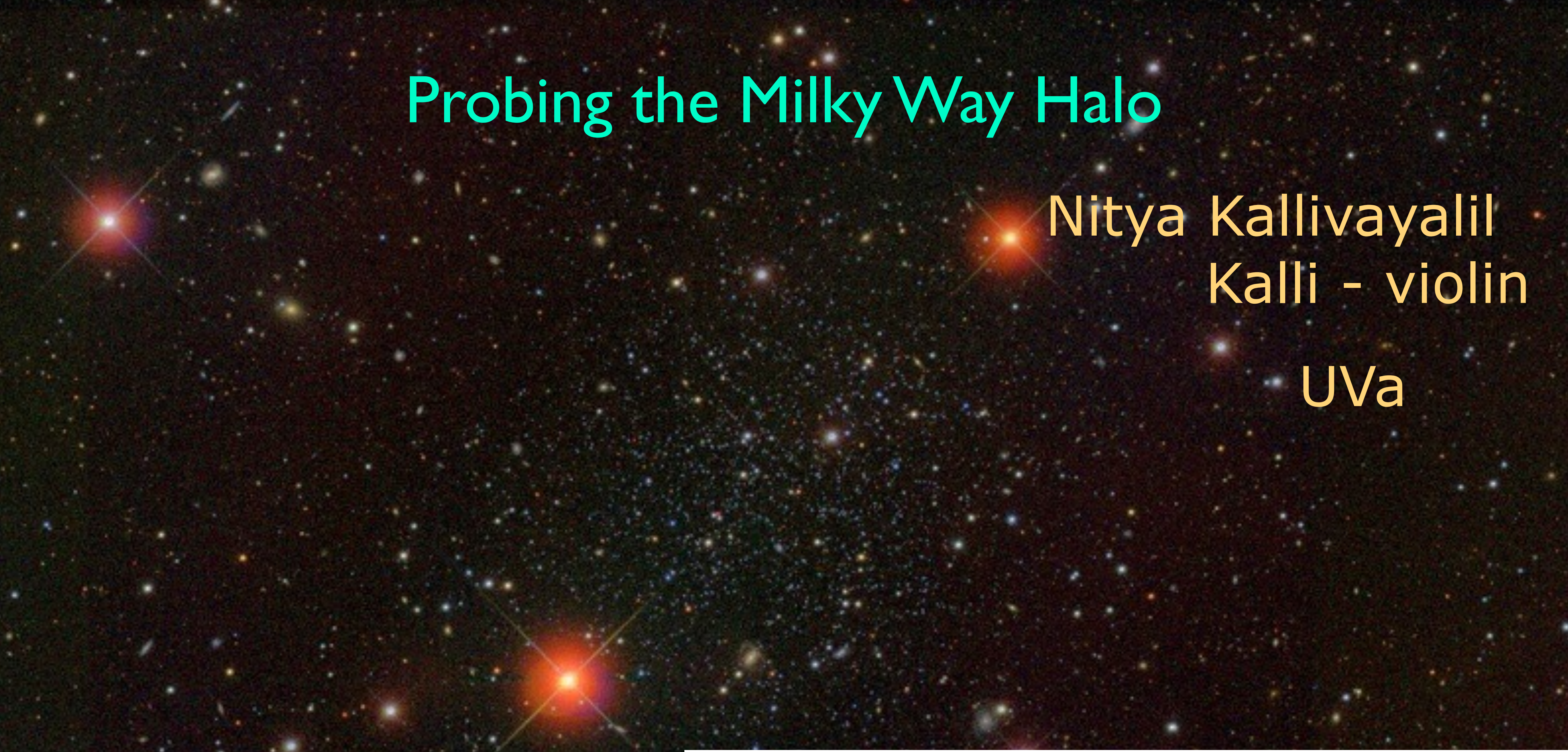
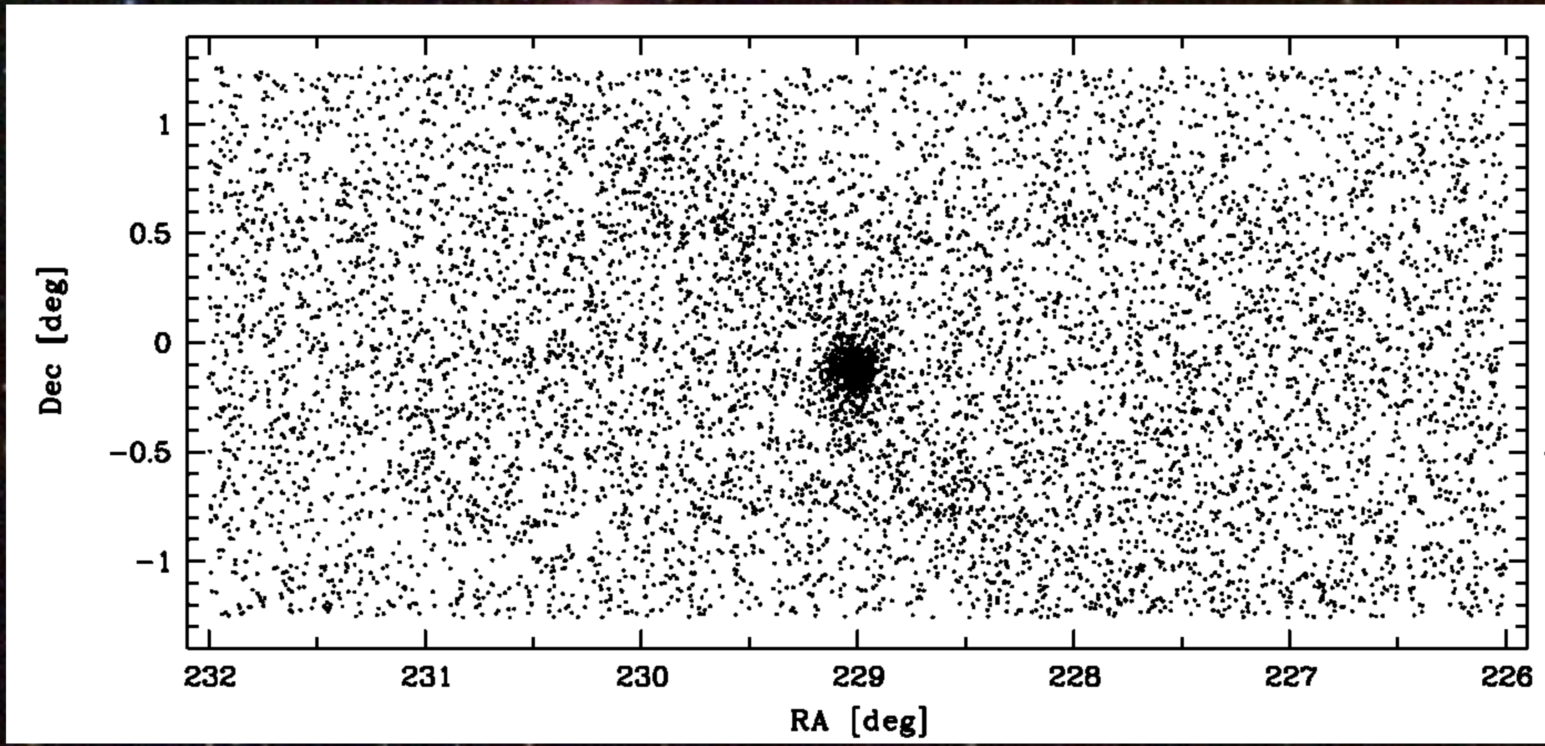
Probing the Milky Way Halo

Nitya Kallivayalil
Kalli - violin

UVa



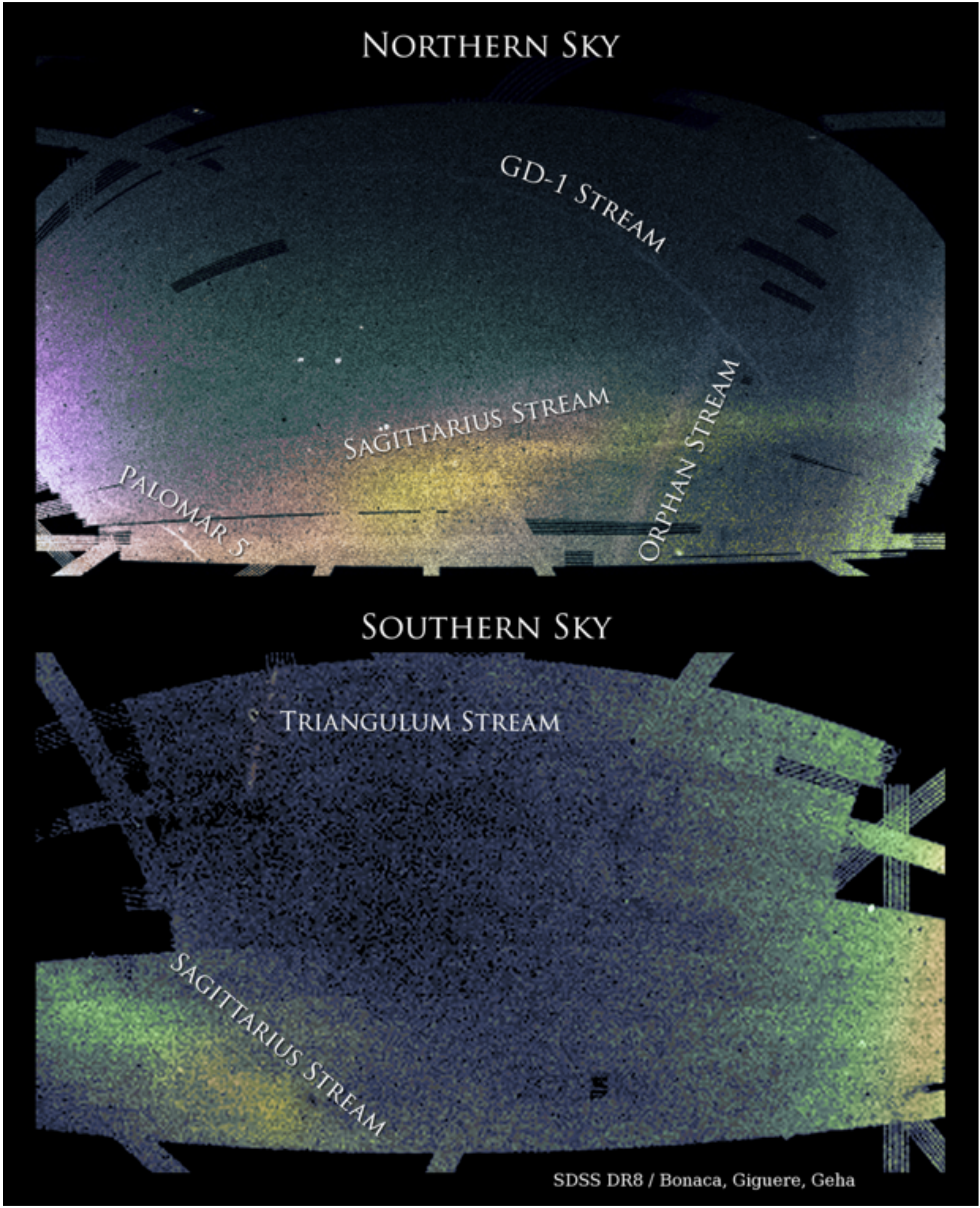


KITP, March 2015

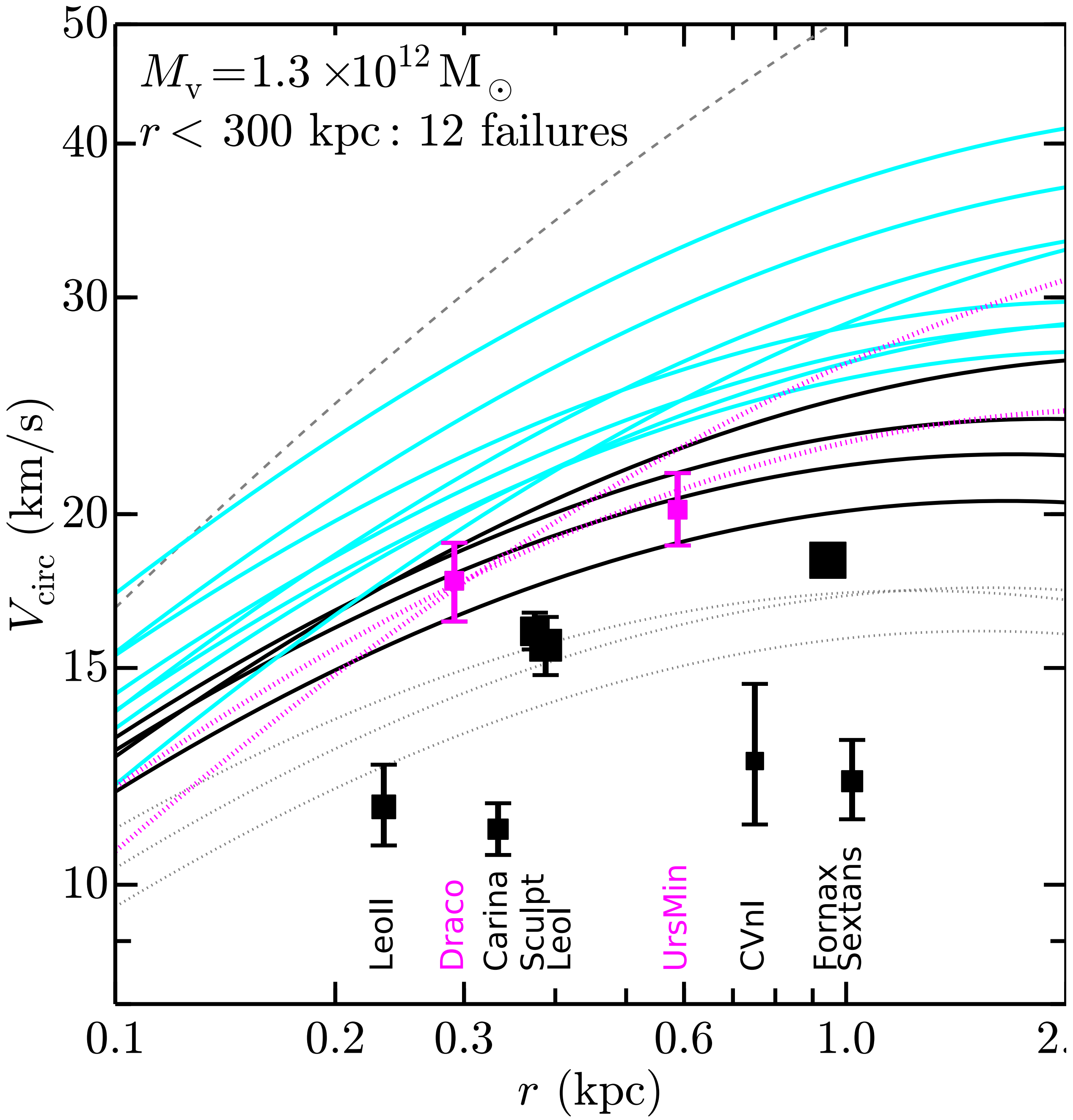
Heyday for Near-Field Cosmology

- 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)

Bonaca, Geha & NK (2012)

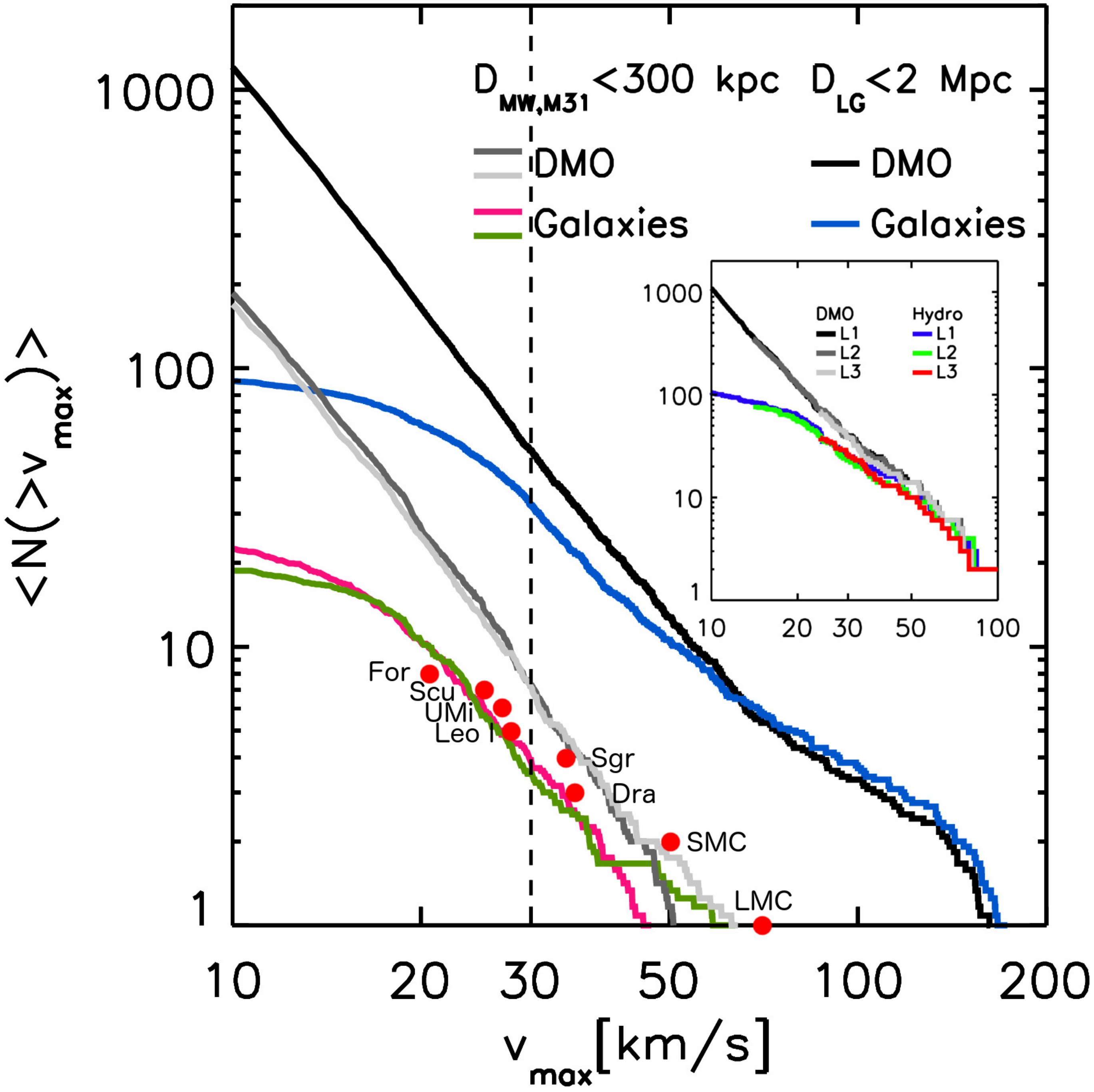


Too Big To Fail



Milky Way: Garrison-Kimmel et al. 2014

Including M31: see Collins et al. 2014

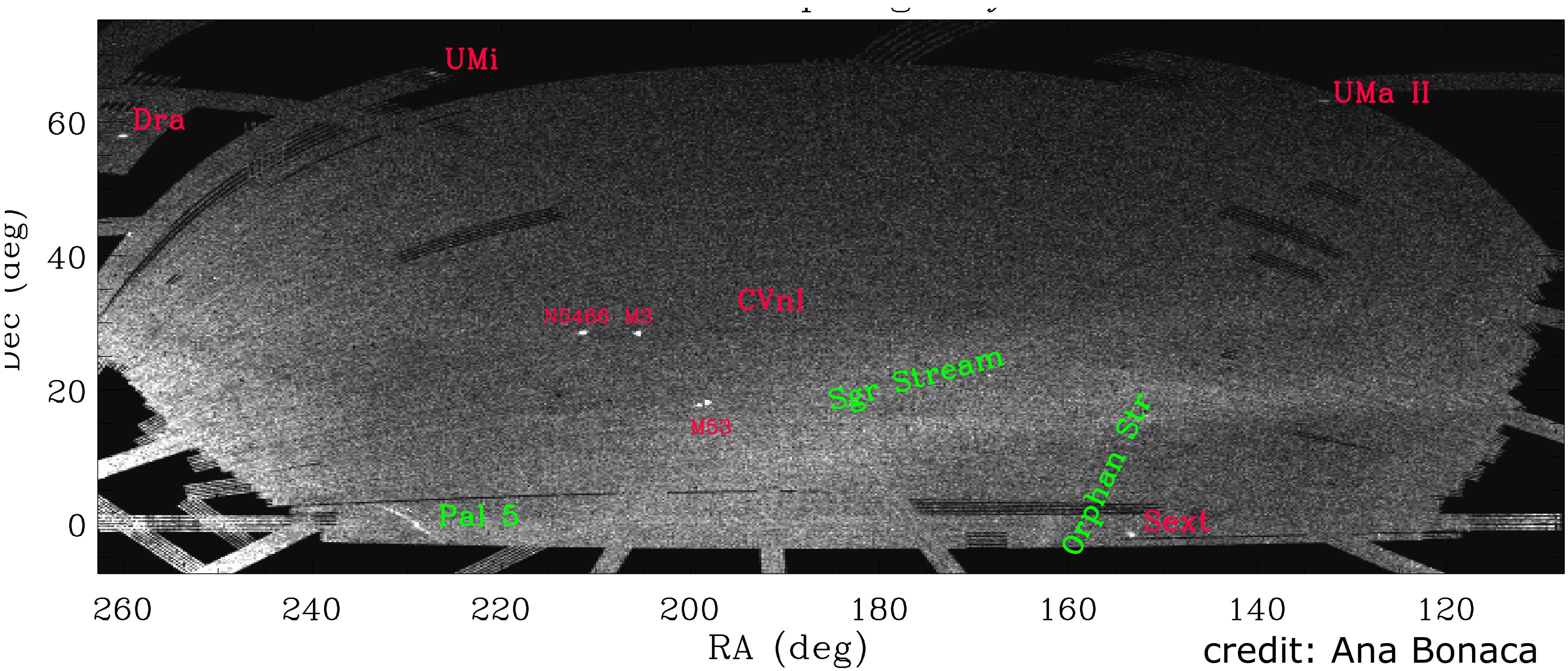


Sawala et al. 2014

- Total mass of the Milky Way is unknown to a factor of six!
    - Recent estimates range from 5 - 30 x 10^11 M_sun (e.g., Deason et al. 2012, Belokurov et al. 2014).
- Total mass of Milky Way+M31 well-determined from Timing Argument, so if one loses the other gains (e.g., van der Marel et al. 2012).

- Proper Motions are a major missing component in the effort to measure masses.

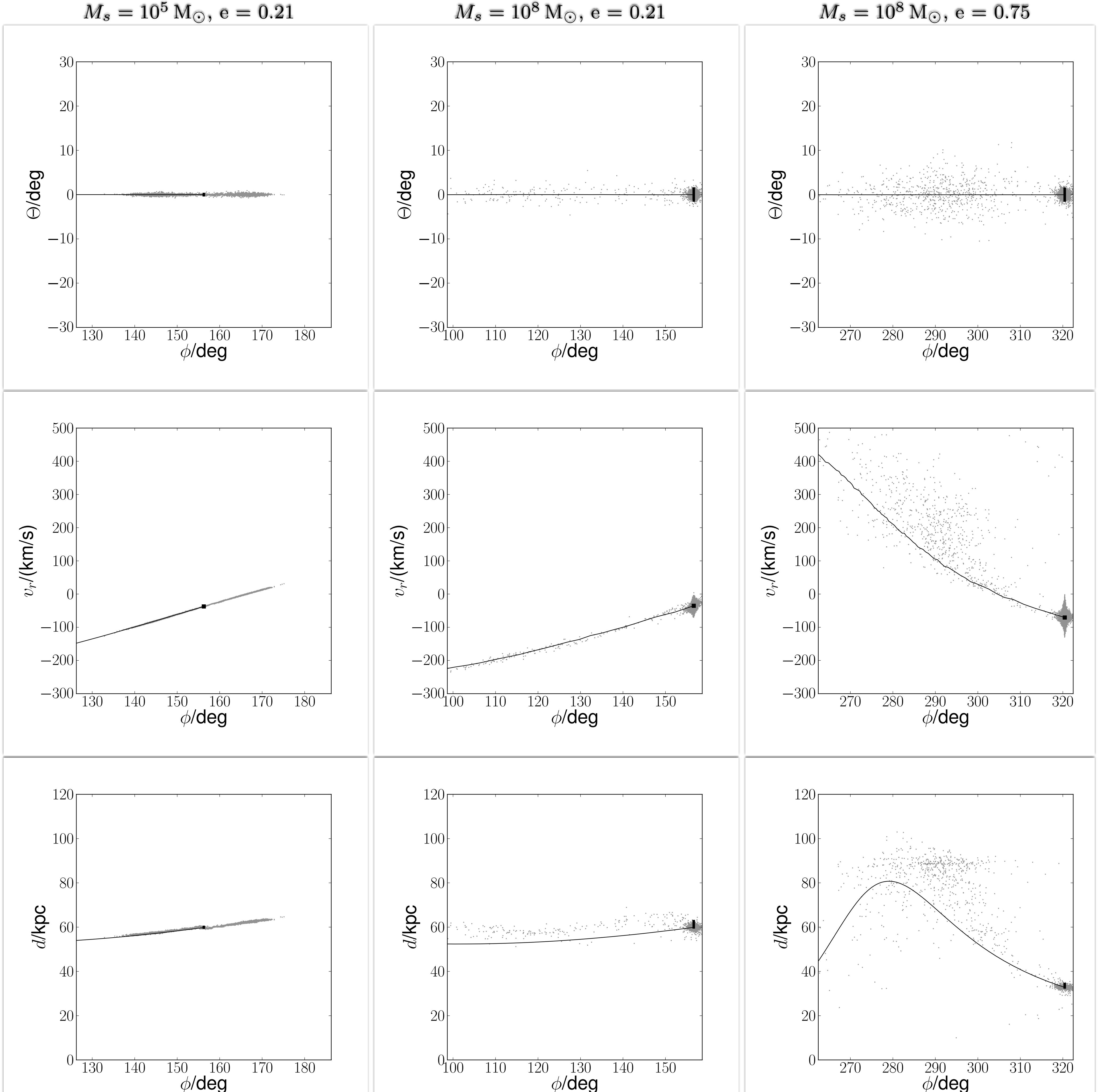
Stellar streams in the Milky Way



credit: Ana Bonaca

- $M >> M_{sat}$: $GM/R >> r_{tid} d\phi/dR >> GM_{sat}/r_{sat}$ (Kesden & Kamionkowski 2006, Johnston+ 2002)

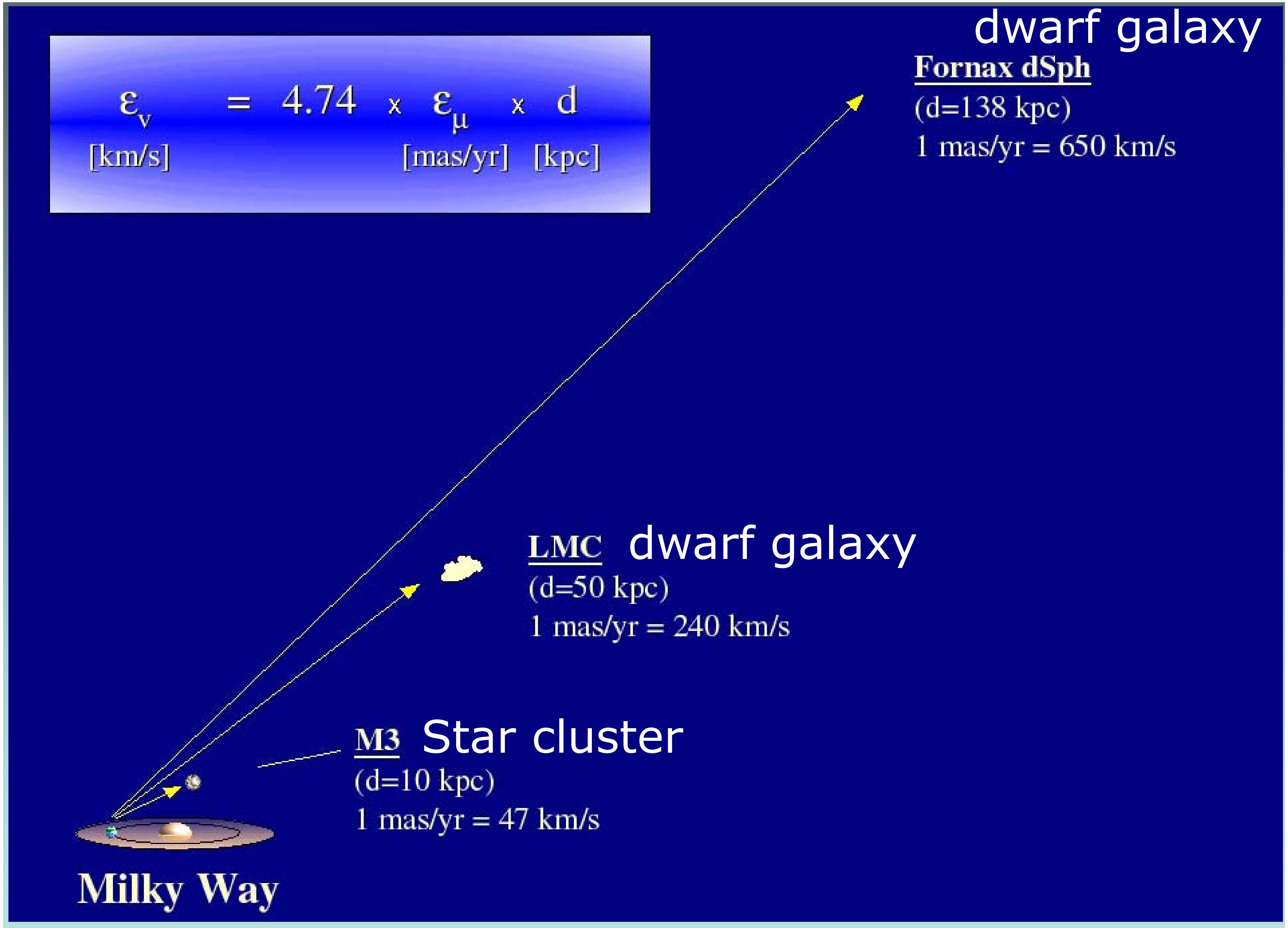
- Going down the luminosity sequence: Magellanic Clouds —> Sagittarius —> Pal 5



Streams do not follow orbits: Lux et al. (2013); Bovy (2014); Eyre & Binney (2011); Varghese et al. (2011)

Major missing phase-space component -- proper motions

Required Proper Motion Uncertainty



$$\varepsilon_v = 4.74 \times \varepsilon_\mu \times d$$

[km/s] [mas/yr] [kpc]

dwarf galaxy

Fornax dSph

(d=138 kpc)

1 mas/yr = 650 km/s

LMC dwarf galaxy

(d=50 kpc)

1 mas/yr = 240 km/s

M3 Star cluster

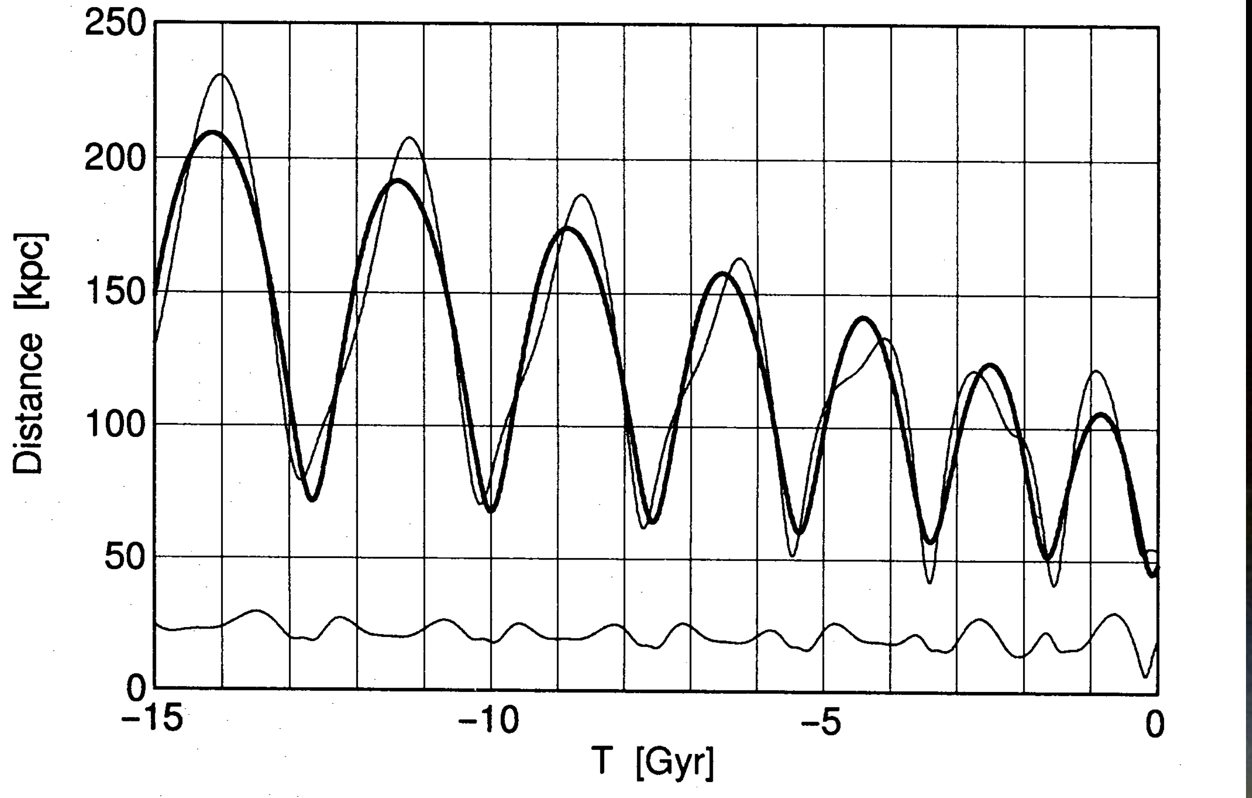
(d=10 kpc)

1 mas/yr = 47 km/s

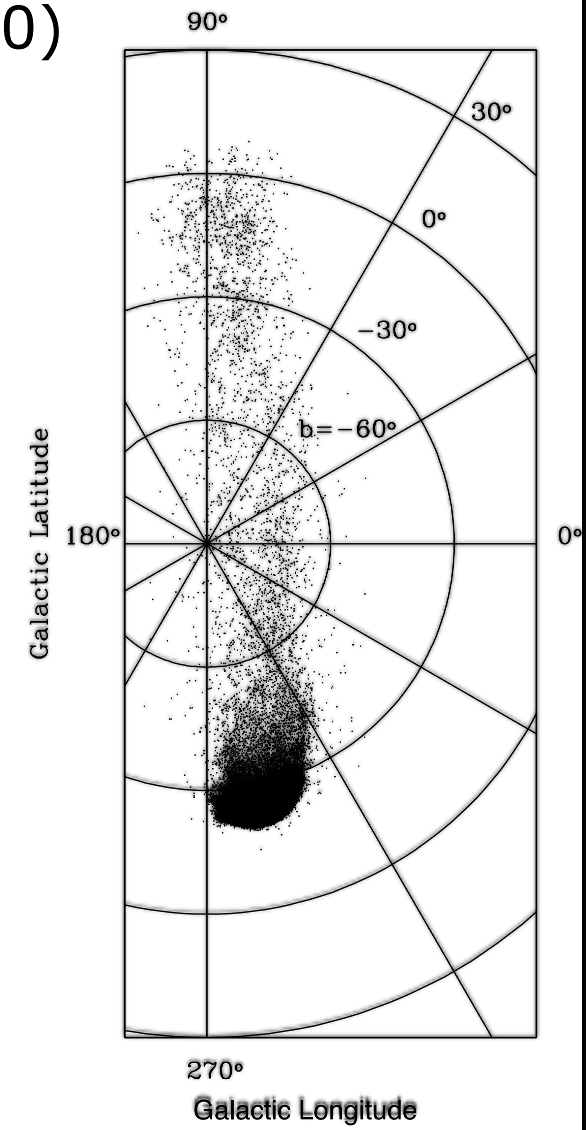
Milky Way

image credit: Dana Dinescu

Tidal Stripping: Gardiner & Noguchi (1996)



Ram Pressure Stripping: Mastropietro+ (2010)



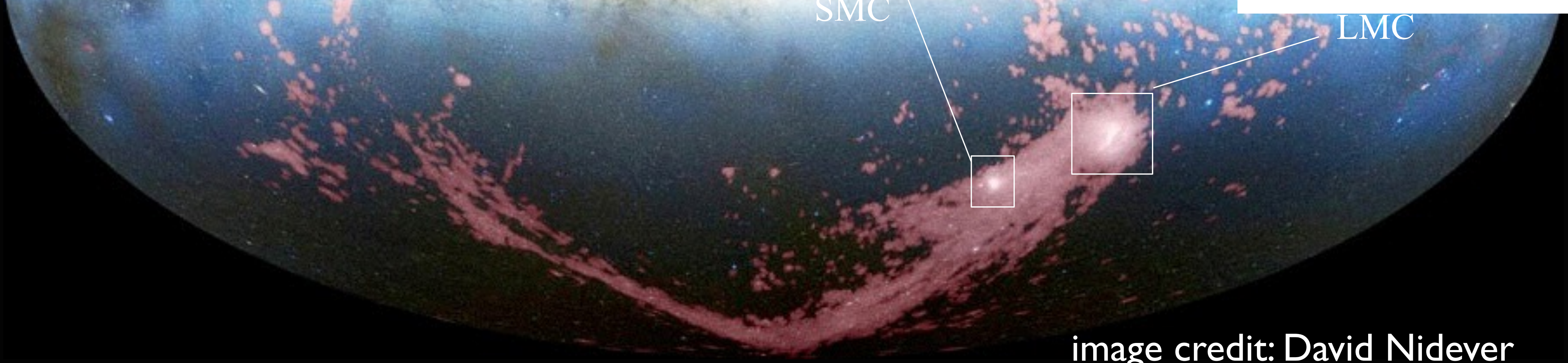
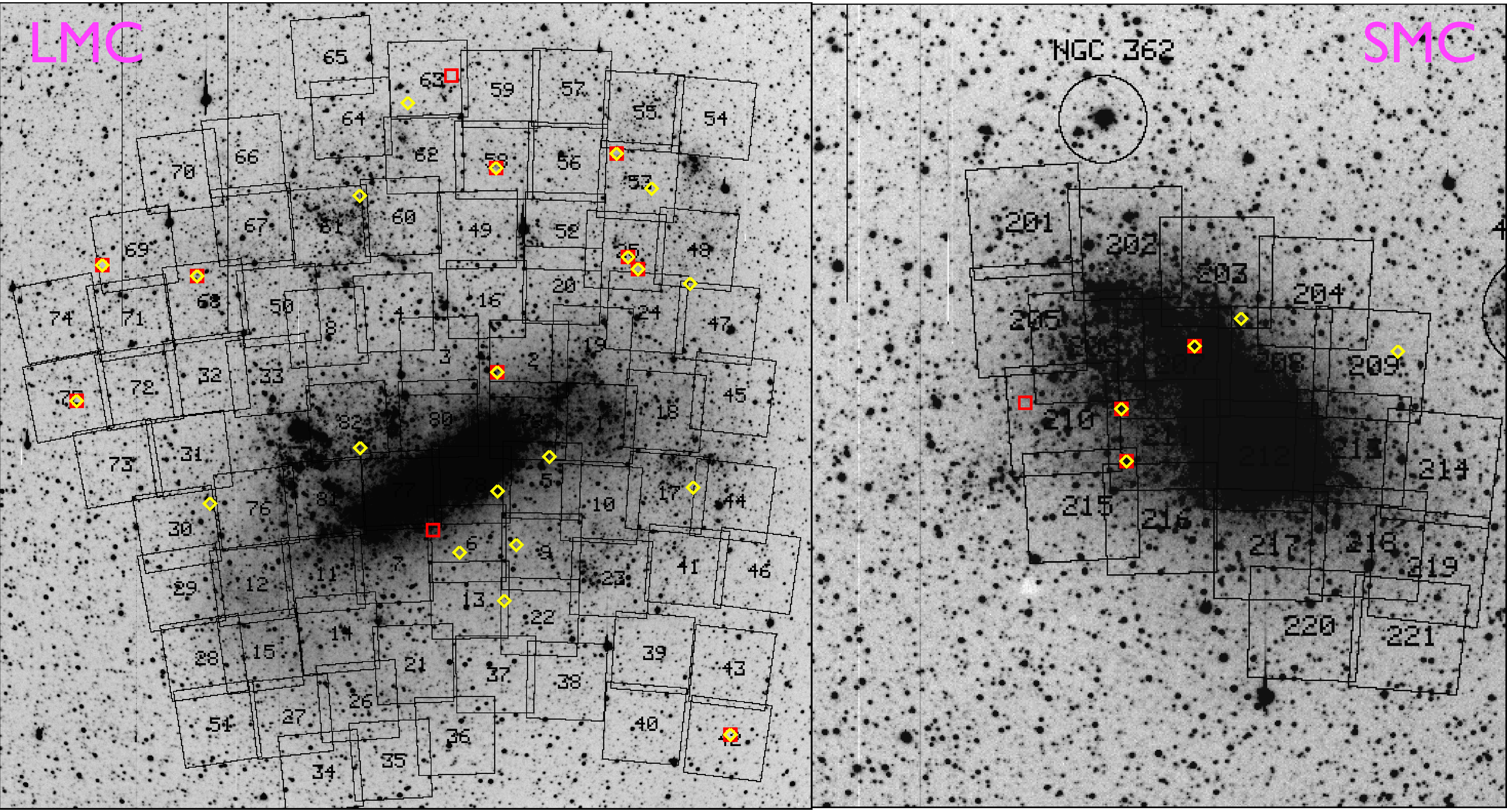


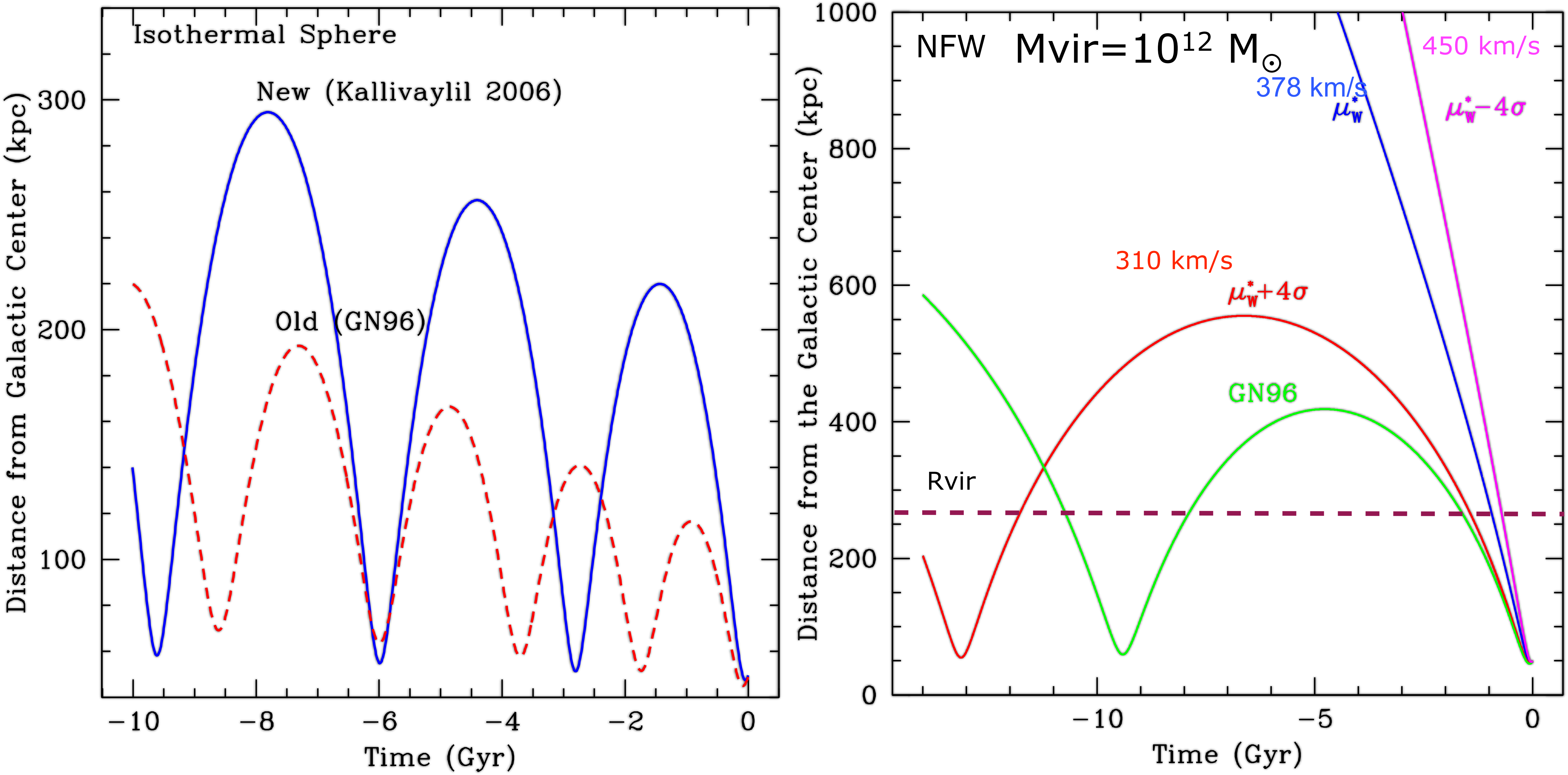
image credit: David Nidever

Reference Frame



Geha et al. 2003

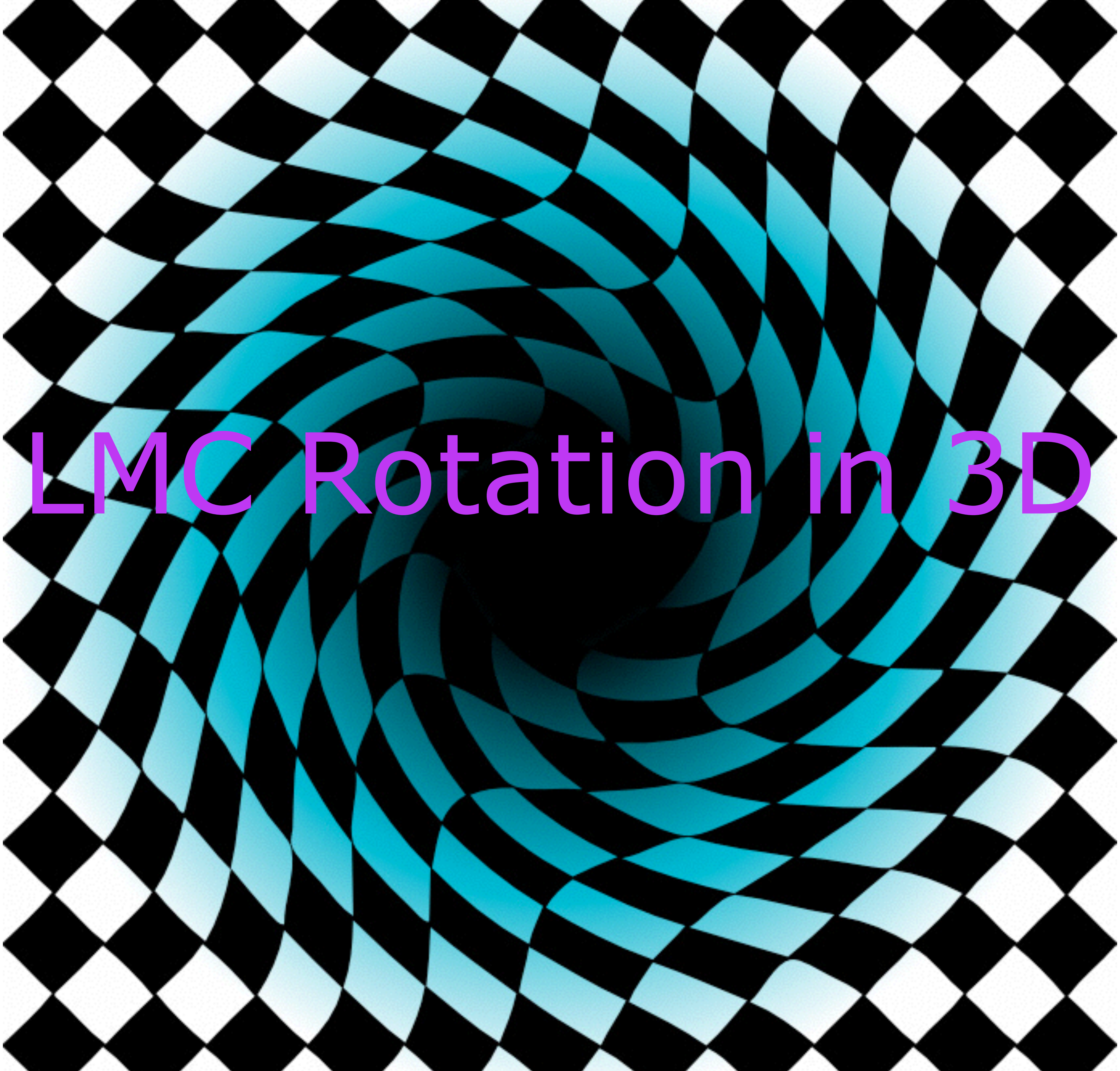
Orbital properties in a cosmological context



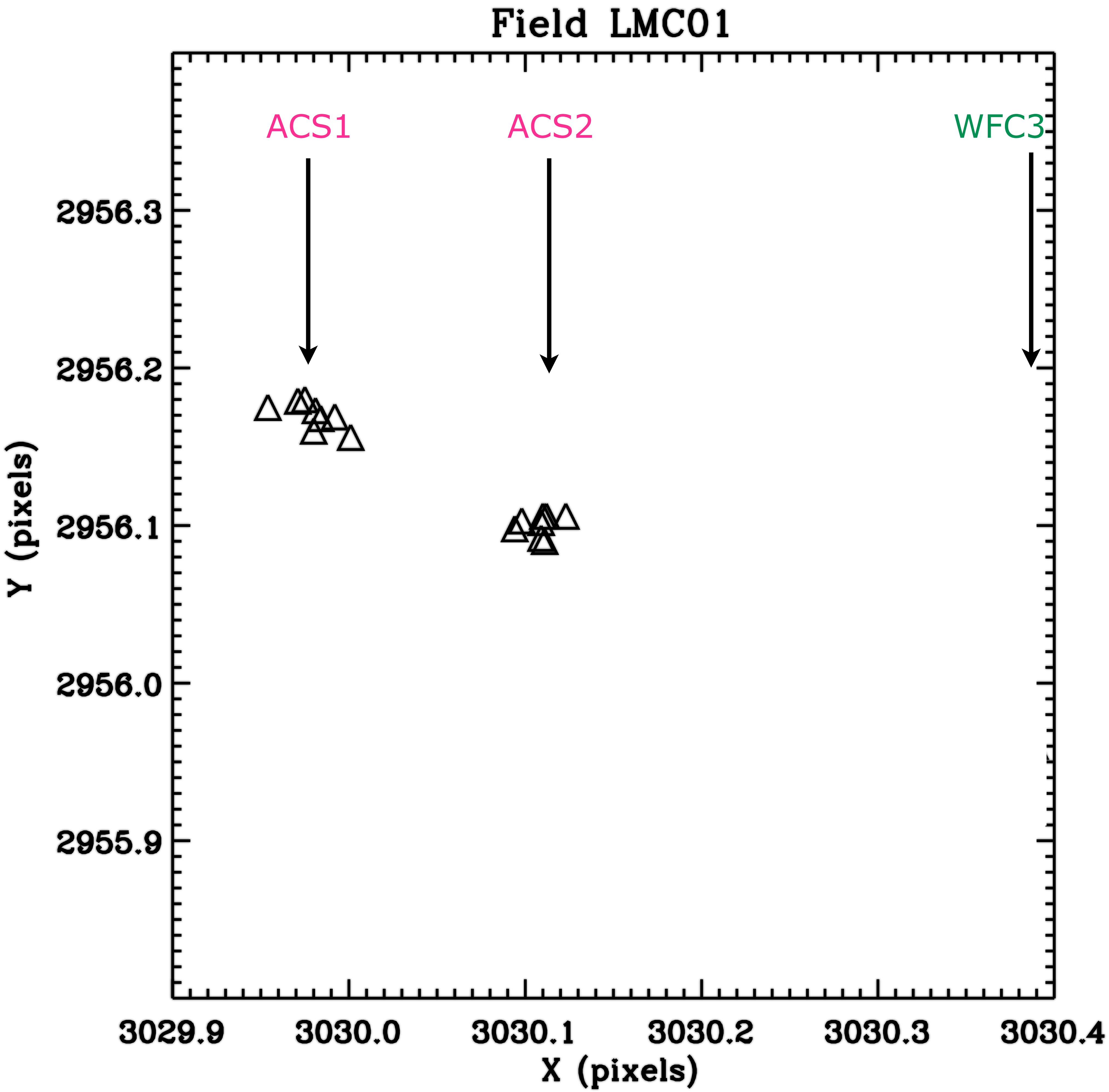
Note that models are static in time

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

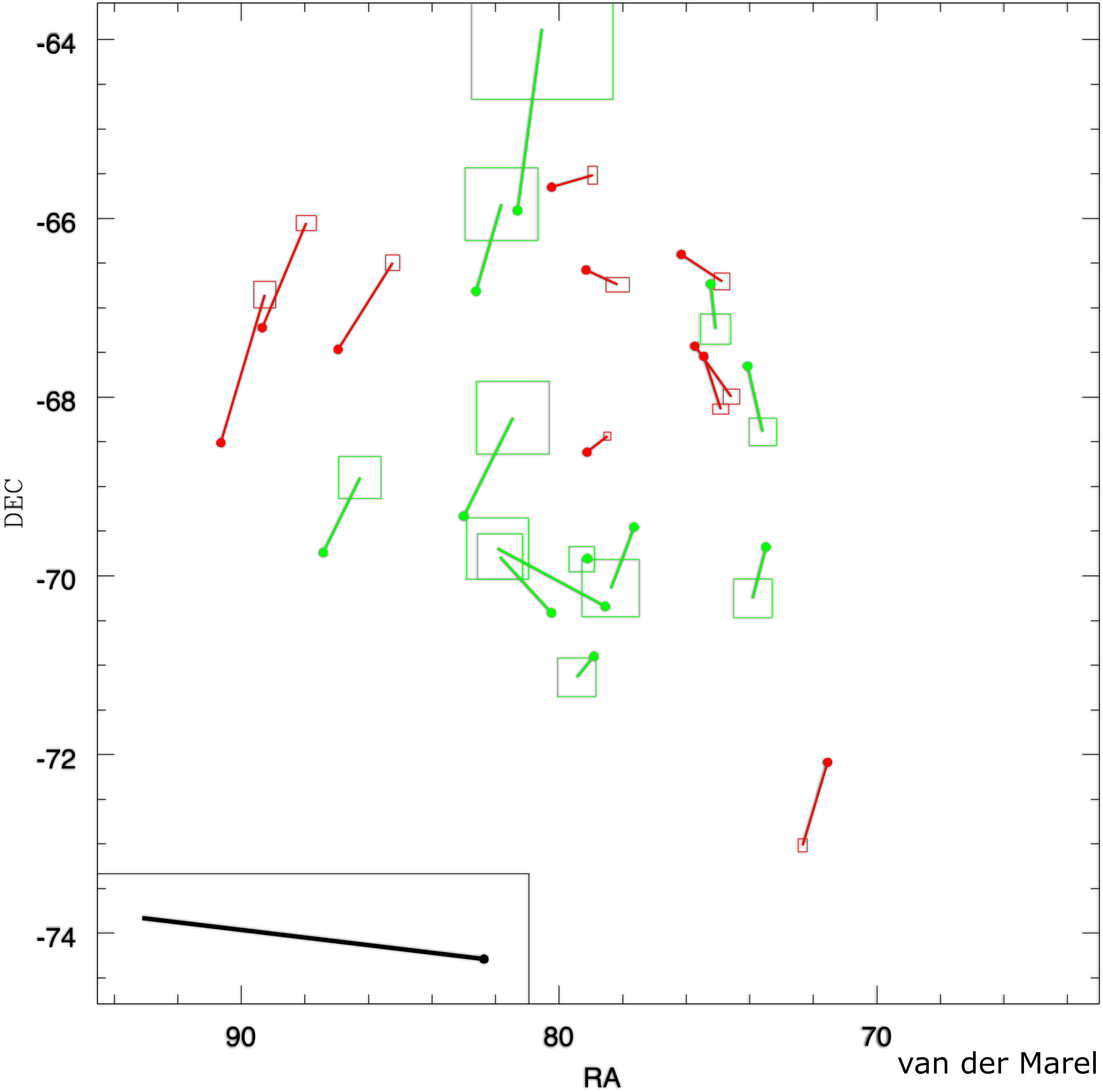
LMC Rotation in 3D



3 Epcoh Analysis (ACS+WFC3) Random Errors:

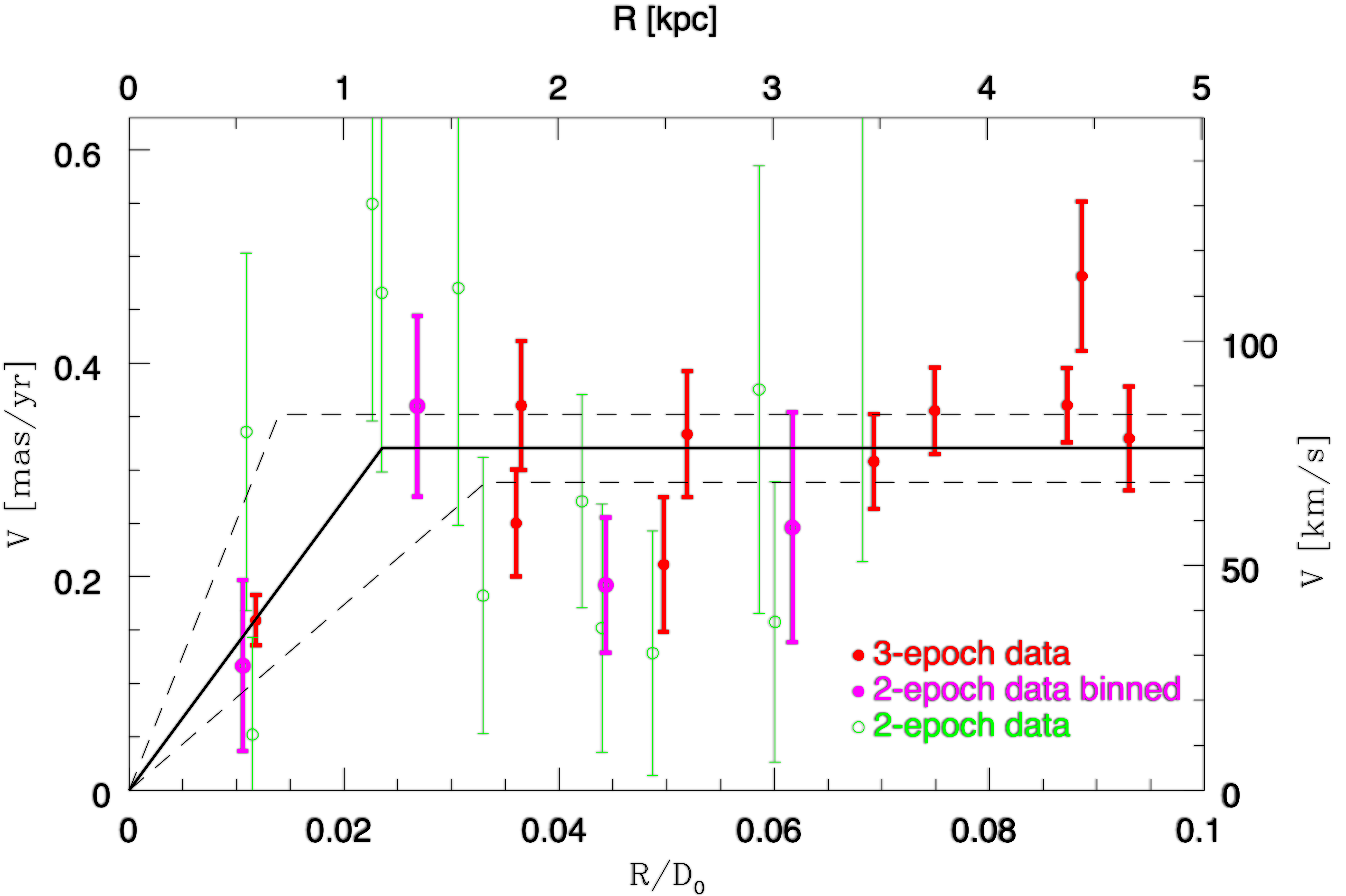


NK+ (2013)

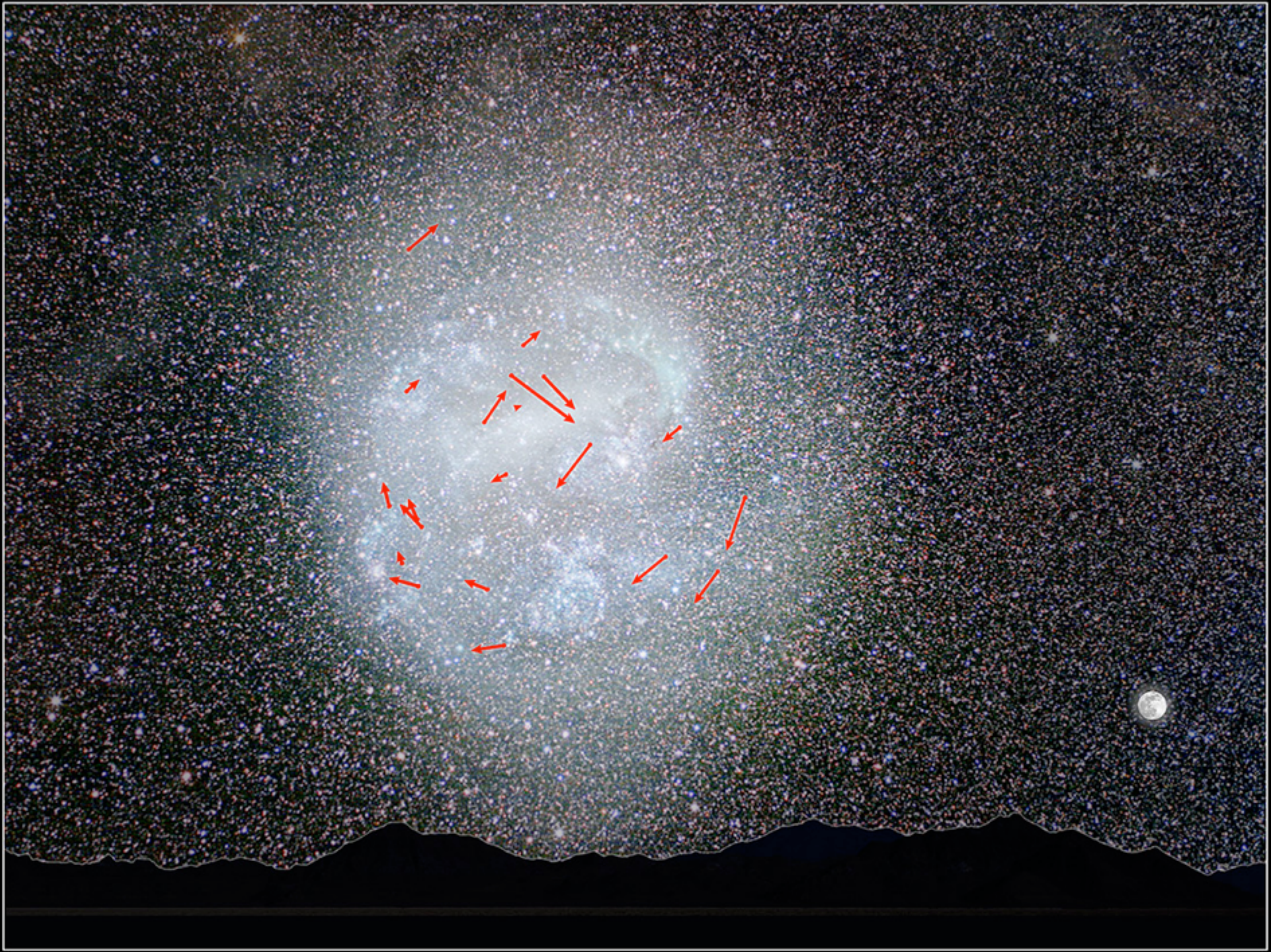


van der Marel & NK (2014)

LMC Proper Motion Rotation Curve



van der Marel & NK (2014)

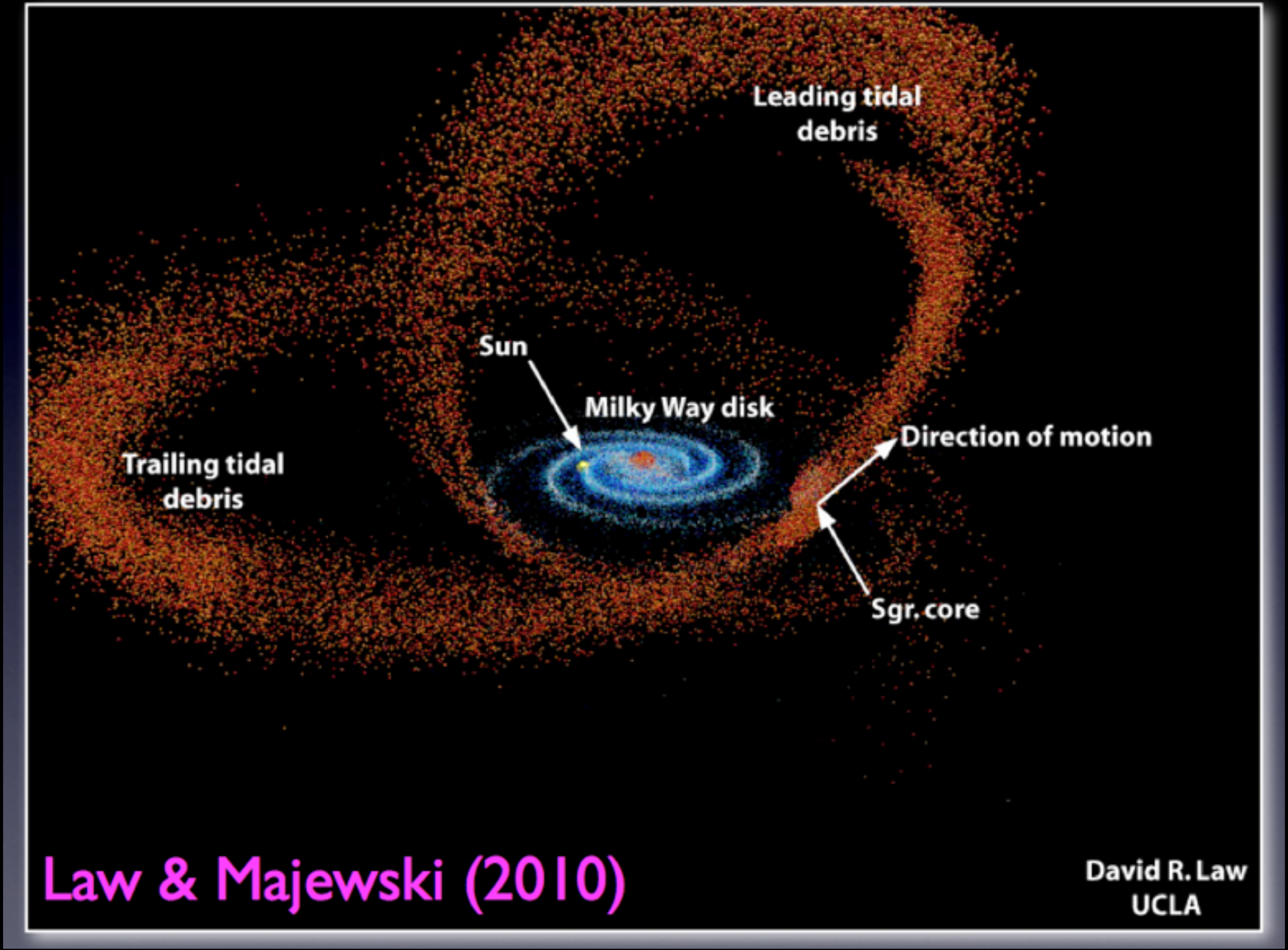


Hubble Measures Rotation of the Large Magellanic Cloud • Photo Illustration

NASA and ESA ▪ STScI-PRC14-11a

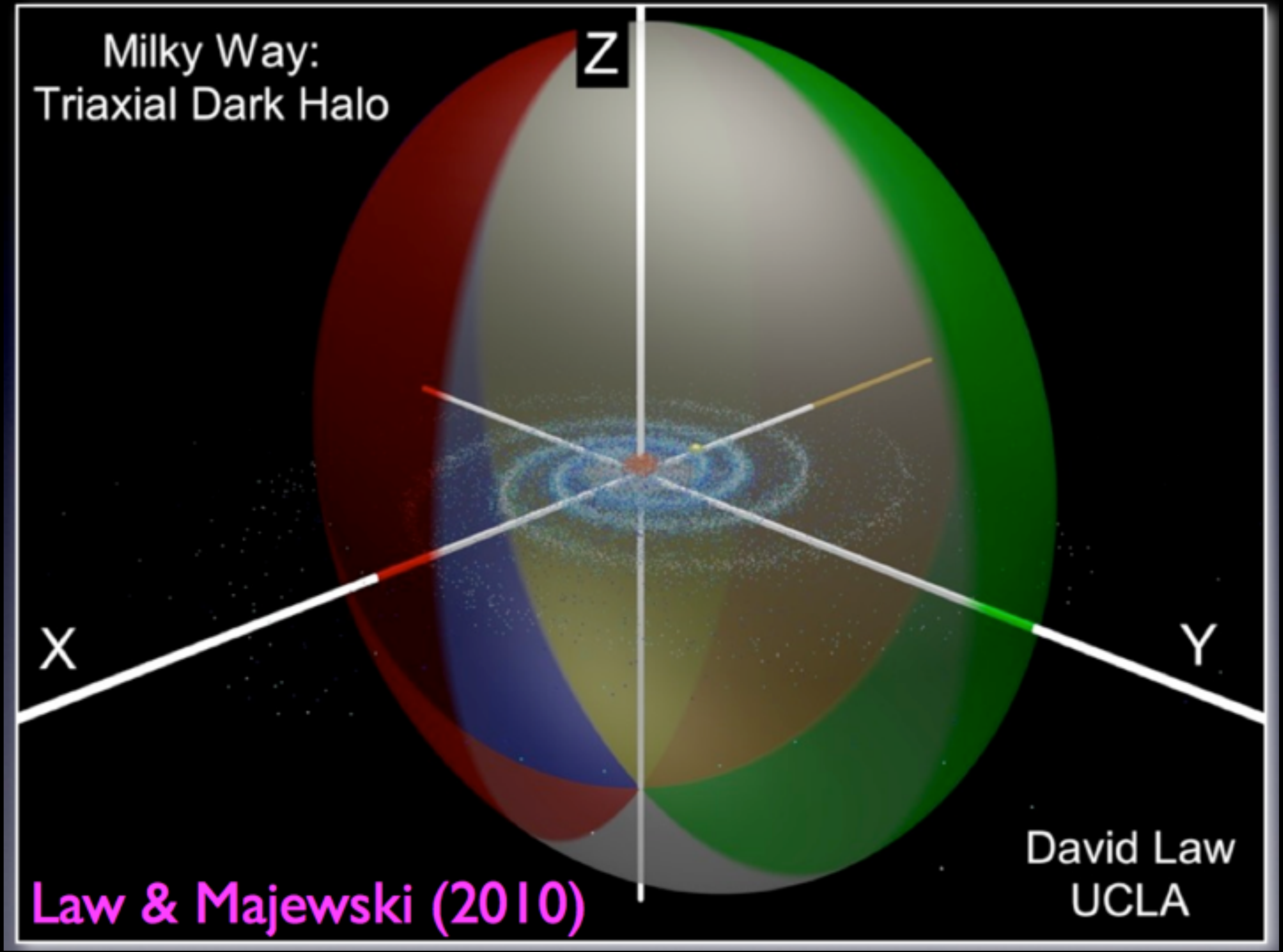
Sagittarius Stream

- Stellar Tidal Stream from Sgr dSph at D~26 ± 2 kpc



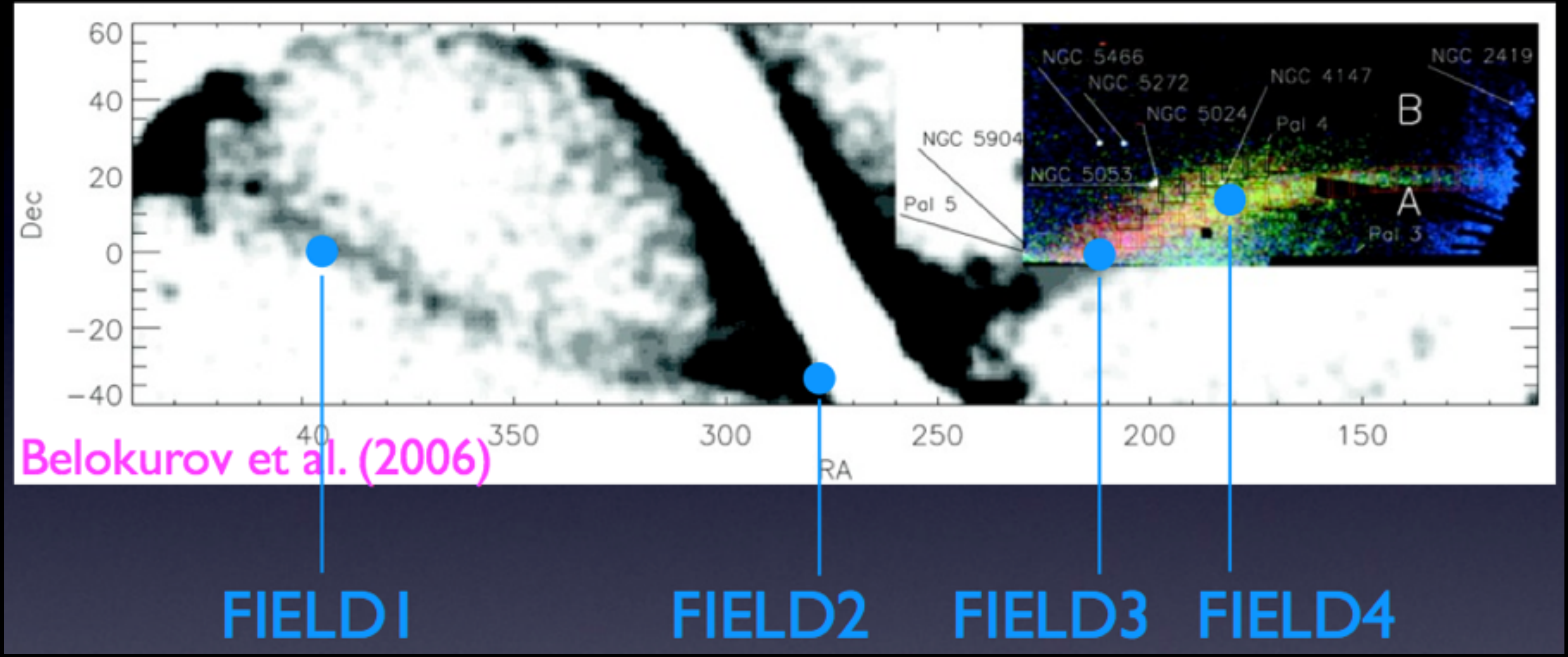
Triaxial Dark Halo Model

- 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



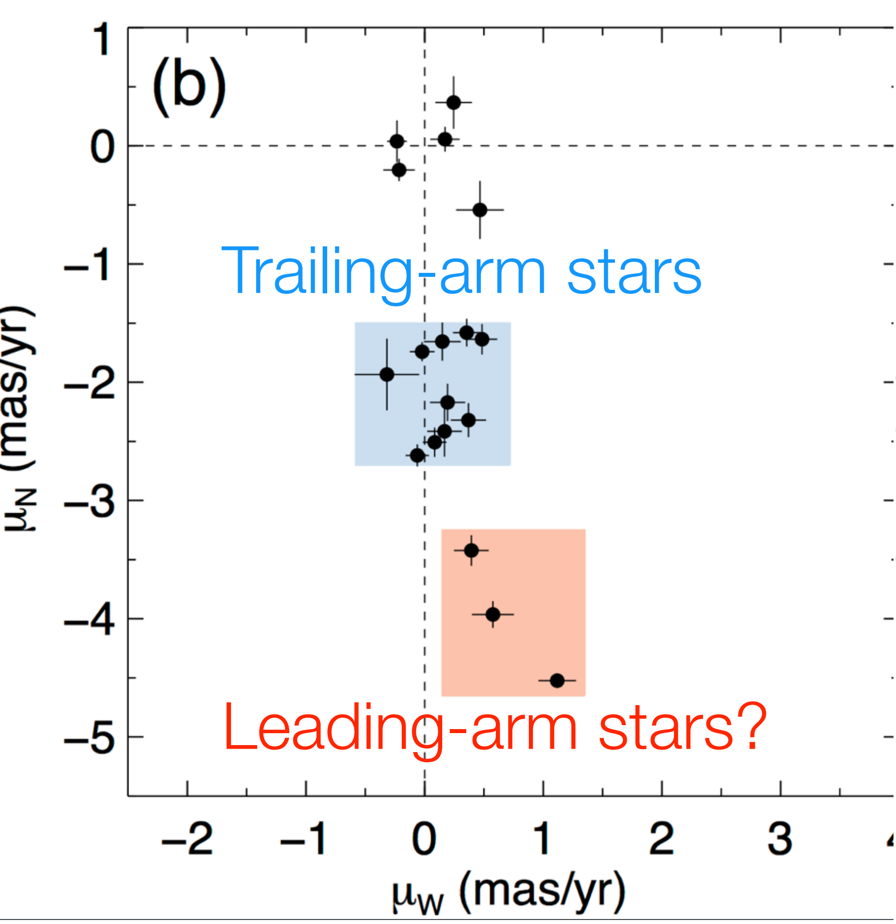
Belokurov et al. (2006)

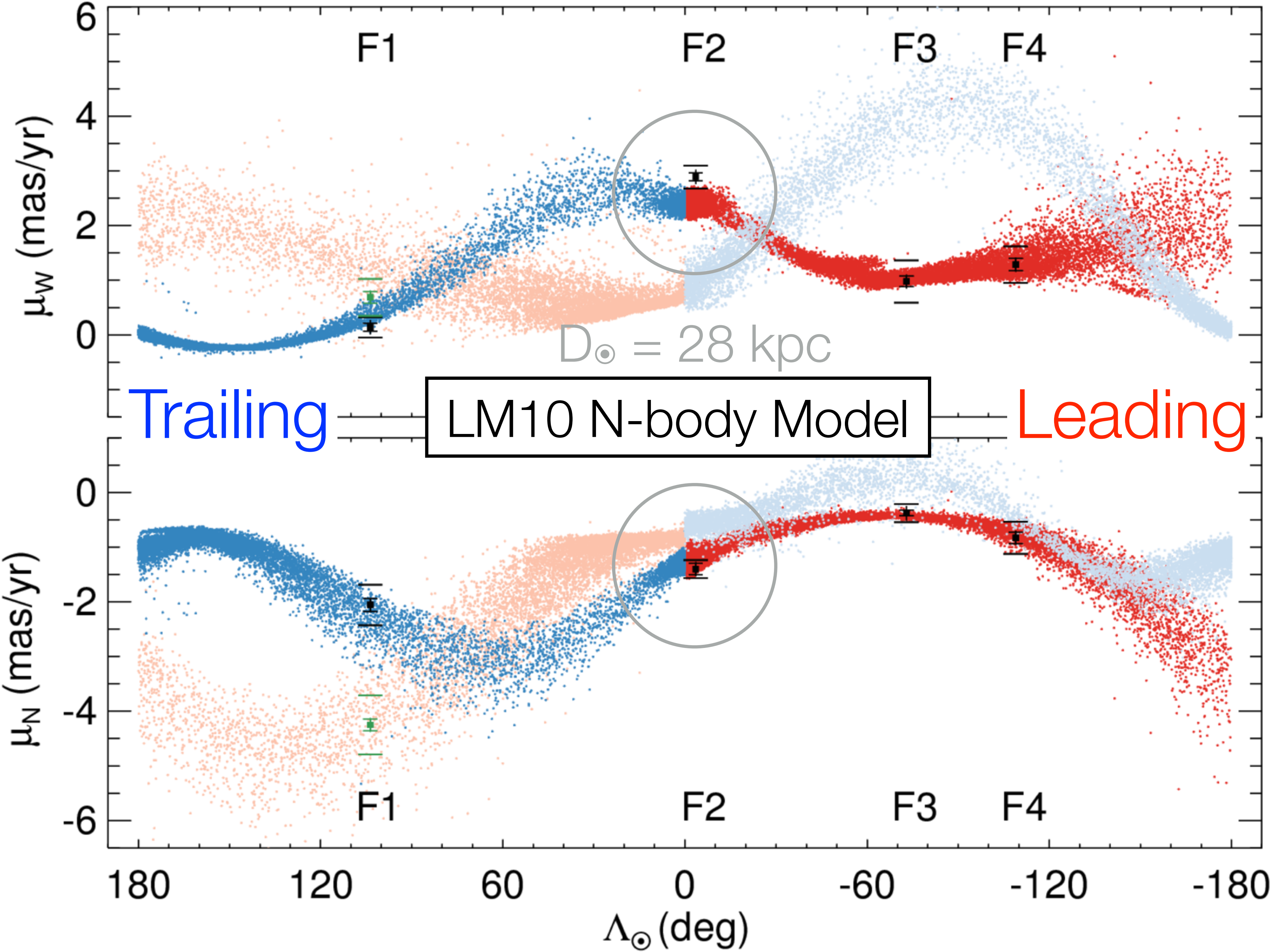
- HST w/ 6-9 year time baselines
- Two additional components of motion can strongly constrain models

PM to N-body Comparison

- Remarkably good fit ….

Sohn et al. 2015



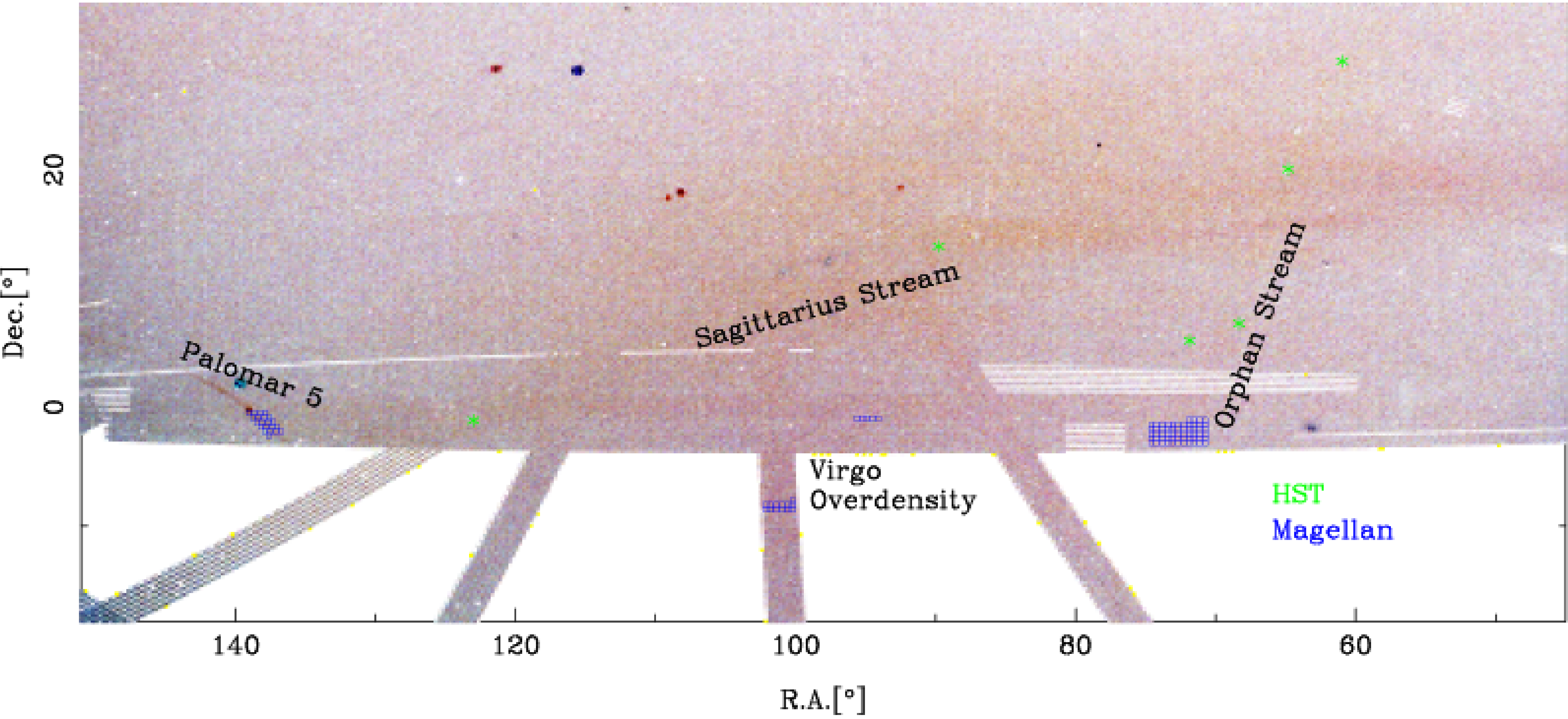


Further down the luminosity function: Palomar 5 Stream.

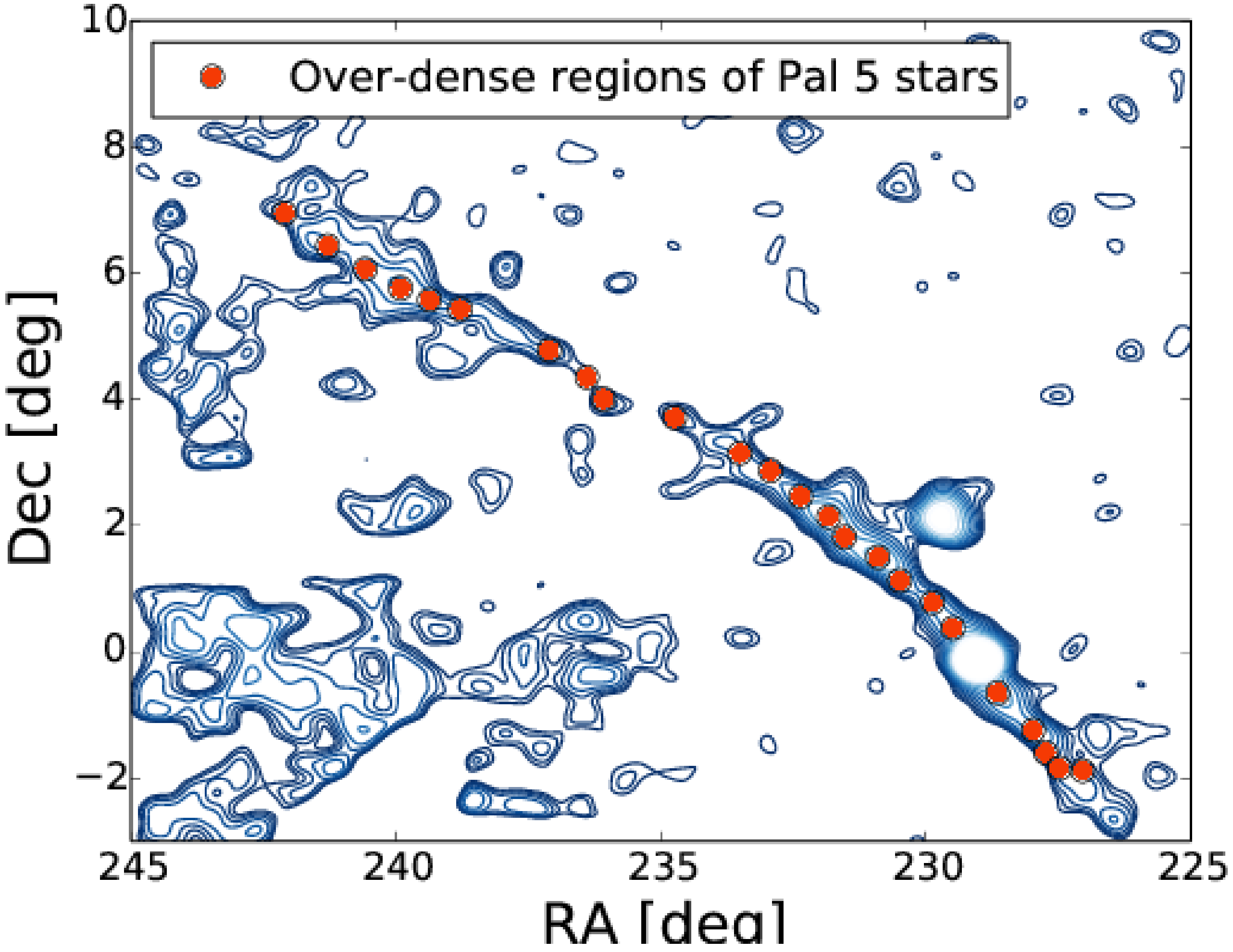
Switching from space-based to ground-based techniques.

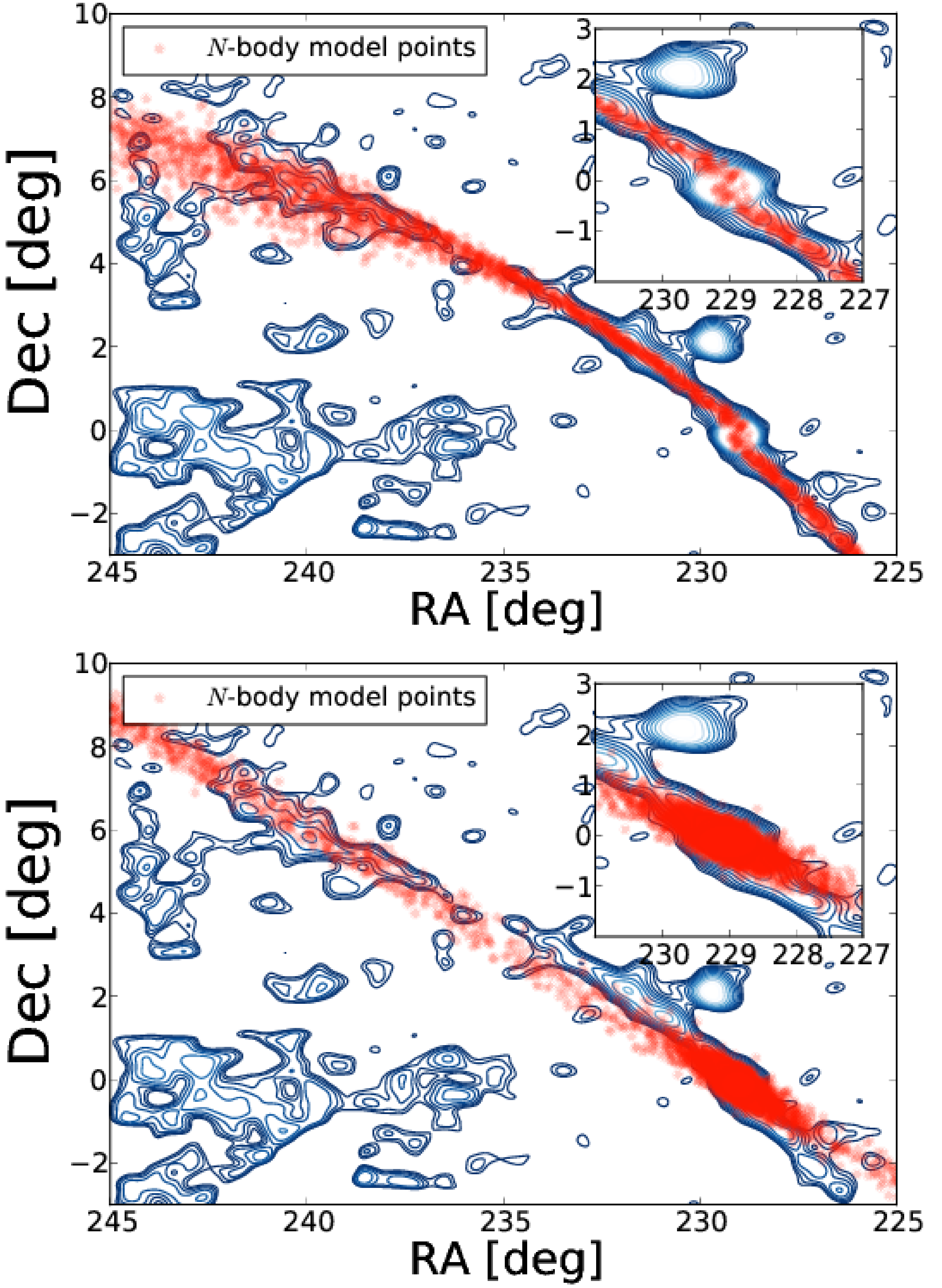
Proper Motions from SDSS - Magellan/LBT

FOV = 50 x HST
~24’ x 24’
small pixels
SDSS filters
First epoch available

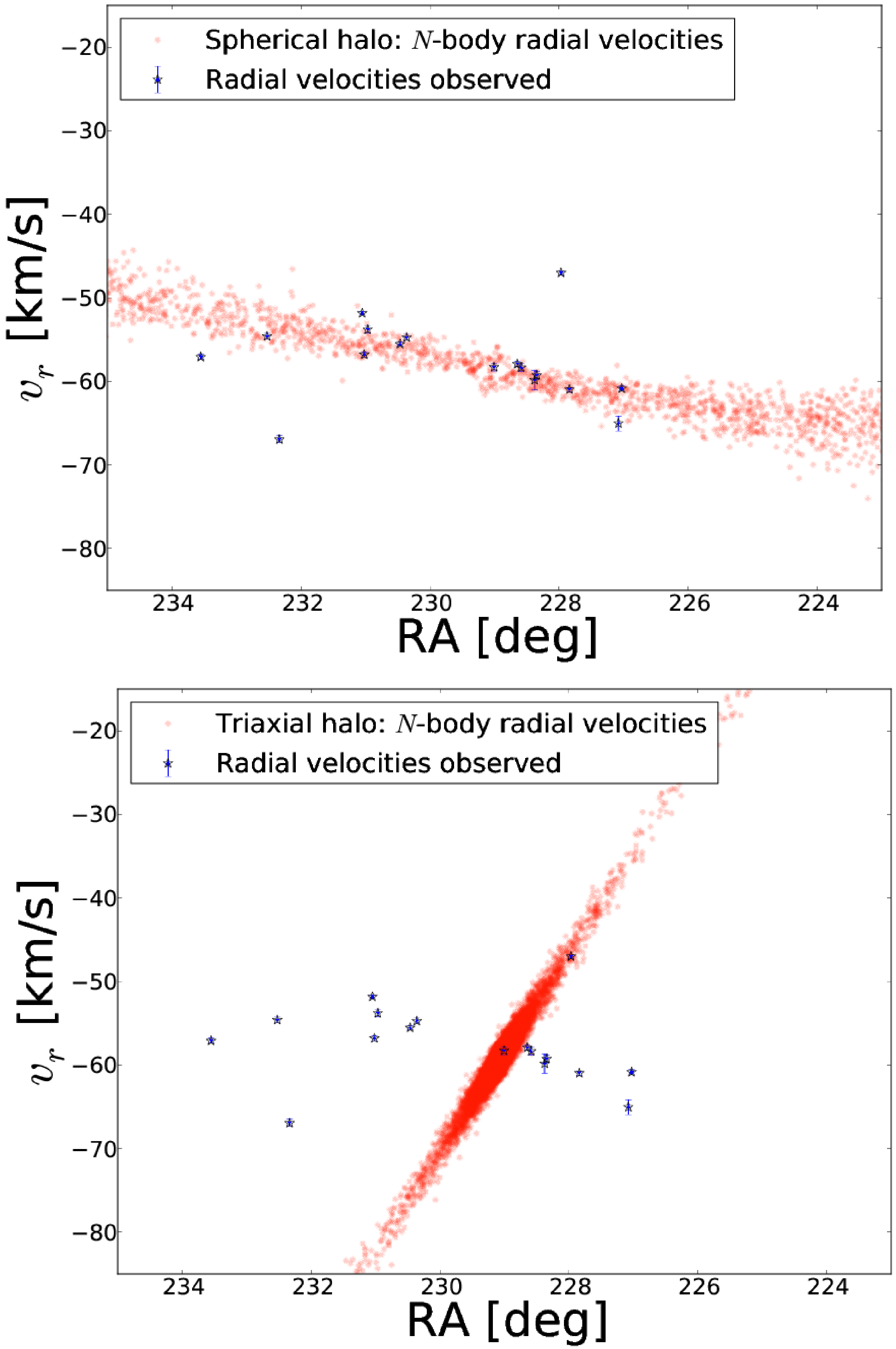


Even further down the luminosity function: Pal 5 Theory (Pearson+ 2014)



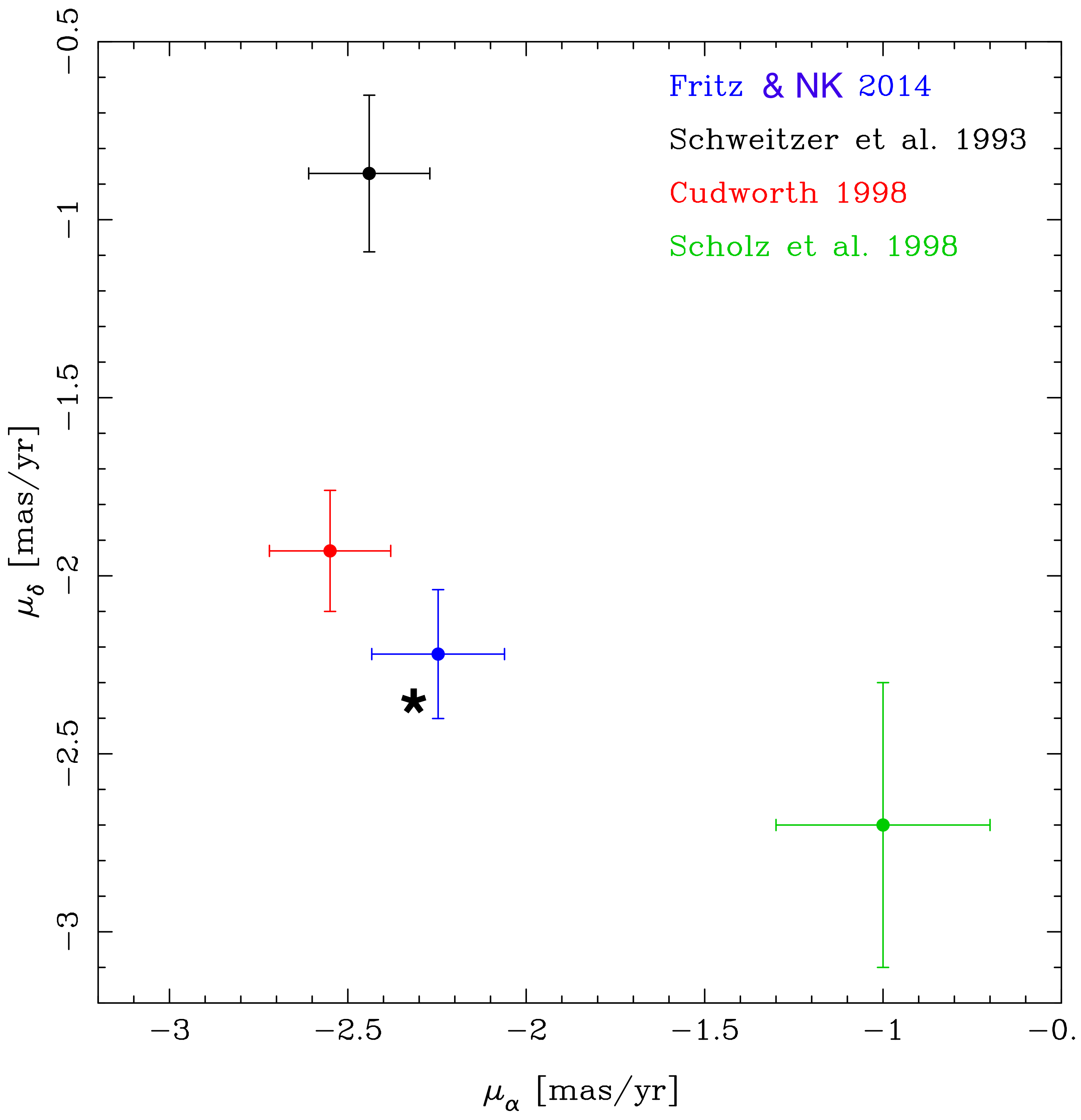


Best fit halo model is spherical, not the triaxial model of Law & Majewski.

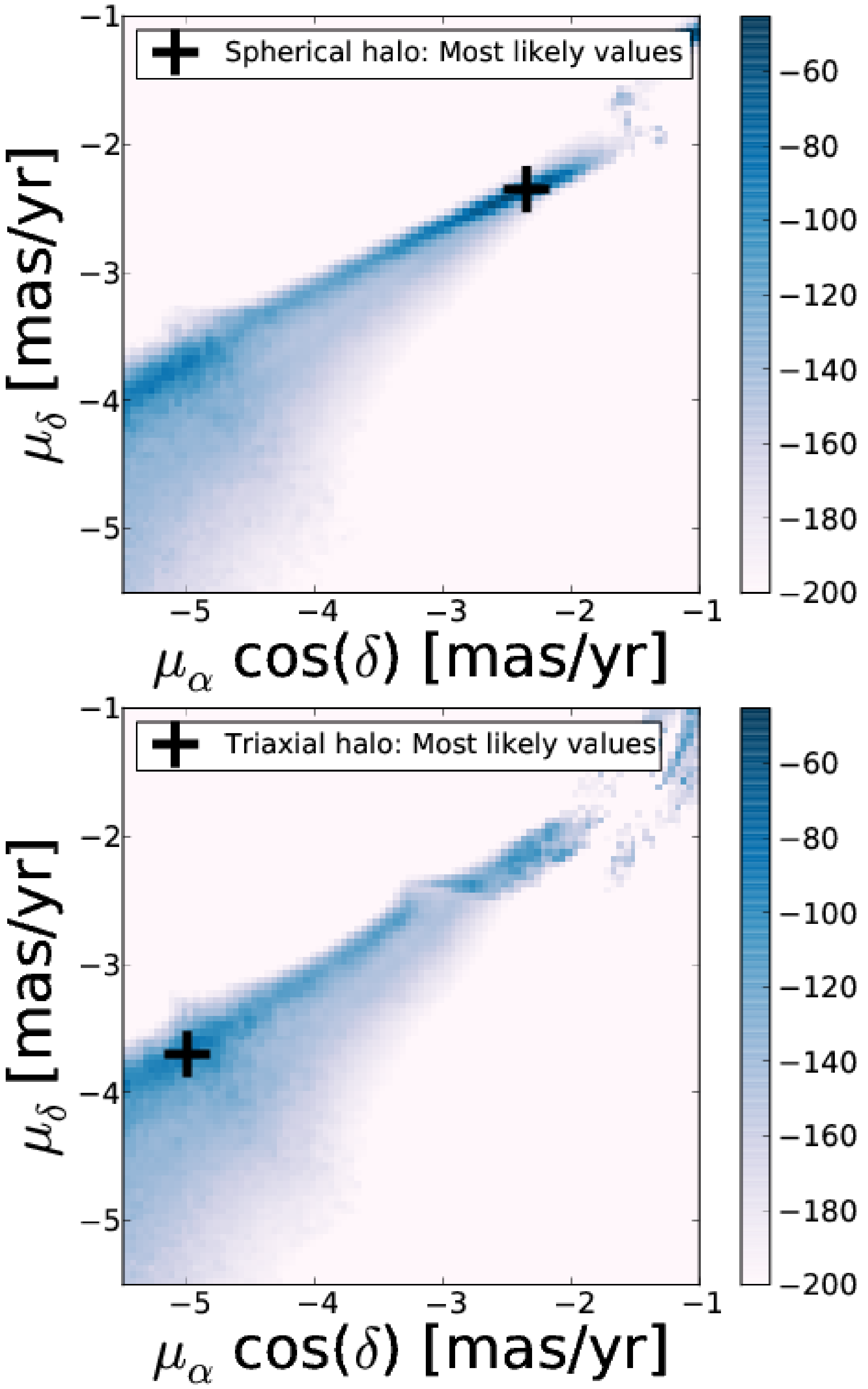


Pearson et al. 2014; Odenkirchen et al. 2009

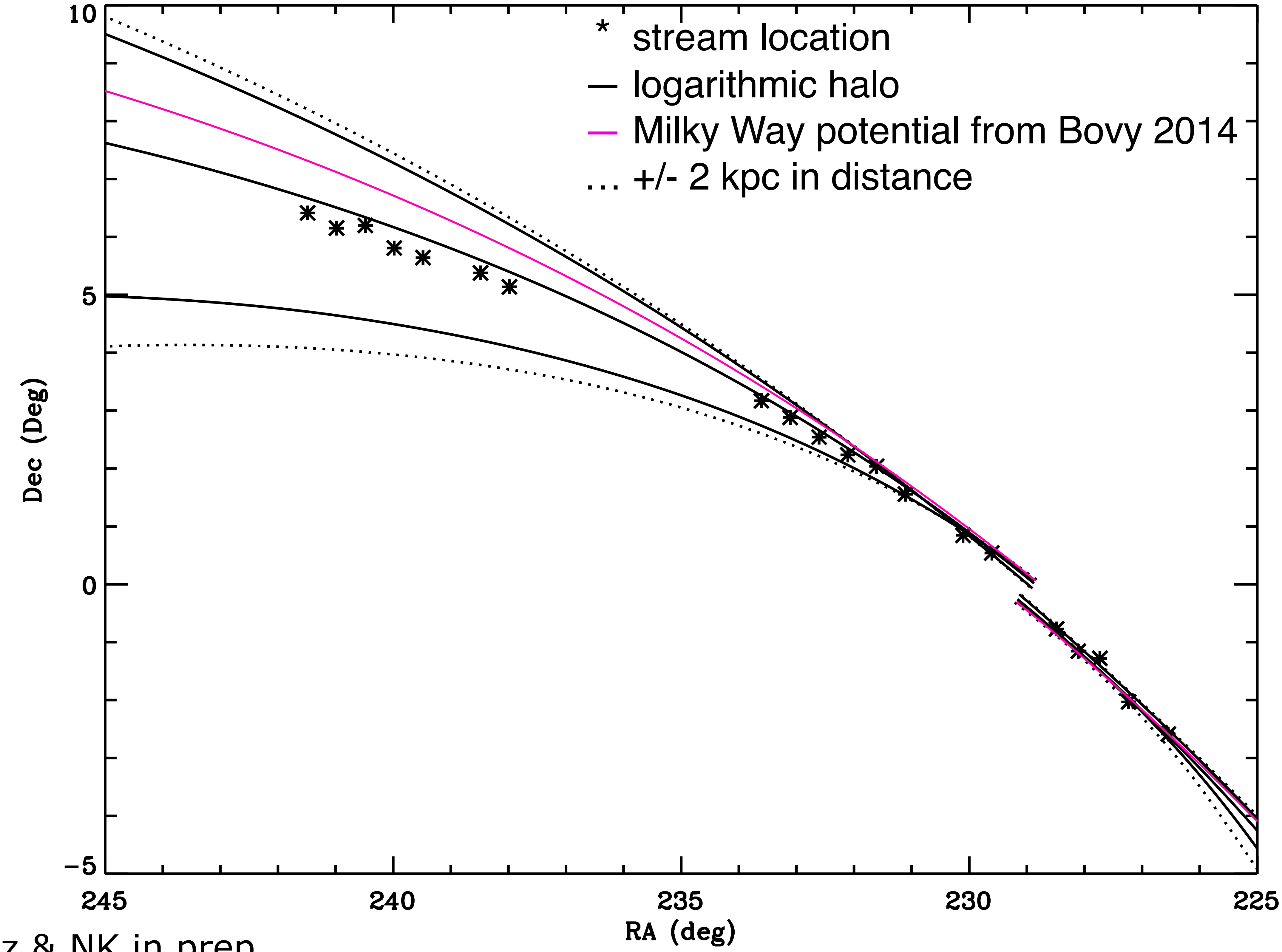
Radial velocity gradient also best fit by spherical halo



Fritz & NK in prep

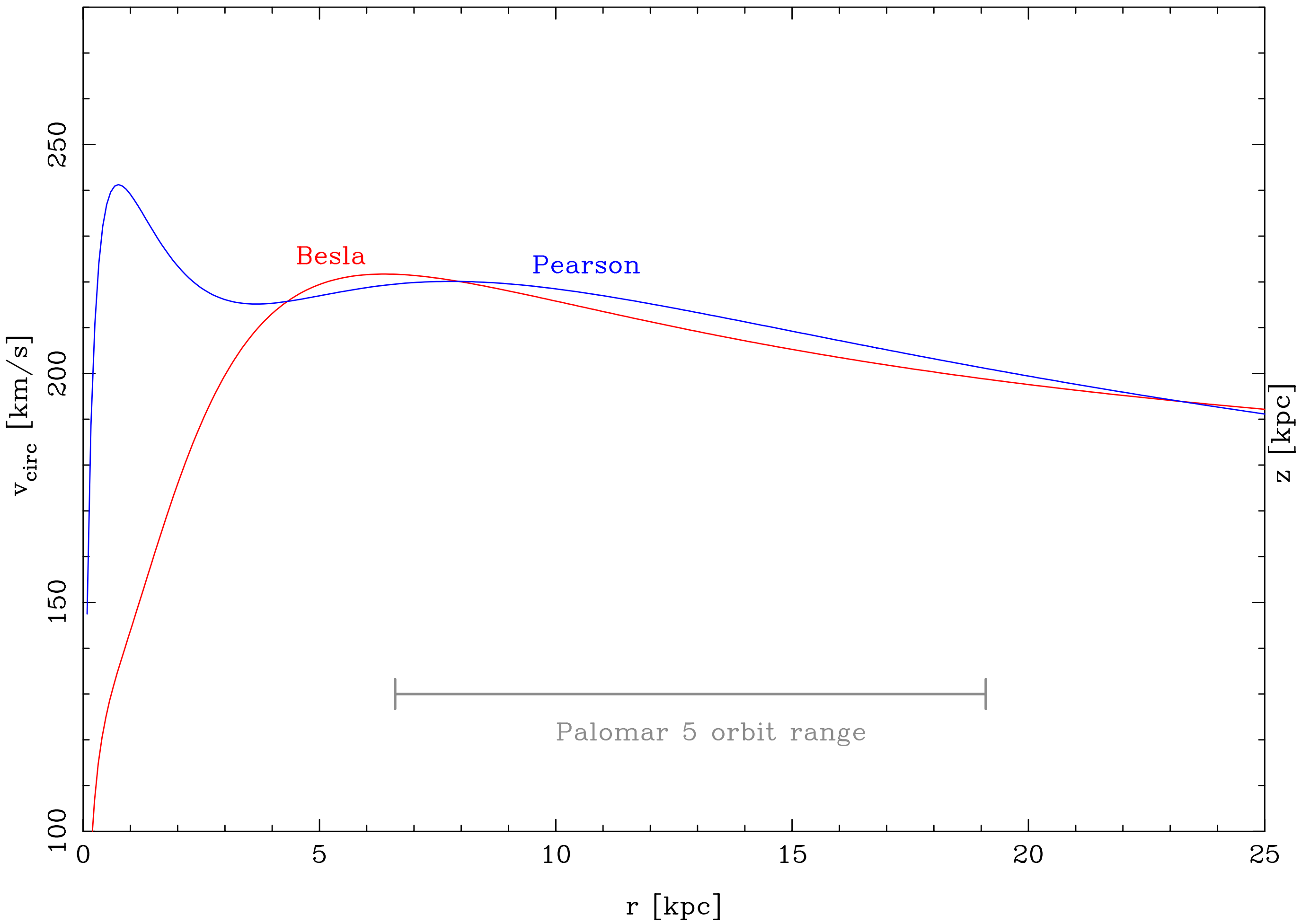


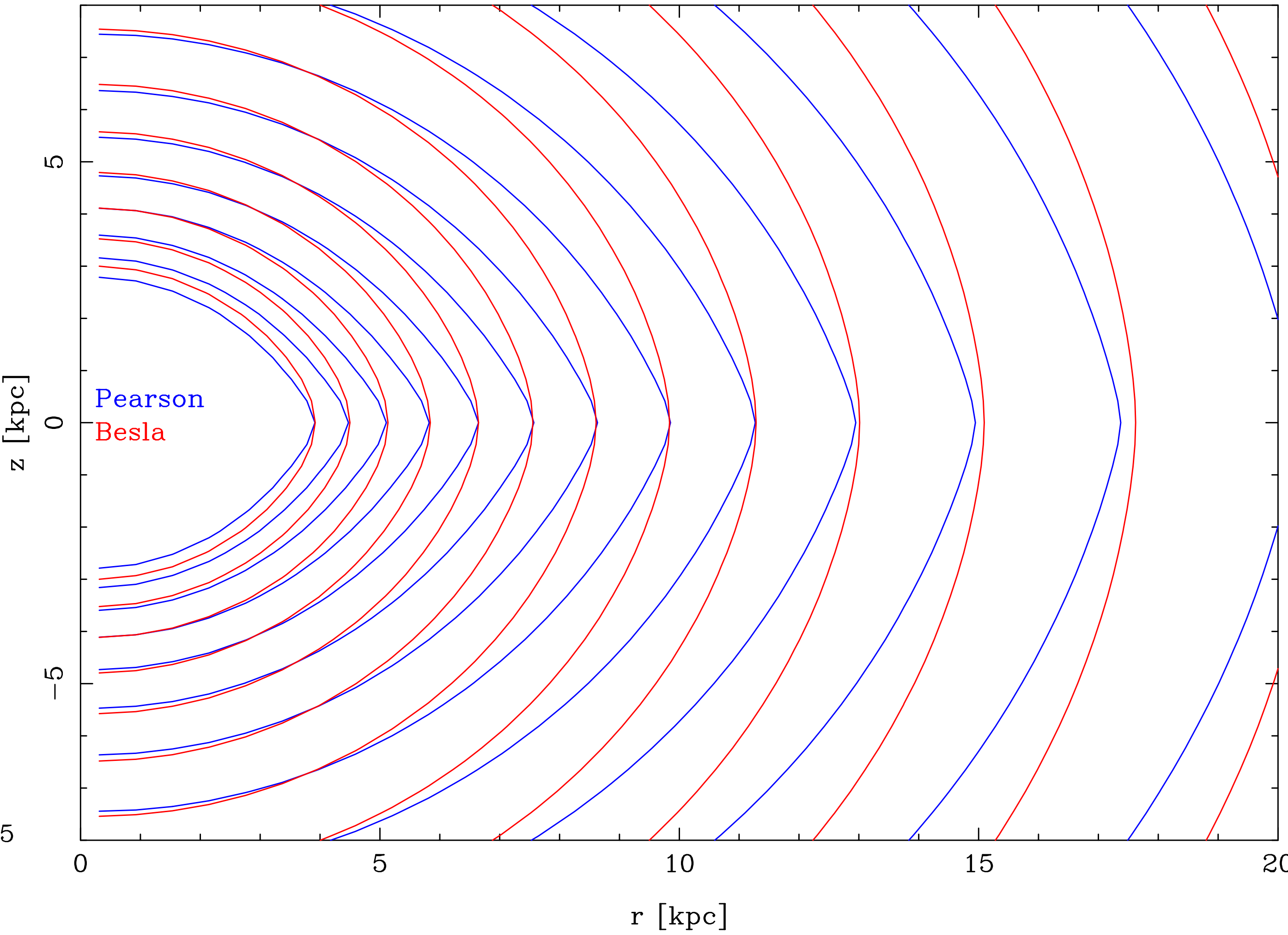
Pearson et al. 2014



Fritz & NK in prep

We use galpy (Bovy 2014). Spherical halo is indeed a good fit.





Fritz & NK in prep

In detail, a slightly less flattened halo is a better fit to both RV and stream-streak space. PM's allow to discriminate between models.

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

Nitya Kallivayalil (University of Virginia)
Andrew R. Wetzel (Caltech & Carnegie Observatories)
Joshua D. Simon (Carnegie Observatories)
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)

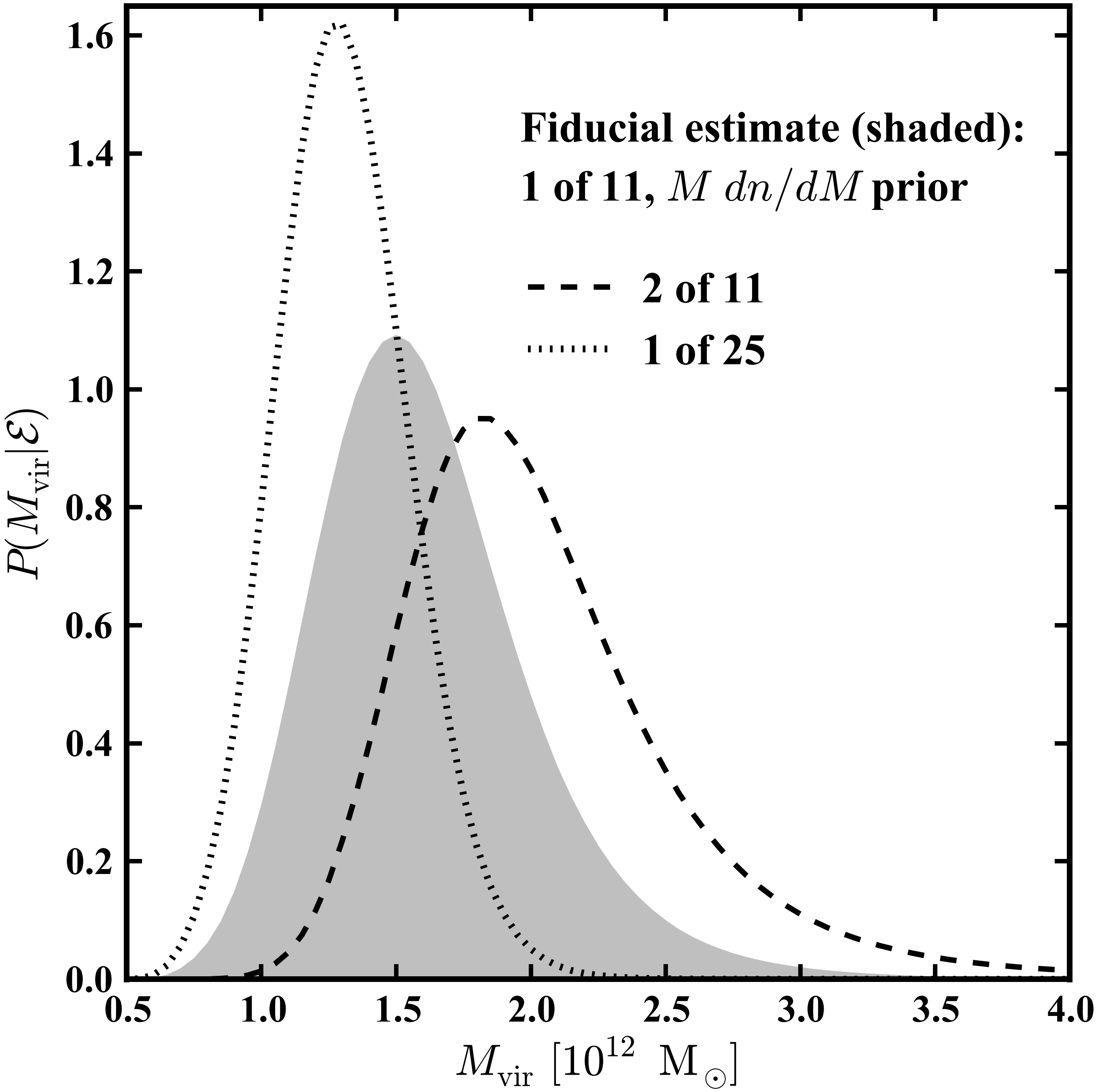
March 4, 2015

Abstract

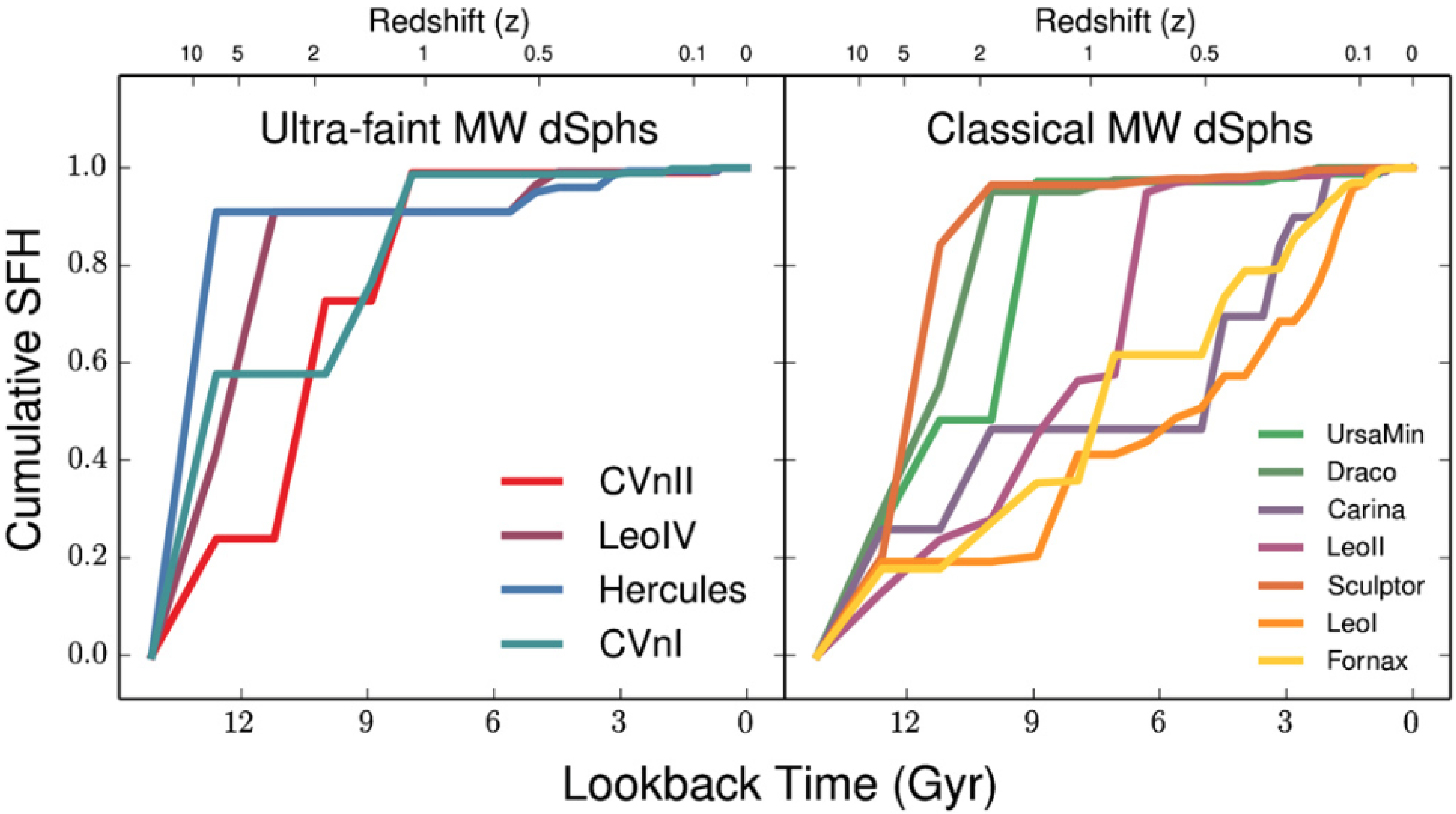
High-precision astrometry throughout the Local Group is a unique capability of the Hubble Space Telescope (HST), with potential for transformative science, including constraining the nature of dark matter, probing the epoch of reionization, and understanding key physics of galaxy evolution. While Gaia 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:

(1) **Direct dynamical measurements of the mass of the Milky Way and M31.** Current constraints come from either using only line-of-sight velocities (e.g., Tollerud et al., 2012), or using just one satellite with a very accurate PM measurement (Boylan-Kolchin et al., 2013), both of which are limited by systematics.

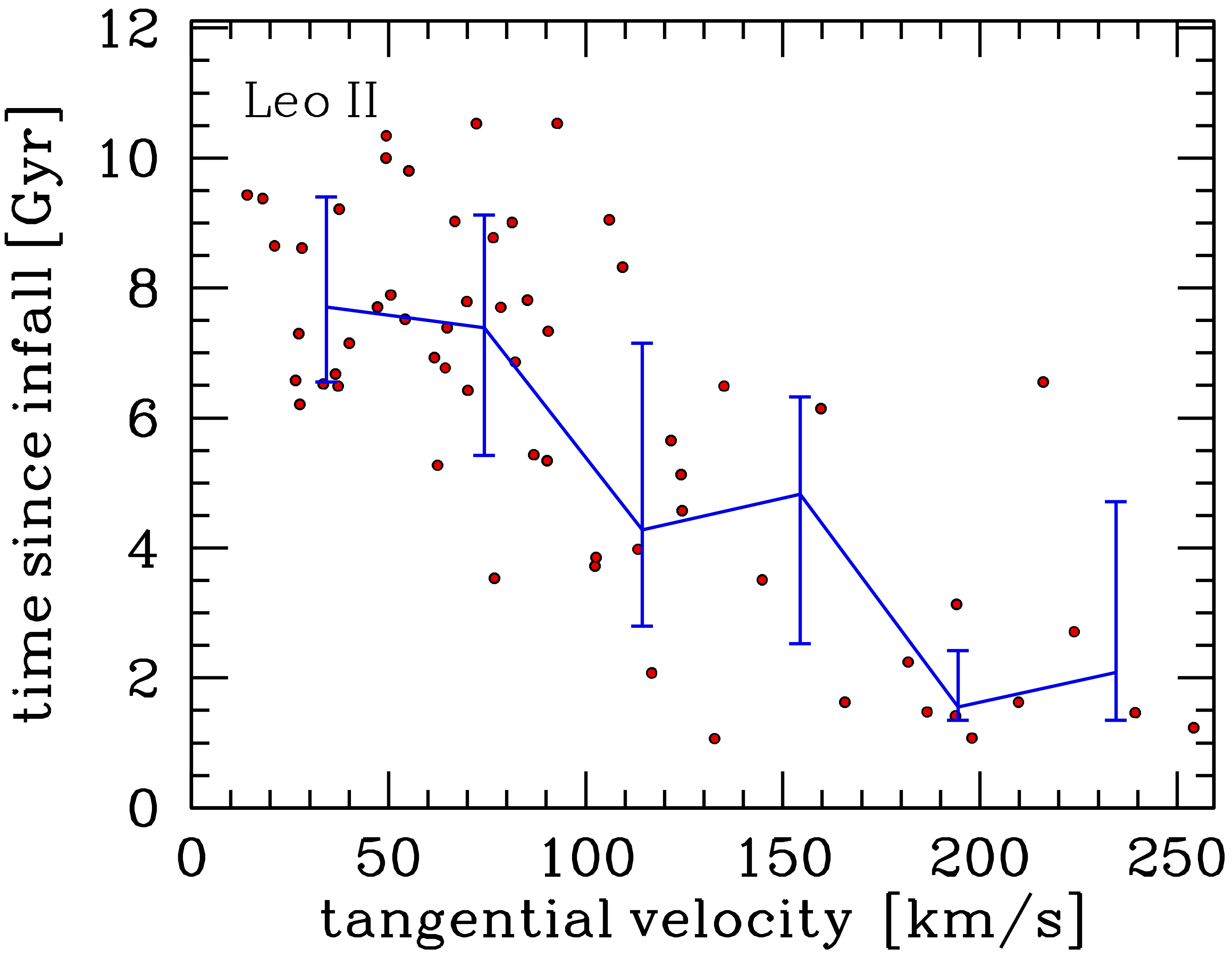


Boylan-Kolchin et al. 2013



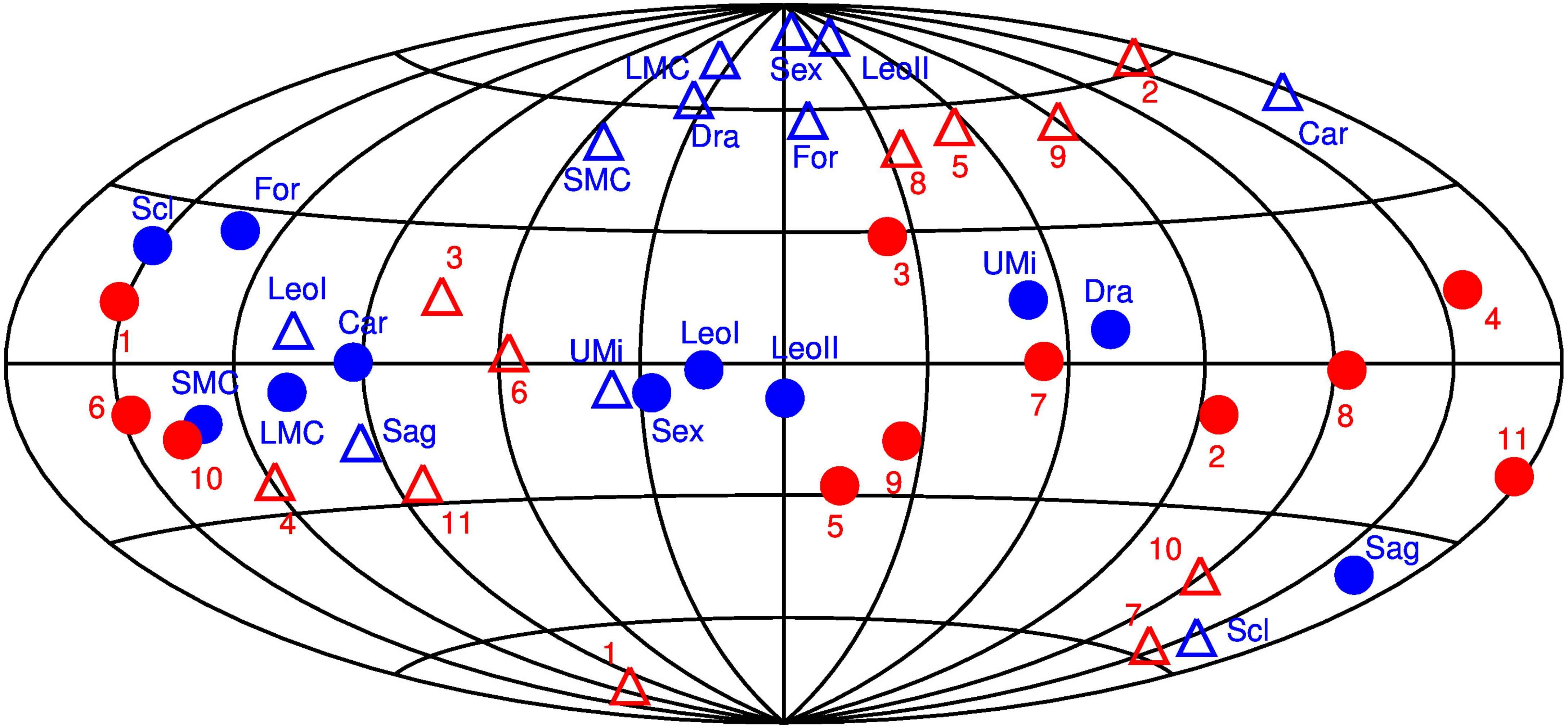
(2) Understanding the physics of environment on satellite galaxies. The dwarf galaxies in the LG show a strikingly sharp and nearly complete transition within the virial radii (300 kpc) of the MW and M31, towards elliptical/spheroidal morphology, little-to-no cold gas, and quenched star formation (e.g., Einasto et al., 1974).

Brown et al. 2014, Weisz et al. 2014



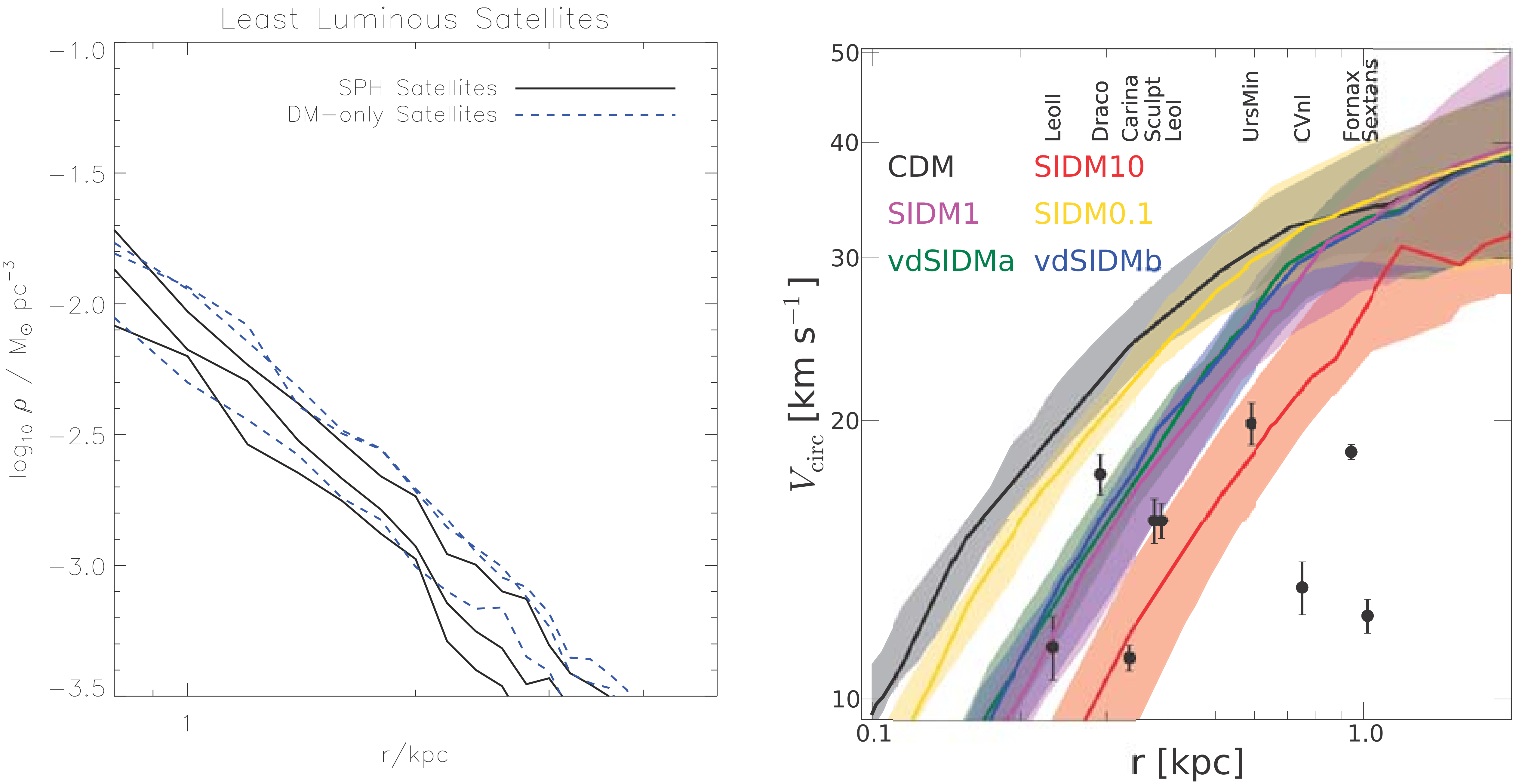
Wetzel et al. in prep

(3) Dwarf galaxies as probes of cosmic reionization. Ultra-faint galaxies provide promising probes of the effects of reionization (at $z > 6$) on the evolution of dwarf galaxies, using the above recently measured SFHs. However, a significant challenge to using ultra-faints as probes of reionization is knowing where they were at $z > 6$, to disentangle the effects of reionization from the environmental effects of the MW halo (e.g., Wetzel et al., 2015).



Sawala et al. 2014

(4) Physical associations of dwarf galaxies and stellar streams. Significant debate persists regarding the "plane" of satellites, and whether several dwarfs and/or streams are part of the same physical associations/sub-groups (e.g., Watkins et al., 2013). In both cases, PM measurements would definitively determine whether these "planes of satellites" are physical structures or merely chance alignments.



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. Unfortunately, constraining whether dwarf halos are cuspy using projected light profiles and radial velocities has proven difficult (e.g., Breddels & Helmi, 2013).