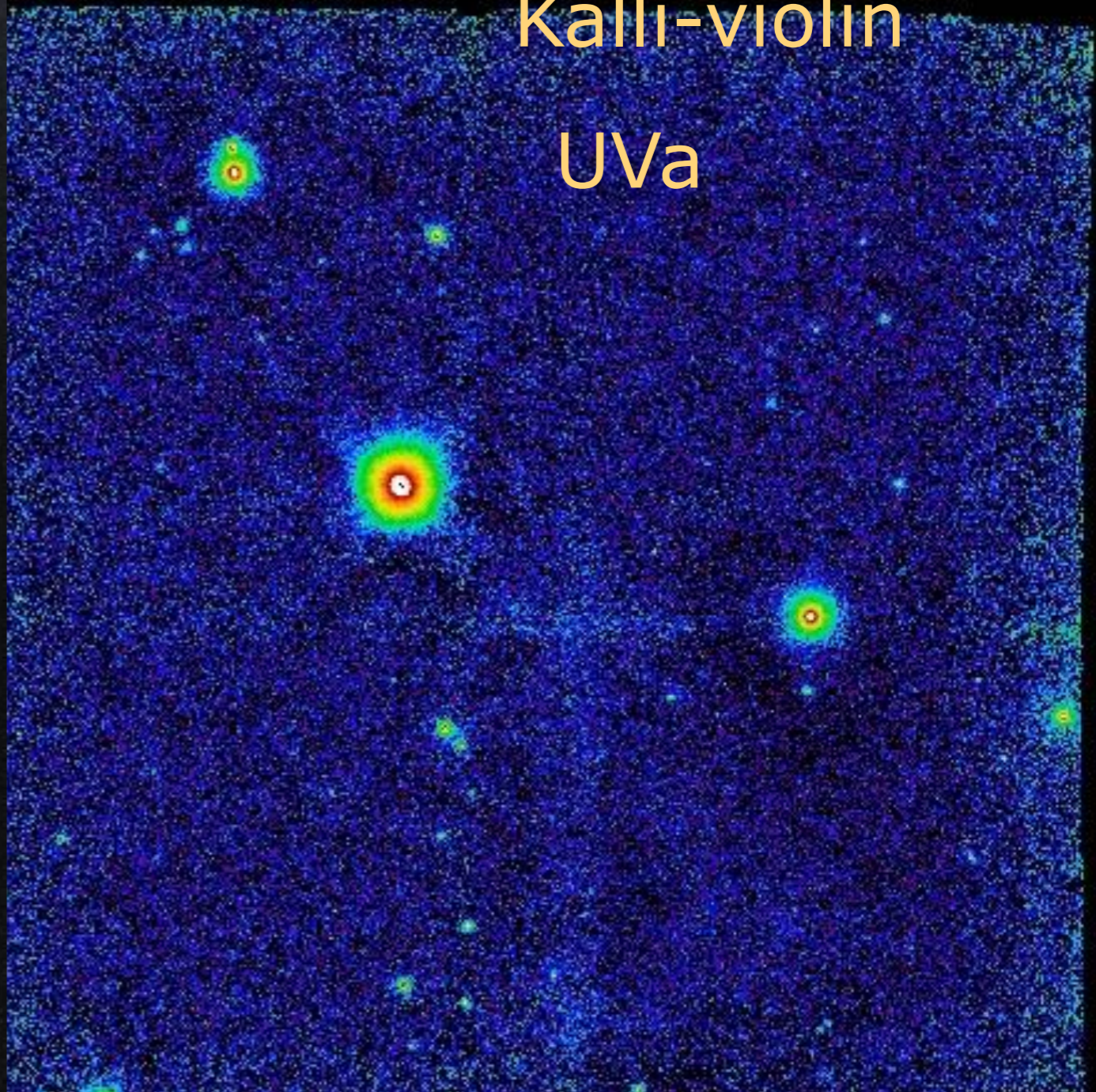
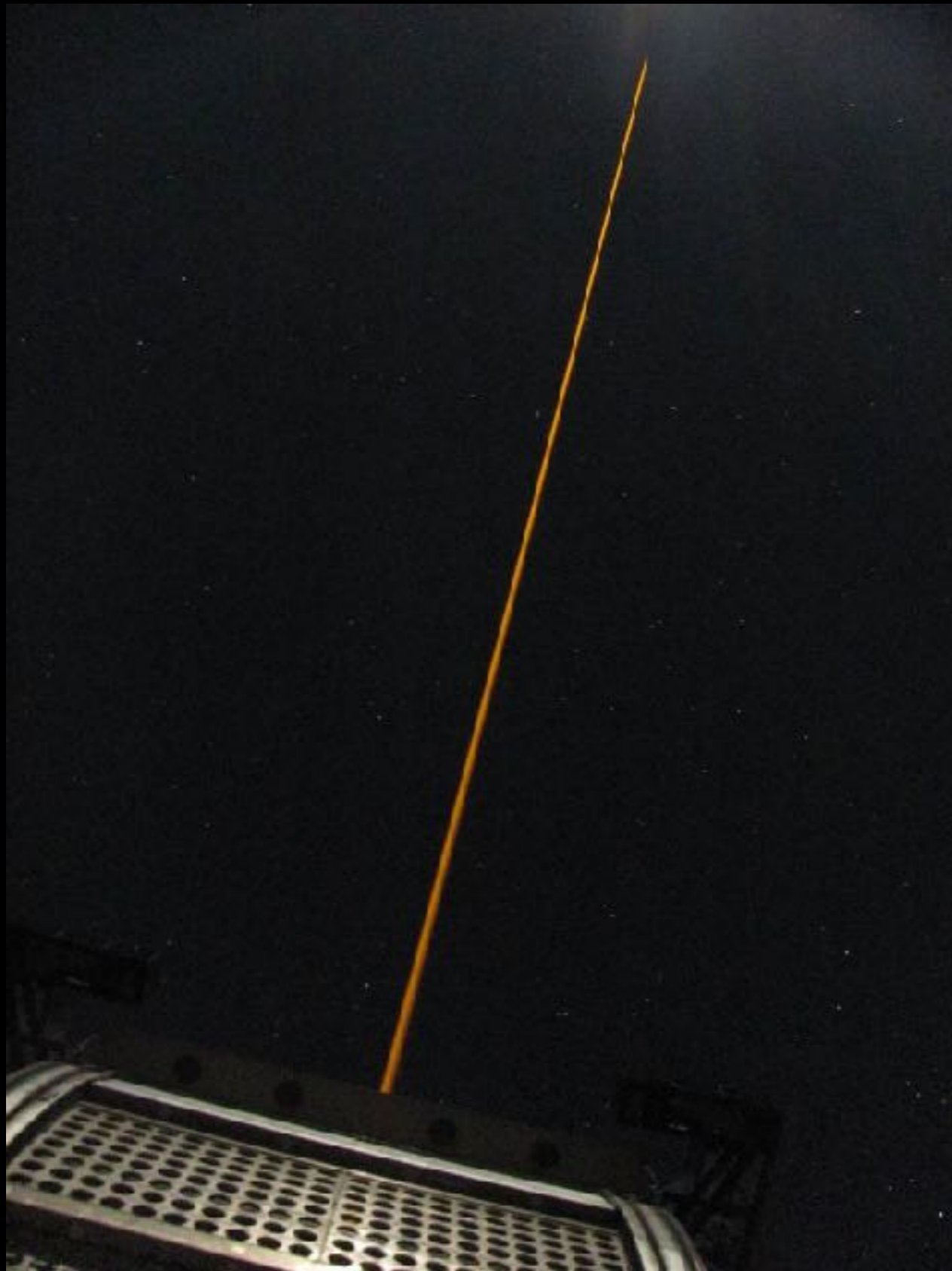


Probing the Dark Halo of the Milky Way

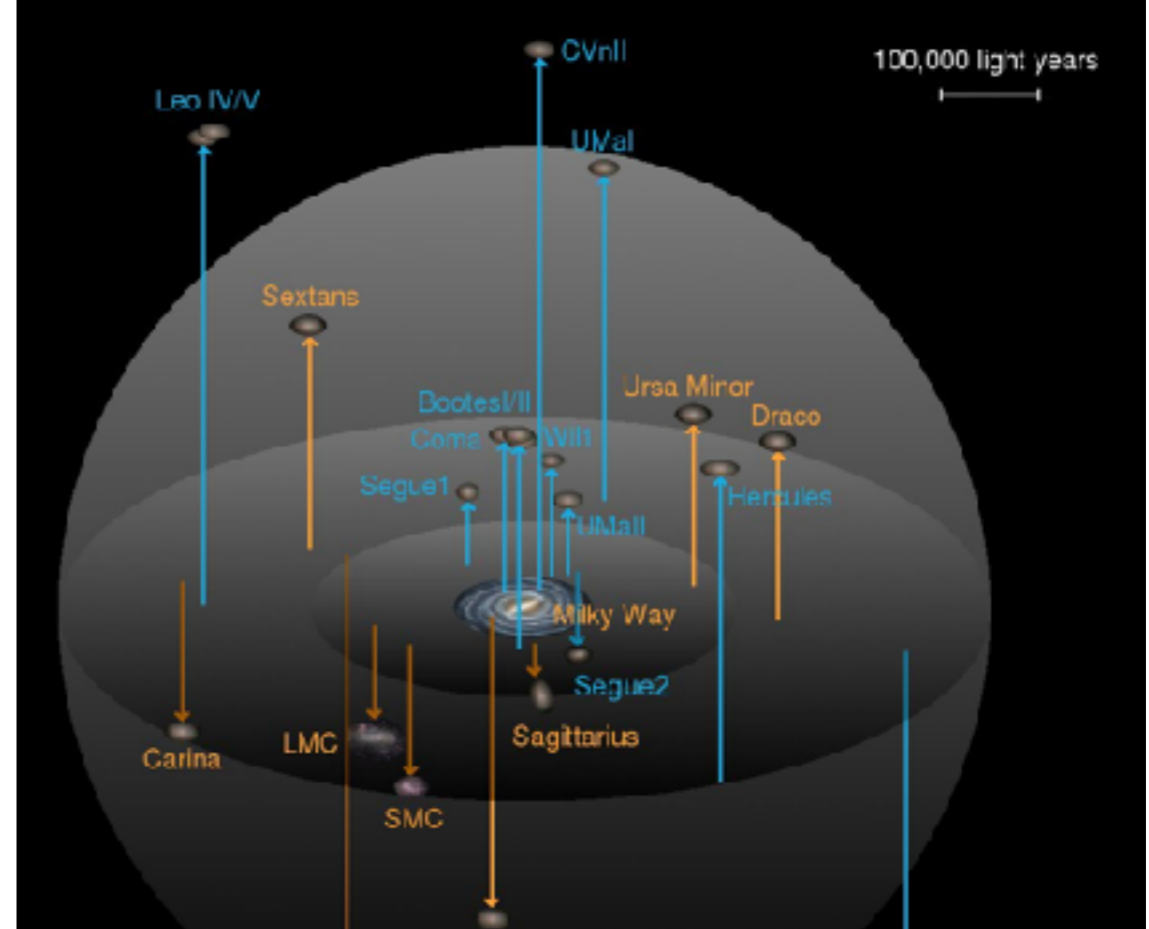
Nitya Kallivayalil
Kalli-violin

UVa



Meaningful Discrepancies:

- Missing Satellites Problem (e.g., Klypin et al. 1999; Moore et al. 1999; see Nierenberg+ 2016 at higher z)

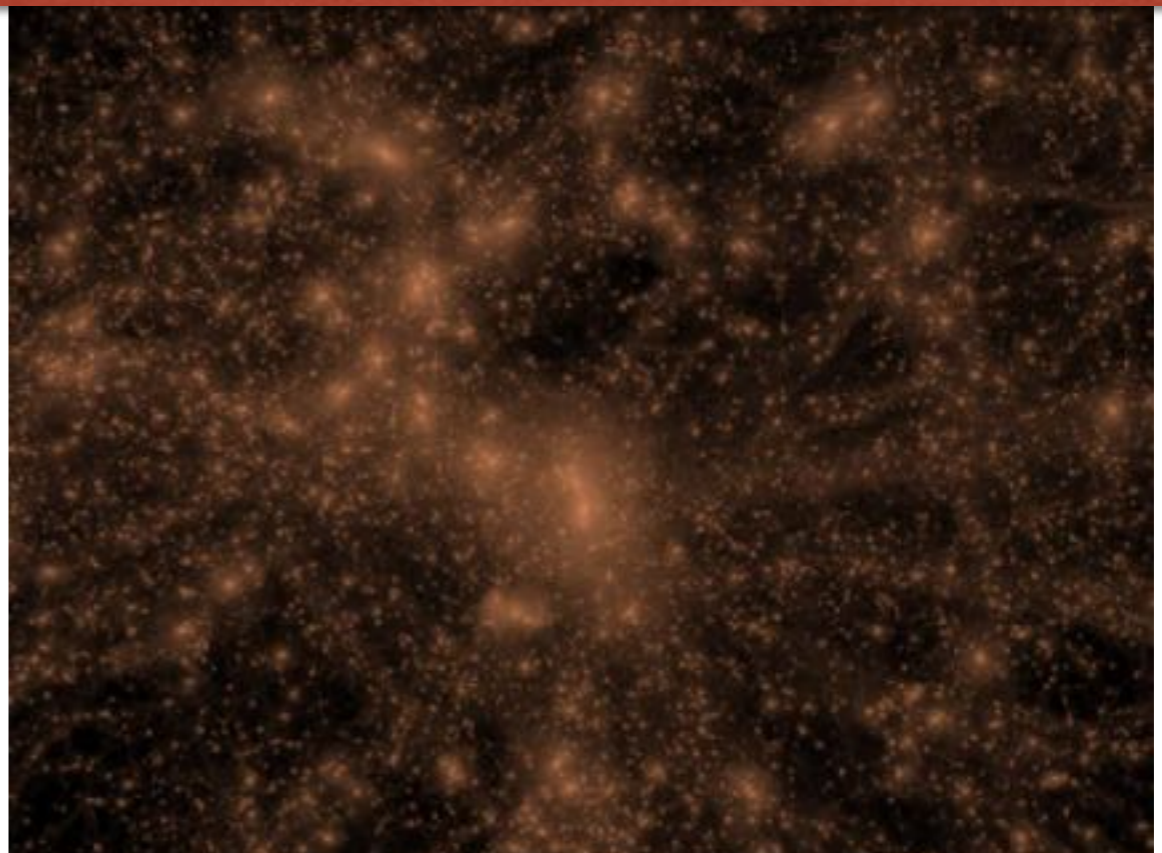


ALL RELY IN ONE WAY OR ANOTHER ON TOTAL
MILKY WAY MASS

& Penarrubia 2011; Boylan-Kolchin et al. 2011; Tollerud et al. 2014, Garisson-Kimmel et al. 2014)

- Shape of dark matter halo (e.g., Law & Majewski 2010)

J.T.A de Jong; Diemand et al.



- Total mass of the Milky Way is unknown to a factor of five!

Recent estimates range from $0.55 - 2.62 \times 10^{12} M_{\text{sun}}$ (e.g., Gibbons et al. 2014, Watkins et al. 2010; Bland-Hawthorn & Gerhard 2017).

- Proper Motions are a major missing component in the effort to measure masses, mass profiles.
- Orbits also provide the dynamical context for other observables, e.g., SFHs \rightarrow origins.

Required Proper Motion Uncertainty

$$\varepsilon_v \text{ [km/s]} = 4.74 \times \varepsilon_\mu \text{ [mas/yr]} \times d \text{ [kpc]}$$

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

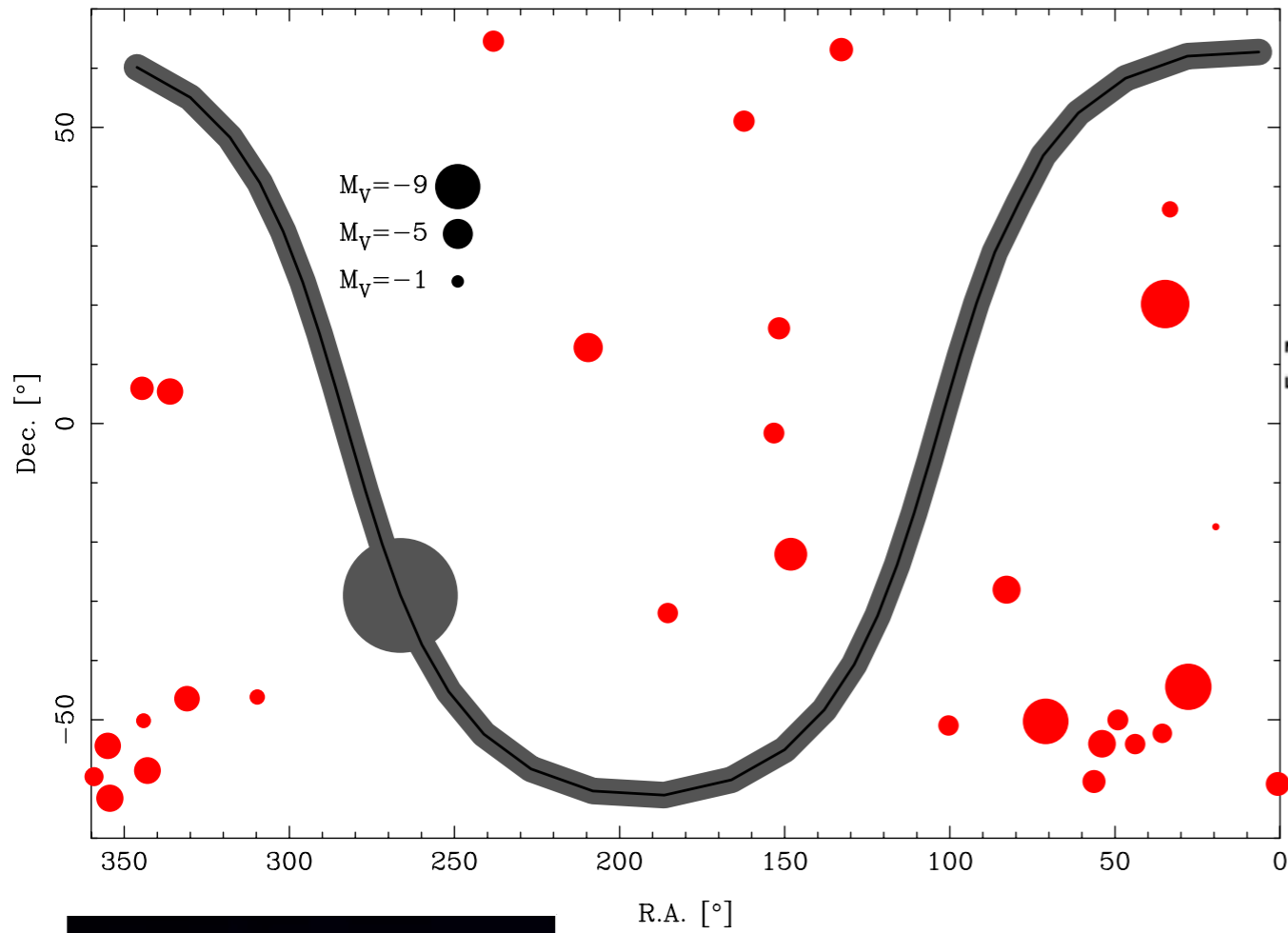
(d=10 kpc)

1 mas/yr = 47 km/s

Milky Way

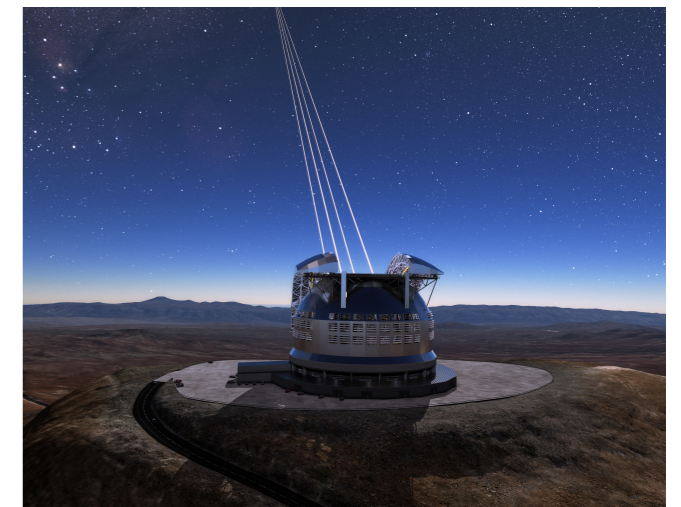
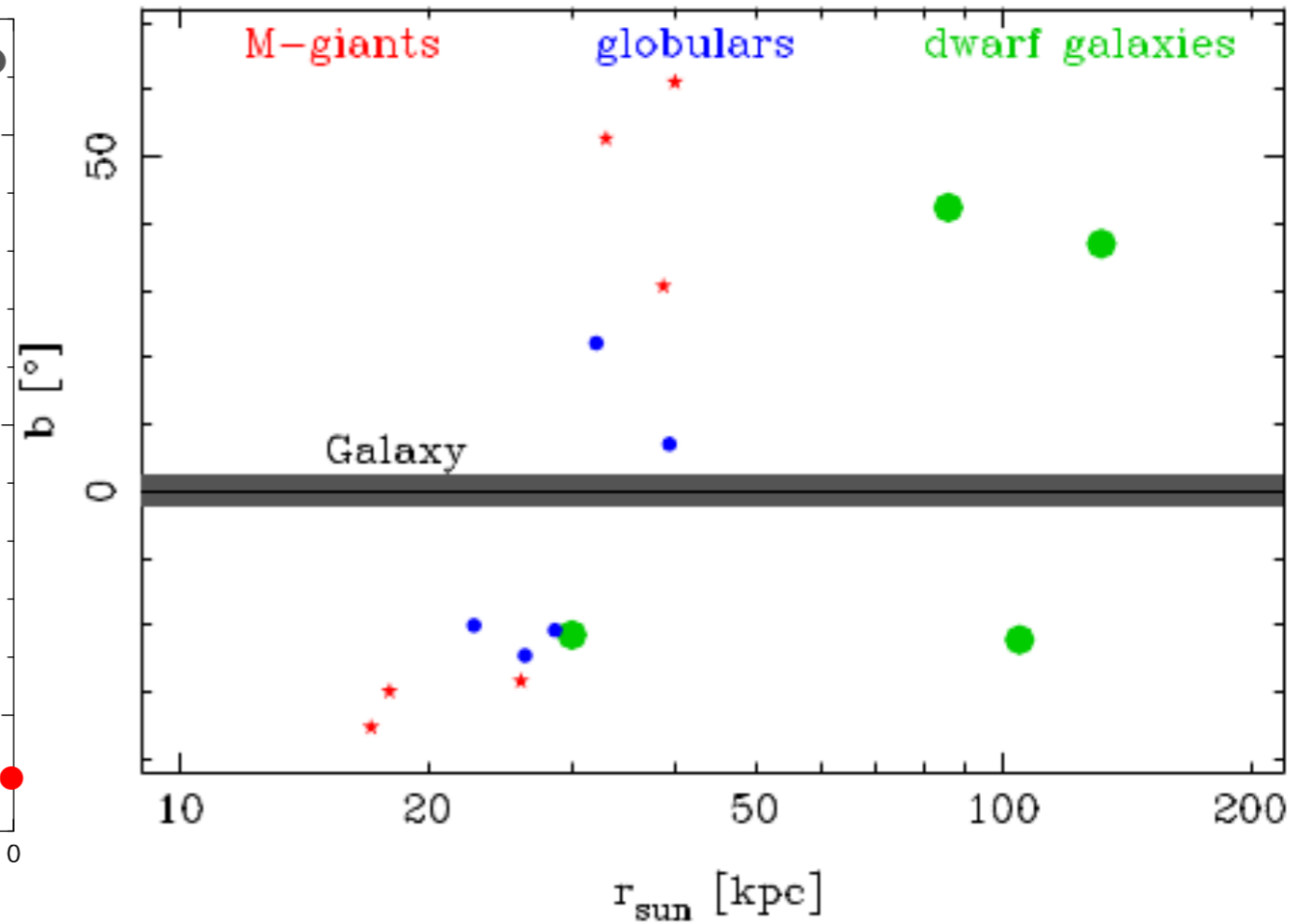
HST Treasury Program

30 dwarf galaxy targets, 164 orbits



Gemini Large Program

15 targets, 143 hr over 3 yrs



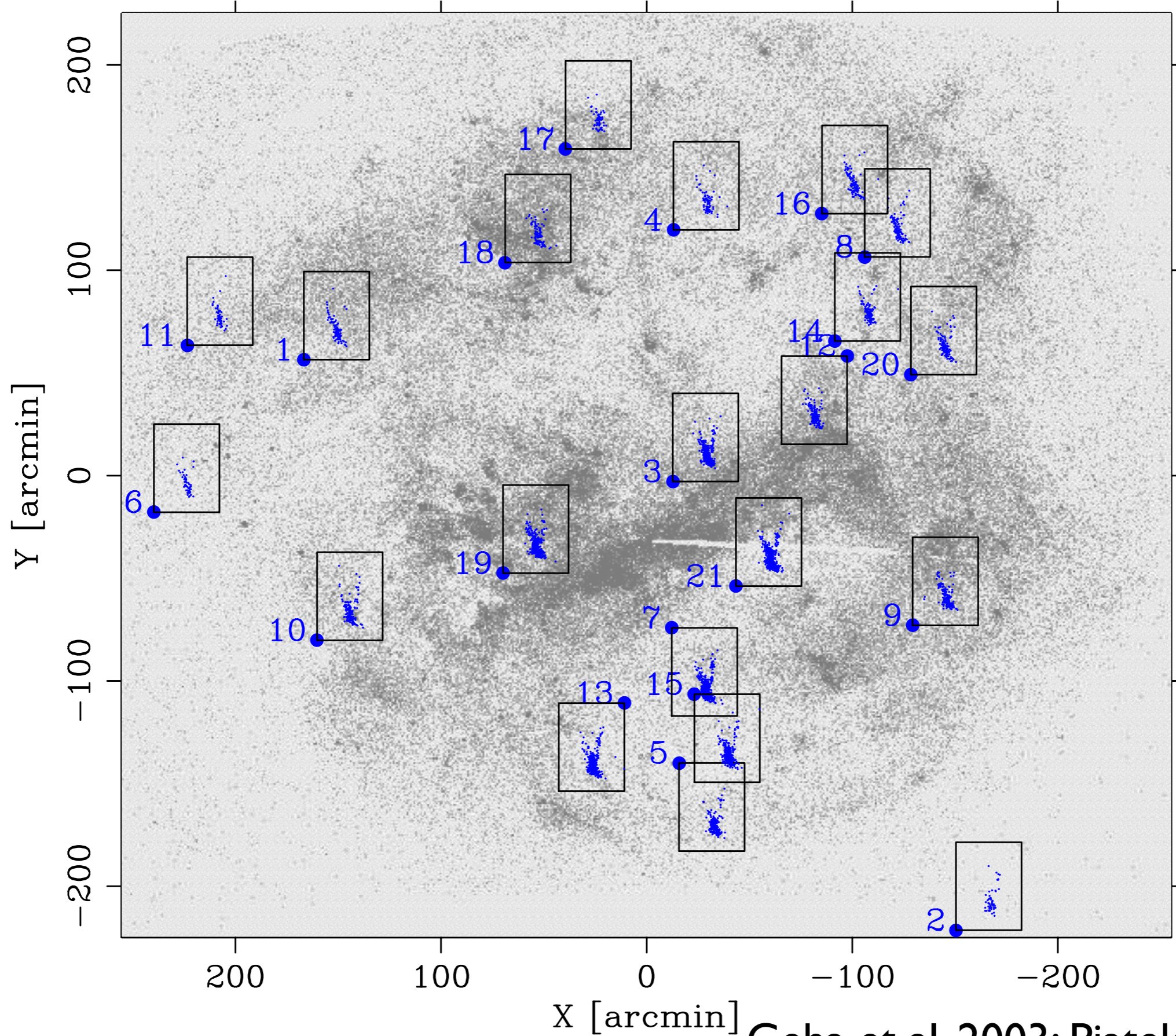
Outline: HST versus AO techniques:

- LMC --> Pal 5 —> Pyxis



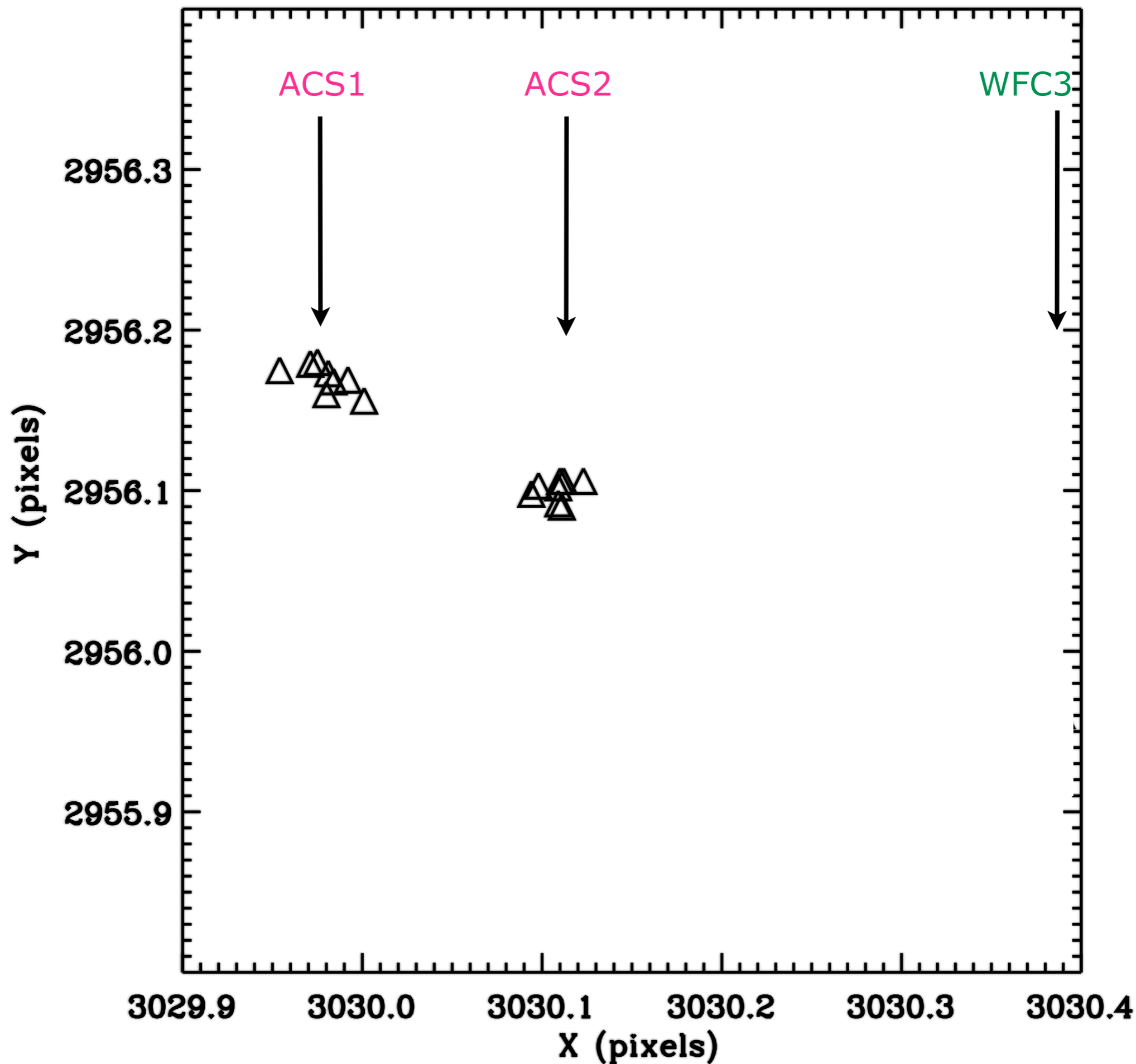
Internal Motions in the LMC

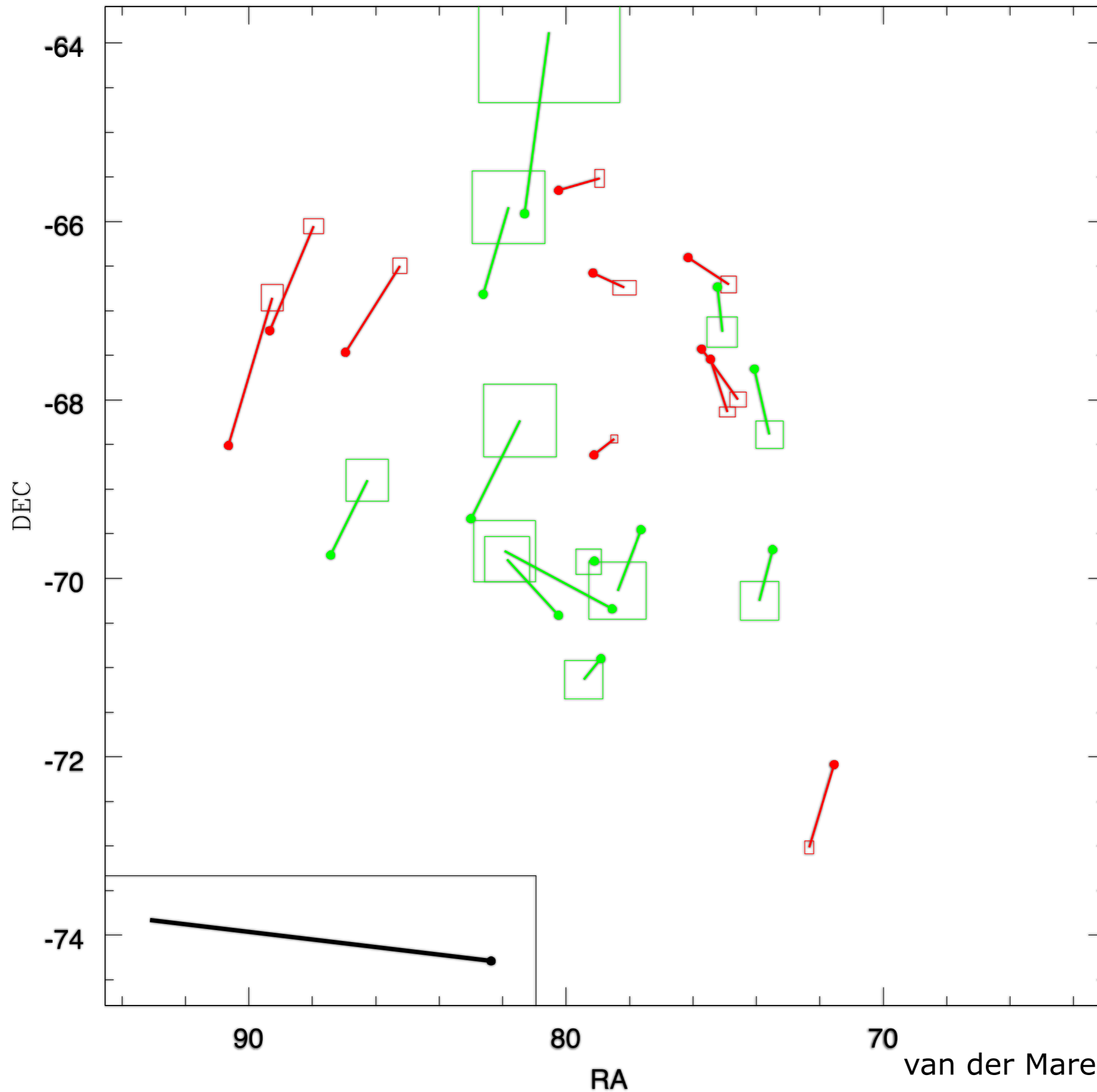
Reference Frame



Geha et al. 2003; Piatek et al. 2008

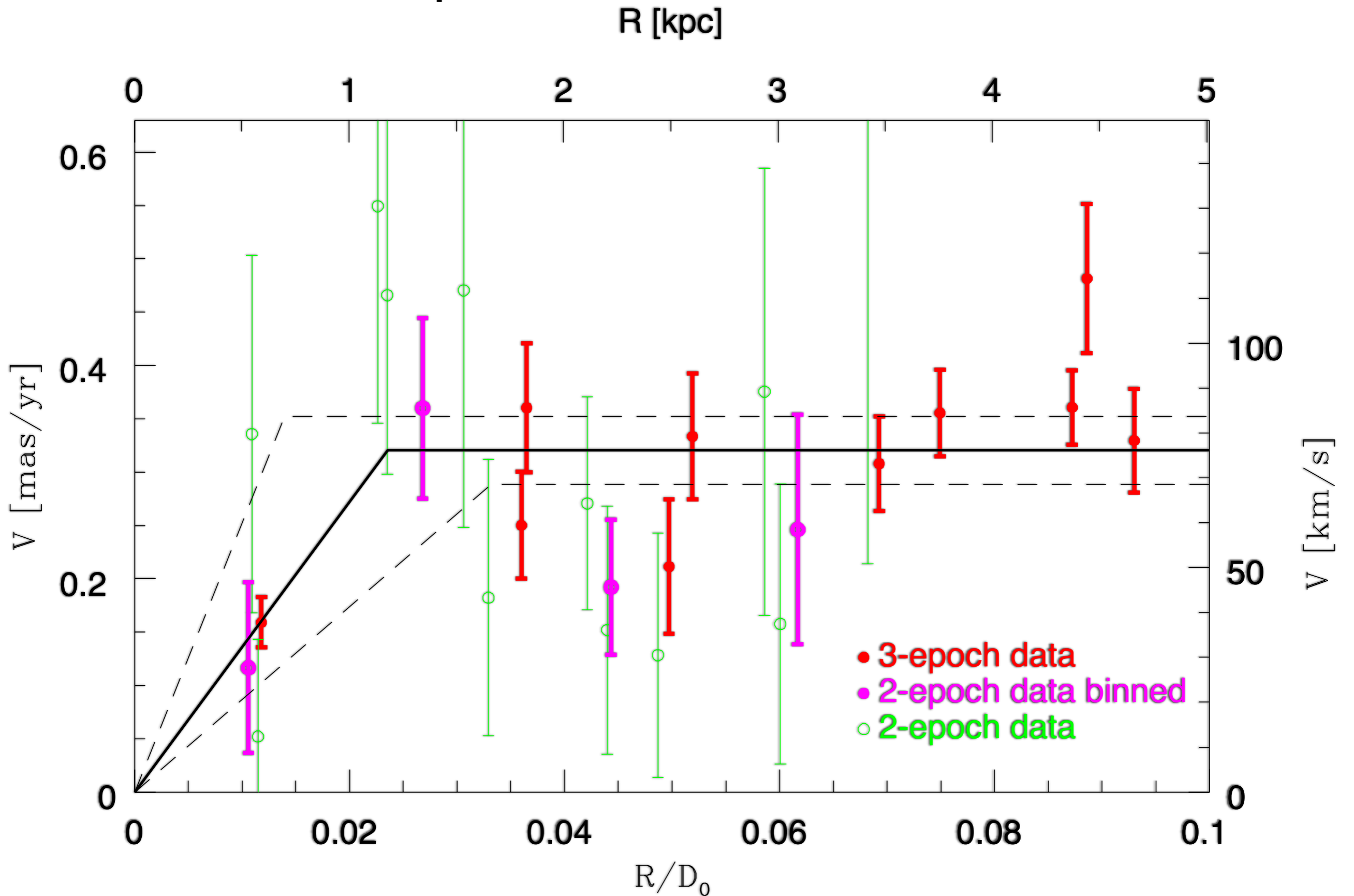
Field LMC01

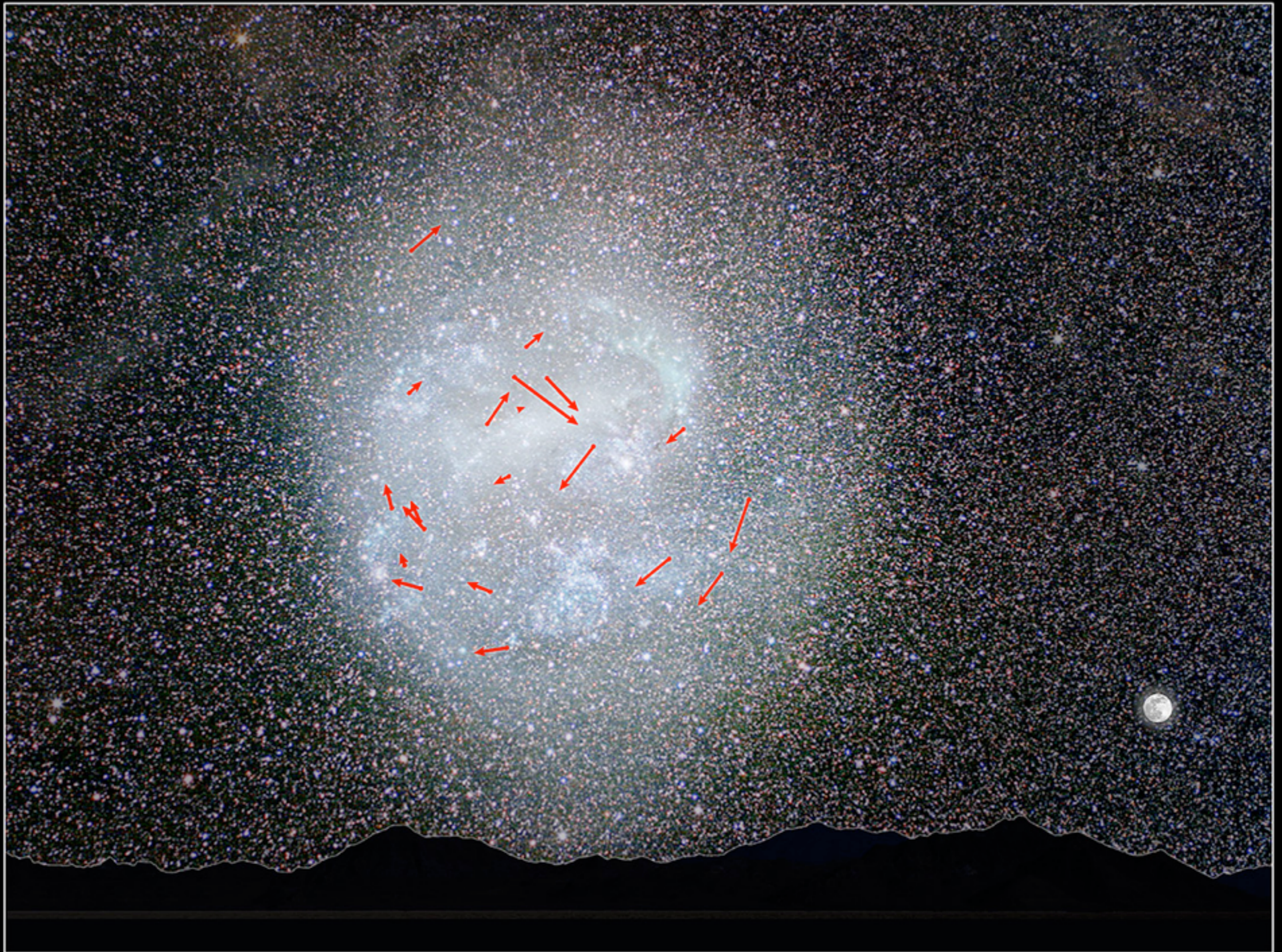




van der Marel & NK (2014)

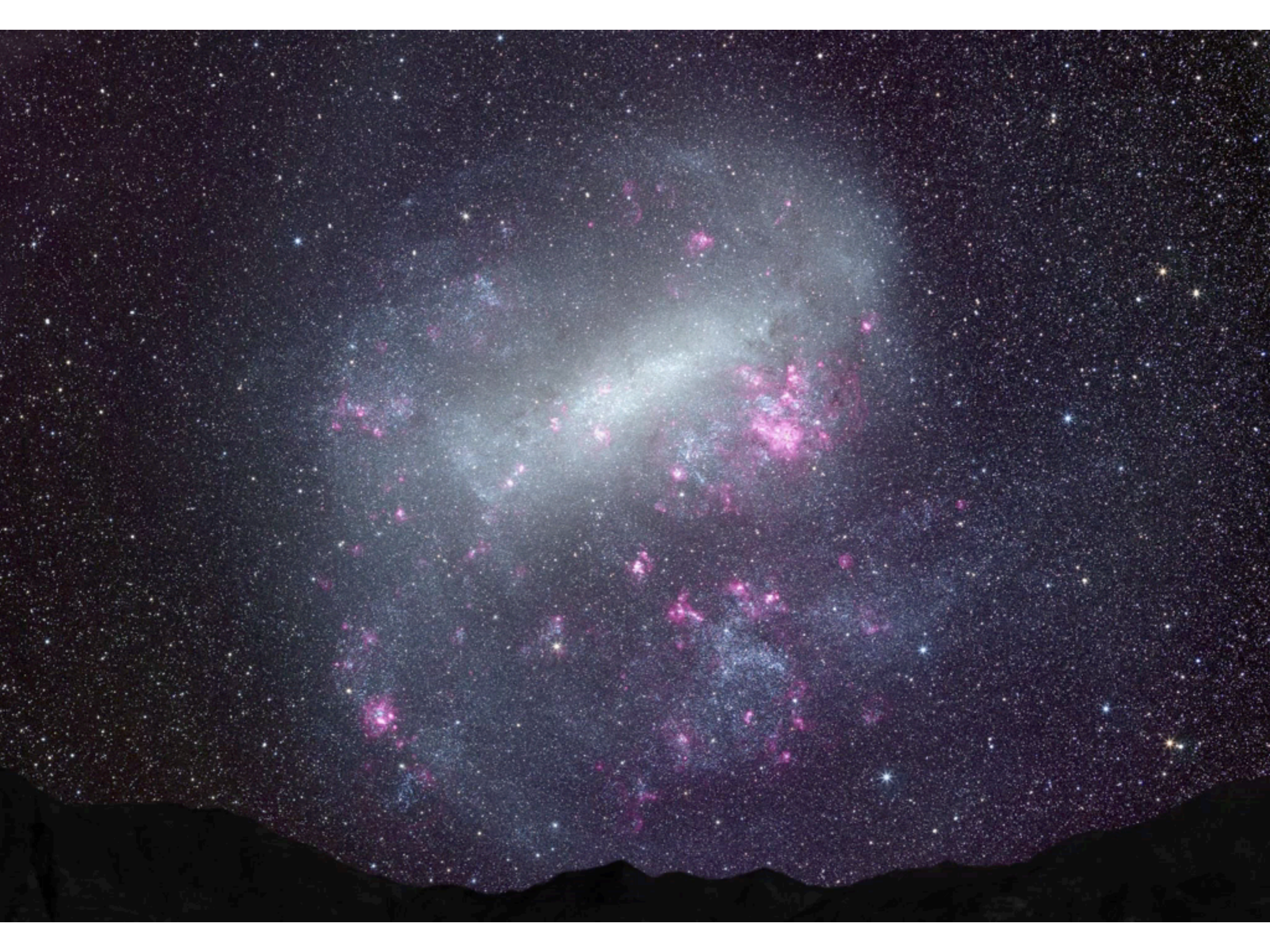
LMC Proper Motion Rotation Curve



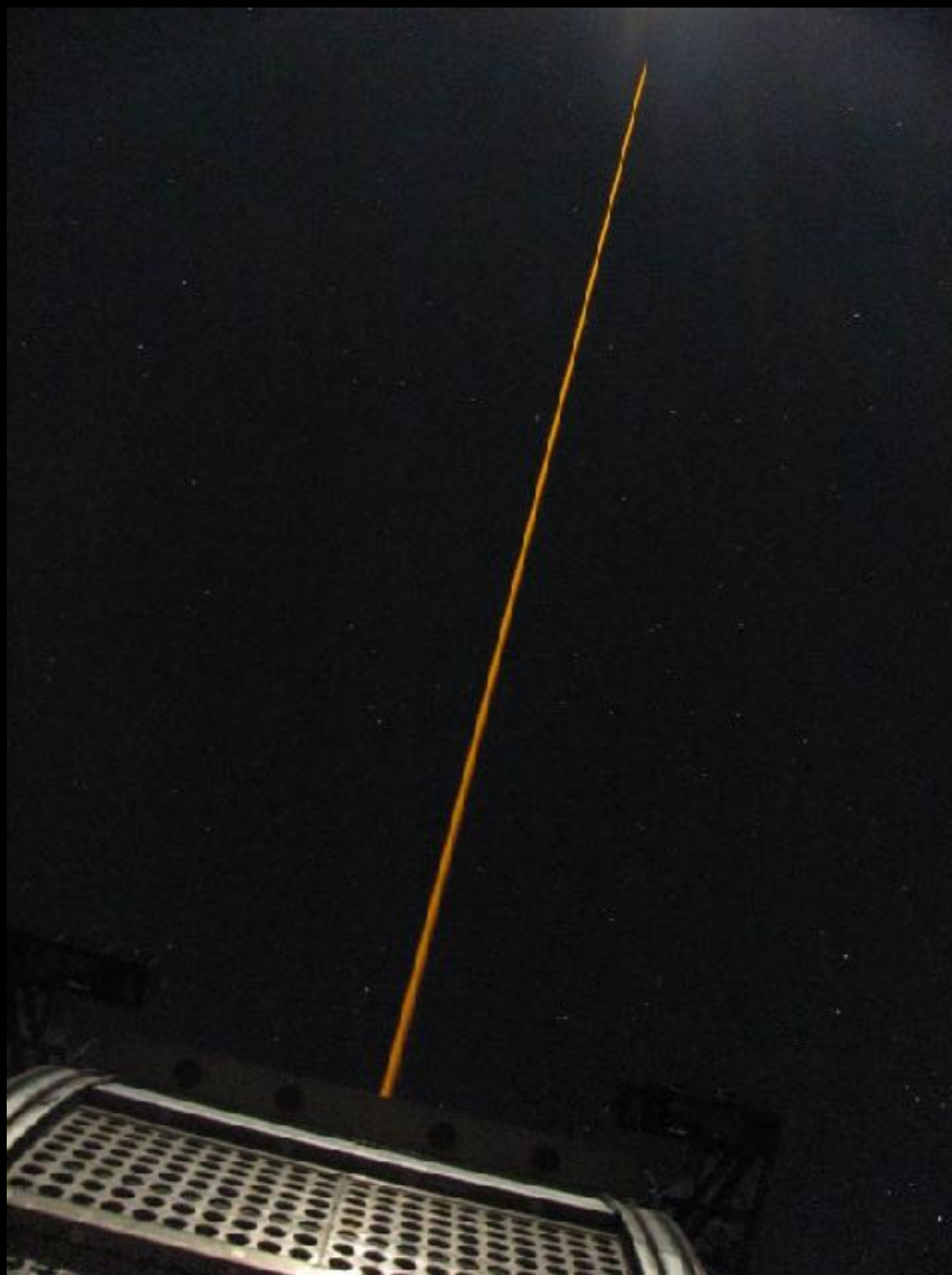


Hubble Measures Rotation of the Large Magellanic Cloud • Photo Illustration

NASA and ESA ■ STScI-PRC14-11a



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



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

Pyxis: HST (~2009) + Gemini AO (2015)

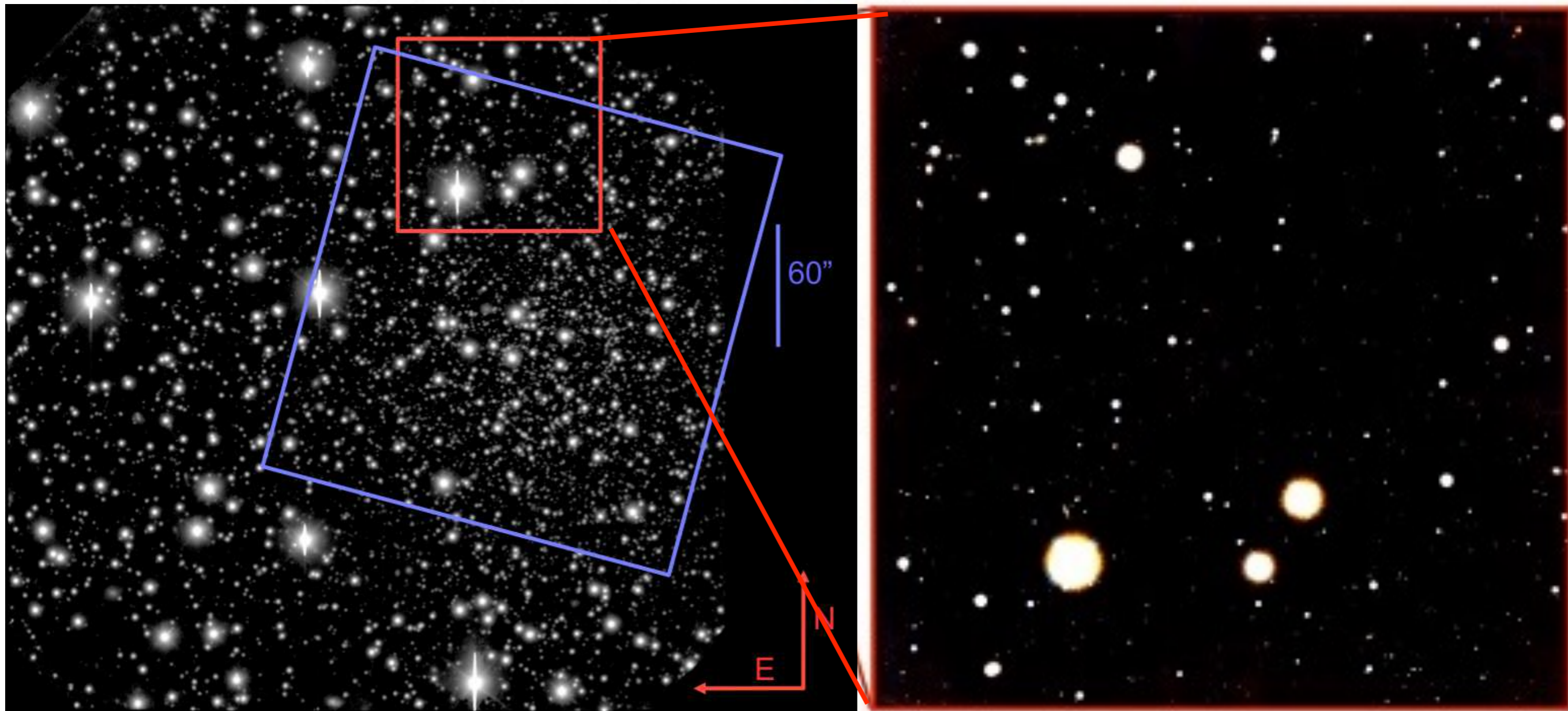
Pyxis

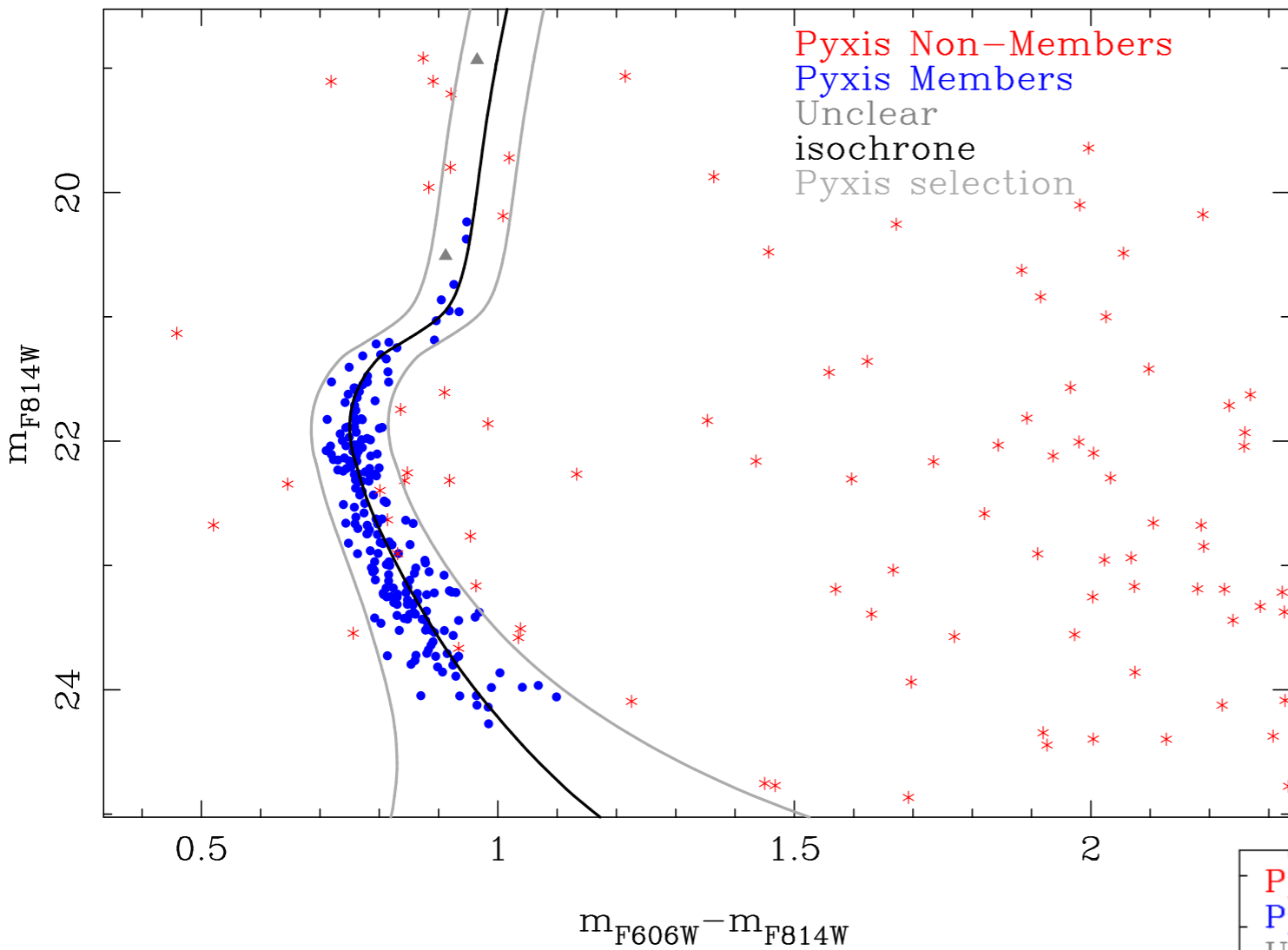
Halo globular cluster

$D_{\text{sun}} = 39.4$ kpc

$M_V = -6.0$

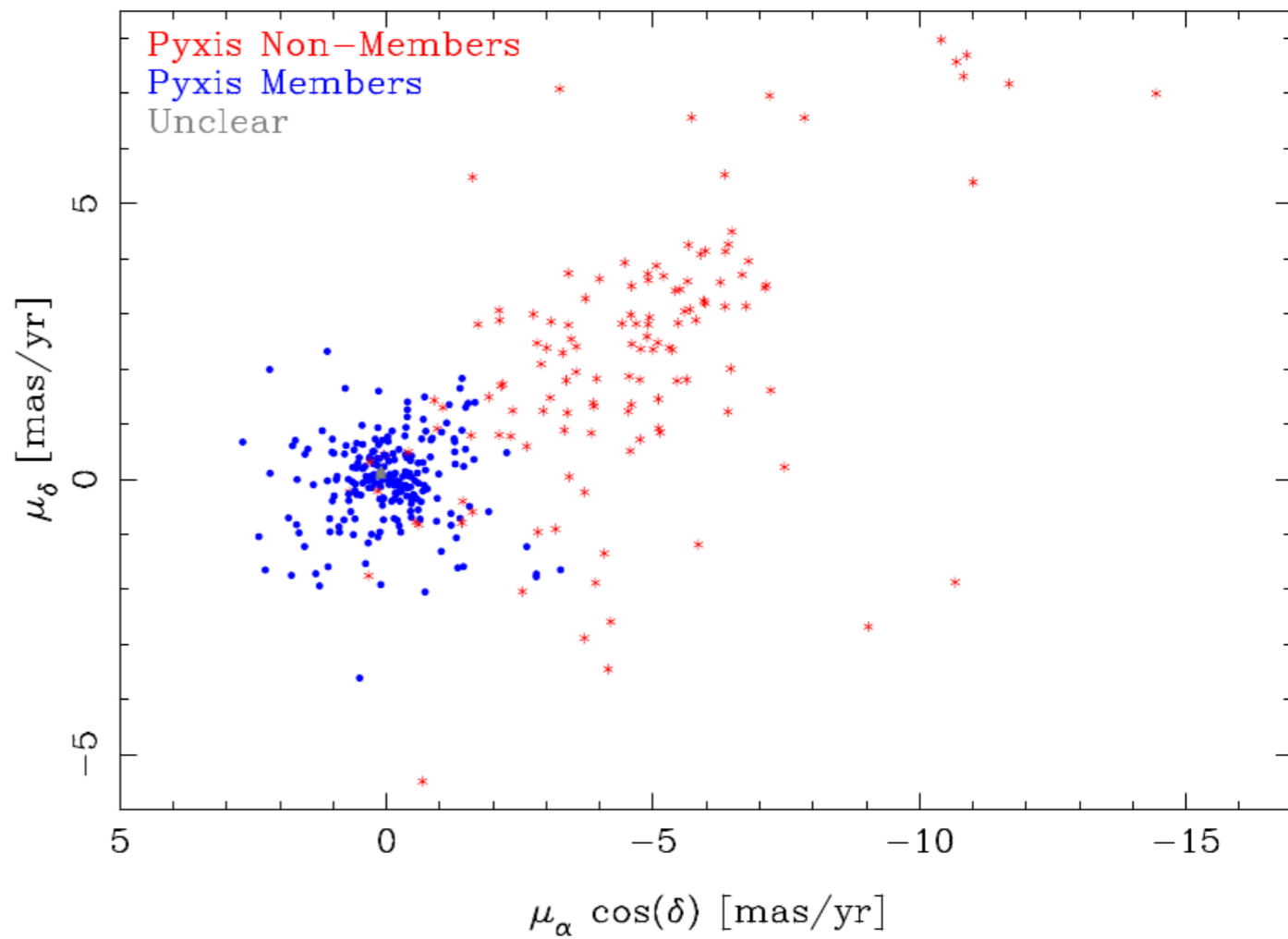
$[\text{Fe}/\text{H}] = -1.45$



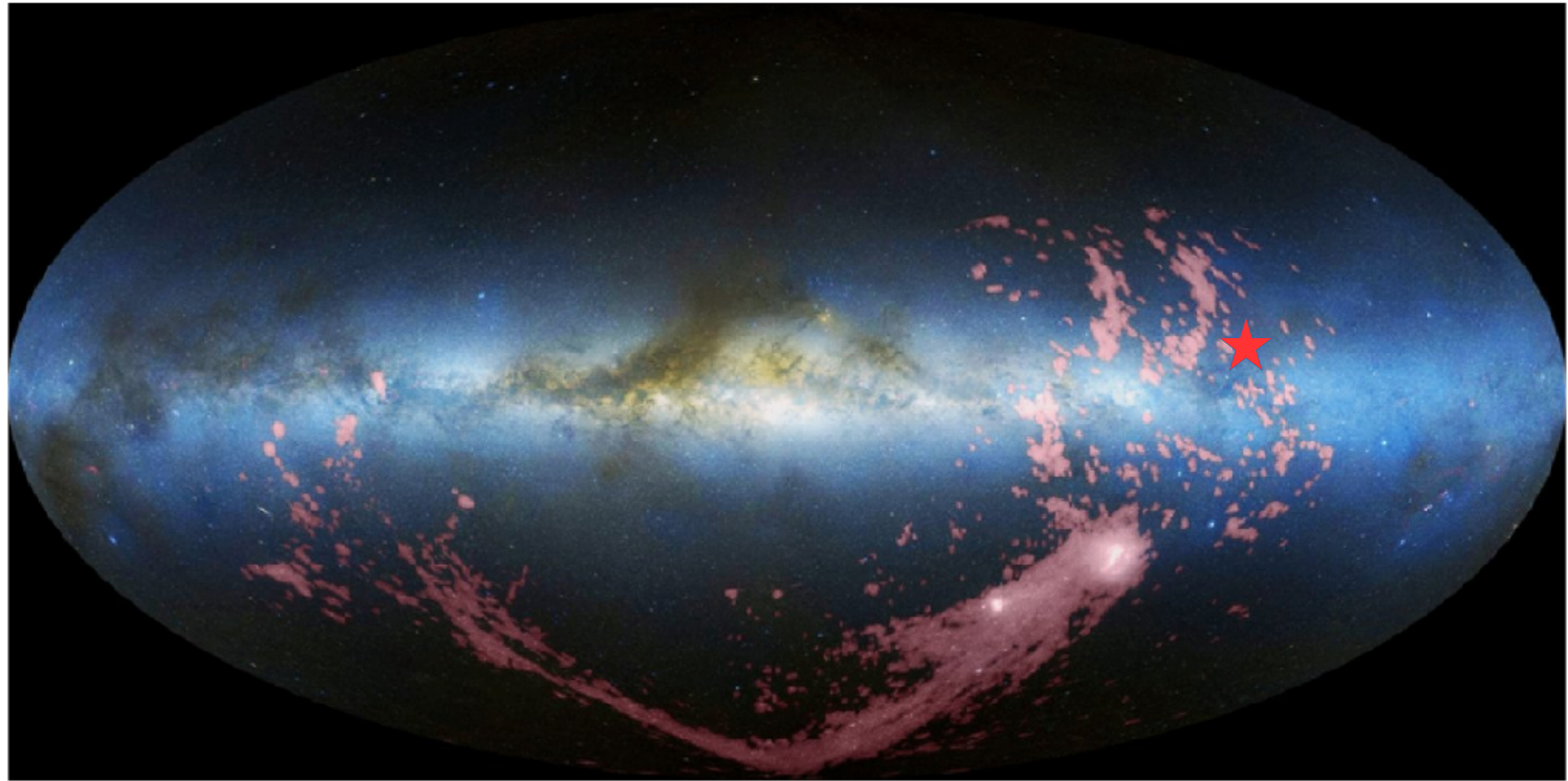


AO Proper Motions:

Pyxis motions are easily discernible from Milky Way foreground

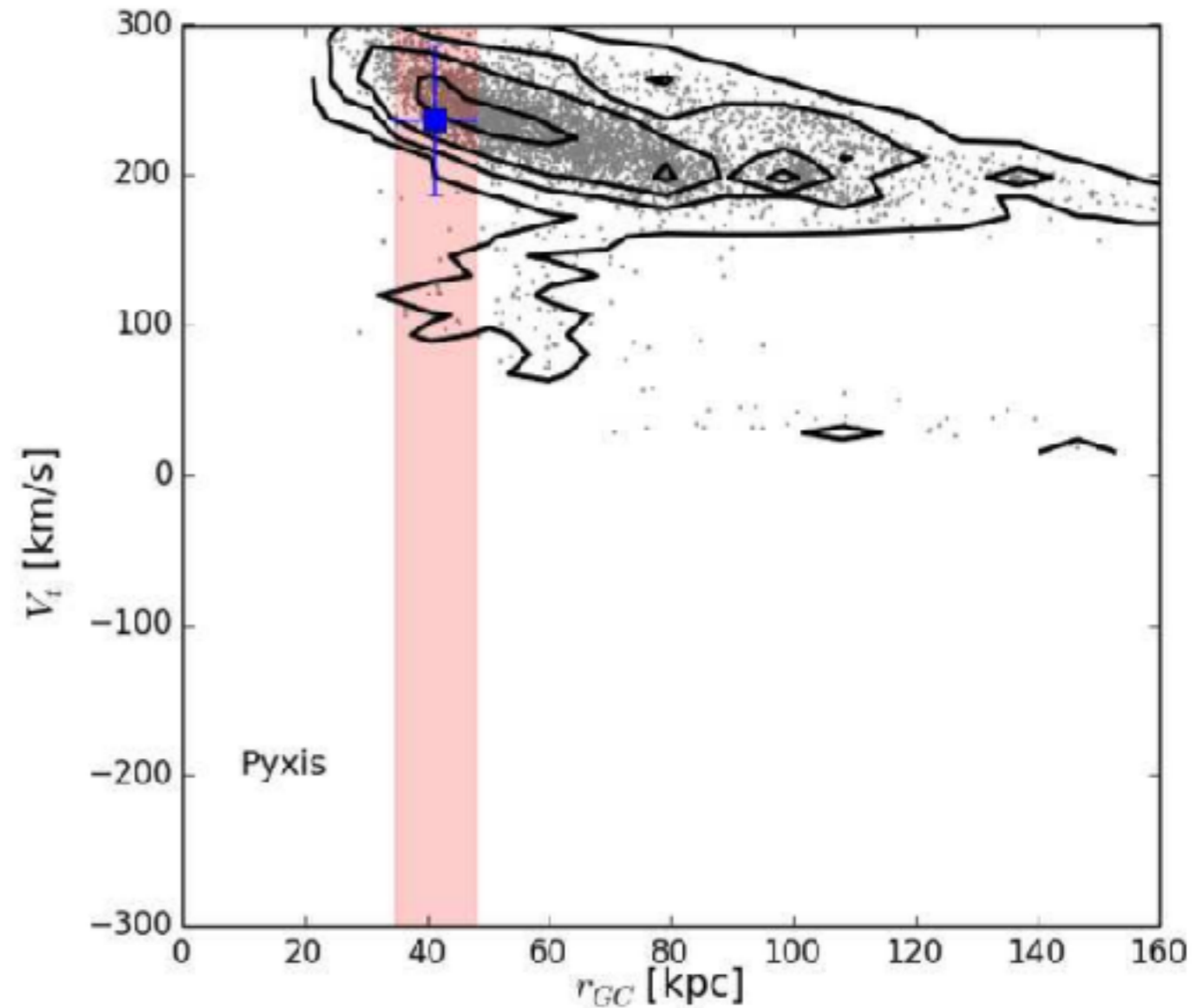
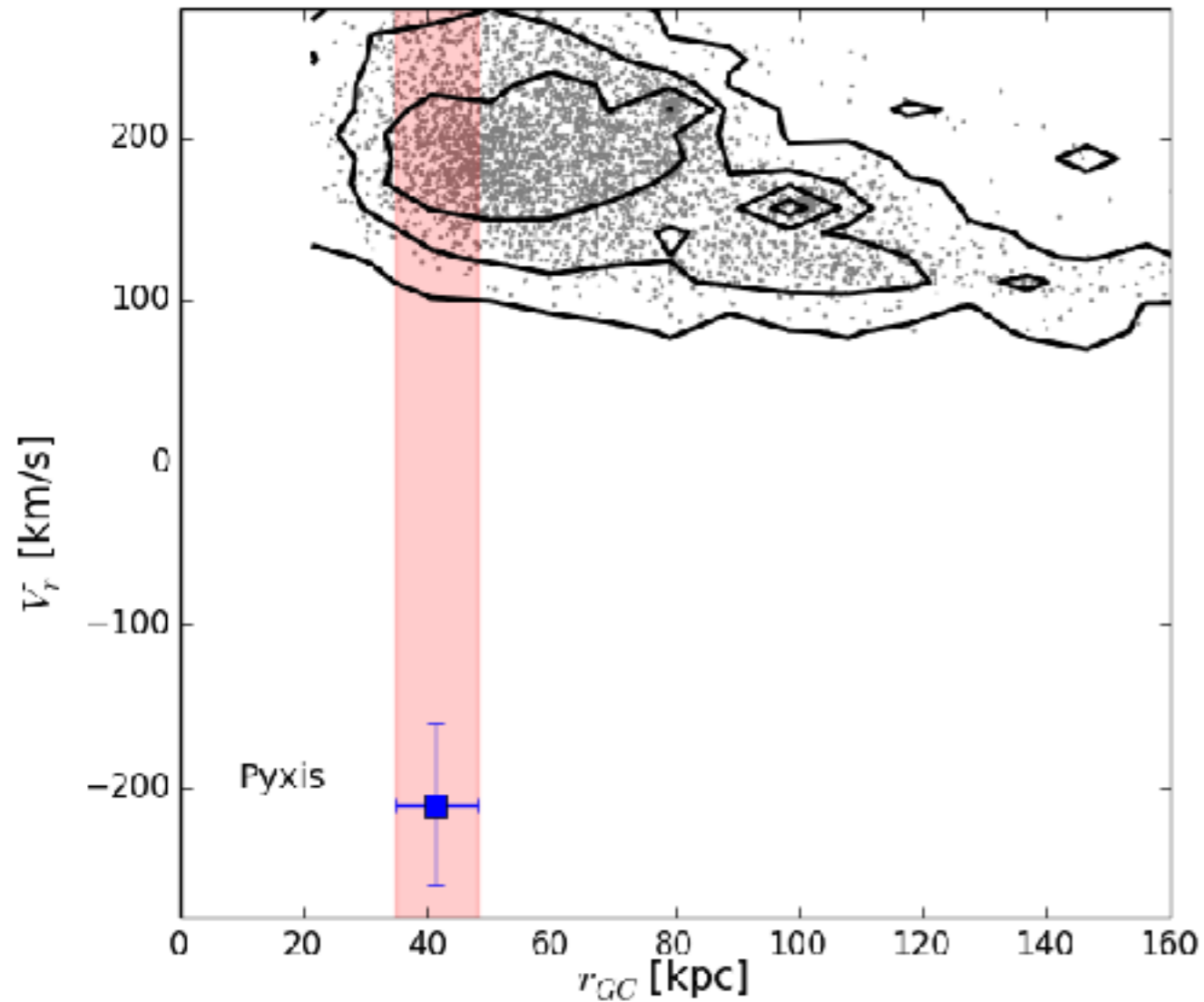


Origin of Pyxis: connected with Magellanic Clouds?



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

Origin of Pyxis



- **Associated with MC's?** Unlikely!
- **Did it form in situ?** Unlikely!
 - Average distance ≥ 60 kpc, low gas density even in mergers (Renaud et al. 2016)
- Donated by an unknown galaxy that is fully disrupted today.
- We derive **Milky Way mass** is larger than $0.95 \times 10^{12} M_{\text{sun}}$

Conclusions

- Galaxy \rightarrow Halo

But thus far I just keep telling stories about the tracers...