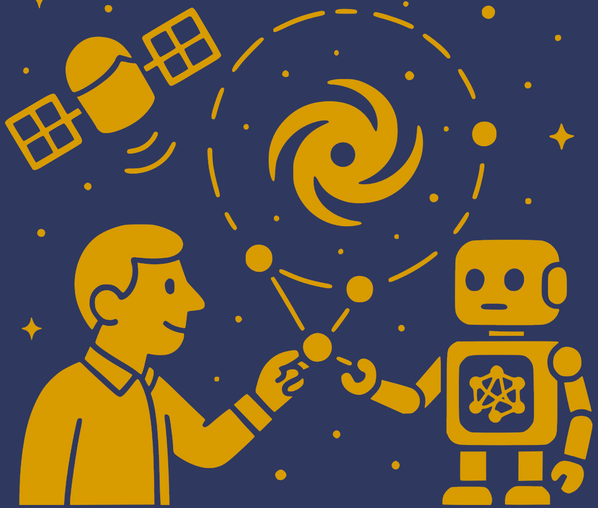
Hunting Dark Matter with Stellar Wakes



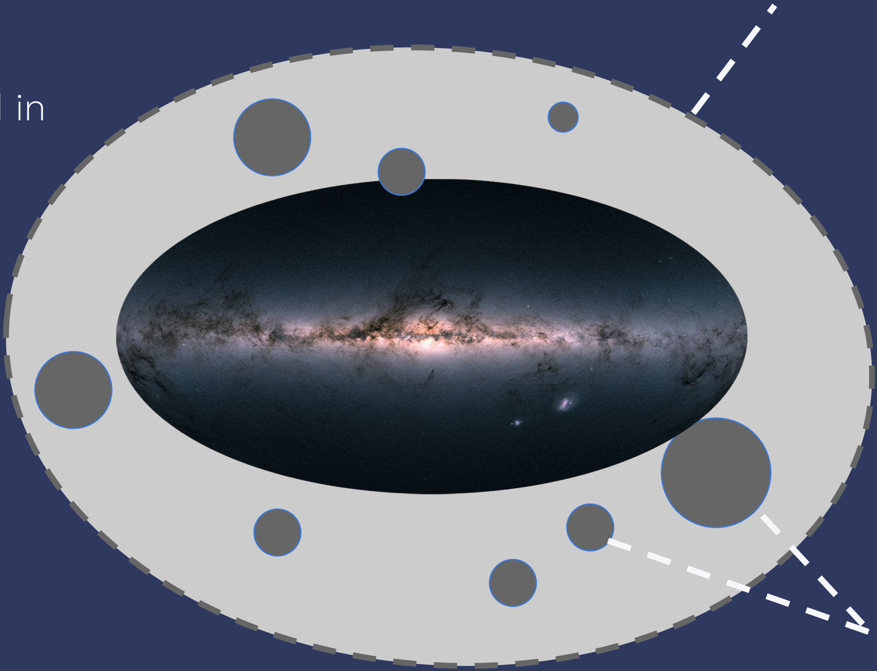
Speaker: Sven Põder
KBFI/SISSA

Frascati 2026

Dark matter halos

Galaxies are embedded in extended dark matter (DM) halos
Einasto, Kaasik & Saar (1974)

Halo shape and substructure are dependent on the properties of the DM particle

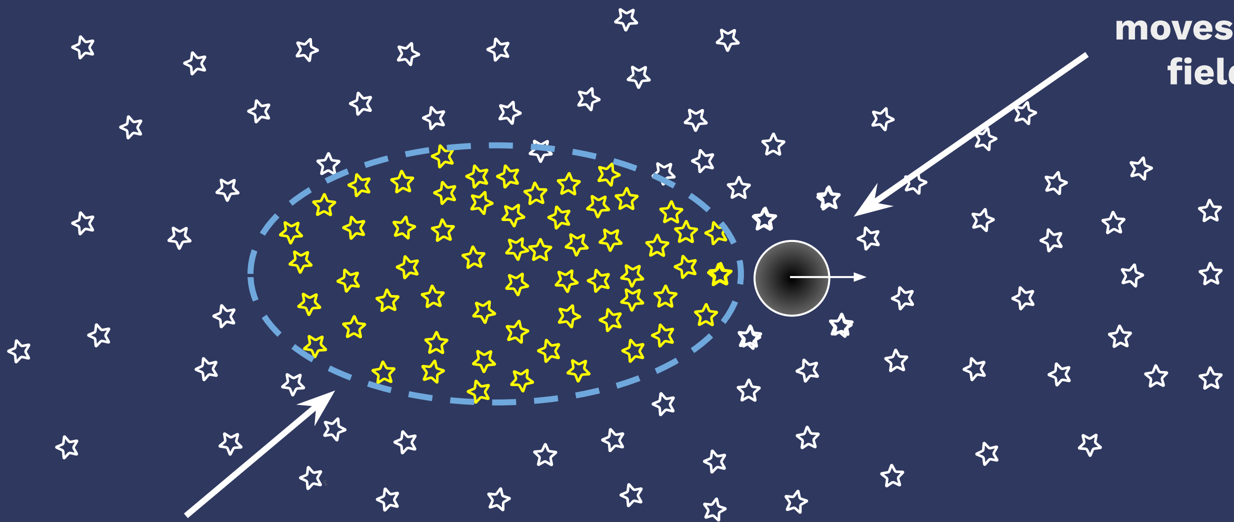


Credit: ESA/Gaia/DPAC

The abundance of subhalos is a function of the DM particle model – powerful discriminator between viable DM models at sub-galactic scales

What is a stellar wake?

Subhalo orbits Galaxy - moves through uniform field of halo stars



Region of increased overdensity

Wake effects also expected in other observables: mean velocity, velocity dispersion and divergence, etc.

See also!

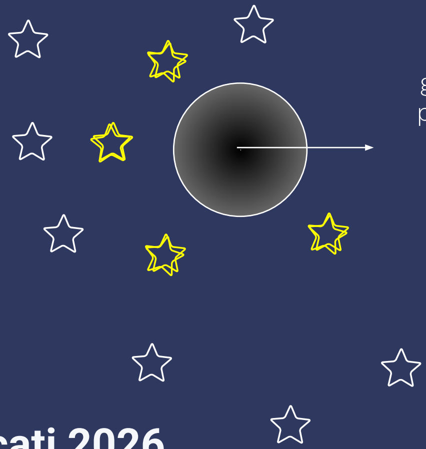
Analytic wake: Buschman et al. (2017)
LMC wake simulation: Foote et al. (2023)
First observation of LMC wake: Conroy et al. (2021)

Searches in MW-like simulations

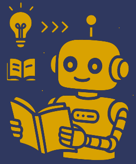
Sensitivity estimation for dark matter subhalos in synthetic Gaia DR2 using deep learning

A. Bazarov [a], M. Benito [a b], G. Hütsi [a], R. Kipper [b], J. Pata [a], S. Põder [a]

Searched for stellar phase-space perturbations induced by DM subhalos in MW-like simulated galaxies [Wetzel et al. (2016), Sanderson et al. (2020)]



Orbiting subhalo imprints a gravitational signature in the position and velocity of stars



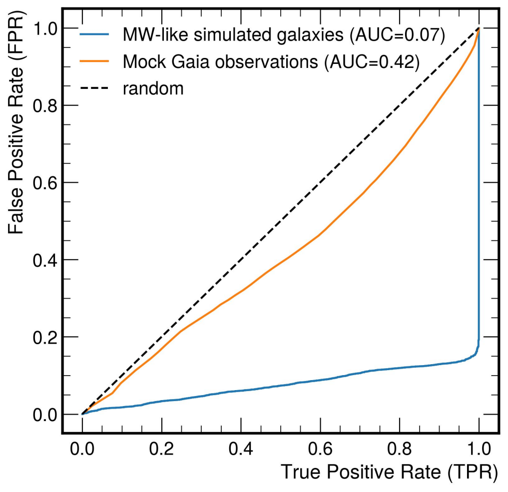
Can we detect these disturbances from the data using machine learning?

Takeaways

MW-like simulated galaxies (ideal data) = strong signal

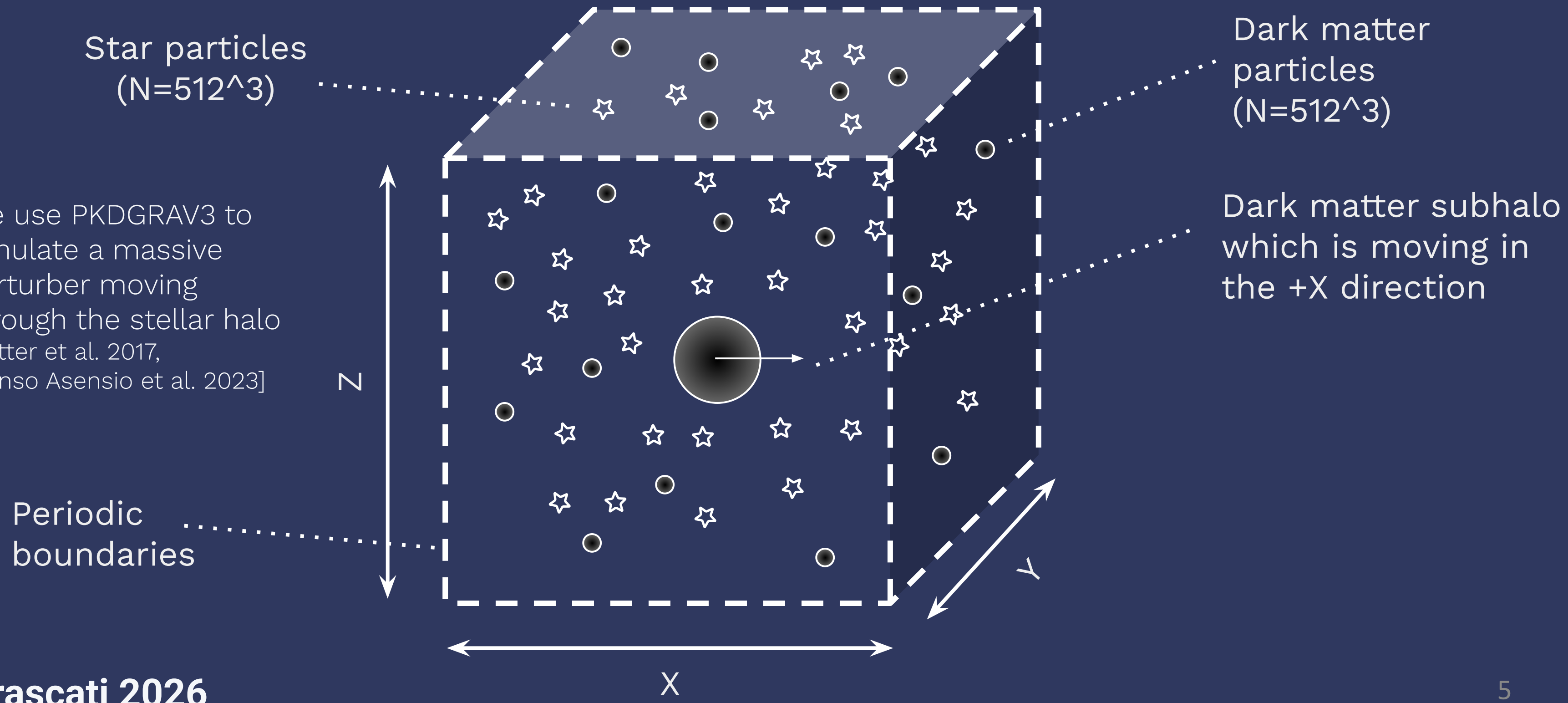
Mock observations (noisy data) = degraded signal

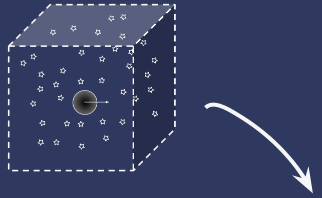
To understand the wake signal better we performed our own simulations in the next study



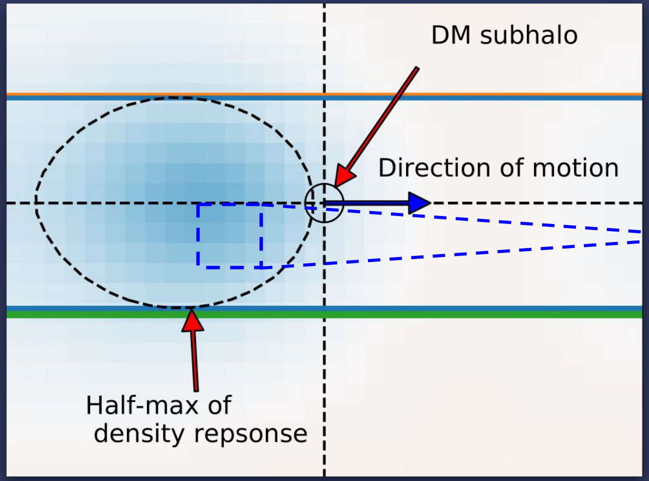
Stellar wake "laboratory"

We use PKDGRAV3 to simulate a massive perturber moving through the stellar halo
[Potter et al. 2017,
Alonso Asensio et al. 2023]



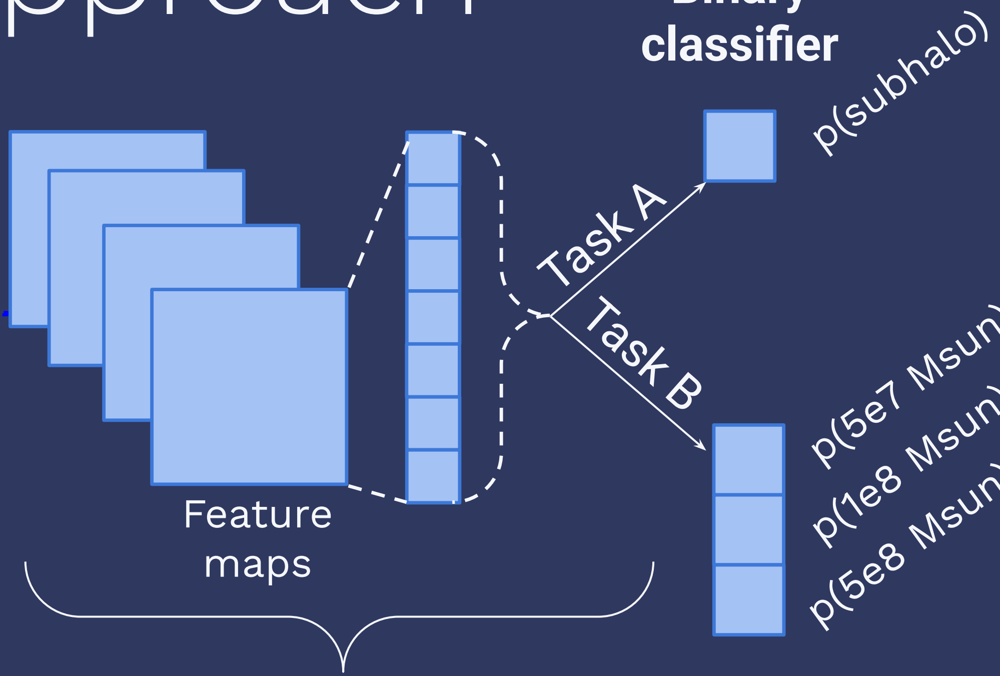


ML approach



Simulated data binned into image-like samples (2D histograms)

Binary classifier



Harmonic network (CNN-like model)

[Ulicny et al. 2019]

Multiclass classifier

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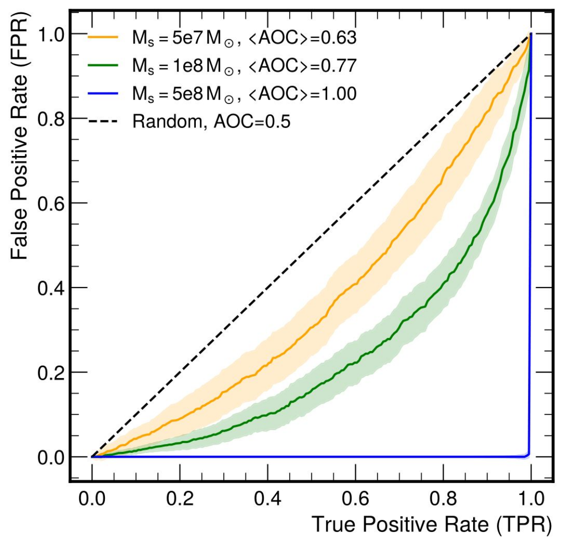
Detection performance in N-body simulations

A&A, 693, A227 (2025)

Detection of stellar wakes in the Milky Way: A deep learning approach

Sven Põder[1,2] ★, Joosep Pata[1], María Benito[3] ★, Isaac Alonso Asensio[4,5] and Claudio Dalla Vecchia[4,5]



Takeaways

Even in a limited data regime, we saw non-trivial detection performance down to subhalo mass 5e7 Msun

Discrepancy between our wake simulations and those predicted using analytics e.g. in Buschman et al. (2017)

The idea is to start looking for wakes behind known MW satellites – this is going to be a lot **more tricky**!

[Ongoing work]

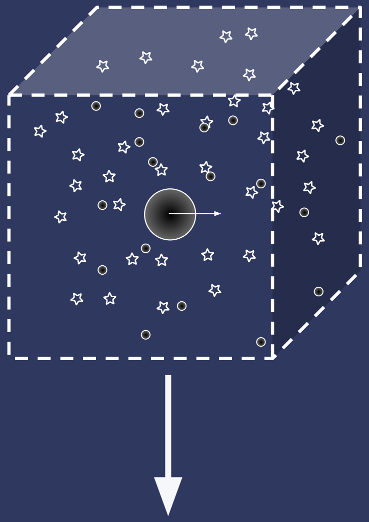
Going forward

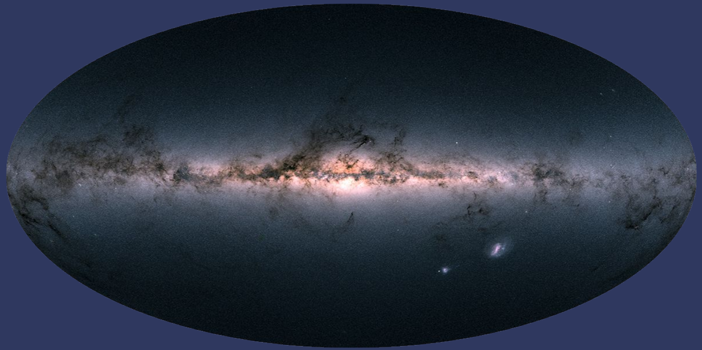
We aim to develop insights and diagnostic tools that will be helpful in future searches of stellar wakes

The gap: No attention has been devoted to assessing whether the analytic treatment accurately reproduces the structure seen in numerical experiments

In particular, we relax simplifying assumptions by including **self-gravity** in the presence of **ambient DM**

In our ongoing work we ...
1. examine wake formation (time evolution + morphology) in detail
2. test analytic predictions against controlled N-body simulations including assumption of **steady-state**





Crédit: ESA/Gaia/DPAC

LMC as a wake testbed

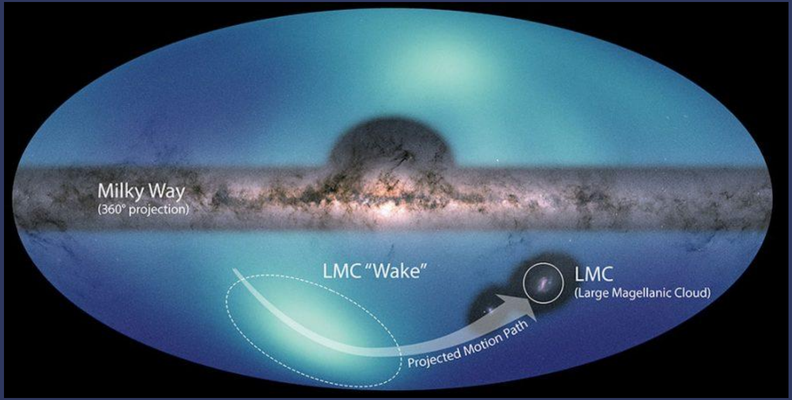
We want a better understanding of the physics underlying stellar wakes

The Large Magellanic Cloud provides an ideal testbed
 Large mass -> strong response

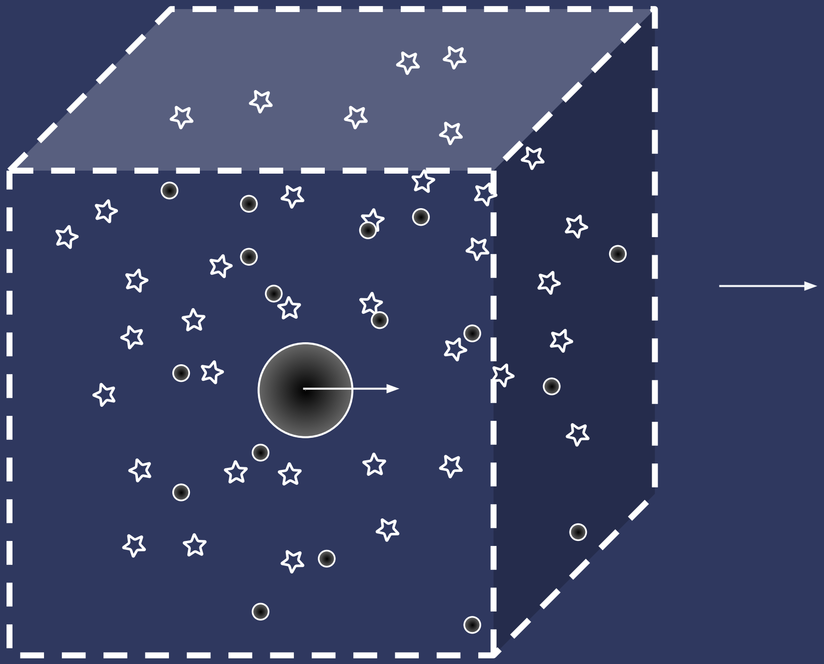
We simulate the LMC wake adopting a mass of 1.8e11 Msun [Foote et al. (2023)] and Plummer density profile

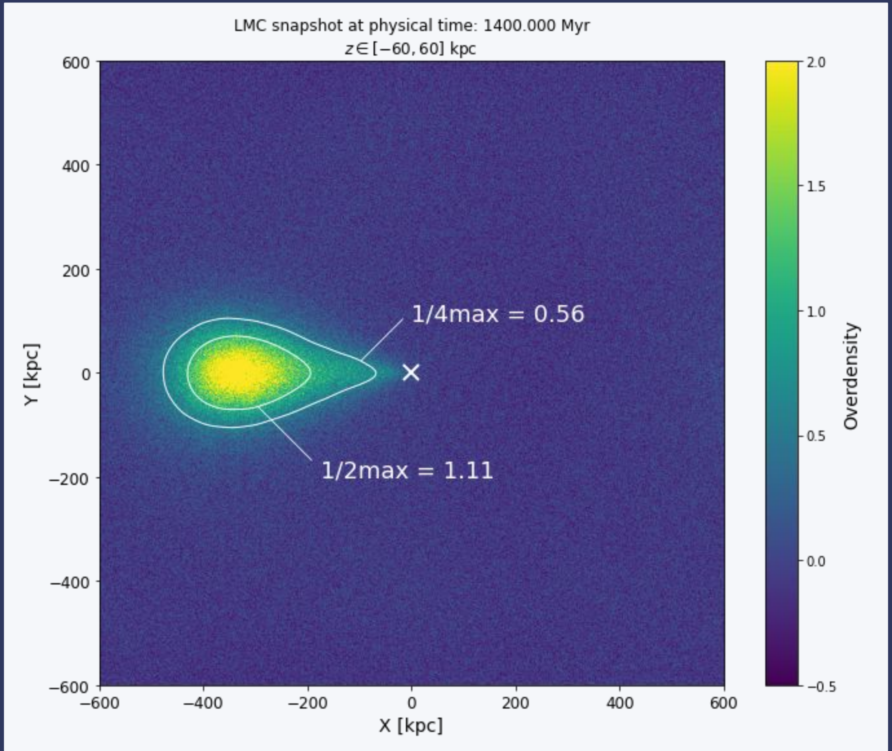
Background parameters chosen to mimic the MW stellar (and DM) halo at a distance of 70 kpc

	Parameter	Value
Background	ρ_* [$M_\odot$ kpc^{-3}]	5.8181×10^{-3}
	σ_* [km s^{-1}]	90
	ρ_{DM} [$M_\odot$ kpc^{-3}]	1.0831×10^{5}
	σ_{DM} [km s^{-1}]	103.9



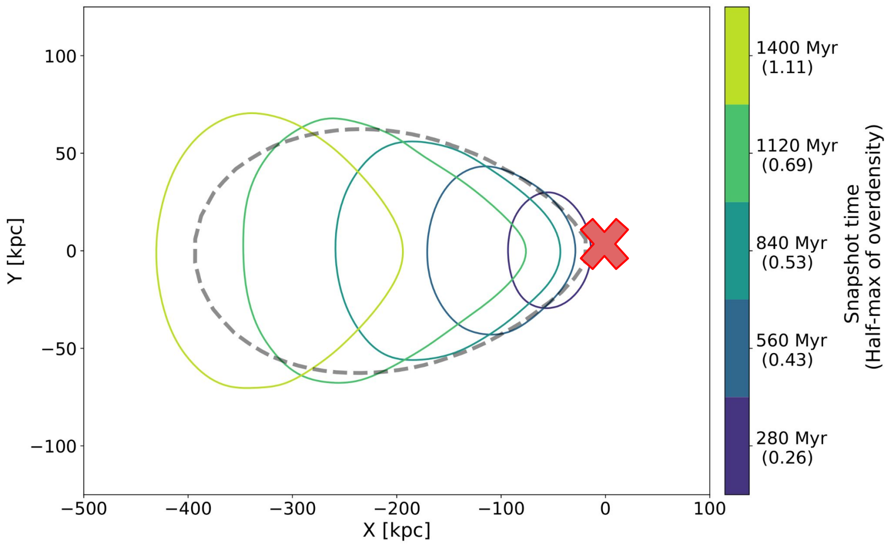
Structure that is consistent with a wake already detected in Conroy et. al. 2021



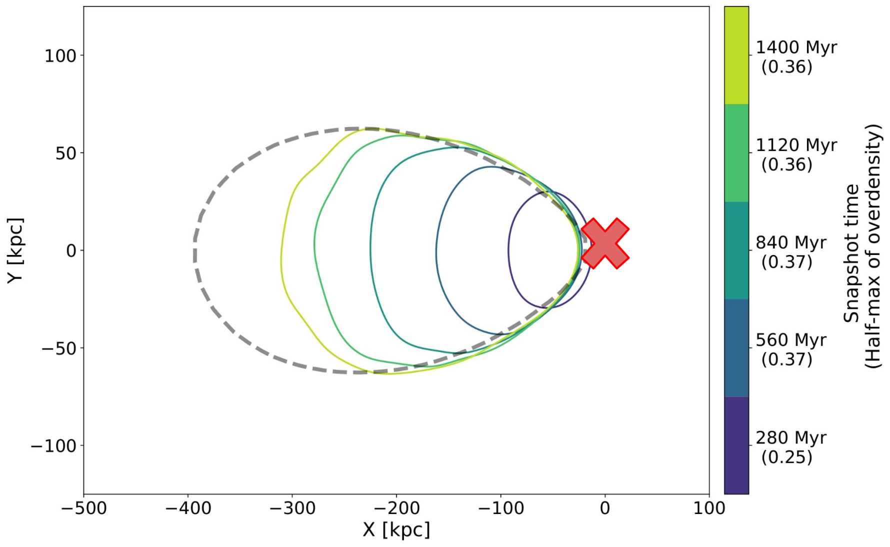

LMC snapshot at physical time: 1400.000 Myr
$z \in [-60, 60]$ kpc
1/4max = 0.56
1/2max = 1.11
Y [kpc]
X [kpc]
Overdensity
600
400
200
0
−200
−400
−600
200
400
2.0
1.5
1.0
0.5
0.0
−0.5

Time-evolution of the LMC wake

We use the half-max region of the overdensity to describe the spatial extension of the wake



Self-gravity



No self-gravity

Density response profiles

Using overdensity maps, we can construct density response profiles →

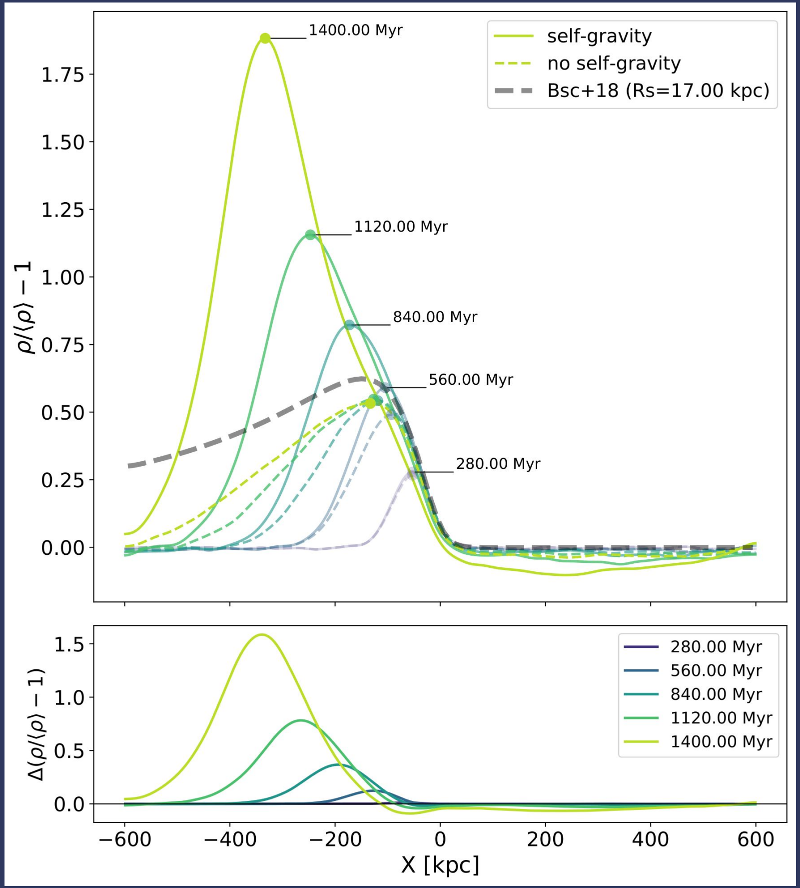
Similar to before, we see markedly different behaviour between the two gravity scenarios

Without self-gravity -> stars only interact with perturber

- No self-gravity approaches the analytic solution

With self-gravity ->

- The underlying DM density enhances the density response significantly



Takeaways

Stellar wakes are new and exciting astrophysical probes for DM

They encode information about both the perturber (e.g. DM subhalo mass) and the distribution of DM in the host halo which the perturber orbits

We are learning what makes them tick

In the case of the LMC, numerical wakes deviate from the predictions of the linear perturbative steady-state solution

Self-gravity + background DM density plays a significant role in wake formation

Many questions to explore

Is there a subhalo configuration where the analytic approximation holds?

What is the effect of the perturber density profile (e.g. cuspy vs core) on the resultant wakes? Can we hope to distinguish them?

We aim to find out!

Thank you!