Why I think that dark matter has large self-interactions

-Manoj Kaplinghat
Hidden sector dark matter

In this scenario, dark sector particles (including DM) can interact strongly with each other (like SM particles).
A motivating Standard Model example

Imagine dark matter is made up of stable hidden sector neutrons.

Rotation curves

\( v \approx 1000 \text{ km/s} \) (Bullet ball cluster)

\( v \approx 3000 \text{ km/s} \) (Bullet cluster)
Hidden sector dark matter model with

$$\frac{\sigma}{m} \approx \text{few} \ \text{cm}^2/\text{g}$$

(in galaxies)

Qualitative predictions similar for a range of cross sections (Elbert et al 2014).

DM halo becomes insensitive to star formation history because self-interactions push system towards equilibrium.

No demonstrated need for velocity dependence for $v < 200 \ \text{km/s}$.

Cross section must be significantly smaller at $v > 1000 \ \text{km/s}$. 
SIDM and CDM predictions deviate in the inner part of galaxies. 

Spergel and Steinhardt (2000)

Large-scale structure is the same as ΛCDM.

With James Bullock, Miguel Rocha, Annika Peter (2013)
Diversity built into SIDM, but is it the right kind?

Small-scale issues stretch from 30-50 km/s (too-big-to-fail) to more massive galaxies (100-150 km/s). In this talk, the focus is on galaxies with Vmax > 50 km/s.
Field galaxies: SIDM halo profile is uniquely determined for large cross sections

\[ E_{\text{SIDM}}(r) \propto \Phi_{\text{total}}(r)/kT \quad \text{for } r < r_1 \]

- \( r > r_1 \) : \( E_{\text{SIDM}} \approx E_{\text{CDM}} \)

- Interaction rate \( \approx \frac{\text{age}}{\text{at } r_1} \)

- \( kT \approx \frac{V_{\text{rms}}}{\sqrt{3}} \approx \frac{V_{\text{max}}}{\sqrt{3}} \)

With Ryan Keeley, Tim Linden and Hai-Bo Yu (2014)
With Oliver Elbert and James Bullock (2017)
Field galaxies: both Cored and Cuspy

- SIDM does not predict large cores in all galaxies

cores small / cuspy

$\rho_{*} + \rho_{\text{gas}}$

$\downarrow$ core size $\sim r_s$ (large!)

Creasey et al (2017)
Plot motivated by Oman et al (2015)
SIDM fits to the rotation curves in the SPARC sample

Blue to red: decreasing surface brightness in each panel.

With Tao Ren, Anna Kwa and Hai-Bo Yu (to be posted)
The radial acceleration relation in the SPARC sample

\[ a_{\text{CDM}} \approx 4 \left( \frac{V_{\text{max}}}{r_{\text{max}}} \right)^2 \approx 3-7 \times 10^{-11} \text{ m/s}^2 \]

\[ a_{\text{SIDM}} \approx 10^{-11} \text{ m/s}^2 \]

(for \( \sigma/M = 3 \text{ cm}^2/\text{g} \))
SIDM model predictions closely track the radial acceleration relation for the full range of galaxy masses.

With Tao Ren, Anna Kwa and Hai-Bo Yu (to be posted)
SIDM allows for superior fits compared to MOND

With Tao Ren, Anna Kwa and Hai-Bo Yu (to be posted)
Why are the SIDM fits better than MOND fits?

Likely because of the diversity in the inner rotation curves. It is hard to capture this with a single parameter.
SIDM fits get the cosmology right.

With Tao Ren, Anna Kwa and Hai-Bo Yu (to be posted)
Stellar mass – halo mass connection (from the SIDM fits)

Stellar mass - halo mass relation (output)

With Tao Ren, Anna Kwa and Hai-Bo Yu (to be posted)
Feedback models that produce large cores don’t seem to make high surface brightness galaxies.

Strong Feedback vs. SIDM

NIHAO simulations
strong feedback
Santos-Santos et al. (2017)

SIDM
with Kaplinghat, Kwa, Ren (in prep)

No ΛCDM-based solution can yet explain the diversity of inner rotation curves in galaxies with $50 \text{ km/s} \leq V_{\text{rot}} \leq 150 \text{ km/s}$
Connected clue 1: Ultra-diffuse satellite galaxies

We have argued that galaxies with V_{max} \sim 100 \text{ km/s} have cores. When they fall into a cluster potential, the stars expand (Penarrubia et al 2010).

This can explain the numbers, radial distribution and scaling with host mass for UDGs

Beasley et al 2016

Carleton et al, arXiv:1805.06896
Connected clue 2: Elliptical galaxies are deficient in dark matter compared to LCDM estimates

Lovell et al 2018 (using IllustrisTNG)
Connected clue 3: Densities of the satellites of the Milky Way are in line with observations

Measuring densities within 50-100 pc using ultra-faint galaxies will be a crucial test (with Sheldon Campbell and Tim Carleton, in prep).

Vogelsberger, Zavala and Loeb (2012)

Measuring densities within 50-100 pc using ultra-faint galaxies will be a crucial test (with Sheldon Campbell and Tim Carleton, in prep).
There is a simple way to preserve all the successes of the ΛCDM model and explain the distribution of dark matter in the inner parts of galaxies: *allow for thermalization of dark matter*. This solution is likely to work with a wide range of feedback models.