chance, assuming that they are drawn from isotropic distributions. If the observed arrangement were not unlikely to arise by chance, no particular formation mechanism for the planetary alignment would be required. Using several estimates, he found the probability to be very low, between 2.7×10^{-6} and 7×10^{-7}. According to Bernoulli, '[...] cette probabilié est si petite, quelle doit passer pour une impossibilité morale'.[1] Consequently, a formation mechanism for coherently orbiting planetary systems had to be invoked. While the details of his estimations can be criticized, it is tempting to adopt his standard (and phrasing) of statistical significance.

Today, we face a similar challenge on a (spatially) much larger scale. The Milky Way (MW) is surrounded by a vast polar struc-

close alignment of the SDSS satellites with it. For the rms height, $P_{\mathrm{rms}}^{\mathrm{VPOS}} = P_{\mathrm{rms}}^{\mathrm{class}} \times P_{\mathrm{rms}}^{\mathrm{SDSS}} = 9.8 \times 10^{-7}$ (equivalent to 4.9σ), while for the axial ratio $P_{c/a}^{\mathrm{VPOS}} = P_{c/a}^{\mathrm{class}} \times P_{c/a}^{\mathrm{SDSS}} = 3.7 \times 10^{-7}$ (equivalent to 5.1σ). Adding the information provided by the SDSS satel-

Pawlowski, Kroupa & Jerjen (2013 MNRAS)

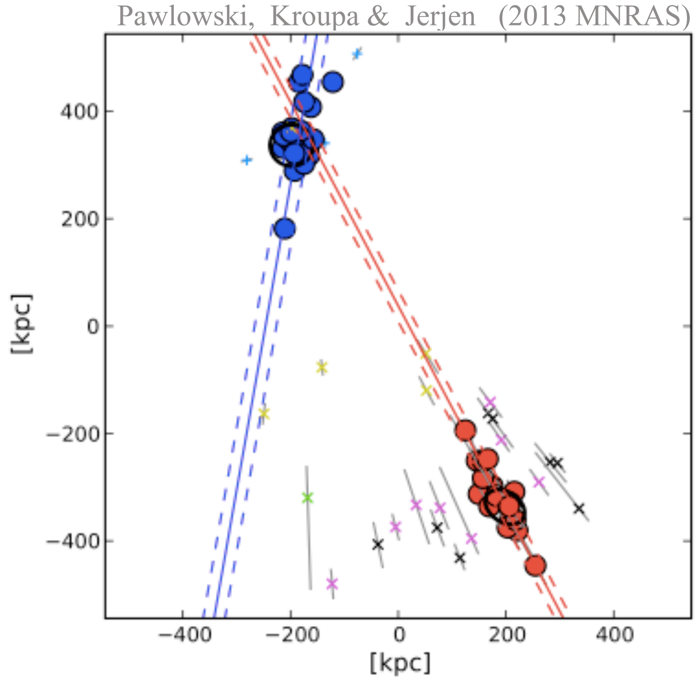


Figure 16. Edge-on view of the satellite galaxy planes around the MW and M31, similar to Fig. 9 for the LG planes. As before, galaxies which are

How can the MW and Andromeda satellite systems be so correlated, if they are sub-halos falling-in individually ?

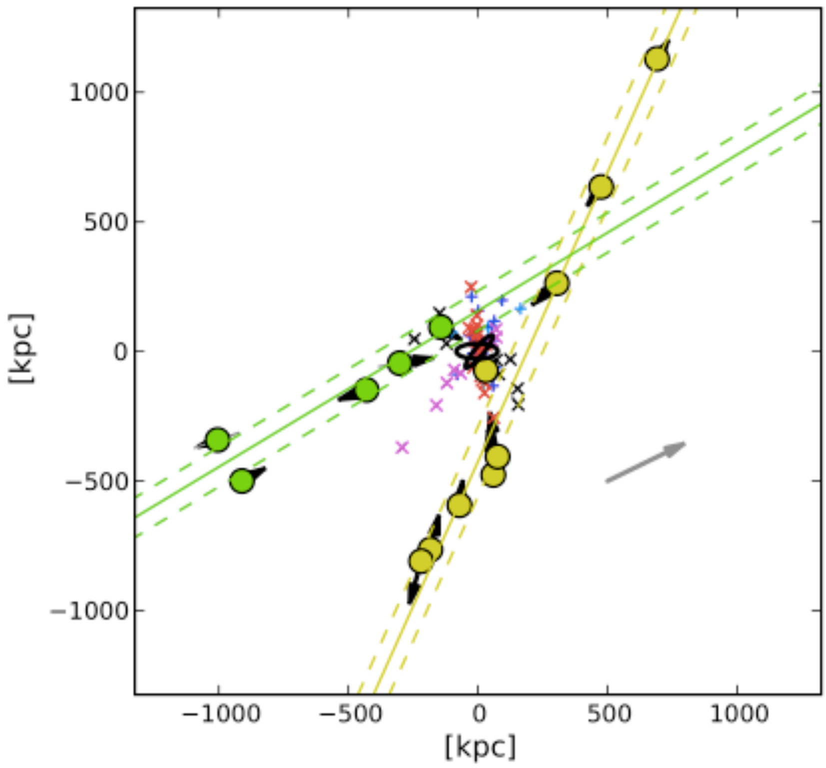


Figure 9. Edge-on view of both LG planes. The orientation of the MW and M31 are indicted as black ellipses in the centre. Members of the LGP1 are plotted as yellow points, those of LGP2 as green points. MW galaxies are plotted as plus signs (+), all other galaxies as crosses (×), the colours code their plane membership as in Fig. 6. The best-fitting planes are plotted as

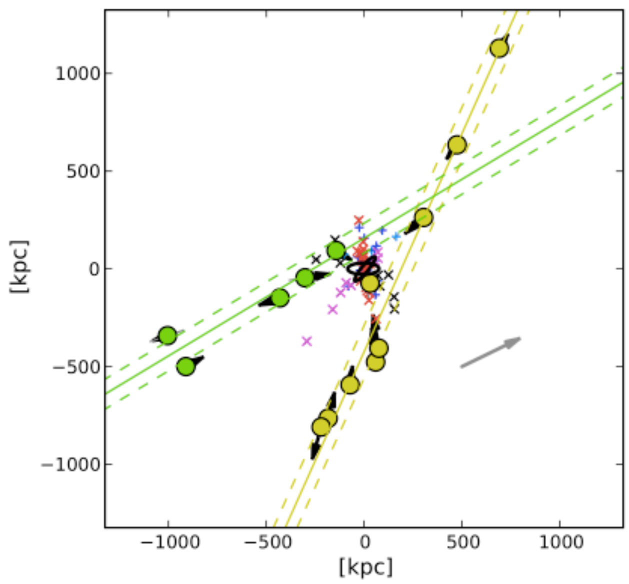
Everything we know about the Local Group today

Pawlowski, Kroupa & Jerjen (2013 MNRAS)

"The discovery of symmetric structures in the Local Group"

A frightening symmetry

Pawlowski, Kroupa & Jerjen (2013 MNRAS)



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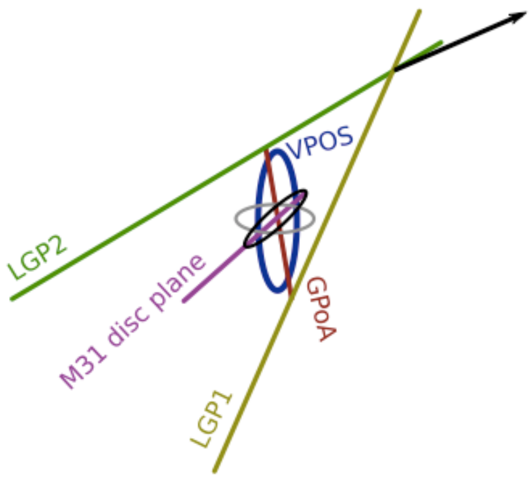


Figure 18. Cartoon of the LG structure (compare to Fig. 9). The positions and orientations of the galactic discs of the MW (grey) and of M31 (black) are indicated by the ellipses in the centre. Looking along the MW–M31 line, most planes in the LG are seen approximately edge-on, the only exception is the VPOS plane (blue), which is inclined relative to this view. The arrow indicates the direction of motion of the LG relative to the CMB.

Dark matter beyond the Local Group II

LCDM, Modified Gravity or new Dark Matter models?

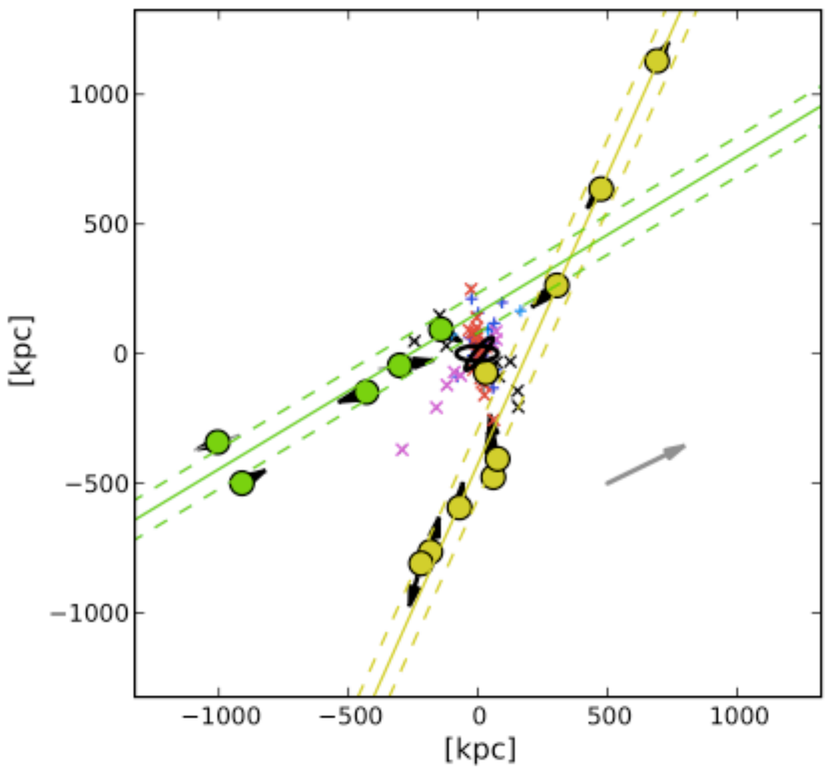
May 29-31, 2017

Universite Pierre a Marie Curie, Paris

Pavel Kroupa
Helmholtz-Institute for Radiation und Nuclear Physics (HISKP)
University of Bonn

Astronomical Institute,
Charles University in Prague

c/o Argelander-Institut für Astronomie
University of Bonn



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Everything we know about the Local Group today

Pawlowski, Kroupa & Jerjen (2013 MNRAS)

"The discovery of symmetric structures in the Local Group"

A frightening symmetry

. . . the structure of the

Local Group of Galaxies

appears to be incompatible

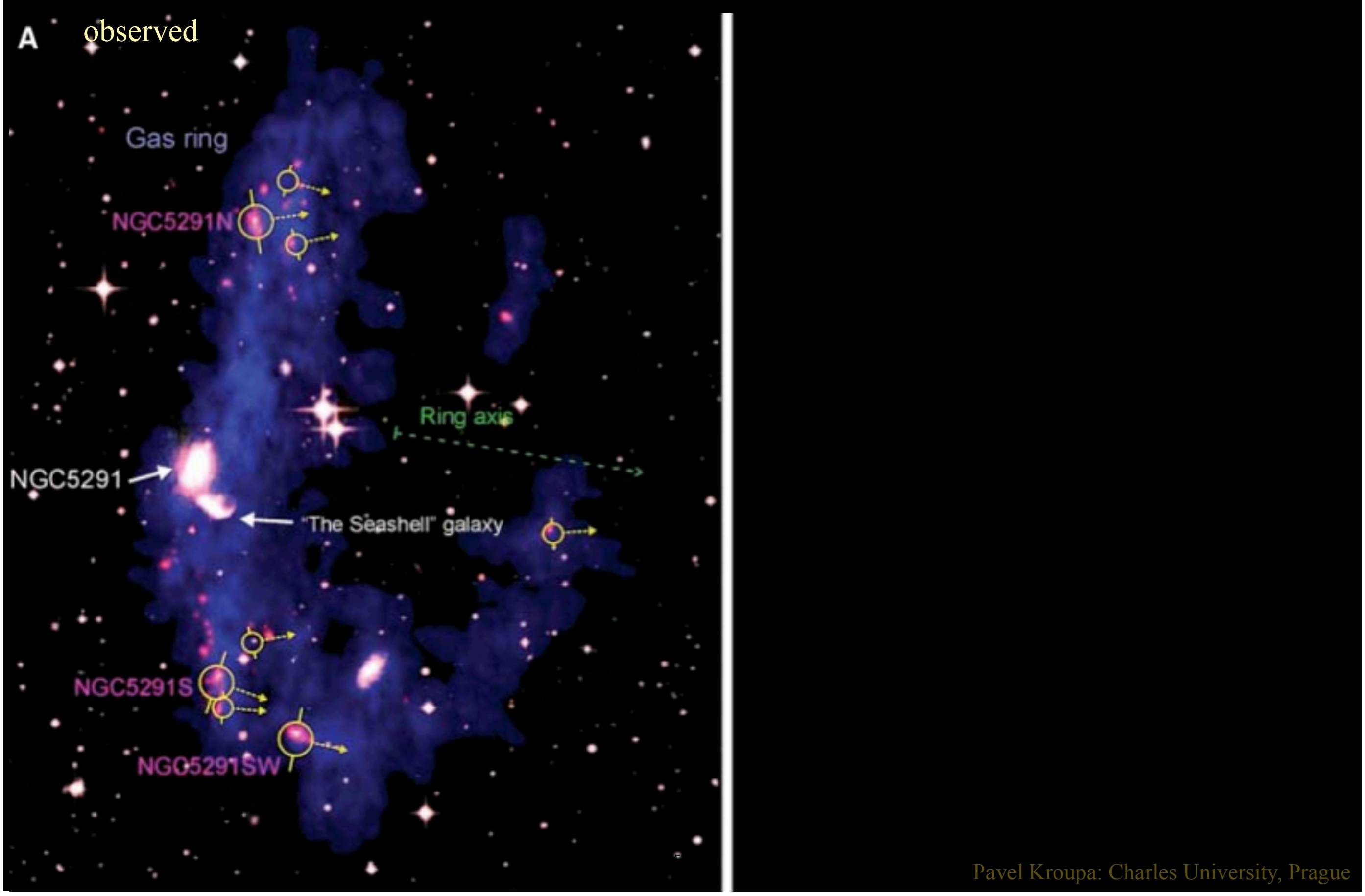
with the SMoC.

Concistency Check

Other, extra-galactic,
phase-space correlated distributions
of satellite systems.

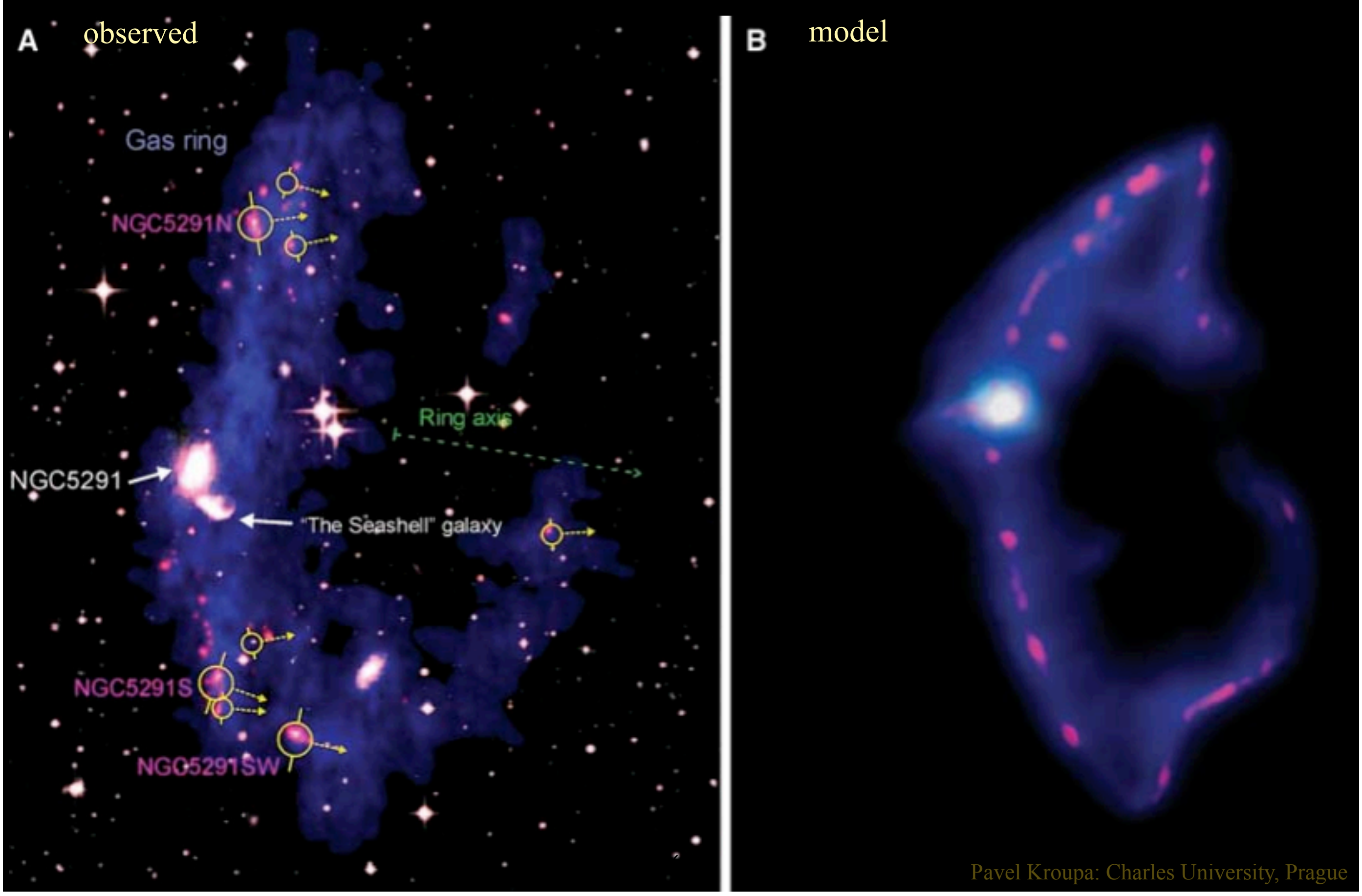
Are the Milky Way & Andromeda
unique or
extreme outliers ?

Bournaud et al. (2007, Science)

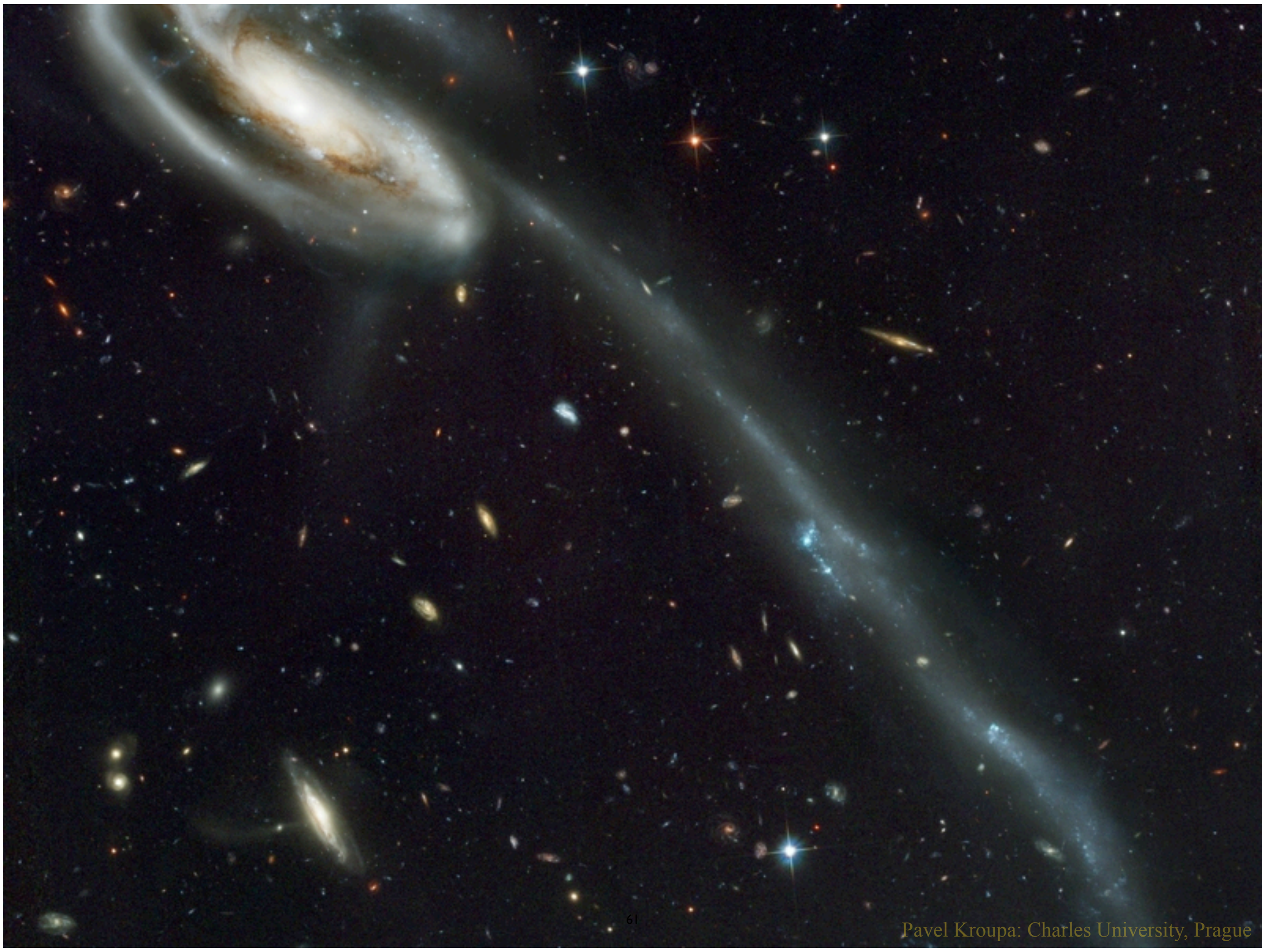


Pavel Kroupa: Charles University, Prague

Bournaud et al. (2007, Science)

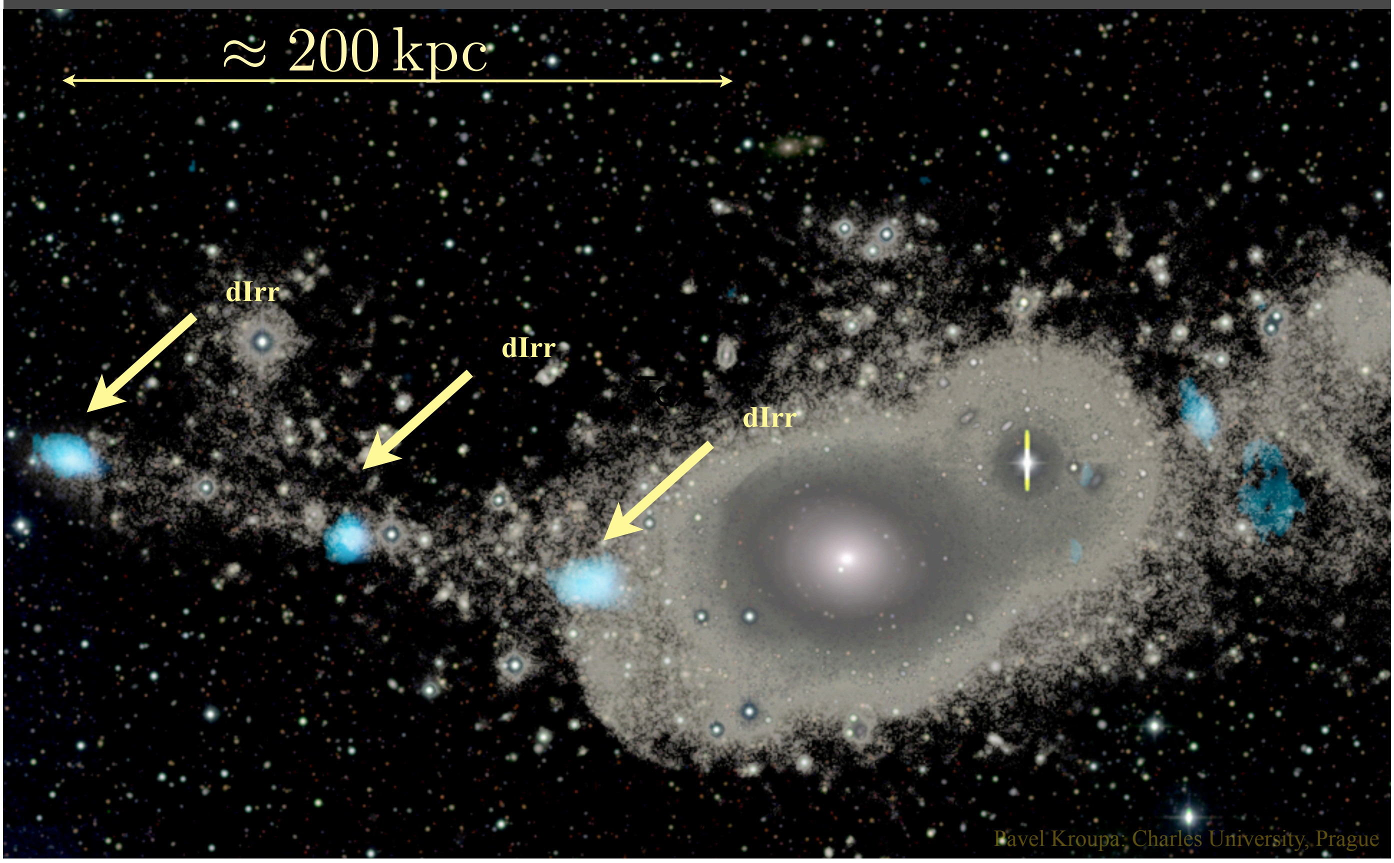


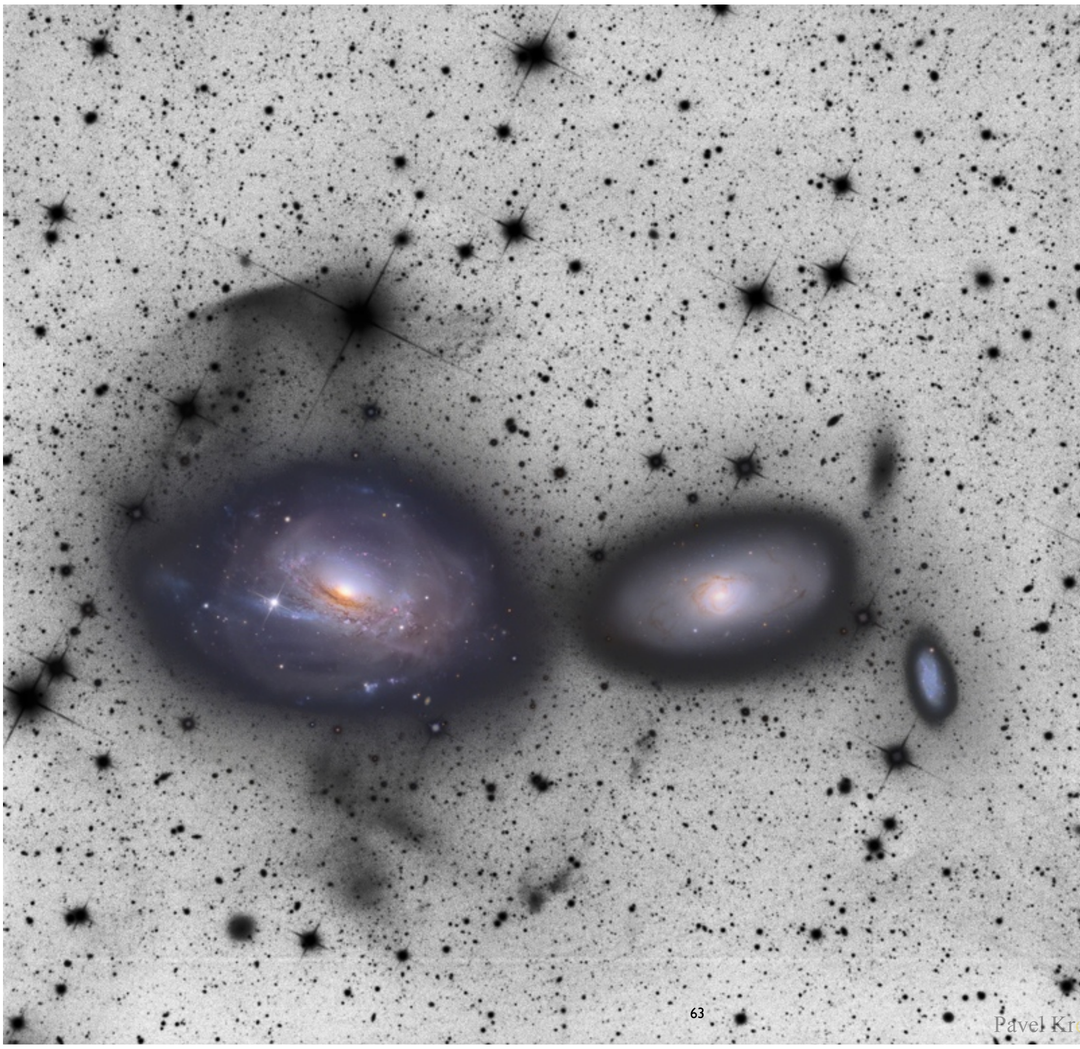
Pavel Kroupa: Charles University, Prague



NGC 5557

(post-interaction 2-3 Gyr)

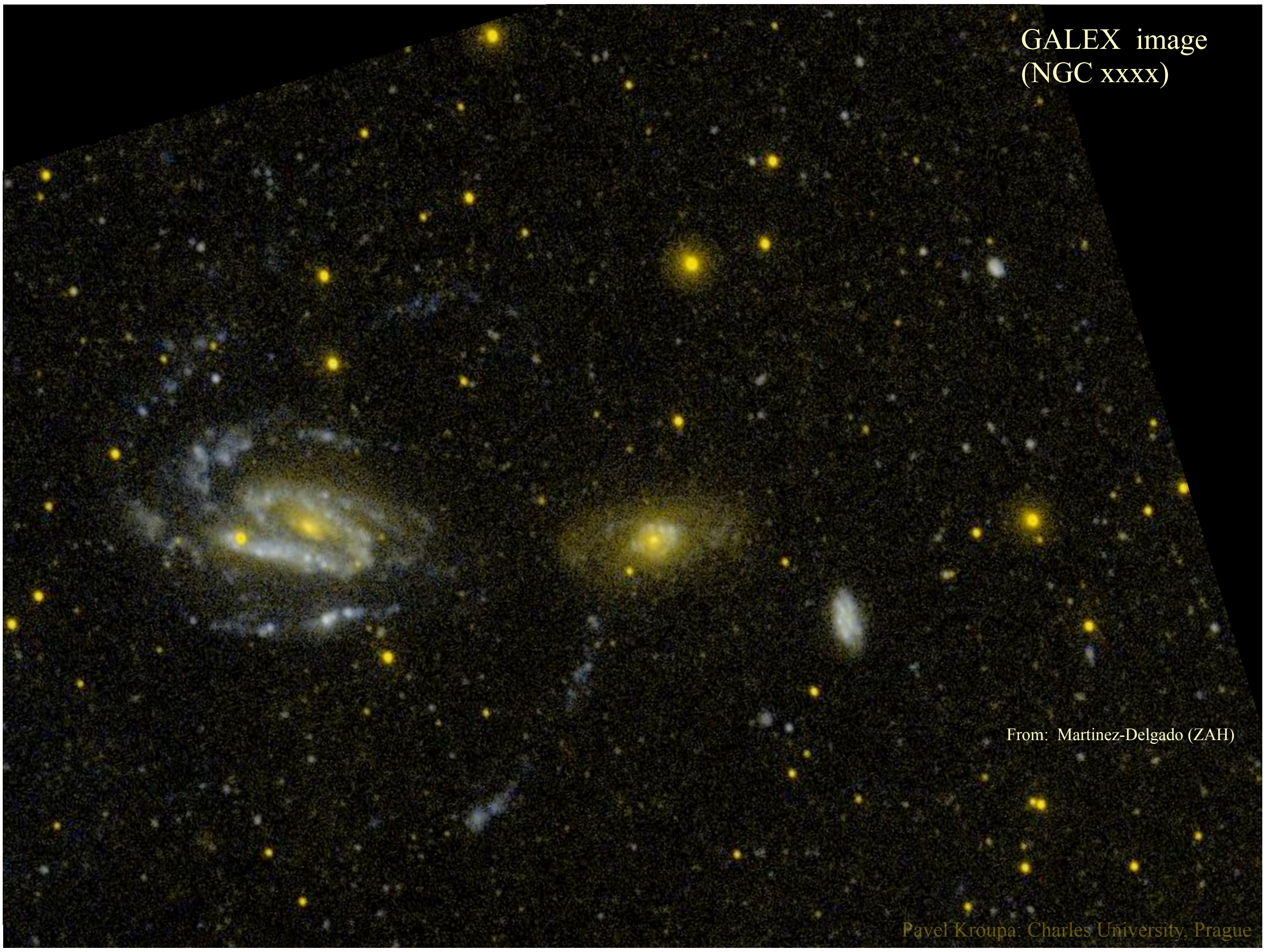




The formation of faint dwarf galaxies in the interaction between two spirals (NGC xxxx)

Credit: Martinez-Delgado (ZAH) and
Adam Block (MtLemmon Obs)

GALEX image (NGC xxxx)



From: Martinez-Delgado (ZAH)

Concistency Check

Other, extra-galactic,
phase-space correlated distributions
of satellite systems.

Is the Milky Way galaxy unique or
an extreme outlier ?

NO, it is not !

Chiboucas et al. (2013, AJ) write

"In review, in the few instances around nearby major galaxies where we have information, in every case there is evidence that gas poor companions lie in flattened distributions"

Consequences of random mergers :

I. Phase-space distribution of satellite galaxies.

Satellite galaxies populate not-yet merged sub-halos (in the SMoC) !

These are spheroidally distributed, a largely pressure-supported 3D population around any large galaxy.

→ not observed !

Consequences of random mergers :

I. Phase-space distribution of satellite galaxies.

→ disagreement with SMoC **!**

II. Classical bulges :

Weinzirl et al. (2009) and Kormendy et al. (2010)**:** too many [>50%, 94% according to Fernández Lorenzo et al. 2014] of all late-type galaxies (with baryonic mass $10^{10} M_{Sun}$) do not have a classical bulge.

Thus, the very large fraction of observed bulgeless disc galaxies and disk-dominated galaxies (70% in edge-on disk galaxies) is inconsistent with the high incidence (>70%) of significant mergers (Kormendy et al. 2010)

Consequences of random mergers :

I. Phase-space distribution of satellite galaxies.

→ disagreement with SMoC **!**

II. Classical bulges : → disagreement with SMoC **!**

III. Galaxies are simpler than thought **:**

Disney et al. (2008, Nature) **:**

Galaxies are complex systems the evolution of which apparently results from the interplay of dynamics, star formation, chemical enrichment and feedback from supernova explosions and super-massive black holes[1]. The hierarchical theory of galaxy formation holds that galaxies are assembled from smaller pieces, through numerous mergers of cold dark matter[2–4]. The properties of an individual galaxy should be controlled by six independent parameters including mass, angular momentum, baryon fraction, age and size, as well as by the accidents of its recent haphazard merger history. Here we report that a sample of galaxies that were first detected through their neutral hydrogen radio-frequency emission, and are thus free from optical selection effects[5], shows five independent correlations among six independent observables, despite having a wide range of properties. This implies that the structure of these galaxies must be controlled by a single parameter, although we cannot identify this parameter from our data set. ***Such a degree of organization appears to be at odds with hierarchical galaxy formation, a central tenet of the cold dark matter model in cosmology***[6]

Consequences of random mergers :

I. Phase-space distribution of satellite galaxies.

→ disagreement with SMoC **!**

II. Classical bulges : → disagreement with SMoC **!**

III. Galaxies are simpler than thought :

→ disagreement with SMoC **!**

IV. No evidence for E galaxies forming from mergers :

Consequences of random mergers :

IV. No evidence for E galaxies forming from mergers :

1) Downsizing Recchi et al. (2009) **:**

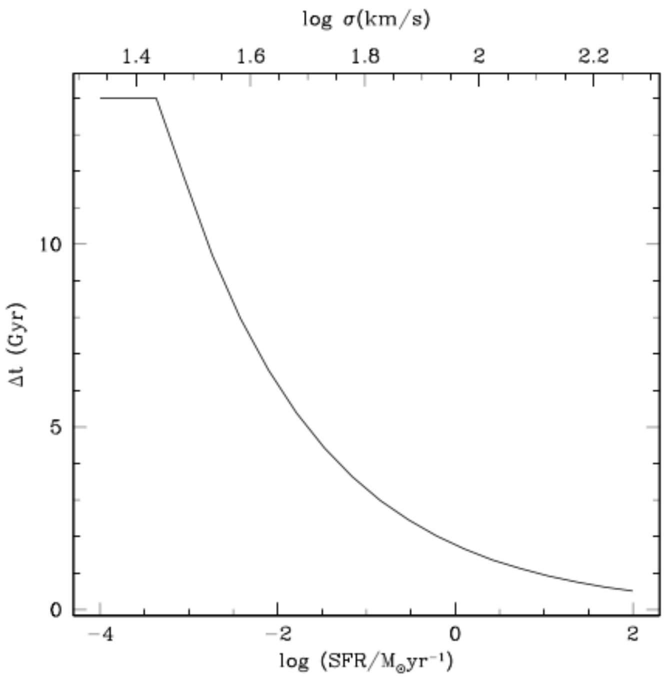


Fig. 8. Duration Δt of the star formation (assumed constant) as a function of SFR (lower scale) and σ (upper scale) assuming the Δt-luminous mass relation of THOM05 (see text).

the global chemical evolution of a galaxy and of [α/Fe] abundance ratios

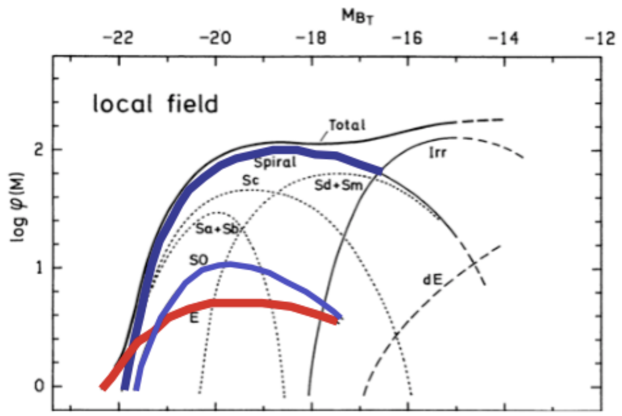
In the SMoC the most massive ellipticals take a longer time to assemble and therefore form stars for a longer time than less massive galaxies, thus producing a a trend of [α/Fe] vs. mass which is opposite to what is observed (see Thomas et al. 2002; Matteucci 2007).

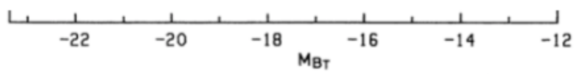
Consequences of random mergers :

IV. No evidence for E galaxies forming from mergers **:**

2) E galaxy population does not increase,
E galaxies constitute a negligible fraction of the galaxy population

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).

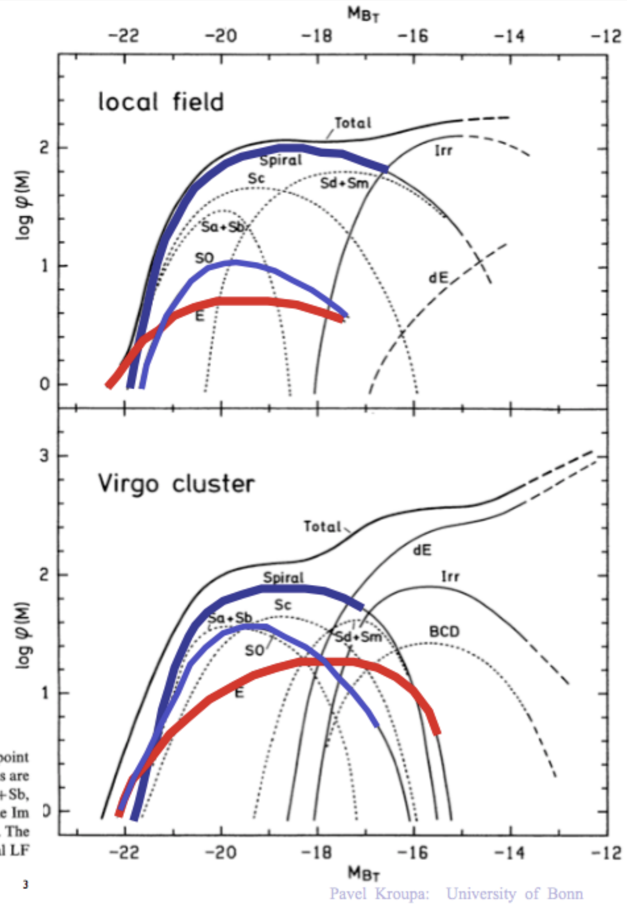
The luminosity function of galaxies

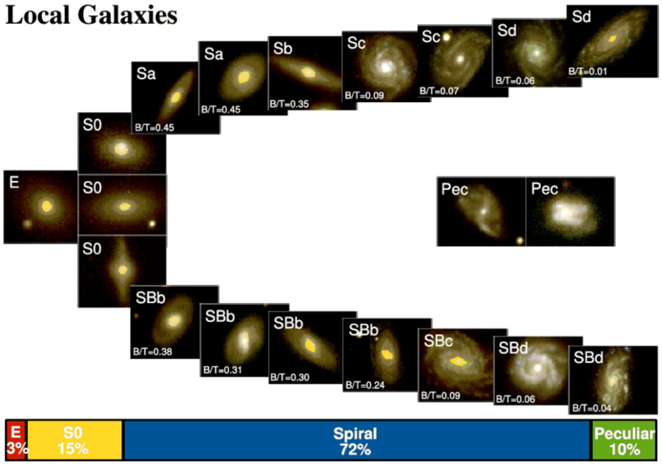
Disk galaxies dominate overwhelmingly (>95%) above 10^{10} Msun

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).

3





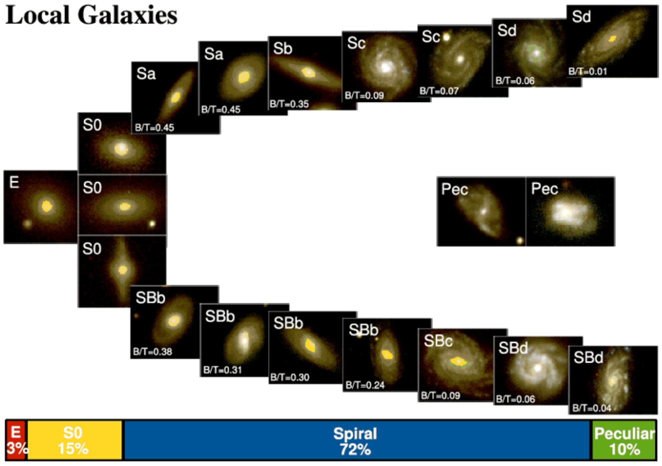
Ratio of E to other galaxies unchanging ?

Delgado-Serrano et al. (2010)

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

6 Gyr ago

Local Galaxies

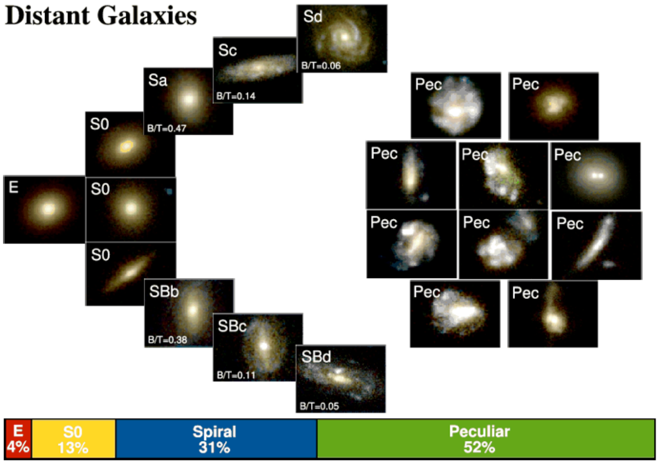


Ratio of E to other galaxies unchanging ?

Delgado-Serrano et al. (2010)

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

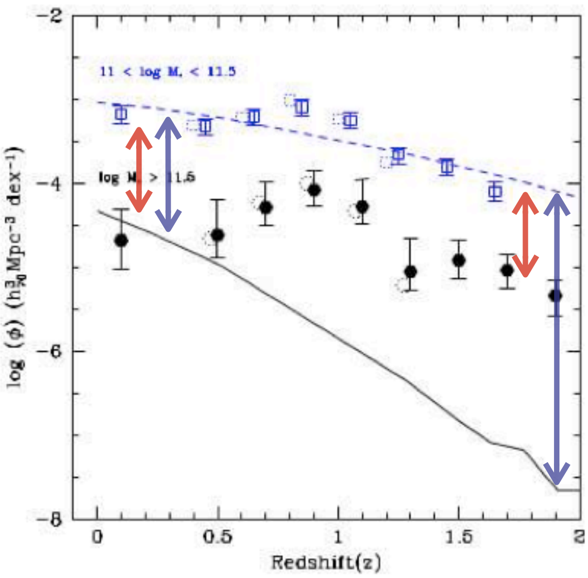
Distant Galaxies



6 Gyr ago

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

Conselice 2012



observations

SMoC (model)

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.

Consequences of random mergers :

I. Phase-space distribution of satellite galaxies.

→ disagreement with SMoC **!**

II. Classical bulges : → disagreement with SMoC **!**

III. Galaxies are simpler than thought :

→ disagreement with SMoC **!**

IV. No evidence for E galaxies forming from mergers :

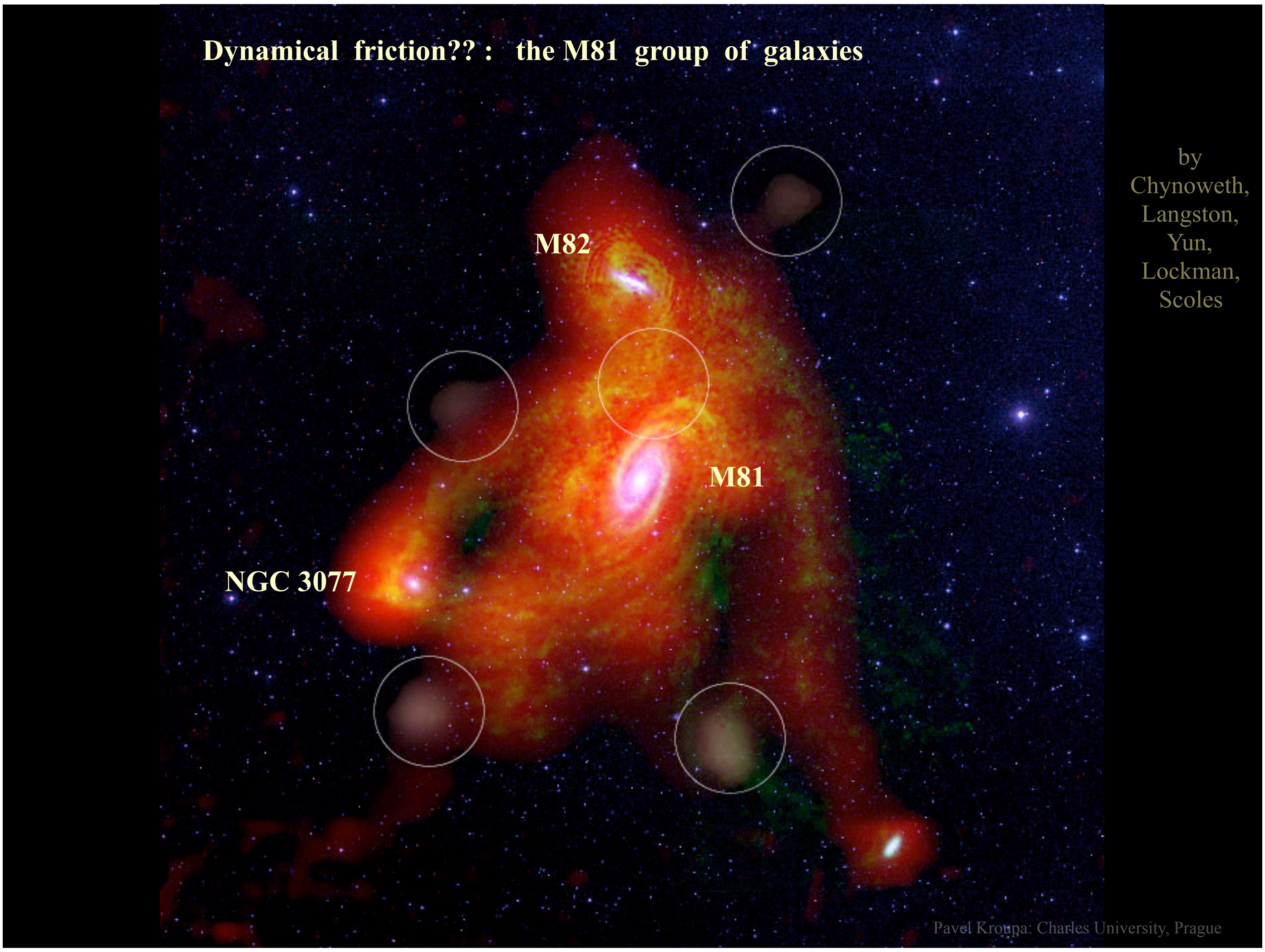
→ disagreement with SMoC **!**

V. Compact groups of galaxies . . .

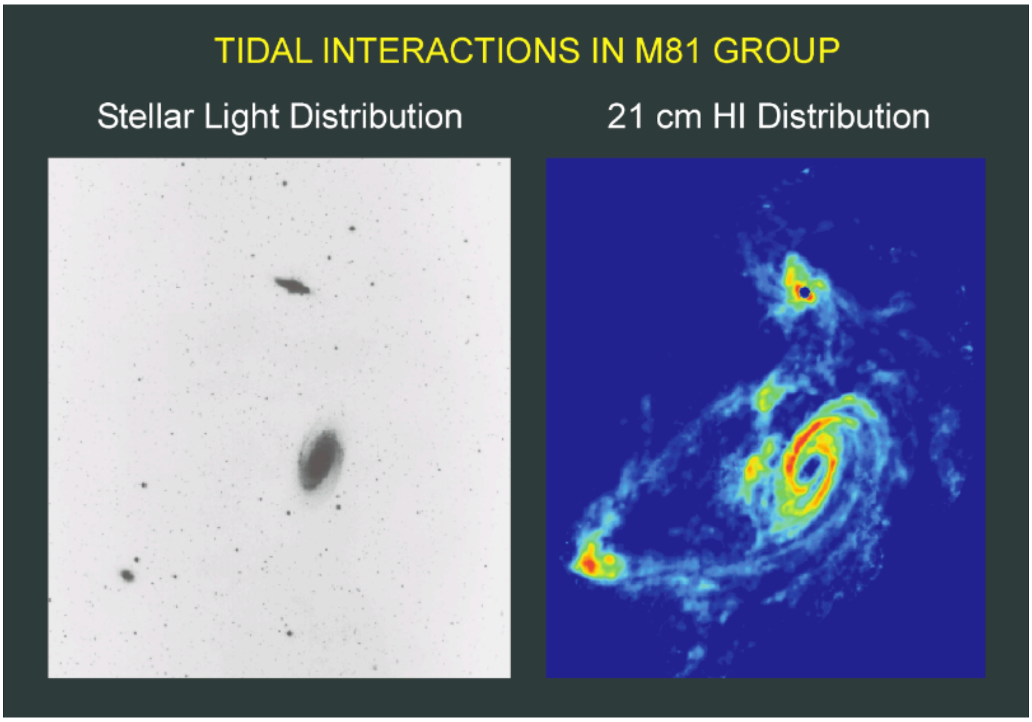
V. Compact groups of galaxies . . .

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

. . . basically, all members of the M81 group would have to have fallen in synchronously from large distances and have a peri-galactic encounter with M81 at nearly the same time without having merged yet.

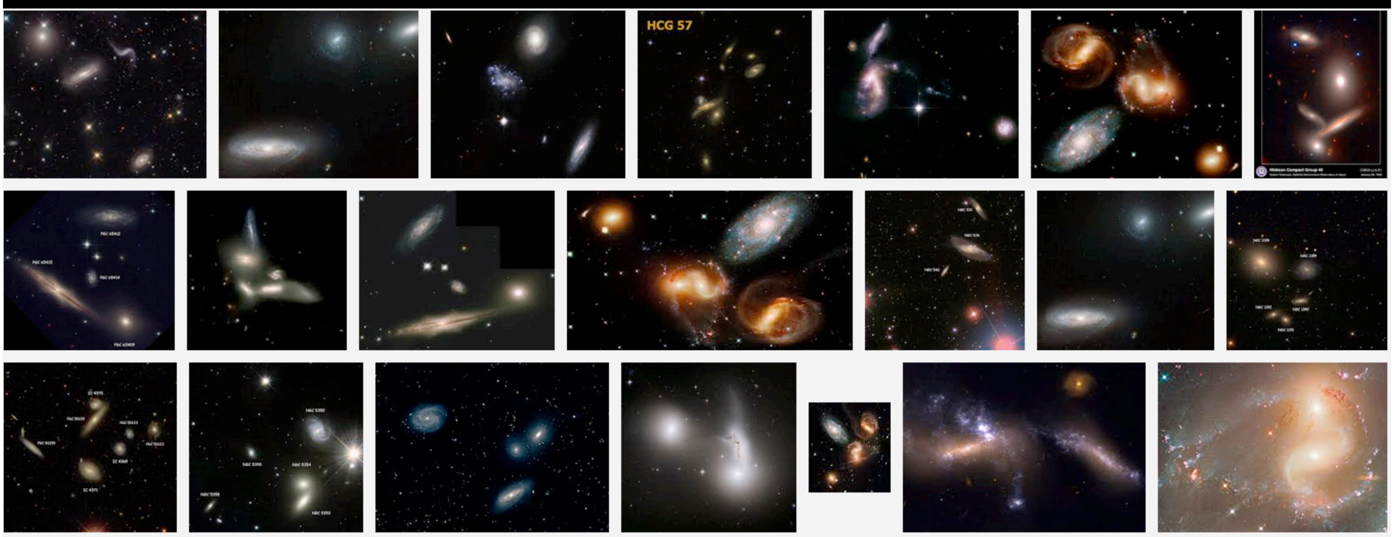
This is arbitrarily unlikely.

Oehm et al. (2017)

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



Pavel Kroupa: Praha Lecture 2

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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However, this makes the formation of compact groups something of a mystery, as the close proximity of the galaxies means that they should merge into a single galaxy in a short time, leaving only a fossil group.

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This would mean that compact groups are a shorted-lived phase of group evolution, and we would expect them to be extremely rare.

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This would mean that compact groups are a shorted-lived phase of group evolution, and we would expect them to be extremely rare.

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)

Consequences of random mergers :

I. Phase-space distribution of satellite galaxies.

→ disagreement with SMoC **!**

II. Classical bulges : → disagreement with SMoC **!**

III. Galaxies are simpler than thought :

→ disagreement with SMoC **!**

IV. No evidence for E galaxies forming from mergers :

→ disagreement with SMoC **!**

V. Compact groups of galaxies

→ disagreement with SMoC **!**

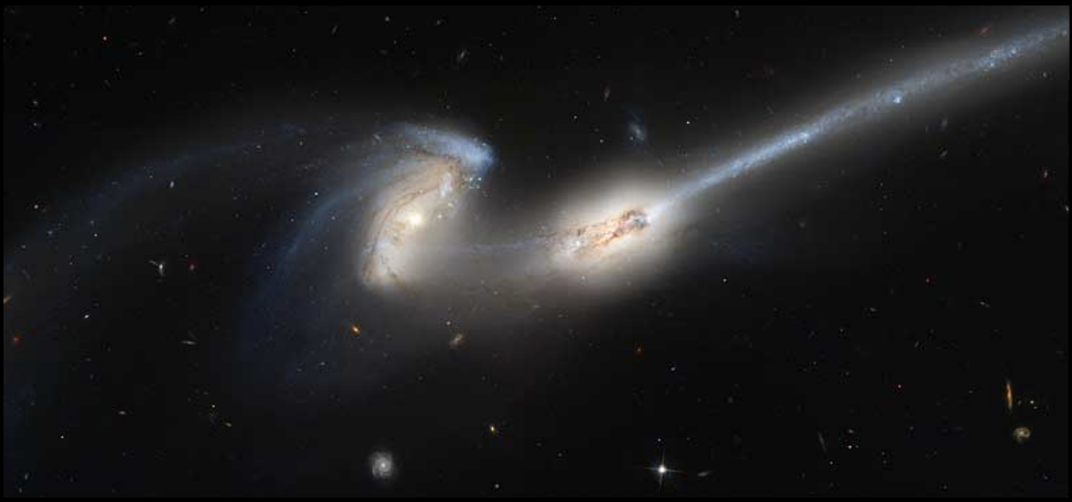
Given all the above,

are the following mergers ?

Pavel Kroupa: Charles University, Prague

NGC 5257/8

The Mice



Pavel Kroupa: Charles University, Prague

Antennae

NGC 2623

Given all the above,

why does everyone talk about mergers ?

Pavel Kroupa: Charles University, Prague

Conclusions

Dark matter halos (i.e. SMoC) ==> dynamical friction

But evidence for dynamical friction non-existing :

I. Phase-space distribution of satellite galaxies.

II. Classical bulges :

III. Galaxies are simpler than thought :

IV. No evidence for E galaxies forming from mergers :

V. Compact groups of galaxies

all in disagreement with SMoC **!**

Can dynamical friction be reduced significantly while keeping *Newtonian / Einsteinian* gravitation **?**

Or, rather (and simpler), is this telling us that there is *no dark matter* and *effective gravity is non-Newtonian / non-Einsteinian* **?**

THE END