Galactic rotation curves vs. ultra-light dark matter

Kfir Blum (CERN & Weizmann Institute)

1805.00122

Work with:
Nitsan Bar (Weizmann)
Diego Blas (CERN; King’s College)
Sergey Sibiryakov (CERN; EPFL; INR)

ICTP, Giant Telescopes, July 2018
Motivation
(estimated) mass profile of the Milky Way, radially-averaged, from a variety of tracers
WIMP cold dark matter:

thought to affect outer part of rotation curve

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram}
\caption{Graph showing enclosed mass versus radius for different mass values and various authors.}
\end{figure}
Ultra-Light Dark Matter (ULDM):

makes predictions for the inner part of galaxies
Ultra-Light Dark Matter (ULDM):

makes predictions for the inner part of galaxies
Ultra-Light Dark Matter (ULDM):

makes predictions for the inner part of galaxies
Summary
In the last ~five years, numerical structure formation simulations with ULDM have become available.

The inner part of simulated galaxies forms a core: “soliton”.

Simulations have discovered a scaling relation, connecting the core to the host halo.
Soliton—host halo relation predicts a bump in the inner part of rotation curves.

We study the theoretical implications, trying to understand the underlying physics of the soliton—host halo relation. *(Not in this talk.)*

We study high-resolution rotation curves of ~100 intermediate size galaxies, in the ballpark of halo mass that was numerically simulated.

As far as we could see, the bump isn’t there.

$m \sim 1 \times 10^{-22} - 1 \times 10^{-21} \text{ eV}$ seems to be in tension with observations of many galaxies.

Comparable independent constraints from Ly-alpha Forest analyses; see talk by Viel earlier today. Armengaud (1703.09126), Irsic (1703.04683), Zhang (1708.04389), Kobayashi (1708.00015)
Soliton—host halo relation predicts a bump in the inner part of rotation curves.

As far as we could see, the bump isn’t there. m~1e-22 - 1e-21 eV seems to be in tension with observations of many galaxies.

This particular range of m is of special interest, because it was thought to address small-scale puzzles of LCDM

Soliton—host halo relation predicts a bump in the inner part of rotation curves.

As far as we could see, the bump isn’t there. m~1e-22 - 1e-21 eV seems to be in tension with observations of many galaxies.

m >~1e-20 cannot yet be constrained, because of spatial resolution of rotation curve data: cannot resolve the core.

Better observational resolution may probe m > 1e-20eV
Analysis
A soliton — host halo relation?

\[ M_c \approx \alpha \left( \frac{|E_h|}{M_h} \right)^{1/2} \frac{M_{pl}^2}{m} \]

\[ \alpha = 1 \]
The Milky Way

$10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$

$r [\text{pc}]$

$10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$ $10^{12}$

enclosed mass $[M_\odot]$

$m=10^{-19}$ eV
$m=10^{-20}$ eV
$m=10^{-21}$ eV
$m=10^{-22}$ eV

Ghez 2003
McGinn 1989
Fritz 2016
Lindqvist 1992
Schodel 2014
Sofue 2009
Sofue 2012
Sofue 2013
Chatzopoulos 2015
Deguchi 2004
Oh 2009
Trippe 2008
Gilessen 2008

NFW fit, Pfiff (2015)
Empirical soliton—host halo relation, equivalent to this statement:

\[
\frac{E}{M}|_{\text{soliton}} \approx \frac{E}{M}|_{\text{halo}}
\]

*Derivation: Not in this talk… (1805.00122)*
Empirical soliton—host halo relation, equivalent to this statement:

$$\frac{E}{M}\big|_{\text{soliton}} \approx \frac{E}{M}\big|_{\text{halo}}$$

Equal specific energy $$\Rightarrow$$ equal specific kinetic energy
$$\Rightarrow$$ ~equal peak rotation velocity

Compare directly to simulations

![Graph showing radial profiles of the halo rotational velocity in different units with labels Schive (2014) and Chan (2017).](image-url)
This is a powerful prediction. It is easy to compare to data:

i. Look at galaxies
ii. Find halo peak rotation curve
iii. This determines the soliton & soliton peak velocity in the inner part of the galaxy
High-resolution rotation curves of low surface brightness galaxies

W. J. G. de Blok and A. Bosma
$V_{\text{circ}}$ [km/s]

$V_{\text{circ}}$ vs. $x$ [kpc]

UGC 1281

Bosma & de Block 2002
HI+Halpha
Of the 175 galaxies in [25], 160 pass the $m_{gal}$ cut for $m = 10^{-22}$ eV, and 174 pass it for $m = 10^{-21}$ eV.

Next, for each galaxy we determine the observed maximal halo rotation velocity $V_{circ,h}$, and use it to compute the soliton prediction from Eq. (49). Our first pass on the data includes only galaxies for which the predicted soliton is resolved, namely, $x_{peak}$, from Eq. (50), with $V_{circ,h}$, lies within the rotation curve data. For these galaxies, we compute from data the ratio $V_{circ,obs}(x_{peak},)$ $max V_{circ,h}$. (A1)

Here, $V_{circ,obs}(x_{peak},)$ is the measured velocity at the expected soliton peak position. We compute it by averaging the two data points corresponding to measured $0 1 2 3 4 5 6 x[kpc] 0 20 40 60 80 V_{circ}[km/s]$.

The results of this first pass on the data are shown in Fig. 14. 46 galaxies passed the resolved soliton cut for $m = 10^{-22}$ eV, and 4 galaxies pass it for $m = 10^{-21}$ eV.

Including only galaxies with a resolved soliton causes us to lose many relevant rotation curves, with discriminating power. To overcome this, yet maintain a simple analysis, we perform a second pass on the data. Here, we allow galaxies with unresolved soliton, as long as the lowest radius data point is located not farther than $3 \times x_{peak}$. We need to correct for the fact that the soliton peak velocity is outside of the measurement resolution. To do this, we modify the velocity observable.
m=1e-22 eV
**SPARC data base:**
175 rotation curves
Lelli et al, 1606.09251

- $\max \frac{V_{\text{bar}}}{V_{\text{DM}}} < 1$
- $\max \frac{V_{\text{bar}}}{V_{\text{DM}}} < 0.5$
- $\max \frac{V_{\text{bar}}}{V_{\text{DM}}} < 0.3$

* 3.6mum surface photometry
* HI + Halpha rotation curves
Conclusions:

Soliton—host halo relation predicts an inner bump in the rotation curve.

As far as we could see, the bump isn’t there.

$m \approx 10^{-22} - 10^{-21} \text{ eV}$ appears to be in tension with observations of many galaxies.

Comparable independent constraints from Ly-alpha Forest analyses; see talk by Viel earlier today. Armengaud (1703.09126), Irsic (1703.04683), Zhang (1708.04389), Kobayashi (1708.00015)
Xtra
The Milky Way: nuclear bulge vs. soliton

Nuclear Bulge (disc+star cluster) from photometry, Launhardt (2002)

NFW fit, Piffl (2015)

- Ghez 2003
- McGinn 1989
- Fritz 2016
- Lindqvist 1992
- Schodel 2014
- Sofue 2009
- Sofue 2012
- Sofue 2013
- Chatzopoulos 2015
- Deguchi 2004
- Oh 2009
- Trippe 2008
- Gilessen 2008

enclosed mass $[M_\odot]$

$r [\text{pc}]$

Enclosed mass $[M_\odot]$

- $m=10^{-19} \text{ eV}$
- $m=10^{-20} \text{ eV}$
- $m=10^{-21} \text{ eV}$
- $m=10^{-22} \text{ eV}$

- Ghez 2003
- McGinn 1989
- Fritz 2016
- Lindqvist 1992
- Schodel 2014
- Sofue 2009
- Sofue 2012
- Sofue 2013
- Chatzopoulos 2015
- Deguchi 2004
- Oh 2009
- Trippe 2008
- Gilessen 2008