High-Precision Astrometry of Small Stellar Systems

Laura Watkins she/her/hers

AURA for ESA, ESA Office, Space Telescope Science Institute

A Future Space Mission with Very-High Precision Astrometry · IAP · September 2024

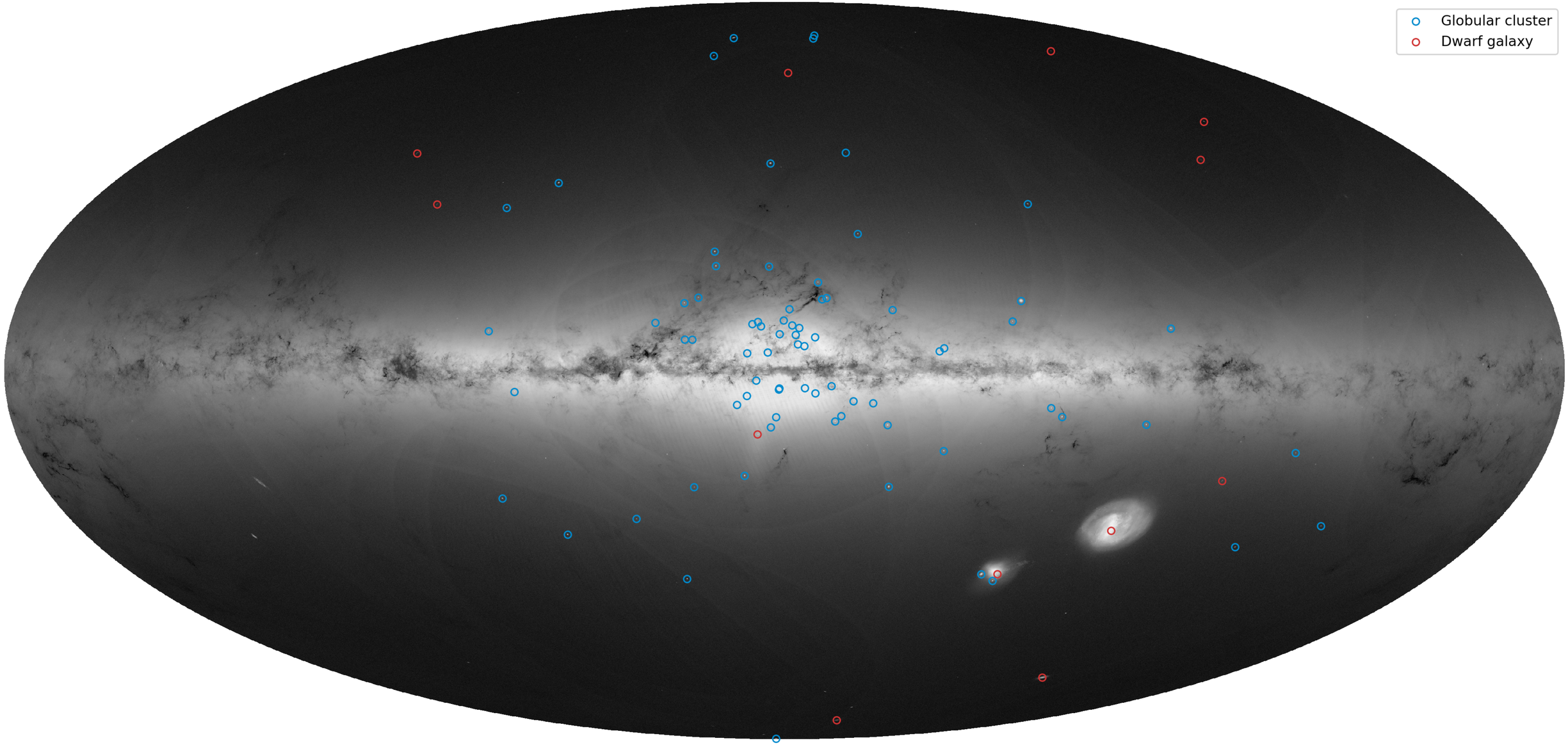
NASA, ESA and the Hubble Heritage Team (STScI/AURA)

Small Stellar Systems

Dwarf Galaxies (Carina, ~100 kpc)

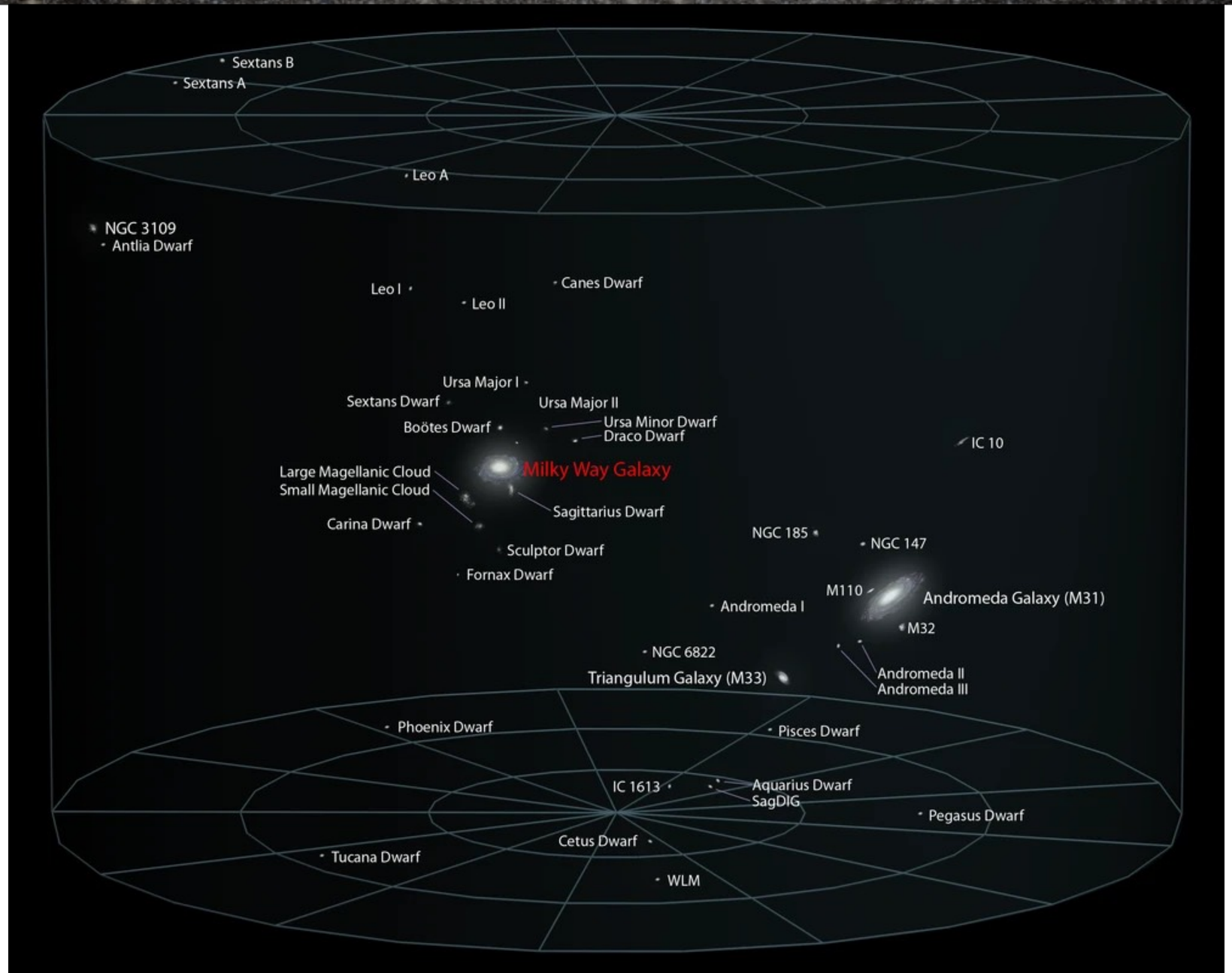
Globular Clusters (M15, ~10 kpc)

Gaia DR2 view of the Milky Way



https://www.astro.rug.nl/~ahelmi/research/dr2-dggc/

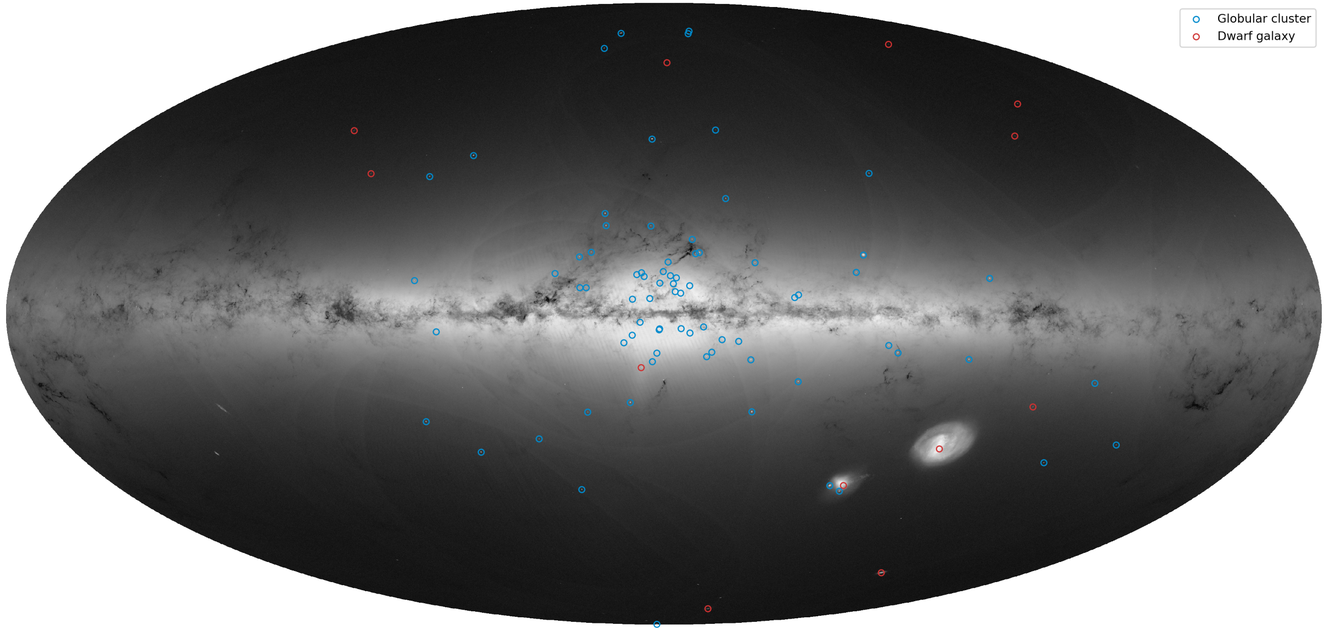
The Local Group



Astrometry for Small Stellar Systems in the Local Group

Formation and **Evolution**

- **Global Motions:**
  - Orbits / environments / link to star formation histories
  - Planes of satellites, streams
  - Properties of the Milky Way / M31 / Local Group



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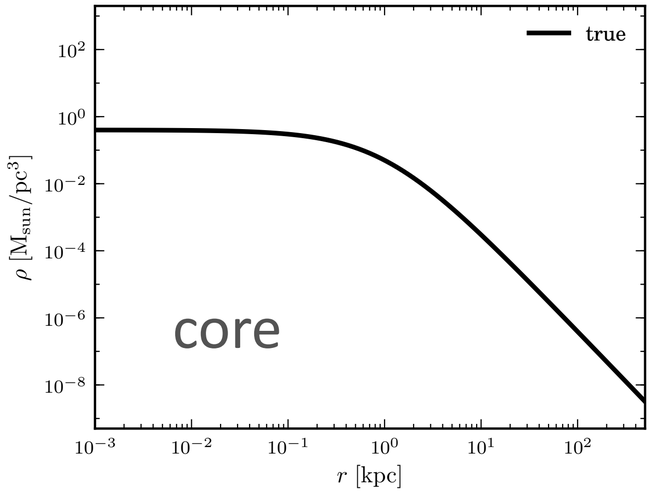
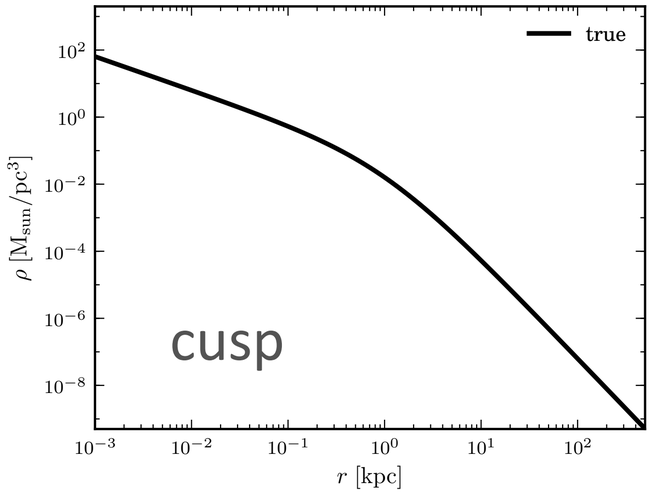
- **Internal Motions:**
  - Mass (dark matter, core/cusp, IMBH)
  - Rotation, anisotropy
  - Dynamical differences with mass, chemistry, colour





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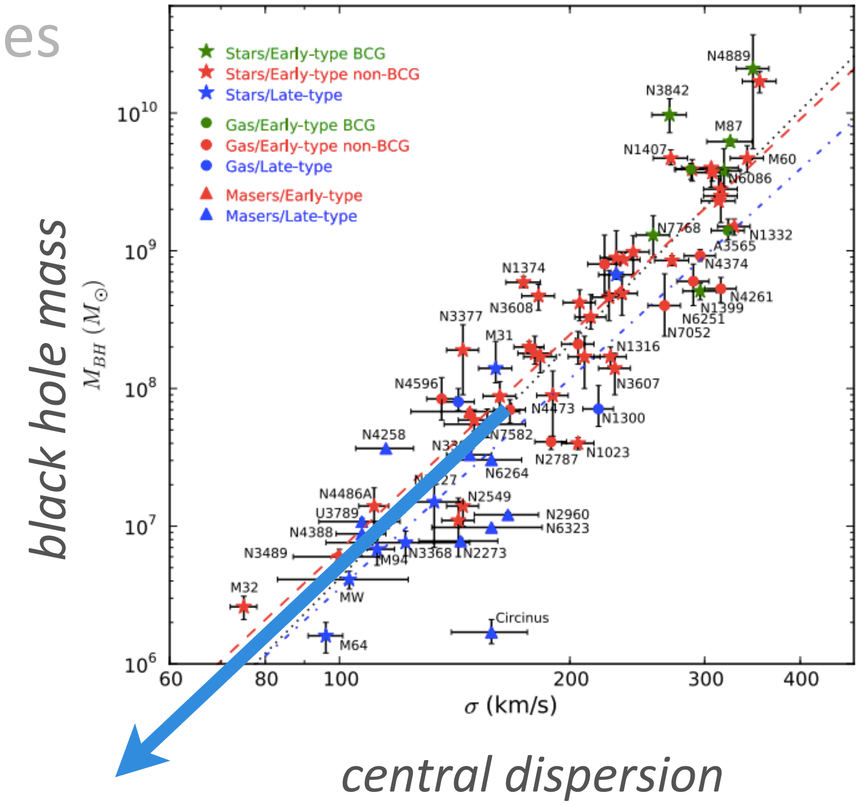
McConnell & Ma 2012



Astrometry for Small Stellar Systems in the Local Group

Formation and **Evolution**

- **Global Motions:**
  - Orbits / environments / link to star formation histories
  - Planes of satellites, streams, effects of tides
  - Properties of the Milky Way / M31 / Local Group
- **Internal Motions:**
  - Mass (dark matter, core/cusp, IMBH)
  - Rotation, anisotropy
  - Dynamical differences with mass, colour
- **Membership selection for other studies**

What factors do we need to consider?

Precision and **Accuracy**

- **Time baseline between first and last epoch**
- **Number of epochs, observations at each epoch**
- **Precision of measuring stellar positions, PSFs**
  - Effects of crowding
- **Number of stars with proper motions**
  - Overall, in region of interest / spatial coverage, depth, filter
- **Measuring proper motions using multiple instruments/observatories**
  - Often increases baseline but introduces systematics
- **Availability of line-of-sight velocities, distances**

What can we already do?
And what can’t we do?
(not an exhaustive list)

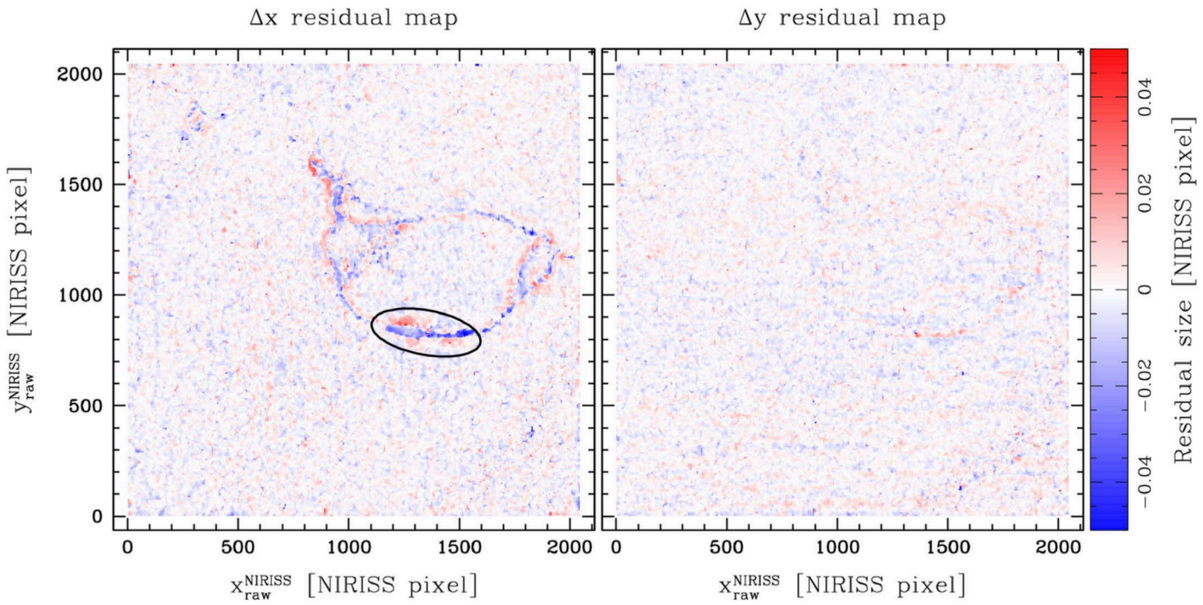
We can already do a lot!

BUT

For individual objects or small samples over limited ranges → biased/incomplete.

Combining Observatories

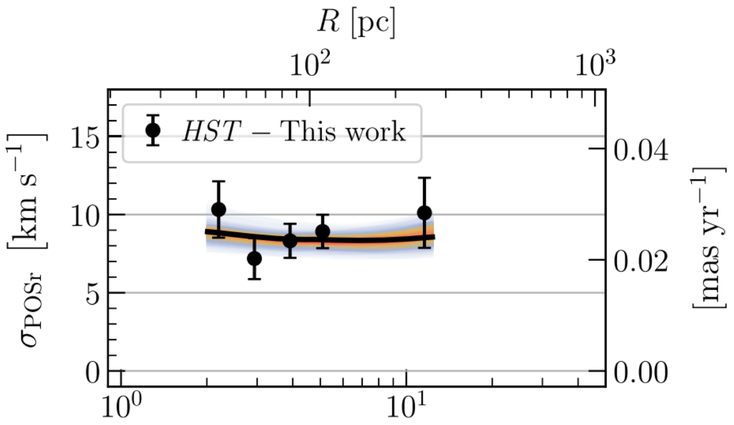
- **Hubble + Gaia**
  - **GaiaHub** (del Pino et al. 2022) — optimised for crowded fields
  - **BP3M** (McKinnon et al. 2024) — optimised for sparse fields
  - Hubble baselines and Hubble spatial coverage for Gaia-bright stars
- **Hubble + JWST**
  - Libralato et al. (2022)
  - H+JW PMs in JWST calibration field in LMC, Hubble baseline (~16 years)
  - JWST Telescope Scientist Team:
    - JWST-JWST PMs for MW and M31 dwarfs (coming in Cycle 3)

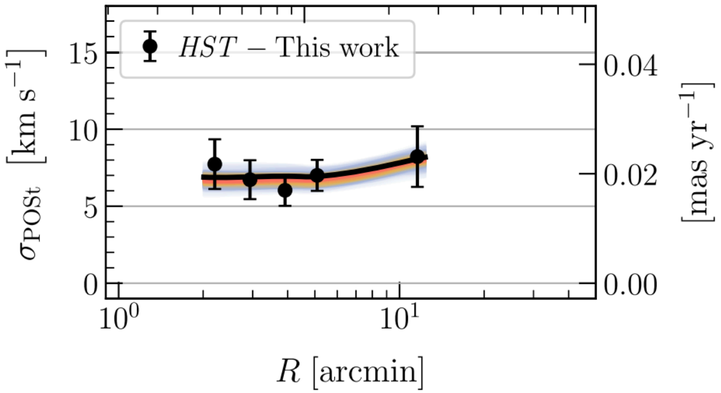


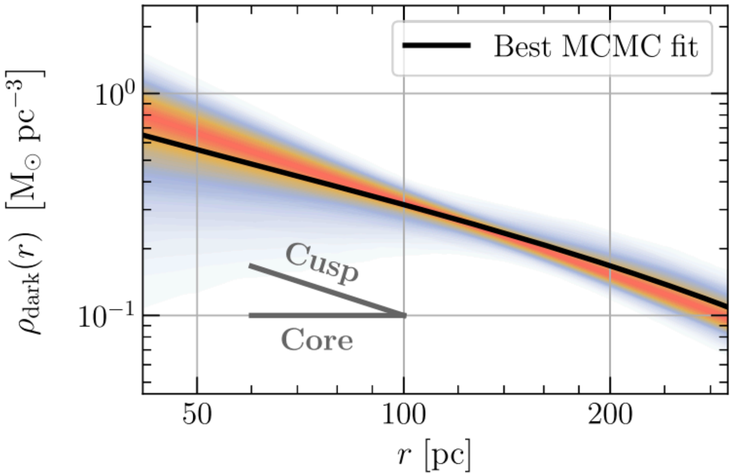
Dwarf Galaxy Internal Kinematics

See Eduardo's talk from Wednesday

- **Hubble**
  - 18 year baseline, first PM dispersion profile in a dwarf (Vitral+ 2024)
  - Central density profile
  - Gaia too bright, too few stars, pushing limits of HST, JWST data coming



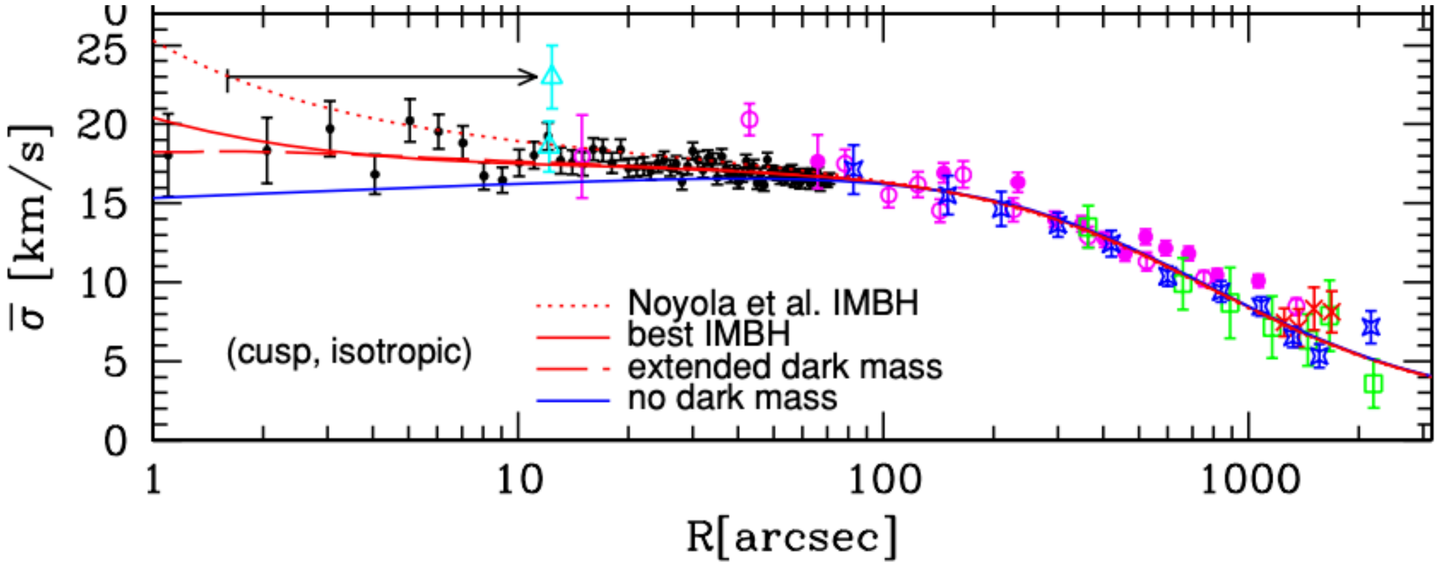


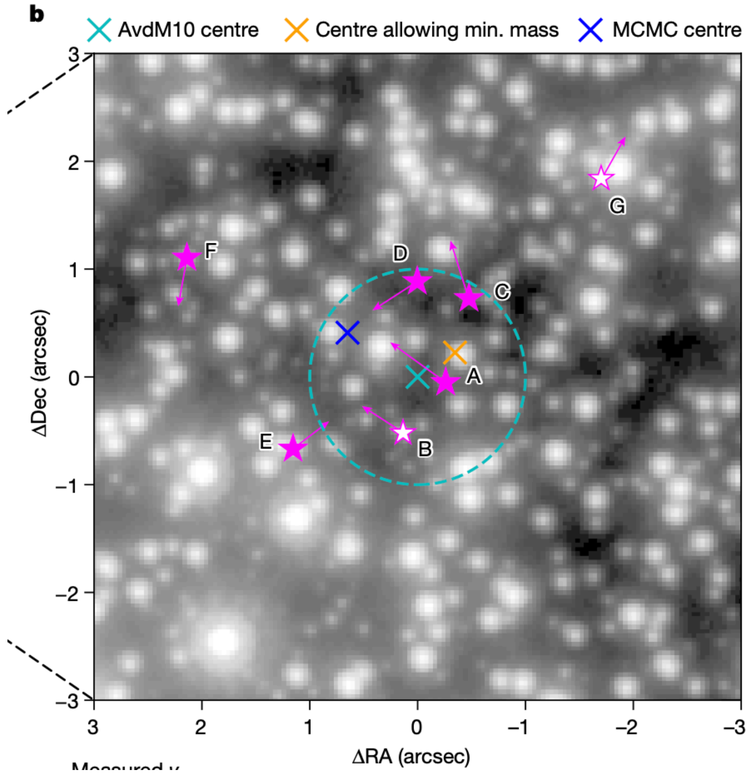


Intermediate Mass BHs in omega Centauri

For other GCs: for every confirmed detection, there is a confirmed non-detection. Very few PMs close enough to GC centres.

- **Hubble + LOSVs**
  - van der Marel & Anderson (2010): upper limit $M_{IMBH} < \sim 1.2 \times 10^4\ M_{sun}$
  - Häberle+ (2024): lower limit $M_{IMBH} < \sim 8.2 \times 10^3\ M_{sun}$



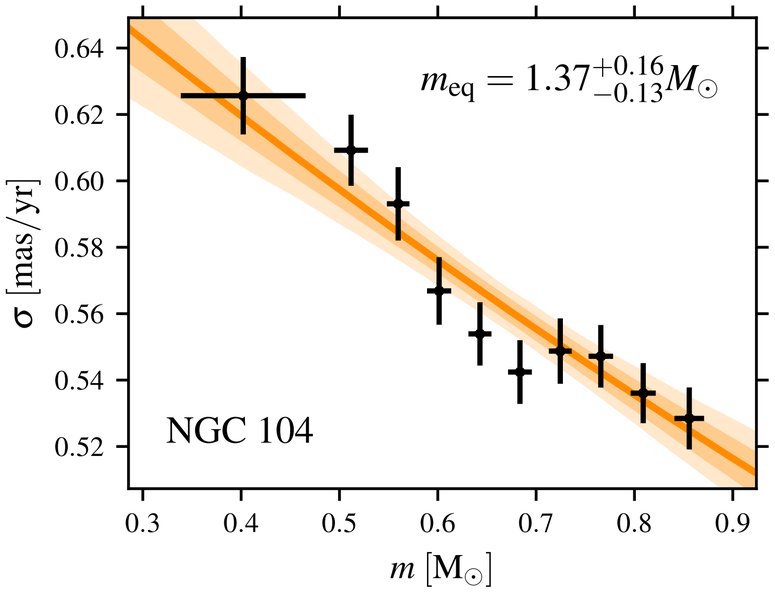


Globular Clusters - Energy Equipartition

- **Hubble**
  - Relative internal PMs of 22 MW GCs (Bellini+ 2014)
  - Energy equipartition in 9 of sample, support theory (Watkins+ 2022)

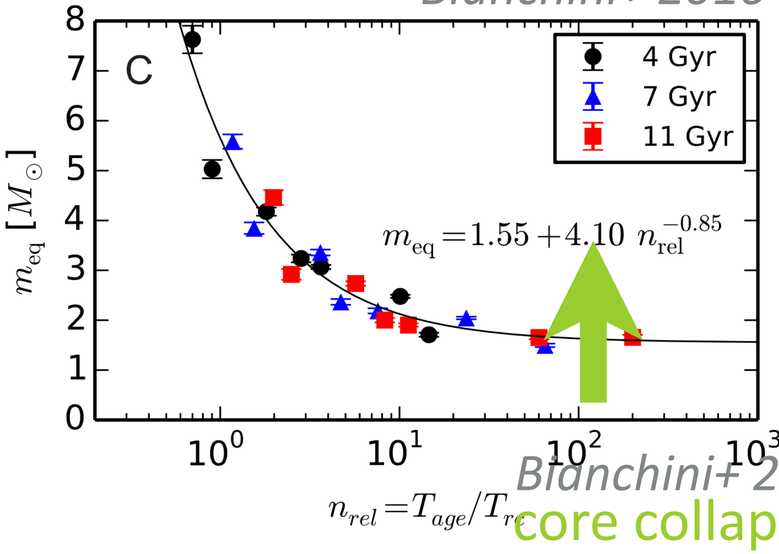
Watkins+ 2022

$\sigma \propto m^{-\eta}$ *Watkins+ 2022*



pre-core-collapse

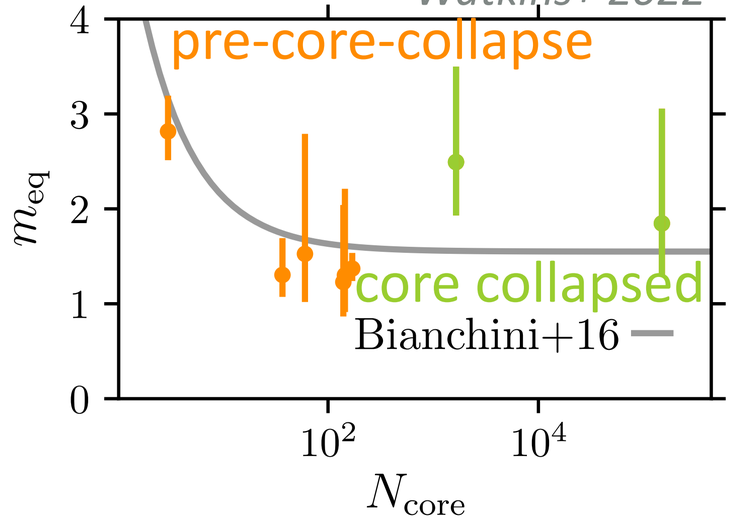
Bianchini+ 2016



Bianchini+ 2018

core collapsed

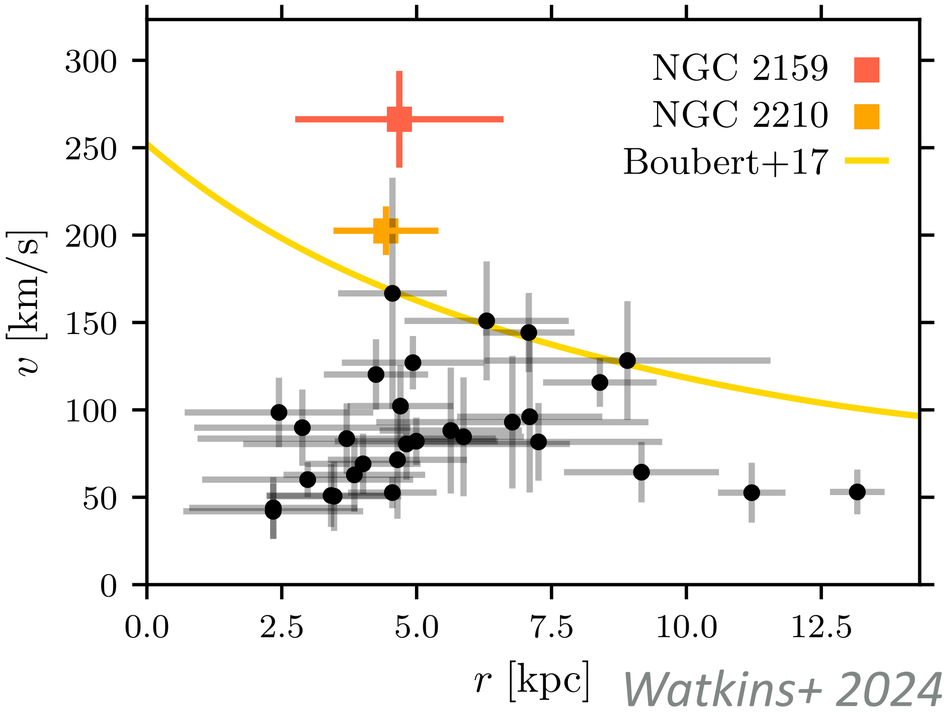
Watkins+ 2022



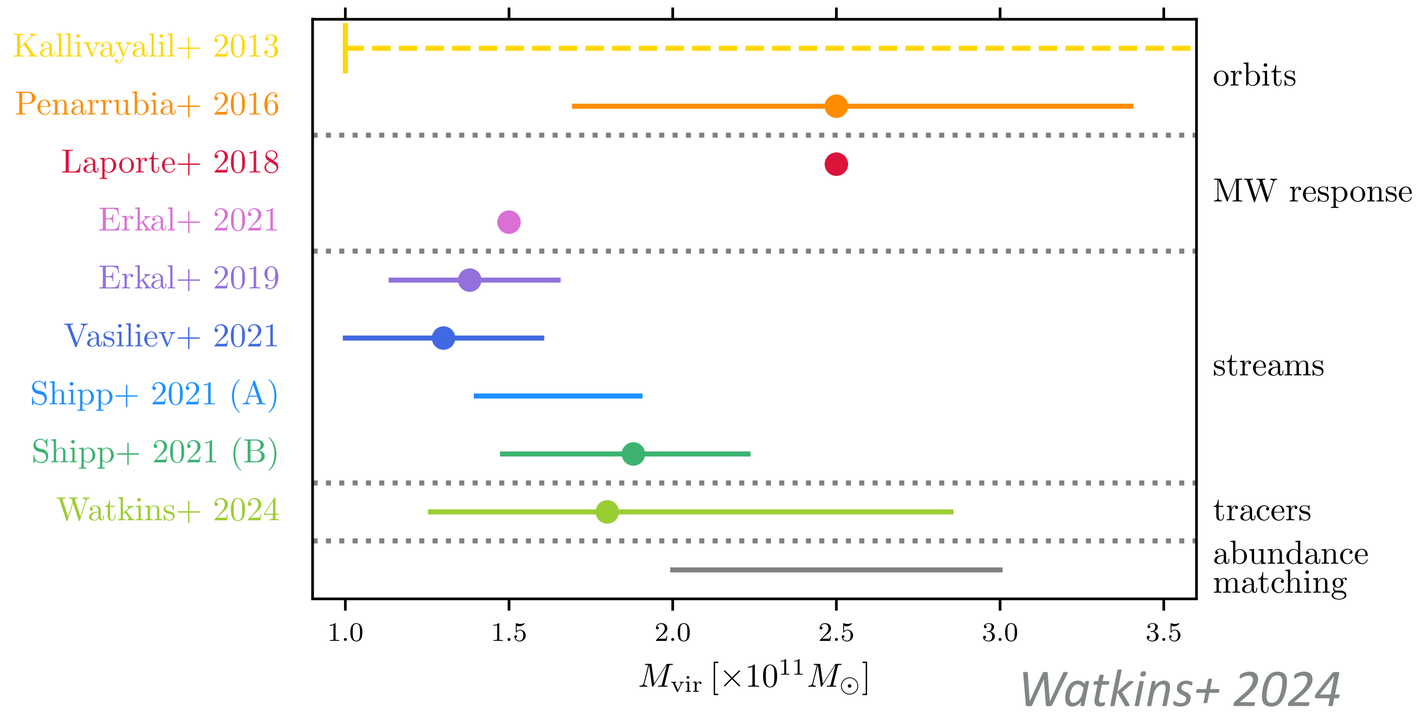
Mass of the Large Magellanic Cloud

- **Gaia, Hubble or Gaia+Hubble**
  - 6D catalogue of 32 GCs using PMs from GaiaHub (Bennet+ 2022)
  - Used 30 GCs: mass out to ~13 kpc, extrapolate total mass (Watkins+ 2024)

Some GCs excluded because no D or LOSV.



Watkins+ 2024



Watkins+ 2024

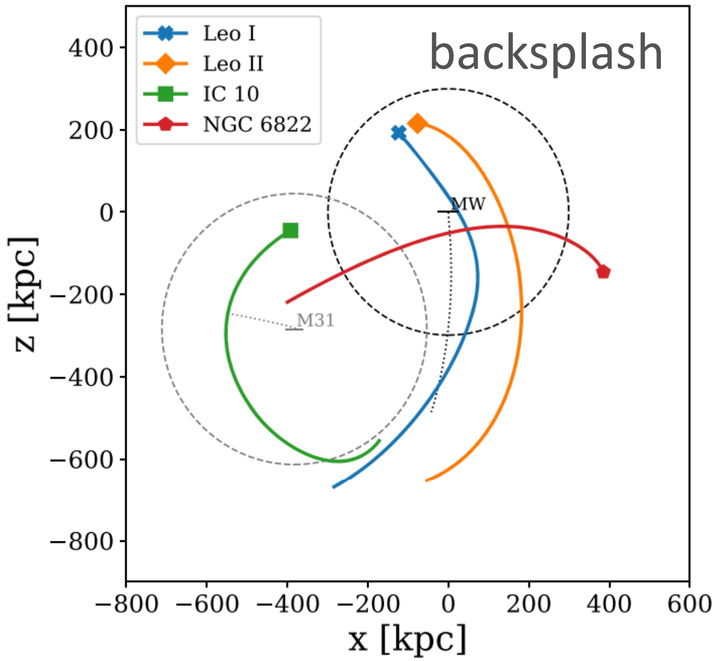
~~Mass of the Small Magellanic Cloud~~

- **Gaia, Hubble or Gaia+Hubble**
  - PMs of SMC GCs using GaiaHub (Bennet+ in prep)
  - Uncertainties too large + too few GCs to measure anisotropy or estimate mass

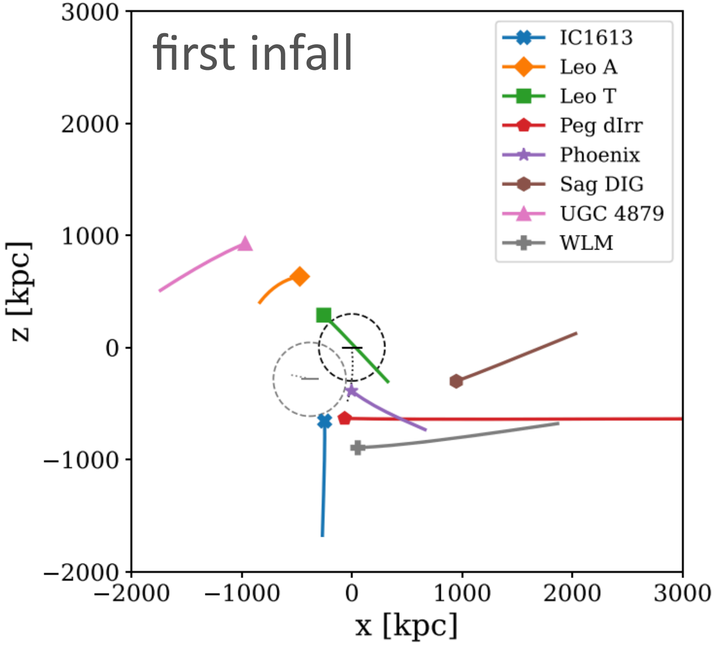
Orbits of Local Group Dwarfs ↔ SFHs

- **Gaia+Hubble (GaiaHub)**
  - PMs of LG dwarfs (Bennet, Patel+ 2024)
  - Orbits of dwarfs within the Local Group
  - More coming with Hubble

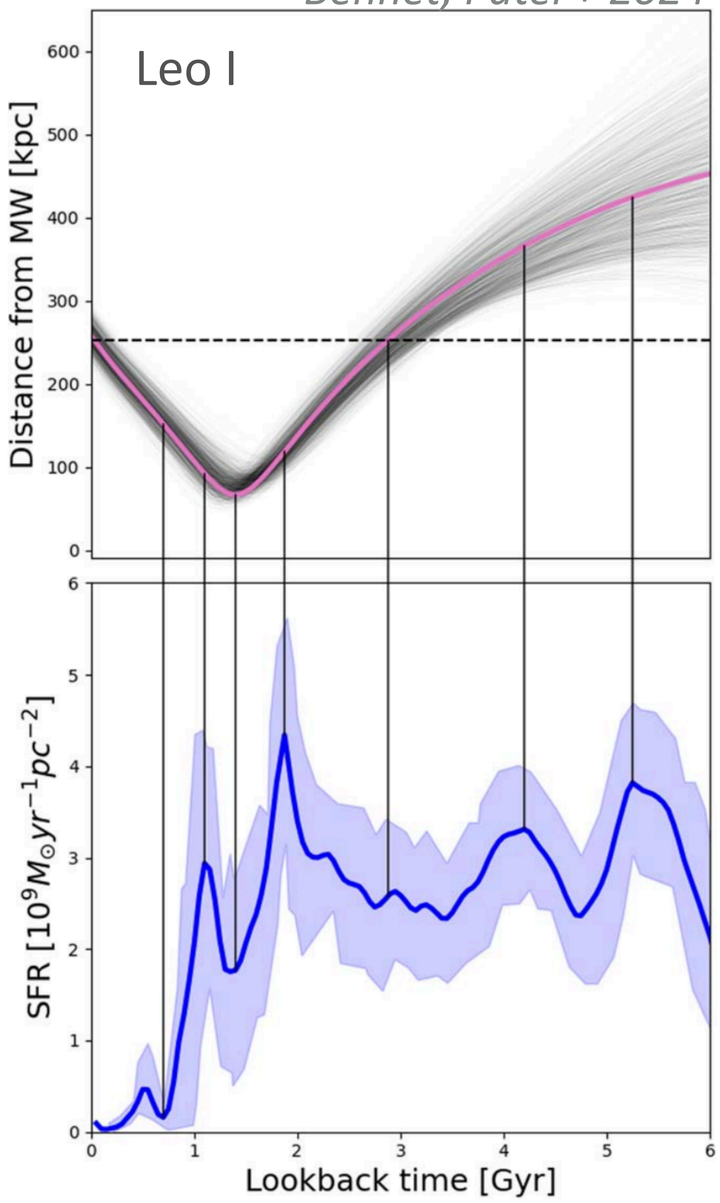
Bennet, Patel + 2024



Bennet, Patel + 2024



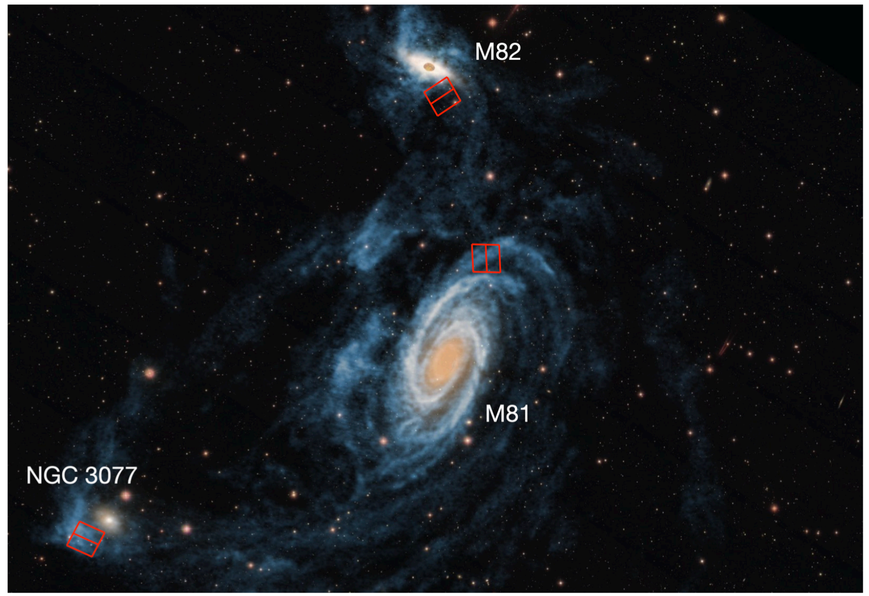
Bennet, Patel + 2024



PMs Outside the Local Group(!)

- **Hubble**
  - Cycle 31 program to measure PMs in M81, M82 and NGC 3077 (PI: Bennet)
  - ~3.6 Mpc, 20-year baseline
  - First time measuring PMs outside of the Local Group
    - Future of the M81 group?
    - Masses?
    - Motion of the M81 group relative to the LG?

Stay tuned!



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- **Internal Dwarf Kinematics**
  - Central density of **Draco** with 18 years of Hubble — *just one classical dwarf*
- **Internal GC Kinematics**
  - IMBH in **ωCen** — *just one (weirdo) GC*
  - Central equipartition in **9 nearby GCs** — *only 9/150 GCs, no radial profiles*
- **Global Dwarf and GC Kinematics**
  - MW mass, LMC mass, M31 mass — *SMC not possible, error bars still large*
  - MW/M31/LG dwarf orbits — *error bars still large*
  - M81 group kinematics — *only 1 system outside LG, what about GC systems outside the LG?*

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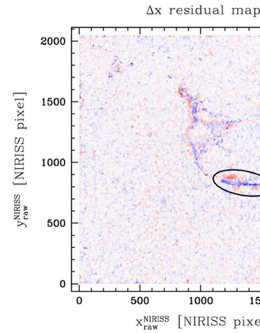
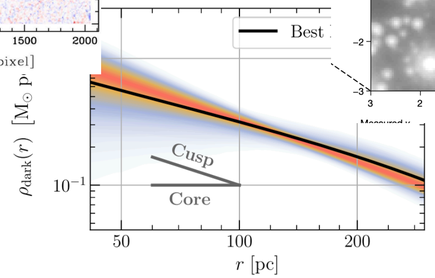
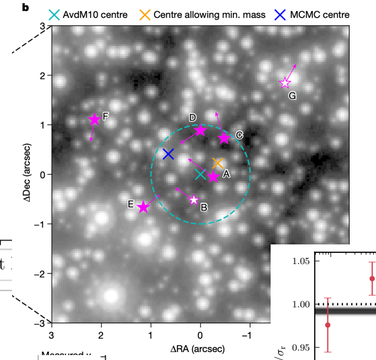
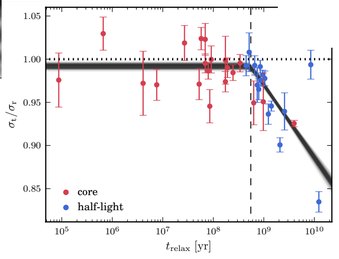
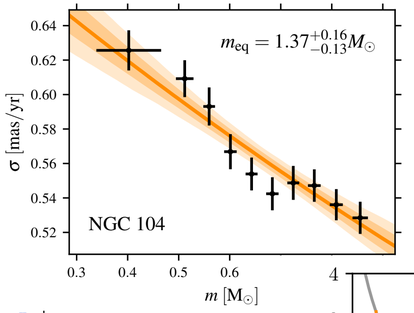
- **Hubble + Gaia : astrometric powerhouses (excited for JWST, Euclid, Roman!)**
  - We can already do a lot of cool stuff, separately and combined! **BUT**
  - Single/few objects, small samples, distance limited, spatially limited, biased.

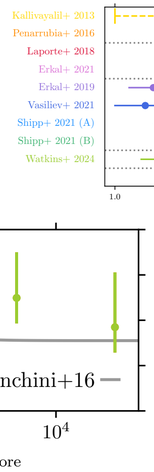


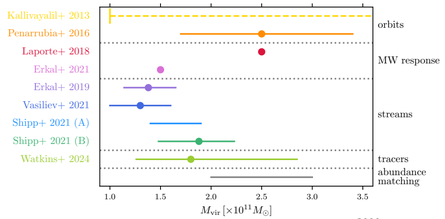


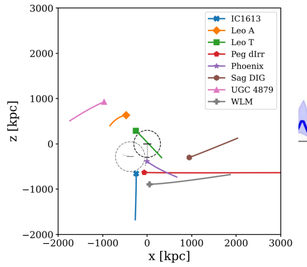


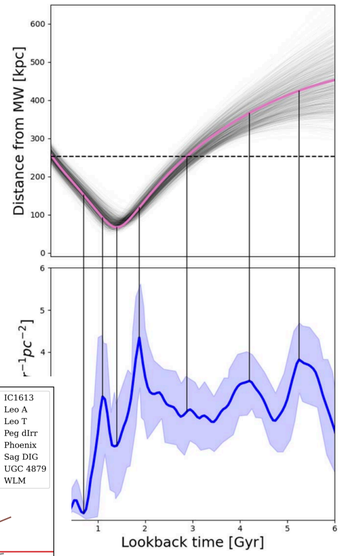












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