Metal-poor stars with disc-like orbits Possible traces of the Galactic disc at very early epochs

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Date: 2024/11/18

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Introduction

Metal-Deficient Stars:

- Key to understanding early Galaxy evo
- Previously thought to exist only in sphe

Recent Discoveries:

- Extremely metal-poor stars with disc-like kinematics.
- Preference for prograde orbits.

Origins and Simulations:

- Majority from accretion events; some may form in situ
- Simulations suggest varied evolutionary paths.

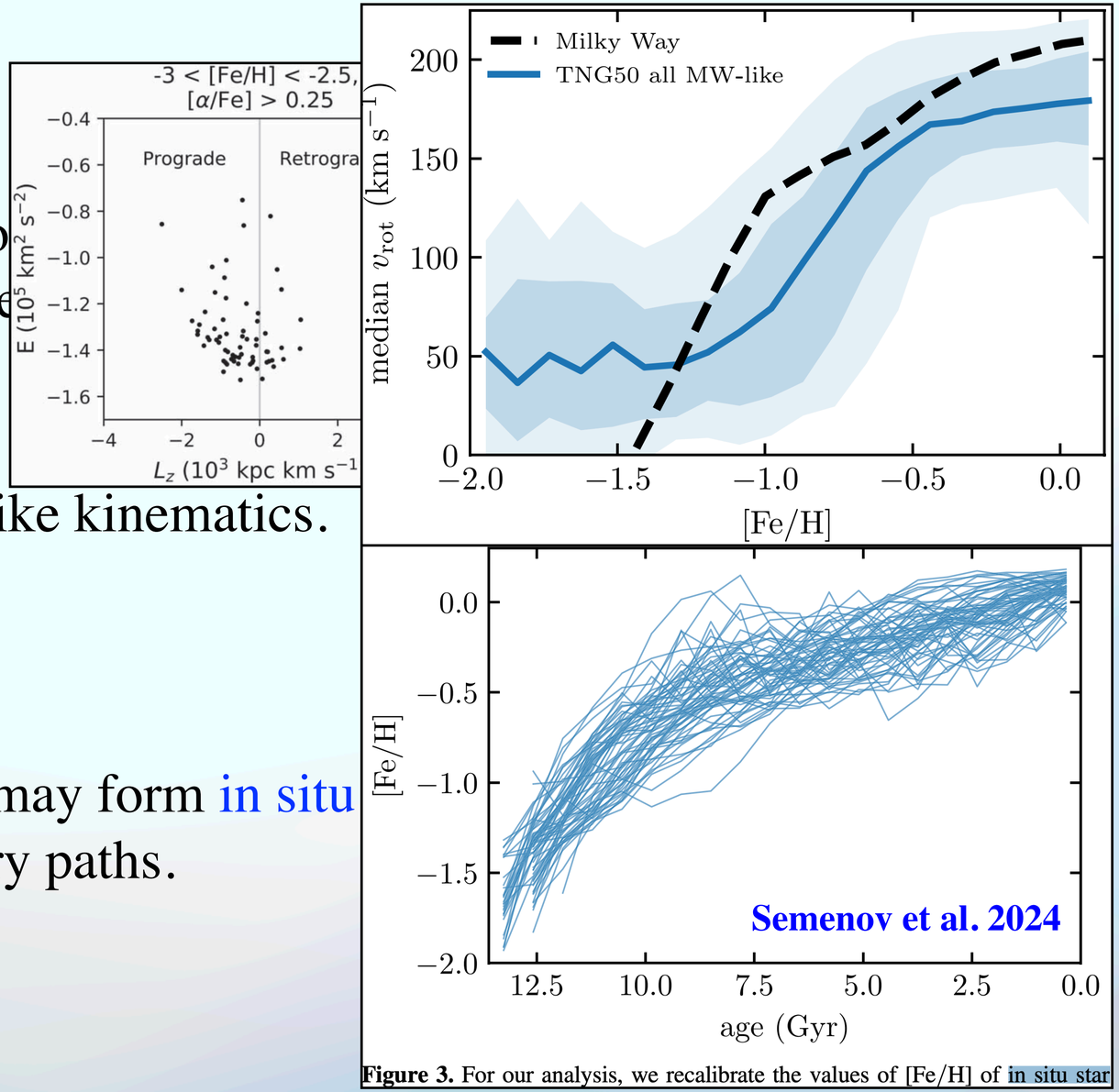


Figure 3. For our analysis, we recalibrate the values of [Fe/H] of in situ star

The kinematics of metal-poor disc-like stars

Data and Methods

Data Source

Main Sample (Bellazzini et al. 2023)

- ~700,000 red giant branch stars
- Located within a few kpc of the Sun
- Metallicity range: -3.0 ≤ [Fe/H] ≤ +0.8
- Photometric metallicity accuracy: ~0.1 dex
- Photometric metallicity precision: ≤0.2 dex

Sample Quality & Selection

High-Quality Astrometric Data (Gaia DR3)

- Parallax errors < 10%
- 685,087 stars with valid radial velocity
- 95% of stars: RV uncertainties < 5 km/s

The kinematics of metal-poor disc-like stars

Data and Methods

Key Parameters

Main Sample (Bellazzini et al. 2023)

- Based on Calamida et al. (2007) relation
- [Fe/H] = f(m0, (v-y)0)
- Recalibrated using APOGEE DR17 data

Orbital Parameters

- Computed using AGAMA software
- Adopts McMillan (2017) Galactic potential
- Key measurements:
  - L_Z (orbital angular momentum)
  - Orbital eccentricity
  - Prograde/retrograde motion

The kinematics of metal-poor disc-like stars

Data and Methods

Z_{max}: the maximum absolute height over the Galactic plane reached by a star orbit.

Concentrated around $L_Z = L_{Z\odot}$ = 1909 km/s kpc.

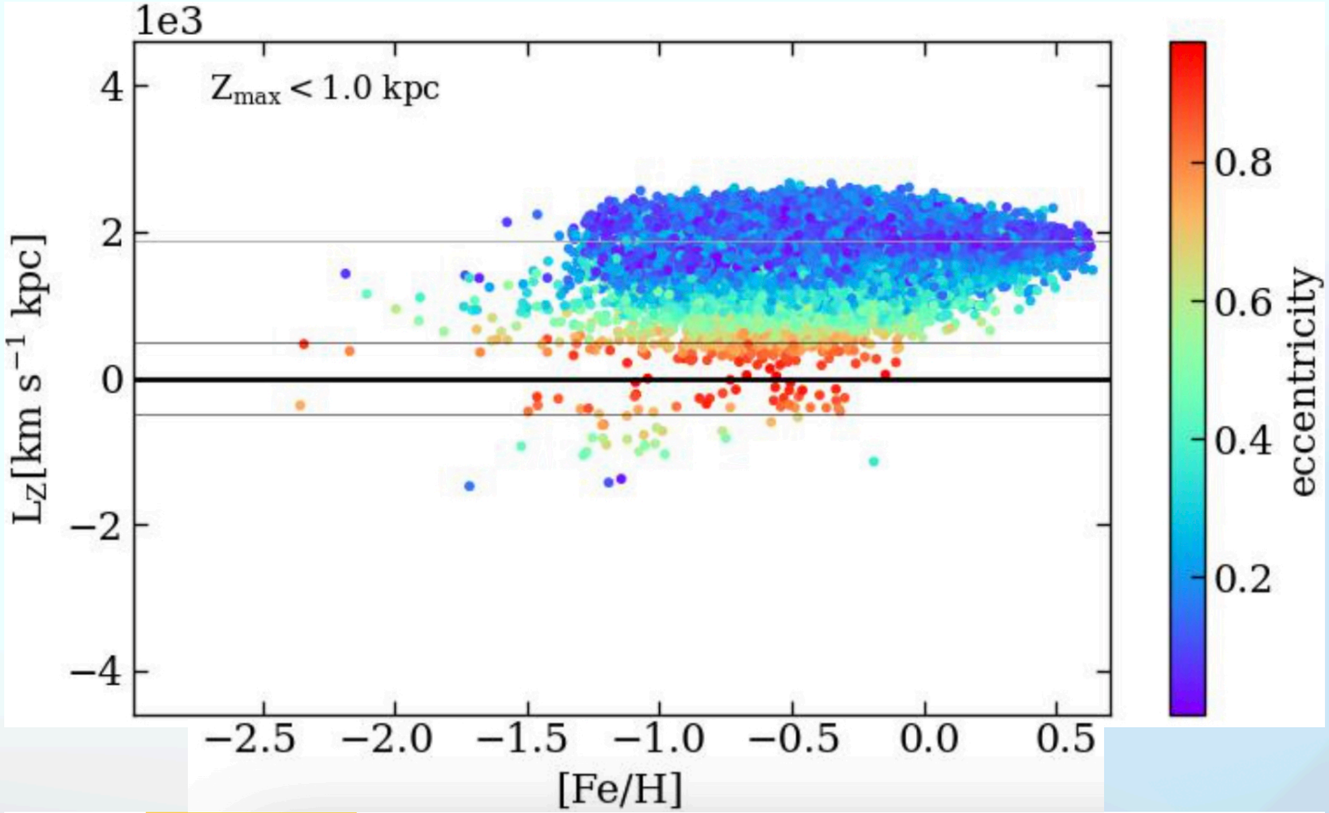


Fig. 1. Metallicity of stars in our sample versus component of angular momentum perpendicular to disc plane for three different slices in

The kinematics of metal-poor disc-like stars

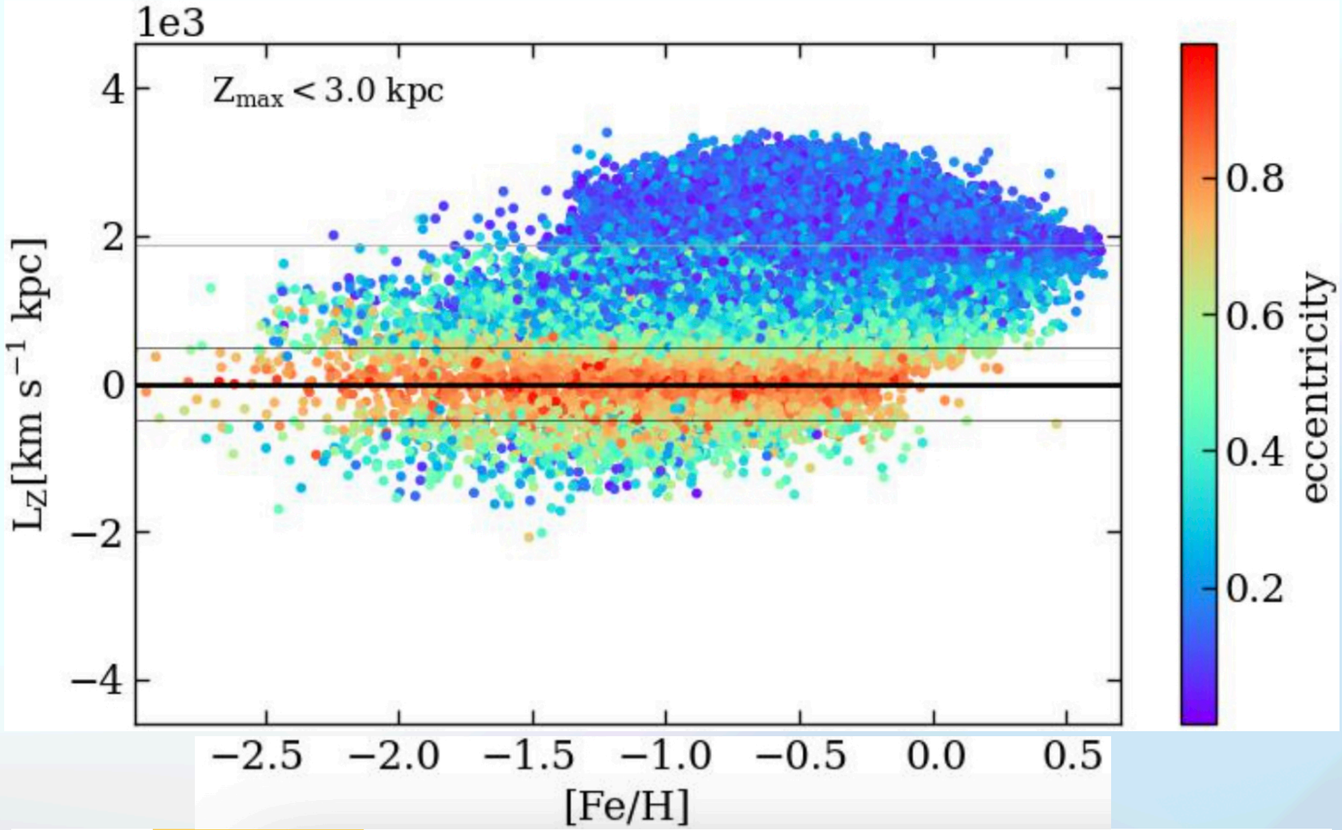
Data and Methods

- **Wider LZ distribution compared to Zmax < 1.0 kpc.**
- **Dominated by thick disk stars.**
- **Stars with LZ > LZ⊙ disappear at [Fe/H] < -1.4**

High-eccentricity and LZ = 0.0 km/s kpc:

Gaia-Enceladus/Sausage (GES) remnant.

Heated disc stars, that is, the so called Splash population.



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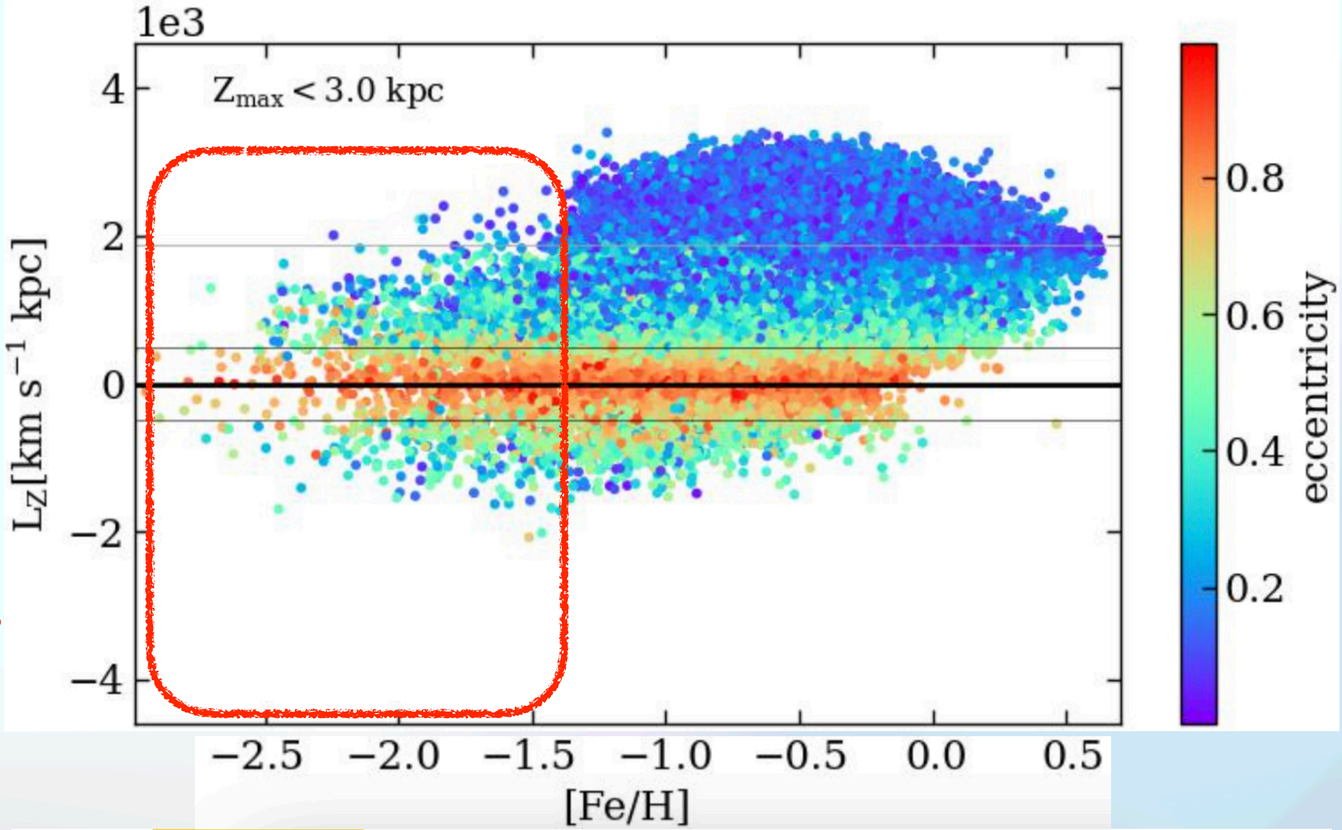
The kinematics of metal-poor disc-like stars

Data and Methods

Metal-Poor Disk-like Stars ([Fe/H] < -1.4):

- **Moderate eccentricity orbits.**
- **Slower rotation than the Sun.**
- **Present in both prograde and retrograde directions.**
- **Clear dominance of prograde motion.**
- **Prograde-to-retrograde ratio (P/R) = 2.58 ± 0.13**



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The kinematics of metal-poor disc-like stars

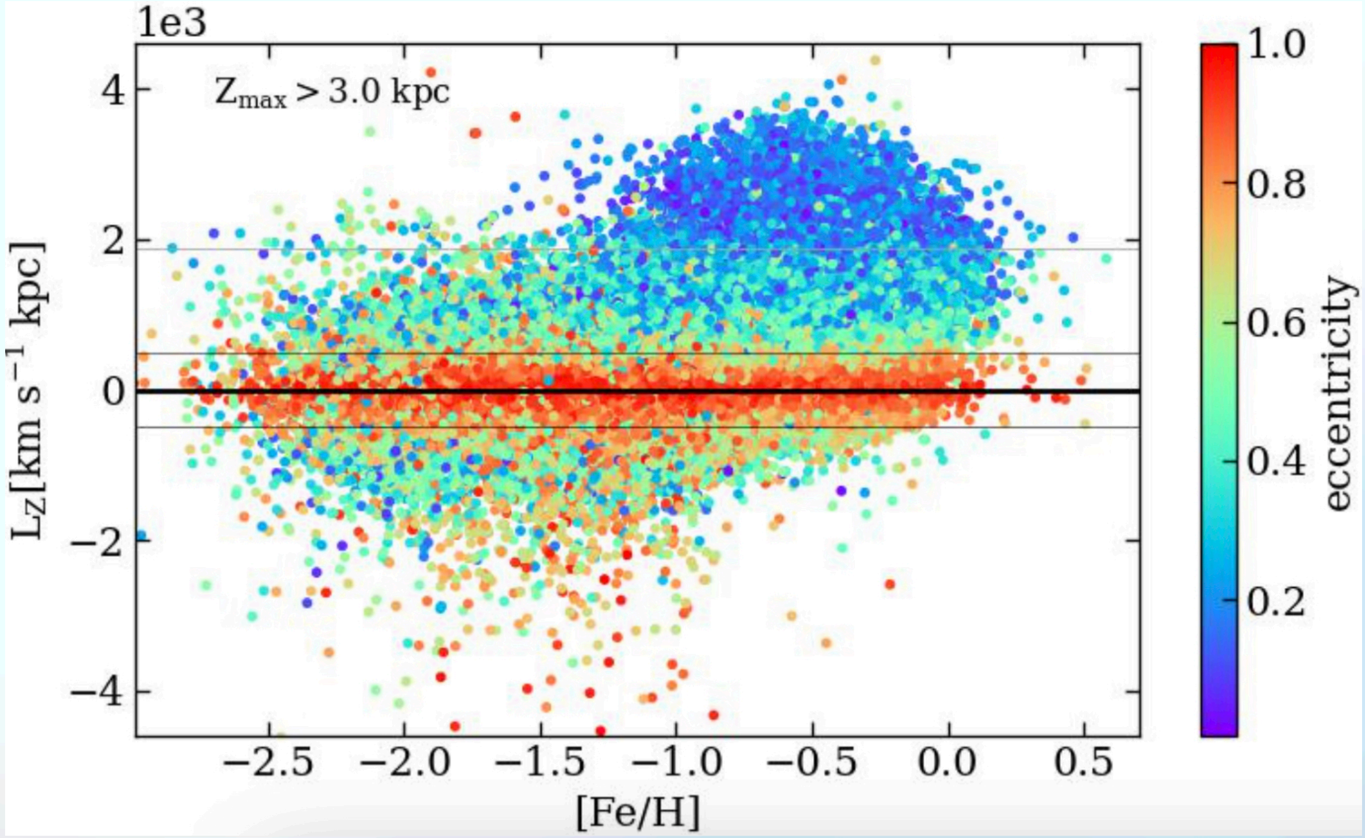
Data and Methods

Thick Disk Component:

- **Dominant in -1.4 ≤ [Fe/H] ≤ 0.0 range**
- **No thin disk contamination**

Low Metallicity Stars ([Fe/H] ≤ -1.0):

- **More dispersed LZ distribution**
- **Typical halo population characteristics**
- **Nearly symmetric prograde/ retrograde distribution**



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The kinematics of metal-poor disc-like stars

Prograde versus retrograde comparison

Definition of disc-like metal-poor stars sample.

Metallicity:

Metal-Poor (MP) Stars($-2.0 < [Fe/H] \leq -1.5$)

Very Metal-Poor (VMP) Stars($[Fe/H] \leq -2.0$)

Rotation: $|L_Z| > 500$ km/s kpc

Orbital Confinement: $Z_{max} < 3.0$ kpc

Kolmogorov–Smirnov test:

P < 0.05 typically indicates statistical difference.

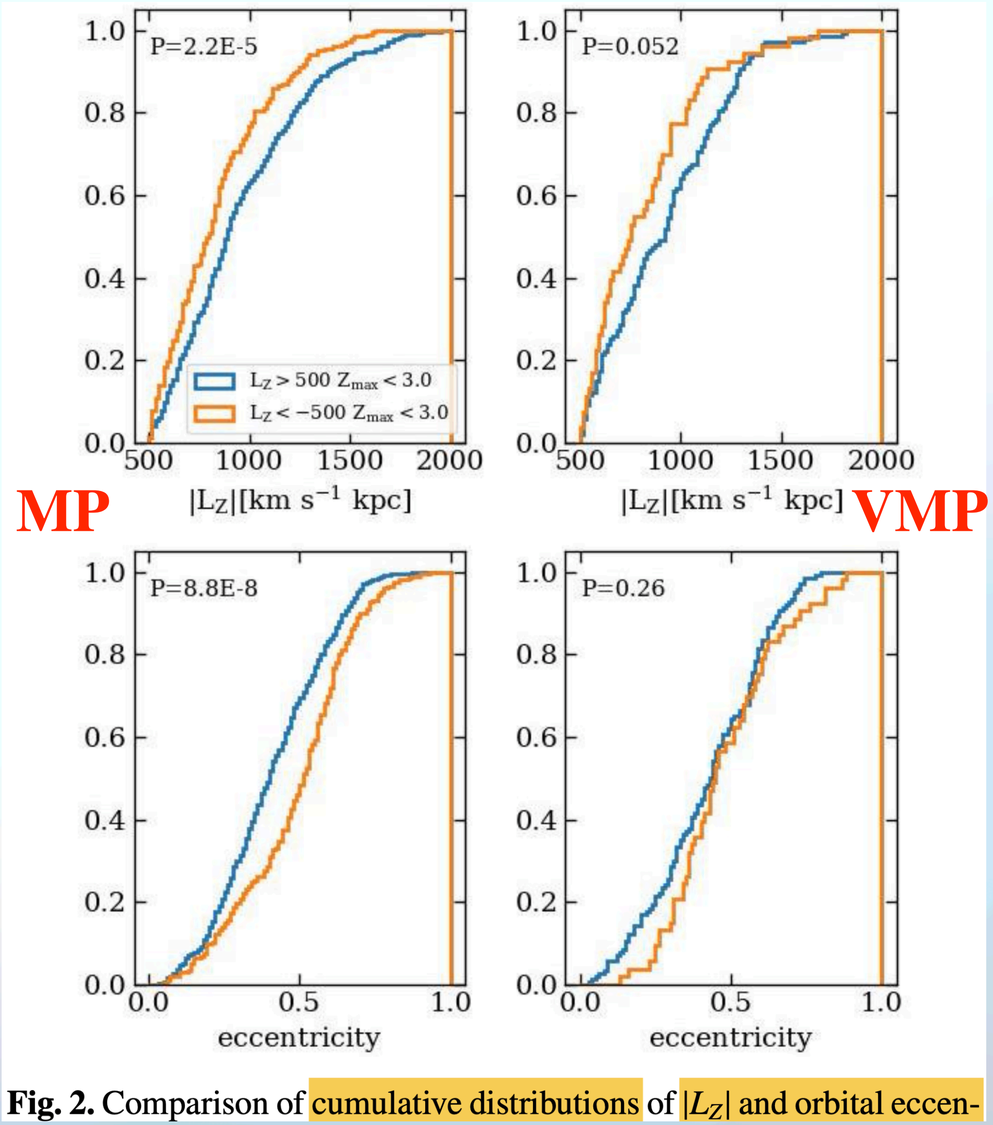


Fig. 2. Comparison of cumulative distributions of $|L_Z|$ and orbital eccen-

The kinematics of metal-poor disc-like stars

Prograde versus retrograde comparison

Left column of panels

Prograde population:

- **Higher |LZ| values (stronger planar rotation)**
- **Lower orbital eccentricity**
- **Highly significant differences (P)**
- **Maximum difference at $|L_Z|$ = 878 km/s kpc**
- **Eccentricity difference peaks at ε = 0.25**

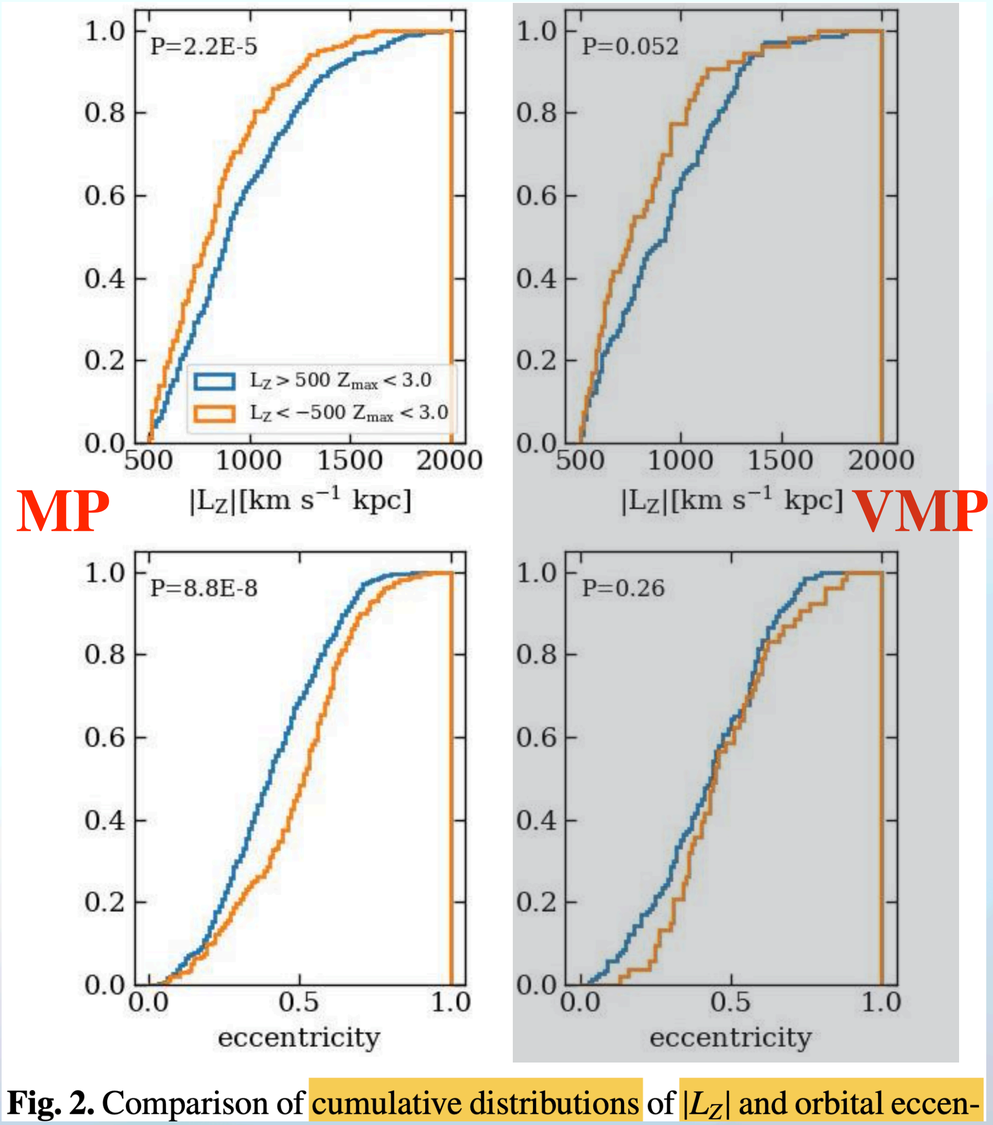


Fig. 2. Comparison of cumulative distributions of $|L_Z|$ and orbital eccen-

The kinematics of metal-poor disc-like stars

Prograde versus retrograde comparison

Right column of panels

Similar pattern to MP stars but with lower statistical significance likely due to smaller sample size.

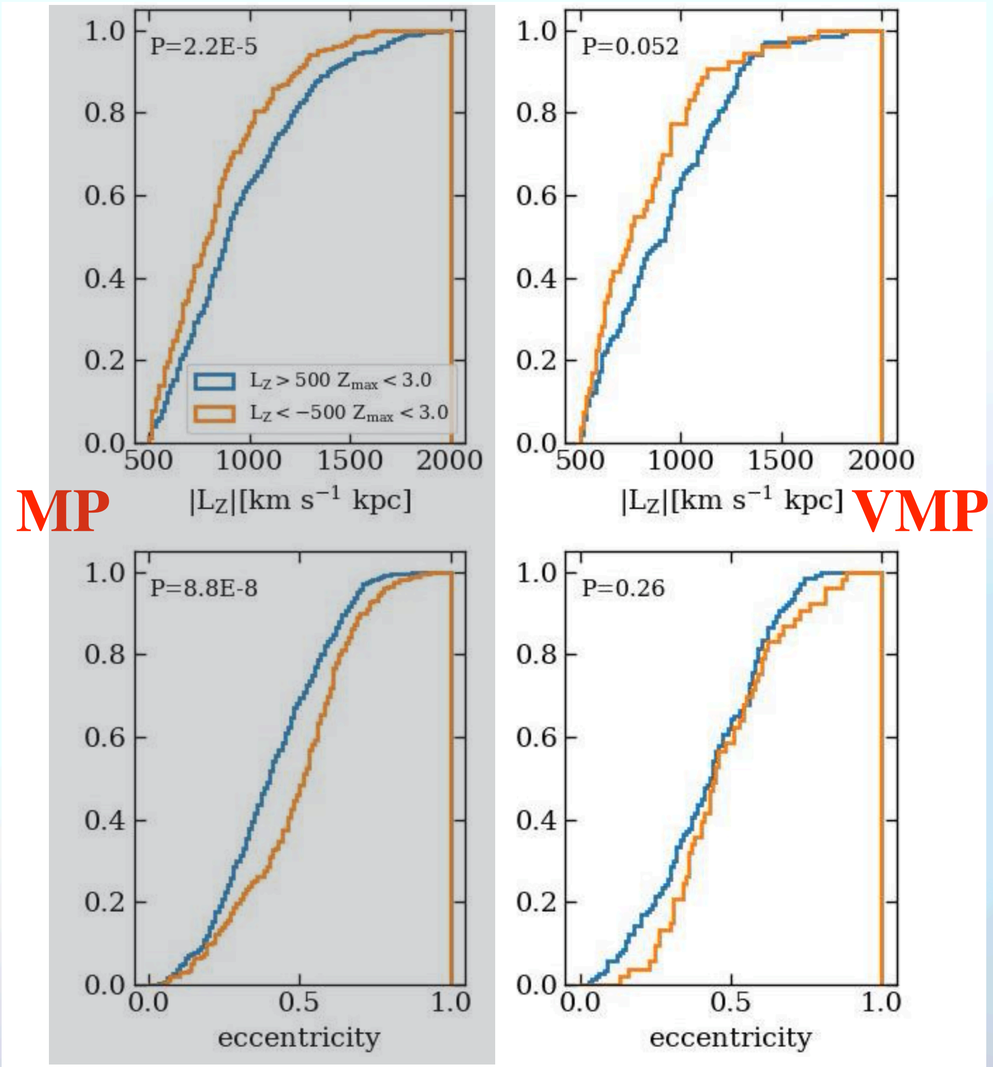


Fig. 2. Comparison of cumulative distributions of $|L_Z|$ and orbital eccen-

The kinematics of metal-poor disc-like stars

Prograde versus retrograde comparison

- **Similar shape patterns in both populations**
- **Main peak: |LZ| ≈ 900 km/s kpc**
- **Additional broad component**
- **Secondary peak at |LZ| ≈ 1200 km/s kpc (the metal-weak thick disc)**

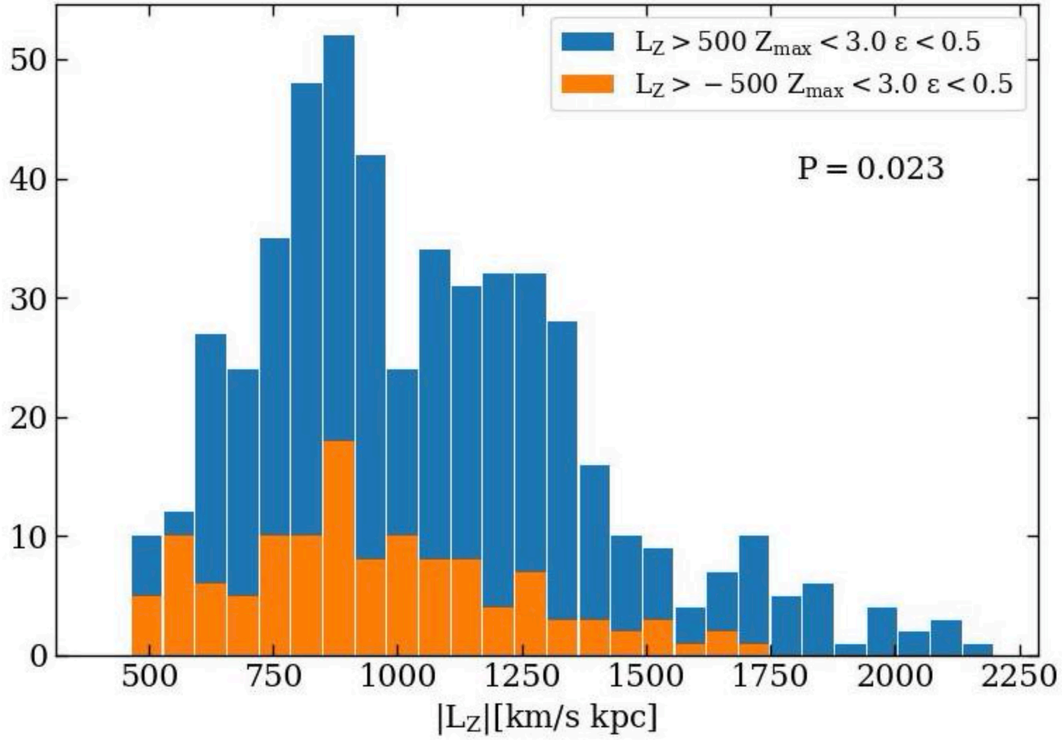


Fig. 3. Comparison of $|L_Z|$ distributions for samples of prograde (blue) and retrograde (orange) stars with disc-like orbits (as defined in Fig. 2) and low orbital eccentricity ($\epsilon < 0.5$). All stars with [Fe/H] ≤ -1.5

The kinematics of metal-poor disc-like stars

The early evolution of the MW disc

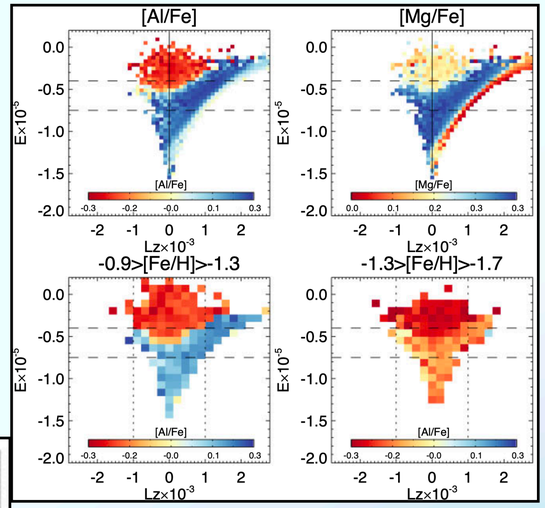
Belokurov & Kravtsov (2022) Framework

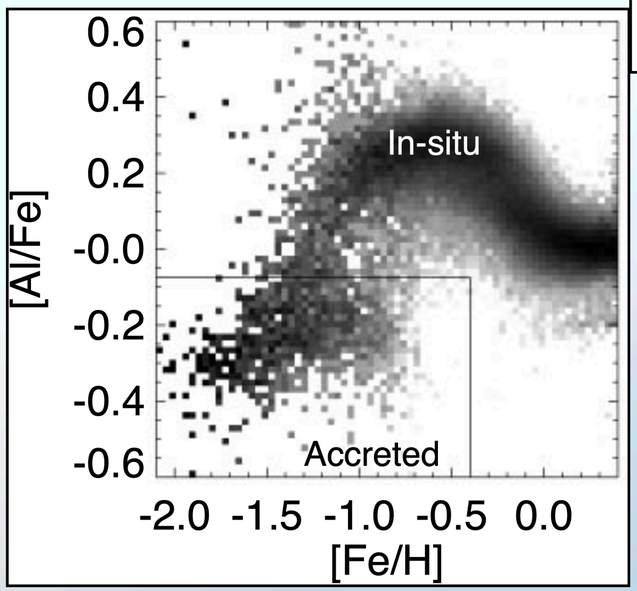
Galaxy evolution from chaotic phase (Aurora) to ordered disc

- **From: irregular, turbulent filamentary flows**
- **To: ordered cooling flows from hot gaseous halo**

In-situ Star Selection:

- **Aluminum abundance as discriminator**
- **Energy constraints**
- **Sample: ~80,000 in-situ stars**





The kinematics of metal-poor disc-like stars

The early evolution of the MW disc

Early Epoch ([Fe/H] ≤ -1.5):

- **Very low/null net rotation**
- **High velocity dispersion (~150 km/s)**
- **Vϕ ≈ 40 km/s at [Fe/H] ≈ -1.5**

Transition Phase (-1.5 ≤ [Fe/H] ≤ -0.9):

- **Strong increase in median Vϕ**
- **Reaches ~130 km/s**

Mature Phase ([Fe/H] > -0.9):

- **Milder increase in Vϕ**
- **Plateaus at ~210 km/s for [Fe/H] ≥ 0.0**
- **Reduced velocity dispersion (tens of km/s)**

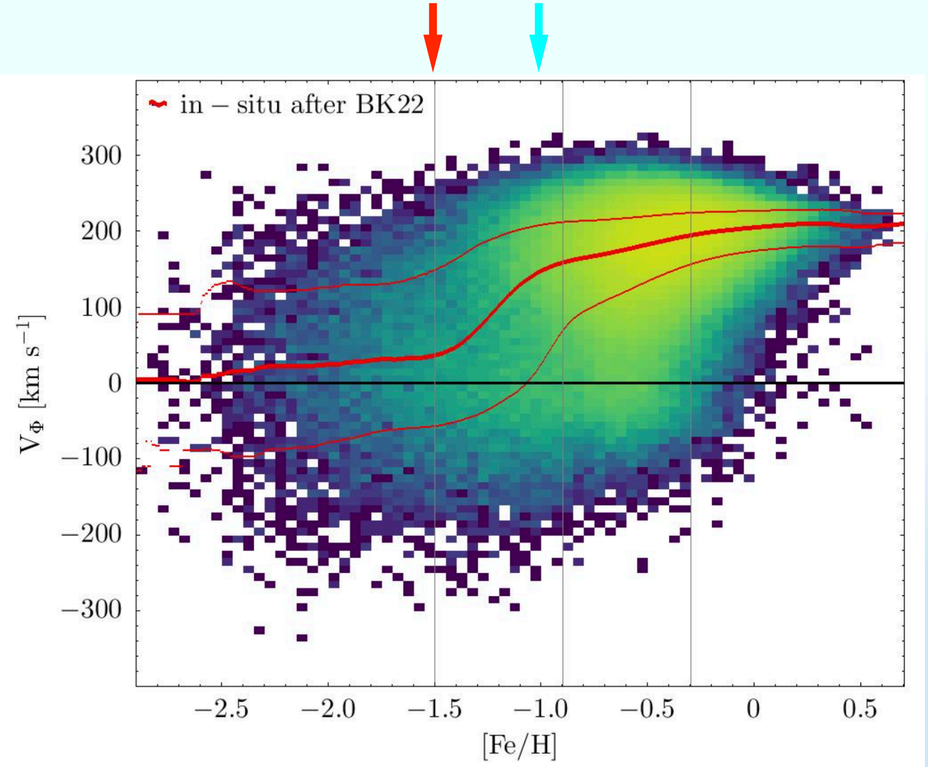


Fig. 5. Distribution in metallicity versus azimuthal velocity for 446 754 stars in our sample that were likely born in situ according the selection in orbital energy shown by BK22 in their Fig. 1. The thick red line traces

The kinematics of metal-poor disc-like stars

The early evolution of the MW disc

Retrograde: Smooth, bell-shaped

Prograde: Enhanced high $|L_Z|$ component

Clear prograde dominance even at low [Fe/H].

Early establishment of rotation preference.

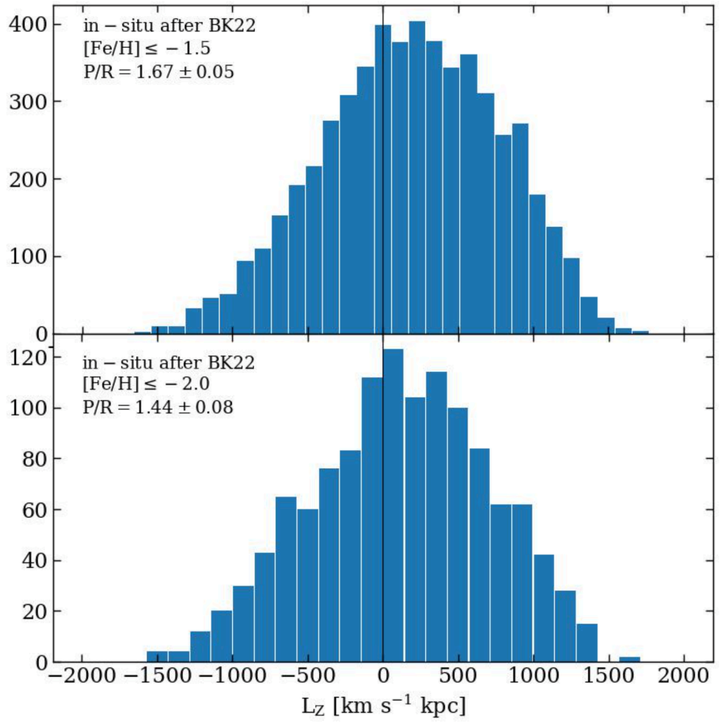


Fig. 6. L_Z distributions of in situ stars with [Fe/H] ≤ −1.5 (MP+VMP; upper panel) and with [Fe/H] ≤ −2.0 (VMP; lower panel). The prograde-

Summary and conclusions

- **Confirmed significant fraction of MP and VMP stars with disc-like orbits.**
- **Found prograde orbits prevalent among them (P/R ratio ~3).**
- **Discovered statistically significant difference in LZ and orbital eccentricity distribution between prograde and retrograde MP stars.**
- **Identified additional high-|LZ| component in prograde disc-like MP/VMP stars.**
- **Results suggest possible existence of a pristine prograde disc in early Milky Way.**