Prospects for the Direct Detection of the Cosmic Neutrino Background

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0. Introduction

- Progress in observational cosmology

⇒ Cosmic recipe emerged:

<table>
<thead>
<tr>
<th>Material</th>
<th>Particles</th>
<th>$\langle E \rangle$ or $m$</th>
<th>$N$</th>
<th>$\langle p \rangle/\rho_c$</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation</td>
<td>$\gamma$</td>
<td>0.1 meV</td>
<td>$10^{87}$</td>
<td>0.01%</td>
<td>CMB</td>
</tr>
<tr>
<td>Hot Dark Matter</td>
<td>Neutrinos</td>
<td>$&gt; 0.04$ eV</td>
<td>$10^{87}$</td>
<td>$&gt; 0.1$%</td>
<td>BBN, CMB</td>
</tr>
<tr>
<td>Ordinary Matter</td>
<td>$p, n, e$</td>
<td>MeV-GeV</td>
<td>$10^{78}$</td>
<td>5%</td>
<td>BBN</td>
</tr>
<tr>
<td>Cold Dark Matter</td>
<td>WIMPs?</td>
<td>$\gtrsim 100$ GeV</td>
<td>$\lesssim 10^{77}$</td>
<td>25%</td>
<td>LSS</td>
</tr>
<tr>
<td></td>
<td>Axions?</td>
<td>$\lesssim$ meV</td>
<td>$\gtrsim 10^{91}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dark Energy</td>
<td>?</td>
<td>$10^{-33}$ eV</td>
<td>?</td>
<td>70%</td>
<td>SN</td>
</tr>
</tbody>
</table>

⇒ Direct, weak interaction based detection of the **Cosmic Neutrino Background (CNB)**?

A. Ringwald (DESY)
• Indirect evidence for **CNB** from cosmological probes:
  – **BBN** prefers \( N_\nu > 0 \) (expansion rate during BBN \( \Rightarrow \) He-4 abundance)
  – **CMB** and **LSS** prefer \( N_\nu > 0 \) (matter/radiation eq. \( \Rightarrow \) fluctuation power spectra)

• **CNB** has not been detected **directly in laboratory**:
  \( \Leftarrow \) neutrinos interact only weakly
  \( \Leftarrow \) smallness of neutrino mass \( \Leftarrow \) small momentum-transfer

• Design of **direct, weak interaction based detection experiment**
  \( \Leftarrow \) need phase space distribution of relic neutrinos
  \( \Leftarrow \) **theoretically known better than ever!**

**Further content:**
1. How many, how fast?
2. How to detect?
3. Conclusions
1. How many, how fast?

- Relic neutrinos decoupled at \( t \approx 1 \text{ s} \)
1. How many, how fast?

- Relic neutrinos decoupled at \( t \sim 1 \text{ s} \)
- Predictions (for small degeneracy):
  \[
  \bar{n}_{\nu_i} 0 = \bar{n}_{\bar{\nu}_i} 0 = \frac{3}{22} \bar{n}_{\gamma} 0 = 56 \text{ cm}^{-3}
  \]
  \[
  \begin{align*}
  \# \text{relic neutrinos} & \approx \# \text{relic photons} \\
  C_{\nu B} & \quad C_{\text{CMB}}
  \end{align*}
  \]
1. How many, how fast?

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At least two neutrino mass eigenstates nonrelativistic (\( m_{\nu_i} \gg 5 \times 10^{-4} \text{ eV} \))
1. How many, how fast?

- Relic neutrinos decoupled at $t \sim 1 \text{ s}$

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  \]

  \[
  \# \text{ relic neutrinos} \approx \# \text{ relic photons}
  \]

  \[
  \bar{p}_{\nu_i}^0 = \bar{p}_{\bar{\nu}_i}^0 = 3 \left( \frac{4}{11} \right)^{1/3} \frac{T_{\gamma_0}}{\text{CMB}} = 5 \times 10^{-4} \text{ eV}
  \]

- At least two neutrino mass eigenstates nonrelativistic ($m_{\nu_i} \gg 5 \times 10^{-4} \text{ eV}$)

  \[
  \Rightarrow \text{ Gravitational clustering on CDM}
  \]

  \[
  \Rightarrow \text{ Density enhanced in galactic halos}
  \]

A. Ringwald (DESY)
Relic neutrinos in neighbourhood of Earth ($r_\oplus \approx 8$ kpc):

- Overdensity $\approx 1 - 20$

[AR,Wong '04]
Relic neutrinos in neighbourhood of Earth ($r_\oplus \approx 8$ kpc):

- Overdensity $\approx 1 - 20$

- Momentum distribution:
  - almost isotropic
  - flat at low momenta
  - turning point at $\equiv p_{\text{esc}} = m_\nu v_{\text{esc}} \\ m_\nu \sqrt{2|\phi(r_\oplus)|}$
  - matches Fermi-Dirac at high momenta

[AR, Wong '04]
2. How to detect?

- Some possibilities of direct detection:
  - mechanical force through coherent scattering of relic neutrinos
  - neutrino capture on $\beta$ decaying nuclei
  - Pauli blocking effects near thresholds for atomic neutrino pair emission enhanced by laser irradiation
  - scattering of accelerator beams off the relic neutrinos
Mechanical force based detection

- Low average momentum of relic neutrinos corresponds to a (reduced) de Broglie wavelength of macroscopic dimension,

\[ \lambda = 1/\langle p \rangle = 0.12 \text{ cm}/\langle y \rangle \]

\[ \Rightarrow \]

Envisage scattering processes in which many target atoms act coherently over a macroscopic volume \( \lambda^3 \) \( \Rightarrow \) elastic scattering rate enhanced by

\[ \frac{N_A}{A} \rho_t \lambda^3 \approx 6 \times 10^{18} \left( \frac{100}{A} \right) \left( \frac{\rho_t}{\text{g/cm}^3} \right) \left( \frac{\lambda}{0.1 \text{ cm}} \right)^3 \]

compared to case where neutrinos are elastically scattered coherently only on the individual nuclei of the target [Shvartsman et al. ’82; Smith, Lewin ’83]
Test body will experience **neutrino wind force** through random neutrino scattering:

\[ a_t \approx \sum_{\nu, \bar{\nu}} n_{\nu} v_{\text{rel}}^{\text{flux}} \frac{4\pi}{3} N_A^2 \rho_t r_t^3 \sigma_{\nu N} \left( \frac{m_{\nu}}{v_{\text{rel}}} \right)^{\text{mom. transfer}} \]

\[ \approx 2 \times 10^{-28} \left( \frac{n_{\nu}}{\bar{n}_{\nu}} \right) \left( \frac{10^{-3}}{v_{\text{rel}}} \right) \left( \frac{\rho_t}{\text{g/cm}^3} \right) \left( \frac{r_t}{\lambda} \right)^3 \frac{\text{cm}}{\text{s}^2} \]

Majorana neutrinos: suppressed by factor \((v_{\text{rel}}/c)^2\)
- Prospects for the Direct Detection of the CNB –

• Test body will experience **neutrino wind force** through random neutrino scattering:

  \[ a_t \approx \frac{n_\nu v_{\text{rel}}}{\nu,\bar{\nu} \text{ flux}} \left( \frac{4 \pi}{3} N_A \rho_t r_t^3 \sigma_{\nu N} \right) \left( \frac{2 m_\nu v_{\text{rel}}}{\text{mom. transfer}} \right) \]

  \[ \approx 2 \times 10^{-28} \left( \frac{n_\nu}{\bar{n}_\nu} \right) \frac{10^{-3} c}{v_{\text{rel}}} \left( \frac{\rho_t}{\text{g/cm}^3} \right) \left( \frac{r_t}{\lambda} \right)^3 \frac{\text{cm}}{\text{s}^2} \]

  Majorana neutrinos: suppressed by factor \((v_{\text{rel}}/c)^2\)

• At present, smallest measurable acceleration \(\gtrsim 10^{-13} \text{ cm/s}^2\), using conventional **Cavendish-type torsion balance**. Improvements to \(\gtrsim 10^{-23} \text{ cm/s}^2\) proposed

  \[ \text{[Hagmann '99]} \]

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• Test body will experience **neutrino wind force** through random neutrino scattering:

\[
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\]

\[
\approx 2 \times 10^{-28} \left( \frac{n_{\nu}}{\bar{n}_{\nu}} \right) \frac{10^{-3}}{\nu_{rel}} \left( \frac{\rho_t}{g/\text{cm}^3} \right) \left( \frac{r_t}{\lambda} \right)^3 \frac{\text{cm}}{s^2}
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\[\text{[Hagmann '99]}\]

\[\Rightarrow\] Detection possible in 30–40 years, if neutrinos are Dirac particles

\[\text{[Smith '03]}\]
Neutrino capture of radioactive nuclei based detection

[Irvine,Humphrey ’83; Cocco,Mangano,Messina ’07; Lazauskas,Vogel,Volpe ’08; Blennow ’08]

- Consider neutrino capture on e.g. tritium,

\[ \nu_i + ^3\text{H} \rightarrow e + ^3\text{He} \]

- Capture rate of CNB neutrinos,

\[ N_{i,\text{CNB}} \simeq 6.5 \text{ yr}^{-1} \left(100 \text{ g } ^3\text{H}\right)^{-1} |U_{ei}|^2 \frac{n_{\nu_i}}{\bar{n}_{\nu_i}} \]

- **Signature**: monoenergetic electrons with kinetic energy

\[ T_{\text{kin}} = Q_\beta + m_{\nu_i} \]

where \( Q_\beta = 18.6 \text{ keV} \) is the energy release in \(^3\text{H}\) \( \beta \)-decay for \( m_{\nu_i} = 0 \)
Main challenge: Separation of signal electrons from overwhelming background of electrons from $^3$H $\beta$-decay

$\Rightarrow$ Need very good energy resolution $\Delta \lesssim 0.5$ eV (degenerate masses), 0.05 eV (inverted hierarchy), 0.005 eV (normal hierarchy)

$\Rightarrow$ Opportunity for KATRIN ($\Delta \sim 0.5$ eV) and future $^3$H $\beta$ decay campaigns

[Blennow '08]

A. Ringwald (DESY)
Pauli blocking of atomic neutrino pair emission

[Yoshimura ’07; Takahashi, Yoshimura ’07]

- Laser irradiated neutrino pair emission from metastable ions or atoms,

\[ \gamma + I^* \rightarrow I^{**} + \nu_i \bar{\nu}_i \]

- **Signature:** detection of \( I^{**} \); rate resonantly enhanced by tuning \( \omega \)
- In presence of CNB, rate reduced near threshold due to Pauli blocking
Accelerator beam based detection

- For center-of-mass energies below $W$- and $Z$-resonances, cf.

$$\sqrt{2m_\nu E} \simeq 4.5 \left(\frac{m_\nu}{\text{eV}}\right)^{1/2} \left(\frac{E}{10\ \text{TeV}}\right)^{1/2} \text{MeV}$$

weak interaction cross sections grow rapidly with energy

$\Rightarrow$ Exploit a flux of extremely energetic particles

- accelerator beams
- from cosmic rays [Weiler ‘82;...;Fodor,Katz,AR;...;Eberle,AR,Song,Weiler;...;L.Schrempp,AR;...]

for scattering on relic neutrinos as target
Exploit accelerator beams:

- Scattering rate \[ R_{\nu A}^Z \simeq n_\nu \sigma_\nu A^2 L I/(Ze) \]
  \[ \simeq 2 \times 10^{-8} \left( \frac{n_\nu}{n_\nu} \right) \left( \frac{m_\nu}{eV} \right) \frac{A^2}{Z} \left( \frac{E_N}{10 \text{ TeV}} \right) \left( \frac{L}{100 \text{ km}} \right) \left( \frac{I}{0.1 \text{ A}} \right) \text{ yr}^{-1} \]

⇒ Too small to give rise to an observable effect in the foreseeable future (LHC, VLHC)
⇒ Need **Ultimate Large Hadron Collider**
  - Few **elastic** scattering events per year; hard to detect, due to small momentum transfers (\( \sim 1 \) GeV at \( E_N \sim 10^7 \) TeV)
  - Alternative: exploit inverse beta decay

\[ ^{A}Z N + \nu_e \rightarrow ^{A+1}Z N + e^- \]
⇒ detect \( ^{A+1}Z N \) on exit of machine

<table>
<thead>
<tr>
<th>accel.</th>
<th>( N )</th>
<th>( E_N ) [TeV]</th>
<th>( L ) [km]</th>
<th>( I ) [A]</th>
<th>( \frac{R_{\nu A}}{n_\nu [eV]} [\text{yr}^{-1}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>( p )</td>
<td>7</td>
<td>26.7</td>
<td>0.6</td>
<td>( 2 \times 10^{-8} )</td>
</tr>
<tr>
<td></td>
<td>Pb</td>
<td>574</td>
<td>26.7</td>
<td>0.006</td>
<td>( 1 \times 10^{-5} )</td>
</tr>
<tr>
<td>VLHC</td>
<td>( p )</td>
<td>87.5</td>
<td>233</td>
<td>0.06</td>
<td>( 2 \times 10^{-7} )</td>
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<tr>
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<td>Pb</td>
<td>7280</td>
<td>233</td>
<td>0.0006</td>
<td>( 1 \times 10^{-4} )</td>
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<tr>
<td>ULHC</td>
<td>( p )</td>
<td>( 10^4 )</td>
<td>40000</td>
<td>0.1</td>
<td>( 10 )</td>
</tr>
</tbody>
</table>

A. Ringwald (DESY) [Melissinos ‘99; Zavattini unpubl]
3. Conclusions

- **BBN, CMB, and LSS** provide presently the only evidence for the CNB

- **Roadmap for direct CNB detection**

  A more direct, weak interaction based detection of the big bang relic neutrinos may proceed by measuring

  - neutrino capture in $\beta$ decaying nuclei
    Remarks: current technology 1-2 orders of magnitude off
  - coherent elastic scattering of relic $\nu$'s off nucleons in terrestrial detector
    Remarks: current technology 3 orders of magnitude off
  - Pauli blocking effects in laser induced atomic neutrino pair emission
    Remarks: needs more study to estimate discovery potential
  - interactions of very high energy particles from terrestrial accelerator beams with the relic neutrinos as target
    Remarks: needs design of specialized accelerator (beyond our lifetime?)

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