Globular Clusters in relation to the VPOS of the Milky Way

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think beyond the possible™

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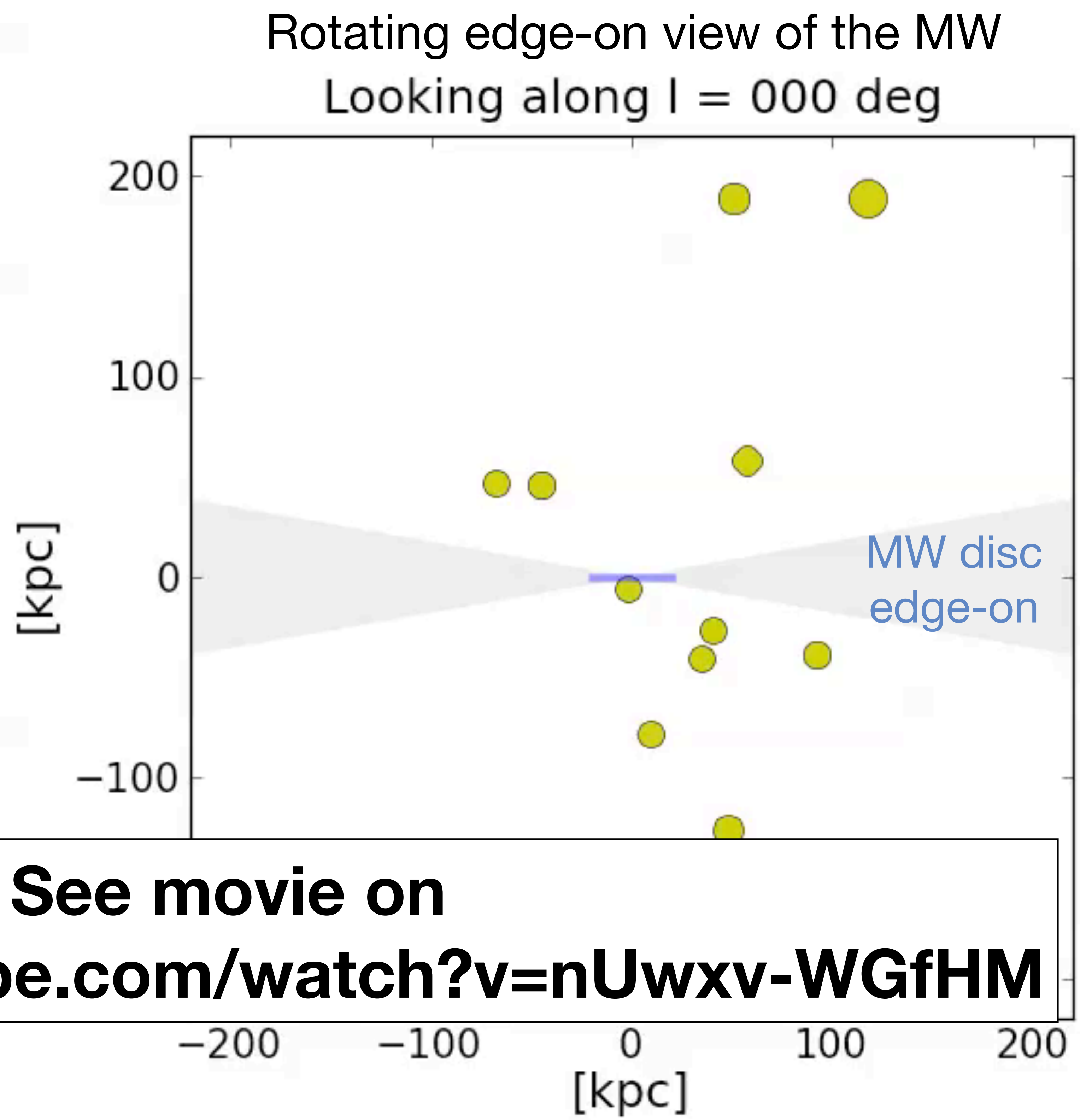
Germany: **Pavel Kroupa**, **Fabian Lüghausen**

United States: Stacy McGaugh, David Merritt

The MW is surrounded by a **V**ast **PO**lar **S**tructure of satellite objects

The VPOS consists of:

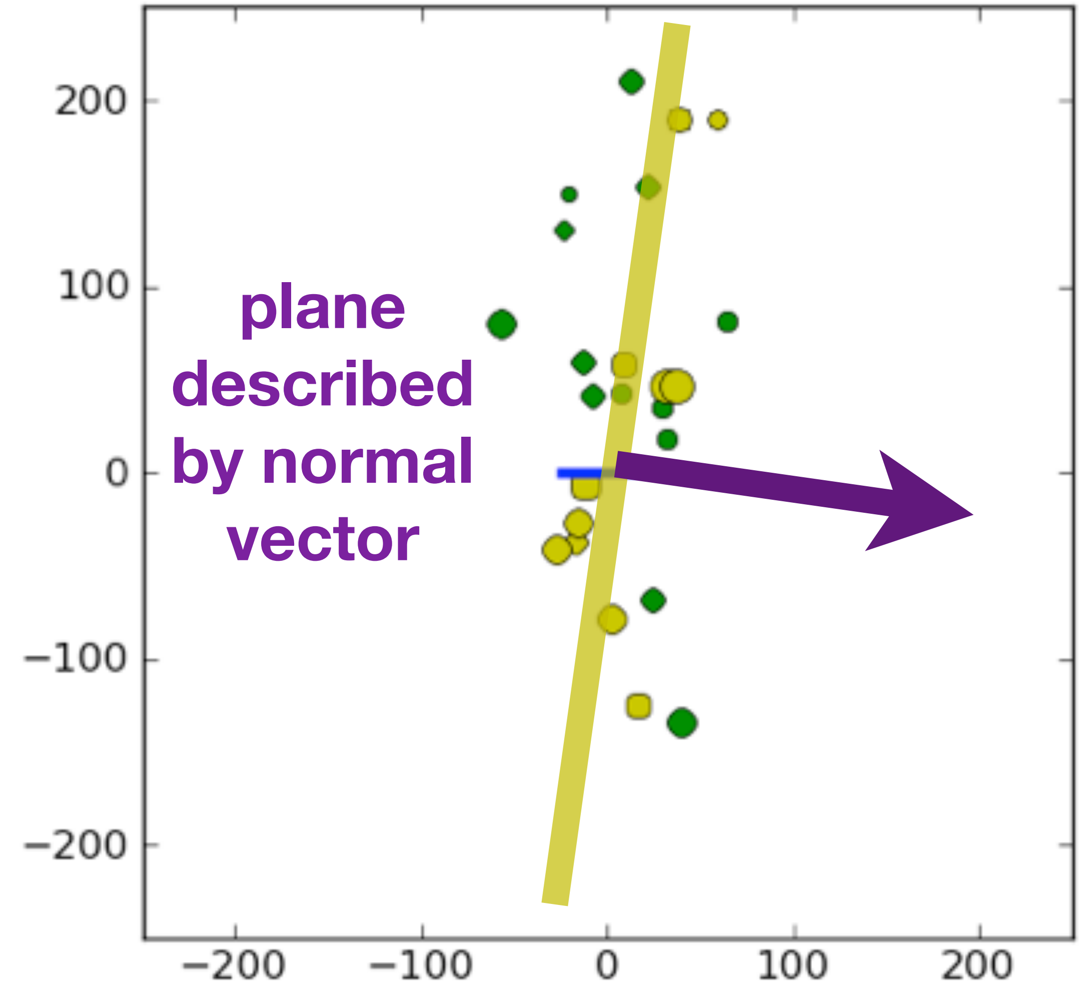
- Classical satellite galaxies
- Faint satellite galaxies
- Young halo globular cluster
- Streams (3x magnified)

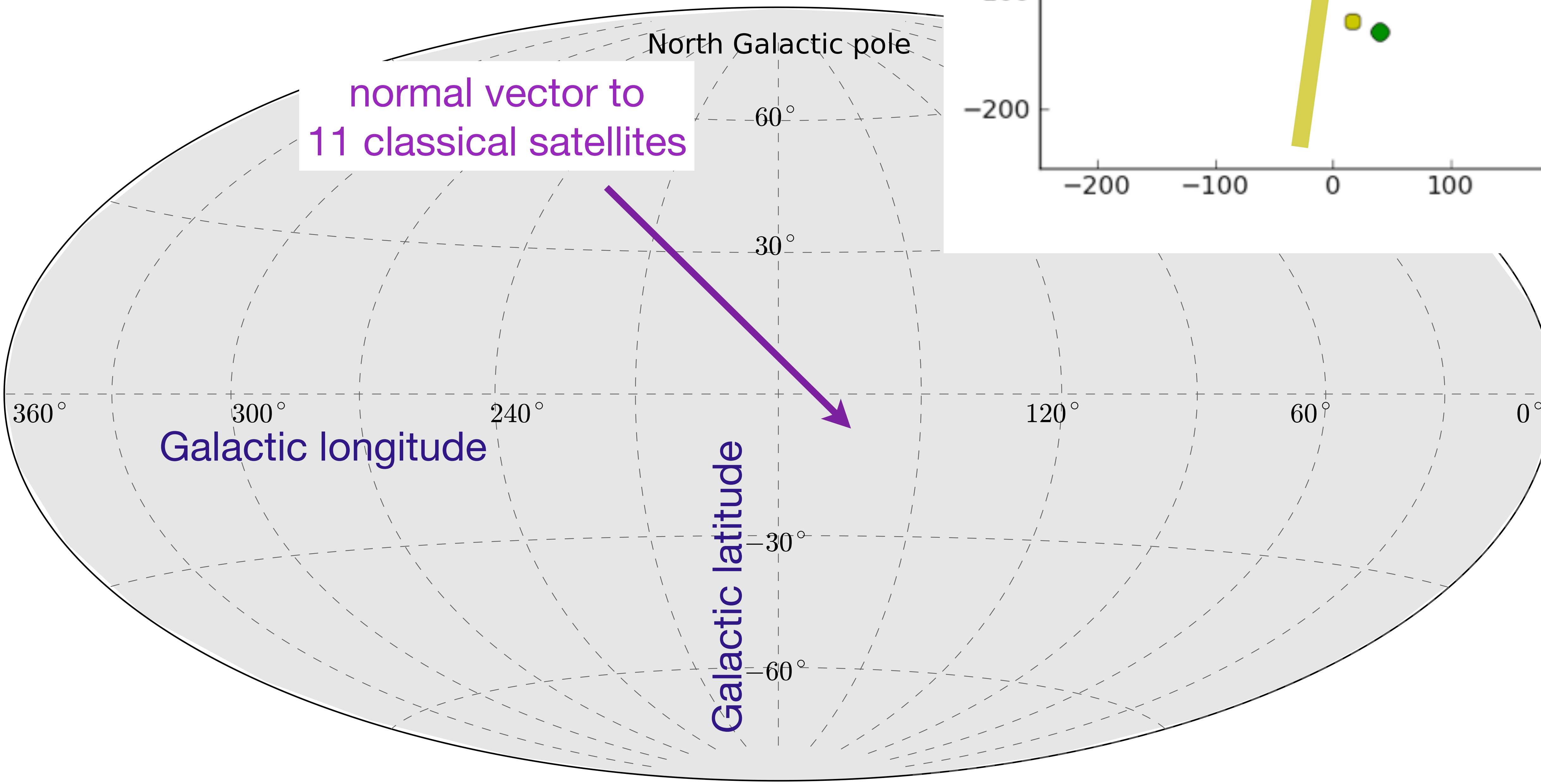


See movie on
http://www.youtube.com/watch?v=nUwxv-WGfHM

Pawlowski, Pflamm-Altenburg & Kroupa (2012)

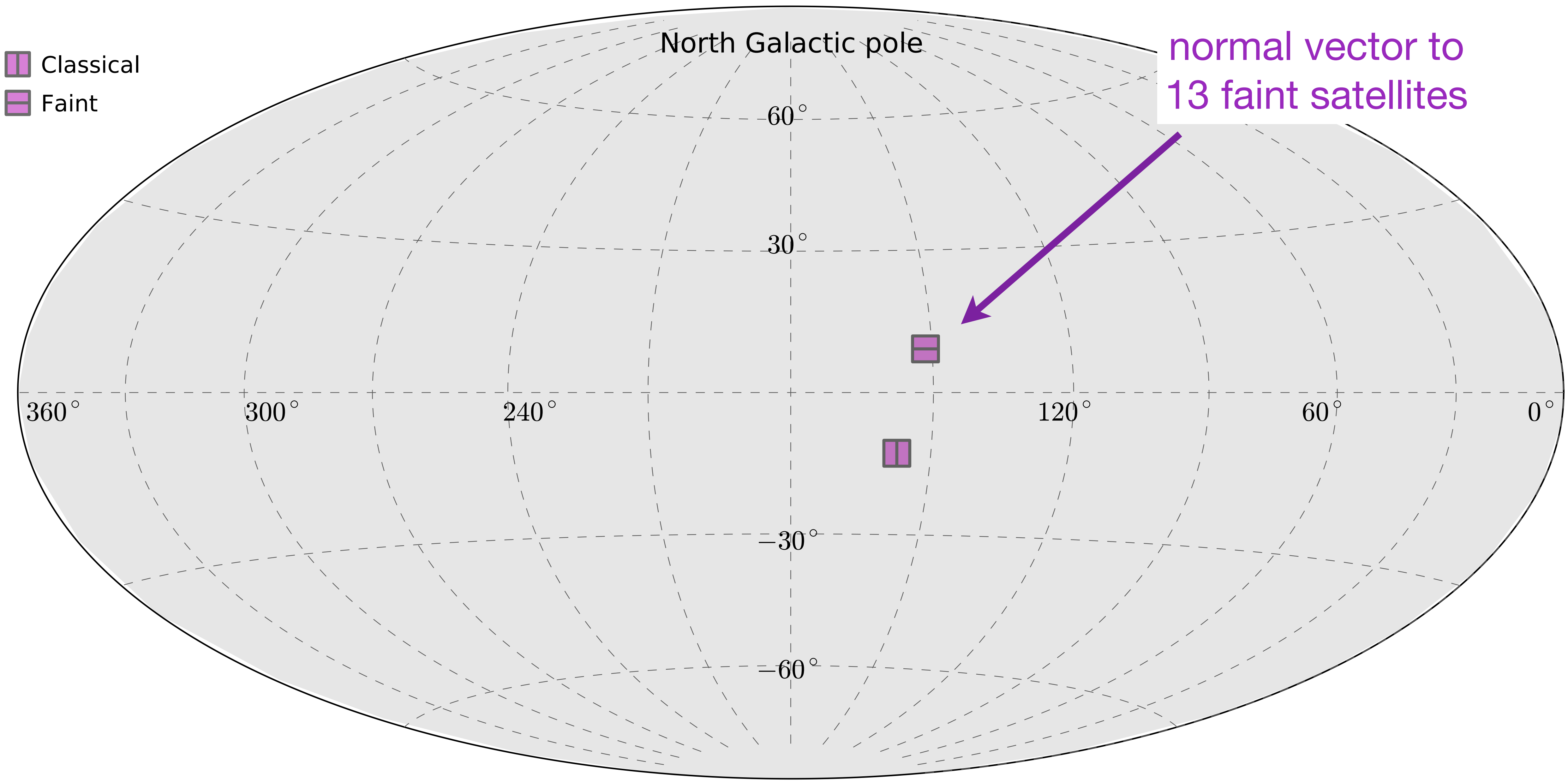
Plane of satellite galaxies described by its normal vector





Pawlowski, Pflamm-Altenburg & Kroupa (2012)

Different types of objects trace the same Vast Polar Structure



Pawlowski, Pflamm-Altenburg & Kroupa (2012)

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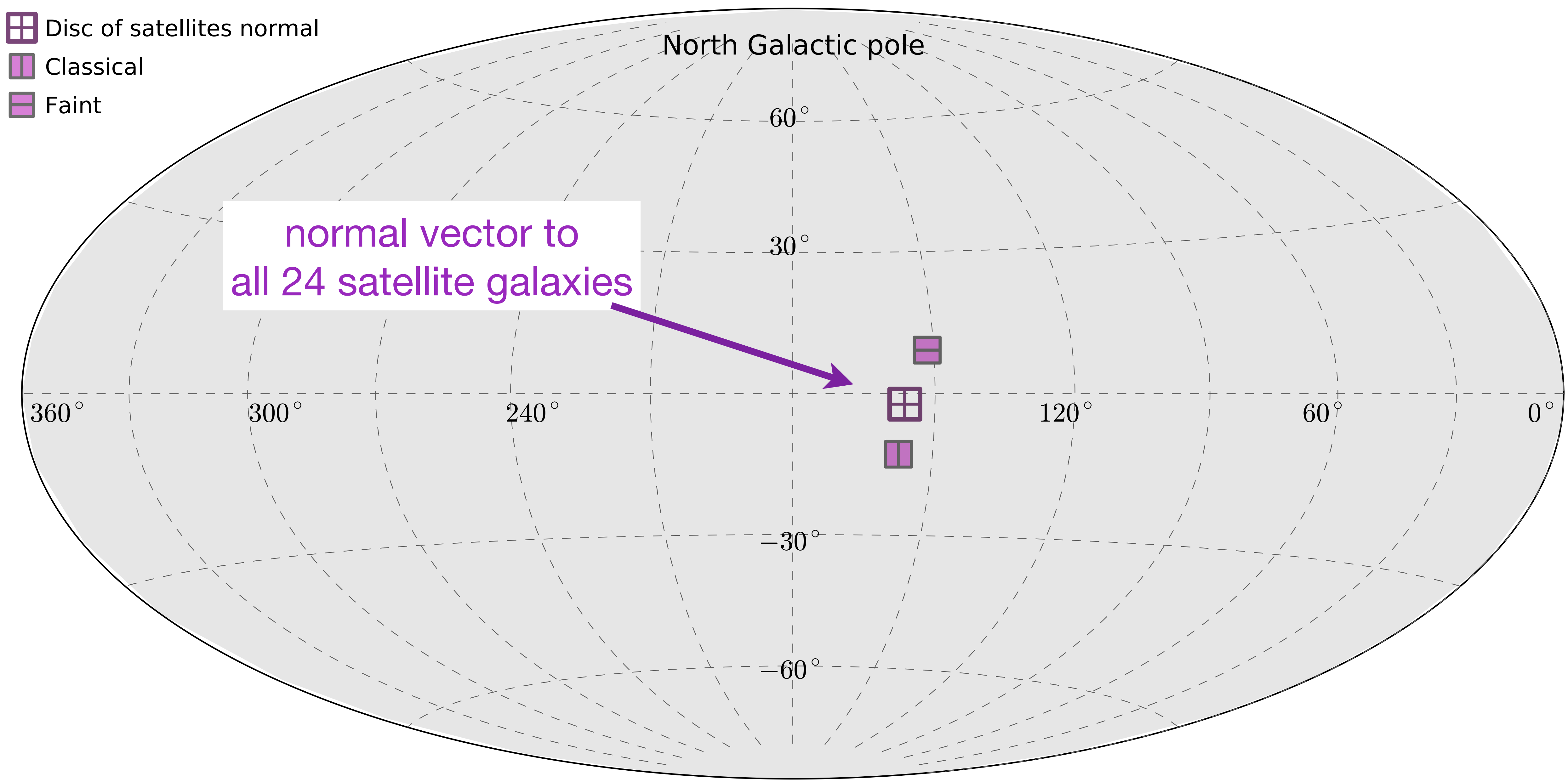
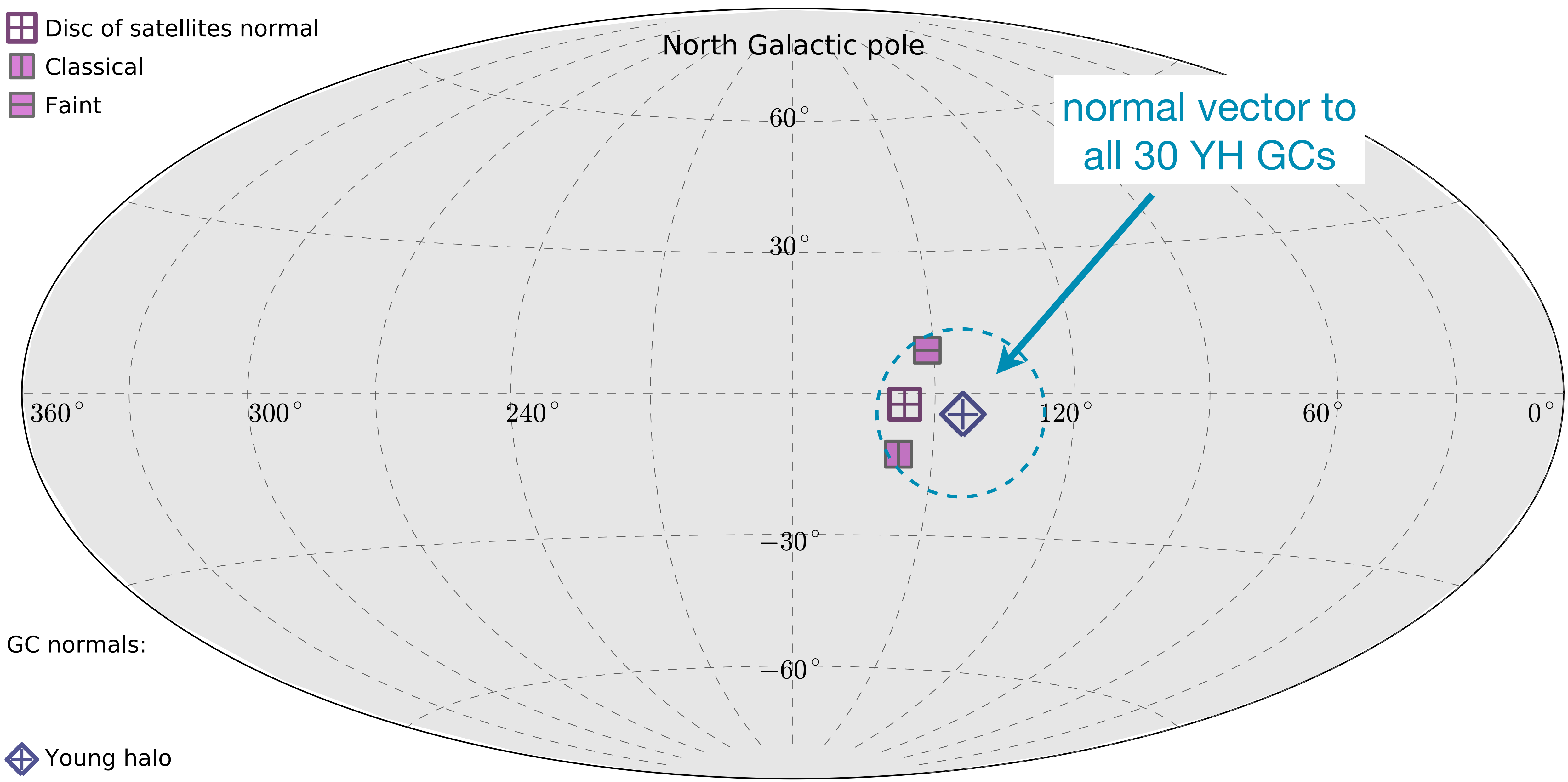


Pawlowski, Pflamm-Altenburg & Kroupa (2012)

Different types of objects trace the same Vast Polar Structure

- Positions of young halo globular clusters (YH GCs)



Pawlowski, Pflamm-Altenburg & Kroupa (2012)

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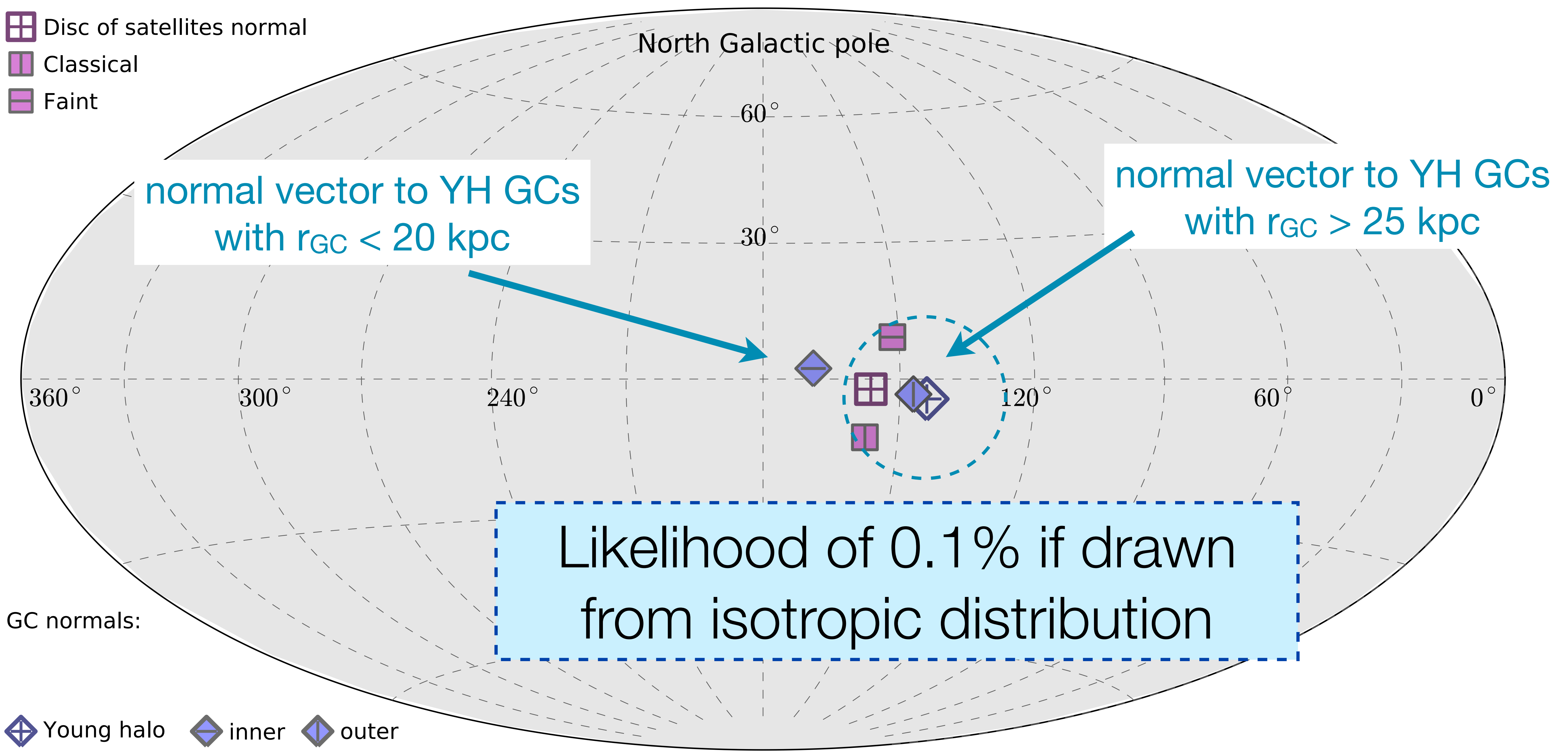
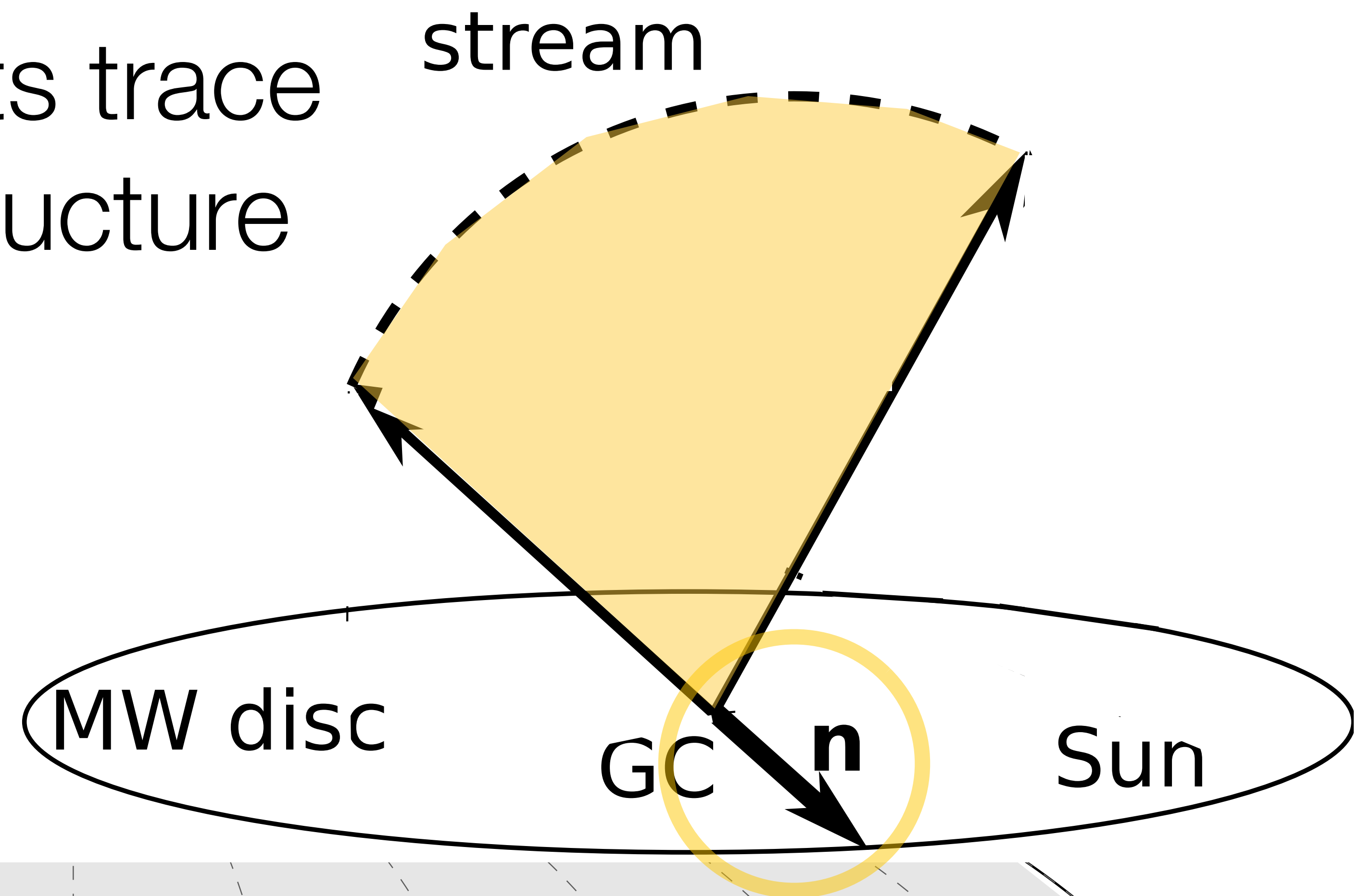
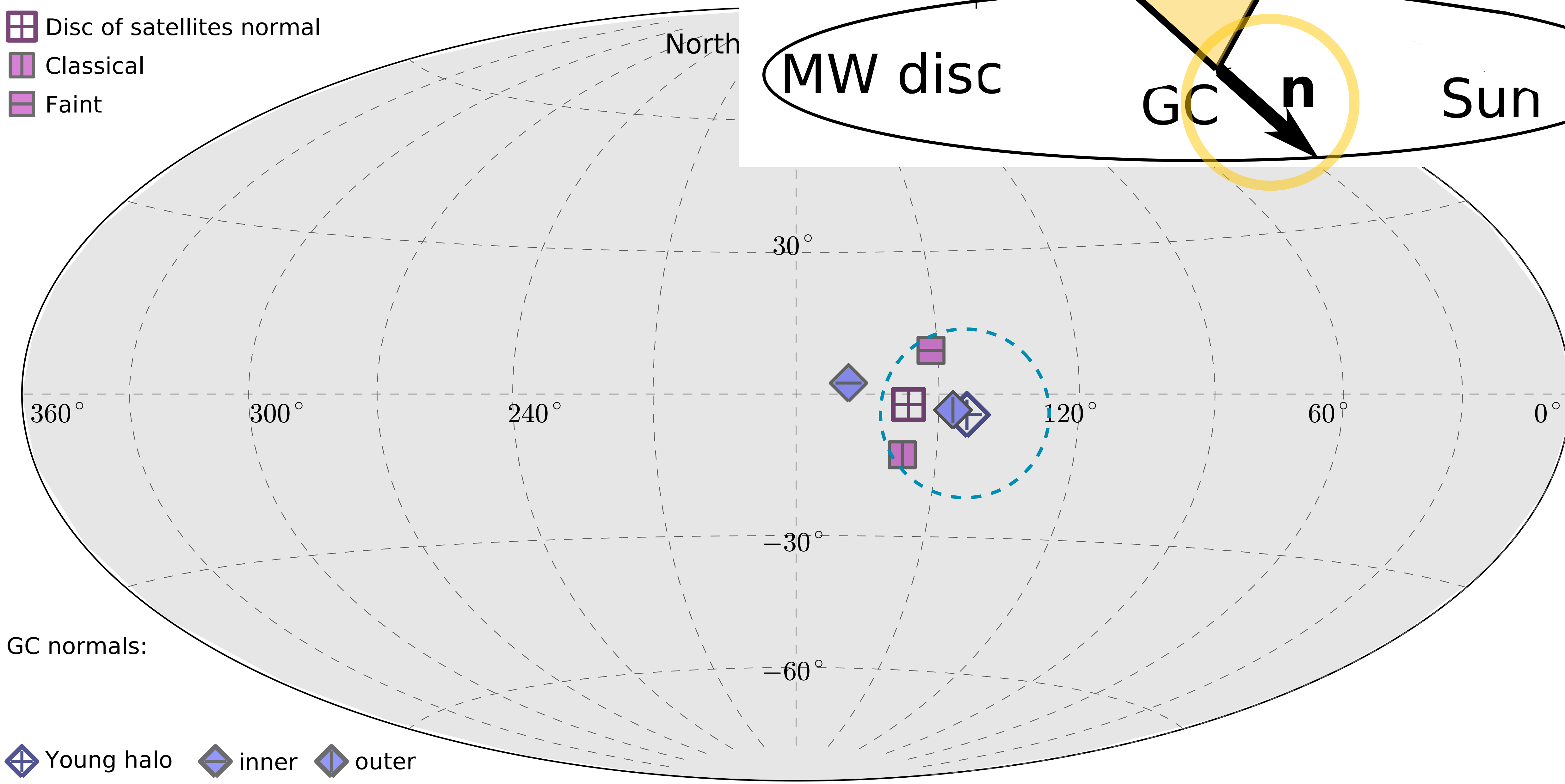


Pawlowski, Pflamm-Altenburg & Kroupa (2012)

Different types of objects trace the same Vast Polar Structure

- Streams of stars and gas
  - ➡ normal vector to orbital plane





Pawlowski, Pflamm-Altenburg & Kroupa (2012)

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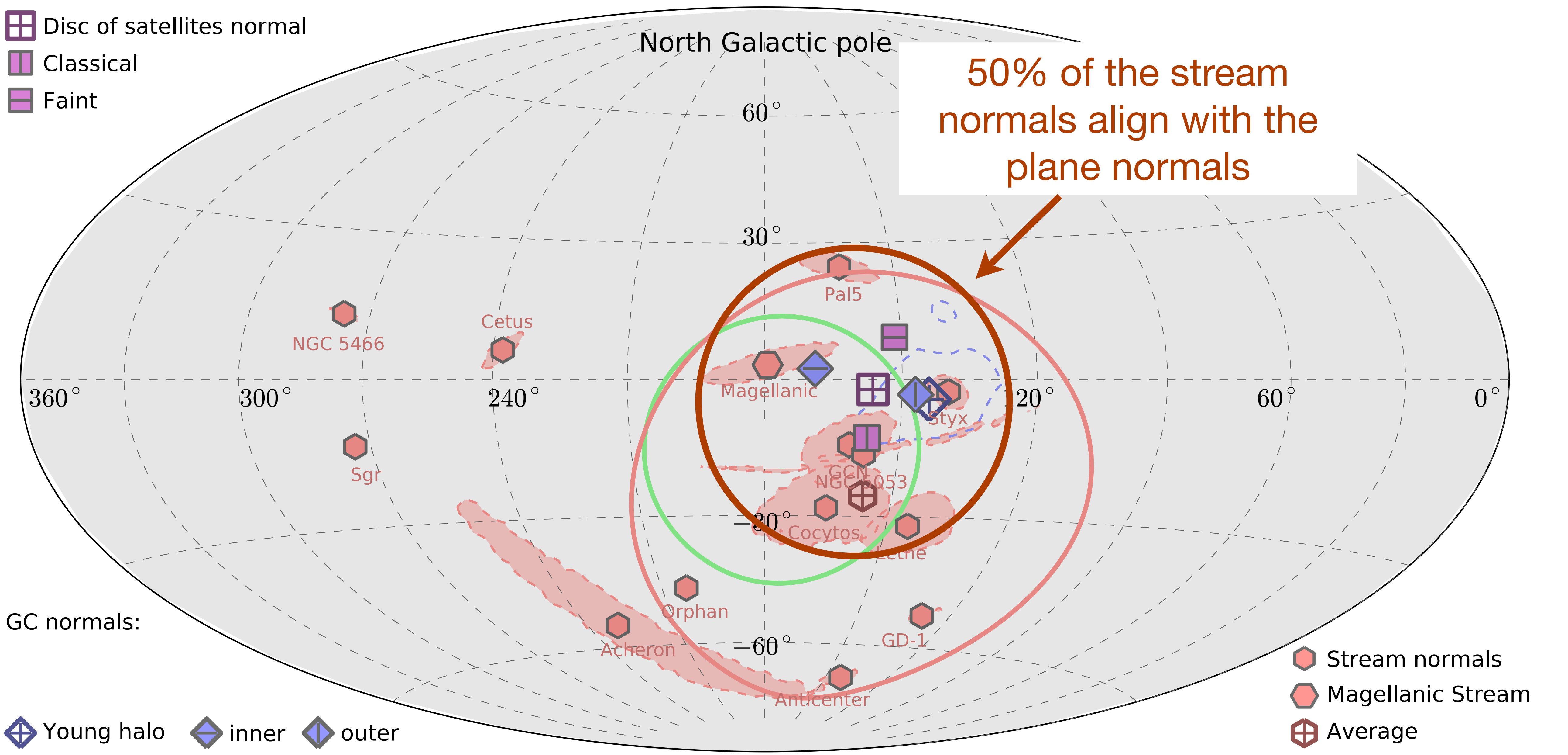
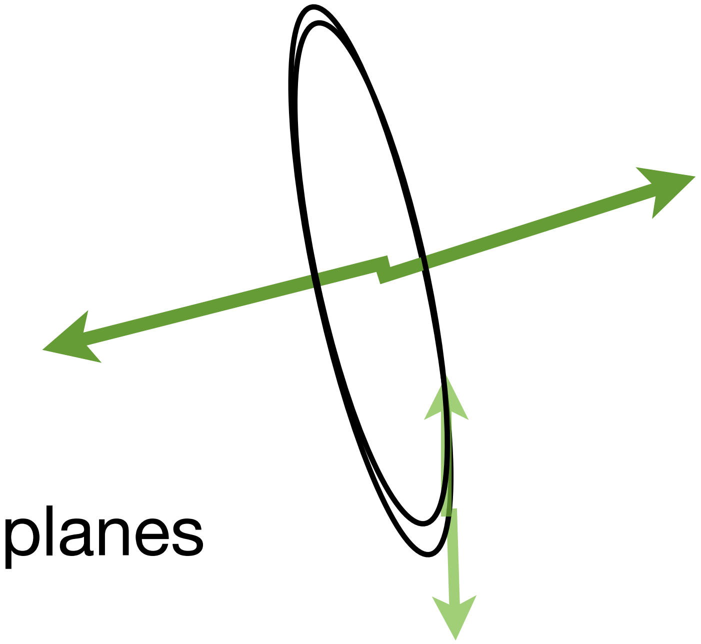
Likelihood of 0.3% if drawn from isotropic distribution

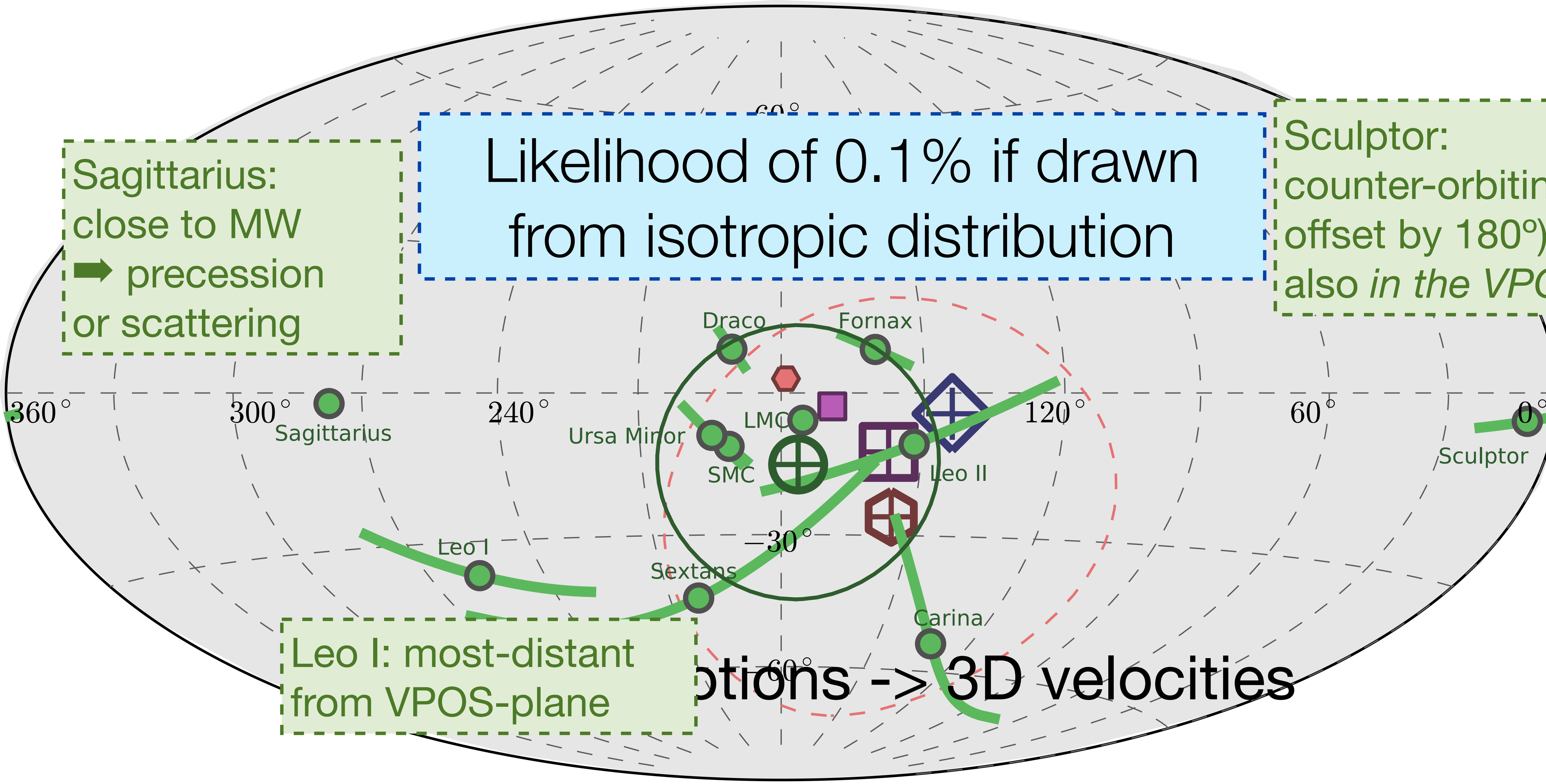


Pawlowski, Pflamm-Altenburg & Kroupa (2012)

The VPOS is rotationally stabilized



- Orbital poles of the MW satellites
  - ➡ directions of angular momenta = normals to orbital planes



Likelihood of 0.1% if drawn from isotropic distribution

Sagittarius: close to MW ➡ precession or scattering

Sculptor: counter-orbiting (***L*** offset by 180°) but also *in the VPOS*

Leo I: most-distant from VPOS-plane

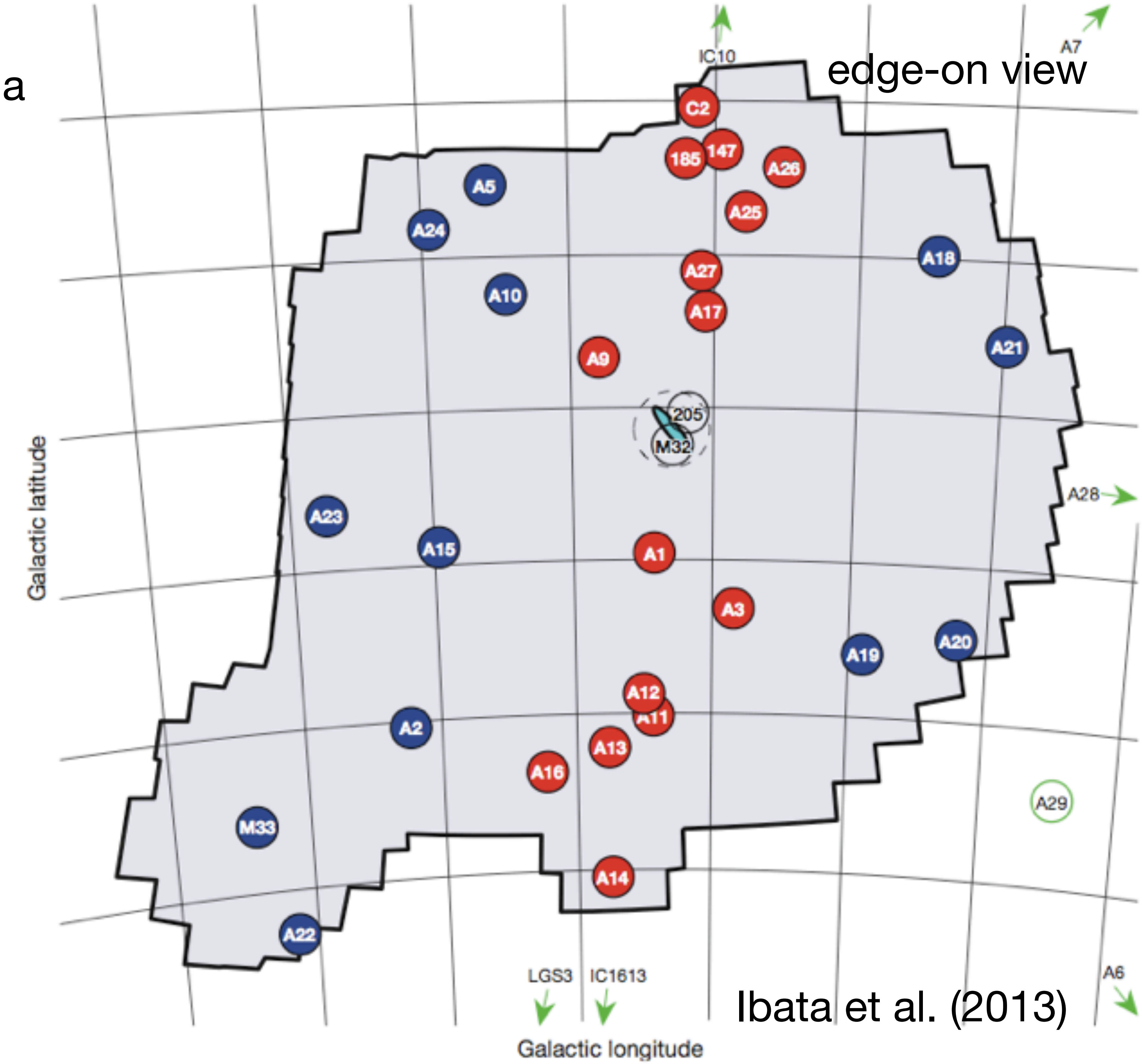
otions -> 3D velocities

Pawlowski & Kroupa (2013)

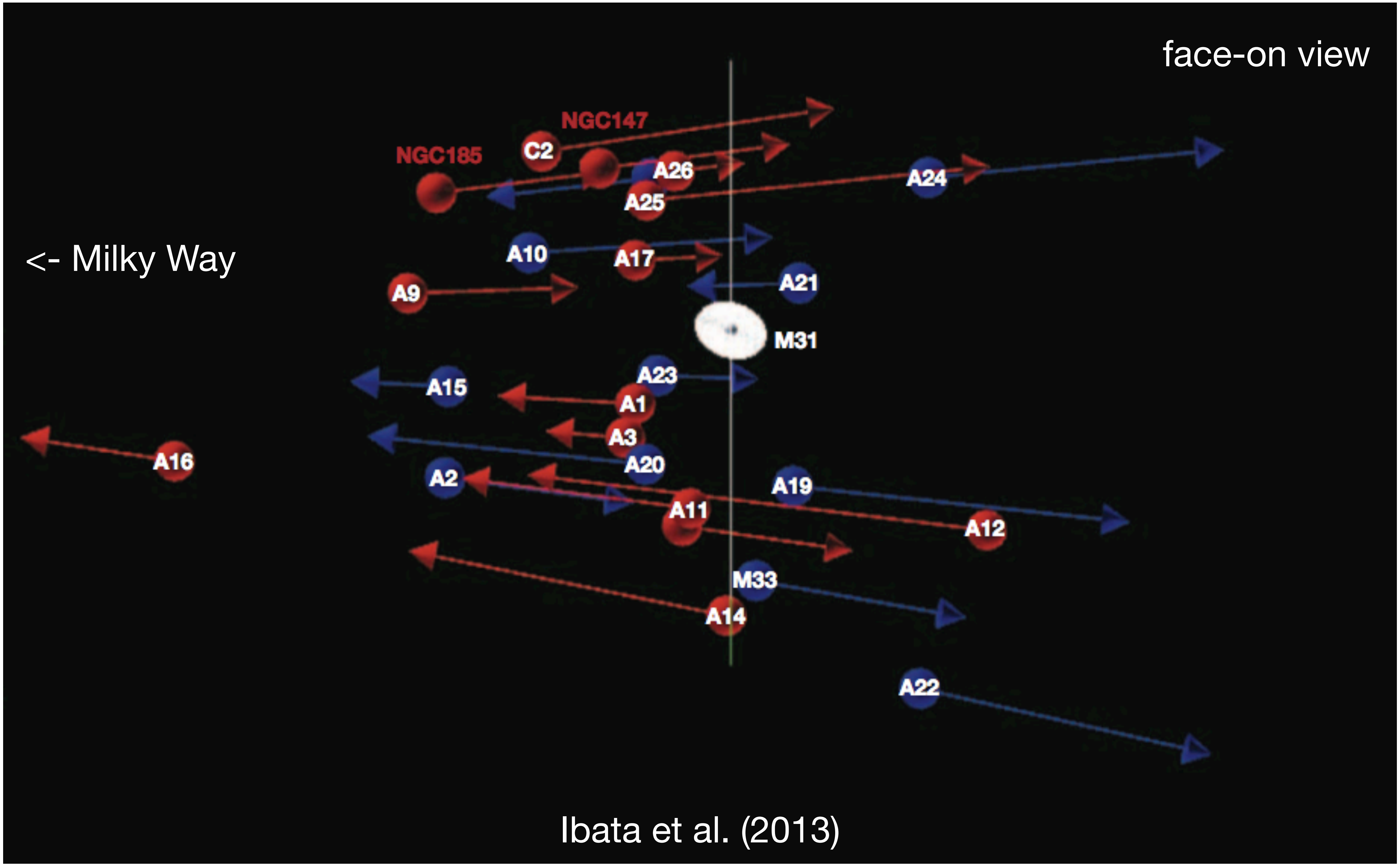
The Great Plane of Andromeda (GPoA)

(Ibata et al. 2013; Conn et al. 2013)

15 satellites out of 27 in the **PAndAS survey area** lie within a highly significant disc.



Line-of-sight velocities in M31 rest-frame indicate rotation of the satellite plane



Edge-on view of both satellite planes (from MW north)

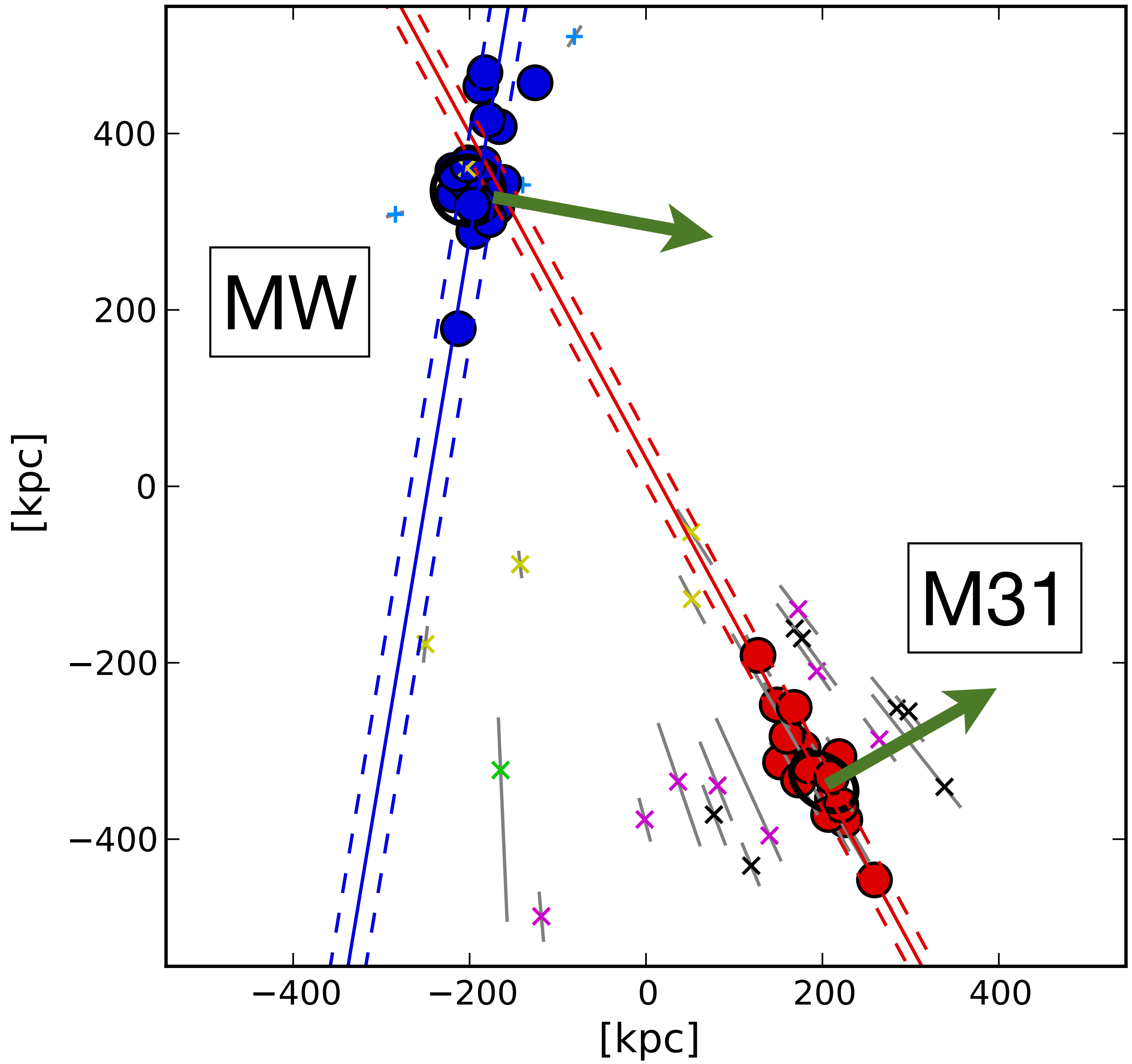
The **VPOS** / **GPoA** have:

- Similar heights:

  VPOS: 20-30 kpc

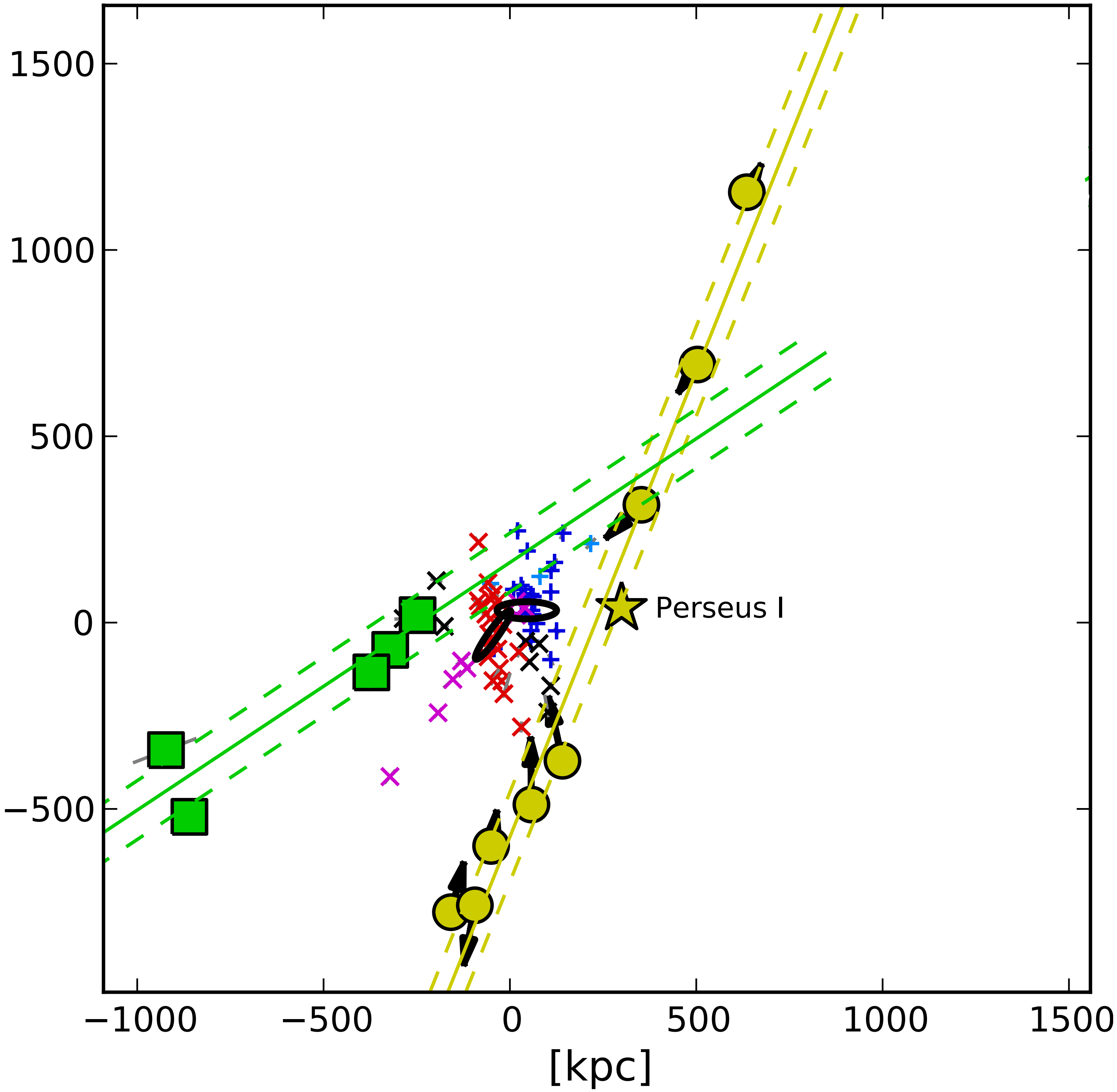
  GPoA: 14 kpc

- Similar diameters: 400 kpc
- Similar **spin directions**



Pawlowski, Kroupa & Jerjen (2013)

Discovery of two highly symmetric planes of non-satellite dwarf galaxies in the Local Group



Edge-on view of both LG planes

Almost all non-satellites are in one of two thin planes which have:

- similar heights (~ 60 kpc, diameter 1-2 Mpc!)
- similar offsets from MW and from M31 (130 to 170 kpc).
  ➡ parallel to MW-M31 line.
- the same inclination to M31 (20º)

NGC 3109 association might also be related (Pawlowski & McGaugh 2014a)

Pawlowski, Kroupa & Jerjen (2013)

What can GCs tell us about the VPOS?

Age of the VPOS (from GC ages)

Star formation histories of MW satellite galaxies not well-enough constrained for t > 10 Gyr.

➡ Use GCs to estimate the age of the VPOS.

Collect data from the literature:

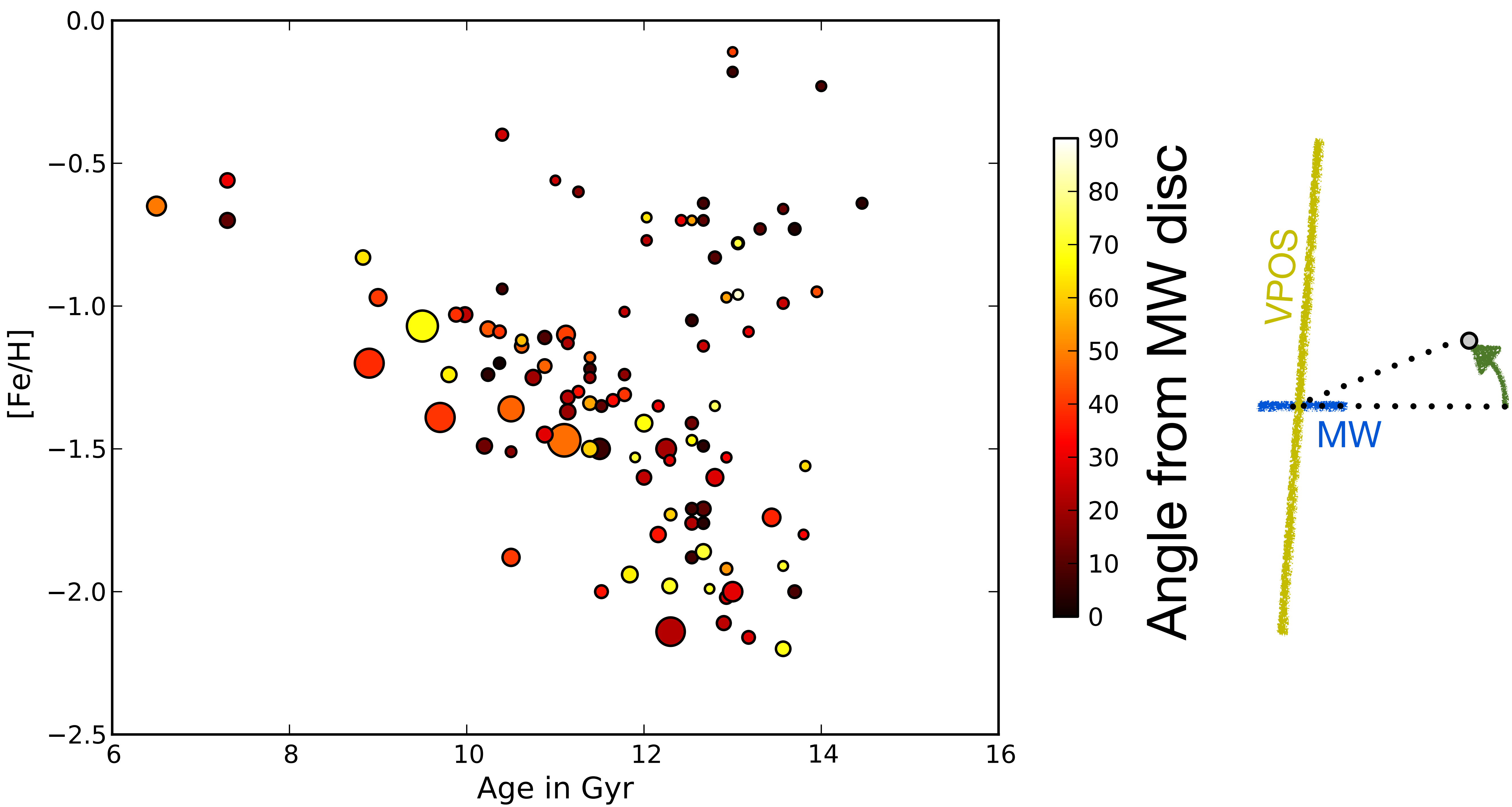
- Positions, radial velocities etc. from Harris-Catalog.
- 78 proper motion estimates for 54 GCs.
- Age and [Fe/H] estimates for 105 GCs (extending Forbes & Brides 2010).

➡ Two different, but not completely independent age estimates.

Pawlowski et al., work in progress

Age of the VPOS (from GC ages)

Angle between GC position and MW disc

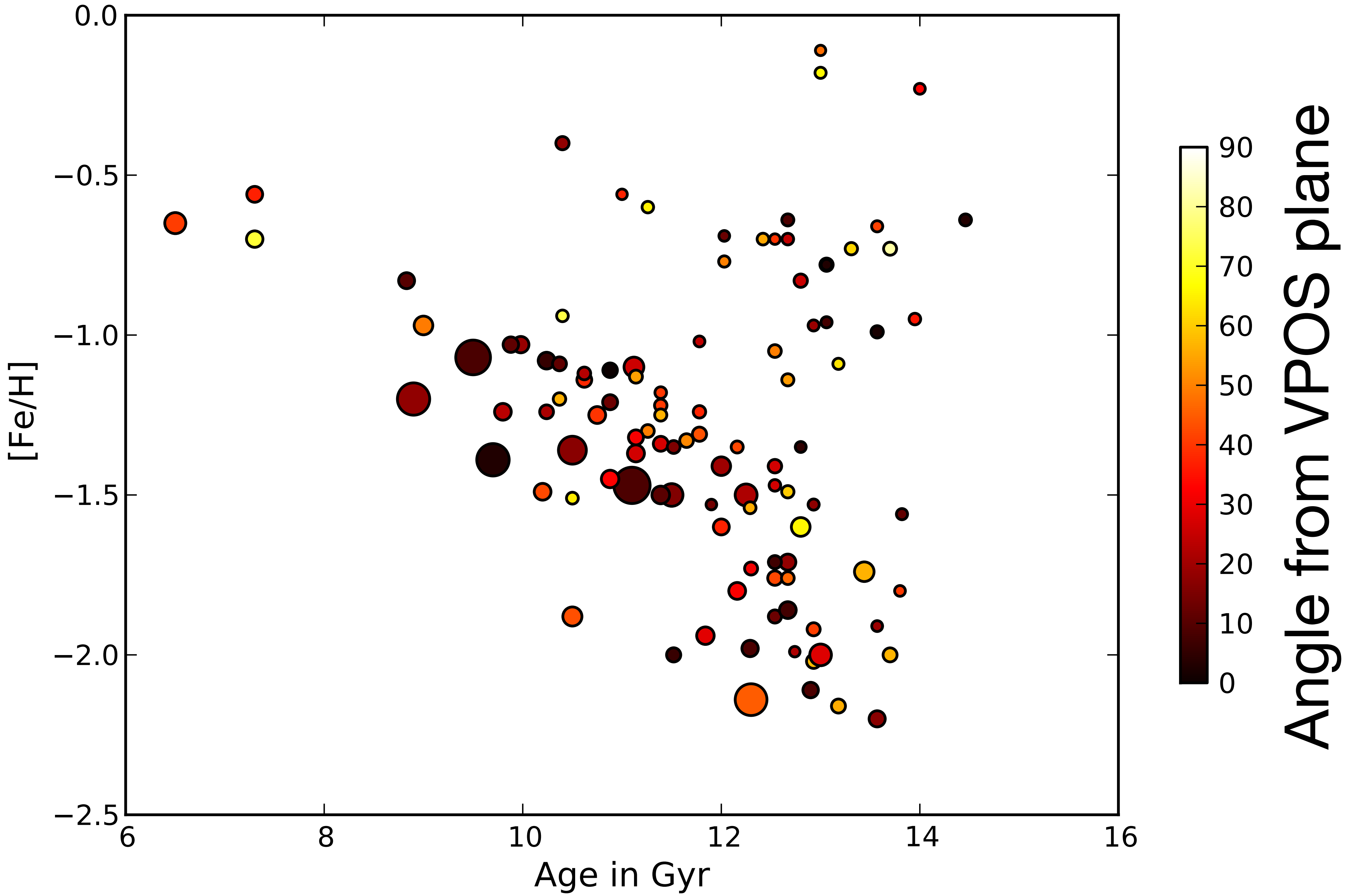


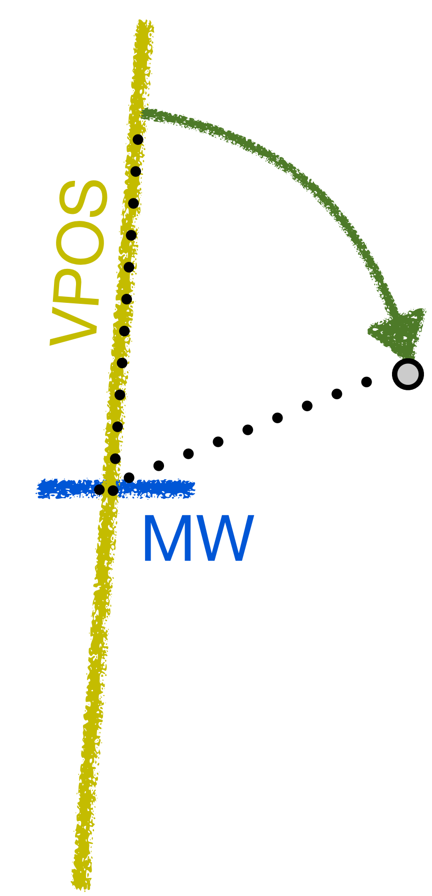
Pawlowski et al., work in progress

GCs more distant from MW have bigger symbols

Age of the VPOS (from GC ages)

Angle between GC position and VPOS

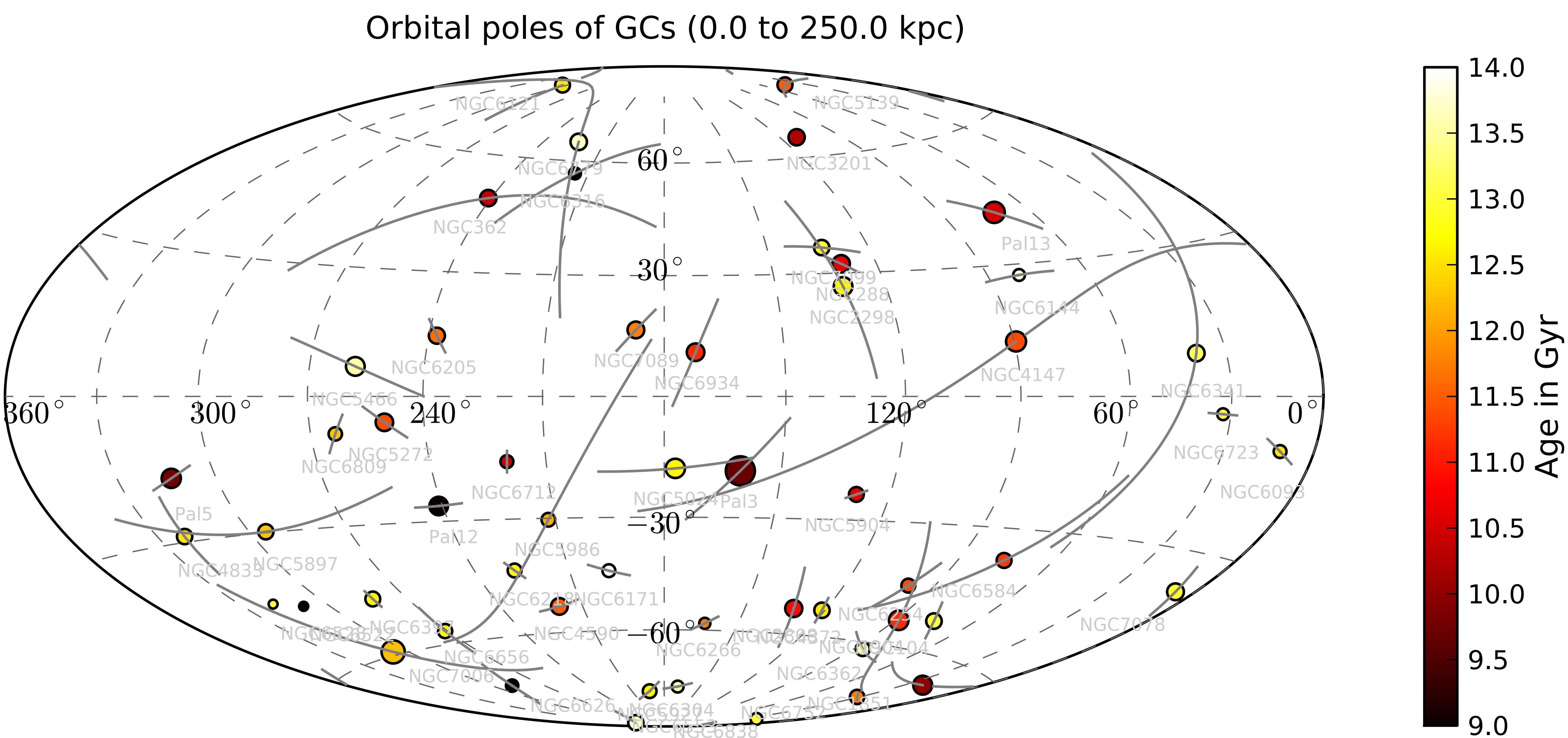




Pawlowski et al., work in progress

GCs more distant from MW have bigger symbols

Orbital Poles of MW Globular Clusters

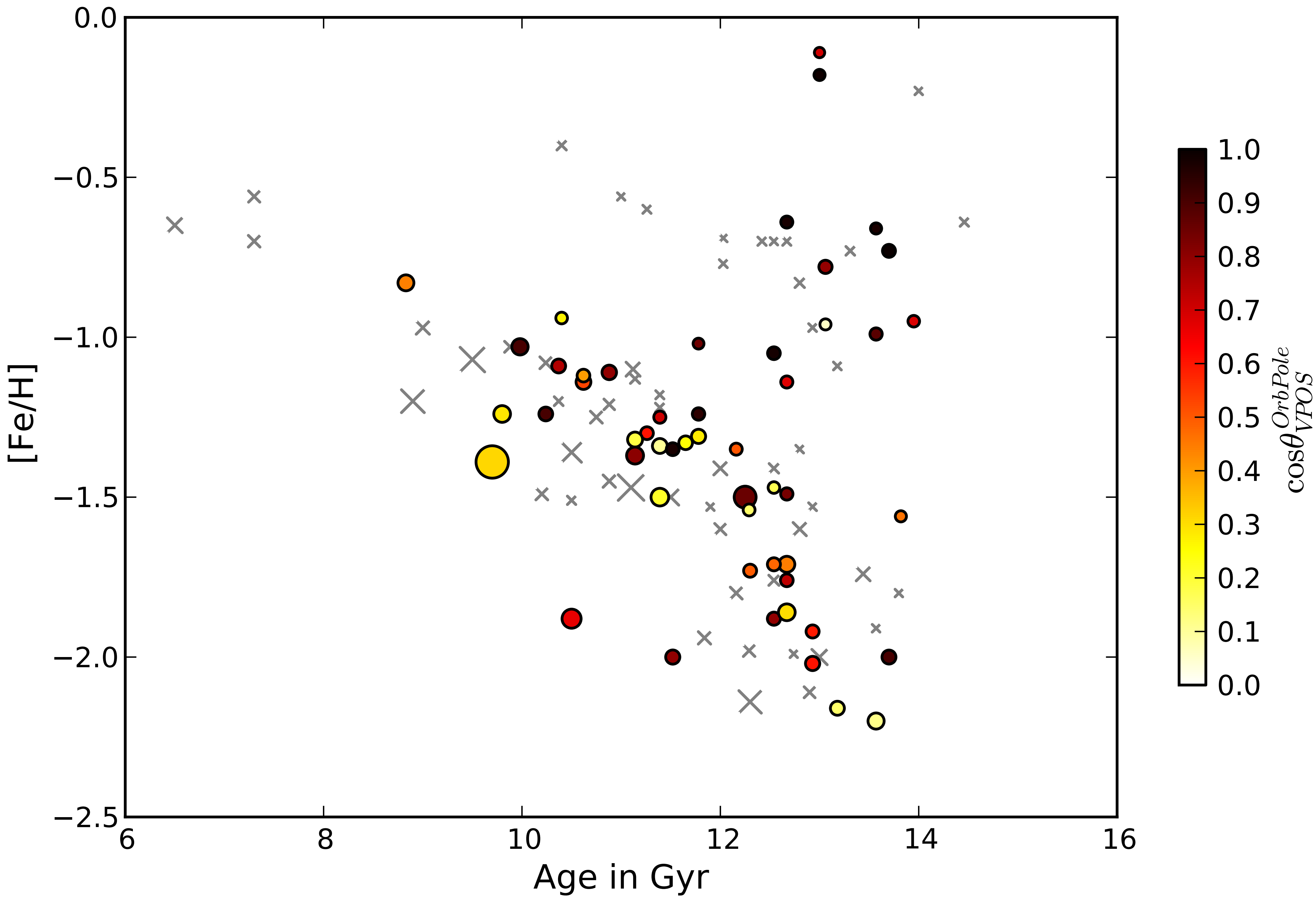


Pawlowski et al., work in progress

GCs more distant from MW have bigger symbols

Age of the VPOS (from GC ages)

Angle of Orbital Poles from MW spin

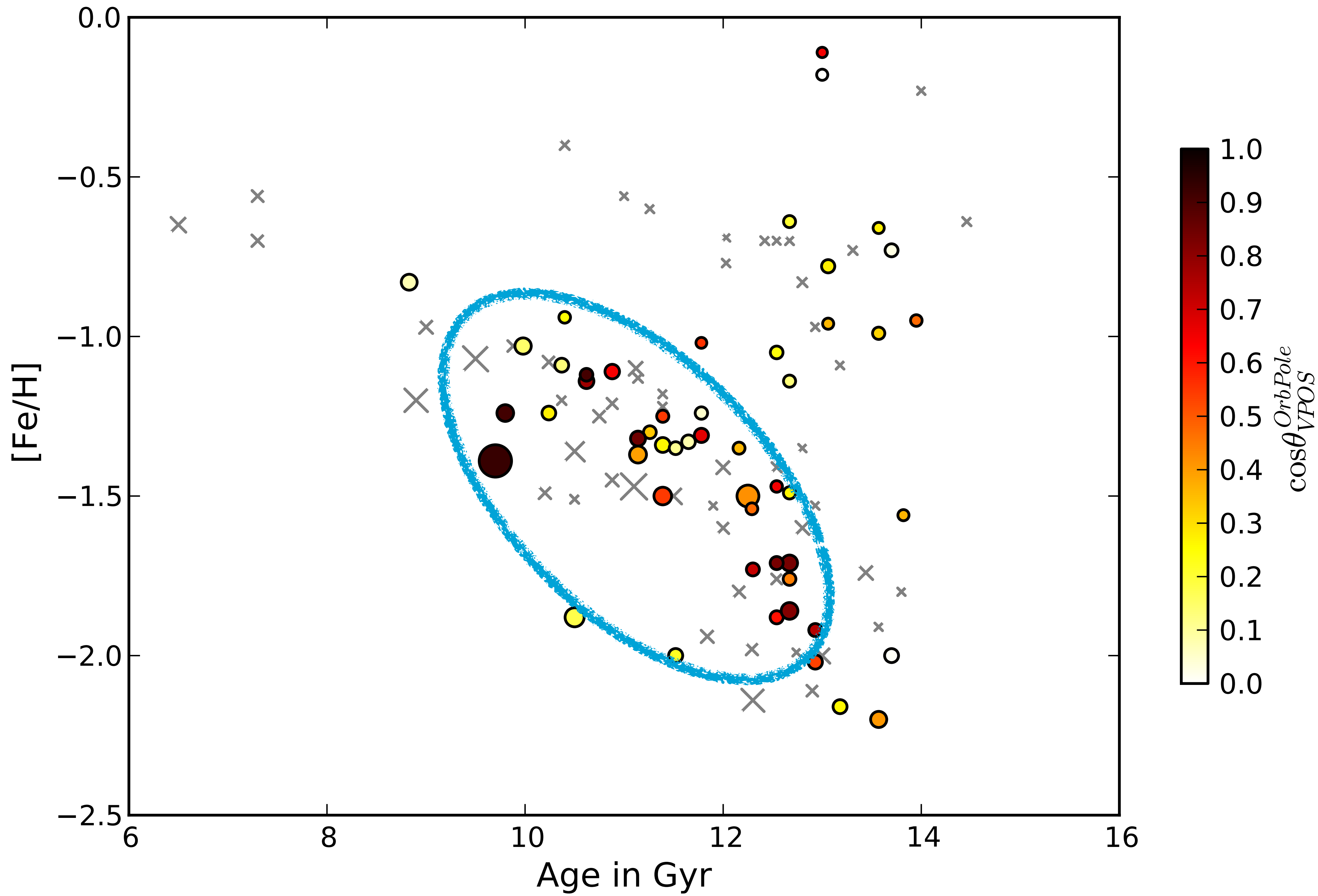


Pawlowski et al., work in progress

GCs more distant from MW have bigger symbols

Age of the VPOS (from GC ages)

Angle of Orbital Poles from VPOS normal



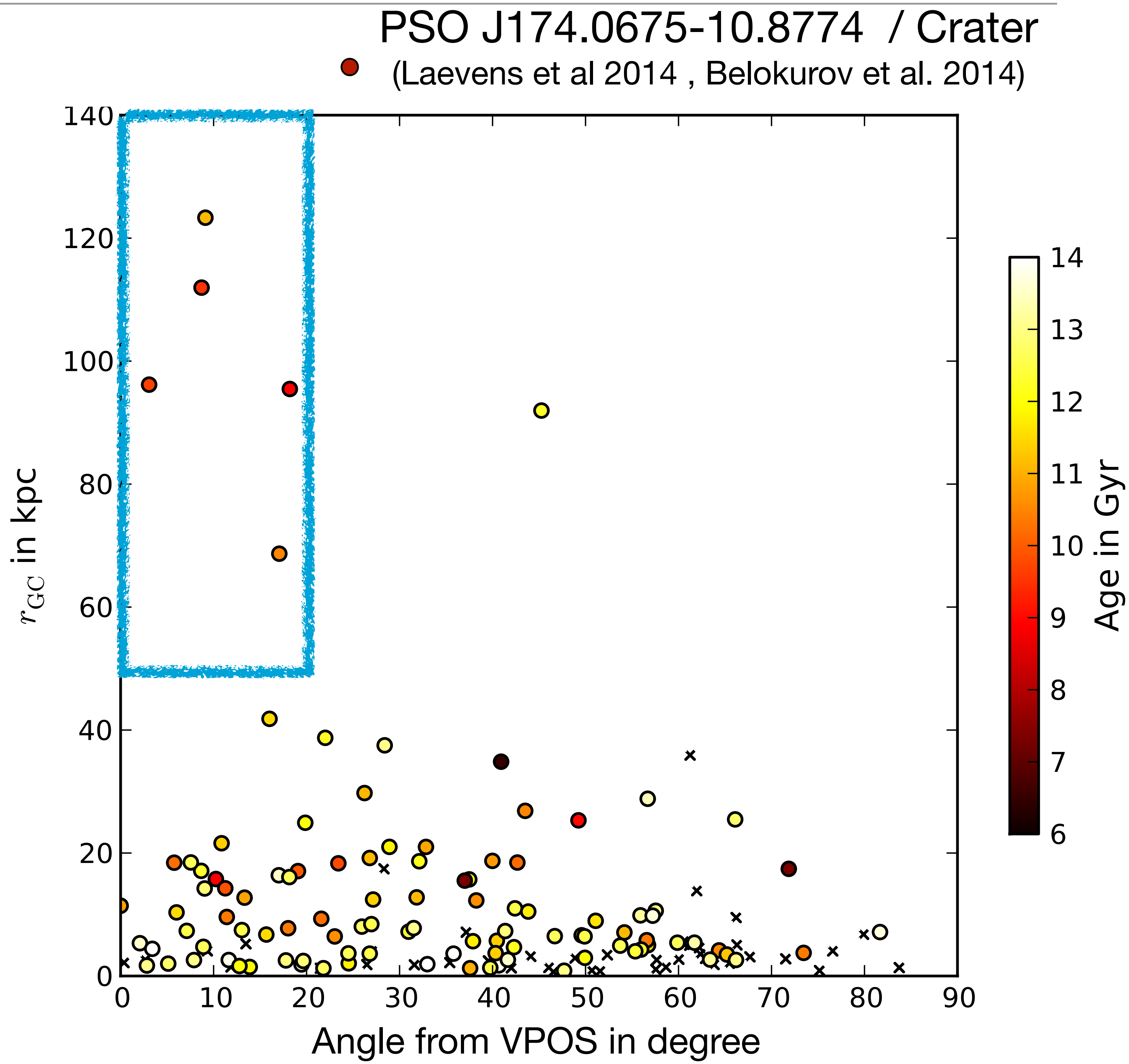
Pawlowski et al., work in progress

GCs more distant from MW have bigger symbols

Age of the VPOS (from GC ages)

Distance vs. Angle between Position and YH GC plane

- Of the 6 GCs with $r_{GC} > 50$ kpc, 5 are within 20-30° of the VPOS plane.
- These are the 5 youngest.
- Ages of 9 to 11 Gyr

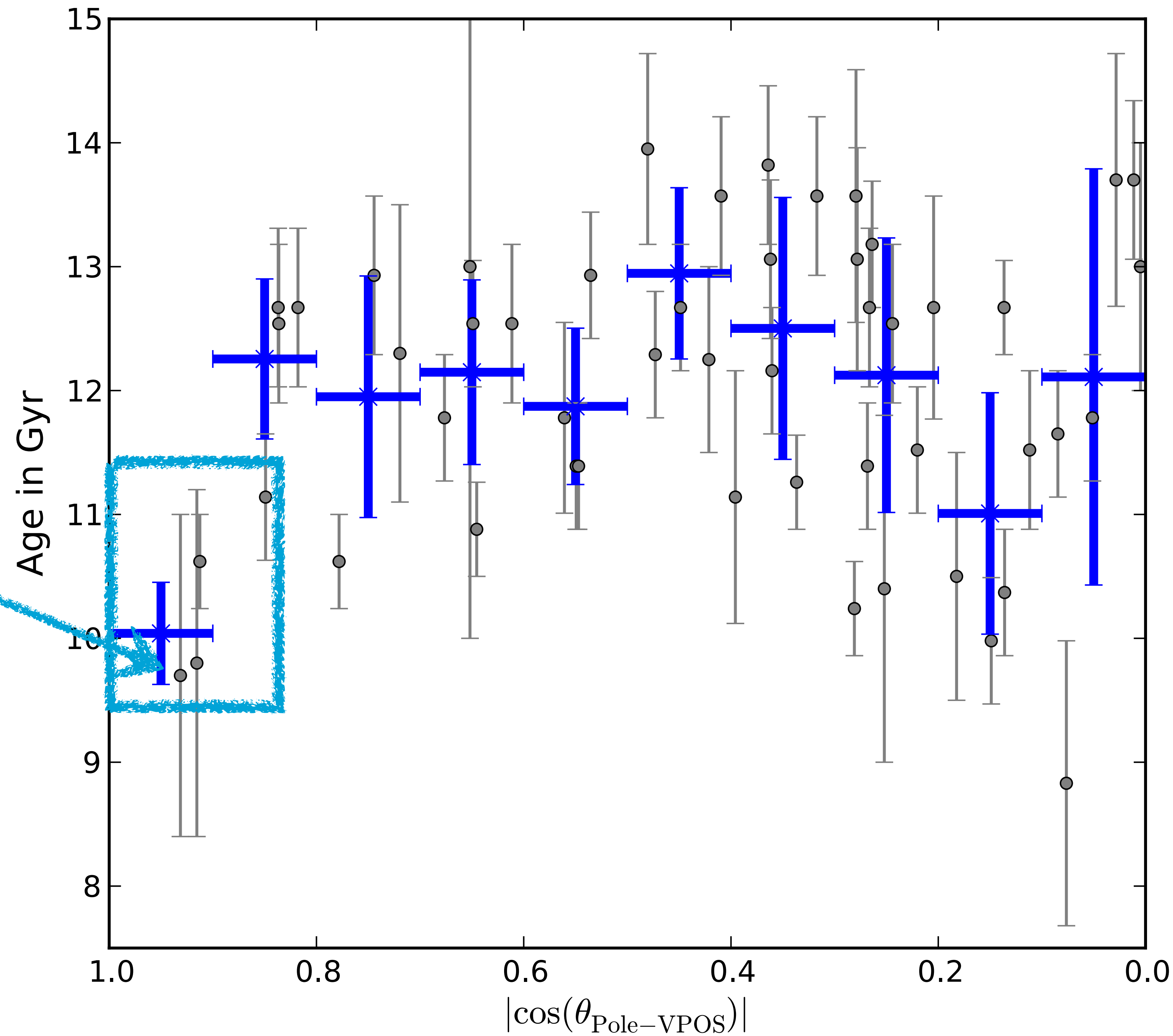


Pawlowski et al., work in progress

Age of the VPOS (from GC ages)

Age vs. Angle between Orbital Pole and YH GC plane

- The 4 GCs with orbits closest to the YH GC plane are all young.
- Ages of 9.5 to 11 Gyr.
- Only one GC overlaps with the previous sample.



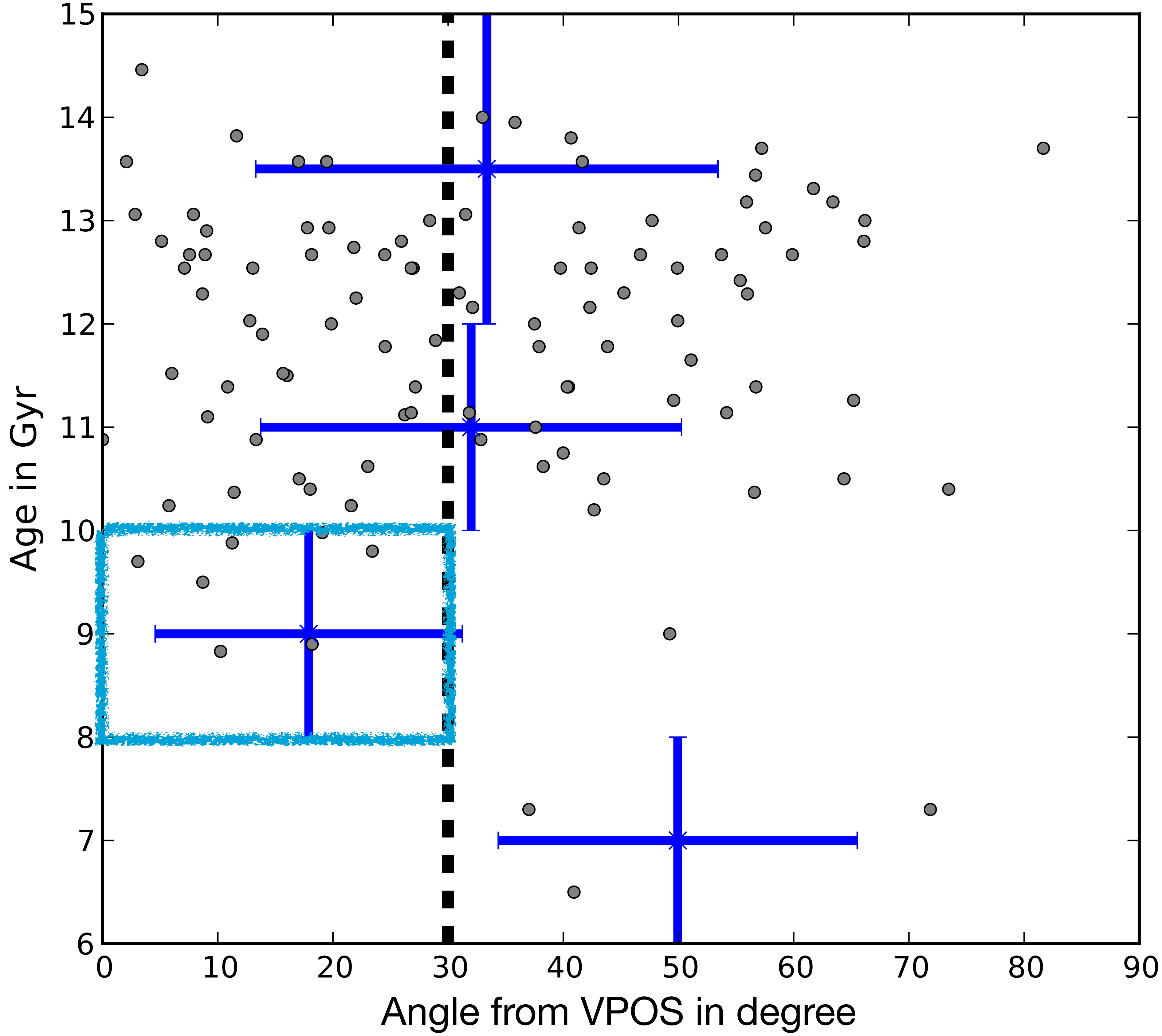
Pawlowski et al., work in progress

Age of the VPOS (from GC ages)

Age vs. Angle between Position and YH GC plane

- Consistency-check:

- GCs in the age range are preferentially be close to the YH GC plane



Pawlowski et al., work in progress

What can the VPOS tell us about GCs?

What can the VPOS tell us about GCs?

VPOS-membership can help to constrain the origin of a GC:

- *Position*: Does the GC lie in the VPOS?
- *Associated stream*: Does the GC orbit in the VPOS?
- *Proper motion*: Does the GC (co-)orbit in the VPOS?

If yes, supports interpretation of the GC as being related to satellite galaxies (GC formed with satellite or even dissolving dwarf galaxy)

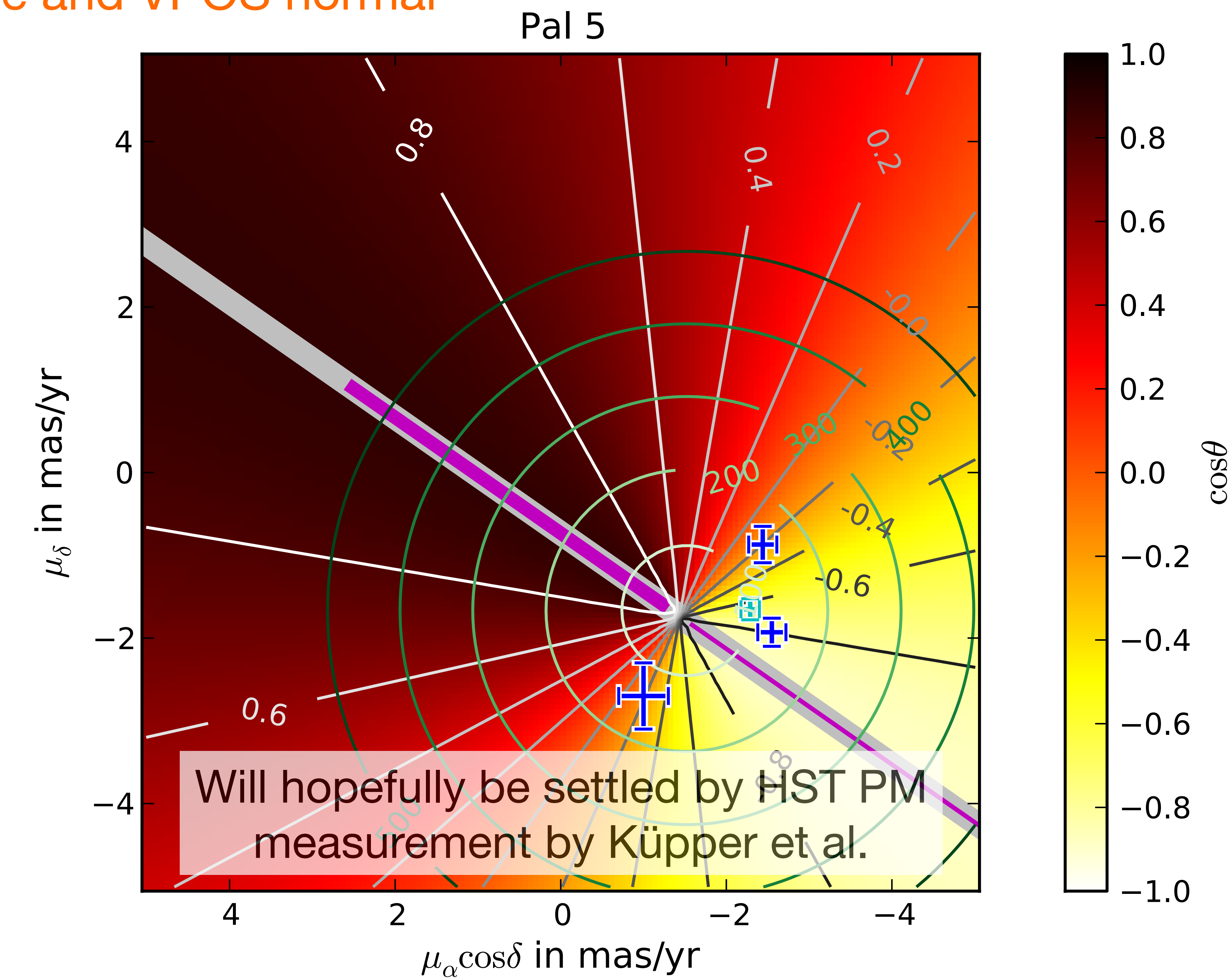
Anisotropy and co-rotation increases chance of satellite collisions.

Predicting Proper Motions

Predict proper motion using two criteria (Pawlowski & Kroupa, 2013):

- Angle between orbital pole and VPOS normal
- Absolute 3D-velocity

- Measurements



Pawlowski et al., work in progress

Streams: Example ATLAS stream

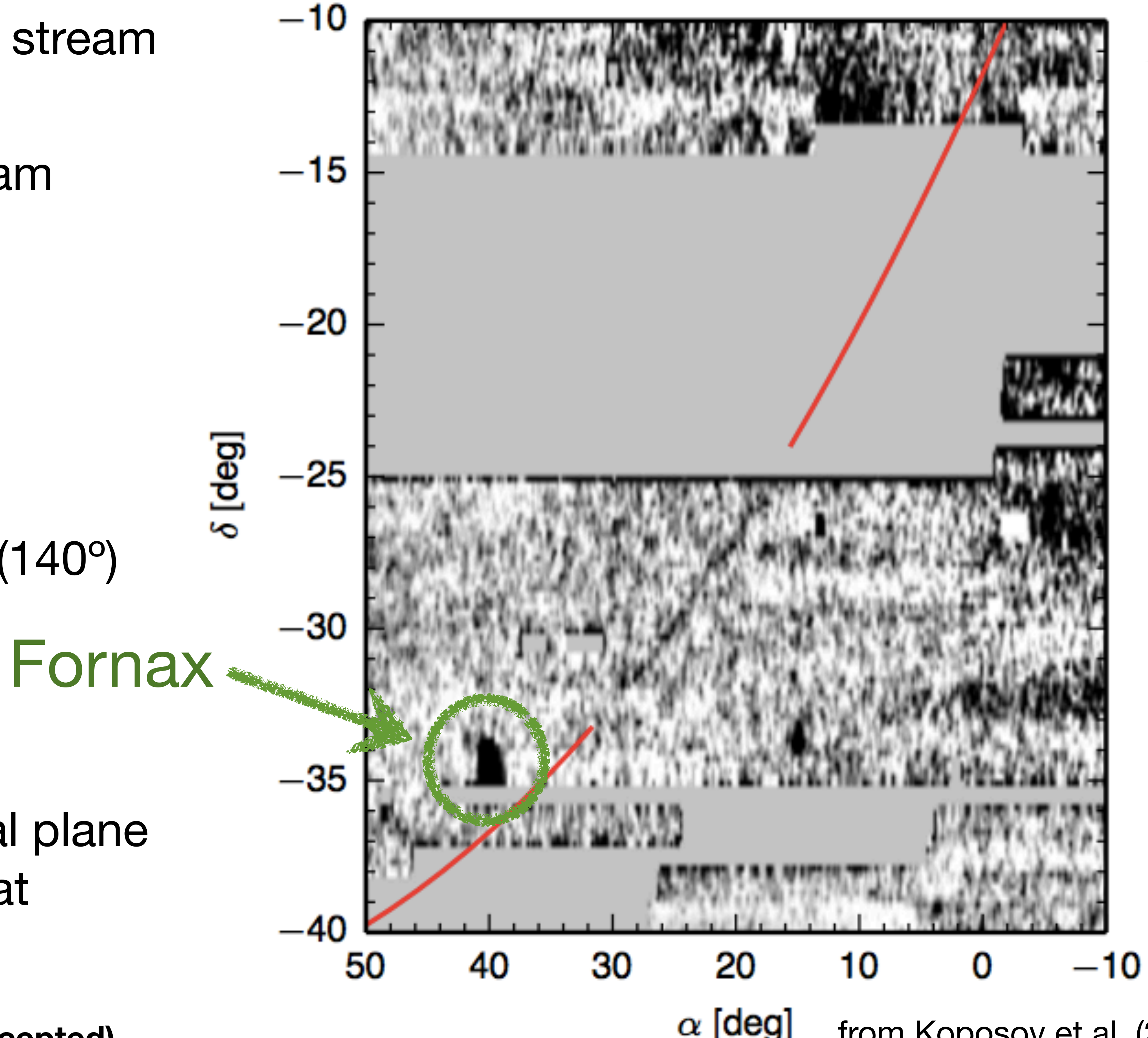
New discovery: ATLAS stream (Koposov et al. 2014):

- Aligns with Pal 5 stream
- same distance
- consistent metallicity

➡ direct connection?

Stream would be long (140º) need models to test if possible

But also close to orbital plane of Fornax (if stream is at much larger distance)



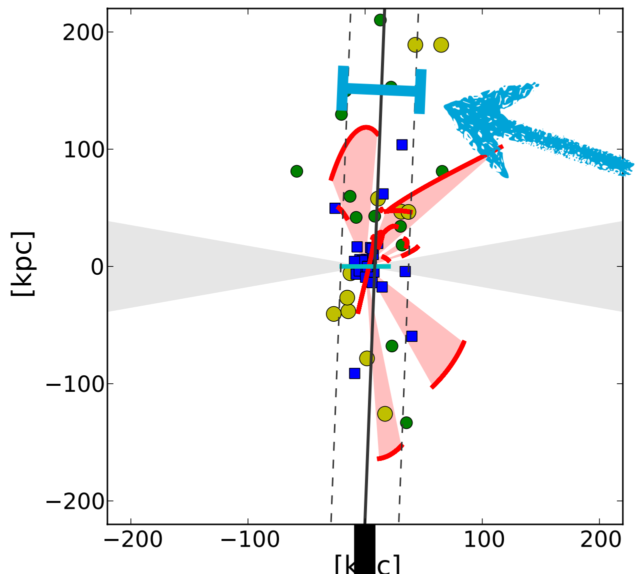
from Koposov et al. (2014)

Pawlowski & Kroupa (2014, ApJ, accepted)

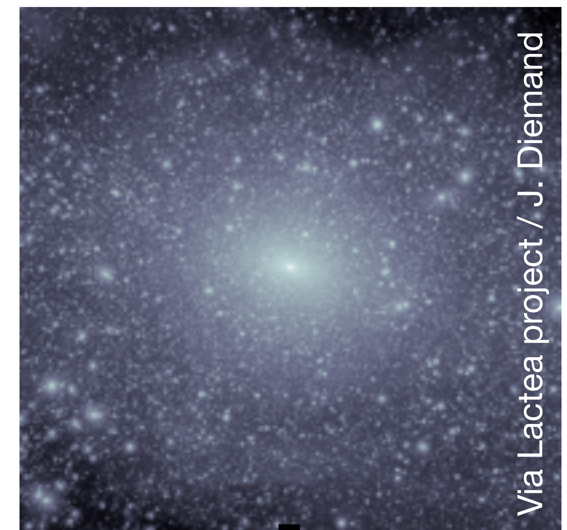
Is the VPOS consistent with standard galaxy formation theory?

Testing the satellite orbital pole concentration

Observed

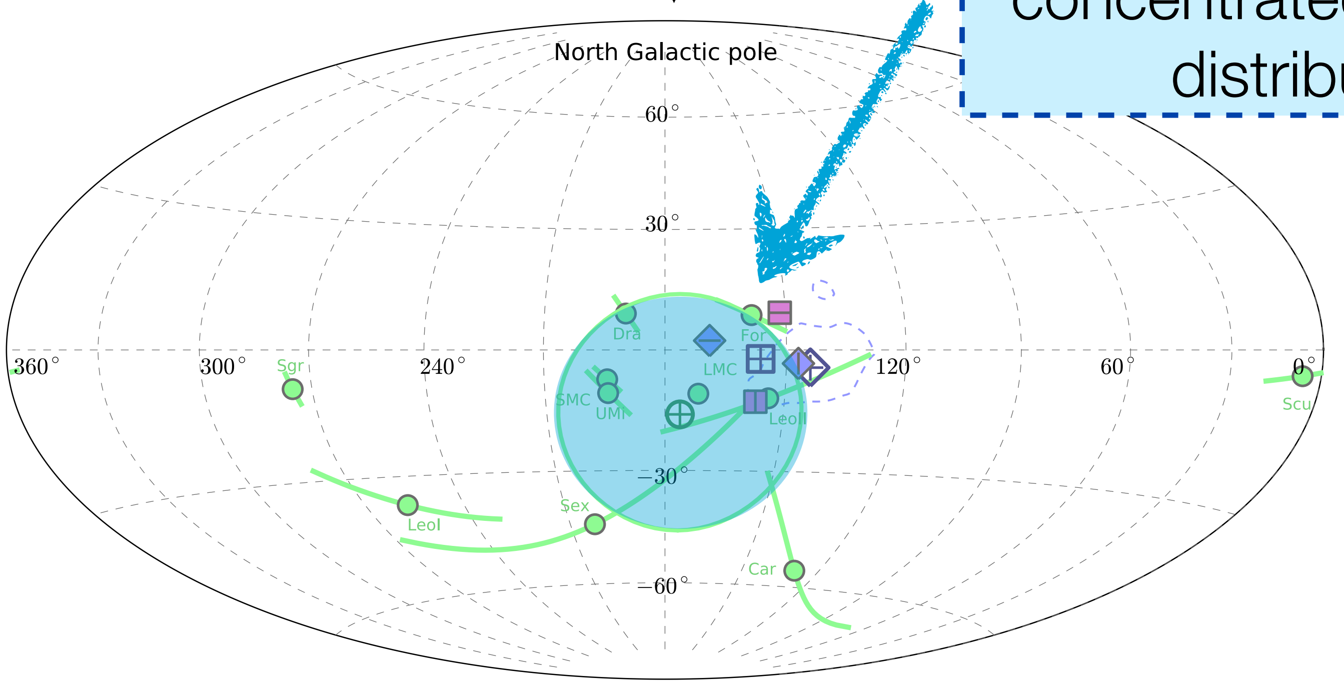


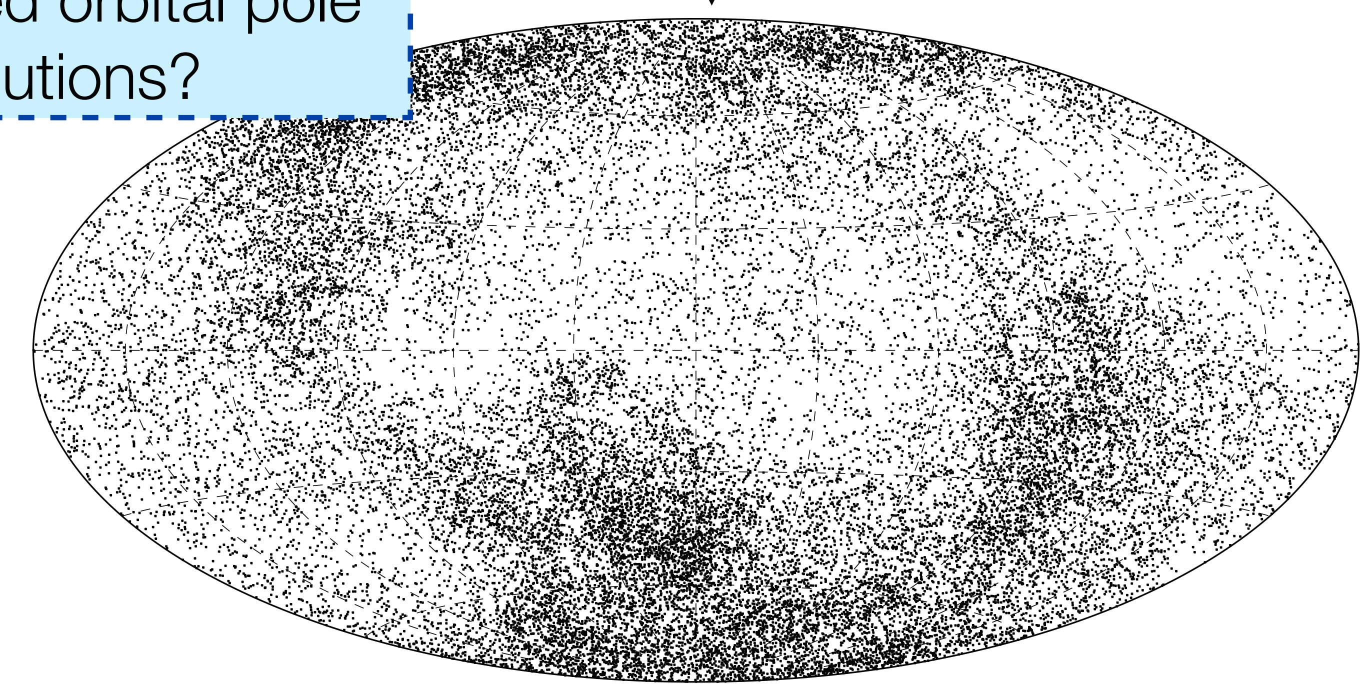
Simulated (sub-halos)



How frequent are similarly narrow planes among sub-halo satellite populations?

How frequent are similarly concentrated orbital pole distributions?

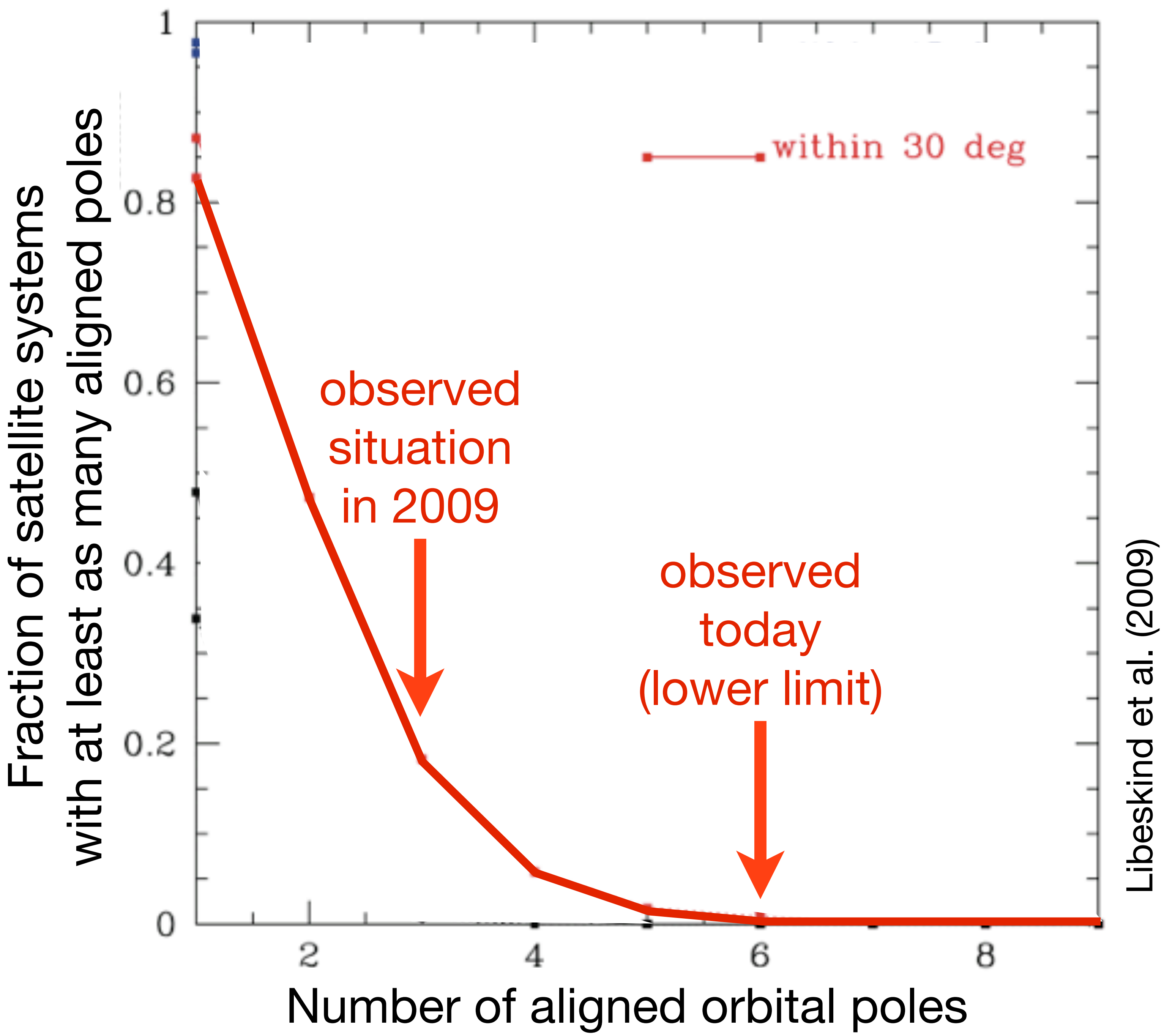




Pawlowski et al. (2012b) and Pawlowski & Kroupa (2013)

Data provided by Lovell et al. (2011)

Most-luminous simulated (sub-halo-) satellites have less-concentrated orbital poles than observed



13 satellites co-orbit around M31

Pawlowski & Kroupa (2013)

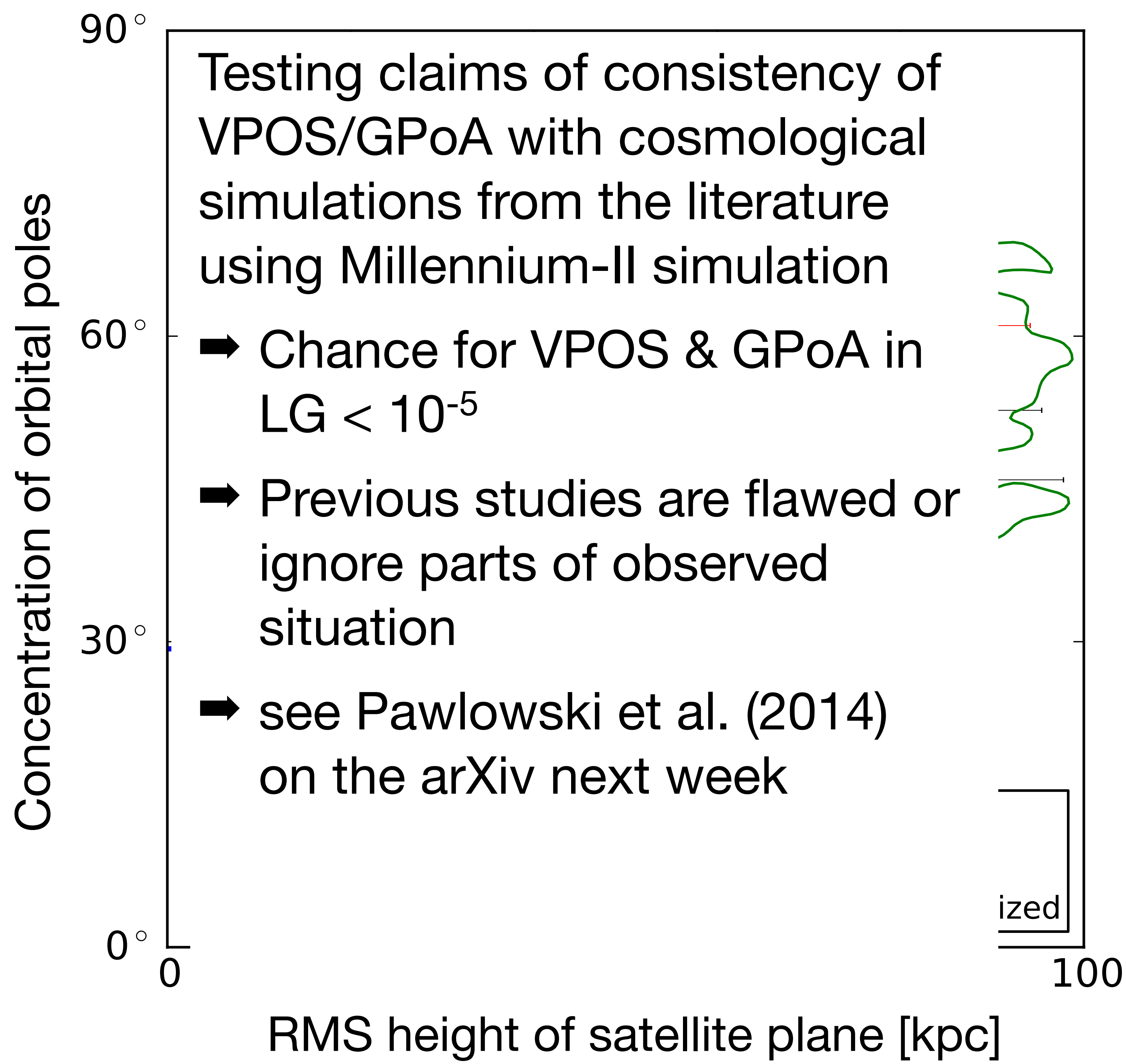
MW-like host halos do not contain VPOS-analogs

- Compare shape of sub-halo satellite distribution and orbital pole alignment
- Effect of MW disc obscuration included

ELVIS simulations (Garrison-Kimmel et al. 2014): LG-like pairs

➡ only 1 of 4800 realizations fulfills thickness and orbital pole criterion simultaneously

➡ Paired host halos as unlikely to contain VPOS as isolated hosts



Testing claims of consistency of VPOS/GPoA with cosmological simulations from the literature using Millennium-II simulation

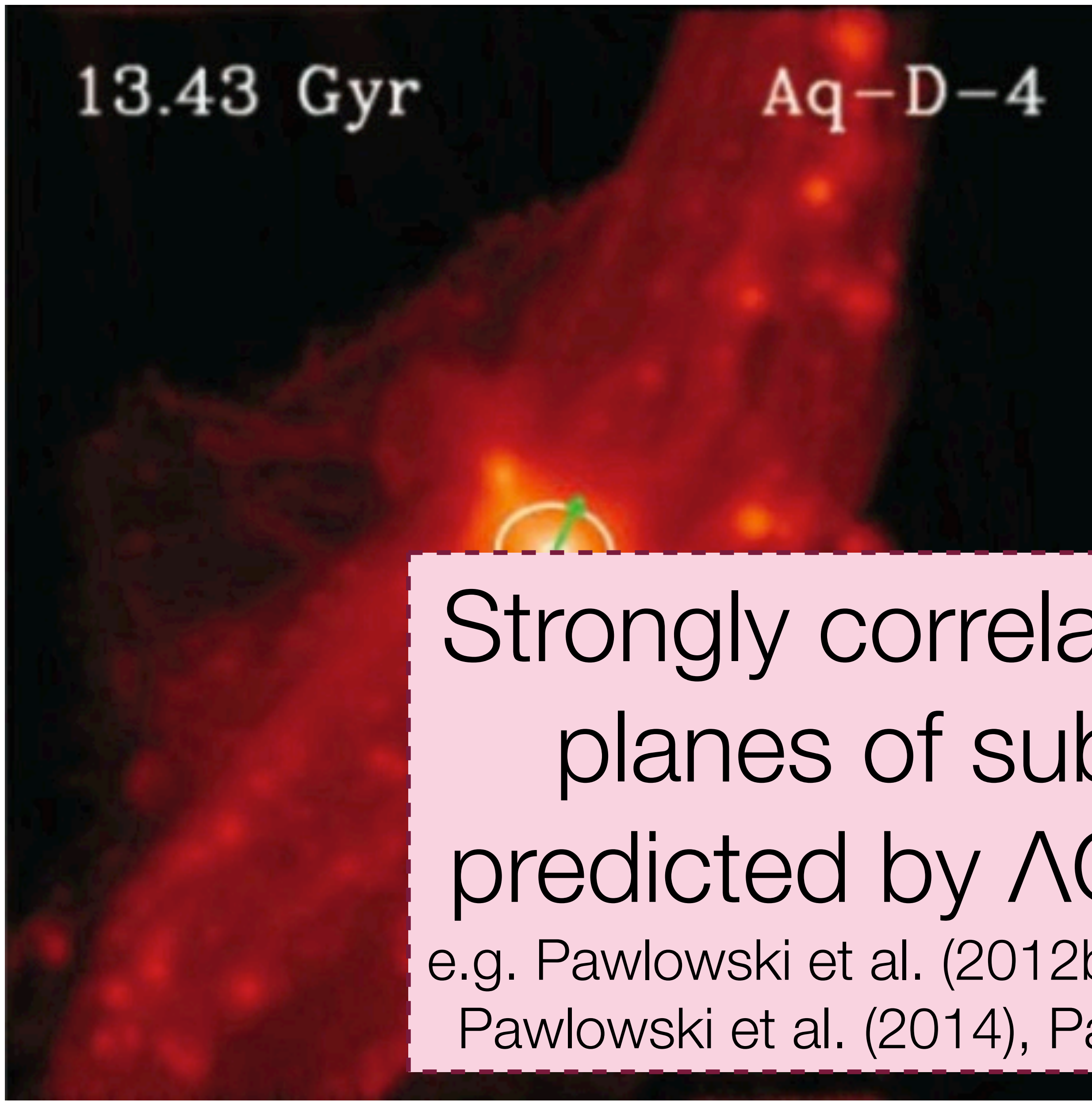
➡ Chance for VPOS & GPoA in LG < 10^{-5}

➡ Previous studies are flawed or ignore parts of observed situation

➡ see Pawlowski et al. (2014) on the arXiv next week

Pawlowski & McGaugh (2014b, ApJL accepted) + Pawlowski et al. (2014, MNRAS accepted)

Satellite planes are inconsistent with distributions expected for accreted dark matter sub-halos



Strongly correlated, thin, rotating planes of sub-halos are not predicted by ΛCDM simulations.

e.g. Pawlowski et al. (2012b), Pawlowski & Kroupa (2013), Pawlowski et al. (2014), Pawlowski & McGaugh (2014b)

Dark matter filament around MW-like halo
Vera-Ciro et al. (2011)

The VPOS on the *same scale*!

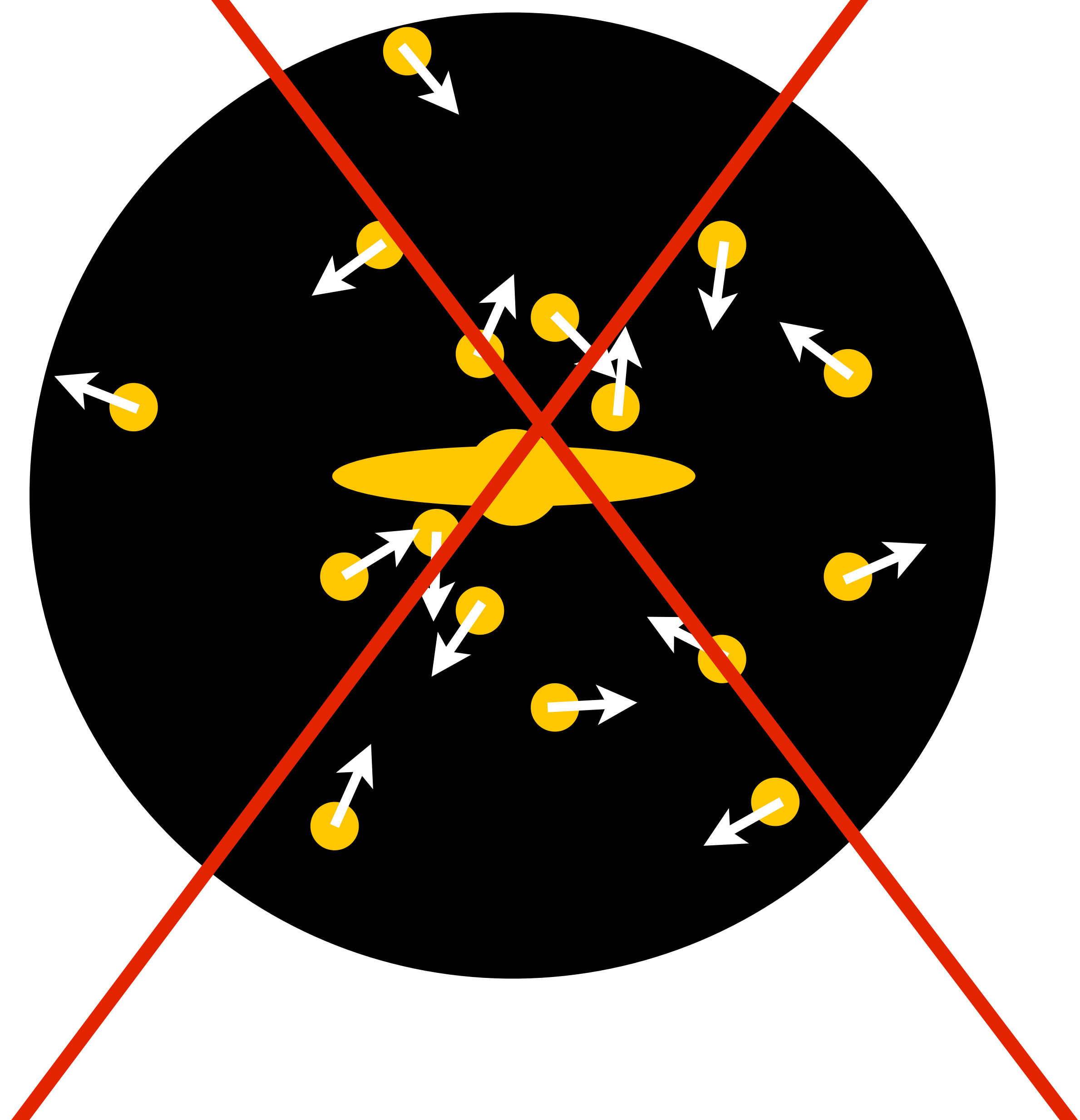
Green arrow: direction of main halo minor axis

Both RMS thickness and extend are to scale.

Primordial vs. tidal dwarf galaxies: Different phase-space distributions

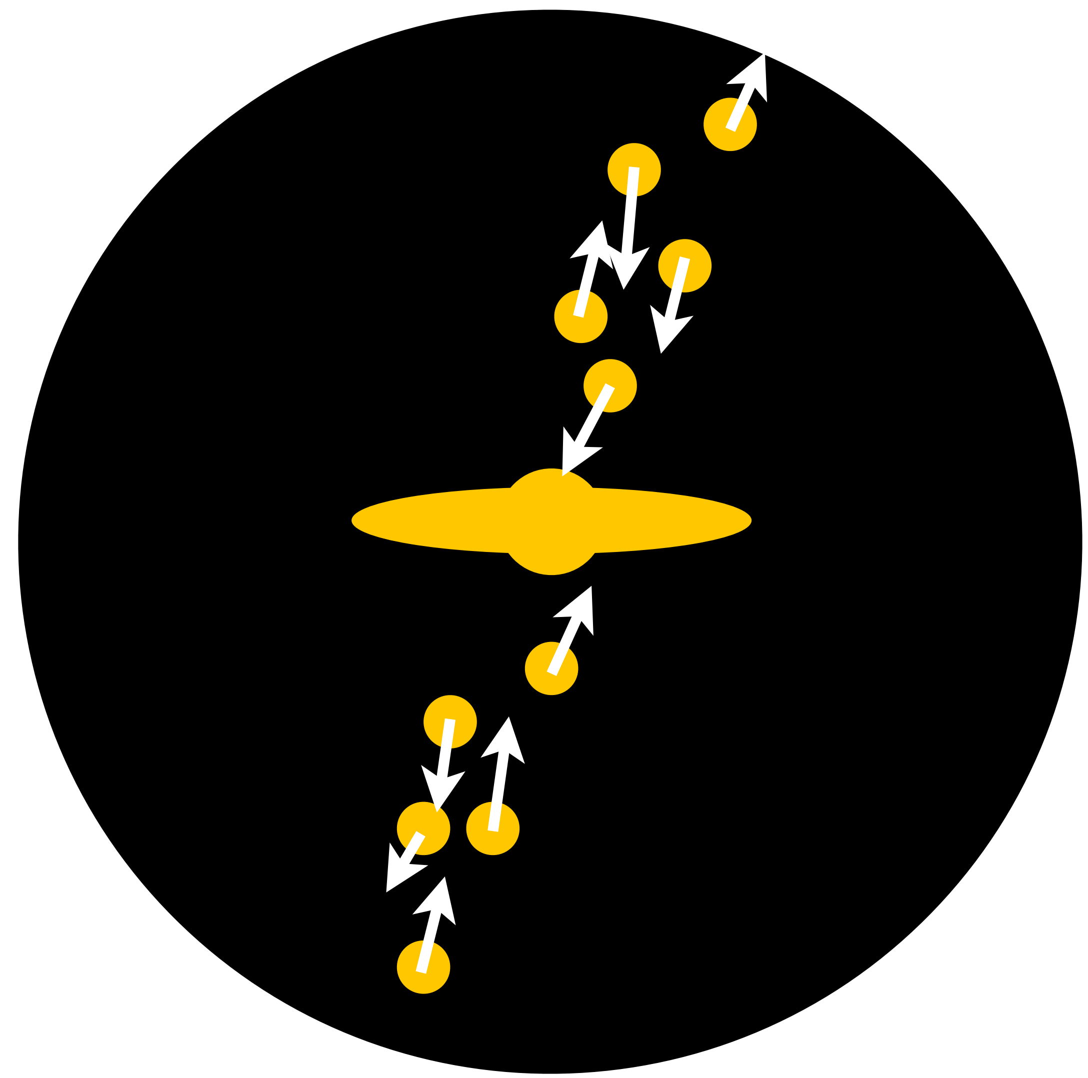
Primordial dwarf galaxies (PDGs):

➡ no overall correlation



Tidal dwarf galaxies (TDGs):

➡ strongly phase-space correlated



Conclusions

- MW is surrounded by a **V**ast **Po**lar **S**tructure (co-orbiting satellite galaxies, YH GCs, streams)
- GCs allow age estimate: 9-11 Gyr
- Alignment with VPOS provides info about individual objects: support for connection to satellite galaxies, prediction of PM, reveals aligned streams

- Standard galaxy formation theory in conflict with co-orbiting satellite planes
- Tidal dwarf galaxies are naturally phase-space correlated

Additional indications for tidal origin in LG:

- Pawlowski, Kroupa & Jerjen (2013)
- Pawlowski & McGaugh (2014a)

Similar structures are being discovered beyond the Local Group

Table 2: Known correlated dwarf galaxy structures.

Host	Name	$N_{\rm dwarf}$[a]	Kinematic coherence[b]	Aligned streams[c]	Reference
Milky Way	VPOS	≥ 24	yes[d]	yes (stellar & gaseous, incl. MS)	1, 2
Andromeda	GPoA	≥ 15	yes[e]	yes (stellar NW-S1 & GS)	3, 4, 5
NGC 1097	Dog Leg	2	unknown	yes, stellar	6
NGC 5557	Tidal Tail-E	3	yes[f]	yes, stellar	7, 8
NGC 4216	F1	3	unknown	yes, stellar	9, 10
NGC 4631	bridge	3	unknown	possible stellar, Hα & HI bridge	11
M 81 group		19	unknown	unknown[g]	12
Local Group	NGC 3109 association	5	yes[h]	no stream known	13, 14

References. — (1) Pawlowski et al. (2012b); (2) Pawlowski & Kroupa (2013); (3) Ibata et al. (2013); (4) Conn et al. (2013); (5) Hammer et al. (2013); (6) Galianni et al. (2010); (7) Duc et al. (2011); (8) Duc et al. (2014); (9) Paudel et al. (2013); (10) Martínez-Delgado et al. (2010); (11) Karachentsev et al. (2014); (12) Chiboucas et al. (2013); (13) Bellazzini et al. (2013); (14) Pawlowski & McGaugh (2014).

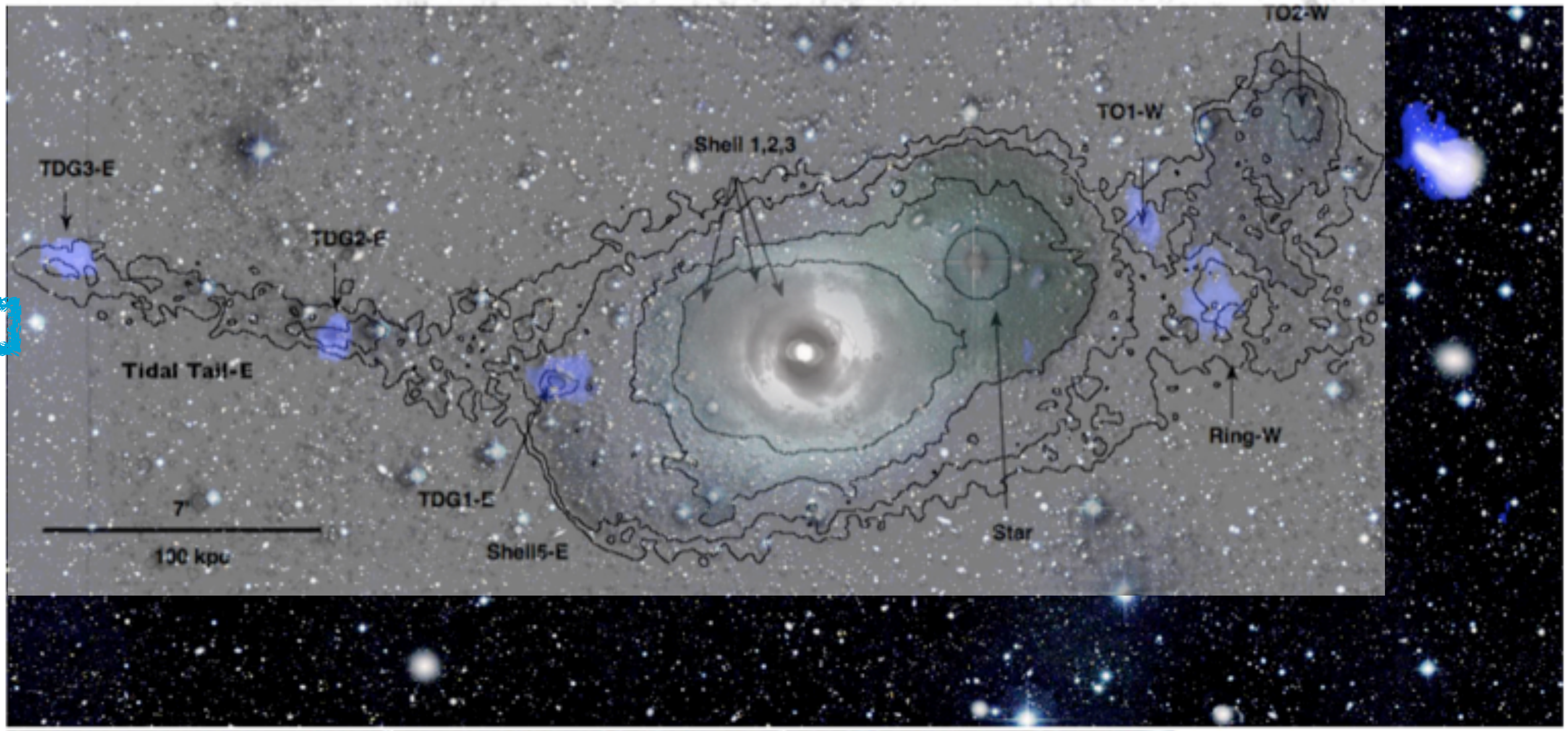
Pawlowski & Kroupa (2014, submitted)

Similar structures are being discovered beyond the Local Group

Table 2: Kn

Host	Reference
Milky Way	1, 2
Andromed	3, 4, 5
NGC 1097	6
NGC 5557	7, 8
NGC 4216	9, 10
NGC 4631	11
M 81 grou	12
Local Grou	13, 14

References. … et al. (2013);
(5) Hammer … . (2013); (10)
Martínez-Del … . (2013); (14)
Pawlowski &



Duc et al. (2011)

Pawlowski & Kroupa (2014, submitted)

Similar structures are being discovered beyond the Local Group

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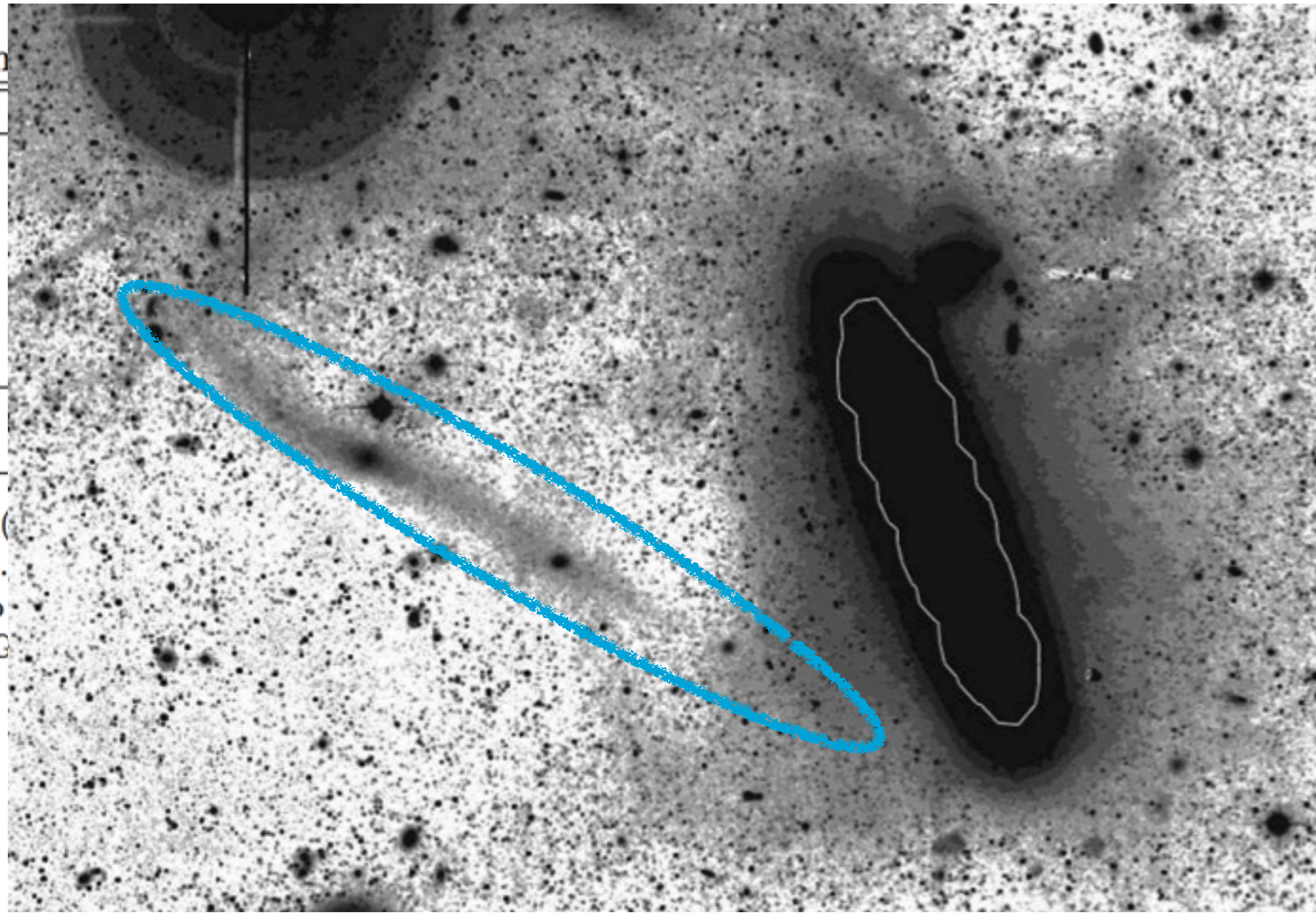

Paudel et al. (2013)

Pawlowski & Kroupa (2014, submitted)

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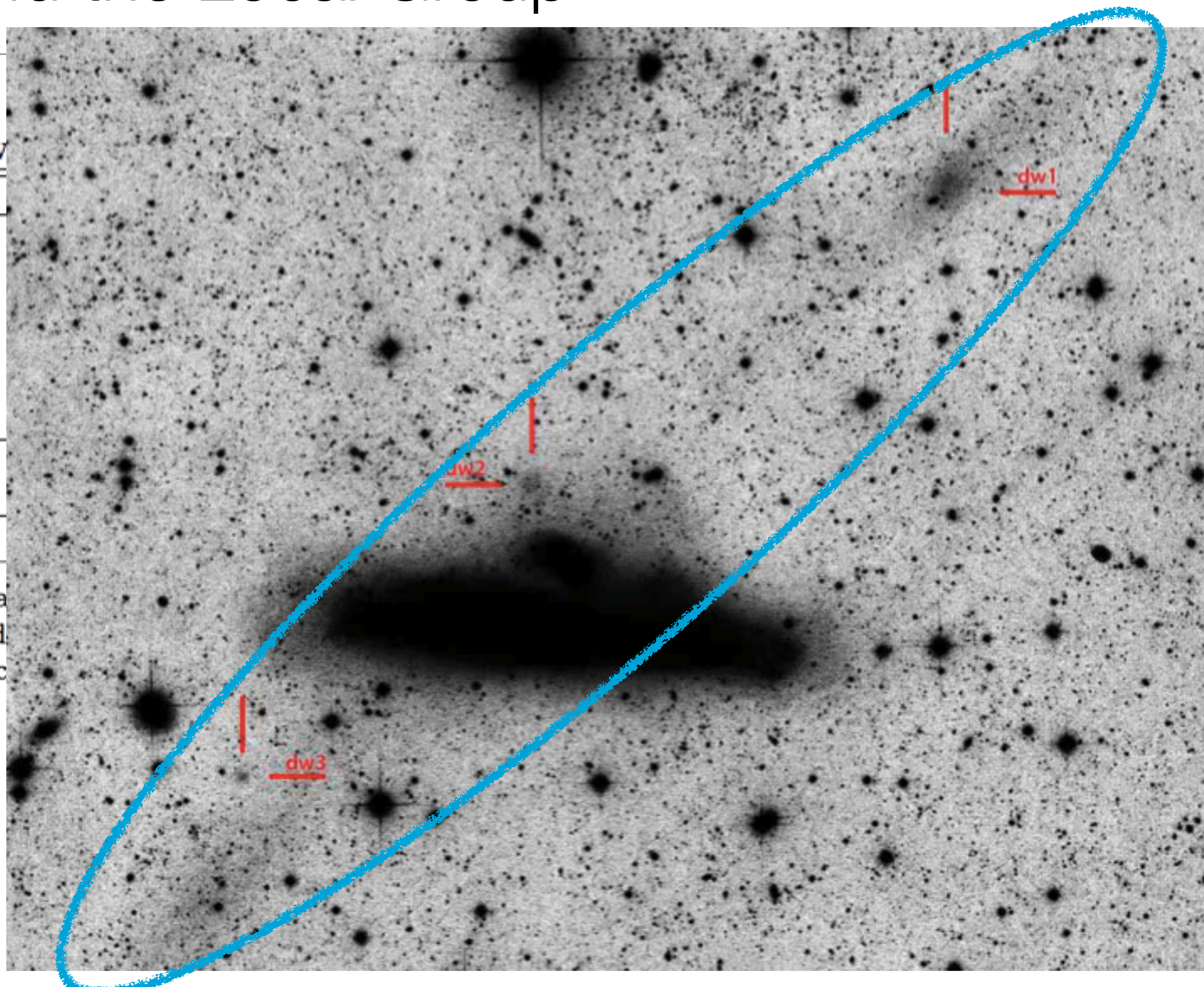

Karachentsev et al. (2014)

Pawlowski & Kroupa (2014, submitted)