Title: Strong Constraints on Superfluid Dark Matter from Milky Way Dynamics

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Abstract: Many well-known correlations between dark matter and baryons exist on galactic scales. These can essentially be encompassed by a simple scaling relation between observed and baryonic accelerations, historically known as the Mass Discrepancy Acceleration Relation (MDAR). This relation has prompted many theories that attempt to explain the correlations by invoking additional fundamental forces on baryons. Since a collisionless cold dark matter (CDM) model is desirable on scales of clusters and above, the standard lore has been that a theory which reduces to the MDAR on galaxy scales but behaves like CDM on larger scales provides an excellent fit to data. However, this statement should be revised in light of recent results showing that a fundamental force that reproduces the MDAR is often challenged at accommodating Milky Way dynamics. In this study, we test this claim on the example of Superfluid Dark Matter. We find that a standard CDM model is strongly preferred over a static superfluid profile. This is due to the fact that the superfluid model over-predicts vertical accelerations, even while reproducing galactic rotation curves. Our results establish an important criterion that any dark matter model must satisfy within the Milky Way.
Inconsistency of SuperFluid DM with Milky Way Observables

Oren Slone, Princeton University

Great things from the 80’s
Great things from the 80’s

Vera Rubin, Ford and Thonnard, June 1980
A Naive Solution

\[ \nabla^2 \Phi = 4\pi G \rho \]

IR Modification to GR \hspace{2cm} Some mix \hspace{2cm} Dark Matter

Amazingly: Still not clear-cut on galactic scales
Outline

- Missing Mass and Galaxy Scale Observables
- Features of Various Classes of Solutions
- SuperFluid Dark Matter
- Framework to Test Various Models using MW data
- Results and Conclusions
The Missing Mass Problem on Galactic Scales, 2019

- Flat Rotation Curves
- Issues with Small Scales:
  - Missing Satellites (maybe solved)
  - Too Big To Fail
  - Core vs Cusp
- DM Correlates with Baryons:
Galaxy Scale Observables
The Diversity Problem

- Diversity of inner rotation curves even for galaxies with similar halo and stellar mass.
- Rotation curves correlate with baryons
Galaxy Scale Observables
The Diversity Problem

DM dominated galaxies!

- Low surface brightness - halo is cored
- High surface brightness - halo is cusped
- Self similar if scaled to baryonic scale radius

Kamada et al., 2016

\[ V_f \approx 79-91 \text{ km/s} \]
Galaxy Scale Observables

Renzo’s Rule

Sancisi, 2003
Galaxy Scale Observables
The Radial Acceleration Relation (RAR)

A tight correlation and an acceleration scale appear in rotation curve data from the SPARC catalog

Lelli et. al, 2017

McGaugh, Lelli, 2017
Galaxy Scale Observables
What models resolve these issues?

- Galaxies provide clues that DM correlates with baryons.
- Examples of solutions are:
  - CDM with baryonic feedback
  - Self Interactions SIDM
Fitting the MDAR with a Fundamental Force

- Produce flat rotation curves: \( \Phi \propto \log r \rightarrow a \propto \frac{1}{r} \rightarrow v_c \propto \text{const} \)

- Different models do this in various ways

- They typically reduce to: \( a = \nu \left( \frac{a_N}{a_0} \right) a_N \)

- With an interpolation function with asymptotes: \( \nu (x_N) = \begin{cases} x_N^{-1/2} & x_N \ll 1 \\ 1 & x_N \gg 1 \end{cases} \)

- This reproduces the MDAR: \( a = \begin{cases} a_N & a \gg a_0 \\ \sqrt{a_0 a_N} & a \ll a_0 \end{cases} \)
What can we do?

1. Ask a **model independent** question:
   - Can local MW measurements fit a generic model that predicts the MDAR with a fundamental force?

2. Test a **specific realization**:
   - e.g. A specific interpolation function
   - e.g. Superfluid dark matter

   *(Test these models where they’re supposed to shine!)*
Superfluid DM

\[ T \approx m v_{\text{vir}} \]

**Galaxies**

\[ T_{\text{gal}} \approx 0.1\text{mK} \]

Super Fluid Phase
MOND-Like Emergent Force

**Galaxy Clusters**

\[ T_{\text{cluster}} \approx 10\text{mK} \]

Cold DM
Standard DM Dynamics
Superfluid DM

\begin{center}
\begin{tikzpicture}
  \begin{axis}[
    title={\(\rho [10^{-26} \text{ g/cm}^3]\)},
    xlabel={r [kpc]},
    ylabel={\(\rho [10^{-26} \text{ g/cm}^3]\)},
    xmin=0, xmax=50,
    ymin=0, ymax=0.8,
    xtick={0,10,20,30,40,50},
    ytick={0,0.2,0.4,0.6,0.8},
    xmajorgrids=true,
    ymajorgrids=true,
    legend pos=north east,
    ]
    \addplot[blue, thick] coordinates {
        (0,0.8)
        (10,0.6)
        (20,0.4)
        (30,0.2)
        (40,0.1)
        (50,0.0)
    };
    \addplot[red, thick, dashed] coordinates {
        (0,0.8)
        (10,0.6)
        (20,0.4)
        (30,0.2)
        (40,0.1)
        (50,0.0)
    };
    \addplot[black, thick, dotted] coordinates {
        (40,0.75)
        (40,0.8)
        (50,0.8)
        (50,0.75)
    } node[above] at (40,0.8) {\(R_{\text{NFW}}\)};
    \addplot[black, thick, dotted] coordinates {
        (50,0.75)
        (50,0.8)
        (60,0.8)
        (60,0.75)
    } node[above] at (50,0.8) {\(R_{\text{T}}\)};
  \end{axis}
\end{tikzpicture}
\end{center}

Berezhiani, Famaey, Khoury, 2017
Superfluid DM

\[ \mathcal{L}_{\text{DM}, T=0} = \frac{2\Lambda (2m)^{3/2}}{3} X \sqrt{|X|} - \alpha \frac{\Lambda}{M_{\text{Pl}}} \phi \rho_b \]

\[ X = -m\Phi - \left( \vec{\nabla} \phi \right)^2 / 2m. \]

\[ \rho_{\text{SF}} = \frac{\partial \mathcal{L}}{\partial \Phi} \]

Berezhiani, Famaey, Khoury, 2017
Superfluid DM

The SF Interpolation Function:

\[ \ddot{a}_\phi = \alpha \frac{\Lambda}{M_{Pl}} \vec{\nabla} \phi. \]

\[ a_\phi = \sqrt{\frac{\alpha^3 \Lambda^2}{M_{Pl}} a_b}. \]

\[ a_0 = \frac{\alpha^3 \Lambda^2}{M_{Pl}}. \]

E.O.M. for \( \phi \)
Local MW Observations Provide Differentiating Power

Compare accelerations in the R and z directions:

- Data requires amplification in $a_R$ but essentially none in $a_z$.

- A spherical DM halo does precisely this:
  $$a_{DM} \approx -G \frac{M(R_0)}{R_0^2} \left(1, \frac{z}{R_0}\right)$$

- A slightly prolate halo is slightly better.

- A MOND-like force amplifies $a_R$ too little or $a_z$ too much:
  $$\frac{a_z}{a_R} = \frac{a_{z,N}}{a_{R,N}} \bigg|_{\text{disk}}$$

Lisanti, Moschella, Outmezguine, O.S., 2018
Local MW Observations Provide Differentiating Power

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Lisanti, Moschella, Outmezguine, O.S., 2018
Local MW Observations Provide Differentiating Power

Superfluid Dark Matter is even more predictive:

Galactic Acceleration
- CDM
- SFDM
- Data

Vertical Velocity Dispersions

Rotation Curve

Lisanti, Moschella, Outmezguine, O.S., 2019
Local MW Observations Provide Differentiating Power

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Lisanti, Moschella, Outmezguine, O.S., 2019
Local MW Observations Provide Differentiating Power
Bayesian Approach

- Given a model: $M = \text{CDM vs SFDM} / \text{a generic MOND-like force}$
- With parameters: $\theta_M$
- Construct a likelihood function: $\mathcal{L}(\theta_M) \propto \exp \left[ -\frac{1}{2} \sum_{j=1}^{N} \left( \frac{X_{j,\text{obs}} - X_j(\theta_M)}{\delta X_{j,\text{obs}}} \right)^2 \right]$
- $X_{\text{obs}}$: a set of measured values imposed as constraints
- $X(\theta_M)$: the corresponding model predictions
- Impose reasonable priors on $\theta_M$ and recover posterior distributions
Analysis Procedure
Milky Way Model

SFDM/MOND-like
For MOND use a Taylor expansion of the interpolation func

Dark Matter
A generalized NFW profile

Model baryonic profile:
- Double exponential stellar disk
- Double exponential gas disk
- Hernquist stellar bulge

Perform a Markov Chain Monte Carlo analysis and fit parameters to MW measurements
Analysis Procedure

Baryonic Density Profiles

\[ \rho_B = \rho_{*,\text{bulge}} + \rho_{*,\text{disk}} + \rho_{g,\text{disk}} \]
Analysis Procedure

Milky Way Observables

- Local stellar surface density
- Local gas surface density
- Disk scale radii (stars and gas)
- Disk scale heights (stars and gas)
- Bulge mass
- Rotation curve
- Vertical acceleration
Analysis Procedure
Milky Way Observables

- Local stellar surface density
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- Vertical acceleration

\[ v_c(R) = \sqrt{R \cdot a(R)} \bigg|_{z=0} \]

Eilers et. al., 2018
Analysis Procedure

Milky Way Observables

- Local stellar surface density
- Local gas surface density
- Disk scale radii (stars and gas)
- Disk scale heights (stars and gas)
- Bulge mass
- Rotation curve

- Vertical acceleration
  Inferred from 9000 K-dwarfs in the SEGUE sub-survey of the SDSS

\[
\sigma_{i,z}(z)^2 = \frac{n_i(0) \sigma_{i,z}(0)^2}{n_i(z)} + \frac{1}{n_i(z)} \int_0^z n_i(z') a_z(z') \, dz'
\]
Results of MCMC Scans
Interpolation Function Parameters

Interpolation function fitted to RAR:

\[ \nu \left( \frac{a_N}{a_0} \right) = \frac{1}{1 - e^{-\sqrt{a_N/a_0}}} \]

with

\[ a_0 = 1.20 \pm 0.24 \times 10^{-10} \text{ m s}^{-2} \]

Excluded at 95% confidence
Results of MCMC Scans

Tension with MW Observations

**Local Milky Way Analysis**

$h_{*,z} = 300$ pc

- **MOND-like (ML)**
- **Dark Matter (DM)**

**Driven by stellar surface density constraint**

$$M_{*,\text{disk}} = \frac{2\pi h_{*,R}^2 \Sigma^*_{*,\text{obs}} \exp(R/\Sigma_{*,R})}{1 - \exp(-z_{max}/h_{*,z})}$$

**Driven by local value of rotation curve constraint**

$$v_c(R) = \sqrt{R \cdot a(R)}$$

1812.08169 - Lisanti, Meschella, Outmezguine, O.S.
Results of MCMC Scans
Stellar Scale Radius vs Stellar Bulge Mass

Driven by local surface density and rotation curve

Interpolation Functions
- $P = \left(1 - \frac{v^2}{v_{esc}^2}\right)$
- $P = v_0 + v_1 \cdot \alpha_S$
- prior

$N_{\ast,bulge}$ vs $h_{*,R}$ (kpc)

1812.08169 - Lisanti, Moschella, Oudmezguine, O.S.
Results for SuperFluid DM
Full Rotation Curve and Vertical Accelerations

Cold Dark Matter
- total
- dark matter
- baryons
  - Eilers et al. (2018)

Superfluid Dark Matter
- total
- dark matter
- phonons
- baryons
  - Eilers et al. (2018)
Additional Tests

Redo analysis with:

- Only one mono-abundance population for velocity dispersions
- Various choices of priors for all parameters
- Artificially enhanced errors by factor of 2

⇒ Qualitatively same results for all cross checks
Conclusions

- Standard lore is that “MOND-like forces work on Galactic scales”. This is not precisely true.

- Our results establish a new criterion for any DM model which attempts to reproduce the MDAR.

- SFDM is a representative example of a broad class of such theories.

- MW measurements seem to prefer CDM over these models.