Galactic Rotation Curves with Dark Matter Self-Interactions

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Based on
AK, M. Kaplinghat, A. B. Pace, H.-B. Yu, arXiv:1611.02716

Dec. 5, 2016 @ Focus Workshop on Particle Physics and Cosmology
Enclosed mass increases outside the disk

Andromeda

1970 Rubin and Ford
Measurements of Rotation Curves

M(<R): implied enclosed mass
V: observed rotation velocity
expected rotation velocity
distance from the center

Evidence of Dark Matter
Evidence of Dark Matter

1970 Rubin, Ford
Measurements of Rotation Curve

Evidence of Dark Matter

Andromeda

Spiergel et al., PRL, 2000

DM

DM

DM

DM

[Graph showing rotation curve and dark matter]

Distance from the center

V [Km/s]

R [kpc]

Enclosed mass increases outside the disk

M(<R):

Implied enclosed mass

V:

Observed rotation velocity

Expected rotation velocity

Andromeda distance from the center

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The $\Lambda$CDM model reproduces well the large scale (>Mpc) structure of the Universe.

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**Large scale structure of the Universe**

- **SDSS DR7** (Reid et al. 2010)
- **LyA** (McDonald et al. 2006)
- **ACT CMB Lensing** (Das et al. 2011)
- **ACT Clusters** (Sehgal et al. 2011)
- **CCCP II** (Vikhlinin et al. 2009)
- **BCG Weak lensing** (Tinker et al. 2011)
- **ACT+WMAP spectrum** (this work)

**$\Lambda$CDM (linear)**

**+non-linear evolution**

- **observational data converted to the linear**

Small scale crisis I

When $N$-body simulations in the $\Lambda$CDM model and observations are compared, problems appear at (sub-)galactic scales: **small scale crisis**

**missing satellite problem**

$N$-body (DM-only) simulations in the $\Lambda$CDM model $\rightarrow$ Milky Way-size halos host $O(10)$ times larger number of subhalos than that of observed dwarf spheroidal galaxies

\[
V^2_{\text{circ}}(r) = \frac{GM(<r)}{r} \quad V_{\text{max}} = \max_r \{V_{\text{circ}}(r)\}
\]

(maximum) circular velocity

\[
\text{cumulative number of subhalos}
\]

\[
\begin{align*}
V_{\text{max}} &= 160 \text{ km/s} \\
V_{\text{max}} &= 208 \text{ km/s}
\end{align*}
\]

Kratsov, Advances in Astronomy, 2010
Small scale crisis II

**cusp vs core problem**

*N-body (DM-only) simulations in ΛCDM model → UNIVERSAL DM profile independent of halo size: NFW profile*

\[
\rho_{\text{DM}}(r) \propto r^{-\alpha}
\]

**inner profile:**

\[
\alpha = 1 \text{ (NFW)}
\]

\[
\alpha = 0 \text{ (isothermal)}
\]

Observations infer the **CORED** isothermal profile in the inner region rather than the **CUSPY** NFW profile

**NFW profile:**

\[
\rho_{\text{DM}}(r) = \frac{\rho_s}{r/r_s(1 + r/r_s)^2}
\]

**isothermal profile:**

\[
\rho_{\text{DM}}(r) = \begin{cases} 
\rho_{\text{DM}}^0 & (r \ll r_0) \\
(r_0/r)^2 & (r \gg r_0)
\end{cases}
\]

field dwarf spheroidal galaxies ~10^9 Msun
Possible solution I

The above discussions are based on $N$-body (DM-only) simulations in the $\Lambda$CDM model.

Gravitational potentials are shallower at smaller scales $\rightarrow$ BARYONIC HEATING and COOLING processes may be important.

Baryonic processes

- heating from ionizing photons - ionizing photons emitted and spread around reionization of the Universe heat and evaporate gases

- mass loss by supernova explosions - supernova explosions blow gases from inner region $\rightarrow$ DM redistribute along shallower potential
Inner mass deficit problem

Rephrasing cusp vs core problem to emphasize that not only the slope but also the **WHOLE MASS DISTRIBUTION** should be examined.

10\textsuperscript{th}-90\textsuperscript{th} percentile range from the state-of-the-art hydrodynamical simulations in the \(\Lambda\) CDM model (EAGLE, Local GROUPS) with modeled subgrid baryonic physics (radiative cooling, star formation, stellar and chemical enrichment, energetic stellar feedback, black hole accretion and mergers, and AGN feedback).

The simulated enclosed mass is about **FOUR times** higher than the observed!
Concentration-mass relation

Why is a simulated rotation curve (almost) DEFINITE for a given $V_{\text{max}}$?

Two parameters for the NFW profile

$$\rho_{\text{DM}}(r) = \frac{\rho_s}{r/r_s(1 + r/r_s)^2}$$

A relation between two parameters usually given as the CONCENTRATION-MASS RELATION

$$c_{200} = 10^{0.905 \pm 0.11} \left(\frac{M_{200}}{10^{12} h^{-1} M_\odot}\right)$$

small intrinsic scatter

$$c_{200} = \frac{r_{200}}{r_s}$$

$$M_{200}(< r_{200}) = \frac{4\pi}{3} \bar{\rho} M_{200} r_{200}^3$$

Dutton et al., MNRAS, 2014
Unexpected diversity problem

The inner mass deficit is **NOT UNIVERSAL**, but should be elaborated in a **GALAXY-BY-GALAXY** manner even with $V_{\text{max}}$ fixed.

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**Oman et al., MNRAS, 2015**

- **UGC 5721**
  - DMO sims: LG-MR + EAGLE-HR,
  - $V_{\text{max}} = 89 \text{ km s}^{-1} \pm 10\%$ [113]
  - Hydro sims: LG-MR + EAGLE-HR,
  - $V_{\text{max}} = 89 \text{ km s}^{-1} \pm 10\%$ [113]

- **UGC 11707**
  - DMO sims: LG-MR + EAGLE-HR,
  - $V_{\text{max}} = 101 \text{ km s}^{-1} \pm 10\%$ [73]
  - Hydro sims: LG-MR + EAGLE-HR,
  - $V_{\text{max}} = 101 \text{ km s}^{-1} \pm 10\%$ [73]

- **LSB F583-1**
  - DMO sims: LG-MR + EAGLE-HR,
  - $V_{\text{max}} = 88 \text{ km s}^{-1} \pm 10\%$ [120]
  - Hydro sims: LG-MR + EAGLE-HR,
  - $V_{\text{max}} = 88 \text{ km s}^{-1} \pm 10\%$ [120]

- **IC 2574**
  - DMO sims: LG-MR + EAGLE-HR,
  - $V_{\text{max}} = 80 \text{ km s}^{-1} \pm 10\%$ [149]
  - Hydro sims: LG-MR + EAGLE-HR,
  - $V_{\text{max}} = 80 \text{ km s}^{-1} \pm 10\%$ [149]
**Dark matter self-interaction**

**Self-Interacting Dark Matter: SIDM**

**SIDM structure formation starts with**
the same linear (initial) matter power spectra as $\Lambda$CDM,
but self-interactions become important
as structure formation proceeds $\leftrightarrow \rho$ increases
SIDM halo - mass density

SIDM-only simulation

As $\sigma/m$ increases, central density decreases

Inverted at some point $\leftarrow$ gravo-thermo instability $\leftrightarrow$ core-collapse

$\sigma/m=0.5-5 \text{ cm}^2/\text{g}$ may solve the inner mass deficit problem

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Elbert et al., MNRAS, 2015
Origin of the diversity

Unexpected diversity problem??

For a given cross section ($\sigma/m=3 \text{ cm}^2/g$ in the following), the SIDM halo profile is still **DEFINITE** and characterized by only one parameter $V_{\text{max}}$

Scatter in distributions of the baryons even in similar-size halos!!

Extended stellar disk

Compact stellar disk
Influence of the baryons

SIDM static distribution with a thin exponential disk potential from the Poisson equation

\[ \Delta \phi = \frac{4\pi G \rho_{DM}^0}{\sigma^2} \exp \left( -\frac{\phi}{\sigma^2} \right) \]
\[ \phi(0) = 0 \]
\[ \phi(\vec{x}) \to V_\infty^2 \ln \left( \frac{r}{r_0} \right) \]
\[ (r = |\vec{x}| \to \infty) \]
\[ V_\infty^2 = 2\sigma^2 = \frac{4\pi G \rho_{DM}^0}{r_0} \]

SIDM profile **CONTRACTS** under the presence of a **COMPACT** stellar disk

**$V_{\text{max}}=70 \text{ km/s}$**

**observed scatter**

**$V_{\text{max}}=120 \text{ km/s}$, $M_{200}=3.6 \times 10^{11} M_{\odot}$, $M_d=10^{10} M_{\odot}$**
In MASSIVE spiral galaxies, stellar disks can change WHOLE SIDM MASS DISTRIBUTIONS.
Case study II

SIDM halo profile reflects **HOW COMPACT** the hosted stellar disk is even with similar $V_{\text{max}}$ AND $M_\star$.

NGC 6503, $c_{200}:\text{median, } M_{200}:2.5 \times 10^{11} M_\odot$

UGC 128, $c_{200}:\text{median, } M_{200}:3.8 \times 10^{11} M_\odot$

$M_\star: 0.83 \times 10^{10} M_\odot$

$M_\star: 0.57 \times 10^{10} M_\odot$

Extended stellar disk

Compact stellar disk

$V_{\text{cir}}$ (km/s) vs Radius (kpc)
Halo shape - ellipticity
- galaxy cluster MS 2137–23
  \((e=0.18@r=70\,\text{kpc})\)
(estimate) \(\sigma/m<0.02\,\text{cm}^2/\text{g}\)
(simulation/l.o.s. effect)
\(\sigma/m<1\,\text{cm}^2/\text{g}\)
Peter et al., MNRAS, 2013

Bullet cluster - transparency
- 1E0657-558
  (offset) \(\sigma/m<1.25\,\text{cm}^2/\text{g}\)
  (massloss) \(\sigma/m<0.7\,\text{cm}^2/\text{g}\)
- an ensemble (72)
  (offset) \(\sigma/m<0.47\,\text{cm}^2/\text{g}\)
Harvey et al., Science, 2015

\(V_{\text{max}}\approx1000\,\text{km/s}\)
\(\leftrightarrow\) galaxy: \(V_{\text{max}}\approx100\,\text{km/s}\)
\(\sigma/m=0.5-5\,\text{cm}^2/\text{g}\)

\(\sigma/m=1\,\text{cm}^2/\text{g}\)
Peter et al., MNRAS, 2013

\(\sigma/m=1\,\text{cm}^2/\text{g}\)
CDM

\(\sigma/m=0.5-5\,\text{cm}^2/\text{g}\)
Peter et al., MNRAS, 2013

\(V_{\text{max}}\approx1000\,\text{km/s}\)
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Particle physics models I

The constraints from galaxy clusters likely imply that dark matter self-interaction should **DIMINISH WITH INCREASING VELOCITY**, even though not necessarily so far

+ interestingly strong lensing of galaxy clusters may support SIDM with a smaller cross section $\sigma/m=0.1 \text{ cm}^2/\text{g}$

**velocity-DEPENDENT cross section:**

- WIMP dark matter
- + light mediator with $m_{\text{med}} \sim m_{\text{DM}} v_{\text{gal}}/c$
- $\sigma \sim 1/m_{\text{med}}^2$: const.
- @(dwarf)galaxies ($V_{\text{max}} \sim 10-100 \text{ km/s}$)
- $\sigma \sim 1/v^4$: suppressed
- @galaxy cluster ($V_{\text{max}} \sim 1000 \text{ km/s}$)

[Tulin et al., PRL, 2012]

[Kaplinghat et al., PRL, 2015]
If a **velocity-INDEPENDENT** cross section is concordant at both galaxy cluster and galaxy scales, self-interaction may originate from a **HIDDEN STRONG** interaction (geometrical cross section of strongly-interacting massive particle: SIMP).

A simple hidden pion theory of $m_\pi \sim f_\pi \sim 100$-$300$ MeV (non-linear sigma model with CP symmetry) works well: Wess-Zumino-Witten term (coefficient may be quantized and/or determined once a UV theory is specified) freeze-out of $3 \rightarrow 2$ reaction correct relic abundance

If the hidden sector is completely decoupled from the SM sector, the hidden sector is **HEATED UP** by the rest mass energy of SIMP through the $3 \rightarrow 2$ reaction comoving entropy density conservation $\rightarrow \frac{1}{\ln(a)}$ ($T \propto \frac{1}{a}$)

**KINETIC DECOUPLING** from the SM sector has a big impact on the relic density of dark matter!! (cannibalism)
Summary

- The long-standing cusp vs core problem is now highlighted as an inner mass deficit problem by state-of-the-art hydrodynamical simulations.

- The inner mass deficit should be elaborated in a galaxy-by-galaxy basis, in contrast to the concentration-mass relation, which is hold even under the baryonic processes (diversity problem).

- Dark matter self-interaction, which intrinsically makes a mass distribution shallower in inner region, can solve the inner mass deficit problem, and also solve the diversity problem with the help of scatter in baryon distributions.