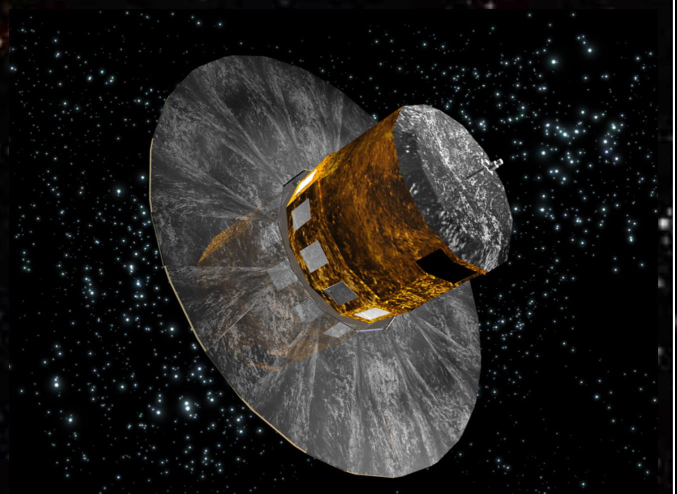

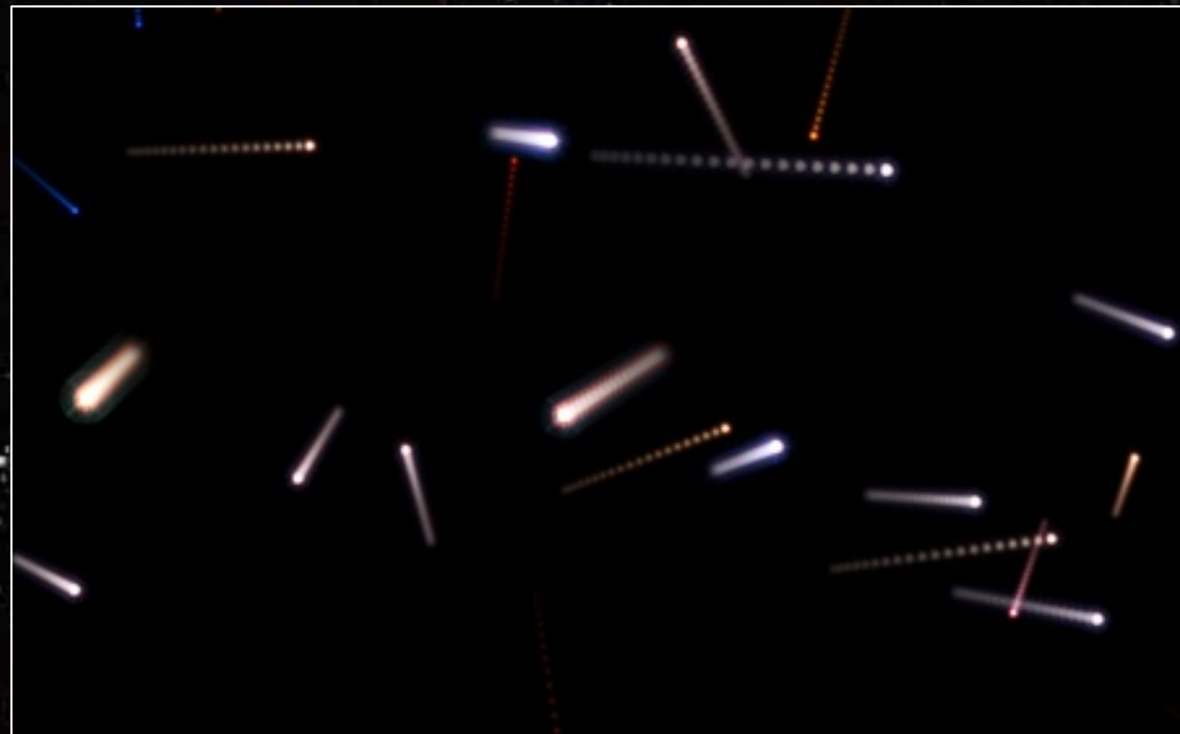

New Gaia Insights into the Dynamics of the Local Group

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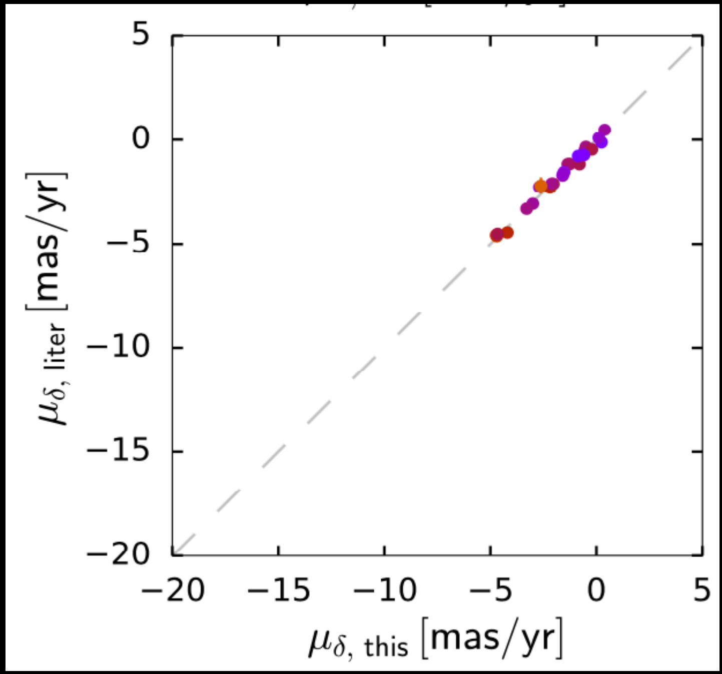
(STScI)

Local Group Proper Motion Dynamics

- Dynamics of stars, clusters, and galaxies inform about Formation, Evolution, Structure, Mass, Dark Matter, …
- Line of Sight velocities (from spectroscopy) provide limited 1D information (assumptions, degeneracies)
- Proper Motions (PMs) yield better insights, by themselves (2D) or combined with LOS data (3D)
  - ASTRO2010 Decadal Survey: Astrometry = 1 of 5 "Discovery Areas"
- Local Group (LG) is the only place to study these issues in detail (Galactic Archeaology)
- Required accuracies are tens of μas/yr
  - High spatial resolution and stability → space observatories
  - Long time baselines; exquisite control of systematics
- Now: HST, Gaia
- Future: JWST, WFIRST, LSST, 30m-ground, …

Unique Observational Capabilities

- Gaia
  - Detections down to G ~ 21; PMs useful for LG to G ~ 17
  - Accuracies will increase relative to DR2 by factor ~10
  - Full Sky coverage
  - Ancillary information (parallax, LOS velocity, …)
- HST
  - High Accuracies down to V ~ 25
  - Small FOV
  - Archive going back 30 years
- WFIRST:
  - 100x the HST FOV
  - Extends time baseline for PMs relative to HST, JWST, Gaia, …



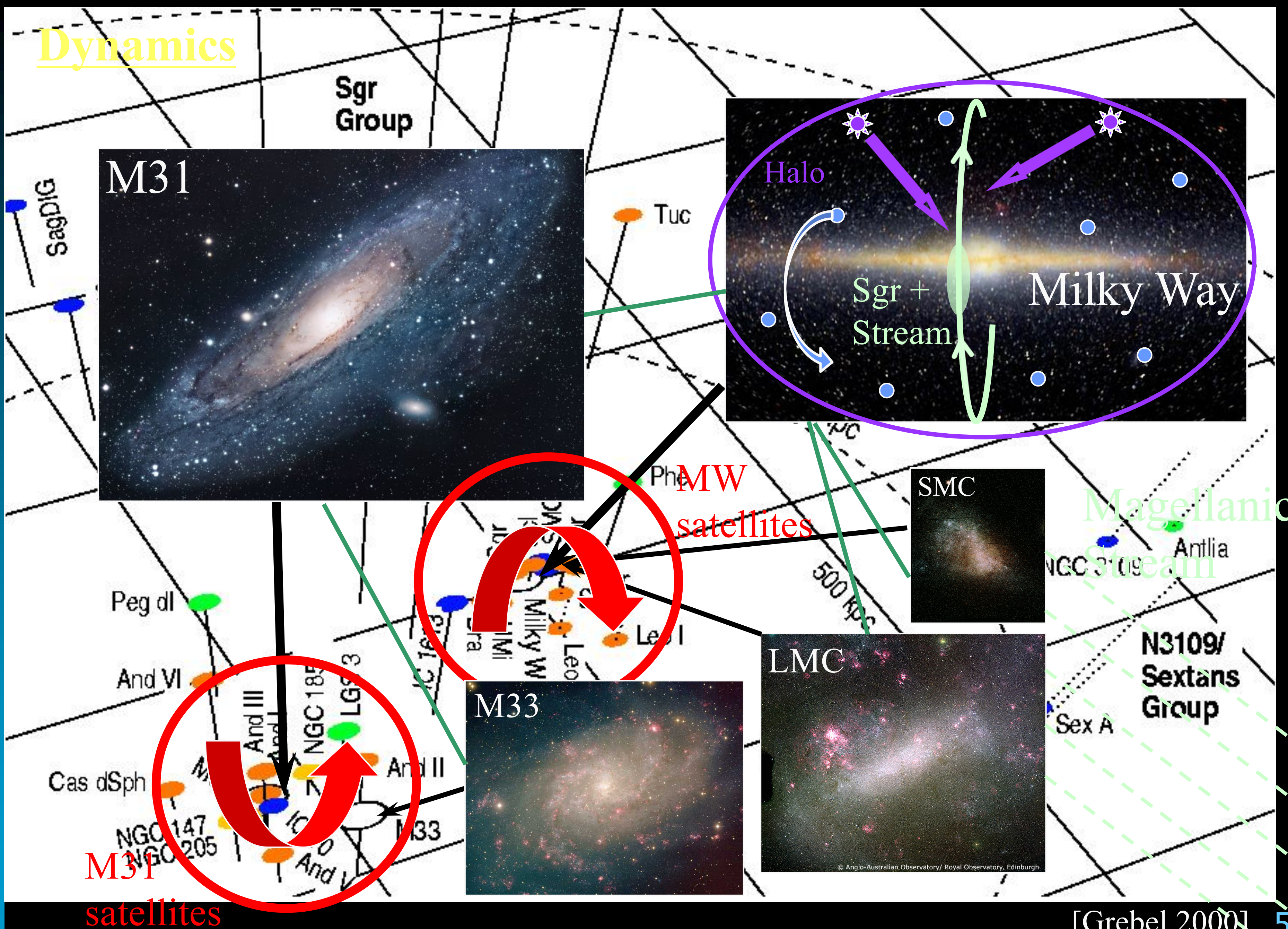
Globular Clusters PMs; HST vs Gaia [Sohn et al. 2018; Vasiliev 2018]

HSTPROMO: High-Resoultion Space Telescope Proper Motion Collaboration

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

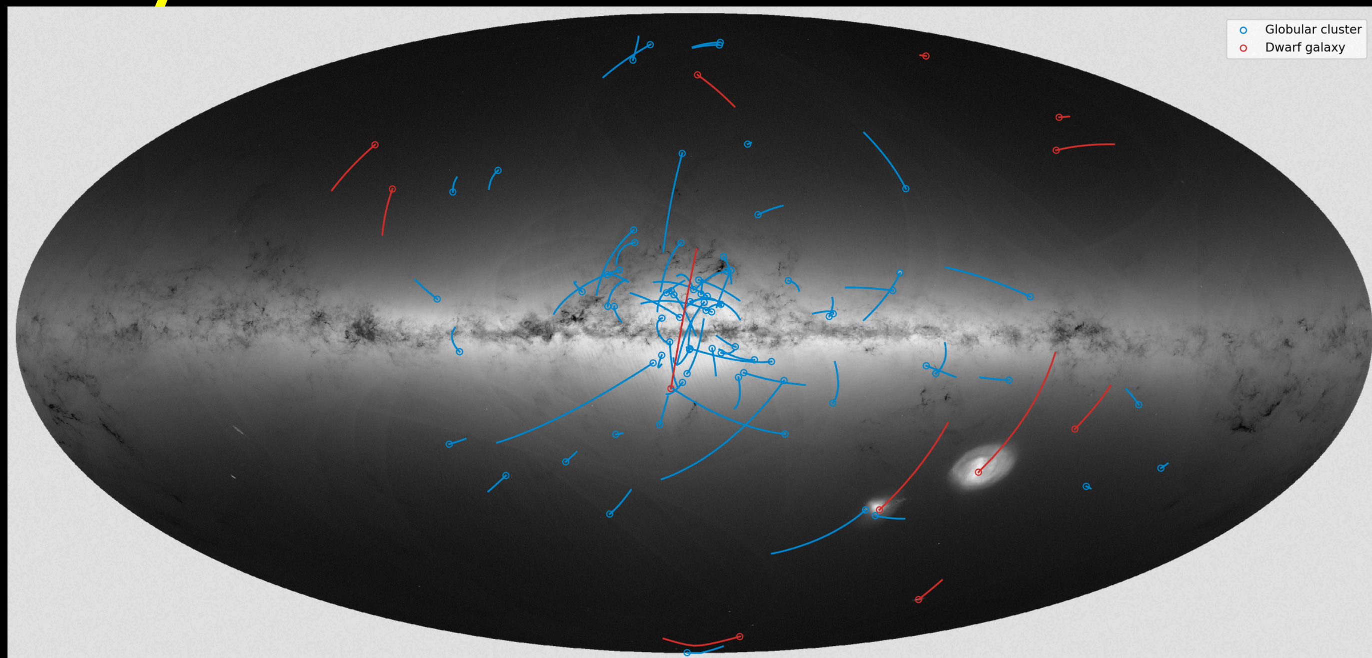
- Set of many different HST, Gaia, JWST investigations, with detailed theory components
  - Lead coordinators: van der Marel & Anderson
  - Project/Paper Leads: Sohn, Watkins, Bianchini, Fardal, del Pino, Fritz, Libralato, Bellini, Patel, …..
  - Many Other Members
- Status/Achievements
  - 15+ years of work
  - 50 HST + 12 Gaia papers

Dynamics



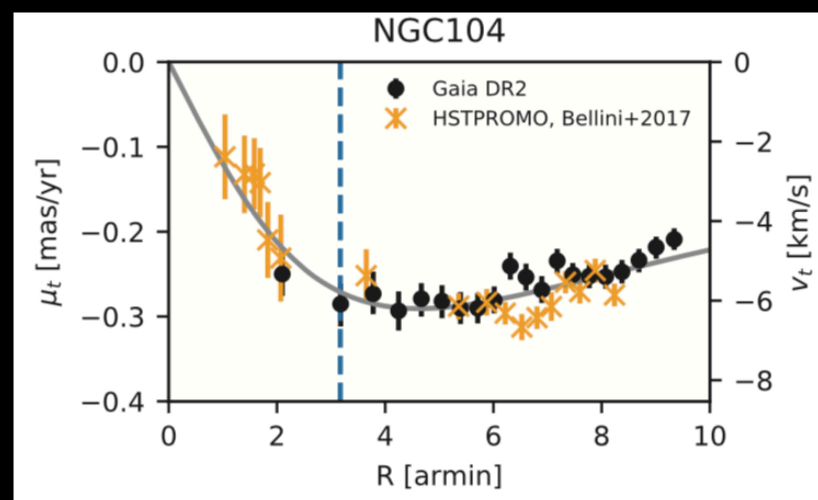
[Grebel 2000]

Milky Way Globular Clusters with Gaia



[Helmi et al. 2018; Vasiliev 2018]

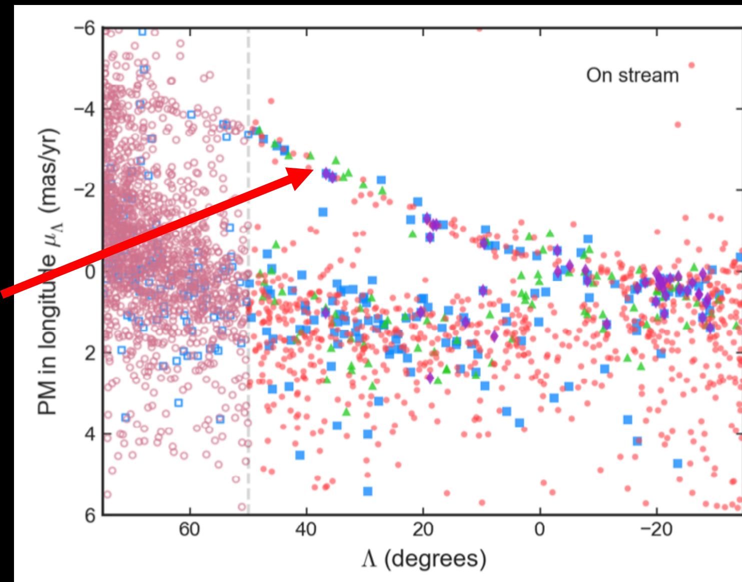
- Dynamical Modeling of bulk 3D velocities constrains MW $M_{vir} \sim (1.5 \pm 0.6) \times 10^{12}\ M_\odot$ (Watkins et al. 2019)
- Rotation curve on the sky constrains internal dynamics



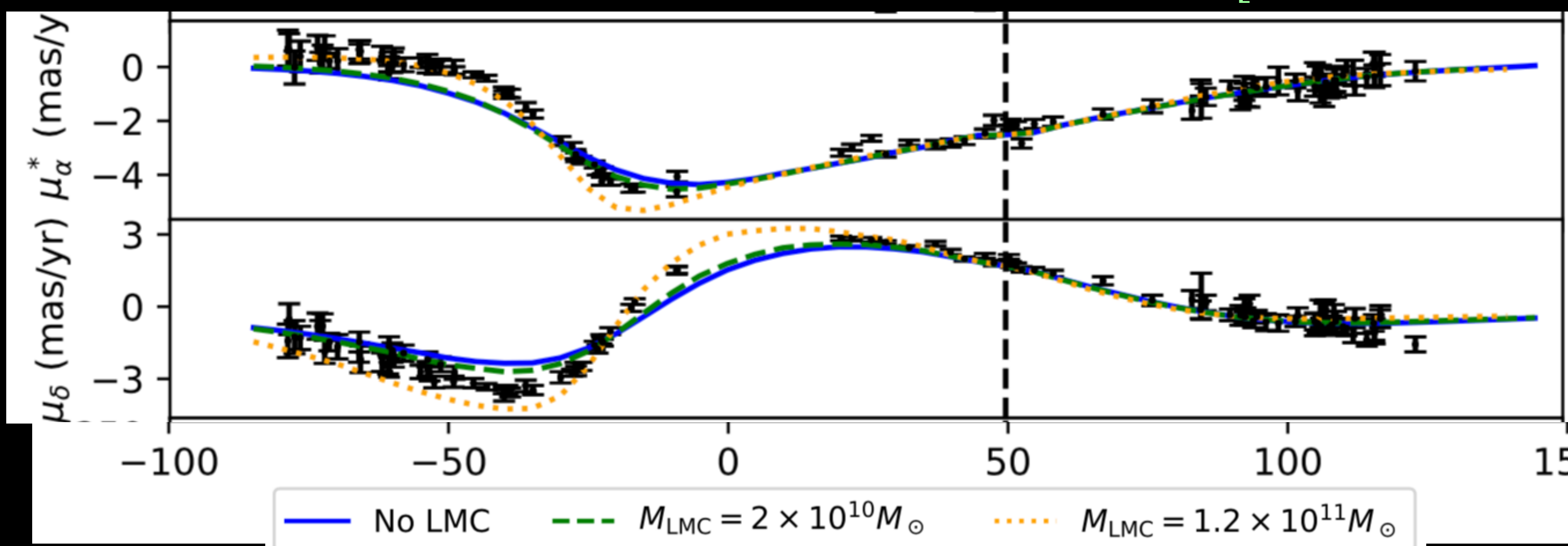
[Bianchini et al. 2018]

Milky Way Stellar Streams with Gaia

- Orphan Stream: Clearly separated from foreground populations (Fardal et al. 2019) and traced across sky (Koposov et al. 2019)

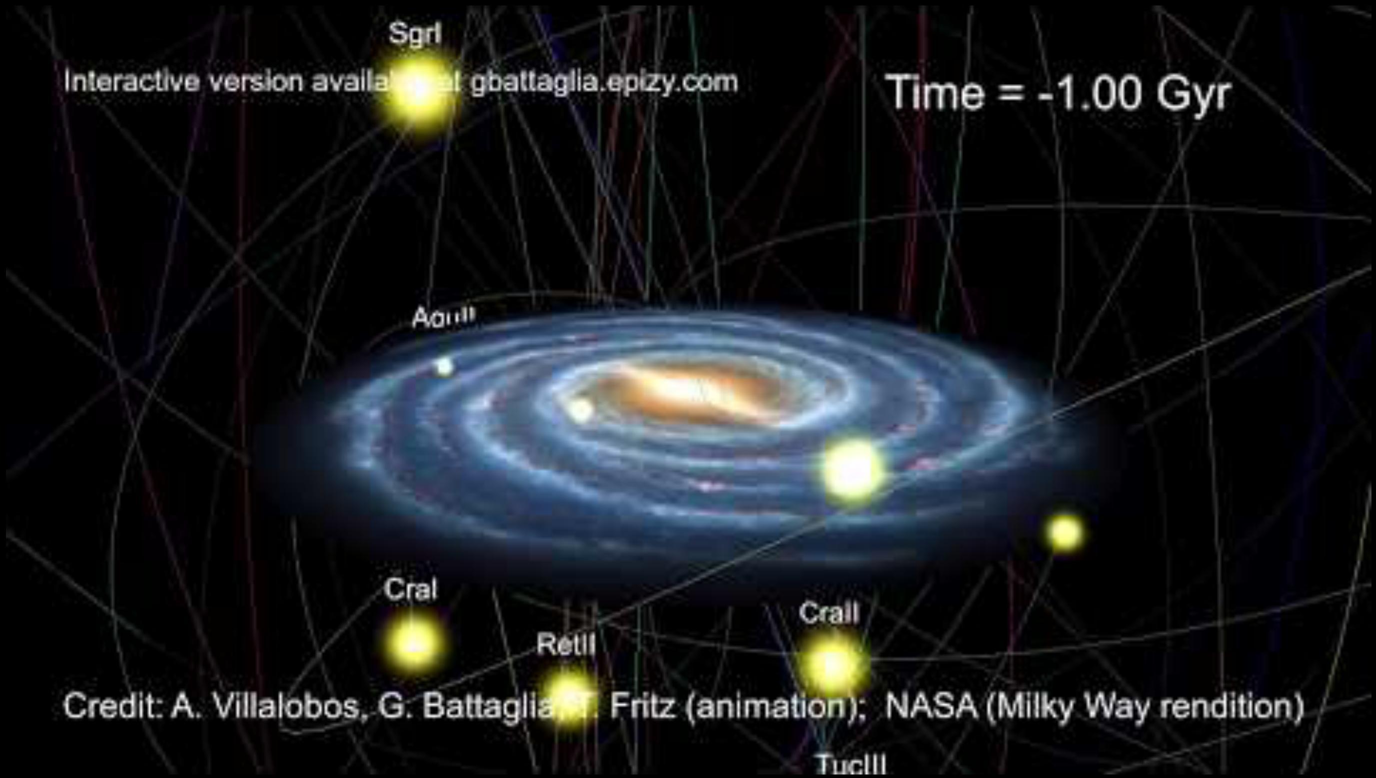


[Fardal et al. 2019]



- PMs imply track is perturbed by an LMC of mass $M_{vir} \sim (1.4 \pm 0.3) \times 10^{11}\ M_\odot$ (Erkal et al. 2019)

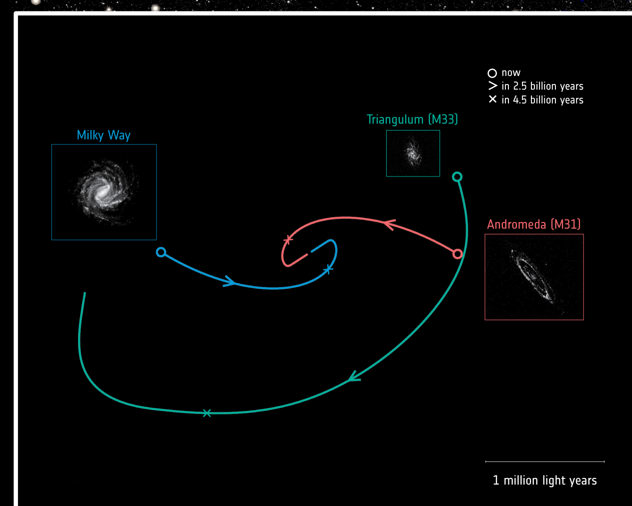
Milky Way Dwarf Satellites with Gaia



- Bulk PMs of dSphs out to few hundred kpc (Simon 2018; Fritz et al. 2018; Massari et al. 2018; …)
- Applications: plane of satellites, satellite infall and tidal perturbations, mass modeling, etc.

Andromeda/ Triangulum with Gaia

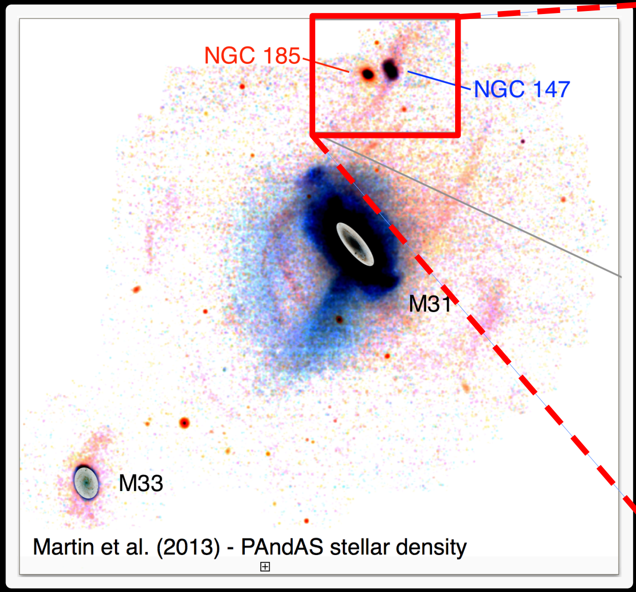
- Brightest blue/red supergiants in M31 and M33 are accessible with Gaia (van der Marel et al. 2019)
- Detects the rotation of each galaxy in the plane of the sky
- Yields absolute PMs consistent with prior HST/VLBA measurements
- Suggests M33 is on first infall into M31

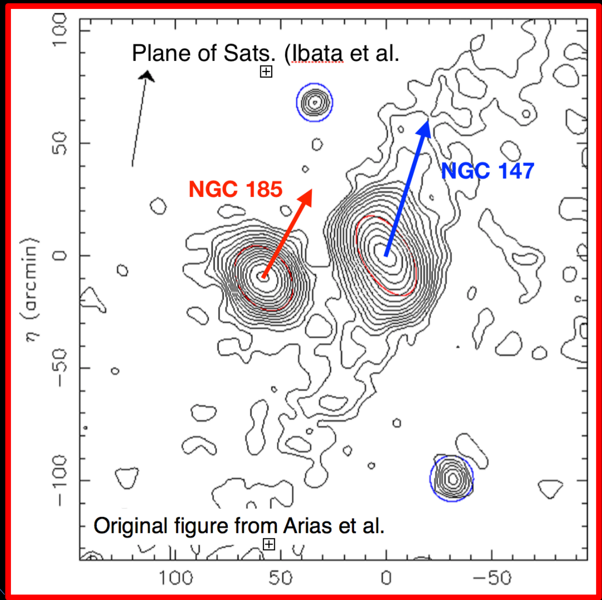


[Patel]

Distant Dwarfs with HST

- Gaia cannot study dSphs beyond a few hundred kpc (TRGB of old population has G~21 at M31's distance)
- HST can study PMs of such galaxies, e.g., the NGC 147 and 185 pair (Sohn et al. 2019, in prep.)

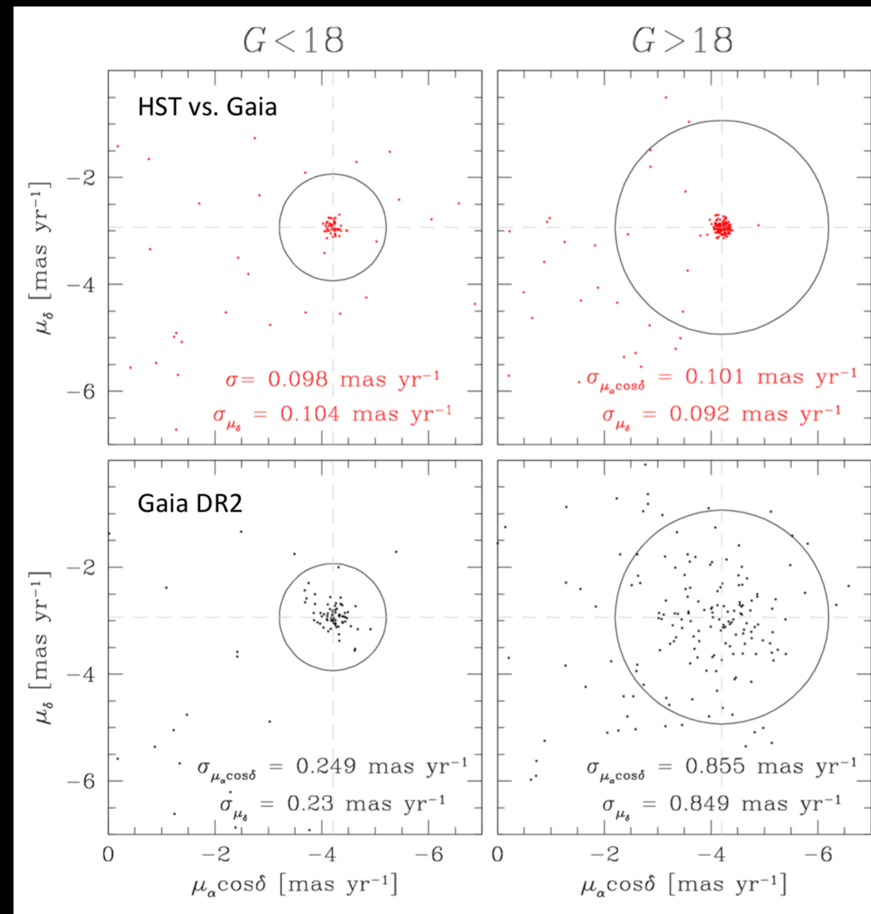




- Applications: plane of satellites, satellite infall and tidal perturbations, mass modeling, etc.
- Other HST/JWST studies ongoing/planned (e.g., M32)

Combining Gaia with HST

- Fainter magnitudes G>18
  - HST (relative) positions are more accurate than Gaia
  - Improved PMs are obtained by combining HST and Gaia positions
  - Example (right): Globular cluster NGC 6535



[Libralato, priv. comm.]

- Ongoing HST Archival Study (del Pino et al); see also Massari et al. (2018, 2019) for Draco/Sculptor

WFIRST Astrometry

- WFIRST will be powerful for astrometry and proper motion studies
  - Especially useful at faint magnitudes over wide areas
  - Can use existing HST methodologies (PSF fitting etc.)
  - Can be used by itself (over limited time baseline) or in combination with existing data/catalogues (incl. Gaia)
- Astrometry Working Group White paper (Sanderson, Bellini, et al. 2017) provides details

Context	**Estimated performance**	**§**
Single-exposure precision	0.01 px; 1.1 mas	1.1
Typical guest-observer program (100 exposures of one field)	0.1 mas	1.1
Absolute astrometry accuracy	0.1 mas	3.3
Relative proper motions derived from High-Latitude Survey	25 μas yr^{-1}	4.1
Relative astrometry, Exoplanet MicroLensing Survey (per image)	1 mas	4.2
Relative astrometry, Exoplanet MicroLensing Survey (full survey)	3–10 μas	4.2
Spatial scanning, single scan	10 μas	2.4
Spatial scanning, multiple exposures	1 μas	2.4
Centering on diffraction spikes	10 μas	2.4

§	**Science case**	**Astrometric precision**	
2.1	Motions of dwarf satellites in the Local Group	2.2×10^{-4} pixel yr^{-1}	25 μas yr^{-1}
2.2	Motion of stars in the distant MW stellar halo	$\leq 2 \times 10^{-4}$ pixel yr^{-1}	≤ 25 μas yr^{-1}
2.3	Low-mass end of the subhalo mass function	1.8×10^{-4} pixel yr^{-1}	20 μas yr^{-1}
2.4	Detection & characterization of exoplanets	$\leq 9 \times 10^{-5}$ pixel	≤ 10 μas
2.5	Structure of the MW bulge	$\leq 9 \times 10^{-5}$ pixel	≤ 10 μas
2.6	Star formation in the MW	$\leq 4.5 \times 10^{-4}$ pixel yr^{-1}	≤ 50 μas yr^{-1}
2.7	Isolated black holes & neutron stars	4.5×10^{-4} pixel	50 μas
2.8	Internal kinematics in GCs	$\lesssim 1.8 \times 10^{-4}$ pixel yr^{-1}	$\lesssim 20$ μas yr^{-1}

Table 2. Required astrometric precision (in units of both WFI pixels and μas) for the different science cases discussed in §2.

Conclusions

- Proper Motions yield new insights into Local Group Galaxy Dynamics
  - Can be reliably measured with various observatories
- Great progress has been made, first with HST and now with Gaia
- WFIRST and other future observatories will yield further advances
- Key for progress in Galactic Archeology
  - Understand galaxy formation and evolution through resolved studies of nearby galaxies