The Neutrino-Dark Matter Connection

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Based on:
& others
Could neutrinos and DM really be connected?

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\]

But too light (and too hot) to be all of the dark matter...

(See talk by J. Hamann yesterday)
Of course, sterile neutrinos are dark matter!
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(See talk by S. Horiuchi yesterday)
Outline

• Quick recap of DM & structure formation & the physics that sets the scales of DM halos

• Heard about other solutions yesterday, but could interactions between DM and neutrinos fix problems at small scales?

• What would an actual model that does this look like? What are its implications?
Why Dark Matter?

DISTRIBUTION OF DARK MATTER IN NGC 3198

\[ v \propto \sqrt{\frac{M_{\text{enc}}(r)}{r}} \]

\[ \Omega_d \sim 0.2 \]
\[ \Omega_b \sim 0.04 \]

Goes w/o saying at this conference!
Structure Formation

We live in an expanding and cooling universe.

Perturbations on smaller scales enter the horizon earlier, when it was hotter.

⇒ hierarchical DM clustering:
small scale structures form earlier.

Roughly, gravity vs. pressure compete.

(See talk by S. Watson yesterday)
Acoustic Oscillations

Before DM is decoupled, it “feels” pressure due to relativistic fluid

\[
H_d^{-1} = a_d \eta_d, \quad \eta_d = \int_0^{t_d} \frac{dt}{a(t)}
\]

This damps structure on scales smaller than the horizon at decoupling

\[
M_{\text{ao}} = \rho \chi(T_d) \frac{4\pi}{3} (a_d \eta_d)^3 = 2 \times 10^8 M_\odot \left( \frac{g_{\text{eff}}(T_d)}{3.36} \right)^{-1/2} \left( \frac{T_d}{\text{keV}} \right)^{-3}
\]
Kinetic Decoupling

DM sitting in relativistic fluid (provides the pressure)

\[ p_{DM} \sim \sqrt{m_{DM}T} \]

Change in DM momentum after \( N \) collisions \( O(1) \)

\[ \Delta p_{\text{tot}} \sim \sqrt{NT} \sim p_{DM} \]
\[ \Rightarrow N \sim \frac{m_{DM}}{T} \]

Equilibrium maintained so long as

\[ \frac{n_r \sigma}{N} \sim \frac{T}{m_{DM}} n_r \sigma > H \]

Temperature at decoupling estimated:

\[ \sigma = \frac{T^2}{\Lambda^4}, \quad H \propto \frac{T^2}{M_{\text{Pl}}} \Rightarrow T_d \sim \left( \frac{\Lambda^4 m_{\chi}}{M_{\text{Pl}}} \right)^{1/4} \]
After decoupling, DM free streams washing out structure on scales smaller than

$$\ell_{eq} = \pi a_{eq} \int_{t_d}^{t_{eq}} dt \frac{v_{phys}}{a(t)}, \quad v_{phys} = v/a(t)$$

$$M_{fs} = \rho_{\chi}(T_0) \frac{4\pi}{3} \ell_0^3$$

$$= 3 \times 10^5 M_\odot \left( \frac{g_{\text{eff}}(T_d)}{3.36} \right)^{-1/2} \left( \frac{m_\chi}{10 \text{ MeV}} \right)^{-3/2} \left( \frac{T_d}{\text{keV}} \right)^{-3/2} \left\{ 1 + \ln \left[ \left( \frac{g_{\text{eff}}(T_d)}{3.36} \right) \left( \frac{T_d}{\text{keV}} \right) \right] / 6.0 \right\}^3.$$
Smallest DM Objects

Smallest possible DM halos have masses \( \sim \) larger of \( M_{ao} \) or \( M_{fs} \)

\[
\frac{M_{fs}}{M_{ao}} = 1.5 \times 10^{-3} \left( \frac{m_\chi}{10 \text{ MeV}} \right)^{-3/2} \left( \frac{T_d}{\text{keV}} \right)^{3/2} \left\{ 1 + \ln \left[ \left( \frac{g_{\text{eff}}(T_d)}{3.36} \right) \left( \frac{T_d}{\text{keV}} \right) \right]/6.0 \right\}^3.
\]

For \( T_d \lesssim 100 \text{ keV} \left( \frac{m_\chi}{10 \text{ MeV}} \right) \)

\( M_{ao} \) dominates

\[
\Rightarrow M_{\text{cut}} = M_{ao} = 2 \times 10^8 M_\odot \left( \frac{g_{\text{eff}}(T_d)}{3.36} \right)^{-1/2} \left( \frac{T_d}{\text{keV}} \right)^{-3}
\]

Hooper et al., 0704.2558
Vanilla WIMP Scales

For a DM-SM scattering cross section of

\[ \sigma \sim \frac{T^2}{\Lambda^4}, \quad \Lambda \sim 100 \text{ GeV} \]

the decoupling temperature is

\[ T_d = \left( \frac{\Lambda^4 m_\chi}{M_{Pl}} \right)^{1/4} = 10 \text{ MeV} \left( \frac{\Lambda}{100 \text{ GeV}} \right) \left( \frac{m_\chi}{100 \text{ GeV}} \right)^{1/4} \]

This results in a cut off mass of \( M_{\text{cut}} \ll M_\odot \)

i.e. tiny!

What does the data say?
Large Scales Look Good

But what about smaller scales?

astro-ph/0310725

astro-ph/0604561
Missing Satellites

Compared to expectation, fewer small halos orbiting Milky Way-sized galaxy

Suggestive of a cut off $\sim 10^{7-9}$ $M_\odot$, much larger than WIMP case
“Too Big to Fail” & Core vs. Cusp

N-body simulations indicate that most massive MW satellites more massive than those we know, large enough to form stars

DM density profiles appear less cuspy than NFW

\[ \rho_{\text{NFW}}(r) = \frac{\rho_H}{r/R_H (1 + r/R_H)^2} \]

(See talks by H.-B. Yu & S. Horiuchi)
Potential Resolutions

Could be fixed by baryonic effects
(Brooks, Governato, Pontzen, +)

DM could be “warm”
(See talk by S. Horiuchi)

DM could self-interact
(See talk by H.-B. Yu)

DM could stay in kinetic equilibrium with the plasma longer...
Coupling to Neutrinos?

Recall \( M_{ao} = 2 \times 10^8 M_\odot \left( \frac{T_d}{\text{keV}} \right)^{-3} \)

Neutrinos are another form of radiation

Want \( T_d \sim \text{keV} \)

So if \( \sigma \sim \frac{T^2}{\Lambda^4}, \ T_d \sim \left( \frac{\Lambda^4 m_\chi}{M_{Pl}} \right)^{1/4} \)

\[ \Rightarrow \Lambda^4 m_\chi = (10 - 100 \text{ MeV})^5 \]

\[ \sigma_{\text{ann}} \nu \gg 3 \times 10^{-26} \ \frac{\text{cm}^3}{\text{s}} \Rightarrow \text{Asymmetric DM} \]

What would a model of this look like?
Model Building

Safest to couple through the “neutrino portal”

Portals: low-dimensional gauge singlet operators connecting SM & “dark sector”, e.g.

neutrino:

\[ \ell H \xrightarrow{} N \]

kinetic mixing:

\[ F_{\mu\nu} \xrightarrow{} V_{\mu\nu} \]

Higgs:

\[ H^\dagger H \xrightarrow{} S^2 \]
Model Building

Safest to couple through the “neutrino portal”

Portals: low-dimensional gauge singlet operators connecting SM & “dark sector”, e.g.

\[ \nu \text{ masses} \]

\[ \ell H \leftrightarrow N \]

\[ F_{\mu\nu} \leftrightarrow V_{\mu\nu} \]

\[ H^\dagger H \leftrightarrow S^2 \]
Model Building

Safest to couple through the “neutrino portal”

\[ \ell H \chi \] is bad (DM decays) so use \[ \frac{1}{\Lambda} \ell H \phi \chi \]

⇒ add “sterile” neutrino

\[ \mathcal{L} \supset -\frac{m_{ij}}{v^2} (H \ell_i) (H \ell_j) - MN_1 N_2 - \chi_i N_1 H \ell_i - y_1 \phi^* N_1 \chi - y_2 \phi N_2 \chi + \text{h.c.} \]

lepton number conserved (for small ν masses & large mixing)

\[ 4 \times 4 \text{ mixing matrix: } \nu_i = U_{ij} \hat\nu_j \]

\[ g \equiv y_2 \sqrt{|U_{e4}|^2 + |U_{\mu 4}|^2 + |U_{\tau 4}|^2} \]

\[ \sigma_{\nu \chi} = \sum_{i=1}^{3} \sigma_{\nu_i \chi} = \frac{g^4}{8\pi} \frac{E_{\nu}^2}{(m_{\phi}^2 - m_{\chi}^2)^2} = 8 \times 10^{-38} \text{cm}^2 \left( \frac{g}{0.3} \right)^4 \left( \frac{E_{\nu}}{1 \text{ keV}} \right)^2 \left( \frac{35 \text{ MeV}}{\sqrt{m_{\phi}^2 - m_{\chi}^2}} \right)^4 \]
Model Building

3 light & 1 heavy neutrinos

Heavy neutrino is Dirac:

\[ \hat{N} = \begin{pmatrix} \hat{\nu}_4 = c_\theta N_2 + s_\theta \nu_\tau \\ N_1^* \end{pmatrix} \]

decays invisibly (visible decays are \( G_F \) suppressed):

\[ \Gamma_{\hat{N} \rightarrow \nu \chi \bar{\chi}} = \frac{(y_1^2 + y_2^2 c_\theta^2) m_4}{32\pi} \approx 3 \text{ MeV} \left( \frac{m_4}{300 \text{ MeV}} \right) \]

\[ \Gamma_{\hat{N} \rightarrow \nu e^+ e^-} = \frac{s_\theta^2 G_F^2 m_4^5}{192\pi^3} \approx 5 \times 10^{-15} \text{ MeV} \left( \frac{s_\theta}{0.3} \right)^2 \left( \frac{m_4}{300 \text{ MeV}} \right)^5 \]
What parameter values do we need?

Require:

\[ \Lambda \sim \frac{\sqrt{m_{\phi}^2 - m_{\chi}^2}}{\sqrt{|U_{e4}|^2 + |U_{\mu4}|^2 + |U_{\tau4}|^2}} \sim \mathcal{O}(10 \text{ s of MeV}) \]

\[ \Rightarrow \sqrt{|U_{e4}|^2 + |U_{\mu4}|^2 + |U_{\tau4}|^2} \gtrsim 0.1 \]
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\[ \Rightarrow \sqrt{|U_{e4}|^2 + |U_{\mu4}|^2 + |U_{\tau4}|^2} \gtrsim 0.1 \]

\[ \Rightarrow \text{couple to the } \nu_\tau \text{ neutrino} \]
Neutrino Oscillations

can decompose mixing matrix as

\[
U = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & c_\theta & s_\theta \\
0 & 0 & -s_\theta & c_\theta \\
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & c_{23} & s_{23} & 0 \\
0 & -s_{23} & c_{23} & 0 \\
0 & 0 & 0 & 1 \\
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} & 0 \\
0 & 1 & 0 & 0 \\
-s_{13} & 0 & c_{13} & 0 \\
0 & 0 & 0 & 1 \\
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 & 0 \\
-s_{12} & c_{12} & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{pmatrix}
\]

\[
= \begin{pmatrix}
c_{12}c_{13} & c_{13}s_{12} & s_{13} & 0 \\
-c_{23}s_{12} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} & 0 \\
-c_\theta \left(c_{12}c_{23}s_{13} - s_{12}s_{23}\right) & -c_\theta \left(c_{23}s_{12}s_{13} + c_{12}s_{23}\right) & c_\theta c_{13}s_{23} & s_\theta \\
s_\theta \left(c_{12}c_{23}s_{13} - s_{12}s_{23}\right) & s_\theta \left(c_{23}s_{12}s_{13} + c_{12}s_{23}\right) & -s_\theta c_{13}s_{23} & c_\theta \\
\end{pmatrix}
\]

\(U_{e3}: \) Daya Bay, unaffected by \(\theta_T\) given by \(\theta_{13}\)
\(U_{\mu3}: \) K2K and MINOS, unaffected by \(\theta_T\) given by \(\theta_{23}\)
\(U_{e2}: \) Kamland, unaffected by \(\theta_T\) given by \(\theta_{12}\)

Solar neutrino flux sensitive to \(\theta_T, \theta_{12}: ^8B\) flux theory limits
\(\sin \theta_T < 0.6\)
Neutrino Spectrum

Large mass splitting: tiny oscillation length

\( m_4 \sim 10 - 100 \text{ MeV} \)

\( m_{1,2,3} \lesssim 0.1 \text{ eV} \)
Sterile Neutrinos
Generic

Models avoiding neutrino portal/sterile neutrino via, e.g. coupling to Lepton number highly constrained by electron-DM scattering

Work in progress w/ R. Essig & Y. Zhong
Aside: Sterile Neutrinos

Generic

Can also charge sterile neutrino & DM w.r.t. new U(1)

Shoemaker
Cherry, Friedland, & Shoemaker
Dasgupta & Kopp
Boehm+

... 

Leads to DM/neutrino self-interactions

Only occur at loop level in model with charged mediator
Neutrino Oscillations

Light neutrinos are a linear combination of
\[ \nu_e, \nu_\mu, c_\theta \nu_\tau - s_\theta N_2 \]
\[ \nu_\tau N \]

\[ \nu_\mu \rightarrow \nu_\tau \] changed due to matter effects

Equivalent to NSI:
\[ \epsilon_{ij} = \frac{U_{i4} U_{j4}}{6} \]

Super-K & IceCube: \( \sin \theta_\tau < 0.4 \)
Parameter Range

\[ g = y_2 |U_{\tau 4}| \]

Fixed \[ y_2 = 1 \]

As advertised, 10s of MeV
Supernovae

Neutrinos produced in SN at T~30 MeV

Initial neutronization burst of $\nu_e$

DM light enough to be produced but doesn’t contribute to cooling, thermal dist. with neutrinos to large radii

Neutrinos free stream when density is low, T~5 MeV: DM production suppressed, similar to strong $\nu$ self-interactions

Fayet, Hooper, & Sigl, hep-ph/0602169 find $m_\chi > 10$ MeV

Mangano et al., hep-ph/0606190 & Boehm et al., 1303.6270:

$$\sigma_{\bar{\nu}_i\chi} \lesssim 10^{-25} \text{ cm}^2 \left(\frac{m_\chi}{\text{MeV}}\right)$$
Neutrinos from SN

MeV energy neutrinos from SN scatter on DM

Resonance at $E_{\nu} = \frac{m_\phi^2 - m_\chi^2}{2m_\chi}$ can be in the right range

Electron neutrino fraction (SN1987A)
$m_\chi=10$ MeV, $m_\phi=20$ MeV, $l=51$ Kpc
DSNB

Same process as for nearby SN

Potentially visible at Hyper-K
Implications for IceCube

Cherry, Friedland, & Shoemaker
Implications for IceCube

Cherry, Friedland, & Shoemaker
Neutrinos from SN: Core vs. Cusp?

Feedback from baryons could be a possible sol’n for cuspy halo problem

\[ 10^{51} \text{ ergs} \times \epsilon_{\text{SN}} \]

transferred from SN to DM

\[ \epsilon_{\text{SN}} \sim 0.1 - 0.4 \]

an interesting value

Pontzen & Governato, 1402.1764
Neutrinos from SN: Core vs. Cusp?

Feedback from baryons could be a possible sol’n for cuspy halo problem

$10^{51}$ ergs $\times \epsilon_{SN}$ transferred from SN to DM

$\epsilon_{SN} \approx 0.1 - 0.4$ an interesting value

$10^{53}$ ergs $\times \epsilon_{\nu\chi}$

$\epsilon_{\nu\chi} \approx \frac{1}{2} \times \frac{1}{3} \times \frac{1}{E_{\nu}} \int dE_{\nu}' (E_{\nu} - E_{\nu}') \frac{d\sigma_{\nu\chi}}{dE_{\nu}'} \times \int dl n_{\chi}$

Find $\epsilon_{\nu\chi} \approx 10^{-3}$ for $M_{cut} = 10^9 M_{\odot}$

compare against

$[\rho(r) = \frac{1}{r} \rightarrow \text{const.}]$

$\Delta W \approx \frac{1}{30} \frac{GM_{\text{enc}}^2}{r_0} \approx 3 \times 10^{54}$ ergs $\left( \frac{M_{\text{enc}}}{10^9 M_{\odot}} \right)^2 \left( \frac{r_0}{\text{kpc}} \right)$

But only a small fraction of DM scattered...maybe including all stars?

(In progress w/ Nelson & Weiner)
Future tests

$\tau$ decays

$\tau \rightarrow \nu \pi \pi$, FlaviaNet 2010

$\theta_\tau = 0.7$

$m_4 = 300 \text{ MeV}$

$\tau \rightarrow K \pi$ decays

slightly low...

$|U_{us}|$ conservative, optimistic

$|U_{ud}|^2$

$\tau$ decays, FlaviaNet 2010
$0.2254 \pm 0.0013$

$K_2$ decays, FlaviaNet 2010
$0.2252 \pm 0.0013$

CKM unitarity
$0.2255 \pm 0.0010$

$\tau \rightarrow K^+ / \tau \rightarrow K^-$, HFAG 2012
$0.2229 \pm 0.0021$

$\tau \rightarrow K^-$, HFAG 2012
$0.2214 \pm 0.0022$

$\tau \rightarrow s$ inclusive, HFAG 2012
$0.2173 \pm 0.0022$

$\tau$ average, HFAG 2012
$0.2202 \pm 0.0015$
Future tests

Super-K limit on $U_{T4}$ is statistics limited

PINGU could provide factor of 1.5 improvement

LBNF/DUNE (Study by A. E. Nelson & K. Hicks in progress)
Wrap up

• Possible sign of interesting departure from standard DM paradigm at small scales

• A large coupling of DM to neutrinos could help alleviate this

• New neutral lepton states (sterile neutrinos) fairly general requirement

• In a simple model heavy neutrino is mostly sterile with a small(ish) $\nu_\tau$ admixture

• Implications for $\tau$ decays, SN observations, long-baseline neutrino exp’ts, ...
Wrap up

New physics is a gamble...

but the payoff is immense!