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IceCube and High Energy Neutrinos

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IceCube is a 1km^3 neutrino telescope that was designed to discover astrophysical neutrinos and to find their sources. The construction of the detector was completed in 2010 and shortly thereafter, in 2013, the IceCube collaboration announced the discovery of astrophysical neutrinos. The first observation of $\sim$ PeV neutrinos has started a new era in neutrino astronomy. We present recent IceCube results on the astrophysical neutrinos flux measurements.

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1. Introduction

Neutrinos are unique probes in our quest to identify and understand the most powerful cosmic accelerators, such as Active Galactic Nuclei and Gamma Ray Bursts. Neutrino telescopes are designed to search for transient and for time-independent individual point sources of astrophysical neutrinos. A complementary approach to gain knowledge about the possible acceleration and neutrino production mechanisms, and thus the astrophysical sources, is to characterize and measure the flux of astrophysical neutrinos. Neutrinos from so-called pp sources, such as AGN cores, originate from the reaction $p+p \to N[\pi^+,\pi^-,\pi^0]+X$, where N denotes the multiplicity, and subsequent decay of the reaction products [1]. Neutrinos from $p\gamma$ sources, such as GRBs or AGN jets, originate from $p+\gamma \to \Delta^+ \to n\pi^+$ and subsequent decays [1]. When muon decay is suppressed relative to pion decay, this leads to a different neutrino flavor composition at the source. The neutrino flux flavor composition at Earth is further modified due to oscillation effects. The differences in these production chains cause observable differences in the astrophysical neutrino energy spectrum and its flavor composition [2]. Measurements and characteristics of neutrino energy spectra separated by flavor are thus of particular interest. In this paper, we describe the IceCube detector and neutrino detection channels, review recent results on the energy spectrum of the astrophysical neutrino flux, and present an outlook for the future.

2. The IceCube detector

IceCube, the South Pole neutrino observatory, is a gigaton neutrino detector [3], which recently discovered the highest-energy (PeV) extraterrestrial neutrinos [4]. It encompasses 1 km^3 of ice at depths between 1450 and 2450 m below the Antarctic surface and is capable of detecting neutrinos with energies from $\sim$10 GeV up to $\sim$100 EeV. The ice is instrumented with a total of 5160 optical sensors, digital optical modules or DOMs, on 86 strings deployed on a 125 m triangular grid. The IceCube array is complemented with the dense infill array DeepCore and the IceTop surface detector. The 60 DOMs on each string digitize the arrival time and intensity of Cherenkov radiation from particles produced in neutrino interactions and by cosmic ray background showers inside or near the detector. Data have been recorded with the completed instrument since 2011. The IceCube detector offers opportunities to disentangle the neutrino flavor content. The main neutrino detection signatures with IceCube are muon tracks, cascades (electromagnetic and hadronic showers) and hybrids, as is illustrated in Fig. 1 (top-left), and described below.

• Muon tracks. Muon neutrinos that undergo charged current (CC) interactions, $\nu_\mu + N \to \mu + X$, are identified by the pattern of DOM hits left by the final-state muon track. The hadronic shower, X, escapes detection if the neutrino interaction takes place outside of the detector volume. Reconstructed muon tracks have excellent angular resolution (better than 1°, dependent on the zenith angle) and an energy resolution of $\sim 0.2-0.3$ in $\log E$ [5].

• Cascades (electromagnetic and/or hadronic showers). Neutral current (NC) interactions of neutrinos of all flavors inside or near the detector volume, $\nu_{e,\mu,\tau} + N \to \nu_{e,\mu,\tau} + X$, as well as CC interactions of electron and tau neutrinos, $\nu_{e,(\tau)} + N \to e(\tau) + X$, are identified from the patterns of DOM hits from the produced electromagnetic and/or hadronic showers, so-called cascades. In CC interactions, on average 80% of the neutrino energy is transferred to the produced lepton. The

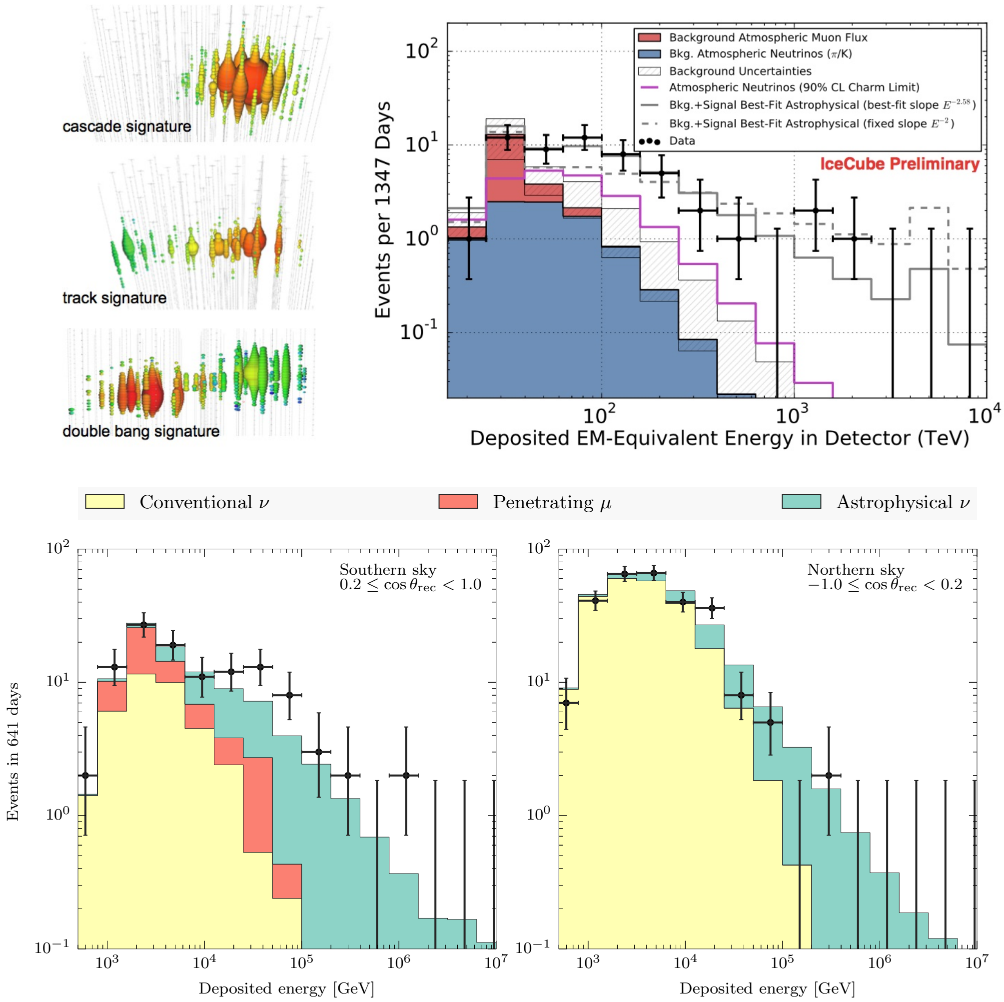

Figure 1: Top-Left: Neutrino event signatures in IceCube. Top-Right: 2010 – 2014 (4yr) all-sky HESE analysis [9]. Bottom: 2010 – 2012 (2yr) all-sky MESE neutrino results [10].

remaining 20% of the energy is transferred to the target nucleon, producing a hadronic cascade. In NC interactions, only a hadronic shower is produced. A cascade thus effectively appears as a point source of Cherenkov light in the detector. Cascades have very good energy resolution: $\sim 15(30)\,\%$ for fully (partially) contained events. The cascade angular resolution is about $15^\circ(30^\circ)$, depending on the specific event position in the detector, for fully (partially) contained cascades [6].

• Hybrids (examples). Muon neutrinos that undergo CC interactions inside the detector volume are identified by a combination of a track and a cascade (“Starting Events"). The $\sim$ PeV and more energetic ν_τ are expected to produce the so-called “double bang", a cascade pair separated by the τ decay length, $\nu_\tau + N \to \tau + X \to$ hadrons. No ν_τ events have been identified by IceCube so far [7].

3. Astrophysical neutrinos

In 2012 IceCube discovered the highest-energy (PeV) extraterrestrial neutrinos [4]. The first dedicated follow-up analysis was the *High Energy Starting Events* (HESE) analysis, sensitive to all neutrino flavors, and all directions in the sky. This analysis was later expanded towards lower energies (1 TeV) and is called *Medium Energy Starting Events* (MESE). The search for and the measurement of astrophysical neutrino fluxes was also performed in the muon track channel, sensitive to ν_μ from the Northern sky, and in the the cascade channel, sensitive to the $\nu_e + \nu_\tau$ from all directions in the sky. Below we discuss the results from these four analyses.

High Energy Starting Event (HESE) analysis. The HESE analysis was designed to discover a flux of astrophysical neutrinos of all flavors [8]. The most recent HESE analysis used the data from a 1347-day sample collected between 2010 and 2014 (4 years) [9]. The event selections required that all neutrino interaction events originated within the fiducial volume of the detector, which was done by employing an anti-coincidence veto method, and that the event total charge was larger than 6000 p.e. (corresponding to $\sim$ 30 TeV of energy deposited in the detector). The final event sample consisted of 54 events, and the highest energy event observed in this sample was 2 PeV. The atmospheric muon background was evaluated from the data and amounts to an estimated 12.6 ± 5.1 events. The contribution from atmospheric neutrinos, *conventional* neutrinos from π and K decays and *prompt* neutrinos from heavy quark decays, was estimated to be $9.0^{+8.0}_{-2.2}$ events. Such neutrinos are highly suppressed for events whose directions are from the Southern Sky, since they are expected to be accompanied by a muon track. In order to evaluate the astrophysical neutrino flux two maximum likelihood fits were performed, assuming an unbroken power-law spectrum $E^{-\gamma}$, with a variable spectral index and normalization. The results are shown in Fig. 1 (top-right), and as a green line in Fig. 3 (top-left). The best-fit spectral index was found to be $\gamma = 2.58 \pm 0.25$. The best-fit power law is $E^2\Phi(E) = (2.2 \pm 0.7) \times 10^{-8} (E/100\,\mathrm{TeV})^{-0.58}\,\mathrm{GeV} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$ in the energy range of $60\,\mathrm{TeV} < E_{\mathrm{dep}} < 3\,\mathrm{PeV}$. The spectral index of the flux and the flux normalization are correlated quantities. The HESE data sample is superior to identify a sample of astrophysical neutrinos, but it is by comparison not all that sensitive to evaluate precisely the astrophysical neutrino flux parameters given the limited number of neutrino events.

Medium Energy Starting Event (MESE) analysis. The HESE analysis [8] was extended to achieve better precision in the astrophysical flux spectrum measurement, primarily by lowering the charge and energy ($\sim$ 1 TeV) thresholds and by making the fiducial volume cut energy dependent. This so-called *Medium Energy Starting Event* (MESE) analysis is described in Ref. [10]. It is sensitive to all neutrino flavors and to all directions in the Sky. The MESE analysis used 641 days of data taken in $2010-2012$, and yielded 388 events (283 cascades and 105 muon tracks), with a neutrino purity of 92%). At the highest energies, the selection overlaps nearly completely with the selection of the HESE analysis. The results are given in Fig. 1 (bottom), which shows the deposited energy distributions from the Northern and Southern Skies. Both spectra have been fitted using a maximum likelihood method under the assumption that the data consist of atmospheric muons and neutrinos (both conventional and prompt), evaluated from Monte Carlo simulations, and an astrophysical flux. The best-fit power law is $\Phi(E) = (2.06^{+0.4}_{-0.3}) \times 10^{-18} (E/100\,\mathrm{TeV})^{-2.46 \pm 0.12}\,\mathrm{GeV}^{-1} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1} \cdot \mathrm{sr}^{-1}$ in the energy range of $25\,\mathrm{TeV} < E_\nu < 1.4\,\mathrm{PeV}$. Unexpectedly, the spectral index

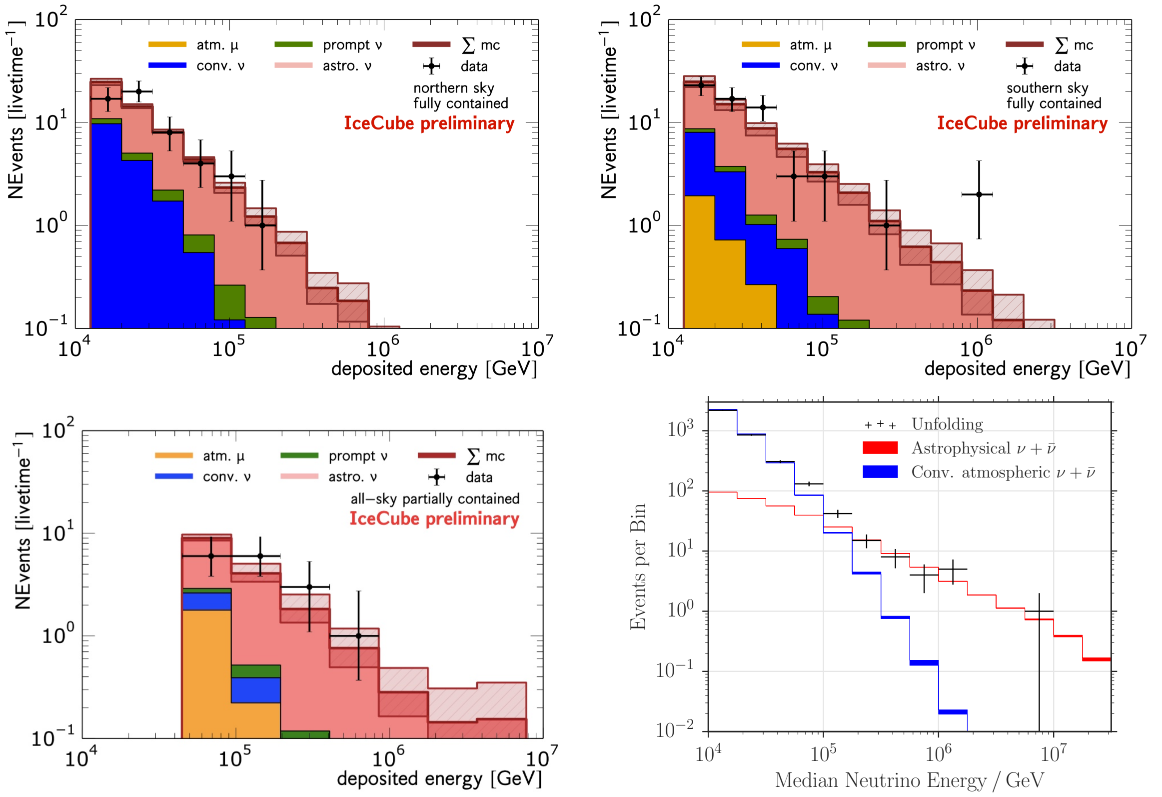

Figure 2: Top: 2010 – 2012 (2yr) all-sky fully contained $\nu_e + \nu_\tau$ induced cascade energy spectrum [6]. Bottom-Left: 2010 – 2012 (2yr) all-sky partially contained $\nu_e + \nu_\tau$ induced cascade energy spectrum [6]. Bottom-Right: 2009 – 2015 (6yr) Northern Sky median expected ν_μ energy spectrum [12].

was found to be softer than $\gamma = 2$ predicted by the Fermi acceleration model. Neutrinos of astrophysical origin(s) are present down to a deposited energy of 10 TeV (even though the simple power-law model does not describe the data very well in that energy range). The apparent excess around 30 TeV is not statistically significant, and additional data are needed to clarify the situation. The MESE analysis of data collected in 2012 and beyond is in progress.

Cascade analysis. Cascades, due to their good energy resolution compared to that for muon tracks, are particularly well suited for spectral characterizations. The most recent results from the cascade analysis used 641 days of data from 2010 – 2012 (2 years) [6]. The cascade analysis was extended at high energies by adding events with vertices outside but near the detector volume, thereby enlarging the event sample by a factor of two for $E > 100$ TeV. Such partially contained cascades have energy resolutions of $\sim 30\%$, worse than for fully contained cascades, but sufficient for energy spectrum measurements. By definition, partially contained cascades are not part of MESE nor HESE event sample. A total of 172 events with energies from 10 TeV to 1 PeV, have been selected for the analysis presented here after imposing event topology cuts to reduce atmospheric backgrounds. Approximately 60% (75% above 100 TeV) are events not selected by the HESE and MESE analyses. The neutrino event sample purity of 90% was estimated from Monte Carlo simulations. The analysis primarily selects electron and tau neutrinos. The result for the astrophys-

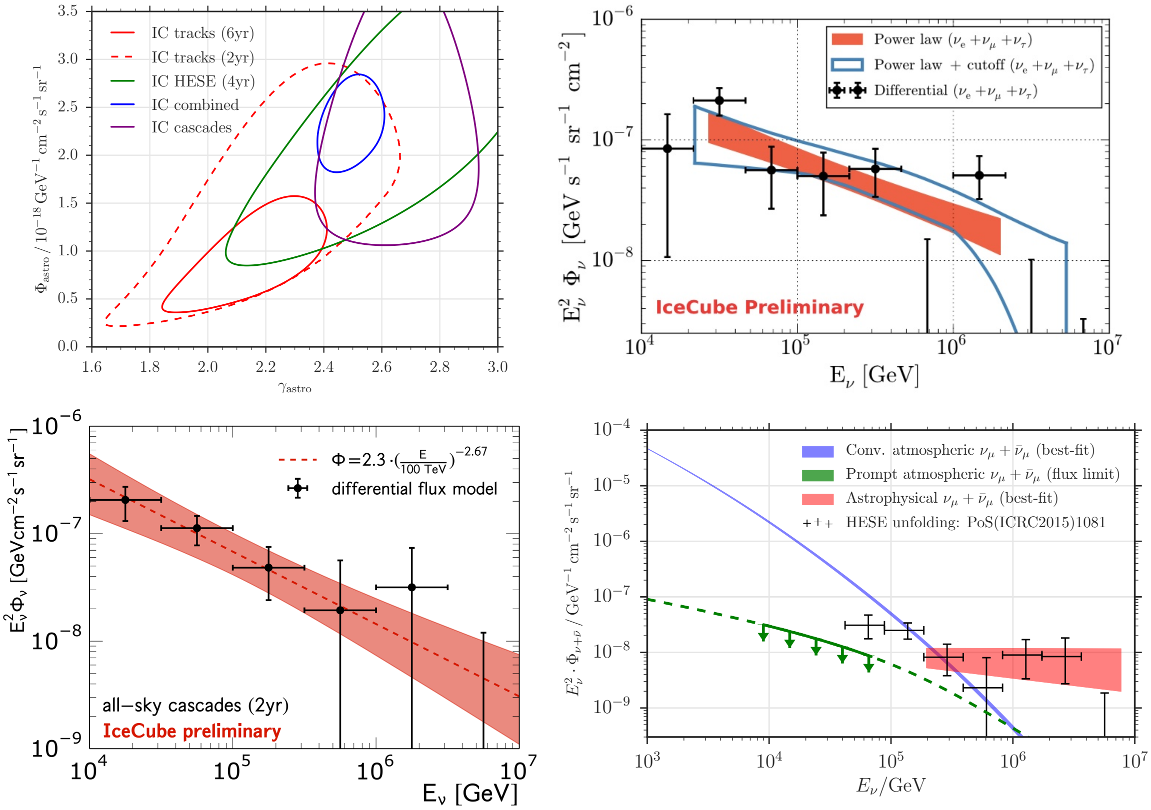

Figure 3: Top-Left: Results of different IceCube analyses measuring the astrophysical flux parameters $\Phi_{\rm astro}$ and $\gamma_{\rm astro}$ [12]. The contour lines show the 90% CL. Top-Right: The unfolded astrophysical neutrino flux of the combined IceCube samples. Shown are the spectra allowed at 68% C.L. for the power law and power law + cutoff hypotheses [13]. The unfolded astrophysical neutrino flux of the cascade analysis ($\nu_e + \nu_\tau$) [6] (Bottom-Left) and the HESE analysis [9, 12] (Bottom-Right).

ical neutrino flux of $\Phi(E) = (2.3^{+0.7}_{-0.6}) \times 10^{-18}(E/100\,\mathrm{TeV})^{-2.67^{+0.12}_{-0.13}}\,\mathrm{GeV}^{-1}\cdot\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}\cdot\mathrm{sr}^{-1}$ in the energy range of $25\,\mathrm{TeV} < E_\nu < 1.4\,\mathrm{PeV}$, was obtained by fitting a combination of atmospheric background contributions (evaluated from the Monte Carlo simulations) and the single unbroken power-law distribution of astrophysical neutrinos to the data, as shown in Fig. 2. The cascade data disfavor a E^{-2} spectrum at 3.5σ. Astrophysical neutrino fluxes evaluated separately for events from the Northern and from the Southern skies were found to be consistent to within large uncertainties. An improved cascade analysis, expanding to energies below 10 TeV with better systematic uncertainties (mostly due to energy scale) and a larger sample from four years of data $(2012-2015)$ is in progress.

Muon tracks analysis. A complementary muon neutrino flux from the Northern Sky was reported in [11]. The most recent results were obtained from six years of data $(2009-2015)$ [12]. The ν_μ analyses select charged current ν_μ events with the interaction vertex typically located outside the detector volume, which significantly enlarges the effective area compared to the starting event (HESE, MESE) and cascade analyses. Due to irreducible cosmic ray muon background, the muon neutrino sample is restricted to only those originating from the Northern sky. A likelihood approach was used to analyze the data, with reconstructed muon energy and zenith angle as observables. Fig. 2 (bottom-right) shows that the data are described well by the best-fit unbroken power law flux $\Phi(E) = (0.90^{+0.30}_{-0.27}) \times 10^{-18} (E/100\,\mathrm{TeV})^{-2.13\pm0.12}\,\mathrm{GeV}^{-1}\cdot\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}\cdot\mathrm{sr}^{-1}$. The flux normalization and spectral index parameters are correlated. The 90% CL contour is shown as a continuous red line in Fig. 3. At the highest neutrino energies between 194 TeV and 7.8 PeV a significant astrophysical contribution is observed, excluding a purely atmospheric origin of these events at 5.6σ significance.

Comparisons between IceCube astrophysical neutrino diffuse flux analyses. Figure 3 (top-left) shows the results from different IceCube analyses measuring the astrophysical flux parameters Φ_{astro} and γ_{astro}. The contour lines show the 90% CL. The results of 6 yr (2 yr) ν_μ analysis is shown as the red solid (dashed) contour line. There is a slight tension between the fitted astrophysical neutrino spectrum parameters of the ν_μ analysis and the analyses with lower energy thresholds. This might indicate a break in the astrophysical neutrino spectrum, around 200 TeV, as indicated in Fig. 3 (bottom-right). New multi-year data analyses with lower energy thresholds (MESE and cascade analyses) and needed to further clarify the situation. Such analyses are on-going.

4. Summary and Outlook

We have presented a summary of recent results on astrophysical neutrino fluxes measured by IceCube in complementary detection channels and in different energy ranges. The observed flux is large, at the level of Waxmann-Bahcall bound [14]. The flux is isotropic, so its origin must be predominantly extragalactic. The spectral index evaluated from the ν_μ data from the Northern sky is harder than the index evaluated from the all-sky data analyses (HESE, MESE and cascades) with lower energy thresholds. More statistics is needed to clarify the situation, in particular to test more complex models of the astrophysical flux, beyond a single power-law spectrum. Such multi-year analyses are on-going. The origin of the astrophysical neutrinos is unknown. Even high energy muon neutrinos, which are characterized by very good angular resolution, show no correlation with known γ-ray sources, even though neutrinos and gammas are produced in the same hadronic interactions. IceCube searches for transient and for time-independent individual point sources of astrophysical neutrinos have so far yielded a null-result [5]. The quest for cosmic accelerators and acceleration mechanisms thus continues. Even though IceCube is anticipated to take data for the foreseeable future, an even larger detector may eventually be needed. An upgrade, IceCube-Gen2 [15], is currently being designed. The goal is to increase the observation rate of cosmic neutrinos by a factor of ten, and to discover sources at least five times fainter compared to IceCube. Stay tuned!

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PoS(NOW2016)041

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PoS(NOW2016)041