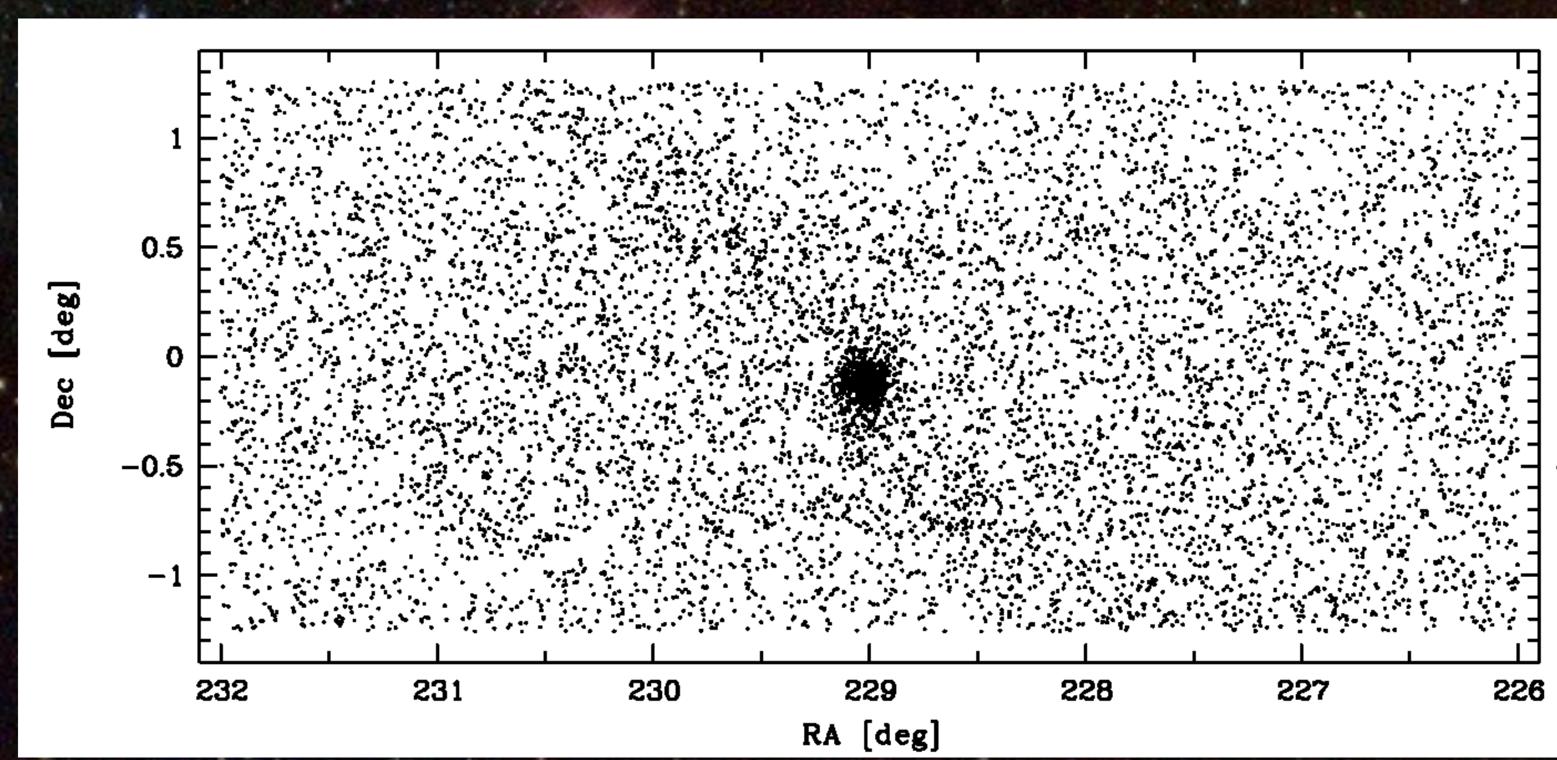
Proper Motions in the Local Group: Next Generation Astrometry.

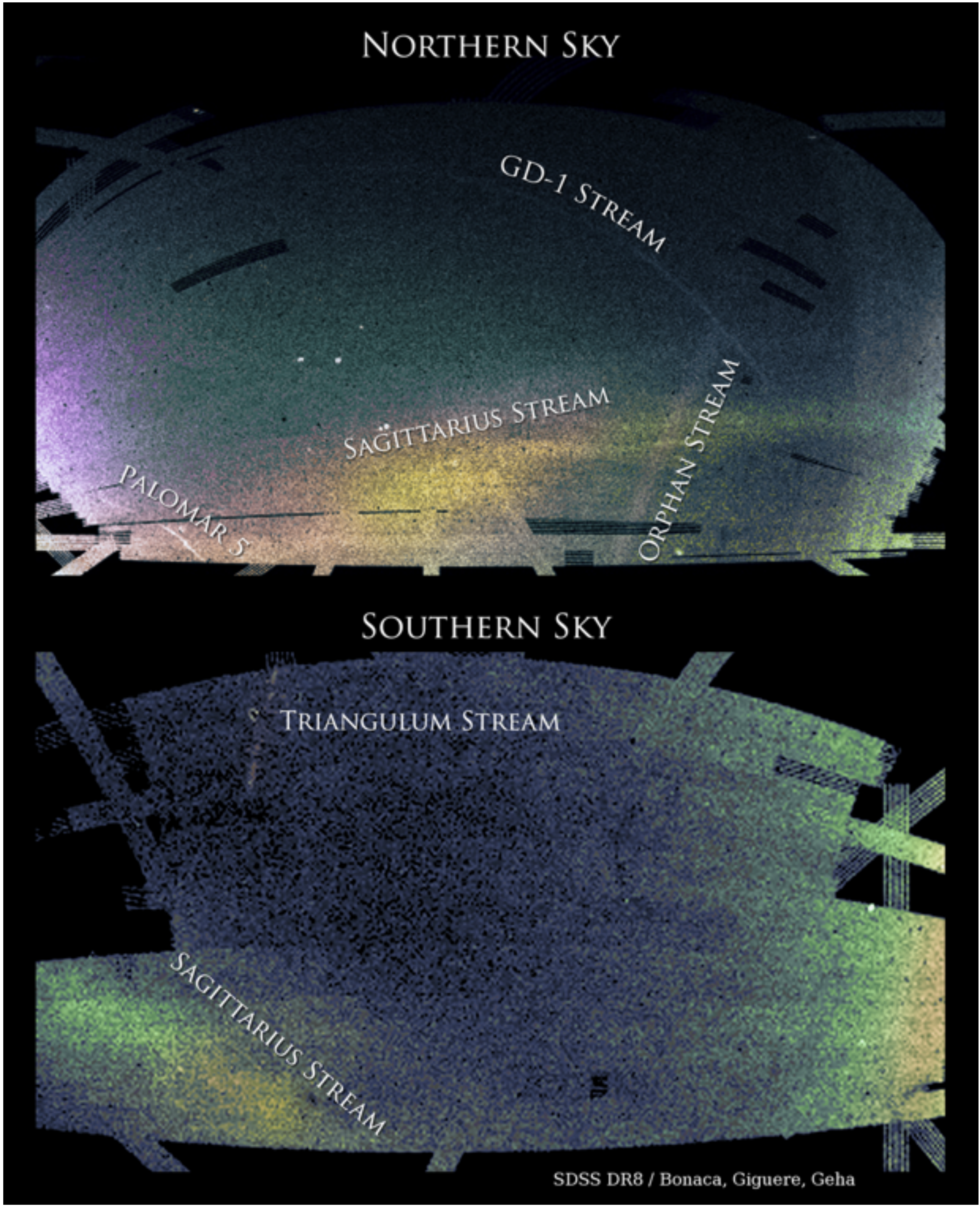
Nitya Kallivayalil
Kalli - violin

UVa

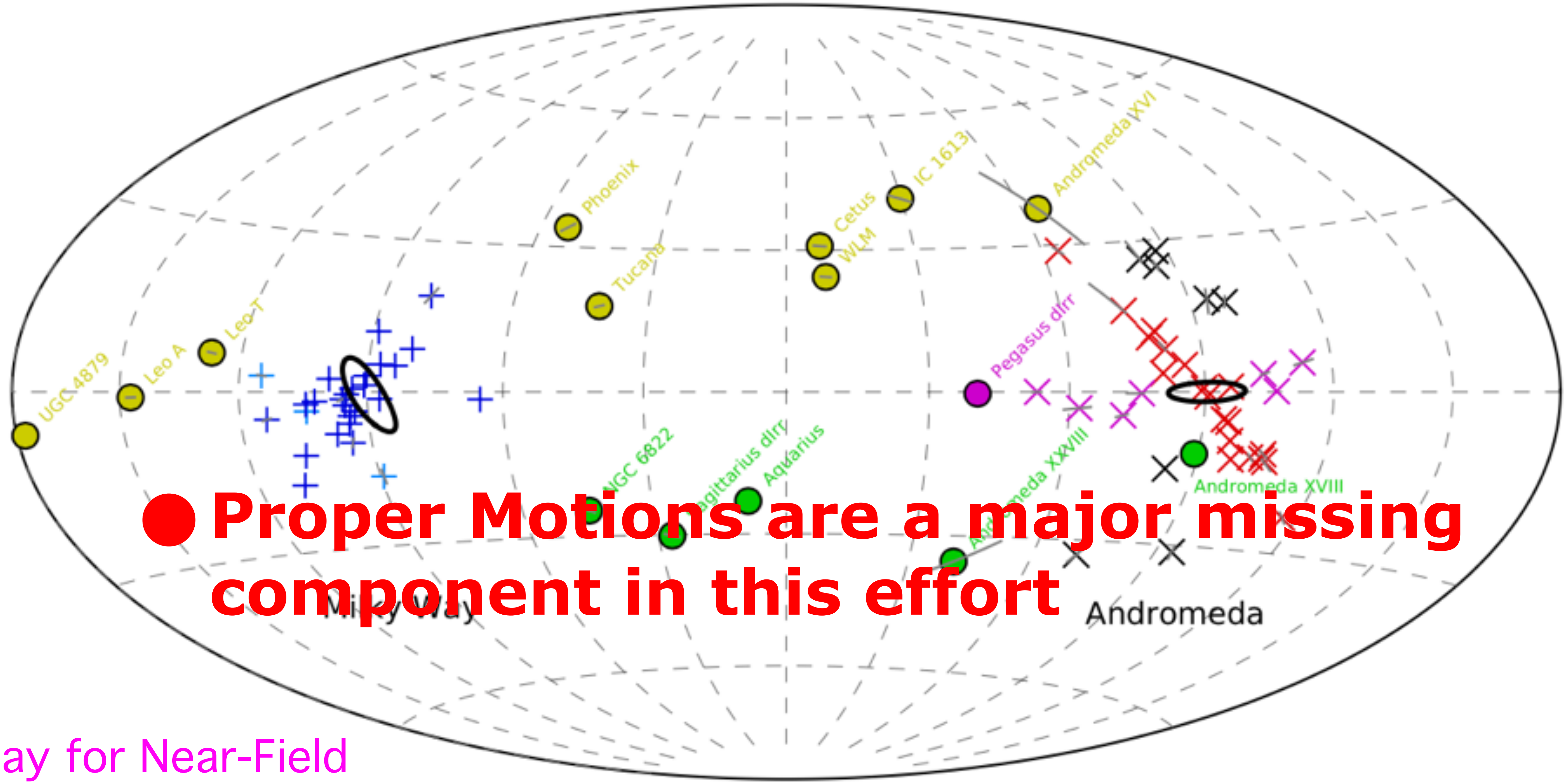


ATLAST Symposium, July 2015

Heyday for Near-Field Cosmology



SDSS DR8: Bonaca, Geha & NK (2012)



● Proper Motions are a major missing component in this effort

Heyday for Near-Field Cosmology

- Missing Satellites Problem (e.g., Moore et al. 1999)
- Low densities of dwarf galaxies: core vs. cusp, and Too Big to Fail (e.g., Walker & Penarrubia 2011; Boylan-Kolchin et al. 2011)
- Shape of dark matter halo (e.g., Law & Majewski 2010)
- Planes of satellites (e.g., Pawlowski et al. 2013)

HST has been an extremely successful astrometry machine!

(1) determining the orbit of the LMC & SMC (Kallivayalil et al. 2013)

(2) detecting internal rotation in the LMC (van der Marel & Kallivayalil 2014)

(3) measuring the tangential motion of M31 (Sohn et al. 2012, van der Marel et al. 2012a,b)

(4) measuring the space motion of Leo I and dynamically measuring the mass of the Milky-Way halo (Sohn et al. 2013, Boylan-Kolchin et al. 2013)

(5) constraining the presence of intermediate-mass black holes in globular clusters (Anderson & van der Marel 2010)

(6) measuring the proper motion of tidal streams (Sohn et al. 2015)

Anderson & King 2006; Anderson 2007; van der Marel et al. 2007, Bellini et al. 2011

Required Proper Motion Uncertainty

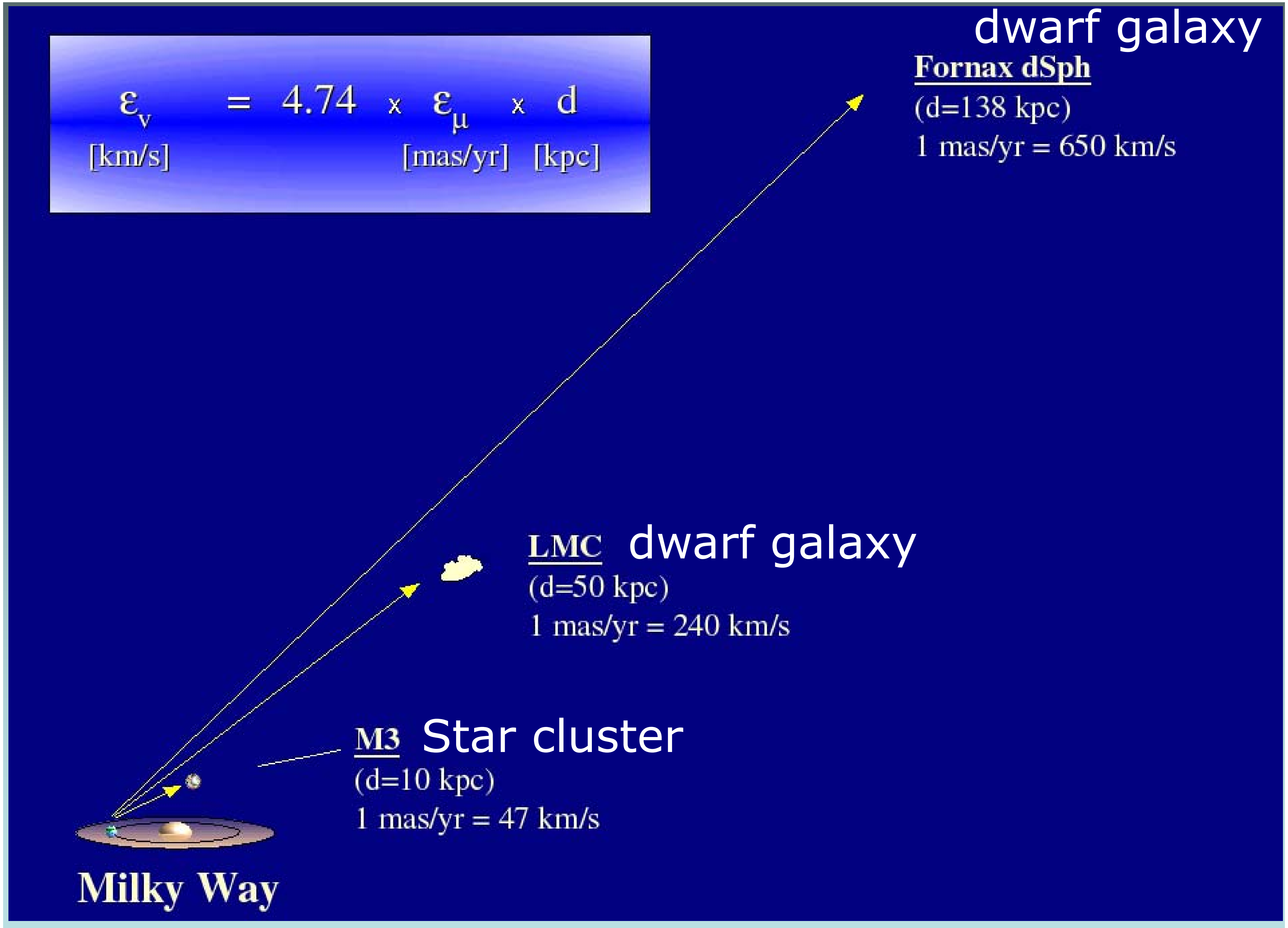
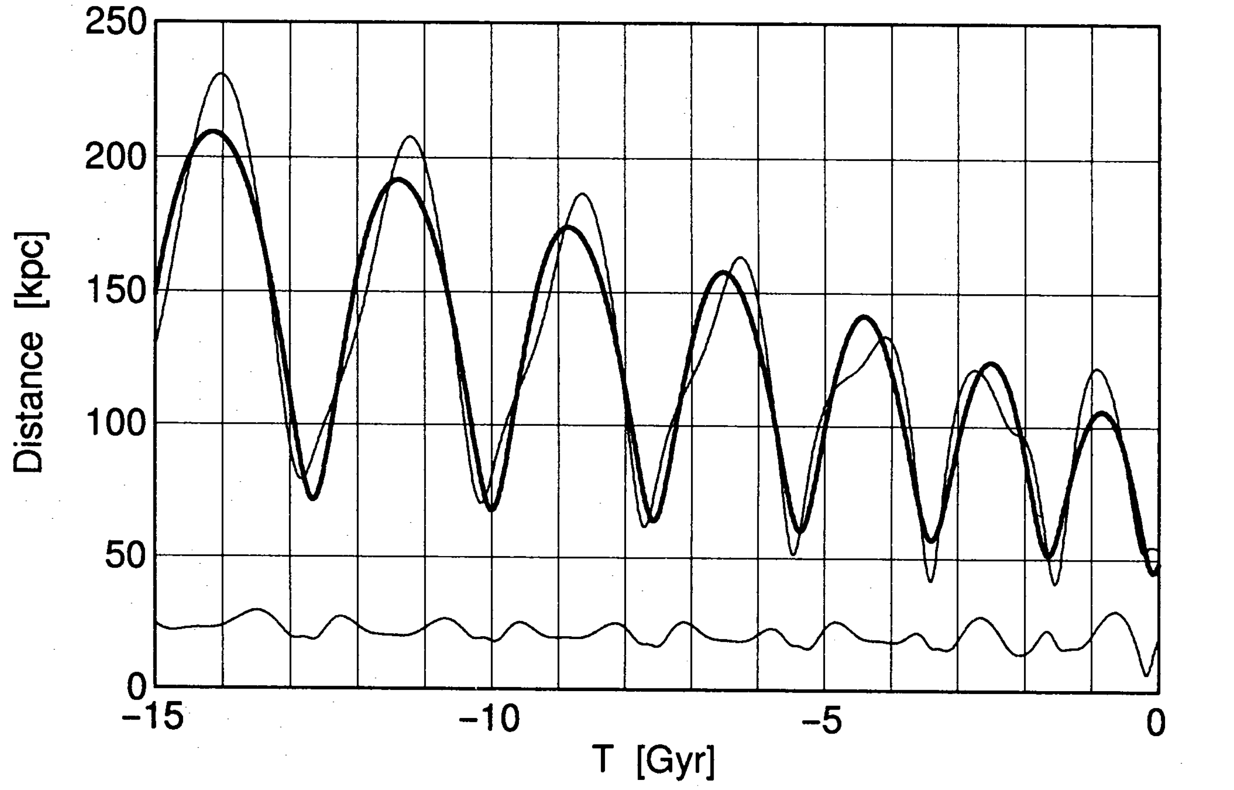
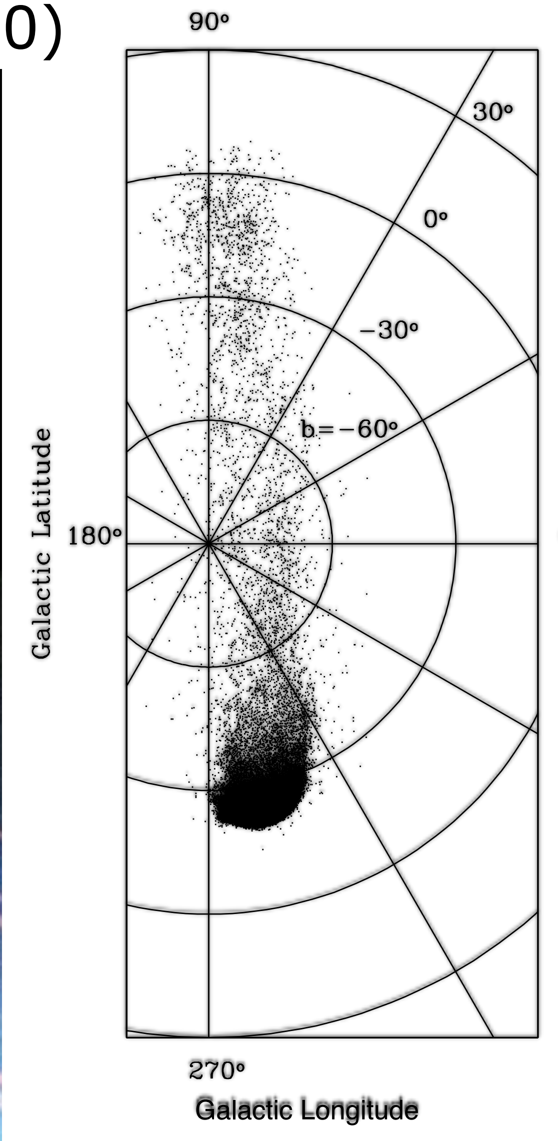


image credit: Dana Dinescu

Tidal Stripping: Gardiner & Noguchi (1996)



Ram Pressure Stripping: Mastropietro+ (2010)



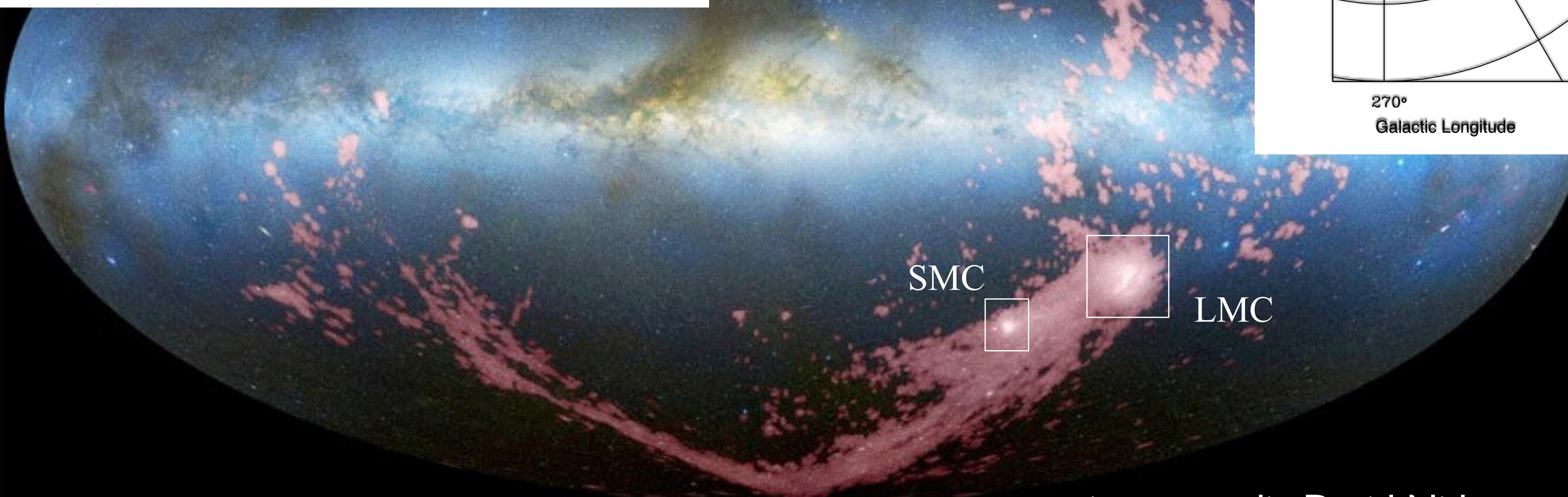
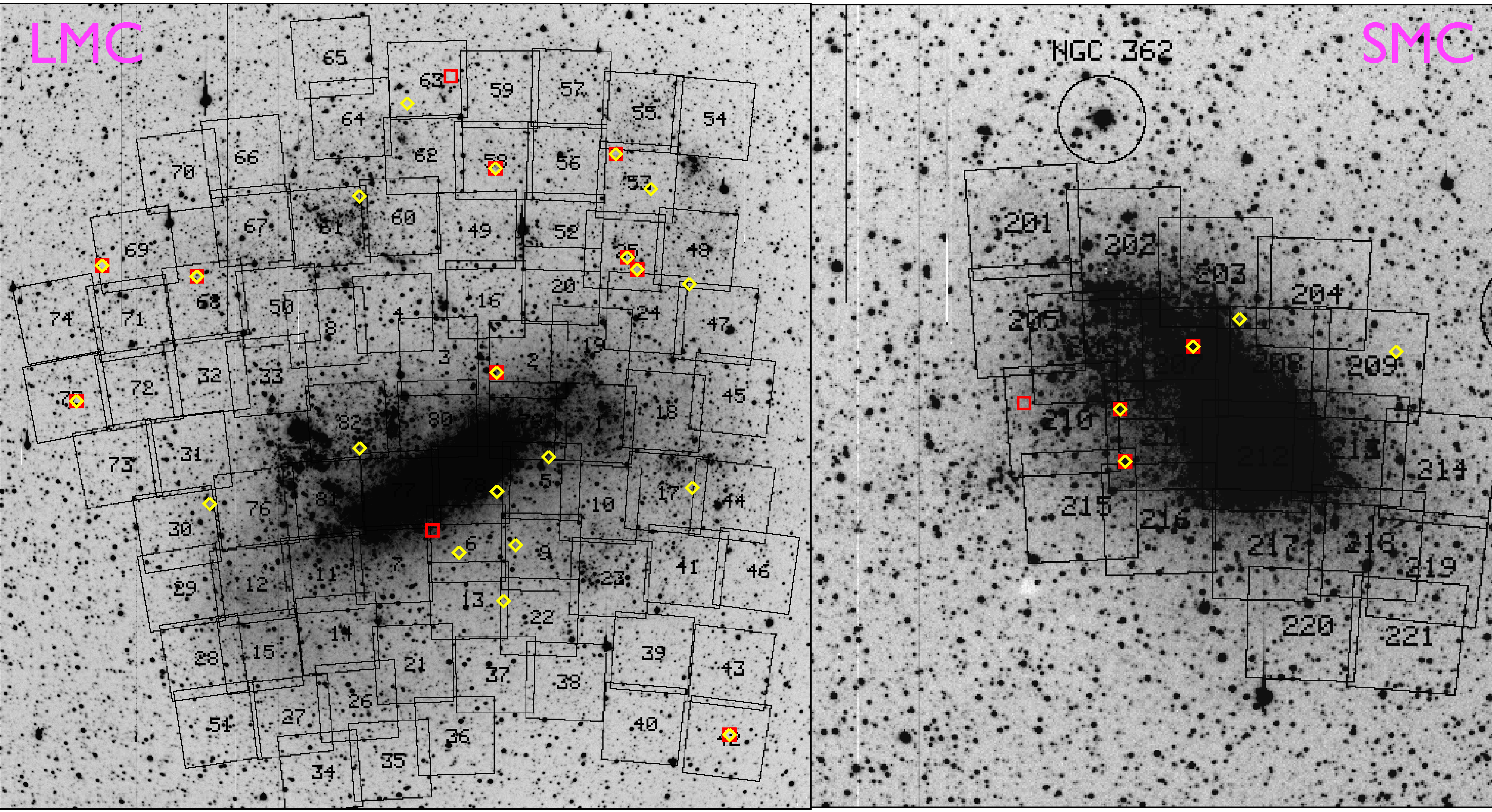


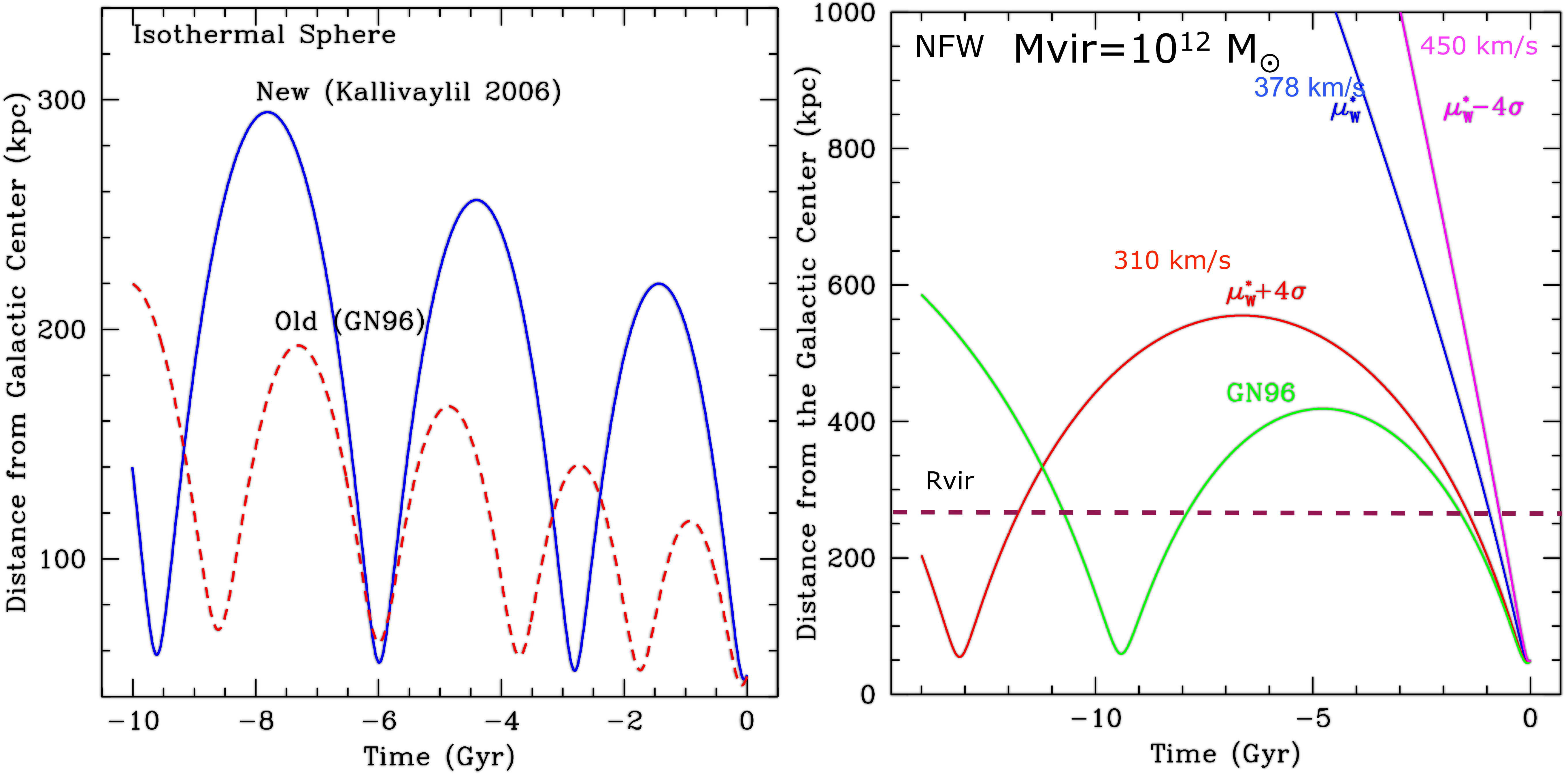
image credit: David Nidever
Putman et al. 2003

Reference Frame



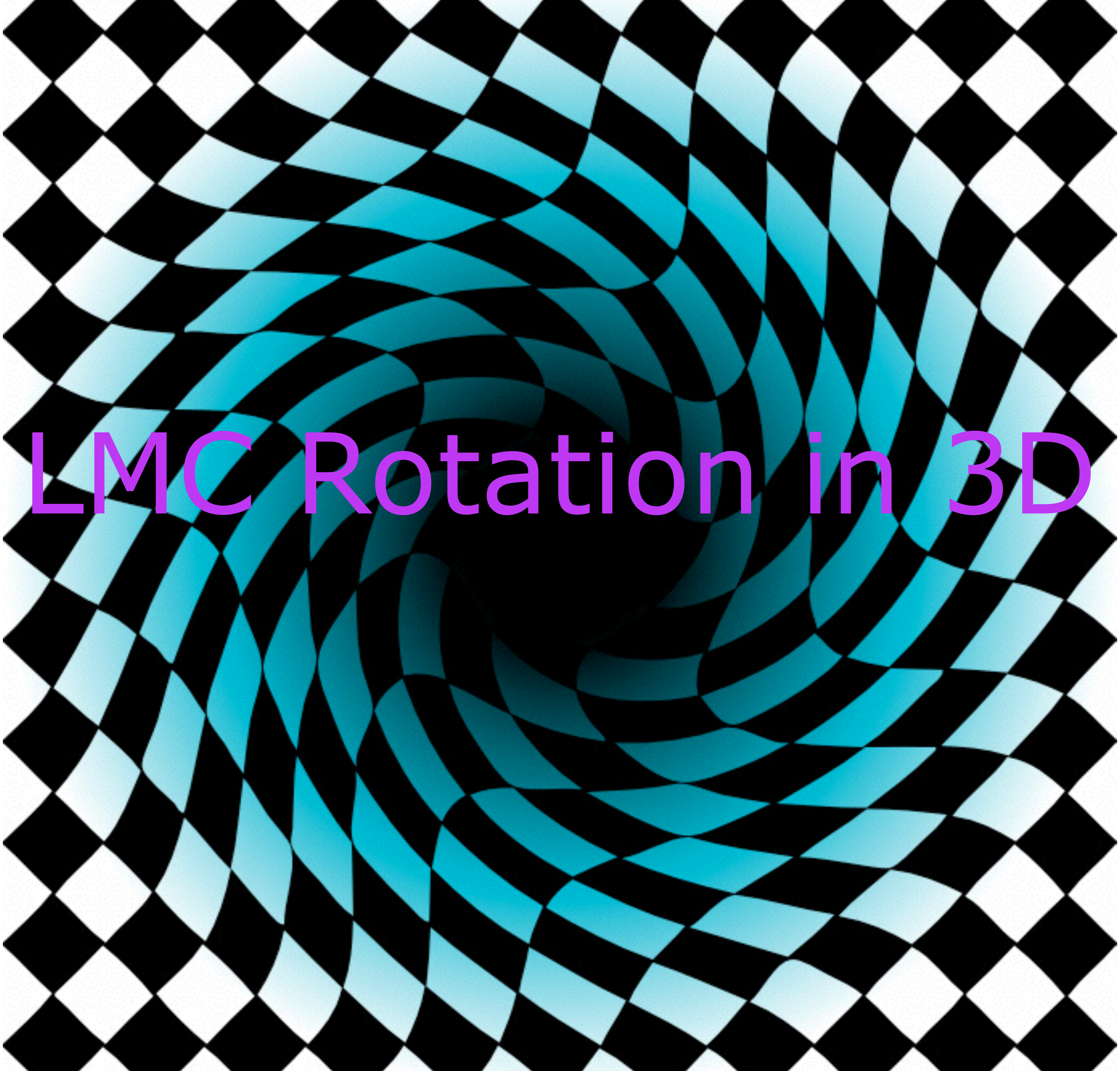
Geha et al. 2003

Orbital properties in a cosmological context

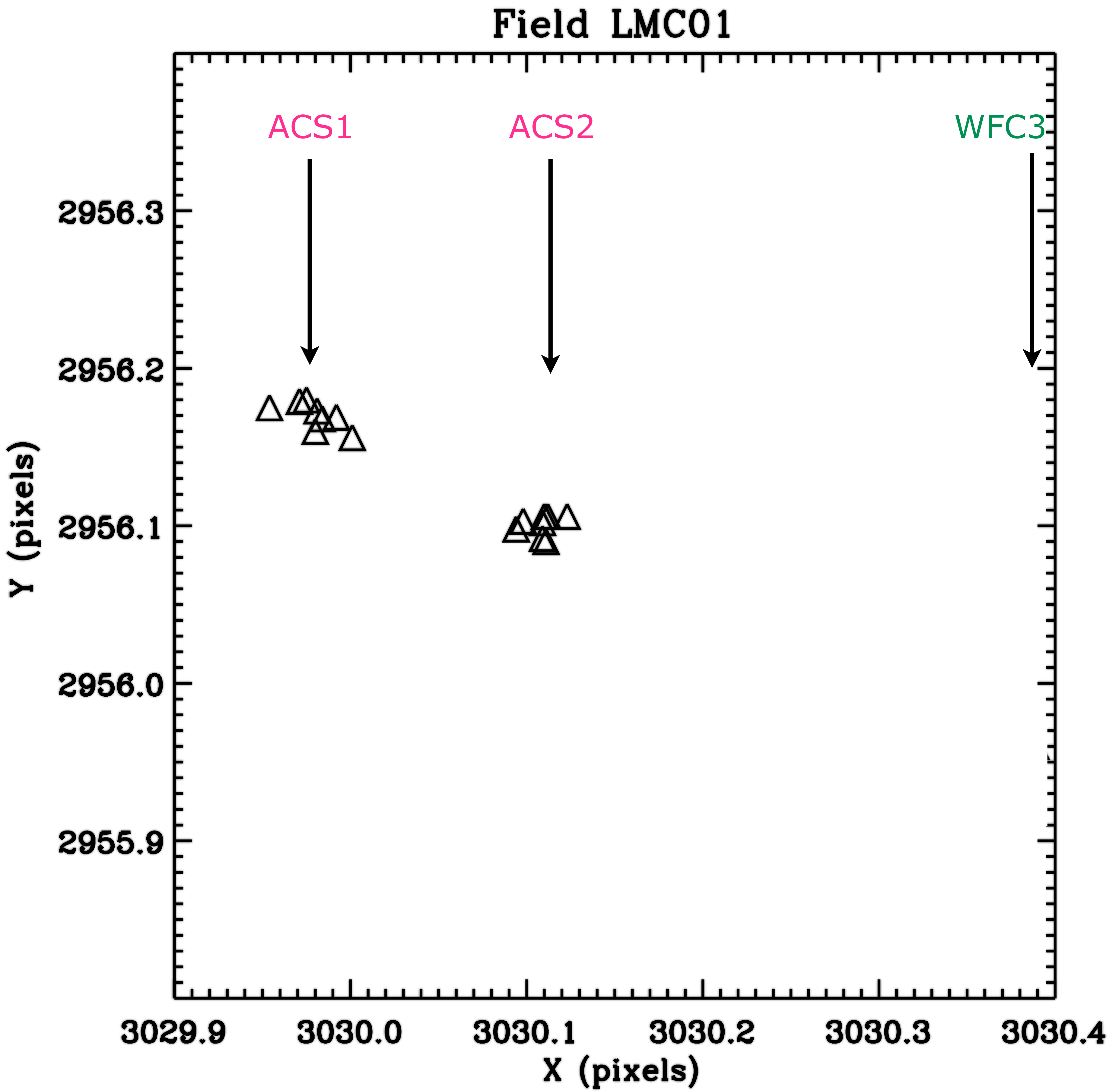


Note that models are static in time

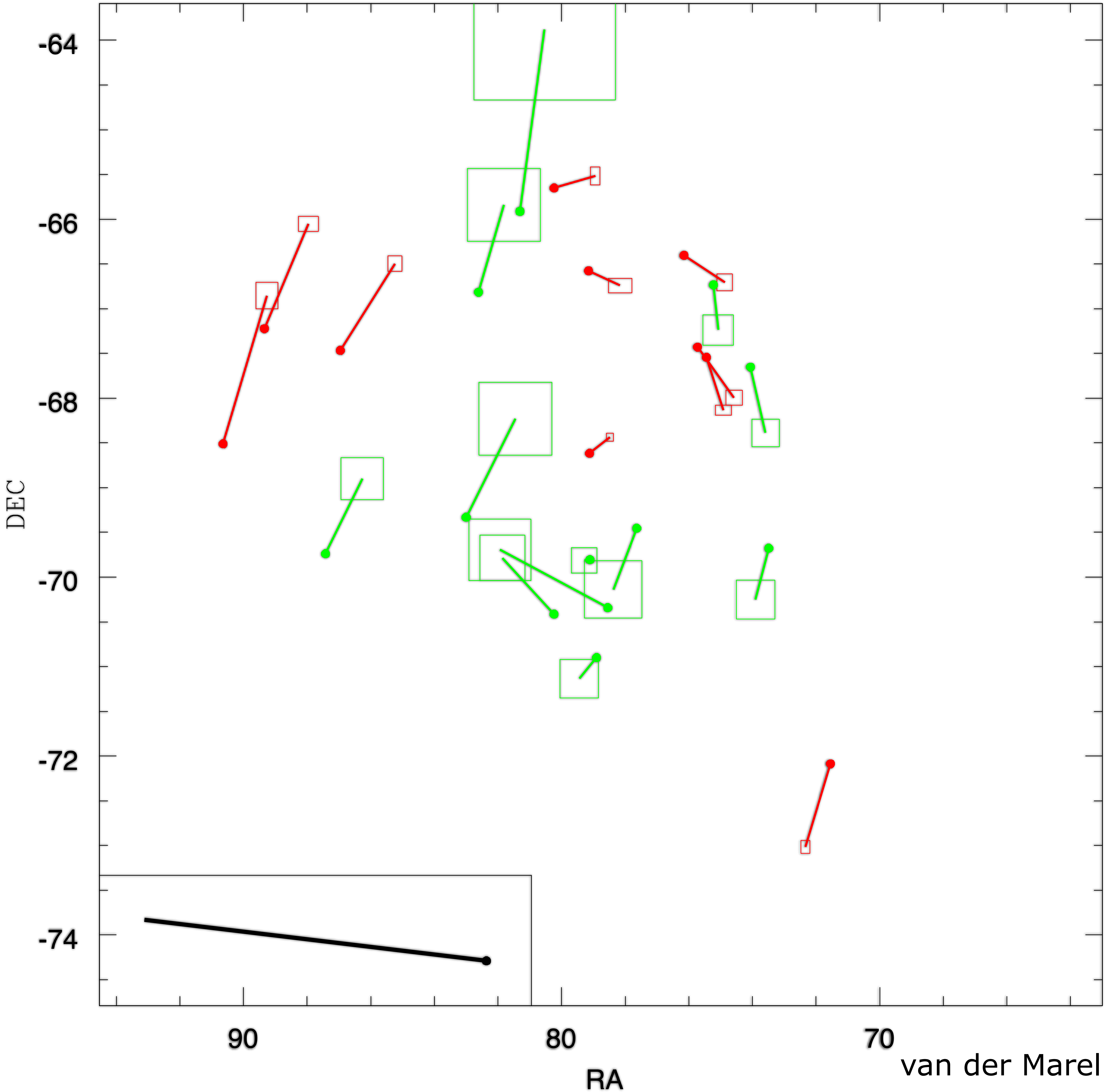
NK + (2009); Besla, NK+ (2007)


LMC Rotation in 3D

3 Epcoh Analysis (ACS+WFC3):

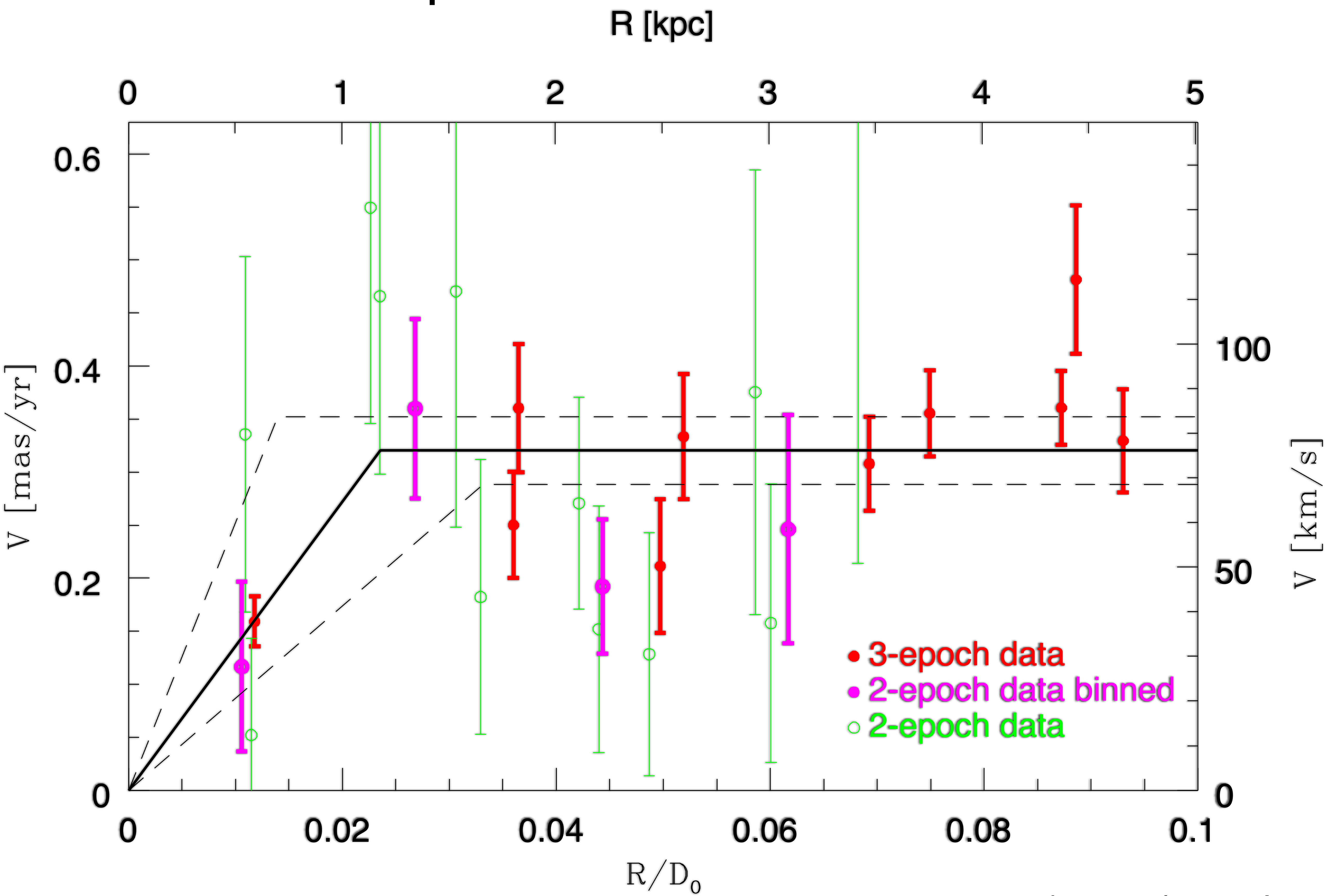


NK+ (2013)

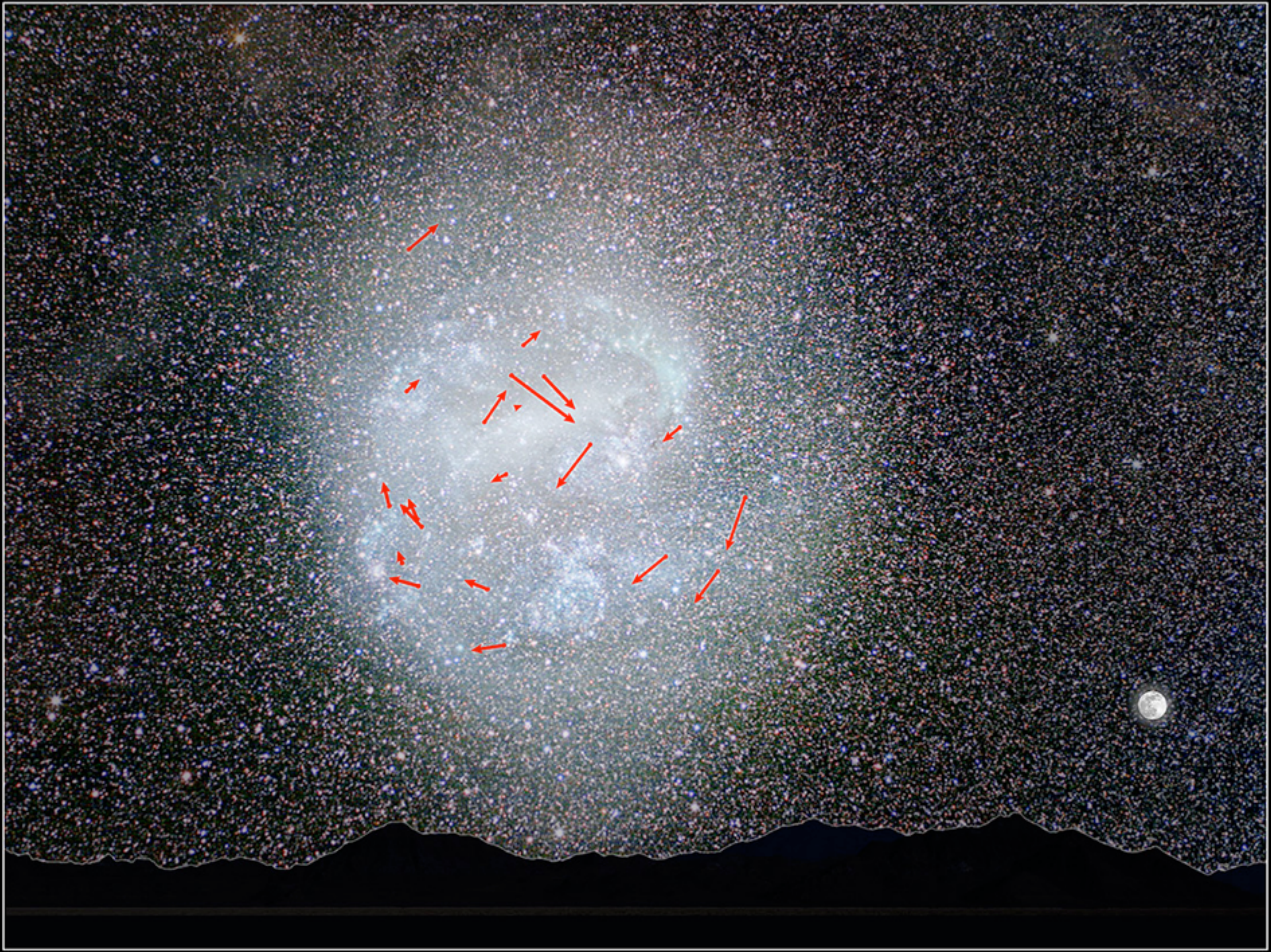


van der Marel & NK (2014)

LMC Proper Motion Rotation Curve



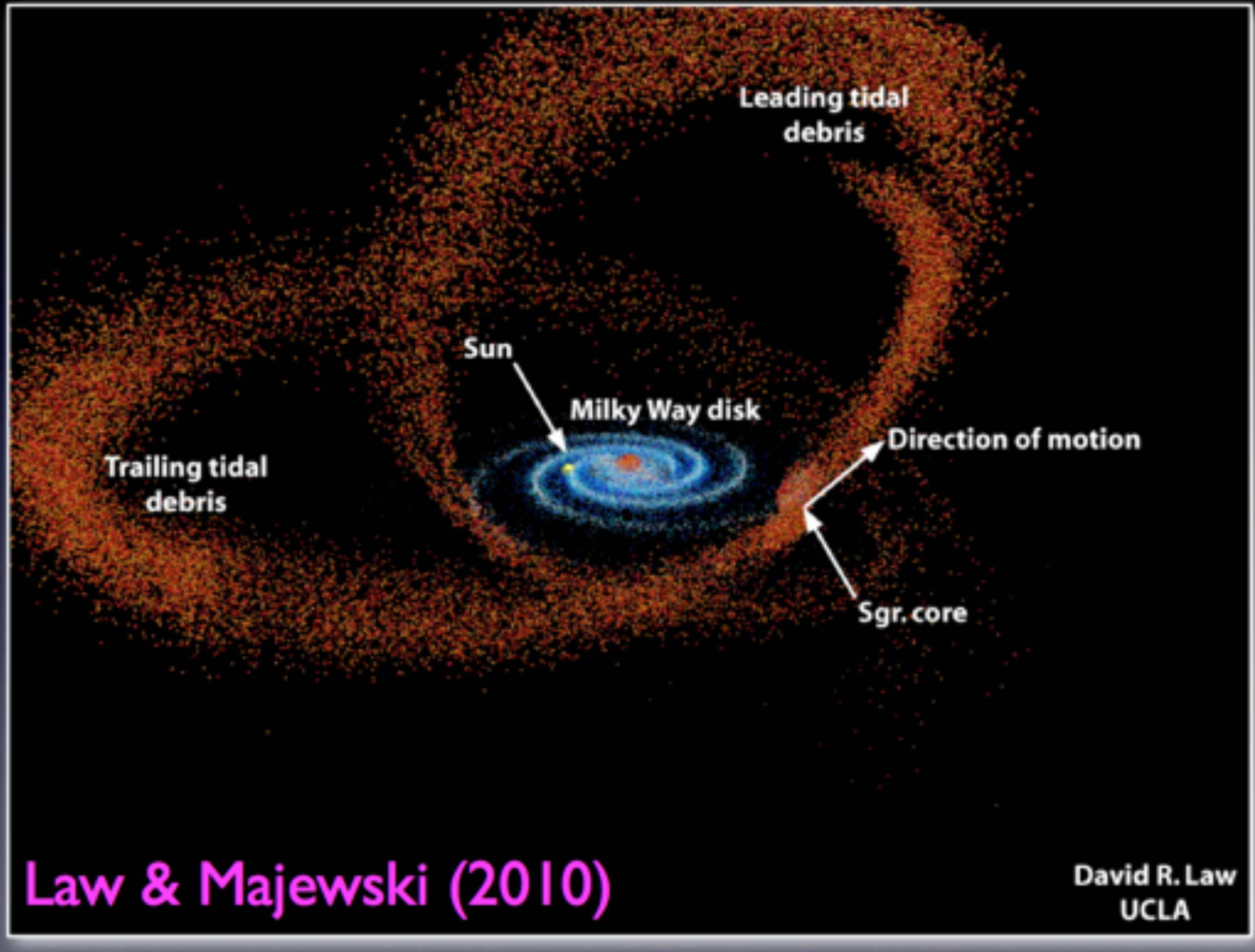
van der Marel & NK (2014)

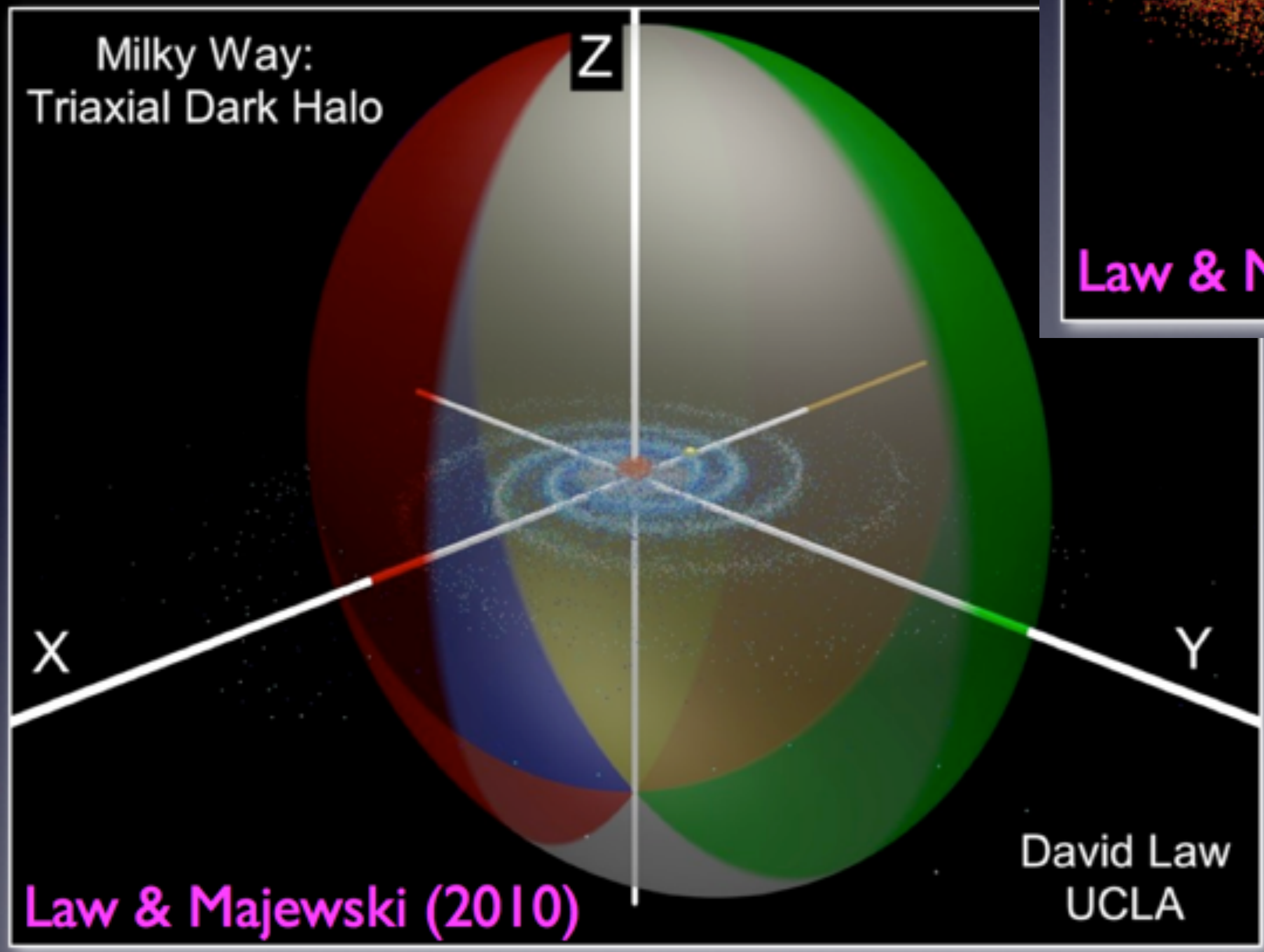


Hubble Measures Rotation of the Large Magellanic Cloud • Photo Illustration
NASA and ESA ▪ STScI-PRC14-11a

Sagittarius Stream

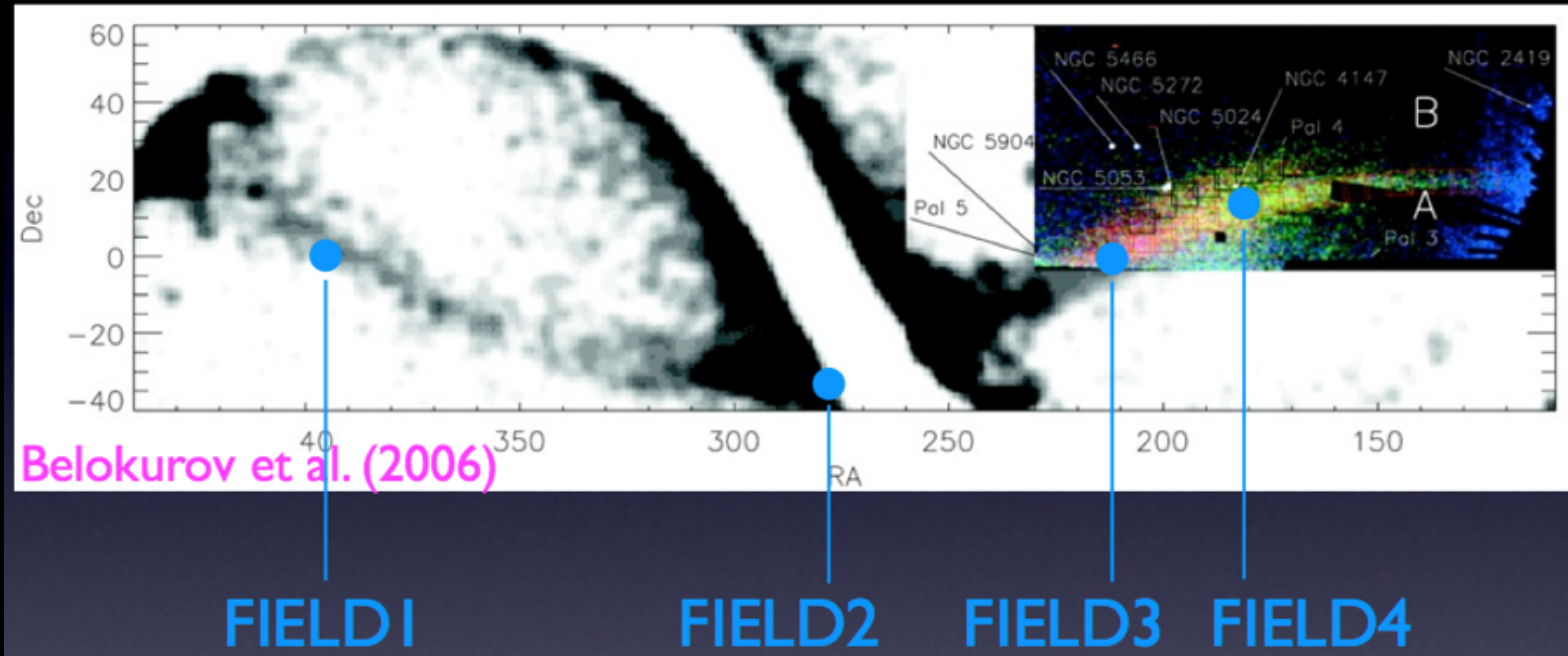
- Near-oblate, q = 0.72, short axis in disk plane!





Unexpected from galaxy formation models/sims (Debattista et al. 2012); see also Vera-Ciro & Helmi (2013)

HST Proper Motions

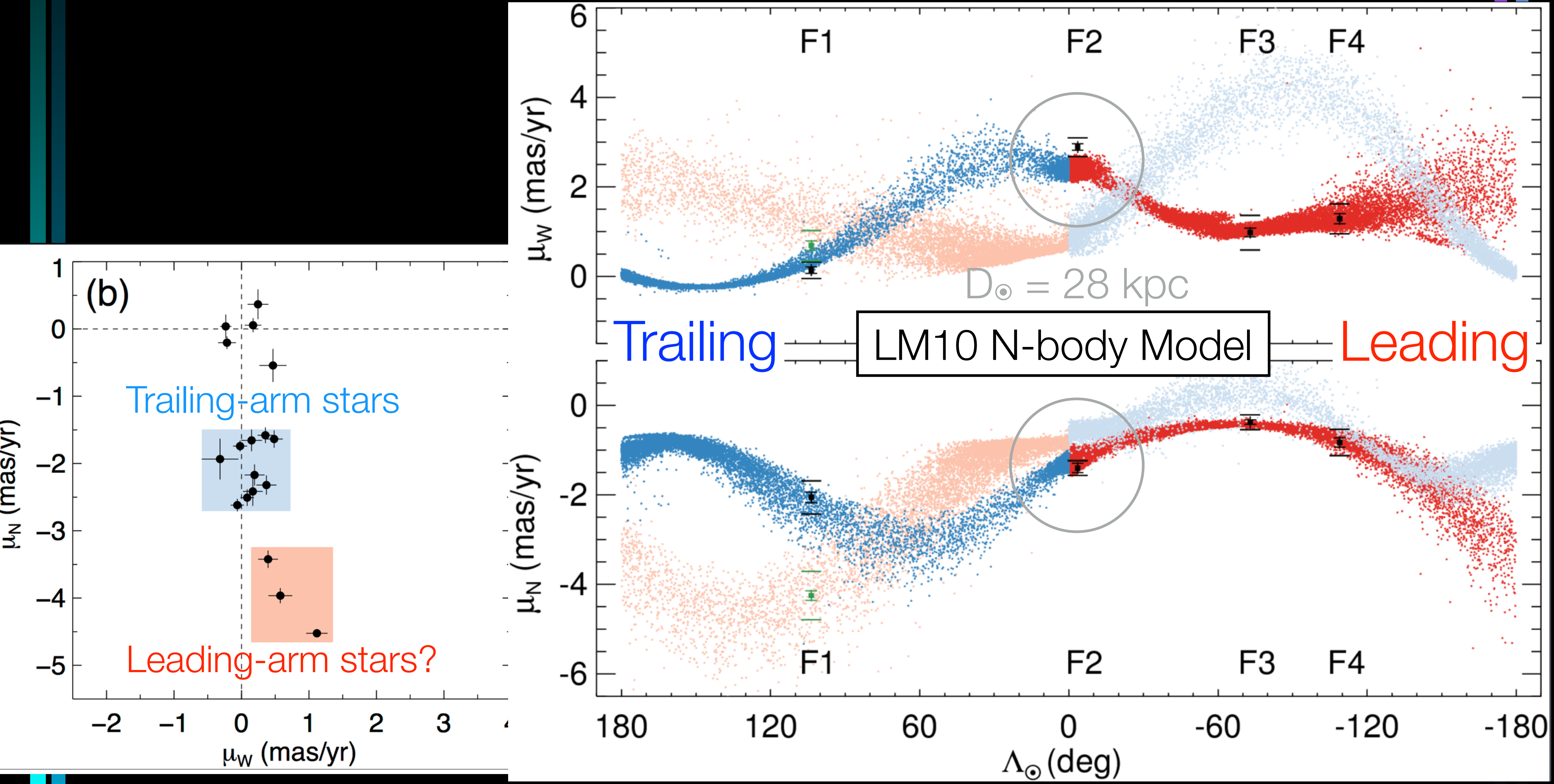


- HST w/ 6-9 year time baselines
- Two additional components of motion can strongly constrain models

PM to N-body Comparison

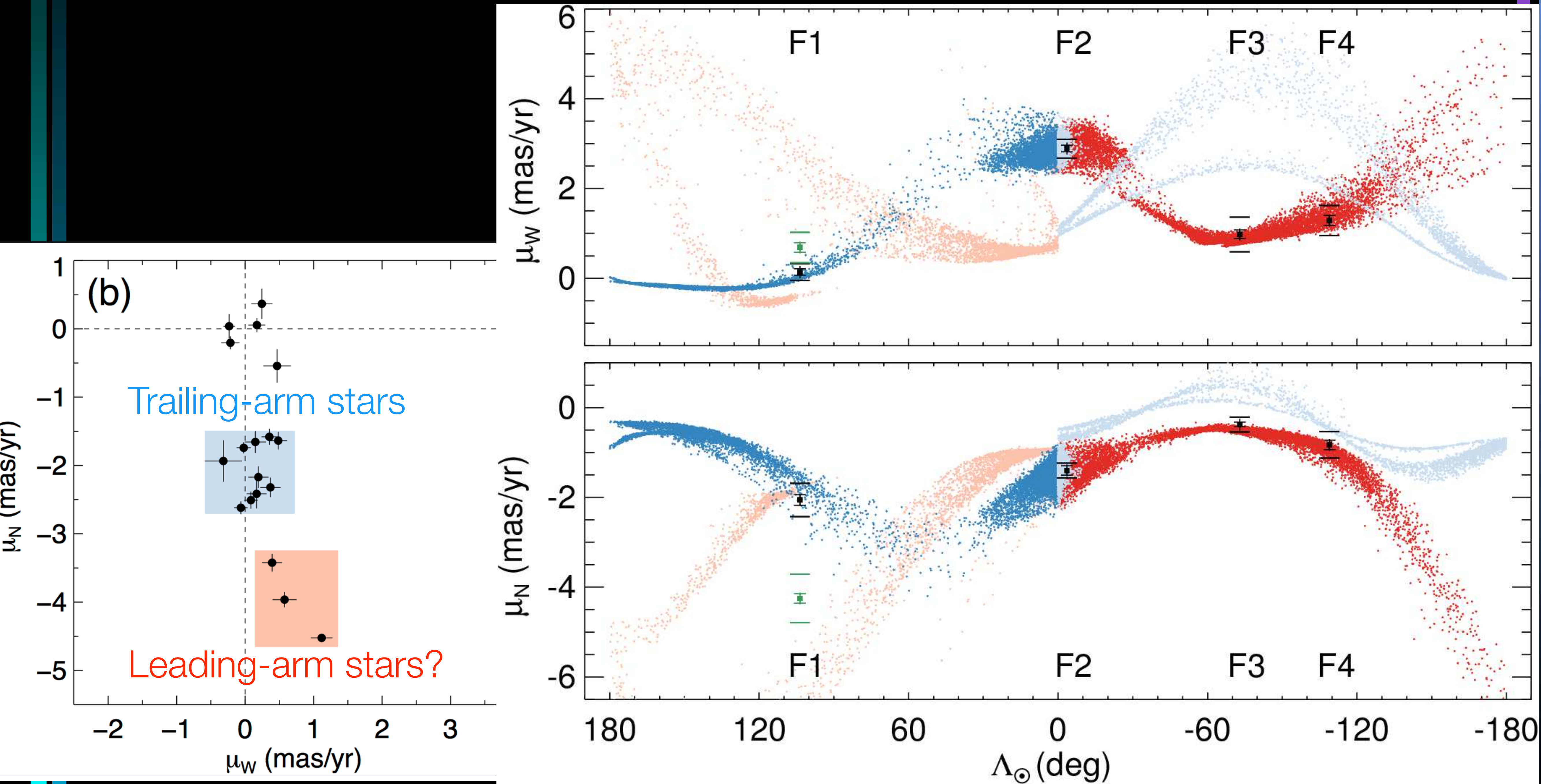
- Remarkably good fit ….

Sohn..,NK et al. 2015
Law & Majewski 2010



PM to N-body Comparison

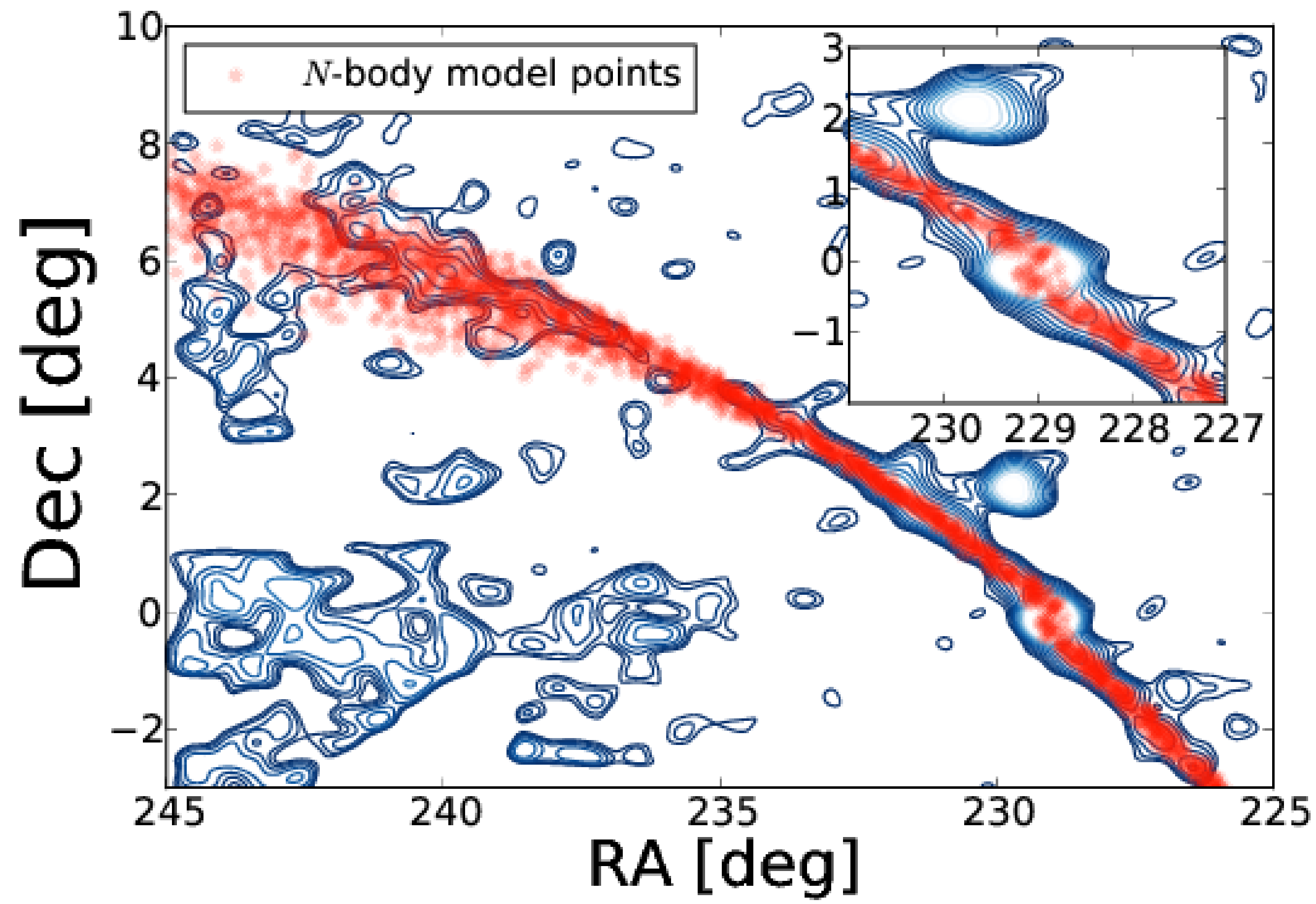
Sohn..,NK et al. 2015
Penarrubia et al. 2010

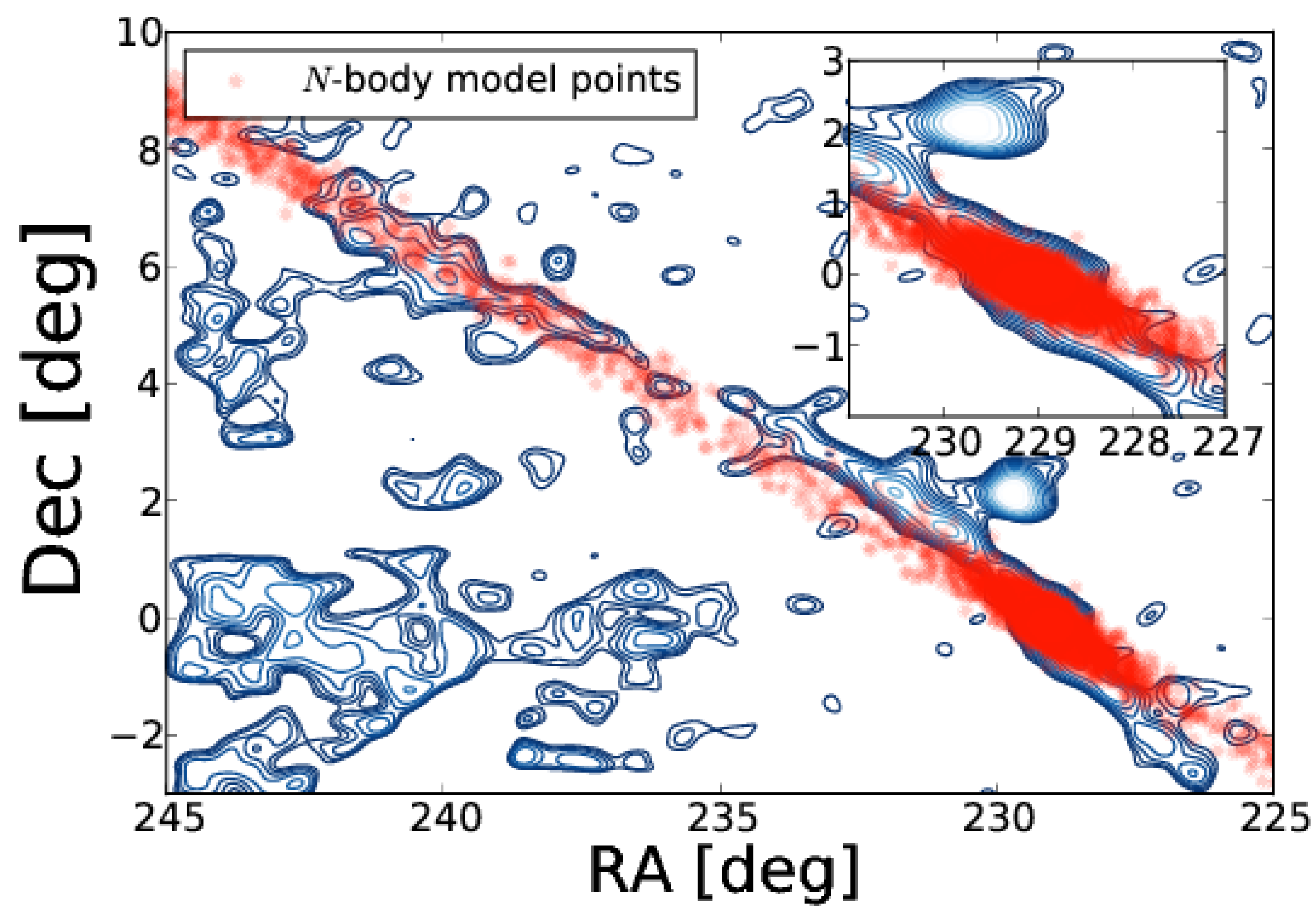


Even further down the luminosity function: Pal 5 Theory (Pearson+ 2014, Kupper et al. 2015)

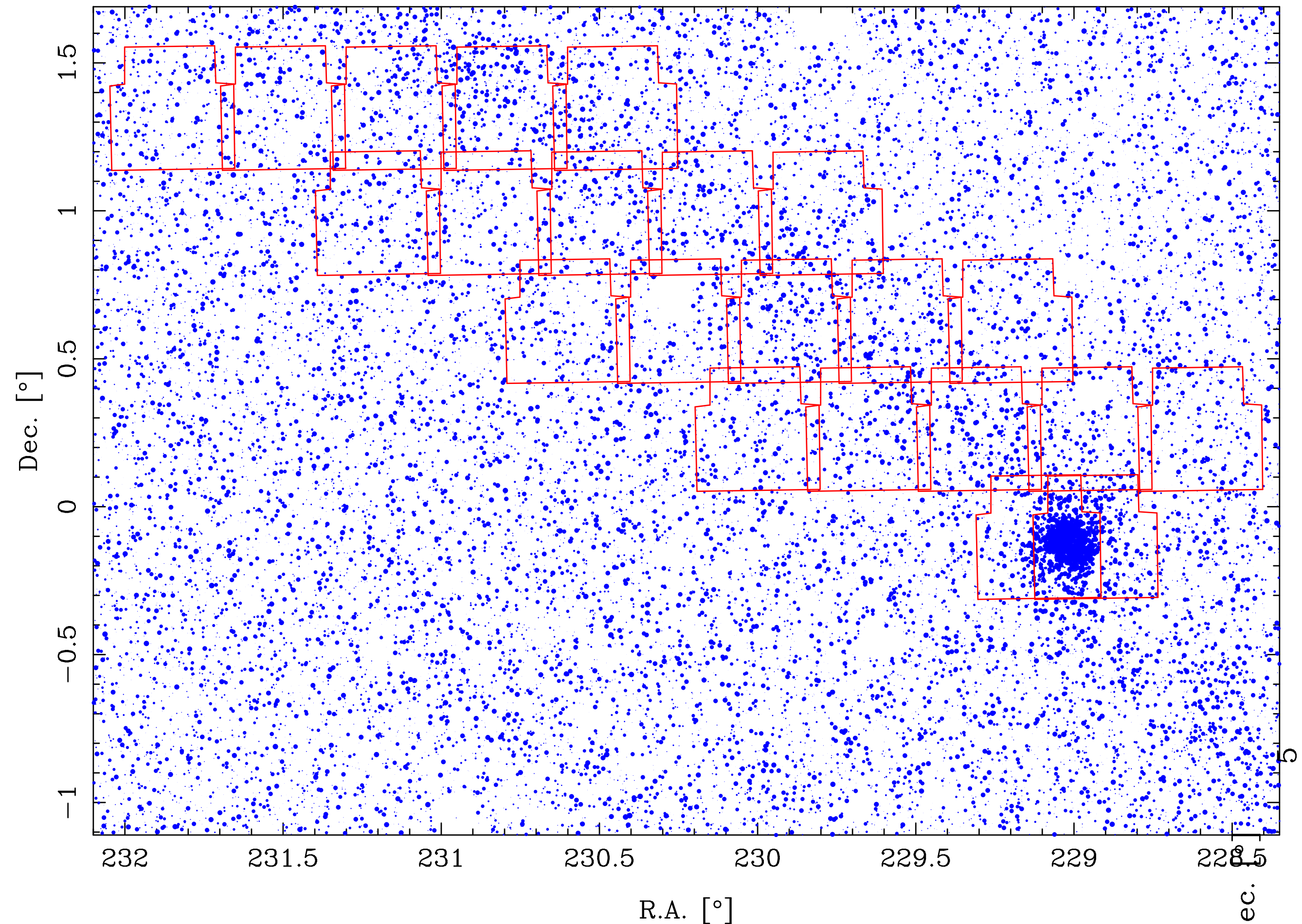
Best fit halo model is spherical, not the triaxial model of Law & Majewski.

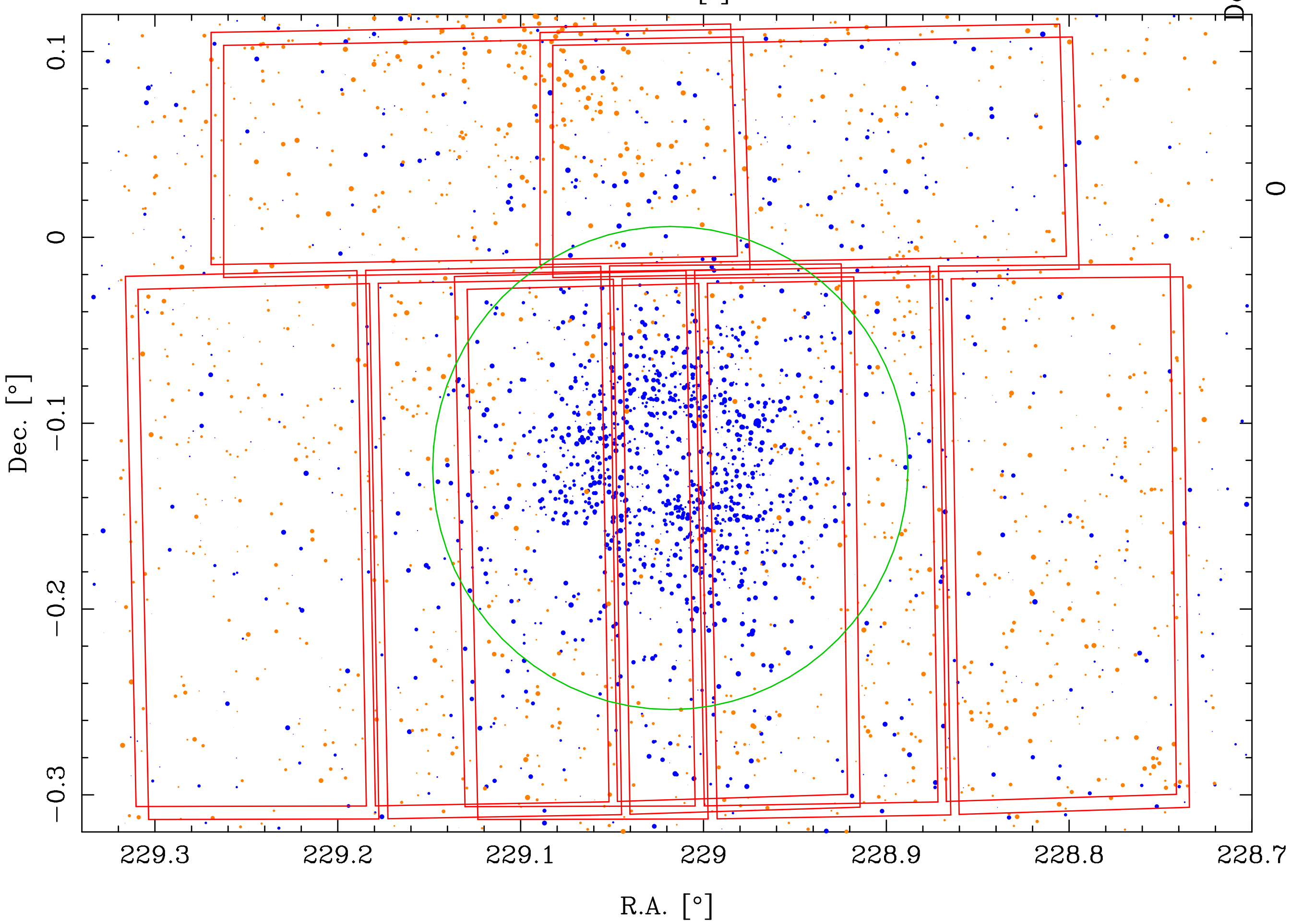
Tails hint at a pattern of over- and under-densities that have been attributed to sub-halo encounters (e.g. Siegel-Gaskins & Valluri 2008; Carlberg 2013).

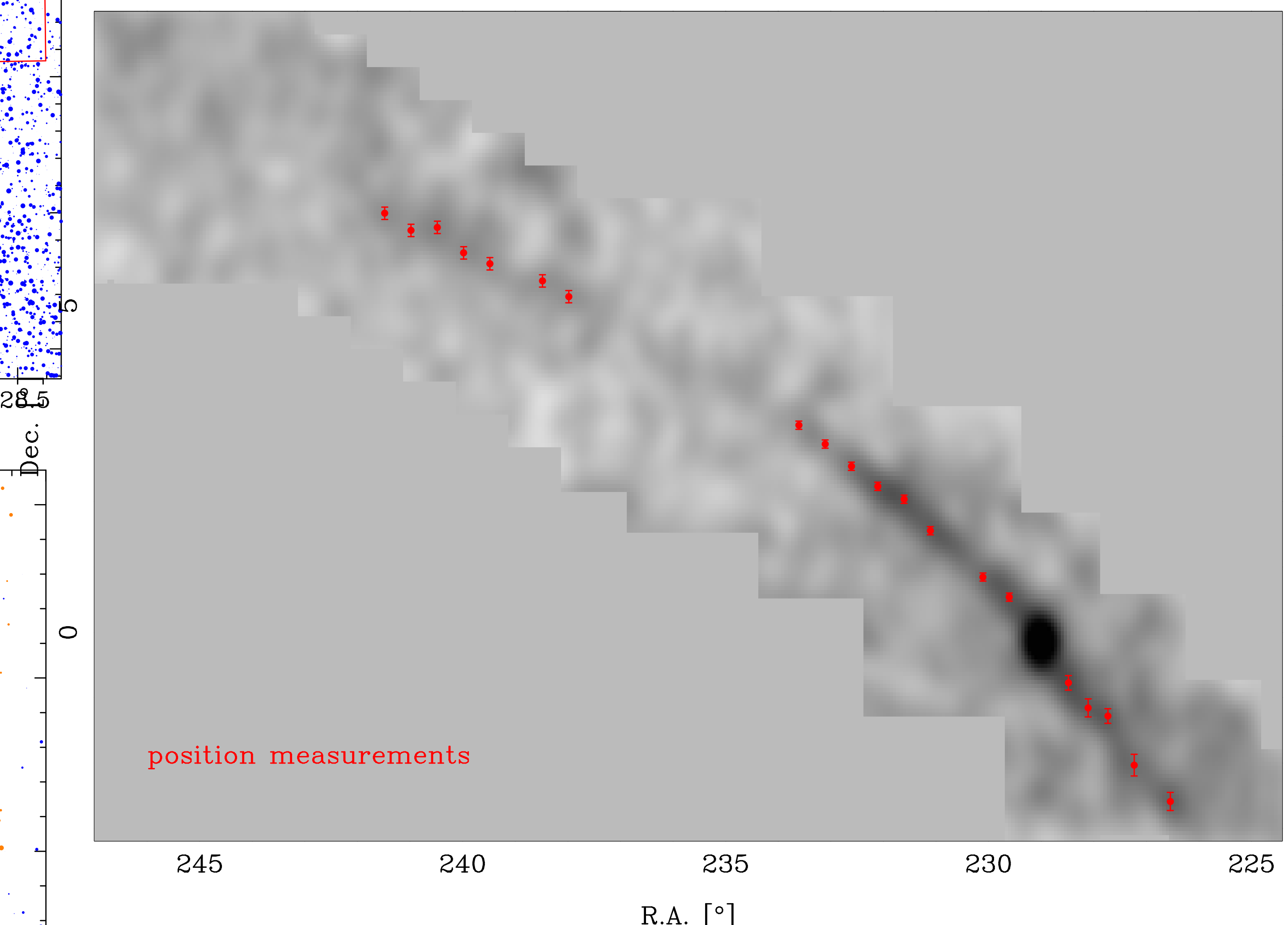




First CCD-based PM: SDSS-LBT/LBC Data 15 year baseline

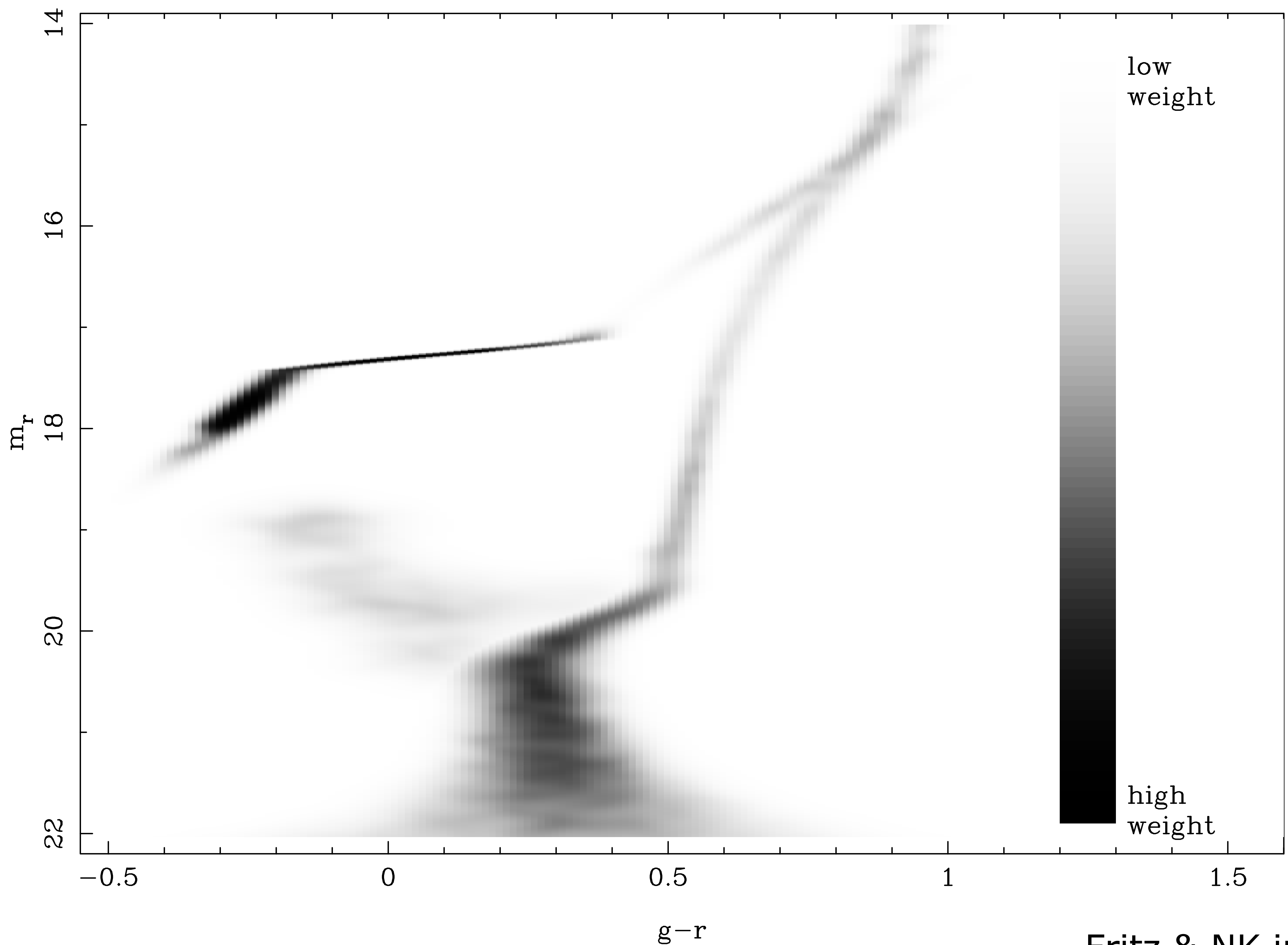




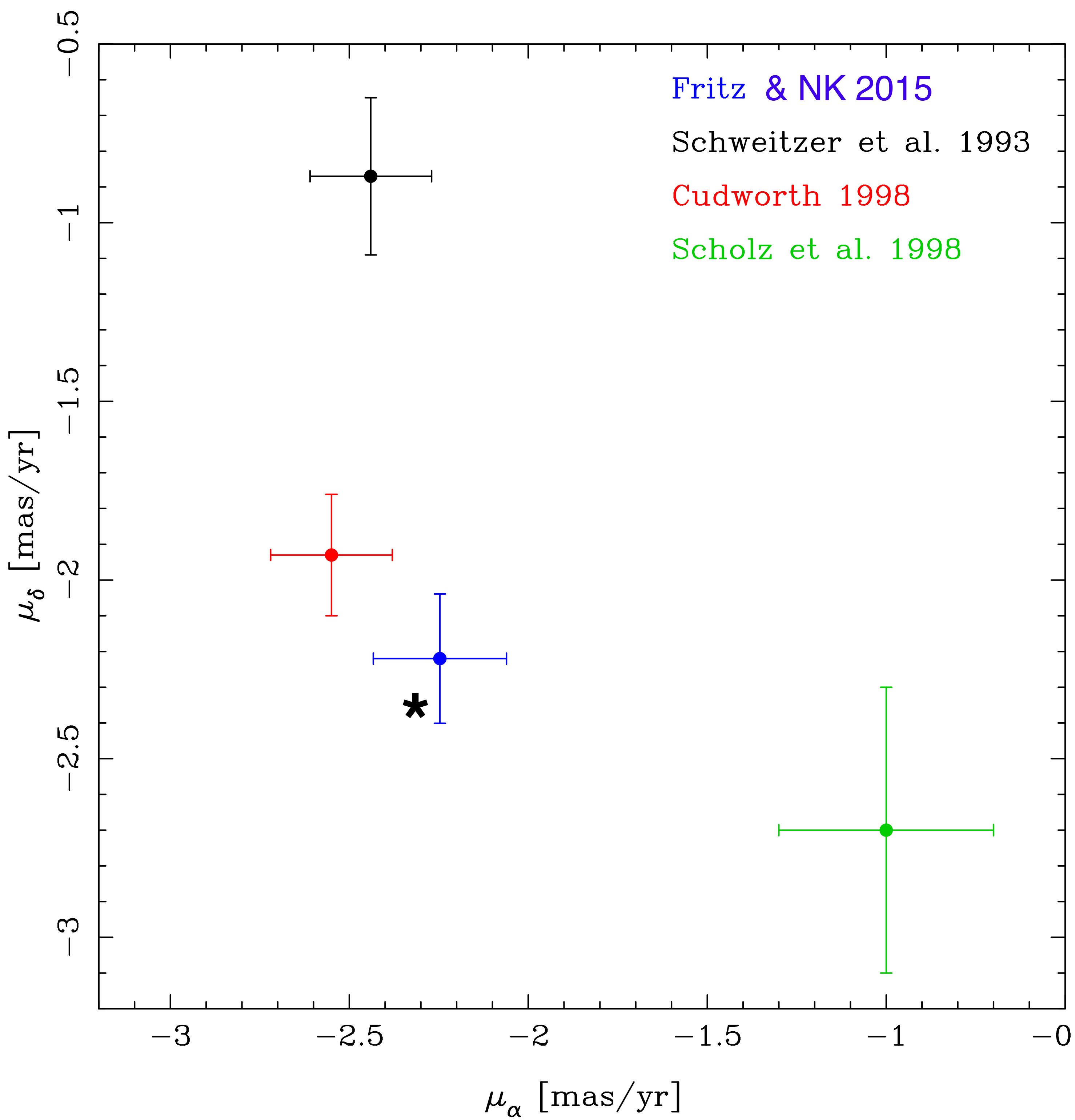


Fritz & NK submitted

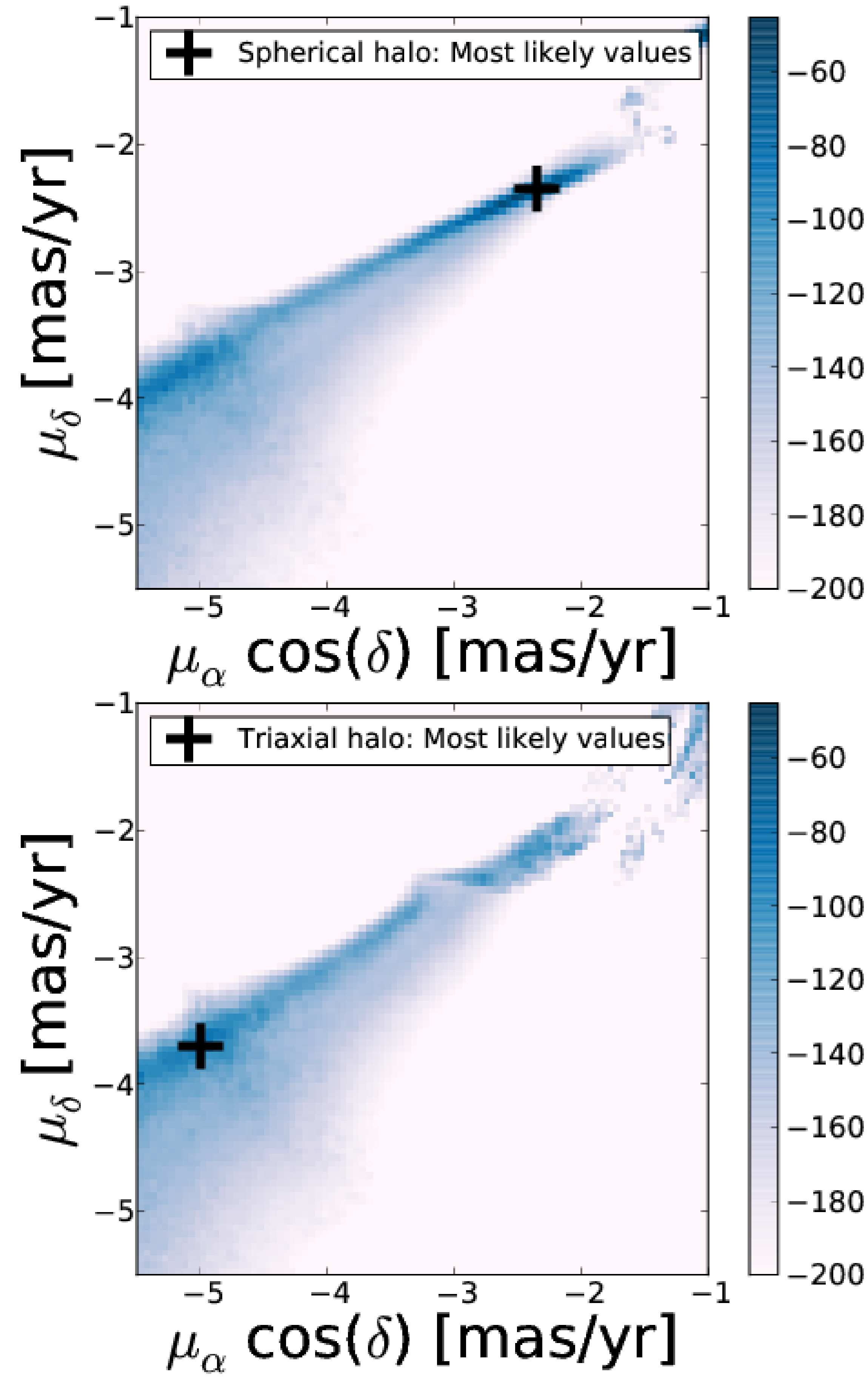
Ground-based PMs: stars must be selected by means of a matched filter



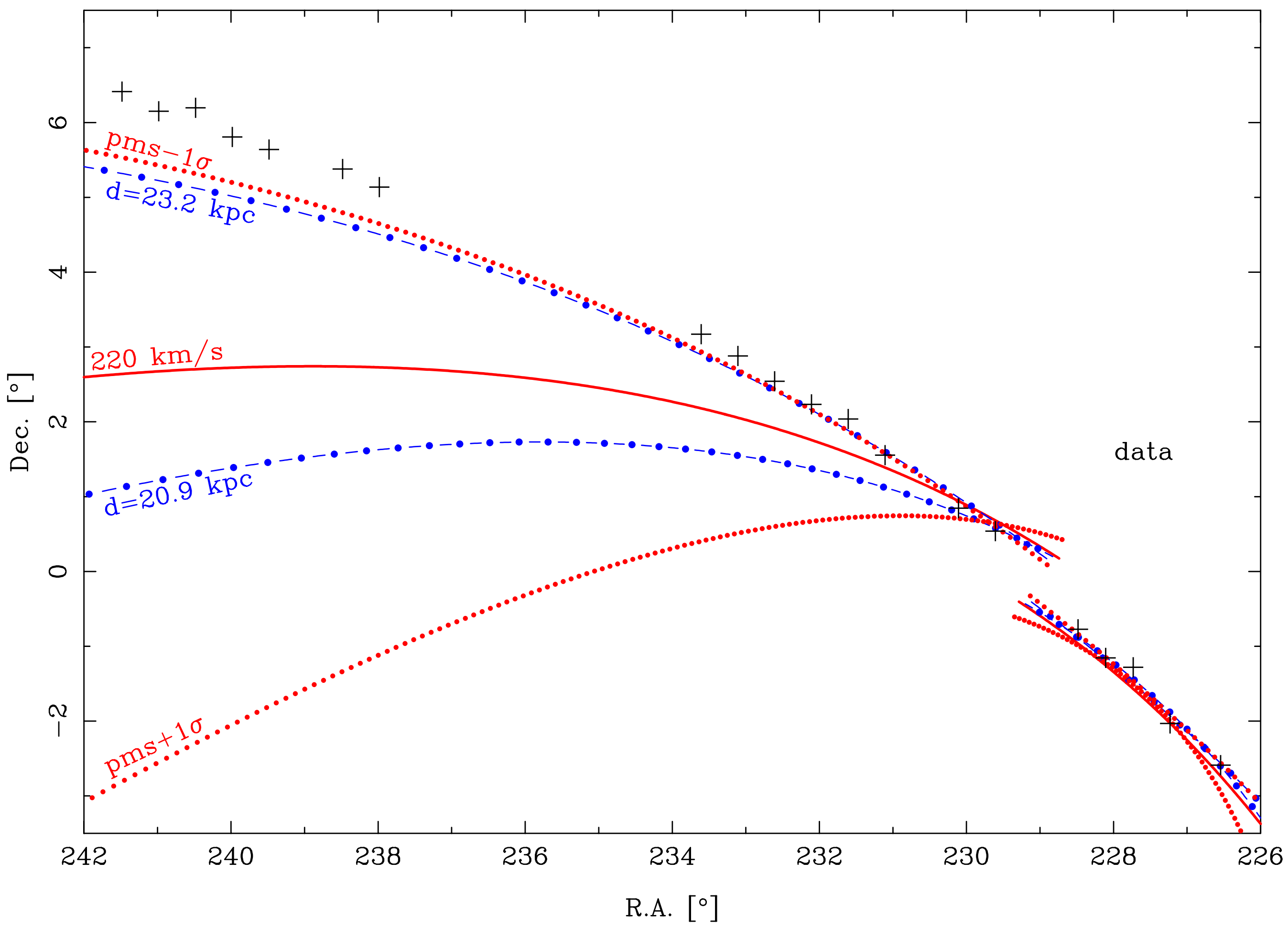
Fritz & NK in prep

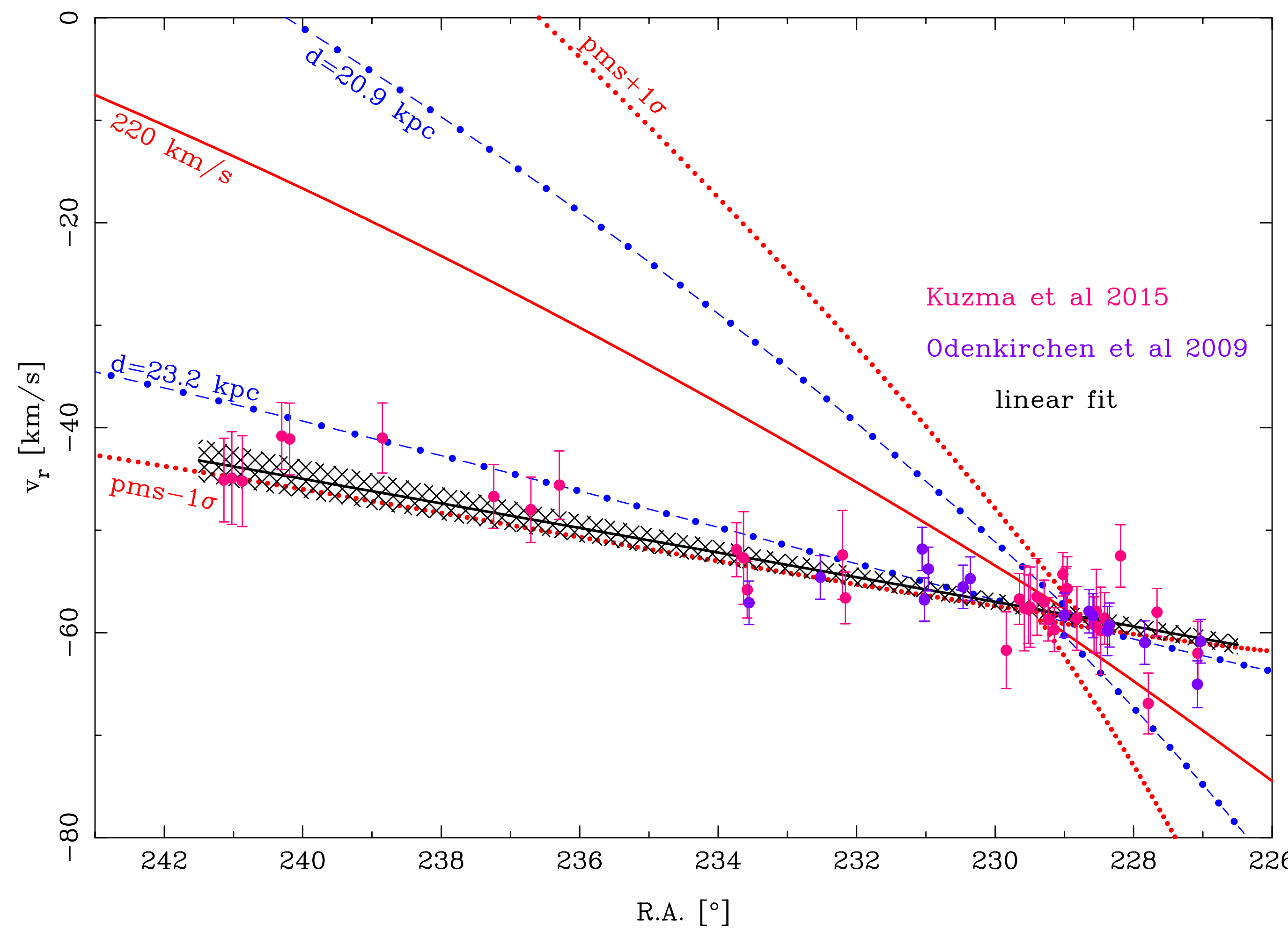


Fritz & NK submitted



Pearson et al. 2014





We use galpy (Bovy 2014). Spherical halo fits, but with preference for high distance.

A Hubble Astrometry Initiative: Laying the Foundation for the Next-Generation Proper-Motion Survey of the Local Group

White Paper for Hubble's 2020 Vision

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Michael Boylan-Kolchin (University of Maryland)
Alis J. Deason (UC Santa Cruz)
Tobias K. Fritz (University of Virginia)
Marla Geha (Yale University)
Sangmo Tony Sohn (Johns Hopkins University)
Erik J. Tollerud (Yale University)
Daniel R. Weisz (University of Washington)

March 4, 2015

Abstract

High-precision astrometry throughout the Local Group is a unique capability of the Hubble Space Telescope (HST), with potential for transformative science, including constraining the nature of dark matter, probing the epoch of reionization, and understanding key physics of galaxy evolution. While Gaia will provide unparalleled astrometric precision for bright stars in the inner halo of the Milky Way, HST is the only current mission capable of measuring accurate proper motions for systems at greater distances ($\gtrsim$ 80 kpc), which represents the vast majority of galaxies in the Local Group. The next generation of proper-motion measurements will require long time baselines, spanning many years to decades and possibly multiple telescopes, combining HST with the James Webb Space Telescope (JWST) or the Wide-Field Infrared Survey Telescope (WFIRST). However, the current HST allocation process is not conducive to such multi-cycle/multi-mission science, which will bear fruit primarily over many years. We propose an HST astrometry initiative to enable long-time-baseline, multi-mission science, which we suggest could be used to provide comprehensive kinematic measurements of all dwarf galaxies and high surface-density stellar streams in the Local Group with HST's Advanced Camera for Surveys (ACS) or Wide Field Camera 3 (WFC3). Such an initiative not only would produce forefront scientific results within the next 5 years of HST's life, but also would serve as a critical anchor point for future missions to obtain unprecedented astrometric accuracy, ensuring that HST leaves a unique and lasting legacy for decades to come.

Five science drivers that motivate a comprehensive proper-motion survey of the Local Group:

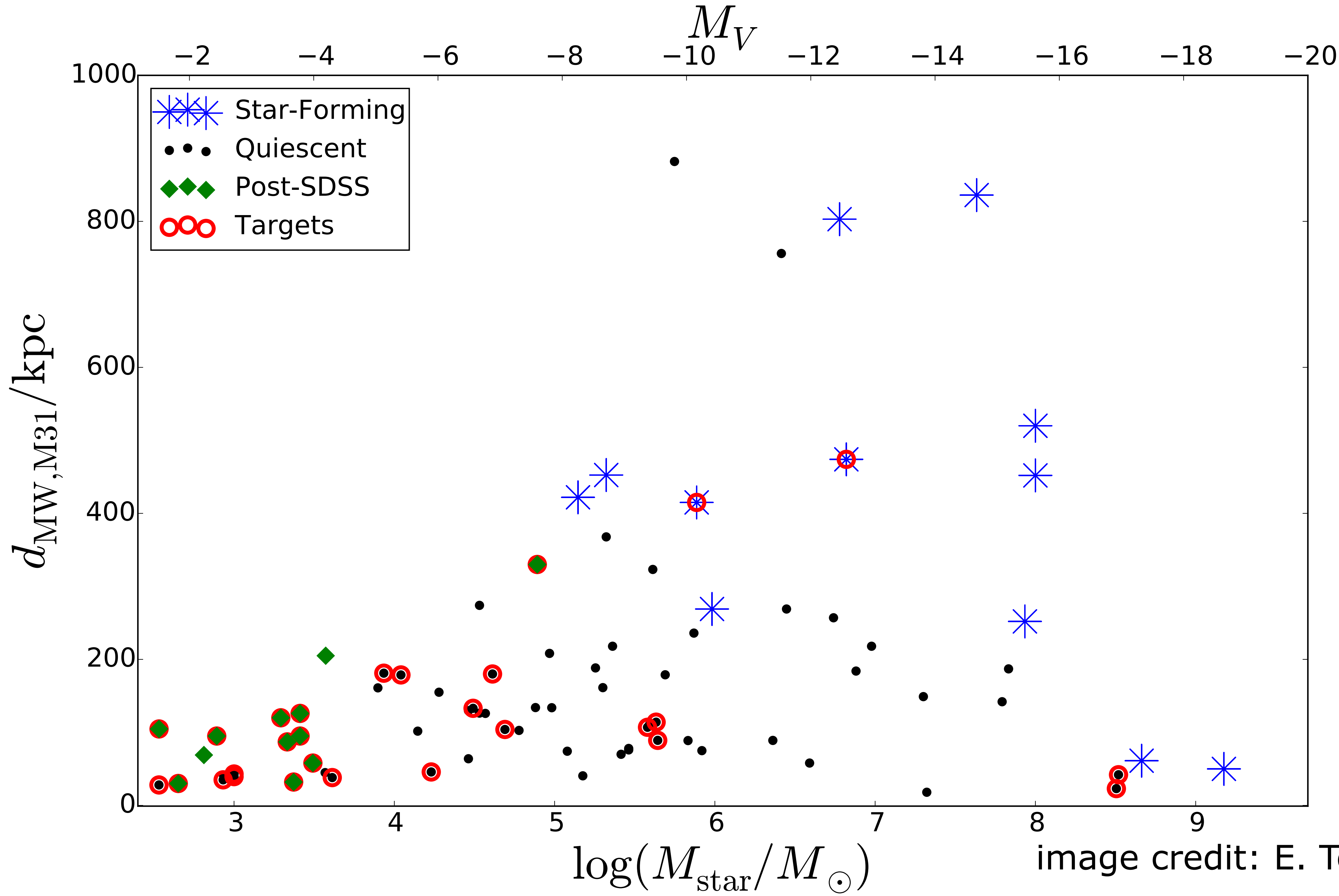
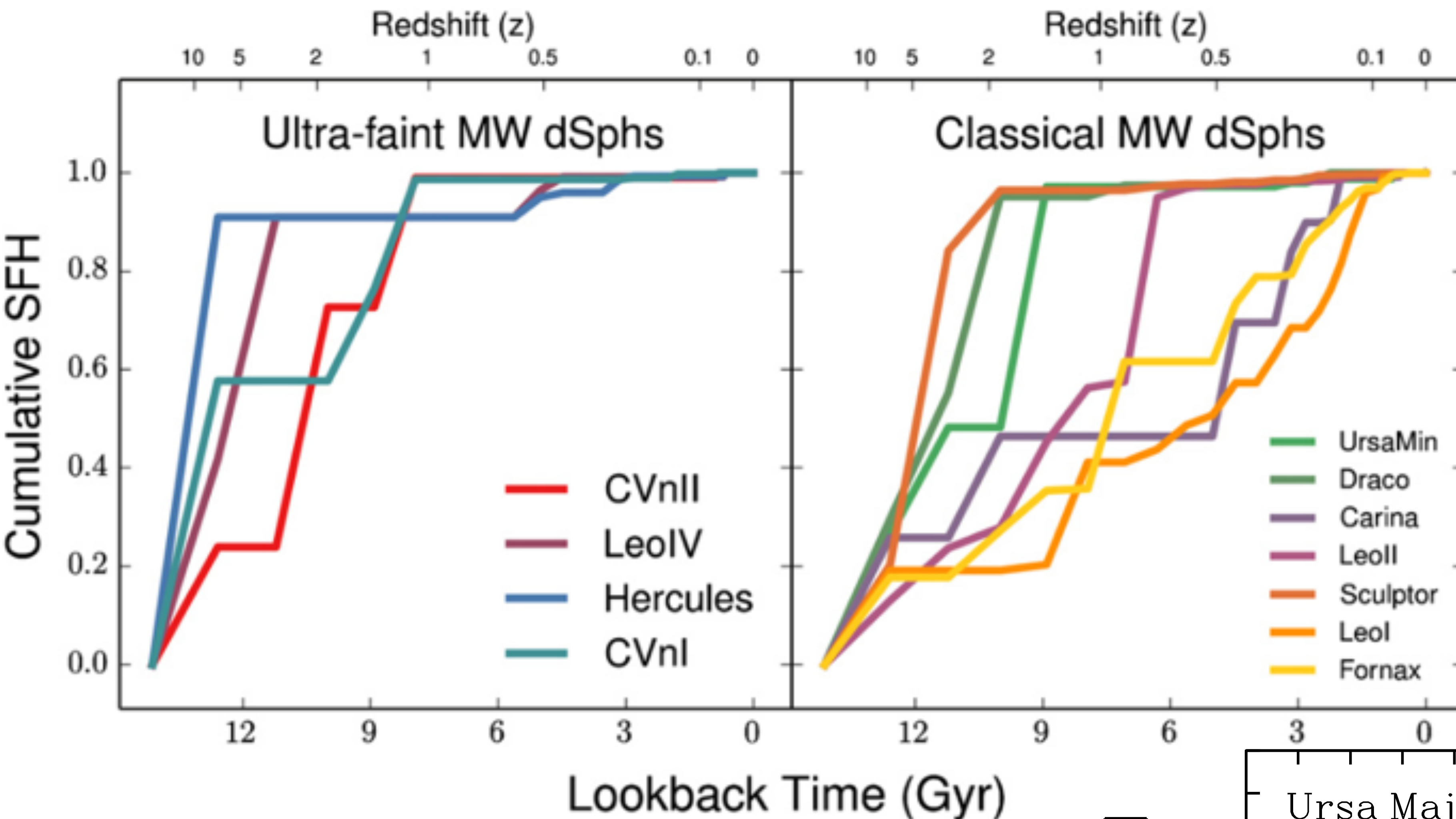


image credit: E. Tollerud

(1) Direct dynamical measurements of the mass of the Milky Way and M31.

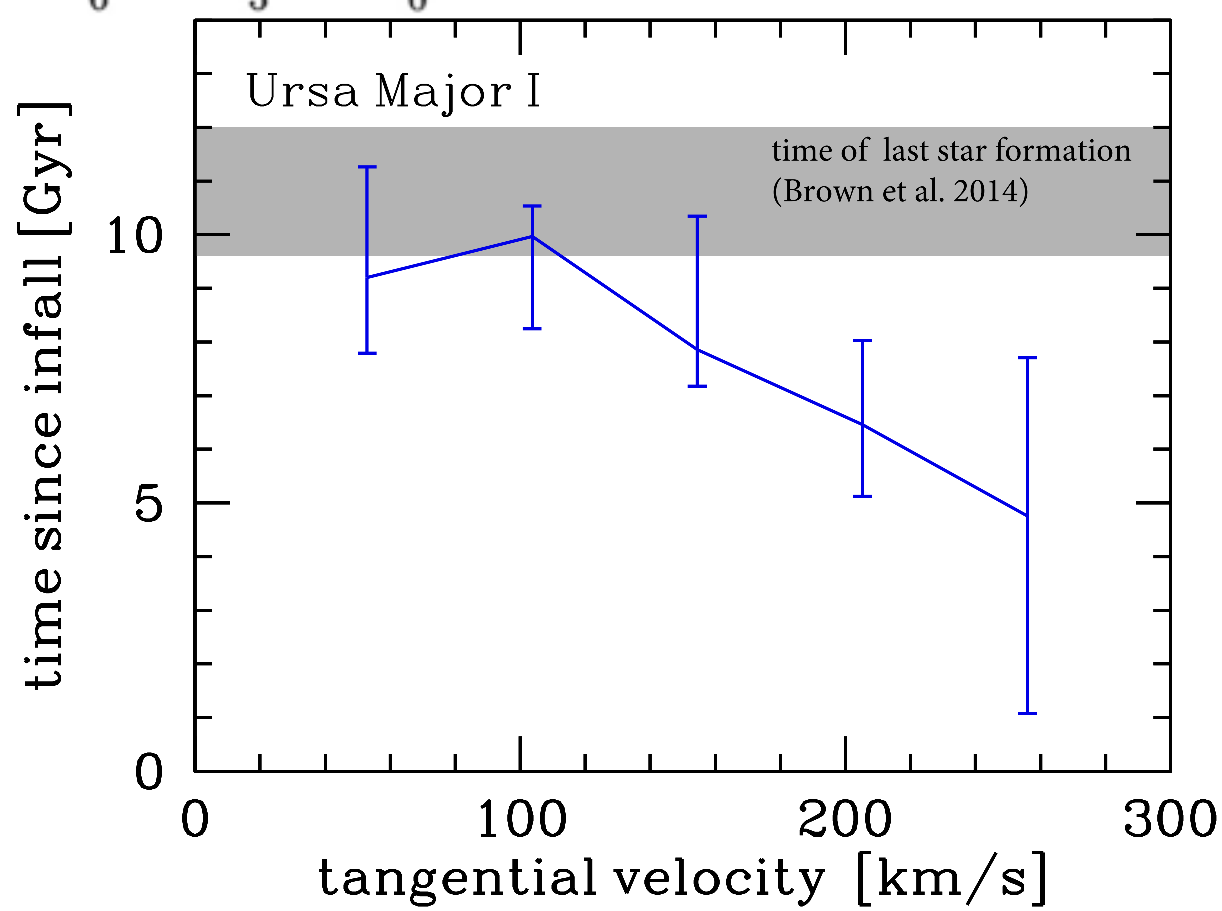
(2) Understanding the physics of environment on satellite galaxies.

(3) Physical associations of dwarf galaxies and stellar streams, i.e. "planes of galaxies".

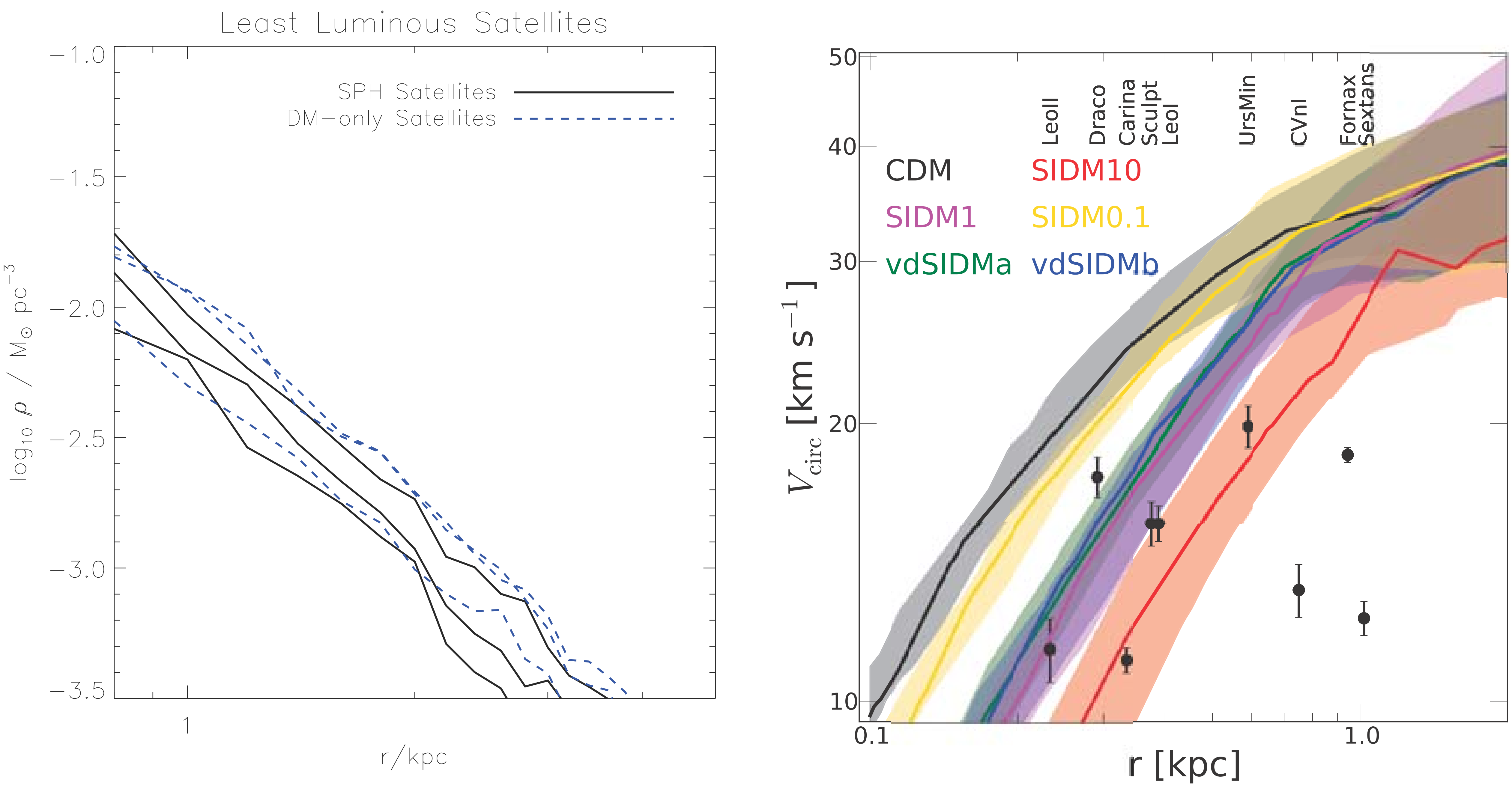


Brown et al. 2014, Weisz et al. 2014

(4) Dwarf galaxies as probes of cosmic reionization.



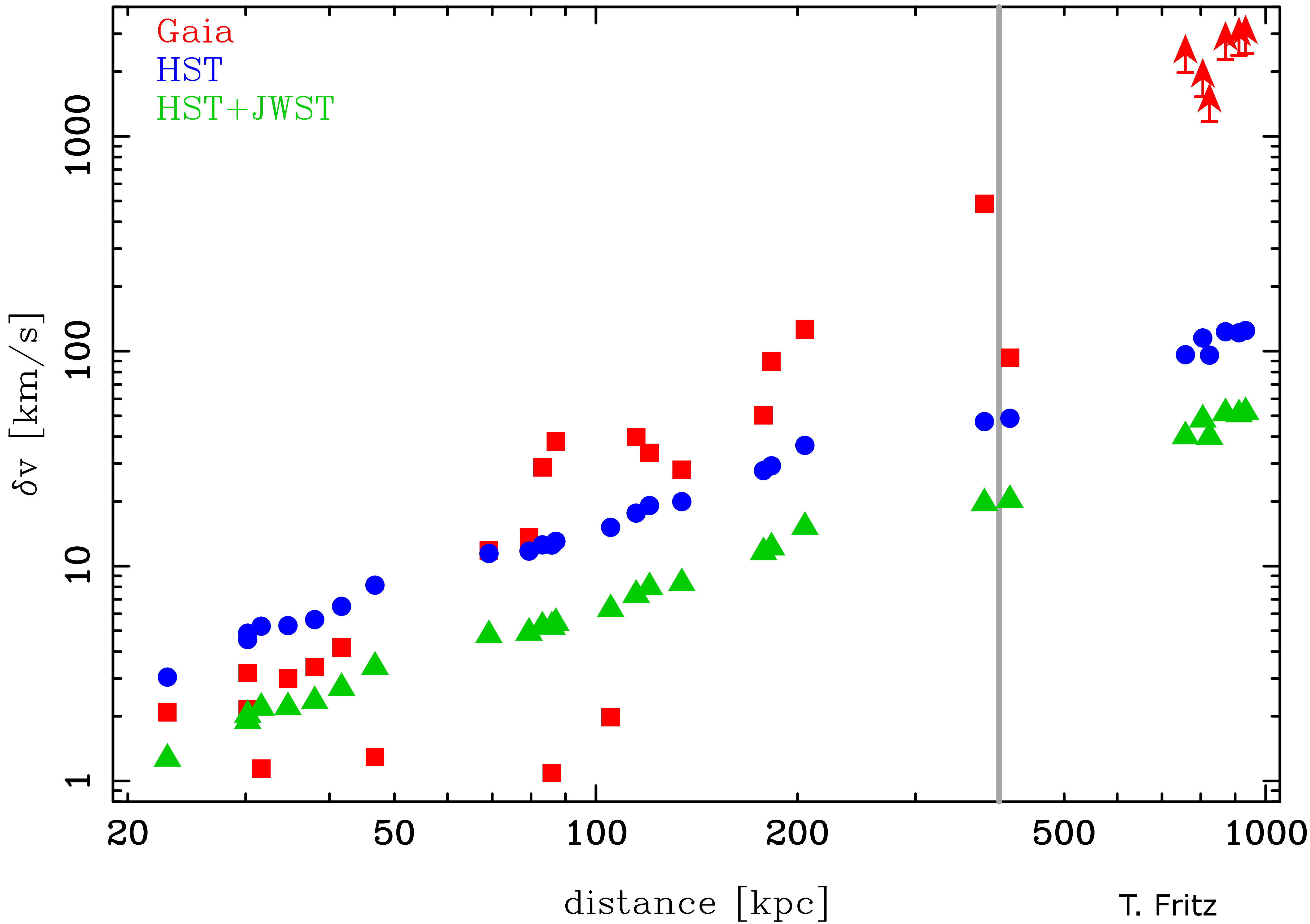
Wetzel et al. in prep.



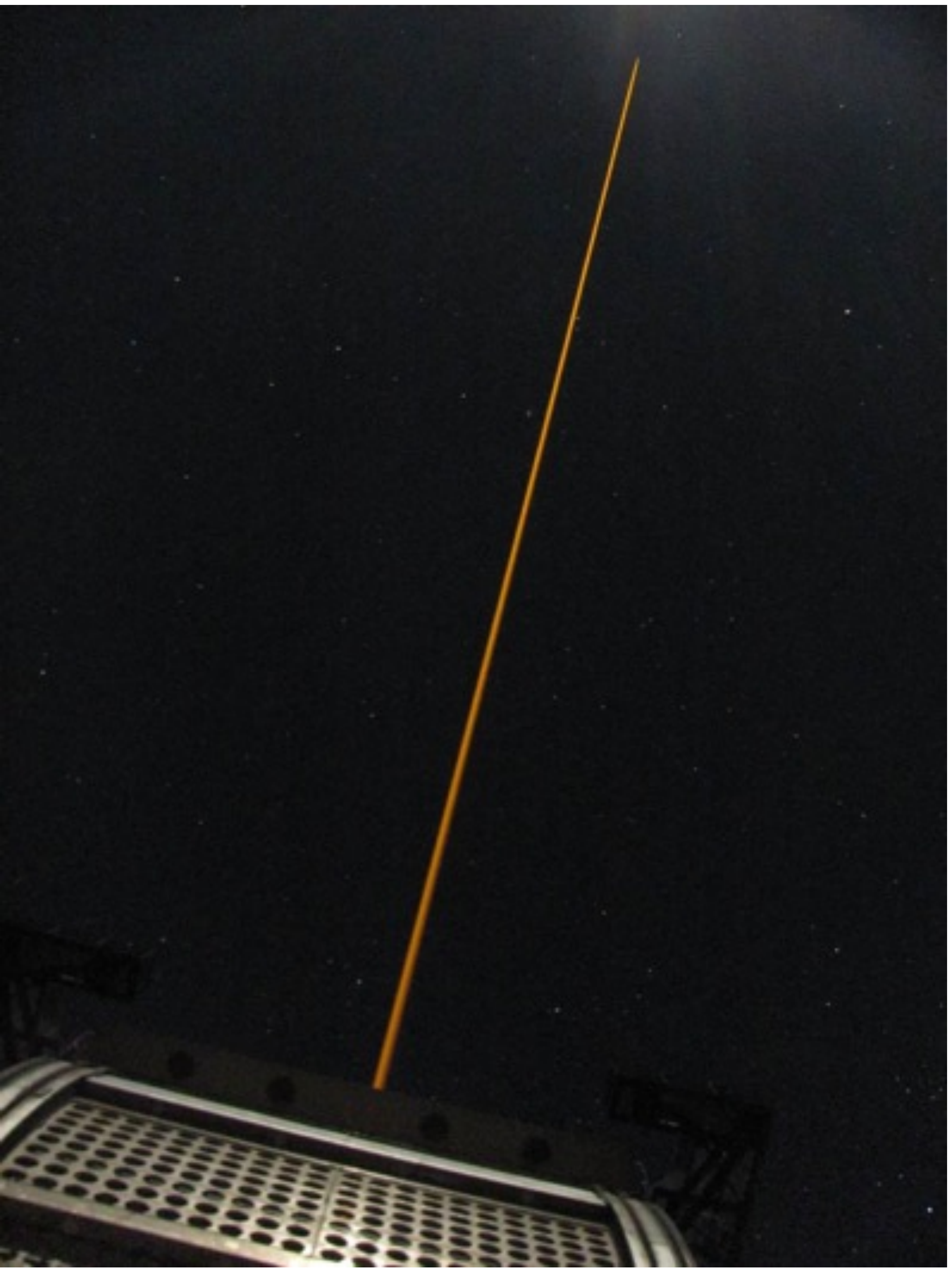
From Alyson Brooks: Zolotov et al. 2012; Zavala et al. 2013

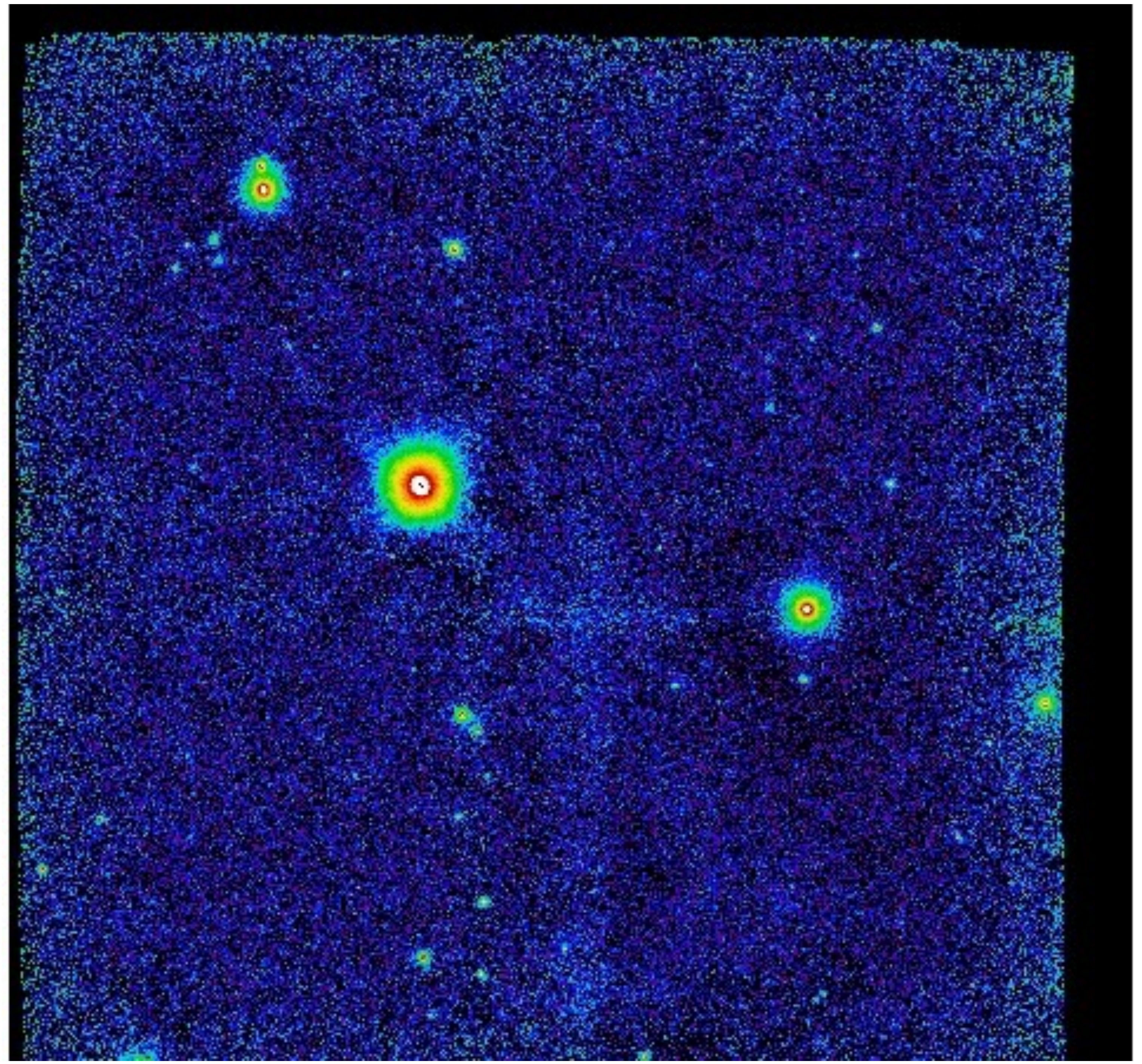
(5) Internal kinematics of dwarf galaxies. The inner mass profile of dwarfs perhaps the most important test of the nature of dark matter, as well as the strength of galactic feedback.

What will Gaia do?

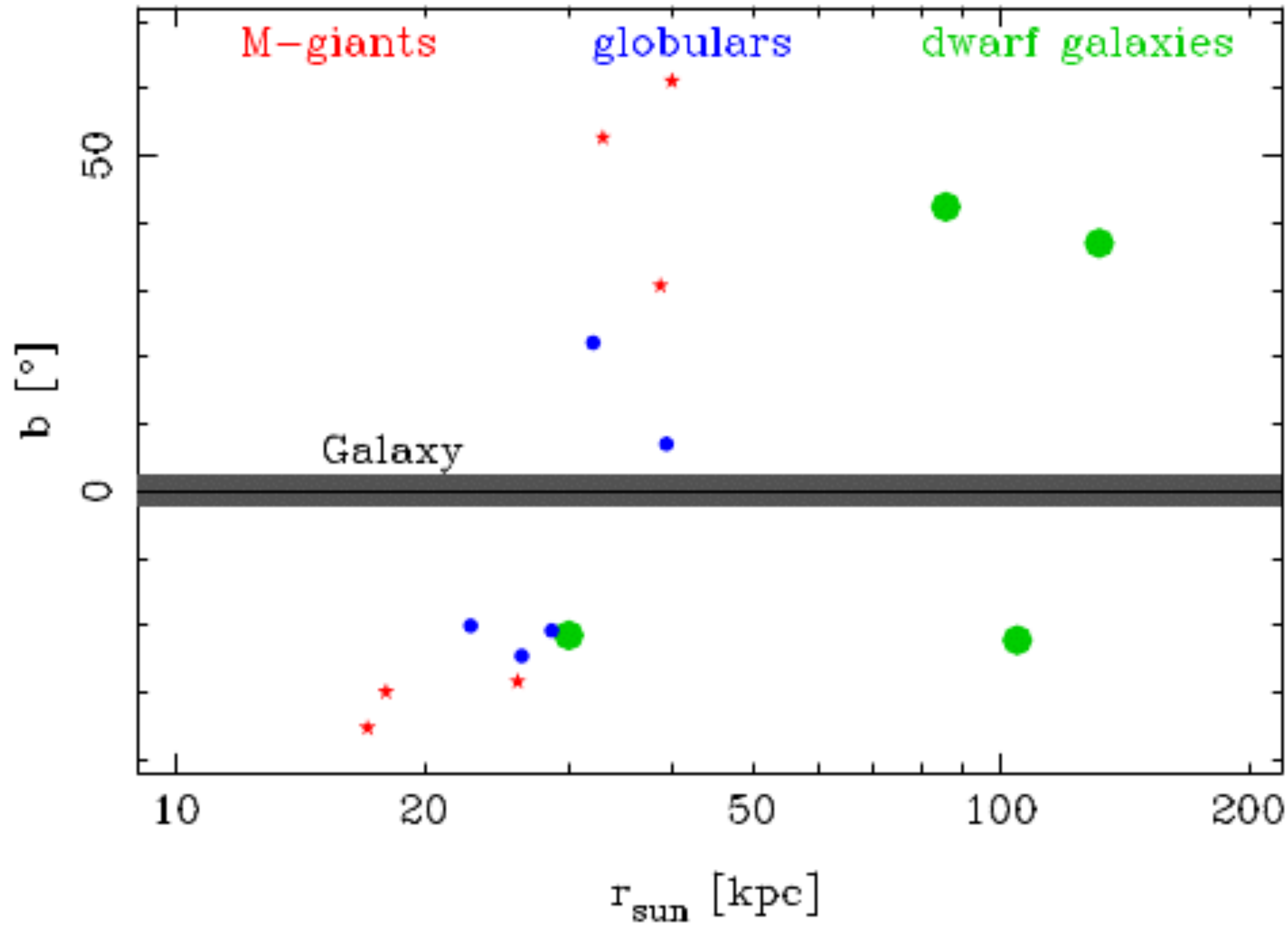


Probing the dark halo of the Milky Way with GeMS/GSAOI



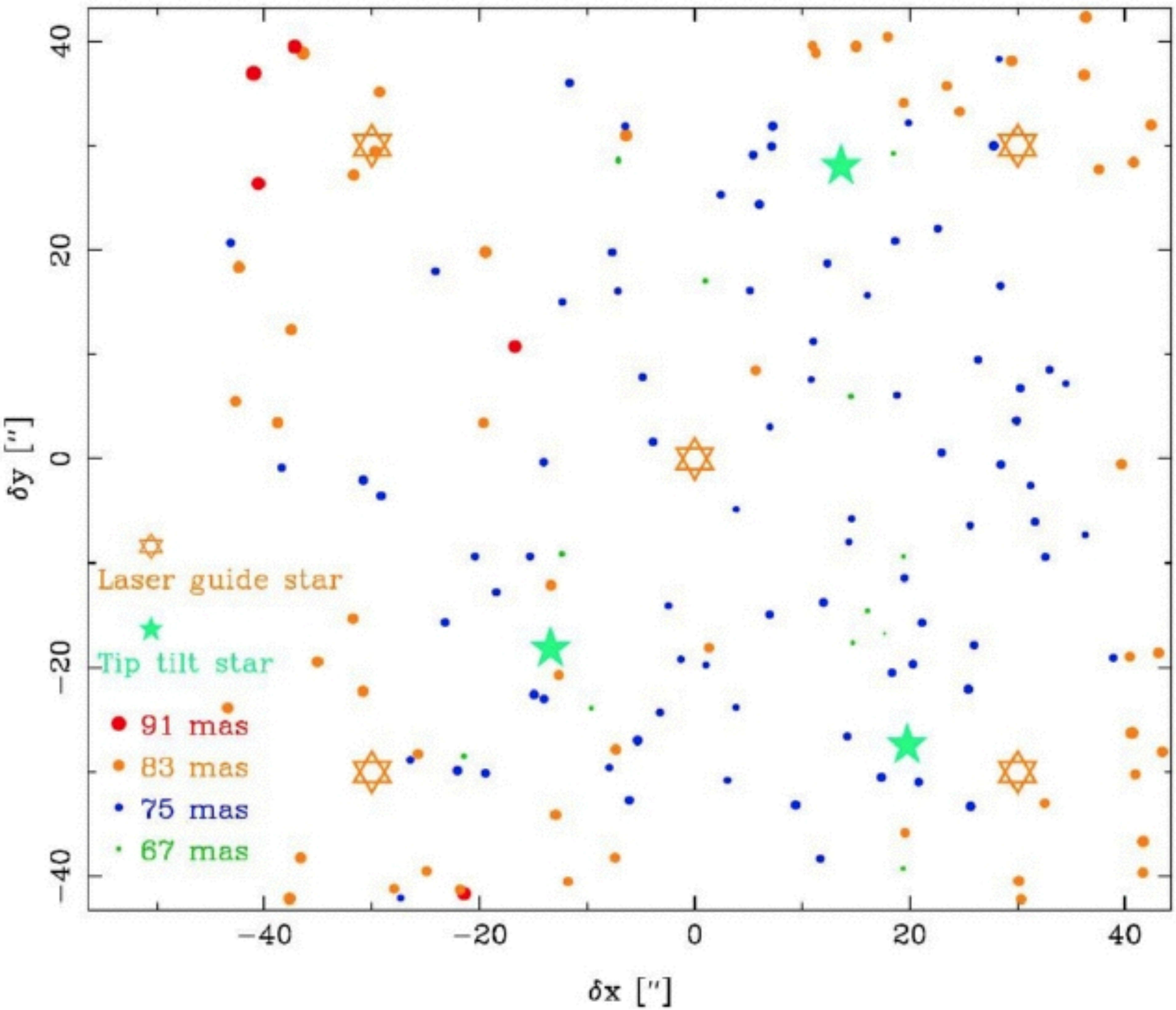


T. Fritz, N. Kallivayalil, S. Majewski, G. Damke, R. Beaton, J. Bovy, M. Boylan-Kolchin, R. Carrasco, R. van der Marel, T. Sohn, R. Davies, D. Angell, P. Zivick, B. Neichel



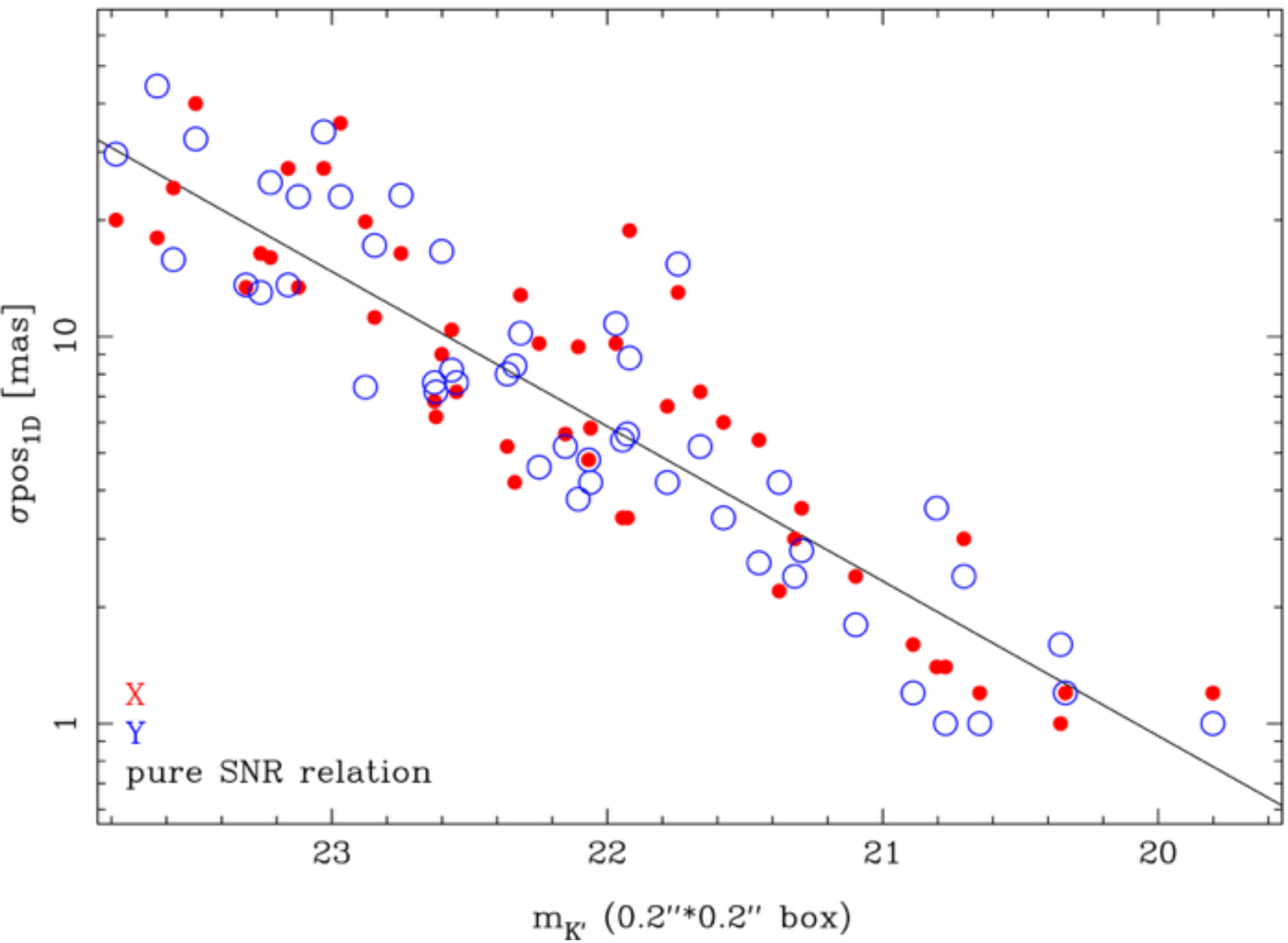
- 15 targets
- 6 M-giants in the Sagittarius stream
- 5 globular clusters:
  - 3 possible members of Sagittarius system: Arp 2, Terzan 7, Terzan 8
  - 2 others in outer halo: NGC5824, Pyxis
- 4 dwarf galaxies:
  - Sagittarius, Hercules, Sextant, Carina

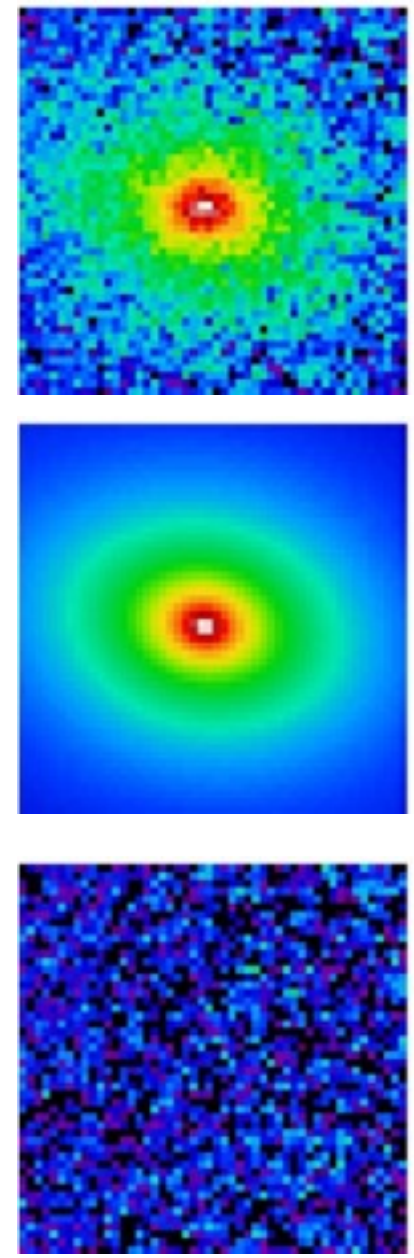
High image quality: FWHM of 79 mas



Pyxis field 1 K'-band

Position uncertainty of galaxies





Image

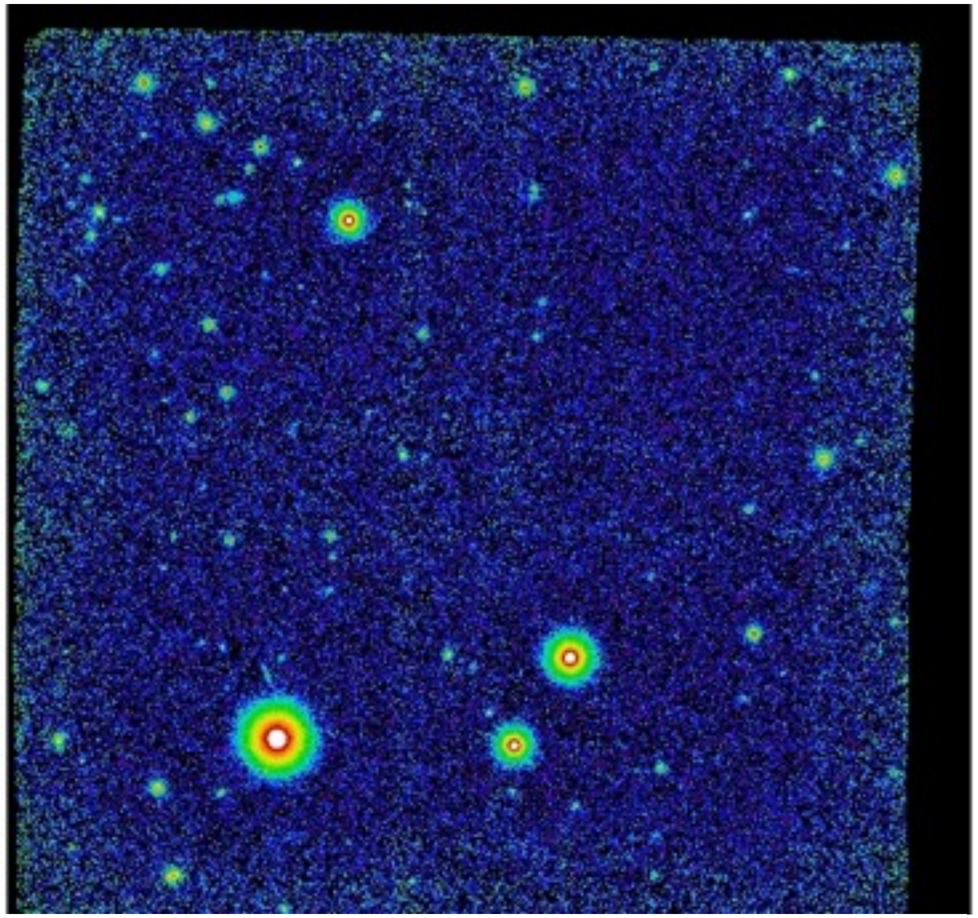
Model

Residuals

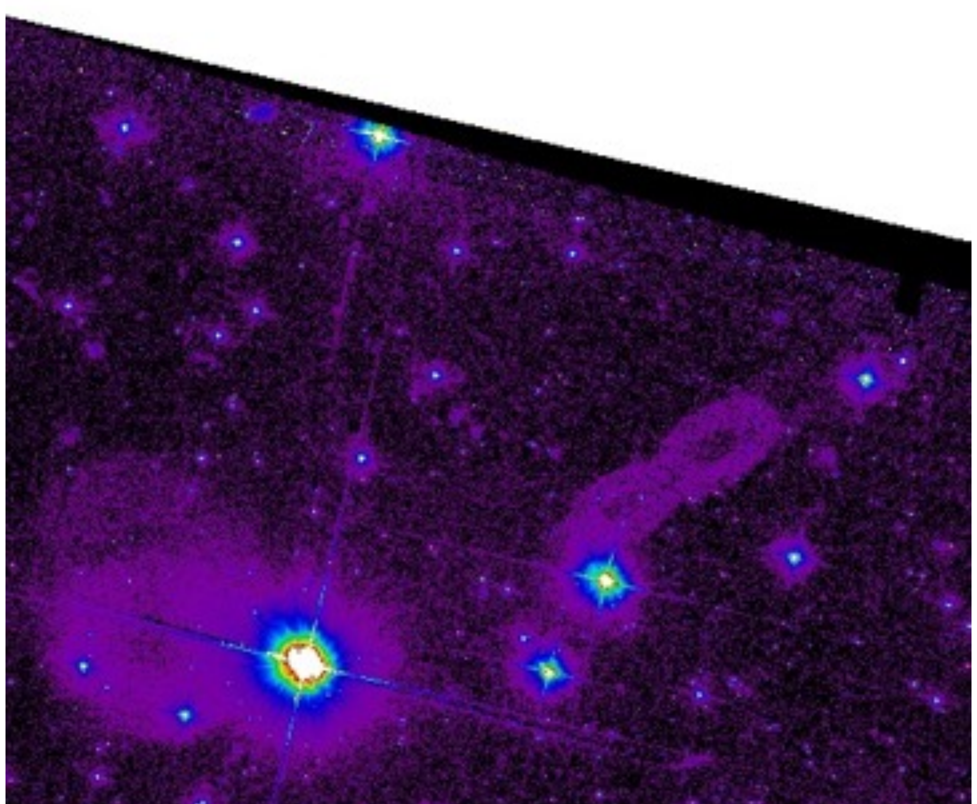
- Pyxis
- Position fit: single Sersic with Galfit
- Results in total registration error of ~0.3 mas.
- → total proper motion error of ~0.15 mas/yr per target

(Preliminary)

Pyxis Field 1: HST + Gemini

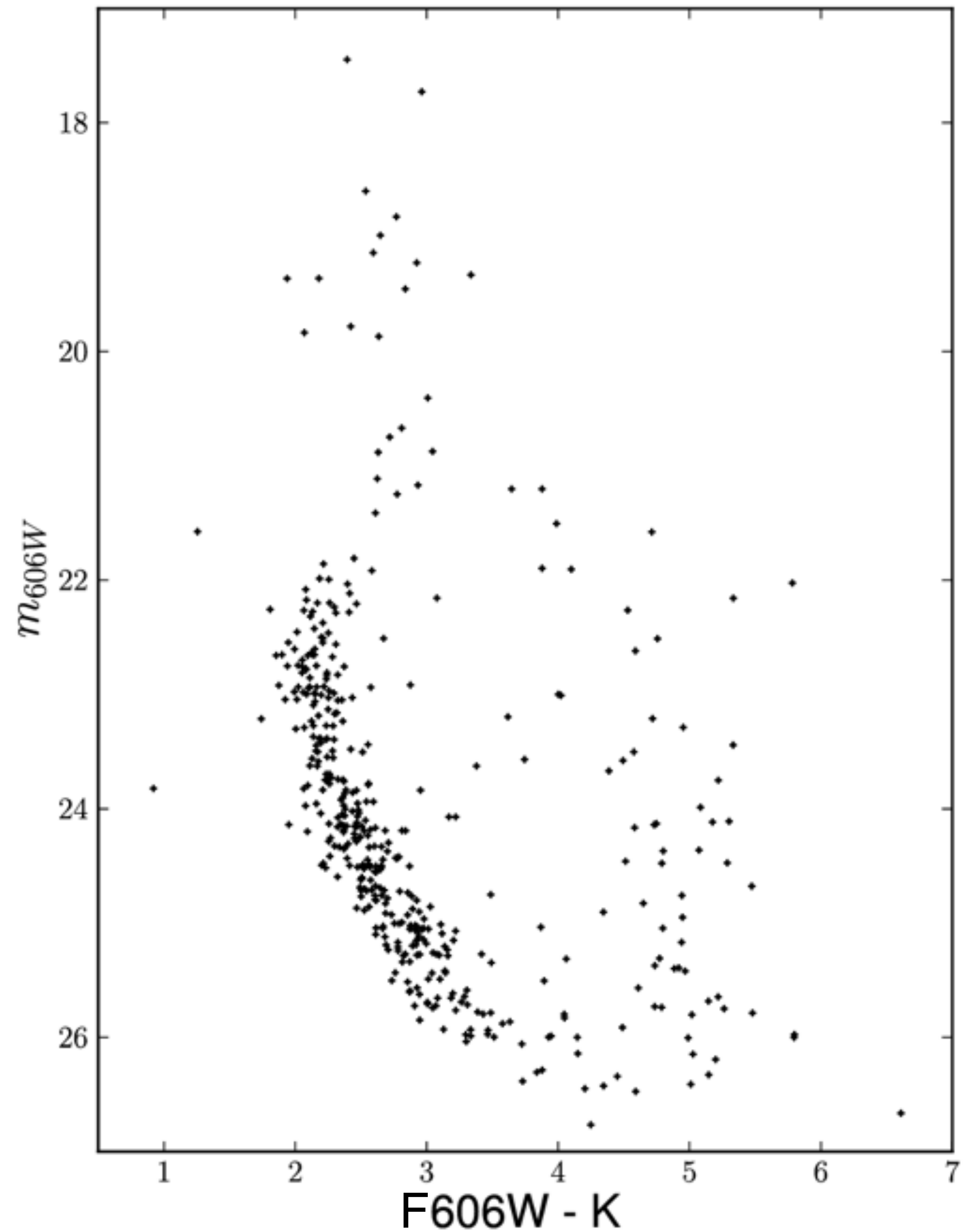


K' GSAOI
2015



F606W ACS
2009

(Preliminary)



Conclusions

- At HST precision it is possible to separate out substructure via PMs alone. Expensive.
- Ground-based efforts can compete if there is wide coverage of stream. Much cheaper. RV's and chemistries can greatly aid ground-based PM efforts. We have a first result for Pal 5.
- Models have come a long way. Realistic treatment of errors as well as stream-orbit offsets (Bovy 2014, Lux et al. 2013, et al. 1999, Eyre & Binney 2011, Varghese et al. 2011)
- Many stars with low accuracy vs. few targets with very high accuracy? e.g., SDSS-PanSTARRs or some other large FOV imager.
- Beyond Gaia/inner halo: HST - AO provides a powerful way to obtain very high precision motions in the outer halo (for a few stars) in a relatively efficient way.