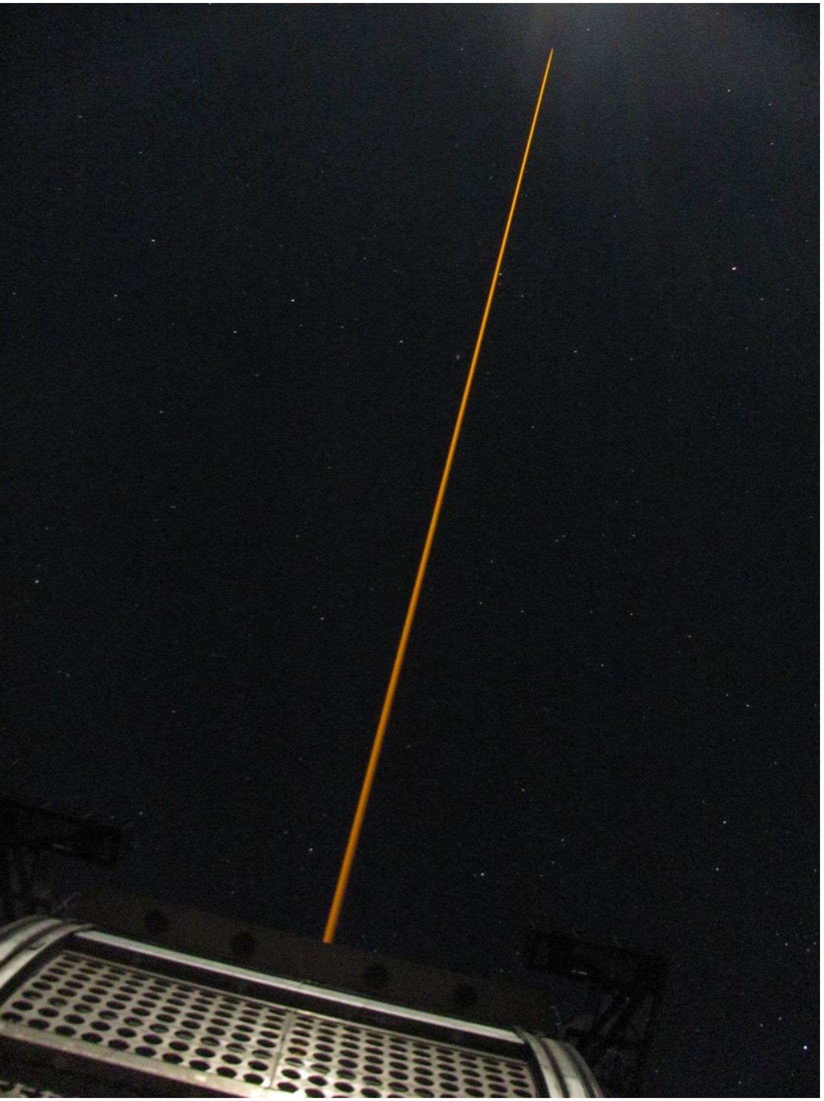
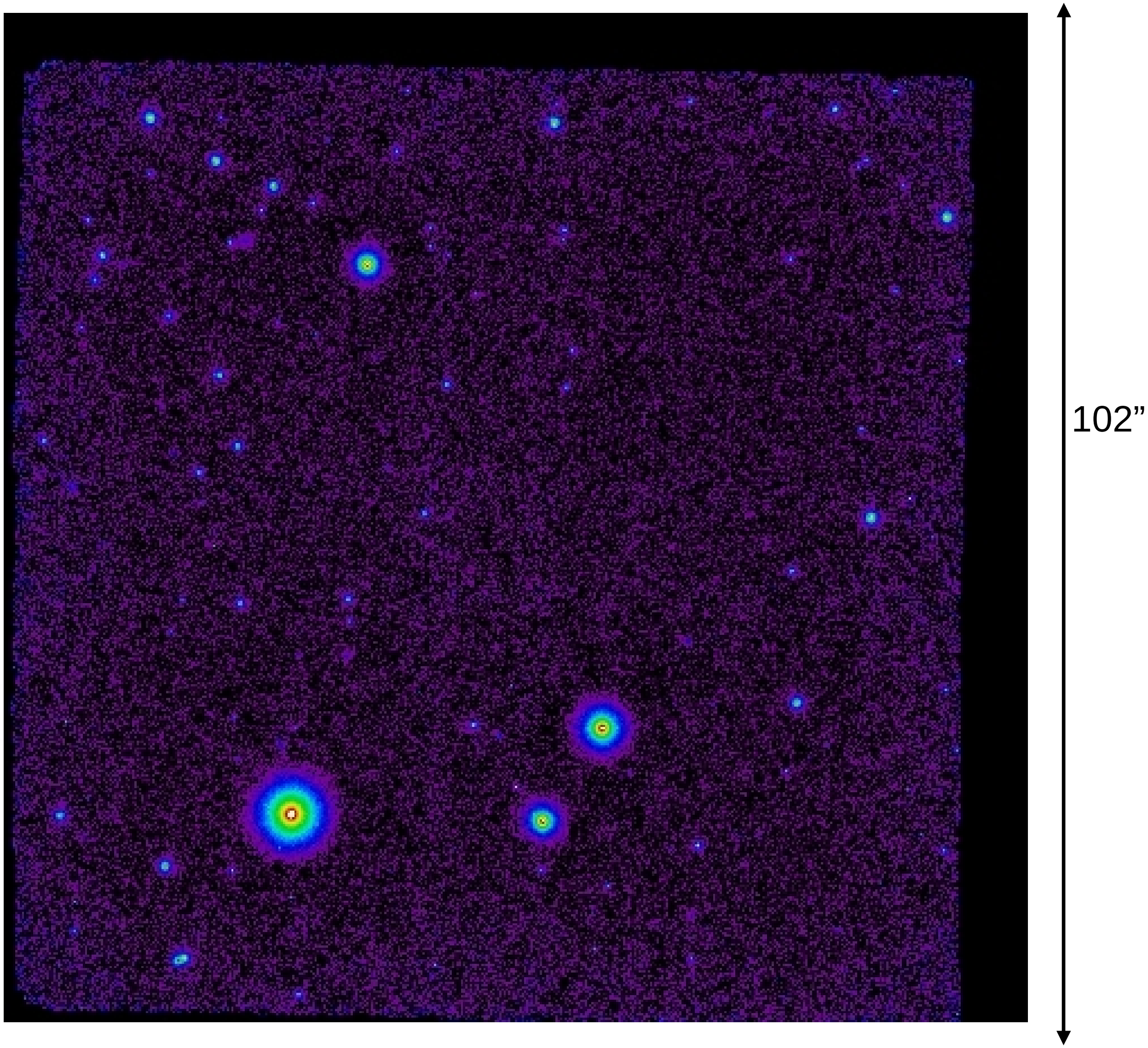
Using proper motions to constrain Milky Way properties and the Origin of its satellites



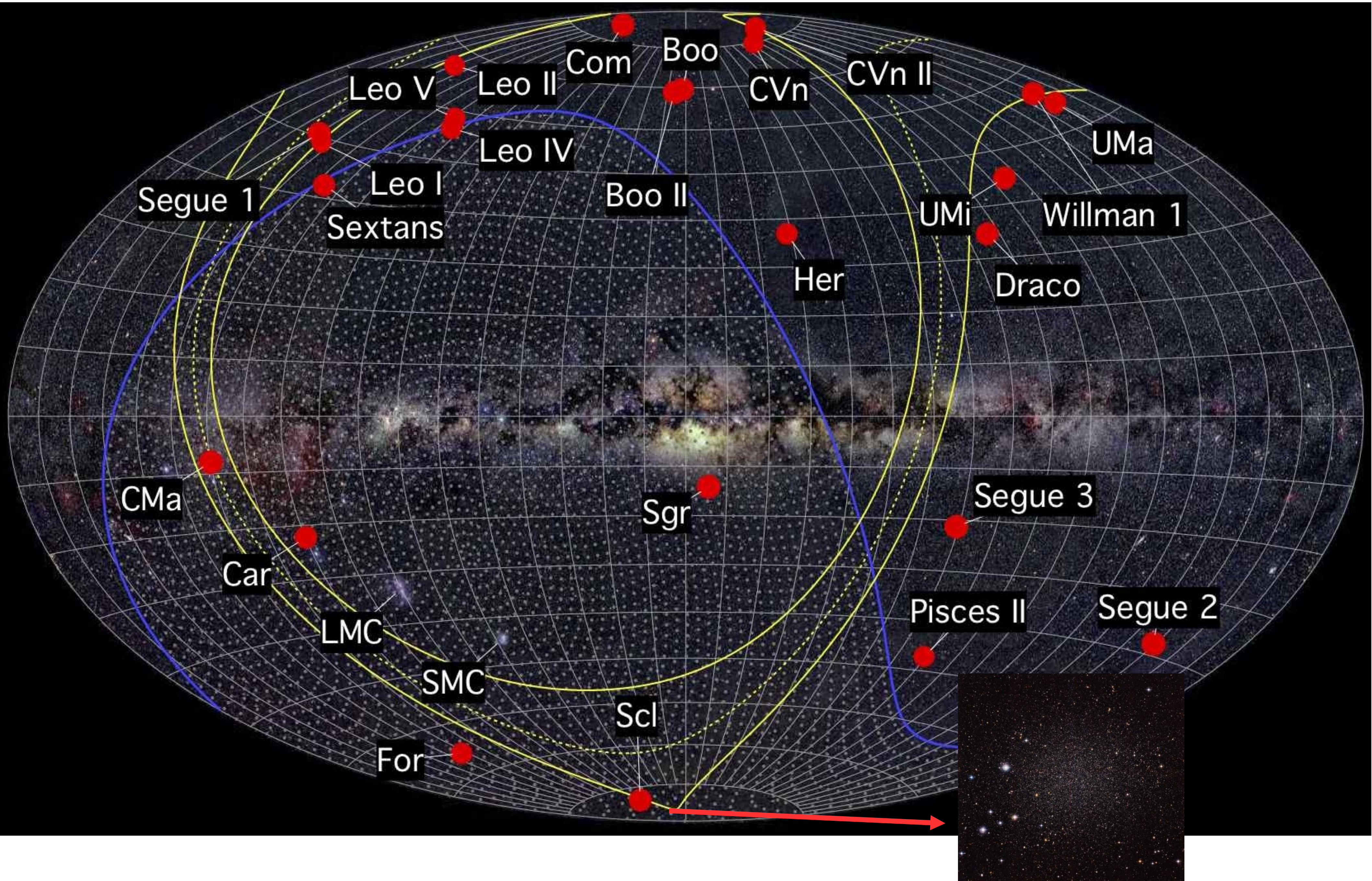


T. K. Fritz, **N. Kallivayalil**, J. Bovy, S.Linden, P. Zivick, R. Beaton, M. Lokken, T. Sohn, D. Angell, M. Boylan-Kolchin, R. Carrasco, G. Damke, R. Davies, S. Majewski, B. Neichel, R. van der Marel

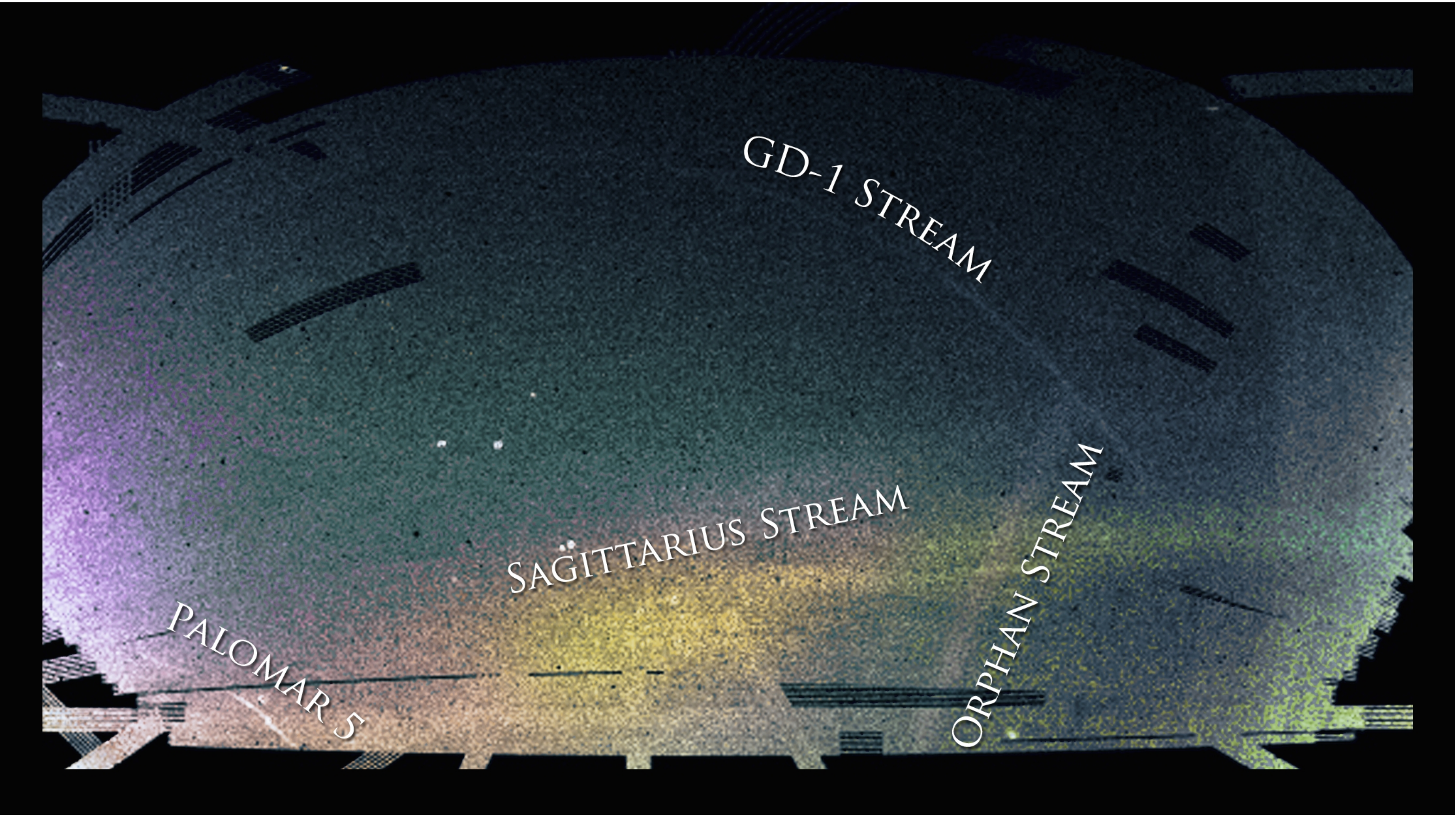
Open questions in near field cosmology

- **Mass** of the **Milky Way** uncertain, e.g. Boylan-Kolchin et al. 2013: 1.6±0.4 10^{12} M_{sol} compare to Gibbons et al. 2013: 0.56±0.12 *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~<$v_{central}$~<60 km/s) missing? (Zavala et al 2009, Boylan-Kolchin et al. 2012)
- **Missing galaxies**: low mass halo possibly starless due to reionization (Alvares et al. 2009), Can we prove their existence?

Possible probes I: Dwarf galaxies

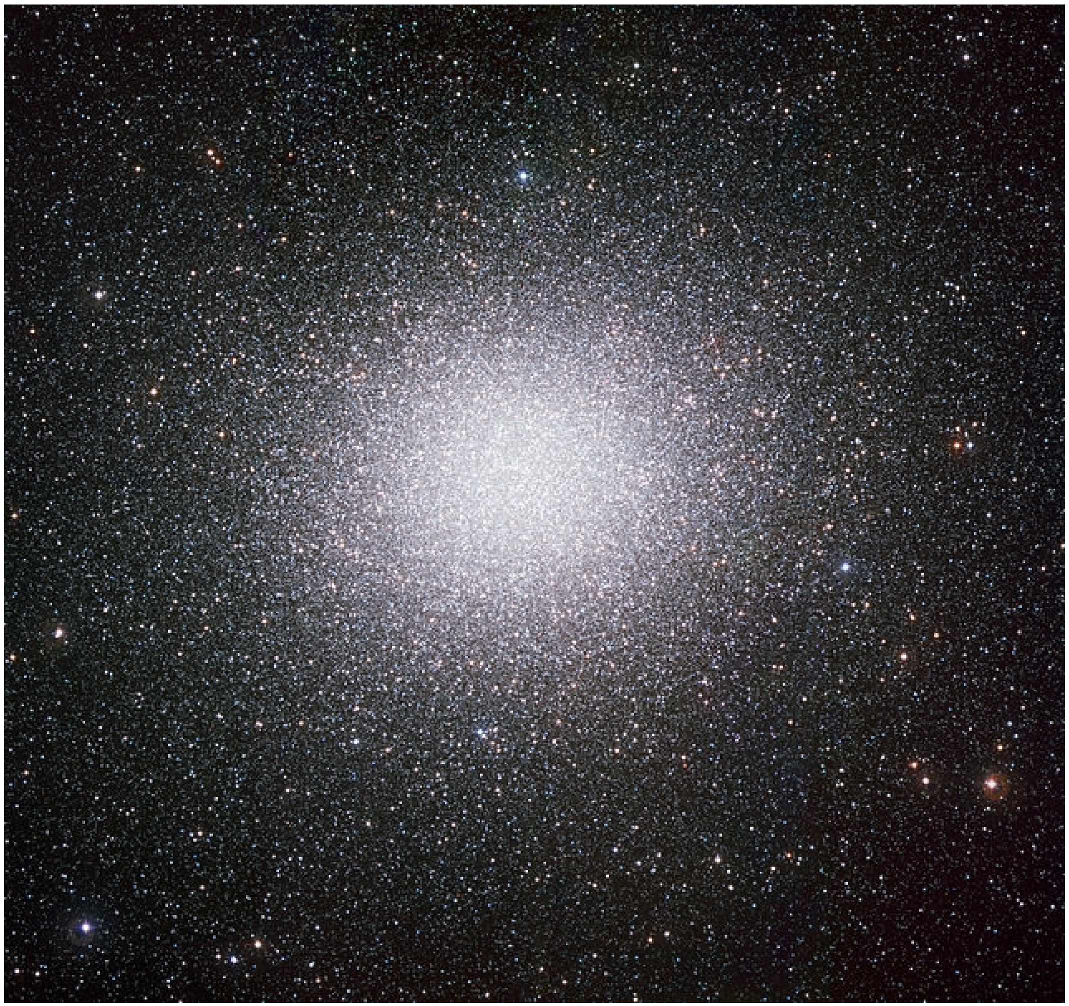


Possible probes II: Tidal streams



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

Possible probes III: globular clusters



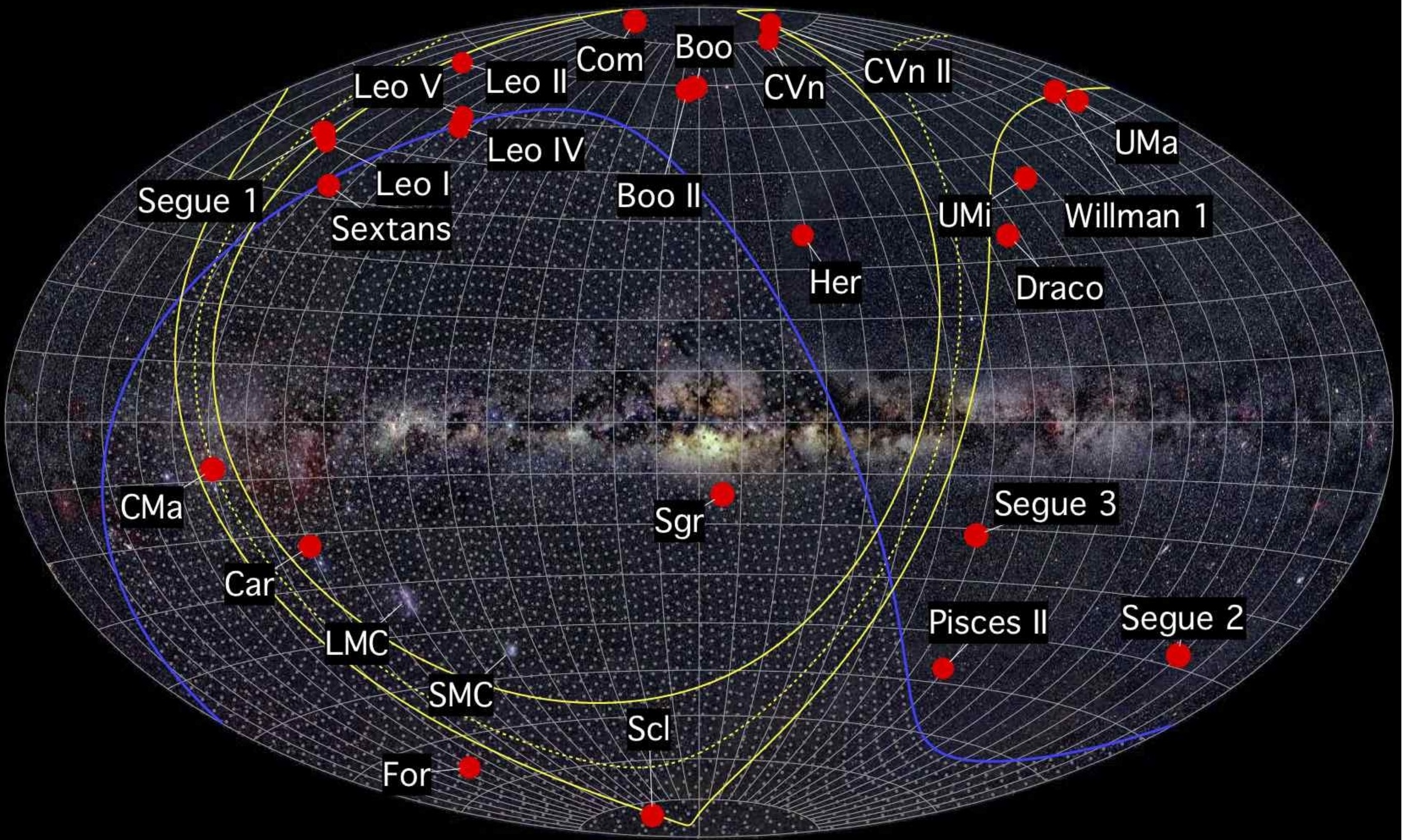
Omega Centauri

NGC7006

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 $t_{\text{shut down}} > t_{\text{accrete}}$ 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).

Dwarf galaxies plane?

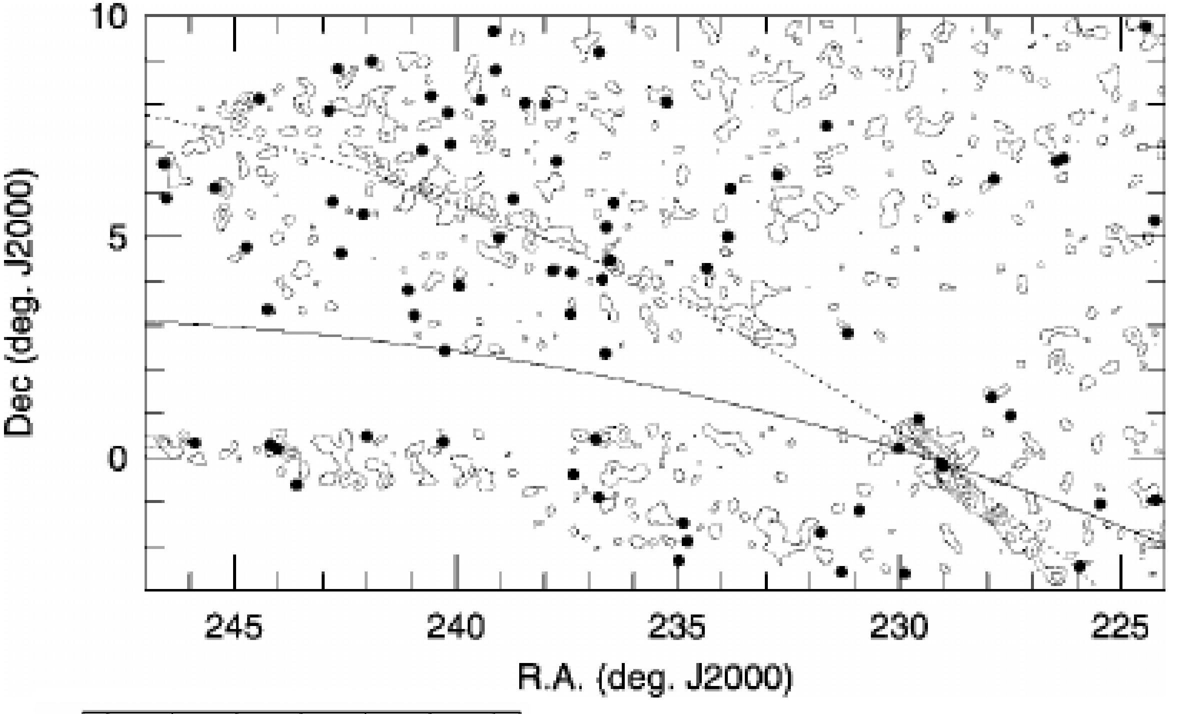


Palomar 5: globular cluster +stream

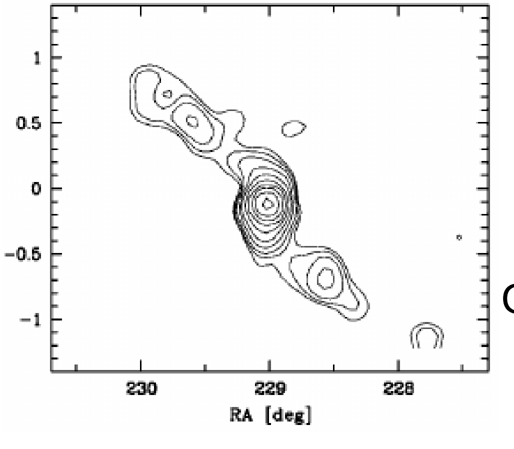
10'

Faint (M_V=-5.2), low mass
(σ<1 km/s, Odenkirchen et al. 2002)

Fritz & Kallivayalil 2015



22 degree long tails
Grillmaier & Dionatos 2006

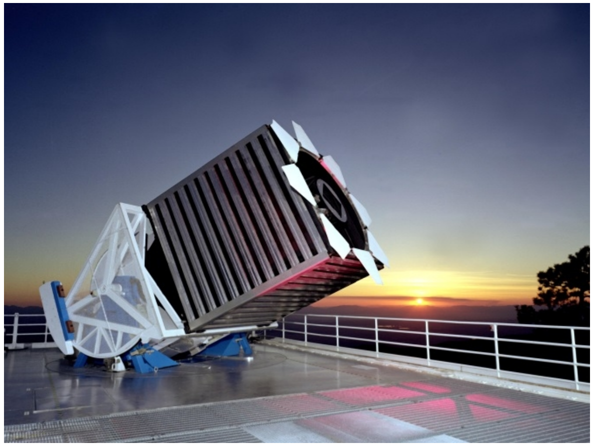


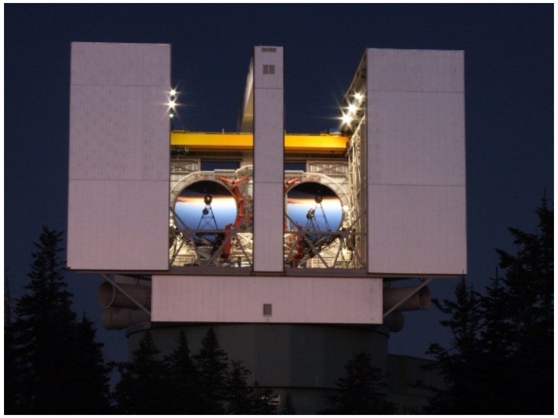
Odenkirchen et al. 2001

Known properties

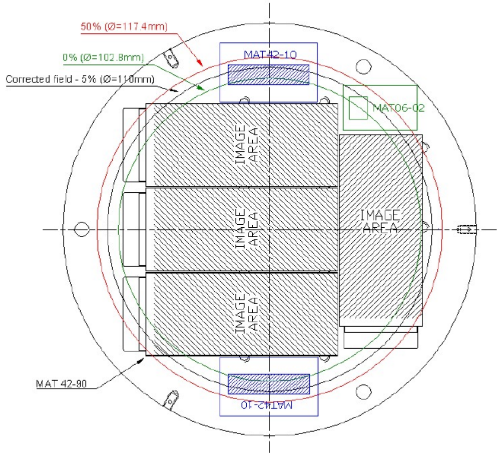
- In the halo (d~20.9 kpc, Dotter et al 2011, d~23.2 kpc, Harris 1996; d~22.3 kpc, Vivas & Zinn 2006)
- Small radial velocity gradient of 1±0.1 km/(s*deg) (Kuzma et al. 2014)
- Tail with tantalizing gaps, evidence for passing masses like subhalos, i.e 'dark galaxies' (Dehnen et al. 2004, Carlberg et al. 2012) or epicyclic effects (Küpper et al. 2008)? Disputed whether there are gaps in deeper data (Ibata et al. 2016, Erkal et al. 2016). Gaps could also be caused by giant molecular clouds (Amorisco et al. 2016) or the bar (Erkal et al. 2016).
- Three contradicting photographic plate proper motion of cluster (Schweitzer et al. 1993, Cudworth 1999, Scholz et al. 1995), **Missing: CCD proper motion of cluster or stream**

SDSS and LBT/LBC for Pal 5 cluster





LBT



SDSS catalog positions observed in 1999, DR9 release

19.8'

18'

12 LBC images

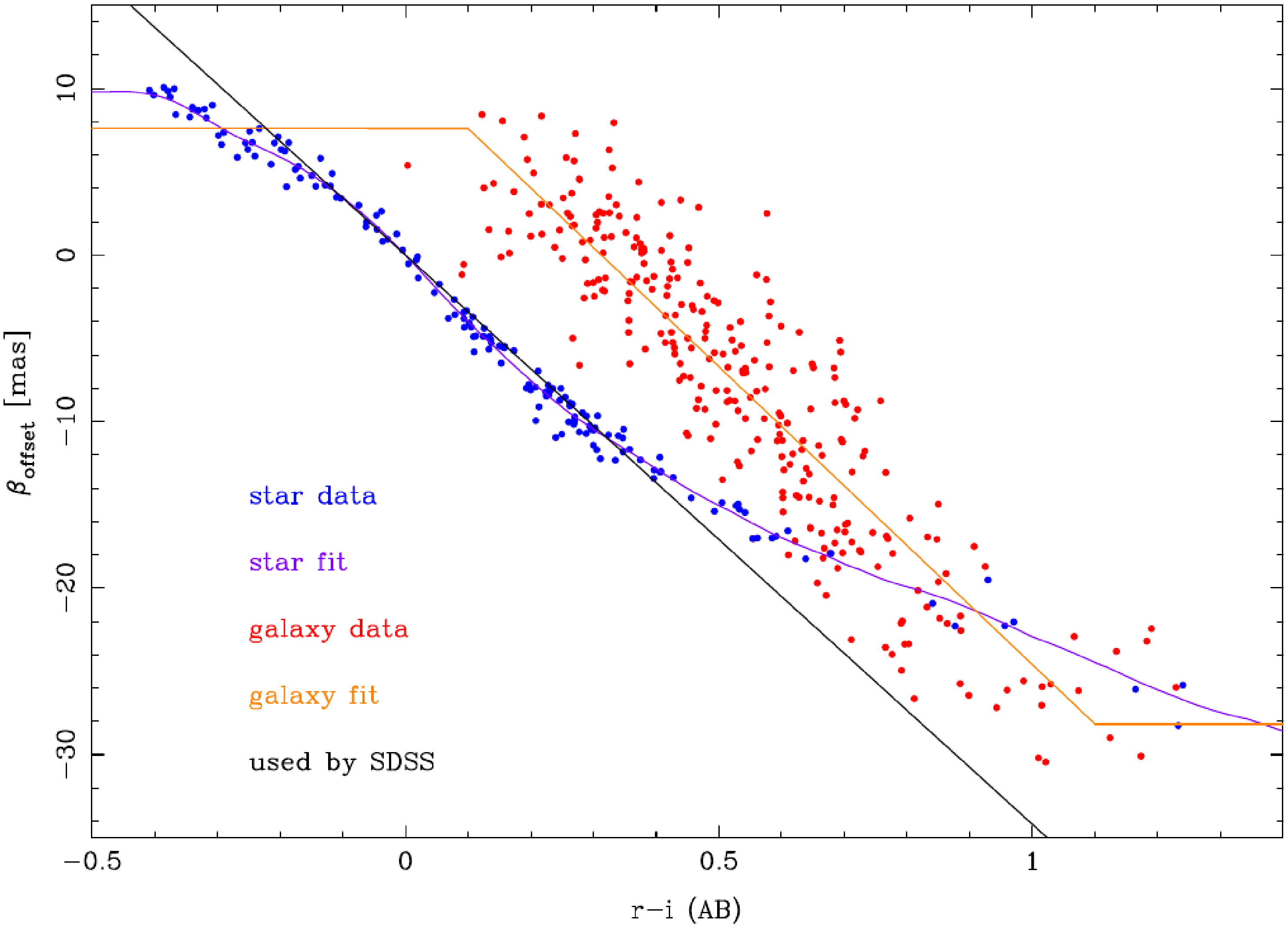
Fritz & Kallivayalil 2015

Measuring the proper motion

- SDSS DR9 catalog (observed in 1999) and LBT/LBC (July 2014)
- Motion of Palomar 5 stars (selected spatially and in CMD) measured relative to **background galaxies.**
- Galaxies are cleaned from double stars in the cluster core.
- Distortion correction on SDSS.
- The positions in both data sets are corrected for differential chromatic refraction (DCR) dependent on color and object type.
- Total astrometric accuracy mainly limited by the number of galaxies and their random flux dependent and systematic errors.

Fritz & Kallivayalil 2015

DCR: object class dependent



Correction for Palomar 5
$\delta\mu_{\alpha}$=-0.04 mas/yr
$\delta\mu_{\delta}$=0.38 mas/yr

- Using flux calibrated spectra
- Main reason for galaxy star offset:
- Galaxies are mixtures of different kinds of stars.

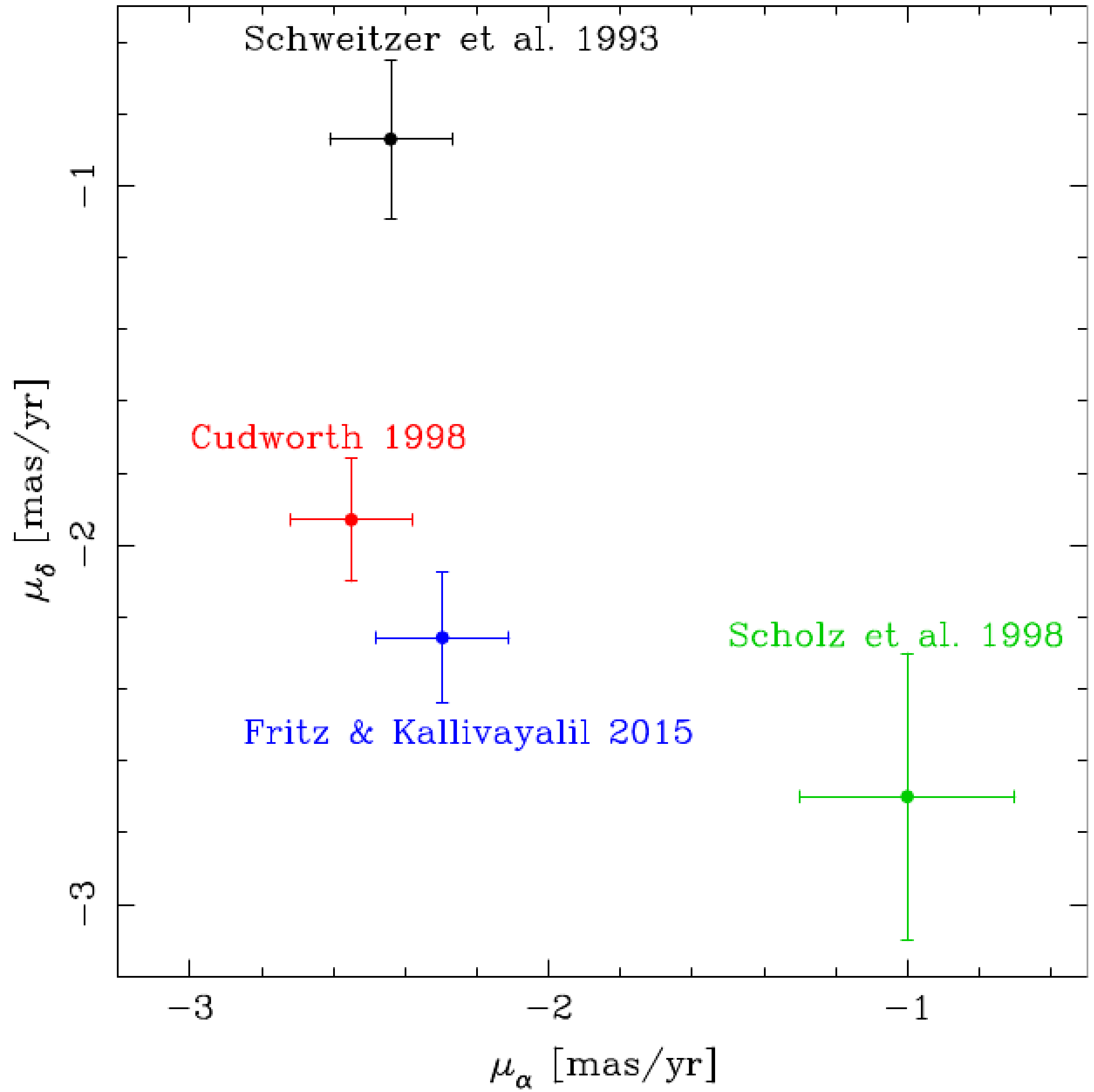
Already single stellar populations are similar offset.

Fritz & Kallivayalil 2015

Proper motion of Palomar 5

μ_α=-2.25+/-0.19 mas/yr

μ_δ=-2.21+/-0.18 mas/yr



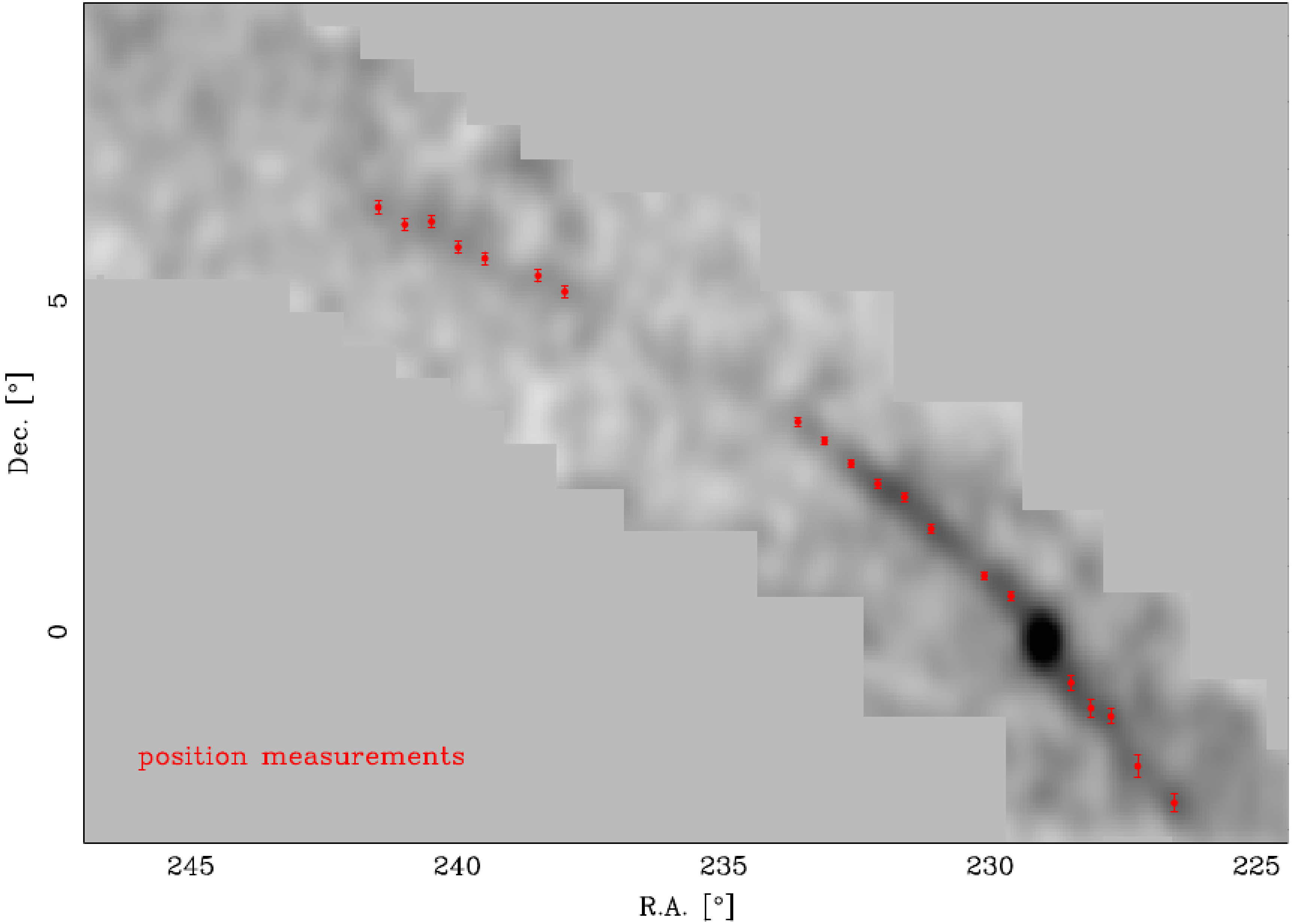
Fritz & Kallivayalil 2015

Data for modeling

- Motion of cluster: proper motion + radial velocity
- Position of cluster: on the sky + distance
- Positions of stream
- Radial velocity gradient along the stream
- Position + Velocity of the Sun

Fritz & Kallivayalil 2015

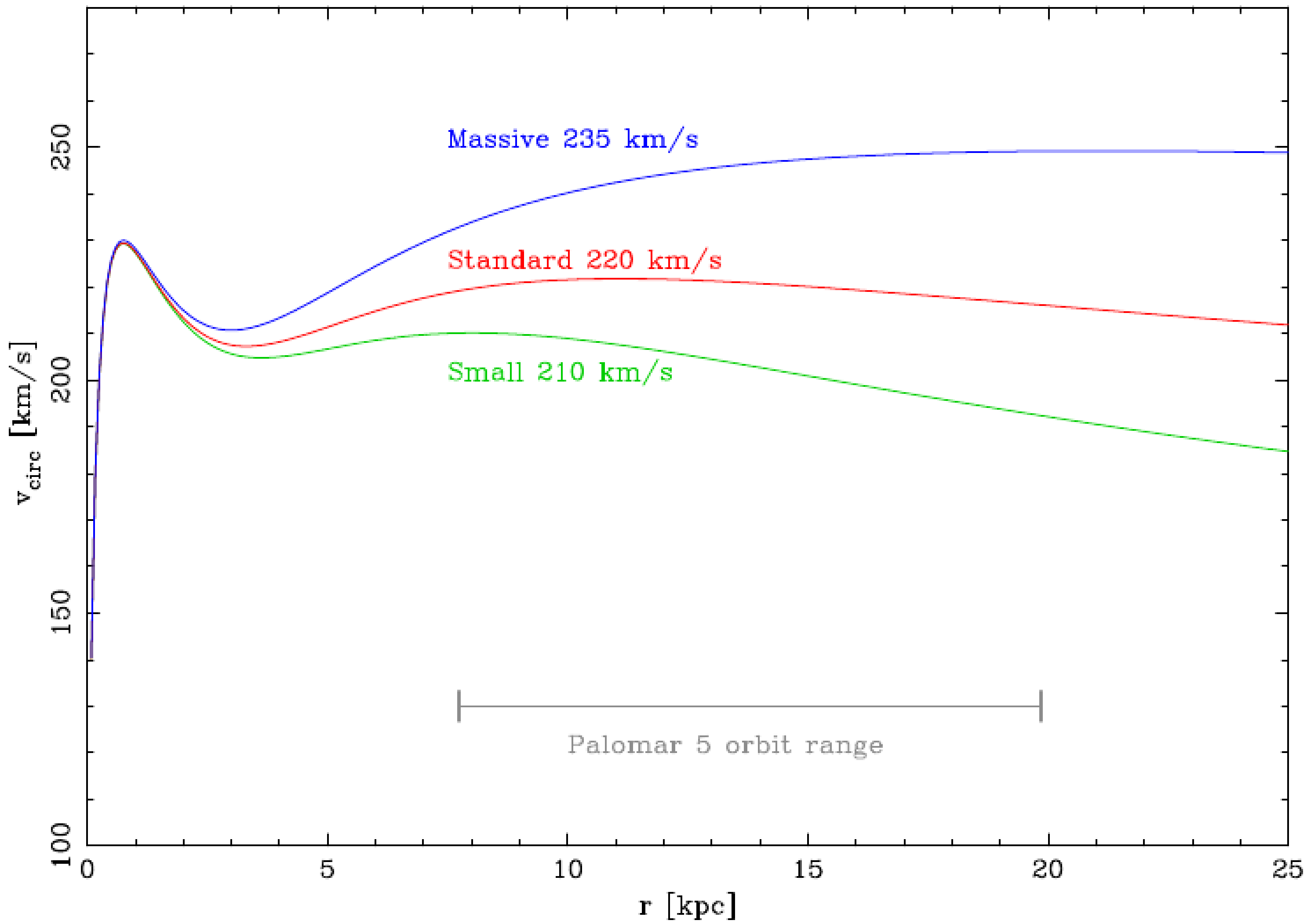
Stream positions



Fritz & Kallivayalil 2015

Positions consistent with Kuepper et al 2015

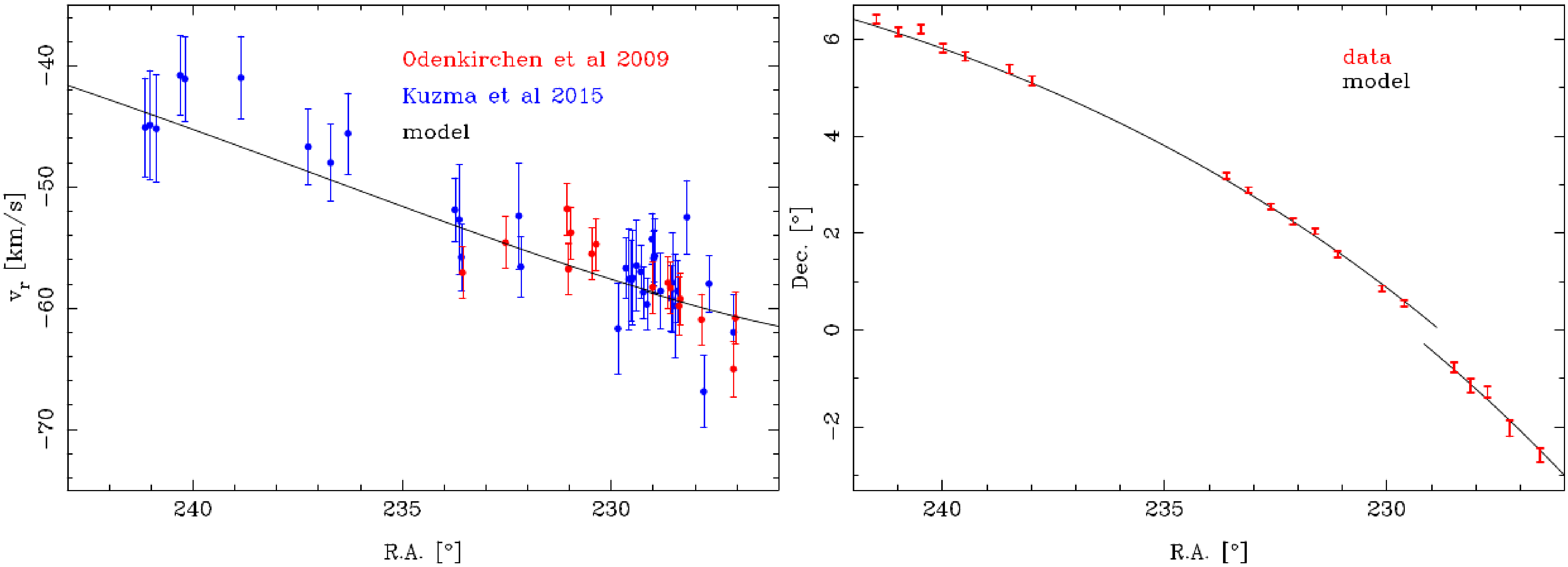
Galaxy models



Our Models: spherical (Hernquist) Bulge + (Miyamoto) Disk + spherical (logarithmic) halo

Fritz & Kallivayalil 2015

Comparing data with models

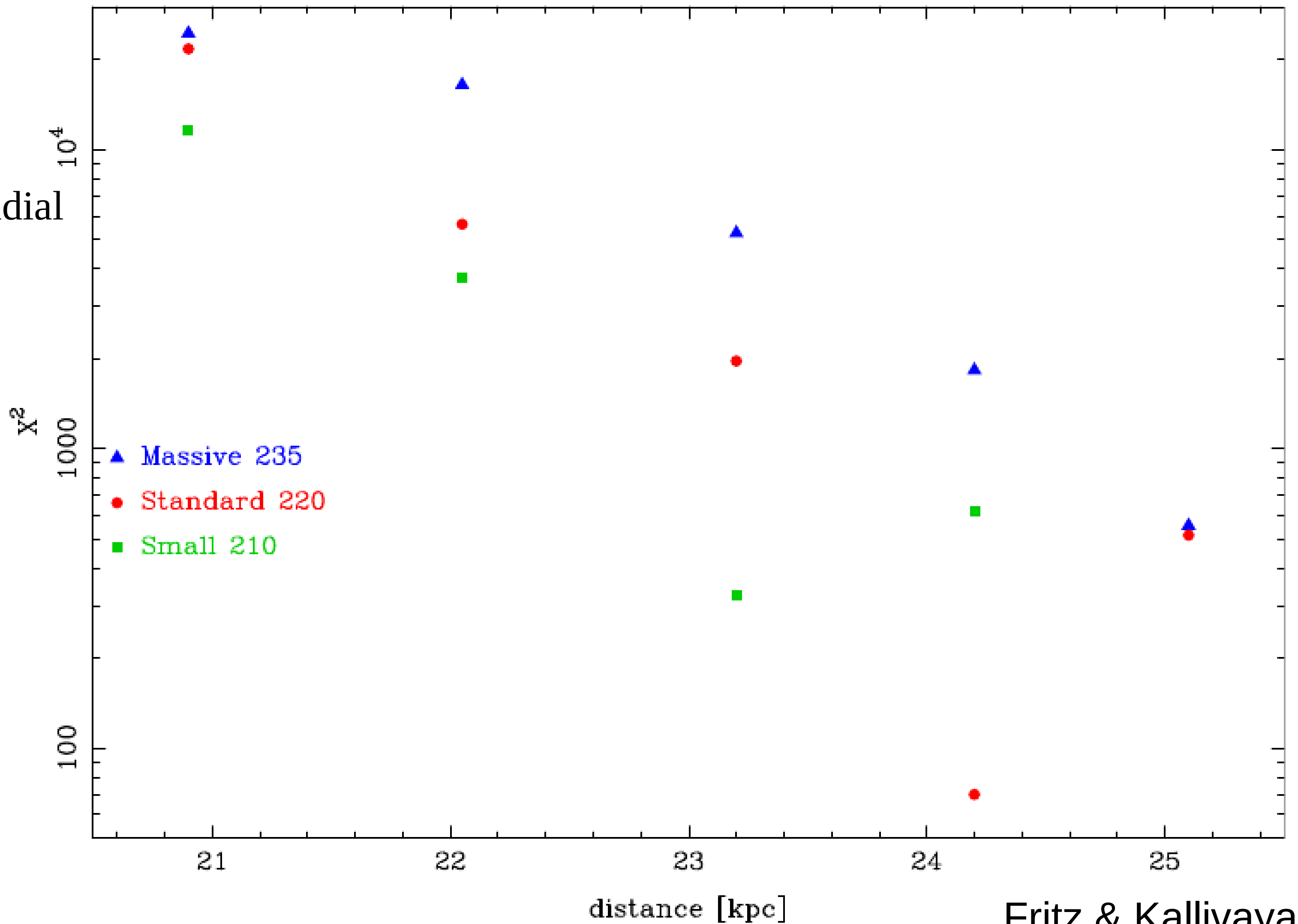


We use Galpy (Bovy 2015) to generate stream tracks.

Fritz & Kallivayalil 2015

Models with V_0~220 fit best

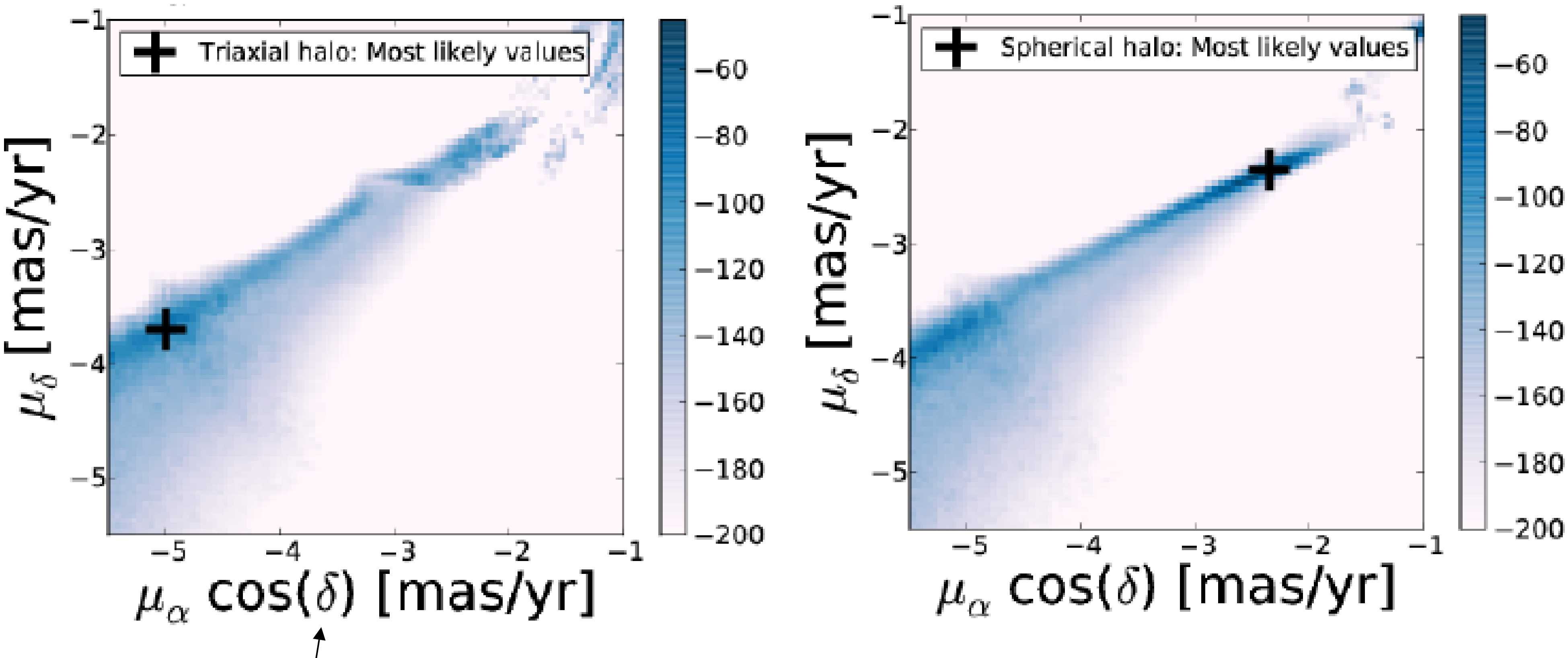
X^2 combines radial velocities and stream track



Fritz & Kallivayalil 2015

However, no full exploration of parameter combinations. For example also model with V_0=238 km/s of Kuepper et al. 2015 fits similar good.

Matches prediction for spherical halo



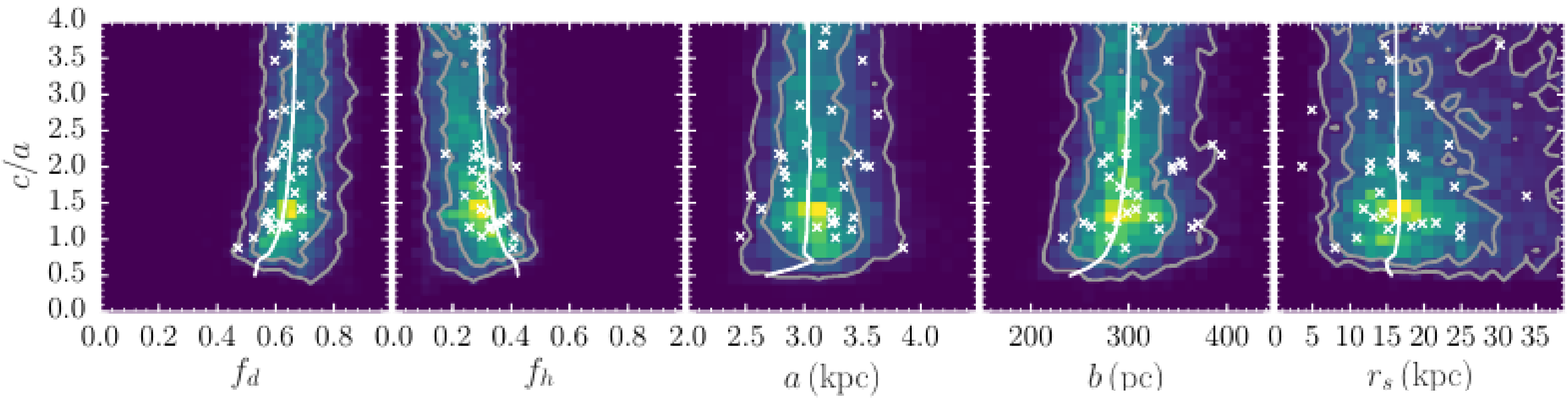
- Law& Majewski 2010 halo; both from Pearson et al. 2014

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).

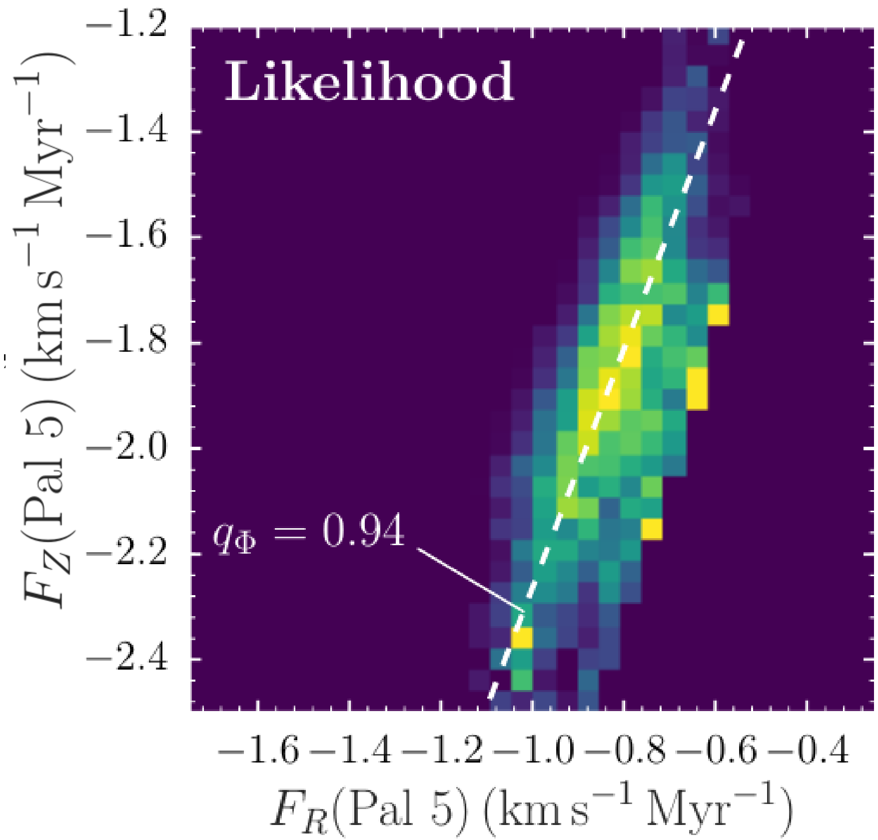
- Also L&M halo makes a stream nearly invisible due to chaotic orbits.

Fritz & Kallivayalil 2015

Fitting for c/a flattening



Priors



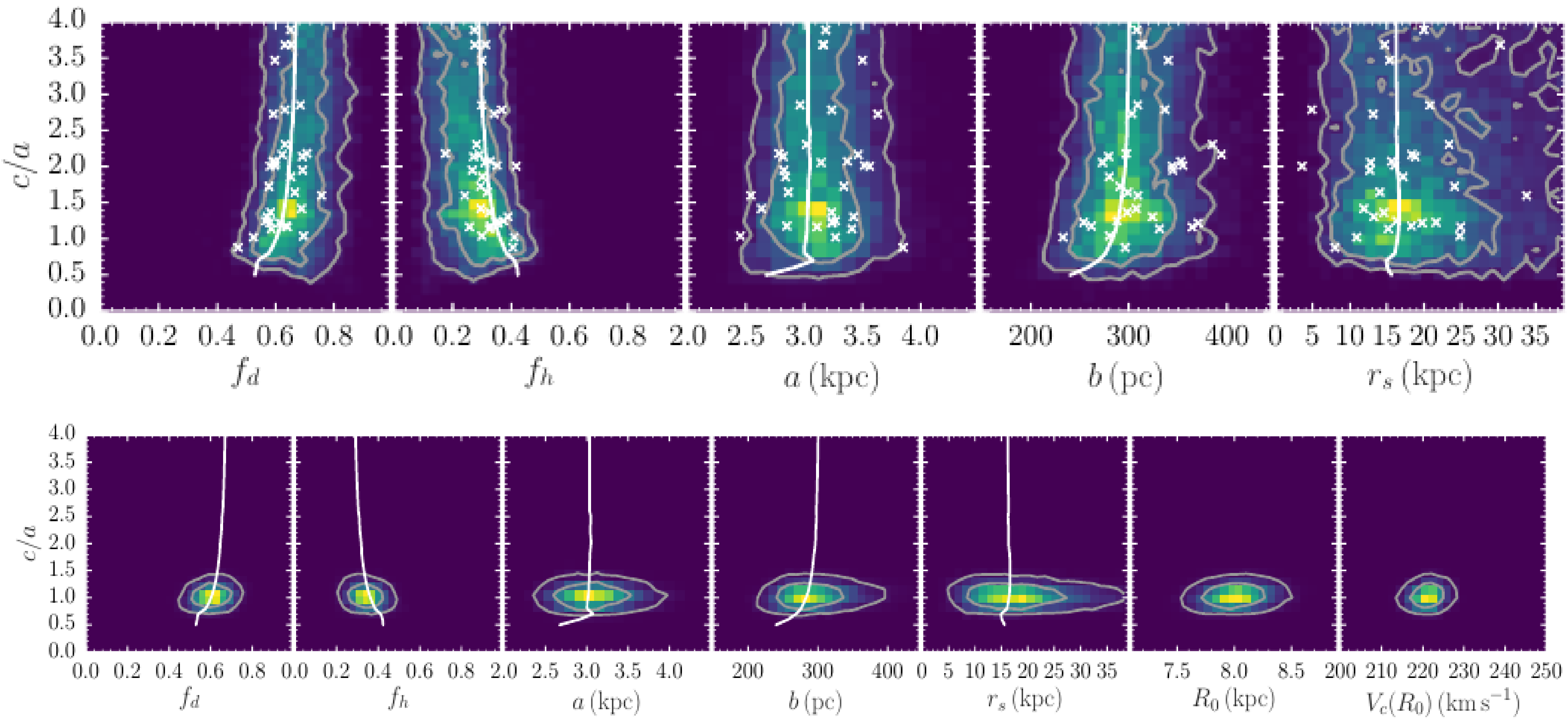
- b/a (in disk plane) set to 1.
- c/a is flattening with same axis as disk.
- Bovy et al. 2016 variant of MW2014 model, in contrast to Kuepper atl 2015 not only one disk model is used, but several.
- Then fit for V_C and c/a.

Potential flattening: q_ϕ=0.94±0.05

→ c/a(halo)=0.9±0.2

Bovy, Bahmanyar, Fritz & Kallivayalil 2016

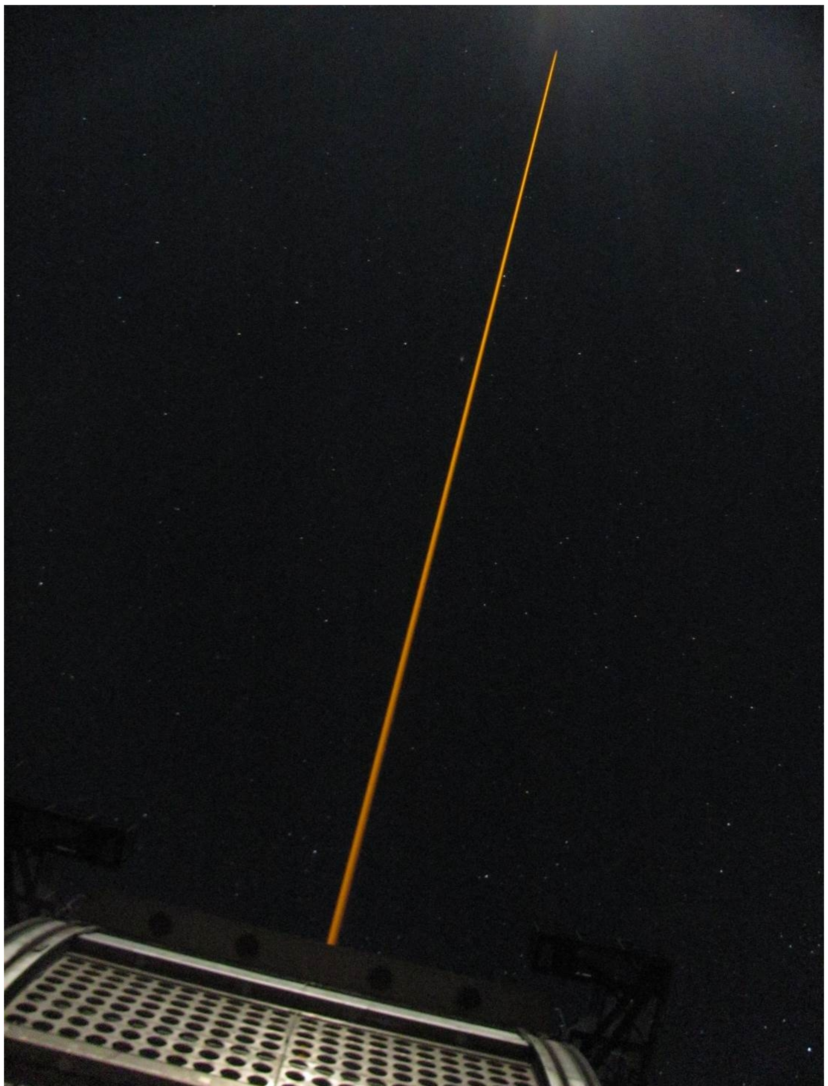
Combined with GD-1

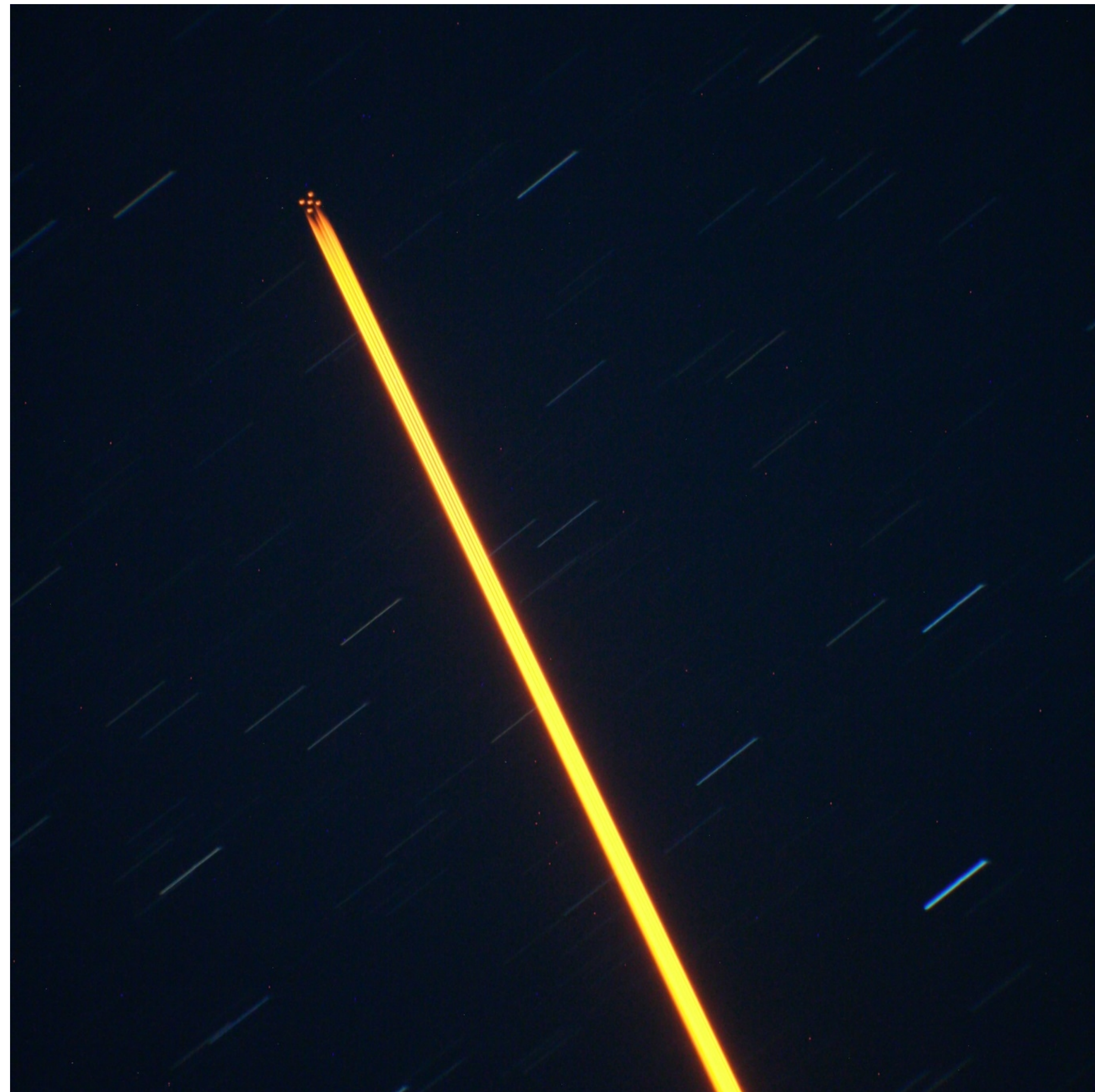


- c/a=1.05±0.14, that is in slight tension with the expected value of 0.8 (Kazantzidis et al. 2010) for the Milky Way, which has probably a maximal disk (Bovy & Rix 2013)
- r_s=18±7.5 kpc
- M_halo(R<20 kpc)=1.1±0.1*10^11 M_solar

Bovy, Bahmanyar, Fritz & Kallivayalil 2016

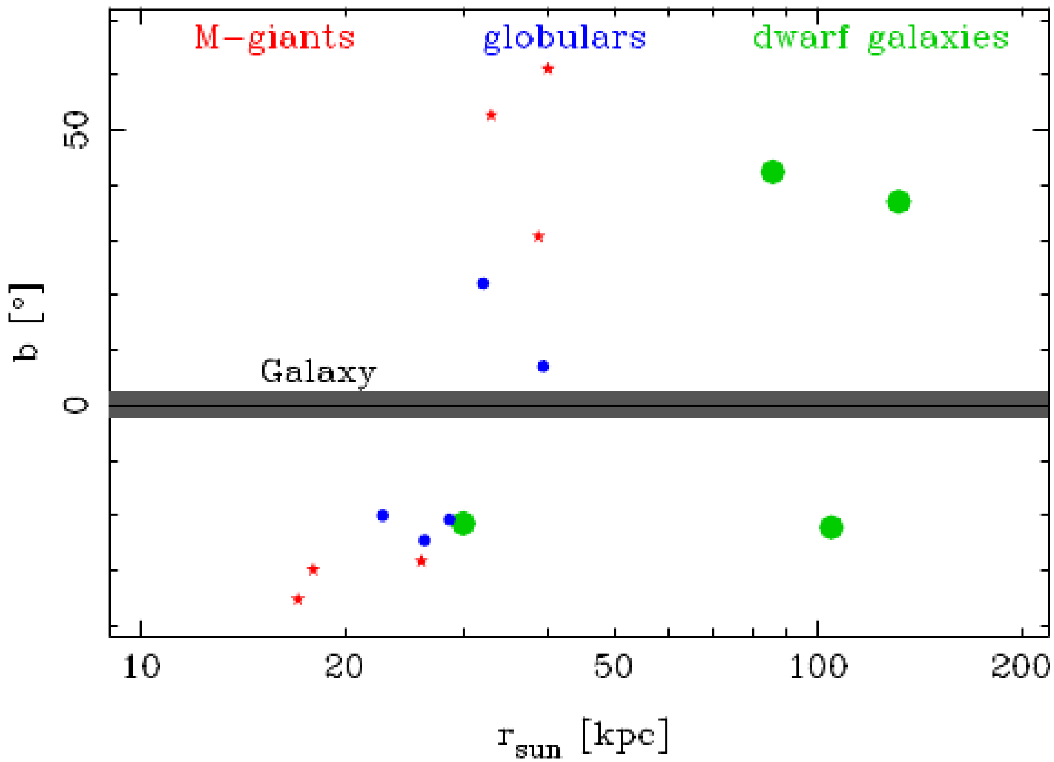
Gemini Large Program: Probing the dark halo of the Milky Way with GeMS/GSAOI



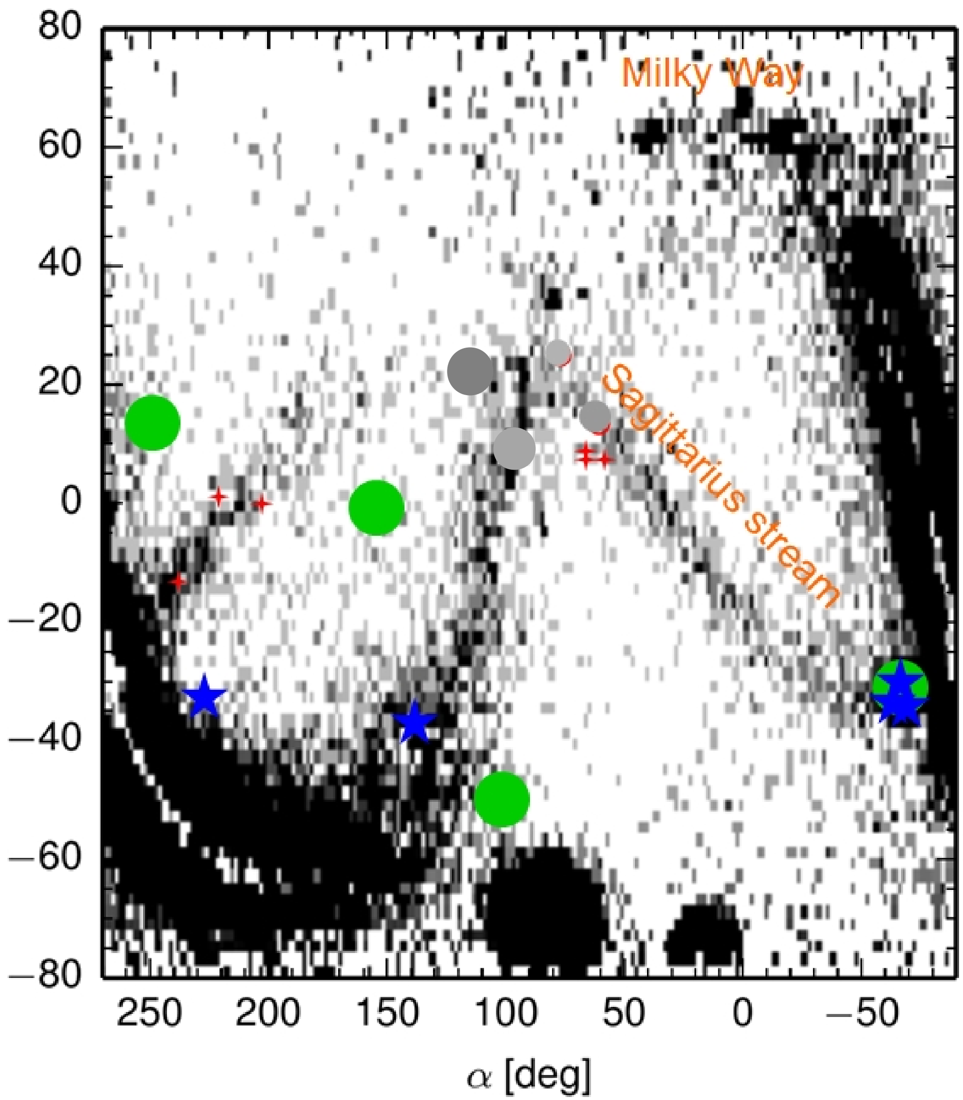


PI Tobias Fritz

The Targets

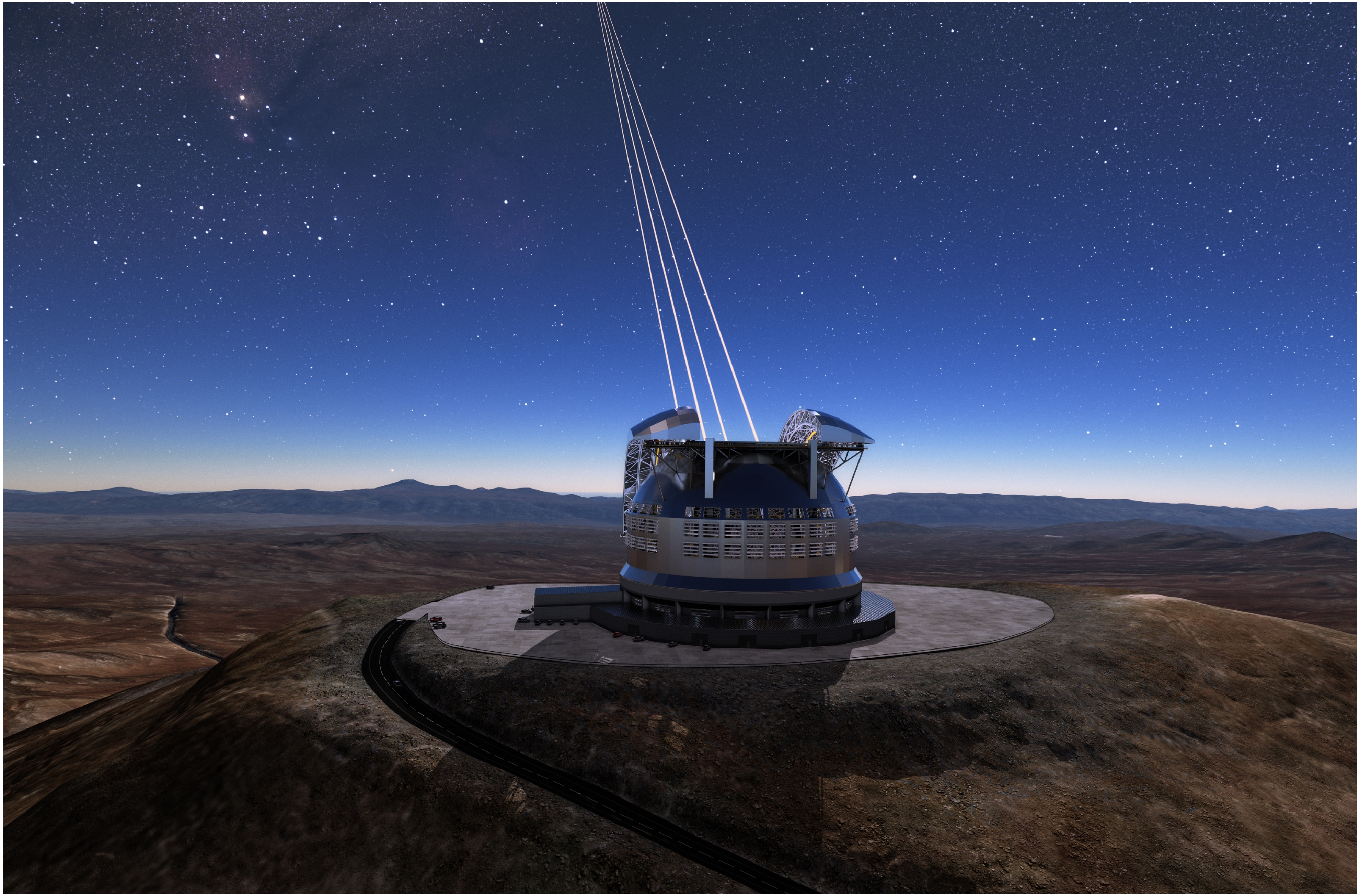


- **15 targets,** 143 h over 3 years
- **6 M-giants** in the Sagittarius stream
- **5 globulars**
  - 3 possible members of Sagittarius system: Arp 2, Terzan 7, Terzan 8
  - 2 others in outer halo: NGC5824, Pyxis
- **4 dwarf galaxies**:
  - Sagittarius, Hercules, Sextant, Carina

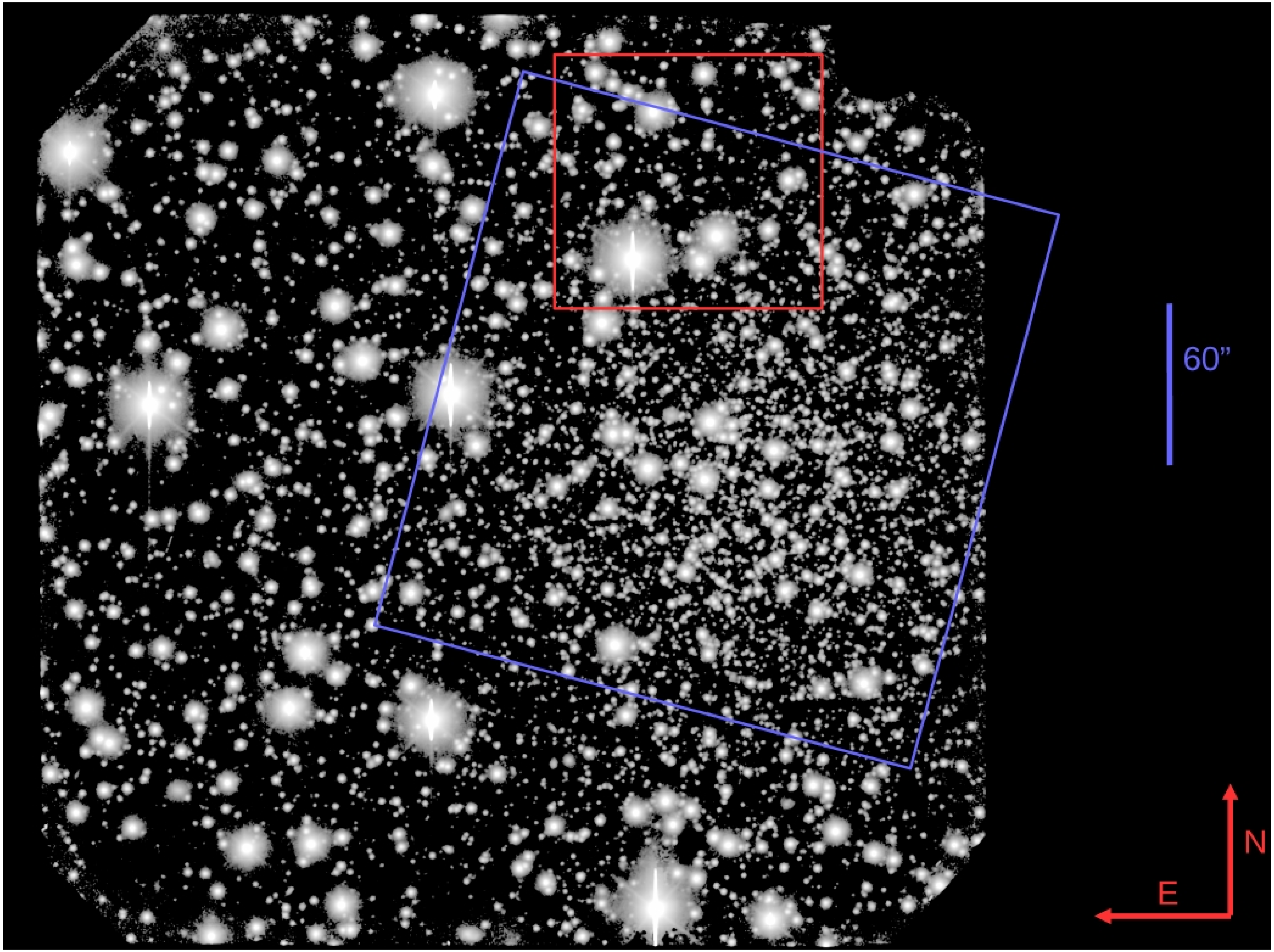


M-giant density map from Koposov et al. 2015

Preparation for future telescopes



Getting a proper motion fast with Pyxis Field 1: GMOS+ HST + GSAOI



Pyxis

Halo globular cluster
D_{sun}=39.4 kpc
M_V=-6.0
[Fe/H]=-1.45+/-0.1

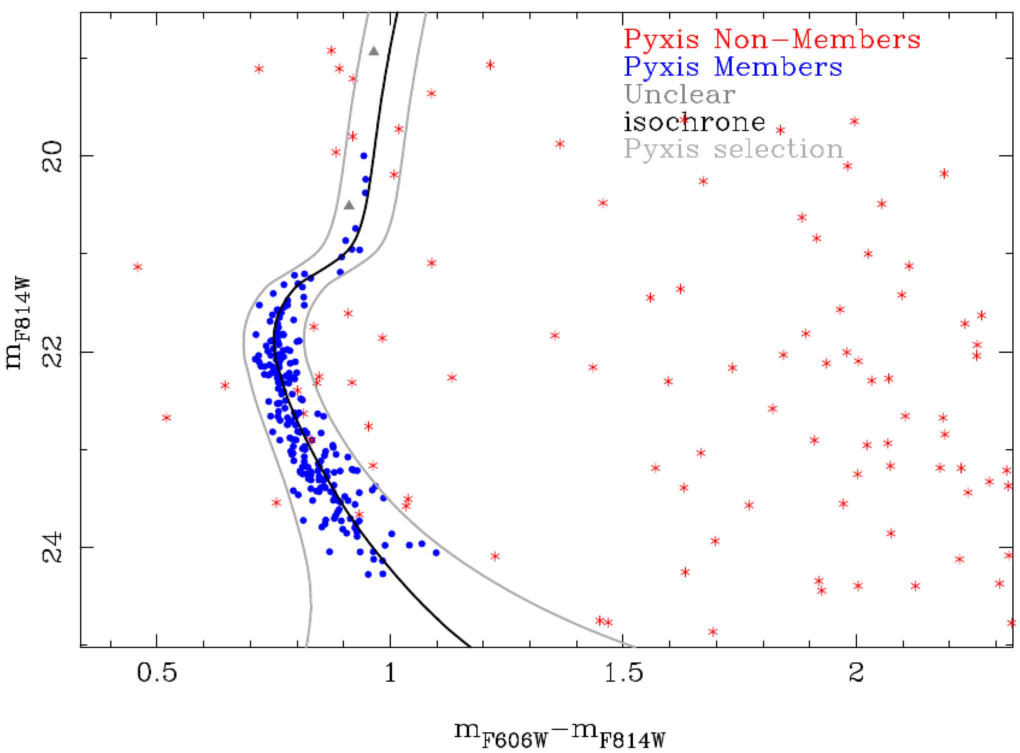
Fritz et al. 2016 arXiv:1611.08598

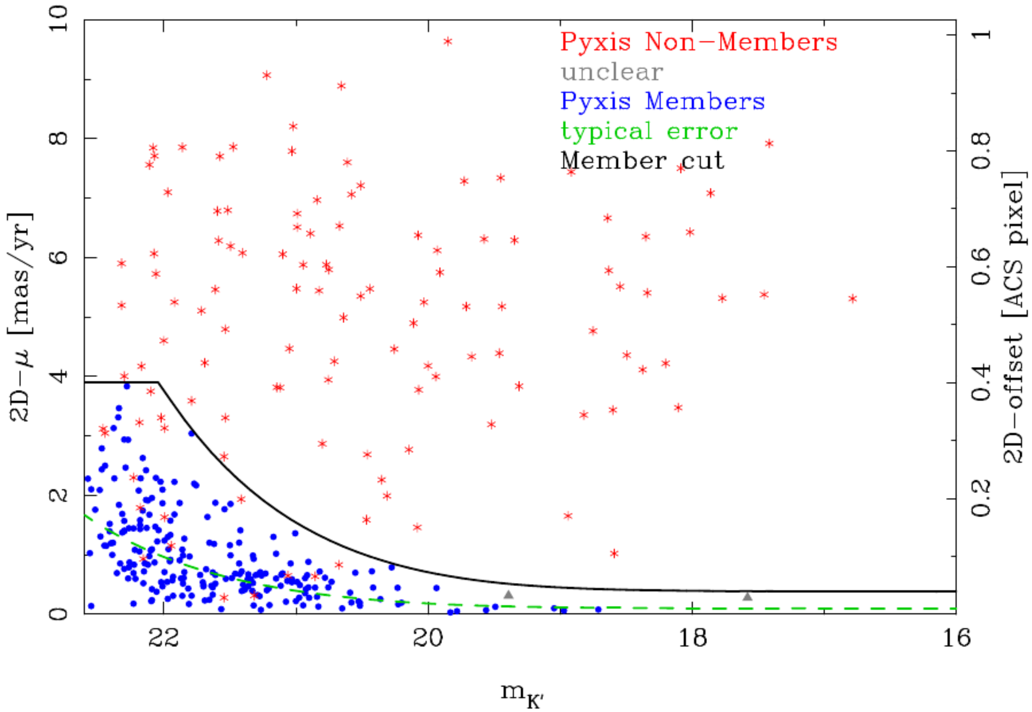
Measuring the proper motion

- HST FLC images and Gemini single images
- Motion of Pyxis stars (selected in CMD and astrometrically) measured relative to **background galaxies.**
- First applying the stable HST distortion solution, then correcting Gemini on it using mainly Pyxis stars.
- Galaxies cleaned from astrometrically bad galaxies. Fitted by Sersics convolved with the PSF.
- DCR does not matter, because DCR is small in K'-band data close to zenith.
- Total astrometric accuracy is mainly limited by the SNR of the galaxies.

Fritz et al. 2016 arXiv:1611.08598

Member selection: photometry + astrometry

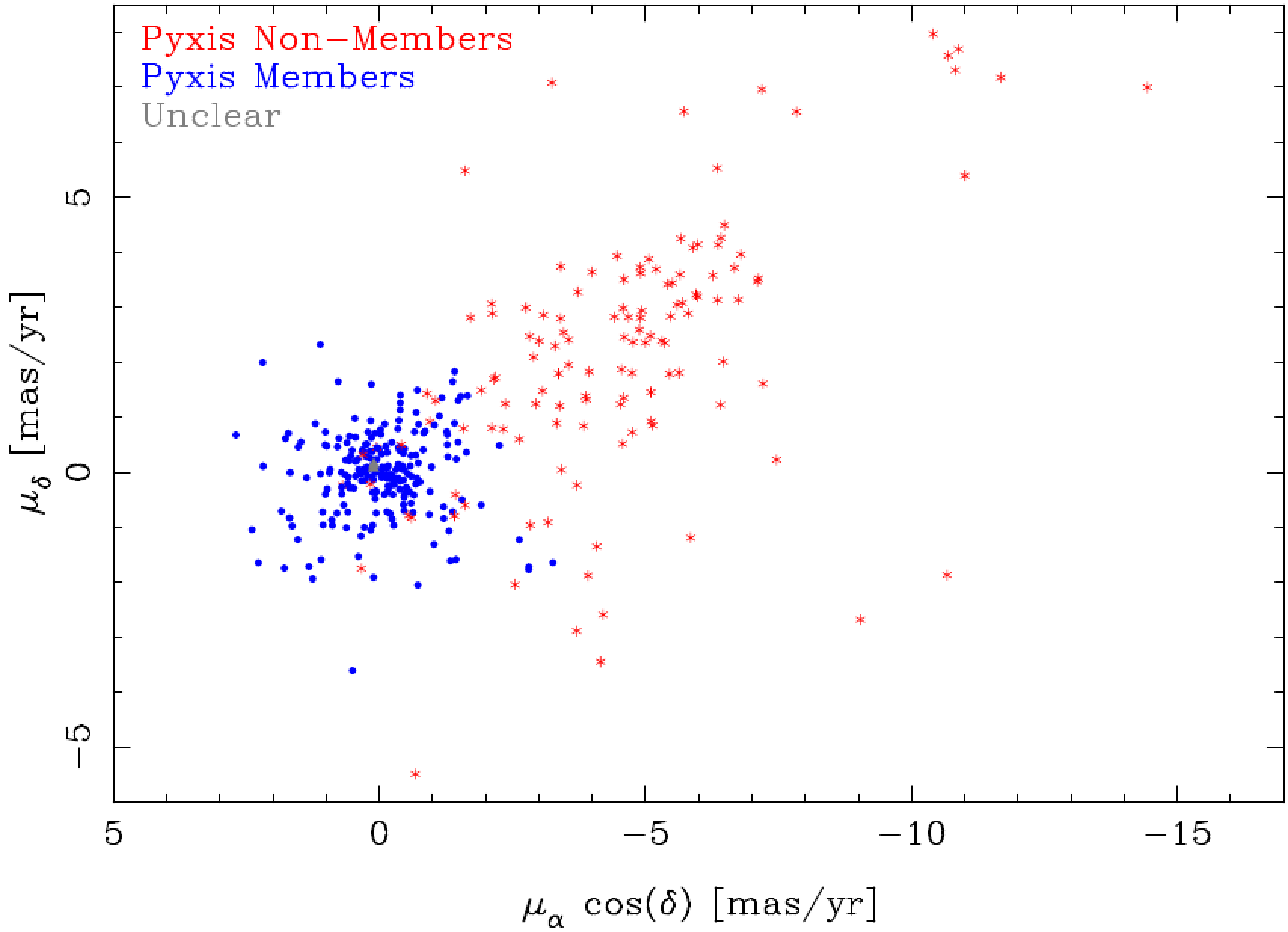




Both criteria need need to be fullfilled at once.

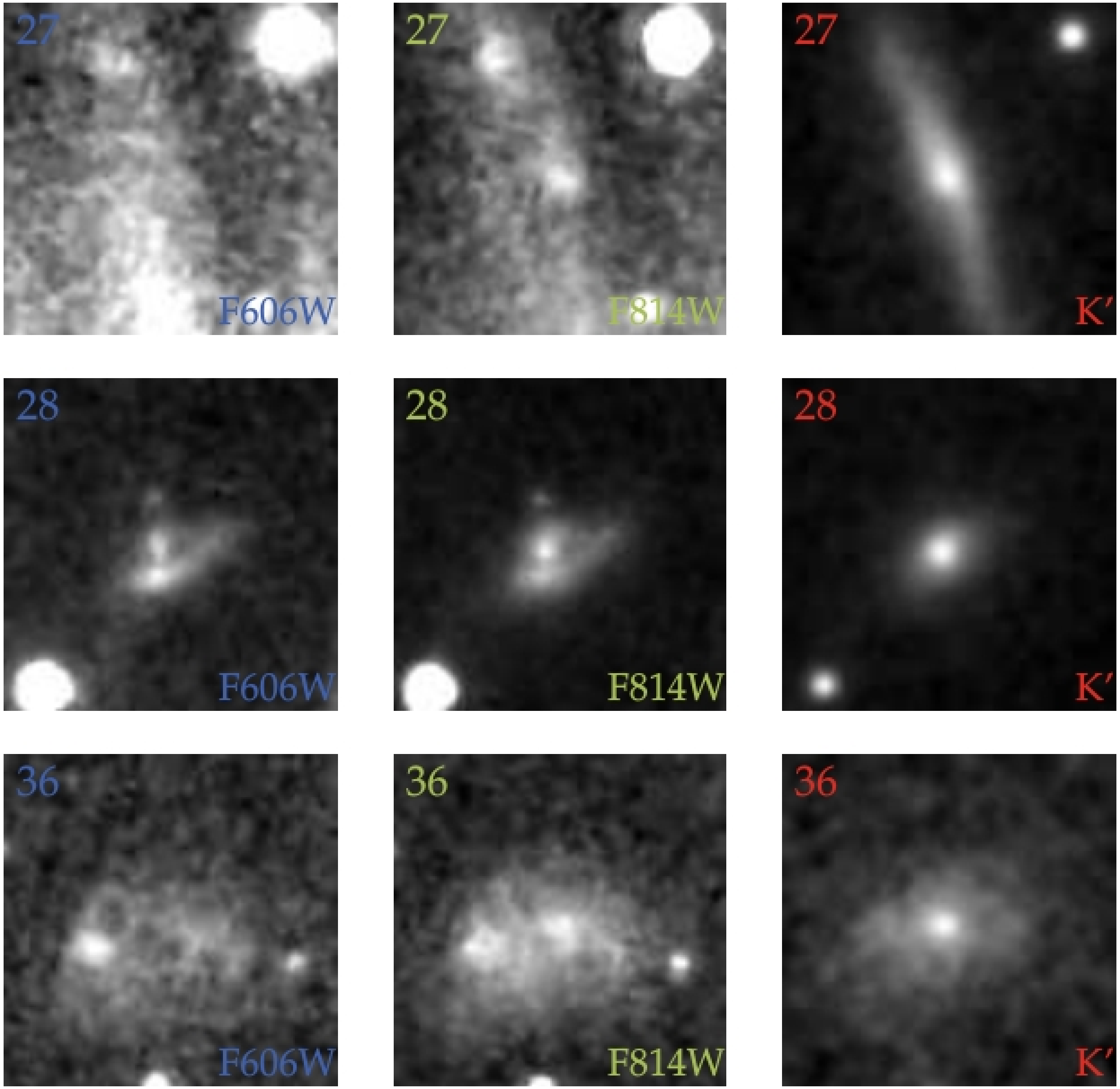
Fritz et al. 2016 arXiv:1611.08598

Motions relative to Pyxis



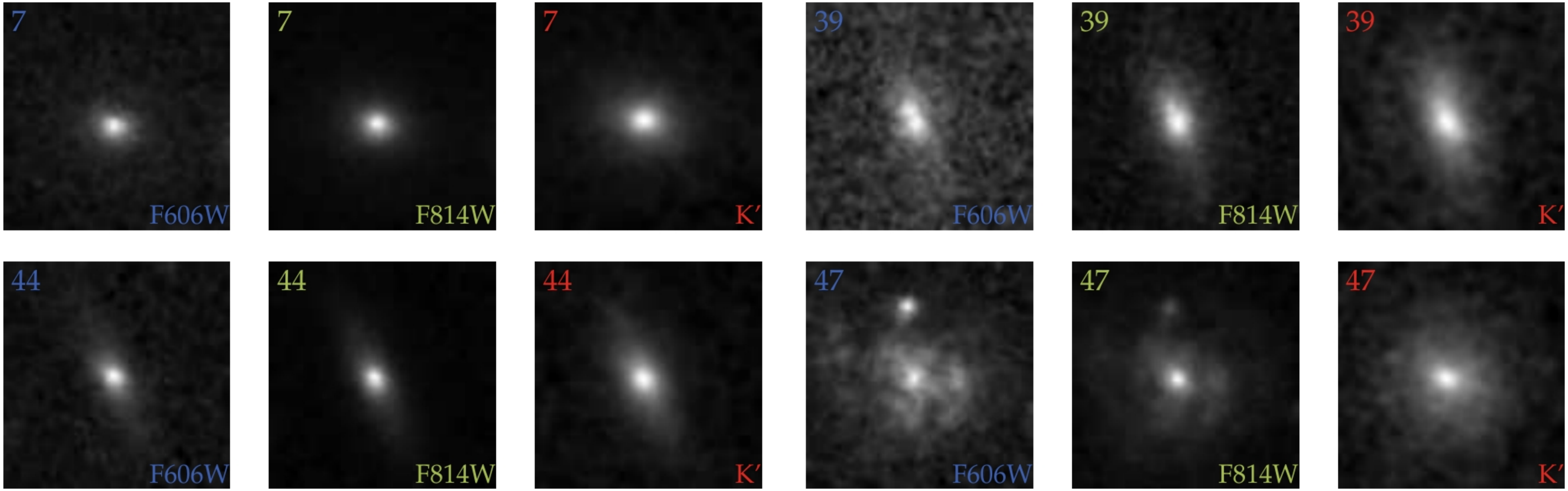
Fritz et al. 2016 arXiv:1611.08598

Bad galaxies



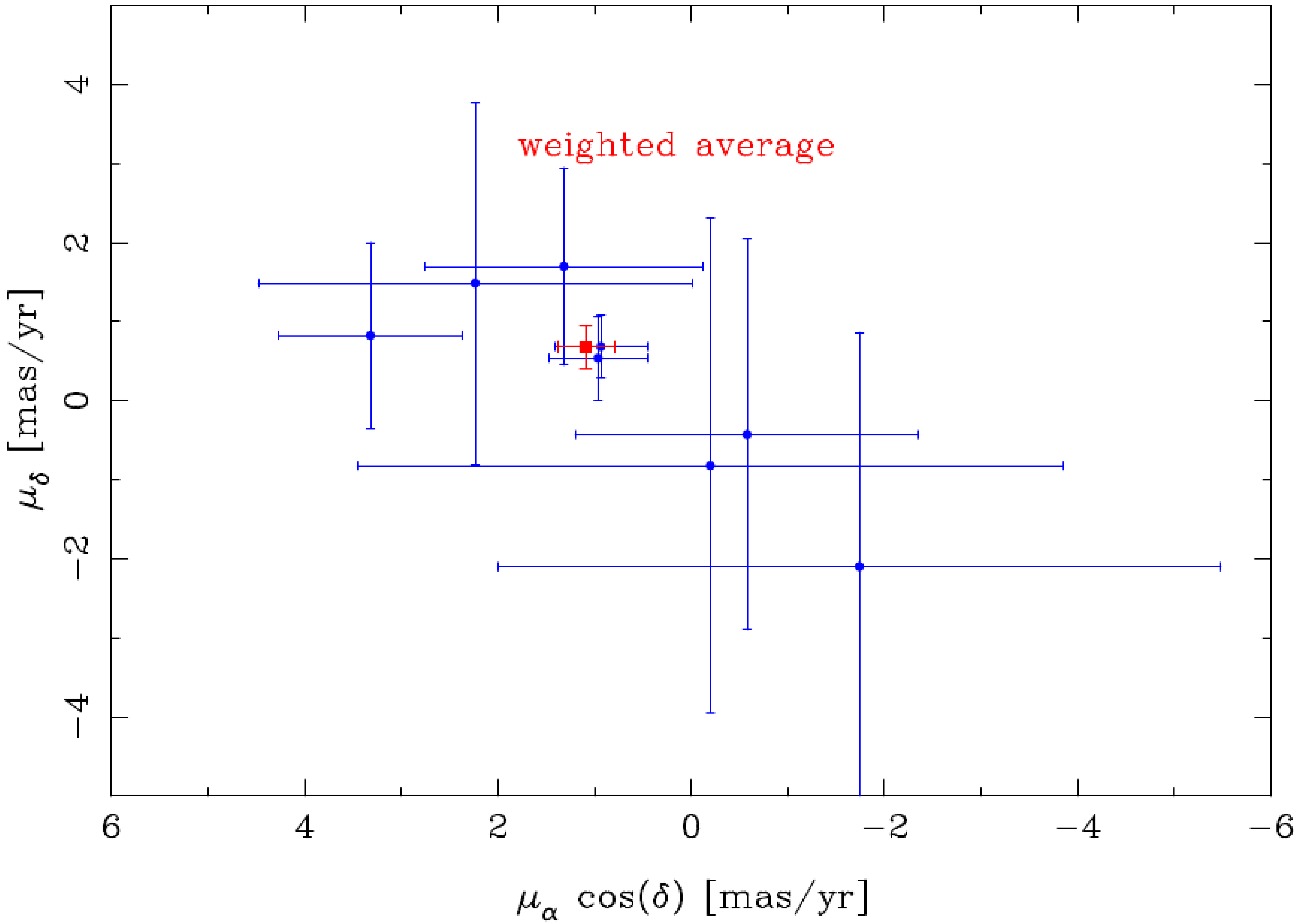
Fritz et al. 2016 arXiv:1611.08598

Some good galaxies



Fritz et al. 2016 arXiv:1611.08598

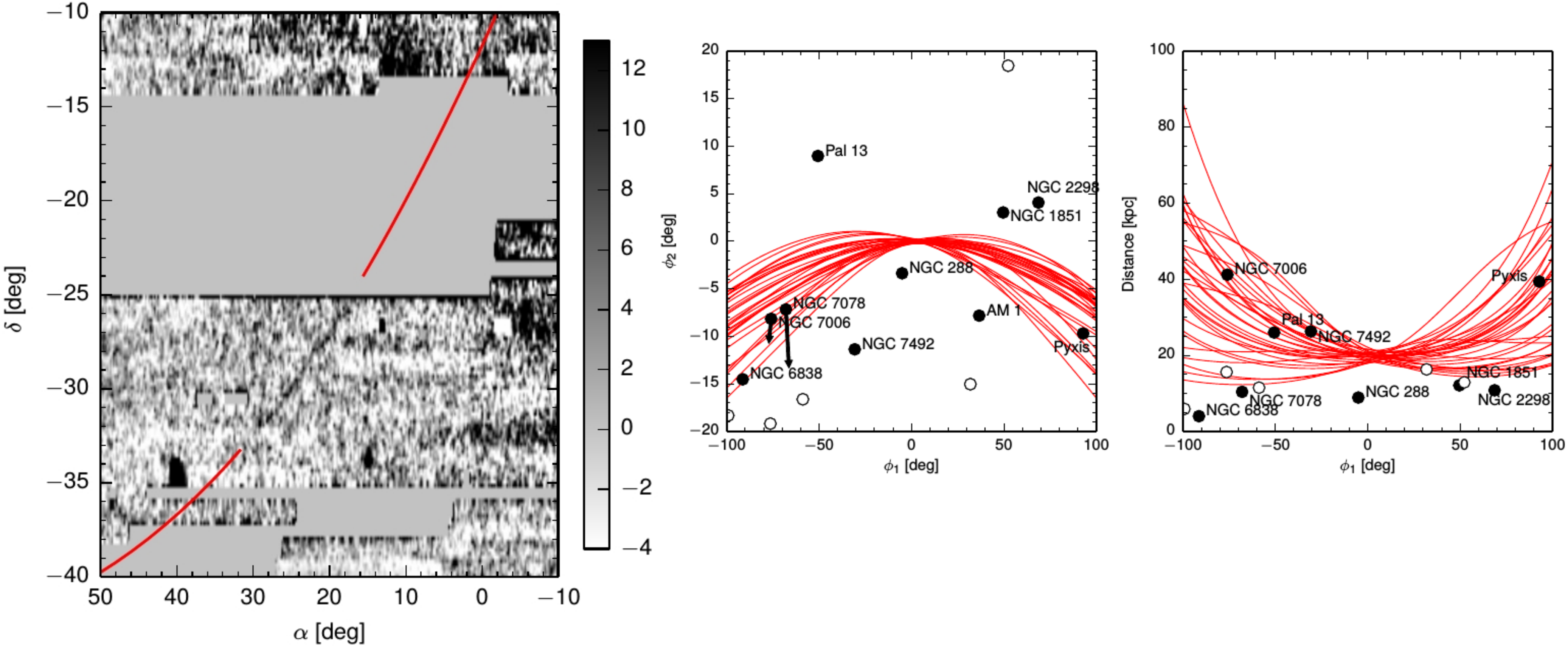
Absolute motion of Pyxis



Proper motion: $\mu_\alpha \cos(\delta)$ =1.09+/-0.31 mas/yr μ_δ=0.68+/-0.29 mas/yr

Fritz et al. 2016 arXiv:1611.08598

Connected with ATLAS stream?

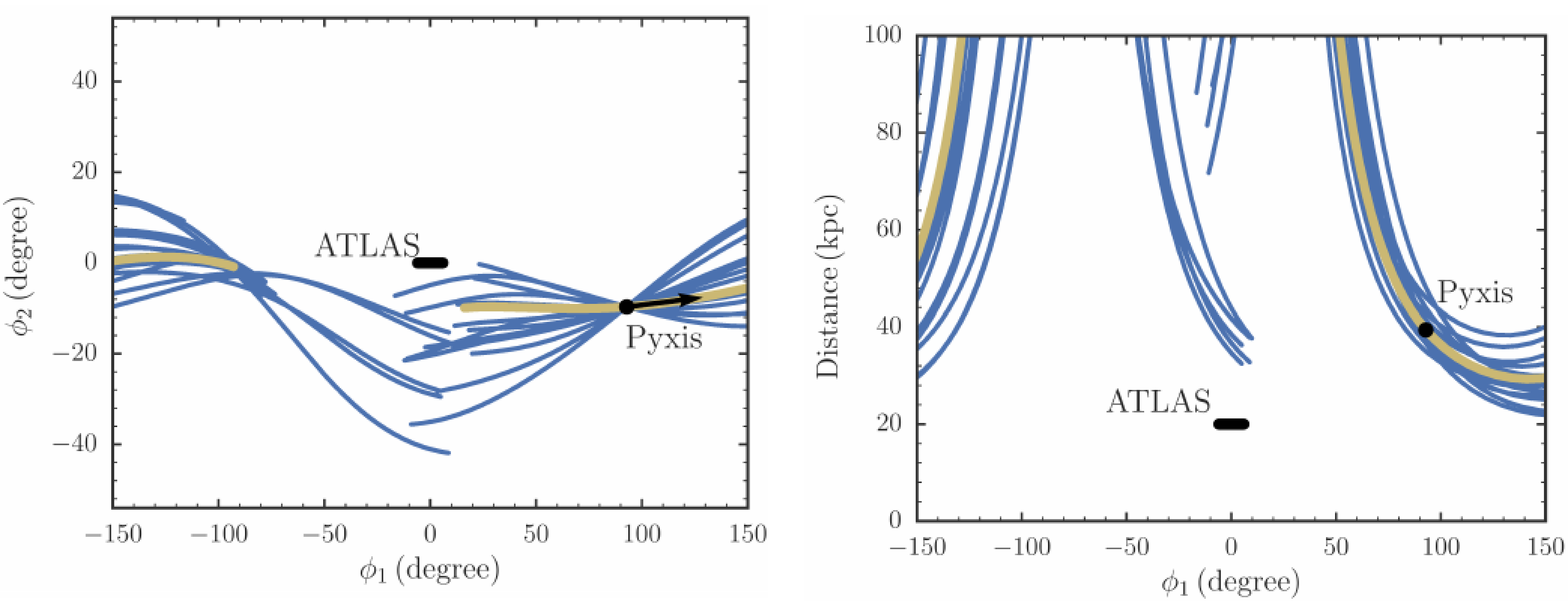


Koposov et al. 2014

- Pyxis is only known globular cluster within 90 degree of the stream which is consistent with being the origin of the stream.
- Partly, that is because no proper motion was measured for Pyxis.

Fritz et al. 2016 arXiv:1611.08598

Pyxis cannot be ATLAS progenitor



- We obtain orbital path Galpy (Bovy 2015), main uncertainties proper motion and distance.
- No realization matches the ATLAS stream.

Fritz et al. 2016 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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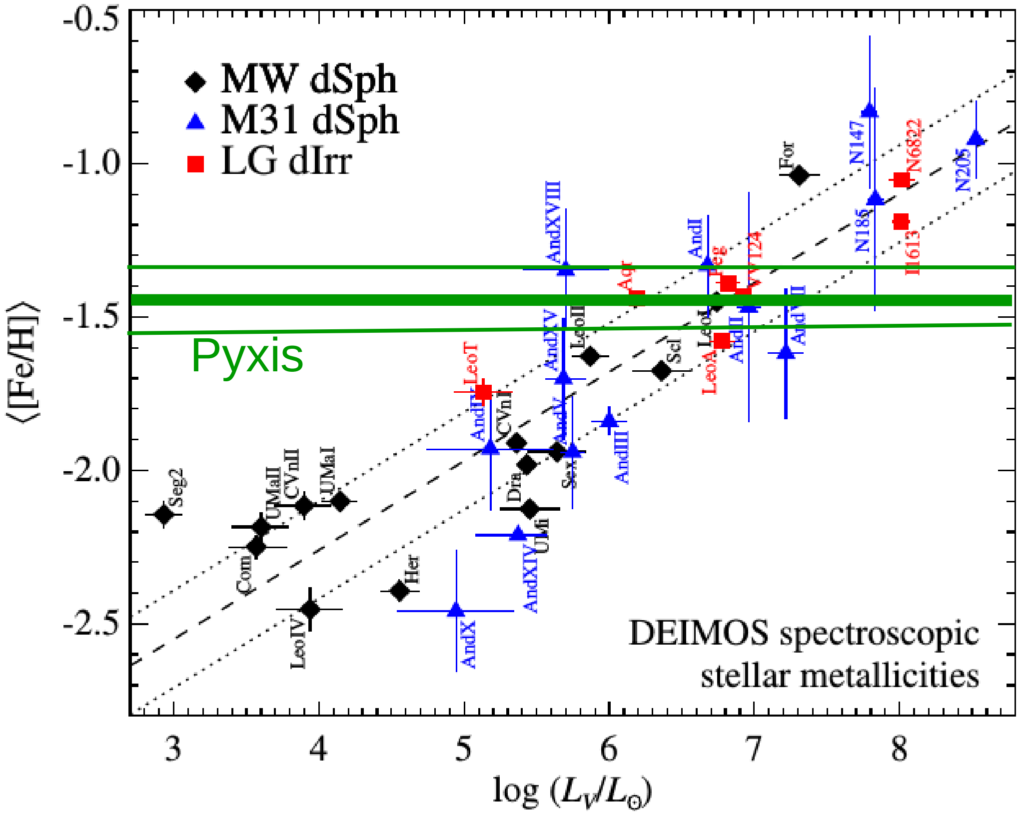
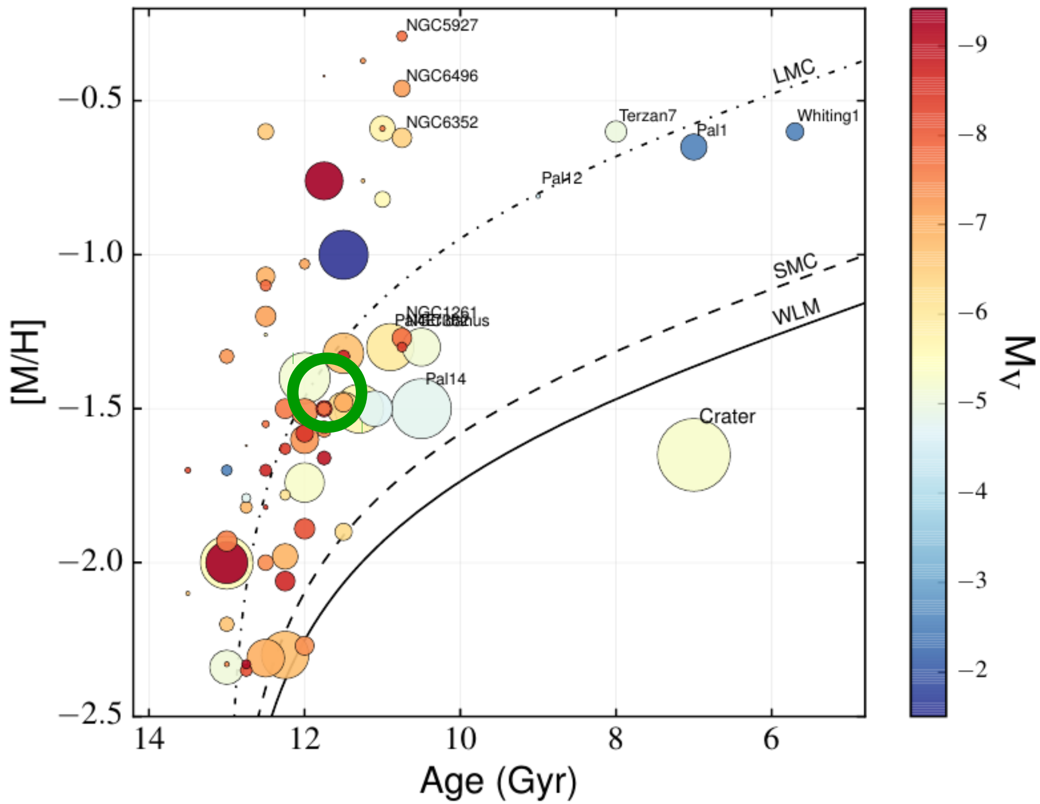
What is the size of the host galaxy?



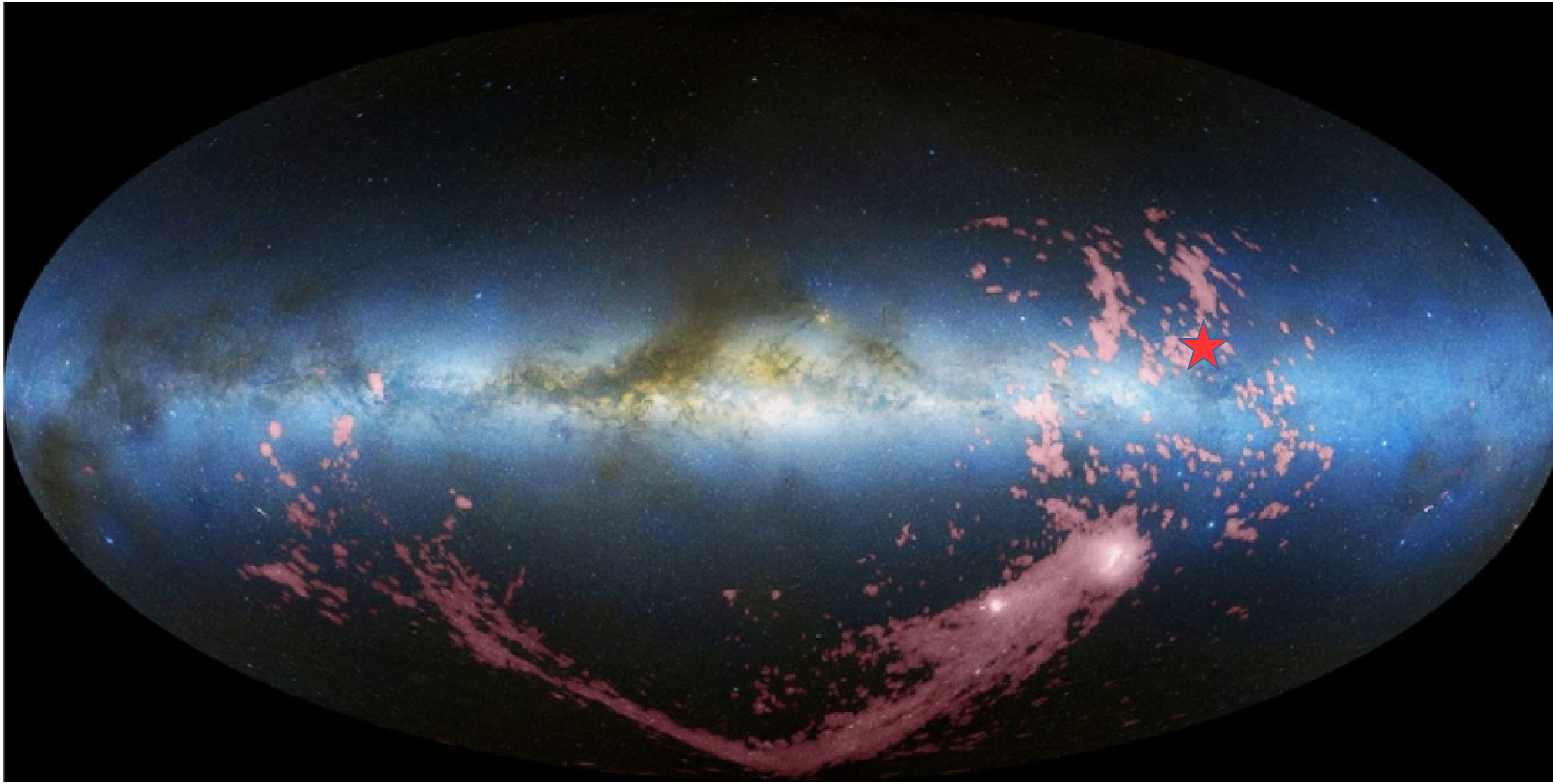


Kirby et al. 2013
I assume [Fe/H]_globular<=[Fe/H]_host
host at least Leo II size

Weisz et al. 2016
LMC size host

Fritz et al. 2016 arXiv:1611.08598

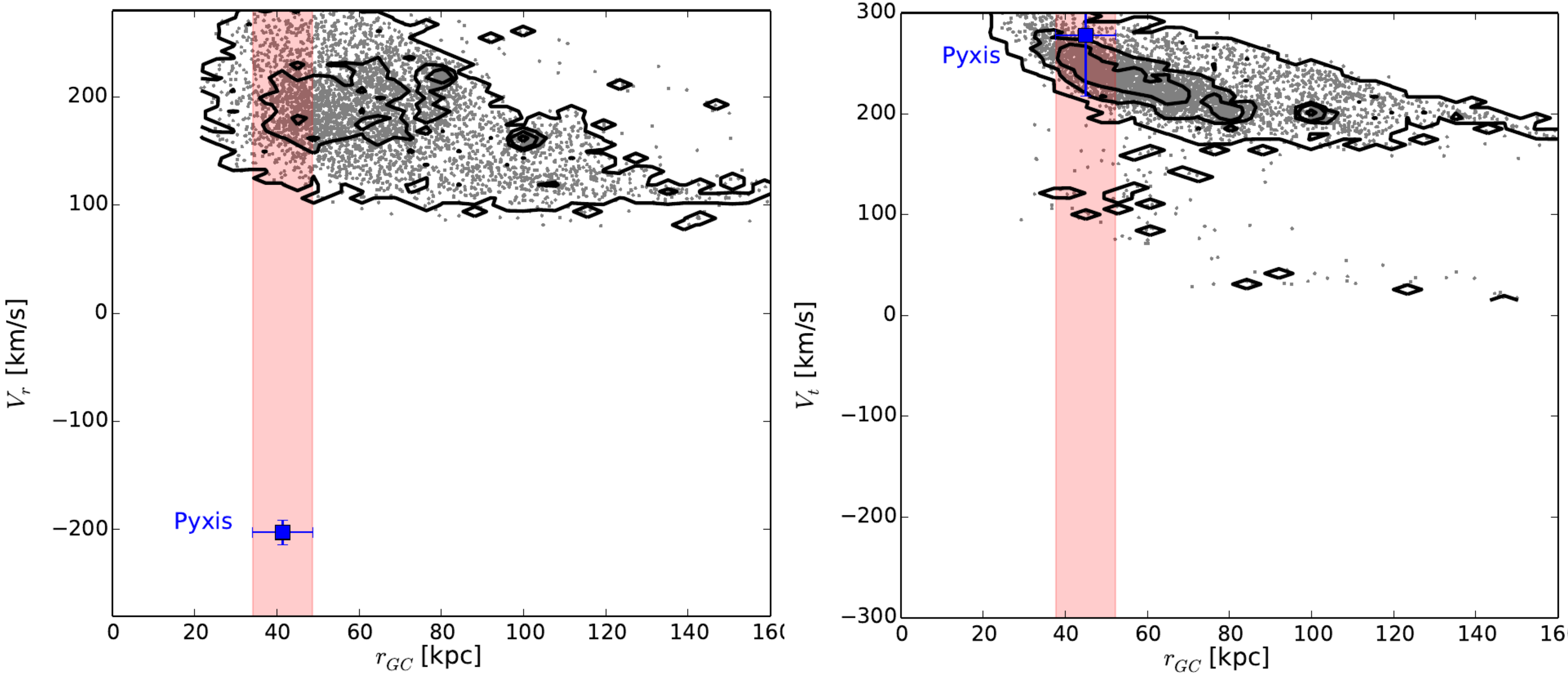
Pyxis connected with Magellanic Clouds?



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

Fritz et al. 2016 arXiv:1611.08598

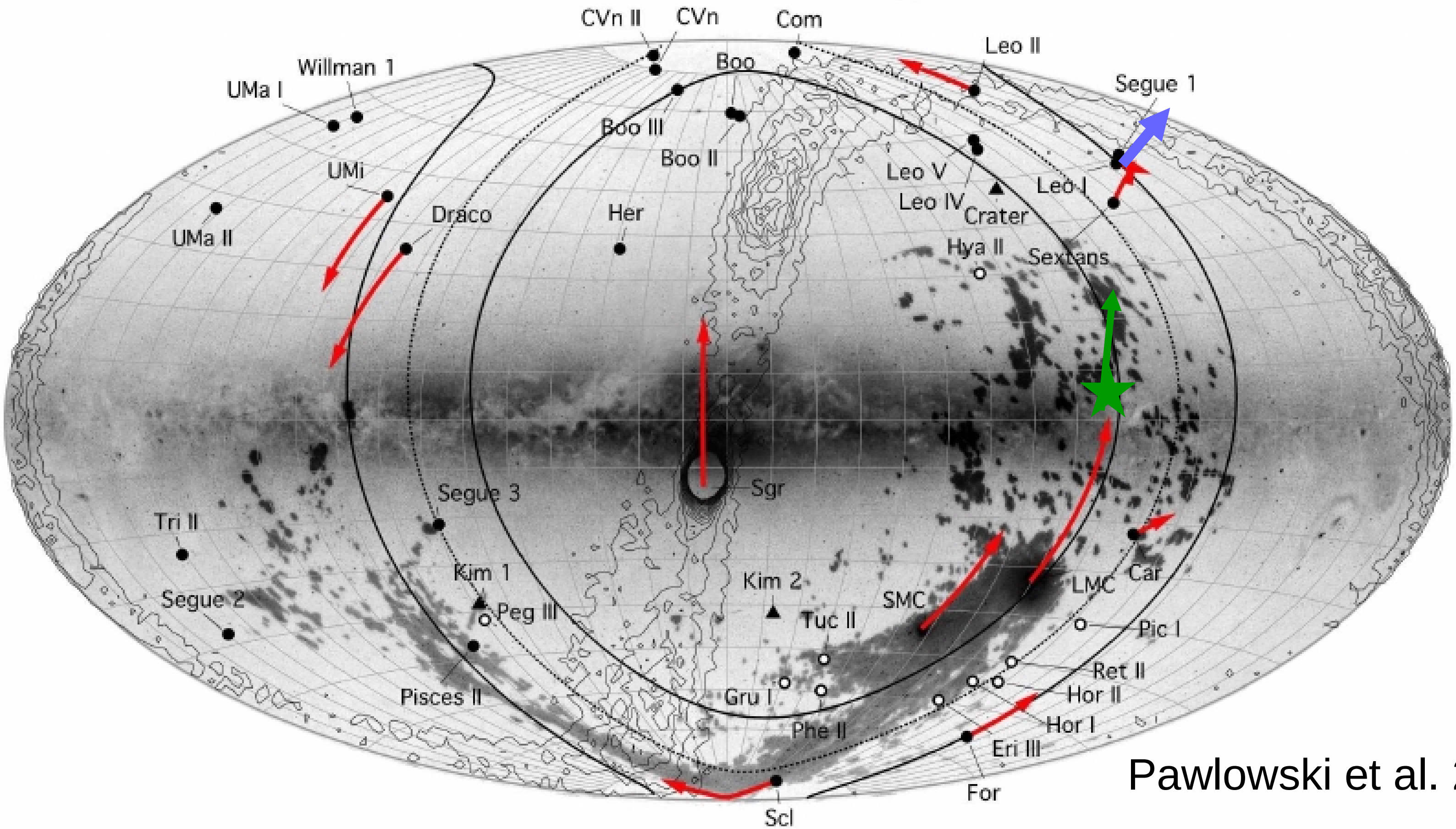
Pyxis motion does not match



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

Fritz et al. 2016 arXiv:1611.08598

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

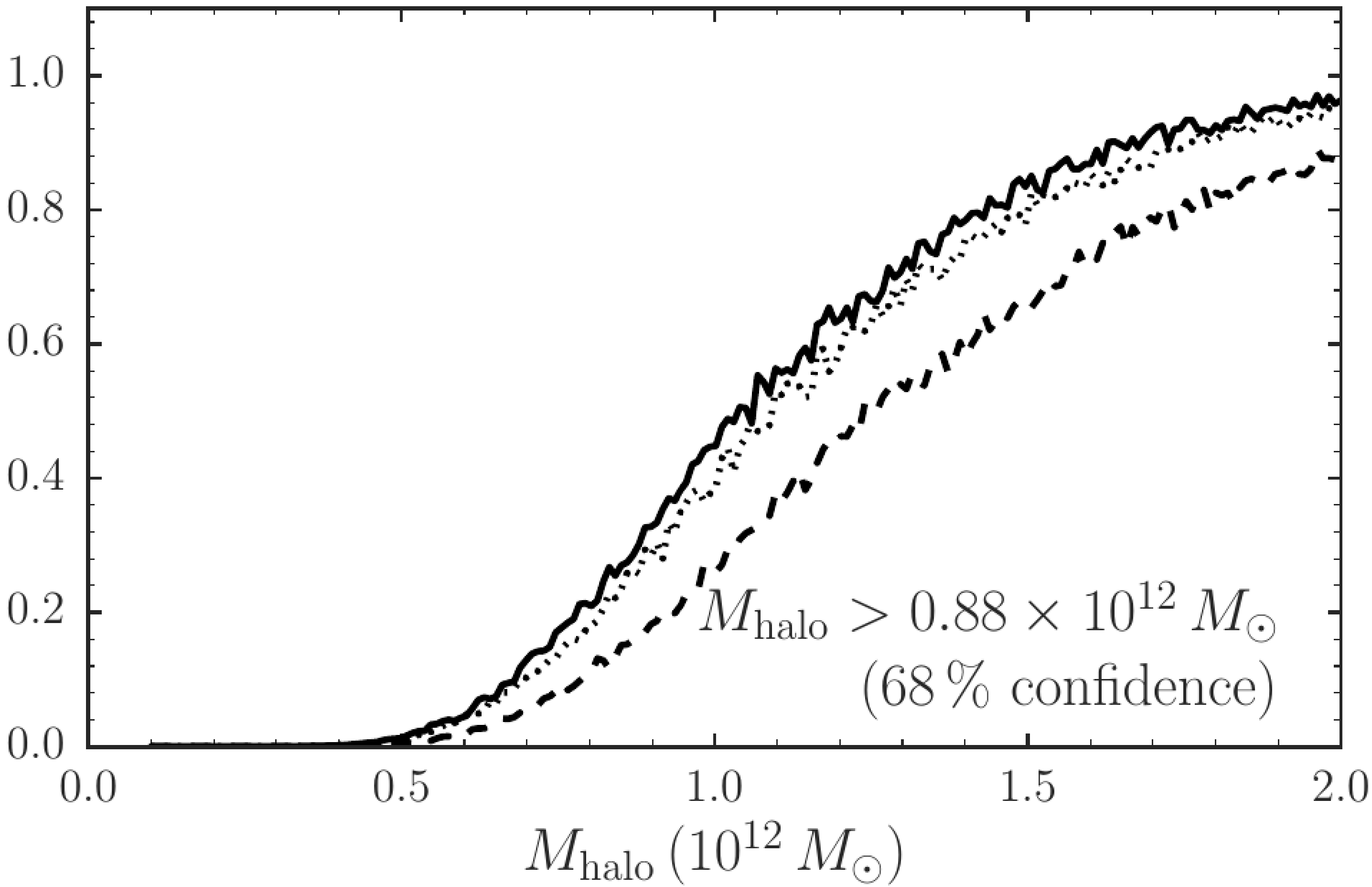


Pawlowski et al. 2015

- 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.

Fritz et al. 2016 arXiv:1611.08598

Require that Pyxis is bound to the Milky Way



- We use MW2014 (Bovy 2015) for disk and bulge (together 0.073*10^12 M_sun). M_halo>0.58*10^12 if on first approach.
- In addition, require that Pyxis is on second approach →M_halo>0.88*10^12
- Concentrations from left 15.3, 12, and 6

Fritz et al. 2016 arXiv:1611.08598

Conclusions

- A Law & Majewski halo is excluded for the Pal 5 orbit range (R<20 kpc). A spherical halo fits the data.
- First use of HST + AO for absolute motion (Pyxis) using background galaxies.
- Pyxis is not the progenitor of ATLAS stream.
- Pyxis is not associated with the Magellanic clouds and any other large dwarf.
- Pyxis former host is probably not known.
- Mass of the Milky Way is larger than 0.95*10^12 M_sun