LMS-1:
A dwarf galaxy stream populating the inner Milky Way halo

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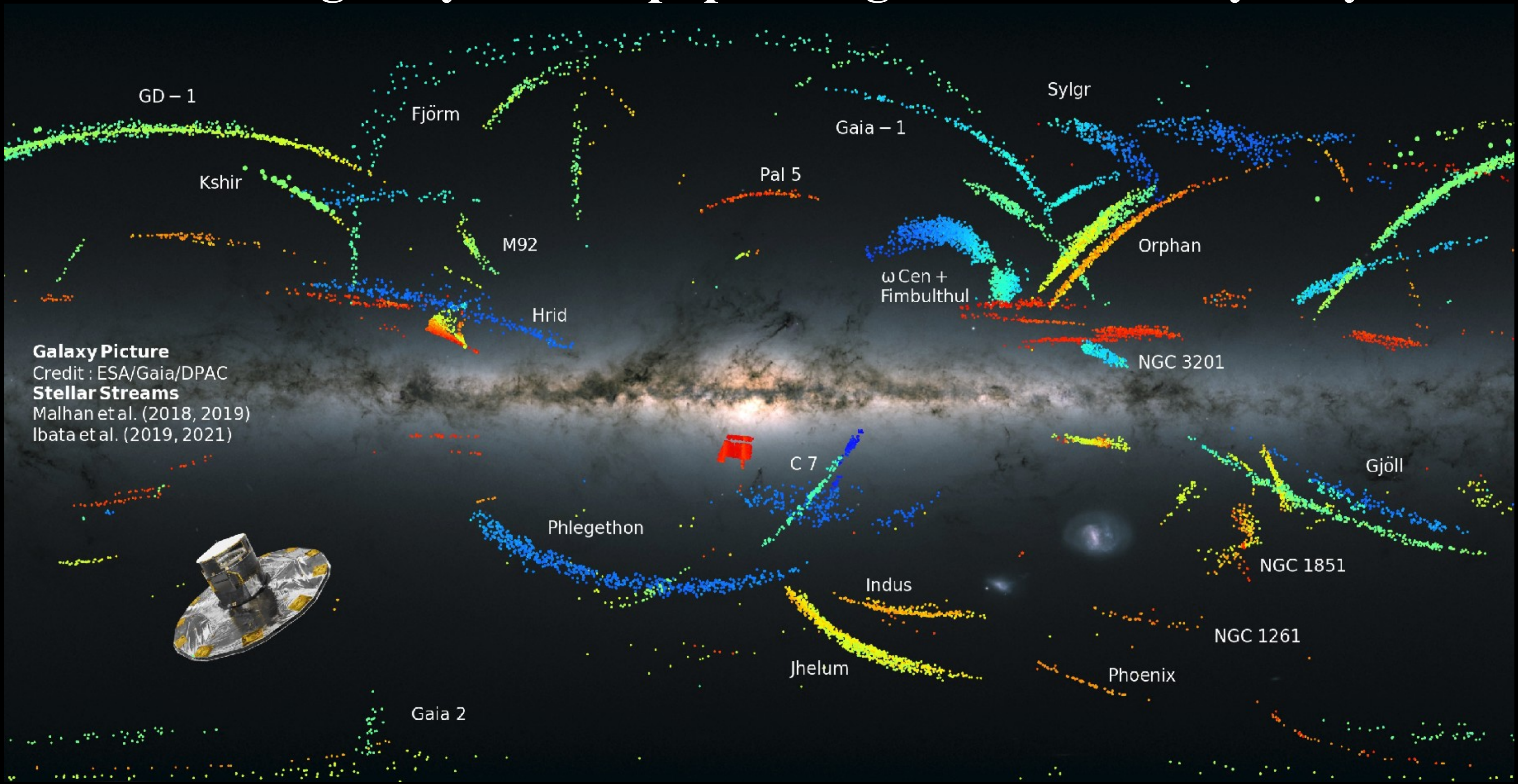

Galaxy Picture
Credit : ESA/Gaia/DPAC
Stellar Streams
Malhan et al. (2018, 2019)
Ibata et al. (2019, 2021)

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Outline

- Inspiration to understand the formation of the Milky Way halo using “Stellar Streams”
- Detecting the “LMS-1” stream (using STREAMFINDER and ESA/Gaia EDR3), and its chemo-dynamical analysis.
- LMS-1 has advanced our knowledge about the *early formation* of the Milky Way halo
- Concluding remarks + discussion.

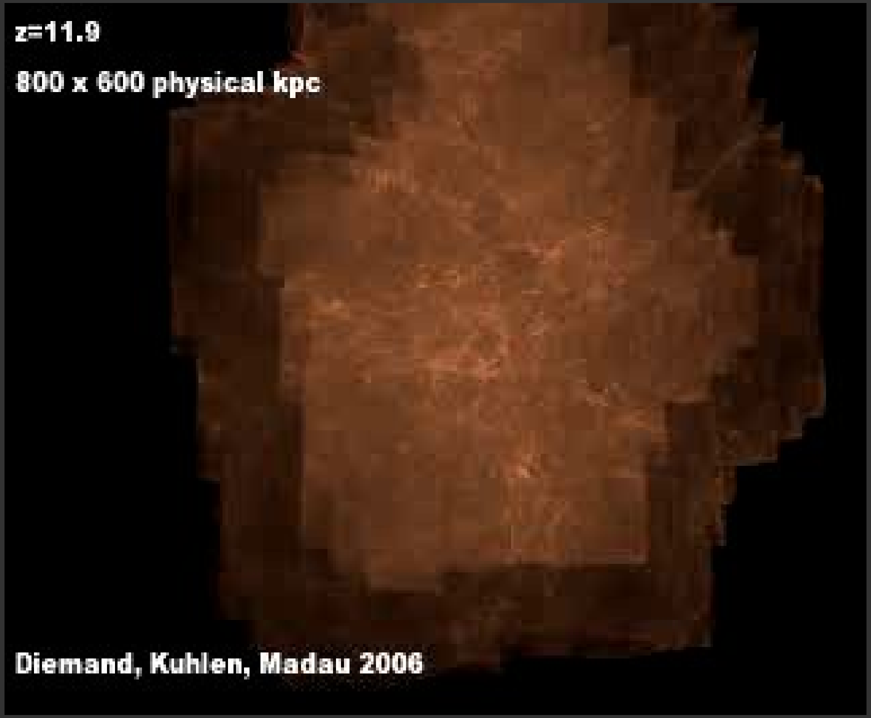
with: **Rodrigo Ibata**
Zhen Yuan
Anke Arentsen
Michele Bellazzini
Nicolas Martin

How do galaxies form in a DM dominated Universe?

- Galactic halo formed via accretion of "multiple" DM subhalos (smaller galaxies) →

- **z>1.5** [early]: higher rate of merging and mass assembly
- **z<1.5** [recent]: passive and stationary phase of merging

- It is hard to connect this scenario of hierarchical growth of DM halos [prediction of LCDM] with the galaxies [observations]



Simulation: Via Lactea
(600kpc x 800kpc)

How do galaxies form in a DM dominated Universe?

Present day:
observation

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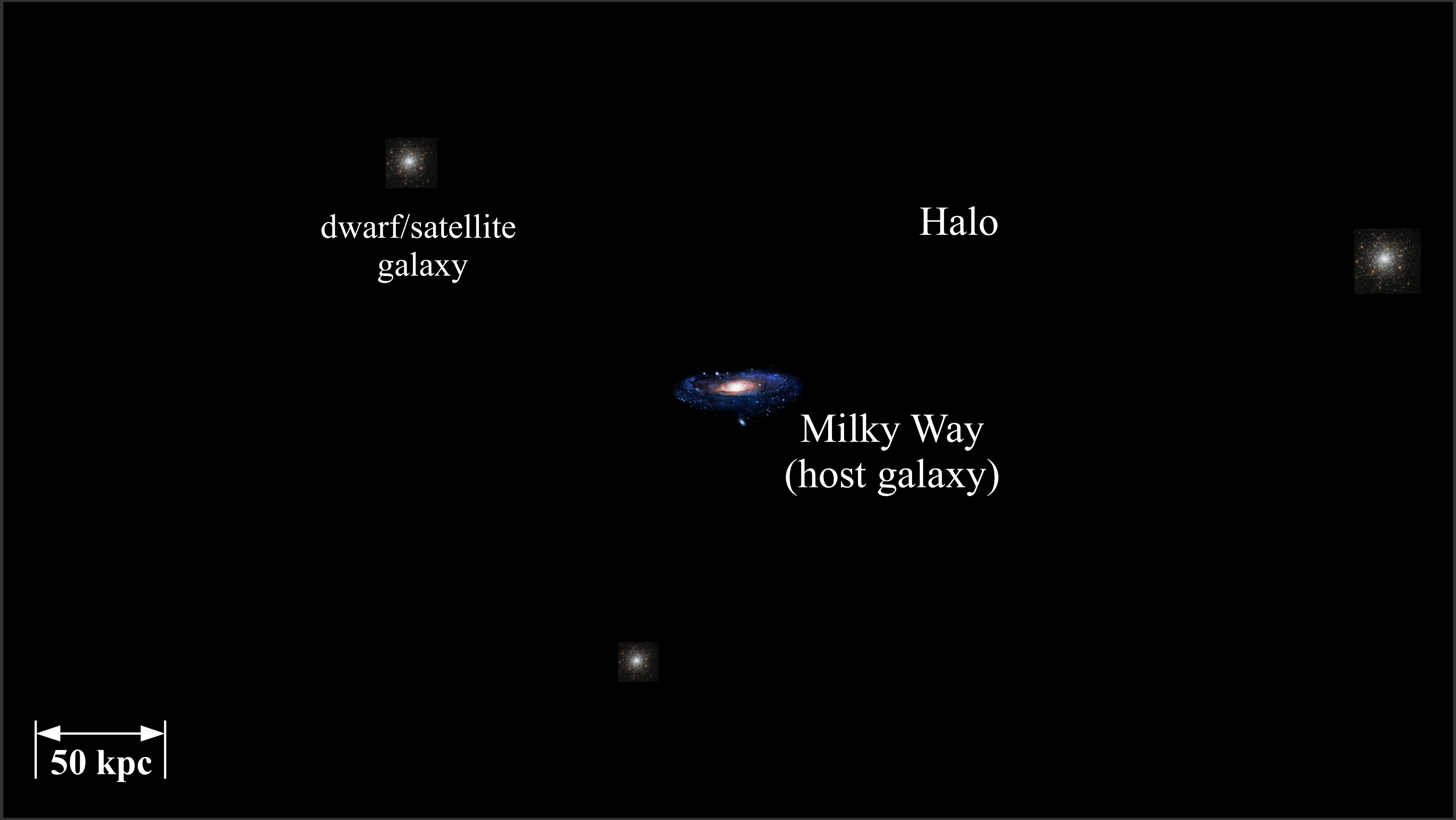
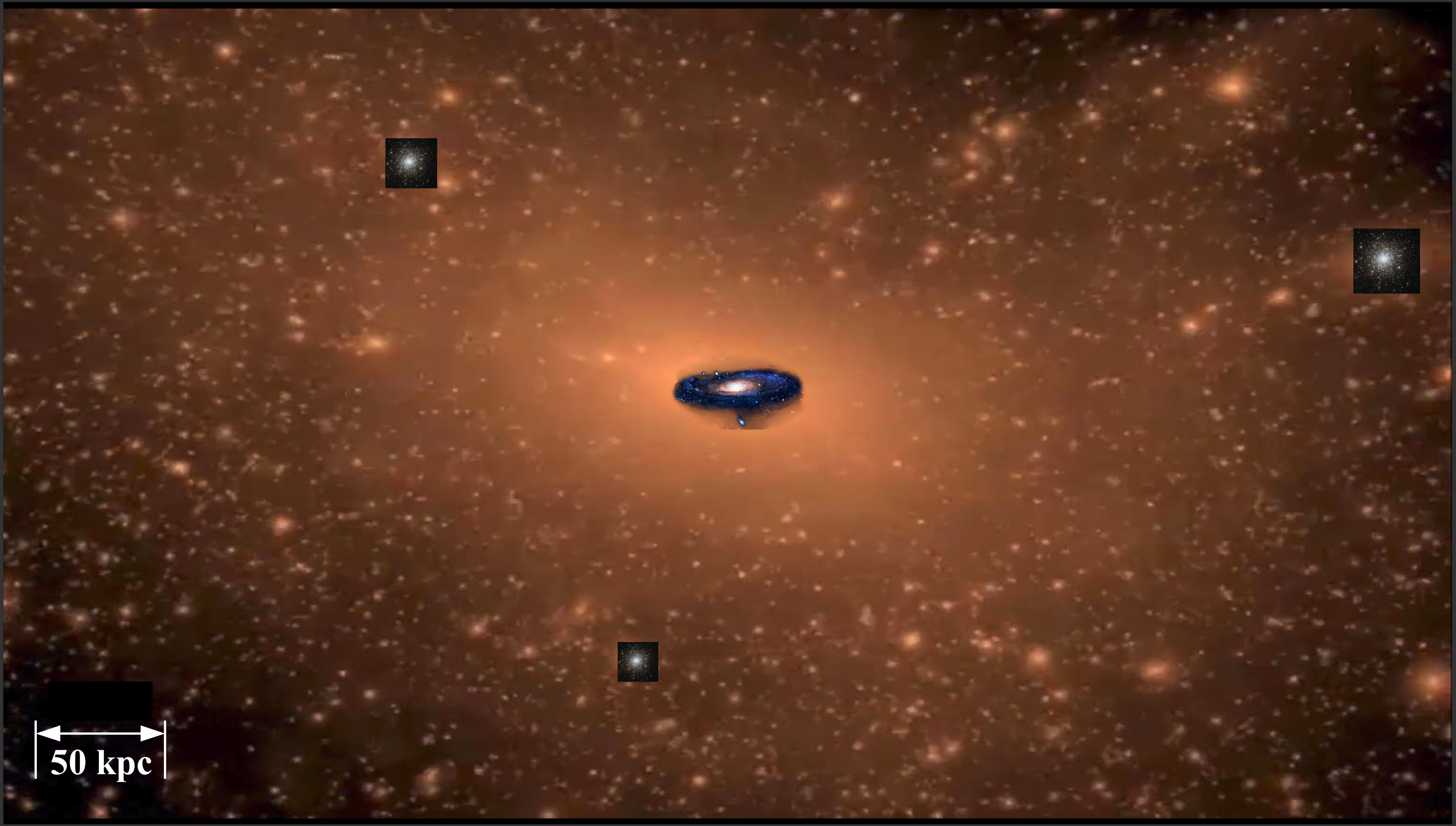
observation



How do galaxies form in a DM dominated Universe?

Present day:
observation
+ prediction

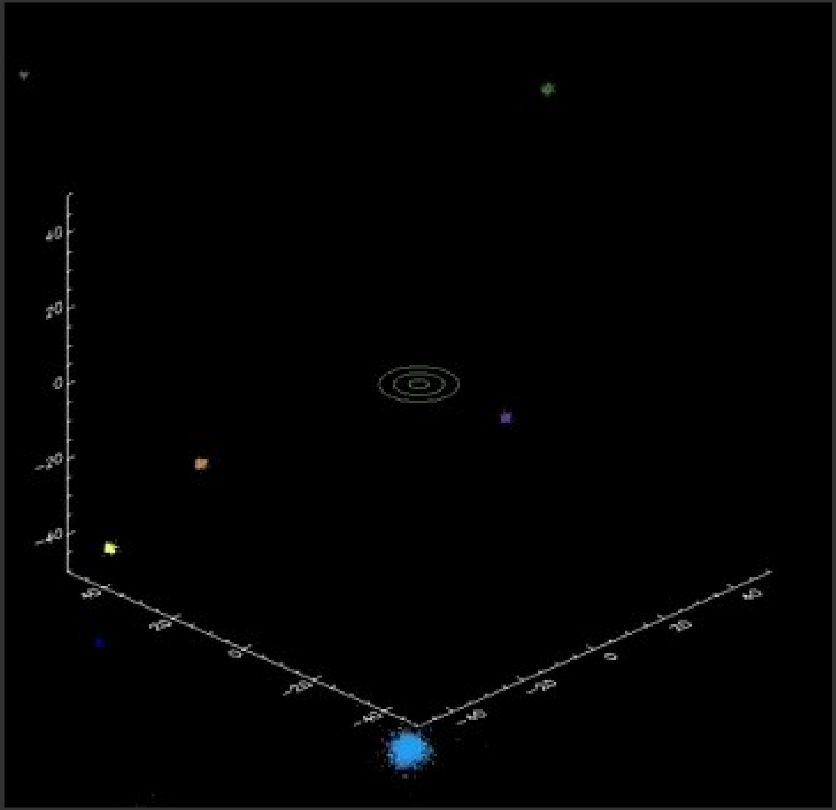

[redacted]

Unravelling the Halo formation using Stellar Streams

- LCDM: Majority of stars (+DM) in the Halo resulted from the “accretion” of several dwarf galaxies [a.k.a. hierarchical growth of halos]

- The infalling dwarf galaxies form Stellar Streams – testimony of the hierarchical growth history of the halos

- The stellar streams provide an excellent opportunity to constrain the **hierarchical formation history of the Milky Way Halo**
  > Number of accretions ?
  > **f(x,v)** of accretions ?



Bullock & Johnston (2005)

Dwarf galaxy streams of the Milky Way (detected pre-*Gaia*)

- Known dwarf galaxy streams of the MW (~4-5):
  e.g., **Sagittarius, Cetus**

Dwarf galaxy streams of the Milky Way (detected pre-*Gaia*)

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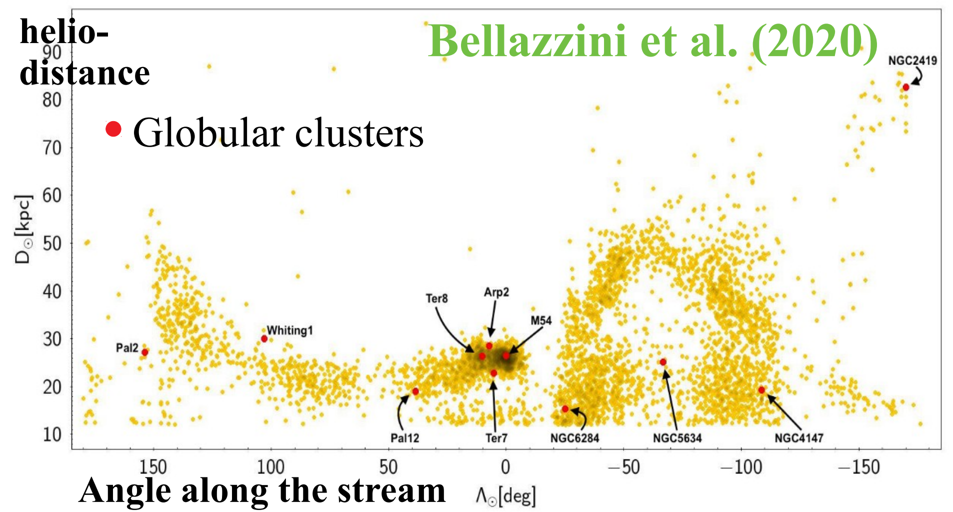
- **Sagittarius stream:**
  > Dynamical/chemical models indicate ~3-6 Gyr ago accretion (e.g., Ruiz-Lara et al. 2020)
  > Sgr brought in a population of ~10 GCs
  > The parent galaxy (Sgr dwarf) has a mass of $M_{halo} \sim 10^{9\text{-}10}$ M_{sun} (from dynamical models) and $M_{star} \sim 10^{6\text{-}7}$ M_{sun}
  > Populates the outer halo (~15-100 kpc)

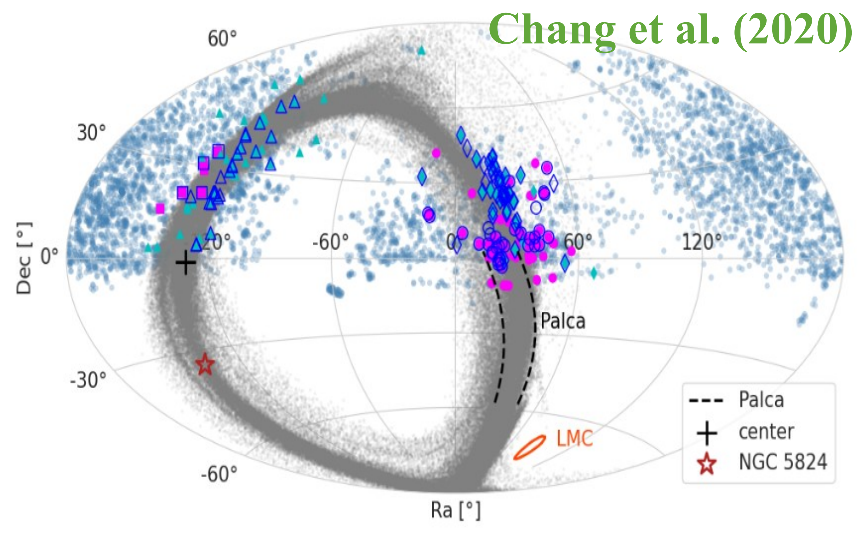


GCs that match Sagittarius stars in position, distance and velocity space

Dwarf galaxy streams of the Milky Way (detected pre-*Gaia*)

- Known dwarf galaxy streams of the MW (~4-5):
  e.g., **Sagittarius, Cetus**

- **Cetus stream:**
  \> Dynamical models indicate ~5 Gyr ago accretion
  \> Brought in a population of (atleast) 1 GC (NGC 5824)
  \> The parent galaxy, $M_{halo} \sim 10^9\ M_{sun}$, and $M_{star} \sim 10^5\ M_{sun}$
  \> Populates the <u>intermediate halo</u> (~24-35 kpc)

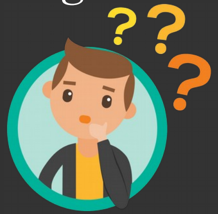

Chang et al. (2020)

Dwarf galaxy streams of the Milky Way (detected pre-*Gaia*)

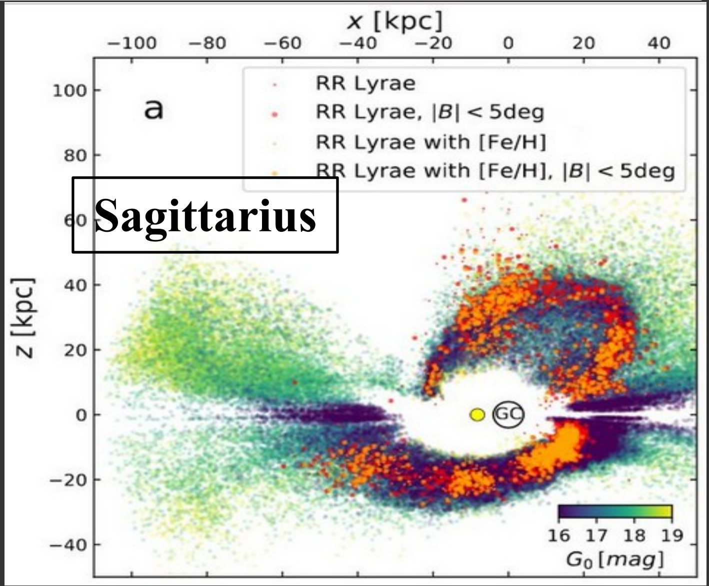
- Known dwarf galaxy streams of the MW (~6):
  e.g., **Sagittarius, Cetus**

- All the known streams are **<u>dynamically-young</u>** systems (accreted <~3-6 Gyrs ago):
  > they are phase-space coherent
  > they have large apocentres (>~35-40 kpc)

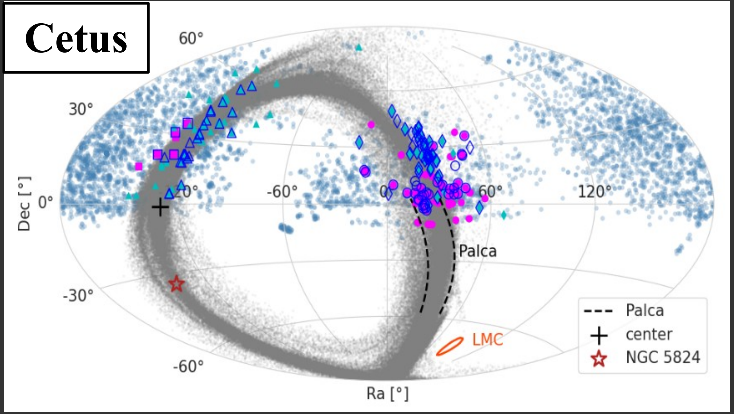
- Question:
  *At the present day, does the Milky Way contain signatures of **<u>dynamically-old dwarf galaxy streams</u>** (accreted ~8-10 Gyrs ago) ?*



Dynamical old+new streams = 'chronological' formation history of the MW Halo

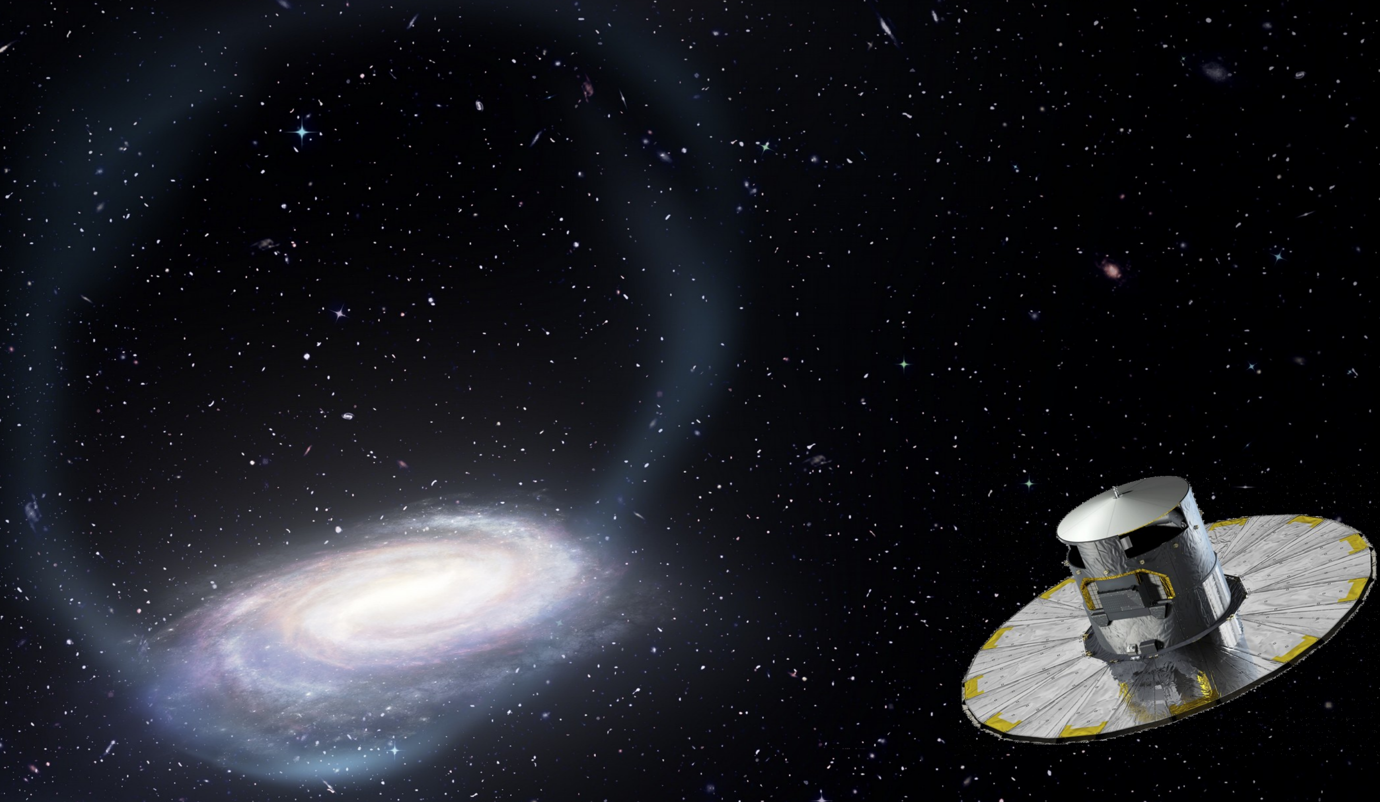


Sagittarius



Cetus

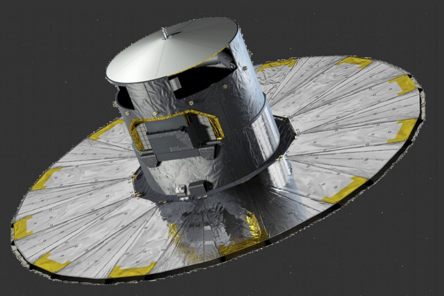
ESA/Gaia provides key to the detection of these dynamically-old streams (i.e., of early accretions, >~8-10 Gyrs ago)



Swinburne Astronomy Productions, James Josephides

STREAMFINDER: Finding streams in the ESA/Gaia dataset

(Malhan & Ibata 2018; Malhan et al. 2018, Malhan, Ibata & Martin 2018; Ibata, Malhan et al. 2018; Ibata, Malhan & Martin 2019; Malhan et al. 2019a, Malhan et al. 2019b; Ibata et al. 2019; Ibata et al. 2020a; Ibata et al. 2020b; Ibata et al. 2021; Malhan et al. 2021)



Input (*Gaia* data)

> 2D positions (RA,Dec.)
> parallaxes (+unc)
> 2D proper motions (+unc)
> Photometry (G, G_{BP}, G_{RP}+unc)

STREAMFINDER

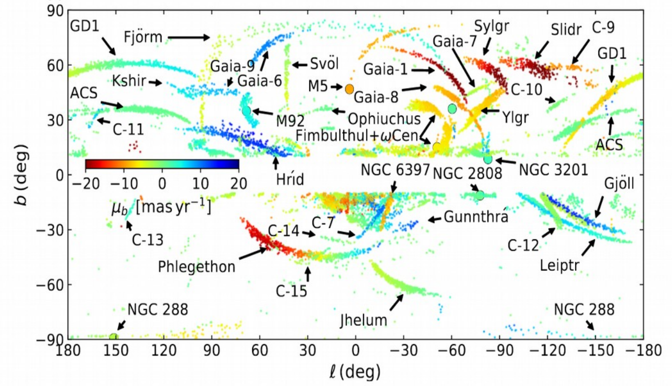
Processing (automated)

> Integrates and samples orbits using input Gaia information
> Stars with more friends = "stream stars"
0 or less friends = "not stream stars"
> Accounts for background

$$\ln\mathcal{L} = \sum_{\text{data}} \ln\left[\eta\mathcal{P}_{\text{stream}}(\theta) + (1-\eta)\,\mathcal{P}_{\text{cont}}\right]$$

Stream Model

Contamination model (using the Gaia data)



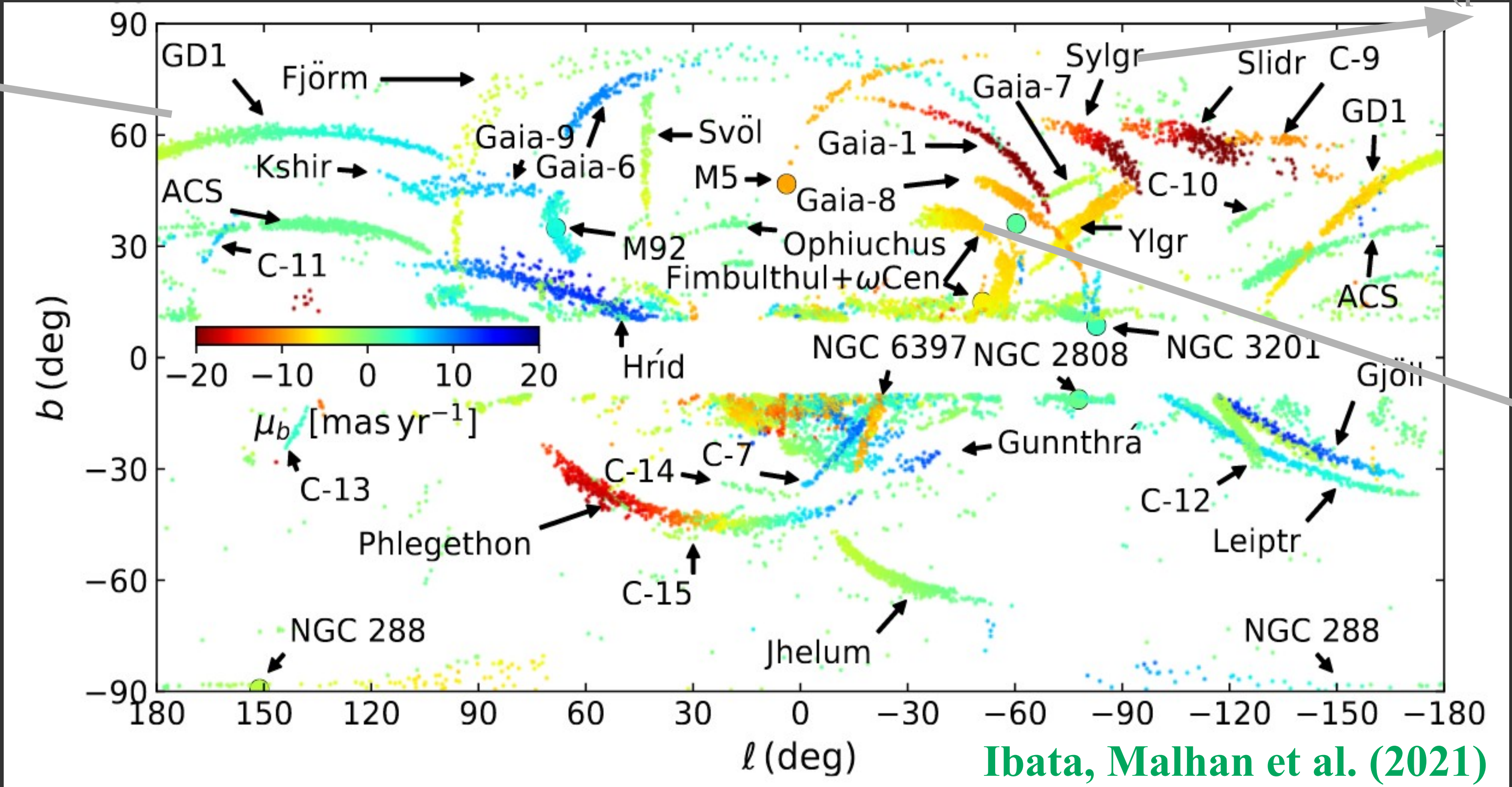
Output

Gaia stars that have
``streamy" characteristics

STREAMFINDER: Finding streams in the Gaia dataset

(Malhan & Ibata 2018; Malhan et al. 2018, Malhan, Ibata & Martin 2018; Ibata, Malhan et al. 2018; Ibata, Malhan & Martin 2019; Malhan et al. 2019a, Malhan et al. 2019b; Ibata et al. 2019; Ibata et al. 2020a; Ibata et al. 2020b; Ibata et al. 2021; Malhan et al. 2021))

Stellar streams of our Galaxy detected using Gaia EDR3 and STREAMFINDER



Ibata, Malhan et al. (2021)

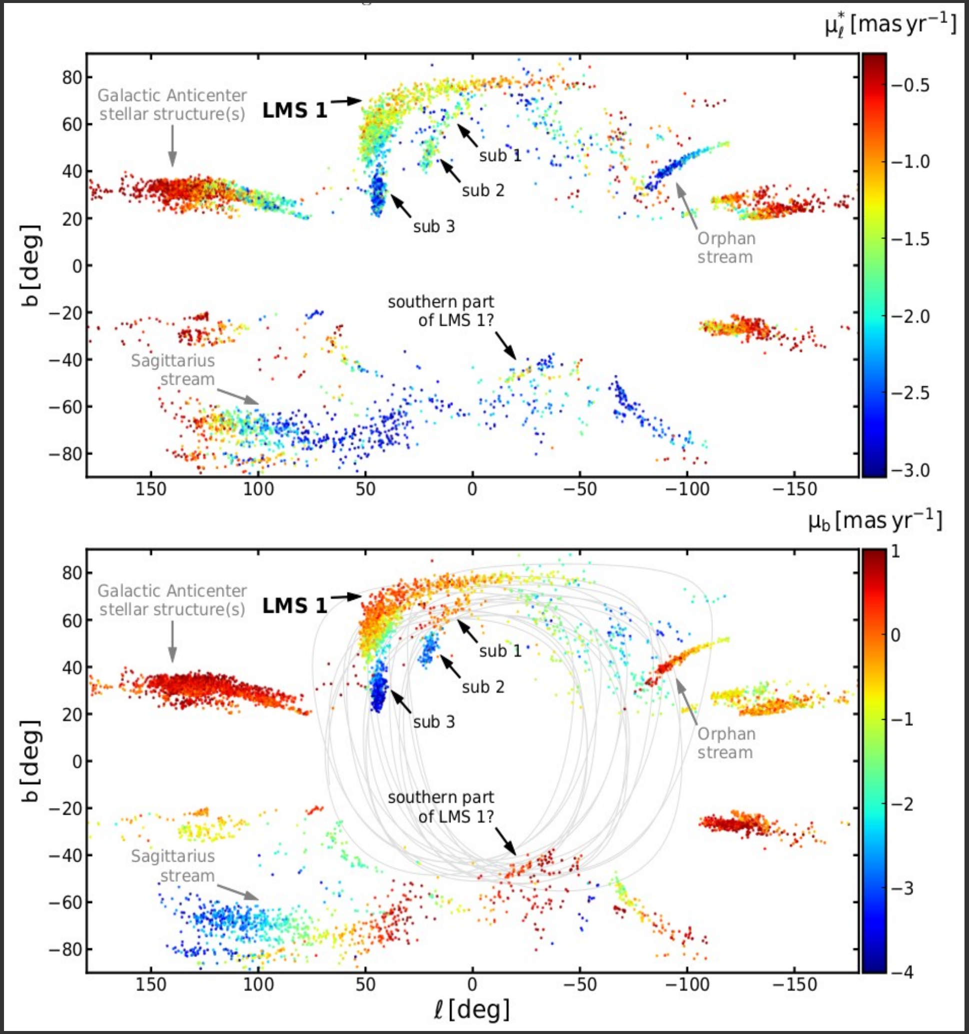
Sylgr
([Fe/H]=-2.92)

GD-1
(>100 deg
long)

Many
GC streams

Stream
of Omg.
Cen

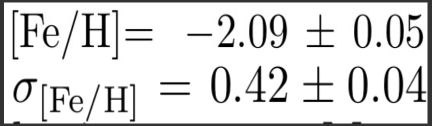
LMS-1 stream detection by STREAMFINDER using Gaia EDR3



- Gaia EDR3 processed with STREAMFINDER

- LMS-1 is detected as one of the most striking features in this map (+other known streams)

- LMS-1's width (Gaussian) ~750 pc, distance~20 kpc
- Low [Fe/H] +significant [Fe/H] dispersion+ large physical width => LMS-1 is a dwarf galaxy stream.



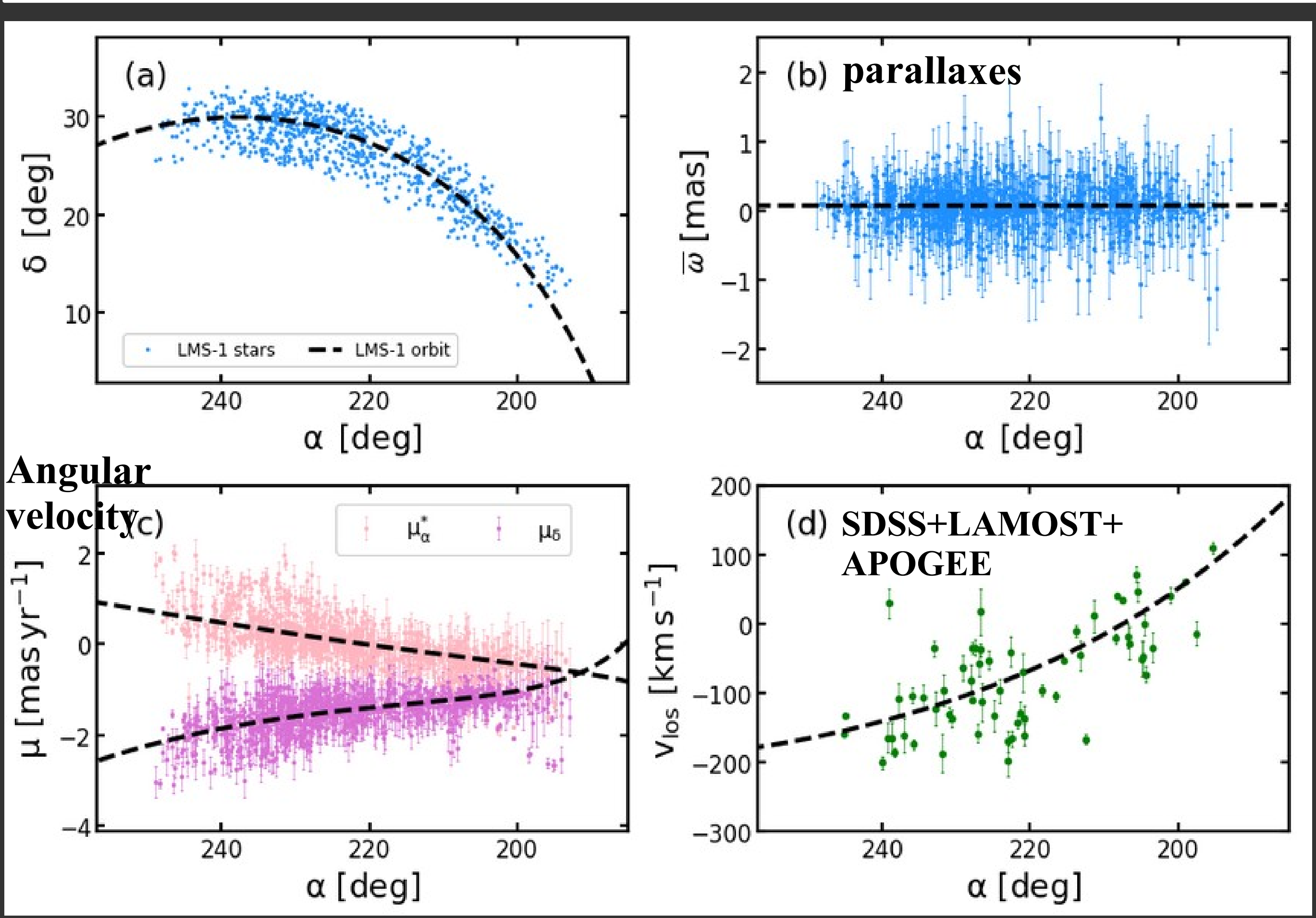
$$[\mathrm{Fe/H}] = -2.09 \pm 0.05$$
$$\sigma_{[\mathrm{Fe/H}]} = 0.42 \pm 0.04$$

[Fe/H] implies parent galaxy M_{*}~$10^{5\text{-}6}$ M_{sun}(~ Draco dwarf galaxy)

- LMS-1 is "wrapped" around the inner Galactic Halo
  > Off-stream features adjacent to LMS-1 (sub-1, sub-2, sub-3)
  > agglomeration of stars in the southern galactic sky

"LMS-1/Wukong" discovered by Yuan+2020/Naidu+2020.

Orbit of LMS-1



parallaxes

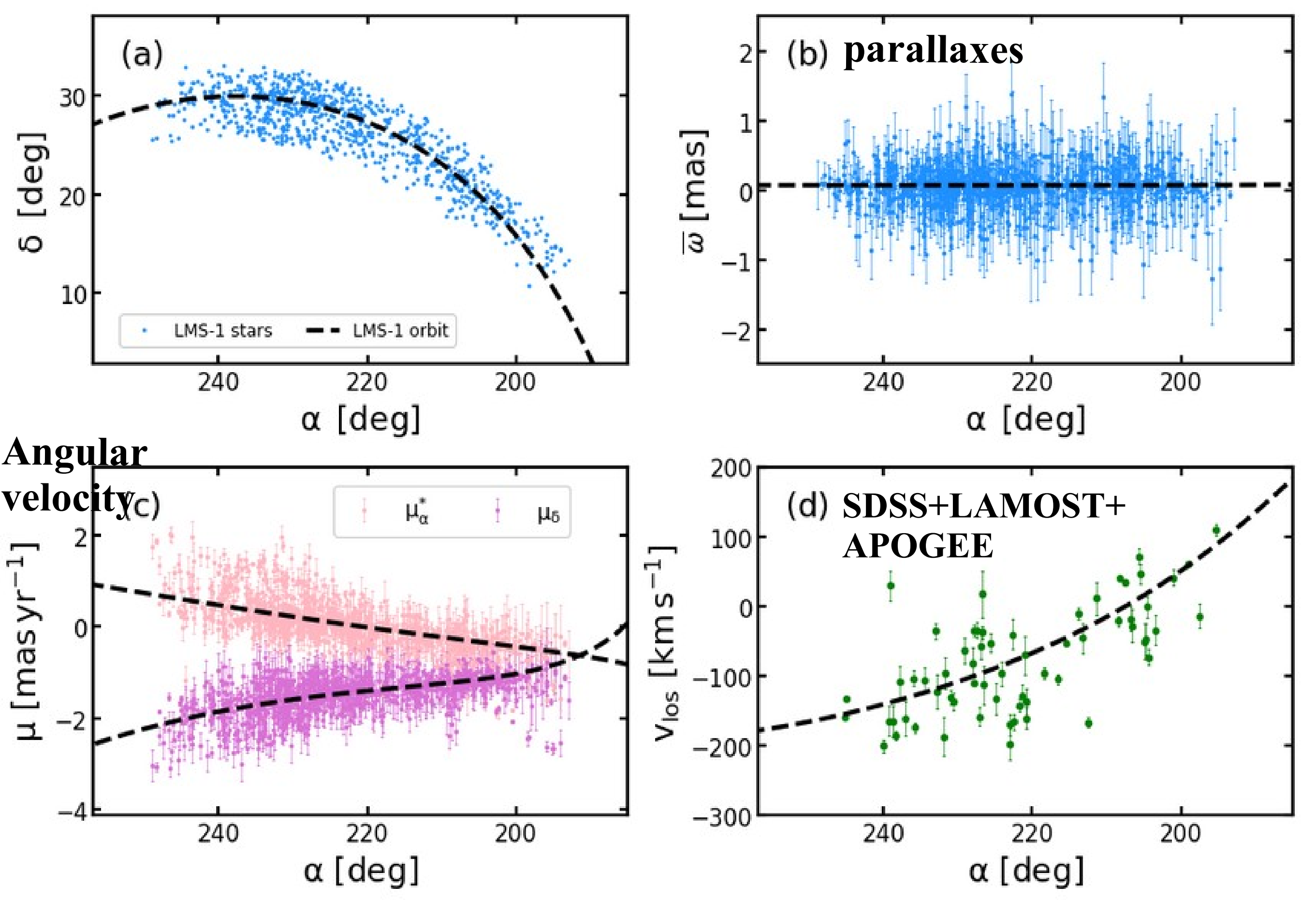
Angular velocity

SDSS+LAMOST+APOGEE

- Cross-match Gaia sources with the spectroscopic surveys to get the missing RV info.
- LMS-1's orbit
(in McMillan2017 mass model)

><u>Eccentricity~0.2 (nearly circular)</u>
>Lz= - 700 kpc kms-1(prograde)
<u>> r-apo=16 kpc</u>
> r-peri =10 kpc

Orbit of LMS-1



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<u>> r-apo=16 kpc</u>
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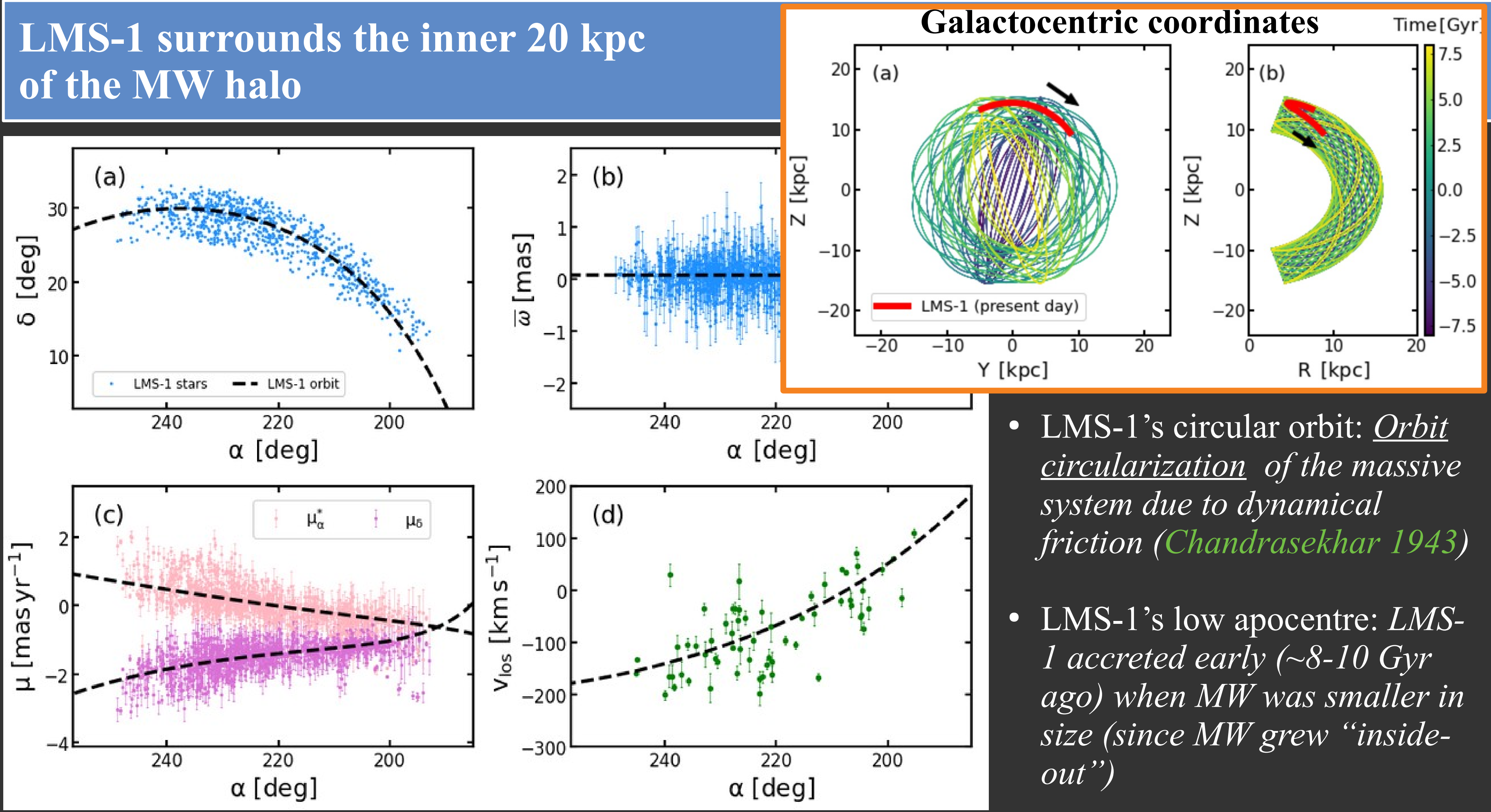
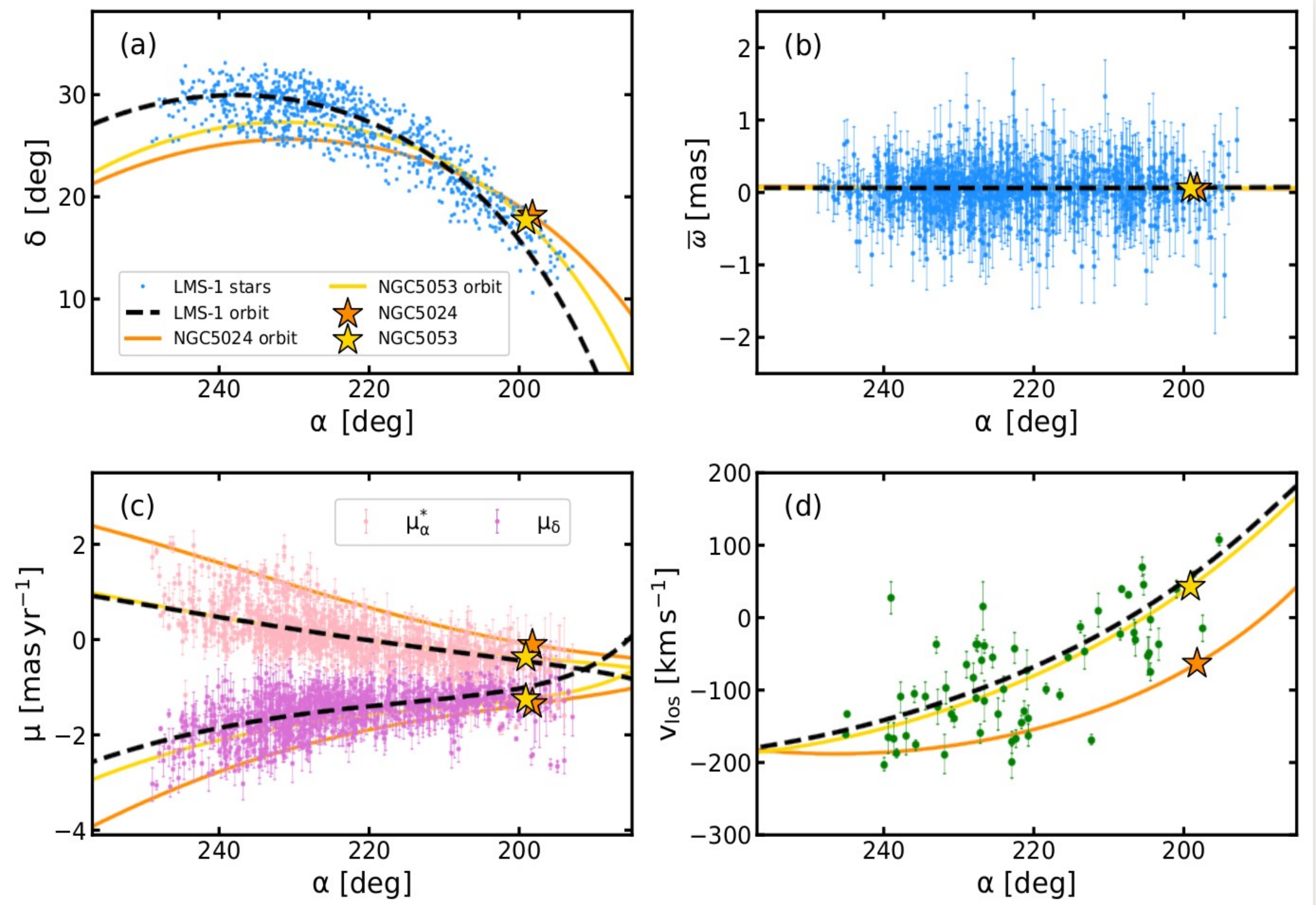
Almost all the intact dwarf galaxies + dwarf galaxy streams:
>eccentricity>~0.7
>r-apo >35-40 kpc

LMS-1 surrounds the inner 20 kpc of the MW halo

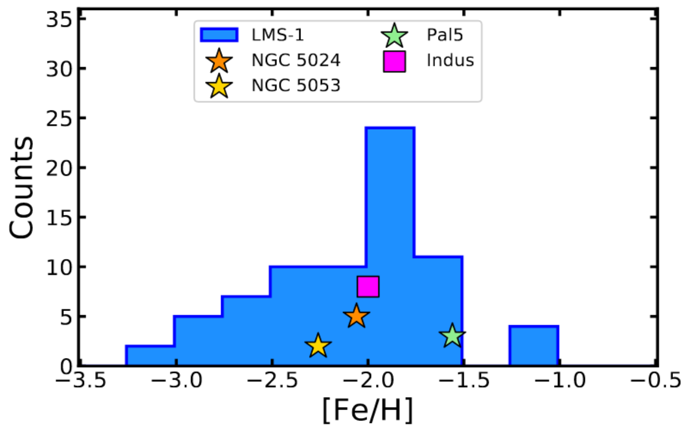


- LMS-1’s circular orbit: *Orbit circularization of the massive system due to dynamical friction (Chandrasekhar 1943)*
- LMS-1’s low apocentre: *LMS-1 accreted early (~8-10 Gyr ago) when MW was smaller in size (since MW grew “inside-out”)*

Comparing the orbits of LMS-1 and globular clusters (NGC5024 and NGC5053)

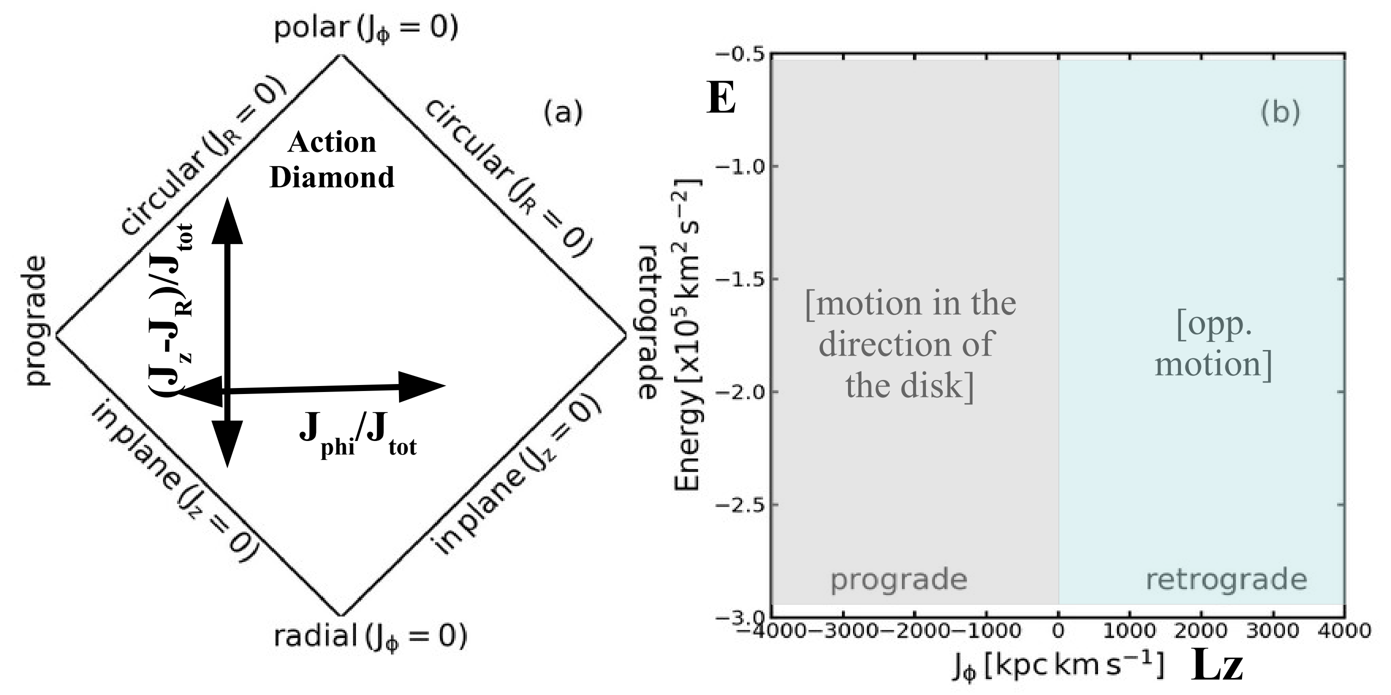


- NGC 5053 and NGC 5024 have very similar orbits as LMS-1. This co-incidence in orbit (and [FeH]) suggests that these two GCs were accreted inside LMS-1’s parent galaxy



Comparing properties of LMS-1 with the MW globular clusters and other streams in the dynamical (E, J) space

- Objects with similar Energy (E) and actions (**J**) are expected to have been accreted inside the same parent galaxy.

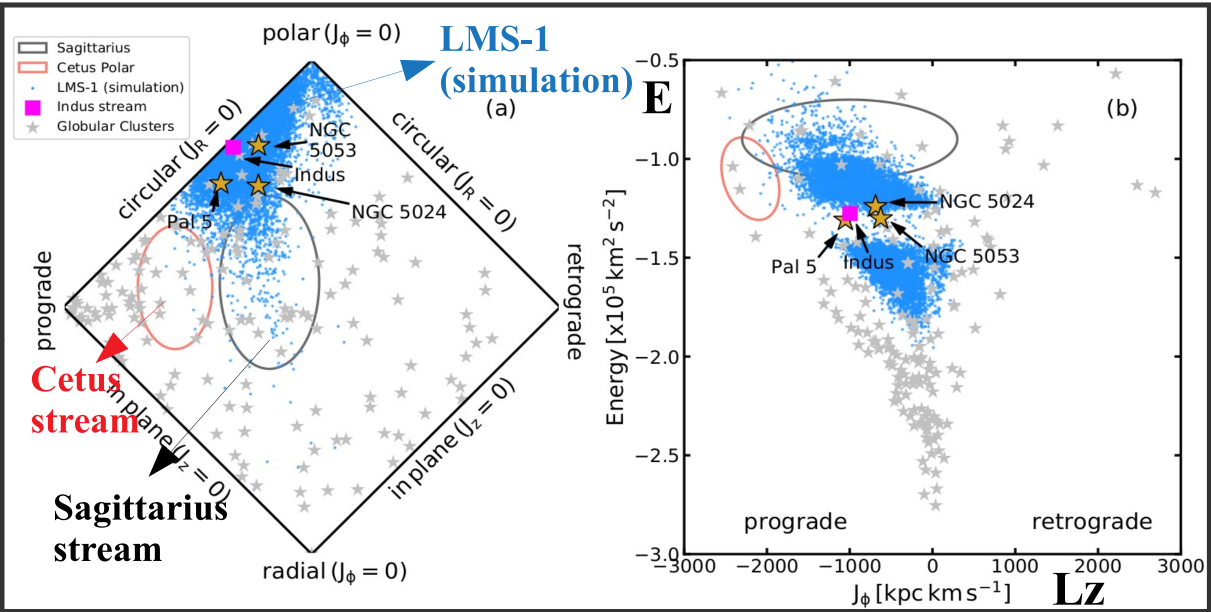


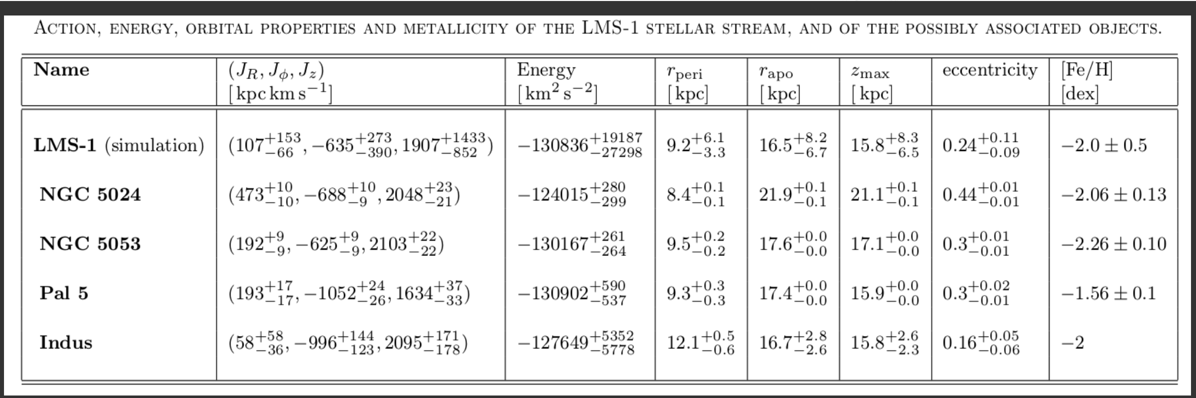
E-**J** space of the Milky Way

[**J** represent the amplitude of the orbit along different directions in a given coordinate system.
We use cylindrical coordinate system (J_R, J_phi, J_z)]

Comparing properties of LMS-1 with the MW globular clusters and other streams in the dynamical (E, J) space

- Objects with similar Energy (E) and actions (**J**) are expected to have been accreted inside the same parent galaxy.
- (E,**J**), and other orbital properties, of NGC 5024, NGC 5053, Pal 5 and the Indus stream are very similar to LMS-1. [although orbital pole of Pal5 is different]





ACTION, ENERGY, ORBITAL PROPERTIES AND METALLICITY OF THE LMS-1 STELLAR STREAM, AND OF THE POSSIBLY ASSOCIATED OBJECTS.

Name	(J_R, J_ϕ, J_z) [kpc km s^{-1}]	Energy [km^2 s^{-2}]	$r_{\rm peri}$ [kpc]	$r_{\rm apo}$ [kpc]	$z_{\rm max}$ [kpc]	eccentricity	[Fe/H] [dex]
LMS-1 (simulation)	$(107^{+153}_{-66}, -635^{+273}_{-390}, 1907^{+1433}_{-852})$	$-130836^{+19187}_{-27298}$	$9.2^{+6.1}_{-3.3}$	$16.5^{+8.2}_{-6.7}$	$15.8^{+8.3}_{-6.5}$	$0.24^{+0.11}_{-0.09}$	-2.0 ± 0.5
NGC 5024	$(473^{+10}_{-10}, -688^{+10}_{-9}, 2048^{+23}_{-21})$	-124015^{+280}_{-299}	$8.4^{+0.1}_{-0.1}$	$21.9^{+0.1}_{-0.1}$	$21.1^{+0.1}_{-0.1}$	$0.44^{+0.01}_{-0.01}$	-2.06 ± 0.13
NGC 5053	$(192^{+9}_{-9}, -625^{+9}_{-9}, 2103^{+22}_{-22})$	-130167^{+261}_{-264}	$9.5^{+0.2}_{-0.2}$	$17.6^{+0.0}_{-0.0}$	$17.1^{+0.0}_{-0.0}$	$0.3^{+0.01}_{-0.01}$	-2.26 ± 0.10
Pal 5	$(193^{+17}_{-17}, -1052^{+24}_{-26}, 1634^{+37}_{-33})$	-130902^{+590}_{-537}	$9.3^{+0.3}_{-0.3}$	$17.4^{+0.0}_{-0.0}$	$15.9^{+0.0}_{-0.0}$	$0.3^{+0.02}_{-0.01}$	-1.56 ± 0.1
Indus	$(58^{+58}_{-36}, -996^{+144}_{-123}, 2095^{+171}_{-178})$	-127649^{+5352}_{-5778}	$12.1^{+0.5}_{-0.6}$	$16.7^{+2.8}_{-2.6}$	$15.8^{+2.6}_{-2.3}$	$0.16^{+0.05}_{-0.06}$	-2

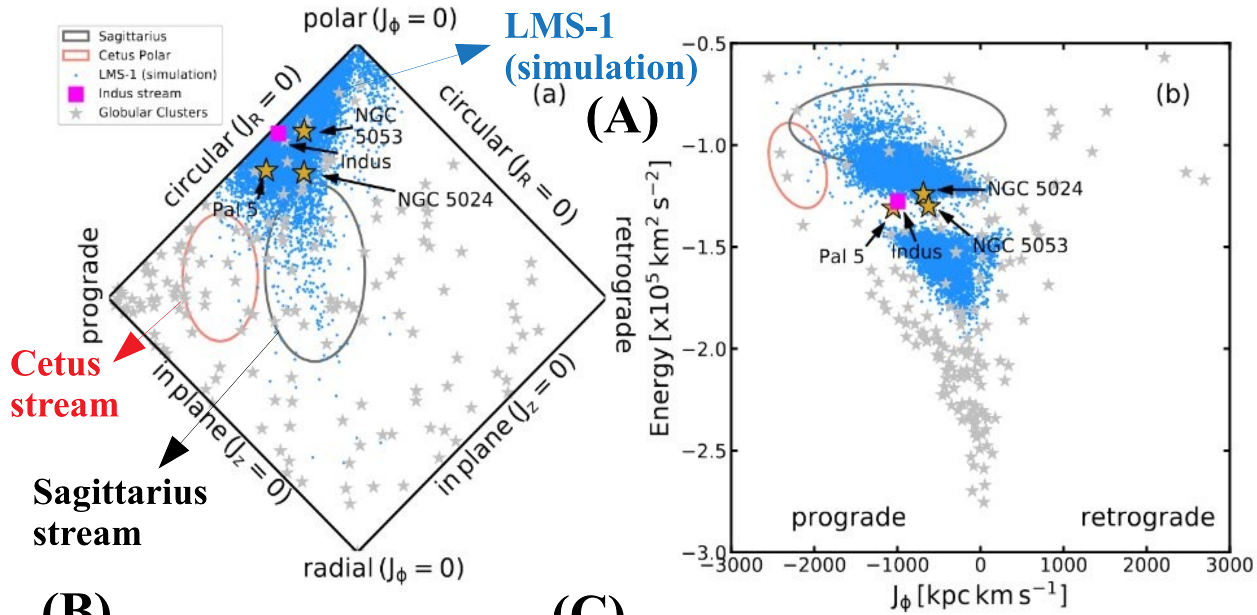
Comparing properties of LMS-1 with the MW globular clusters and other streams in the dynamical (E, J) space + [Fe/H] + stellar population

- Objects with similar Energy (E) and actions (**J**) are expected to have been accreted inside the same parent galaxy.
- (E,**J**), and other orbital properties, of NGC 5024, NGC 5053, Pal 5 and the Indus stream are very similar to LMS-1. [although orbital pole of Pal5 is different]

- NGC 5024, NGC 5053, Indus have very similar [Fe/H] and CMDs as LMS-1. [for Pal5 it is slightly different]

- **NGC 5024, NGC 5053, Pal 5* and Indus were accreted inside LMS-1's parent galaxy**

(A)

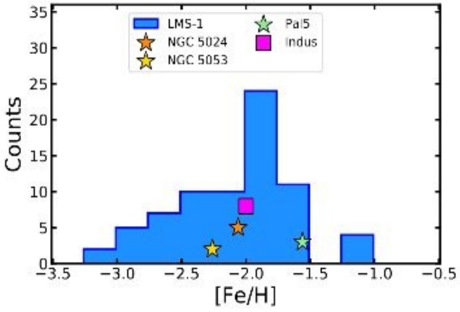


LMS-1 (simulation)

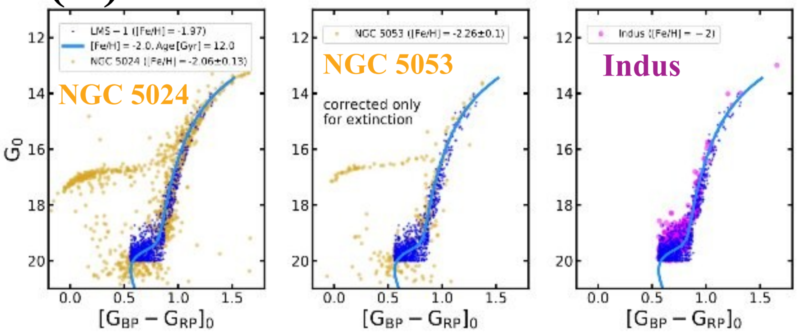
Cetus stream

Sagittarius stream

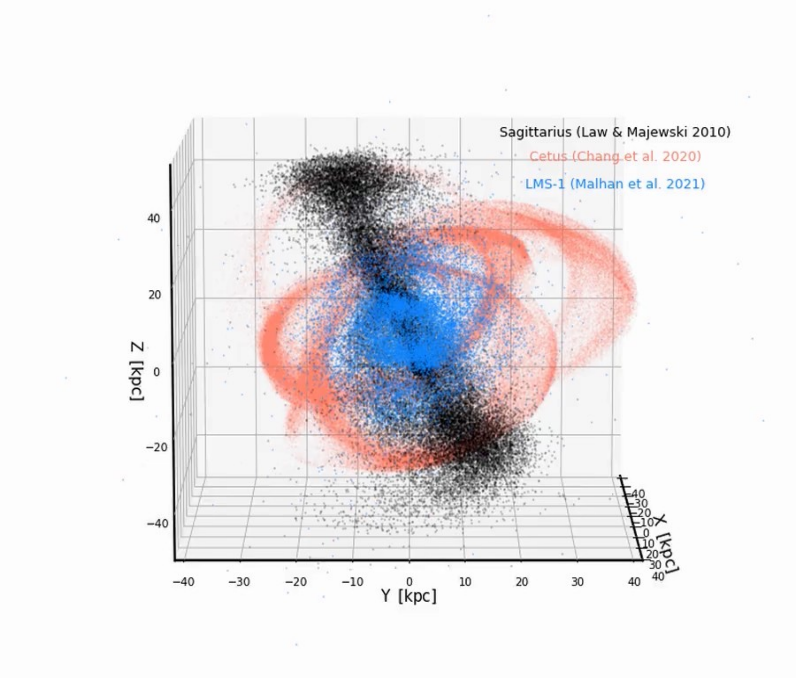
(B)



(C)



Analyses of the dynamical old+new streams = Knowledge of the ‘chronological’ formation history of the MW Halo



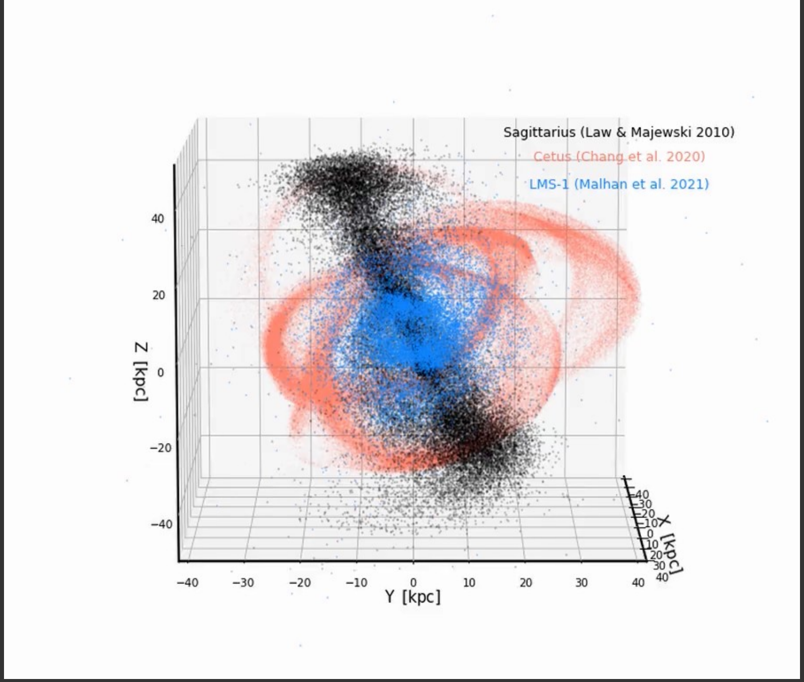
1) **Sagittarius** (*i*=76^o):
>Spans outer Galactic Halo (15-100 kpc)
Dynamically-young, recently accreted (~3-6 Gyr ago)
>[Fe/H]∼ −0.5 to −2.5
>8-10 GCs to the MW

2) **Cetus** (*i*=60^o)**:**
>Spans intermediate Galactic Halo (24-36 kpc)
>[Fe/H]∼ −2
>1 GC to the MW (NGC 5824)

3) **LMS-1** (*i*=75^o):
>Spans inner Galactic halo (10-20 kpc)
Dynamically-old, early accreted (~8-10 Gyrs ago)
>[Fe/H]∼ −2.1
> 2-3 GCs + 1 stream to the MW

Chronological perspective: Did LMS-1 accrete early (inner halo), then Cetus (intermediate halo) and finally Sagittarius (outer halo)?

What are the 3 polar dwarf galaxy streams telling us?



How common are such polar dwarf galaxy streams in MW-mass galaxies as per cosmological simulations?

If common
Are polar streams
the major source
of stellar population in
the halos of
MW-mass galaxies?

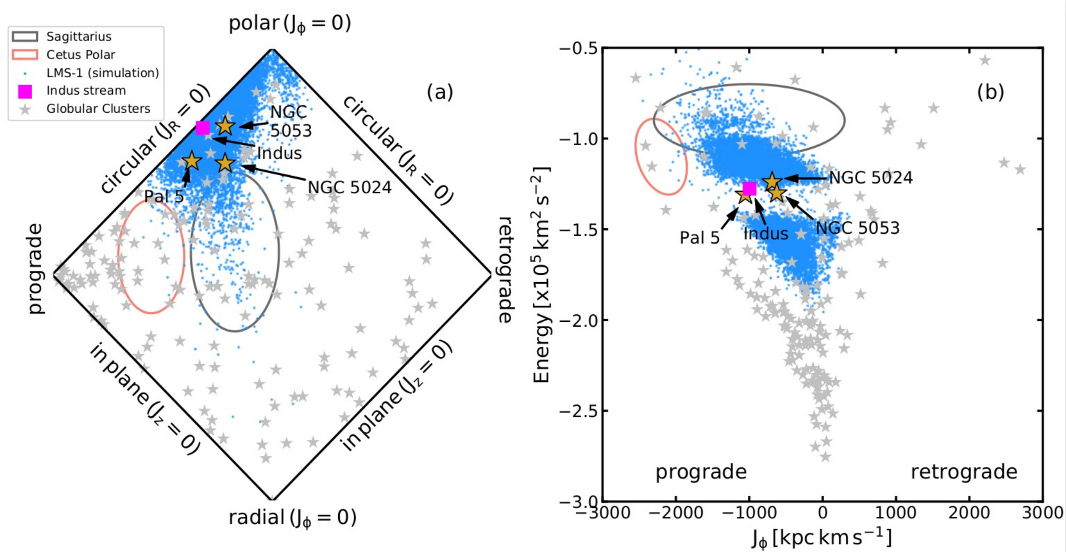
If uncommon
Is our MW galaxy
special?

(connected to the VPOS
phenomenon?
cf. works by M.Pawlowski)

Summary

- Stellar streams provide direct evidence of the hierarchical formation of the Milky Way.

- LMS-1 is an interesting stellar stream:
  > unique orbit = polar, low “ecc.”, low “r_apo”
  > possibly accreted very early (>~8-10 Gyrs ago)
  > $M_{halo} \sim 10^{9-10} M_{sun}$ ($M_{star} \sim 10^{5-6} M_{sun}$)
  > evidence that LMS-1 is completely wrapped around the inner 20 kpc of the Milky Way
  > brought in NGC 5024, NGC 5053, Pal 5* and Indus



- LMS-1 is an important fossil remnant of the early formation of our Galaxy !!

Thank you for your attention:)
Khyati Malhan
MPIA, Heidelberg