

# La galaxia fuera de equilibrio y la naturaleza de la materia oscura



Nicolas Garavito-Camargo  
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Origenes  
02-23-2022

Gurtina Besla, Adrian Price-Whelan, Emily Cunningham, Ekta Patel, Chervin Laporte,  
Facundo Gomez, Kathryn V. Johnston, Martin Weinberg, Rohan Naidu, Charlie Conroy

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## Estructura de la Vía Láctea

Halo estelar externo

Halo estelar interno

Disco

Halo de  
materia  
oscura

## Estructura de la Vía Láctea

Halo estelar externo

Halo estelar interno

Disco

# Primeras evidencias de la presencia de la materia oscura en el cúmulo de Virgo



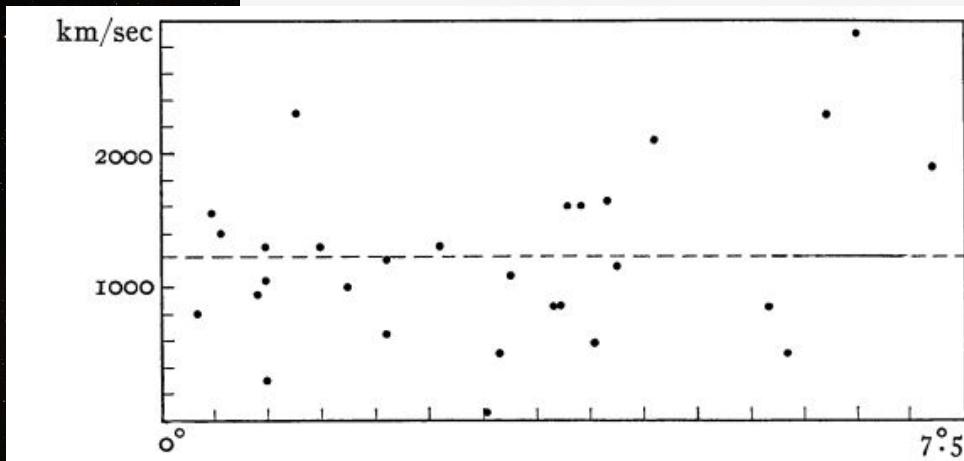
Smith, Sinclair 1936

© Colombari/Paglioli

# Primeras evidencias de la presencia de la materia oscura en el cúmulo de Virgo



Smith, Sinclair 1936

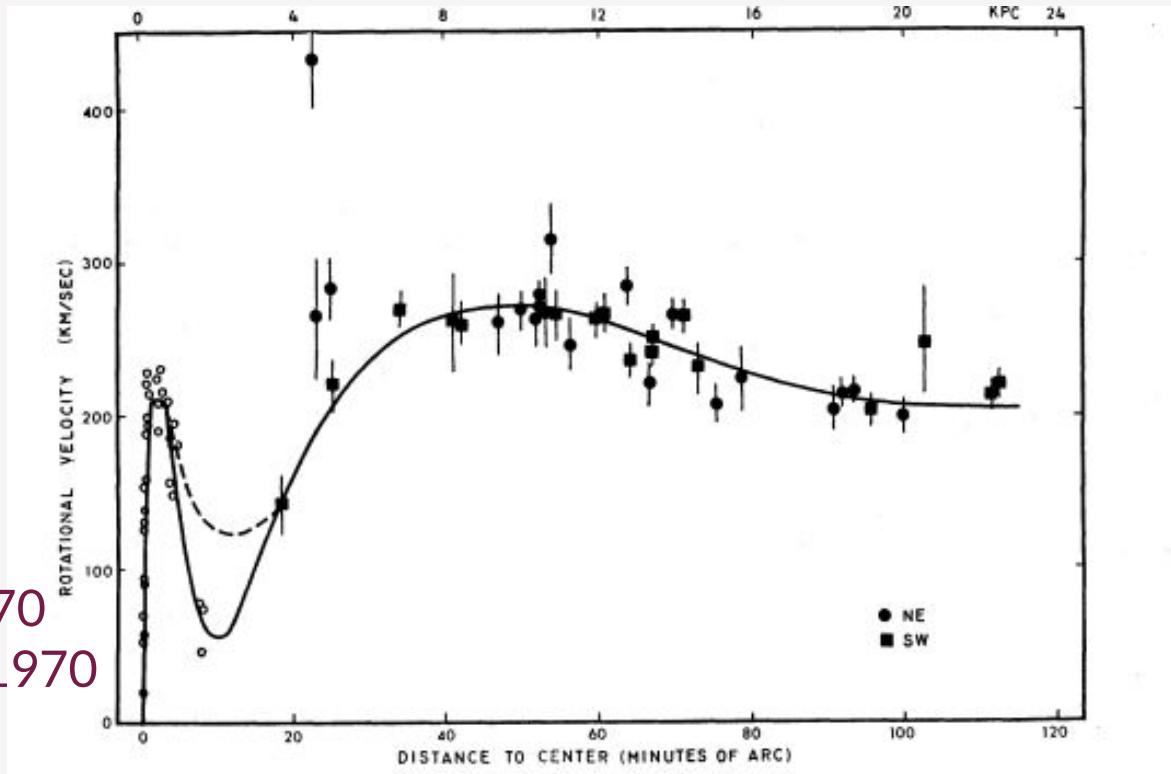


1000x más masa que la observada en estrellas.

Resultados similares fueron encontrados el cúmulo de Coma por F. Zwicky en 1933



Las curvas de rotación de las galaxias también sugieren una masa total 20x a la masa observada



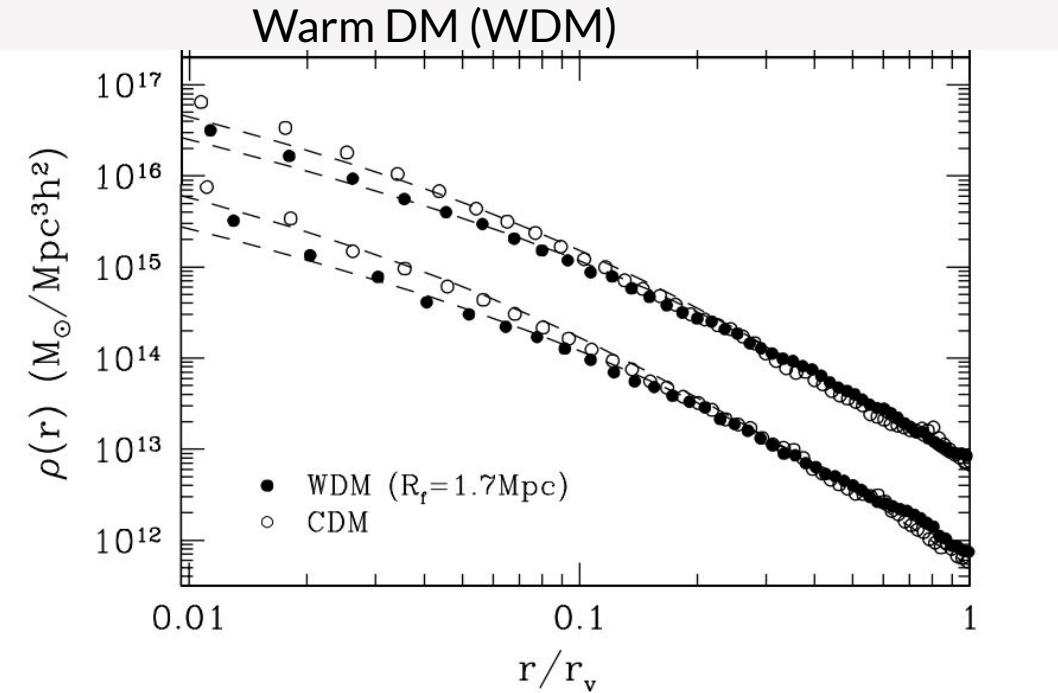
Rubin & Ford 1970  
Tambien Freeman 1970

Articulo recomendado: Bertone & Hooper 2016

Credit: B. Diemer

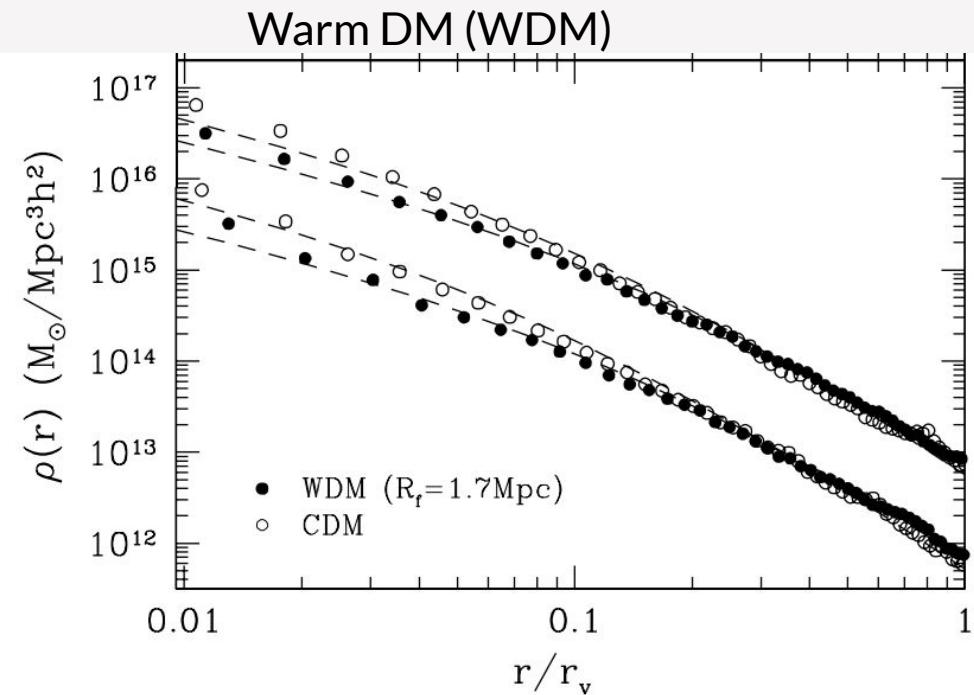
$t = 0.1 \text{ Gyr}$

# Las estructuras de los halos (forma y cinematica) varían en diferentes modelos de materia oscura

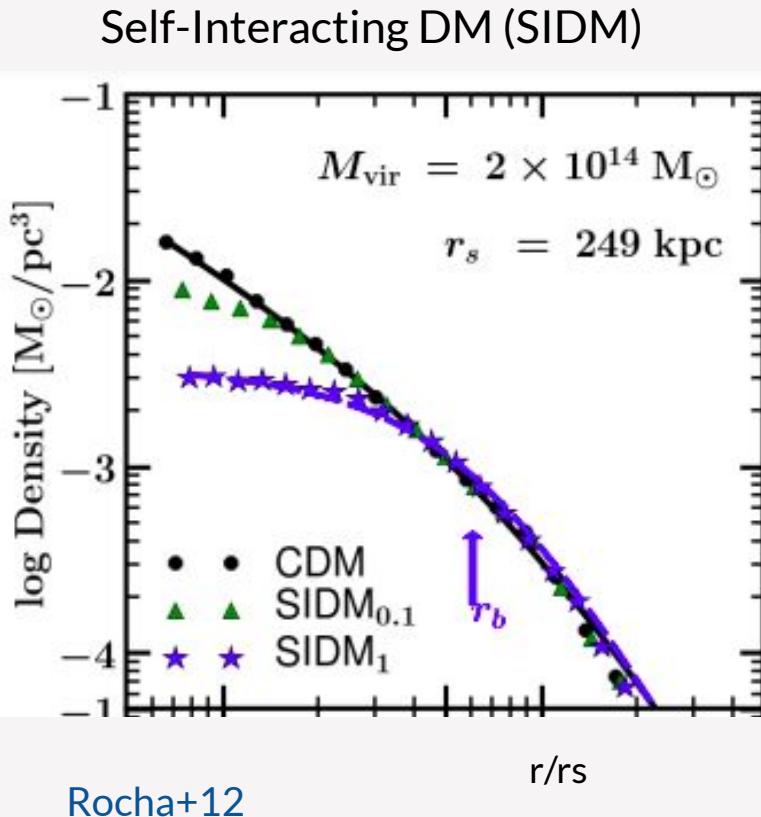


Avila-Reese+01

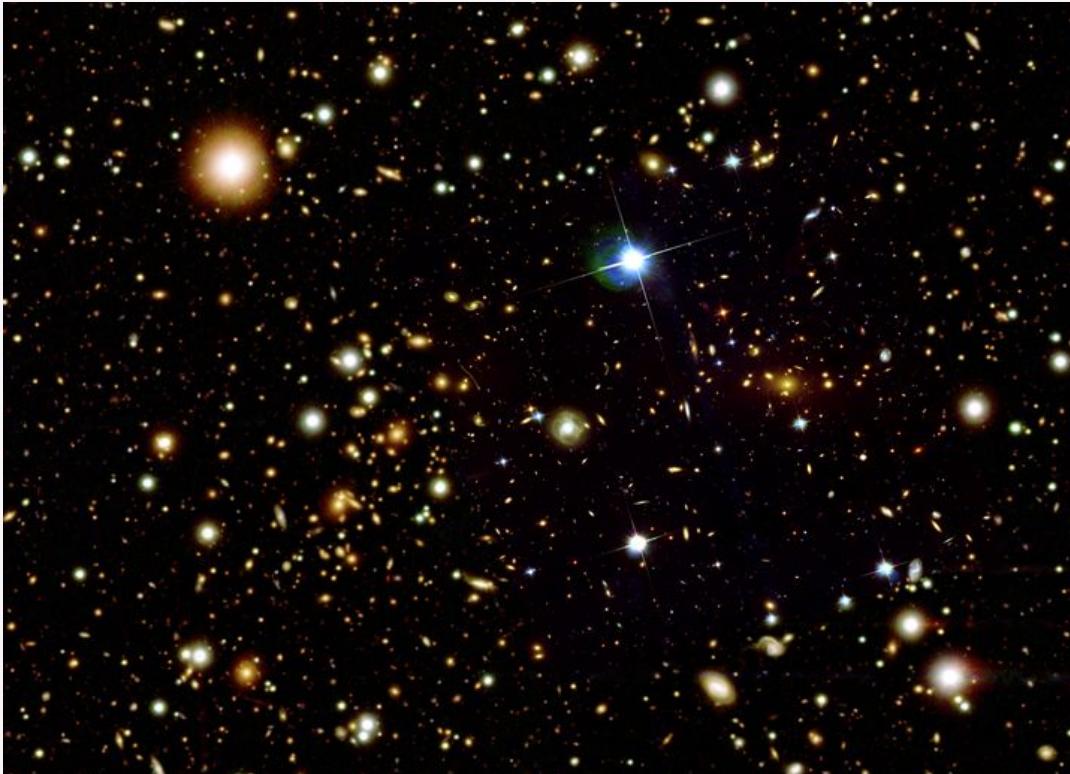
# Las estructuras de los halos (forma y cinematica) varían en diferentes modelos de materia oscura



Avila-Reese+01



# Sistemas fuera del equilibrio nos enseñan más sobre la naturaleza de la materia oscura



Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

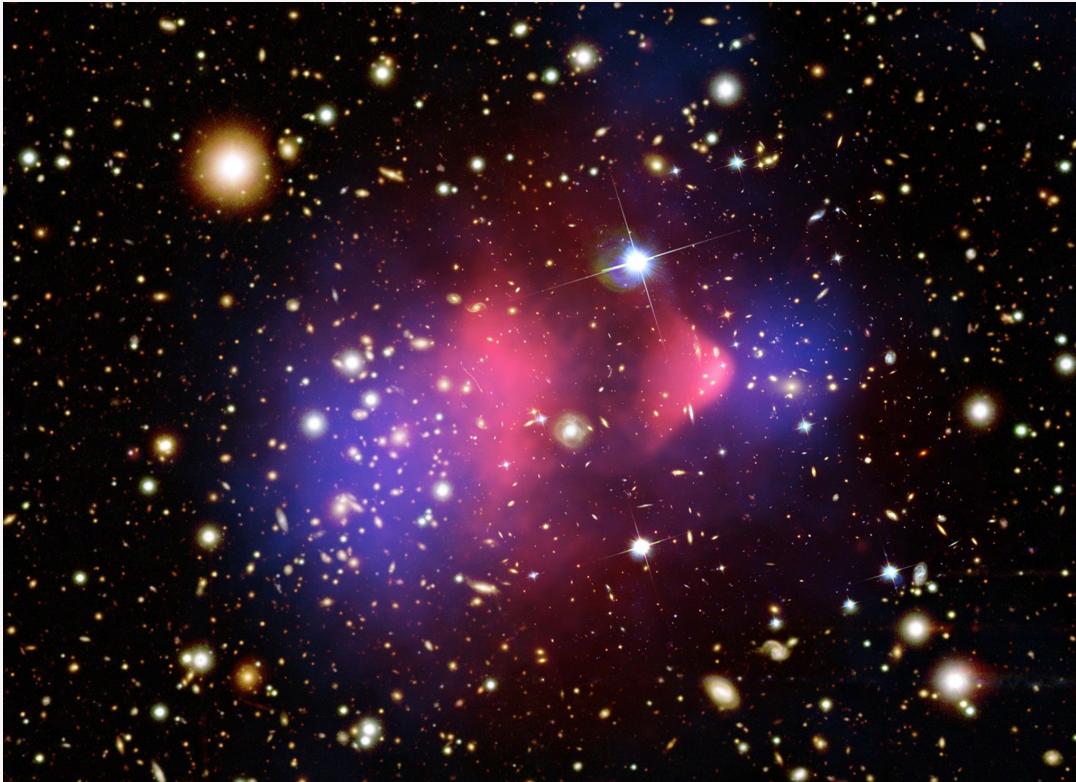
# Sistemas fuera del equilibrio nos enseñan más sobre la naturaleza de la materia oscura



Lensing Maps  
of the DM  
distribution

Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

# Sistemas fuera del equilibrio nos enseñan más sobre la naturaleza de la materia oscura



Lensing Maps  
of the DM  
distribution  
+  
Gas (x-ray)

Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.



NGC 474

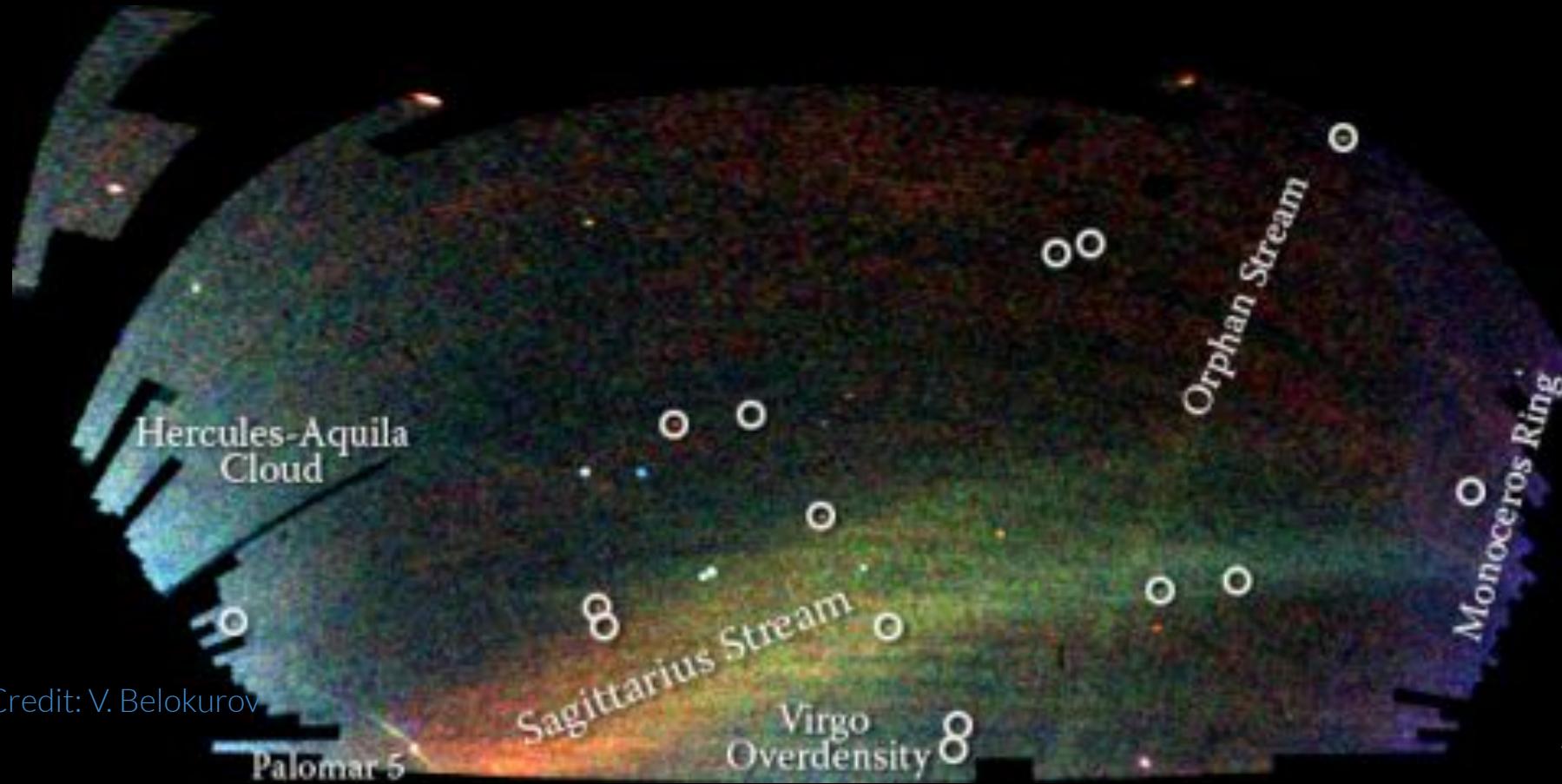


NGC 474

Los halos estelares son trazadores del potencial del halo de materia oscura en el cual orbitan

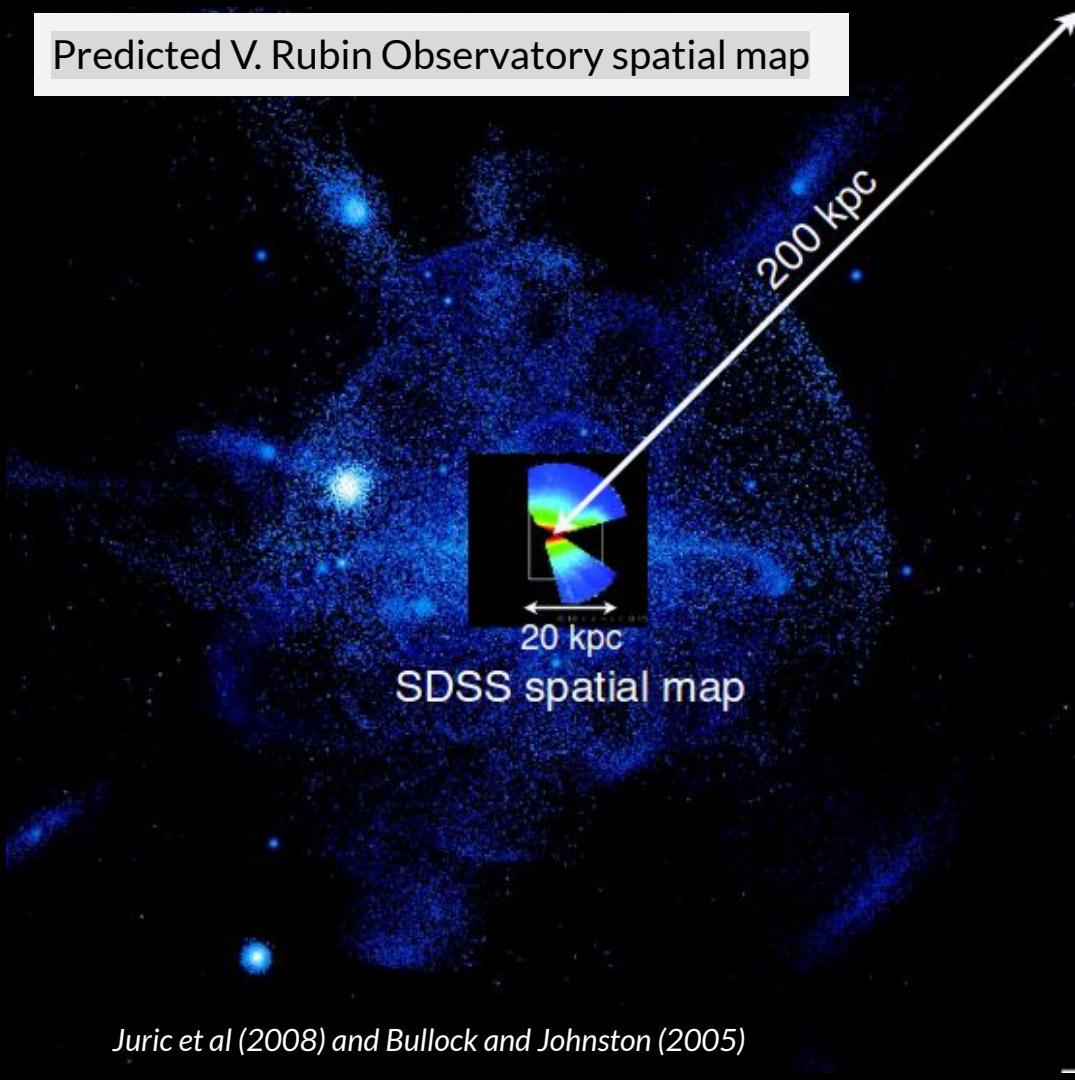
Estructura del halo, forma, y masa.

# Field of streams in the northern hemisphere SDSS



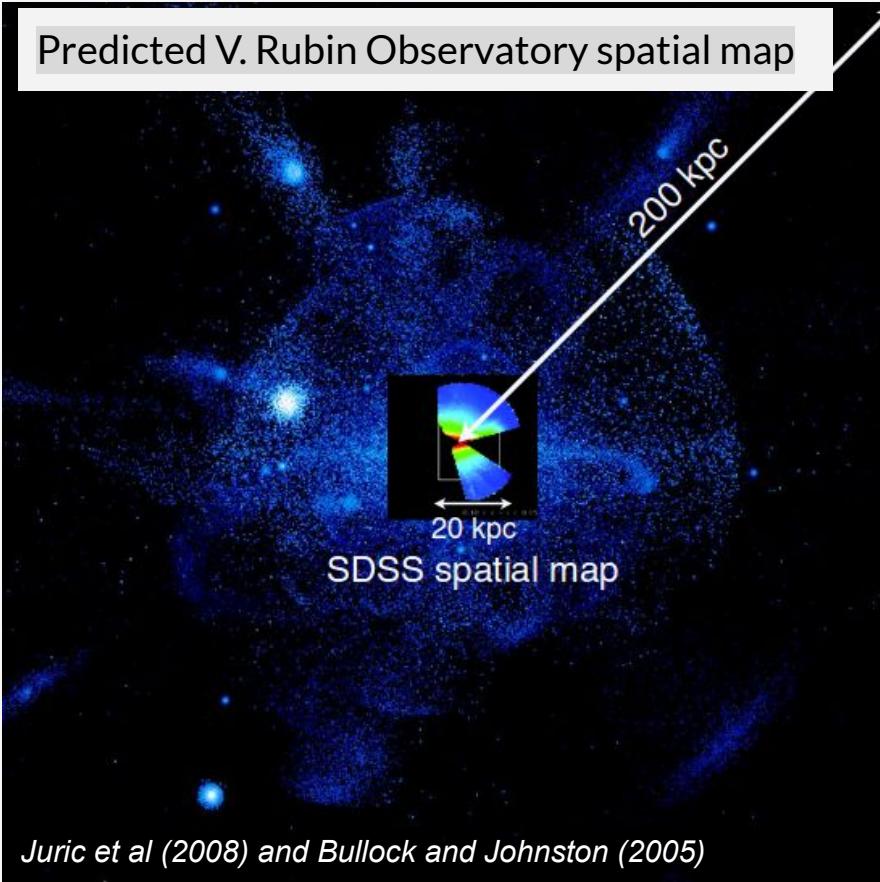
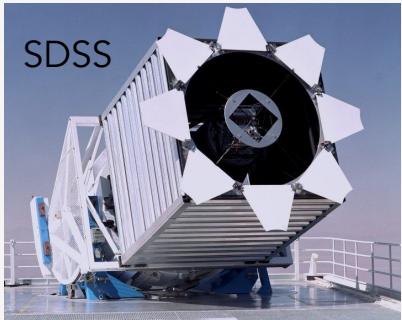
Credit: V. Belokurov

## Predicted V. Rubin Observatory spatial map



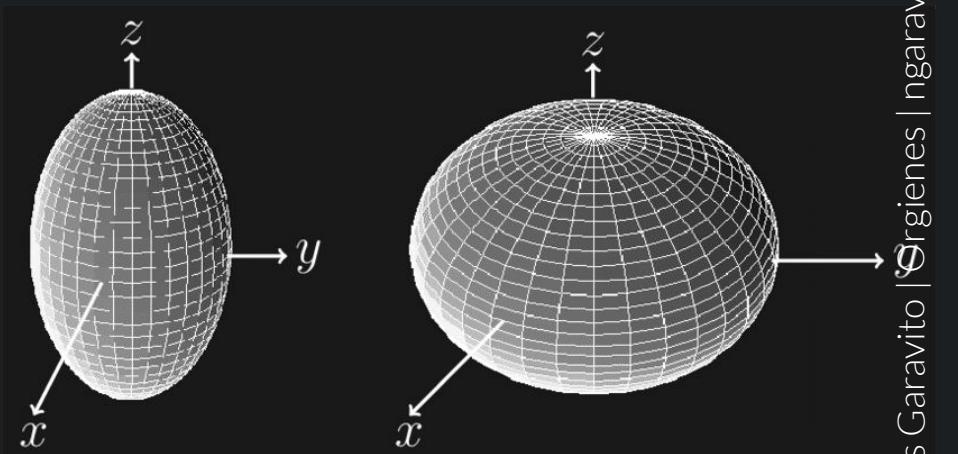
Juric et al (2008) and Bullock and Johnston (2005)

# Programas observaciones actuales y futuros están relevando una visión multidimensional de la Vía Láctea (VL): Fotometría, espectroscopía, mp

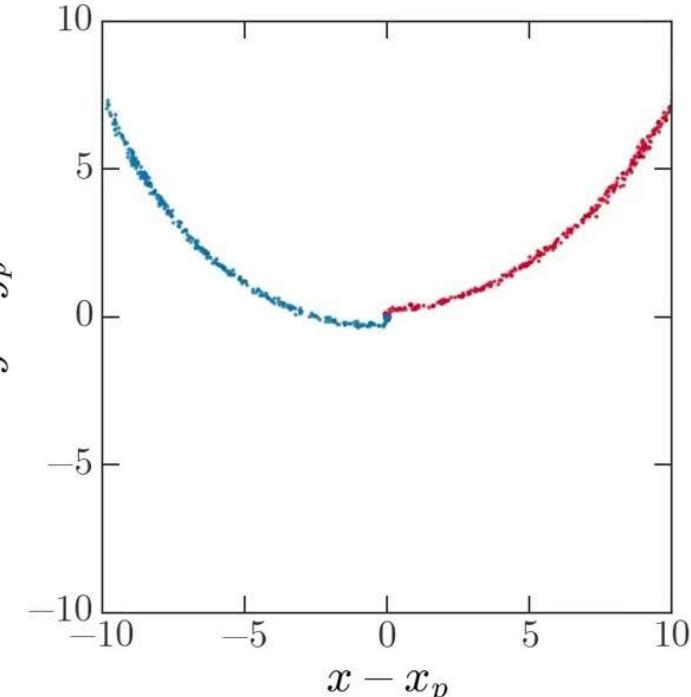
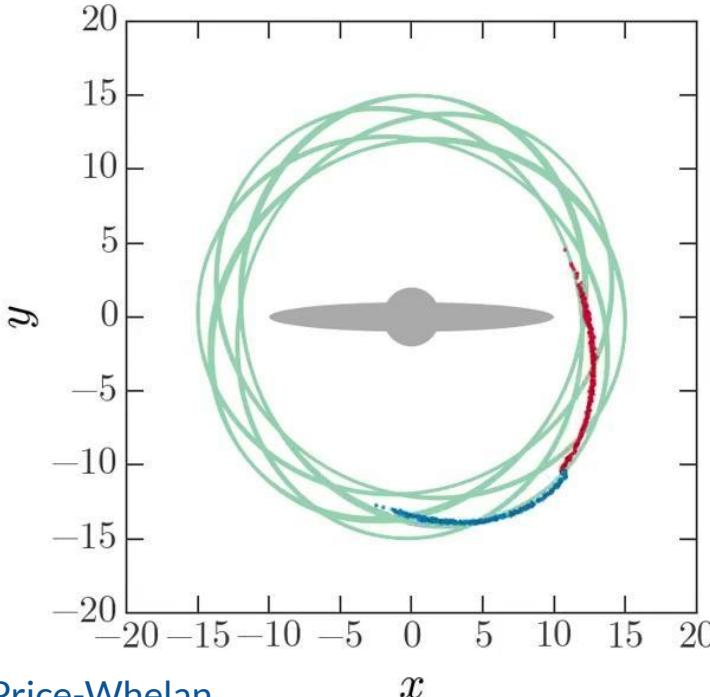


# Potential recovering from streams modelling

- Shape of the halo:
  - Oblate, prolate, triaxial
  - Direction of principal axis
- Density profile of the halo:
  - NFW, concentration, extent



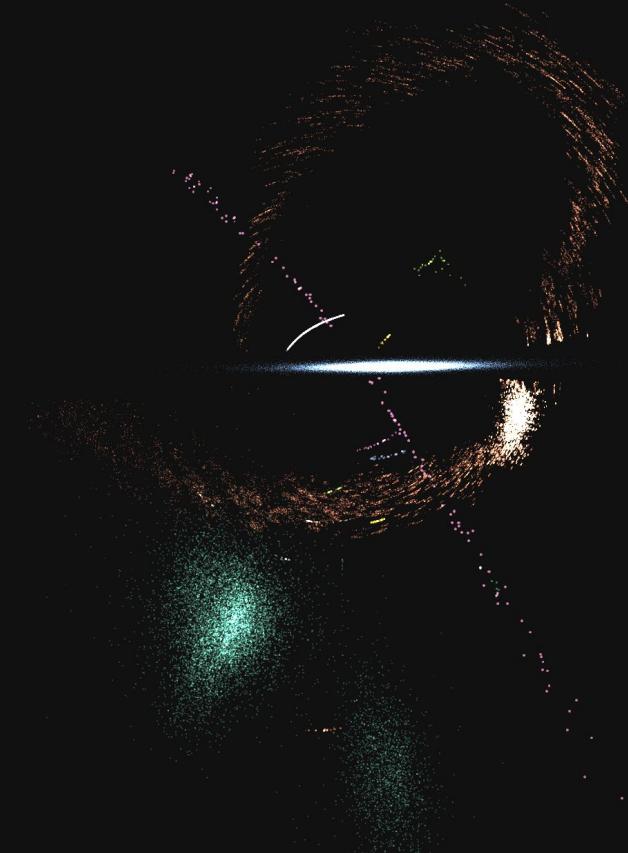
# Midiendo el potencial del halo de materia oscura usando “stellar streams” (e.g.; Bonaca+14, Pearson+15, Bovy+16)



Credit: Adrian Price-Whelan

El potencial gravitacional se puede recuperar a lo largo del halo usando “streams” a diferentes distancias

≈60 streams in the MW

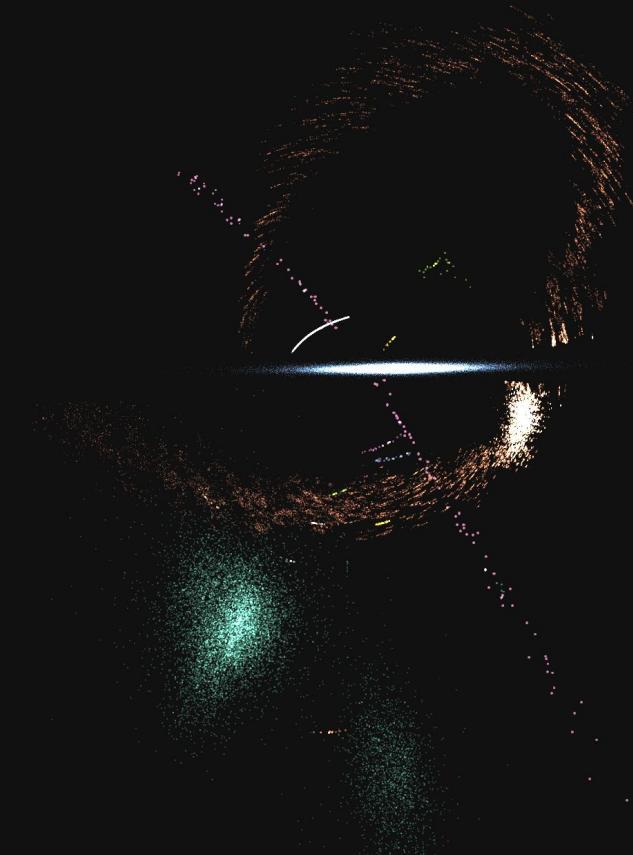


Credit: Adrian Price-Whelan

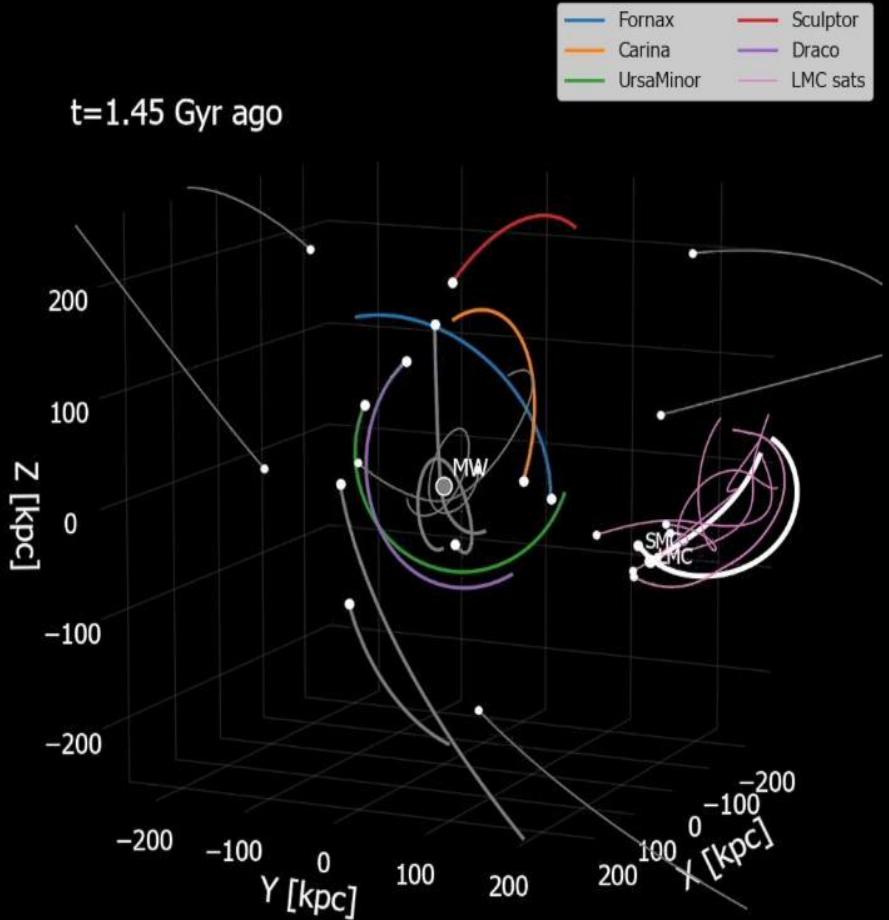
Cual es la forma del halo de la  
Vía Láctea?  
alargada/achatada/triaxial?  
*Prolate/oblate/triaxial?*

- Stream morphology:  
Achatada  
(Ibata et al. 2001;  
Johnston, Law & Majewski 2005)
- Stream L.O.S velocities:  
Alargada  
(Helmi 2004)
- Law & Majewski (2010)  
Triaxial!

≈60 streams in the MW



Credit: Adrian Price-whelan





© Ryan Trainor

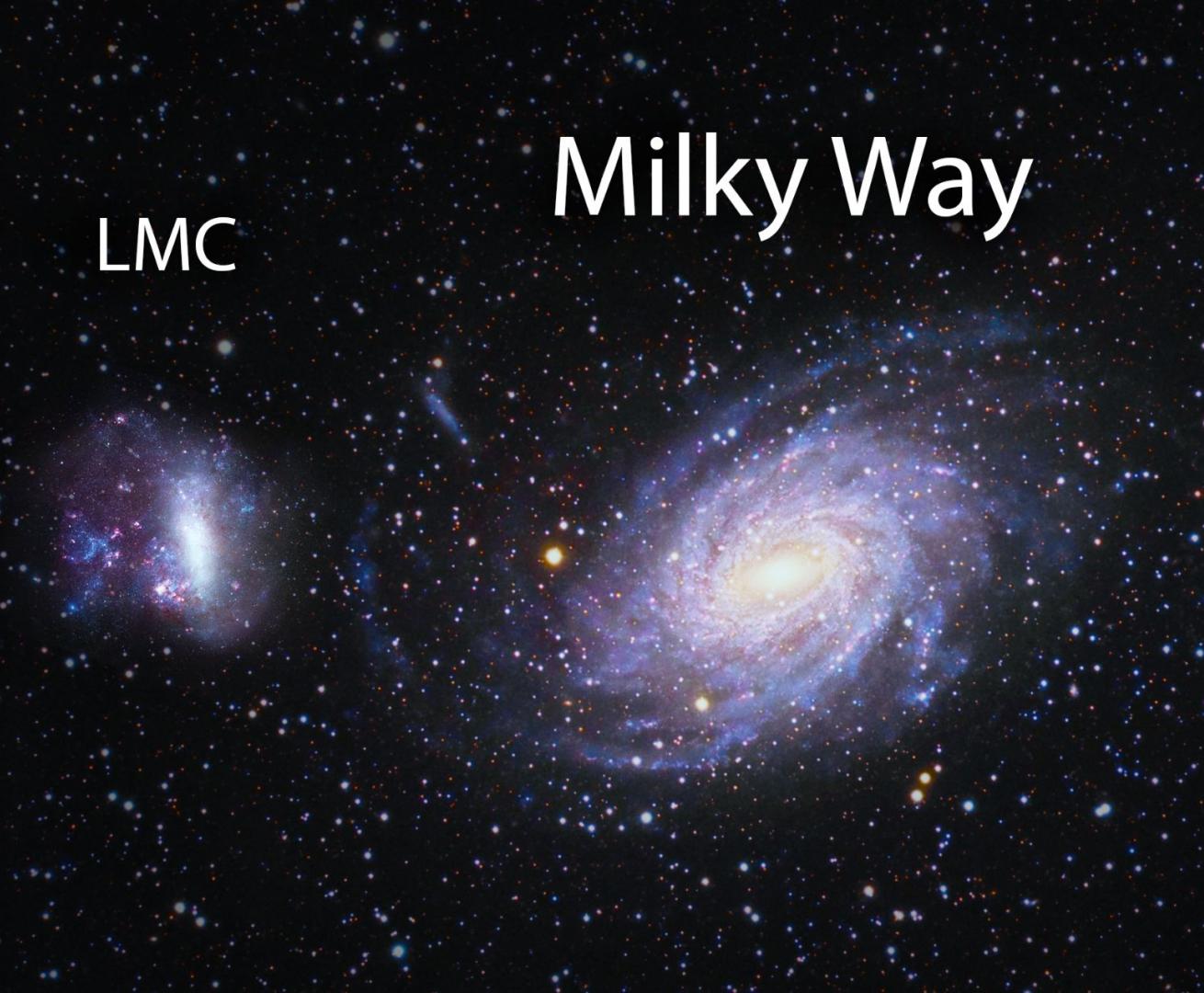
Nicolás Garavito | Orgienes | [ngaravito@flatironinstitute.org](mailto:ngaravito@flatironinstitute.org)



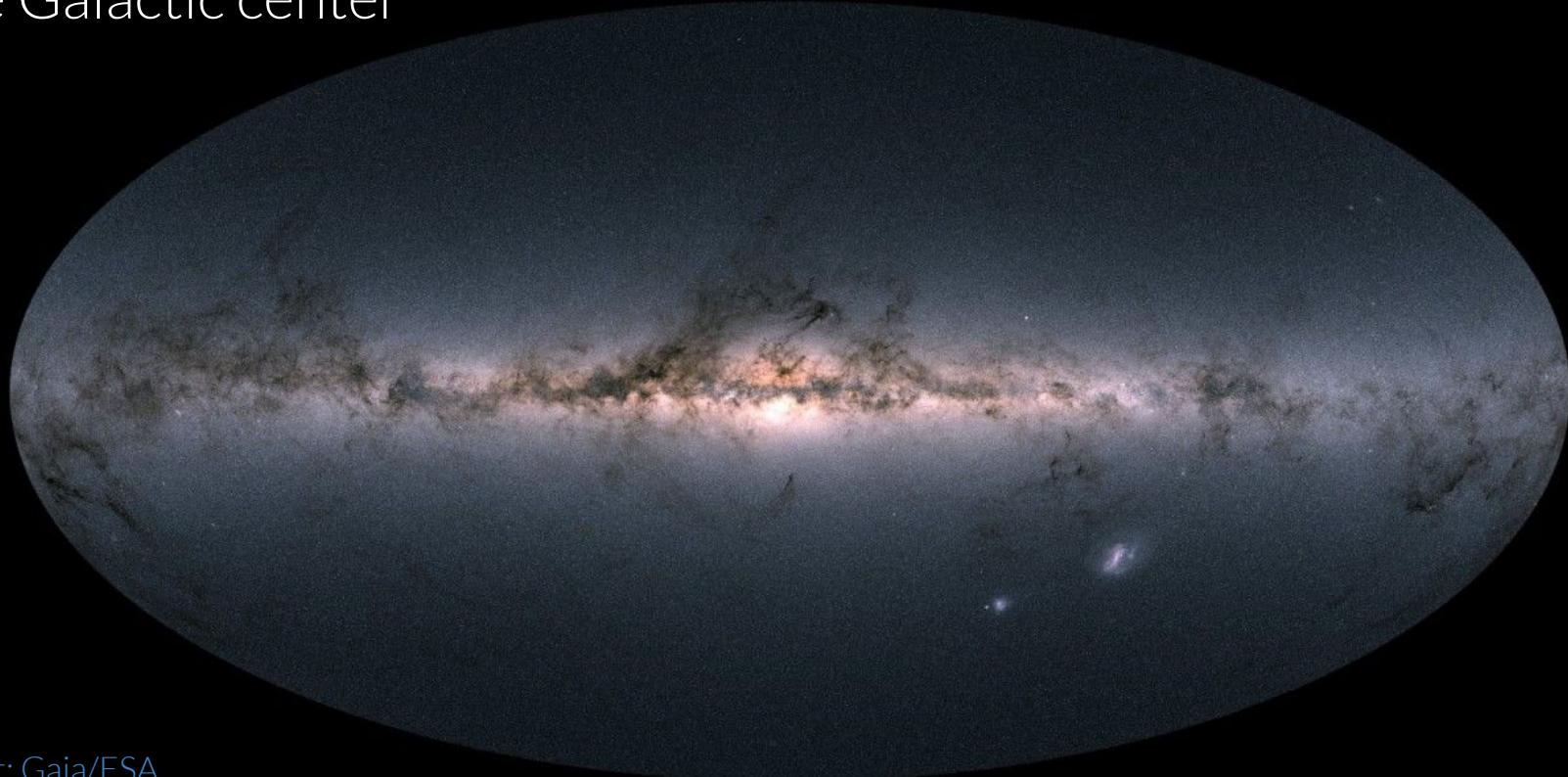
Small Magellanic  
Cloud

Moon

Large Magellanic  
Cloud



LMC is 10%-20% the total mass of the MW and it is at 50 kpc from the Galactic center

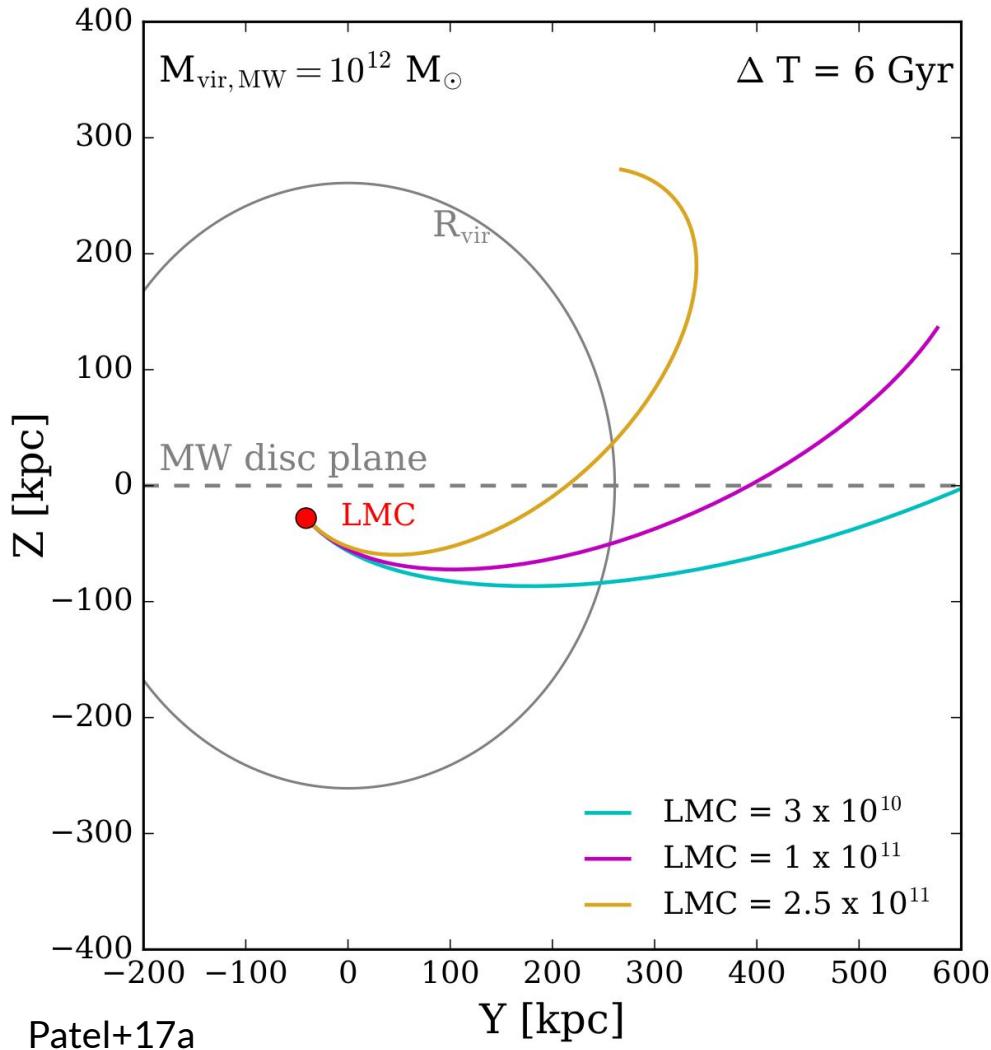


credit: Gaia/ESA

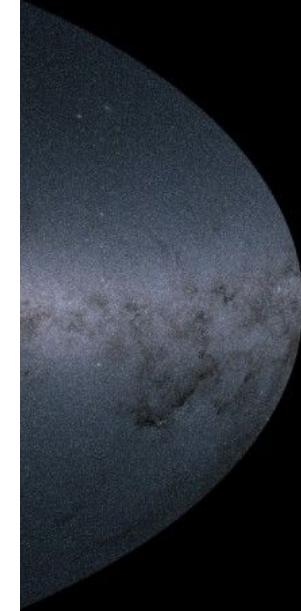
LMC is 10%-20%  
the Galactic center



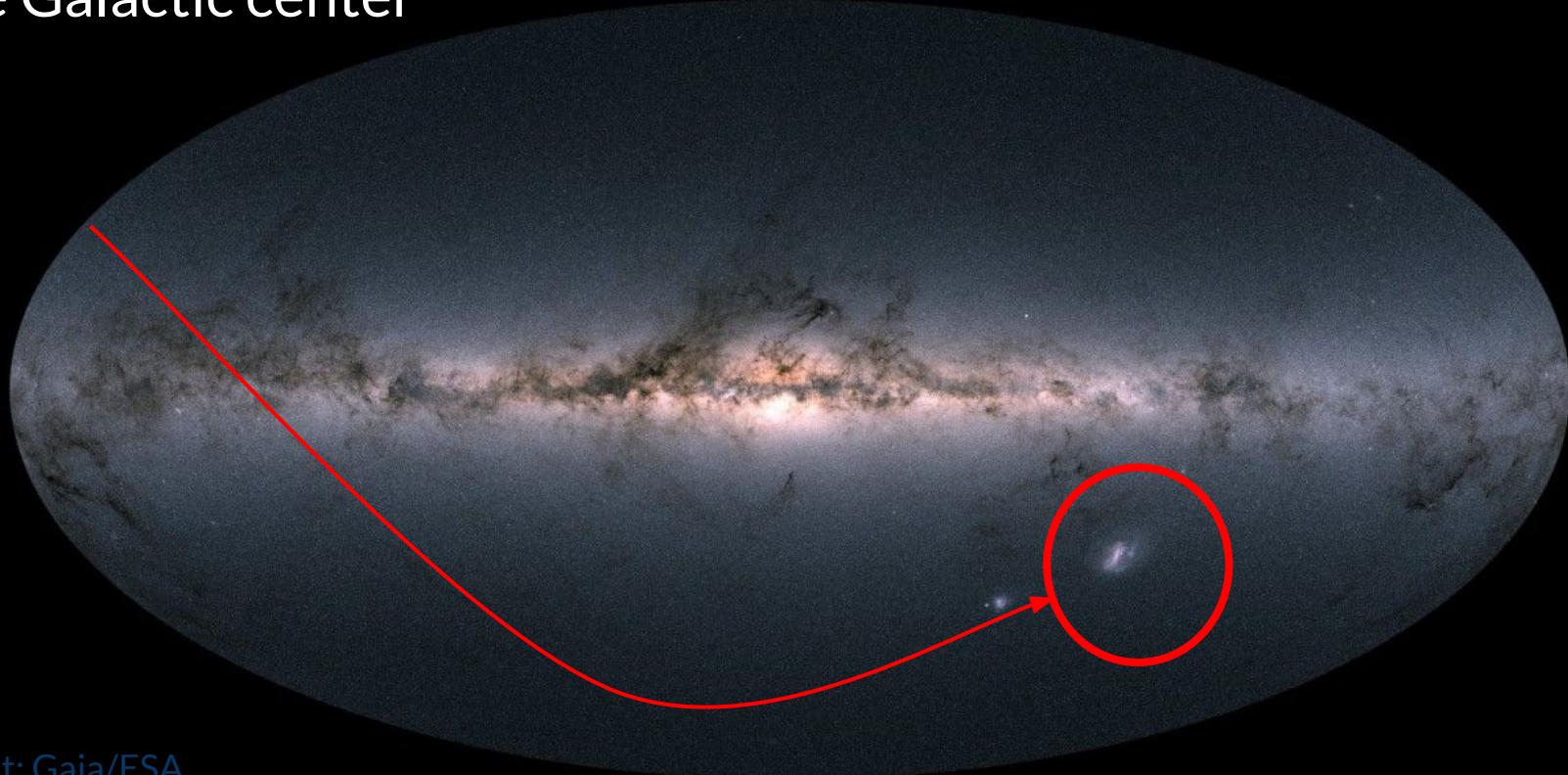
credit: Gaia/ESA



at 50 kpc from

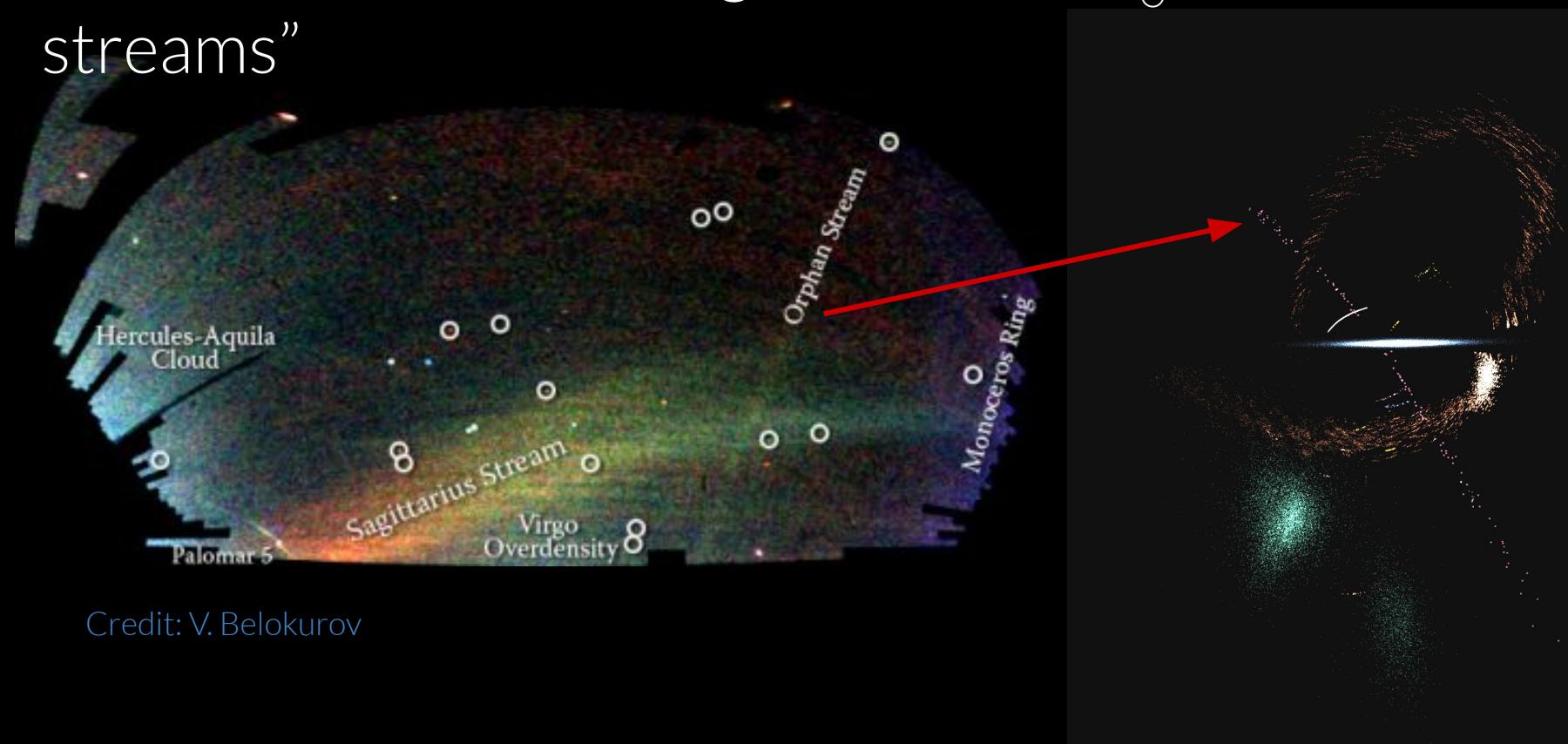


LMC is 10%-20% the total mass of the MW and it is at 50 kpc from the Galactic center



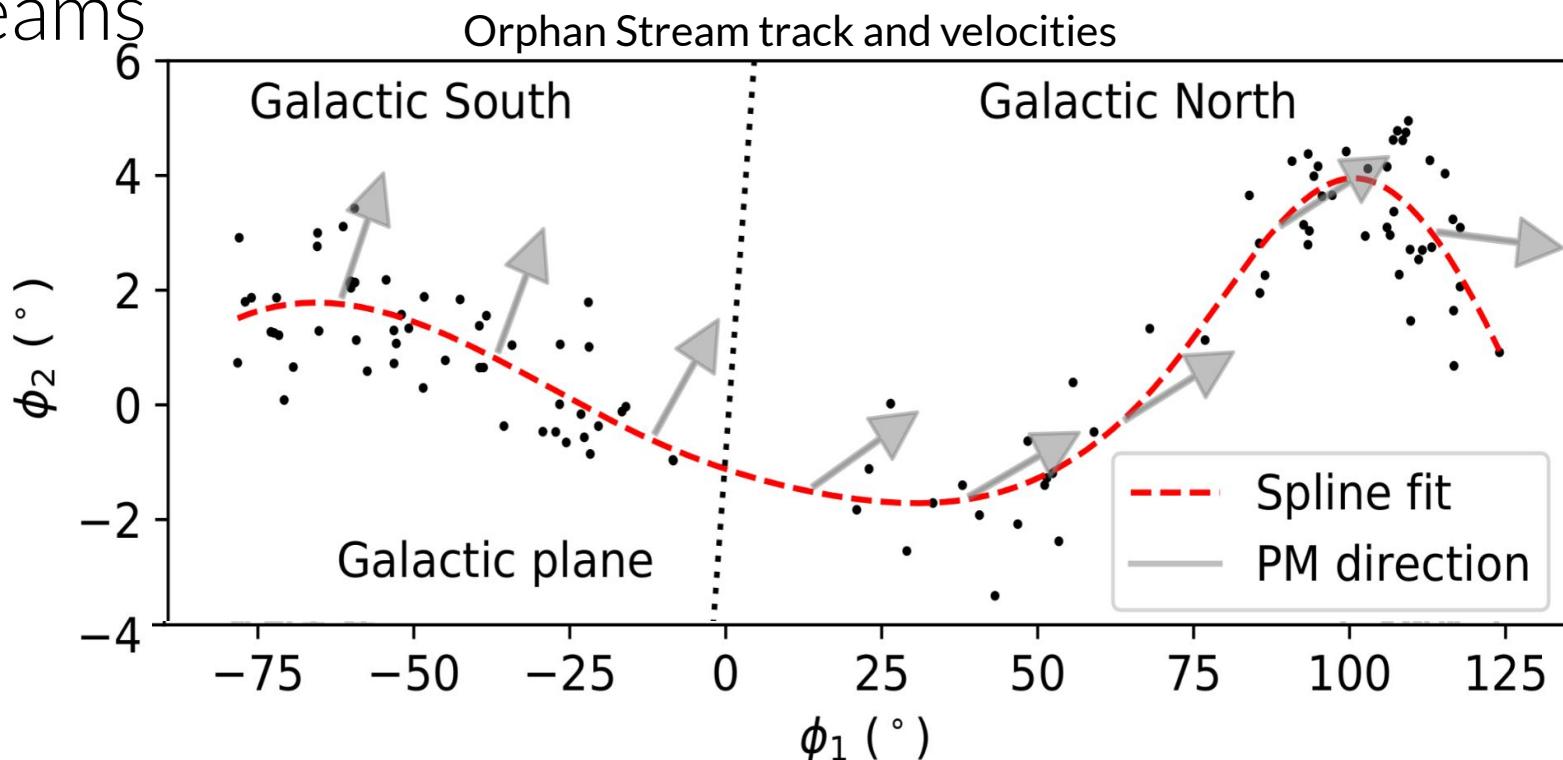
credit: Gaia/ESA

# Evidencia observacional de la influencia gravitacional de la Gran Nube de Magallanes $\sim 10^{11} M_{\odot}$ en “stellar streams”



Credit: V. Belokurov

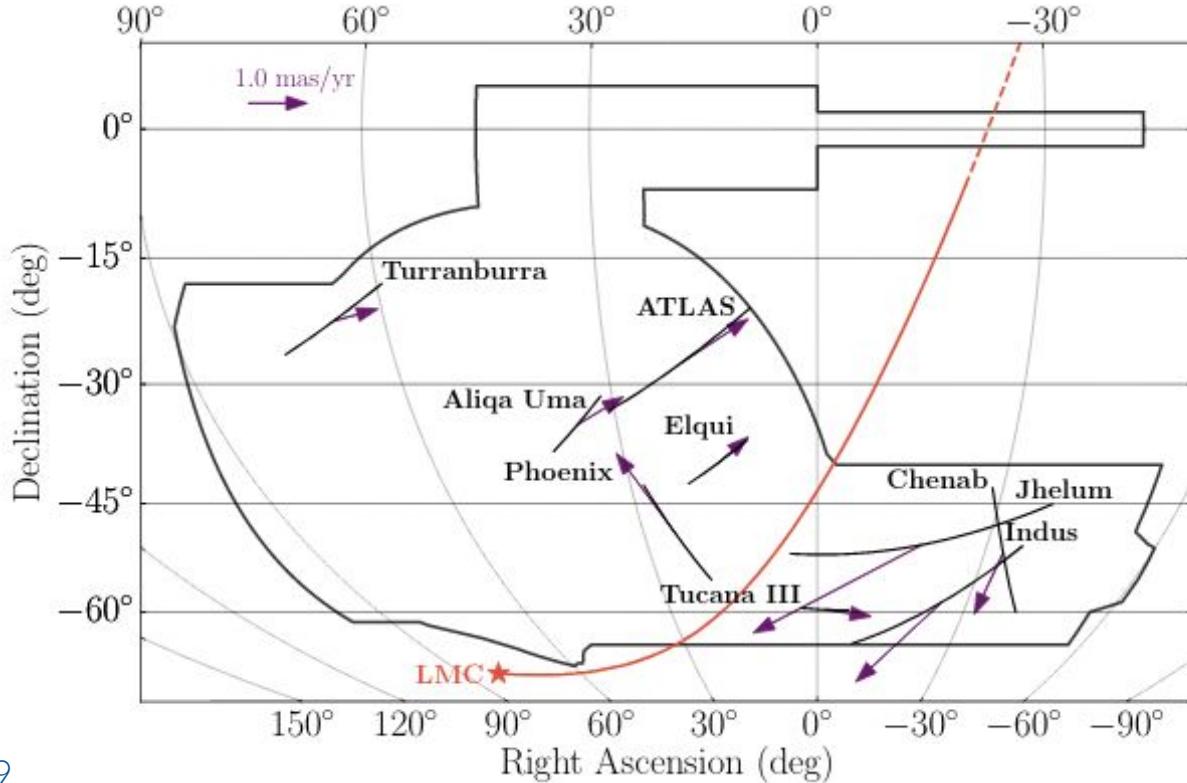
# Evidencia observacional de la influencia gravitacional de la Gran Nube de Magallanes $\sim 10^{11} M_{\odot}$ en “stellar streams”



Koposov+2018, Erkal+2018

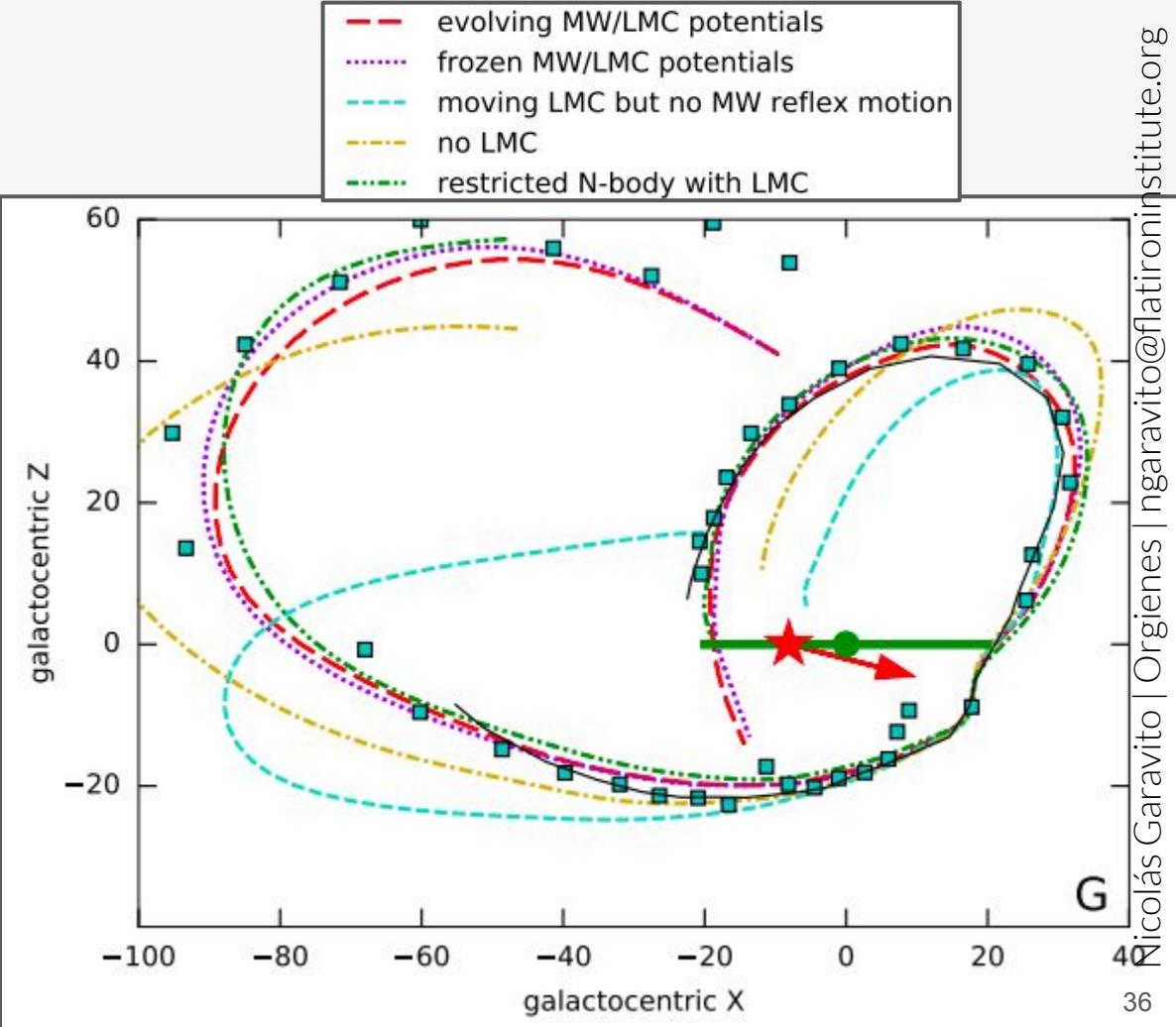
# Evidencia observacional de la influencia gravitacional de la Gran Nube de Magallanes $\sim 10^{11} M_{\odot}$ en “stellar streams”

S<sup>5</sup> survey  
Collaboration



Shipp, N et al 2019

Si se incluyen los efectos de la nube de Magallanes se puede reproducir la morfología del “stream” de Sag. Vasiliev+20



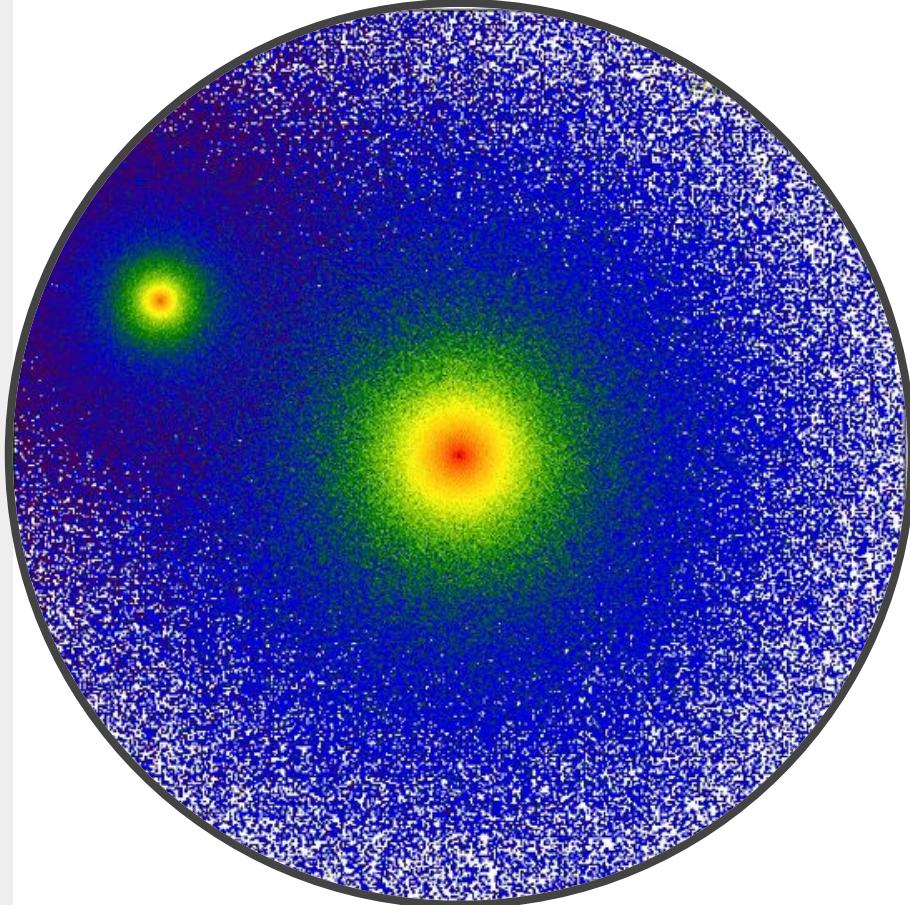
# 1. El movimiento del halo interior producido por la nube de magallanes (*Reflex motion*)

# Simulando la interaction de la VL y la NM

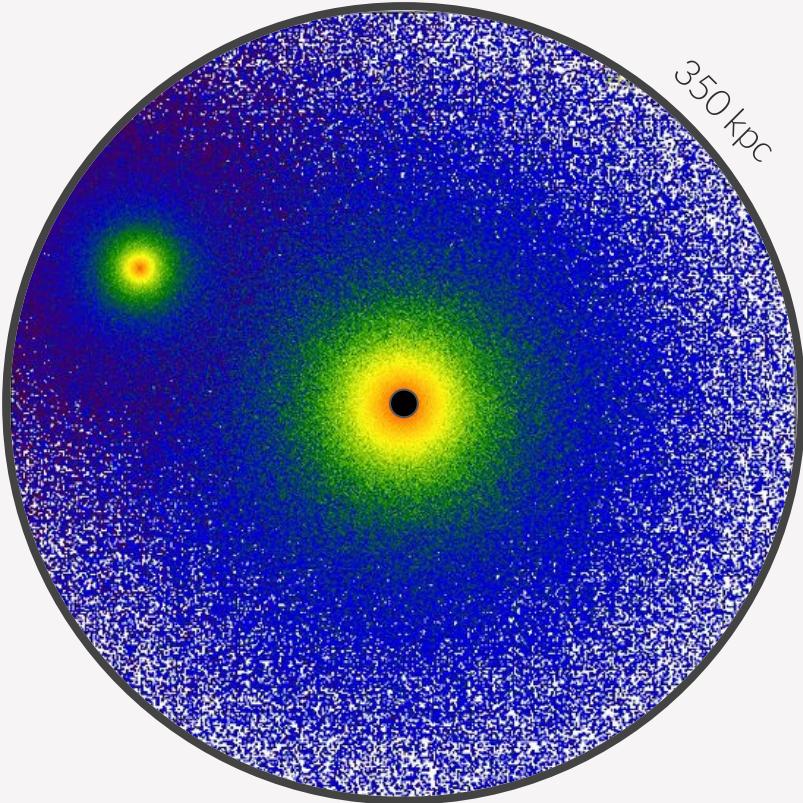
Suite of 8 high resolution  
N-body simulations:

- 4 LMC mass models
- 2 MW models

Reproduce the LMC present  
day position and velocity within  
 $2\sigma$  of HST observations  
(Kallivayalil+13)



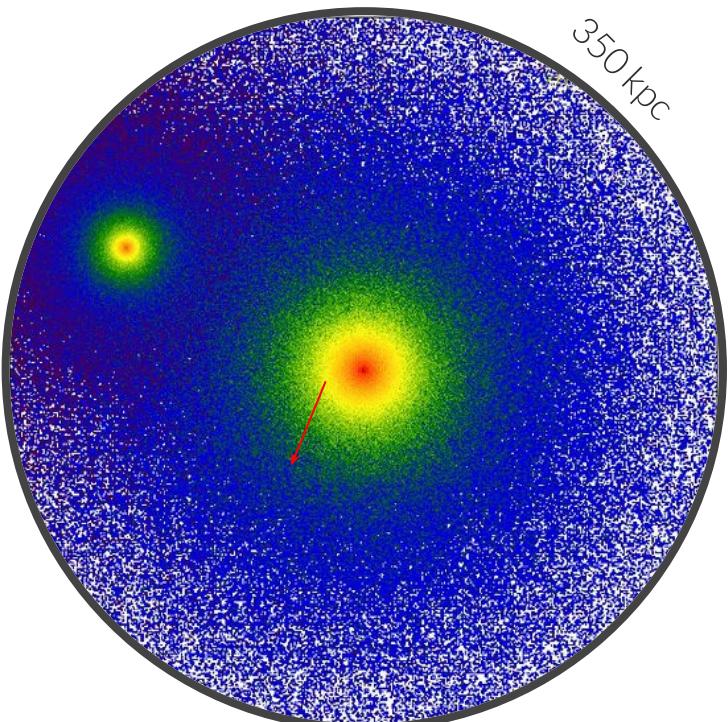
# La nube de magallanes está moviendo el baricentro de la Vía Láctea



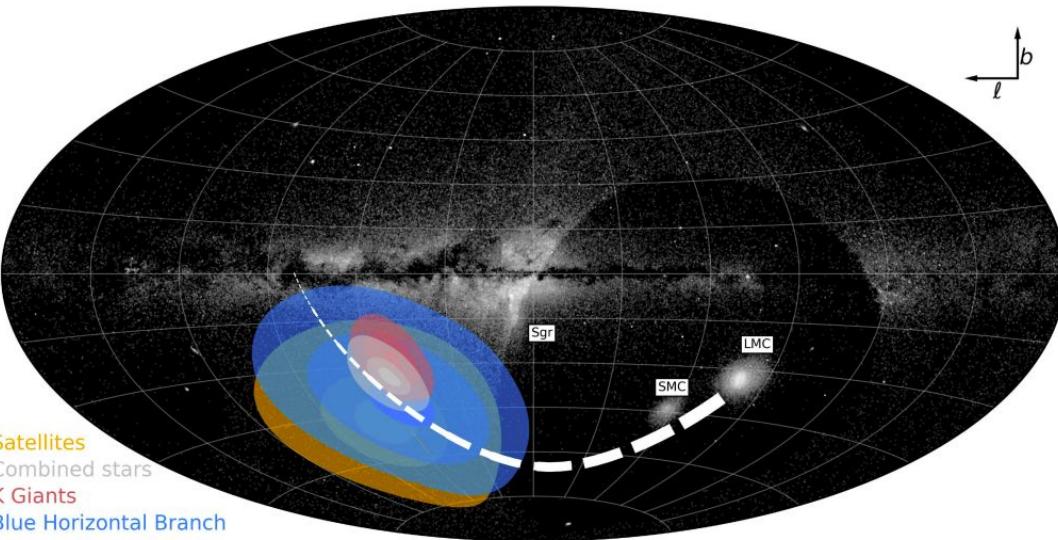
Este movimiento se observa en la cinemática de las partículas del halo exterior de la Vía Láctea.

El halo interno ( $< 30 \text{ kpc}$ ) esta ha sido movido ***50 kpc and 50 km/s***

El movimiento del baricentro se ha detectado en estrellas y satélites en halo exterior de la Vía Láctea

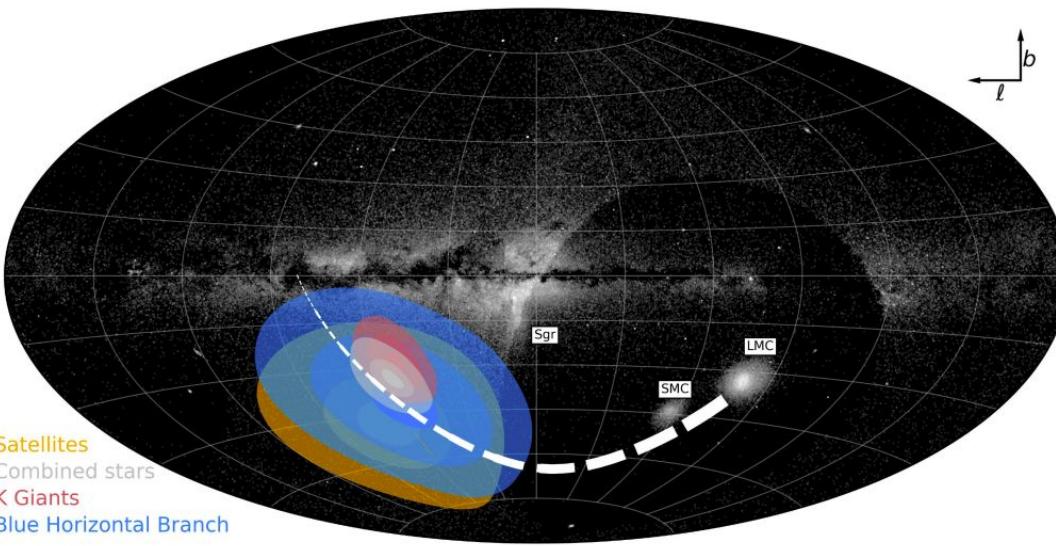
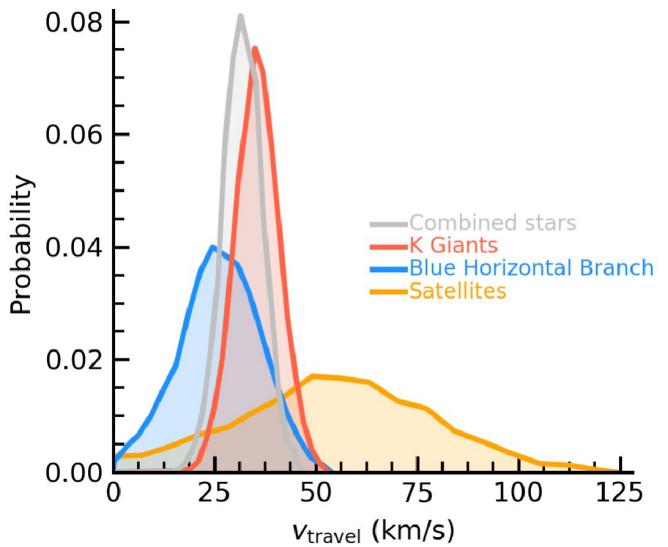


Garavito-Camargo+19, 20



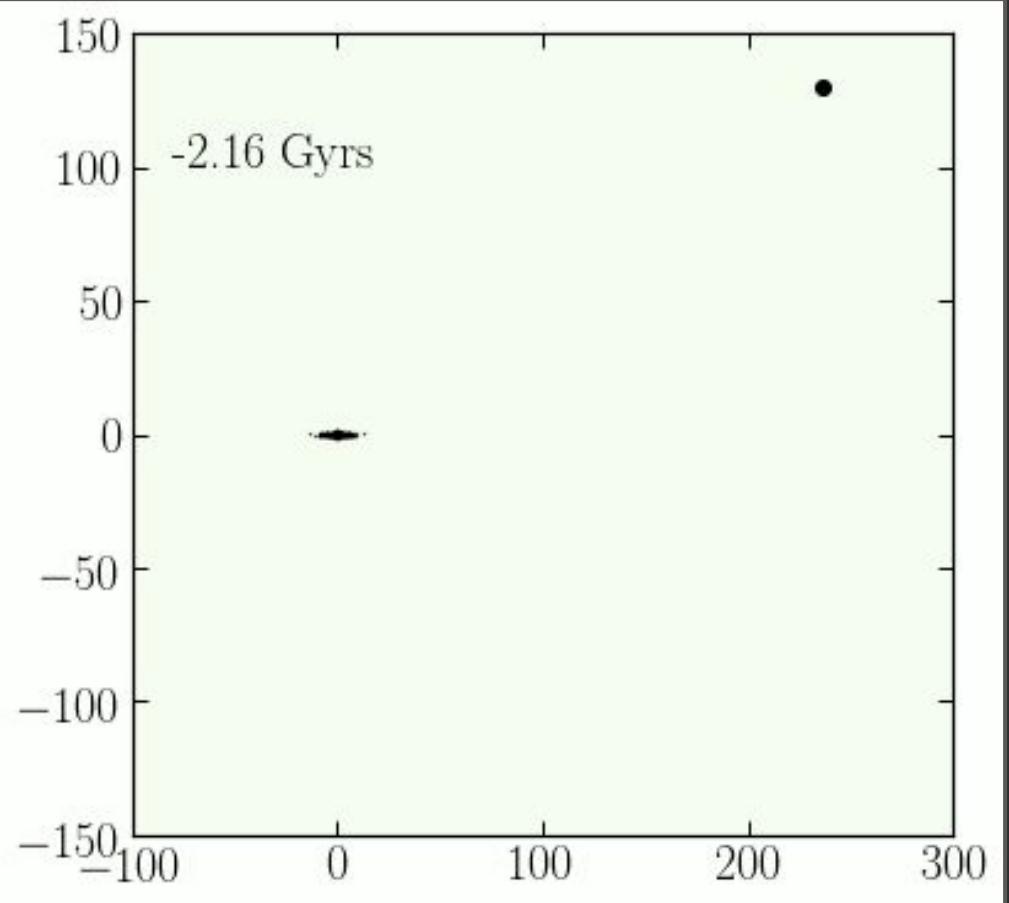
Petersen & Peñarrubia 20

El movimiento del baricentro se ha detectado en estrellas y satélites en halo exterior de la Vía Láctea

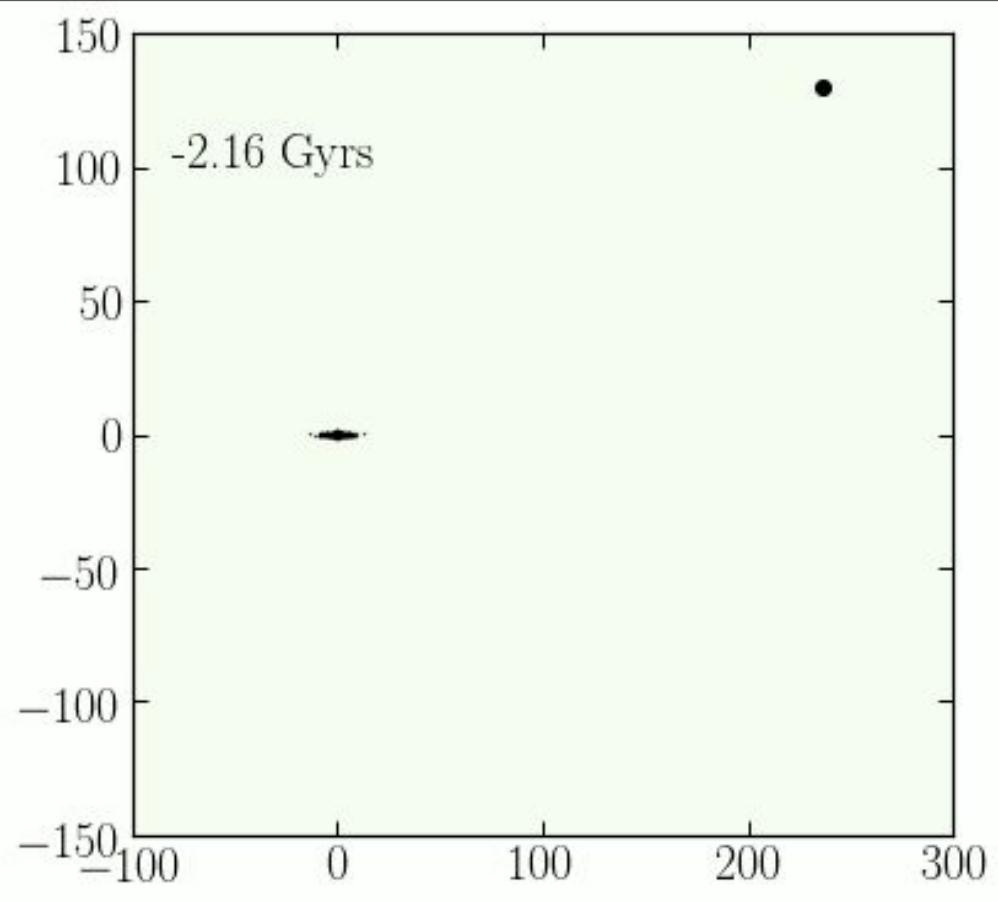


Petersen & Peñarrubia 20

# 2. La estela (*wake*) de materia oscura inducida por la Nube de Magallanes en el halo de la Vía Láctea

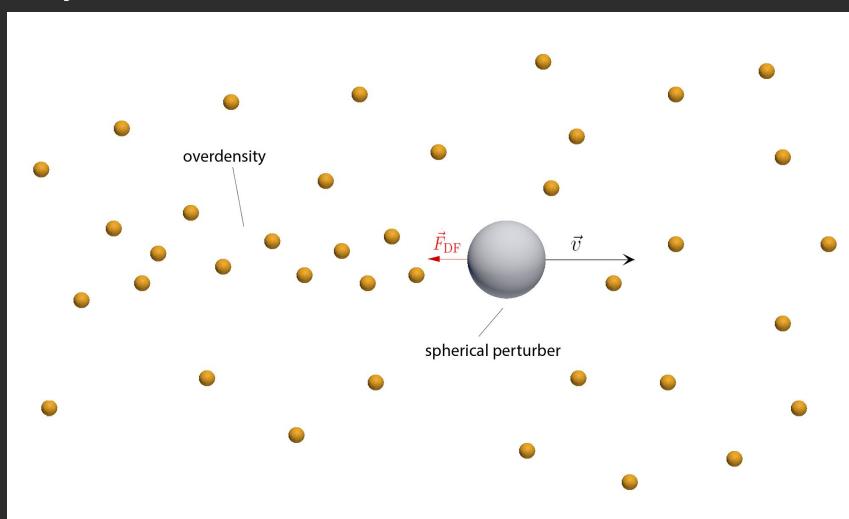


La estela de materia oscura es el resultado de la respuesta del halo a la presencia de una satélite masiva. ***dynamical friction.***



Garavito-Camargo, 2019, 2021a

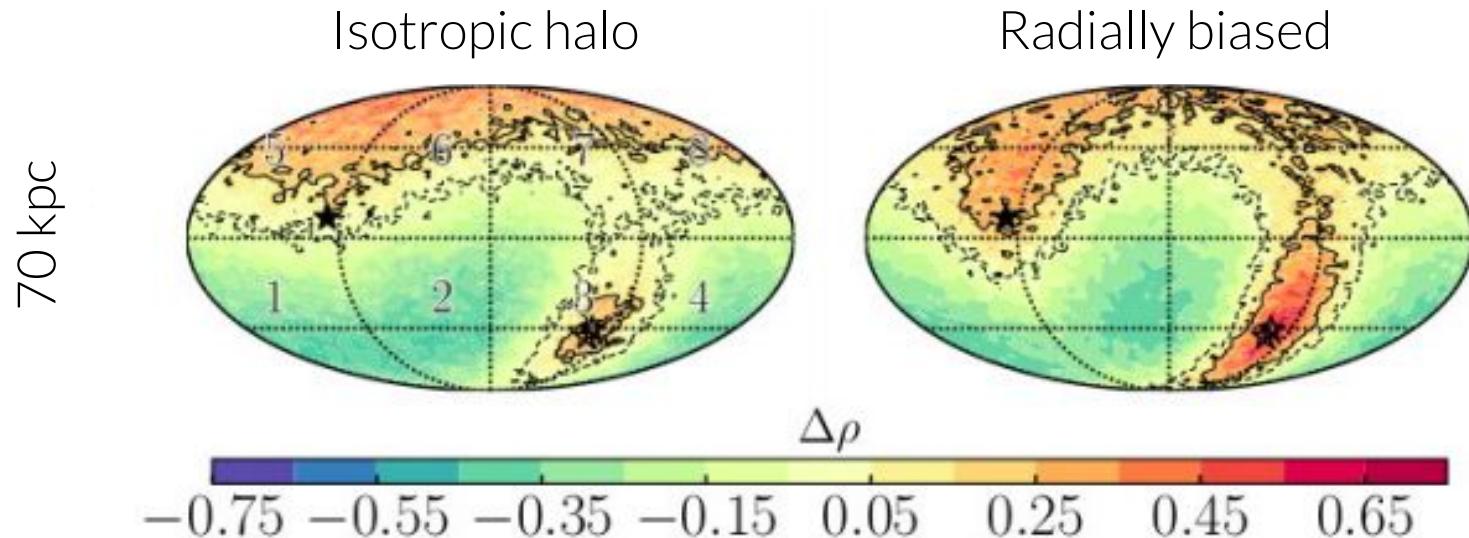
La estela de materia oscura es el resultado de la respuesta del halo a la presencia de una satélite masiva. ***dynamical friction.***



Chandrasekhar 43, Mulders 83, Weinberg 86

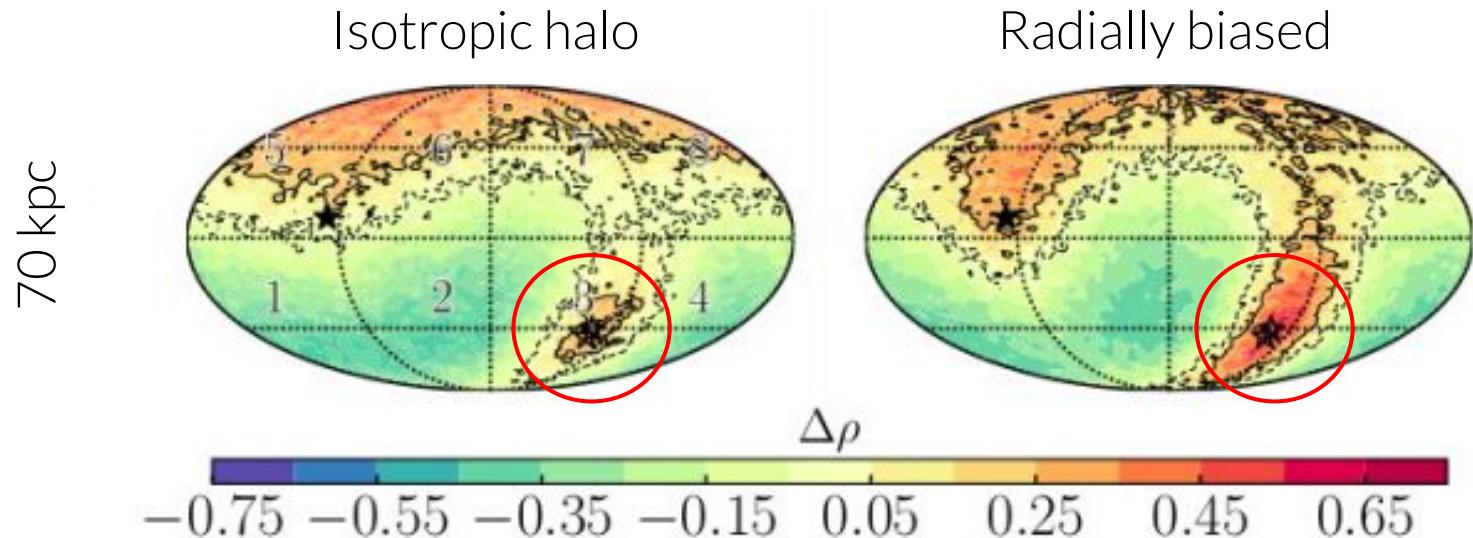
Image Credit: Franziska Schmidt

Maps del cielo (coordenadas Galactocentricas) de la amplitud de la estela de materia oscura (wake)



Garavito-Camargo+19

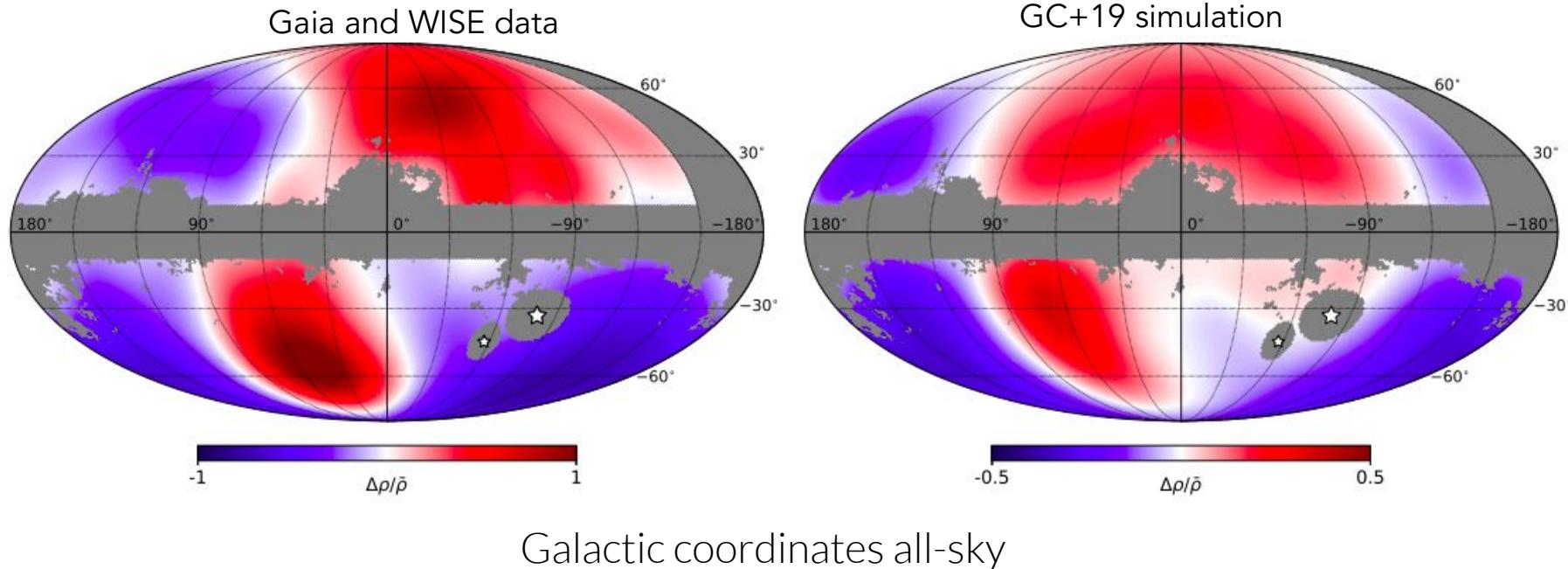
Maps del cielo (coordenadas Galactocentricas) de la amplitud de la estela de materia oscura (wake)



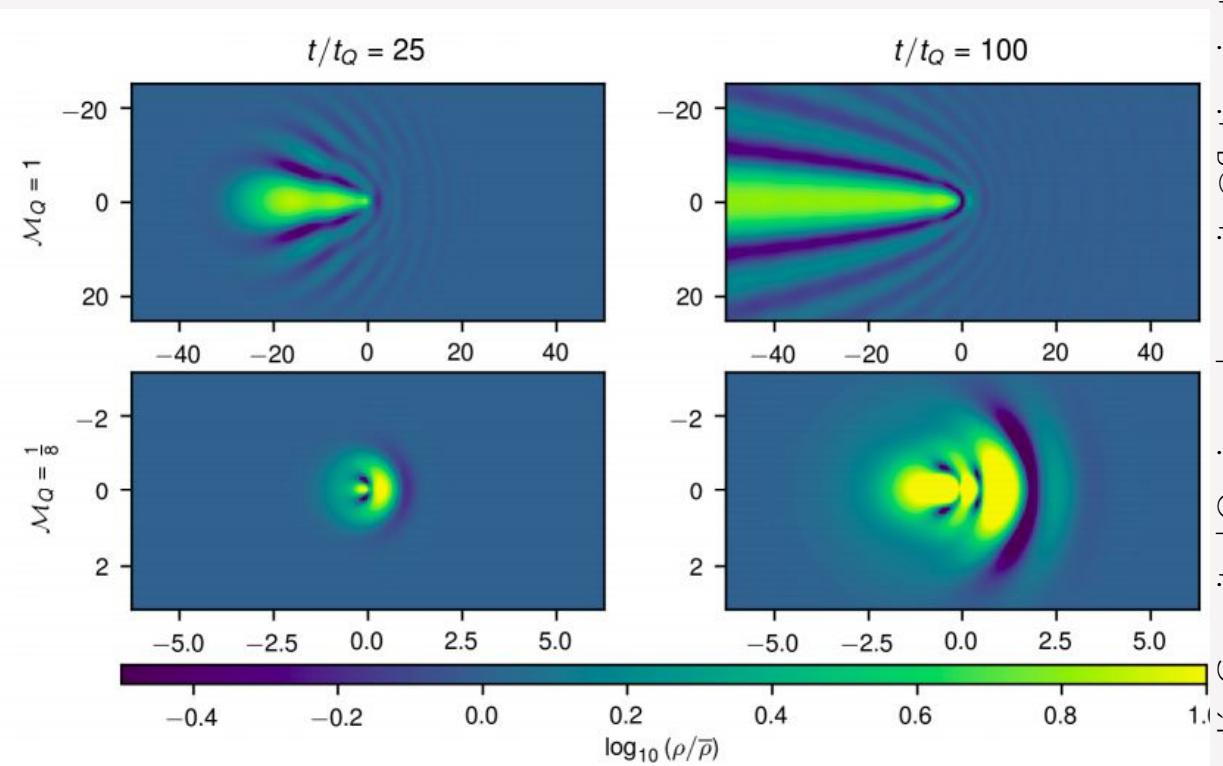
Garavito-Camargo+19



# **Possible detección del “wake” en el halo externo de la Vía Láctea (60-100 kpc) confirmando las simulaciones**

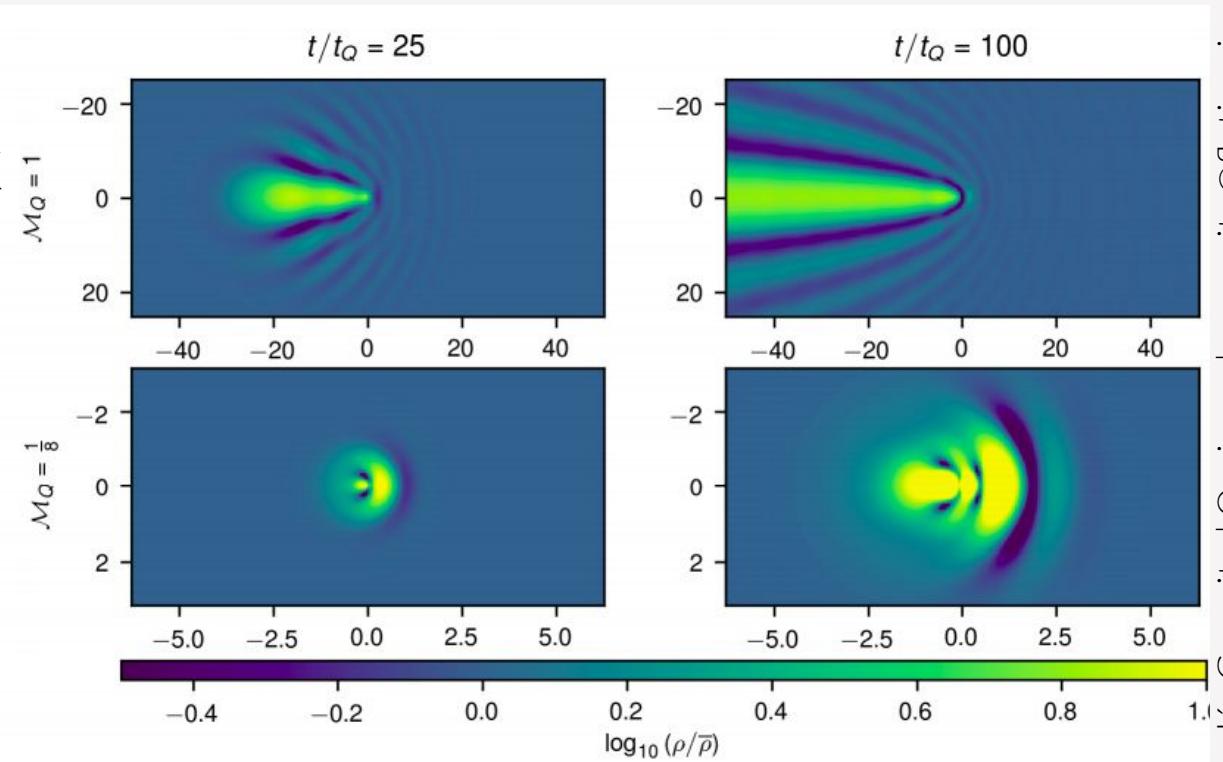


# La estructura y la amplitud del “wake” depende del modelo de materia oscura y en MOND



# La estructura y la amplitud del “wake” depende del modelo de materia oscura y en MOND

Wakes in Fuzzy Dark Matter are different than in CDM\*



\*This seems to be also the case for the LMC's wake  
Hayden Foote (in prep)

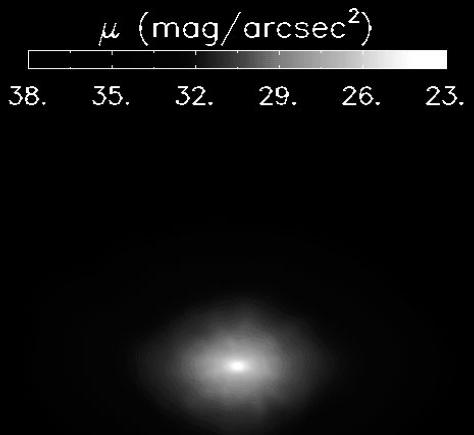
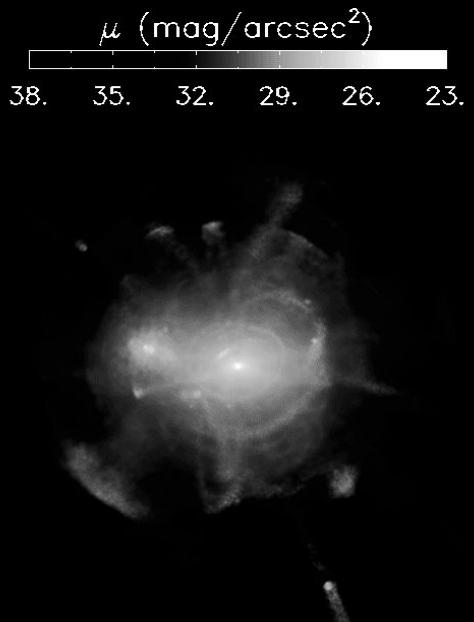
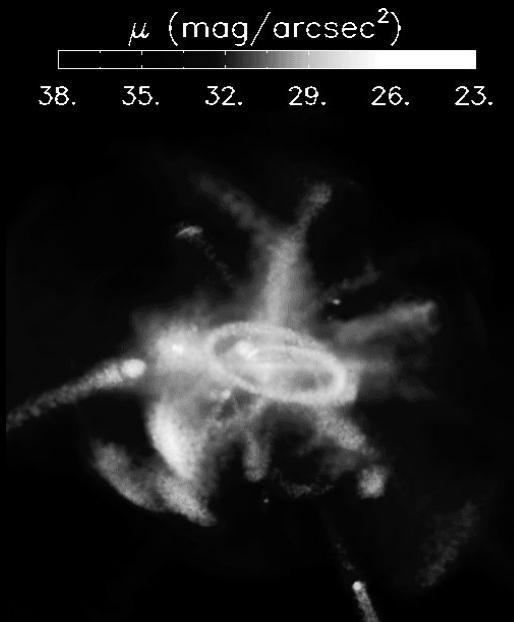
# Wakes in CDM paradigm ***upcoming challenges***

- Las estelas de DM “wakes” son una predicción del cualquier modelo de materia oscura. Serán estas predicciones observables? (see upcoming work by Hayden Foote, Garavito-Camargo)

# Wakes in CDM paradigm ***upcoming challenges***

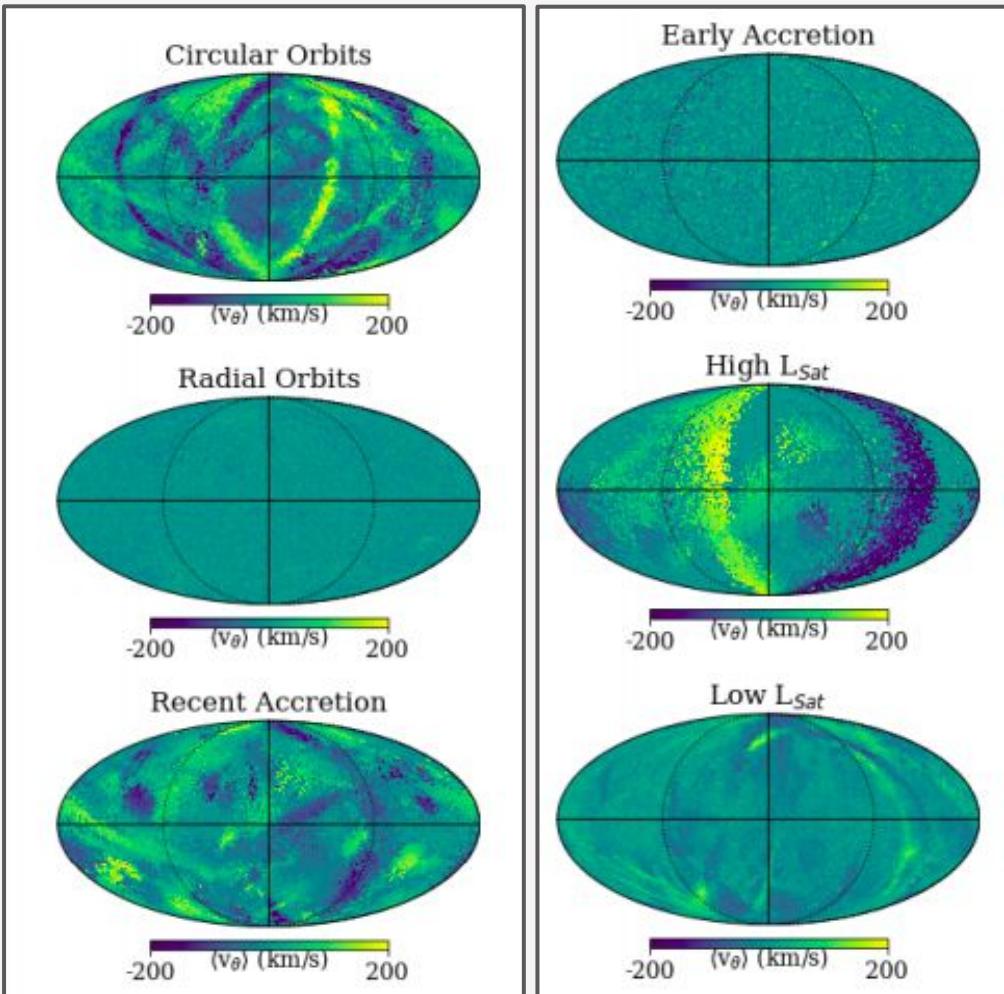
- Las estelas de DM “wakes” son una predicción del cualquier modelo de materia oscura. Serán estas predicciones observables? (see upcoming work by Hayden Foote, Garavito-Camargo)
- En la VL, varias campañas observacionales están mapeando en 6D la estructura del “wake” en su contraparte estelar.

How does the velocity space of the stellar halo with substructure compares to the perturbations induced by the LMC?

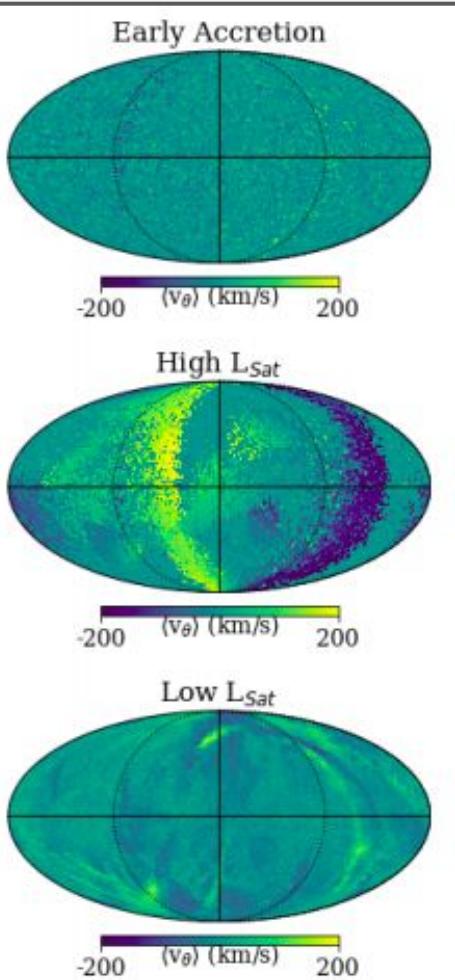
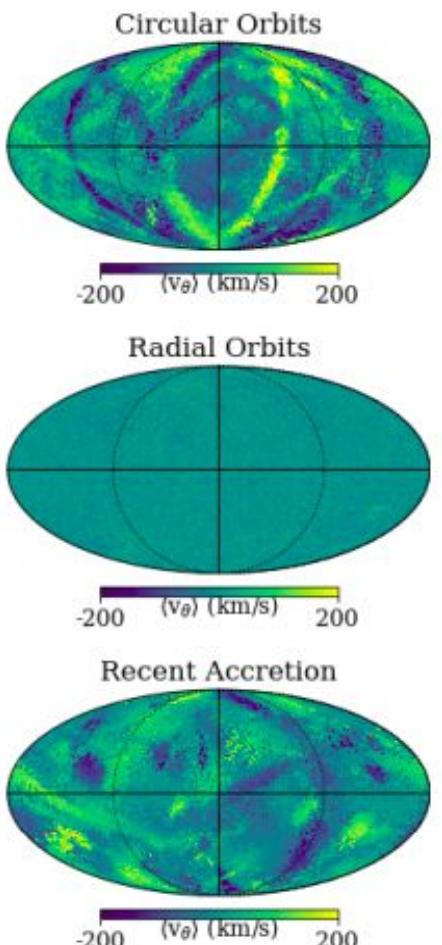


Bullock and Johnston stellar halos

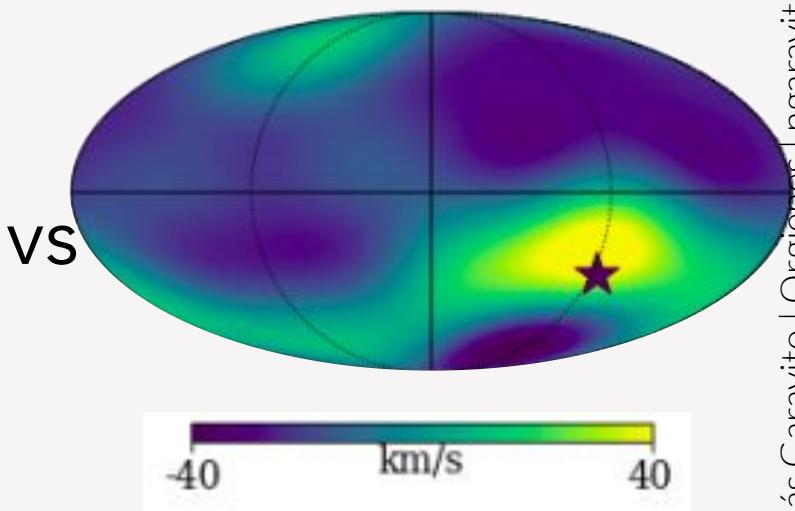
Emily Cunningham, Garavito-Camargo et al 20



Emily Cunningham, Garavito-Camargo et al  
20

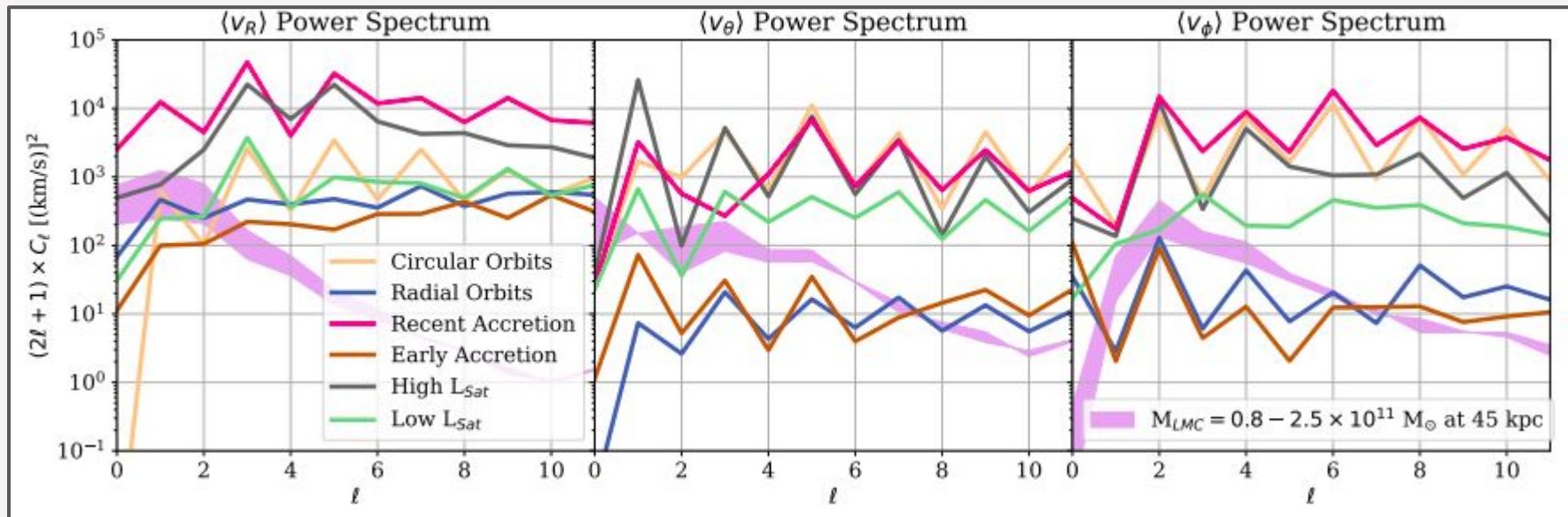


Sin embargo, el halo estelar no es homogéneo!



Cunningham, Garavito-Camargo et al 20

En ausencia de eventos de acreción masivos y recientes los efectos de las nubes de Magallanes pueden ser observados.



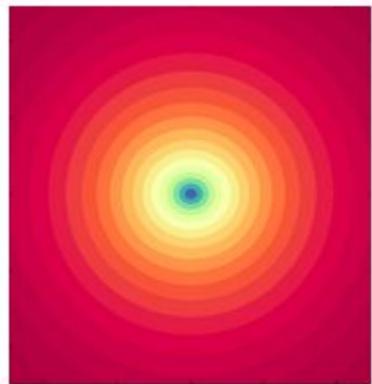
Cunningham, Garavito-Camargo+20  
See also Tamfal+20

# Dinámica fuera del equilibrio usando Basis Function Expansions (BFE)

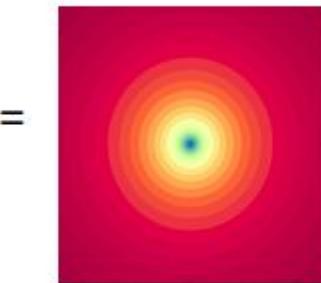
$$\check{\rho}(\mathbf{x}) = \sum_{\mu=1}^M a_\mu d_\mu(\mathbf{x})$$

$$\check{\Phi}(\mathbf{x}) = \sum_{\mu=1}^M a_\mu \phi_\mu(\mathbf{x})$$

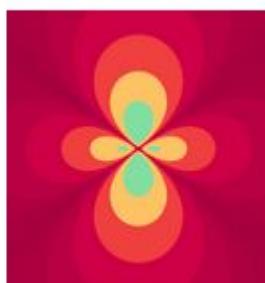
Oblate halo



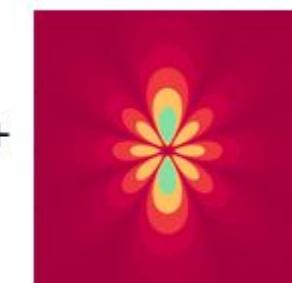
Monopole



Quadrupole

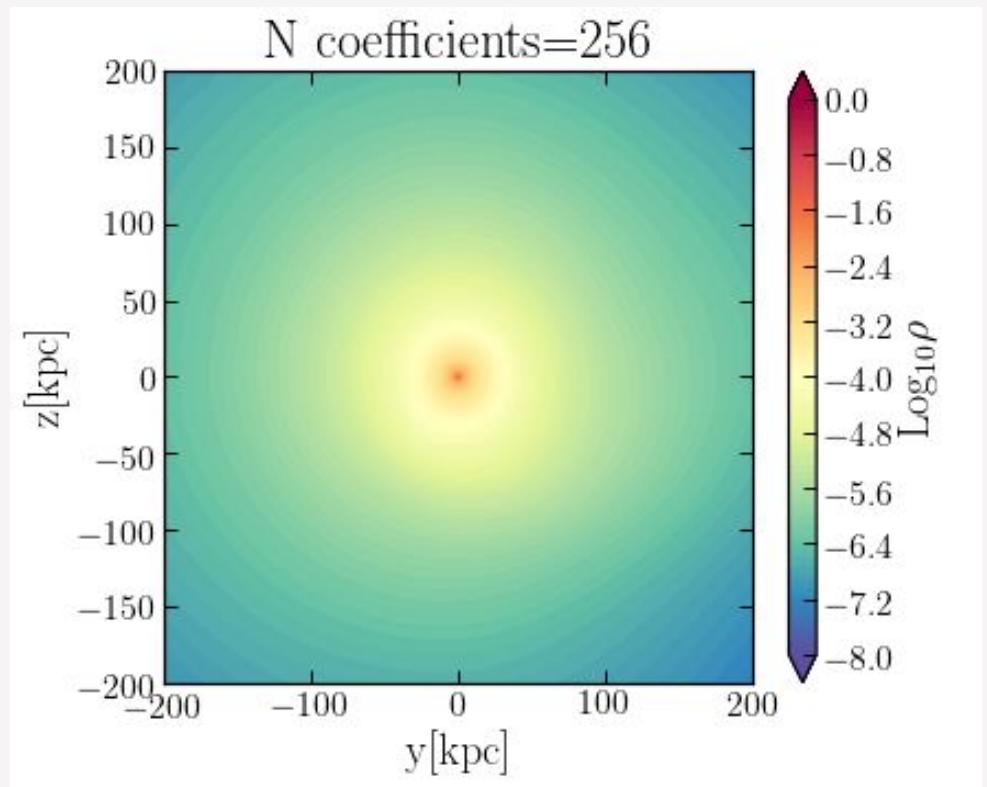


Octopole

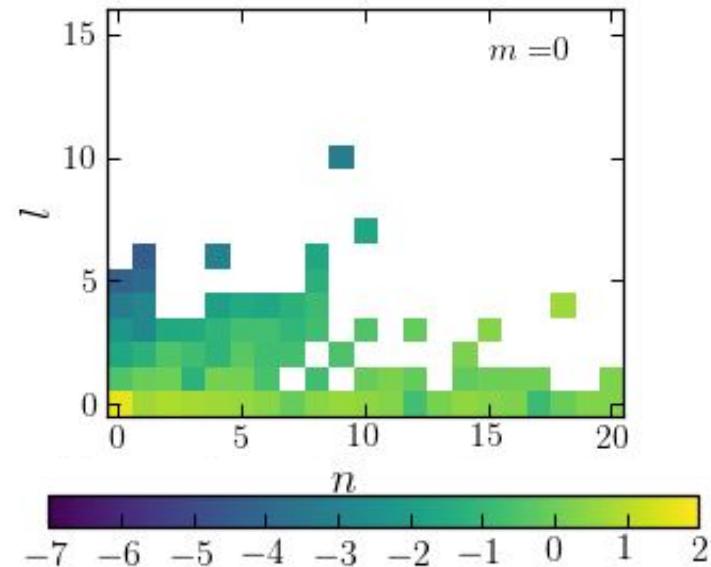
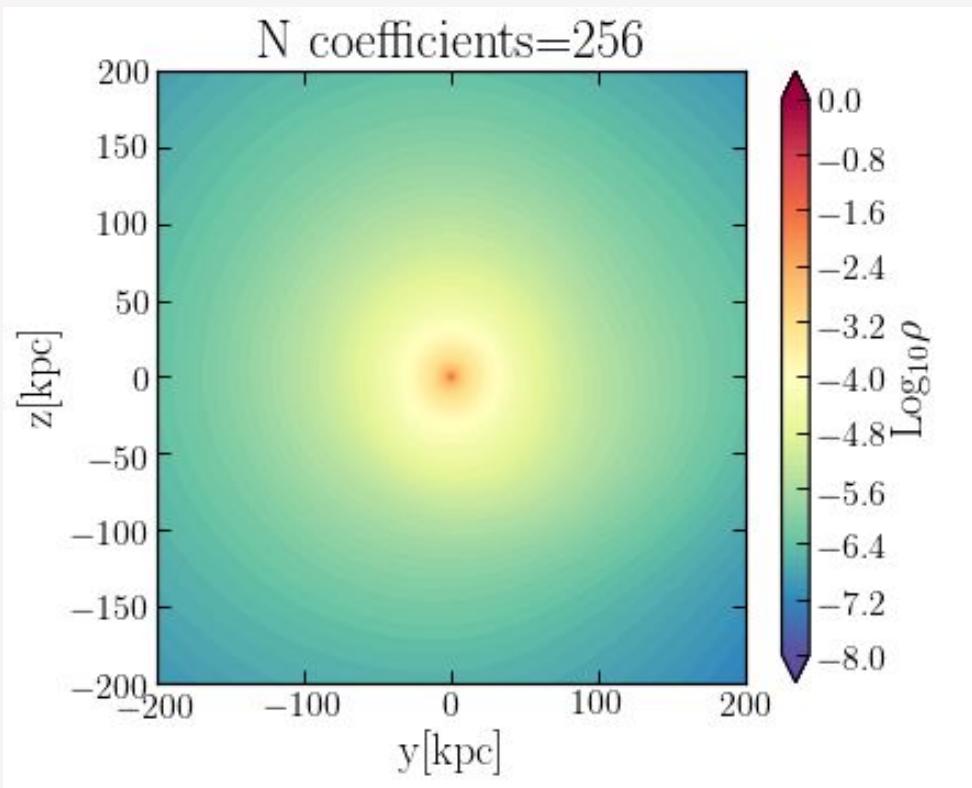


Clutton-Brock 73 (Plummer), Hernquist & Ostriker 92 (Hernquist), Weinberg 99 (numerical)

La estructura de un halo puede ser descrita en el espacio de los coeficientes de la expansión

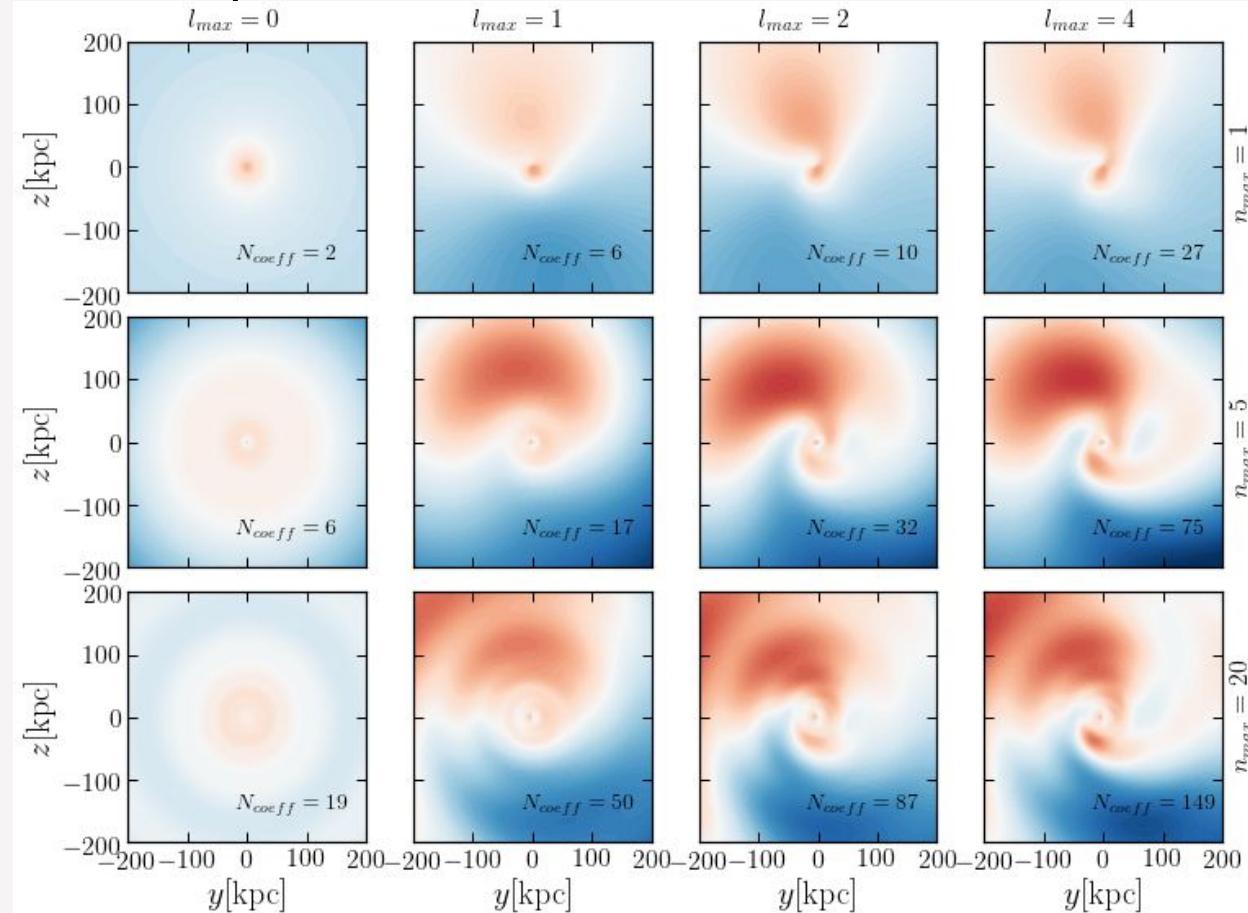


La estructura de un halo puede ser descrita en el espacio de los coeficientes de la expansión



The structure of the halo is now described by the amplitude of the coefficients in the expansion

Garavito-Camargo+21a



# Basis Function Expansions

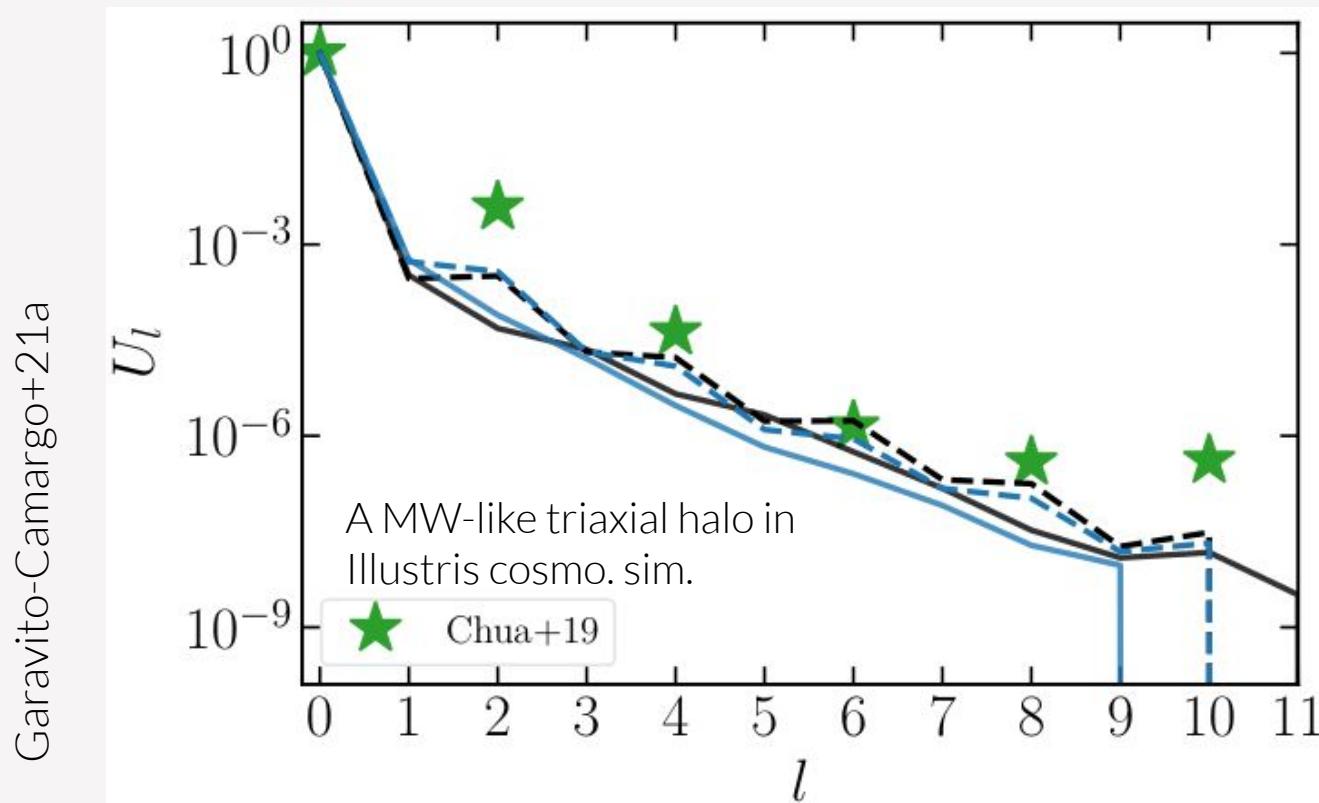
*Beefy collaboration*

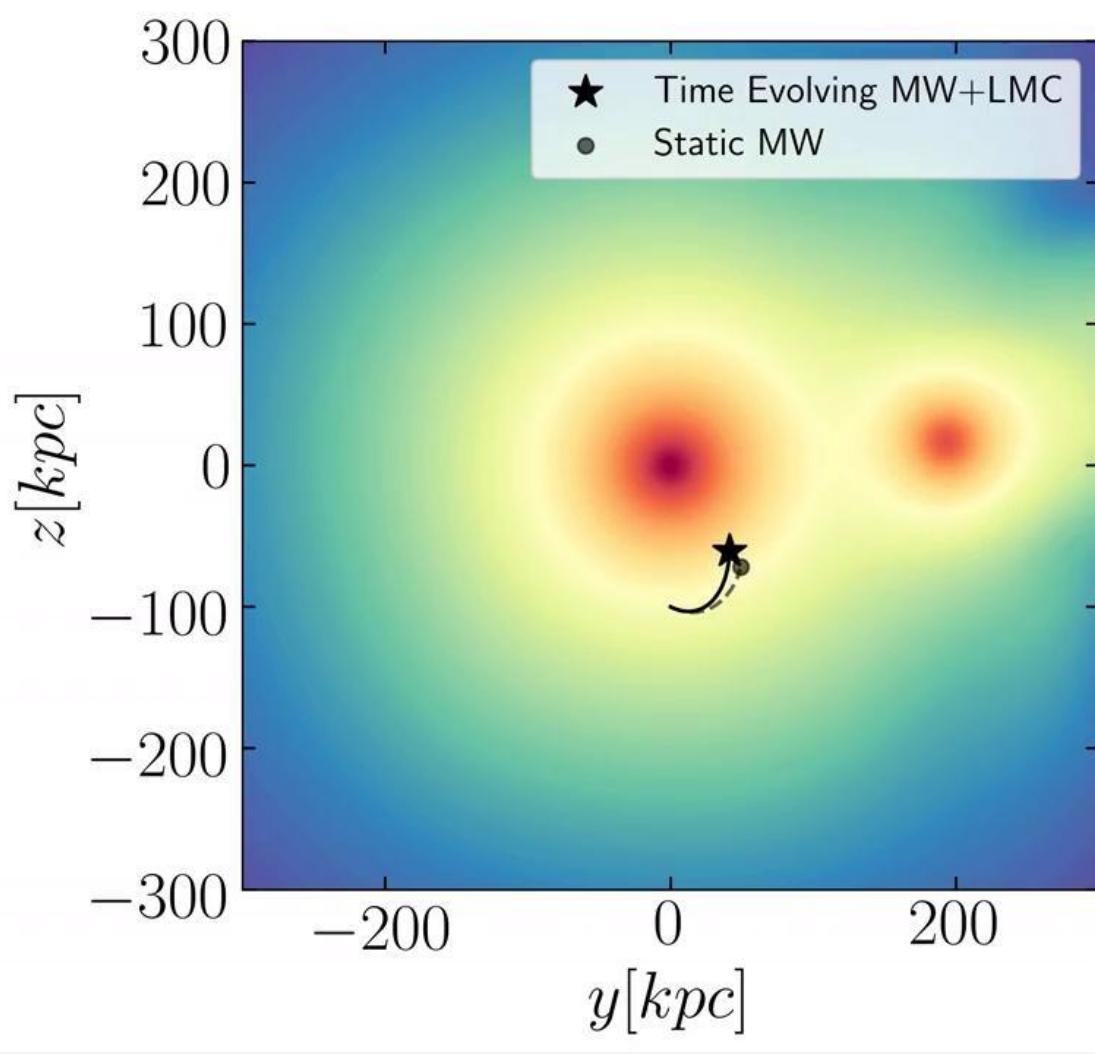
19 members: 5 postdocs, 7 graduate students, and 7 professors & staff

Leadership: Mike Petersen, Jason Hunt, Kathryn Johnston, and Martin Weinberg

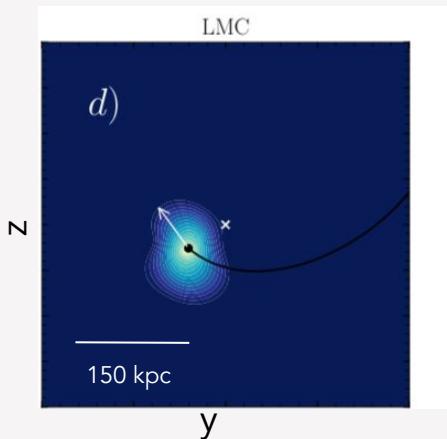


What is the present-day **MW's DM halo shape** in the presence of the LMC? Not prolate/oblate/triaxial



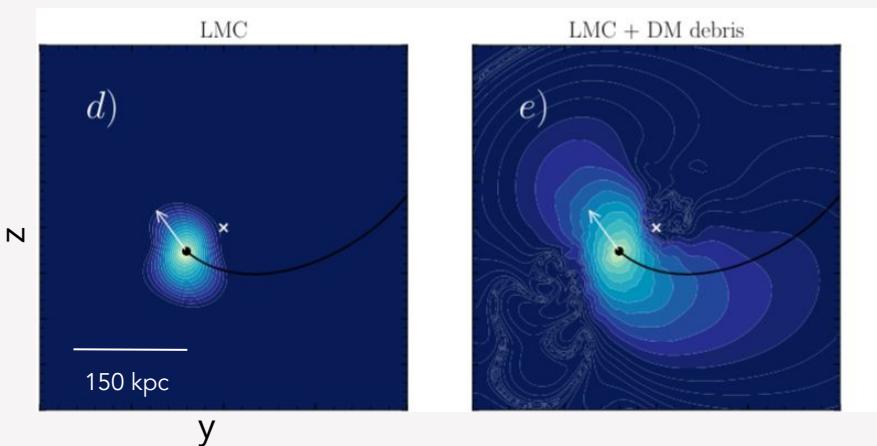


Basis Functions Expansion representation of the present-day  
MW-LMC system.  $10^8$  particles  $\rightarrow \sim 2000$  coefficients per snapshot



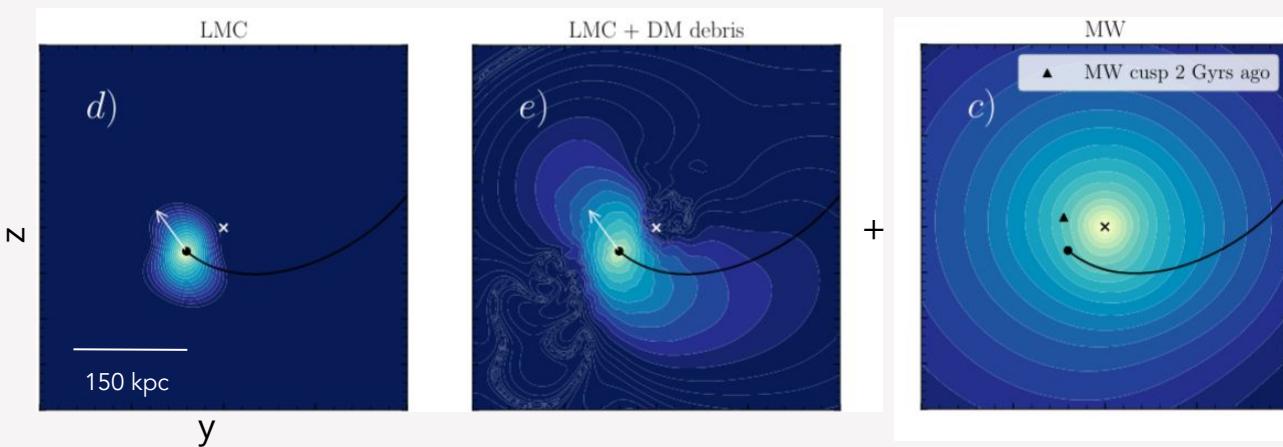
Garavito-Camargo+21a

Basis Functions Expansion representation of the present-day MW-LMC system.  $10^8$  particles  $\rightarrow \sim 2000$  coefficients per snapshot



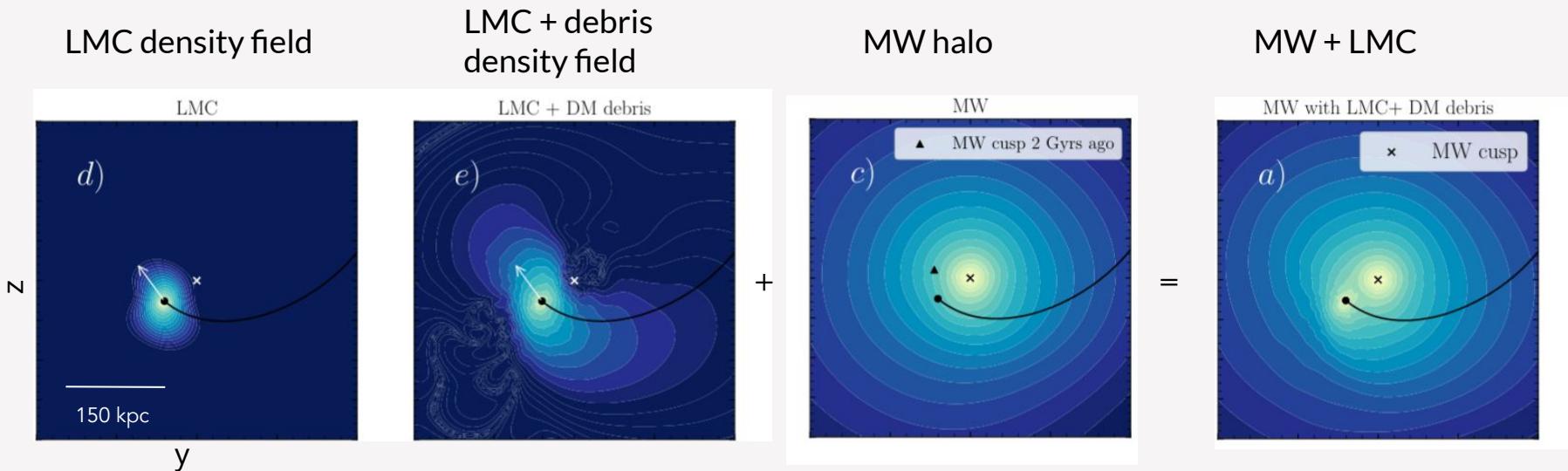
Garavito-Camargo+21a

Basis Functions Expansion representation of the present-day  
MW-LMC system.  $10^8$  particles  $\rightarrow \sim 2000$  coefficients per snapshot



Garavito-Camargo+21a

# Basis Functions Expansion representation of the present-day MW-LMC system. $10^8$ particles $\rightarrow \sim 2000$ coefficients per snapshot

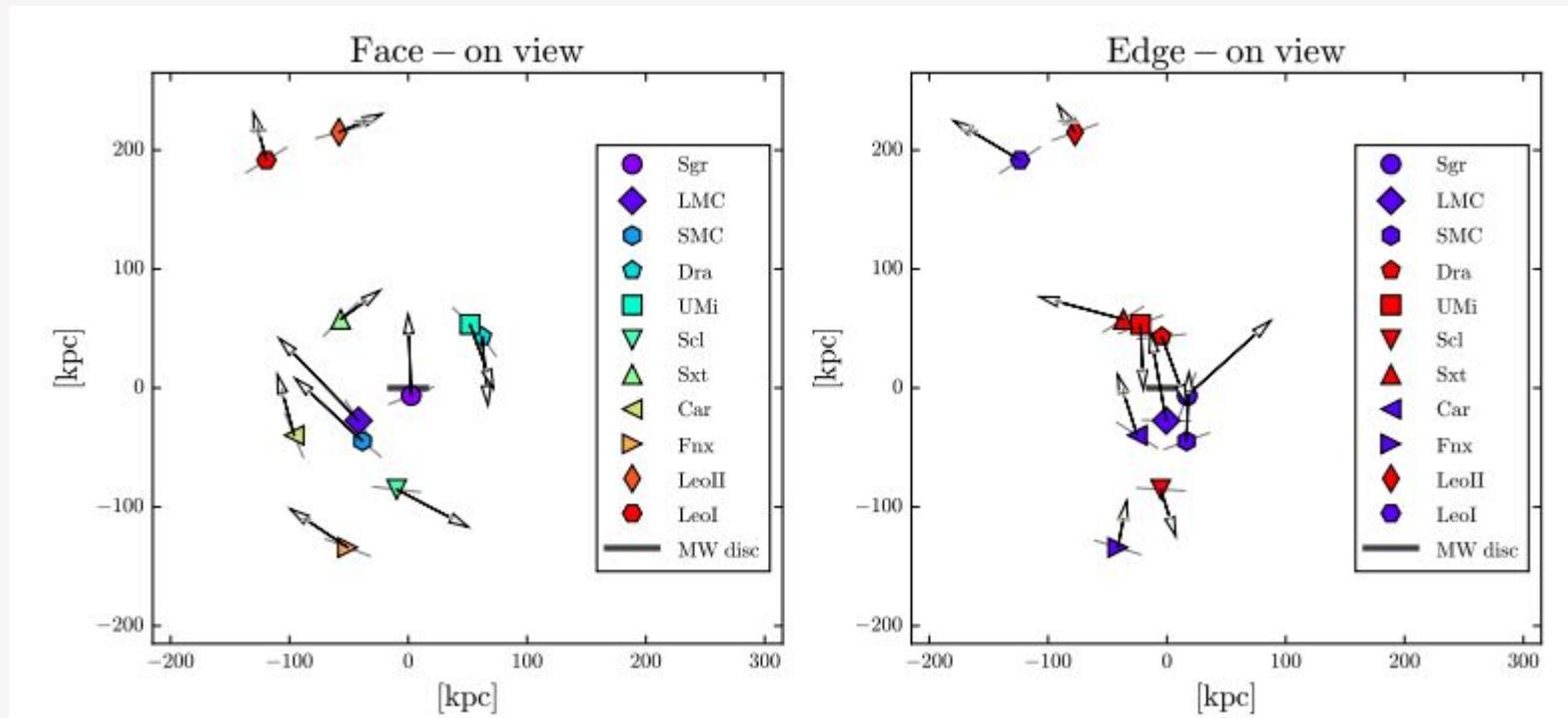


Garavito-Camargo+21a

- La naturaleza de la materia oscura se manifiesta en la estructura de los halos de materia oscura.
- Halos fuera del equilibrio (como la VL) pueden constreñir más los modelos de materia oscura.
- La VL + Nubes de Magallanes son un excelente sistema para estudiar la naturaleza de la materia oscura (*reflex motion, wake*).

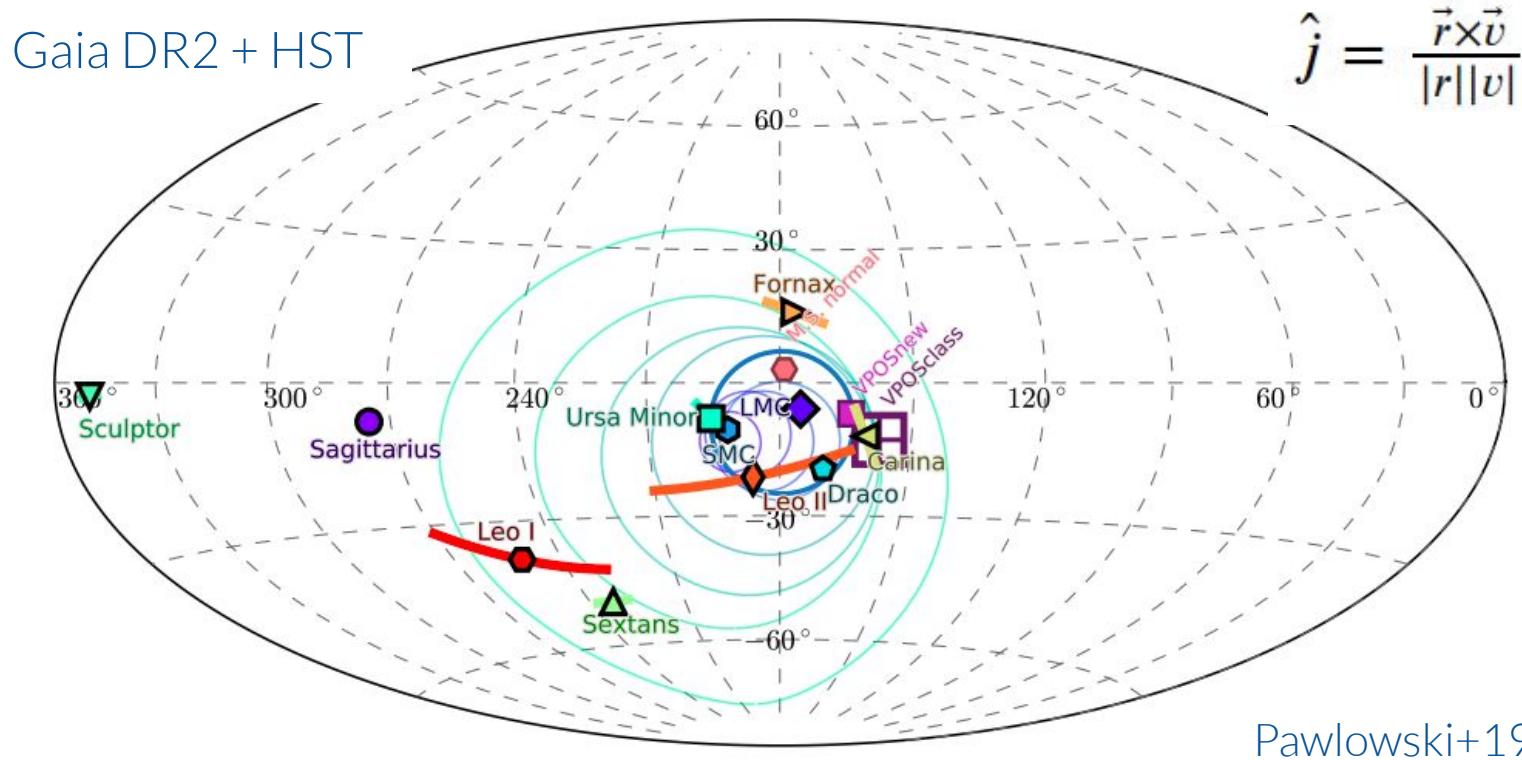
Dinámica fuera del  
equilibrio en la VL una  
posible solución al problema  
de los planos

# Las galaxias clásicas de la VL estan distribuidas y co-rotando en un disco



Pawlowski+19

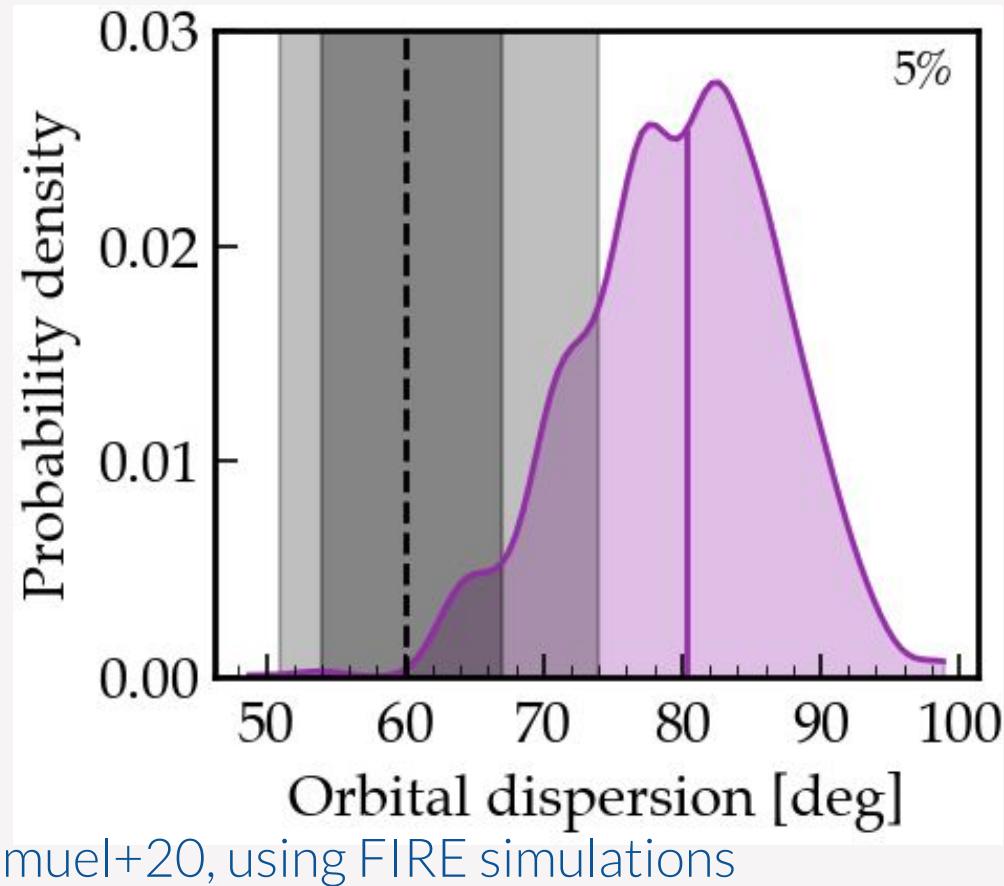
# Orbital poles clustering of the MW Satellite galaxies



7 out of 11 Classical satellites of the Milky Way are co-orbiting in a plane

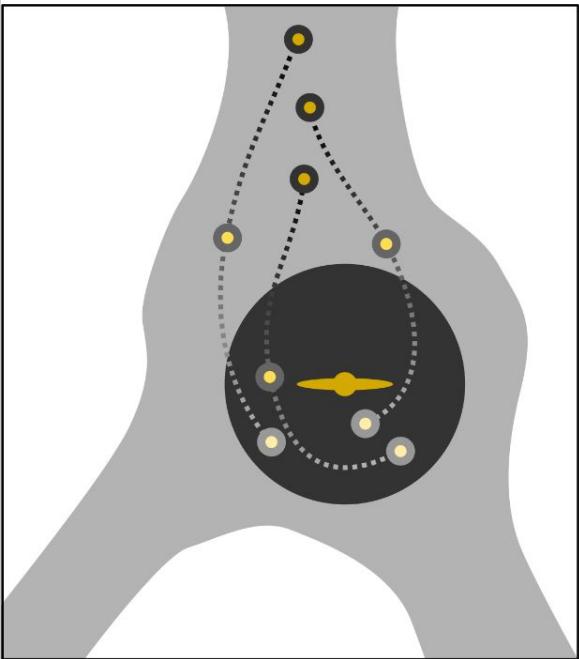
# Planos de satélites son difíciles de encontrar en **CDM**

- Galaxias analogas a la VL  
 $\sim 10^{12} \text{Msun}$
- La distribución de galaxias satélites es  $\sim$  isotrópica en las simulaciones
- Planos delgados solo ocurren en 1-5% de las simulaciones
- Planos delgados y que co-rotan solo existen en 0.3% de las simulaciones



# Posibles escenarios de formación de planos co-rotantes

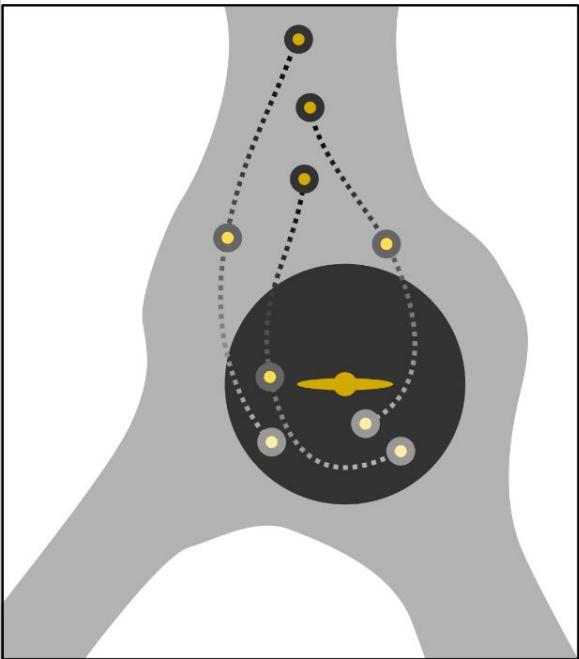
## Filamentary Accretion



Already included in cosmo sims.  
Mainly produce thick planes!

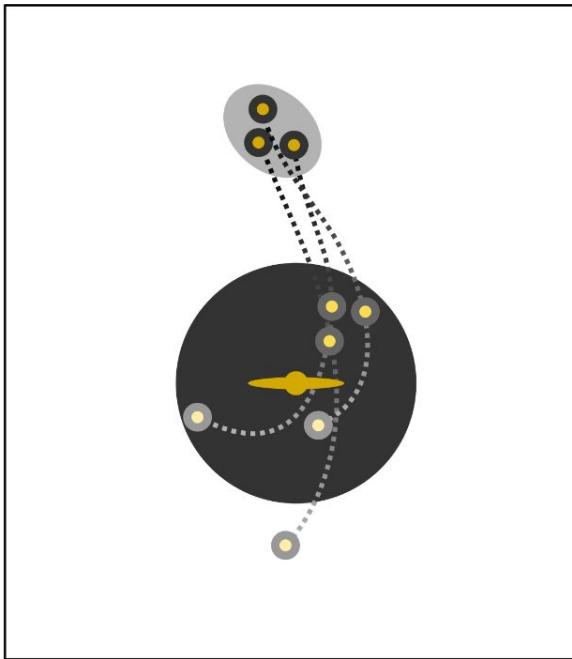
# Posibles escenarios de formación de planos co-rotantes

Filamentary Accretion



Already included in cosmo sims.  
Mainly produce thick planes!

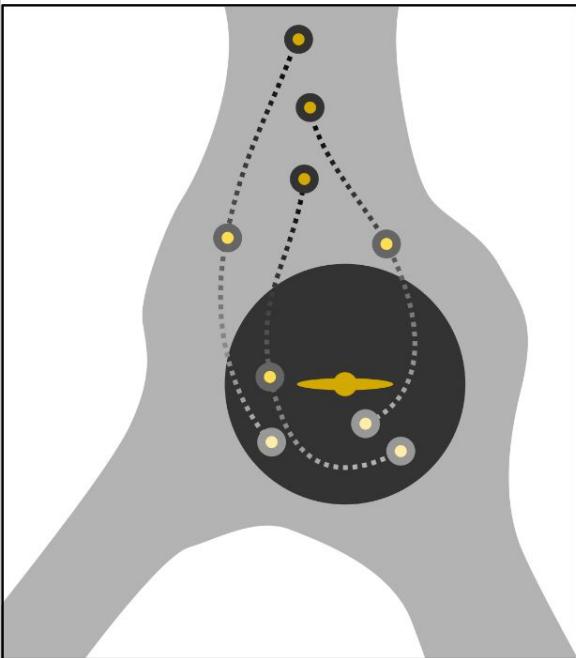
Group Infall



Do not produce long lived planes  
Effect already included in cosmo sims.  
The LMC didn't bring many satellites into the plane

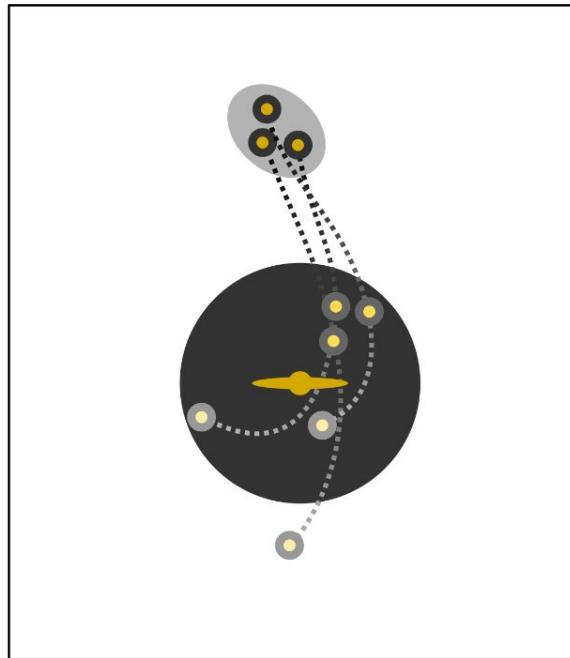
# Posibles escenarios de formación de planos co-rotantes

Filamentary Accretion



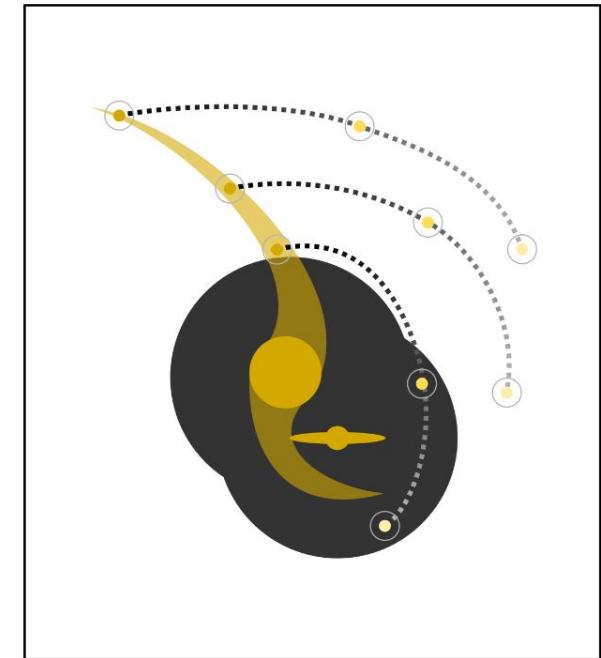
Already included in cosmo sims.  
Mainly produce thick planes!

Group Infall



Do not produce long lived planes  
Effect already included in cosmo sims.  
The LMC didn't bring many satellites into the plane

Tidal Dwarf Galaxies

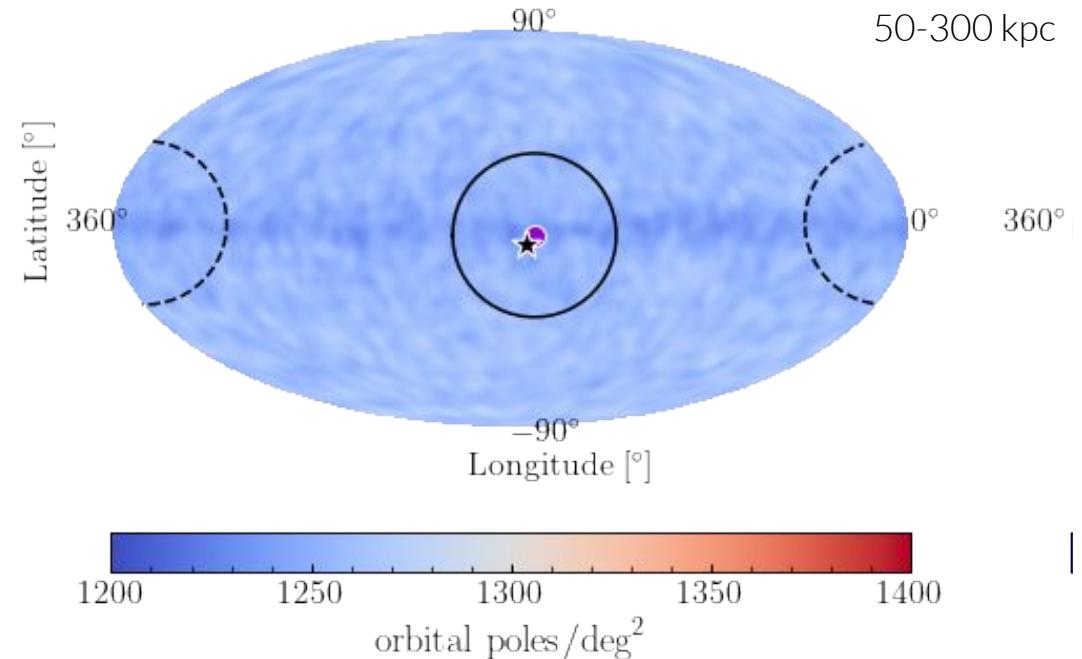


Pawlowski (2018)

MW's satellites have  
low metallicities

# Orbital poles in the MW-LMC N-body simulation

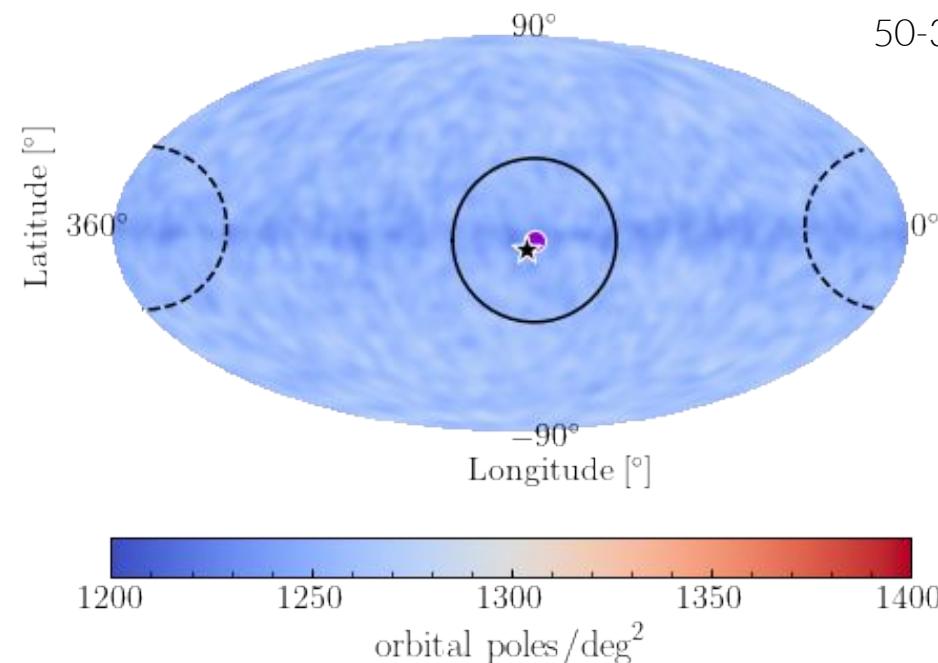
MW in isolation: Random distribution



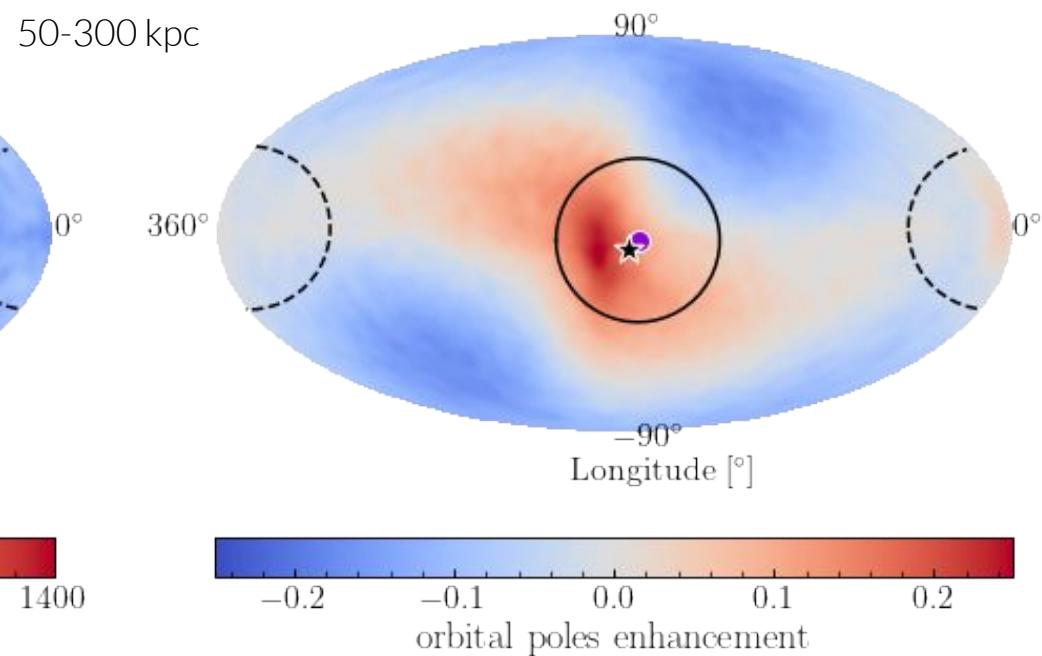
Garavito-Camargo+21b

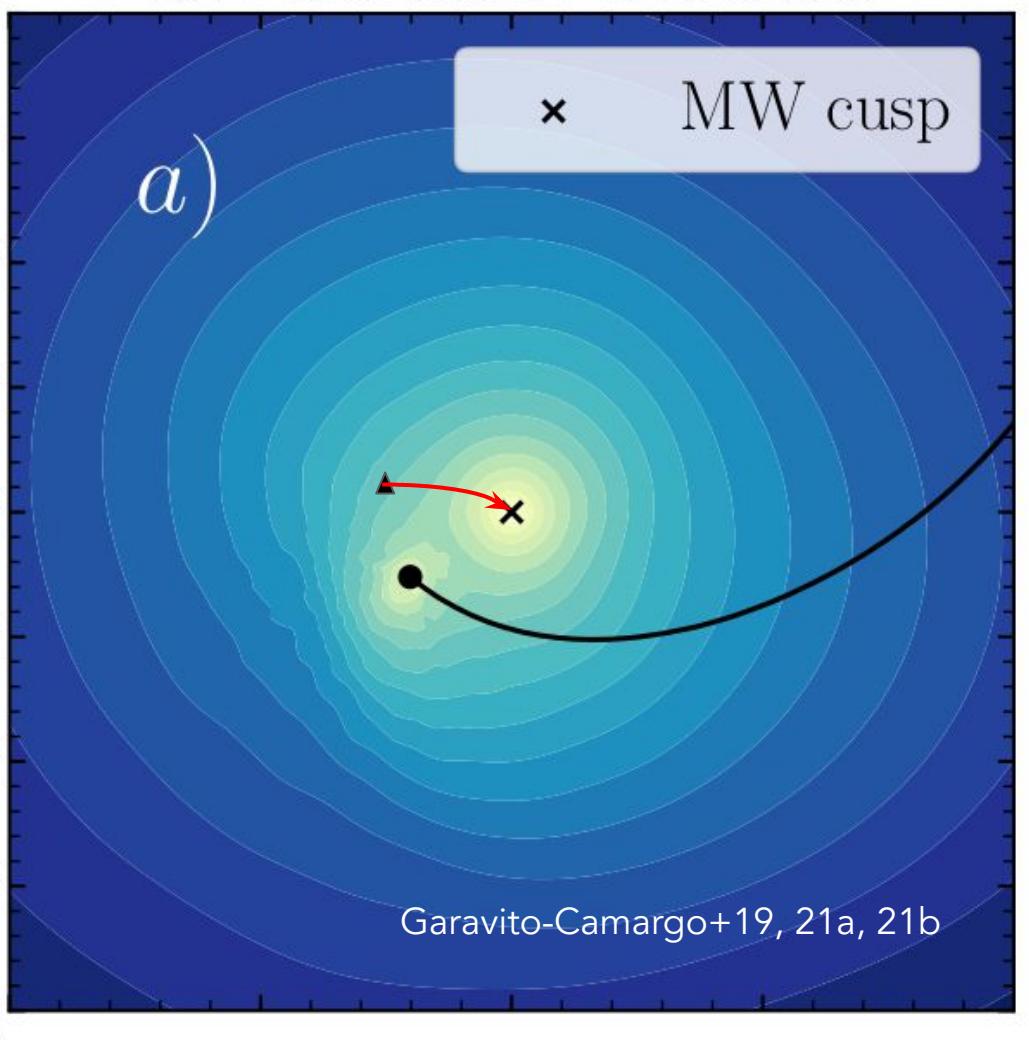
# Orbital poles in the MW-LMC N-body simulation ***are clustered***

MW in isolation: Random distribution



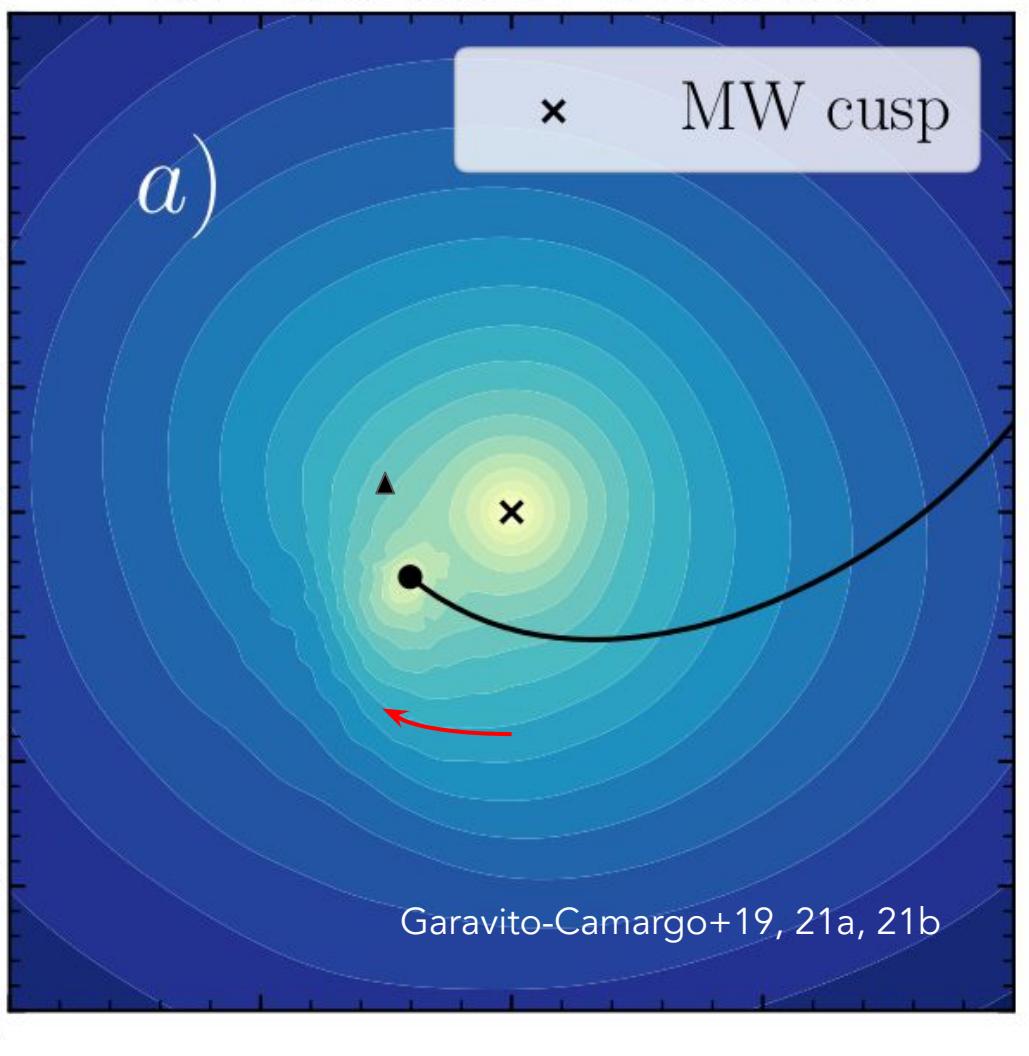
MW in presence of LMC: z-shape pattern





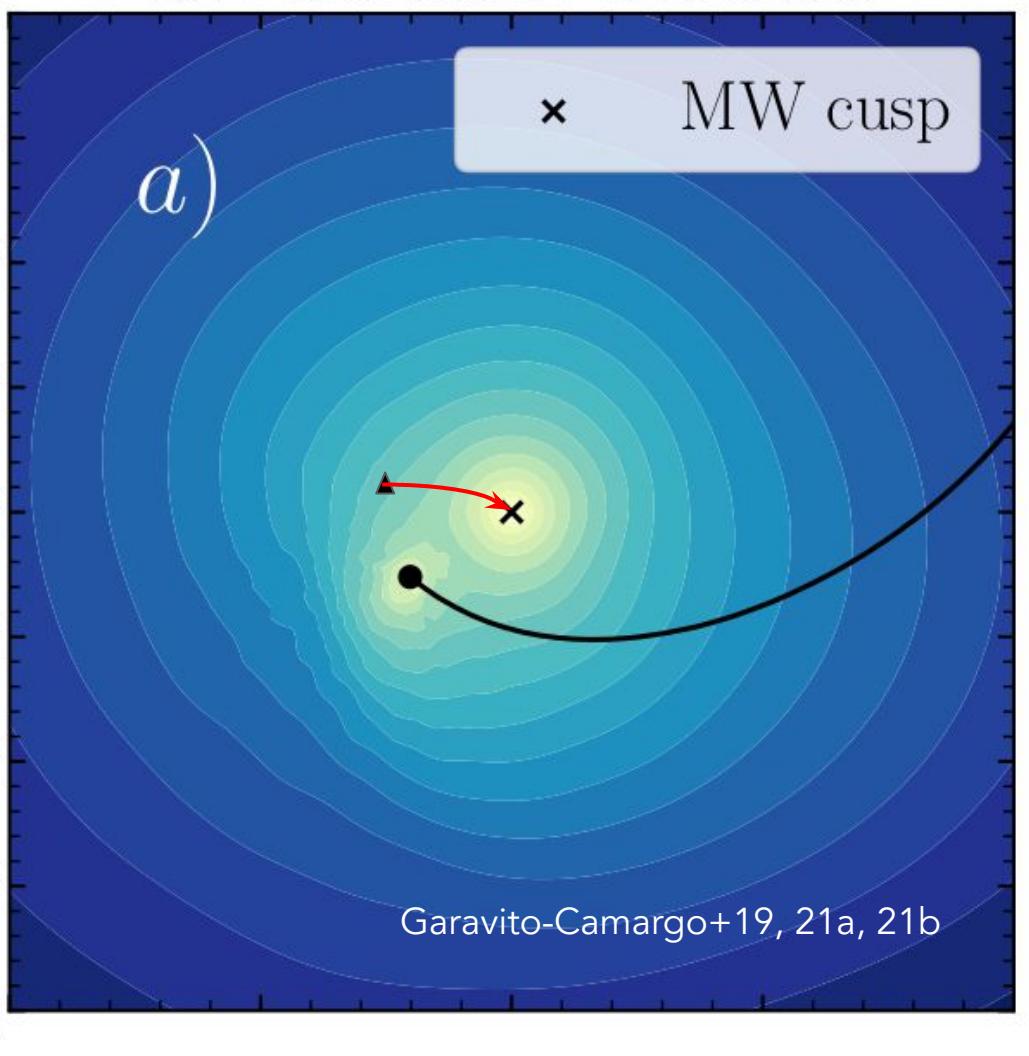
El movimiento del baricentro crea un movimiento aparente entre el halo interno y el externo

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From the inner halo the outer halo seems to be co-rotating with the LMC



The barycenter motion induces an apparent motion between the inner and outer halo.

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Desde el halo interno, el halo externo está co-rotando en la misma dirección de la nubes de Magallanes!

## Trabajo en progreso sobre planos de satélites:

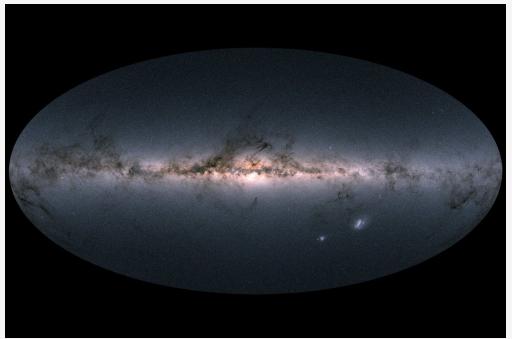
- Integrar las órbitas de las galaxias satélites en potenciales que incluyan realísticamente el efecto de la Nube de Magallanes. (BFE)
- Analizar simulaciones cosmológicas en sistemas análogos a la VL+Nub. Mag.

# Conclusiones

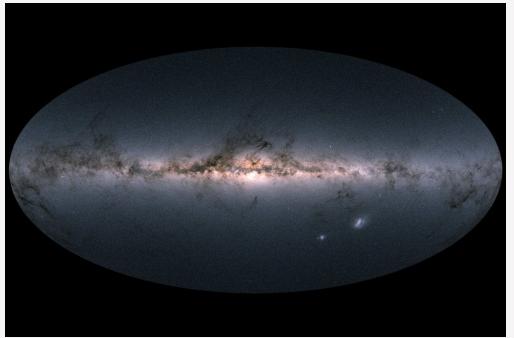
?



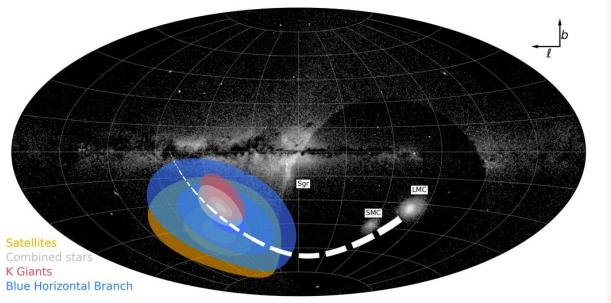
# Conclusiones



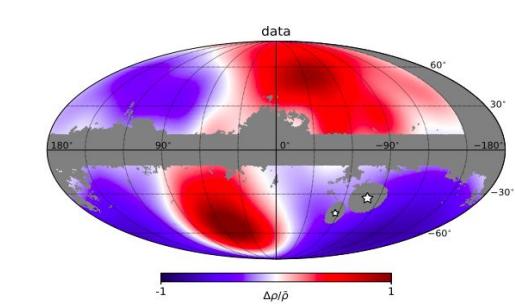
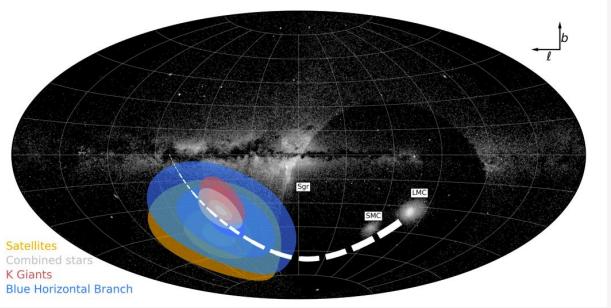
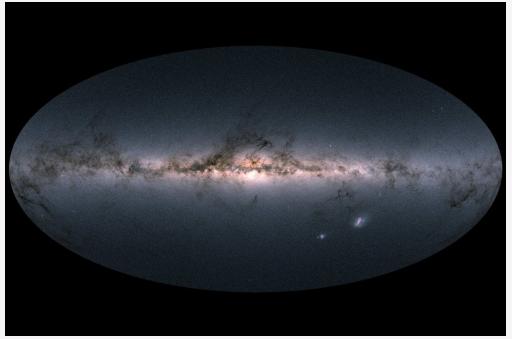
# Conclusiones



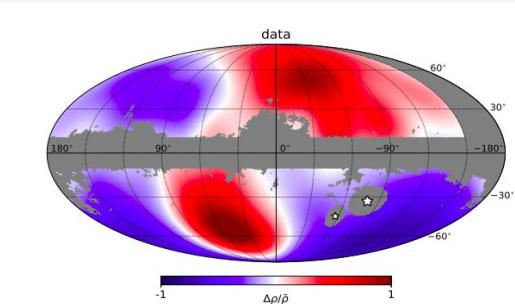
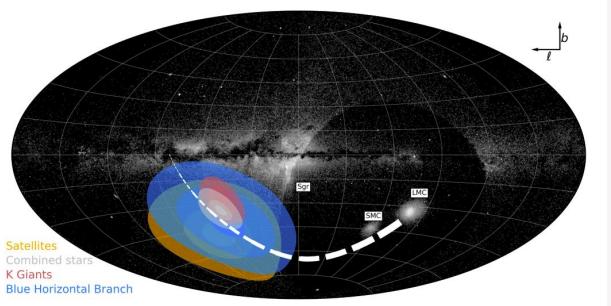
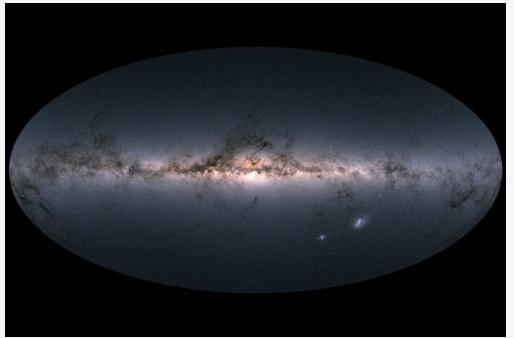
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# Conclusiones

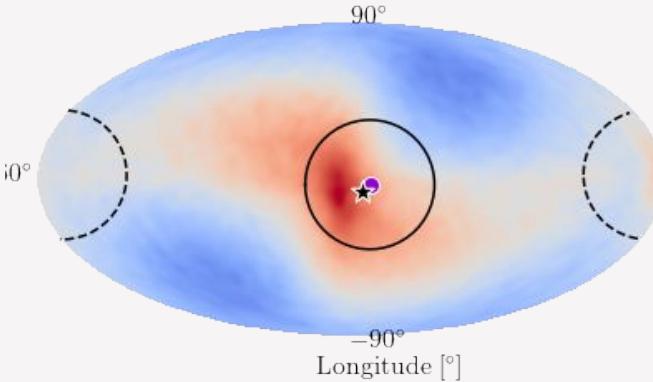
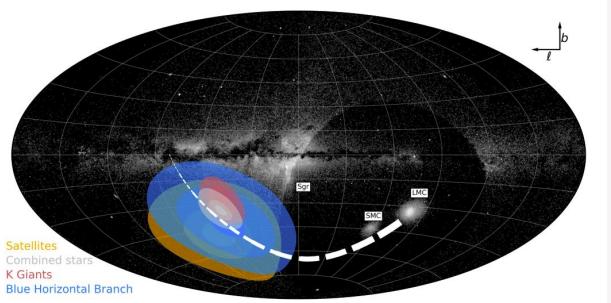
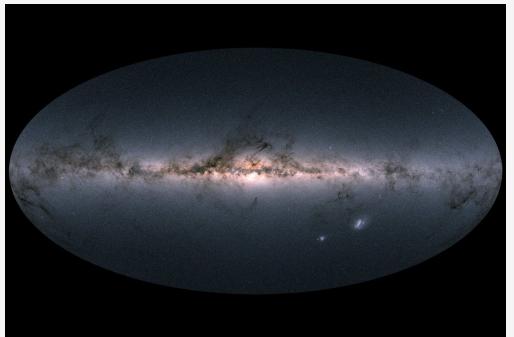


# Conclusions

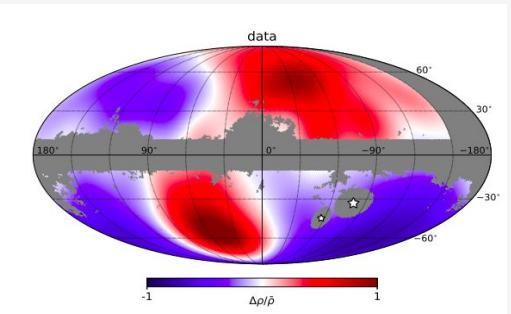


$$\check{\rho}(\mathbf{x}) = \sum_{\mu=1}^M a_\mu d_\mu(\mathbf{x})$$

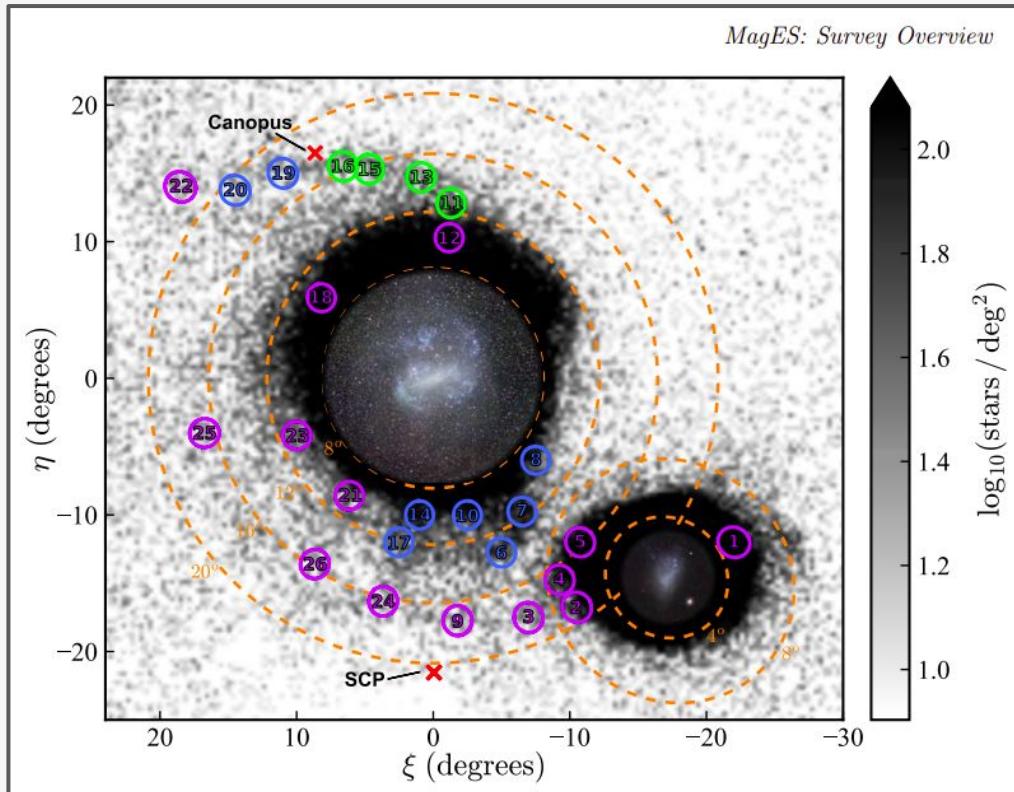
# Conclusiones



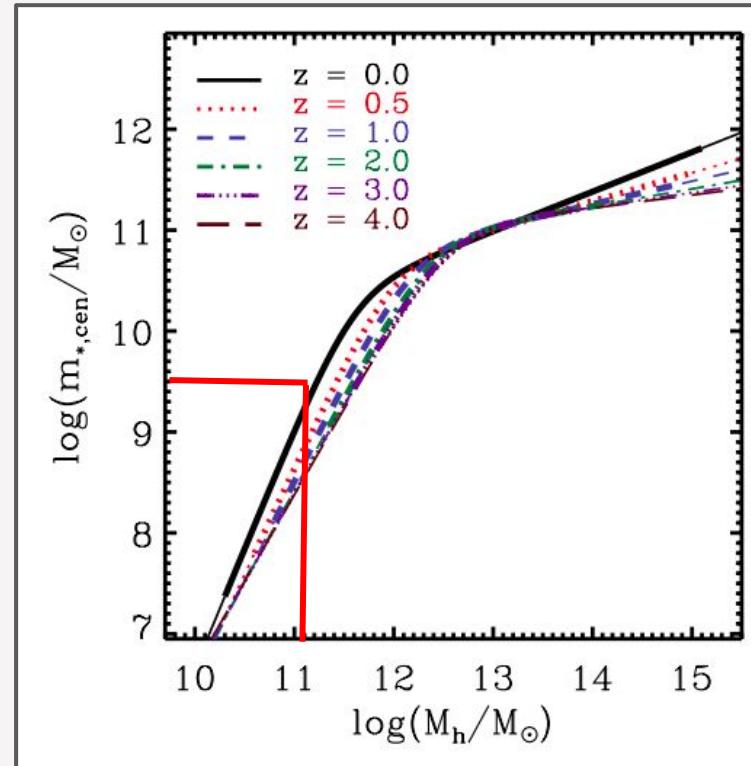
$$\check{\rho}(\mathbf{x}) = \sum_{\mu=1}^M a_\mu d_\mu(\mathbf{x})$$



# The LMC is massive: Its likely in a dark matter halo of $\sim 10^{11} M_{\odot}$ 10-20% the mass of the Milky Way

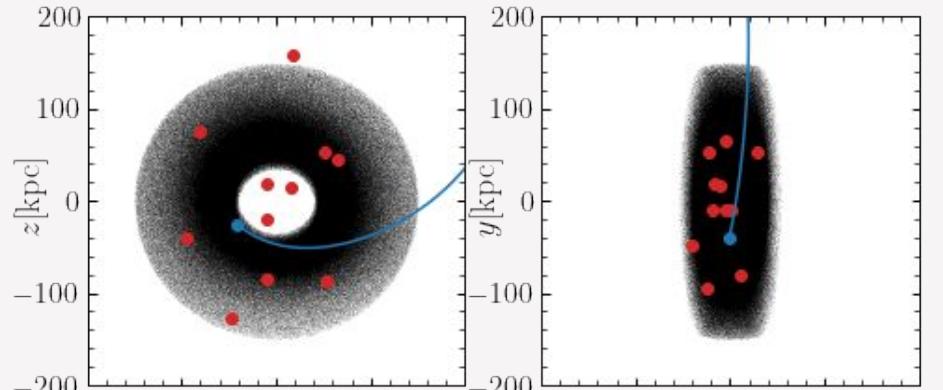


Cullinane+20

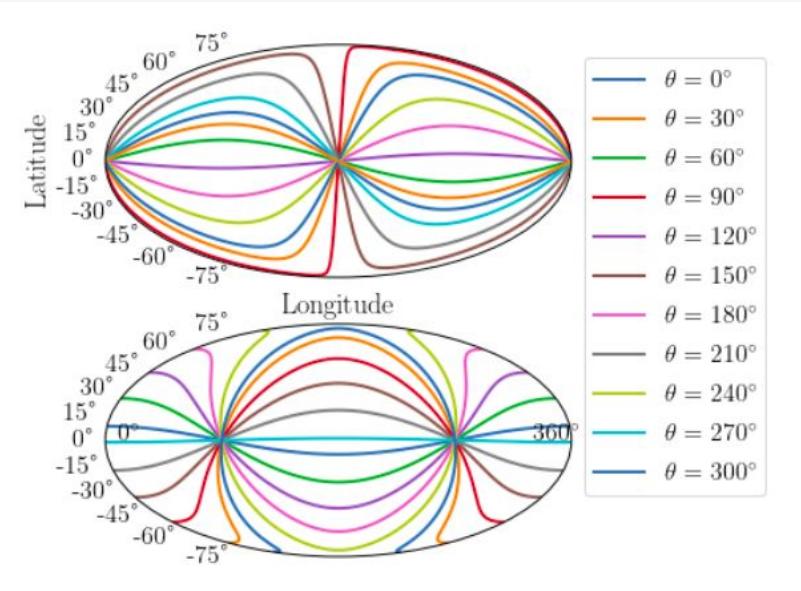
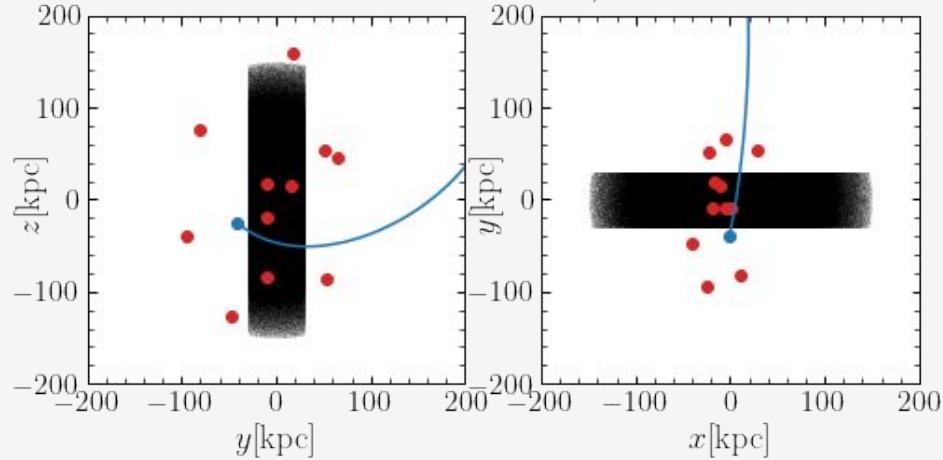


Moster+13

Plane 1:  $l = 10^\circ$ ,  $b = 90^\circ$  tilt

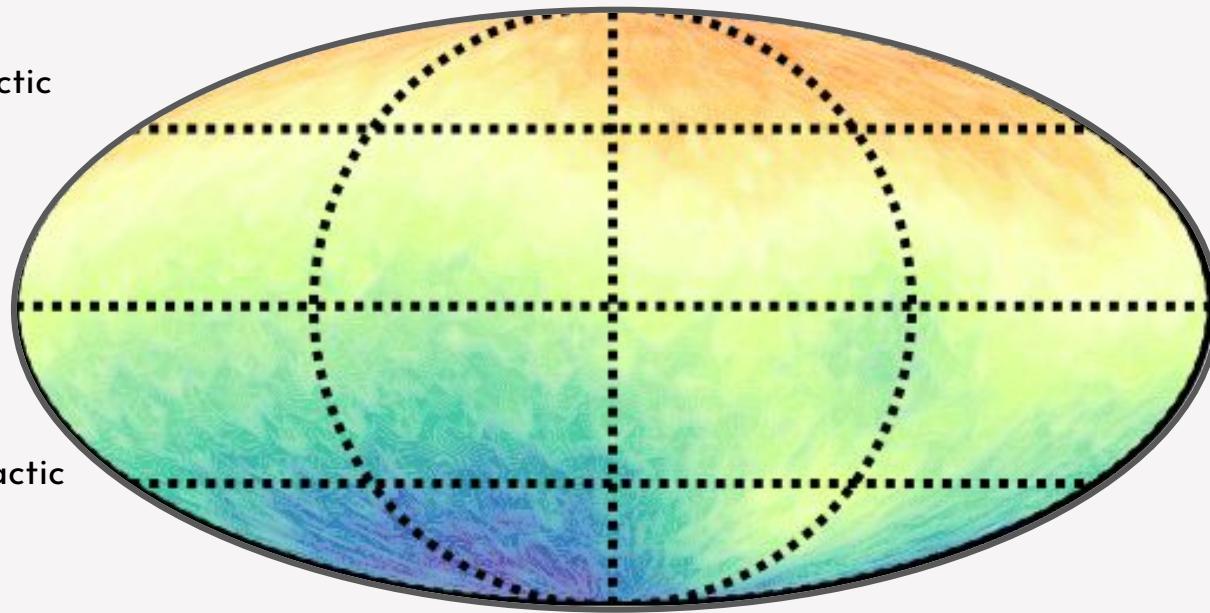


Plane 2:  $l = 90^\circ$ ,  $b = 90^\circ$  tilt

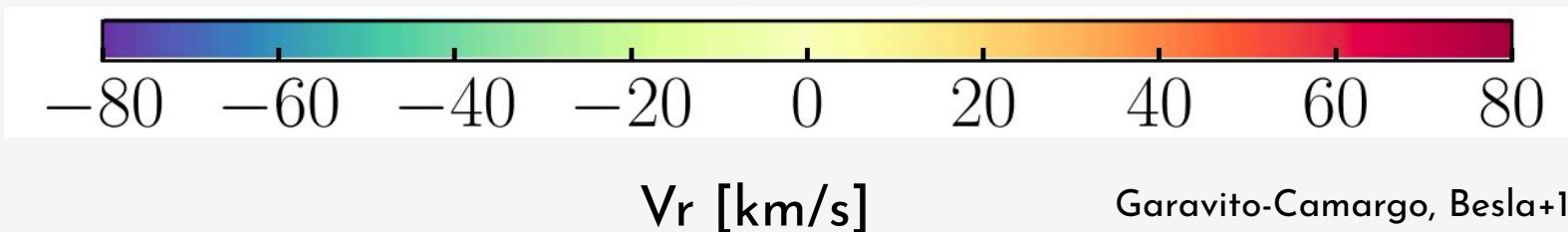


# Reflex motion observed at $R_{\text{gal}}=100$ kpc

Northern Galactic Hemisphere



Southern Galactic Hemisphere



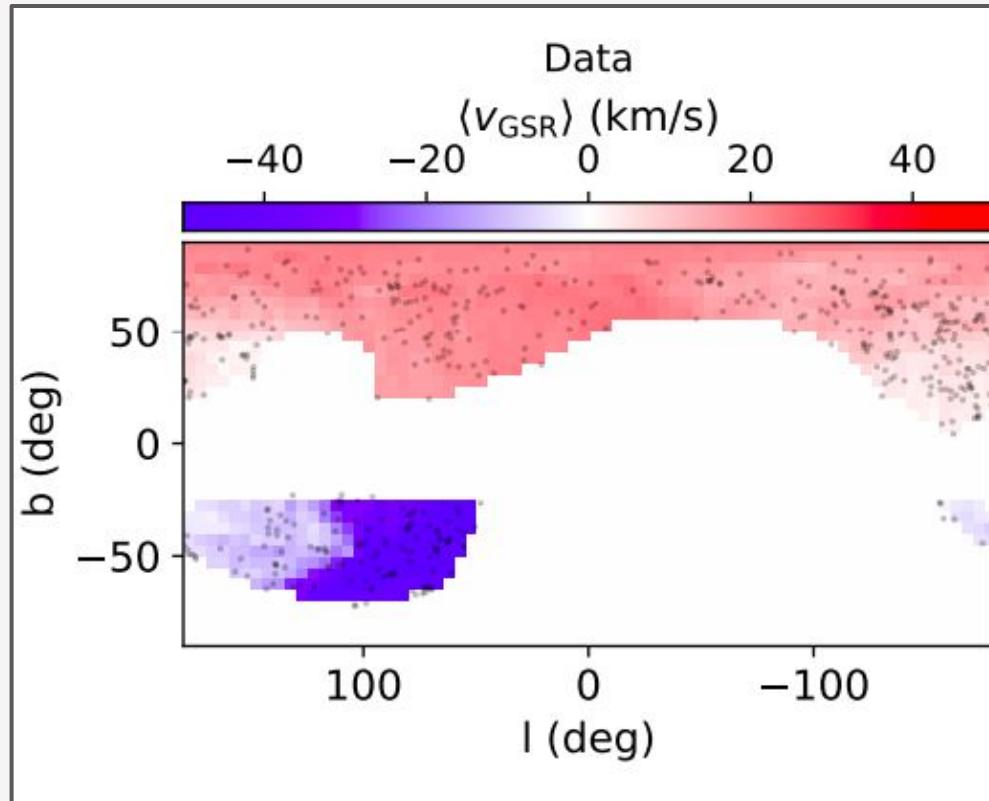
$V_r$  [km/s]

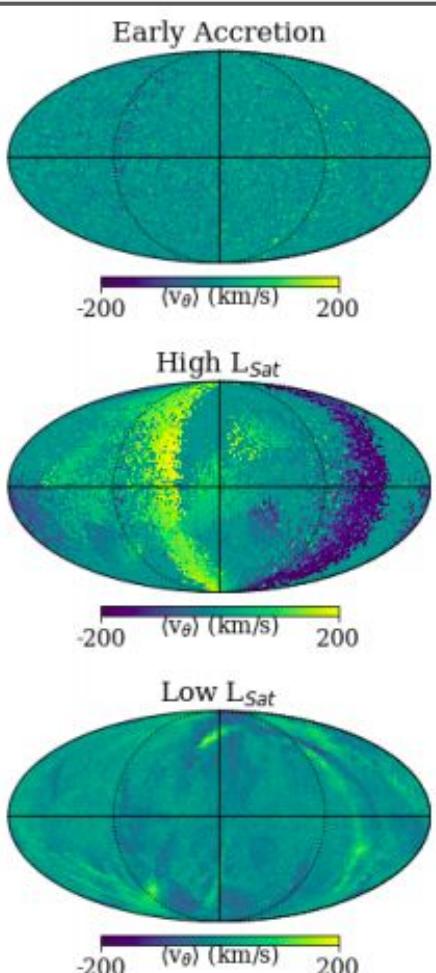
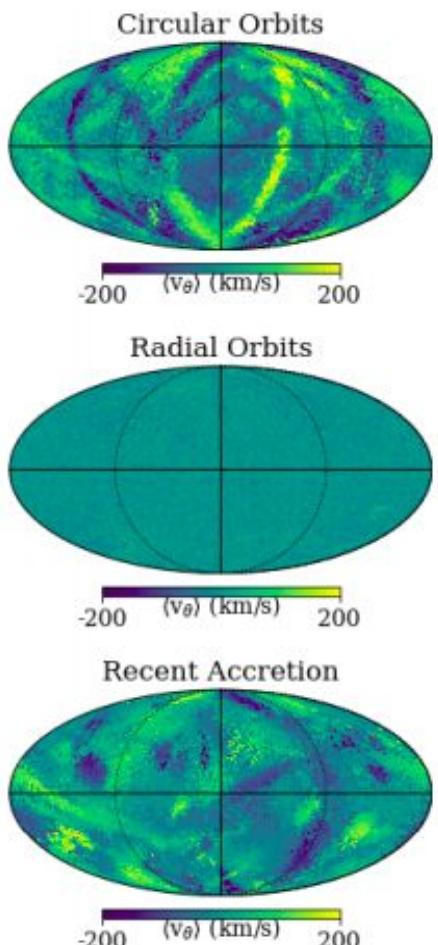
Garavito-Camargo, Besla+19

# Gaia's detection of the reflex motion direction

K-giants  
K-giants  
BHB/BS  
RR Lyrae  
BHB/BS  
BHB

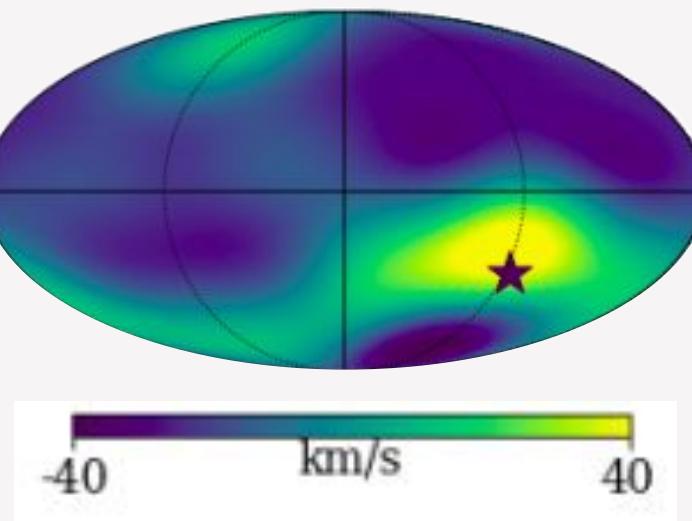
846 stars between  
50 -105 kpc





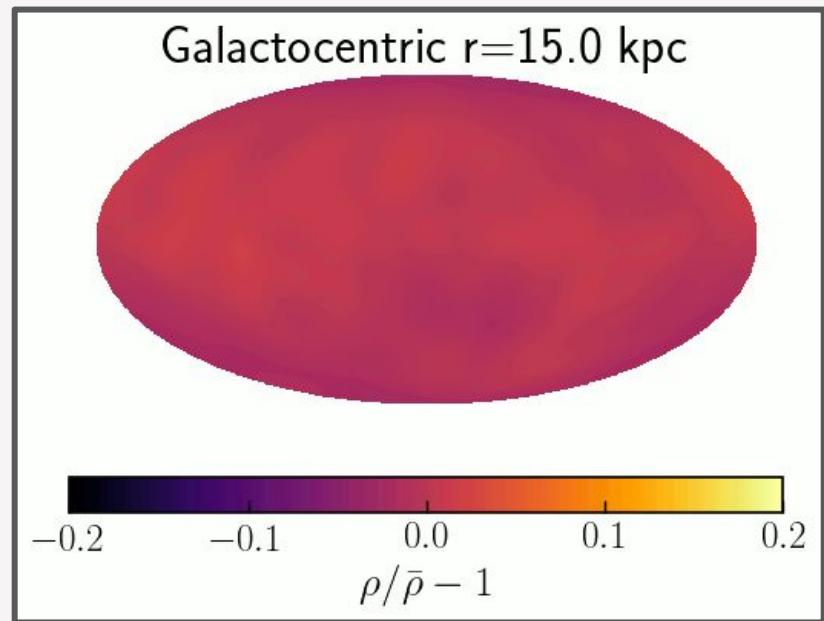
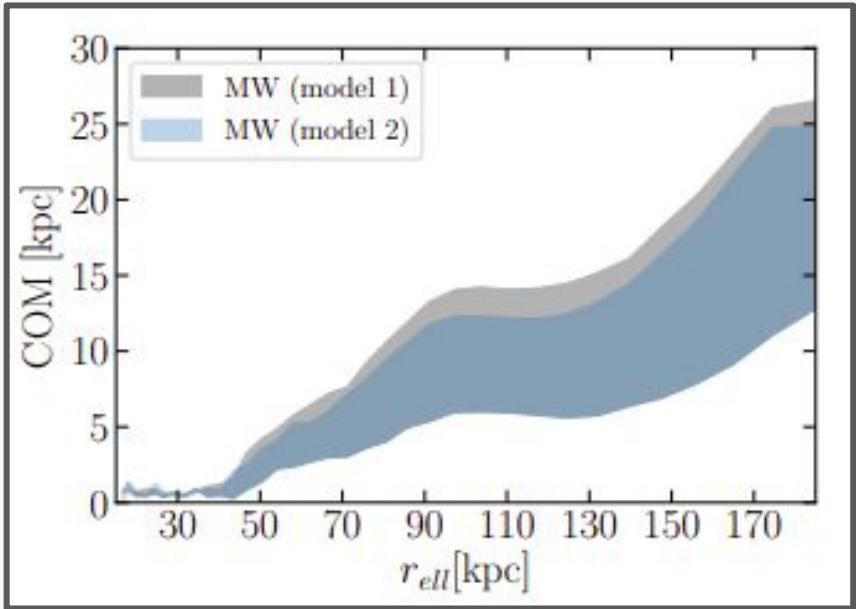
However, the halo is not smooth, there is substructure

VS



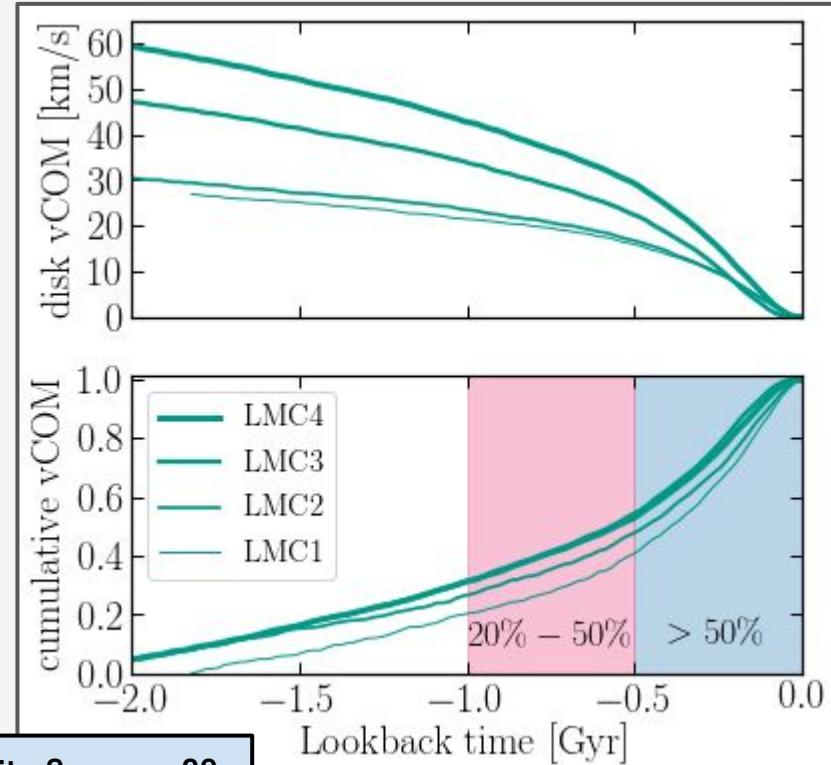
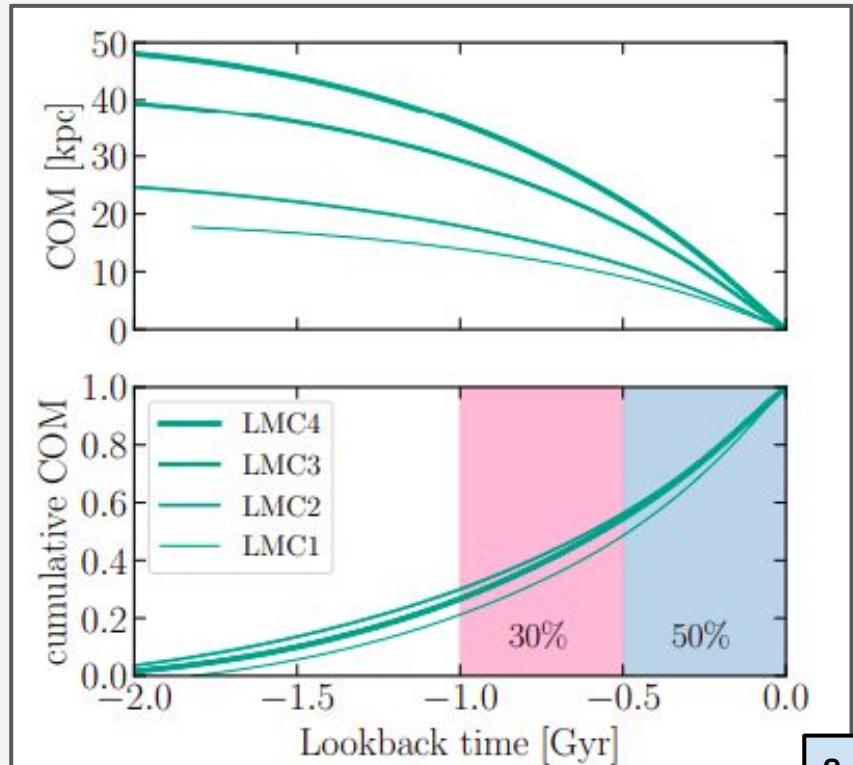
Cunningham, Garavito-Camargo et al 20

## B. Effect in the positions of the MW's outer stellar halo:



Garavito-Camargo+20

We are in a particular time in the MW-LMC interaction, *near pericenter*, were the CUSP motion is the strongest



# LMC orbit