Labatory tests for the Cosmic Neutrino Background using beta-decaying nuclei

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Properties of the Neutrino Background

The Cosmic Neutrino Background (CNB) is in a thermal distribution in a frame u^α, which we assume to be coincident with the dipole of the Cosmic Microwave Background (CMB). The rest frame of this fluid is in the direction

$$(264.85 \pm 0.10)^\circ, (48.25 \pm 0.04)^\circ$$

in galactic coordinates, with velocity 368 ± 2 km/s.

Its thermal distribution at temperature $T_\nu = 1.952$ K is then

$$F_i(\vec{p}) = \left[e^{(p^\alpha u_\alpha - E_F)/kT} + 1 \right]^{-1} \tag{1}$$

with Fermi momentum $p_F = \sqrt[3]{\frac{\rho_\nu}{3\pi}} = 3.6 \times 10^{-5}$ eV per flavor i, for both neutrinos and anti-neutrinos. $E_F = \sqrt{m^2 + p_F^2}$.

The asymmetry of neutrinos to to antineutrinos is proportional to the baryon-to-photon ratio, and therefore

$$\eta_\nu = \frac{n_\nu - n_{\overline{\nu}}}{n_\nu + n_{\overline{\nu}}} \simeq 10^{-10},$$

and $n_\nu \simeq n_{\overline{\nu}}$.

Spectrum of ideas

Why use beta-decaying nuclei?

Using neutrinos (capture or emission) is a *specific* test for the CNB.

Ideas involving coherent motion of bodies (e.g. Aluminum blocks) could not separate a neutrino contribution from a Dark Matter or other contribution.

Z-burst has the problem that the injection spectra is unknown.

Initial state neutrino capture is a specific test, is it the only one?

Pauli Blocking

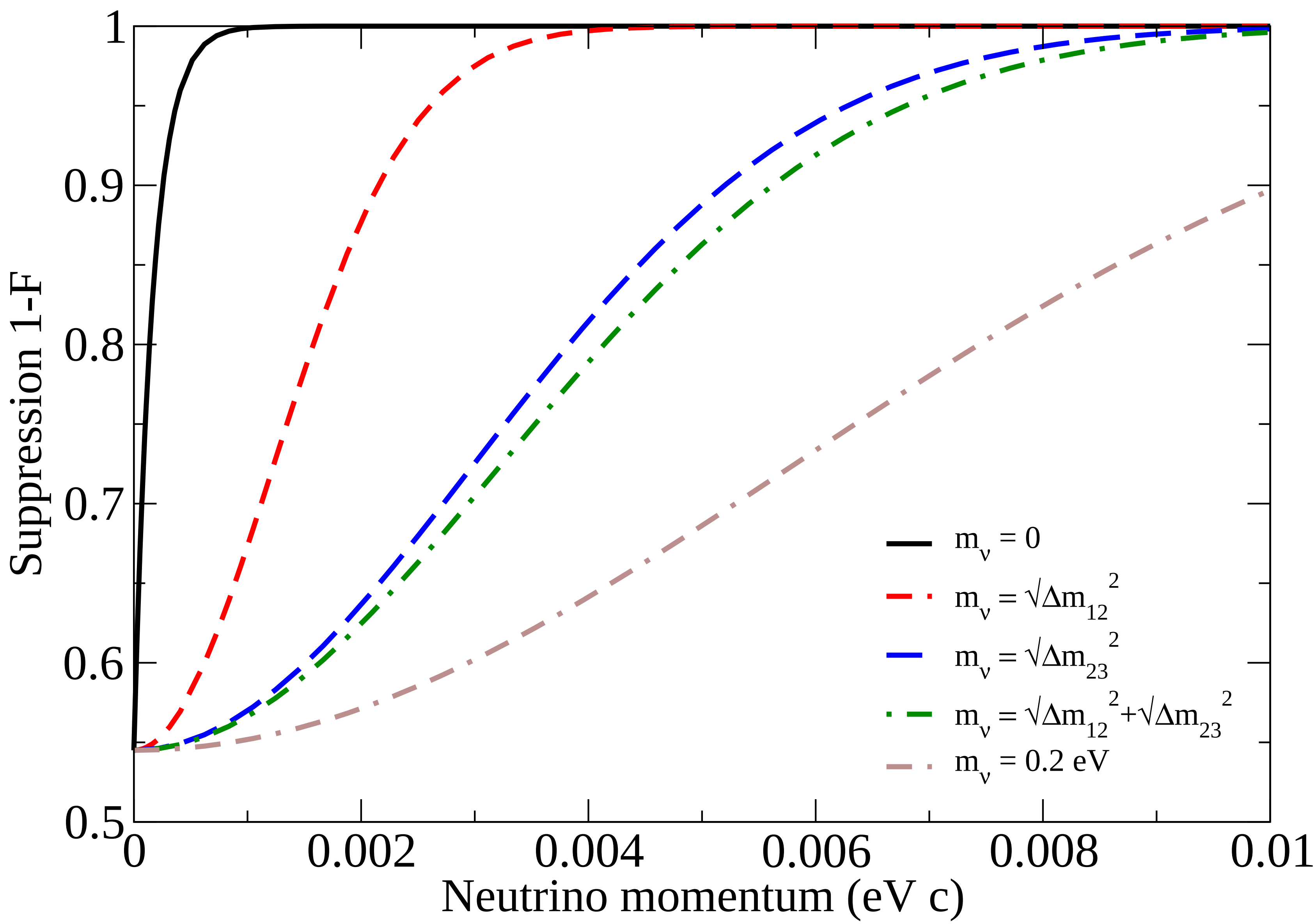
The presence of the background means that emission of neutrinos into wave numbers that are already occupied is suppressed by $1-F_i(\vec{p})$:

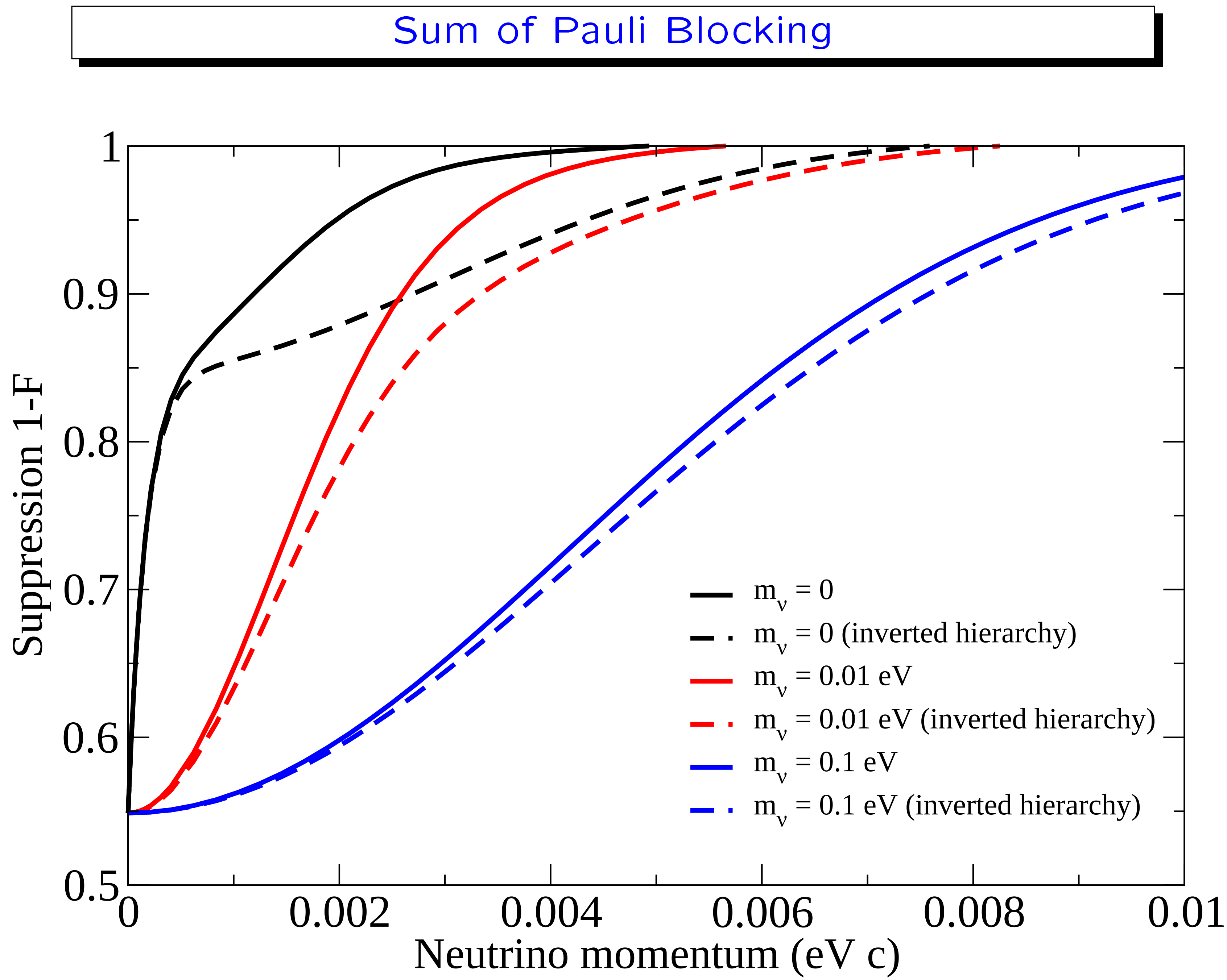
$$d\Gamma = 2\pi \sum_i \int |\mathcal{M}_i|^2 \xi_i^2 [1 - F_i(\vec{p})] dPS$$

where dPS is the differential phase space and ξ_i is the eigenvector component of neutrino mass eigenstate i, in the electron-neutrino direction.

This has sensitivity to the mass hierarchy, mixing, and chemical potential of each neutrino species.

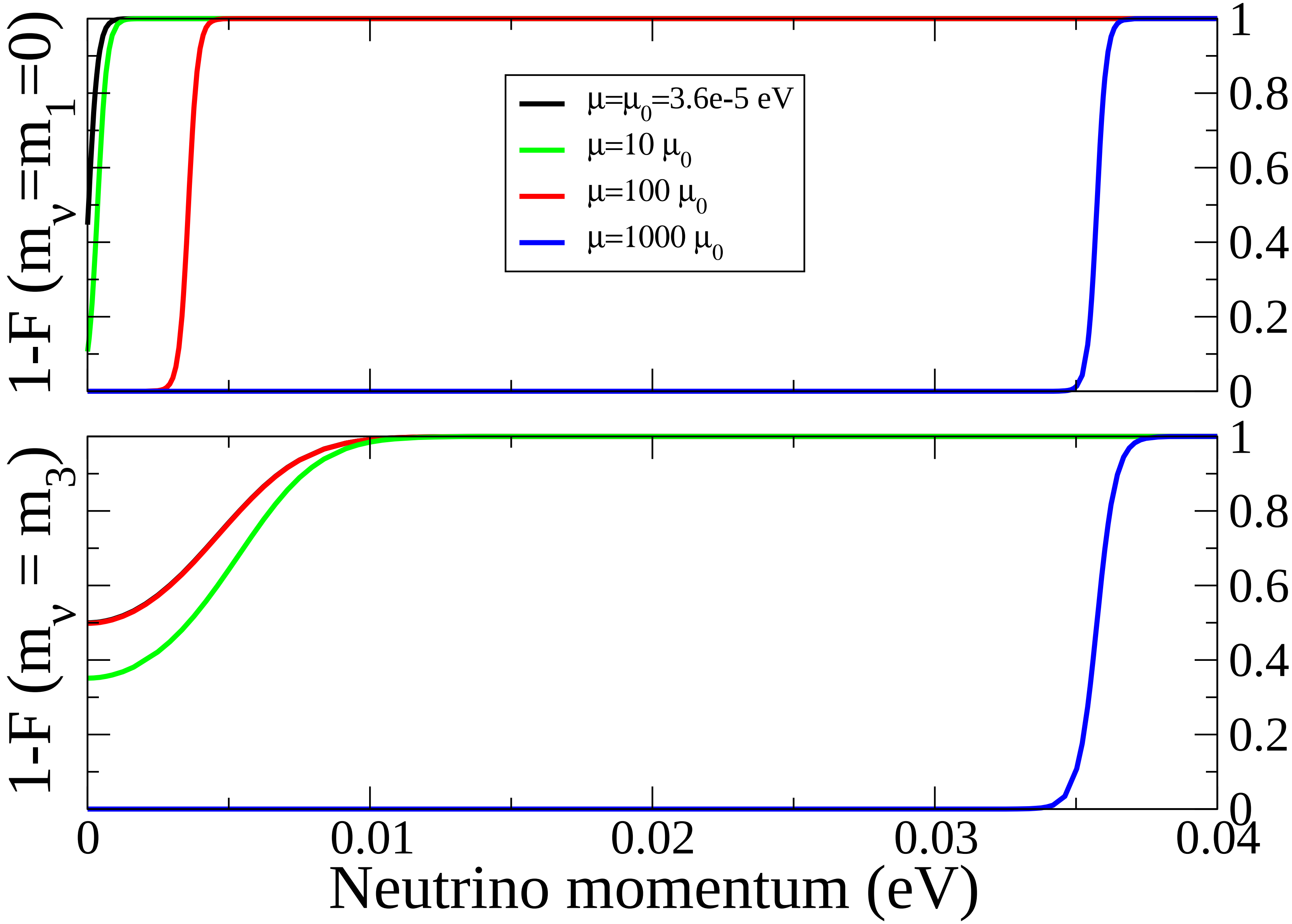
Pauli Blocking





Sum of Pauli Blocking
Suppression 1-F
Neutrino momentum (eV c)
1
0.9
0.8
0.7
0.6
0.5
0
0.002
0.004
0.006
0.008
0.01
m_ν = 0
m_ν = 0 (inverted hierarchy)
m_ν = 0.01 eV
m_ν = 0.01 eV (inverted hierarchy)
m_ν = 0.1 eV
m_ν = 0.1 eV (inverted hierarchy)

Pauli Blocking with Chemical Potential



The bad news: Matrix Element

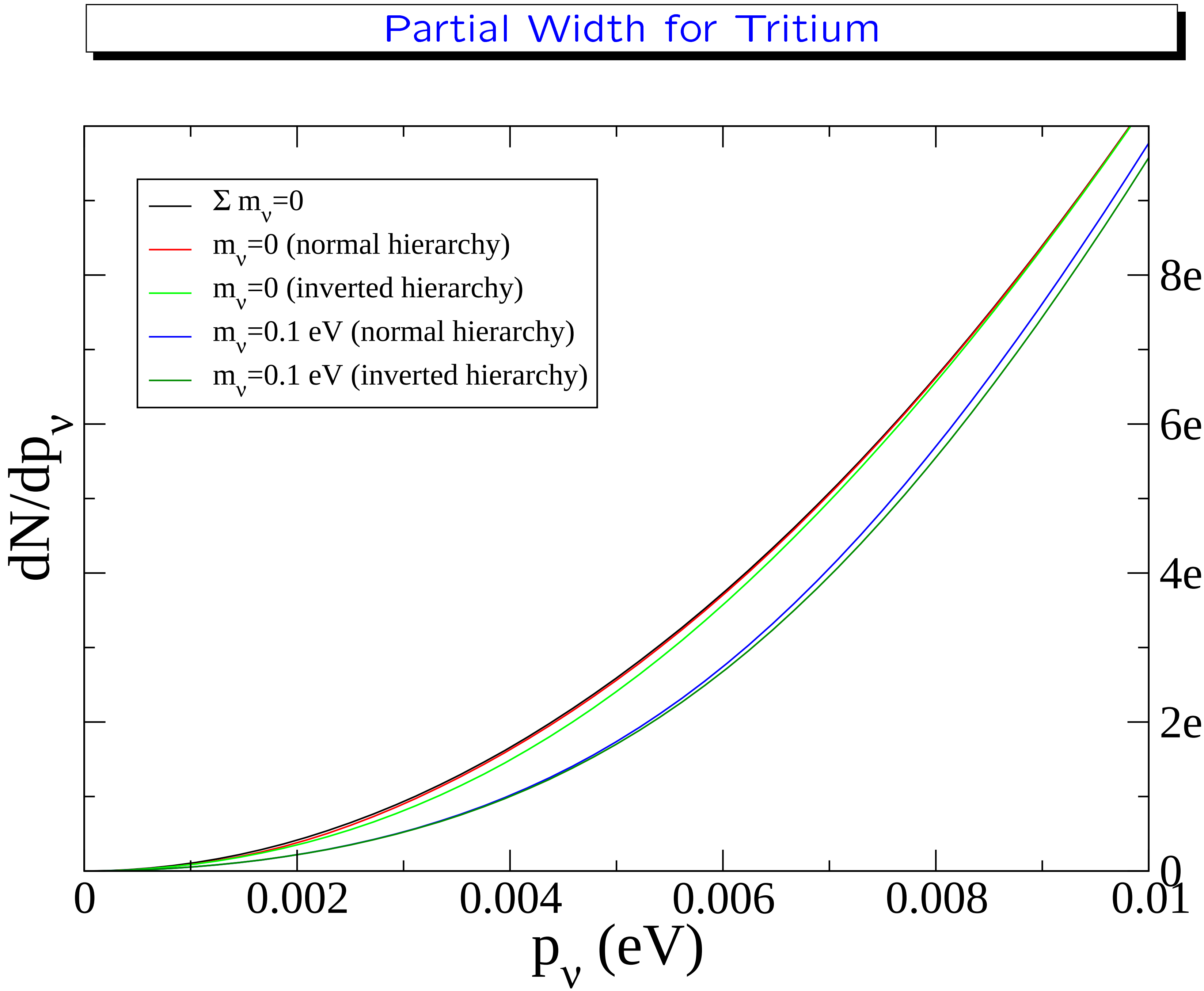
The Matrix Element for Beta-decay $I \to J + e + \nu$ is

$$
\begin{aligned}
|\mathcal{M}|^2 = & (g_V + g_A)^2 (p_J \cdot p_e)(p_I \cdot p_\nu) \\
& + (g_V - g_A)^2 (p_I \cdot p_e)(p_J \cdot p_\nu) \\
& + (g_V^2 - g_A^2)(p_I \cdot p_J)(p_e \cdot p_\nu)
\end{aligned}
$$

where g_V and g_A are the vector and axial vector weak couplings of the nuclide.

Unfortunately, this reaches a minimum when the Pauli blocking is largest, at $\vec{p}_\nu = 0$.

The Earth's velocity is only $\beta \sim 10^{-3}$ so is not a significant effect.



Partial Width for Tritium
Σ m_ν=0
m_ν=0 (normal hierarchy)
m_ν=0 (inverted hierarchy)
m_ν=0.1 eV (normal hierarchy)
m_ν=0.1 eV (inverted hierarchy)
dN/dp_ν
8e-17
6e-17
4e-17
2e-17
0
0.002
0.004
0.006
0.008
0.01
p_ν (eV)

Boosting to other frames

One might ask next: can I point a beam of isotopes in the right direction, and put neutrinos in the CNB?

Unfortunately this is very hard. Galilean relativity works for the atom and electron, so one might think a low velocity beam $v/c \simeq 10^{-3}$ would work. But the neutrino does not even approximately obey Galilean relativity, and must be treated properly using Special Relativity.

Then one needs

$$\gamma = \frac{1}{\sqrt{1-v^2}} = E_\nu / T_\nu \tag{2}$$

Assuming one could use the LHC beam ($\gamma = 5500$ for heavy elements), this would require finding an isotope with $Q \simeq 1$ eV. Such an isotope would have a half-life in the billions of years ($\times\gamma$).

More bad news: Uncertainty

The required precision is $\Delta p_\nu = 10^{-3}$ eV, corresponding to

$$\frac{\Delta p_\nu}{p_\nu} = 6 \times 10^{-7} \tag{3}$$

Because the neutrino momentum is only inferred from the sum of the other initial atom, final atom, and electron, this is the precision required on *each* of them.

For Tritium this corresponds to 1.3 pK. (pico-Kelvin) This is a BEC. Another useful technology may be "crystallized beams".

This is hard but maybe not impossible. It's only a couple orders of magnitude away from current technology.

Bad news triple threat: Rate

This would require $10^{19} - 10^{20}$ decays for first observation (Tritium) with $m_\nu = 0.1$ eV, or 10^{23} decays if $m_\nu = 0$.

The volume in phase space of the Pauli-Blocked region is approximately constant with respect to Q. Therefore this effect scales approximately as

$$\frac{\max(m_\nu, \mu_\nu)^3}{Q^3}$$

therefore it's very useful to find and use low-Q isotopes.

The lowest currently known are around 2 keV.

Summary

Neutrino emission is significantly affected by Pauli blocking from the CNB, such that emission of low-momentum neutrinos is suppressed by a factor 1/2.

The matrix element for beta decay goes to zero if the neutrino momenta is zero.

It is interesting to note that nearly any experiment which has the precision to measure neutrino mass kinematically can also search for this effect. Therefore it is important to push on new kinematic mass measurement ideas.

This effect is enhanced by low Q isotopes as Q^{-3}, so finding very low Q isotopes helps. Unfortunately these also have very long lifetimes.

Performing this experiment in a moving frame does not appear to be an option, because large boosts are required.