# The distortion of the Tucana IV by the recent close passage of the Large Magellanic Cloud

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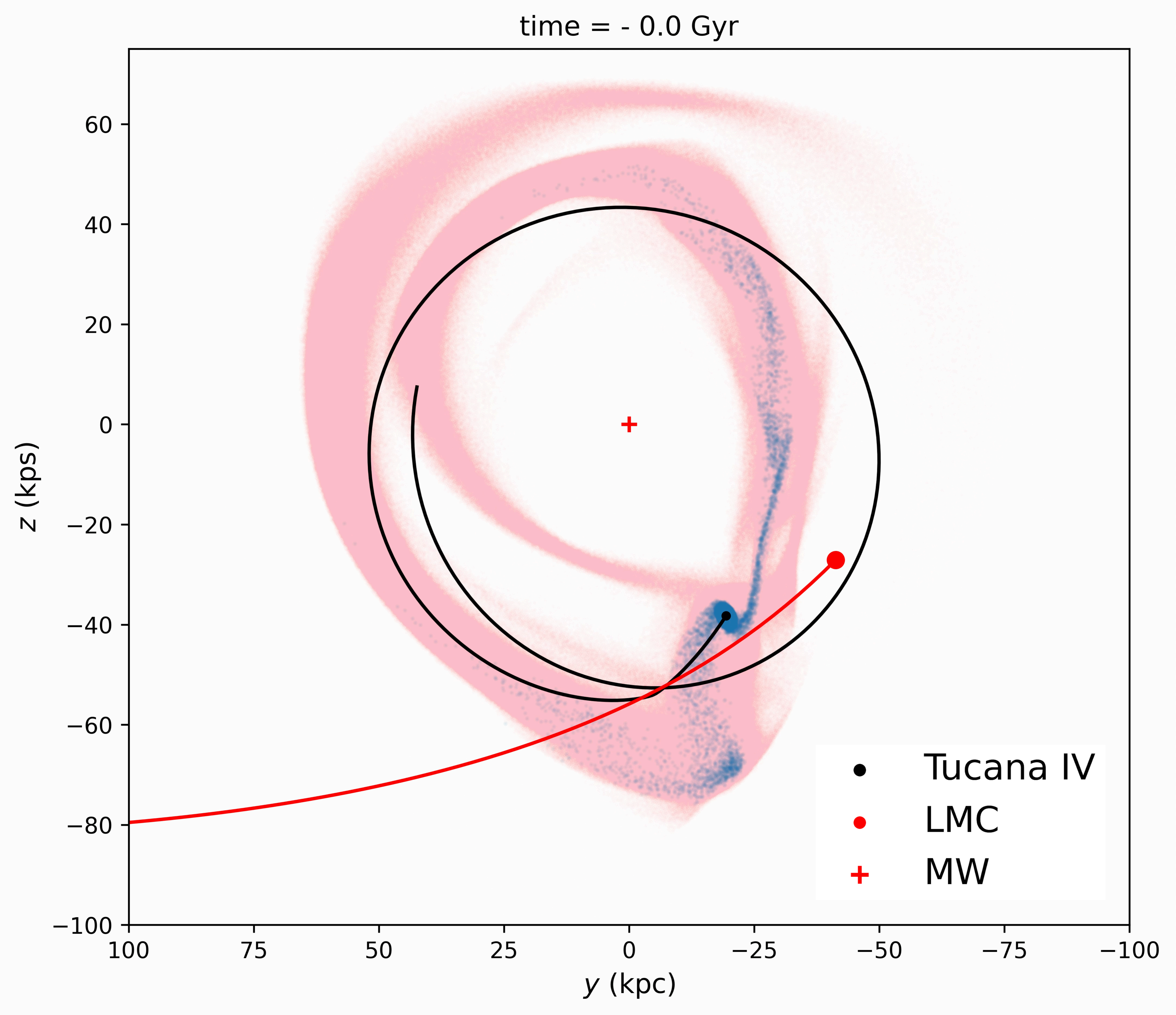
**National Astronomy Meeting (NAM) 2025**

# Results of the Tucana IV N-body simulations with Gadget-3

- Tucana IV dwarf had a **close passage** (~4 kpc) **with the LMC** ~130 Myr ago [Simon et al. 2020].

- Tucana IV **tidal radius ≈ its' half-light radius** with respect to the LMC at their closest approach.

- The effect of the LMC on Tucana 4 is pronounced. Simulation results match the observations at the outer area (>2 degrees), but not in the inner observed region.



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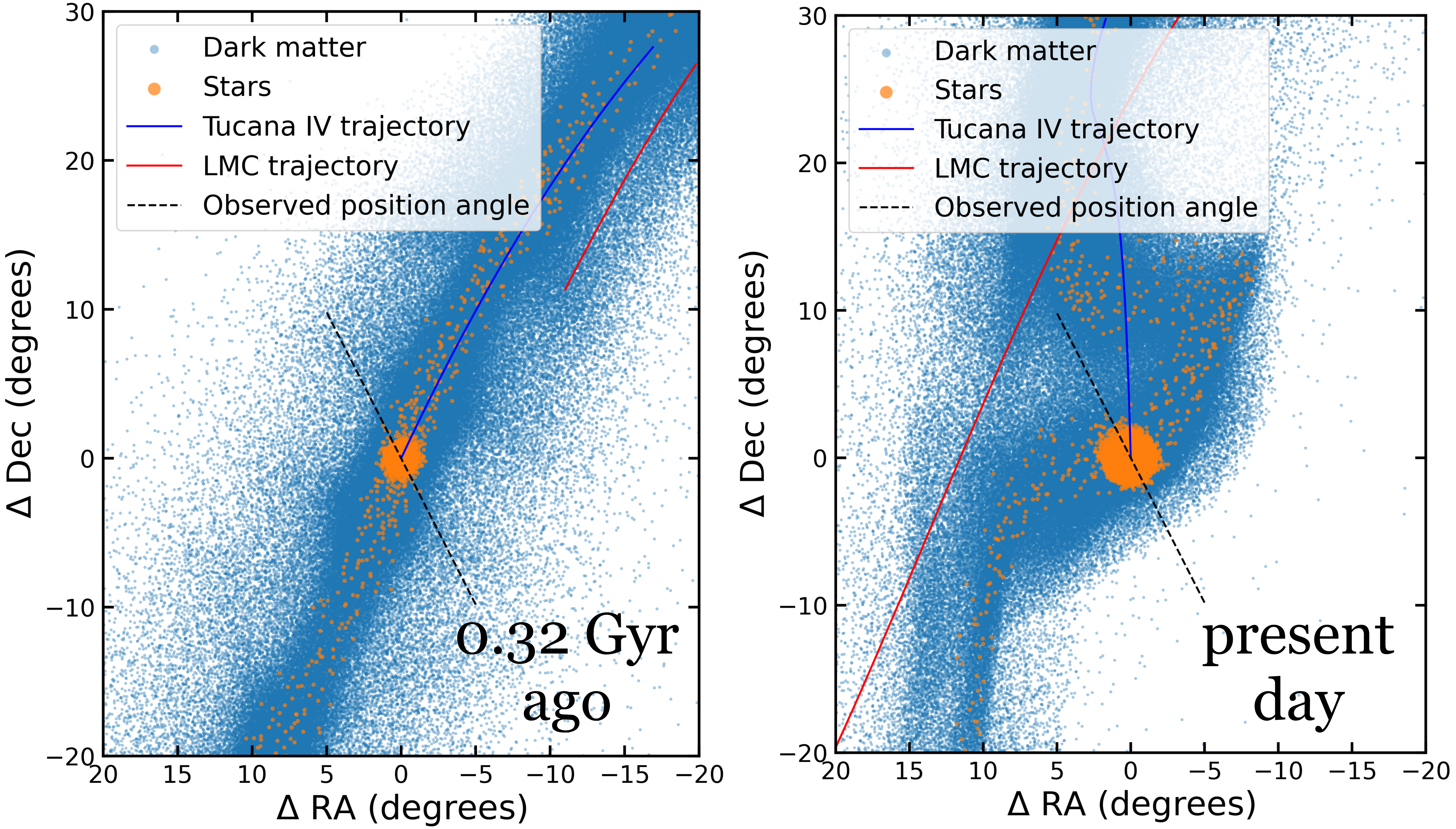


On-sky distribution of dark matter (blue) and stars (orange) of Tucana IV, its past trajectory (blue line) and past trajectory of the LMC (red line).

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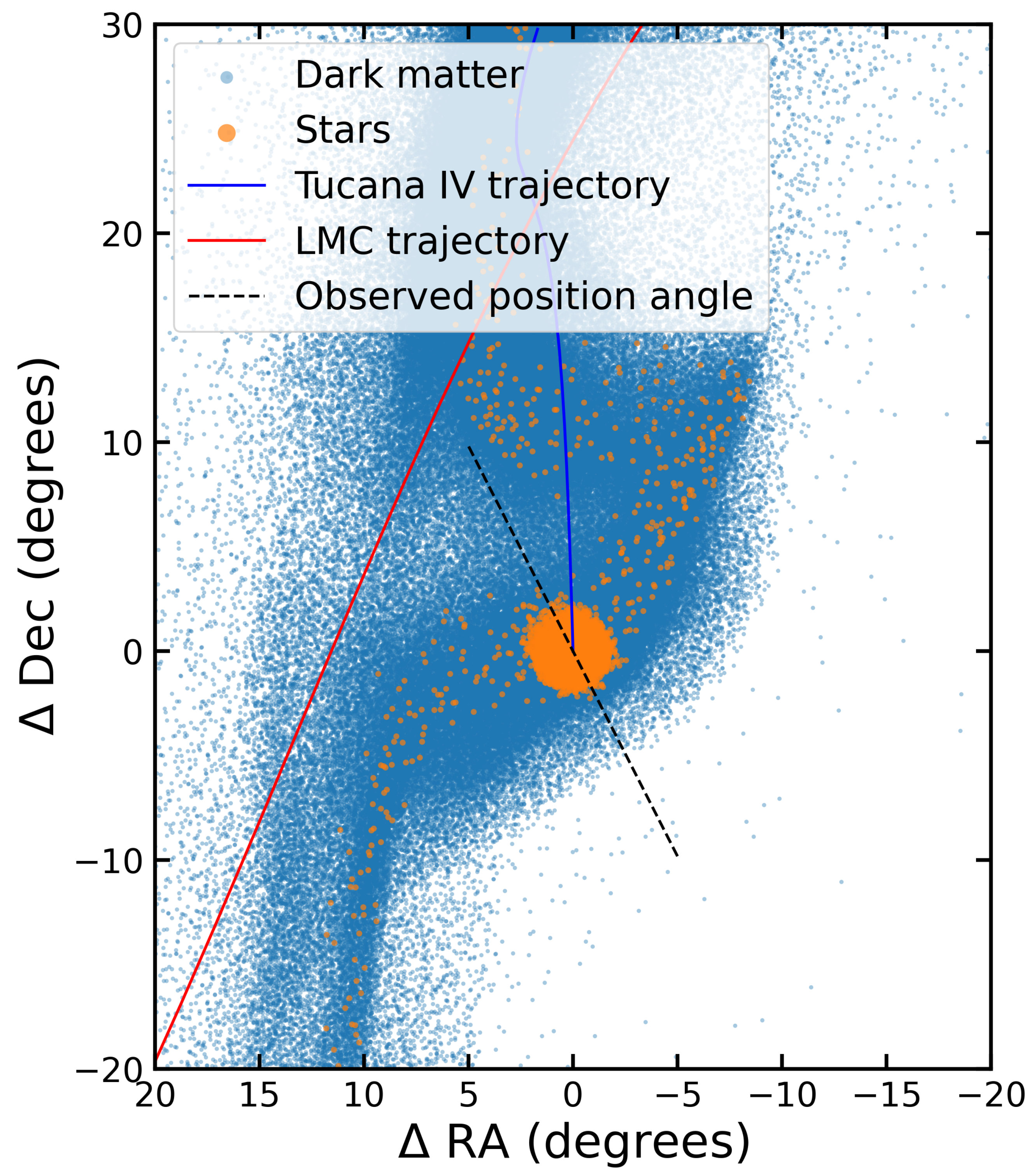
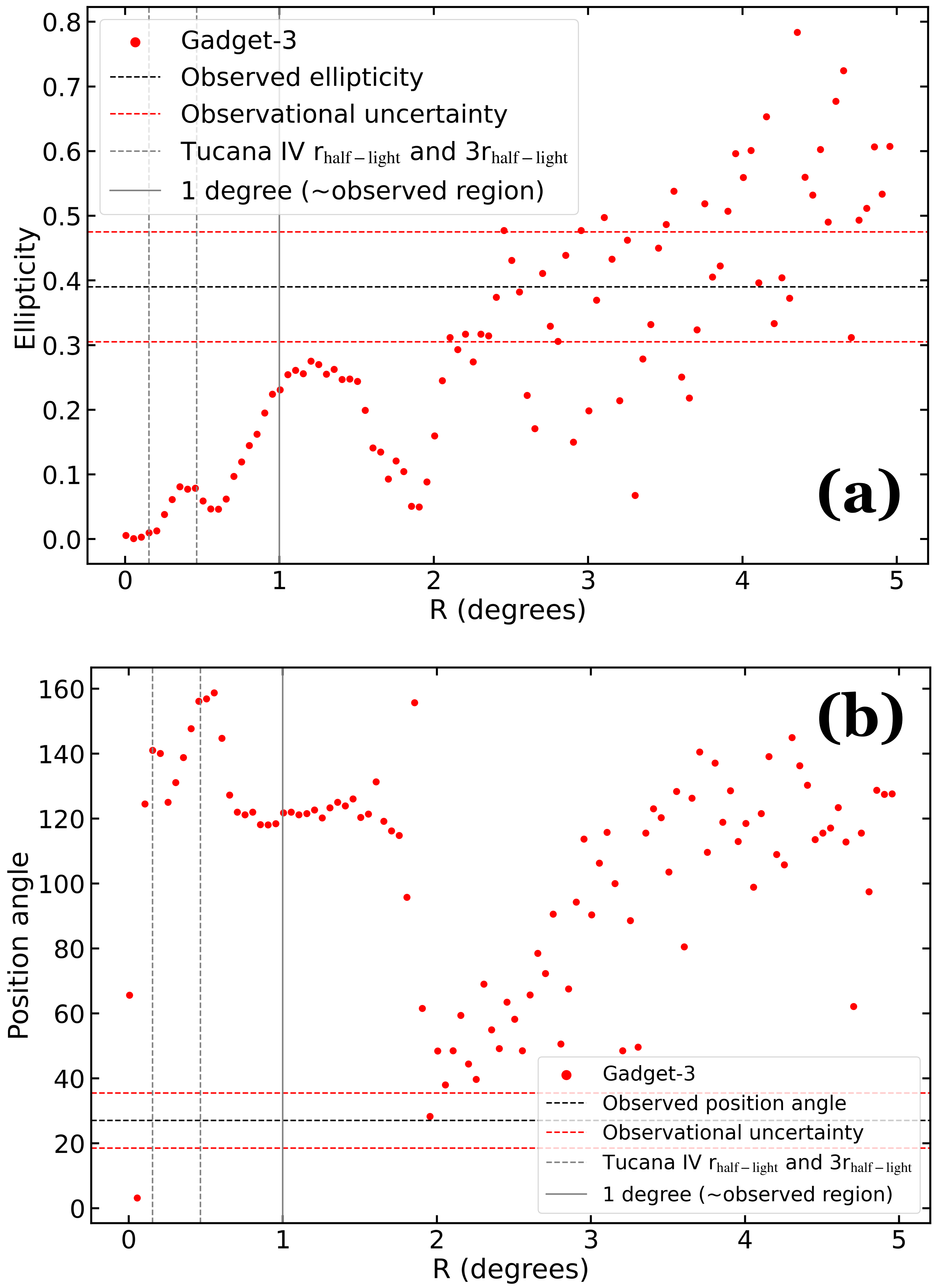


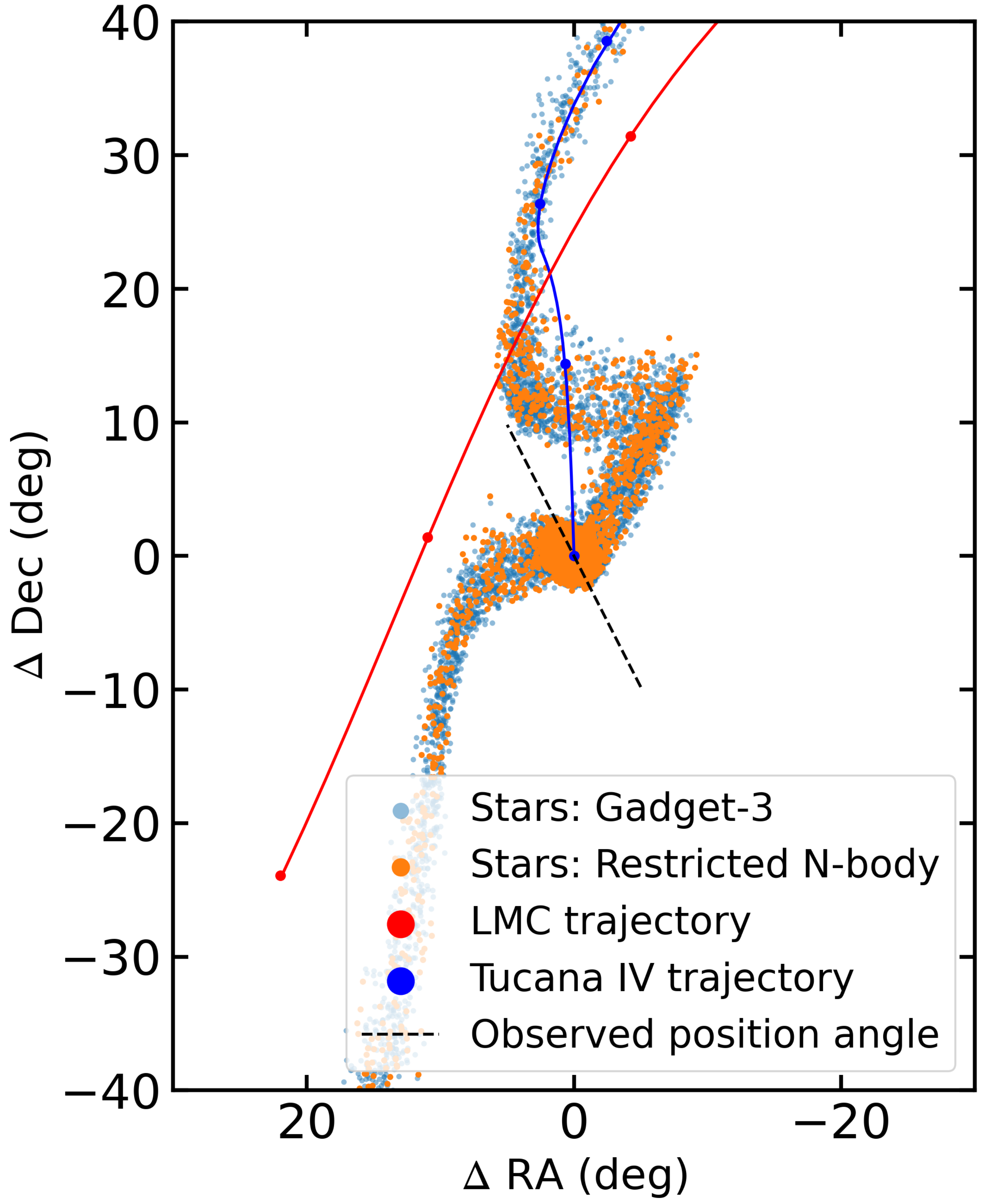



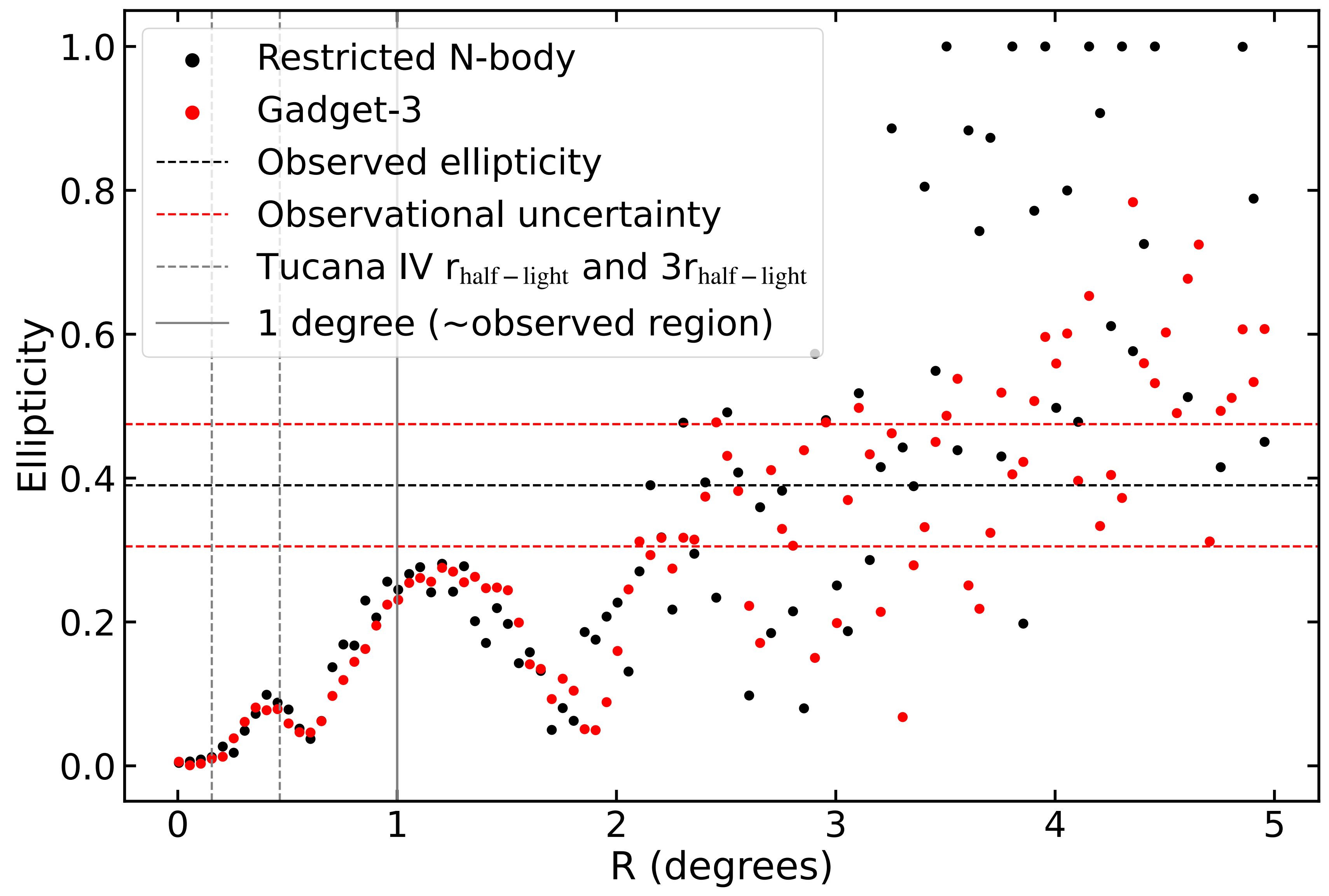

Ellipticity **(a)** and position angle **(b)** as a function of radius

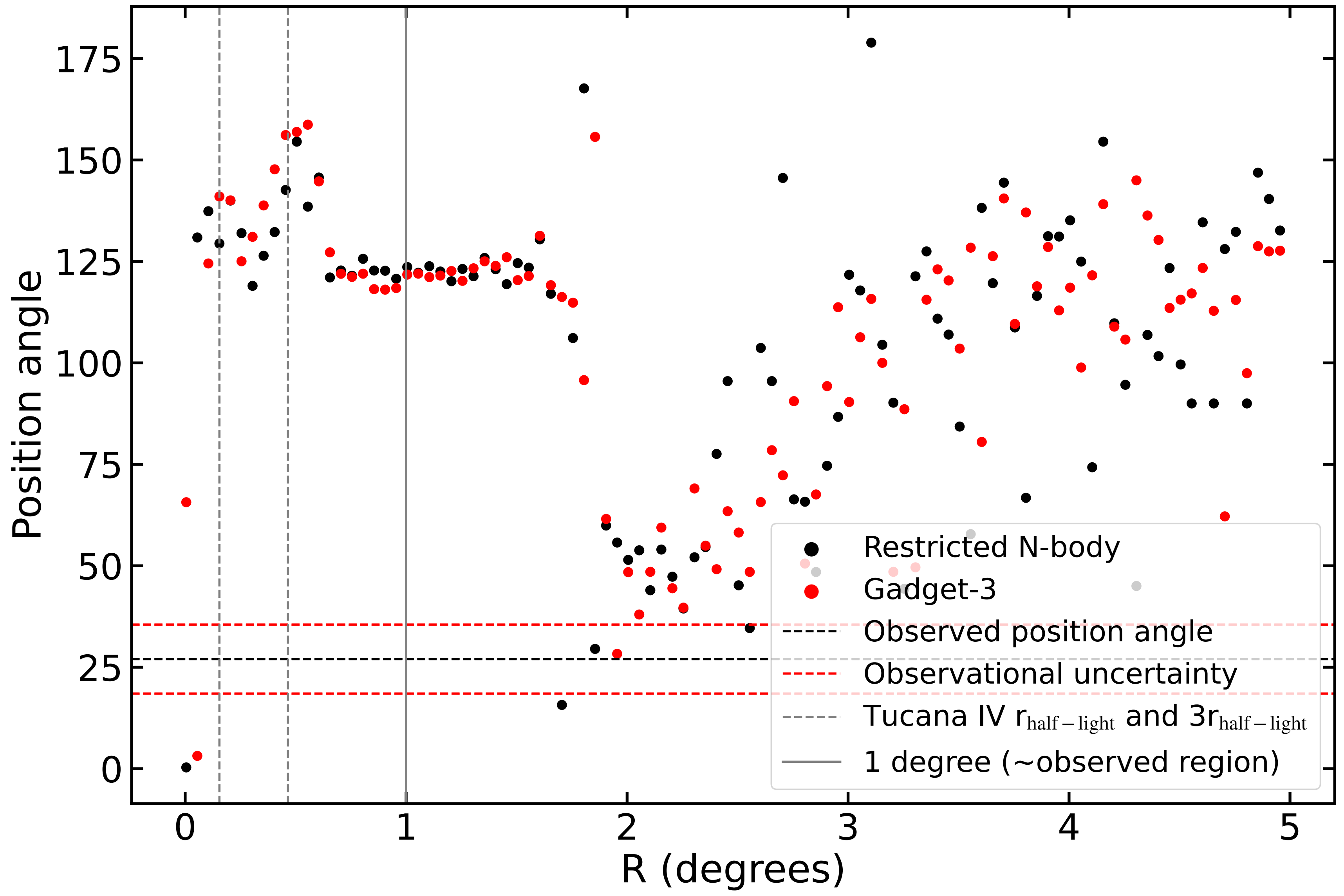
# Restricted N-body method

- Uses the **low-order multipole expansion** of the effective particle potential to compute the forces. → **reduce computational time.**

- **Trajectory at forward integration = trajectory at rewinding.** → Final pos/vel exactly match the observed values. —no need for the Gauss-Newton method. →**reduce computational time**



# Restricted N-body method: results

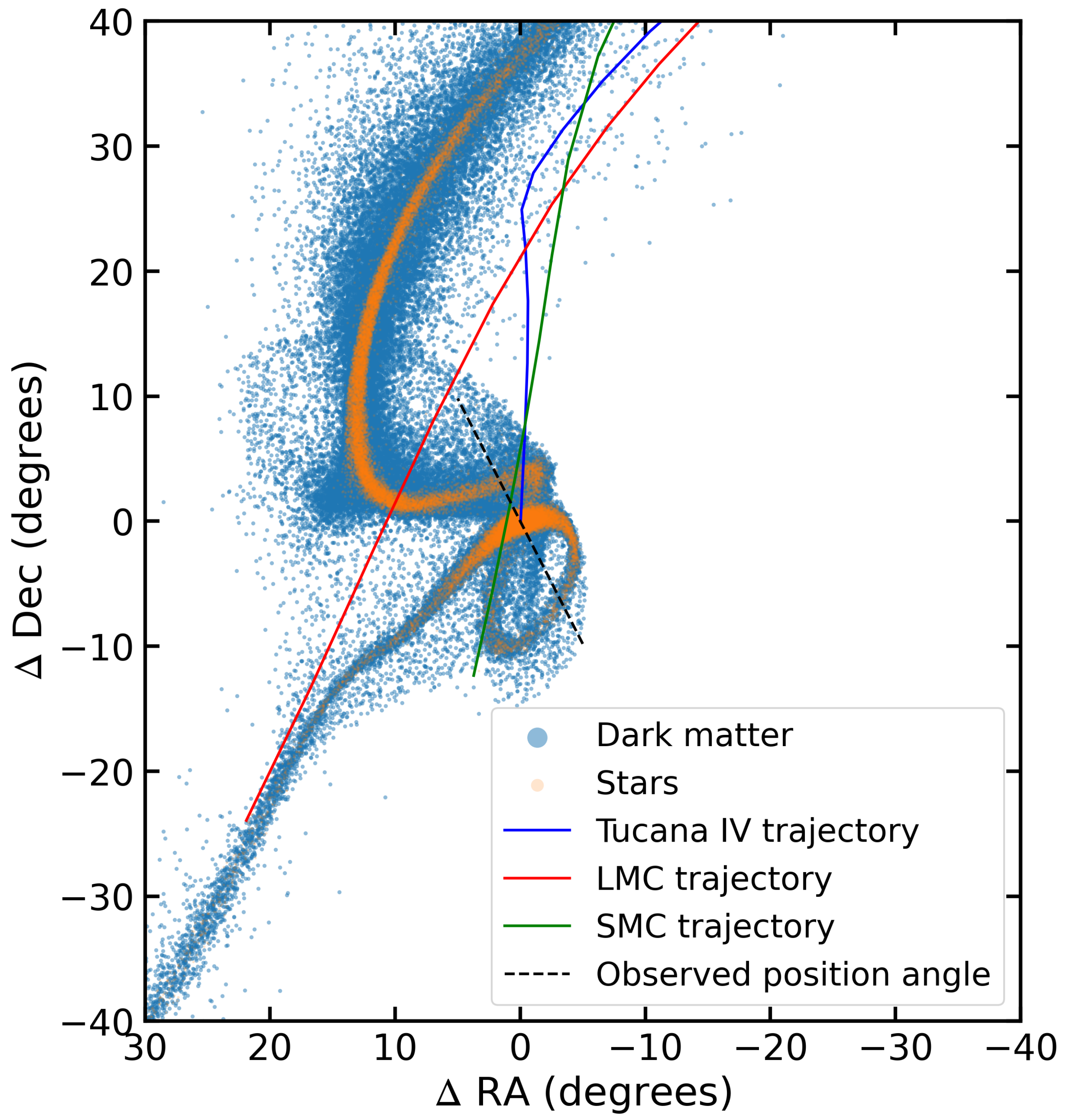
Run multiple simulations **samling over the uncertainties** in Tucana IV's and the LMC's phase space coordinates and the LMC's mass.

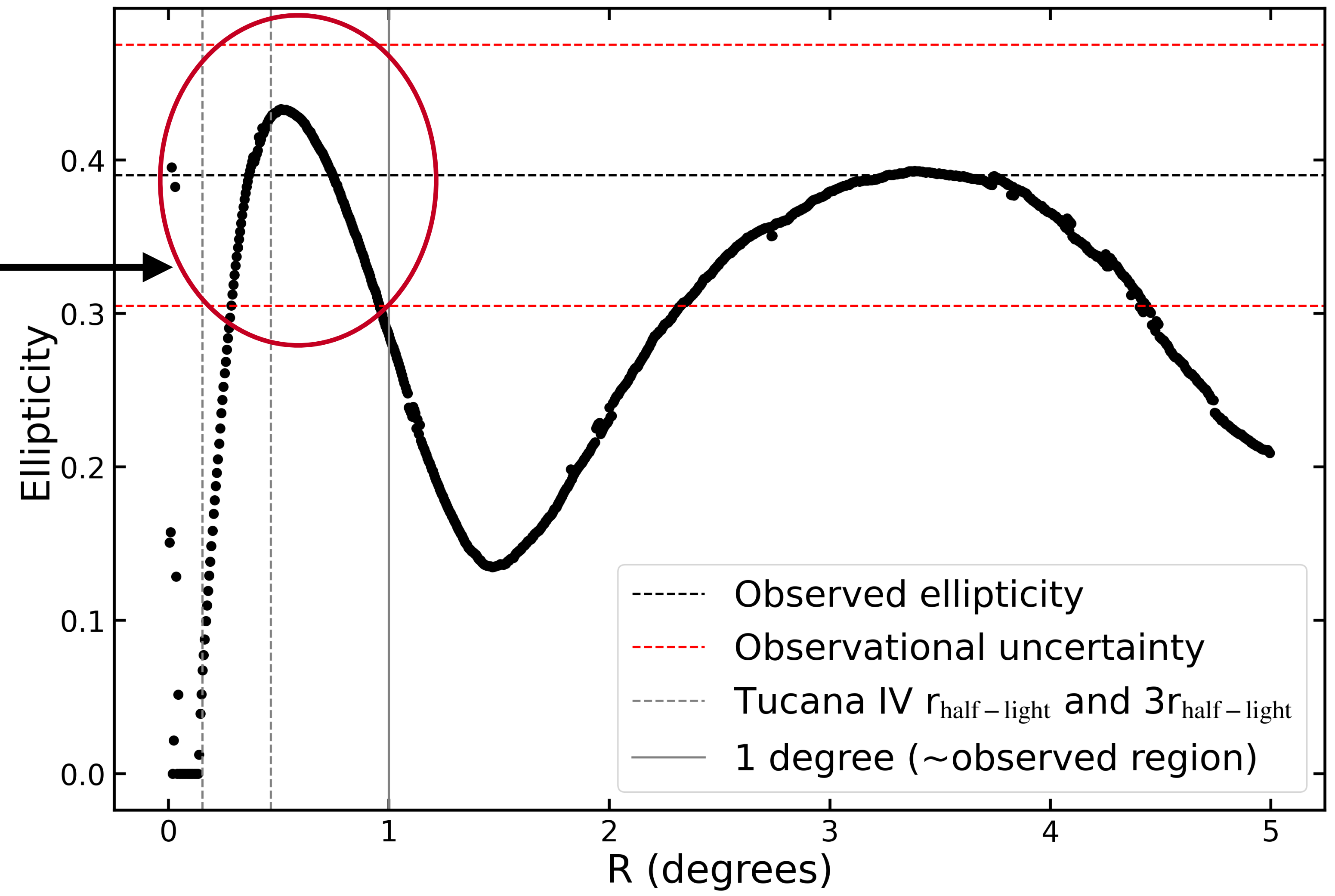
Modifications:

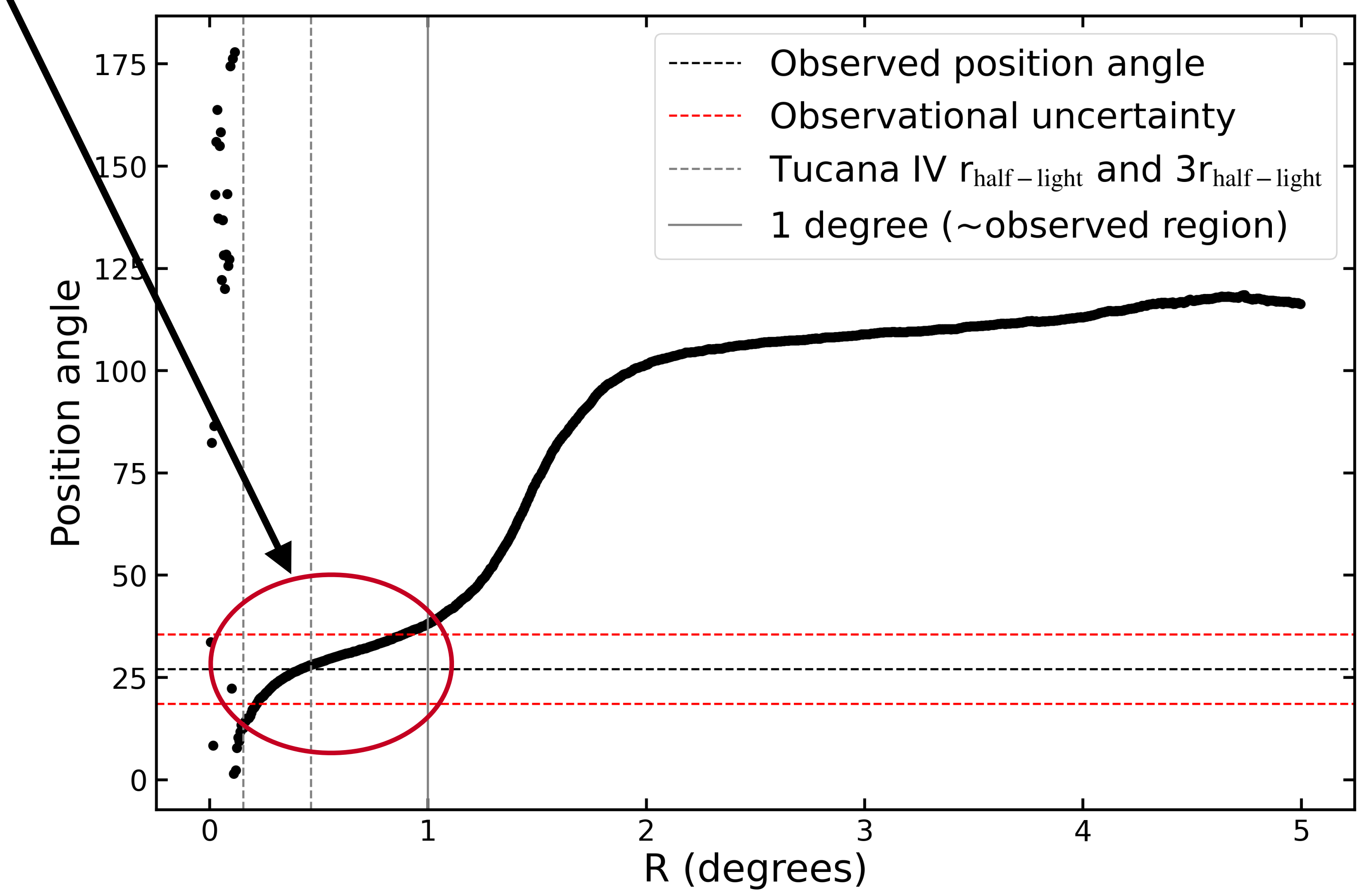
- Add the **SMC** to the model
- Initialise DM with the **cored** profile
- **Reduce DM mass** by two orders of magnitude: from 3.0×10^8 M⊙ to 3.0×10^6 M⊙.

DM reduced mass +cored profile +SMC

Agrees with the observations in the inner region!



# Summary:

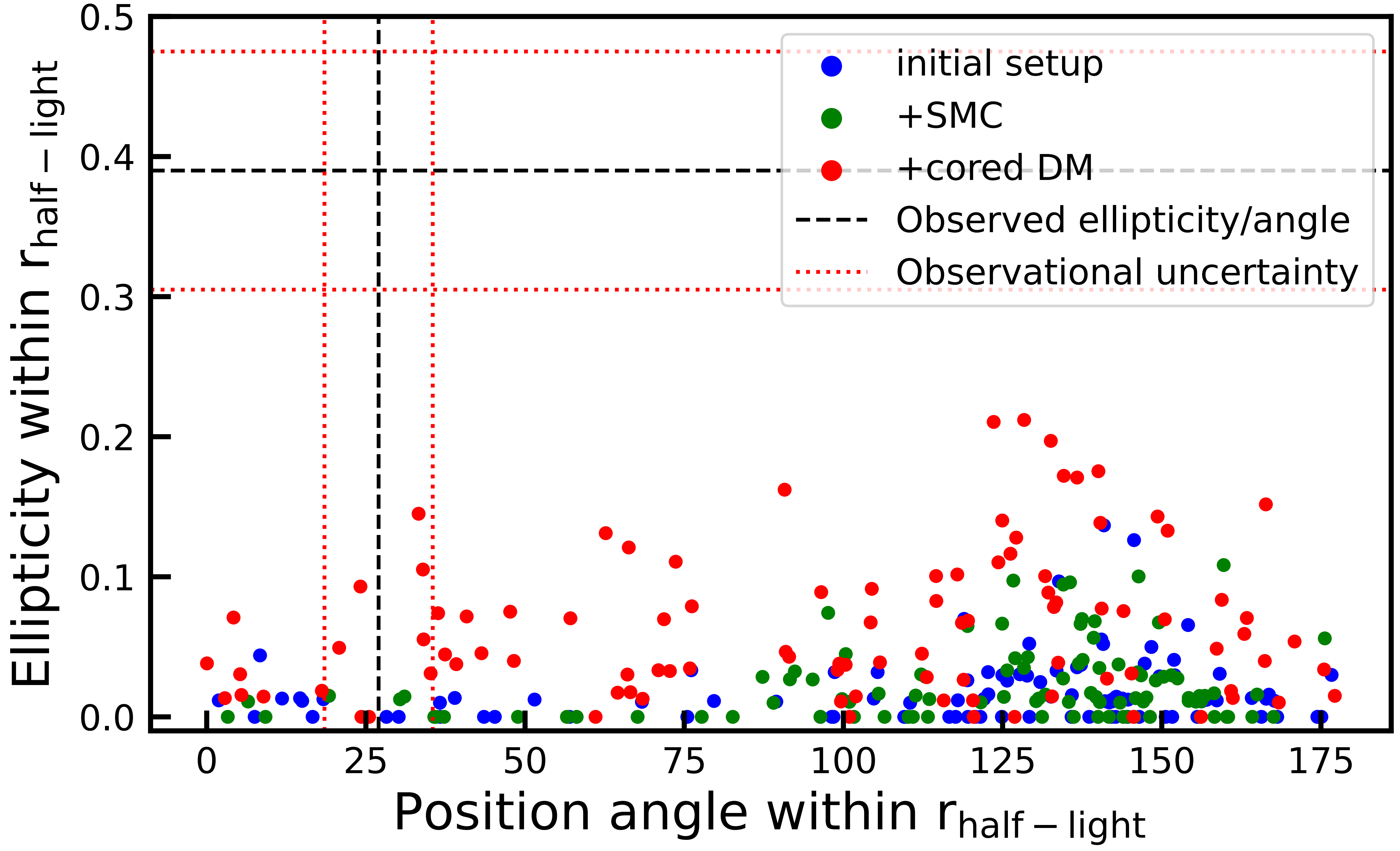
1. The LMC could have a significant impact on the morphology of Tucana IV.

2. Some N-body simulations of Tucana IV have a position angle and ellipticity of the outskirts that closely match the observed values. At the same time, the inner region does not agree with the observations.

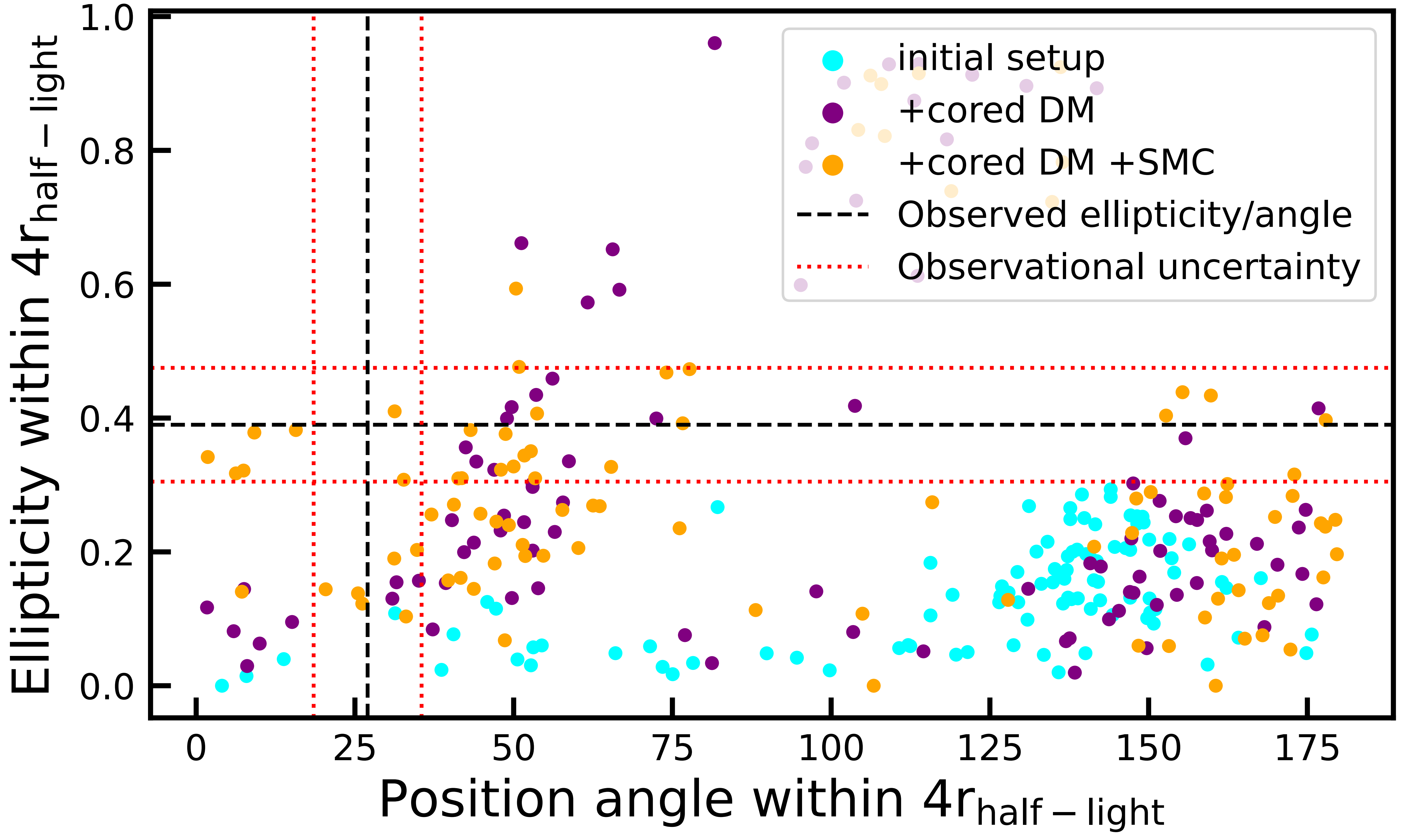
3. Adding the DM cored profile to the model increases the effect on Tucana IV.

4. In the model with SMC, cored dark matter profile and reduced mass, position angle and ellipticity agree with observations in the inner region for some realisations.

**Poster location: F2PB2a**



Ellipticity within $r_{half-light}$
Position angle within $r_{half-light}$
initial setup
+SMC
+cored DM
Observed ellipticity/angle
Observational uncertainty
0.0
0.1
0.2
0.3
0.4
0.5
0
25
50
75
100
125
150
175

Ellipticity within $4r_{half-light}$
Position angle within $4r_{half-light}$
initial setup
+cored DM
+cored DM +SMC
Observed ellipticity/angle
Observational uncertainty
0.0
0.2
0.4
0.6
0.8
1.0
0
25
50
75
100
125
150
175

$$M_{\mathrm{cNFW}}(< r) = M_{\mathrm{NFW}}(< r) f^n$$

$$f^n = \left[\tanh\left(\frac{r}{r_c}\right)\right]^n$$

sampling SMC mass within 2.15e9-6.5e9 solar masses. This corresponds to the assumed SMC's mass within 2 kpc to be (0.8 – 2.4) × 10e9 M⊙ (from https://arxiv.org/pdf/2504.16163 (We demonstrate that the SMC's torques on the LMC's bar during the collision are sufficient to explain the observed bar tilt, provided the SMC's total mass within 2 kpc was (0.8–2.4)×109 M⊙.))

Schwarzschild method

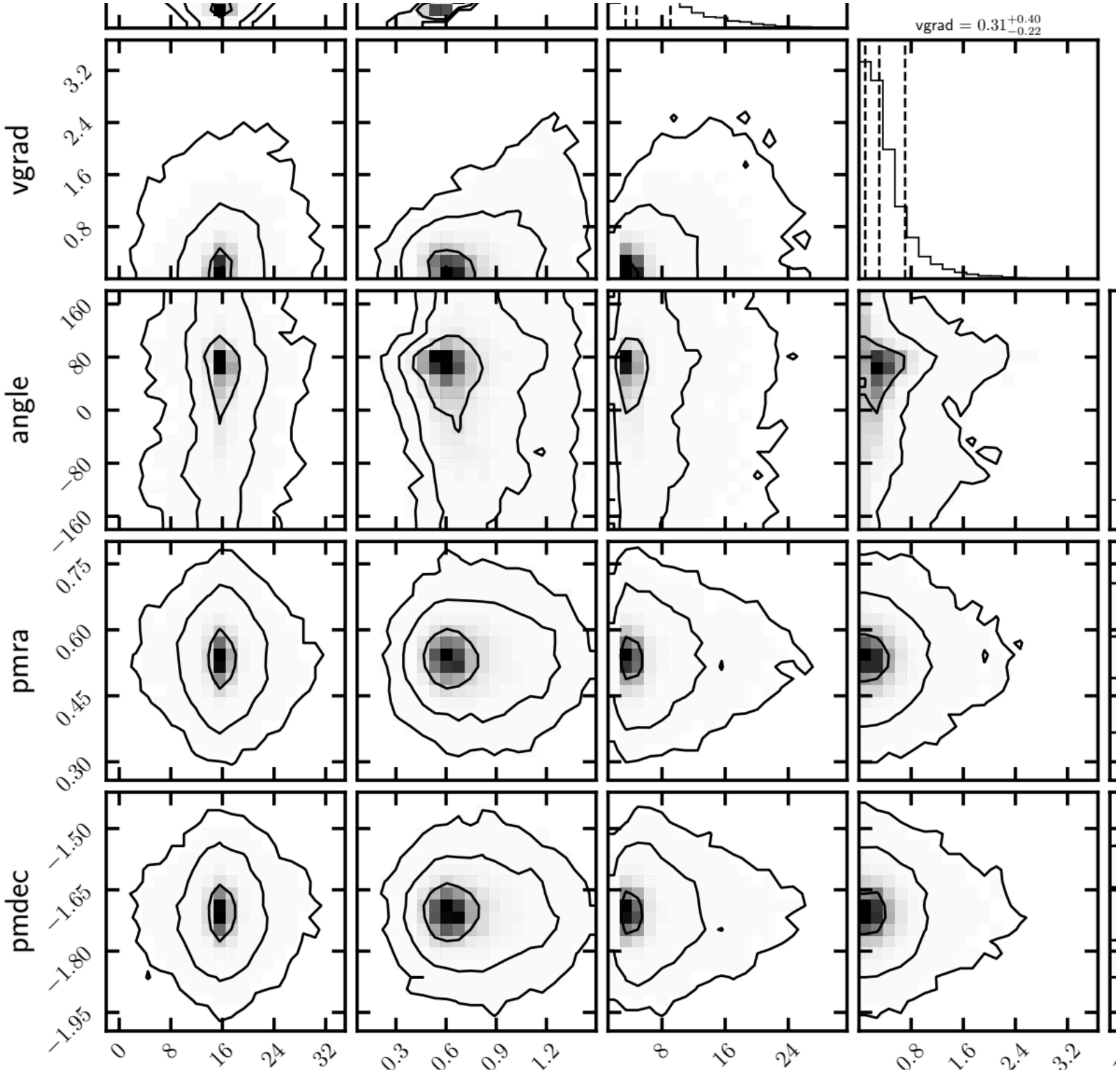
The LMC gravitational potential is defined as the Hernquist potential with a mass of $1.38 \pm 0.26 \times 10^{11}$ M⊙ and a scale radius motivated by the LMC enclosed mass at 8.7 kpc [4].

The MW gravitational potential is represented with the MWPotential2014 model [galpy].

The procedure is the following: we rewind Tucana IV orbit in the combined potential of the MW and the LMC for 4.47 Gyr (~3 pericentres), then we initialise Tucana IV dark matter and stars' density distributions with NFW halo and Plummer sphere correspondently, after that the N-body system is integrated forward in time.

The dark matter halo mass is set to 3.0×108 M⊙ to match the observed velocity dispersion [1, 2]. Mass of the Plummer sphere is 3080 M⊙ [1, 2].

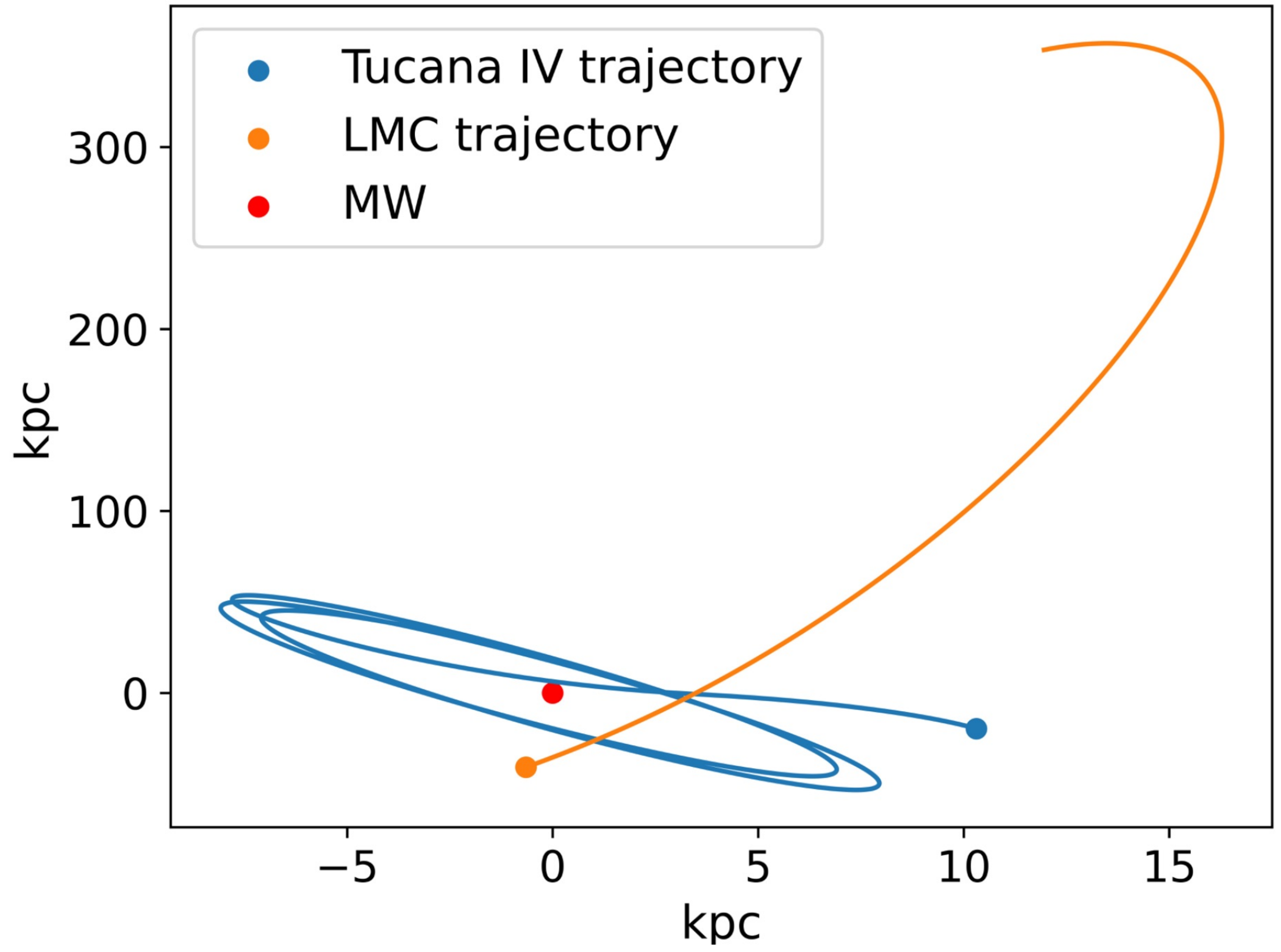
We add the SMC to our model, sampling its mass within (2.15 - 6.5)×10^9 M⊙, which corresponds to the assumed SMC's mass within 2 kpc to be (0.8 - 2.4)×10^9 M⊙ [9].

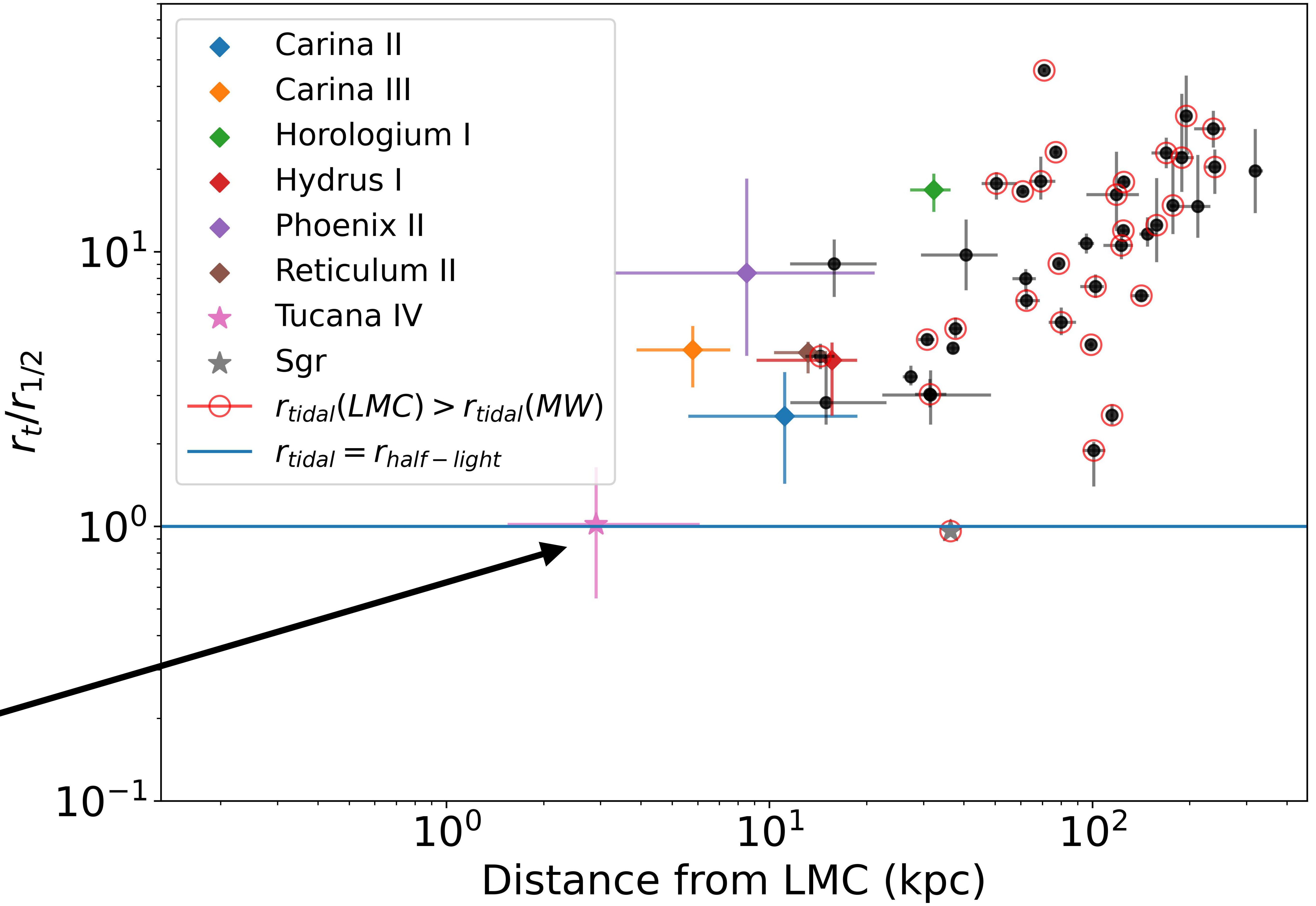



km/s/arcmin

# Motivation: Tucana IV orbit rewinding results

- Tucana IV had a close passage (~3 kpc) with the LMC ~130 Myr ago [Simon et al. 2020].

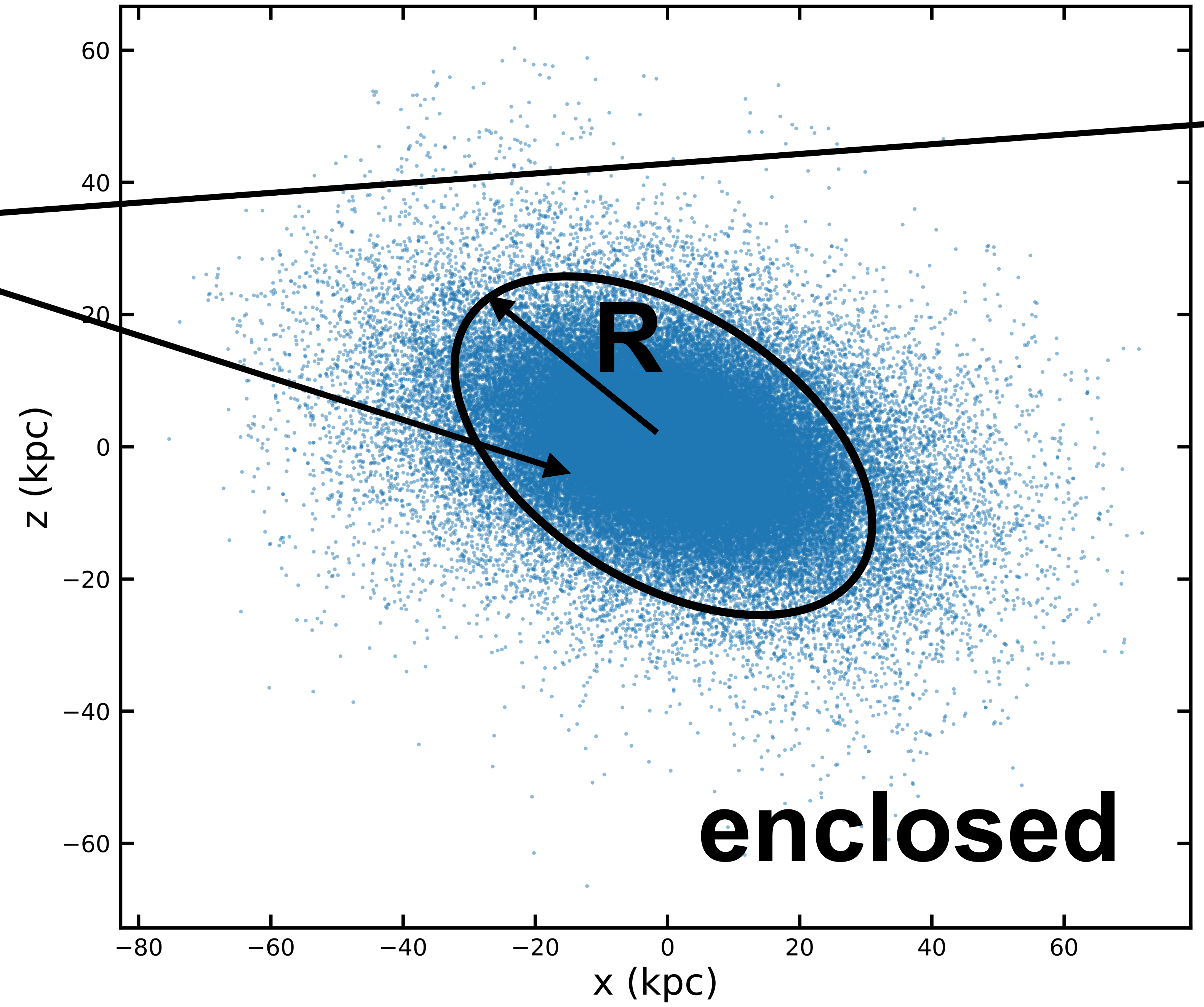


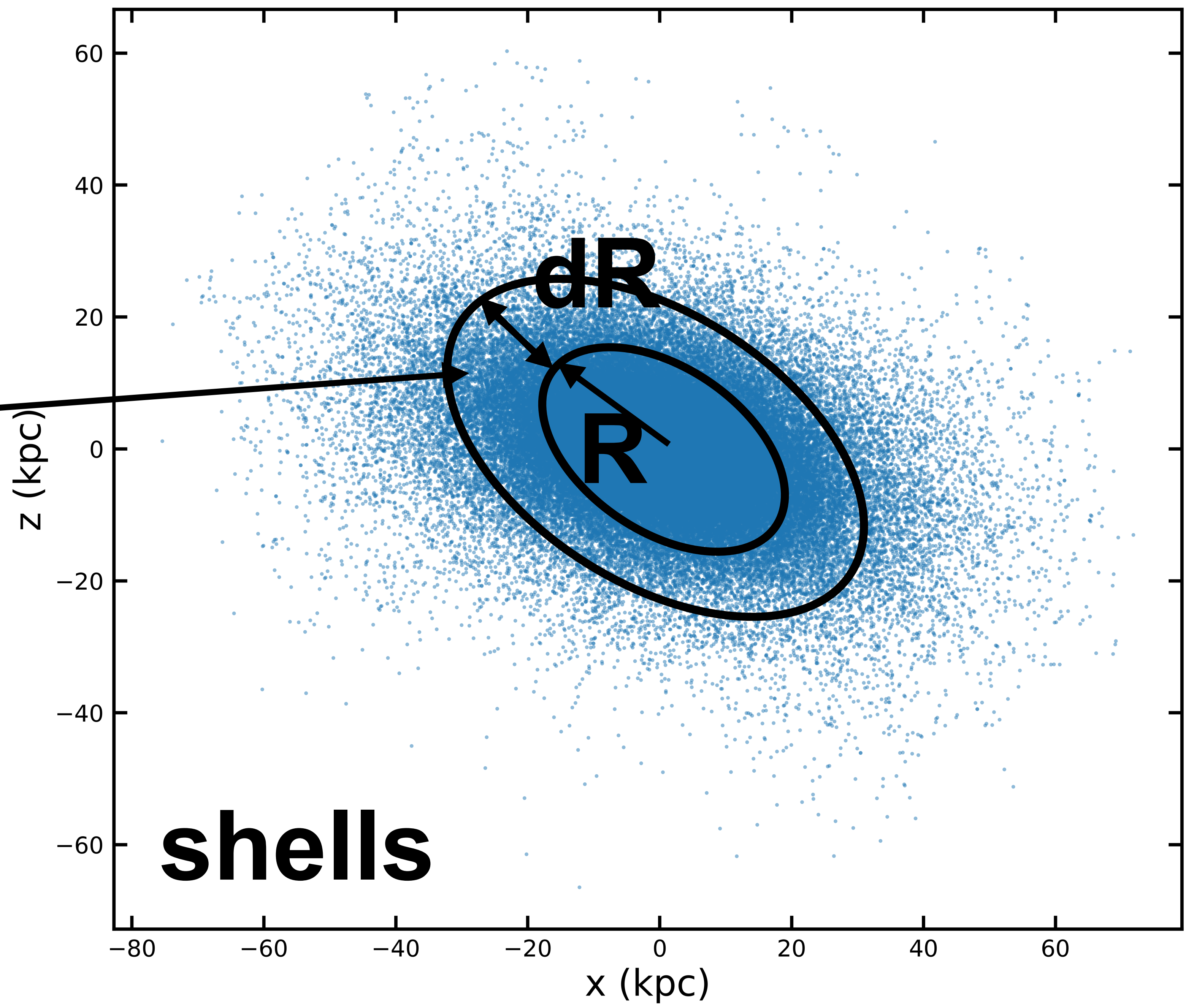



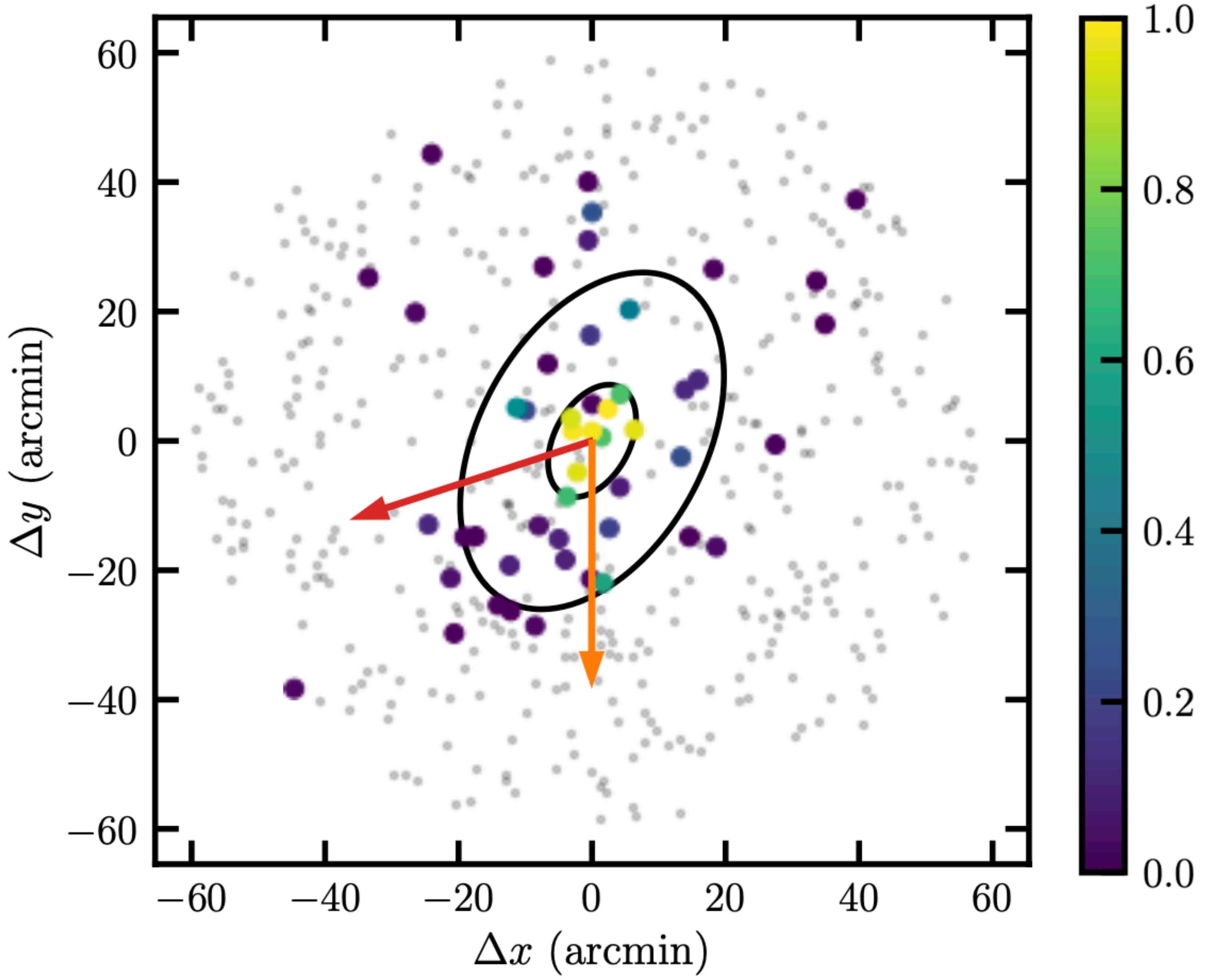

- Tucana IV tidal radius with respect to the LMC at their closest approach ≈ half-light radius.

# Tucana IV: observations

- Half-light radius = 9.30 ± 1.15 (arcmin)
- Ellipticity = 0.39 ± 0.085
- Position angle = 27.0 ± 8.5 (degrees)
- Line-of-sight velocity dispersion = 4.3 ± 1.35 (km s–1)




Tucana IV stars distribution on the sky. Points are colored according to their membership probability. Two ellipses - one and three times the half-light radius.
[Andrew B. Pace *et al* 2022]

In simulations we will measure ellipticity and position angle both within **elliptical shells** with **dR** width and ellipses with radiuses **R** (**enclosed**).

# Tucana IV N-body simulations with Gadget-3 (N-body part)

**<u>Simulation stages</u>**

1) **Rewind** Tucana IV as test particle in MW and LMC combined potential;
2) **Generate** Tucana IV stars and dark matter **density distributions**;
3) **Integrate system forward** till the present time.

**<u>Potentials:</u>**
**Tucana IV** - Plummer (stars) and NFW (dark matter) profiles.

**LMC** - particle sourcing Hernquist potential.

**MW** - particle sourcing NFW, Miyamoto-Nagai and broken power-law bulge potential.

**<u>Final position and velocity mismatch</u>**

**Problem:** Tucana IV simulational and observed positions and velocities discrepancy ~ **5 kpc.** Distance between Tucana IV and LMC at closest approach ~ **3 kpc** - can be crucial.
**Explanation:** possible **spatial asymmetry** in dwarfs' **particle loss** → extra force on Tucana IV centre of mass.

**Solution:** iterative **Gauss-Newton** method (~Newton's method for vectors). But then we need to run 7*Number of iterations simulations - costly …

After **7*4 = 28 simulations** finally got all positions and velocities right apart from RA and Dec.

| | Observations | Simulation |
|---|---|---|
| RA (deg) | 0.717 | 0.526 |
| Dec (deg) | -60.83 | -61.01 |
| distance (kpc) | 47.0 ± 4.0 | 46.6 |
| pm ra (mas/yr) | 0.534 ± 0.052 | 0.523 |
| pm dec (mas/yr) | -1.707 ± 0.055 | -1.728 |
| radial velocity (km/s) | 15.9 ± 1.75 | 14.79 |

$$dr_{\mathrm{start}}^{\mathrm{model}} = [r_{\mathrm{start}_1}^{\mathrm{model}} - r_{\mathrm{start}_0}^{\mathrm{model}}, \ldots, r_{\mathrm{start}_6}^{\mathrm{model}} - r_{\mathrm{start}_0}^{\mathrm{model}}]$$

$$dr_{\mathrm{fin}}^{\mathrm{model}} = [r_{\mathrm{fin}_1}^{\mathrm{model}} - r_{\mathrm{fin}_0}^{\mathrm{model}}, \ldots, r_{\mathrm{fin}_6}^{\mathrm{model}} - r_{\mathrm{fin}_0}^{\mathrm{model}}]$$

rix $J \approx dr_{\mathrm{fin}}^{\mathrm{model}} \times dr_{\mathrm{start}}^{\mathrm{model}-1}$. The initial position for

$$r_{\mathrm{start}_0}^{\mathrm{model}}\mathrm{new} = \mathrm{r}_{\mathrm{start}_0}^{\mathrm{model}} - \mathrm{J}^{-1} \times (\mathrm{r}_{\mathrm{fin}_0}^{\mathrm{model}} - \mathrm{r}_{\mathrm{fin}}^{\mathrm{true}})$$