Testing Cold, Fuzzy, and Self-Interacting Dark Matter Models Using Late-Type Galactic Rotation Curves

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Introduction

Flat rotation curves at the outer galactic radii are among the observational evidence of dark matter (DM) on the galactic scale. The standard **cold dark matter (CDM)** model successfully explained the formation of the large-scale structures in the universe. However, many issues arise on the galactic scale (small-scale problems), such as the **core-cusp problem**, i.e., the discrepancy between the observed **cored** DM profile of dwarf galaxies and the predicted **cuspy Navarro-Frenk-White (NFW)** profile based on CDM simulations. This problem had motivated astronomers to propose empirical DM density profile that better matches various observations, e.g., the **Burkert** profile.

NFW

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

ρ_s: characteristic density
r_s: characteristic radius

Burkert

$$\rho_{\rm Burkert}(r) = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)^2\right]}$$

Another issue is the **rotation curves diversity problem**, i.e., the scatter in the inner shape of rotation curves of galaxies of similar masses is much broader than predicted by CDM simulations.

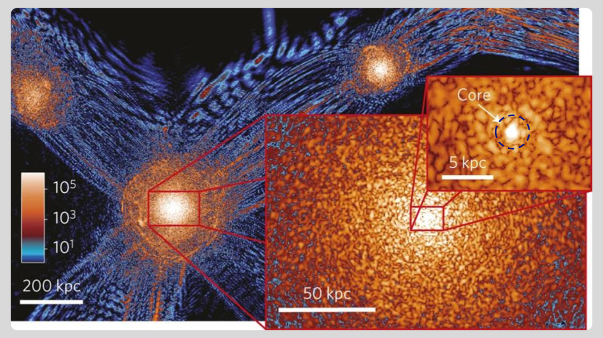
One commonly proposed solution is to use alternative DM models, e.g., **fuzzy dark matter** and **self-interacting dark matter**.

Fuzzy Dark Matter (FDM)

- Consists of ultralight DM particles ($10^{-24} \lesssim \frac{m_{FDM}}{\rm eV} \lesssim 10^{-19}$), e.g., axion and axion-like particles (ALPs).

$$\lambda_{dB} = \frac{h}{m_{FDM}v}$$

- FDM exhibit wave-like behavior on galactic scales, described by a Schrödinger-Poisson equation. Its de Broglie wavelength is in the order of ~1 kpc.



FDM (DM-only) simulation by Schive et al. (2014)

- On the scale $\lambda < \lambda_{dB}$, quantum pressure provides stability against gravitational collapse, forming a constant density **soliton core** (~0.3 – 1.6 kpc) at the halo center, which alleviates the **core-cusp problem**.
- On the outside, quantum pressure become less significant, and FDM shows interference patterns in the form of granules and fringes which shows the DM distribution.
- FDM halo density profile can be modeled as a soliton core on the inside, transitioning to an NFW halo on the outside.

FDM

$$\rho_{FDM}(r) = \begin{cases}\rho_{sol}(r), & r \le r_a \\ \rho_{NFW}(r), & r \ge r_a\end{cases}$$

$$\rho_{sol}(r) = \frac{\rho_{sol,0}}{\left(1+0.091\left(\frac{r}{r_{sol}}\right)^2\right)^8}$$

$$\rho_{sol,0} = \frac{0.019}{m_{22}^2\left(\frac{r_{sol}}{\rm kpc}\right)^4}\frac{M_\odot}{\rm pc^3}$$

$$r_a = \alpha r_{sol} \qquad m_{22} = \frac{m_{FDM}}{10^{-22}\ {\rm eV}}$$

$\rho_{sol,0}$: soliton core density
r_{sol}: soliton characteristic radius
r_a: halo transition radius

Schive et al. (2014)

- The mass of FDM particle is currently have not been well constrained. The constraints from previous works are in tension with each other and are strongly inconsistent with many cosmological constraint. Further observations and simulations have to be done to get a more stringent constraint.

Self-Interacting Dark Matter (SIDM)

- SIDM suggests interactions among DM particles with a large scattering cross section (σ/m_χ) due to short-range interactions or weak interactions mediated by light particles exchange.
- DM self-interactions allow **thermalization** to occur in the innermost halo region, leading to the formation of a constant density **isothermal core** (~0.5 – 1 kpc), solving the **core-cusp problem**. The transition radius is defined as radius r_1 at which the DM particles have only interacted once in the halo's lifetime.
- Thermalization ties the core sizes and shapes of DM halos to the stars' spatial distribution, which explained the **rotation curves diversity problem.**

SIDM

$$\rho_{\rm SIDM}(r) = \begin{cases}\rho_{\rm iso}(r), & r \le r_1 \\ \rho_{\rm NFW}(r), & r \ge r_1\end{cases}$$

$$\rho_{\rm iso}(r) = \rho_0 \exp\frac{[\Phi_{\rm tot}(0) - \Phi_{\rm tot}(r)]}{\sigma_{\rm v0}^2}$$

$\rho_{iso}(r)$ is obtained by solving the Poisson's equation:

$$\nabla^2\Phi_{\rm tot}(r) = 4\pi G[\rho_{\rm iso}(r) + \rho_{\rm bar}(r)]$$

The profile transition occurs at a radius where:

$$\text{Number of interactions} \approx \frac{\langle\sigma v_{\rm rel}\rangle}{m_\chi}\rho_{\rm iso}(r_1)\, t_{\rm age} \approx 1$$

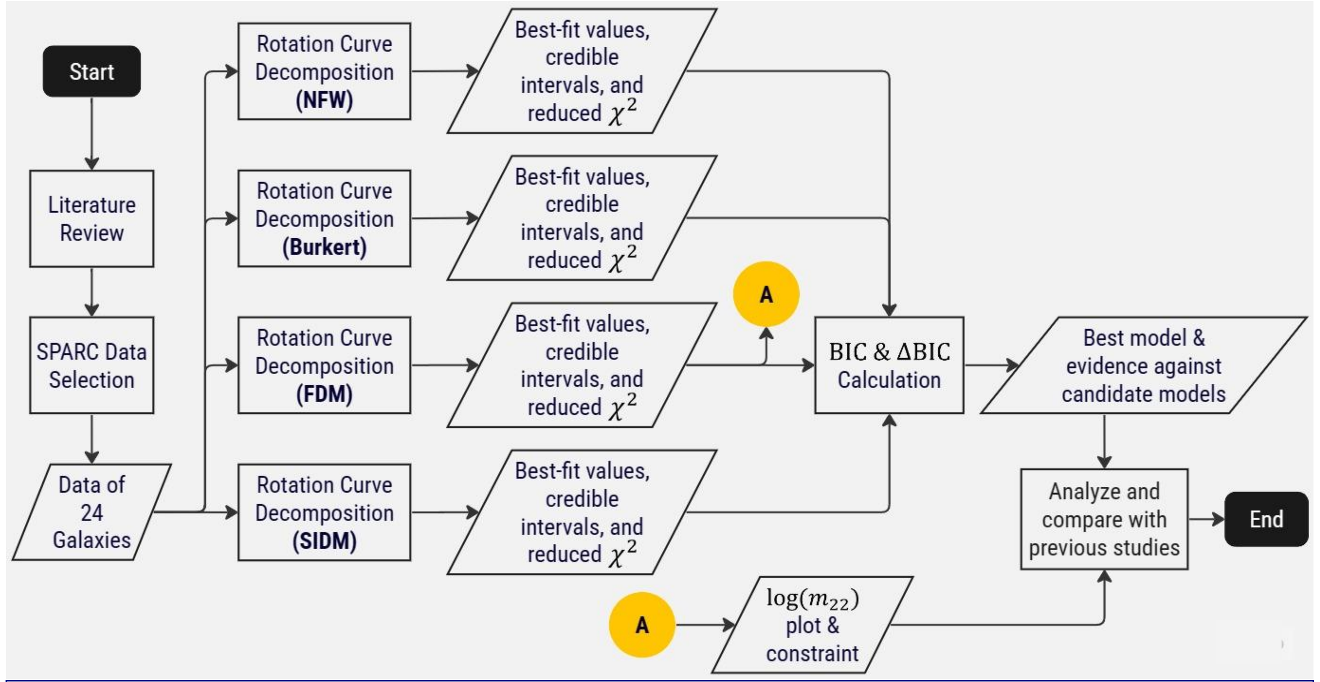
For spherical halos:

$$\langle\sigma v_{\rm rel}\rangle = \sigma\left(\frac{4}{\sqrt{\pi}}\right)\sigma_{\rm v0}$$

$t_{\rm age}$: age of the halo
$v_{\rm rel}$: relative scattering velocity
$\sigma_{\rm v0}$: 1D velocity dispersion
$\Phi_{\rm tot}$: total potential gravity
$\rho_{\rm bar}$: baryon density profile
ρ_0: isothermal core central density

Ren et al. (2019) & Zentner et al. (2022)

Methods



V_{200}: DM velocity at R_{200}, C_{200}: DM concentration at R_{200}, R_{200}: radius at which the spherically averaged DM density reached $200\rho_{\rm crit}$, Υ_*: stellar disk mass-to-light ratio, α: r_a/r_{sol}, δ: uncertainty (up to 50%) of FDM halo-soliton mass scaling relation, Γ_0: SIDM particles scattering rate, σ_{v0}: 1-D DM velocity dispersion

SPARC Data Selection:

Q = 1 | Data points > 5 | $M_* \le 10^{10} M_\odot$ | $V_{\rm flat} \neq 0$ | $R_{\rm min} < 0.5$ kpc

→ 24 sample galaxies

- The rotation curves are decomposed into **disk**, **gas**, and **DM halo** using the Markov Chain Monte Carlo (MCMC) method in Python (the `emcee` package). We assumed that the DM halos have spherical symmetry.
- We followed Khelashvili et al. (2023), Ren et al. (2019) and Zentner et al. (2022) for deriving the velocity profile of the FDM and SIDM halo models.
- The free parameters used for each model are shown in the table below. We used a constant σ/m_χ for the SIDM model ($3\ {\rm cm^2/g}$).

Model	Parameters
NFW	$V_{200}, C_{200}, \Upsilon_*$
Burkert	$V_{200}, C_{200}, \Upsilon_*$
FDM	$V_{200}, m_{22}, \alpha, \delta, \Upsilon_*$
SIDM	$\Gamma_0, \sigma_{v0}, \Upsilon_*$

- For model comparison, we calculated BIC & ΔBIC value from each fitting.

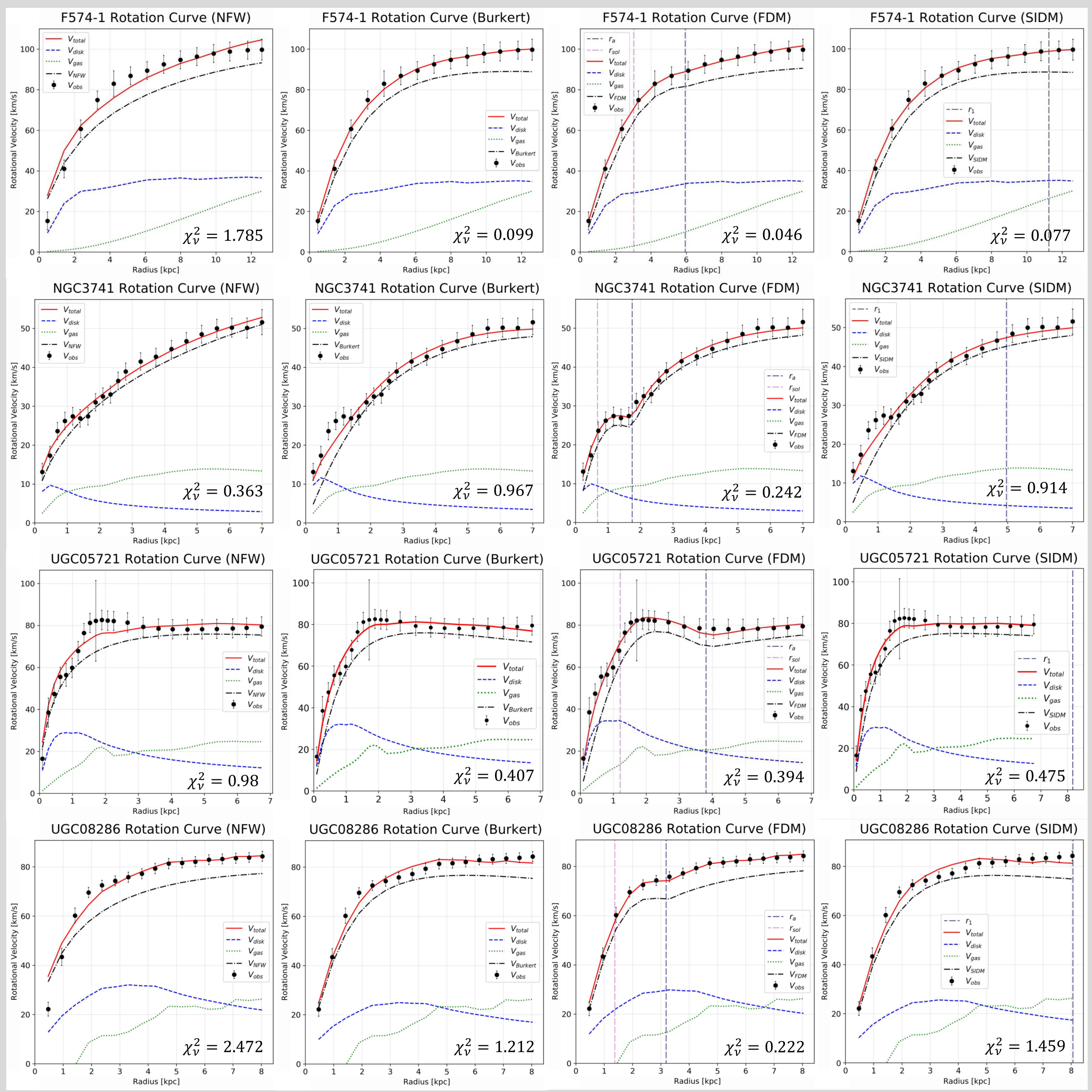
$$\mathrm{BIC} = -2\ln\hat{L} + k\ln N$$

$$\Delta\mathrm{BIC} = \mathrm{BIC}_{\rm alternative} - \mathrm{BIC}_{\rm best}$$

$\hat{L}$: maximum likelihood, k: number of free parameters, N: number of data points

Results

Rotation Curve Fits

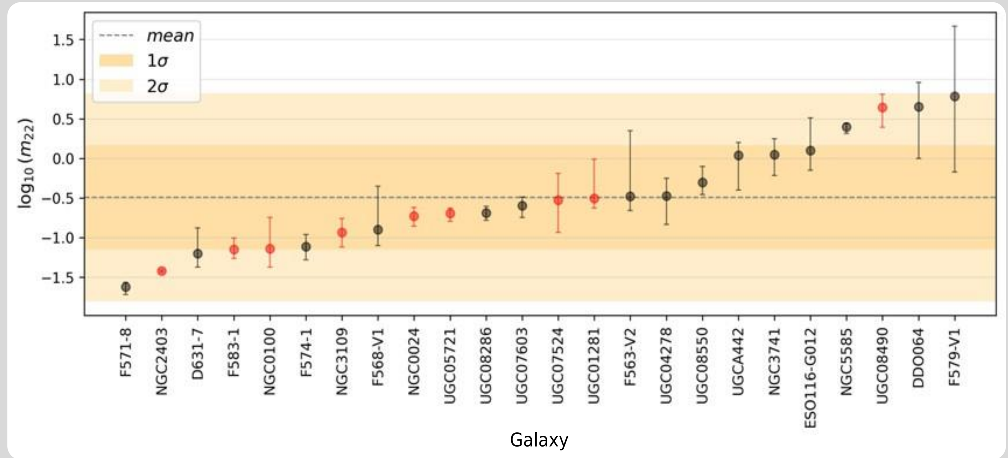


Rotation curve fits of 4 of the sample galaxies using NFW, Burkert, FDM, and SIDM halo models.

- Generally, **NFW** halo (average χ_ν^2 of 2.146) produces total rotation curves model that are too high in the inner radii due to the cuspy nature of the halo.
- **Burkert** halo (average χ_ν^2 of 1.092) produces fits that matches the data better in the inner radii than NFW. However, for some galaxies it fits quite worse at the outer radii.
- **FDM** halo (average χ_ν^2 of 0.529) produces the best fits for most of the galaxies. Some galaxies that have a "sharp" turn on their rotation curves can be fitted well using the FDM halo by the presence of soliton-NFW transition. The soliton's characteristic radius (r_{sol}) and transition radius (r_a) have an average of 1.89 kpc and 3.62 kpc, respectively.
- Visually, **SIDM** halo (average χ_ν^2 of 1.16) produces similar fits as the Burkert halo in most cases. For many galaxies, it produces an isothermal core-NFW transition far at the outer radii, even outside of the SPARC's data points, which agrees with the results of a previous work (Loizeau et al., 2021). In these cases, it indicates that the observational data can be sufficiently fitted using a pure isothermal halo model. The transition radius (r_1) have an average of 10.64 kpc.

- Based on the **BIC** values, 10 galaxies support the Burkert model, 9 galaxies support the SIDM model, and 5 galaxies support the NFW model.
- Despite the remarkable fits, none of the galaxies in the sample supports the FDM model.
- Based on the **ΔBIC** values, there are **positive** evidence and **strong** evidence to **reject** the **FDM** model from **15** and **9** galaxies, respectively.
- There is only one positive evidence to reject each of the NFW, Burkert, and SIDM model, and one strong evidence to reject the NFW model.

FDM Particle Mass

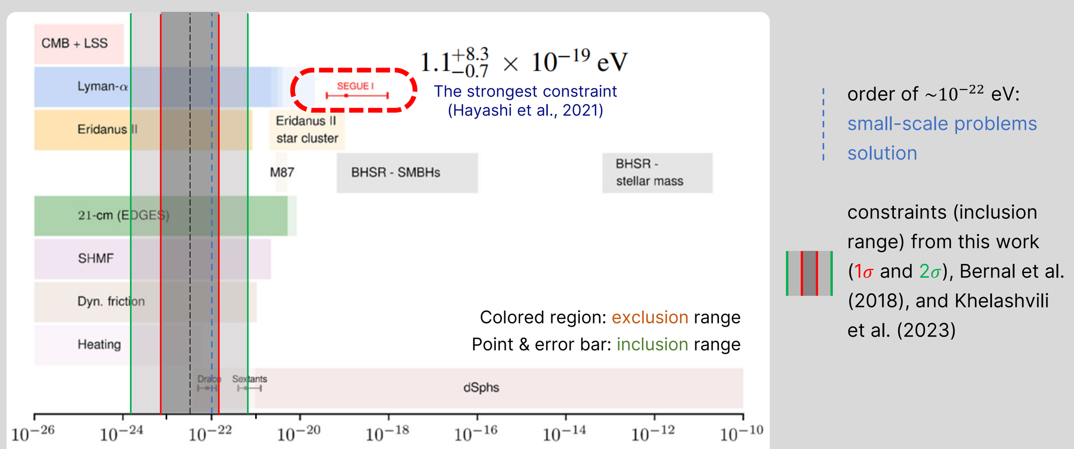


MAP (Maximum A Posteriori) values and 95% credible intervals of $\log m_{22}$ from the 24 sample galaxies.

$$m_{FDM}(1\sigma) = 0.322^{+1.141}_{-0.251} \times 10^{-22}\ {\rm eV}$$

$$m_{FDM}(2\sigma) = 0.322^{+6.324}_{-0.307} \times 10^{-22}\ {\rm eV}$$

- Based on the rotation curves fitting, we obtained a constraint on the FDM particle mass as above. The 95% credible intervals of the mass are in tension for different individual galaxies, which agrees with the results of a previous work (Khelashvili et al., 2023).



FDM particle mass constraints from various astrophysical observations (Ferreira, 2021), this work, Khelashvili et al. (2023), and Bernal et al. (2018).

- The constraint set from this work is strongly inconsistent with various astrophysical observations. It is also inconsistent with the strongest constraint to date ($1.1^{+8.3}_{-0.7} \times 10^{-19}$ eV), which is obtained from dynamical analysis of an ultrafaint dwarf, Segue I (Hayashi et al., 2021).

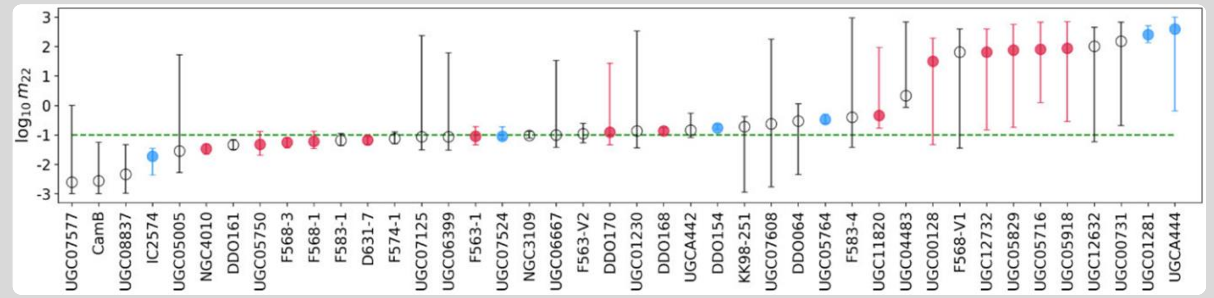
Discussion & Conclusions

Rotation Curve Fits

- For many galaxies, the reduced chi-squared (χ_ν^2) values obtained from the rotation curves fitting were not representing the fit qualities well, due to the wide uncertainties on the data points. Therefore, the BIC value was chosen for model comparison.
- The fits using the FDM halo model are strongly penalized by the BIC, probably due to the high complexity of the model. In this work, we used 5 free parameters ($k = 5$) for the FDM model, contrast to the three other models with only 3 free parameters ($k = 3$). As from the formula, BIC penalize models with a higher number of free parameters (k). Using a more simplified model of FDM might be useful for a "fairer" comparison, if the constraints on the model had been more stringent.

FDM Particle Mass

- The constraints on FDM particle mass of this work overlap with the results from Khelashvili et al. (2023) ($m_{FDM} \approx 10^{-23}$ eV). There are some differences on the 95% credible intervals for some overlapping galaxies, due to the additional free parameters used in the latter work (distance and inclination of the galaxies).



MAP (Maximum A Posteriori) values and 95% credible intervals of $\log m_{22}$ of 42 LSB galaxies from SPARC (Khelashvili et al., 2023)

- Bernal et al. (2018) fitted the rotation curves of 18 LSB galaxies and 6 NGC galaxies (4 of them are from the SPARC catalog). They also found that the constraints from each galaxy did not overlap. Based on individual galaxies analysis, they obtained a constraint in the range:

$$2.12 \times 10^{-24} < m_{FDM}/{\rm eV} < 2.7 \times 10^{-22}$$

Based on combined analysis (all of the galaxies are fitted simultaneously), they obtained a best-fit value:

$$m_{FDM} = 5.54 \times 10^{-24}\ {\rm eV}$$

Conclusions:

- For the standard **CDM** model, the Burkert model fits most galaxies better than NFW. Based on the BIC value, Burkert is the most supported model (10 galaxies), while NFW was only supported by 5 galaxies.
- The **FDM** model produces the best fits for most of the galaxies. However, it is rejected by all galaxies based on the ΔBIC criterion, due to penalties on the BIC value because of the high complexity of the model (5 free parameters).
- For most galaxies, the **SIDM** model produces similar fits to those of the Burkert model. Based on the BIC value, it received the most support after Burkert (9 galaxies). It can explain the rotation curves diversity problem in the samples.
- Based on the fitting results, we obtained a constraint on the FDM particle mass which overlaps with the results of Bernal et al. (2018) and Khelashvili et al. (2023). However, it contradicts various astrophysical observations.

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