Cosmological searches for a non-cold dark matter component

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Mixed Dark Matter

1) Motivation

2) Probes:
   a) CMB
   b) Weak Lensing
   c) Dwarf Satellites

3) Constraints:
   a) Planck
   b) KIDS
   c) SDSS

4) Conclusions & Outlook
Motivation

Precision Cosmological observations of the large scale structure of the universe perfectly agree with a totally cold dark matter component.
Motivation

Small scale crisis:

- Too big to fail
- Missing satellites
- Core/cusp


Very well motivated theoretical candidates with a free-streaming nature:

- Sterile Neutrinos
  - Dodelson & Widrow arXiv:9303287
- Gravitinos
  - Pagels & Primark (1982)
- Majorons
  - Lattanzi & Valle arXiv:0705.2406
- WIMP DM and pseudo-Goldstones
  - Weinberg, Okada, Chacko, Yanagida, Ibarra, Rius ...

Previous studies: 0501562 Viel et al., 0812.0010 Boyarsky et al., 1701.03128 Diamanti et al.
Our approach

Analyze the Mixed Dark Matter scenario at all scales

Analysis: MCMC
CLASS
Monte Python
Camb
CosmoMC
Mixed Dark Matter

Defining properties

\[
\begin{align*}
  f_X &= \frac{\omega_X}{\omega_{DM}} \\
  T_X
\end{align*}
\]

CMB spectra fixes:

\[\omega_{DM} = \omega_X + \omega_{cdm}\]

Thermal Relics:

\[
\omega_X \simeq \left( \frac{T_X}{T_\nu} \right)^3 \left( \frac{m_X}{94 \, \text{eV}} \right) \quad \frac{T_X}{T_\nu} = \left( \frac{10.75}{g_*(T_D)} \right)^{1/3}
\]

Parameter Space in this study:

\[-1.5 \leq \log_{10}(T_X/T_\nu) \leq 0 \quad 0 \leq f_X \leq 1\]

Derived

\[
m_X \simeq 94 \times f_X \times \omega_{DM} \times \left( \frac{T_X}{T_\nu} \right)^3 \, \text{eV}
\]

\[0 < m_X < 5 \, \text{MeV}\]
Effects

\[ f_X = \omega_X/\omega_{DM} = 0.01 \]

- \( T_X/T_\nu = 1.0, \ m_X = 0.1 \text{ eV} \)
- \( T_X/T_\nu = 0.7, \ m_X = 0.3 \text{ eV} \)
- \( T_X/T_\nu = 0.5, \ m_X = 0.9 \text{ eV} \)

\( \Lambda \)CDM

\[ f_X = \omega_X/\omega_{DM} = 0.99 \]

- \( T_X/T_\nu = 1.0, \ m_X = 11.0 \text{ eV} \)
- \( T_X/T_\nu = 0.7, \ m_X = 33.0 \text{ eV} \)
- \( T_X/T_\nu = 0.5, \ m_X = 89.0 \text{ eV} \)
- \( T_X/T_\nu = 0.3, \ m_X = 414.0 \text{ eV} \)
- \( T_X/T_\nu = 0.1, \ m_X = 11167.0 \text{ eV} \)

\( \Lambda \)CDM

Small \( f_X \): constraints from \( \Delta N_{\text{eff}} \)

Large \( f_X \): constraints from suppressed Matter power spectrum
Non-Linear Theory

\[ f_X = 0.5 \]

- Halofit
- Halo Model
- Accurate Halo Model
- Kamada et al, PRD94 (2016)

\[
\frac{P_{\text{MDM}}(k) - P_{\text{CDM}}(k)}{P_{\text{CDM}}(k)}
\]

\[
k (\text{h/Mpc})
\]

\[
\begin{align*}
\Lambda \text{CDM} \\
T_X &= 0.79 T_\nu \\
m_X &= 11 \text{ eV} \\
T_X &= 0.63 T_\nu \\
m_X &= 22 \text{ eV} \\
T_X &= 0.50 T_\nu \\
m_X &= 44 \text{ eV} \\
T_X &= 0.40 T_\nu \\
m_X &= 89 \text{ eV} \\
T_X &= 0.32 T_\nu \\
m_X &= 178 \text{ eV} \\
T_X &= 0.25 T_\nu \\
m_X &= 355 \text{ eV} \\
T_X &= 0.20 T_\nu \\
m_X &= 710 \text{ eV} \\
T_X &= 0.16 T_\nu \\
m_X &= 1416 \text{ eV} \\
T_X &= 0.13 T_\nu \\
m_X &= 2826 \text{ eV} \\
T_X &= 0.10 T_\nu \\
m_X &= 5639 \text{ eV}
\end{align*}
\]
2-point shear correlation
sky coverage 450 deg²
0.1 < z < 0.9
discrepancy with Planck

Although see Efstathiou & Lemos 1707.00483
and KIDS+GAMMA 1706.05004
and DES results 1708.01530

Kuijken et al. 1507.00738
Hildebrandt et al. 1606.05338
Dwarf Galaxies

Observational Status

Classical: 11
SDSS: 15
\( f_{\text{sky}}^{\text{SDSS}} = 0.28 \)

DES and others: (candidates) \( 8+14=22 \)

\( N_{\text{sat}} = 65 \pm 11 \)

We modelled it by imposing a half Gaussian likelihood

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Drlica-Wagner et al. 1508.03622

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Theory

Schneider, 1412.2133 & 1601.07553

Based on the sharp-k method

Extended Press-Schechter

Matching between simulations and formulae

Further confirmation of the validity of the approach

Murgia et al. arXiv:1704.07838
Results

Satellites Gaussian

\[
0.15 < \frac{T_X}{T_\nu} < 0.17 \quad 0.95 \text{ keV} < m_X < 2.9 \text{ keV} \quad f_X > 0.34
\]

Satellites Half Gaussian

\[
\frac{T_X}{T_\nu} < 0.19 \quad m_X > 0.09 \text{ keV} \quad 0 \leq f_X \leq 1
\]

KIDS data not completely able resolving the NCDM temperature or mass
BUT prefers small masses/high temperatures
H0 tension slightly alleviated in the Mixed Dark Matter scenario
Complementary constraints with others from different data sets

CMB+Satellites
This work 1704.02991

Strong Lenses
Kamada et al. 1604.01489

Lyman$\alpha$ 17'
Baur et al. 1706.03118

$m_X$ (eV) vs $f_X$
$\sigma_8 / \Omega_m$  Tension alleviated within MDM, but not in the region favoured by Satellites data
Outlook

DES Cosmology Results

1708.01530

DES satellites

Drlica-Wagner et al. 1508.03622
Conclusions

Mixed Dark Matter tested in the linear and non-linear regimes against the most recent cosmological observations.

Dwarf galaxies counts provide very strong constraints.

The addition of a non-cold dark matter component could account for the Sigma8 discrepancy as measured by KIDS but in a region not favoured by dwarf satellite counts.
Questions welcome!!!
Back up: Satellites Counts

Schneider, 1412.2133 & 1601.07553

\[
\frac{dN_{\text{sat}}}{d \ln M_s} = \frac{1}{C_n} \frac{1}{6\pi^2} \left( \frac{M_h}{M_s} \right) \frac{P(1/R_s)}{R_s^3 \sqrt{2\pi(S_s - S_h)}}
\]

\[
S_i(M) = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k) W^2(k|M) dk
\]

\[
M_i = \frac{4\pi}{3} \Omega_m \rho_c (cR_i)^3
\]

Sharp-k

\[
W(k|M) = \begin{cases} 
1, & \text{if } k \leq k_s(M) \\
0, & \text{if } k > k_s(M)
\end{cases}
\]

Lovell et al. 1104.2929
Kamada et al. 1604.01489

\[
\frac{P_{\text{MDM}}(k)}{P_{\text{CDM}}(k)} = T^2(k; r_X, k'_d)
\]

\[
= (1 - r_X) + \frac{r_X}{(1 + k/k'_d)^{0.7441}}
\]

\[
r_X(f_X) = 1 - \exp \left( -a \frac{f_X^b}{1 - f_X^c} \right),
\]

\[
k'_d(k_d, f_X) = k_d \cdot f_X^{-5/6}.
\]

\[
k_d(m_X, z) = \left( \frac{m_X}{\text{keV}} \right)^{2.207} D(z)^{1.583} \times 388.8 \, h \, \text{Mpc}^{-1}.
\]

Simulation Matching \quad a = 1.551, \quad b = 0.5761, \quad c = 1.263.