Dark matter simulations

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Dark matter annihilation in galaxy clusters

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The Virgo cluster in Fermi

Fermi-LAT image
100MeV – 100 GeV
2-year data
(Also Coma and Fornax)

Han, Frenk, Eke, Gao, White arXiv:1201.1003
Modelling $\gamma$-ray emission in clusters

Virgo best-fit model

Diffuse bckgs: Fermi templates

Point sources: 2FGL catalogue

Han, Frenk, Eke, Gao, White '12
$b\bar{b}$ channel

$TS = -2\ln(L_0/L)$

$L$ = likelihood full model

$L_0$ = likelihood for null hypothesis (i.e. no DM)

$TS$ follows a $\chi^2$ distr

Significance is $\sqrt{TS} \sigma$

4.9$\sigma$ detection of Virgo (for no CR)!

$M_\chi \sim 30$ GeV
Analysis used published 2-yr point source catalogue 2FGL

Alerted by Boyarski & Ruchayskiy searched point sources in 45-month data

Found several new points sources in Virgo region!

Some are blazars

Han, Frenk, Eke, Gao, White
Boyarski, Ruchayskiy, Malyshev ‘12
The Virgo cluster in Fermi

Significance of DM detection reduced from $4.9\sigma$ to $2.9\sigma$

Han, Frenk, Eke, Gao, White
Boyarski, Ruchayskiy, Malyshev '12
Upper limits on x-section

Bands = uncertainty in CR

Canonical x-section:

\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

excluded for \( M < 100 \text{ GeV} \)

(for \( M_{\text{cut}} = 10^{-6} M_o \))

Han, Frenk, Eke, Gao, White
Boyarski, Ruchayskiy, Malyshev ‘12
Upper limits on x-section

Bands = uncertainty in CR

Canonical x-section:
\[\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}\]

excluded for \(M<10\) GeV
(for \(M_{\text{cut}} = 10^{-6}M_\odot\))

Han et al '12
Bands = uncertainty in CR

Canonical x-section:
\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \]

excluded for M<50 GeV
(for \( M_{\text{cut}} = 10^{-6} M_\odot \))

Han et al ‘12
Conclusions: analysis of Fermi data

Using 2-year data and point source catalogue
- $4.9\sigma$ detection of DM annihilation in Virgo
- marginal detections in Coma and Fornax

But, 45 month data find new point sources, some are blazars

⇒ Significance of DM detection in Virgo drops to $2.9\sigma$

Upper limits

<table>
<thead>
<tr>
<th>$M_\chi$</th>
<th>Channel</th>
<th>$\mu^+\mu^-$ and $\tau^+\tau^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;100\text{GeV}$</td>
<td>$\bar{b}b$</td>
<td></td>
</tr>
<tr>
<td>$&lt;10 \text{GeV}$ and $50 \text{GeV}$</td>
<td>$\mu^+\mu^-$</td>
<td></td>
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Thermal x-section excluded for $M_\chi <100 \text{GeV}$
Dark matter simulations

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<table>
<thead>
<tr>
<th>Type</th>
<th>Example</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>hot</td>
<td>neutrino</td>
<td>a few eV</td>
</tr>
<tr>
<td>warm</td>
<td>sterile ν; majoron; KeVin</td>
<td>keV-MeV</td>
</tr>
<tr>
<td>cold</td>
<td>axion neutralino</td>
<td>$10^{-5}$ eV to $&gt;100$ GeV</td>
</tr>
</tbody>
</table>
Free streaming $\rightarrow$

\[ \lambda_{\text{cut}} \propto m_x^{-1} \]

for thermal relic

\[ m_{\text{CDM}} \sim 100\text{GeV} \]

susy; \( M_{\text{cut}} \sim 10^{-6} M_\odot \)

\[ m_{\text{WDM}} \sim \text{few keV} \]

sterile \( \nu \); \( M_{\text{cut}} \sim 10^9 M_\odot \)

\[ m_{\text{HDM}} \sim \text{few eV} \]

light \( \nu \); \( M_{\text{cut}} \sim 10^{15} M_\odot \)
Supercomputer simulations are the best technique for calculating how small primordial perturbations grow into galaxies today.
Non-baryonic dark matter cosmologies

Frenk, White & Davis ‘83
Neutrino DM → unrealistic clust’ing

Neutrinos cannot make appreciable contribution to $\Omega$ → $m_\nu << 10$ ev

CfA redshift survey

Davis, Efstathiou, Frenk & White ‘85

Neutrinos $\Omega=1$

Frenk, White & Davis ‘83
Non-baryonic dark matter cosmologies

In CDM structure forms hierarchically

Early CDM N-body simulations gave promising results

Neutrino DM \rightarrow unrealistic clust’ing

Neutrinos cannot make appreciable contribution to $\Omega$ \rightarrow $m_\nu << 10$ ev

Davis, Efstathiou, Frenk & White '85

CfA redshift survey

$\Lambda$CDM $\Omega = 0.2$

Frenk, White & Davis '83

$\Omega = 1$

Neutrinos
Free streaming →

\[ \lambda_{\text{cut}} \propto m_x^{-1} \]

for thermal relic

- \( m_{\text{CDM}} \sim 100 \text{GeV} \)
- \( m_{\text{WDM}} \sim \text{few keV} \)
- \( m_{\text{HDM}} \sim \text{few eV} \)

- \( m_{\text{CDM}} \sim 10^9 \text{M}_\odot \)
- \( m_{\text{WDM}} \sim 10^{-6} \text{M}_\odot \)
- \( m_{\text{HDM}} \sim 10^{15} \text{M}_\odot \)
Cosmology on small – strongly non-linear – scales

→ key to the identity of the dark matter
cold dark matter  
warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12
$z = 48.73$
cold dark matter

warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12
N-body simulations: CDM vs WDM

Simulations make 2 important predictions on galactic scales:

**Cold dark matter**
- The main halo and its subhalos have “cuspy” density profiles
- Large number of self-bound substructures (10% of mass) survive

**Warm dark matter**
- Main halo profile identical to CDM; subhalos still “cuspy” but less concentrated than in CDM
- Far fewer self-bound substructures (3% of mass) survive
The Density Profile of Cold Dark Matter Halos

Halo density profiles are independent of halo mass & cosmological parameters.

There is no obvious density plateau or `core' near the centre.

(Navarro, Frenk & White '97)

\[
\rho(r) = \frac{\delta_c}{\rho_{\text{crit}}(r/r_s)(1+r/r_s)^2}
\]

Halos that form earlier have higher densities (bigger $\delta$)
CDM subhalos also have cuspy profiles

Aquarius

Springel et al '08
A warm dark matter universe

CDM

2.3 keV
2.0 keV
1.6 keV
1.4 keV

Lovell et al '12

WDM subhalos also have cuspy profiles
Tests of the nature of the DM

cold dark matter
cold dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12

Spot the difference!
The satellites of the Milky Way

~25 satellites known in the MW
Spot the difference!

cold dark matter

warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12
CDM simulations produce $>10^5$ subhalos

Most of these subhalos never manage to make a visible galaxy
• Median model → correct abund. of sats brighter than $M_V=-9$ and $V_{cir}>12$ km/s
• Model predicts many, as yet undiscovered, faint satellites
• LMC/SMC should be rare (~2% of cases)

Benson, Frenk, Lacey, Baugh & Cole ’02
Counting satellites cannot distinguish CDM from WDM!

Need to look in more detail at the structure of small halos

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘12
A warm dark matter universe

CDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV

Lovell et al '12
Dwarf galaxies around the Milky Way

- Fornax
- Leo I
- Sagittarius
- Carina
- Sextans

Kinematical data ➔ mass within half-light radius (Wolf, Walker)
Is CDM compatible w. luminosity & structure of observed satellites?

\[ V_c = \sqrt{\frac{GM}{r}} \quad V_{\text{max}} = \max V_c \]

Mass within half-light radius for 9 dwarf satellites of the Milky Way

\[ V_{\text{circ}} \text{ within } r_{1/2} \text{ for MW satellites} \]
Is CDM compatible w. luminosity & structure of observed satellites?

\[ V_c = \sqrt{\frac{GM}{r}} \]
\[ V_{\text{max}} = \max V_c \]

Rotation curves of 12 subhalos with most massive progenitors

Red 3 halos with most massive progenitors (LMC, SMC, Sagittarius?)

Lovell, Eke, Frenk, Gao et al '11; see also Boylan-Kolchin et al '11a,b

Too massive & concentrated to host observed sats

\[ V_{\text{circ}} \text{ within } r_{1/2} \text{ for MW satellites} \]

Lovell, Eke, Frenk, Gao et al '11; see also Boylan-Kolchin et al '11a,b
Rotation curves of Aquarius subhalos

Boylan-Kolchin et al. '11

Too big to fail?
The Aquarius halos have \( \sim 10 \) subhalos with too large a \( V_{\text{max}} \) (i.e. much too concentrated) to be compatible with observed kinematics of MW dwarfs.
cold dark matter

warm dark matter

Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy ‘11
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns, Boyarski & Ruchayskiy '11
“Formation redshift” $\rightarrow$ $z$ at which $M_{\text{halo}}$ first exceeded $M_{\text{infall}}(<1\text{kpc})$

WDM halos form later & have lower central masses than their CDM counterparts!

$\rightarrow$

WDM subhalos are still cuspy but are less concentrated than CDM subhalos

Lovell, Eke, Frenk, Gao, Jenkins et al ‘11
Is this the end of CDM?

1. Baryon effects
2. The mass of the MW
The cores of dwarf galaxy haloes

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ABSTRACT

We use N-body simulations to examine the effects of mass outflows on the density profiles of cold dark matter (CDM) haloes surrounding dwarf galaxies. In particular, we investigate the consequences of supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy disc after a vigorous episode of star formation. We show that this sudden loss of mass leads to the formation of a core in the dark matter density profile, although the original halo is modelled by a coreless (Hernquist) profile. The core radius thus created is a sensitive function of the mass and radius of the baryonic disc being blown up. The loss of a disc with mass and size consistent with primordial nucleosynthesis constraints and angular momentum considerations imprints a core radius that is only a small fraction of the original scalelength of the halo. These small perturbations are, however, enough to reconcile the rotation curves of dwarf irregulars with the density profiles of haloes formed in the standard CDM scenario.
Let baryons cool and condense to the galactic centre.

Rapid ejection of large fraction of gas during starburst can lead to a core in the halo dark matter density profile.

Navarro, Eke, Frenk '96

Pontzen & Governato '12

Brooke et al. '12
The satellites of the Milky Way

SPH simulations of galaxy formation in one of the Aquarius halos

Parry, Eke, Frenk & Okamoto '11
Baryon effects in the MW satellites

Parry, Eke & Frenk '11

Institute for Computational Cosmology
Is this the end of CDM?

1. Baryon effects → could reduce central concentration of CDM subhalos
2. The mass of the MW
Number of massive subhalos increases rapidly with halo mass.

Aquarius halos have $M \sim 2 \times 10^{12} M_\odot$.

But: is this the mass of the MW halo?
Probability of massive subhalos

Probability of having no more than 3 subhalos with $V_{\text{max}} > 30$ km/s

Depends strongly on $M_{200}$ (and $V_{\text{cut}}$)

If mass of MW $> 2x10^{12}M_\odot$, CDM is ruled out!

If mass of MW $\sim 1x10^{12}M_\odot$, CDM is OK

Wang, Frenk, Navarro, Gao '12
ΛCDM: problems/possible solutions

• ΛCDM great success on scales > 1Mpc: CMB, LSS, gal evolution

A problem on subgalactic scales?

NOT a problem:

The satellite LF → can be explained by galaxy formation

However:

• CDM models place brightest sats in most massive subhalos and these appear to be too concentrated to be compatible w. kinematics

Possible solutions:

• Warm dark matter

• Baryon effects that make large CDM subhalos less concentrated

• $M_{MW-halo} \leq 10^{12}M_\odot$ rather than $2 \times 10^{12}M_\odot$
Cold dark matter?

If mass of MW halo $>2 \times 10^{12} M_{\odot}$

Annihilation radiation

Direct detection

UK DM search (Boulby mine)

Unless baryonic effects are important

Evidence for SUSY
Warm dark matter?
Sterile neutrino detection possible

Decay line in X-rays

Tritium $\beta$ - decay

$^3\text{H}$

$^3\text{He}$

Constellation X

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