Are all satellite galaxies TDGs ?
THAT IS
Are there no dark-matter satellites ?

Satellites and Streams

ESO, Santiago, Chile

April, 13th-17th, 2015

based on **Kroupa, 2012**,
http://adsabs.harvard.edu/abs/2012PASA...29..395K
and **Kroupa 2014**,
http://adsabs.harvard.edu/abs/2014arXiv1409.6302K
and **Kroupa 2015**,
http://adsabs.harvard.edu/abs/2015CaJPh..93..169K

Pavel Kroupa

Helmholtz-Institut fuer Strahlen und Kernphysik (HISKP)

Helmholtz Institute for Radiation and Nuclear Physics

c/o Argelander-Institut für Astronomie

University of Bonn

Assume

the standard model of cosmology

(SMoC)

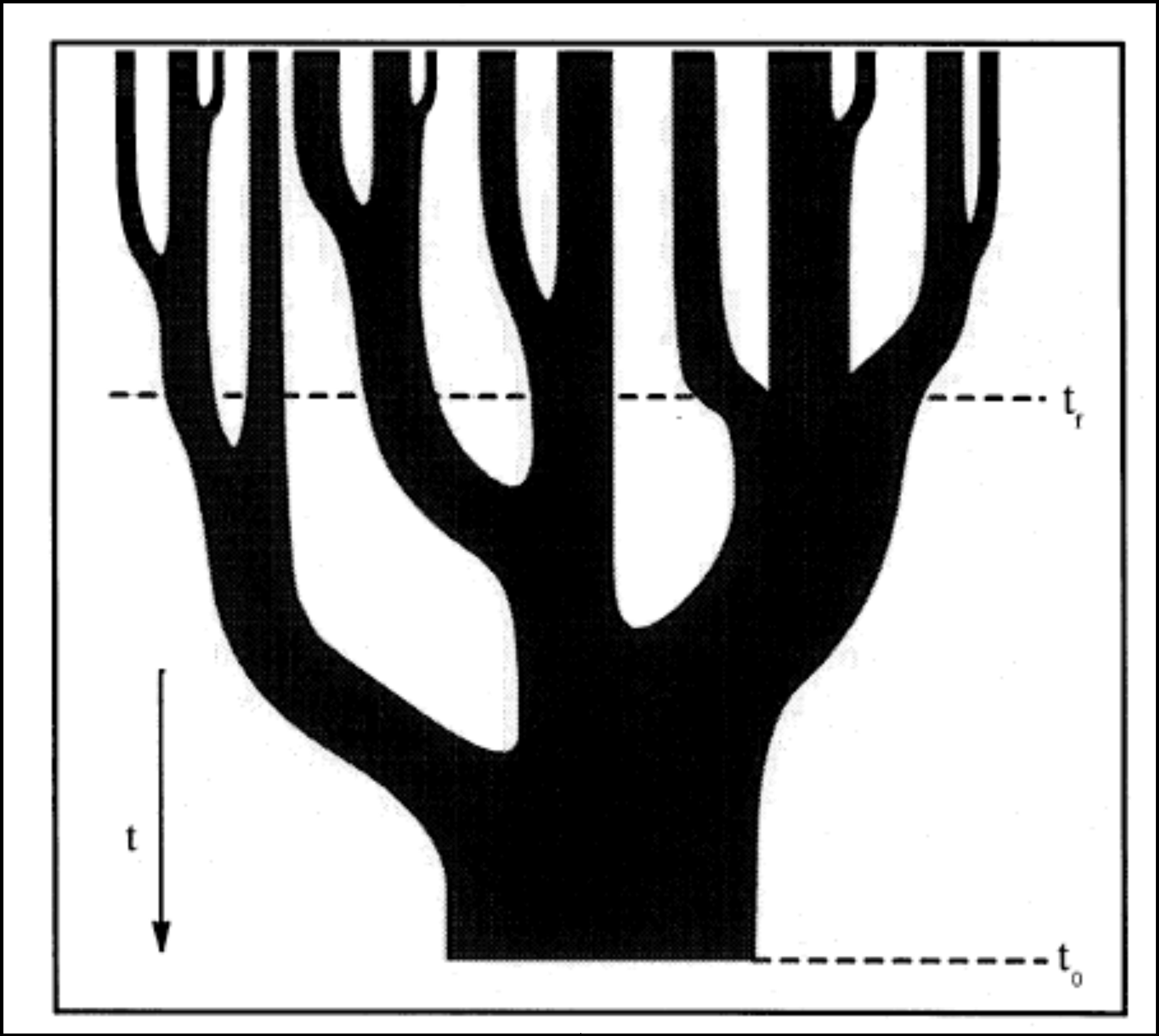
is a valid description of the universe.

this is synonymous to ***extrapolating*** the law of gravitation, derived empirically only on scales of the Solar System, by ***many orders of magnitude***.

Formation of primoridal / DM dominated dwarf galaxies (PDGs)

Structures form according to the cosmological merger tree

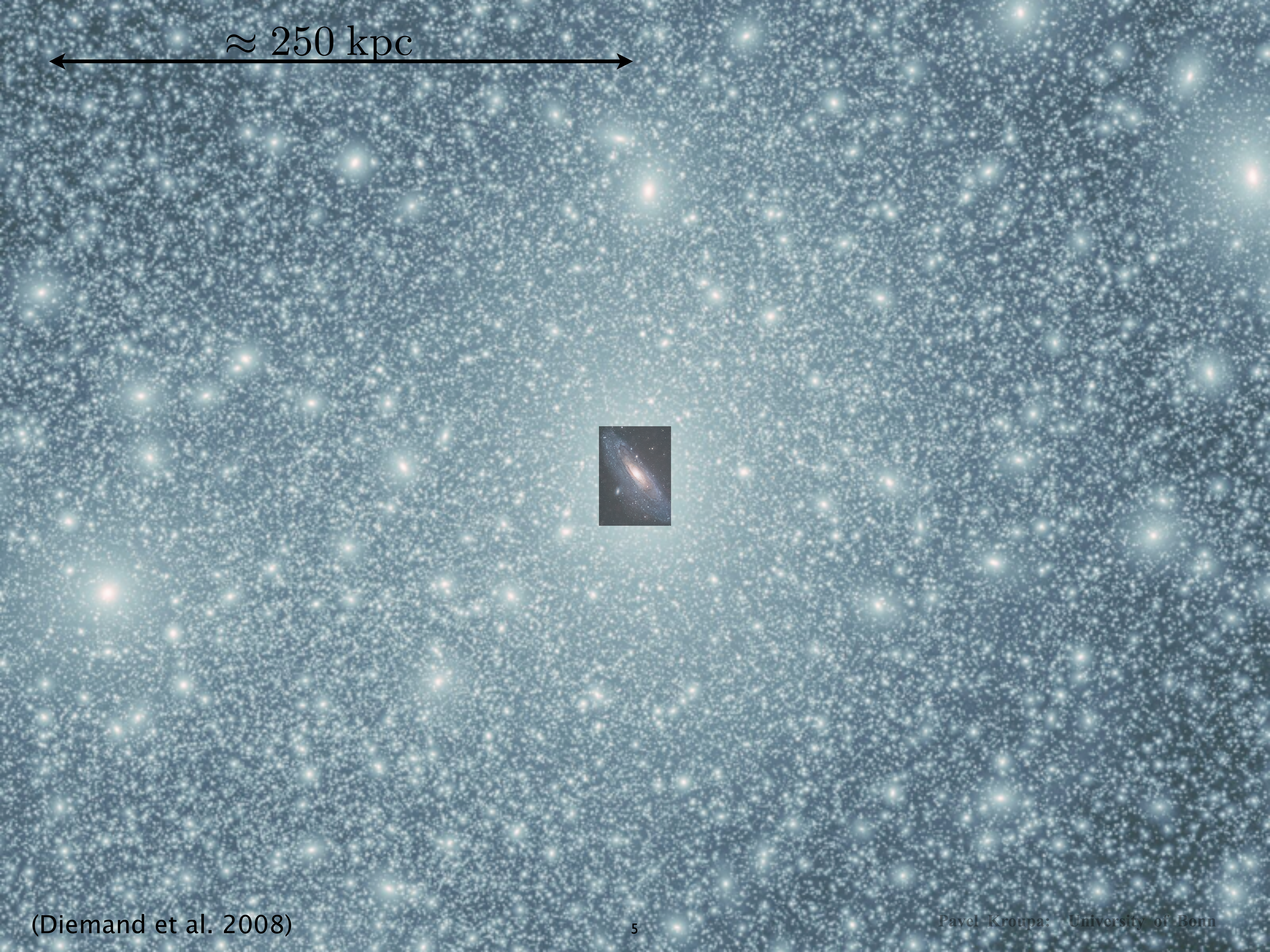
Lacey & Cole (1993)



the beginning Big Bang

DM sub-structures form first and coalesce to larger structures

today



(Diemand et al. 2008)

. . . a *fabulously huge industry* of scientists

(worth millions of Euros annually)

work

on trying to understand why the observed dwarfs

DO NOT

look like the theoretical ones

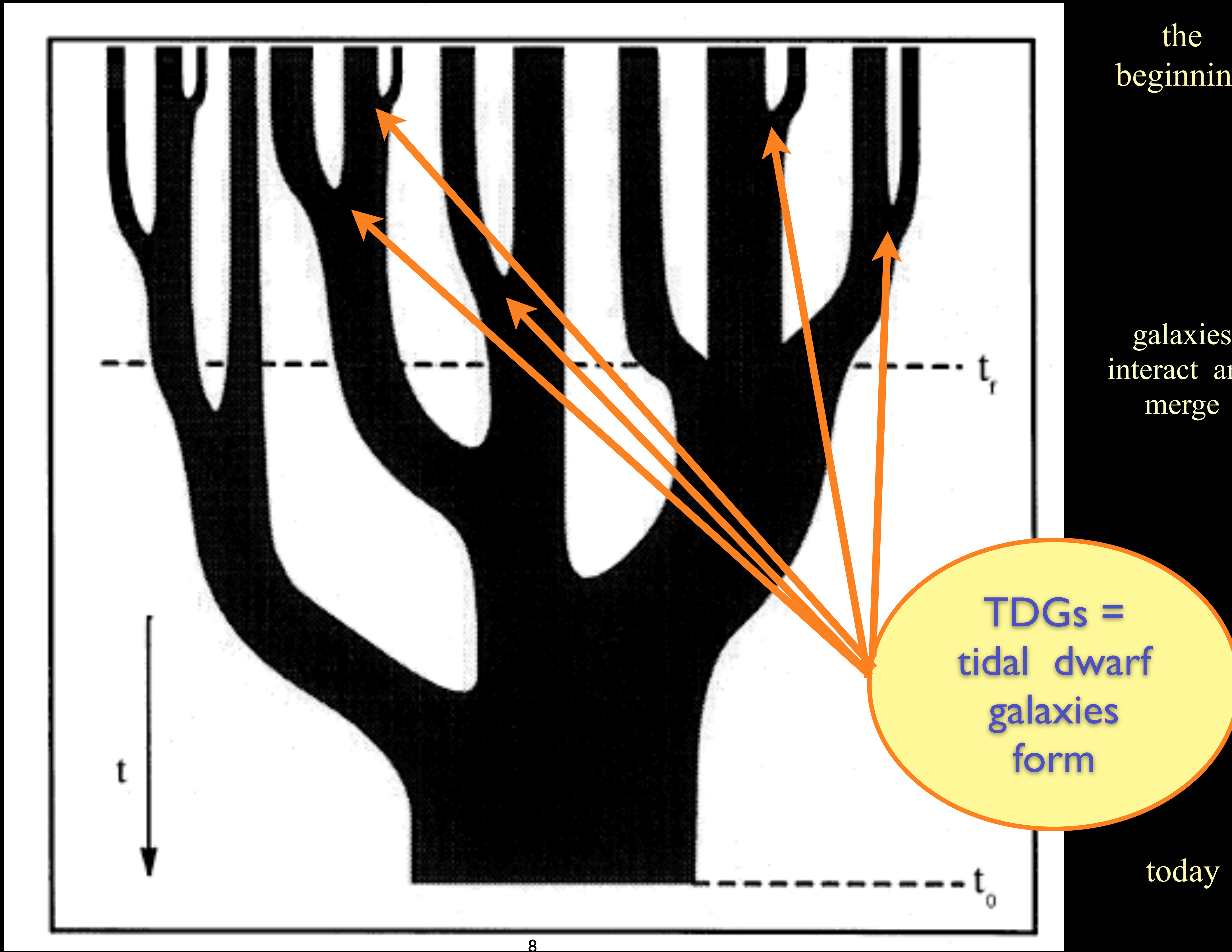
(e.g. cusp/core problem; missing dwarf galaxy problem; "*inner mass deficit*" . . .).

Oman, Navarro, ... Frenk, Sawala, White, ... Shaye et al. :
http://arxiv.org/abs/1504.01437

Formation of tidal dwarf galaxies (TDGs)

Structures form according to the cosmological merger tree

Lacey & Cole (1993)

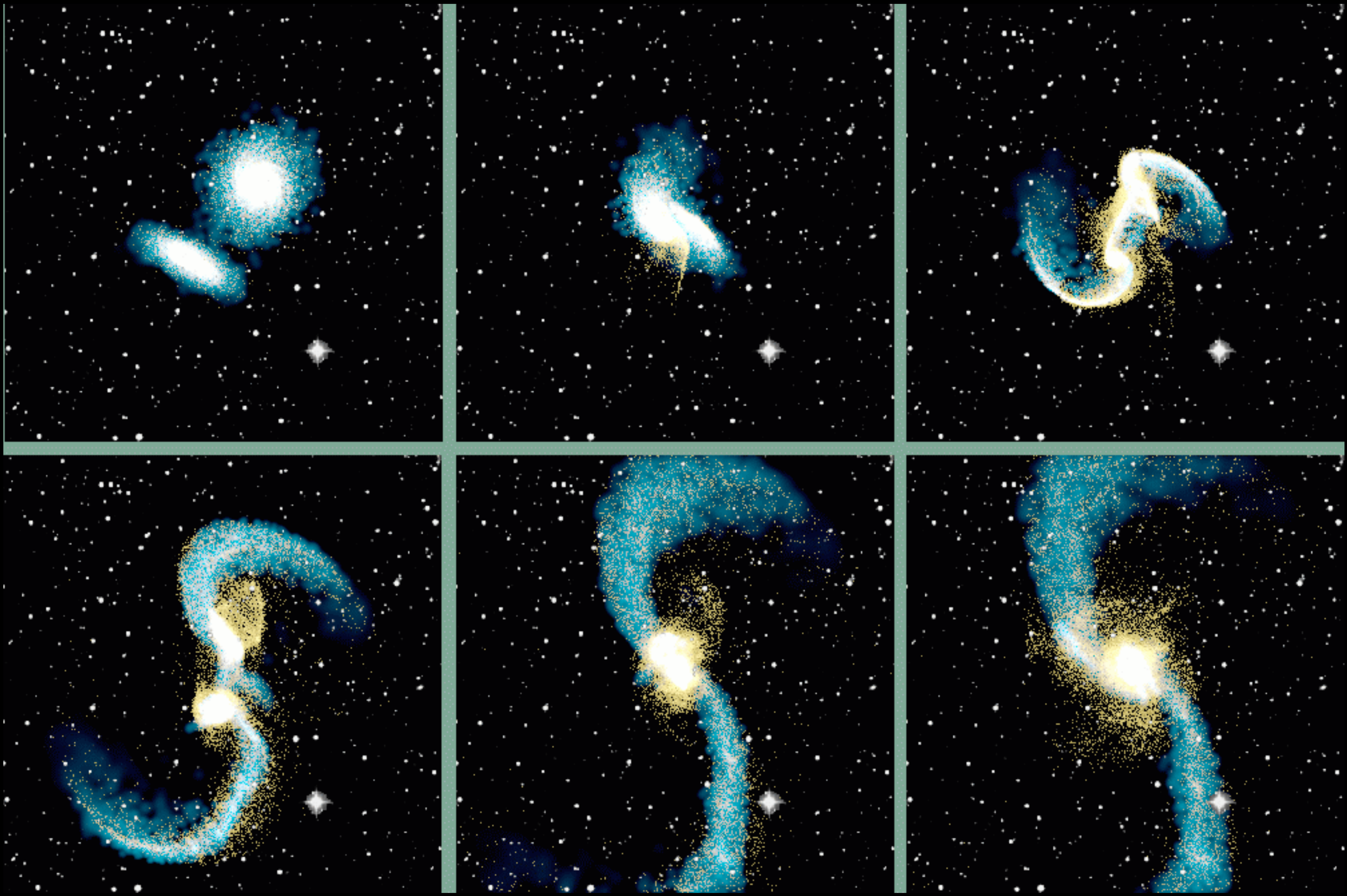


the beginning

galaxies interact and merge

today

Tidal tails



Miho & Maxwell, web

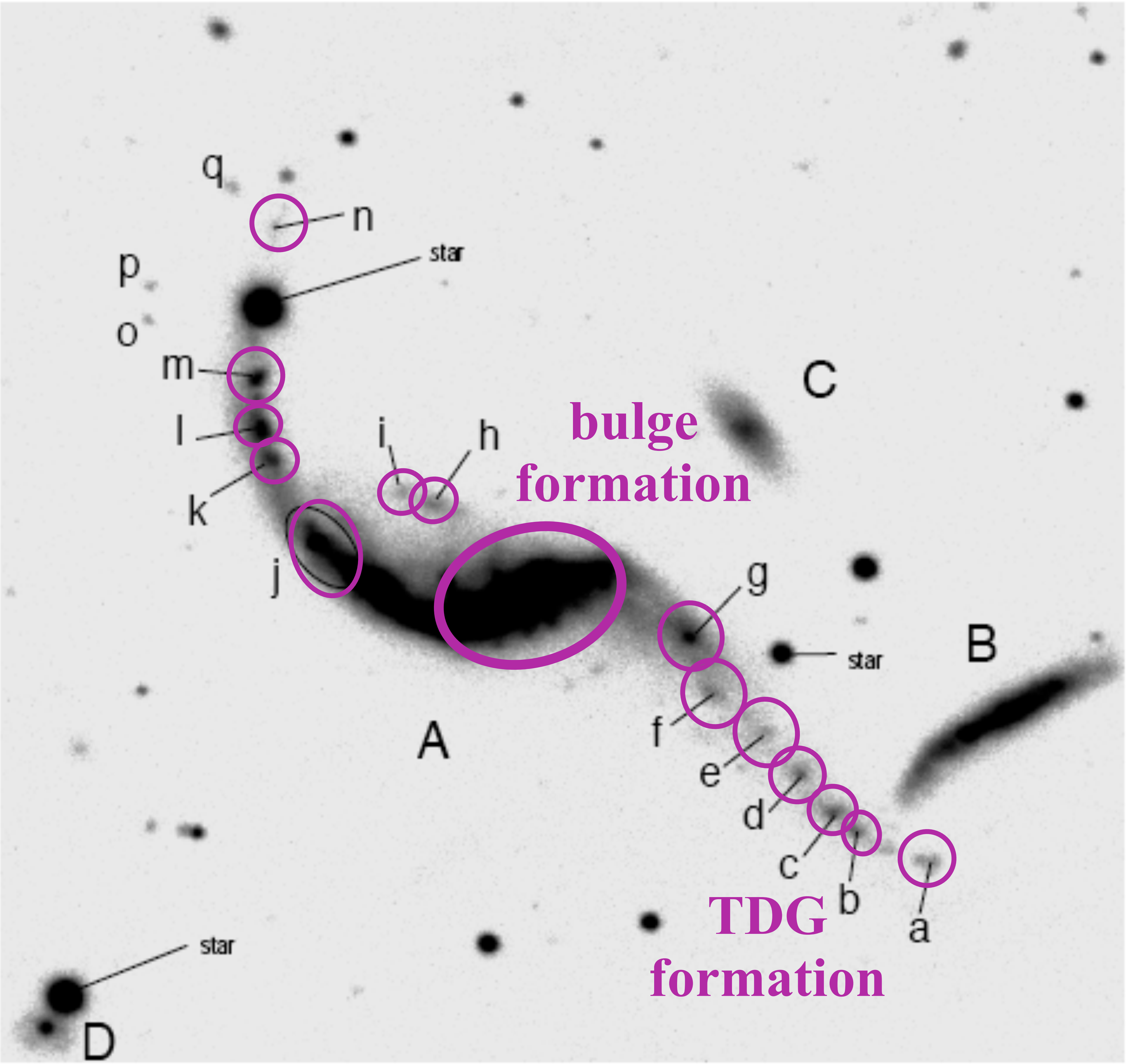


Fig. 21. Identification chart of field 10 around AM 1353-272.

(Weilbacher et al. 2000)

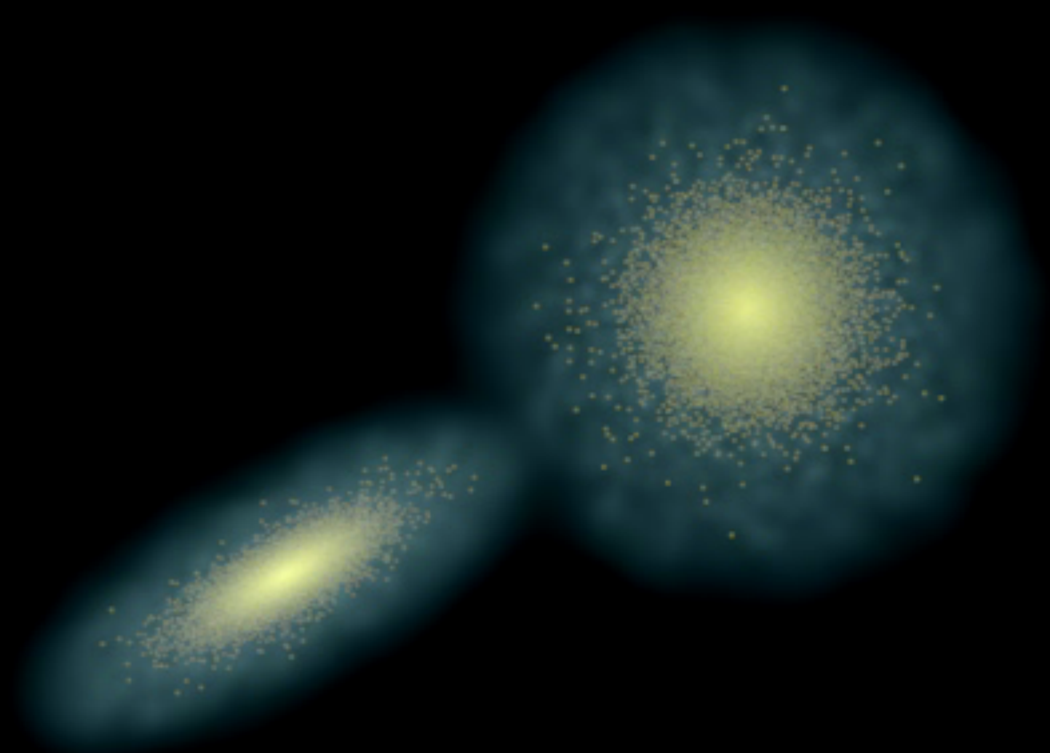
$$N_{\rm TDG} \approx 14$$

Phase-space correlated satellites form in the same event

Pavel Kroupa: University of Bonn

Relevance

redshift



Wetzstein, Naab & Burkert 2007

Intermediate-term evolution of TDGs

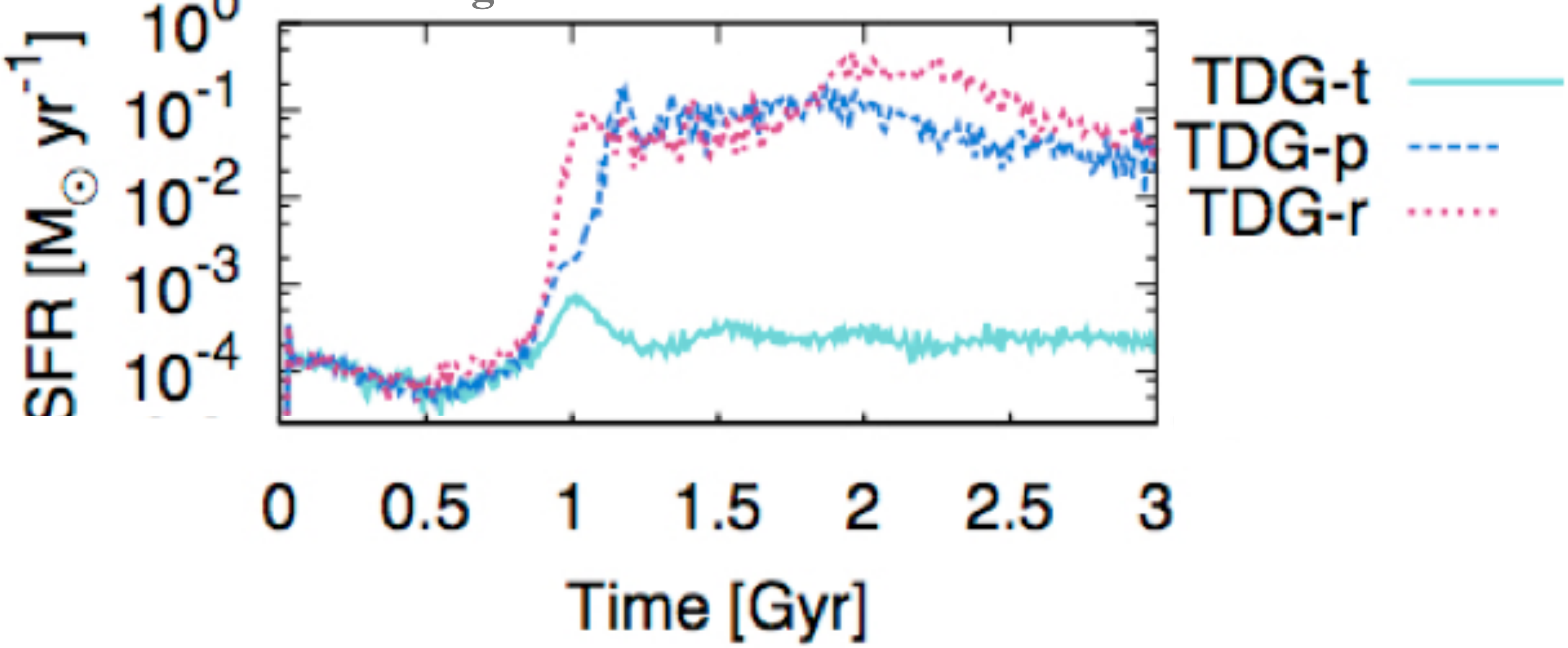
The Time

TDG formation and evolution over first 3 Gyr

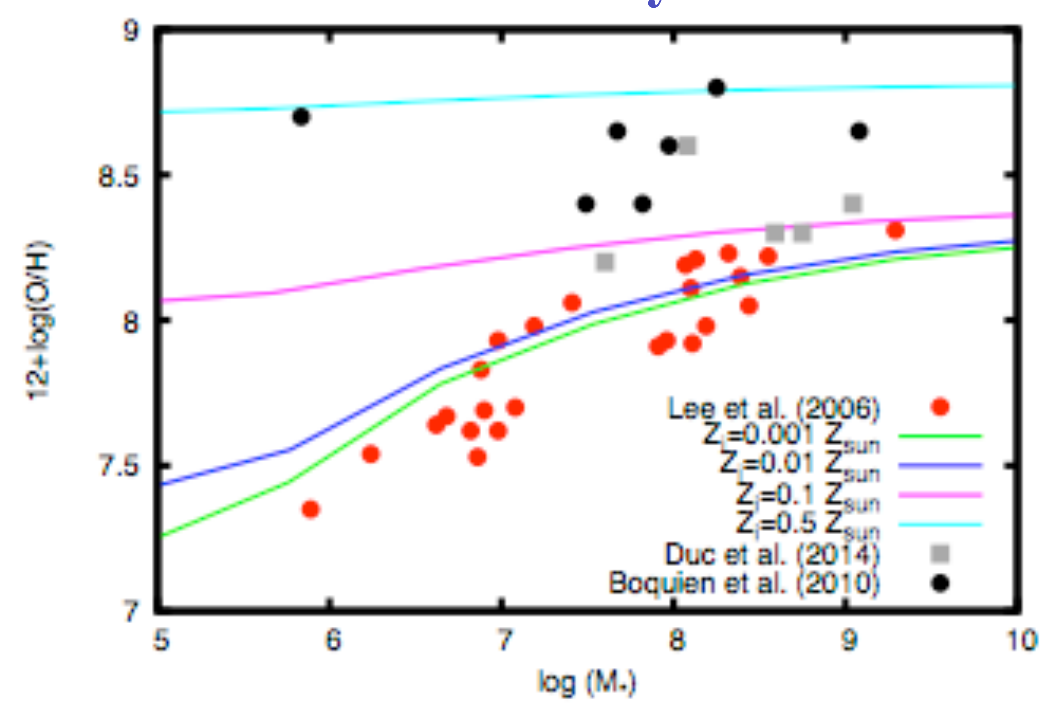
Self-consistent high-resolution simulations of self-regulated TDGs show these to not disrupt

Recchi et al. 2007;
Ploeckinger et al. 2014, 2015

Ploeckinger et al. 2015



Mass--metallicity relation



Recchi et al. 2015 (in press, **yesterday on arXiv**)

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 Eq. 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).

Identification of old tidal dwarfs near early-type galaxies from deep imaging and H I observations

Pierre-Alain Duc,[1⋆] Sanjaya Paudel,[1] Richard M. McDermid,[2] Jean-Charles Cuillandre,[3] Paolo Serra,[4] Frédéric Bournaud,[1] Michele Cappellari,[5] Eric Emsellem[6,7]

[1] *Laboratoire AIM Paris-Saclay, CEA/IRFU/SAp, CNRS/INSU, Université Paris Diderot, 91191 Gif-sur-Yvette Cedex, France*
[2] *Gemini Observatory, Northern Operations Centre, 670 N. A'ohoku Place, Hilo, HI 96720, USA*
[3] *Canada-France-Hawaii Telescope Corporation, 65-1238 Mamalahoa Hwy., Kamuela, Hawaii 96743 USA*
[4] *CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia*
[5] *Sub-department of Astrophysics, Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH*
[6] *European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany*
[7] *Centre de Recherche Astrophysique de Lyon, Université Lyon 1, Observatoire de Lyon, Ecole Normale Supérieure de Lyon, CNRS, UMR 5574, 9 avenue Charles André, F-69230 Saint-Genis Laval, France*

Accepted for publication in MNRAS

ABSTRACT

It has recently been proposed that the dwarf spheroidal galaxies located in the Local Group disks of satellites (DoSs) may be tidal dwarf galaxies (TDGs) born in a major merger at least 5 Gyr ago. Whether TDGs can live that long is still poorly constrained by observations. As part of deep optical and H I surveys with the CFHT MegaCam camera and Westerbork Synthesis Radio Telescope made within the ATLAS^{3D} project, and follow-up spectroscopic observations with the Gemini-North telescope, we have discovered old TDG candidates around several early-type galaxies. At least one of them has an oxygen abundance close to solar, as expected for a tidal origin. This confirmed pre-enriched object is located within the gigantic, but very low surface brightness, tidal tail that emanates from the elliptical galaxy, NGC 5557. An age of 4 Gyr estimated from its SED fitting makes it the oldest securely identified TDG ever found so far. We investigated the structural and gaseous properties of the TDG and of a companion located in the same collisional debris, and thus most likely of tidal origin as well. Despite several Gyr of evolution close to their parent galaxies, they kept a large gas reservoir. Their central surface brightness is low and their effective radius much larger than that of typical dwarf galaxies of the same mass. This possibly provides us with criteria to identify tidal objects which can be more easily checked than the traditional ones requiring deep spectroscopic observations. In view of the above, we discuss the survival time of TDGs and question the tidal origin of the DoSs.

Observational evidence :

. . . with 4 Gyr the oldest TDGs identified until now

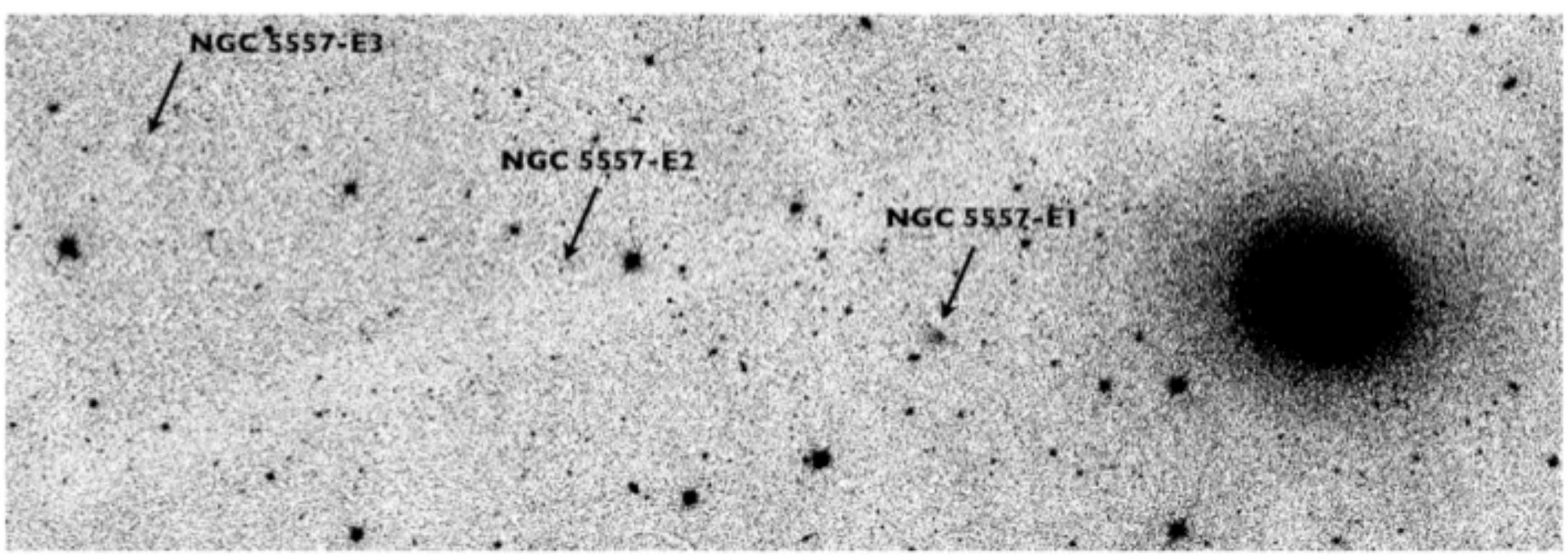
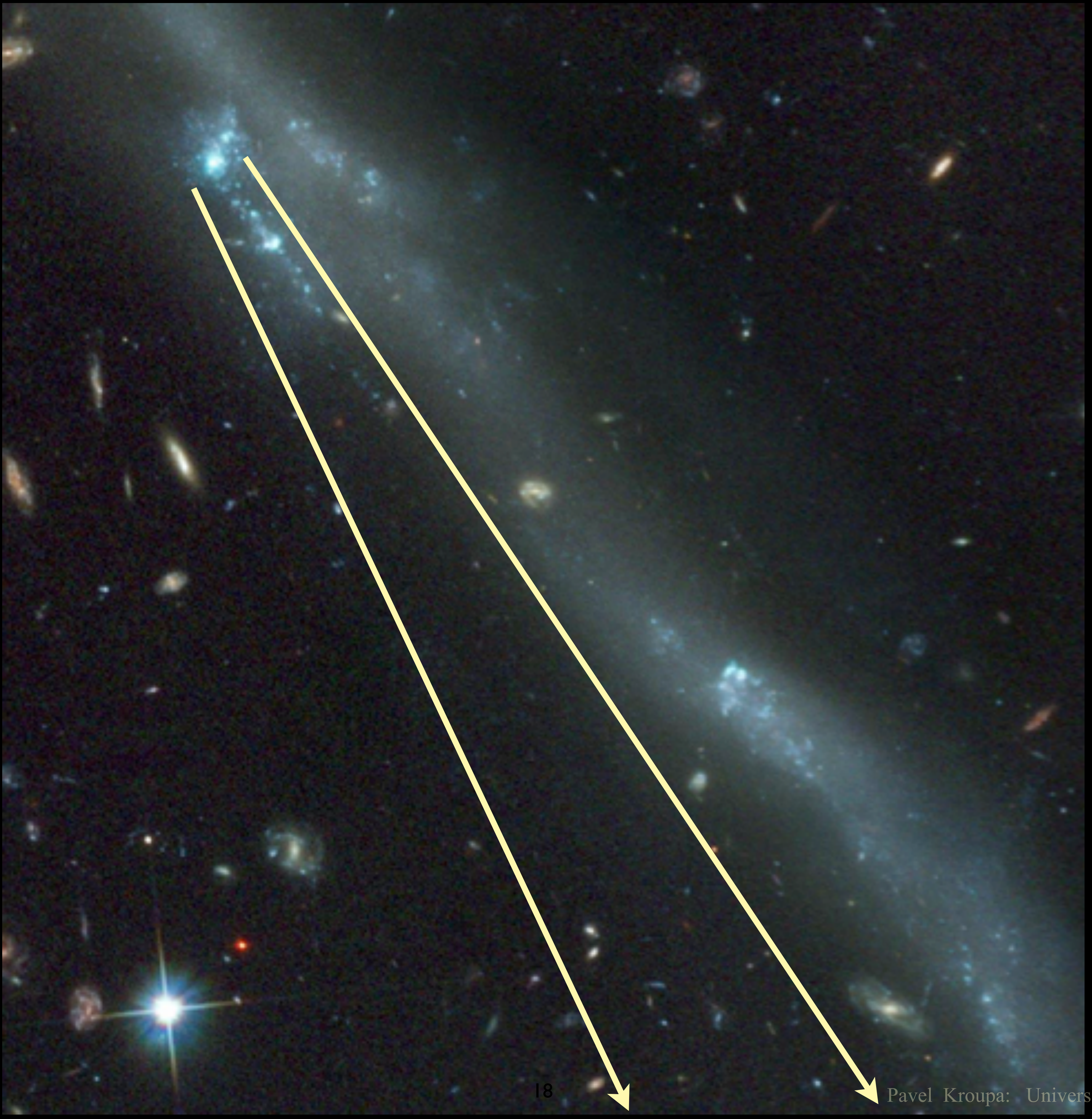


Figure 10. SDSS g-band image of the field around NGC 5557

Long-term evolution of TDGs

The Time


Evolve dwarf galaxies
w/o dark matter
in a computer



Star-cluster complex (cf *Tadpole*)

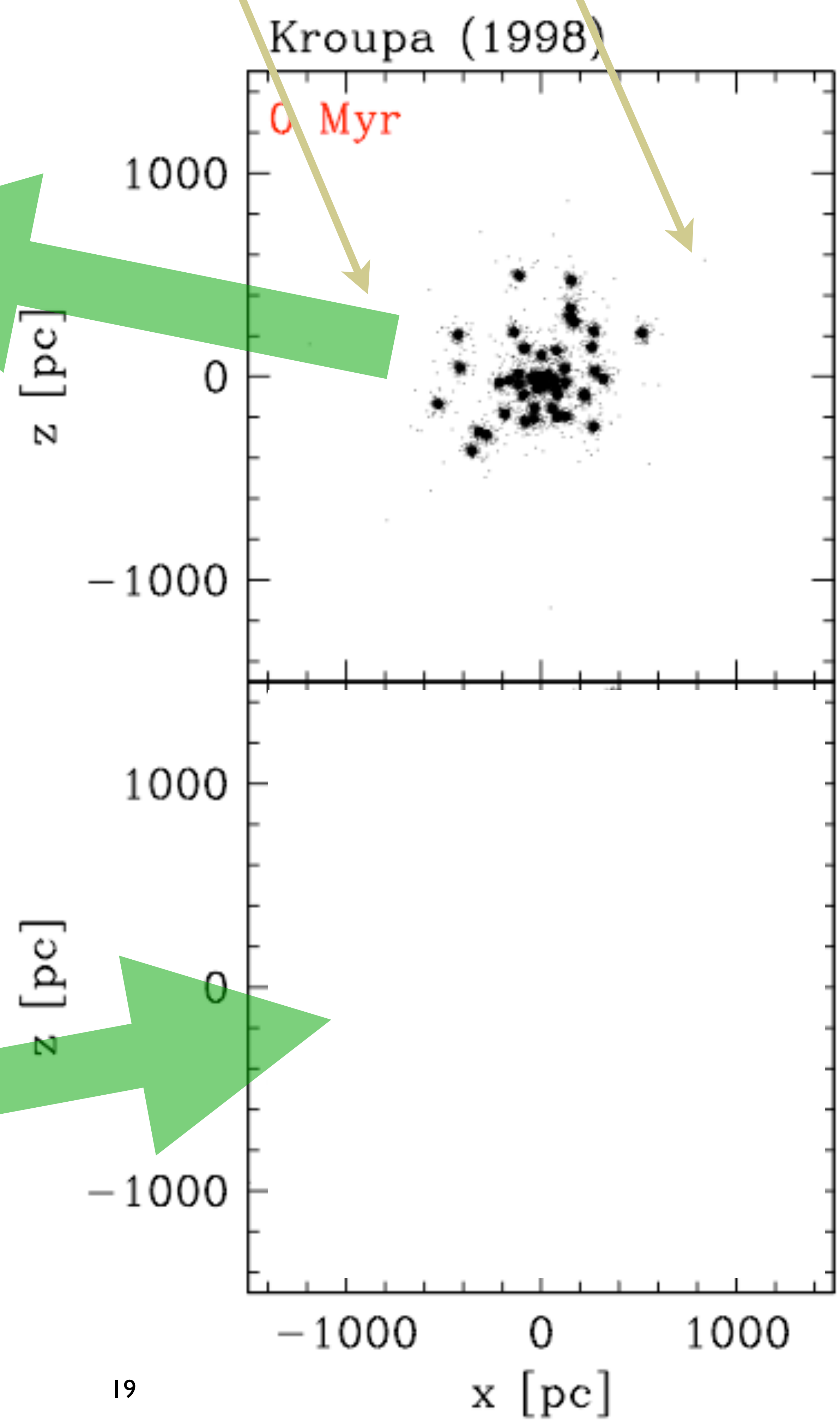
50 clusters
each $10^6\ M_\odot$

clusters as *fundamental galactic building blocks*

$\Downarrow$

Spheroidal dwarf galaxy !

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



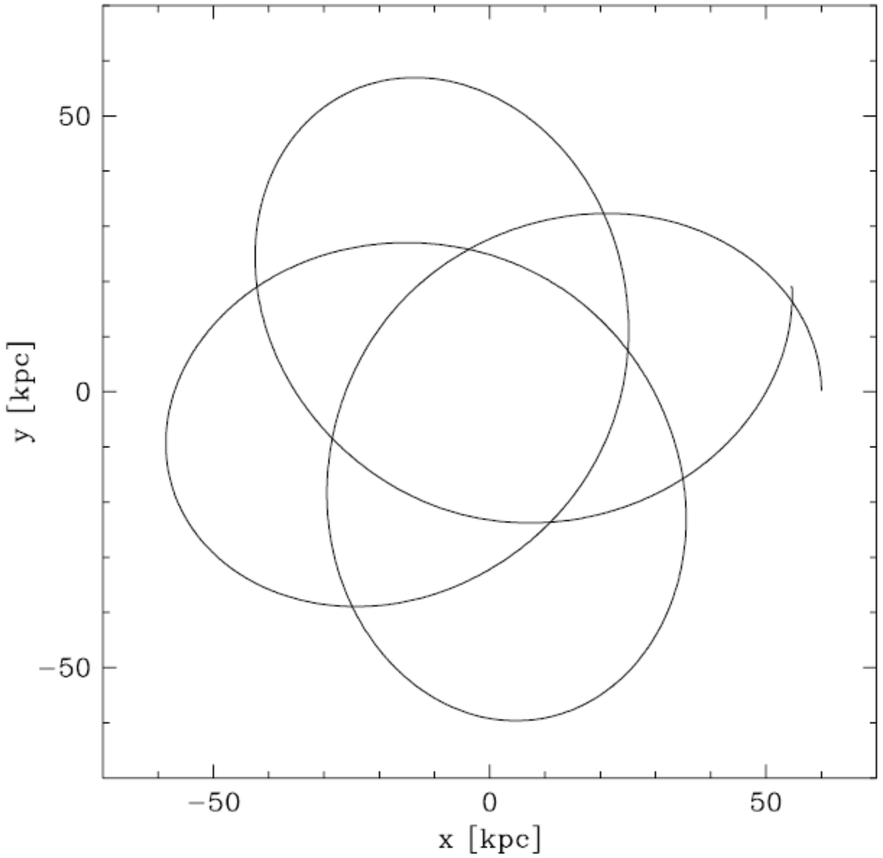
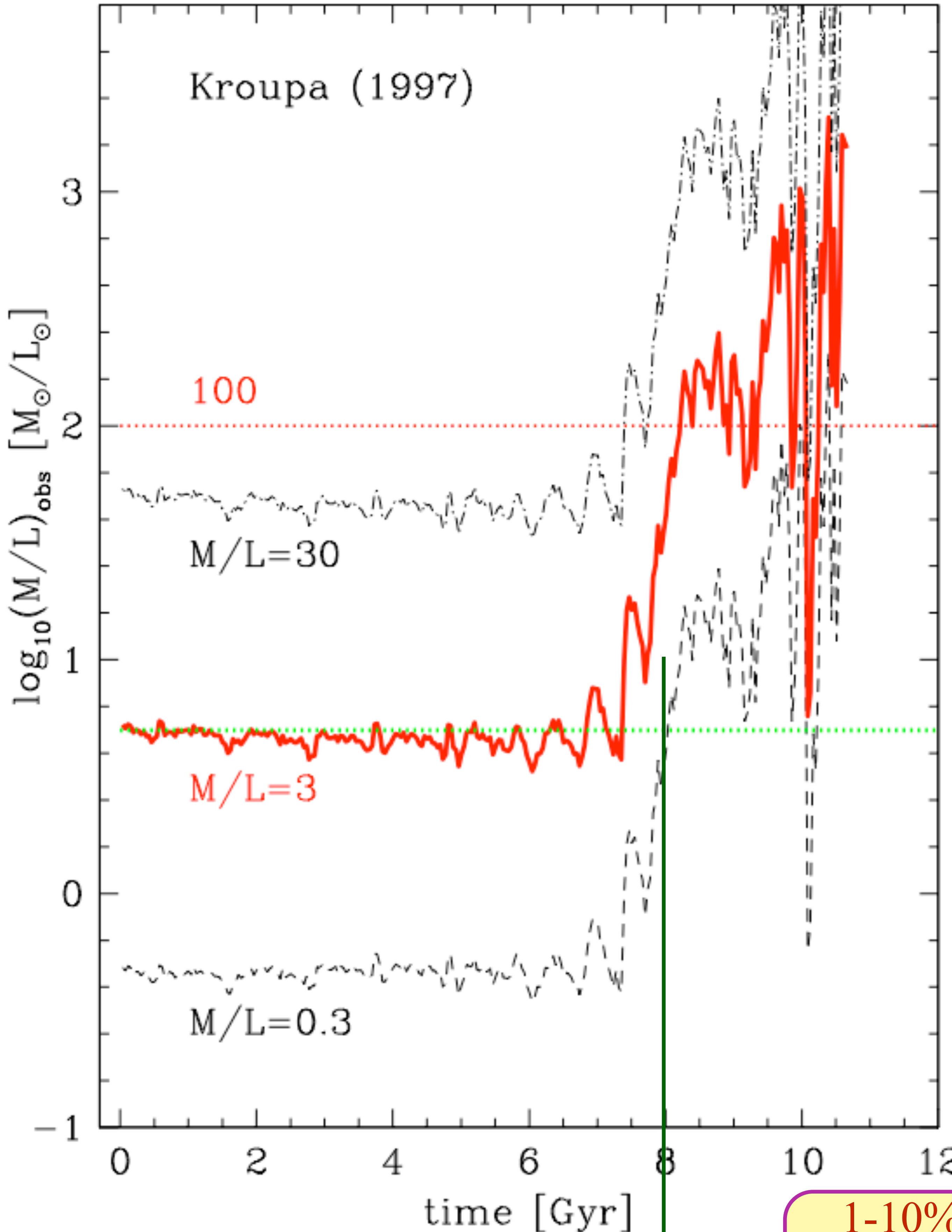


FIG. 3.—Orbital path of the satellite in simulations RS1-113 and Sat-M2.

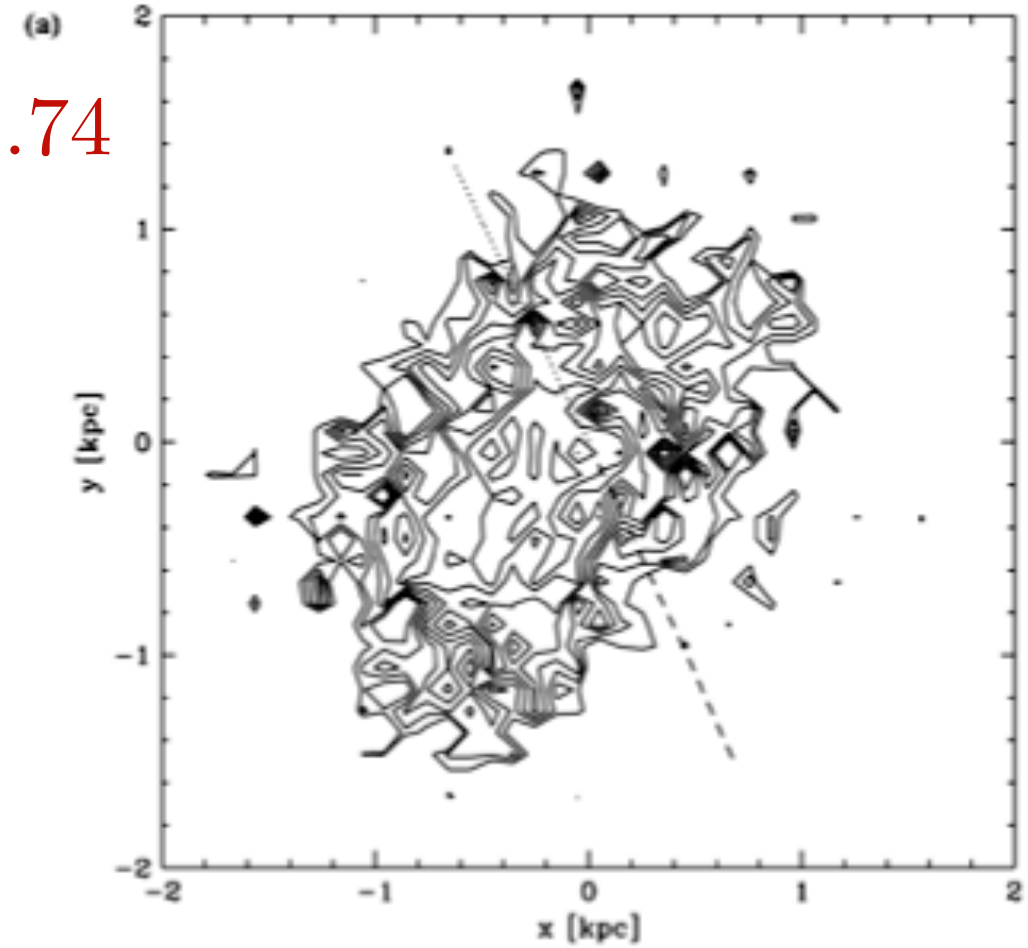


1-10% of population in remnant

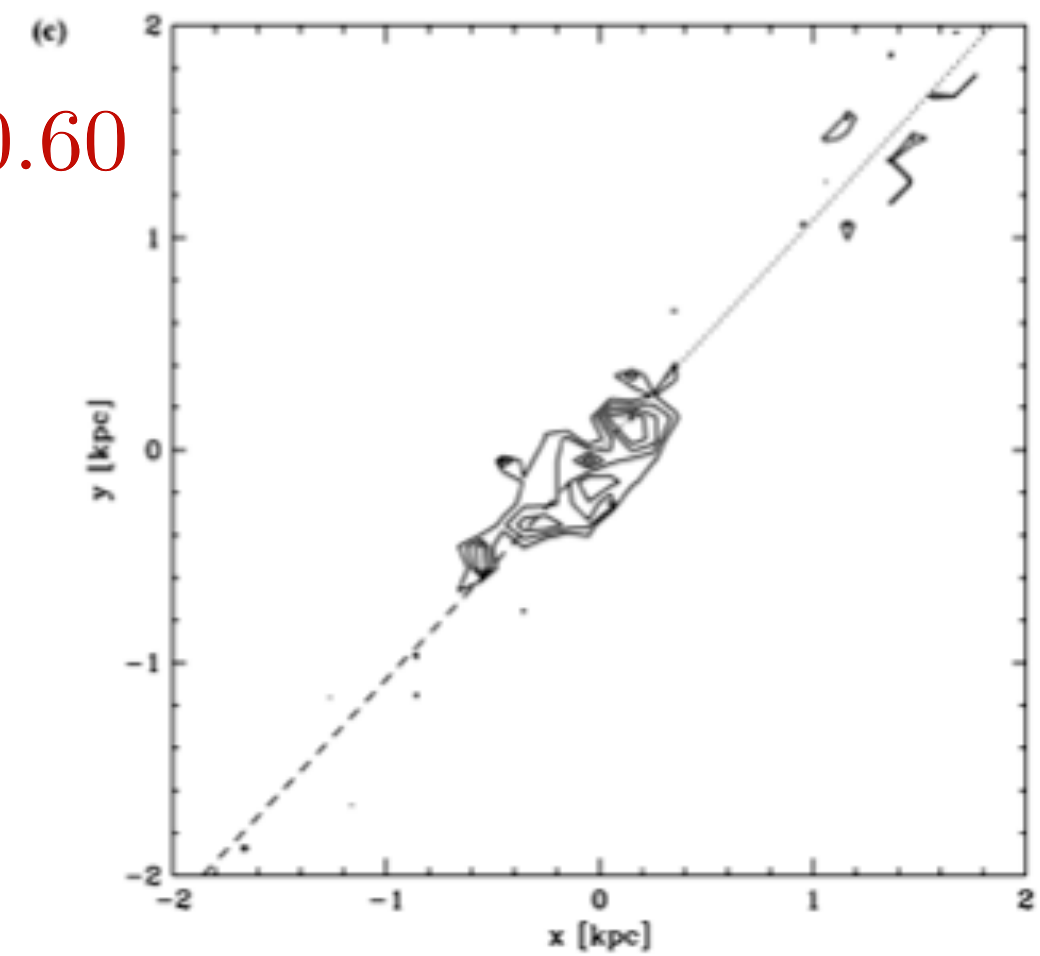
(Kroupa 1997)

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

$e = 0.74$



$e = 0.60$



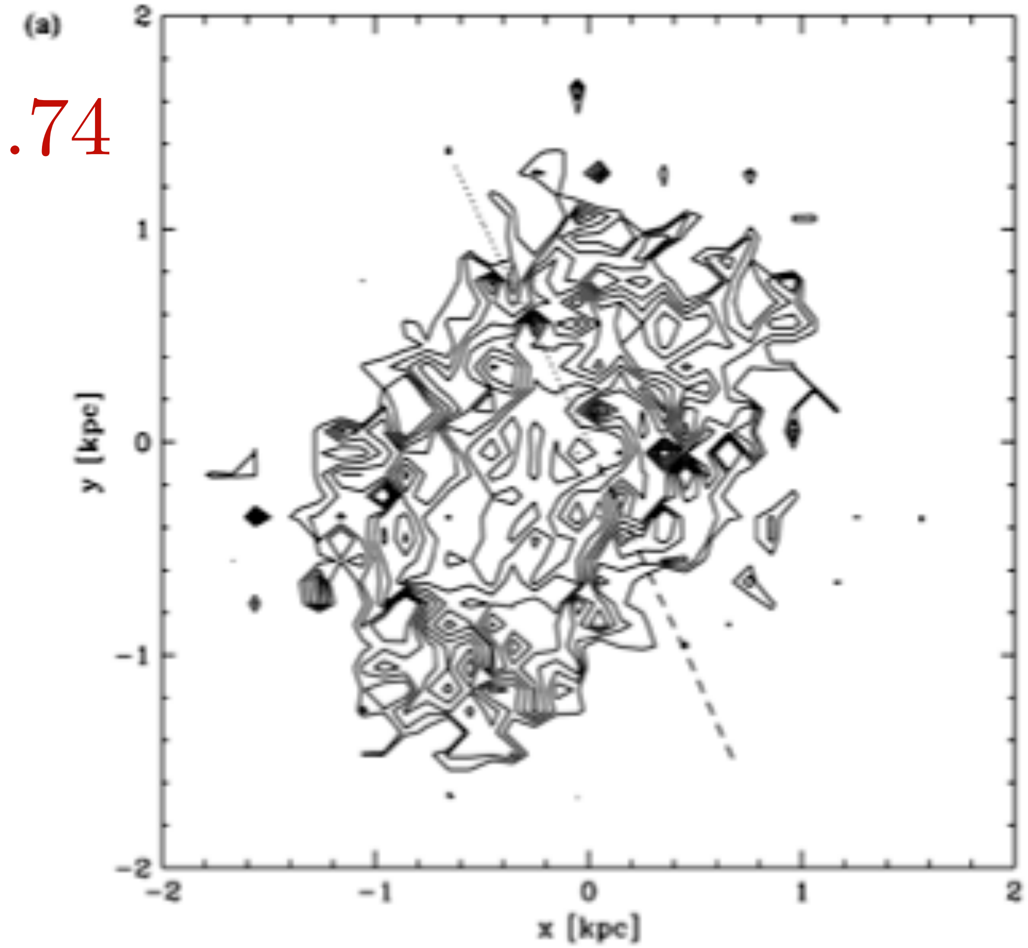
(Kroupa 1997)

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

$R \approx$ few 100 pc

and $\boxed{\dfrac{M}{L} \approx 10^{2-3}\ !}$

$e = 0.74$



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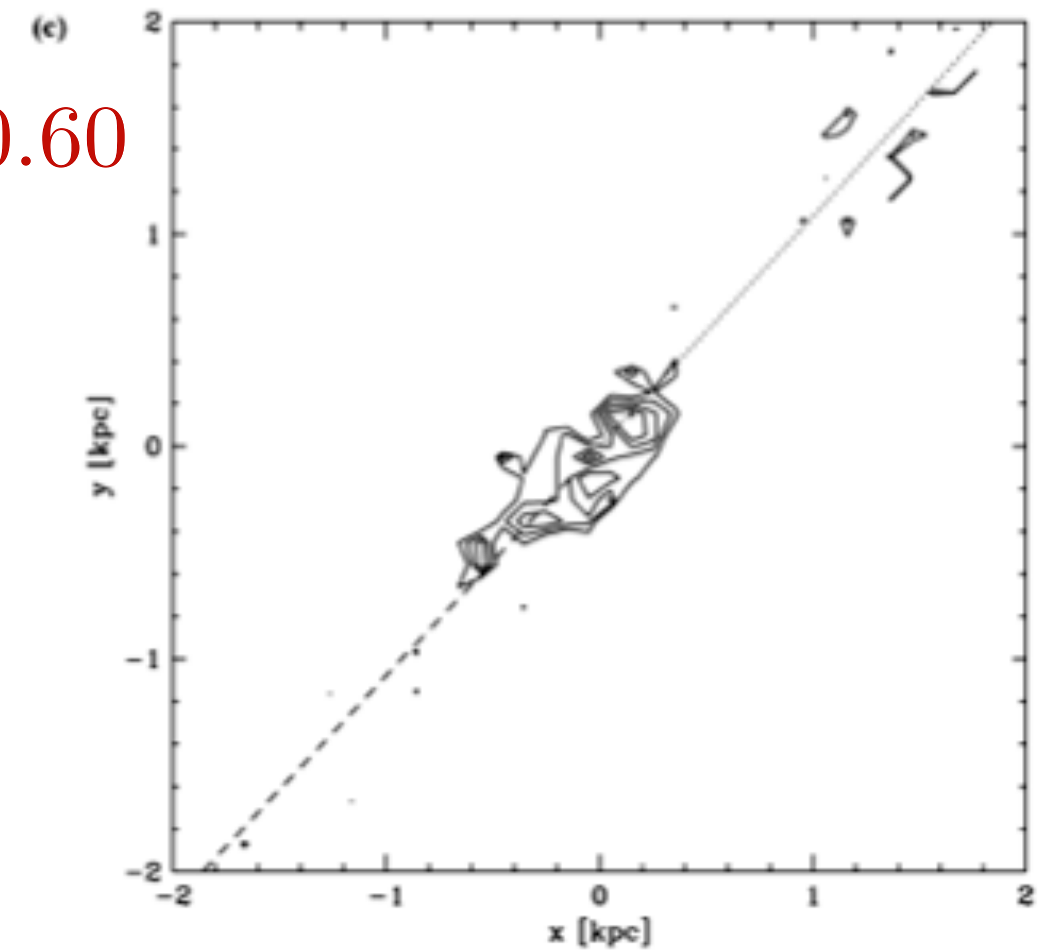
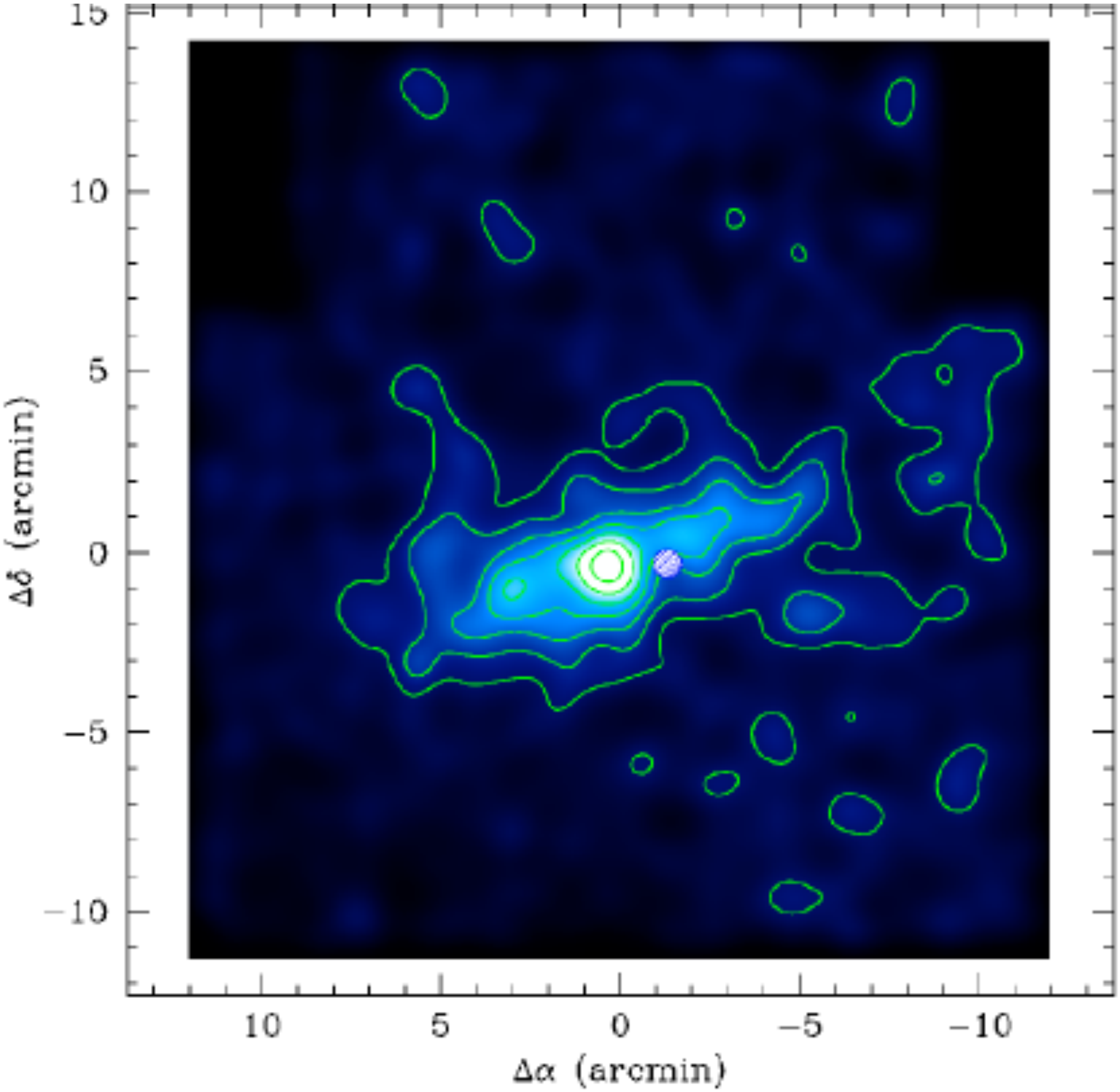


No evidence that TDGs dissolve,

and

predictions become successful !



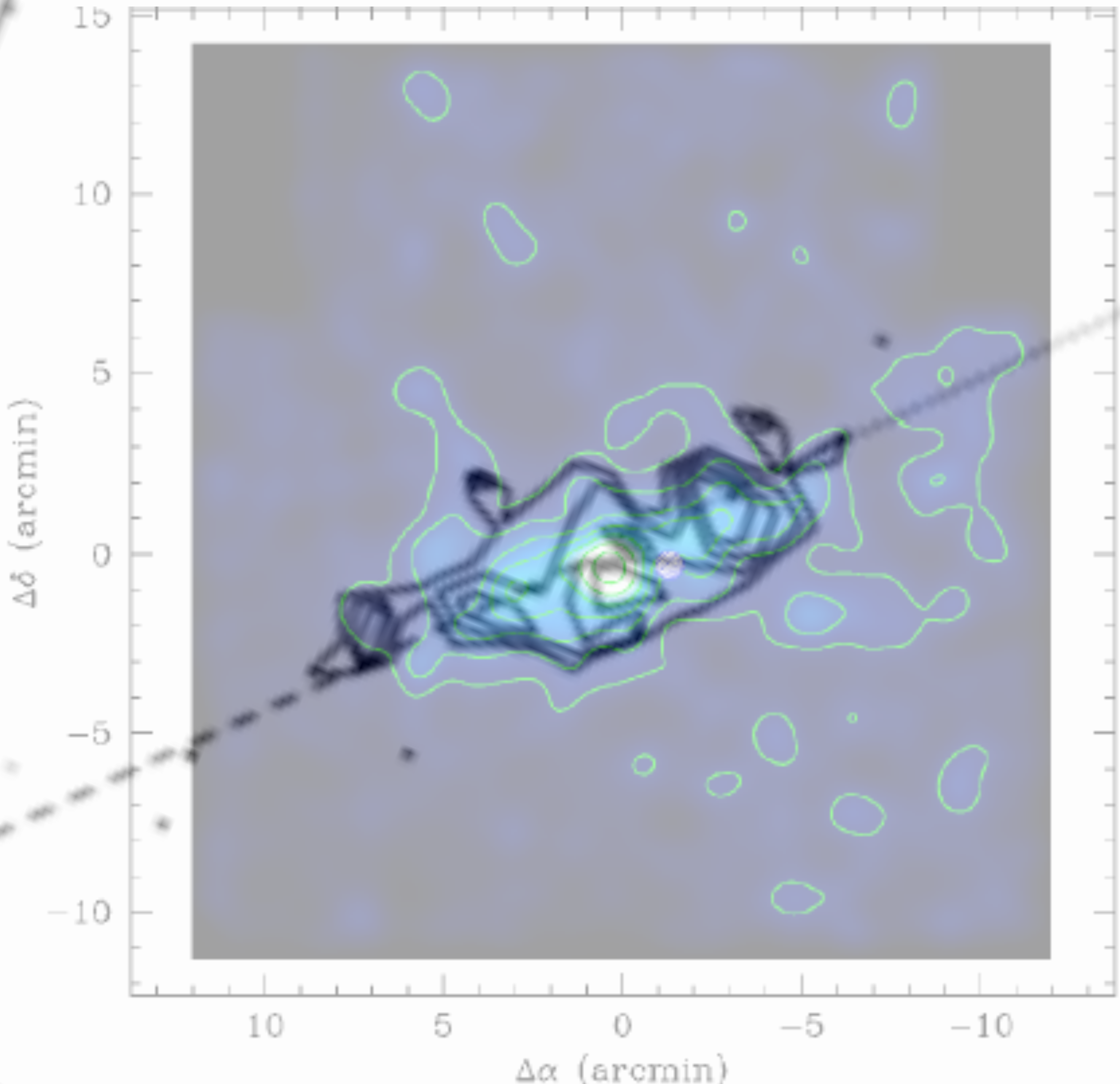
Hercules

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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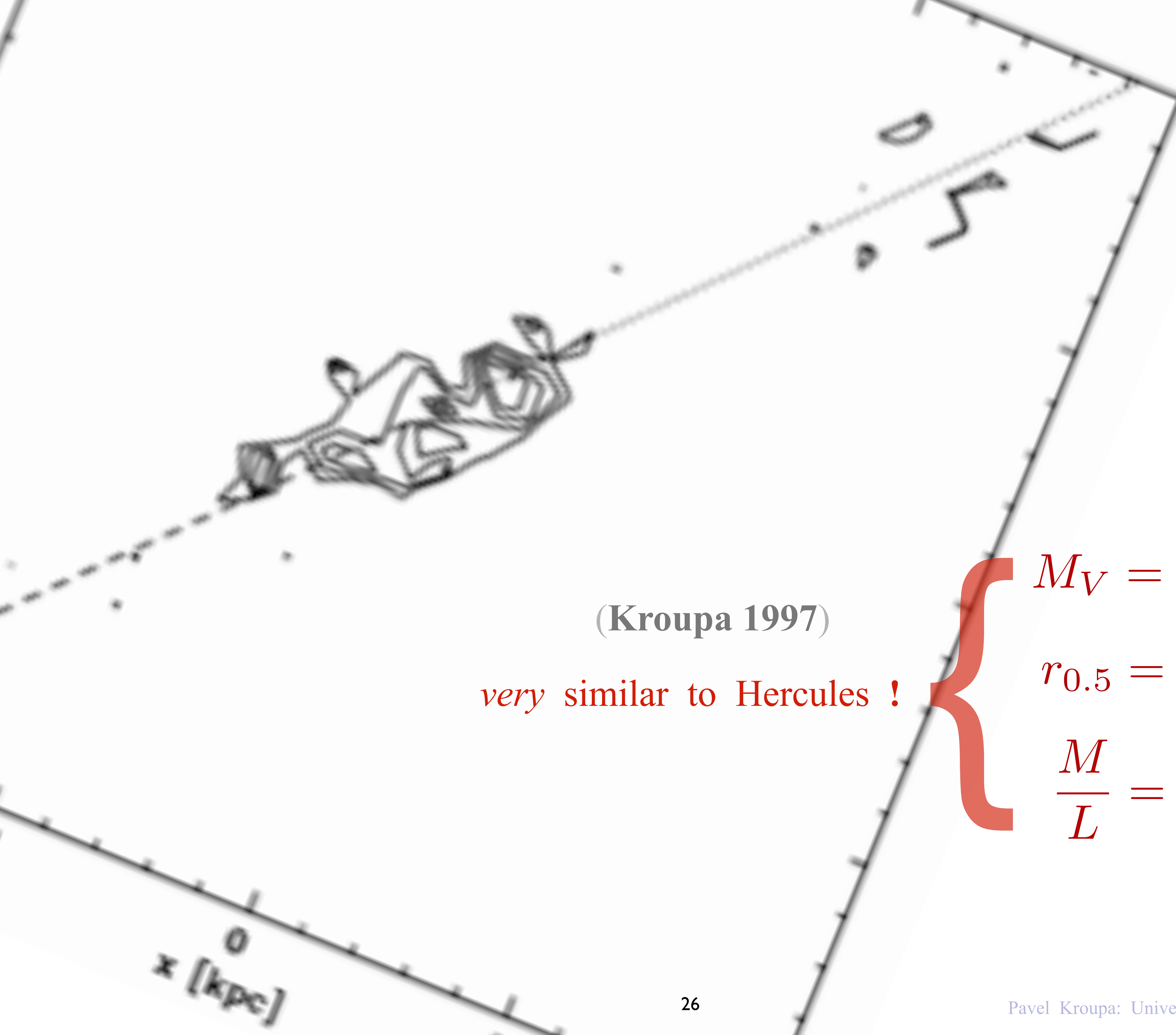


(**Kroupa 1997**)

very similar to Hercules !

$$\left\{ \begin{array}{l} M_V = -9\,\mathrm{mag} \\ r_{0.5} = 180\,\mathrm{pc} \\ \dfrac{M}{L} = 10^{2.3} \end{array} \right.$$

This is a

real prediction

10 years before

the discovery

of this

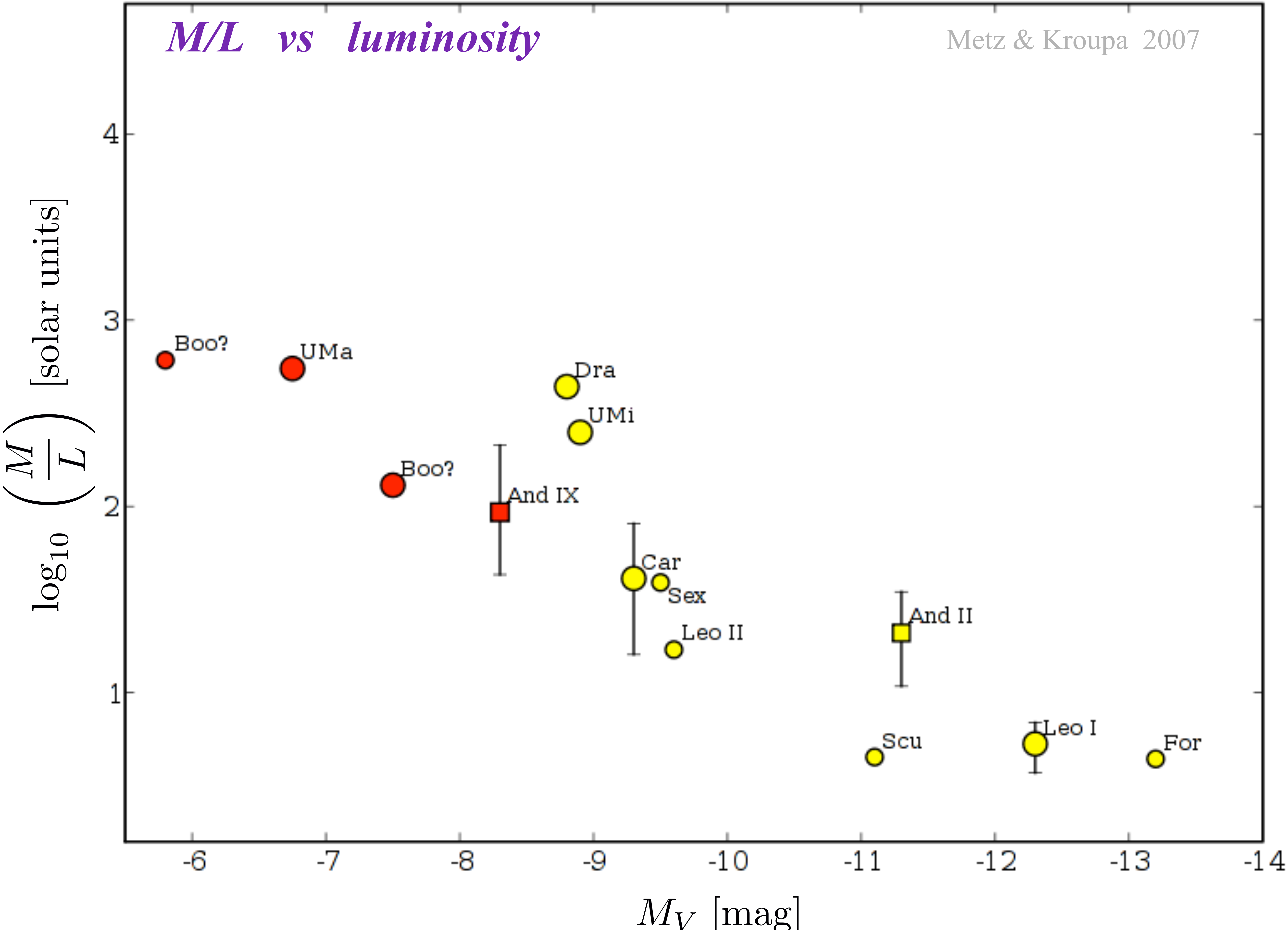
type of celestial object !

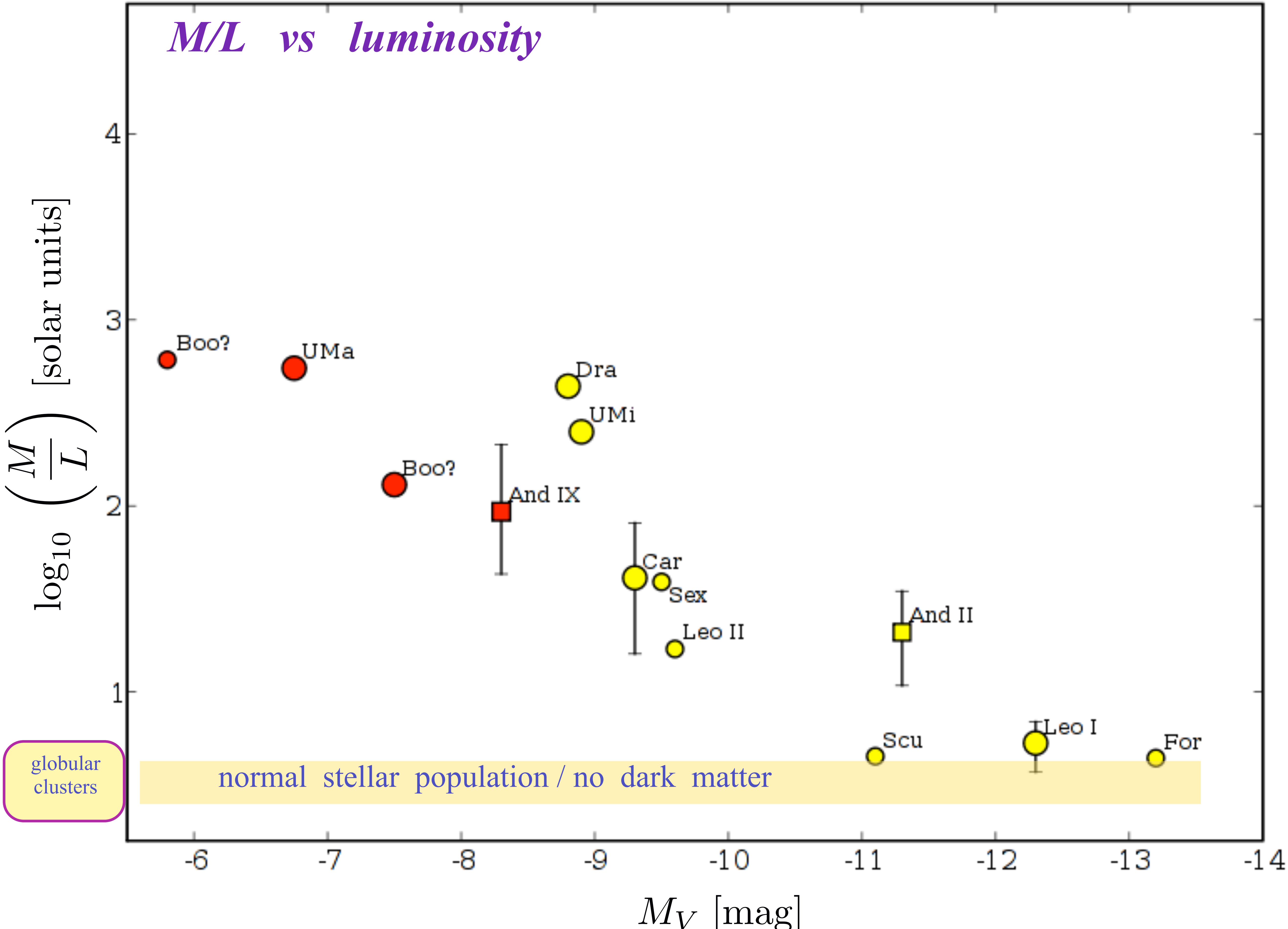
(see also Fellhauer et al.)

For the young scientists:

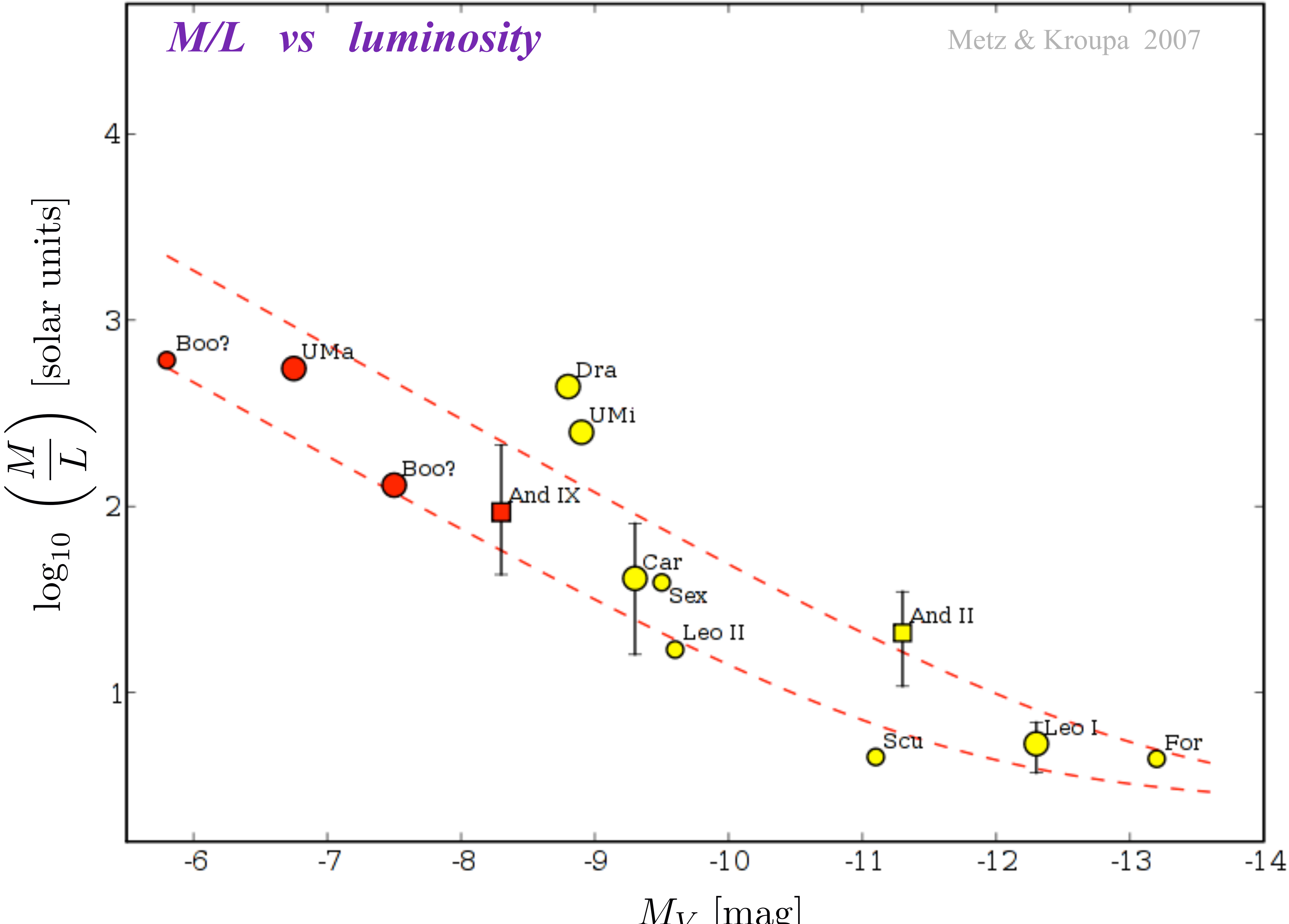
It is not so clear whether the SMoC ever predicted anything of success !

M/L vs luminosity

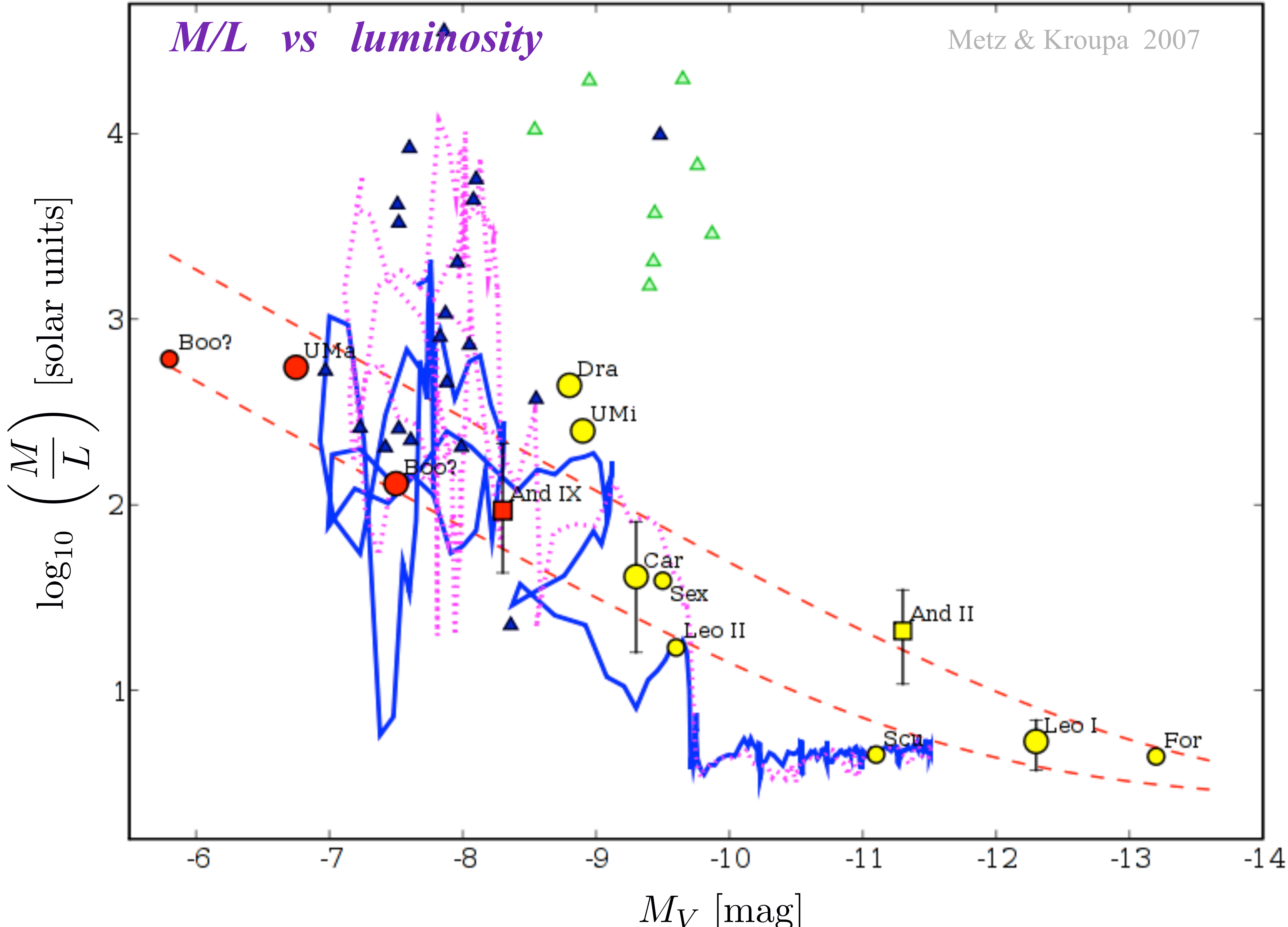




Pavel Kroupa: AIfA, University of Bonn



M/L vs luminosity
Metz & Kroupa 2007
Boo?
UMa
Dra
UMi
Boo?
And IX
Car
Sex
Leo II
And II
Scu
Leo I
For
$\log_{10}\left(\frac{M}{L}\right)$ [solar units]
M_V [mag]
4
3
2
1
-6
-7
-8
-9
-10
-11
-12
-13
-14



Pavel Kroupa: AIfA, University of Bonn

. . . once we leave the
framework of dark matter,
things brighten up :

one obtains
full predictability

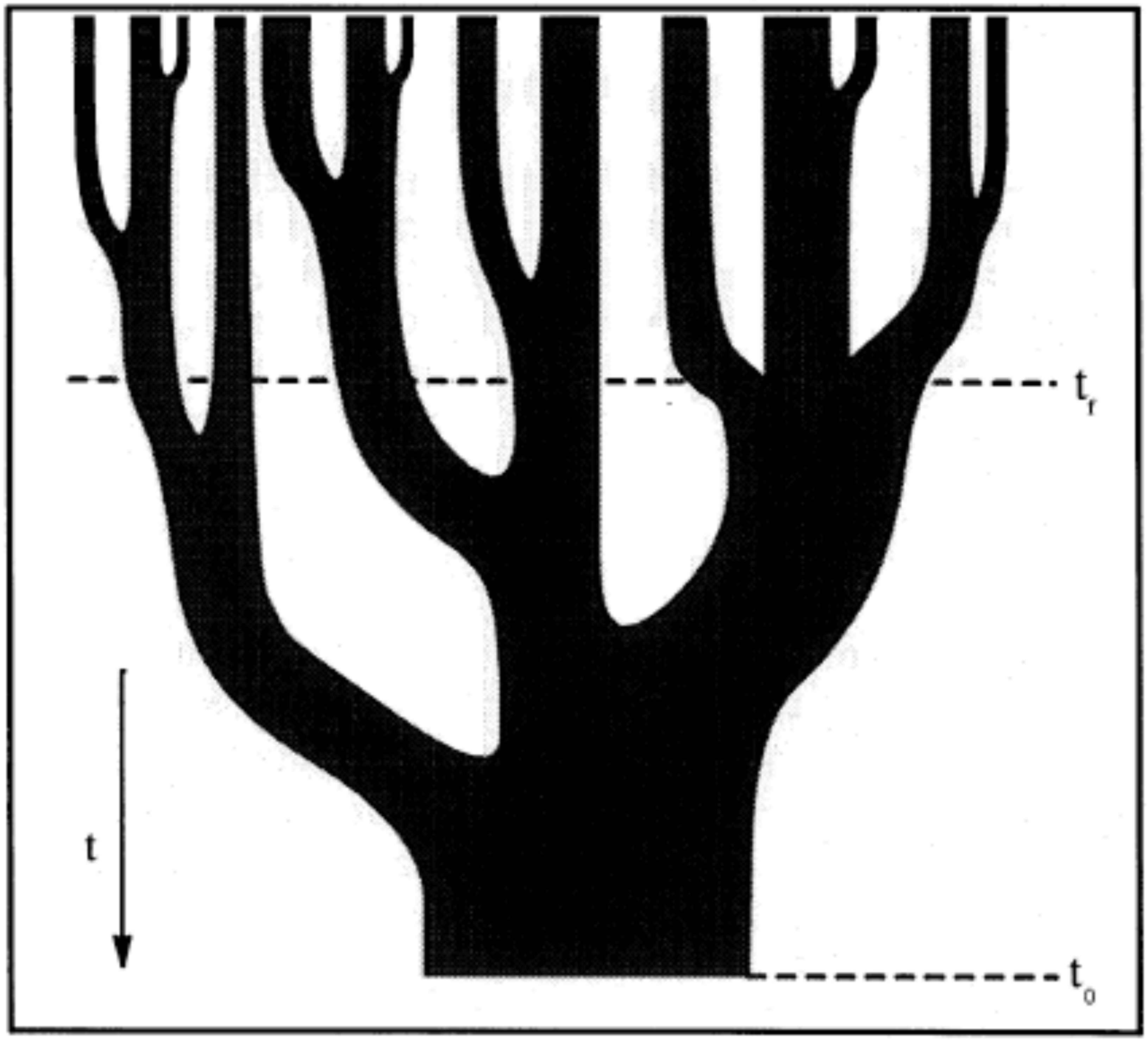
And, there is
no existing evidence
that TDGs dissolve

How many TDGs are expected in the SMoC?

Okazaki & Taniguchi (2000) :

The galaxy interaction scheme proposed by Silk & Norman (1981)

(Lacey & Cole 1993)



Okazaki & Taniguchi (2000, ApJ)

"Dwarf galaxy formation induced by galaxy interactions"

TABLE 1

MERGER SCHEME

Scheme	Collision	Parameter	Result
1	Sp + Sp		S0 + k_1 dEs
2	Sp + S0	a	E + k_2 dEs
		$1 - a$	S0 + S0 + k_3 dEs
3	S0 + S0	b	E + k_4 dEs
		$1 - b$	S0 + S0 + k_5 dEs

NOTE.—In this scheme, a merger between two spiral galaxies evolves not into an elliptical galaxy but into an S0 one. The reason for this is as follows: It is widely accepted that elliptical-like products are formed by dissipationless collapse. Mergers between gas-rich spiral galaxies can achieve a similar physical condition in their final phase. However, if the star formation timescale is longer significantly than the dynamical timescale, the remaining gas will settle to a disk and then the end product will not become an elliptical-like galaxy. This is confirmed by analytical and numerical methods.

Based on the above assumption, we obtain a set of kinetic equations for morphological-type evolution as a consequence of galaxy interactions in the following form:

$$\frac{1}{\gamma}\frac{dn_{\mathrm{Sp}}}{dt} = -2n_{\mathrm{Sp}}^2 - n_{\mathrm{S0}}\, n_{\mathrm{Sp}} , \qquad (1)$$

$$\frac{1}{\gamma}\frac{dn_{\mathrm{S0}}}{dt} = n_{\mathrm{Sp}}^2 + (1-2a)n_{\mathrm{Sp}}\, n_{\mathrm{S0}} - 2bn_{\mathrm{S0}}^2 , \qquad (2)$$

$$\frac{1}{\gamma}\frac{dn_{\mathrm{E}}}{dt} = bn_{\mathrm{S0}}^2 + an_{\mathrm{S0}}\, n_{\mathrm{Sp}} , \qquad (3)$$

$$\frac{1}{\gamma}\frac{dn_{\mathrm{dE}}}{dt} = k_1 n_{\mathrm{Sp}}^2 + [k_2 a + k_3(1-a)]n_{\mathrm{S0}}\, n_{\mathrm{Sp}} + [k_4 b + k_5(1-b)]n_{\mathrm{S0}}^2 , \qquad (4)$$

where n_{Sp}, n_{S0}, n_{E}, and n_{dE} are the number densities of spirals, S0s, ellipticals, and dwarfs, respectively, γ is the mean collision rate, and k_i ($i = 1$–5) is the number of dwarfs formed by one collision in each case. Note that the first three equations are the same as those in SN81.

Okazaki & Taniguchi (2000) :

The galaxy interaction scheme proposed by Silk & Norman (1981)

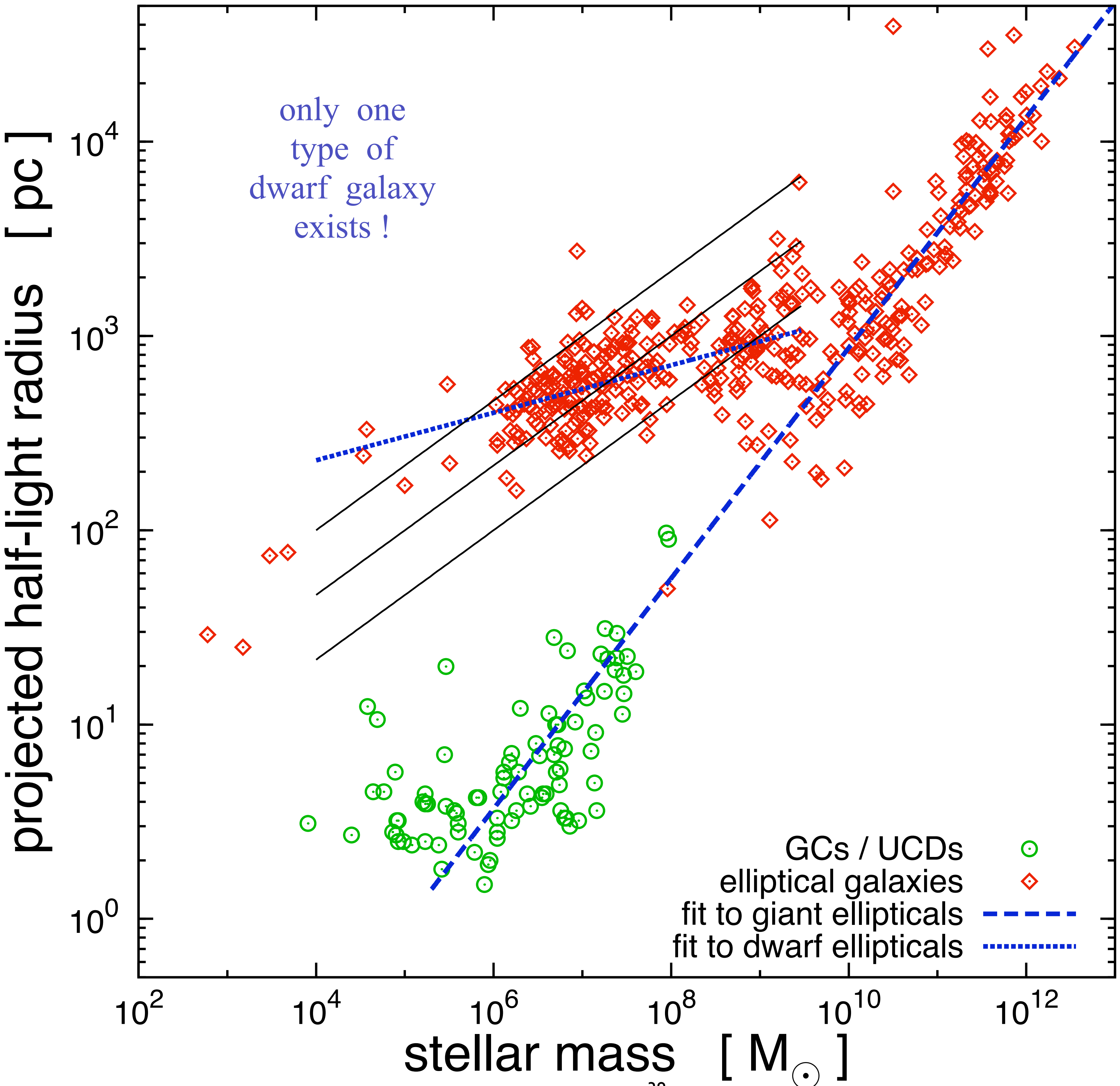
"can be *responsible for the observed numbers of dEs* in the various environs from poor groups of galaxies to the usual rich clusters of galaxies. The *formation rate of long-lived TDGs* is estimated to be *1–2 in each galaxy interaction*."

i.e. *standard cosmology* inherently means ***all dE's*** to be ***TDGs***

But note, N_{TDG} *scales with gas content* and thus evolutionary status / cosmological epoch of interacting galaxies (*many more formed in the past*).

Pressure / random-motion supported stellar systems

Dabringhausen et al. 2012



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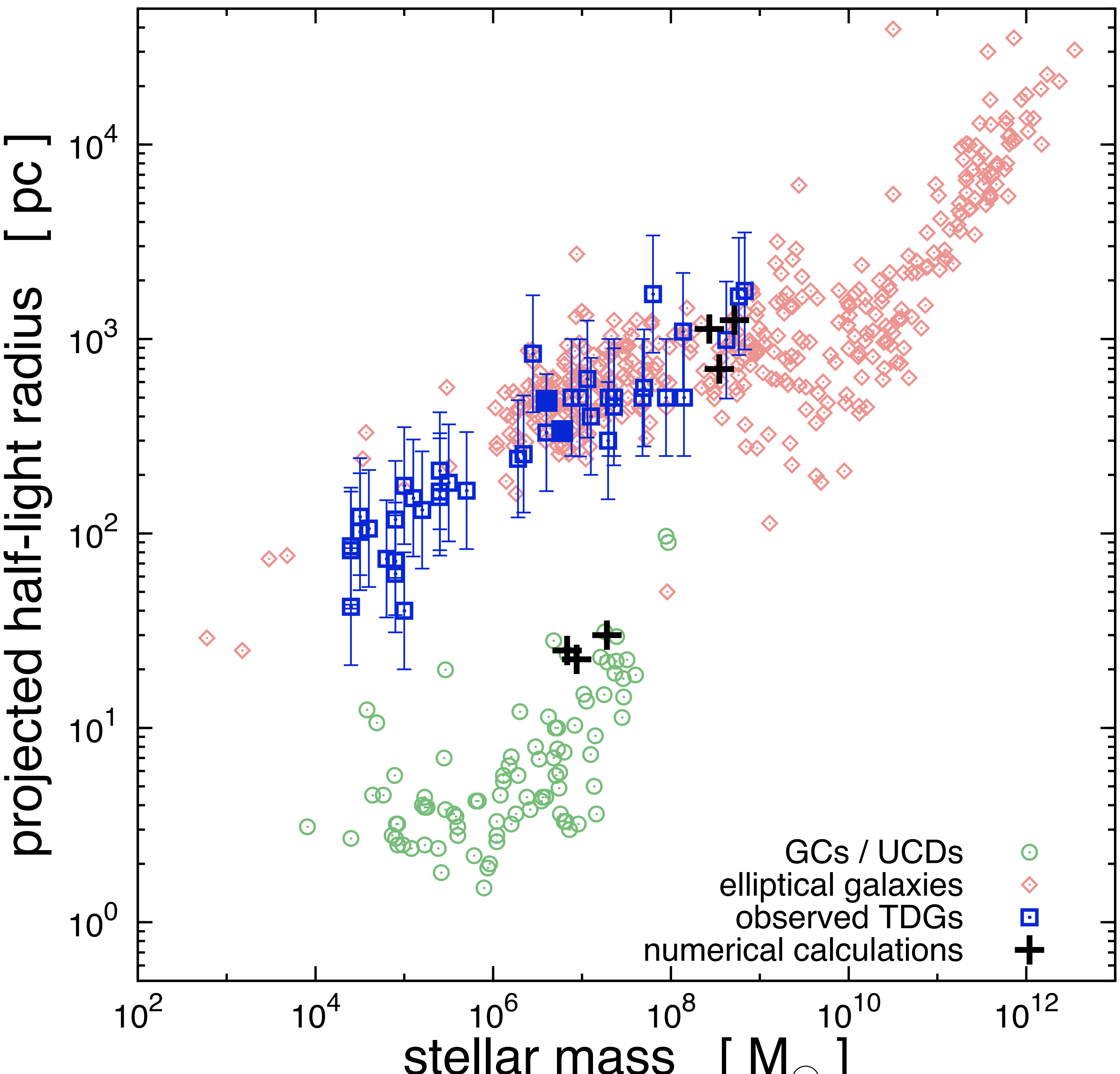


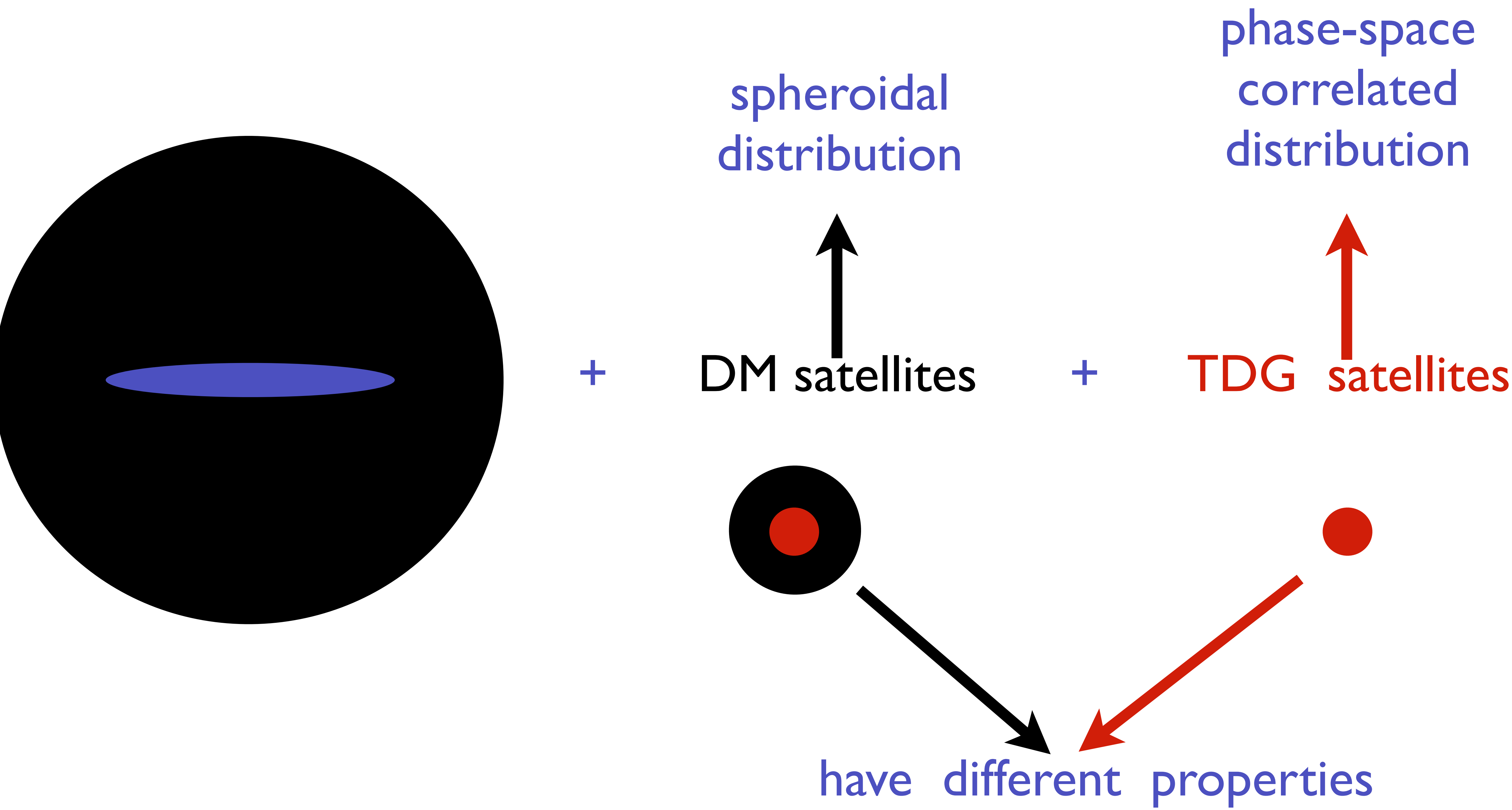
TDGs coincide with dE / dSph satellites

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

Therefore

if the SMoC is valid
then . . .

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 $\Longrightarrow$ $\exists$ Type A dwarfs $\wedge$ Type B dwarfs

Kroupa 2012, 2015

with Dark Matter (DM) — TDGs w/o DM

spheroidal distribution — correlated in phase-space

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 **?**

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

(no role of baryonic physics on these scales)

MW satellites are in a disk-like configuration:

(Kroupa, Theis & Boily 2005)

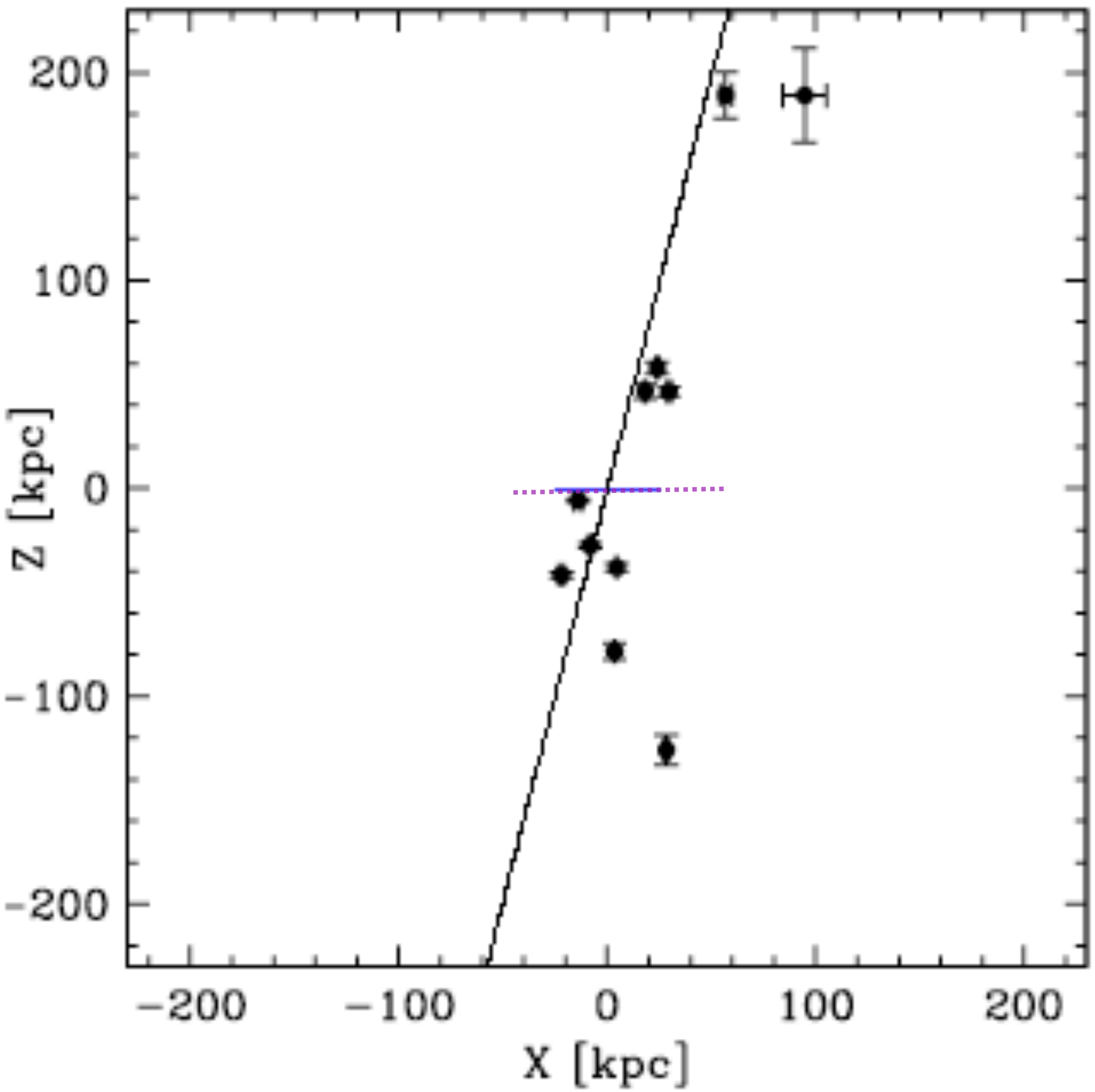
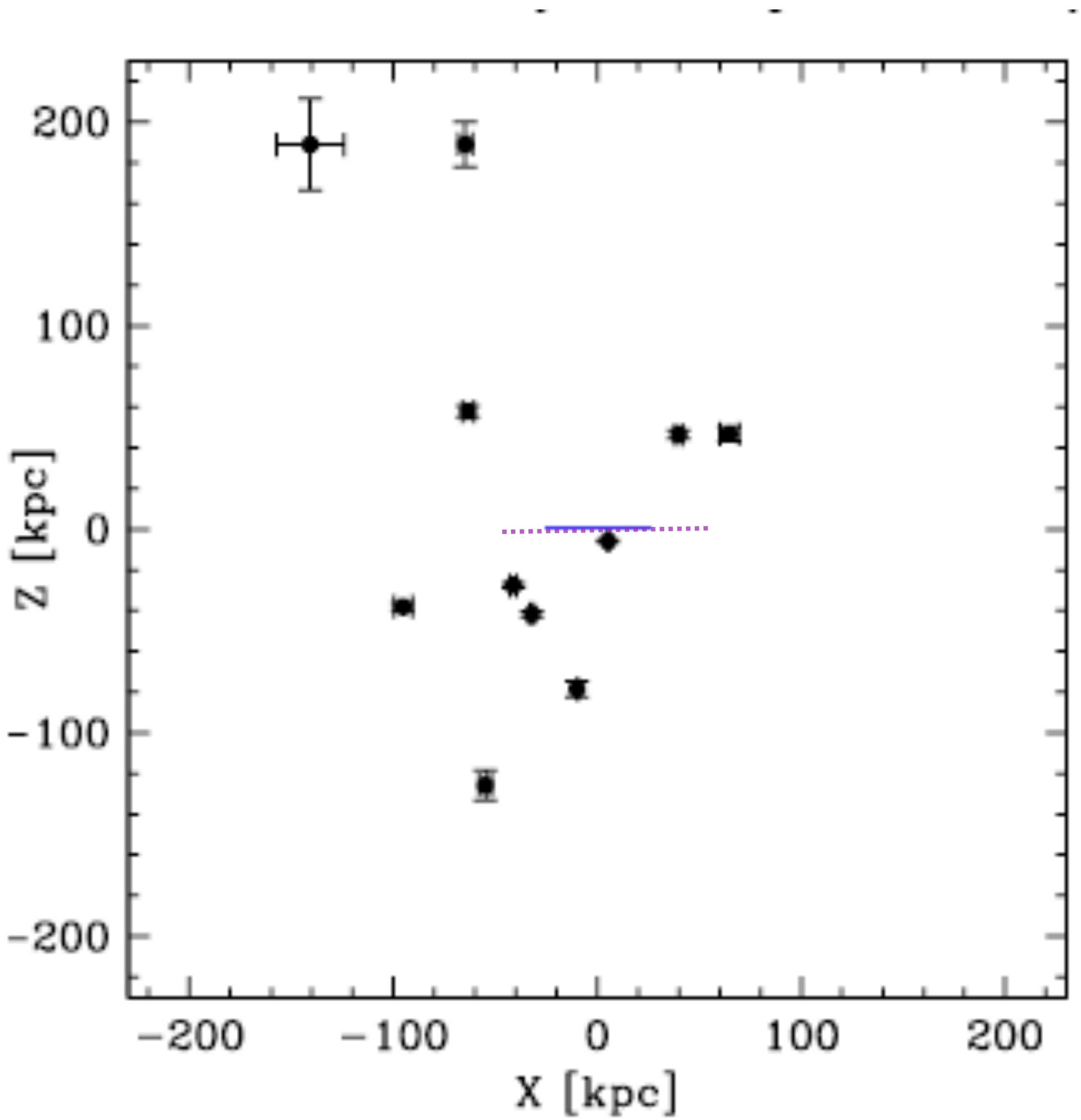


Fig. 1. The position of the innermost 11 MW satellites (Table 1) as viewed from a point located at infinity and $l = 167^\circ.91$. The MW disk is indicated by the horizontal line $-25 \leq X/\text{pc} \leq 25$, and the centre of the coordinate system lies at the Galactic centre. The dashed line marks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

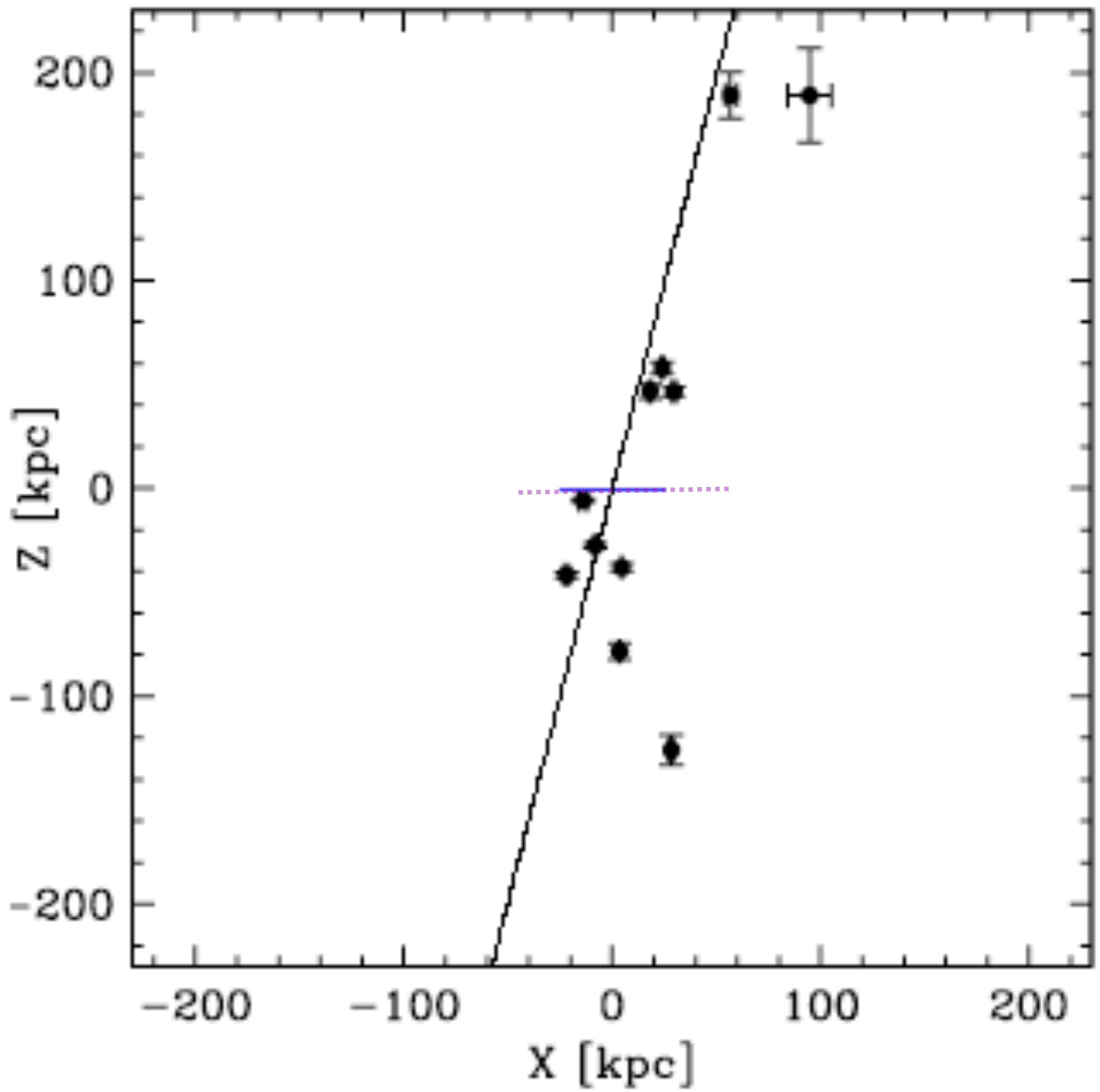
MW satellites are in a disk-like configuration:



(Kroupa, Theis & Boily 2005)

==> incompatible with expected spheroidal distribution

(Kroupa, Theis & Boily 2005)



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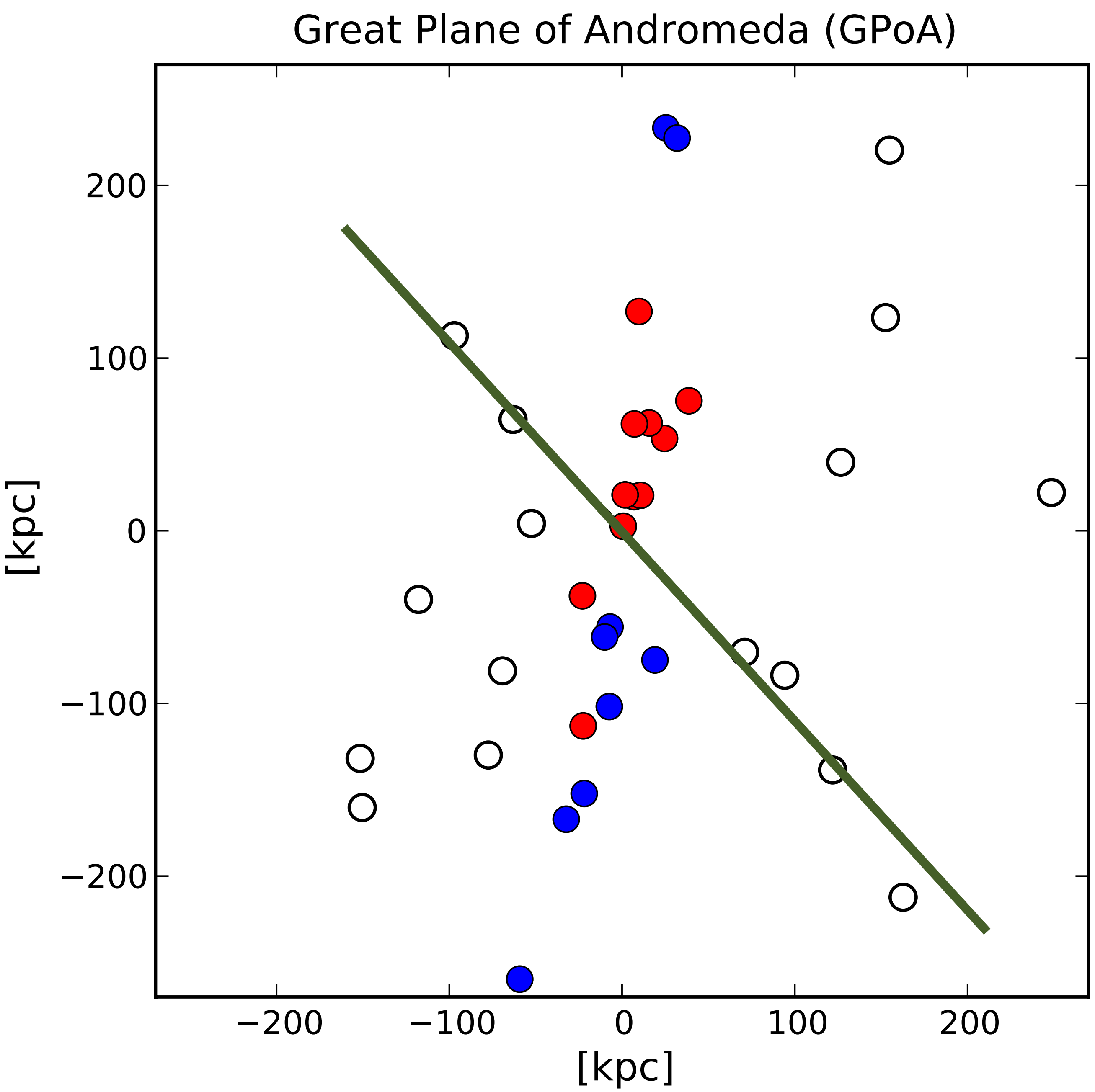
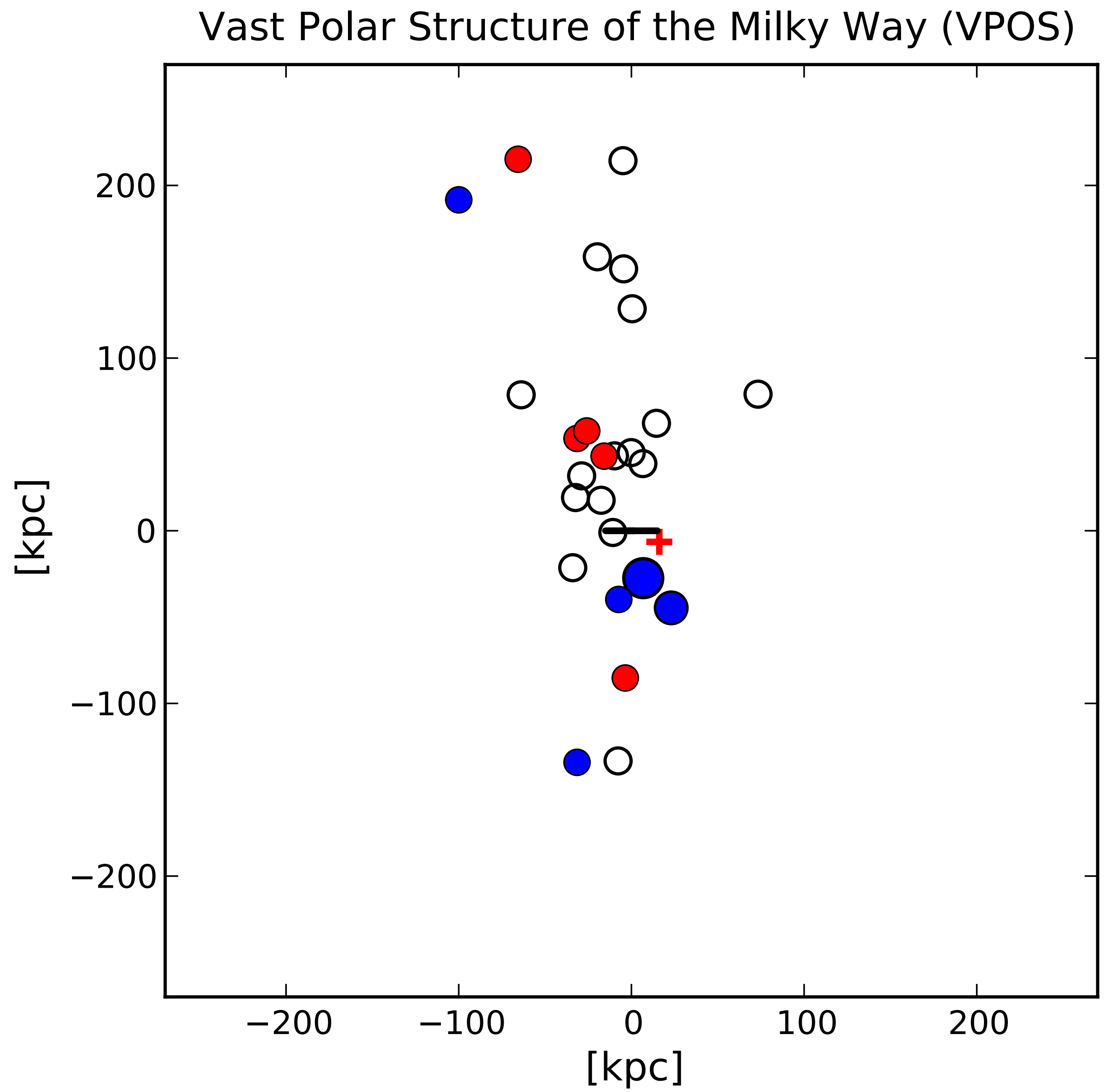
THE largest (*unsolvable*) problem
in the SMoC !

Andromeda

Milky Way





Ibata et al. 2013, 2014

Pawlowski & Kroupa 2013

Pawlowski, Kroupa & Jerjen (2013 MNRAS)

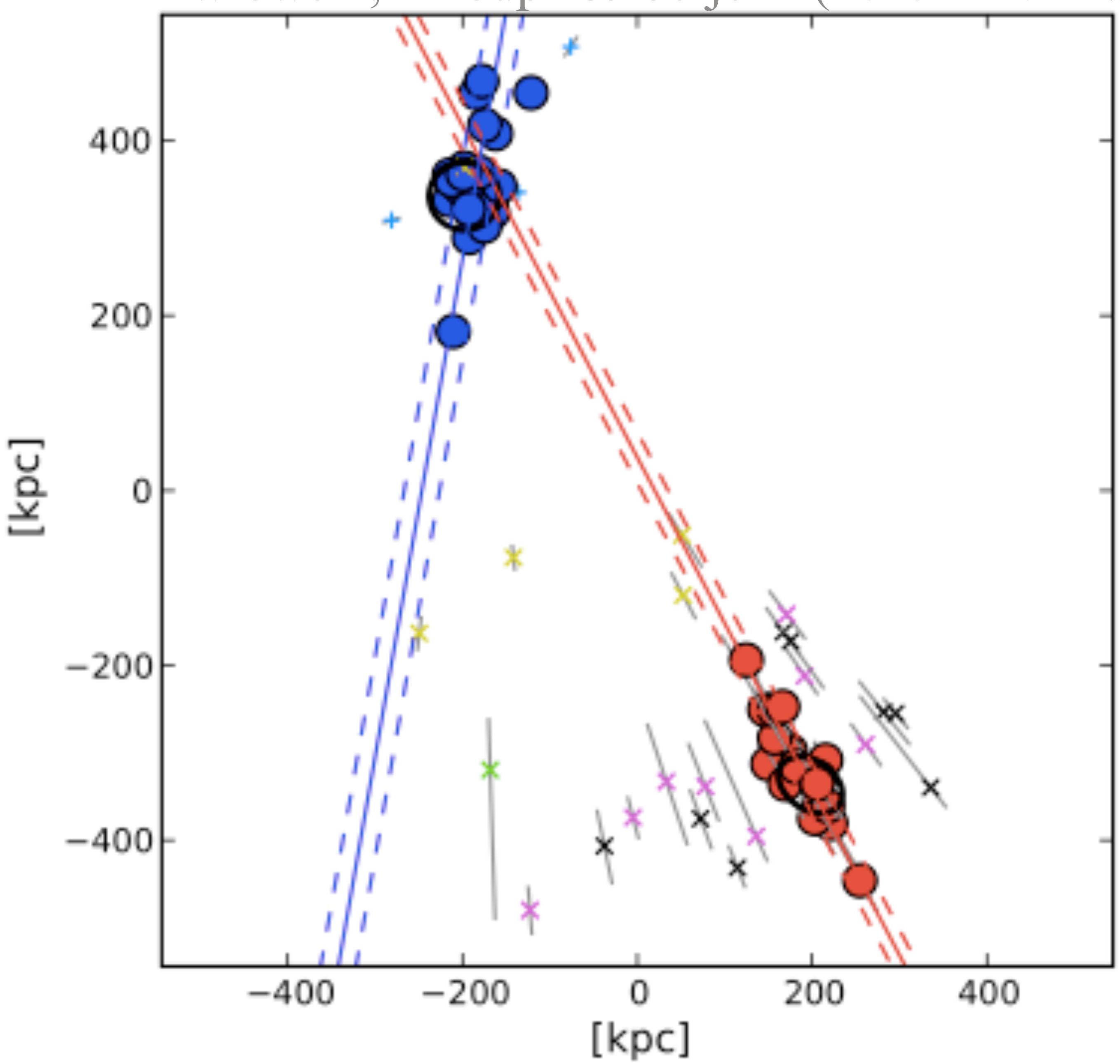


Figure 16. Edge-on view of the satellite galaxy planes around the MW and M31, similar to Fig. 9 for the LG planes. As before, galaxies which are

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

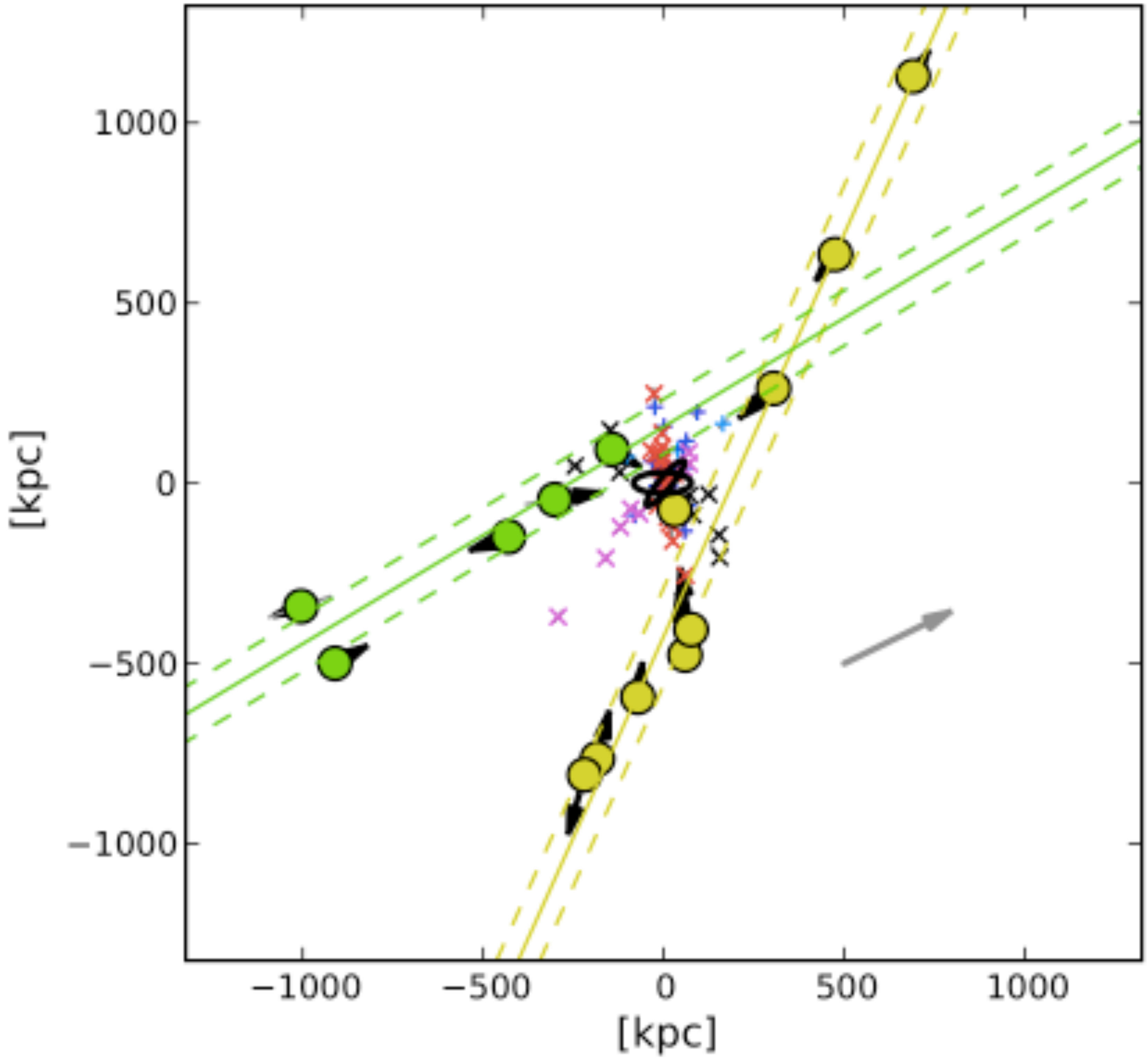


Figure 9. Edge-on view of both LG planes. The orientation of the MW and M31 are indicted as black ellipses in the centre. Members of the LGP1 are plotted as yellow points, those of LGP2 as green points. MW galaxies are plotted as plus signs (+), all other galaxies as crosses (×), the colours code their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

Pawlowski, Kroupa & Jerjen (2013 MNRAS)

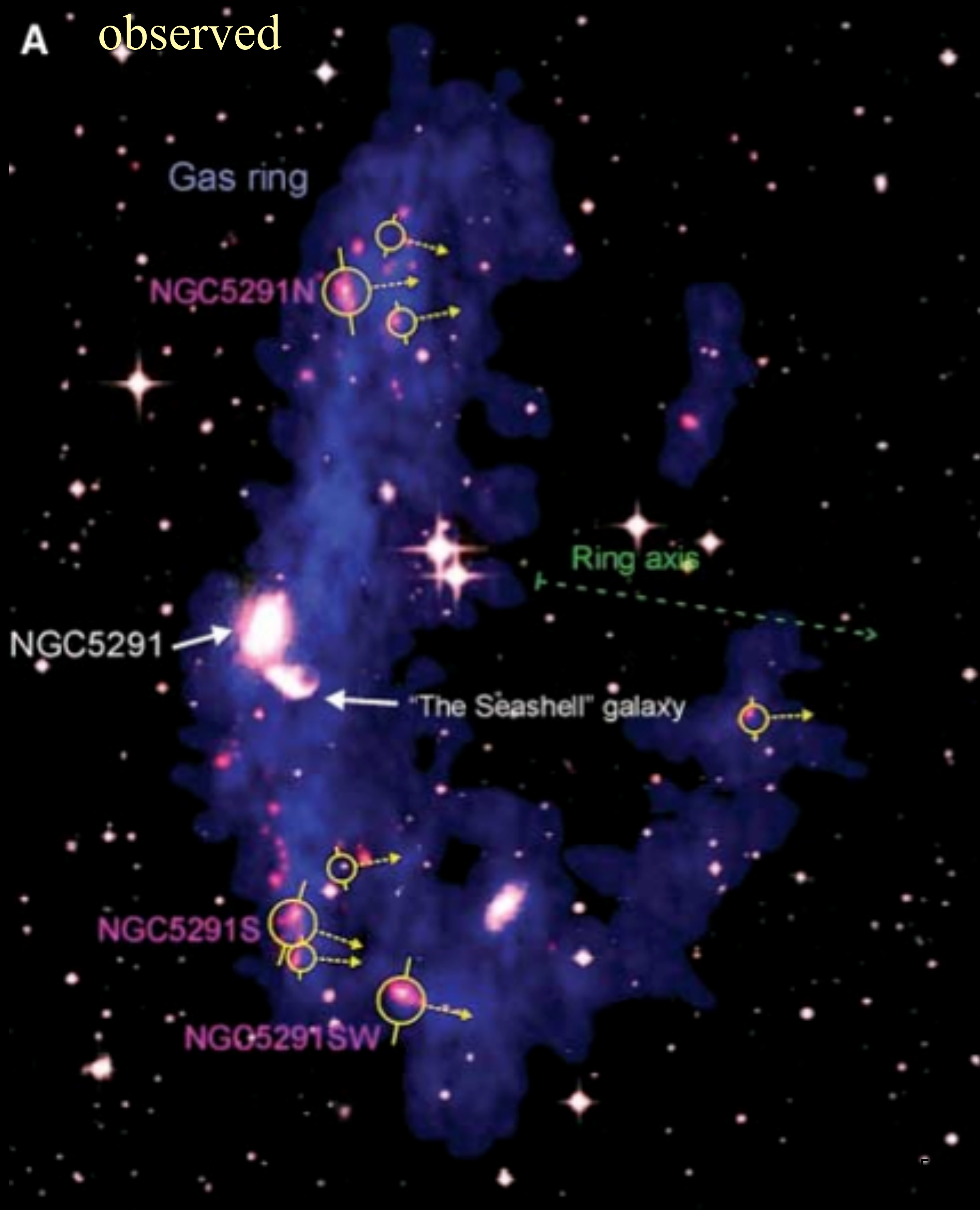
"The discovery of symmetric structures in the Local Group"

A frightening symmetry

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

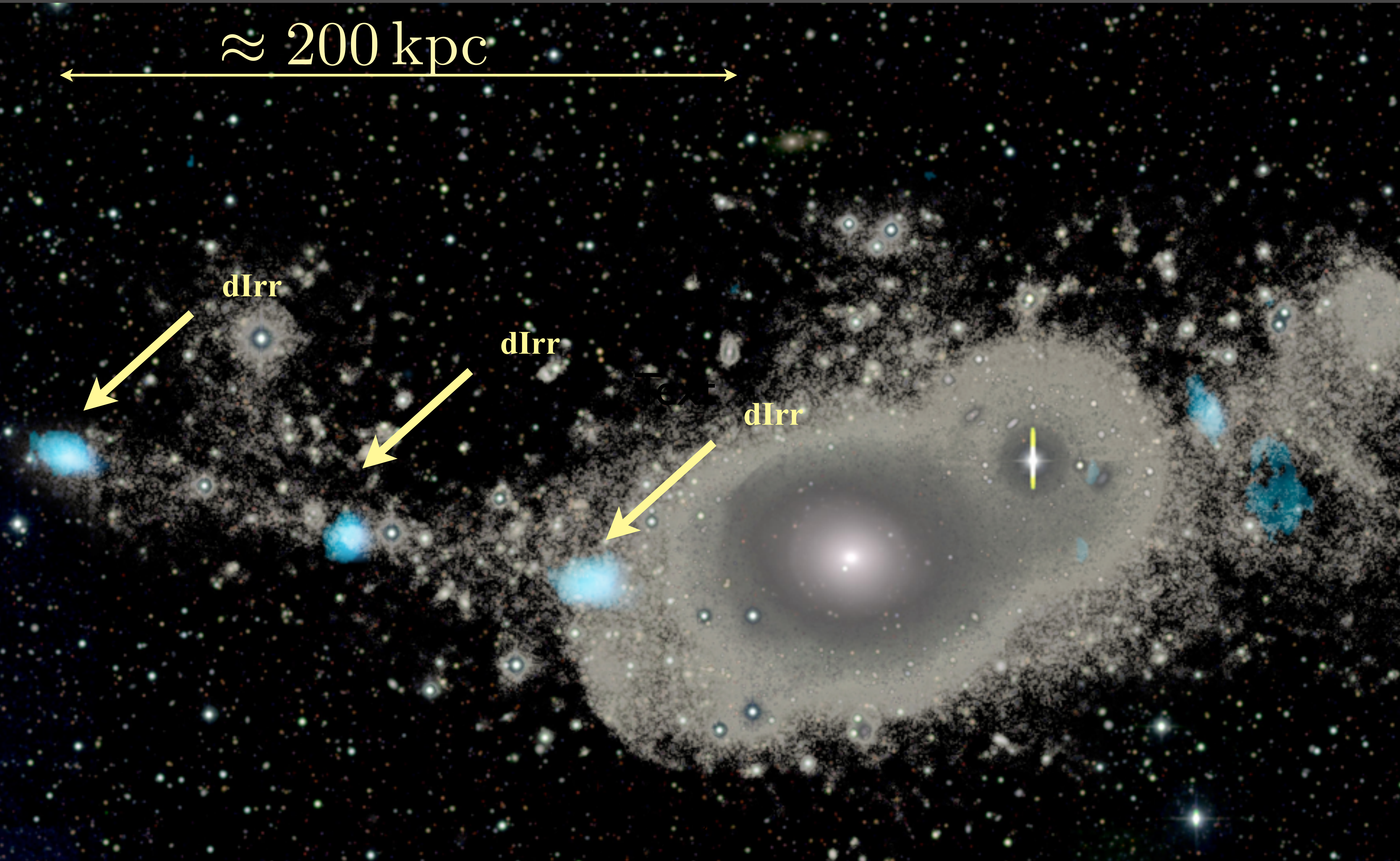
Are the Milky Way & Andromeda
unique or
extreme outliers ?

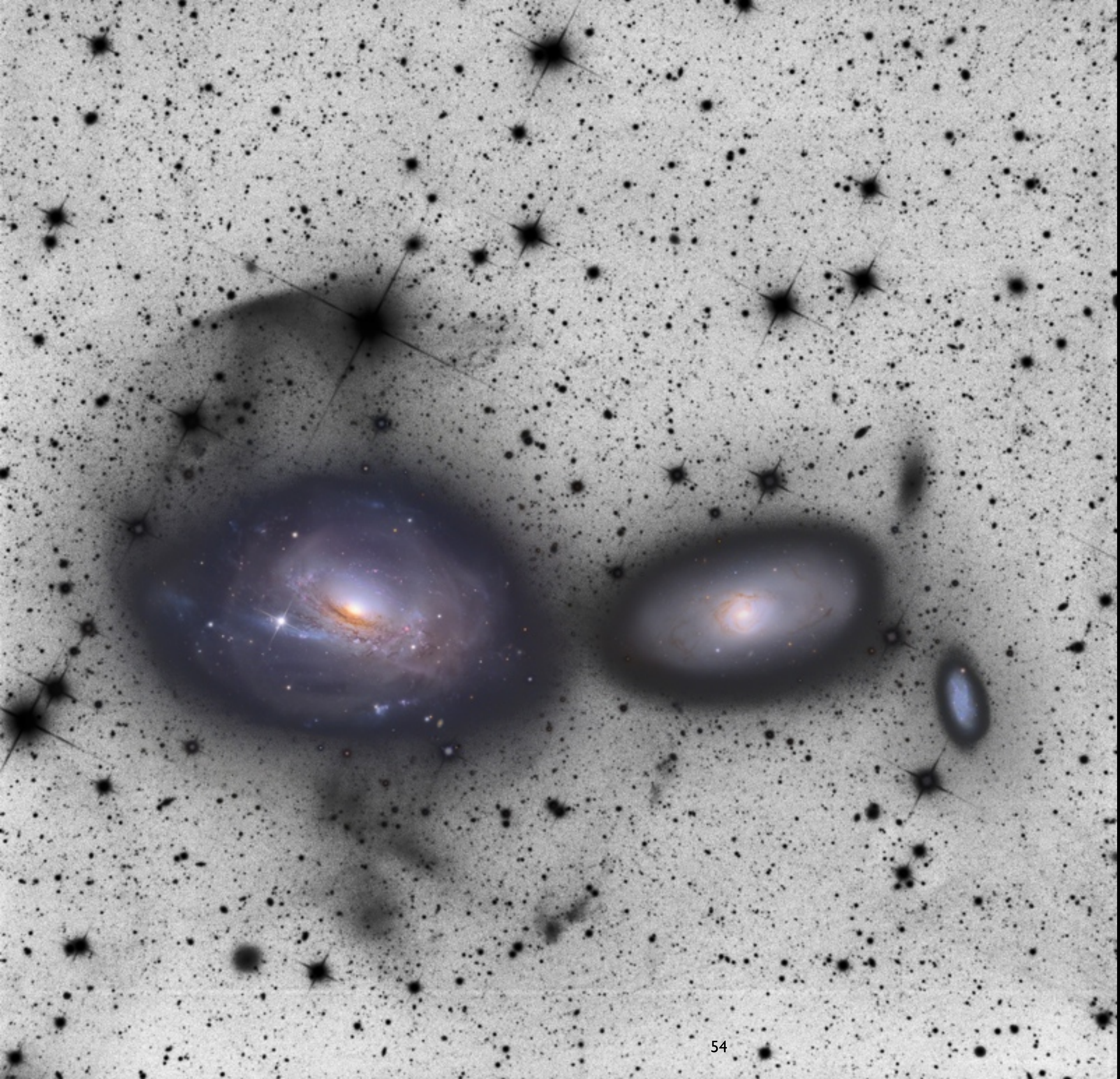
Bournaud et al. (2007, Science)



NGC 5557

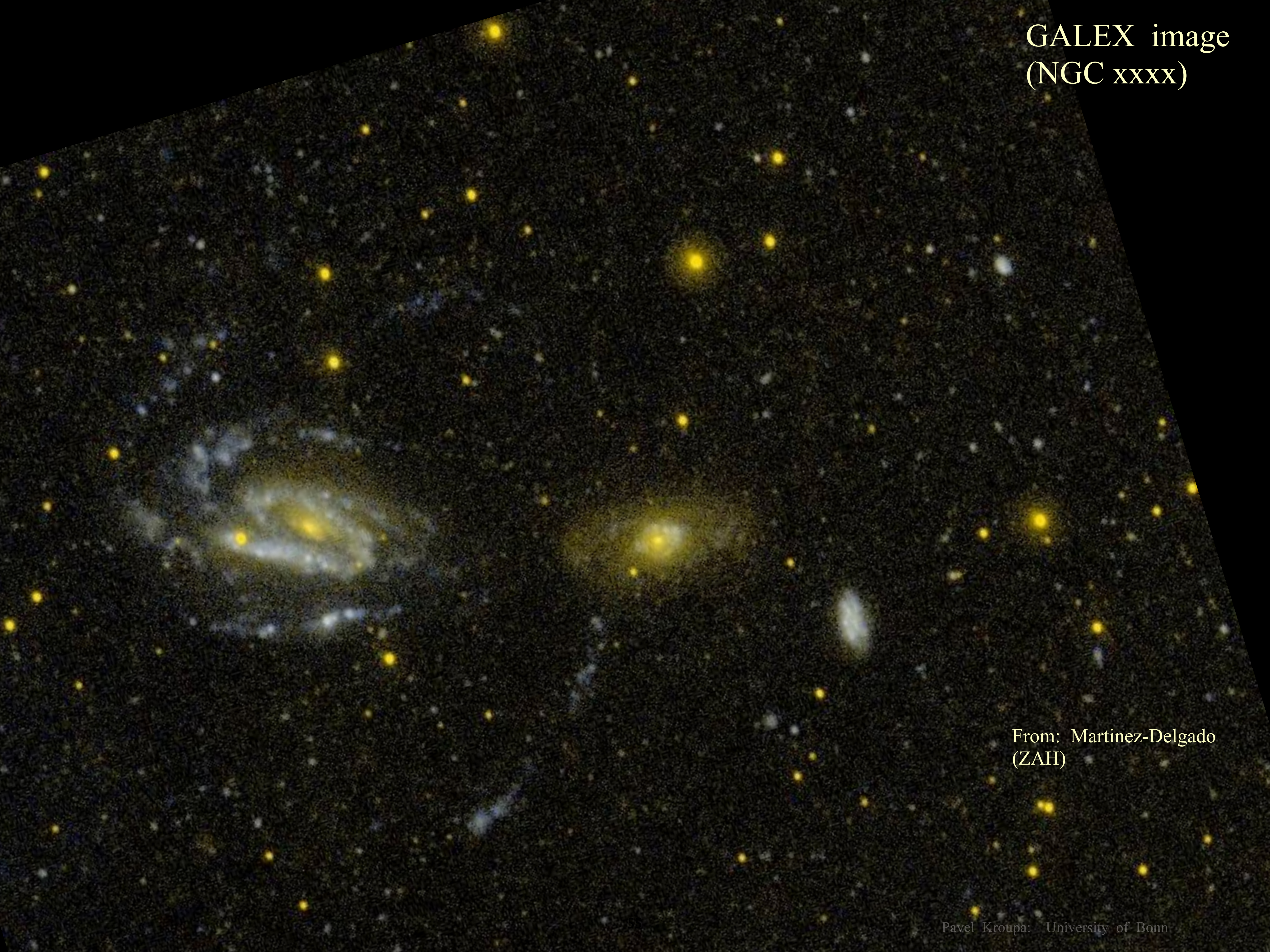
(post-interaction 2-3 Gyr)





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

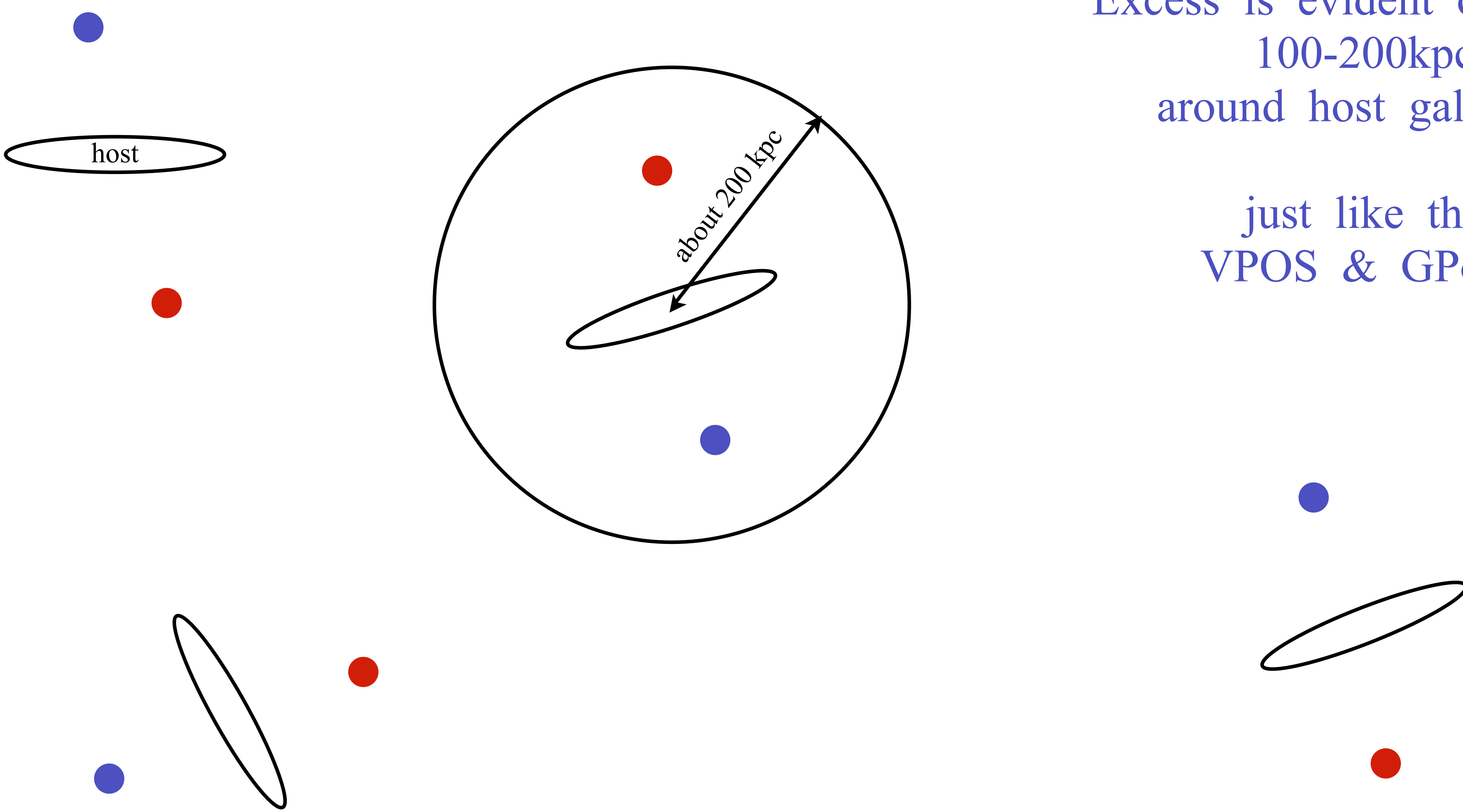
Credit: Martinez-Delgado (ZAH) and Adam Block (MtLemmon Obs)


GALEX image
(NGC xxxx)
From: Martinez-Delgado
(ZAH)
Pavel Kroupa: University of Bonn

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.

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~~

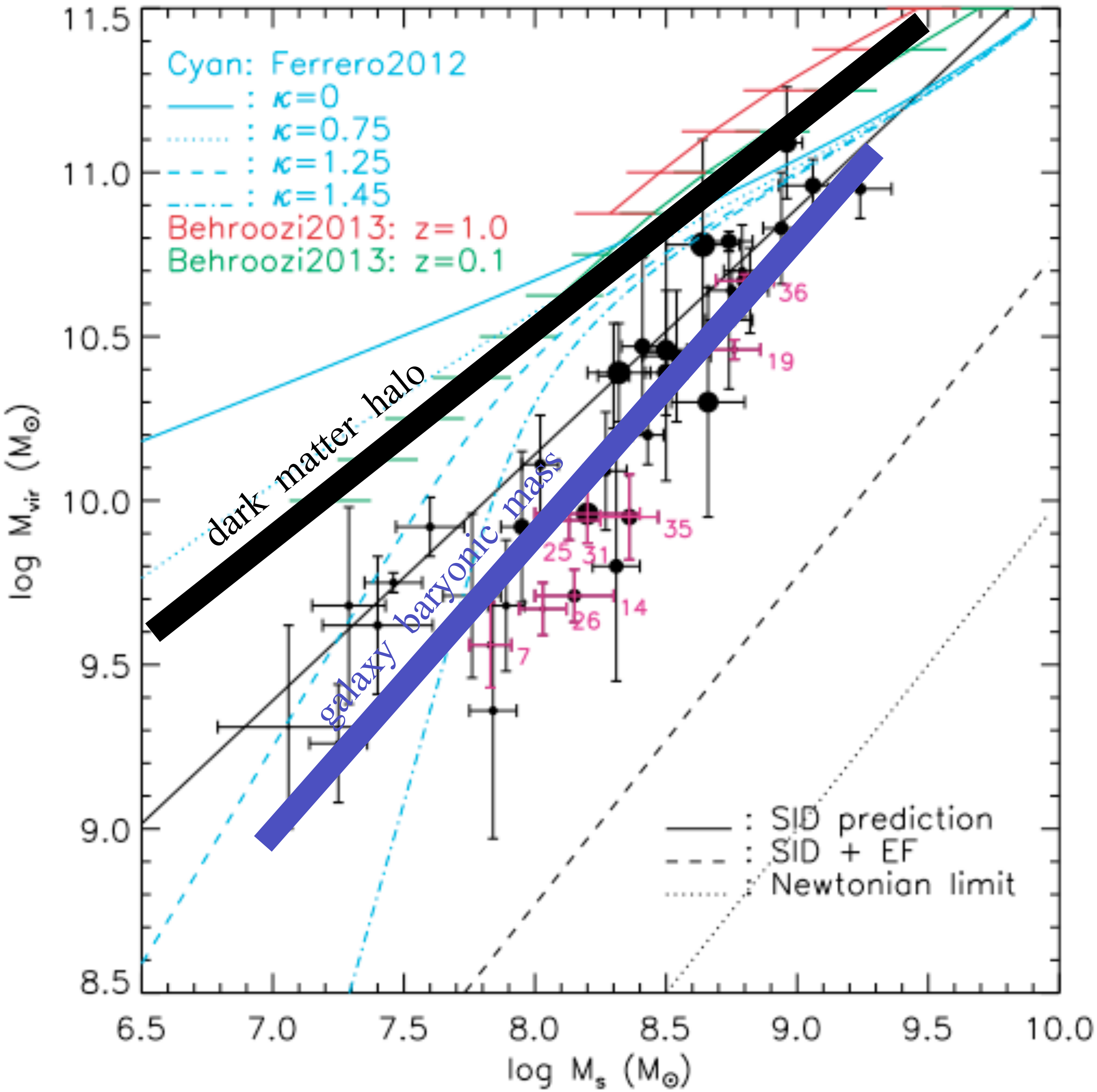
TDGs w/o DM

~~spheroidal distribution~~

correlated in phase-space

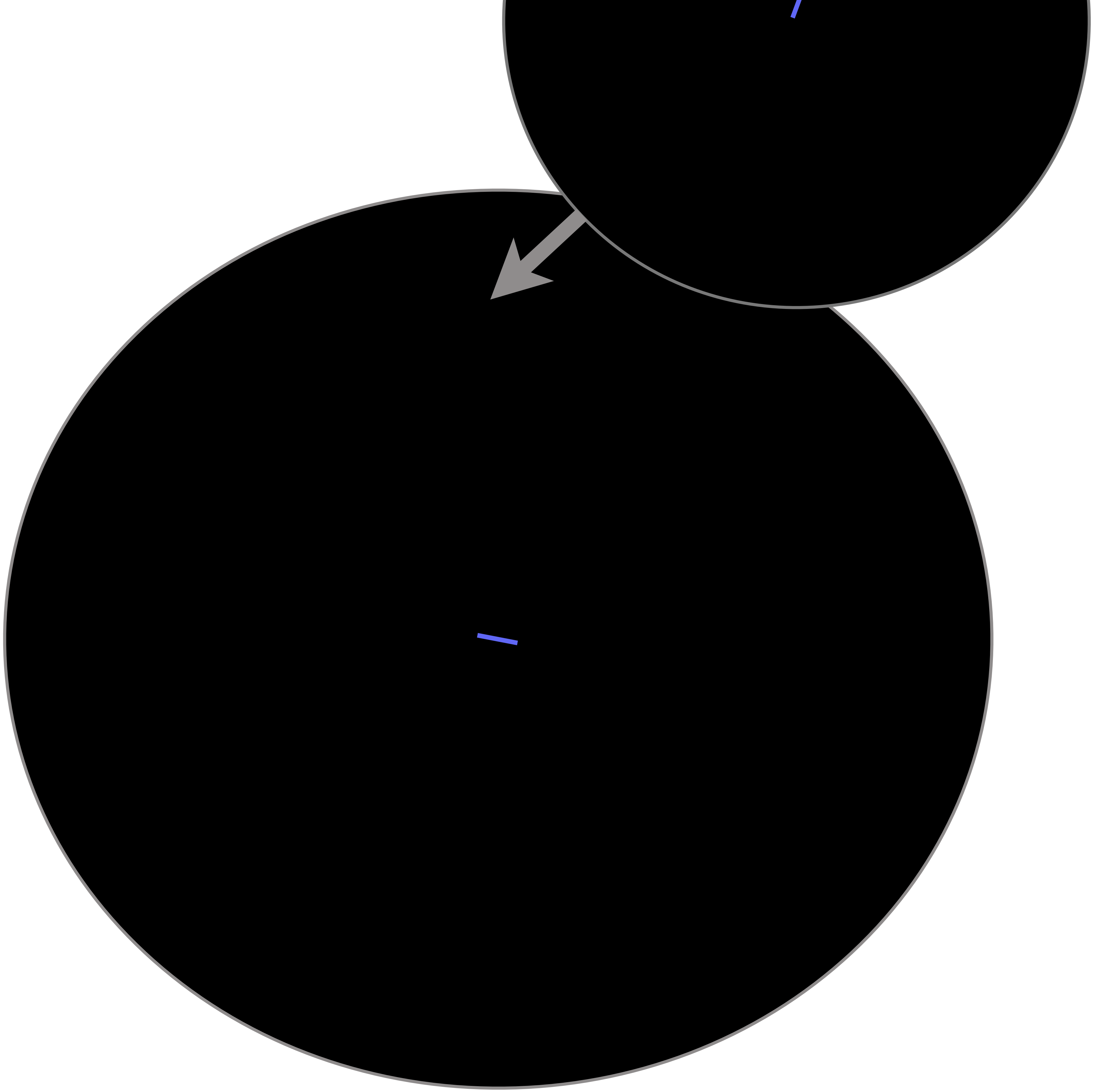
consistency check next . . .

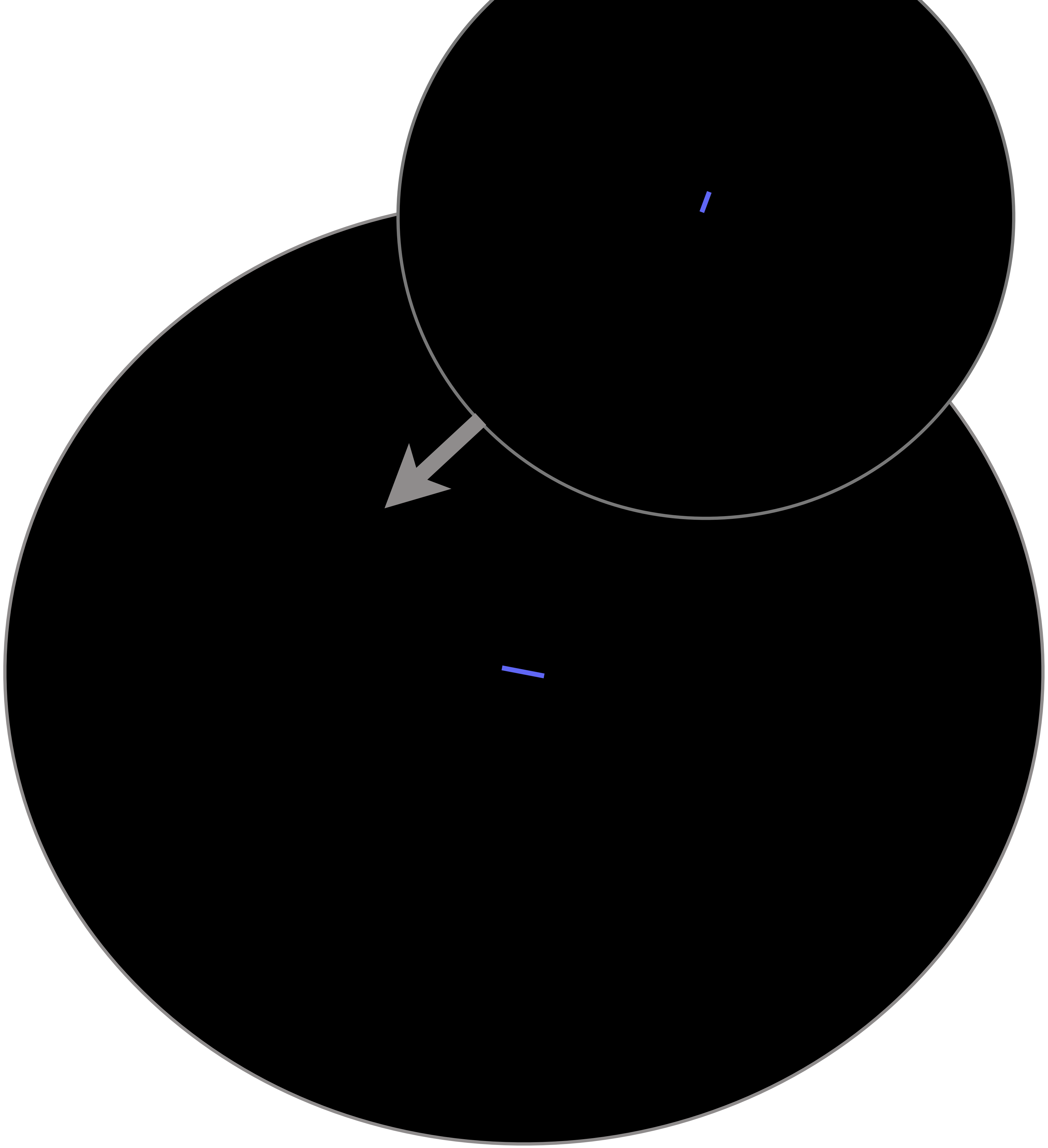
Is there any solution of this
in terms of
primordial
(DM-dominated)
dwarfs
?

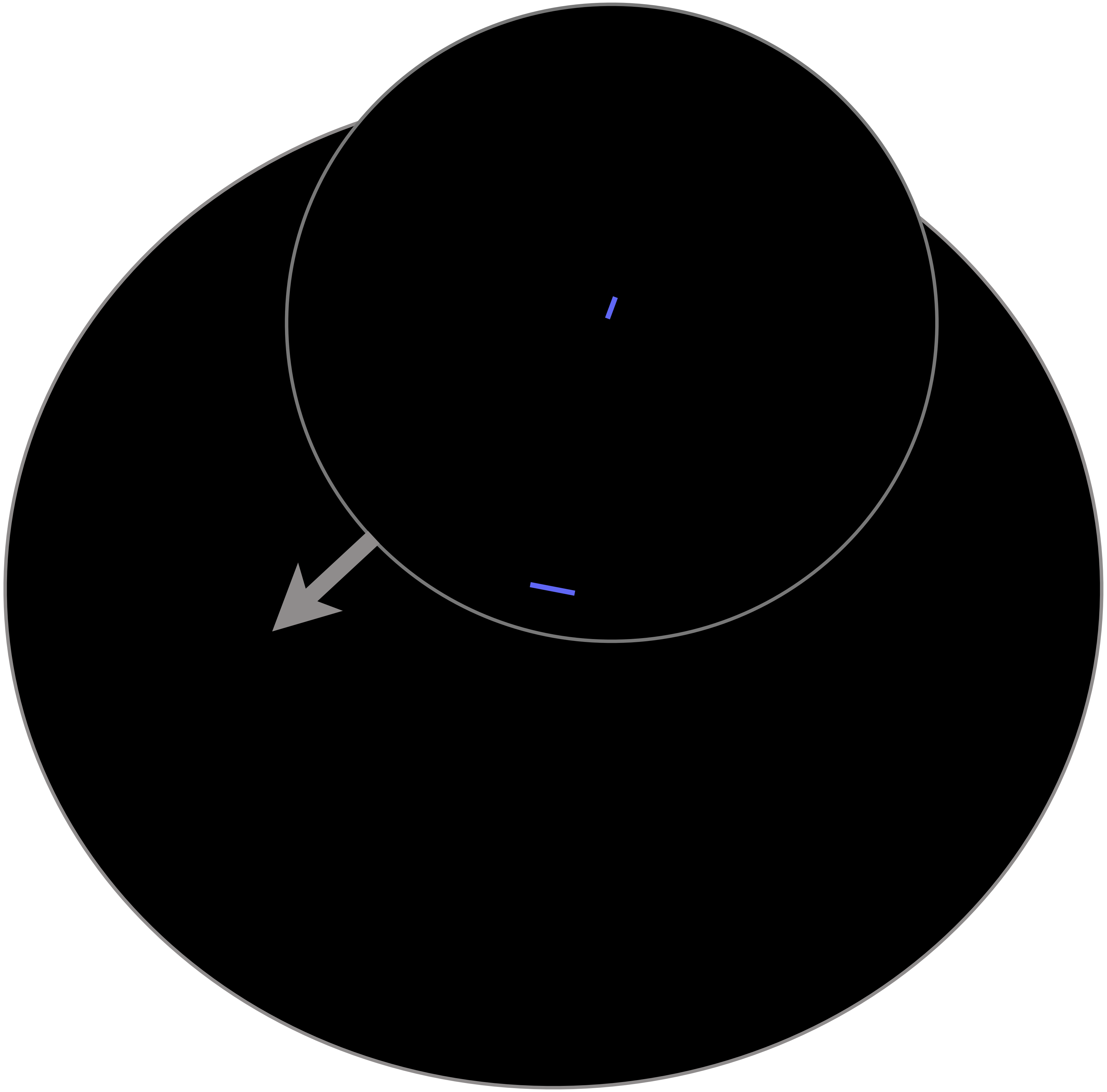


Wu & Kroupa 2014

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.



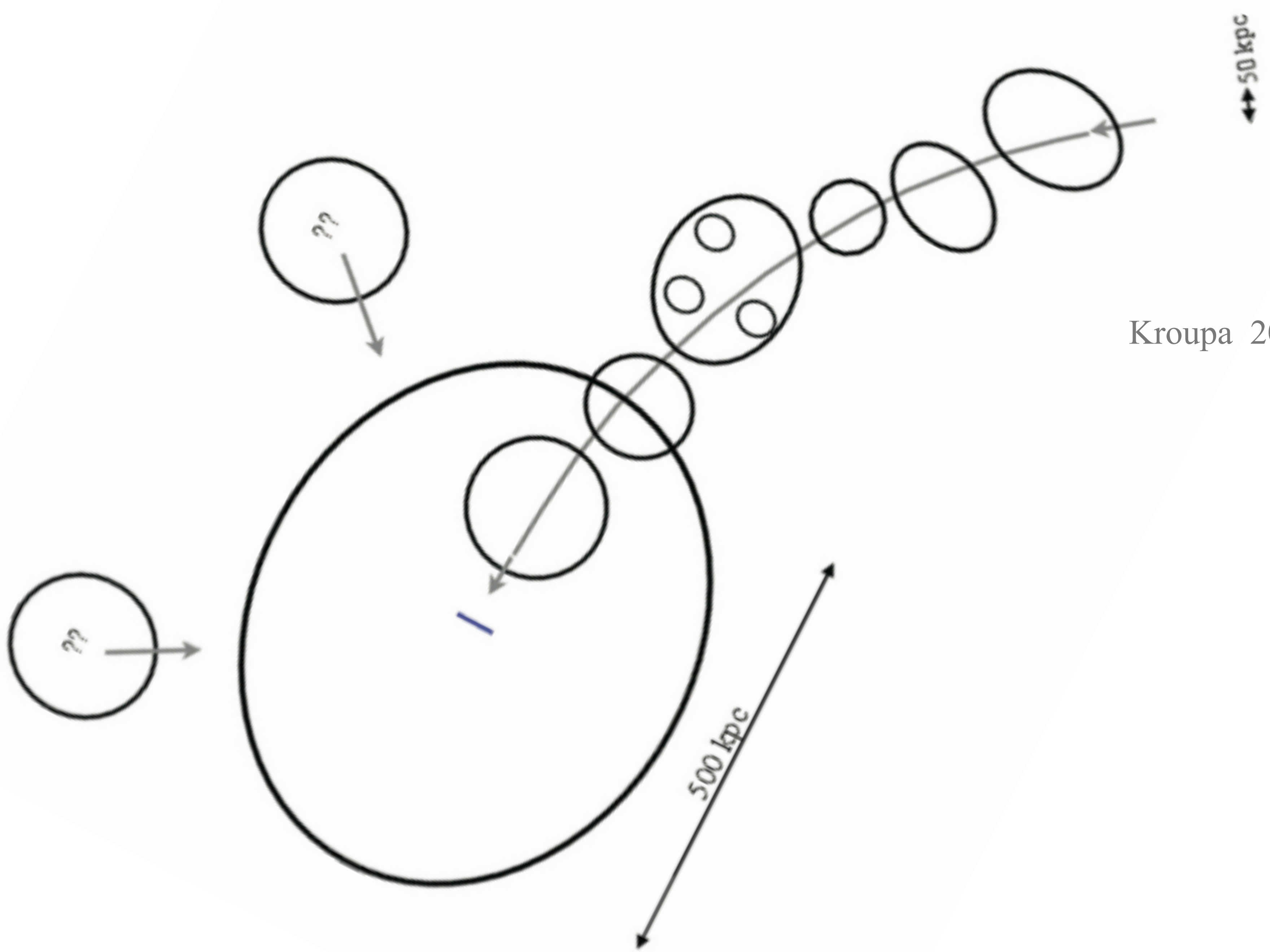




Infall from a filament ?

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

--> no in-fall solutions for MW satellites

Angus, Diaferio & Kroupa 2011

Talk by Marcel Pawlowski:
Can we tell the plane's truth? On the suggested origins of co-orbiting planes of satellite galaxies

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From his abstract:

VPOS and **GPoA :**

NOT predicted by the LCDM model of cosmology **!**

BUT several recent studies claim that the VPOS and GPoA are consistent with sub-halo based satellites.

ALL these studies are either flawed in their model satellite selection,
do not consider all observational constraints, or are internally inconsistent.

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CORRECTING the
analyses changes their results dramatically :
The observed satellite galaxy planes remain extremely rare in LCDM simulations.

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REBUTTALS by many papers by Metz et al., Pawlowski et al., Ibata et al.

Disks of Satellites

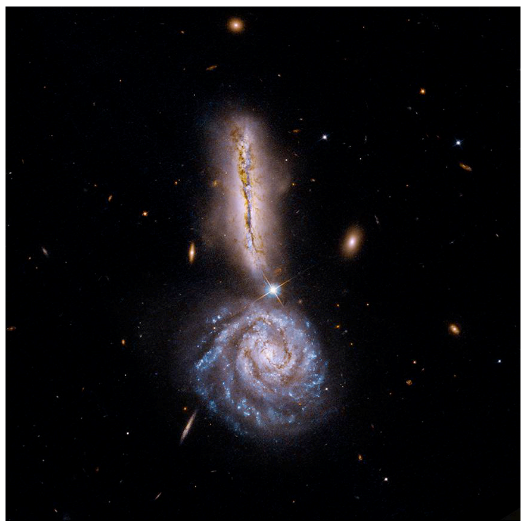
==> they can only be highly phase-space correlated at birth

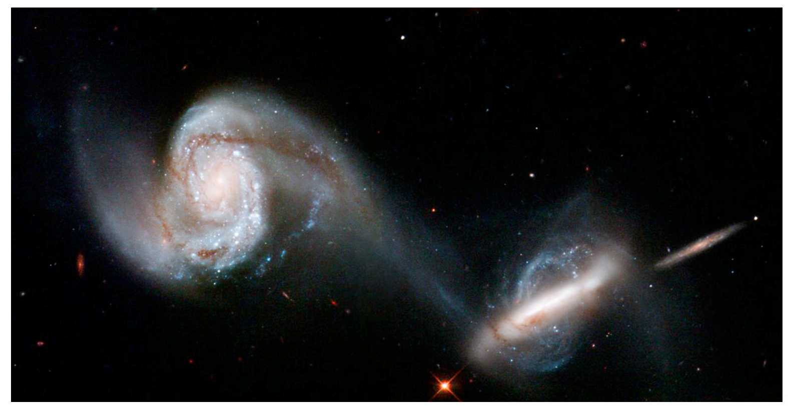
==> TDGs

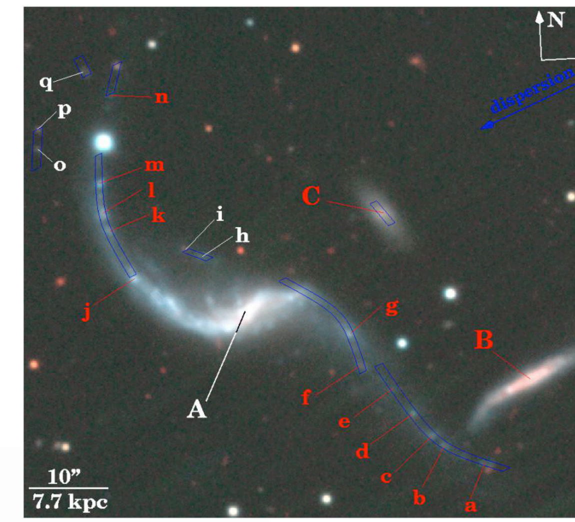
Origin of the Vast Polar Structure ?

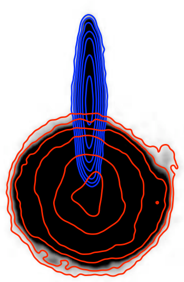
Phase-space-correlated tidal debris

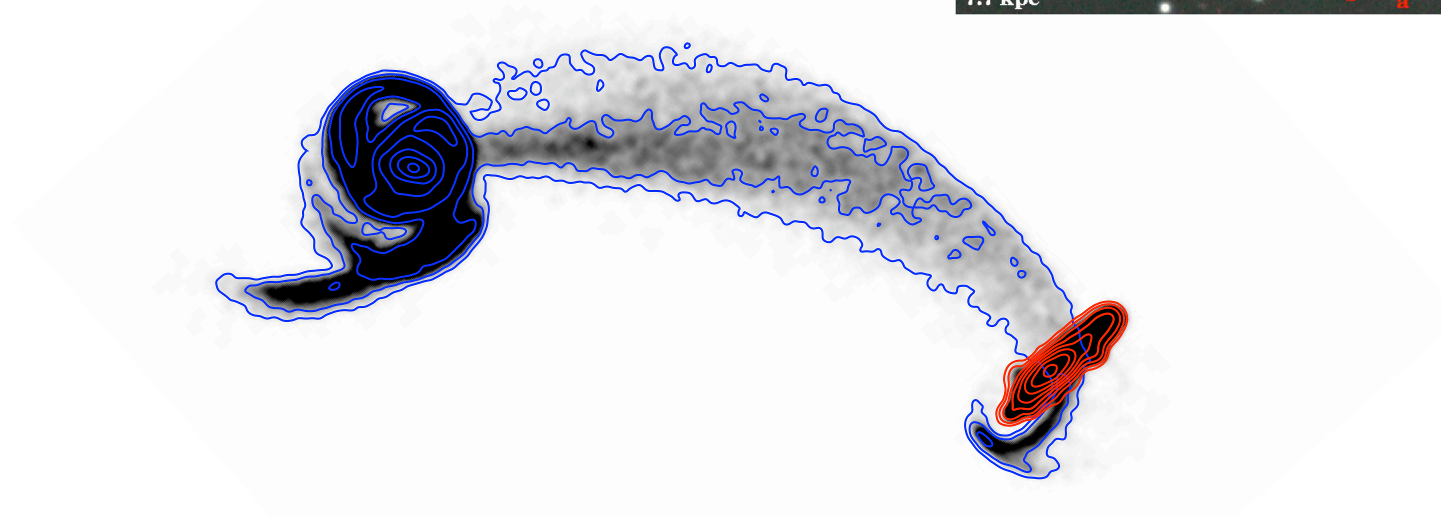
Pawlowski et al. 2012





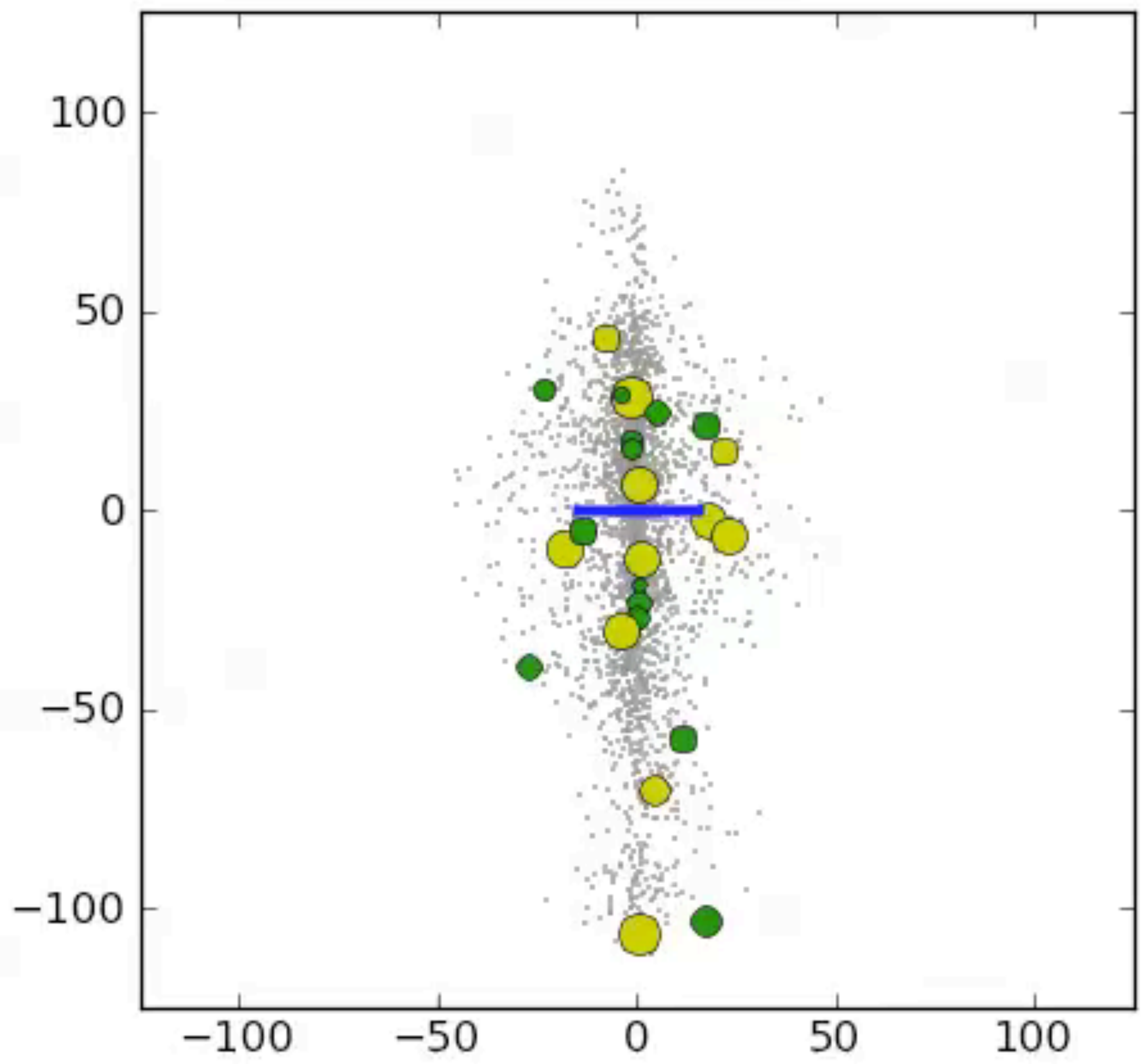






Fly-by encounter: e.g. Milky Way and Andromeda ? about 10-11 Gyr ago

Pawlowski et al. 2011



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

Within the framework of
standard cosmology,
there is
little room
for
shining cosmological
sub-structures
with $< 10^{10}\ M_\odot$**!**

(taking account of only the TDGs, not even counting "fireballs")

Conclusions

There is no evidence for two types of satellite galaxies : PDGs vs TDGs

Disks of Satellites (DoSs, VPOSs, GPoAs) ==> TDGs seem to rule

TDGs have normal SFHs and follow the mass--metallicity relation; ***no evidence that young TDGs dissolve***.

The *dual dwarf galaxy theorem* is violated by the real universe and thus the standard model of cosmology is falsified **:**

Cold or warm dark matter cannot exist

Thus galaxies merge rarely .