Science and technology roadmap for µas studies of the Milky Way

Lund : 18-20 Jul 2023

Lund Observatory invites scientists to join the MW-Gaia 2023 meeting:

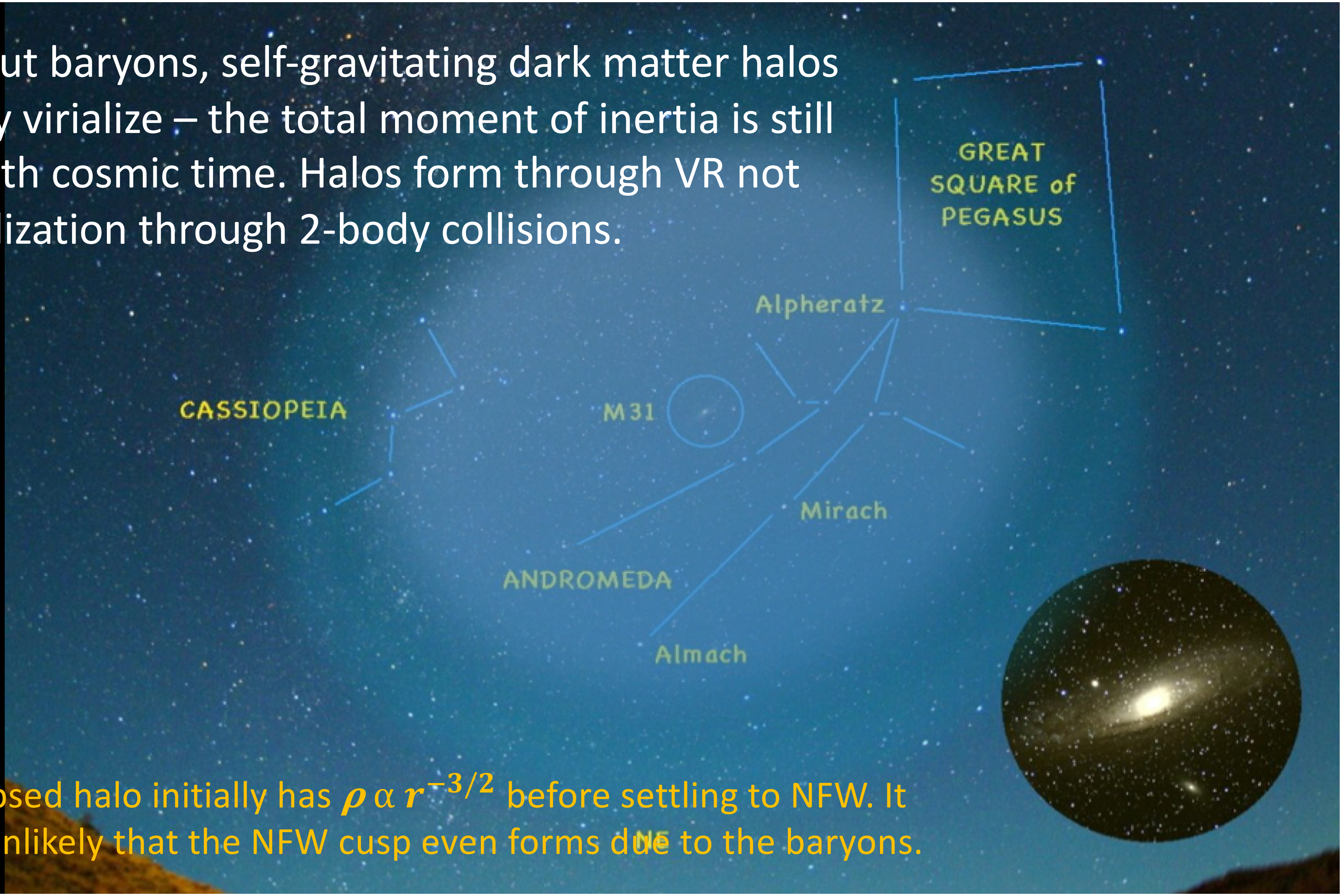
A new experiment in nearfield cosmology

Joss Bland-Hawthorn
Director, Sydney Institute for Astronomy
Laureate Professor, U. Sydney, Australia

With **Sanjib Sharma**, Joe Silk, Celine Boehm

Credit: Benedikt Diemer

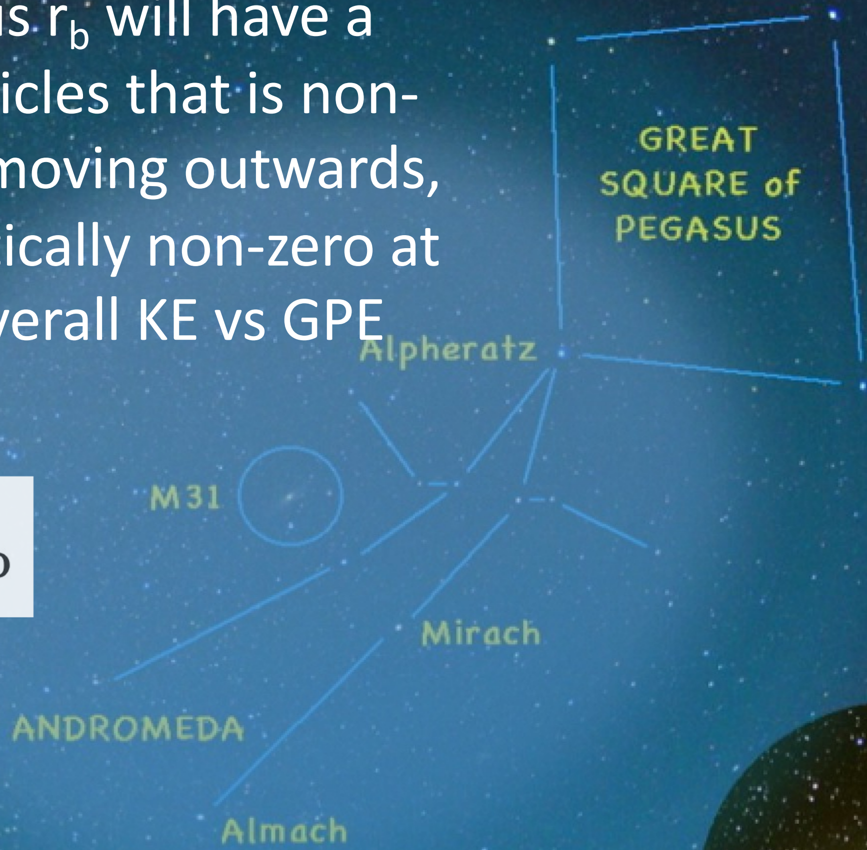
Even without baryons, self-gravitating dark matter halos cannot fully virialize – the total moment of inertia is still evolving with cosmic time. Halos form through VR not via thermalization through 2-body collisions.



The VR collapsed halo initially has $\boldsymbol{\rho}\ \alpha\ \boldsymbol{r}^{-3/2}$ before settling to NFW. It now seems unlikely that the NFW cusp even forms due to the baryons.

An imaginary outer surface with radius r_b will have a momentum flux of shell-crossing particles that is non-zero. Subject to NFW concentration, moving outwards, P_b is roughly zero, becoming systematically non-zero at some **virial radius**. In this shell, the overall KE vs GPE balance breaks down.

$$E_{kin} = -\frac{1}{2}E_G + 2\pi r_b^3 P_b$$



Can we identify a shell of stars that are **~steady state** such that their **net motion** is a probe of the Galaxy's mass change?

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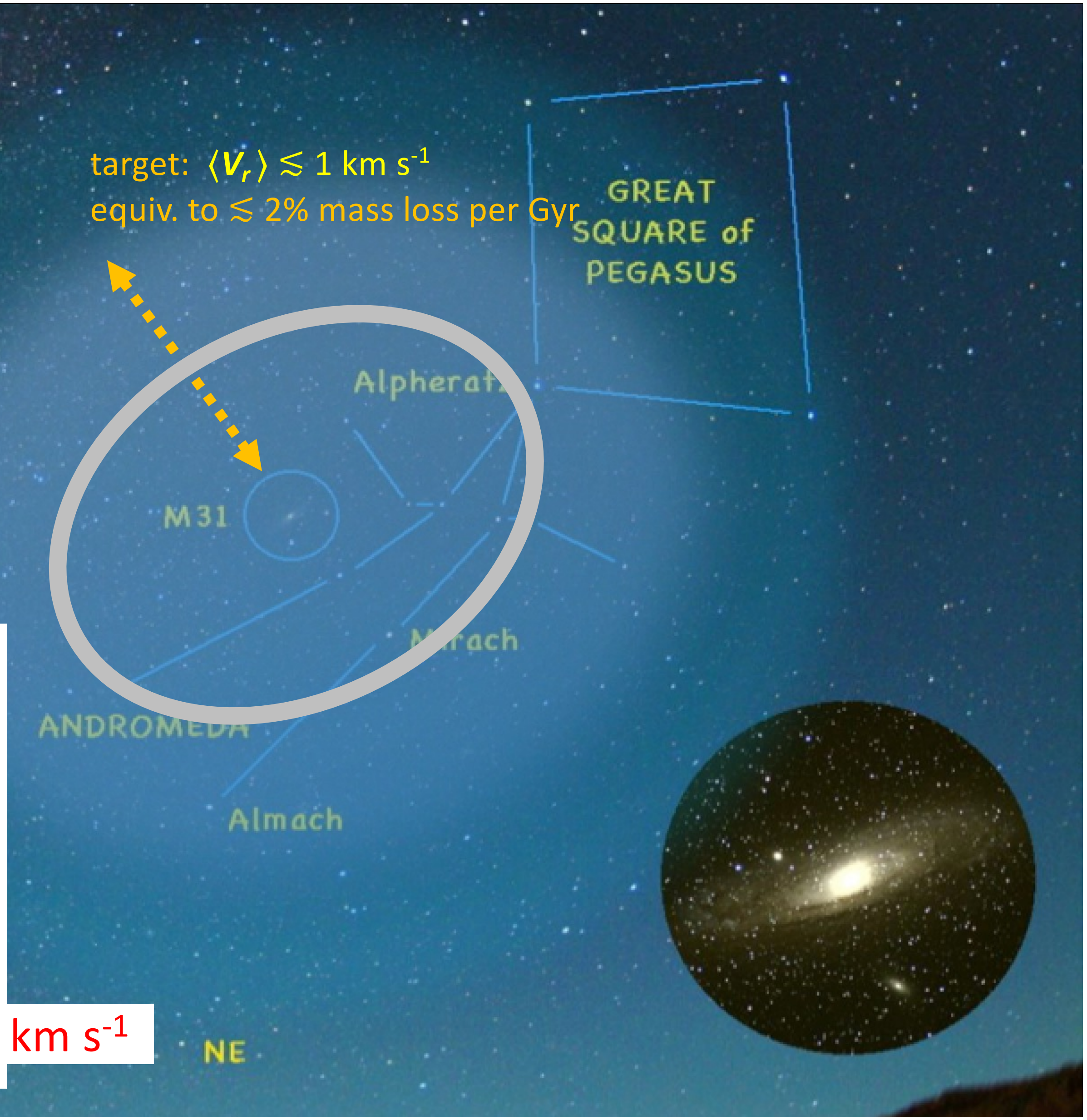
Can radial motions in the stellar halo constrain the rate of change of mass in the Galaxy?

Sanjib Sharma[1,2,3★] Joss Bland-Hawthorn[1,2] Joseph Silk[4] and Celine Boehm[5,6]
[1]Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia
[2]ARC Centre of Excellence for All Sky Astrophysics in Three Dimensions (ASTRO-3D), Australia
[3]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[4]Institut d'Astrophysique de Paris, 98 Bis Bd Arago, 75014 Paris, France
[5]School of Physics, The University of Sydney, NSW 2006, Australia
[6]ARC Centre of Excellence for Dark Matter Particle Physics, Australia

target: $\langle V_r \rangle \lesssim 1$ km s^{-1}
equiv. to $\lesssim$ 2% mass loss per Gyr



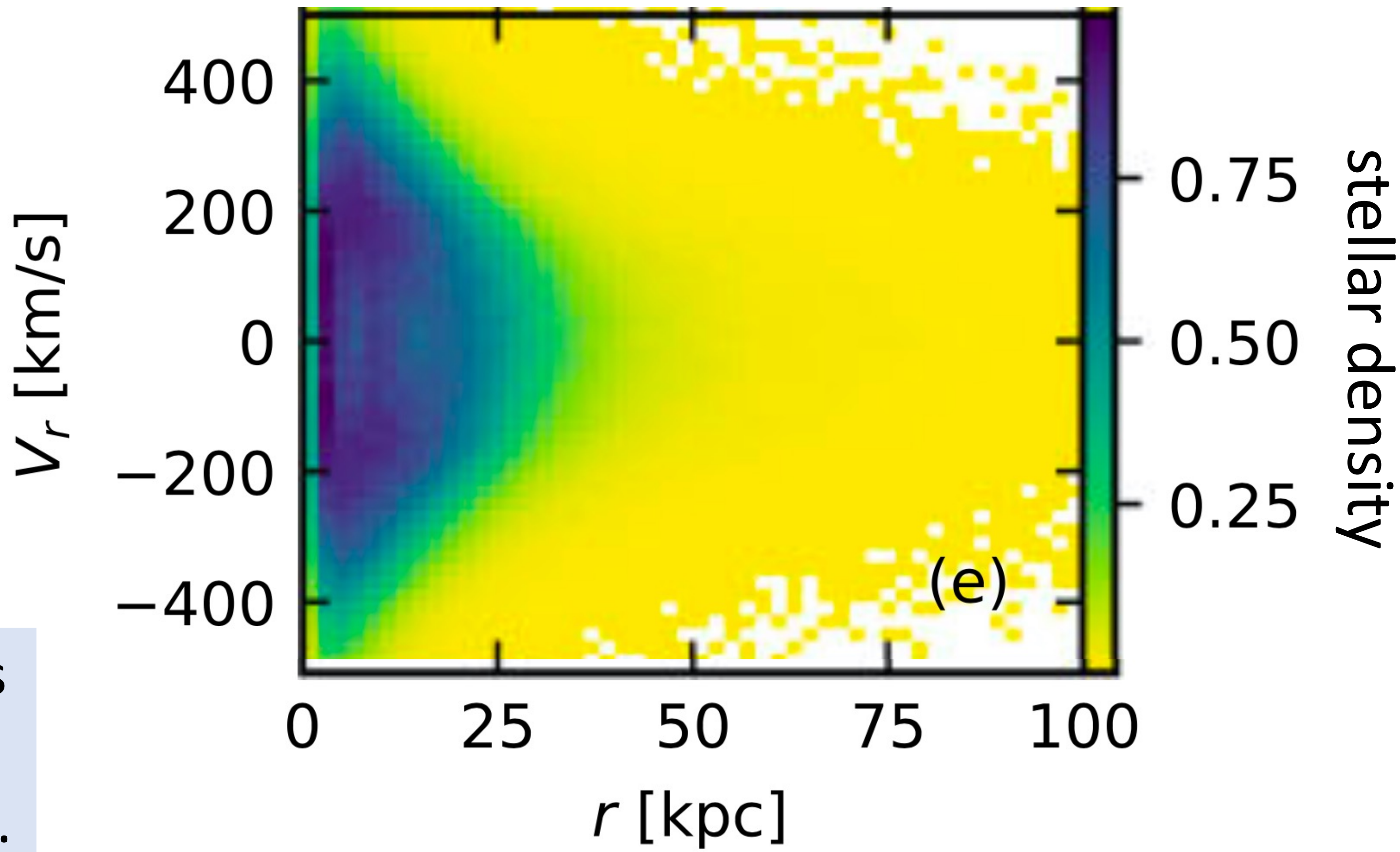
A population of stars that, to begin with, are in equilibrium with the Galaxy will drift radially outwards if the mass of the Galaxy decreases, or drift inwards if the mass increases. If the change of potential is slow, and the angular momentum is an adiabatic invariant during this change, than the net average radial motion in a spherical shell is proportional to the radius r of the shell and to the fractional rate of change of mass M enclosed by the shell

$$V_{\rm R} \equiv \frac{{\rm d}r}{{\rm d}t} = -\left(\frac{\dot{M}}{M}\right) r \qquad (1)$$

$$\approx \left(\frac{\dot{M}/M}{\rm Gyr^{-1}}\right)\left(\frac{r}{\rm kpc}\right) \ {\rm km\,s^{-1}}.$$

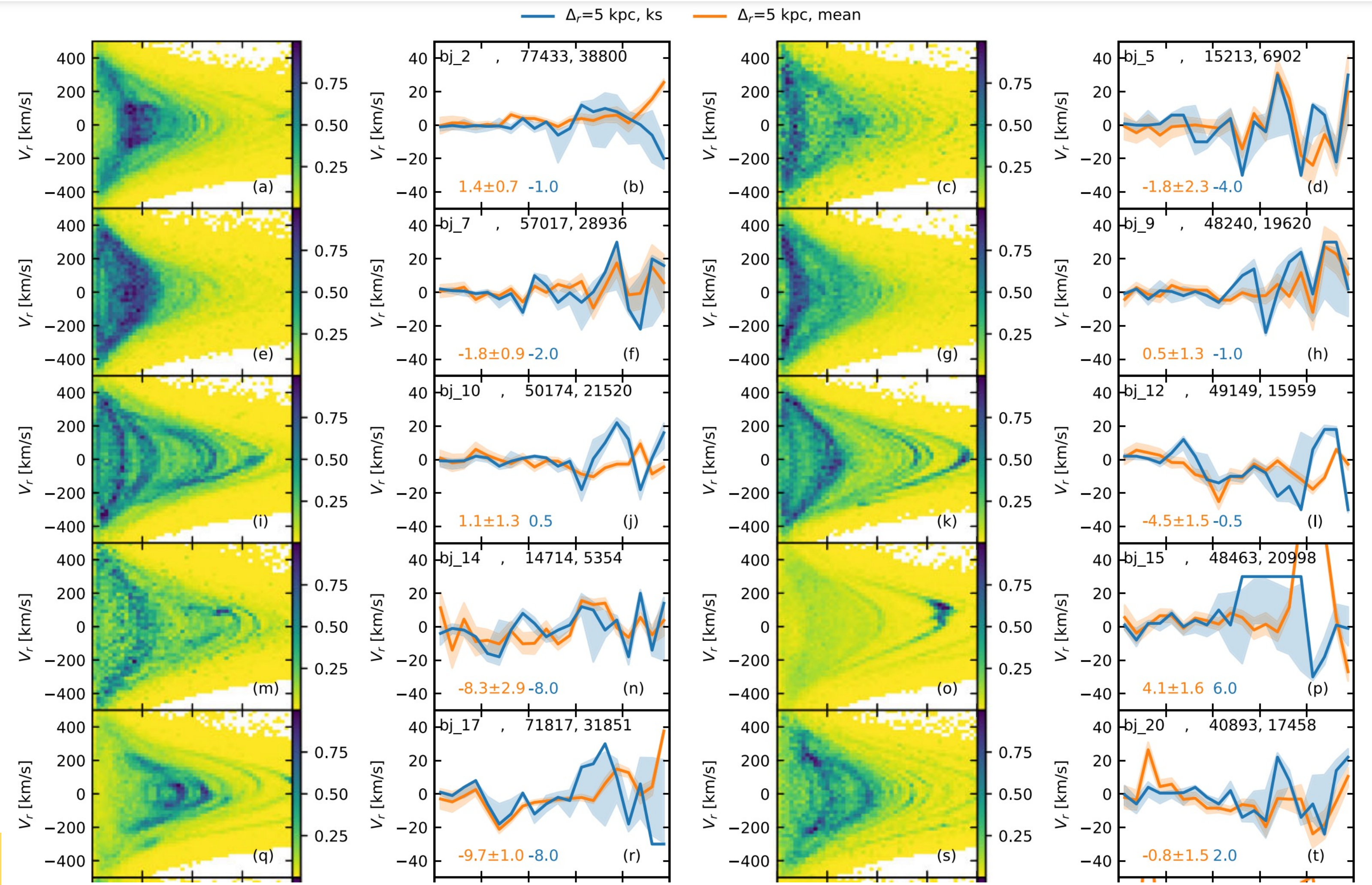
$\approx 0.02 \times 50 \approx 1$ km s^{-1}

Radial motions $\boldsymbol{V_r}$ in an isothermal halo, density colour-coded.



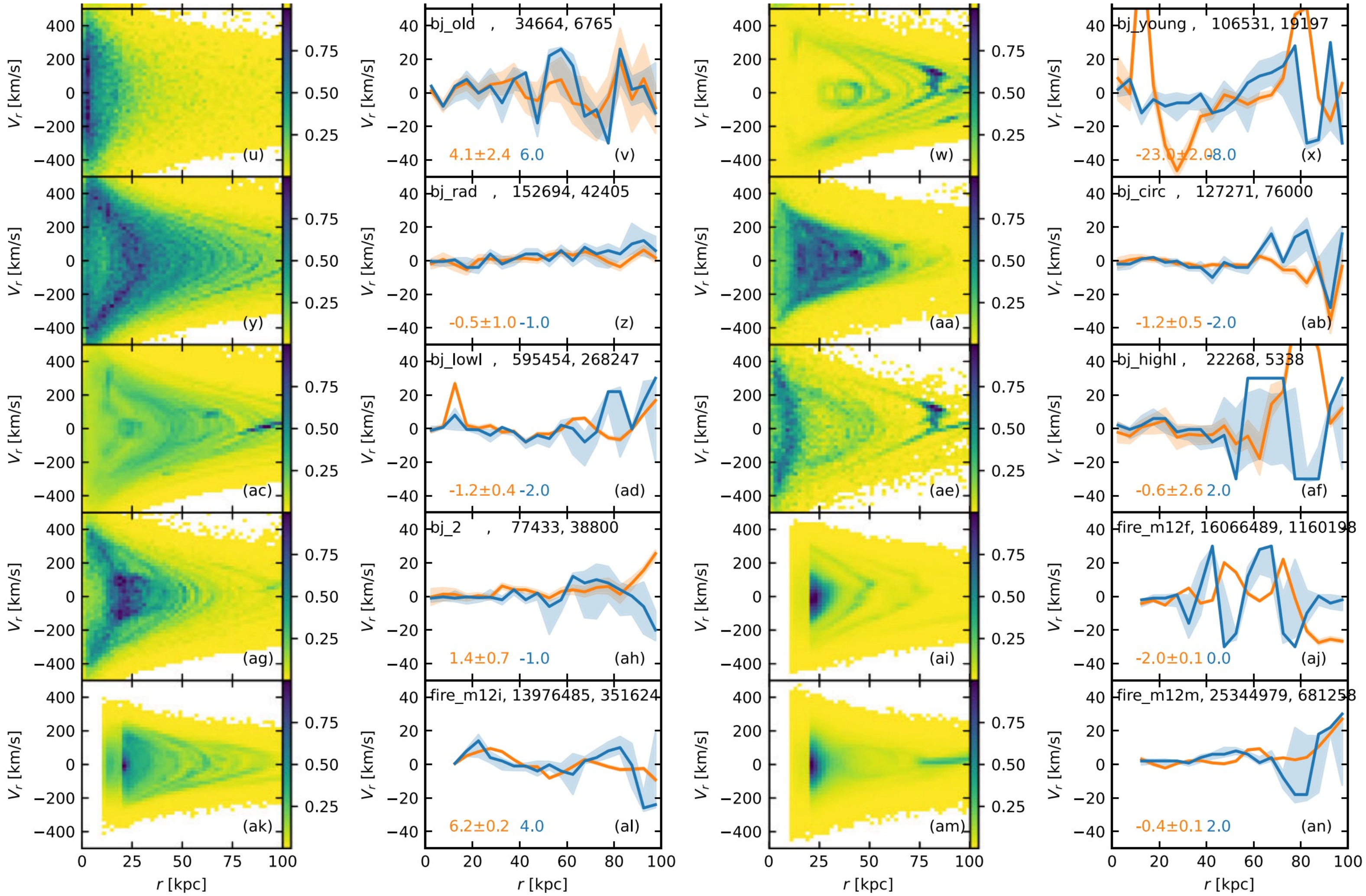
But this distribution does **not** describe the Milky Way's dark matter at z=0.

10 Milky Way (z=0) analogue simulations



Prima facie, $\langle \boldsymbol{V_r} \rangle < 1$ km s^{-1} looks problematic, assuming representative halos.

10 more Milky Way (z=0) analogue simulations



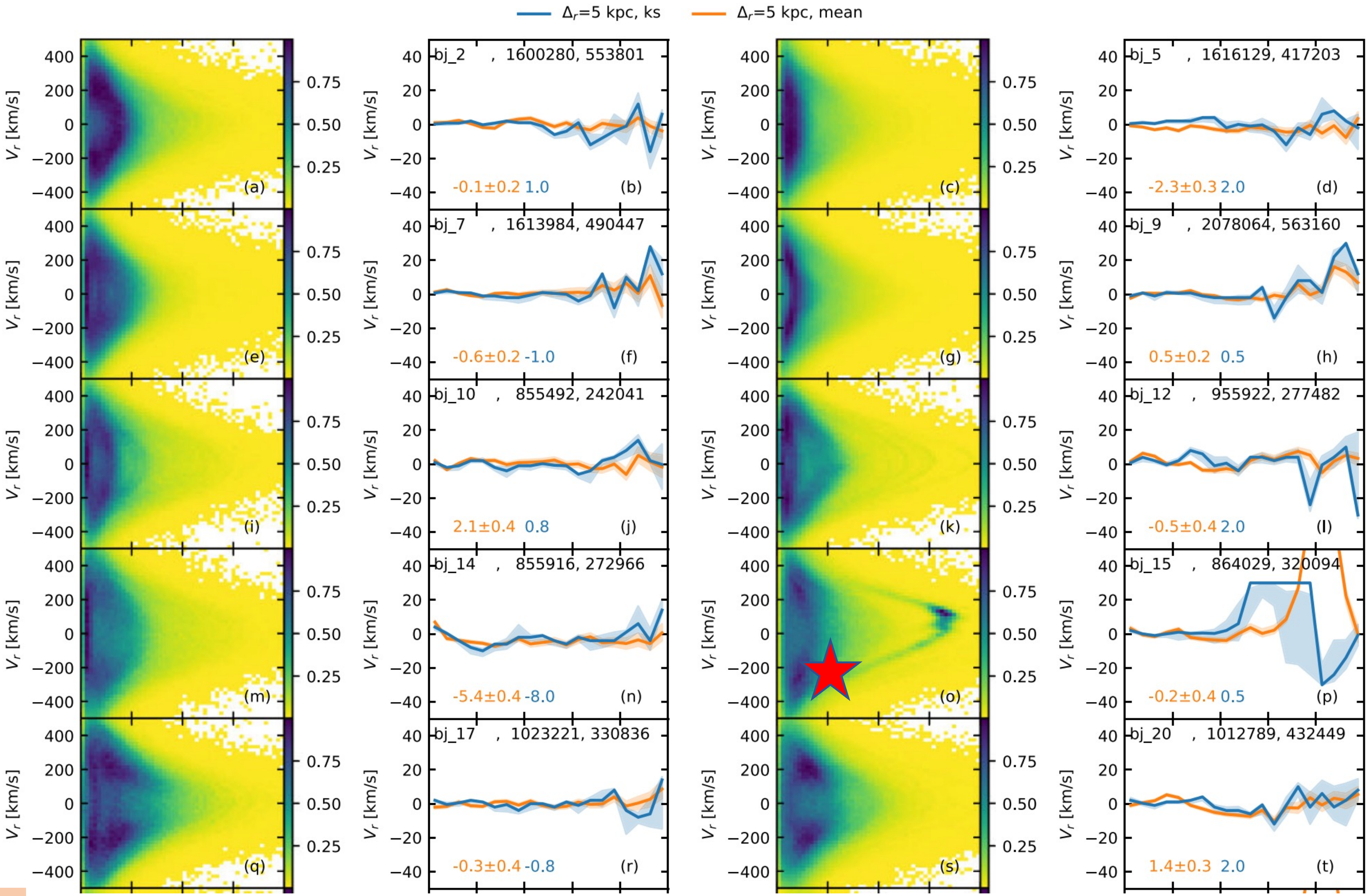
Prima facie, $\langle \boldsymbol{V_r} \rangle < 1$ km s^{-1} looks problematic, assuming representative halos.

Sharma's ENLINK (2006) is used to remove fine structure in 6D phase space, **F**($r\ \phi\ z\ V_r\ V_\phi\ V_z$).

We now show before and after – I will toggle these.

1st ten simulations.

★ I return to this case below



In most haloes, $\langle V_r \rangle < 1$ km s^{-1} is finally achieved.

Sharma's ENLINK (2006) is used to remove fine structure in 6D phase space, **F**($r\ \phi\ z\ V_r\ V_\phi\ V_z$).

We now show before and after – I will toggle these.

2nd ten simulations.

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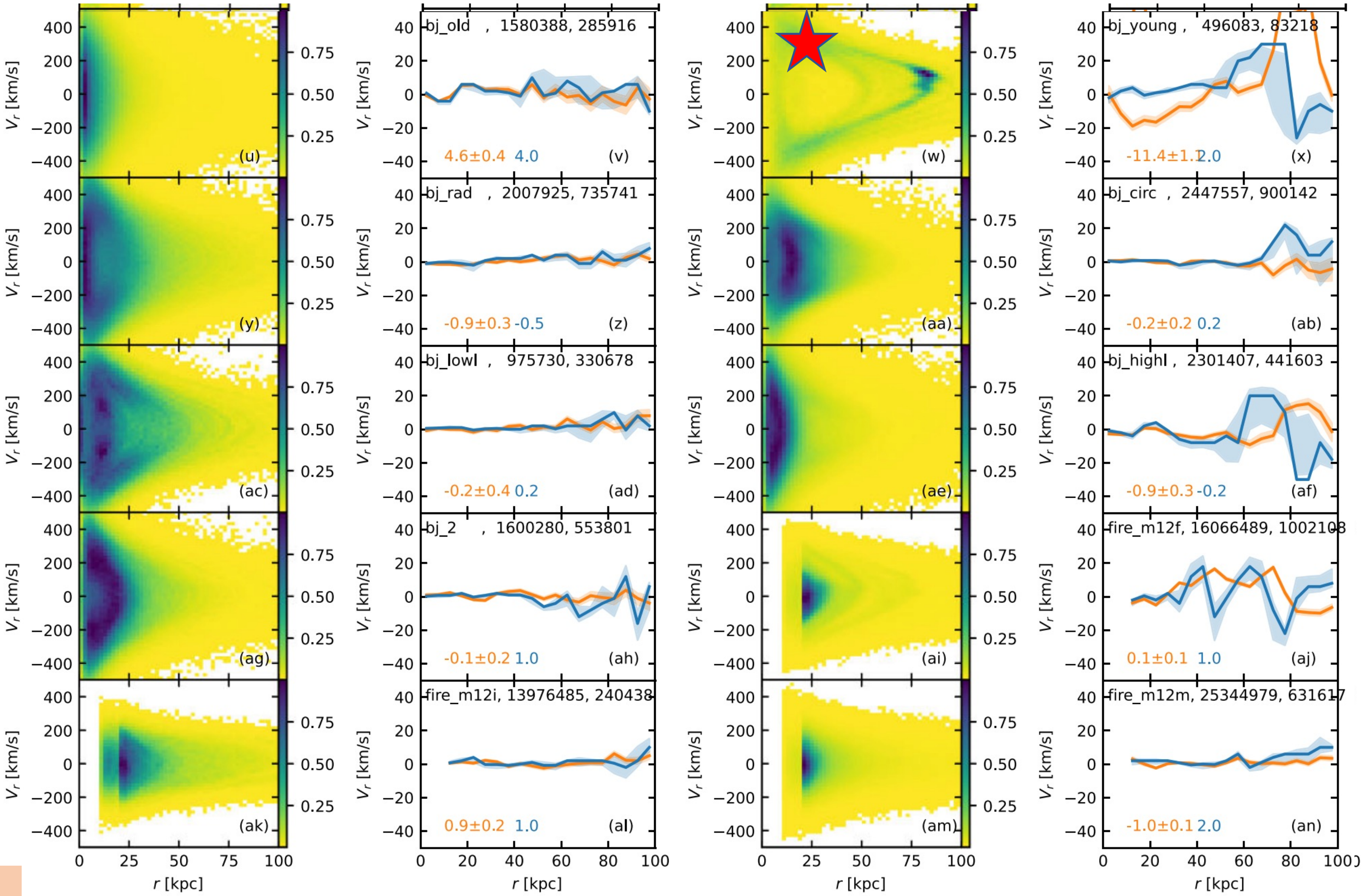
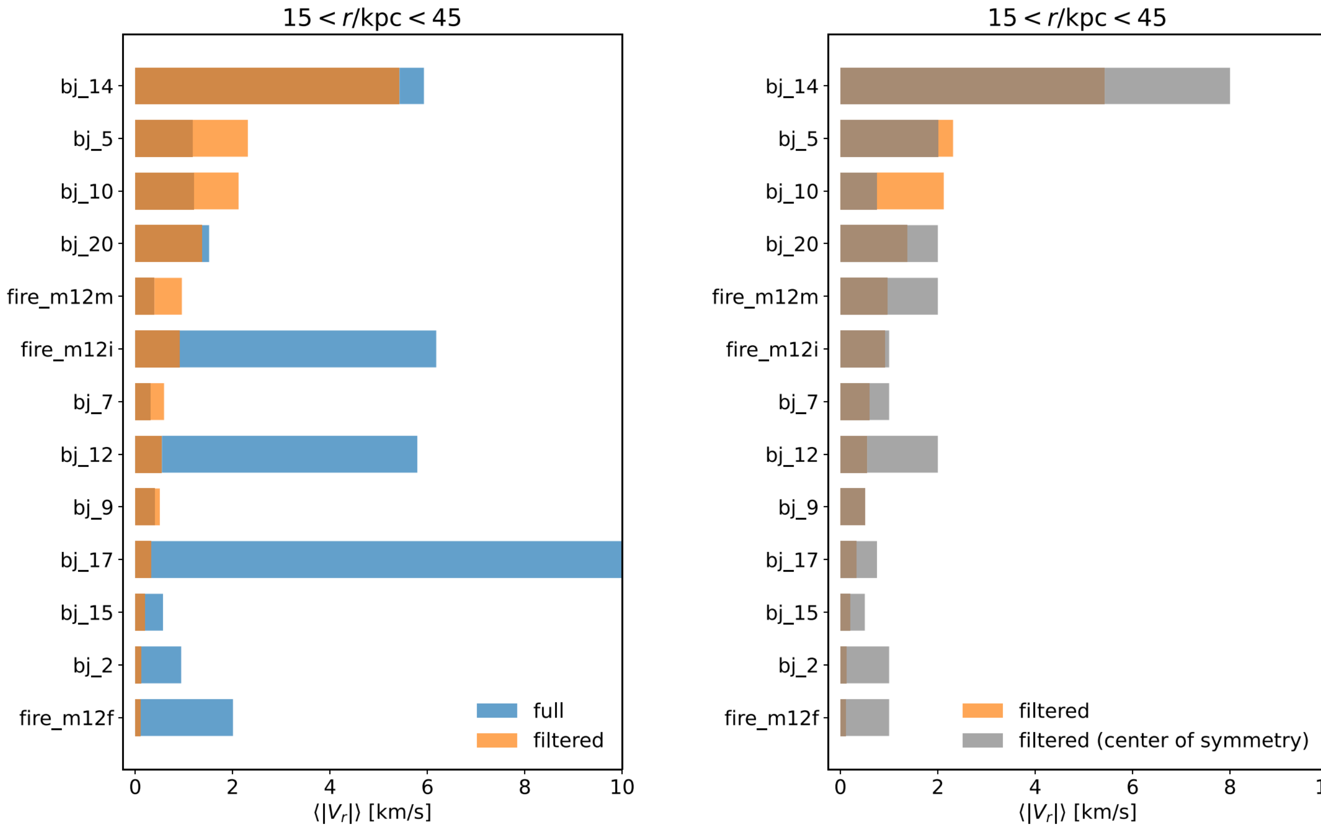


In most haloes, $\langle V_r \rangle < 1$ km s^{-1} is finally achieved.

Sharma's ENLINK (2006) before and after stats for shells in the range, *r* = 15 to 45 kpc.

We can do better with proper motions and/or better algorithms.



$\langle \boldsymbol{V_r} \rangle$ ~ 1 km s^{-1} is equivalent to ~3 μas astrometry at ~10 kpc.

~30 μas astrometry at ~10 kpc for G ~ 20 would be fantastic.

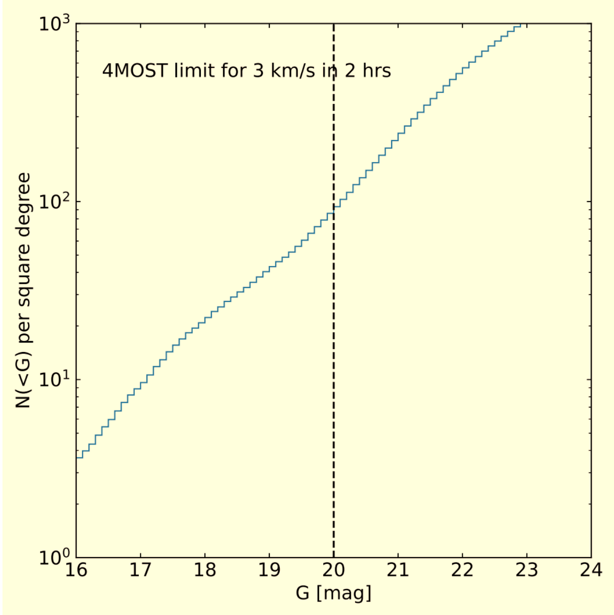
But this is beyond Gaia where ~300 μas (5 yrs) is the best we can expect (Lindegren et al 2022)?

Massive multiplex advantage

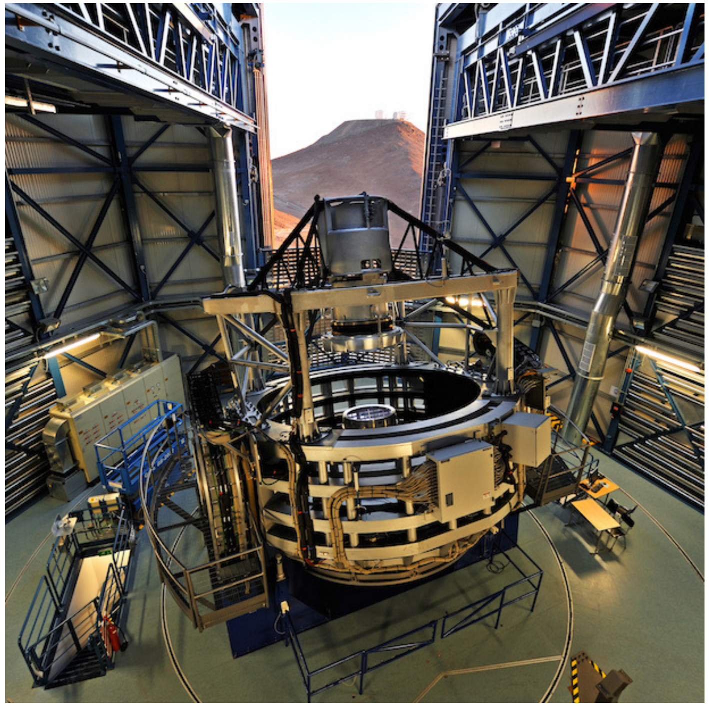
4MOST low resolution survey will observe 1.5M giants over 10,000 square degrees (5 yrs) to G ~ 20.

~0.5M stars lie within a 15-45 kpc shell.

~3 km s^{-1} per star is good enough with a view to low-order spherical harmonic analysis...



Galaxia simulation (Sharma+ 2011) galaxia.sourceforge.net



Systematic effects (due to astrophysics) are bound to make any detection harder, but these are likely to be very interesting... Here, I give four examples.

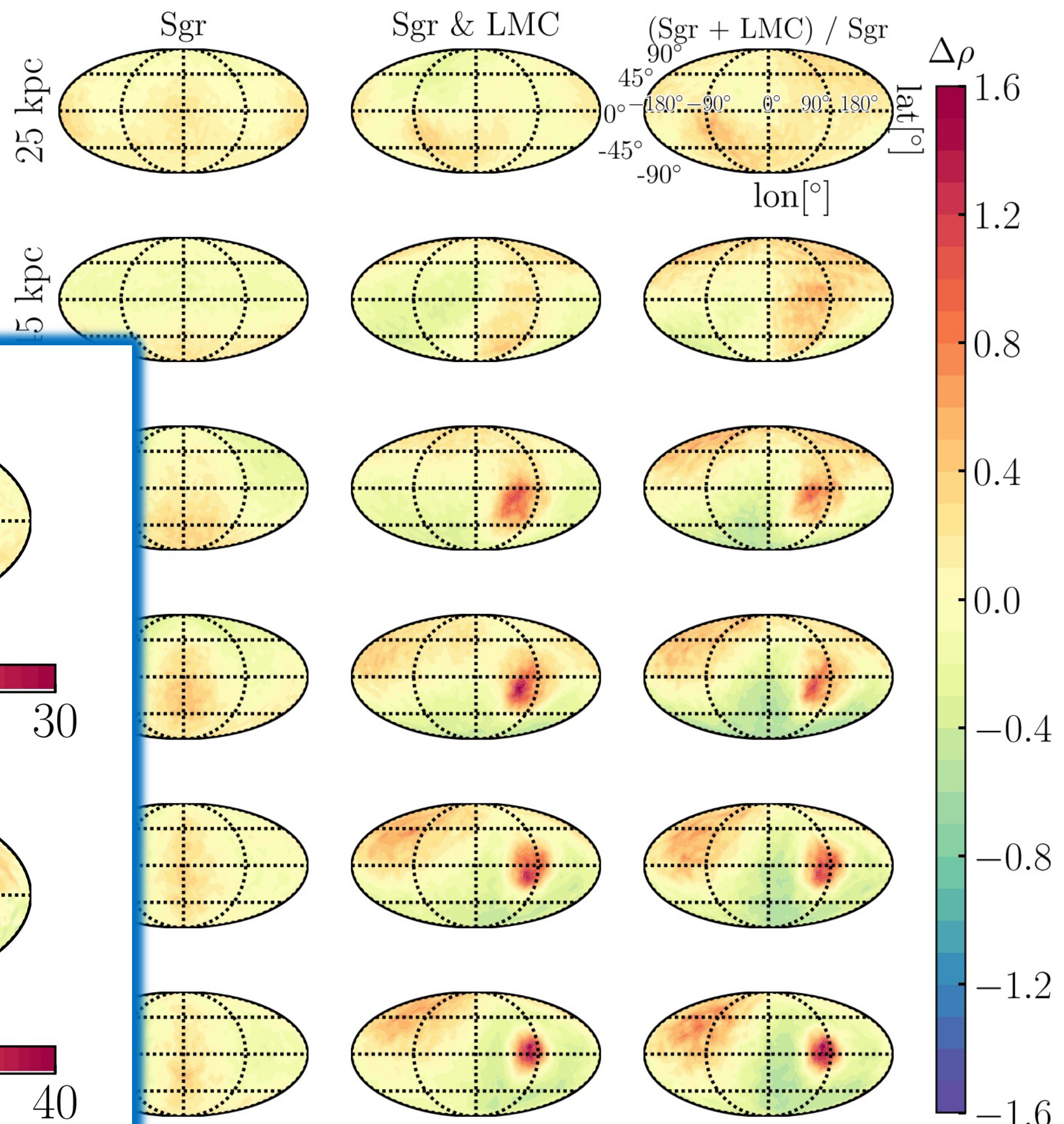
1 THE ASTROPHYSICAL JOURNAL

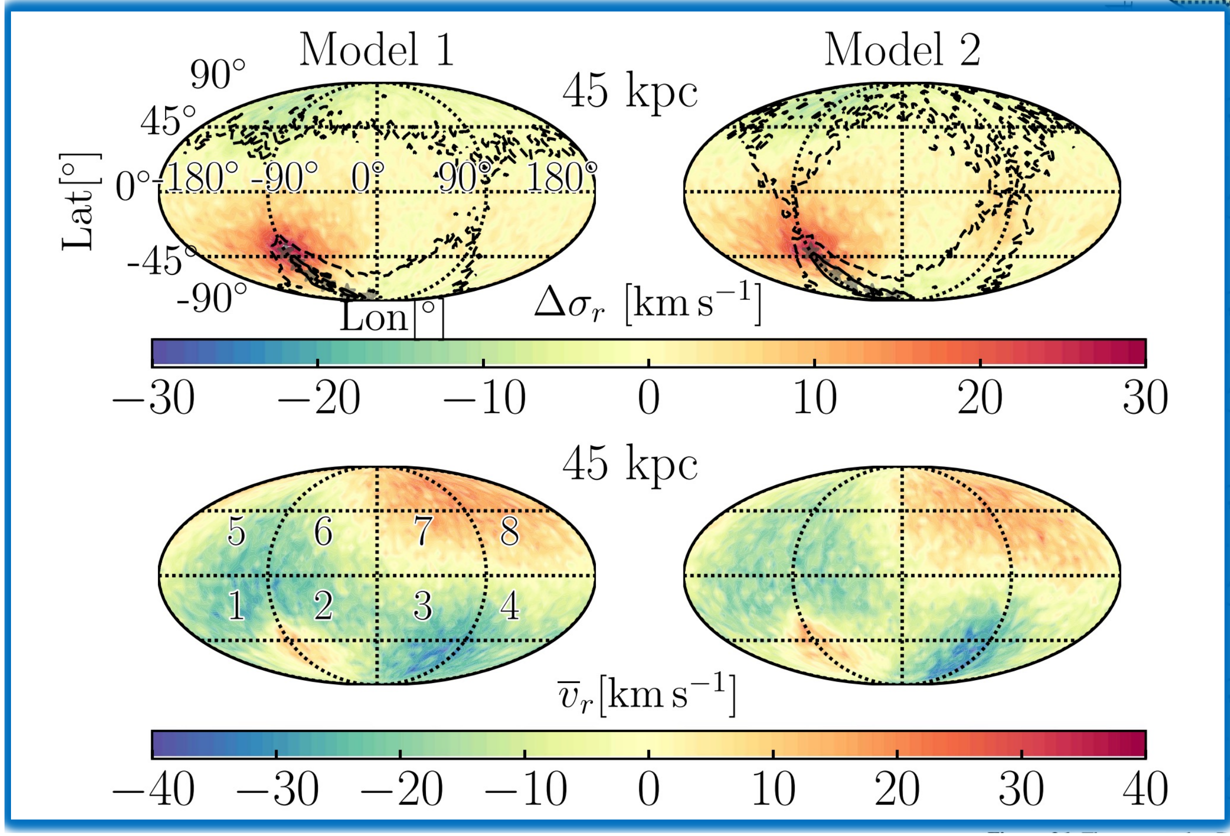
Hunting for the Dark Matter Wake Induced by the Larg Magellanic Cloud

Nicolas Garavito-Camargo[1], Gurtina Besla[1], Chervin F. P. Laporte[8,2], Kathryn
Facundo A. Gómez[4,5], and Laura L. Watkins[6,7]

Published 2019 October 11 •

The Astrophysical Journal, 884:51 (29pp), 2019 October 10 Garavito-Ca





2 Stellar halo striations from assumptions of axisymmetry

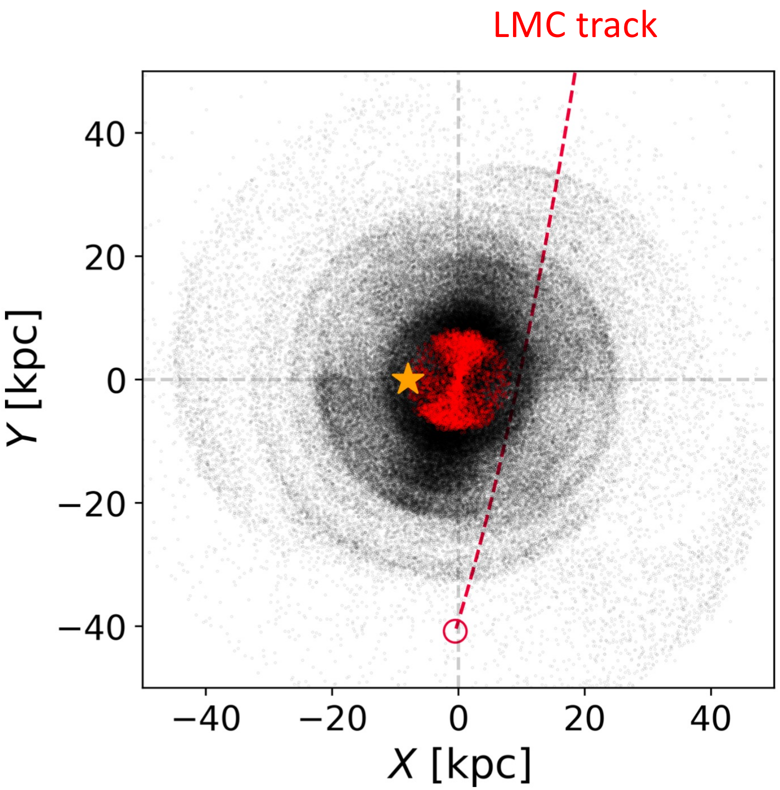
Elliot Y. Davies [1★], Adam M. Dillamore [1], Vasily Belokurov [1] and N. Wyn Evans [1].
[1] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*

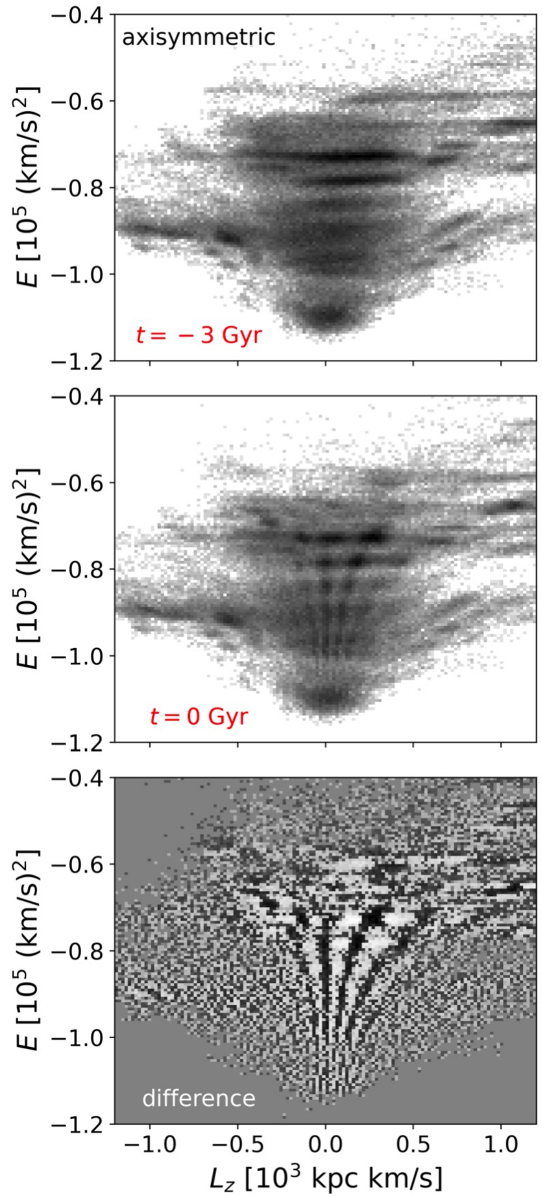
Last updated 2020 June 10; in original form 2013 September 5

ABSTRACT

Motivated by the LMC's impact on the integral of mo
produce a population of halo-like stars. We subsequen
debris. When an axisymmetric potential is assumed fo
striations in (L_z, E) space form as the LMC approaches
momentum owing to a relationship between the precess
This effect is heavily dependent on the shape of the inne
striations become significantly less apparent due to the
these features in data, and the dramatic change in orbita
for highly eccentric orbits accreted from a massive GSI
the shape of the potential, this effect may provide a new

★ There are some structures, esp. when phase-mixing, that will be hard to remove.





3

Momentum recoil and baryon sloshing within dark matter halos

Exploring the centre of mass properties of LG-like galaxies

Jean-Baptiste Salomon,[1,2,3]⋆ Noam Libeskind[2] and Yehuda Hoffman[1]
[1] *Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel*
[2] *Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany*
[3] *Institut UTINAM, CNRS UMR6213, Univ. Bourgogne Franche-Comté, OSU THETA, Observatoire de Besançon, BP 1615, 25010 Besançon Cédex, France*

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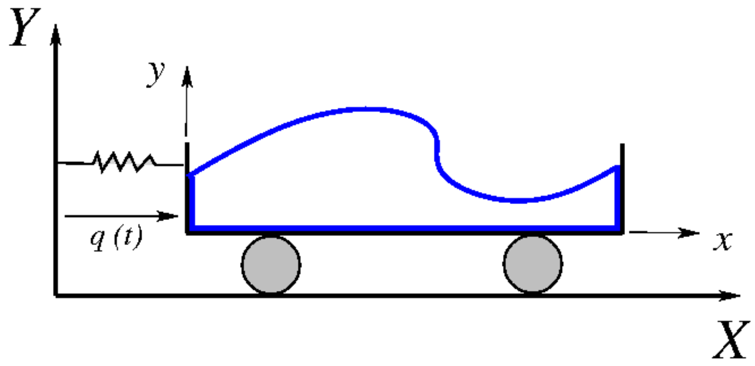
ABSTRACT
From high resolution cosmological simulations of the Local Group in realistic environment, namely HESTIA simulations, we study the position and kinematic deviations that may arise between the disc of a Milky Way (or Andromeda)-like galaxy and its halo. We focus on the 3-dimensional analysis of the centres of mass (COM). The study presents two parts. We first consider individual particles to track down the very nature and amplitude of the physical deviations of the COM with respect to the distance from the disc centre. Dark matter dominates the behaviour of the COM of all particles at all distances. But the total COM is also very close to the COM of stars. In the absence of a significant merger, the velocity offsets are marginal ($10\,\mathrm{km\,s^{-1}}$) but the positional shifts can be important compared to the disc characteristics (> 10 kpc). In the event of a massive accretion, discrepancies are of the same order as the recent finding for the MW under the Magellanic Clouds influence. In a second part, the accent is put on the study of various populations of subhaloes and satellites. We show that satellites properly represent the entire subhalo population. There exists strong mismatch in phase space between the satellites' COM and the host disc. Moreover, the results are highly inhomogeneous between the simulations, and thus between the accretion histories. Finally, we point out that these shifts are mainly due to a few of the most massive objects.



4

Simple, stretched and twisted halos

Emami et al 2021

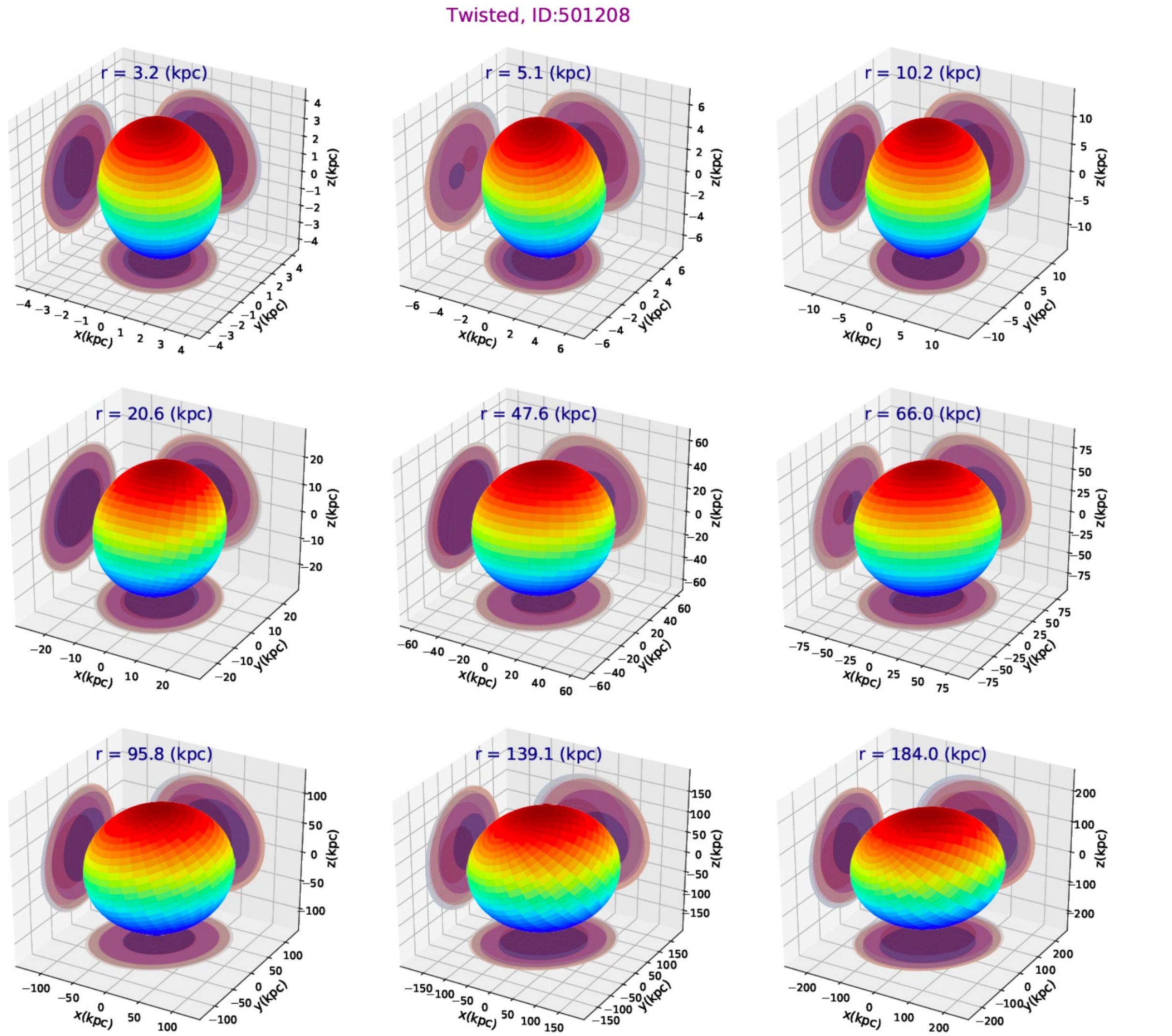
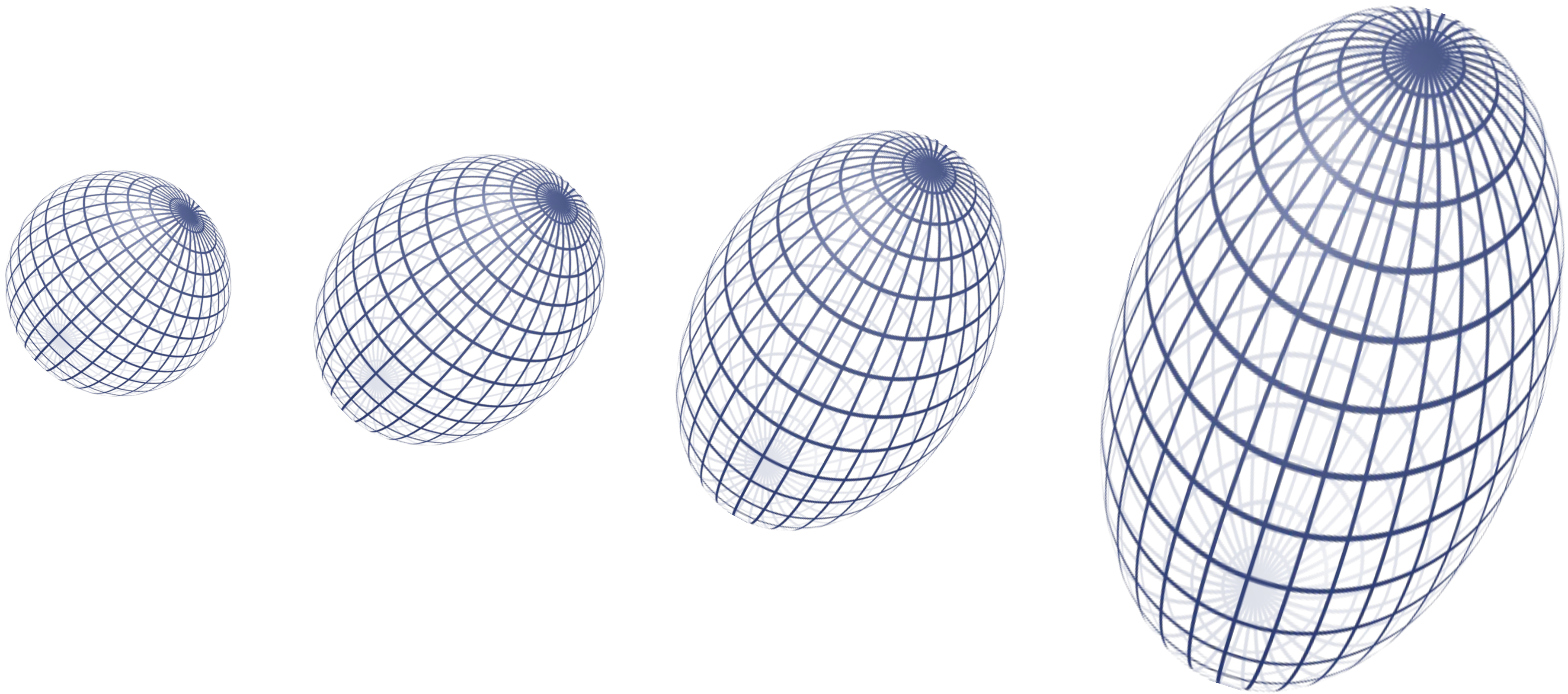


Figure 7. 3D Ellipsoidal for a twisted halo. The halo establishes some levels of gradual rotations in its radial profile.

See also: Shao et al 2020

We anticipate a complex optimization problem within triaxial ellipsoidal shells – the mathematical framework exists.



Ellipsoidal Harmonics

The triaxial ellipsoidal coordinates are defined as [*Dassios*, 2012]

$$\rho = \sqrt{a_1^2 - q_1}$$
$$\mu = \sqrt{a_1^2 - q_2}$$
$$\nu = \sqrt{a_1^2 - q_2},$$

where q_1,q_2,q_3 are the real roots of the cubic polynomial

$$\frac{x^2}{a_1^2 - q} + \frac{y^2}{a_2^2 - q} + \frac{z^2}{a_3^2 - q} = 1$$

and a_1,a_2,a_3 are the descendingly ordered semiaxes of a reference ellipsoid center
origin.

The exterior potential parameterized in ellipsoidal harmonics is given by

$$V(\rho, \mu, \nu) = GM \sum_{n=0}^{\infty} \sum_{m=0}^{2n} \overline{\alpha}_{nm} \frac{F_{nm}(\rho)}{F_{nm}(a_1)} \times \overline{E}_{nm}(\mu) \overline{E}_{nm} \quad (9)$$

where $\overline{E}_{nm}$ and F_{nm} are the Lamé functions of the first and the … The second-kind function, $F_{nm}(\rho)$, accounts for the radial attenuatio … al, analogous to the functions Q_{nm} in the spheroidal case. The coeffic … d to the SH, OH, and PH coefficients $\overline{c}_{nm}$ and $\overline{s}_{nm}$.

Lamé Functions of the Second Kind

The functions of the second kind can be computed by

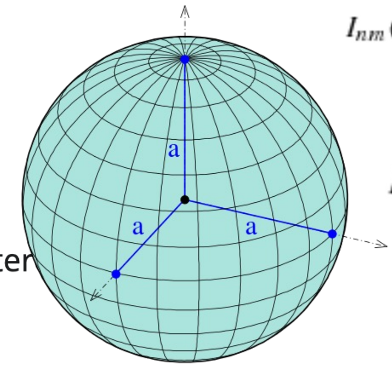
$$F_{nm}(\rho) = E_{nm}(\rho) I_{nm}(\rho)$$

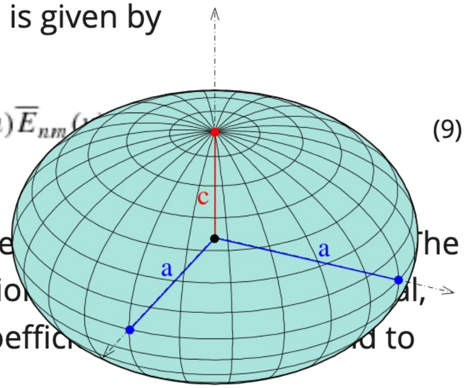
where I_{nm} are integrals of the form

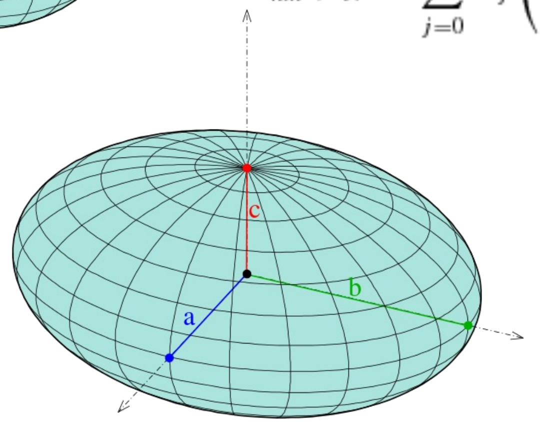
$$I_{nm}(\rho) = \int_0^{\rho^{-1}} \frac{t^{2n} \mathrm{d}t}{(E_{nm}(t))^2 \sqrt{1 - k_3^2 t^2} \sqrt{1 - k_2^2 t^2}},$$

$$E_{nm}(w_i) = \psi_{nm}(w_i) T_{nm}(w_i).$$

$$T_{nm}(w_i) = \sum_{j=0}^{N_{\mathcal{F}}-1} \kappa_j \left(1 - \frac{w_i^2}{k_2^2}\right)^j,$$





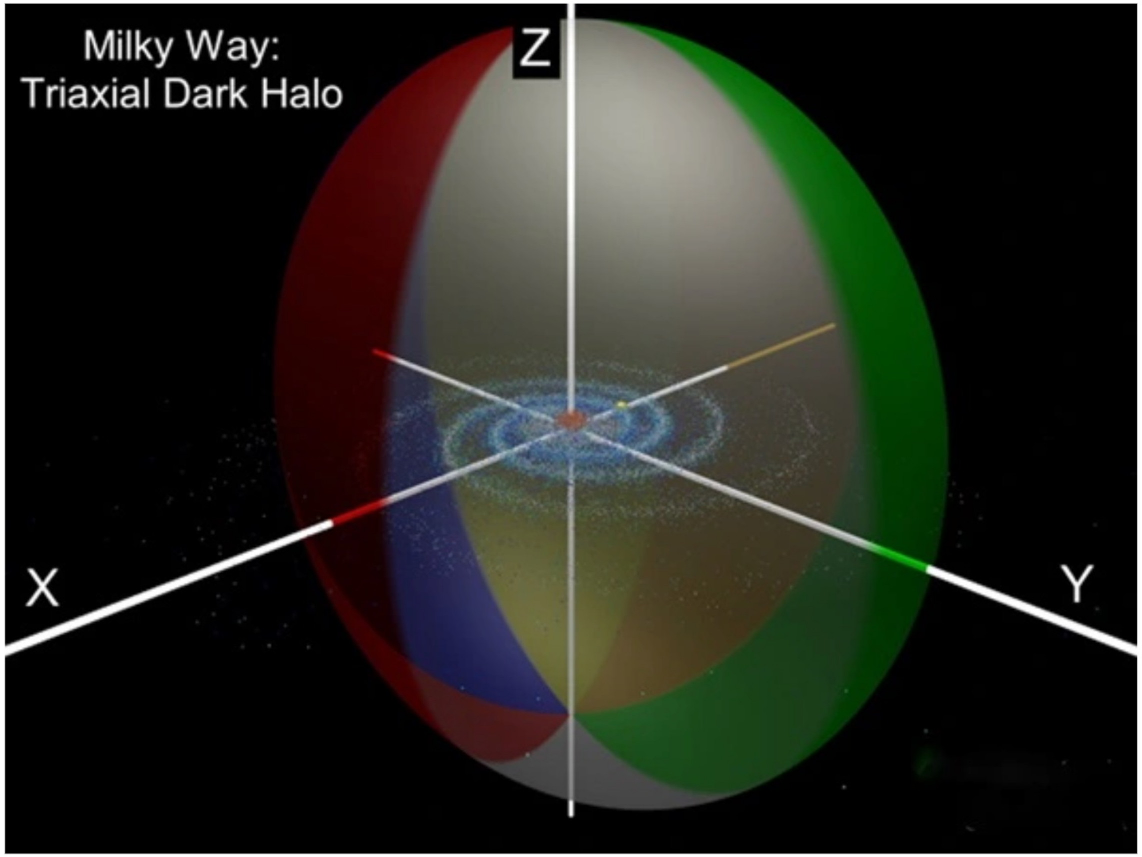


Summary

We know very little about the nature, structure and distribution function of **any** dark matter halo.

This is just **one possible experiment** in near field cosmology. There are many others (e.g. Klioner 2018).

In combination with future lensing, stream/halo kinematics, simulations and dynamical studies, we can expect real progress in the period 2025-35.



Credit: David Law, UCLA