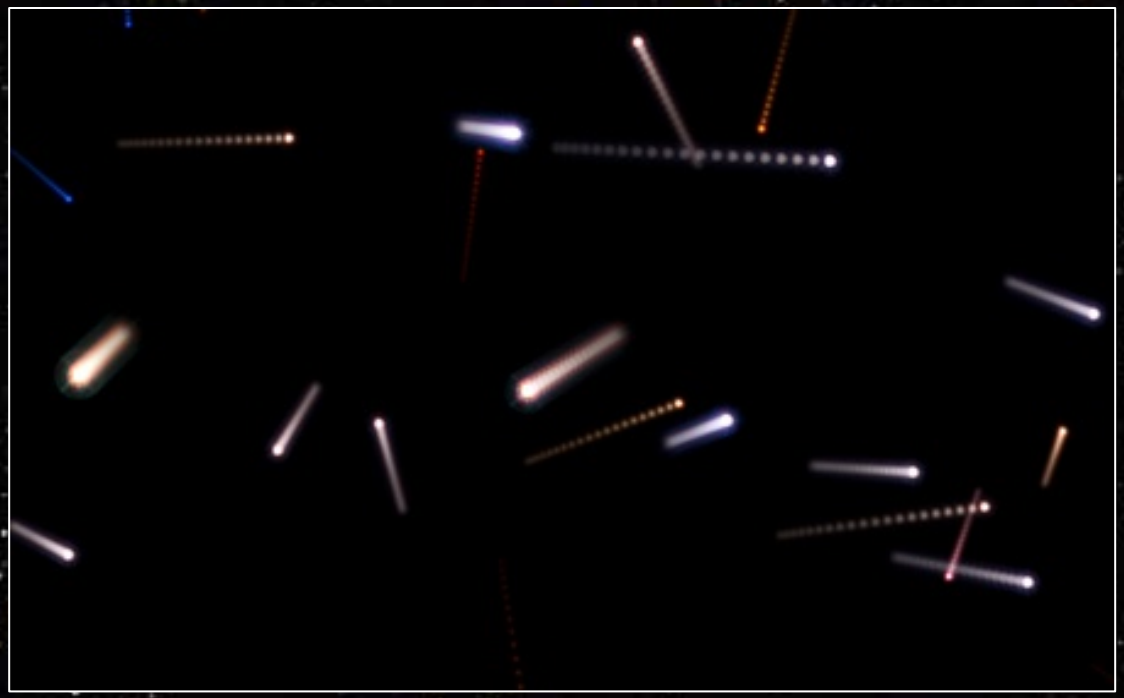


Local Group Proper Motion Science from Wide Field Surveys

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
- Many assumptions/unknowns/degeneracies in LOS velocity modeling

Proper Motions (PMs)

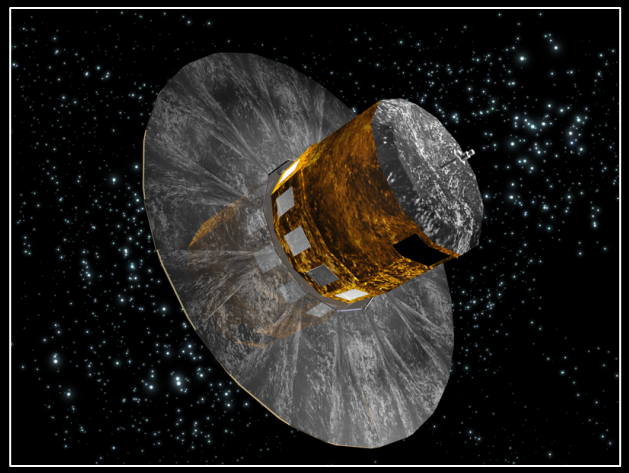
- PMs provide much added information, either by themselves (2D) or combined with LOS data (3D)
- Characteristic velocity accuracy necessary
  - 1 km/s at 7 kpc (internal globular cluster dynamics)
  - 10 km/s at 70 kpc (Milky Way halo/satellite dynamics)
  - 100 km/s at 700 kpc (Local Group dynamics)
- 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

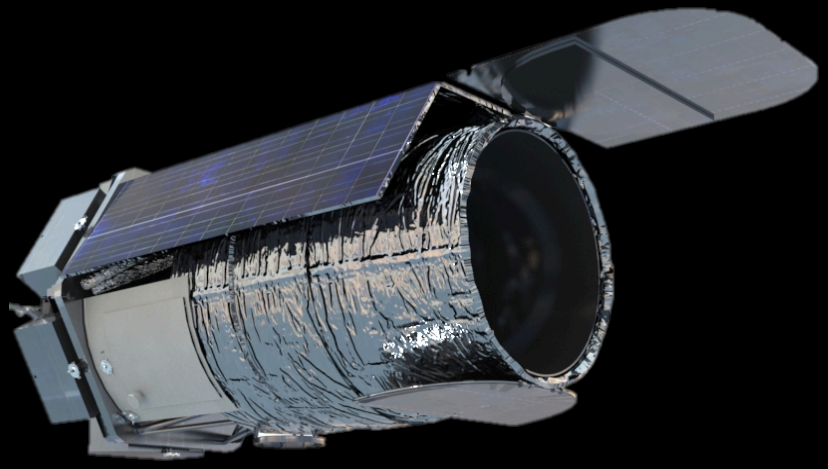
- ASTRO2010 Decadal Survey: Astrometry - 1 of 5 Discovery Areas

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

- Advantages:
  - Wide areas: more sources, wider-scale phenomena
  - Big mirrors: fainter sources, lower random errors
  - 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)

Example: WFIRST-AFTA

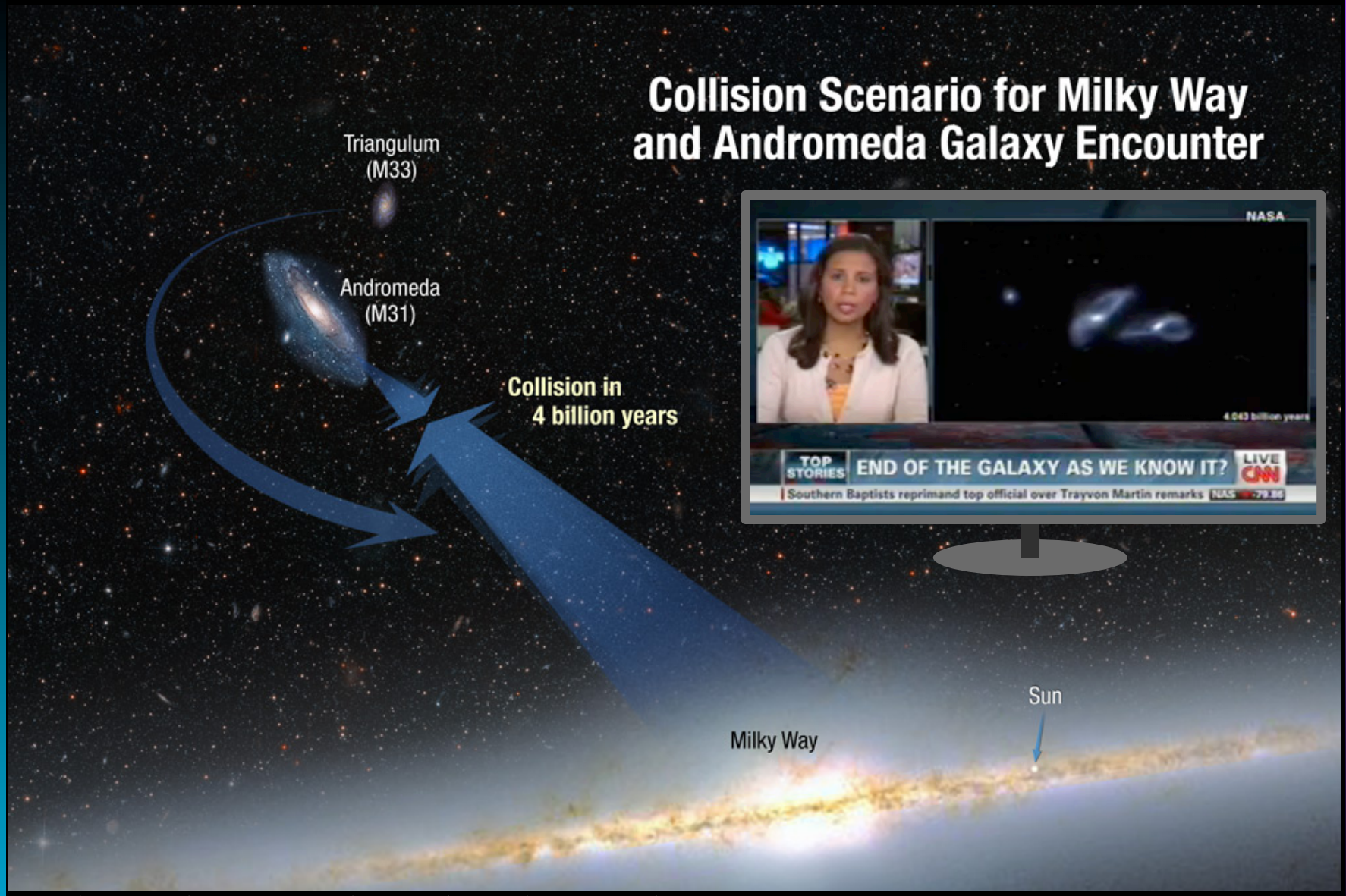


- Like HST, but ~100x the FOV
- Similar pixel scale as WFC3/IR
- ~2x the pixel scale of ACS and WFC3/UVIS
- Use background galaxies as stationary references

HSTPROMO: The Hubble Space Telescope Proper Motion Collaboration

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

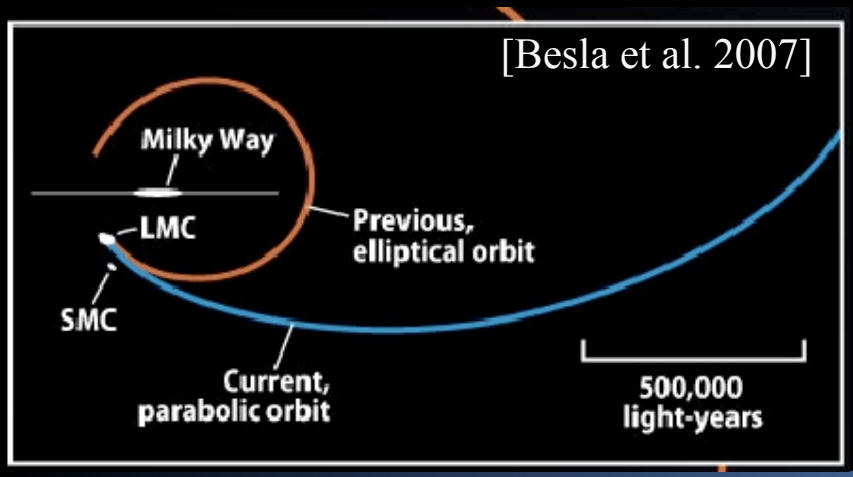
- Set of many different HST investigations, with detailed theory components
  - Lead coordinators: van der Marel & Anderson
  - Project/Paper Leads: Sohn, Kallivayalil, Besla, Bellini
  - Many Other Members
- Status/Achievements
  - 10+ years of work
  - 33 HST projects (many ongoing)
  - 25 refereed papers (many more in preparation)



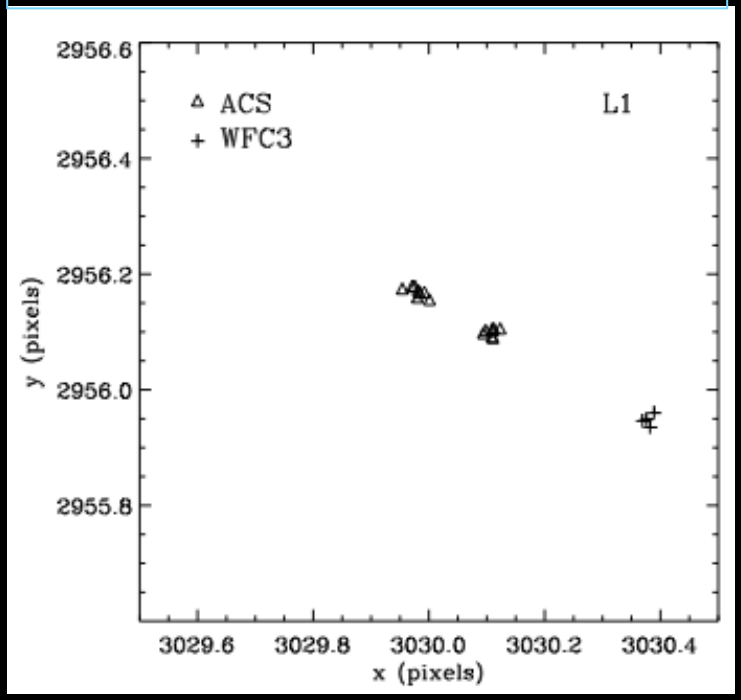
[Sohn et al. 2012; vdMarel et al 2012a,b]

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

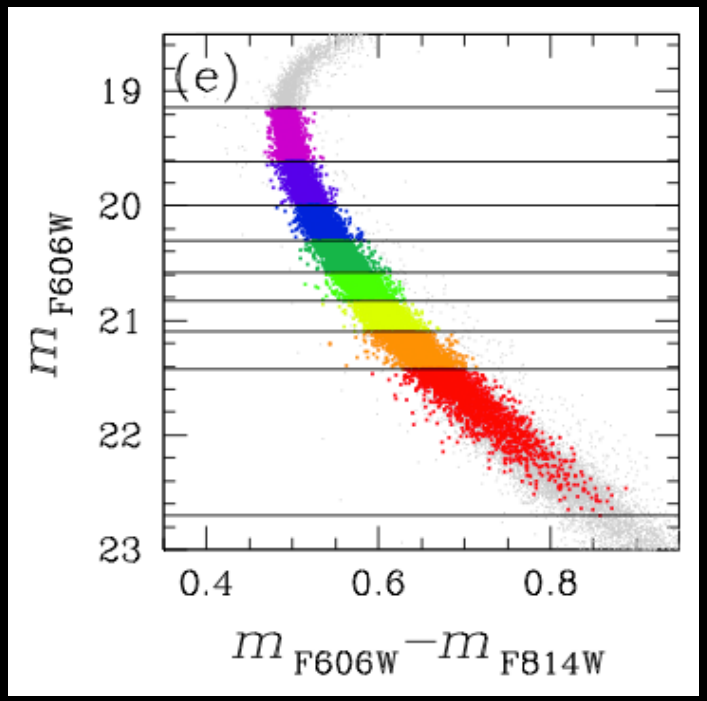


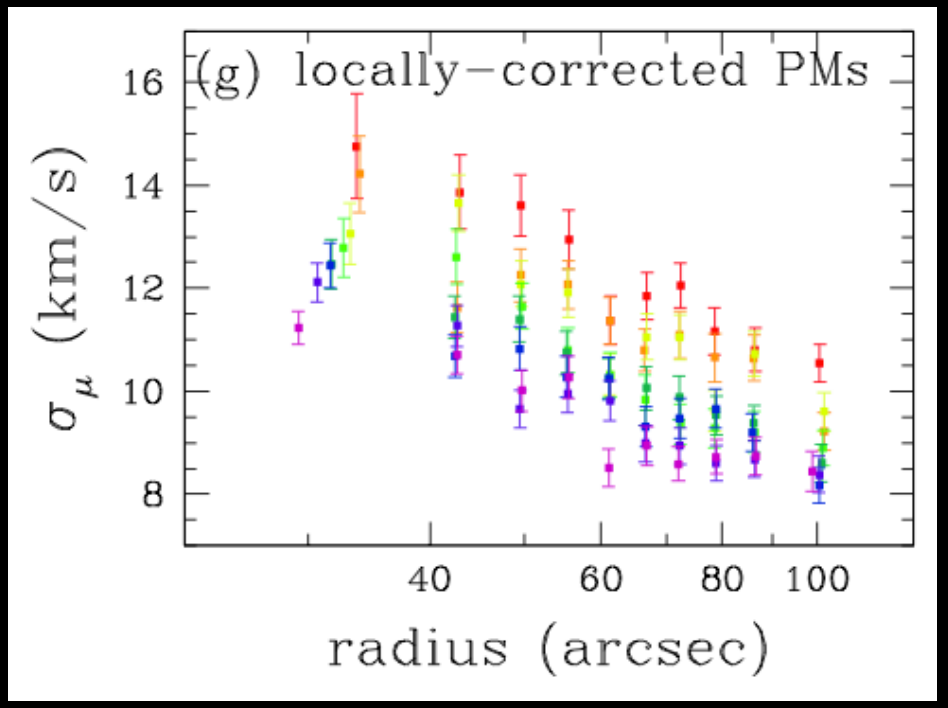
[Kallivayalil et al. 2006,2013]


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

Internal Dynamics of Globular Clusters

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



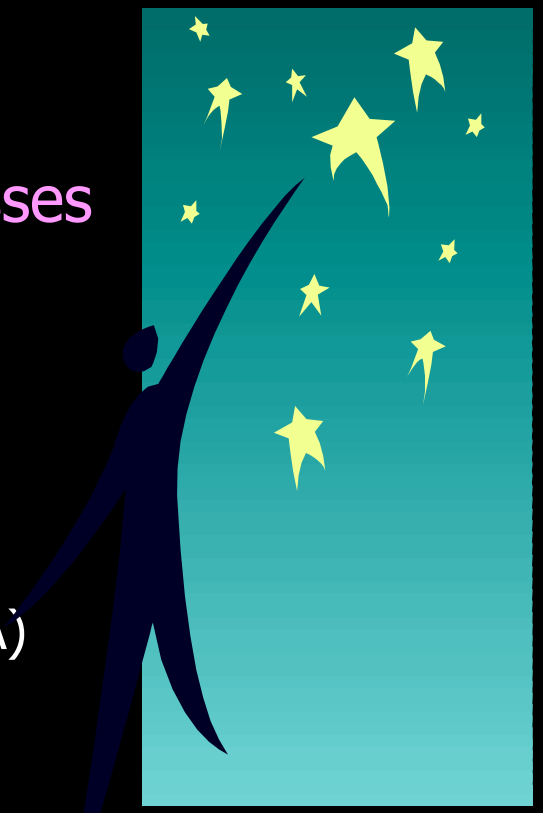


- Allows detailed studies of (lack of) internal equipartition (Trenti & van der Marel 2013)
- Similar data available for ~25 globular clusters

Expected Progress with wider-area Space Facilities: WFIRST-AFTA

- High-Latitude Survey (gravitational lensing) and Bulge Survey (microlensing)
  - will provide many PMs at magnitudes fainter than GAIA
- Targeted GO observations, or combination with already existing space data (HST, JWST)
  - can further improve accuracy for smaller areas
- Science Topics
  - Stellar streams
  - Bulge/Halo kinematics
  - Hypervelocity stars
  - Dwarf galaxies

Conclusions

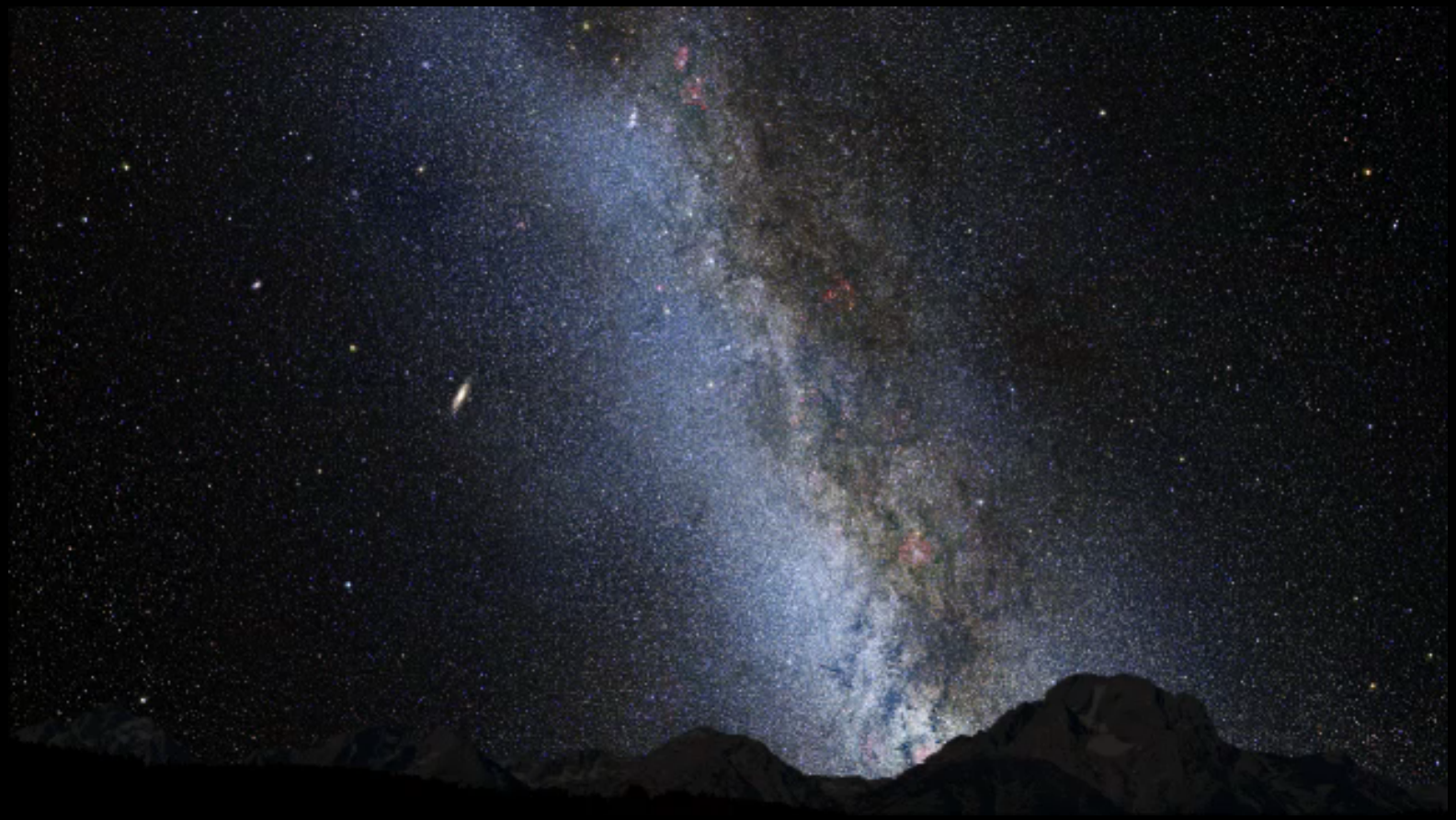


- Proper Motions yield new insights into Local Group Galaxy Dynamics and Masses
  - Can be reliably measured with various techniques, HST being especially powerful
- Great prospects for future advances
  - Dedicated missions (GAIA)
  - Wider areas (LSST, EUCLID, WFIRST-AFTA)
  - Bigger mirrors (JWST, 30m-ground, ….)
- Key for progress in Galactic Archeology
  - Understand galaxy formation and evolution through resolved studies of nearby galaxies
- Movies: will run while you ask me questions

Large Magellanic Cloud Sky View Showing Rotation next 14 Myr

[vdMarel & Kallivayalil 2014; visualization: Greg Bacon and Ann Feild]

Zoom-in to M31 Spheroid Field with 30,000 years of projected motion



[Sohn et al. 2012; visualization: Zolt Levay, Greg Bacon, and Jay Anderson]

Zoom-in to Omega Cen with 10,000 years of projected motion

[Anderson & vdMarel 2010; vdMarel & Anderson 2010; visualization: Greg Bacon]

MW-M31-M33 N-body simulation

(one of several scenarios consistent with PMs)

[vdMarel, Besla, et al. 2012; visualization: Frank Summers]