NOW 2022 Multi-messenger Astrophysics

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In this paper, we resume the Multi-messenger Astrophysics parallel session of the Neutrino Oscillation Workshop (NOW) 2022. The session highlighted recent experimental and theoretical works concerning astrophysical neutrino and correlated signatures in cosmic/gamma rays and gravitational waves.

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1. Introduction

In this paper we draw a summary of the contributions included in the parallel session covering experimental and theoretical aspects of neutrino production and detection, and their interplay with cosmic/gamma rays and Gravitational Waves (GW), in the context of Multi-Messenger (MM) astronomy. In particular, the experimental talks included the latest results and prospects from the ANTARES and KM3NeT neutrino telescopes, LHAASO and Tibet AS-gamma observatories, DAMPE and HERD cosmic/gamma ray missions. On the other hand, theoretical talks covered galactic and extragalactic sources of neutrino, such as Core-Collapse Supernovae, Active Galactic Nuclei (AGN), Tidal Disruption Events and binary mergers. In particular, detection of high-energy neutrinos is important for the study of PeVatrons – sources capable of cosmic ray acceleration to the knee and higher energies.

In the subsequent sections we first give a brief recap of the status of experiments, presented in the NOW 2022 MM parallel session. We start with an overview of the under-sea neutrino telescopes, then we continue with the ground-based high-energy gamma-ray instruments, and finish with the spaceborne astroparticle detectors. After that, we focus on key discussion items in the session, both in theoretical and experimental parts of the community: search for extragalactic neutrino factories, galactic neutrino sources, and hunt for PeVatrons. Summary is given in the last section.

2. Neutrino under-sea telescopes

ANTARES is the first under-sea neutrino telescope and a precursor of the next generation KM3NeT instrument. It started operation in 2006 and was decommissioned in June 2022. The detection principle is aimed on two type of events: muon tracks and cascade shower-like interactions. The latter provides better energy resolution, however at the cost of reduced angular accuracy. **M. Spurio** summarised the physics program of ANTARES, which includes the studies of neutrino oscillations (energies up to $\sim$10 GeV), Dark Matter (DM) and exotics searches (10 GeV–10 TeV), and searches for galactic and extragalactic sources (TeV–PeV) which may be associated with the production of high-energy cosmic rays. Among the key results are the exclusion of neutrino no-oscillation hypothesis (ν_μ) at 4.6 σ [2], eV-scale sterile neutrino searches [3, 2] complementary to IceCube and Super-Kamiokande, indirect search for DM from the Sun [4, 5, 6, 7], measurement of the atmospheric neutrino background [8], searches for excess in the diffuse flux [9], search for cosmic-ray sources [10] and catalog-based searches [11]. An intriguing overlap in time of the flaring emission in radio, gamma-ray and neutrino was found from the direction of the blazar J0242+1101, studied from 2008 to 2021 [12]. A dedicated alert systems is implemented – TAToO (Telescopes and Antares Target of Opportunity), operating since 2009 [13]. Notably, no ANTARES candidates were found compatible with any of the IceCube alerts [14, 15, 16]. Similarly, no candidates were found associated with LIGO/Virgo GWs events, Fermi and Swift Gamma-Ray Bursts, and HAWK alerts [17]. Following the ANTARES decommissioning, the construction has started for the MK3NeT – the next generation neutrino telescope in the Mediterranean Sea. The detecting units (DU) are currently being placed in two sites – ARCA (Astroparticle Research with Cosmics at the Abyss) at 3400 m, and ORCA (Oscillation Research with Cosmics In the Abyss) at 2470 m, with 19 and 10 DUs respectively, installed so far. MK3NeT will provide better median angular resolution ($\sim$0.1° @ 1 PeV) and $\times$100 ANTARES instrumented volume (ARCA).

3. High-energy gamma ray telescopes

T. K. Sako presented the latest results of Tibet AS-gamma muon detector array, located in Tibet, China. The detection principle relies on the measurement of number of muons in the air shower, with the total detector surface of about 3400 m^2. In 2019, the experiment provided the first detection of gamma rays with energy higher than 100 TeV from an astrophysical source, Crab nebula [18], which was later also confirmed by LHAASO-KM2A measurement, in 2021 [19]. The energy spectrum of photons can be explained by Inverse Compton scattering of electrons. A series of further gamma-ray observations at 100 TeV, were published recently, with a potential Supernovae Remnant (SNR) PeVatron G106.3+2.7 [20], and sources in Cygnus [21] and HESS J1843–033 [22] regions. An observation of sub-PeV diffuse gamma rays from the Milky Way galaxy were reported in 2021 [23], with no correlation with the known TeV sources. The measured fluxes after excluding the contribution from the known TeV sources are reasonably consistent with Lipari's galactic diffuse gamma-ray model assuming the hadronic cosmic-ray origin [23, 24]. It is emphasised that the observed gamma rays are isolated, not coming from known gamma-ray sources, which speaks in favour of hadronic origin of the detected sub-PeV photons, since in case of electron origin the photons would tend to cluster near the sources. It is therefore claimed to be the first evidence for existence of PeVatrons, in the past and/or present Galaxy, which accelerate protons up to the PeV region.

D. Della Volpe presented the status and prospects of LHAASO. The facility comprises four DU types: surface water Cherenkov detectors ($\sim$78000 m^2); $\sim$1200 underground water Cherenkov tanks; $\sim$5200 scintillator detectors; a Wide Field-of-View Cherenkov Telescope Array (WFCTA), consisting of 12 telescope units. Notably, WFCTA covers 1/7 of the sky at any moment and about 60% of sky per day. It is capable of detecting photons in the range from 0.1 to 100 PeV. Among the prominent results of LHAASO is the discovery of sources in $\sim$100 TeV region: LHAASO J0341+5258 [25] with no counterpart in other wavelengths and lack of association with an energetic pulsar or a young SNRs in the vicinity, which finds challenging explanations in both leptonic and hadronic scenarios; LHAASO J2108+5157 [26] compatible with both leptonic and hadronic origins, but a nearby molecular cloud favouring a hadronic one; PSR J0622+3749 consistent with scenario of particles in the turbulent medium around pulsars as inferred from the of Geminga and Monogem [27]. LHAASO also provides new insights in the Crab spectrum measurement [19], which agrees with the other experiments below 100 TeV but challenges the electron acceleration hypothesis [27]. The LHAASO spectrum unambiguously suggest PeVatron of a clear well-known Pulsar Wind Nebula (PWN) origin [19, 27]. Next, the LHAASO measurement of Lorentz Invariance Violation [28] improves one order of magnitude over the existing limits. Finally, the cosmic ray results were presented, including the measurement of H+He spectrum around the knee [29] from the combination of ARGO-YBJ and LHAASO WFCTA data, and the prospects for the Iron knee measurements, which would require from 3 to 6 years of data taking.

4. Cosmic rays and gamma rays in Space

C. Perrina outlined the recent results from the DArk Matter Particle Explorer (DAMPE) – a particle detector in space capable of measuring cosmic ray protons/ions up to few hundreds TeV and electrons/photons up to tens of TeV. The status and prospects were also presented for the next-generation experiment, High Energy Radiation Detection Facility (HERD), to be launched to space in the observable future. DAMPE is collecting data since 2015, providing new insights into cosmic rays at highest energies accessible in direct-detection experiments. In particular, the first observation of a break in cosmic ray electron spectrum at ∼0.9 TeV was reported in 2017 [30]. Later, the measurements of cosmic ray proton [31] and helium [32] spectra up to particle kinetic energies of 100 TeV and 80 TeV respectively were published, indicating of a spectrum softening structure both for protons and helium at about ∼10 TeV per nucleon. The collaboration is also working on the combined H+He spectrum, as well as extending the standalone H and He measurements towards the knee energies [33]. Recent detection of hardening in B/C ratio sheds new light on cosmic ray propagation mechanisms [34]. The results in gamma ray domain put new constraints on DM annihilation and decay cross-sections [35]. While DAMPE is by far the biggest calorimeter detector in Space, HERD mission will boost the acceptance even further, providing the detection of cosmic ray proton and helium at least up to a few PeV. Thanks to even better energy resolution and order of magnitude larger acceptance it will be an excellent instrument for cosmic ray electron (plus positron) measurements, with a goal of distinguishing potential DM contributions from conventional astrophysical sources. HERD is planned to be installed on board of Chinese Space Station after 2027.

5. Extragalactic Neutrino Factories

Among other, high-energy neutrinos provide an indirect probe of cosmic ray accelerators, in attempt to identify the cosmic rays sources and their contribution to different parts of cosmic ray spectra, mechanisms of cosmic ray acceleration and their propagation. High-energy neutrinos are detected in deep sea water telescopes like ANTARES and KM3Net, or large ice volume detectors like IceCube in Antarctica. Currently, IceCube provides the highest quality data for neutrino point-source searches publicly available. However, a blind all-sky search of 10 years data as well as tests with the extragalactic candidates made before the NOW 2022 conference, show neither individual neutrino-source detected at high confidence, nor source classes – events are isotropically distributed, favoring extragalactic origin. On the other hand, a significant astrophysical contribution is observed at the highest neutrino energies, ∼100 TeV. The observed spectrum is harder in comparison to previous IceCube analyses with lower energy thresholds which may indicate a break in the astrophysical neutrino spectrum of unknown origin. A plausible candidates are blazars – a class of extragalactic sources powered by supermassive black holes, that produced jets pointed towards the Earth. In her talk, based on [36], **S. Buson** presented an interesting statistical study of cross-correlation among the IceCube 7 years data and the 5BZCat catalog of radio loud blazars. In this work, it is shown that blazars can be unambiguously associated to high-energy IceCube neutrinos at high level of confidence corresponding to chance probability of 6×10^{-7} [36]. In particular, 10 blazars in the Southern celestial hemisphere are confidently associated with IceCube neutrino clusters. The intriguing and new hint in this result is that only one of these blazars is also emitting high-energy GeV gamma rays [14]. This supports the idea that hidden high-energy neutrino sources, opaque to the electromagnetic high-energy emission could be the best candidates to look for correlations. This hypothesis is in agreement with the very recent discovery on November 2022 of a 4.2σ IceCube neutrinos emitted by the nearby active galaxy NGC 1068 [37].

While AGNs are considered as potential steady sources of high-energy neutrinos, also transient phenomena are deeply discussed as candidates for the high-energy neutrinos observed by IceCube. In particular, in the MM parallel session we had two contributions on this topic, one from E. Guarini, discussing Gamma Ray Burst (GRBs) and Luminous Fast Blue Optical Transients (LFBOTs), and one from S. Reusch, discussing Tidal Disruption Events. Concerning GRBs, **E. Guarini** discussed the high-energy neutrino emission from a subset of GRBs with afterglow light curves exhibiting very complex temporal and spectral features, such as a sudden intensity jump about one hour after the prompt emission in the optical band. This peculiar sudden re-brightening cannot be explained inside the standard fireball model while could be interpreted as due to the late collision of two relativistic shells. This collision will increase the neutrino expectations by about an order of magnitude with respect to the self-similar afterglow scenario [38].

Concerning LFBOTs, that constitute an intriguing new class of transients evolving on timescales < 10 days, their astrophysical engine is still debated. Supposing that they are powered by a compact object launching an asymmetric and fast outflow, Guarini et al.[39] explored neutrino production mechanisms. In particular, neutrinos could be produced by internal shocks in a choked jet and by interaction between the outflow and the circumstellar medium.

Tidal Disruption Events (TDEs) are rare transient phenomena occurring when stars pass close enough to a super massive black hole and get destroyed by tidal forces. This event produces a luminous electromagnetic flare with a timescale of months and can also generate a correlated high-energy neutrino emissions. In his talk, **S. Reusch** summarized on three TDEs associations with IceCube high energy neutrino events, i.e. AT2019dsg [40], AT2019fdr [41] and AT2019aalc. Atmospheric origin of the high-energy neutrinos in these associations cannot be excluded, however the temporal and spatial coincidences of TDEs multi-wavelength electromagnetic and neutrino emissions reinforce the evidence in favor of a common astrophysical origin. Interestingly, both AT2019dsg and AT2019fdr show also a dust echo indicating the presence of large amounts of matter and an associated high star formation rate in the environment.

6. Galactic Neutrino Sources

High energy neutrinos and gamma rays carry direct information on cosmic ray density and propagation. Indeed, both signals are produced by the hadronic interaction of cosmic rays with the interstellar gas. In particular, non-homogeneous diffusion can enhance gamma ray and neutrino emission, while molecular clouds/dense environments boost the corresponding fluxes. **L. Fusco** discussed the searches for galactic diffuse high-energy neutrinos with the galactic plane templates performed using the combined ANTARES and IceCube data set [42]. Similar to the blazar analysis, the source patterns are expected to yield harder spectrum compared to the expected atmospheric neutrino background. The ANTARES+IceCube sensitivities are at the edge of discovery for the diffuse galactic signal. In order to boost the sensitivity, both collaborations are working on increasing the data statistics, in particular by including the shower events in addition to the track events. ANTARES already used shower events in their sample. However, a new analysis is being performed at the moment which will increase further the shower event sample. Depending on the energy, the effective acceptance will be increased by factor of 2 to 10 [8]. IceCube has already produced a first result with showers from the galactic plane, with ~ 5 times worse angular resolution than ANTARES [43]. However, a new IceCube sample is recently obtained using Neural Network selection to expand towards southern sky, which yields $\sim$5 times more statistics with similar foregrounds and improved direction reconstruction [44]. The new sample demonstrate significantly higher sensitivity and credible discovery potential. The actual data analysis is yet to come. While ANTARES and IceCube are at the edge of the discovery, KM3Net will further increase sensitivity, with better angular precision and good rejection of foregrounds [45]. Note that the northern hemisphere telescopes offer better source pointing, as most of galactic gamma ray sources are in the southern sky.

As stated before, the study of the diffuse Galactic high-energy neutrino and gamma-ray signals can provide a handle to investigate the cosmic ray distribution and propagation in our galaxy. **C. Evoli** provided an overview of the galactic cosmic ray phenomenology with a special focus on cosmic ray composition. In particular, he highlighted that the AMS-02 data reporting the spectra of intermediate-mass nuclei are in good agreement with the standard diffusive Galactic Halo model. Parameters derived from lighter primary and secondary elements in cosmic radiation also lead to a good description of the data on heavier nuclei, with no need to invoke different injection spectra for such nuclei. Only the Fe/O flux is hard to reconcile within this model [48]. Moreover, Evoli has also discussed the cosmic electrons and positrons from random sources like supernova remnants and pulsars, distributed within the spiral arms of the Galaxy. He showed that the spectrum of positrons is very well described by the contribution of pulsars and the rising positron fraction originates naturally [49].

A relevant discussion of the NOW 2022 MM parallel session has been devoted to Core-Collapse Supernovae (CCSNe). These transient sources are the prime example of multi-messenger sources with total energy emitted of several 10^{53} ergs not equally distributed among MeV neutrinos, photons and GWs. While neutrinos and photons have been contemporarily observed already in one case, SN1987A, and their detection for future Galactic CCSNe is a certainty, while the detection of the related GW burst is still challenging. **K. Kotake** summarized the last results and updates concerning neutrino and GW signals from CCSNe obtained by the 3D “MHD” supernova modeling for rotating progenitors[46]. In particular, the peak frequencies of SASI (Standing Accretion Shock Instability)-modulated neutrino and GW signals become higher with progenitor rotation, because rapid rotation leads to rapidly rotating proton-neutron star and neutrino sphere. Moreover, the peak frequency of the GW signal is twice of the neutrino modulation frequency, providing a smoking gun signature of a rapid core rotation. He also reported on observable signatures of a first-order quantum chromodynamics phase transition in the context of CCSNe with a distinct second burst signals both in GWs and neutrinos [50]. In the contest of CCSNe, the role of fast-pairwise collective neutrino oscillations is still a key uncertainty. **L. Johns** in his talk provided a complete and updated summary of the current state of our understanding of neutrino flavour mixing in CCSNe and neutron-star mergers. In particular, there is a strong evidence for the appearance of fast flavour instabilities, related to the asymmetrical angular distribution of neutrinos and antineutrinos in CC-

SNe [51]. Several phenomena can generate an electron neutrino lepton number asymmetry, like proto-neutron star convection, asymmetric neutrino emission, neutrino absorption and scatterings. These results suggest that we need to incorporate fast flavor conversions in realistic CCSN models, however we are still far away from reaching this goal [52].

Finally, **S. Goswami** suggested an alternative approach for analytic treatment of neutrino decay and oscillation in matter [53, 54]. It is emphasized that in the presence of decay the Hamiltonian is non-hermitian, hence decay eigenstates and mass eigenstates are not simultaneously diagonalisable by Unitary transformations [55]. Subsequently, a formalism is developed for the two-flavor [53] and three-flavor [54] neutrino propagation through matter of uniform density with invisible neutrino decay. Neutrino oscillation probabilities are derived as perturbative expansions for different decay scenarios. Such calculations of probabilities in varying density are relevant for astrophysical sources of neutrinos like Sun and Supernovae.

7. Search for Galactic PeVatrons

Supernovae Remnants (SNRs) are considered the most plausible cosmic ray accelerators in the galaxy [56]. An important confirmation of SNR cosmic ray origin comes from the detection of gamma rays produced in hadronic (pion decay) and leptonic (inverse Compton scattering) processes, see e. g. [57]. However, it is difficult to explain galactic cosmic ray acceleration up to PeV or higher energies in SNR with conventional production and propagation mechanisms [56, 58, 59]. An overview of searches for galactic PeV cosmic ray sources (PeVatrons) is presented by **P. Cristofari**. In particular, data indicates that knee of protons is at $\sim$PeV [29], while for heavier elements the knee is likely Z dependent [60]. The galactic sources must therefore accelerate cosmic rays up to at least the knee, $\sim$100 TeV [61]. As of now, numerous PeVatrons are detected by LHAASO [62], HESS [63], HAWK [64] and Tibet AS-gamma [23]. However, none of them seem to be attributed to SNR. It appears that multiple galactic sources contribute to the knee: superbubbles, stellar clusters, massive stars, young pulsars, leptonic sources, supernovae, SNRs. It is debatable what is the dominant source at the knee and whether it could be SNRs, e.g. young energetic SNRs in the initial period after supernovae explosion. Major contribution may still be coming from SNRs, however they may not be detected with CTA. Sensitivity to SNR PeVatrons is now actively discussed in the CTA community.

8. Summary

In the NOW 2022 MM parallel session the latest results from the deep-sea neutrino, gamma ray and cosmic ray experiments were presented, together with the latest theoretical developments focused on the description of high-energy neutrino data. In particular, transition from ANTARES to KM3NET will boost the sensitivity to neutrino sources thanks to the two orders of magnitude increase in the instrument volume. As of now, combined IceCube+ANTERES data is already at the edge of discovery of neutrino sources and the corresponding analysis is ongoing. Tibet AS-gamma and LHAASO in the past few years discovered a series of $\sim$100 TeV gamma-ray sources, and sub-PeV diffuse gamma rays, indicative of a hadronic PeVatron. While there are potential SNR PeVatrons, majority of discovered sources are likely of non-SNR origin. An active discussion is ongoing about the origin of ∼100 TeV IceCube neutrinos, which could be attributed both to steady sources, like AGNs and Blazars, or transients like GRBs or TDEs. Finally, the cosmic ray data appear to be in reasonable agreement with the standard diffusive Galactic Halo model, however significant tensions are still present, in particular in Fe/O ratio.

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References

[1] K. Murase and E. Waxman, *Constraining High-Energy Cosmic Neutrino Sources: Implications and Prospects*, Phys. Rev. D **94** (2016) 103006 [1607.01601].

[2] ANTARES collaboration, *Measuring the atmospheric neutrino oscillation parameters and constraining the 3+1 neutrino model with ten years of ANTARES data*, JHEP **06** (2019) 113 [1812.08650].

[3] ANTARES collaboration, *Search for non-standard neutrino interactions with 10 years of ANTARES data*, JHEP **07** (2022) 048 [2112.14517].

[4] ANTARES collaboration, *Search for Dark Matter Annihilation in the Earth using the ANTARES Neutrino Telescope*, Phys. Dark Univ. **16** (2017) 41 [1612.06792].

[5] ANTARES collaboration, *Limits on Dark Matter Annihilation in the Sun using the ANTARES Neutrino Telescope*, Phys. Lett. B **759** (2016) 69 [1603.02228].

[6] ANTARES collaboration, *A search for Secluded Dark Matter in the Sun with the ANTARES neutrino telescope*, JCAP **05** (2016) 016 [1602.07000].

[7] ANTARES collaboration, *First results on dark matter annihilation in the Sun using the ANTARES neutrino telescope*, JCAP **11** (2013) 032 [1302.6516].

[8] ANTARES collaboration, *Measurement of the atmospheric ν_e and ν_μ energy spectra with the ANTARES neutrino telescope*, Phys. Lett. B **816** (2021) 136228 [2101.12170].

[9] ANTARES collaboration, *All-flavor Search for a Diffuse Flux of Cosmic Neutrinos with Nine Years of ANTARES Data*, Astrophys. J. Lett. **853** (2018) L7 [1711.07212].

[10] ANTARES collaboration, *First all-flavor neutrino pointlike source search with the ANTARES neutrino telescope*, Phys. Rev. D **96** (2017) 082001 [1706.01857].

[11] ANTARES collaboration, *ANTARES Search for Point Sources of Neutrinos Using Astrophysical Catalogs: A Likelihood Analysis*, Astrophys. J. **911** (2021) 48 [2012.15082].

[12] ANTARES collaboration, *ANTARES search for neutrino flares from the direction of radio-bright blazars*, PoS **ICRC2021** (2021) 972.

[13] M. Ageron et al., *The ANTARES telescope neutrino alert system*, Astroparticle Physics **35** (2012) 530.

[14] ANTARES collaboration, *The Search for Neutrinos from TXS 0506+056 with the ANTARES Telescope*, Astrophys. J. Lett. **863** (2018) L30 [1807.04309].

[15] ANTARES collaboration, *Search for Neutrinos from the Tidal Disruption Events AT2019dsg and AT2019fdr with the ANTARES Telescope*, Astrophys. J. **920** (2021) 50 [2103.15526].

[16] ANTARES collaboration, *ANTARES neutrino search for time and space correlations with IceCube high-energy neutrino events*, Astrophys. J. **879** (2019) 108 [1902.09462].

[17] ANTARES, ICECUBE, PIERRE AUGER, LIGO SCIENTIFIC, VIRGO collaboration, *Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory*, Astrophys. J. Lett. **850** (2017) L35 [1710.05839].

[18] M. Amenomori et al., *First Detection of Photons with Energy Beyond 100 TeV from an Astrophysical Source*, Phys. Rev. Lett. **123** (2019) 051101 [1906.05521].

[19] LHAASO*†, LHAASO collaboration, *Peta–electron volt gamma-ray emission from the Crab Nebula*, Science **373** (2021) 425 [2111.06545].

[20] TIBET ASγ collaboration, *Potential PeVatron supernova remnant G106.3+2.7 seen in the highest-energy gamma rays*, Nature Astron. **5** (2021) 460 [2109.02898].

[21] TIBET ASγ collaboration, *Gamma-Ray Observation of the Cygnus Region in the 100-TeV Energy Region*, Phys. Rev. Lett. **127** (2021) 031102 [2107.01064].

[22] M. Amenomori et al., *Measurement of the Gamma-Ray Energy Spectrum beyond 100 TeV from the HESS J1843–033 Region*, Astrophys. J. **932** (2022) 120.

[23] TIBET ASGAMMA collaboration, *First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies*, Phys. Rev. Lett. **126** (2021) 141101 [2104.05181].

[24] P. Lipari and S. Vernetto, *Diffuse galactic gamma-ray flux at very high energy*, Phys. Rev. D **98** (2018) 043003.

[25] LHAASO collaboration, *Discovery of a New Gamma-Ray Source, LHAASO J0341+5258, with Emission up to 200 TeV*, Astrophys. J. Lett. **917** (2021) L4 [2107.02020].

[26] LHAASO collaboration, *Discovery of the Ultrahigh-energy Gamma-Ray Source LHAASO J2108+5157*, Astrophys. J. Lett. **919** (2021) L22 [2106.09865].

[27] LHAASO collaboration, *Extended Very-High-Energy Gamma-Ray Emission Surrounding PSR J0622+3749 Observed by LHAASO-KM2A*, Phys. Rev. Lett. **126** (2021) 241103 [2106.09396].

[28] LHAASO collaboration, *Exploring Lorentz Invariance Violation from Ultrahigh-Energy γ Rays Observed by LHAASO*, Phys. Rev. Lett. **128** (2022) 051102 [2106.12350].

[29] ARGO-YBJ, LHAASO collaboration, *Knee of the cosmic hydrogen and helium spectrum below 1 PeV measured by ARGO-YBJ and a Cherenkov telescope of LHAASO*, Phys. Rev. D **92** (2015) 092005 [1502.03164].

[30] DAMPE collaboration, *Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons*, Nature **552** (2017) 63 [1711.10981].

[31] DAMPE collaboration, *Measurement of the cosmic-ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite*, Sci. Adv. **5** (2019) eaax3793 [1909.12860].

[32] F. Alemanno et al., *Measurement of the cosmic ray helium energy spectrum from 70 GeV to 80 TeV with the DAMPE space mission*, 2105.09073.

[33] A. Tykhonov et al., *A deep learning method for the trajectory reconstruction of cosmic rays with the DAMPE mission*, Astropart. Phys. **146** (2023) 102795 [2206.04532].

[34] DAMPE collaboration, *Detection of spectral hardenings in cosmic-ray boron-to-carbon and boron-to-oxygen flux ratios with DAMPE*, Sci. Bull. **67** (2022) 2162 [2210.08833].

[35] DAMPE collaboration, *Search for gamma-ray spectral lines with the DArk Matter Particle Explorer*, Sci. Bull. **67** (2022) 679 [2112.08860].

[36] S. Buson et al., *Beginning a Journey Across the Universe: The Discovery of Extragalactic Neutrino Factories*, Astrophys. J. Lett. **933** (2022) L43 [2207.06314].

[37] R. Abbasi *et al.* [IceCube], Science **378** (2022) no.6619, 538-543 doi:10.1126/science.abg3395

[38] E. Guarini, I. Tamborra, D. Bégué, T. Pitik and J. Greiner, JCAP **06** (2022) no.06, 034 doi:10.1088/1475-7516/2022/06/034 [arXiv:2112.07690 [astro-ph.HE]].

[39] E. Guarini, I. Tamborra and R. Margutti, Astrophys. J. **935** (2022) no.2, 157 doi:10.3847/1538-4357/ac7fa0 [arXiv:2205.12282 [astro-ph.HE]].

[40] R. Stein, S. Van Velzen, M. Kowalski, A. Franckowiak, S. Gezari, J. C. A. Miller-Jones, S. Frederick, I. Sfaradi, M. F. Bietenholz and A. Horesh, *et al.* Nature Astron. **5** (2021) no.5, 510-518 doi:10.1038/s41550-020-01295-8 [arXiv:2005.05340 [astro-ph.HE]].

[41] S. Reusch, R. Stein, M. Kowalski, S. van Velzen, A. Franckowiak, C. Lunardini, K. Murase, W. Winter, J. C. A. Miller-Jones and M. M. Kasliwal, *et al.* Phys. Rev. Lett. **128** (2022) no.22, 221101 doi:10.1103/PhysRevLett.128.221101 [arXiv:2111.09390 [astro-ph.HE]].

[42] ANTARES, IceCube collaboration, *Joint Constraints on Galactic Diffuse Neutrino Emission from the ANTARES and IceCube Neutrino Telescopes*, Astrophys. J. Lett. **868** (2018) L20 [1808.03531].

[43] IceCube collaboration, *Search for Sources of Astrophysical Neutrinos Using Seven Years of IceCube Cascade Events*, Astrophys. J. **886** (2019) 12 [1907.06714].

[44] IceCube collaboration, *A Search for Neutrino Sources with Cascade Events in IceCube*, PoS **ICRC2021** (2021) 1150 [2107.09103].

[45] KM3NeT collaboration, *Sensitivity of the KM3NeT/ARCA neutrino telescope to point-like neutrino sources*, Astropart. Phys. **111** (2019) 100 [1810.08499].

[46] T. Takiwaki, K. Kotake and T. Foglizzo, Mon. Not. Roy. Astron. Soc. **508** (2021) no.1, 966-985 doi:10.1093/mnras/stab2607 [arXiv:2107.02933 [astro-ph.HE]].

[47] J. Matsumoto, Y. Asahina, T. Takiwaki, K. Kotake and H. R. Takahashi, Mon. Not. Roy. Astron. Soc. **516** (2022) no.2, 1752-1767 doi:10.1093/mnras/stac2335 [arXiv:2202.07967 [astro-ph.HE]].

[48] B. Schroer, C. Evoli and P. Blasi, Phys. Rev. D **103** (2021), 123010 doi:10.1103/PhysRevD.103.123010 [arXiv:2102.12576 [astro-ph.HE]].

[49] C. Evoli, E. Amato, P. Blasi and R. Aloisio, Phys. Rev. D **103** (2021) no.8, 083010 doi:10.1103/PhysRevD.103.083010 [arXiv:2010.11955 [astro-ph.HE]].

[50] T. Kuroda, T. Fischer, T. Takiwaki and K. Kotake, Astrophys. J. **924** (2022) no.1, 38 doi:10.3847/1538-4357/ac31a8 [arXiv:2109.01508 [astro-ph.HE]].

[51] H. Nagakura, L. Johns, A. Burrows and G. M. Fuller, Phys. Rev. D **104** (2021) no.8, 083025 doi:10.1103/PhysRevD.104.083025

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[52] L. Johns and H. Nagakura, Phys. Rev. D **106** (2022) no.4, 043031 doi:10.1103/PhysRevD.106.043031 [arXiv:2206.09225 [hep-ph]].

[53] D.S. Chattopadhyay, K. Chakraborty, A. Dighe, S. Goswami and S.M. Lakshmi, *Neutrino Propagation When Mass Eigenstates and Decay Eigenstates Mismatch*, *Phys. Rev. Lett.* **129** (2022) 011802 [2111.13128].

[54] D.S. Chattopadhyay, K. Chakraborty, A. Dighe and S. Goswami, *Analytic treatment of 3-flavor neutrino oscillation and decay in matter*, 2204.05803.

[55] J.M. Berryman, A. de Gouvêa, D. Hernández and R.L.N. Oliveira, *Non-Unitary Neutrino Propagation From Neutrino Decay*, *Phys. Lett. B* **742** (2015) 74 [1407.6631].

[56] P. Blasi, *The Origin of Galactic Cosmic Rays*, *Astron. Astrophys. Rev.* **21** (2013) 70 [1311.7346].

[57] HESS collaboration, *H.E.S.S. observations of RX J1713.7−3946 with improved angular and spectral resolution: Evidence for gamma-ray emission extending beyond the X-ray emitting shell*, *Astron. Astrophys.* **612** (2018) A6 [1609.08671].

[58] S. Gabici, C. Evoli, D. Gaggero, P. Lipari, P. Mertsch, E. Orlando et al., *The origin of Galactic cosmic rays: challenges to the standard paradigm*, *Int. J. Mod. Phys. D* **28** (2019) 1930022 [1903.11584].

[59] V. Tatischeff and S. Gabici, *Particle acceleration by supernova shocks and spallogenic nucleosynthesis of light elements*, *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 377 [1803.01794].

[60] KASCADE collaboration, *KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems*, *Astropart. Phys.* **24** (2005) 1 [astro-ph/0505413].

[61] E. Parizot, *Cosmic Ray Origin: Lessons from Ultra-High-Energy Cosmic Rays and the Galactic/Extragalactic Transition*, *Nucl. Phys. B Proc. Suppl.* **256-257** (2014) 197 [1410.2655].

[62] Z. Cao et al., *Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray galactic sources.*, *Nature* **594** (2021) 33–36.

[63] H.E.S.S. collaboration, *Evidence of 100 TeV γ-ray emission from HESS J1702-420: A new PeVatron candidate*, *Astron. Astrophys.* **653** (2021) A152 [2106.06405].

[64] CTA Consortium collaboration, *HAWC J2227+610: a potential PeVatron candidate for the CTA in the northern hemisphere*, *PoS* **ICRC2021** (2021) 904 [2110.07939].