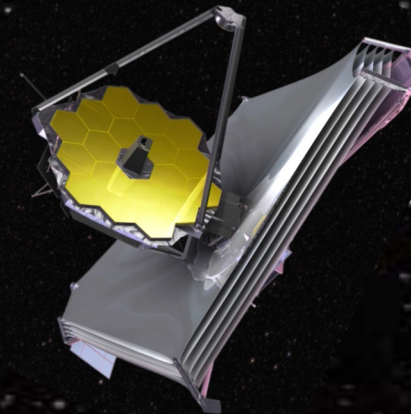
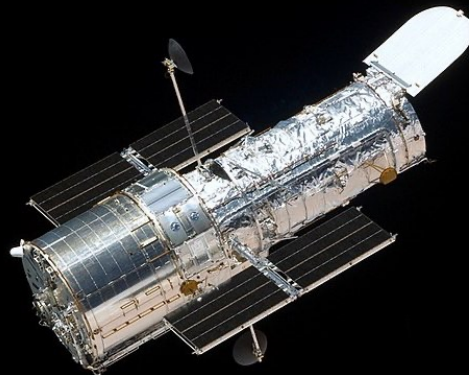
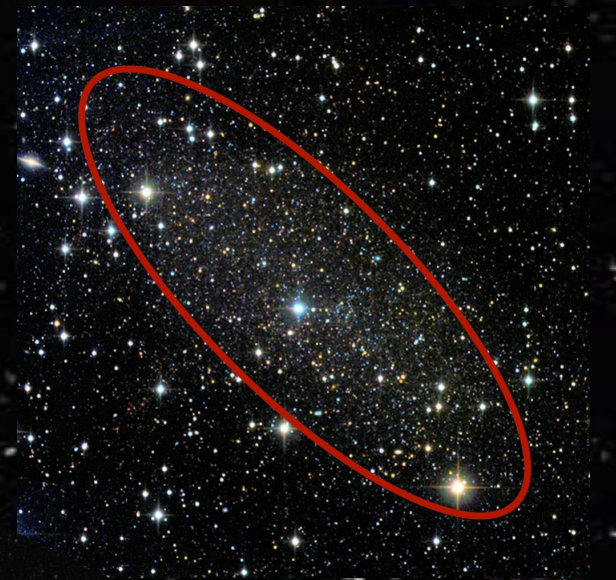


Dark Matter Cusp Slopes in Dwarf Spheroidal Galaxies from Hubble and JWST Proper Motions

Roeland van der Marel (STScI)

with

[Eduardo Vitral](#), Tony Sohn (STScI), et al.



(ApJ, 2024, 970, 1
& more papers in prep.)

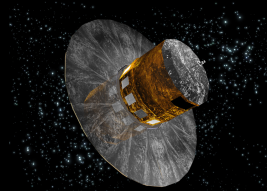
HSTPROMO: High-Resolution Space Telescope Proper Motion Collaboration

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

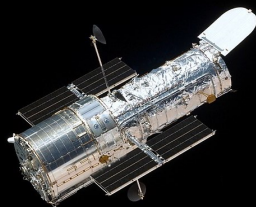
- Set of many different HST, Gaia, JWST investigations, with detailed theory components
 - Lead coordinators:
van der Marel & Anderson
 - Current key members:
Bellini, Bennet, Besla, del Pino, Fardal, Griggio, Guhathakurta, Kallivayalil, Libralato, McKinnon, Patel, Pawlowski, Sohn, Vitral, Warfield, Watkins
 - Many other (former) associates
- Status/Achievements
 - 20 years of work
 - 61 HST, 22 Gaia, 1 JWST papers



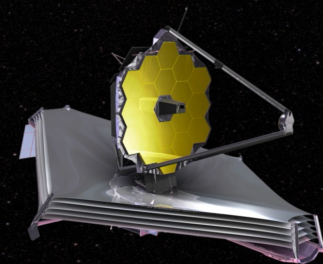
Proper Motion (PM) Capabilities from Space



- **GAIA:**
 - Fantastic for innumerable things + full sky coverage
 - Limited to $G < 20$ (and hence, “nearby” distances)



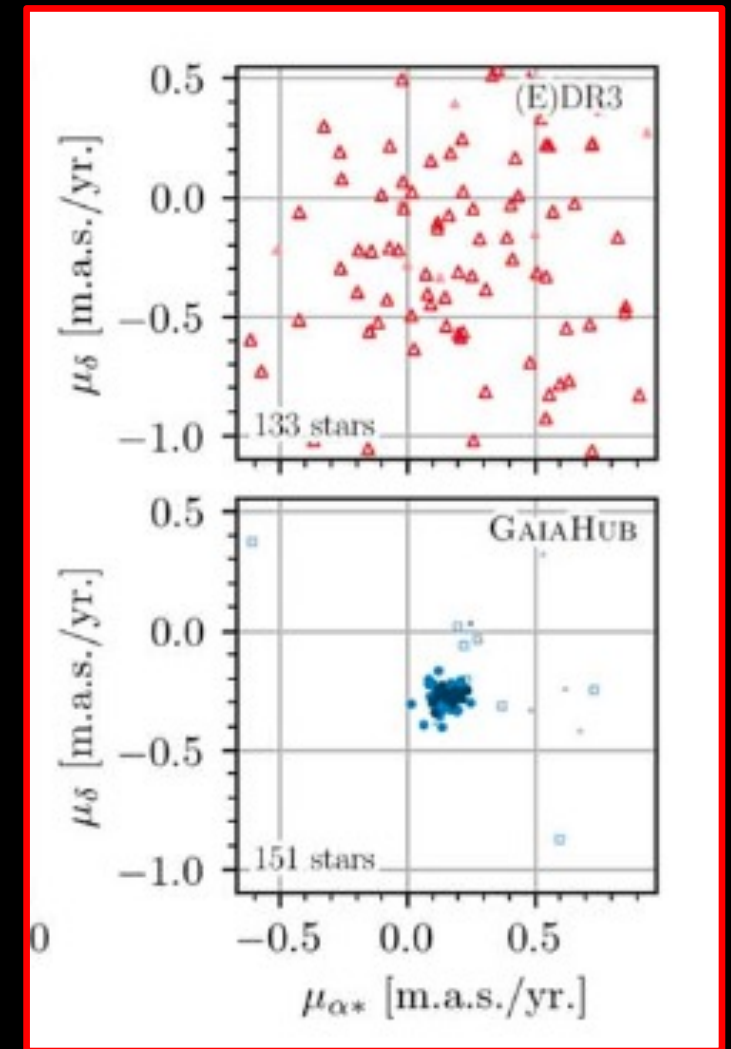
- **HST:**
 - Long time baselines with small FOV
 - High Accuracies to much fainter limits ($V \sim 25$)



- **JWST:**
 - Similar spatial resolution and FOV to HST
 - Large mirror enables deeper studies
 - Infrared opens up extincted regions

Going beyond Gaia with Hubble and/or Webb

- Internal Dynamics
 - Galactic Center
 - Globular clusters
 - nearby dSphs (this talk)
- Bulk PMs of nearby-Universe galaxies (relative to background galaxies)
 - M31, M32, M33, Andromeda dSph system
 - Distant Isolated Local Group Dwarfs
 - Galaxies beyond the Local group (Cycle 31+32: Leo P, M81 group, Cen A)
- Improved PM accuracies from HST+Gaia
 - GaiaHub (del Pino+ 2022) →
 - BP3M (McKinnon+ 2024)



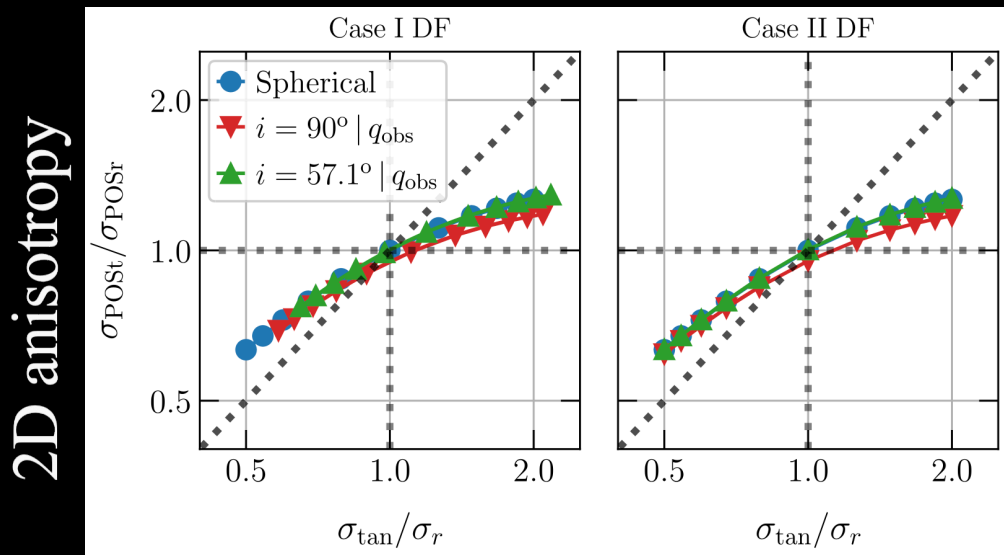
Draco

Central Dark Matter (DM) Cusp Slopes

- Collisionless Λ CDM predicts a central $\rho(r) \sim r^{-\gamma}$ density **cusp** with $\gamma \sim 1$ (e.g., NFW)
- Other DM candidates (e.g., hot, warm, self-interacting) predict a more homogeneous **core**
- Baryonic processes inside a DM halo can lower the cusp slope
- These processes are more applicable in more massive galaxies
- Hence:
 - Measurements of central DM density cusps can constrain both the nature of DM and the physics of galaxy formation
 - Low-mass dSph galaxies provide the cleanest constraints on DM properties

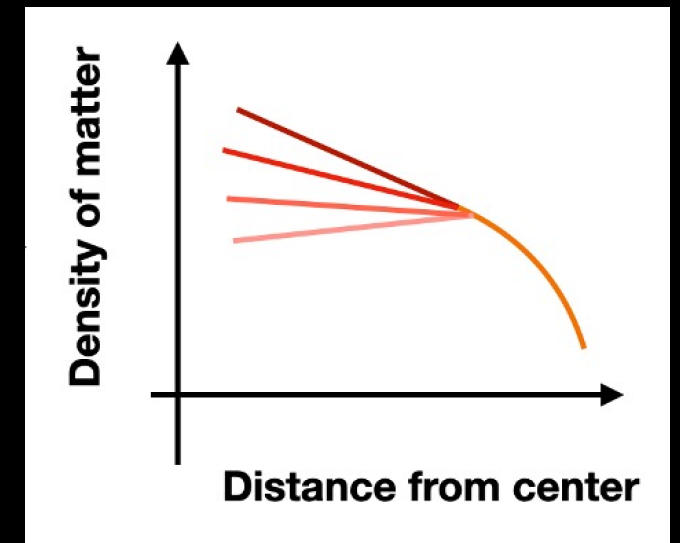
The Role of Proper Motions

- Line-of-sight velocities: Mass-anisotropy degeneracy
 - Different density profiles with different velocity dispersion anisotropies can all fit a given dataset equally well
- Proper Motions: directly constrain the anisotropy
 - Even in absence of line-of-sight velocities

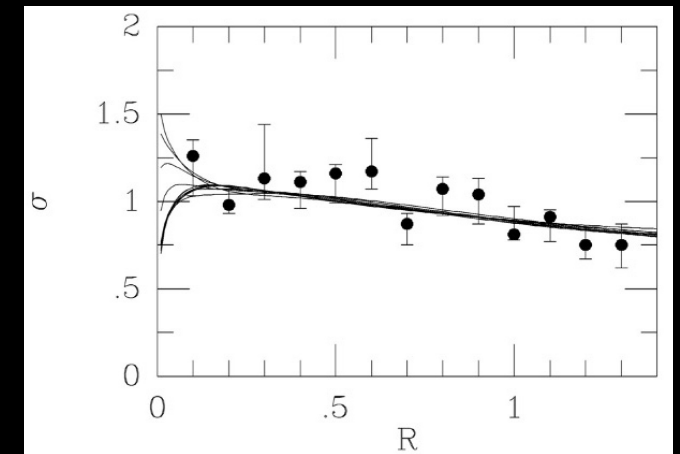


2D anisotropy

3D anisotropy



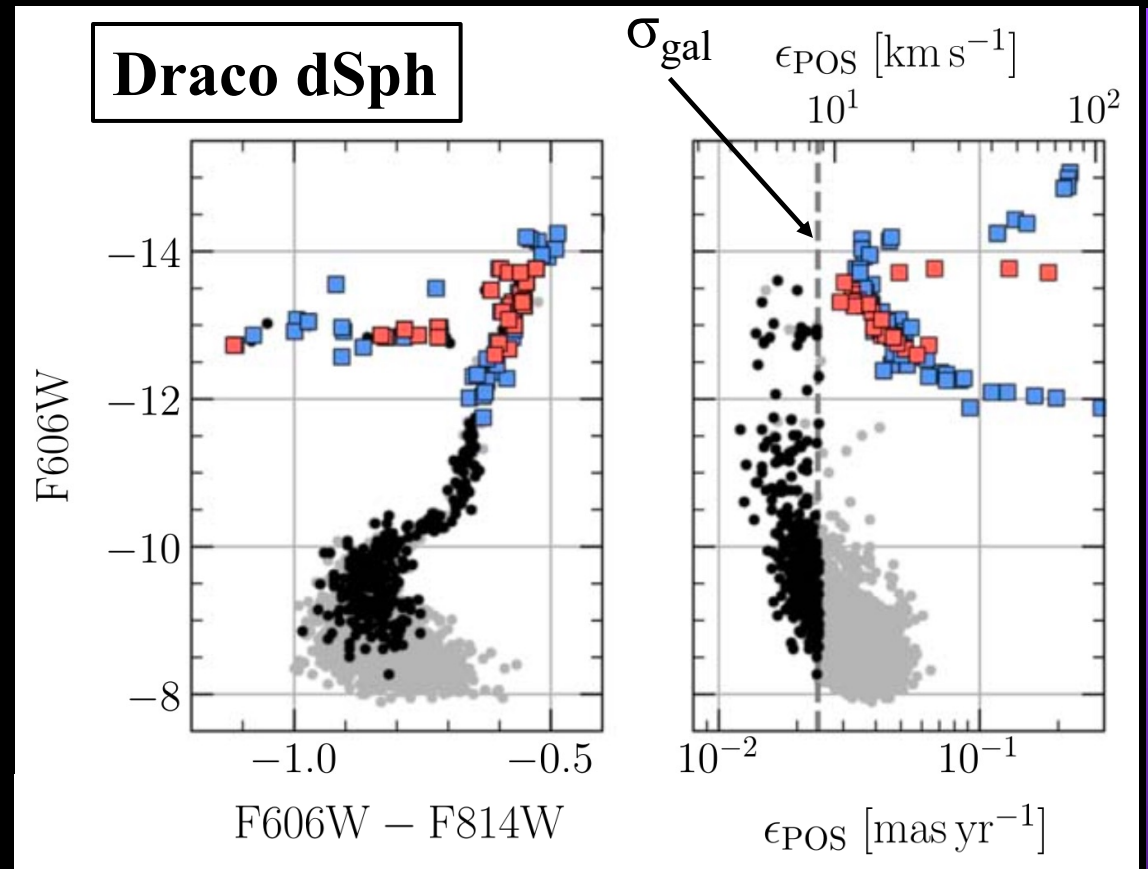
↓ Jeans



[vdM et al. 2000]

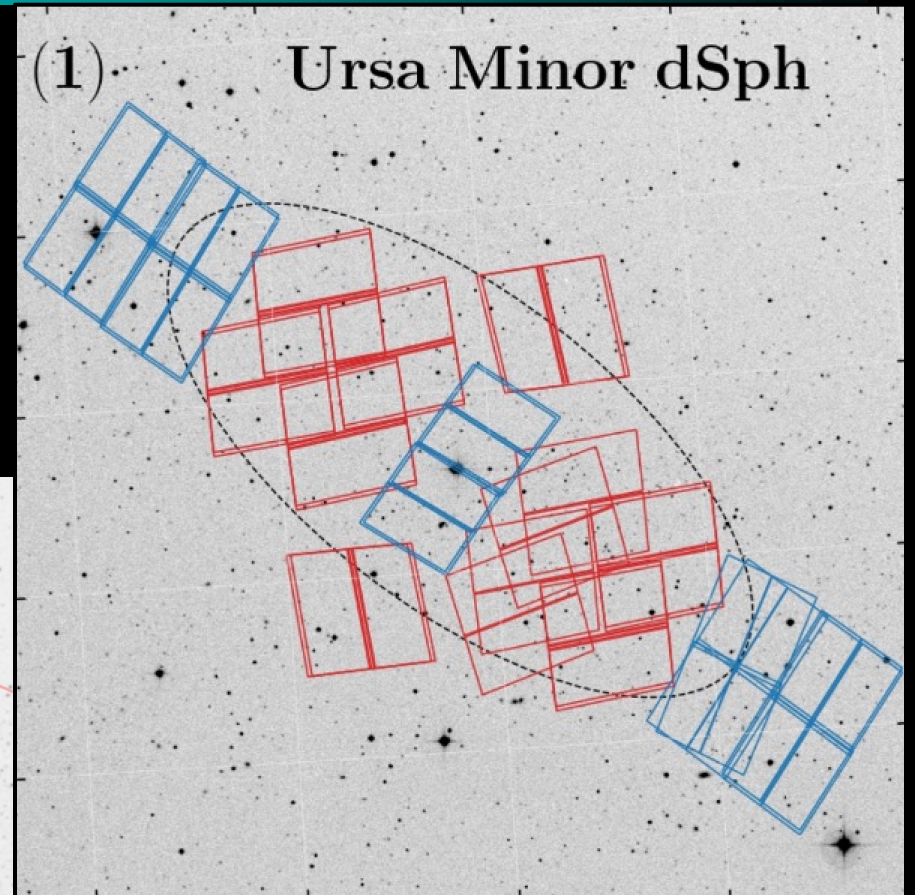
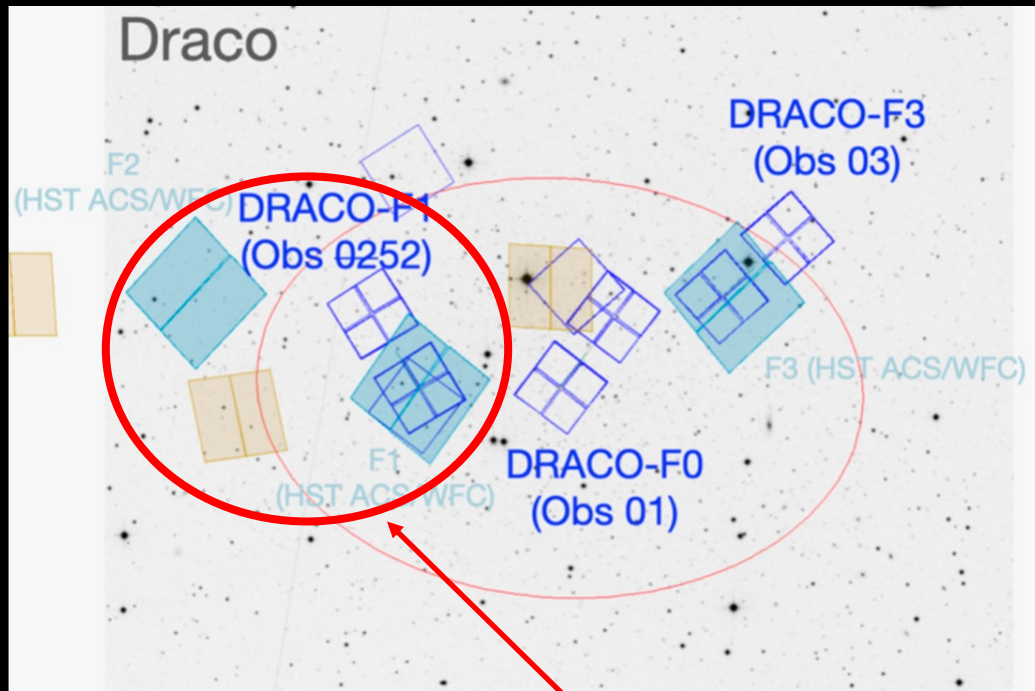
HST/JWST vs. Gaia

- Gaia can determine **bulk PMs** even for UFDs out to hundreds of kpc
 - Large per-star uncertainties combined with $1/\sqrt{N}$ averaging
- Measuring **PM dispersions** more difficult, not possible with Gaia even for classical dSphs at ~ 100 kpc
 - Requires per-star uncertainties below galaxy dispersion
- HST/JWST can do this over small fields
 - Fainter stars, yet smaller uncertainties
- (Note: Libralato et al. 2023 with HST vs. JWST in LMC over 16yr time baseline obtain 13 $\mu\text{as}/\text{yr}$ accuracy at $G\sim 20$, better than median Gaia eDR3 error at $G\sim 9-12$!)

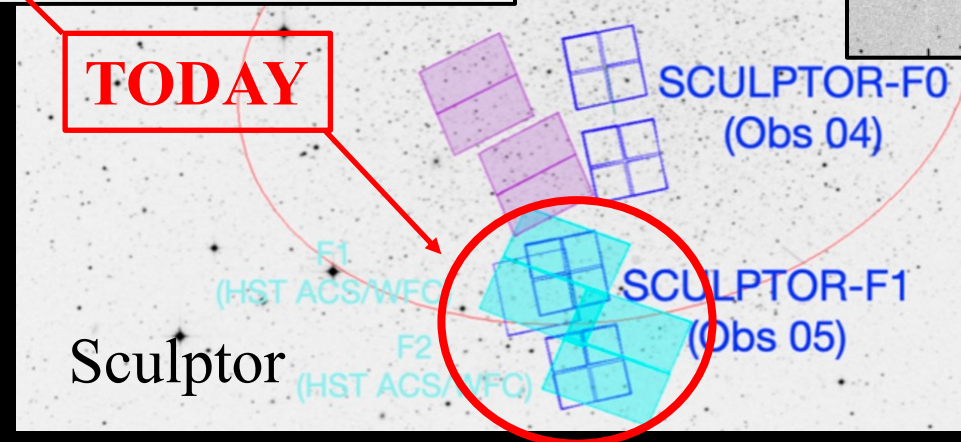


colored: HST vs. Gaia
(Massari et al. 2020; del Pino et al. 2022)
black/gray: HST 18 yr

Ongoing Observational Programs



- Various HST+JWST programs, up to 22yr time baseline (PIs: vdM, Sohn, Bennet)

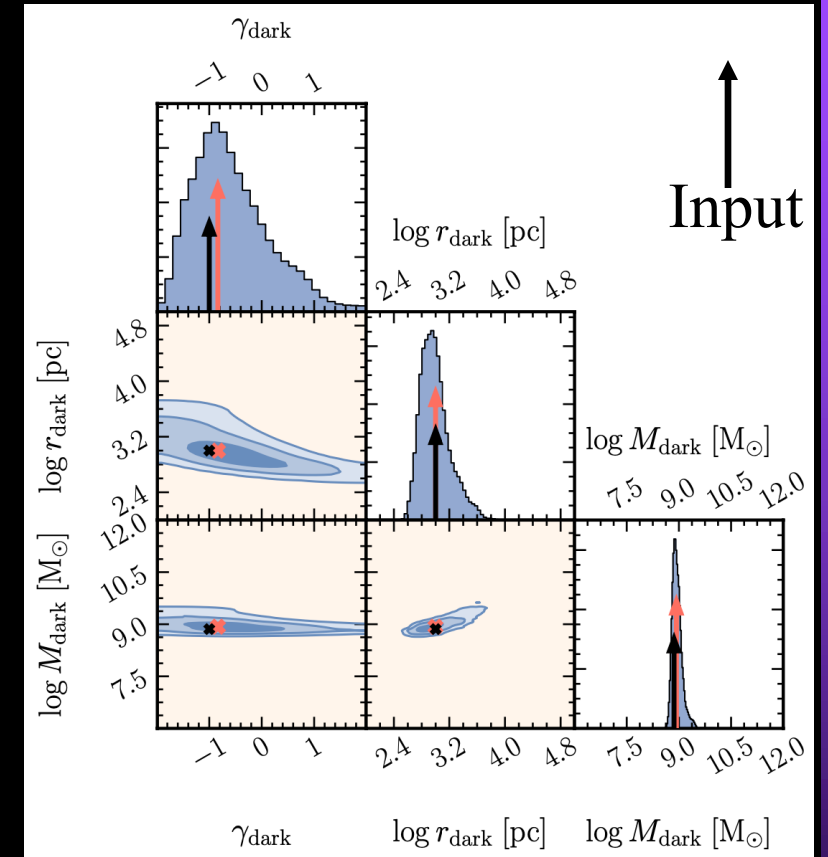


- HST only, 10yr time baseline (PI: Vitral)

Oblate Axisymmetric Jeans Models

JAMPY implementation (Cappellari 2020)

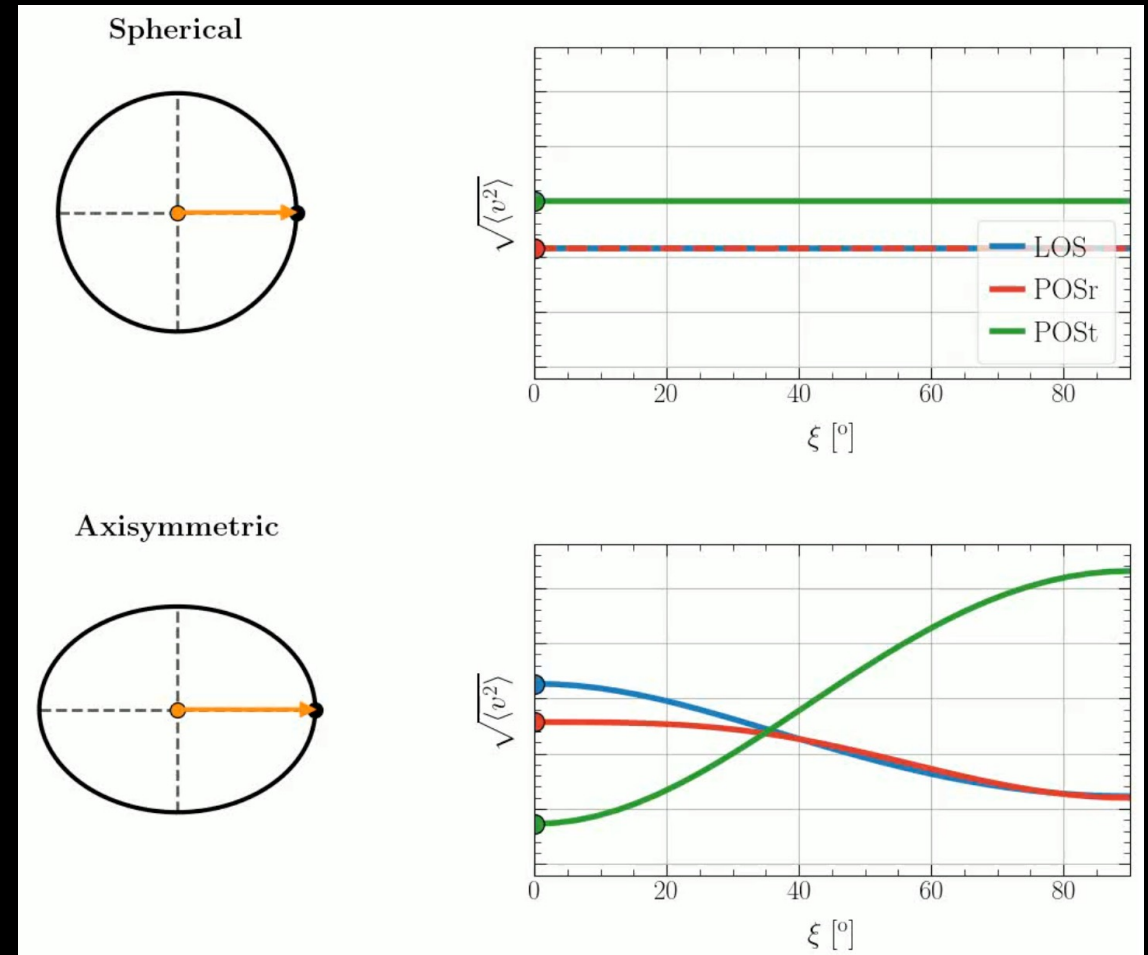
- Parameterized forms of
 - Dark halo density
 - Velocity dispersion anisotropy (β)
 - Separation into azimuthal rotation and dispersion
 - Choice of viewing inclination
-
- Tracer density chosen to fit number counts
 - Model parameters chosen to fit kinematics
 - Tested on mock datasets created using AGAMA
-
- Unlike past work, addresses all of the following:
non-sphericity, rotation, proper motions



Mock data test

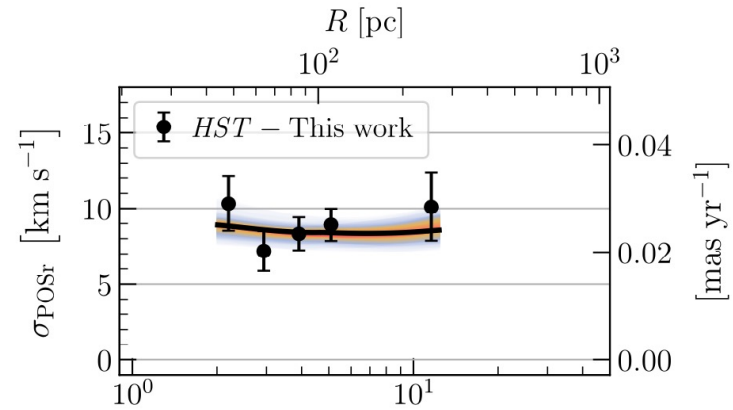
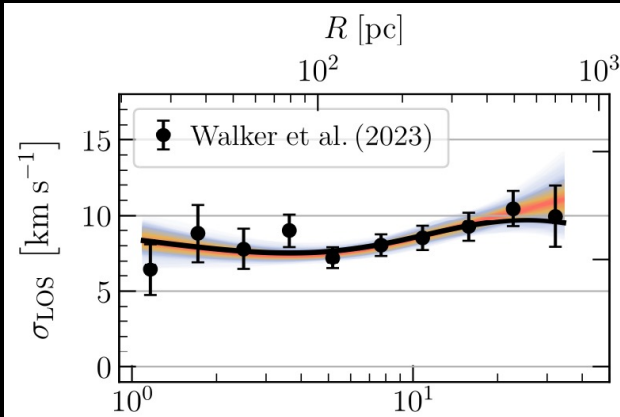
Inadequacy of Spherical Models

- In axisymmetric galaxies, projected quantities depend strongly on sky position angle (ξ)
- Especially when (PM) data is only available for fields at specific angles, axisymmetric modeling is essential
- For example, for the Draco dSph spherical models yield significantly biased results:
 - $\Delta \beta \sim +0.59$ (anisotropy too radial)
 - $\Delta \gamma \sim -0.47$ (cusp slope too flat)

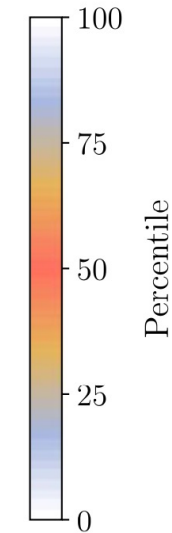
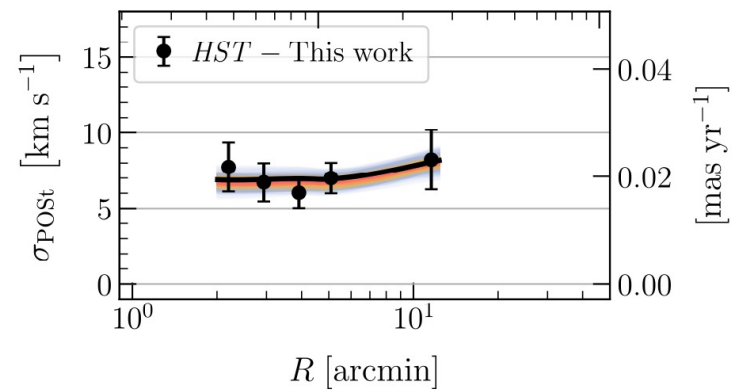
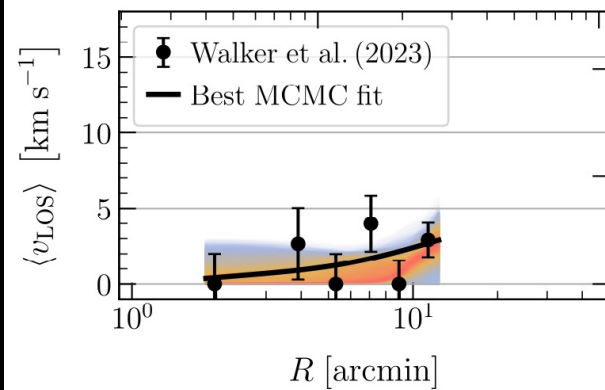


Data-Model Comparison: Draco

LOS dispersion



LOS rotation

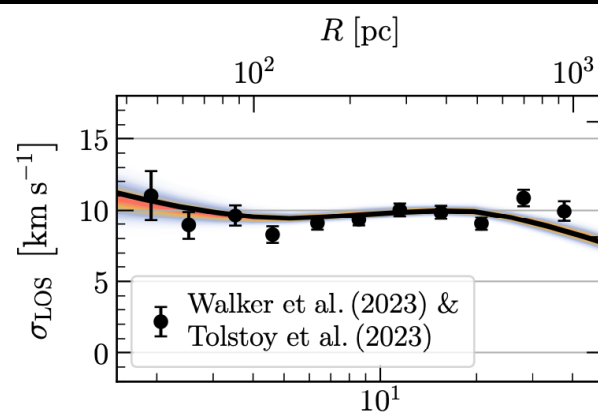


PM radial dispersion

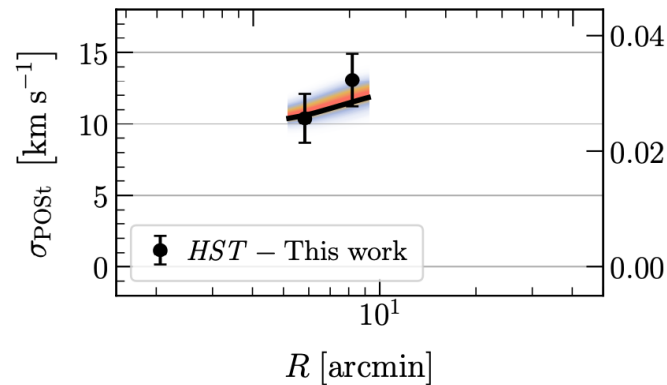
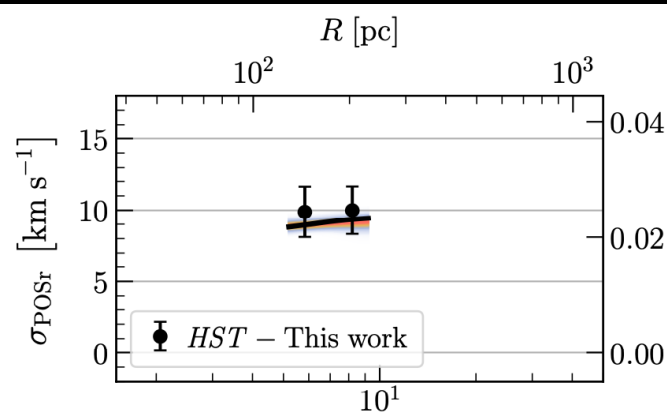
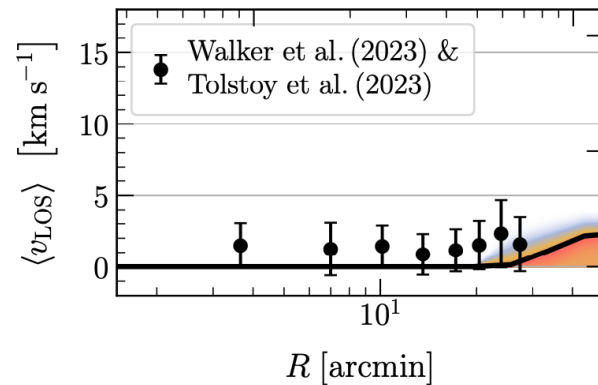
PM tangential dispersion

Data-Model Comparison: Sculptor

LOS dispersion

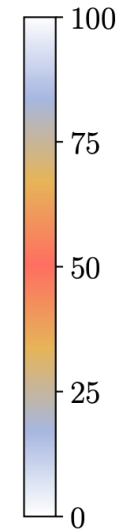


LOS rotation



[mas yr⁻¹]

[mas yr⁻¹]

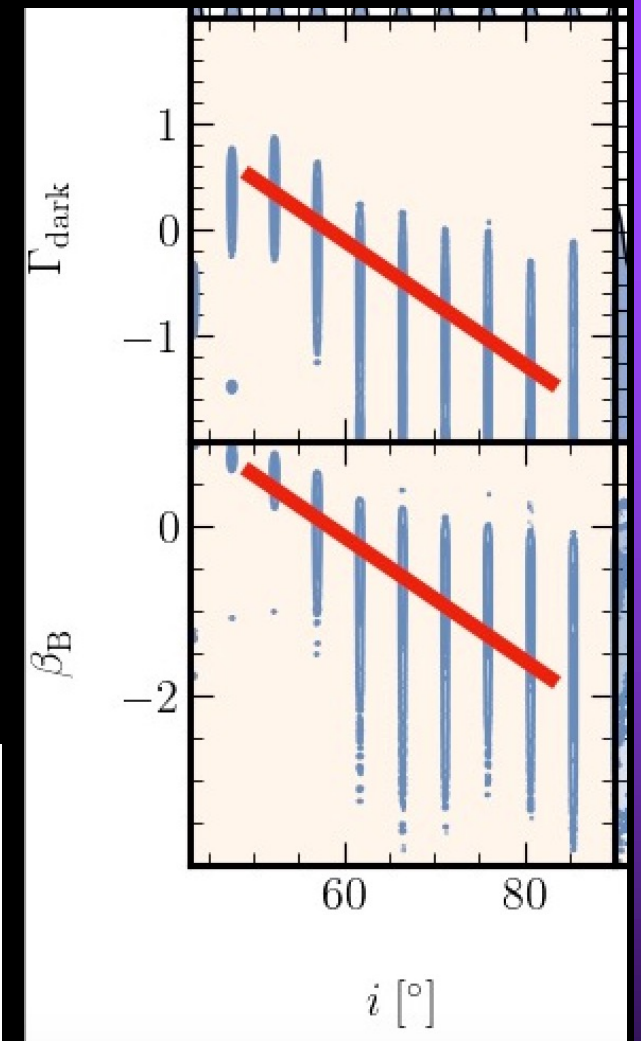
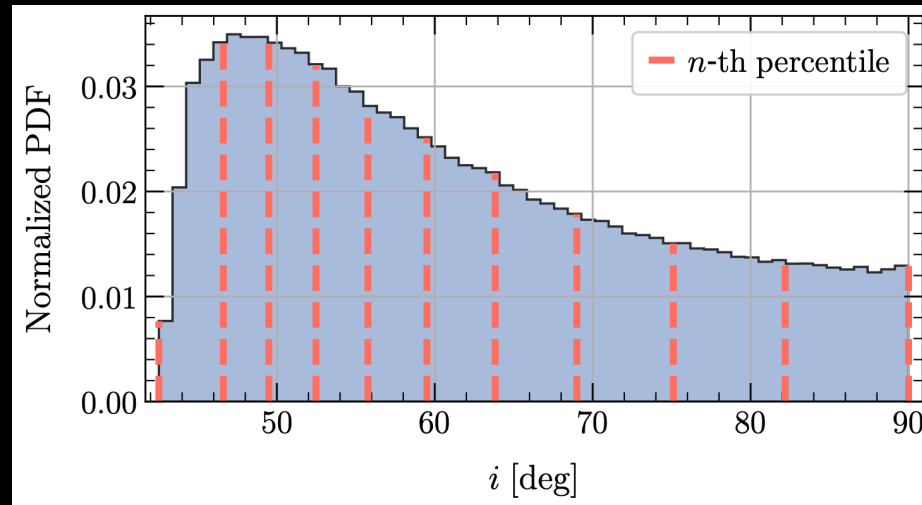


PM radial dispersion

PM tangential dispersion

Inclination Dependence

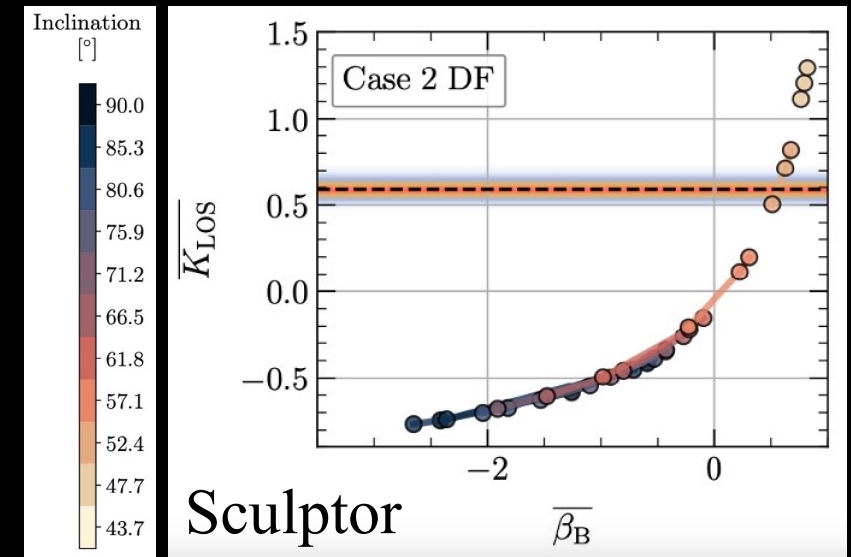
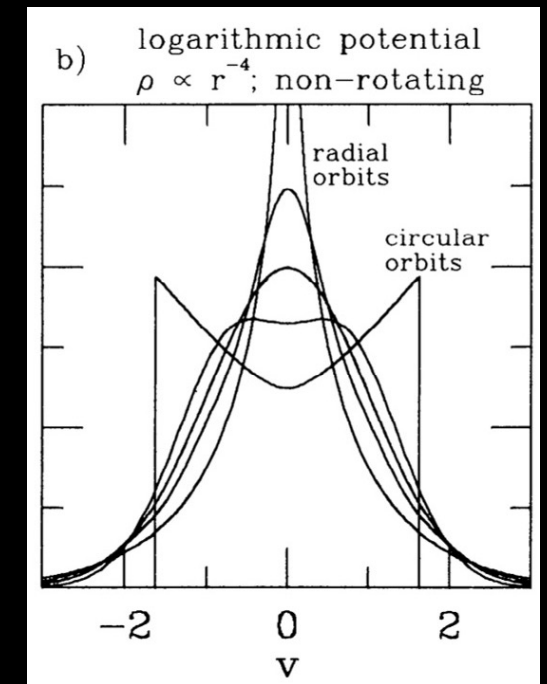
- Inferred cusp slope and velocity dispersion anisotropy can depend strongly on assumed galaxy inclination
- Galaxy inclination in general only constrained statistically from inversion of the overall galaxy shape distribution
- Can add significant uncertainty to inferred DM cusp slope



Sculptor dSph

Higher-Order Velocity Moments

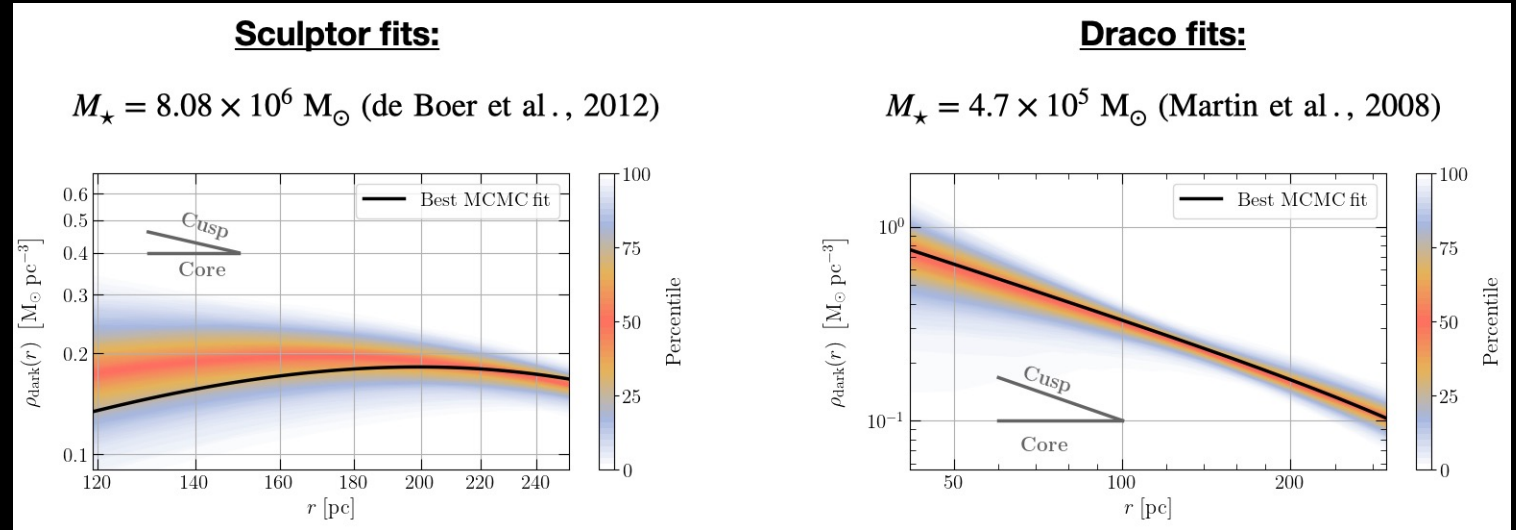
- Kurtosis can be reliably determined for LOS velocities
- Quantifies the shape of the velocity distribution, which correlates strongly with the velocity dispersion anisotropy
- Requires distribution function (DF) models to interpret (Jeans equations don't suffice)
- Scale-free DF models (deBruijne, vdM et al. 1997) provide useful insight
- For Sculptor, only highly inclined models can reproduce the observed LOS kurtosis



Caveats/Complications

- HST/JWST relative PM measurements do not measure PM rotation
 - Taken into account in data-model comparison
- Measured PM dispersions are sensitive to systematics when measurement errors are comparable to galaxy dispersion
 - Various corrections and tests for systematics are applied
- Binaries can inflate LOS dispersion relative to PM dispersion
 - Assessed via stars with multiple-epoch measurements
- Tides can perturb the hydrostatic equilibrium of the galaxy
 - Not believed to be significant for Draco and Sculptor dSphs
- Multiple distinct kinematic components can bias the results
 - Assessed via tests on mock datasets

Inferred DM Density Profiles



- Sculptor: consistent with a DM core. NFW slope ruled out at 98% conf.
 - $\gamma = +0.17 (+0.04 -0.70)$ [over observationally constrained range]
- Draco: consistent with NFW slope, core >0.7 kpc ruled out at 95% conf.
 - $\gamma = -0.83 (+0.32 -0.37)$ [over observationally constrained range]
- Difference consistent with simulations showing impact of baryonic physics becomes important above $M_{\star} \sim 10^6 M_{\odot}$ (e.g., Fitts et al. 2017)

Conclusions

- HST and JWST enable PM studies in subject areas beyond the reach of Gaia, including 3D internal kinematics of dSph galaxies
 - High accuracy to faint magnitudes, but over small FOV
- Datasets with up to 20+ yr time baselines are being assembled for several classical dSph galaxies
- Axisymmetric modeling is key to exploit such data
 - Jeans models adequate, but DF/Schwarzschild models would be even better
- Results for Draco and Sculptor are broadly consistent with the predictions of Λ CDM + baryonic physics

