Community paper

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Astroparticle physics with gamma rays and neutrinos: The decade of the great observatories

Executive summary

Astroparticle physics is frontier science striving to answer questions emerging where astrophysics meets particle physics and cosmology. *What happened in the first moments of creation and how did this shape our present-day Universe? Can we find out more about the nature of the elusive dark matter? Why is the Universe filled with energetic particles far beyond energies that can be achieved with man-made accelerators? How are they accelerated? Can we stand the test of physics under extreme conditions? Which role do the energetic particles play for the physical state of the interstellar matter and interstellar chemistry? What are the sources of anti-matter?* Such intellectual challenges foster young people to pursue careers in science and engineering. Astroparticle physics experiments are technology drivers for a wide range of applications in modern society (*e.g.,* medical imaging, nuclear safety, material diagnostics, big data pipelines, ultrafast digital electronics).

The growing astroparticle physics community in Germany has prioritized their needs for new experimental facilities in the frame of the KAT, ASPERA and ASTRONET recommendations. Among the diversity of recommended facilities, observatories for very high energy gamma rays and neutrinos are most interesting for the astronomical community. These cosmic messengers carry directional information which is needed to identify astrophysical sources of energetic particles. They probe the realm of non-thermal plasma in the Universe (*see chapter by M. Pohl, S. Funk, and M. Kadler*).

The **Cherenkov Telescope Array (CTA)** will be an open observatory for gamma rays between 30 GeV and 300 TeV. Compared to the present-generation H.E.S.S. and MAGIC arrays, the next-generation CTA will be much larger (up to 4 square-kilometer), providing a sensitivity better by an order of magnitude, a larger field of view, as well as improved angular and energy resolutions. CTA will be the world-leading facility in ground-based gamma-ray astronomy in the coming decades. An international consortium with more than 1200 scientists from 32 countries plans to build an array optimized for deep observations of our Milky Way Galaxy from the southern hemisphere in Chile, and another array with a layout optimized for extragalactic research from the northern hemisphere to be built on the Canarian Island of La Palma. The large number of gamma-ray sources visible for CTA turn it into a truly astronomical observatory that stimulates competition for the best observation proposals and maximal scientific return. CTA unlocks discovery space for new physics, pursuing searches for signatures of dark matter, large-scale magnetic fields, or the coarse-grained structure of space-time predicted by quantum gravity.

IceCube-Gen2 describes the concept for an extension of the IceCube neutrino telescope at the South Pole towards an instrumentation of 10 cubic-kilometer volume. IceCube achieved a major breakthrough by detecting a diffuse flux of astrophysical neutrinos of unknown origin. The large volume of IceCube-Gen2 will allow to increase the low neutrino event rates caused by the feeble interactions of these “ghost” particles among the elementary particles. The larger count rates will show if the neutrinos originate from astronomical sources. In the northern hemisphere, the **KM3NeT** telescope in the abyss of the Mediterranean Ocean will allow for observations of our Milky Way Galaxy through the Earth shield and with a much improved

angular resolution. Both observatories could host densely instrumented subdetectors (PINGU, ORCA) for measurements of the neutrino mass hierarchy and mixing angles, protagonists of a tell-tale story about the creation of matter in the early Universe.

We recommend implementing these great all-sky observatories with high priority. This measure will advance a particularly exciting and technologically demanding branch of science in a major way to the benefit of society and strengthen the leading role of gamma-ray and neutrino astroparticle physics in Germany, in close and vibrant partnership with the international community.

1. Introduction

The current generation of very high energy telescopes found a surprisingly bright sky even at energies where no high-temperature plasma can conceivably exist. Whereas stars are basically hot gas spheres in thermodynamic equilibrium held together by their own gravity, the observed very high-energy sources emit non-thermal spectra with photon and neutrino energies of more than a stunning thousand times the rest mass energy of the proton, the main constituent of ordinary matter. To emit such high-energy radiation, relativistic particles moving at almost the speed of light must be present in the sources. The observed radiation is produced when the particles hit targets such as gas clouds or magnetic and radiation fields. Our understanding of the physical mechanisms powering the sources and accelerating the particles to the extremely high energies is still at an early stage. Astronomical precision observations are clearly needed to obtain a complete census of the source populations and to resolve their morphological structures. This will lead to physically self-consistent models of the sources and an in-depth understanding of the physics involved in the high-energy processes. By improving the understanding of the high-energy astronomical inventory, astroparticle physics unfolds its discovery potential for new physics. Weakly interacting massive particles (WIMPs) are among the prime candidates for the elusive dark matter, dominating the mass density in our Universe. Apparently, the dark matter particles are too massive for being produced with the Large Hadron Collider. *Very high energy astrophysics probes new types of heavy particles which could produce secondary gamma rays and neutrinos due to scattering, decay, or annihilation*.

The sensitivity and resolution of the current generation of instruments is insufficient to make significant progress and to obtain new breakthrough results. With the next-generation observatories, however, a real progress in our theoretical understanding of the non-thermal Universe can be achieved, and unknown territory can be explored. In a world-wide effort, the infrastructure required for gamma ray and neutrino astroparticle physics has been planned and is now ready to be built by the united forces of the international CTA consortium and the Global Neutrino Network, including the IceCube and KM3NeT collaborations, with leading participation of German groups.

2. Upcoming Facilities in the Coming Decade

The Cherenkov Telescope Array

The Cherenkov Telescope Array, CTA, will be the major global observatory for very high energy gamma-ray astronomy over the next decades. It is recognized on the strategic ESFRI plan. The broad scientific scope of CTA engulfs the realm of the non-thermal Universe, covering phenomena related to the presence of energetic particles in the

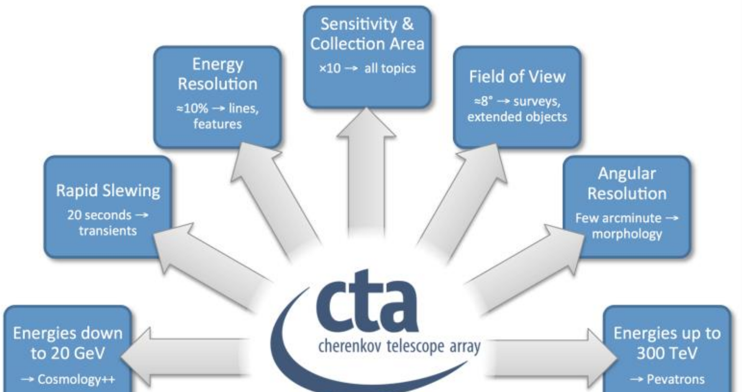

Fig.1: *CTA advances beyond the state of the art in ground-based gamma-ray astronomy.*

astrophysical plasma. CTA will probe particle acceleration across a vast range of scales and will observe a zoo of objects, from pulsars, supernova remnant shock waves, accreting binary stars, star forming regions, radio galaxies, active galactic nuclei, to mergers of clusters of galaxies (*Seeing the High-Energy Universe with the Cherenkov Telescope Array,* Eds. J. Hinton, S. Sarkar, D. Torres, J. Knapp, Astroparticle Physics, Vol. 43, 1-356, 2013; Hinton, J. & Hofmann, W.: *Teraelectronvolt Astronomy*, Annual Review of Astronomy and Astrophysics, Vol. 47, 523-565, 2009).

Covering a huge range in photon energy from ca. 20-30 GeV to beyond 300 TeV, CTA will improve on all aspects of performance with respect to current instruments (Fig. 1). Wider field of view and improved sensitivity will enable CTA to survey hundreds of times faster than previous TeV instruments. The angular resolution of CTA will approach 1 arcminute at high energies – the best resolution of any instrument operating above the X-ray band – allowing detailed imaging of a large number of gamma-ray sources. A one to two order-of-magnitude collection area improvement makes CTA a powerful instrument for time-domain astrophysics, three orders of magnitude more sensitive on hour timescales than Fermi-LAT at 30 GeV. The observatory will operate arrays on sites in both hemispheres to provide full sky coverage, hence maximising the potential for the rarest phenomena such as very nearby supernova, gamma-ray bursts or gravitational wave transients. Figure 1 illustrates the performance advances made by CTA will respect to the state-of-the-art, and example associated scientific opportunities.

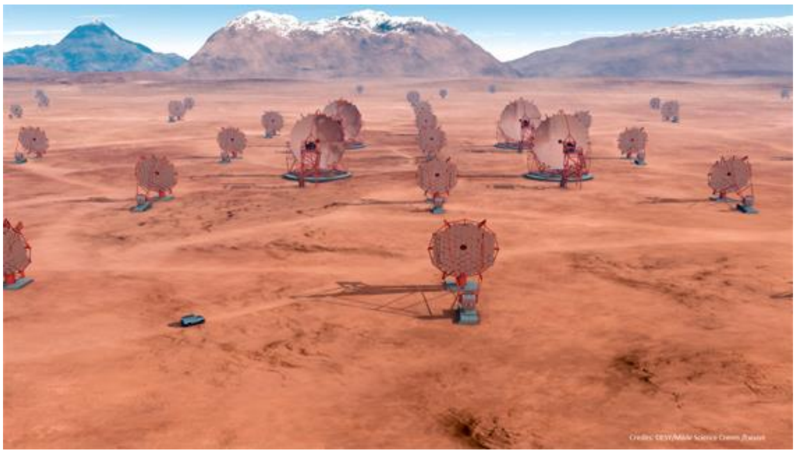

Fig. 2: *Artists impression of the Southern CTA array.*

CTA will have significant synergies with many of the new generation of major astronomical and astroparticle observatories. Multi-wavelength and multi-messenger approaches combining CTA data with those from other instruments will help understanding the broad-band non-thermal properties of target sources, as well as the nature, environment, and distance of gamma-ray emitters, and mutual provision of alerts and triggers.

Uniquely for ground-based gamma-ray astronomy, CTA (Fig. 2) will be operated as an open observatory, annually issuing an announcement of opportunity for proposals by guest observers. In the first ten years of operation, 50%-60% of the available observation time will be assigned to proposals from the community, according to the results of a competitive peer review. All data will become available on a public archive after a one year proprietary period, with user tools and support provided by the Observatory. Proprietary access to CTA is guaranteed by (primarily) in-kind contributions to the implementation of the Observatory.

To cover the wide energy range of CTA efficiently requires three different sizes of telescopes (LST, MST, and SST with diameters of 23m, 12m, and 4 meters, respectively). The baseline CTA configuration has 70 SSTs, 25 MSTs and 4 LSTs in the South (see Fig. 2), providing the full energy range, and 15 MSTs and 4 LSTs in the North, providing all-sky capability in the lower part of the CTA range. Figures 3 and 4 illustrate the performance expected from the baseline in terms of sensitivity and angular resolution. The field of view (FoV) of the system increases with energy, with camera FoV >4.5 degrees for LSTs, >7 degrees for MSTs and >8 degrees for SSTs. Conversely the slewing speed requirement becomes shorter with telescope size, with a 20 seconds goal to reposition the large sized telescopes (which have the lowest energy threshold and hence the largest redshift reach) to any point on the sky in response to a gamma-ray burst or gravitational wave transient.

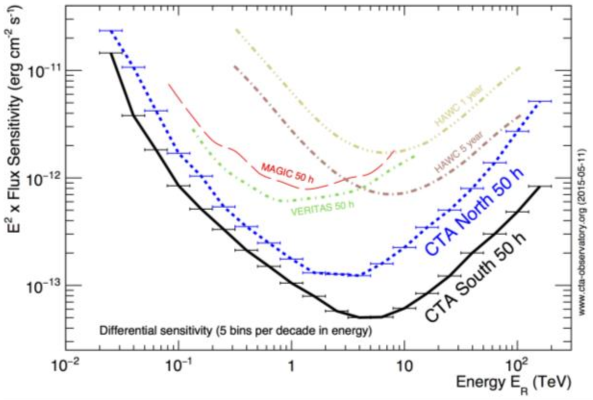

***Fig. 3**. CTA sensitivity compared to existing instruments (https://portal.cta-observatory.org).*

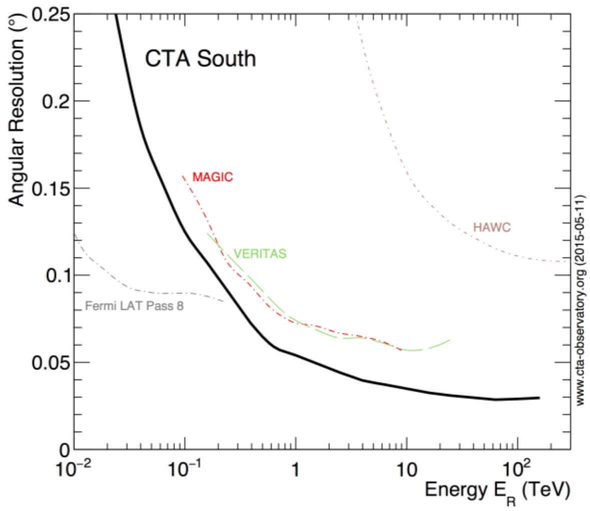

***Fig.4:** CTA angular resolution compared to existing instruments (similar for CTA North, see https://portal.cta-observatory.org).*

The project is now in an advanced preparatory stage, on track for the construction of the first 'pre-production' sets of telescopes on the final sites in 2017, and the completion of the array early in the 2020s. Full-scale prototypes of MST and SST structures exist and a prototype LST is now under construction in La Palma. Full-scale camera prototypes for all telescopes exist or are under construction. Negotiations with the preferred Northern and Southern sites at ORM in La Palma and close to the ESO Paranal in Chile are ongoing. Planning of the on-site infrastructure is now moving into its final stage. Due to the modular nature of CTA, and the large step with respect to the state of the art, significant scientific output is expected prior to the completion of construction.

CTA Key Science Projects will generate high-level public data products that will benefit a wide community, invite multi-frequency astronomical observations, and together they will provide a long-lasting legacy for CTA.

Finally, whilst designed for the detection of gamma-rays, CTA has considerable potential for a range of astrophysics and astroparticle physics based on charged cosmic ray observations (e.g. with the Pierre Auger Observatory and JEM-EUSO featuring strong German contributions) and use of the CTA telescopes for optical measurements.

Neutrino Astronomy

Neutrinos interact only weakly with matter - hence they escape energetic and dense astrophysical environments, which are otherwise optically thick to electromagnetic radiation. Neutrinos therefore promise to provide unique insights into a number of extreme astrophysical phenomena, ranging from stellar explosions to the accretion onto massive black holes. Furthermore, neutrinos can help to decipher the more than 100 year old mystery of cosmic rays, the origin of charged cosmic rays reaching energies of more than 10^{20} eV, ten million times higher than the beam particles of the Large Hadron Collider at CERN. Charged cosmic rays are expected to produce high-energy neutrinos through the interaction with ambient matter or radiation fields. However, while charged cosmic rays are deflected by magnetic fields on the way from the source to the Earth, neutrinos always point back to their origin, unaffected by matter or radiation fields encountered on their path. Hence high-energy neutrinos can provide direct information about the extreme accelerators producing the highest-energy cosmic rays.

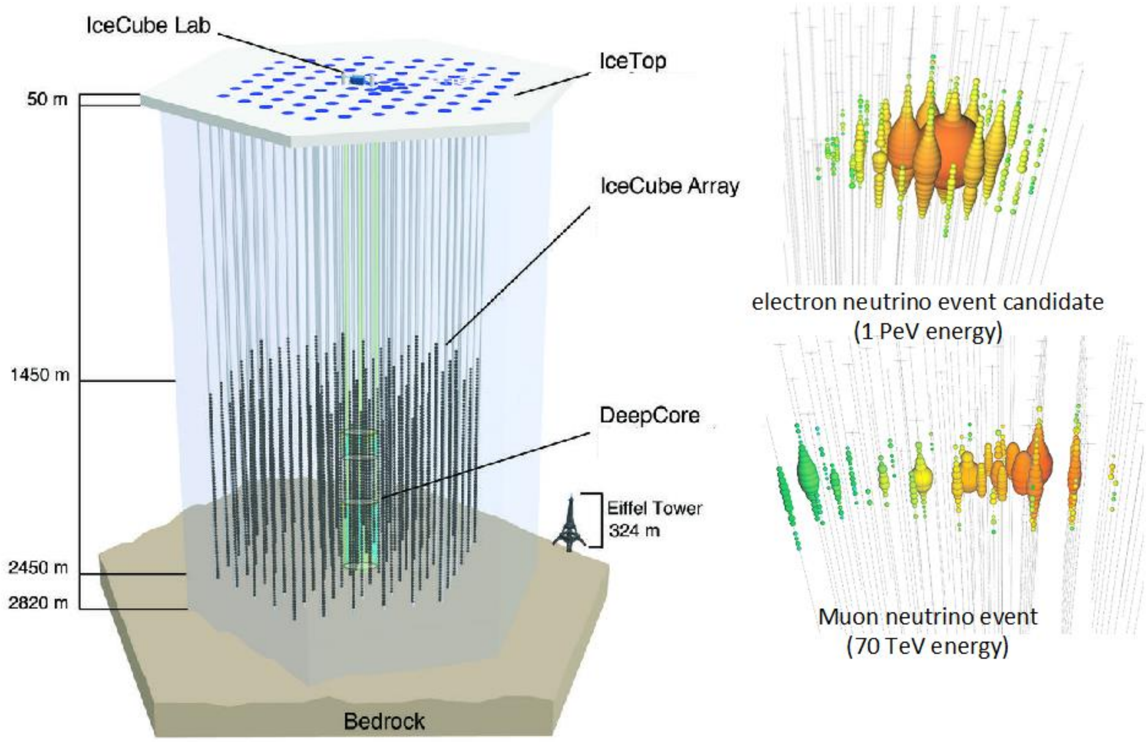

Fig. 5: *The IceCube Observatory (left) and two neutrino events that are candidates for being of astrophysical origin (right). The detector consists of 5360 light sensors which instrument a km^3-large volume of Antarctic ice at depths between 1450m and 2450m. The reconstruction of neutrino events is based on timing and the charge registered by the light sensors (red circles indicate early, green late photons while the size of the circles indicate the number of Cherenkov photons detected).*

With the first detection of high-energy neutrinos of extra-terrestrial origin in 2013 (M. G. Aartsen et al., Science 342 (2013) 6161, 1242856) by the IceCube observatory, a long experimental endeavor including a first generation of pioneering detectors operated in Lake Baikal, the Mediterranean Ocean (ANTARES), or at the South Pole (AMANDA) has reached a major milestone. The detection principle for these detectors is similar: Cherenkov-light produced by charged particles - either background muons produced in air showers above the detector, or particles produced in a neutrino interaction - is recorded by a three-dimensional array of photomultiplier tubes contained in appropriate pressure-resisting glass housings (see Fig. 5).

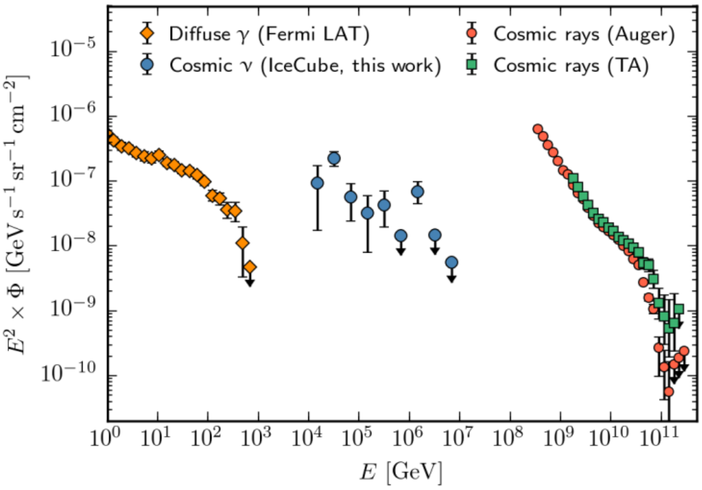

***Fig. 6:** High-energy multi-messengers from the Universe. Extragalactic diffuse gamma-rays observed by FERMI, neutrinos observed by IceCube, and charged cosmic rays observed by Auger and the Telescope Array (from …).*

We now know that the detection of astrophysical high-energy neutrinos requires cubic-kilometer sized detectors, the first being the IceCube neutrino telescope at the South Pole that was completed in 2011. While the low statistics of only a few dozen events observed by IceCube does not yet allow for the identification of their sources, their distribution in the sky points towards being predominantly of extra-galactic origin (although the data still allow for a smaller contribution from Galactic sources). Interestingly, the total energy required to be produced in neutrinos by the sources suggests a connection between neutrinos, gamma-rays and cosmic rays, already leading to important constraints on the sources of neutrinos (see Fig. 6) but also raising new questions.

To fully exploit the scientific potential of neutrino astrophysics, a new generation of neutrino telescopes is required. Phase 1.0, the construction of the first stage of KM3NeT (http://arxiv.org/abs/1601.07459) has started off the coasts of Sicily and the Provence. It marks the beginning of a pan-European effort to build a cubic-kilometer detector (phase 2.0) in the Mediterranean Sea complementing the IceCube detector in the South (see Fig. 7). The detector will have an exquisite angular resolution of 0.1 degrees for high energy events. Together with IceCube, it would continuously provide high sensitivity over the complete sky. The KM3NeT collaboration consists of more than 200 members from 10 European countries and the project has been recognized as a key European research infrastructure (ESFRI). IceCube is a global effort lead by the US (NSF is operating the South Pole station), with strong contributions from Europe. Six European countries out of 12 in total are hosting about half of the more than 300 authors.

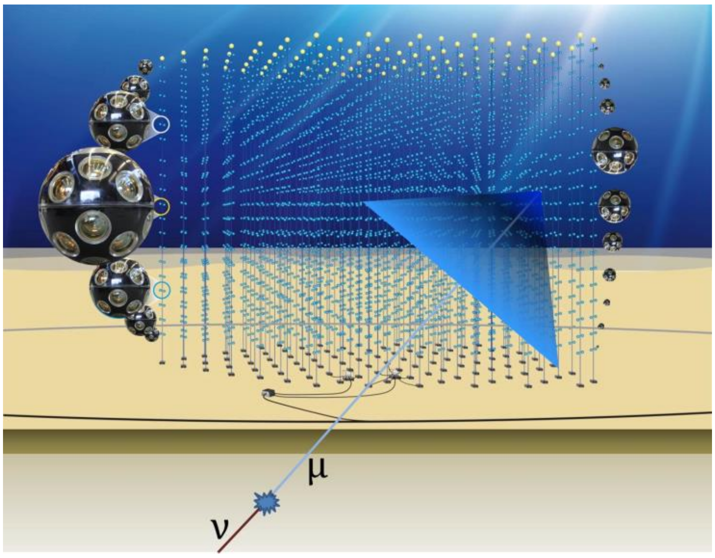

***Fig. 7:** Image of the KM3NeT detector with the optical sensors magnified for better visibility. The detection principle is illustrated with an interaction of a muon-neutrino below the detector.*

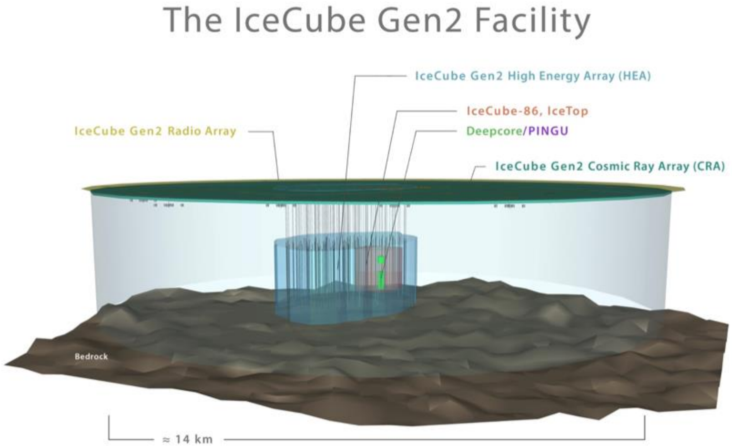

Figure 8*: Sketch of a possible configuration of the IceCube-Gen2 facility. The final layout is still under evolution.*

Meanwhile, plans for a factor 10 larger detector at the South Pole are maturing: IceCube-Gen2 (http://arxiv.org/abs/1412.5106) will target neutrino energies for which a flux of astrophysical neutrinos has been established (> TeV) and combine a range of technologies to expand the energy range beyond 10^{18} eV (see Fig. 8).

3. Main Achievements in the Past Decade

In the past decade, the emerging field of astroparticle physics transformed to a new physics discipline at the crossroads of astrophysics, particle physics, nuclear physics, and cosmology. The overlap with astrophysics is biggest where electrically neutral probes such as very high energy gamma rays and neutrinos are being used for observations of astrophysical objects.

In very high energy gamma ray astronomy, the H.E.S.S. and MAGIC telescope arrays have significantly advanced the field both technologically and observationally. Mirrors, light concentrators, single-photon counting multi-pixel devices, and fast read-out systems were brought to perfection, allowing to operate a large number of telescopes under the harsh conditions of remote locations and mountain altitudes. Together with sophisticated analysis methods, these achievement have cemented the basis for an ongoing observational success.

For the first time, the long-expected spatially resolved tera-electronvolt emission from shell-type supernova remnants was observationally confirmed. A Galactic Plane survey revealed a large population of very high energy gamma ray emitters in our Galaxy, consisting of pulsar wind nebulae, supernova remnants, X-ray binaries, OB associations of young stars, and the Galactic Center itself. These sources play a key role for the acceleration of Galactic cosmic rays.

Observations of extragalactic sources showed that the Universe is crowded with gamma-ray emitting blazars and radio galaxies, highly luminous sources with spectra extending up to tens of teraelectronvolt energies. Their gamma ray flux sometimes varies on extremely short time scales indicative of emission regions more compact than the inner solar system but more luminous than our entire Galaxy. The gamma ray spectra from distant sources were found to curve in a unique way, from which the density of extragalactic background (infrared to ultraviolet) light due to galaxies evolving in cosmic time could be probed, confirming the current paradigm for cosmic structure formation independently of conventional astronomical methods. Some of the best dark matter limits from the non-observation of gamma rays due to dark matter annihilation were obtained using H.E.S.S. and MAGIC targeting the Galactic Center, globular clusters, dwarf galaxies, and clusters of galaxies.

In neutrino astrophysics, a long and winding road of experimental exploration has reached a milestone. IceCube and ANTARES have shown that the deep-ice or deep-ocean operation of single-photon counting devices is possible in a controlled way, allowing for the construction of cubic-kilometer sized instrumented volumes.

IceCube wrote a new chapter in the history book of physics, discovering for the first time an astrophysical flux of neutrinos at very high energies. Very likely this flux is due to astrophysical objects yet to be identified. Already, this breakthrough result has sparked numerous scientific follow-up investigations. Like Columbus in search of new ocean routes, science now has the chance to reach out for discovery.

4. Particular Role/Strengths of Research Groups in Germany

CTA builds on the successes of the previous generation of TeV instruments: H.E.S.S., MAGIC, FACT and VERITAS and is being realised by a broad international consortium (32 nations, over 1200 scientists), which includes the scientists from all of these collaborations. It is recognised as a key project in astroparticle physics (ASPERA roadmap) and in astronomy (ASTRONET roadmap) and as a key European scientific infrastructure (ESFRI roadmap).

Germany is one of the world leaders in the area of astroparticle physics and non-thermal astrophysics in general, and has a particularly strong community in the area of very high energy gamma-ray astronomy. Significant expertise and high interest – both regarding the analysis of data and the theoretical modelling and interpretation – exists in the German science community, regarding nearly all aspects of the CTA program. German institutes are playing a major technical role in the development and large-scale implementation of the instrumentation. For the medium sized telescopes of CTA, Germany leads the development of the telescope structure and one of the two camera developments. For the large-sized telescopes Germany leads the work on the telescope structure. For the small-sized telescope German institutes play a major role in camera development. Germany is also one of the biggest contributors to the development of array control and data analysis software for CTA. By building the FACT telescope as a technology demonstrator, groups in Germany have also helped to establish a novel camera technology based on silicon-photomultipliers for the first time in Cherenkov astronomy. Silicon photomultiplier cameras will serve for the SSTs in CTA and will also be further exploited as a possible next-generation instrumentation for larger sized telescopes.

In the field of neutrino astrophysics, the German community is exceptionally well positioned also. With 9 Universities, two Helmholtz-Centers and one Max Planck Institute participating in IceCube-Gen2 as well as three Universities participating in KM3NeT, and with altogether more than 120 people (mostly full time) involved, it has already made very strong contributions to both projects. German groups have been key players in breakthrough studies connected to the analyses and interpretation of the astrophysical neutrino flux detected by IceCube and are leading the multi-messenger studies (frequently done in real time) in connection with gamma-rays, cosmic rays and optical and X-ray data. Moreover, the fact that groups are active in both water and ice experience provides the German community with a unique and strategic advantage in exploiting technological and scientific synergies. The German community is united behind the claim to continue playing a leading role in at least one of the future projects. Current activities focus on IceCube-Gen2 R&D. A long-term commitment will depend on progress in IceCube-Gen2 R&D, ongoing experimental efforts within KM3NeT, as well as the funding situation in the EU and USA.

5. Dominant Science Cases

A preliminary 'Key Science Programme' has been developed by the CTA consortium. One major element of this programme is the search for dark matter, in particular the annihilation signature of WIMPs. The strategy followed places the expected annihilation cross-section for a thermal relic within reach for a very wide range of WIMP masses from ~200 GeV to 20 TeV, making CTA complementary to other approaches. CTA will also conduct a census of particle accelerators in the Universe, with planned surveys of the full Galactic plane, of the Large Magellanic Cloud, and of a quarter of the extragalactic sky, typically providing an order of magnitude improvement in flux sensitivity over existing surveys. Additional targets are galactic and extragalactic transient phenomena, as well as objects and mechanisms capable of accelerating cosmic rays up to PeV energies in our own galaxy. Studies of gamma ray emission by active galaxies explore particle acceleration around supermassive black holes, and probe factors influencing intergalactic propagation and interactions of high energy photons, including the redshift-dependent density of extragalactic background light, intergalactic magnetic fields, and the possible violation of Lorentz invariance at short distance scales and high energies. Gamma ray emission from star-forming systems on a wide range of scales characterises universality – or deviation therefrom – of particle acceleration and particle propagation across astrophysical systems. Clusters of galaxies like the Perseus cluster are targets since the confine both cosmic rays and dark matter.

Neutrino (and also gravitational wave) astrophysics probes the realm of the high-energy Universe in a complementary way. Hidden regions from where high energy gamma rays are unable to escape such as compact objects, exploding stars, or high-energy sources at large cosmological redshifts are observable only with neutrinos. Now that IceCube has shown the existence of an observable flux of astrophysical neutrinos, the next challenges are to resolve the sources of the observed high energy astrophysical neutrinos. Neutrino point sources must be discriminated from a possible diffuse neutrino background, *e.g.* due to decays of massive relic particles of the early Universe. Employing astronomical multi-wavelength observations and theoretical models, the physical nature of the neutrino sources will be deciphered. The extreme physical conditions and mechanisms of particle acceleration inside of astrophysical neutrino sources will provide insights into plasma states of matter far from what can be studied under laboratory conditions. Transient sources will also allow for testing the equivalence principle and neutrino oscillations across cosmological baselines.

The revenue of all these efforts will be the answer to the hundred-year-old question of the origin and propagation of cosmic rays in galactic and extragalactic objects.

Overarching Science Topics

Improving our understanding of the role of energetic particles in the Universe will also shed new light on astrophysical questions about the non-thermal feedback with star formation, the heating of the interstellar medium, the ionization of molecules inside the high-density cores of dust clouds, and the abundances of light elements as spallation products from cosmic ray collisions between heavy nuclei. The full physics case and its tight connections with other branches of astrophysics is described in more detail in the chapter about high-energy astrophysics. Clearly, there is ample synergy with other astronomical infrastructure: Radio, X-ray, MeV and GeV gamma ray observations are of crucial importance to characterize multi-wavelength properties of sources. This emphasizes the need for a coherent development of the astronomical infrastructure (e.g. SKA, eROSITA, Athena, ESA/NASA space mission for MeV gamma rays). Spectroscopic surveys (EUCLID) are needed to identify extragalactic high-energy source populations. The interplay between energetic particles and neutral gas is another major science theme, requiring high-resolution field spectroscopy of interstellar shock waves at optical frequencies (ESO instrumentation). For the deepening of our understanding of particle acceleration and transport, space measurements of energetic particles and magnetic fields in the heliosphere (*see chapter by H. Peter et al.)* are required. Theoretical models of particle acceleration have to be validated in the limit of weak turbulence, slow shock speed, and low particle energy. High energy observatories also play an important role for the exploration of the transient Universe in the era of LSST and gravitational wave detectors (eLISA), providing follow-up observations of coalescing compact objects. Observatories for charged cosmic rays such as the Pierre Auger Observatory and JEM-EUSO (or LOFAR) will be important, as they can trace the origin of particles at ultrahigh energies where the deflection angles of particles due to interstellar magnetic fields become small (see ASPERA Roadmap). They take part in preparations for the *era of multi-messenger astroparticle physics* by providing open-access data inviting for correlation studies with gamma ray, neutrino, and gravitational wave events.

6. Summary and Conclusion

H.E.S.S., MAGIC, IceCube, and ANTARES have revolutionized the field of gamma-ray and neutrino astroparticle physics and our current understanding of the non-thermal Universe. The astroparticle physics community is well prepared for the next decade. The groups in Germany plan to contribute to the upcoming next-generation observatories for high-energy gamma rays (CTA) and neutrinos (IceCube-Gen2, KM3NeT) in a major way. Intellectual leadership paired with international partnership, pioneering technological developments, and a substantial science case with discovery potential, promise to carry on this field of research towards ambitious goals.

The prerequisites for sustaining the success story are a reliable funding profile and vibrant interactions with the astronomical community. A theory priority program to raise the synergy in the topics overarching with astronomy will provide the depth of understanding needed to unfold the full discovery potential. Auxiliary measures to provide computing and big data performance are an essential part of the research infrastructure allowing University groups to get access to the observatories. Since astroparticle physics does not benefit from existing infrastructures in particle physics (CERN) or astrophysics (ESA, ESO), new models for funding the contributions to the operating costs are urgently needed in this highly competitive field of research.