Study of Cold, Fuzzy, and Self-Interacting Dark Matter Halos in Dwarf Galaxies

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Background

The standard **cold dark matter (CDM)** model successfully explained the formation of large-scale structures in the universe. However, this model encounters **small-scale problems**, mostly related to the distribution of dark matter in the central halos and properties of dwarf galaxies. One commonly proposed solution for the small-scale problems is to use alternative DM models, e.g., **fuzzy dark matter** and **self-interacting dark matter**.

Research Goals

We examine selected dwarf galaxies from **SPARC** (Spitzer Photometry and Accurate Rotation Curves) and **LITTLE THINGS** (Local Irregulars That Trace Luminosity Extremes, The HI Nearby Galaxy Survey) **in 3D** to study the properties of cold, fuzzy, and self-interacting dark matter halos.

Method

- Data Selection

Quality flag Q = 1 | Datapoints > 6 | $M_* < 10^{10} M_\odot$ | $30° \le i \le 75°$ | $r_{min} < 0.5\ kpc$

- The rotation curves are decomposed into **disk, gas, and DM halo** using the **Markov Chain Monte Carlo (MCMC)** method in Python (EMCEE package).
- The free parameters used for each model are shown in the table below. We set $\boldsymbol{\sigma/m_\chi = 3\ cm^2 g^{-1}}$ for the SIDM model.

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

Models

Cold Dark Matter (CDM)

- **Cold and collisionless**, with 100-1000 GeV neutralinos as the most popular candidate.
- Halo is well described by **Navarro-Frenk-White (NFW)** profile derived from DM-only N-body simulations.

NFW

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

ρ_s characteristic density
r_s scale radius

Navarro et al. (1997)

Fuzzy Dark Matter (FDM)

- Consists of **ultralight** ($10^{-24} < m_{FDM} < 10^{-19}$ eV) DM particles, e.g., axion and axion-like particles (ALPs).
- On the inner halo, **quantum pressure** provides stability against gravitational collapse, forming a **soliton** core with constant density (~0.3 – 1.6 kpc).

FDM

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

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

$\rho_{sol,0}$ soliton density
r_{sol} soliton radius
r_a transition radius

Schive et al. (2014)

Self-Interacting Dark Matter (SIDM)

- Allows non-gravitational **interactions among DM particles** with a large scattering cross-section (σ/m_χ).
- **Thermalization** in the innermost halo region leads to the formation of a **constant-density isothermal core** (0.5 – 1 kpc).

SIDM

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

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

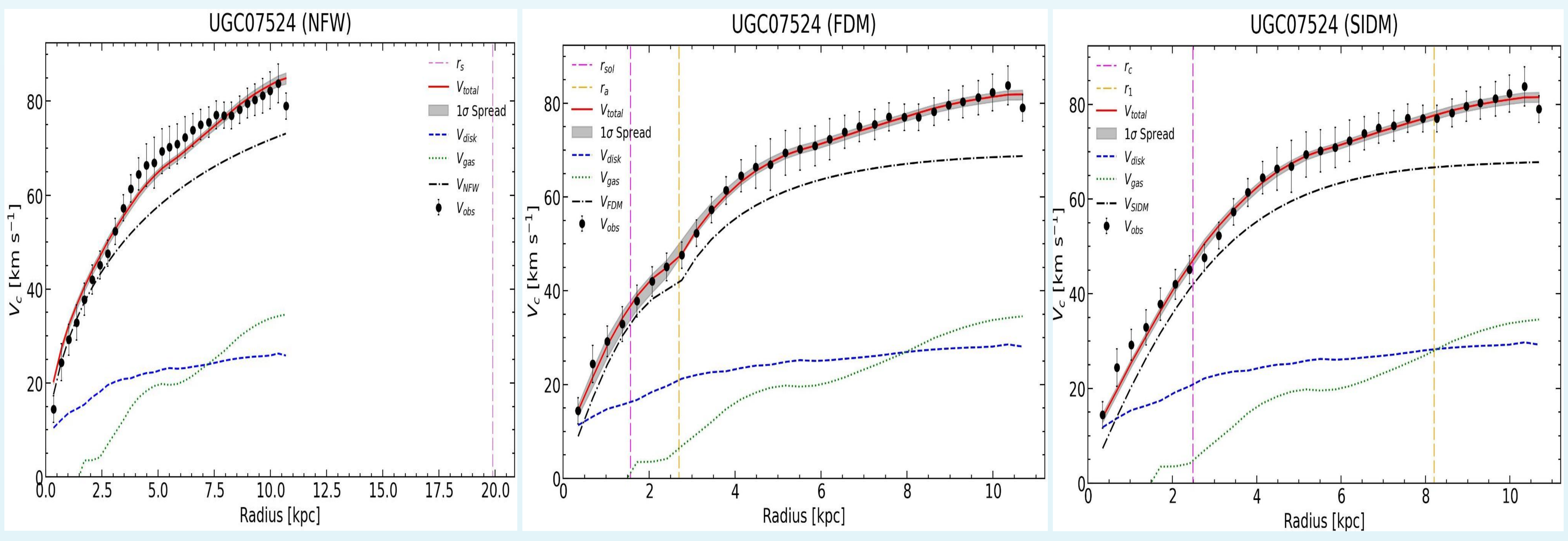
$$\nabla^2 \Phi_{tot}(r) = 4\pi G[\rho_{ISO}(r) + \rho_{bar}(r)]$$

σ_{v0} velocity dispersion
Φ_{tot} total gravity potential
ρ_{bar} baryonic density
ρ_0 core density

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

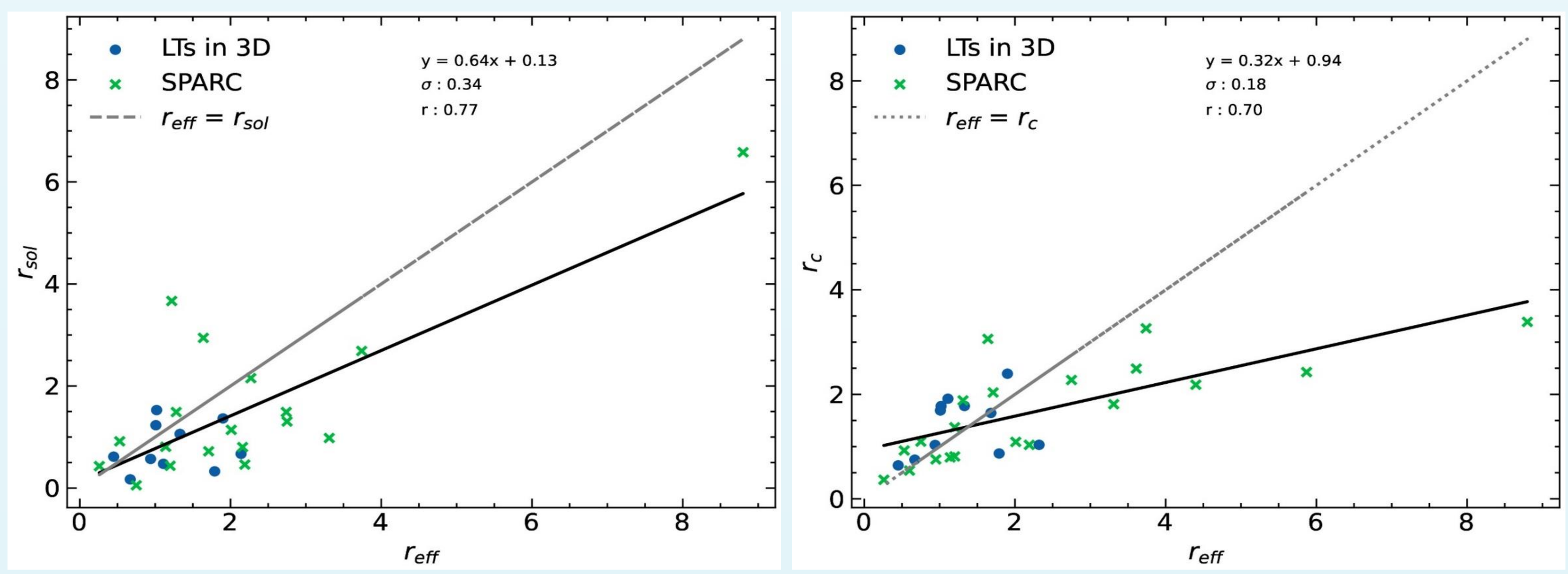
Results

Rotation Curve Fits



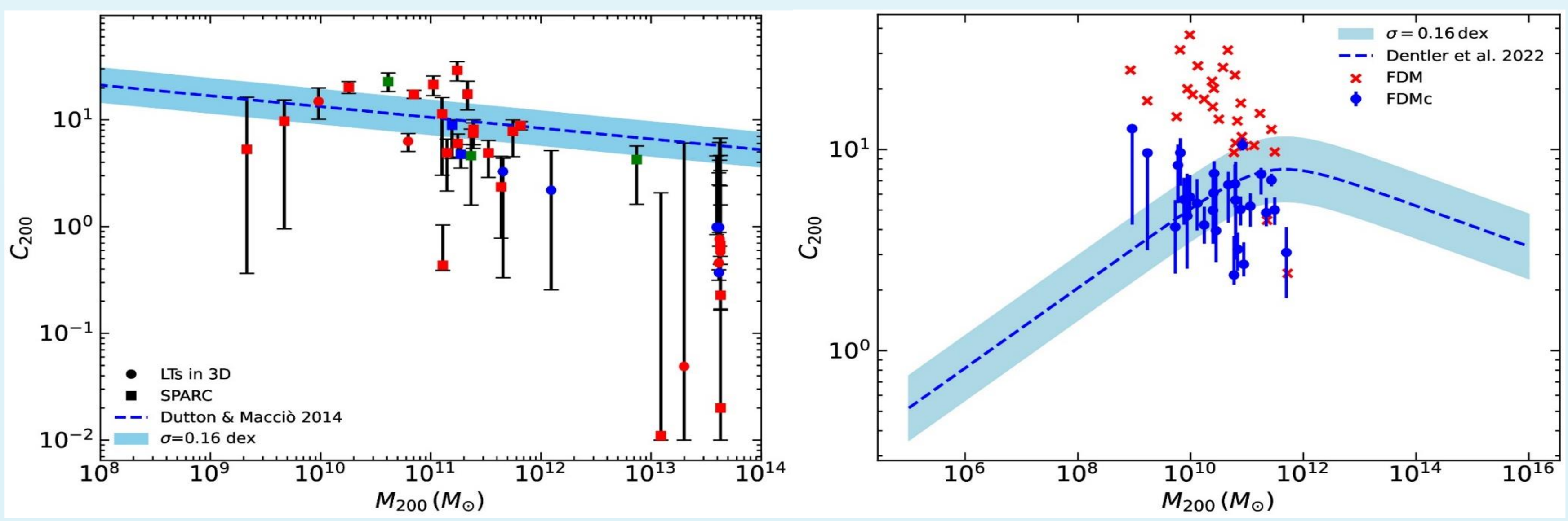
Most of galaxies preferred FDM and SIDM model than standard CDM model.

Dark Matter Core



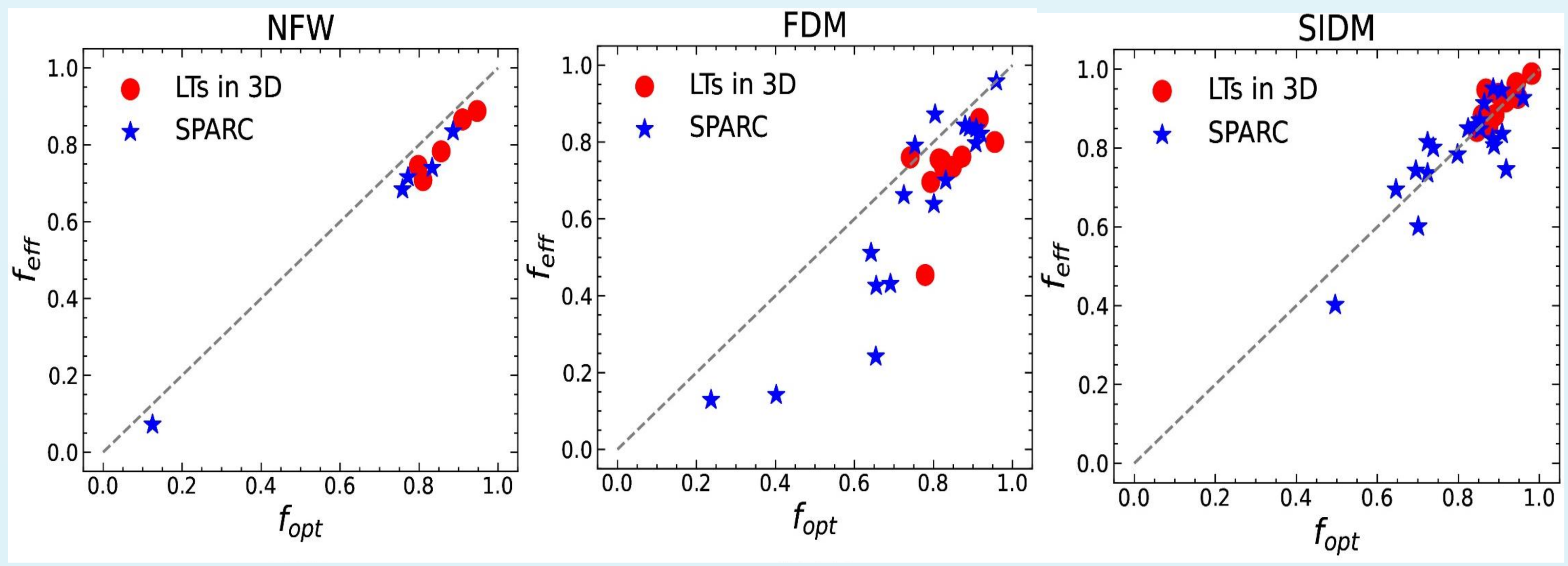
A **positive correlation** between effective and core radius in the FDM and SIDM models suggests a relation between DM and stellar distribution.

Concentration- Mass Relation



The discrepancies between simulation-based relations (dashed lines) and our result are possibly because the **simulations do not account for baryons or other physical processes** that affect matter distribution in the halo.

Dark Matter Fraction



The FDM and SIDM models show a **broader range of distributions** than the NFW model, suggesting they may better explain the diverse rotation curves and dark matter structures in galaxies.

References

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Ren, T., et al. 2019, Phys. Rev. X, 9, 031020
Schive, H.-Y., et al. 2014a, Nat. Phys., 10, 496
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