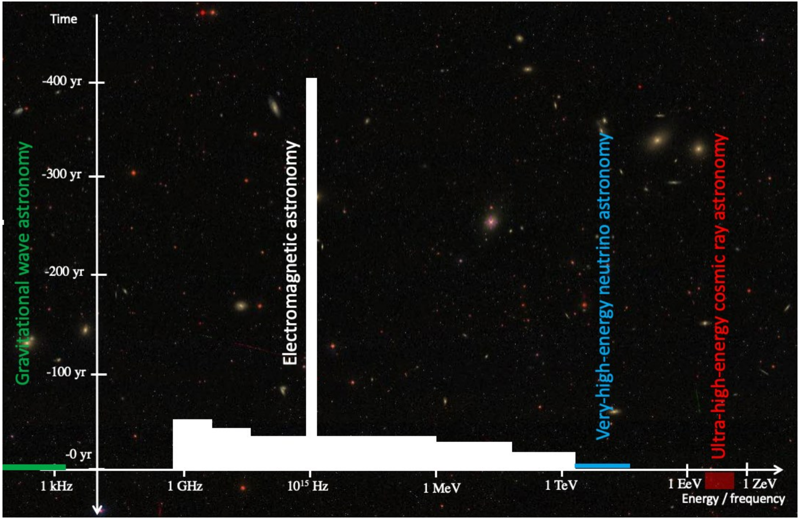
Astroparticle Physics and Multimessenger Astronomy

Dmitriy Kostunin

October 11, 2023

Development of astronomy



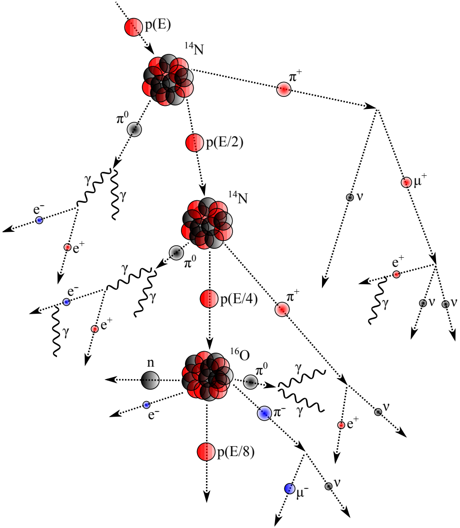
Source: A. Neronov, J.Phys.Conf.Ser. 1263 (2019) no.1, 012001

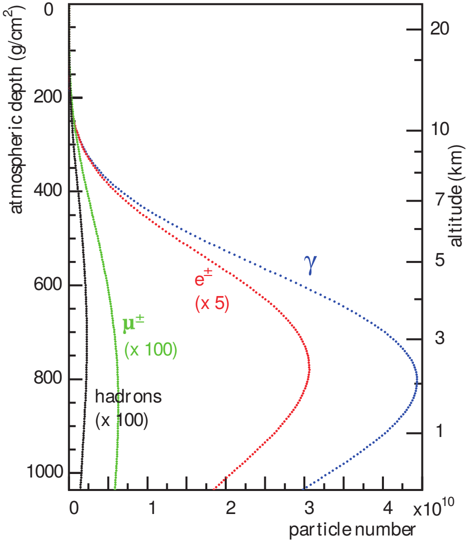
From cosmic rays to astroparticle physics

Discovery of cosmic rays

Cosmic rays have been discovered by Victor Hess (Austria) in 1912

(Extensive) air-showers





billions of gamma-quanta and leptons, and *millions* of hadrons at shower maximum with $E_p \sim$EeV

Discovery of air-showers

JULY–OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France

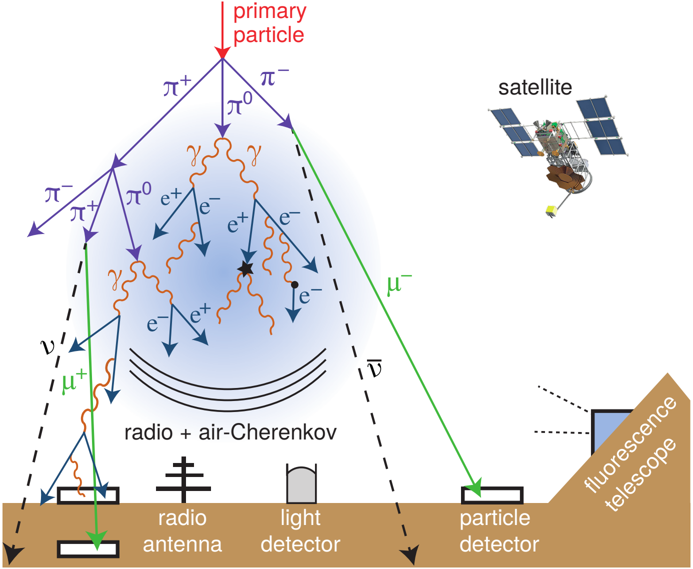
PHYSICAL REVIEW VOLUME 71, NUMBER 5 MARCH 1, 1947

The Lateral Extension of Auger Showers

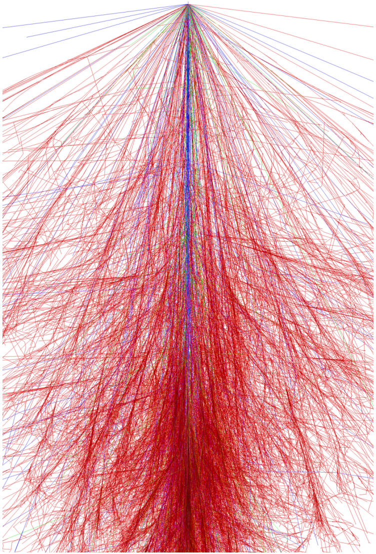
D. V. SKOBELTZYN, G. T. ZATSEPIN, AND V. V. MILLER
P. N. Lebedev Physical Institute of the Academy of Sciences of U.S.S.R., Moscow, U.S.S.R.

(Received January 7, 1947)

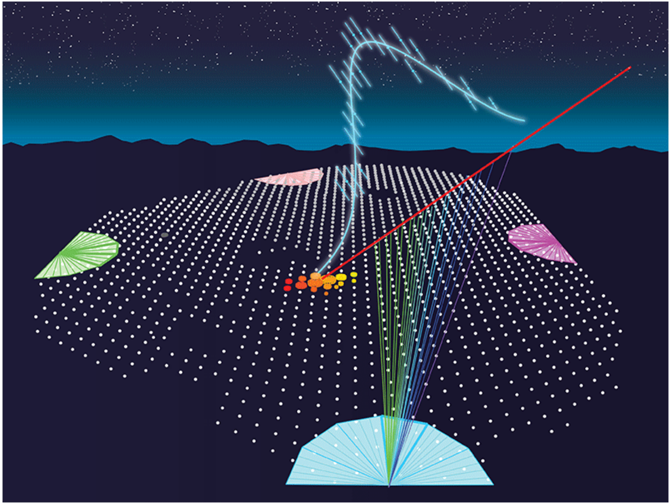
Air-shower detection



Realistic simulation



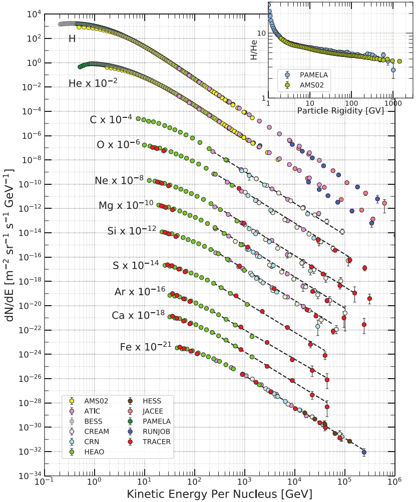
Detection example (Pierre Auger Observatory)

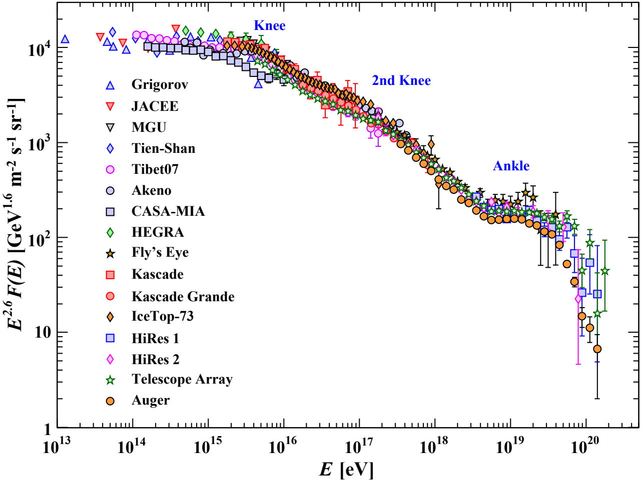


1660 surface detectors on $\sim$3000 km^2 + fluorescence telescopes

Maximum detected energy $\sim$ZeV$= 10^{21}$ eV (LHC energy $\sim$TeV)

Cosmic ray spectrum

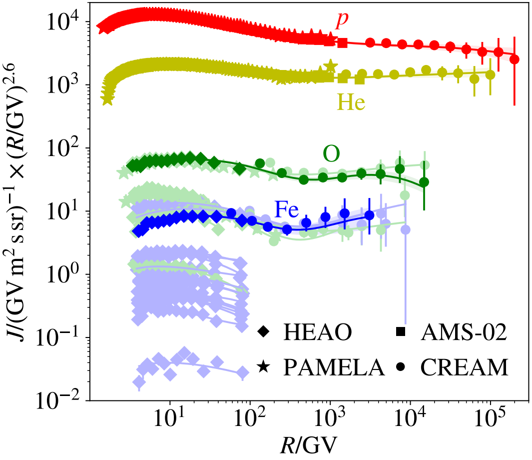


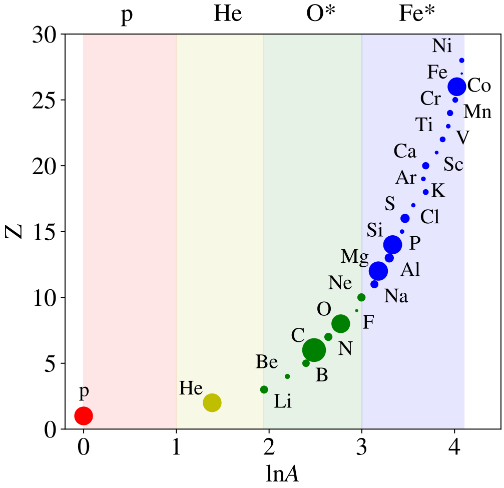


Fundamental properties are flux $F = (E/E_0)^\gamma$ and mass composition (A, Z)

Cosmic ray mass composition

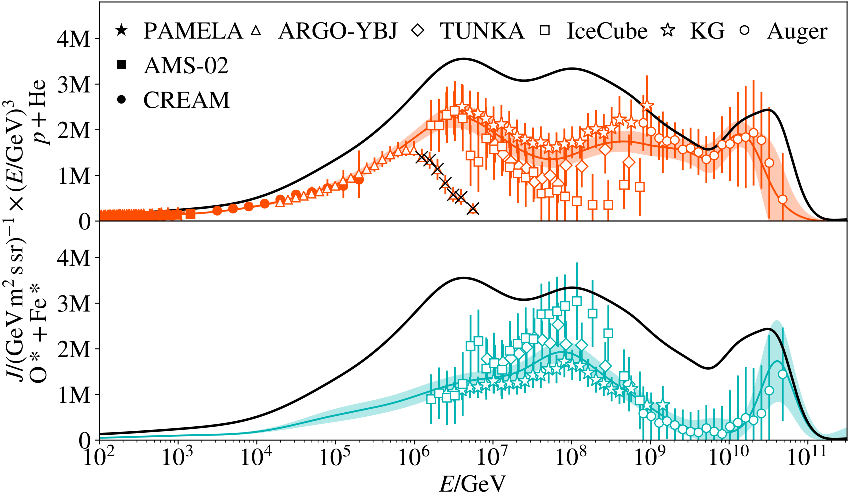
Values obtained from direct measurements



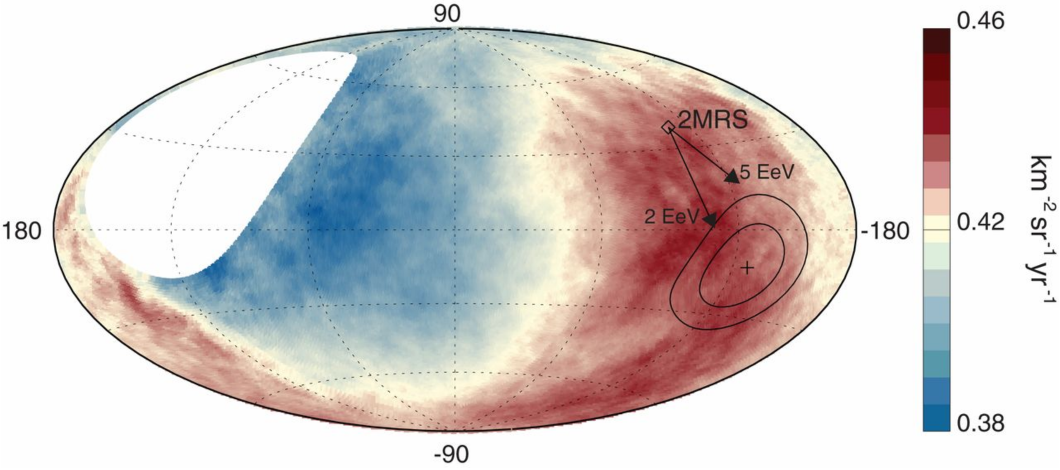


Cosmic ray mass composition

Values obtained from indirect (air-shower) measurements



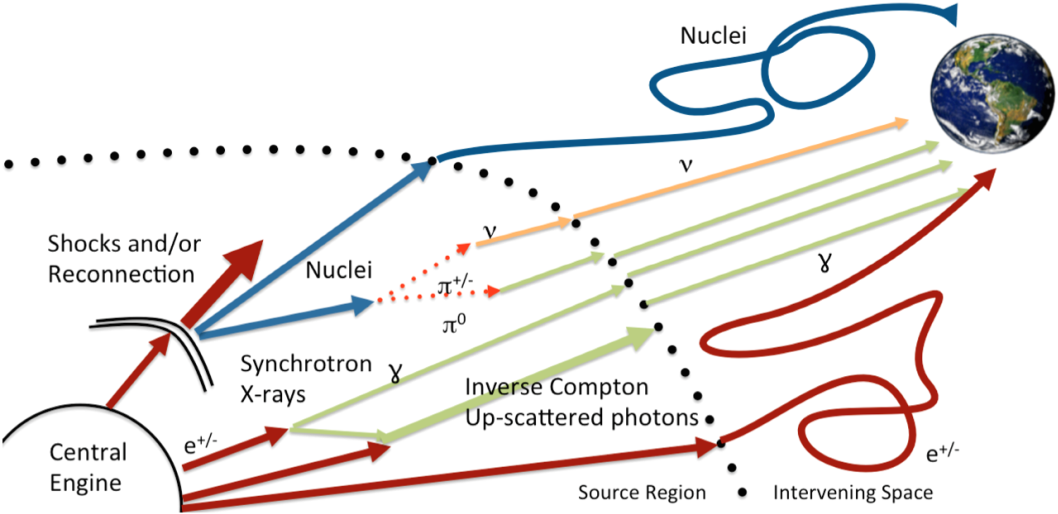
Sky in cosmic rays



Pierre Auger Collaboration, “Large-scale cosmic-ray anisotropies above 4 EeV measured by the Pierre Auger Observatory,” Astrophys. J. **868**, no.1, 4 (2018) doi:10.3847/1538-4357/aae689. arXiv:1808.03579.

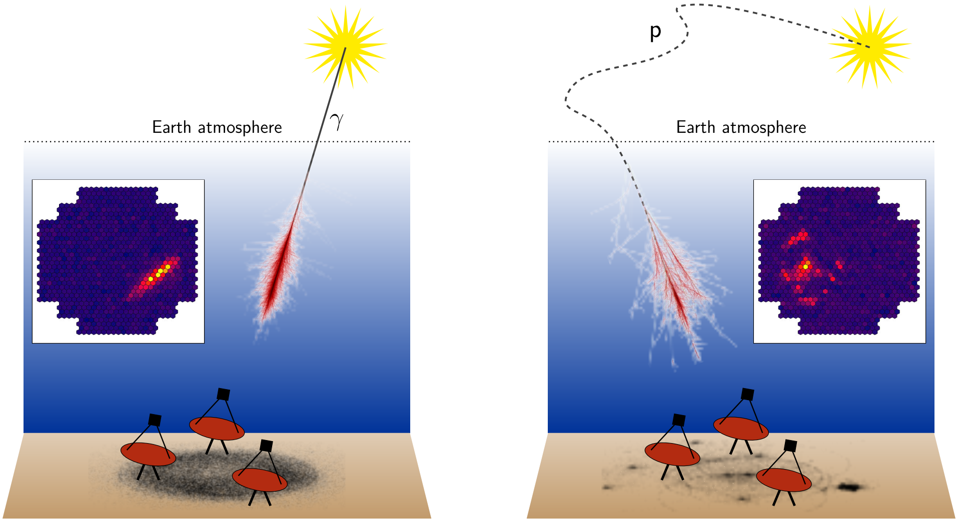
Search for cosmic-ray accelerators

Cosmic accelerator



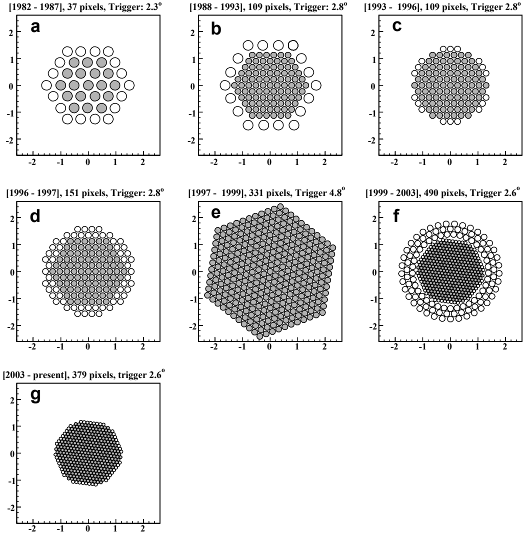
Credit: HAWC Observatory

Imaging Atmospheric Cherenkov Telescopes

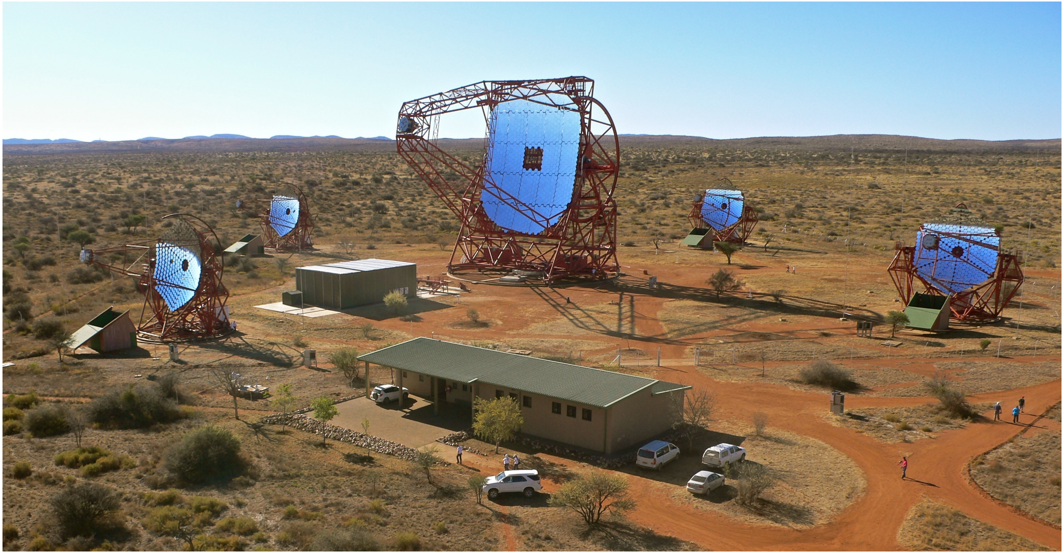


Credit: Tim Lucas Holch, PhD thesis

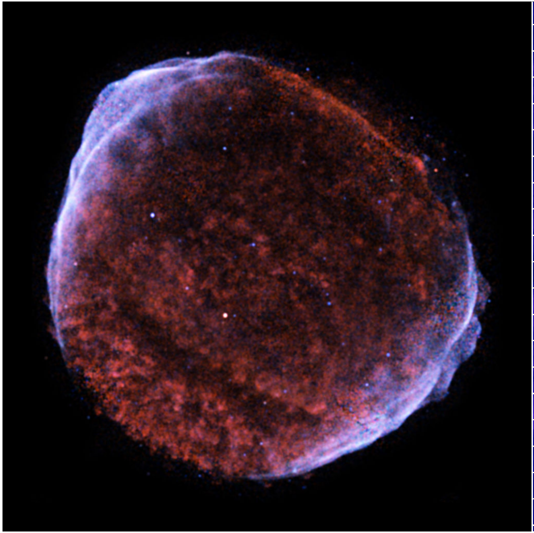
Whipple Telescope

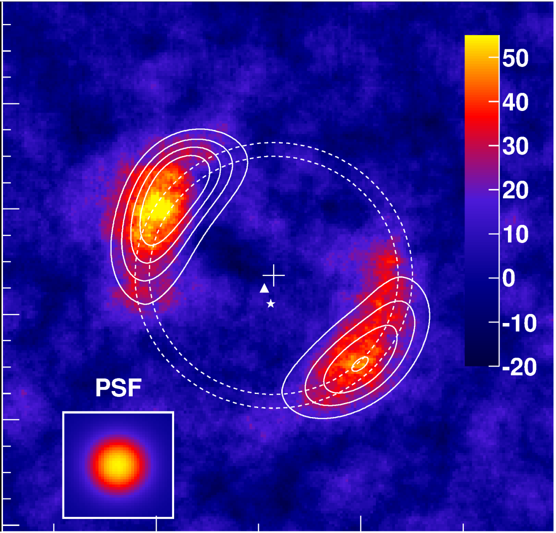


High Energy Stereoscopic System (H.E.S.S.)

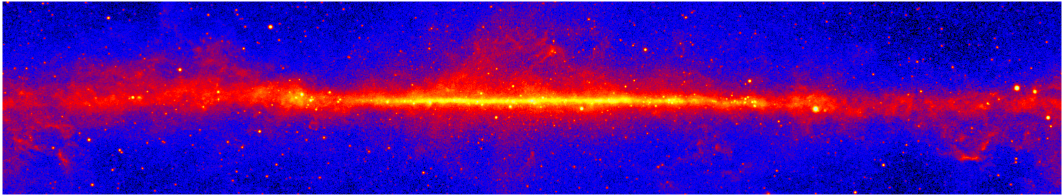


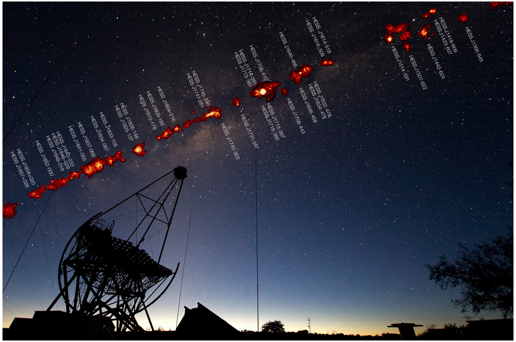
SN 1006

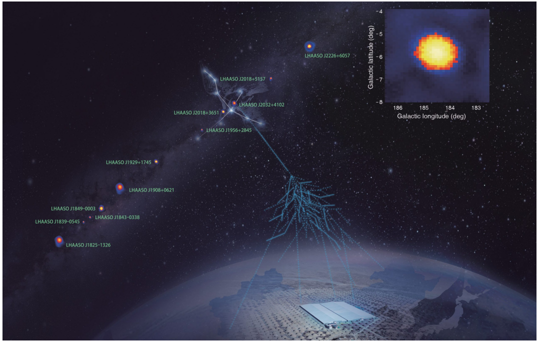




HE → VHE → UHE (GeV → TeV → PeV)

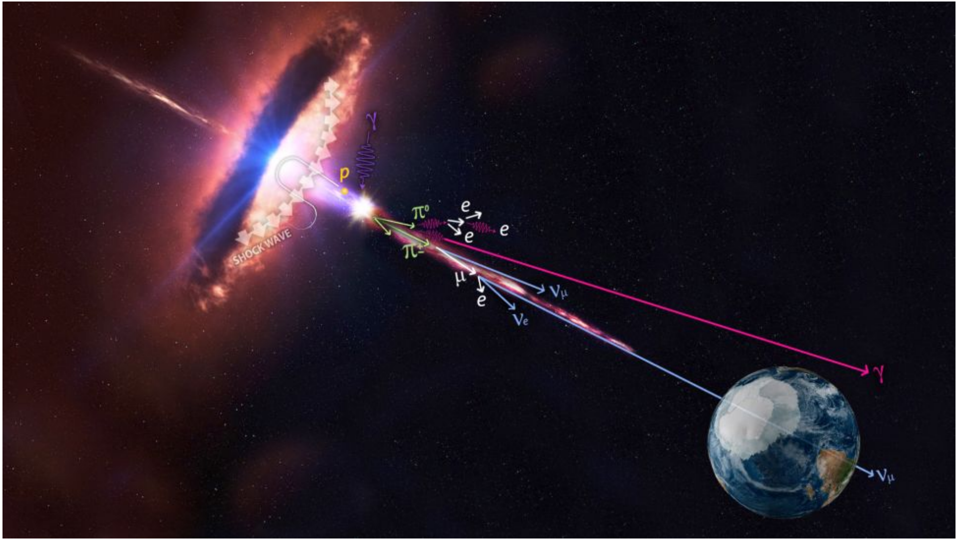






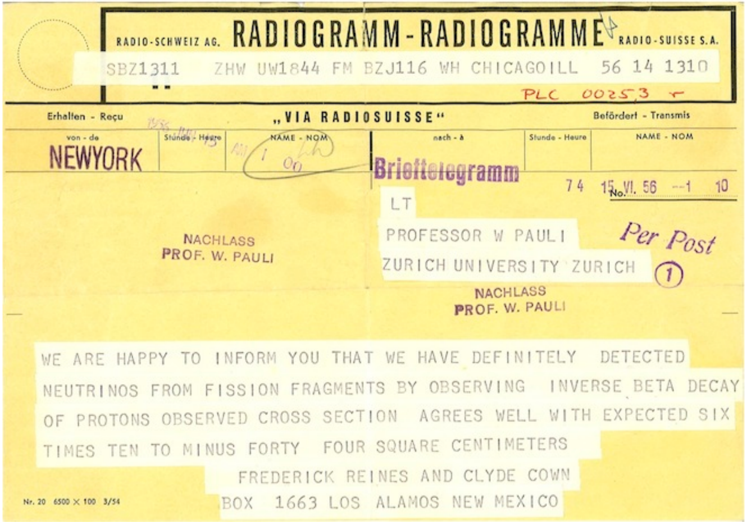
Hunting for the lightest particle

Astrophysical neutrinos



Credit: IceCube/NASA

1956: first detection of neutrino



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LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

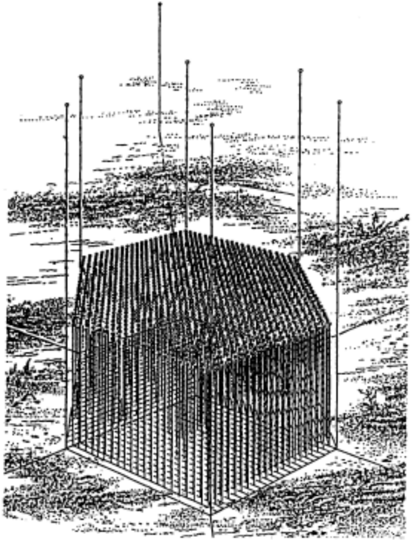
Nr. 20 6500 × 100 3/54

Cross-section of MeV neutrino $\sigma \sim 6 \cdot 10^{-44}$ cm^2 $\Rightarrow$ full absorption in the water with thickness of 100 light years!

1960: Report by M.A. Markov at ICHEP

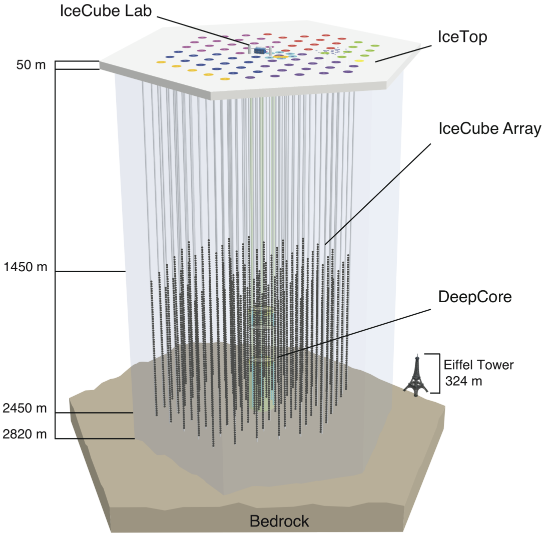
We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation

Deep Underwater Muon And Neutrino Detector (DUMAND) project



- 1975: First workshop in Washington
- Proposed volume of 1.26 km^3 with 1261 strings and 22698 optical modules
- Acoustic detector with volume of 100 km^3
- Active collaboration between USSR and USA till 1980
- Project is being developed until 1995, then terminated
- Despite of failure, the experience was used in AMANDA and NT-200

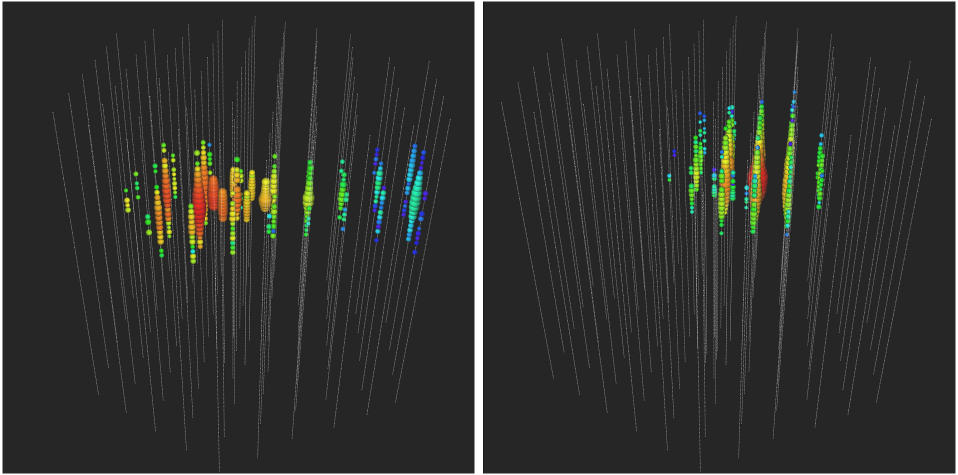
IceCube observatory



- Gigaton ice-Cherenkov telescope at South pole
- 60 optical modules (OM) per string
- **78 IceCube strings** in triangle grid (L=125 m)
- **8 DeepCore strings** in pure ice
- **81 IceTop stations**, two detectors per station, 2 OM per detector
- Deployment from 2004 to 2011

Detection of high-energy astrophysical neutrinos

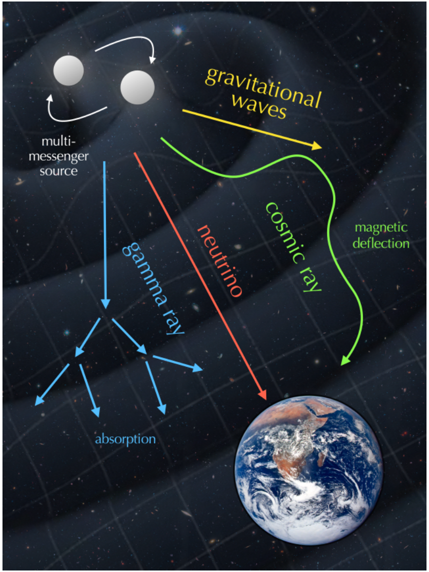
First detection (IceCube): Science 342 (2013) 1242856



Size $\sim$ signal amplitude, color $\sim$ arrival time (early $\to$ later)

Multimessenger astronomy

Multimessenger astronomy



Hadronic reactions

$$pp \to \pi^0 \ldots \to \gamma\gamma \ldots$$
$$pp \to \pi^\pm \ldots \to \mu\nu \ldots \to e\nu_e\nu_\mu\nu_\mu \ldots$$

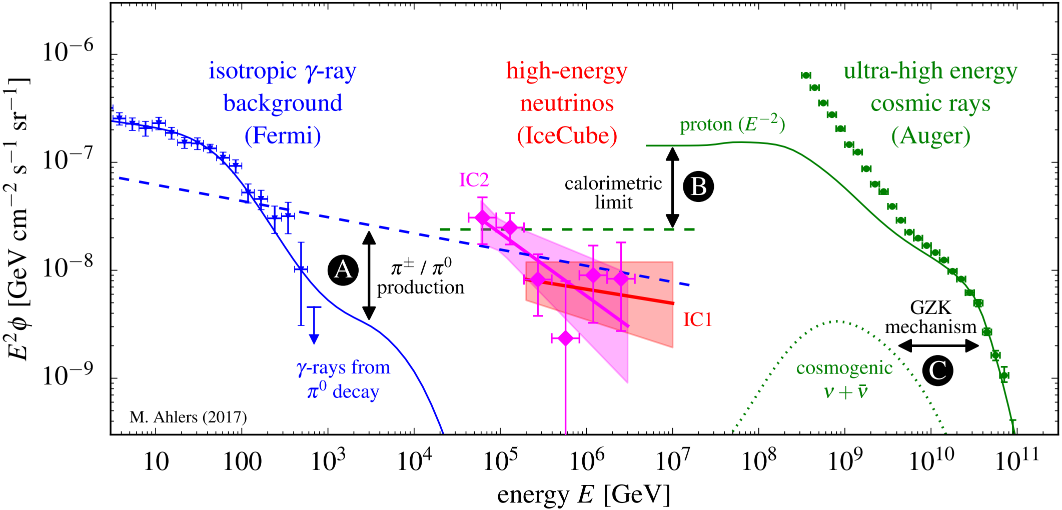
Photo-hadronic reactions

$$p\gamma \to \Delta^+ \to p\pi^0 \to p\gamma\gamma$$
$$p\gamma \to \Delta^+ \to n\pi^+ \to n\mu\nu_\mu \to ne\nu_e\nu_\mu\nu_\mu$$

$$\nu(1\ \text{PeV}) \leftrightarrow p(20\ \text{PeV}) \leftrightarrow \gamma(2\ \text{PeV})$$

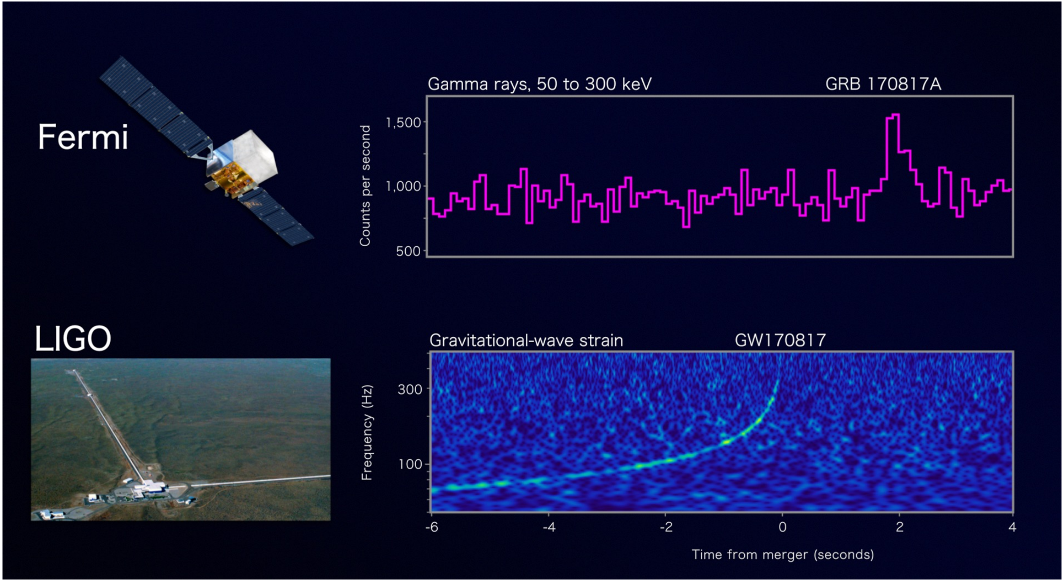
CR: ultra-easy to detect, not point to source, Gpc horizon
GR: easy to detect, point to source, Mpc horizon
Nu: hard to detect, point to source, no horizon
GW: ultra-hard to detect, point to source, no horizon

Linking astrophysical messengers

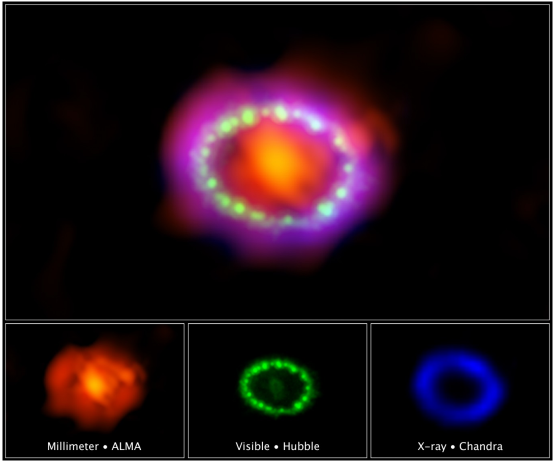


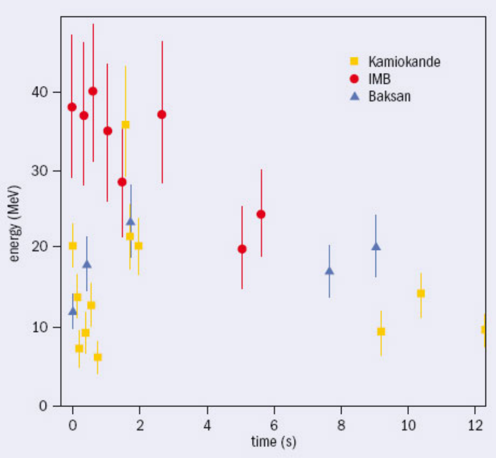
(A) joint production of $\pi^0/\pi^\pm$ in cosmic-ray interactions leads to emission of γ (—) and ν (- - -); **(B)** most energetic cosmic rays (—) imply a maximal flux (calorimetric limit) ν from the same sources (- - -) and **(C)** cosmogenic ν (···)

The famous multimessenger detection



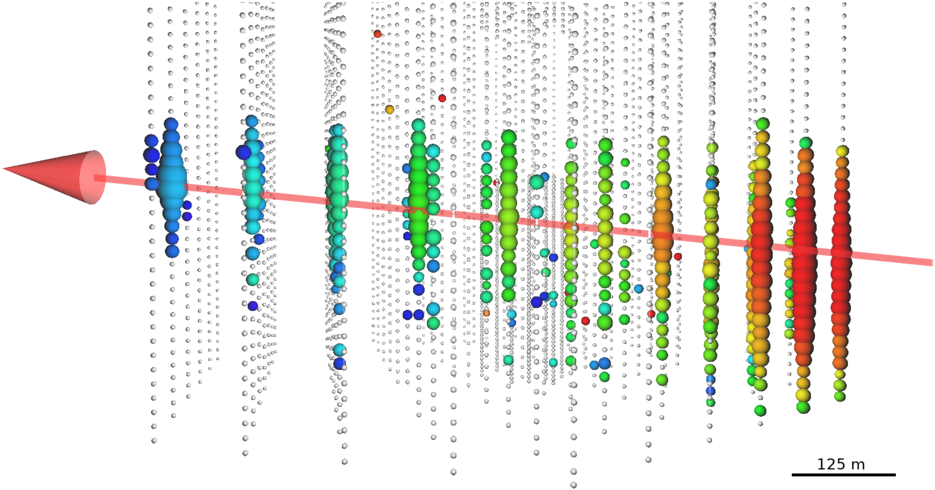
The first multimessenger detection





In 1987 neutrino observatories IMB, Baksan and Kamiokande detected about 20 neutrinos emitted by supernova explosion in Large Magellanic Cloud at the distance of about 50 kpc.

IceCube alert IC-170922A



IceCube EHE ("extremely-high energy") alert IC-170922A
Upcoming muon track with altitude of 5.7° detected on 2017.09.22

IceCube alert IC-170922A follow-up

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; ***Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration***
on ***28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

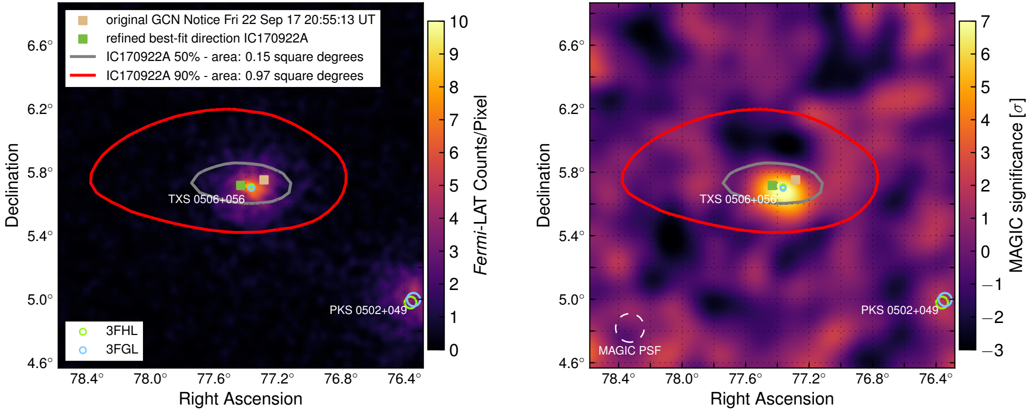
ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
on ***4 Oct 2017; 17:17 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Telescopes Fermi-LAT and MAGIC detected high-energy gamma emission from **flare of TXS 0506+056 blazar**, in the direction of alert

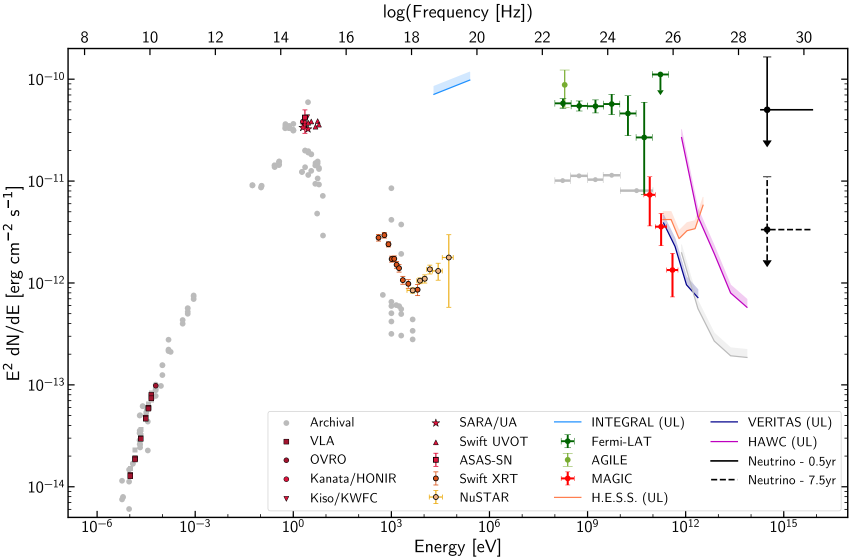
Multimessenger observation of TXS



TXS 0506+056 are in top 3% brightest blazars of Fermi-LAT

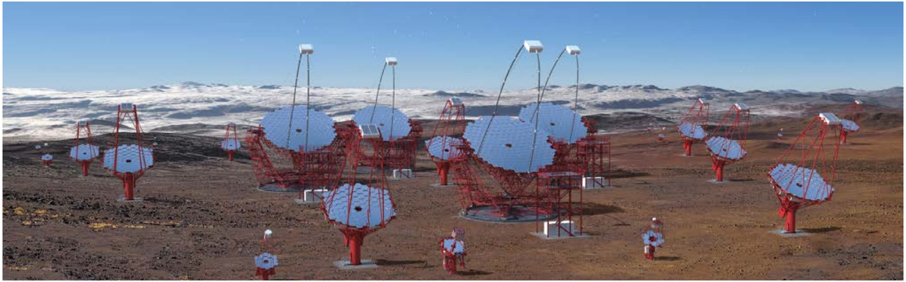
Random correlation is excluding with significance of 3σ
Science 361 (2018) no.6398, eaat1378

Multimessenger observation of TXS



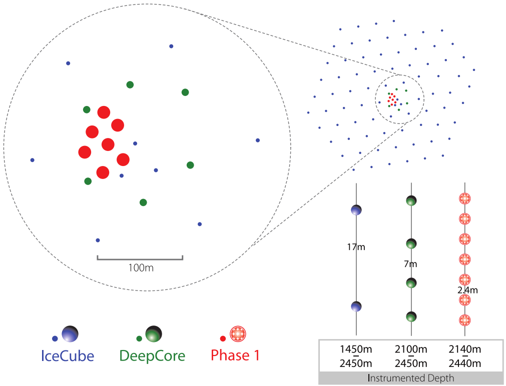
Next-generation astroparticle experiments (few examples)

Cherenkov Telescope Array

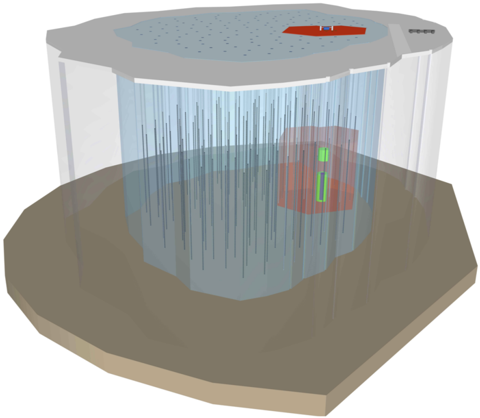


IceCube-Gen2

Phase I



Phase II



In its final stage the effective volume will be increased in 10 times

+ GW detectors

KAGRA, eLISA, Einstein telescope, etc

Conclusion

- Astroparticle physics is the only field able to probe interactions at highest energies
- Astrophysical facilities have reached sensitivities to all messengers including gravitational waves
- Modern communication technologies allow us to coordinate operations in real time
- Events including $\gamma + \nu$ and $\gamma + g$ are detected, looking forward for $\gamma + \nu + g$!
- Next-generation facilities uniting astrophysicists around the world are under constructions, big data approaches are under active developments