Decay of neutrinos from cosmological sources and prospects of observation at neutrino telescopes

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Neutrinos are stable particles . . . *are they?*

So far, they seem to be

Bounds on "lifetimes" $\kappa^{-1} \equiv \tau_0/m$ of eigenstates $\nu_{1,2,3}$:

- $\kappa_1^{-1} \gtrsim 10^5$ s eV^{-1} (from SN 1987A)
- $\kappa_2^{-1} \gtrsim 10^{-4}$ s eV^{-1} (from solar ν's)
- $\kappa_3^{-1} \gtrsim 10^{-10}$ s eV^{-1} (from atm. and long-baseline)

Very long baselines might reveal their true unstable nature

$\Rightarrow$ cosmological neutrinos

If $\nu_{1,2,3}$ decay, their populations are governed by

$$\frac{dN_i}{dt} = -\lambda_i N_i$$

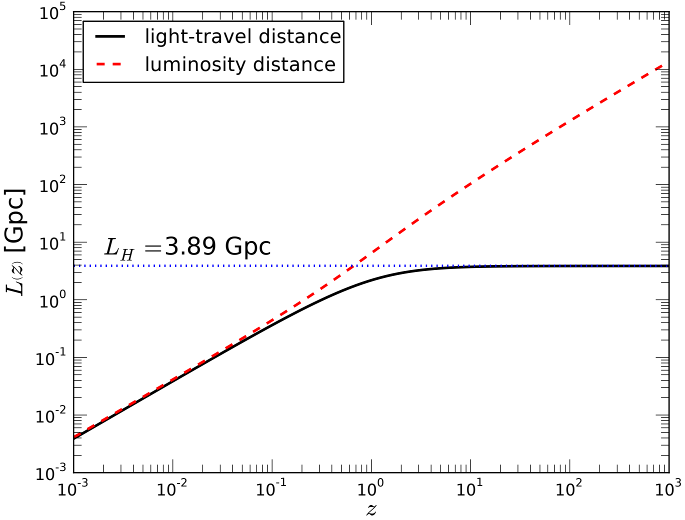
with the decay rate (s^{-1})

$$\lambda_i \equiv \frac{1}{\tau_i} = \frac{m_i}{\tau_{i,0}} \frac{1}{E} \equiv \frac{\kappa_i}{E}$$

Consider only decay into products invisible to the detector

Neutrinos are ultra-relativistic, so $t \approx L$
— if they are produced at a source with redshift z,

$L(z) \equiv$ light-travel, or lookback distance


light-travel distance
luminosity distance
L_H =3.89 Gpc
$L(z)$ [Gpc]
z
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
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10^{1}
10^{2}
10^{3}

$\nu_\alpha \to \nu_\beta$ flavour-transition probability, oscillations washed out:

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \qquad (\alpha, \beta = e, \mu, \tau)$$

What if neutrinos decay?

$$P_{\alpha\beta}(E_0, z) = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \underbrace{\frac{N_i(E_0, z)}{N_i^0(E_0)}}_{D_i(E_0, z) \leq 1}$$

Damping factor $D_i(E_0, z)$ found by solving the decay equation

When solving, take into account:

1. $L = L(z)$ is the light-travel distance
2. Cosmological expansion: $E(z) = (1+z) E_0 \Rightarrow \lambda_i(z) = \frac{\kappa_i}{E_0 (1+z)}$

The traditional, simplified solution

$$\frac{dN_i}{dt} = -\lambda_i N_i \xrightarrow{\text{assume } \lambda_i \text{ constant}} N_i(t) = N_i^0 e^{-\lambda_i t}$$

Only now introduce the z-dependence of λ_i and L:

$$e^{-\lambda_i t} \longrightarrow D_i(E_0, z) = [\mathcal{Z}_1(z)]^{-\kappa_i L_H / E_0}$$

vs.

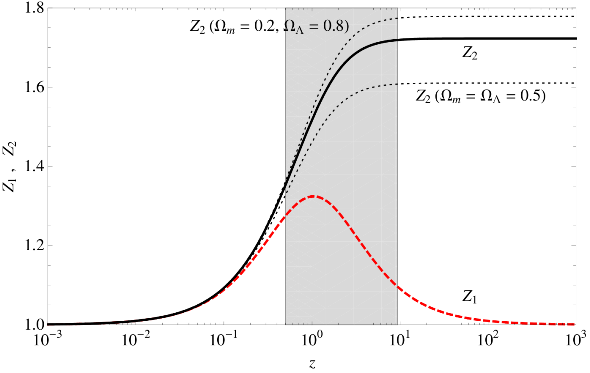
The proper solution

Rewrite the decay equation in terms of z from the start,

$$\frac{dN_i(E_0, z)}{dz} = -\frac{\kappa_i}{E_0} \frac{dL}{dz} \frac{N_i(E_0, z)}{1+z}$$

and then solve it:

$$D_i(z) = [\mathcal{Z}_2(z)]^{-\kappa_i L_H / E_0}$$



$\mathcal{Z}_1$ is unphysical after $z \approx 1$

$\mathcal{Z}_2 \simeq a - be^{-cz}$, so decay not automatically complete for large z

Complete decay is instead an energy-dependent condition:

$$D_i\left(E_0, z\right) = \left[\mathcal{Z}_2\left(z\right)\right]^{-\kappa_i L_H / E_0} \rightarrow 0 \Leftrightarrow \kappa_i L_H / E_0 \gg 1$$

GRBs are the sources of the most energetic photons
— if produced by hadronic acceleration, they could also be the sources of the most energetic cosmic rays and neutrinos

e.g.,

$$p + \gamma_b \to \Delta^+(1232) \to \begin{cases} n + \pi^+ & (\mathrm{BR} = 1/3) \\ p + \pi^0 & (\mathrm{BR} = 2/3) \end{cases}$$

Gamma-rays: $\pi^0 \to \gamma + \gamma$

UHE ν's: $\begin{cases} \pi^+ \to \mu^+ + \nu_\mu \\ \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$

Escaped n's become the UHECRs: $n \to p + e^- + \bar{\nu}_e$

Perhaps also direct escape of protons (see P. Baerwald, MB, and W Winter, arXiv:1301.6163)

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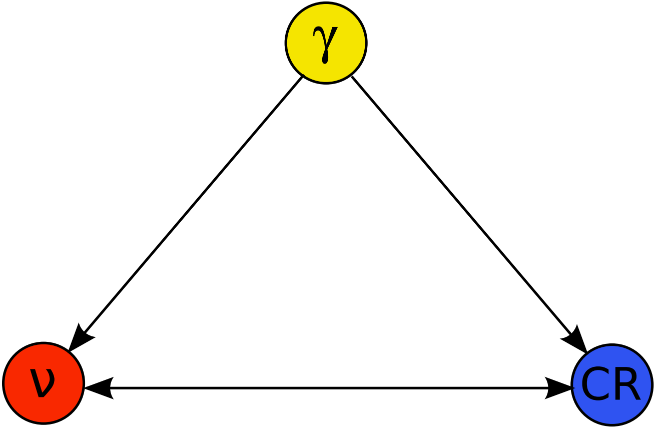


We use a sophisticated prediction of the GRB neutrino flux (HÜMMER ET AL.):

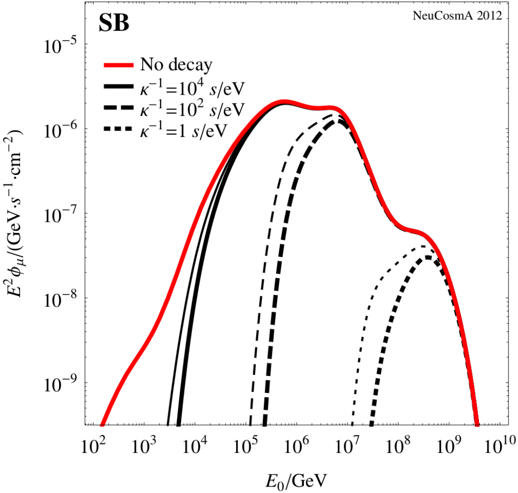
- full background photon spectrum (not only peak energy)
- energy dependence of the mean free path of protons
- cooling of secondaries
- high-energy photopion processes
- neutrinos from decay of $\mu^{\pm}$, $\pi^{\pm}$, K, n
- helicity dependence of μ decays
- flavour mixing (affected by neutrino decays)

One order of magnitude below prediction of benchmark models used by IceCube — see P. Baerwald's talk T21.5 tomorrow

S. HÜMMER, P. BAERWALD, AND W. WINTER, PRL **108**, 231101 (2012) [ARXIV:1112.1076]
S. HÜMMER, M. RUGER, F. SPANIER, AND W. WINTER, ASTROPHYS. J. **721**, 630 (2010) [ARXIV:1002.1310]

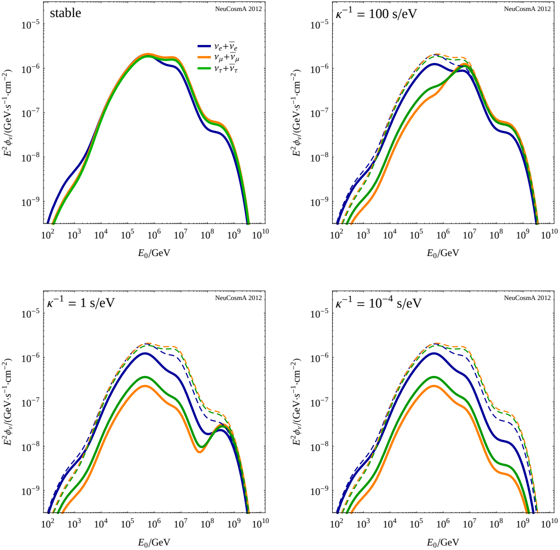
Let us first assume that the three neutrinos have equal lifetimes:

thick: proper
thin: simplified

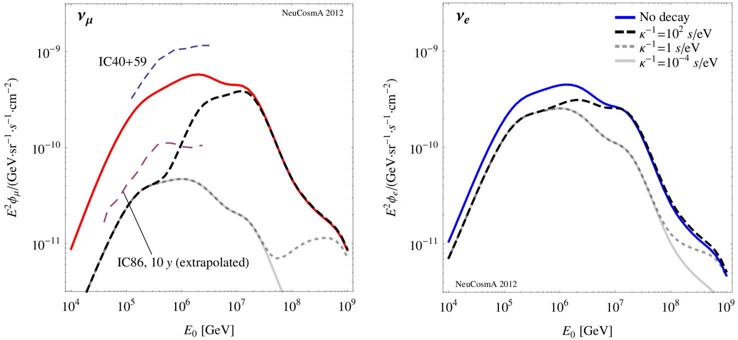


P. Baerwald, MB, W. Winter, **JCAP** 10, 020 (2012) [arXiv:1208.4600]

Now keep ν_1 stable (from SN 1987A) and let $\nu_{2,3}$ decay:



Quasi-diffuse flux (stacking the 117 GRBs from IC-40 analysis):



No neutrinos found because they decay, or because the baryonic loading in GRBs is smaller than anticipated?

No reliable information on astrophysical neutrino sources can be obtained from muon tracks only

We studied neutrino decays into invisible products and found:

- "the longer the distance, the longer lifetimes can be tested" is valid only up to $z \approx 1$
- complete decays do not automatically occur for large z, but only for low enough energies
- if ν_1 stable and $\nu_{2,3}$ unstable, the GRB ν_μ flux can fall by $\sim$ one order of magnitude, while the ν_e flux is barely affected

IceCube has observed 2 PeV cascades, with no muon tracks
Sign of decay? Only more data will tell

Backup slides

Four sample bursts:

	SB	GRB080916c	GRB090902b	GRB091024
α	1	0.91	0.61	1.01
β	2	2.08	3.80	2.17
$\epsilon_{\gamma,\text{break}}$ [MeV]	1.556	0.167	0.613	0.081
Γ	$10^{2.5}$	1090	1000	195
t_v [s]	0.0045	0.1	0.053	0.032
T_{90} [s]	30	66	22	196
z	2	4.35	1.822	1.09
$\mathcal{F}_\gamma$ [erg cm^{-2}]	$1 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$	$5.1 \cdot 10^{-5}$
L_γ^{iso} [erg s^{-1}]	10^{52}	$4.9 \cdot 10^{53}$	$3.6 \cdot 10^{53}$	$1.7 \cdot 10^{51}$

SB: standard burst

S. Hümmer, P. Baerwald, and W. Winter,
Private note on neutrino emission from GRBs in the fireball model

Flavour ratio $R = \phi_\mu / (\phi_e + \phi_\tau)$: