Dark Matter halo response to gas inflows and outflows

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Cold Dark Matter works on large scales

Tegmark et al 2004

4 orders of magnitude in scale

Tegmark et al 2004
Cold Dark Matter fails on small scales

Subhalos
Field halos

MW satellites
Field galaxies

Garrison-Kimmel, Boylan-Kolchin, Bullock, Kirby 2014
Cold Dark Matter fails on small scales

Moore et al. 1994, Flores & Primack 1994, de Blok et al. 2001, 2008, ...

**Discrepancy:** Factor $\sim 2$ in velocity $\Rightarrow$ factor $\sim 4$ in mass

![Circular Velocity vs. Radius Graph](Image)

- **APOSTLE hydro simulations**
- **IC 2574**
- **4.6 kpc**
**Cold Dark Matter** works on small scales

SN driven gas outflows *can* expand the dark matter halo

e.g., Navarro, Eke, Frenk 1996; Read & Gilmore 2005; Mashchenko et al. 2006, 2008; Governato et al. 2010; Pontzen & Governato 2012; Teyssier et al. 2013; Di Cintio et al. 2014a,b; Chan et al. 2015; Trujillo-Gomez et al. 2015

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**Figure 5.** Rotation curves of galaxies IC 2574 and UGC05750 compared to that of their most similar NIHAO counterpart. For NIHAO galaxies we show the DM-only circular velocity, the spherical circular velocity, and the true circular velocity. In this last case, the agreement with observed data is remarkable.

**NIHAI0 XIV** - Santos-Santos et al. 2018 - see poster
What determines how Galaxy Formation modifies the Dark Matter distribution in LCDM simulations?

\[ \frac{M_{\text{star}}}{M_{\text{halo}}} \]

Star Formation Efficiency

\[ n \]

Star Formation Threshold
Toy Model

Consider a shell of radius \( r_i \) and mass \( M_i \)

Adiabatic Inflow

\[
\frac{r_a}{r_i} = (1 - f_{\text{in}}), \quad \frac{M_a}{M_i} = \frac{1}{(1 - f_{\text{in}})}. \tag{Contraction}
\]

Impulsive Outflow

\[
\frac{r_f}{r_a} = \frac{1 - f_{\text{out}}}{1 - 2f_{\text{out}}}, \quad \frac{M_f}{M_a} = 1 - f_{\text{out}}. \tag{Expansion}
\]

1 cycle

\[
f_{\text{out}} = \beta f_{\text{in}}
\]

\[
\frac{r_f}{r_i} = \frac{(1 - \beta f_{\text{in}})(1 - f_{\text{in}})}{1 - 2\beta f_{\text{in}}}, \quad \frac{M_f}{M_i} = \frac{1 - \beta f_{\text{in}}}{1 - f_{\text{in}}}. \]

N cycles

\[
\frac{r_f}{r_i} = \left[\frac{(1 - f_{\text{in}})(1 - \beta f_{\text{in}})}{(1 - 2\beta f_{\text{in}})}\right]^N, \quad \frac{M_f}{M_i} = \left[\frac{1 - \beta f_{\text{in}}}{1 - f_{\text{in}}}\right]^N
\]

NIHAO IX - Dutton et al. 2016b
Toy Model

N cycles $\beta=1$ \[ \frac{r_f}{r_i} = (1 - 2f + f^2)^N / (1-2f)^N \]

Net Expansion

\[ \frac{r_f}{r_i} = 1 + N f^2 + O(f^3) \]

- Need many cycles, with $f \approx 0.1$ to generate significant expansion
- If outflow events are small, then halo cannot expand much
Halo Response depends on Star Formation Efficiency

Di Cintio et al. 2014a, MaGICC simulations (Stinson et al. 2013)

![Graph showing the relationship between inner DM slope (α) and log M_{star}/M_{halo}.]
Halo Response depends on Star Formation Efficiency

Figure 13: The impact of baryonic feedback on the inner profiles of dark matter halos. Plotted is the inner dark matter density slope at $r = 0.015 R_{\text{vir}}$ as a function of $M_*/M_{\text{vir}}$ for simulated galaxies at $z = 0$. Large values of $\alpha$ imply cusps, while low values of $\alpha$ imply cusps. The shaded gray band shows the expected range of dark matter profile slopes for NFW profiles as derived from dark-matter-only simulations (including concentration scatter). The filled magenta stars and shaded purple band (to guide the eye) show the predicted inner density slopes from the NIHAO cosmological hydrodynamic simulations by Tollet et al. (2016). The cyan stars are a similar prediction from an entirely different suite of simulations from the FIRE-2 simulations (Fitts et al. 2016; Hopkins et al. 2017; Chan et al., in preparation). Note that dark matter core formation peaks in efficiency at $M_*/M_{\text{vir}} \approx 0.005$, in the regime of the brightest dwarfs. Both simulations find that for $M_*/M_{\text{vir}} > 10^{-4}$, the impact of baryonic feedback is negligible. This critical ratio below which core formation via stellar feedback is difficult corresponds to the regime of classical dwarfs and ultra-faint dwarfs.

Halo Response depends on Star Formation Efficiency


Bullock & Boylan-Kolchin 2017

\begin{align*}
\alpha [1.5\% R_{\text{vir}}] &= M_*/M_{\text{halo}} \\
\log_{10}(M_*/M_{\text{halo}}) &\approx f_b M_{\text{halo}}
\end{align*}
Star Formation Threshold is a common sub-grid parameter in galaxy formation simulations.

Hydrogen Density / cm$^3$
Re-simulate 20 NIHAO haloes with three SF thresholds
$n=10, 1, 0.1 \ \text{n}_H \ \text{cm}^{-3}$
Stellar Mass vs Halo Mass

- Abundance Matching
  - Moster et al. 2018

- Re-calibrated efficiency for n=0.1

NIHAO XIX - Dutton et al. 2018 in prep
Enclosed Dark Matter Density Profiles

NIHAO XIX - Dutton et al. 2018 in prep

measure slope between 1 and 2% of R200

measure mass ratio at 1% of R200

Agrees with APOSTLE EAGLE
Halo Response depends on $(M_{\text{star}}/M_{\text{halo}}, n)$

$\text{DM slope (}0.01-0.02 R_{200}\text{)}$

$\Delta \log M_{\text{dark}}(0.01 R_{200})$

$n=10$  DMO  $n=1$  $n=0.1$

NIHAO XIX - Dutton et al. 2018 in prep
TBTF problem for field Dwarf Galaxies

$10^6 < M_{\text{star}} < 10^8$

$D > 500 \text{ kpc}$ from MW

NIHAO XIX - Dutton et al. 2018 in prep
TBTF problem for field Dwarf Galaxies

$10^6 < M_{\text{star}} < 10^8$

$D > 500$ kpc from MW

NIHAO XIX - Dutton et al. 2018 in prep
How do we test which SF threshold is most realistic?
Re-simulate 20 NIHAO haloes with three SF thresholds

\[ n=10, 1, 0.1 \] \( n_H \, \text{cm}^{-3} \)
Higher SF threshold gives more bursty SFH

- Left panel: SFR$_{200}$ vs. Time/[Gyr] for 200 Myr
- Right panel: SFR$_{5}$ vs. Time/[Gyr] for 5 Myr
Summary

- **Low threshold** star formation ($n \leq 1$) EAGLE / APOSTLE / ILLUSTRIS produces **cuspy haloes** ($\Rightarrow$CDM fails!)

- **High threshold** star formation ($n \geq 10$) NIHAO/FIRE produces **expanded haloes** when $0.001 < M_{\text{star}}/M_{\text{halo}} < 0.01$ (CDM ok)

- Field galaxies in LG with $M_{\text{star}} \sim 10^7$ favor high threshold (Need more observations to improve statistics)

- High threshold yields **2x larger scatter** in sSFR measured over 5 Myr timescale. Testable with Halpha?