10^{20}eV Cosmic Ray and Particle Physics with IceCube

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Abstract. We show that a kilometer-scale neutrino observatory, though optimized for detecting neutrinos of TeV to PeV energy, can reveal the science associated with the enigmatic super-EeV radiation in the Universe. Speculations regarding its origin include heavy relics from the early Universe, particle interactions associated with the Greisen cutoff, and topological defects which are remnant cosmic structures associated with phase transitions in grand unified gauge theories. We show that it is a misconception that new instruments optimized to EeV energy can exclusively do this important science. Because kilometer-scale neutrino telescopes such as IceCube can reject the atmospheric neutrino background by identifying the very high energy of the signal events, they have sensitivity over the full solid angle, including the horizon where most of the signal is concentrated. This is critical because upgoing neutrino-induced muons, considered in previous calculations, are absorbed by the Earth. Previous calculations have underestimated the event rates of IceCube for EeV signals by over one order of magnitude.

I   INTRODUCTION

It is nothing less but exhilarating to contemplate future neutrino detectors reaching effective volumes of 10^{13} tons and effective areas of $10^6 \, \mathrm{km}^2$ by exploiting totally novel detection methods such as radio, acoustic, atmospheric fluorescence and horizontal air shower techniques. This is at a time when we are operating a single neutrino telescope of only 10^3–$10^5 \, \mathrm{m}^2$ effective area, depending on the science [1]. Its extension to a kilometer-scale neutrino observatory, IceCube, is still at the proposal stage. Neutrino detectors can be classified in four categories, which are delineated by the energy for which the instruments have been optimized:

1. **MeV** detectors: for studying the sun and detecting supernovae,

2. **GeV–TeV** DUMAND-class telescopes: possibly, the first instruments to look beyond the sun, but, more importantly, with sufficiently low threshold to demonstrate the novel techniques that use ice and water as a Cherenkov medium by detecting atmospheric neutrinos. AMANDA is the first in this category, others will be commissioned in Mediterranean waters,

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3. **TeV–PeV** kilometer-scale observatories such as IceCube [2]. These represent, as far as we know, the best-buy for opening up the field of high energy neutrino astronomy,

4. **EeV** detectors specializing in answering the mystifying questions raised by the existence of 100 EeV cosmic rays, and the apparent absence of a Greisen cutoff.

Although optimized in different energy bands, the missions of these instruments can overlap. In this talk we discuss the potential of IceCube to do the science envisaged for the projects of interest to this meeting, such as the radio observatories, the Auger air shower array and the space-based atmospheric fluorescence detector OWL. These discussions are important for two reasons: i) for exploring the full potential of a detector, possibly beyond the specific goals it was designed for, and ii) in order to avoid compromising the performance of an instrument by concentrating on science better done by others. While i) is obvious, ii) is important and often controversial. For instance, should one consider the study of oscillating atmospheric neutrinos, superbly performed with Superkamiokande-type detectors, when optimizing the performance a high energy neutrino telescope?

II   ICECUBE

As far as astronomy beyond the GeV signals of EGRET is concerned, the case for using neutrinos as messengers is compelling [3]. Of all high-energy particles, only weakly interacting neutrinos can directly convey astronomical information from the edge of the universe and from deep inside the most cataclysmic high-energy processes. Copiously produced in high-energy collisions, travelling at the velocity of light, and undeflected by magnetic fields, neutrinos meet the basic requirements for astronomy. Their unique advantage arises from a fundamental property: they are affected only by the weakest of nature's forces (but for gravity) and are therefore essentially unabsorbed as they travel cosmological distances between their origin and us.

The first suggestions that kilometer-size neutrino telescopes were required to do the science originated with early estimates of the flux produced by the highest energy cosmic rays interacting with microwave photons. With time, and after consideration of the diverse scientific missions of astroparticle physics with high energy neutrinos, we have confirmed that the science does require construction of a kilometer-scale neutrino detector, and the challenge has therefore been one of technology. The only demonstrated solution is to use a "natural" detector consisting of a thousand billion liters (a teraliter) of instrumented natural water or ice. After commissioning and operating the Antarctic Muon and Neutrino Detector Array (AMANDA), the AMANDA collaboration is ready to meet this challenge and has proposed to construct IceCube, a one-cubic-kilometer international high-energy neutrino observatory in the clear deep ice below the South Pole Station.

IceCube will be an array of 4,800 optical modules within a cubic kilometer of clear ice. Frozen into holes 2.4 kilometers deep, to be drilled by hot water, the uppermost optical modules will lie 1,400 m below the surface. Simulations anchored to AMANDA data show that the direction of muon tracks can be reconstructed to 0.5 degrees above 1 PeV. IceCube will be capable of identifying neutrino type, or flavor, by mapping showers of Cherenkov light from electron and from tau neutrinos. Most important, it will measure neutrino energy. Energy resolution is critical, because there should be very little background from atmospheric neutrinos at energies above 100 TeV.

III   EeV SCIENCE

In this talk we concentrate on super-EeV science such as topological defects, super-heavy relics and neutrinos associated with the Greisen cutoff. Their detection is usually not considered as a high priority in designing the architecture of neutrino telescopes.

It has been realized for some time that topological defects are unlikely to be the origin of the structure in the present Universe [4]. Therefore the direct observation of their decay products, in the form of cosmic rays or high energy neutrinos, becomes the only way to search for these remnant structures from grand unified phase transitions [5]. This search represents an example of fundamental particle physics that can only be done with cosmic beams. We here point out that a kilometer-scale neutrino observatory, such as IceCube, has excellent discovery potential for topological defects. The instrument can identify the characteristic signatures in the energy and zenith angle distribution of the signal events. Our conclusions for topological defects extend to other physics associated with $10^{20} \sim 10^{24}$ eV energies.

To benchmark the performance of IceCube relative to OWL [6], chosen as an example of an instrument optimized to $\sim 10^2$ EeV energy, we use the following theorized sources of super-EeV neutrinos:

- generic topological defects with grand-unified mass scale M_X of order 10^{15} GeV and a particle decay spectrum consistent with all present observational constraints [7],

- superheavy relics [8,9], which we normalize to the Z-burst scenario [10] where the observed cosmic rays with $\sim 10^{20}$ eV energy, and above, are locally produced by the interaction of super-energetic neutrinos with the cosmic neutrino background,

- neutrinos produced by superheavy relics which themselves decay into the highest energy cosmic rays [11], and

- the flux of neutrinos produced in the interactions of cosmic rays with the microwave background [12]. This flux, which originally inspired the concept of a kilometer-scale neutrino detector, is mostly shown for comparison.

TABLE 1. Comparison of neutrino event rates for three representative neutrino fluxes for OWL [6] and IceCube [13].

	Volume	Eff. Area	Threshold
OWL	10^{13} ton	10^6 km^2	3×10^{19} eV
IceCube	10^9 ton	1 km^2	10^{15} eV*

	Events per Year		
	TD	Z_{burst}	$p\gamma_{2.7}$
OWL ν_e	16	9	5
IceCube ν_μ	11	30	1.5

*actual threshold ~100 GeV; requiring >1 PeV eliminates atmospheric ν background.

Our results are summarized in Table 1 where we compare the event rates for IceCube, discussed later, with those for OWL calculated in reference [6]. The conclusion is clear, while effective volume and area for OWL apparently exceed those of IceCube by many orders of magnitude, the events rates are comparable. This is a consequence of the duty cycle, reduced efficiency, and higher threshold of the OWL detector.

Cognoscenti will notice that the event rates claimed for IceCube are roughly two orders of magnitude larger than those found in the literature for a generic detector with $1\,\mathrm{km}^2$ effective area. The reason for this is simple. Unlike first-generation neutrino telescopes, IceCube can measure energy, and can therefore separate interesting high energy events from the background of lower energy atmospheric neutrinos by energy measurement. The instrument can identify high energy neutrinos over 4π solid angle, and not just in the lower hemisphere where they are identified by their penetration of the Earth, as is the case with AMANDA. This is of primary importance here because neutrinos produced, for instance by the decay of topological defects, have energies large enough to be efficiently absorbed by the Earth. The observed events are dominated by neutrinos interacting in the ice or atmosphere *above* the detector and near the horizon where the atmosphere alone represent a target density for converting neutrinos of $36\,\mathrm{kg/cm}^2$. This event rate typically dominates the one for up-going neutrinos by an order of magnitude. We will show that the zenith angle distribution of neutrinos associated with EeV signals form a striking signature for their extremely high energy origin.

IV NEUTRINO EVENTS

We calculate the neutrino event rates by convoluting the $\nu_\mu + \bar{\nu}_\mu$ flux from the different sources considered in this talk, with the probability of detecting a muon produced in a muon-neutrino interaction in the Earth or atmosphere:

$$N_{\text{events}} = 2\pi \ A_{\text{eff}} \ T \ \int \int \ \frac{dN_\nu}{dE_\nu}(E_\nu)P_{\nu\to\mu}(E_\nu, E_\mu(\text{thresh}), \cos\theta_{\text{zenith}}) \ dE_\nu \ d\cos\theta_{\text{zenith}}$$

$$(1)$$

where T is the observation time and θ_{zenith} the zenith angle. We assume an effective telescope area of $A_{\text{eff}} = 1 \ \text{km}^2$, a conservative assumption for the very high energy neutrinos considered here. It is important to notice that the probability $(P_{\nu\to\mu})$ of detecting a muon with energy above a certain energy threshold $E_\mu(\text{threshold})$, produced in a muon-neutrino interaction, depends on the angle of incidence of the neutrinos. This is because the distance traveled by a muon cannot exceed the column density of matter available for neutrino interaction, a condition not satisfied by very high energy neutrinos produced in the atmosphere. They are absorbed by the Earth and only produce neutrinos in the ice above, or in the atmosphere or Earth near the horizon. The event rates in which the muon arrives at the detector with an energy above $E_\mu(\text{threshold}) = 1$ PeV, where the atmospheric neutrino background is negligible, are summarized in Table 2. We discuss them in more detail by introducing Figs. 1–5.

TABLE 2. Neutrino event rates (per year per km^2 in 2π sr) in which the produced muon arrives at the detector with an energy above $E_\mu(\text{threshold})=1$ PeV. Different neutrino sources have been considered. The topological defect models (TD) correspond to highest injection rates Q_0 (ergs $\text{cm}^{-3} \ \text{s}^{-1}$) allowed in Fig. 2 of [7]. Also shown is the number of events from p-γ_{CMB} interactions in which protons are propagated up to a maximum redshift $z_{\text{max}} = 2.2$ [12] and the number of neutrinos from the Waxman and Bahcall limit on the diffuse flux from optically thin sources [14]. The number of atmospheric background events above 1 PeV is also shown. The second column corresponds to downward going neutrinos (in 2π sr). The third column gives the number of upward going events (in 2π sr). We have taken into account absorption in the Earth according to reference [15]. IceCube will detect the sum of the event rates given in the last two columns.

| Model	$N_{\nu_\mu + \bar{\nu}_\mu}$ (downgoing)	$N_{\nu_\mu + \bar{\nu}_\mu}$ (upgoing)
TD, $M_X = 10^{14}$ GeV, $Q_0 = 6.31 \times 10^{-35}$, p=1	11	1
TD, $M_X = 10^{14}$ GeV, $Q_0 = 6.31 \times 10^{-35}$, p=2	3	0.3
TD, $M_X = 10^{15}$ GeV, $Q_0 = 1.58 \times 10^{-34}$, p=1	9	1
TD, $M_X = 10^{15}$ GeV, $Q_0 = 1.12 \times 10^{-34}$, p=2	2	0.2
Superheavy Relics Gelmini *et al.* [8]	30	1.5×10^{-7}
Superheavy Relics Berezinsky *et al.* [11]	2	0.2
Superheavy Relics Birkel *et al.* [9]	1.5	0.3
p-γ_{CMB} ($z_{\text{max}} = 2.2$) [12]	1.5	1.2×10^{-2}
W-B limit $2 \times 10^{-8} \ E^{-2}$ $(\text{cm}^2 \ \text{s sr GeV})^{-1}$	8.5	2
Atmospheric background	2.4×10^{-2}	1.3×10^{-2}
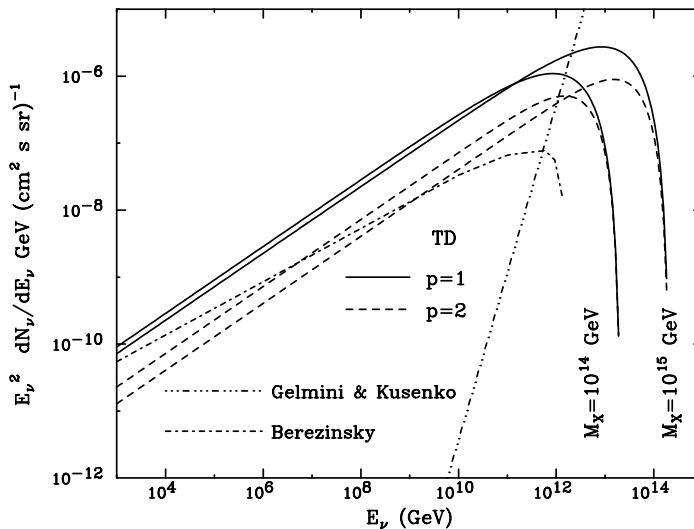
FIGURE 1. Maximal predictions of $\nu_\mu + \bar{\nu}_\mu$ fluxes from topological defect models by Protheroe and Stanev (p=1,2). Also shown is the $\nu_\mu + \bar{\nu}_\mu$ from superheavy relic particles by Gelmini and Kusenko and the flux by Berezinsky *et al.*.

Figure 1 shows the $\nu_\mu + \bar{\nu}_\mu$ fluxes used in the calculations. We first calculate the event rates corresponding to the largest flux from topological defects [7] allowed by constraints imposed by the measured diffuse γ-ray background in the vicinity of 100 MeV. The corresponding proton flux has been normalized to the observed cosmic ray spectrum at 3×10^{20} eV; see Fig. 2 of reference [7]. Models with $p < 1$ appear to be ruled out [16] and hence they are not considered in the calculation. As an example of neutrino production by superheavy relic particles, we consider the model of Gelmini and Kusenko [8]. In Figs. 2 and 3 we show the event rates as a function of neutrino energy. We assume a muon energy threshold of 1 PeV. We also show in both plots the event rate corresponding to the Waxman and Bahcall "bound" [14]. This bound represents the maximal flux from astrophysical, optically thin sources, in which neutrinos are produced in p-p or p-γ collisions. The atmospheric neutrino events are not shown since they are negligible above the muon energy threshold we are using. The area under the curves in both figures is equal to the number of events for each source. In Fig. 4 we plot the event rates in which the produced muon arrives at the detector with an energy greater than E_μ(threshold). In Fig. 5 we finally present the angular distribution of the neutrino events for the different sources. The characteristic shape of the distribution reflects the opacity of the Earth to high energy neutrinos, typically above $\sim$100 TeV. The limited column density of matter in the atmosphere essentially reduces the rate of downgoing neutrinos to interactions in the 1.5 km of ice above the detector. The events are therefore concentrated near the horizontal direction corresponding to zenith angles close to $90°$. The neutrinos predicted by the model of Gelmini and
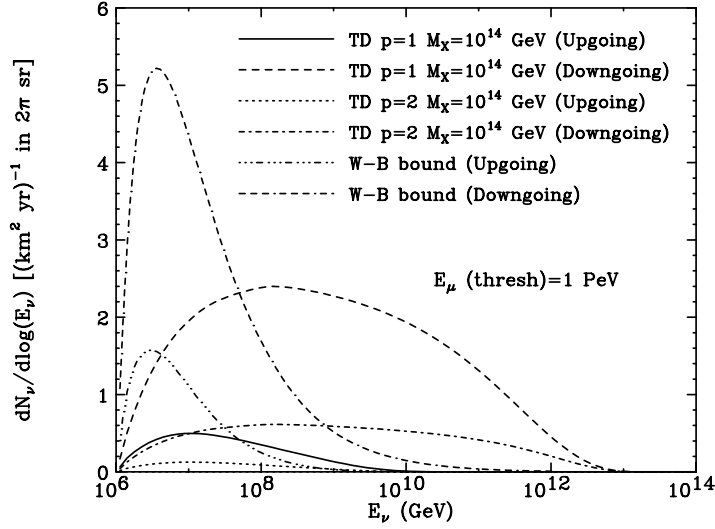
FIGURE 2. Differential $\nu_\mu + \bar{\nu}_\mu$ event rates in IceCube from the topological defect fluxes in Fig.1. The muon threshold is E_μ(threshold)=1 PeV. We have separated the contribution from upgoing and downgoing events to stress the different behavior with energy. The event rate expected from the Waxman and Bahcall bound (see text) is also shown for illustrative purposes. The rate due to atmospheric neutrinos is negligible (see Table 2) and hence it is not plotted.
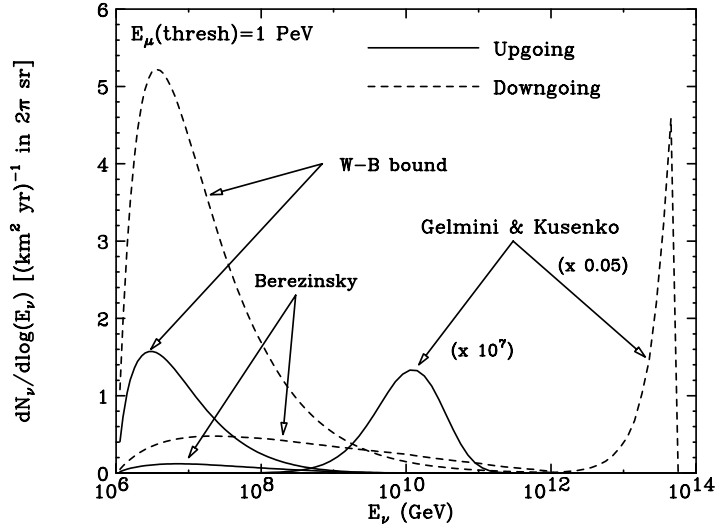
FIGURE 3. Differential $\nu_\mu + \bar{\nu}_\mu$ event rates in IceCube from super-heavy relic particles. We have separated the contribution from upgoing and downgoing events to stress the different behavior with energy. The muon threshold is E_μ(threshold)=1 PeV. The event rate due to atmospheric neutrinos as well as the one expected from the Waxman and Bahcall bound (see text) is shown for illustrative purposes. The rate due to atmospheric neutrinos is negligible (see Table 2) and hence it is not plotted.
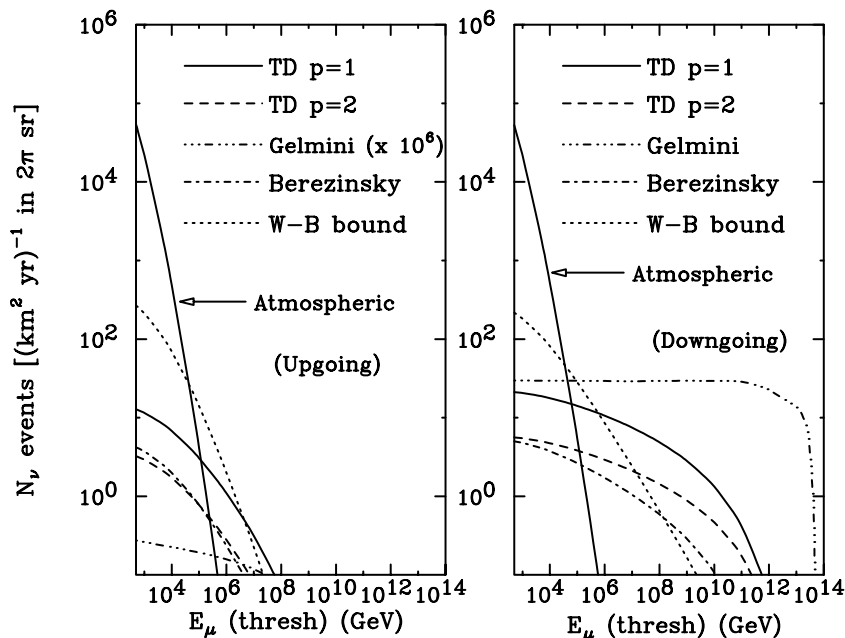
FIGURE 4. $\nu_\mu + \bar{\nu}_\mu$ event rates in IceCube from the fluxes in Fig.1. The plot shows the number of events in which the produced muon arrives at the detector with an energy above E_μ(thresh). Atmospheric neutrino events and the event rate expected from the Waxman and Bahcall upper bound (see text) are also plotted. The topological defect (TD) models shown (p=1 and p=2) correspond to $M_X = 10^{14}$ GeV. Upgoing and downgoing events are shown separately.

Kusenko are so energetic that they are absorbed, even in the horizontal direction as can be seen in Fig. 5.

Energy measurement is critical for achieving the sensitivity of the detector claimed. For muons, the energy resolution of IceCube is anticipated to be 25% in the logarithm of the energy, possibly better. The detector is definitely able to determine energy to better than an order of magnitude, sufficient for the separation of EeV signals from atmospheric neutrinos with energies below 100 TeV. Notice that one should also be able to identify electromagnetic showers initiated by electron and tau-neutrinos. The energy response for showers is linear, and expected to be better than 20%. Such EeV events will be gold-plated, unfortunately their fluxes are expected to be even lower. For instance for the first TD model in Table 2 (p=1, $M_X = 10^{14}$ GeV and $Q_0 = 6.31 \times 10^{-35}$ ergs cm^{-3} s^{-1}), we expect ~ 1 contained shower per year per km^2 above 1 PeV initiated in charged current interactions of $\nu_e + \bar{\nu}_e$. The corresponding number for the Gelmini and Kusenko flux is ~ 4 yr^{-1} km^{-2}.

One should also worry about the fact that a very high energy muon may enter the detector with reduced energy because of energy losses. It can, in principle, become indistinguishable from a minimum ionizing muon of atmospheric origin [17]. We
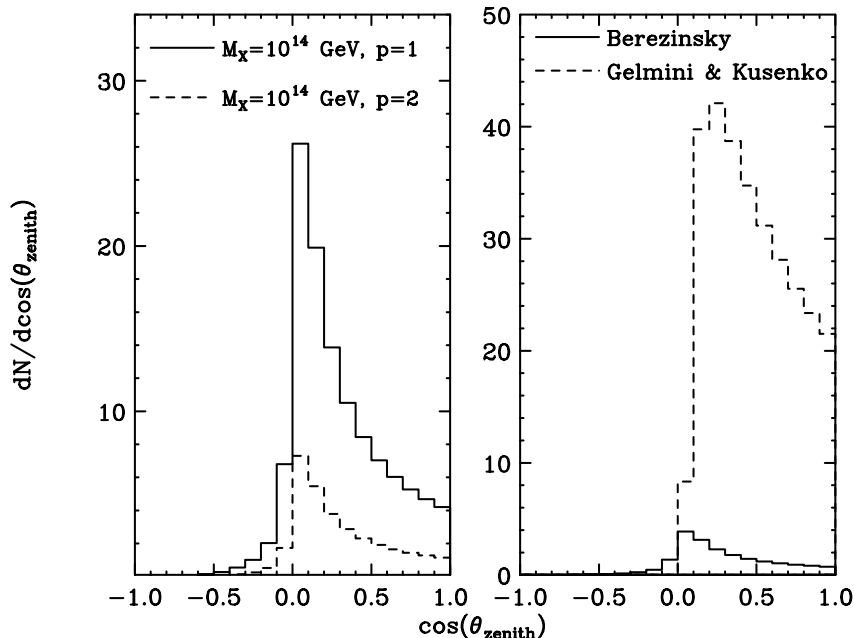
FIGURE 5. Zenith angle distribution of the $\nu_\mu + \bar{\nu}_\mu$ events in IceCube in which the produced muon arrives at the detector with energy above 1 PeV. Left: Topological defect models. Right: Superheavy relics. $\cos(\theta_{\text{zenith}}) = -1$ corresponds to vertical upgoing neutrinos, $\cos(\theta_{\text{zenith}}) = 0$ to horizontal neutrinos and $\cos(\theta_{\text{zenith}}) = 1$ to vertical downgoing neutrinos. The detector is located at a depth of 1.8 km in the ice.

have accounted for the ionization as well as catastrophic muon energy losses which are incorporated in the calculation of the range of the muon. In the PeV regime region this energy reduction is roughly one order of magnitude, it should be less for the higher energies considered here.

In conclusion, if the fluxes predicted by our sample of models for neutrino production in the super-EeV region are representative, they should be revealed by the IceCube observatory operated over several years.

ACKNOWLEDGEMENTS

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