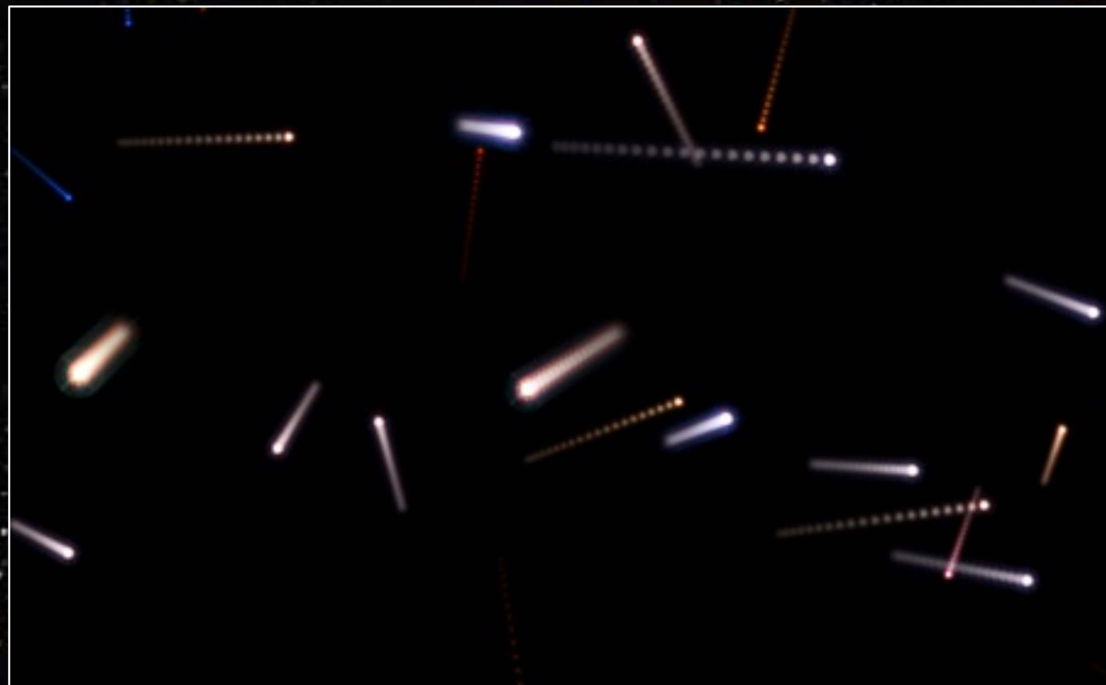


Proper Motions in the Local Group as a Probe of Galaxy Dynamics and Masses

Roeland van der Marel (STScI)

Stellar Dynamics

- Many reasons to understand the dynamics of stars, clusters, and galaxies in the nearby Universe

- Formation: The dynamics contains an imprint of initial conditions
- Evolution: The dynamics reflects subsequent (secular) evolution
- Structure: dynamics and structure are connected
- Mass: Tied to the dynamics through gravity
  → critical for studies of dark matter, galaxy masses and mass profiles

Line-of-Sight (LOS) Velocities

- Almost all observational knowledge of stellar dynamics derives from LOS velocities (spectroscopy)

- Yields only 1 component of motion
  - Limited insight from 1D information
  - 3D velocities needed for mass modeling

$$\boxed{M = \sigma^2_{3D} \, R_{grav} \, / \, G}$$

- Many assumptions/unknowns/degeneracies in LOS velocity modeling

Proper Motions (PMs)

- PMs provide much added information, either by themselves (2D) or combined with LOS data (3D)

- Characteristic velocity accuracy necessary
  - 1 km/s at 7 kpc (internal globular cluster dynamics)
  - 10 km/s at 70 kpc (Milky Way halo/satellite dynamics)
  - 100 km/s at 700 kpc (Local Group dynamics)

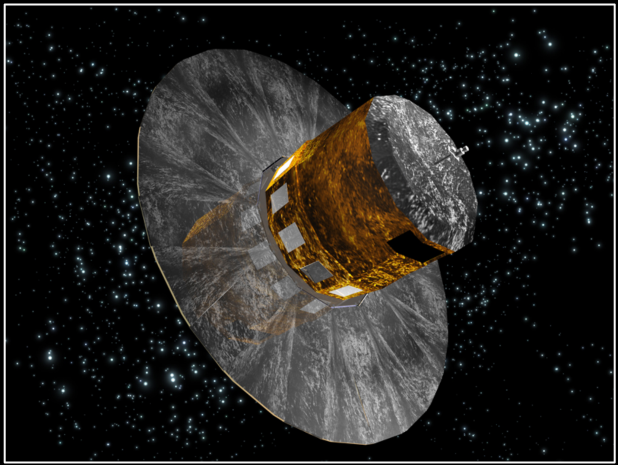
- Corresponding PM accuracy
  - 30 μas / yr (~ speed of human hair growth at Moon distance)

Current Observational Approaches

- VLBI, radio, water masers [highest PM accuracy]
  - Only a few galaxies with suitable water masers
- Ground-based, optical-IR [low-medium PM accuracy]
  - Use old photographic 1st-epoch data w/ long time baselines
  - Combine modern data and surveys (e.g., SDSS, USNO, 2MASS, ….)

- HST, optical-IR [high PM accuracy]
  - High spatial resolution, low background, stable, long time baselines
  - 30 μas / yr ~ 0.006 HST ACS/WFC pixels in 10 yr
  - Many sources per field ($N = 10^2 – 10^6$, $\Delta \sim 1/\sqrt{N}$)

Emerging Observational Prospects



- GAIA
  - Spectacular PM Dynamics of Milky Way
    - Accuracy at V~15 will be ~10 μas / yr
  - Some PM Dynamics for MW Satellites and Local Group
    - Accuracy at V~20 will be ~400 μas / yr
  - HST will continue to be unique for faint targets and crowded areas
    - Accuracy at V~25 of ~100 μas / yr already “routine”

Future Observational Prospects

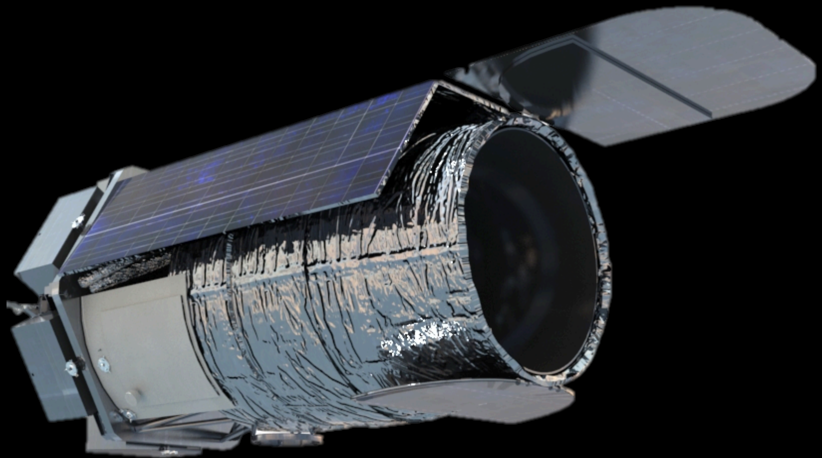
- ASTRO2010 Decadal Survey: Astrometry - 1 of 5 Discovery Areas

- Ground: LSST, 30-m class telescopes (TMT, GMT, ELT), …
- Space: JWST, EUCLID, WFIRST-AFTA, LUVOIR (8-16m),….

- Advantages:
  - Wide areas: more sources, wider-scale phenomena
  - Big mirrors: fainter sources, higher spatial resolution
  - Longer time baselines: when compared to existing high-resolution data (e.g. HST)

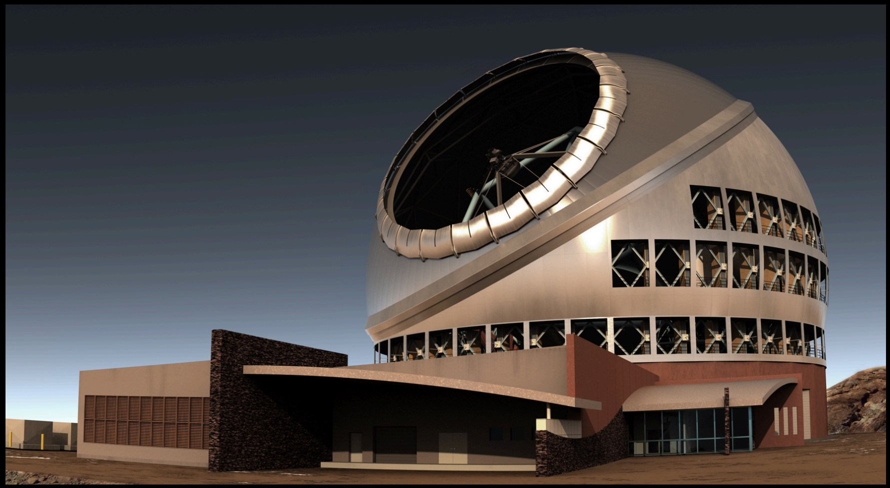
- Prospects
  - New studies *inside* the Local Group
  - First studies *outside* the Local Group (e.g., internal PM dynamics of the Virgo cluster)

WFIRST-AFTA



- Like HST, but ~100x the FOV
- Launch ~ 2024
- Similar pixel scale as WFC3/IR (~2x ACS and WFC3/UVIS)

Proper Motions with TMT



- PM accuracy ~ (λ/D) max $(\varepsilon, [S/N]^{-1})$ / ΔT
  - D = mirror Diameter (TMT wins by factor ~12)
  - λ = wavelength (HST wins by factor ~2)
  - ε = fraction of resolution element to which astrometry can be calibrated (HST wins by factor ~3)
  - ΔT = time baseline (HST wins by factor ~2 for first decade)
- Conclusions:
  - TMT limiting PM accuracy *per source* not vastly better than HST
  - TMT wins big by being able to reach the same limiting accuracy for much fainter sources
    - TMT can obtain accurate PMs for many more sources N in a given area
    - TMT does much better for the average PM of a sample ($\Delta \sim 1/\sqrt{N}$)

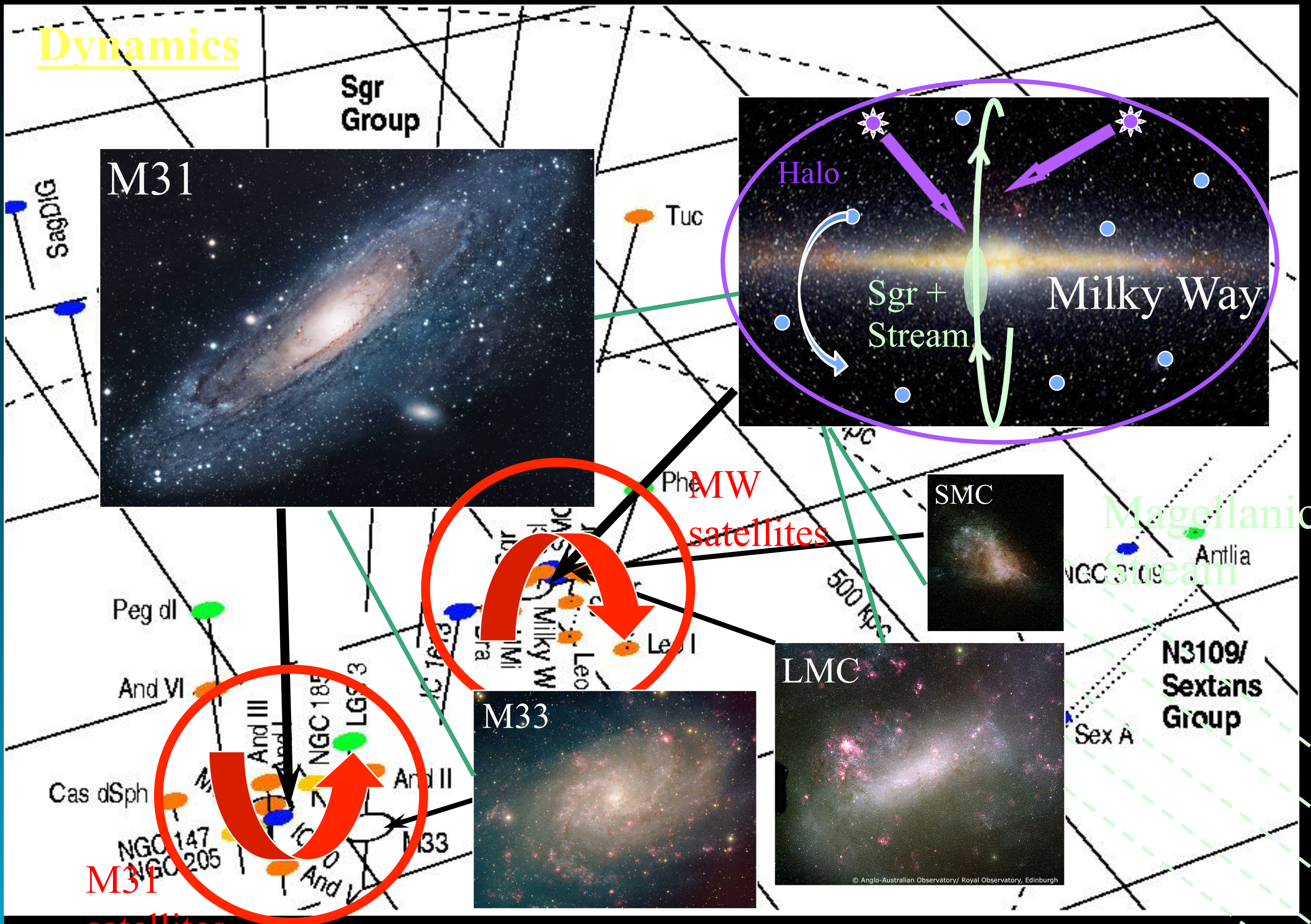
HSTPROMO: The Hubble Space Telescope Proper Motion Collaboration

(http://www.stsci.edu/~marel/hstpromo.html)

- Set of many different HST investigations, with detailed theory components
  - Lead coordinators: van der Marel & Anderson
  - Project/Paper Leads: Sohn, Kallivayalil, Bellini, Watkins, Besla, Boylan-Kolchin, Deason, Meyer
  - Many Other Members

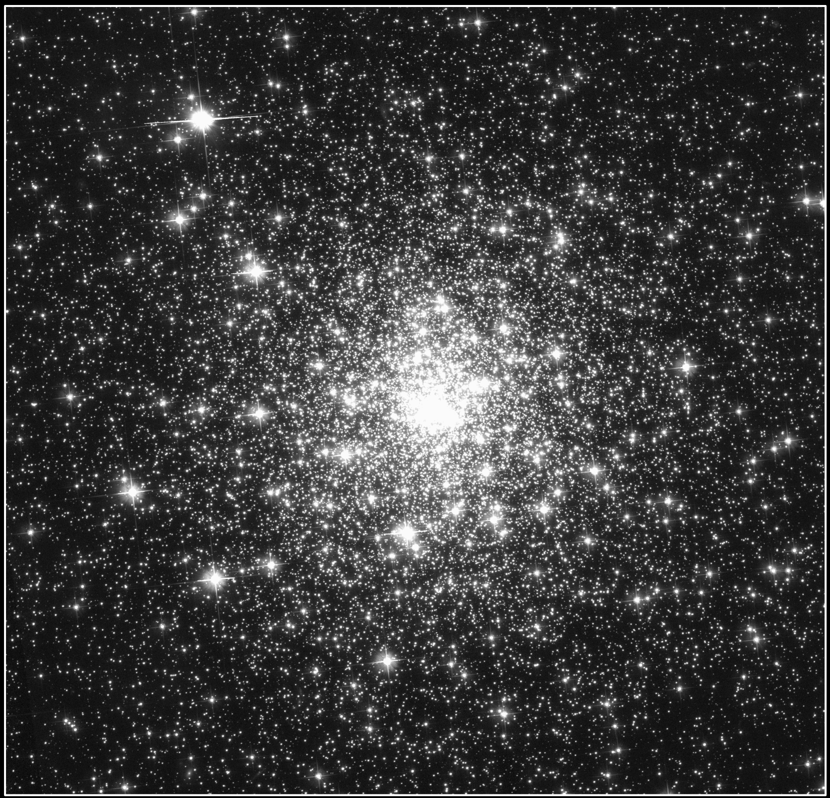
- Status/Achievements
  - 10+ years of work
  - 34 HST projects (many ongoing)
  - 28 refereed papers (many more in preparation)

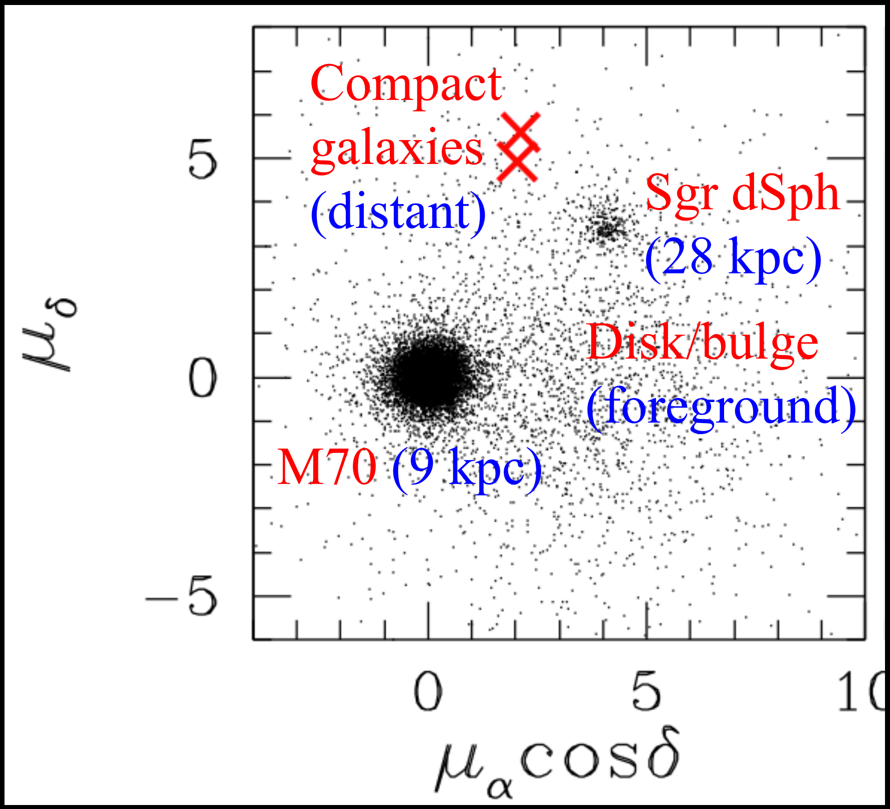
Dynamics



[Grebel 2000]

Illustration: Globular Cluster NGC 6681 (M70) and Sagittarius dSph

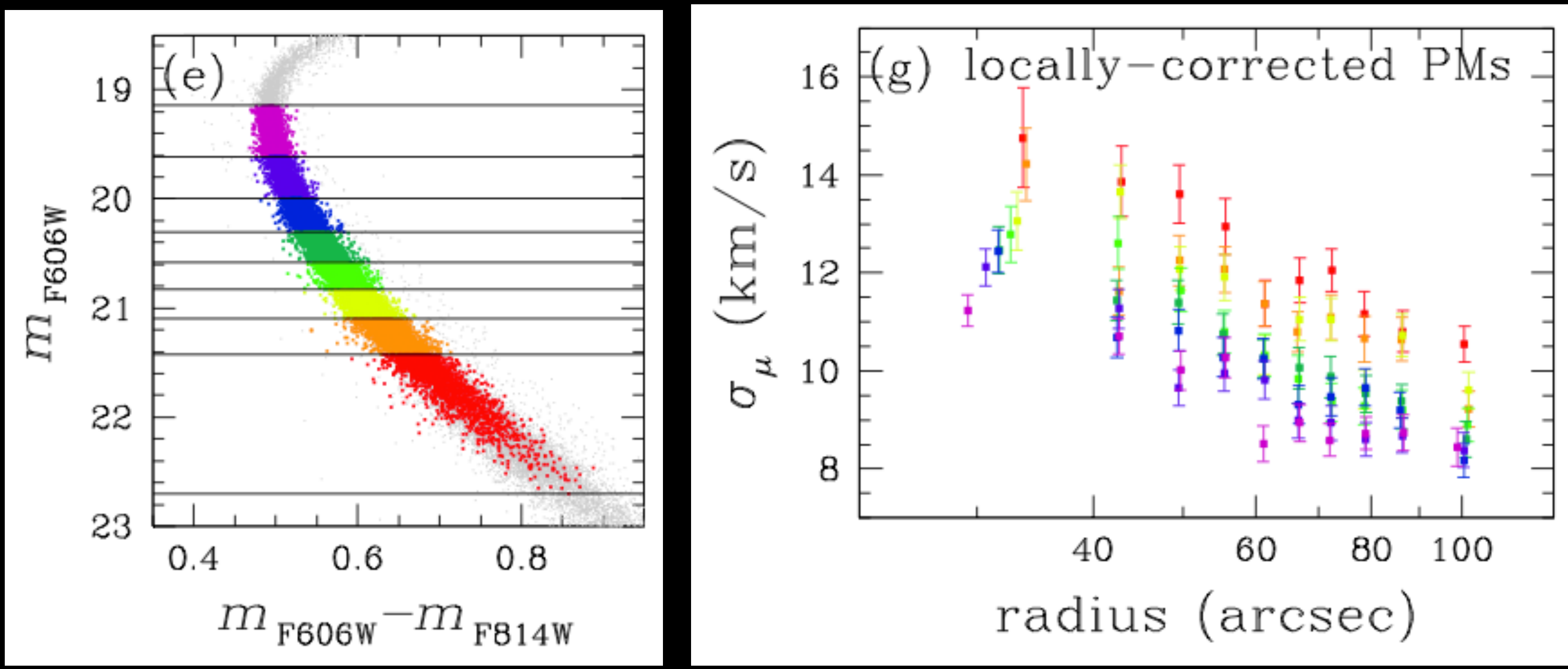




[Massari et al. 2013, Bellini et al. 2013]

Internal Dynamics of Globular Clusters: Mass Dependence

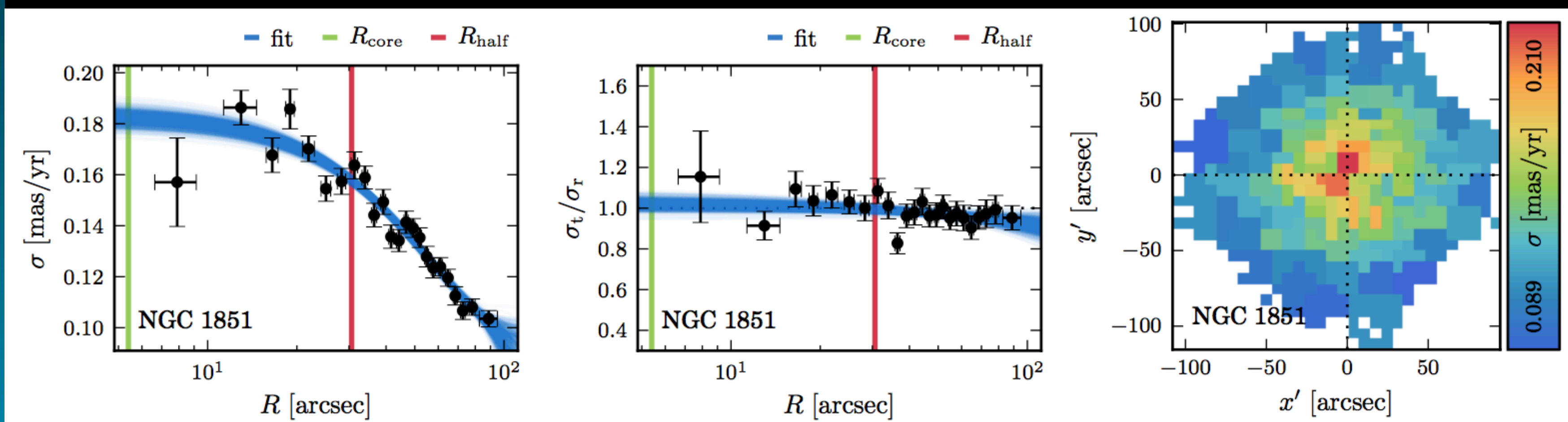
- For example, 75,000 M15 stars (Bellini et al. 2014)



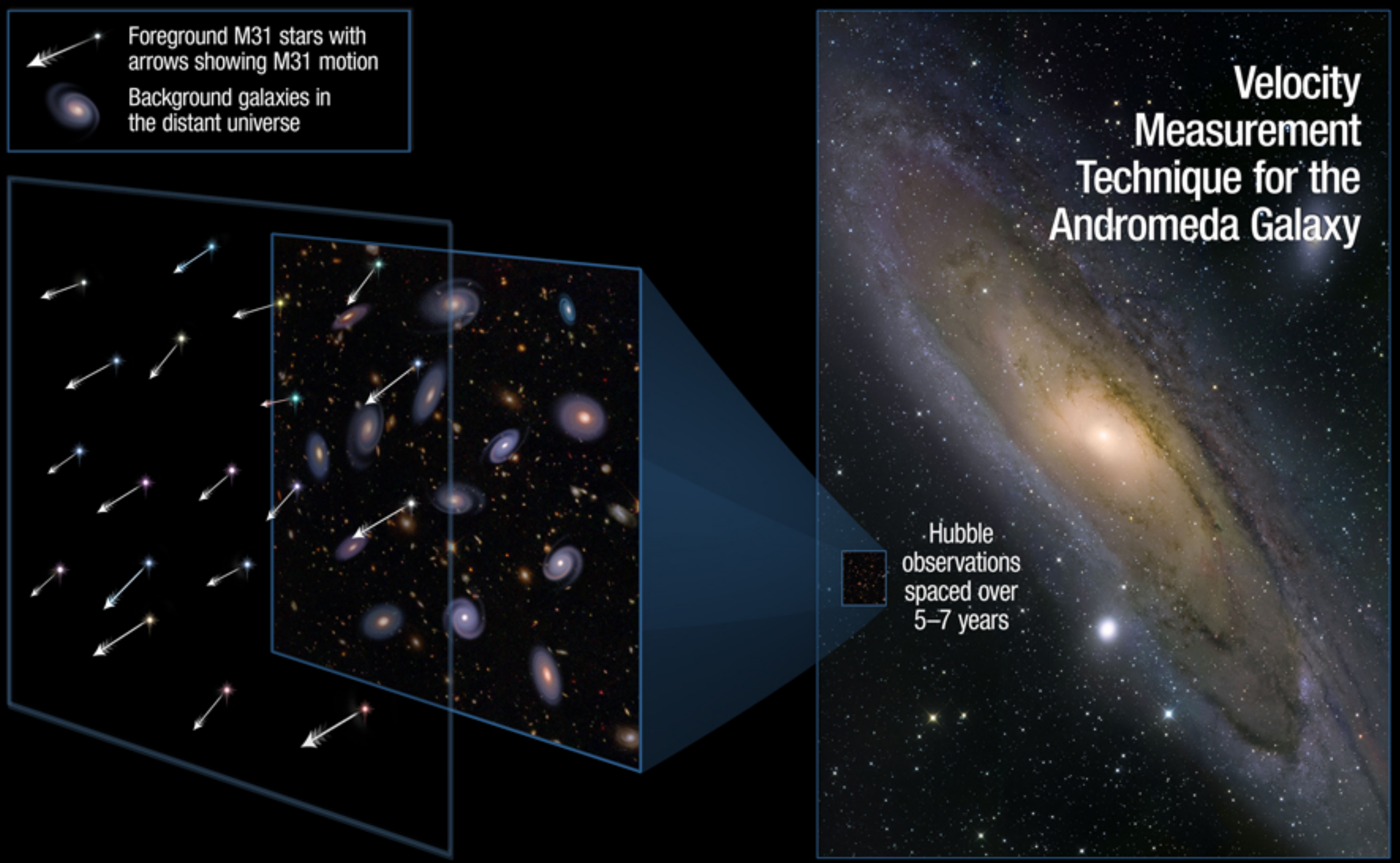
- Allows detailed studies of (lack of) internal equipartition (Trenti & van der Marel 2013)
- Similar data available for ~25 globular clusters

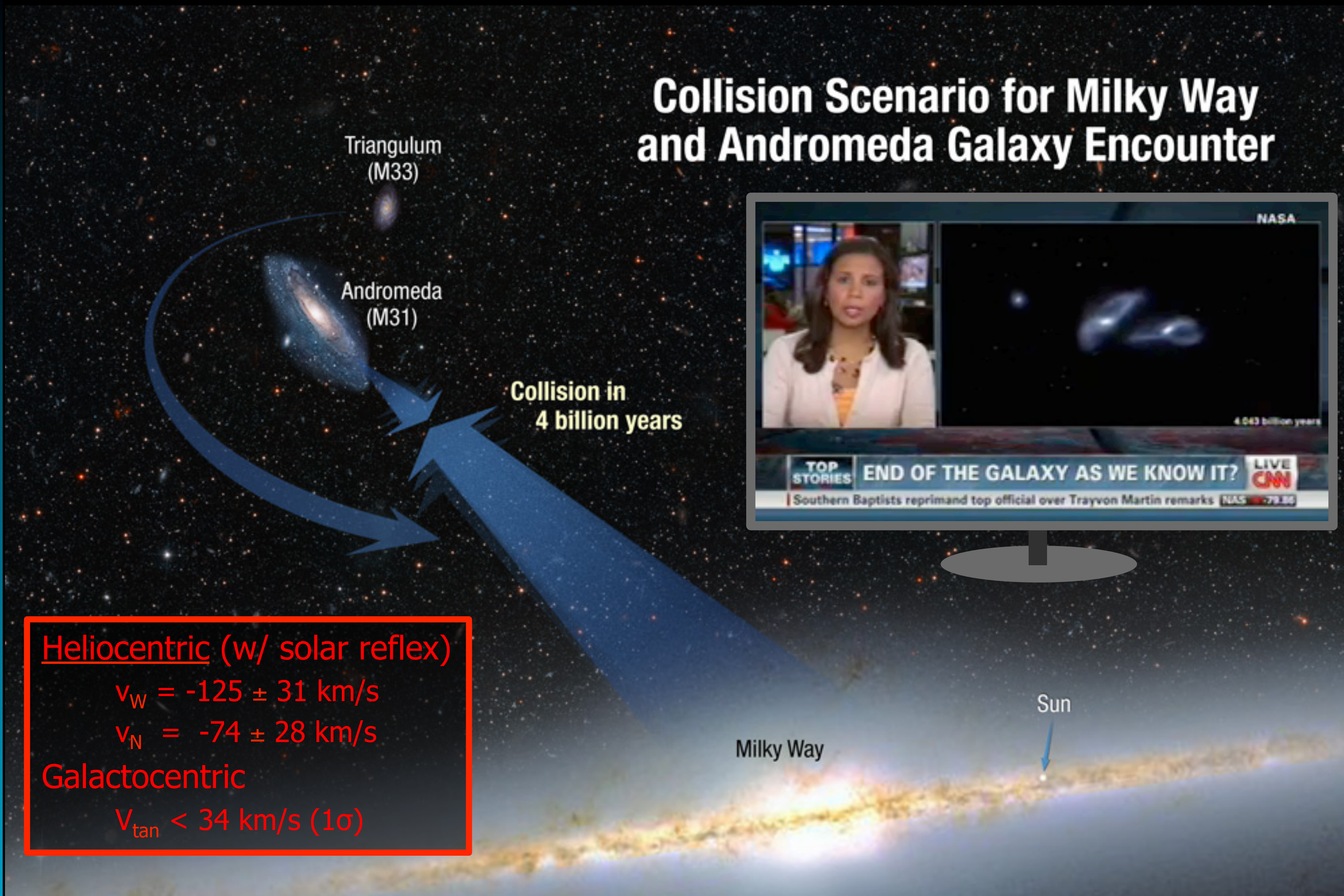
Internal Dynamics of Globular Clusters: 2D properties

- For example (Watkins et al. 2015)
  - Anisotropy profiles
  - 2D maps (IFU-like)



- Allows detailed mass modeling, constraints on intermediate-mass black holes
- Breaks mass-anisotropy degeneracy


Foreground M31 stars with arrows showing M31 motion
Background galaxies in the distant universe
Velocity Measurement Technique for the Andromeda Galaxy
Hubble observations spaced over 5–7 years



Heliocentric (w/ solar reflex)

v_W = -125 ± 31 km/s

v_N = -74 ± 28 km/s

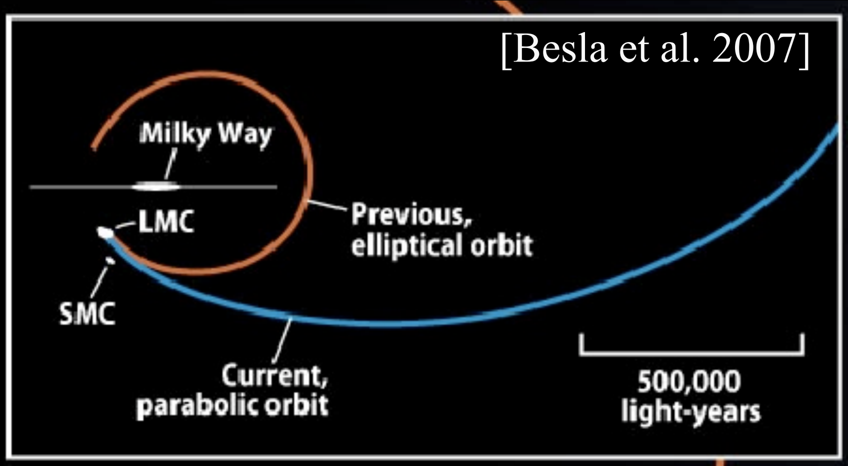
Galactocentric

V_{tan} < 34 km/s (1σ)

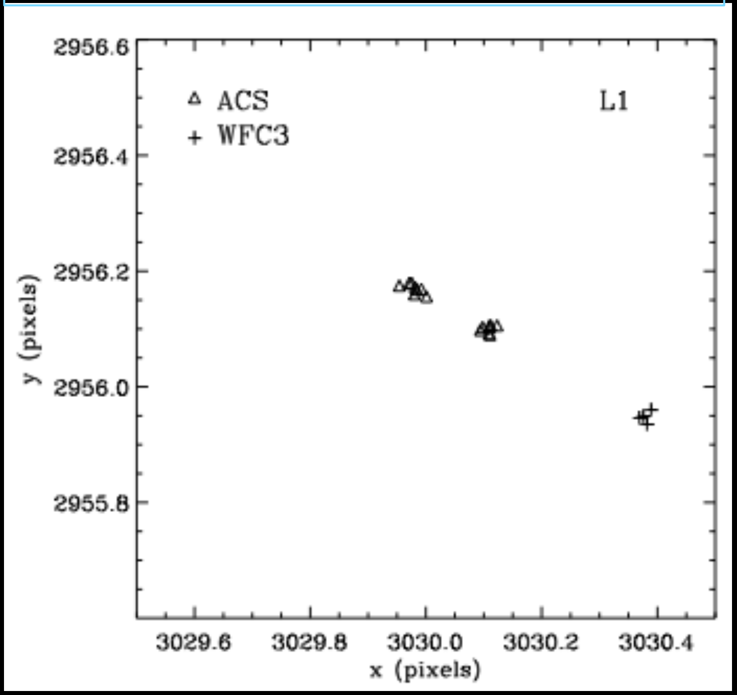
[Sohn et al. 2012; vdM et al 2012a,b]

PM and Orbit of Magellanic Clouds

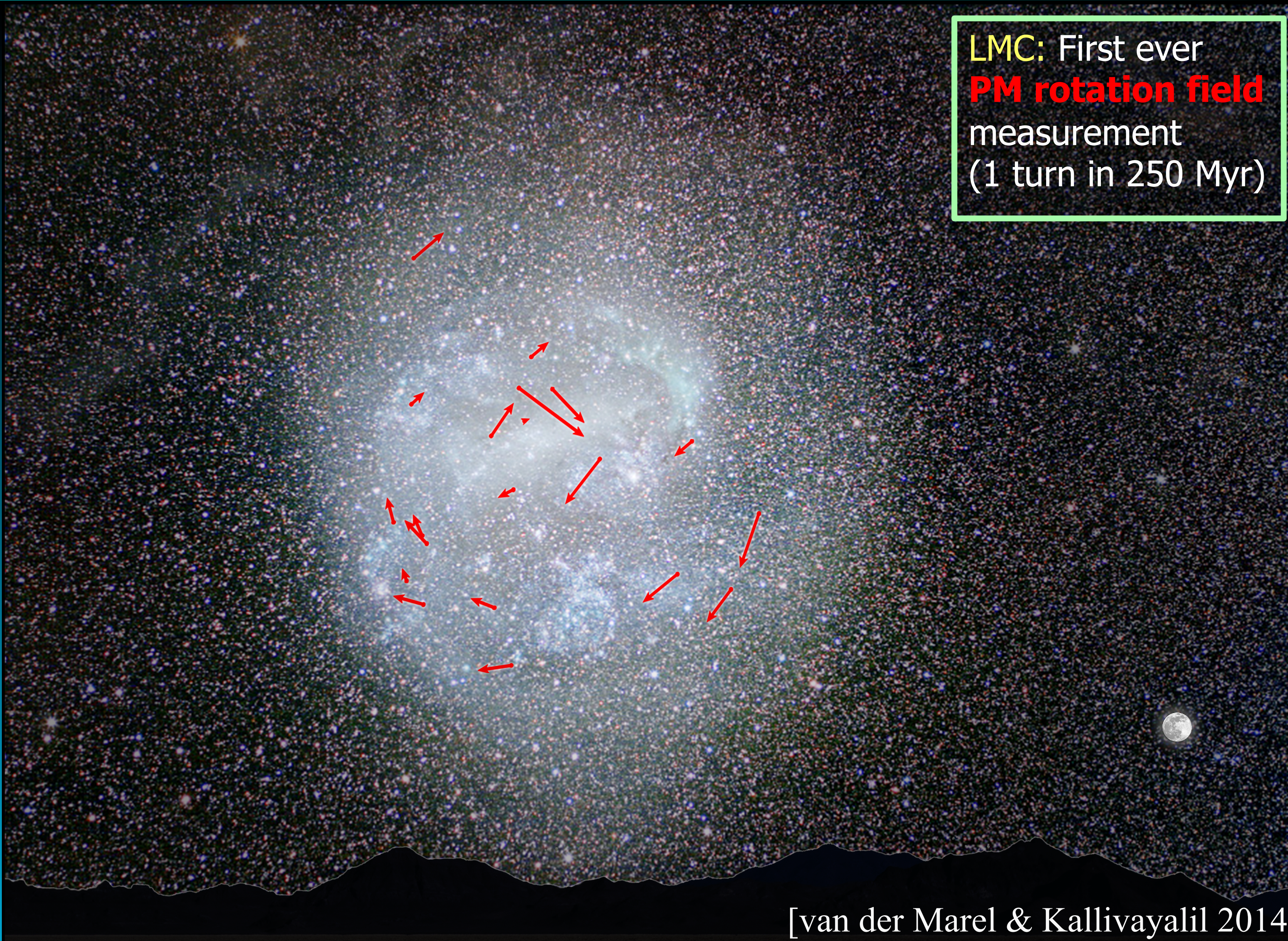
- Traditional view
  - Clouds have orbited Milky Way many times
  - Logarithmic Milky Way halo implies ~2 Gyr period
- HST PM measurements
  - Reflex motion of QSO wrt LMC/SMC stars over 7 years
  - Clouds move faster than traditionally believed
    ➔ wider, longer-period orbit



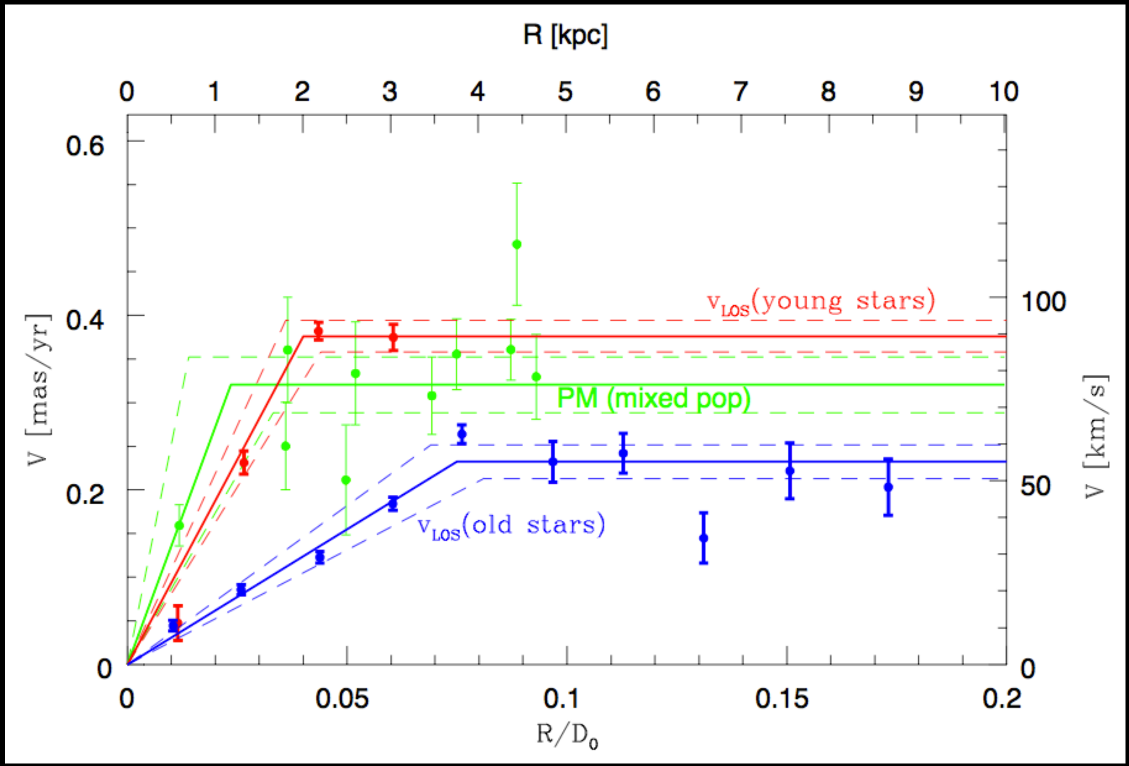
LMC Field 1 of 22; 3 epochs
1x1 pixel box



[Kallivayalil et al. 2006,2013]


LMC: First ever
PM rotation field
measurement
(1 turn in 250 Myr)
[van der Marel & Kallivayalil 2014]

LMC Rotation Curve



[vdMarel & Kallivayalil 2014;

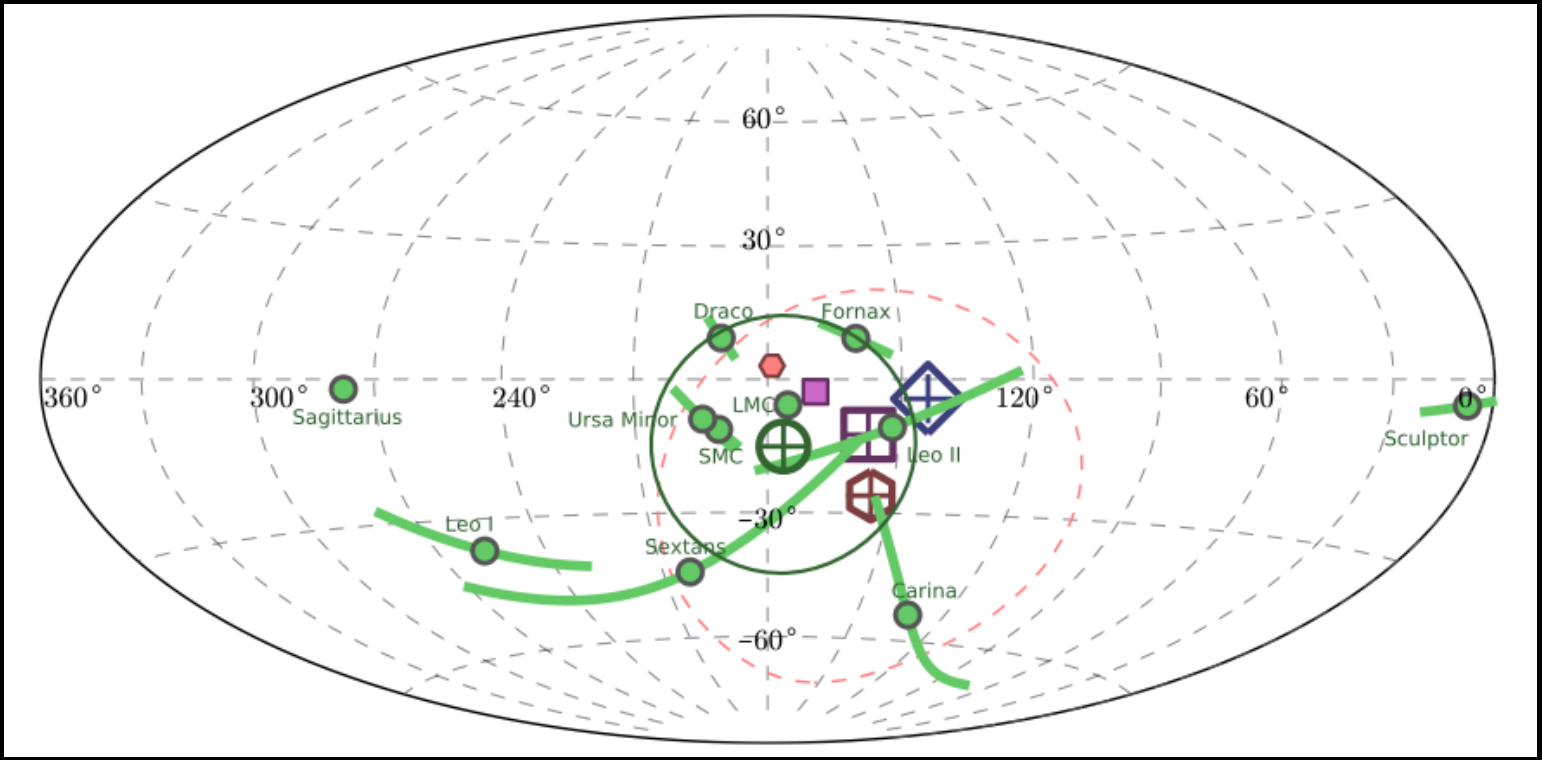
- Rotation curve depends on stellar population
- PM and LOS rotation curves consistent
- Combined 3D information yields new insights into LMC geometry, structure, distance

Milky Way Satellite System

- PMs of most classical dSph measured with HST
  - Fornax (2002, 2007), Carina (2003), Ursa Minor (2005), Sculptor (2006), Sagittarius (2010), Draco (2014) [all by Piatek, Pryor and collaborators]
  - Leo II (Lepine et al. 2011)
- Future
  - More accurate PM data of Milky Way satellites
  - First PM data for (many) M31 satellites
- Applications
  - Past orbits of individual satellites
  - Hydrostatic equilbrium modeling (e.g., Watkins et al. 2010)
  - Assessment of Planes of Satellites (i.e., are the angular momentum vectors = orbital poles aligned?)

Distribution of Orbital Poles

- Orbital poles not distributed randomly

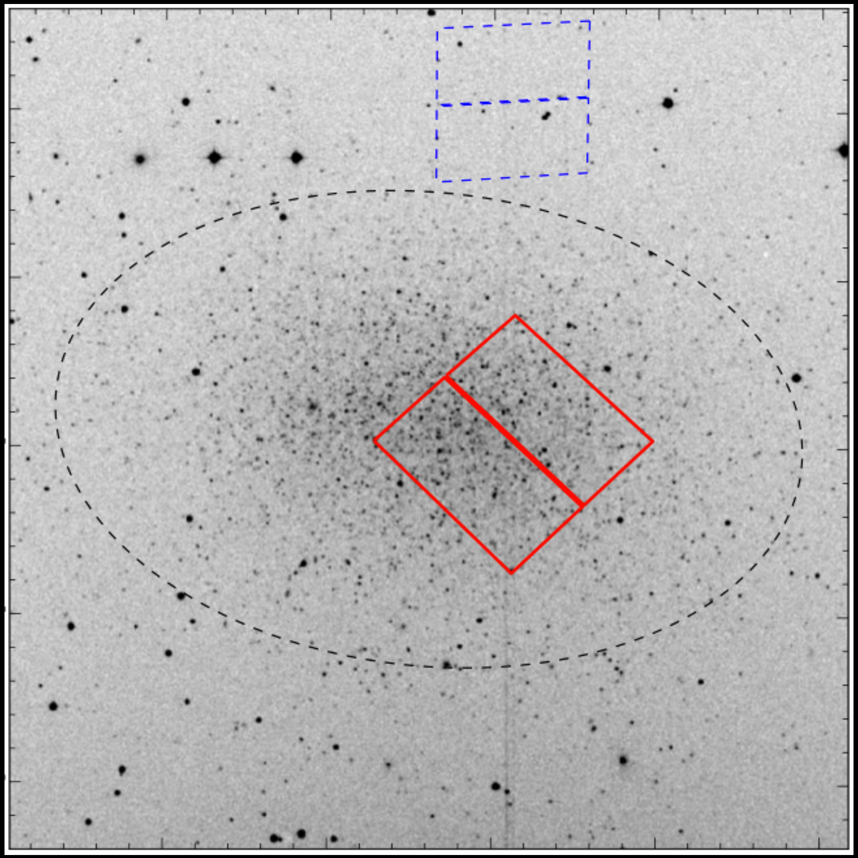


[Pawlowski & Kroupa 2013]

- Existence/Interpretation of Planes of Satellites continues to be controversial

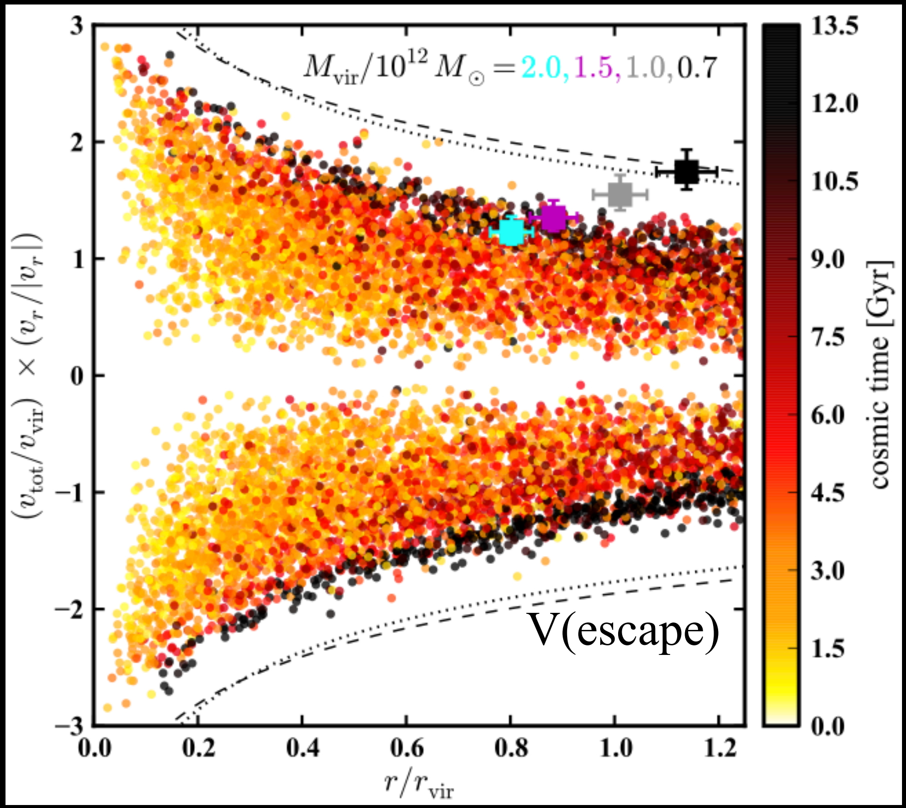
Leo I dSph

- Unusually distant and rapidly moving galaxy
  - Galactocentric:
    r = 261 ± 13 kpc
    v(radial) = 168 ± 3 km/s
- Proper Motion
  - Galactocentric
    v(tangential) = 101 ± 34 km/s (Sohn et al. 2013)



Leo I compared to ΛCDM subhalos

- Highest resolution numerical simulations of Galaxy-size dark matter halos (Aquarius)
- Assuming that Leo I is the least bound Milky Way satellite, $M_{MW} = (1.6 \pm 0.3) \times 10^{12}\ M_\odot$



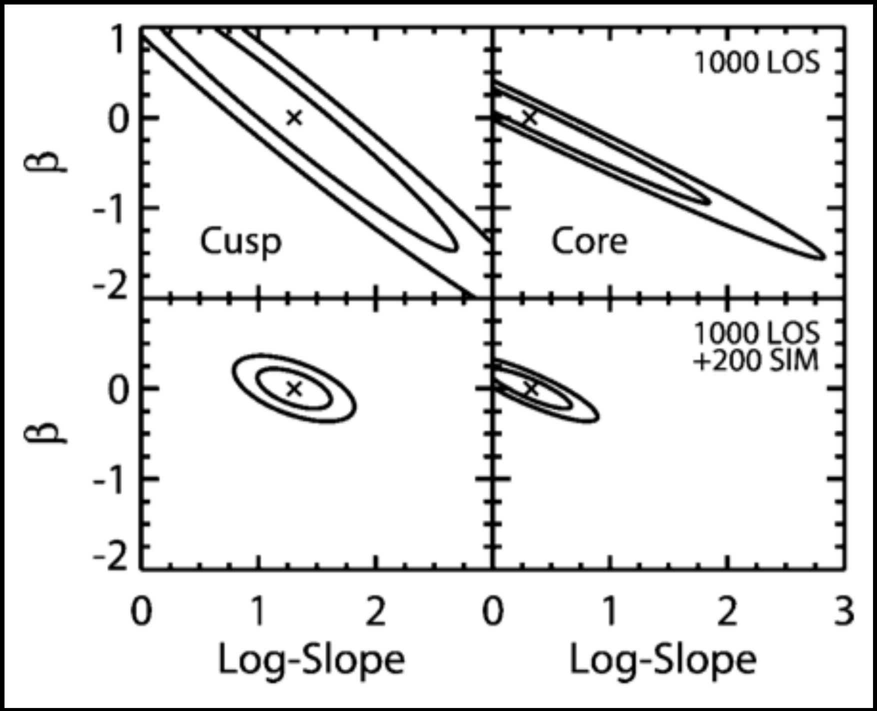
[Boylan-Kolchin et al. 2013]

Internal Kinematics of dSph galaxies

- Mass-velocity anisotropy degeneracy of stellar dynamics makes it difficult to uniquely determine mass profile from LOS velocities

- PMs can help; relevant to core-cusp question

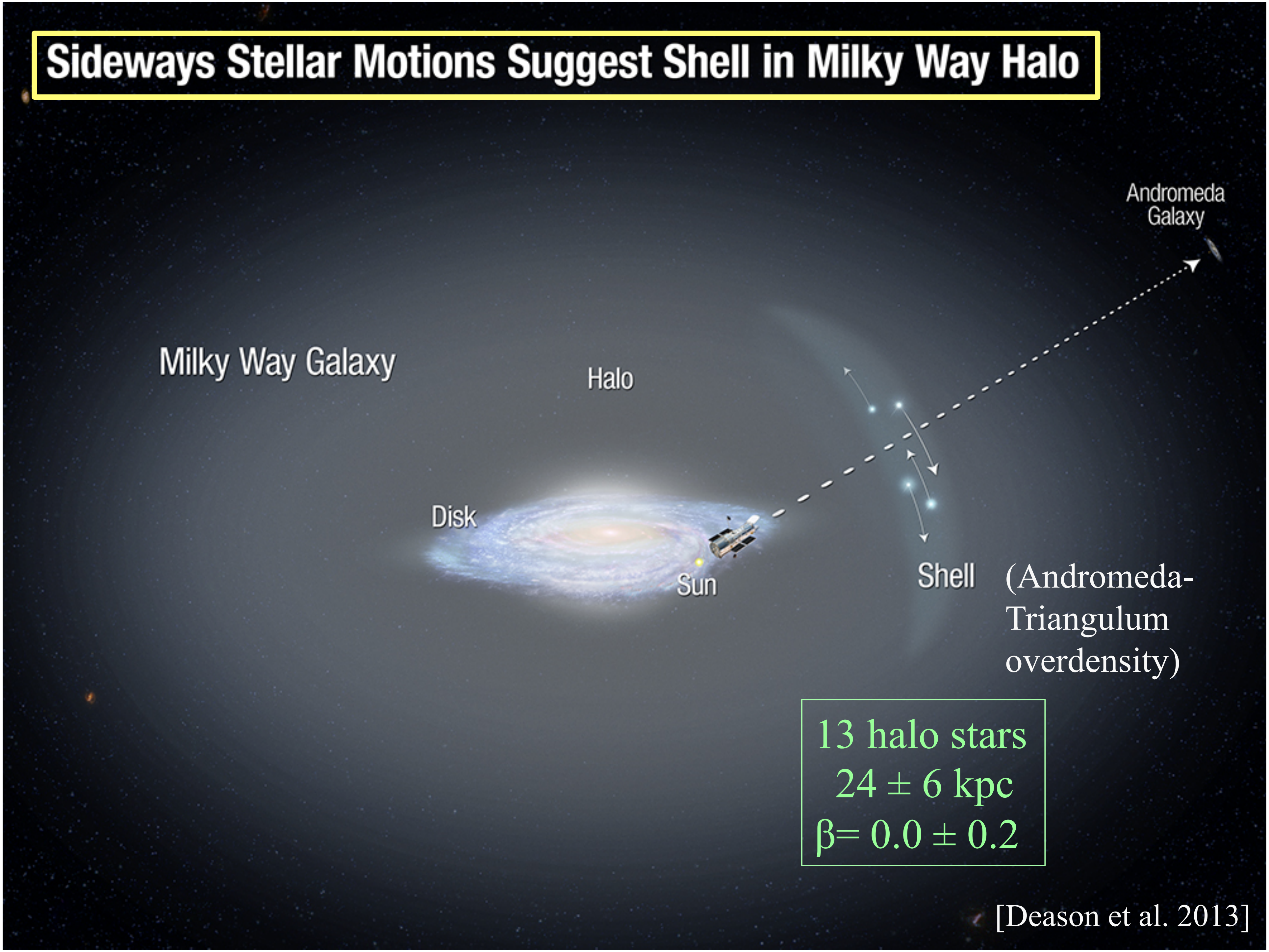
- HST PM measurements for Draco and Sculptor in progress



[Strigari et al. 2007]

Milky Way Metal-Poor Halo Kinematics

- Lack of PMs at large distances limits our understanding
- HST CMD+PMs of random fields
  - allows identification of MSTO halo stars at 10-100 kpc (~5 per HST field)
  - 13 stars measured in 3 fields towards M31
  - We are extending this work from to 150 fields, to get a PM sample for ~1000 halo stars (with matching Keck spectra; HALO7D, Guhathakurta et al.)


Sideways Stellar Motions Suggest Shell in Milky Way Halo
Andromeda
Galaxy
Milky Way Galaxy
Halo
Disk
Sun
Shell
(Andromeda-
Triangulum
overdensity)
13 halo stars
24 ± 6 kpc
β= 0.0 ± 0.2
[Deason et al. 2013]

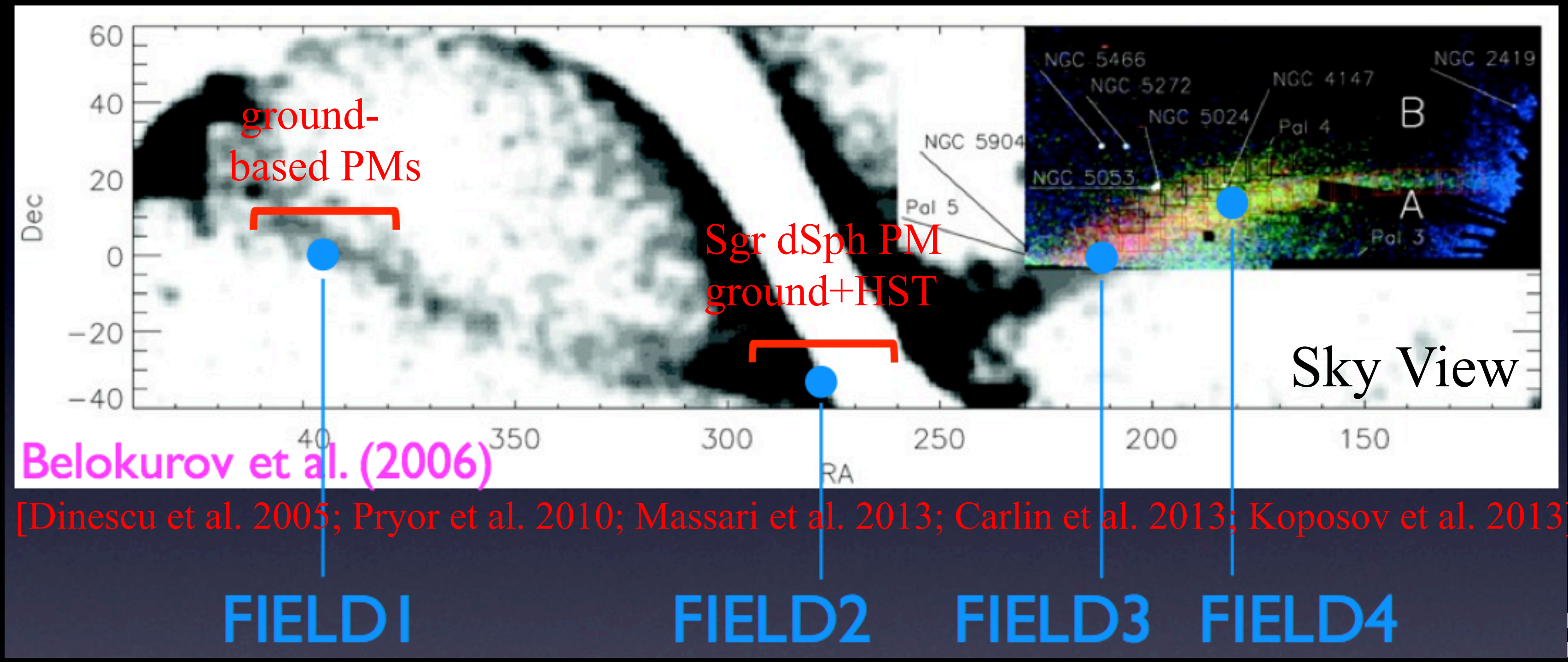
Dynamics of Tidal Streams

- PMs are generally the only missing phase-space coordinates
  - Necessary to mitigate modeling degeneracies

- Ground-based studies
  - GD1: Koposov et al. (2010)
  - Sagittarius Stream: Carlin et al. (2012), Koposov et al. (2013)

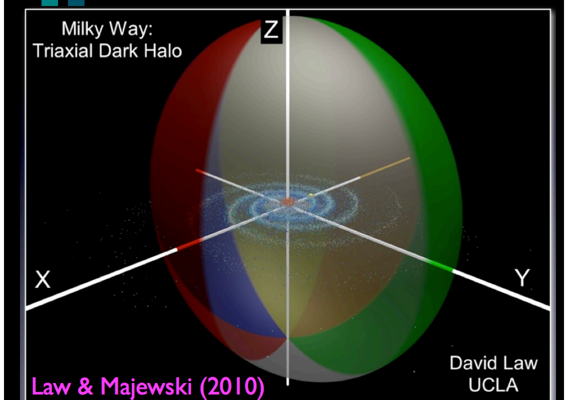
Sagittarius Stream

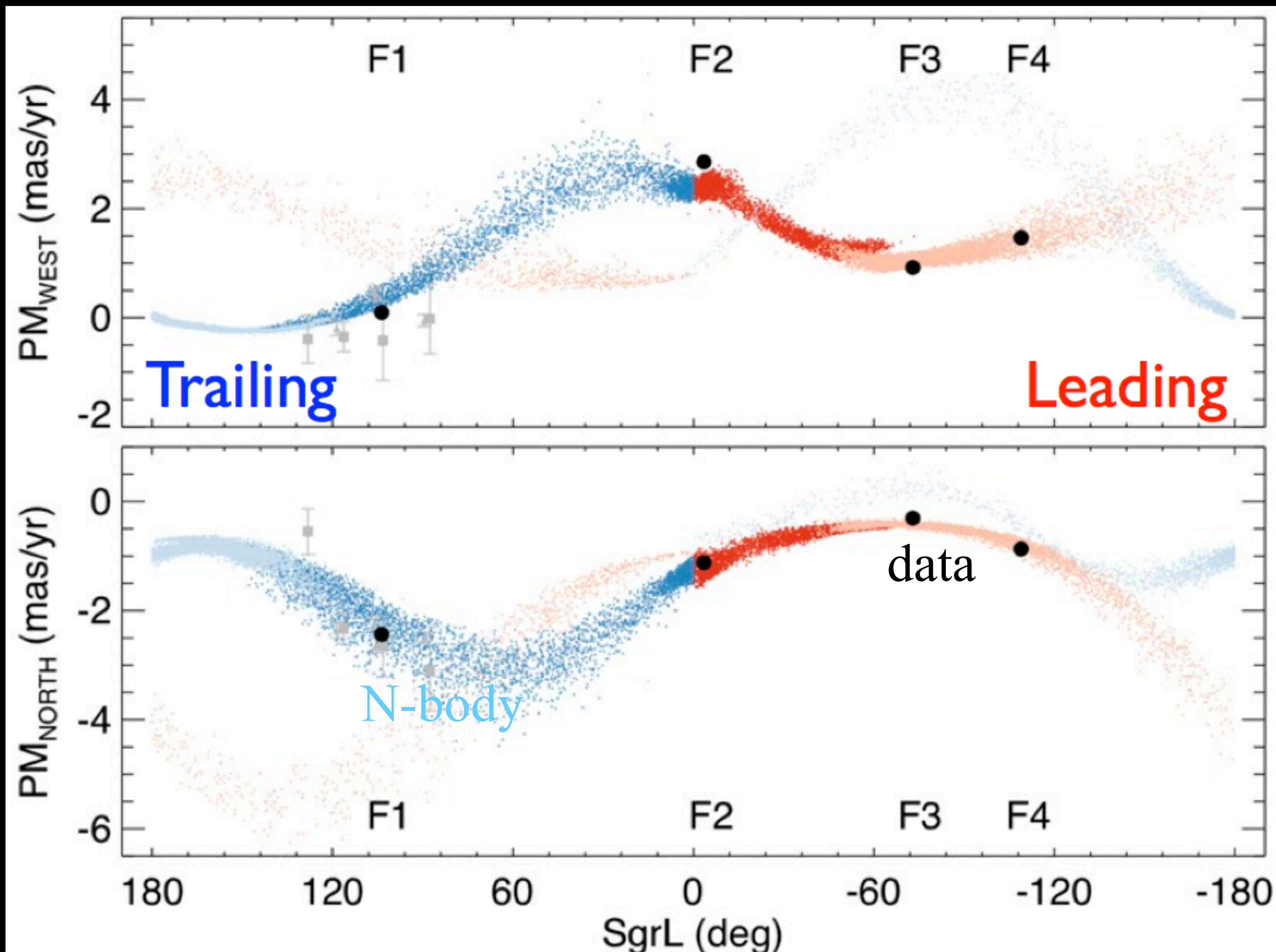
- New HST PMs with 6-9 year time baselines (Sohn, vdM et al. in prep)



PM to N-body model comparison

- Law & Majewski (2010) best dist + vLOS fit:
  Halo potential near-oblate, q = 0.72, short axis in disk plane!
- Remarkably good match to PMs….



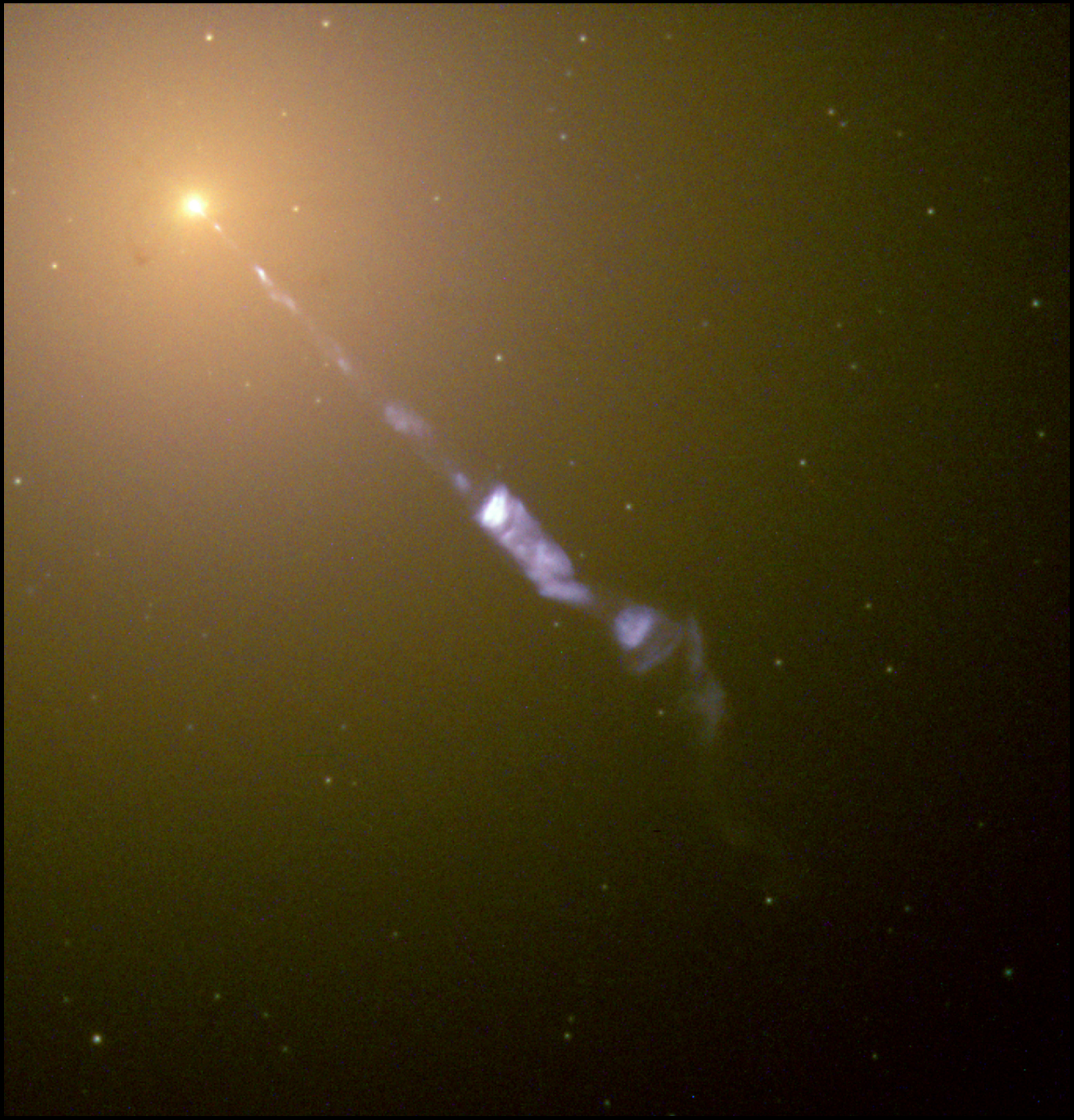


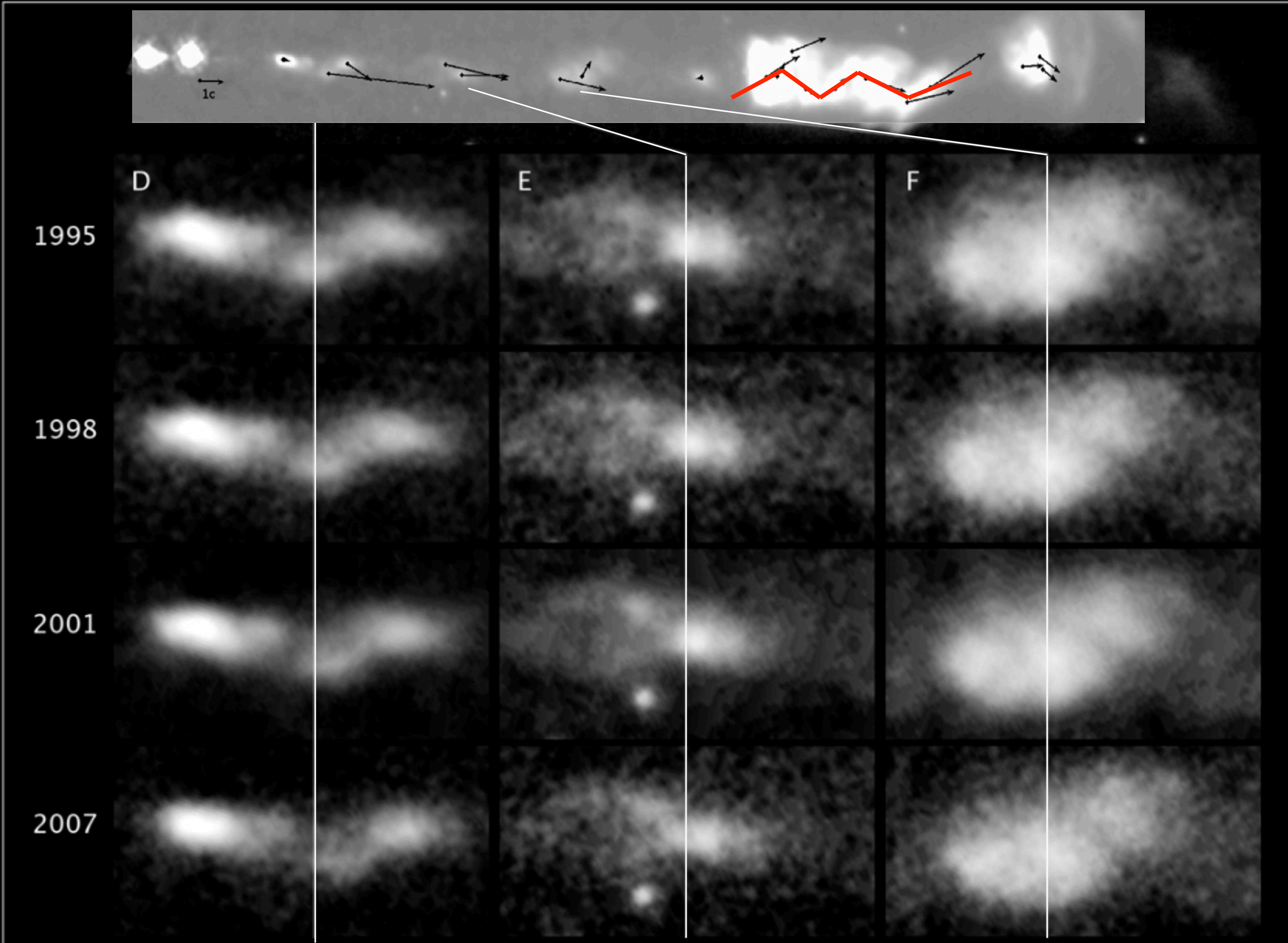
[Sohn et al. 2014;
vdM et al. 2014]

Other HSTPROMO Projects

- Internal dynamics of ~25 Globular Clusters
  - Central black holes, multiple populations
- Runaway O/B Stars
  - 30 Doradus in LMC, Galactic Center clusters
- Other Stellar Streams & Tidal Features
  - Orphan, Magellanic Bridge
- dwarf Galaxy internal PM dynamics
  - SMC, Draco, Sculptor
- Local Group infall of distant dSph galaxies
  - Leo T, Tucana, Cetus, …
- Relativistic Flows in AGN jets
  - M87, 3C273, ….

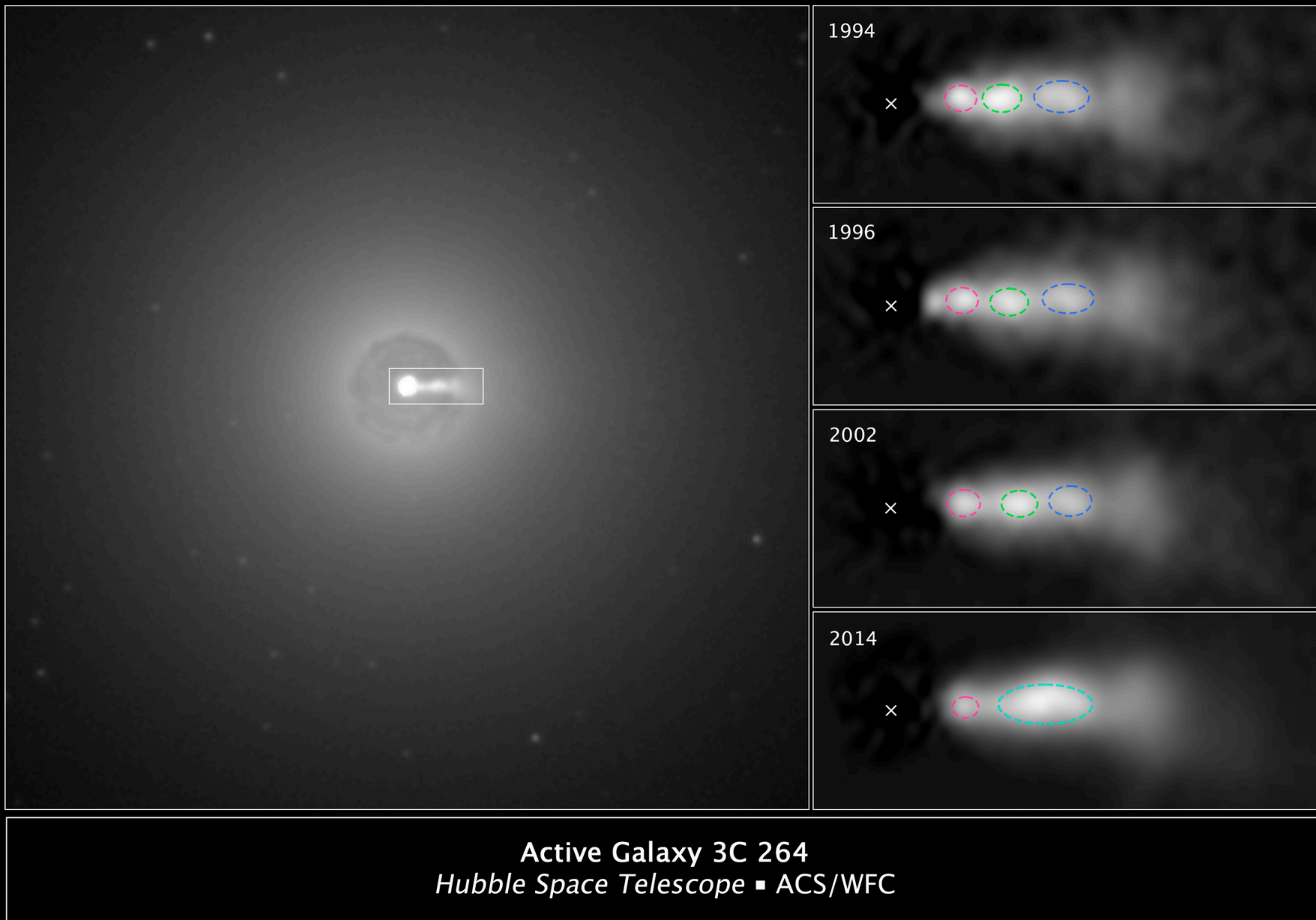
M87 Jet





M87 Jet: Helical Motion?

[Meyer et al. 2013]



3C264 Jet: Colliding Knots

[Meyer et al. 2015]

Conclusions

- Proper Motions yield new insights into Local Group Galaxy Dynamics and Masses
  - Can be reliably measured with various techniques, HST being especially powerful
  - Great prospects for future advances, with TMT and other telescopes

- Buildup of Local Group through galaxy/ satellite infall continues to present day

- Dark Matter in Local Group
  - Milky Way : $M_{MW} > 10^{12}\ M_{\odot}$ [95% confidence]
  - Local Group : $M_{LG} = (3.2 \pm 0.6) \times 10^{12}\ M_{\odot}$
  - Density profiles & halo shapes: need future data

- Movies: will run while you ask me questions