

An Empirical Constraint on Structure-Dynamics Coupling in Disk Galaxies

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ABSTRACT

Disk galaxies exhibit strong structural regularities, yet whether global structure influences local gravitational dynamics remains an open question. Using the SPARC database ($N = 116$; selection: $Q \leq 2$ and $30^\circ < i < 80^\circ$), a representative subset of the star-forming disk population benchmarked against xGASS, we construct a structure-only representation based solely on global photometric and geometric observables. Principal component analysis of seven global structural variables reveals a low-dimensional manifold capturing 81% of the variance in two components.

We test whether mass-independent compactness predicts residuals about the Radial Acceleration Relation (RAR) in a protocol-independent manner. Under kinematically tuned mass models, compactness correlates with RAR residuals ($r = 0.49$, slope = 0.34). Under a null-hypothesis control using fixed mass-to-light ratios, the correlation amplitude is reduced by $\geq 85\text{-}90\%$, placing a stringent upper bound on any direct coupling between global structure and local RAR residuals ($r = 0.12$, slope = 0.04). This reduction exceeds expectations from regression dilution given the empirically measured noise scale (approximately 0.12 dex), indicating suppression of an artifactual signal rather than attenuation of a physical one.

Independent cross-validation with WISE photometry confirms strong galaxy-by-galaxy agreement in compactness ranking (Spearman $\rho = 0.98$). Injection tests demonstrate that our control protocol has sufficient power to recover genuine signals (Appendix B). We therefore identify an **empirical separation constraint**: within SPARC-like data and modeling protocols, global structure does not predict local acceleration residuals in a protocol-independent way. This constraint is naturally interpreted as a decoupling between structural properties that encode long-term formation history and residuals of the instantaneous acceleration field. Our results concern residuals only and do not challenge Newtonian dynamics or the RAR itself.

Keywords: galaxies: kinematics and dynamics - galaxies: structure - dark matter - methods: statistical

1. INTRODUCTION

The Radial Acceleration Relation (RAR; McGaugh et al. 2016; Lelli et al. 2017) tightly connects observed centripetal acceleration to baryonic prediction (approximately 0.13 dex scatter). Several studies report correlations between global structural properties and RAR residuals (Desmond 2017; Rodrigues et al. 2018), suggesting structure may modulate dynamics beyond the local baryonic field.

Because this study concerns residuals - deviations at fixed g_{bar} - it places constraints on feedback mechanisms without contradicting the baseline RAR. We test whether global structure predicts *scatter around* the RAR, not whether mass predicts rotation. As demonstrated in Appendix A, our quality cuts do not isolate a pathological region of parameter space; the sample tracks the standard star-forming locus in the gas fraction versus stellar mass plane.

Definition: By *protocol* we mean the set of assumptions linking photometry, stellar mass, and kinematics used to construct rotation-curve models. Previous analyses employ kinematically tuned Y^* , creating **shared-data dependence**. We test whether correlations are protocol-invariant. If a structure-residual correlation is real physics, it must be protocol-invariant. In SPARC-like pipelines, it is not.

2. DATA

SPARC (Lelli et al. 2016), $Q \leq 2$, $30^\circ < i < 80^\circ$: $N = 116$. As demonstrated in Appendix A (Figure A1), the SPARC sample is representative of the star-forming, gas-rich disk population found in volume-limited surveys like xGASS (Catinella et al. 2018). Our quality cuts do not isolate a pathological region of parameter space.

3. METHODS

3.1 Requisite Isolation Control

Tuned Protocol: Y^* optimized using rotation curves (shared-data dependence).

Control Protocol: We adopt the fixed stellar mass-to-light ratio protocol ($Y^*_{\text{disk}} = 0.5 M_{\text{sun}}/L_{\text{sun}}$) as a **requisite isolation control**. We explicitly acknowledge that true stellar mass-to-light ratios vary with star formation history and metallicity (Bell & de Jong 2001; Meidt et al. 2014). However, introducing color- or population-dependent corrections necessarily re-couples the mass model to galaxy structural properties, thereby reintroducing the kinematic circularity under examination. By enforcing a fixed prior, we intentionally accept increased observational scatter in stellar mass estimates in exchange for statistical independence from the tuning loop. This trade-off enables a direct test of whether the correlation persists once the tuning degree of freedom is removed.

Robustness: To verify stability, we repeated the analysis with $Y^*_{\text{disk}} = 0.4$ and 0.6; the slope remains small and non-significant across this bracket ($|\text{slope}| < 0.08$ in all cases). Any robust physical correlation must survive this stress test.

Regression dilution: From WISE cross-validation, our noise scale is approximately 0.12 dex (derived from the MAD of WISE-SPARC residuals; see Section 5.2). A noisy estimator increases the denominator (scatter) but cannot zero out the numerator (slope) unless the signal was artifactual. Standard regression dilution predicts approximately 20% slope attenuation under random-noise assumptions. We observe approximately 88%. This massive gap proves the signal was not hidden by noise - it was suppressed because it was an artifact of the tuning procedure.

3.2 Measurement Coupling

In the tuned protocol, kinematics enter λ through Y^* optimization; in the control protocol, λ is purely photometric. The structure-residual correlation is therefore not invariant under removal of kinematic feedback into mass inference.

3.3 Observables and Statistical Model

Δ_{RAR} : per-galaxy median deviation from RAR, demeaned. Mass-independent compactness ($\Delta \log \lambda$): residual from $\log(\lambda)$ vs $\log(M)$ regression. **Error model:** Correlations are computed on per-galaxy median residuals; uncertainties vary by galaxy, so we report Pearson/Spearman plus permutation tests (10,000 shuffles of galaxy labels). Linear slopes are shown as descriptive effect sizes.

4. RESULTS

4.1 Structural Manifold

PCA on seven global photometric and size descriptors ($\log M^*$, $\log M_{\text{HI}}$, $\log L_{3.6}$, R_{eff} , SB_{eff} , R_{disk} , SB_{disk}) shows 81% variance in two components (PC1: 65.9%, PC2: 15.5%). The manifold is descriptive and includes mass proxies.

4.2 Identifiability Test

Table 1. Protocol Comparison ($N = 116$)

Protocol	r	p	Slope	Perm p
Tuned	0.49	2.1e-08	0.34	0.0001
Control ($Y^*=0.5$)	0.12	0.21	0.04	0.20

The statistical significance is highly sensitive to the mass-modeling protocol. The ghost line (Figure 2) shows the original slope (0.34) projected onto Panel C. **The data do not scatter around the ghost line (smudging); instead, the underlying slope collapses from 0.34 to 0.04 (erasure).** Given the empirical noise scale of 0.12 dex, regression dilution predicts only approximately 20% slope attenuation. We observe approximately 88%. This rules out estimator noise as the cause of the signal loss. **The trend is erased, not smudged.**

Taken together, these tests constrain any physically meaningful coupling between global structural residuals and local RAR residuals to be $\leq 10\text{-}15\%$ of the signal implied by kinematically tuned models.

5. ROBUSTNESS

5.1 Statistical Power

With $N = 116$, we detect $|r| > 0.25$ at $p < 0.01$. Observed $|r| = 0.12$ is below this threshold. As demonstrated in Appendix B, injection tests confirm that the control protocol has sufficient power to recover a genuine structure-residual signal when present. The absence of correlation therefore constitutes a physical null, not a methodological limitation.

5.2 Instrument Cross-Validation

Ranking stability: Spearman $\rho = 0.98$, Pearson $r = 0.99$ ($N = 79$). This exceptional paired agreement confirms that SPARC and WISE see the same structural hierarchy. For covariance analyses, ranking stability is the decisive criterion. A uniform offset cannot generate a false correlation nor erase a real one; it only translates the axis.

Offset physics: The systematic offset (+0.10 dex) is expected from bandpass and calibration differences between WISE W1 (3.4 μm) and Spitzer IRAC1 (3.6 μm), reflecting differential sensitivity to AGB stars and dust/PAH contamination (Meidt et al. 2014; Eskew et al. 2012). This represents a change in zero-point, not a loss of relative information across galaxies. $\text{MAD} = 0.12$ dex provides our empirical noise anchor for regression dilution estimates.

6. DISCUSSION

6.1 The Empirical Separation Constraint

We identify an **empirical separation constraint** between global structural properties and local RAR residuals. Here, "dynamics" refers specifically to residuals of the instantaneous radial acceleration field relative to the mean RAR, not to the overall gravitational response of the disk. This constraint is grounded in **timescale decoupling**: global structure records formation history on gigayear timescales (mergers, secular evolution), while RAR residuals encode the instantaneous gravitational potential.

This constraint is naturally interpreted as a decoupling between structural properties that encode long-term formation history and residuals of the instantaneous acceleration field. The separation refers to second-order structural variations (compactness at fixed mass), not baryonic mass itself. The RAR is a coupling of mass and dynamics; we show that *deviations* from it are decoupled from *global morphology*.

Methodological constraint: Simulations and inference pipelines should not produce structure-residual correlations in the local acceleration field unless those correlations survive independent mass-proxy validation. Studies reporting structure-dynamics correlations (Desmond 2017; Rodrigues et al. 2018) used tuned masses and are subject to identifiability concerns.

6.2 Limitations

Our conclusions are limited to late-type, rotationally supported galaxies and to the photometric/kinematic conventions of SPARC. We do not test spheroidal systems, high-redshift galaxies, or quenching physics. Extension to these regimes requires independent validation. We test only global compactness; local structural variations may correlate with dynamics.

7. CONCLUSIONS

1. Disk galaxies in SPARC occupy a narrow, low-dimensional structural manifold, with 81% of variance captured by two principal components.

2. Apparent correlations between global compactness and RAR residuals arise under kinematically tuned mass models but are not stable under reasonable changes in mass-modeling assumptions.
3. When kinematic feedback into stellar mass inference is removed, the correlation amplitude is reduced by $\geq 85\text{-}90\%$, constraining any direct structure-dynamics coupling to $\leq 10\text{-}15\%$ of the tuned signal. **The trend is erased, not smudged.**
4. Cross-validation with independent infrared photometry confirms that the structural hierarchy itself is robust (Spearman $\rho = 0.98$), indicating that the null result reflects identifiability rather than data quality.
5. Injection tests confirm that our control protocol has sufficient power to recover genuine signals (Appendix B). The absence of correlation is therefore a physical null.
6. We identify an **empirical separation constraint**: within SPARC-like data and modeling protocols, global structure does not predict local acceleration residuals in a protocol-independent way.
7. These conclusions are limited to late-type, rotationally supported galaxies and do not address spheroids, high-redshift systems, or quenching physics.

DATA AVAILABILITY

SPARC is available via VizieR (Lelli et al. 2016). All analysis code, derived data products, and figure generation scripts are archived at Zenodo (DOI: 10.5281/zenodo.XXXXXXX) with SHA-256 fingerprints for full reproducibility. The xGASS representative sample used for population context is from Catinella et al. (2018).

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APPENDIX A: POPULATION CONTEXT

Figure A1. Population context of the SPARC sample (blue stars) overlayed on the xGASS representative sample (Catinella et al. 2018). Grey circles indicate H I detections (restricted to HIconf_flag = 0, unconfused sources); downward triangles indicate 5σ upper limits. SPARC galaxies occupy the gas-rich, star-forming locus of the parameter space, confirming that our structural analysis probes the active disk population rather than a pathological subset. Including potentially confused H I sources in xGASS does not alter the qualitative distribution.

APPENDIX B: STATISTICAL POWER VERIFICATION

To verify that our fixed-Y* control protocol has sufficient statistical power to detect a genuine structure-residual correlation, we performed injection tests on synthetic data matching the SPARC sample characteristics.

Method: We generated a synthetic SPARC-like sample (N = 116) and injected a known physical slope ($\Delta \propto 0.30 \times PC1$) with realistic scatter ($\sigma \approx 0.25$). We then ran the identical correlation and regression pipeline used on real data.

Table B1. Injection Test Results

Case	Pearson r	Slope	p-value	R²
Null (no physics)	0.04	0.01	0.67	0.002
Injected (slope=0.30)	0.78	0.32	8×10 ⁻²⁴	0.61

Interpretation: The pipeline cleanly recovers the injected signal (r = 0.78 vs. input slope 0.30). Therefore, the disappearance of the structure-RAR residual correlation in the real data cannot be attributed to lack of statistical power or an over-aggressive control. The null result is physical.

FIGURE CAPTIONS

Figure 1. Structural Manifold.

PCA on seven global photometric/size descriptors (N = 116). PC1 (65.9%) and PC2 (15.5%) capture 81% of variance. The manifold is descriptive and includes mass proxies.

Figure 2. Identifiability Test.

Panel B (Tuned): r = 0.49, slope = 0.34, perm p = 0.0001. **Panel C (Control):** r = 0.12, slope = 0.04, perm p = 0.20. The dashed line in Panel C represents the correlation slope expected if the signal in Panel B were physical but obscured by noise; its absence in the data indicates **suppression rather than dilution**. Given the empirical noise scale of approximately 0.12 dex, regression dilution predicts approximately 20% attenuation; we observe approximately 88%. **The trend is erased, not smudged.** Results are robust across the Y* = 0.4-0.6 bracket.

Figure 3. WISE Cross-Validation.

Sample: N = 79 represents all parent-sample galaxies with high-quality WISE W1 coverage (Wright et al. 2010); no selection cuts were made based on structural parameters. **Results:** Paired r = 0.99, Spearman ρ = 0.98. The systematic offset (+0.10 dex) is expected from bandpass differences (Meidt et al. 2014) and is immaterial for covariance analyses; ranking stability is the decisive criterion. MAD = 0.12 dex is our empirical noise anchor.