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

Lecture 1

The standard model of cosmology (SMoC)
and
arguably the greatest question of 20th/21st century physics :
Do the postulated dark matter particles exist ?
14.12.2016

Selected Chapters on Astrophysics
Charles University, Praha,
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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.

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.

References

1	2016arXiv161003854K Kroupa, Pavel	1.000	10/2016	A			X		R					U
		The observed spatial distribution of matter on scales ranging from 100kpc to 1Gpc is inconsistent with the standard dark-matter-based cosmological models												
1	2015CaJPh..93..169K Kroupa, Pavel	1.000	02/2015	A	E		X		R	C				U
		Galaxies as simple dynamical systems: observational data disfavor dark matter and stochastic star formation												
2	2014arXiv1409.6302K Kroupa, Pavel	1.000	09/2014	A			X		R	C				U
		Lessons from the Local Group (and beyond) on dark matter												
3	2014ASPC..486..183K Kroupa, P.	1.000	05/2014	A	E			T	R					U
		The Planar Satellite Distributions around Andromeda, the Milky Way and Other Galaxies, and Their Implications for Fundamental Physics												
4	2012IJMPD..2130003K Kroupa, Pavel; Pawlowski, Marcel; Milgrom, Mordehai	1.000	12/2012	A	E	F	X		R	C				U
		The Failures of the Standard Model of Cosmology Require a New Paradigm												
5	2012PASA...29..395K Kroupa, P.	1.000	06/2012	A	E		X		R	C	S			U
		The Dark Matter Crisis: Falsification of the Current Standard Model of Cosmology												
6	2010A&A...523A..32K Kroupa, P.; Famaey, B.; de Boer, K. S.; Dabringhausen, J.; Pawlowski, M. S.; Boily, C. M.; Jerjen, H.; Forbes, D.; Hensler, G.; Metz, M.	1.000	11/2010	A	E	F	X		R	C	S	N		U
		Local-Group tests of dark-matter concordance cosmology . Towards a new paradigm for structure formation												

. . . to be continued . . .

Prelude

Standard Model of Cosmology :
(the SMoC)

Postulate I : Einstein's field equation is valid everywhere

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

where $R_{\mu\nu}$ is the Ricci curvature tensor, R the scalar curvature, $g_{\mu\nu}$ the metric tensor, Λ is the cosmological constant, G is Newton's gravitational constant, c the speed of light in vacuum, and $T_{\mu\nu}$ the stress–energy tensor.

Postulate II : Matter is conserved

The SMoC

The model is immediately falsified :
-Prediction of a highly curved highly inhomogeneous universe

Solution:
-Postulate (III) a mathematical trick (*inflation*) — not understood

This composite model is immediately falsified :
-Prediction of falling *rotation curves* of galaxies and *structure formation* too slow

Solution:
-Postulate (IV) existence of unknown exotic matter (*dark matter*) — not found

This composite model is immediately falsified :
-Universe expands today faster, than it should

Solution: — not understood
-Postulate (V) a mathematical trick (*dark energy*)

Problem ? :
-Model (=*Standard Model of Cosmology* = *LCDM*) does **not conserve energy ?**

(Baryshev 2006; Lopez-Corredoira 2010)

End

of

Prelude

This SMoC is

not

a satisfactory model **!**

It requires posterior introduction of **:**

inflation

dark matter particles

dark energy

Neither of these are needed independently,
none are understood nor found,

despite decades of research.

Assume **the standard model of cosmology (SMoC)**

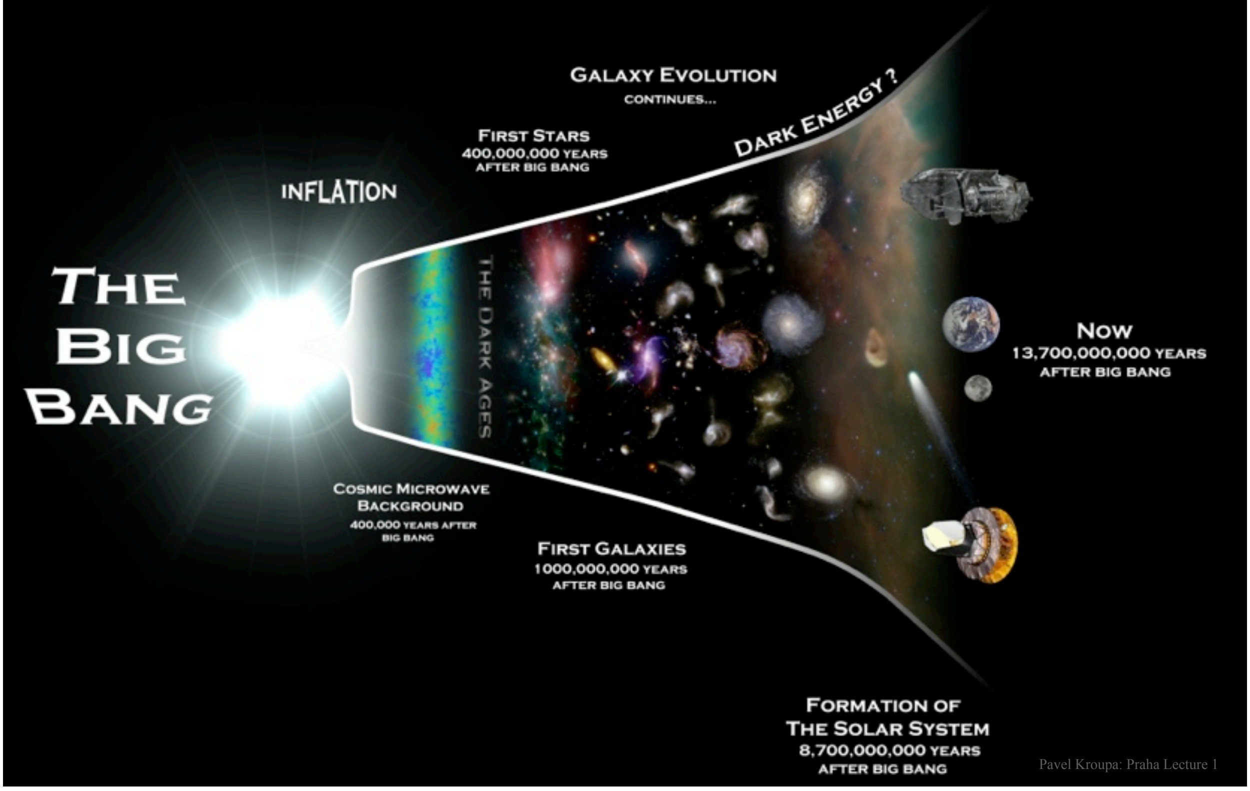
is a valid description of the universe,

then test it where the data are of best quality . . .

The Standard Modell of Cosmology (SMoC) :

1. Einstein is valid
2. All matter created at Big Bang

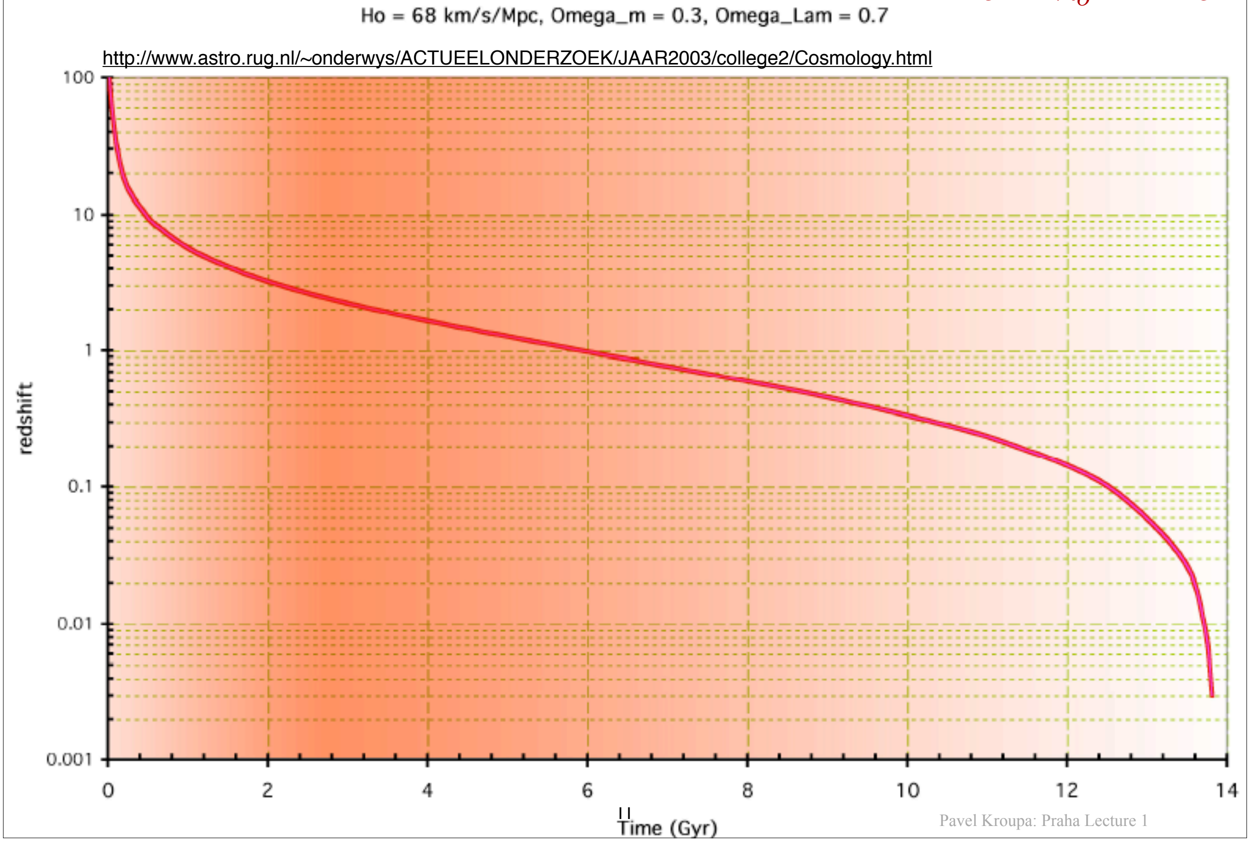
⇨ dark matter + dark energy needed



The redshift - time relation

depends on the cosmological model, e.g.:

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



Cosmological structure formation

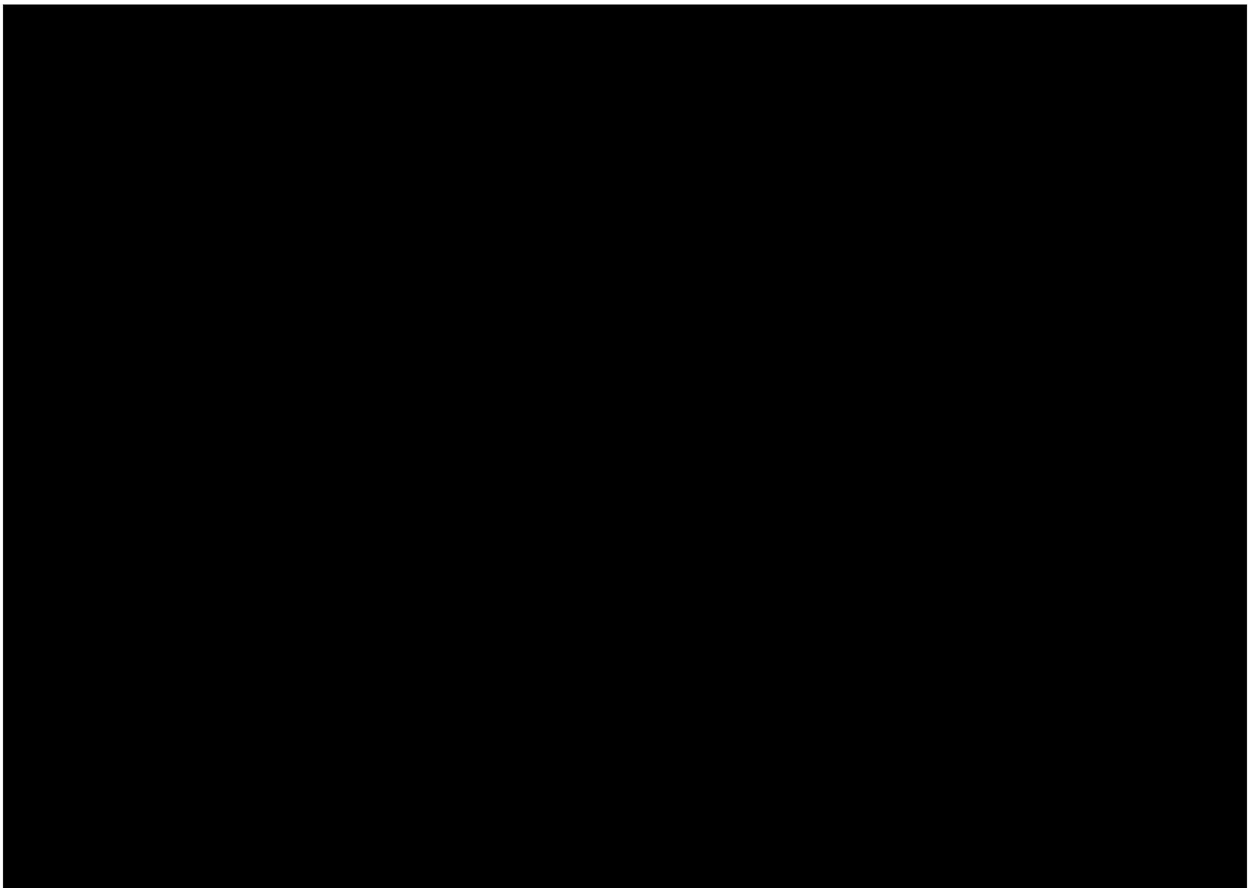
Movie by John Dubinski and Kameel Farah (CITA) of structure formation.

(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.

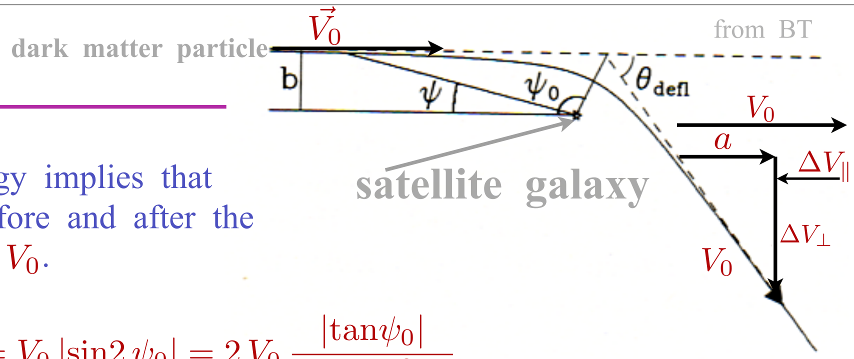


Cosmic structure formation

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.

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

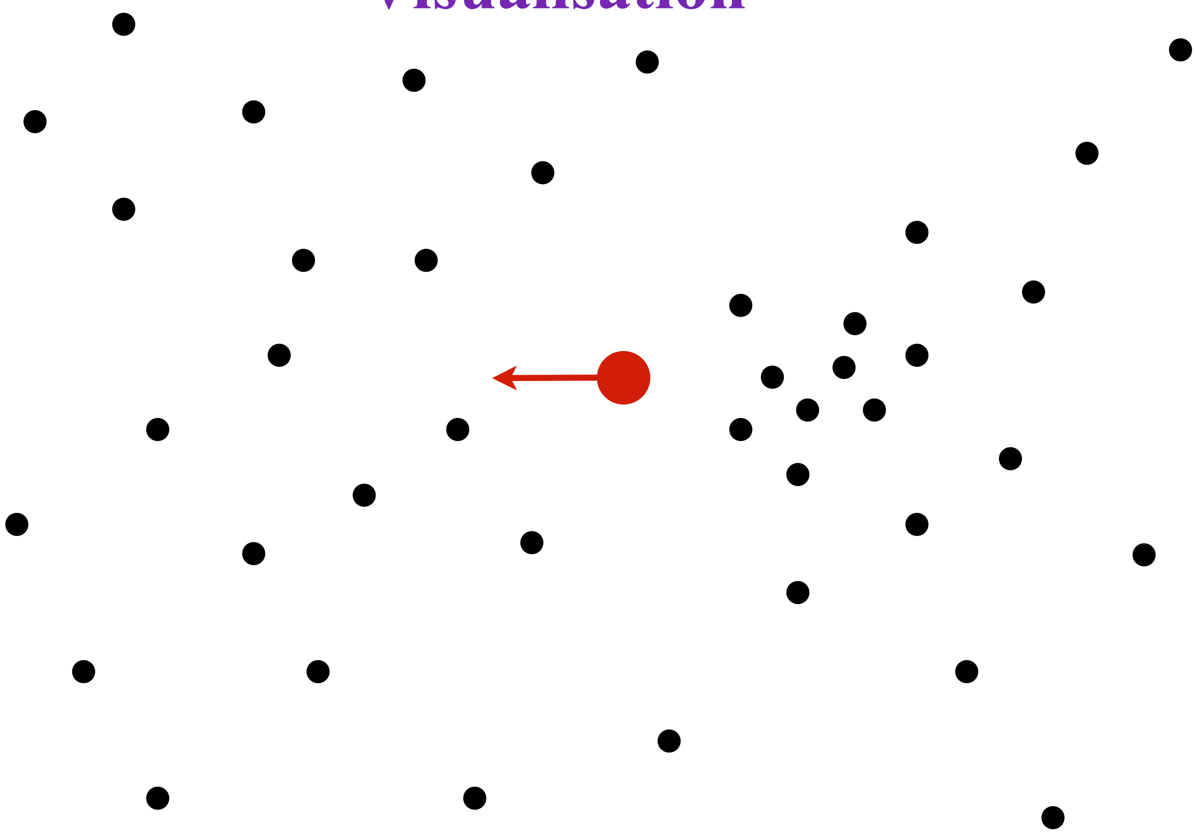
$$= \frac{2\,b\,V_0^3}{G\,(M+m)}\left[1+\frac{b^2\,V_0^4}{G^2\,(M+m)^2}\right]^{-1}$$

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

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

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

Visualisation



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

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 ($M_{\mathrm{sat}} \ll M_{\mathrm{host}}$ and $R_{\mathrm{sat}} \ll R_{\mathrm{host}}$).

The Coulomb parameter is somewhat arbitrary through an uncertain.

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

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

$$\vec{T} = \vec{r} \times \vec{F}_{\mathrm{DF}} = \frac{d\vec{L}}{dt}$$

where

$$\vec{F}_{\mathrm{DF}} = M\,\frac{d\vec{v}_M}{dt}$$

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

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

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

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

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

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

Assume $v_c(r) \approx$ constant

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

(good assumption for an isothermal dark-matter halo)

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

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

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

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

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

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

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

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

$\ln\Lambda \approx 3$

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

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

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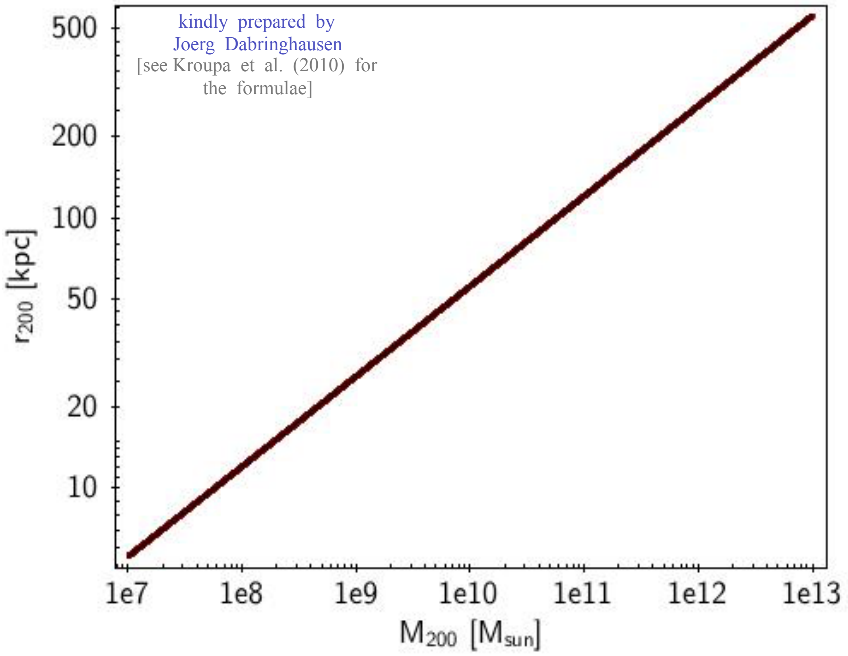
Binney & Tremaine (1987, p. 427)

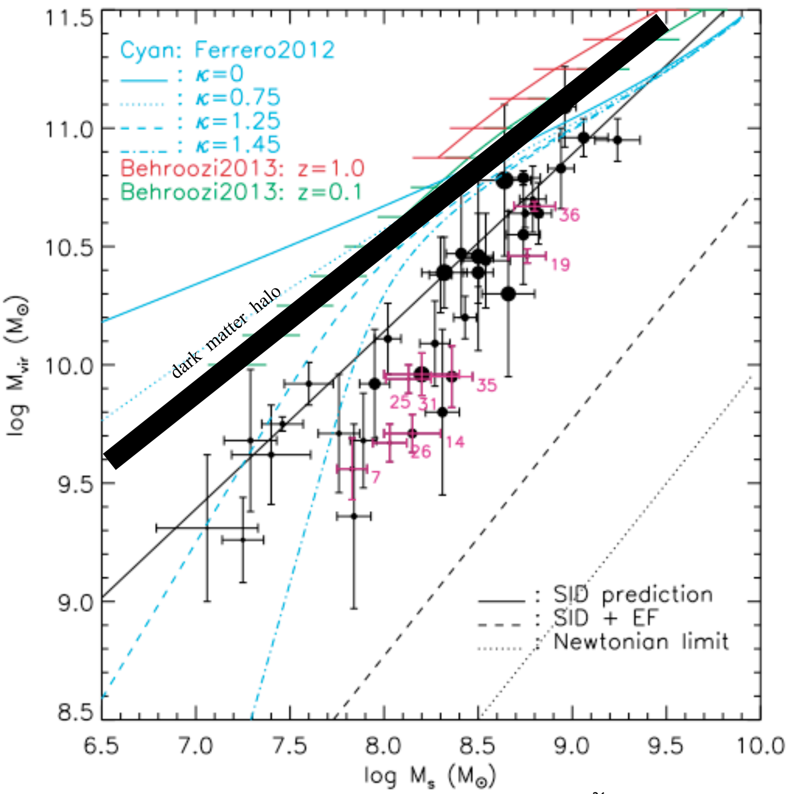
A pre-infall (z=0) DM halo has a virialised radius :

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.

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.

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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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$10^{6.25}$	10^7	50	100
$10^{6.75}$	10^8	200	200
$10^{5.25}$	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

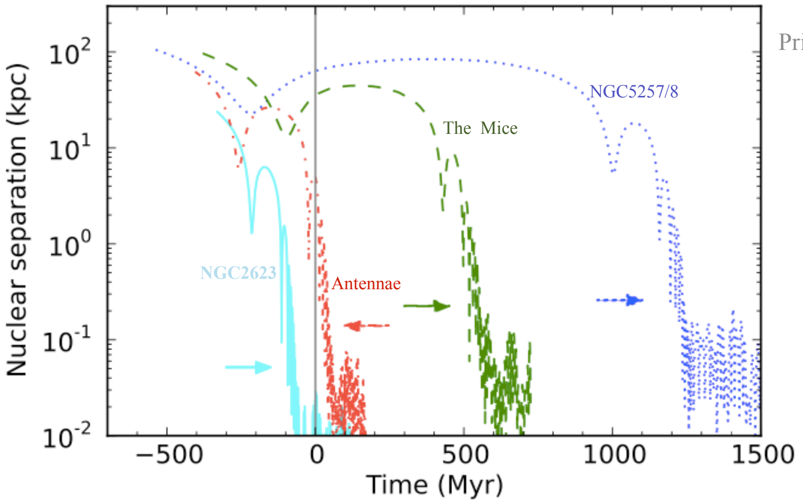
Table 2
Dynamical models derived from Identikit matching

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.

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 ...

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Using dwarf satellite proper motions to determine their origin

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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.

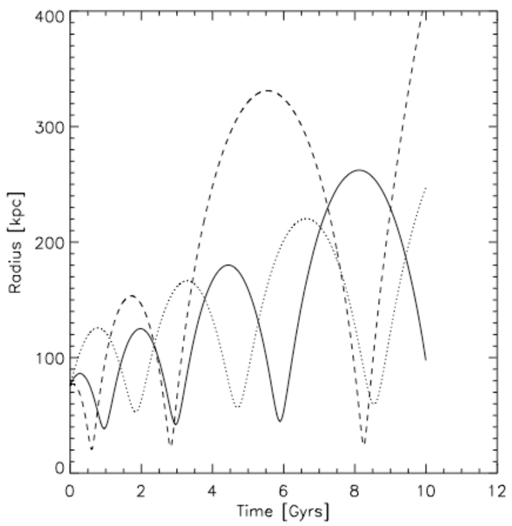
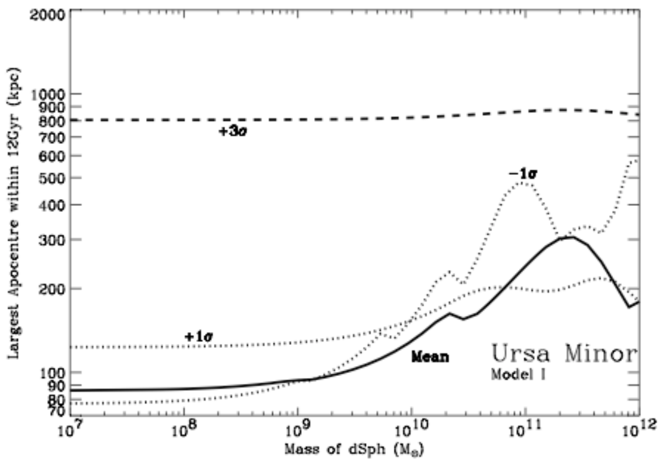


Figure 2. Here we show sample orbits for the Ursa Minor dSph (using a $5 \times 10^{10}\,M_\odot$ mass and Galactic model I) to demonstrate how the orbital apocentre decays with time due to DF. The different lines are for different values of the observed proper motion. The solid line is the mean, the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

Angus et al. 2011



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Using dwarf satellite proper motions to determine their origin

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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

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

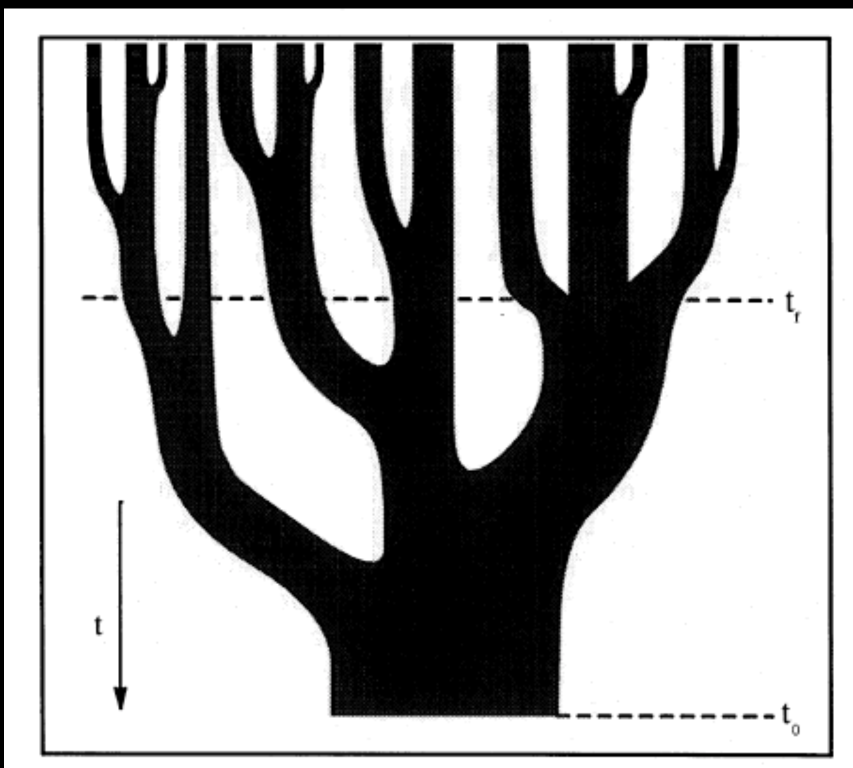
Therefore . . .

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.

Structures form according to the cosmological merger tree

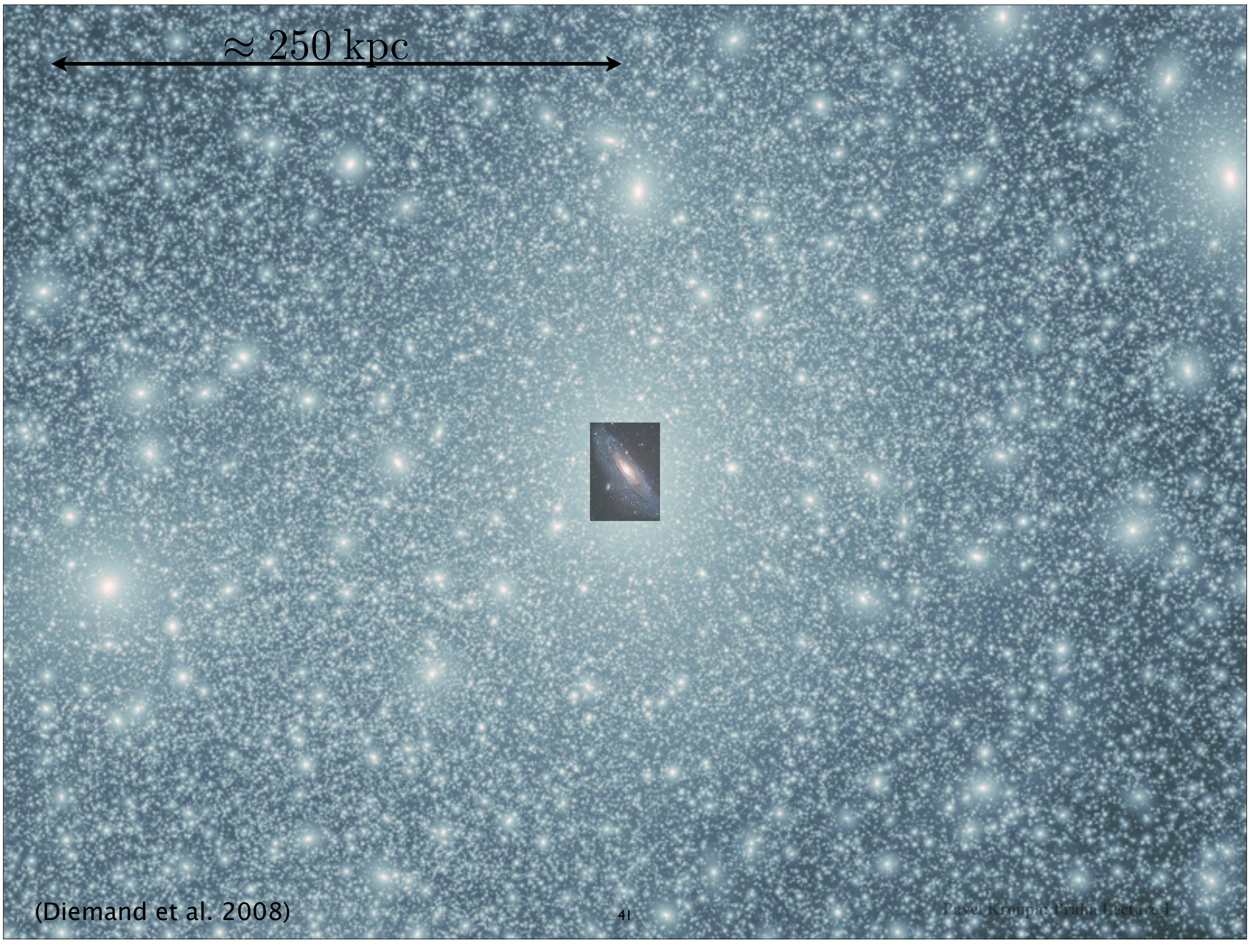
Lacey & Cole (1993)



the beginning Big Bang

DM sub-structures form first and coalesce to larger structures

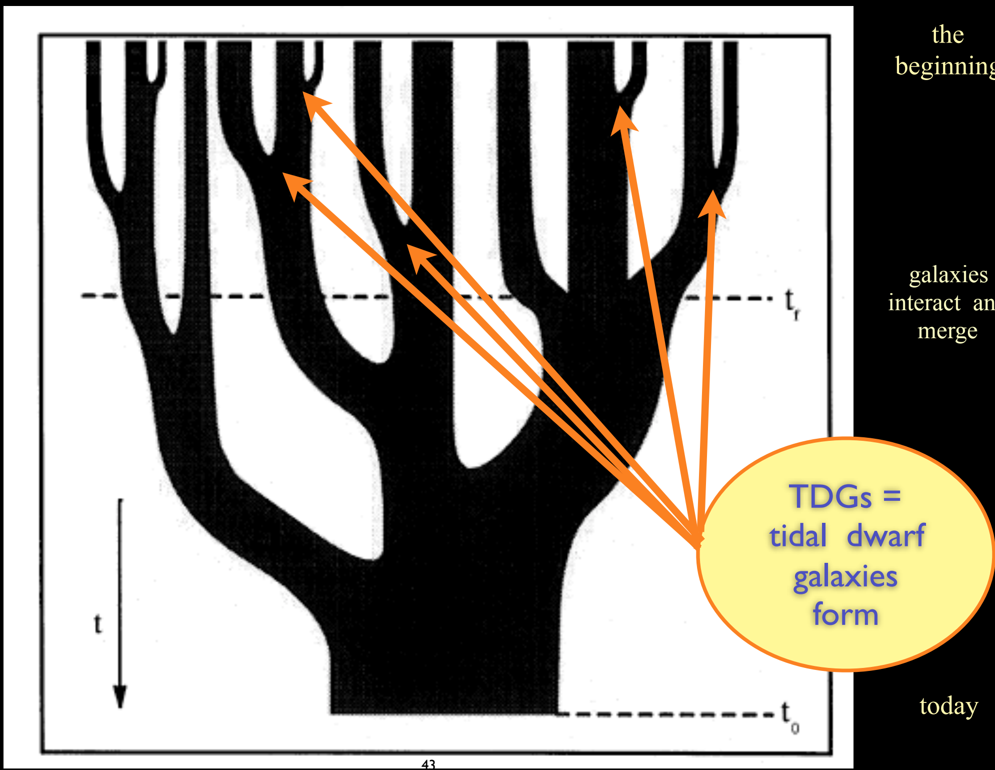
today



Another consequence

Structures form according to the cosmological merger tree

Lacey & Cole (1993)

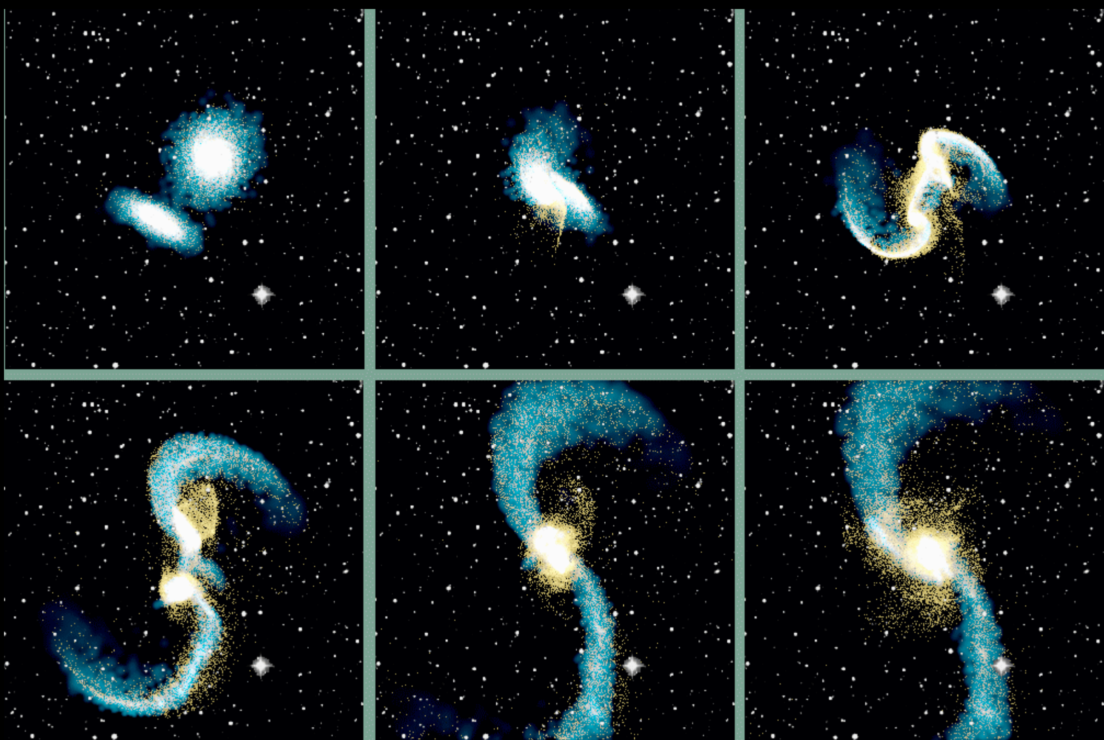


the beginning

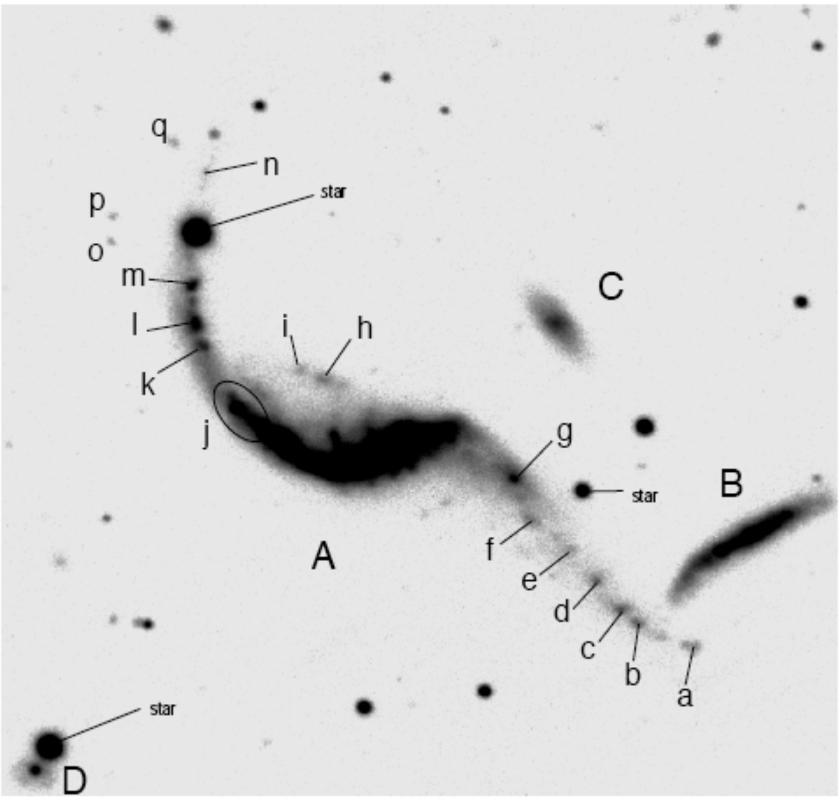
galaxies interact and merge

today

tidal arms



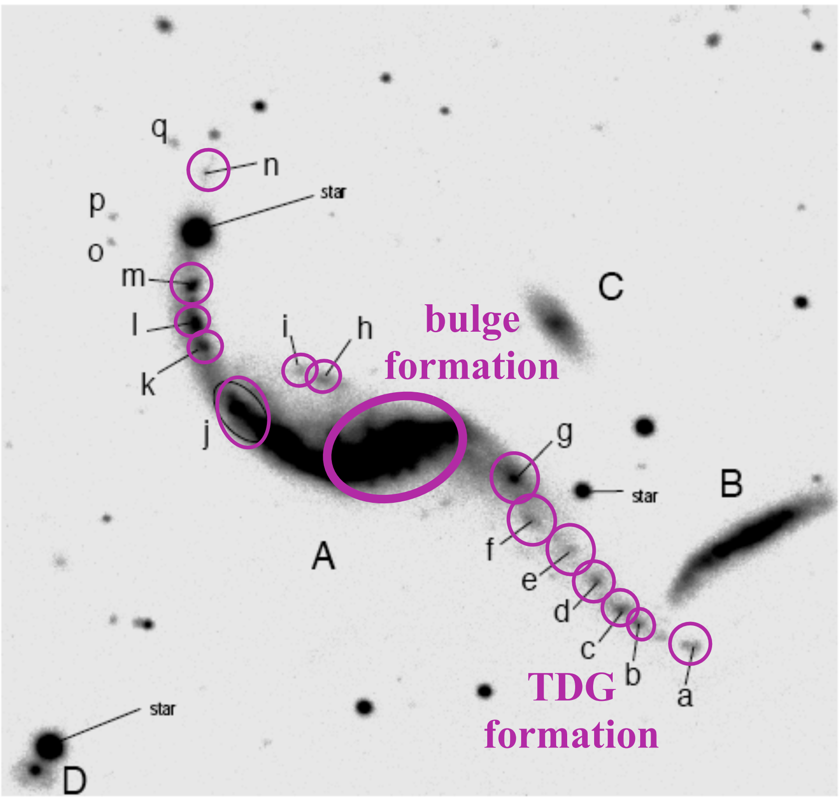
Miho & Maxwell, web



(Weilbacher et al. 2000)

$N_{\mathrm{TDG}} \approx 14$

Fig. 21. Identification chart of field 10 around AM 1353-272.

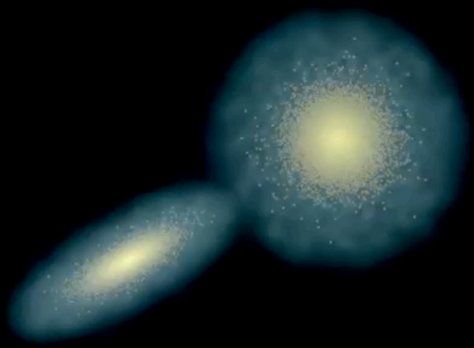


(Weilbacher et al. 2000)

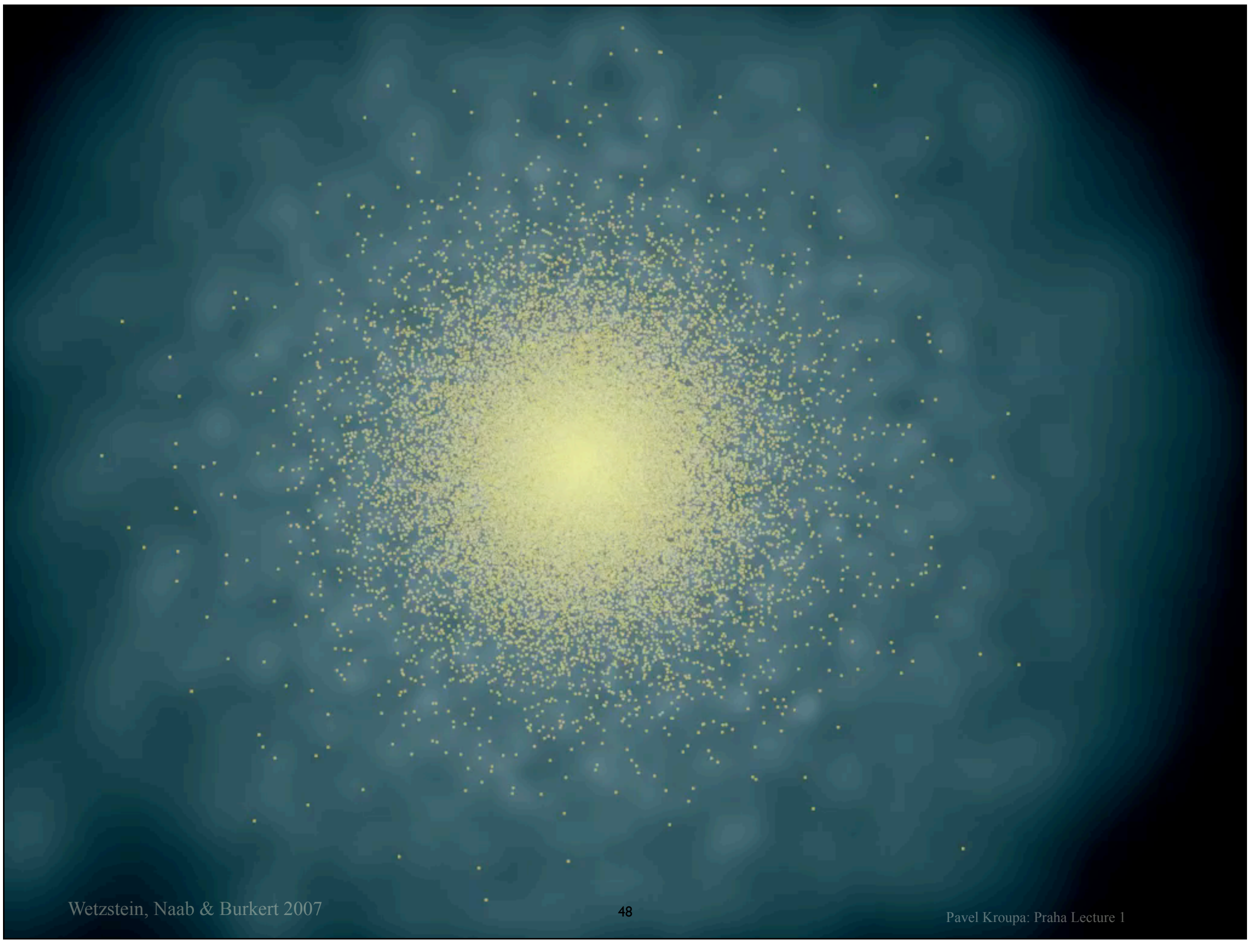
Phase-space correlated satellites form naturally in the same event as a *bulge* does.

Fig. 21. Identification chart of field 10 around AM 1353-272.

Relevance : The collision of two disks at high redshift



Wetzstein, Naab & Burkert 2007



. . . Consequence :

. . . each major galaxy (e.g. the MW)

ought to have

tidal-dwarf galaxies (TDGs) !

These TDGs have

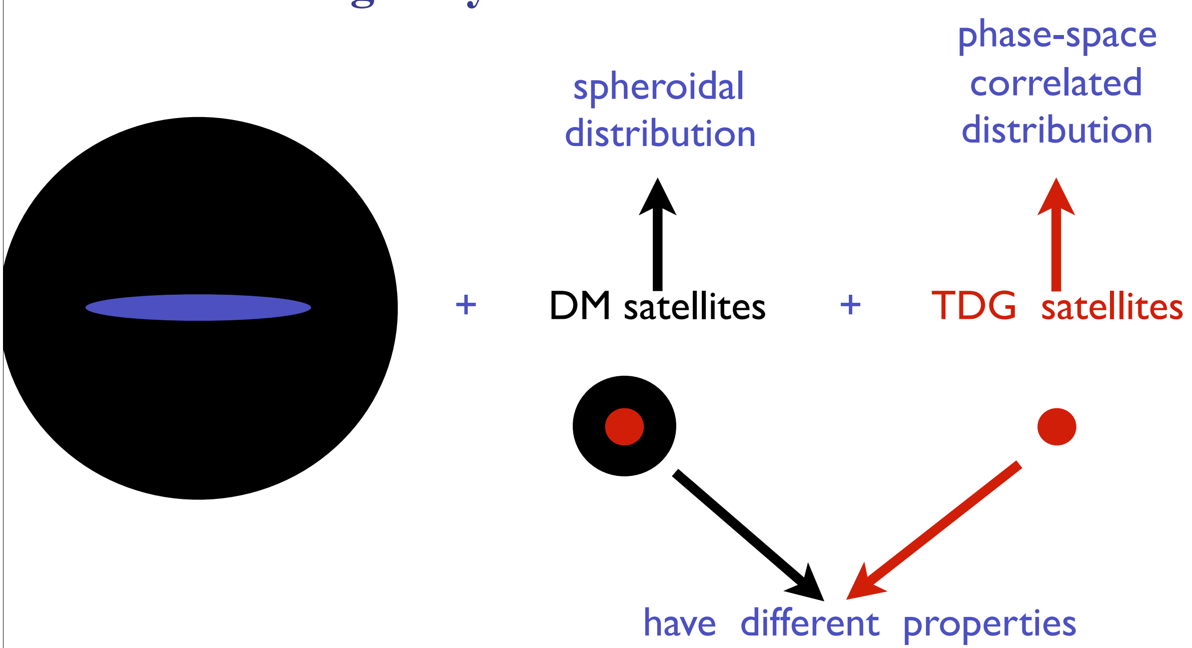
no

dark mater.

The Dual Dwarf-Galaxy Theorem

(Kroupa 2012)

Thus in the *Standard Model of Cosmology* (SMoC) a galaxy must look as follows:



The Dual Dwarf Galaxy Theorem must be true if the SMoC is true :

The Dual Dwarf Galaxy Theorem :

SMoC $\Rightarrow$ $\exists$ Type A dwarfs $\wedge$ Type B dwarfs

with Dark Matter (DM) — TDGs w/o DM

spheroidal distribution — correlated in phase-space

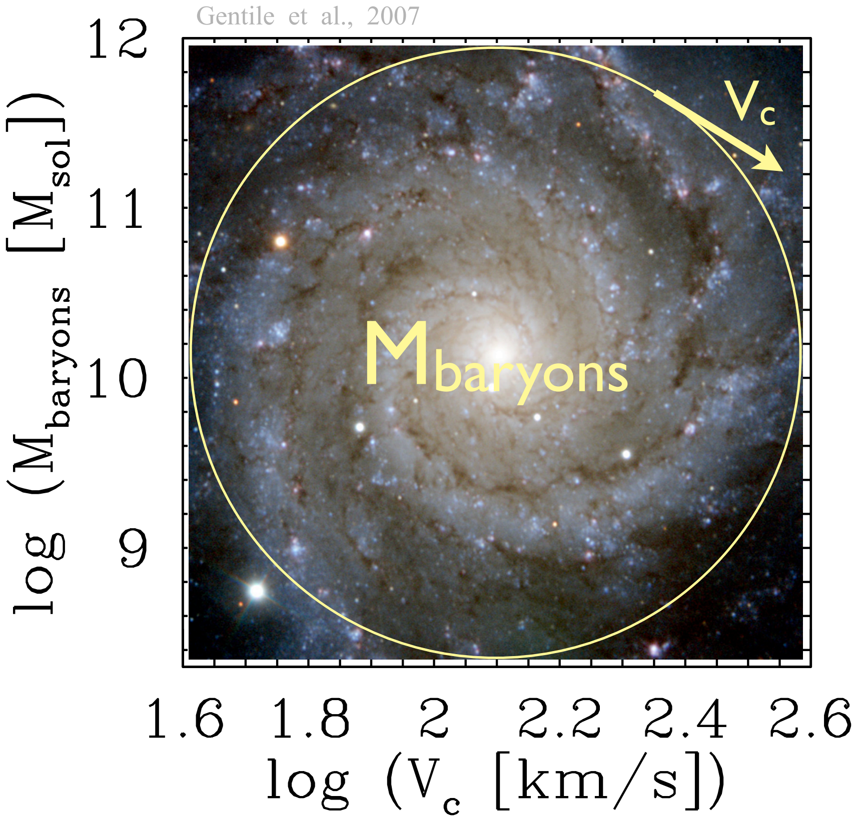
Kroupa 2012, 2014, 2015

If only one type exists then the Dual Dwarf Galaxy Theorem is falsified.

Is there any evidence for the co-existence of two types of dwarf galaxy ?

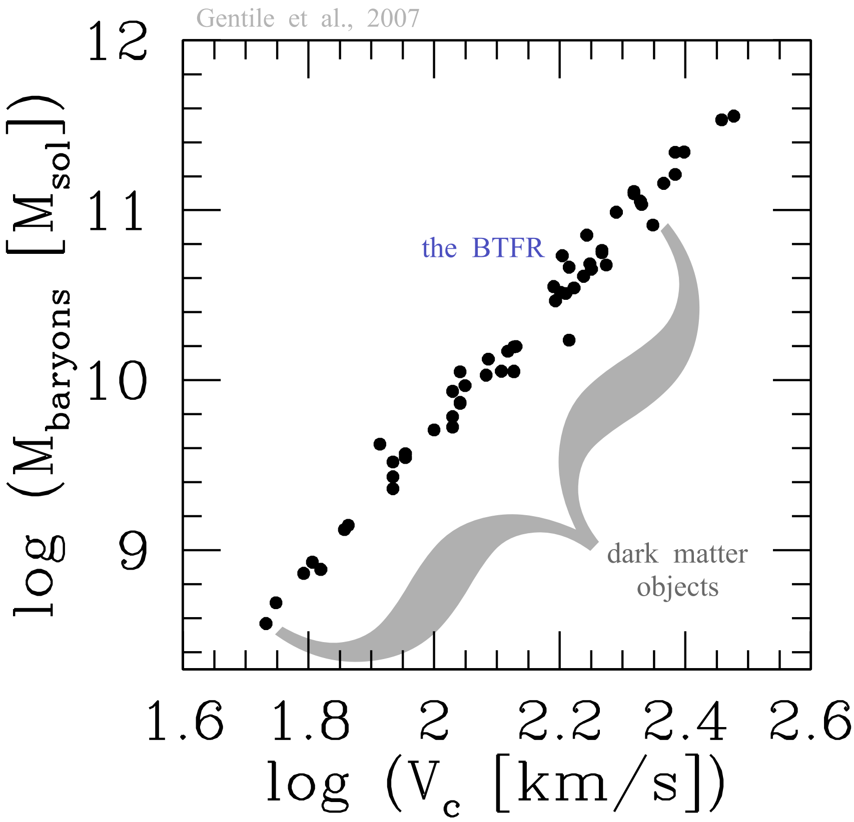
Testing the dual dwarf-galaxy theorem

Rotationally-supported stellar systems



The Baryonic Tully -Fisher Relation :

Rotationally-supported stellar systems

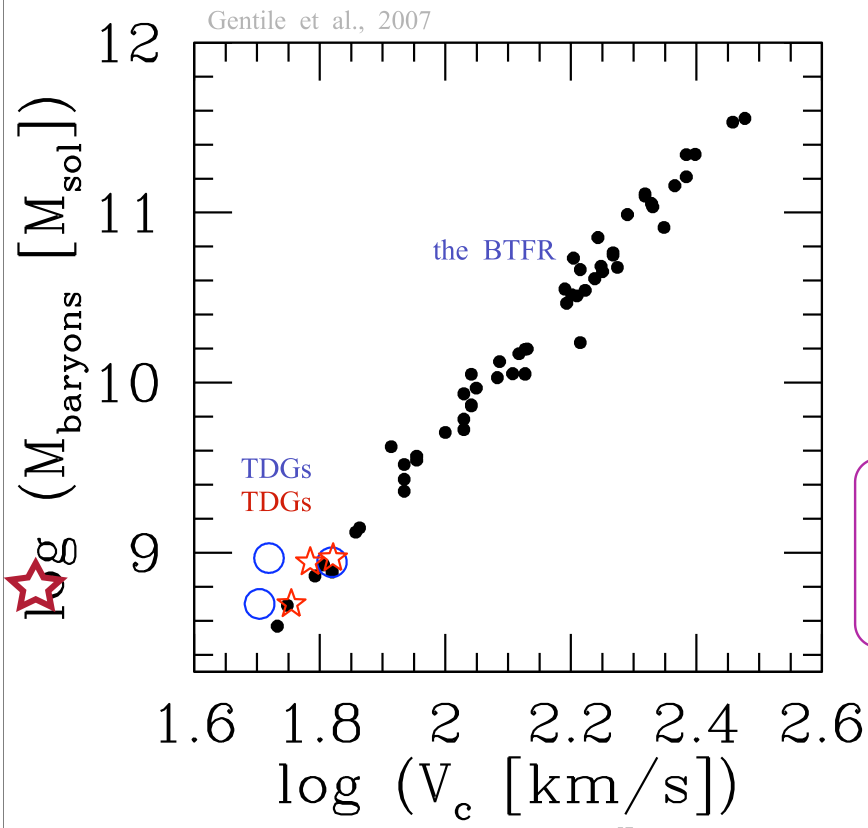


The Baryonic Tully -Fisher Relation :

If the SMoC is true
then the
BTFR
must
be given
by the dark matter halo

and
tidal dwarf galaxies
cannot
lie on the same BTFR !

Rotationally-supported stellar systems

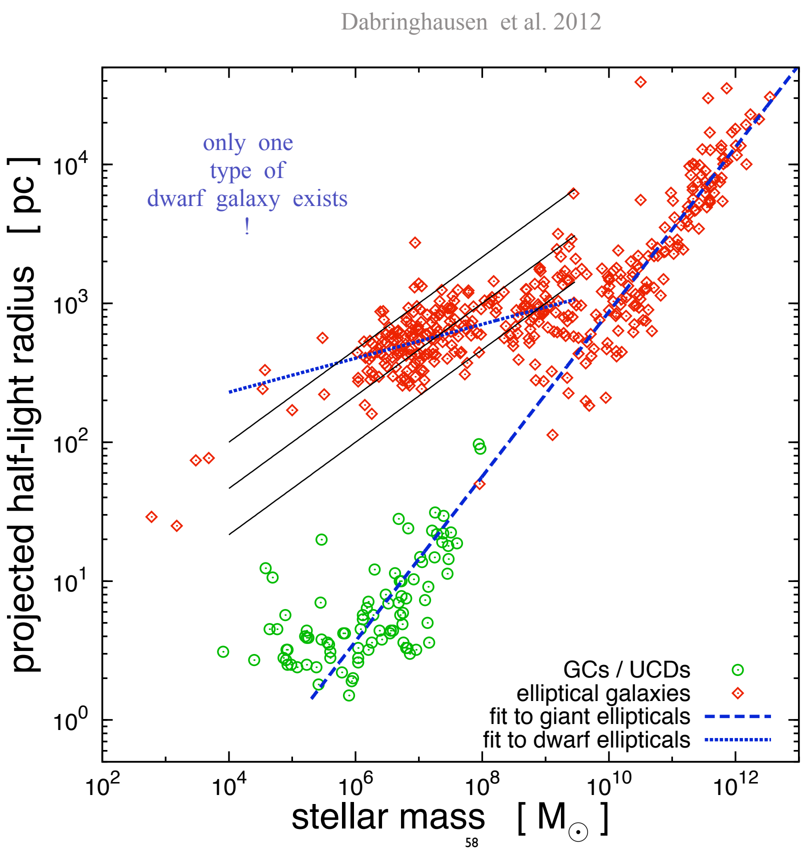


The Baryonic Tully -Fisher Relation :

But TDGs do lie on the same BTFR

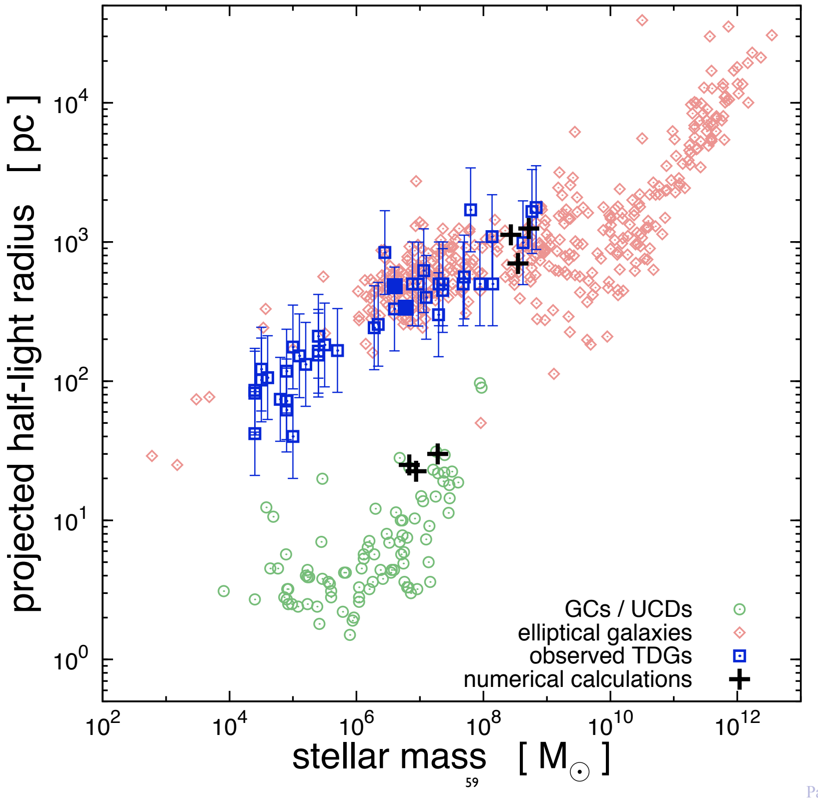
galaxies with dark matter
=
galaxies w/o dark matter
!

Pressure / random-motion supported stellar systems



Pressure / random-motion supported stellar systems

Dabringhausen et al. 2012



TDGs coincide with dE / dSph satellites

galaxies with dark matter

=

galaxies w/o dark matter

!

Thus:

Kroupa 2012;
Dabringhausen & Kroupa 2013

The Dual Dwarf Galaxy Theorem **:**

SMoC $\Rightarrow$ $\exists$ Type A dwarfs $\wedge$ Type B dwarfs

only one type of dwarf galaxy is observed.

Dual Dwarf Galaxy Theorem is falsified.

Remember now elementary logics:

if A then B

$\Leftrightarrow$

if not B then not A

$\Updownarrow$

Type A dwarf = Type B dwarf $\Rightarrow$ ~~SMoC~~

has been shown

Consistency Check

Remember :

The Dual Dwarf Galaxy Theorem must be true if the SMoC is true :

Kroupa 2012, 2014, 2015; Dabringhausen & Kroupa 2013

The Dual Dwarf Galaxy Theorem :

SMoC $\Rightarrow$ $\exists$ Type A dwarfs $\wedge$ Type B dwarfs

with DM — TDGs w/o DM

spheroidal distribution — correlated in phase-space

consistency check next . . .

Concistency Check I

If
the Milky Way satellites are
TDGs without dark matter
then
they ought to be in a
phase-space correlated distribution.

The phase-space distribution of satellites on scales of 100-300kpc

(no role of baryonic physics
on these scales)

Pawlowski et al. 2015

MW satellites are in a disk-like configuration:

(Kroupa, Theis & Boily 2005)

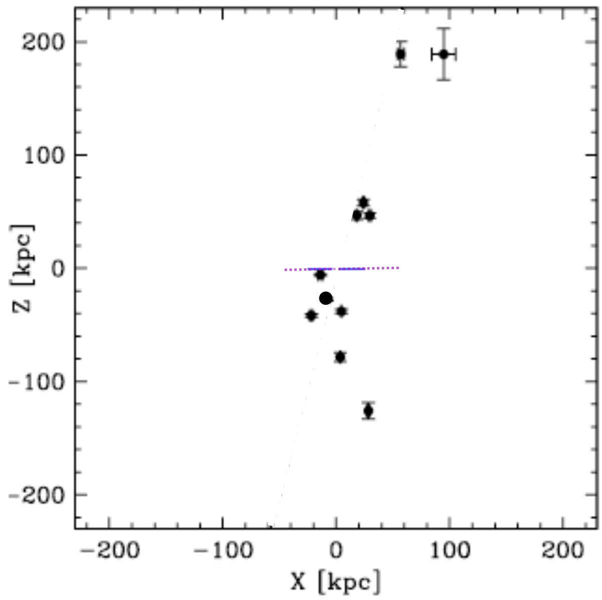
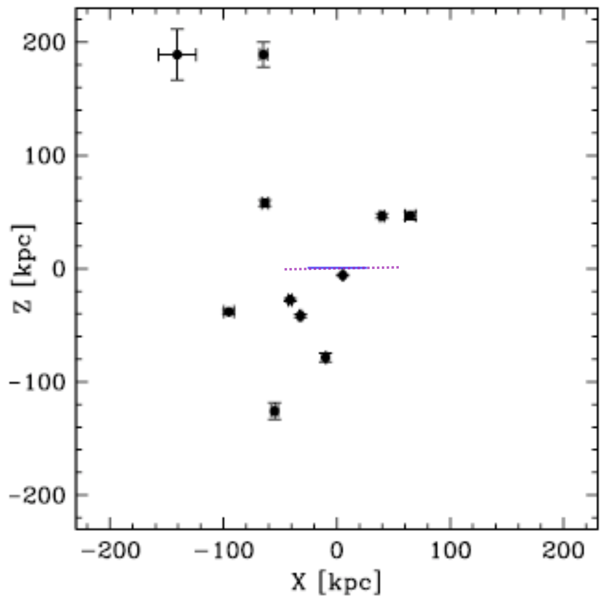


Fig. 1. The position of the innermost 11 MW satellites (Table 1) as viewed from a point located at infinity and $l = 167°.91$. The MW disk is indicated by the horizontal line $-25 \leq X/\mathrm{pc} \leq 25$, and the centre of the coordinate system lies at the Galactic centre. The dashed line marks the fitted plane for $N = 11$ seen edge-on in this projection.

MW satellites are in a disk-like configuration:

(Kroupa, Theis & Boily 2005)



==> incompatible with expected spheroidal distribution

(Kroupa, Theis & Boily 2005)

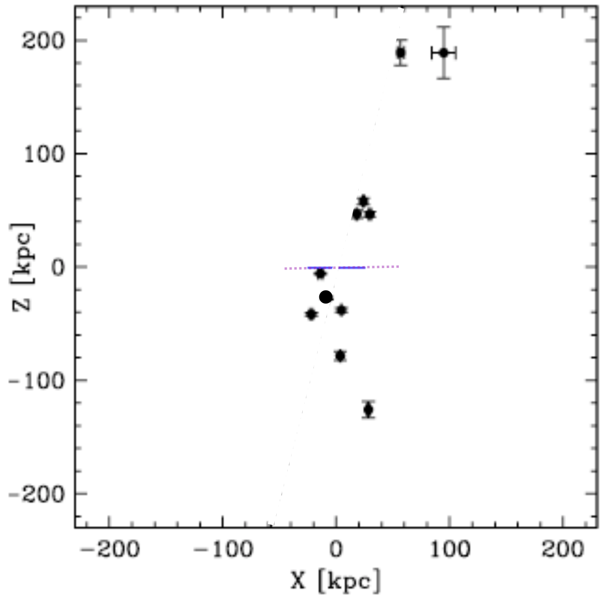
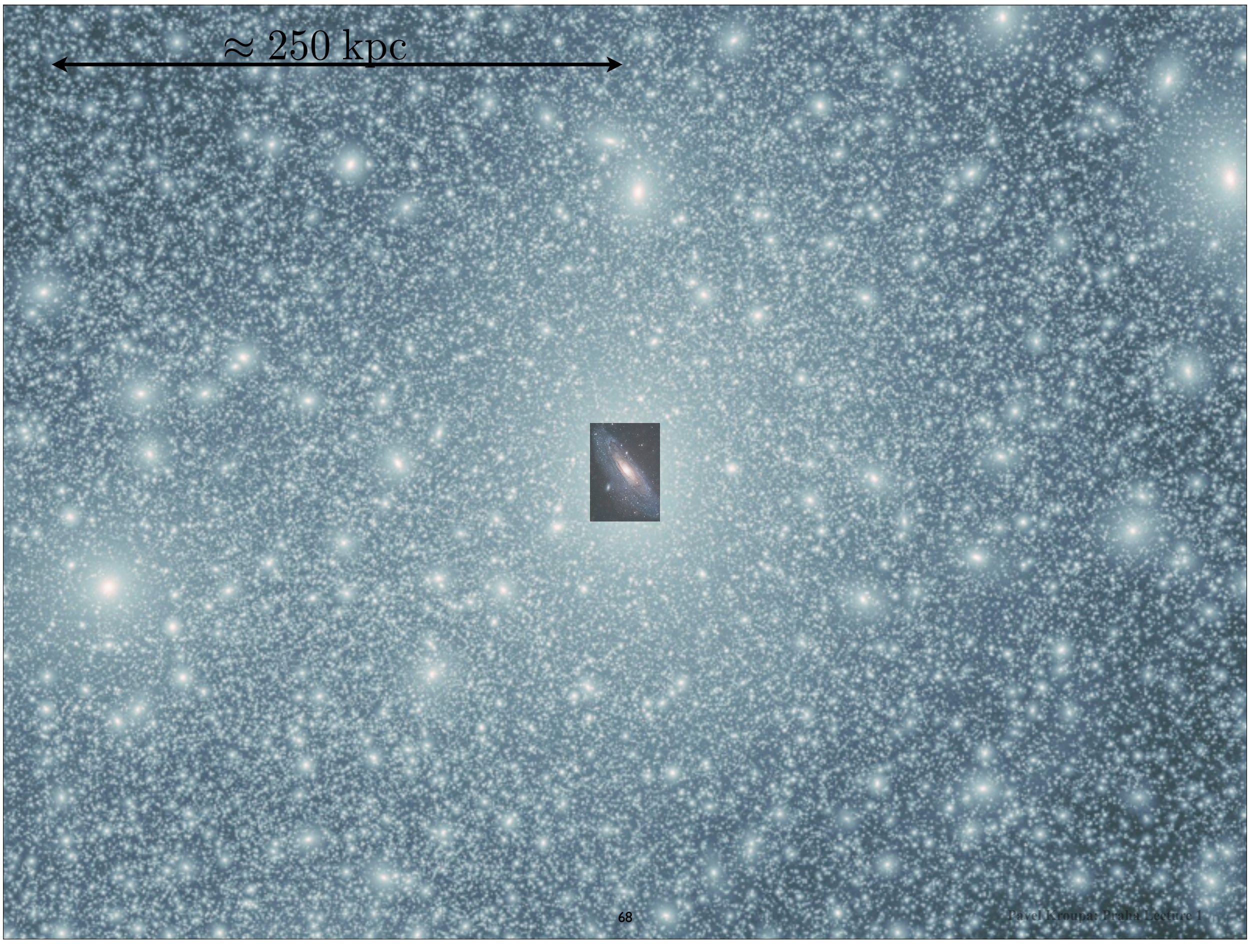
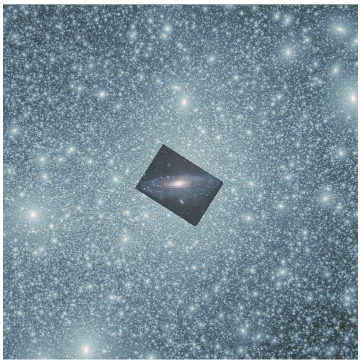


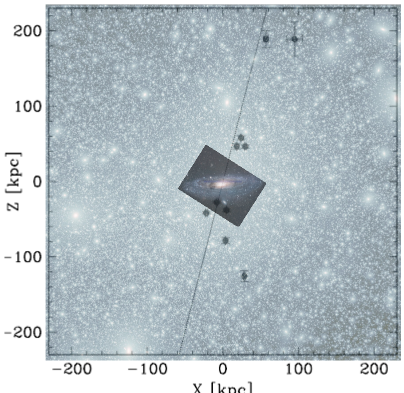
Fig. 1. The position of the innermost 11 MW satellites (Table 1) as viewed from a point located at infinity and $l = 167°.91$. The MW disk is indicated by the horizontal line $-25 \leq X/\mathrm{pc} \leq 25$, and the centre of the coordinate system lies at the Galactic centre. The dashed line marks the fitted plane for $N = 11$ seen edge-on in this projection.

THE largest (*unsolvable*) problem in the SMoC !

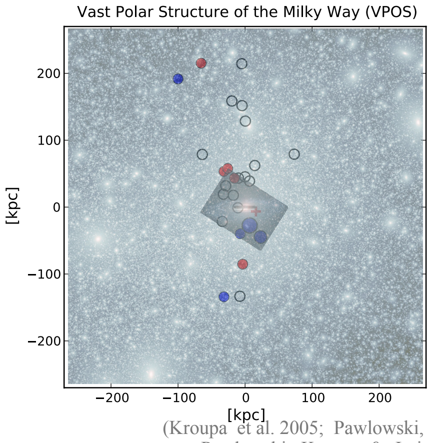




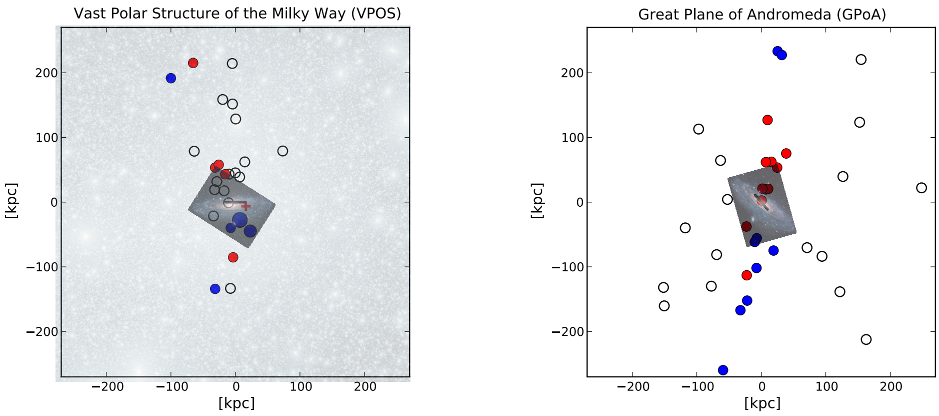
(Kroupa et al. 2005; Pawlowski, Pflamm-Altenburg & Kroupa 2012, Ibata et al. 2013
Pawlowski, Kroupa & Jerjen 2013; Pawlowski et al. 2015; Pawlowski 2016)



(Kroupa et al. 2005; Pawlowski, Pflamm-Altenburg & Kroupa 2012, Ibata et al. 2013
Pawlowski, Kroupa & Jerjen 2013; Pawlowski et al. 2015; Pawlowski 2016)



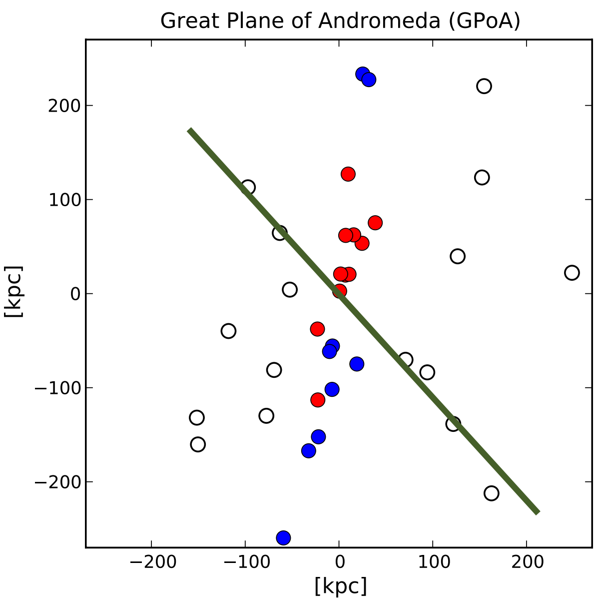
(Kroupa et al. 2005; Pawlowski, Pflamm-Altenburg & Kroupa 2012, Ibata et al. 2013
Pawlowski, Kroupa & Jerjen 2013; Pawlowski et al. 2015; Pawlowski 2016)



(Kroupa et al. 2005; Pawlowski, Pflamm-Altenburg & Kroupa 2012, Ibata et al. 2013
Pawlowski, Kroupa & Jerjen 2013; Pawlowski et al. 2015; Pawlowski 2016)

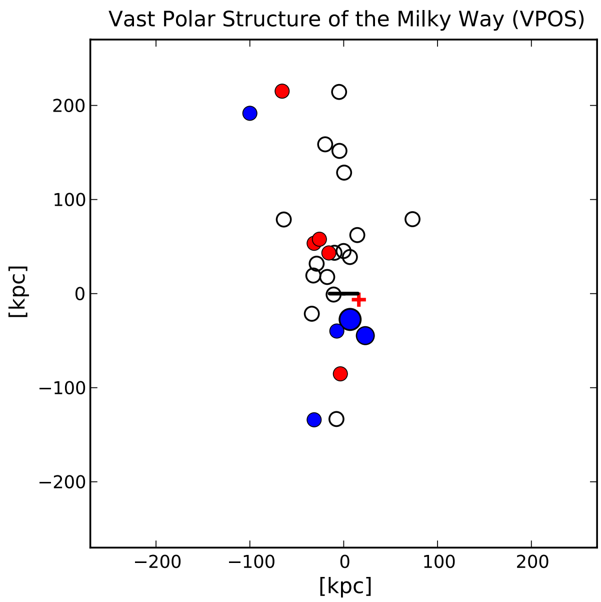
Our neighbour: the Andromeda galaxy

Andromeda



Ibata et al. 2013, 2014

Milky Way



Pawlowski & Kroupa 2013

Milky Way

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

Is the VPOS or DoS or plane of satellites significant **?**

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, $P_{\rm rms}^{\rm VPOS} = P_{\rm rms}^{\rm class} \times P_{\rm rms}^{\rm SDSS} = 9.8 \times 10^{-7}$ (equivalent to 4.9σ), while for the axial ratio $P_{c/a}^{\rm VPOS} = P_{c/a}^{\rm class} \times P_{c/a}^{\rm SDSS} = 3.7 \times 10^{-7}$ (equivalent to 5.1σ). Adding the information provided by the SDSS satel-

Pawlowski, Kroupa & Jerjen (2013 MNRAS)

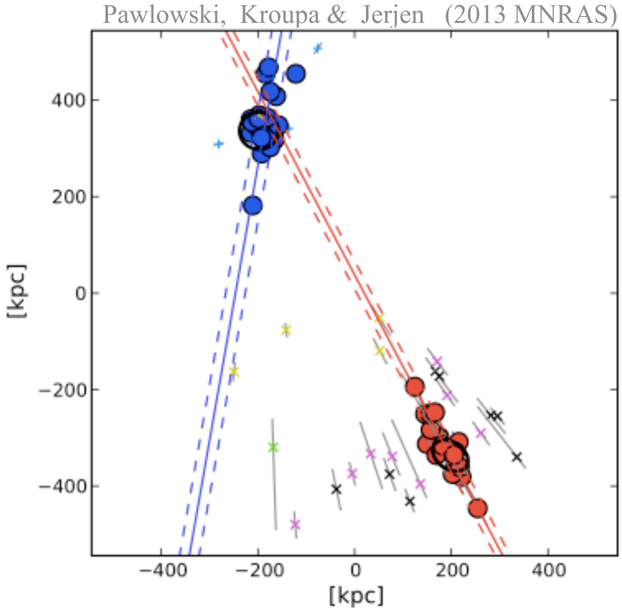


Figure 16. Edge-on view of the satellite galaxy planes around the MW and M31, similar to Fig. 9 for the LG planes. As before, galaxies which are

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

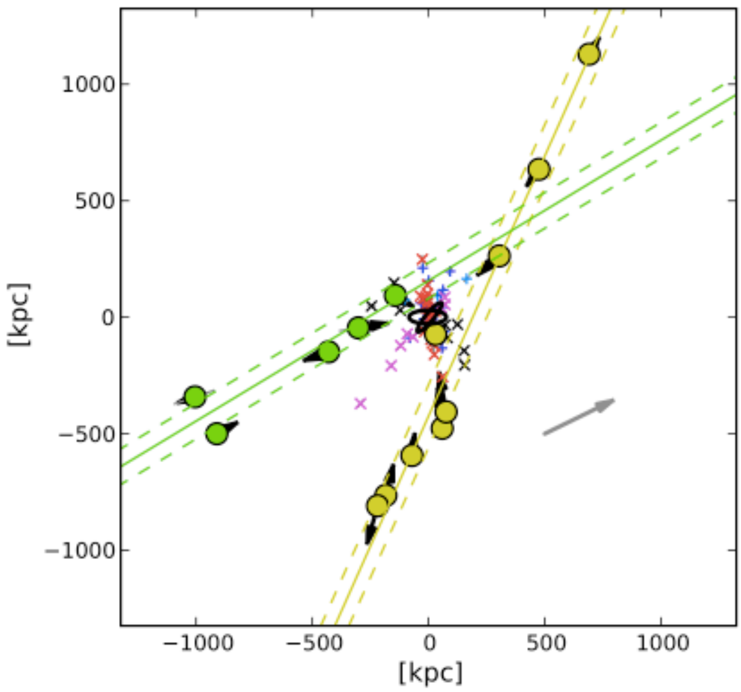


Figure 9. Edge-on view of both LG planes. The orientation of the MW and M31 are indicted as black ellipses in the centre. Members of the LGP1 are plotted as yellow points, those of LGP2 as green points. MW galaxies are plotted as plus signs (+), all other galaxies as crosses (×), the colours code their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

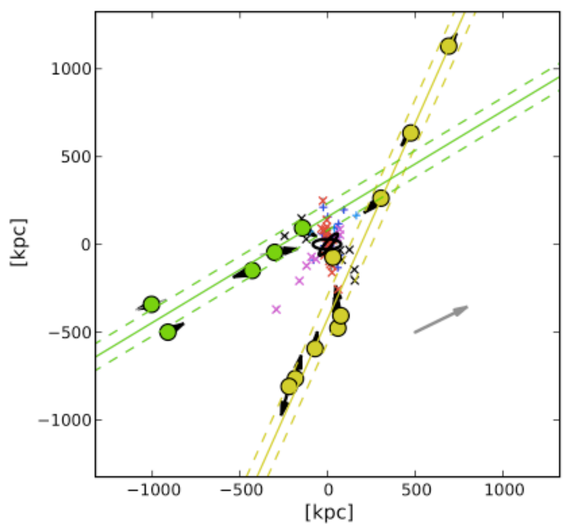


Figure 9. Edge-on view of both LG planes. The orientation of the MW and M31 are indicted as black ellipses in the centre. Members of the LGP1 are plotted as yellow points, those of LGP2 as green points. MW galaxies are plotted as plus signs (+), all other galaxies as crosses (×), the colours code their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

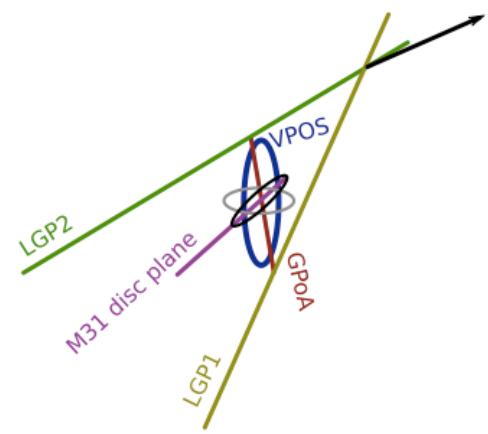


Figure 18. Cartoon of the LG structure (compare to Fig. 9). The positions and orientations of the galactic discs of the MW (grey) and of M31 (black) are indicated by the ellipses in the centre. Looking along the MW–M31 line, most planes in the LG are seen approximately edge-on, the only exception is 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.

. . . the structure of the

Local Group of Galaxies

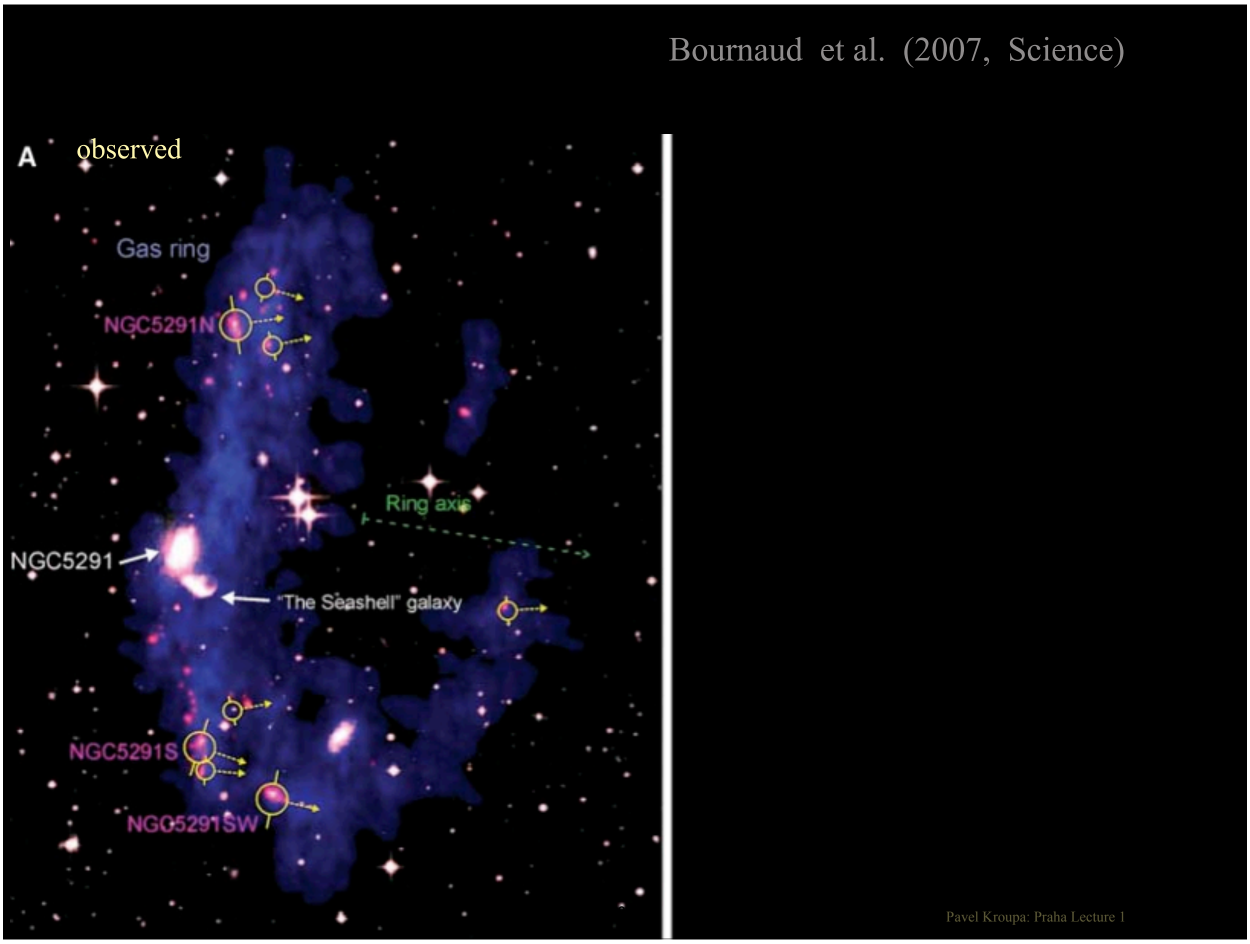
appears to be incompatible

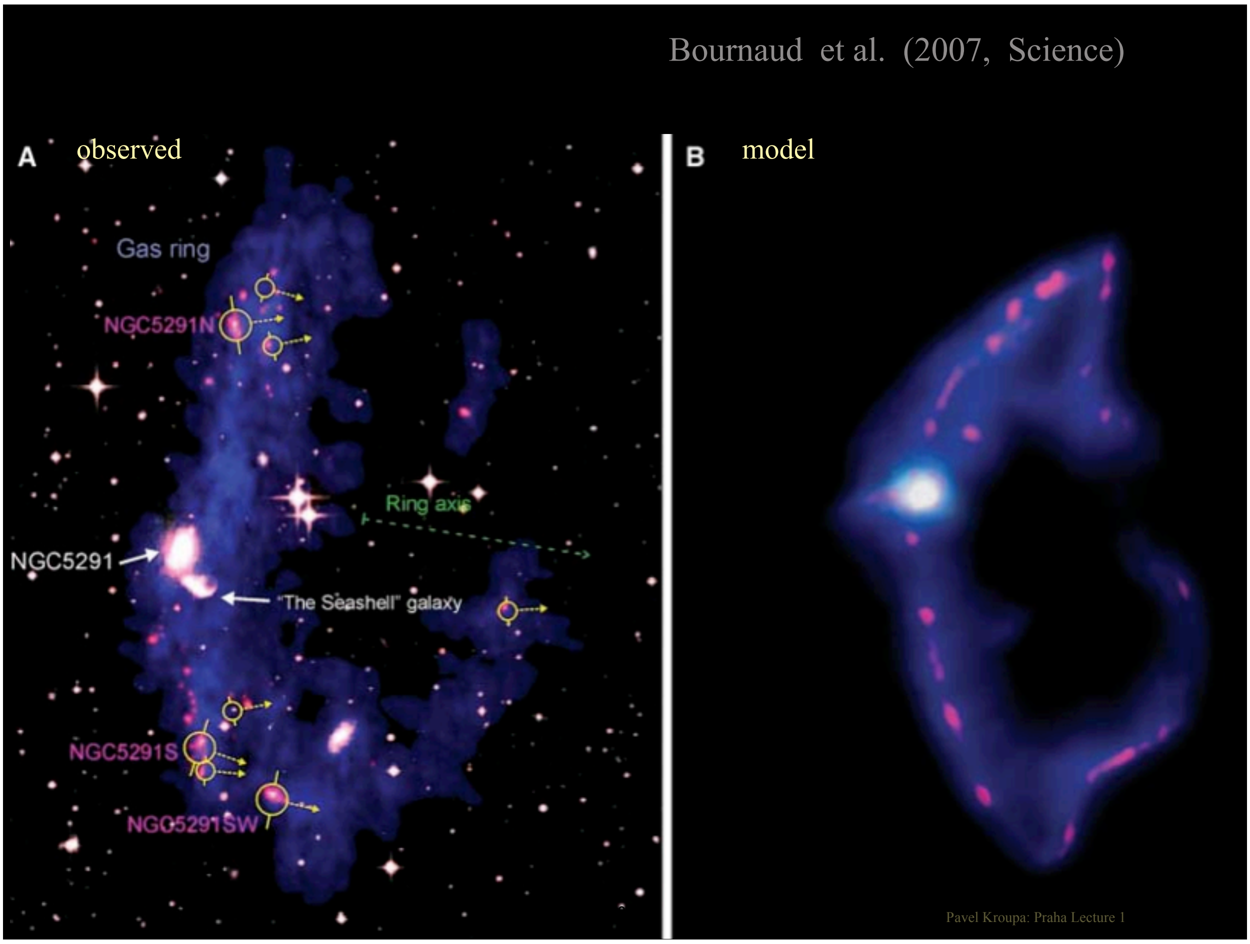
with the SMoC.

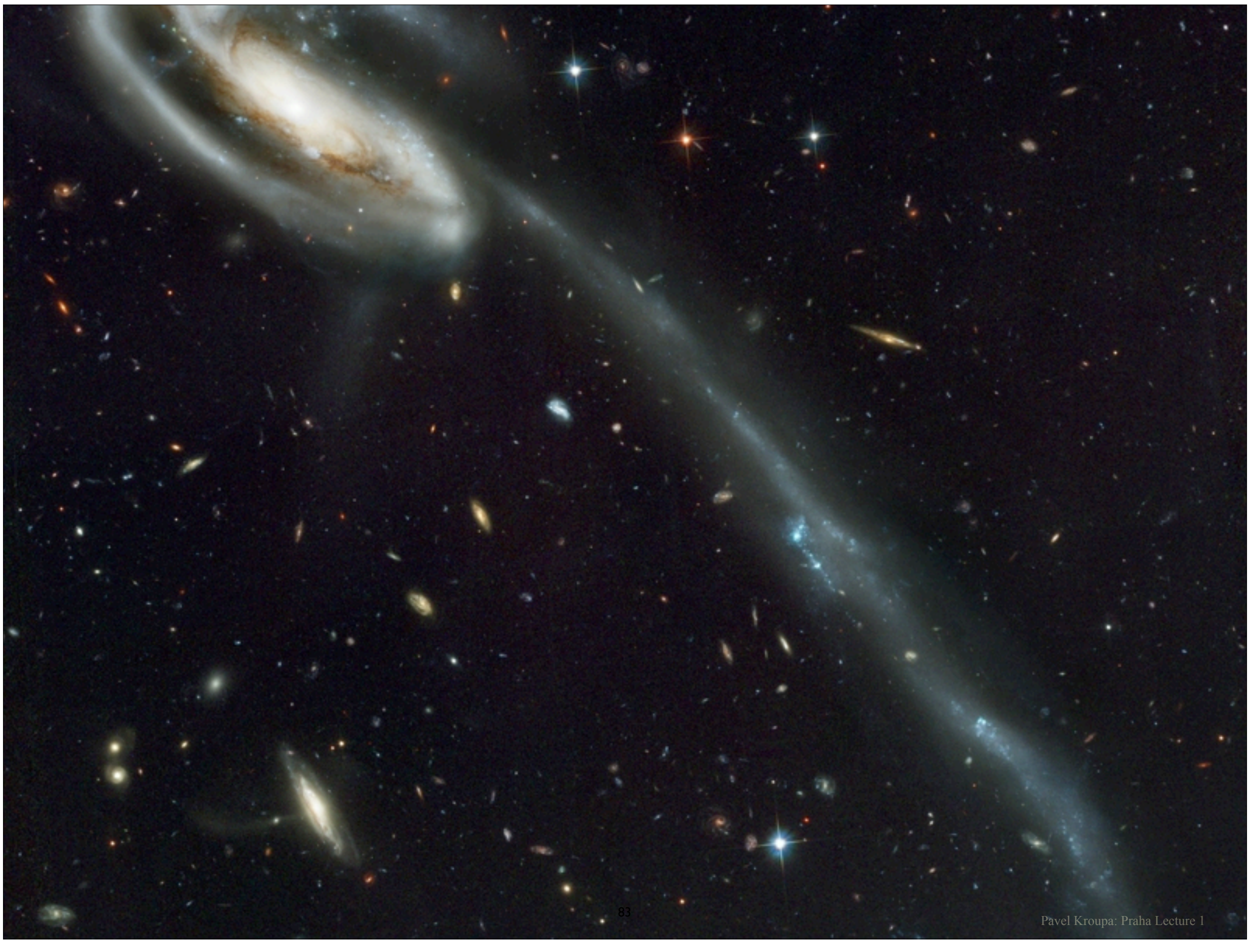
Concistency Check II

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

Are the Milky Way & Andromeda
unique or
extreme outliers ?

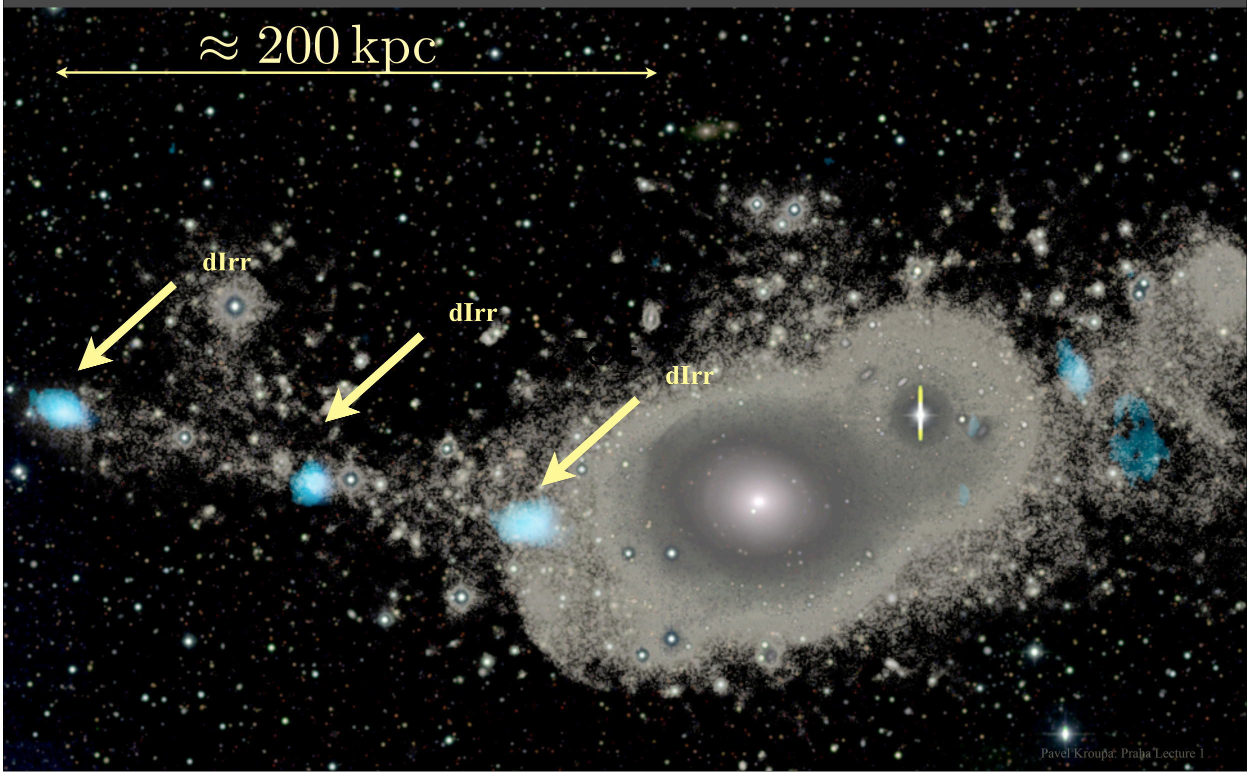

Bournaud et al. (2007, Science)
A observed
Gas ring
NGC5291N
Ring axis
NGC5291
"The Seashell" galaxy
NGC5291S
NGC5291SW
Pavel Kroupa: Praha Lecture 1

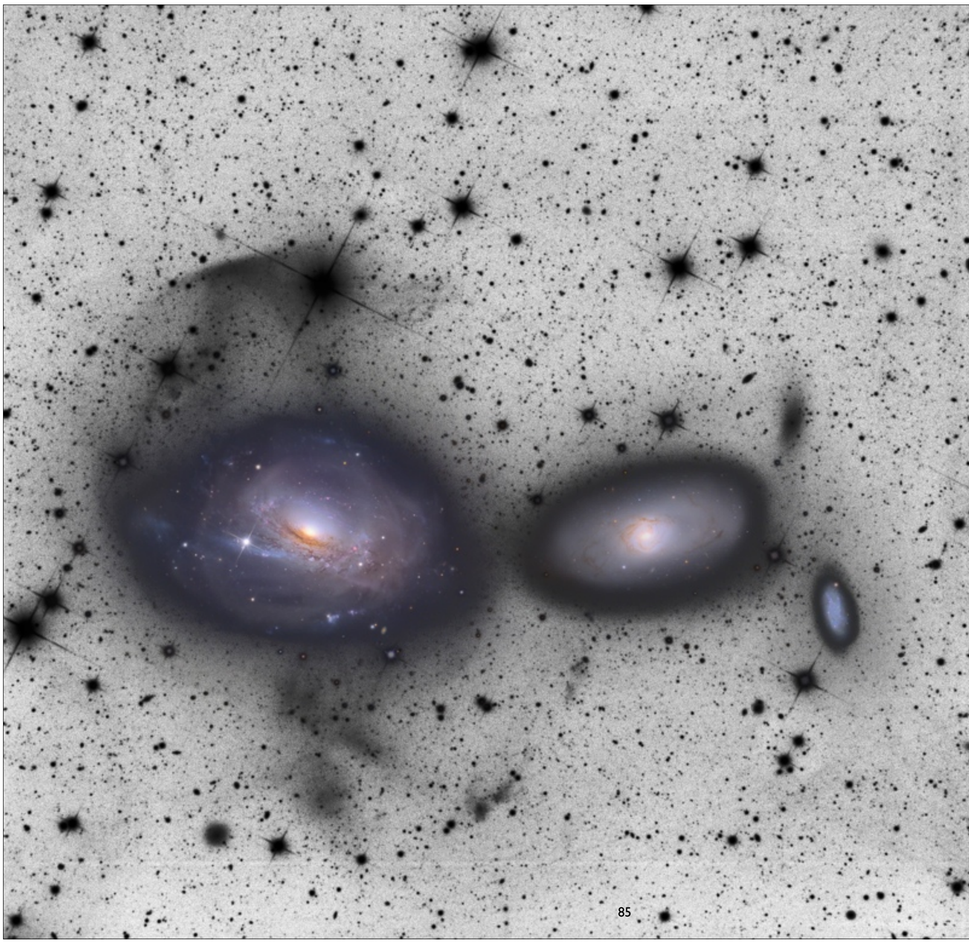

Bournaud et al. (2007, Science)
A observed
Gas ring
NGC5291N
Ring axis
NGC5291
"The Seashell" galaxy
NGC5291S
NGC5291SW
B model
Pavel Kroupa: Praha Lecture 1



NGC 5557

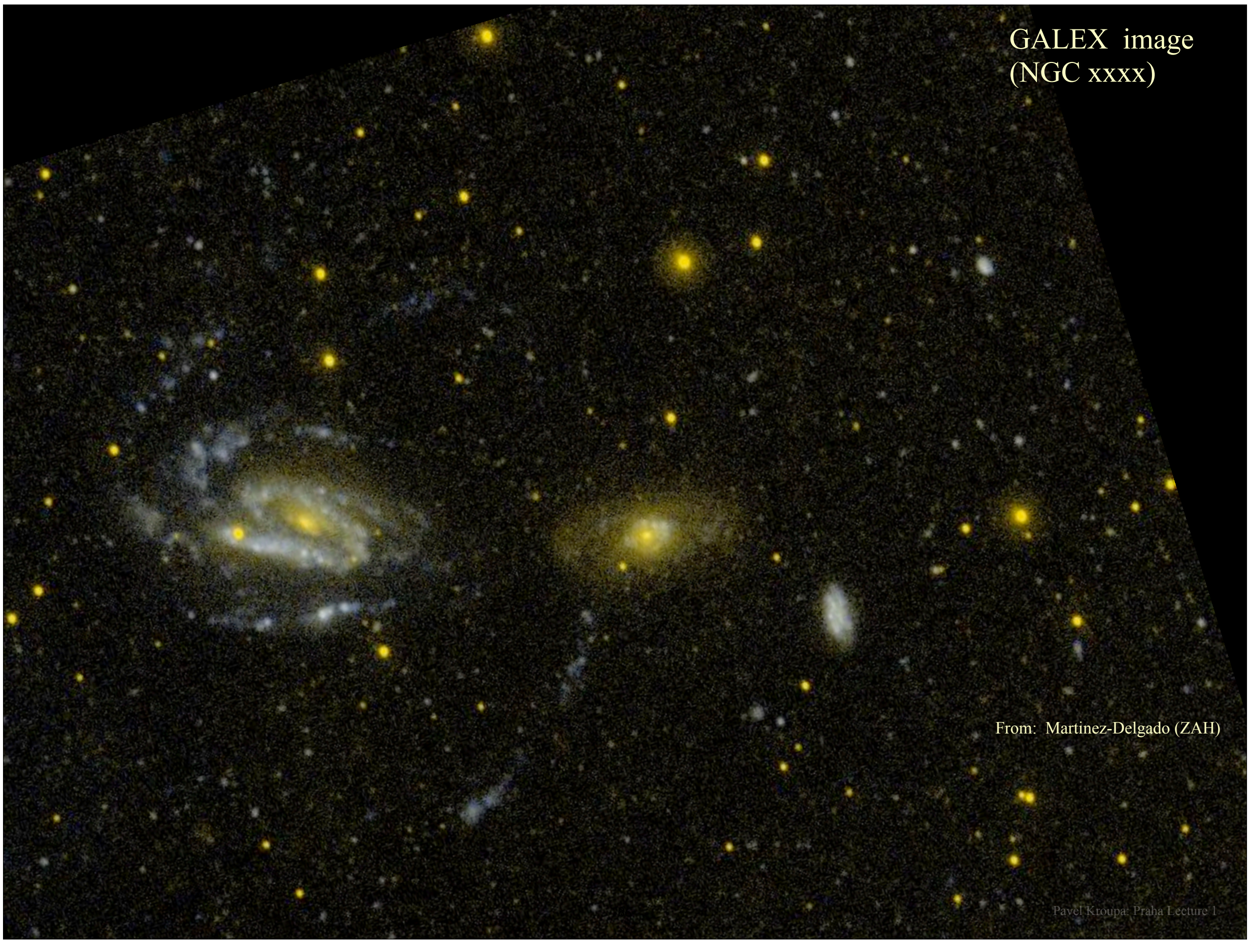
(post-interaction 2-3 Gyr)





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

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



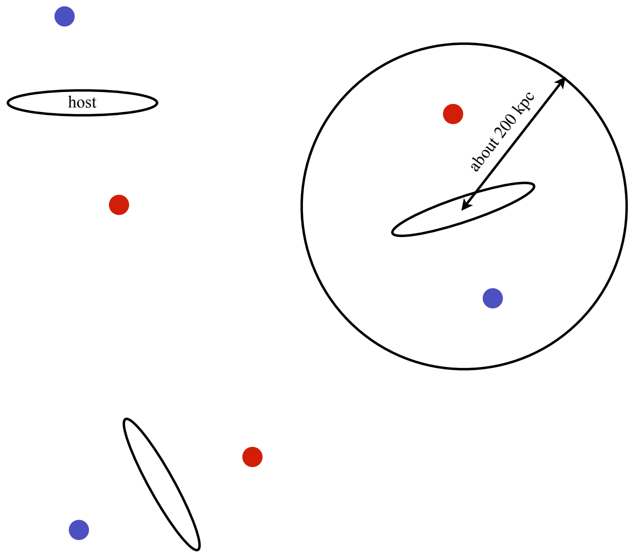
GALEX image (NGC xxxx)

From: Martinez-Delgado (ZAH)

Significant excess of anti-correlated satellites

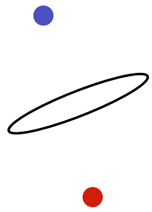
Ibata, Ibata et al. (2014 Nature)
Ibata et al. (2015, ApJ) **:**

~~Cautun et al. (2014) http://xxx.lanl.gov/abs/1410.7778~~



Excess is evident on scales
100-200kpc
around host galaxies,

just like the
VPOS & GPoA.



Concistency Check II

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"

Remember :

Kroupa 2012, 2015

The Dual Dwarf Galaxy Theorem must be true if the SMoC is true :

The Dual Dwarf Galaxy Theorem :

SMoC $\Rightarrow \exists$ Type A dwarfs $\wedge$ Type B dwarfs

with DM

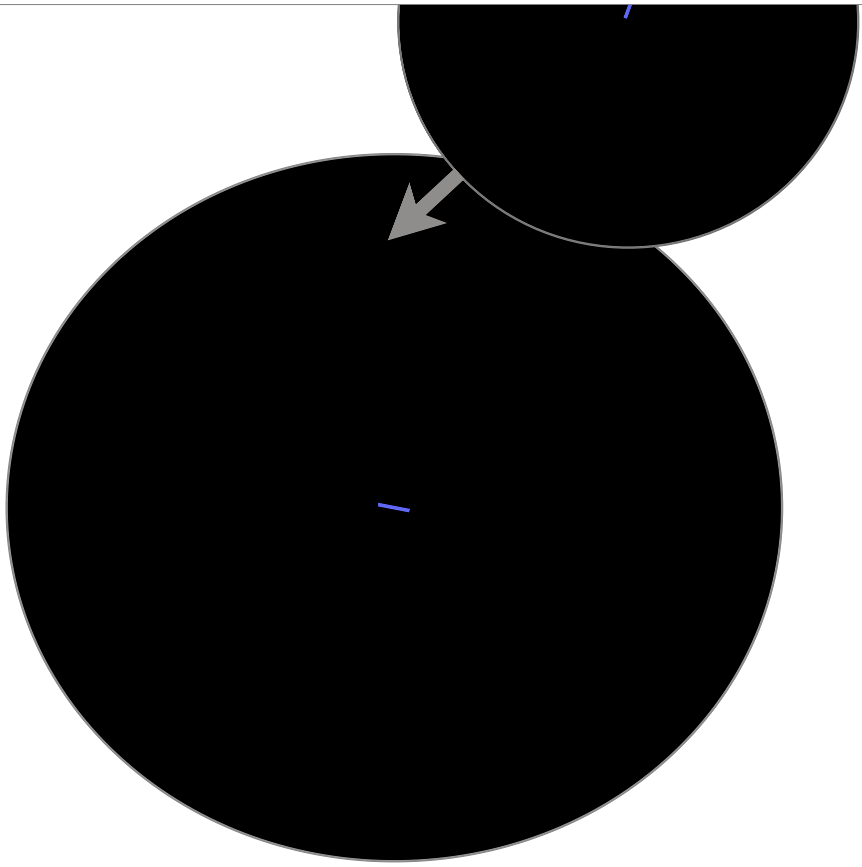
TDGs w/o DM

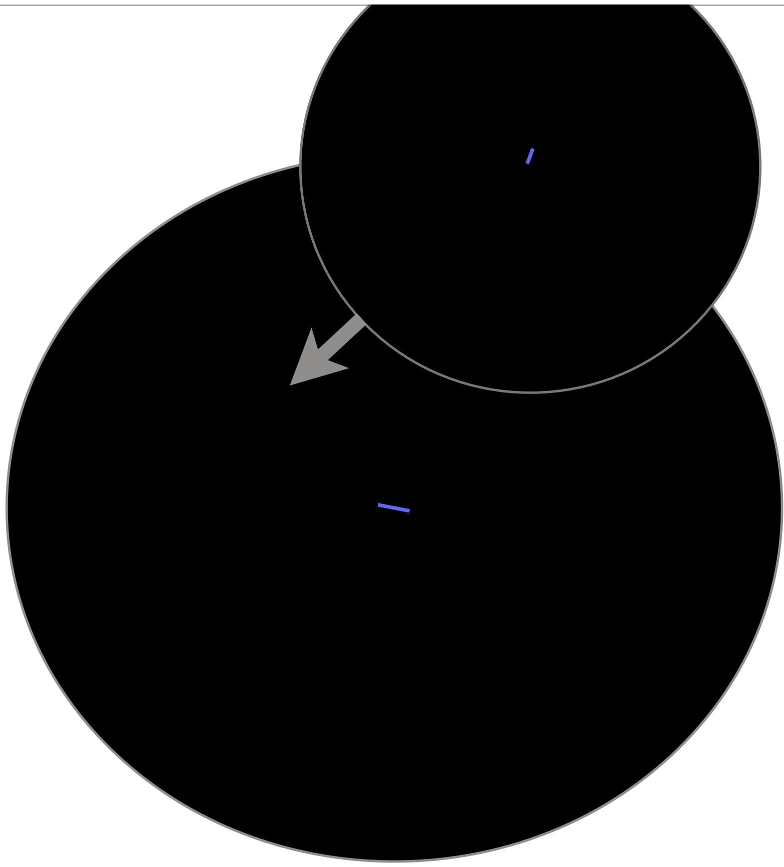
spheroidal distribution

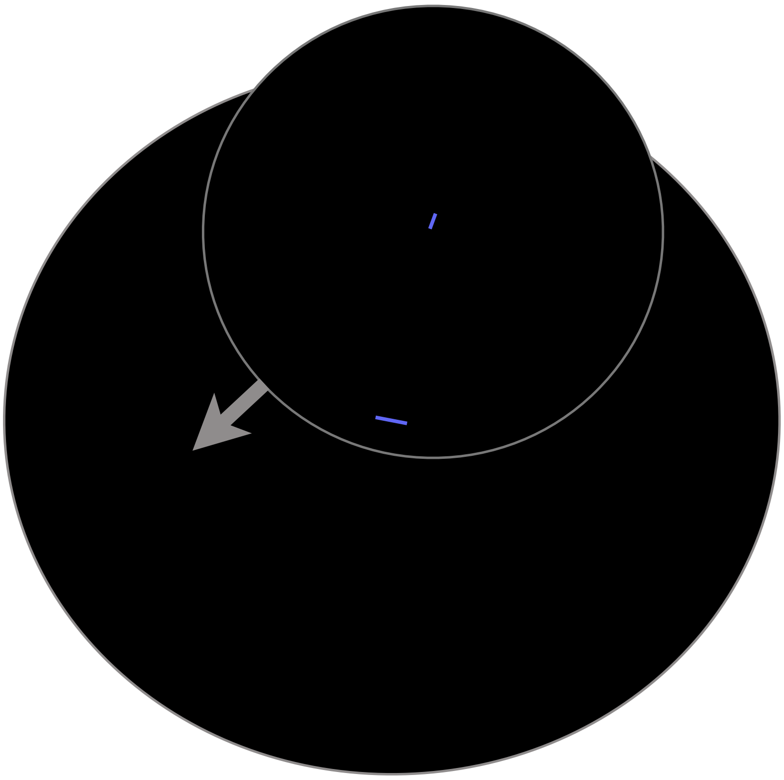
correlated in phase-space

The Milky Way is no exception !

Is there any solution of this
in terms of
primordial
(DM-dominated)
dwarfs
?







MW satellites are in a disk-like configuration:

(Kroupa, Theis & Boily 2005)

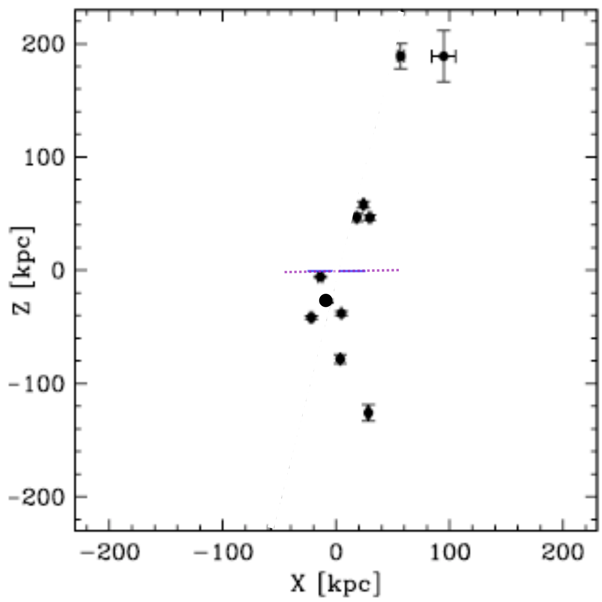
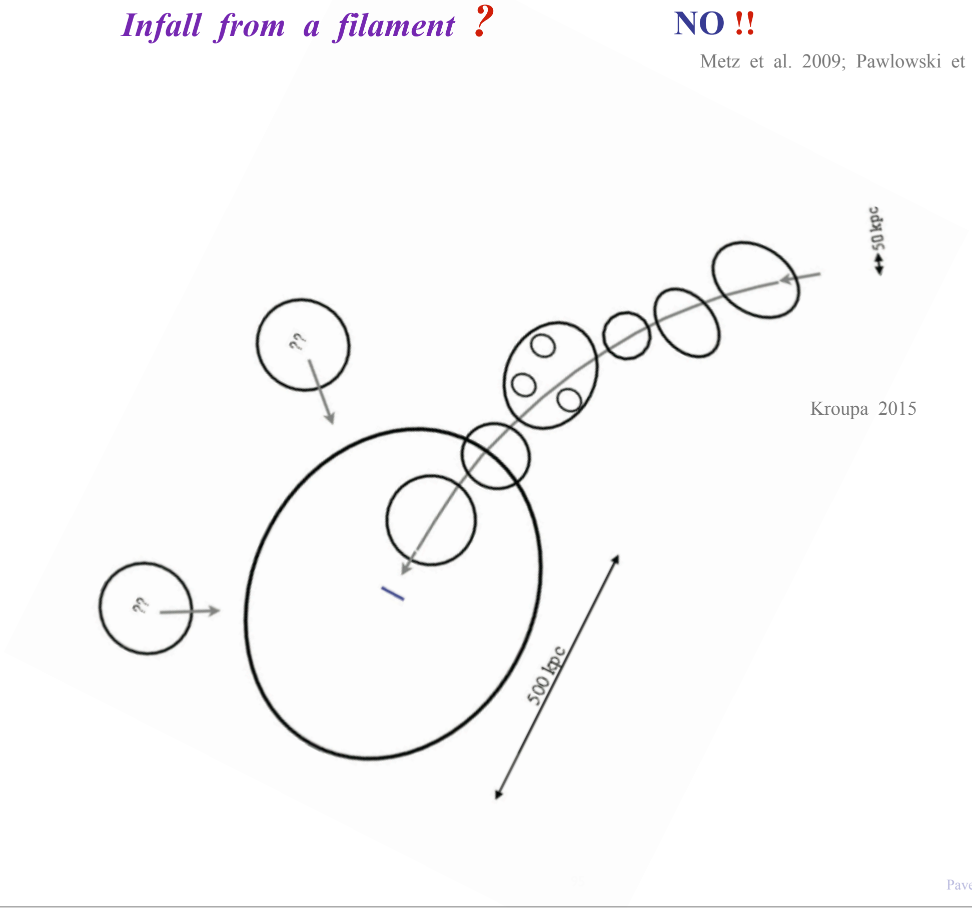


Fig. 1. The position of the innermost 11 MW satellites (Table 1) as viewed from a point located at infinity and $l = 167°.91$. The MW disk is indicated by the horizontal line $-25 \leq X/\mathrm{pc} \leq 25$, and the centre of the coordinate system lies at the Galactic centre. The dashed line marks the fitted plane for $N = 11$ seen edge-on in this projection.

Infall from a filament ? NO !!

Metz et al. 2009; Pawlowski et al. 2012, 2014



Kroupa 2015

. . . need to strip most of the DM halo, depositing the baryonic satellite
at its distance with its proper motion before it merges with MW,
and, as shown above,

--> no in-fall solutions for MW satellites

Angus, Diaferio & Kroupa 2011

Disks of Satellites

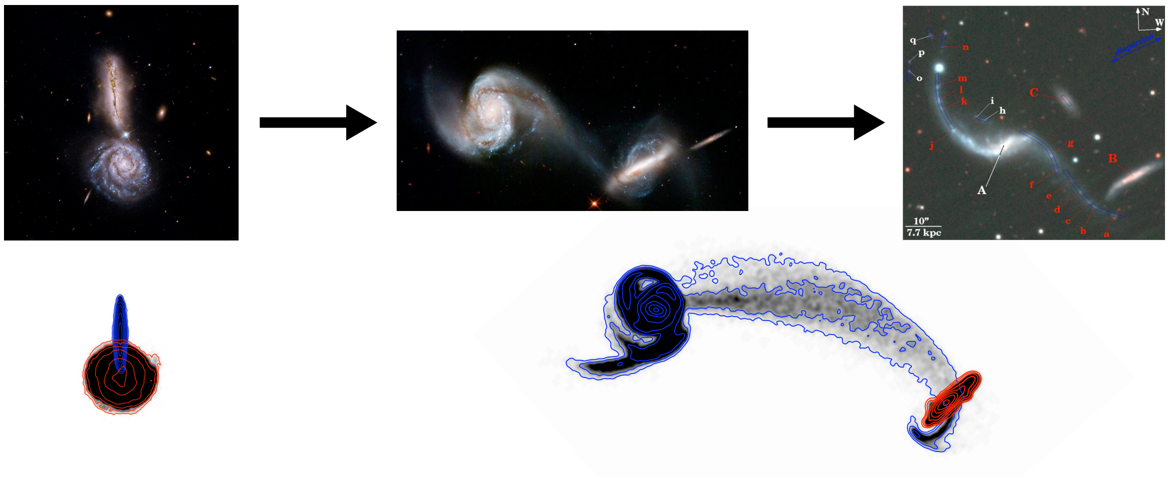
==> they need to be highly phase-space correlated at birth

==> TDGs

Origin of the Vast Polar Structure ?

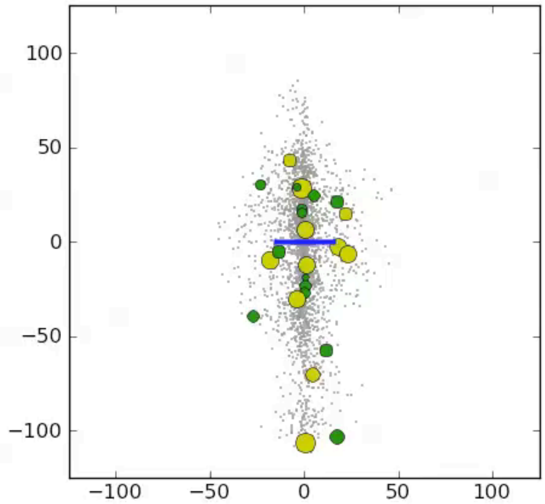
Phase-space-correlated tidal debris

Pawlowski et al. 2012



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

Pawlowski et al. 2011



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

END of

Lecture 1