



Fig. 4 | Measured flux of astrophysical neutrinos. Global picture of astrophysical neutrino flux measurements^{21,24}, cosmogenic neutrino upper limits (UL)^{15,34,35} and the ultra-high-energy cosmic-ray spectrum³⁶. The y axis is given in terms of the energy, E , squared times the flux, Φ . We assume the ratio $\bar{\nu}:\nu=1:1$, a flavour ratio of 1:1:1 at Earth, an astrophysical spectrum measured

from ref.², and cross-sections according to equation (1) and ref.³². This result extends the measured astrophysical flux to 6.3 PeV. The luminosity densities of high-energy neutrinos and extragalactic ultra-high-energy cosmic rays are found to be comparable.

measurement of the differential neutrino energy spectrum to 6.3 PeV, while 68% upper limits are shown for the lower and upper energy bins. Arguments based on energetics²⁵ and astrophysical unification models^{26–30} suggest a common origin of diffuse γ -rays, high-energy neutrinos and ultra-high-energy cosmic rays. A precise measurement of the cosmic neutrino flux at the Glashow resonance energy would be able to test these predictions, and possibly uncover the origins of ultra-high-energy cosmic rays if the sources can be identified directly via multimessenger observations.

Although the present results focus on just one event, the techniques developed here have implications for the future direction of neutrino astrophysics. For example, the idealized $p\gamma$ muon damped model of neutrino production is already inconsistent with the result presented here of a likely Glashow resonance because such sources produce no electron antineutrinos. With just one event, pp source models cannot be constrained, but the planned IceCube-Gen2 experiment¹⁹ will increase the instrumented volume by an order of magnitude. The statistics collected by such a detector should allow us to differentiate between pp and idealized $p\gamma$ models at a high significance level.

In more realistic source models³¹, multi-pion production in $p\gamma$ sources generates antineutrinos and the $\bar{\nu}_e:\nu_e$ ratio depends on the photon density, the mass composition of cosmic rays and also the magnetic field strength of the source. In such cases, a multi-messenger campaign to detect the sources of future Glashow resonance candidates could help determine their production mechanisms. Using the hybrid (early muon and cascade reconstruction) approach could reduce the angular uncertainty by a factor of about 5, and, as this technique shows, an uncertainty of about 68 deg² at 90% containment is possible for hadronic cascades. In the near future, such techniques would greatly aid searches for multimessenger counterparts in real time.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-021-03256-1>.

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