A Gaia DR2 view of proper motions and internal properties of Milky Way satellite galaxies

Giuseppina Battaglia, RyC fellow, IAC Tenerife

Fritz, Battaglia et al. submitted to A&A, May 2
Fritz, Carrera & Battaglia, submitted to A&A, May 20

Multitude of tiny dwarf galaxies and candidate dwarf galaxies around the Milky Way (and M31)

Only 11 dwarf galaxies satellites of the Milky Way known before 2003.

Nowadays there are ~40-50 and the number is ever growing (thanks to SDSS, PS1, DES, SMASH, Hyper-SuprimeCam programs etc.)

Note: not for all the nature as dwarf galaxies is confirmed.

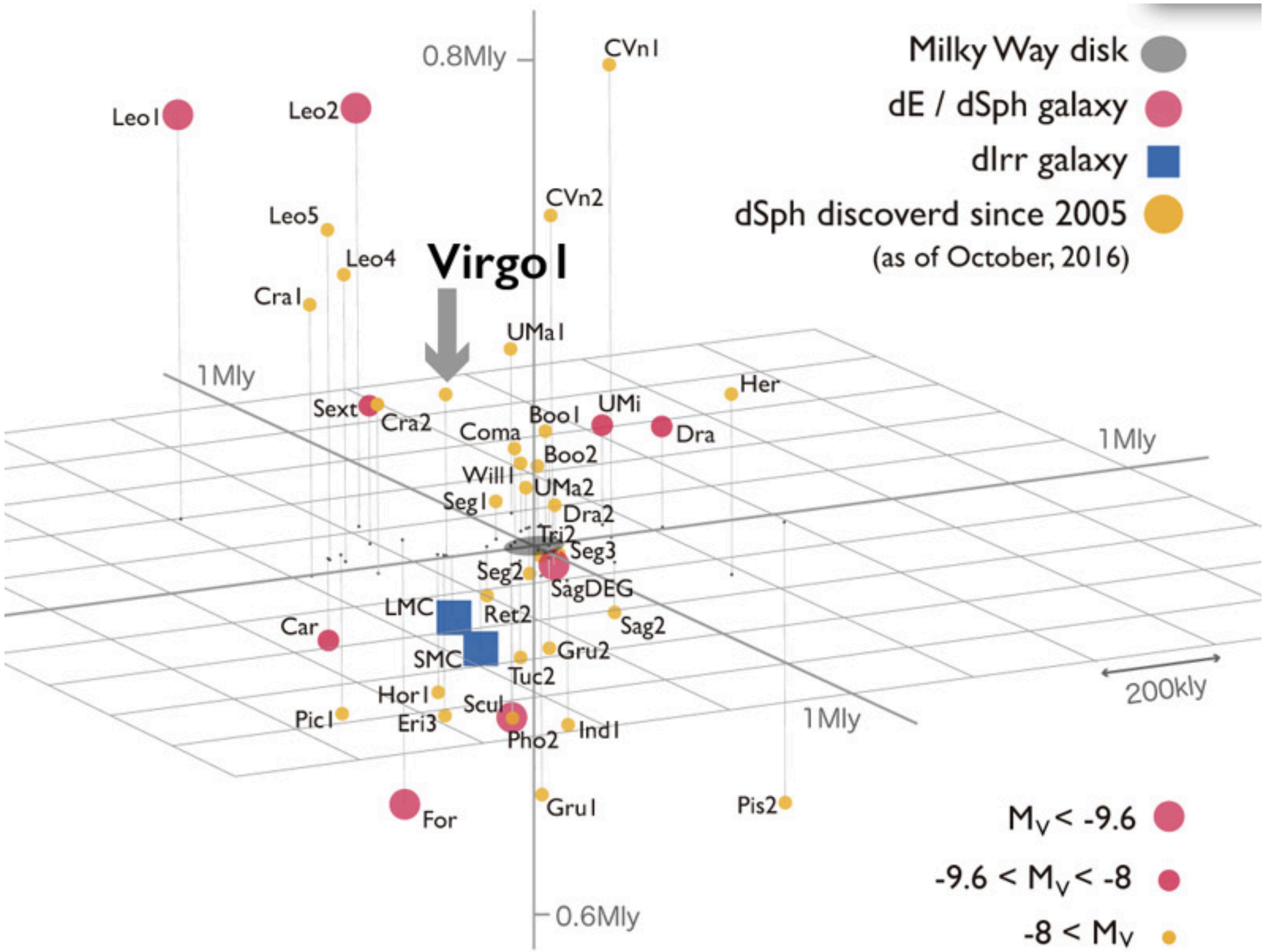
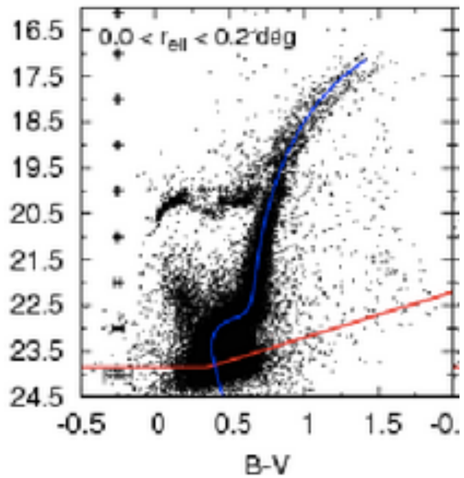


Figure from Homma et al. 2016

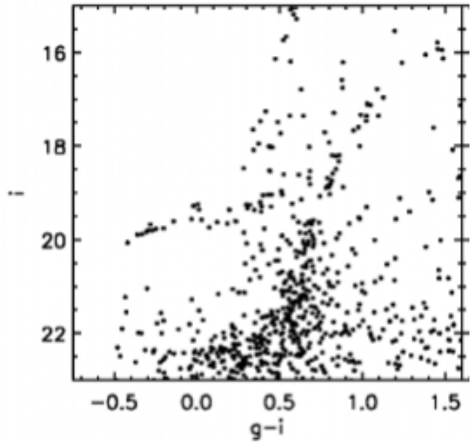
Some examples

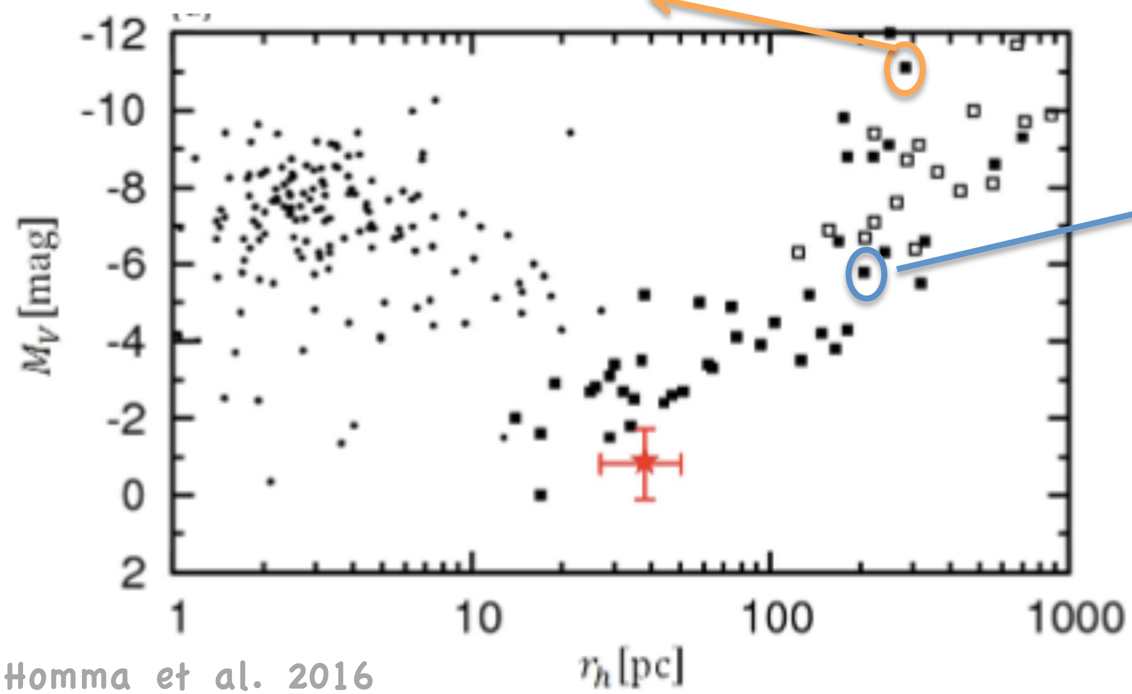
A “classical” (pre-SDSS) dwarf spheroidal galaxy: Sculptor

De Boer et al. 2012



A Ultra-faint dwarf (post-SDSS): BootesI



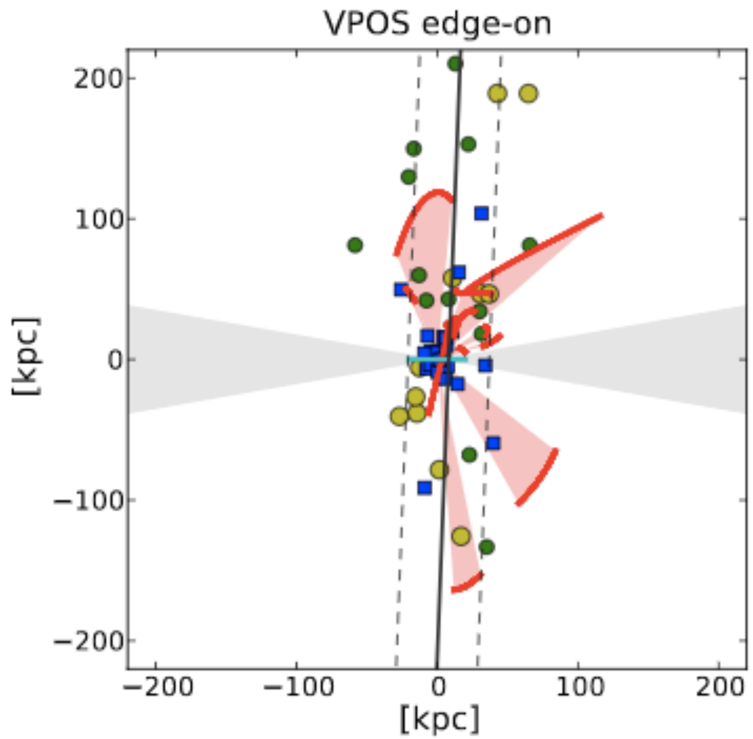


Homma et al. 2016

Importance of knowledge of their 3D motions and orbital properties

- Is the environment (e.g. tidal & ram-pressure stripping) affecting the SFH and chemical properties of these galaxies?
- Assessing the possible impact of tidal disturbance -> dark matter content and distribution of dwarf galaxies

- Tracers of the Milky Way potential out to large radii -> determinations of the Milky Way dark matter halo mass
- Plane of satellites
- Group infall: Association to the LMC satellite system?



e.g. Pawloski et al. 2012

e.g. Hammer et al. arXiv: 1805.01469

Life before Gaia DR2

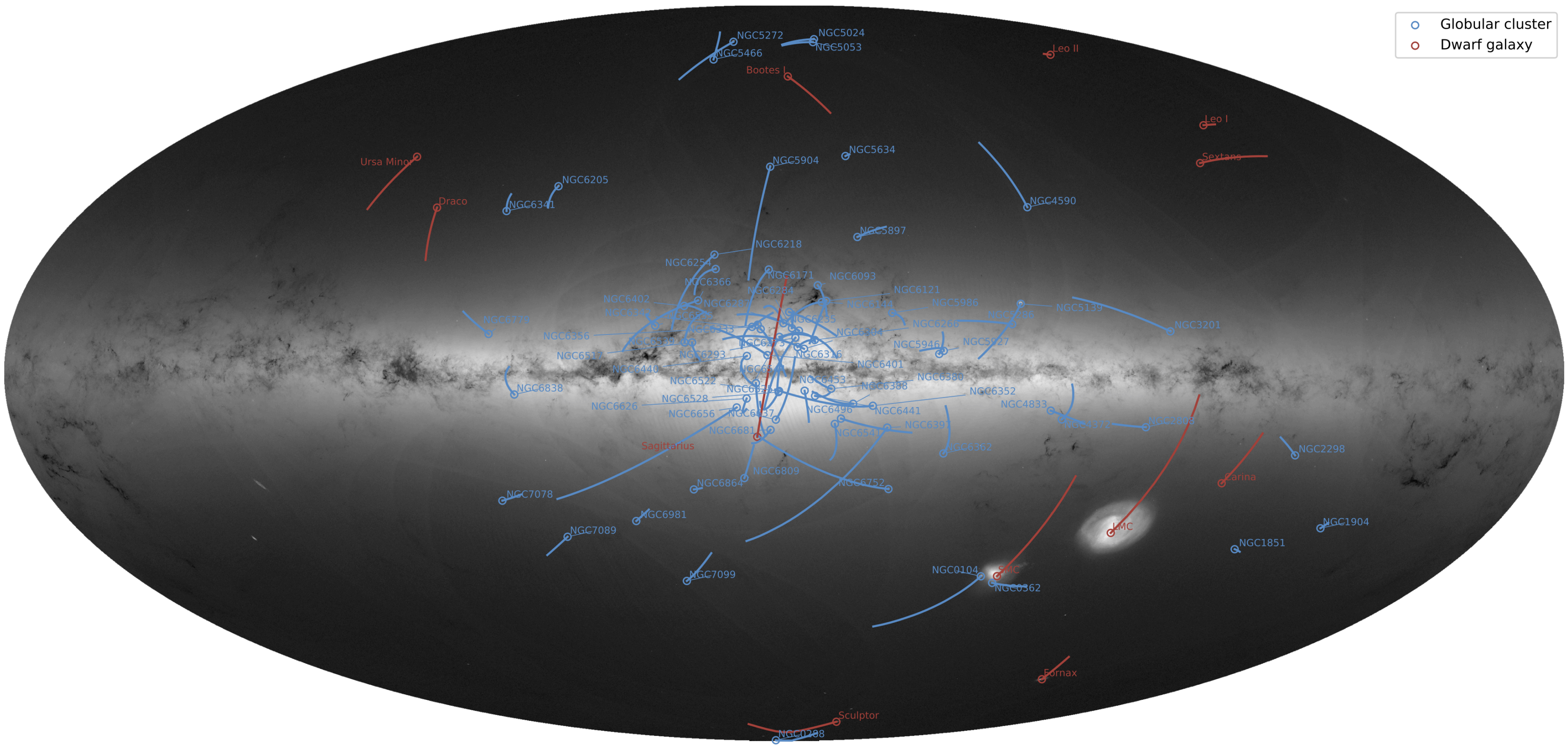
- Mostly HST but also ground-based measurements for all the classical dSphs and the Magellanic Clouds

- Only one UFD (Segue1, Fritz et al. 2017)

- Combination of HST + Gaia DR1 positions -> first measurement *ever* of the internal tangential velocity dispersion in a dSph (Massari et al. 2018, Nature)

Systemic proper motions of Milky Way satellites by the Gaia Collaboration (Helmi et al. 2018)

11 Milky Way classical dwarf galaxies (including the Magellanic Clouds), 1 UFD & 75 globular clusters



Credits: ESA/Gaia/DPAC, Amina Helmi, Maarten Breddels and co-authors of the paper "The kinematics of globular clusters and dwarf galaxies around the Milky Way

A very active field! Within a few days from Gaia DR2 data release:

- Simon arXiv:1804.10230-> 17 UFDs within 100kpc and with prior spectroscopic information from the literature

- Fritz, Battaglia et al. arXiv:1805.00908 -> 39 dwarf galaxies (and candidates) within 420kpc (UFDs + classical dSphs)

- Kallivayalil et al. arXiv:1805.01448 -> systemic proper motions for 13 dwarfs (&candidates) close to the Magellanic Clouds & predictions for the motions of other 14 such systems.

- Massari & Helmi arXiv:1805.01839 -> 7 UFDs

Gaia DR2 proper motions of the great majority of dwarf galaxies within 420 kpc

Fritz, Battaglia et al. submitted to A&A on May 2 :

39 Milky Way dwarf galaxies and galaxy candidates <u>with prior spectroscopic information</u> -> to ease selection of probable member stars

satellite	$d_{GC}[kpc]$	$\mu_{\alpha^*}[mas/yr]$	$\mu_\delta[mas/yr]$	$C_{\mu_{\alpha^*},\mu_\delta}$	$V_{3D}[km/s]$	$V_{rad}[km/s]$	$V_{tan}[km/s]$
Aqu II	105	-0.252 ± 0.527	0.011 ± 0.448	0.131	294^{+141}_{-145}	43^{+20}_{-21}	291^{+141}_{-146}
Boo I	64	-0.554 ± 0.092	-1.111 ± 0.068	0.163	195^{+26}_{-25}	95^{+4}_{-4}	170^{+30}_{-29}
Boo II	39	-2.686 ± 0.389	-0.53 ± 0.287	−0.186	395^{+82}_{-74}	-48^{+15}_{-16}	392^{+84}_{-77}
CanVen I	218	-0.159 ± 0.094	-0.067 ± 0.054	0.105	143^{+53}_{-46}	84^{+4}_{-3}	116^{+53}_{-51}
CanVen II	161	-0.342 ± 0.232	-0.473 ± 0.169	−0.006	218^{+109}_{-88}	-93^{+8}_{-8}	197^{+109}_{-94}
Car I	107	0.485 ± 0.018	0.132 ± 0.016	0.084	166^{+23}_{-22}	1^{+3}_{-3}	166^{+23}_{-22}

satellite	peri(1.6)[kpc]	apo(1.6)[kpc]	ecc(1.6)[kpc]	peri(0.8)[kpc]	apo(0.8)[kpc]	ecc(0.8)[kpc]
Aqu II	103^{+7}_{-16}	307^{+634}_{-305}	$0.5^{+0}_{-0.31}$	105^{+7}_{-10}	13425^{+10615}_{-13297}	$0.98^{+0}_{-0.33}$
Boo I	33^{+13}_{-10}	76^{+11}_{-8}	$0.4^{+0.11}_{-0.07}$	45^{+9}_{-12}	115^{+70}_{-27}	$0.43^{+0.08}_{-0.03}$
Boo II	39^{+2}_{-3}	203^{+1556}_{-121}	$0.68^{+0.29}_{-0.29}$	40^{+3}_{-3}	21309^{+20097}_{-20920}	$1^{+0}_{-0.18}$
CanVen I	75^{+36}_{-46}	260^{+327}_{-45}	$0.55^{+0.25}_{-0.13}$	118^{+35}_{-63}	371^{+6823}_{-217}	$0.52^{+0.17}_{-0.14}$
CanVen II	121^{+17}_{-71}	281^{+15337}_{-178}	$0.4^{+0.13}_{-0.17}$	137^{+16}_{-55}	1583^{+2813}_{-1553}	$0.84^{+0.01}_{-0.29}$
Car I	65^{+32}_{-22}	107^{+10}_{-8}	$0.24^{+0.17}_{-0.16}$	106^{+8}_{-24}	137^{+115}_{-43}	$0.13^{+0.13}_{-0.09}$

(short extracts from the tables in the manuscript)

Methodology

- Search for matches between stars with literature spectroscopic information and Gaia DR2 kinematic information (parallax and proper motion)
- Selection of spectroscopically observed stars with probability of membership > 40% (either on probability estimate from the literature or our own)
- Parallax consistent with zero within 2sigma (distant objects)
- Broad proper motion selection (stars are required to have tangential velocities within 2sigma from escape speed at the distance of the corresponding dwarf galaxy; largish halo mass = 1.2x10^12 Msun)
- Depending on number of stars passing criteria above, further 3sigma selection in systemic proper motion

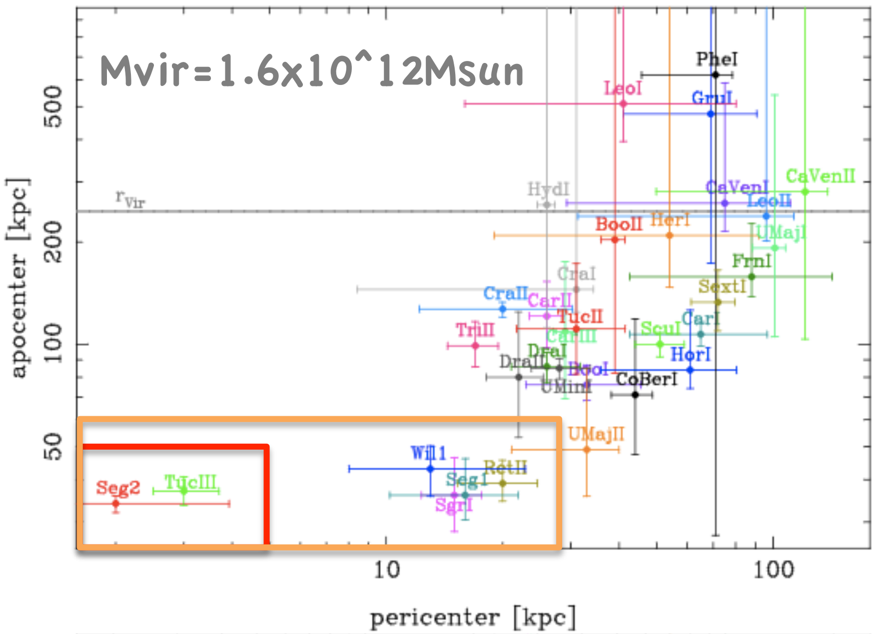
Systemic proper motion & line-of-sight velocity -> Galactocentric velocities -> orbital properties using *galpy* (Bovy 2015) in a "low" and "high" mass Milky Way (virial mass 0.8x10^12 and 1.6x10^12 Msun)

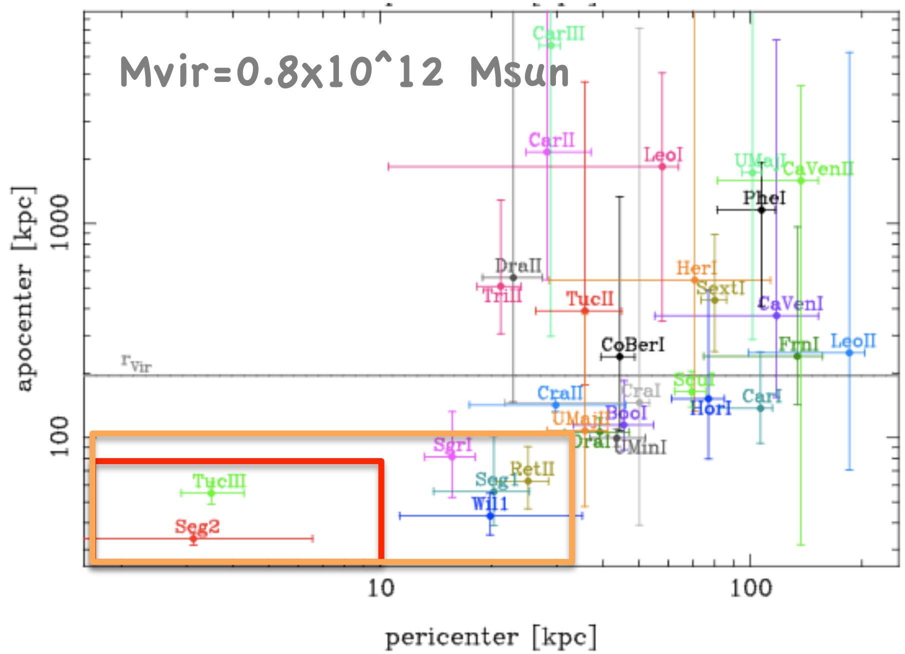
=> For the galaxies in common, our systemic proper motions agree well within Helmi+, Simon, Massari&Helmi determination (mostly within 1sigma, max. 2sigma, apart from SagittariusI, due to different samples used).

CAVEATS: only average correlation coefficient for members is carried on in the error-propagation. Due to large errors in some cases, a rescaling is applied to error-bars to avoid unphysical values (i.e. negative 3D velocities, since they are defined positive)

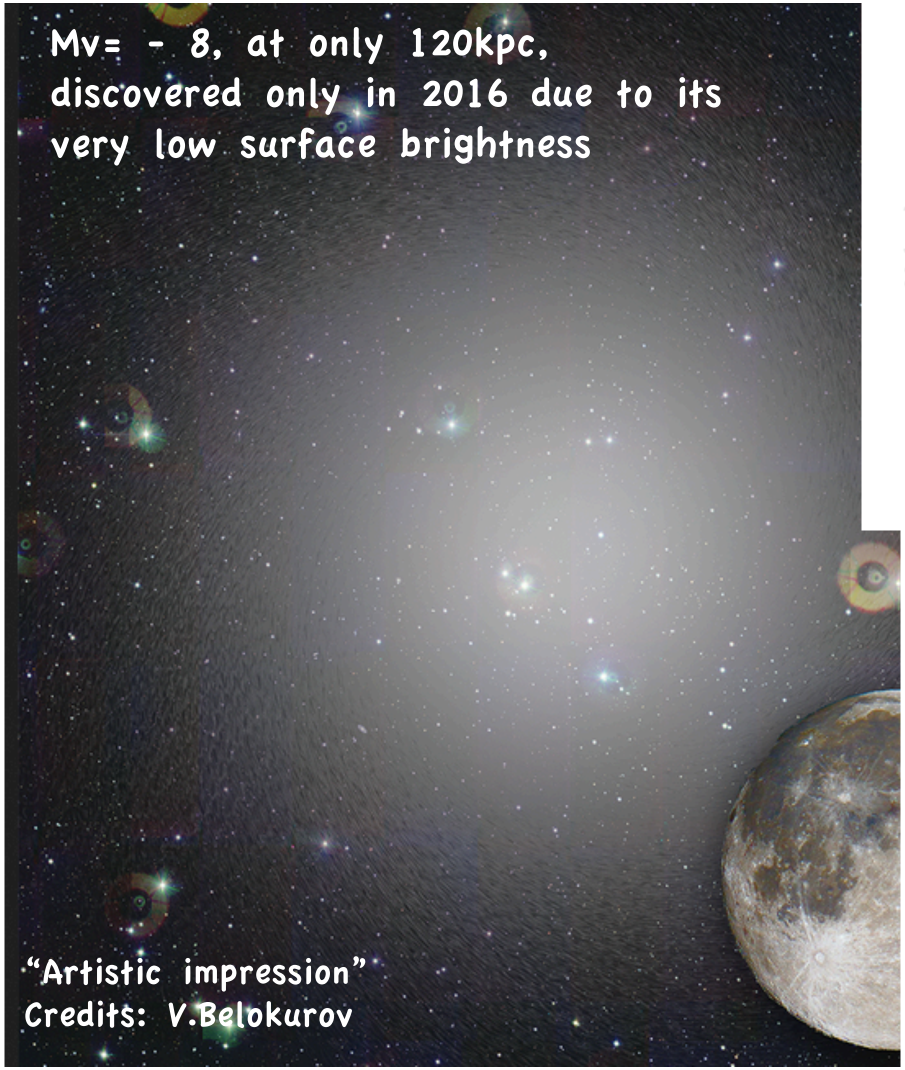
Results : MW halo mass - tidal disturbance

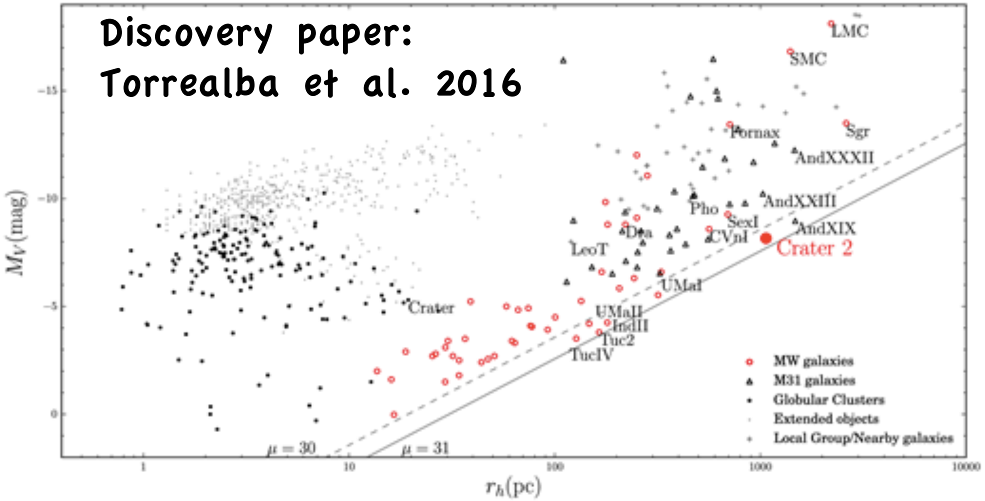
- In the low-mass case several galaxies would have orbits that bring them in and out of the MW halo
- Segue2 and TucIII have very internal orbits (TucIII is indeed known to show a stream); also Wil1, RetII, Segue1 might be at risk of tidal disturbance
- Carina, BootesI and Hercules exhibit signs of tidal disturbance : what do their orbits say?

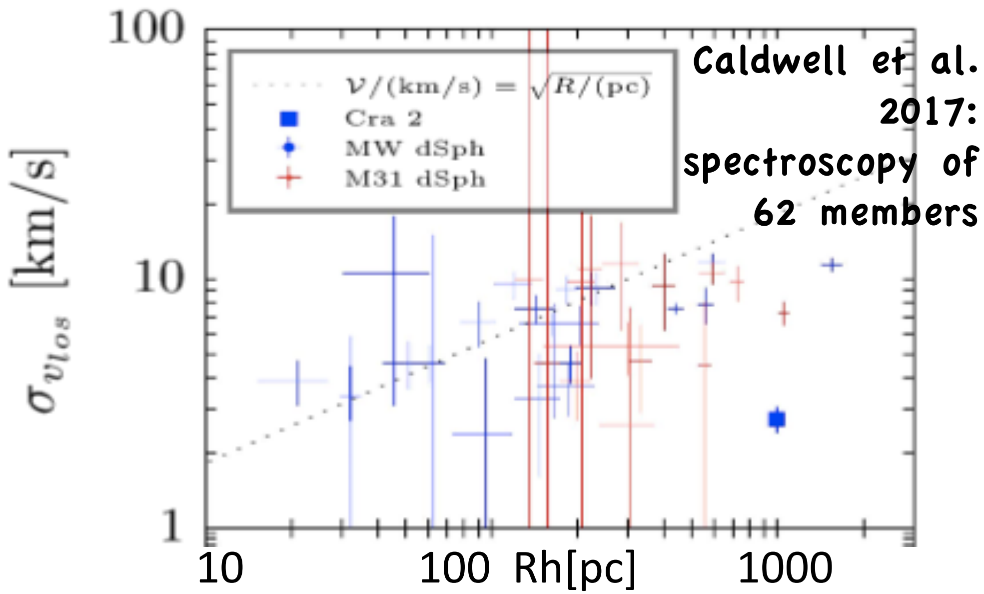




Results : orbit of CraterII, the "feeble giant"

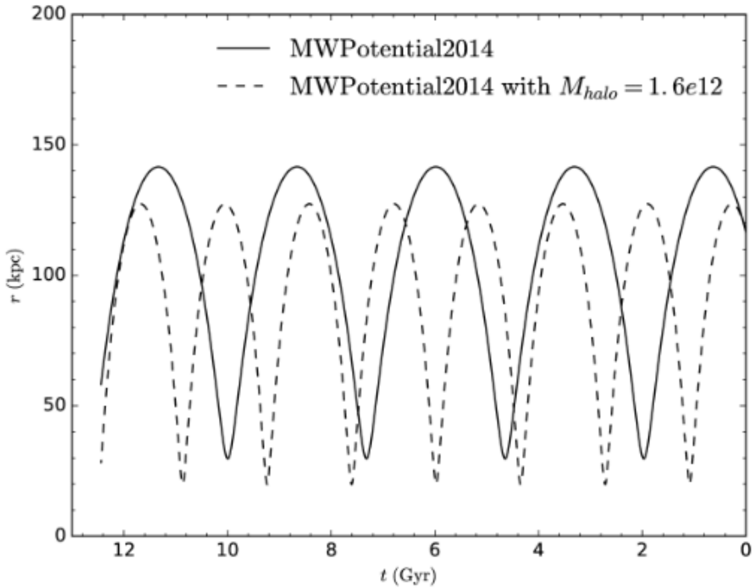




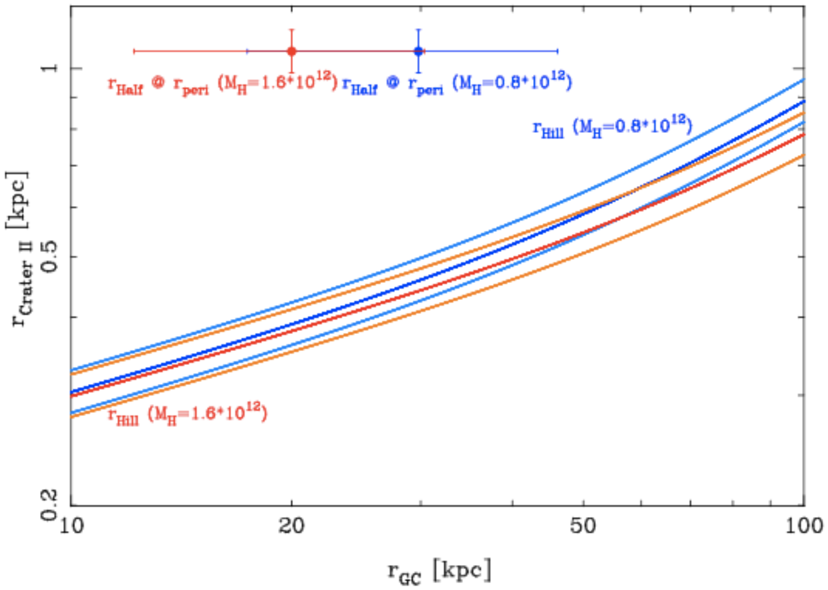


Results : orbit of CraterII, the “feeble giant”

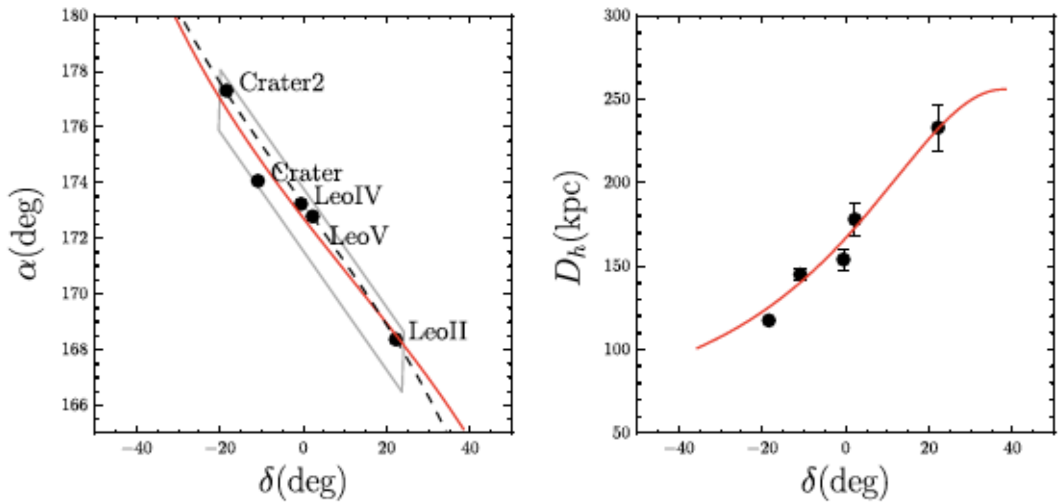
McGaugh (2016) predicted the extremely low velocity dispersion of CraterII in MOND but within the assumption of dynamical equilibrium. To be revised?



Our proper motion is consistent at the 0.3/1.3sigma level with the models by Sanders et al. 2018 (see also Fattahi et al. 2018) which explain Crater II as an heavily tidally disrupted dwarf embedded in a LambdaCDM halo.

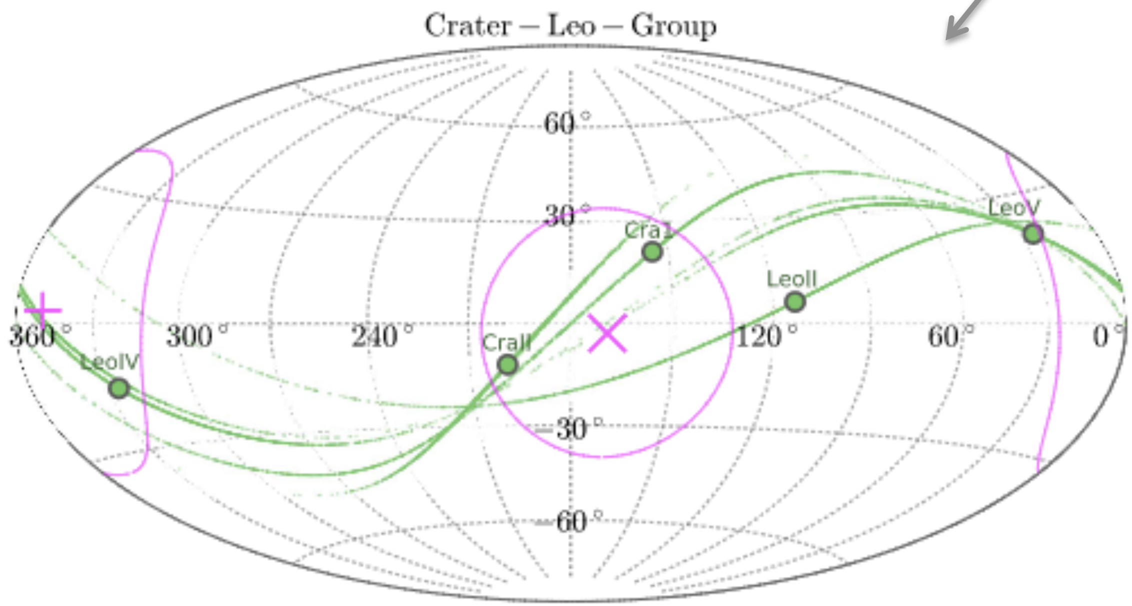


Orbital poles: The Crater-Leo "group" might not be a group

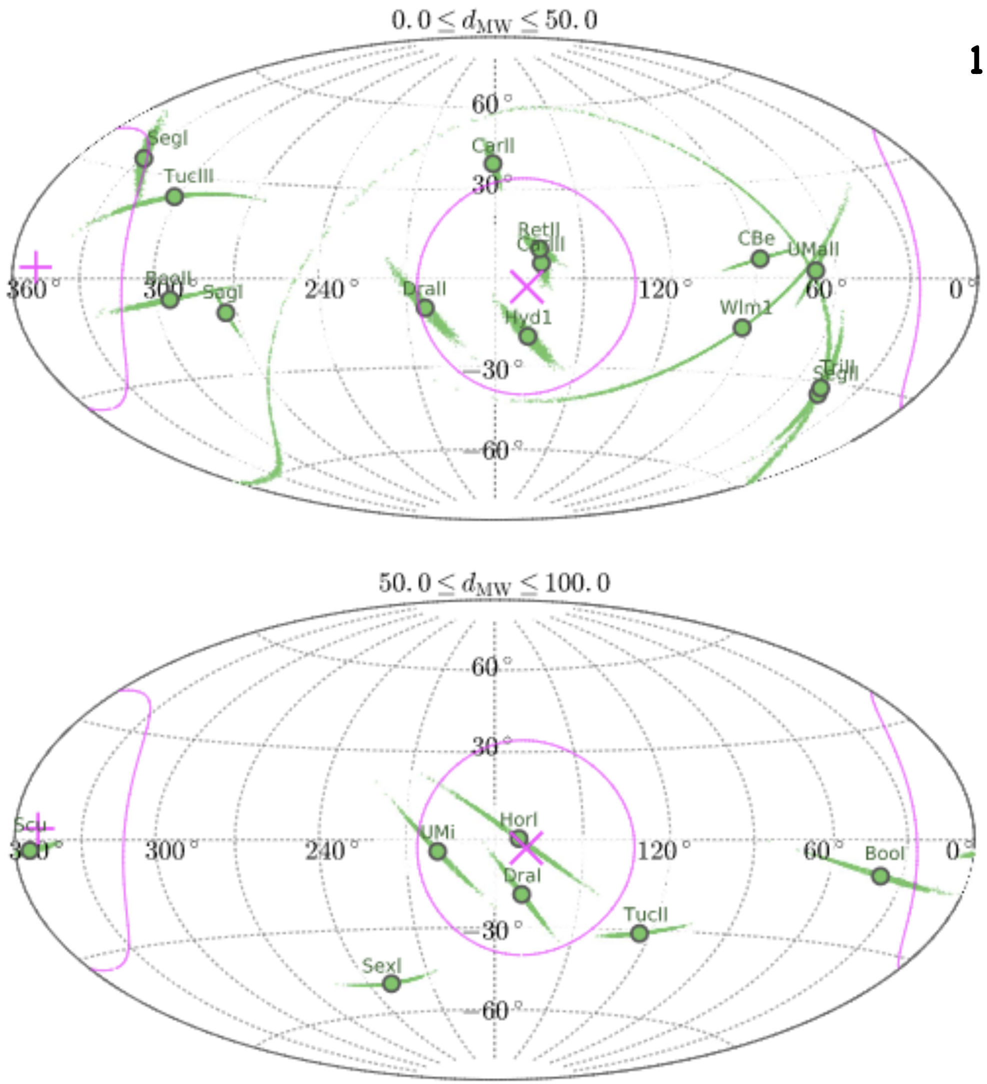


Torrealba et al. 2016 suggested these 5 systems might have come in as a group

Our orbital poles do not appear to confirm this hypothesis

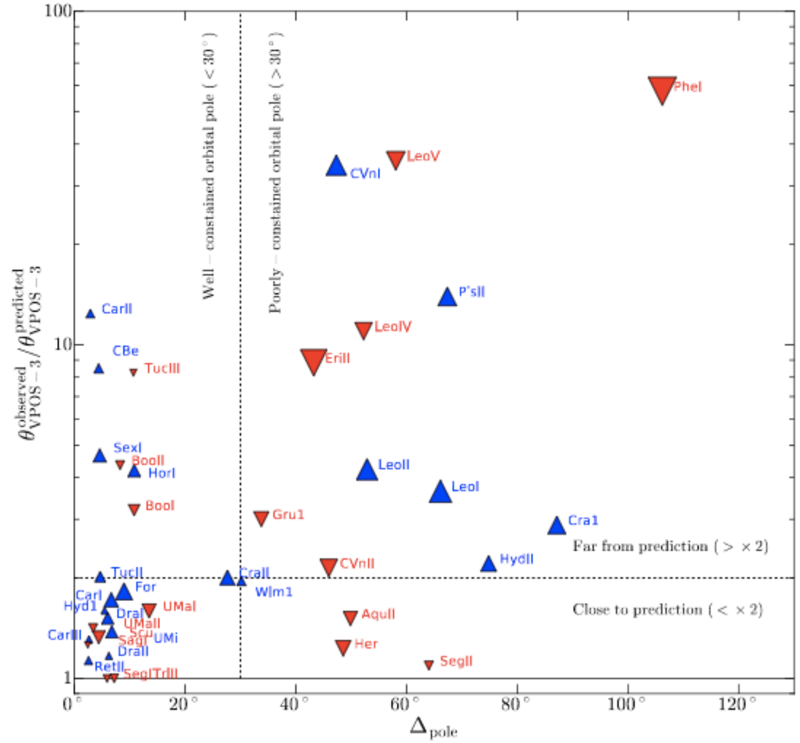


Orbital poles and alignment with the Vast Polar Structure



16 satellites align with the VPOS (5 counter-orbiting), 12 do not, 11 have too large uncertainties to be conclusive

To be further investigated in Pawlowski et al. in prep.



Satellites of the LMC ?

of 32 candidate low mass, dwarf galaxies in close proximity on the sky to the Magellanic Clouds (Bechtol et al. 2015; Drlica-Wagner et al. 2015; Koposov et al. 2015b; Martin et al. 2015; Laevens et al. 2015a; Torrealba et al. 2016a; Torrealba et al. 2016b; Torrealba et al. 2018; Kim & Jerjen 2015; Kim et al. 2015; Drlica-Wagner et al. 2016; Koposov et al. 2018; Homma et al. 2018) present a

How many and which ones are associated to the LMC/SMC or are genuine satellites of the Milky Way has implications on the LMC mass, luminosity/mass function of MW satellite system, and gives the opportunity to study group pre-processing.

Several works have explored association on the basis of the satellites sky position, distance, line-of-sight velocities & comparison to simulations/dynamical models (e.g. Sales+2011, Deason+2016, Jethwa+2016, Sales+2017)

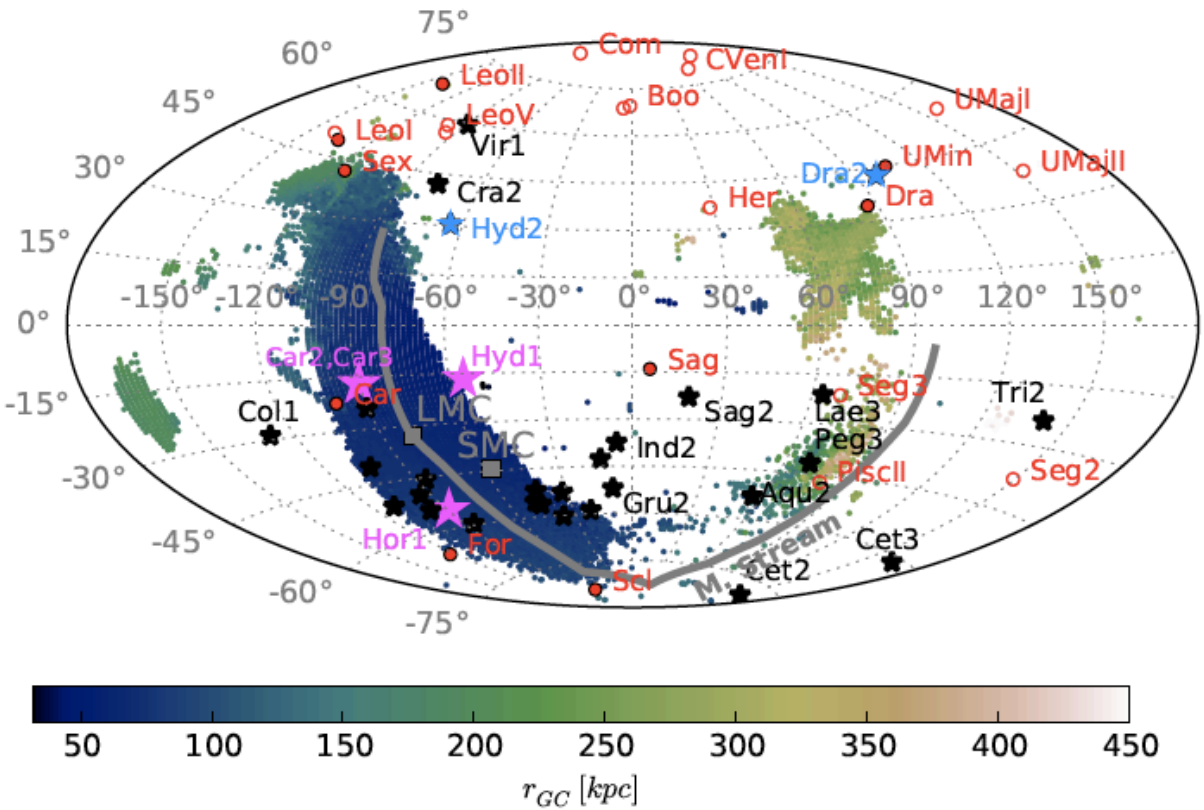
=> All agree that proper motions are crucial -> accreted LMC satellites should have similar angular momentum to the LMC

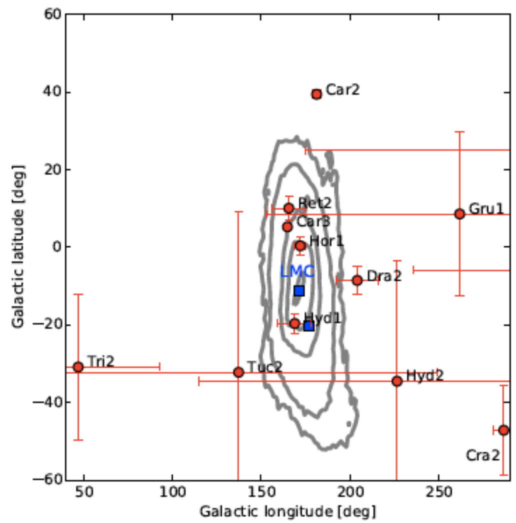
Gaia DR2 based search by Kallivayalil et al.

Of the 13 UFDs with systemic proper motions, 4 are highly likely LMC satellites, 2 favorable, 3 likely not, 4 are ruled out.

6 objects without proper motions are excluded on the basis of the position, distance and/or line-of-sight velocities

Predicted bulk motion for other 13 systems.





Figs. from Kallivayalil et al., using simulations by Sales et al. 2011, 2017

A Gaia DR2 & VLT/FLAMES search for new satellites of the LMC

Fritz, Carrera, Battaglia, submitted to A&A on May 20

- ColumbaI, HorologiumII, PhoenixII, ReticulumIII
- -4 < MV< -2 ; Galactoncentric distance: 80-190kpc
- Published data were only imaging and photometry -> even their nature as galaxies or stellar clusters is unknown
- Both Kallivayalil et al. and Jethwa et al. 2016 give predicted bulk motions in the hypothesis of a prior association to the LMC

We use ESO archive VLT/FLAMES GIRAFFE data that became recently public + Gaia DR2 & NOAO Source Catalogue DECam photometry.

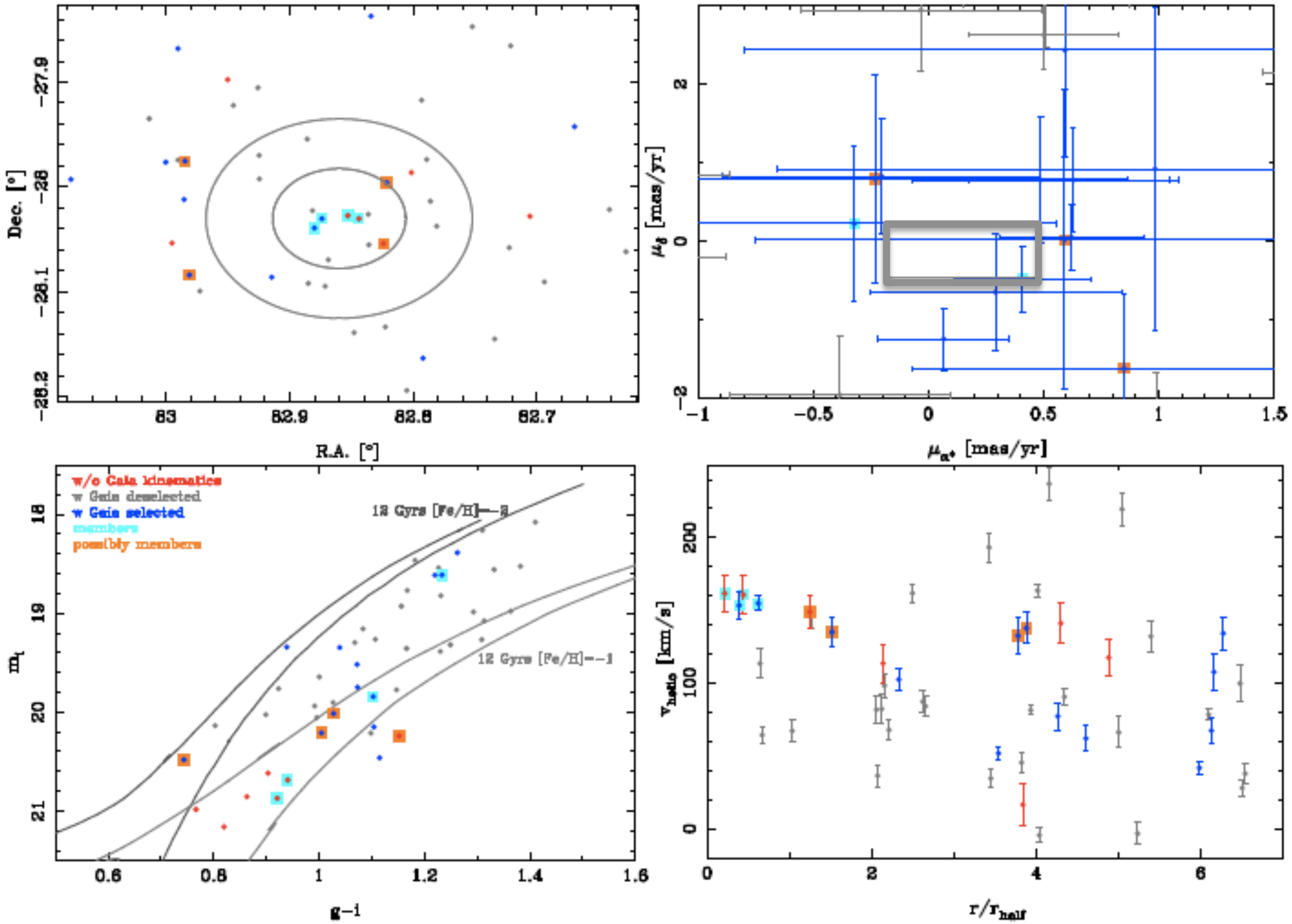
Combination of spectroscopy + astrometry crucial to spot members in these very faint systems.

Methodology:

parallax & escape speed selection as in Fritz+2018a
+ CMD selection
further members searched for once the vlos,sys in known

Columba I

2 likely members + 3 additional candidates

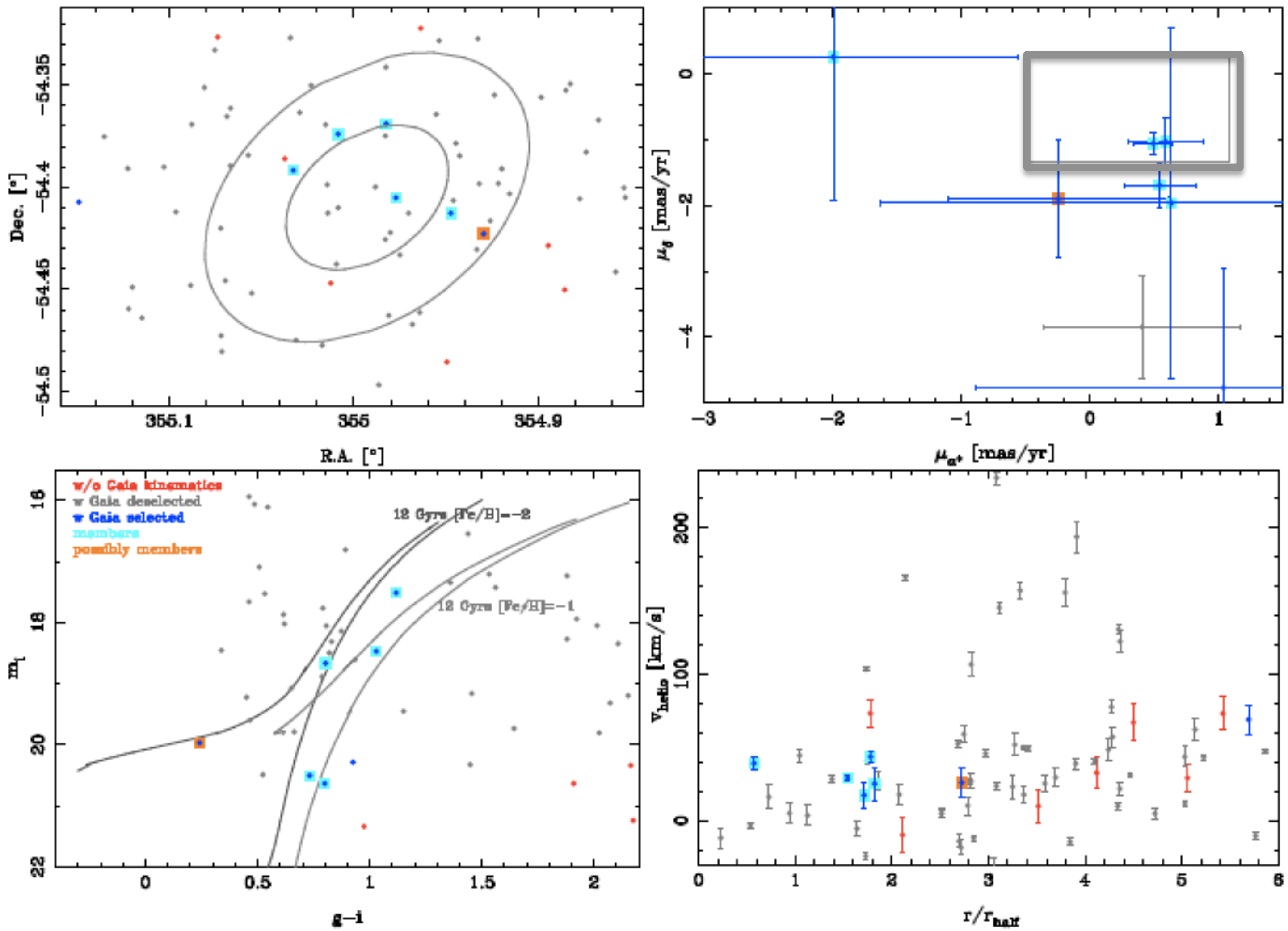


Methodology:

parallax & escape speed selection as in Fritz+2018a
+ CMD selection
further members searched for once the vlos,sys in known

Phoenix II

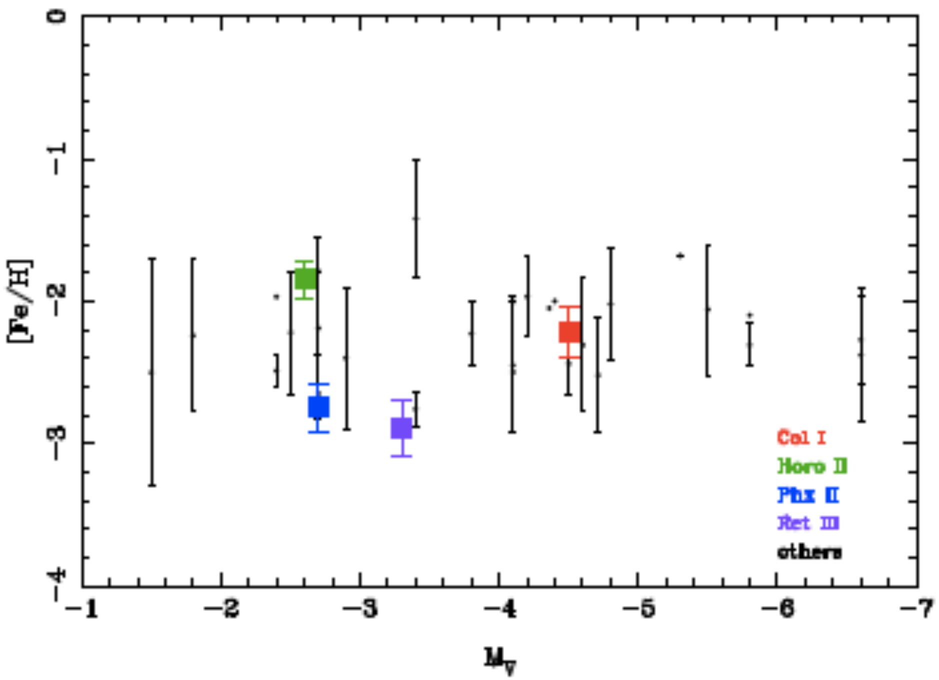
5 likely members + 1 additional candidate



Results: existence and nature

Chance to observe the velocity "spikes" due to contamination by MW stars is < 0.1 % (< 2.4% for HoroII) -> they are real.

satellite	$<V_{helio}>[km/s]$	$\sigma V_{helio}[km/s]$	$\mu_{\alpha^*}[mas/yr]$	$\mu_\delta[mas/yr]$	$C_{\mu_{\alpha*},\mu_\delta}$	$<[Fe/H]>$	$\sigma[Fe/H]$
ColumbaI	149.4 ± 3.6	< 5.6	0.35 ± 0.26	-0.45 ± 0.34	-0.13	-2.01 ± 0.1	$0.21^{+0.03}_{-0.02}$
Horologium II	169.4 ± 9.2	$12.9^{+8.5}_{-4.4}$	1.52 ± 0.25	-0.47 ± 0.39	0.07	-1.85 ± 0.13	< 0.12
Phoenix II	32.4 ± 3.9	$7.1^{+1.5}_{-1.1}$	0.49 ± 0.12	-1.18 ± 0.14	-0.47	-2.44 ± 0.32	$0.77^{+0.09}_{-0.07}$
Reticulum III	274.3 ± 4.5	< 3	-0.39 ± 0.53	-0.32 ± 0.63	0.45	-2.89 ± 0.19	$0.26^{+0.15}_{-0.06}$
Columba I	155.9 ± 4.1	< 5	0.33 ± 0.28	-0.38 ± 0.38	-0.14	-2.22 ± 0.18	< 0.20
Horologium II	173.7 ± 15.8	< 30	0.36 ± 0.68	-0.5 ± 1.08	-0.17	-1.85 ± 0.13	< 2
Phoenix II	32.9 ± 4.5	$8.2^{+1.9}_{-1.5}$	0.5 ± 0.12	-1.16 ± 0.14	-0.47	-2.75 ± 0.17	$0.34^{+0.07}_{-0.05}$



PhoenixII is the only system for which we can safely say it is a galaxy, since we resolve both a large los dispersion and the spread in metallicity.

The other ones do not have limits that exclude their nature as such, but data are inconclusive.

Results: association to the LMC

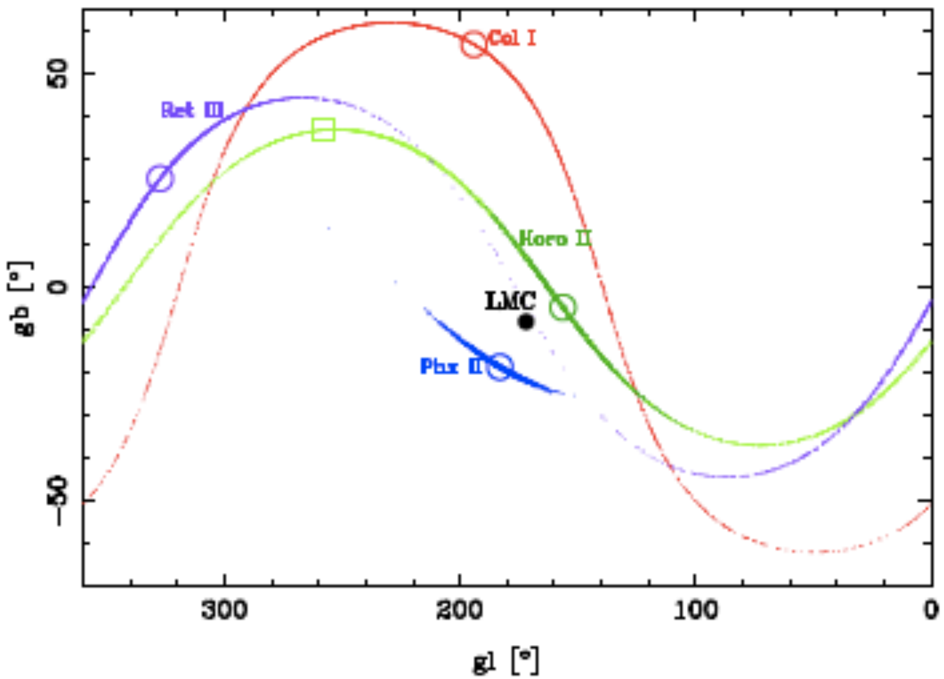
Even if RetIII, HoroII and ColI are clusters they can still give information on the orbit of their host, if they originated in an accreted dwarf galaxy (as it is thought to be the case for outer halo globular clusters)

ColI orbital pole always > 32deg away from the LMC one.

RetIII unlikely to be associated

HoroII very much dependent on the sample

PhxII well determined orbital pole, it gets as close as 16deg to the LMC one. Good candidate. Proper motion agrees well with Kallivayalil+ predictions.



Summary and conclusions

In Fritz+2018a we provided systemic proper motions and orbital properties for the great majority of dwarf galaxies (and candidates) within 420kpc:

-> several systems are likely to have experienced strong tidal disturbance, including the "feeble giant" CraterII
-> orbits would be better explained in a "high-mass" MW halo
-> 16 satellites align with the VPOS (5 counter-orbiting), 12 do not, 11 have too large uncertainties to be conclusive
-> it is unlikely that Crater1, CraterII, LeoII, LeoIV and LeoV have all come in as a group.

In Fritz+201b we present systemic proper motions for other 4 UFDs AND the first line-of-sight systemic velocities by analyzing unpublished VLT/FLAMES spectroscopic observations from the ESO archive + Gaia DR2 data:

We establish that PhxII is a dwarf galaxy and that it is a good candidate for having been another one of the LMC satellites (making them 5 in total).