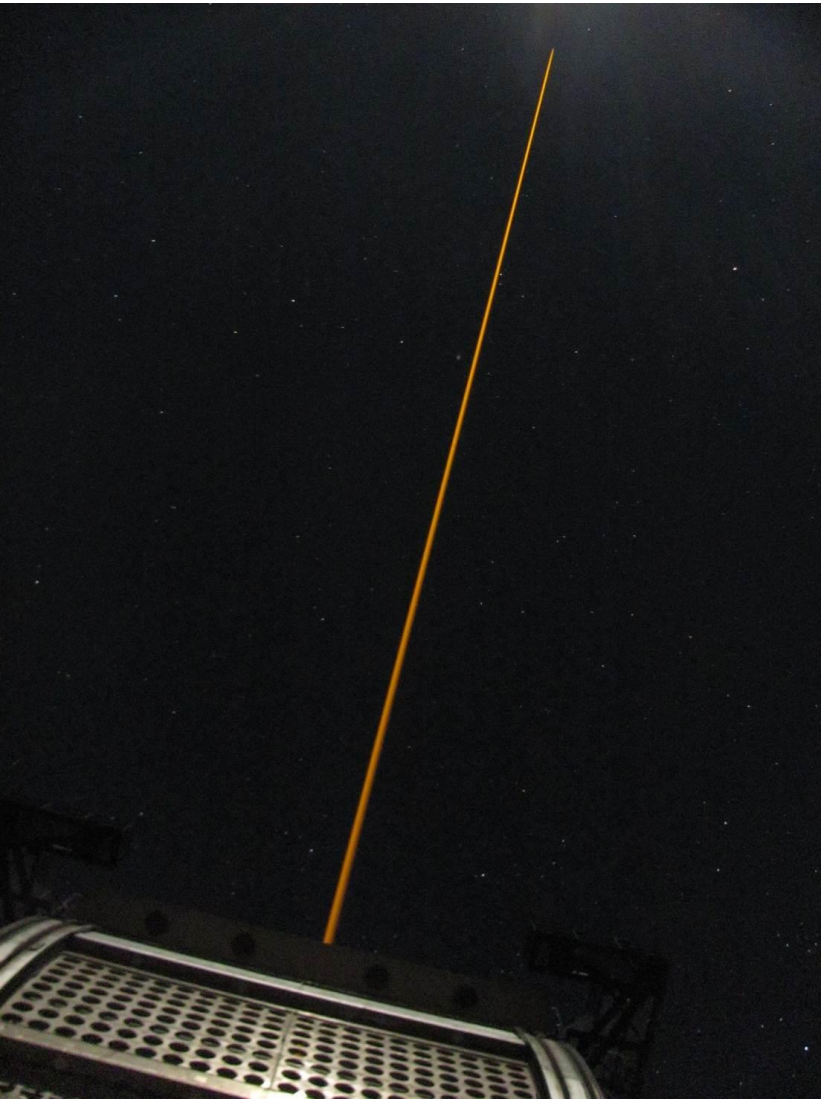
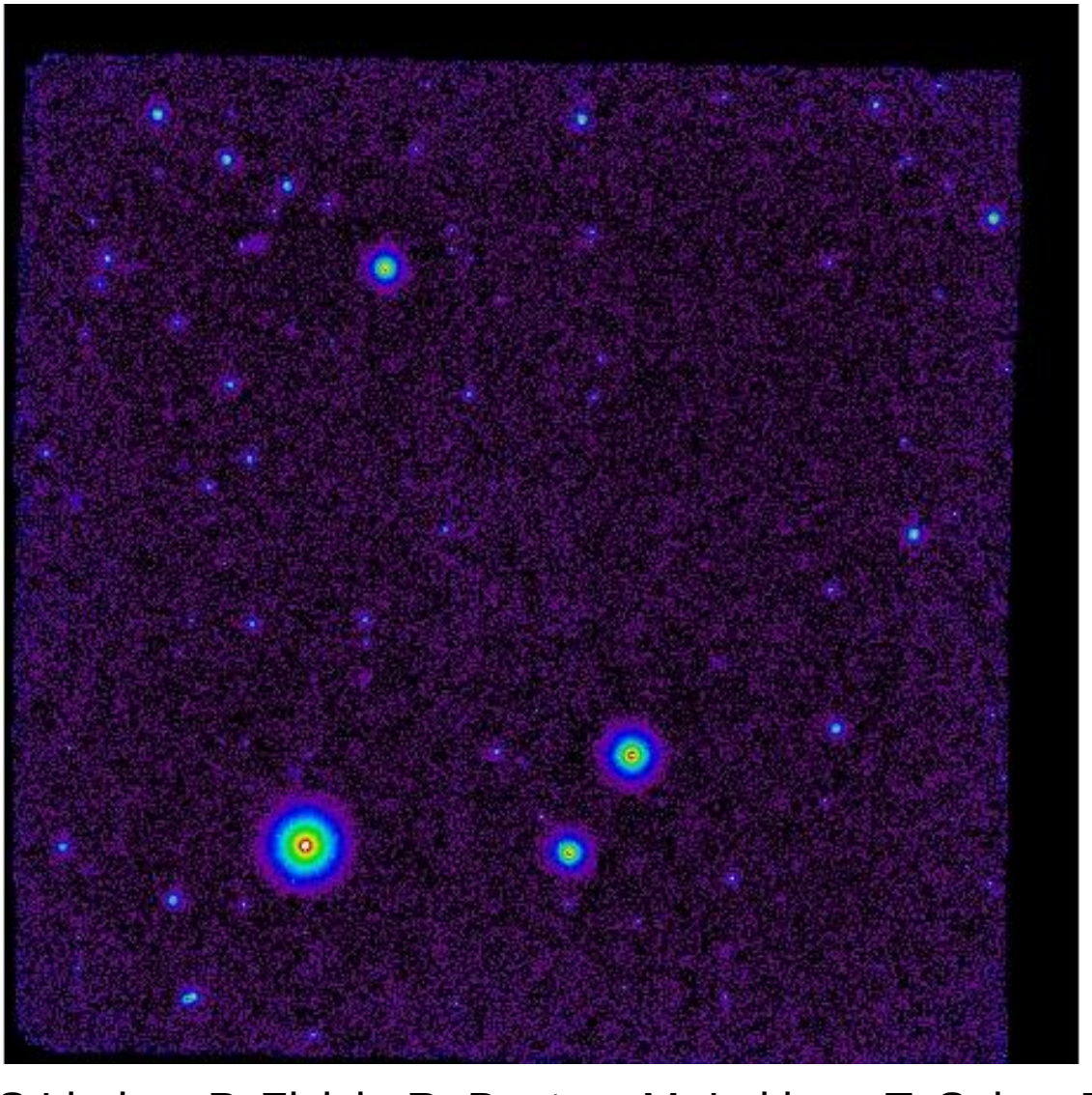
Using ground based data as a precursor for Gaia-based proper motions of satellites





T. K. Fritz, **N. Kallivayalil**, J. Bovy, S.Linden, P. Zivick, R. Beaton, M. Lokken, T. Sohn, D. Angell, M. Boylan-Kolchin, R. Carrasco, G. Damke, R. Davies, S. Majewski, B. Neichel, R. van der Marel

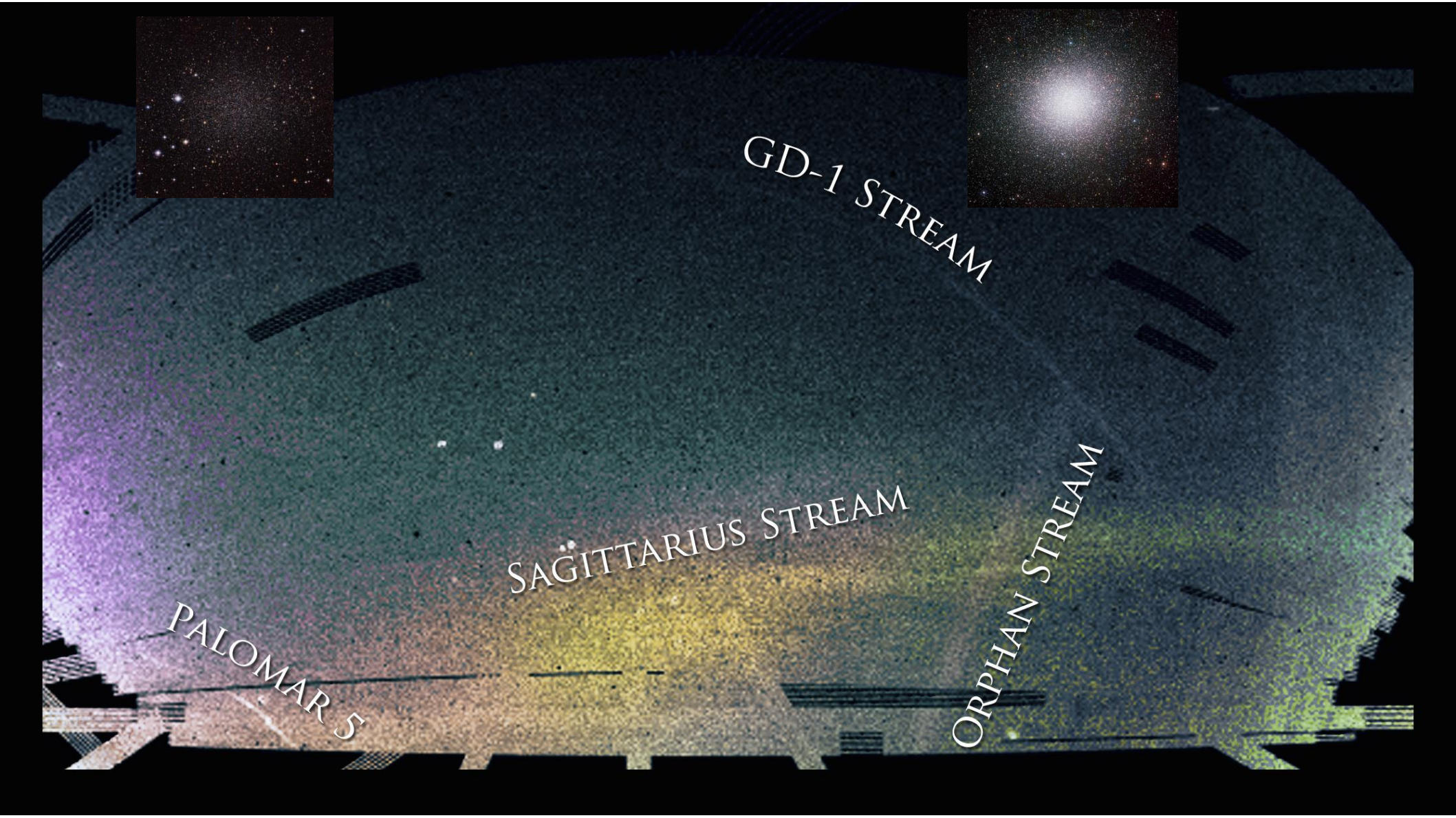
Open questions in near field cosmology

- **Mass** of the **Milky Way** uncertain, e.g. Boylan-Kolchin et al. 2013: $1.6\pm0.4\ 10^{12}\ M_{sol}$ compare to Gibbons et al. 2013: $0.56\pm0.12\ *10^{12}\ M_{sol}$
- **Shape of the halo**: oblate but edge on the disk? (Law & Majewski 2010)
- **Too big to fail**: Are massive dwarf galaxies ($30\sim<v_{central}\sim<60$ km/s) missing? (Zavala et al 2009, Boylan-Kolchin et al. 2012)
- **Missing galaxies**: low mass halos possibly starless due to reionization (Alvares et al. 2009), Can we prove their existence?

Probes: Satellites (with Tidal streams)

Sculptor dwarf spheroidal

Globular cluster Omega Centauri



Field of streams: Turnoff stars from SDSS: color codes distance, blue closest, from Ana Bonaca

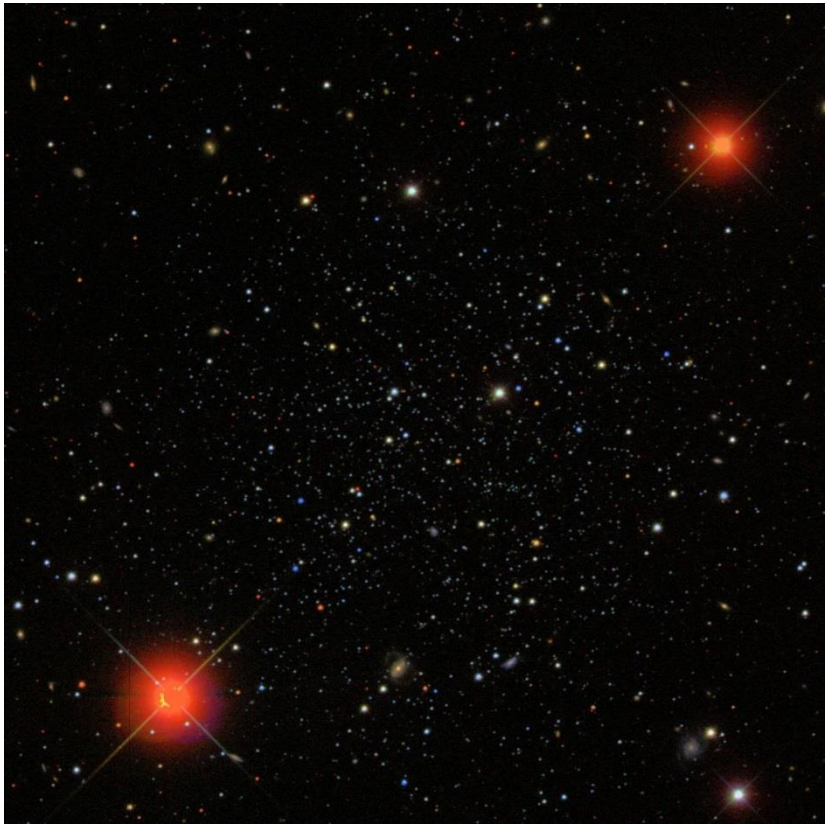
Constraining the origin of the probes

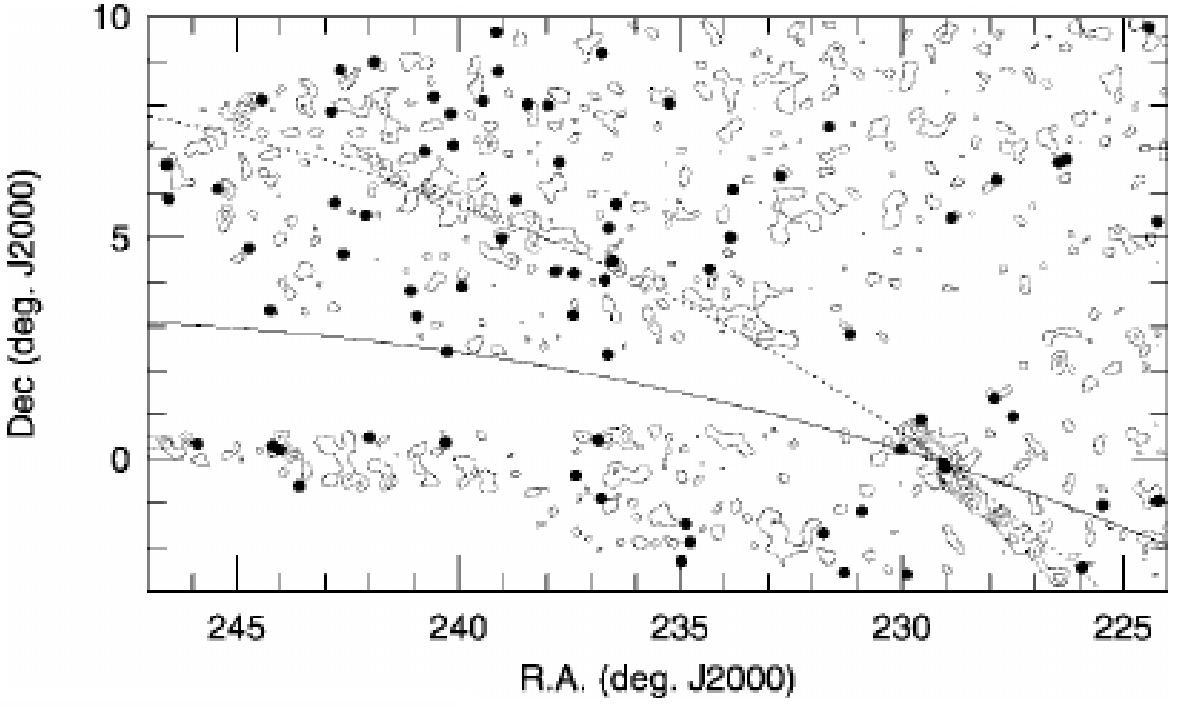
- How many probes (dwarf galaxies/globular clusters) share the same origin?
- → How many were **satellites of other satellites**? N_{sat} gives a hint on the mass of the larger satellite (Sales et al. 2013)
- Do orbital poles of satellites align? → Are there **planes of satellites**? (Lynden-Bell 1976, Ibata et al. 2013)
- When were they accreted?
- Did the **star formation shut down** before or after they were accreted? When $t_{shut\ down} > t_{accrete}$ environmental effects like tidal stripping (e.g. Weisz et al. 2014) were not responsible for the shut down. Reionization is then a likely reason (e.g. Brown et al. 2014, Wetzel et al. 2015).

Proper motion measurements method

- Positions of objects are measured on single images.
- Positions are corrected for DCR if necessary.
- We select target stars mainly with photometry (+spatially, +relative proper motion)
- The distortion correction relies on the fact that one of the two data sets has a known distortion solution.
- The proper motions are measured relative to background galaxies, which are selected morphologically.
- Total precision is mainly limited by the SNR of the reference galaxies.

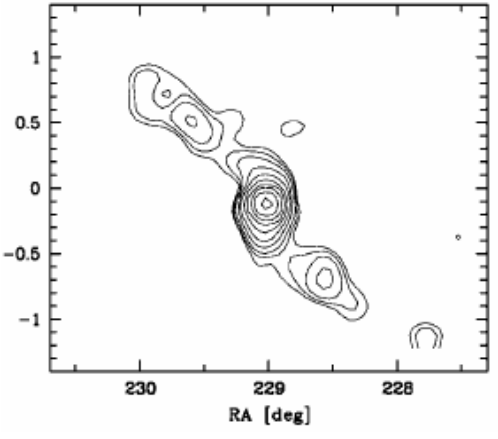
Palomar 5: globular cluster +stream



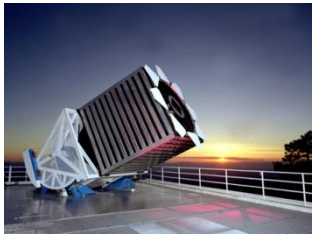


22 degree long tails
Grillmaier & Dionatos 2006

- Faint (M_V=-5.2), low mass
- (σ<1 km/s, Odenkirchen et al. 2002)
- In the halo (d~22 kpc, Dotter et al 2011, Harris 1996; Vivas & Zinn 2006)
- Small radial velocity gradient of 1±0.1 km/(s*deg) (Kuzma et al. 2014)



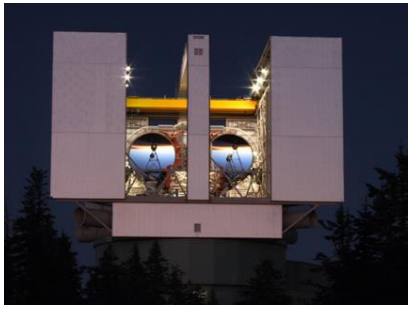
Odenkirchen et al. 2001



SDSS 1999

Fritz & Kallivayalil 2015

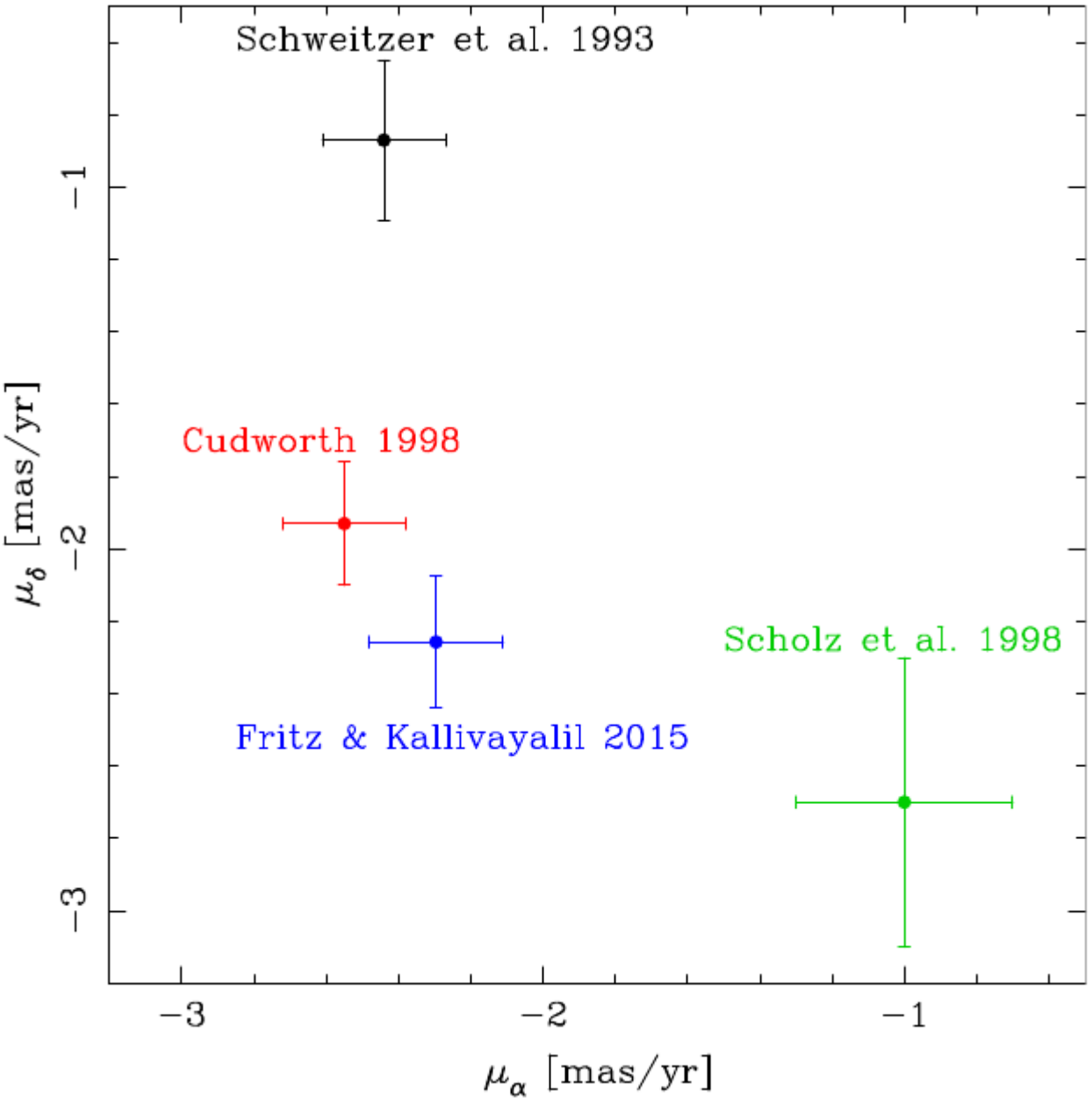
LBC/LBT 2014



Proper motion of Palomar 5

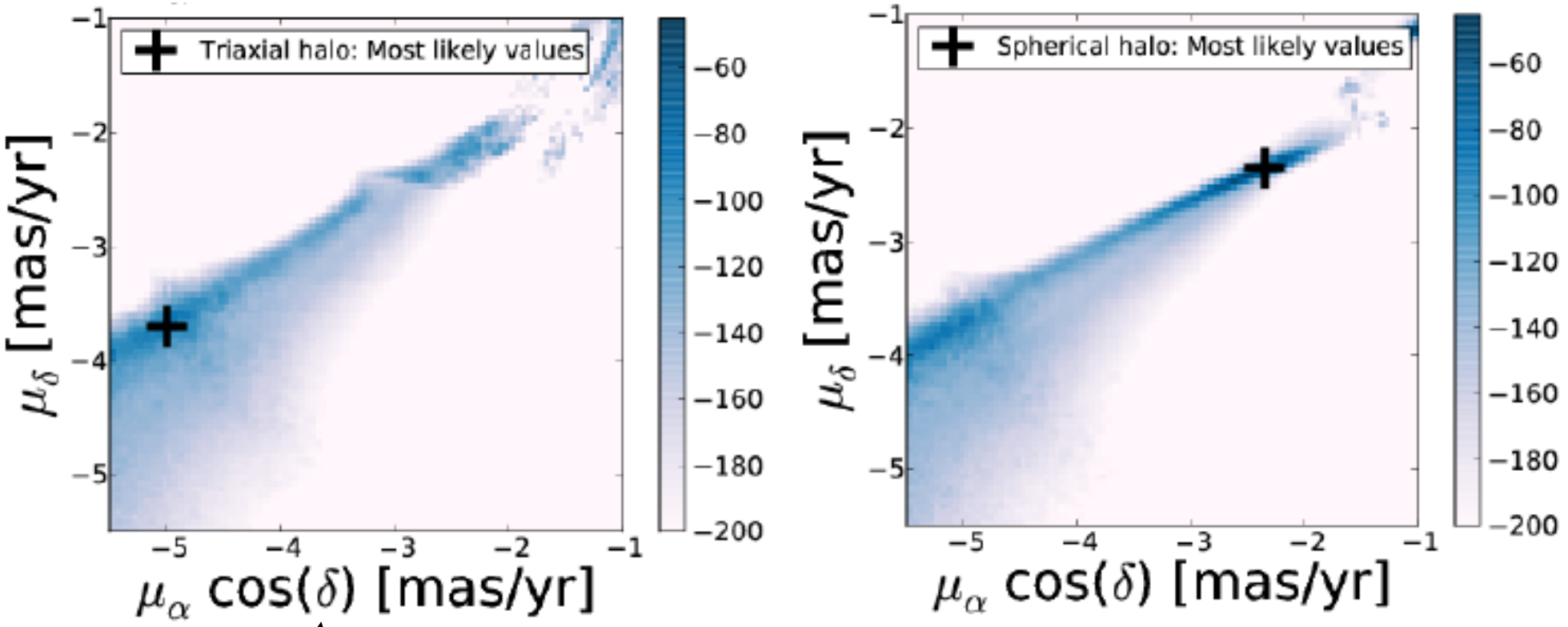
μ_α=-2.25±0.19 mas/yr

μ_δ=-2.21±0.18 mas/yr



Fritz & Kallivayalil 2015

Matches prediction for spherical halo



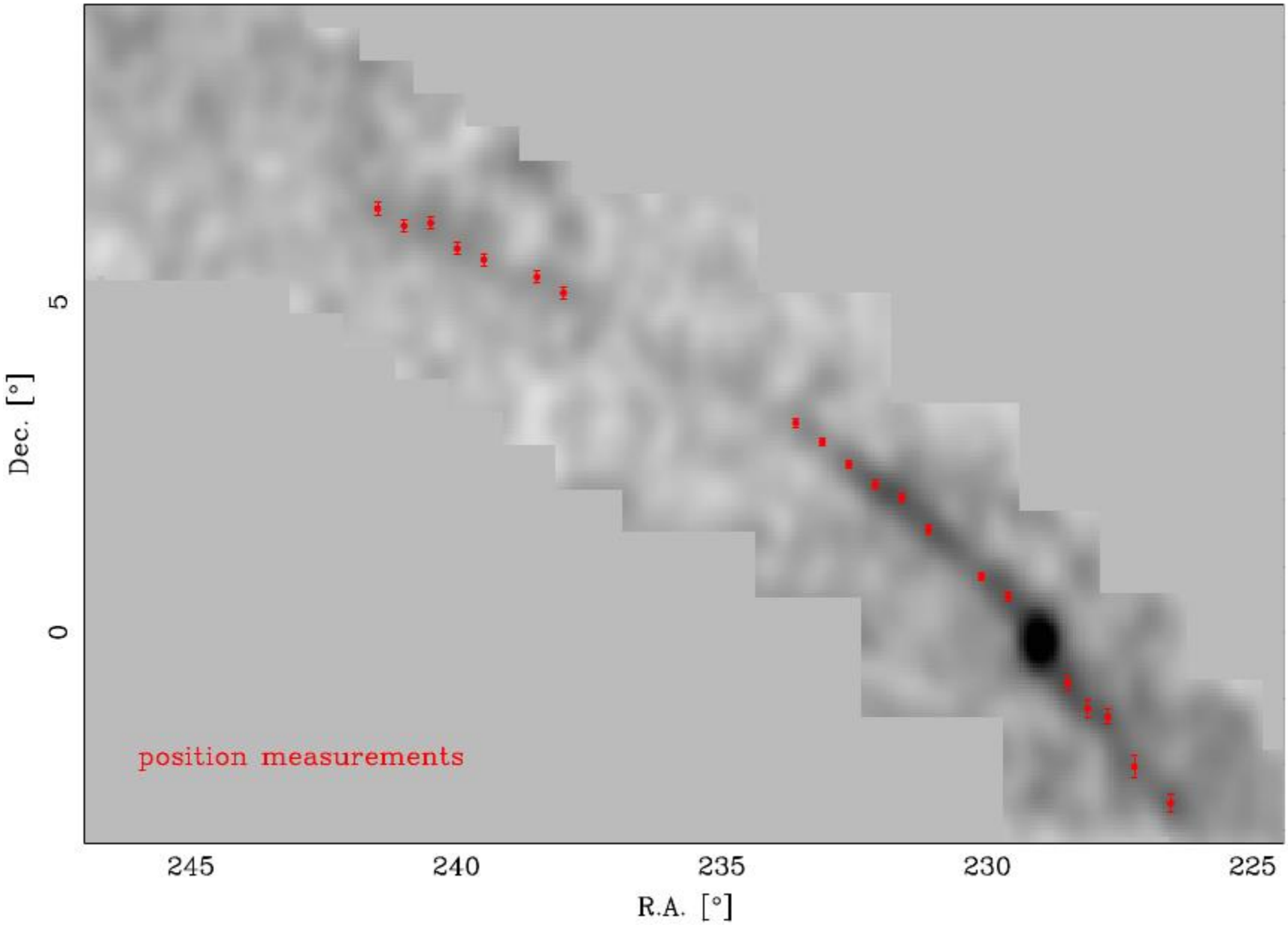
- Law& Majewski 2010 halo; both from Pearson et al. 2014

Our proper motion (μ_α/μ_δ=-2.25/-2.21±0.18 mas/yr) fits much better to the spherical halo (μ_α/μ_δ =-2.35/-2.35 mas/yr).

- Also L&M halo makes a stream wider due to chaotic orbits.

Fritz & Kallivayalil 2015

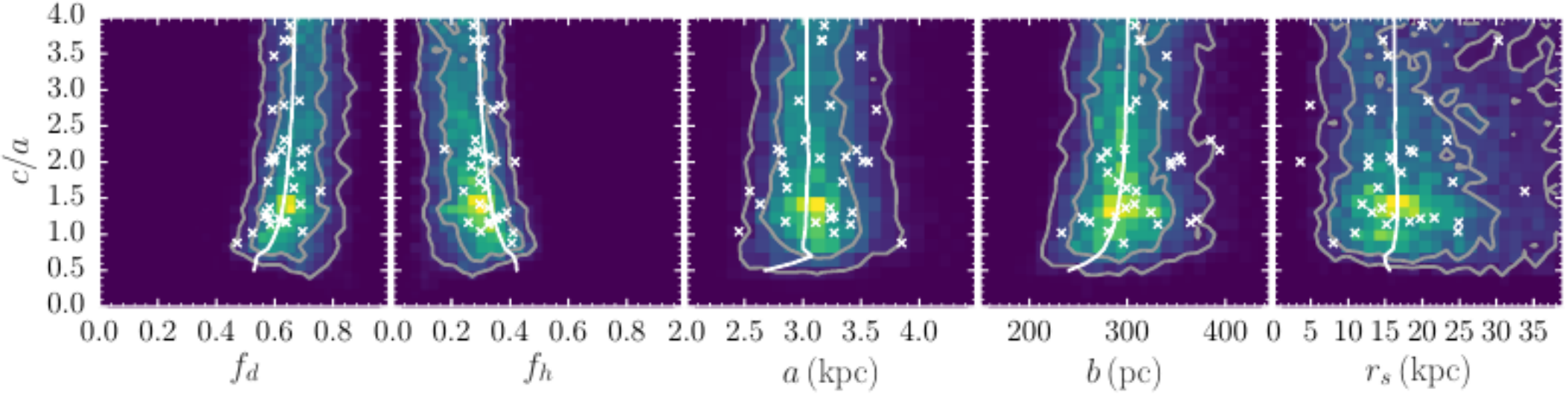
Stream positions



Fritz & Kallivayalil 2015

Positions consistent with Kuepper et al 2015

Fitting for flattening aligned with disk

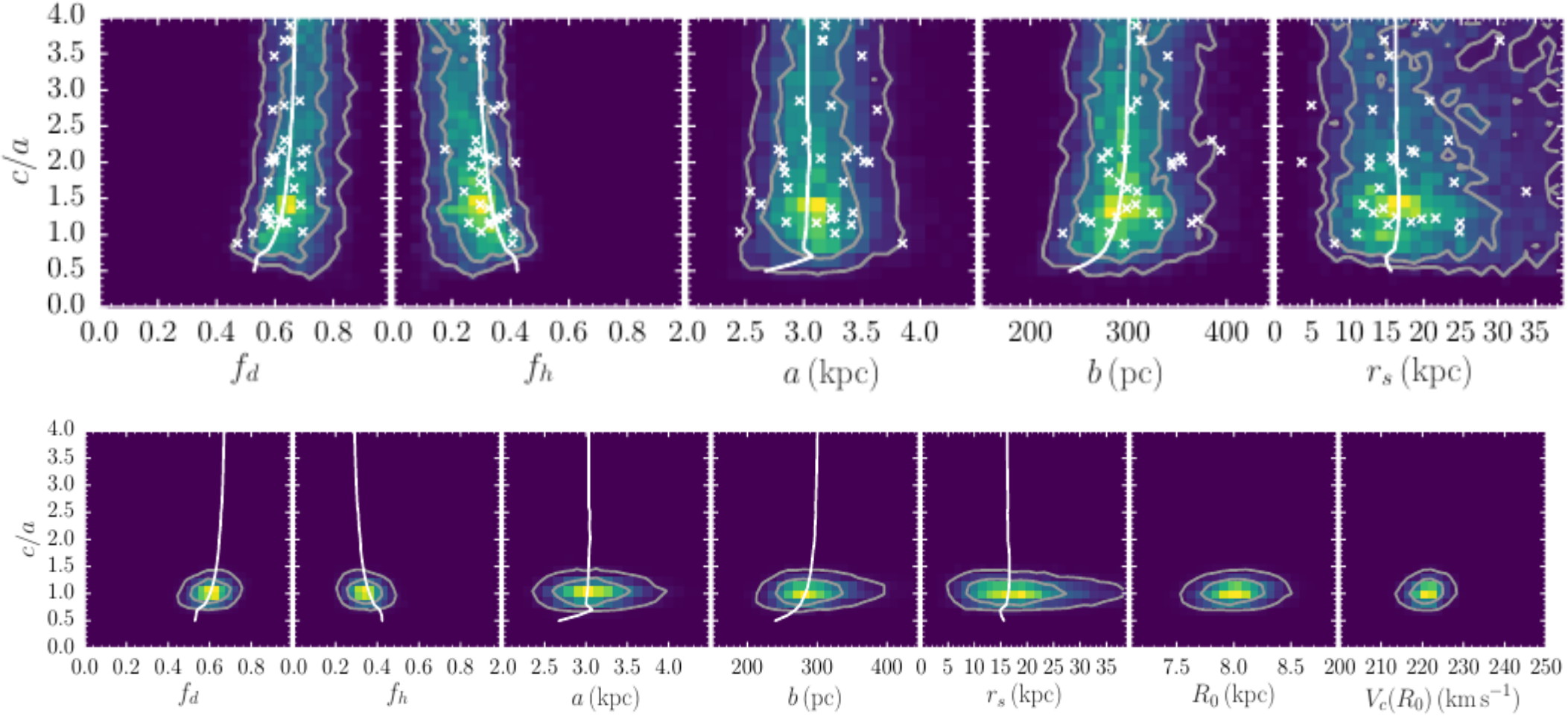


Priors

- b/a (axis in disk plane) set to 1.
- c/a is minor to major axis ratio with same symmetry as disk.

Bovy, Bahmanyar, Fritz & Kallivayalil 2016

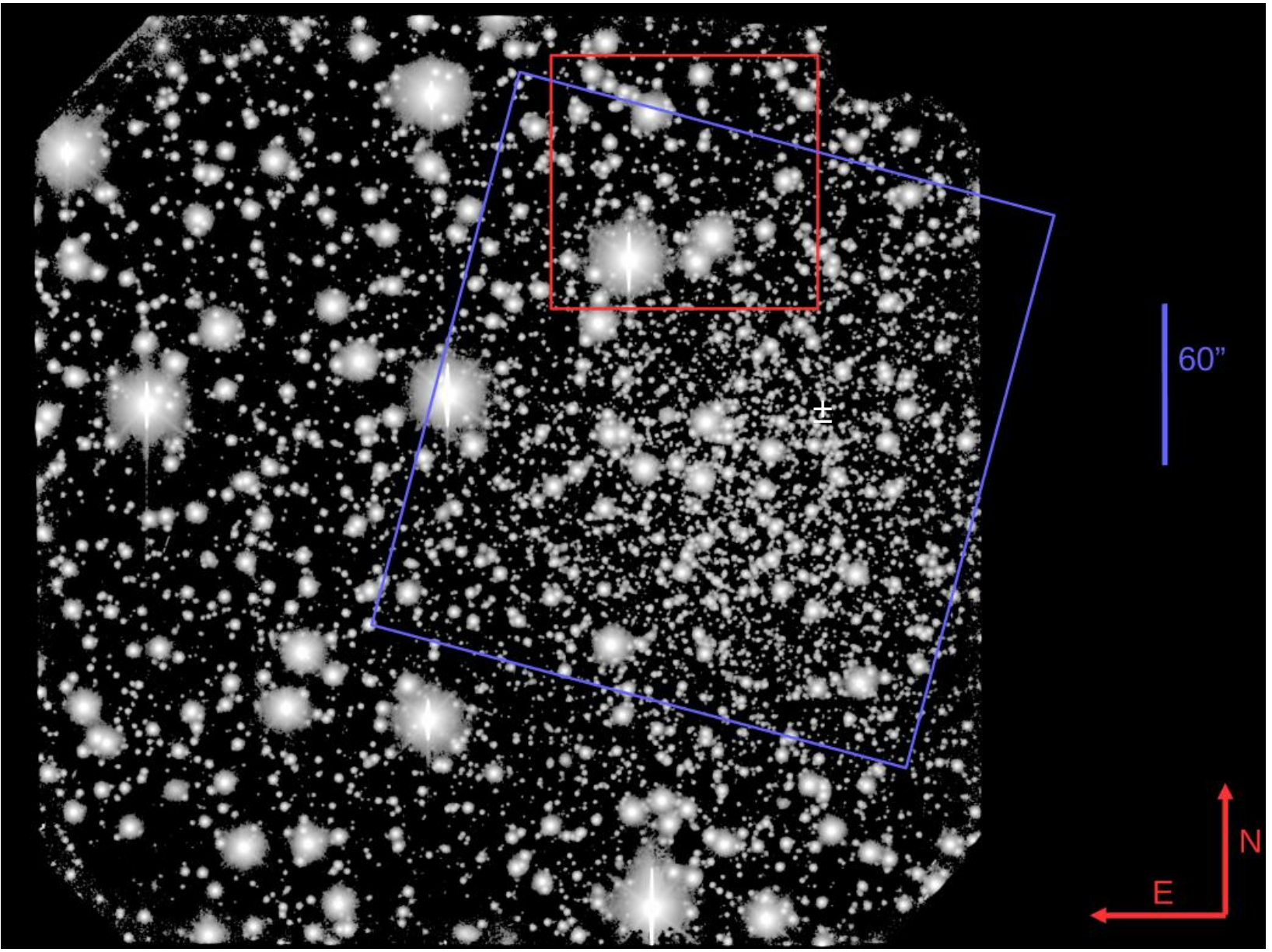
Using Pal 5 + GD-1streams



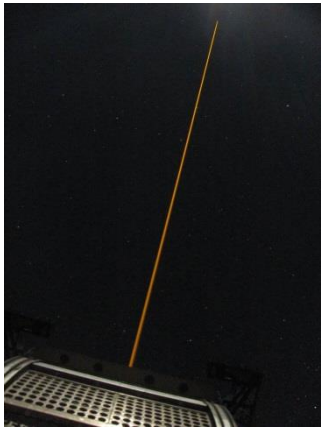
c/a=1.05±0.14, that is in slight tension with the expected value of 0.8 (Kazantzidis et al. 2010) for the Milky Way, which probably has a maximal disk (Bovy & Rix 2013)

Bovy, Bahmanyar, Fritz & Kallivayalil 2016

Proper motion of the globular cluster Pyxis: ACS/HST + GSAOI/Gemini-S

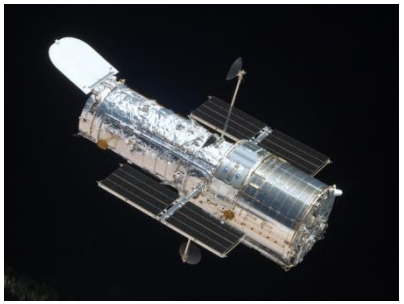


GSAOI+GeMS
Gemini-S 2015



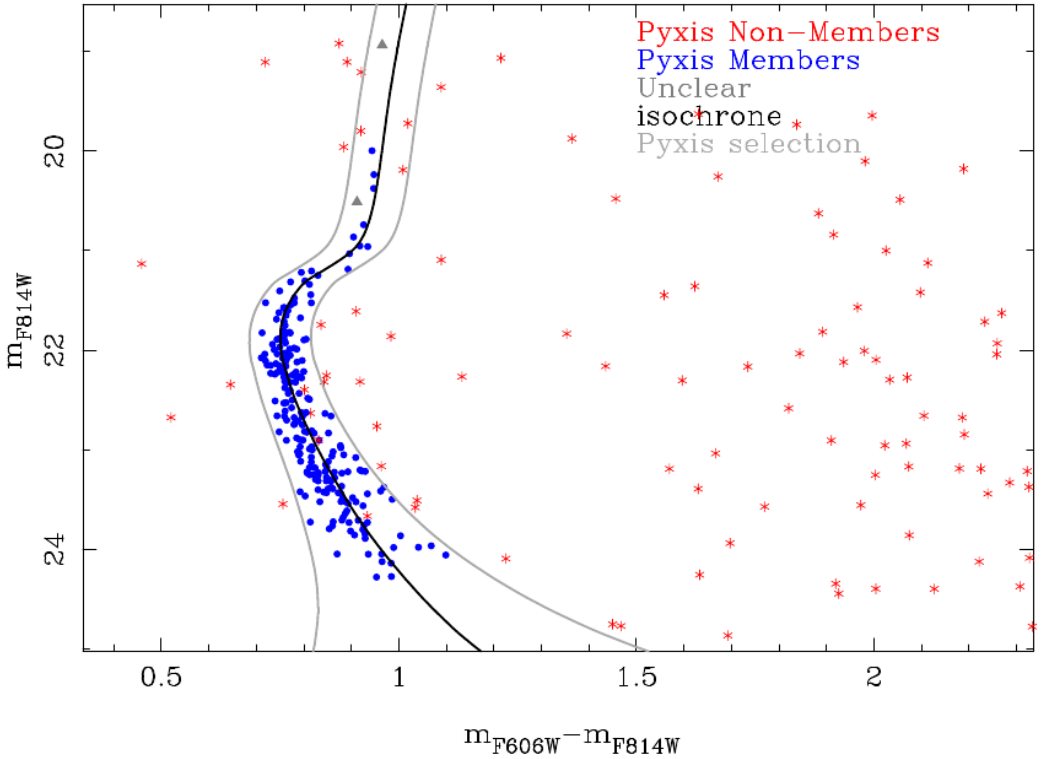
Halo globular cluster
D_{sun}=39.4 kpc
M_V=-6.0
[Fe/H]=-1.45±0.1
Age=11.5±1 Gyrs

ACS/HST 2009

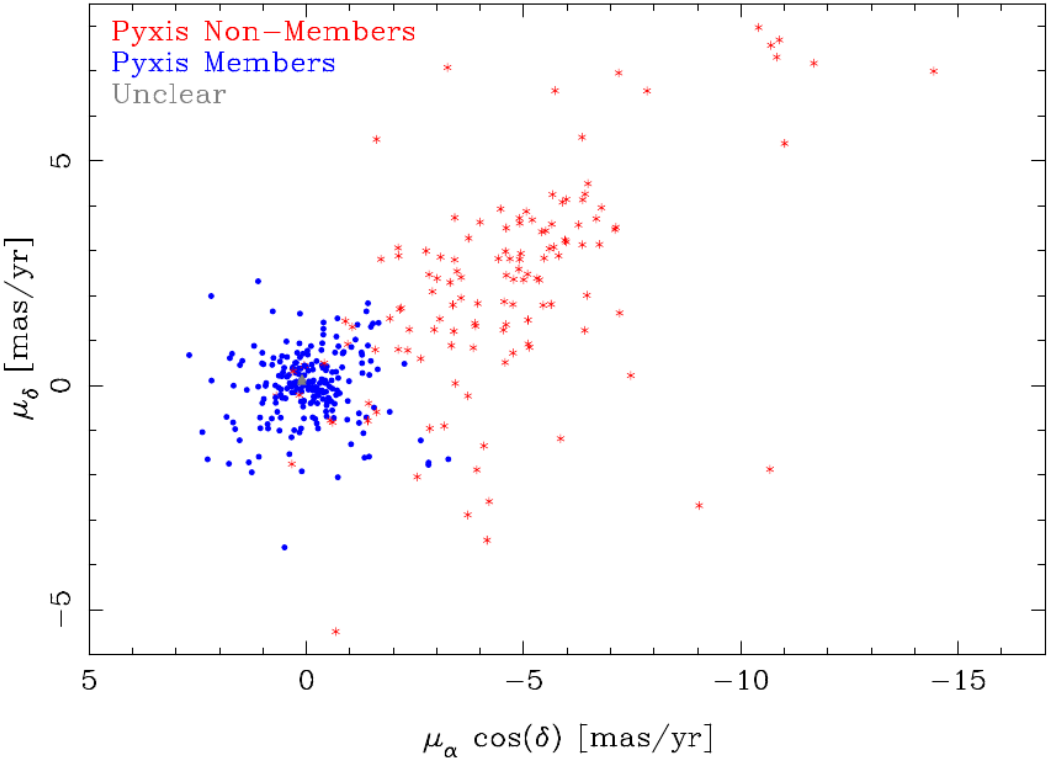


Fritz et al. 2016 ApJ accepted arXiv:1611.08598

Pyxis membership and final motion



Photometric member selection

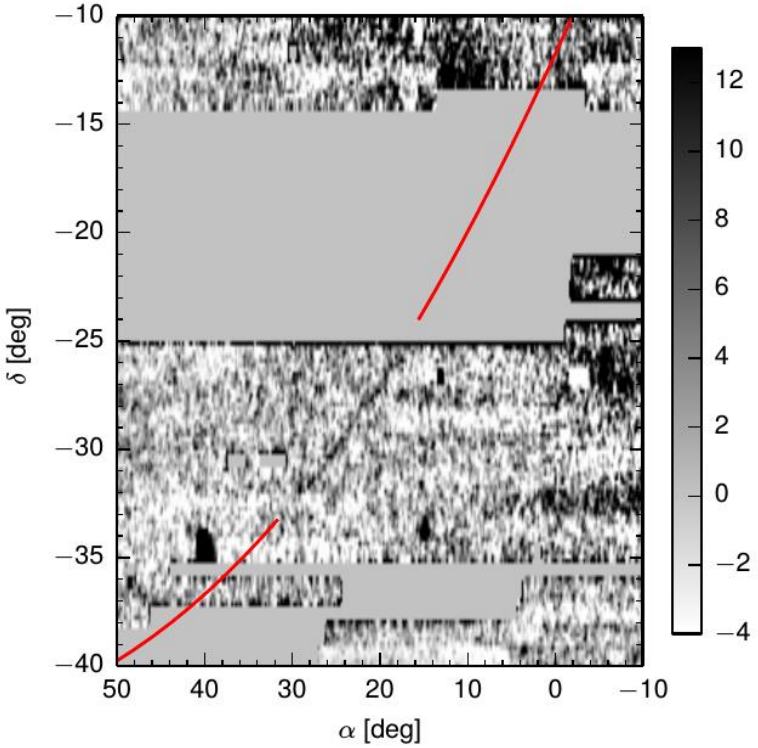


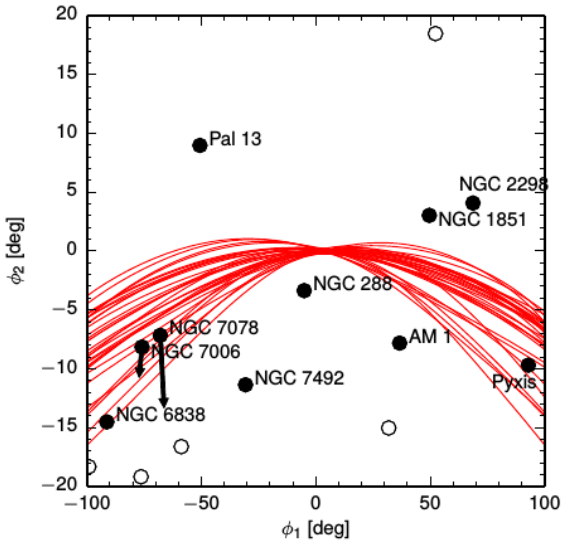
Relative proper motions

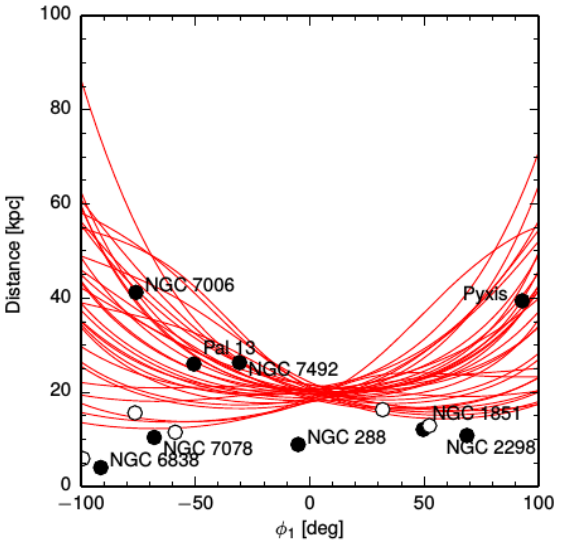
Absolute proper motion: $\mu_\alpha \cos(\delta)$ =1.09±0.31 mas/yr μ_δ=0.68±0.29 mas/yr

Fritz et al. 2016 ApJ accepted arXiv:1611.08598

Connected with ATLAS stream?

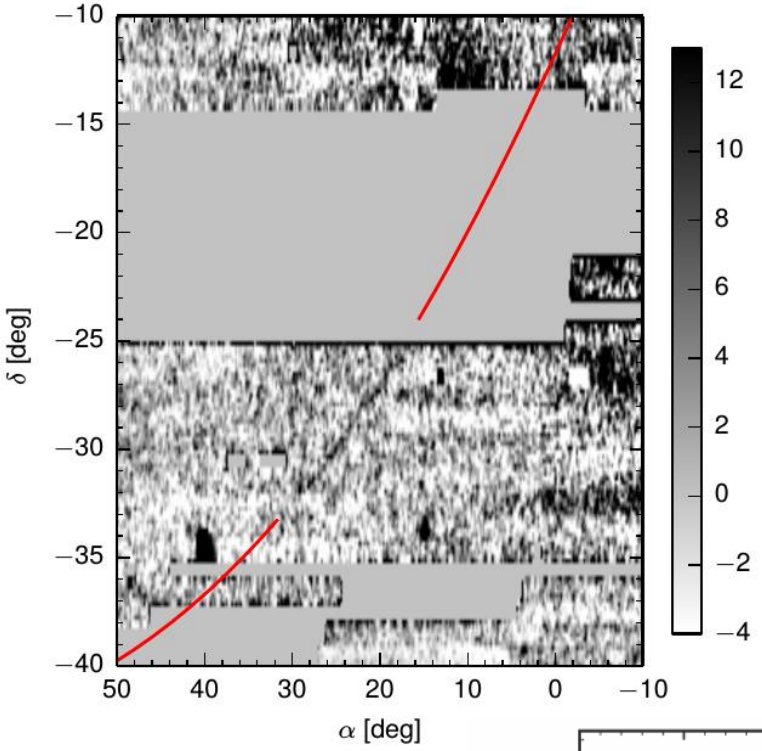


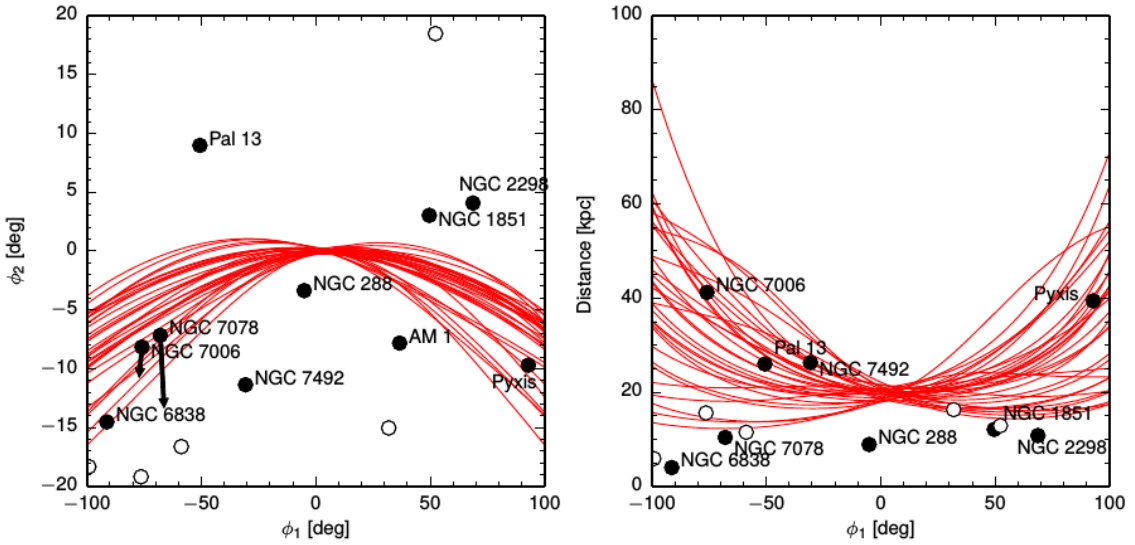




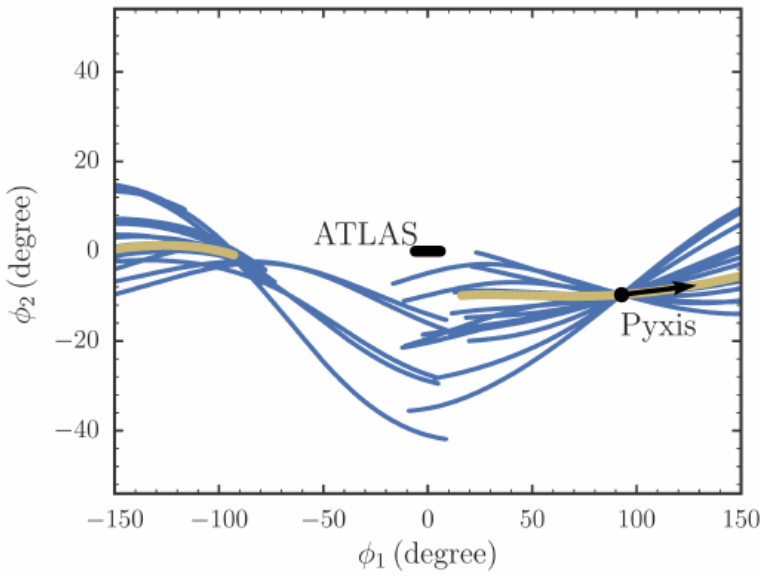
Koposov et al. 2014

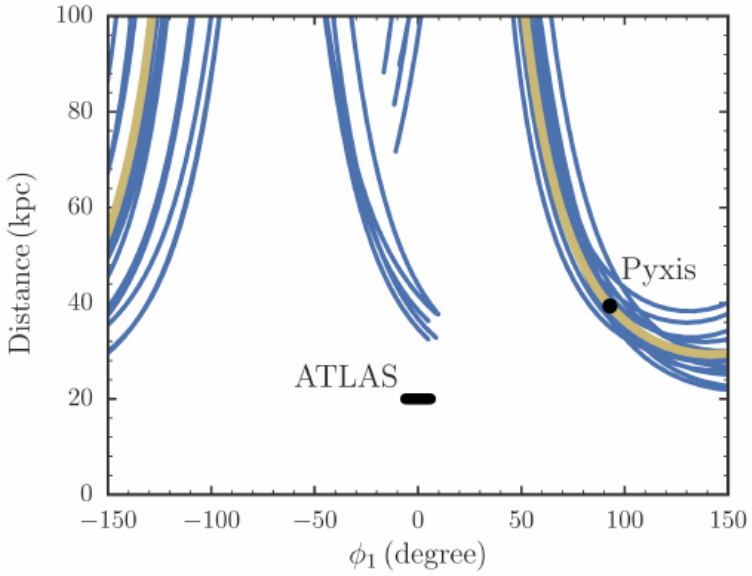
Connected with ATLAS stream? No





Koposov et al. 2014





Fritz et al. 2016 ApJ accepted
arXiv:1611.08598

What is the origin of Pyxis?

- Did it form in situ?
- Average distance is >=60 kpc. The gas density is too low for star formation at that distance even in mergers (Renaud et al. 2016).
- Pyxis is in metallicity-age space somewhat offset from the main population which formed in major mergers. (Lin & Gnedin et al. 2014)
- →Pyxis probably did not form in situ.
- Pyxis is probably a young halo cluster (Zinn et al. 1993), which formed in a dwarf galaxy, which later merged with the Milky Way.

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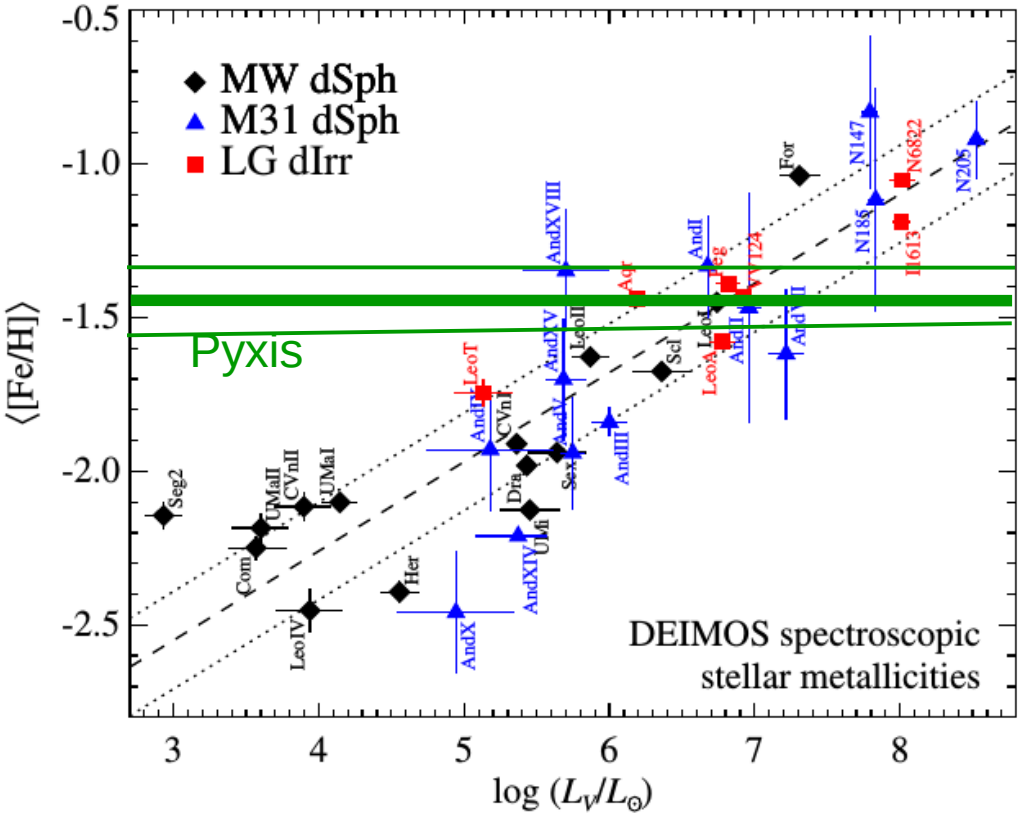
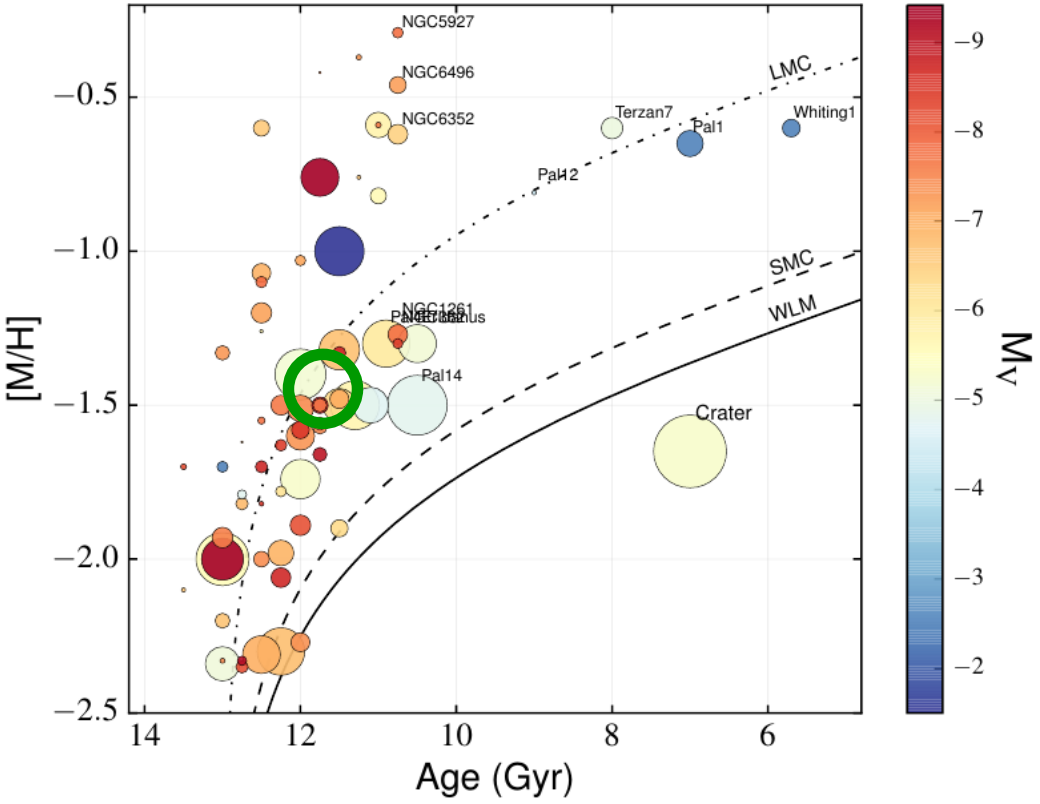
What is the size of the host galaxy?



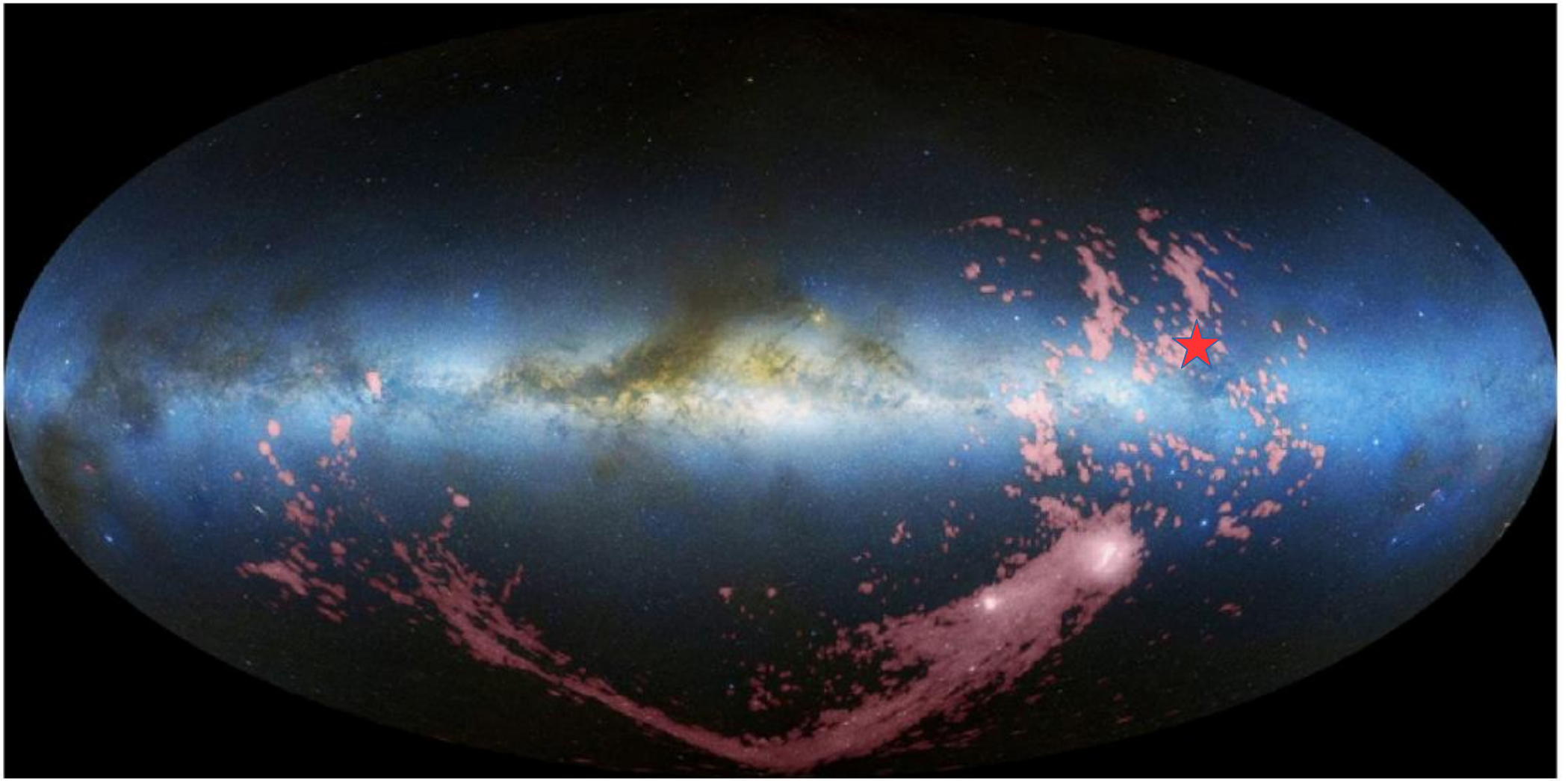


Kirby et al. 2013
We assume [Fe/H] $_{globular}$<=[Fe/H]$_{host}$
→ Host at least of Leo II size

Weisz et al. 2016
LMC size host

Fritz et al. 2016 ApJ accepted arXiv:1611.08598

Pyxis connected with Magellanic Clouds?



Hypothesis since discovery (Irwin et al. 1995), see also Palma et al. 2000

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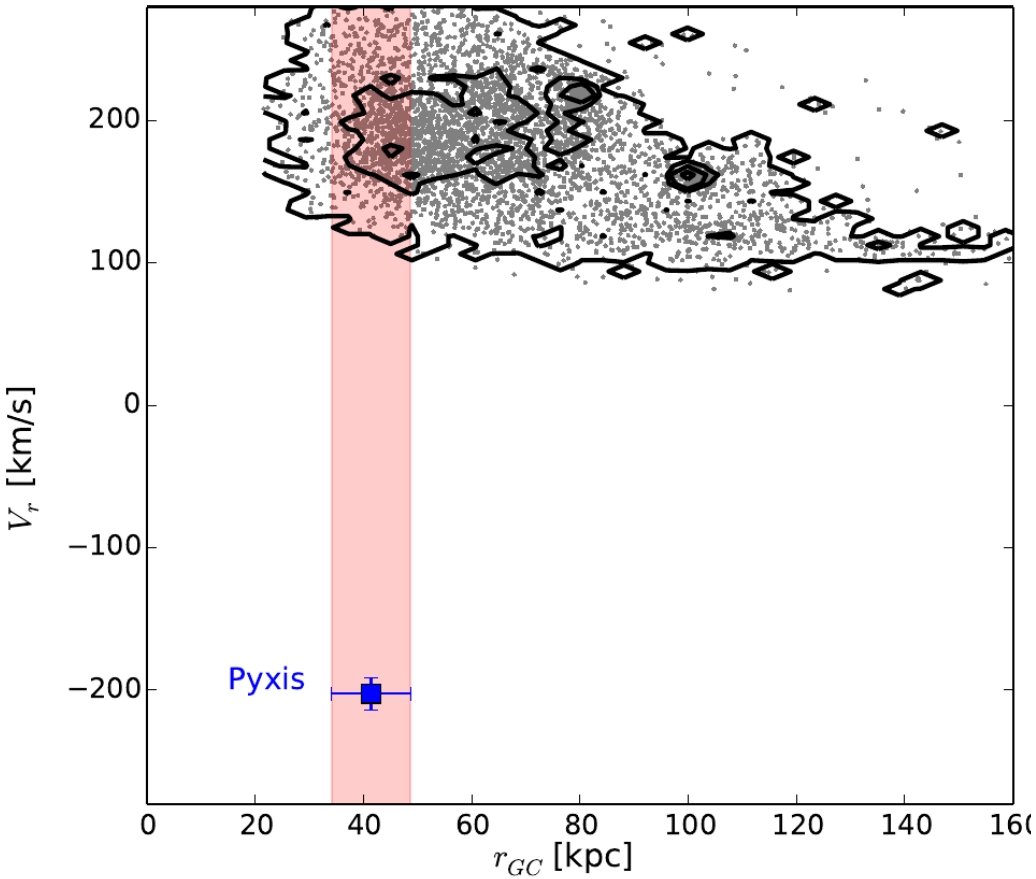
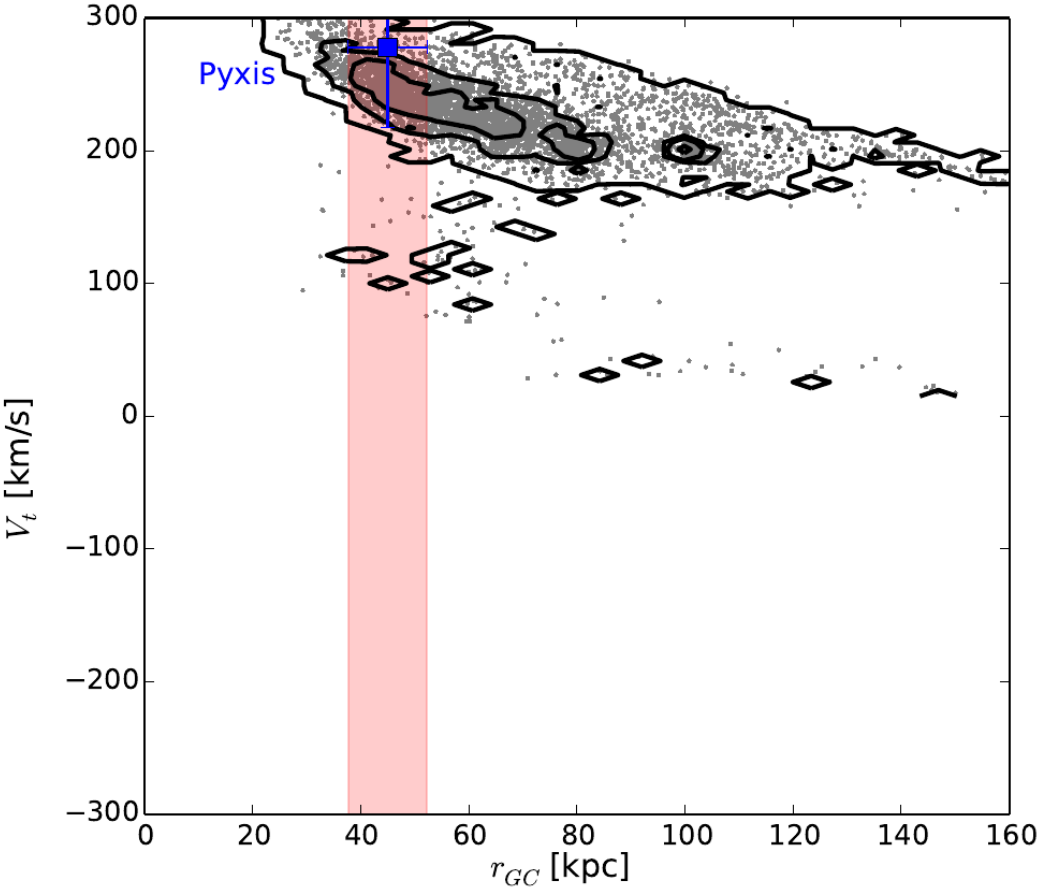
Pyxis motion does not match





- LMC analog selection from simulation like in Sales et al. 2016
- Here shown LMC is in first approach, but second approach is very similar.
- Pyxis is approaching, although it is ahead of the LMC (which is moving away) on the orbit.

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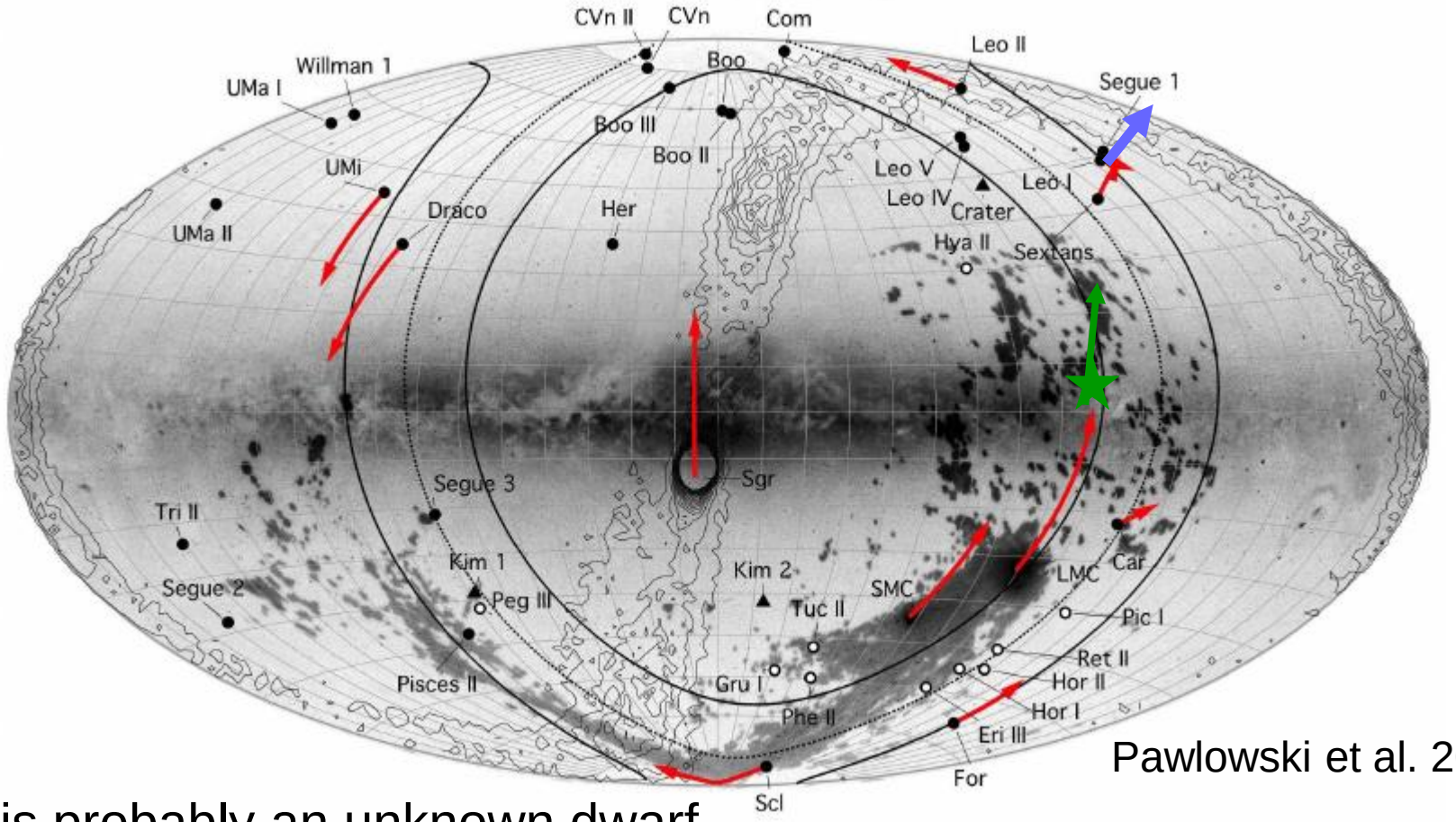
Other massive dwarfs (down to Leo II) are excluded dynamically



Pyxis

Pawlowski et al. 2015

- Thus it is probably an unknown dwarf.
- Maybe it is hiding behind the Galactic plane.
- It cannot be in first approach since the associated star formation would be detectable.
- More likely the host was disrupted long ago.

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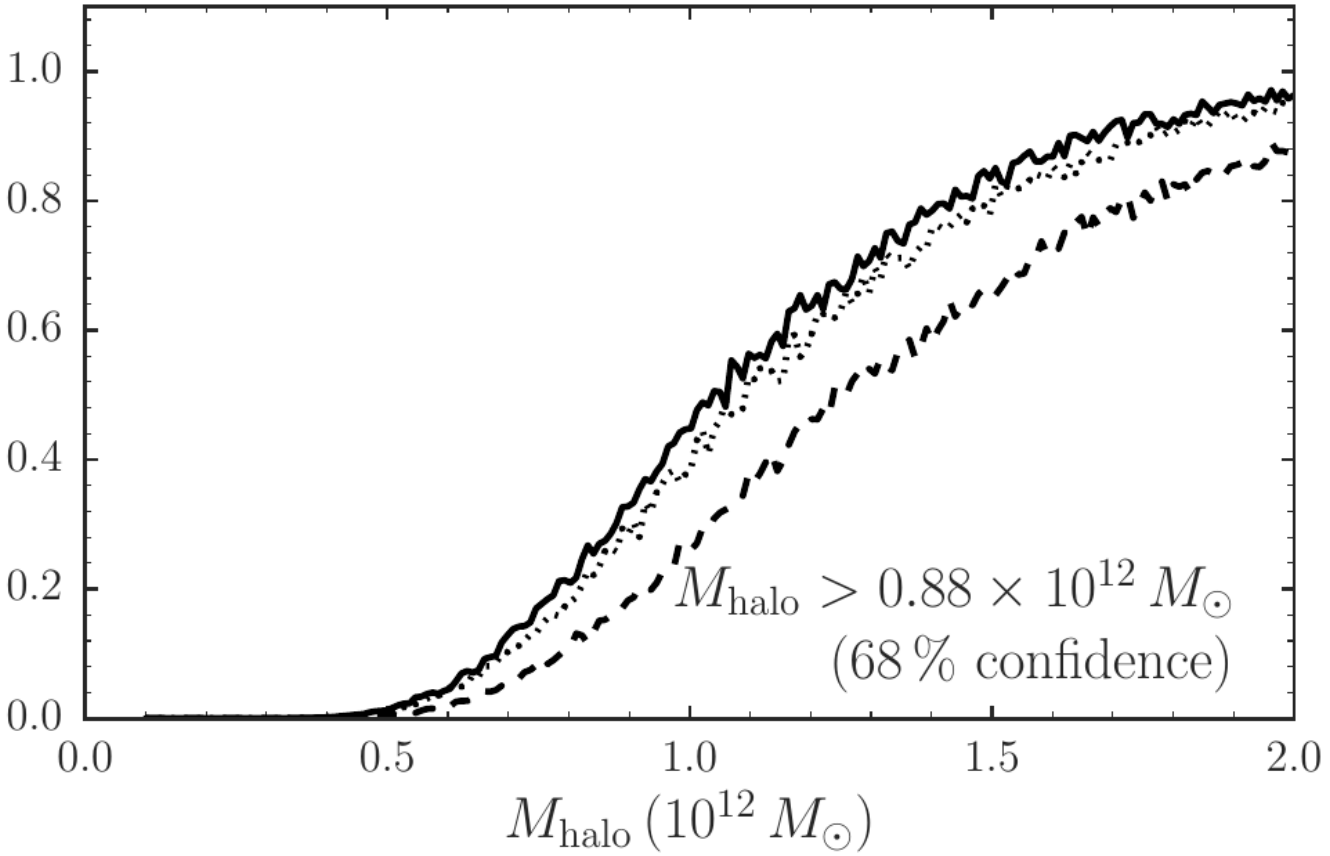
Milky Way mass determination with Pyxis orbit



We assume that Pyxis is bound
We use MW2014 (Bovy 2015) for disk and bulge (together 0.073*10^12 M_{sun}).
M_{halo}>0.58*10^12 for all orbits.
In addition, require that Pyxis is on second approach →M_{halo}>0.88*10^12
Concentrations from left **15.3**, 12, and 6

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Conclusions

- Ground based proper motion can delivery useful proper motions in the halo.
- A Law & Majewski halo is excluded for the Pal 5 orbit range (R<20 kpc).
- In that range a spherical halo of c/a=1.05±0.14 fits the data.
- Pyxis is not the progenitor of ATLAS stream.
- Pyxis is not associated with the Magellanic clouds and any other large dwarf.
- The former host of Pyxis was a satellite galaxy that is likely now fully disrupted.
- Mass of the Milky Way is to 68% larger than 0.95*10^12 M_{sun}