

Revealing dark matter haloes with kinematic tracers using action-based modelling

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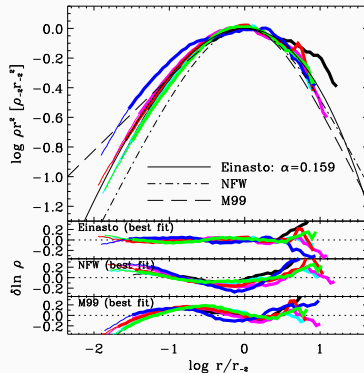


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Motivation

The current cosmological paradigm (Λ CDM) predicts nearly universal density profiles for dark matter haloes

- Not strictly universal: small halo-to-halo differences
- A template to compare real galaxies against



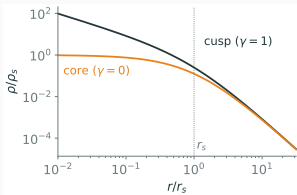
Colours: six simulated Milky-Way-mass haloes (Aquarius). Black: Einasto, NFW and Moore fits; lower panels: residuals. Navarro et al. 2010, Fig. 3

The universal halo in detail: density profile and shape

Density profile — the universal profile is one member of the (α, β, γ) family:

$$\rho(r) = \rho_s \left(\frac{r}{r_s} \right)^{-\gamma} \left[1 + \left(\frac{r}{r_s} \right)^\alpha \right]^{(\gamma-\beta)/\alpha}$$

inner slope γ , outer slope β , sharpness α
scale radius r_s : where the slope turns over



- **Global parameters:** mass M_{200} inside r_{200} ; concentration $c_{200} = r_{200}/r_s$ — higher means more centrally concentrated
- **Shape:** axis ratios $p = b/a$, $q = c/a$, via $r \rightarrow \sqrt{x^2 + (y/p)^2 + (z/q)^2}$; may vary with radius

Simulations show departures from Λ CDM change the halo — but so do baryons

	Inner slope	Concentration	Shape	References
Λ CDM	$\gamma \approx 1$ (cusp)	decreases with mass	triaxial, mostly prolate	Allgood et al. 2006; Ludlow et al. 2016
WDM	$\gamma \approx 1$ (cusp, lower central density)	lower in dwarfs	like Λ CDM	Bose et al. 2016; Lovell et al. 2014
SIDM	core, grows with mass ($\lesssim 1$ kpc in dwarfs); can collapse	like Λ CDM outside the core	rounder centre	Despali et al. 2026; Rocha et al. 2013
FDM	soliton core, shrinks with mass ($\sim$ kpc in dwarfs)	lower in dwarfs*	prolate near R_{vir}^*	Dome et al. 2023; Schive et al. 2014b
Baryons	$\gamma \approx 0.1\text{--}0.4$ (bright dwarfs, bursty feedback); $\gamma \gtrsim 1$ (MW)	raised at MW mass	rounder, oblate (MW mass)	Chua et al. 2022 Di Cintio et al. 2014a,b

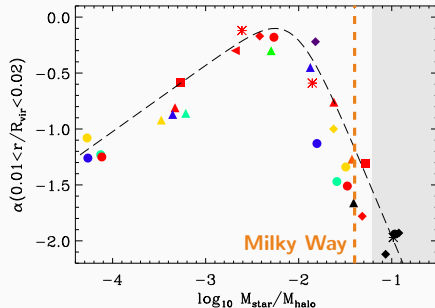
* simulations with FDM-like initial conditions only, at high redshift

To test dark matter physics, measure several halo properties across a range of masses

- The signatures depend on mass: cores from bursty feedback are strongest at $M_{\star}/M_{\text{halo}} \approx 0.5\%$ ($M_{\star} \sim 10^8 M_{\odot}$: bright dwarfs)

Di Cintio et al. 2014a

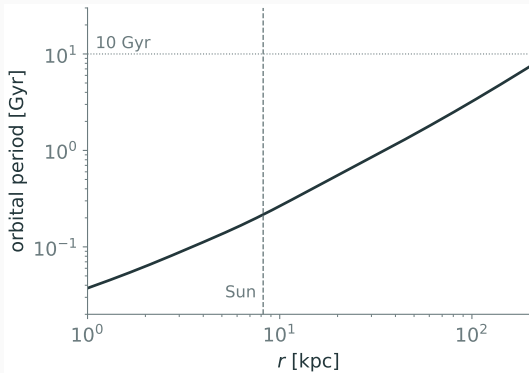
- One galaxy can't decide: measure inner slope, concentration and flattening together, in a sample from dwarfs to Milky Way-mass galaxies



Inner slope of the dark matter density ($-1 = \text{cusp}$, $0 = \text{core}$) vs stellar-to-halo mass ratio in MaGICC hydrodynamical simulations; dashed black: fit. From Di Cintio et al. 2014a, Fig. 3; Milky Way line added (our estimate)

Equilibrium models and action-based distribution functions

Galaxies are close to equilibrium

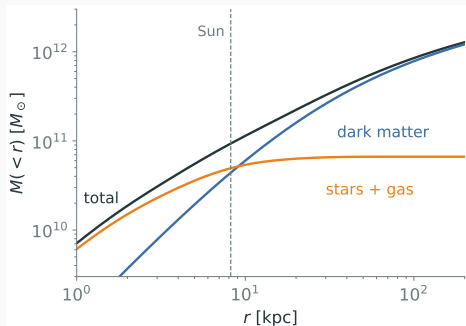


Period of a circular orbit, computed from the McMillan
2017 Milky Way mass model

- Orbits take ~ 0.2 Gyr near the Sun: stars have phase-mixed into a steady state
- In a steady state, the motions of tracers map the potential
- Far out, only a few orbits in 10 Gyr: equilibrium is weaker there

Equilibrium models are simplest where dark matter dominates

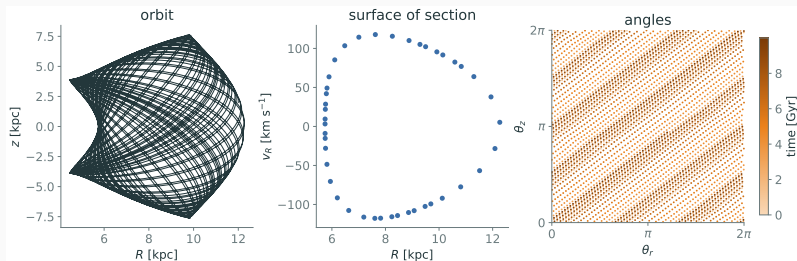
Two ingredients, fitted together: the **tracers'** distribution (the DF) and the **potential** they move in, made by all the mass



Enclosed mass, computed from the McMillan 2017 Milky Way mass model

- Milky Way: about half the mass inside the Sun's radius is dark matter; further out, almost all of it
- Most dwarf galaxies are dominated by dark matter throughout
- There, the potential is essentially all dark matter

Actions label orbits; a steady state is a function $f(\mathbf{J})$



One orbit over 10 Gyr in the axisymmetric McMillan 2017 Milky Way potential. Left: (R, z) . Middle: (R, v_R) at each upward crossing of $z = 0$ — a closed curve for a regular orbit. Right: angles, coloured by time — straight lines that wrap and fill the square.

- Actions $\mathbf{J} = (J_r, J_z, L_z)$ are constant along an orbit; angles $\boldsymbol{\theta}$ advance uniformly
- Phase mixing spreads stars evenly in $\boldsymbol{\theta} \Rightarrow$ equilibrium DF $f(\mathbf{J})$ (Jeans theorem)

Fitting DFs to data in dark-matter-dominated systems

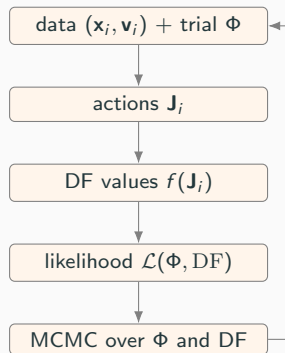
DF: generally well described by a double power law in actions:

$$f(\mathbf{J}) = \frac{M_0}{J_0^3} \frac{[1 + J_0/h(\mathbf{J})]^{(6-\gamma)/(4-\gamma)}}{[1 + g(\mathbf{J})/J_0]^{2\beta-3}}$$

Potential Φ : simply that of the dark matter — the (α, β, γ) density, oblate and axisymmetric ($p = 1$, flattening q)

Likelihood is given rather simply by:

$$\ln \mathcal{L}(\Phi, \text{DF}) = \sum_{i=1}^{N_*} \ln \frac{f(\mathbf{J}_i(\mathbf{x}_i, \mathbf{v}_i | \Phi))}{\mathcal{N}}$$



Advantages of working with $f(\mathbf{J})$ models

- Full likelihood for each star — no binning, no moments
- Self-consistent models possible: the tracers can also make the potential
- Chemistry and age fold in naturally: *extended* DFs $f(\mathbf{J}, [\text{Fe}/\text{H}], \tau)$

Binney & Piffl 2015; Binney & Vasiliev 2023; Pascale et al. 2019; Piffl et al. 2015

Das & Binney 2016; Das et al. 2016; Sanders & Binney 2015

**Ability to constrain dark matter
distribution with action-based
dynamical models**

Few tests on realistic simulated galaxies: is the model applicable, and how well are haloes recovered?

- Action-based models have been applied to real data, but rarely tested on **realistic simulated galaxies**, where the true halo is known
- **1. Is the model applicable at all?** DF form, potential form, axisymmetry, approximate actions; mergers, substructure
- **2. If so, how well are the halo parameters recovered?** Uncertainties and systematics in mass, concentration, flattening

Much of what follows was led by Paula Gherghinescu



- PhD at the University of Surrey
- Now a postdoctoral researcher at Durham, working with Francesca Fragkoudi
- Led two papers testing action-based models on simulated galaxies with 6D data (2024), and with 3D to 6D data (2026)

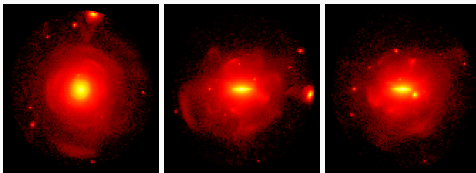
General approach: apply the pipeline to idealised mocks, then simulated galaxies

1. Idealised mocks

Stars with positions and velocities, generated from the same model that is then fitted $\Rightarrow$ tests the pipeline itself

2. Realistic simulated galaxies

M31-like Auriga galaxies, whose stars are *not* in perfect equilibrium; tracers in the outskirts, where dark matter dominates $\Rightarrow$ tests the model form and the equilibrium assumption

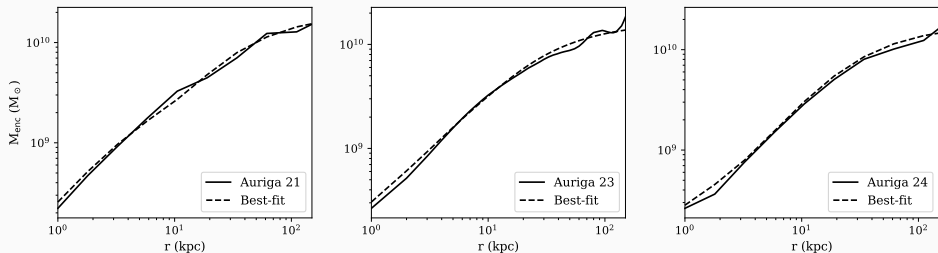


Stars in one simulated galaxy, face-on and from two sides; each panel 500 kpc across

Free: DF parameters; halo ρ_0 , r_s , flattening q ; bulge and disc mass; inclination (2026)

Fixed: halo slopes (NFW: $\gamma = 1$, $\beta = 3$); bulge and disc scale lengths.

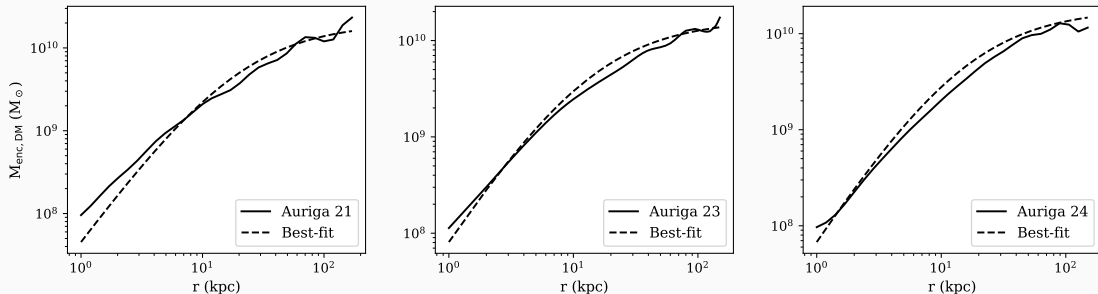
With 6D data (15 000 stars), total mass is recovered to $\sim 10\%$ out to 100 kpc



Enclosed mass $M(< r)$ in the three simulated galaxies: true (solid) vs best fit (dashed)

- **Idealised mock:** truth within the uncertainties — no systematic bias
- **Simulated galaxies:** systematic offset $\sim 10\%$ out to 100 kpc, $\lesssim 20\text{--}25\%$ at 150 kpc — well beyond the (very narrow) uncertainties

The inner dark matter profile is the weak point



Dark matter enclosed mass: true (solid) vs best fit (dashed) (Gherghinescu et al. 2024, Fig. 10)

- The inner slope (NFW, $\gamma = 1$) **and** the bulge and disc scale lengths were fixed, so the misfit inside a few kpc can't be pinned on either

With 6D data, the halo flattening is well recovered

	fitted $q = c/a$	true (15–120 kpc)	
		c/a	b/a
Au21	$0.93^{+0.01}_{-0.02}$	0.74–0.88	0.97–0.99
Au23	$0.58^{+0.03}_{-0.01}$	0.64–0.69	0.92–0.96
Au24	$0.72^{+0.01}_{-0.02}$	0.63–0.68	0.97–1.00

Model: oblate, so $b/a = 1$ and $q = c/a$. Fitted:

Gherghinescu et al. 2024; true: Prada et al. 2019, full-physics runs

- **Idealised mocks:** q within the uncertainties — no systematic bias
- **Simulated galaxies:** nearly axisymmetric, as assumed; systematic offset ~ 0.1 – 0.2 , well beyond the uncertainties (± 0.01 – 0.03)

The data we get depend on the system

System	Typical data	References
Milky Way outskirts	6D for $\sim 20\,000$ stars out to ~ 100 kpc, thinning beyond 40 kpc (Gaia + spectroscopy)	Bird et al. 2021
Dwarf spheroidals	3D for ~ 400 – 2600 stars each; proper motions for a few hundred (Draco) or ~ 100 (Sculptor)	Massari et al. 2018; Vitral et al. 2024; Walker & Peñarrubia 2011
M31 and other nearby galaxies	3D, $\sim 10^3$ tracers (planetary nebulae, globular clusters)	Bhattacharya et al. 2023; Coccato et al. 2009

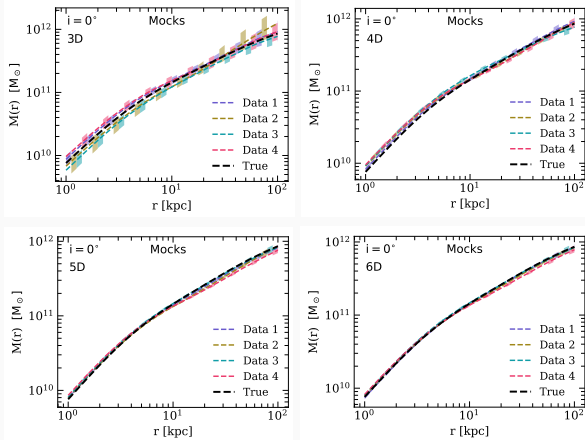
3D sky position + line-of-sight velocity

5D sky position + all 3 velocities

4D sky position + proper motions

6D 5D + distance (full position and velocity)

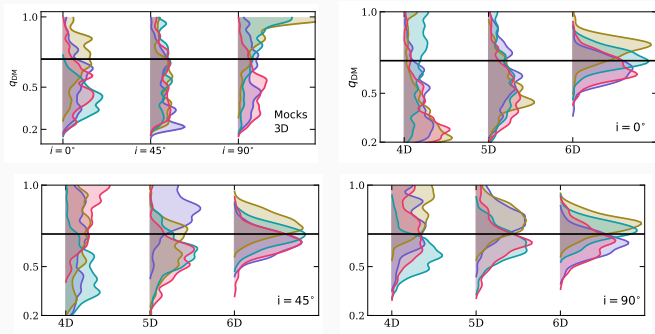
With 3D to 6D data (1000 stars, 3 inclinations), the mass is still well recovered



$M(< r)$, idealised mocks, face-on; colours: four mock data sets; black dashed: truth. Gherghinescu et al. 2026, Figs 3, 13

- **Idealised mocks** (6D down to 3D; inclination fitted): truth within the uncertainties at all inclinations (widest face-on) — no systematic bias
- **Simulated galaxy** (Au23, 3D only; inclination given to the fit): within the uncertainties at 45° and edge-on; face-on, systematically low beyond ~ 10 kpc

The halo flattening, however, is not as well constrained



Posterior of q , four mock data sets; black line: true $q = 0.7$. Top left: 3D at three inclinations; others: 4D, 5D, 6D at $i = 0^\circ, 45^\circ, 90^\circ$.

Gherghinescu et al. 2026, Figs 5, 15

- **Idealised mocks**
(inclination fitted): 6D peaked at the truth; 5D only partly; 3D and 4D broad — truth mostly within the uncertainties
- **Simulated galaxy** (Au23, 3D; inclination given): broad, and systematically biased to smaller q

Literature tests with axisymmetric potentials: mass is robust, flattening is hard

Study	Method	System	Data	Flattening q
Hagen+19	orbits	dwarf, idealised	3D binned	unconstrained
Lipka+24	orbits	dwarf, simulated	3D binned (IFU)	0.8 (grid 0.7–1.0, edge-on)
Hattori+21	actions	MW-like, idealised	5D, 6D	recovered
	actions	MW-like, simulated	5D, 6D	too high by 0.1–0.2

Orbits: Schwarzschild; actions: $f(\mathbf{J})$. Idealised: equilibrium model; simulated: N-body/hydro. Binned: velocities per spatial bin.

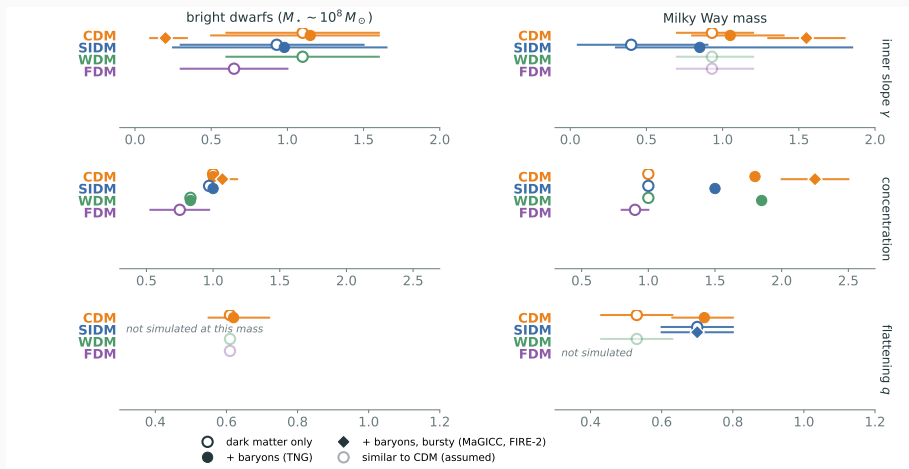
Caveats of our approach

Caveats: what the tests don't yet include

1. **Observational errors** — e.g. 5D relies on proper motions, whose errors can be large
2. **Other disequilibria** — tilted haloes, an LMC-like perturber, tidal stripping of dwarfs
3. **Selection functions** — they enter the normalisation $\mathcal{N}$, recomputed for every new set of model parameters
4. **Cost** — actions for every star at every MCMC step: days for the fits shown, far longer with a selection function

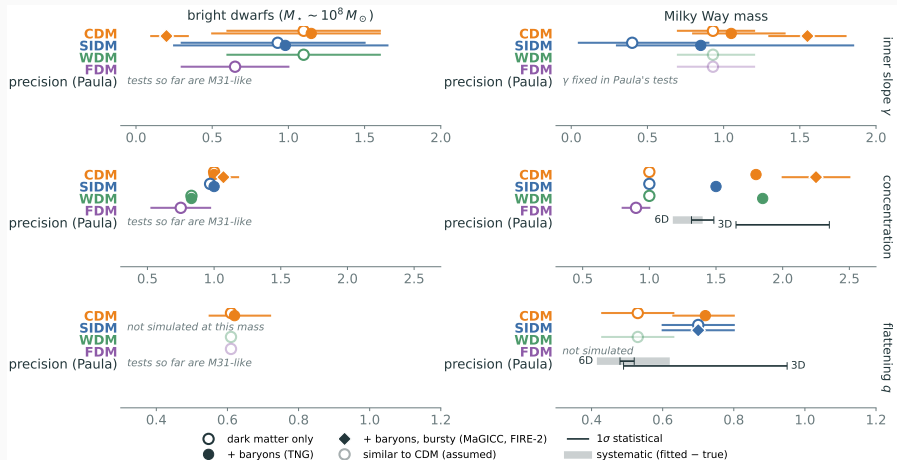
Prospects

Different halo properties separate the scenarios at different masses

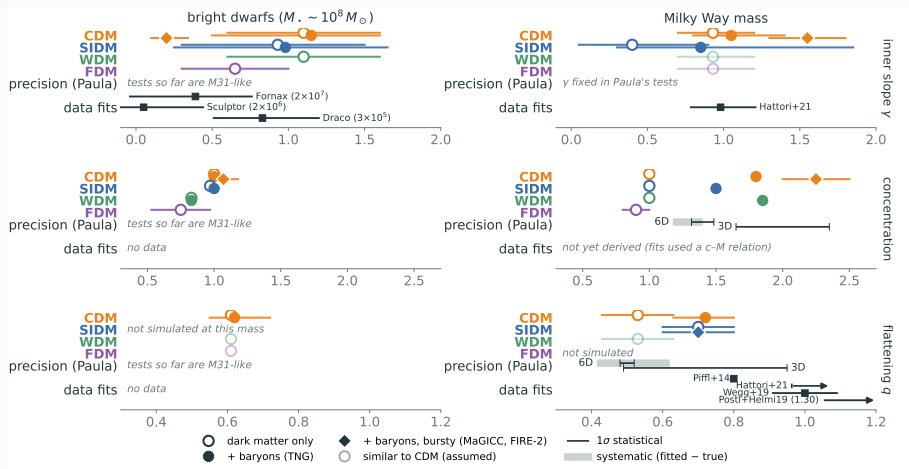


Bose et al. 2016; Chua et al. 2022; Despali et al. 2026; Di Cintio et al. 2014b; Dome et al. 2023; Peter et al. 2013; Schive et al. 2014a; Vargya et al. 2022

Adding the precision from Paula's mock tests



Data: dwarf slopes don't yet discriminate; the Milky Way halo is rounder



Hattori et al. 2021; Piffl et al. 2014; Posti & Helmi 2019; Vitral et al. 2024; Walker & Peñarrubia 2011; Wegg et al. 2019

What needs to be done, on three fronts

1. **Simulations:** every dark matter model, across masses, with and without baryons, several feedback models hard
2. **Mock tests** like Paula's, now with the **inner slope** free; triaxial or tilted haloes, an LMC, selection functions doable
3. **Fits to data** with γ and c free (Gaia DR4, DESI MWS, WEAVE, 4MOST); for dwarfs, is 5D within reach with deep imaging (Rubin, Euclid)? data arriving

Take-home

1. **Mass is robust:** recovered from 3D to 6D data, even in disturbed simulated galaxies
2. **Flattening needs proper motions:** well constrained with 6D, not with 3D
3. **Separating dark matter models needs several properties across masses,** in simulations (every model, with and without baryons, several feedback models) and in data

Look out for

Das et al. (2026, to be submitted),
Gration et al. (2026, to be submitted),
Gherghinescu et al. (in prep.):
likelihood + inversion of the Hessian,
and SBI — runtimes cut significantly; γ
recovered very well from 6D data in
dwarf-type systems