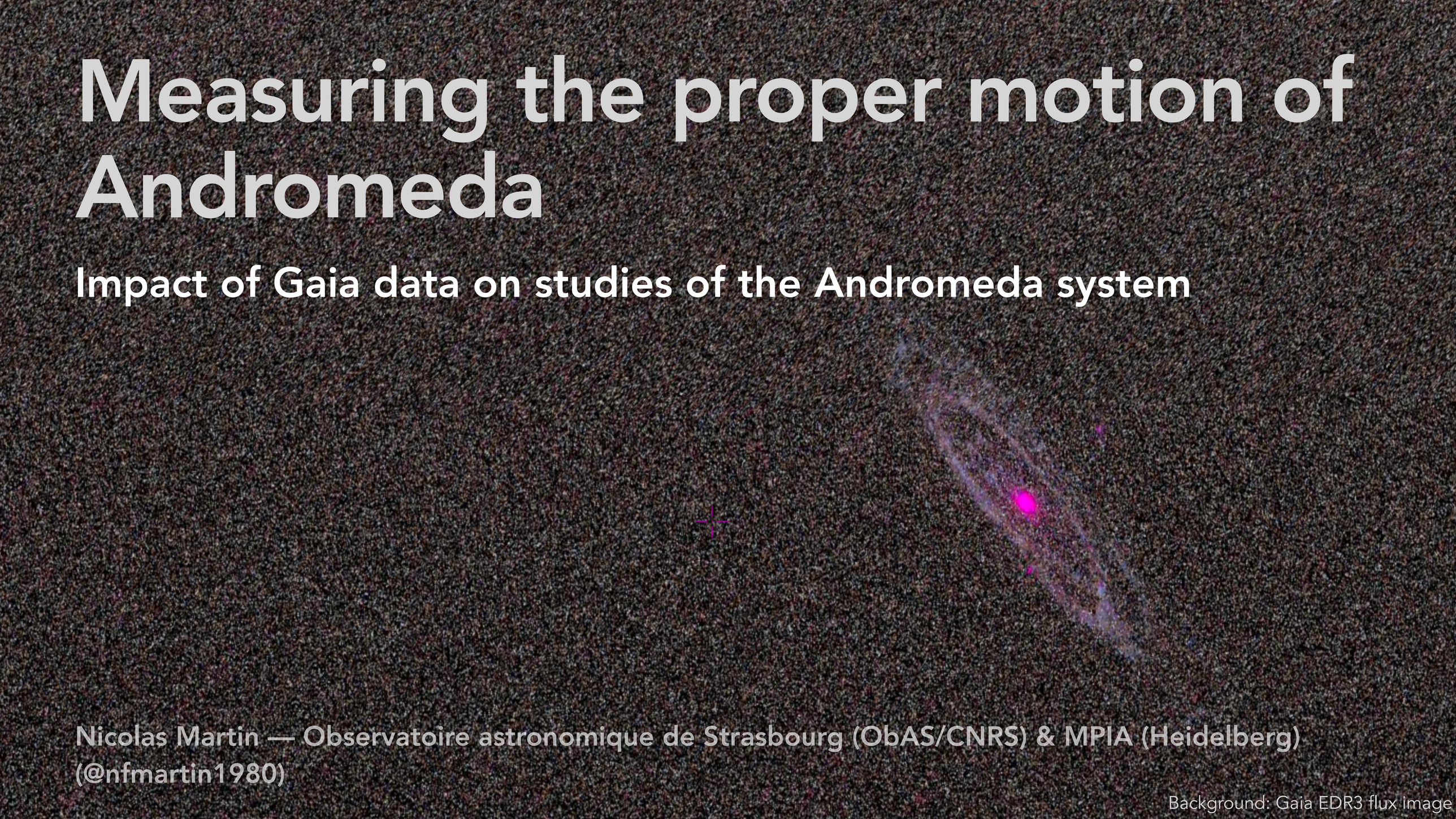
# Measuring the proper motion of Andromeda

## Impact of Gaia data on studies of the Andromeda system



Nicolas Martin — Observatoire astronomique de Strasbourg (ObAS/CNRS) & MPIA (Heidelberg)
(@nfmartin1980)

Background: Gaia EDR3 flux image

# Why measure the proper motion of Andromeda?

- The satisfaction of knowing how we are moving wrt our closest large neighbor and sister inhabitant of the Local Group

- Inferring how the past and future of the Local Group → if large tangential motion, a Local Fly-By instead of a Local Group. Refine measurements of the mass of the Local Group

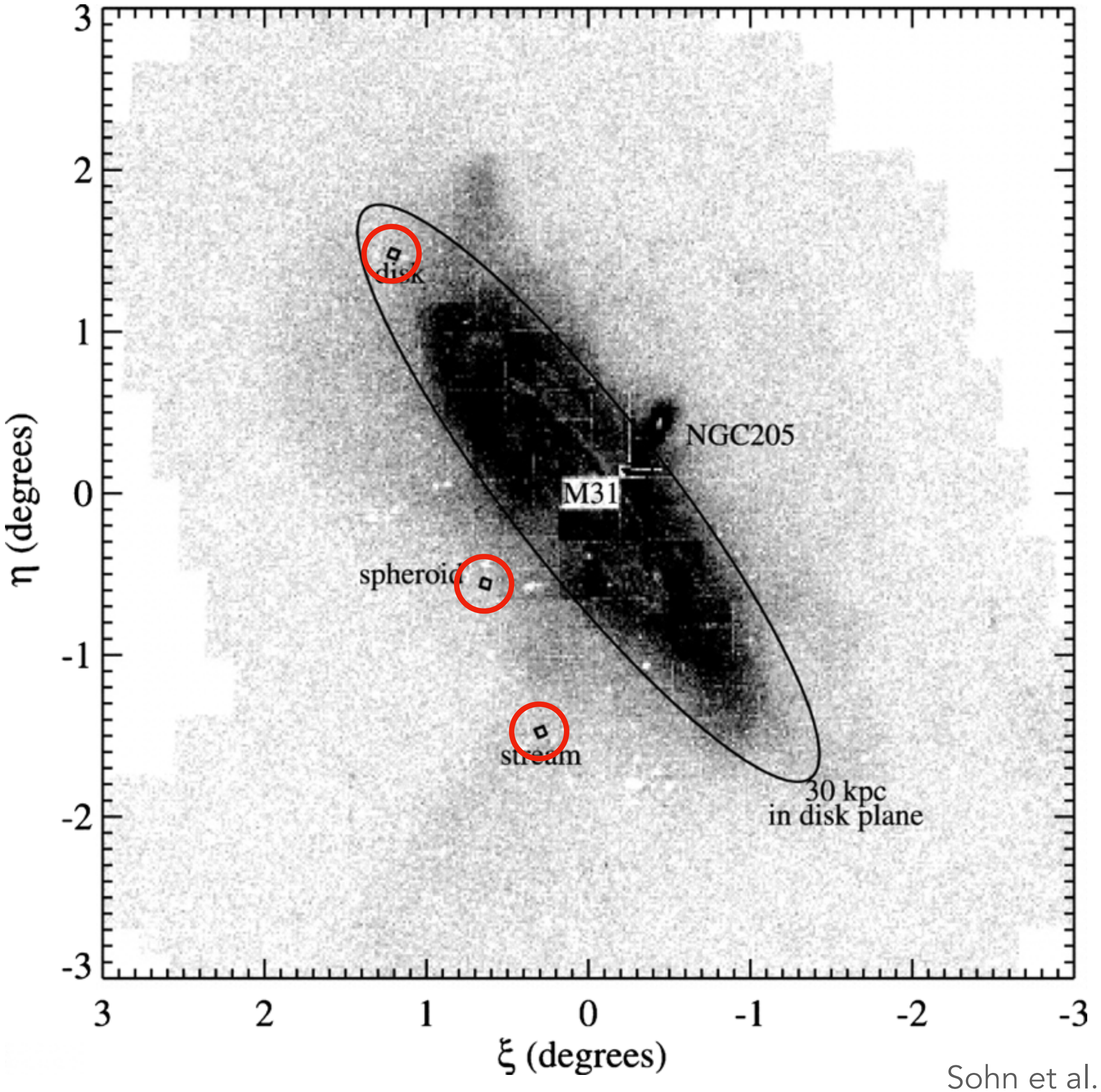
- Proper motion impossible to measure without strong (dynamical) assumptions until recently

- A lot of wonderful work to get a direct measurement/inference over the last 10-15 years but ***it's very hard*!**

- ***But*** 10 μas/yr ~ 40 km/s at the distance of M31 (~800 kpc)

# Measurements with HST

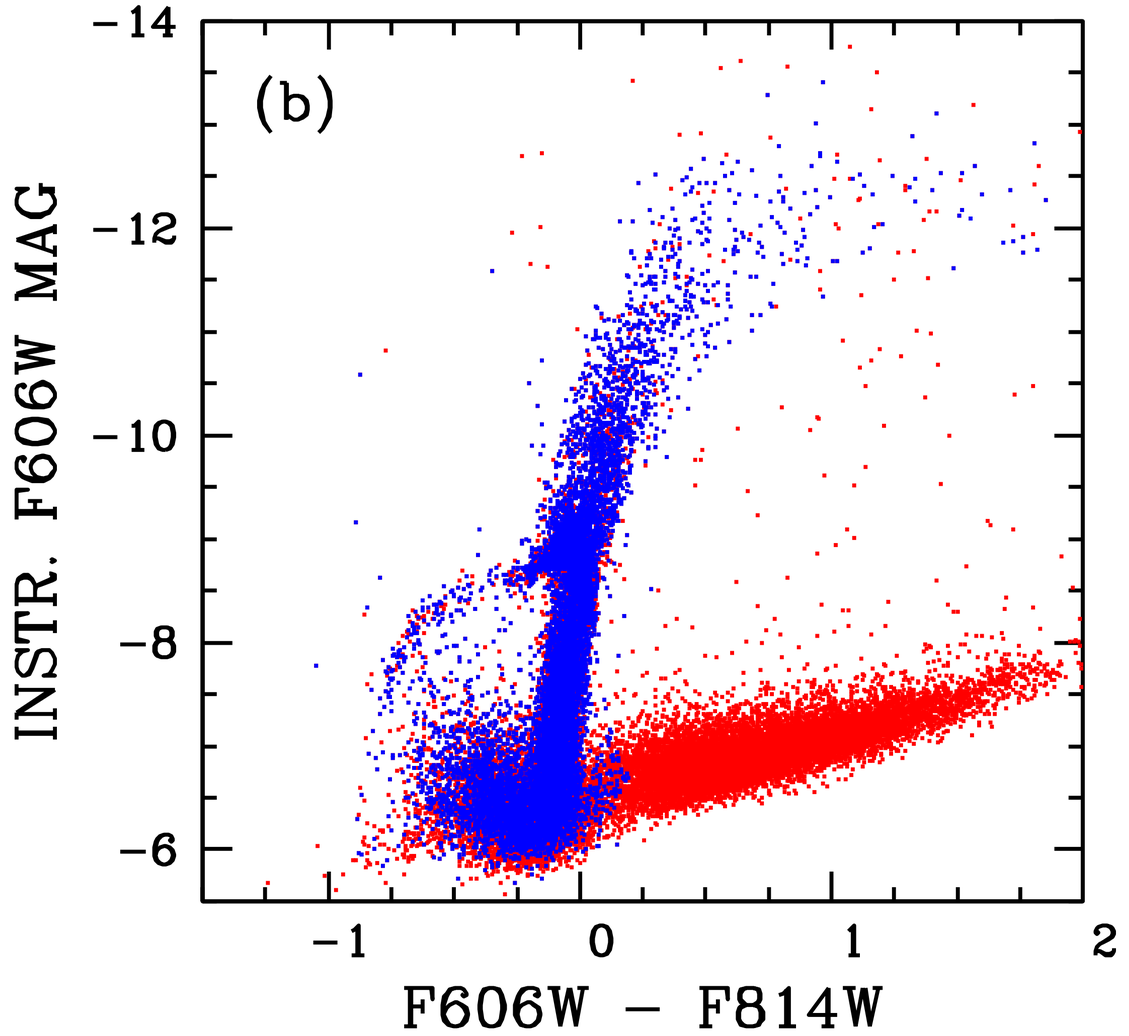
- Using previous deep photometry in 3 HST fields of the M31 outskirts
- Using thousands of (faint) stars
- 5–7 yr baseline
- Ideally would use QSOs for reference ***but*** not enough in ACS/WFC3 fields…
- Use galaxy centers for reference frame ***but*** they are extended…




Sohn et al. (2012)

# Measurements with HST

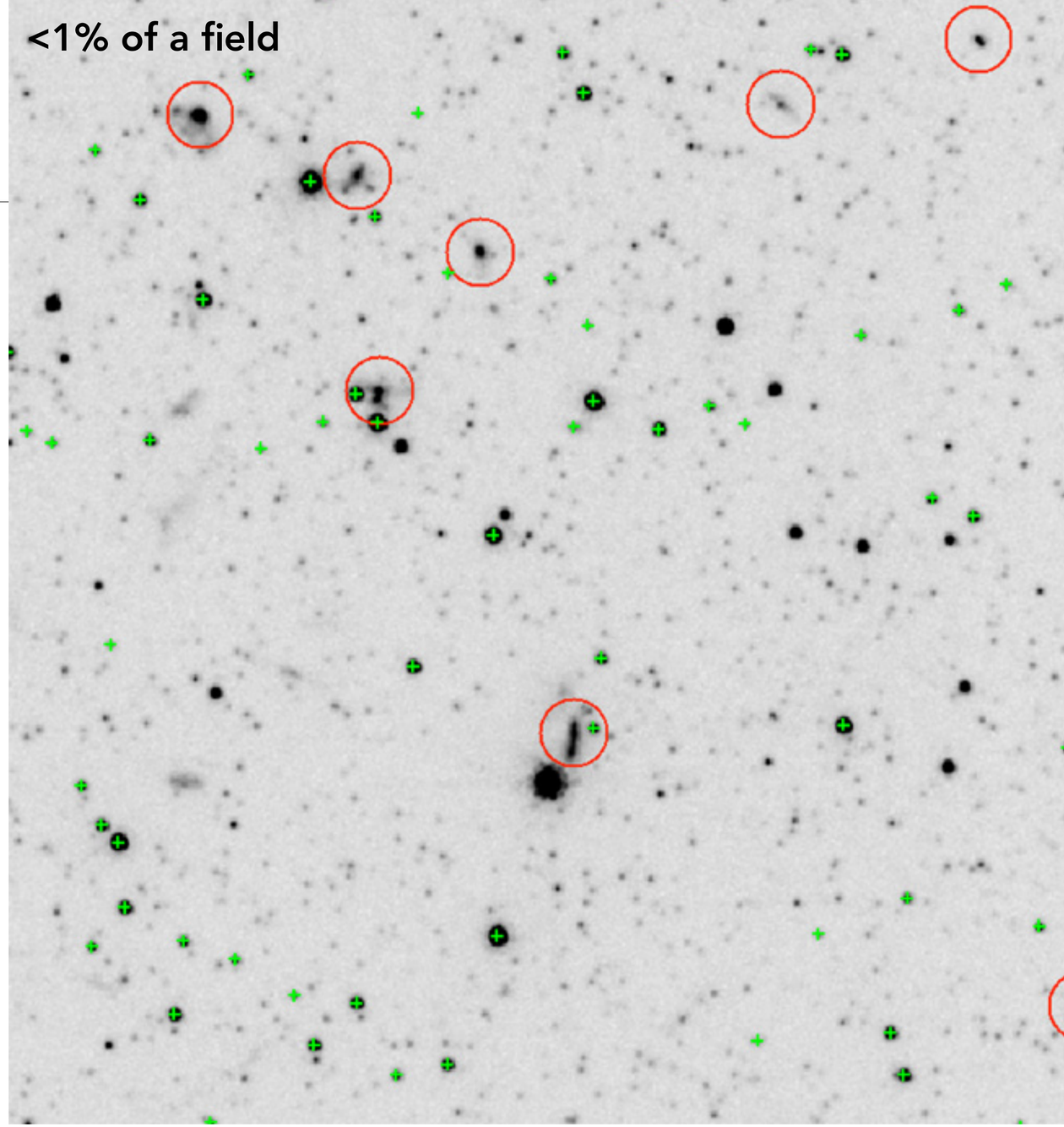
- Using previous deep photometry in 3 HST fields of the M31 outskirts
- Using thousands of (faint) stars
- 5–7 yr baseline
- Ideally would use QSOs for reference ***but*** not enough in ACS/WFC3 fields…
- Use galaxy centers for reference frame ***but*** they are extended…




Sohn et al. (2012)

# Measurements with HST

- Using previous deep photometry in 3 HST fields of the M31 outskirts
- Using thousands of (faint) stars
- 5–7 yr baseline
- Ideally would use QSOs for reference ***but*** not enough in ACS/WFC3 fields…
- Use galaxy centers for reference frame ***but*** they are extended…

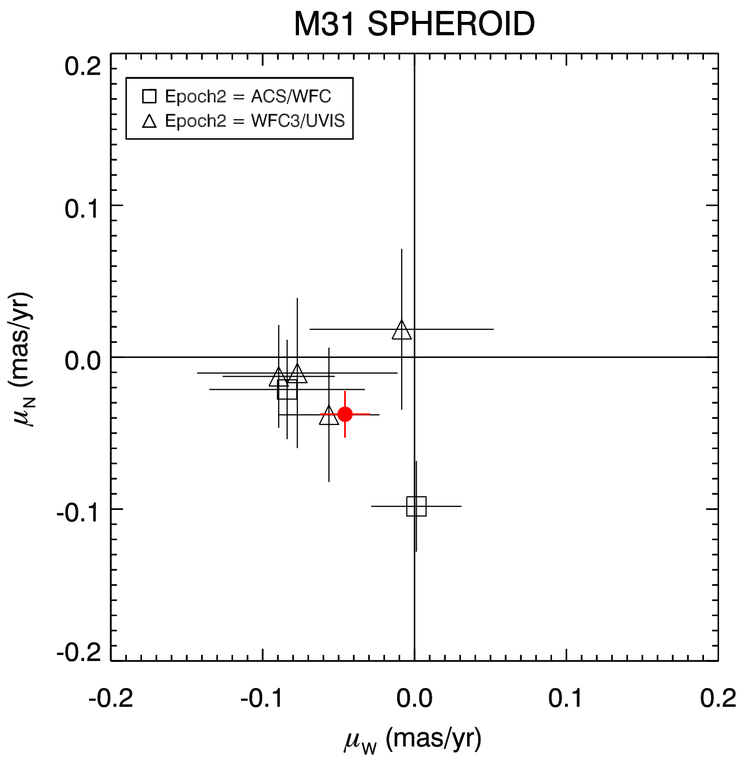



Sohn et al. (2012)

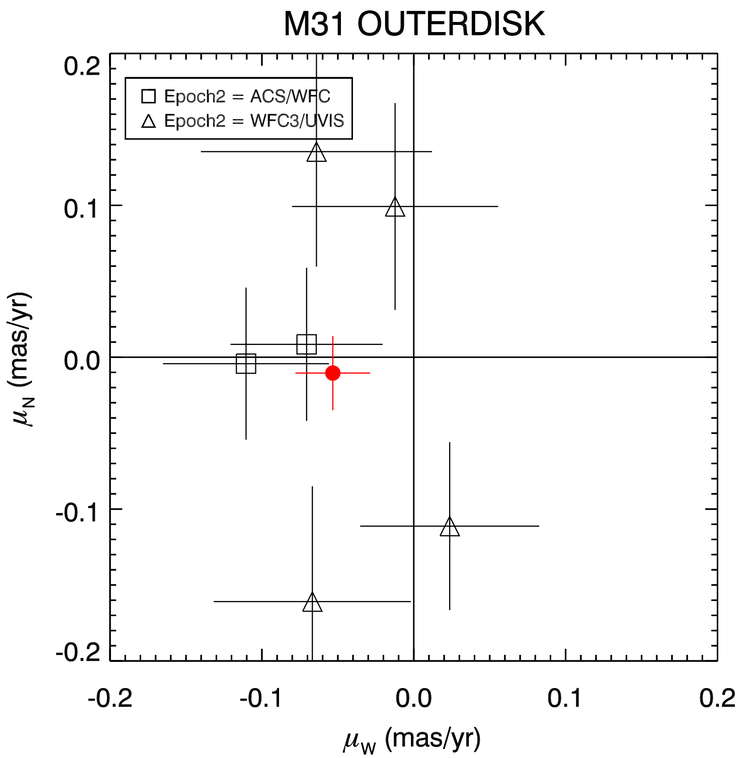
# Measurements with HST

(0.1 mas/yr ~ 400 km/s)

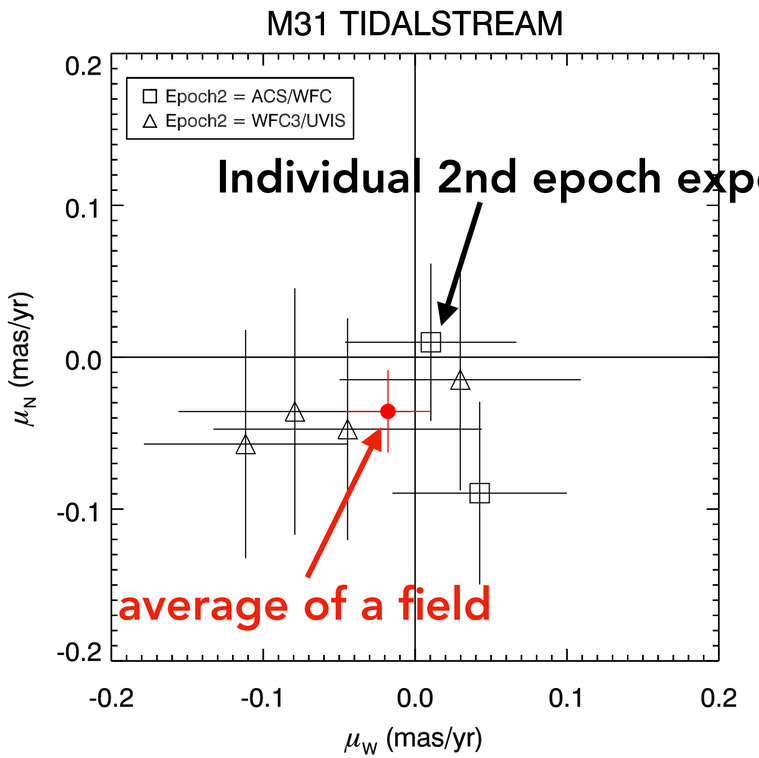
- Results for the 3 individual fields:




~10k stars




~10k stars

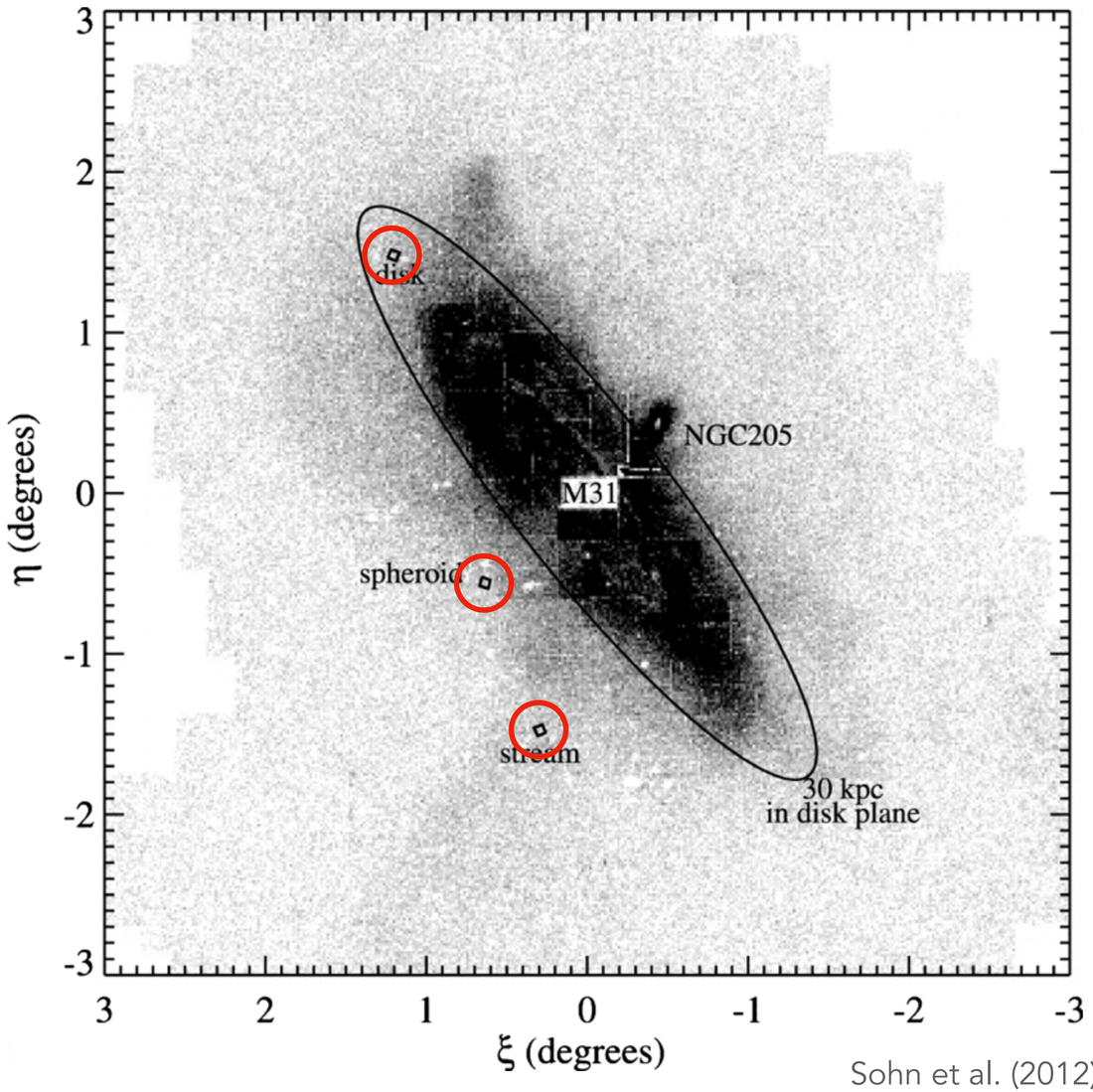



~5k stars

Sohn et al. (2012)

# Measurements with HST

- ***But*** the stars in each field have their own peculiar motion wrt the M31 center of mass…
  - Rotation of the disk
  - Motion of Giant Stream

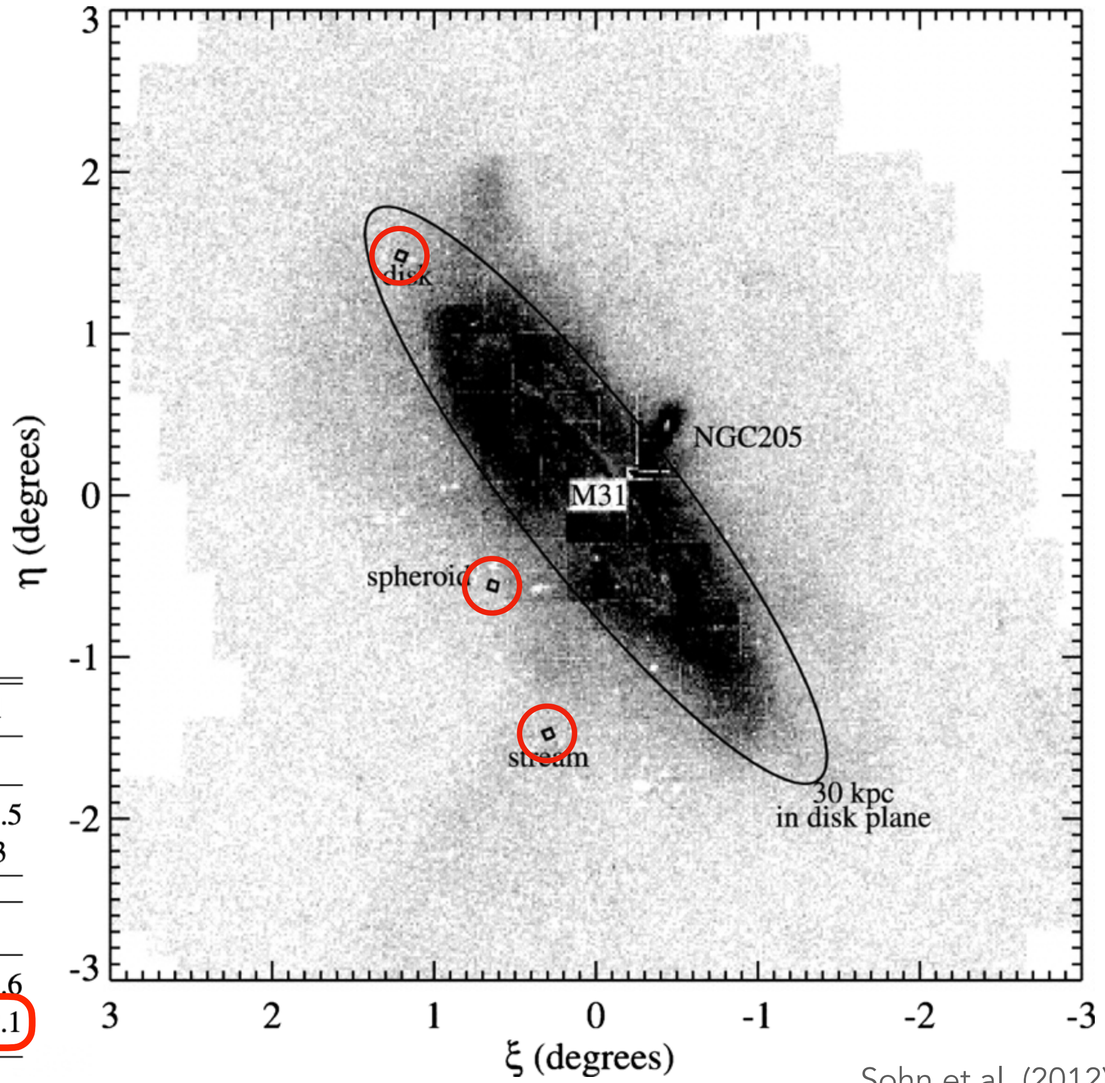



Sohn et al. (2012)

# Measurements with HST

- ***But*** the stars in each field have their own peculiar motion wrt the M31 center of mass…
  - Rotation of the disk
  - Motion of Giant Stream
- (Model-dependent) corrections for those yield:

| | | Spheroid Field | Disk Field | Stream Field |
|---|---|---|---|---|
| | | *HST* PM measurements | | |
| $v_W$ (*HST*) | (km s$^{-1}$) | $-167.2 \pm 60.2$ | $-194.6 \pm 89.8$ | $-65.3 \pm 101.5$ |
| $v_N$ (*HST*) | (km s$^{-1}$) | $-137.2 \pm 56.2$ | $-38.0 \pm 89.1$ | $-130.3 \pm 99.3$ |
| | | M31 COM motion (*HST* PMs + internal-kinematics model + viewing perspective) | | |
| $v_W$ (COM) | (km s$^{-1}$) | $-179.1 \pm 64.1$ | $-158.0 \pm 92.4$ | $-126.3 \pm 103.6$ |
| $v_N$ (COM) | (km s$^{-1}$) | $-122.6 \pm 60.0$ | $-0.5 \pm 91.3$ | $-247.5 \pm 102.1$ |

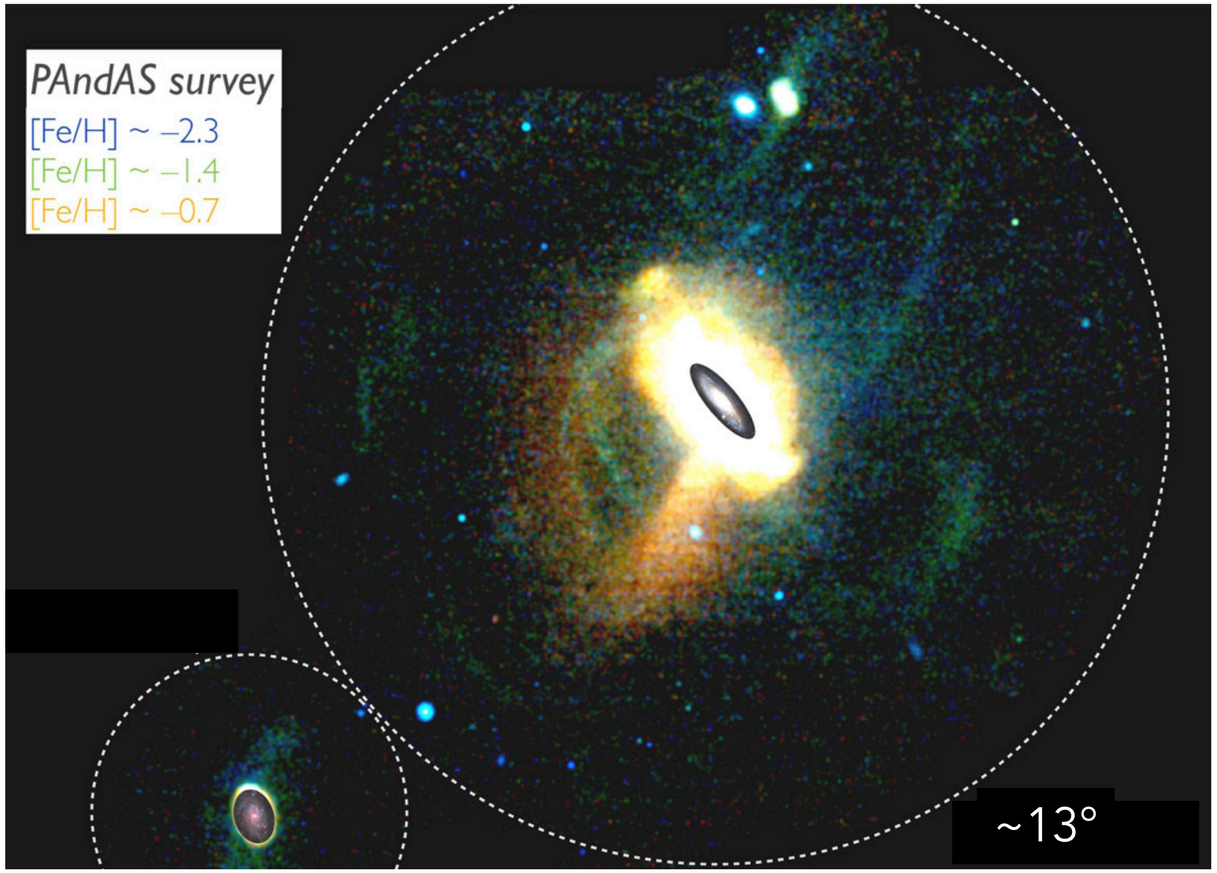



Sohn et al. (2012)

# Using M31's satellite dwarf galaxies

- The M31 system is so big on the sky that the radial velocity of satellites includes a significant component of the center of mass velocity

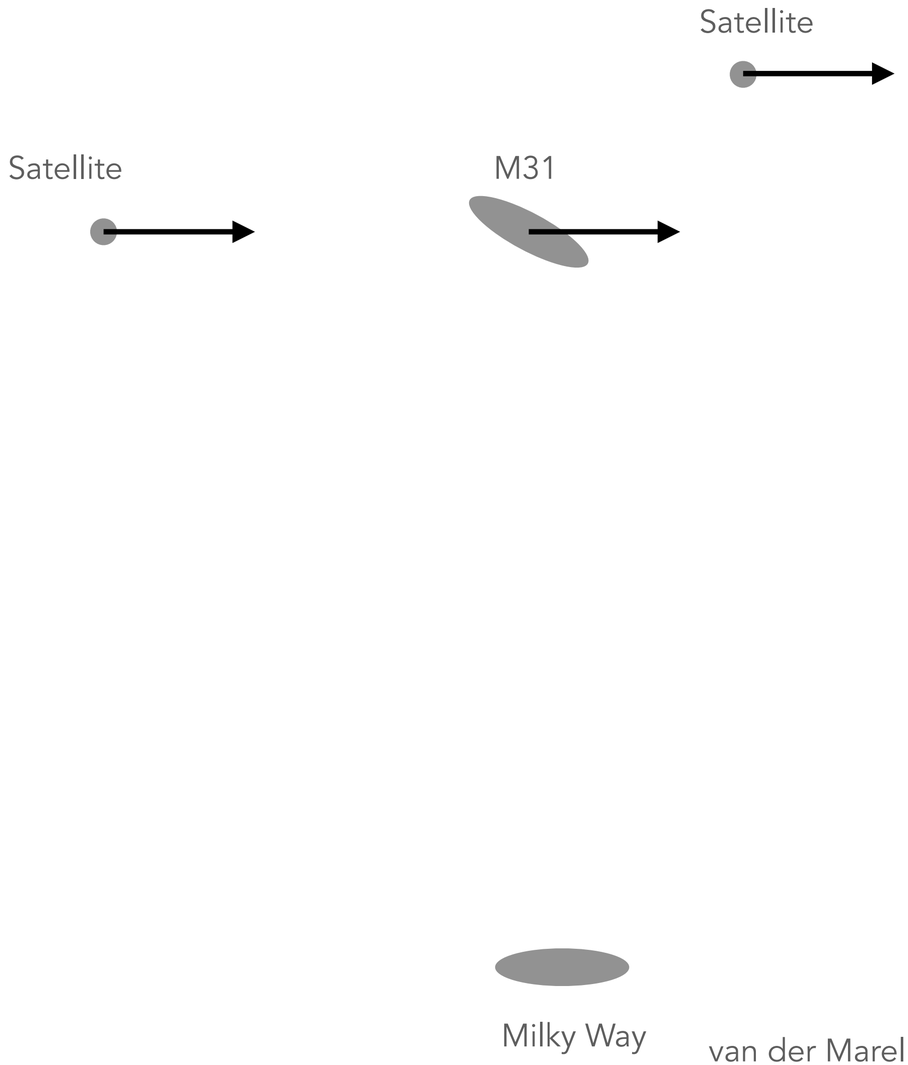
Density map of Red Giant Branch stars in the stellar halo of Andromeda




Martin et al. (2013)

# Using M31's satellite dwarf galaxies

- The M31 system is so big on the sky that the radial velocity of satellites includes a significant component of the center of mass velocity



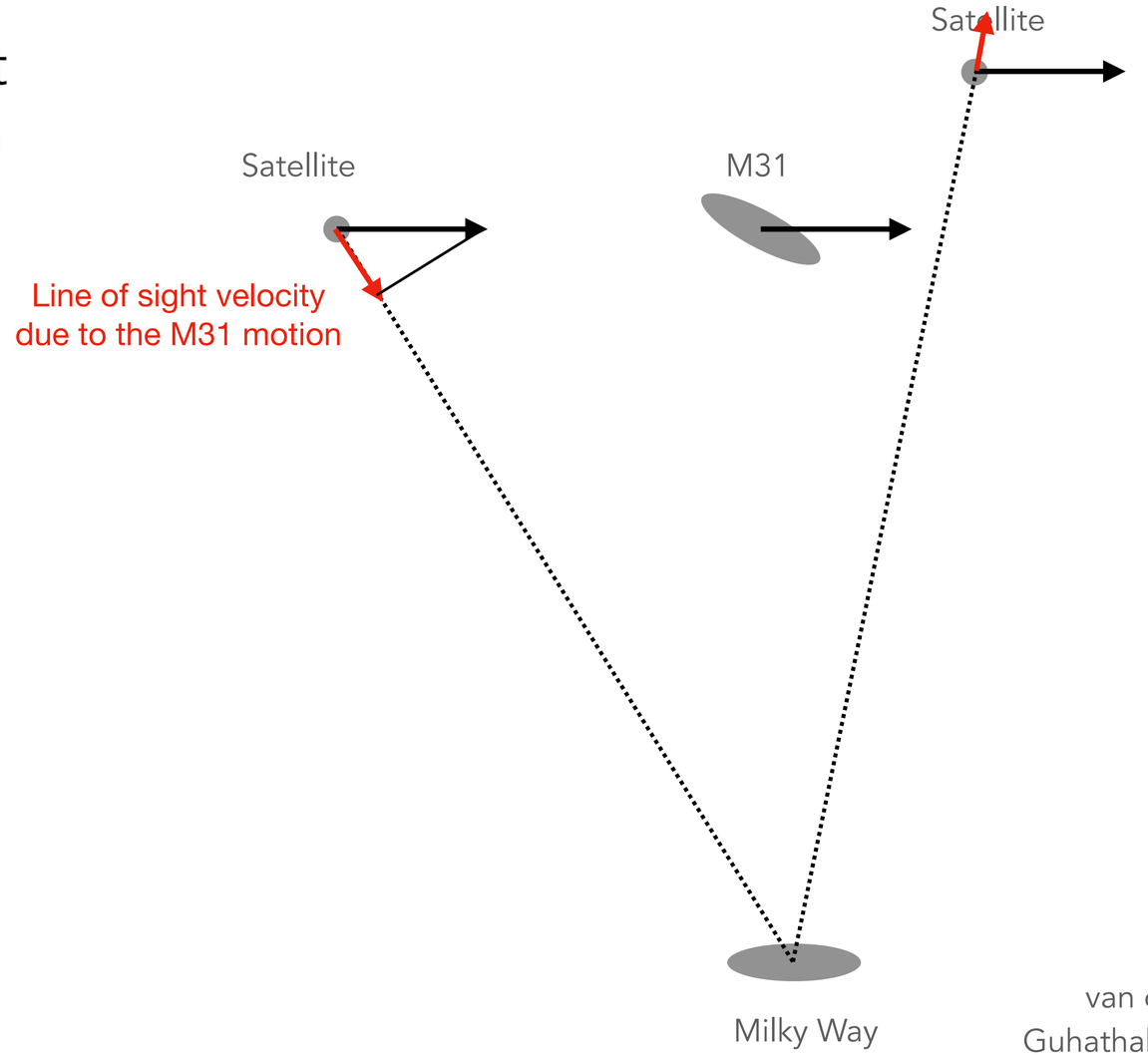

van der Marel et al. (2012)

# Using M31's satellite dwarf galaxies

- The M31 system is so big on the sky that the radial velocity of satellites includes a significant component of the center of mass velocity

- There are now 40+ satellite dwarf galaxies around M31.

- Can tease out the (tangential) motion of M31 from the line-of-sight velocities of the ensemble population of satellites




van der Marel & Guhathakurta (2012)

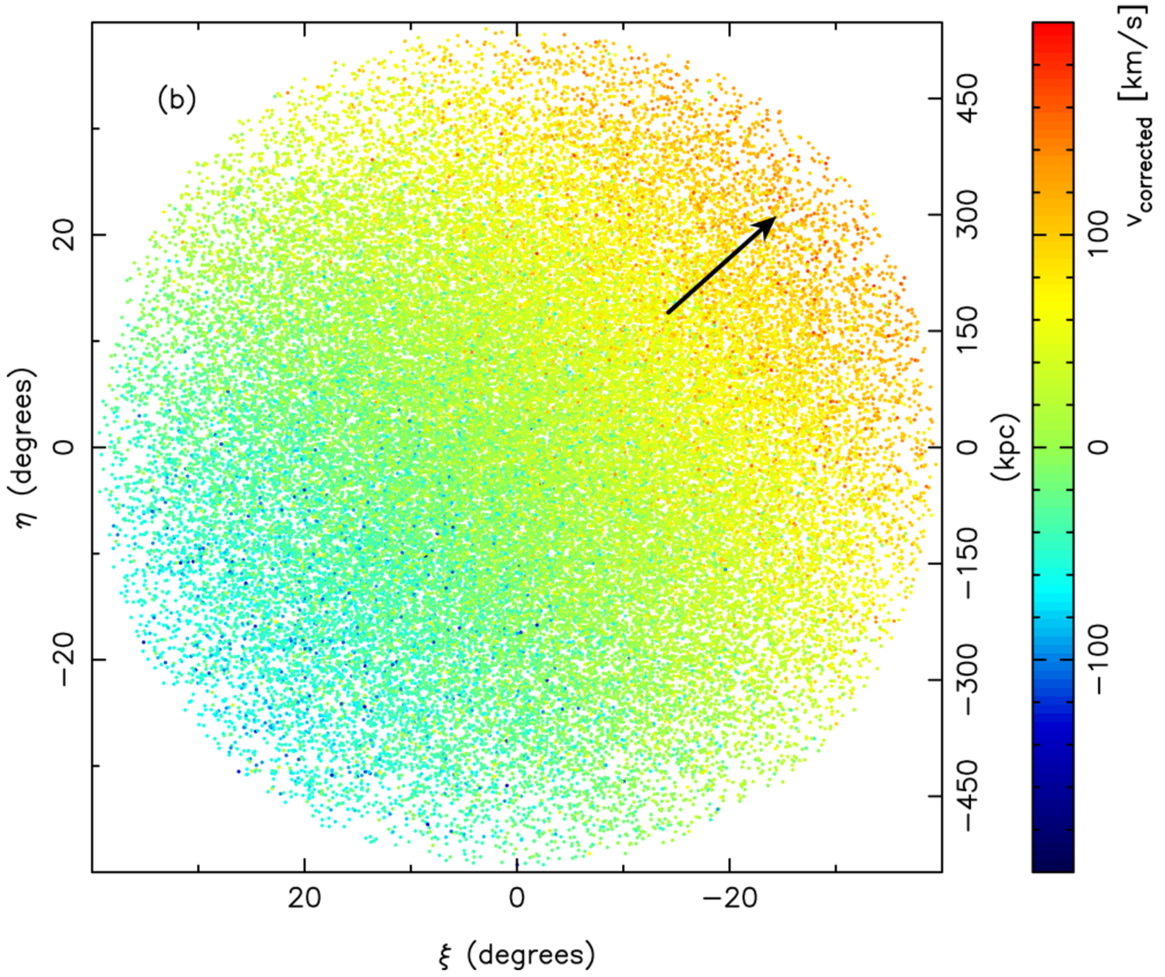
# Using M31's satellite dwarf galaxies

- The M31 system is so big on the sky that the radial velocity of satellites includes a significant component of the center of mass velocity

- There are now 40+ satellite dwarf galaxies around M31.

- Can tease out the (tangential) motion of M31 from the line-of-sight velocities of the ensemble population of satellites

Simulation with 50k satellites




Salomon et al. (2016)

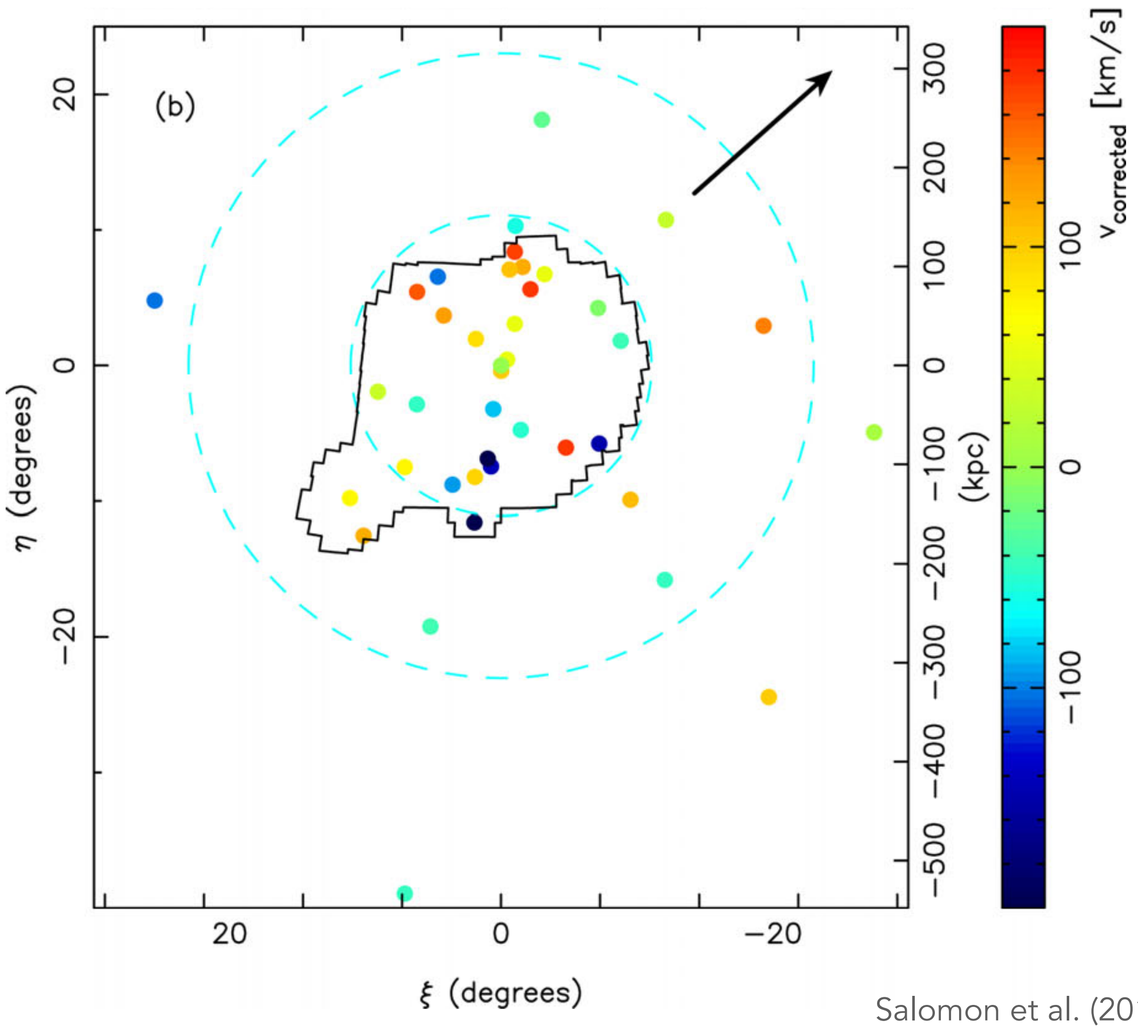
# Using M31's satellite dwarf galaxies

- The M31 system is so big on the sky that the radial velocity of satellites includes a significant component of the center of mass velocity

- There are now 40+ satellite dwarf galaxies around M31.

- Can tease out the (tangential) motion of M31 from the line-of-sight velocities of the ensemble population of satellites

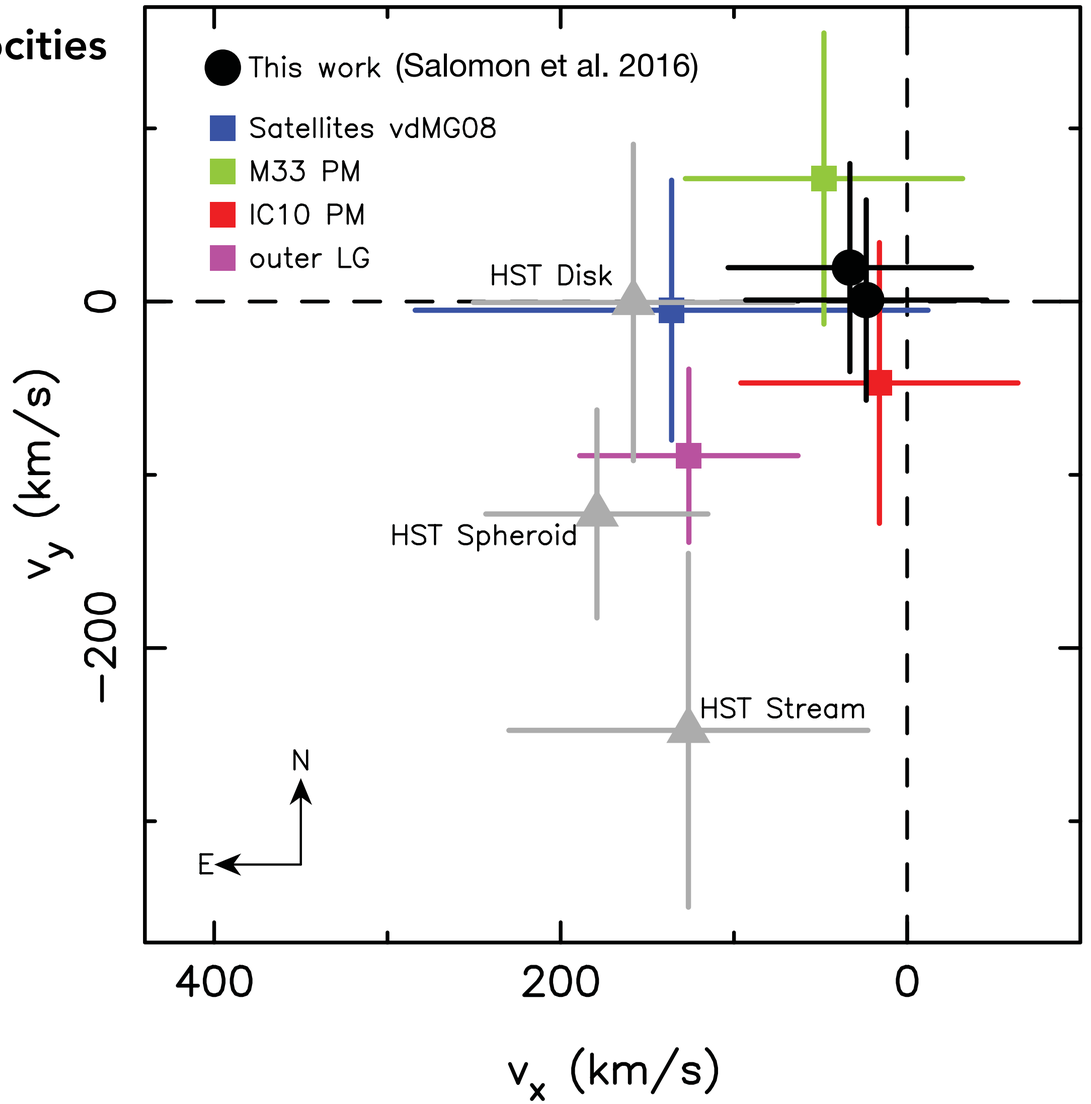
*Signal is much less obvious with 40 satellites!*




Salomon et al. (2016)

# Global state pre-Gaia DR2

**Heliocentric velocities**




Salomon et al. (2016)
with
van der Marel & Guhathakurta (2008)
Sohn et al. (2012)
van der Marel et al. (2012)

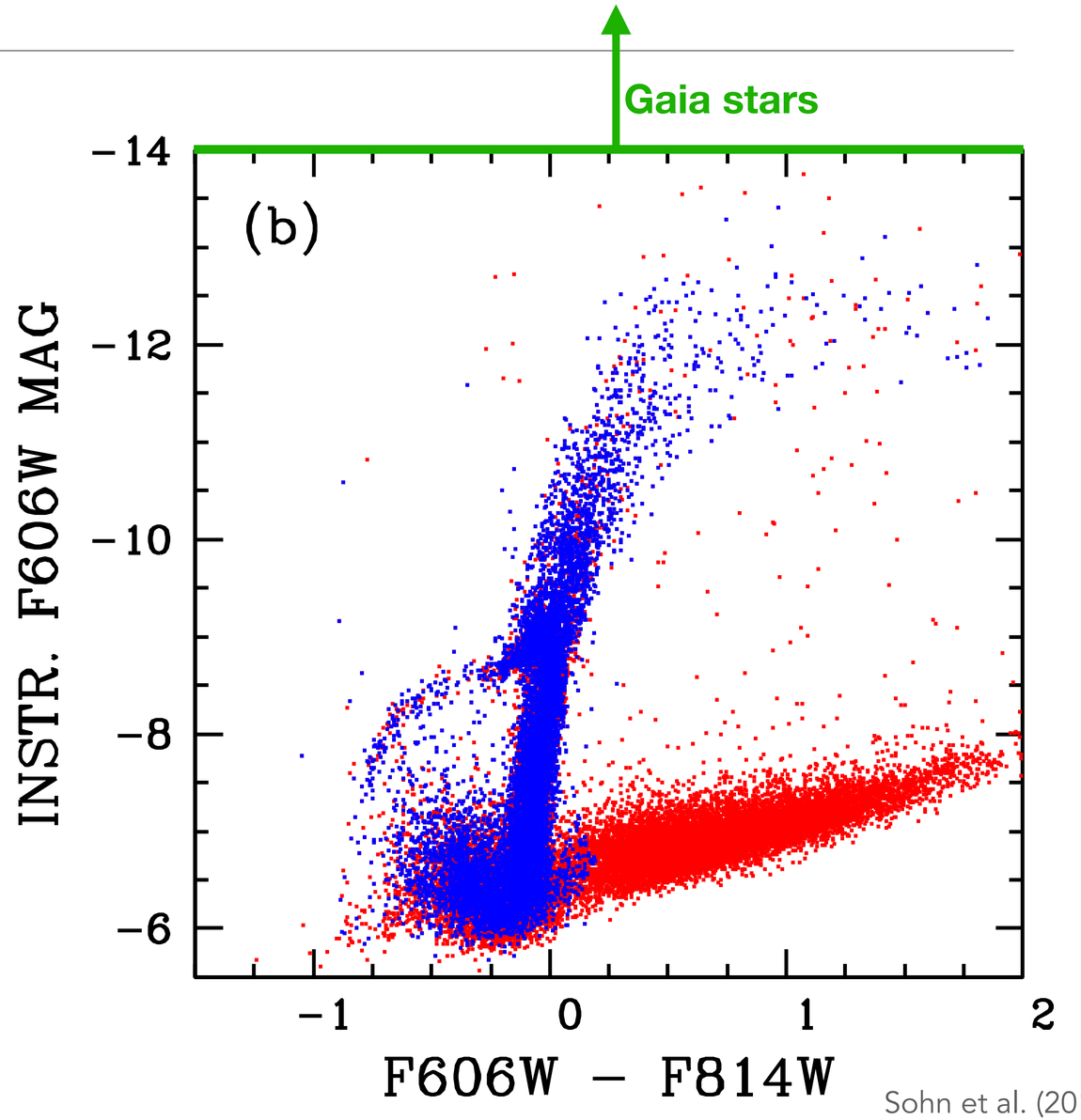
# Caveats

- ***HST measurement***
  - Very small fields
  - Using (extended) galaxies for reference because no/not enough QSOs
  - Need to correct for bulk motion of individual fields around M31 (disk rotation, stream,…)
  - Lots of averages…

- ***Satellite motion inference***
  - Evidence for structure in M31 satellites
    - Plane of satellites
    - Anisotropic distribution
    - Pairs of satellites
  - Are all dwarf galaxies satellite of M31 (M33 satellites? Unbound systems?)

# Enters Gaia DR2

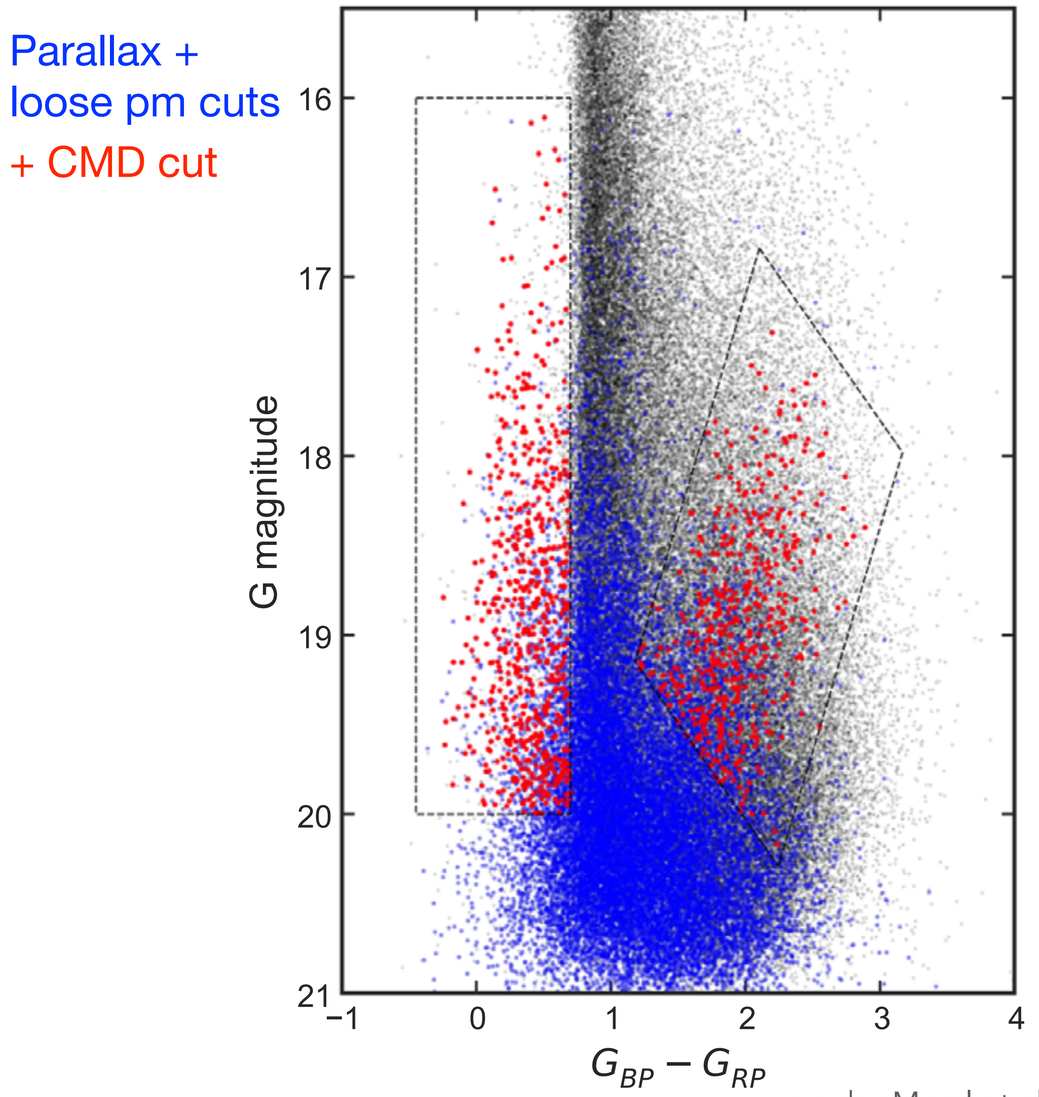
- Much shallower data…
- But much larger field of view
- Can rely on bright super-giants/young stars in the disk of M31!




Sohn et al. (2012)

# Enters Gaia…

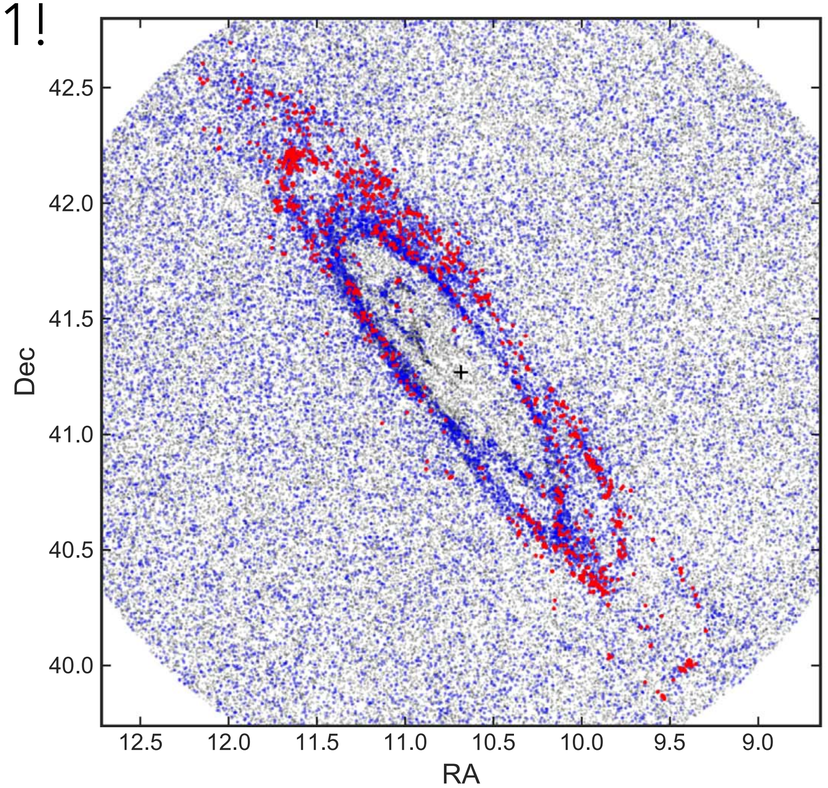
- Much shallower data…
- But much larger field of view
- Can rely on bright super-giants/young stars in the disk of M31!



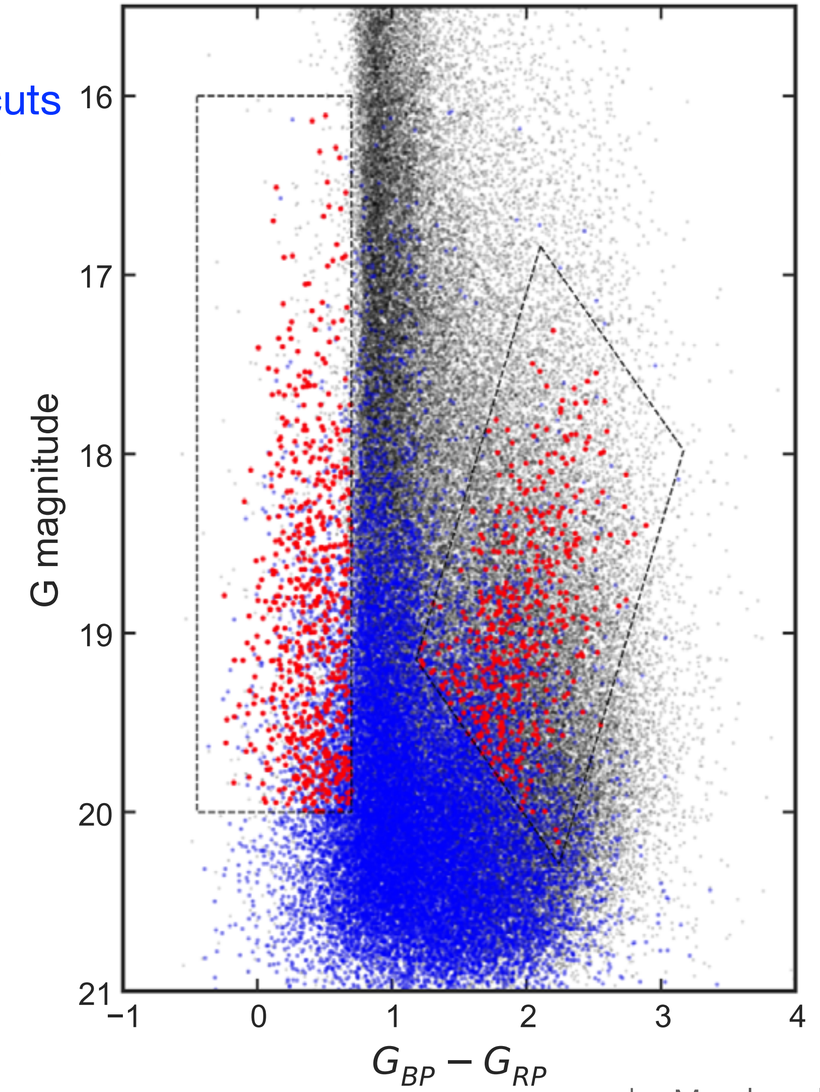

van der Marel et al. (2019)

# Enters Gaia…

- Much shallower data…
- But much larger field of view
- Can rely on bright super-giants/young stars in the disk of M31!



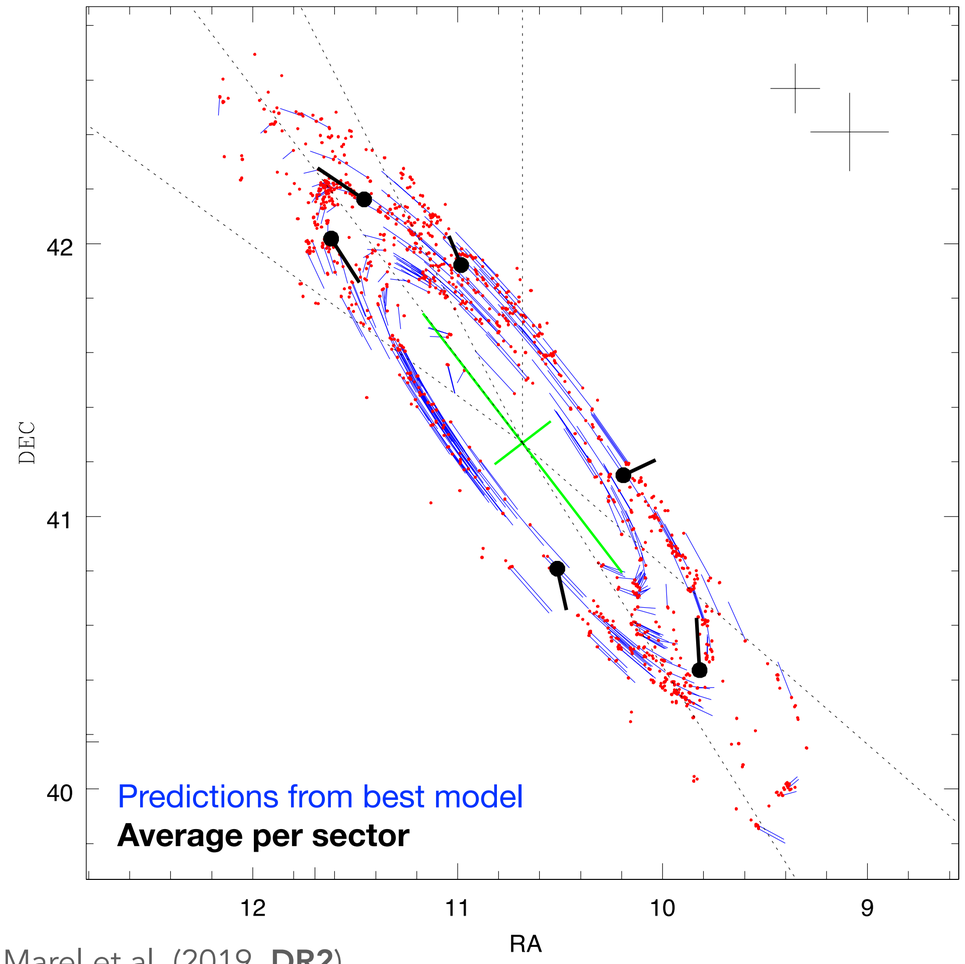

Parallax +
loose pm cuts
+ CMD cut



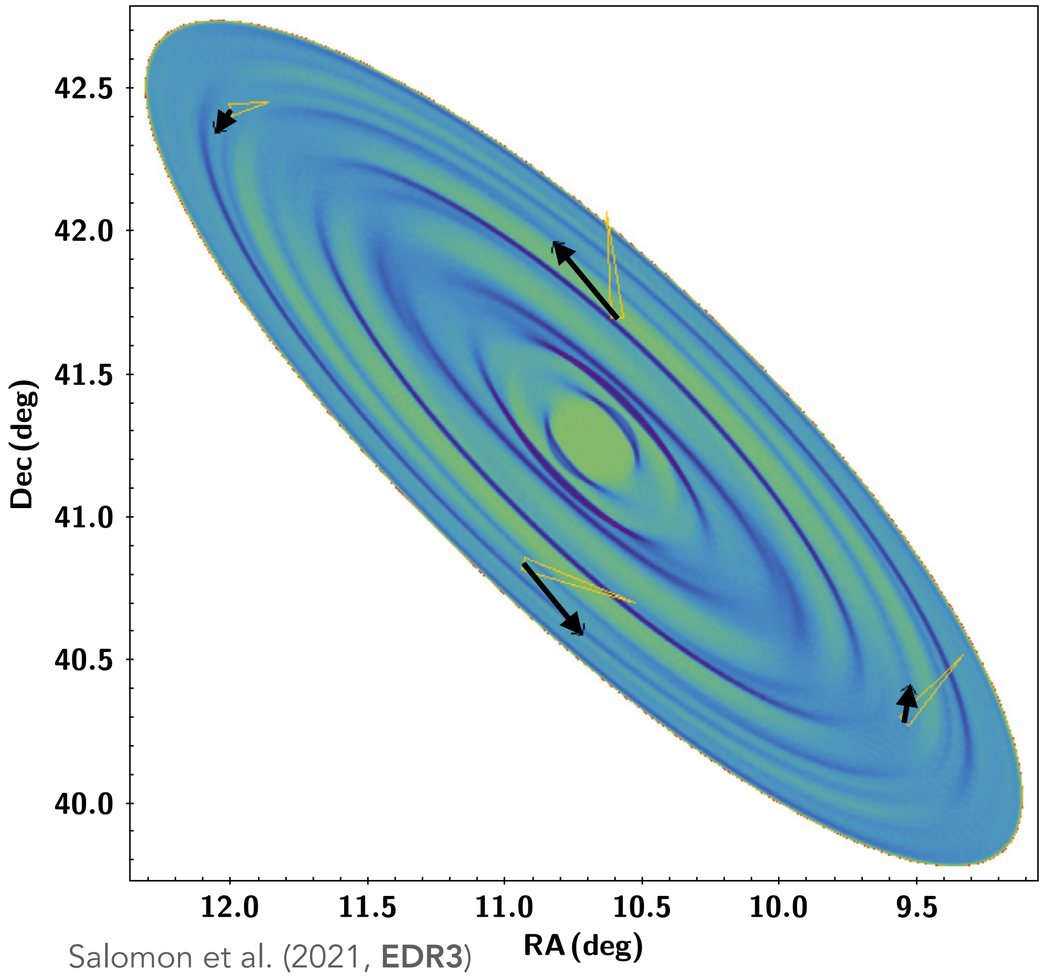

van der Marel et al. (2019)

# Gaia measurements

- Assuming a 3-parameter model $(\mu_\alpha, \mu_\delta, v_{\rm rot})$, and inference (not fit!) from 1k–2k stars




van der Marel et al. (2019, **DR2**)

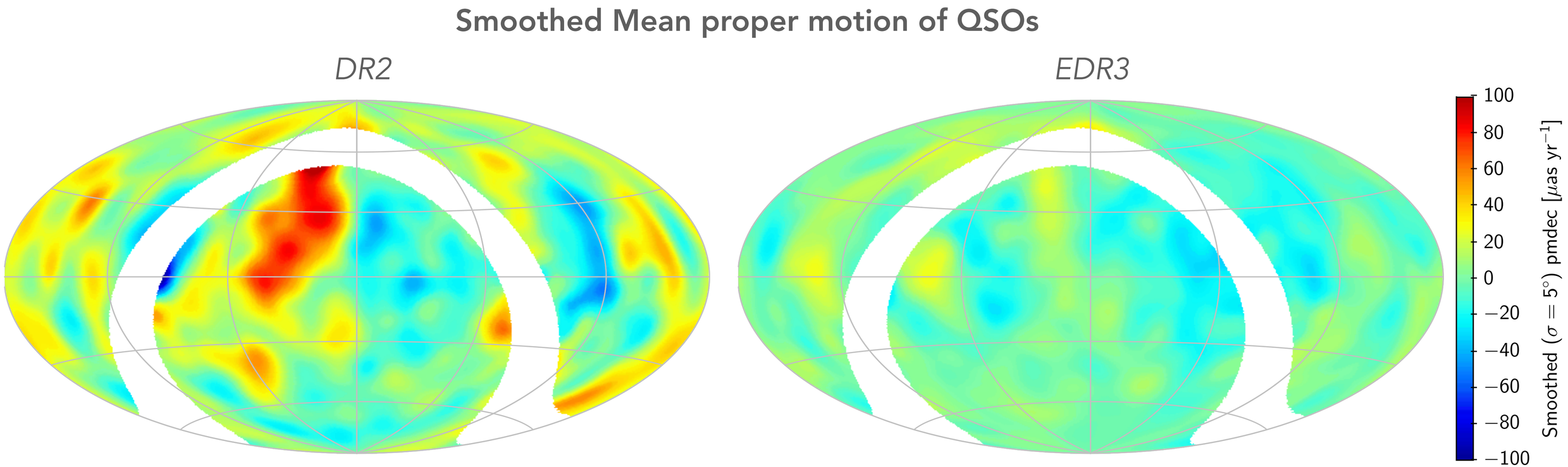



Salomon et al. (2021, **EDR3**)

# What about systematics?

- We know Gaia has (small) proper motion systematics. At least a few (10s?) μas/yr

- Has improved with EDR3, but still present. Needs to be taken into account…

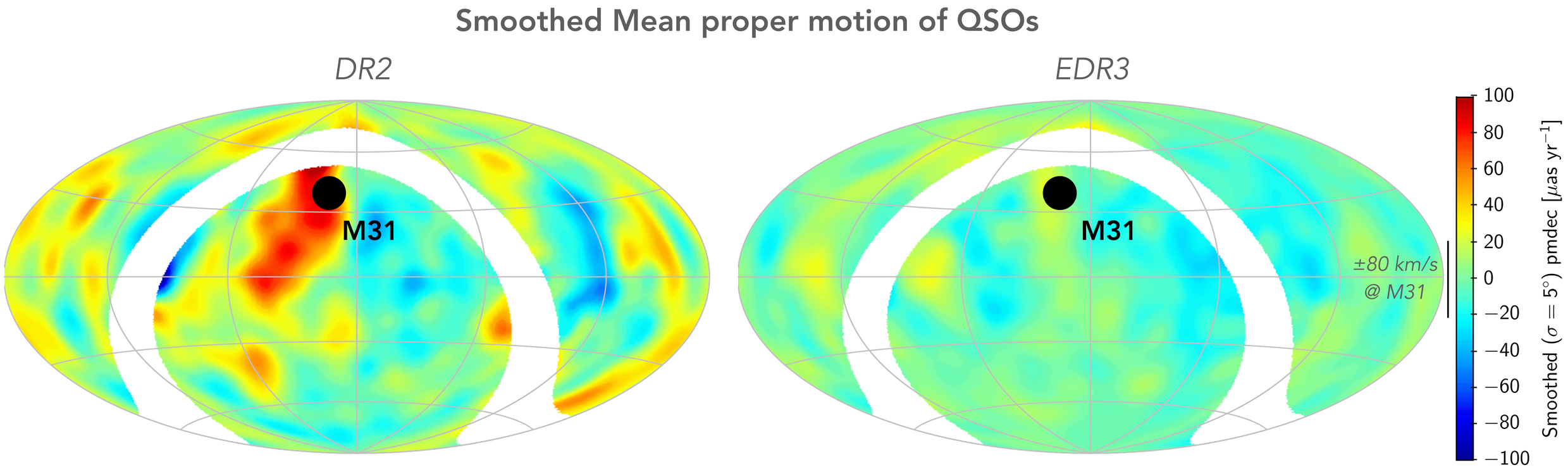



Gaia collaboration, Lindegren et al. (2021)

# What about systematics?

- We know Gaia has (small) proper motion systematics. At least a few (10s?) μas/yr

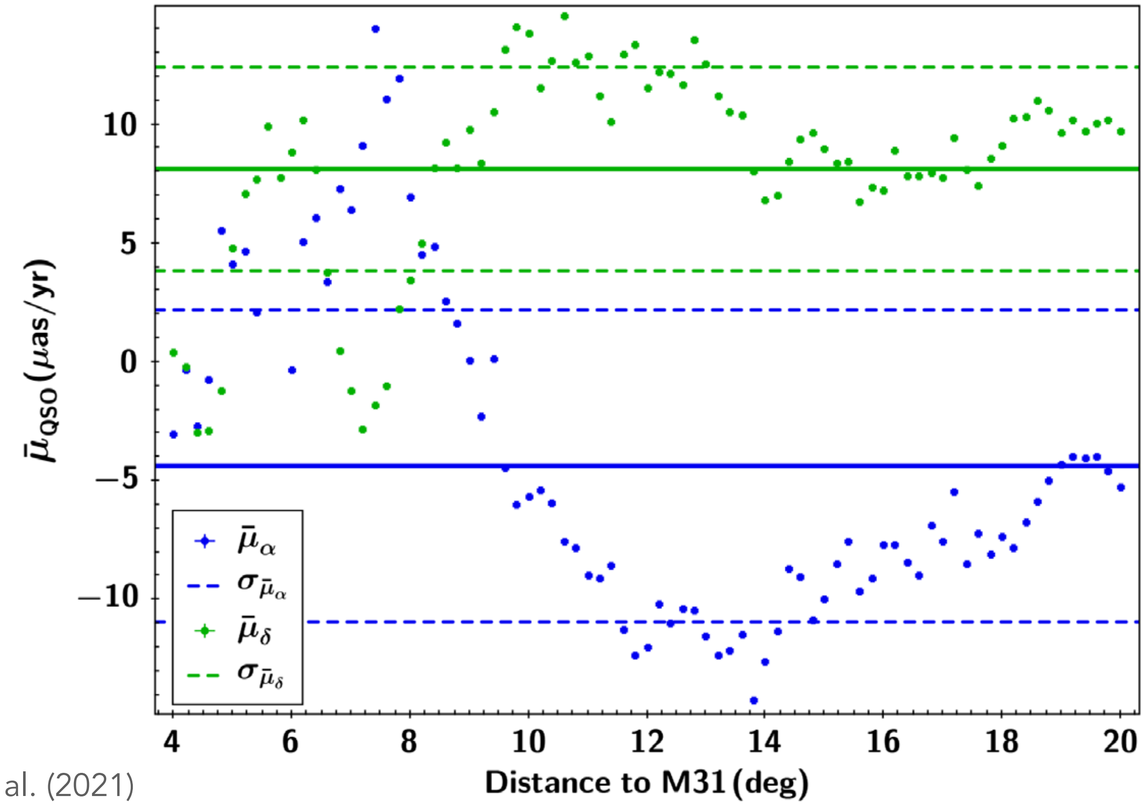
- Has improved with EDR3, but still present. Needs to be taken into account…




Gaia collaboration, Lindegren et al. (2021)

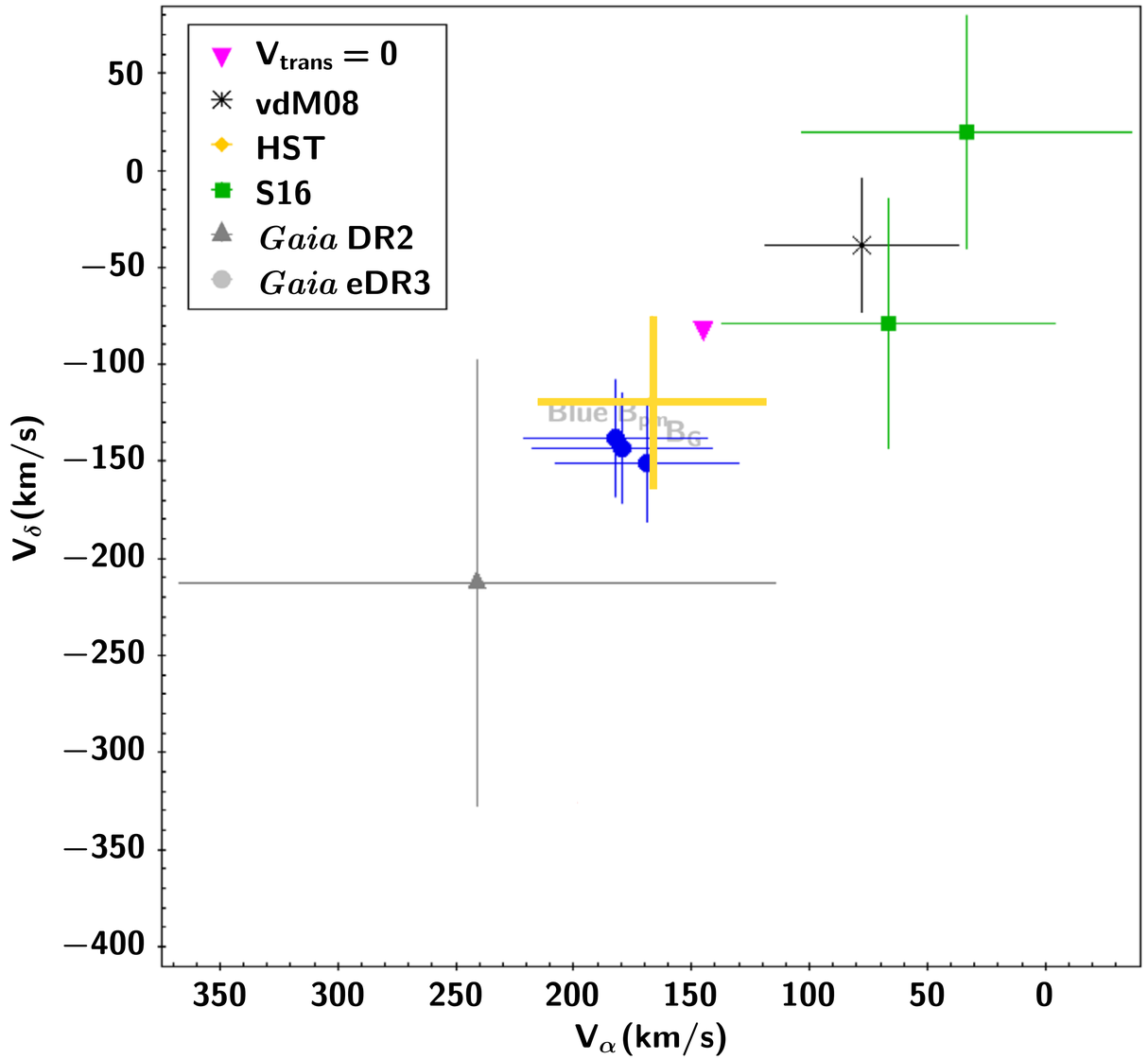
# What about systematics?

- We know Gaia has (small) proper motion systematics. At least a few (10s?) μas/yr
- Has improved with EDR3, but still present. Needs to be taken into account…
- Determination of mean "local" correction:



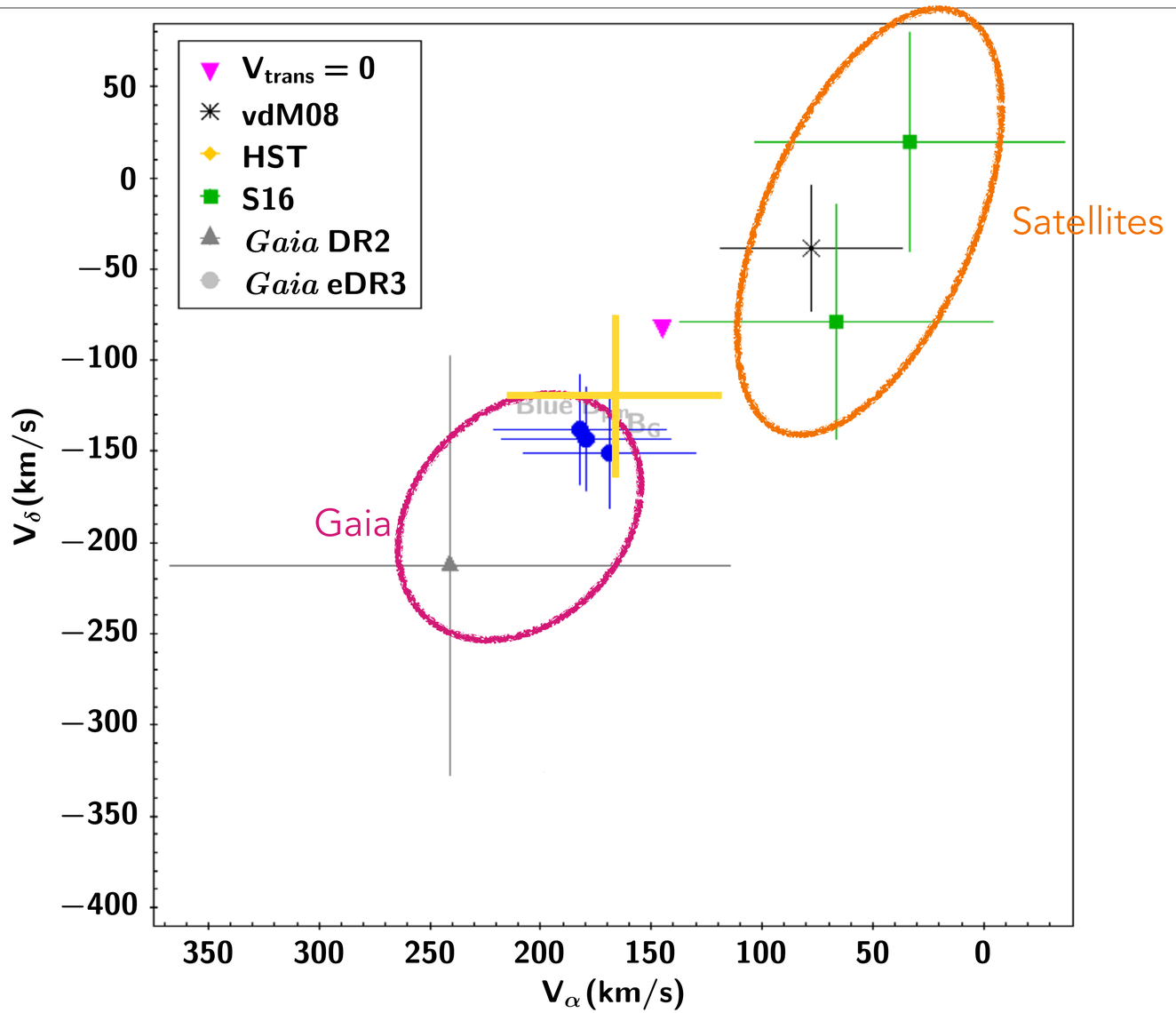

Salomon et al. (2021)

# The current state of affairs



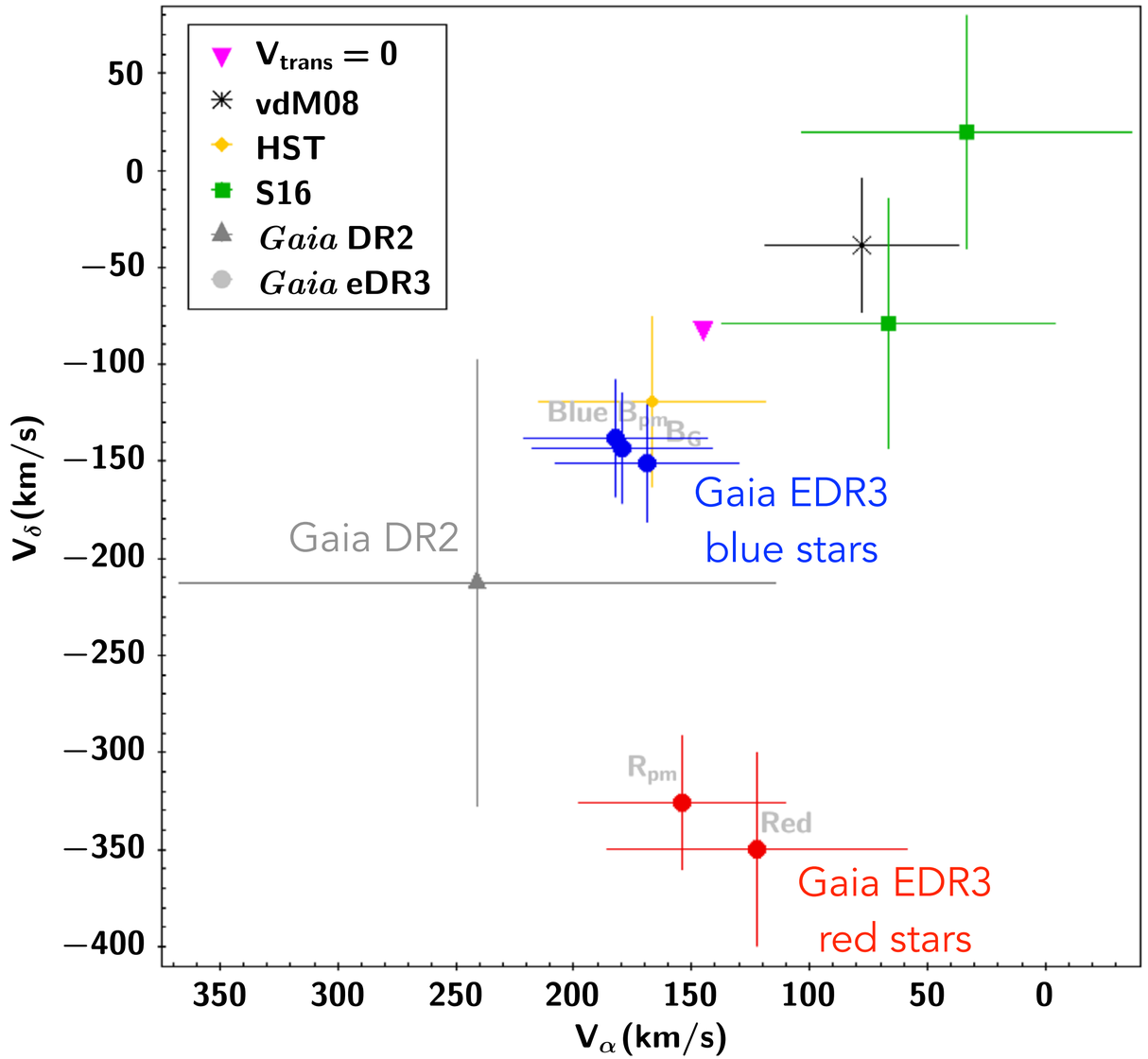

**Salomon et al. (2021, EDR3)**
**van der Marel et al. (2019, DR2)**
with
van der Marel & Guhathakurta (2008)
Sohn et al. (2012)
van der Marel et al. (2012)
Salomon et al. (2016)

# The current state of affairs




**Salomon et al. (2021, EDR3)**
**van der Marel et al. (2019, DR2)**
with
van der Marel & Guhathakurta (2008)
Sohn et al. (2012)
van der Marel et al. (2012)
Salomon et al. (2016)

# The current state of affairs



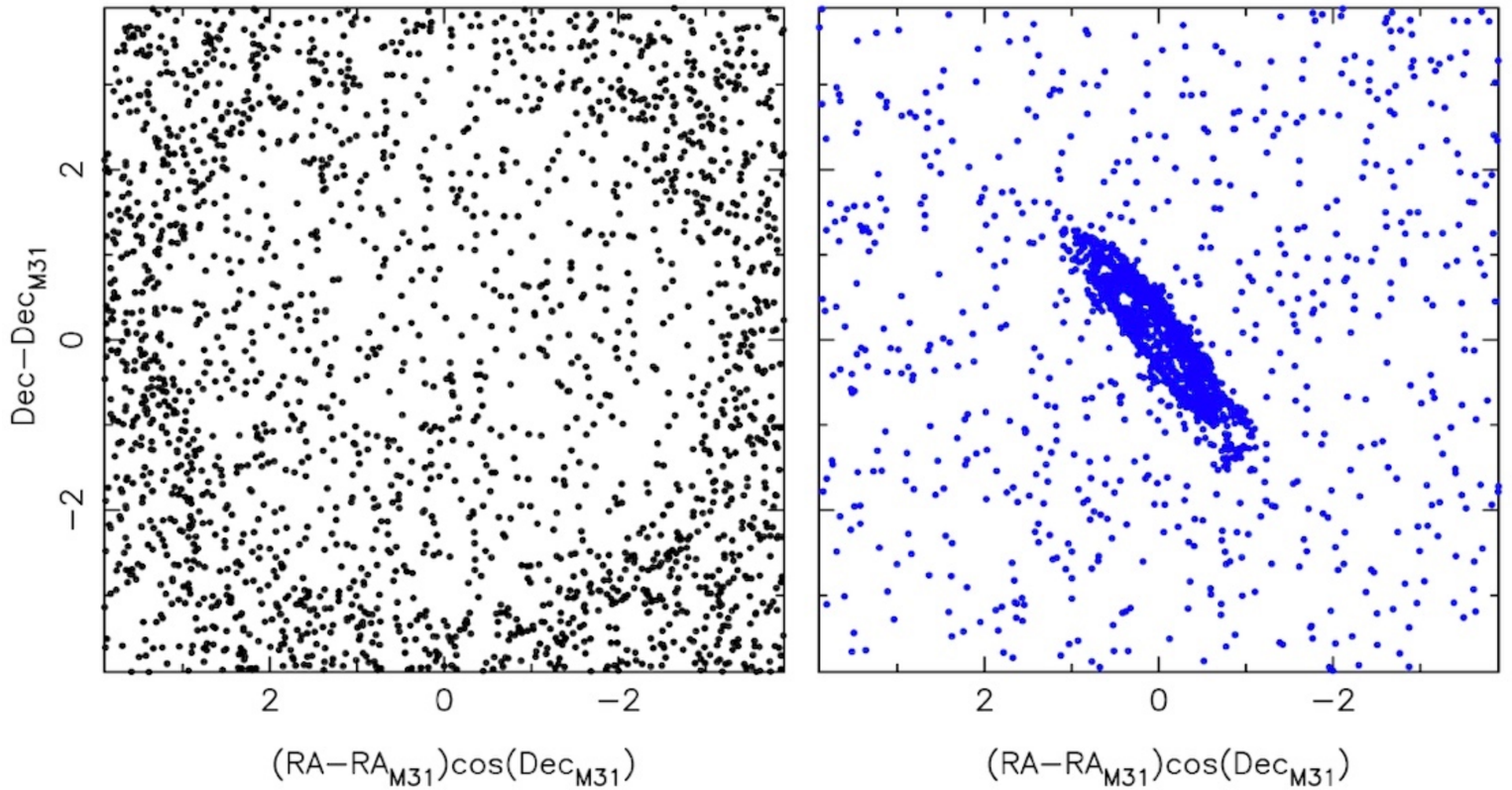

**Some systematics are still clearly present…**

**Salomon et al. (2021, EDR3)**
**van der Marel et al. (2019, DR2)**
with
van der Marel & Guhathakurta (2008)
Sohn et al. (2012)
van der Marel et al. (2012)
Salomon et al. (2016)

# Where to from here?

- DR4 will be better… but not before the end of 2025. What can we do in the meantime?
- Squashing systematics by refining the QSO correction is likely key

Distribution of QSOs used for Gaia EDR3 reference frame



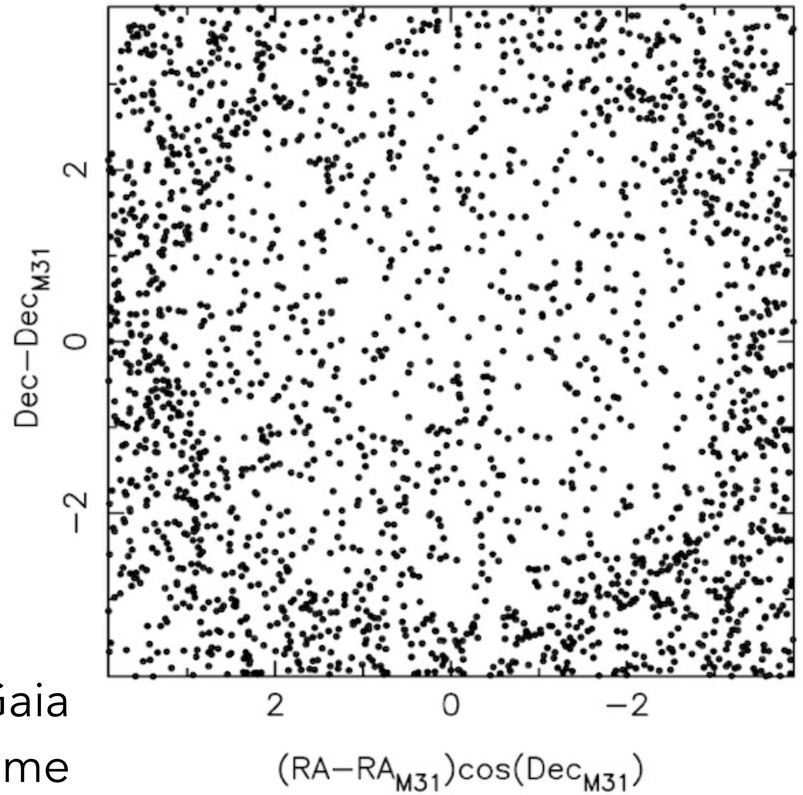

Distribution of blue stars (in M31 disk)

# Where to from here?

- DR4 will be better… but not before the end of 2025. What can we do in the meantime?
- Squashing systematics by refining the QSO correction is likely key

- Why the structure?
  - Far from M31, using photometric selection of QSO
  - Near M31, too much contamination for this selection; using spectroscopic quasars instead

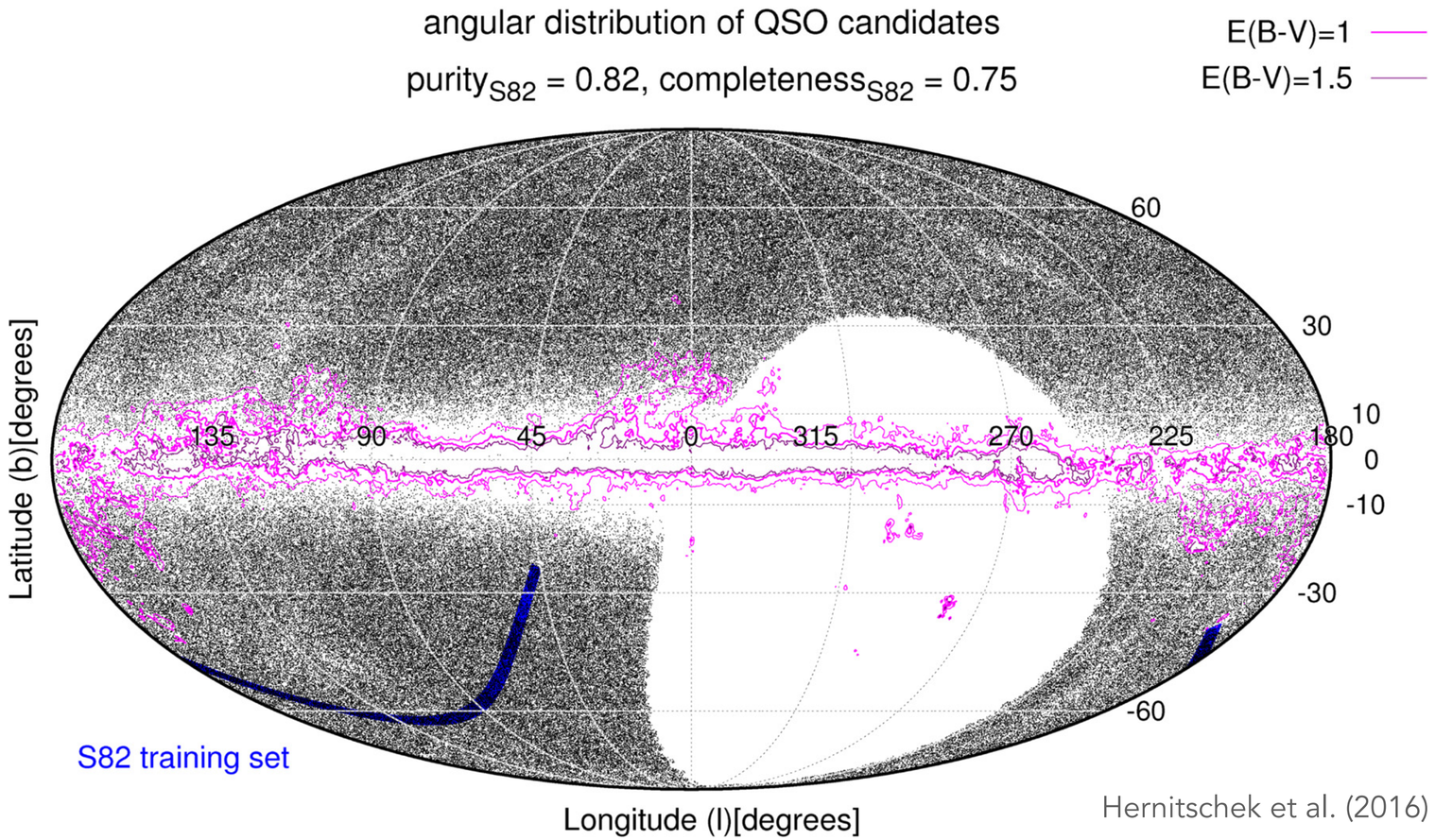
- Can we improve the catalogue?




QSOs used for Gaia EDR3 reference frame

# How to improve the QSO catalogue?

- QSO photometry varies differently from bulk of variable stars (stochastic vs. periodic)
- How point-source varies in Pan-STARRS1 → catalogues of QSOs (and RRLyr)

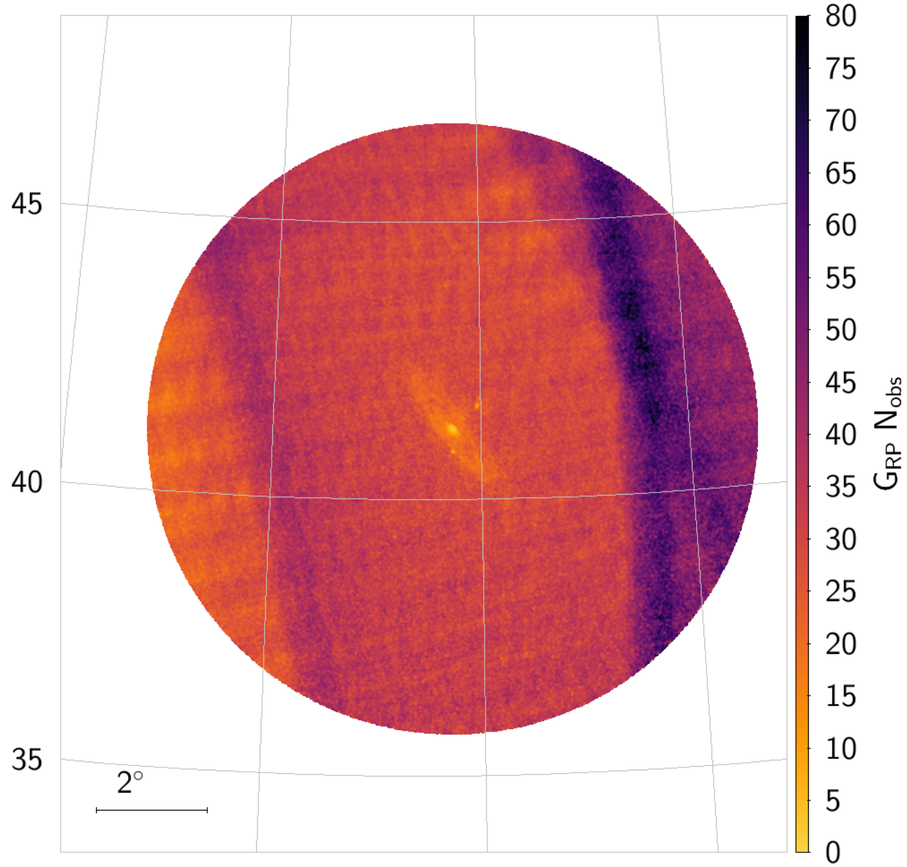



Hernitschek et al. (2016)

# How to improve the QSO catalogue?

- QSO photometry varies differently from bulk of variable stars (stochastic vs. periodic)
- How point-source varies in Pan-STARRS1 → catalogues of QSOs (and RRLyr)

- PS1 catalogue can be improved/replaced with the **Gaia Andromeda Photometric Survey**
  - Photometric time series for 1.2 millions sources with 5.5° of M31
  - Space-based observations, so fewer issues than with PS1 near M31 (e.g., crowding)?
  - Exquisite Gaia photometry → more accurate variability measurements
  - + confirmation with wide-field multi-object spectroscopy (e.g. WEAVE)




Evans et al. (2022)

# Measuring the proper motion of M31

- ***It's incredibly hard!***
- A lot of ***beautiful work*** was done over the years using HST, satellites, and now Gaia
- It's likely none are perfect and they all have (different?) systematics

- But there's a clear path forward with ***3 independent avenues***:
  - **HST** with longer baselines and segue into **JWST** era (20–30 year baseline?)
  - Refine **satellite-based inference** with increasing sample of satellite dwarf galaxies and globular clusters (esp. more distant)
  - Better **Gaia-based inference** by reducing the systematics around M31 with a more populated QSO reference frame