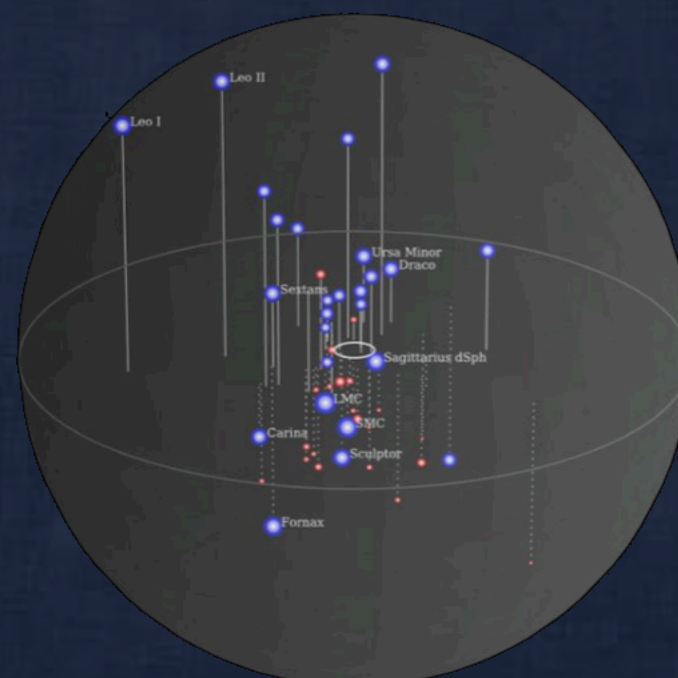
Orbits and Tidal Stripping of the Milky Way's Satellites

Josh Simon

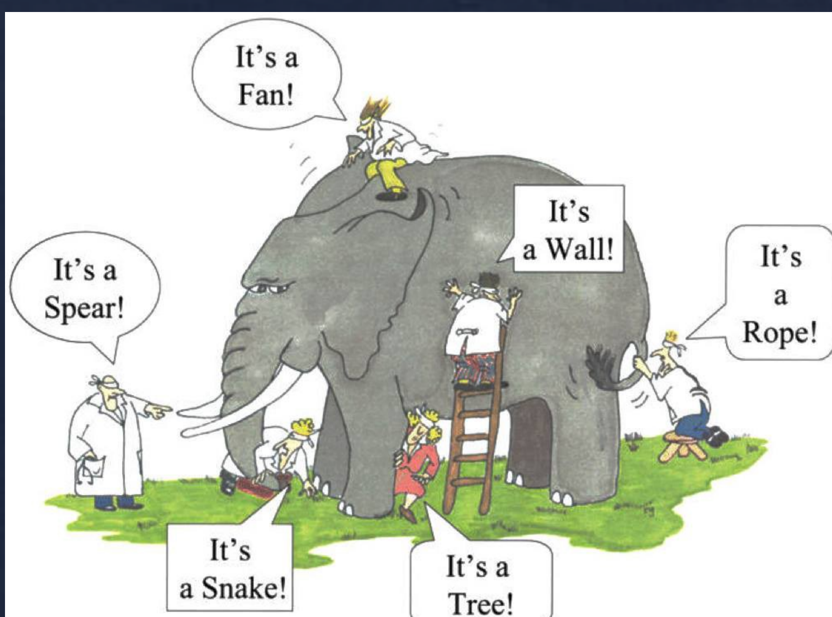
Carnegie Observatories



Pawlowski/Bullock/Boylan-Kolchin

Orbits and Tidal Stripping of the Milky Way’s Satellites

Josh Simon
Carnegie Observatories

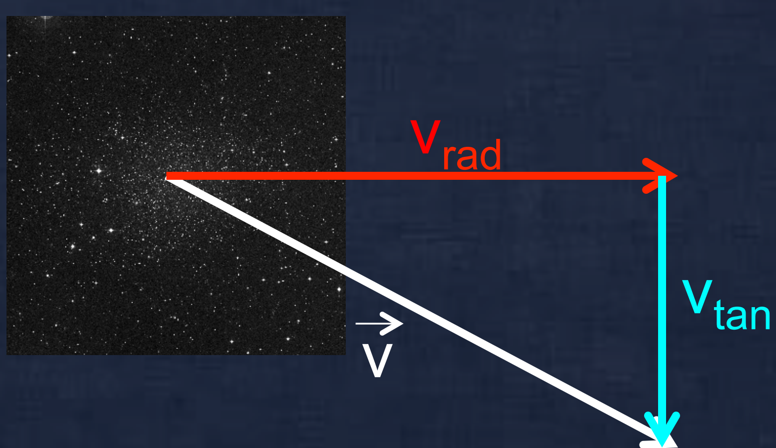


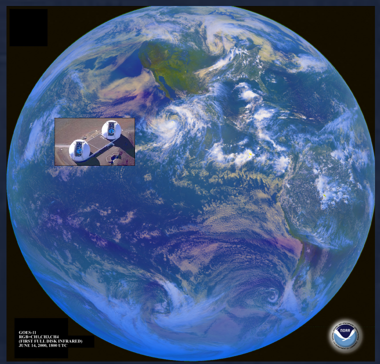
Formation and Evolution of Dwarfs

- Key unknown: What are the orbital histories of the Milky Way's satellites?
  - Have they suffered significant tidal stripping?
  - Do the properties of faint dwarfs vary with environment?
  - Why and how did star formation end in these systems?

3D Kinematics of Nearby Galaxies

- Radial velocities measured via spectroscopy
- Tangential velocities (proper motions) measured via astrometry



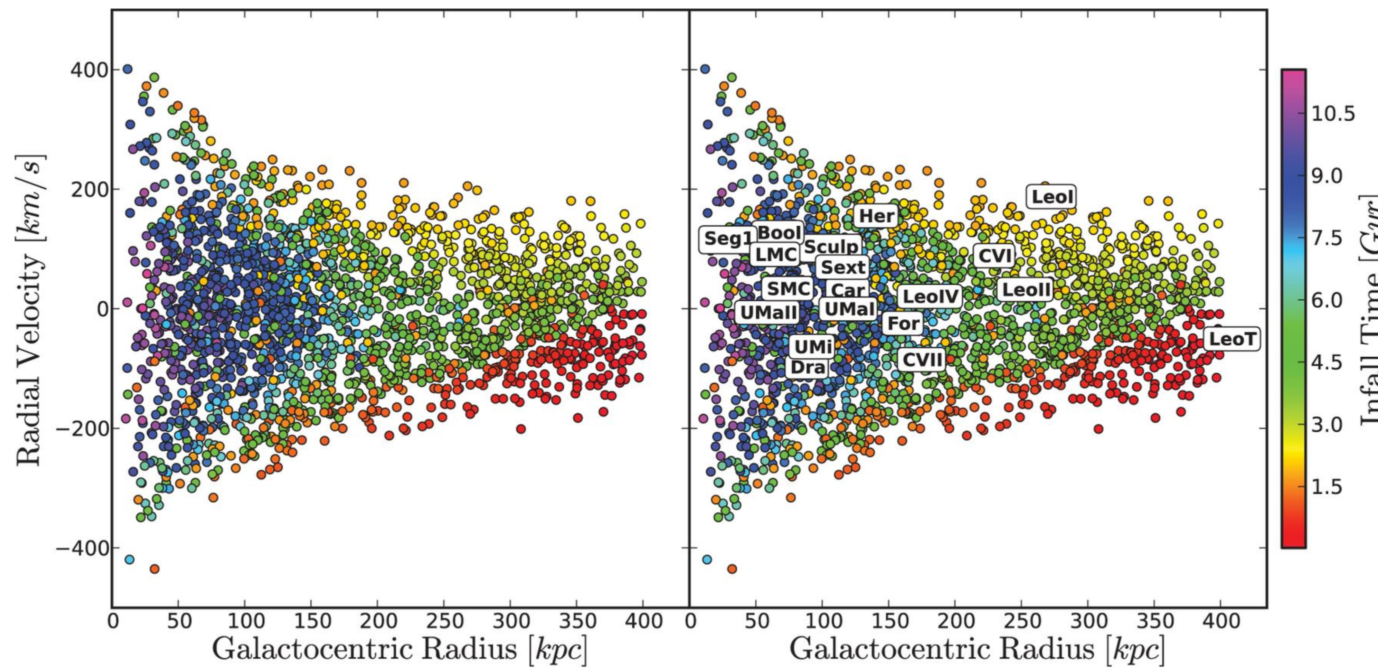


Existing Orbital Constraints

- Proper motions measured either with HST or from the ground
  - Fornax: $v_{tan} = (316 \pm 33, -237 \pm 26)$ km s^{-1}
    $r_{peri} = 114^{+20}_{-35}$ kpc (Piatek et al. 2007)
    $v_{tan} = (422 \pm 53, -7 \pm 72)$ km s^{-1}
    $r_{peri} = 140^{+3}_{-3}$ kpc (Mendez et al. 2010)
  - Draco: $v_{tan} = (-109 \pm 19, -113 \pm 16)$ km s^{-1}
    $r_{peri} = 18^{+6}_{-5}$ kpc (Dinescu et al. 2016)
    $v_{tan} = (-7 \pm 23, -109 \pm 23)$ km s^{-1}
    $r_{peri} = 33^{+10}_{-8}$ kpc (Pryor et al. 2015)

Existing Orbital Constraints

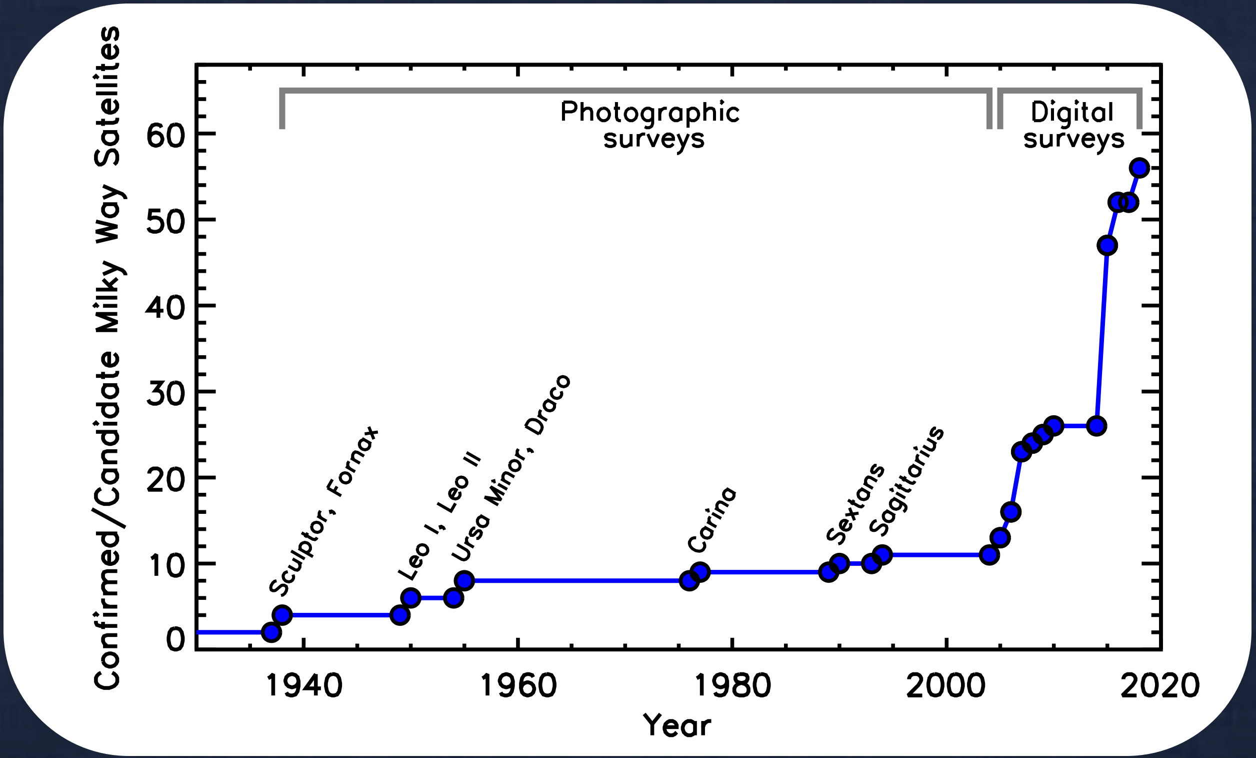
- RVs alone can be used to estimate infall times



Rocha et al. (2012)

An Explosion of Ultra-Faint Dwarfs

- 30 new satellites reported in the last 4 years! >100% increase in # of MW dwarfs

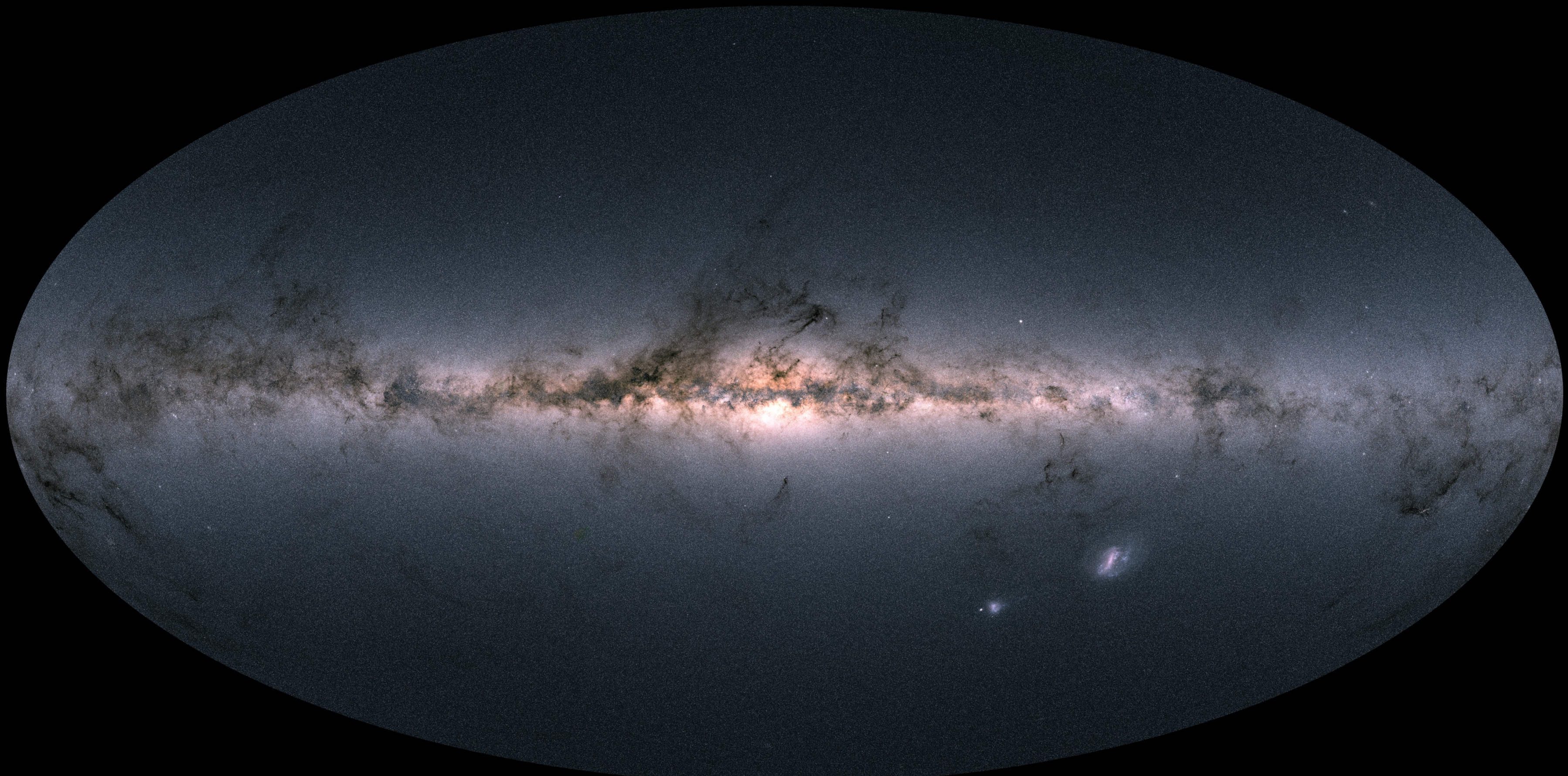


Simon (2019)

Are Ultra-Faint Dwarfs Being Tidally Disrupted?

- Irregular outer structure: Ursa Major II, Leo V, Unusual ellipticities: Hercules, Ursa Major I, Ursa Major II
- Possible tidal tails: Segue 1, Tucana III
- Possible extratidal structure: Hercules, Bootes I
- Kinematic peculiarities: Hercules, Willman 1
- Velocity gradients: Hercules, Leo V
- High metallicity: Coma Berenices, Segue 2, Leo V, Bootes II

The Gaia Revolution



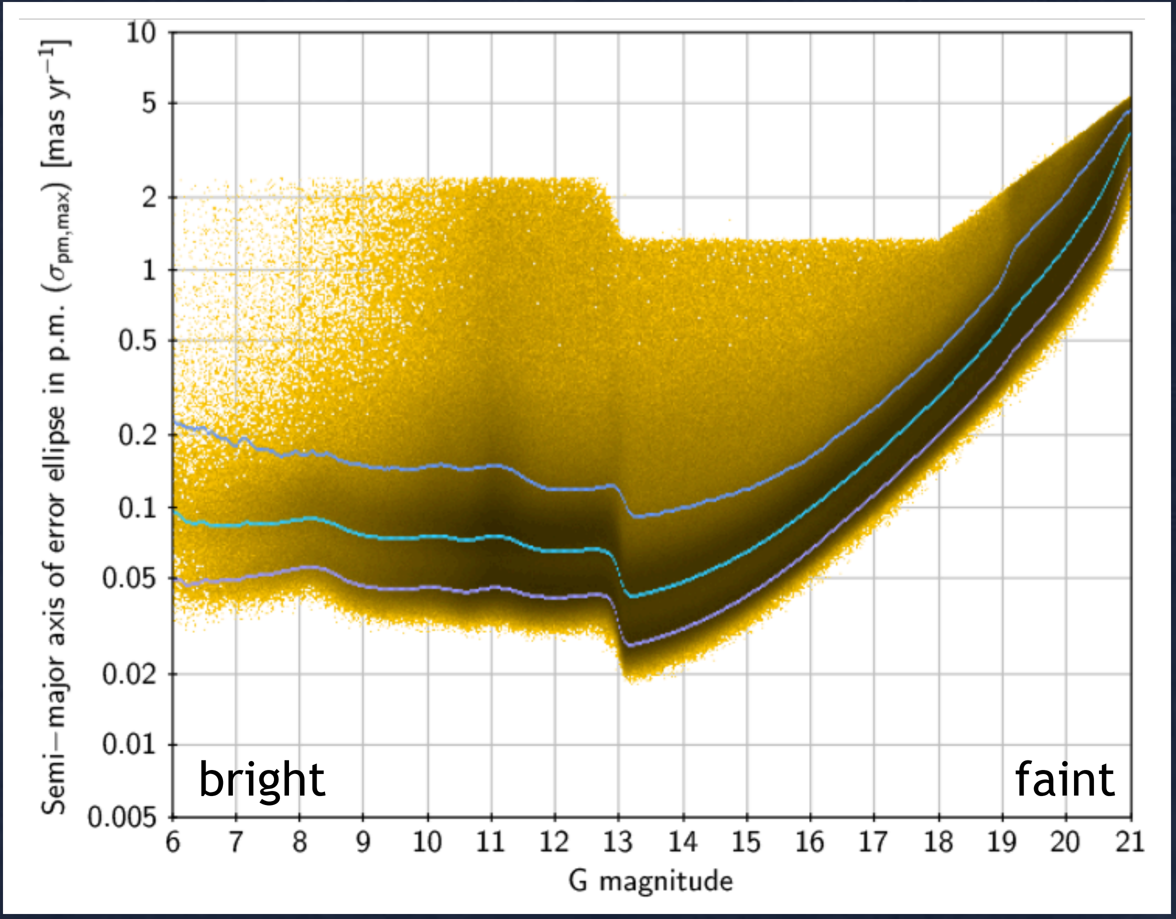
Gaia collaboration, Brown et al. (2018)

Gaia Astrometric Accuracy

0.1 mas yr^{-1}

= 7.7 inches yr^{-1}

. . . on the Moon

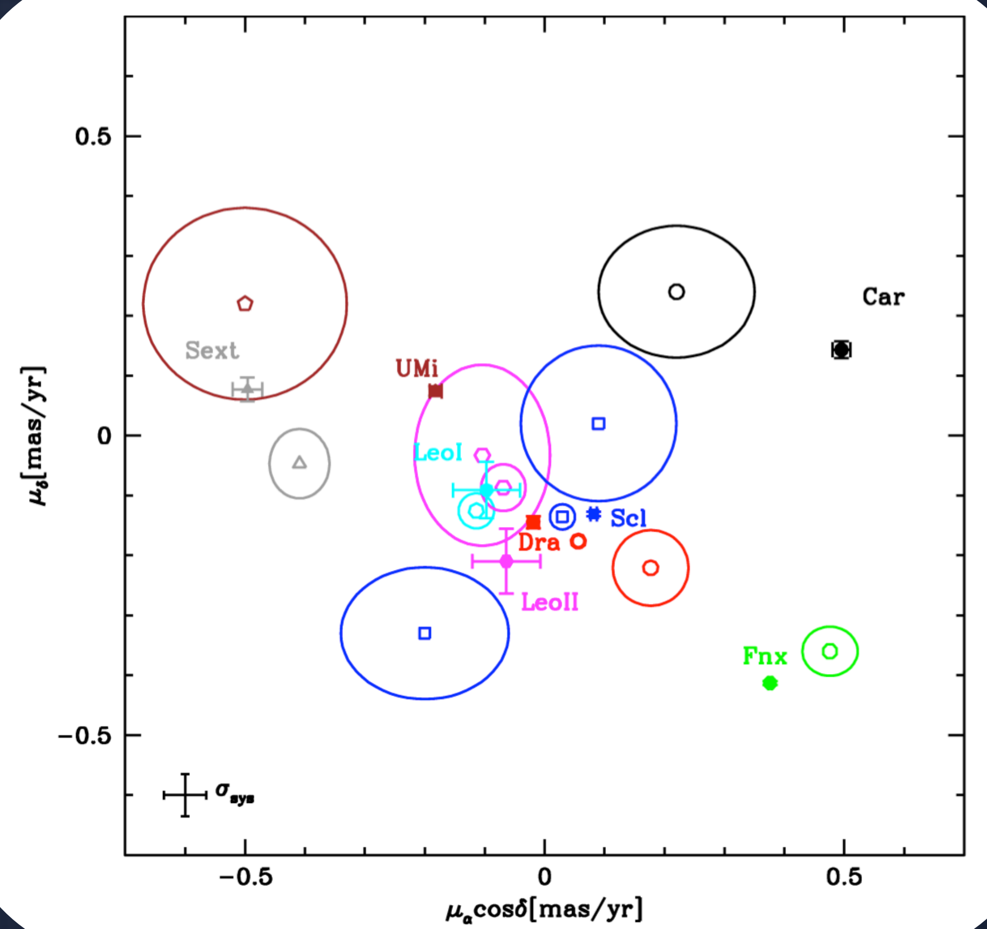


Lindegren et al. (2018)

Proper Motions of Dwarf Galaxies

- Brightest stars are ~18th magnitude
- Each dwarf galaxy star in Gaia has a PM uncertainty of ~0.2 mas yr^{-1}
- Typical uncertainties for HST PMs (hundreds of stars) are ~0.05 mas yr^{-1}

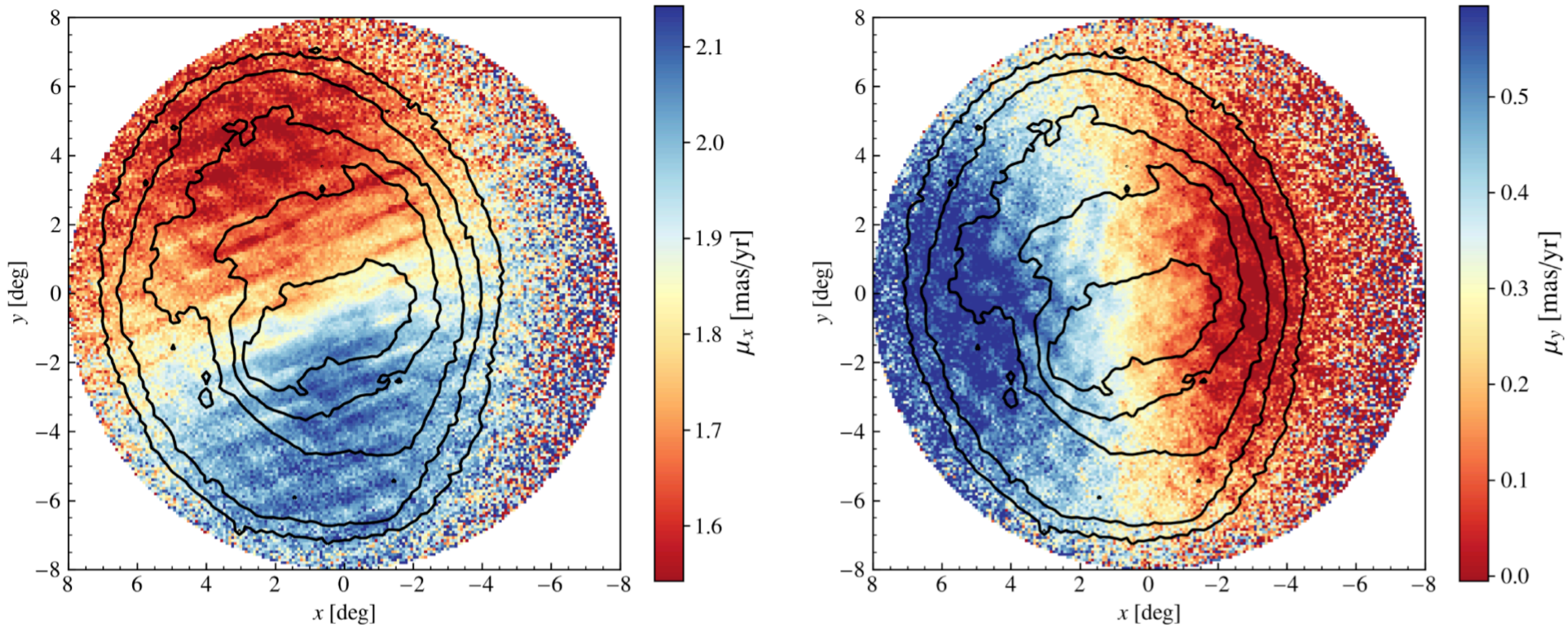
Gaia: Classical Dwarf Spheroidals



Gaia collaboration, Helmi et al. (2018)

Gaia: Large Magellanic Cloud

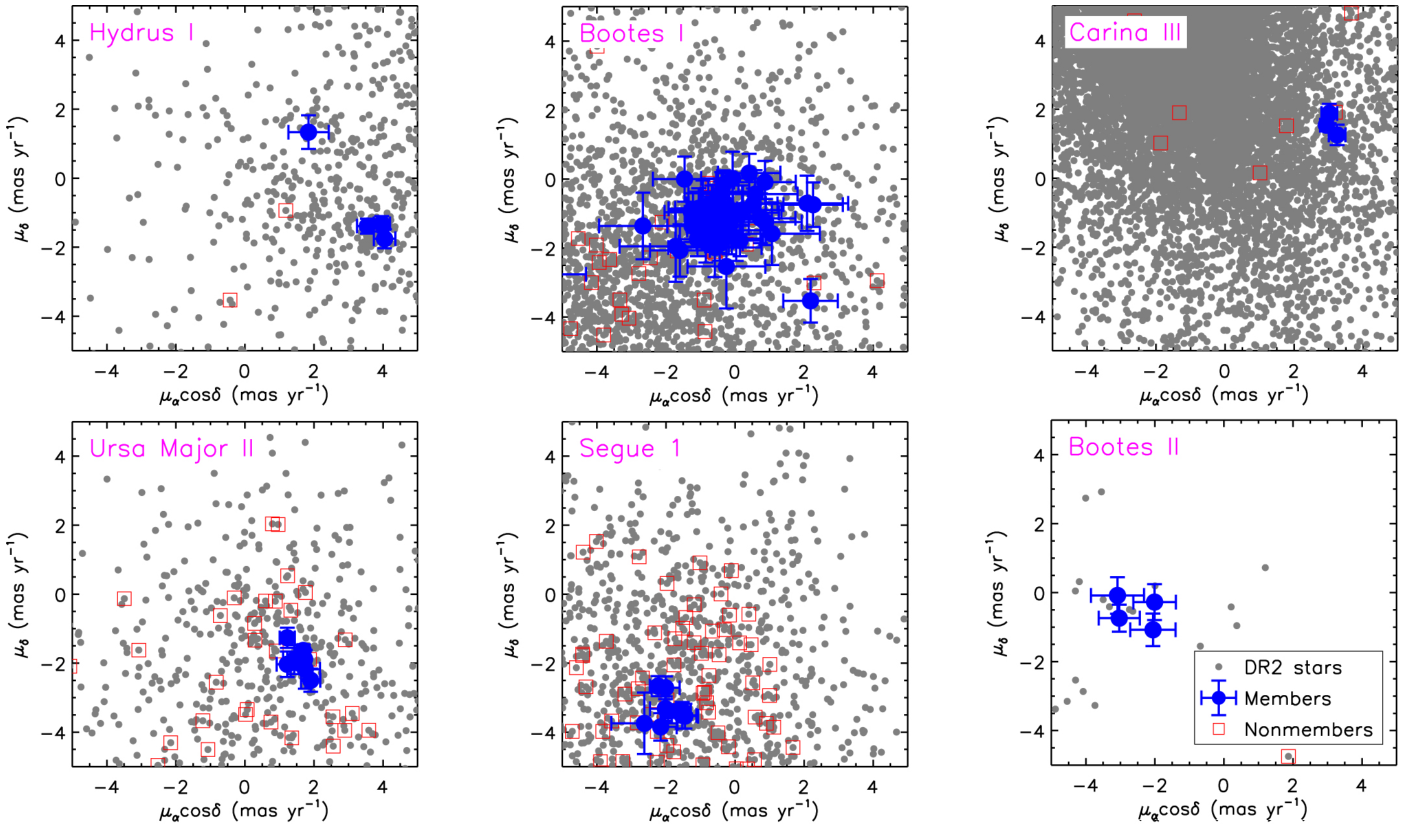
- Rotation of LMC is directly visible



Gaia collaboration, Helmi et al. (2018)

Gaia: Ultra-Faint Dwarfs

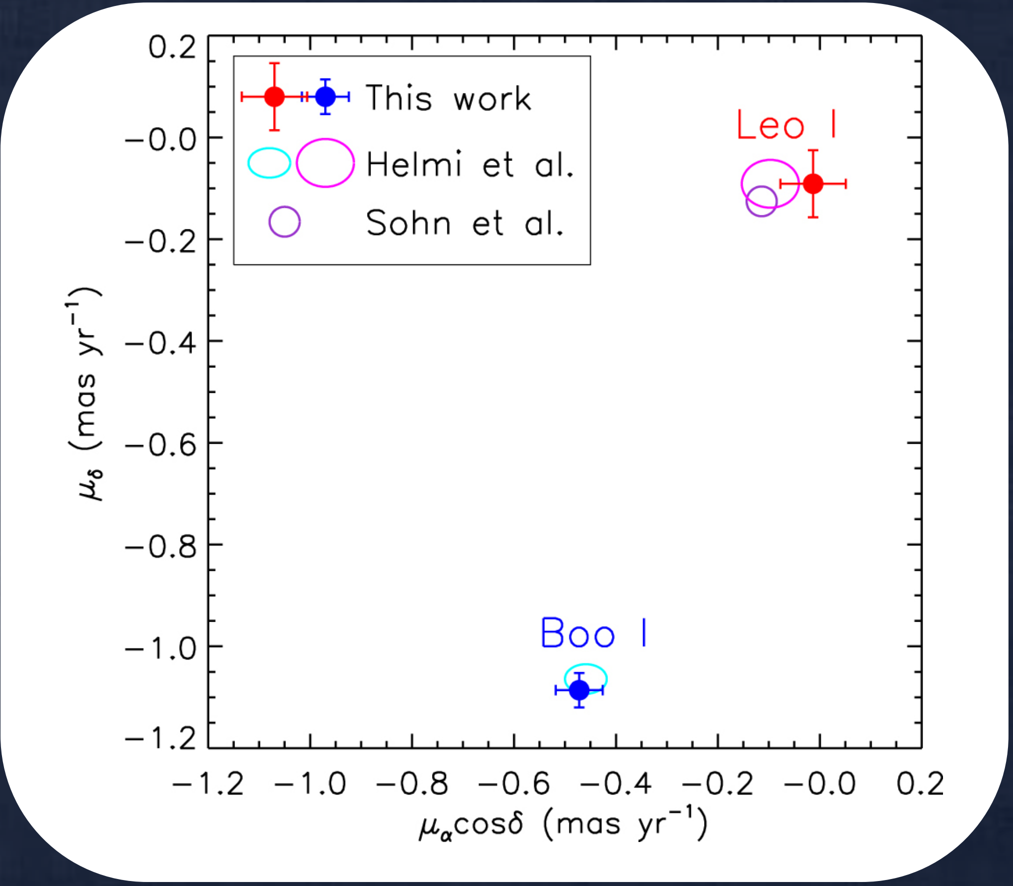
- Determining PMs with Gaia is trivial



Simon (2018)

Gaia: Ultra-Faint Dwarfs

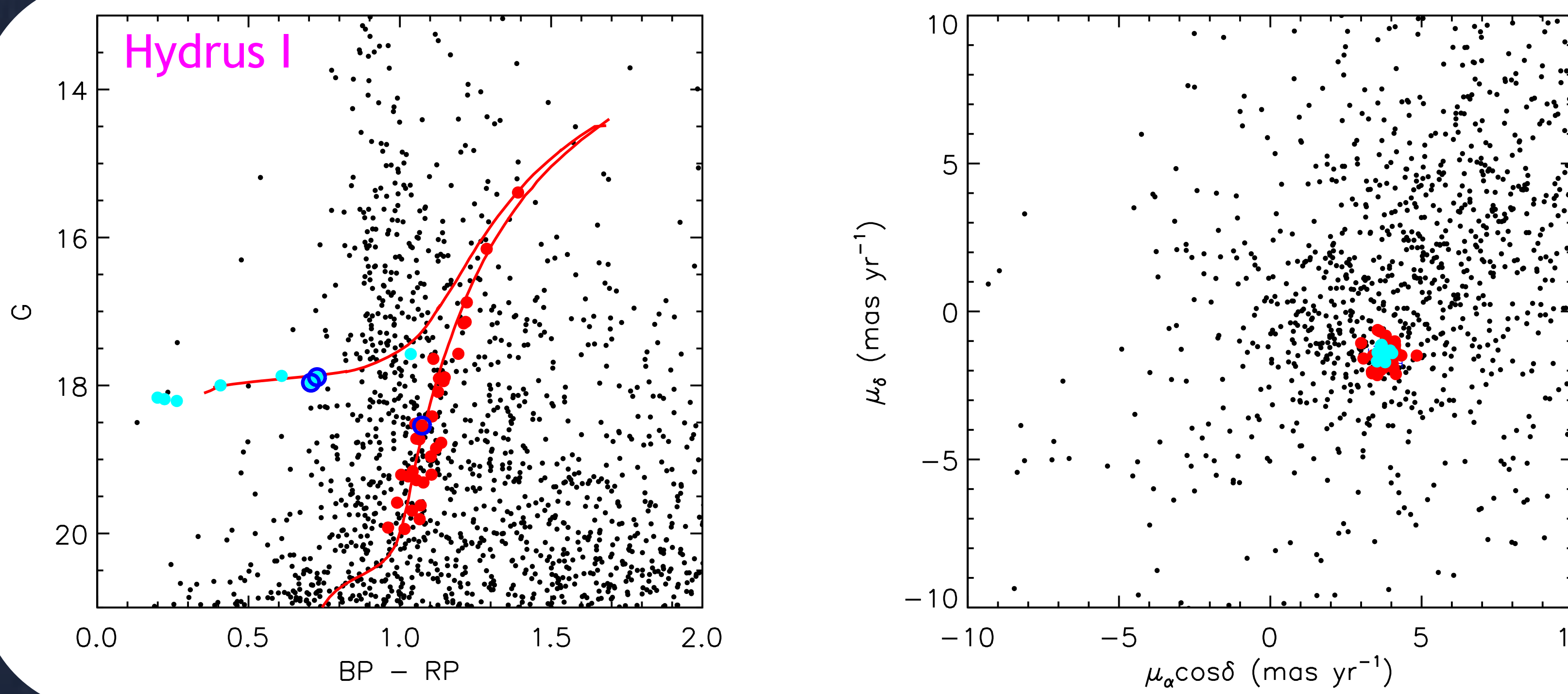
- Proper motions agree with literature



Simon (2018)

Finding Dwarf Galaxy Stars with Gaia

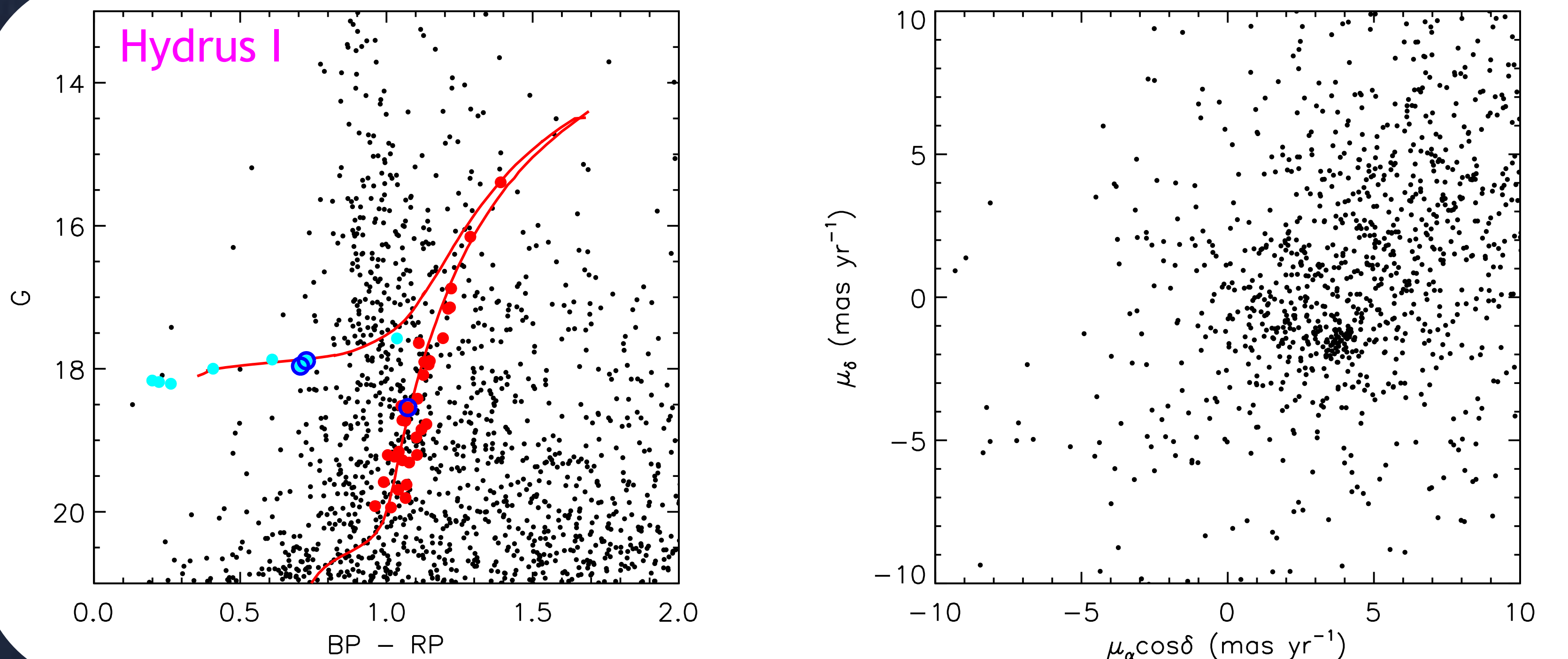
- Full member sample and systemic PM can be bootstrapped from 3 stars



Simon (2018)

Finding Dwarf Galaxy Stars with Gaia

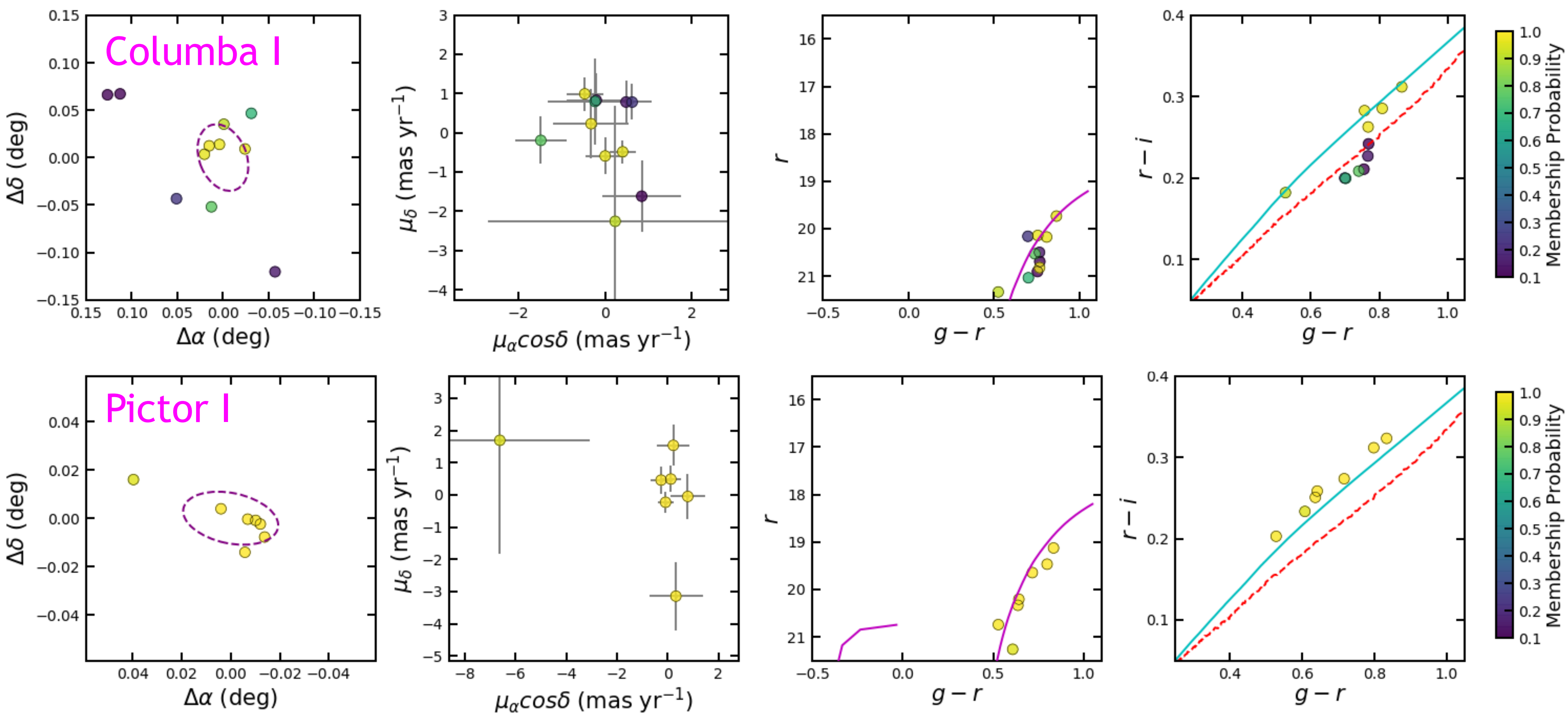
- Full member sample and systemic PM can be bootstrapped from 3 stars



Simon (2018)

Finding Dwarf Galaxy Stars with Gaia

- Can be done even without spectroscopy!



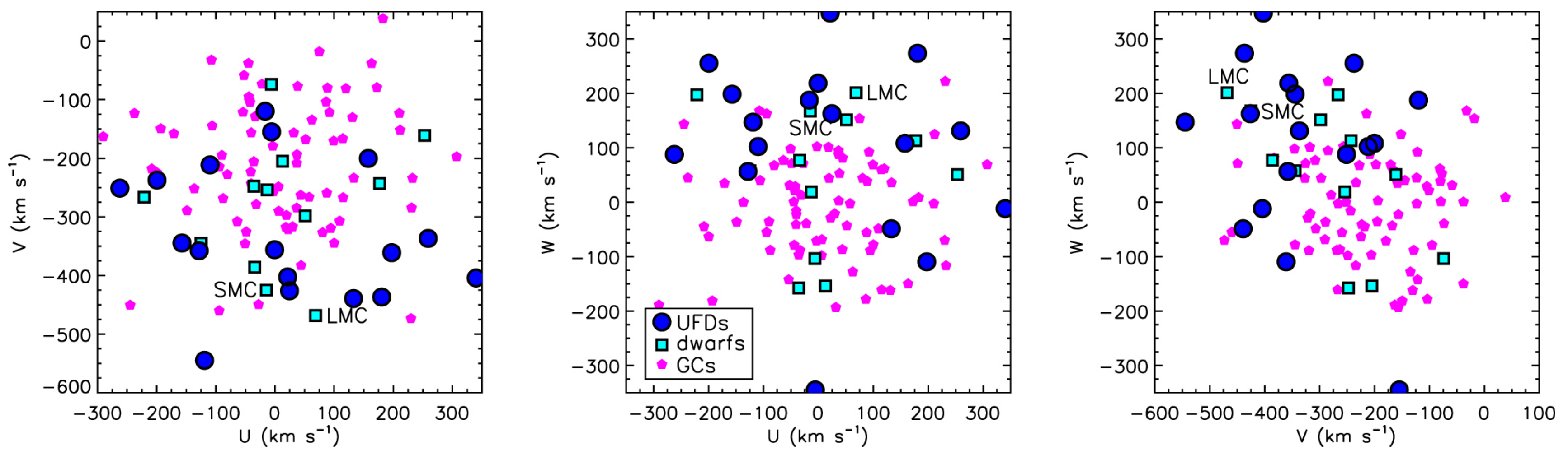
Pace & Li (2018)

Radial Velocities Are Now the Limiting Factor!

- 44 Milky Way satellites (31 ultra-faints) have published radial velocities
- 46 (33 UFDs) have published proper motions

3D Velocities

- Combining proper motions with previously known positions, radial velocities, and distances yields 3D velocities

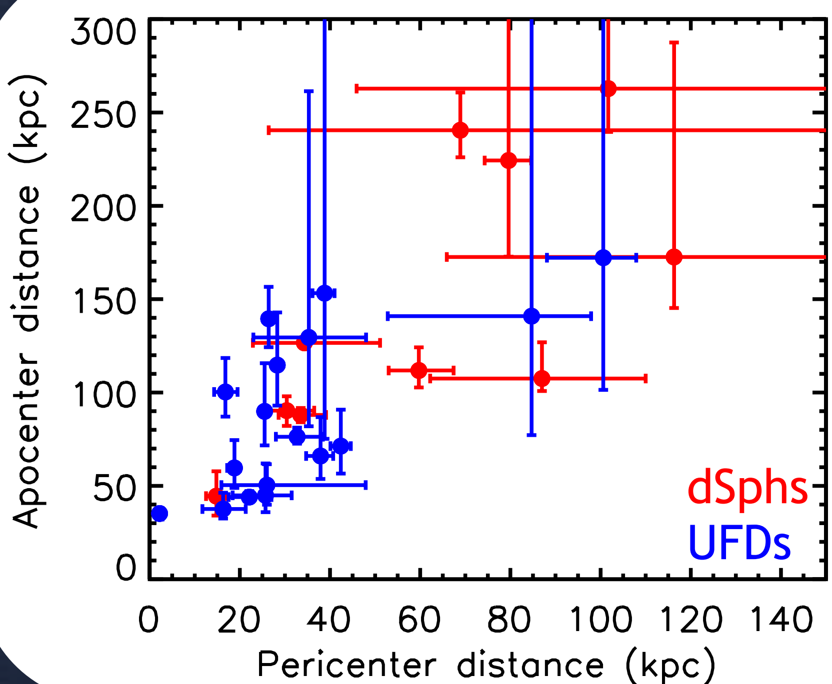


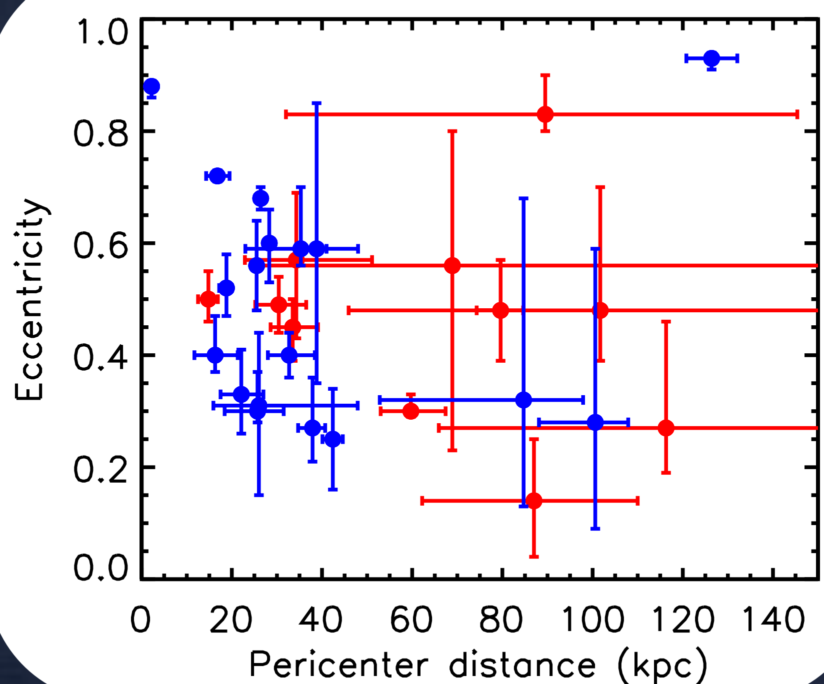
U: toward Galactic anticenter, V: along Galactic rotation, W: toward Galactic north pole

Simon (2018)

Orbital Parameters

- Similar orbits for ultra-faint & classical dwarfs





Helmi et al. (2018); Simon (2018)

Surprising Results

- Tangential velocities of dwarf galaxies are very high
  - Median 3D velocity is 395 km s^{-1}
  - 5 dwarfs at v_{3D} > 500 km s^{-1}

Suggests a more massive Milky Way

Simon (2018)

Surprising Results

- Nearly all ultra-faint dwarfs are currently at their orbital pericenters
  - 13 out of 17 are within 120 Myr of closest approach to Milky Way

Suggests large selection biases against discovering distant dwarfs

Simon (2018)

Not Surprising Results

- Almost no dwarfs have pericenters of less than 15-20 kpc

Suggests tidal disruption of objects on more extreme orbits (e.g., Garrison-Kimmel et al. 2017)

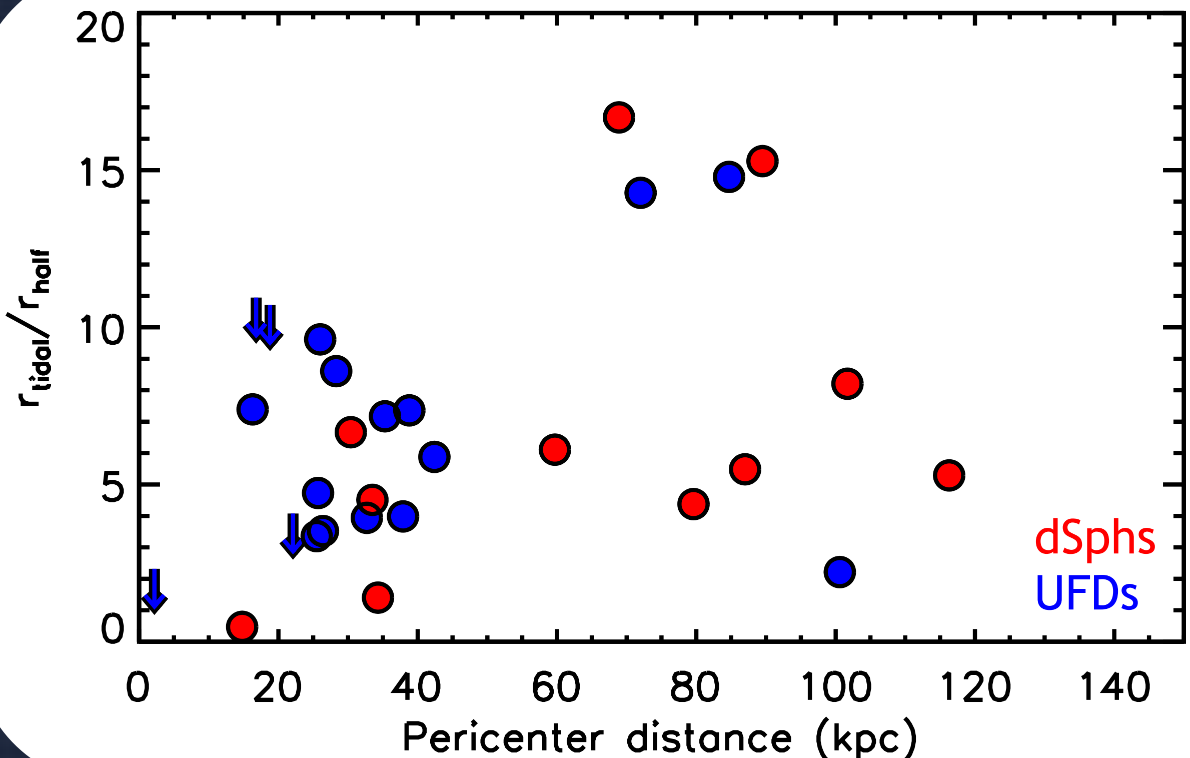
Simon (2018)

Tidal Stripping of MW Satellites

$$r_{tidal} = \left(\frac{m}{3M_{MW}}\right)^{1/3} d$$

- Assume total mass = measured mass within the half-light radius
- If $r_{tidal}/r_{half} < 3$ then >10% of the stars are vulnerable to being stripped

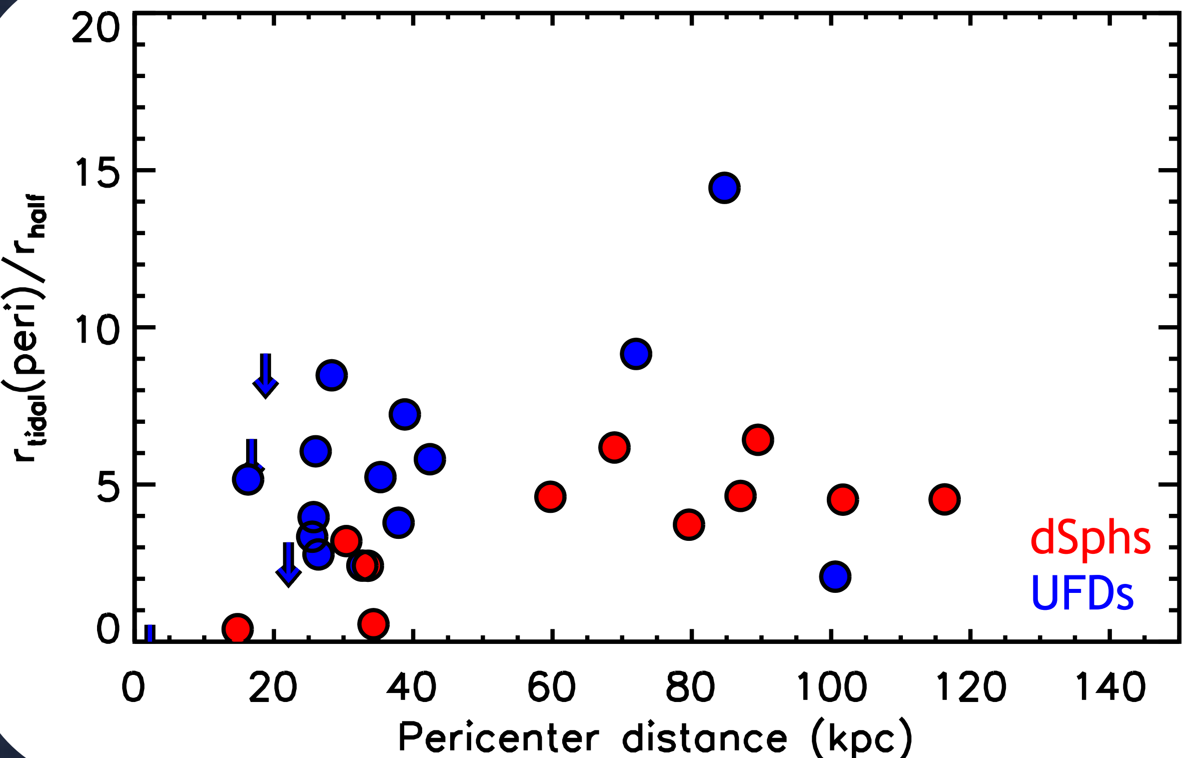
Tidal Stripping of MW satellites



Possibly stripped dwarfs: Tuc III, Sgr, Cra II, UMa I

Simon (2019)

Tidal Stripping of MW Satellites

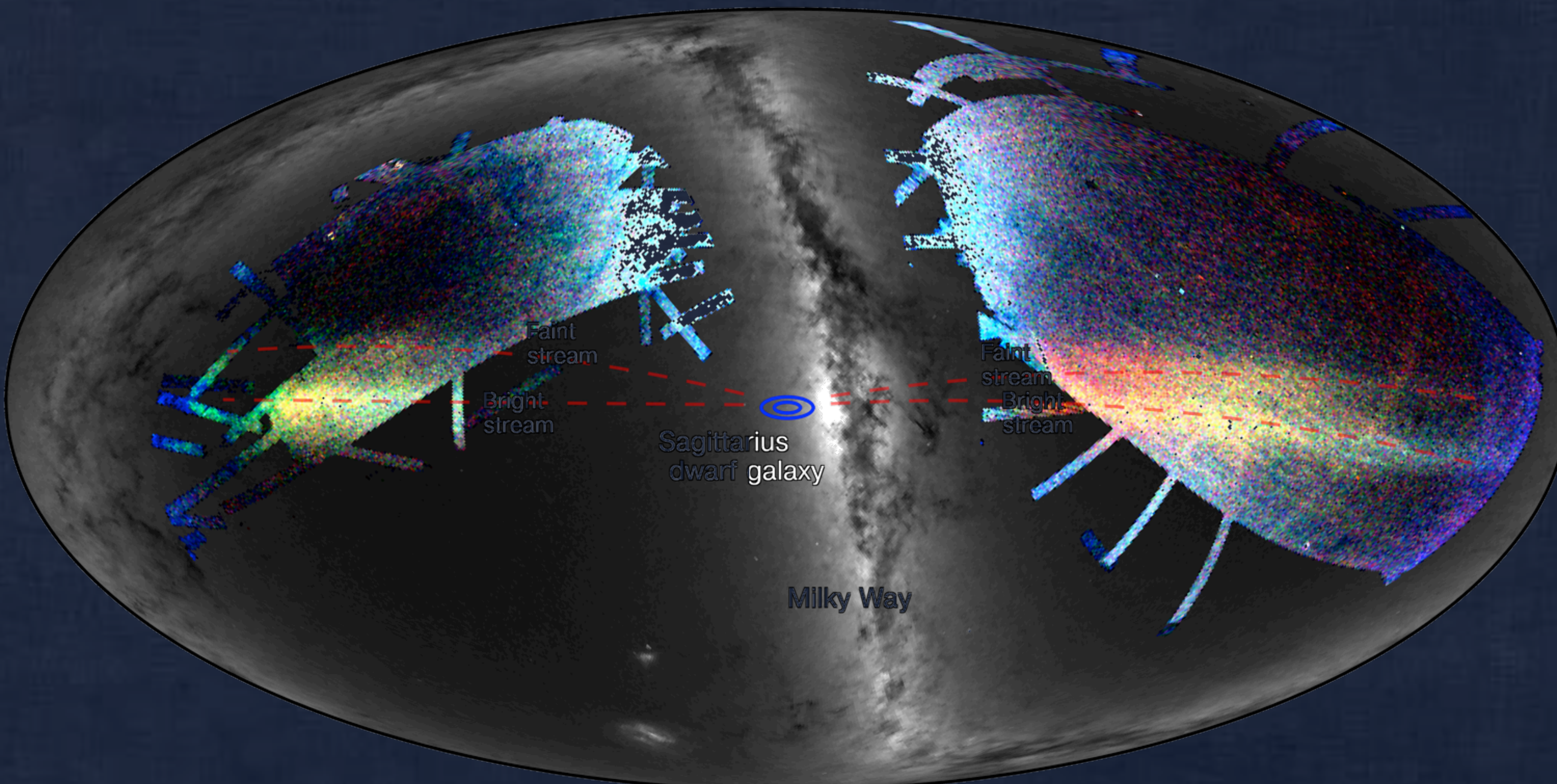


Possibly stripped dwarfs: Tuc III, Sgr, Cra II, UMa I

Simon (2019)

Tidal Stripping of Sagittarius

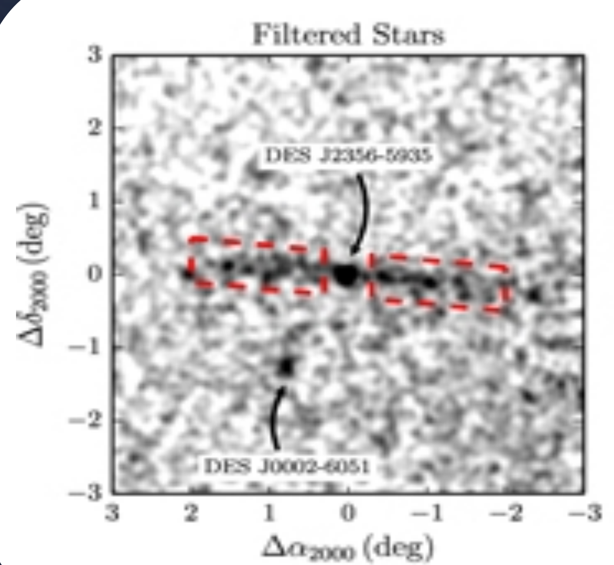
- Tidal tails spanning the entire sky

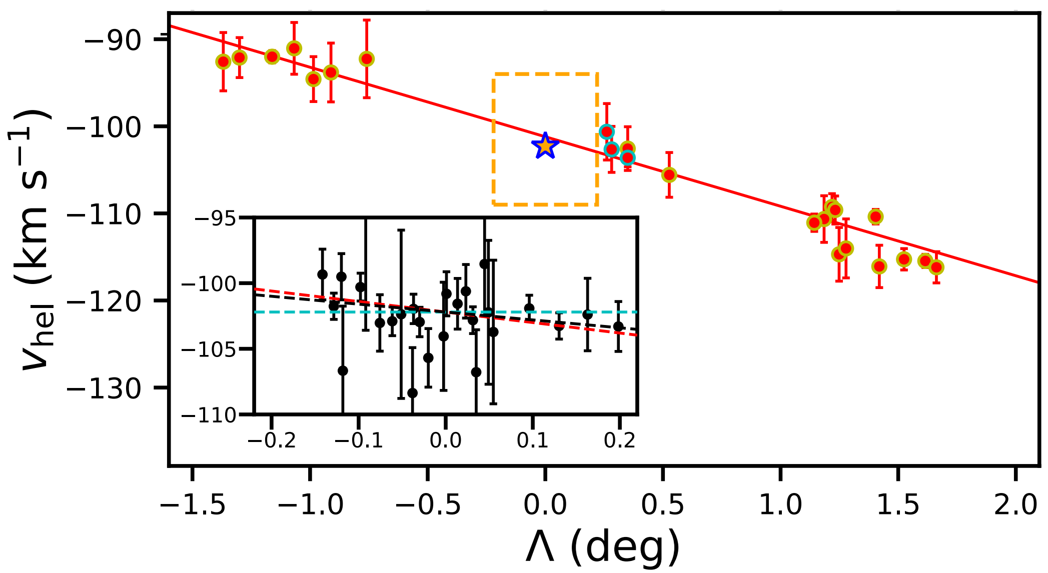


Koposov et al. (2018)

Tidal Stripping of Tucana III

- Tidal tails extending 2.4° away from dwarf, with a strong velocity gradient



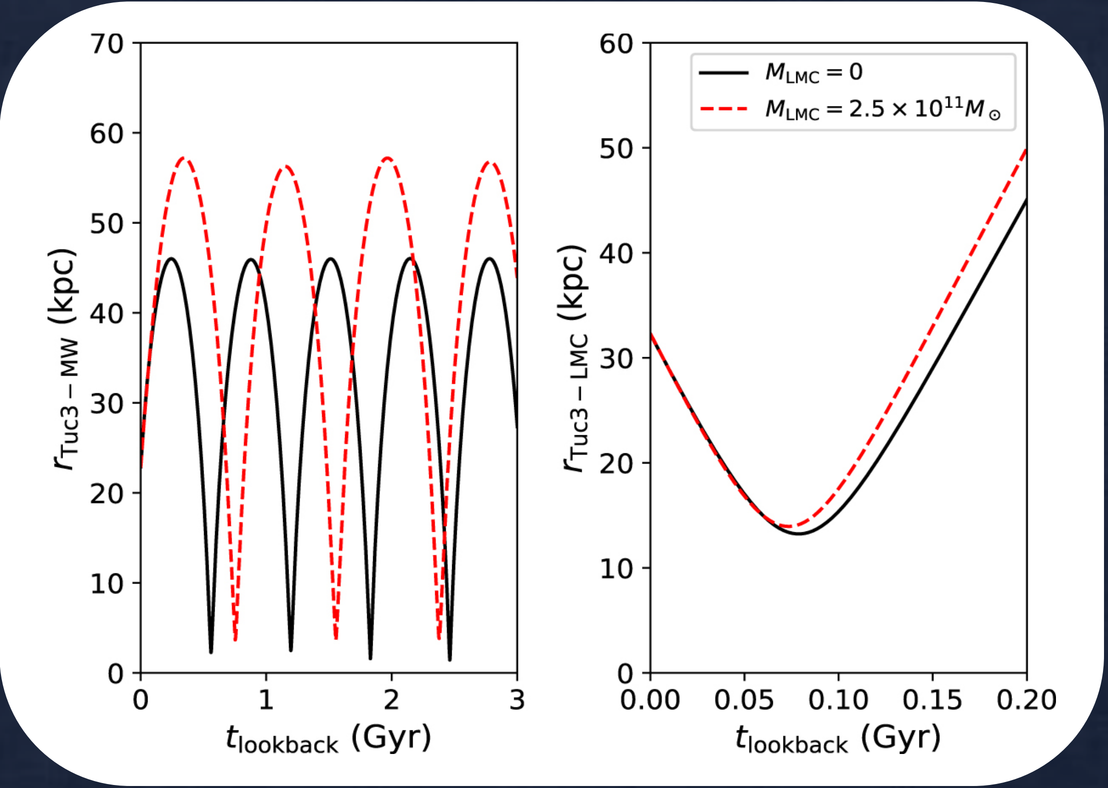


Drlica-Wagner et al. (2015)

Li et al. (2018)

Tidal Stripping of Tucana III

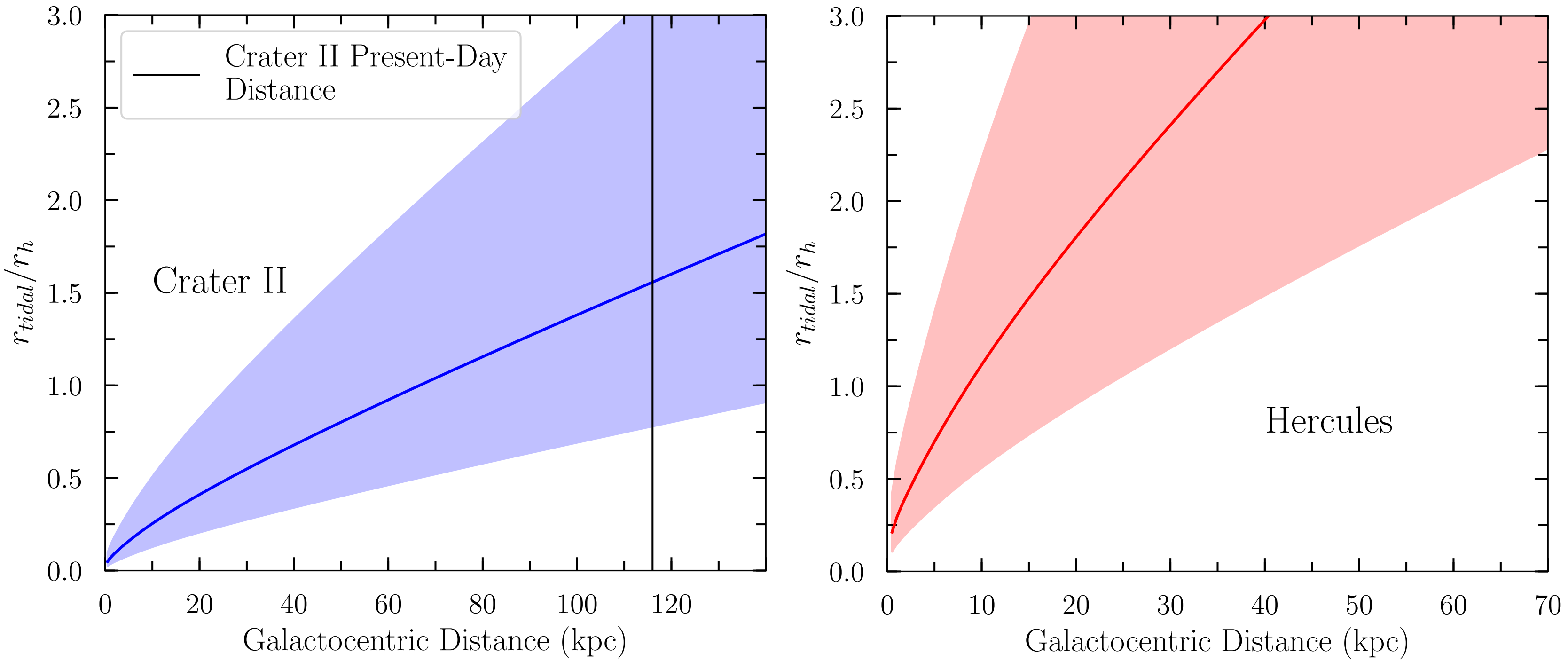
- Tuc III was also recently deflected by the LMC



Erkal et al. (2018)

Tidal Stripping of Crater II & Hercules

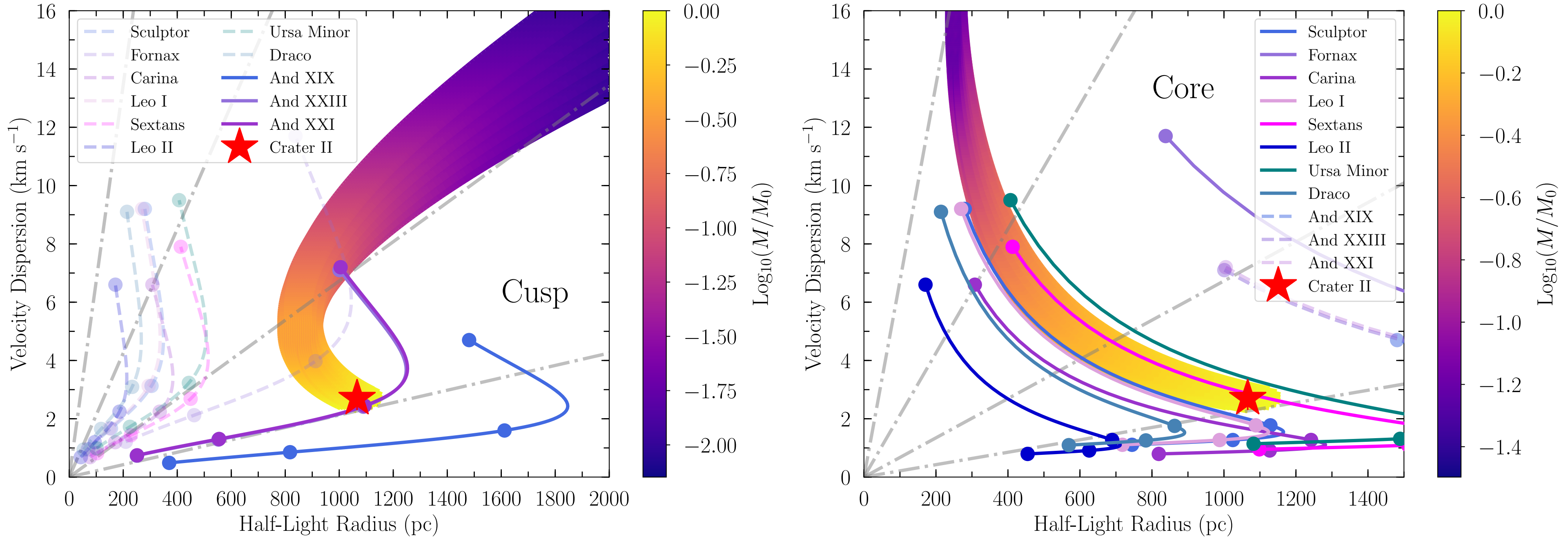
- Cra II definitely vulnerable to stripping



Fu et al. (2019)

Tidal Stripping of Crater II

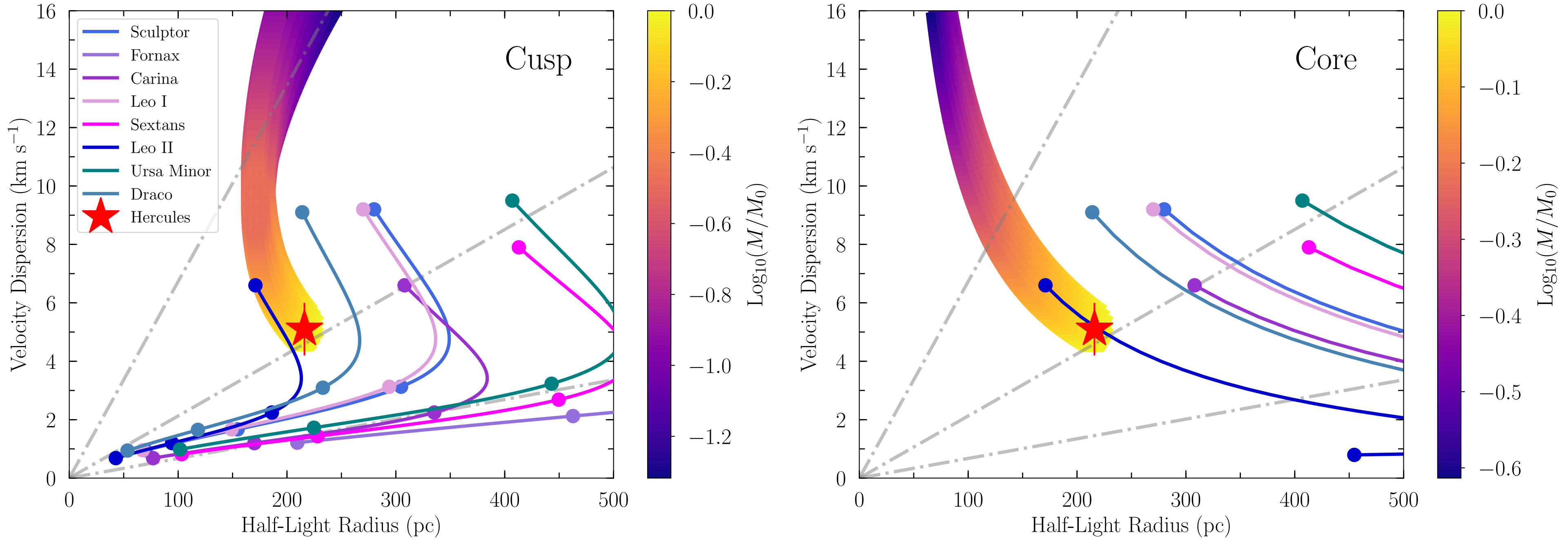
- Comparison to Penarrubia et al. (2008) tidal evolution tracks



Fu et al. (2019)

Tidal Stripping of Hercules

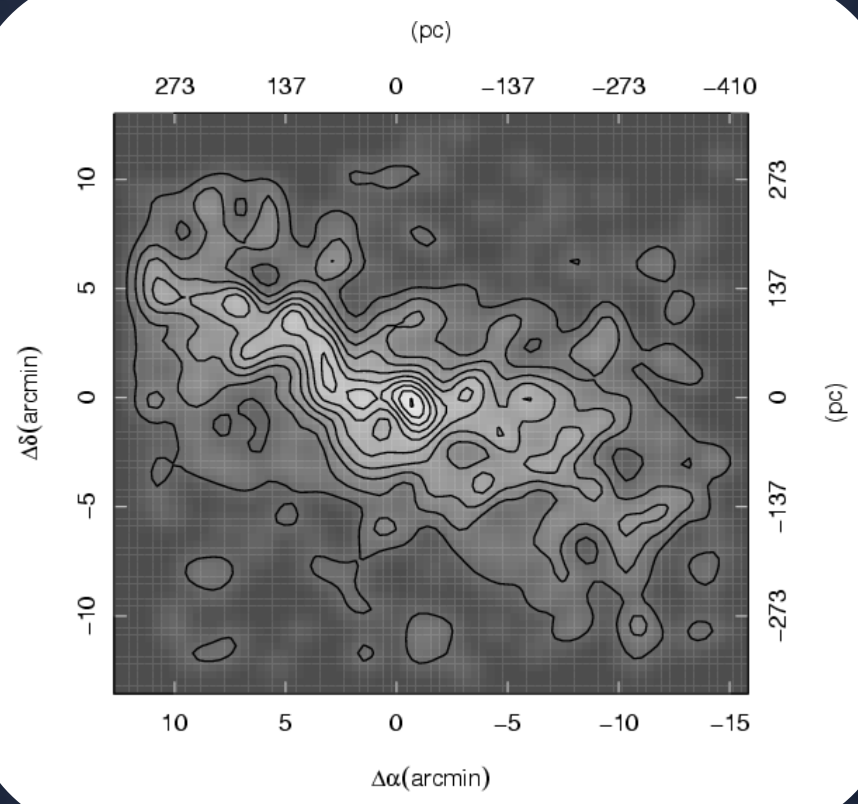
- Widely assumed to be stripped because of extreme shape (e=0.69)



Fu et al. (2019)

Tidal Stripping of Ursa Major I?

- No strong evidence previously



Okamoto et al. (2008)

Summary

- Gaia provides ultra-faint dwarf galaxy proper motions for the first time
  - Nearby dwarfs are moving at very high velocities and are mostly near orbital pericenter
- 3D kinematics enable calculations of which dwarfs are tidally interacting
  - Only a minority likely to have been stripped: Sgr, Tuc III, Cra II, possibly Hercules and UMa I, conceivably Hyi I, Boo I, and Segue 2