The Hot Dark Matter Conundrum

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One- and three-neutrino hot dark matter
Two-neutrino dark matter with 4 neutrinos
The astrophysical paradox: universe structure
Important new input from LSND and KARMEN
Corroberation from supernova nucleosynthesis
Bad News for Neutrino Dark Matter?

$\Sigma m_{\nu_i} = 93 \Omega_\nu h^2$

One-neutrino dark matter

$\nu_\tau$ is the most likely candidate (solar: $\nu_e \rightarrow \nu_\mu$)

CHORUS and NOMAD do not see $\nu_\mu \rightarrow \nu_\tau$

Atmospheric $\nu_\mu / \nu_e$ likely due to $\nu_\mu \rightarrow \nu_\tau$ with $\Delta m^2 \sim 10^{-3} \text{eV}^2$

Not $\nu_\mu \rightarrow \nu_e$: CHOOZ $\nu_e \rightarrow \nu_1$; Super-K $\Delta \ell$ distributions

$\nu_\mu \rightarrow \nu_5$ (sterile) unlikely: nucleosynthesis limit

$\nu_\mu \rightarrow \nu_\tau$ fits Super-K data best (would kill 1-\nu DM)

Three-\nu dark matter (D.O.C.+R. Mohapatra, Phy. Rev. '93; rediscoveries)

$\nu_\mu \rightarrow \nu_\tau$ (atm.), $\nu_\mu \rightarrow \nu_e$ (solar); $m_{\nu_e} \approx m_{\nu_\mu} \approx m_{\nu_\tau} \sim 1.5 \text{eV}$

$\beta\beta_{0\nu}$ presents difficulties for Majorana $\nu$ (LSND kills it)

Two-\nu dark matter (also D.O.C.+R. Mohapatra ‘93; J. Peltoniemi + J. Valle)

$\nu_\mu \rightarrow \nu_\tau$ (atm.), $\nu_e \rightarrow \nu_5$ (solar); $m_{\nu_e}, m_{\nu_5}$ light; $m_{\nu_\mu} \approx m_{\nu_\tau} \sim 2.3 \text{eV}$

Since '93, $\nu_\mu \rightarrow \nu_e$ (LSND)
Universe Structure and Neutrino Dark Matter

Fit to all published CMB, galaxy survey data

E. Gawiser and J. Silk used 10 models [Science 280, 1405, 98]

Covers 3 orders of magnitude in spatial scale

Only one model fits: $\Omega_m = 1$, $\Omega_\nu = 0.2$, $\Omega_{\bar{\nu}} = 0.1$

Most more direct measurements give $0.2 \leq \Omega_m \leq 0.5$

Will conflict remain with more precise data coming soon?

Conclusion now: low $\Omega_m$ and $\Omega_m + \Lambda$ models don't work

Neutrinos help, but not enough (Primack and Gross)
<table>
<thead>
<tr>
<th>Model</th>
<th>$X^2/70$</th>
<th>Probability</th>
<th>$X^2/62$</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard CDM</td>
<td>3.8</td>
<td>$&lt;10^{-7}$</td>
<td>3.7</td>
<td>$&lt;10^{-7}$</td>
</tr>
<tr>
<td>Tilted CDM</td>
<td>2.1</td>
<td>$1.8\times10^{-7}$</td>
<td>2.0</td>
<td>$1.1\times10^{-5}$</td>
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<tr>
<td>Hot+CDM</td>
<td>1.2</td>
<td>0.09</td>
<td>1.06</td>
<td>0.34</td>
</tr>
<tr>
<td>$\Omega=0.5$ CDM</td>
<td>1.8</td>
<td>$2.9\times10^{-5}$</td>
<td>1.67</td>
<td>$6.7\times10^{-4}$</td>
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<tr>
<td>$\Lambda$+CDM</td>
<td>1.9</td>
<td>$1.1\times10^{-5}$</td>
<td>1.71</td>
<td>$4.3\times10^{-4}$</td>
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<tr>
<td>Late $\phi$+CDM</td>
<td>2.2</td>
<td>$&lt;10^{-7}$</td>
<td>2.0</td>
<td>$3.8\times10^{-6}$</td>
</tr>
<tr>
<td>$\Lambda=0.88$+BCDM</td>
<td>7.3</td>
<td>$&lt;10^{-7}$</td>
<td>7.7</td>
<td>$&lt;10^{-7}$</td>
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<tr>
<td>Isocurv. CDM</td>
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<td>$&lt;10^{-7}$</td>
<td>2.5</td>
<td>$&lt;10^{-7}$</td>
</tr>
<tr>
<td>PBH BDM</td>
<td>2.0</td>
<td>$8.3\times10^{-7}$</td>
<td>1.9</td>
<td>$1.4\times10^{-5}$</td>
</tr>
<tr>
<td>Strings+$\Lambda$</td>
<td>2.6</td>
<td>$&lt;10^{-7}$</td>
<td>2.6</td>
<td>$&lt;10^{-7}$</td>
</tr>
</tbody>
</table>

Uses $H_0=65\pm15$ km/s Mpc; cf. Nevalainen, Roos 68$\pm5$; Tammann 57$\pm7$
$P(k) \left( h^{-1} \text{Mpc} \right)^3$

$\Omega_\nu = 0.2, \ \Omega_b = 0.1$

$\chi^2$/dof = 1.2

$10^{-3}$ $10^{-2}$ $10^{-1}$ 1

$k \ (h \ \text{Mpc}^{-1})$
Simulations for the Nonlinear Region

$\Lambda$CDM ($\Omega_m = 0.3$)

Galaxies

Dark Matter

Primack et al.

$P(k)$ (h$^{-3}$ Mpc$^3$) vs. k (h Mpc$^{-1}$)

$Cv^2$DM

Linear theory

$z = 0$

$z = 0.99$

CHDM, 2nu, Pcold(k)
2ν Better than 1ν Dark Matter

Problems of 1ν dark matter at ~10h⁻¹ Mpc
Galaxy clusters overproduced
Galaxy pairwise velocities too low
Void regions incorrect

2ν increased streaming length solves these

\[
\frac{\text{Power (2ν)}}{\text{Power (1ν)}}
\]

Primack, Holtzman, Klypin, D.O.C. '95
Can $\Delta m_{e\mu}^2$ be Big Enough for Hot Dark Matter?

Past comparisons of LSND with other experiments

LSND’s “likelihood” vs. others’ confidence levels

Typical values: 90% likelihood ($-2.3 \text{ LLU}$) → 90% C.L. ($-3.3 \text{ LLU}$)

KARMEN ($\nu$98): no events “excluded” LSND (Feldman-Cousins)

Now have ~8 events, about the expected background

Joint LSND/KARMEN analysis (Eitel, Yellin)

Overlap of 95% C.L.’s to give joint 90% (at IS/OSII)

Better method (adding likelihoods) emphasizes $\sim 6 \text{ eV}^2$

LSND’s $\nu_\mu \rightarrow \nu_e$ favors this region

Coming: more KARMEN data, better LSND analysis

Later: MiniBooNE, I216 (?)
Cylindrical coordinates:

- \( A m^2 [eV^2] \)
- \( \sin^2 2\Theta \)

Graph showing data points and curves for \( \nu_\mu \rightarrow \nu_e \), with regions labeled as LSND, CCFR, NOMAD, and KARMEN.

- LSND and KARMEN combined 90% confidence as overlap of 95% CL's.
Evidence for $\nu_e$: Heavy-Element Nucleosynthesis

Rapid neutron capture (supernova r process)

Occurs far outside the neutron star at late time ($\sim 10^5$ yr)

Needs very neutron-rich region ($\nu_e n \rightarrow p e^-$ vs. $\nu_e p \rightarrow n e^+$)

Problem if LSND MSW region is inside r region

Thermal $\nu_e$ have $\langle E \rangle \approx 11$ MeV, but $\nu_x$ have $\langle E \rangle \approx 25$ MeV

If $\nu_x \rightarrow \nu_e$, high-energy converted $\nu_e$ have larger $\sigma \sim E^2$

$\nu_e n \rightarrow p e^-$ depletes neutrons, stopping the r process

Sure problem: models give too few neutrons in r region

Too few neutrons per seed nucleus (e.g., Fe)

Need $\sim 10^2 n/"Fe"$ to make the heaviest elements

Fatal problem: $\alpha$ effect kills the r process

All protons form $\alpha$'s, removing neutrons

More neutrons removed by $\nu_e n \rightarrow e^- p$, so $p \rightarrow \alpha$, etc.
Elements Produced by nu capture for no $^7$Be
Same n-capture calculation in the flux of the region.
Solving the Problems

What is needed

Large $\nu_\ell$ flux to eject baryons near the neutron star
Near removal of $\nu_\ell$ flux farther out where $\alpha$'s form

Neutrino features to accomplish this

Existence of at least one light sterile neutrino
Near-maximally-mixed $\nu_\mu - \nu_\tau$
Small $\nu_\mu - \nu_\ell$ mixing

Two neutrino doublets well separated ($\gtrsim 2$eV$^2$)

Exactly model needed for solar, atmospheric, LSND, HDM!
First level crossing: $\nu_{\mu,\tau} \rightarrow \nu_e$

Gets rid of dangerous high-energy $\nu_{\mu,\tau}$

Near radius where $V(\nu_{\mu,\tau}) \propto (n_{\nu_e} - n_{\mu}/2) \rightarrow 0$

Second level crossing: $\nu_e \rightarrow \nu_{\mu,\tau}$

LSND MSW region now not $\nu_{\mu,\tau} \rightarrow \nu_e$, since few $\nu_{\mu,\tau}$

Outside neutron star but inside weak freezeout radius

Needed density puts a requirement on $\Delta m_{\nu\nu}^2$

Two resonances are close, so coherence + maximal mixing gives

$\text{Prob.}(\nu_{\mu} \rightarrow \nu_{\mu}) = \frac{1}{4}$, $\text{Prob.}(\nu_{\mu} \rightarrow \nu_{\tau}) = \frac{1}{4}$, $\text{Prob.}(\nu_{\mu} \rightarrow \nu_{e}) = \frac{1}{2}$

$\text{Prob.}(\nu_{\tau} \rightarrow \nu_{\tau}) = \frac{1}{4}$, $\text{Prob.}(\nu_{\tau} \rightarrow \nu_{\mu}) = \frac{1}{4}$, $\text{Prob.}(\nu_{\tau} \rightarrow \nu_{e}) = \frac{1}{2}$

$\text{Prob.}(\nu_{\mu} \rightarrow \nu_{e}) = 0$, $\text{Prob.}(\nu_{\tau} \rightarrow \nu_{e}) = 0$, $\text{Prob.}(\nu_{e} \rightarrow \nu_{e}) = 0$

r-process problems are solved!
\( \nu_e \quad \nu_\mu \quad \nu_s \quad \nu_a \)

- r-process region
- \( \bar{\nu}_e \rightarrow n \rightarrow e^- \)
- \( t \approx 10^5 \) s
- MSW density "LSND"
- \( V(\nu_\mu) \approx 0 \)

Neutrinosphere
Astrophysical Need for Large $\Delta m_{\mu e}^2$

5.5 eV$^2$ region gives desired 15-20% hot dark matter

$\Sigma m_{\nu_i} = 2 \times 2.35 = 4.7$ eV and $\Omega_{\nu} = \frac{4.7}{93h^2}$

If $\Omega_m = 1$, $h = 0.55$, then $\Omega_{\nu} = 0.17$

If $h = 0.65$, then $\Omega_{\nu} = 0.12$, or 20% of $\Omega_m = 0.6$

Supernova nucleosynthesis needs resonances ordered $\nu_\mu \rightarrow \nu_s$ inside of $\nu_\mu \rightarrow \nu_e$ and both inside of WFO radius

Density variation with radius sets $\Delta m_{\mu e}^2$

$\sim 6$ eV$^2$ is ideal
New Astrophysical Inputs

Doubts about the distance scale

Geometric measurement to galaxy NGC4258 (H$_2$O maser)
Disagrees with Cepheid ladder by 15-20%
Shorter universe age would agree with $\Omega_m=1$, not 0.3

Doubts about Supernova Ia determination of $\Omega_m, \Lambda$

Possibilities of dust or evolution
Close SN take >2d. longer for peak brightness than far SN
May not be a true standard candle

Measurements in next few years should settle issues
Distance from Space Interferometry Mission (2005)
MAP, Planck, Sloan Digital Sky Survey $\rightarrow$ # $\nu$'s, $m_\nu$
Conclusions

Hot dark matter is most likely 2ν ($\nu_e + \nu_\tau$)

1ν dark matter ruled out if atmospheric $\nu_\mu \rightarrow \nu_\tau$

If correct, LSND rules out 3ν dark matter

r-process nucleosynthesis works with this 4ν scheme

$\Omega_m = 1$, $\Omega_\nu \approx 0.2$ fits universe structure

2ν dark matter works better than 1ν ($\nu_e + \nu_\tau \sim 5$ eV)

If $\Omega_m \lesssim 0.5$, just CDM or CDM+$\Lambda$ does not work

Conflict with low-$\Omega_m$ results needs new measurements of physics?