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Multi-messenger high-energy astrophysics is the extension of the multi-wavelength exploration of the cosmos with multiple messengers with a common origin, including neutrinos, gravitational waves, and cosmic rays. This branch of astrophysics has currently achieved the potential to unravel the origin of cosmic rays, their relation to the diffuse radiation in the extragalactic space, and their role to forge their galaxies of origin while wandering in their magnetic fields for millions of years. Recent results of IceCube indicate that neutrino astronomy can complement photon astronomy providing insights into opaque sources of high-energy radiation. Starburst galaxies and jetted black holes in active galaxies are favored candidates to explain the diffuse cosmic neutrino background at > 100 TeV energies and its relation to the extragalactic background light. Additionally, gamma-ray bursts remain an intriguing mystery now enriched by joint observations of gamma-rays and gravitational waves. Events with energies up to more than 10 TeV complement these observations possibly opening new windows on new physics.

The galactic diffuse flux, produced by cosmic ray interactions on the interstellar matter of our galaxy and peaking at lower energies, is within the reach of neutrino detectors. Together with the measured galactic gamma-ray flux up to PeV energies, they will shed light on the knee region of cosmic rays and on the possible existence of dark matter in the Galactic plane.

1. Extragalactic diffuse background radiation and cosmic particle fluxes

In 1953, indirect detection of gamma rays from the ground was at its primitive attempts with a photomultiplier (PMT) and a mirror in a garbage can by Galbraith and Jelley [1, 2]. In 1960, Greisen suspected that "*within the next decade cosmic ray neutrino detection will become one of the tools of both physics and neutrino astronomy*" [3]. He also envisaged neutrino astronomy connection with measured cosmic rays (CRs) and with the emerging field of gamma-ray astronomy. In the same year, Markov discussed in a proceeding a vision of deep natural media used as neutrino detectors [4]. After 2 decades, the optical observation of the cataclysmic core-collapse supernova 1987A followed a few hours after the detection of a few neutrino events by the underground detectors Kamiokande, IMB and Baksan. For this, the 2002 Nobel prize was awarded to M. Koshiba [5]. While this set a milestone for multi-messenger astrophysics, the future observation of a similar event would allow a revolution for understanding the formation of compact objects after a supernova collapse by using neutrinos, gravitational waves (GWs) and photons from many bands of the electromagnetic spectrum [6].

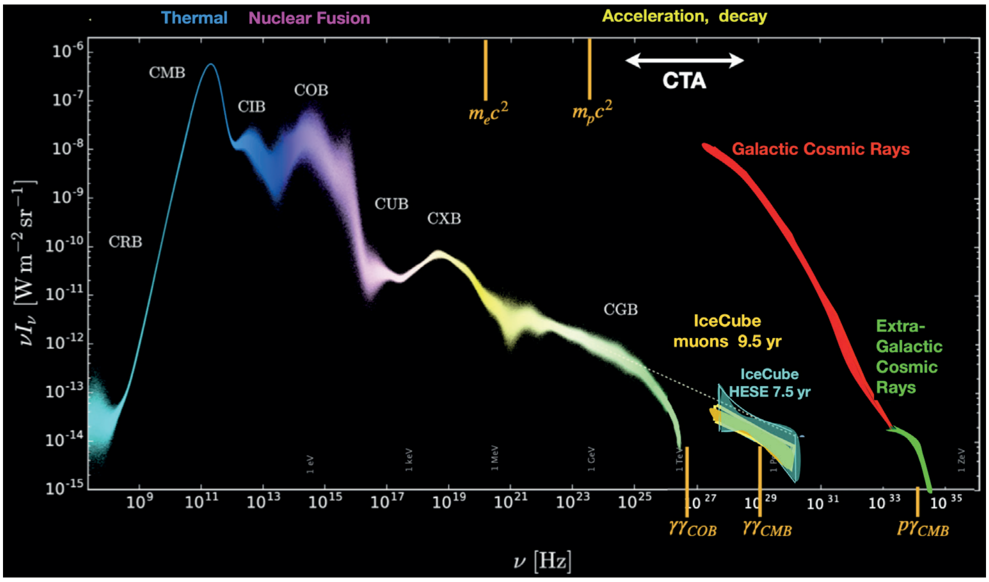

Figure 1: Energy spectrum of EBL from radio to gamma rays in [9] adapted from [10]. The CR spectrum is indicatively drawn from 10^{13} eV [87]. The diffuse spectra of the IceCube HESE sample in 7.5 yr [23] and from the diffuse muon tracks accumulated in 9.5 yr [24] are shown.

The first TeV source from ground, the Crab Nebula, was detected in 1988 by the Whipple telescope in Arizona [7]. In 1990, Ressel and Turner presented the *Grand Unified Photon Spectrum* (GUPS). On the extragalactic background radiation or light (EBL) spanning about 19 orders of magnitude in energy from the radio to the gamma-ray band [8], they superimposed the CR flux, persisting to energies beyond 10^{20} eV, hinting to the existence of extreme extragalactic accelerators. The CR flux extended well beyond the reach of the highest energy colliders on earth, also beyond the reach of *Imaging Atmospheric Cherenkov Telescopes* (IACTs), which at hundreds of TeV recorded only photon flux upper limits. As a matter of fact, high-energy photons are absorbed during propagation by pair production on the diffuse radiation limiting the gamma-ray horizon. Based on the observed energy density of 3 × 10^{-19} eV/cm^3, calculated integrating the measured CR flux above 10^{17} eV [1], it was speculated that *gamma-ray bursts* (GRBs) and black holes and their jets embedded in *active galaxies* (AGNs) are powerful enough to sustain *ultra-high energy cosmic rays* (UHECRs).

Since the first GUPS was presented, the EBL spectrum has been further updated (see the colored spectral emission in Fig. 1 from [9, 10]) using measurements of many experiments. The EBL is dominated by the thermal relic radiation from the last scattering surface observed today as the *Cosmic Microwave Background* (CMB) of ~ 400 photons / cm^3. At about 10 % of it, the *Cosmic Optical Background* (COB) and the *Cosmic Infrared Background* (CIB) play a very relevant role to understand star formation as diagnostic for stellar nucleosynthesis, mass accretion onto black hole processes and gravitational collapse of stars. Optical emission from stars is reprocessed by dust and attenuated by it to be re-radiated in the infrared band. The COB and CIB bumps in the EBL are studied by gamma-ray telescopes in space

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[1] The CR flux is related to the energy density of their sources. For instance, the comparable number obtained for Galactic cosmic rays, integrating their spectrum below the knee energy, is $\rho_E = 4\pi \int_{1\,GeV}^{10^6\,GeV} \frac{E}{\beta c}\frac{dN_{CR}}{dE}\,dE$ = 1 eV/cm^3, a number comparable to the galactic magnetic field energy density.

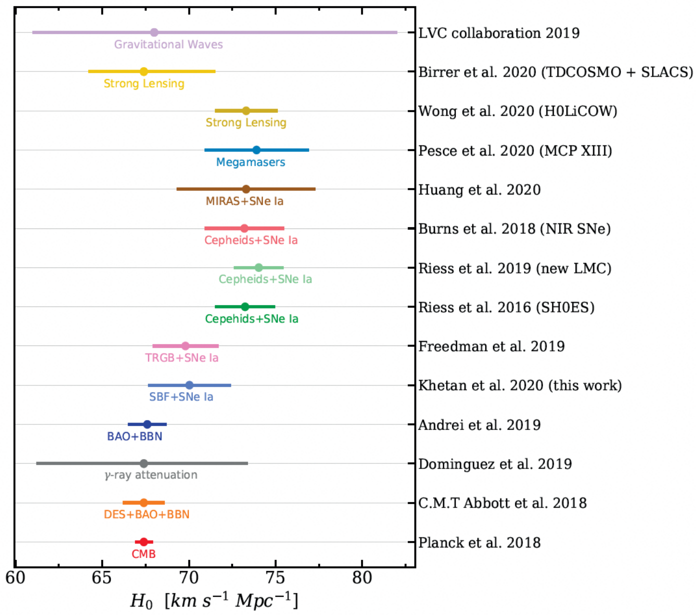

Figure 2: Compilation of Hubble constant late and early universe measurements with inputs from multi-messengers (gamma-rays and GWs). From [17].

and on the ground as they can sample a large population of flaring AGNs at different redshifts z. They infer their injection spectra from the measured ones at energies where EBL attenuation is negligible. The effect of attenuation, namely the optical depth as a function of energy and redshift, has been measured by Biteau and Williams using 106 blazar spectra [11], by the Fermi-LAT collaboration with 739 blazars up to redshift $z \sim 3$ and a gamma-ray burst at 4.3 [12]. A joint analysis of 12 blazars using Fermi-LAT and MAGIC data for AGNs with $z \sim 0.03 - 0.944$ covered the widest wavelength region [13]. These measurements offer a new approach to infer the Hubble constant of the late universe and to constrain the matter content in the universe, though these estimates depend on the still large uncertainty on the number density of the EBL as a function of energy. As an example from [14], fitting data combining two different models [15, 16] considering them equally probable, results in the most probable value of $H_0 = 67.4 \pm 6.2$ km·s^{-1}·Mpc^{-1} and $\Omega_m = 0.14 \pm 0.07$ [2], as shown in Fig. 2. Fixing the matter density to $\Omega_m = 0.32$, the obtained value is $H_0 = 65.8 \pm 3.1$ km·s^{-1}·Mpc^{-1} (all errors are at 1σ). This dependency on the EBL uncertainty is a limitation as well as the fact that gamma-ray experiments do not provide the source distance which is taken from optical data. Together with gamma-rays, another new messenger, GWs, contributed such a measurement (see Fig. 2 from [17]). Standard sirens, such as the famous GW170817 neutron star merger, provide the absolute luminous distance D_L from the fit of the gravitational chirp data, hence a simple relation provides H_0 from the known redshift from electromagnetic counterparts: $H_0 \cdot D_L = c \cdot z$ [18]. The uncertainty on H_0 principally depends on the degeneracy between distance and inclination of the plane of the binary system. Both gamma-ray telescopes and GW interferometers have still a limited horizon, despite both GWs and neutrinos are messenger potentially covering a horizon reaching the early universe and propagating through absorbing media in cosmic sources.

Nonetheless, future advanced detectors may make them players to solve the controversy on the early and late universe measurements of the Hubble constant [19]. The *Cherenkov Telescope Array Observatory* (CTAO), thanks to three different sizes of telescopes, will improve this measurement reaching redshifts up to $z \sim 2$ thanks to the better sensitivity by about a factor of 10 and its wide energy range from about 20 GeV to 300 TeV [20]. LIGO and Virgo are expected to reach a few percent precision in 5 yr of data and the Einstein Telescope will reach redshifts beyond 10 becoming a relevant player in cosmology [19].

2. The diffuse gamma-ray and neutrino fluxes

At higher energies than the region of the COB and CIB in Fig. 1, the gamma-ray part of the EBL is named *Extragalactic Gamma-ray Background* (EGB) and it has been measured by Fermi-LAT [21]. When the Galactic Plane contribution is subtracted, only the extragalactic diffuse emission from faint and unresolved extragalactic sources remains, mostly blazars and starburst galaxies. The EGB gives the non-thermal perspective on the cosmos, together with the extragalactic CR flux and the diffuse cosmic flux of neutrinos recently discovered by the IceCube cubic-kilometer neutrino telescope, shown in Fig. 1 [22, 23, 24]. These events are cascade-like when induced by electron or tau neutrinos, or neutral current interactions of all flavor neutrinos with their vertex inside a detector fiducial volume. They are called *high-energy starting events* (HESE) and selected at an en-

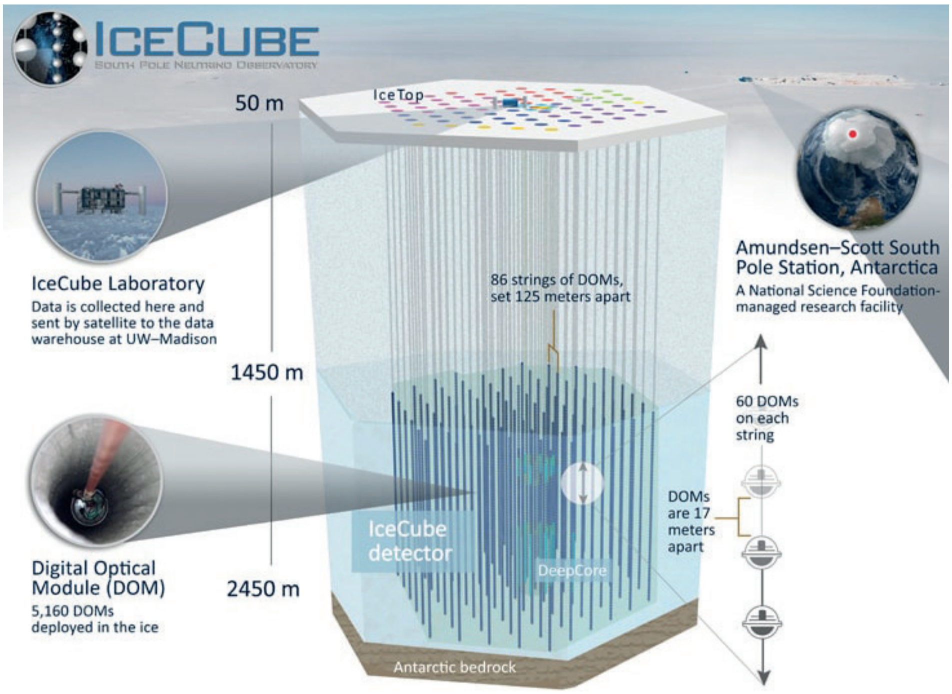

Figure 3: Artistic view of the in-ice detector and the surface extensive air shower array of the IceCube Observatory. In the inserts on the top left the ICLab at the South Pole, also shown in the map on the top right. In the middle on the left a drilled string hole with a Digital Optical Module (DOM) entering in it, on the middle right the inner components of a PMT and a part of a string. There are 86 strings each holding 60 DOMs.

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[2] Each model provides the most likely values of: $H_0 = 71.8 \pm 3.6$ km·s^{-1}·Mpc^{-1} and $\Omega_m = 0.15 \pm 0.06$ for the Finke et al. 2010 model [16] and $H_0 = 63.0 \pm 4.0$ km·s^{-1}·Mpc^{-1} and $\Omega_m = 0.13 \pm 0.06$ for Dominguez et al. 2011 [15].

ergy beyond 60 TeV and over 7.5 yr of data taking [23] is dominated by down-going cascade-like events with limited angular resolution of the order of 10° and energy resolution of about 20 % and a smaller fraction of high-energy neutrino-induced muon tracks with pointing accuracy below 1° and energy resolution of a factor of 2, as muons may be born kilometers outside the detector. Another sample is up-going-muons induced by muon neutrinos selected in an independent analysis using 9.5 yr of data taking [24]. Both the HESE and muon track samples constitute evidence with larger significance than 5σ that cosmic neutrinos are required on top of the background of atmospheric muon and neutrinos to explain the IceCube data.

As seen from Fig. 1, the highest energy end of the multi-messenger plot reveals comparable energy rate densities for the Ultra-High Energy CRs (UHECRs) measured by the *Pierre Auger Observatory* (PAO) [25] and the IceCube neutrinos between 60 TeV to PeV energies. This can be explained by a **unified origin** (as already hypothesized by Ressel and Turner) assuming photo-meson interactions in extragalactic sources [26]. The measurements of these events require challenging detectors. PAO in Argentina includes fluorescence telescopes and sampling detectors of extensive air showers (EAS) covering a surface of 3000 km^2 to detect the time and charge of the electromagnetic and muon components of EAS. IceCube is the first cubic kilometer of ice between 2.5 - 3.5 km depth at the South Pole instrumented with around 5600 optical modules for detecting Cherenkov light of particle showers and muons induced by neutrinos (see Fig. 3). Both are in an upgrade phase towards more sensitive detectors.

The "UHECR-neutrino unification" was discussed in detail by Waxman and Bahcall in 1998, who derived an upper limit on the neutrino flux from extragalactic calorimetric sources, namely sources where CRs lose all their energy in photo-pion production [27]. The chain of pion decay relates neutrinos and gamma-ray secondaries to primary protons or nuclei, namely CRs, as they are the results of proton–proton or proton–photon interactions in cosmic ray sources accelerating protons and ionized nuclei. The Waxman and Bahcall upper bound or **calorimetric limit** [3] is obtained for a fully efficient system for CR energy loss into pion production [4]. This condition corresponds to a diffuse extragalactic neutrino flux upper limit of about $E^2 \frac{dN}{dE} \sim 10^{-8}$ GeV·s^{-1}·sr^{-1}·cm^{-2}. Below this boundary, the system is 'optically thin' and implies that both UHECR and neutrinos originate from systems with an optical depth of less than $\tau_{p\gamma} \sim 0.6$ [28].

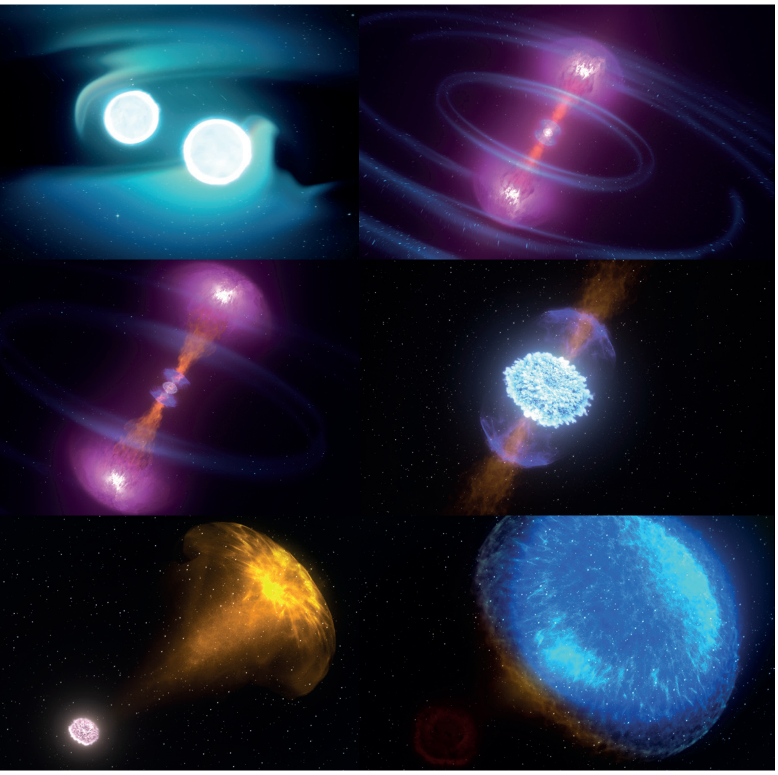

Figure 4: The various phases of a binary star merger producing a GW from the collapsar event and a jet with internal shocks crashing onto the external material to produce a reverse shock (Credit NASA's Goddard Space Flight center/CI Lab, a video can be watched here: https://svs.gsfc.nasa.gov/12740)

Higher neutrino fluxes than this upper bound can be produced in hidden-core AGNs or opaque sources from which only neutrinos escape. The IceCube diffuse flux order of magnitude seems to indicate a large contribution from this topology of sources. Additionally, a joint study between neutrino telescopes (IceCube and ANTARES) and UHECR experiments (PAO and Telescope Array) excluded possible correlations between UHECR directions and neutrinos [29]. This could be due to opaque sources contributing to the diffuse neutrino flux but also to the different horizons of the two cosmic messengers [5].

It has been noted in [28] that, as UHECRs must be accelerated and escape before they lose their energy due to synchrotron radiation, a boundary condition to the magnetic field in the plasma reference frame can be derived. The non-observation of GRBs by IceCube [30, 31, 32] disfavors these powerful yet mysterious sources as accelerators of UHECR sources, as the magnetic field in the jet could overcome this limit in the prompt phase, while the baryon loading might not overcome 10 [33]. Nonetheless, such limit is relaxed by assuming acceleration of heavy nuclei rather than protons and/or models of multiple production zones of neutrinos and gamma-rays.

An extensive review on GRBs with many references is in [34]. In the "canonical" single-zone standard model of GRBs, the prompt phase of gamma-ray emission is due to the ejecta forming an expanding fireball under thermal pressure, with efficient conversion of thermal energy to kinetic energy, then becoming optically thin. These ejecta are caused by the collapse of a rapidly spinning massive star or a binary neutron star merger event forming a powerful engine launching relativistic jets. These dissipate their kinetic energy through accelerating shocks of electrons and protons formed by jet collisions. The prompt phase is followed by an afterglow broadband emission from the radio to gamma-rays, explained by a forward shock formed by the interaction of relativistic jets with the circum-burst material and reverse shock (see Fig. 4).

On Aug. 27, 2017, a splendid example of multi-messenger observation by the three interferometers LIGO and VIRGO of a binary star merger event, GW170817, and the coin-

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[3] The upper bound was criticized as it makes strong assumptions [86], namely that UHECRs are dominantly protons, while in the highest energy end of the spectrum PAO measures heavier composition. The assumed spectrum is E^{-2} fitted from above 10^{19} eV and extrapolated to lower energies, while the energy spectrum might be different.

[4] Namely, the efficiency $f_\pi = 1 - e^{-\tau_{p\gamma}} = 1$ for a very large optical depth of proton-photon interactions ($\tau_{p\gamma} \gg 1$).

[5] In fact, the highest energy neutrinos observed by IceCube could be dominated by sources beyond the O(100) Mpc limited horizon of UHECRs.

cident observation of gamma-rays 1.7 s after it with many observations across the electromagnetic spectrum provided many fundamental physics and astronomical observations (e.g., the Hubble constant determination, the identification of heavy metals in kilonova light curves, the verification of speed of GWs against the speed of light,…) [35]. While this observation directly connected short GRBs to kilonova, this connection is challenged by the long GRB 211211A with optical-infrared emission pointing to a binary merger or kilonova origin [36]. This observation sets the path for the synergy between GW interferometers and the future CTAO, which could be alerted by the merger observations. Observation from ground has proved to be feasible by current ground based IACT arrays and EAS also providing serendipitous observations. GRB 180720B, GRB 190829A and GRB 190114C above 100, 200, 300 GeV have been detected by H.E.S.S. [37] and MAGIC [38] and their measured *Spectral Emission Distributions* (SEDs) favor *Inverse Compton* (IC) scenarios, such as *Synchrotron Self Compton* (SSC) models where emitted synchrotron photons due to gyrating electrons in intense magnetic fields up-scatter by IC on the same emitting lepton population. More recently, GRB 221009A was initially detected by *Swift* and Fermi-GBM and LAT (see Fig. 5) and then detected with significance of about 100σ about 2000 s after the trigger time beyond 500 GeV by LHAASO hybrid array up to about 10 TeV [39]. These observations can be explained by IC scenarios on external seed photons e.g., from the kilonova radiation, named *External Inverse Compton* (EIC), or more exotic phenomena such as axion photon conversion [40].

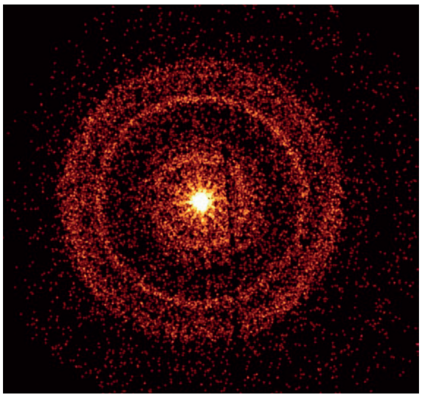

Figure 5: X-ray afterglow captured by Swift of the GRB observed on Oct. 9, 2022 by the detectors on board of the Fermi, Swift and Wind spacecrafts [76].

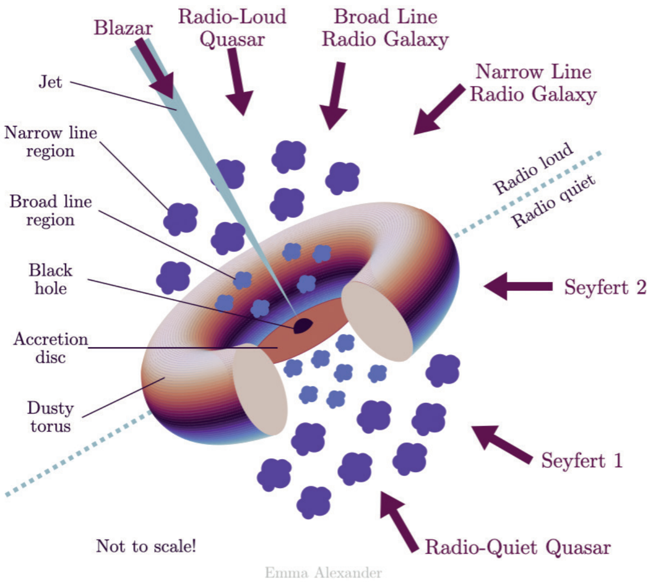

Figure 6 Unification scheme of AGNs (Credit: Emma Alexander, adapted from [82])

In conclusion, while GRBs are disfavored as the UHECR and neutrino sources, we will discuss the case of AGNs (Fig. 6, and see Glossary for more information on what they are).

3. Are active galactic nuclei the sources of the discovered cosmic diffuse neutrino flux?

The evidence of the first neutrino sources took a long time to materialize [41, 26] beginning from DUMAND prototypes [6] in the Pacific Ocean in the 70'ies [42]. A compelling observation of blazars as potential neutrino emitter, relating neutrinos and gamma-rays happened on Sep. 22, 2017. This is expected from CR sources as gamma-rays and neutrinos are the secondaries of hadronic interactions of CRs with matter and ambient radiation. A very high-energy muon neutrino track with most probable energy of 270 TeV was launched as a neutrino alert by IceCube to the astronomical community (IC170922A) [43]. Fermi-LAT and MAGIC follow-up observations [41] confirmed the presence inside the error region of about 0.5° from the IceCube event direction of a flaring blazar, TXS 0506+056, located at redshift of 0.33 with a chance probability of 3σ. Additionally, in an analysis of historical data performed at the University of Geneva, a second neutrino flare was observed in the direction of this source lasting about 100 days between 2014 and 2015 with significance of 3.5σ [44]. While in coincidence with the 2017 neutrino alert a gamma-ray flare was observed, no significant gamma-ray increased-emission was observed during the 2014 - 2015 flare, while two optical flares were detected [45]. These observations cannot be reconciled in models where the high energy emission of gamma-rays and neutrinos is due to single-zone proton synchrotron models.

It was speculated that TXS 0506+056, previously classified as a high-frequency peaked blazar of the class of BL Lacertae (HBL BL Lac) [7], might be a "masquerading" *Flat Spectrum Radio Quasar* (FSRQ) which dissimulate BL Lacs as their broad lines are not clearly visible due to non-thermal jet emission [46]. Typical leptonic models for BL Lacs are SSC models, with synchrotron photons up-scattering by IC on the same emitting lepton population (hence named single zone models), while, for FSRQ, IC can happen on external fields of thermal photons outside of the jet (EIC). Nonetheless, the IceCube observed flares challenge single-zone models as well as EIC and lepto-hadronic models, as the large neutrino flux is in tension with Swift X-ray measurements [47, 48, 49]. More exotic models assuming jet collisions of two jet components, while spine-sheath models [50] have been supported by radio observations [51, 52].

By now several hints indicate that blazars are potentially relevant contributors to the discovered IceCube diffuse neutrino flux. An analysis of IceCube data constrained the blazars in the Fermi 2LAC catalog, as potential contributors to the neutrino diffuse flux up to 27 % (50 %) for unified spectra $E^{-2.2}$ ($E^{-2.5}$) [53], nonetheless under the strong assumption of a common spectral shape for all AGNs. Additionally, in an analysis initiated at the University of Geneva a cumulative emission population study of a 110 catalog of blazars and starburst galaxies produced evidence of an excess at 3.3σ c.l. with respect to the atmospheric background [54].

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[6] Our estimated colleague Peter Grieder, remembered on p. 8 of this issue, was one of the pioneers of the DUMAND project, and a passionate promoter of cosmic ray physics and neutrino astronomy.

[7] HBL and low-frequency peaked LBL are the blazars with the frequency of the synchrotron bump of the SED > 10^{15} Hz or < 10^{14} Hz, respectively.

It is dominated by NGC 1068 and by TXS 0506+056 and PKS 1424+240. TXS 0506+056 and PKS 1424+240 share similar properties compatible to masquerading FSRQ and present hints of neutrino correlation. In addition to what is already discussed about TXS 0506+056, it is noticeable that the location of PKS 1424+240 is compatible with the direction of one of the biggest cascade neutrino events ever observed by IceCube, named Big Bird at PeV energies. After additional hints were collected from a few other blazars, it was speculated that a sub-class of 5 % blazars producing similar fluxes as the observed flux in the TXS 0506+056 long-term flare in 2014 - 2015, could explain the discovered neutrino diffuse flux in 2013 [55, 56, 57]. These could be copious neutrino emitters when inefficient gamma-ray emitters, while the radio and optical emissions generally indicate increasing fluxes. A reanalysis of this catalog with additional 2 years of statistics confirmed this result at 3.7σ c.l. [57].

Noticeably, in the same analyses [54, 57], the Seyfert 2 starburst galaxy NGC 1068 emerged as the hottest source as well as the hottest spot in the full scanned sky map search, despite of the large trial factor. NGC 1068 was one of the first spectroscopic AGN detection with M81 in 1909 [58] and in 1943 Seyfert observed broad line emissions from NGC 1068 and NGC 4151 [59]. Both Seyfert galaxies are compatible with regions with event excesses in IceCube data [57]. For NGC 1068 about 79 signal-like events are fit with a reconstructed spectrum for a single power-law hypothesis of about $E^{-3.2}$ providing evidence at 4.5σ c.l. that neutrinos are messengers from this well-known source at only 14.4 Mpc from us. Nonetheless, this flux is higher by about an order of magnitude than the MAGIC upper limits [60] and the Fermi-LAT flux measured gamma-rays only up to about 10 GeV [61]. The absence of the gamma-ray counterpart to neutrinos in the TeV region triggered AGN corona models [62, 63]. NGC 1068 is a composite system and there might be the contribution of various acceleration processes: it hosts a highly obscured mildly relativistic jet seen in the radio through its accretion disk (as it is a Seyfert 2 galaxy) interacting with interstellar matter or a molecular cloud [64] and eventually originating gamma-rays from IC on IR radiation in the starburst region [65]. Two zone models where gamma-ray emission above 1 GeV results predominantly from the starburst region and TeV neutrinos in the corona have been proposed [66]. Very hard spectra compatible with acceleration of CRs have been obtained in AGN-driven wind models in the circum-nuclear molecular disk [67]. Shock acceleration might take place also in the starburst region, in particular in wind bubbles emerging from the observed radio starburst nuclei with consequent proton-proton interactions [68]. Such a composite object will be an interesting target for CTAO to explore the interplay between the AGN and starburst nature.

4. The granted sources of diffuse neutrinos

Two granted sources of diffuse neutrinos should exist, but marginally contributing to the measured diffuse neutrino flux by IceCube as they are mostly concentrated at lower and higher energies.

Glossary

AGN: Active Galactic Nuclei host large emission lines (differently from stars and galaxies that typically present absorption lines) in their optical spectra and strong luminosity nuclei [59]. They host highly variable cores with a supermassive black hole (SMBH) leading to one of the most efficient processes for energy conversion: the accretion of infalling matter on a SMBH that due to its angular momentum forms a disk of cold material around it. Dissipative processes transport matter inwards and angular momentum outwards, causing heat up of the accretion disc emitting in the optical-ultraviolet waveband, while a corona of hot material forms close to the SMBH horizon emitting up to X-ray energies. Fast outflows or jets with direction along the spin axis of the SMBH can form.

Classifications of AGNs have been for years challenged by the different observed emission characteristics, which are now believed to be caused by the different orientations at which we observe them (see Fig. 6 [82]). Following the classification in [83, 84], radio-quiet AGNs are Seyfert galaxies and characterized by relatively low radio-to-optical flux density ratio (< 10) and radio power at 1.4 GHz < 10^{24} W·Hz^{-1}. For Seyfert 1 galaxies, the observer directly views the nucleus through the Broad Line Region of clouds (BLR), while Seyfert 2 galaxies are viewed through the obscuring structure of the torus surrounding the accretion disk, which obscures the BLR but not the Narrow Line Region (NLR). Radio-loud quasars host jets and are about 10 %, including blazars. They are composed of FSRQ with high excitation lines of emission and BL Lacertae (BL Lacs) with low excitation. Blazars are between AGNs the main gamma-ray emitters, though Seyfert 2 galaxies NGC 1068 and NGC 4945 are also observed in gamma-rays by Fermi-LAT [85]. Blazars have a double-humped spectral emission distribution (SED), with high-energy electrons responsible for the synchrotron radiation in the radio-to-UV bump and gamma-rays due to IC or neutral pion decay from accelerated CRs forming the high energy bump.

CRs: cosmic rays, mostly protons with ionized nuclei in energy-dependent percentages injected by cosmic accelerators and continuously bombarding our atmosphere to produce atmospheric extensive air showers (EAS).

IACTs: Imaging Atmospheric Cherenkov Telescopes. They are ground-based telescopes detecting indirectly gamma-rays through the Cherenkov light produced by secondary EAS in the atmosphere with mirrors and ns-sensitive cameras in their focal plane. The images on the focal plane allow to infer the energy and direction of the primaries and to discriminate the image of a gamma-ray and a cosmic ray shower.

CTAO: The Cherenkov Telescope Array Observatory (see *SPG Mitteilungen* Nr. 68, p. 24) is the new generation of gamma-ray observatory. It will be composed of 2 arrays of IACTs at about 2000 m a.s.l. at the ESO premises in Paranal, Chile, and at the site of Roque de Los Muchachos La Palma, Canary Islands with at least 64 IACTs of 3 sizes covering the 20 GeV - 300 TeV energy range, achieve an angular resolution of about 0.05° above 1 TeV and 2 milli-Crab flux sensitivity in a few years for the Galactic Plane gamma-ray survey.

On the high-energy side, *cosmogenic neutrinos* are expected from interactions of CRs with the CMB in the extragalactic space producing the delta resonance with a threshold of about $10^{19.5}$ eV which fragments in lower energy CRs, gamma-rays and neutrinos. IceCube searches for this neutrino flux and set an upper limit [69]. It should be noticed that, if the UHECR composition is dominated by heavier nuclei than protons, the predicted neutrino flux might be hardly at the reach of current detection [70].

On the low energy side, neutrino telescopes are beginning to observe the granted diffuse neutrino flux produced by *CRs interacting with the interstellar matter* in the Galaxy. Recently, ANTARES published the observation of an excess incompatible with the atmospheric neutrino background at 2σ c.l. with a preferred spectrum of $E^{-2.45}$ from the Galactic Ridge (galactic longitude $|l| < 30°$ and galactic latitude $|b| < 2°$) [71]. Despite the large error, the measured neutrino flux is compatible with a neutral pion decay model from interactions of protons with a power-law spectrum of $E^{-2.4}$, harder than the local CR spectrum of $E^{-2.7}$. The model is normalized to the gamma-ray flux measured by the Fermi-LAT from the same Galactic Ridge region between 19 GeV and 3 TeV [72]. It has been speculated that such a hard spectrum could include the contribution of another component, such as decays of heavy dark matter in the Galactic ridge [73]. Previous results are upper limits to the model in [74] from IceCube only [75] and with ANTARES data, which indicate that the flux will be soon observed [76] and that its contribution to the diffuse IceCube neutrino flux at > 60 TeV is less than 10 % [77]. New analyses exploiting cascade-like events dominated by electron neutrinos will push the energy threshold down increasing sensitivity to the galactic plane flux, as the atmospheric electron neutrino background flux is one order of magnitude lower than the muon one from pion and kaon decays.

New results by LHAASO [78, 79] and Tibet Asγ [80] extend in the ultra-high energy tail the measurement of the flux from the Galactic Plane up to PeV energies, indicating the presence of *PeVatron* accelerators in the Galaxy, still mysterious as standard Diffuse Shock Acceleration (DSA) applied to supernova shocks only achieves one order of magnitude lower energies. IceCube and the KM3NeT upcoming neutrino telescope in the Mediterranean Sea in synergy with CTAO, LHAASO and Tibet Asγ have the potential to unravel the origin of the bending in the CR spectrum at about 4 PeV, called the *knee* [81, 77, 78], to understand its propagation or acceleration origin, explore diffusion processes in the Galaxy and dark matter in the Galactic Plane.

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