Theory: dark matter models from the astro theory point of view

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PIRE Workshop
The Cosmological Dark Matter Problem

First indications: velocity of galaxies in a cluster

\[ GM = \langle v^2 \rangle \frac{r_{1/2}}{2} \alpha^{-1} \]

\[ \Rightarrow M \gg M_{\text{stars}} + M_{\text{gas}} \]

Zwicky (1933):
the “dunkel-materiel”/ the “dark matter”
Dark Matter Today: from large scale cosmology

Cosmic Microwave Background:
Planck, SPT, ACT, PolarBEAR

Large Scale Structure:
SDSS (BOSS), WiggleZ, 6dF

\[ \Omega_{DM} = \frac{\rho_{DM}}{\rho_{crit}} = 0.259 \pm 0.002 \]

Planck 2015 + BAO + SNe + H_0
(Planck Collab. 2015)
What is dark matter?
Large Scale Structure: the cosmological density perturbation spectrum

- Power spectrum of cosmological density fluctuations
  \[ P(k) = \langle |\delta_k|^2 \rangle \]

- Primordial Harrison-Zeldovich: from scale invariance
  \[ P(k) \propto k \]
  - Natural solution to perturbation spectrum: self-similar evolution

- Predicted by inflation
  \[ P(k) \propto k^n \quad n \lesssim 1 \]
Measuring Large Scale Structure $P(k)$

$P(k) \left[ \left( h^{-1} \text{Mpc} \right)^3 \right]$

$\Sigma m_\nu = 0$
$\Sigma m_\nu = 0.2 \text{ eV}$
$\Sigma m_\nu = 0.7 \text{ eV}$
$\Sigma m_\nu = 2 \text{ eV}$

CMB
SDSS 205k
SDSS Ly-α
Ly-α Croft '02
The Cosmological Matter Power Spectrum

\[ P(k) \propto k \]

Perturbations enter horizon:

- Matter Domination: \[ \delta \Phi_{\text{mat}} \text{ const} \]
- Radiation Domination: \[ \delta \Phi_{\text{rad}} \text{ decays} \]

\[ \rho_{\text{matter}} \propto a^{-3} \]
\[ \rho_{\text{radiation}} \propto a^{-4} \]
The Primordial Spectrum: CMB gives a Precision Determination at Large Scales

\[ P(k) = A k^n \]

Planck Collaboration 2015:

\[ \ln (10^{10} A) = 3.094 \pm 0.034 \quad (1.1\%) \]
\[ n = 0.9645 \pm 0.0049 \quad (0.51\%) \]
Perturbation Evolution

How warm is too warm?

Abazajian astro-ph/0511630
CDM has a natural cutoff
kinetic coupling until $T \sim 1$ MeV
CDM has a natural cutoff
kinetic coupling until $T \sim 1 \text{ MeV}$
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kinetic coupling until $T \sim 1$ MeV
Lower Bounds on Mass:
Suppression of Small-Scale Structure

- SDSS 3D P(k) Main Galaxies (Tegmark et al 2003)
- SDSS Lyman-alpha forest (McDonald et al 2005)
- High-Resolution Lyman-alpha forest (Viel, Haehnelt & Springel 2004)
- CMB: WMAP, ACBAR, CBI, VSA, BooMERANG-2K2
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Too big to fail? The most massive apparently don’t light up...

Where are these denser satellites?

Not dependent on resolving about core/cusp

TBTF in the local group

Generic issue in the Local Group (M31, MW and in between)
Observed Dwarf Galaxy Concentrations are Much Too Low, While CDM Subhalos are “Too Big Too Fail”

Boylan-Kolchin et al. 2011, 2012
Cusp/Core: dwarf galaxies to clusters of galaxies
Cores in dwarf galaxies

deBlok and Bosma, 2002

LITTLE THINGS, Oh et al. 2015

The inner power-law slopes of the mass-density profiles in dwarf galaxies are measured assuming a 'minimum disk', giving a steeper slope. The solid and dotted lines represent theoretical slopes of a pseudo-isothermal halo model.

Table 7. In Fig. 15 we again plot the derived slopes against the radius of the innermost point. Open circles overestimate of the true value. The halo rotation curve was found by quadratically subtracting the gas-rotation curve and the rotation curve of the stars. This treatment is likely to be too naive, as in a non-minimum disk case one expects the disk to influence the dark matter distribution to some degree (though this galaxy obviously cannot be used to prove or disprove the CDM simulations but also as an indirect proof for the existence of CDM in the Universe.

CONCLUSION

The inner power-law slopes for the constant mass-to-light ratio are listed in Table 7. In Fig. 15 we again plot the derived slopes against the radius of the innermost point. Open circles overestimate of the true value. The halo rotation curve was found by quadratically subtracting the gas-rotation curve and the rotation curve of the stars. This treatment is likely to be too naive, as in a non-minimum disk case one expects the disk to influence the dark matter distribution to some degree (though this galaxy obviously cannot be used to prove or disprove the CDM simulations but also as an indirect proof for the existence of CDM in the Universe.

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Cores in more massive (LSB) galaxies

Note the linear rise in rotation velocity at small radii for all galaxies => constant density cores

Kuzio de Naray, McGaugh, de Blok, Bosma 2005, 2006
Weak lensing, strong lensing and BCG stellar kinematics used

Masses $\sim 10^{15} M_{\odot}$

Cores of clusters of galaxies

Newman et al 2012
Dark matter densities in the inner regions of galaxies

<table>
<thead>
<tr>
<th>Scales of interest (distance from center of galaxy)</th>
<th>Cores (region of roughly constant density)</th>
<th>Lower densities than predicted by CDM-only simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clusters of galaxies ($10^{14}-10^{15} \text{ M}_{\odot}$)</td>
<td>5-50 kpc</td>
<td>Not clear</td>
</tr>
<tr>
<td>Large spirals and ellipticals ($10^{12}-10^{13} \text{ M}_{\odot}$)</td>
<td>1-20 kpc</td>
<td>Not required</td>
</tr>
<tr>
<td>Dwarf galaxies; Low surface brightness galaxies ($10^{10}-10^{12} \text{ M}_{\odot}$)</td>
<td>0.5-5 kpc</td>
<td>Yes</td>
</tr>
<tr>
<td>Dwarf galaxies within the Milky Way (satellites) ($10^{9}-10^{10} \text{ M}_{\odot}$)</td>
<td>0.3-1 kpc</td>
<td>? (See Walker and Penarrubia and Strigari et al)</td>
</tr>
</tbody>
</table>
Testing WDM vs CDM with Velocity Function

Schneider+ 1611.09362

Warm Dark Matter

- WDM: \( m_{\text{TH}} = 2.0 \) keV
- WDM: \( m_{\text{TH}} = 3.0 \) keV
- WDM: \( m_{\text{TH}} = 4.0 \) keV
- CDM
Testing CDM & fractional WDM with Velocity Function Schneider+ 1611.09362
Testing SIDM with Velocity Function

Schneider+ 1611.09362

Self-Interacting Dark Matter
Rotation curves:
Diversity, uniformity and correlations
Correlations: Tully-Fisher relations

Bradford, Geha, van den Bosch (2016)

Also see Papastergis, Adams and Hulst (2016)
Warm dark matter as a solution of the small-scale puzzles
Warm dark matter structures

Based on a resonant sterile neutrino model
What is the relationship between particle mass and warm dark matter free streaming scale?
WDM Particle Mass: Sterile Neutrinos vs “Thermal” WDM

\[ m_{\tilde{g}} = 0.326 \text{ keV} \left( \frac{m_s}{1 \text{ keV}} \right)^{3/4} \left( \frac{\Omega_{\text{DM}}}{0.12} \right)^{1/4} \]

\[ m_{\tilde{g}} = 2 \text{ keV} \Rightarrow m_{s,\text{DW}} = 11.2 \text{ keV} \]

\( m_{\text{SF}} < m_{\text{DW}} \)
WDM Particle Mass: Sterile Neutrinos vs “Thermal” WDM

• “Thermal” WDM is frozen-out early, then abundance is set by disappearance of degrees of freedom. That is, there is a heating up of plasma after freezeout to reduce WDM abundance to match $\Omega_{dm}$.
• Cools the DM relative to plasma (photons & neutrinos)
• Dodelson-Widrow Sterile Neutrinos have neutrino velocity “thermal” distribution: they are warmer than gravitinos

$$m_{\tilde{\gamma}} = 0.326 \text{ keV} \left( \frac{m_s}{1 \text{ keV}} \right)^{3/4} \left( \frac{\Omega_{DM}}{0.12} \right)^{1/4}$$

$$m_{\tilde{\gamma}} = 2 \text{ keV} \Rightarrow m_{s,\text{DW}} = 11.2 \text{ keV}$$

• Shi-Fuller Sterile Neutrinos are colder versions of Dodelson-Widrow neutrinos ($m_{SF} < m_{DW}$)
Sterile Neutrino Dark Matter Production

\[ \Gamma(\nu_\alpha \rightarrow \nu_s) \sim \frac{\Gamma_\alpha(p)\Delta^2(p)\sin^2 2\theta}{\Delta^2(p)\sin^2 2\theta + D^2(p) + [\Delta(p)\cos 2\theta - V^L(p) - V^T(p)]^2} \]
Sterile Neutrino Dark Matter Production

\[ \Gamma_\alpha(p) \sim G_F^2 p T^4 \sim T^5 \]

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\[ \Delta^2 \sim p^{-2} \sim T^{-2} \]
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\[ D(p)^2 \sim T^{10} \]
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[V^T]^2 \sim T^{10}
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\[ H^2 = \frac{8\pi}{3} G \rho \sim T^4 \]
Sterile Neutrino Dark Matter Production

$$\Gamma_{\alpha}(p) \sim G_F^2 p T^4 \sim T^5$$

$$\Gamma(\nu_\alpha \to \nu_s) \sim \frac{\Delta^2(p) \sin^2 2\theta}{\Delta^2(p) \sin^2 2\theta + D^2(p) + [\Delta(p) \cos 2\theta - V^L(p) - V^T(p)]^2}$$

$$H^2 = \frac{8\pi}{3} G \rho \sim T^4$$

$$\frac{\Gamma}{H} \sim \begin{cases} T^{-9} & \text{High } T \\ T^{-3} & \text{Low } T \end{cases}$$
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Never in Equilibrium!!
Matter (thermal) mixing angle:

\[
\sin^2 2\theta_m = \frac{\Delta^2(p) \sin^2 2\theta}{\Delta^2(p) \sin^2 2\theta + \left[\Delta(p) \cos 2\theta - V^D - V^T(p)\right]^2}
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\]

**\( \Rightarrow \) \hspace{1cm} \epsilon_{\text{res}} \approx \frac{\delta m^2}{(8\sqrt{2}\zeta(3)/\pi^2)G_FT^4L}
\]

\[
\approx 3.65 \left( \frac{\delta m^2}{(7 \text{ keV})^2} \right) \left( \frac{10^{-3}}{L} \right) \left( \frac{170 \text{ MeV}}{T} \right)^4
\]
$7 \text{ keV Resonant Sterile Neutrino:}$

$\text{Free streaming cutoff is very different, even for the same particle mass}$

Equivalent thermal WDM particle masses

Abazajian PRL
arXiv:1403.0954
WDM Solution to TBTF?

Anderhalden et al. arXiv:1212.2967
WDM Solution to TBTF?

Anderhalden et al. arXiv:1212.2967
Anderhalden et al.
arXiv:1212.2967

WDM Solution to TBTF?

“massive failures”

no massive failures
"It seems that only the pure WDM model with a 2 keV [thermal] particle is able to match the all observations" of the Milky Way Satellites: "the total satellite abundance, their radial distribution and their mass profile" (or TBTF)
Self-interacting dark matter as a solution of the small-scale puzzles
SIDM = CDM (almost)

SIDM looks the same as CDM on large scales, so it passes all the cosmological tests. It modifies the inner part of halos [Spergel and Steinhardt 2000].

In its simplest incarnation, SIDM has one extra parameter: scattering cross section over mass.

Rocha et al 2012
Brief history of SIDM
Brief history of SIDM

Brief history of SIDM


Recent revival of SIDM motivated partly by model building: Ackerman, Buckley, Carroll, Kamionkowski (2008), Feng, Kaplinghat, Yu, Tu (2009), Feng, Kaplinghat, Yu 2010, Loeb and Weiner 2011
Cluster halo shape constraints

Figure 2. Surface density profiles for the same halo shown in Fig. 1, now projected along the intermediate axis. Deviations from axisymmetry are highest along this projection.

Figure 3. Host halo shapes in shells of radius scaled by the virial radius in three virial-mass bins as indicated. The black solid lines denote the 20th percentile (lowest), median (middle), and 80th percentile (highest) value of $c/a$ at fixed $r/r_{\text{vir}}$ for CDM. The blue dashed lines show the median and 20th/80th percentile ranges for $\mu/m = 1 \, \text{cm}^2/\text{g}$, and the green dotted lines show the same for $\mu/m = 0 \, \text{cm}^2/\text{g}$. There are 440, 65, and 50 halos in each mass bin (lowest mass bin to highest).

3 SIMULATED HALO SHAPES

3.1 Preliminary Illustration

Before presenting a statistical comparison of CDM and SIDM halo populations, we provide a pictorial illustration of how an individual halo changes shape as we vary the cross section. The columns of Figs. 1 and 2 show surface density maps for the same halo simulated in CDM, SIDM$_{0.1}$, and SIDM$_{1}$ from left to right. In Fig. 1, we project the halo along the major axis, which is the orientation that maximizes the strong-lensing cross section (van de Ven, Mandelbaum & Keeton 2009; Mandelbaum, van de Ven & Keeton 2009). In Fig. 2, we project the halo along the intermediate axis.

Constraints using shapes of LoCuSS clusters (Richards et al 2010) not better than about 1 cm$^2$/g.

Peter, Rocha, Bullock, Kaplinghat 2012
How does SIDM work?

\[ V_{\text{max}} = 159 \text{ km/s} \]
\[ r_s = 20 \text{ kpc} \]

Rocha et al 2012
How does SIDM work?

One interaction on average over halo age

Rocha et al 2012
How does SIDM work?

One interaction on average over halo age

Rocha et al 2012
Outside this core radius, solution is CDM-like.

$\sigma/m = 1 \text{ cm}^2/\text{g}$

Core size $\sim 0.5 \ r_s$, large enough to explain spiral and dwarf galaxy observations.

$\rho_{\text{core}} \propto 1/V_{\text{max}}$

Rocha et al (2012)

Similar results from Fry et al (2015)
TBTF problem can be solved with the production of large cores [Vogelsberger, Zavala and Loeb 2012, Vogelsberger, Zavala and Walker 2012]
SIDM fits to galaxies and clusters

\[ \rho(r) = \begin{cases} 
\rho_{\text{iso}}(r), & r < r_1 \\
\rho_{\text{NFW}}(r), & r > r_1 
\end{cases} \]

rate \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1) t_{\text{age}} \approx 1

Kaplinghat, Tulin and Yu, 2015
A consistent SIDM solution requires a mild velocity dependence!

\[ \mathcal{L} = g_X \bar{X} \gamma^\mu X \phi_\mu + m_X \bar{X} X + m_\phi^2 \phi^\mu \phi_\mu \]

\[ V = \pm \frac{\alpha_x}{r} \exp(-m_\phi r) \]

Kaplinghat, Tulin and Yu, 2015
Uniformity of DM (cored) profiles

- SIDM (analytic)

Graphs showing the relationship between core radius and core density for different stellar masses from rotation curve fits.
Summary
Summary

• There remain persistent problems in CDM theories of galaxy formation
Summary

- There remain persistent problems in CDM theories of galaxy formation
  - Satellite abundance
Summary

• There remain persistent problems in CDM theories of galaxy formation
  • Satellite abundance
  • Satellite halo density
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• There remain persistent problems in CDM theories of galaxy formation
  • Satellite abundance
  • Satellite halo density
  • Halo density profiles (cores)
• There are solutions proposed
  • WDM
  • SIDM
  • Fuzzy DM (though significantly ruled out by Menci+ 2017)