Towards predictive structure formation simulations with baryons

Prof. Justin Read | University of Surrey
Motivation

[Why worry about baryons?]
Background | The standard cosmological model LCDM

- Atoms: 5%
- Dark matter: 27%
- Dark energy: 68%
The standard cosmological model LCDM
Background | Near-field Cosmology

Simulations

[Assume something about dark matter, cosmology, and galaxy formation]
Background | Near-field Cosmology

Simulations

[Assume something about dark matter, cosmology, and galaxy formation]

Observations

[e.g. dwarf galaxy counts; dwarf internal dark matter profile]
Background | Near-field Cosmology

Potter 2006; Springel 2008; Stadel 2009
Background | Near-field Cosmology

Halo mass function

\[ M^{-2} \]

\[ \log_{10}(\text{M/M}_{\odot}) \]

\[ \log_{10}(\text{Mpc}^{-3} \text{M}_{\odot}^{-1}) \]

\( Z=0.18 \)

Potter 2006; Springel 2008; Stadel 2009
'Universal' density profile

Navarro, Frenk & White 1996

\[ r^{-1} \]

'cusps'

Potter 2006; Springel 2008; Stadel 2009
Background | Near-field Cosmology

‘Universal’ density profile

$\rho(r) = \rho_c \left( \frac{r}{r_c} \right)^{-1}$

‘cusp’

$\rho(r) = \rho_c \left( \frac{r}{r_c} \right)^{-3}$

Navarro, Frenk & White 1996

$Z = 0.18$

Potter 2006; Springel 2008; Stadel 2009
<table>
<thead>
<tr>
<th>COLD</th>
<th>WARM</th>
<th>HOT</th>
</tr>
</thead>
</table>

Background | Near-field Cosmology

Bode et al. 2001
Background | The ‘Cusp-Core’ problem

![Graph showing the 'Cusp-Core' problem with data points and model fits.]

- **DDO154**
  - Isothermal: $r_c = 2.5 \text{ kpc}$
  - Hernquist: $m_s = 1.0 \times 10^{10} M_\odot$, $r_s = 4.4 \text{ kpc}$

Moore 1994; Flores & Primack 1994
Background | The ‘Cusp-Core’ problem

\[ \rho \propto r^{-1} \]

- DDO154
- Isothermal: \( r_c = 2.5 \text{ kpc} \), \( m_s = 1.0 \times 10^{10} M_\odot \), \( r_s = 4.4 \text{ kpc} \)
- Hernquist: \( \rho \propto r^{-1} \)
The ‘Cusp-Core’ problem

\[ \rho \propto r^{-1} \]

\[ \rho \propto \text{const.} \]

Moore 1994; Flores & Primack 1994

DDO154

Isothermal: \( r_c = 2.5 \text{ kpc} \)

Hernquist: \( m_s = 1.0 \times 10^{10} M_\odot \)

\( r_s = 4.4 \text{ kpc} \)
Background | The ‘Cusp-Core’ problem

DDO170
- Isothermal: $r_c = 4.6$ kpc
- Hernquist: $m_s = 2.8 \times 10^{10} M_\odot$, $r_s = 6.1$ kpc
Background | The ‘Cusp-Core’ problem

$D(0, t)$

$kpc$

$5 \times 10^{10} M_{\odot}$

$kpc$

$r_g$ (kpc)

$DDO105$

Isothermal: $r_c = 7.5$ kpc

Hernquist: $m_s = 6.0 \times 10^{10} M_{\odot}$ $r_s = 8.2$ kpc

Moore 1994; Flores & Primack 1994
Background | The ‘Cusp-Core’ problem

\[ \nu_c (\text{km s}^{-1}) \]

NGC3109

- Isothermal: \( r_c = 5.5 \text{ kpc} \)
- Hernquist: \( m_s = 2.5 \times 10^{10} M_\odot \)
  \( r_s = 6.1 \text{ kpc} \)

Moore 1994; Flores & Primack 1994
Background | Missing satellites

Moore et al. 1999; Klypin et al. 1999
Background | Missing satellites

Moore et al. 1999; Klypin et al. 1999
Background | Small scale “crisis” for LCDM?
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NO!
[THERE IS NO “SMALL SCALE CRISIS” IN LCDM. NOT UNTIL THE CALCULATION CAN BE DONE PROPERLY. WHICH IT CAN’T ... YET ... ]
Motivation | The cusp/core problem

Read & Gilmore 2005; Navarro et al. 1996; Pontzen & Governato 2013
Motivation | The cusp/core problem

Read & Gilmore 2005; Navarro et al. 1996; Pontzen & Governato 2013
Motivation | The cusp/core problem

\[ \rho(r) \]

Inflow

Outflow

Read & Gilmore 2005; Navarro et al. 1996; Pontzen & Governato 2013
Motivation | The cusp/core problem

\[ \rho(r) \]

Inflow

Outflow

Repeat

Read & Gilmore 2005; Navarro et al. 1996; Pontzen & Governato 2013
Motivation | The cusp/core problem

\[ \rho(r) \]

Read & Gilmore 2005; Navarro et al. 1996; Pontzen & Governato 2013
Motivation | The cusp/core problem

Read & Gilmore 2005; Navarro et al. 1996; Pontzen & Governato 2013
Resolving Feedback

[In which we discuss ‘Ab Initio’ modelling of dwarf galaxies]
Warm H2 in the M82 Galactic wind | Veilleux et al. 2009
Predictive simulations of dwarfs | Resolving feedback

Warm H2 in the M82 Galactic wind | Veilleux et al. 2009

30 Doradus

Image composite credit: Leisa Townsley

~250×250 pc
Predictive simulations of dwarfs | Resolving feedback

\( E_c = 10^{51} \text{ ergs} \)

\[ L = 100 \text{ pc} \]

\[ n = 10 \text{ atoms/cc} \]

\[ \Rightarrow T_c = 1.7 \times 10^4 \text{ K} \]

\[ T_c = \frac{2}{3k_b} \frac{E_c}{nL^3} \]

Agertz et al. 2013; Dalla Vecchia & Schaye 2008
Predictive simulations of dwarfs | Resolving feedback

\[ E_c = 10^{51} \text{ ergs} \]

\[
\begin{align*}
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n &= 10 \text{ atoms/cc}
\end{align*}
\]

\[
\begin{align*}
L &= 10 \text{ pc} \\
\Rightarrow T_c &= 1.7 \times 10^6 \text{ K} \\
n &= 100 \text{ atoms/cc}
\end{align*}
\]

\[ T_c = \frac{2}{3k_b} \frac{E_c}{nL^3} \]

Agertz et al. 2013; Dalla Vecchia & Schaye 2008
Predictive simulations of dwarfs | Resolving feedback

\[
\rho_g = 0.1 \text{ cm}^{-3} \quad \Delta x = 4 \text{ pc}
\]
Predictive simulations of dwarfs | Resolving feedback

5 kpc, Edge-on, t=0.655 Gyr

Face-on, 5 kpc, t=0.655 Gyr

\[ \Delta x = 4 \text{ pc} \mid M_\star \sim 300 \text{ M}_\odot \mid M_{dm} = 250 \text{ M}_\odot \mid n_{th} = 300 \text{ atoms cm}^{-3} \]

\[ M_{200} = 10^9 \text{ M}_\odot \]

Read et al. 2015, submitted
Predictive simulations of dwarfs | Resolving feedback

Read et al. 2015, submitted; and see Navarro et al. 1996; Read & Gilmore 2005; Pontzen & Governato 2012
Cusp-core transforms | #1 :: galaxy masses
Cusp-core transforms | #1 :: galaxy masses

Read et al. 2015, submitted
Cusp-core transforms | #2 :: missing satellites

Cusped

Cored

$t = 3.95 \mid r = 90.53$

$t = 4.50 \mid r = 7.67$

Read et al. 2015 submitted | and see Read et al. 2006; Peñarrubia et al. 2010; Zolotov, Brooks et al. 2012/13
Conclusions

• We are beginning to run predictive simulations of dwarf galaxies, including baryons. These always form dynamically important dark matter cores if star formation proceeds for long enough.

• Such cores:
  • Cause rotation curves to rise much more slowly [cusp/core problem]
  • Lower stellar dispersions ➞ underestimate masses [‘too big to fail’]
  • Make galaxies susceptible to tides ➞ destroy satellites [missing satellites]

• If LCDM is right, dark matter cusps will be found:
  • In galaxies with truncated star formation; and/or
  • At radii beyond the half light radius
Predictive simulations of dwarfs | Resolving feedback

Read et al. 2015, submitted
Predictive simulations of dwarfs | Resolving feedback

\[ \Sigma_* [M_\odot \text{kpc}^{-2}] \]

\[ 10^{-2} \quad 10^{-1} \quad 10^0 \]

\[ R [\text{kpc}] \]

Read et al. 2015, submitted
Predictive simulations of dwarfs | Resolving feedback

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![Graph showing gas velocity vs. distance](image)

Read et al. 2015, submitted
Predictive simulations of dwarfs | Resolving feedback

Read et al. 2015, submitted