Modelling the Milky Way and Sagittarius Dwarf galaxy in the Era of Gaia, LSST and ELT

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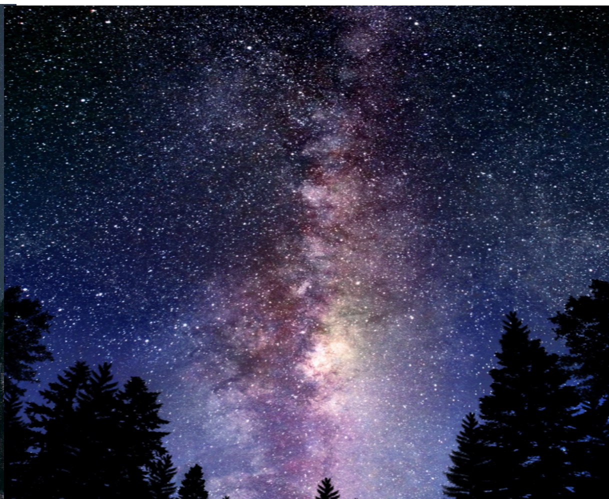
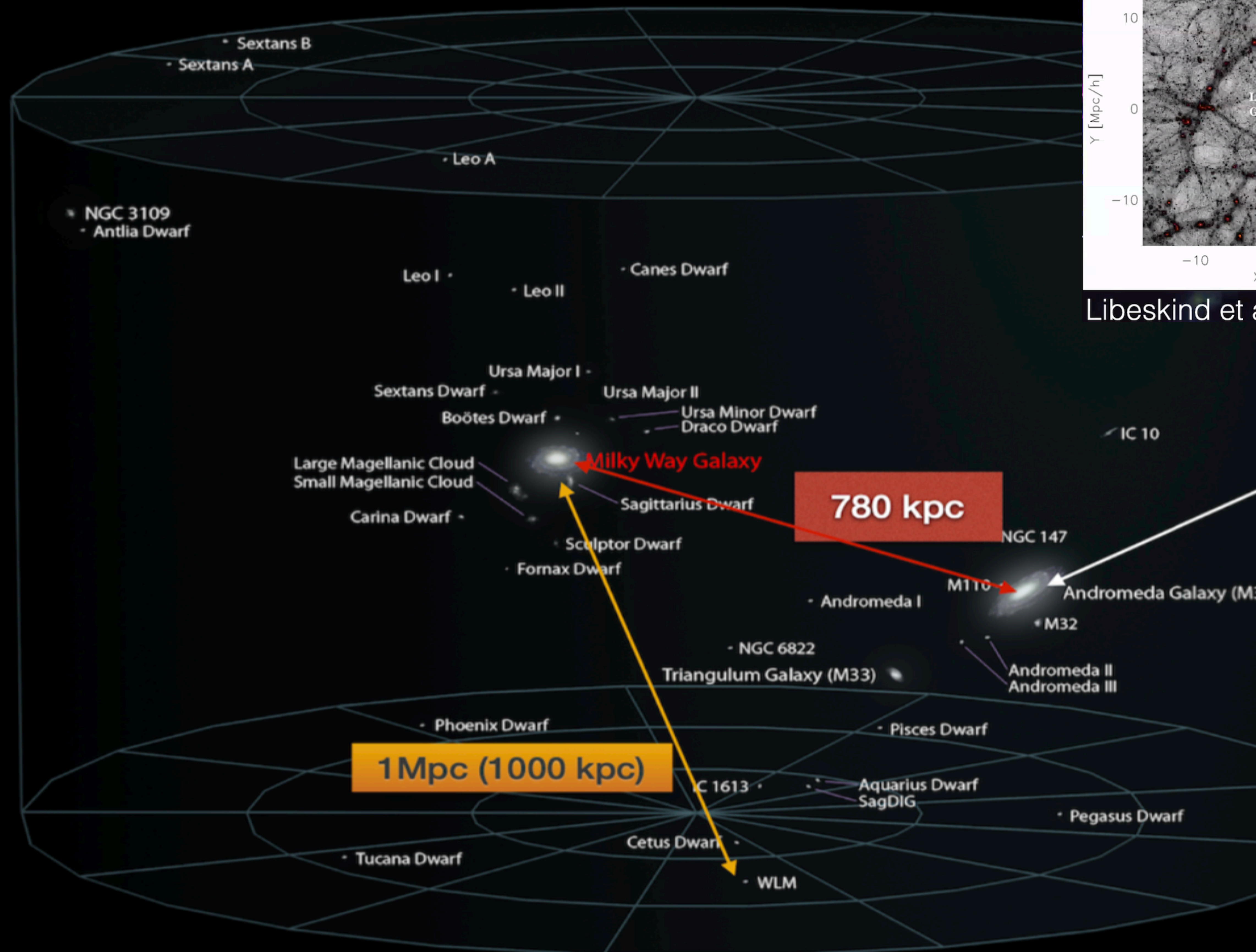
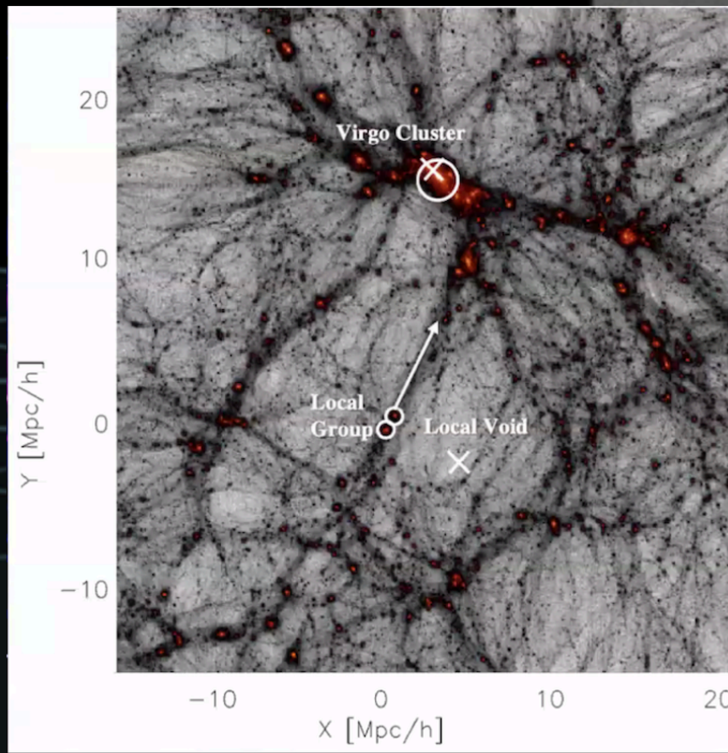
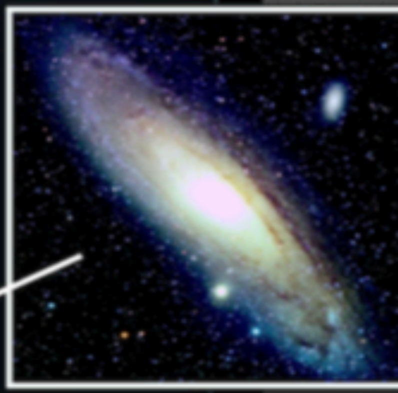


LOCAL GALACTIC GROUP





Libeskind et al. 2020



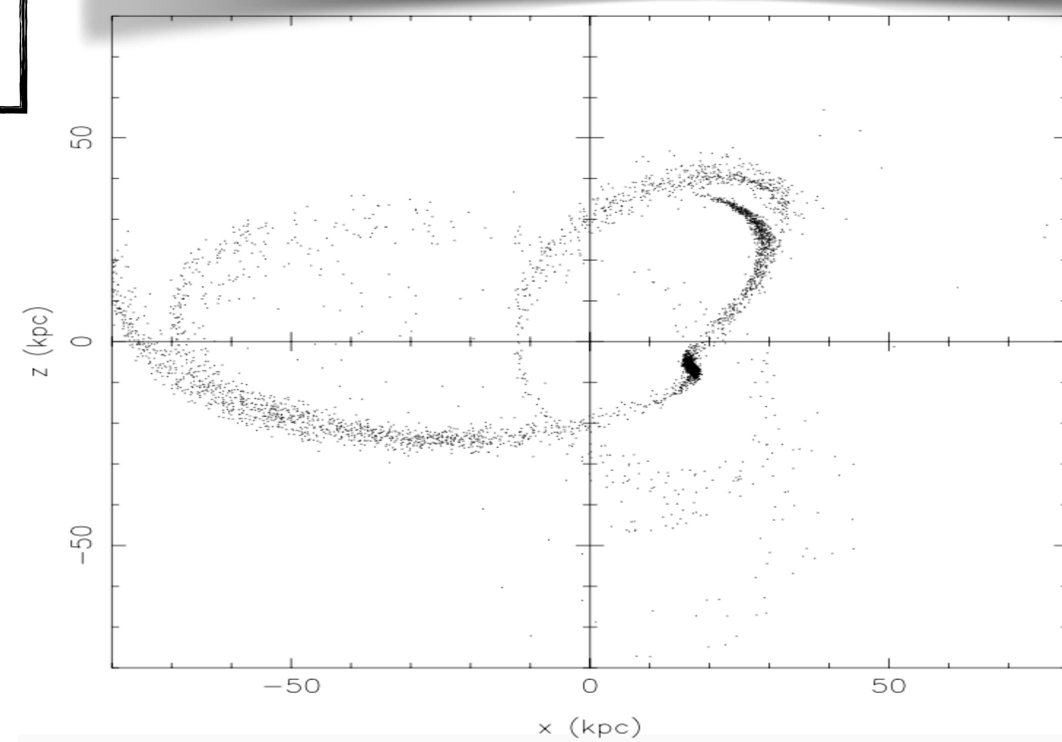
Credit: webpage


Sgr leading arm
Sgr trailing arm
Milky Way
Sun
Sgr core
Simulated by Hai-Feng Wang et al.

Background

*Since it was discovered by Ibata+1994 using UKST and AAT. Many observations/modelling of the Sagittarius (Sgr) stream/core have been attempted, but we still have difficulties to reproduce its full 6D space-phase properties.

Ibata+2001-model, 2020; Helmi+2020; Yanny+2000; Newberg+2001; Majewski+2003; and so on.



LETTERS TO NATURE

A dwarf satellite galaxy in Sagittarius

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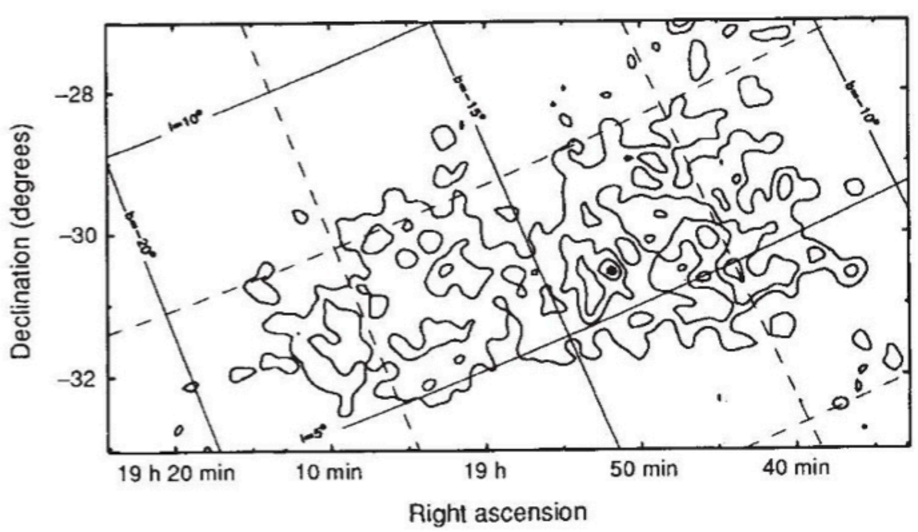
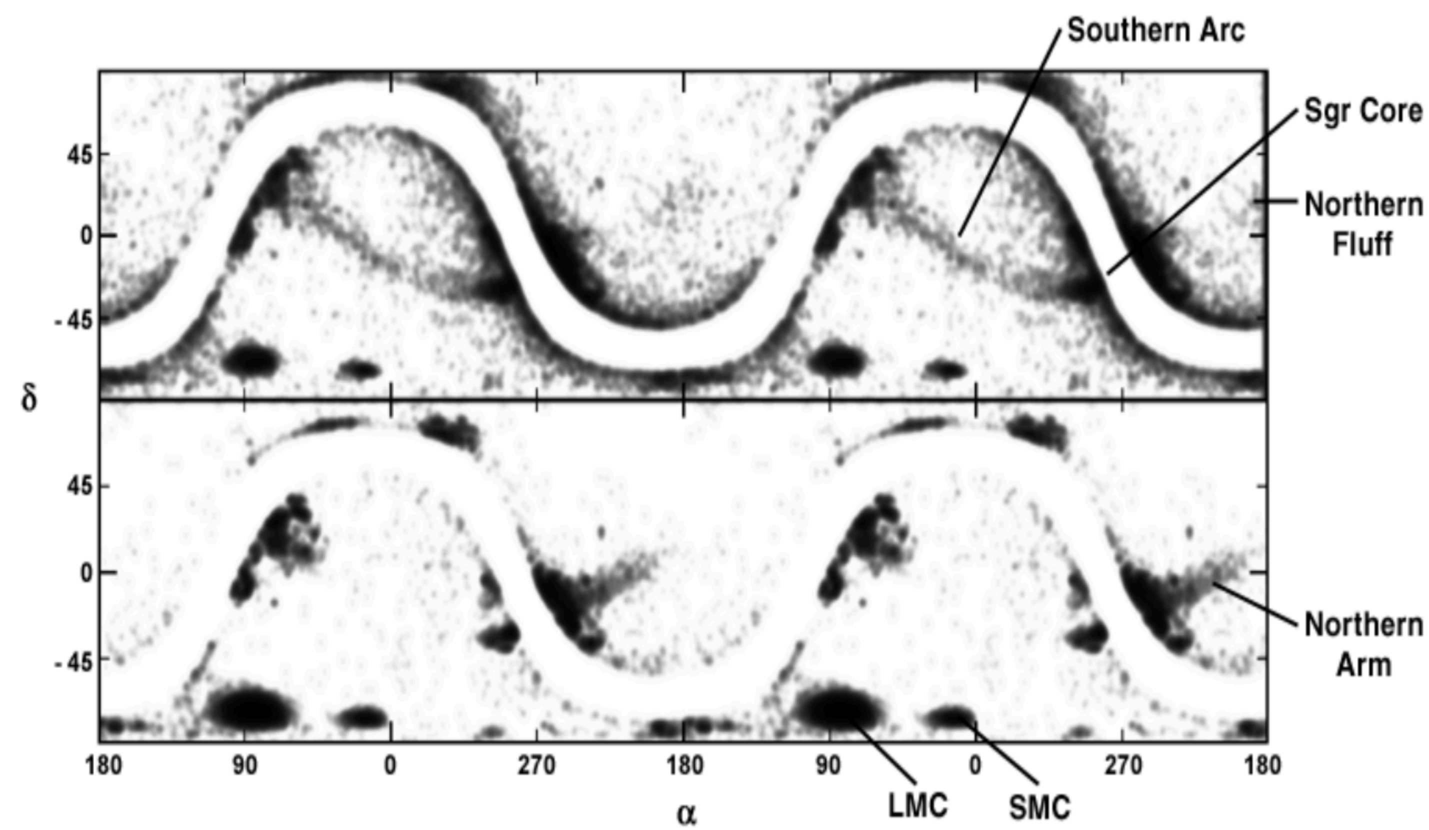
WE have detected a large, extended group of comoving stars in the direction of the Galactic Centre, which we interpret as belonging to a dwarf galaxy that is closer to our own Galaxy than any other yet known. Located in the constellation of Sagittarius, and on the far side of the Galactic Centre, it has not previously been seen because of the large number of foreground stars (in the Milky Way) in that direction. Following convention, we propose to call it the Sagittarius dwarf galaxy. Its properties are similar to those of the eight other dwarf spheroidal companions to the Milky Way, and it is comparable in size and luminosity to the largest of them—the Fornax system. The Sagittarius dwarf is elongated towards the plane of the Milky Way, suggesting that it is undergoing some



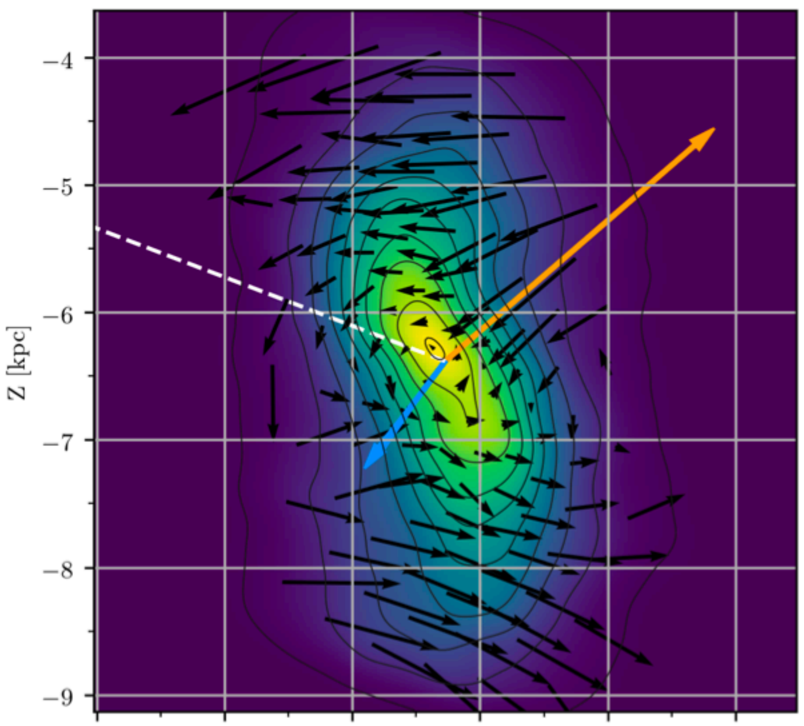
Majewski+2003 (2MASS); model in 2010; See also Belokurov+2006, etc.



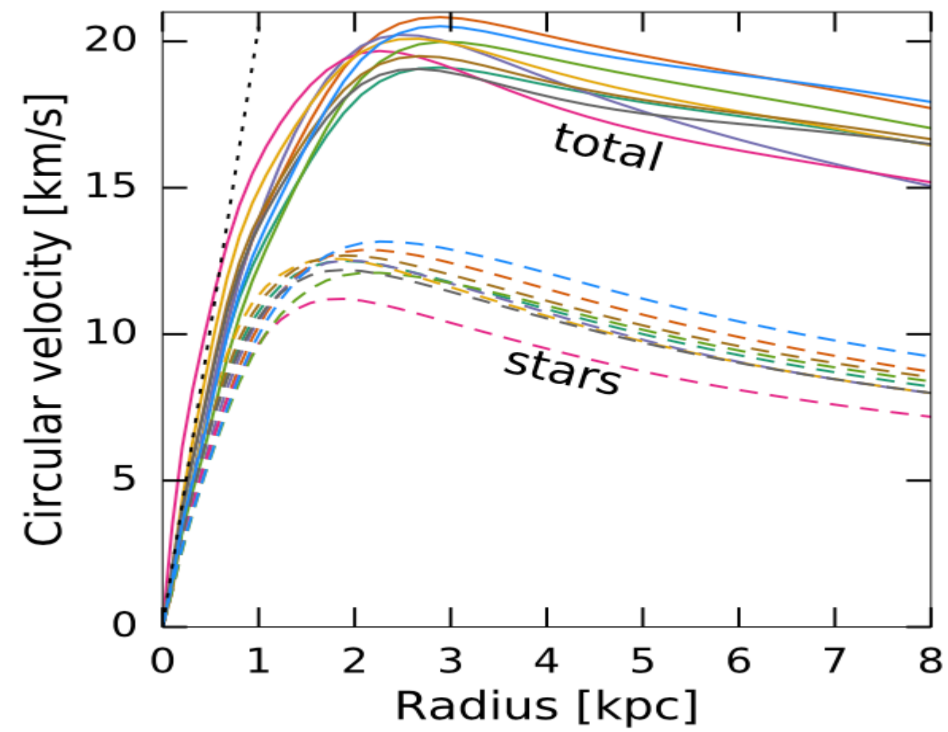
Mild rotation vs. Not rotation model for Core?

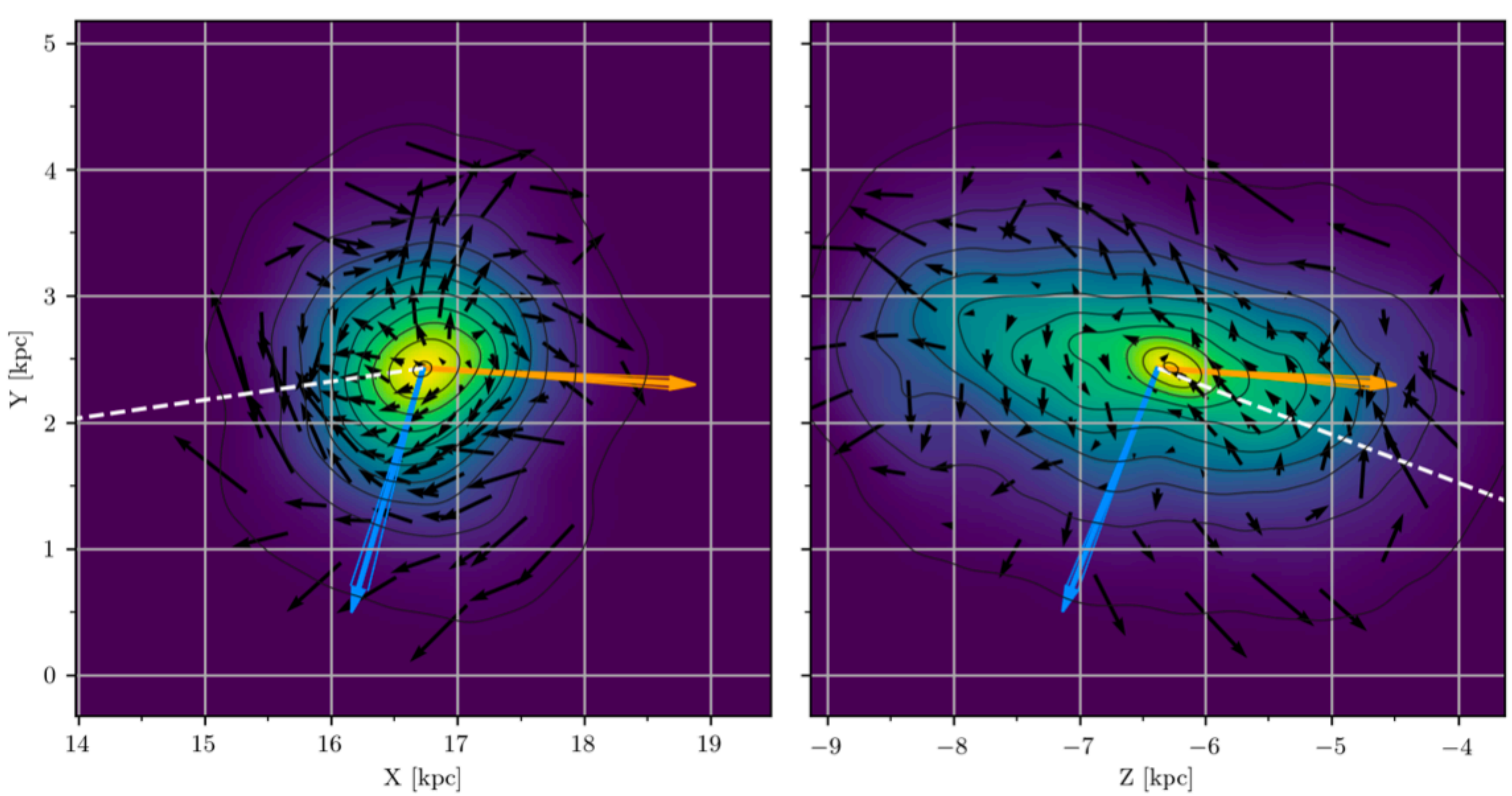
Del Pino+2021: Core morphology, kinematics. MW-Sgr like; has rotation in model

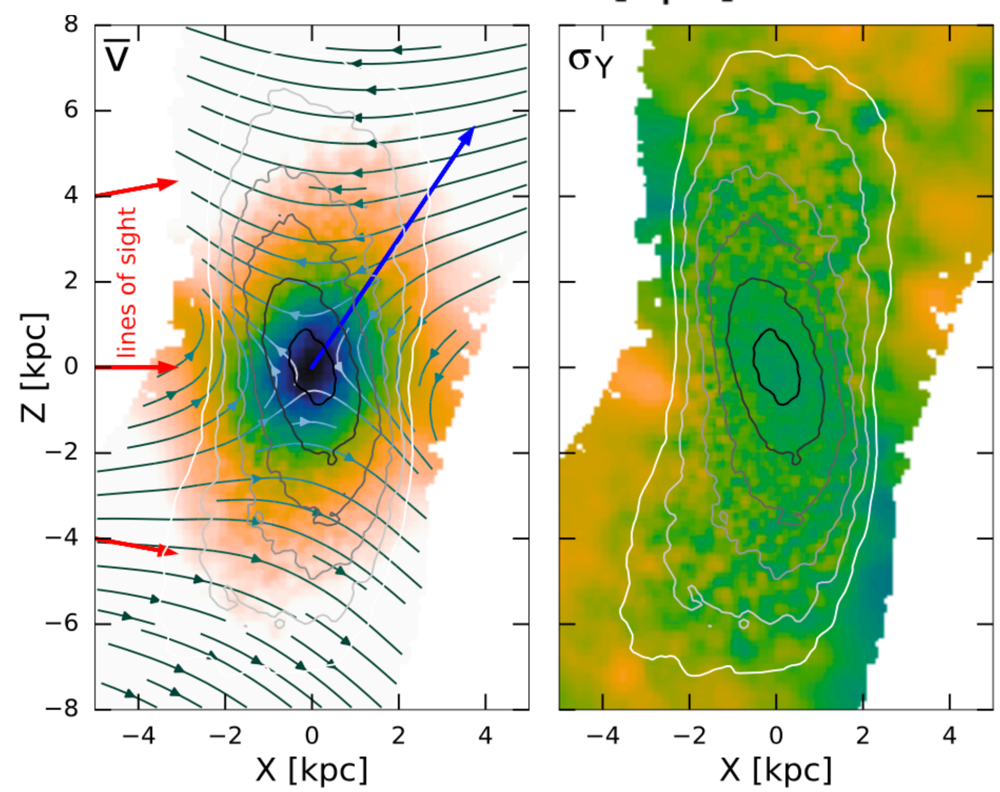
Vasiliev+2020: Core morphology, kinematics; No rotation in core



For the Sgr centre, we adopt the distance $D_0 = 26.5$ kpc, line-of-sight velocity $v_{\mathrm{los},0} = 142\ \mathrm{km\,s^{-1}}$, and PM $\mu_{\alpha,0} = -2.7\ \mathrm{mas\,yr^{-1}}$, $\mu_{\delta,0} = -1.35\ \mathrm{mas\,yr^{-1}}$. We adopt the following values for the Solar position and velocity in the Galactocentric rest frame: $X = -8.1$ kpc, $V_{\{X,Y,Z\}} = \{12.9, 245.6, 7.8\}\ \mathrm{km\,s^{-1}}$ (Astropy collaboration 2018); the corresponding position and velocity of the Sgr centre are $\{X,Y,Z\} = \{17.5, 2.5, -6.5\}$ kpc, $V_{\{X,Y,Z\}} = \{237.9, -24.3, 209.0\}\ \mathrm{km\,s^{-1}}$.





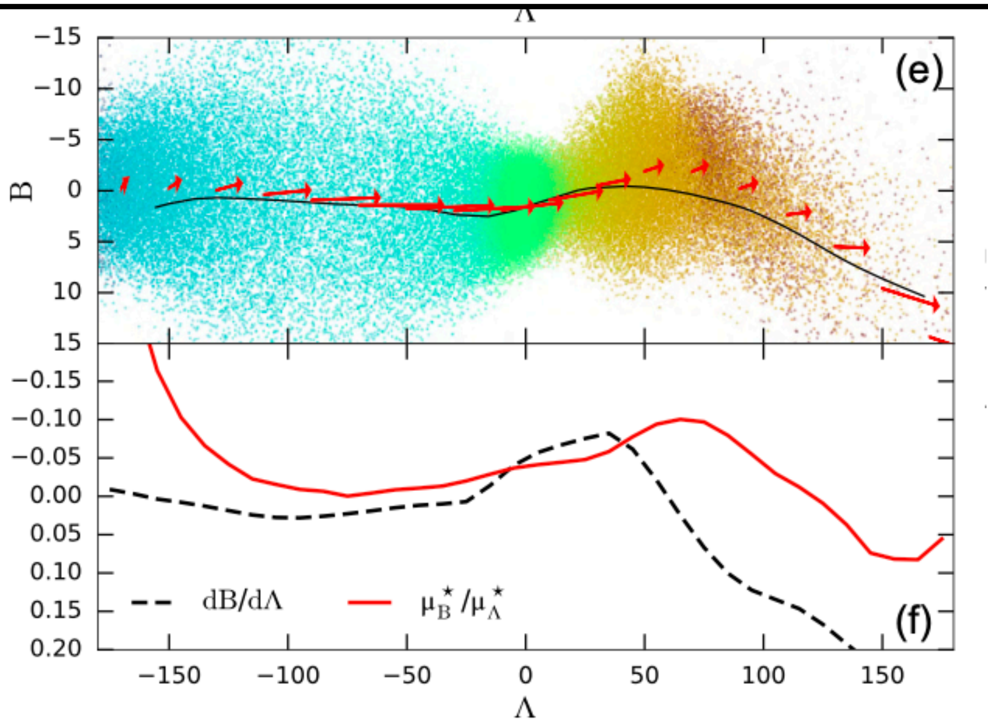


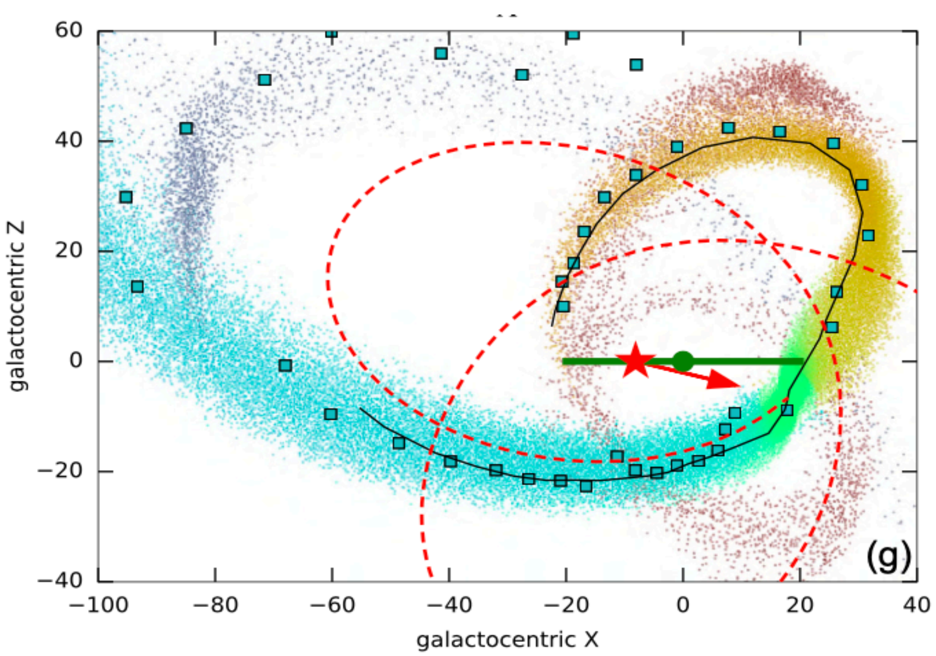
Many mysteries for Sgr Dwarf in Observation and Modelling

Disk or not for stream details? Is gas important?

Vasiliev+2021: RGB/RR Lyrae stars for stream;
N-body simulations with massive LMC.

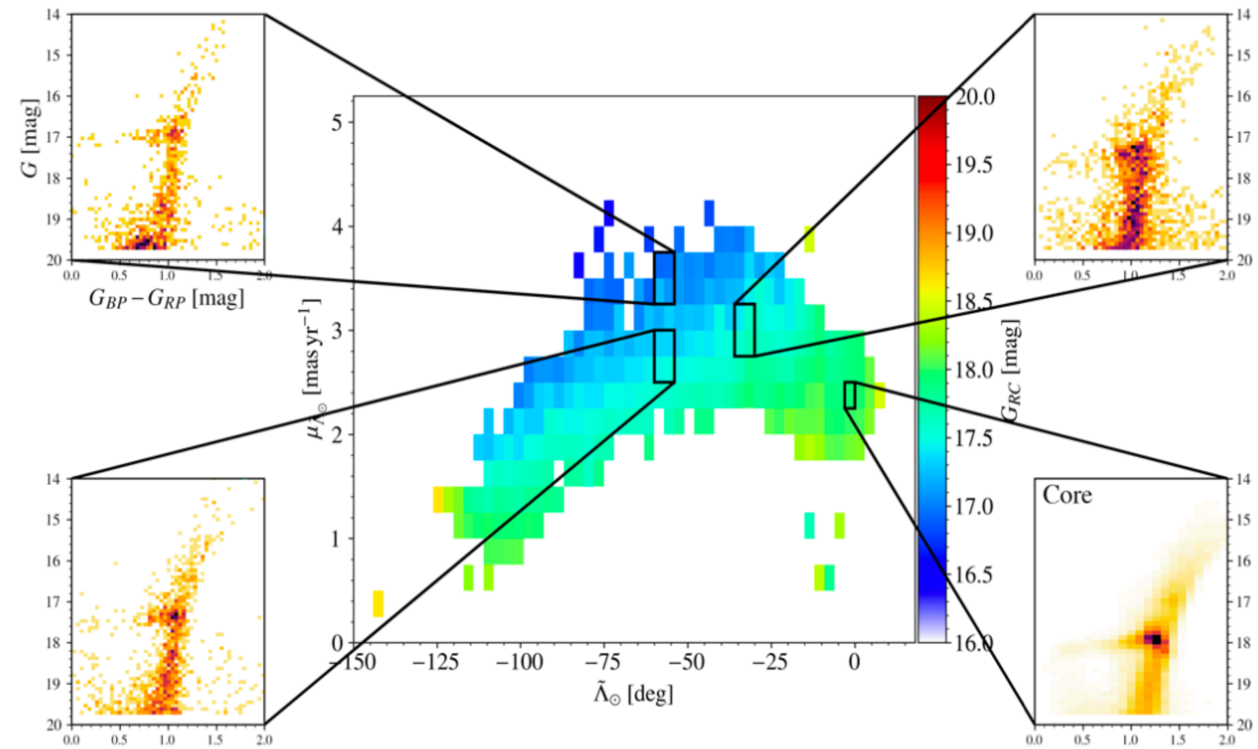
Misalignment for stellar track and proper motion

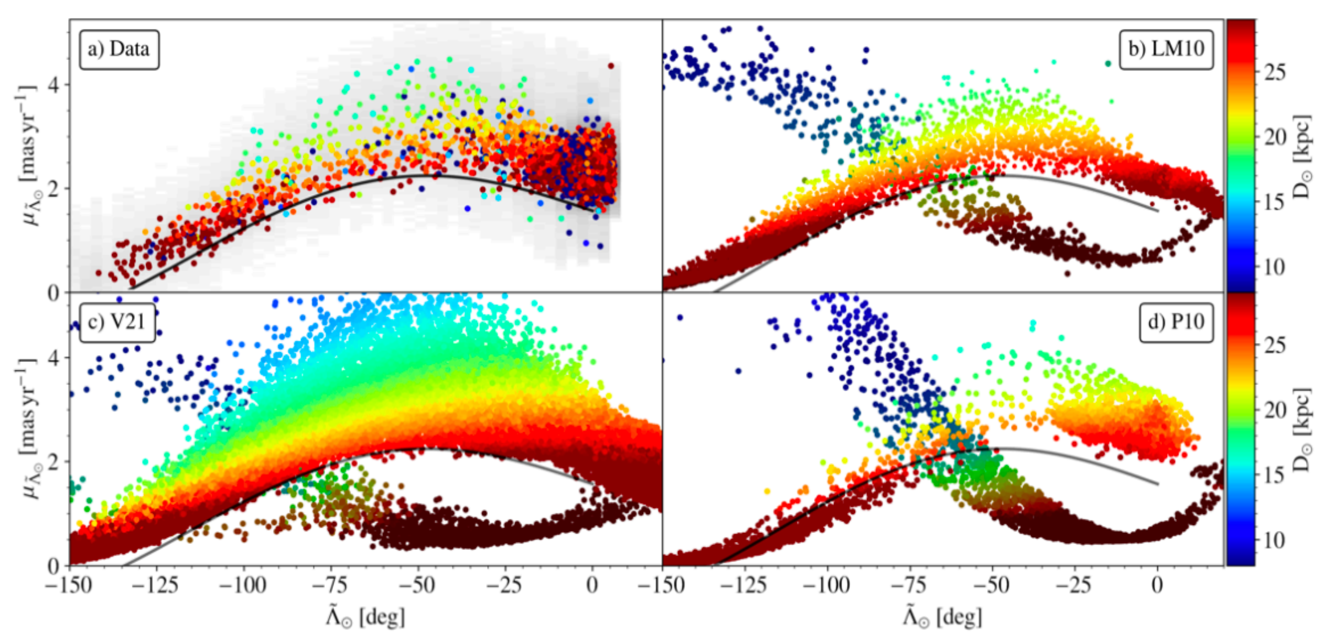




No bifurcation and no gas (MW+Sgr+LMC).
Could gas explain the misalignment?

Ramos+2022: Bifurcations with Gaia EDR3;
Leading/trailing arm bifurcations were discovered by
Belokurov+2006 and Koposov+2012 (SDSS)



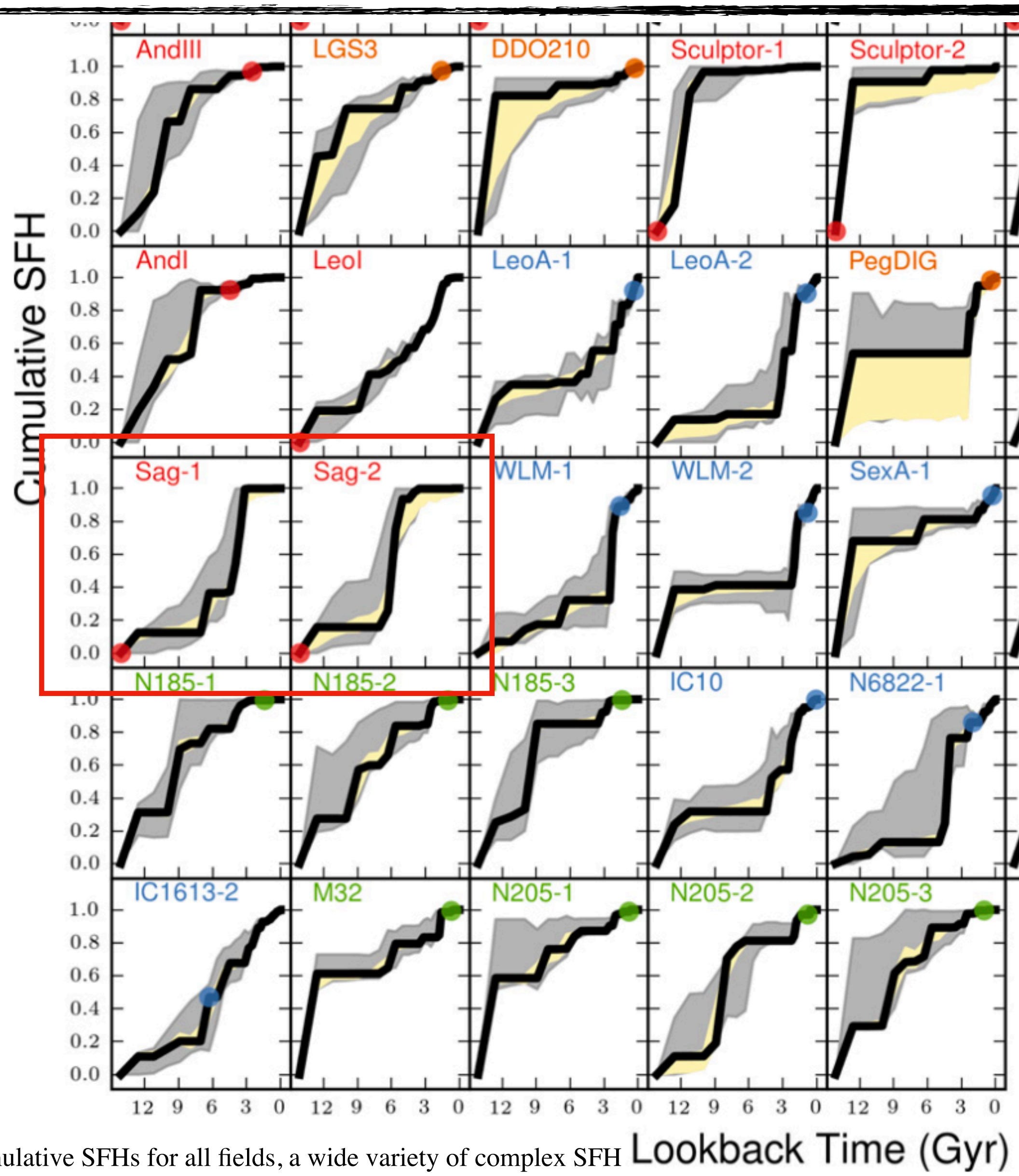


Current models are still not perfect. Q?

Weisz+2014: SFH/Gas for Sgr?

Putman+2014: Gas for Sgr?

See also Grcevich+2009; Tepper-Garcia & Bland-Hawthorn+2018



Cumulative SFHs for all fields, a wide variety of complex SFH

THE GASEOUS TRAIL OF THE SAGITTARIUS DWARF GALAXY

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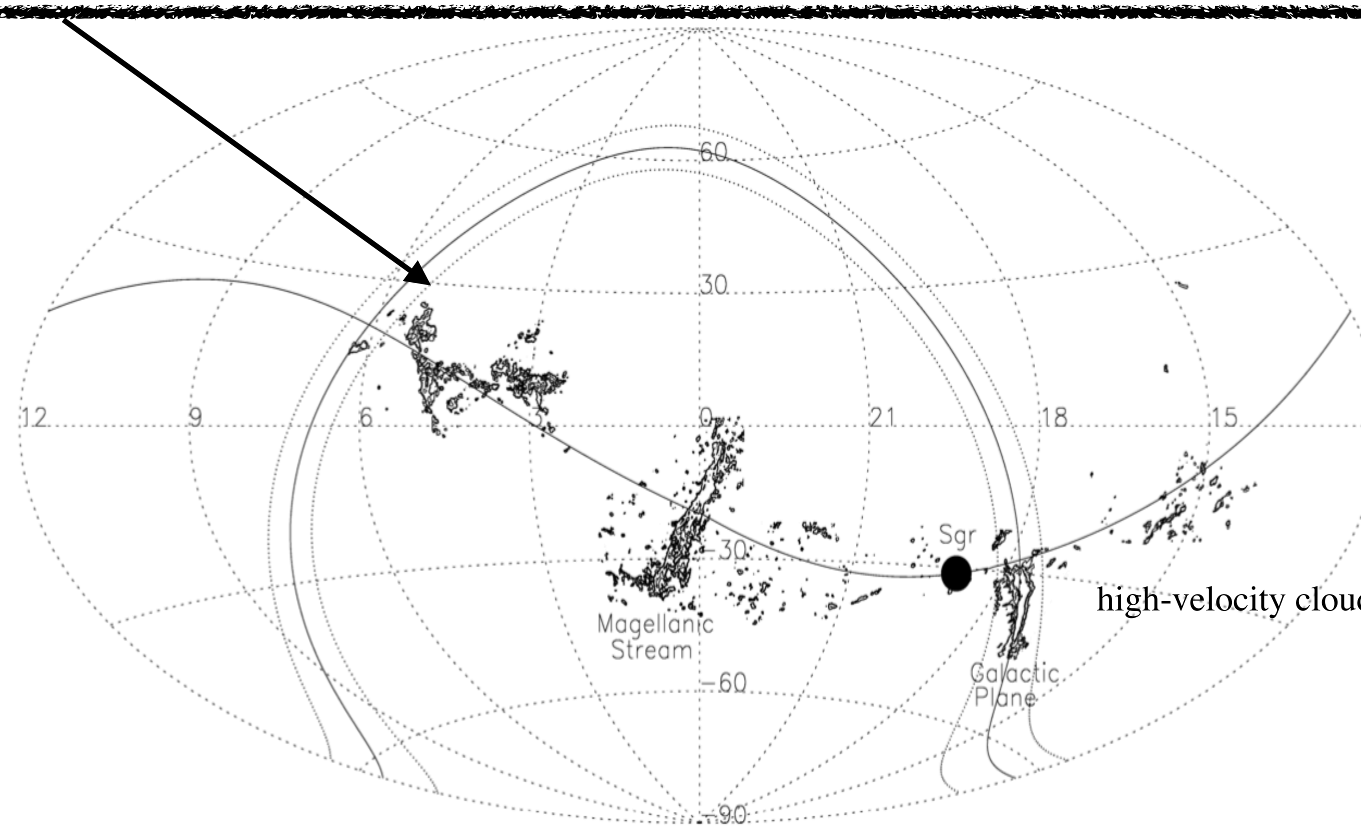
Accepted by The Astrophysical Journal Letters

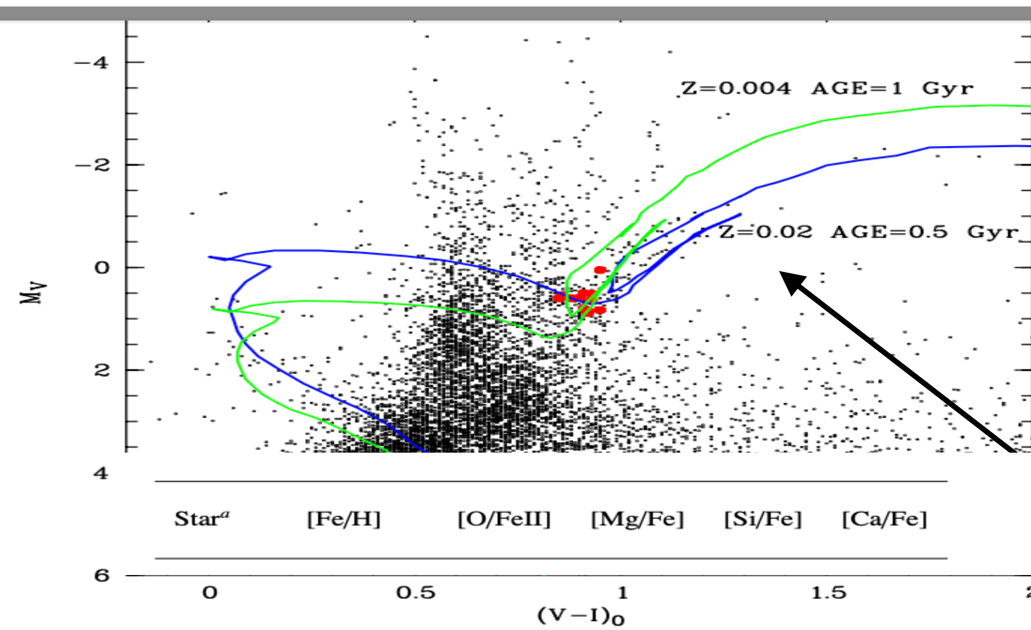
ABSTRACT

A possible gaseous component to the stream of debris from the Sagittarius dwarf galaxy is presented. We identify $4 - 10 \times 10^6$ $M_\odot$ of neutral hydrogen along the orbit of the Sgr dwarf in the direction of the Galactic anticenter (at 36 kpc, the distance to the stellar debris in this region). This is 1-2% of the estimated total mass of the Sgr dwarf. Both the stellar and gaseous components have negative velocities, but the gaseous component extends to higher negative velocities. If associated, this gaseous stream was most likely stripped from the main body of the dwarf 0.2 - 0.3 Gyr ago during its current orbit after a passage through a diffuse edge of the Galactic disk with a density $> 10^{-4}$ cm^{-3}. This gas represents the dwarf's last source of star formation fuel and explains how the galaxy was forming stars 0.5-2 Gyr ago.

Subject headings: galaxies: individual (Sagittarius Dwarf Galaxy) – galaxies: ISM – Galaxy: formation – Galaxy: halo – intergalactic medium – Local Group

Gas stream from Sgr stripped 0.2-0.3 Gyr ago?





See also Siegel+2007; Alfaro-Cuello+2019; Mucciarelli+2017; Barmentloo & Cautun+2023; and so on……

Bonifacio+2003:The Sgr dSph hosts a very young metal-rich population with Mg

Motivation for this long-term ambitious project

Full Modelling of the Milky Way and Sagittarius Dwarf & LMC satellite with hot/cold gas and mass-ratios and better observations:

* 6D accurate stream with N-body, then Gas, chemistry and SF
* Core chemo-dynamical properties & dark matter history and globular clusters
* Interactions with the Milky Way's disk and halo, as well as their possible influence on the bulge structure and dynamics
* More model tests are confronted with increasingly precise observations

Recipe: Current N-body model, the mass ratio could be adjusted with more smoking-gun evidence

Milky Way model: 5.2*10^11Msun

Model Components

Particle mass	1.375*10^5Msun
DM halo	4.8*10^11Msun
DM scale	9.1kpc
Stellar Disk	3.58*10^10Msun
Stellar scale length	2.4kpc
Stellar scale height	0.24kpc
Bulge	1.12*10^10
Bulge scale	0.4kpc
Parameters	mw=1 mu=0.8
Number of particle	1.2M

Adaptive Gravity Softening (AGS) has been adopted. The halo density profile is converging at large radii.V/sigma is stable.

Sgr model, ~10^9Msun, softening is 2.5pc

Model Components

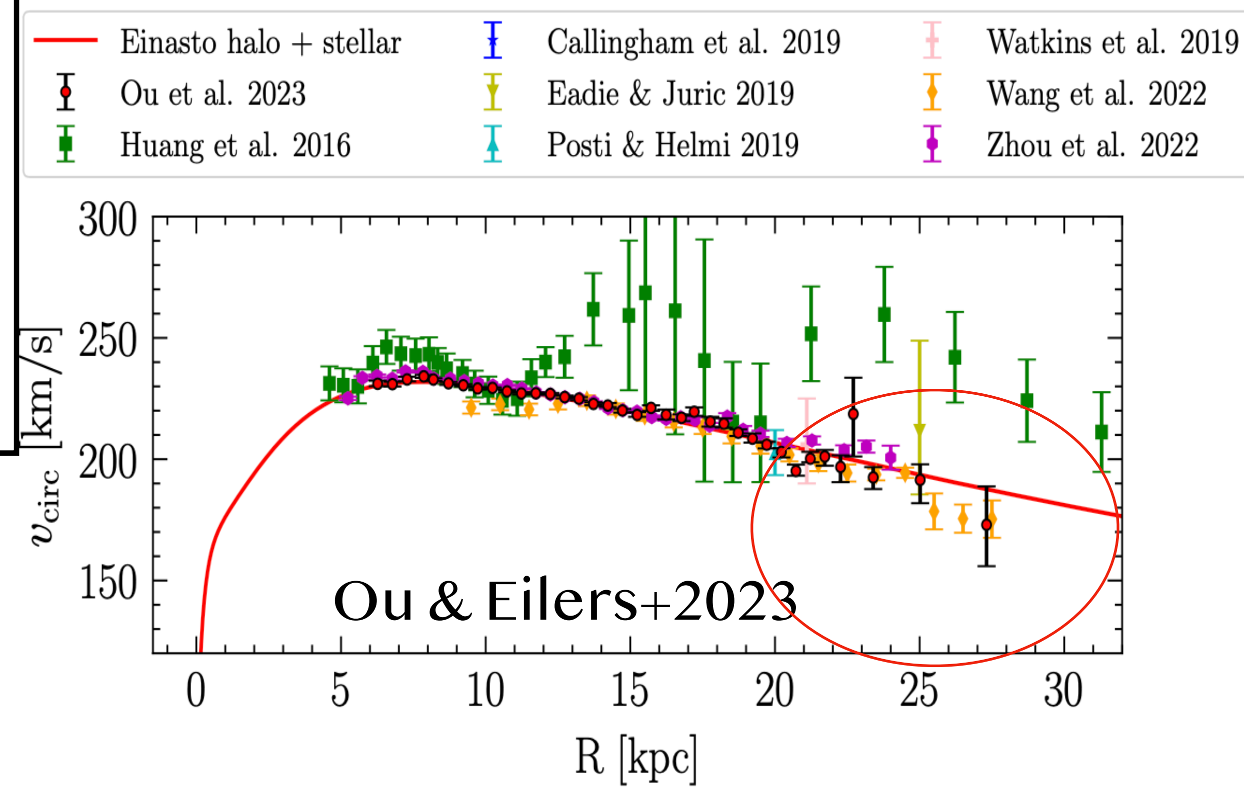
Particle mass	1.37*10^1Msun
DM halo	9*10^8Msun?
DM scale	1.6kpc
Disk	3-9*10^7/10^8Msun?
Scale length	0.3kpc
Scale height	0.15kpc
Initial orbits	66 -9 27
Initial orbits	-48 -17 65
Parameters	mw=1 mu=0.5
Number of particle	18M

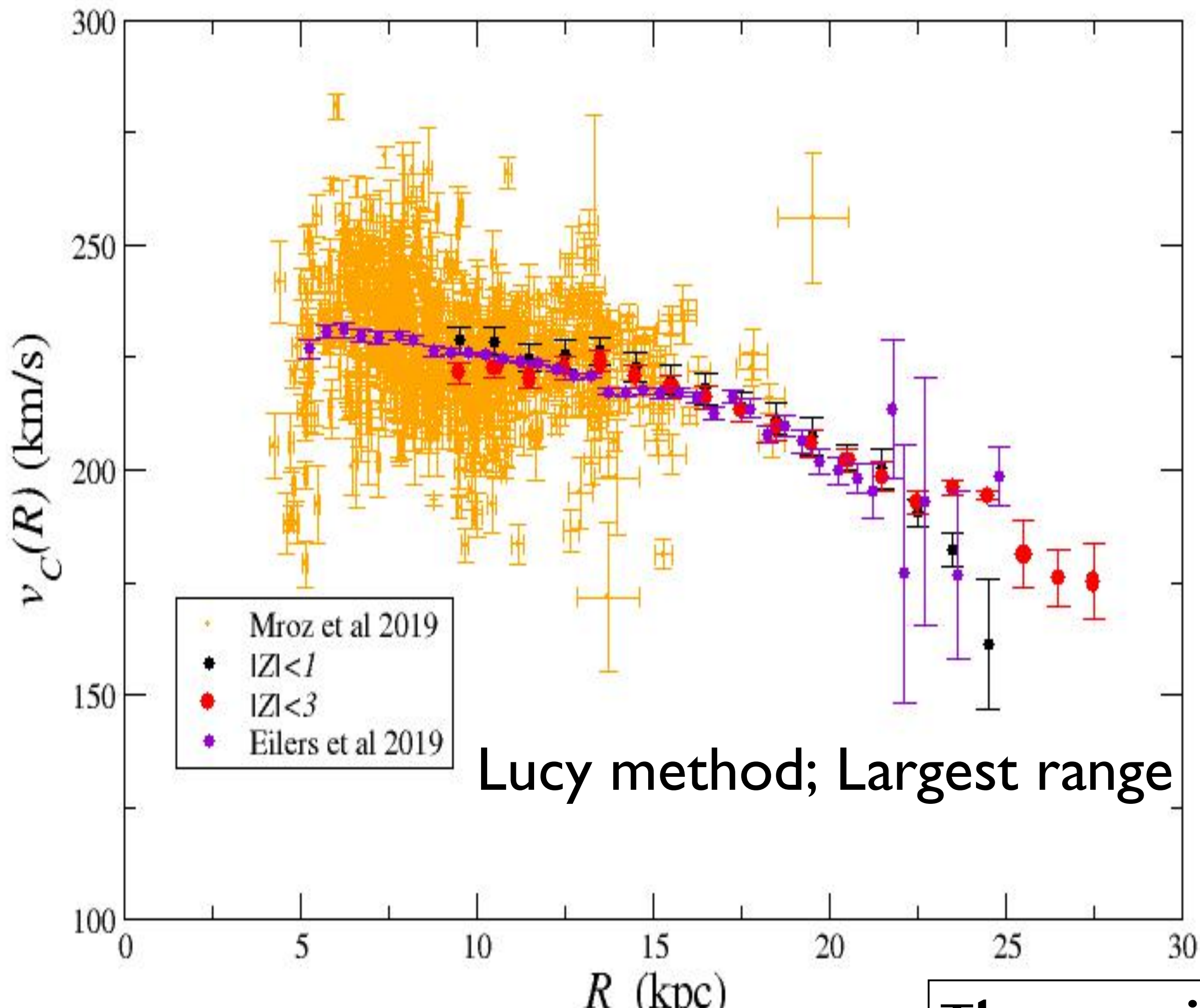
Scalling down Sgr model, M-sigma-[Fe/H]relation.

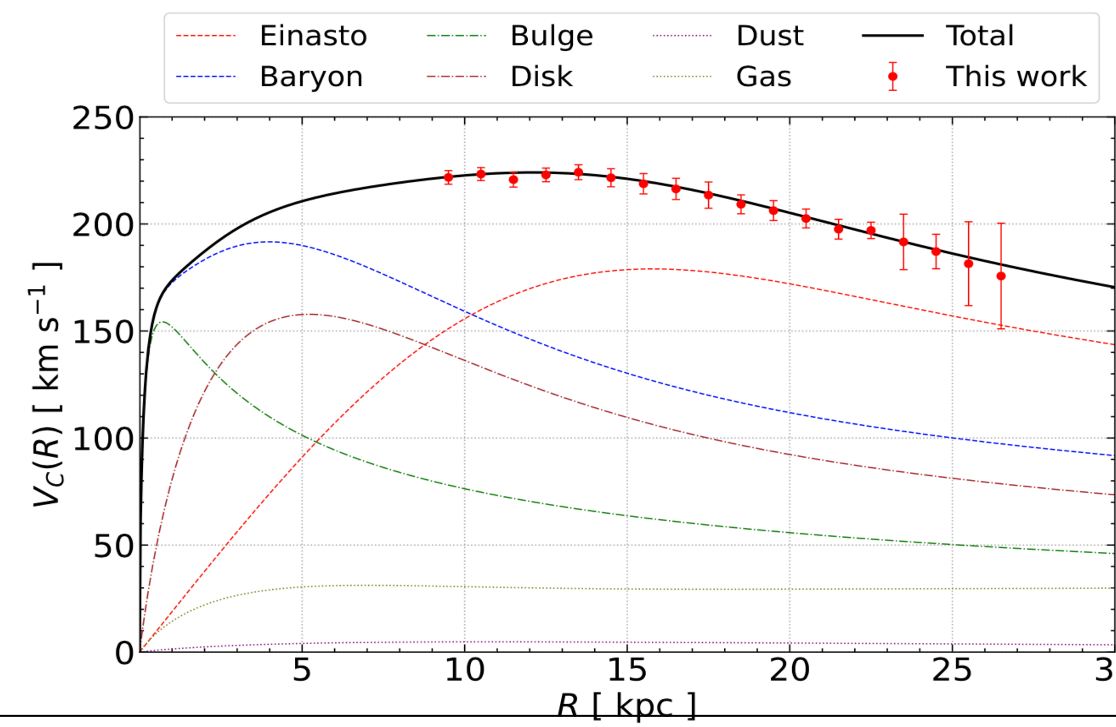
Key Question: How we consider MW rotation curve and potential?

Rotation Curve: Gaia DR3 farthest rotation curve until 30 kpc (Wang+2023a)

Lundmark+1925 (Figure 4); Babcock+1939, Mayall+1951 (reported that the rotation curve of M31).
Rubin+1978 found that several spiral galaxies have flat rotation curves. Bosma+1978 obtained the first sample of galaxies observed in the neutral hydrogen
Gaia DR3 era: First rotation curve, arXiv:2211.05668



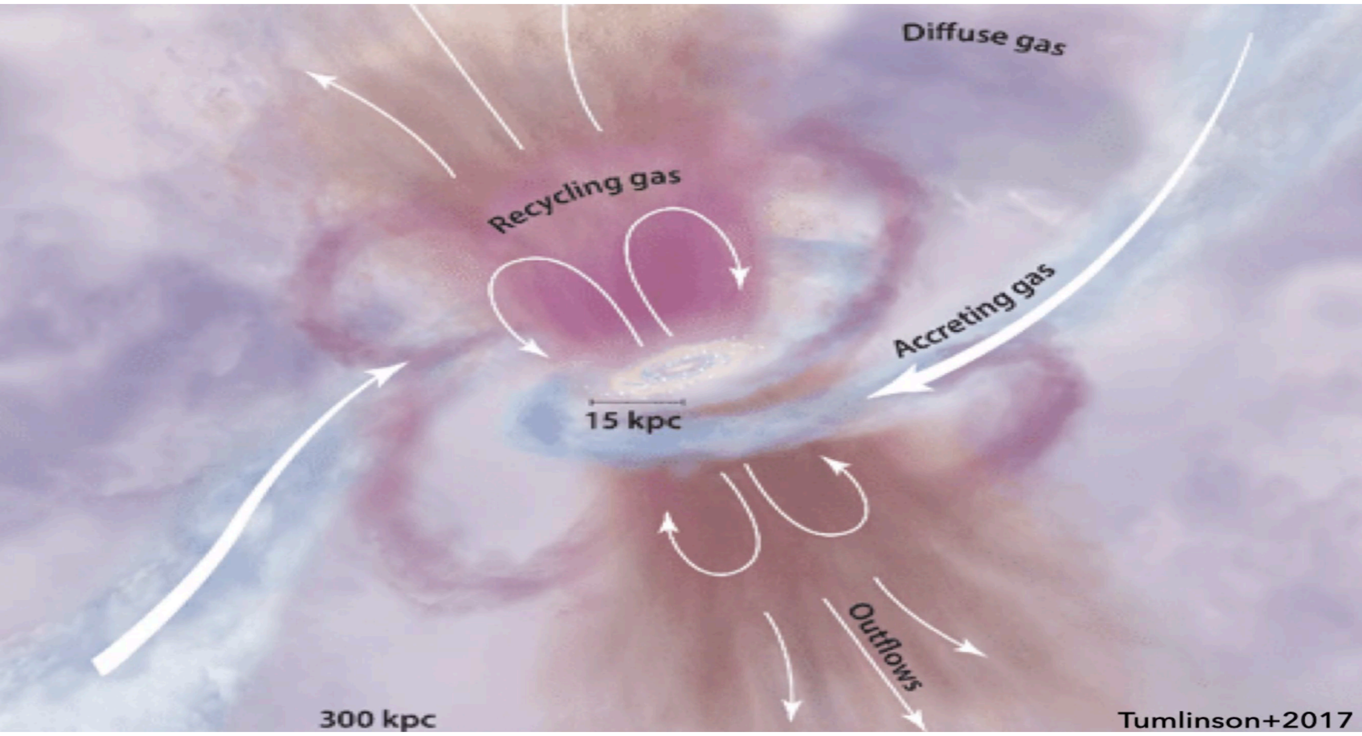


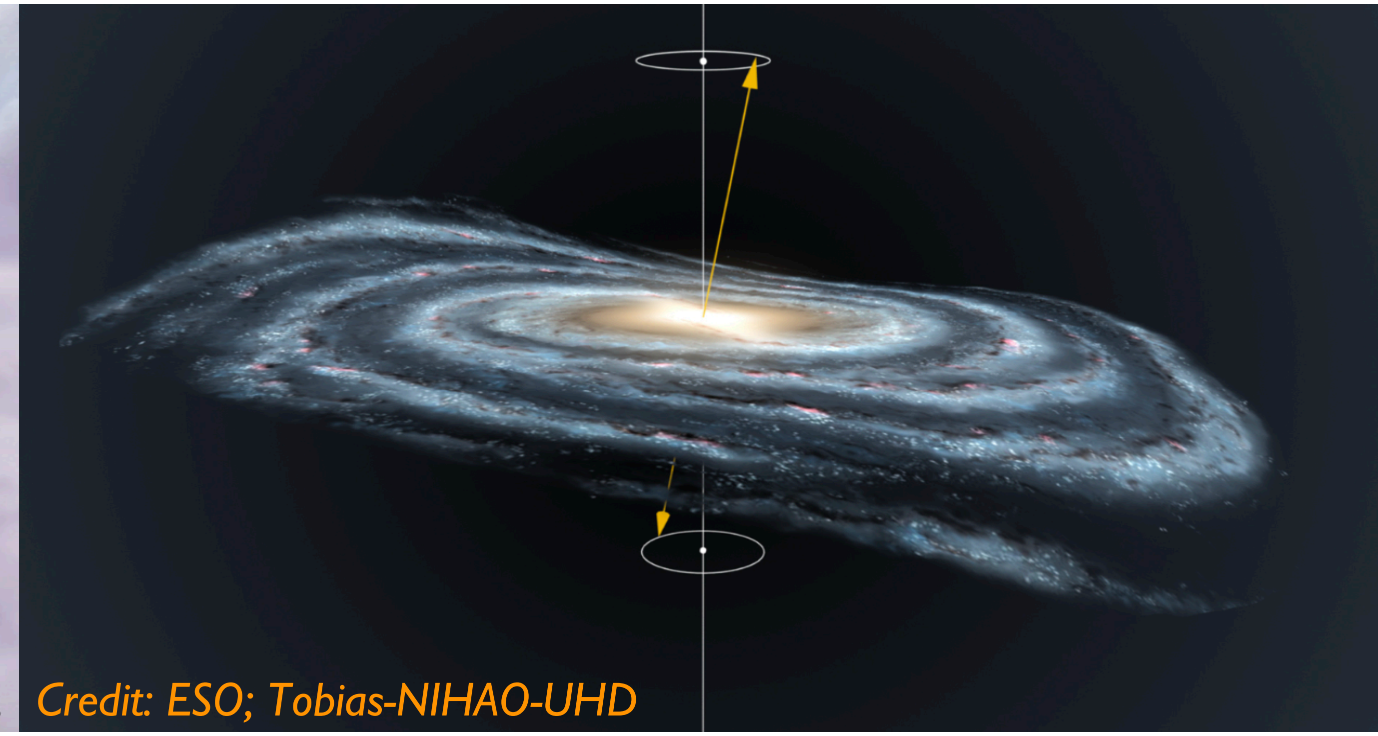


The mass is around 2-5.4^10^11Msun (JYJ, FH & Wang+2023

By extending the rotation curve to 28-30 kpc we find that $\beta = -(2.3 \pm 0.2)$ km s^{-1}kpc^{-1}(Clearly confirmed by Ou & Eilers+2024.). Note the systematics (15-20%) considering the warp, flaring...

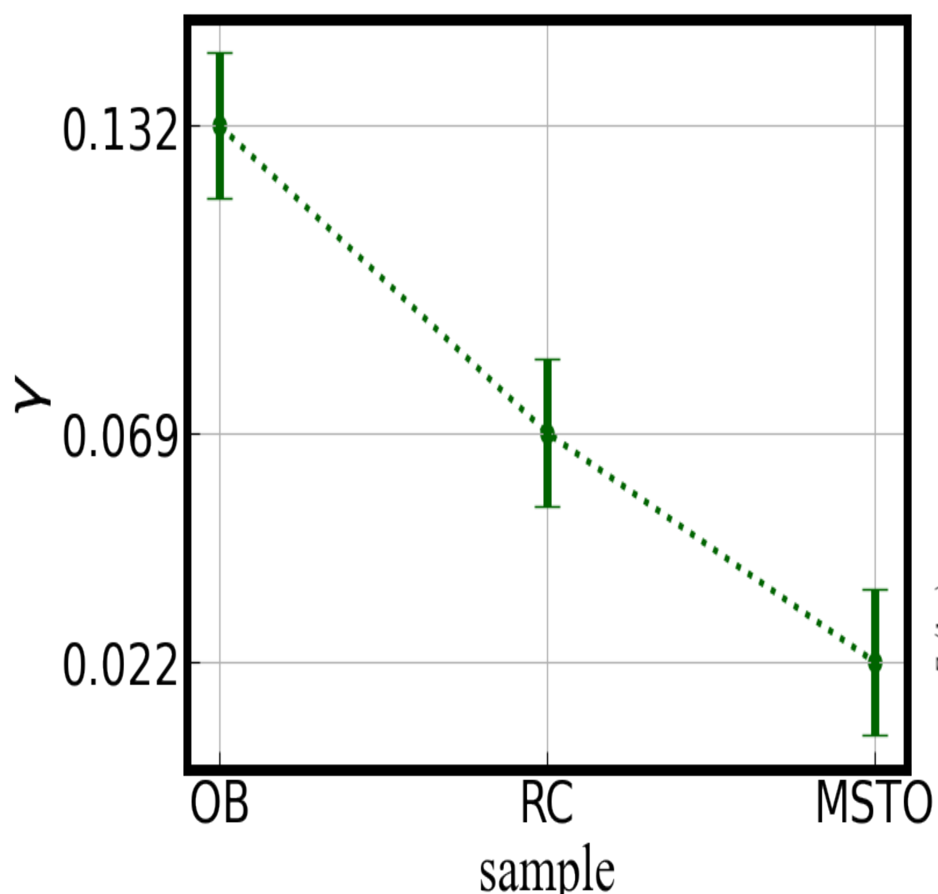
How do we consider warp? Evidence for Populations-dependent vertical motions and the Long-lived Non-Steady Lopsided and time-evolving Milky Way Warp (Wang+2020b; Li & Wang+2023);

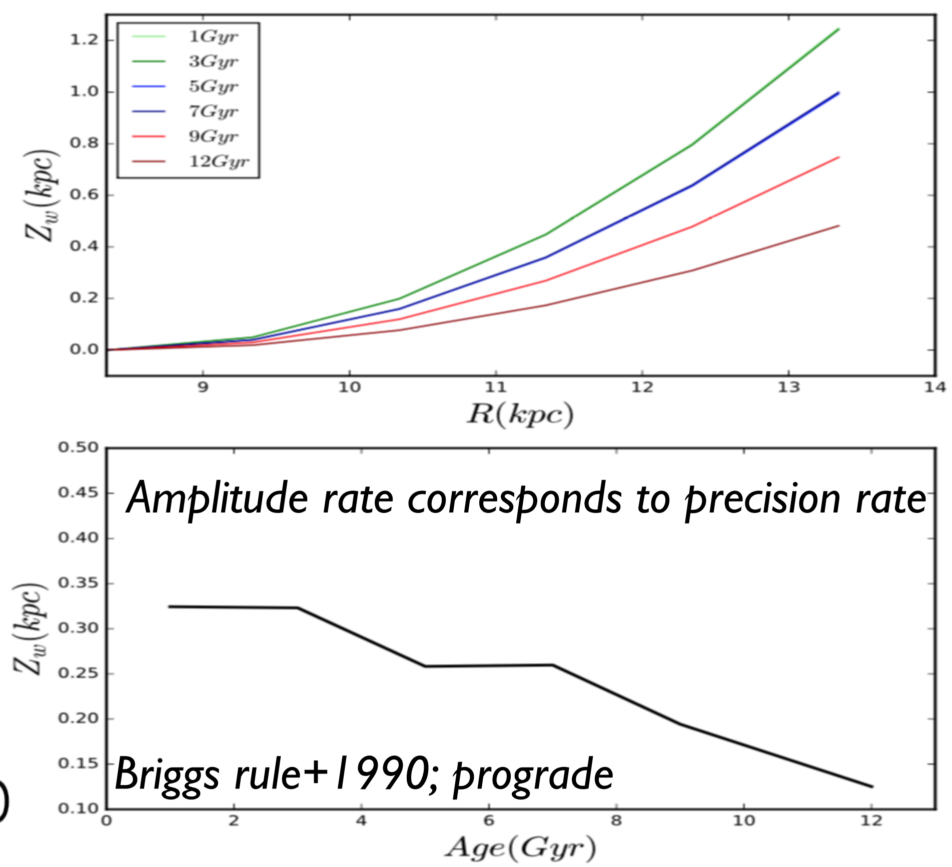


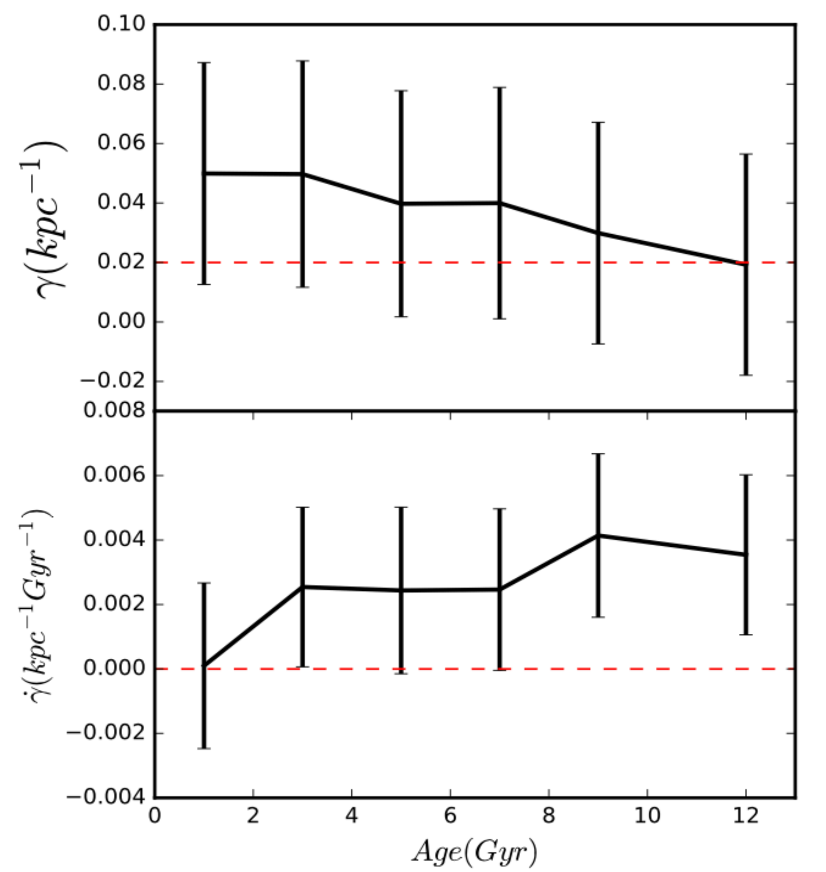


Amplitude ~ precession, see also Poggio et al. works; and Mateu group+2024. gas infall?@2002

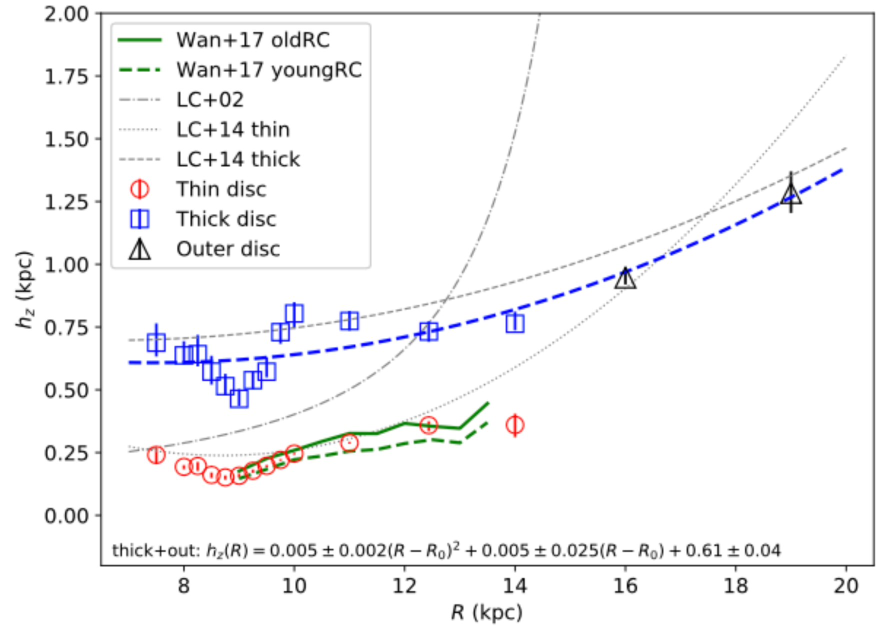
Tips: vertical bulk motions assumption. Our scenario: gravity for trajectory, then gas collisions

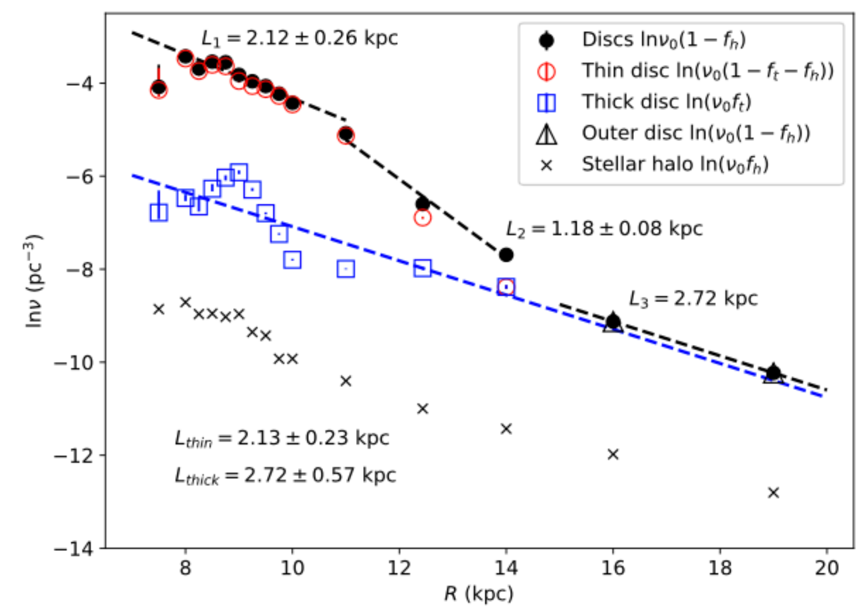


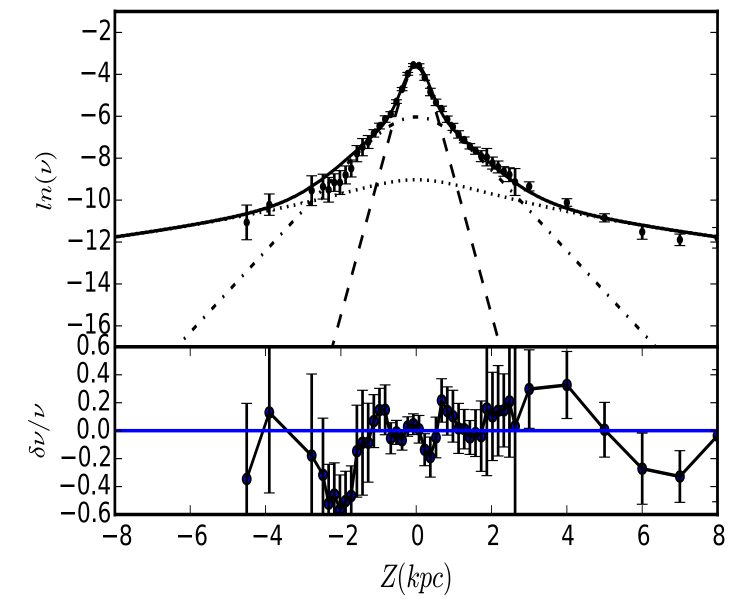




How do we consider flaring disk and non-exponential disk, flaring might be originated from perturbation, perhaps not or not only secular evolution? Need more future works.

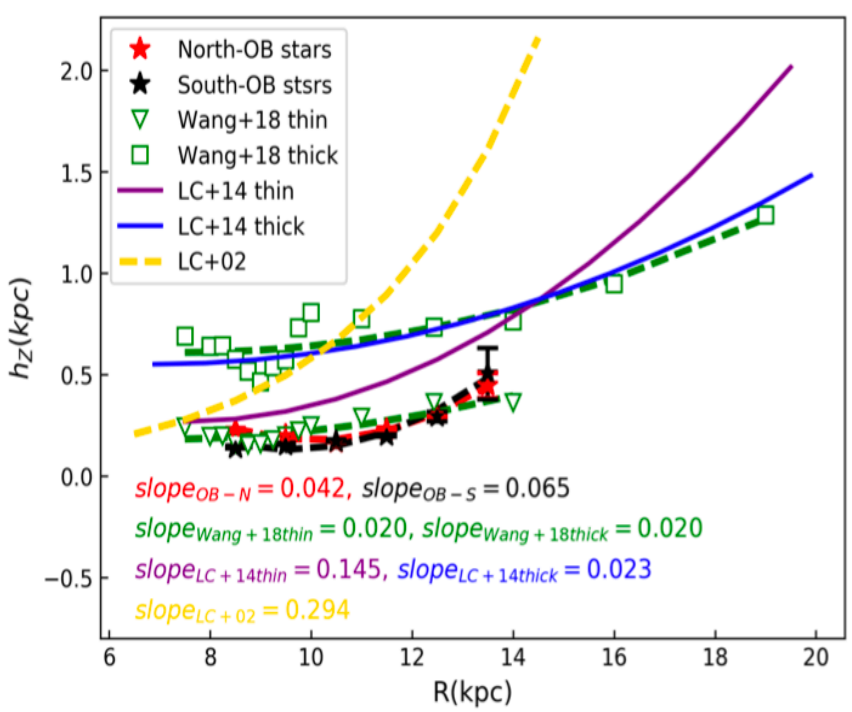


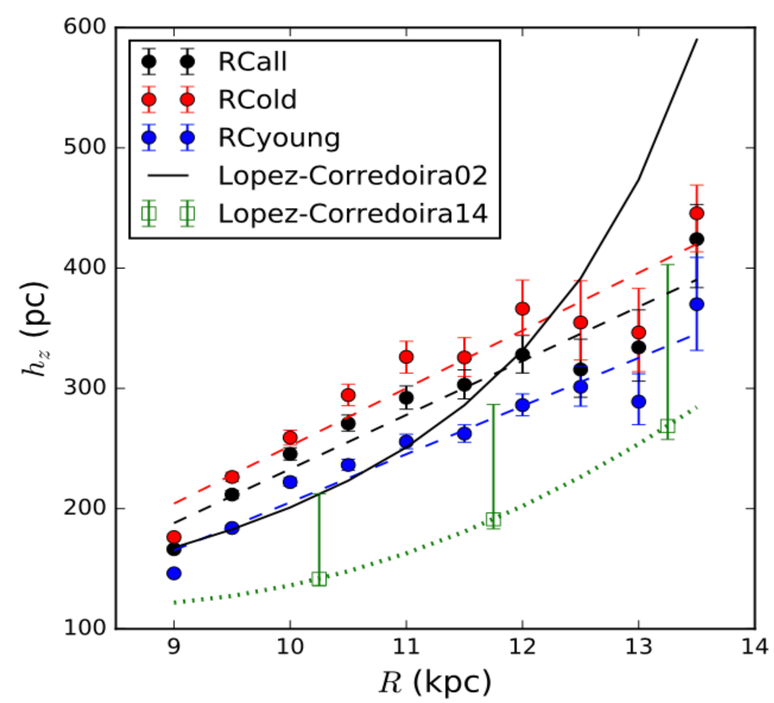


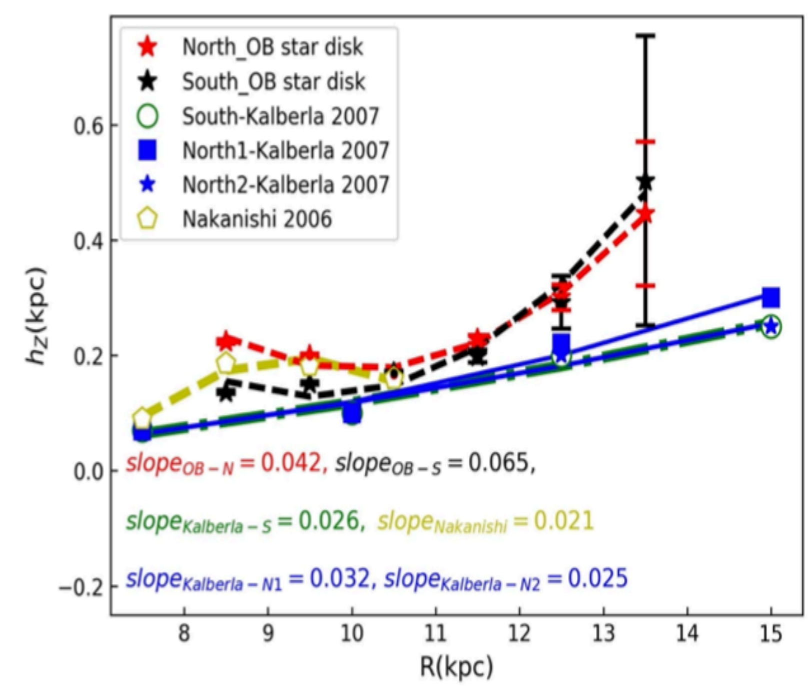


Wang+2018 vs. Yu, Wang & Cui+2021 vs. Artem+ in prep.

@solar neighbourhood



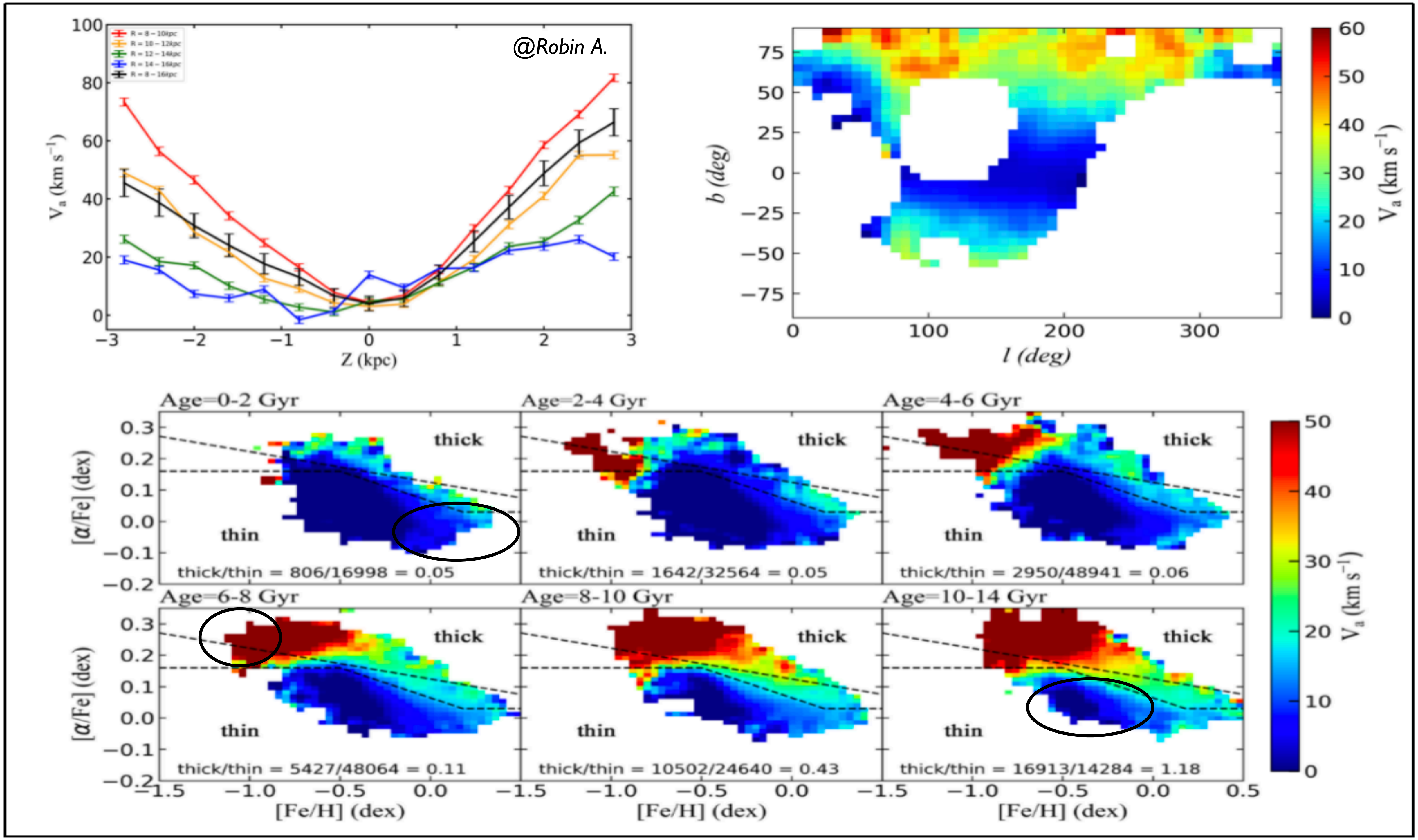




Disk flaring is not significantly populations-dependent! OB disk vs. Gas disk vs. Dust disk.

See Minchev+2015; 2016; Wan+2017. Note Catant & Hans-Walter+2024.

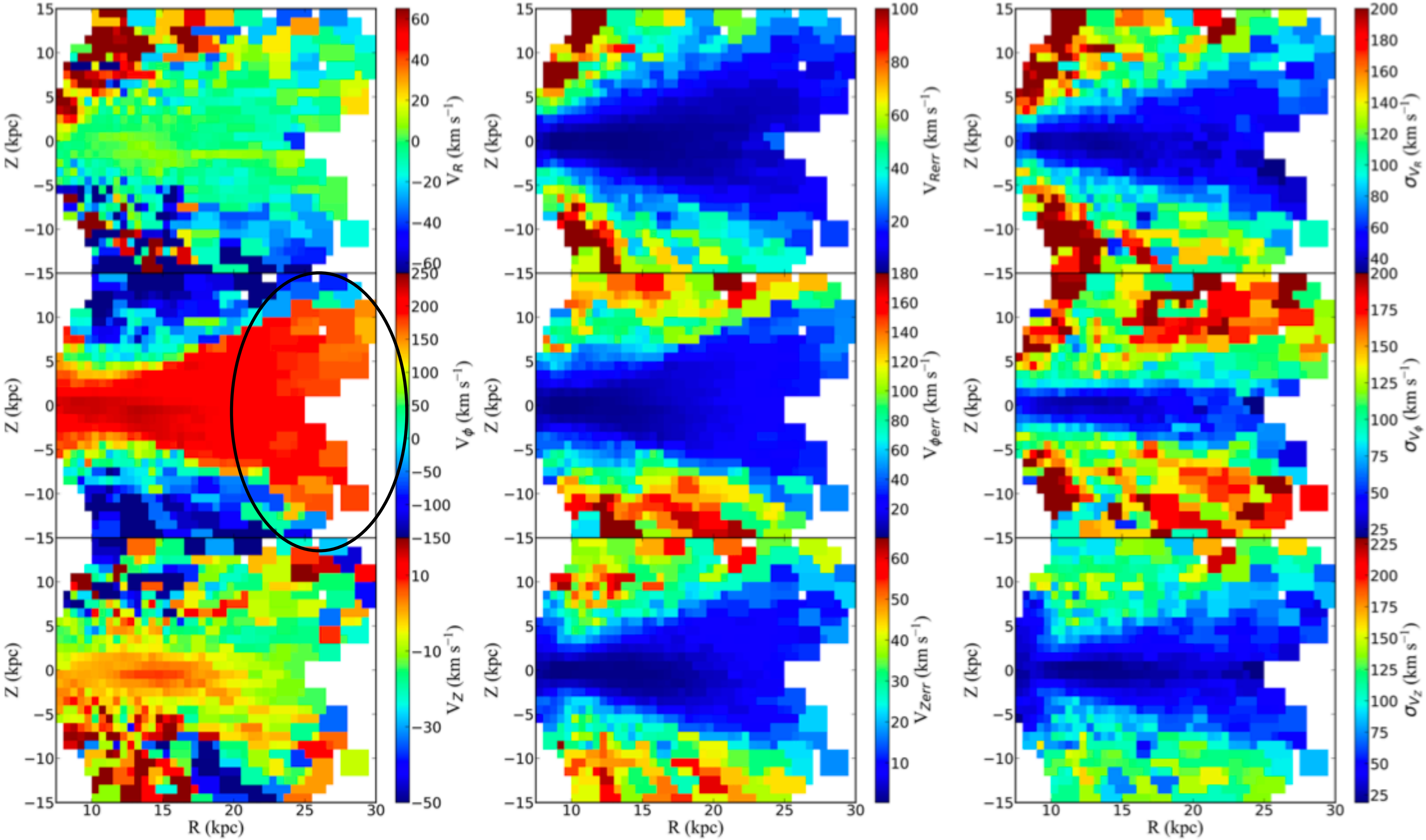
How do you think of Asymmetric drift map? MAP and time scale picture of the Milky Way disk, Li, Yang & Wang+2024, conditioning on Rotation curve: Not so simple for the protogalaxy-MW and GSE?



Very old thin disk? Old Metal poor stars? very metal rich young stars-bar? Peculiar populations? More works are needed. See Gallart+2019, Haywood+2019;Feuillet+2020; Xiang+2022; Ciuca+2023; AIP group papers+2024; MPIA group papers+2024

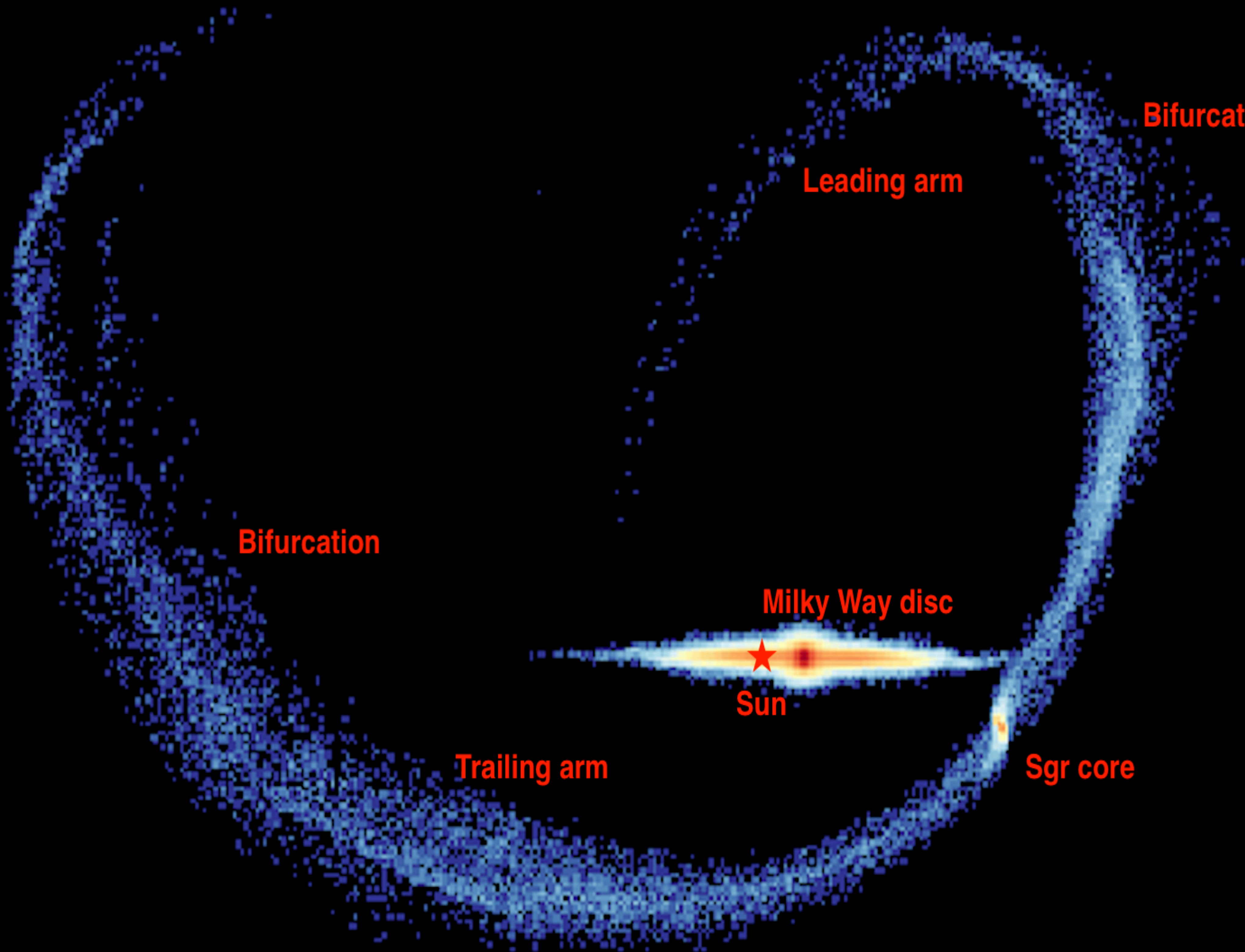
For high-redshift (z>4) cold disc galaxies with ALMA and JWST. See Rizzo+2021; Lelli+2023; Kartaltepe+2023; @ELT-SHARP

Comments on disk truncation and Galactoseismology: in the kinematic space at least 30 kpc, consistent with our star counts and metallicity analysis.



Mechanisms of kinematics and dynamics for these Abundant asymmetries?(See: Wang+2018a,b; 2019; 2020a,b,c; 2022; 2023a; Yu & Wang+2021; MZL, FG & Wang+2020; Li &Wang+2022; Yang & Wang+2023; Li &Wang+2022; Bland-Hawthorn+2020; MZL+2018, etc…..).

MW(LU)DPSG(+) program: More In-depth disk dynamics of the 6-30kpc (Wang+in prep.)



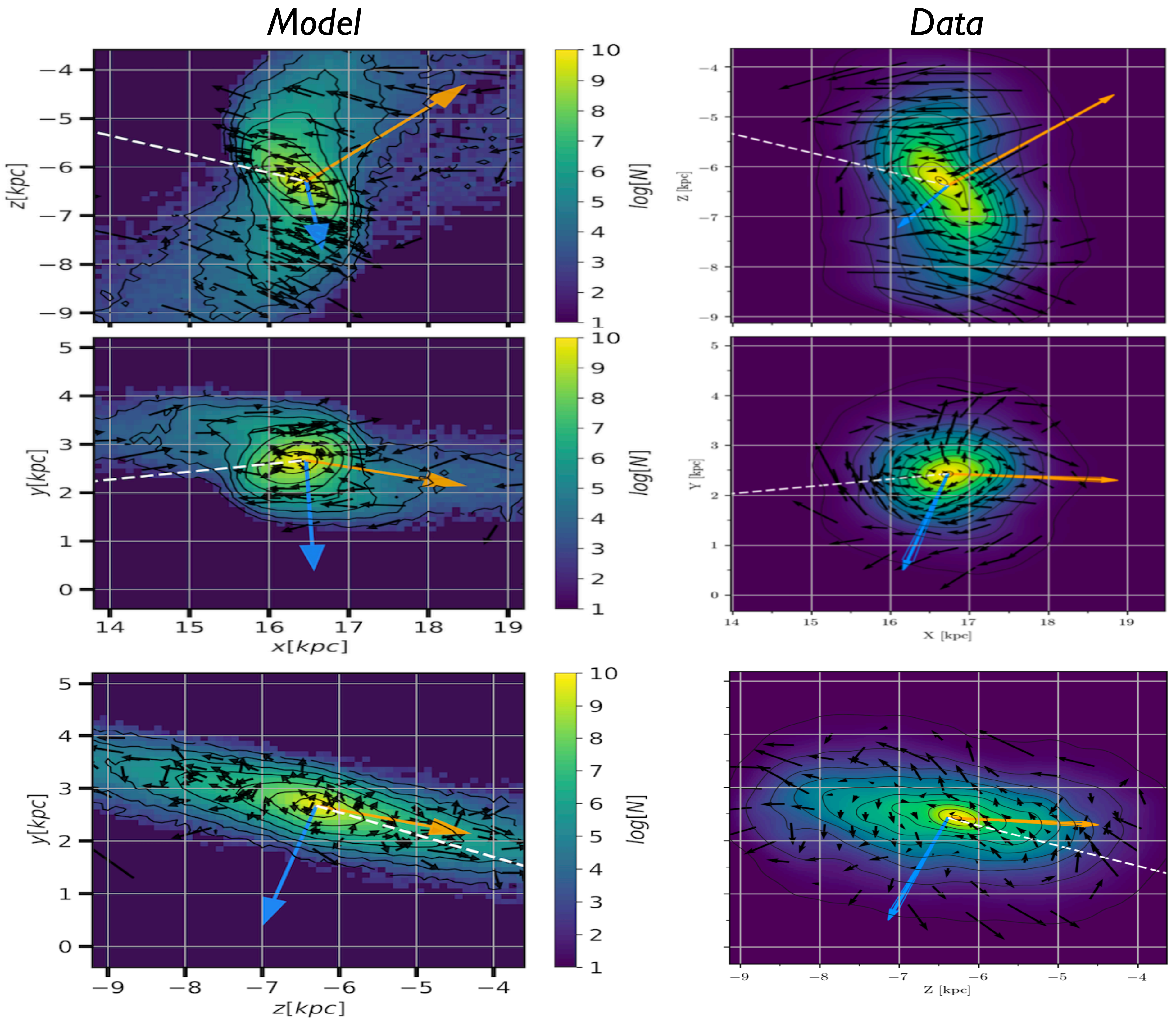
Now we can see the modelling results with “scaling down” Sgr

Simulated by Hai-Feng Wang et al.

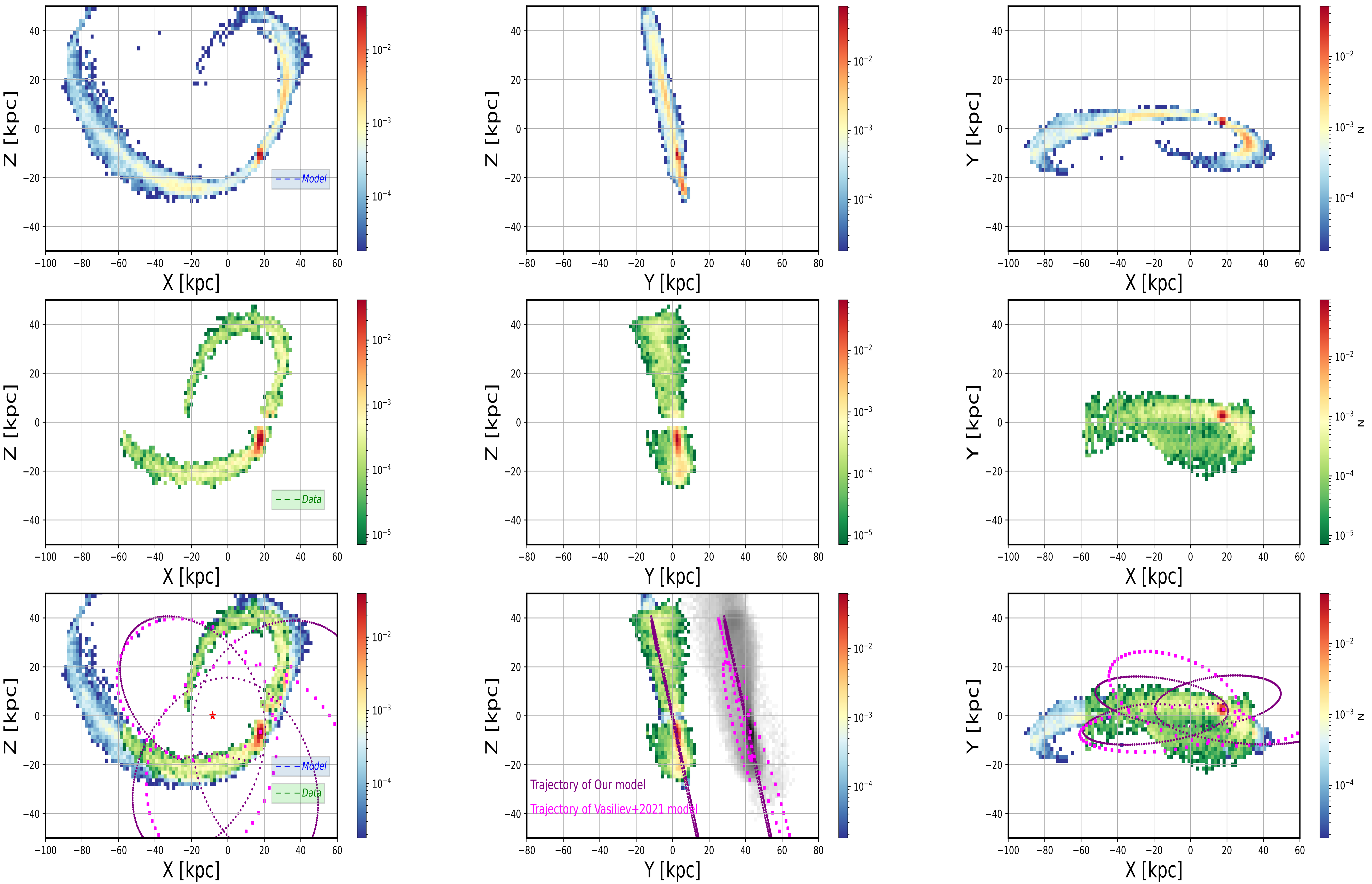
The core dynamics with high resolution

Sgr core morphology and kinematics, matched quite well with Gaia for 6D. See Wang+2022;

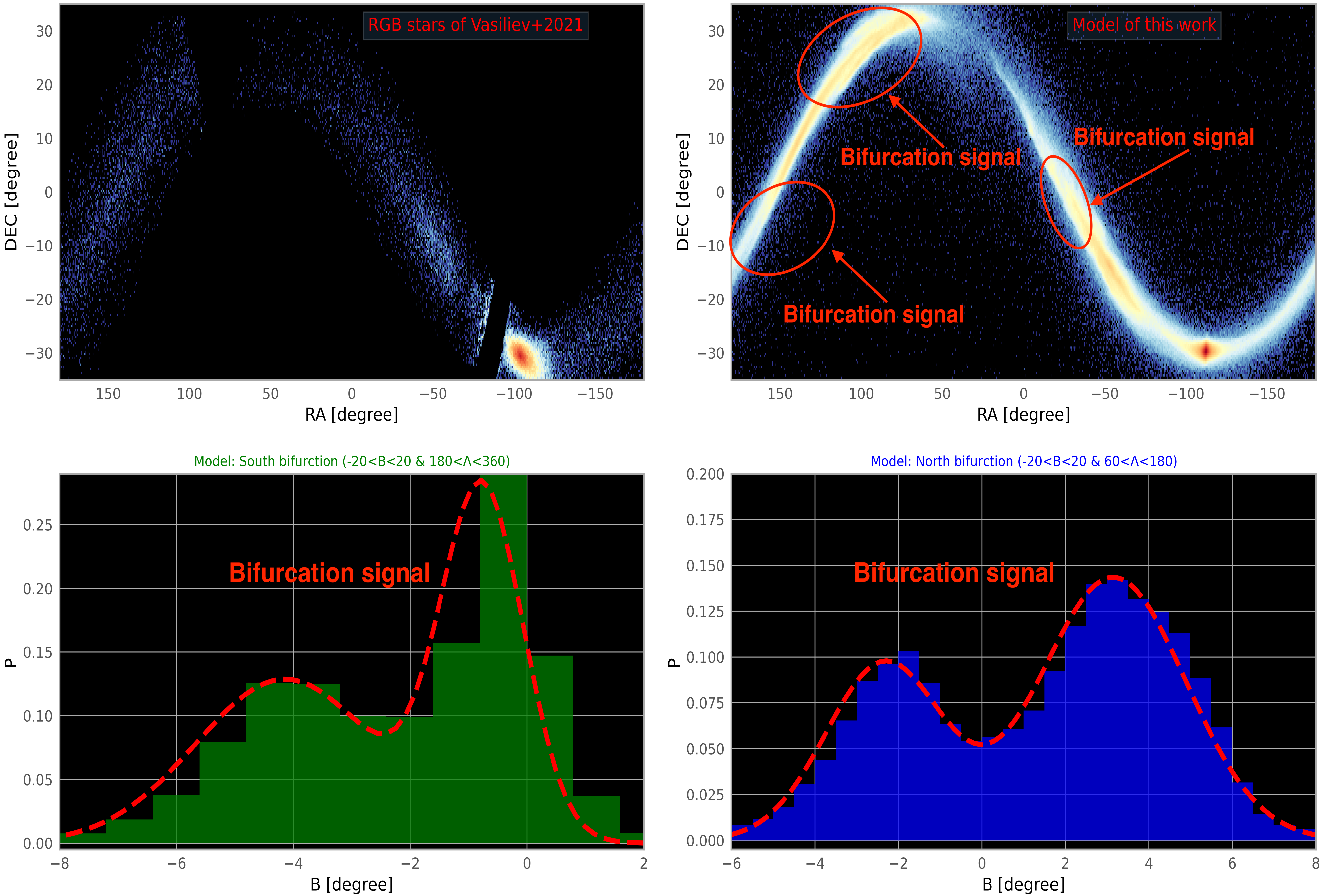
We need more LOS velocity in the future



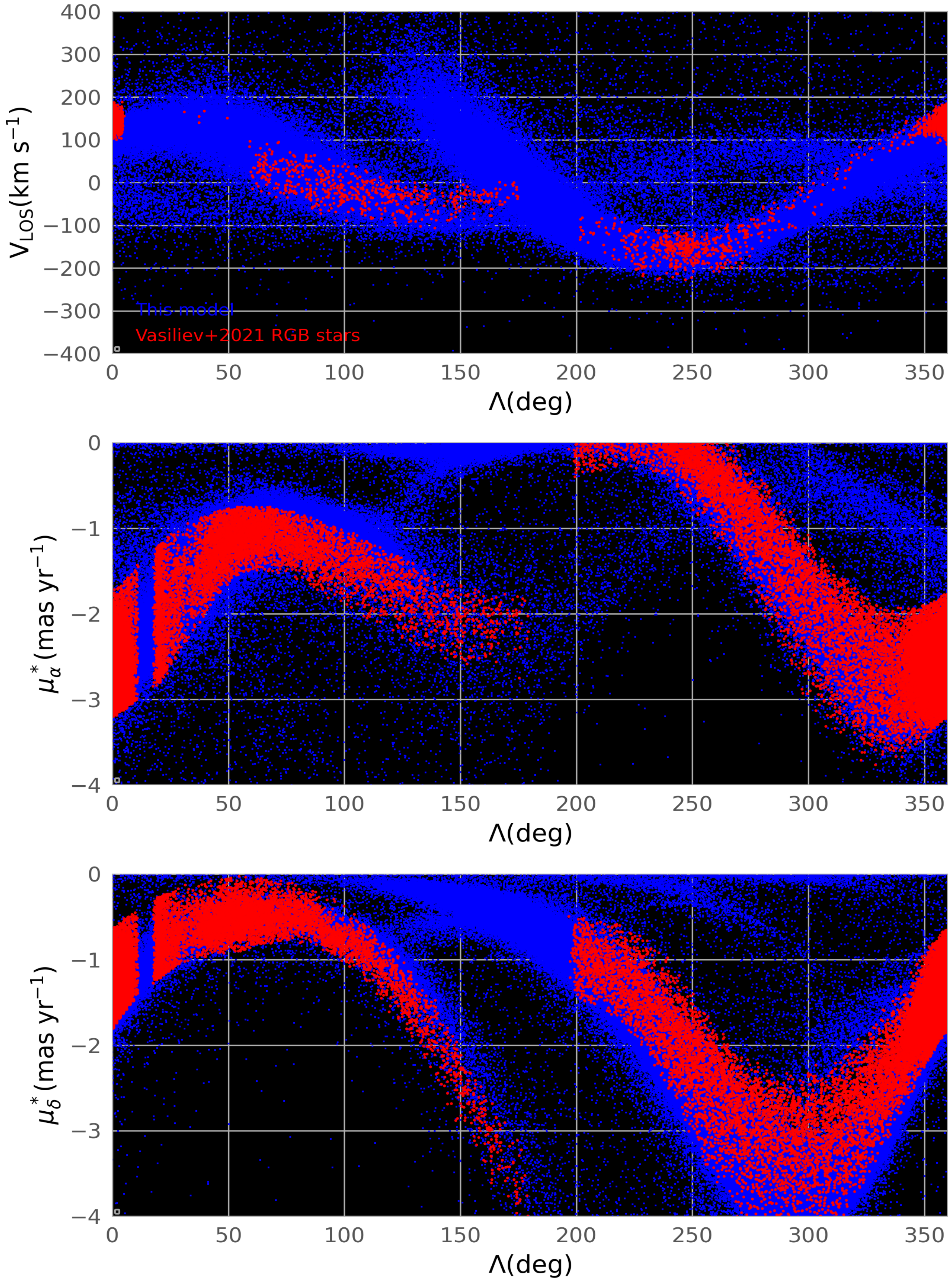
3D Orbit reconstruction for the Sgr stream

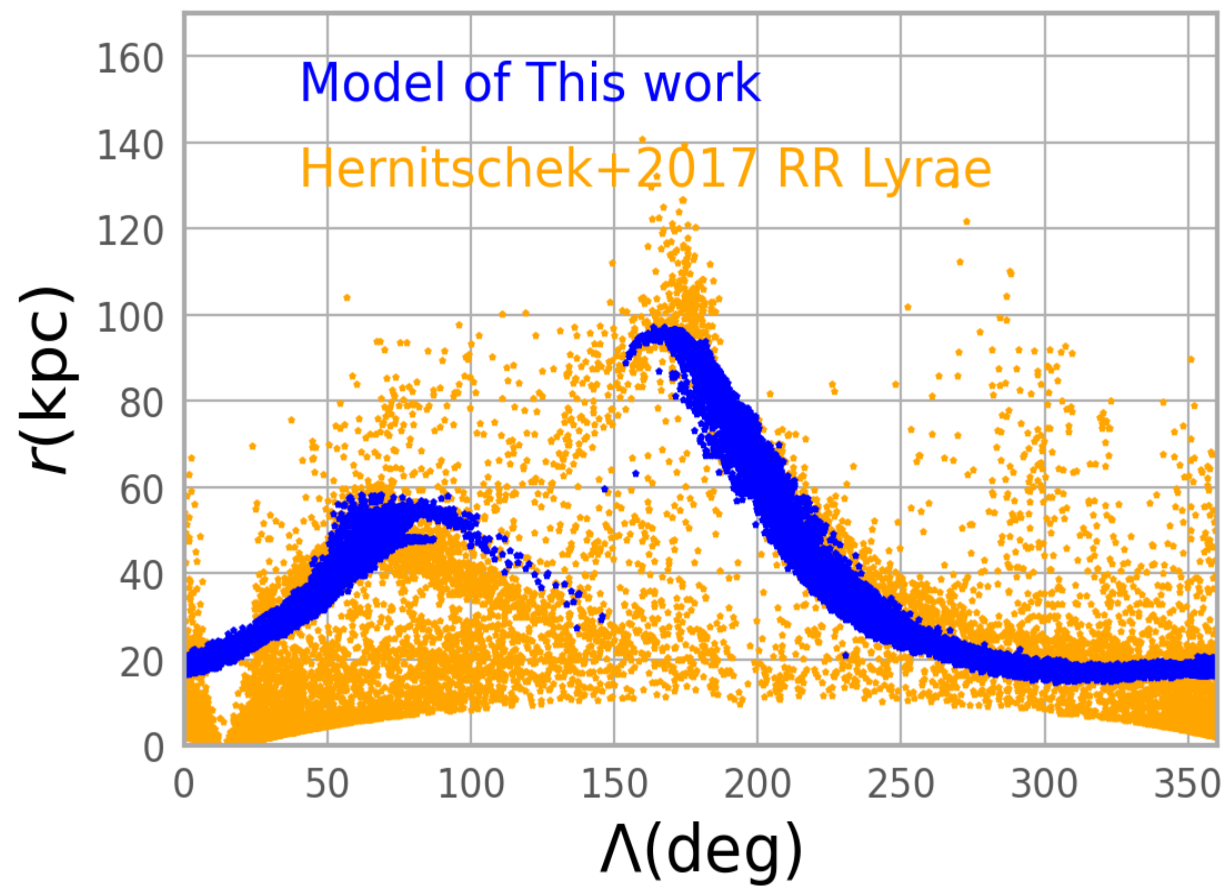


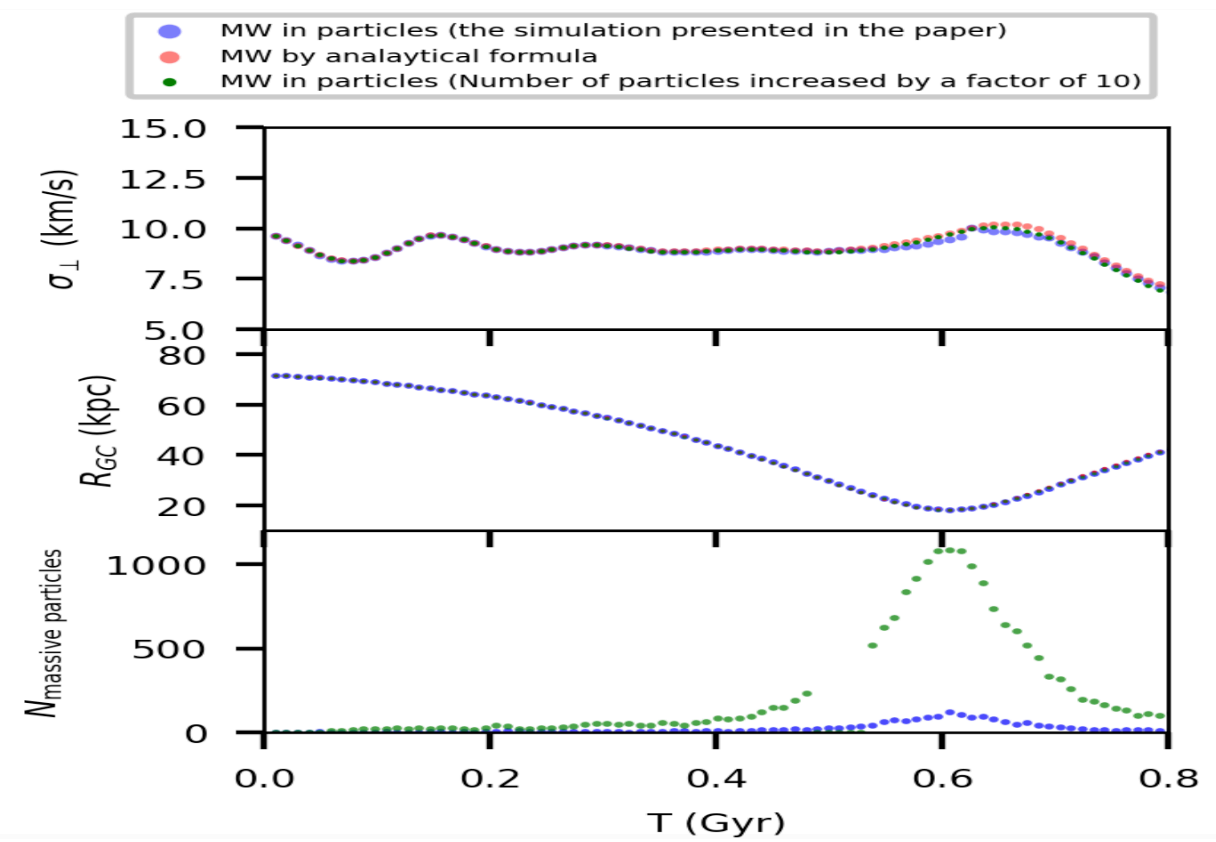
Bifurcation signal reconstruction in 3D



Kinematics and Spatial comparisons; numerical heating not affect



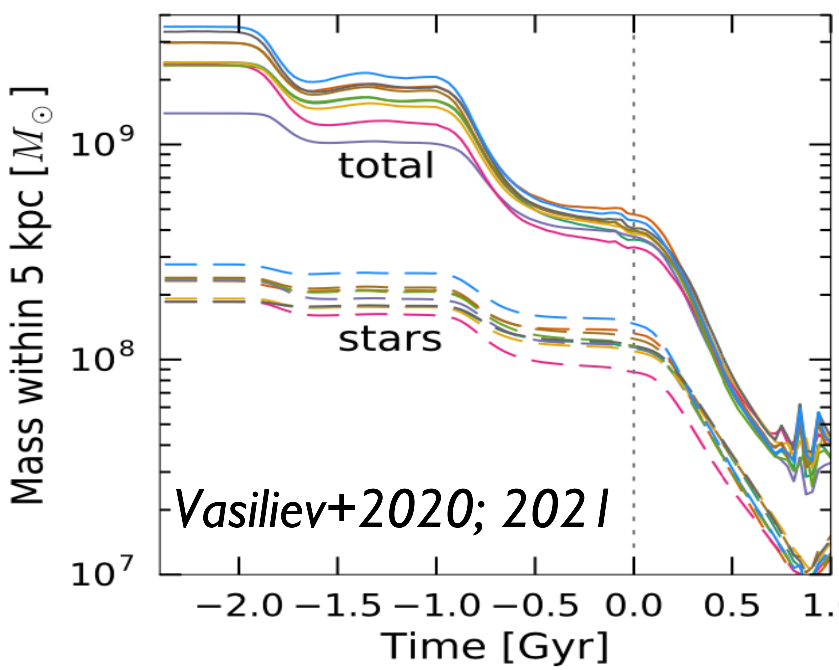


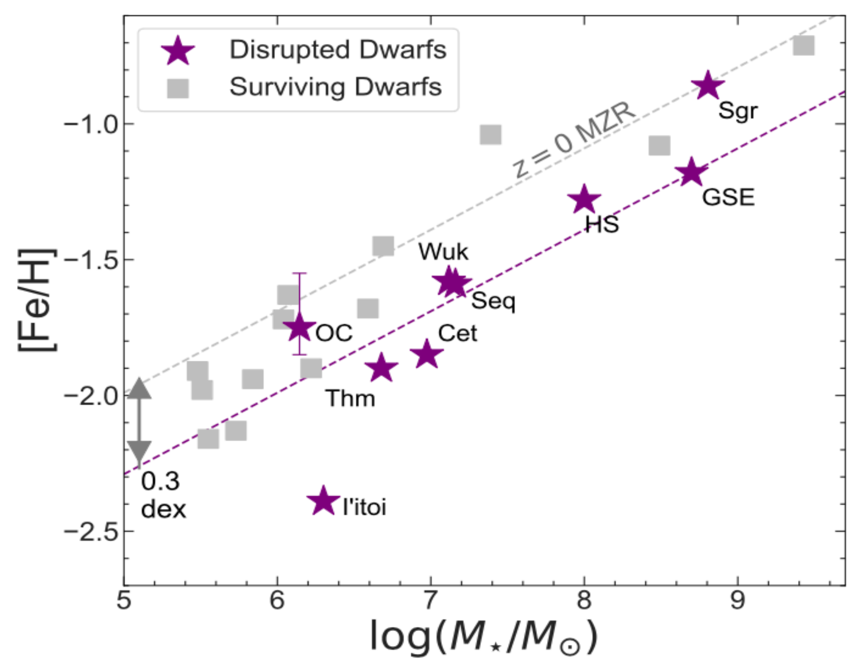


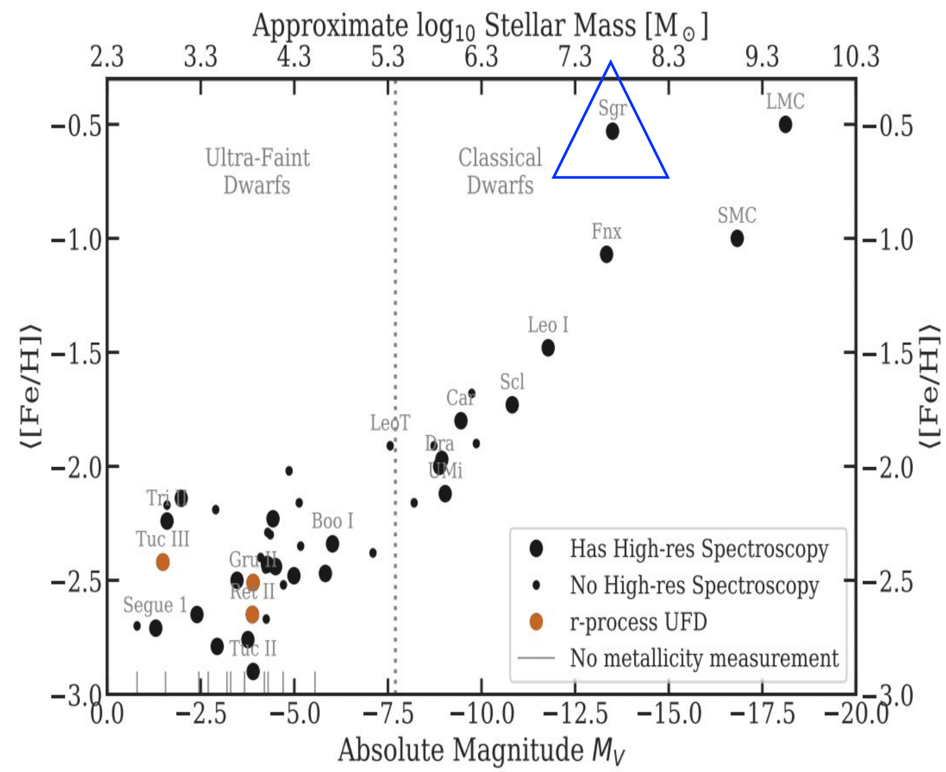
More simulations needed, and also observation: chemo-dynamical analysis for Sgr and also other dwarf galaxy

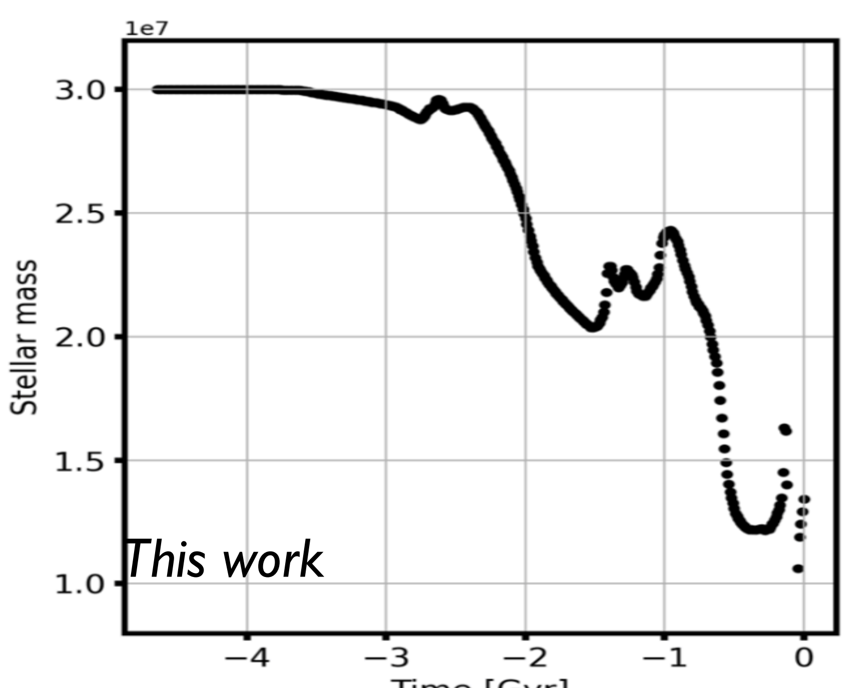
Dark matter tidal stripping history comparisons

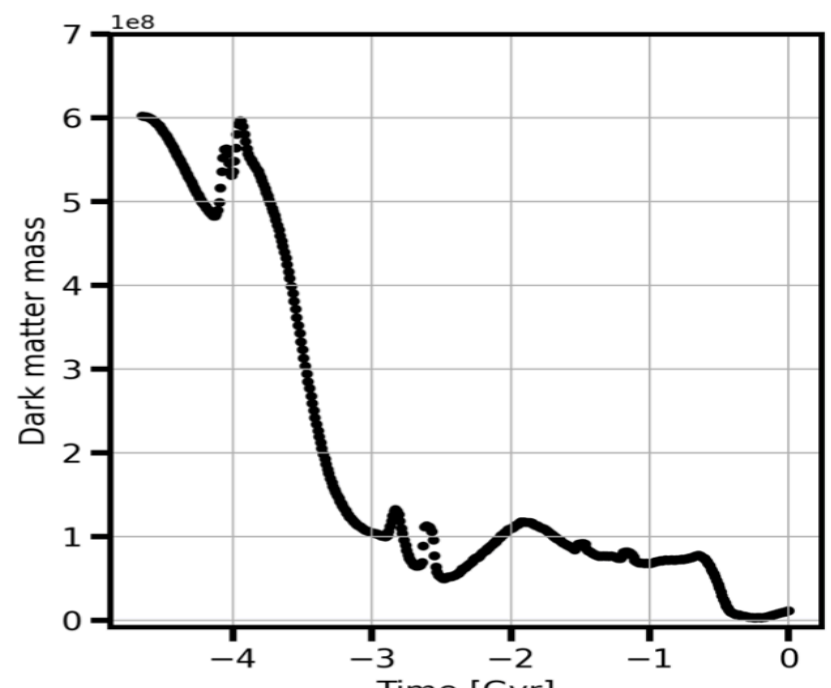
1. Disky Sgr or not; LMC vs. Gas
2. Spherical or twisted non-spherical MW
3. Shallower or deeper potential
4. Bifurcation or not
5. Misalignment is important but gas is too
6. Mass uncertainty

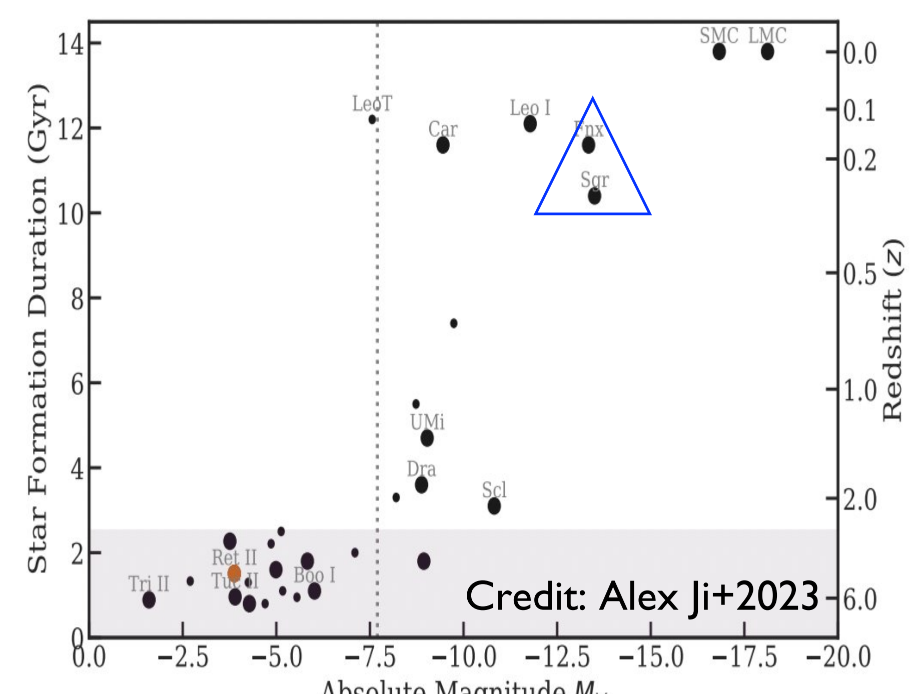






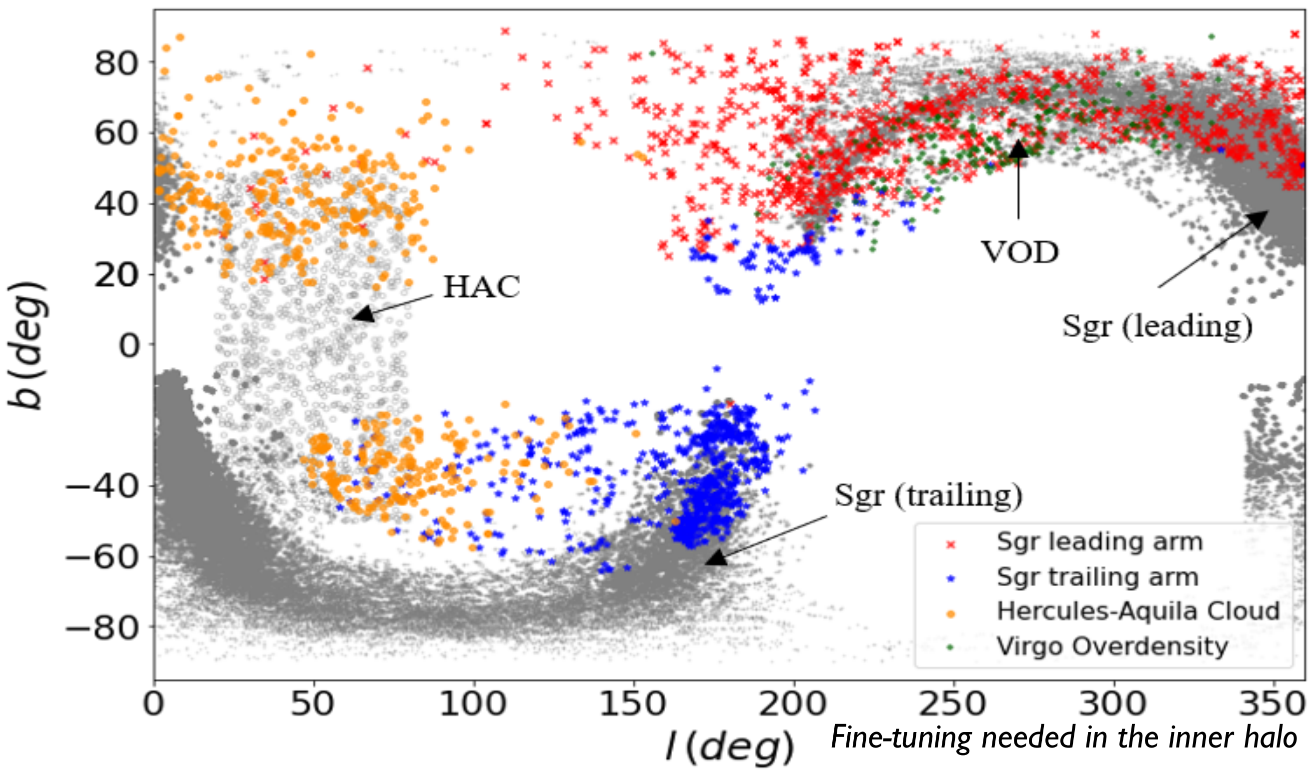






GS3 Hunter to search for Sgr stream in the observation

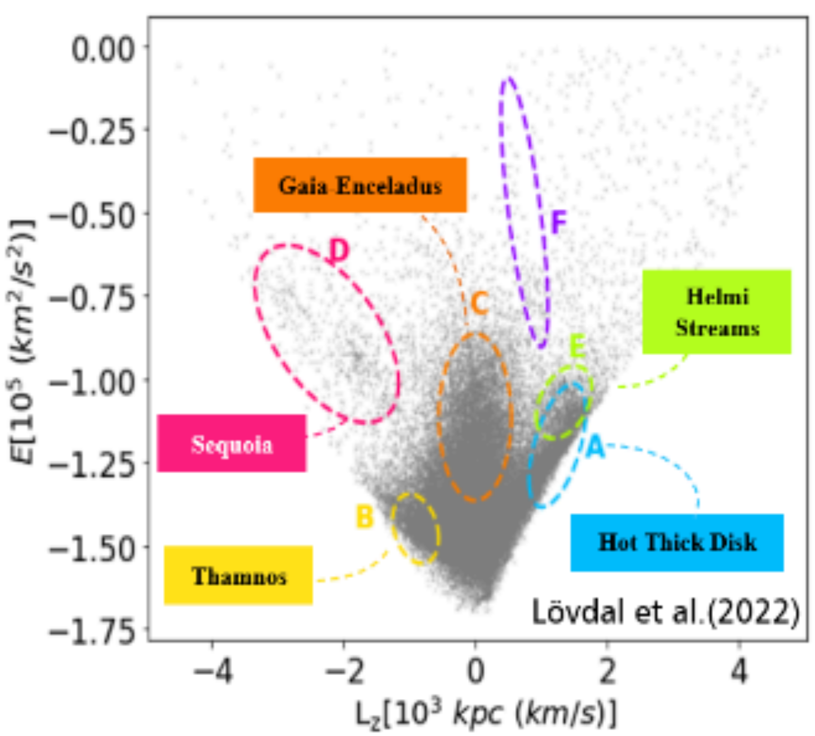
Milky Way Matter Field and Accretion History ? Wang & Wang+2024



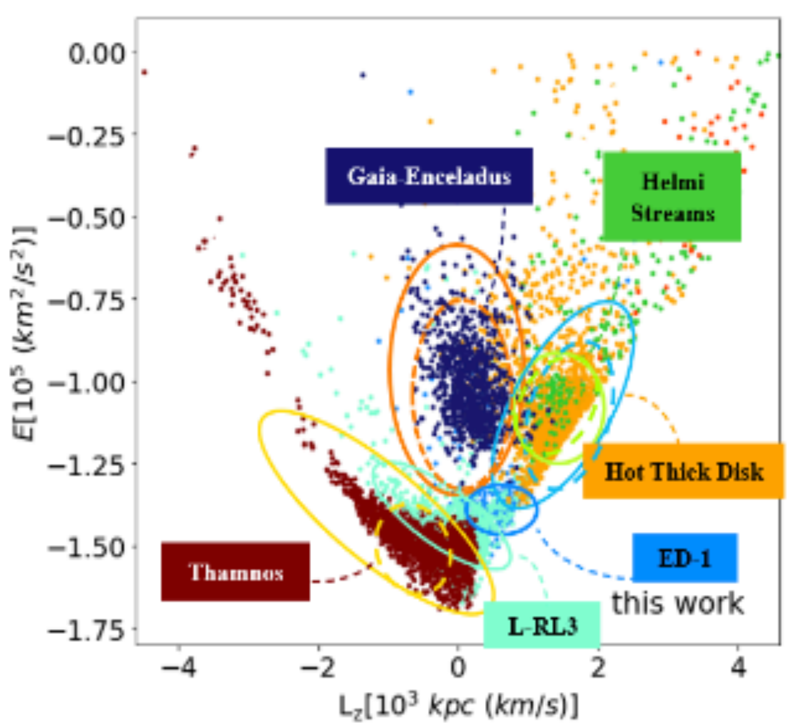
Fine-tuning needed in the inner halo

Galactic Seismology Substructures and Streams Hunter, or GS^3 Hunter for short: Embarking on a large campaign of the halo stream and chemo-dynamics.

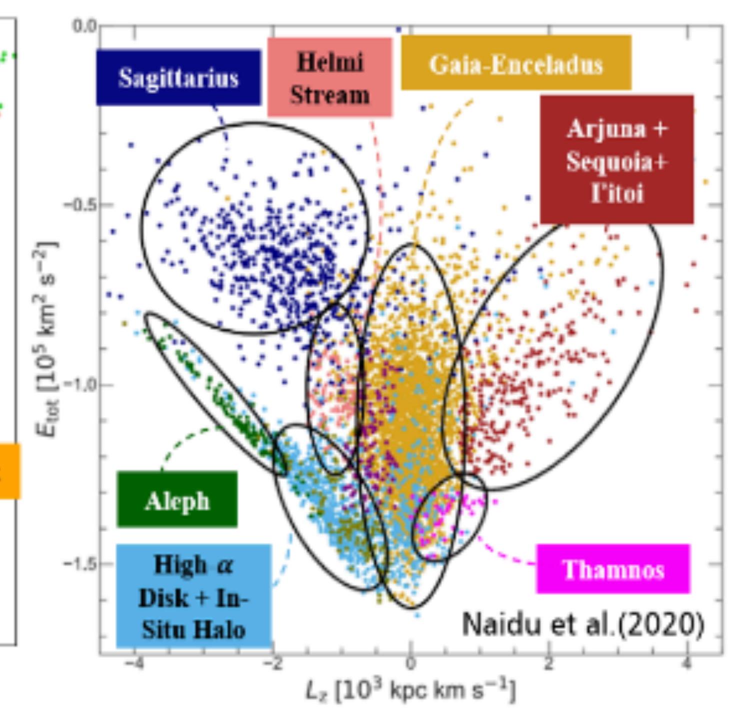
LSST and ELT will be absolutely helpful



Gaia dataset



Local halo streams



H3 survey halo streams

Take home message

1. Using one model we would like to simultaneously reproduce well 3D spatial features of Sgr stream, including its leading and trailing arms, 3D kinematics properties, their associated bifurcations, most of the observed core morphology, kinematic properties.

2. This model reveals the new dark matter tidal stripping history of the Sagittarius Core, the clear time scale picture is implying DM is stripped more efficiently than star.

3. No model is perfect so we suggest that significant further progress can be achievable after introducing a gas component in the Sgr progenitor or adding an extra possible massive LMC or considering a non-spherical Milky Way halo or adjusting high-mass-ratio.

5. Milky Way rotation curve, flaring, warp, asymmetric drift, and the temporal evolution of its disc—factors intricately interwoven within the galaxy's vast and complex ecosystem.

6. We hope to integrate the insights gained from our model with forthcoming datasets, such as those from Gaia, LSST, and the ELT, to further unravel the mysteries of Local Group archaeology and Galactic palaeontology.

Thanks a lot😄