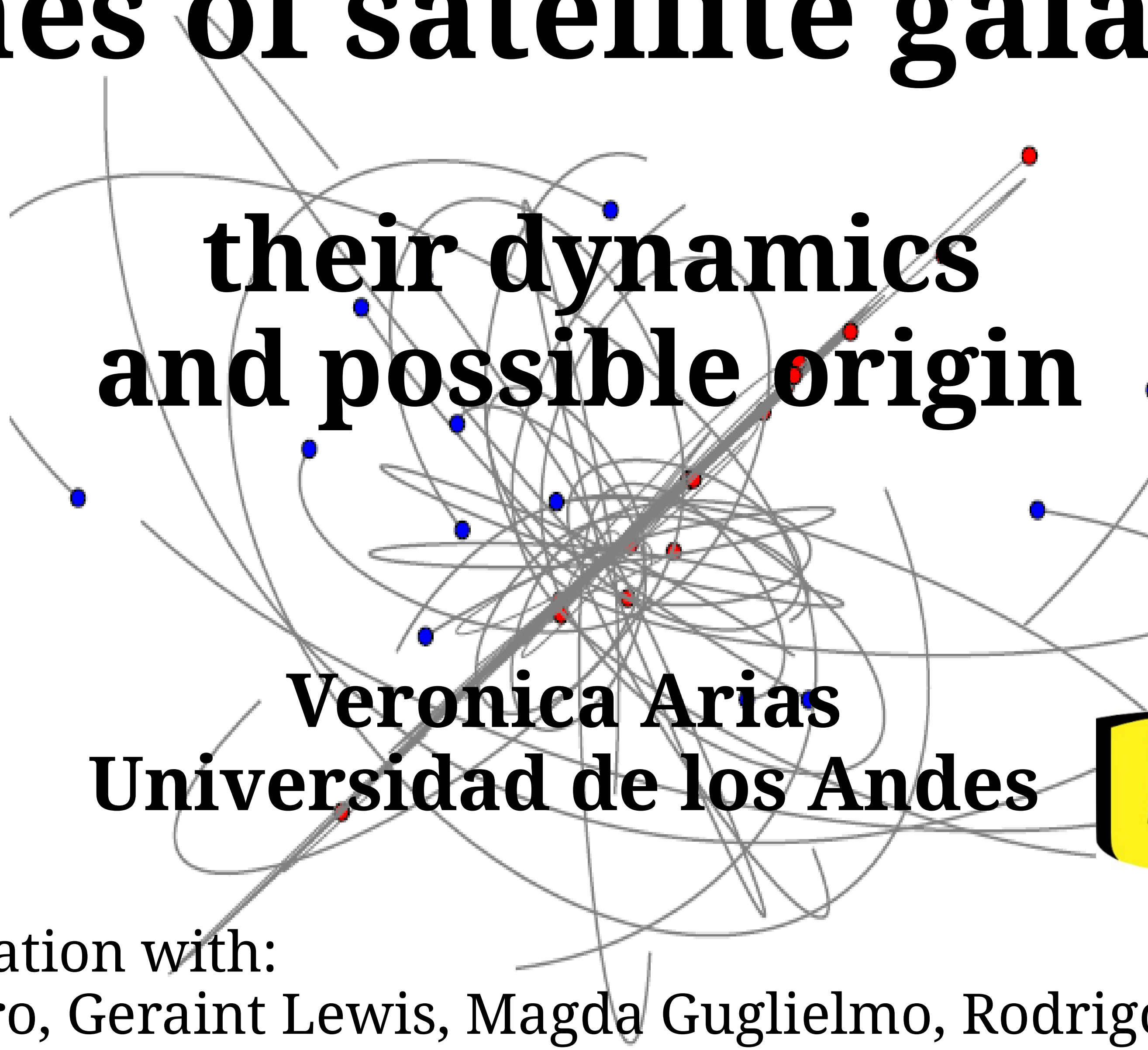
Planes of satellite galaxies:

their dynamics and possible origin



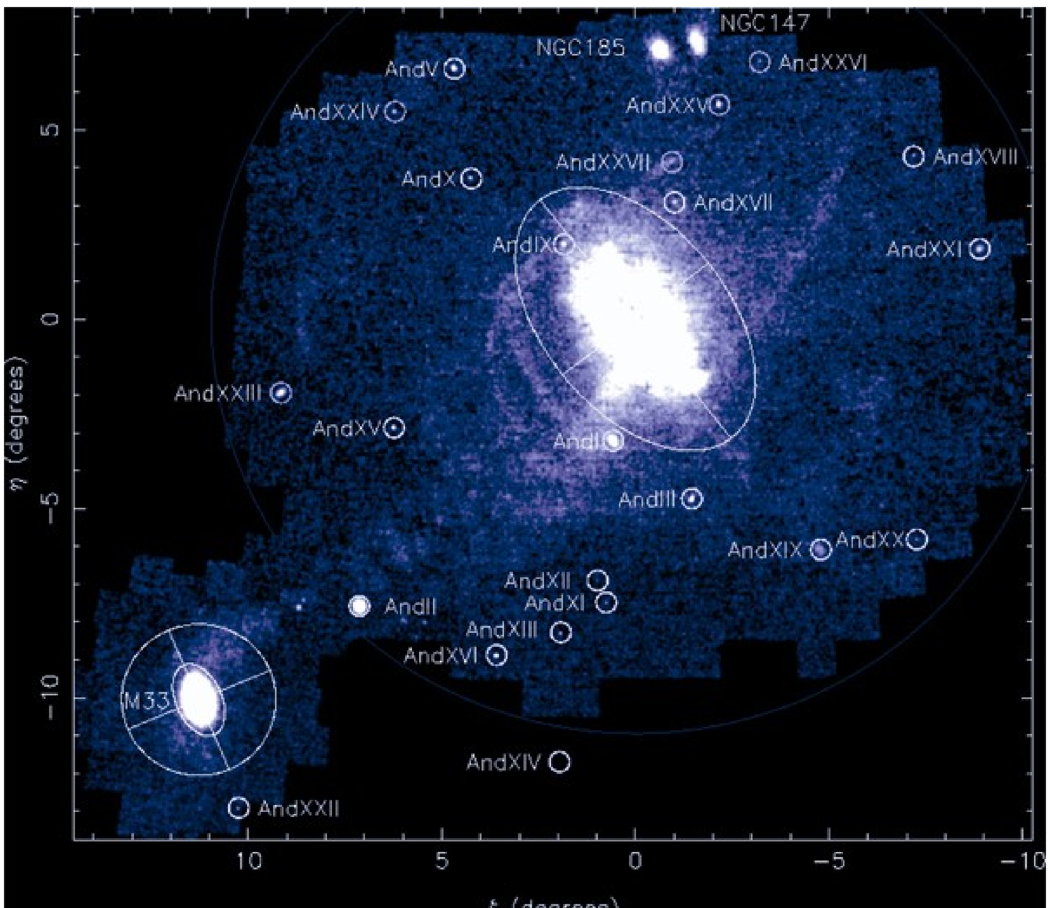
Veronica Arias
Universidad de los Andes

In Collaboration with:
Jaime Forero, Geraint Lewis, Magda Guglielmo, Rodrigo Ibata, Nuwanthika Fernando.

Problems with the small scale structure:

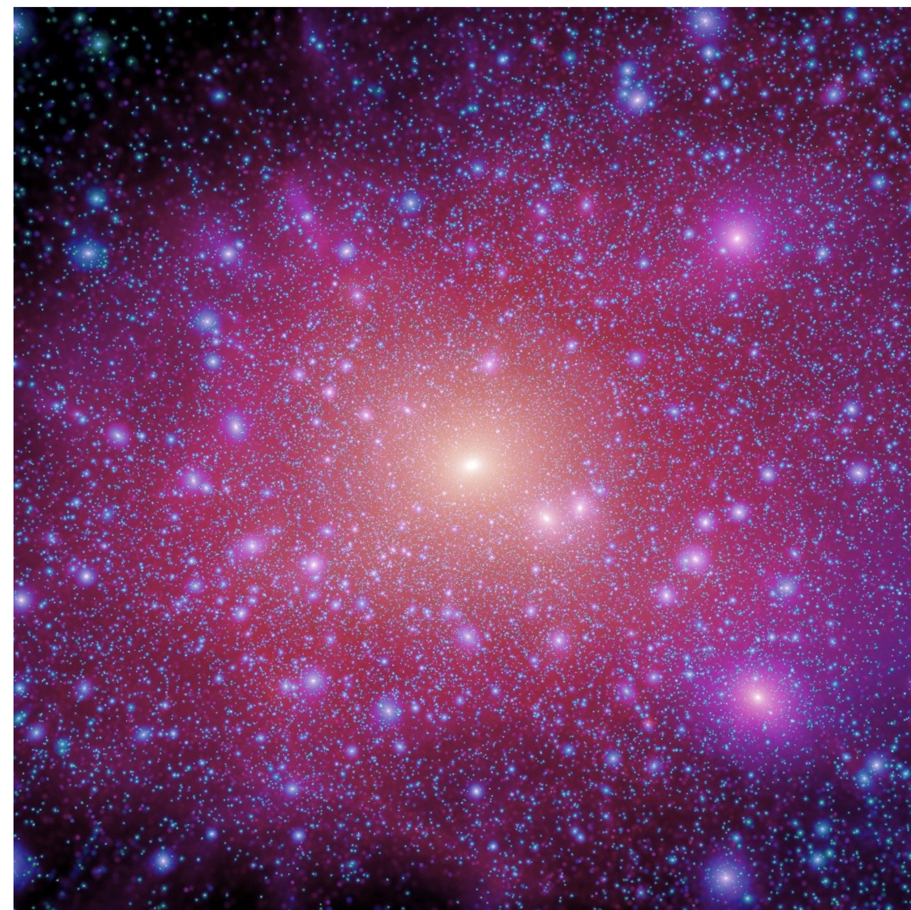
- Missing satellites problem
- Too big to fail

Observations: M31



PAndAS survey,
image: Geraint Lewis

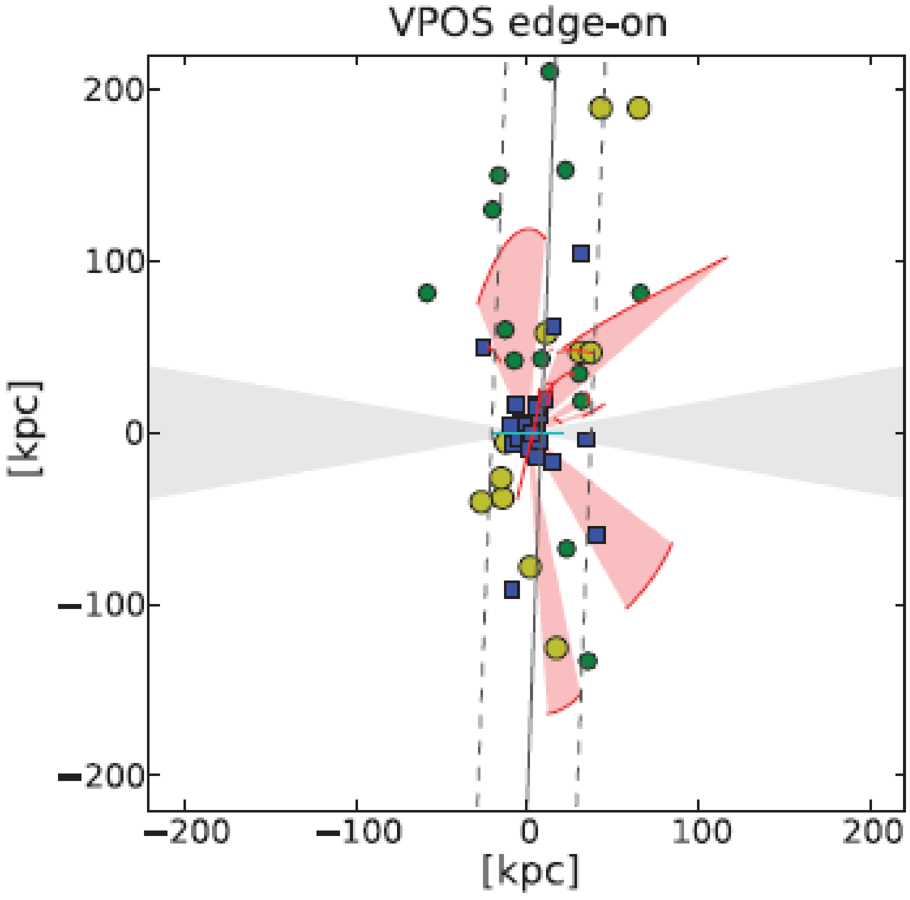
Dark Matter only simulations



Aquarius simulations,
MPA Garching

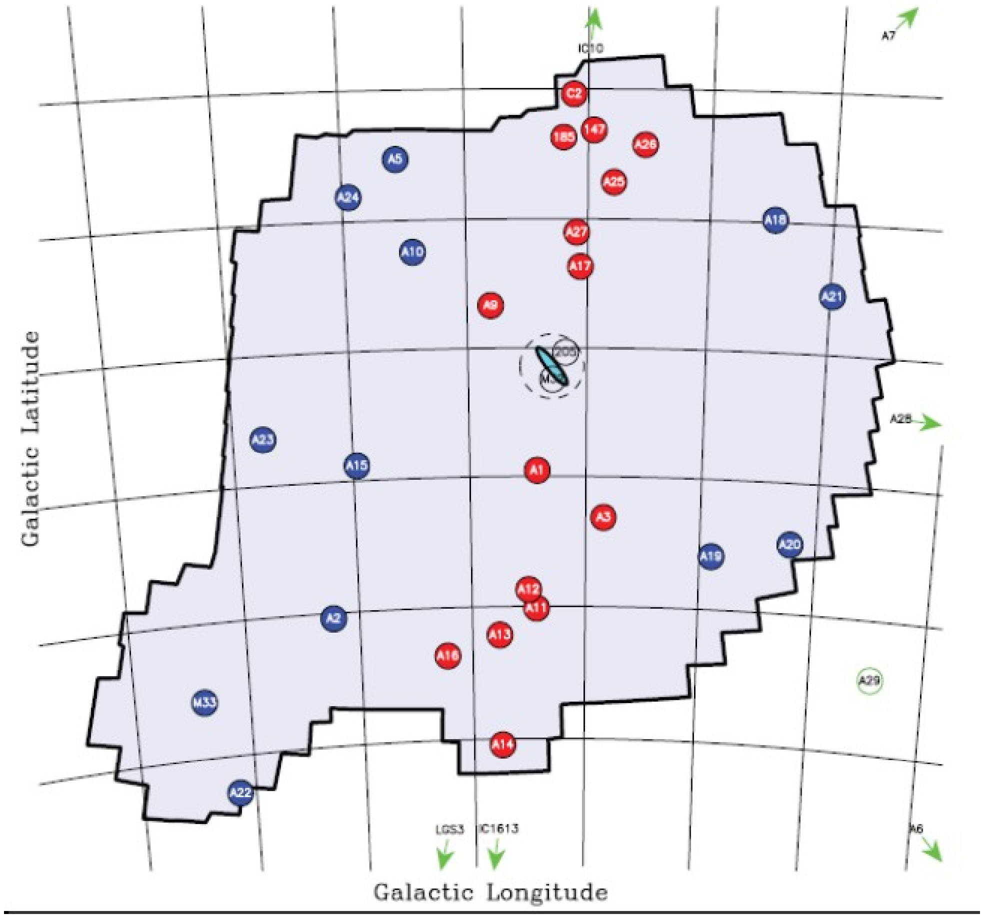
Planes of satellite galaxies:

In the Milky Way



Pawlowski et al. 2012
Linden-Bell 1976

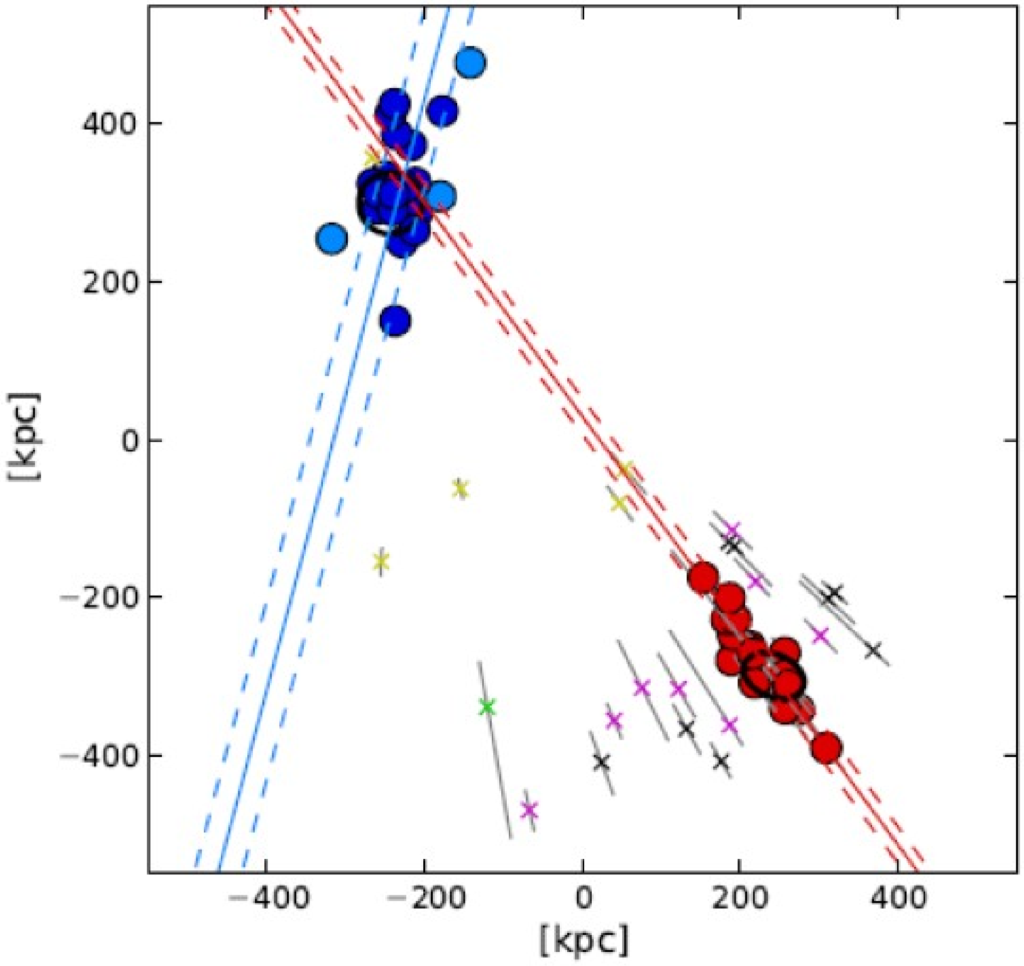
In M31

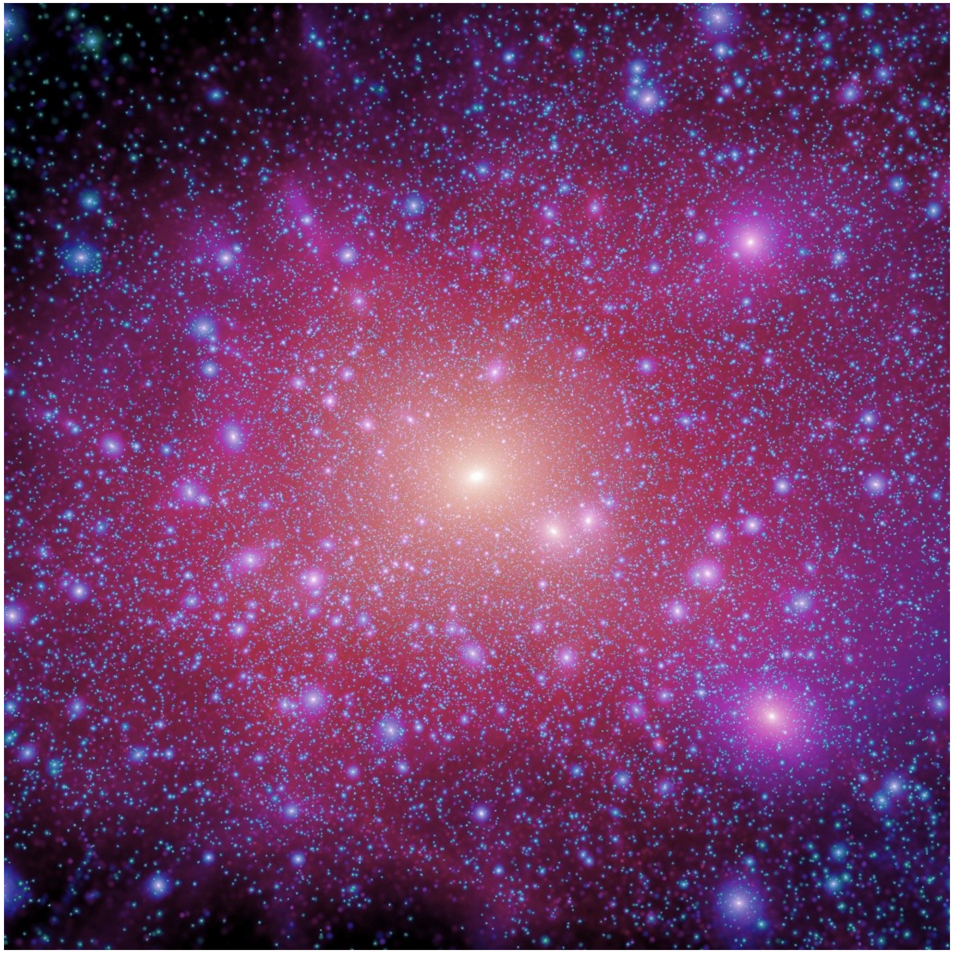


Ibata et al. 2013
Conn et al. 2013

Another small scale problem:

Planes are NOT common in Simulations
(e.g. Ibata et el. 2014, Pawlowsky et al. 2013)





Pawlowski et al. 2013

Imagen: Aquarius simulations,MPA Garching

Planes in simulations:

- Millenium II, Aquarius (DM only). Not really

- CLUES Gillet et al. (2015) : one plane but...

- Buck et al 2015, Sawalla et al. 2015 also found planes but...

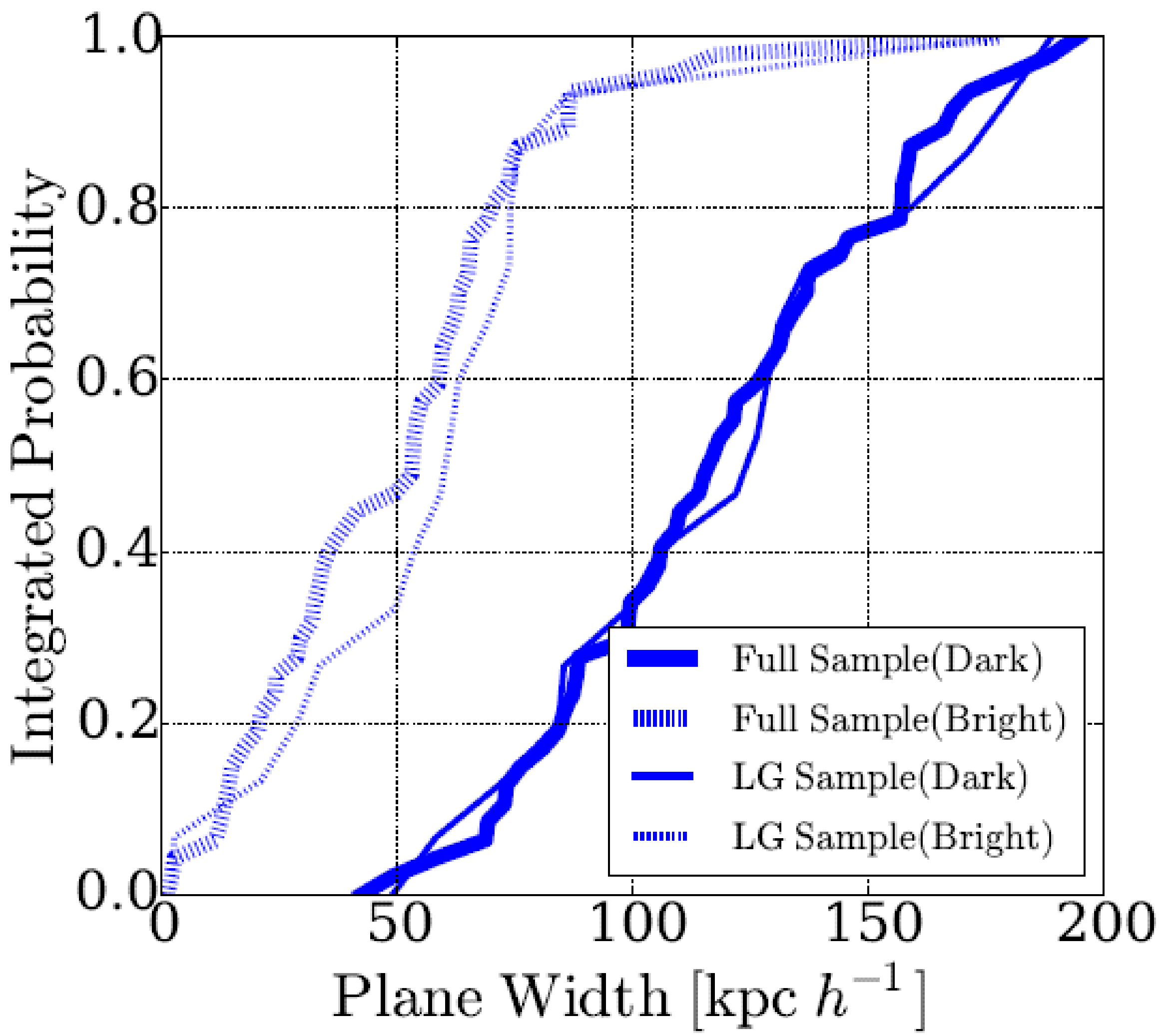
- Cautun et al. 2015 also but...

But:

Planes tend to be thicker than the M31 plane

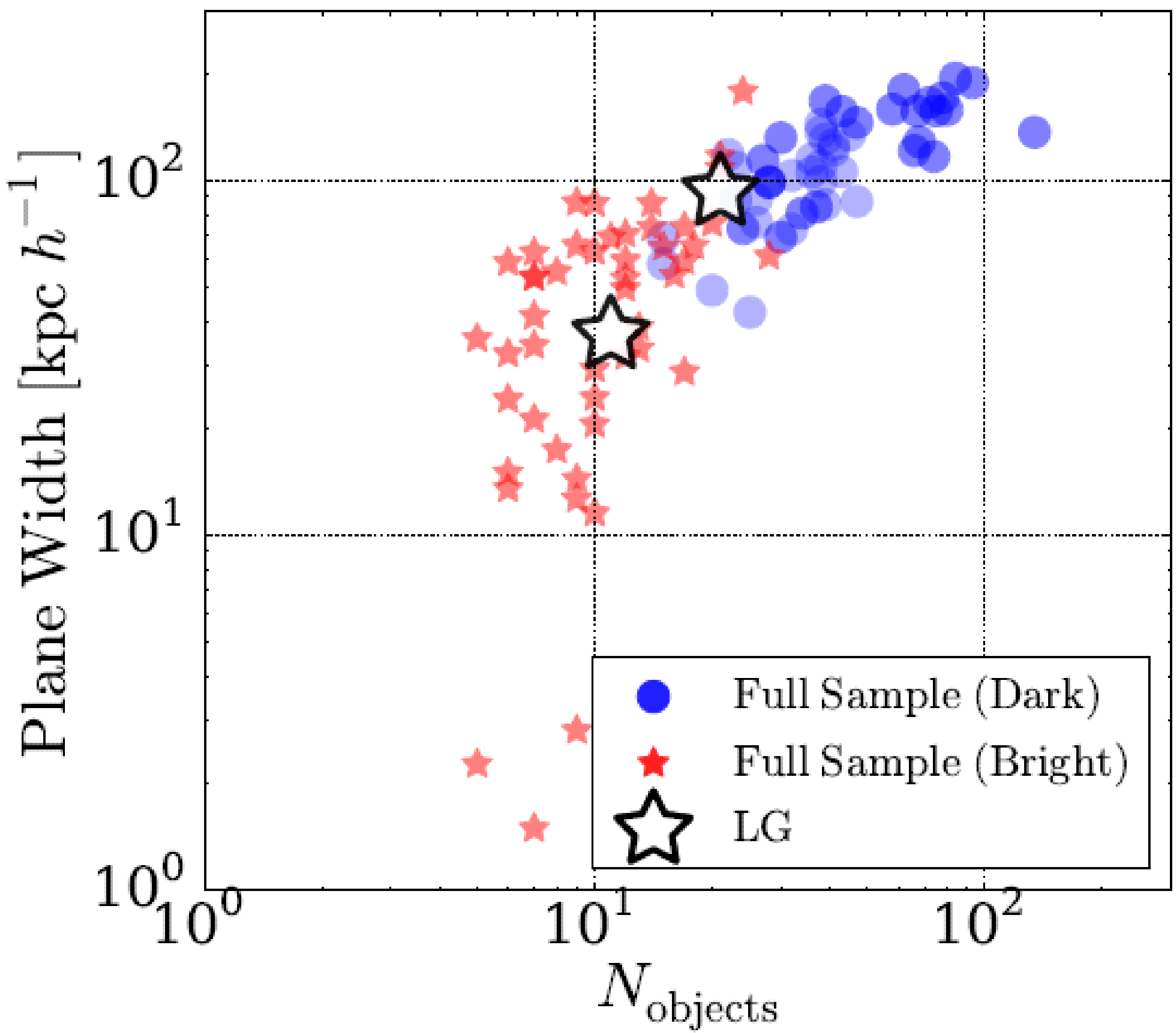
They are transient structures

Looking in Illustris simulation:



Arias & Forero, in prep.

Only a number effect?



BUT...

* M31 is thinner

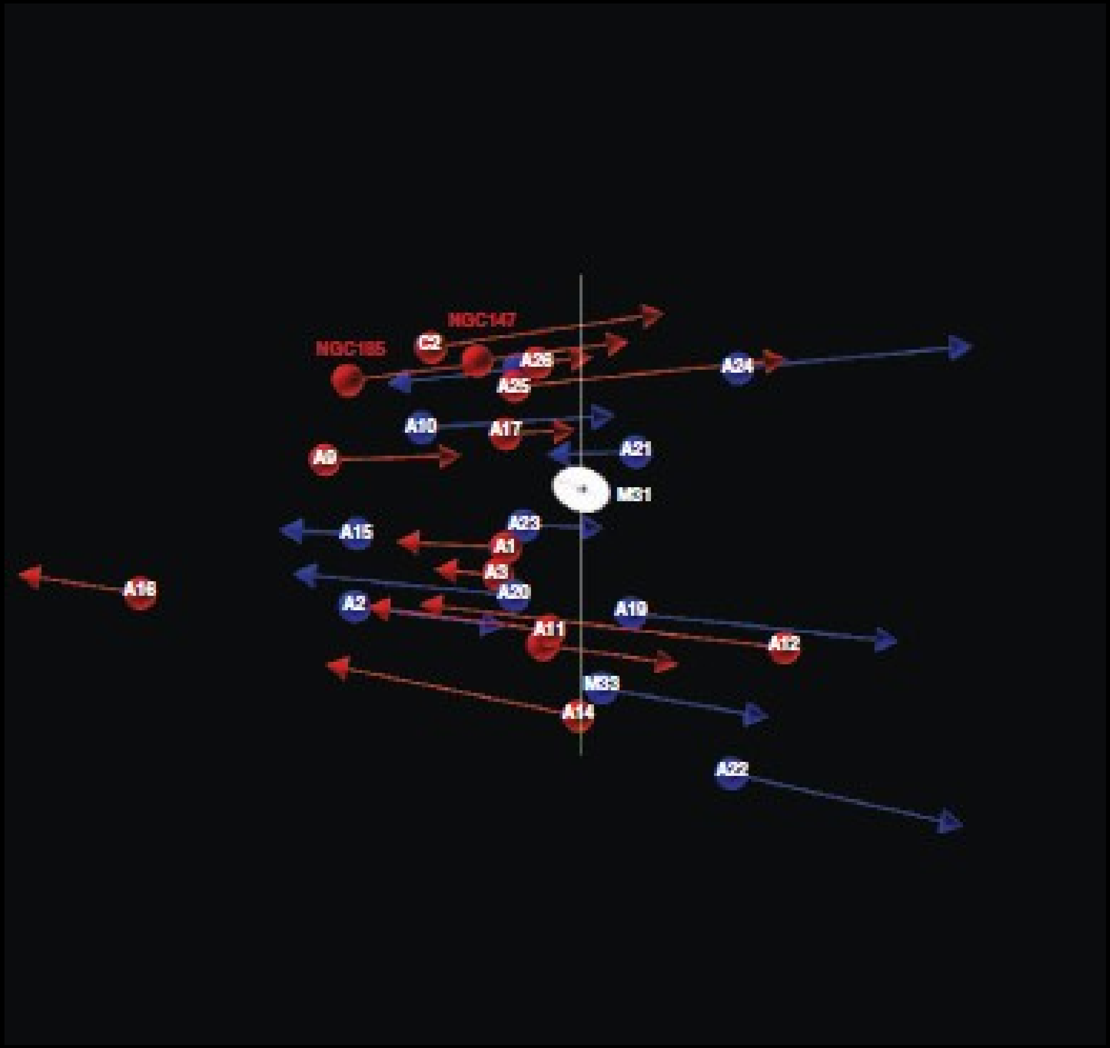
* Number related to host halo size

* kinematics

Arias & Forero, in prep.

More evidence:

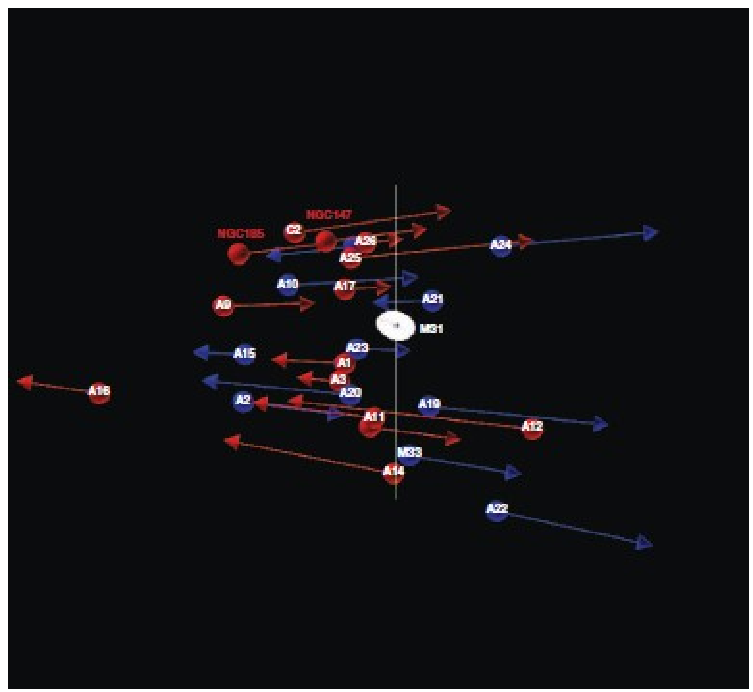
M31 satellite plane seems to be co-rotating



Ibata et al. 2013, Collins et al. 2013

Aims:

Study the orbits of M31 satellite galaxies



We know:

*** The positions**

*** the LoS velocities**

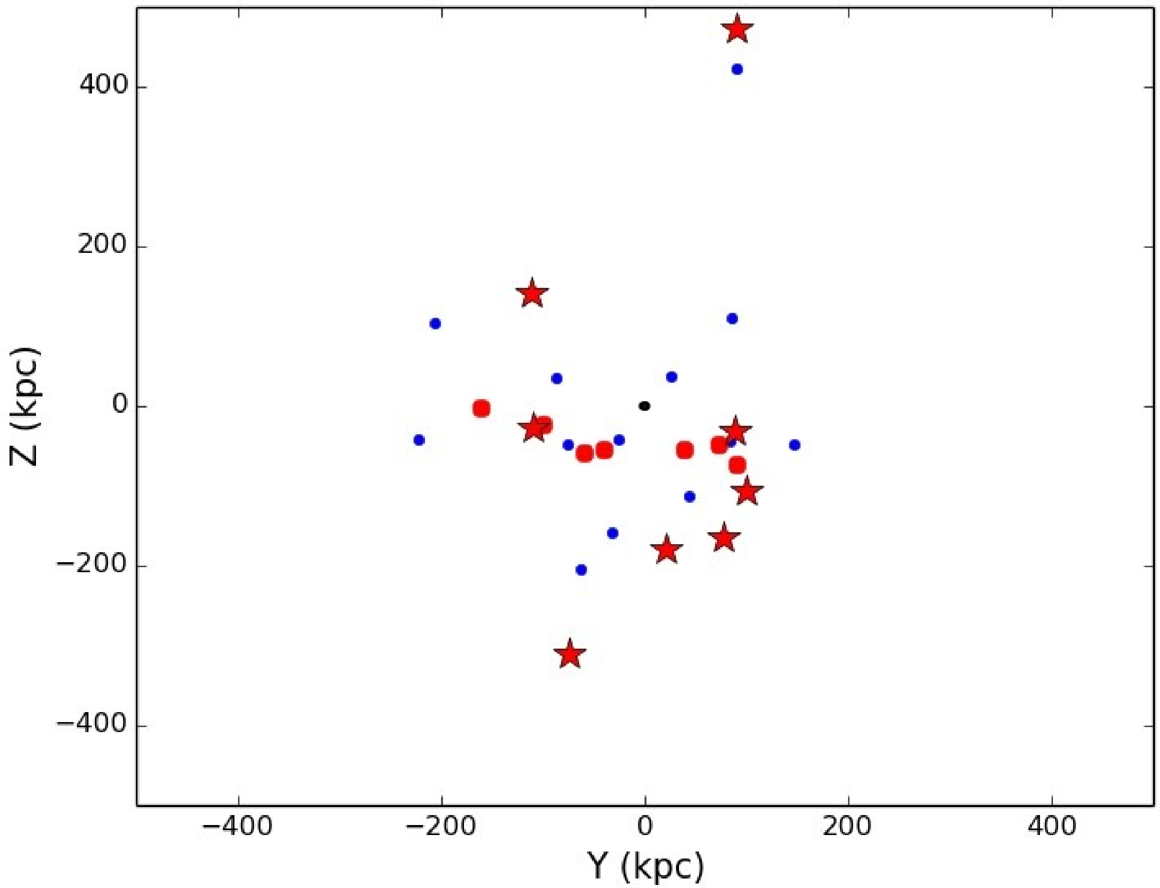
We don not know:

*** the tangential velocities**

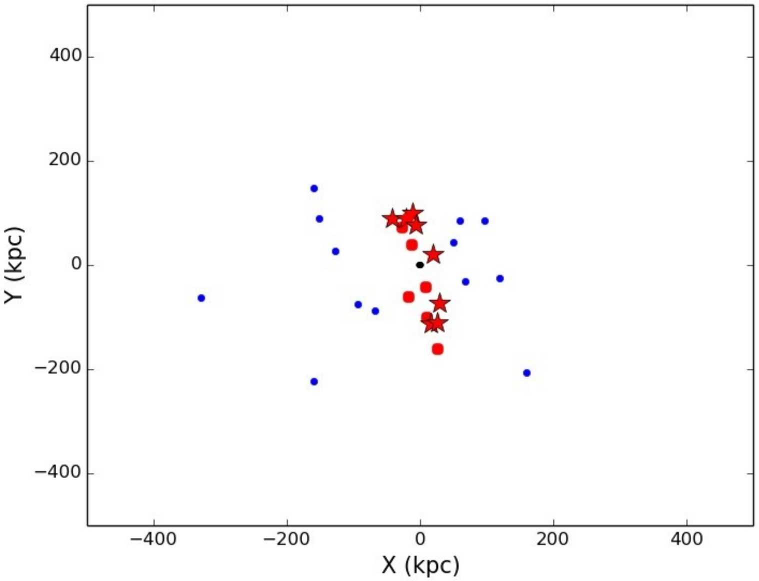
Ibata et al. 2013, Conn et al. 2012, Collins et al 2013, Tollerud et al 2012)

Positions

Face-on



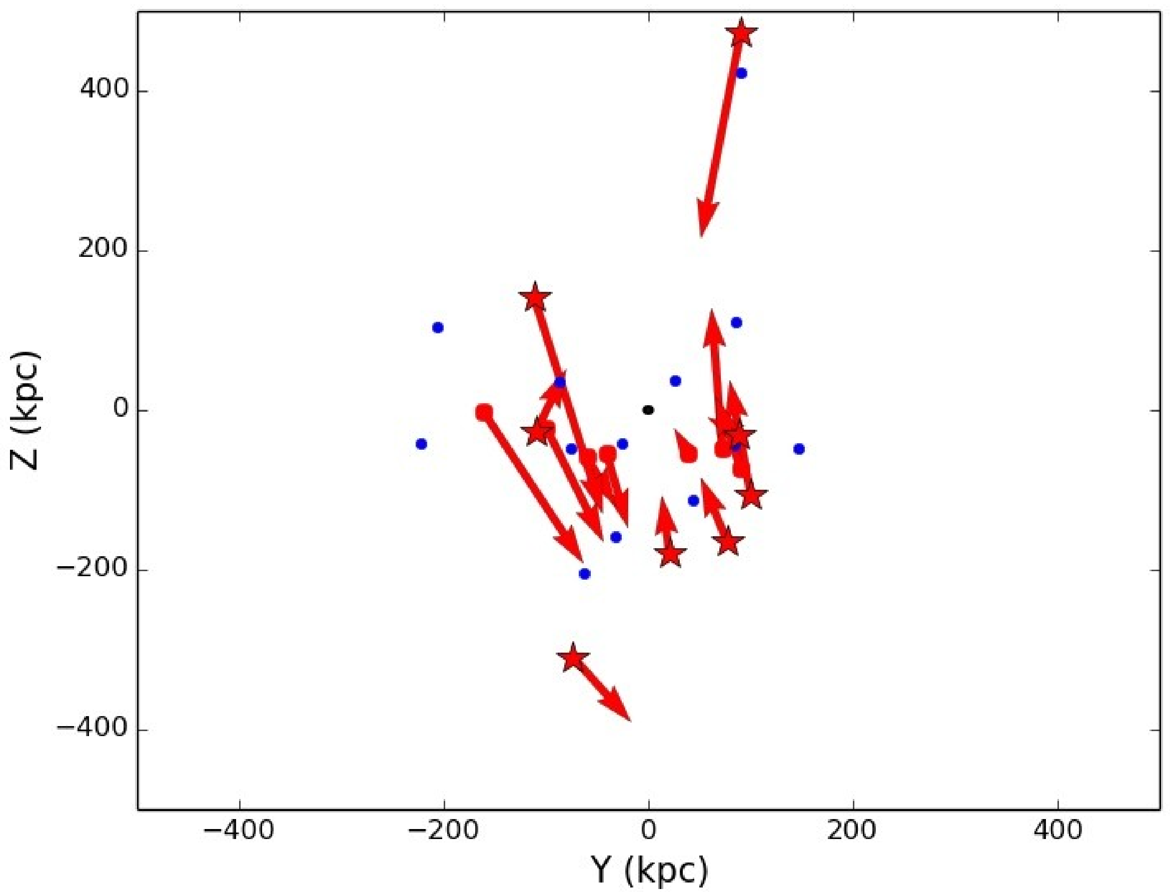
Edge-on
(almost as observed)



MW

LoS velocities

Face-on



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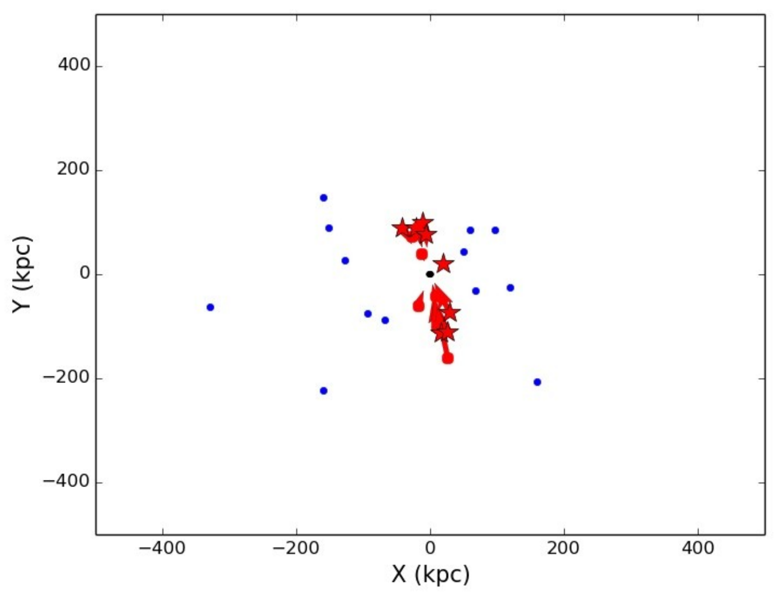


MW

We make the following assumption:

If the plane exist
and if it is a dynamically coherent long-living structure,

Then

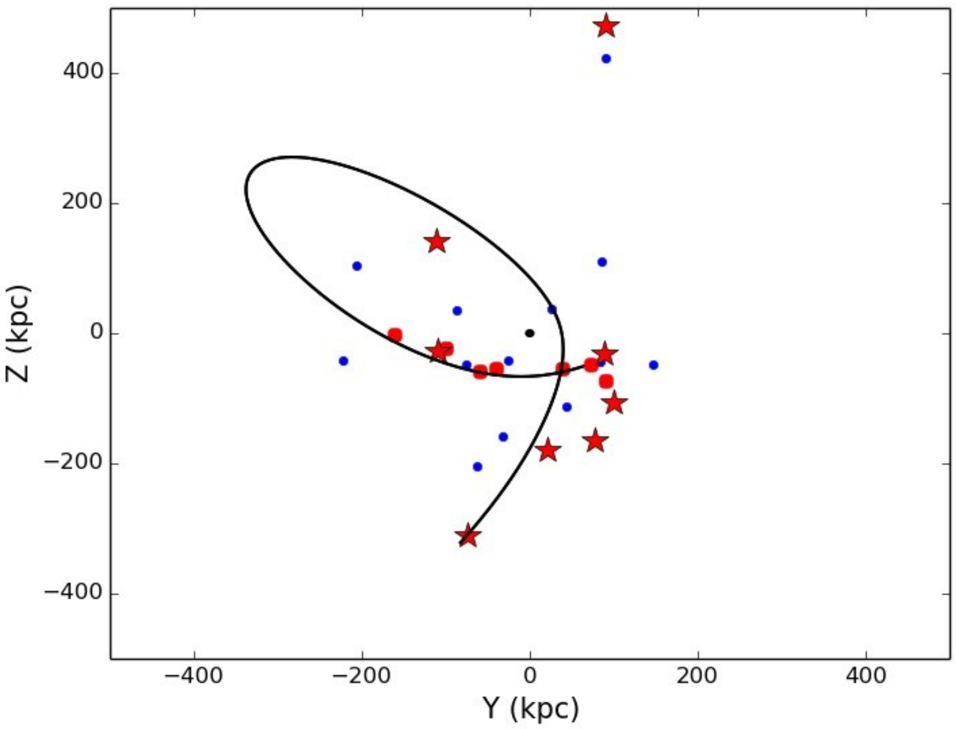
the **velocity vector** should be on the plane.

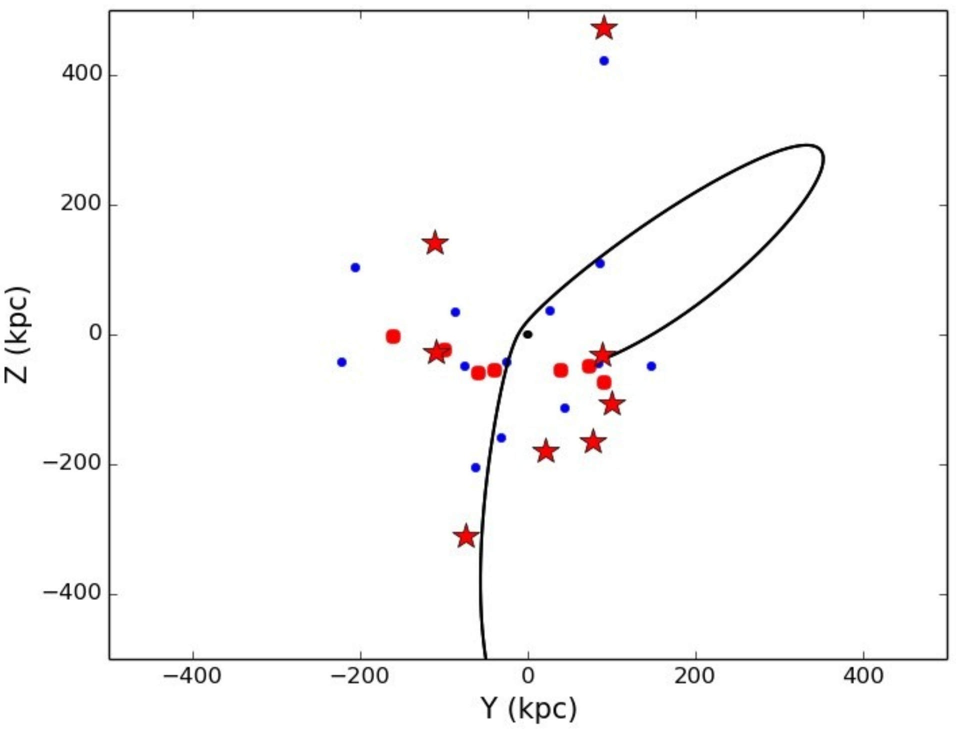
And that determines the **direction** of the **tangential velocity.**

So

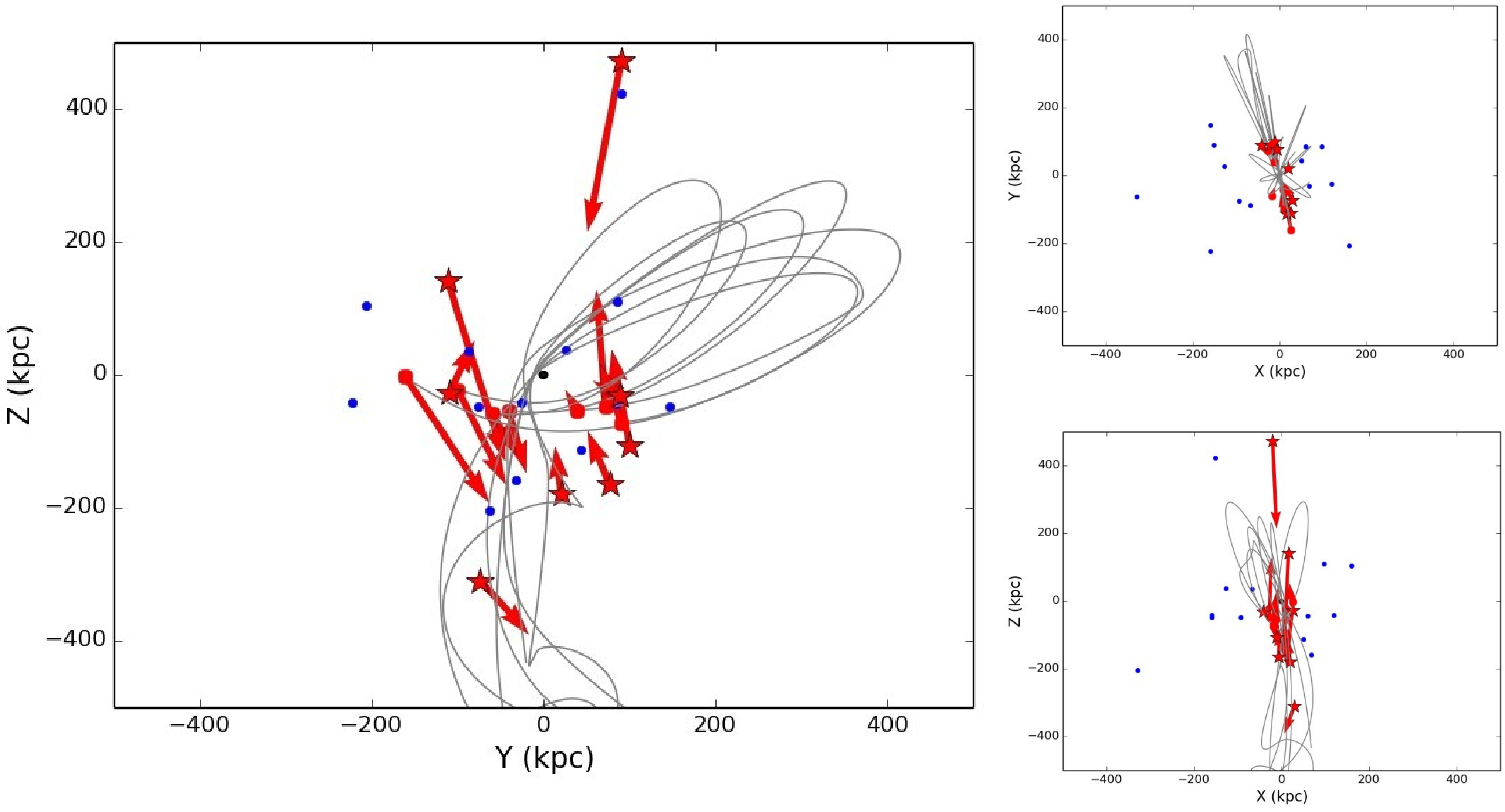
The only unknown is the **magnitude** of the tangential velocity.

Exploring this free parameter:





We find similar orbits for 7 out of 15 satellites…



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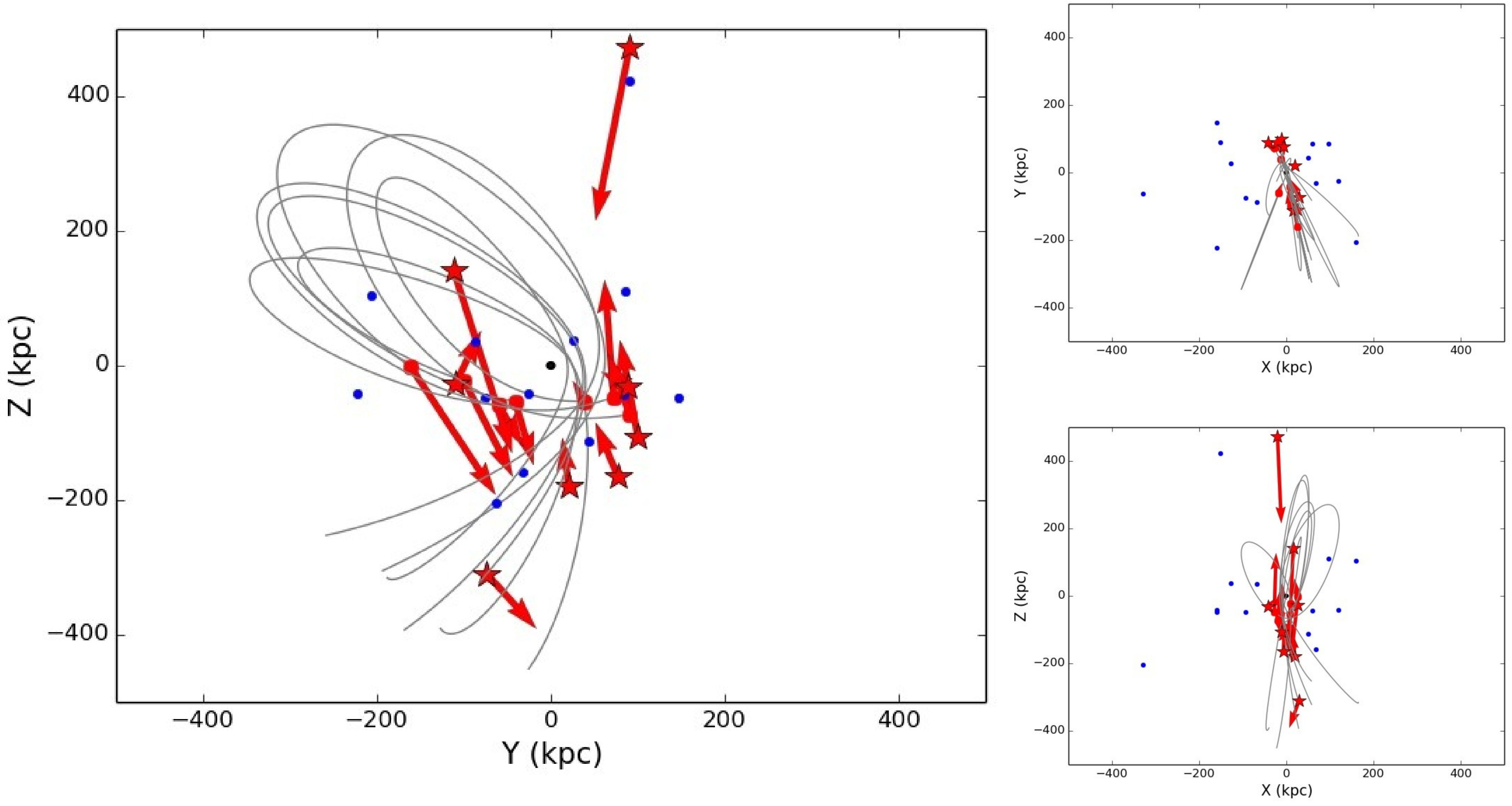
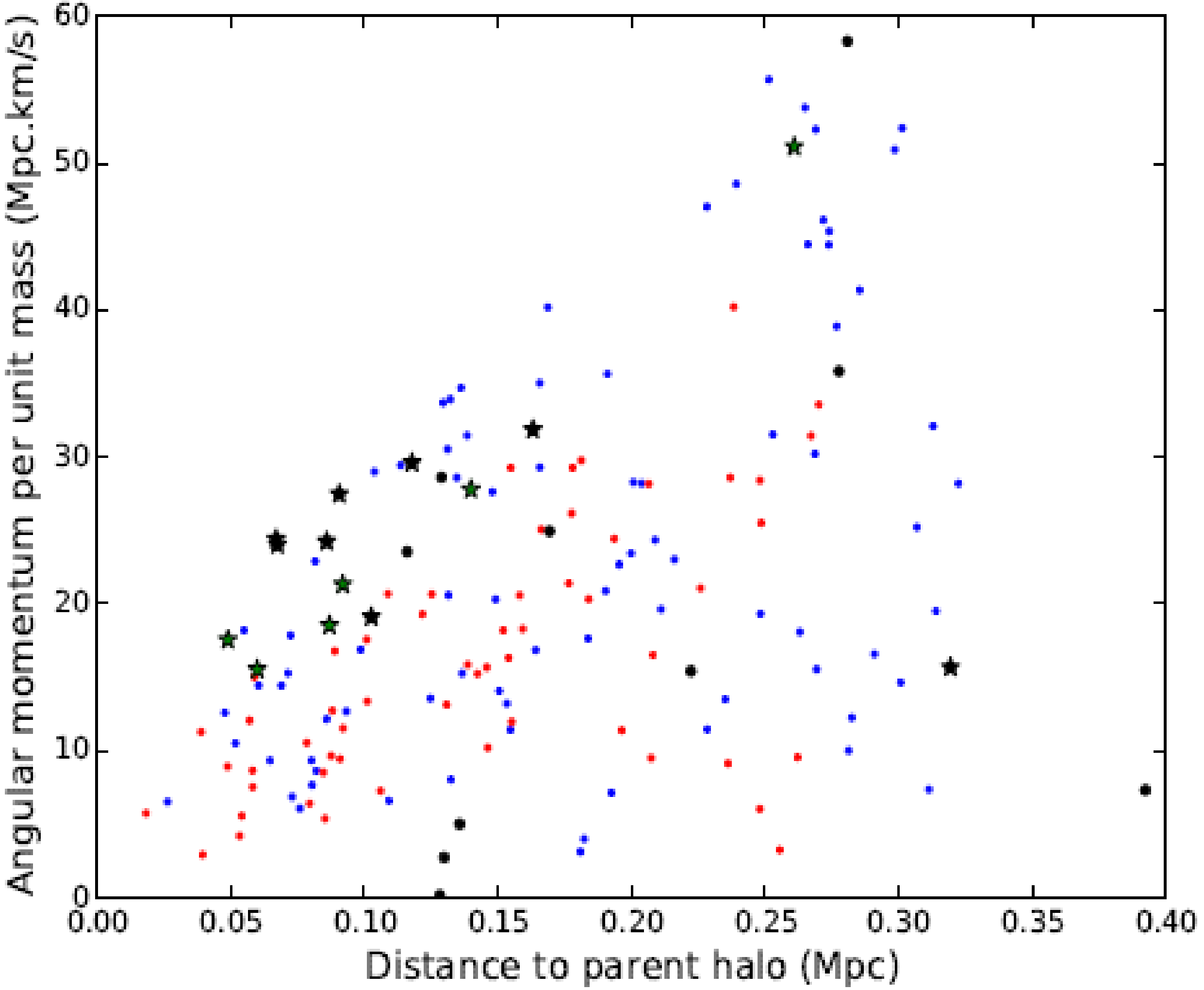


A quick “test” comparison:

With the ELVIS simulation
and with some MW satellites



If the common orbits are real, this opens new questions, in particular:

How does such a structure forms?

We are currently:

Working with an optimization code to explore a wider range of possible tangential velocities

Looking deeper into cosmological simulations (Illustris in particular)

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Thanks

M31 rigid Potential
+
Point mass approximation for Satellites
=
Numerical integration of the orbits

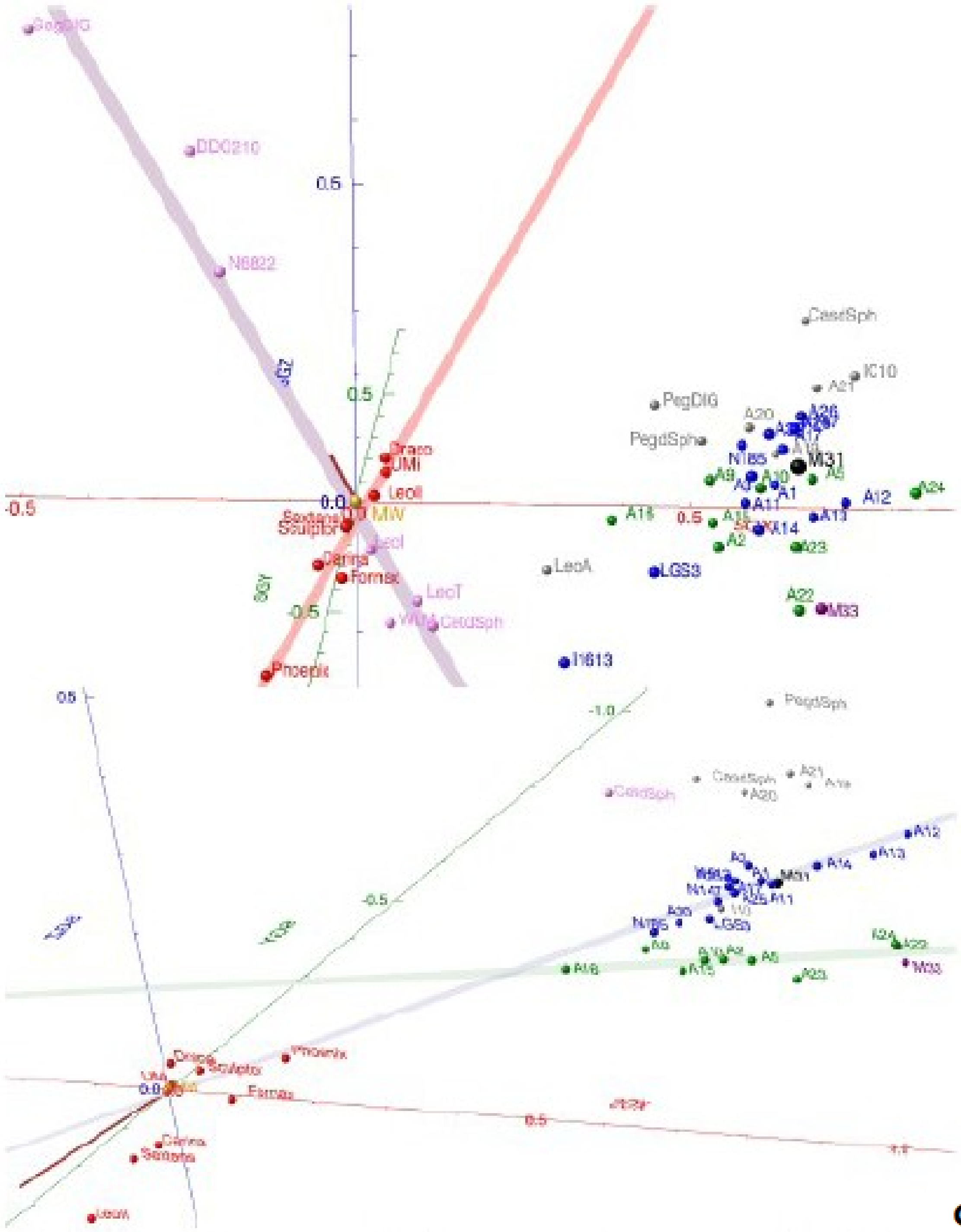
$$\Phi_{\rm halo}(r) = -\frac{GM_{\rm halo}}{r}\log\left(\frac{r}{r_{\rm halo}}+1\right)$$

$$\Phi_{\rm disk}(r) = -2\pi G\Sigma_0 {r_{\rm disk}}^2\left[\frac{1-\exp^{-r/r_{\rm disk}}}{r}\right]$$

$$\Phi_{\rm bulge}(r) = -\frac{GM_{\rm bulge}}{r_{\rm bulge}+r}$$

	M31
$M_{\rm bulge}$	$2.86 \times 10^{10}\,M_\odot$
$r_{\rm bulge}$	0.61 kpc
$M_{\rm disk}$	$8.4 \times 10^{10}\,M_\odot$
$r_{\rm disk}$	5.4 kpc
Σ_0	$4.6 \times 10^{8}\,M_\odot {\rm kpc}^{-2}$
$M_{\rm halo}$	$103.7 \times 10^{10}\,M_\odot$
$r_{\rm halo}$	13.5 kpc

Geehan et al. (2006)



Shaya & Tully 2013

Plane(s) in Centaurus A (Tully et al 2015)

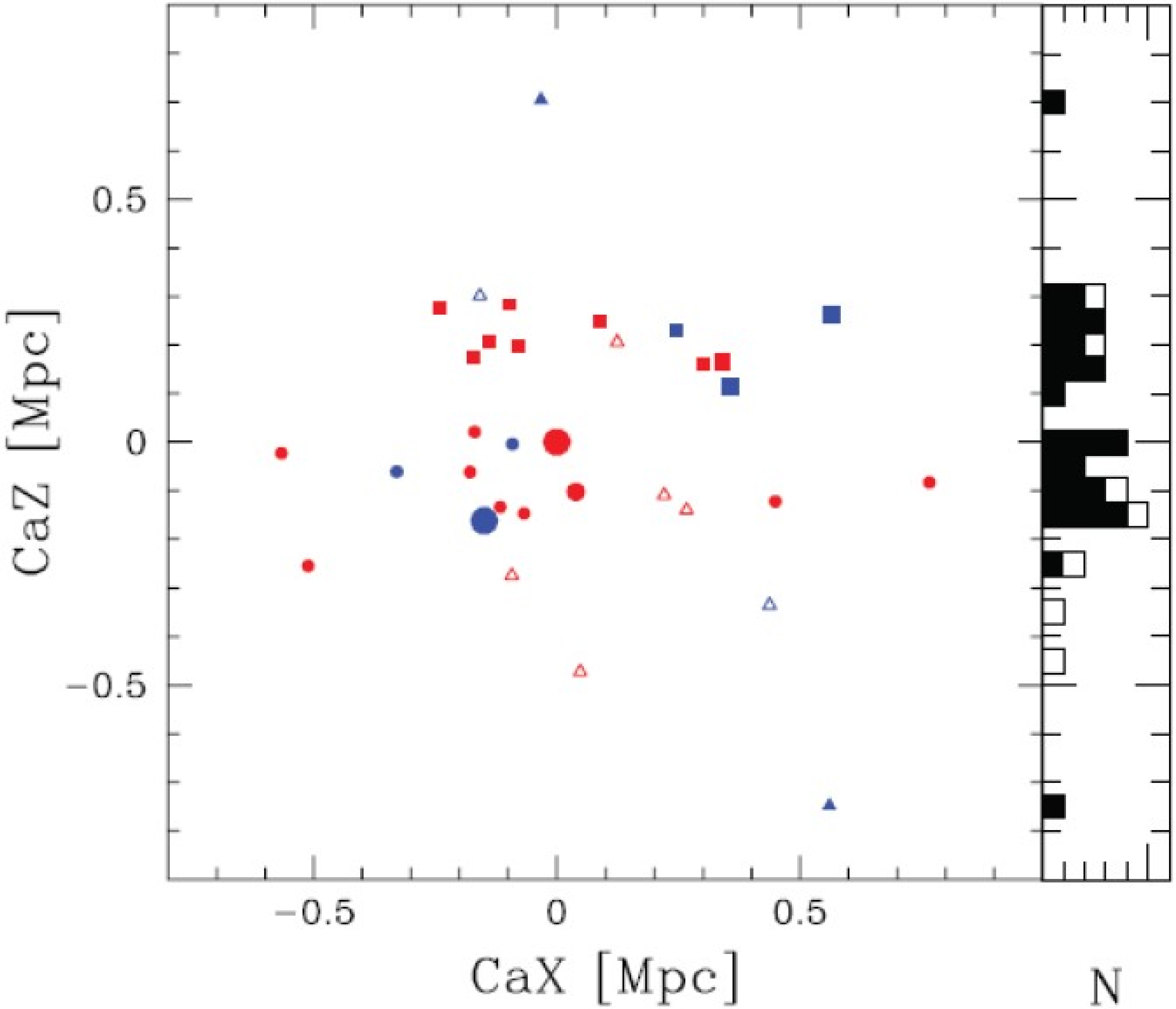
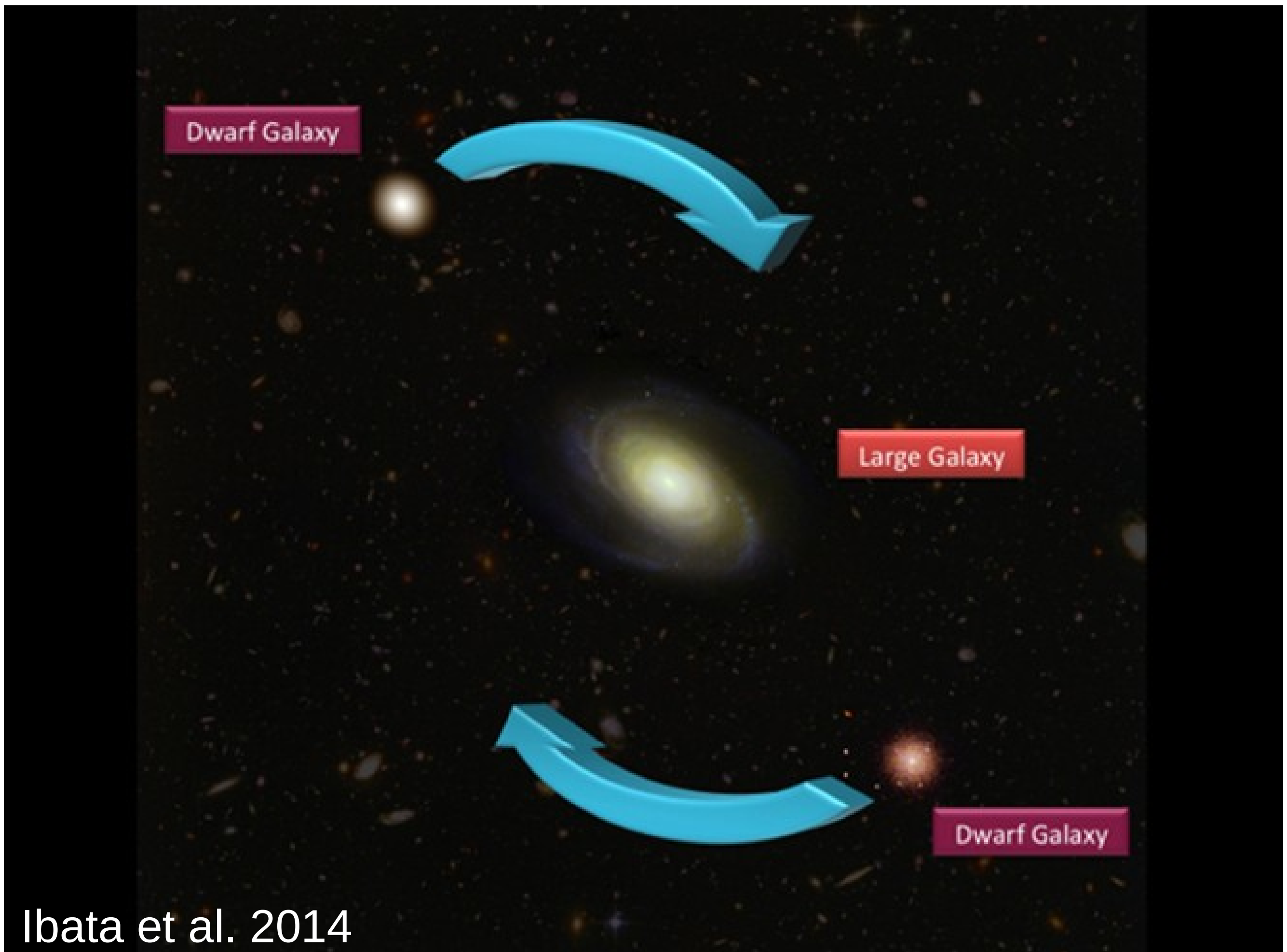
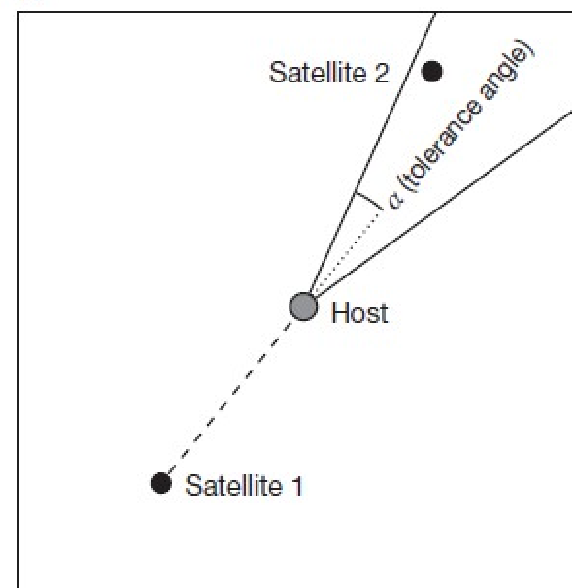
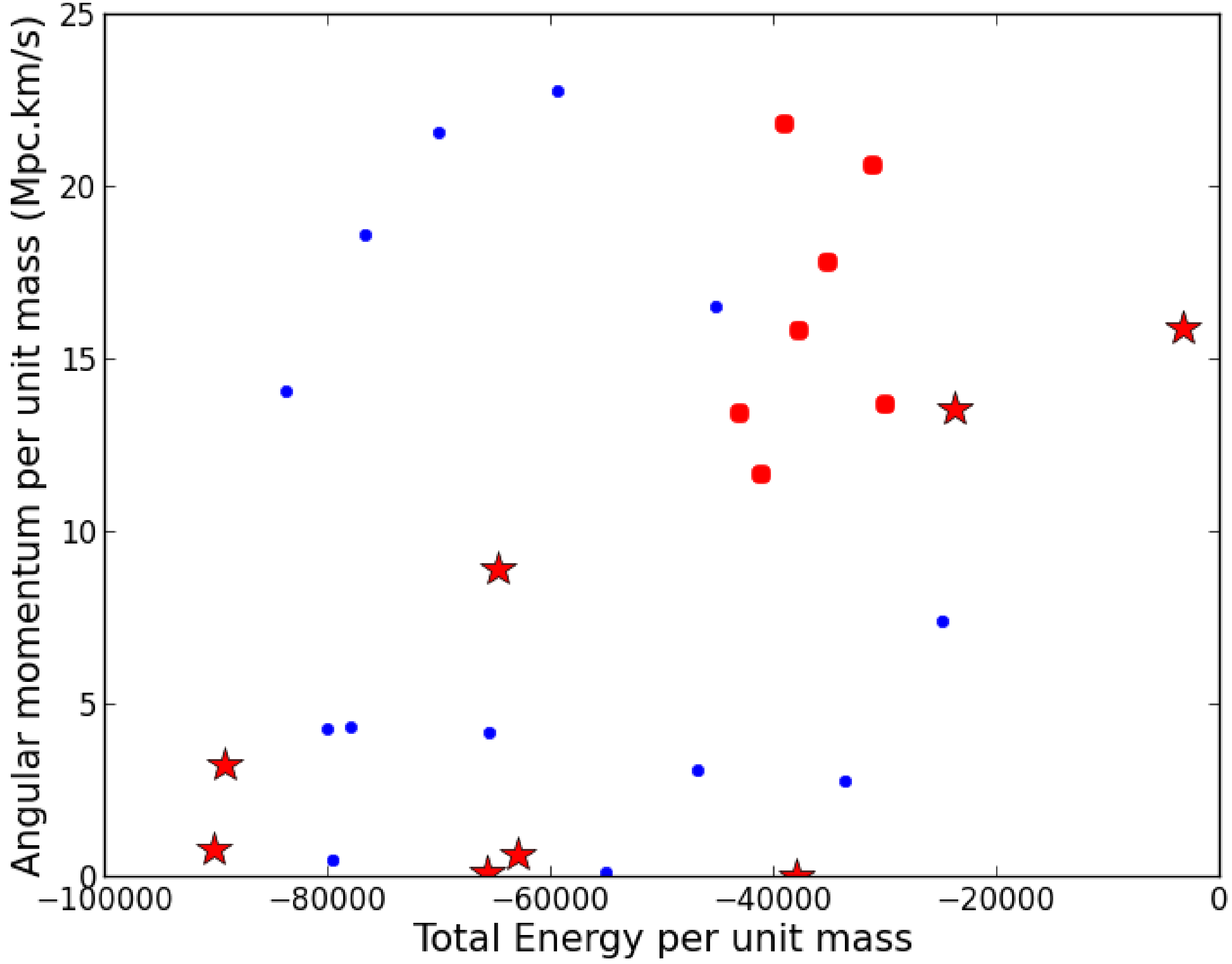


FIG. 2.— Edge-on view of planes. Symbol shapes and colors are same as in Fig. 1. Filled histogram: CaZ distribution of galaxies with measured distances. Open: possible group members without distance measurements.


Dwarf Galaxy
Large Galaxy
Dwarf Galaxy
Ibata et al. 2014

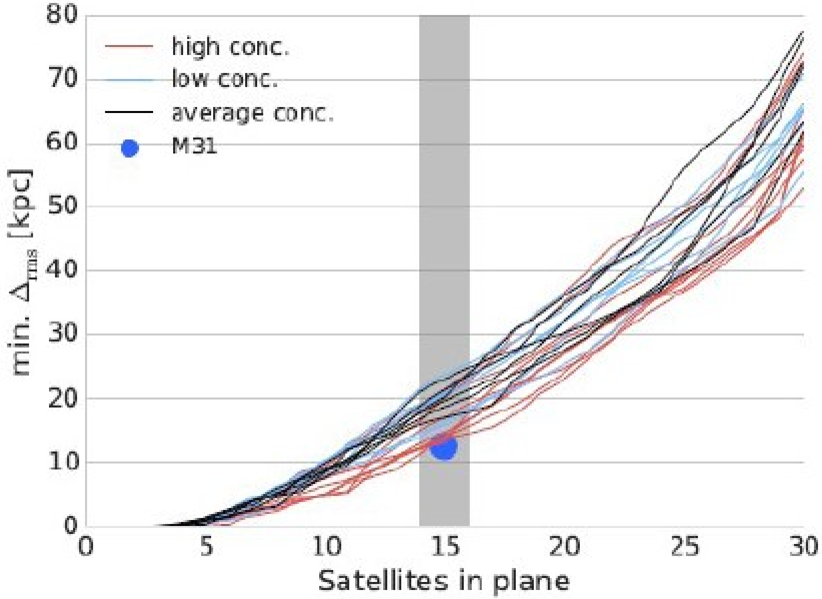
a

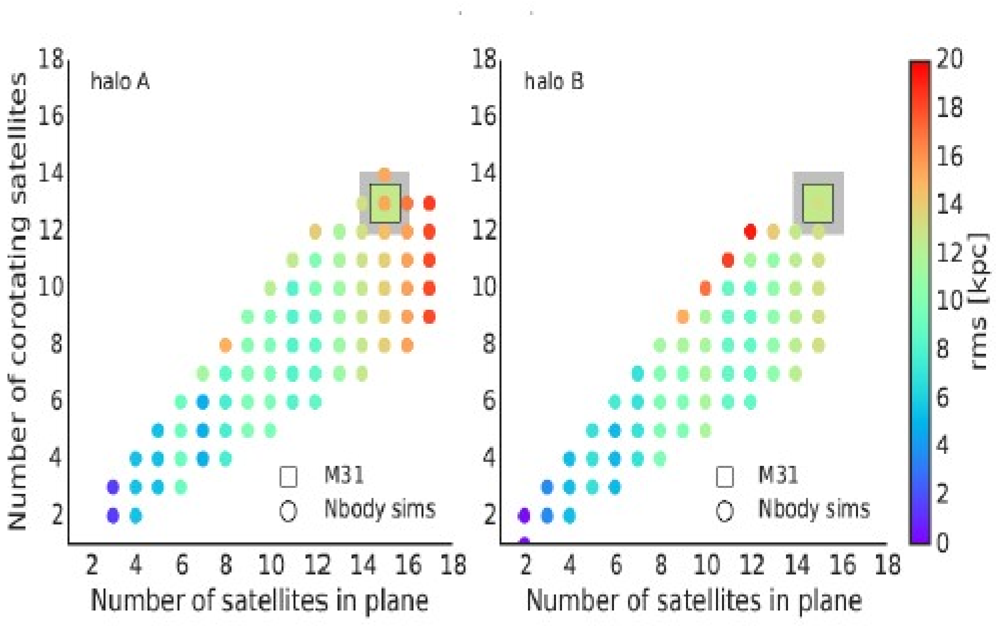

Satellite 2
α (tolerance angle)
Host
Satellite 1



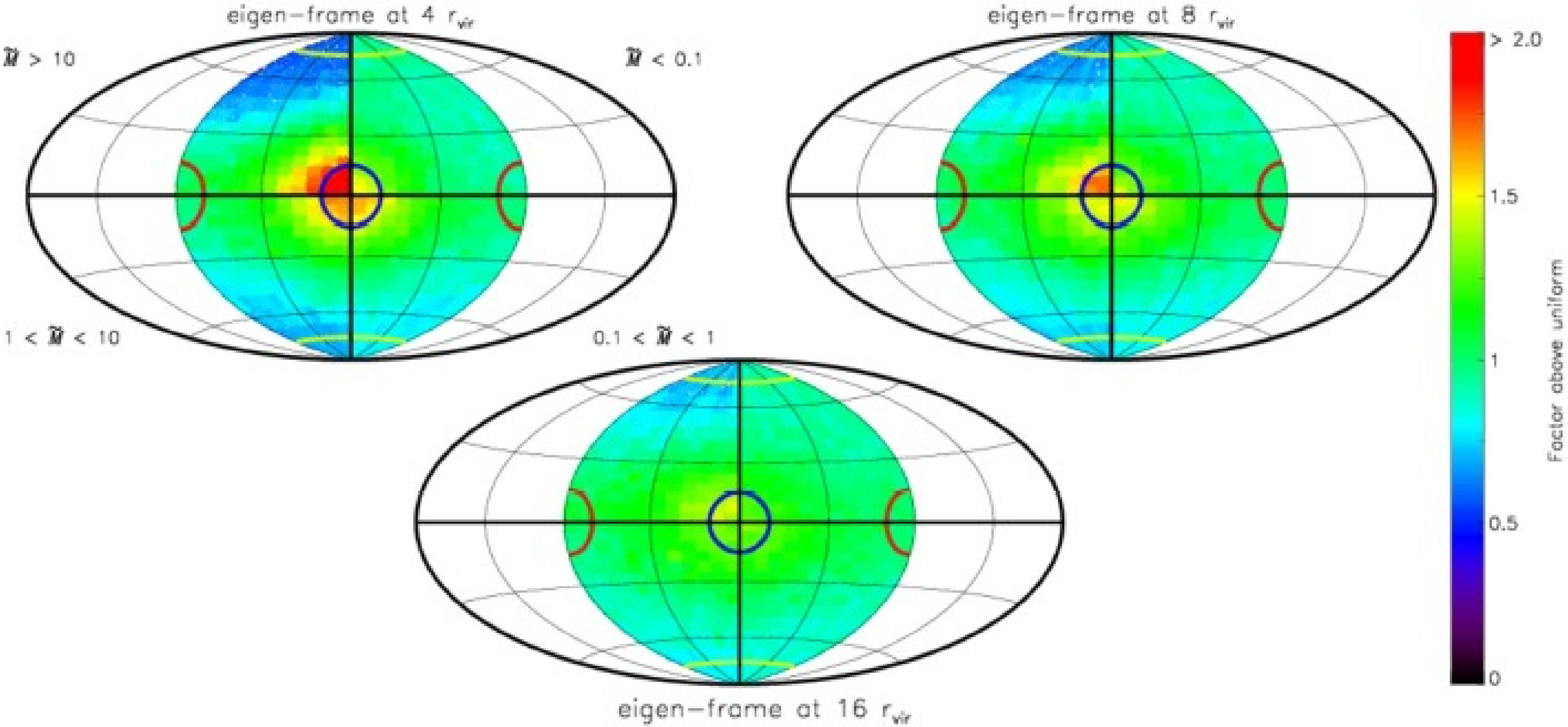
Angular momentum per unit mass (Mpc.km/s)
25
20
15
10
5
0
−100000
−80000
−60000
−40000
−20000
0
Total Energy per unit mass

Evidence for Early Filamentary Accretion from the Andromeda Galaxy's Thin Plane of Satellites (Buck,Maccio & Dutton, 2015)





Libeskind et al. 2014



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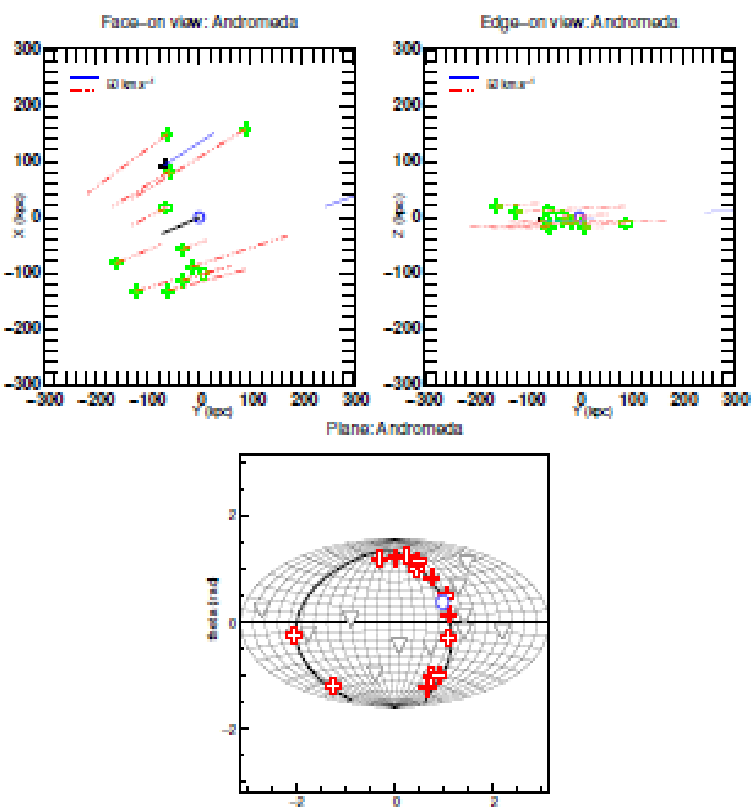
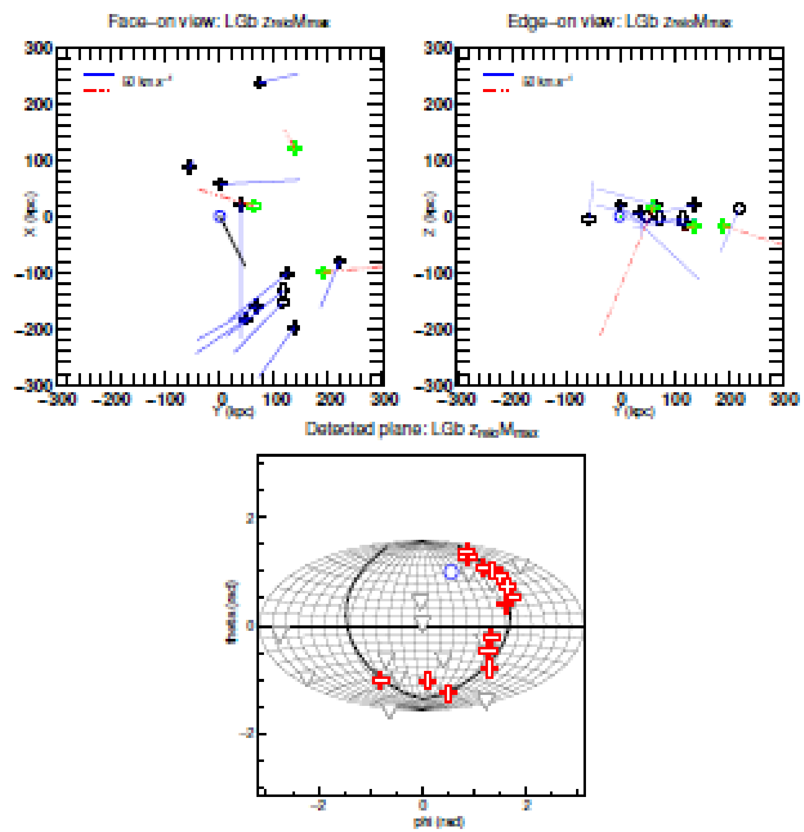
- Cautun et al. 2015 also but...

Planes found in simulations:

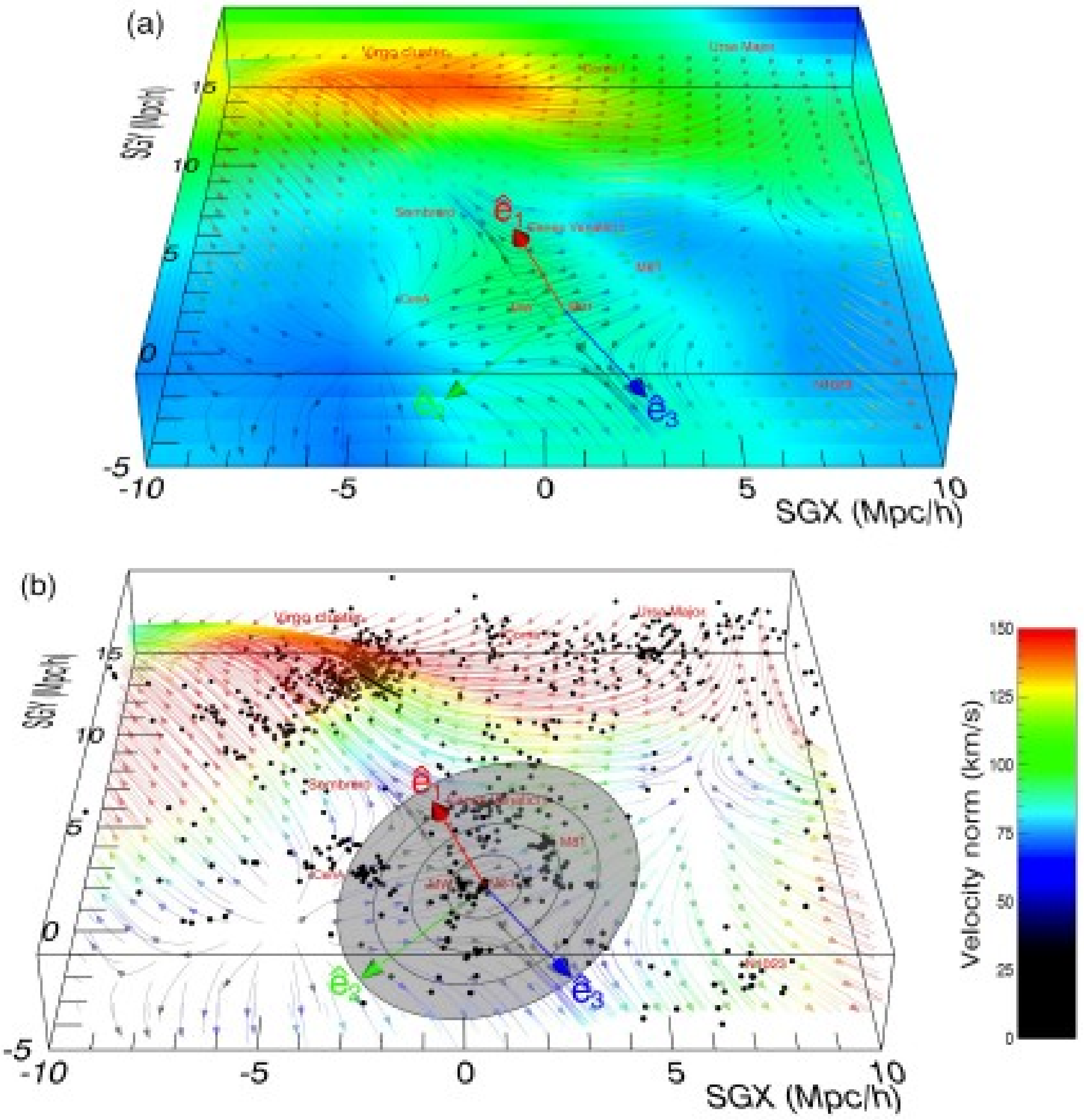
Observaciones (Andrómeda)



Simulaciones (CLUES)

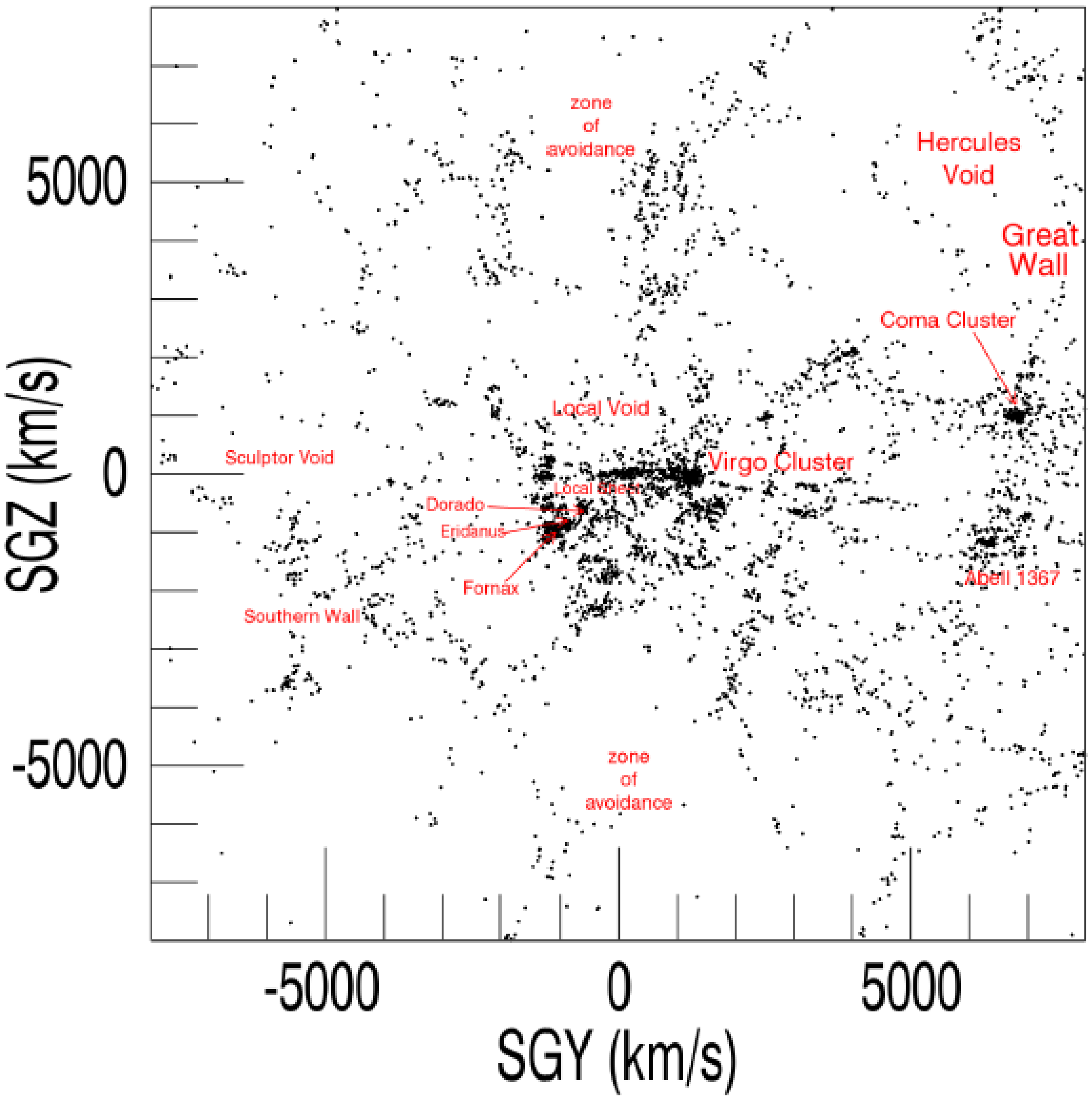


Alineaciones con la estructura a gran escala (observacionales)



Liebeskind et al. 2015

Cosmografía del universo local



Courtois et al 2013

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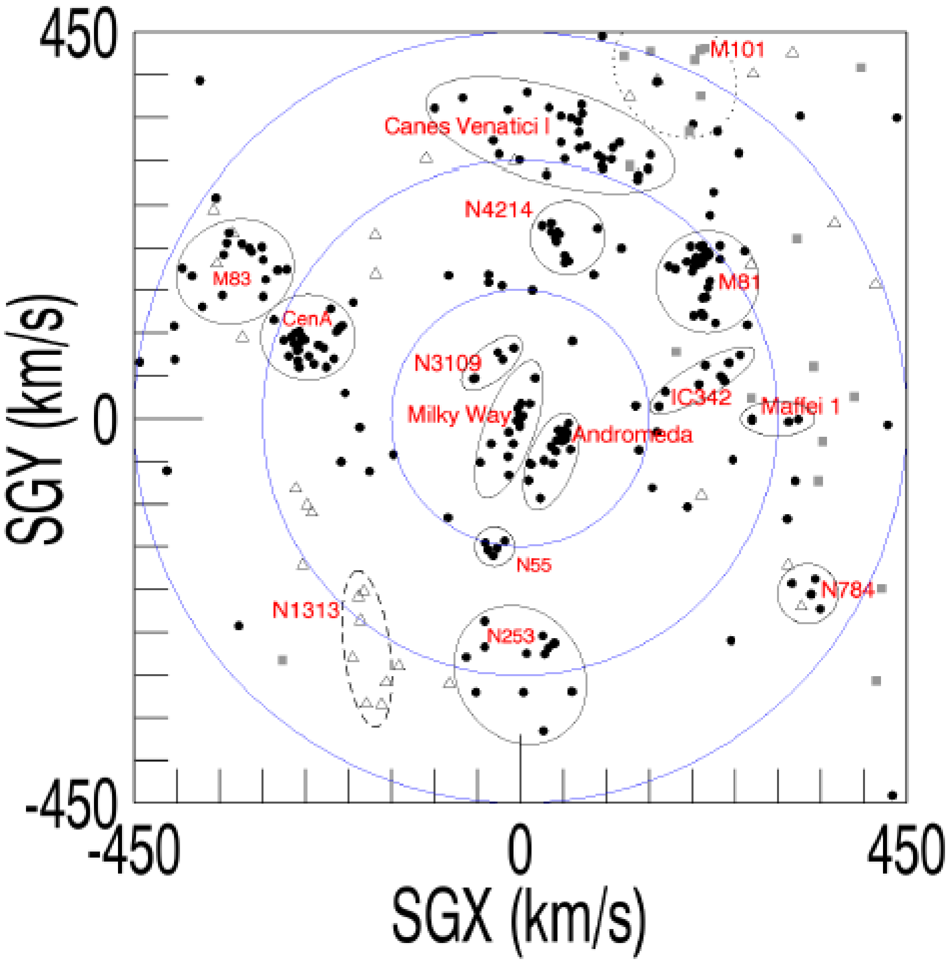

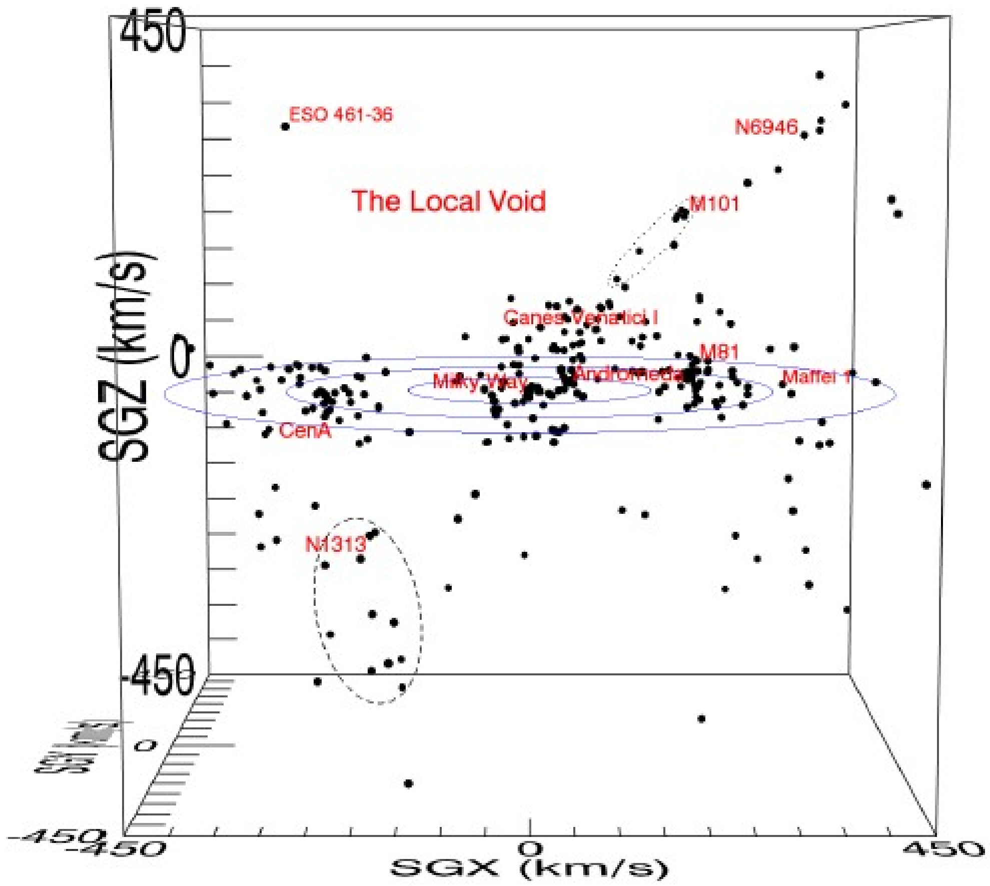

Courtois et al 2013

Propiedades de las galaxias satélite de Andrómeda:

Table 4

Kinematic Properties of Andromeda dSph Galaxies as Derived within This Work, from Keck I/LRIS, and Keck II/DEIMOS Data

Property	η	v_r (km s^{-1})	σ_v (km s^{-1})	M_{half} ($10^7\ M_\odot$)	$[M/L]_{half}$ ($M_\odot/L_\odot$)	[Fe/H]$_{spec}$
And V	2.0	-391.5 ± 2.7	$12.2^{+2.5}_{-1.9}$	$2.6^{+0.66}_{-0.56}$	$88.4^{+22.3}_{-18.9}$	-2.0 ± 0.1
And VI	2.5	-339.8 ± 1.8	$12.4^{+1.5}_{-1.3}$	4.7 ± 0.7	$27.5^{+4.2}_{-3.9}$	-1.5 ± 0.1
And XI	2.5	$-427.5^{+3.5}_{-3.4}$	$7.6^{+4.0(*)}_{-2.8}$	$0.53^{+0.28}_{-0.21}$	216^{+115}_{-87}	-1.8 ± 0.1
And XII	2.5	-557.1 ± 1.7	$0.0^{+4.0}$	$0.0^{+0.3}$	0.0^{+194}	-2.2 ± 0.2
And XIII	2.5	-204.8 ± 4.9	$0.0^{+8.1(*)}$	$0.0^{+0.7}$	0.0^{+330}	-1.7 ± 0.3
And XVII	2.5	$-251.6^{+1.8}_{-2.0}$	$2.9^{+2.2}_{-1.9}$	$0.13^{+0.22}_{-0.13}$	12^{+22}_{-12}	-1.7 ± 0.2
And XVIII	2.5	-346.8 ± 2.0	$0.0^{+2.7}$	$0.0^{+0.14}$	0^{+5}	-1.4 ± 0.3
And XIX	2.0	$-111.6^{+1.6}_{-1.4}$	$4.7^{+1.6}_{-1.4}$	$1.9^{+0.65}_{-0.66}$	84.3^{+37}_{-38}	-1.8 ± 0.3
And XX	2.5	$-456.2^{+3.1}_{-3.6}$	$7.1^{+3.9(*)}_{-2.5}$	$0.33^{+0.20}_{-0.12}$	$238.1^{+147.6}_{-90.2}$	-2.2 ± 0.4
And XXI	5.0	-362.5 ± 0.9	$4.5^{+1.2}_{-1.0}$	$0.99^{+0.28}_{-0.24}$	$25.4^{+9.4}_{-8.7}$	-1.8 ± 0.1
And XXII	2.0	-129.8 ± 2.0	$2.8^{+1.9}_{-1.4}$	$0.11^{+0.08}_{-0.06}$	$76.4^{+58.4}_{-48.1}$	-1.8 ± 0.6
And XXIII	4.0	-237.7 ± 1.2	7.1 ± 1.0	2.9 ± 4.4	58.5 ± 36.2	-2.2 ± 0.3
And XXIV	1.5	-128.2 ± 5.2	$0.0^{+7.3(*)}$	$0.4^{+0.7}_{-0.4}$	82^{+157}_{-82}	-1.8 ± 0.3
And XXV	2.5	-107.8 ± 1.0	$3.0^{+1.2}_{-1.1}$	$0.34^{+0.14}_{-0.12}$	$10.3^{+7.0}_{-6.7}$	-1.9 ± 0.1
And XXVI	3.0	$-261.6^{+3.0}_{-2.8}$	$8.6^{+2.8(*)}_{-2.2}$	$0.96^{+0.43}_{-0.34}$	325^{+243}_{-225}	-1.8 ± 0.5
And XXVII	1.5	$-539.6^{+4.7}_{-4.5}$	$14.8^{+4.3}_{-3.1}$	$8.3^{+2.8}_{-3.9}$	1391^{+1039}_{-1128}	-2.1 ± 0.5
And XXVIII	2.5	-326.2 ± 2.7	$6.6^{+2.9}_{-2.1}$	$0.53^{+0.28}_{-0.21}$	51^{+30}_{-25}	-2.1 ± 0.3
And XXX (Cass II)	2.0	$-139.8^{+6.0}_{-6.6}$	$11.8^{+7.7}_{-4.7}$	$2.2^{+1.4}_{-0.9}$	308^{+269}_{-219}	-1.7 ± 0.4

Notes. (*) indicates velocity dispersions derived from fewer than eight members stars, and require confirmation from further follow-up.