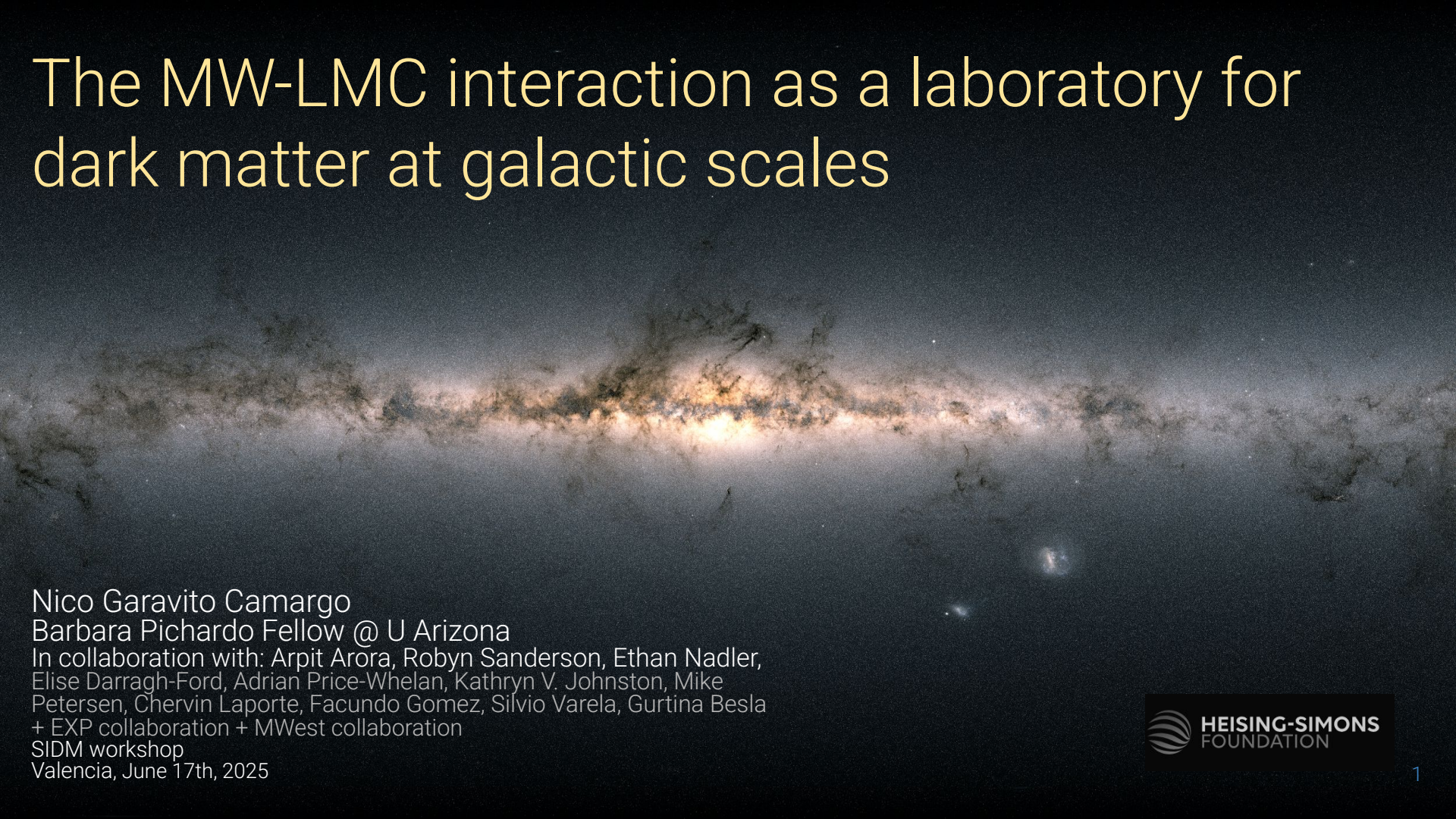
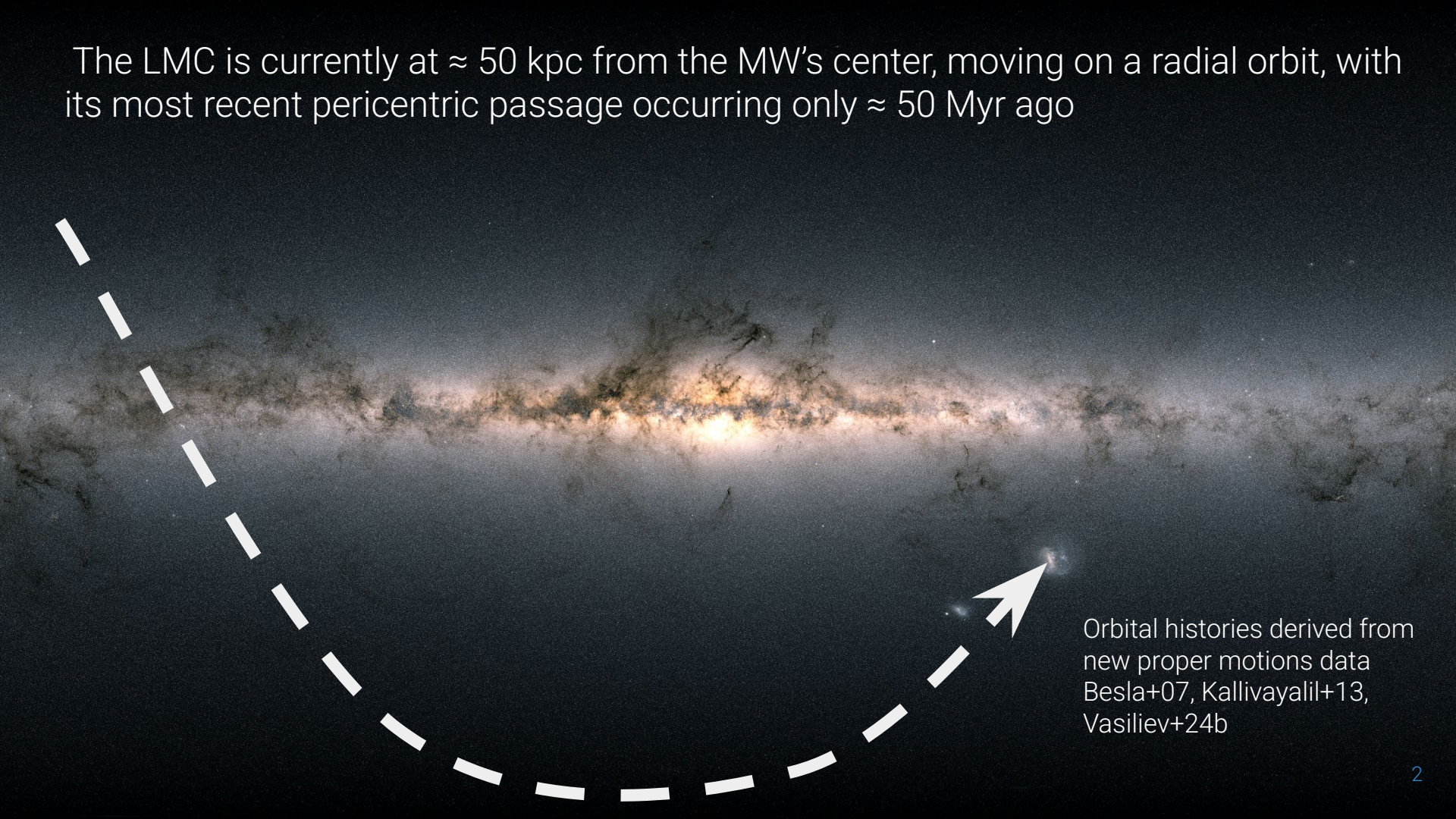
# The MW-LMC interaction as a laboratory for dark matter at galactic scales



Nico Garavito Camargo
Barbara Pichardo Fellow @ U Arizona
In collaboration with: Arpit Arora, Robyn Sanderson, Ethan Nadler, Elise Darragh-Ford, Adrian Price-Whelan, Kathryn V. Johnston, Mike Petersen, Chervin Laporte, Facundo Gomez, Silvio Varela, Gurtina Besla + EXP collaboration + MWest collaboration
SIDM workshop
Valencia, June 17th, 2025

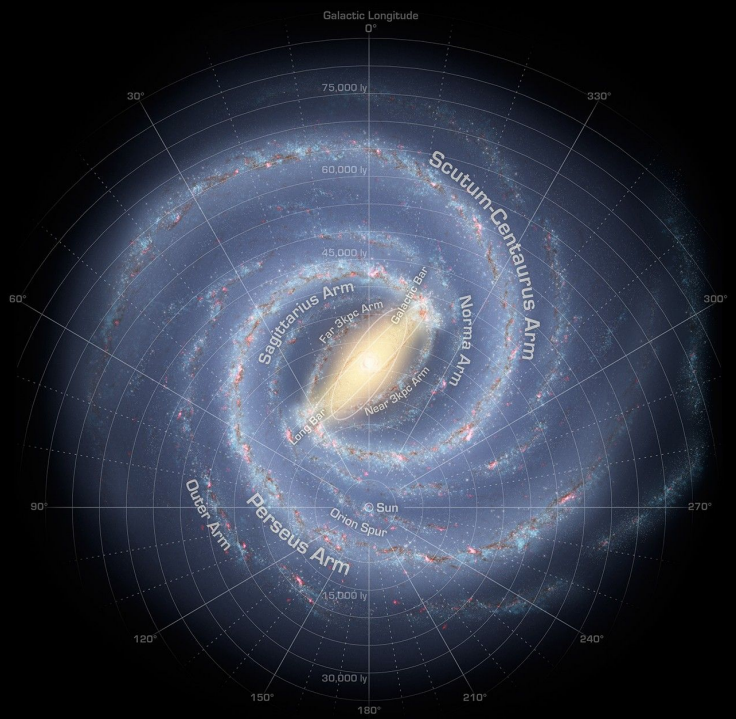
HEISING-SIMONS FOUNDATION

The LMC is currently at ≈ 50 kpc from the MW's center, moving on a radial orbit, with its most recent pericentric passage occurring only ≈ 50 Myr ago



Orbital histories derived from new proper motions data
Besla+07, Kallivayalil+13, Vasiliev+24b

# The MW is currently interacting with the LMC, its most massive satellite with a total mass of  10% the mass of the MW



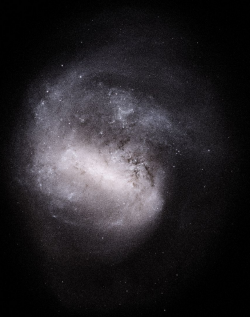
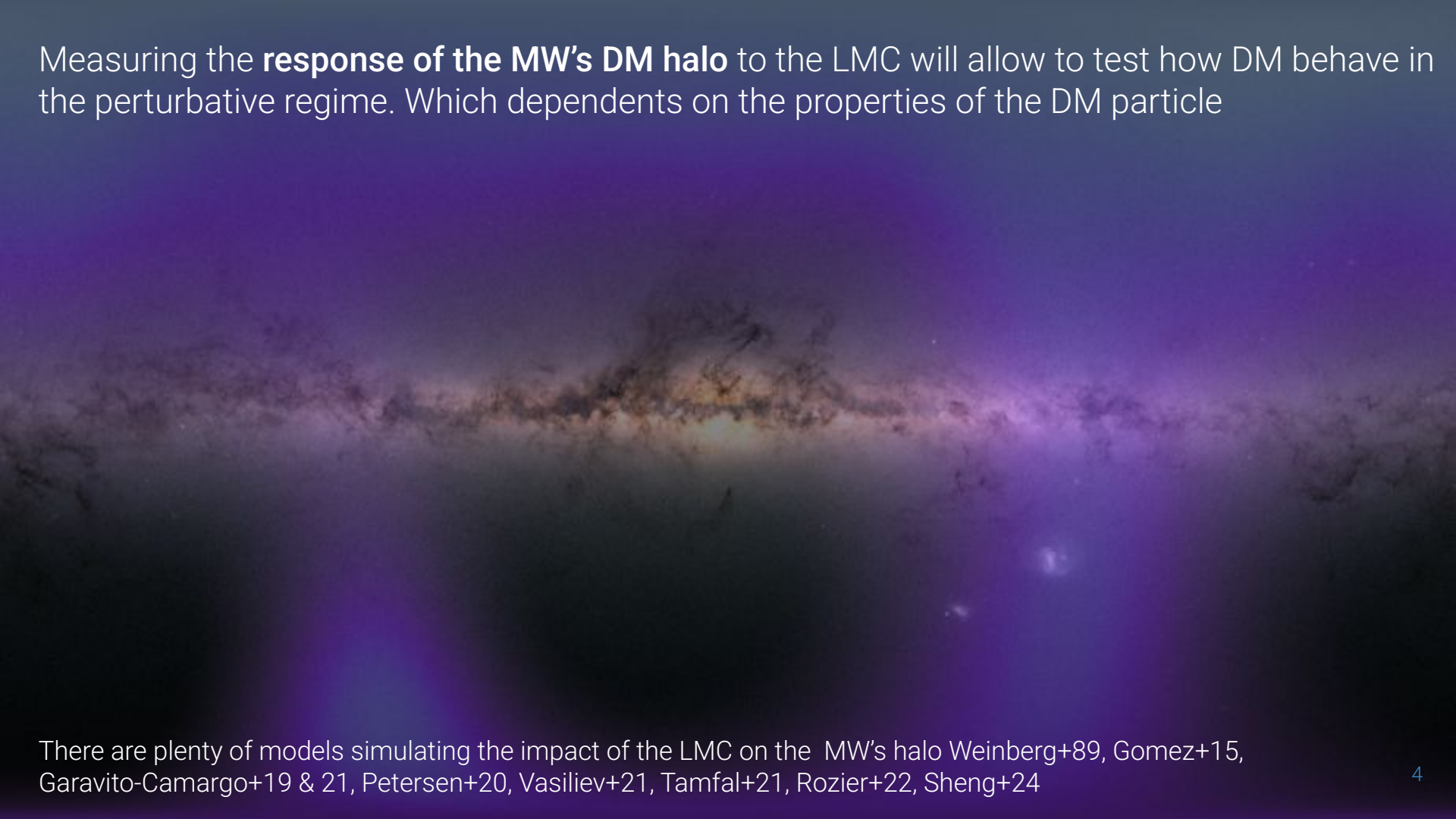



Image credit: Oscar Jimenez Arranz

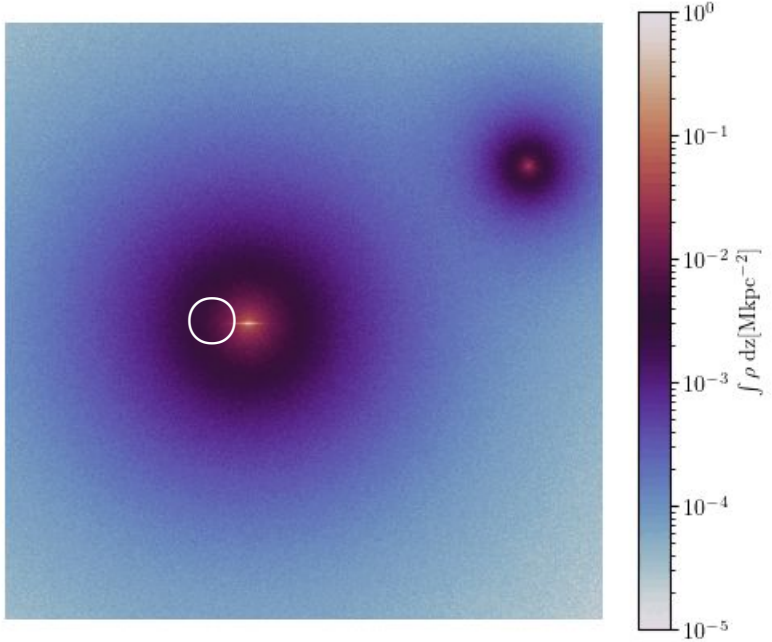
Mass estimates of the LMC come from rotation curve (van der Marel+14, Watkins+24), perturbations on streams (Erkal+19, Shipp+18 & 21, Warren+25), in the MW disk (Laporte+18b), and the timing argument (Penarrubia+16, Chamberlain+24)

Measuring the **response of the MW's DM halo** to the LMC will allow to test how DM behave in the perturbative regime. Which dependents on the properties of the DM particle

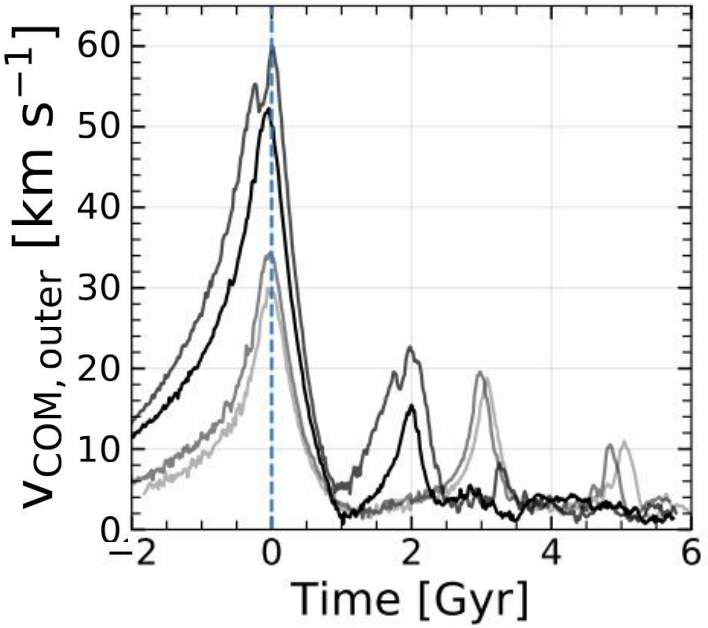


There are plenty of models simulating the impact of the LMC on the MW's halo Weinberg+89, Gomez+15, Garavito-Camargo+19 & 21, Petersen+20, Vasiliev+21, Tamfal+21, Rozier+22, Sheng+24

# The LMC displaces the MW's COM, whose magnitude is maximal soon after the fist pericenter passage (ideal for the MW+LMC system)



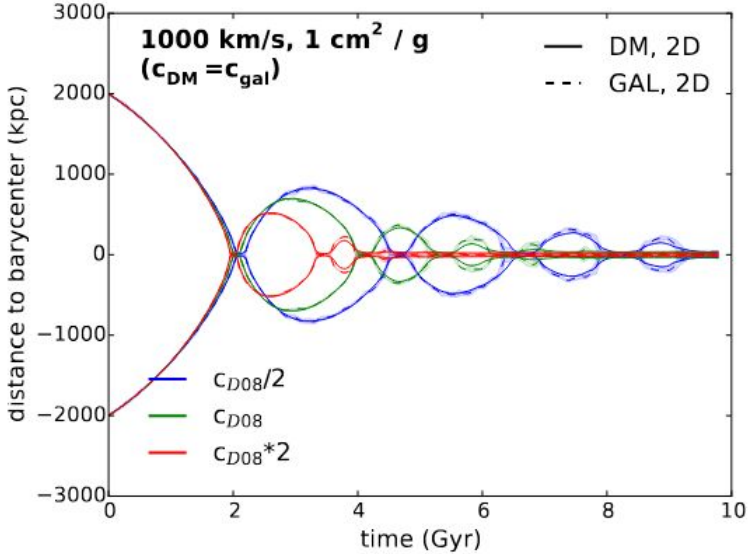

Garavito-Camargo+21



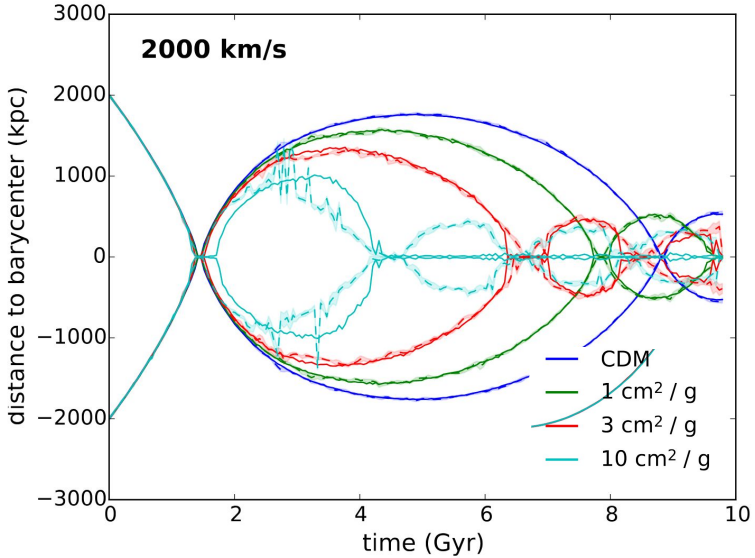

Garavito-Camargo+24

# COM displacements are sensitive to the halos concentration and DM cross section

Higher halo concentration induce smaller the COM displacement.

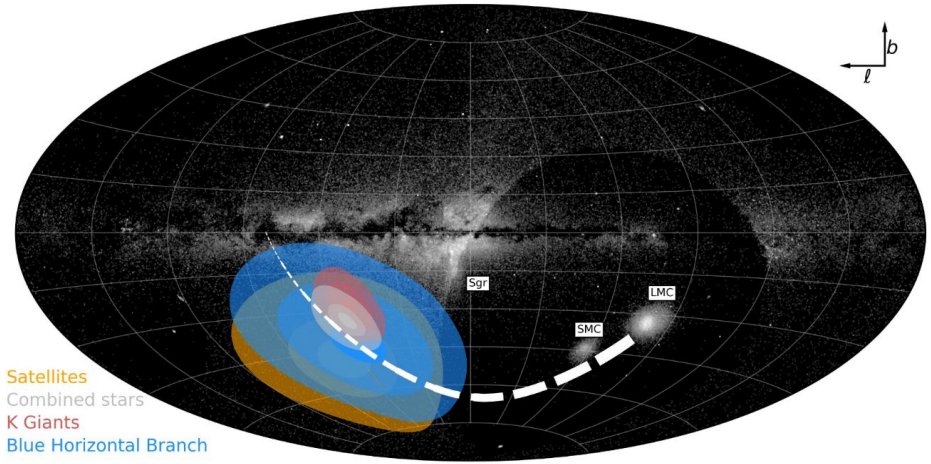



Higher DM cross-sections result in smaller COM displacements

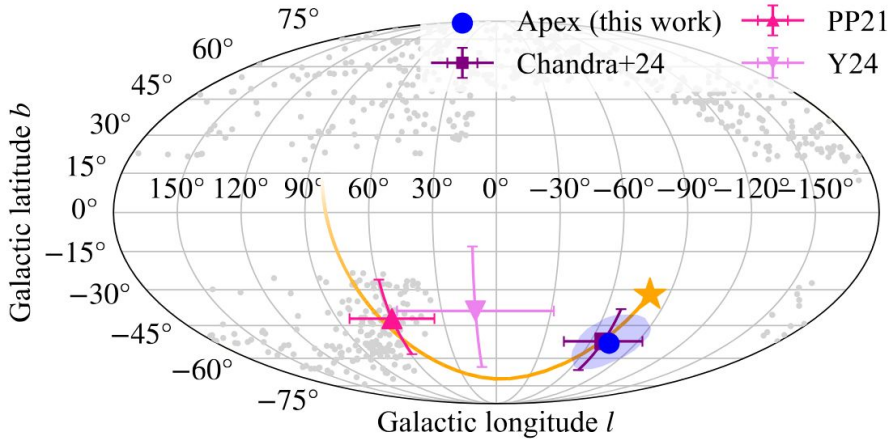



Kim, Stacy + 2016

# The MW's disk is moving at ≈34 km/s towards the south relative to the outer halo of the MW consistent with the predictions from simulations




Petersen & Penarrubia+21

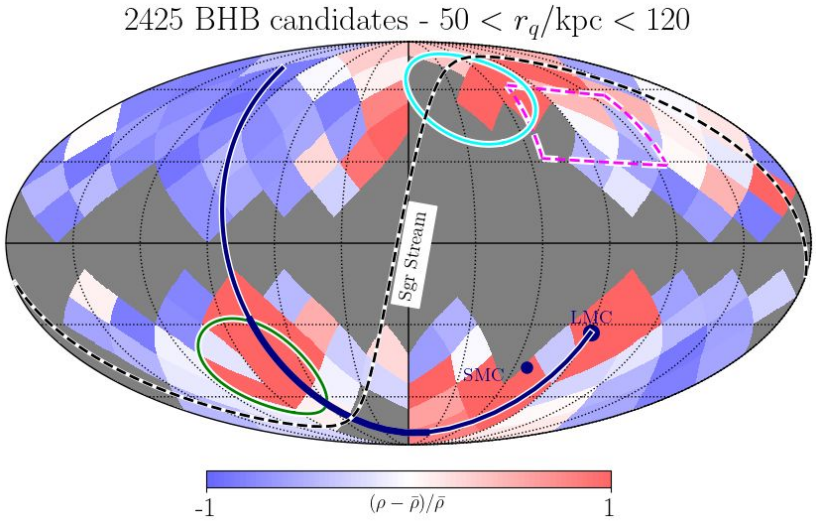



Byström+24

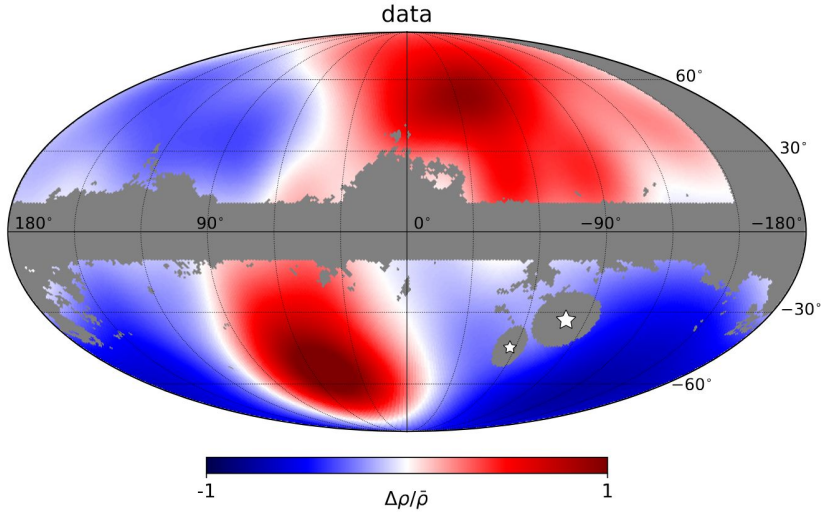
Also shown in: Yaaqib+24, Chandra+24

Thanks to data from Gaia, DESI, H3 and SDSS

# Stellar overdensities and underdensities owing to the perturbations from the LMC has been observed in the MW's stella halo



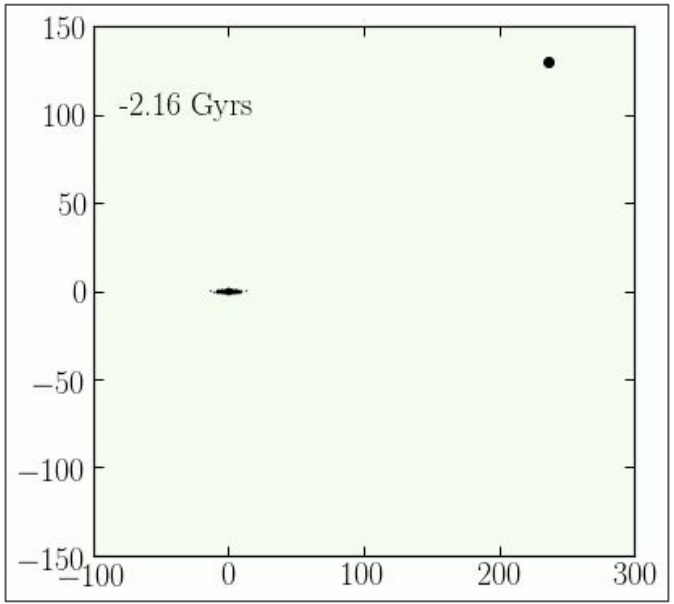

Amarante+24



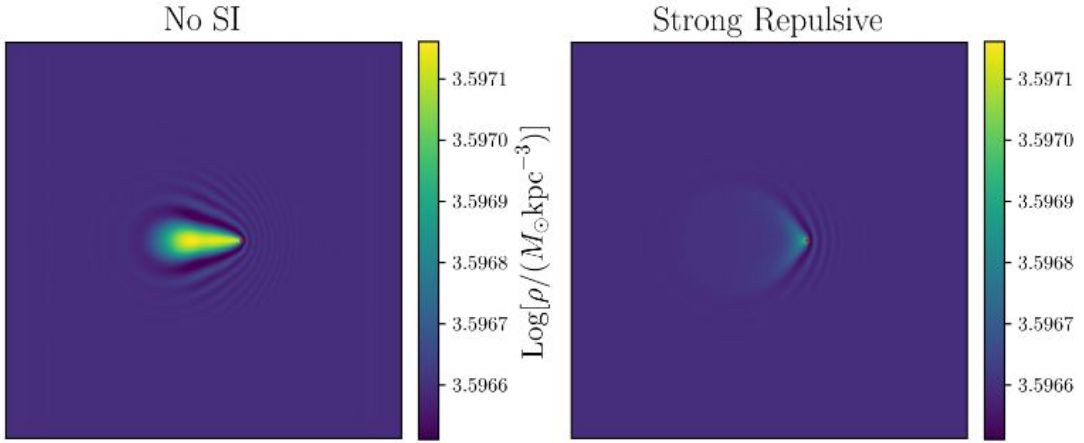

Conroy+21

Also detected by Fushima+24 and Cavieres+24

# The morphology and amplitude of the wakes depend on the host's density profile and velocity dispersion, offering a probe of dark matter in the MW



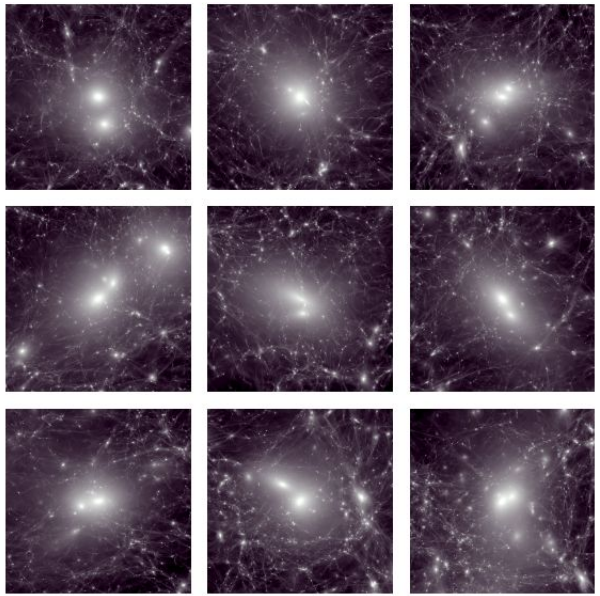

Garavito-Camargo+19




Differences on wake morphologies in a ULDM background without strong interactions (left) and with strong repulsive interactions (right). Glennon+23

See also Foote+23 for a fuzzy DM simulation of the LMC's wake

# Decomposing the halo's response to LMC-like satellites in the **MWest** and **Symphony** cosmological simulations



Nadler et. al., 23 & Buch et. al., 24

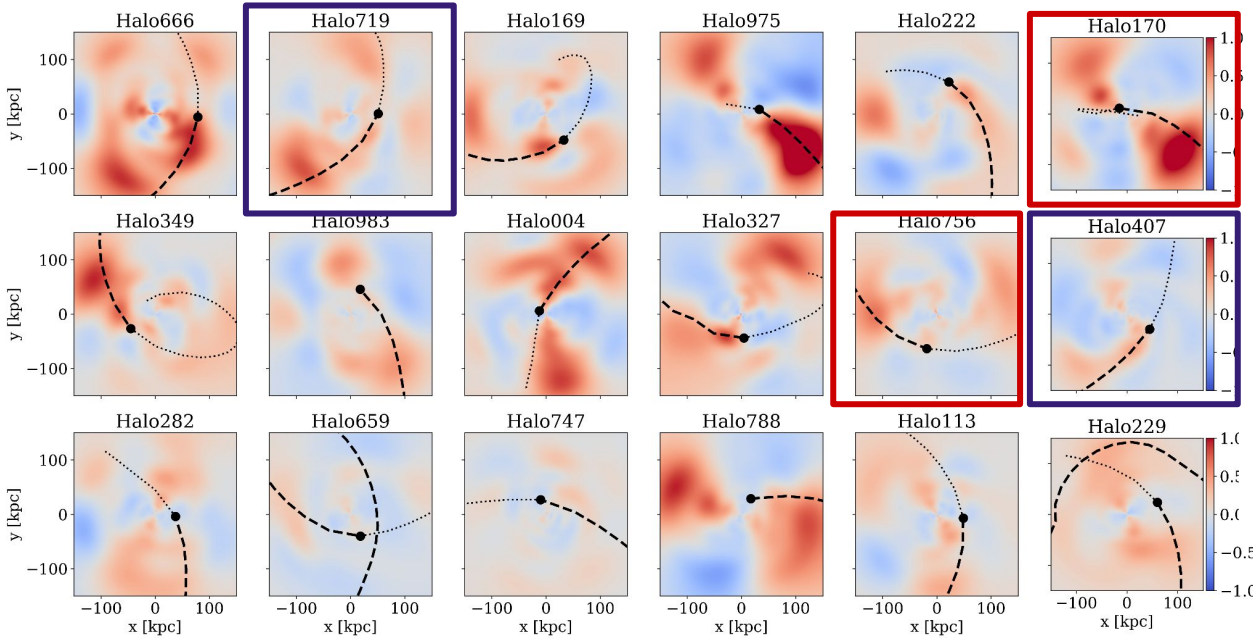
**MWest:**

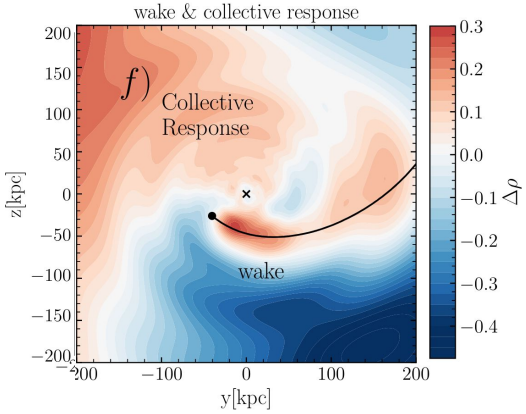
- 18 MW-LMC like DM only halos
- MW/LMC mass ratio mean: 1:6
- 15 satellites on first infall
- 3 on second approach
- Pericenters: 13-77 kpc

**Symphony**:

- 8 MW-like quiet halos
- No massive accretion in the last 5 Gyr

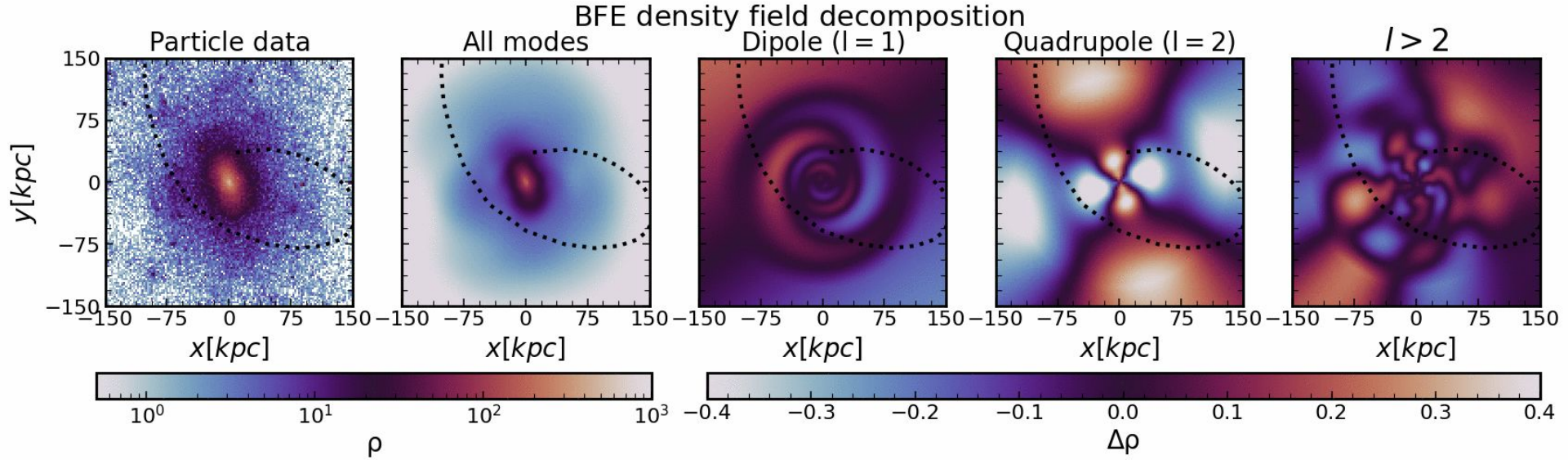
DM wakes are detected in the MWest suite. While their amplitudes align with those in idealized simulations, there are more overdensities with complicated morphologies.




Darragh-Ford, NGC, + in prep

# The halo response can be decomposes in harmonic modes that characterize the COM motion, halo shape and wakes




Darragh-Ford, NGC, + in prep

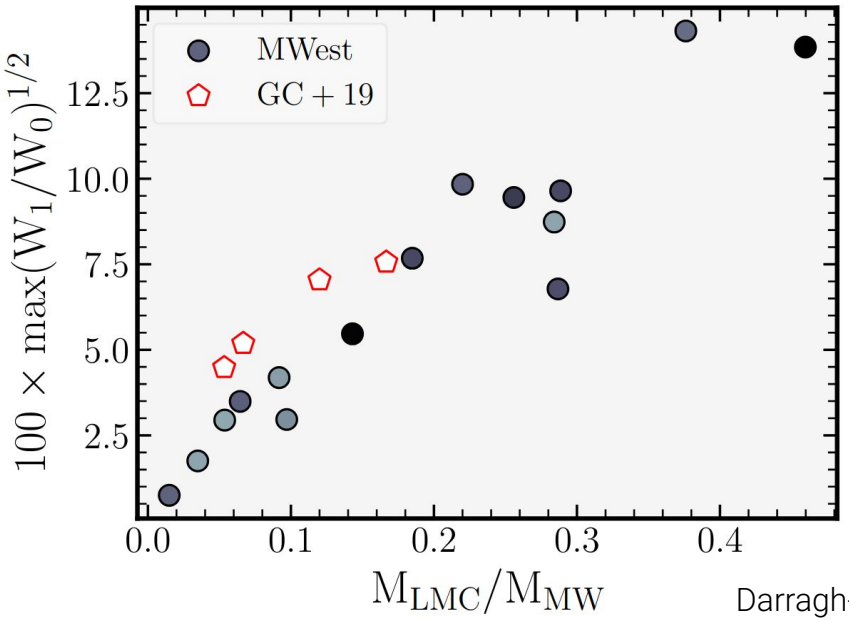
See also: Arpit Arora's+25 paper

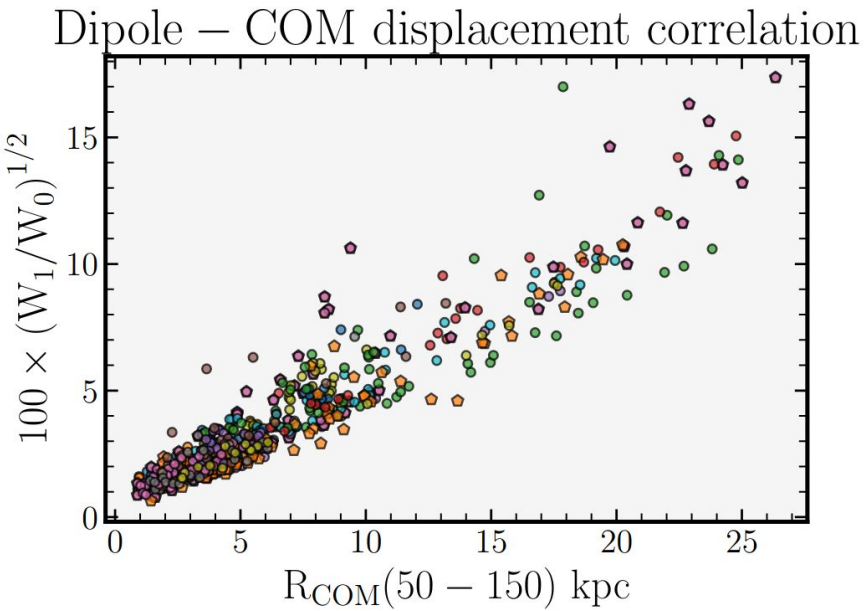
COM motion + wake

Halo triaxiality + wake

Wake

# The amplitude and direction of the dipoles are proportional to the mass of the MW and LMC and the halo displacement (DM dependent) and independent on the halo shape

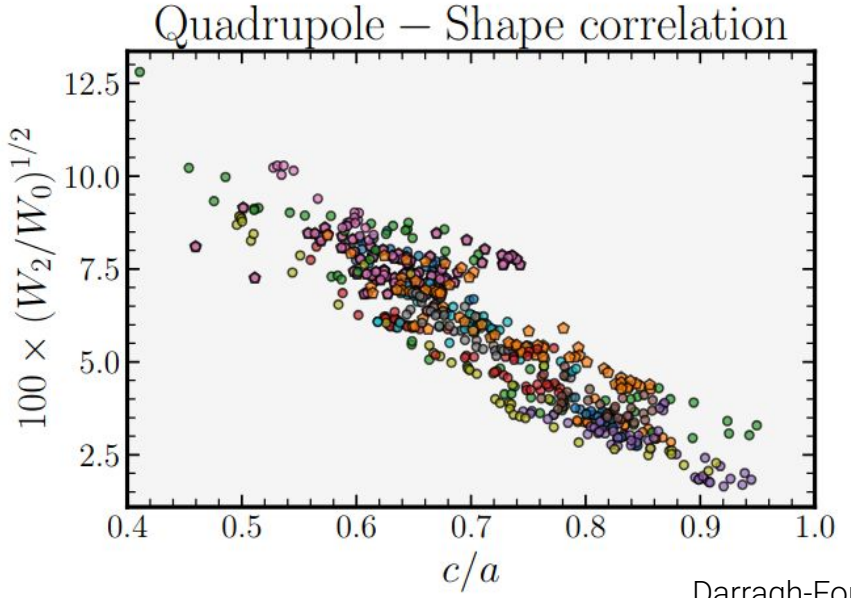


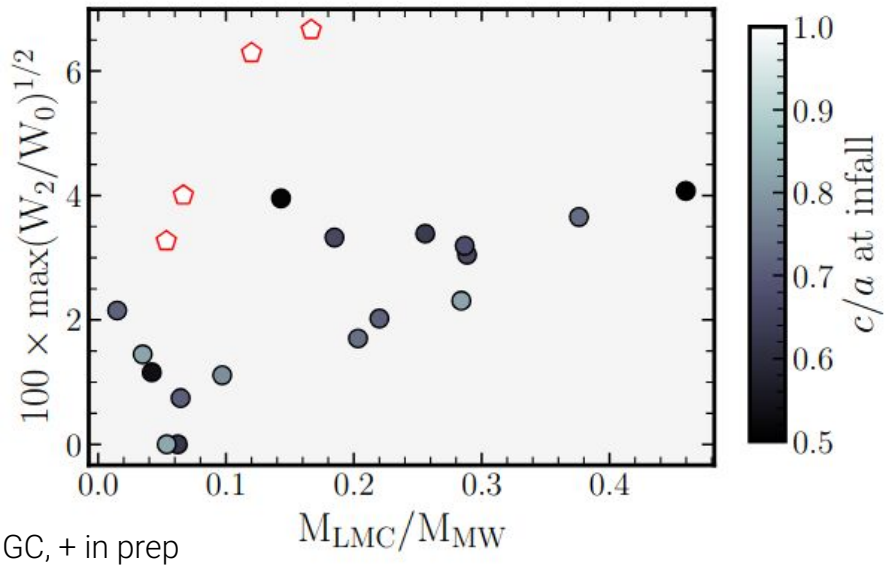




Darragh-Ford, NGC, + in prep

Dipoles have long dynamical times (Weinberg+23) and can produce observable signatures in galaxies such as disk warps (Gomez+16), lopsided galaxies (Varela+24, Shashank+25), isophotal twists (Amvrosiadis+25), and gravitational lensing (Miller+25).

The amplitude of the quadrupole is correlated with the shape of the halo (DM dependent). However, the peak response of the quadrupole at pericenter is not correlated with the LMC mass. Illustrating that the quadrupole response is telling us about how different DM halo shapes respond to satellites perturbations.



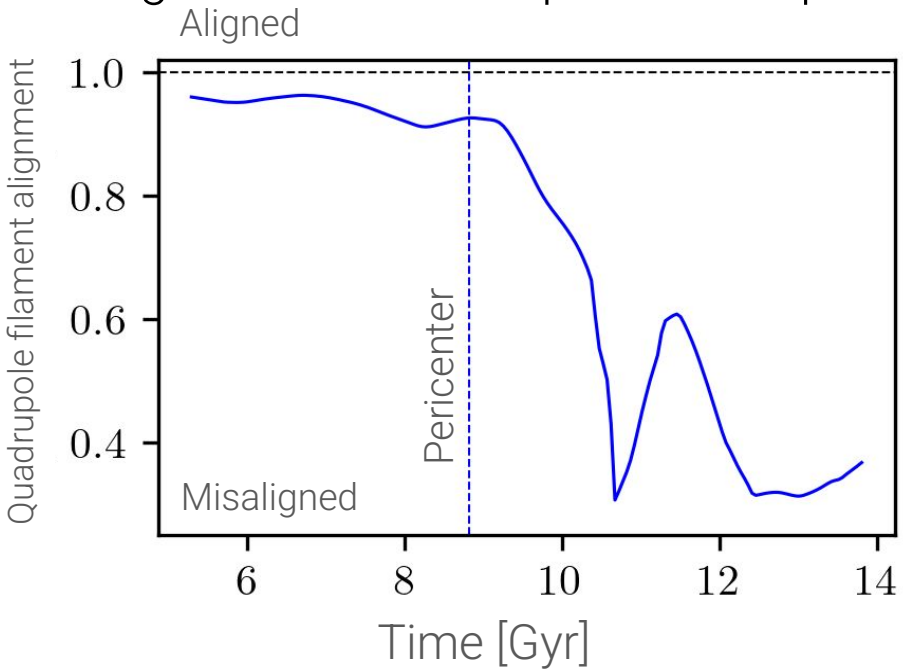




Darragh-Ford, NGC, + in prep

# Current challenges for measuring the MW's DM halo response

- The stellar halo is not smooth, the outer halo is comprised of shells and streams (e.g., Cunningham+21)
- Stellar wakes are collisionless and it's unclear how they will trace DM wakes
- Stellar halos overdensities do not translate to DM overdensities, but the directions do (Han+23b).
- We don't know the MW's halo shape before the LMC, but we could infer ir from disk dynamics (e.g., Han+23a) and streams (e.g., Vasiliev+21).

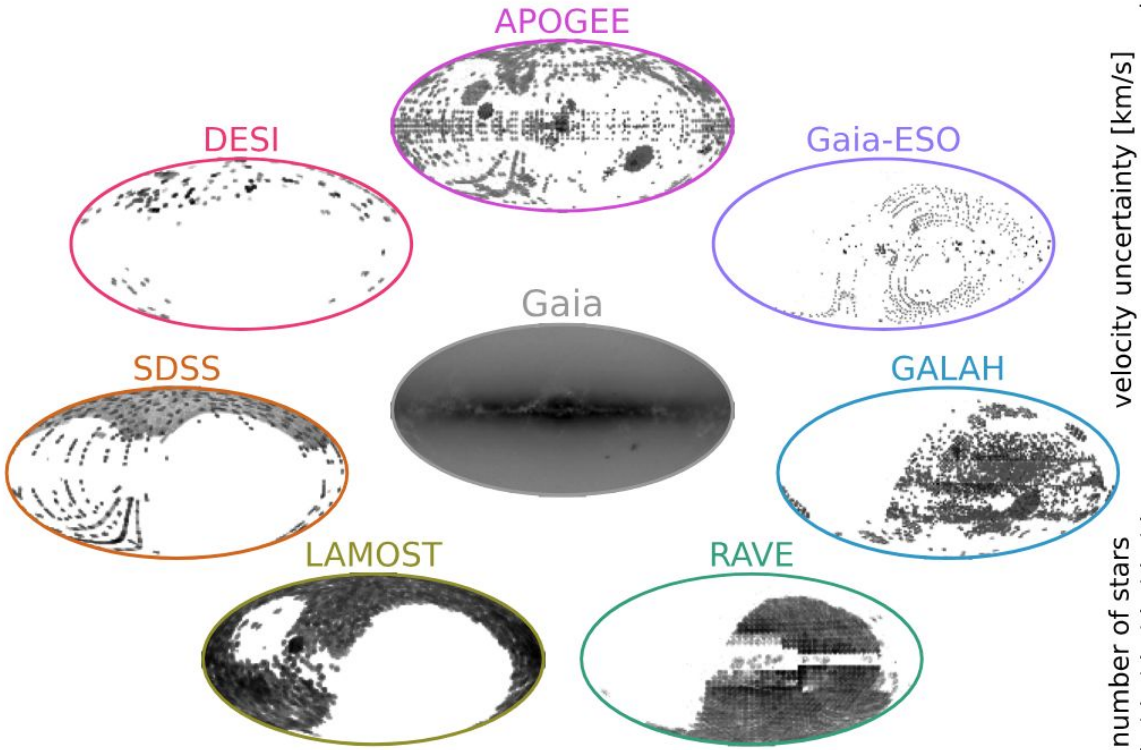
In the FIRE suite of simulations, the quadrupoles are align with the filamentary structure (DM dependent), but the LMC induces misalignment after the pericentric passage.

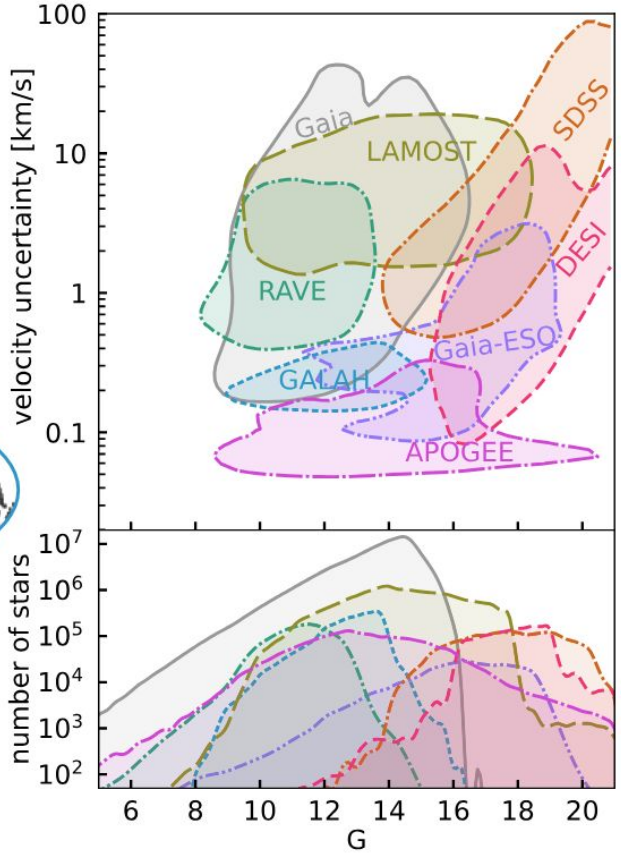



Dr. Arpit Arora
postdoc at UW

Arora, Arpit; NGC, et. al., ApJ submitted 2025 (arxiv: 2504.20133)

The Local Group is the only place where we have access to 6D coordinates + chemistry (ideal for galactic dynamics)



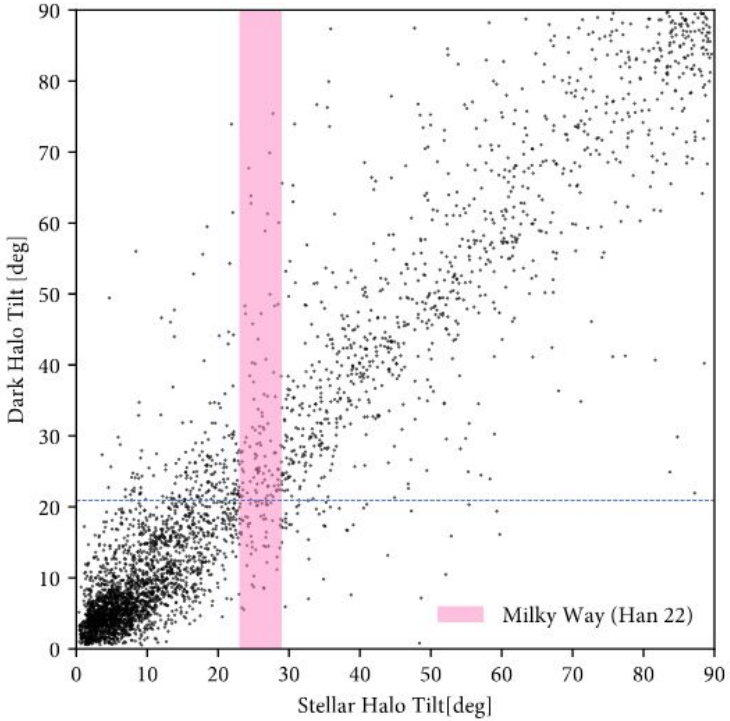

*Milky Way dynamics in light of Gaia. J. Hunt and E. Vasiliev 2025*

# Conclusions:

- The Milky Way's halo response to the LMC's passage offers an unique opportunity to study the behaviour of DM in the disequilibrium regime.
- The dipole is solely correlated with the mass of the LMC and reflects the displacement of the halo, which is sensitive to the nature of dark matter.
- The quadrupole response depends on the intrinsic shape of the halo—dark matter dependent—which in turn modulates the amplitude of the wake.
- The morphology, location, and amplitude of the wake depend on the underlying dark matter model, although the differences may not be large enough to be observationally significant.

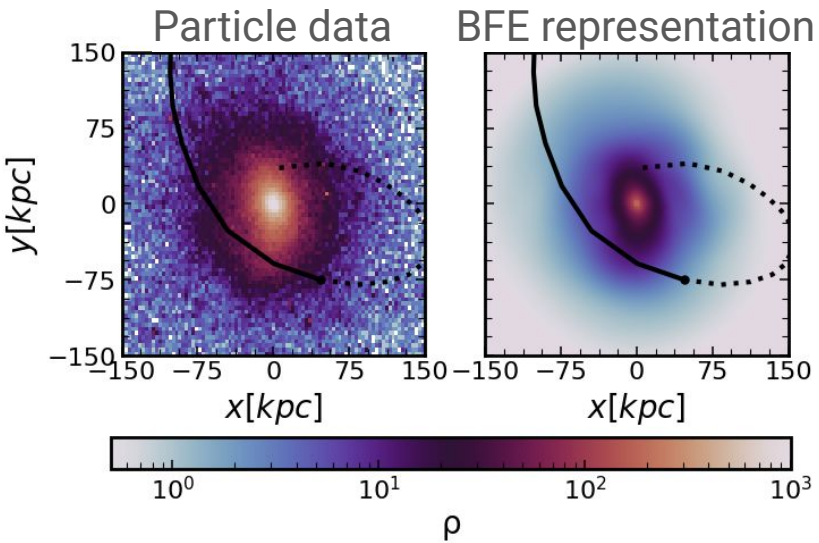
# Back up

# Stellar halo DM halo tilt




Han+23b

# Example: A BFE decomposition of one of the MWest halos

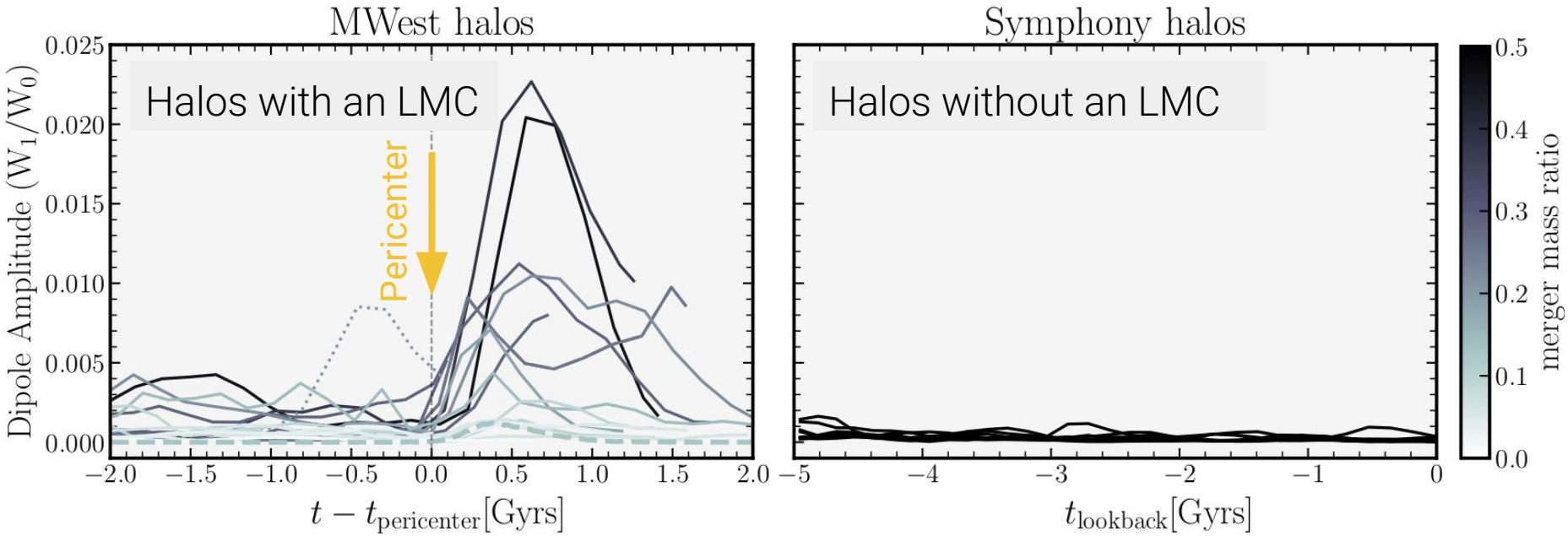



Darragh-Ford, NGC, + in prep

Petersen, Weinberg, and Katz 22

EXP docs: https://exp-docs.readthedocs.io/
Github: https://github.com/EXP-code/
BFEs are also available in AGAMA, Gala and Galpy

# The MW's **dipole response** is only present in halos with LMC's and it peaks right after the pericentric passage

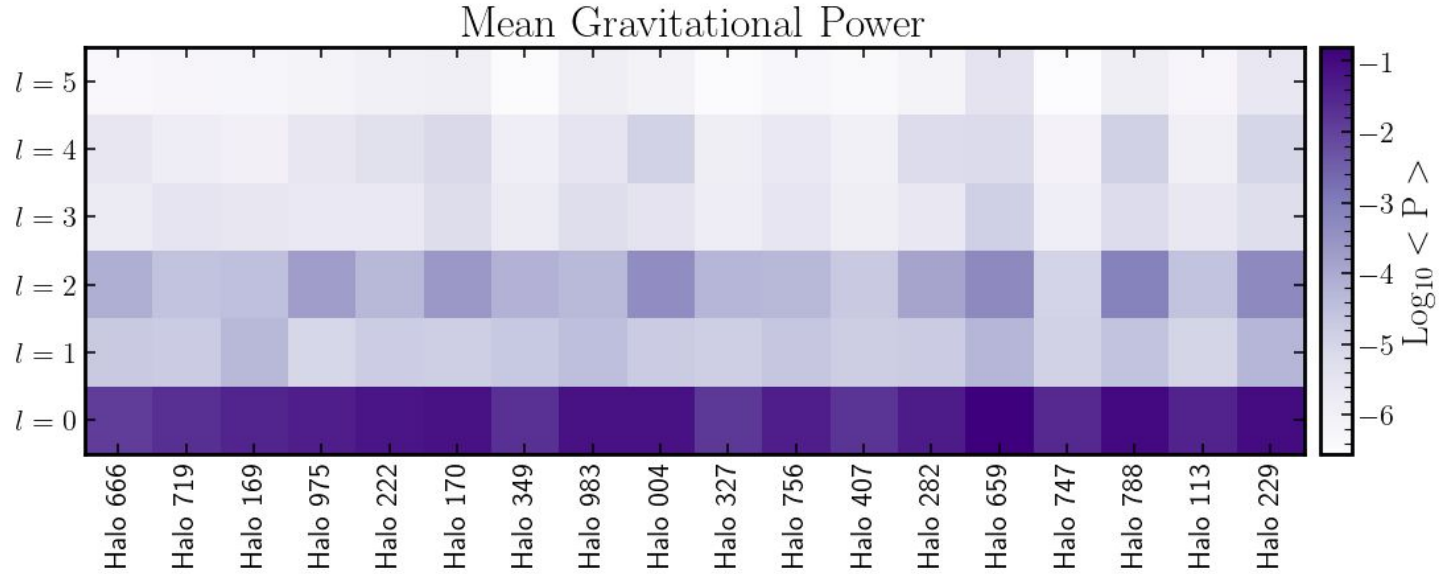



Darragh-Ford, NGC, + in prep

# The gravitational response of the 18 MWest halos is characterized by the amplitudes of the individual BFE terms

Halo shape & response

Halo mass growth




Darragh-Ford, NGC, + in prep

# Basis Function Expansions (BFE) are ideal to study the dynamics of self-gravitating systems

Petersen, Weinberg, and Katz 22

1. The density and potential field of a halo is represented by finite series of basis functions.

$$\rho(r,\theta,\phi) = \sum_{nlm} A_{nlm}\rho_{nlm}(r,\theta,\phi),$$

2. BFE Satisfy poisson's equation.

$$\nabla^2\Phi_{nlm}(r,\theta,\phi) = 4\pi G\rho_{nlm}(r,\theta,\phi),$$

3. Each coefficient only depends on a single potential basis function.

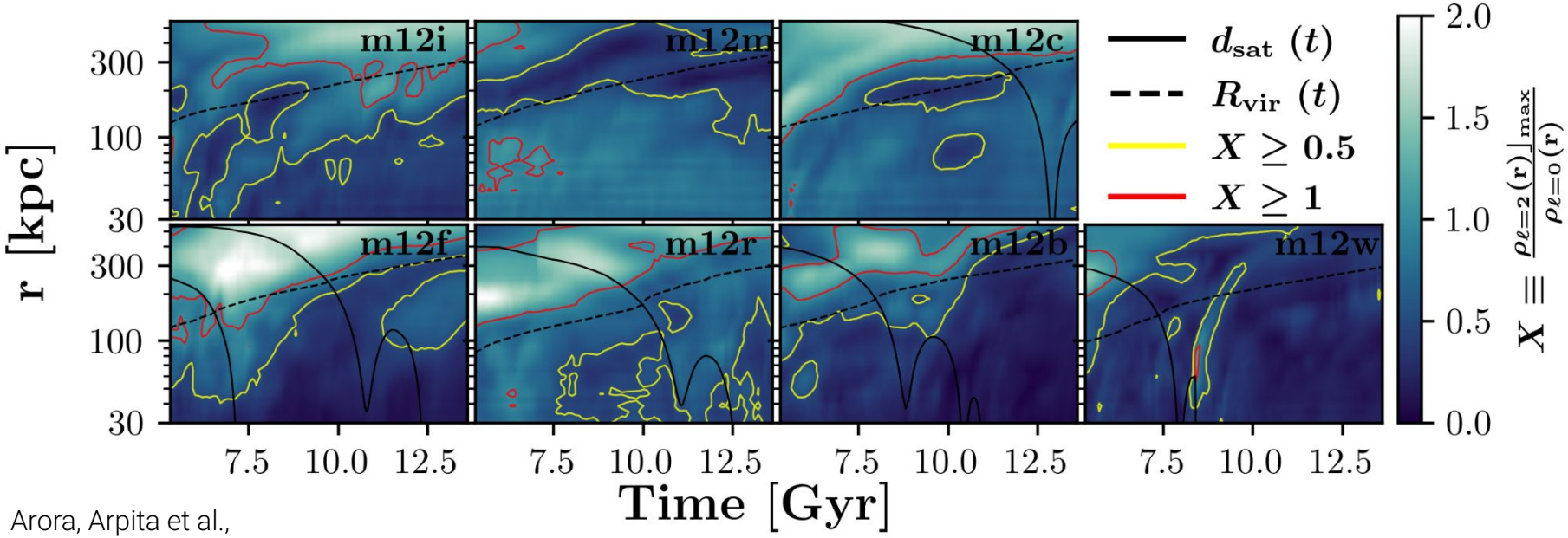
$$\int \rho(\boldsymbol{r})_{nlm}\Phi(\boldsymbol{r})_{n'l'm'}\mathrm{d}\boldsymbol{r} = \delta_{nn'}\delta_{ll'}\delta_{mm'}.$$

bi-orthogonal condition

The temporal evolution of the halo is represented by the time series of coefficients

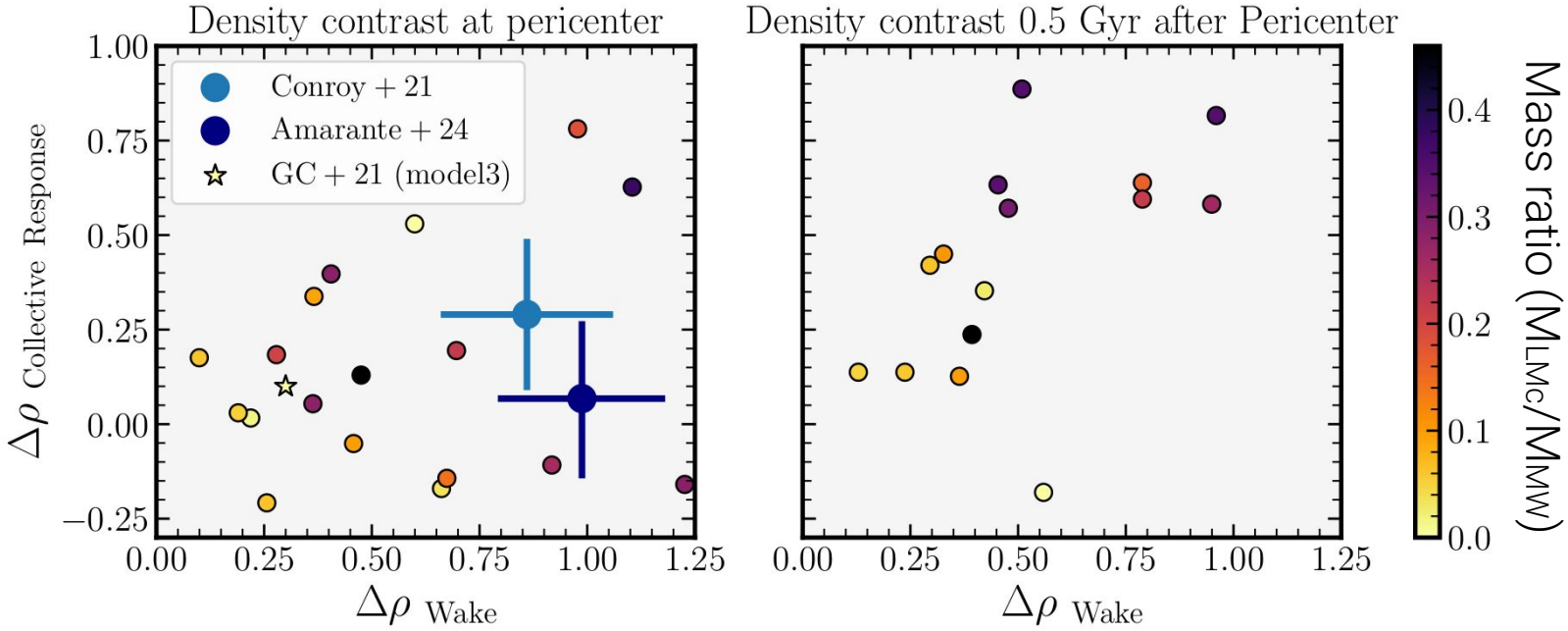
EXP docs: https://exp-docs.readthedocs.io/
Github: https://github.com/EXP-code/
BFEs are also available in AGAMA, Gala and Galpy

# Filaments influence on the DM host is less strong at present day and it is not as strong as

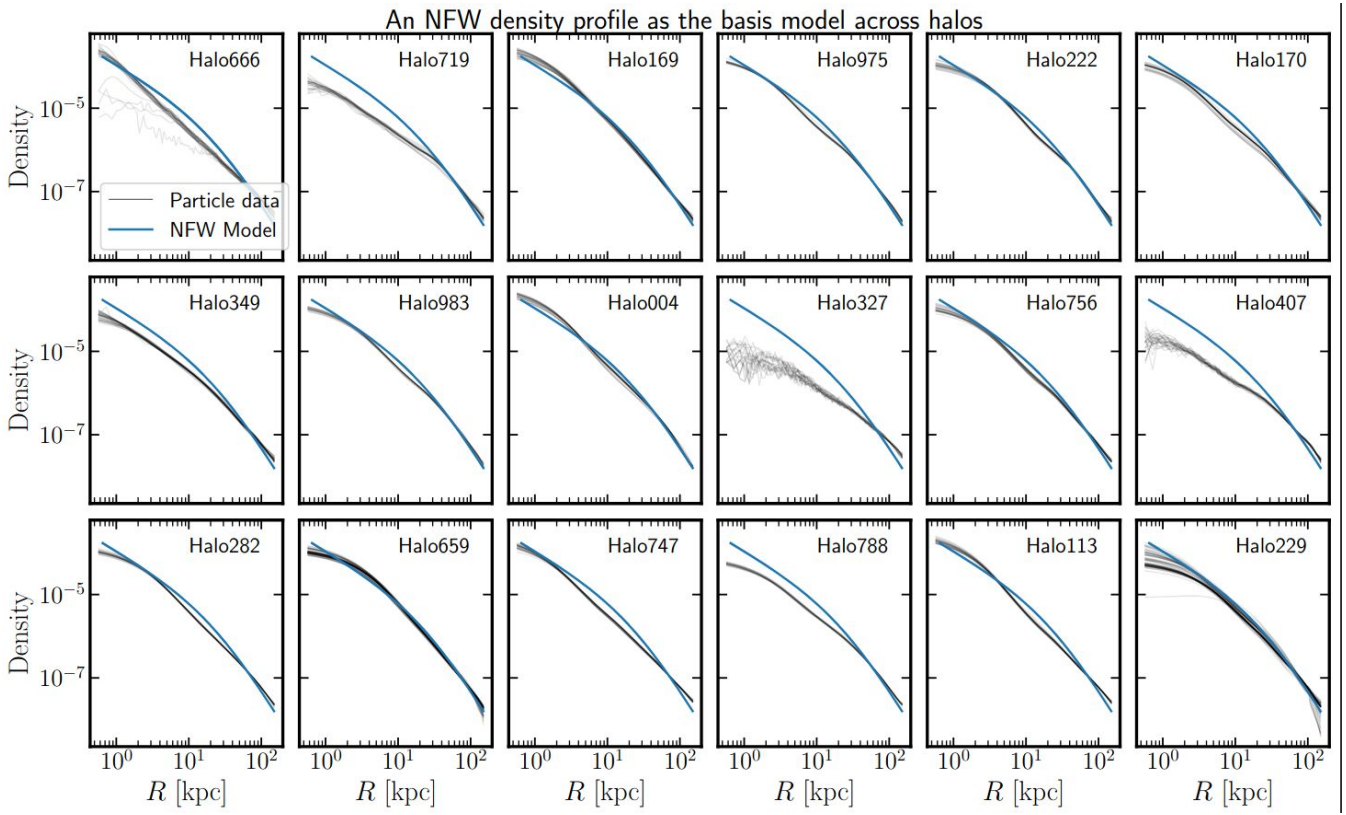



Arora, Arpita et al.,

# DM wakes are detected in the MWest suite. While their amplitudes align with those in idealized simulations, their shapes are more complex.

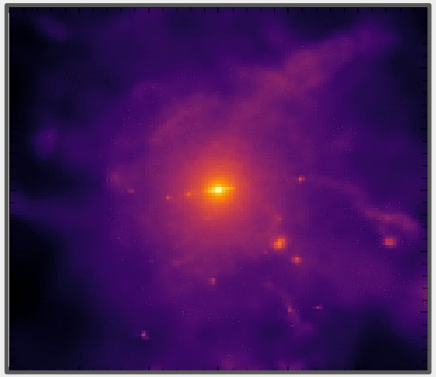



Darragh-Ford, NGC, + in prep

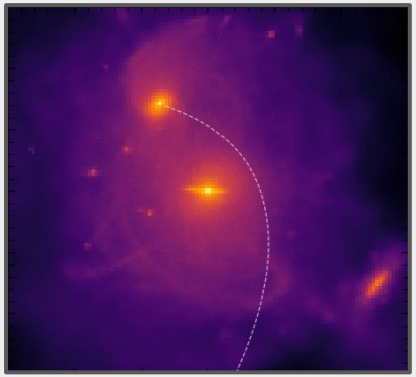

An NFW density profile as the basis model across halos
Halo666
Halo719
Halo169
Halo975
Halo222
Halo170
Halo349
Halo983
Halo004
Halo327
Halo756
Halo407
Halo282
Halo659
Halo747
Halo788
Halo113
Halo229
Particle data
NFW Model
Density
$10^{-5}$
$10^{-7}$
$10^{0}$
$10^{1}$
$10^{2}$
$R$ [kpc]

# Lopsided distributions in cosmological simulations are rare and transient

Stellar halo structure before the infall of the satellite

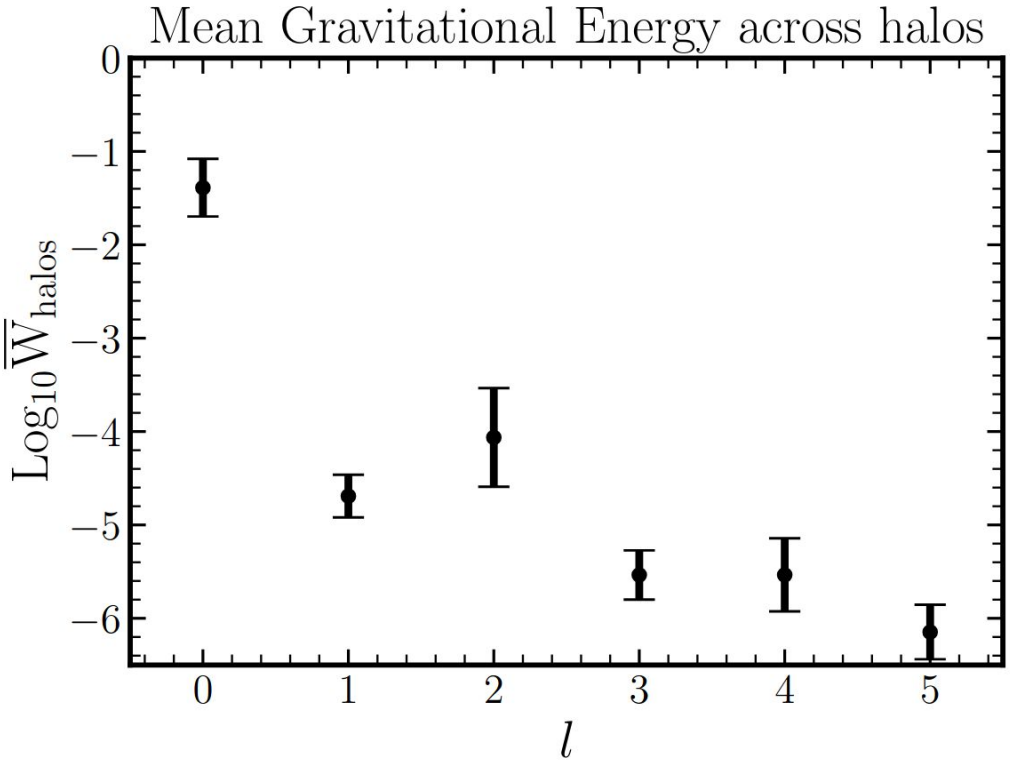


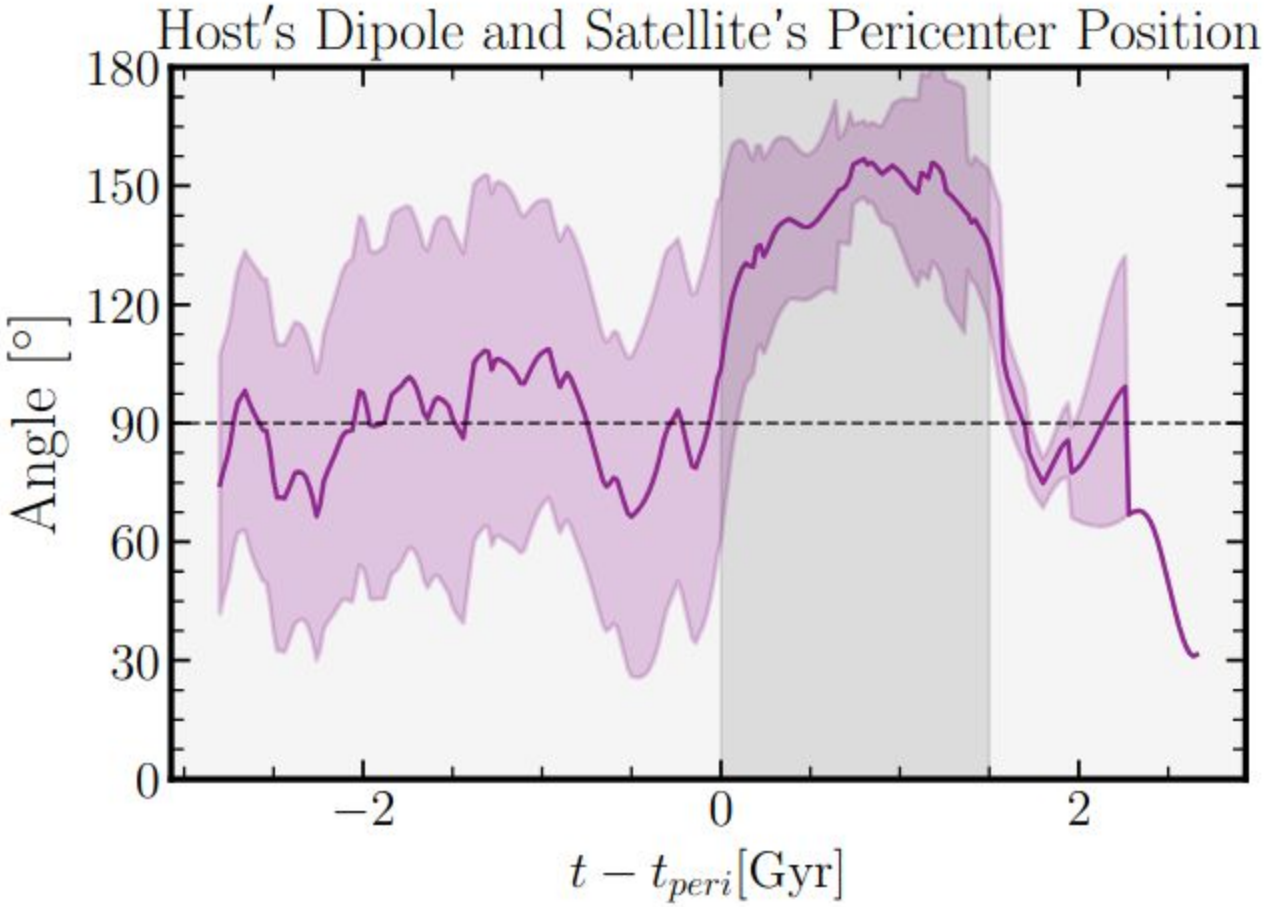
Stellar halo structure at the pericentric passage of the satellite



Garavito-Camargo+24

BFE allow to systematically compare across the halos and simulations!
Monopoles, dipoles, and quadrupoles, capture most of the halos response




Host's Dipole and Satellite's Pericenter Position
180
150
120
90
60
30
0
Angle [°]
−2
0
2
$t - t_{peri}$[Gyr]