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 k we see today? An important question in Galactic Archaeology is *when* the Milky Way's disk 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 disk-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 disk would therefore overturn the *late-disk* 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 disk-like rotation truly appear in each sequence?*

Methodology – Solution Path

To pinpoint *when* disk-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 disk component is physically real.

2. **Simple metallicity binning.** 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-disk paradigm.

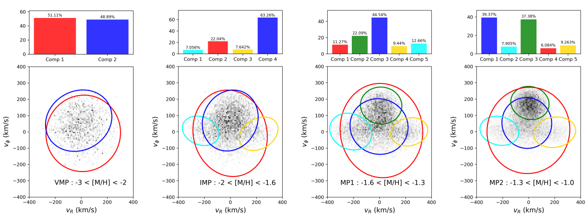
3. **α-sequence split.** We repeat the analysis separately for high- and low-α populations [4], tracers of rapid and prolonged star-formation histories. *Why:* reveals whether the thick and thin disks followed distinct evolutionary timelines.

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

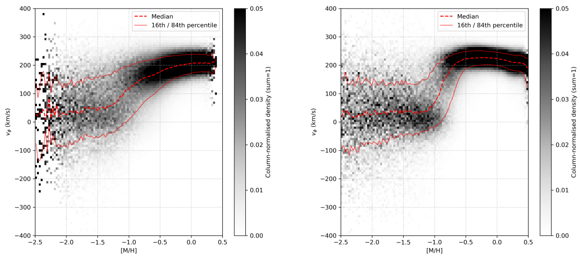
No metal-poor disk. Below $[\mathrm{M/H}] \lesssim -2$ we find only halo kinematics: one nearly stationary Gaussian and a mildly prograde "Aurora" halo component [7]. Monte-Carlo residual tests place a strict upper limit of $< 1\%$ on any hidden, rotation-supported disk in this regime.

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

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

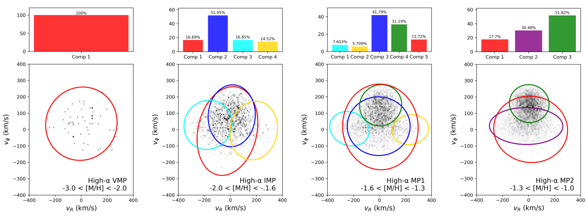
Chemistry splits the timeline. (Fig. 2).

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

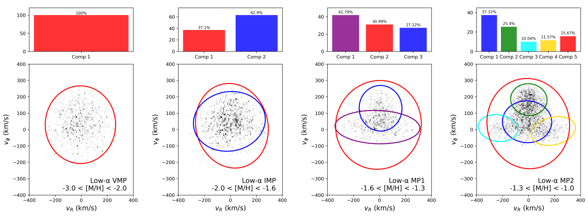


(a) High α stars (b) Low α stars

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 disk growth (Fig. 3).

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

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

Recommendations and Next Steps

- **Upgrade the dynamics.** Move beyond Gaussian mixtures to action-based or distribution-function fitting with ROADMAPPING (a Dynamo code that infers the Galaxy's potential directly from stellar actions) or the AGAMA library (fast orbit integration and DF machinery). These tools turn descriptive fits into physically interpretable dynamical models.
- **Sharpen the chemical ruler.** Cross-match with high-resolution spectra from APOGEE, GALAH, and the forthcoming WEAVE/4MOST surveys to push α-element precision below 0.03 dex. Cleaner chemistry will collapse the current high/low-α overlap.
- **Simulate.** Feed the empirical [M/H]–α spin-up thresholds into Milky-Way-like zoom simulations (AURIGA, Magneto-HydroDynamics; FIRE-2, hydrodynamics) to trace the coupled growth of thick- and thin-disk analogues.
- **Observe.** Post-process the simulations to create mock surveys that mimic JWST/NIRSpec spectra of outer-disk red giants (capturing the CO, CN and Fe-peak lines for precise [M/H] and [α/Fe]) and Rubin LSST multi-epoch imaging with proper-motion maps of complete spiral disk galaxies. Direct comparison of these synthetics with forthcoming JWST and LSST data will offer the first extragalactic test of the Milky Way's two-phase disk-assembly timeline.

Conclusion & Research Impact

High-α stars acquire rotation at $[M/H] \approx -1.6$, inaugurating the thick disk; low-α stars do not spin up until $[M/H] \approx -1.3$, signalling the thin disk's birth, and no rotation-supported disk exists below $[M/H] \approx -2$. These metallicity-α thresholds serve three roles: they provide hard priors for chemo-dynamical and zoom simulations, tightening disk-growth timescales; they offer WEAVE, 4MOST and SDSS-V a clean filter for targeting the Galaxy's oldest disk stars, sharpening age-velocity calibrations; and, when folded into the AURIGA and FIRE-2 suites, they yield testable predictions of twin-disk signatures in external spiral galaxies for JWST and Rubin LSST.

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References

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