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PeV neutrinos of IceCube with very heavy fermion and very light scalar

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Abstract
A new physics scenario to explain PeV neutrinos observed in the IceCube experiment is introduced, with dark matter and dark energy considered. A slowly decaying very heavy fermion with a PeV mass as the dark matter particle is the origin of the PeV neutrinos. They couple to an extremely light field and this light field constitutes the dark energy.

Keywords: PeV neutrinos, ultra light scalar, decaying dark matter

PeV neutrinos have been observed in the IceCube experiment [1, 2]. Their origin, namely how they got to be so energetic, is still unclear. In this work, we consider the possibility that they are a result of new physics beyond the Standard Model (SM) of particle physics.

More remarkably, in fundamental physics nowadays, there are dark matter (DM) and dark energy (DE) problems. Attempting to make the connection between all these phenomena, we will work in a simple scenario that includes DM and DE to understand PeV neutrinos.

To be specific, supposing that the PeV neutrino is a decay product of a heavy fermion N, $N \to \nu + h$ where ν stands for SM neutrinos and h the SM Higgs boson, the observation is explained if the mass of N is about $M_N \sim$ PeV. In such a situation, N should exist in the Universe for a long time which is beyond the age of the Universe. Thus N is naturally a DM constituent that is decaying slowly. We assume N consists of all of the DM. To describe the above process, the relevant interaction Lagrangian is written as follows,

$$\mathcal{L} \supset \frac{\lambda}{M} \phi \bar{l} h N, \tag{1}$$

where a light scalar ϕ is introduced, l stands for the three generation $\mathrm{SU}(2)_{\mathrm{L}}$ doublet leptons, and λ and M are the coupling constant and the high energy scale, respectively. The coupling should be very small for N being long-lived.

The main reason for introducing ϕ is that it is related to DE, also that in this way the small coupling is made to be more natural. Attributing a PeV neutrino to long-lived heavy DM was proposed before [3–30]. Here we also involve DE. The point here is the introduction of the static and free light scalar field $\phi = \frac{\sqrt{2\rho_\phi}}{m_\phi} \sin(m_\phi t)$ [31, 32], where m_ϕ and ρ_ϕ are its mass and energy density, respectively. We consider ρ_ϕ as DE, and it is a kind of time-variational or dynamical DE [33–38]. In this case, m_ϕ is extremely small which is about the inverse of the Universe lifetime.

Taking ϕ as a background field due to Bose–Einstein condensation, the production of PeV neutrinos is a two body decay

$$N \to h + \nu, \tag{2}$$

with a coupling proportional to $\lambda \frac{\langle\phi\rangle}{M} \sim \lambda \frac{\sqrt{2\rho_\phi}}{m_\phi M}$. Since this decay produces Higgs particles, there will be a series of subsequent decays to Standard Model particles.

Now we estimate N's lifetime. With 7.5 year accumulation, the experiment observed about 60 events of PeV neutrinos [2]. For simplicity, the dark matter N is assumed to be uniformly distributed throughout the Universe. Based on the IceCube experimental data, the observed high energy neutrinos have no particular direction. Thus we assume that the PeV neutrinos come from some isotropic sources. Assuming that N has only one decay channel, we divide the detected high energy neutrinos into two parts:

(a) Neutrinos produced BEFORE the IceCube turned on;
(b) Neutrinos produced AFTER the IceCube turned on.

Moreover, high-energy neutrinos move at the speed of light $c = 3 \times 10^8$ m s^{-1} approximately.

For part (a) neutrinos, at the moment the IceCube turned on, they were at least inside a sphere with the IceCube as the sphere's centre and radius $R = 7.5$ ly $= 7.10 \times 10^{16}$ m. Denote neutrinos number density as ρ_ν, then the number of neutrinos in a thin spherical shell with radius r is $4\pi\rho_\nu r^2 \mathrm{d}r$. For a neutrino ν at a distance of IceCube r, its velocity is evenly distributed in all directions. The IceCube detector has a cross-sectional area of S on a sphere with ν as the sphere's centre, and r as radius. A neutrino at a distance r away from the IceCube can be detected with a probability of $\frac{S}{4\pi r^2}$. To sum up, the number of part (a) neutrinos is

$$\int_0^R 4\pi\rho_\nu r^2 \frac{S}{4\pi r^2}\mathrm{d}r. \tag{3}$$

Assuming $\eta = 10\%$ is the detection efficiency of the IceCube, and the above quantity times η is about 60, so $\rho_\nu = 8.46 \times 10^{-21}$ m^{-3}. The energy density of dark matter in the Universe is about 10 GeV · m^{-3} [39], so the number density of N is $\rho_N = 10^{-5}$ m^{-3}. It is known that the lifetime of N follows the exponential distribution of the parameter τ^{-1}, where τ is the mean lifetime. The number density of N that has not decayed is a function of time t:

$$\rho_N(t) = \rho_N(0)\exp\left(-\frac{t}{\tau}\right). \tag{4}$$

Now t is the age of the Universe $t_\mathrm{u} = 4.32 \times 10^{17}$ s. Considering equation (2), $\rho_\nu = \rho_N(0) - \rho_N(t_\mathrm{u})$, so the equation $\frac{t_\mathrm{u}}{\tau} = \ln\left(1 + \frac{\rho_\nu}{\rho_N}\right)$ holds. Then we have N's mean lifetime $\tau = 4.86 \times 10^{32}$ s.

For part (b) neutrinos, suppose that at the moment $t\,(0 \leqslant t \leqslant T,\ T = 7.5\ \mathrm{y})$ after the IceCube turned on, they were generated by N's decay. Since the lifetime of N follows the exponential distribution, the probability that lifetime between t_u and $t_\mathrm{u} + (T - t)$ is

$$\int_{t_\mathrm{u}}^{t_\mathrm{u}+(T-t)} \tau\exp\left(-\frac{\tilde{t}}{\tau}\right)\mathrm{d}\tilde{t} \xlongequal{T-t,t_\mathrm{u}\ll\tau} \frac{T-t}{\tau}.$$

They were at least inside a sphere with the IceCube as the sphere's centre and radius $R - ct$. Similarly, the number of part (b) neutrinos is

$$\eta\int_0^T 4\pi\rho_N(R - ct)^2 \frac{S}{4\pi(R - ct)^2}\frac{T - t}{\tau}\mathrm{d}t = 60. \tag{5}$$

We have $\tau = 2.65 \times 10^{14}$ s. In part (b), N decays more than a dozen orders of magnitude faster than part (a), but we can not tell directly which one is dominant.

If the detected neutrinos are mainly part (a), then part (b) contributes to detected neutrinos a dozen orders of magnitude less than (a), therefore no contradiction arises. However, if the detected neutrinos are mainly part (b), we take $\tau = 2.65 \times 10^{14}$ s in part (a)'s calculation, and we find that ρ_ν is more than a dozen orders of magnitude larger than previously calculated. (a) becomes the dominant source of neutrinos, contradicting the hypothesis.

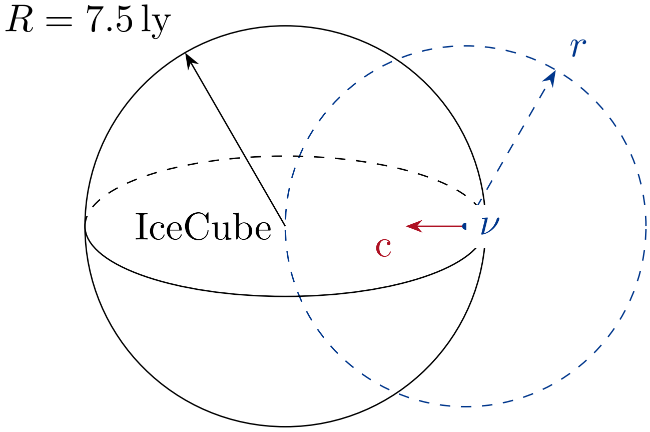


Figure 1. Neutrinos produced before the IceCube is turned on are in a sphere of $R = 7.5$ ly.

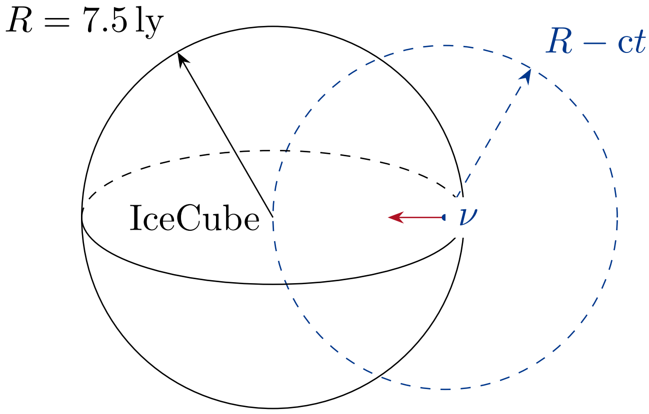


Figure 2. Neutrinos produced after the IceCube is turned on are in a sphere of $R = 7.5$ ly.

So in summary, we have found part (a) is the main source of neutrinos, with N's mean lifetime $\tau_N = 4.86 \times 10^{32}$ s.

Let us consider the model in detail. By introducing a real scalar field ϕ and a Majorana fermion field N, the Lagrangian is written as

$$\mathcal{L} = \mathcal{L}_\mathrm{SM} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \mathrm{i}\bar{N}\gamma^\mu\partial_\mu N - \frac{1}{2}\bar{N}^\mathrm{C}M_N N - \left(\frac{\lambda}{M}\phi\bar{l}\tilde{h}N + \mathrm{h.c.}\right), \tag{6}$$

where $\tilde{h} = \mathrm{i}\sigma^2 h^*$. The Lagrangian follows a $\mathbb{Z}_2$ symmetry with $\mathbb{Z}_2$ quantum numbers assigned as:

$$N: +1, \quad h: +1, \quad \phi: -1, \quad l: -1, \quad e_\mathrm{R}: -1. \tag{7}$$

All other fields have a $\mathbb{Z}_2$ quantum number of 1 (called 'even parity').

The ϕ field behaves like a free field because the coupling λ is very small, and its motion is typically described by plane waves, in the static case,

$$\phi = \phi_0\sin(m_\phi t). \tag{8}$$

We assume that there is a Bose–Einstein condensation in this static ϕ field. In other words, now ϕ field exists as a background field and its vacuum expectation $\langle\phi\rangle$ changes over time:

$$\langle\phi\rangle = \langle\phi\rangle_0 \sin(m_\phi t_{\rm u}), \tag{9}$$

where $t_{\rm u}$ is now the age of the Universe. In this way, the value of ϕ field has increased after the Big Bang, and so does the ϕ's energy density. We take this energy density as the DE.

Suppose that ϕ is extremely light and its current value becomes large for the first time today, namely

$$m_\phi t_{\rm u} \approx \frac{\pi}{2}, \tag{10}$$

it is obtained that $m_\phi \simeq 1.0\times 10^{-32}$ eV. In this model, DE is then

$$\rho_{\rm DE} = \rho_\phi = \frac{1}{2} m_\phi^2 \langle\phi\rangle_0^2. \tag{11}$$

From the measured DE today ($10^{-6}\,{\rm GeV}\cdot{\rm cm}^{-3}$), the field value is obtained: $\langle\phi\rangle_0 \simeq 10^{15}$ GeV. This means that the ϕ field is highly condensed. Therefore N mainly has the two-body decay mode $N\to h+\nu$. Considering $M_N\sim$ PeV, ν is just the PeV neutrino detected by the IceCube experiment. The decay width is

$$\Gamma = \frac{1}{16\pi}\left(\frac{\lambda\langle\phi\rangle}{M}\right)^2 M_N.$$

According to our previous estimate of the mean lifetime of N, when the new physics scale M takes the Planck mass 10^{19} GeV, the value of λ is about 10^{-26}.

Is it possible for N to decay into three particles? It is necessary to take a fresh look at the issue. For two-body decay, the decay width has already been calculated in the previous content. One has to note the fact that the produced ϕ is a boson, and then the probability that ϕ is involved in the Bose–Einstein condensation needs to be considered. It is much easier for ϕ to transition to the state where a large number of ϕ particles already exist [40]. We think of ϕ as the dark energy field, assuming ϕ has zero momentum, thus the vacuum (noted as $|\mho\rangle$, which consists of a large number of ϕ particles with zero momentum) is ϕ's eigenstate whose eigenvalue is $\langle\phi\rangle$: $\phi|\mho\rangle = \langle\phi\rangle|\mho\rangle$. For three-body decay $N\to\phi+\nu+h$, the decay width is

$$\Gamma = \frac{1}{2^6\pi^3}\left(\frac{\lambda}{M}\right)^2 \int {\rm d}E_\phi\, E_\phi(M_N - E_\phi),$$

at the $E_\phi\to 0$ region,

$$\Delta\Gamma \simeq \frac{1}{2^6\pi^3}\left(\frac{\lambda}{M}\right)^2 M_N E_\phi\, \Delta E_\phi.$$

For the above decay process, when $E_\phi\to 0$, at the amplitude level, the amplitude is proportional to $(a^\phi)^\dagger_{\boldsymbol{k}=\boldsymbol{0}}|0\rangle$ with $|0\rangle$ the trivial vacuum, and $(a^\phi)^\dagger_{\boldsymbol{k}}$ is the creation operator of the ϕ field. When we consider the vacuum is a Bose–Einstein condensate, the amplitude will be proportional to $(a^\phi)^\dagger_{\boldsymbol{k}}|\mho\rangle$, then the decay width is proportional to the square of the amplitude, thus proportional to $\langle 0|\,(a^\phi)(a^\phi)^\dagger|0\rangle \sim \langle|\phi|^2\rangle$. Once the ϕ particle is produced by decay, it immediately 'melts into' the Bose–Einstein condensation state $|\mho\rangle$. So in summary, the width of two-body decay is equivalent to the width of three-body decay.

For $(2n+1)$-body decay $N\to(2n-1)\phi+\nu+h$ (corresponding interaction Lagrangian is $\frac{\lambda_n}{M}\phi^{2n-1}\bar{\nu}hN$), the decay width is

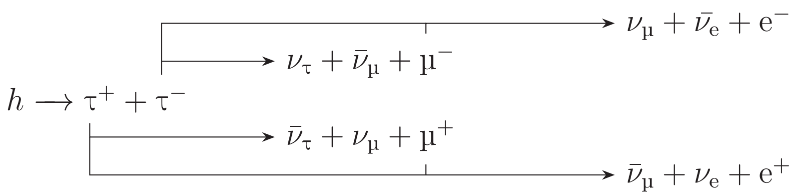
$$\Gamma = \frac{1}{2^{4n+2}\pi^{4n-1}}\left(\frac{\lambda_n}{M^{2n-1}}\right)^2 \times \int\left(\prod_{k=1}^{2n-1}{\rm d}E_{\phi_k}\,E_{\phi_k}\right)\left(M_N - \sum_{k=1}^{2n-1}E_{\phi_k}\right),$$

at the $E_{\phi_1},\dots,E_{\phi_{2n-1}}\to 0$ region,

$$\Delta\Gamma \simeq \frac{1}{2^{4n+2}\pi^{4n-1}}\left(\frac{\lambda_n}{M^{2n-1}}\right)^2 \times M_N E_{\phi_1}\cdots E_{\phi_{2n-1}}\,\Delta E_{\phi_1}\cdots\Delta E_{\phi_{2n-1}}.$$

Similar discussion and analysis as in the previous paragraph can also be carried out.

Discussion to clarify the physics meaning of this work is necessary. (1) The IceCube experiment has observed high energy for TeV up to PeV. While TeV neutrinos are expected to be explained mainly by standard astrophysics, PeV ones are considered using new physics in this work. If this is to be true, with the accumulation of data, the IceCube experiment will observe that TeV neutrinos can be traced back to astrophysical origins, and the PeV neutrinos are more isotropic. In addition, this model predicts the existence of cosmic high energies positrons and electrons with energy up to PeV, since



Thus the neutrino energy spectrum is a continuous distribution with an apparent accumulation at PeV energy. (2) The neutrino masses have alternative origins such as the standard seesaw mechanism. The mass induced by equation (6) is too small to be realistic. (3) DM is decaying slowly. (4) The involvement of a very light scalar field is ad-hoc, however, the model is very simple. It says that DE is oscillating, and DE has been increasing since the Big Bang of the Universe. In the early universe, the cosmological constant is small. More complicated or elegant DE models can be incorporated. (5) The coupling constant is unnaturally small, this interaction seems weaker than the gravity. However, we may introduce higher dimension interaction instead of dimension 5 of equation (1), to make the coupling more natural. Nevertheless, in our way, it is interesting the PeV neutrinos, the DM and the DE are coupled together.

Acknowledgments

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