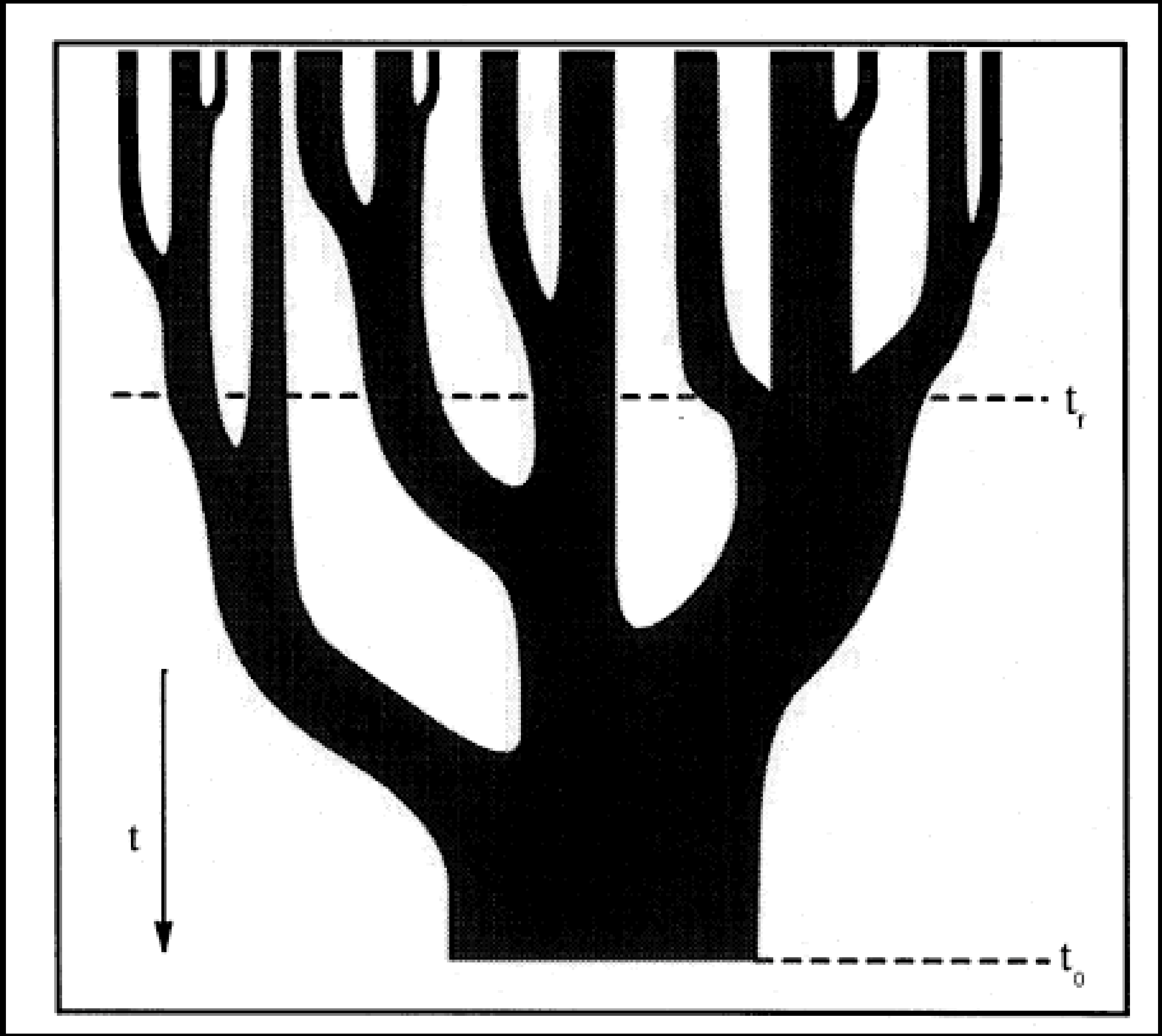
THE BEGINNING

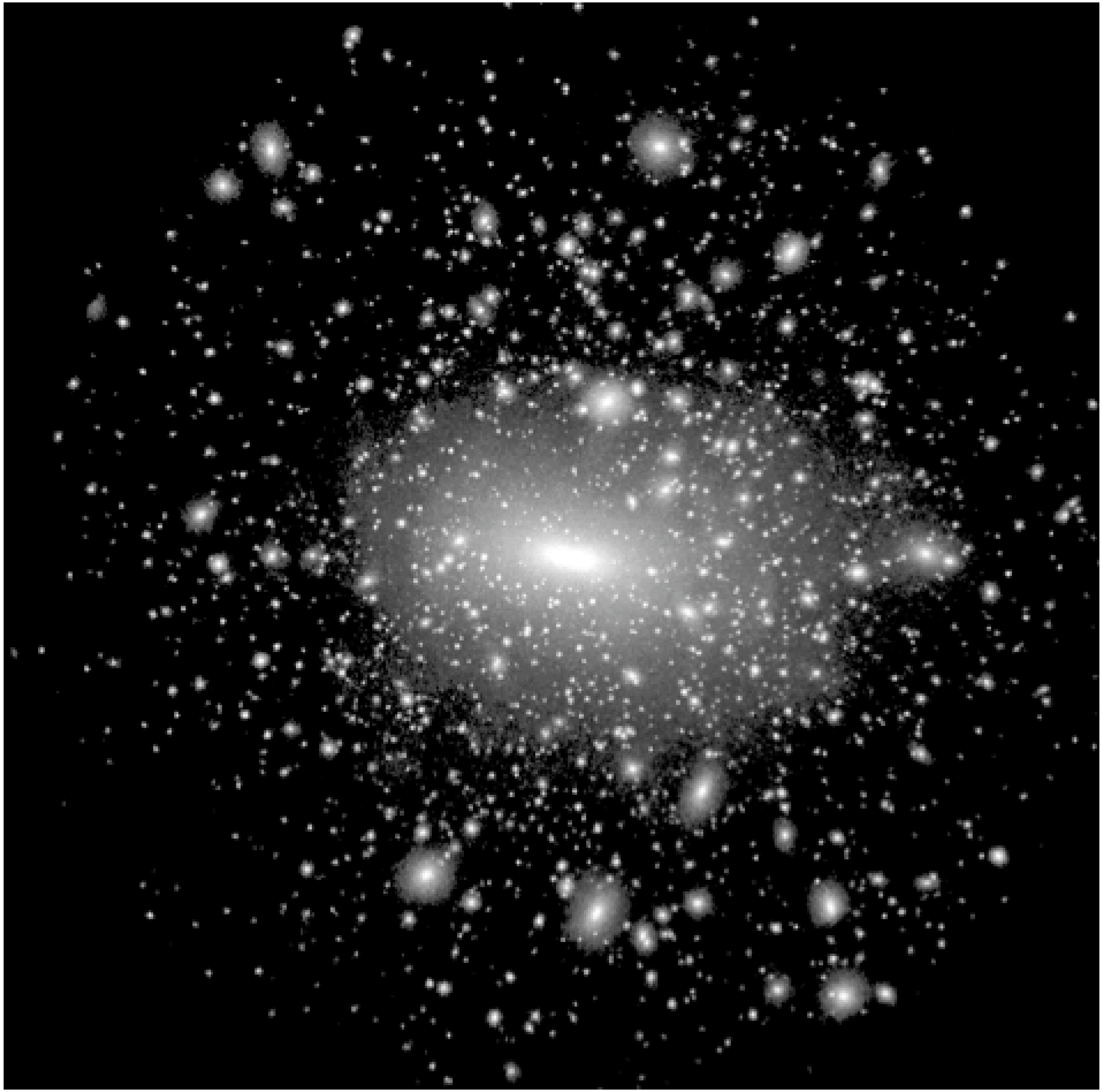
On one of the greatest controversies of modern astrophysics

The structure of CDM halos

Lacey & Cole (1993)



DM halos of major galaxies are heavily sub-structured :



What are the dSph satellites ?

Pavel Kroupa, Manuel Metz

Argelander Institute for Astronomy (AIfA)
Bonn

Simone Recchi, Christian Theis, Gerhardt Hensler

Vienna

Christian Boily

Strasbourg

Helmut Jerjen

Canberra

Background

$$S \quad + \quad d1 \quad + \quad d2 \quad + \quad \ldots \quad + d_n$$

$$n \approx 11\,, \quad d \leq 250\,\mathrm{kpc}$$

If

- virial equilibrium
- spherical symmetry
- isotropic velocity dispersion

then apply *virial theorem* to estimate $\frac{M}{L}$

$$E_{\rm kin} = -E_{\rm tot} \longrightarrow \sigma^2 = G\,\frac{M}{R}$$

Luminosity $L = \pi\, R^2\, I$ | I = surf.lumin.

$$\Longrightarrow \boxed{\frac{M}{L} = \frac{1}{G\,\pi}\,\frac{\sigma^2}{R\,I}}$$

$$\frac{M}{L} = \frac{1}{G\,\pi}\,\frac{\sigma^2}{R\,I} = \frac{1}{G}\,\frac{\sigma^2 R}{L}$$

Globular clusters :

$$R \approx 10\,\mathrm{pc}\,, \quad \sigma \approx 10\,\mathrm{km/s}\,, \quad L \approx 10^5\,L_\odot$$

$$\longrightarrow \frac{M}{L} \approx 1$$

Dwarf spheroidal (dSph) satellite galaxies :

$$R \approx 200\,\mathrm{pc}\,, \quad \sigma \approx 10\,\mathrm{km/s}\,, \quad L \approx 10^5\,L_\odot$$

$$\longrightarrow \frac{M}{L} \approx 20$$

dSph	D_{GC} [kpc]	$r_{1/2}$ [pc]	L_{tot} $[L_\odot]$	σ [km/s]	$(\frac{M}{L})_0$ $[(M/L)_\odot]$	$(\frac{M}{L})_{tot}$ $[(M/L)_\odot]$
UMi	65	150	2×10^5	7.5	$60/121\pm66$	$79/95\pm43$
Dra	75	120	1.8×10^5	13.2	$58/328\pm184$	$84/245\pm155$
Scl	79	94	1.4×10^6	7.0	$11/14\pm9$	$3.0/10.9\pm7.9$
Sex	85	294	4.1×10^5	7.0	$34/94\pm42$	$39/107\pm72$
Car	93	137	2.4×10^5	6.8	$30/74\pm50$	$31/59\pm47$
For	140	339	1.4×10^7	11.0	$4.8/10\pm4$	$4.4/7\pm3$
Leo II	215	123	5.9×10^5	6.7	$10/23\pm11$	$17/23\pm20$
Leo I	270	133	3.4×10^6	3.2	$3.1/1.2:$	$4.6/0.9:$

CDM cosmologists are happy . . .

or are they ?

Most of the dSph satellites

are

not CDM sub-structures

orbiting in the MW halo.

Kroupa, Theis & Boily (2005)

Why ?

I) $N = 11$ within $R < 250$ kpc $\approx R_{\rm vir}$

$\longrightarrow$ $N \ll$ expectation from theory

II) $(\sigma, L) \approx$ GCs but $R \approx 20\,R_{\rm GC} \Longrightarrow \frac{M}{L} \approx 20$

$\longrightarrow$ But DM profiles difficult to re-concile with CDM theory

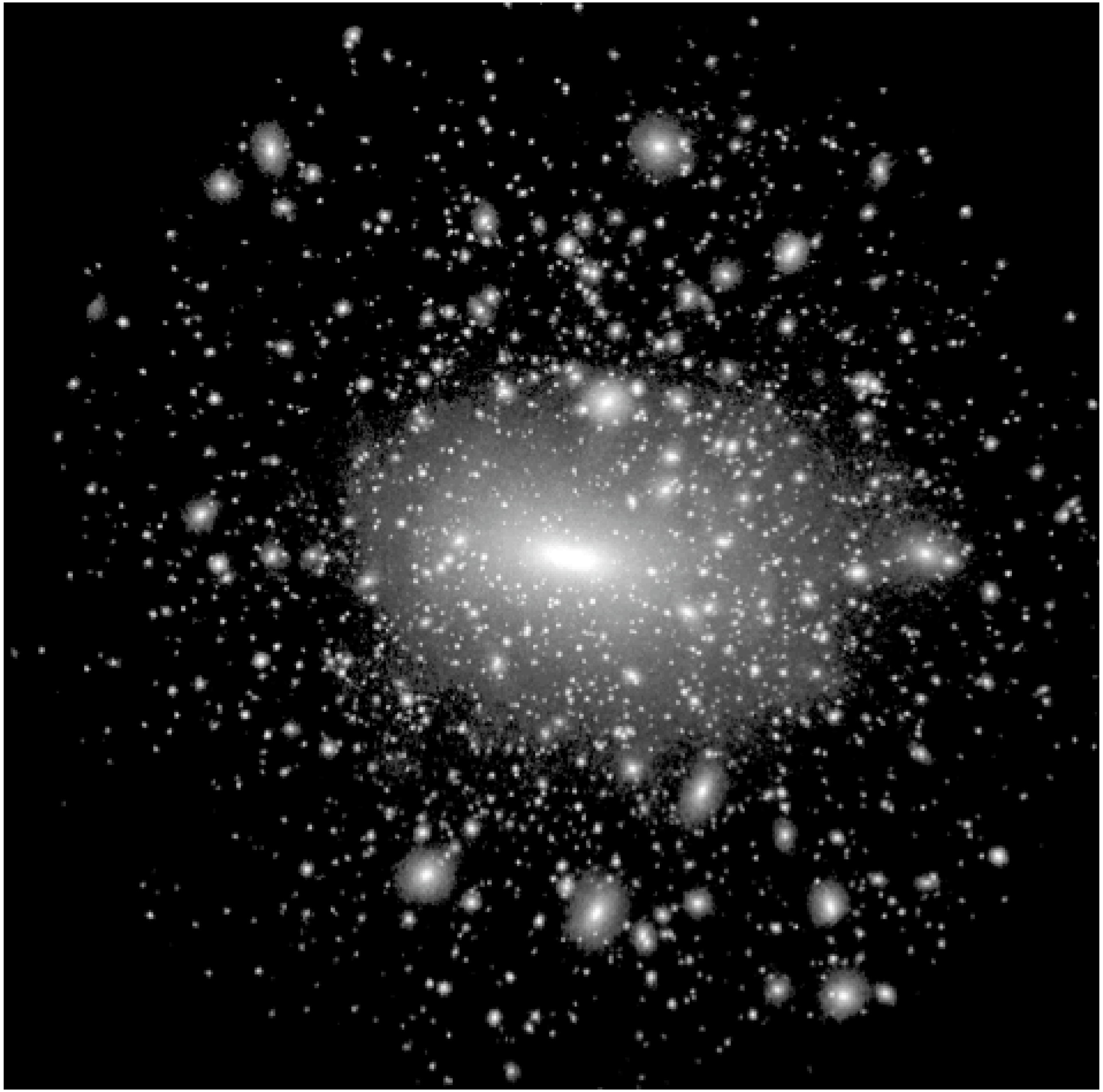
III) Significant isophotal structure despite large $\sigma \approx 700$ pc/100 Myr

$\longrightarrow$ embedded in massive DM halos ??

IV) disk-like spatial distribution

$\longrightarrow$ incompatible with MW halo shape

I) $N \ll N_{\rm CDM} \approx 500$



I) $N \ll N_{\rm CDM} \approx 500$

is usually explained by
galactic-scale baryonic processes
that introduce
very significant bias
between
dark-matter and luminous-matter
distributions.

II) DM profiles *within* dSph satellites:

Measured light and line-of-sight velocity dispersion profiles yield constraints on the total mass distribution. *Excellent results* are available for UMi and Draco through work of Wilkinson, Kleyna, Evans, Gilmore (The IoA Team)

But :

Kleyna et al. (2001): "The data strongly favour models in which the dark matter is significantly more extended than the visible dwarf." "... our data strongly suggest that Draco has not been tidally truncated within 1 kpc" [=60arcmin]

Wilkinson et al. (2004): "... this scenario is only plausible if Draco and UMi have somewhat lower masses than previously estimated and have a low dark-matter density outside about 30arcmin" [outside optical edge]

And, DM profiles are observed
to be too flat;
tidal evolution cannot
sufficiently flatten the CDM profiles
(Kazantzidis et al. 2004).

Does the Fornax dwarf spheroidal have a central cusp or core?

Goerdt, Moore et al. (aph/0601404)

Five globular clusters orbiting at ***several hundred parsecs*** from its centre.

In a cuspy CDM halo the globulars would sink to the centre from their current positions within ***half a billion years***.

We show that this timing problem is even more severe when interactions between the globular clusters are taken into account.

→ Fornax dwarf spheroidal has a shallow inner density profile with a ***core radius*** defined by the observed positions of its globular clusters.

This points to ***Warm Dark Matter*** as being the mass-dominating component.

(Same conclusion by Sanchez-Salcedo et al. 2006 (aph/0601490))

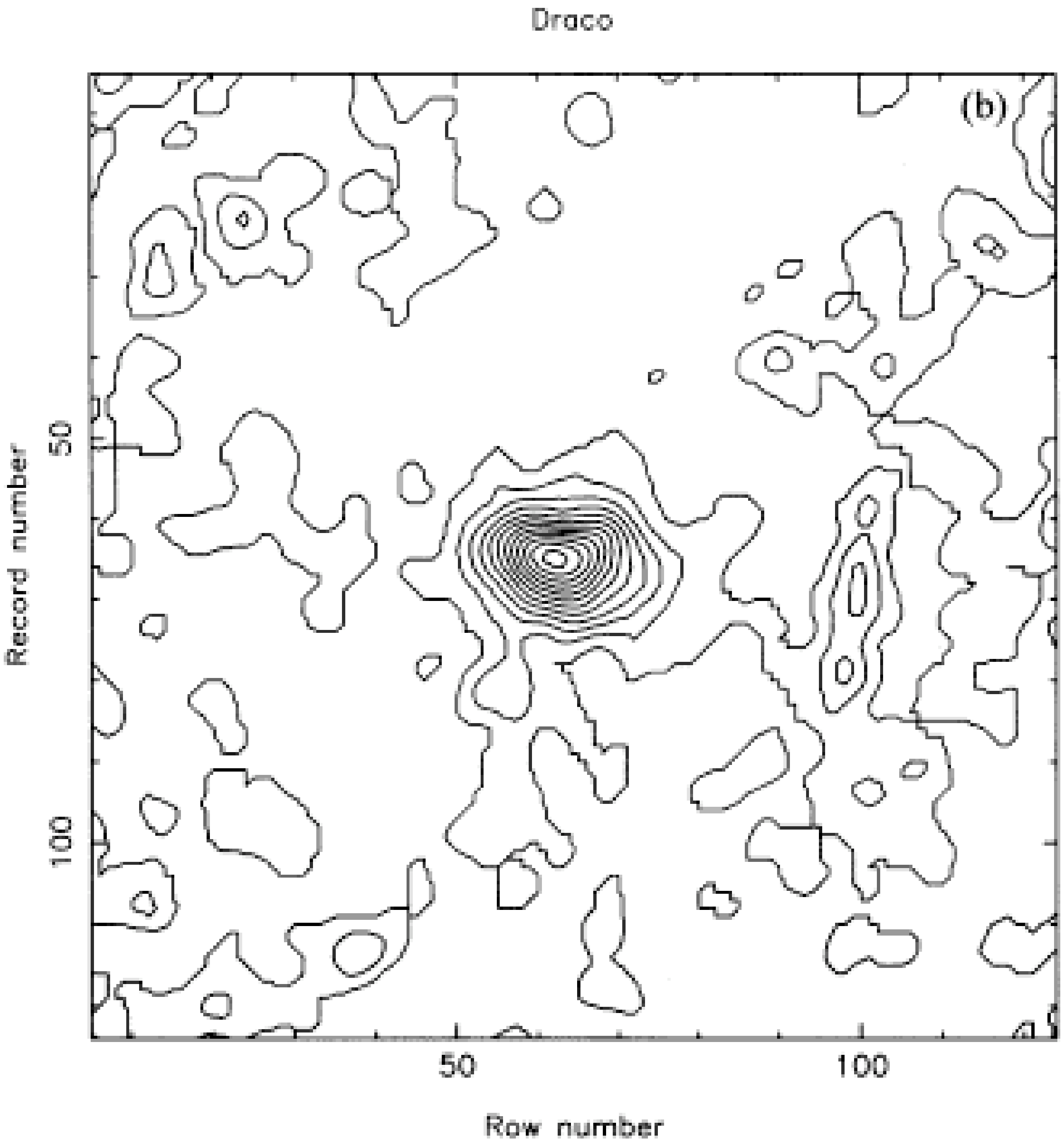
III) Significant isophote structure is present in many dSph satellites despite a large

$$\sigma \approx 700 \text{ pc}/100 \text{ Myr}$$

Substructure should smear-out if σ is really due to a DM halo, unless it has a harmonic core.

UMi and Draco would have a near-homogeneous halo cutoff at the stellar boundary

$\longrightarrow$ inconsistent with CDM theory.



Draco

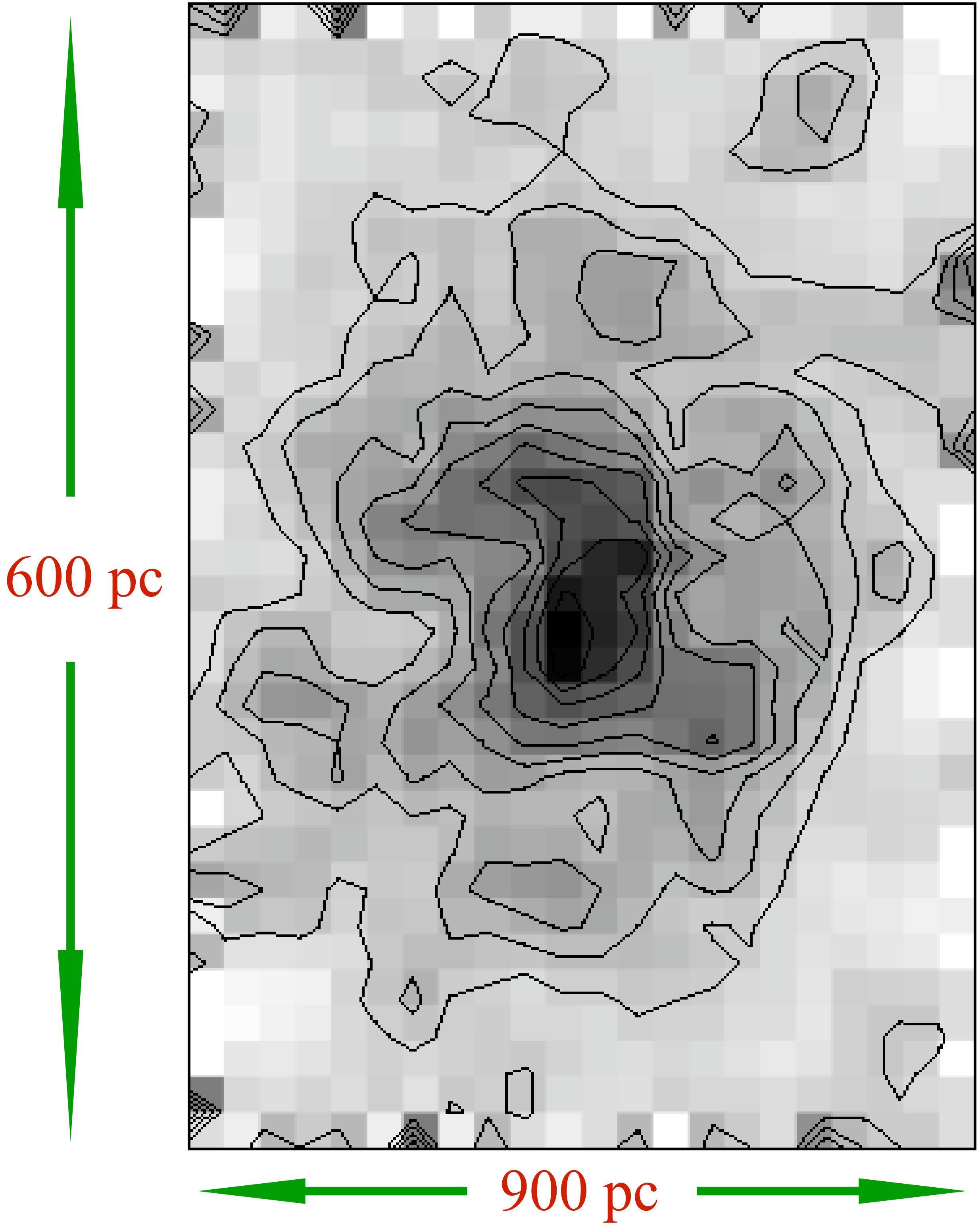
D=75kpc

(Irwin & Hatzidimitriou 1995)

$$\left(\frac{M}{L}\right)_{0,\mathrm{V}} = 58$$

$$\left(\frac{M}{L}\right)_{\mathrm{tot,V}} = 84$$

(Mateo 1998)



Draco

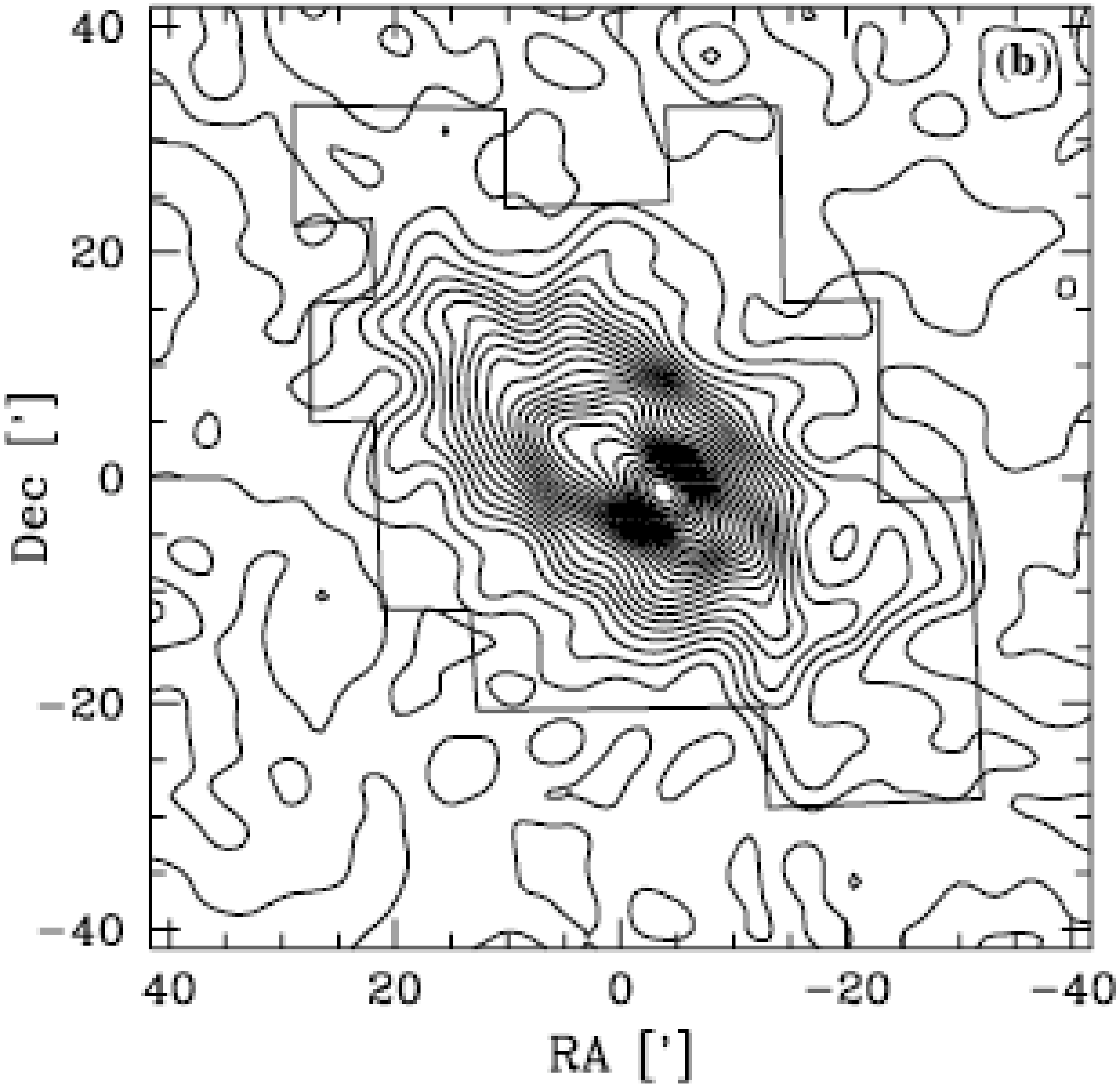
D=75kpc

(Cioni & Habing 2005)

$$\left(\frac{M}{L}\right)_{0,\mathrm{V}} = 58$$

$$\left(\frac{M}{L}\right)_{\mathrm{tot},\mathrm{V}} = 84$$

(Mateo 1998)



UMi

D=65kpc

(Kleyna et al. 1998)

$$\left(\frac{M}{L}\right)_{0,\mathrm{V}} = 60$$

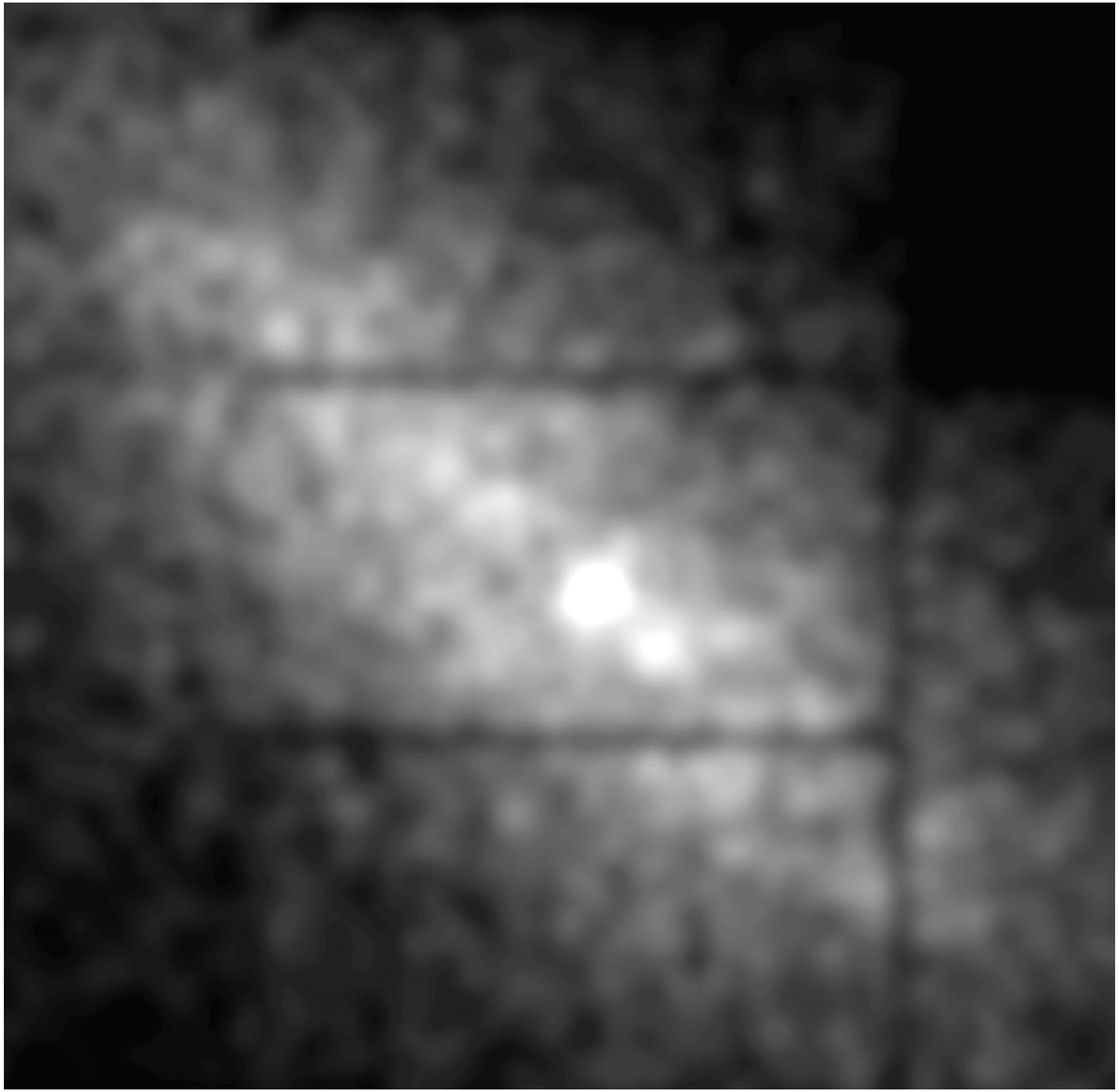
$$\left(\frac{M}{L}\right)_{\mathrm{tot,V}} = 79$$

(Mateo 1998)

But :

$$\left(\frac{M}{L}\right)_{\mathrm{particles}} = 12$$

(Gomez-Flechoso & Martinez-Delgado 2003)



UMi

D=65kpc

(Martinez-Delgado et al., in prep)

Substructure significant :

(Kleyna et al. 2003)

UMi

D=65kpc

(Martinez-Delgado et al., in prep)

***S shape* :**

strong evidence for extra-tidal stars

Massive CDM halo ?

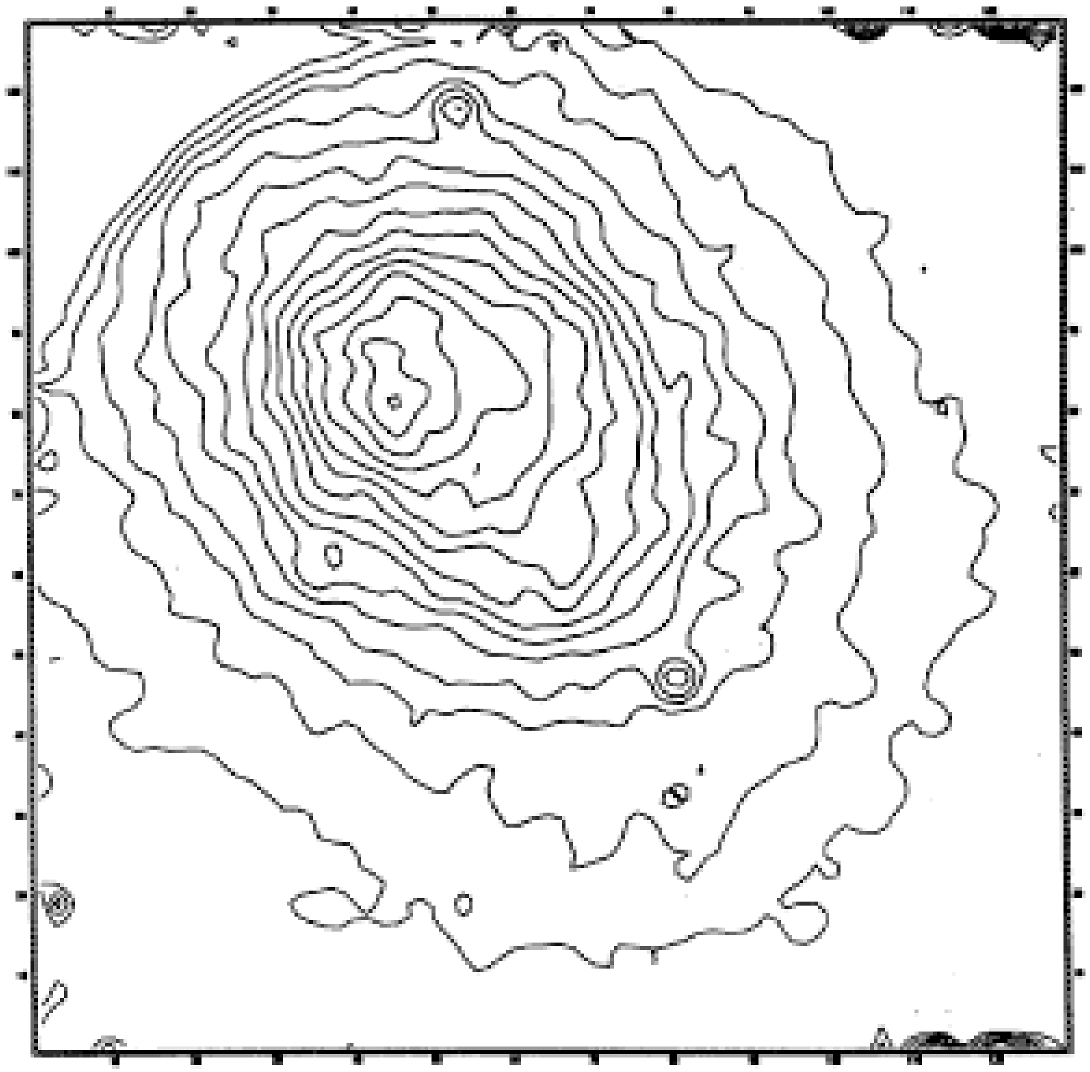


FIG. 4. Isophotes of equal stellar density of field 1 reveal that the structure of Fornax, near the center, is not symmetric.

Fornax

D=140kpc

(Demers et al. 1994)

$$\left(\frac{M}{L}\right)_{0,\mathrm{V}} = 4.8$$

$$\left(\frac{M}{L}\right)_{\mathrm{tot,V}} = 4.4$$

(Mateo 1998)

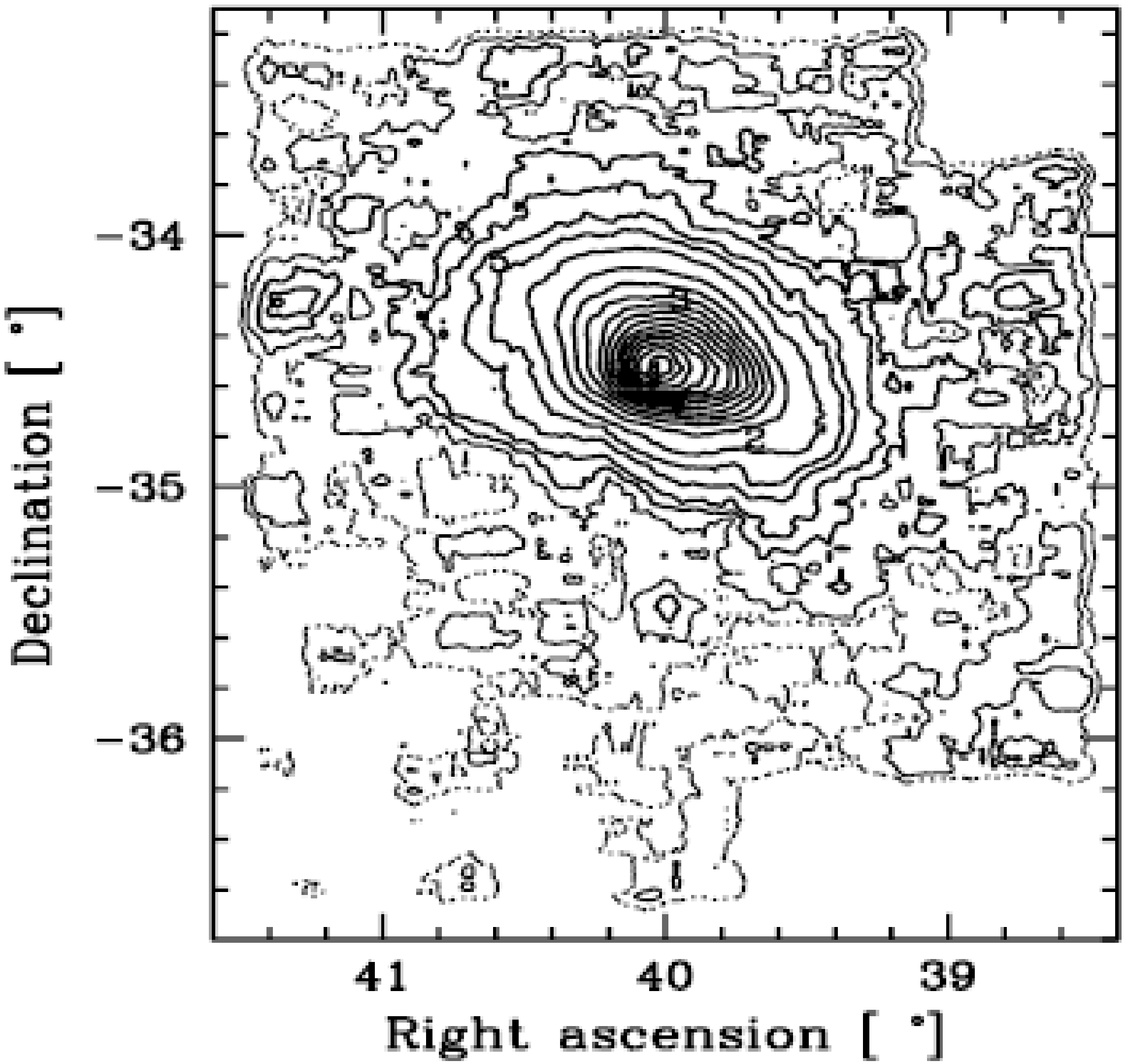


Fig. 3. Contour plot of the Fornax dwarf spheroidal. The density levels correspond to background value (dotted line), 1σ above that (thin solid line), 2σ, 5σ, 10σ and so on (thick solid lines). The inner isopleths show a steeper decline to the south-east than to the north-west. The locations of the five globular clusters are indicated by their numbers.

Fornax

D=140kpc

(Walcher et al. 2003)

↓

Massive CDM halo ?

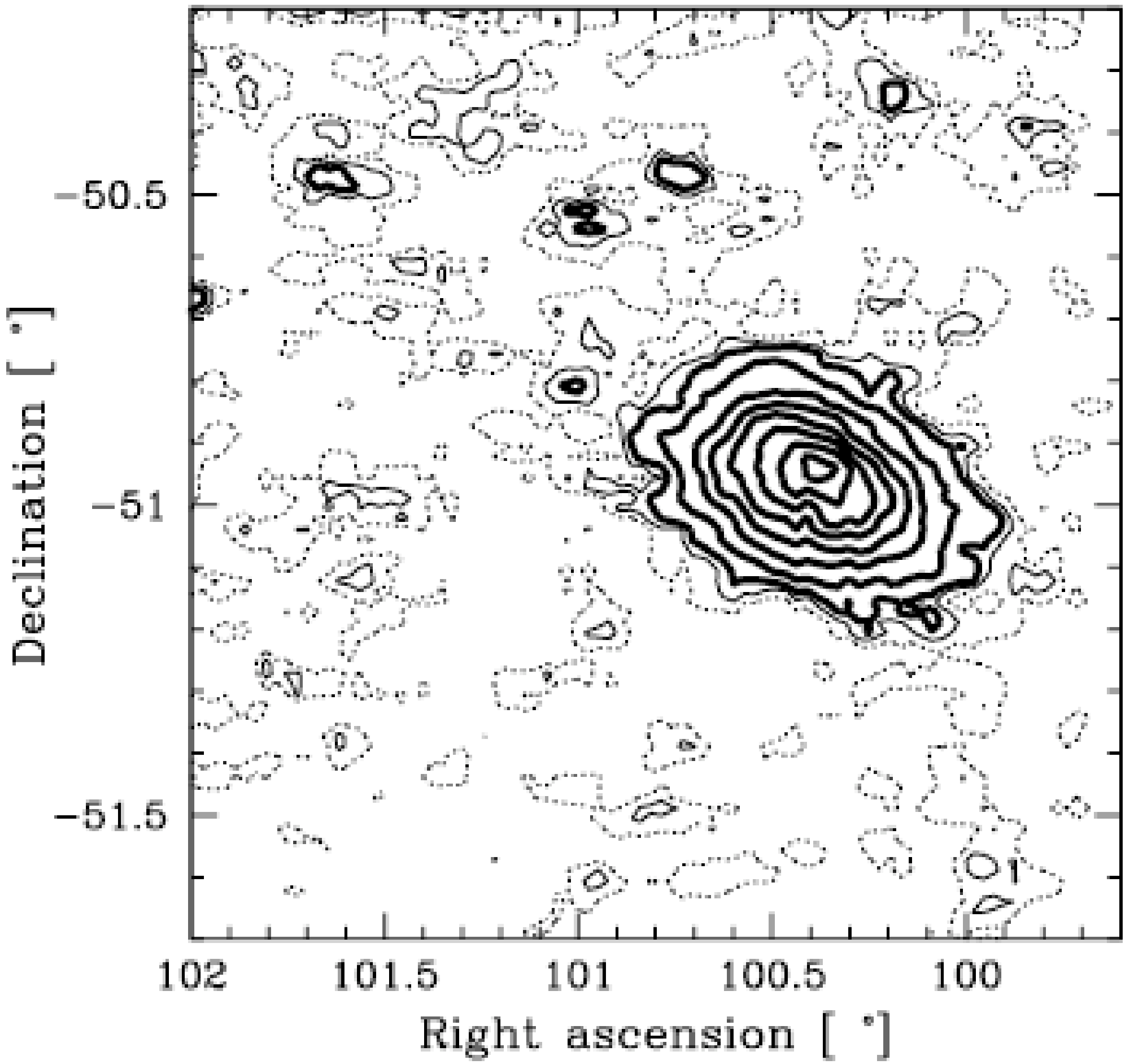


Fig. 1. Contour plot of the Carina dwarf spheroidal. The density levels correspond to background value (dotted line), 1σ above that (thin solid line), 2σ, 5σ, 10σ and so on (thick solid lines). No significant departure from the spheroidal shape can be seen. A galactic gradient can be seen from the northeastern to the southwestern corner.

Carina

D=93kpc

(Walcher et al. 2003)

$$\left(\frac{M}{L}\right)_{0,\mathrm{V}} = 30$$

$$\left(\frac{M}{L}\right)_{0,\mathrm{V}} = 31$$

(Mateo 1998)

But, it may have lost $> 90\%$ of its stars

(Majewski et al. 2000)

Sculptor

D=79kpc

(Walcher et al. 2003)

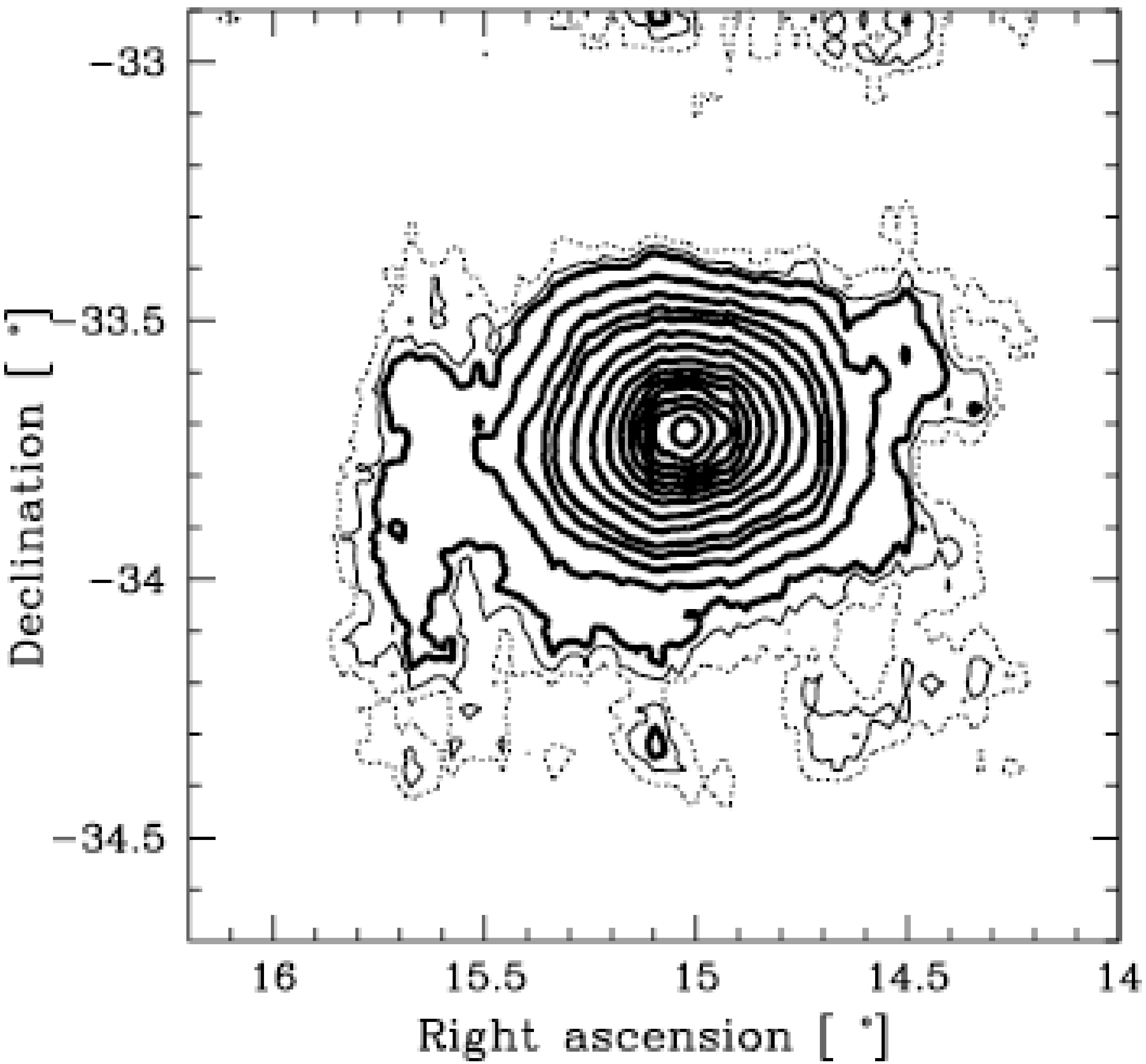
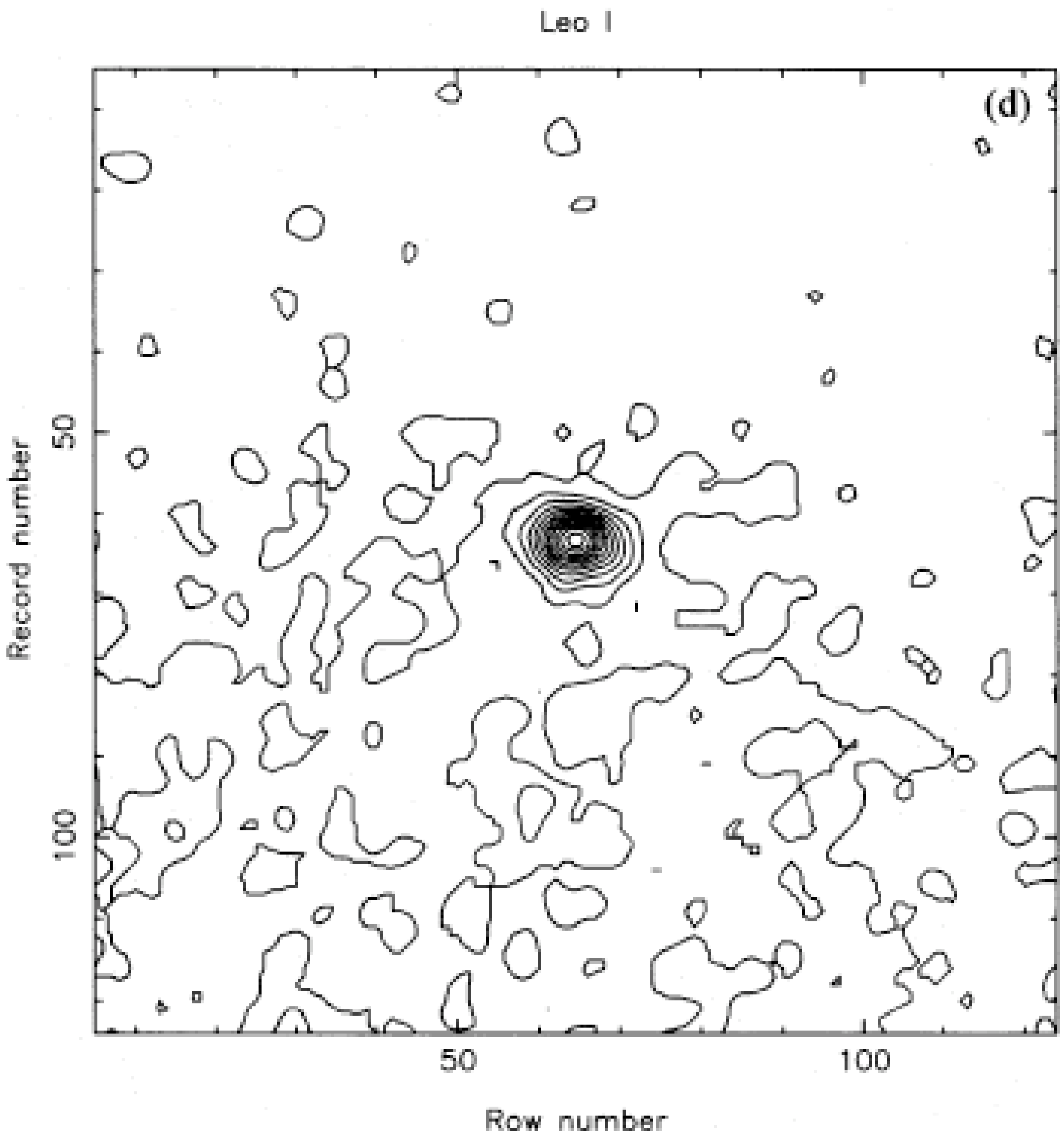


Fig. 2. Contour plot of the Sculptor dwarf spheroidal. The density levels correspond background value (dotted line), 1σ above that (thin solid line), 2σ, 5σ, 10σ and so on (thick solid lines). Note the increase of ellipticity with radius and the potential tidal tails.

$$\left(\frac{M}{L}\right)_{0,\mathrm{V}} = 11$$

$$\left(\frac{M}{L}\right)_{\mathrm{tot,V}} = 3$$

(Mateo 1998)



Leo I

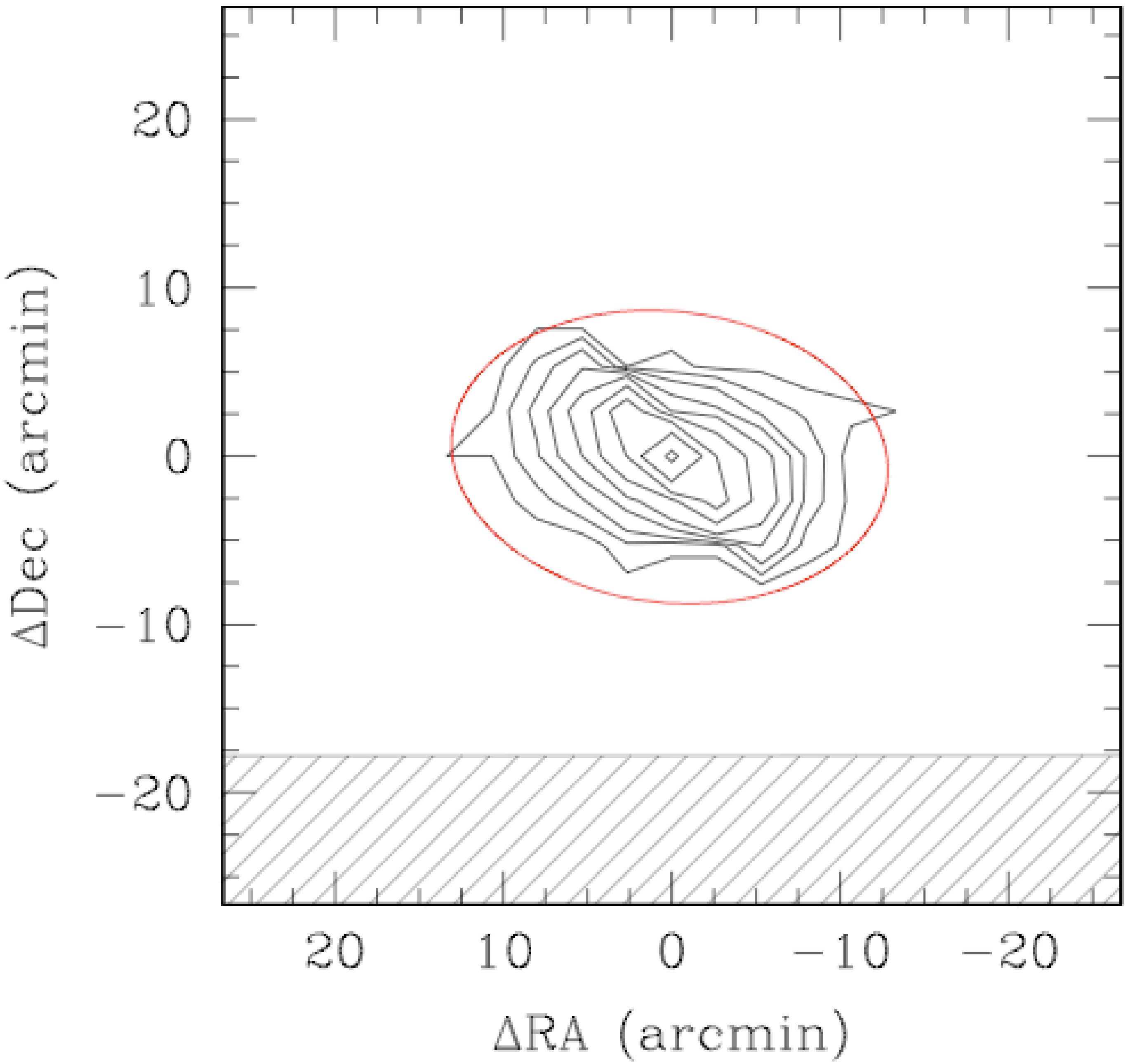
D=270kpc

(Irwin & Hatzidimitriou 1995)

$$\left(\frac{M}{L}\right)_{0,\mathrm{V}} = 3.1$$

$$\left(\frac{M}{L}\right)_{\mathrm{tot,V}} = 4.6$$

(Mateo 1998)



Leo I

D=270kpc

(Sohn, Majewski et al., in prep.)

S shape **:** strong evidence for extra-tidal stars

Massive CDM halo **?**

The dSph satellites ***can*** be filled with DM, but only by leaving the logical framework of CDM theory.

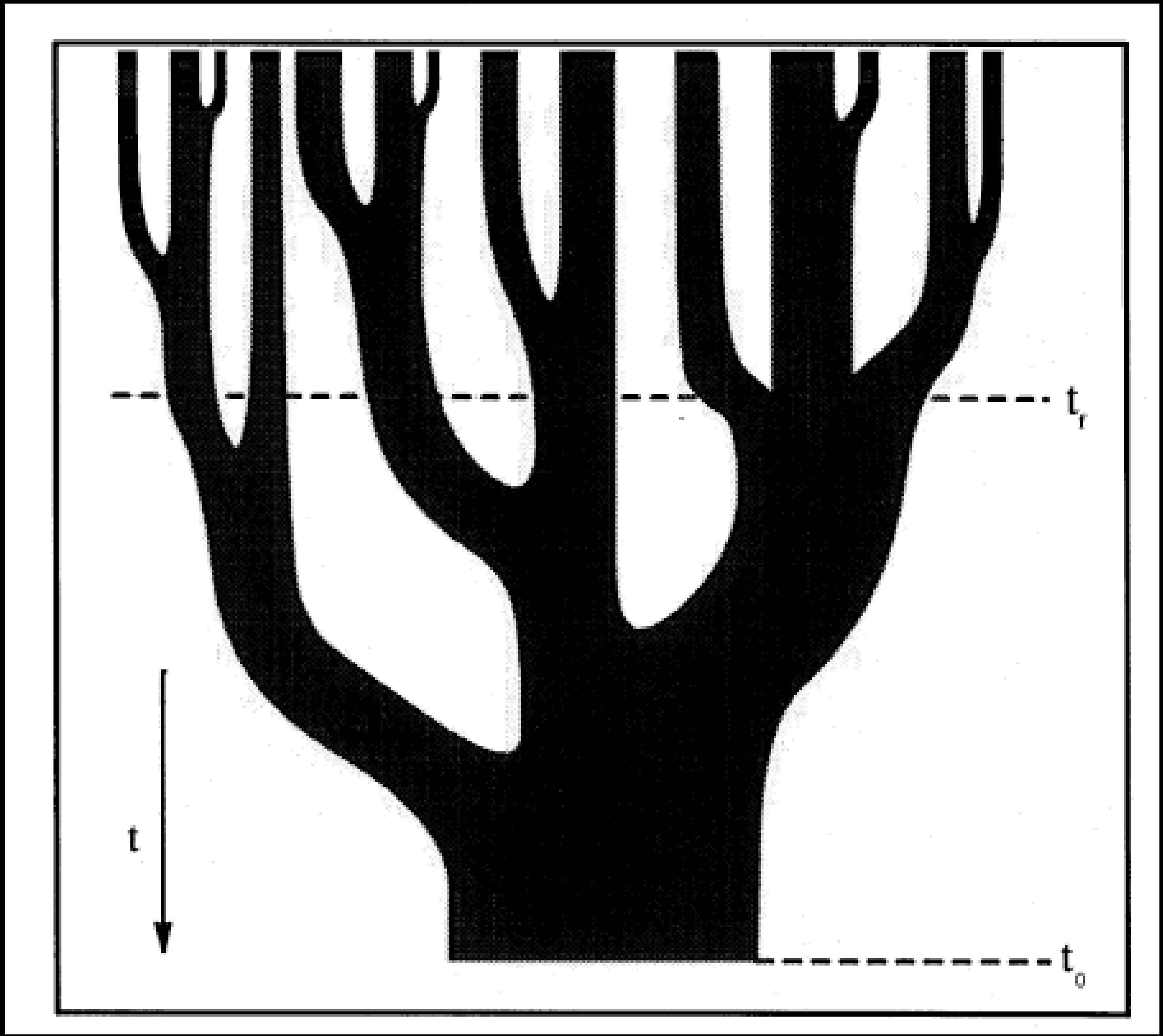
Thus, by adding additional parameters (core radius, cutoff radius) are improved fits obtained.

Is this surprising?

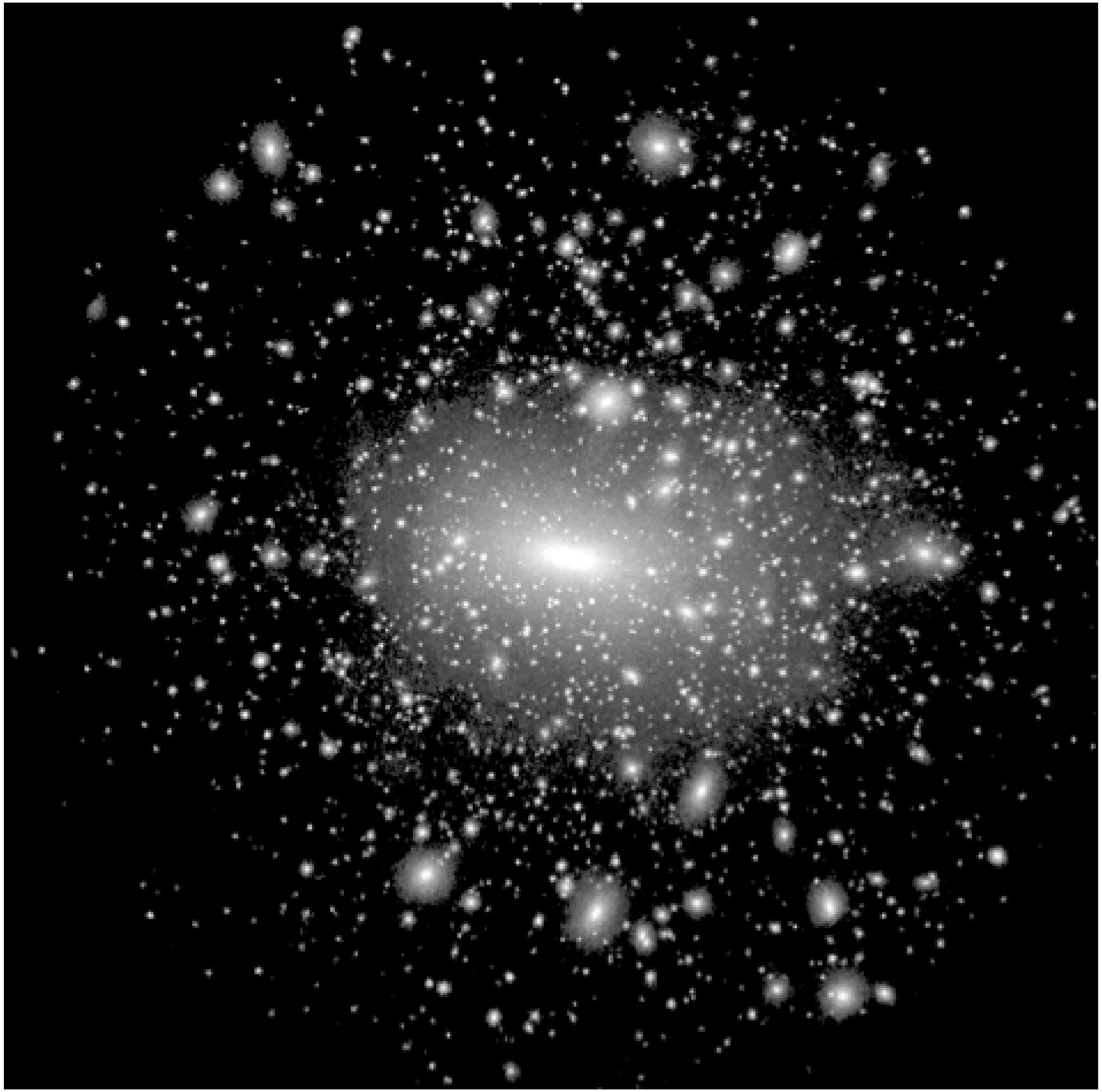
Alternatively, if we want to keep CDM theory, then the dSph satellites can't be DM dominated.

The structure of CDM halos

Lacey & Cole (1993)



IV) The near-self-similar structure of host DM halos:



MW satellites are instead in a disk-like configuration:

(Kroupa, Theis & Boily 2005)

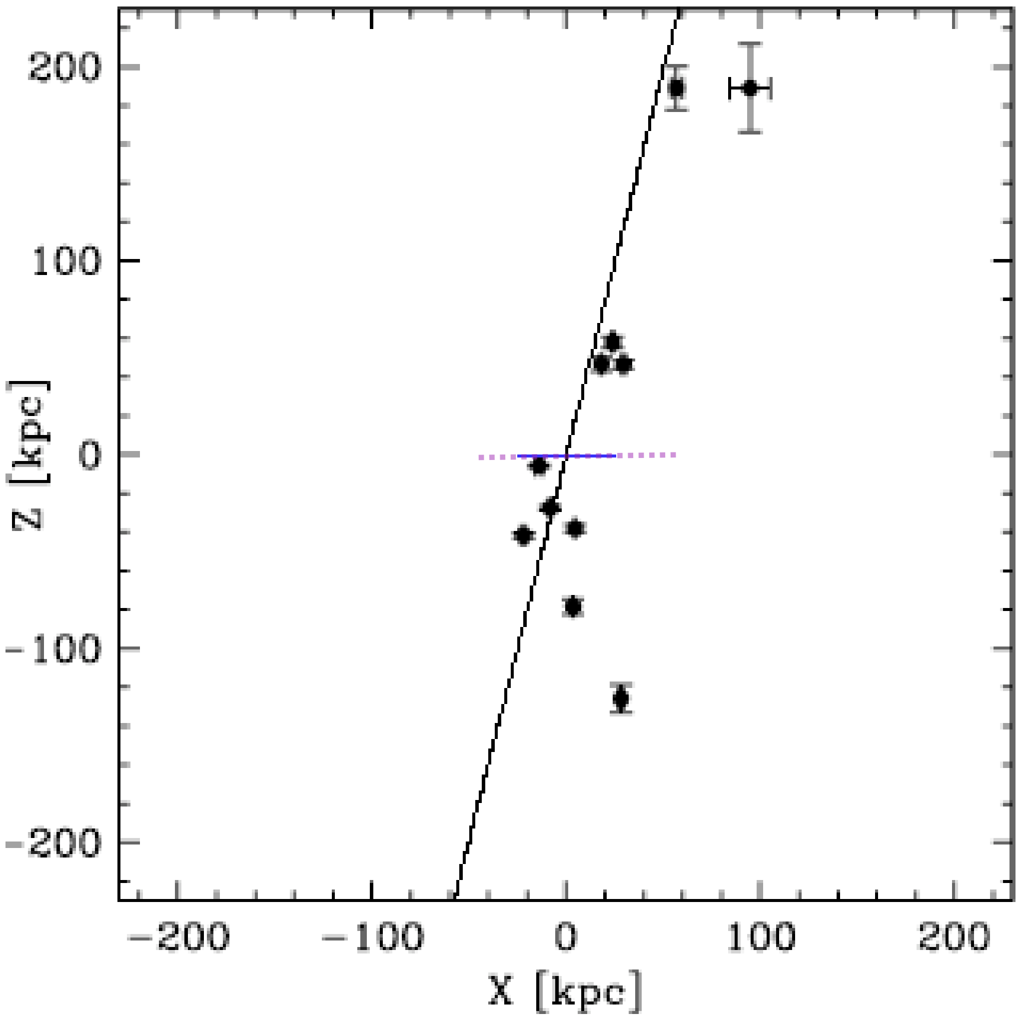
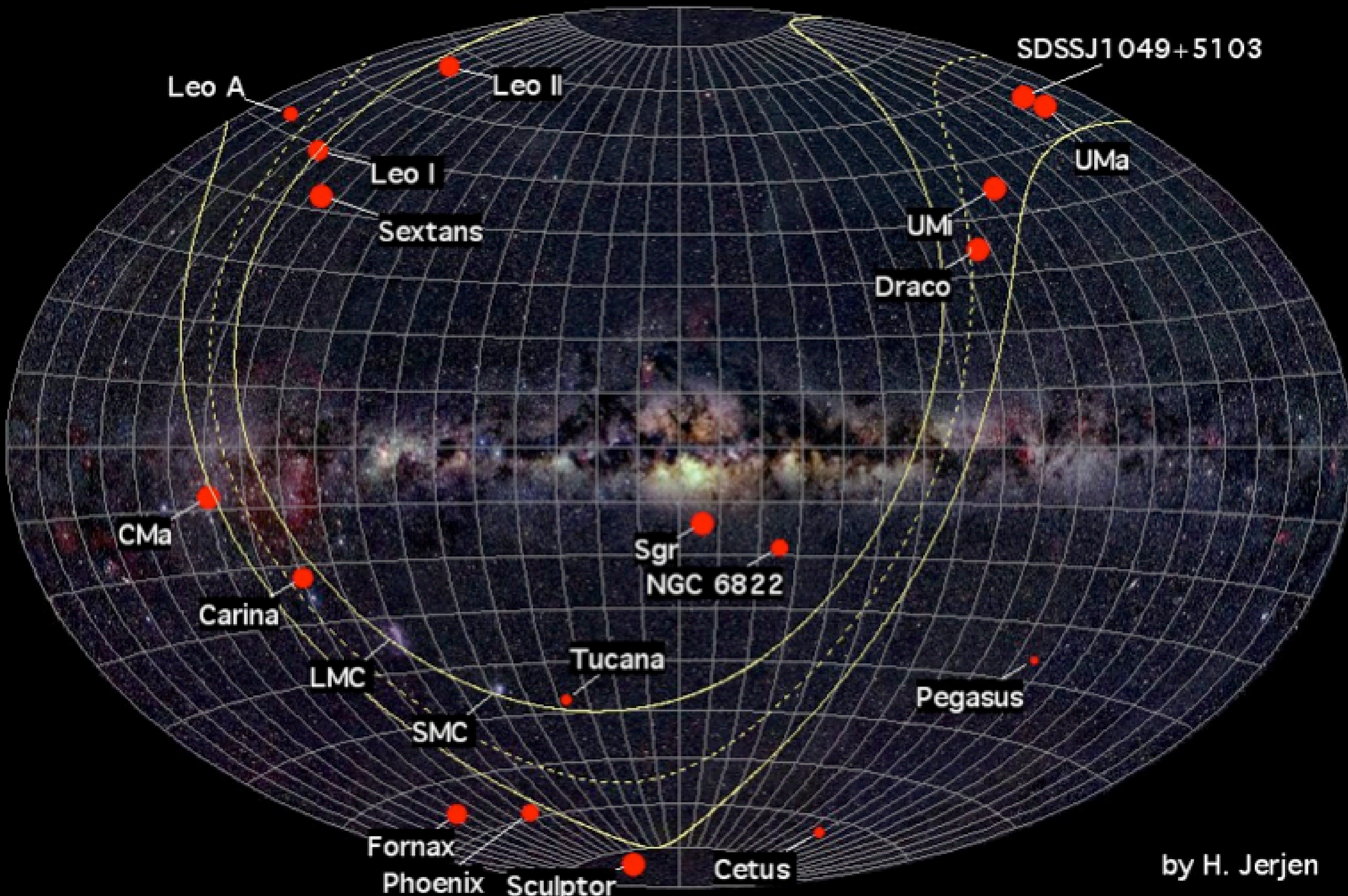


Fig. 1. The position of the innermost 11 MW satellites (Table 1) as viewed from a point located at infinity and $l = 167^{\circ}.91$. The MW disk is indicated by the horizontal line $-25 \leq X/\mathrm{pc} \leq 25$, and the centre of the coordinate system lies at the Galactic centre. The dashed line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


SDSSJ1049+5103
Leo A
Leo II
Leo I
Sextans
UMa
UMi
Draco
CMa
Sgr
NGC 6822
Carina
LMC
Tucana
SMC
Pegasus
Fornax
Phoenix
Sculptor
Cetus
by H. Jerjen

MW satellites are instead in a disk-like configuration:

(Kroupa, Theis & Boily 2005)

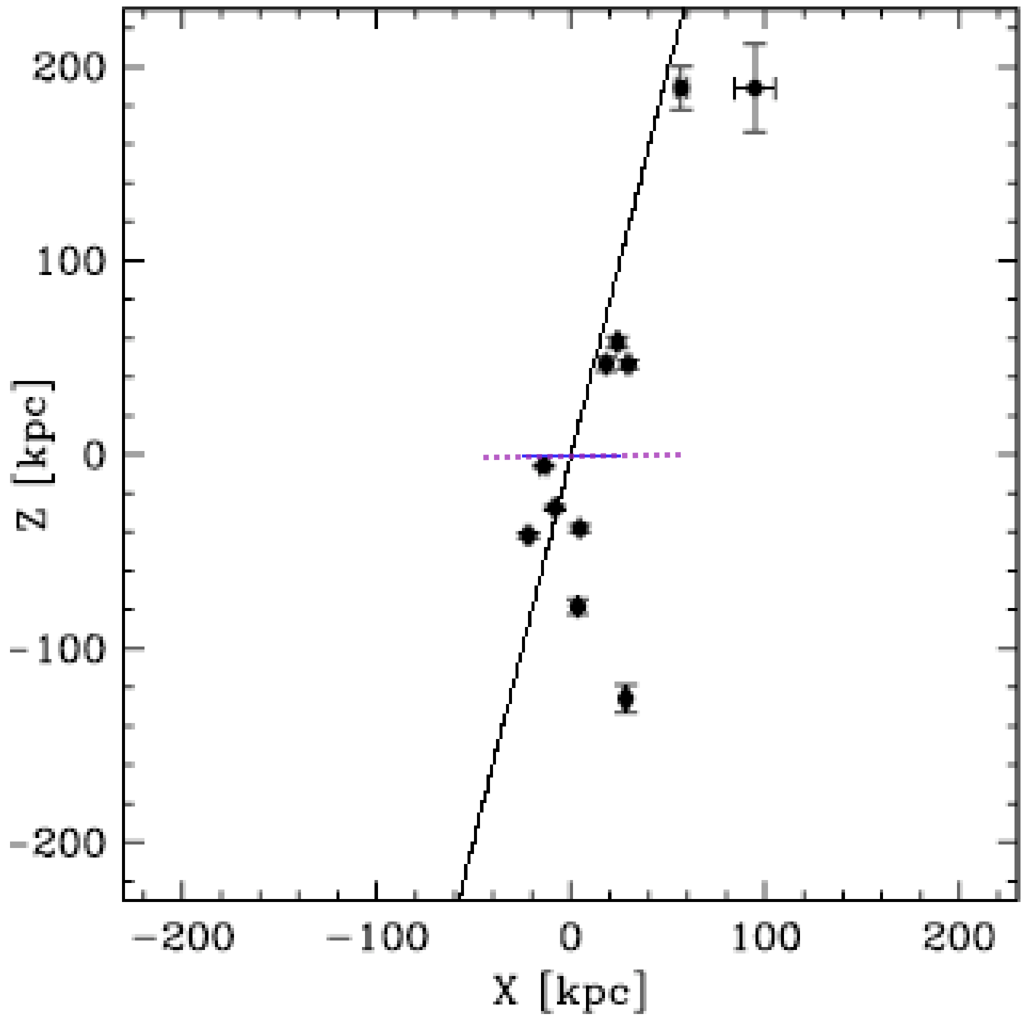


Fig. 1. The position of the innermost 11 MW satellites (Table 1) as viewed from a point located at infinity and $l = 167^\circ.91$. The MW disk is indicated by the horizontal line $-25 \le X/\mathrm{pc} \le 25$, and the centre of the coordinate system lies at the Galactic centre. The dashed line marks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

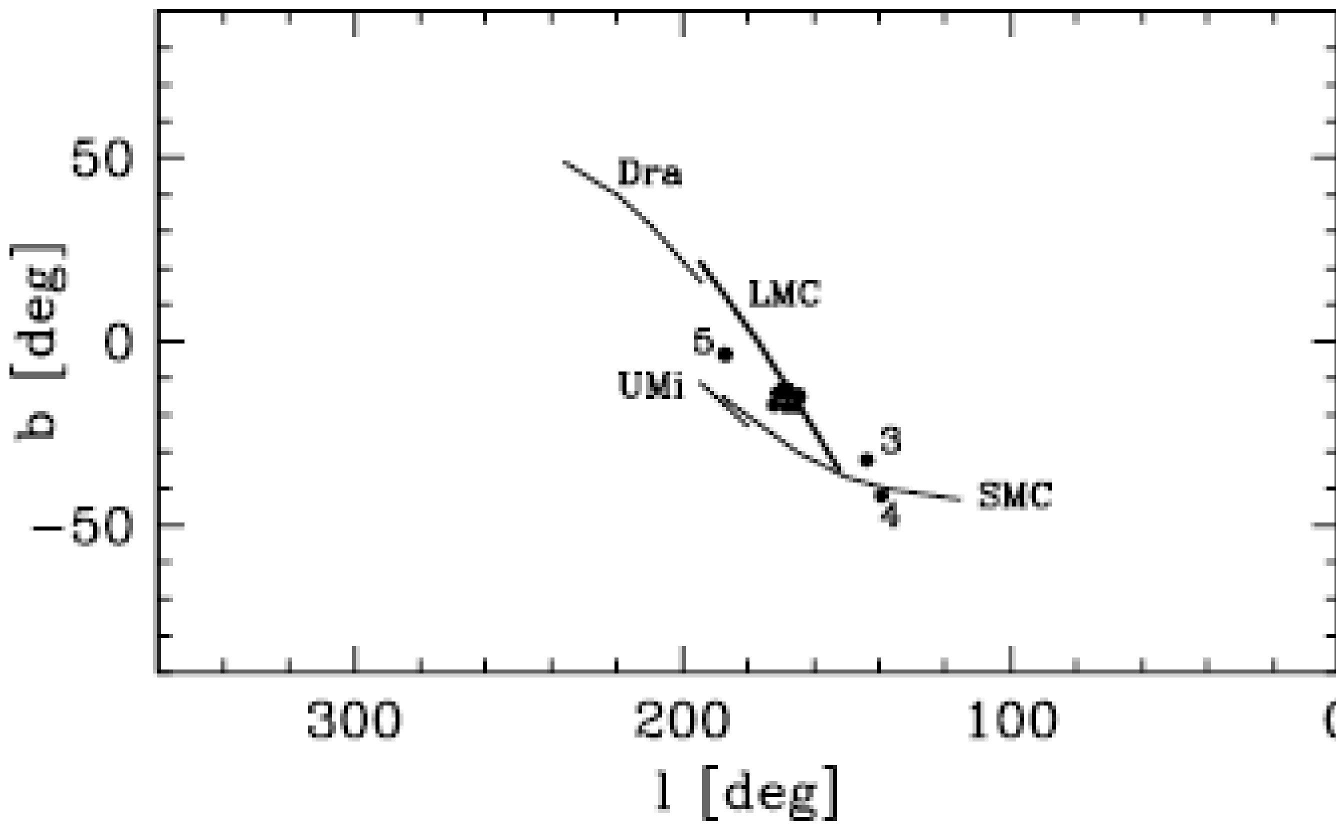


Fig. 3. The position on the Galactic sky of the poles of the planes fitted to the dwarves of Table 1. Plotted are $b_P = -b'_p$ and $l_P = l'_p + 180°$ and the number of dwarves used for the fit ranges from $N = 16$ down to $N = 3$ (Table 1). The cases for $N = 3, 4, 5$ are indicated with numbers. The others cluster very tightly around $l_P \approx 168°, b_P \approx -16°$. The likely position of the orbital poles of the LMC, SMC, Draco and UMi are indicated by the solid curves (from Fig. 3 in Palma et al. 2002).

(Kroupa, Theis & Boily 2005)

The MW dSph satellites thus fulfill:

1) Stable pole position independent of which satellites are picked.

2) A plane that passes close (few kpc) to the GC.

3) A plane highly inclined to the dominant accretion structure (the MW disk).

4) A *thin* plane: $\Delta/R < 0.17$

This is inconsistent with shape of
CDM halo with
> 99.6% confidence
if it is
flattened and approximately co-planar to MW disk.

Observational evidence supports this for the MW
(Merrifield 2001; Ibata et al. 2001; Majewski et al. 2003; Martinez-Delgado et al. 2004; Johnston, Law & Majewski 2005).

Theoretical work incorporating dissipational physics also
(Dubinski 1994; Kazantzidis et al. 2004; Okamoto et al. 2005).

Kroupa, Theis & Boily (2005) prompted

"a cosmological turmoil"

and a

"flurry of activity . . . burst out"

(Lee & Kang 2005) :

Kang, Mao, Gao & Jing (2005, A&A) : . . . I

Abstract. We study the spatial distribution of satellite galaxies by assuming that they follow the dark matter distribution. This assumption is supported by semi-analytical studies based on high-resolution numerical simulations. We find that for a Milky-Way type halo, if only a dozen satellite galaxies are observed, then they can lie on a "great" disk with an rms height of about 40 kpc. The normal to the plane is roughly isotropic on the sky. These results are consistent with the observed properties of the satellite galaxies in the Milky Way. If, however, the satellite galaxies follow the distribution of substructure selected by present mass, then great disks similar to the one in the Milky Way are rare and difficult to reproduce, in agreement with the conclusion reached by Kroupa et al. (2004).

Kroupa, Theis & Boily (2005) prompted

"a cosmological turmoil"

and a

"flurry of activity . . . burst out"

(Lee & Kang 2005) :

Zentner, Kravtsov, Gnedin & Klypin (2005, ApJ) : . . . II

ABSTRACT

We present a study of the spatial distribution of dwarf satellites (or subhalos) in galactic dark matter halos using dissipationless cosmological simulations of the concordance flat Cold Dark Matter (CDM) model with vacuum energy. We find that subhalos are distributed anisotropically and are preferentially located along the major axes of the triaxial mass distributions of their hosts. The Kolmogorov-Smirnov probability for drawing our simulated subhalo sample from an isotropic distribution is $P_{KS} \simeq 1.5 \times 10^{-4}$. An isotropic distribution of subhalos is thus not the correct null hypothesis for testing the CDM paradigm. The nearly planar distribution of observed Milky Way (MW) satellites is marginally consistent (probability $\simeq 0.02$) with being drawn randomly from the subhalo distribution in our simulations. Furthermore, if we select the subhalos likely to be luminous, we find a distribution that is consistent with the observed MW satellites. In fact, we show that subsamples of the subhalo population with a centrally-concentrated radial distribution that is similar to that of the MW dwarfs typically exhibit a comparable degree of planarity. We explore the origin of the observed subhalo anisotropy and conclude that it is likely due to (1) the preferential accretion of satellites along filaments, often closely aligned with the major axis of the host halo, and (2) evolution of satellite orbits within the prolate, triaxial potentials typical of CDM halos. Agreement between predictions and observations requires the major axis of the outer dark matter halo of the Milky Way to be nearly perpendicular to the disk. We discuss possible observational tests of such disk–halo alignment with current large galaxy surveys.

Kroupa, Theis & Boily (2005) prompted
"a cosmological turmoil"
and a
"flurry of activity . . . burst out"
(Lee & Kang 2005) **:**

Libeskind, Frenk, Cole, Helly, Jenkins,
Navarro & Power (2005, MNRAS)**:** . . . III

ABSTRACT

The 11 known satellite galaxies within 250 kpc of the Milky Way lie close to a great circle on the sky. We use high resolution N-body simulations of galactic dark matter halos to test if this remarkable property can be understood within the context of the cold dark matter cosmology. We construct halo merger trees from the simulations and use a semianalytic model to follow the formation of satellite galaxies. We find that in all 6 of our simulations, the 11 brightest satellites are indeed distributed along thin, disk-like structures analogous to that traced by the Milky Way's satellites. This is in sharp contrast to the overall distributions of dark matter in the halo and of subhalos within it which, although triaxial, are not highly aspherical. We find that the spatial distribution of satellites is significantly different from that of the most massive subhalos but is similar to that of the subset of subhalos that had the most massive progenitors at earlier times. The elongated disk-like structure delineated by the satellites has its long axis aligned with the major axis of the dark matter halo. We interpret our results as reflecting the preferential infall of satellites along the spines of a few filaments of the cosmic web.

CDM cosmologists are happy . . .

or are they ?

Zentner et al. (2005, ApJ) (II) attempt to argue that the MW dSph satellites <u>are</u> CDM sub-halos/satellites, but this requires a pronounced prolate MW halo:

$$c/a \approx b/a \approx 0.6$$

which is $\perp$ to the MW disk (i.e. repeat of the argument by Hartwick 2000).

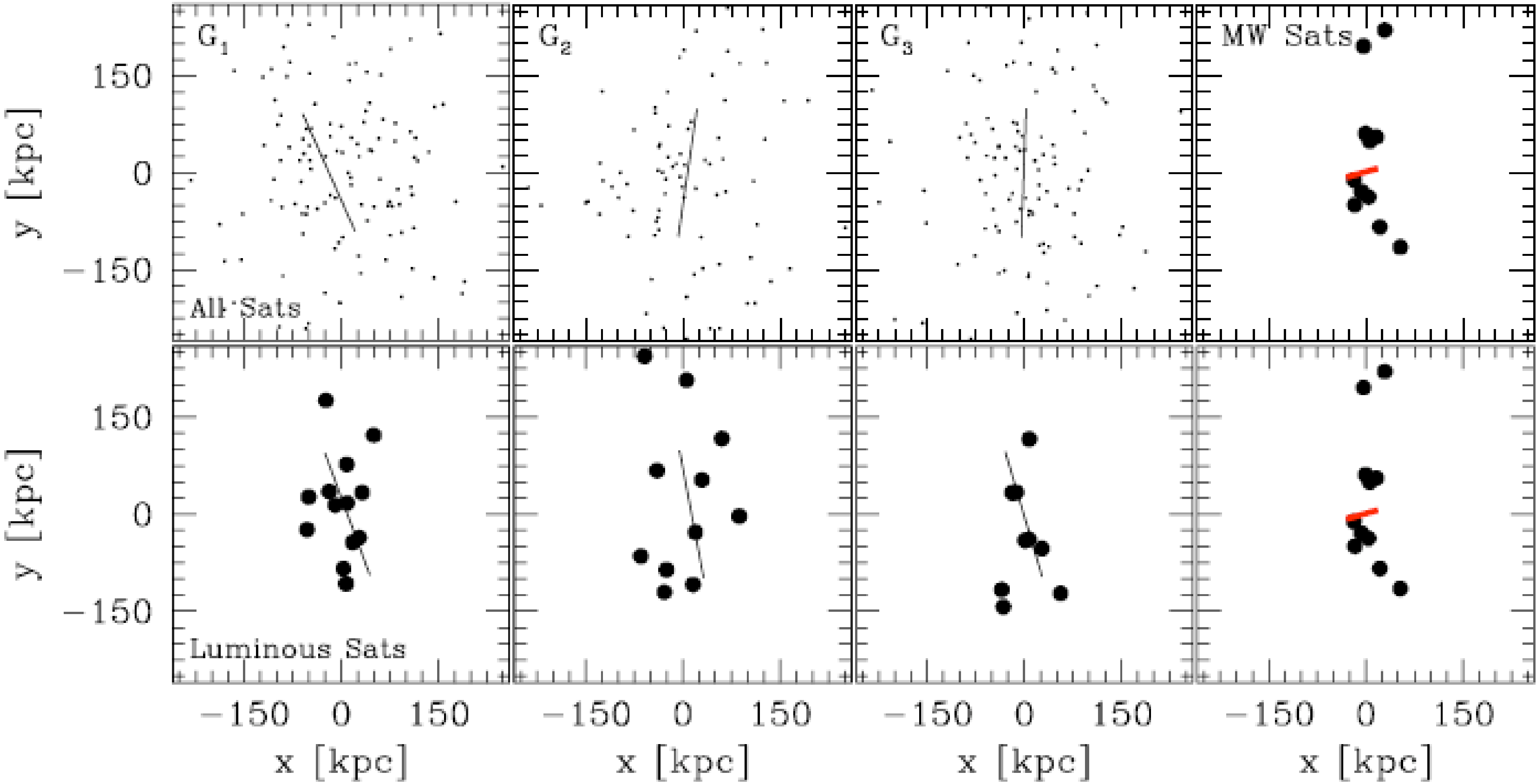
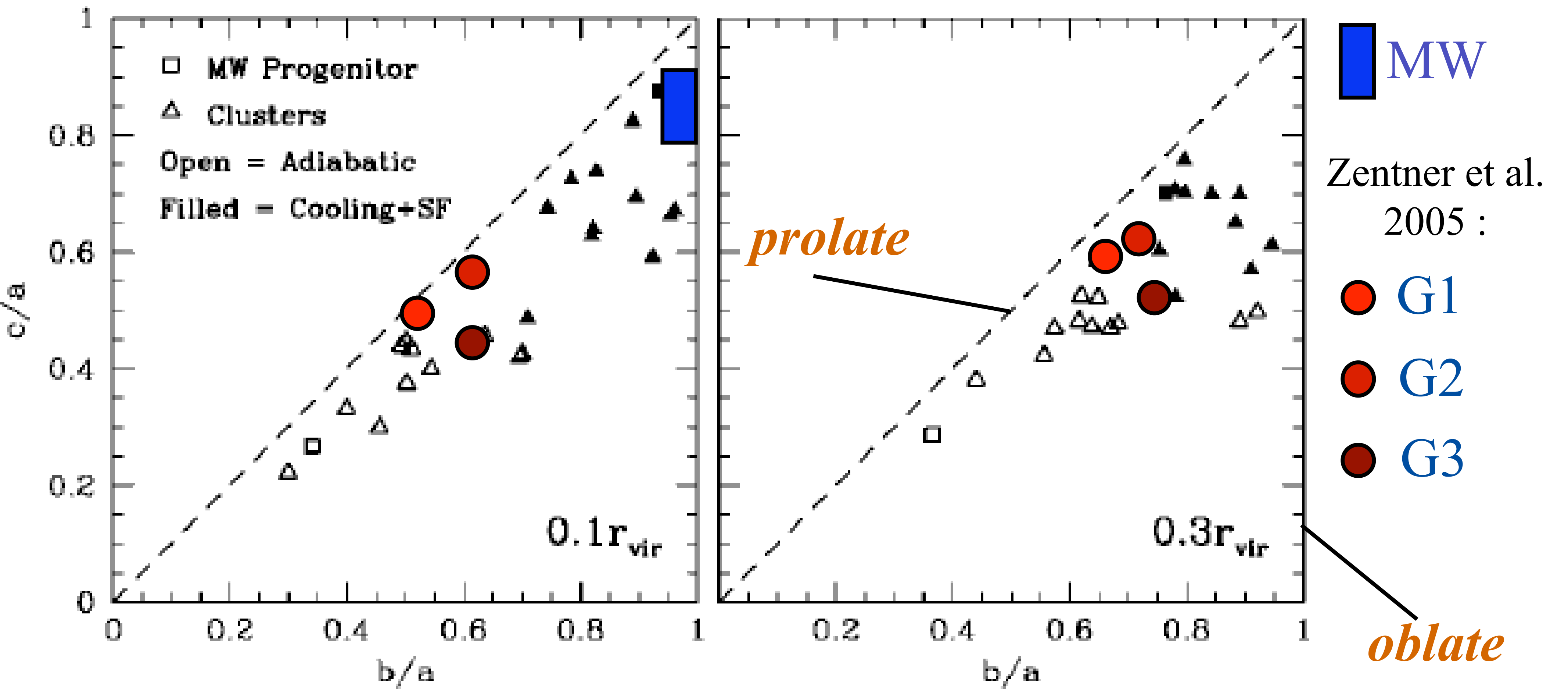


FIG. 2.— Projections of satellites in a plane orthogonal to their best-fit planes (see text). All panels show scatter plots of the positions of satellites projected onto a plane perpendicular to their best-fit plane. The best-fit plane corresponds to the vertical axis in this projection. In both rows, the first panel shows results for the subhalos of halo G_1, the second column for halo G_2, and the third column for halo G_3. The fourth column in each row shows the observed MW satellites. In the first three columns, the projection is such that the major axis of the host halo lies in the plane of the projection. In these panels, the major axis is shown as the *thin, solid* line. In the fourth column, the projection is such that the MW disk is seen edge-on and the MW disk orientation is denoted by the *thick, solid* line. In the top row, we compute the best-fit plane by considering all subhalos within $\approx$ 300 kpc of the center of the host halo. In the bottom row, we compute the best-fit plane with respect to all luminous subhalos within 300*kpc* of the host halo center.

But Kazantzidis et al. 2004 note that ***gas dissipation***

→ ***more spherical*** halo shapes even out to virial radius.



THUS, II is excluded.

Libeskind et al. (2005, MNRAS)

(III)

suggest the "*Durham Pancake*" solution :

They find that the *major axis* of the satellite distribution is approximately *co-aligned* to that of the host DM halo!

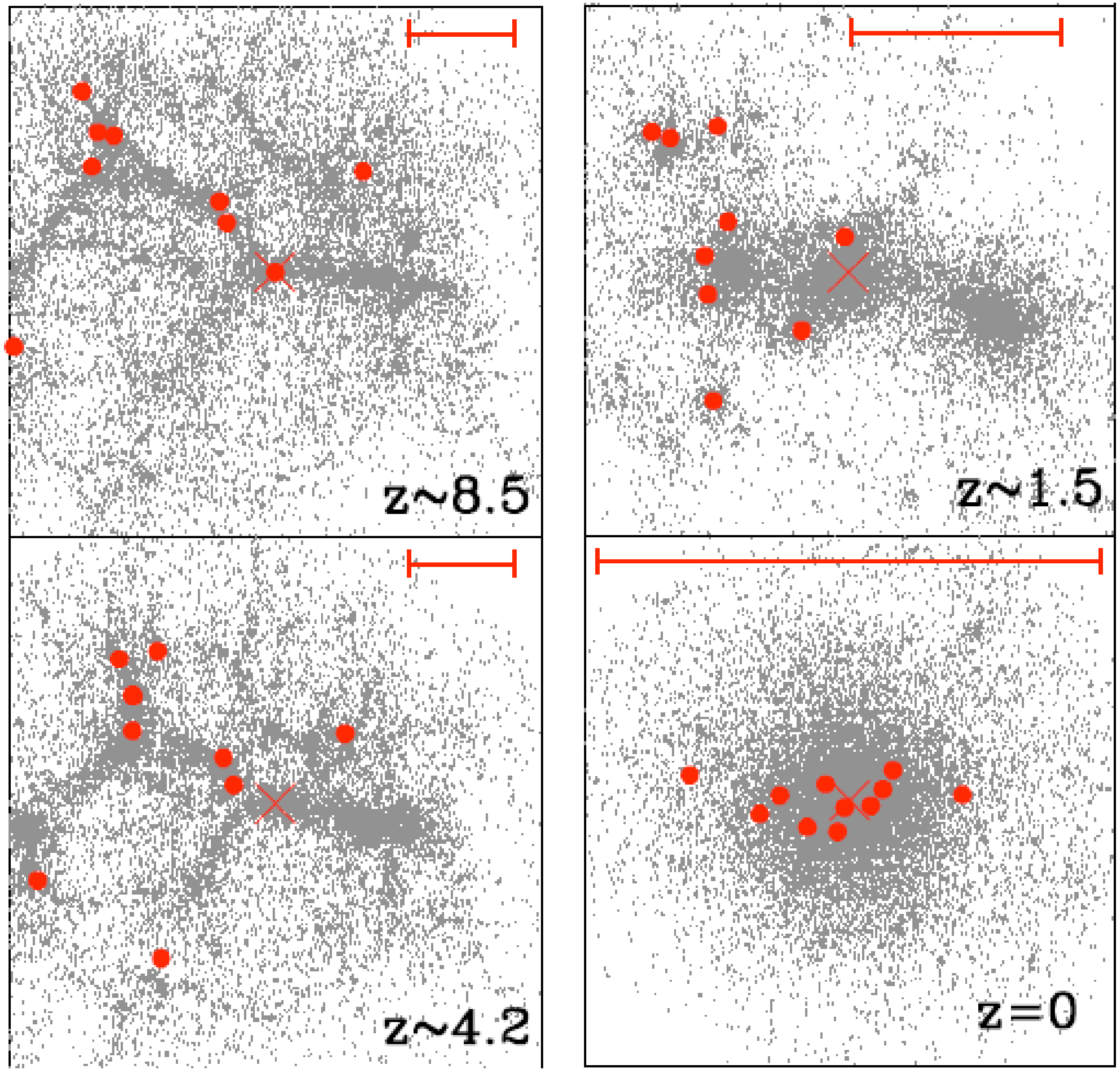
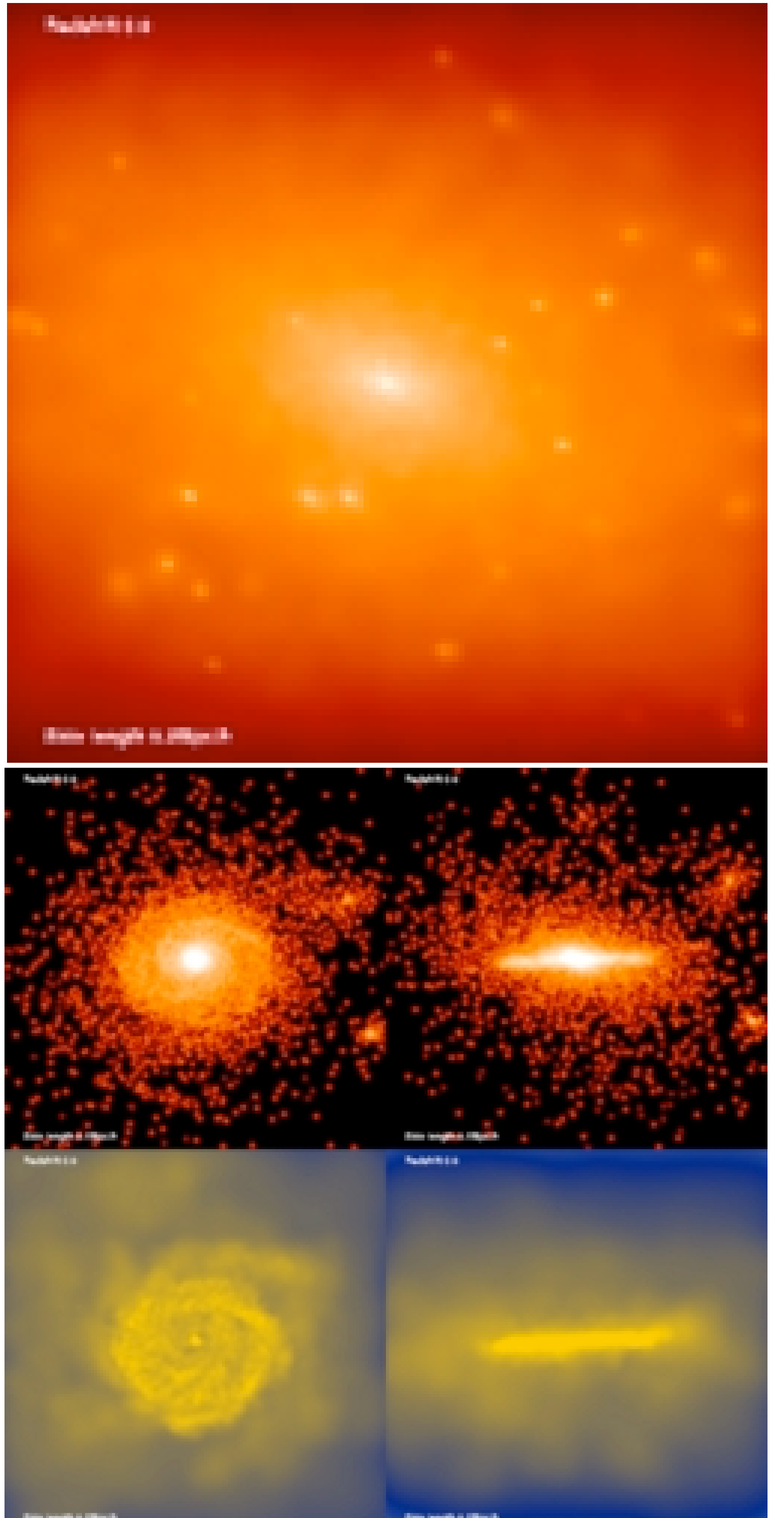


Figure 5. The formation of a galactic halo and its satellites. The points show a random 1% of the dark matter particles that end up in the main halo and the red circles the positions of the 11 most massive satellites that end within 250 kpc of the main galaxy by the present day. The scale of each plot is indicated by the red line which has a co-moving length of 400 kpc. The initial collapse produces a 2D structure – a large pancake of dark matter.

Libeskind, Frenk, Cole, Helly, Jenkins, et al.
(2005, MNRAS)

need to invoke $\perp$ location of the MW disk relative to their satellite distribution.

But, this appears to contradict their own results :



Okamoto, Eke, Frenk, Jenkins (2005, MNRAS)
(again the Durham team)

Here, they state that
the disk is approximately co-planar
to the major plane
of the host DM halo.

And, the host DM halo is flattened
such: .

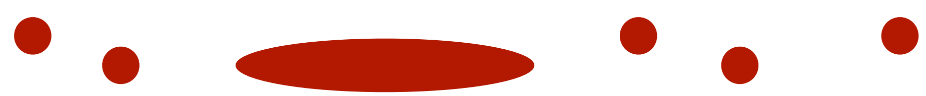
But, the model satellites ought to
lie ,

which ***contradicts*** the assertion by
Libeskind et al. that the
major axis of satellites and of
host DM halo are aligned.

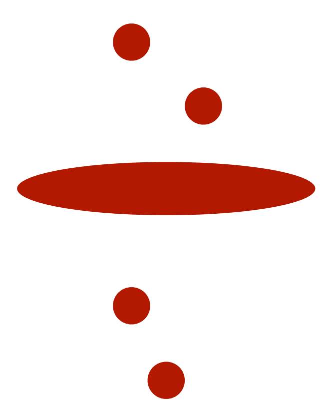
Agustsson & Brainerd (2005, ApJ) :

tion. Here we have shown that the sense of the observed anisotropy (a preference for clustering of satellites near to the major axes of the images of host galaxies) is consistent with the sense of the anisotropy that one would expect in a CDM universe, under the assumption that the major axes of the images of host galaxies are at least modestly correlated with the major axes of their projected halos. A proper resolution to the discrepancies

Thus:

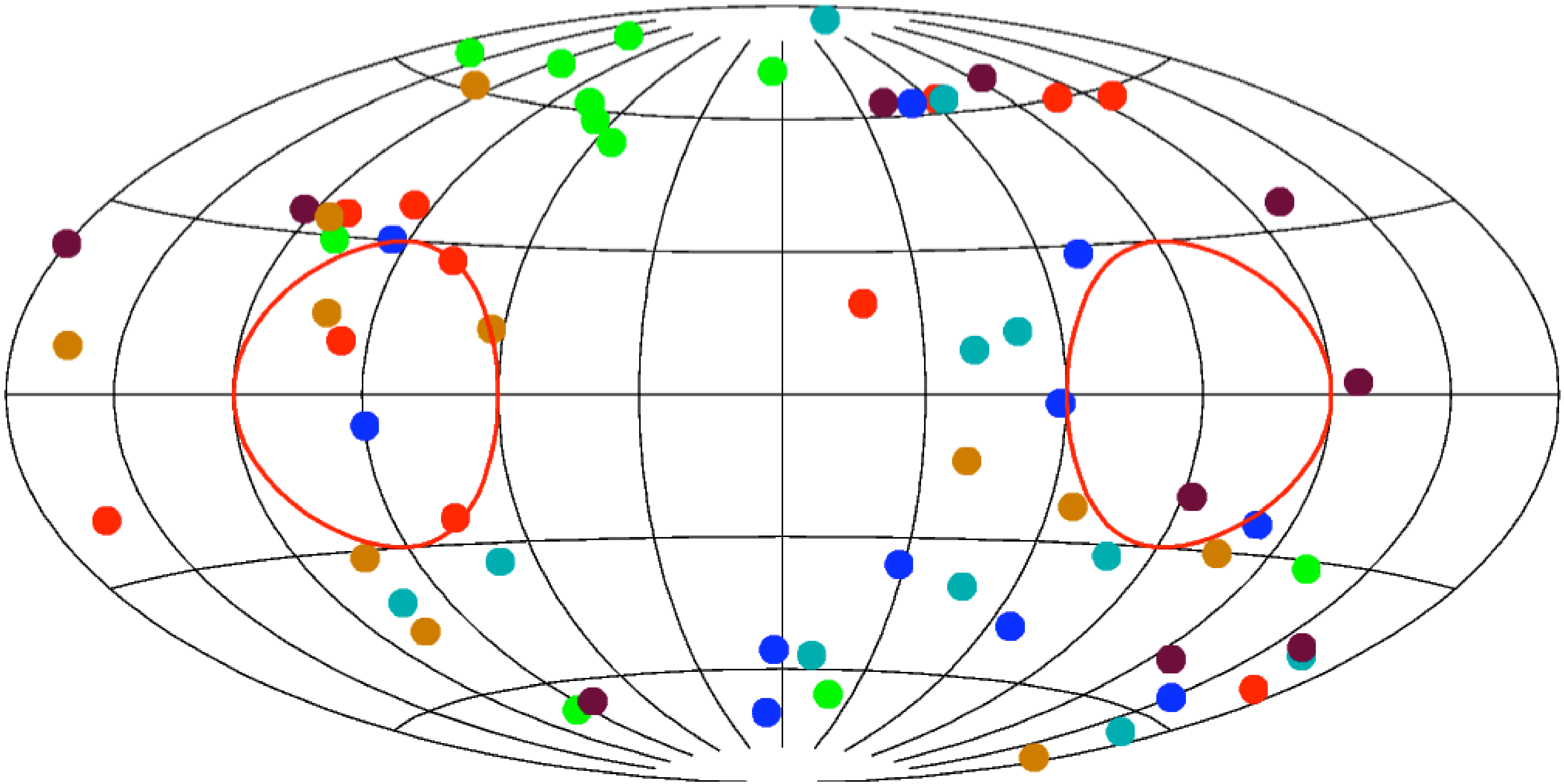


Not:



The correlation of angular momenta

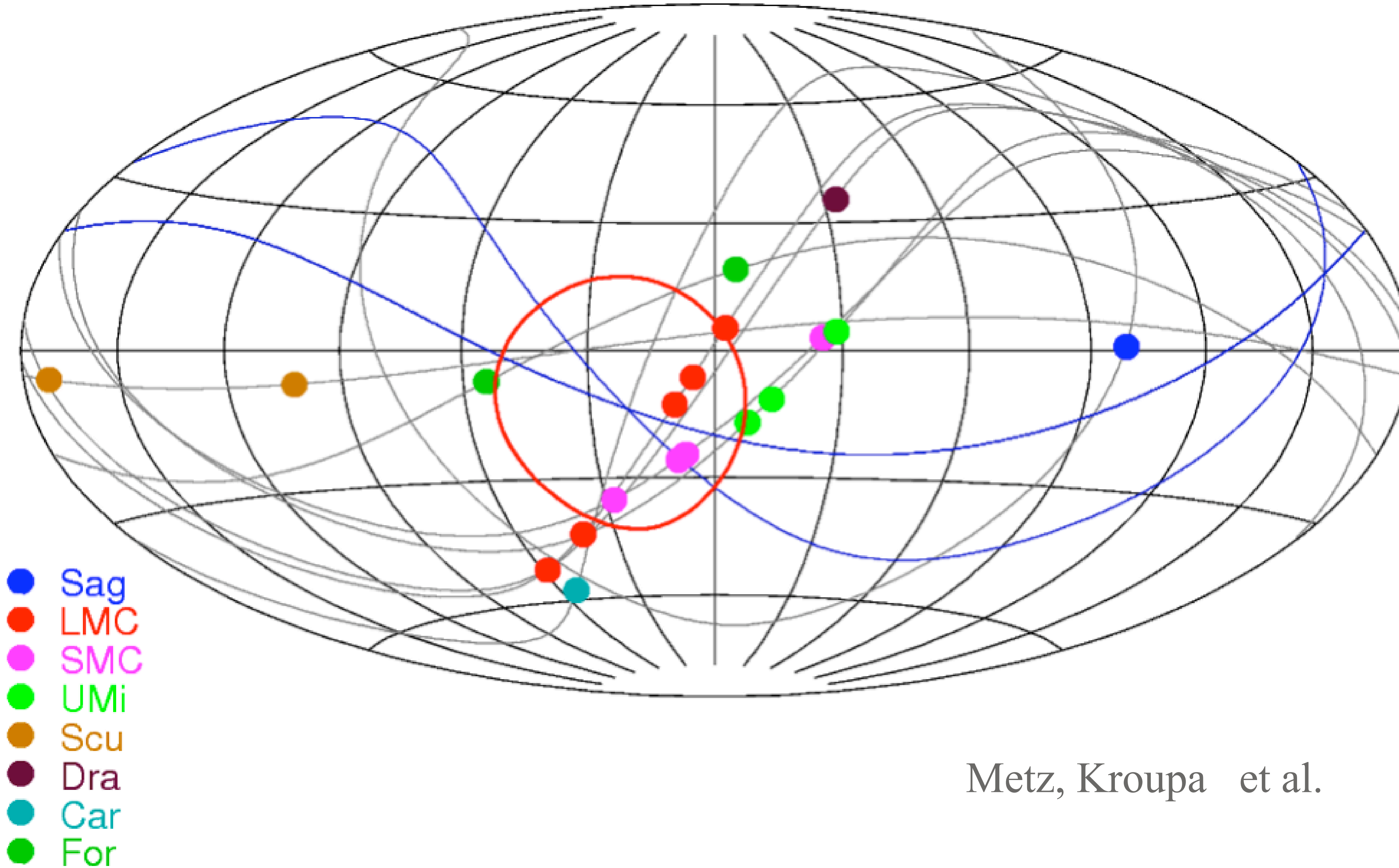
the Durham-Pancake satellites:



Metz, Kroupa et al.

The correlation of angular momenta

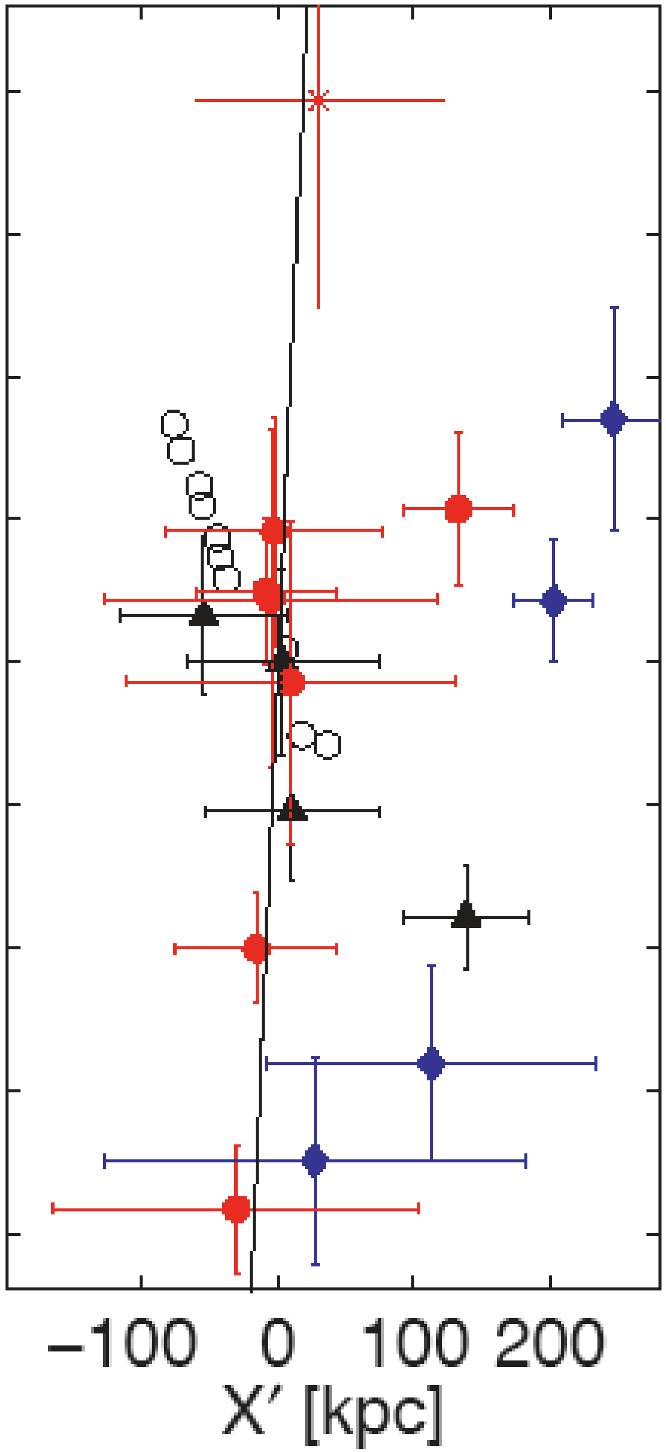
the real satellites:



Metz, Kroupa et al.

THUS, III is excluded.

Andromeda



(Koch & Grebel 2005)

- ● dSph
- ▲ dEs, cEs
- ◆ dIrrs, dIrr/dSph

Polar plane containing
9 out of 15 companions
and
8 out 11
early-type companions.

Significance: 99.7 %

Thickness: 32 kpc

From α to Ω .

The hypothesis that the dSph satellites are related to CDM sub-structures is "uncomfortable" (probably wrong) :

Too many "ifs and twiddles", no consistent theoretical picture within CDM framework, even *contradictions* emerge.

What's the alternative?

Without invoking exotic physics

Instead, the *Disk of Satellites* suggests a causal connection ...

In fact, such a causal connection is supported by detailed kinematical measurements.

The MW *Disk of Satellites* is composed of

A) The *LMC-SMC-UMi-Draco-Carina* stream.

parent: LMC

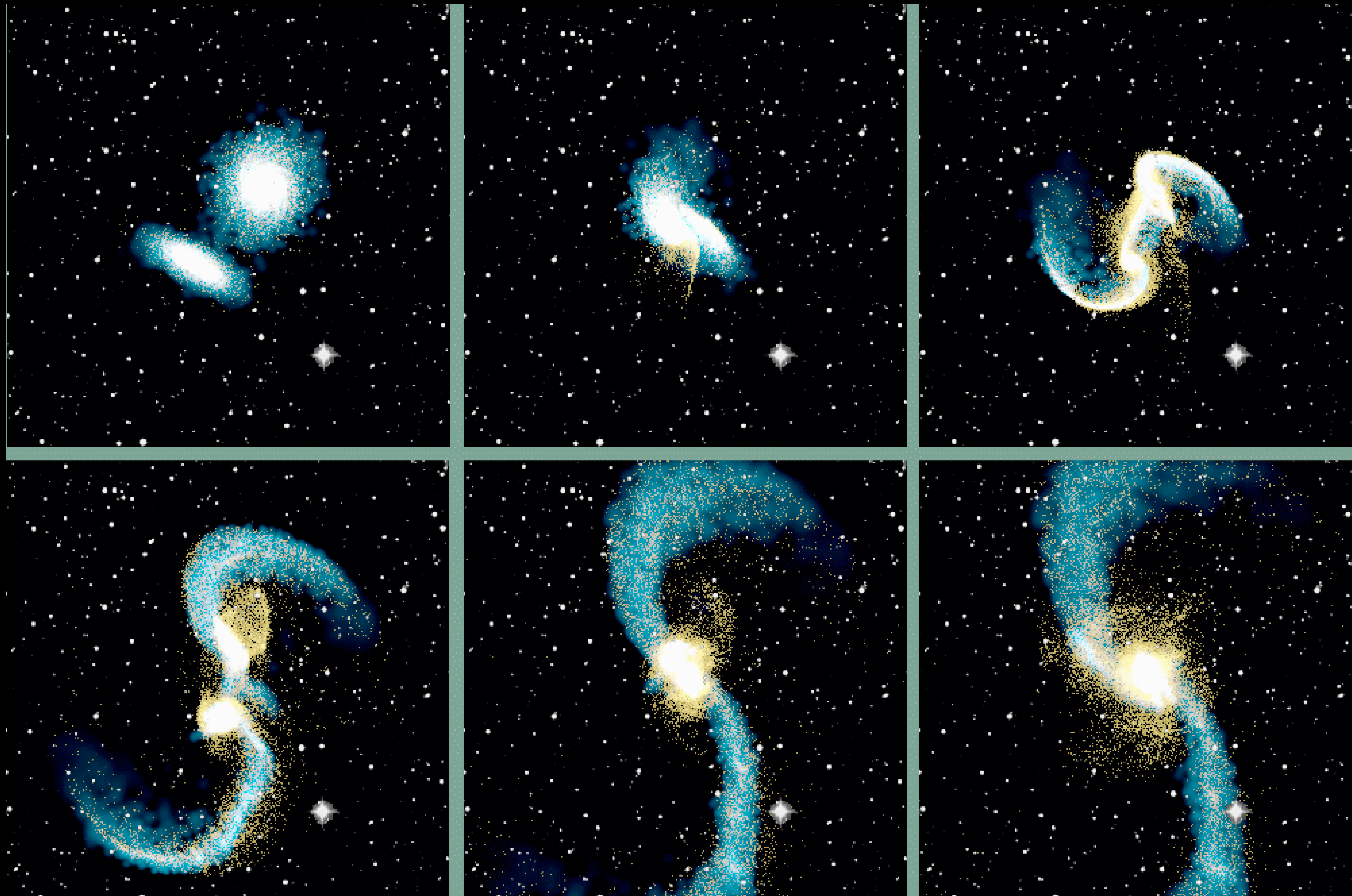
B) The *Fornax-LeoI-LeoII-Sculptor-Sextans* stream:

parent: Fornax

(Lynden-Bell 1976, 1982; Kunkel & Demers 1976; Kunkel 1979; Lynden-Bell & Lynden-Bell 1995; Majewski 1994; Palma et al. 2002; Dinescu et al. 2004)

This then would imply (even prove) that none of *UMi, Draco, Carina* nor *LeoI, LeoII, Sculptor, Sextans* can be DM dominated !!

Tidal tails



Miho & Maxwell, web

Tidal-dwarf satellite galaxies

(Mirabel, Dottori & Lutz 1992; Duc & Mirabel 1994)

A conservative, classical approach to the problem of dSph satellites.

(Weilbacher et al. 2000)

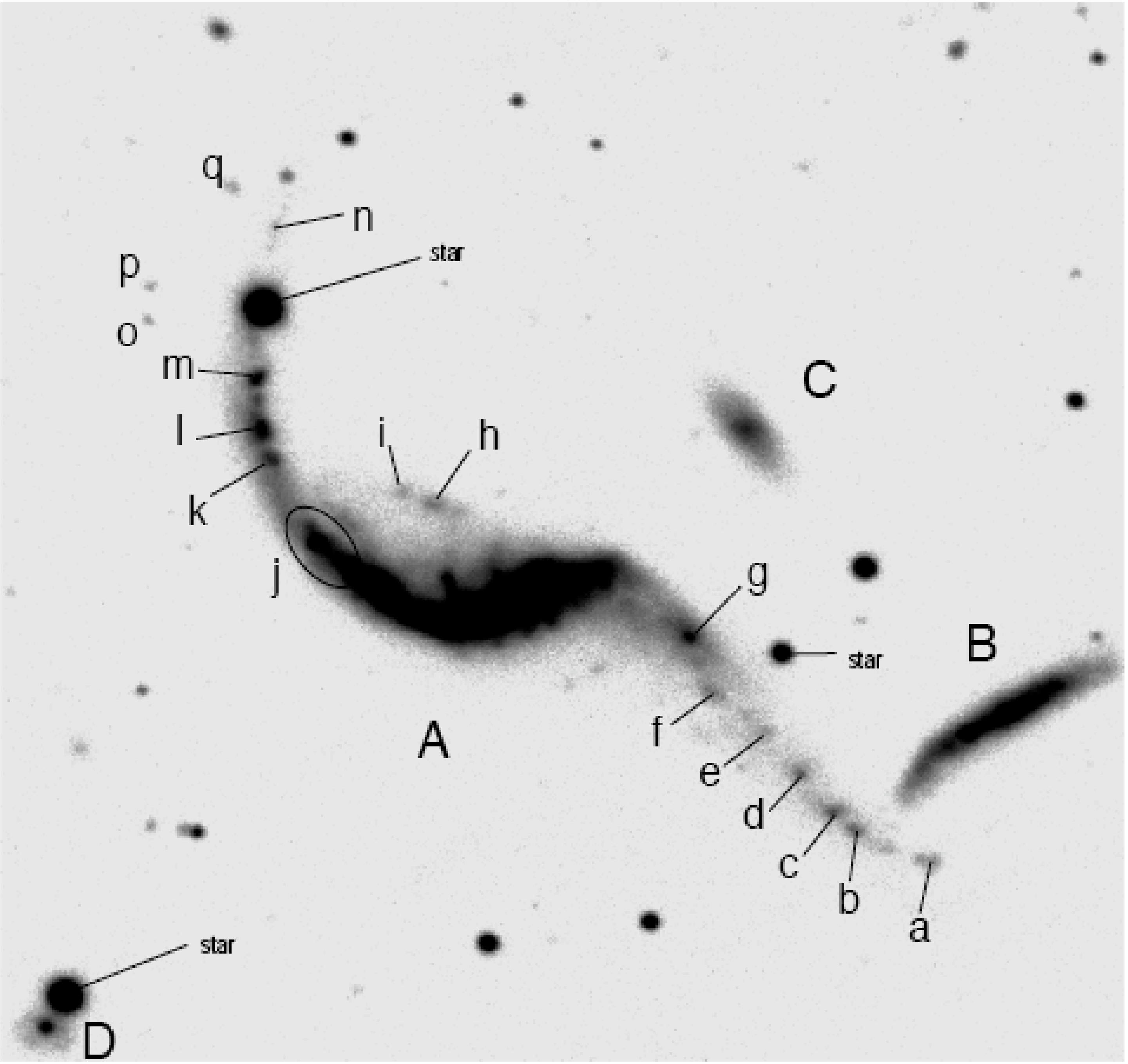


Fig. 21. Identification chart of field 10 around AM 1353-272.

TDG-candidates are observed to form often when gas-rich galaxies interact. Sometimes

$$N_{\rm TDG} \approx 12$$

candidates are seen per event.

Expect $N_{\rm TDG}$ *to scale with gas content* and thus evolutionary status of interacting galaxies.

TDGs are baryon dominated
(Barnes & Hernquist 1992).

Star-cluster complex
(cf *Tadpole*)

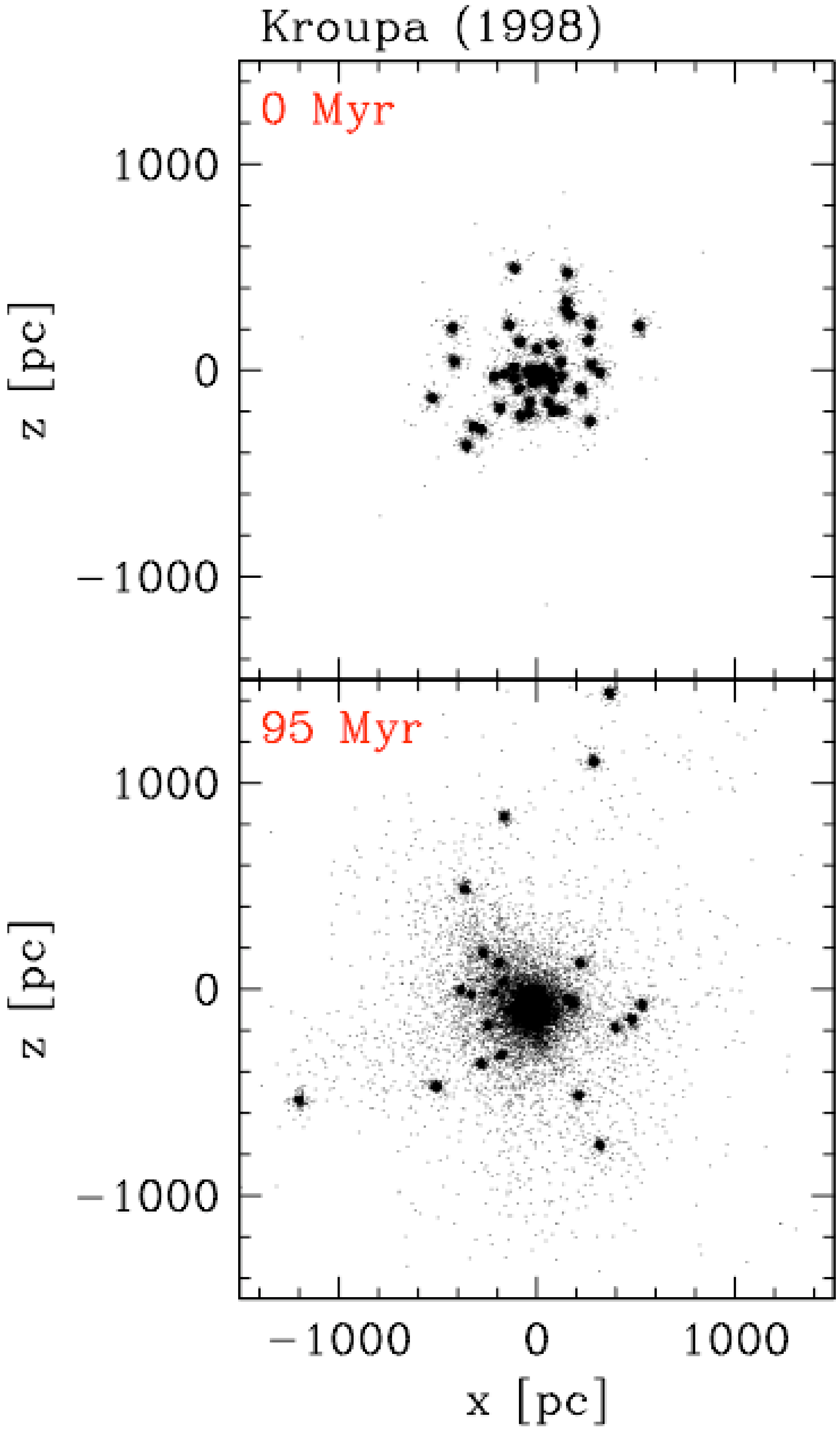
50 clusters
each $10^6\ M_\odot$

clusters as
fundamental galactic building blocks

⇓

Spheroidal dwarf galaxy !

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



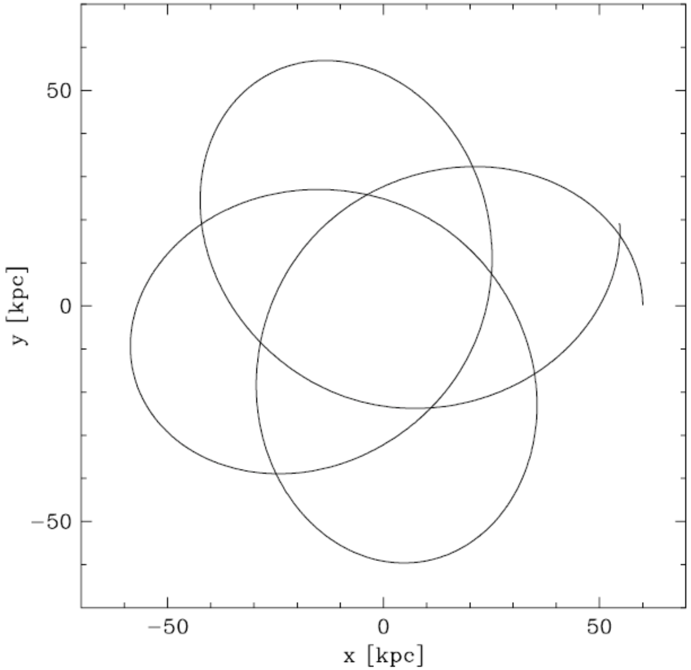
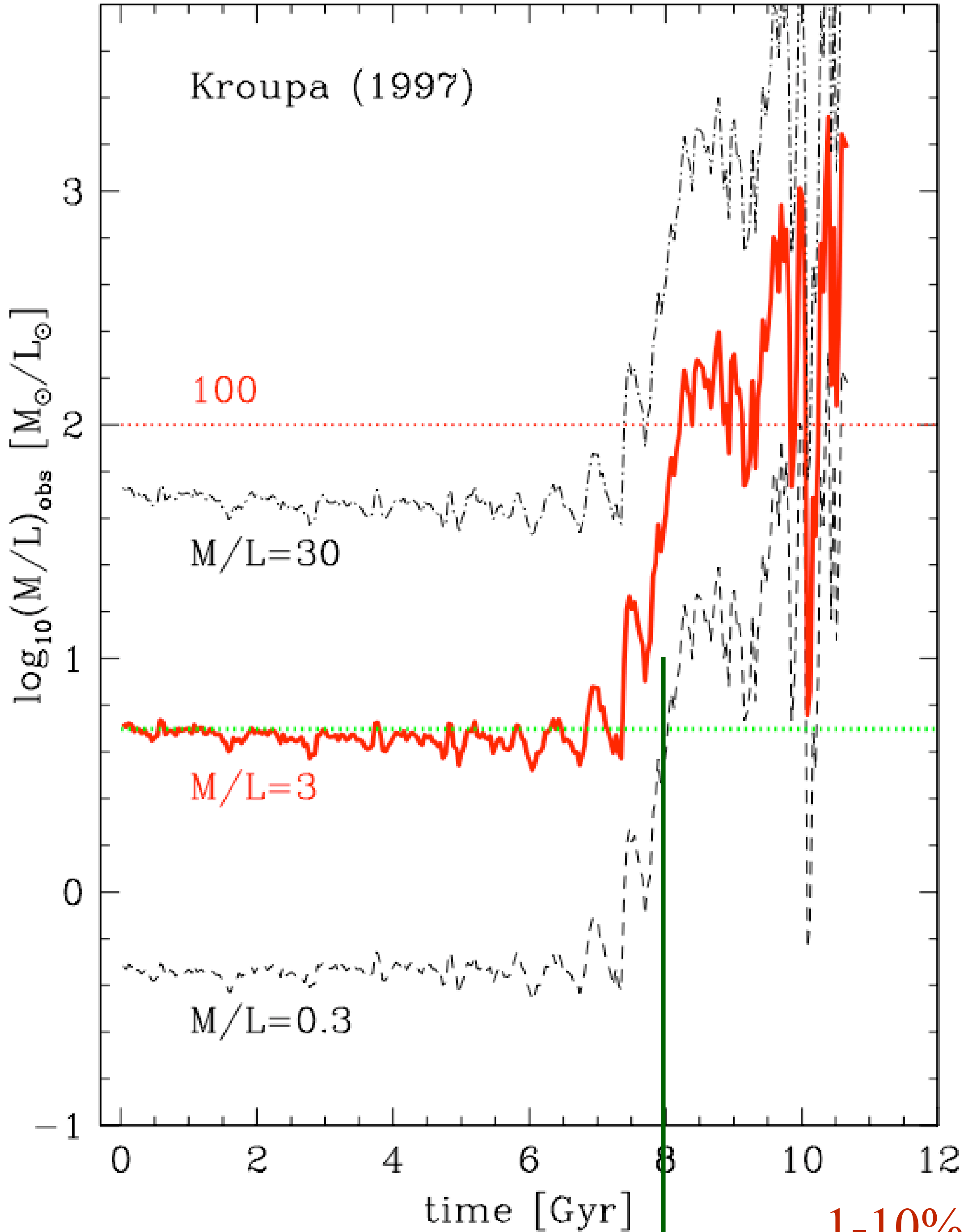


FIG. 3.—Orbital path of the satellite in simulations RS1-113 and Sat-M2.



1-10% of population in remnant

(Kroupa 1997)

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

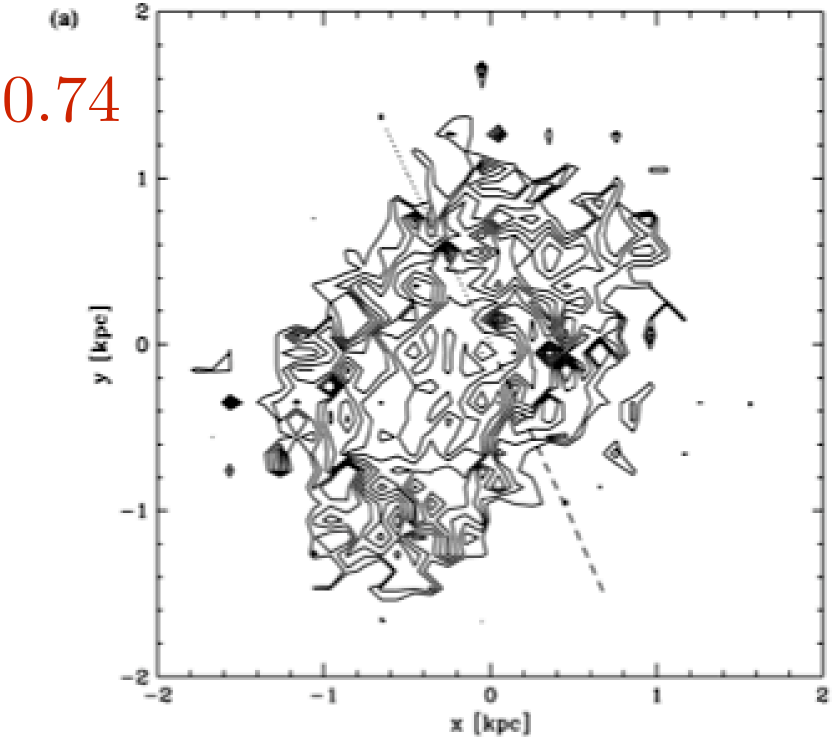
and $\dfrac{M}{L} \approx 10^{2-3}$ **!**

Note:

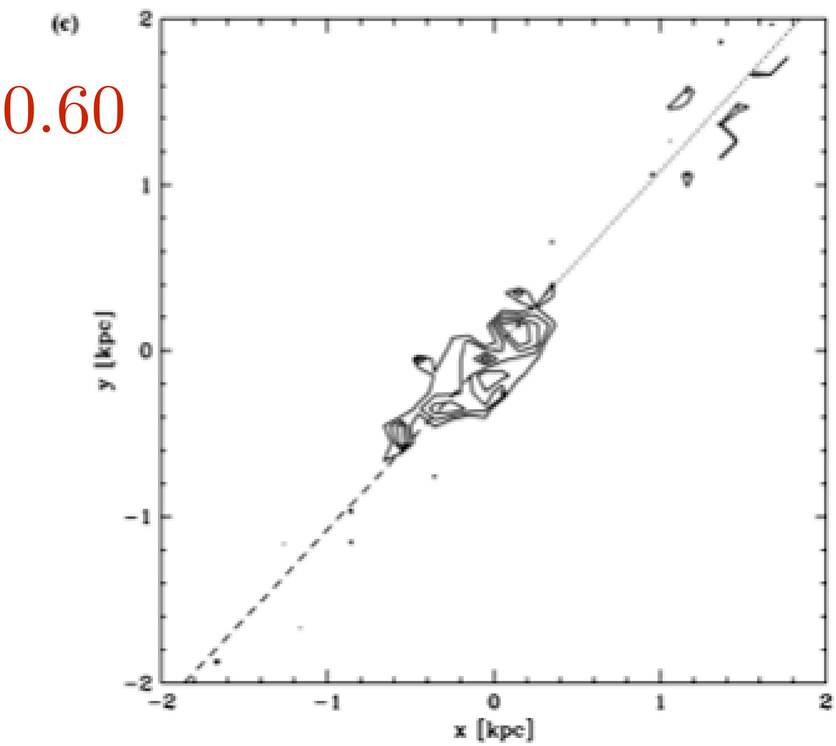
$\sigma_{\rm los} = \text{few} - 20\ \text{km/s}$

depending on projection along orbit.

$e = 0.74$



$e = 0.60$



Conclusions

- Kinematical streams rule-out DM-dominated dSphs!
- Long-lived dSph-like solutions can be obtained from tidal-dwarf-galaxy progenitors.
- Some dSph satellites may be TDGs born as star-cluster complexes (cf. *Tadpole*).
- Remnants have a highly non-isotropic phase-space distribution function with $(M/L)_{\rm obs} > 10$.
- Future theoretical work needs to study the detailed phase-space properties of remnants.
- Contamination of the LF of dwarf-galaxies by TDGs ... (Okazaki & Taniguchi 2000) ?

Conclusions

1) ***If*** streams true
then dSph's cannot be DM dominated.

2) ***If*** streams true ***and*** dSph's are DM dominated
then CDM theory is ruled out (the 'kiss of death").

3) ***If*** streams wrong ***and*** dSph's are DM dominated
then humanity was born during
the Great Galactic Satellite Constellation
("star of Bethlehem scenario")
and CDM theory is ruled out.

Possibility **1)** appears most pallatable *(i.e.* TDGs).

The END