# The Proper Motion of M31

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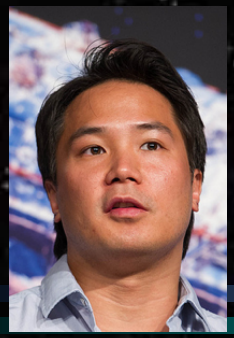
(ApJ, July 2012)

I: HST measurement (Sohn, Anderson & vdMarel)
II: Implied velocity + LG mass (vdMarel et al.)
III: MW-M31-M33 future (vdMarel, Besla, et al.)


[Other collaborators: Fardal, Beaton, Guhathakurta, Brown, Cox]

# History

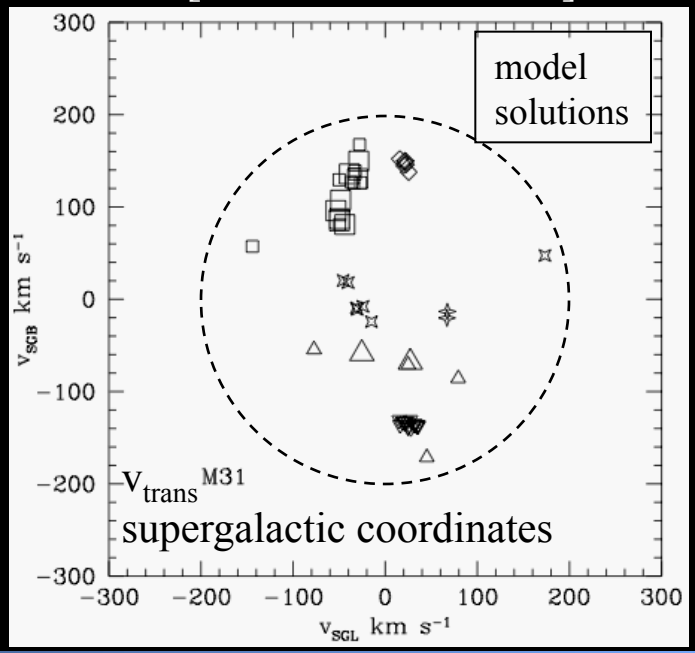
- 1912: Slipher measures $V_{LOS}$ ; implies approach towards Milky Way at ~110 km/s Galactocentric
- 1918: Barnard finds no dectable proper motion (PM) from observations started in 1898
- No successful subsequent proper motion measurements

# Theory

- The MW and M31 protogalaxies started expanding radially outwards after the Big Bang
- Subsequently started falling back together due to their mutual gravity (timing argument)
- Angular momentum induced by tidal torques from surrounding Local Universe: $V_{tan} < 200$ km/s
- Millennium simulation MW-M31-like pairs (Li & White 2008)
  - median $V_{tan} \sim 87$ km/s
- Action modeling shows many possible solutions

➔ wide range of possible orbits

[Peebles et al. 2001]

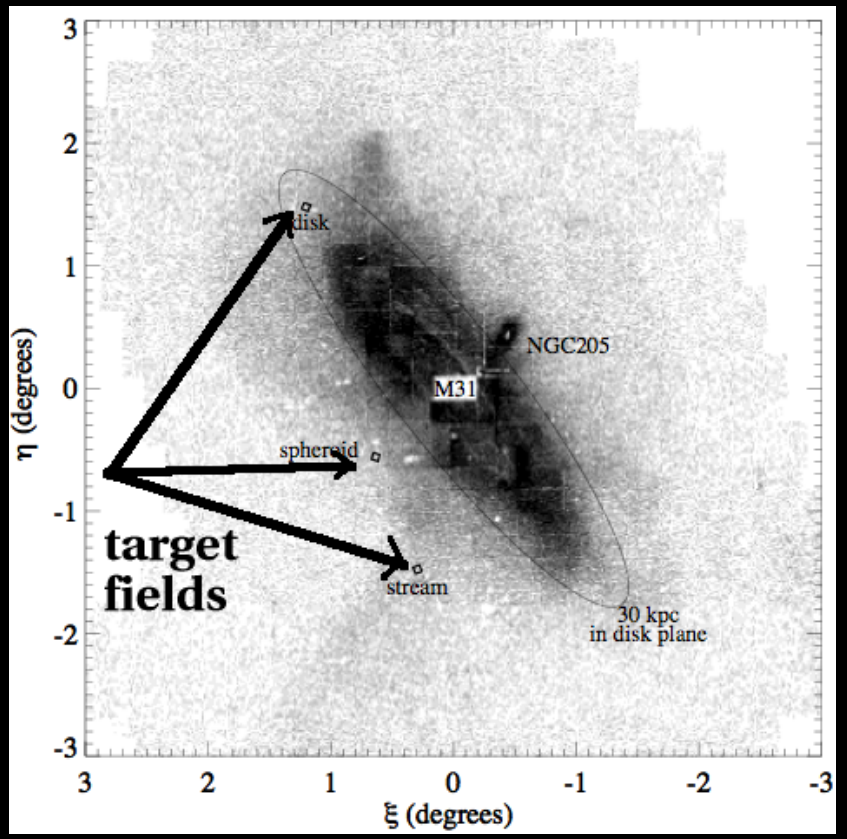


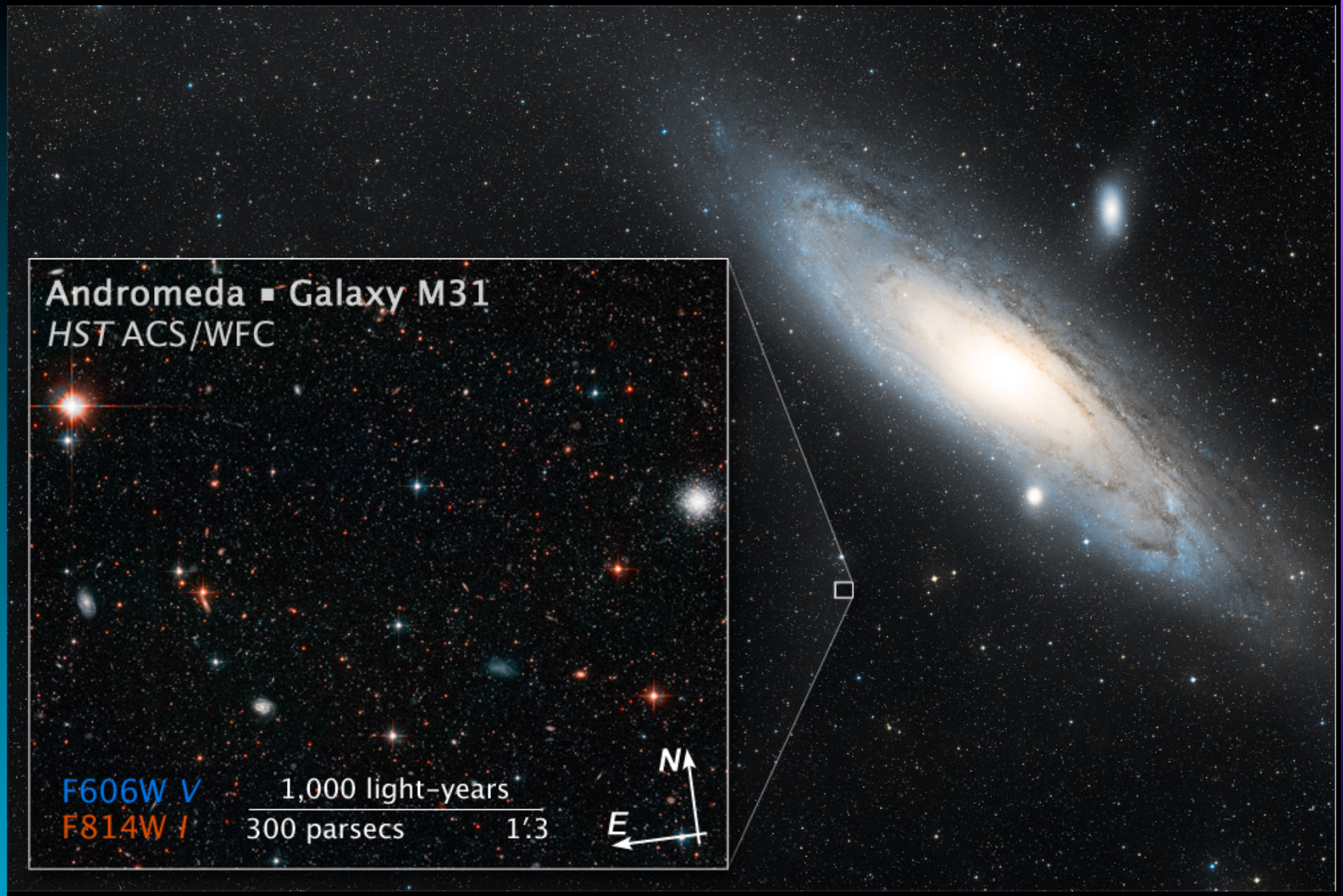
# Proper Motion Challenge

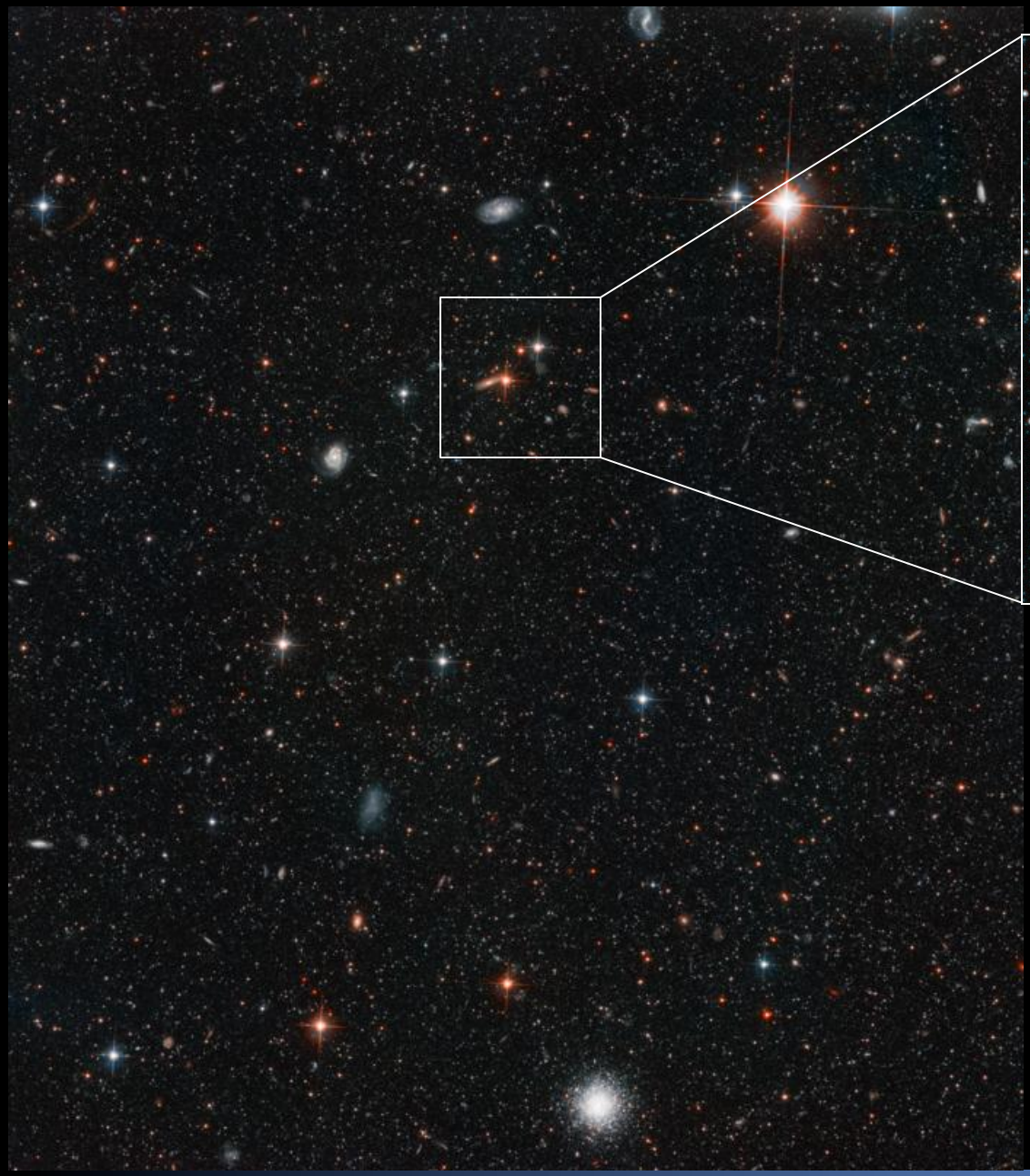
- Relevant proper motions are small
  - 200 km/s at M31 = 55 μas/year
  - 40 km/s at M31 = 11 μas/year
- Maser VLBI – 2014?
  - First discovered in M31 by Sjouwerman et al. (2010) and Darling (2011)
  - Some years of follow-up required
- GAIA – 2018?
  - MW-optimized, but can measure bright uncrowded M31 stars
- HST – now!
  - 200 km/s at M31 = 0.007 ACS/WFC pixels over 7 years

# M31 HST Proper Motion Measurement

- Three fields observed to great depth (>200 orbits)with ACS 2002-2004 to study MSTO (Brown et al.)
  - Spheroid
  - Outer Disk
  - Tidal Stream
- Reobserved in 2010 for 9 orbits to determine proper motions.
  - #Half-orbit exposures per field:
    - 2x ACS/WFC
    - 4x WFC3/UVIS



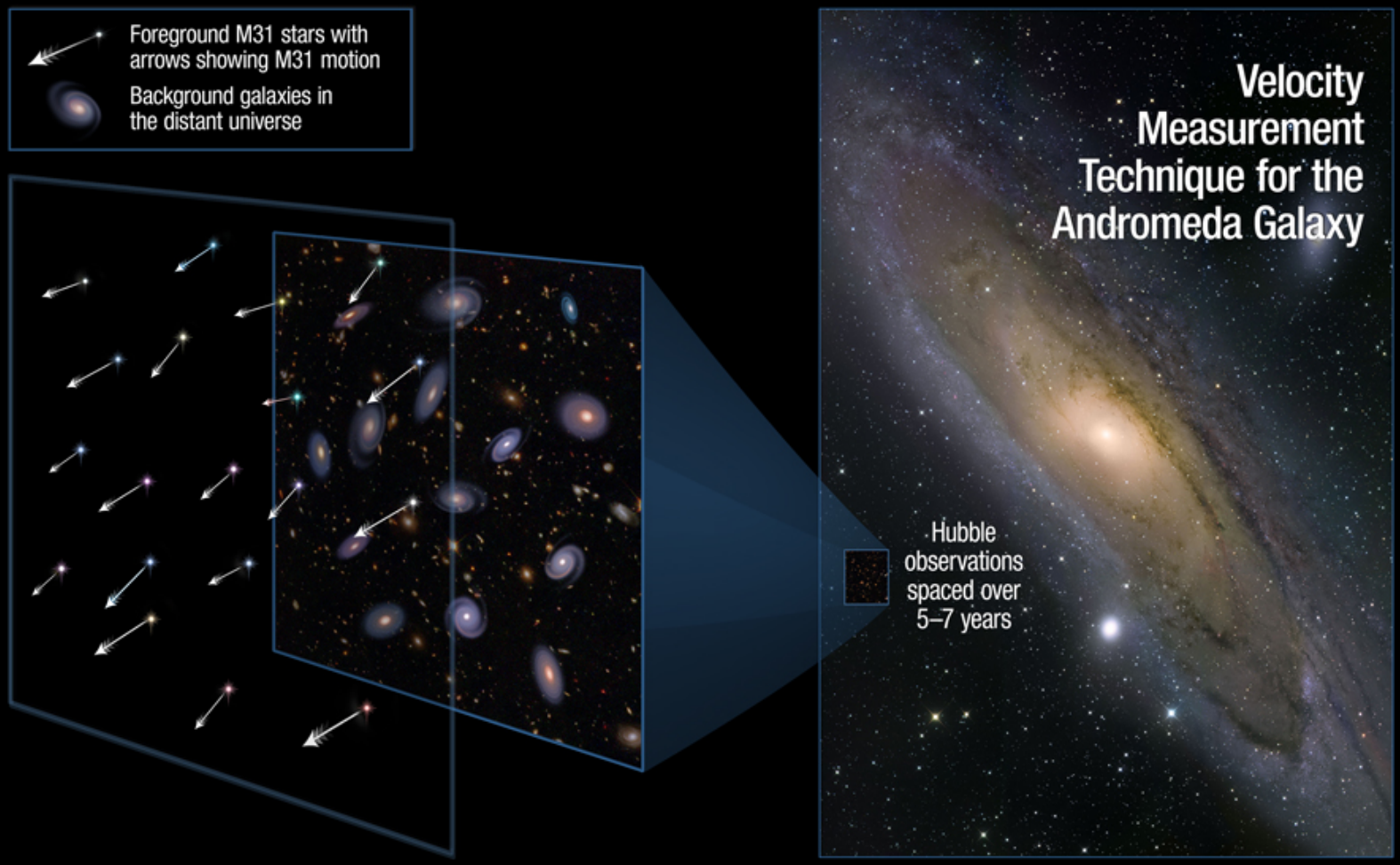

Andromeda ▪ Galaxy M31
*HST* ACS/WFC
F606W *V*
F814W *I*
1,000 light-years
300 parsecs
1′.3
N
E



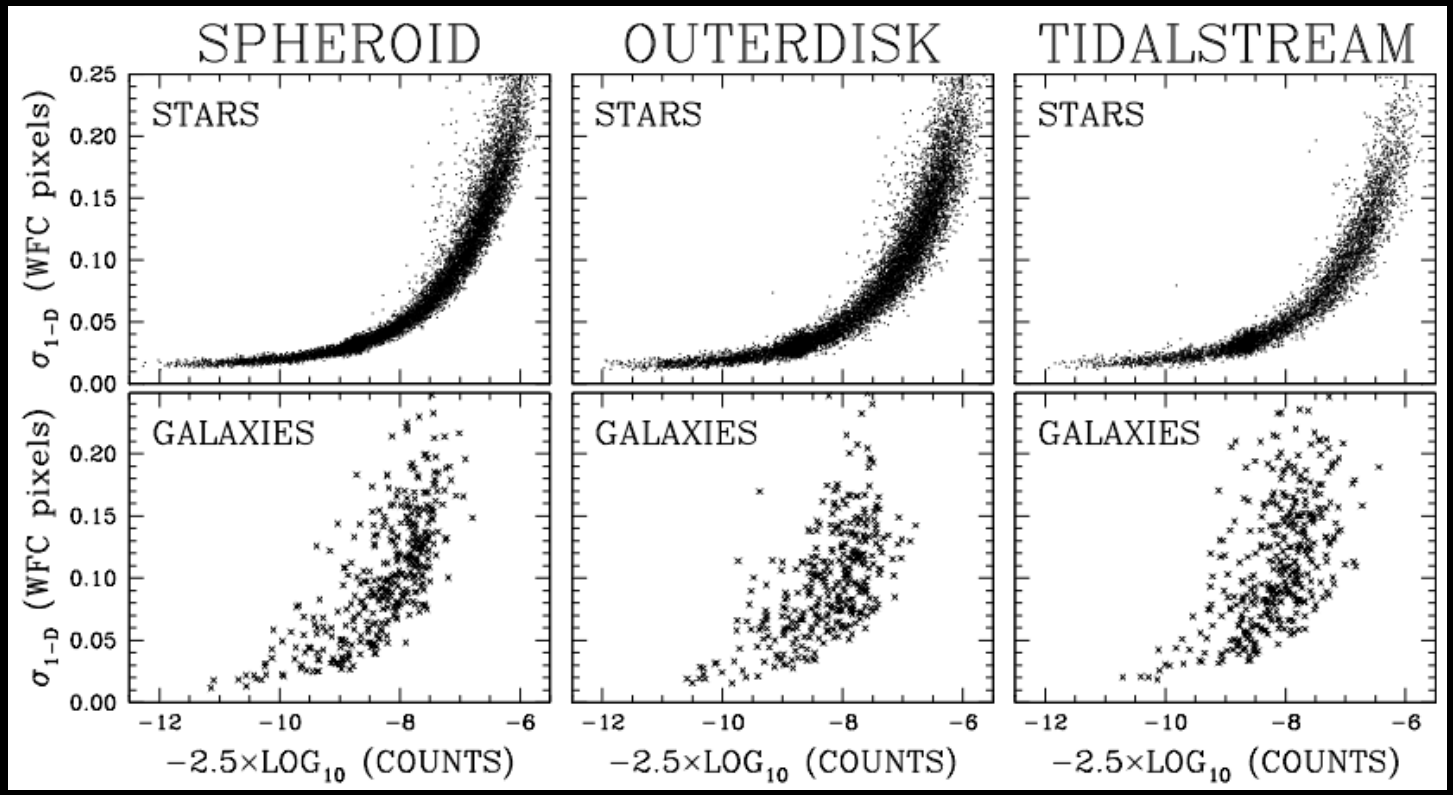
## Astrometrically useful objects per field

* ~10,000 M31 stars
  (CMD, ΔPM selection)

* ~200 background galaxies
  (compact)


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

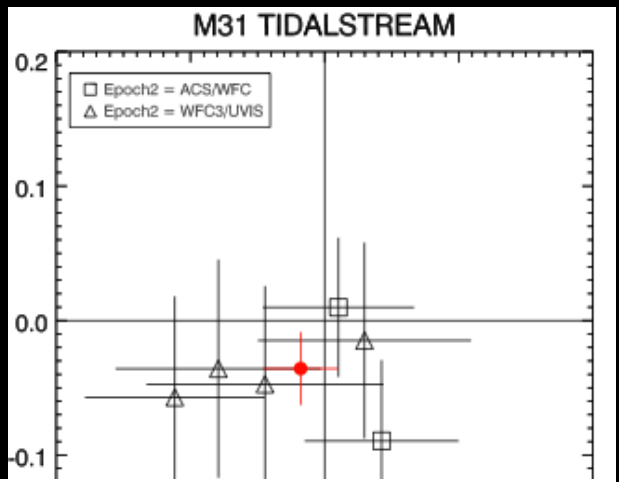
# Positional Accuracy (per object, per exposure)

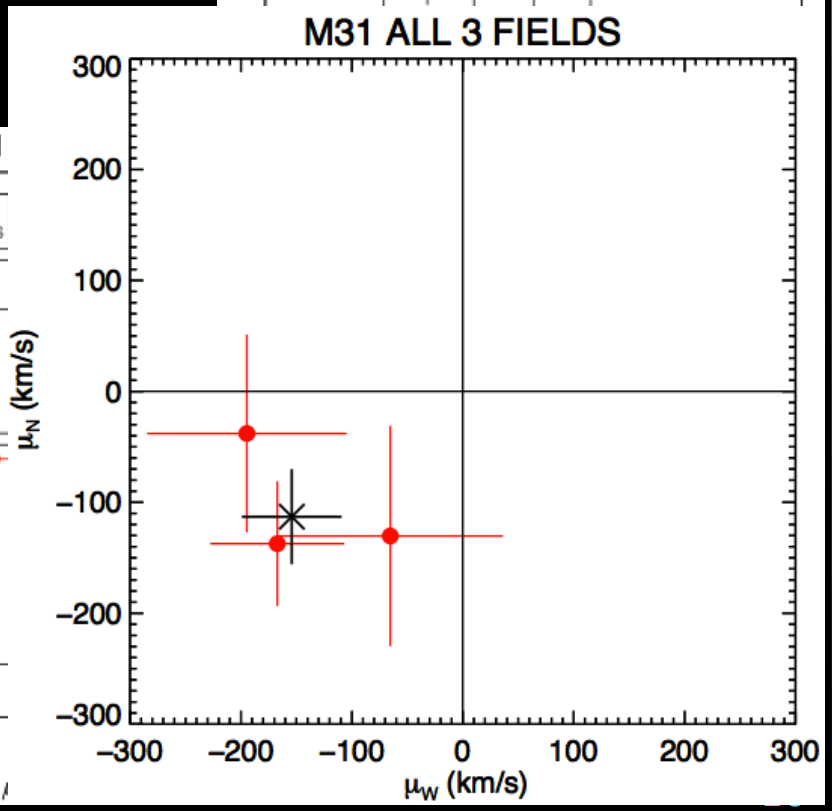


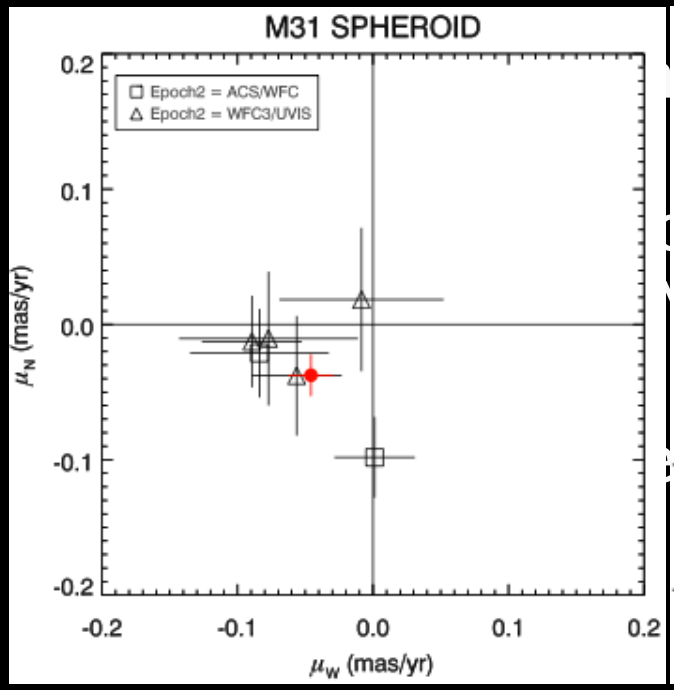

- 0.01 pixels for brightest objects
- Stars more accurate than background galaxies
- High final accuracy results from averaging over many objects, in 6 exposures, for 3 fields

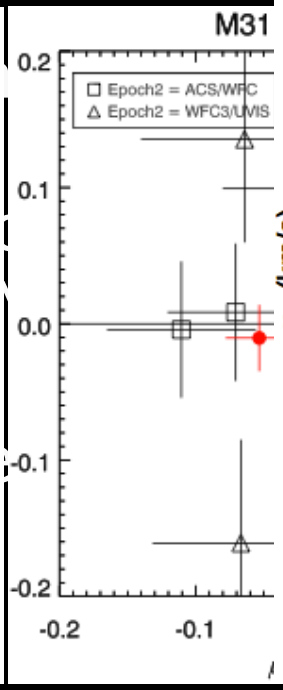
# Heliocentric ($PM_{West}$,$PM_{North}$)

- Black: individual exposures
- Red: weighted averages per field



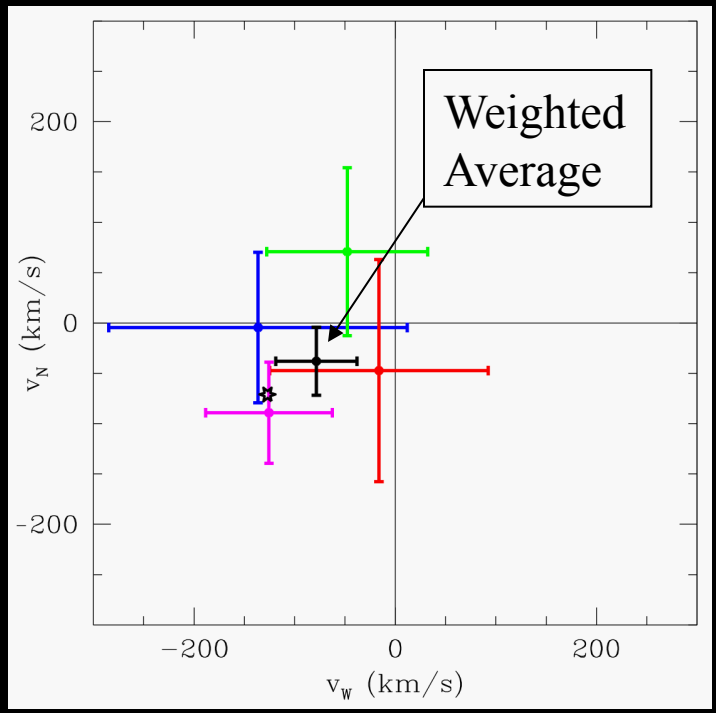



# Zoom-in to Spheroid Field with 30,000 years of projected motion

# Alternative: M31 Transverse Velocity from Satellite Kinematics

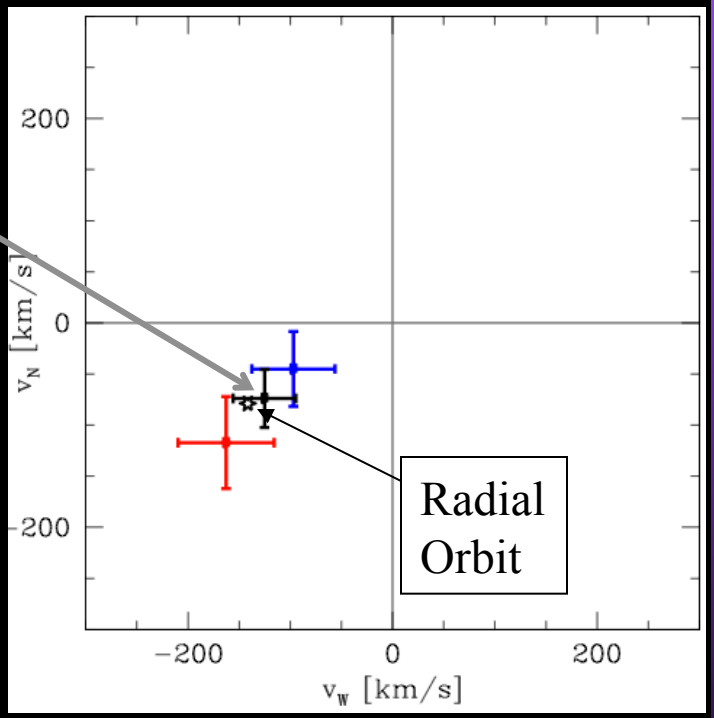
- vdM & Guhathakurta 2008; vdM et al. 2012 Paper II:
  - Line-of-sight velocities of M31 satellites and distant globular clusters (31x)
  - 3D velocity vectors of M31 satellites M33 and IC10 (water maser PMs; Brunthaler et al 2005,2007)
  - Line-of-sight velocities of distant Local Group satellites (6x)
- Results mutually consistent



# M31 Galactocentric Velocity

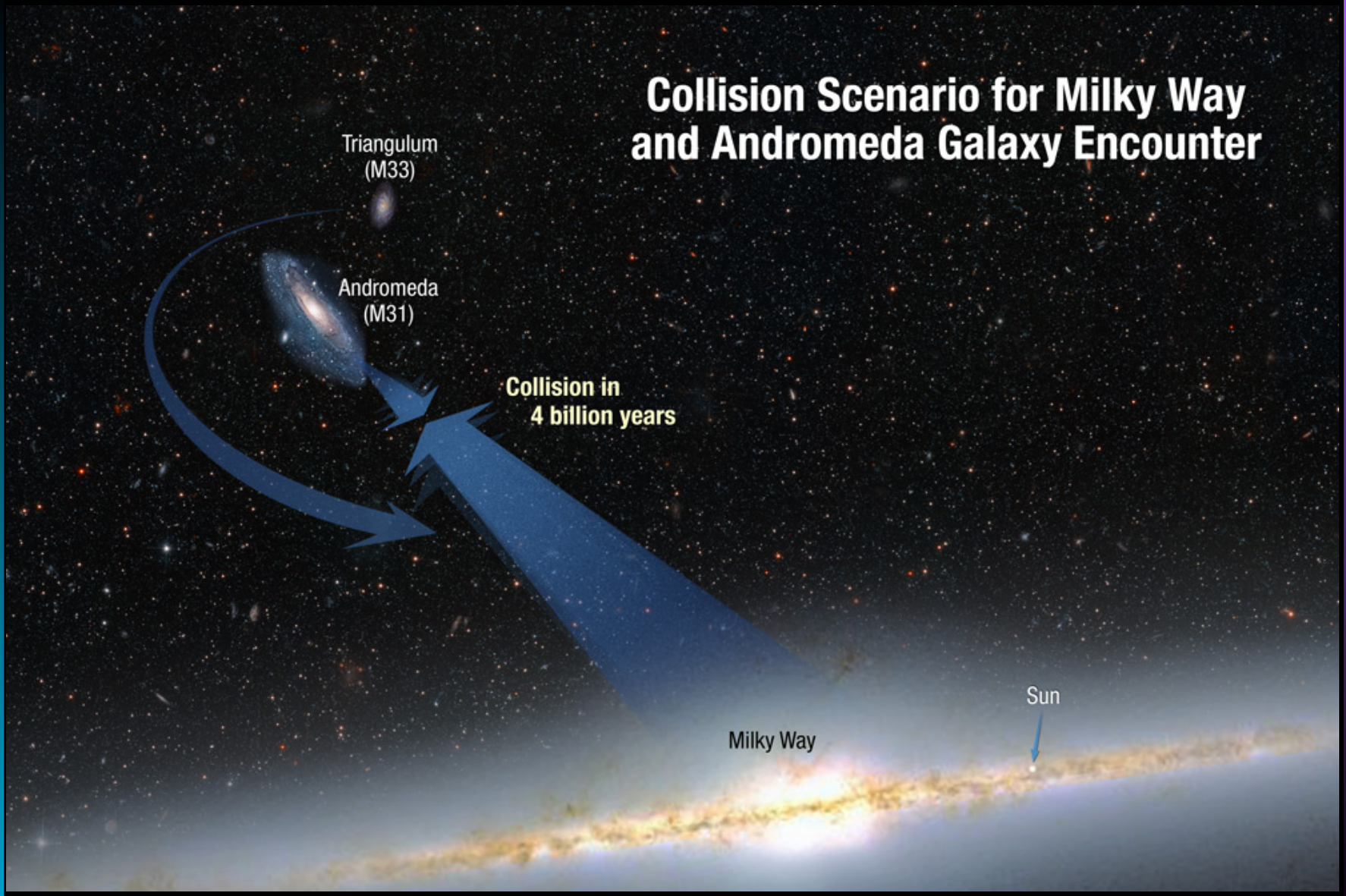
- Agreement HST vs. satellites
- Final weighted average
  - $v_W$ = -125 ± 31 km/s
  - $v_N$ = -74 ± 28 km/s

  (12 μas/yr accuracy)
- Most of heliocentric velocity is reflex solar motion in MW
  - $V_\odot$ = 239 ± 10 km/s (McMillan 2011)
- Galactocentric
  - $V_{tan}$ = 17 km/s (< 34 km/s @68%)
- Consistent with MW-M31 Direct Collision Course!



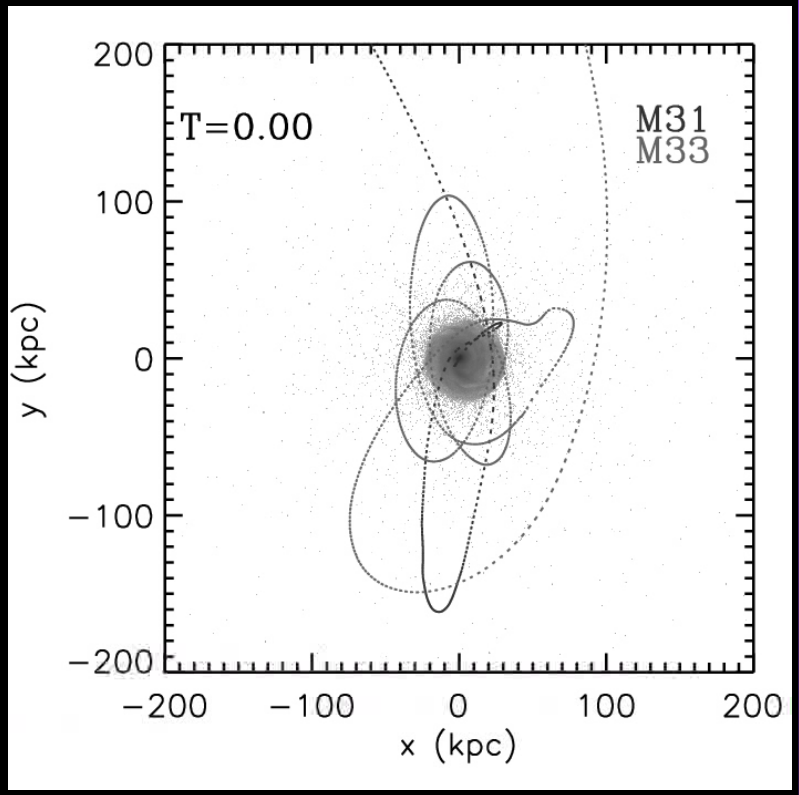
# Future Orbital Evolution + Merging

- MW, M31, M33
  - Three most massive LG galaxies
  - Known positions, distances, velocities, masses
  - "simple" Newtonian orbit calculation problem
- Two approaches
  - N-body simulations (no gas, few specific initial conditions)
    - See also Dubinski et al. (1996), Cox & Loeb (2008)
  - Semi-analytic orbit integrations w/ approximate dynamical friction (exploration observationally allowed parameter space)


Collision Scenario for Milky Way
and Andromeda Galaxy Encounter
Triangulum
(M33)
Andromeda
(M31)
Collision in
4 billion years
Sun
Milky Way

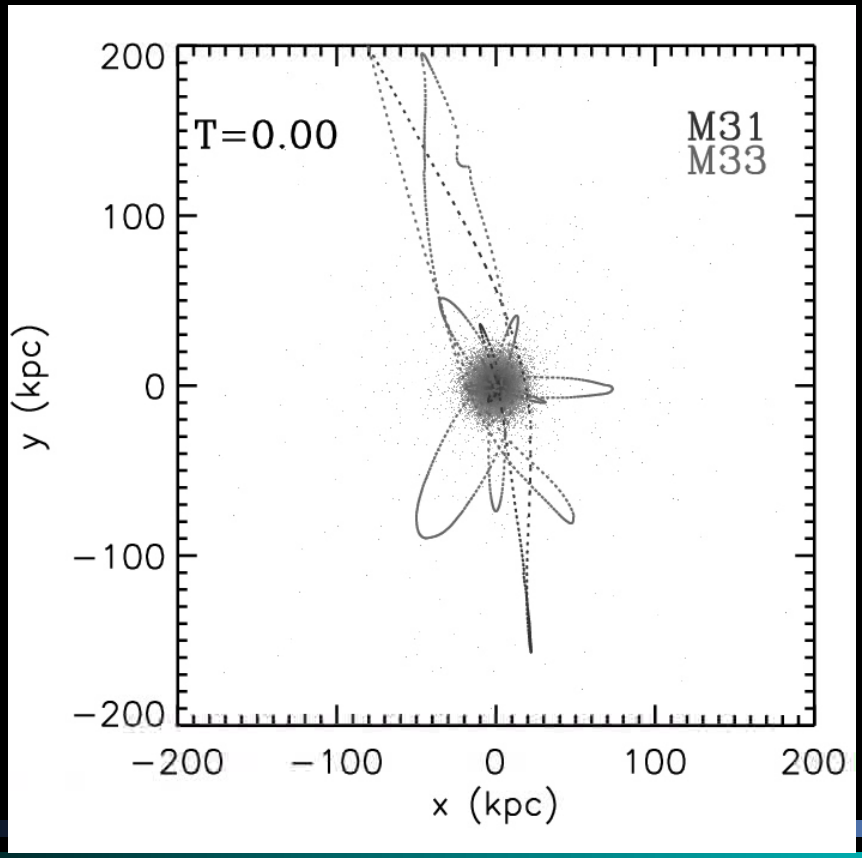
# "Canonical" N-body Evolution

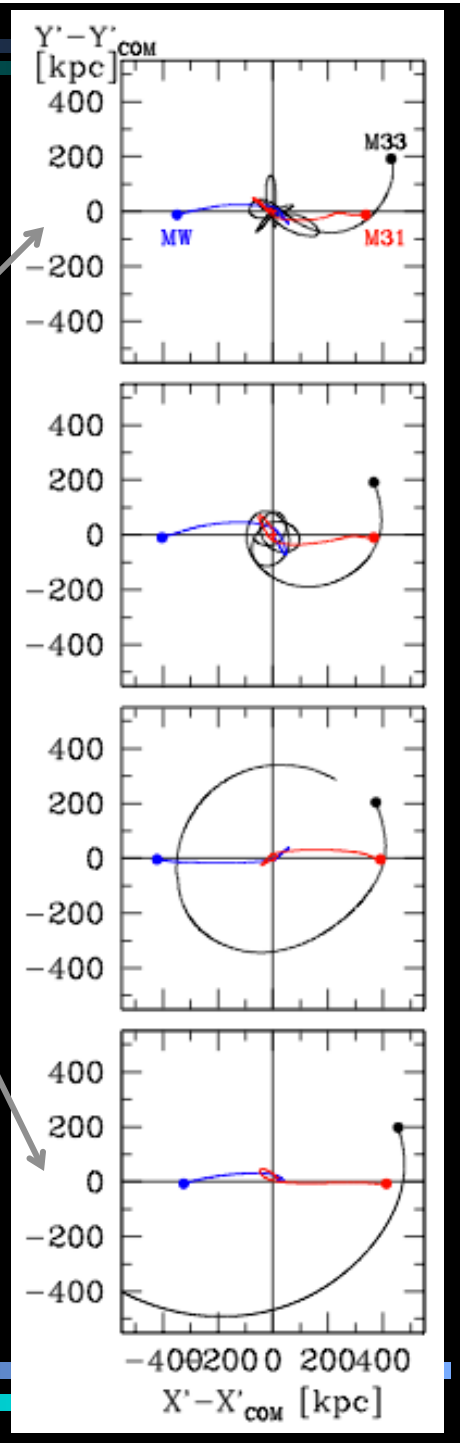
- Vtan = 28 km/s
- Pericenter 35 kpc @ 4.0 Gyr with V=586 km/s
  ["direct hit" <25 kpc: 41%]
- Merger @ 6.3 Gyr
  [always; ± 1.2 Gyr]
- M33 settles onto slowly decaying orbit [84%]
- All three galaxies orbit close to a single plane
- Candidate suns in red



# M33

- bound to M31 (95% confidence)
- Past M33-M31 orbit consistent with models for M33-M31 tidal deformations (HI + RGB stars)
- MW approach distance can span large range
- M33 may hit MW first, before M31 [9%]
- M33 may leave Local Group [7%]



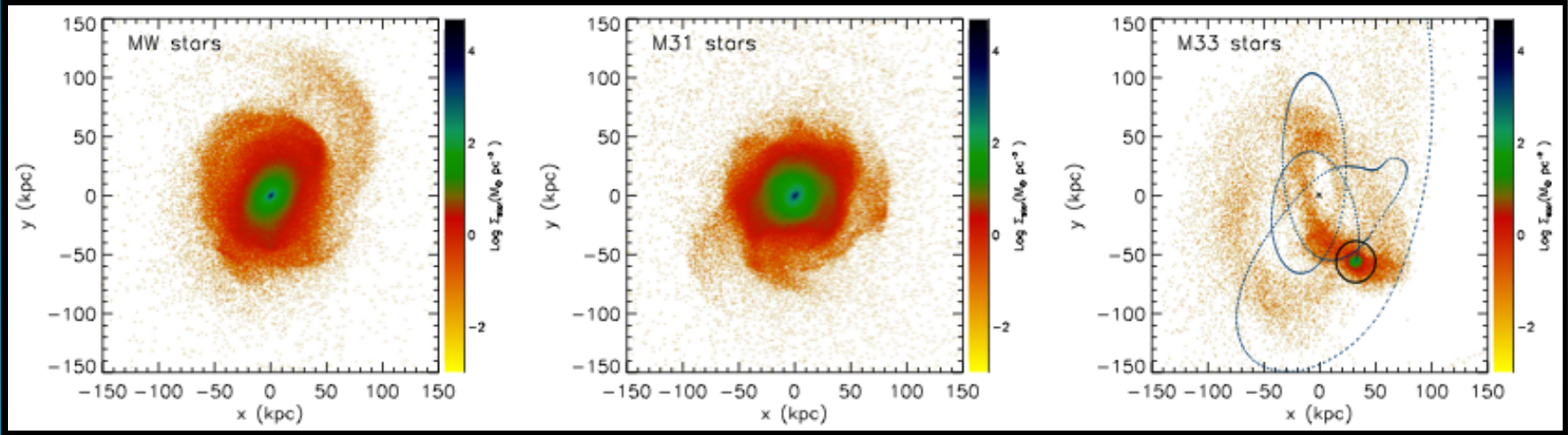
# So what's next for Milky Way, Sun, Earth?


June 1, 2012 Media headlines:

- THE END OF THE GALAXY AS WE KNOW IT?
- THE MAYAN'S WERE 4 BILLION YEARS OFF
- CRASH OF THE TITANS
- MILKY WAY GALAXY DOOMED
- COSMIC SMASHUP PREDICTED
- WHEN WORLDS COLLIDE

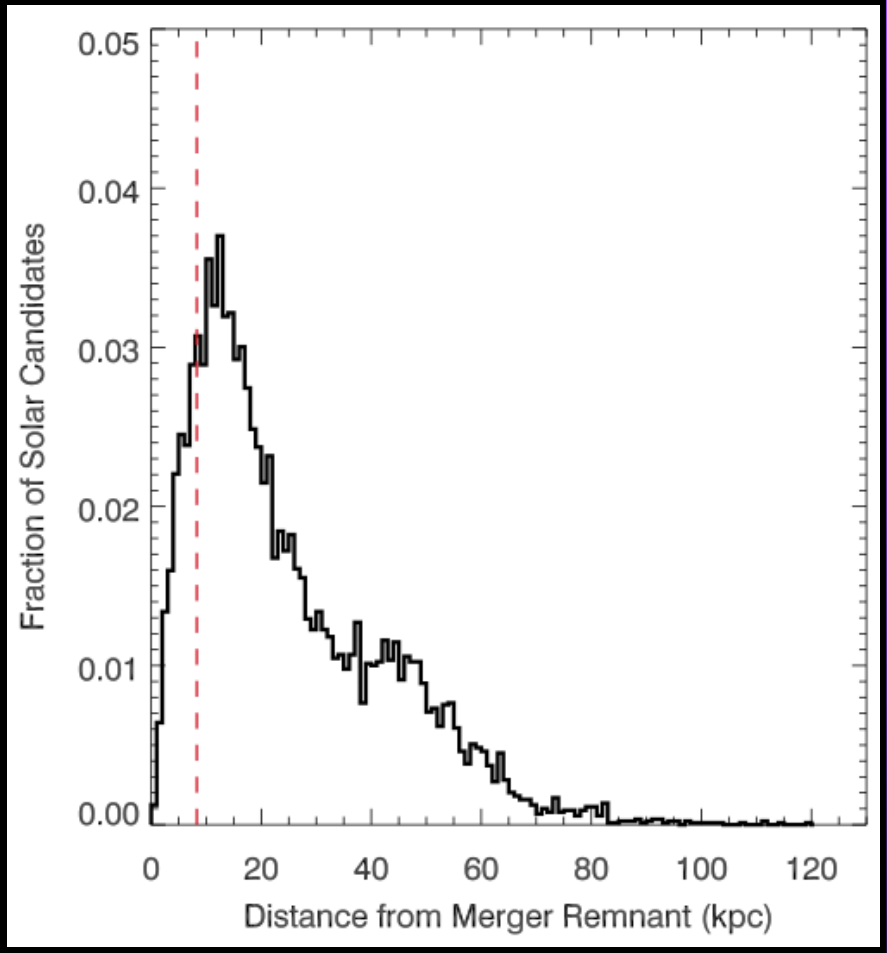
# Milky Way Future

- Merger remnant will be(come) an elliptical galaxy
  - $R^{1/4}$ density profile
  - Kinematics, FP (Cox & Loeb 2008)
- Full mixing takes a long time
  - MW, M31, M33 particles at 10 Gyr:



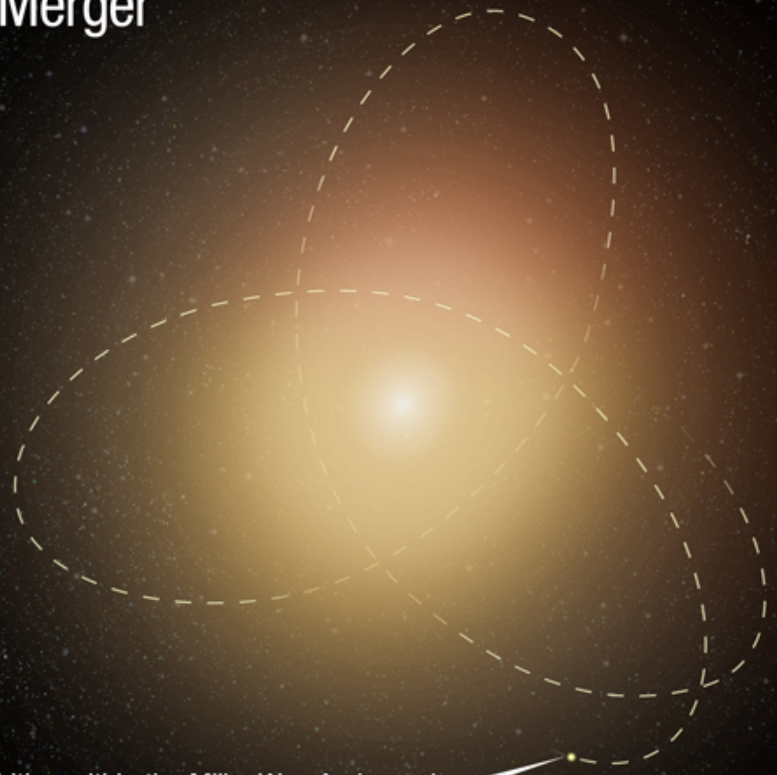
# Sun Future

- Sun will move to larger Galactocentric distance (also: Cox & Loeb 2008) [85%]
- Sun may move to >50 kpc [10%]
- Sun may find itself moving through M33 in next 10 Gyr, while dynamically bound to MW-M31 remnant [20%]




Sun distance at 10 Gyr

# Fate of the Sun:
## Milky Way–Andromeda Merger

# Earth Future

- Sun will still be main-sequence star when Andromeda arrives in 4 Gyr
  - Earth will be too hot for life as we know it
- Sun will become red giant in 6 Gyr
  - Earth will likely be vaporized
- Likelihood that other stars will pass close to the Sun is small
  - Earth orbit likely to remain unperturbed


Today

# Conclusions

- Finally an M31 PM measurement!
- Confirms what has long been hypothesized: MW-M31 will merge
- Many interesting corrollary findings

- HST fantastic tool for Proper Motions and Local Group Dynamics; ask me about our ongoing PM work on
  - Globular Clusters
  - LMC+SMC
  - Sagittarius Stream
  - Leo I
  - Leo T
  - Satellites at Local Group Turnaround Radius

# Direct-hit N-body simulation