A Reproducible SPARC Rotation-Curve Fitting Pipeline and SIDM Toolkit (sidmkit)

SIDMKit Collaboration

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Abstract

We present `sidmkit`, a lightweight Python toolkit for self-interacting dark matter (SIDM) phenomenology, together with a submission-focused pipeline for batch fitting SPARC rotation curves from the published `rotmod` files. The rotation-curve pipeline fits two standard halo profiles (NFW and Burkert) plus stellar mass-to-light parameters using a robust, chunkable batch interface designed for large samples. We emphasize that the SPARC analysis reported here is *phenomenological* (halo-profile baseline fitting) and does not yet constitute a full microphysical SIDM inference of galaxy cores. All outputs (per-galaxy plots, merged summaries, population diagnostics) are produced by a reproducible command-line workflow and are intended as a reliable foundation for subsequent microphysics-to-halo mapping and more detailed astrophysical systematics modeling.

1 Scope and philosophy

Small-scale tensions in collisionless cold dark matter motivate studying SIDM models, but analysis pipelines often couple multiple layers at once: microphysics (particle model), kinetic theory (cross sections and velocity averages), halo modeling (core formation), and data likelihoods. `sidmkit` separates these concerns on purpose. This submission package contains: (i) a general SIDM phenomenology library (cross sections, velocity averaging, constraints/likelihood scaffolding), and (ii) a *standalone* SPARC rotation-curve batch fitter that provides a transparent baseline comparison between cuspy (NFW) and cored (Burkert) halo profiles using the SPARC `rotmod` decomposition.

Critical note. The SPARC pipeline here is a *baseline*: it tests whether a cored or cuspy parametric halo better matches the published rotation curves under simple assumptions. It does **not** claim that Burkert halos are "the truth" nor that SIDM microphysics has been inferred from these fits. Important systematics (distance and inclination uncertainties, non-circular motions, beam smearing, baryonic modeling errors, and correlated uncertainties) are not modeled in this baseline.

2 SIDM microphysics modules in `sidmkit`

The rotation-curve fitter in this submission package is intended to be a stable, transparent *baseline*. In parallel, `sidmkit` provides a modular SIDM phenomenology layer that can be used to connect particle models to astrophysical observables.

2.1 Yukawa interactions and transfer cross sections

A commonly studied SIDM scenario is elastic scattering in an attractive (or repulsive) Yukawa potential,

$$V(r) = \pm\frac{\alpha_\chi}{r}e^{-m_\phi r}, \tag{1}$$

where α_χ is a dark-sector coupling and m_ϕ is the mediator mass. From the differential cross section $d\sigma/d\Omega$, two angle-weighted quantities are especially useful for structure formation: the momentum-transfer cross section and the viscosity cross section,

$$\sigma_T(v) = \int d\Omega\,(1-\cos\theta)\,\frac{d\sigma}{d\Omega}, \tag{2}$$

$$\sigma_V(v) = \int d\Omega\,(1-\cos^2\theta)\,\frac{d\sigma}{d\Omega}. \tag{3}$$

These suppress forward scattering, which is inefficient at isotropizing particle orbits. The toolkit implements a practical hybrid strategy: Born-limit expressions where applicable, classical-regime approximations at large coupling/low de Broglie wavelength, and (optionally) a partial-wave phase-shift solver in intermediate regimes. This layered approach is common in the SIDM literature; it is computationally efficient but must be treated as an approximation whose regime boundaries should be stress-tested for any specific application.

2.2 Velocity averaging

Astrophysical constraints are typically quoted at characteristic relative velocities (e.g. $\sim$30 km/s for dwarf galaxies and $\sim$1000 km/s for clusters). When a velocity distribution $f(v)$ is needed, `sidmkit` provides utilities to compute velocity averages such as

$$\langle\sigma_T v\rangle = \int_0^\infty dv\, f(v)\,\sigma_T(v)\,v, \tag{4}$$

with Maxwell–Boltzmann distributions as a common default. This step matters whenever $\sigma(v)$ is strongly velocity dependent.

2.3 Constraint evaluation as a convenience layer

The package also includes a small collection of literature-derived constraint points for σ/m at representative velocities. These are *not* a substitute for a full re-analysis; rather they provide a consistent, scriptable way to sanity-check a parameter point before investing in expensive inference. The correct scientific posture is to treat these as orientation tools and to consult the original sources for definitive statements.

3 SPARC pipeline methods

3.1 SPARC `rotmod` inputs

Each SPARC `*_rotmod.dat` file provides, as a function of radius r (kpc), an observed rotation speed $V_{\rm obs}$ (km/s) and uncertainty σ_V, along with template velocity contributions for gas, stellar disk, and (when present) stellar bulge. The model prediction combines these components in quadrature:

$$V^2_{\rm model}(r) = V^2_{\rm gas}(r) + \Upsilon_{\star,d}\,V^2_{\rm disk}(r) + \Upsilon_{\star,b}\,V^2_{\rm bul}(r) + V^2_{\rm DM}(r), \tag{5}$$

where $\Upsilon_{\star,d}$ and $\Upsilon_{\star,b}$ are disk and bulge stellar mass-to-light parameters.

3.2 Halo models

We fit two standard parametric halos as a baseline.

NFW. The Navarro–Frenk–White density profile is

$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}. \tag{6}$$

The enclosed mass $M(r)$ has a closed form, yielding $V_{\mathrm{DM}}^2(r) = GM(r)/r$.

Burkert. The Burkert profile is a common cored phenomenological model:

$$\rho_{\mathrm{Bur}}(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)}, \tag{7}$$

with an analytic enclosed mass and circular speed.

3.3 Objective function and priors

For each galaxy we minimize a weighted residual:

$$\chi^2 = \sum_i \left(\frac{V_{\mathrm{model}}(r_i) - V_{\mathrm{obs}}(r_i)}{\sigma_V(r_i)} \right)^2. \tag{8}$$

For numerical stability in batch mode, the default fits include weak Gaussian priors on $\Upsilon_\star$ (configurable); this yields a maximum-a-posteriori (MAP) estimate. For strict likelihood-based information criteria comparisons, the pipeline supports `--no-priors` (pure maximum likelihood).

3.4 Model comparison diagnostics

We report reduced chi-square $\chi_\nu^2 = \chi^2/\nu$ with $\nu = N - k$ degrees of freedom. For each galaxy we also compute AIC/BIC from the data-only χ^2:

$$\mathrm{AIC} = \chi^2 + 2k, \tag{9}$$

$$\mathrm{BIC} = \chi^2 + k \ln N. \tag{10}$$

Since both halo models have the same parameter count k in this baseline setup, ΔBIC is equivalent (up to an additive constant) to $\Delta\chi^2$ for per-galaxy model preference.

3.5 Batch execution: chunking for submission-grade runs

Full-sample plotting is slow if run monolithically. The pipeline is designed to be chunked:

- `--skip N`: skip the first N galaxies in sorted order,
- `--limit M`: process at most M galaxies after the skip,
- `--resume`: avoid recomputing galaxies that already have outputs.

This enables sequential chunking or parallel execution across multiple processes/nodes.

4 Validation and robustness checks

We include: (i) unit tests for parsing and fitting on synthetic rotmod-like inputs, (ii) deterministic JSON/CSV summaries per chunk, and (iii) population-level plots that flag common failure modes (e.g. parameter-bound saturation). We report the fraction of NFW fits saturating the upper bound on $\log_{10}(r_s/\mathrm{kpc})$ as a practical indicator of poorly constrained NFW scale radii in the baseline parameterization.

5 Results on the full SPARC rotmod sample

Using the attached run outputs (191 galaxies, two halo models each), we obtain:

- $N = 191$ galaxies with both NFW and Burkert fits.
- Median $\Delta\mathrm{BIC} = 1.812$, mean $\Delta\mathrm{BIC} = 12.915$, where $\Delta\mathrm{BIC} = \mathrm{BIC}_{\mathrm{NFW}} - \mathrm{BIC}_{\mathrm{Burkert}}$ (positive values favor Burkert).
- Fraction preferring Burkert ($\Delta\mathrm{BIC} > 0$): 0.654.
- "Strong" Burkert preference fraction ($\Delta\mathrm{BIC} > 6$): 0.325; strong NFW preference fraction ($\Delta\mathrm{BIC} < -6$): 0.147.
- Median reduced chi-square: NFW 1.251, Burkert 0.708.
- NFW scale-radius fits saturate the upper bound in 0.215 of galaxies (strict 10^{-9} tolerance), indicating that a non-negligible subset of NFW fits is effectively "pushing" toward very large r_s in this baseline parameterization.

6 Limitations and next steps

This baseline should be treated as a *starting point*. Key limitations:

- The fits use published SPARC templates and per-point uncertainties without modeling covariance or additional observational systematics.
- The NFW and Burkert parameterizations here are phenomenological; physical priors (e.g. M_{200} and concentration) could reduce degeneracies and bound-saturation.
- Microphysical SIDM parameters (e.g. Yukawa mediator models) are not yet mapped to halo core sizes in this SPARC pipeline. That mapping requires additional assumptions and calibration and is best implemented as a distinct inference layer building on the stable batch-fitting substrate presented here.

7 Reproducibility

All commands used to generate the attached outputs are included in the submission runbook. The key workflow is:

1. chunked fits: `python -m sidmkit.sparc_batch batch --skip ...  --limit ...`
2. merge summaries: `python -m sidmkit.sparc_batch merge ...`
3. population report: `python -m sidmkit.sparc_batch report ...`

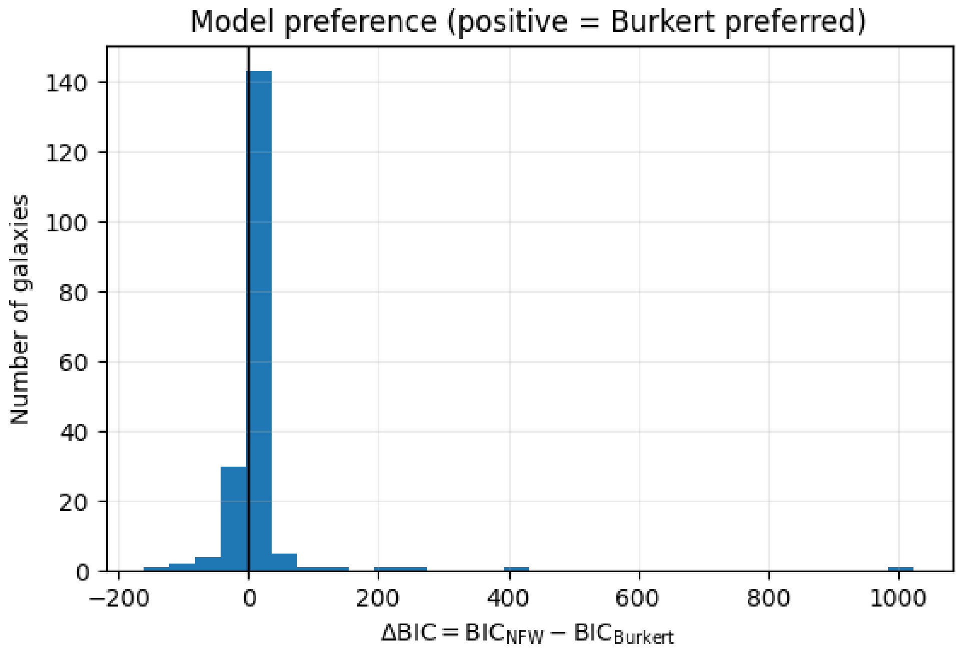


Figure 1: Distribution of $\Delta\mathrm{BIC} = \mathrm{BIC}_{\mathrm{NFW}} - \mathrm{BIC}_{\mathrm{Burkert}}$ across the sample. Positive values favor Burkert. Because both models have the same number of fitted parameters, ΔBIC is essentially a re-scaled $\Delta\chi^2$ in this baseline comparison.

References

[1] F. Lelli, S. McGaugh, and J. Schombert, "SPARC: Mass Models for 175 Disk Galaxies with Spitzer Photometry and Accurate Rotation Curves," *Astronomical Journal* 152 (2016) 157.

[2] J. Navarro, C. Frenk, and S. White, "A Universal Density Profile from Hierarchical Clustering," *Astrophysical Journal* 490 (1997) 493.

[3] A. Burkert, "The structure of dark matter halos in dwarf galaxies," *Astrophysical Journal Letters* 447 (1995) L25.

[4] S. Tulin and H.-B. Yu, "Dark matter self-interactions and small scale structure," *Physics Reports* 730 (2018) 1–57.

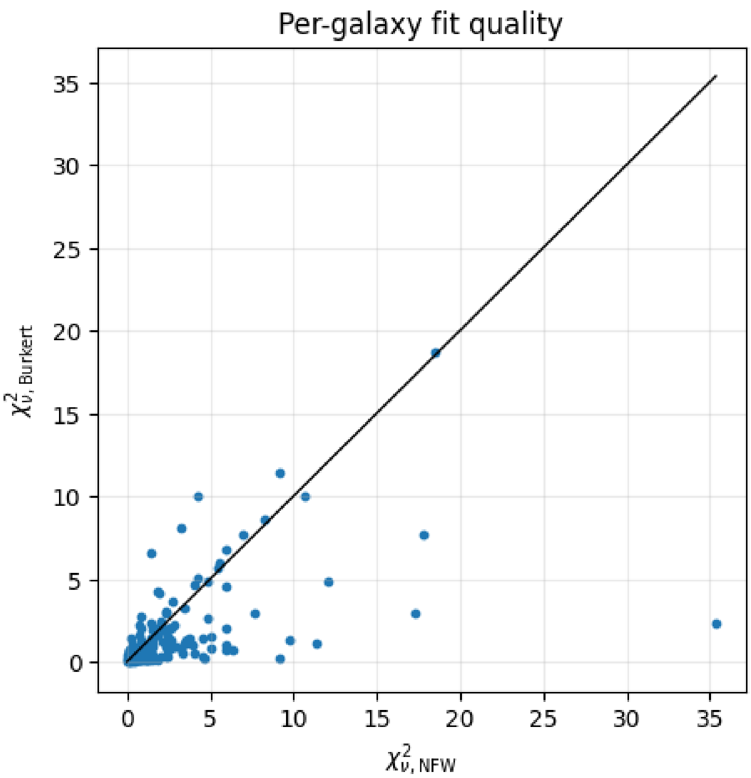
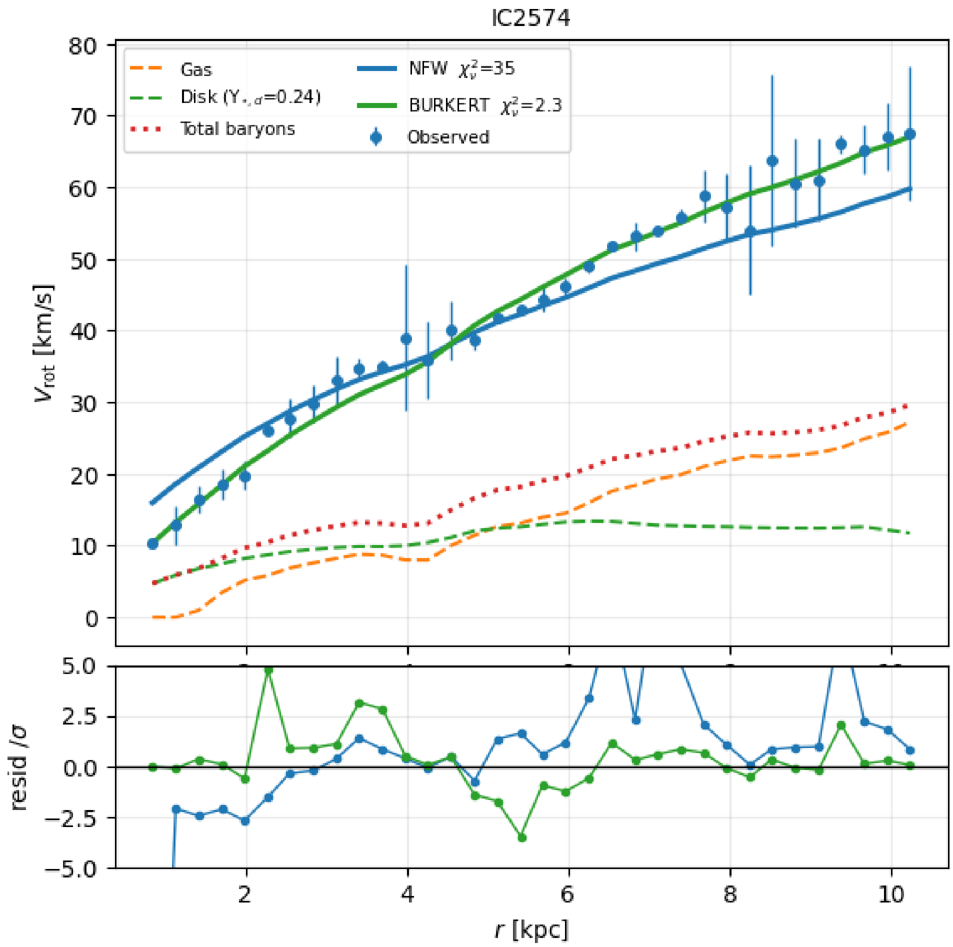
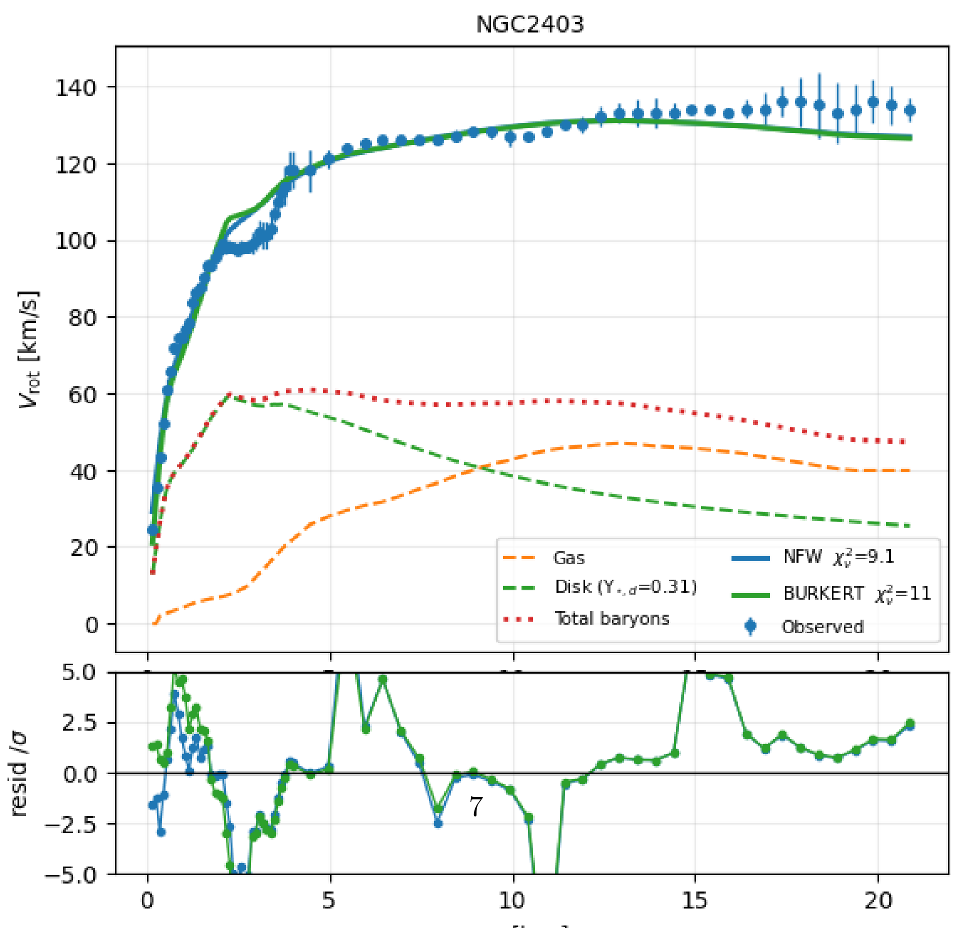


Figure 2: Per-galaxy reduced chi-square comparison. Points below the diagonal indicate galaxies where Burkert yields a smaller χ^2_ν than NFW.


IC2574
Gas
Disk (Υ*,d=0.24)
Total baryons
NFW χ²ν=35
BURKERT χ²ν=2.3
Observed
Vrot [km/s]
resid /σ
r [kpc]


NGC2403
Gas
Disk (Υ*,d=0.31)
Total baryons
NFW χ²ν=9.1
BURKERT χ²ν=11
Observed
Vrot [km/s]
resid /σ