Future of Astroparticle Physics
The European (APPEC) View
Astroparticle Physics is a branch of fundamental science embedded in environment and society!

Understanding the Multi-Messenger and the Dark Universe

Wikipedia:
While it may be difficult to decide on a standard 'textbook' description of the field of astroparticle physics, the field can be characterized by the topics of research that are actively being pursued.
AstroParticle Physics European Consortium

• is an international coordinating structure, founded in 2012

• is based on a MoU and financial agreement with DESY (host of the APPEC Common Fund) by all partners

• has 18 (+1 suspended) member countries with 22 funding agencies

• has a budget of c. 70k€/year
APPEC bodies

- **General Assembly**
  - Strategic, decision making and supervisory body
  - Representatives of funding agencies
  - Chair: Andreas Haungs (KIT);
  - Vice-Chair: Antoine Kouchner (APC)

- **Scientific Advisory Committee**
  - Advisory body
  - Chair: Sijbrand de Jong (Nijmegen);
  - Vice-Chair: Silvia Pascoli (Bologna)

- **Joint Secretariat (distributed office)**
  - Executive body chaired by the General Secretary
  - General Secretary: Katharina Henjes-Kunst (DESY)

- **Observer**
  - CERN (Joachim Mnich)
  - ECFA (Karl Jakobs)
  - NuPECC (Marek Lewitowicz)
  - Astronet (Colin Vincent)
  - ESO (Andy Williams)
  - EPS-HEPP (Ramon Miquel)
Guarantee Coordination of European Astroparticle Physics in Europe between funding agencies and visibility at Ministry level through:

• Structured scientific advising (SAC, dedicated panels to specific challenges)
• Development and update of roadmaps based on scientific strategies and financial considerations
• Establish relations with other bodies in companion fields
• Initiate activities within Horizon Europe
• Express collective views on APP in international fora
• Organize Town meetings
• Support relevant meetings/schools of the community
• Organize TechFora and Open Calls
• Engagement with society (Outreach, Education,...)
• Contribute to Working Groups (R&D panel, Individual Recognition, Early Scientist career, Science WGs) and Organisations (EuCAPT...) and JENA to support the Astroparticle Physics community

APPEC is

• Helping in coordination of large-scale RI
• Helping in transition of mid-scale experiments to large-scale RI
• Helping in support of small-scale and R&D experiments
2008: The six questions of Astroparticle Physics and facilities to attack them:

1) What is the Universe made of? In particular: What is dark matter?
2) Do protons have a finite life time?
3) What are the properties of neutrinos? What is their role in cosmic evolution?
4) What do neutrinos tell us about the interior of the Sun and the Earth, and about supernova explosions?
5) What is the origin of cosmic rays? What is the view of the sky at extreme energies?
6) What will gravitational waves tell us about violent cosmic processes and about the nature of gravity?
APPEC Roadmaps

2008

The Magnificent Seven

CTA

AUGER -N

KM3NET

1 ton dark matter

Einstein telescope

Megaton proton decay

1 ton neutrino mass

https://www.appec.org/roadmap
APPEC Roadmaps

https://www.appec.org/roadmap

2008

2011

2017
APPEC scientific topics

• High-energy gamma rays
• High-energy neutrinos
• High-energy cosmic rays
• Gravitational waves
• Dark Matter
• Neutrino mass and nature
• Neutrino mixing and mass ordering
• Cosmic microwave background
• Dark Energy
• Astroparticle theory
• Detector R&D
• Computing and data policies
APPEC organisational & societal issues

Organisational:
• European Commission
• European and global collaboration and coordination
• Neighboring communities
• Unique infrastructures
• Interdisciplinary opportunities

Societal:
• Gender balance
• Education and outreach
• Open Science and Citizen Science
• Ecological impact
• Connection to industry
Midterm Evaluation of the Roadmap

- A resource aware roadmap (darker colors also show M&O of RI)
- Midterm Evaluation: Preparation of roadmap update
  - Direct Dark Matter working group
  - Double Beta Decay APPEC Sub-Committee
  - Multi-Messenger Discussion Workshop
- Goals
  - Identify new developments and new topics
  - Update recommendations
  - Update of time and cost line
- Timeline
  - Provide information to the communities (2021)
  - Town Meeting June 2022 [https://indico.desy.de/event/25372/](https://indico.desy.de/event/25372/)
  - Census / Survey of time and cost lines
  - Publication end of 2022

From Roadmap 2017: Projected annual capital investment
Multi-Messenger Astroparticle Physics

• Required to understand the sources of cosmic rays and the physics processes in the high-energy Universe
• Needs long-term operational observatories
• And a sophisticated Big Data management: Big Data Analytics; Research Data Management; Data Curation; Open Data

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High-Energy Gamma Rays

- Covers large energy range with different observatories
- Satellites (Fermi, AMEGO (launch 2029), ASTROGAM; THESEUS)
- Imaging Air Cherenkov Telescopes (H.E.S.S., Veritas, MAGIC)
- Ground-based arrays (GRAPES, TAIGA, HAWC, LHAASO, SWGO)
- Main future project within APPEC: CTA (ESFRI)
Cherenkov Telescope Array – CTA
High-Energy Gamma Rays

- ESFRI Project
- Open, proposal-driven observatory
- 3 telescope types: LST, MST, SST
- 2 sites: La Palma + Chile
- Governance: ERIC (established 2022)
- 31 countries, >200 institutes, ~1400 scientists
- Construction next 3-5 years

F.Aharonian

- an order of magnitude better sensitivity
- broader energy coverage: $10^{10}$ to $10^{15}$ eV
- angular resolution down to 1-2 arcmin
- energy resolution 5 to 25 percent
- larger (up to 6-8 degree FoV)
- rapid follow-up capabilities
High-Energy Neutrino Astronomy

- IceCube opened in 2013 the new window of >100 TeV neutrino astronomy
- Several experiments are now organized in the Global Neutrino Network GNN:
  - IceCube → IceCube-Gen2
  - Antares → KM3NeT
  - Baikal-GVD
- R&D phase (in particular for cosmogenic Neutrinos): P-ONE, RNO-G, POEMMA, ANITA, GRAND, …
- European flagship (ESFRI): KM3NeT
- Strong partner of US lead IceCube-Gen2
Cubic Kilometre Neutrino Telescope – KM3NeT
High-Energy Neutrino Astronomy

• ESFRI project
• KM3NeT = ARCA + ORCA
• Discovery and subsequent observation of neutrino sources
• Determination of mass ordering of neutrinos
• ARCA (high-energy neutrino astronomy, Italian site)
  Installation started, completed 2026
• ORCA (low-energy neutrino physics, French site)
  Installation started, completed 2024
• 15 countries, >250 scientists

Science case

♦ Neutrino astroparticle physics
  • Galactic and Extragalactic point sources
  • Diffuse neutrino flux
♦ Dark Matter and exotics
  • Neutrinos from Dark Matter annihilation
  • Magnetic monopoles, nuclearites, strangelets, ...
♦ Neutrino and particle physics ($\sim 10^5 \nu_{\text{atm}}$/year)
  • UHE neutrino cross sections
  • Muons ($\geq 10^8 \mu_{\text{atm}}$/year)
  • Prompt muons from heavy meson decay
♦ Earth and marine sciences
  • Long-term, continuous measurements in deep-sea
• MM alerts and follow-up

27/09/2022
RPC@CERN | Andreas Haungs
High-Energy Cosmic Rays

• Accuracy of measurements in all energy ranges increased dramatically in last 2 decades, but still:
  • Transition energy range ?
  • Hadronic Interaction models ?
  • Composition and Anisotropies at all energies?
  • Suppression mechanism?

• Pierre Auger Observatory is major experiment

• Highest energies: extensions to TAx4, AugerPrime

• At lower energy (LHAASO, IceCube-Gen2)

• Plus future projects: POEMMA, GRAND, GCOS (global, cost effective, sustainable, experiments)
High-Energy Cosmic Rays

- Auger Upgrade to AugerPrime
- High statistics and accuracy required for determining energy spectrum, composition, anisotropy over a large energy range
- Combining data of the various projects (UHECR working groups!)
- 18 countries, ~100 institutes, ~400 scientists
- AugerPrime completes construction in 2023
- Operation time >2030
- Preparation and R&D for GCOS incl. GRAND
Gravitational Waves

- 2015: First direct detection by LIGO / Virgo
- 2022+: Data taking with aLIGO and aVirgo
  - Volume of visible space increases by a factor 50
- 2030+: 3rd Generation: The Einstein Telescope
  - Volume of visible space increases by a factor 1000
- GWIC + GWAC (worldwide collaboration)
  - GWIC Gravitational Wave International Committee [https://gwic.ligo.org](https://gwic.ligo.org)
  - GWAC Gravitational Waves Agencies Correspondents
- Gravitational Waves Ground-Space complementarity
  - Einstein Telescope; Cosmic Explorer
  - LISA; e-LISA
  - Pulsar Timing Arrays; IPTA; SKA
Einstein Telescope - ET
Gravitational Wave Detection

- Science (very interdisciplinary)
  - Formation of Black Holes at the center of galaxies?
  - Is General Relativity (GR) right or do we need new physics?
  - Is Dark Energy the cosmological constant?
  - Understanding the dynamics of ultra dense matter!

- ESFRI
  - The ESFRI roadmap proposal (I, NL, B, E, Pl) was successful;
  - The ESFRI roadmap was updated in June 2021

- Status and Organisation
  - Due to the 3G science case, the interest in ET in Europe is rapidly growing.
  - Boards have been formed:
    - Instrument science, Observational science, Site characterisation, E-Infrastructure.
  - The Instrument science board is the most advanced and is fully operational
  - The ET collaboration had its kick-off meeting in July 2022 (79 Research Units)

- R&D
  - Advanced Virgo and Advanced Ligo; KAGRA; ETpathfinder (NL); may be DZA (D)
  - MoU with CERN on common vacuum R&D
• Topic has large overlap with neighboring fields
• Direct Detection of Dark Matter APPEC SAC Subcommittee Report:
  • [https://www.appec.org/documents](https://www.appec.org/documents)
• Recommendations:
  • Priority of Dark Matter Search
  • Diversified Approach Needed
  • Direct search for WIMPs down to neutrino floor (DARWIN, ARGO)
  • Coordinated detector R&D
  • European Infrastructure for Underground Science
  • Studying of the axion/ALPs mass range
  • Continuation of diverse theoretical activity

dark matter wimp search with liquid xenon
Dark Matter - WIMP

- APPEC recommends to realize worldwide at least one xenon (50t) and one argon (300t) experiment
- DARWIN is currently the European flagship experiment for WIMP search
- In addition, ongoing detector R&D has to be pursued
- XENON/DARWIN and LUX-ZEPLIN collaborations have signed a common MoU https://arxiv.org/abs/2203.02309 (141 institutes, ~600 authors): XLZD experiment
- Needs (European) infrastructures for Underground Science
Neutrino Properties

- $\nu$ CP-violation is still unknown and may give hints to matter-antimatter asymmetry
- $\nu$-mixing is very different from CKM
- $\nu$-nature undetermined (Majorana)
- $\nu$ mass ordering not yet determined
- $\nu$ masses $\ll$ mSM particles gives access to higher mass scales (See-Saw)
- $\nu$ is the first hot “dark” particle and has a role in various stages of the Universe
- Needs (European) infrastructures for Underground Science

Science has large overlap with neighboring fields
$0\nu\beta\beta$ decay: towards ton-scale experiment

CUPID (100 Mo)  
LEGEND-1000 (Ge)  
nEXO (136 Xe)  
NEXT (136 Xe)
Neutrinoless Double Beta Decay

Strategy (Status early 2022):

- Double Beta Decay APPEC Sub-Committee gave advise on the European (and global) program
- It provides an assessment of the current and future scientific opportunities in double beta decay over the next 10 year period
- Close coordination of APPEC with DOE nuclear physics and aligned with Snowmass process
- Spring 2021: DOE portfolio review on Neutrinoless Double Beta Decay Experiments
- 0νββ European-North American Summit at Gran Sasso, Italy, 29/9 -1/10/2021
  - [https://agenda.infn.it/event/27143/](https://agenda.infn.it/event/27143/) Presentation of Underground labs, Experiments, R&D, …
  - Closed session: 19 representatives of funding agencies and director of underground labs
  - Outcome:
    1. Neutrinoless Double Beta Decay should have high priority
    2. funding agencies in Europe and North America should build a network
    3. if possible LEGEND and nEXO should be funded, one in Europe, one in North America
APPEC Flagship Research Infrastructures

This is not a closed, but dynamic list...

- [construction KM3NeT 2020-2026; IceCube-Gen2]
  - HE Neutrinos
- [construction AugerPrime 2019-2023]
  - HE Cosmic Rays
- [construction CTA 2021- ]
  - HE Gamma Rays
- [construction Einstein Telescope 2026- ]
  - Gravitational Waves
- [construction LEGEND-1000 / nEXO 2023- ; ... ]
  - Neutrino Properties
- [construction DARWIN 2024- ; XLZD, ARGO, ... ]
  - Dark Matter
Cosmology; CMB; Dark Energy

- Inflation:
  - Spectral index of fluctuations, $n_s$
  - non-Gaussianity?
  - Inflationary gravitational waves?

- Neutrinos:
  - Number of relativistic species (Neff or “dark radiation”)
  - Sum of the neutrino masses, $\sum m_\nu$
  - through impact on growth of structure

- Dark Energy:
  - Probe growth with SZ clusters, CMB lensing, correlation with galaxy surveys
  - Is GR correct on large scales?
Two approaches of Astroparticle Physics related to Cosmology

1. The cosmic structures from the CMB to the present provide comparable constraints to the standard model of cosmology (inflation, dark energy) and particle physics (neutrino, dark matter).

2. Multi-messenger astronomy involving photons of all frequencies, gravitational waves, neutrinos and high-energy charged particles provides a deeper understanding of violent phenomena regulating structure formation in the Universe and can eventually hint to physics beyond the standard model(s).

⇒ Results will provide confirmation of standard models or new portal to the future.
⇒ Large facilities in extreme environments are needed.
⇒ Both approaches connect different energy/dimensional scales

Adapted from S. Katsanevas
Overarching Topics in the Roadmap

- Ecological Impact
  - ...of satellites, observatories, infrastructures, travel...
  - ...provide spin-offs for other research areas

- Societal Impact
  - Survey and fostering of impact on society

- Open Science and Human Talent Management
  - Outreach and education
  - Open Data and Citizen Science ESCAPE https://projectescape.eu/

- Computing
  - European Centre for Astroparticle Physics Theory EuCAPT
    - https://www.eucapt.org/

- Underground and Large-scale Infrastructures
  - Coordination of European Underground Labs

- Horizon Europe
  - European and global collaboration and coordination, e.g. INFRA-SERV-2023
ECFA Detector R&D Roadmap

"Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields."*

"The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels."*

* 2020 European Particle Physics Strategy Update
https://europeanstrategyupdate.web.cern.ch/

ECFA Detector R&D Roadmap Panel web pages at:
https://indico.cern.ch/event/2784893/

Credit: Phil Allport
Open Data

- Well established in astronomy; coming-up with https://opendata.cern.ch/
- Forerunner in Astroparticle Physics (air-shower data) was KCDC
- Now also other by experiments (in particular in HE-APP); e.g. by the Pierre Auger Observatory www.auger.org/opendata
- Future facilities must provide a dedicated Data Management Plan.

Open Data ≠ Outreach

- as open data serves for community and the research field and the society
- outreach profits from open data
- KCDC is a platform for both, open data and outreach

- KCDC is a web-based platform to provide scientific data for the general public
- KCDC is to offer long-term scientific data for the community as well as for students and the interested public
- What’s new: Independent Data Shops: Allows for Multi-Experimental Analysis ; Data of new experiment: Maket-Ani ; Jupyterhub: https://jupyter.iap.kit.edu supports online in-KCDC analyses ; API (Application Programming Interface): Improves systemic data handling
Strategy Connections

In the APPEC strategy process there are strong connections to:

- ECFA: EPPSU and corresponding roadmaps
- NuPECC: Nuclear Physics Long Range Plans
- Astronet (now in particular for INFRA-SERV-2023)
- Snowmass2021
- Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)
- National communities
- JENAA EoIs
Summary

• Astroparticle Physics is a booming and blooming field
• In search of the wonders of the cosmos
• Going to understand the fundamental law of Nature
• Plenty of opportunities for young scientists

APPEC:
• Publication of Roadmap Update in 2022
• Coordination of European Astroparticle Physics strategy…
• …in cooperation with neighboring fields
• APPEC Newsletter: https://www.appec.org/latest-news/newsletters

…and further foster and coordinate the European Astroparticle Physics!