What are the dSph satellites ?

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Simone Recchi *(Trieste)*
Andrea Marcolini *(Preston)*
Helmut Jerjen *(Canberra)*
Christian Boily *(Strasbourg)*

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.

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

Background

$$S \;+\; d1 \;+\; d2 \;+\; \dots \;+ d_n$$

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

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

Globular clusters :

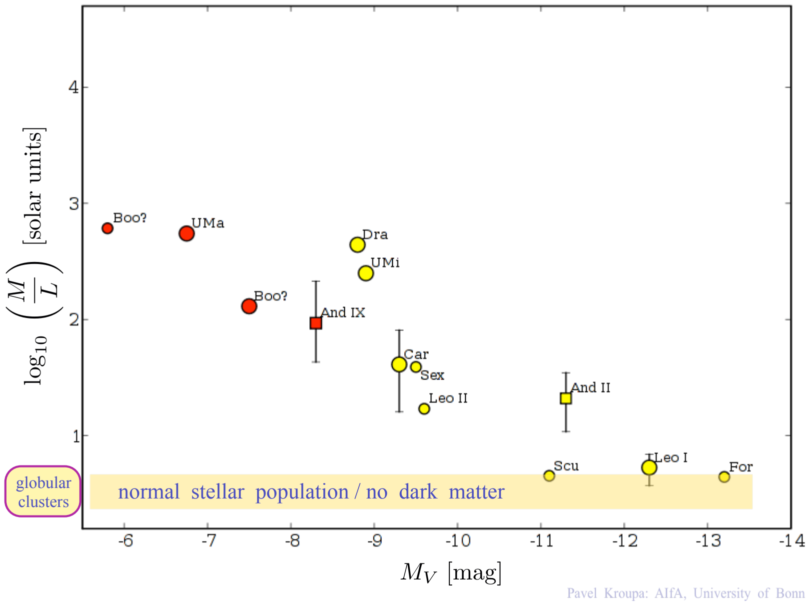
$$R \approx 10\,{\rm pc}\,, \quad \sigma \approx 10\,{\rm km/s}\,, \quad L \approx 10^5\,L_\odot$$

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

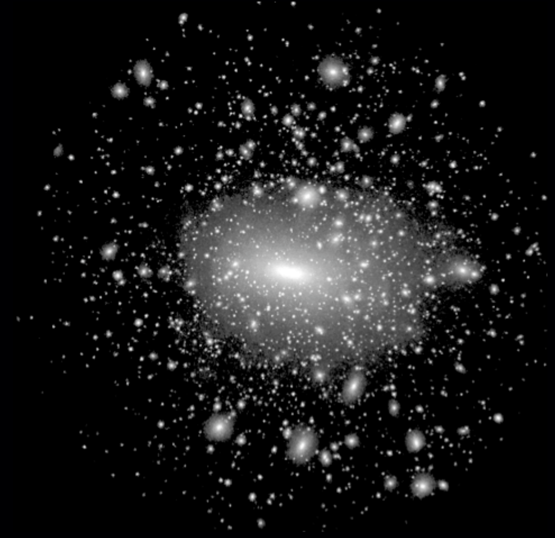
Dwarf spheroidal (dSph) satellite galaxies :

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

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



DM halos of major galaxies are heavily sub-structured :



Standard / most-popular interpretation :

The *dwarf-spheroidal* (dSph) satellite galaxies
are heavily *dark-matter dominated*;

they are part of the
cosmological sub-strucure
surrounding
the Milky-Way.

→ "DM cosmologists" are happy . . .

BUT

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

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

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

$\longrightarrow$ But DM profiles impossible to re-concile with CDM theory (Gilmore et al. 2007)

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

$\longrightarrow$ embedded in massive DM halos ??

IV) disk-like spatial distribution

$\longrightarrow$ incompatible with MW halo shape

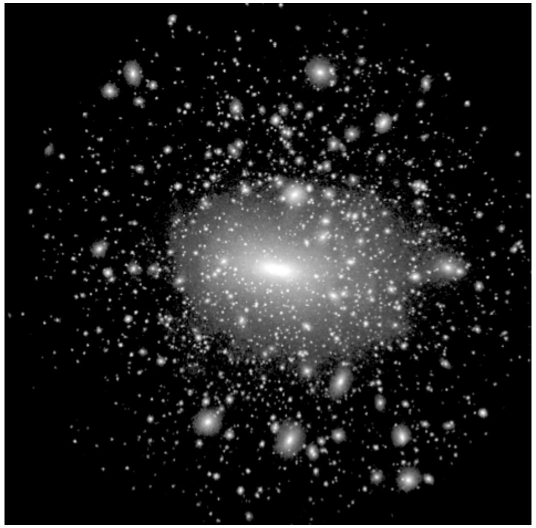
4 independent reasons calling the DM substructure notion into question !

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

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

Different prescriptions by different groups,
most claiming success (which is right?)

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



Today

II)

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

Wilkinson et azl. (2006), Gilmore et al. (2007)

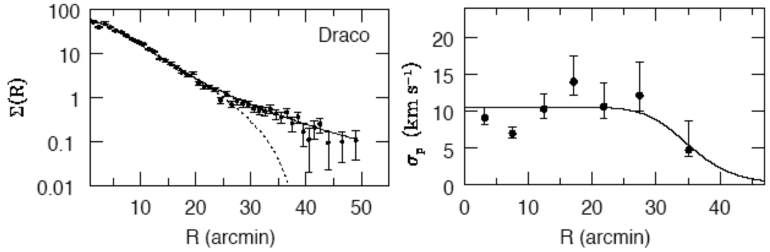


Fig. 3. Surface brightness and velocity dispersion profiles of Draco (Wilkinson et al. 2004). Solid curves show the assumed smooth profiles used in the analysis presented here.

III)

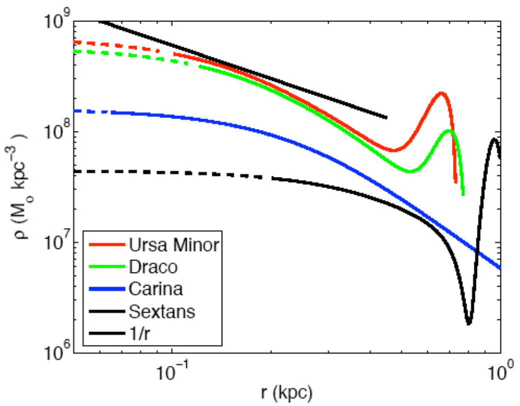
Significant isophote structure is present in many dSph satellites despite a large

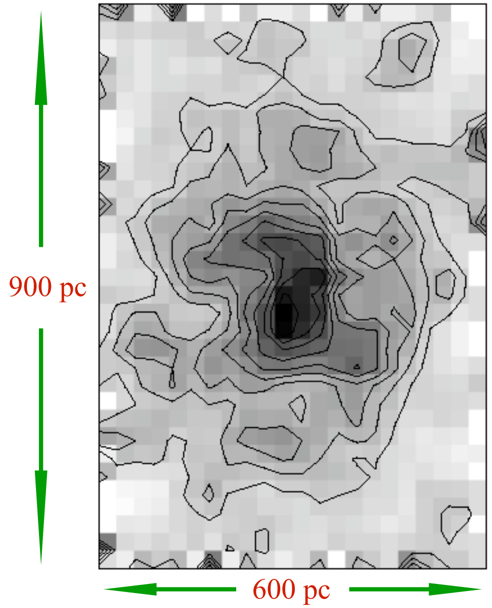
$$\sigma \approx 700 \text{ pc}/100 \text{ Myr}$$

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

⟶ inconsistent with CDM theory.

Wilkinson et al. (2006), Gilmore et al. (2007)





Draco

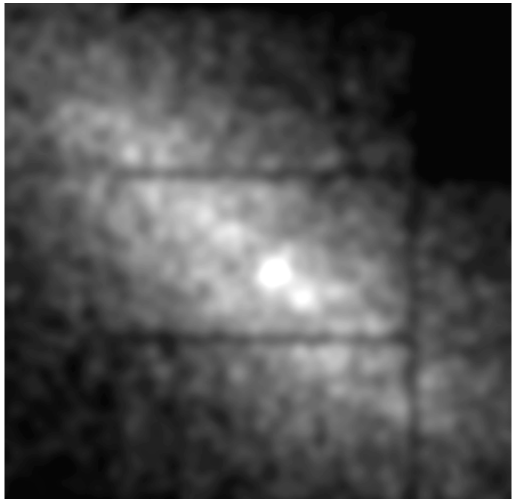
D=75kpc

(Cioni & Habing 2005)

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

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

(Mateo 1998)



UMi

D=65kpc

(Martinez-Delgado et al., in prep)

Substructure significant **:**

(Kleyna et al. 2003)

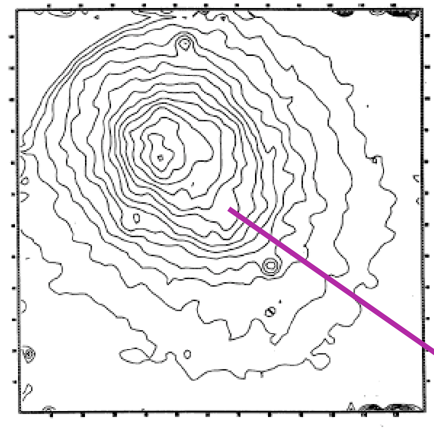


FIG. 4. Isophotes of equal stellar density of field 1 reveal that the structure of Fornax, near the center, is not symmetric.

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)

Not consistent with being embedded / shielded by an extensive dark-matter sub-halo **!**

UMi

D=65kpc

(Martinez-Delgado et al., in prep)

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

↓

Massive CDM halo **?**

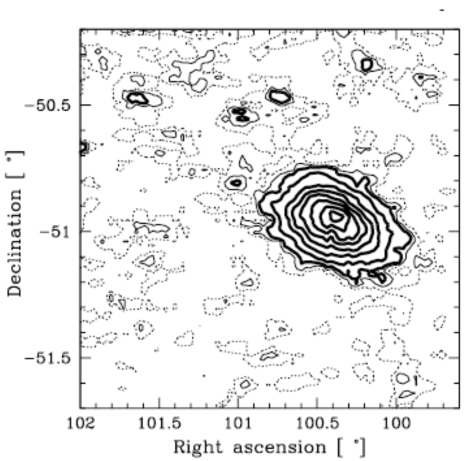


Fig. 1. Contour plot of the Carina dwarf spheroidal. The density levels correspond to background value (dotted line), 1σ above that (thin solid line), 2σ, 5σ, 10σ and so on (thick solid lines). No significant departure from the spheroidal shape can be seen. A galactic gradient can be seen from the northeastern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

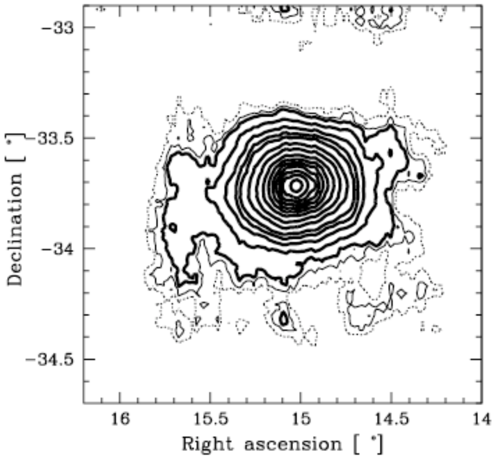


Fig. 2. Contour plot of the Sculptor dwarf spheroidal. The density levels correspond background value (dotted line), 1σ above that (thin solid line), 2σ, 5σ, 10σ and so on (thick solid lines). Note the increase of ellipticity with radius and the potential tidal tails.

Sculptor

D=79kpc

(Walcher et al. 2003)

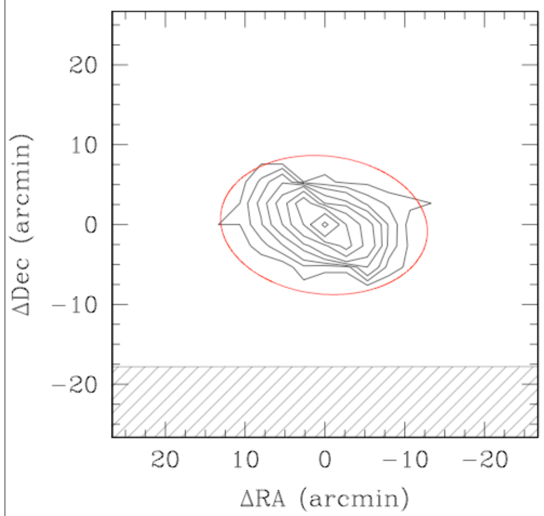
$$\left(\frac{M}{L}\right)_{0,V} = 11$$

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

(Mateo 1998)

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

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



Leo I

D=270kpc

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

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

Massive CDM halo **?**

Contrary to the standard / most-popular interpretation this implies :

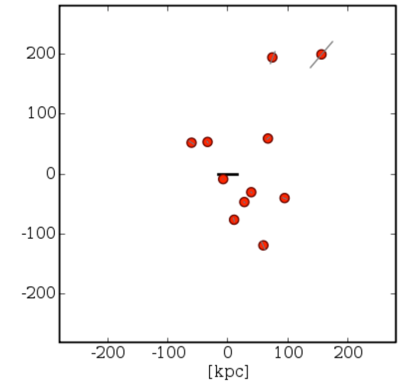
The *dwarf-spheroidal* (dSph) satellite galaxies **are not** *dark-matter dominated*; they **are not** part of the *cosmological sub-strucure* surrounding the Milky-Way.

But then, **what are** the dSph satellites **?**

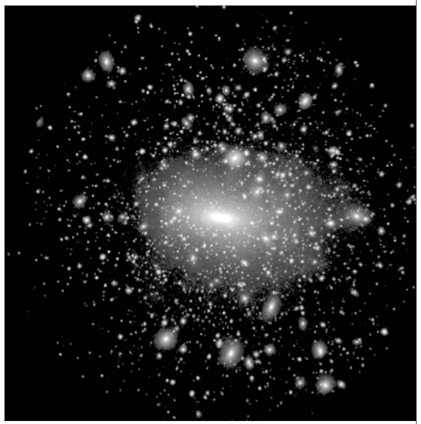
IV)

The spatial distribution of the MW satellites

● the 11 “classical” (brightest) satellites

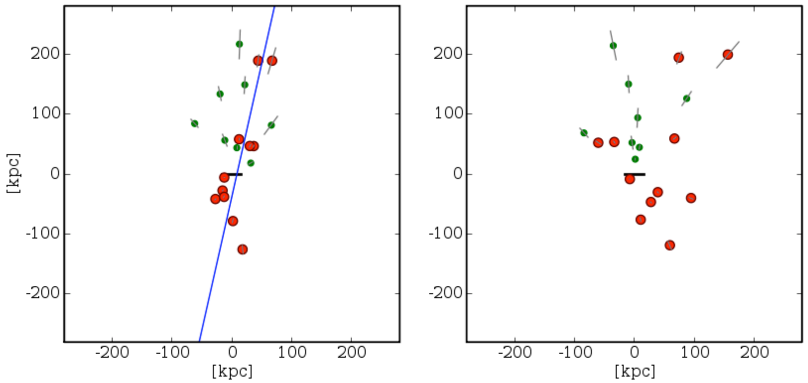


Kroupa, Theis & Boily (2005)
Metz, Kroupa, Jerjen (2006)



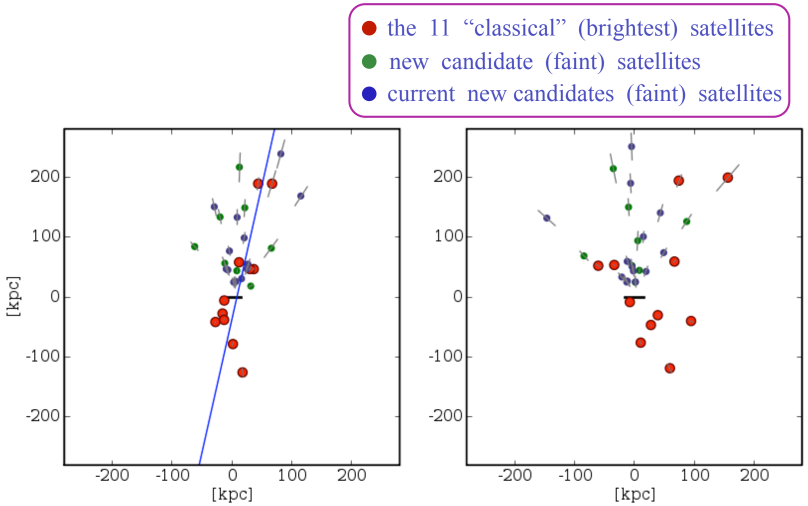
MW satellites are in a disk-like configuration:

● the 11 “classical” (brightest) satellites
● new candidate (faint) satellites



Belokurov et al. (2005);
Zucker et al. (2005)

MW satellites are in a disk-like configuration:



Walsh, Jerjen & Willman (2007)

The 11 brightest ("classical") 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: $\Delta/R < 0.17$

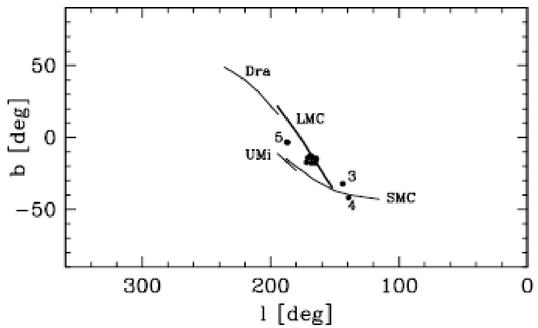


Fig. 3. The position on the Galactic sky of the poles of the planes fitted to the dwarves of Table 1. Plotted are $b_P = -b'_P$ and $l_P = l'_P + 180°$ and the number of dwarves used for the fit ranges from $N = 16$ down to $N = 3$ (Table 1). The cases for $N = 3, 4, 5$ are indicated with numbers. The 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)

This is inconsistent with shape of C/WDM halo with $> 99.6\%$ confidence if it is flattened and approximately co-planar to MW disk.

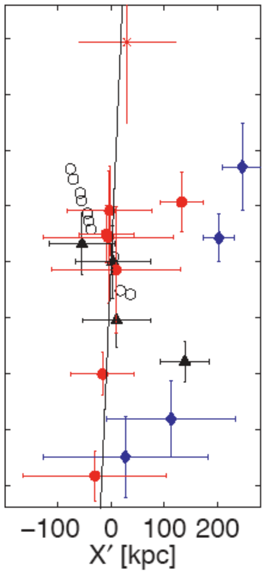
Observational evidence supports this for the MW
(Merrifield 2001; Ibata et al. 2001; Majewski et al. 2003; Martinez-Delgado et al. 2004; Johnston, Law & Majewski 2005).

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

Andromeda

From α to Ω

On their origin.



(Koch & Grebel 2005; but see Metz et al. 2006)

- ● 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

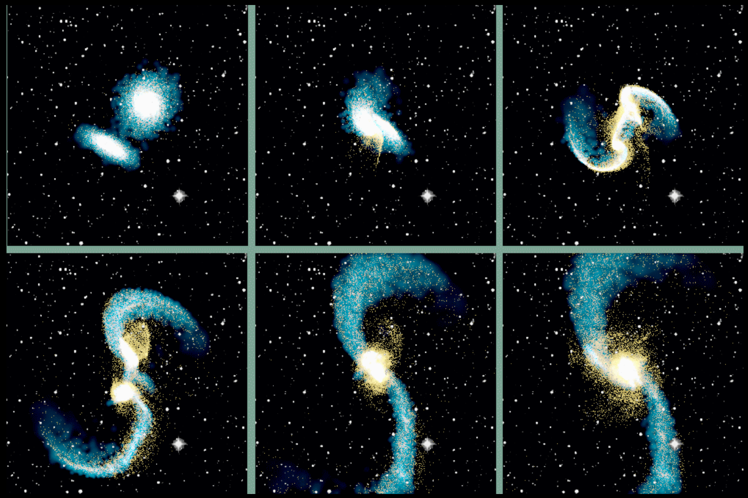
The hypothesis that the dSph satellites are related to DM sub-structures is "uncomfortable" (probably wrong) :

Too many "ifs and twiddles",
no consistent theoretical picture
within DM framework
has emerged so far.

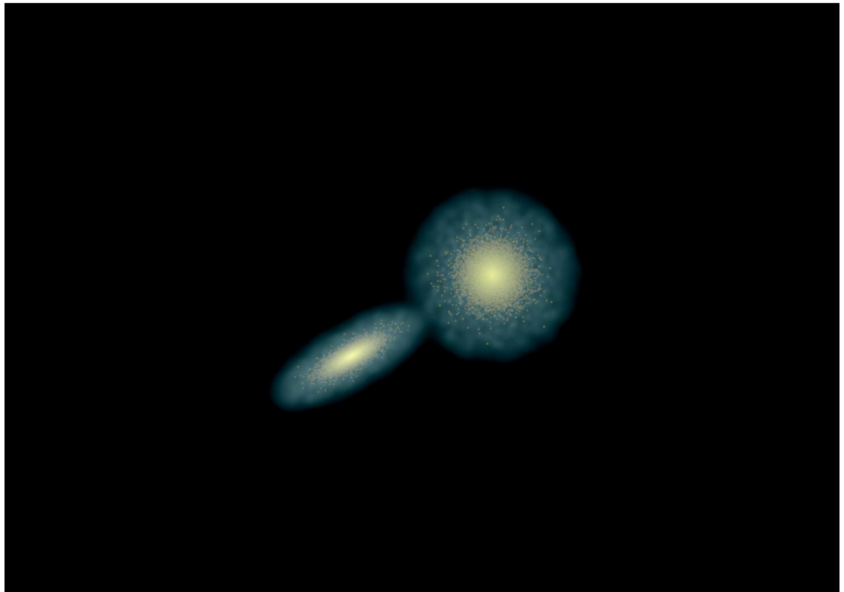
What's the alternative ?
Without invoking exotic physics

Their distribution as a *disk-of-satellites* holds a clue . . .

Tidal tails



Miho & Maxwell, web

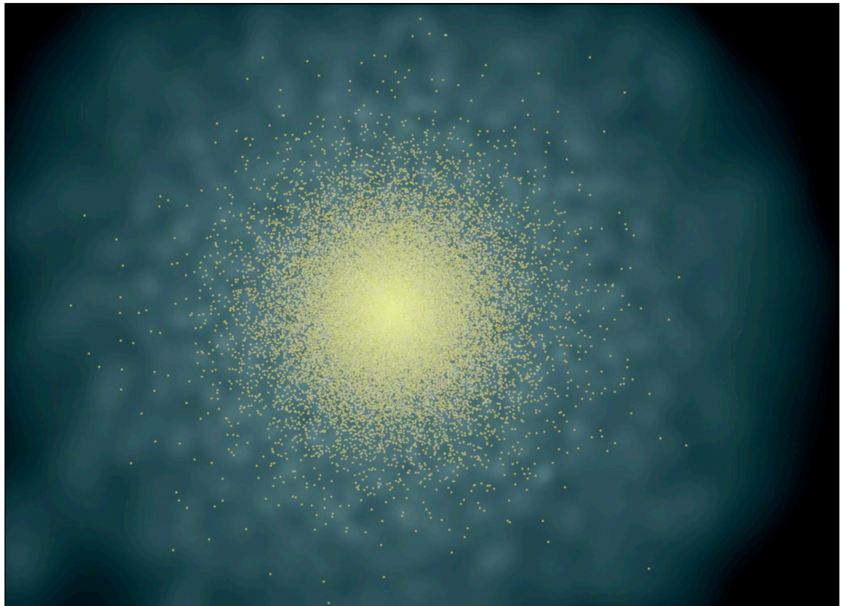


Wetzstein, Naab & Burkert 2007

Tidal-dwarf satellite galaxies (TDGs)

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

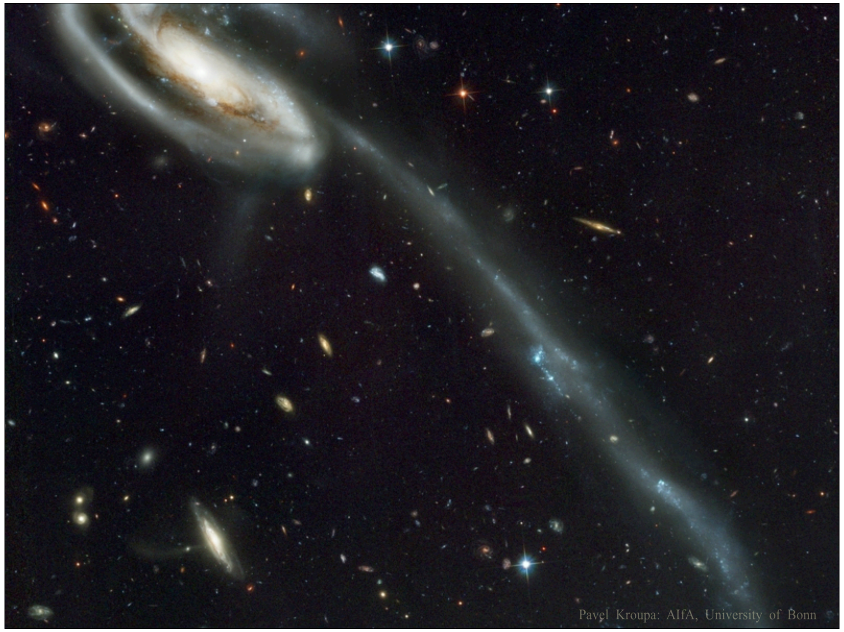
An inherent part of any hierarchical structure formation theory,
and a conservative, *classical approach* to the problem of dSph satellites.



Wetzstein, Naab & Burkert 2007

TDGs are baryon dominated

(Barnes & Hernquist 1992).



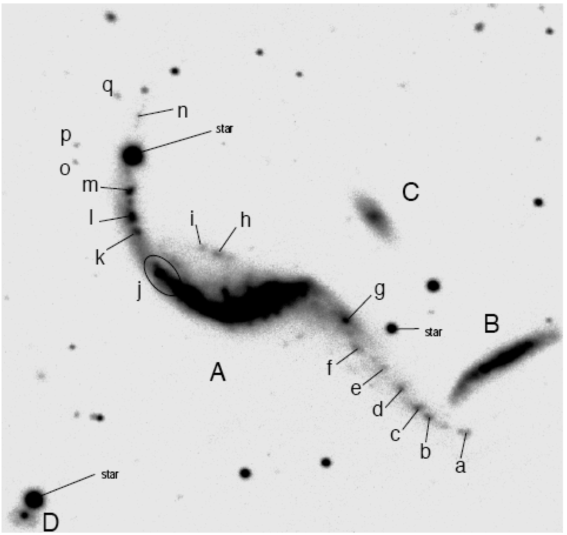
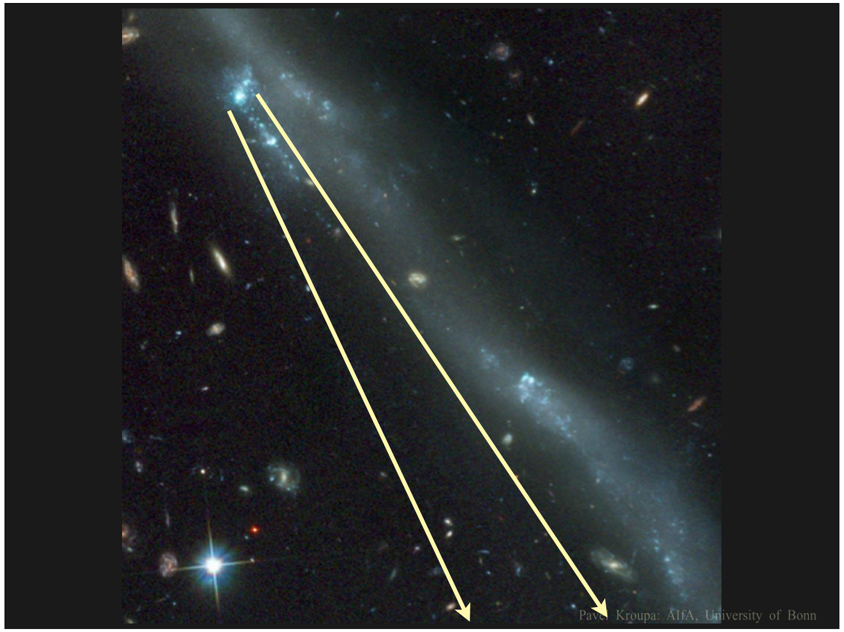


Fig. 21. Identification chart of field 10 around AM 1353-272.

(Weilbacher et al. 2000)

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



Star-cluster complex
(cf *Tadpole*)

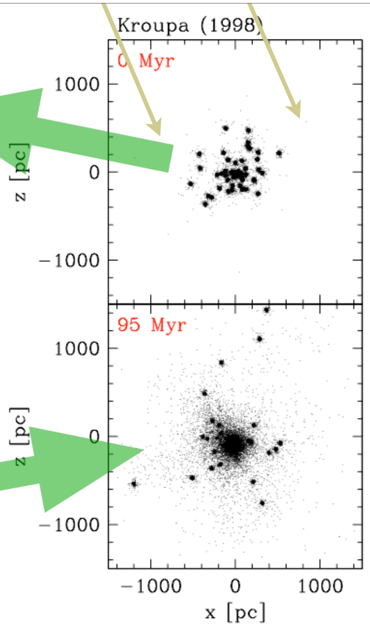
50 clusters
each $10^6\ M_\odot$

clusters as
fundamental galactic building blocks

⇓

Spheroidal dwarf galaxy !

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



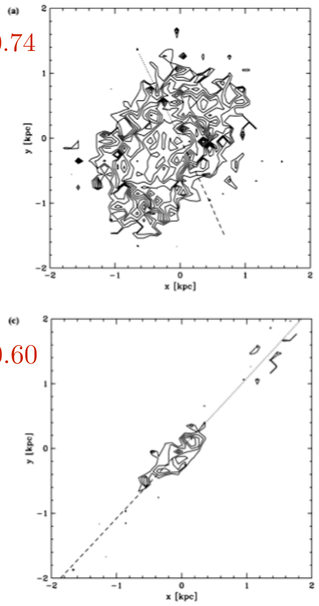
(Kroupa 1997)

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

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

$e = 0.74$

$e = 0.60$



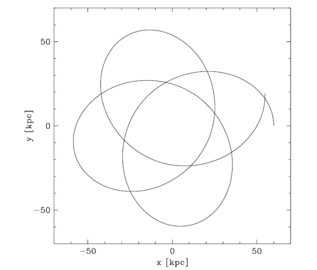
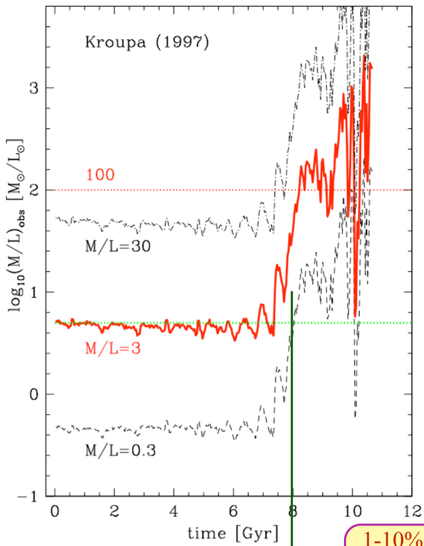


FIG. 3.—Orbital path of the satellite in simulations RS1-113 and Sat-M2.



1-10% of population in remnant

(Grebel, Gallagher & Harbeck 2003)

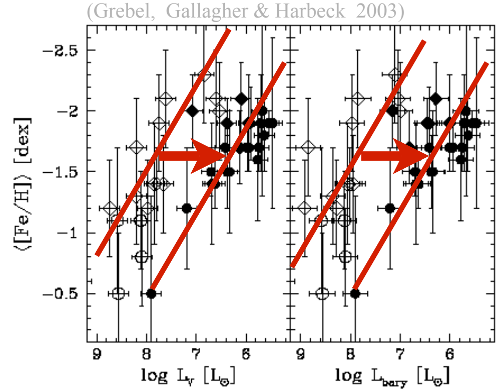


FIG. 1.—*V*-band luminosity (*left*) and baryonic luminosity (*right*, corrected for baryon contribution of gas not yet turned into stars; see § 2.2 for detail) vs. mean metallicity of red giants. Filled circles stand for dSph's, open circles for dE's, filled diamonds for dIrr/dSph transition-type galaxies, and open diamonds for dIrr's. DIrr's are more luminous at equal metallicity than dSph's. However, several dIrr/dSph transition-type galaxies coincide with the dSph locus. These objects are indistinguishable from dSph's in all their properties except for gas content.

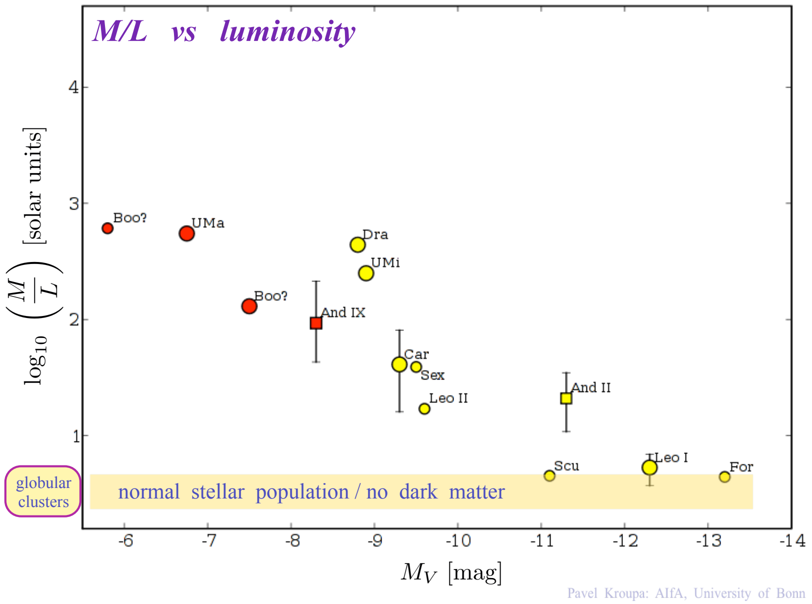
● dSph

○ dE

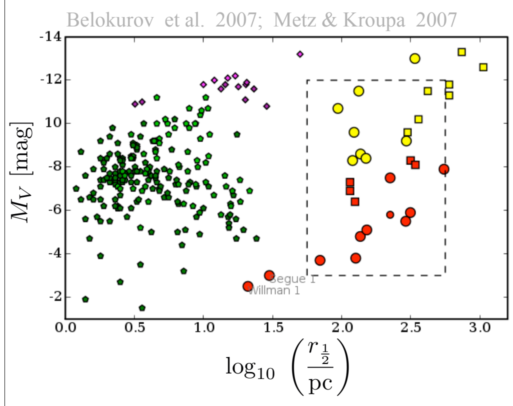
◆ dIrr/dSph transition types

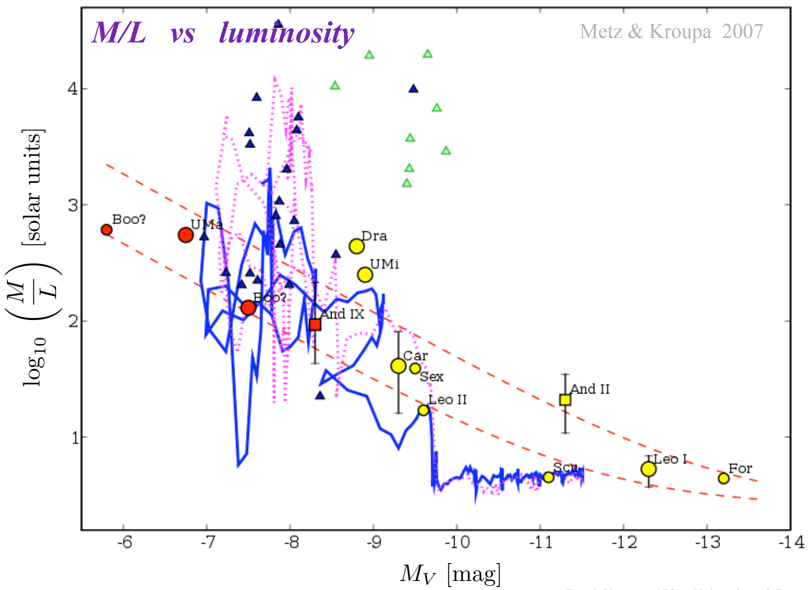
◇ dIrr

. . . suggests a factor of 10-100 mass loss
dIrr/dE ⟶ dSph .



Luminosity vs half-light radius





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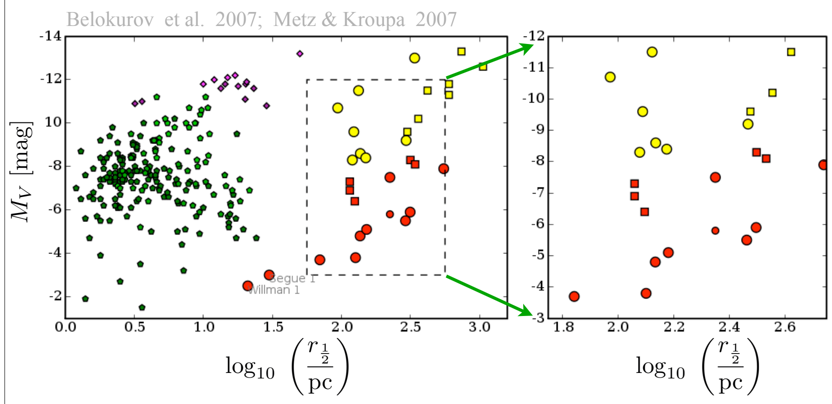
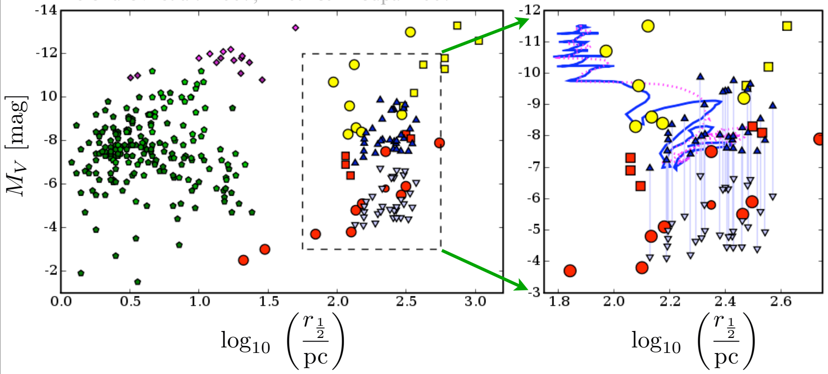


Luminosity vs half-light radius

Belokurov et al. 2007; Metz & Kroupa 2007



But :

further implications of TDG formation . . .

In obtaining these results
no parameters had to be twiddled.

The resulting dSph-like solutions
are a *natural consequence* of
applying *Newtonian dynamics*
and
energy and angular momentum conservation.

In particular, the solutions are obtained
within C/WDM cosmology **!**

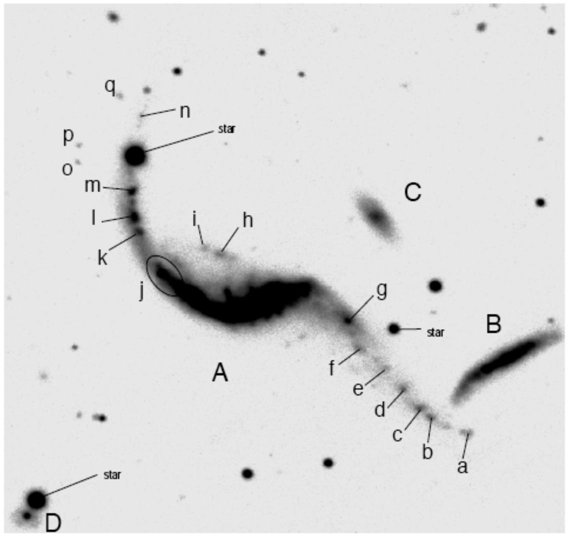


Fig. 21. Identification chart of field 10 around AM 1353-272.

(Weilbacher et al. 2000)

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

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

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

candidates are seen per event.

Delgado-Donate et al. (2003) :
from a local sample of
6 strongly interacting disk galaxies :

"we expect only a few TDG per collision to be formed. The value indicated by our results is *1 TDG per merger*, although *as many as 10 TDG* cannot be ruled out in individual cases."

Okazaki & Taniguchi (2000) :
The galaxy interaction scheme proposed by Silk & Norman (1981)

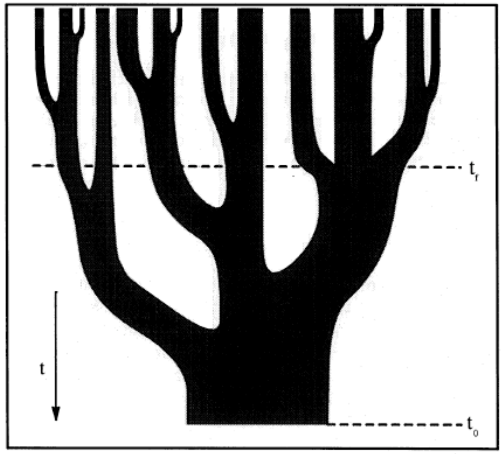
"can be *responsible for the observed numbers of dEs* in the various environs from poor groups of galaxies to the usual rich clusters of galaxies. The *formation rate of TDGs* is estimated to be ~*1–2 in each galaxy interaction*."

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

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

Okazaki & Taniguchi (2000) :
The galaxy interaction scheme proposed by Silk & Norman (1981)

(Lacey & Cole 1993)



Within the framework of *standard cosmology*, there is *little room* for *shining cosmological sub-structures* !

A

contradiction

in standard cosmological theory

thus emerges :

theory + observation :
a large fraction (if not all) of
observed $\lesssim 10^{10}\ M_\odot$ sub-structures are TDGs

Previous and current attempts to get the
$< 10^{10}\ M_\odot$ dark matter subhaloes
to shine would have been ill-fated . . .

Some logics

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

2) ***If*** streams true ***and*** dSph's are DM dominated
then C/WDM 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).

4) Little/no room for shining DM substructure.

Conclusions

dSph satellite galaxies are
dynamically highly evolved TDGs.

They are a *natural by-product* of *early merging events*
that shaped the MW and M31.

This is the *currently most complete theory* for the
nature and origin of dSph satellites.

This theory resorts only to *classical / standard physics*,
and is a natural consequence of
C/WDM cosmological theory.

The END