Disentangling the Components of the Milky Way

Inferring the Structure of the Milky Way in Phase-Space Using Gaussian Mixture Modelling with Extreme Deconvolution

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Motivation and Scientific Justification

When did our Galaxy stop behaving like a chaotic proto-galaxy and settle into the orderly, rotating disc we see today? An important question in Galactic Archaeology is *when* the Milky Way's disc first settled. Standard models place this event relatively late, after the interstellar medium was enriched by multiple generations of stars [1, 2], implying a dearth of disc-like stars at very low metallicity. Because metallicity rises over cosmic time, it serves as a rough stellar clock: metal-poor stars are generally older. Finding a coherent, metal-poor disc would therefore overturn the *late-disc* paradigm and force a rethink of in-situ versus accreted growth.

A practical hurdle is that every Gaia DR3 velocity carries correlated uncertainties; if these "error ellipsoids" are ignored, genuine kinematic sub-structure can be blurred into (or out of) existence, producing components with no physical meaning.

Following the methodology of Zhang et al. 2024 [3], we revisit the same Gaia DR3 sample, now splitting the stars into high- and low-α sequences [4] and using an uncertainty-aware modelling approach to ask: *at what metallicity does disc-like rotation truly appear in each sequence?*

Methodology – Solution Path

To pinpoint *when* disc-like rotation truly emerges, we must see the **intrinsic** velocity field, stripped of Gaia's measurement blur and interpreted in its chemical context. Our five-step pipeline does exactly that, each step mapping onto a question posed in the Motivation.

1. **Uncertainty-aware modelling.** Every star's velocity (v_R, v_ϕ, v_z) carries a 3×3 covariance matrix (its error ellipsoid). We employ *extreme-deconvolution* Gaussian mixtures [5, 6] to find the set of noise-free Gaussians which, once convolved with those ellipsoids, reproduce the observed cloud. *Why:* de-blurring prevents spurious artefacts and ensures any recovered disc component is physically real.

2. **Metallicity slicing with parsimony.** Because [M/H] is an age proxy, we bin the sample in metallicity and let the Bayesian Information Criterion select the minimal number of Gaussians per bin. *Why:* isolates the metallicity (hence epoch) at which rotation support first appears, directly testing the late-disc paradigm.

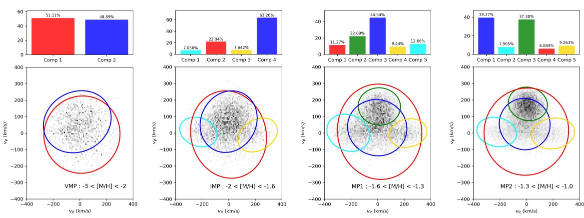
3. **α-sequence split.** We repeat the analysis separately for high- and low-α populations [4], tracers of rapid and prolonged star-formation histories. *Why:* reveals whether the thick and thin discs followed distinct evolutionary timelines.

4. **Disc diagnostic.** For each recovered Gaussian we compute $V_{\rm rot}/\sigma_\phi$; a ratio $\gtrsim 3$ flags a rotation-supported disc. *Why:* gives an objective, quantitative "disc/no-disc" verdict instead of subjective eyeballing.

5. **Residual stress-test.** We Monte-Carlo sample mock data from the best-fit model, convolve them with Gaia errors, and compare to the real sky. Any significant leftover overdensity signals structure the model missed. *Why:* confirms that no low-metallicity disc is hiding below our detection threshold, tightening the upper limit to $< 1\%$ of stars.

Together, these steps yield an unbiased, chemistry-aware map of the Milky Way's phase-space allowing us to answer the core questions: *Is a metal-poor disc present at all, and if not, which stellar population spun up first?*

Key Findings



(a) VMP (b) IMP (c) MP1 (d) MP2

Figure 1: XD-GMM decomposition of red giant kinematics across metallicity bins. Links to the fully interactive 3-D plots for each bin are provided in the subcaptions.

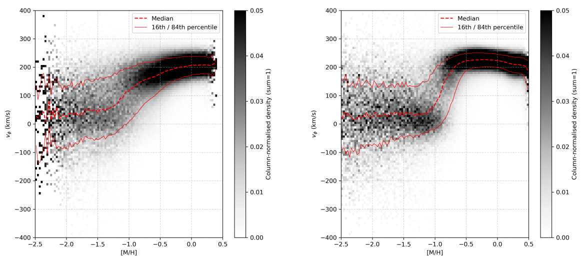
1. No metal-poor disc. Below $[\mathrm{M/H}] \lesssim -2$ we find **only halo kinematics**: one nearly stationary Gaussian and a mildly prograde "Aurora" halo component [7]. Monte-Carlo residual tests place a strict upper limit of $< 1\%$ on any hidden, rotation-supported disc in this regime.

2. Onset of the thick disc. Disc-like rotation emerges at $[\mathrm{M/H}] \gtrsim -1.6$ as a thick-disc Gaussian containing

$\sim 22\%$ of stars and $V_{\rm rot}/\sigma_\phi \approx 2.8$. By $[\mathrm{M/H}] \approx -1.3$ the component grows to $\sim 37\%$ and exceeds the canonical "discy" threshold with $V_{\rm rot}/\sigma_\phi \approx 3.5$.

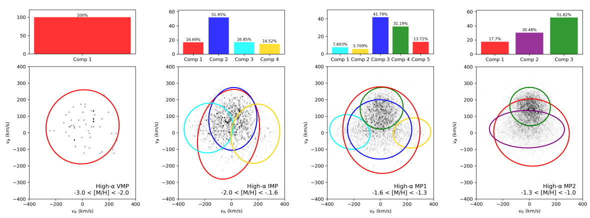
3. Chemistry splits the timeline.(Fig. 2).

- *High-α branch:* rotation support rises gradually from $[\mathrm{M/H}] \sim -2$ to -1, indicating an early, steady build-up of the thick disc.
- *Low-α branch:* remains dispersion-dominated until a sharp spin-up at $[\mathrm{M/H}] \sim -1.3$, marking a later, more rapid disc formation episode.

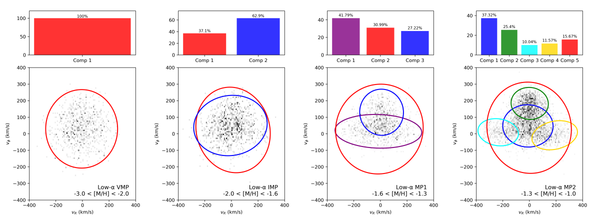


(a) High α stars (b) Low α stars

Figure 2: Median v_ϕ and dispersion vs. metallicity, split by α-sequence.



(a) VMP $\alpha_{\rm high}$ (b) IMP $\alpha_{\rm high}$ (c) MP1 $\alpha_{\rm high}$ (d) MP2 $\alpha_{\rm high}$



(e) VMP $\alpha_{\rm low}$ (f) IMP $\alpha_{\rm low}$ (g) MP1 $\alpha_{\rm low}$ (h) MP2 $\alpha_{\rm low}$

Figure 3: XD-GMM decomposition across α-sequences and metallicity bins. Top row: high-α; bottom row: low-α.

Chemistry-dependent disc growth (Fig. 3).

- **High-α track:** Below $[\mathrm{M/H}] \lesssim -2$ the population is purely halo. A thick-disc component appears at $-1.6 < [\mathrm{M/H}] < -1.3$ with $V_{\rm rot}/\sigma_\phi \approx 2.4$ and grows steadily; by $[\mathrm{M/H}] \approx -1.1$ it comprises $\sim$50% of stars and reaches $V_{\rm rot}/\sigma_\phi \approx 2.8$, indicating a gradual thick-disc build-up.
- **Low-α track:** The distribution remains dispersion-dominated until $-1.3 < [\mathrm{M/H}] < -1.0$, when a thick-disc component ($\sim$25%) emerges with $V_{\rm rot}/\sigma_\phi \approx 3.8$. The high ratio suggests contamination by a colder thin disc and marks a later, rapid disc-formation episode.

Taken together, the two sequences reveal a two-phase assembly: an early, slowly rotating high-α thick disc followed by a later, faster low-α disc that transitions to the present-day thin disc.

Recommendations and Next Steps

- **Richer dynamical models.** Replace Gaussian mixtures with distribution-function or action-based models to capture non-Gaussian and asymmetric structures.
- **Tighter chemistry.** Improve α–abundance precision (or use high-resolution follow-up) to reduce sequence cross-contamination, especially at low metallicity.
- **Explicit selection function.** Model Gaia's magnitude and colour cuts to convert component weights into unbiased population fractions.
- **Chemical-abundance validation at low metallicity.** Gaia XP α-element measurements become unreliable below $[\mathrm{M/H}] \approx -1.5$, so cross-match our sample with high-resolution spectroscopic surveys (e.g., APOGEE, GALAH) to secure precise abundances and verify whether the apparent GS/E signatures persist.

Conclusion and Research Impact

Splitting Gaia DR3 red giants by α abundance reveals a *two-phase* disc build-up: the high-α sequence gains rotational support at $[\mathrm{M/H}] \approx -1.6$, forming a thick disc that grows gradually, while the low-α sequence does not reach disc kinematics until $[\mathrm{M/H}] \approx -1.3$. This confirms that no metal-poor ($[\mathrm{M/H}] < -2$) disc exists and clarifies the distinct evolutionary paths of the thick and thin discs.

Coupling precise chemistry with full 3-D kinematics provides a template for forthcoming surveys (WEAVE, 4MOST, SDSS-V) to isolate, date and map Milky-Way disc components. Pinpointing the metallicity–α thresholds for disc formation tightens constraints on early star-formation, feedback and merger heating in disc galaxies, advancing our reconstruction of the Galaxy's assembly history.

965 / 1000 words

References

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