Shaping the Galactic potential: Environment, Mergers & Stellar Tracers

***Arpit Arora**, Robyn Sanderson, and a long-list of collaborators.*

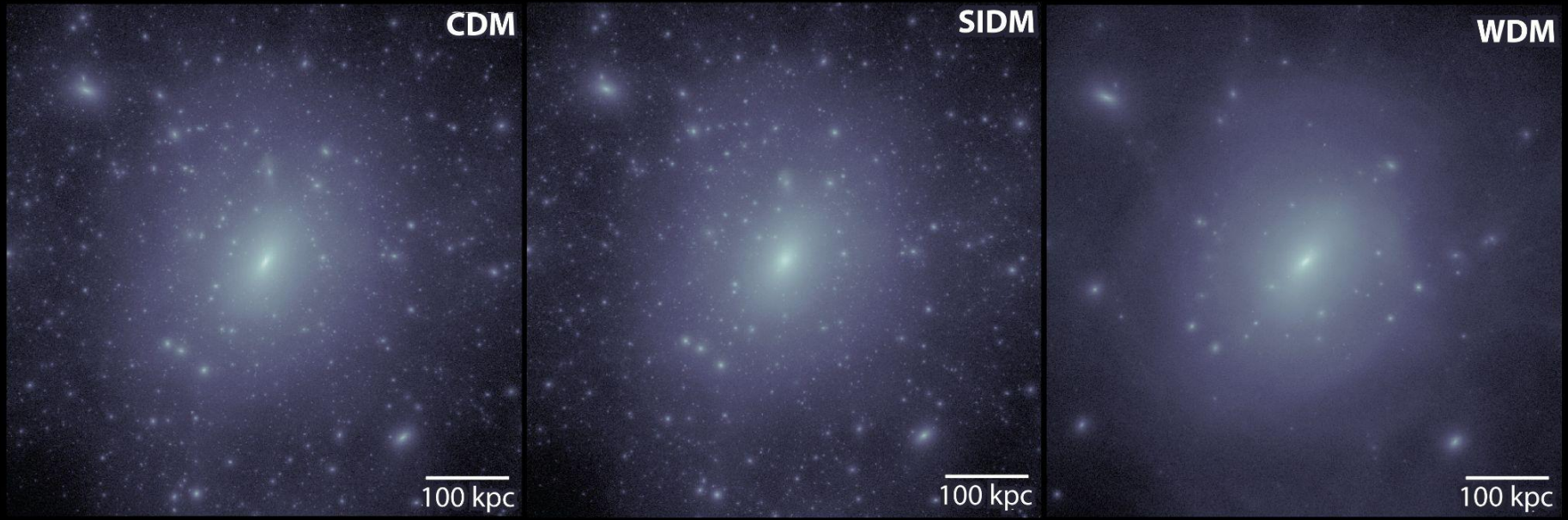
(Gaia mock for a MW-analog in FIRE-2 simulation, made by Prof. Robyn Sanderson)

Evidence for DM substructure at galactic scales:

Small scale dark matter clumps devoid of stars called "*DM subhalos*".

Detecting low mass dark subhalos

- Potentially interact with stellar streams leading to morphological changes.



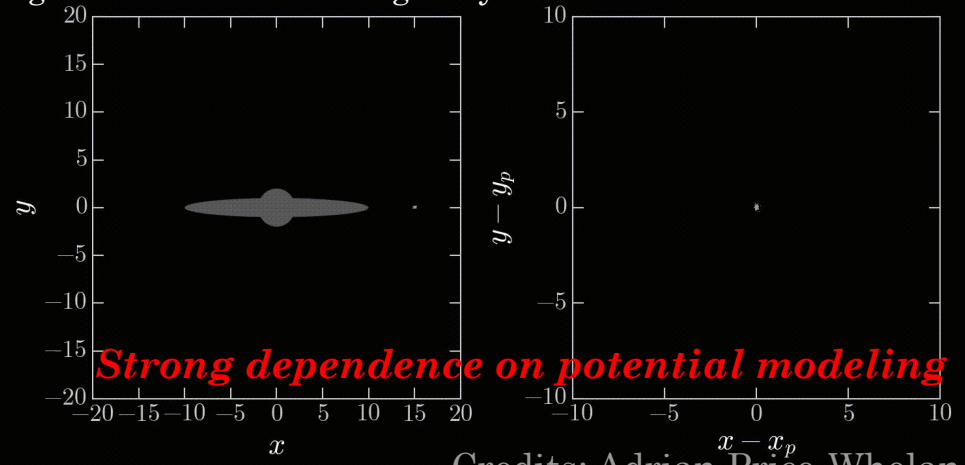
[Adapted from Vogelsberger+2014, Bullock+2017]

DM substructure interaction with Stellar streams.

Detecting low mass dark subhalos

- Potentially interact with stellar streams leading to morphological changes.

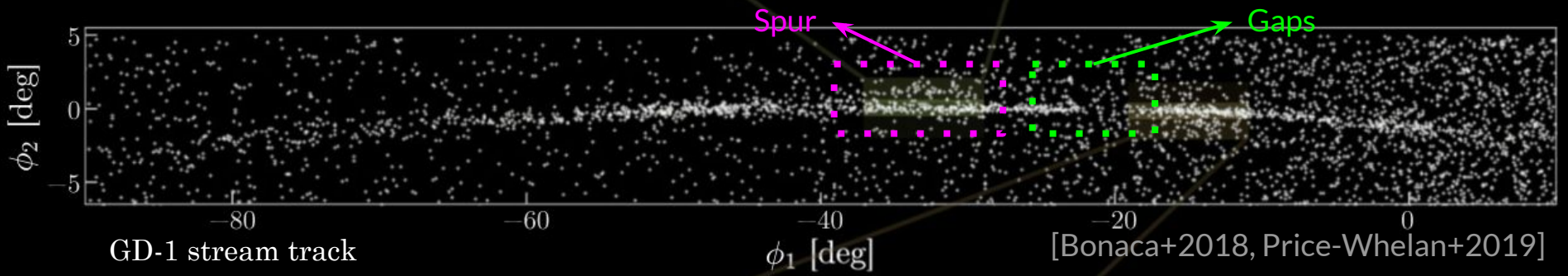
Association of stars orbiting a galaxy that was once a globular cluster/dwarf galaxy.



Strong dependence on potential modeling

Credits: Adrian Price-Whelan

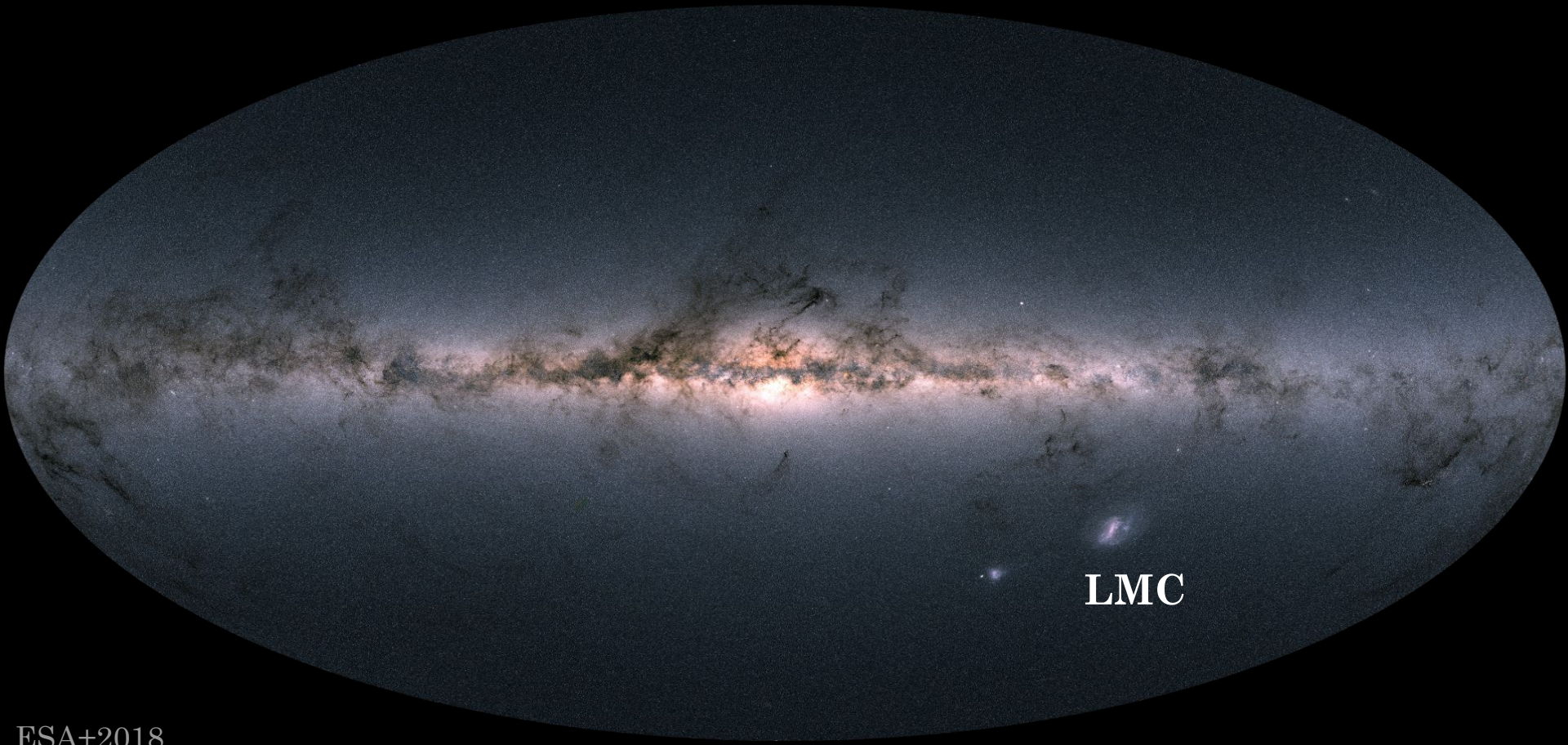
Promising tool to detect lowest mass (~ 10^6 M_{sun}) subhalos.



GD-1 stream track

[Bonaca+2018, Price-Whelan+2019]

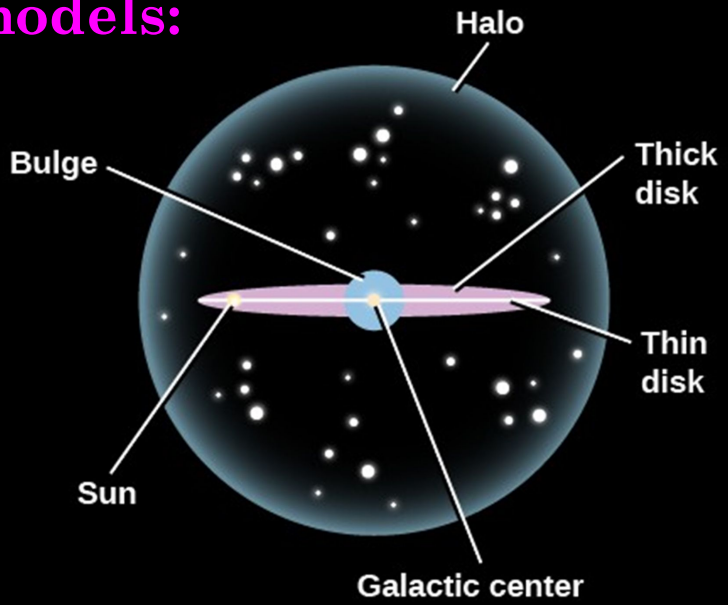
Backyard for testing dark matter! The Milky Way.



ESA+2018

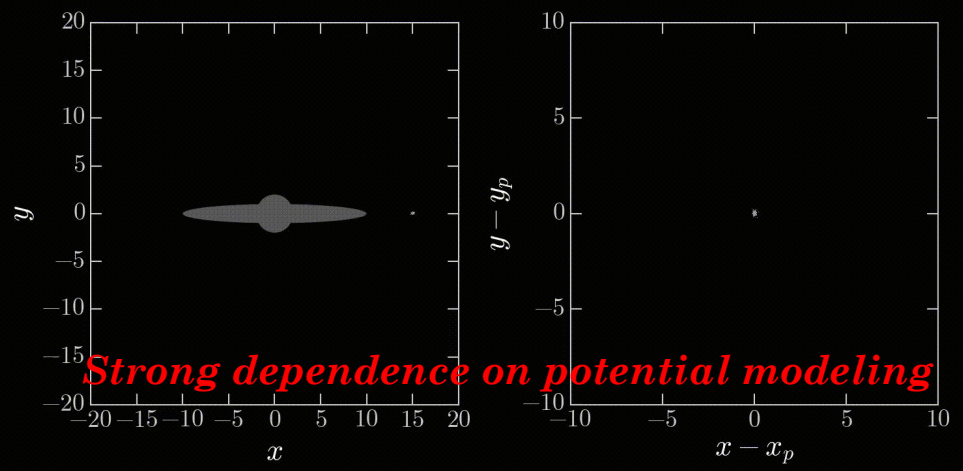
The important step is potential modeling!

Traditional equilibrium models:



Spherical for DM halo + hot gas, bulge.

Axisymmetric for the disk + cold gas.



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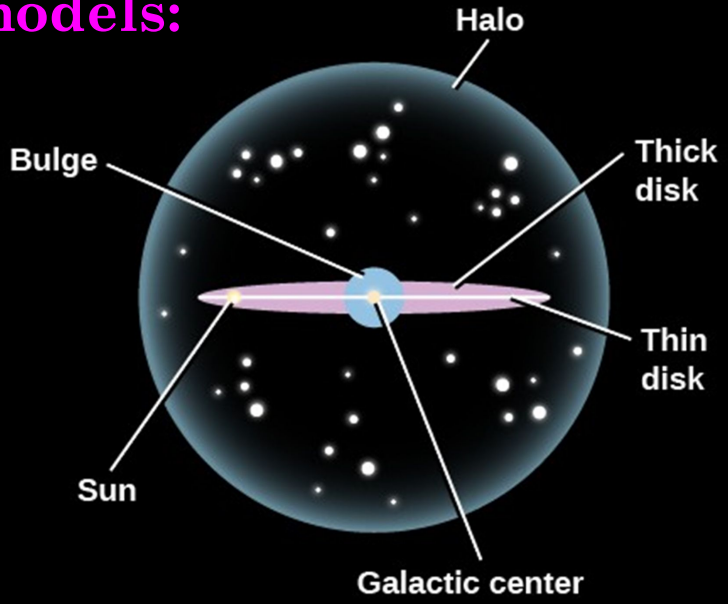

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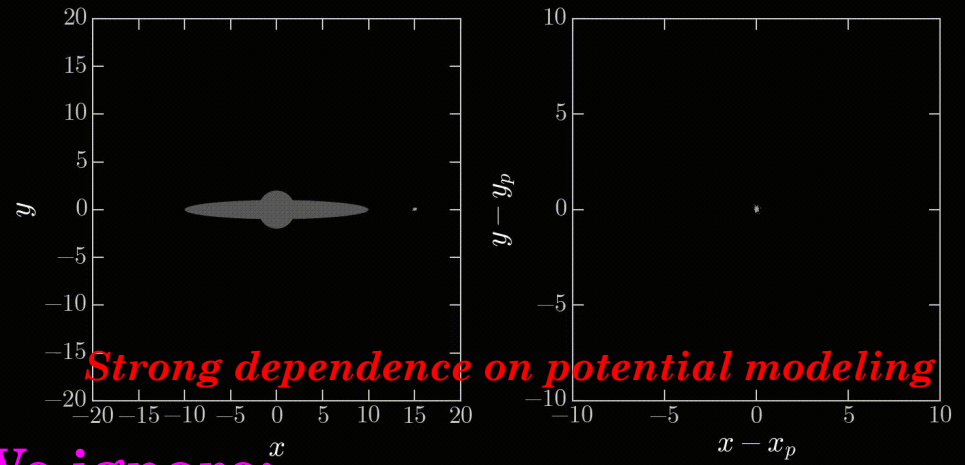

Strong dependence on potential modeling

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We ignore:

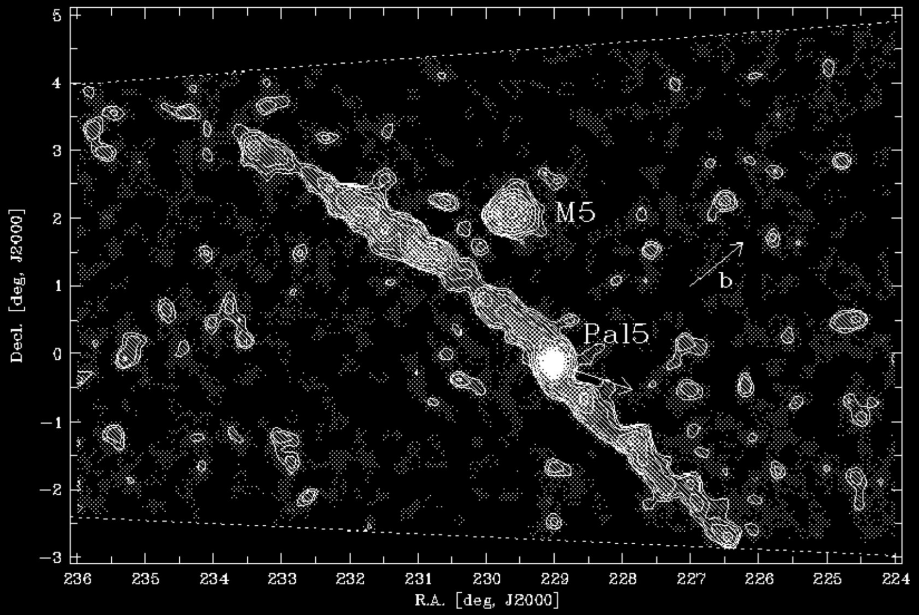
-> time-evolving structure.

-> disequilibrium effects.

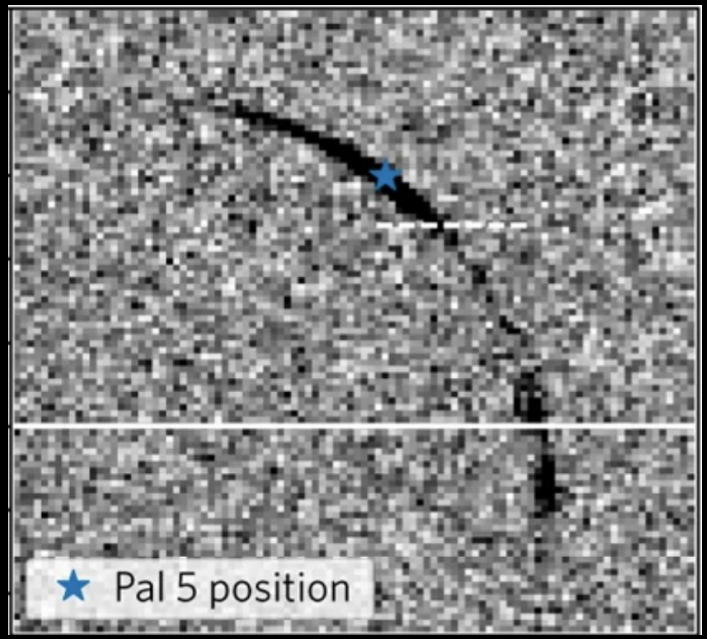
-> inherent shape of the halos.

-> among other properties.

MW disk/bar - stream interactions are well(?) studied!



Odenkirchen+2003



Pearson+2017

Bar causes the morphological changes in Pal5 track.

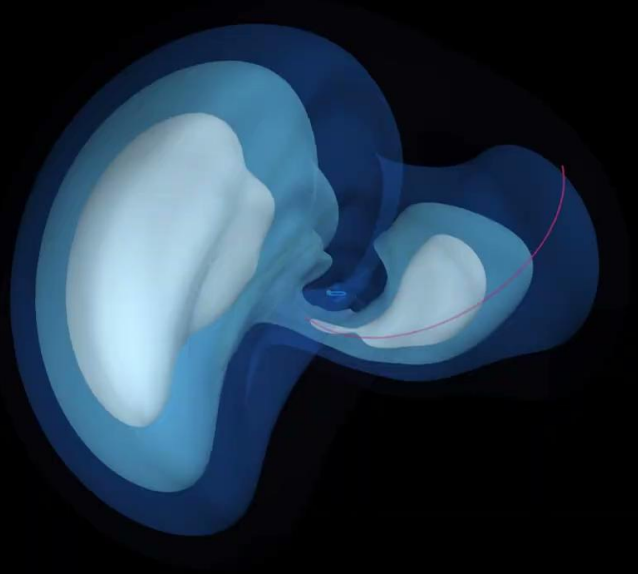
The MW is in <u>disequilibrium</u> . . .

Out of equilibrium due to past and ongoing mergers.

halo ~ LMC is 10-20% mass of the MW.

disk~ Sag is 1-5% MW.

MW response to LMC in Nbody DMO sims. [Garavito+2021]

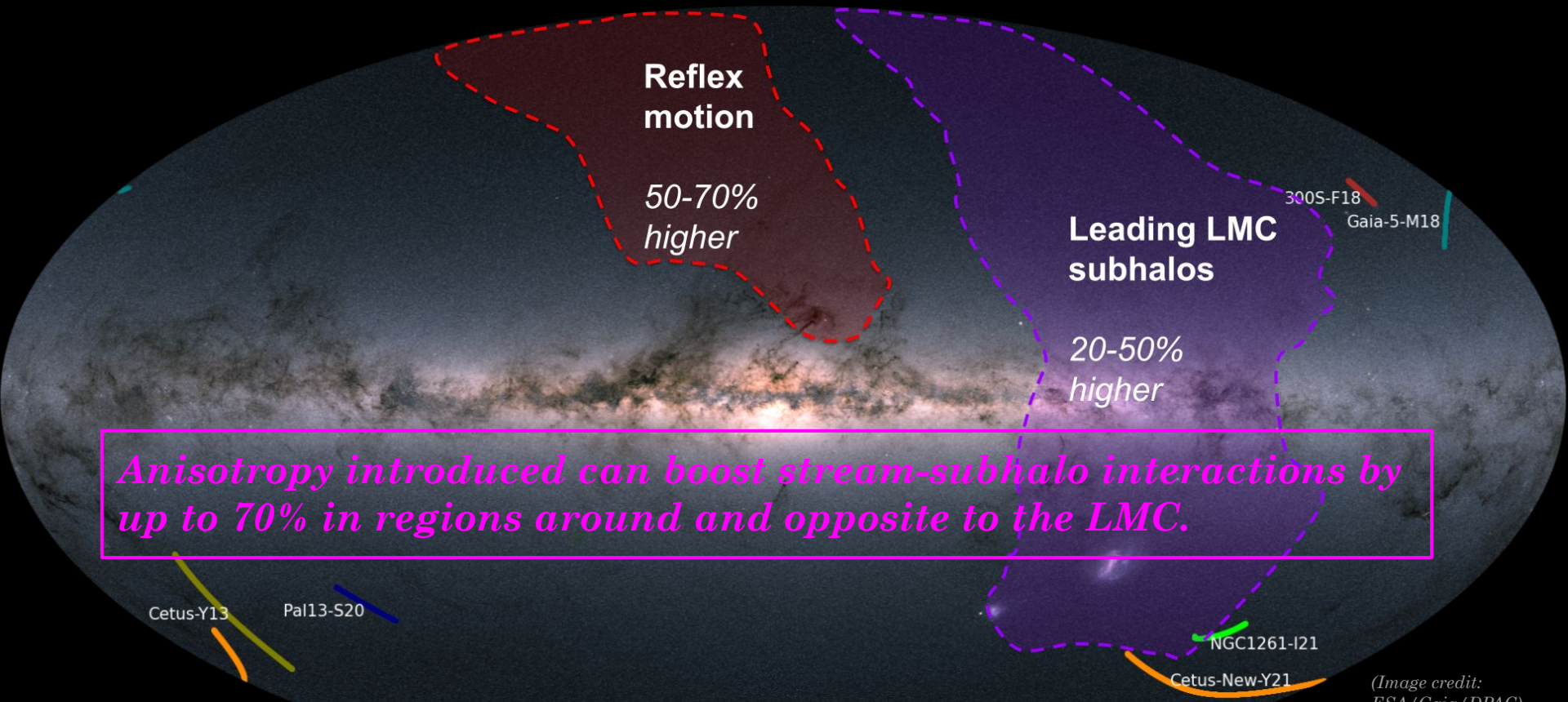


See Gomez+2015, Laporte+2018, Hunt+2018, and more

Enforces the asymmetry in the MW.

See Garavito+2021, Petersen & Pennarubia 2021, Vasiliev+2021 and more

Asymmetrical Boost in stream-subhalo encounters.

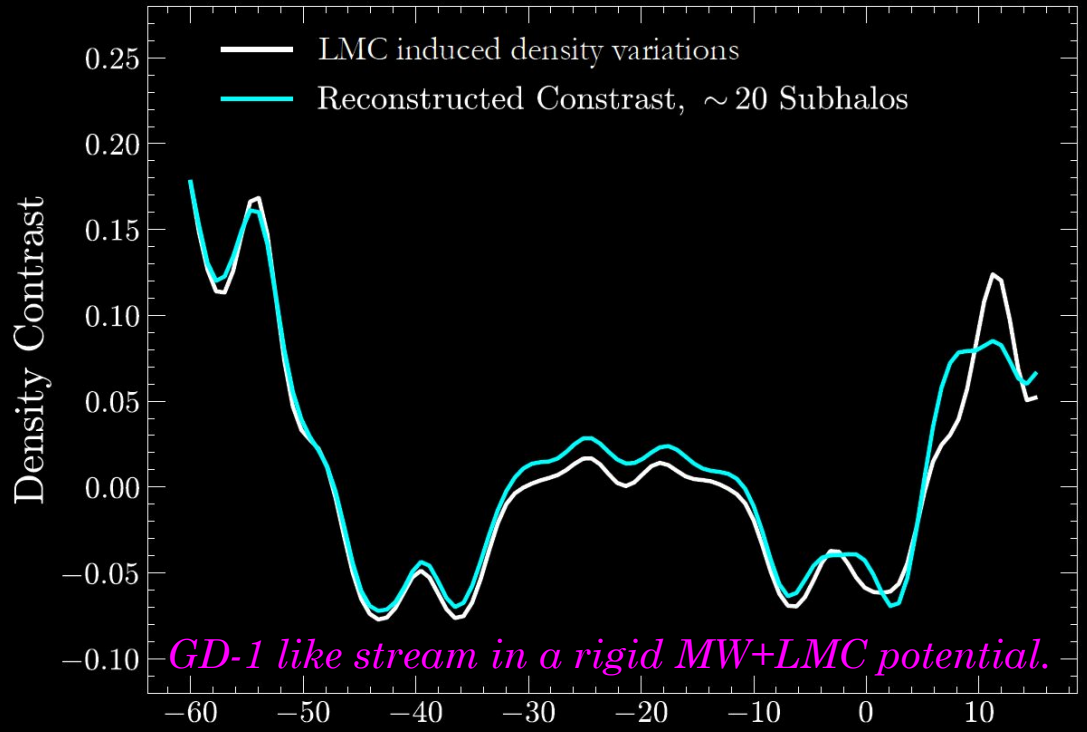


Anisotropy introduced can boost stream-subhalo interactions by up to 70% in regions around and opposite to the LMC.

Top 10% streams outside 20 kpc with highest encounter rates (i.e. > 1 encounter per stream length every 2 Gyr).

Arora+2023

MW-LMC direct/indirect effects on stream preds.



GD-1 like stream in a rigid MW+LMC potential.

Nibauer+2024

Also see: Erkal+2019, Shipp+2021, Vasiliev+2021, Lilleengen+2023, Brooks+2024, Drouplic+in prep, etc.

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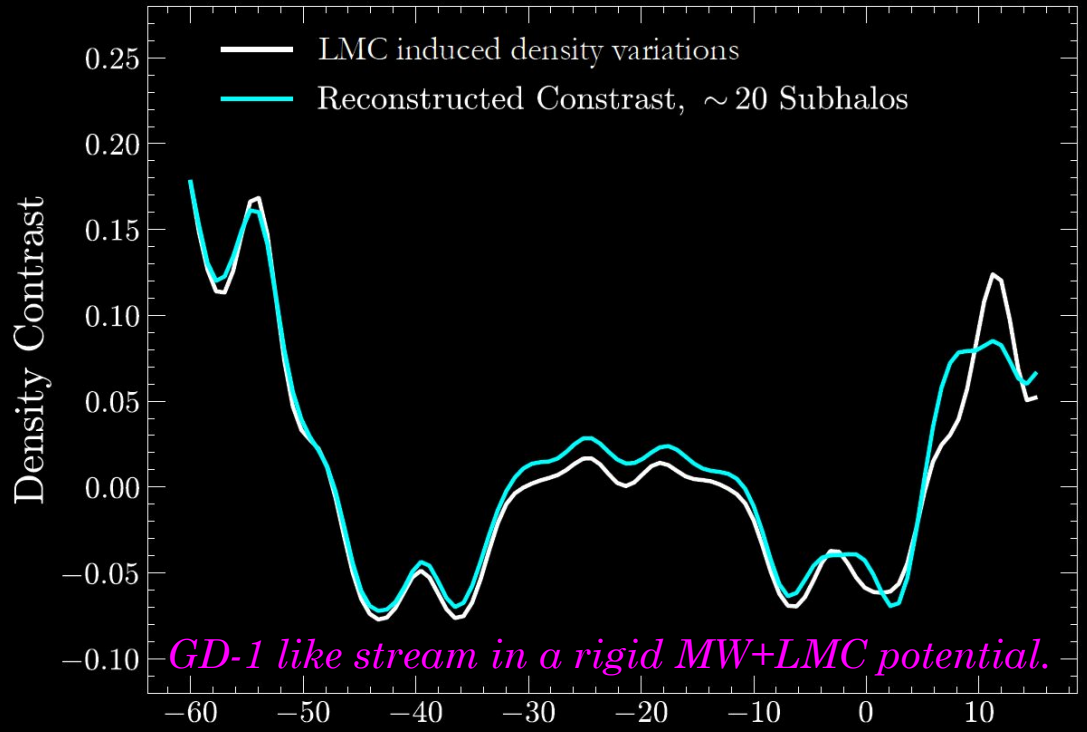

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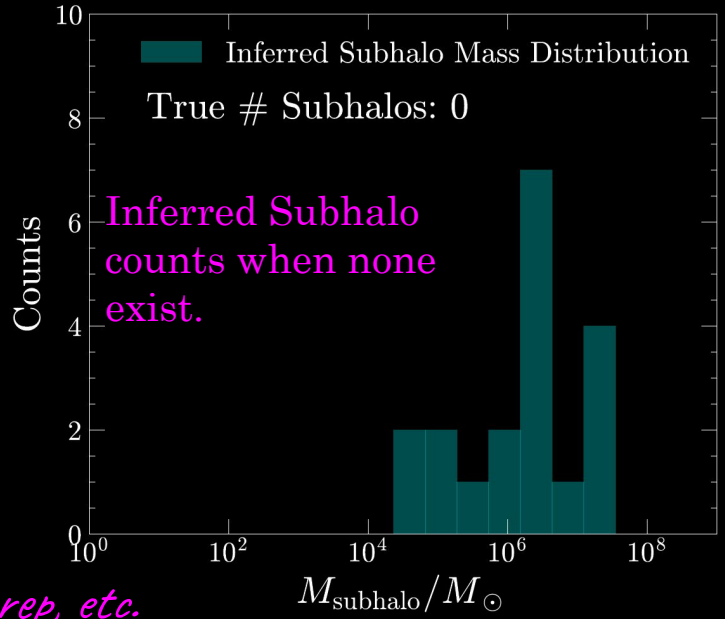
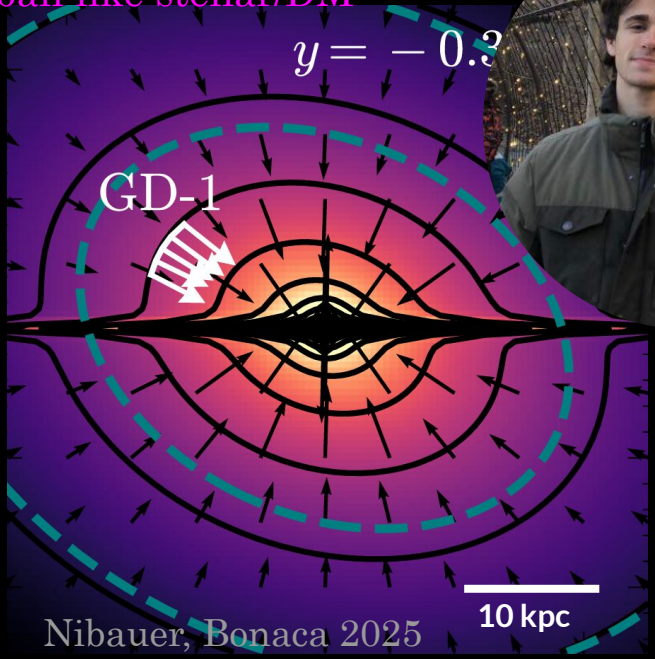


Inferred Subhalo counts when none exist.

Also see: Erkal+2019, Shipp+2021, Vasiliev+2021, Lilleengen+2023, Brooks+2024, Drouplic+in prep, etc.

The MW is asymmetric and in disequilibrium . . .

Tilted (w.r.t to disk) and "*American*" football like stellar/DM halo.



Halo has non-trivial shape in different regions in the galaxy.

(observed both in simulations and observations)

Before we move to Stellar tracers!

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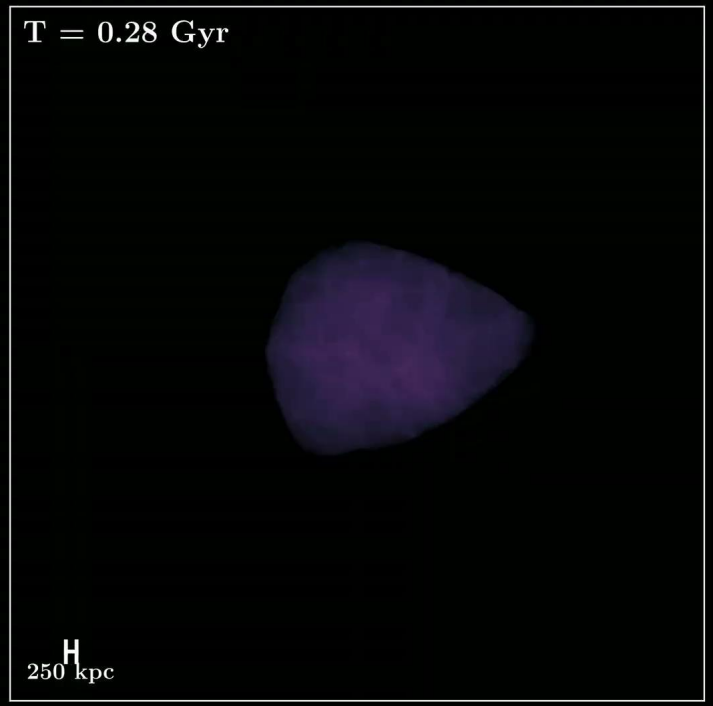
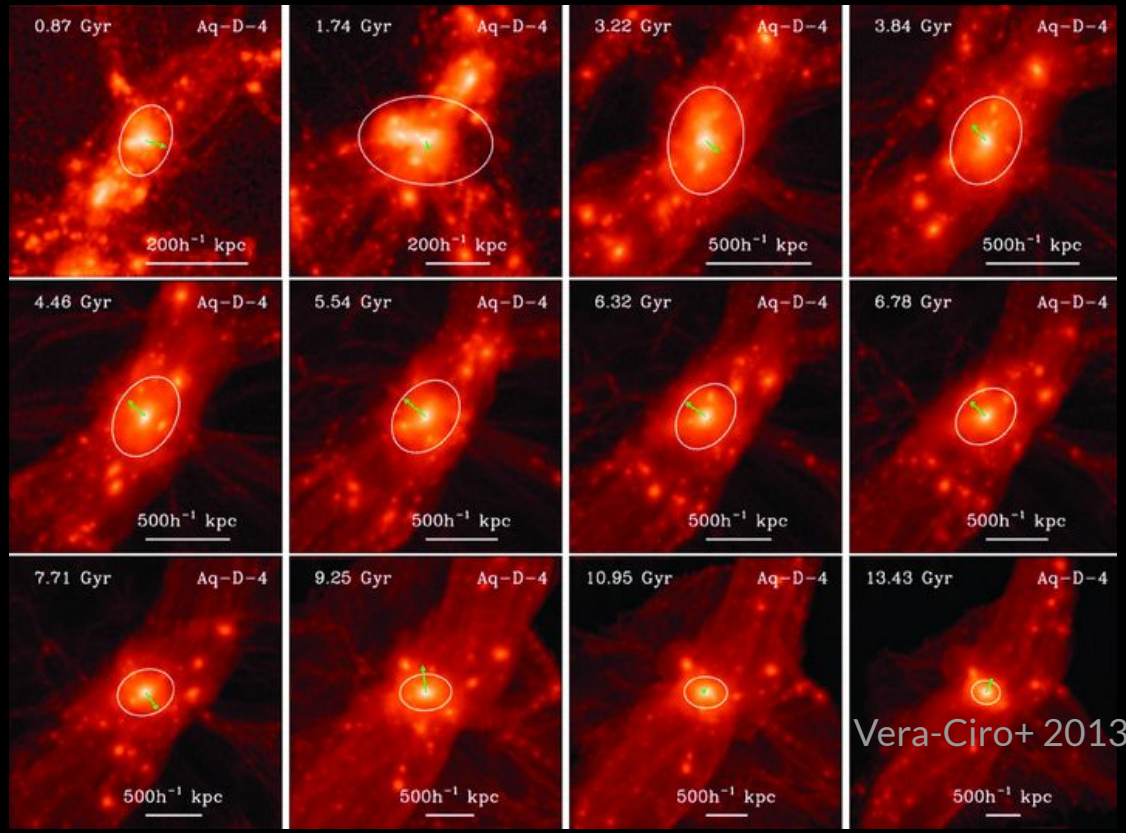
We must study the halo shapes
(and their couplings)

Shaped by filamentary accretion & environment

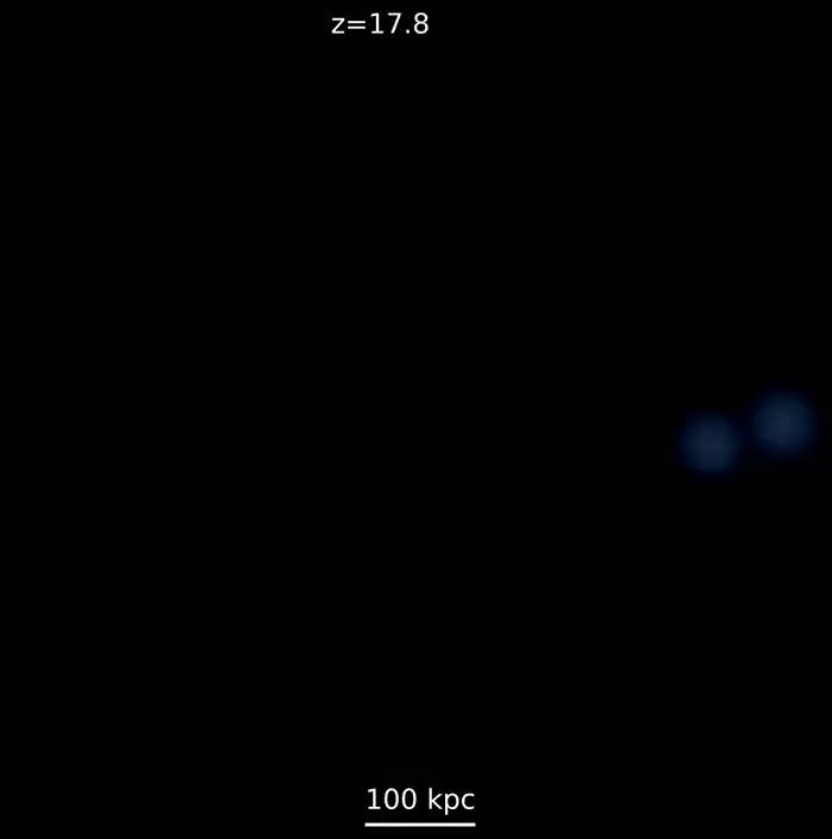


FIRE-2 example DM halo orientation with filaments and mergers.



Aquarius halo oriented with the filaments ~ 7 gyr

MW-mass galaxies with realistic assembly histories!



Wetzel (incl. Arora)+2023

FIRE-2 simulations with realistic formation and assembly history in a cosmic environment.

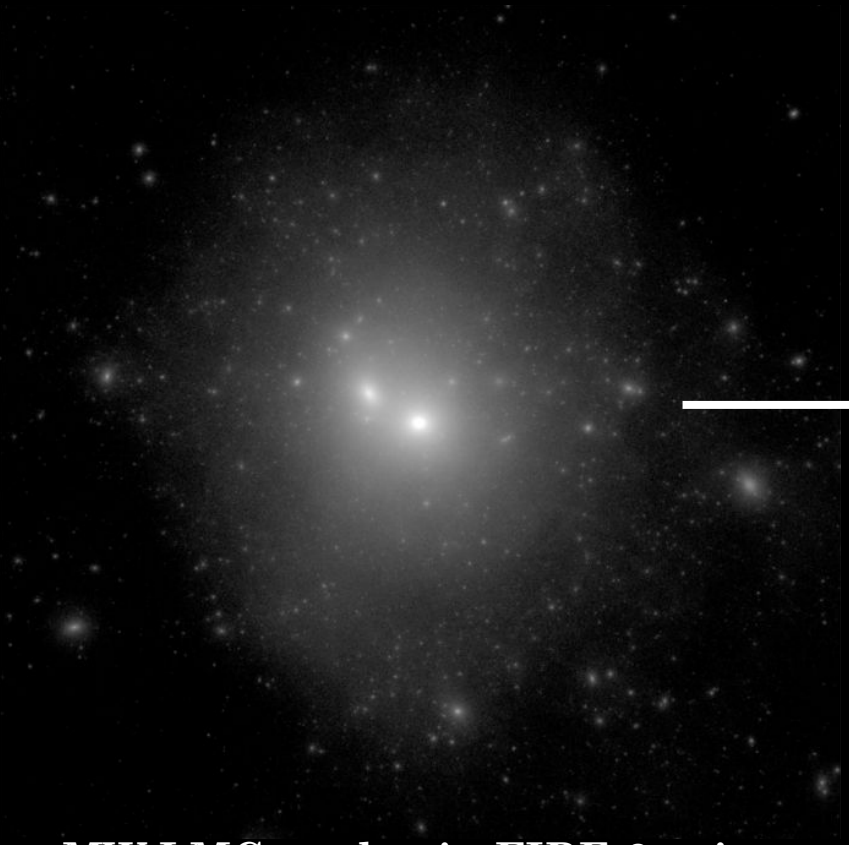
$$M_{\rm baryon} \sim 7100\ M_\odot$$
$$M_{\rm dark} \sim 35,000\ M_\odot$$

FIRE
Feedback In Realistic Environments

Expanding the DM halo as spherical harmonics.

MW-LMC analog in FIRE-2 suite.

Expanding the DM halo as spherical harmonics.

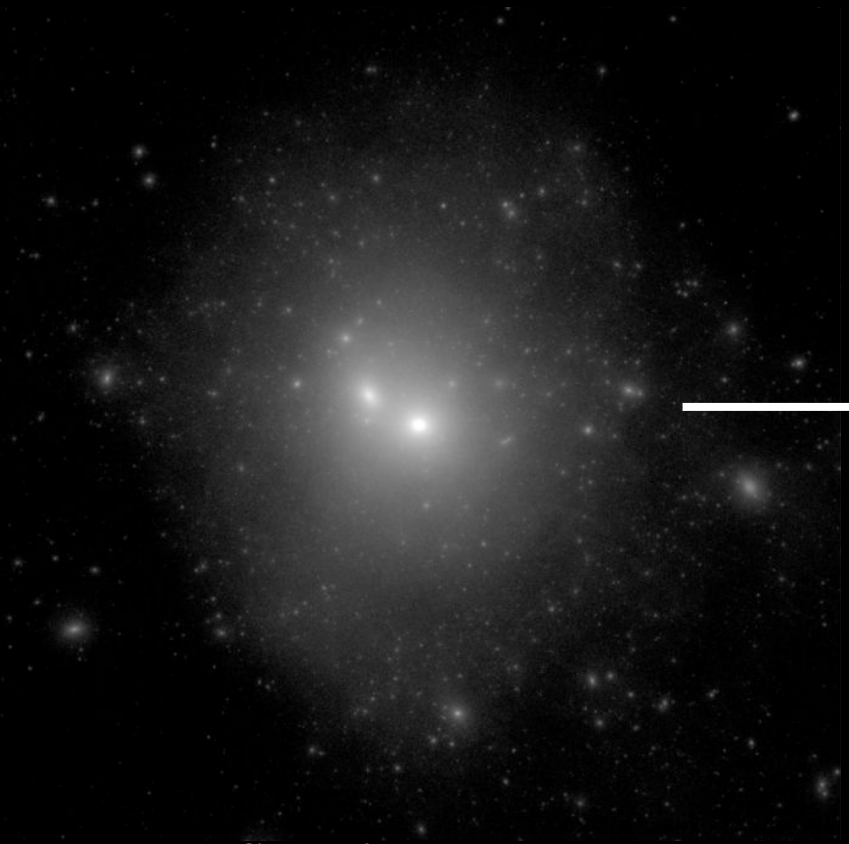


MW-LMC analog in FIRE-2 suite.

$$\Sigma_{\ell,m}\,\rho_{\ell,m}(r)\,Y_{\ell,m}(\theta,\phi)$$

Angular dependence

Expanding the DM halo as spherical harmonics.



MW-LMC analog in FIRE-2 suite.

$$\Sigma_{\ell,m}\,\rho_{\ell,m}(r)\,Y_{\ell,m}(\theta,\phi)$$

Angular dependence

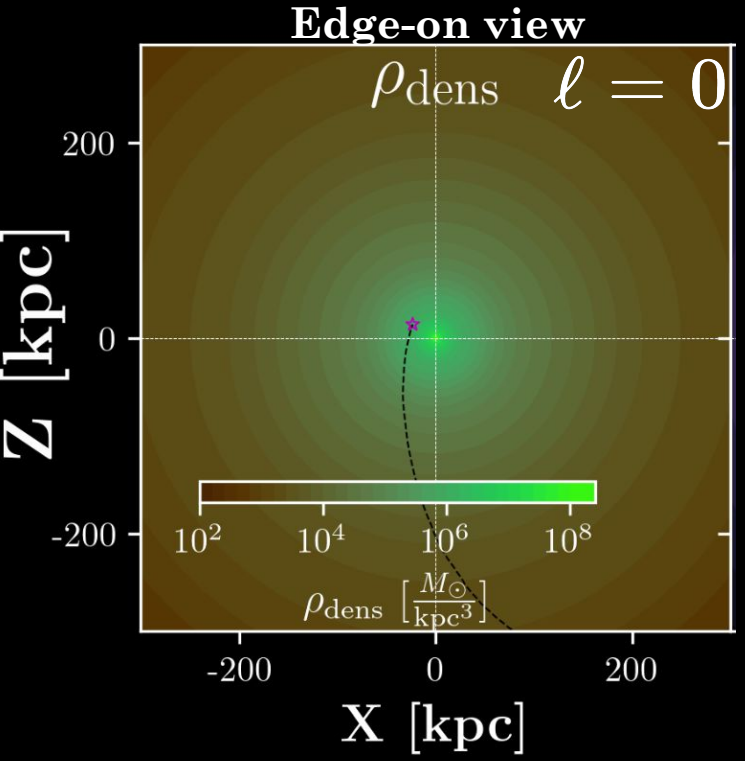
monopole $\ell = 0$ $m = 0$

dipole $\ell = 1$ $m = \pm 1$

quadrupole $\ell = 2$ $m = \pm 2$

octupole $\ell = 3$ $m = \pm 3$

Reconstructed BFE fields capture complex shapes.



$\ell = 0$

$m = 0$

Total mass and radial profile information.

MW-LMC analog in FIRE-2 suite.

Arora+2022

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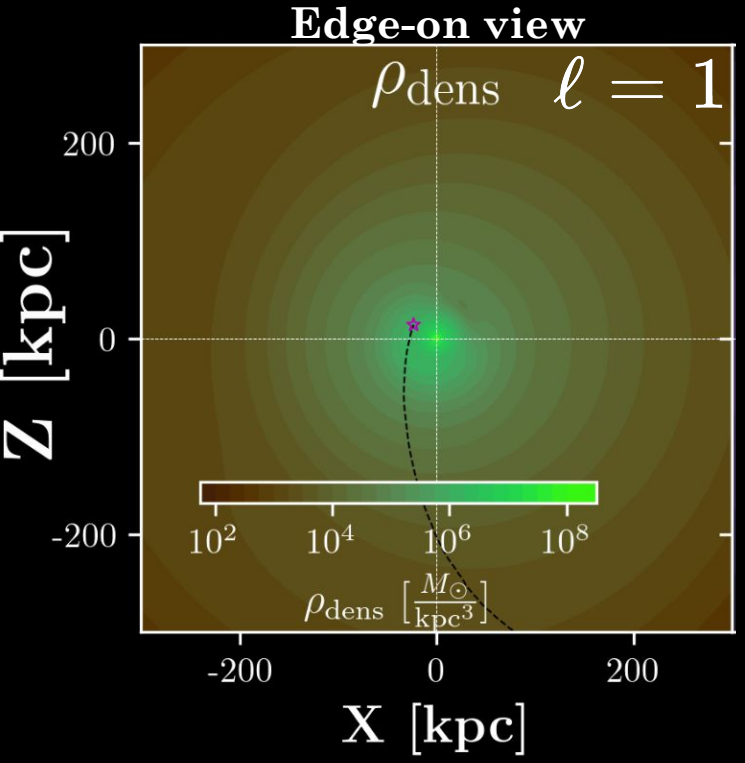

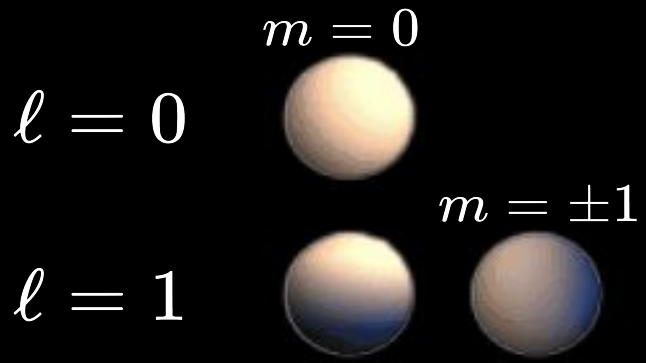

Total mass and radial profile information.

Bulk COM motion.

MW-LMC analog in FIRE-2 suite.

Arora+2022

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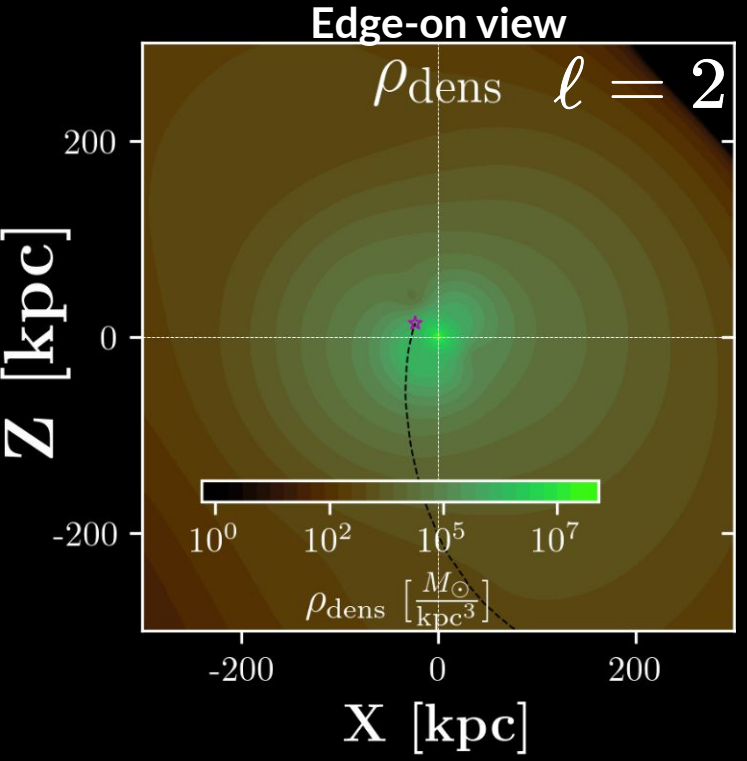

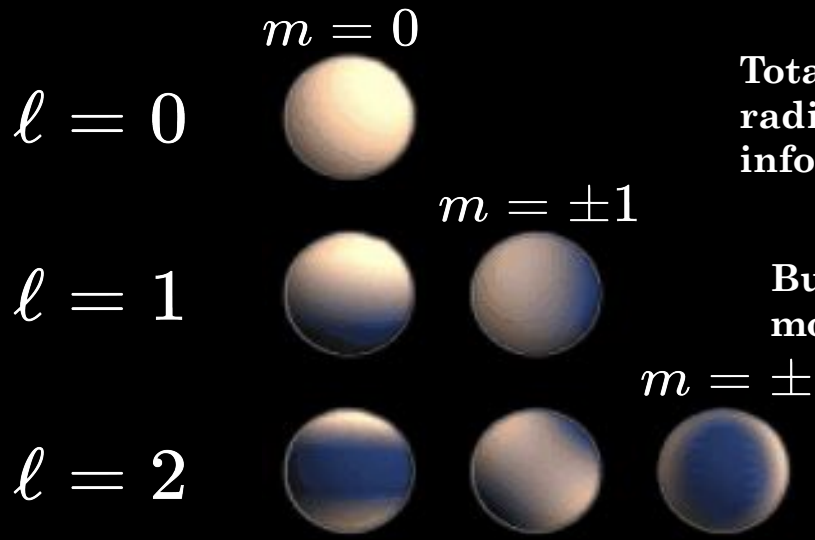

Total mass and radial profile information.

Bulk COM motion.

Shape info.

MW-LMC analog in FIRE-2 suite.

Arora+2022

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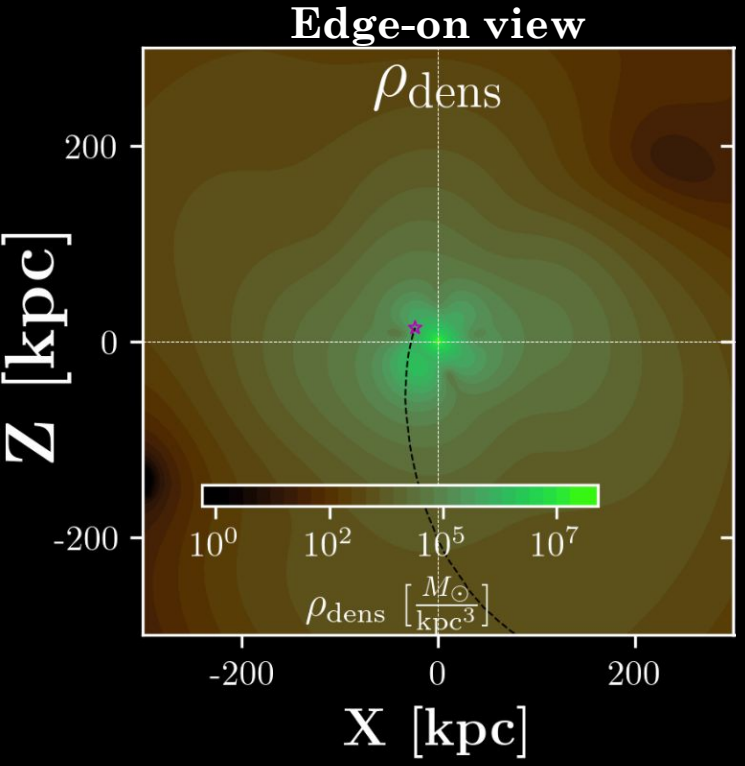
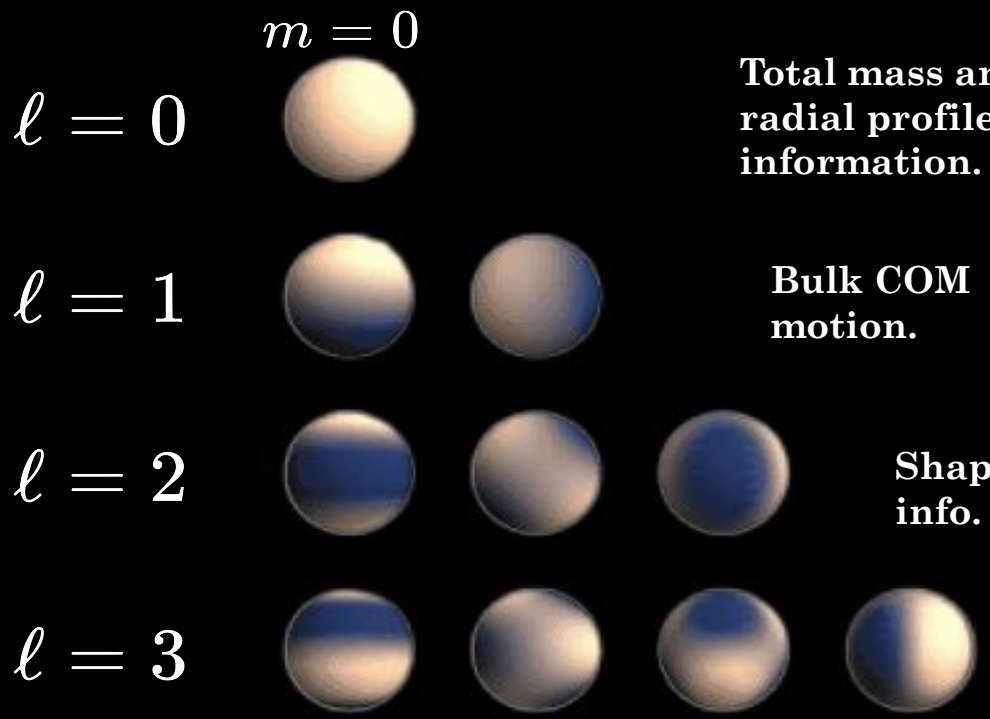




Total mass and radial profile information.

Bulk COM motion.

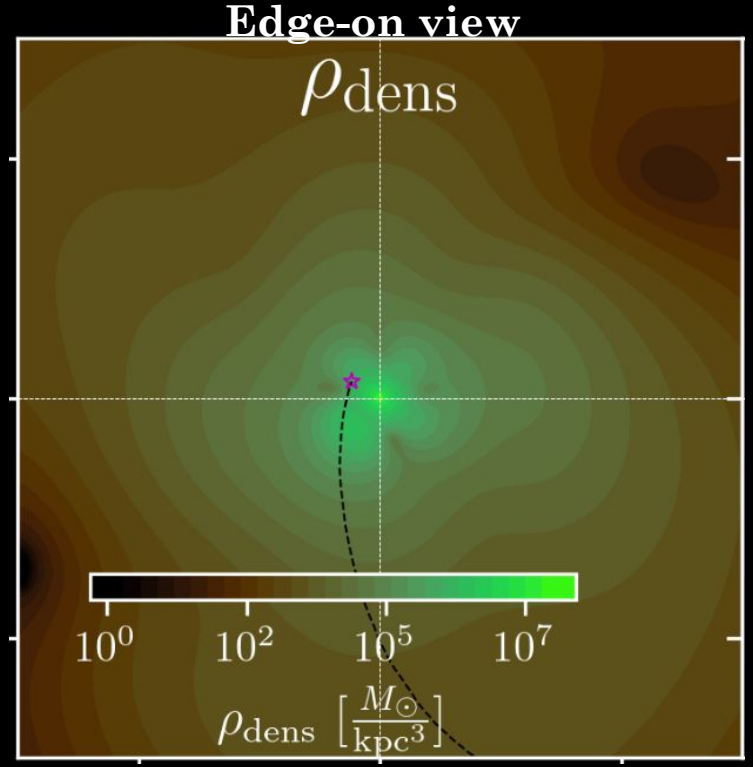
Shape info.

And so on for higher orders....

MW-LMC analog in FIRE-2 suite.

Arora+2022

BFE captures time-evolving halo deformations.



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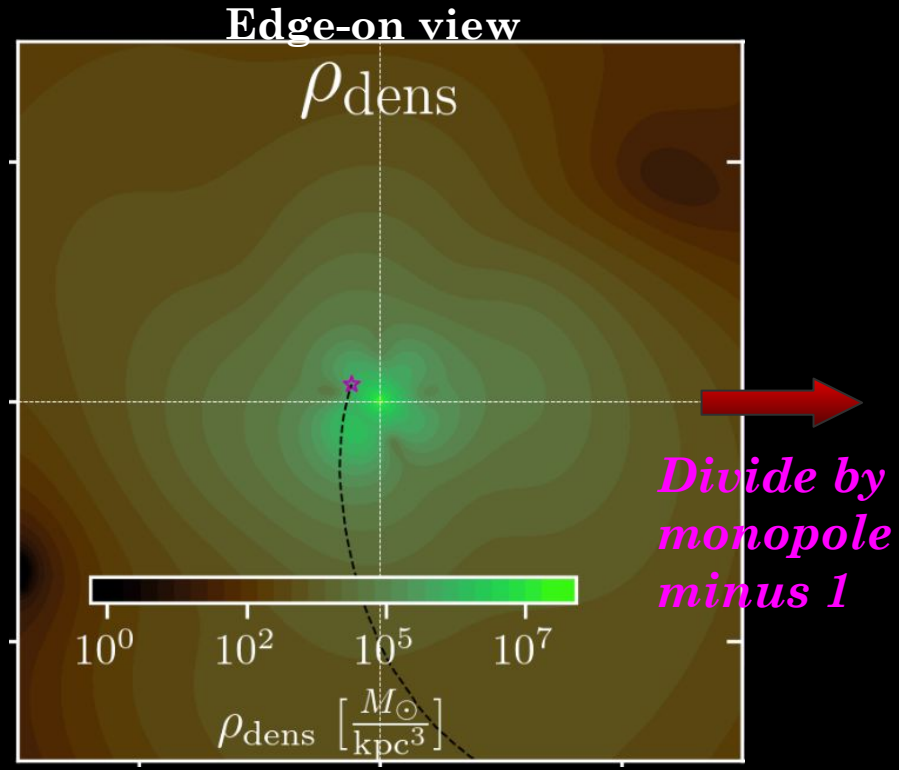


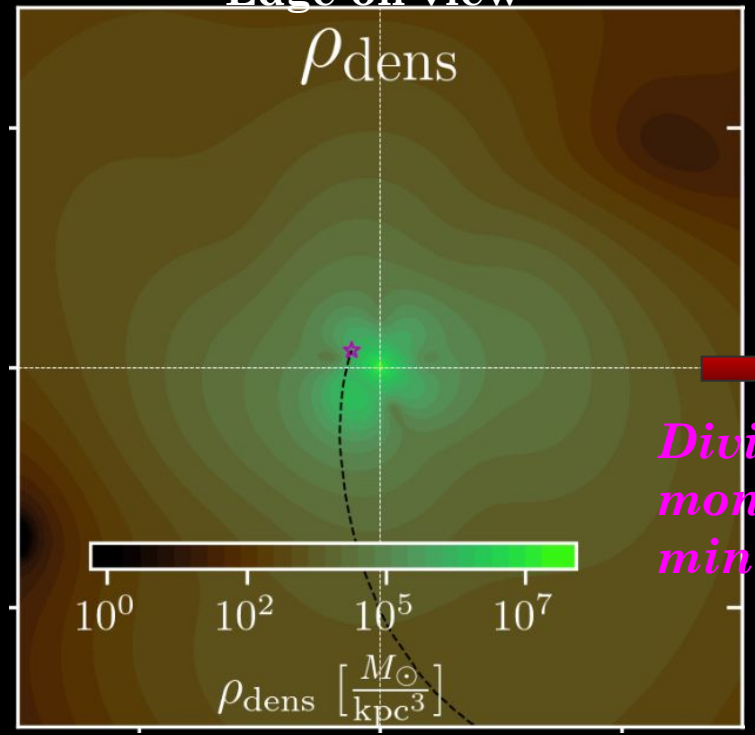
Divide by monopole minus 1

MW-LMC analog in FIRE-2 suite.

BFE captures time-evolving halo deformations.

Edge-on view

MW-LMC analog in FIRE-2 suite.



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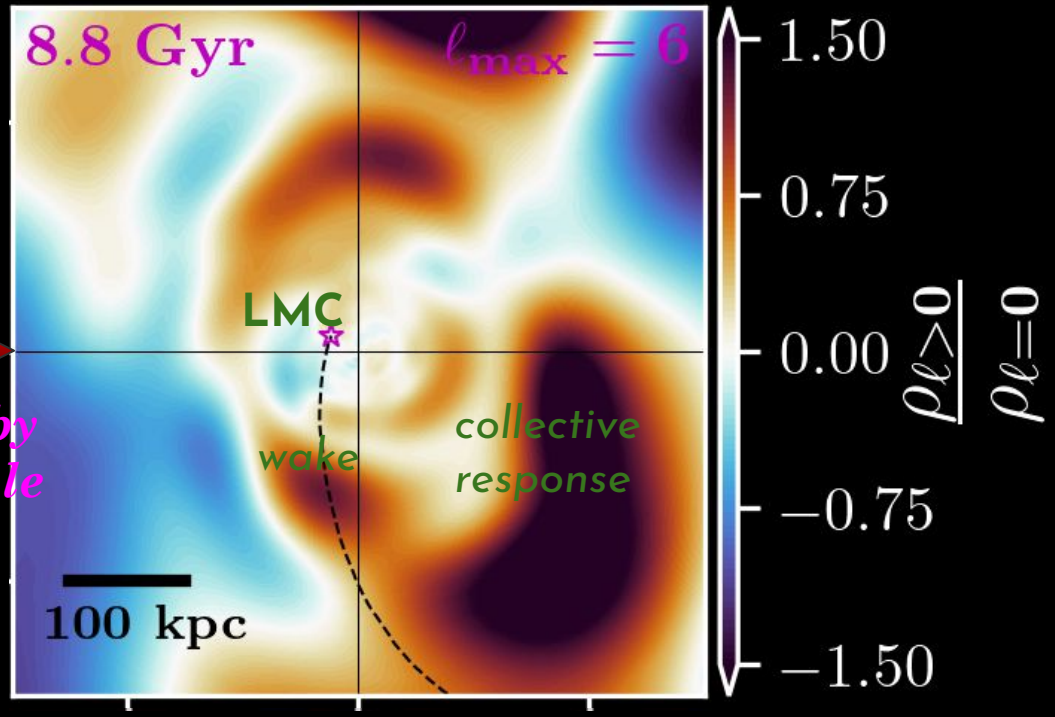

MW-LMC analog in FIRE-2 suite.

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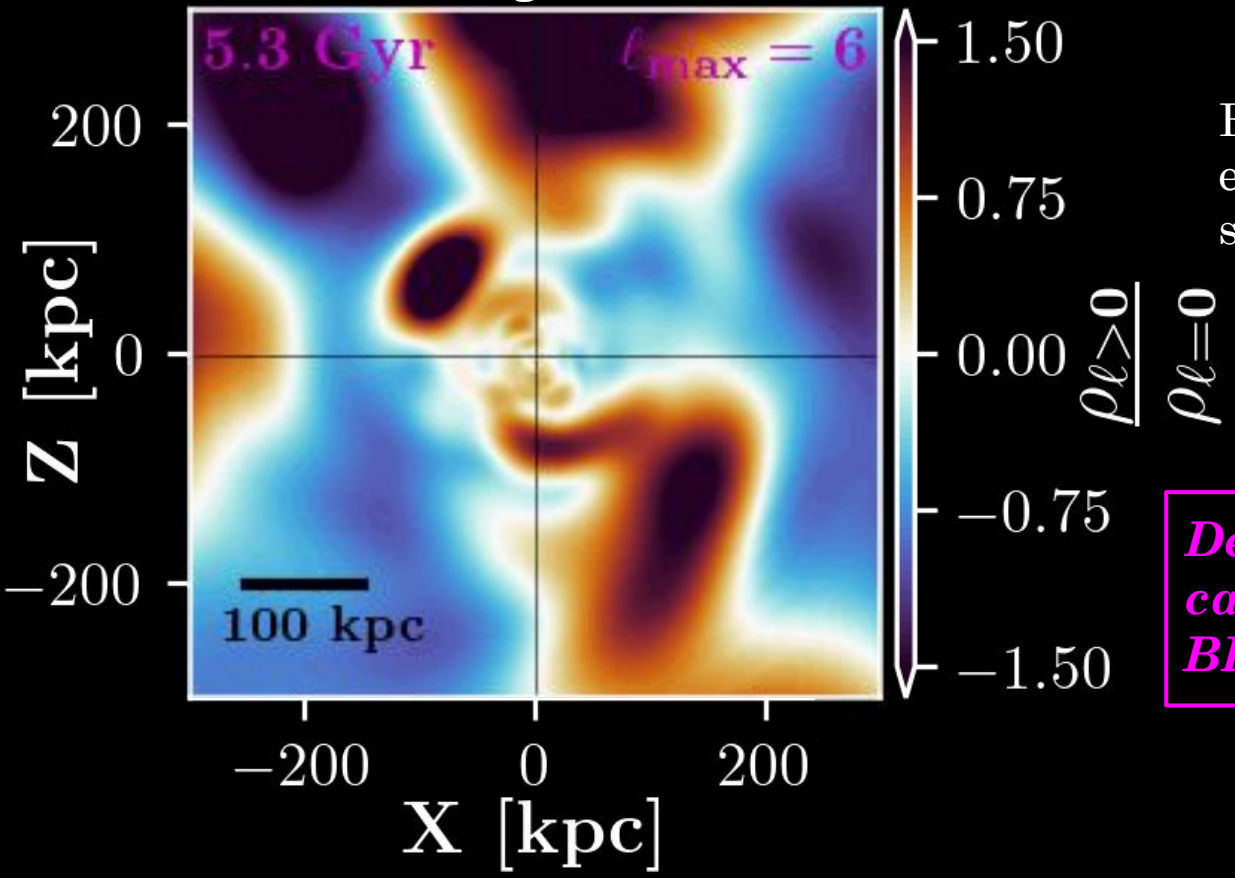
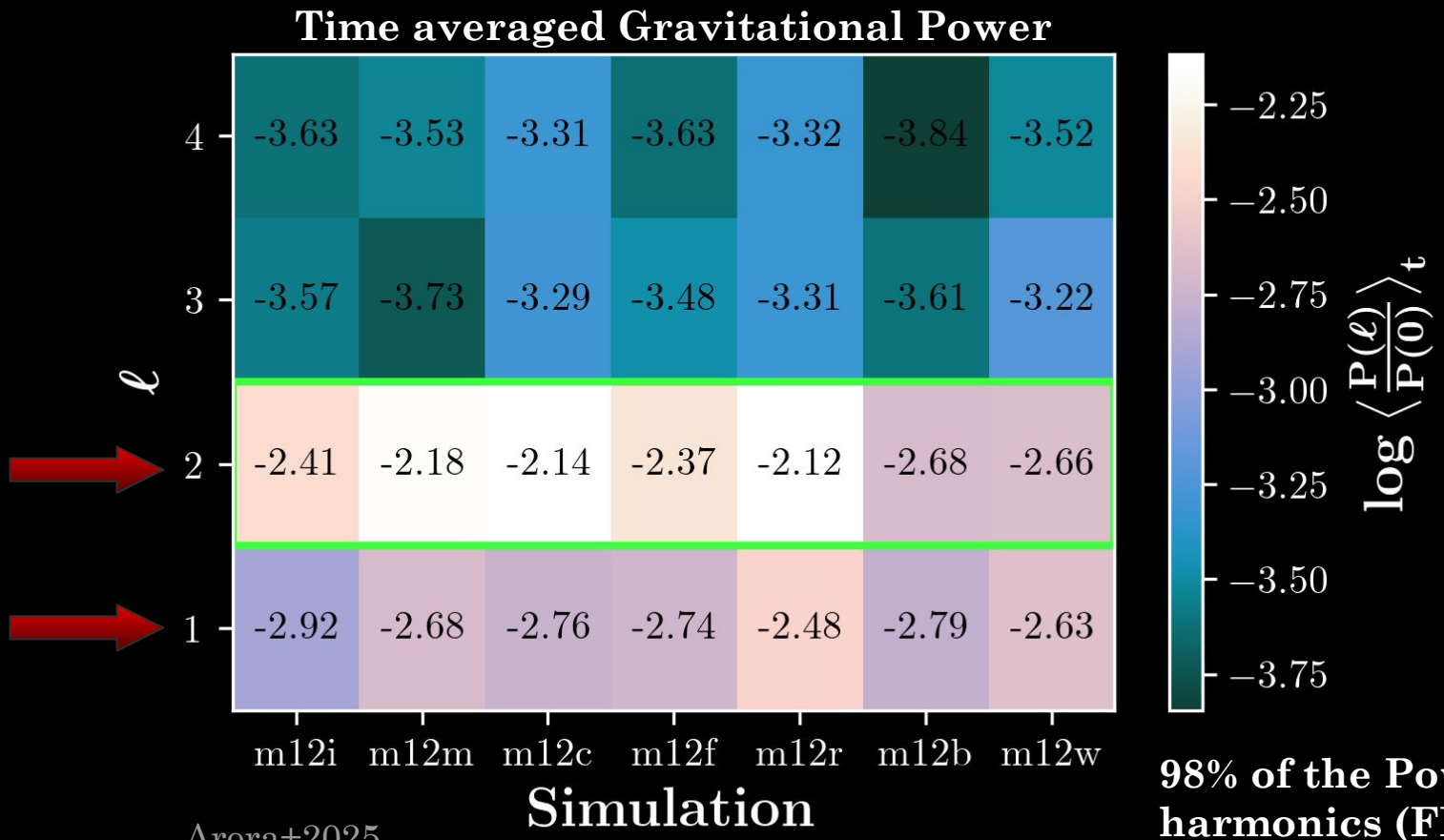


Fractional density enhancement relative to spherically avg value at each r.

Density distortions can be captured in time-evolving BFE with low pole order.

Arora+2023

Halos have most structure in low-order modes.

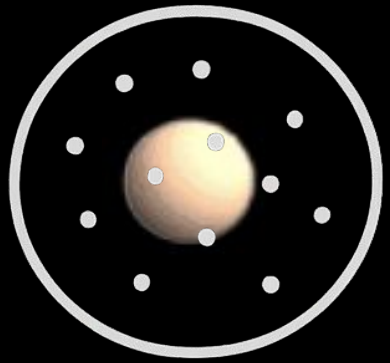


Arora+2025

98% of the Power in low order harmonics (FIRE m12s)

Harmonics describe observable halo properties.

monopole

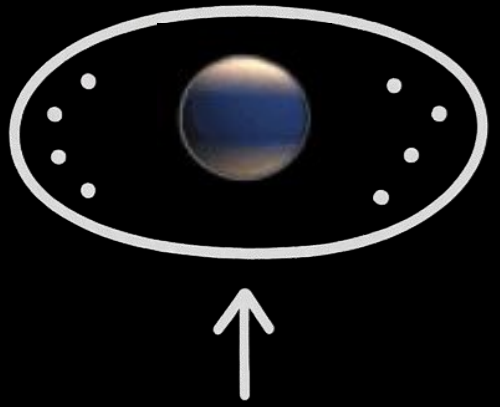


total mass,
radial profile

dipole

bulk
motion

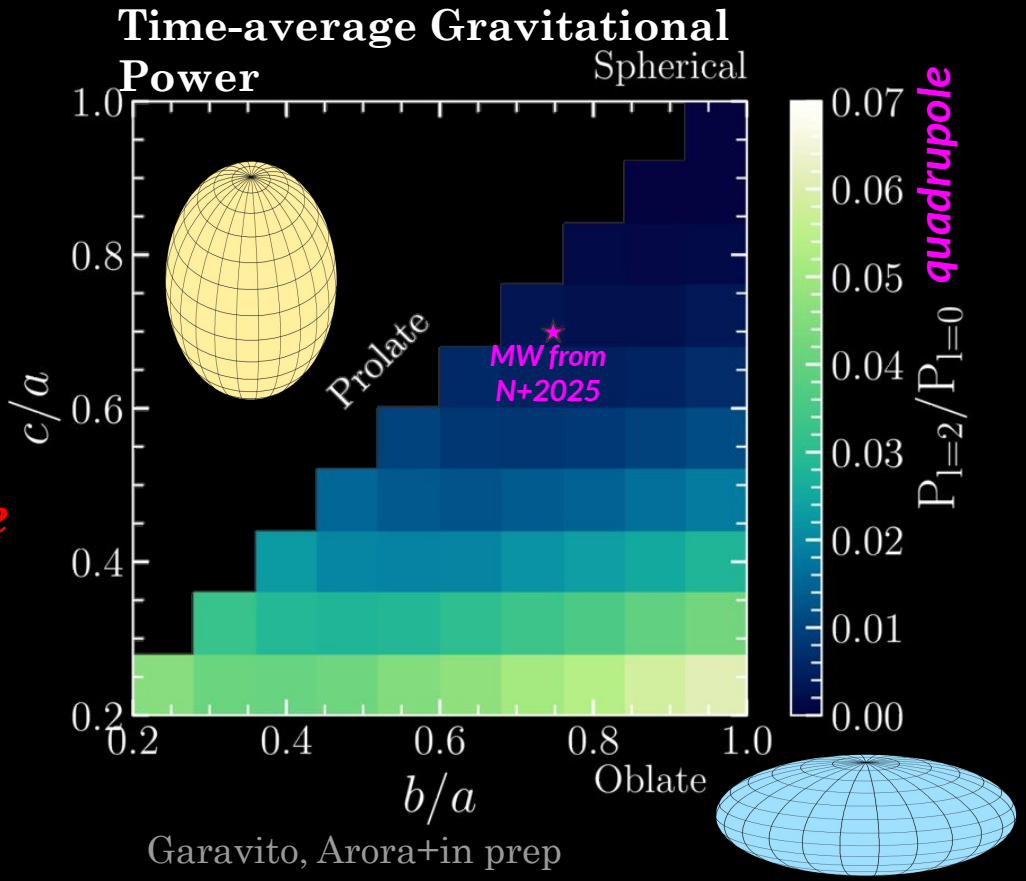
quadrupole



asymmetry

The quadrupole harmonic encodes shape!

Higher Quadrupole = more asymmetry



Garavito, Arora+in prep

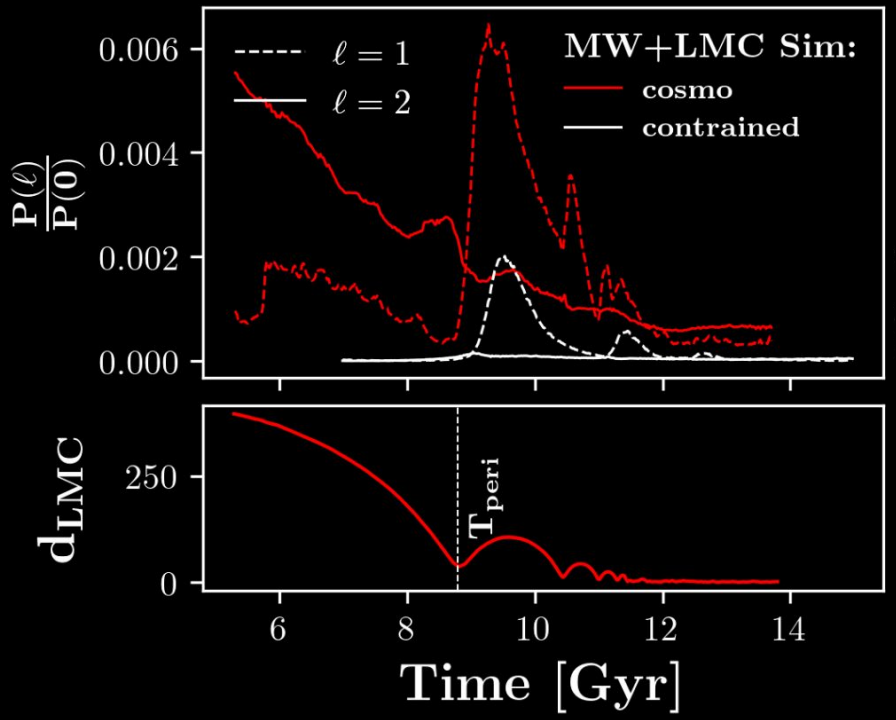
LMC analog in FIRE-2 suite- 1:8 merger ratio

FIRE-2 MW-LMC analog orbit and mass ratio.

Arora+2023

The asymmetry decreases as the halos relax!

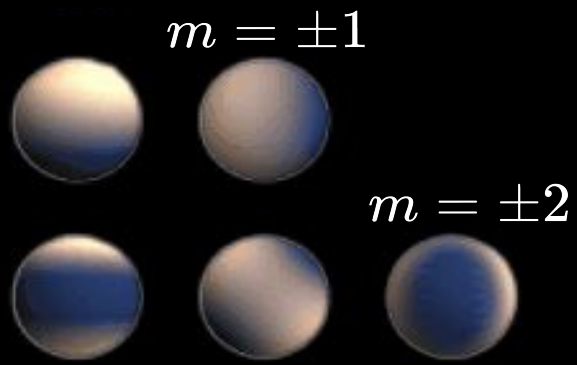
Gravitational Power in each harmonic.



Spectrum analysis to the rescue?

dipole
$\ell = 1$

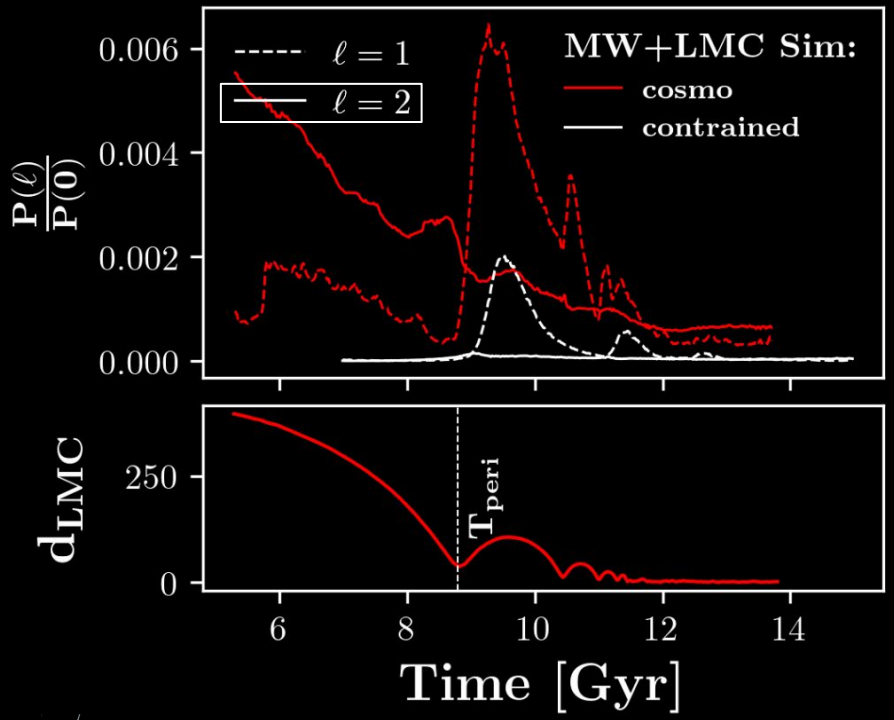
quadrupole
$\ell = 2$



Arora+2025

Dynamical data mining through spectrum analysis

Gravitational Power in each harmonic.

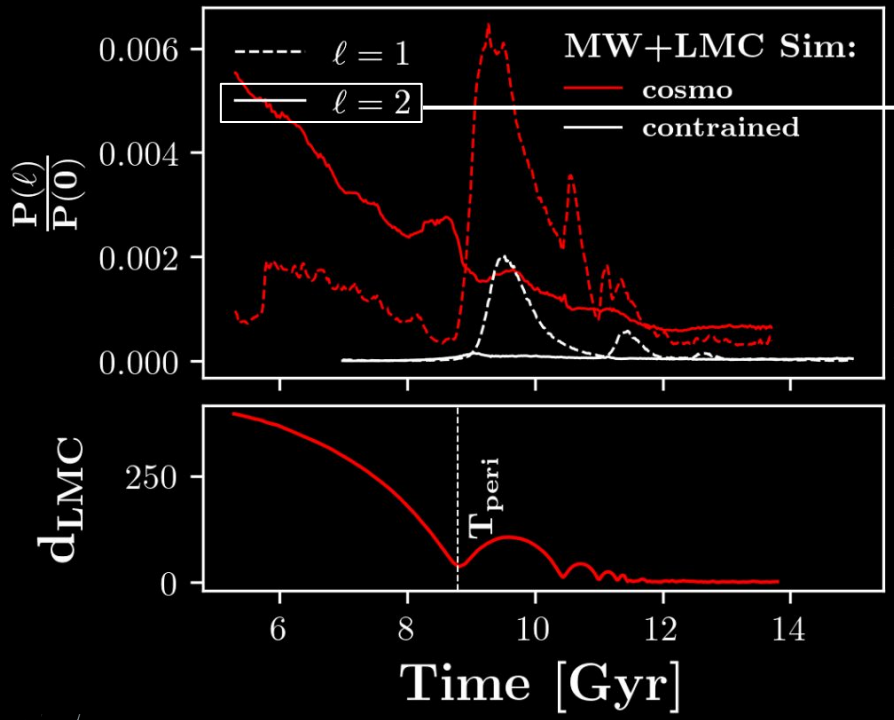


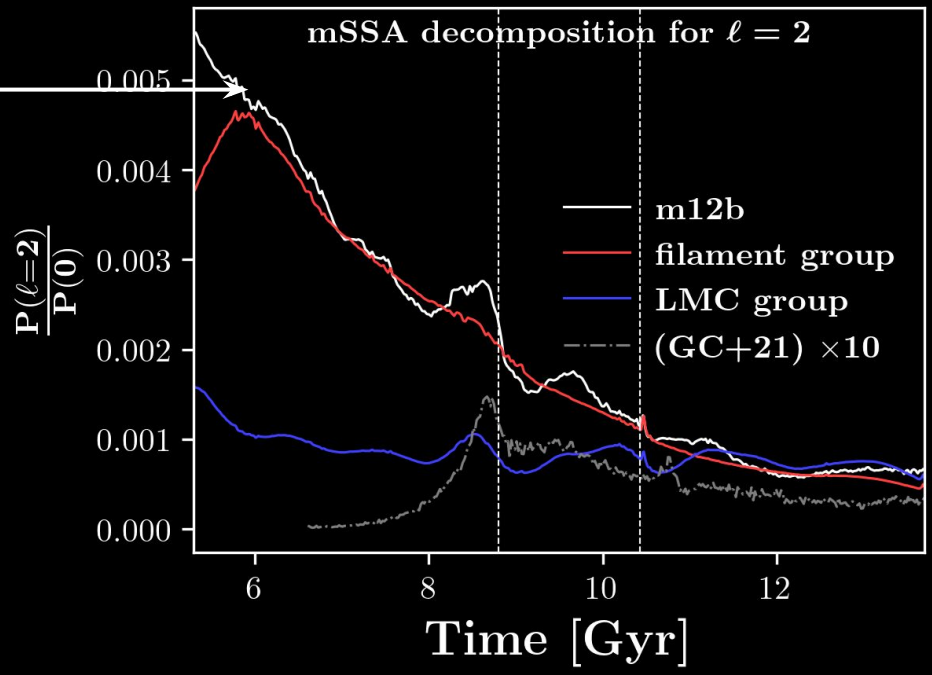
There are multiple time series of coefficients required to compute the Gravitational Power.

Arora+2025

Dynamical data mining through spectrum analysis

Gravitational Power in each harmonic.





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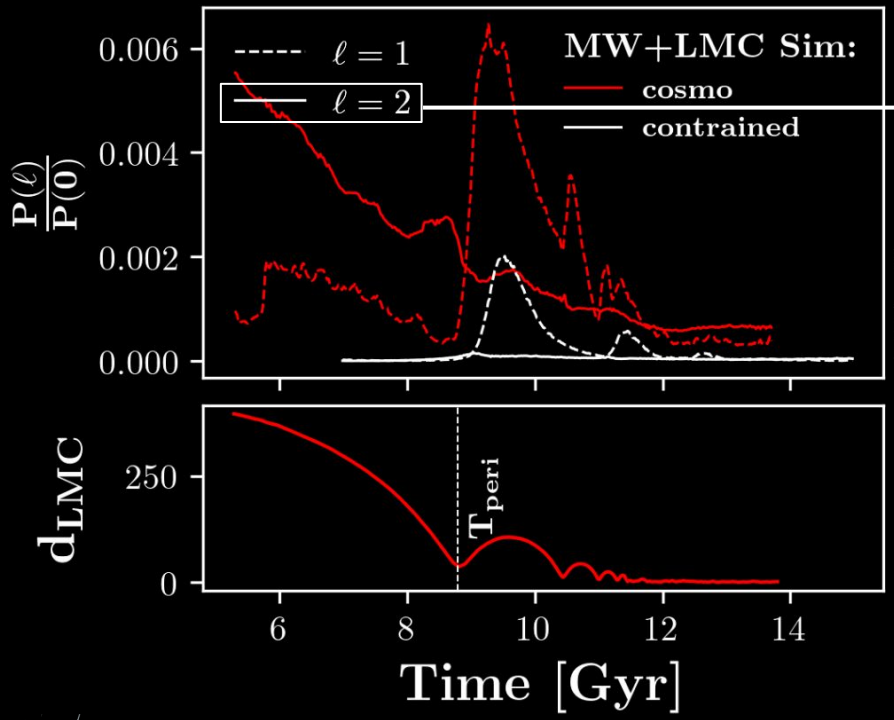

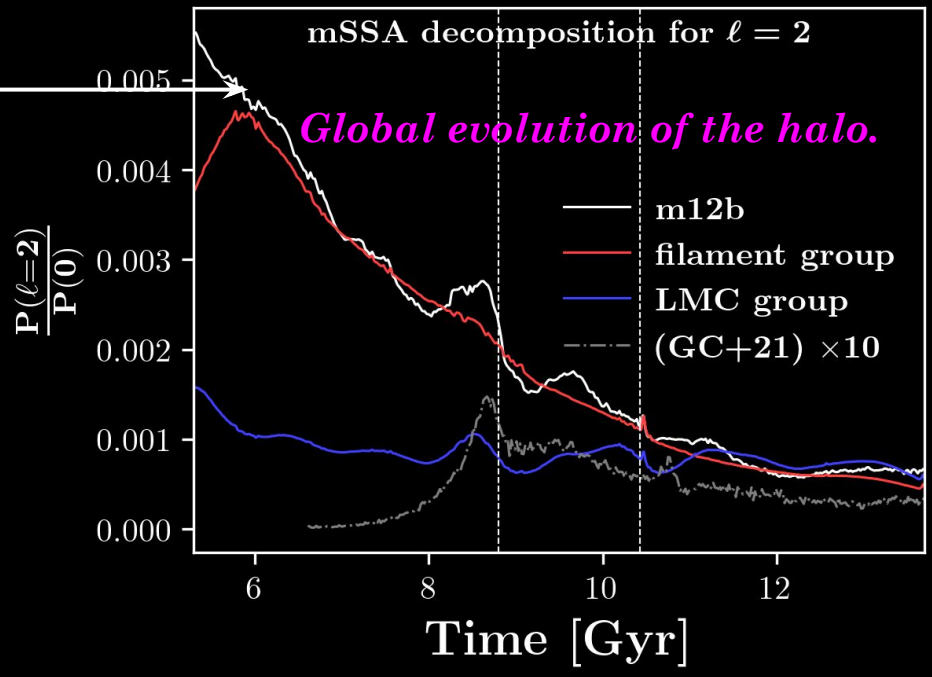

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Dynamical data mining through spectrum analysis

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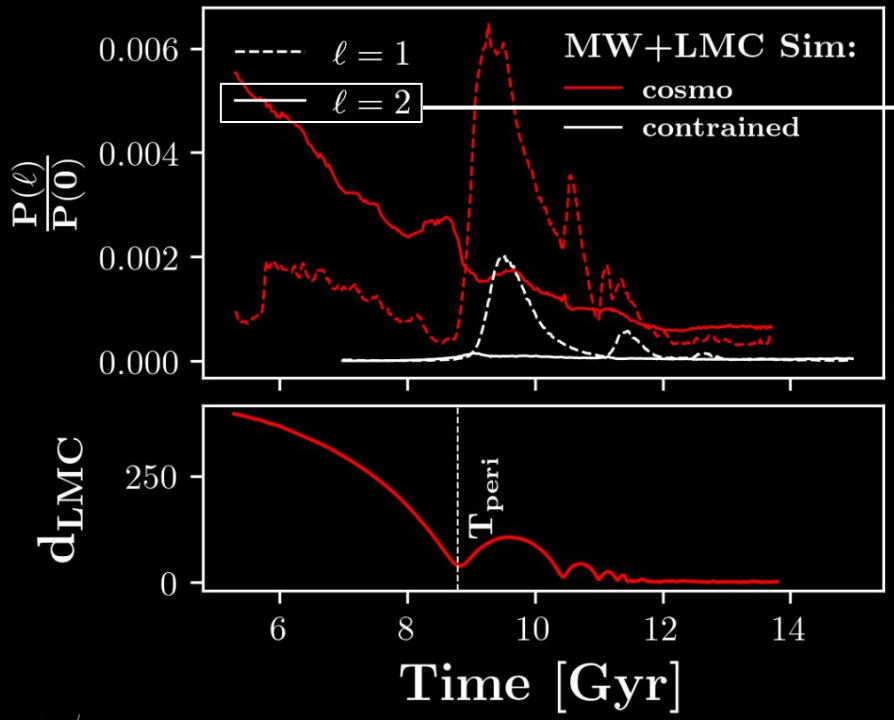
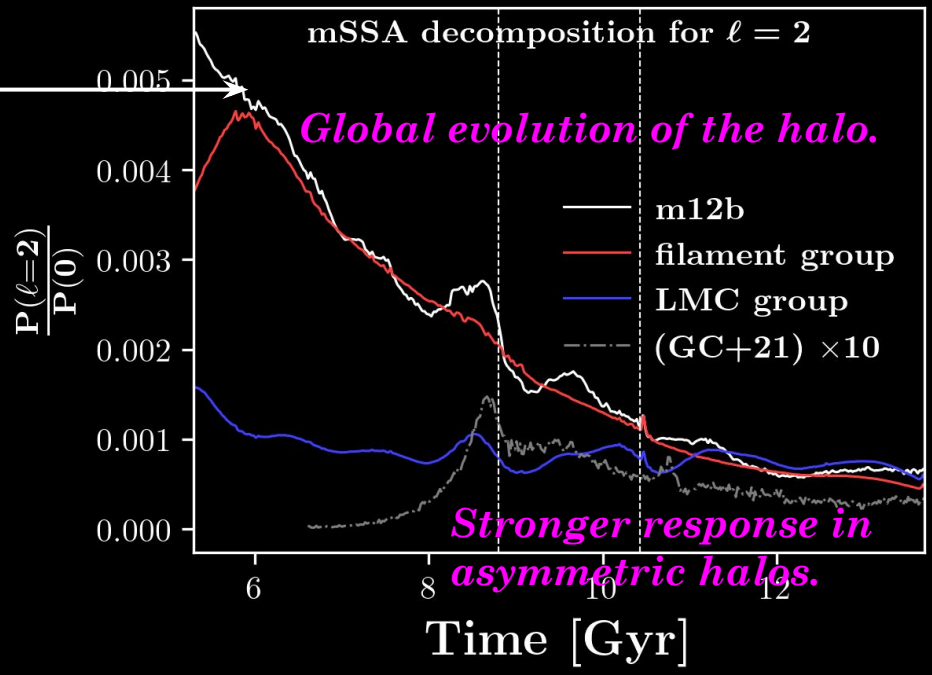
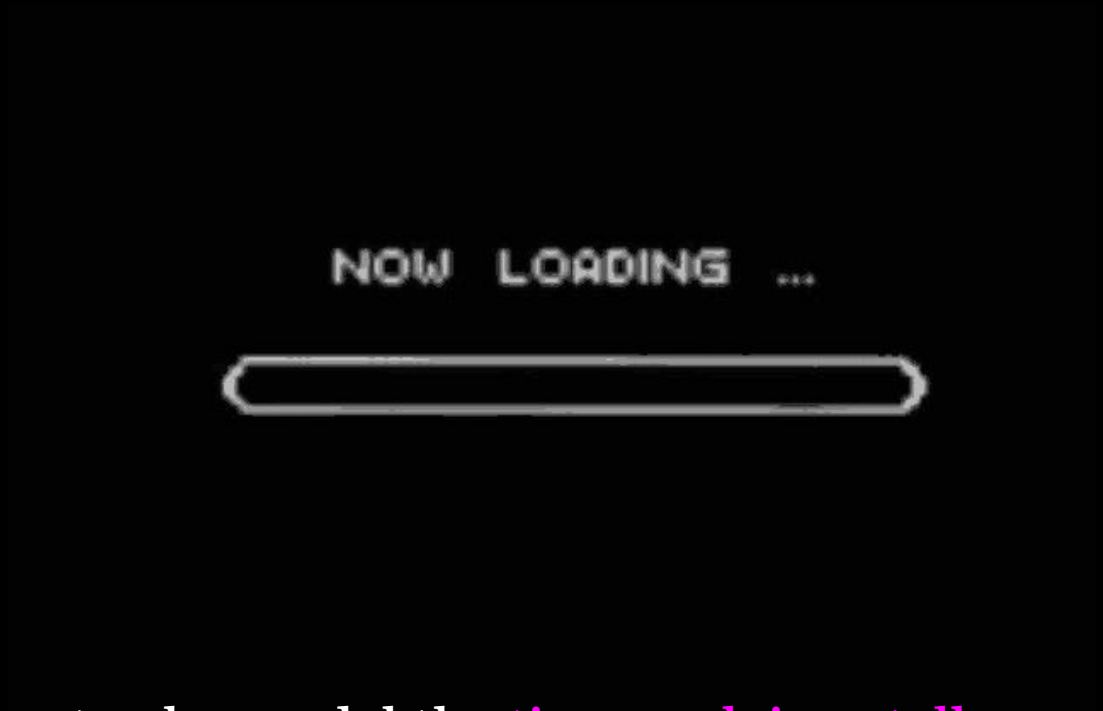




There are multiple time series of coefficients required to compute the Gravitational Power.

Arora+2025

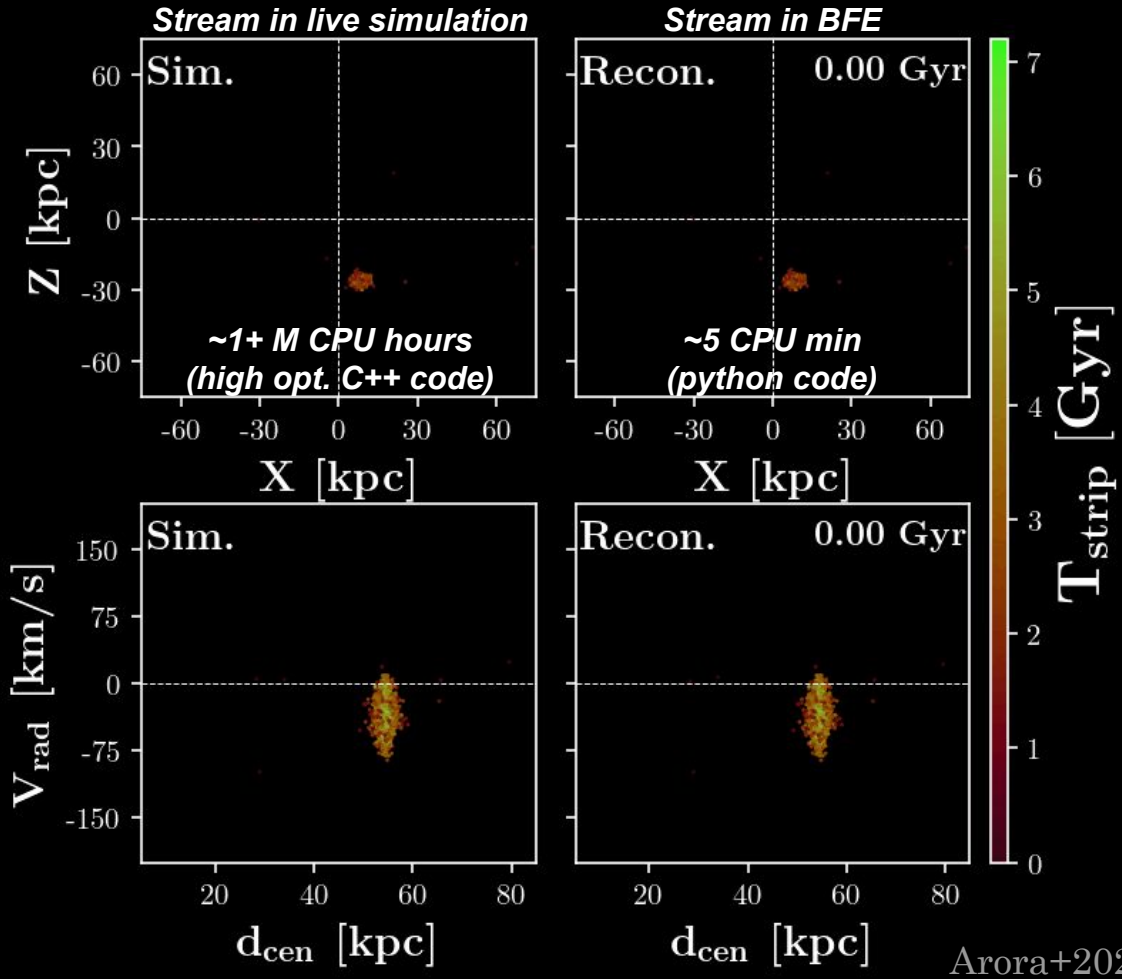
Finally we can move to Stellar tracers!



But remember to also model the time-evolving stellar component!!!

Also easily add subhalos!

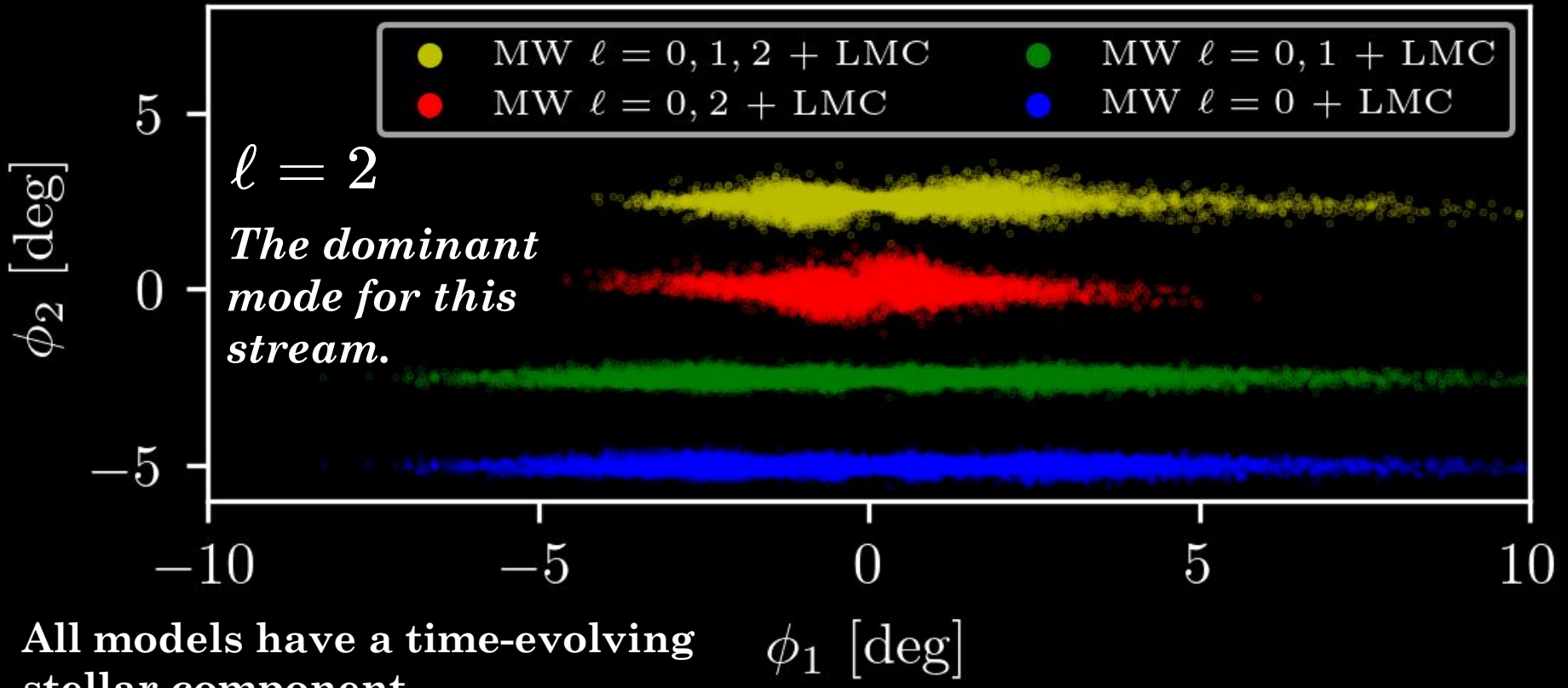
Simulating satellite disruption with BFEs.



Can be used to re-simulate and integrate: e.g., GCs, dwarf galaxies!

Arora+2024b

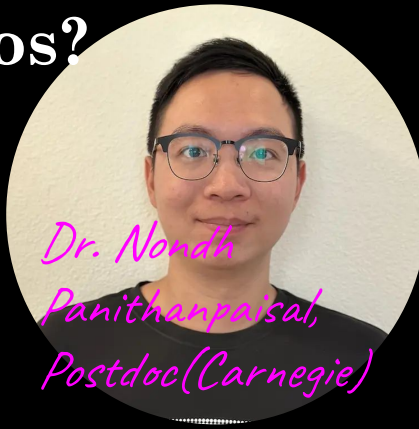
Let's look at a stream in a distorting halo.



All models have a time-evolving stellar component.

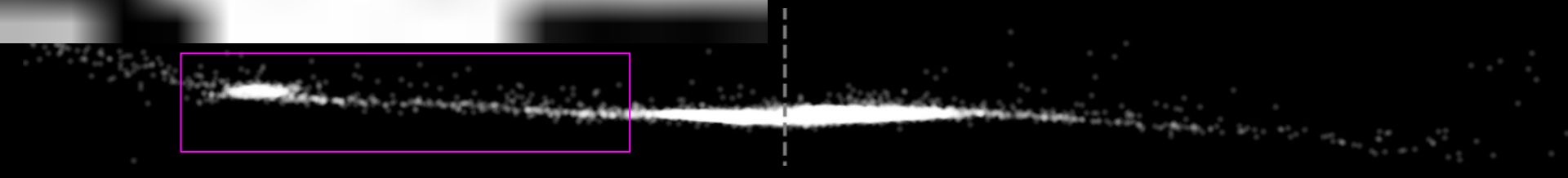
Drouplic, Arora+in prep.

Let's make a GC stream! Maybe with subahalos?



Ques. Raise your hands if you believe this stream has been perturbed by subhalos?

Panithanpaisal, Sanderson, (incl. Bonaca, Arora)+in prep



TLDR:

- Filamentary environments and mergers contribute to the present-day shape/potential of the halo.

- Satellite-induced response in triaxial halos is **boosted** (?) Should be taken into consideration for stellar tracers!

- We can use BFEs to study shapes systematically! All of this tech can and will be expanded to SIDM.

My wishlist for you:

- Please save **manyyy snapshots** of your simulations (~500).
- Statistical set zoomed cosmo sims: **MW-LMC** analogs? With alt-DM & hydro
- I want vel-dep anisotropic cross-sec sims : resolution of 100 M particles!

Inspired by Lina's recent wishlist for DREAMS collaboration.


THANK YOU FOR LISTENING
IF YOU HAVE ANY QUESTIONS I AM SURE
~~GOOGLE~~ LLMs WILL ANSWER THEM

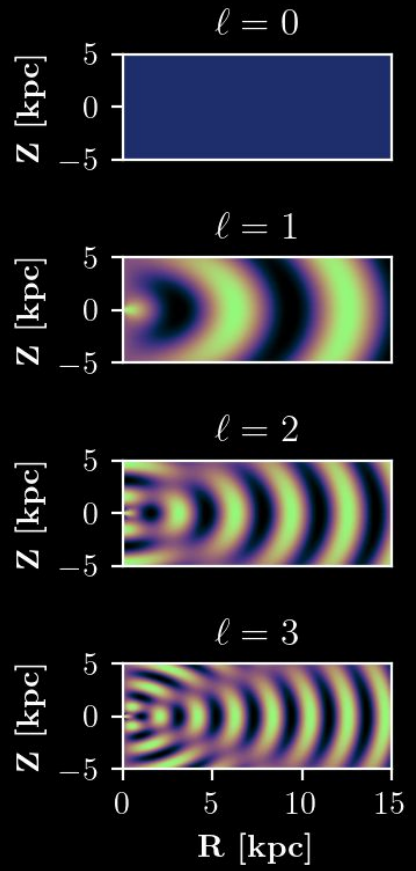
(Gaia mock for a MW-analog in FIRE-2 simulation, made by Prof. Robyn Sanderson)

Supplementary slides

(Gaia mock for a MW-analog in FIRE-2 simulation, made by Prof. Robyn Sanderson)

Potential/density as a basis function expansion!

$$\Delta\Phi = 4\pi G\rho$$ *Poisson's eq.*



We can do the azimuthal harmonic expansion For stars and cold gas.

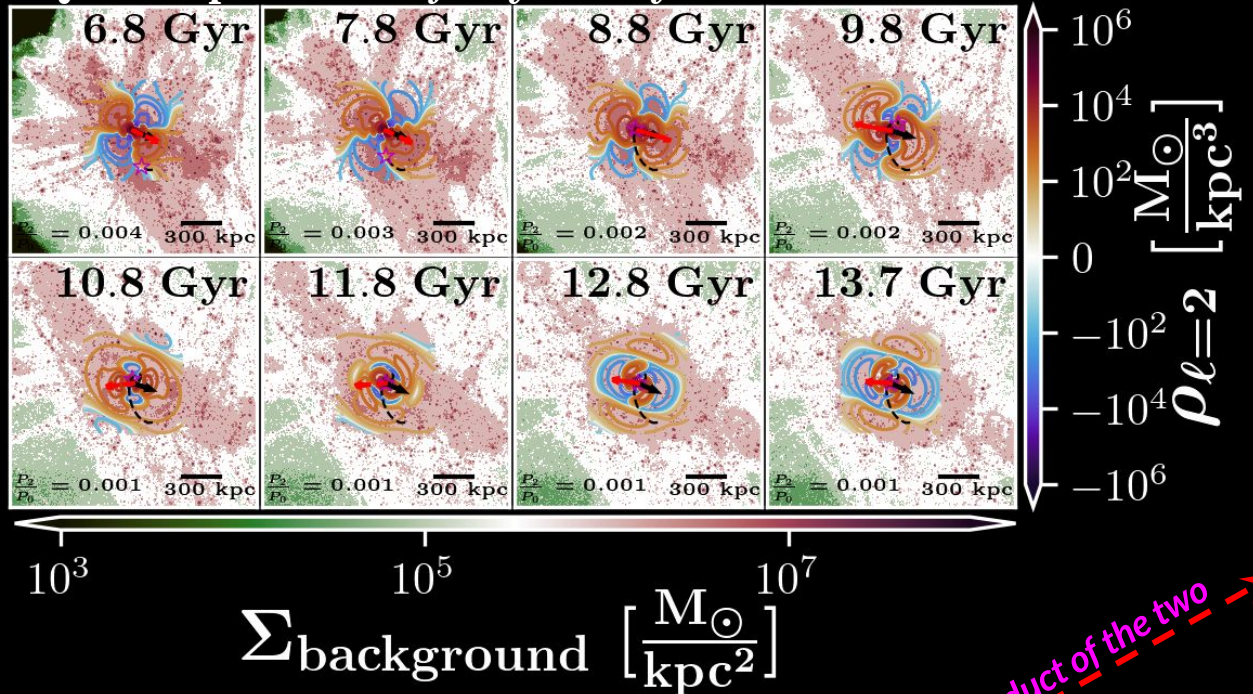
$$\Sigma_\ell \rho_\ell(R, Z) \exp(i\ell\phi)$$

(Let's ignore today!)

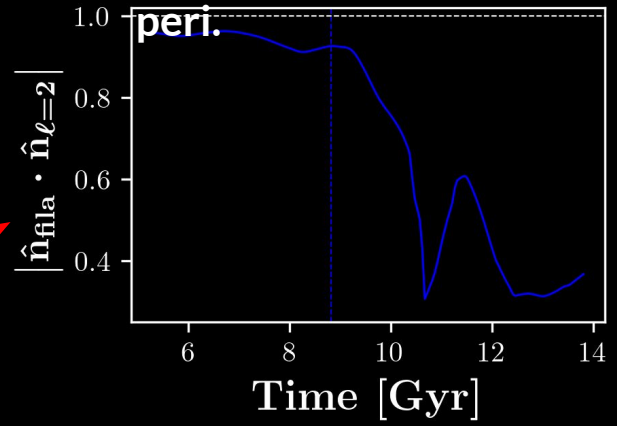
Novel techniques

$\ell = 2$ is set by major filaments (in all sims).

Quadrupole is majorly set by the filaments.

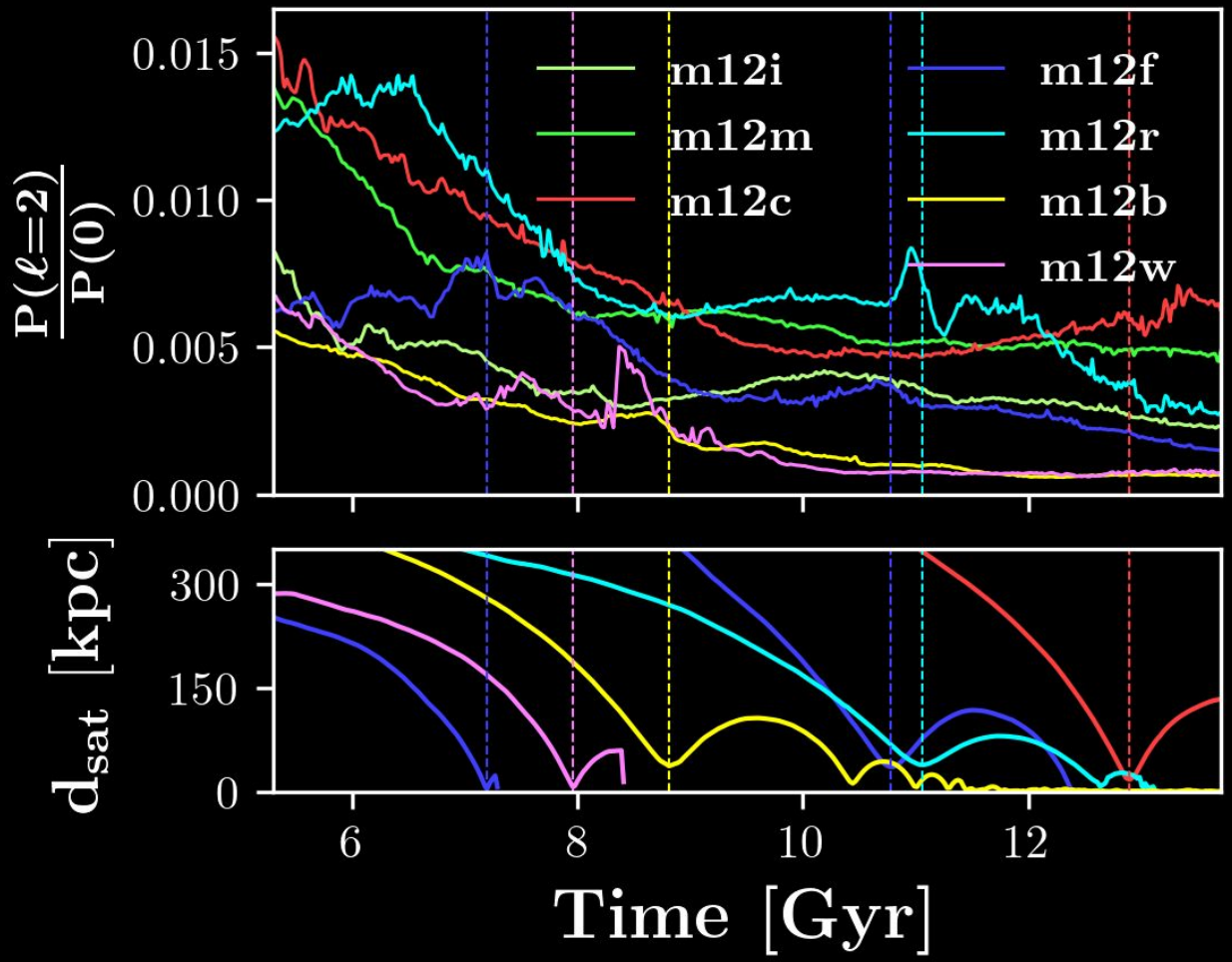


Dot product of the two



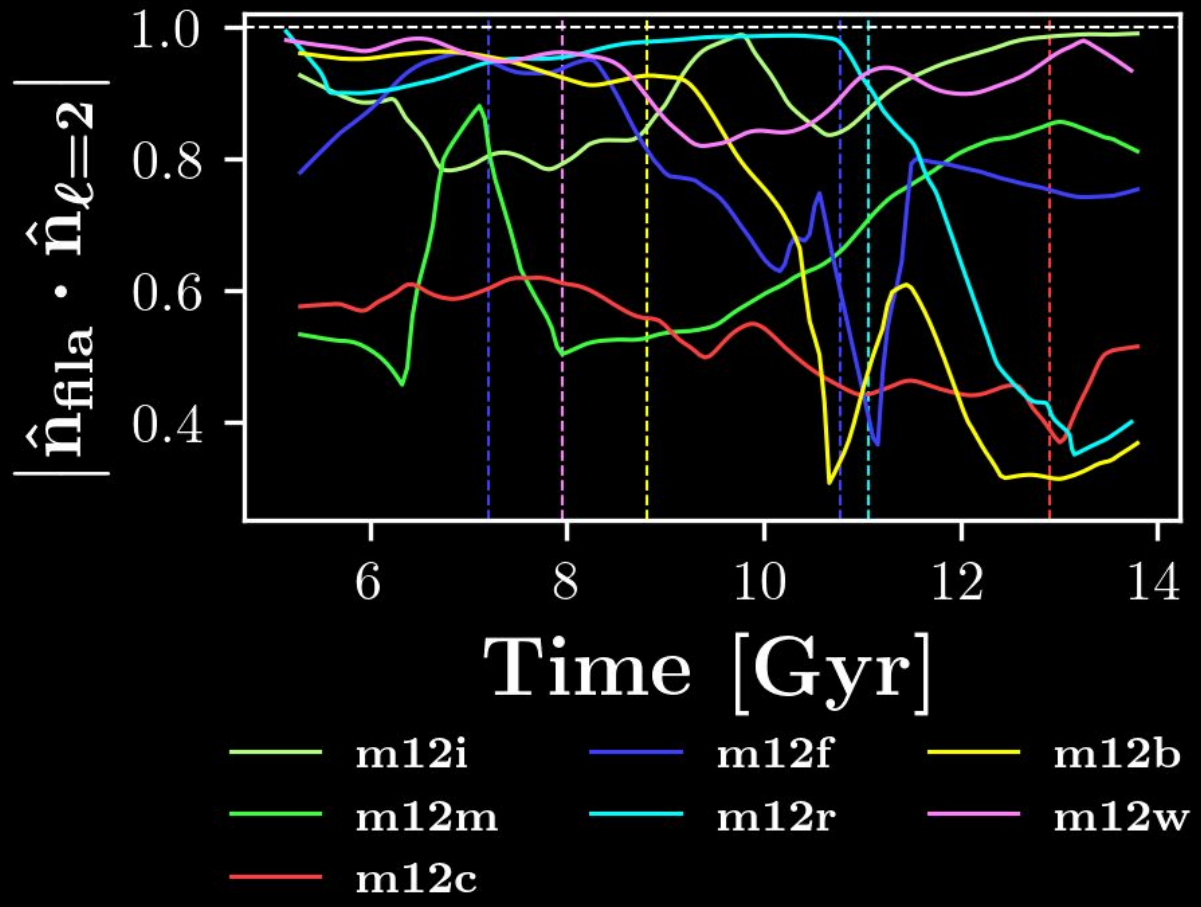
Red arrow: Quadrupole orientation
Black arrow : major filament orientation

Arora+2025 (in prep)



The evolution of quadrupoles amplitude for FIRE-2 simulations.

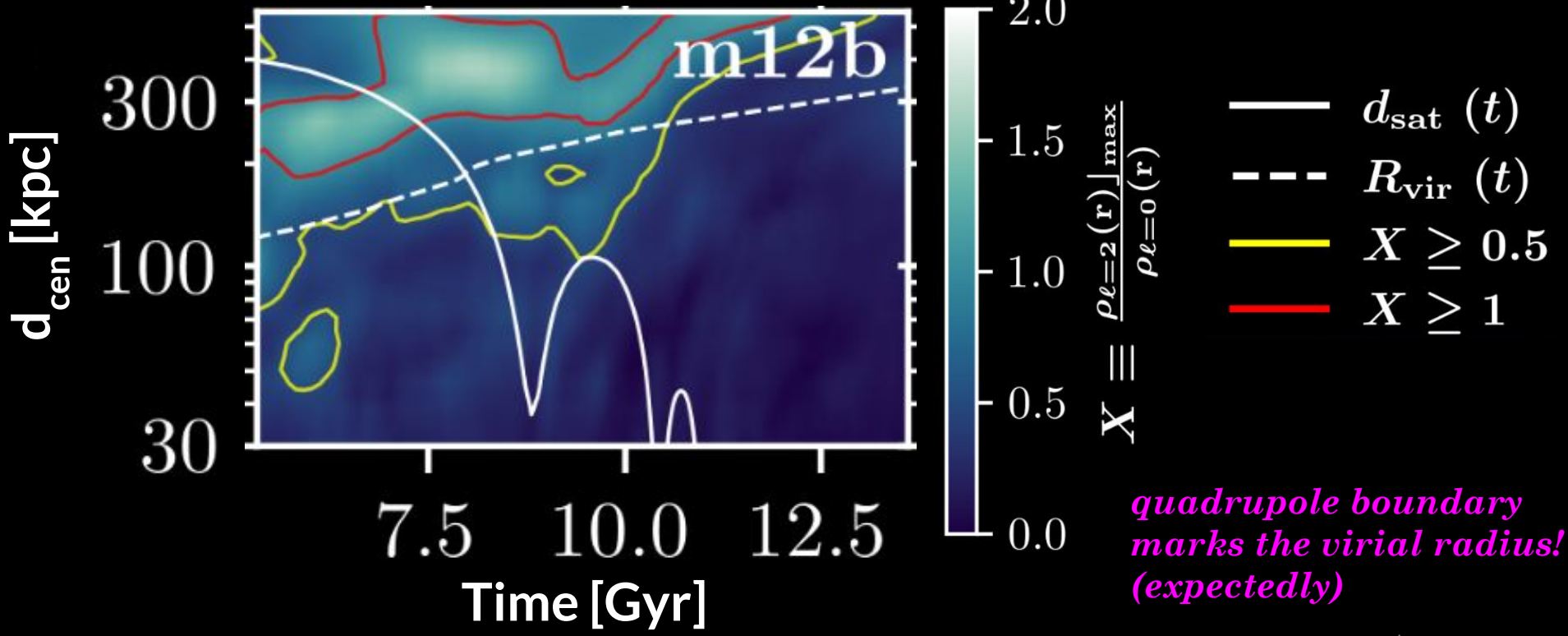
Arora+2025



The orientation of of quadrupoles in FIRE-2 simulations.

Arora+2025

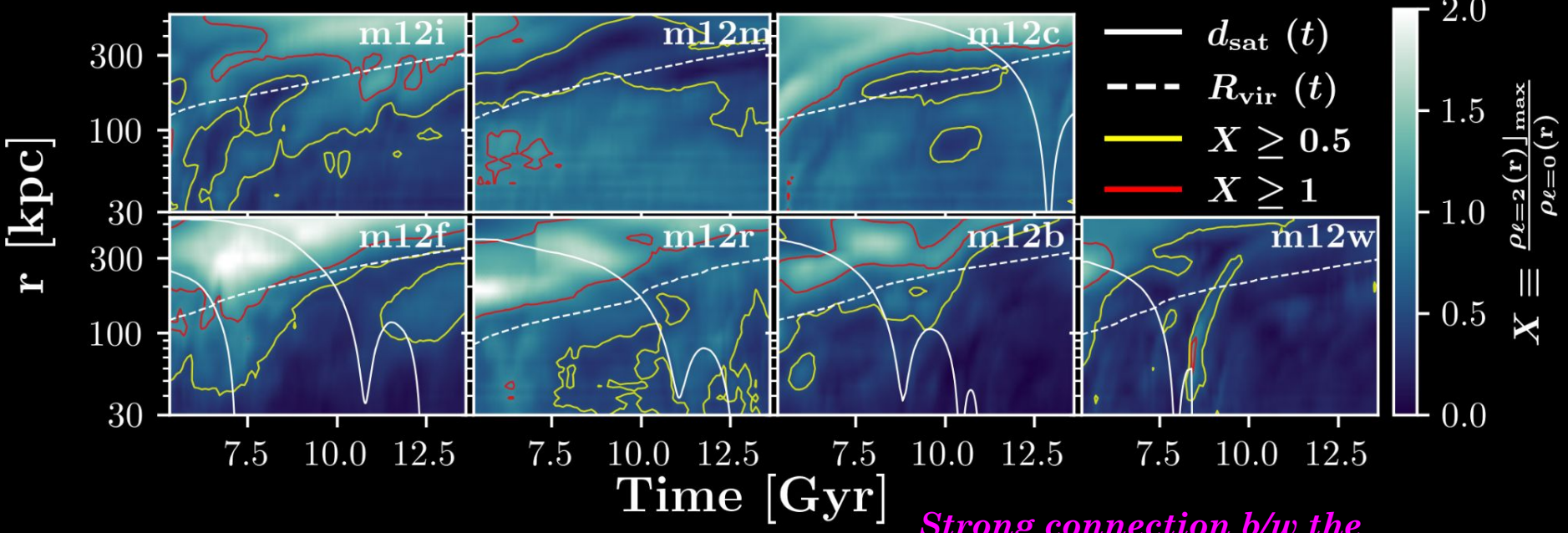
Filaments extend asymmetries up to 30 kpc in a halo.



quadrupole boundary marks the virial radius! (expectedly)

Arora+2025

Filaments extend asymmetry up to 30 kpc in a halo.

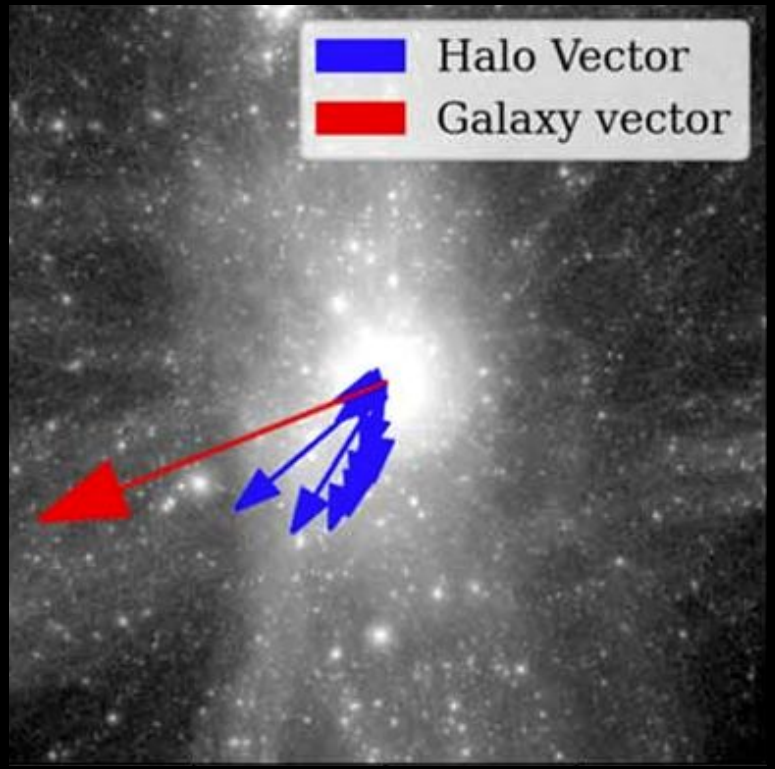


Strong connection b/w the quadrupole boundary and the virial radius!

Arora+2025

Tilted DM halos w.r.t to the galactic disk in FIRE.

m12i



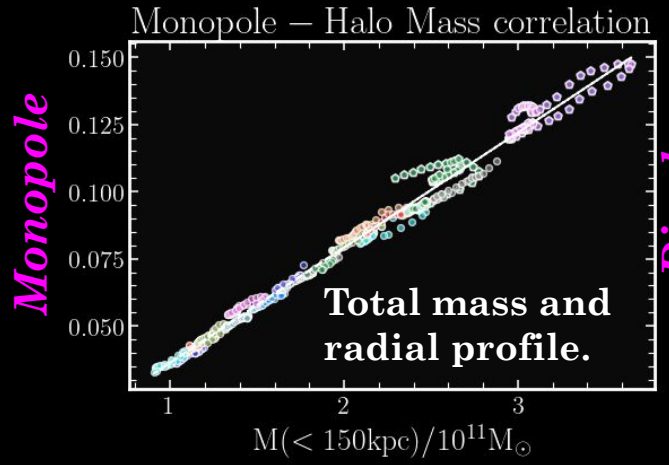
Baptista+2023

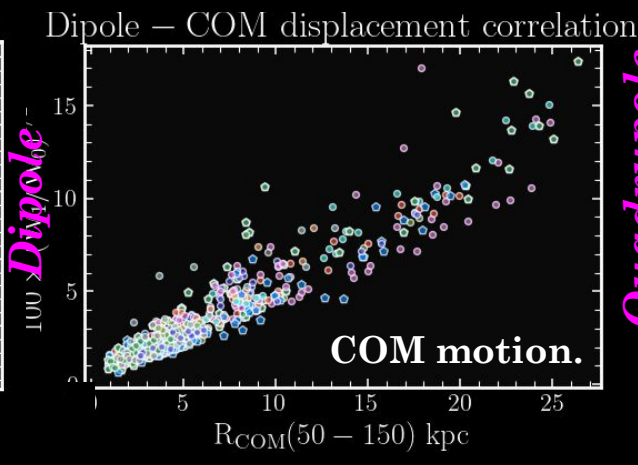
30^{0} misalignment b/w DM halo and the baryonic disk.

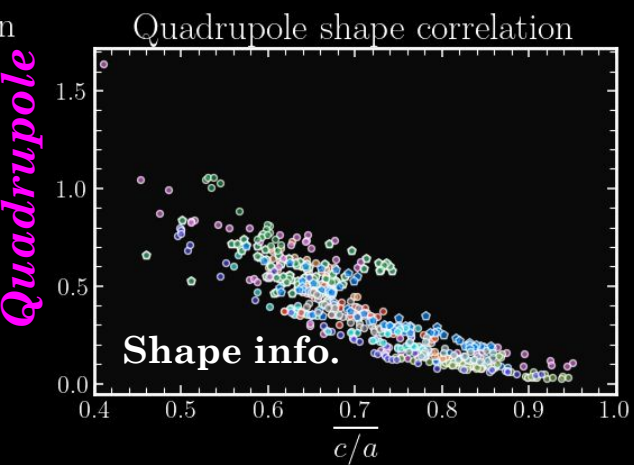
(Similar-ish tilt in all halos.)

Most information is captured in low orders.

MW-est DMO (Buch+2024) **simulations.**

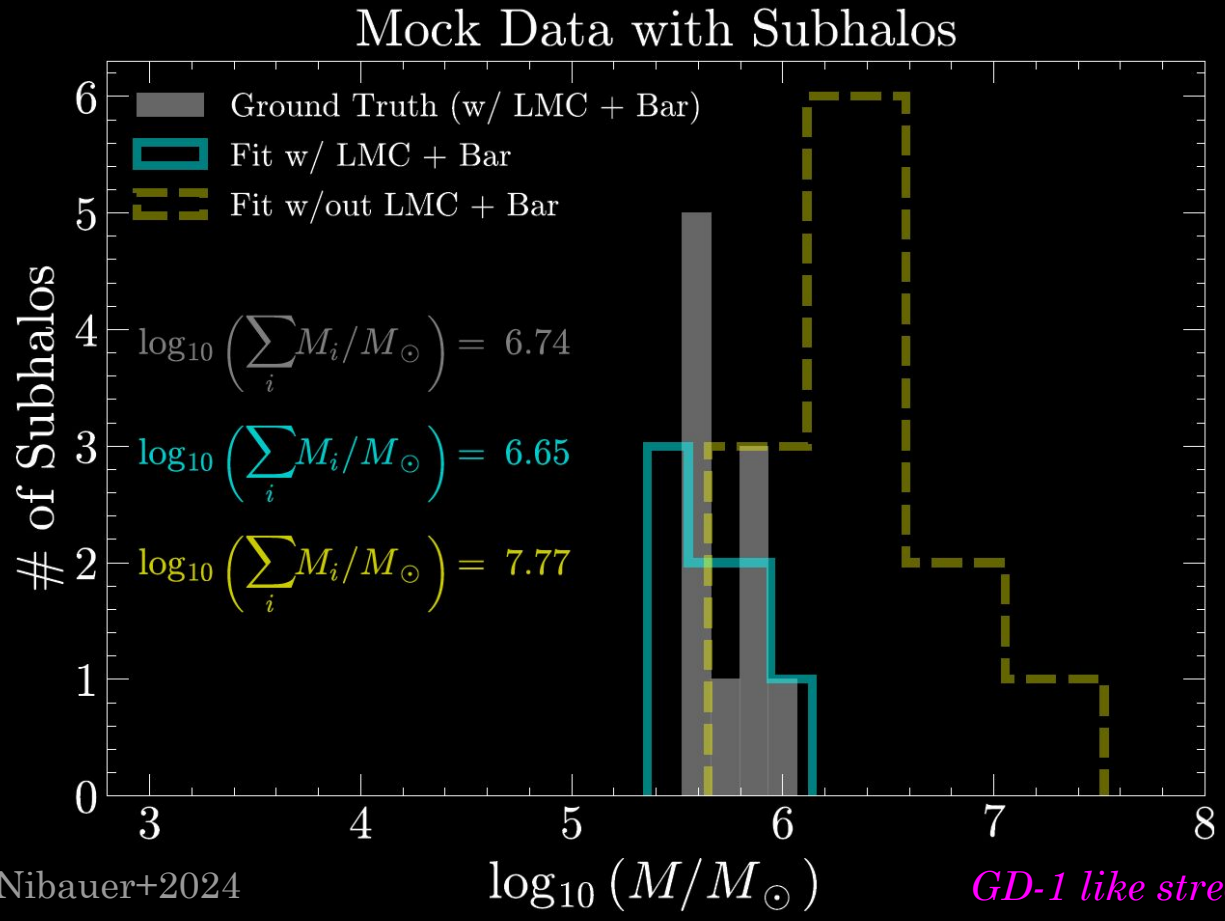






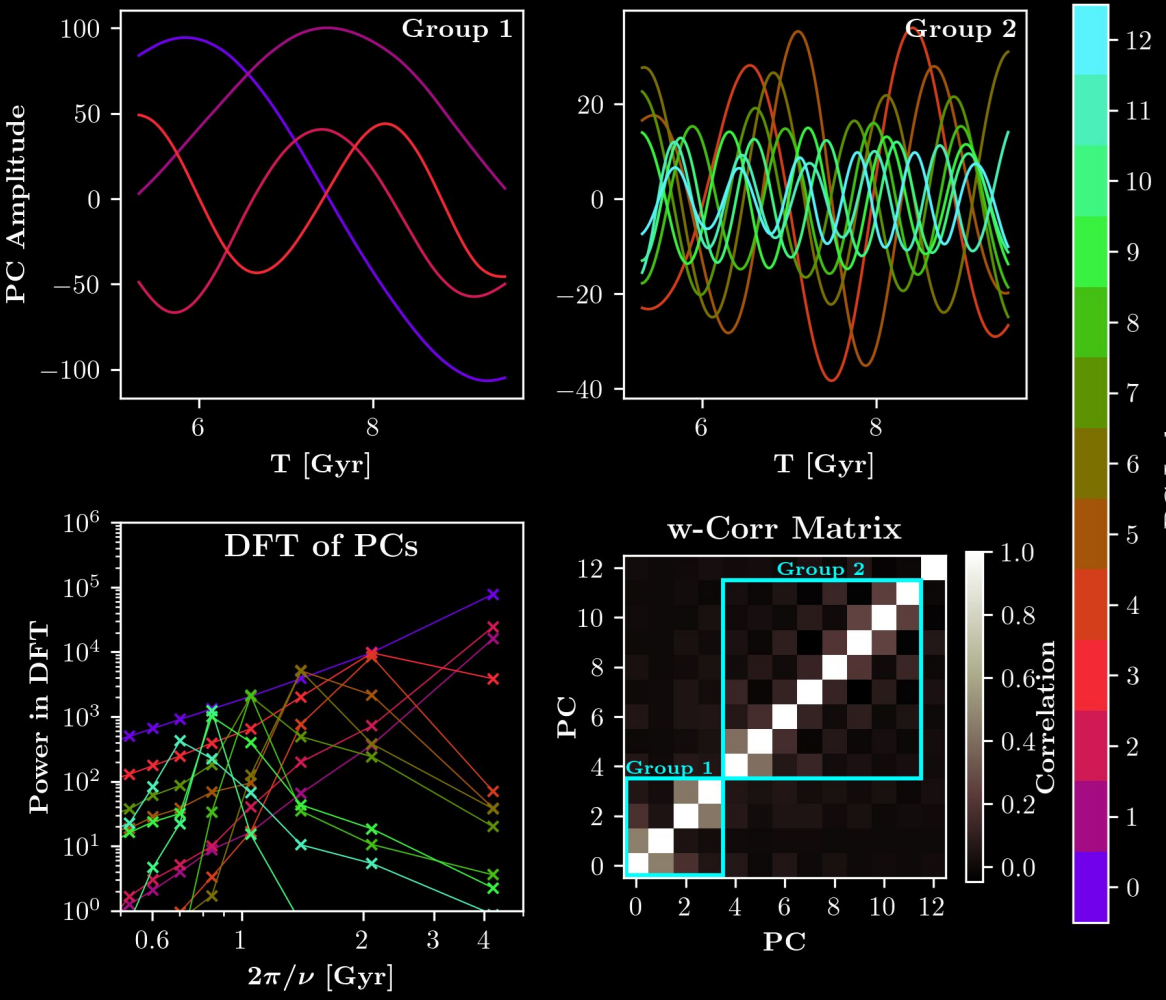
Darragh-Ford, Garavito, Arora+in prep.

Inferring Subhalo Mass fx with streams.

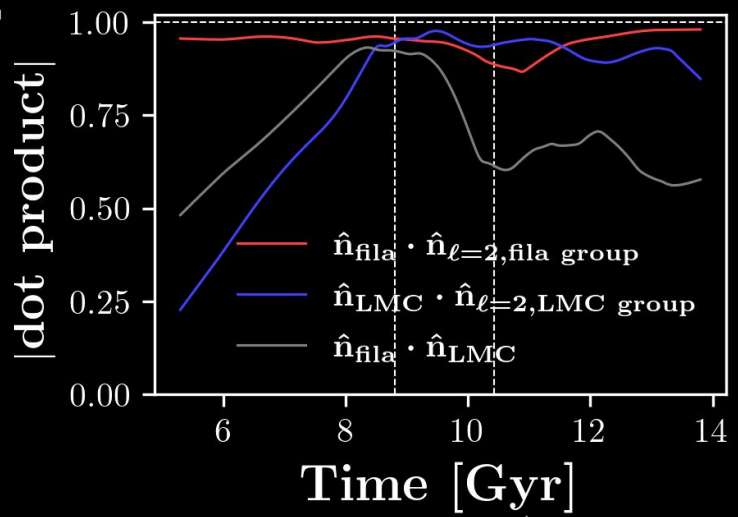


Nibauer+2024

GD-1 like stream in a rigid MW+LMC potential.



Grouping mSSA principal components.

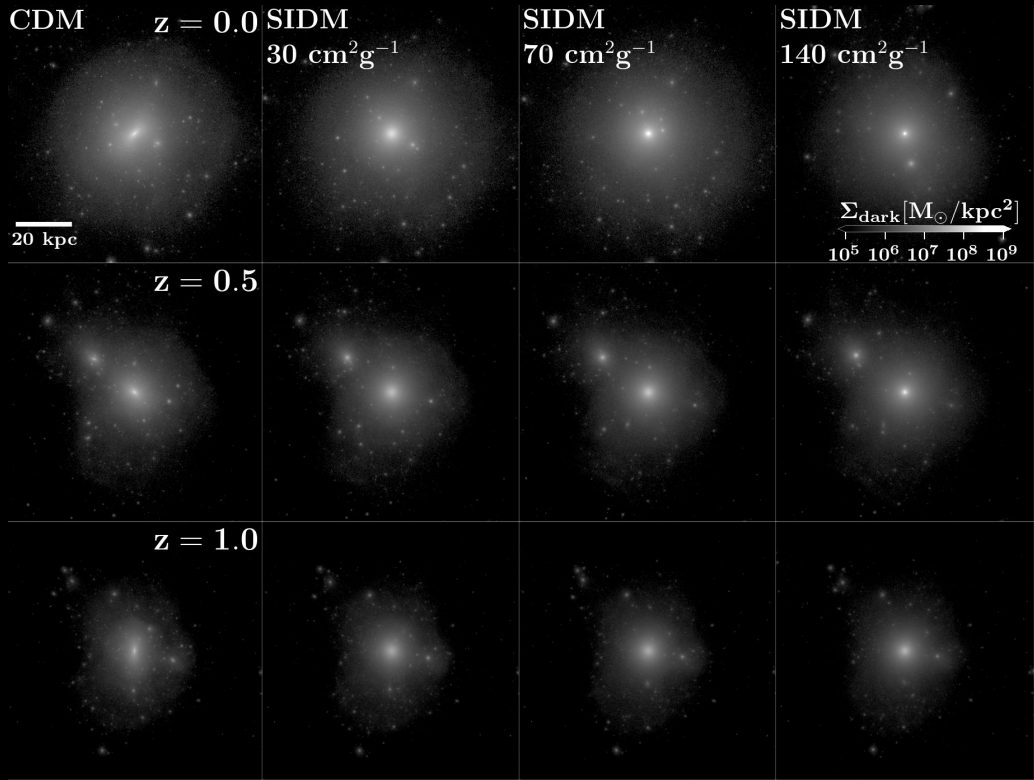


Arora+2025

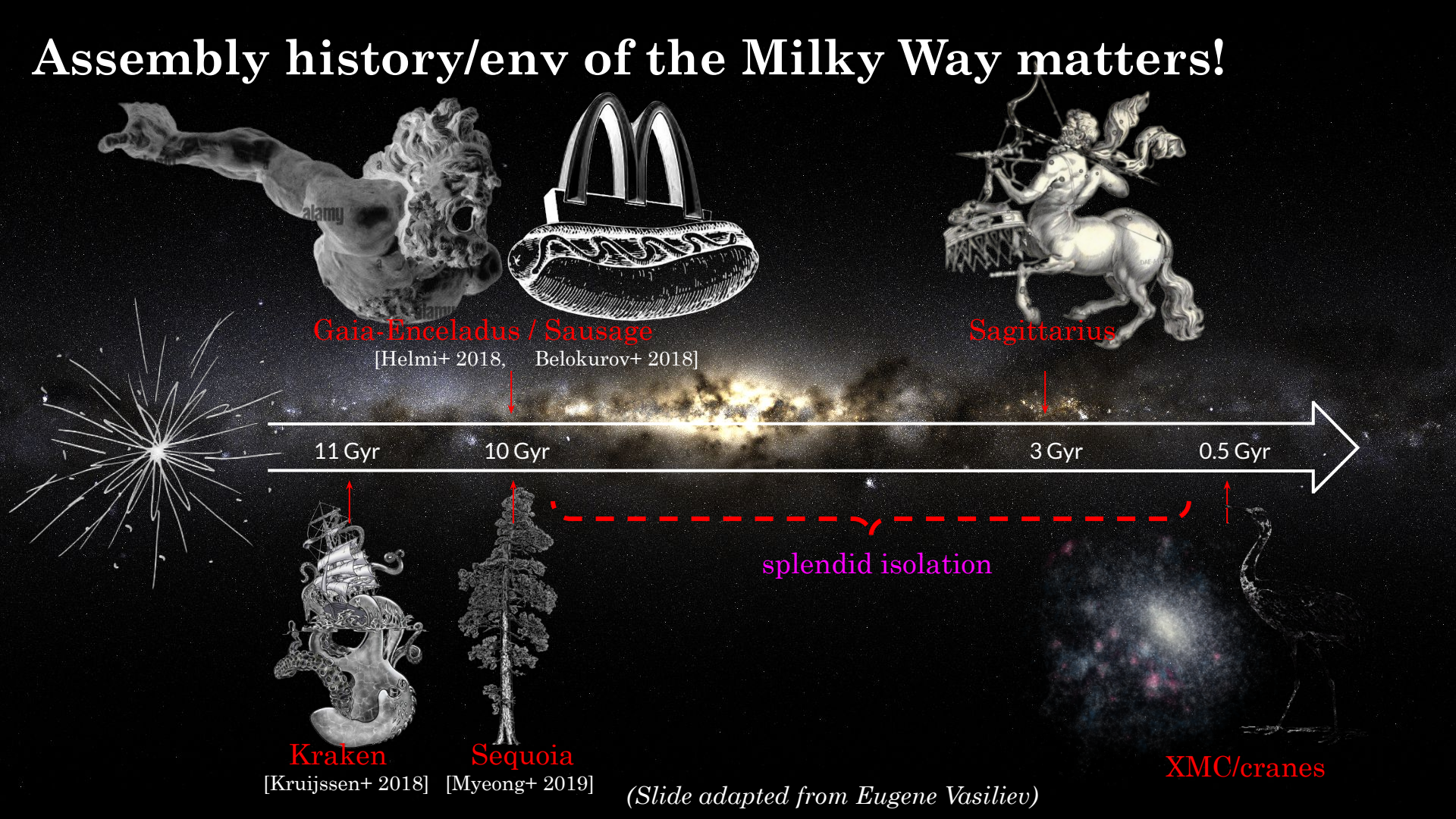
Simulating SIDM at intermediate mass scales.

First of it's kind MW–LMC with SIDM 1 cm^2 g^{-1}

SIDM dwarf galaxies $M_{\rm tot} \approx 10^{10} M_\odot$



Assembly history/env of the Milky Way matters!



(Slide adapted from Eugene Vasiliev)