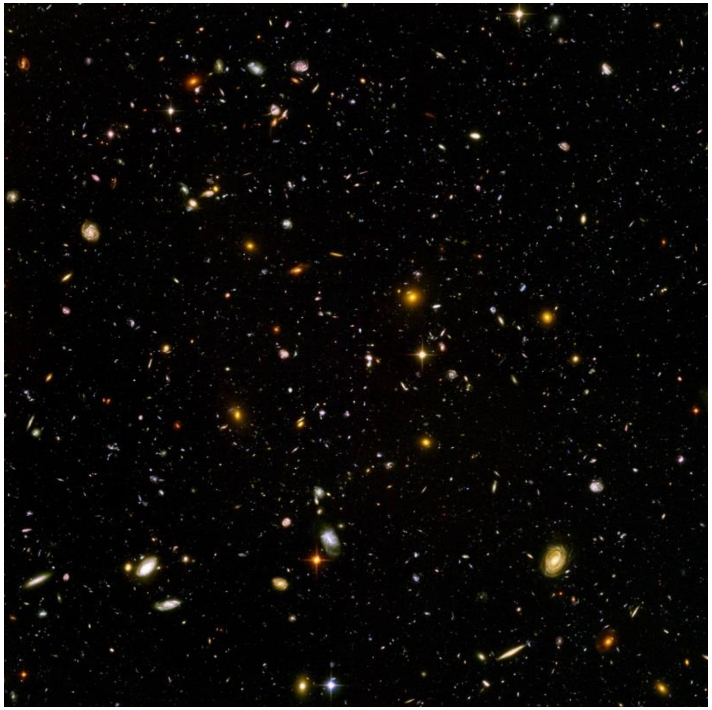
Introduction to astroparticle physics

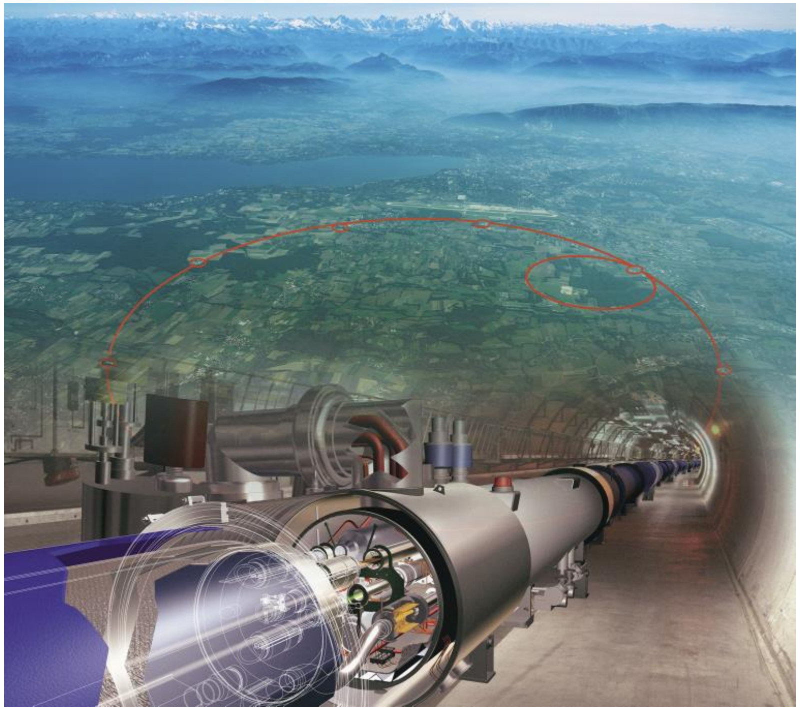
Part 1:

Andrii Neronov
LASTRO, EPFL and
Astroparticle & Cosmology laboratory, University of Paris
Volodymyr Savchenko
LASTRO, EPFL

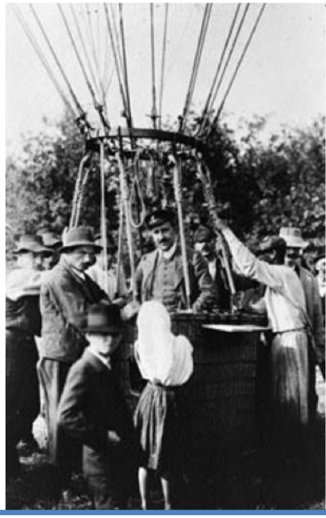
Part 2:

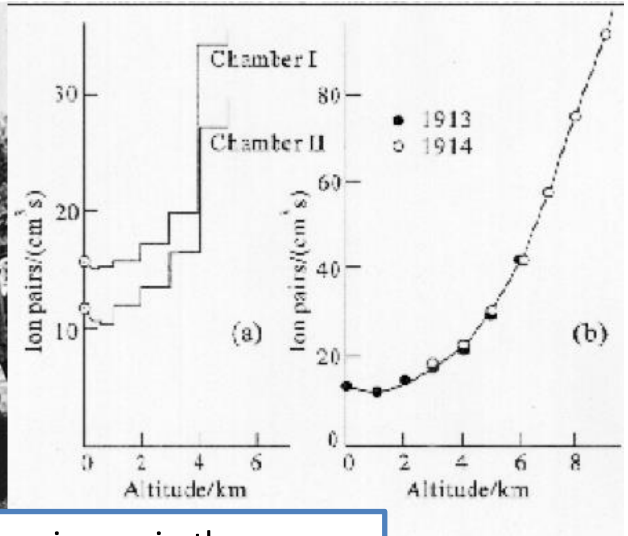
Chiara Perrina
LPHE, EPFL

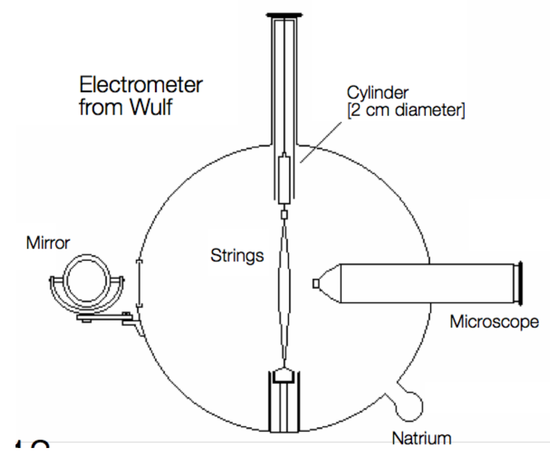




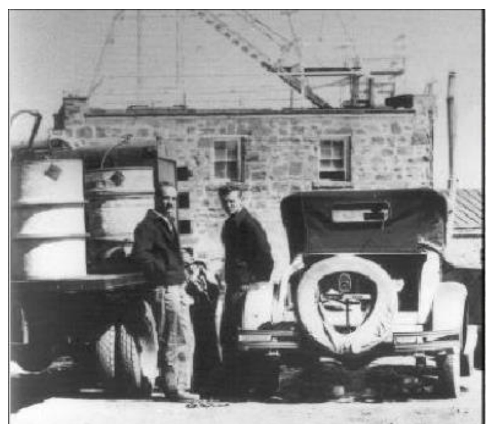
High-energy particles from space

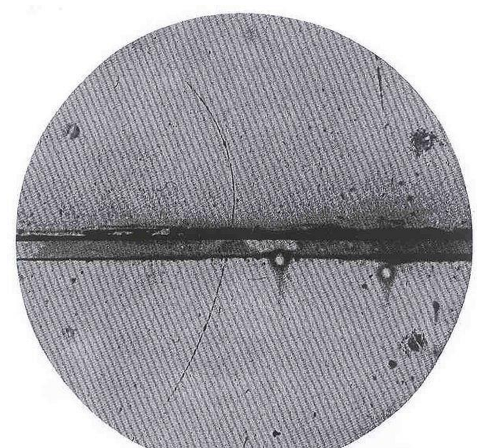






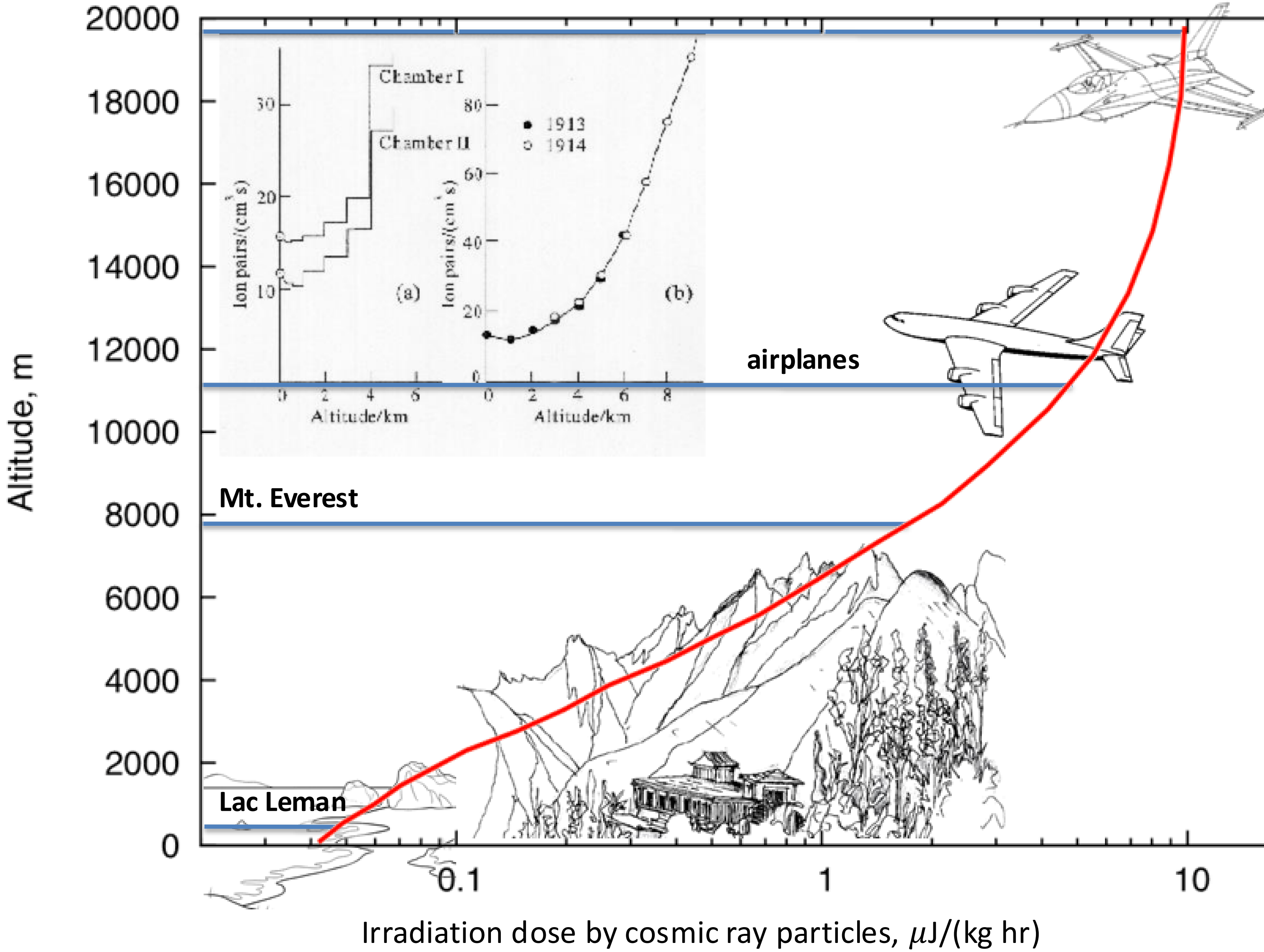
Evidence for existence of cosmic rays in the measurements of the rate of discharge of electrometer as function of altitude
(Hess, 1912, Kohlhorster 1914)





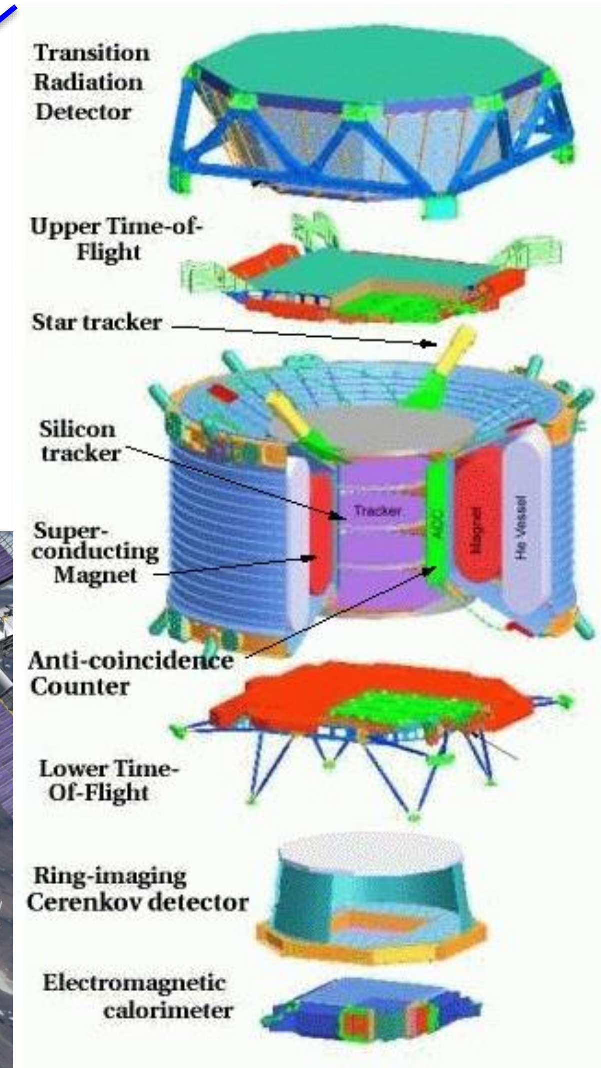
Positron track in a cloud chamber
(Anderson 1932)

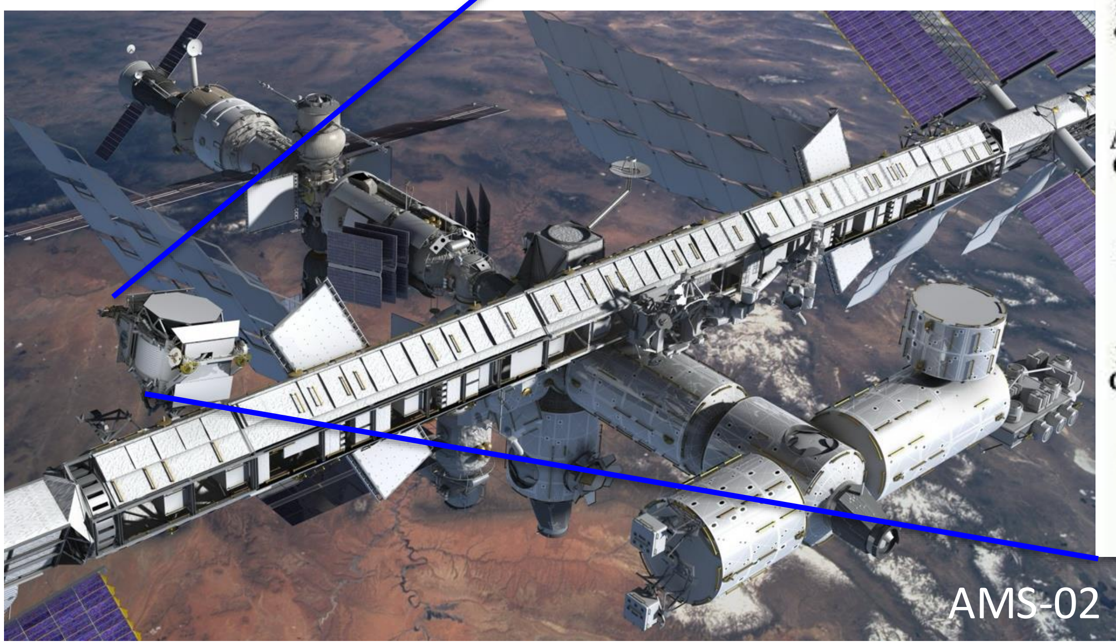
High-energy particles from space



High-energy particles from space

Modern version of approach pioneered by V.Hess: particle detectors are lifted on high-altitude balloons and installed at spacecrafts.





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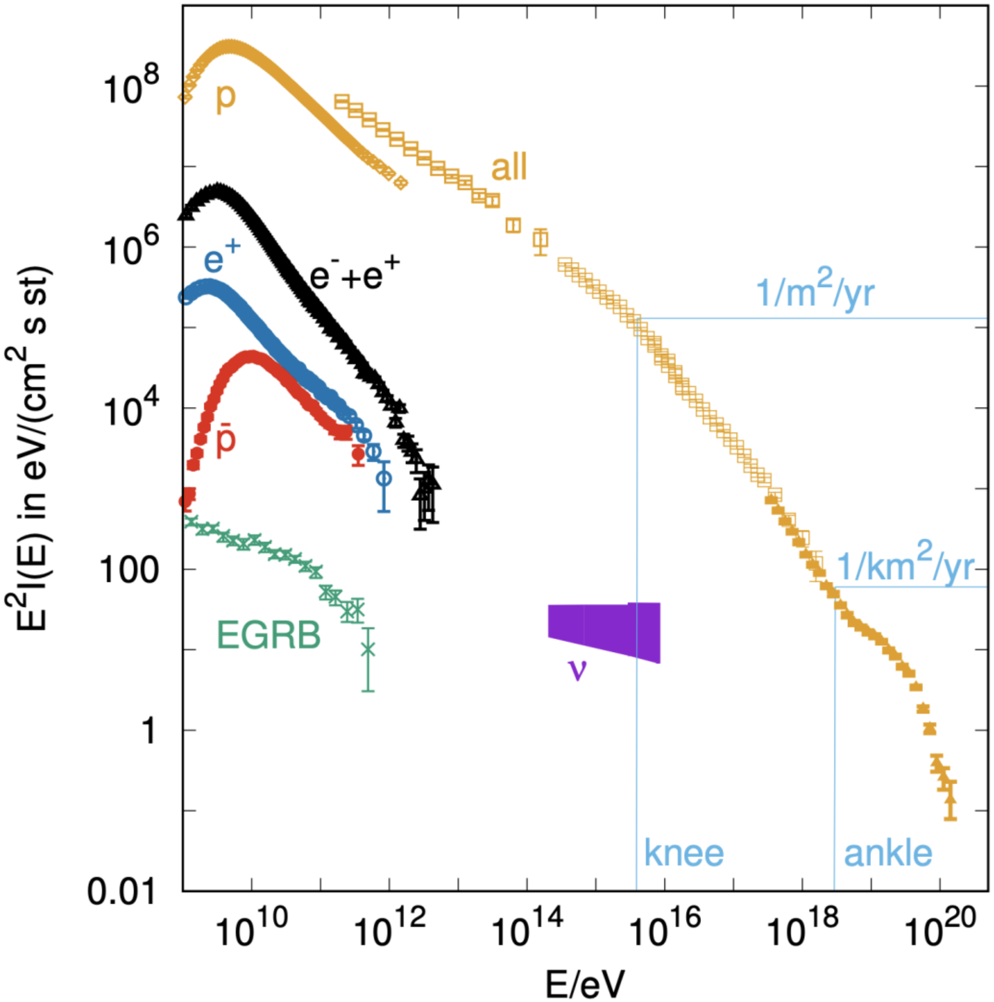
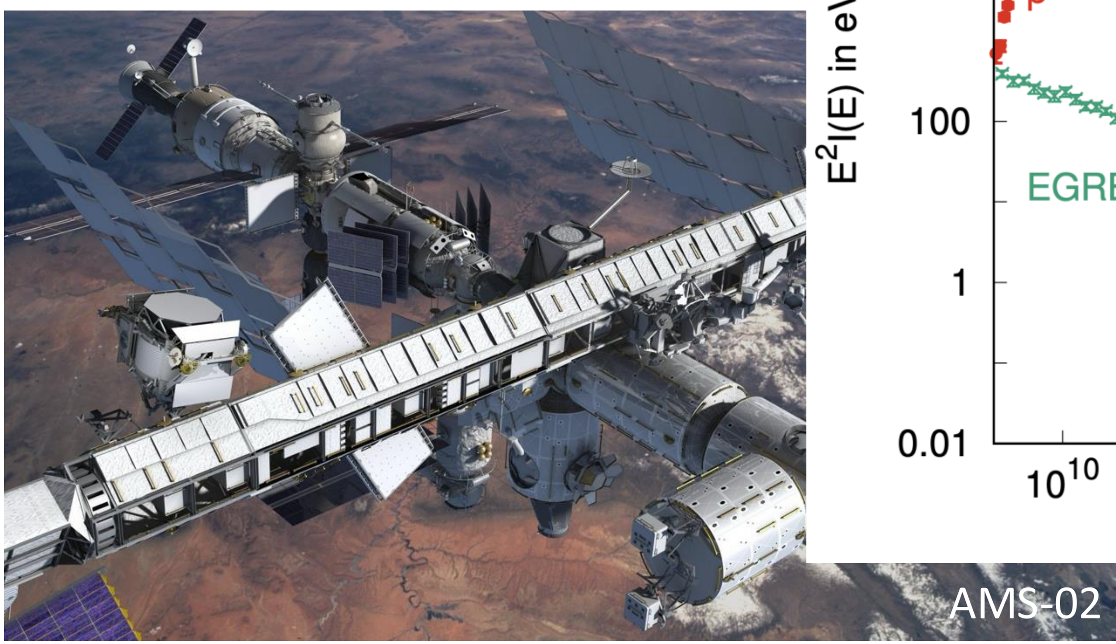
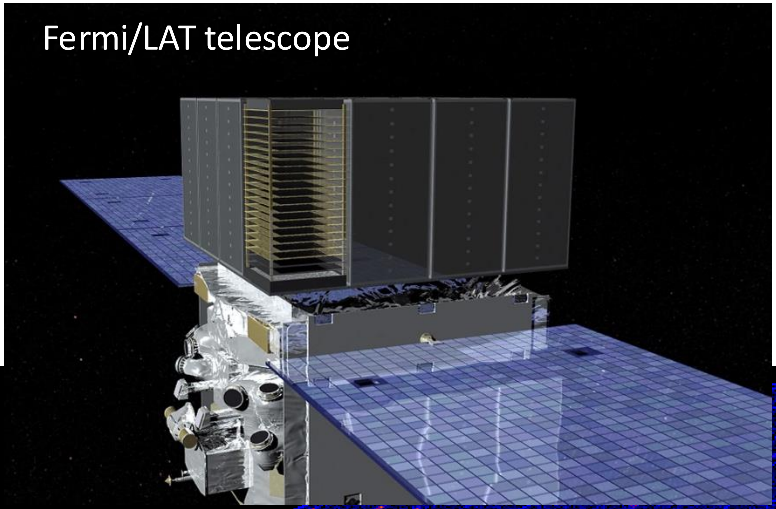
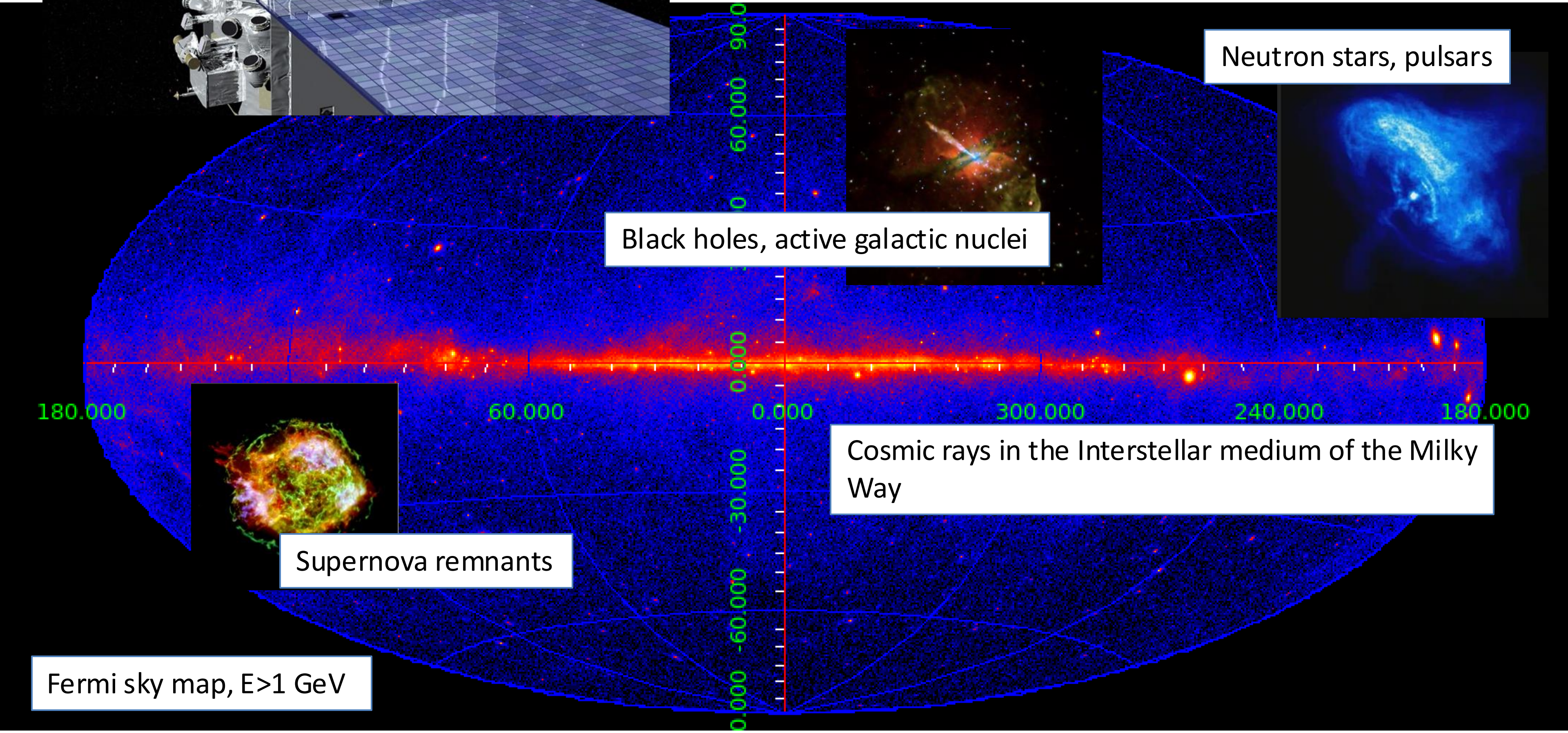




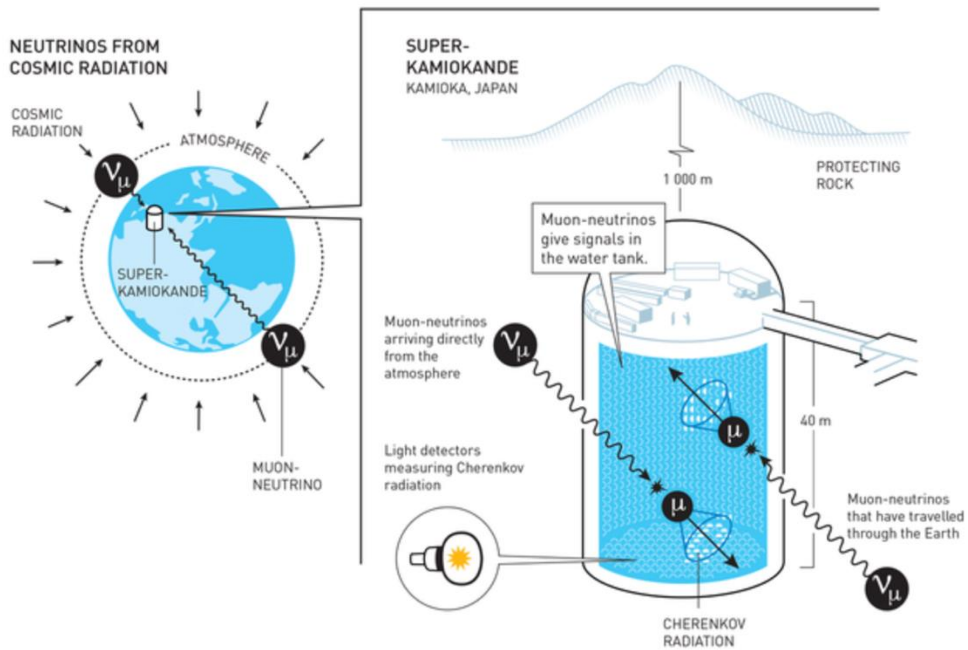
Gamma-ray astronomy

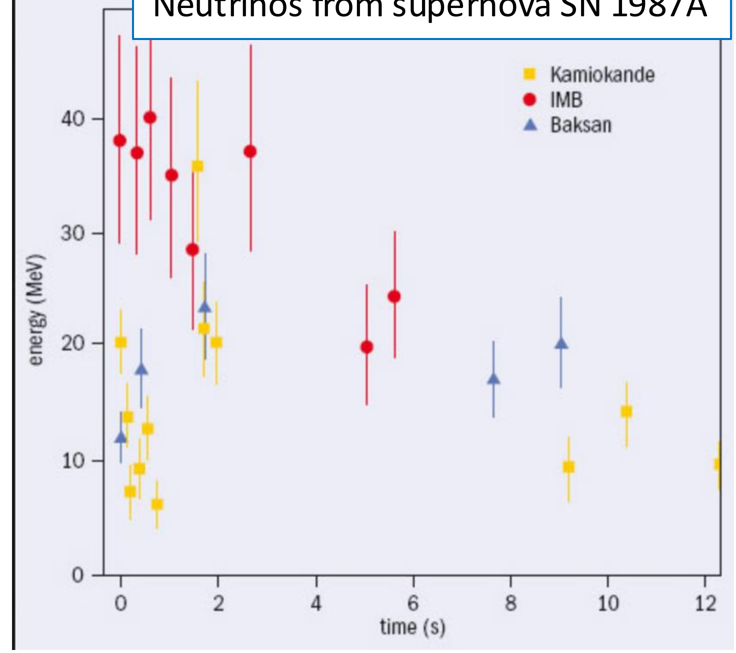


Most of high-energy particles coming from space are cosmic ray protons and atomic nuclei. However, a small fraction of high-energy particle flux is made of gamma-rays. Gamma-rays can be used for astronomical observations.



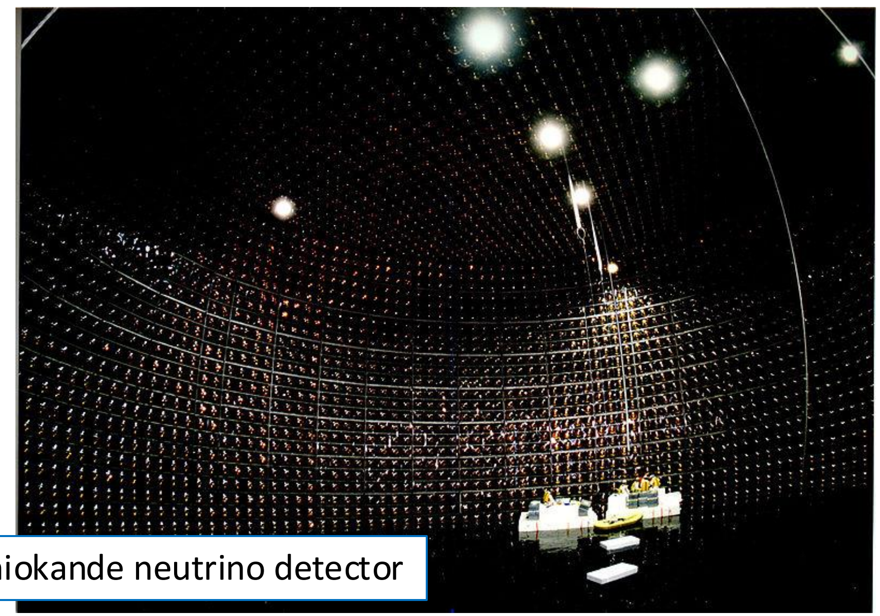
Neutrino astronomy





Neutrinos from supernova SN 1987A

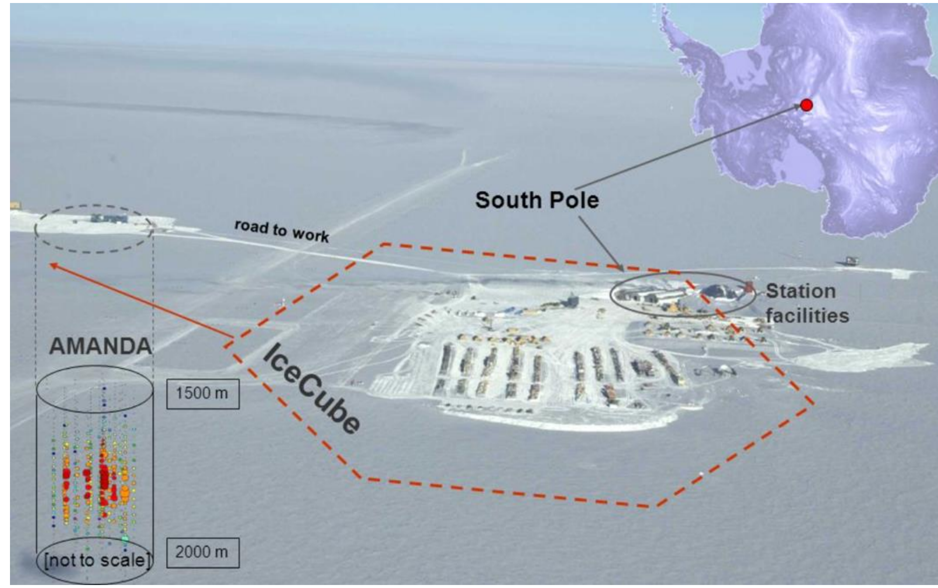
Apart from gamma-rays neutrinos can also be used for astronomical observations: they are neutral particles that are not deflected by cosmic magnetic fields. Their trajectories can be traced back to their production sites in astronomical objects.

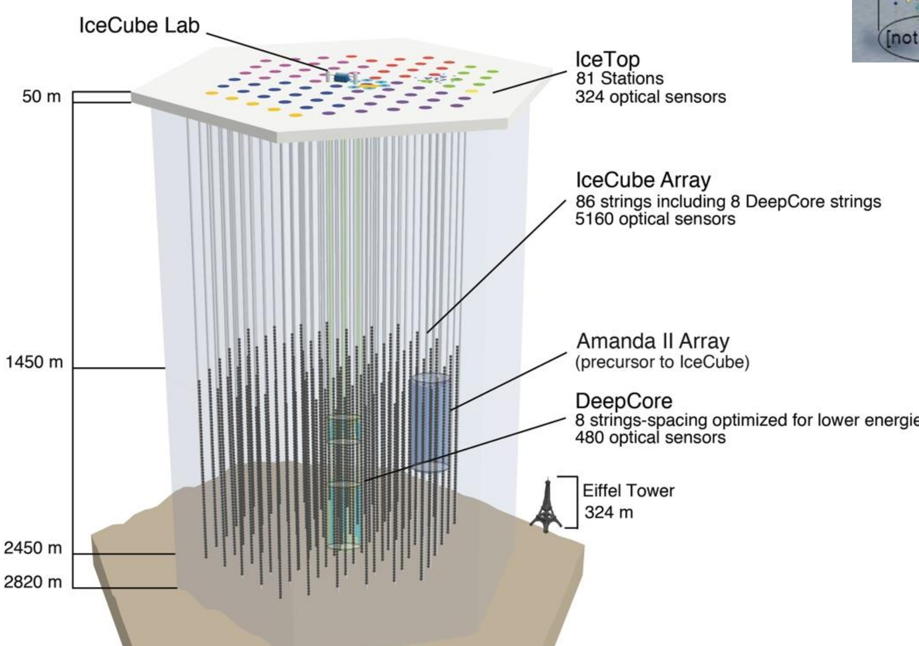


Super-Kamiokande neutrino detector

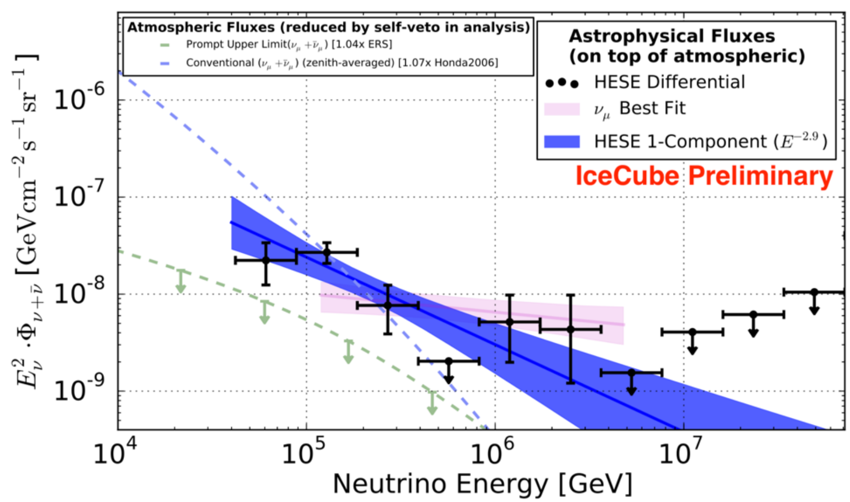
Neutrino astronomy

Neutrinos with energies up to 10 Peta-electronvolt ($\sim 10^3$ times higher than the energy achieved in Large Hadron Collider) coming from unknown astronomical source(s) have been detected. This energy scale is currently the "energy frontier" of astronomy.





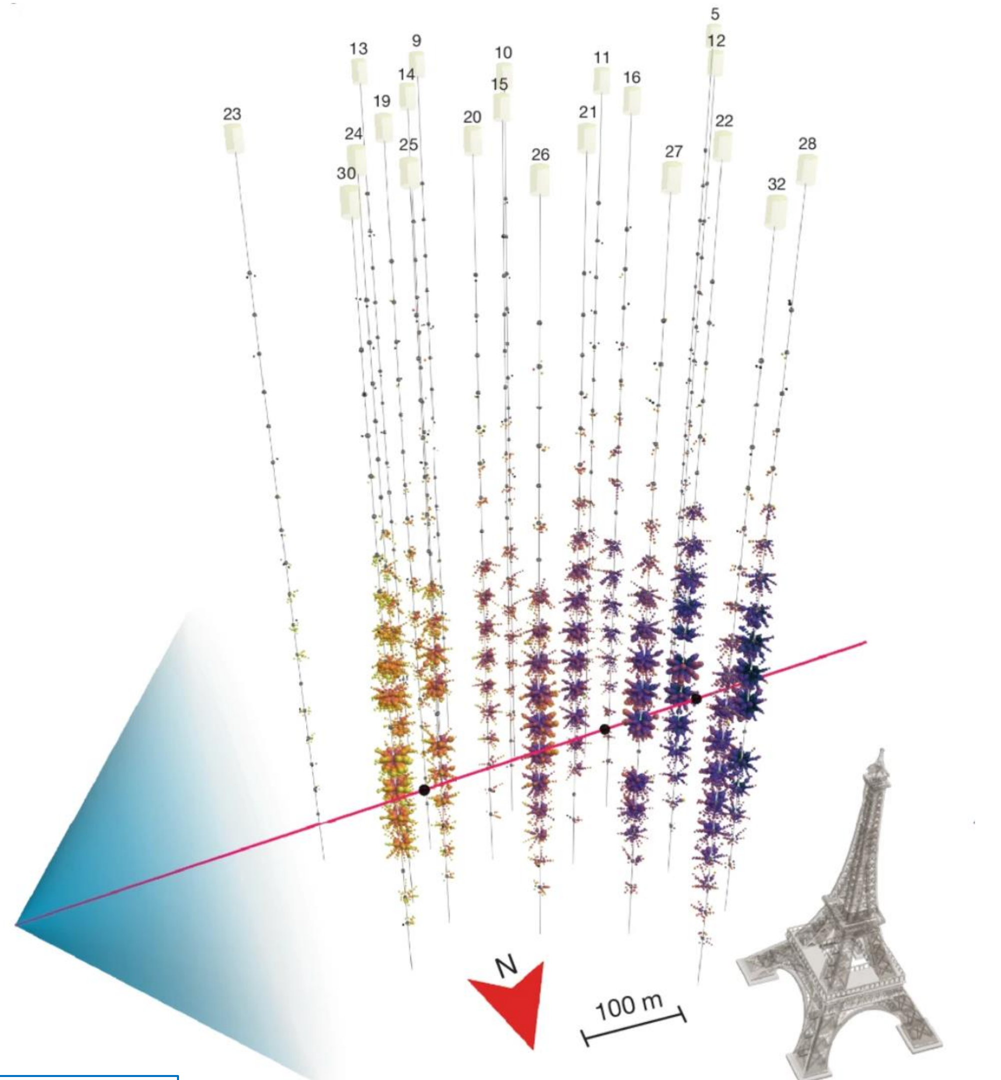
IceCube neutrino detector



Astrophysical neutrino flux detected by IceCube

Neutrino astronomy

Cover of « Nature » journal last week

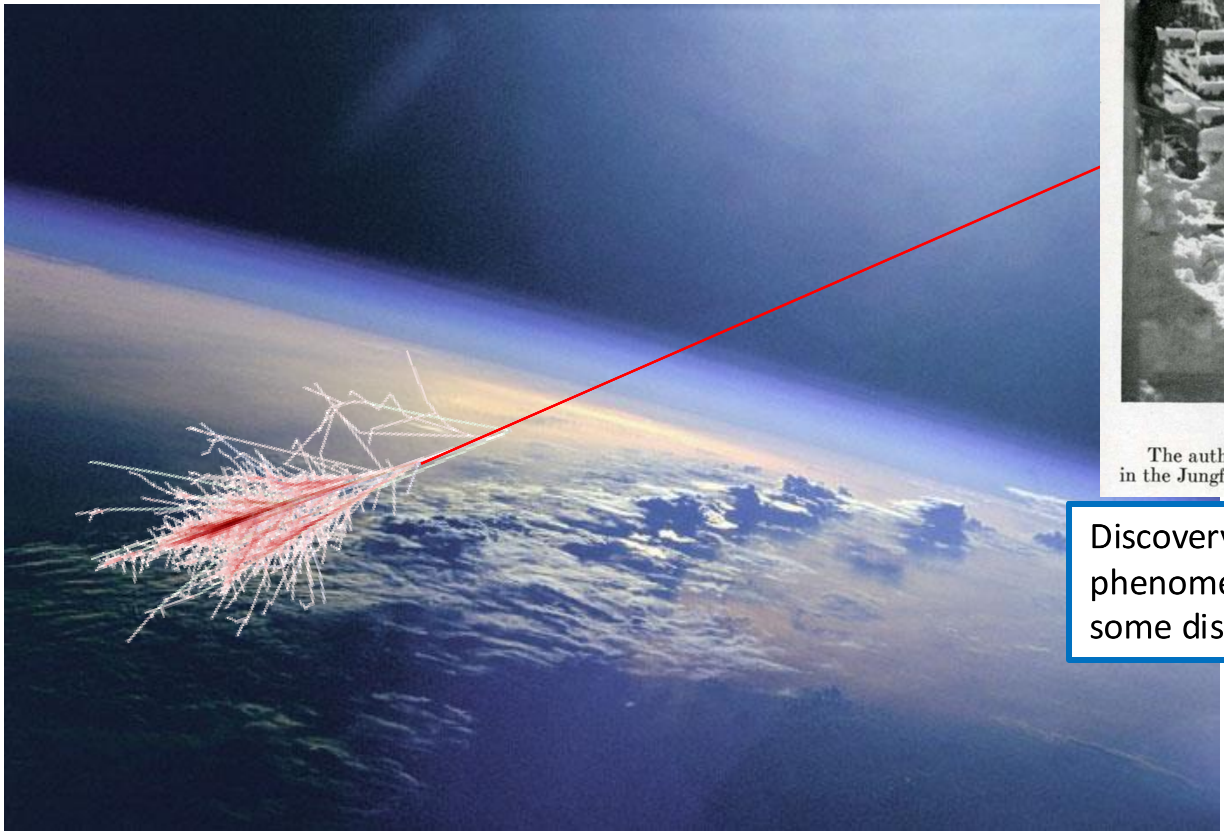


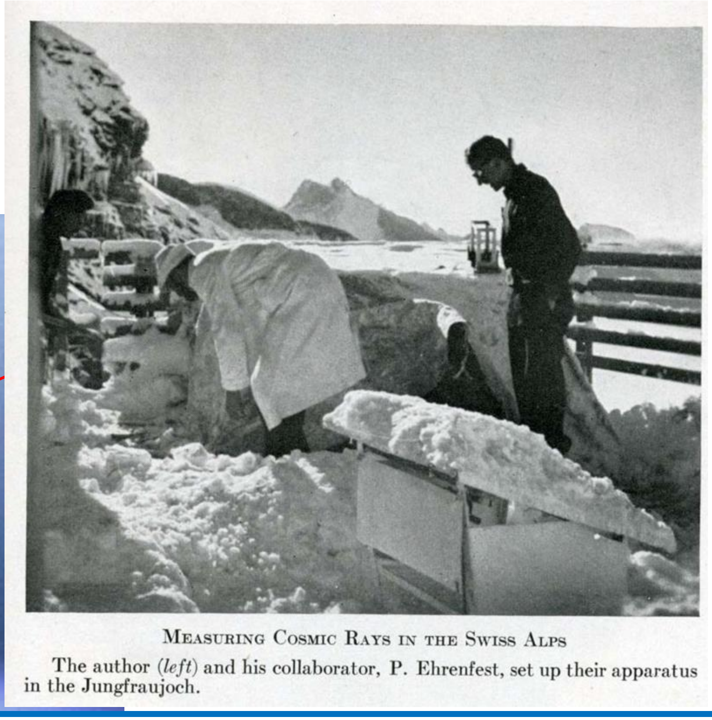
New neutrino telescope KM3NeT has detected highest energy neutrino ever, with $E_\nu \sim 200$ PeV, of unknown origin.

Press conference from last week:
https://www.youtube.com/watch?v=pBBJIeOVLXE

Extensive air showers

10 PeV neutrinos are produced in interactions of protons and atomic nuclei of still higher energies. The flux of cosmic rays contains particles with energies up to 10^{20} eV. Such particles are called Ultra-High-Energy Cosmic Rays (UHECR). It is not clear which objects in the Universe are able to produce particles with such energies.

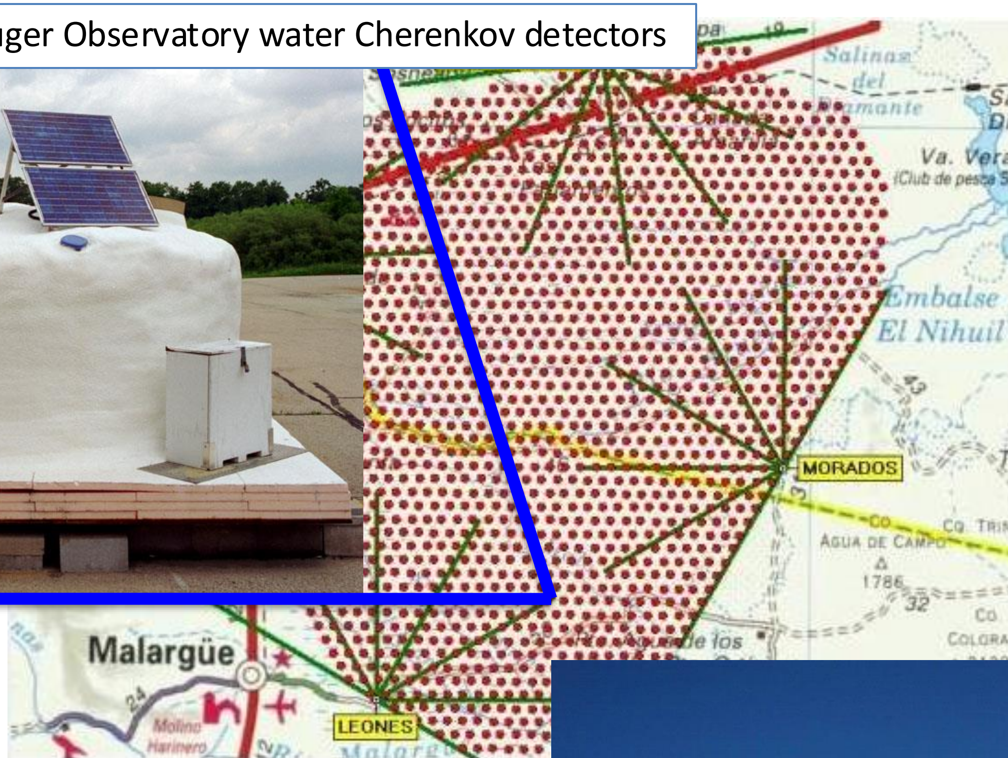




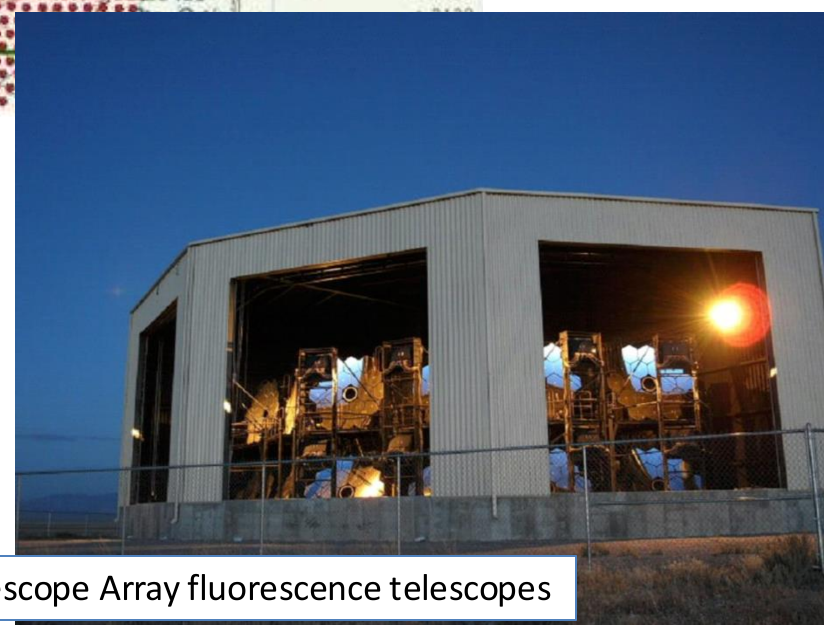
Discovery of Extensive Air Shower (EAS) phenomenon: several particle detectors spaced by some distance trigger simultaneously (P.Auger, 1938)

Extensive air shower arrays

Pierre Auger Observatory water Cherenkov detectors

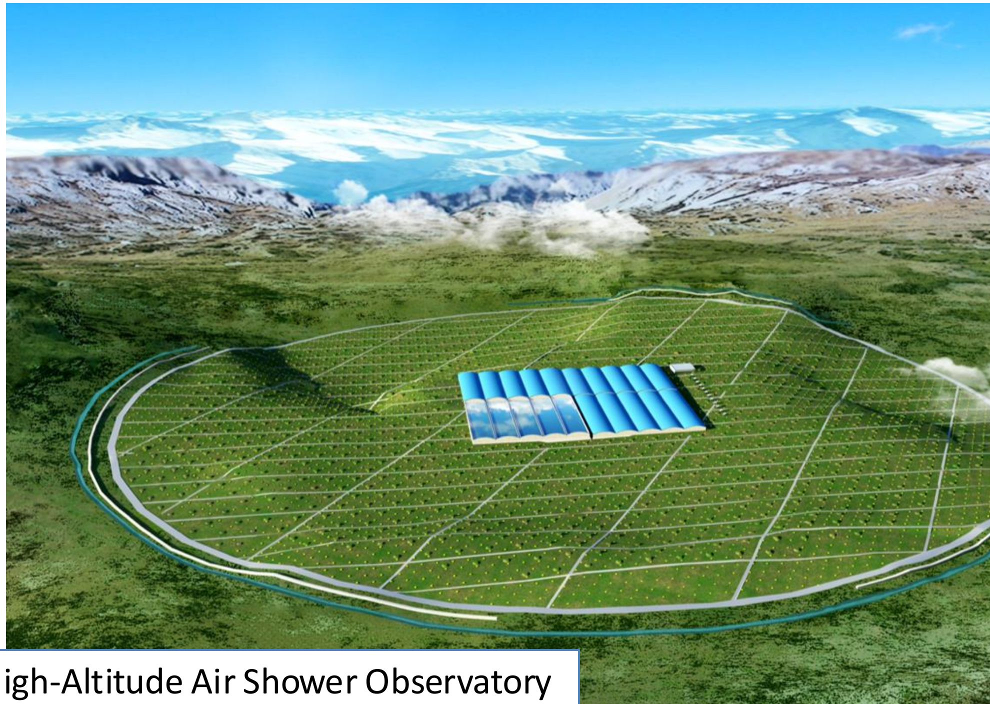


Modern versions of approach pioneered by P.Auger: Air Shower Arrays. High-energy particles in EAS are detected by networks of particle detectors on the ground or by telescopes sensing fluorescence and Cherenkov light along EAS tracks in the atmosphere.



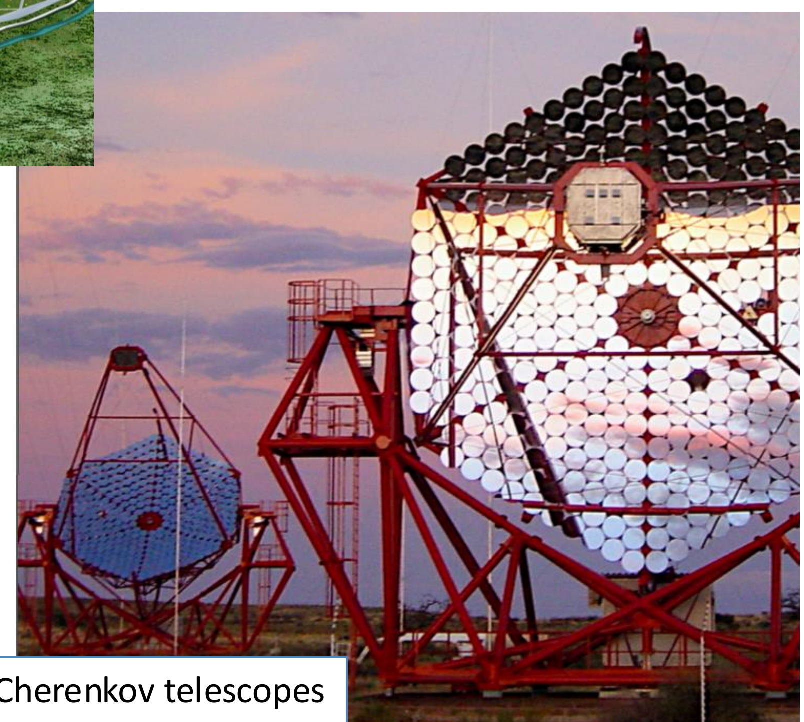
Telescope Array fluorescence telescopes

Extensive air shower arrays



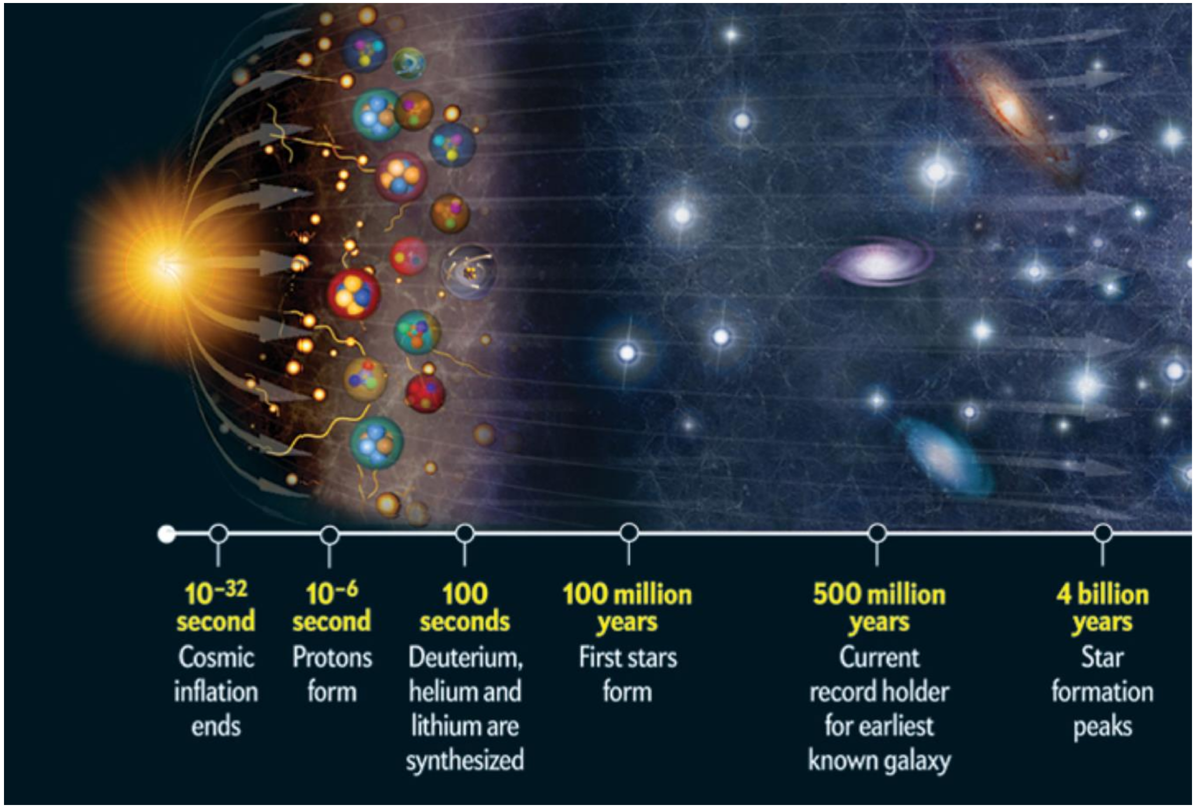
Large High-Altitude Air Shower Observatory

The Extensive Air Shower phenomenon is also used for gamma-ray observations: both networks of particle detectors and telescopes sensing Cherenkov light from EAS tracks can be used to trace gamma-rays back to their origin in astronomical objects.



HESS Cherenkov telescopes

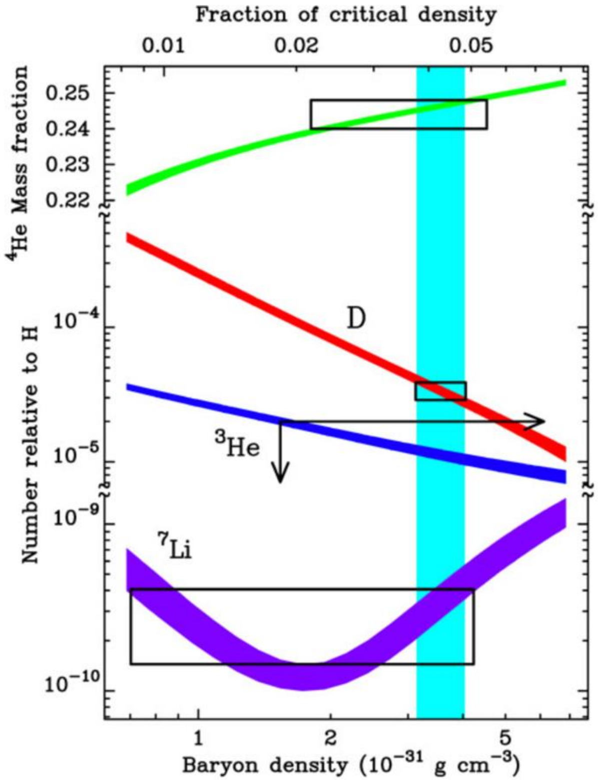
High-energy particles in the Universe



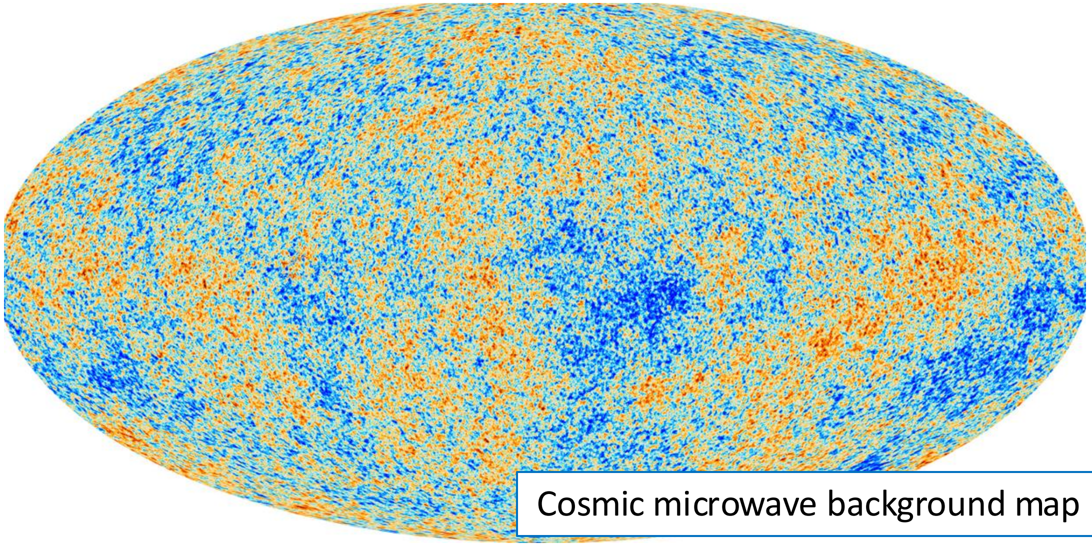
Abundances of chemical elements in the Universe can be explained only under assumption that most of helium was not synthesised in stars, but rather in early period of existence of the Universe, when it was dense and "hot", with temperatures reaching $\sim 10^9$ K and energies of particles reaching MeV and higher.

(Gamow1948)

High-energy particles in the Universe

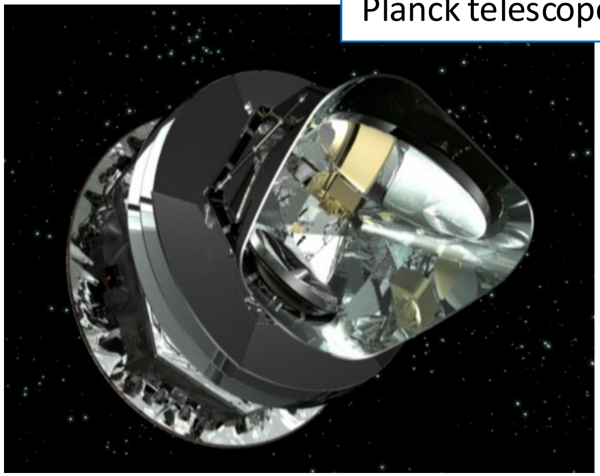


Element abundance data compared to Big Bang nucleosynthesis theory predictions.



Cosmic microwave background map

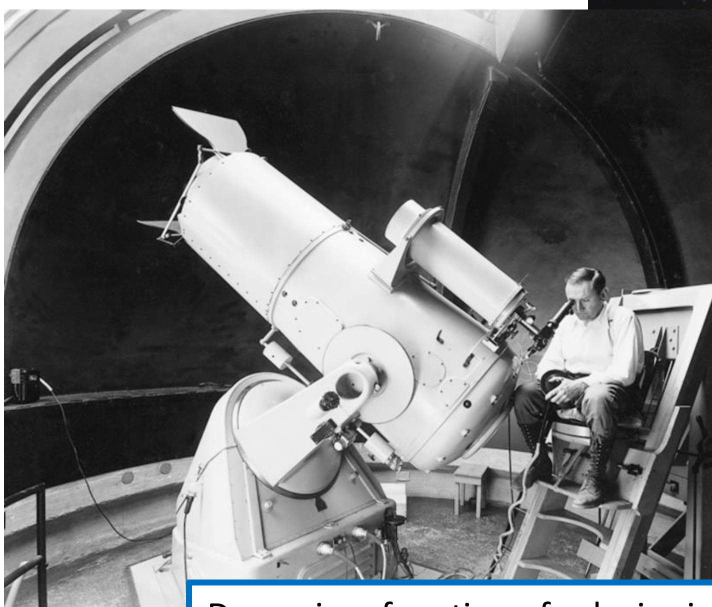
Planck telescope



Modern versions of approach pioneered by G.Gamow: cosmological tests of fundamental physics laws using abundances of elements, properties of relic thermal radiation (Cosmic Microwave Background) and other cosmological data.

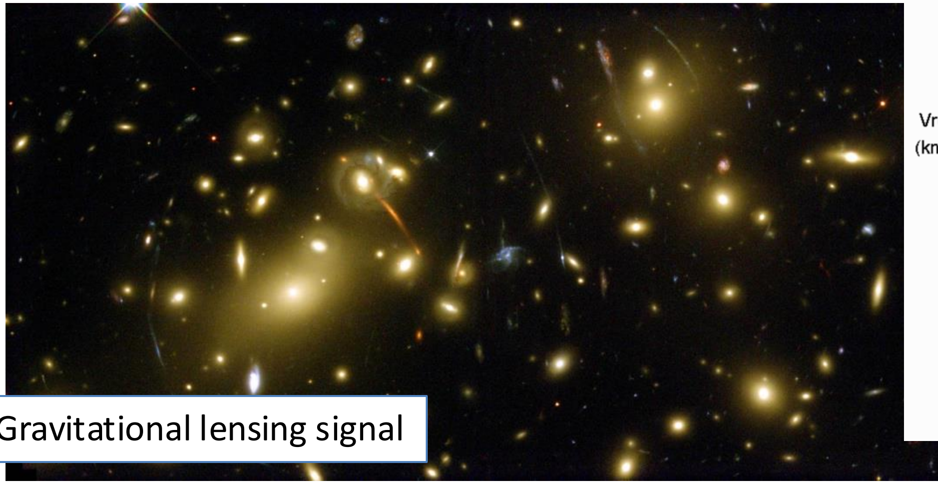
Dark matter

Coma galaxy cluster with two dominant elliptical galaxies in its centre.

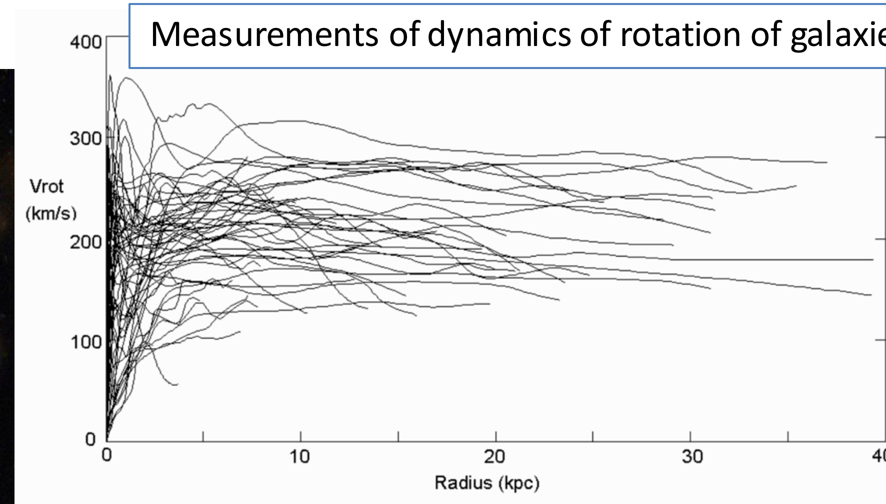


Dynamics of motion of galaxies in galaxy clusters cannot explained by the gravity of known forms of matter. Instead, it is dominated by an unknown form of matter, the "dark matter".
(Zwicky 1933)

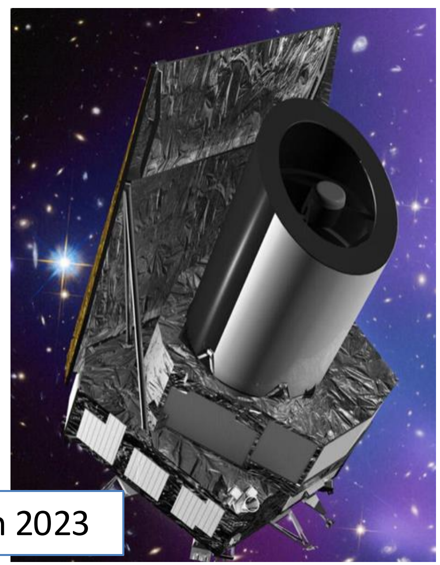
Dark matter



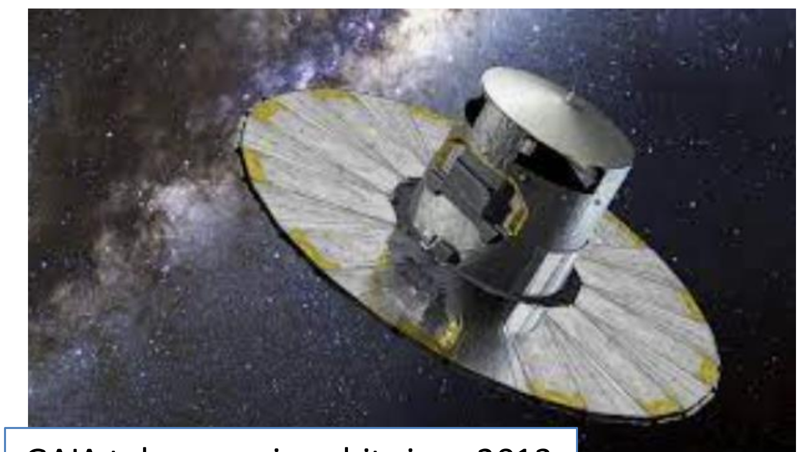
Gravitational lensing signal



Measurements of dynamics of rotation of galaxies



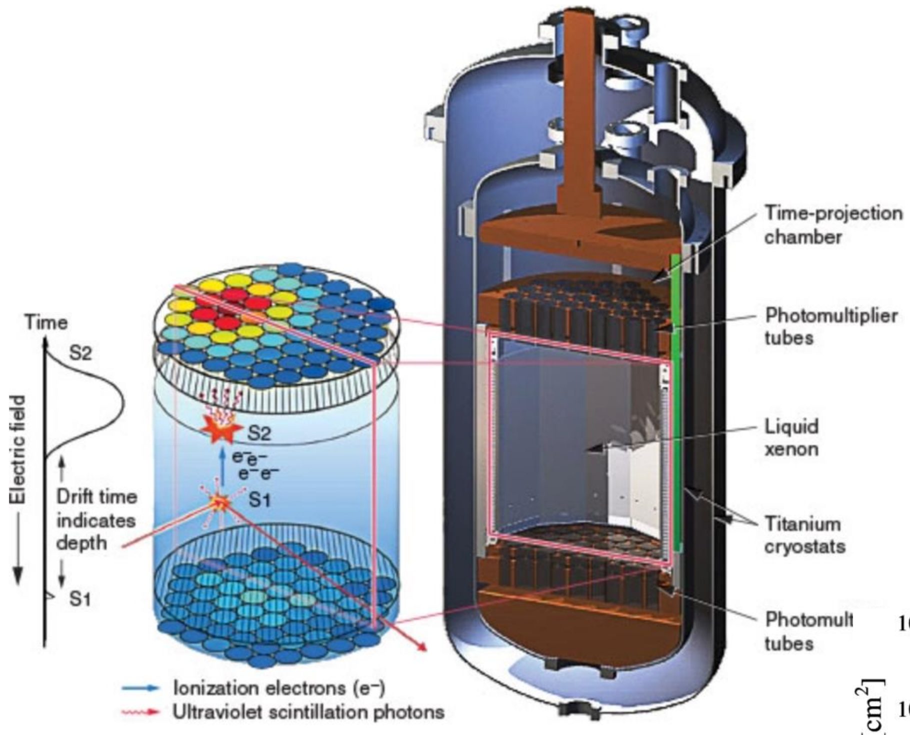
Euclid telescope, launched in 2023



GAIA telescope, in orbit since 2013

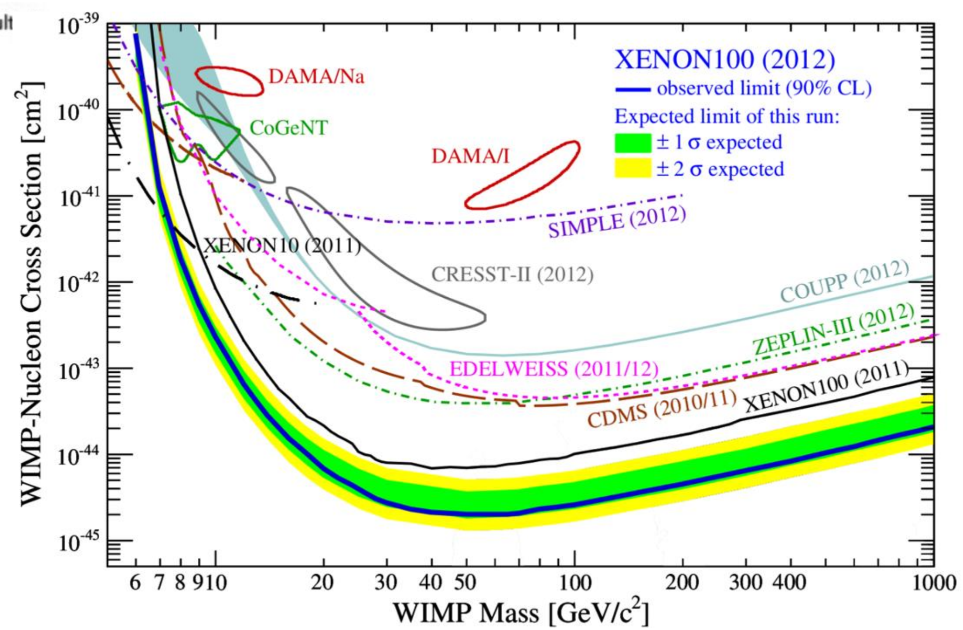
Modern versions of approach pioneered by F.Zwicky: measurements of distribution of dark matter in galaxies and galaxy clusters, using telescopes operating in the visible band.

Dark matter

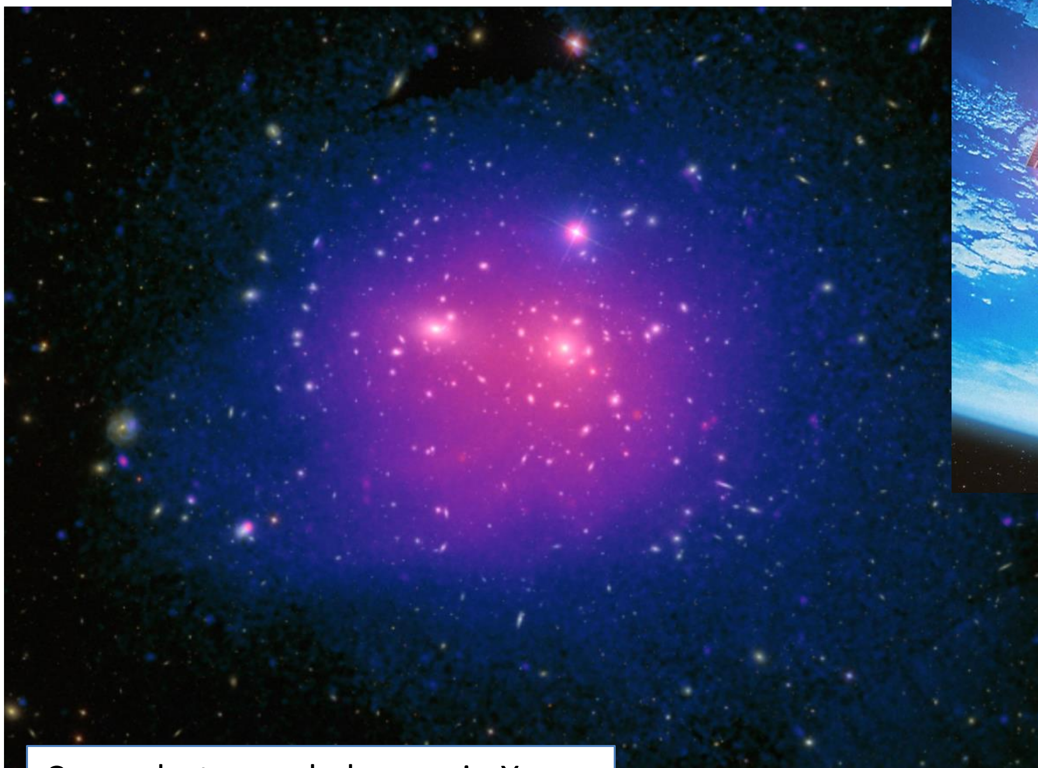


Laboratory experiments for direct detection of dark matter particles aim to directly intercept dark matter particles passing through the experimental site.

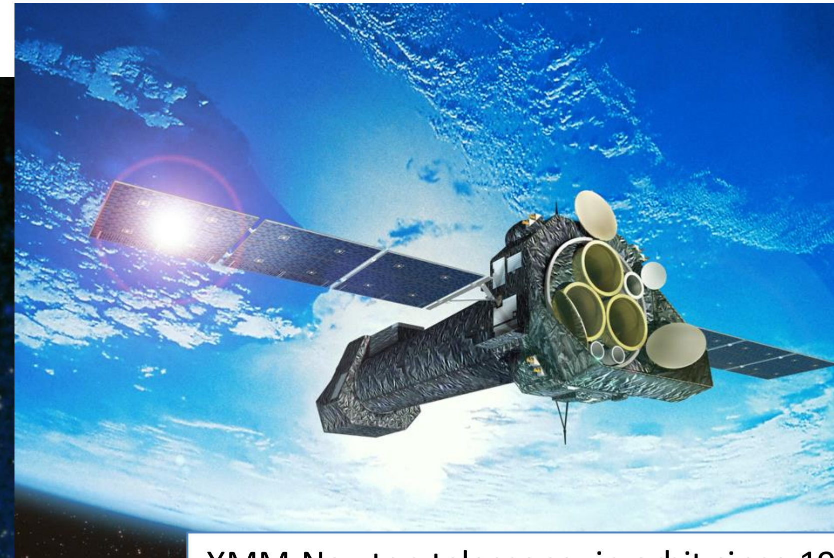
XENON dark matter detector



Dark matter



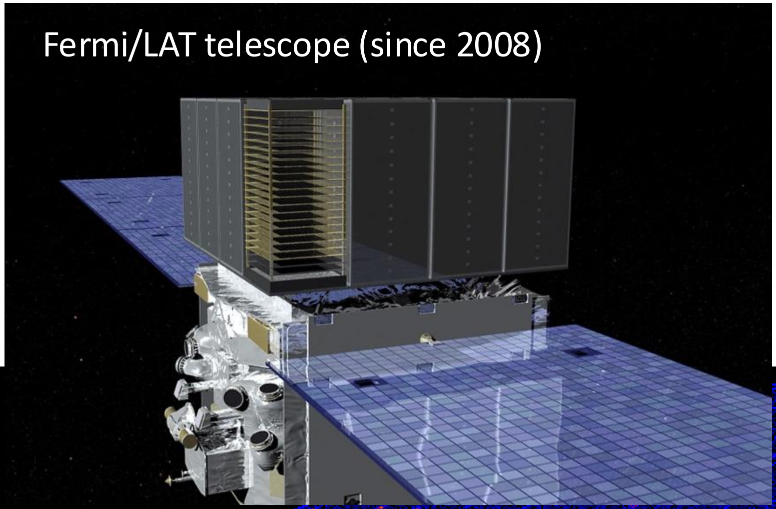
Coma cluster gas halo seen in X-rays



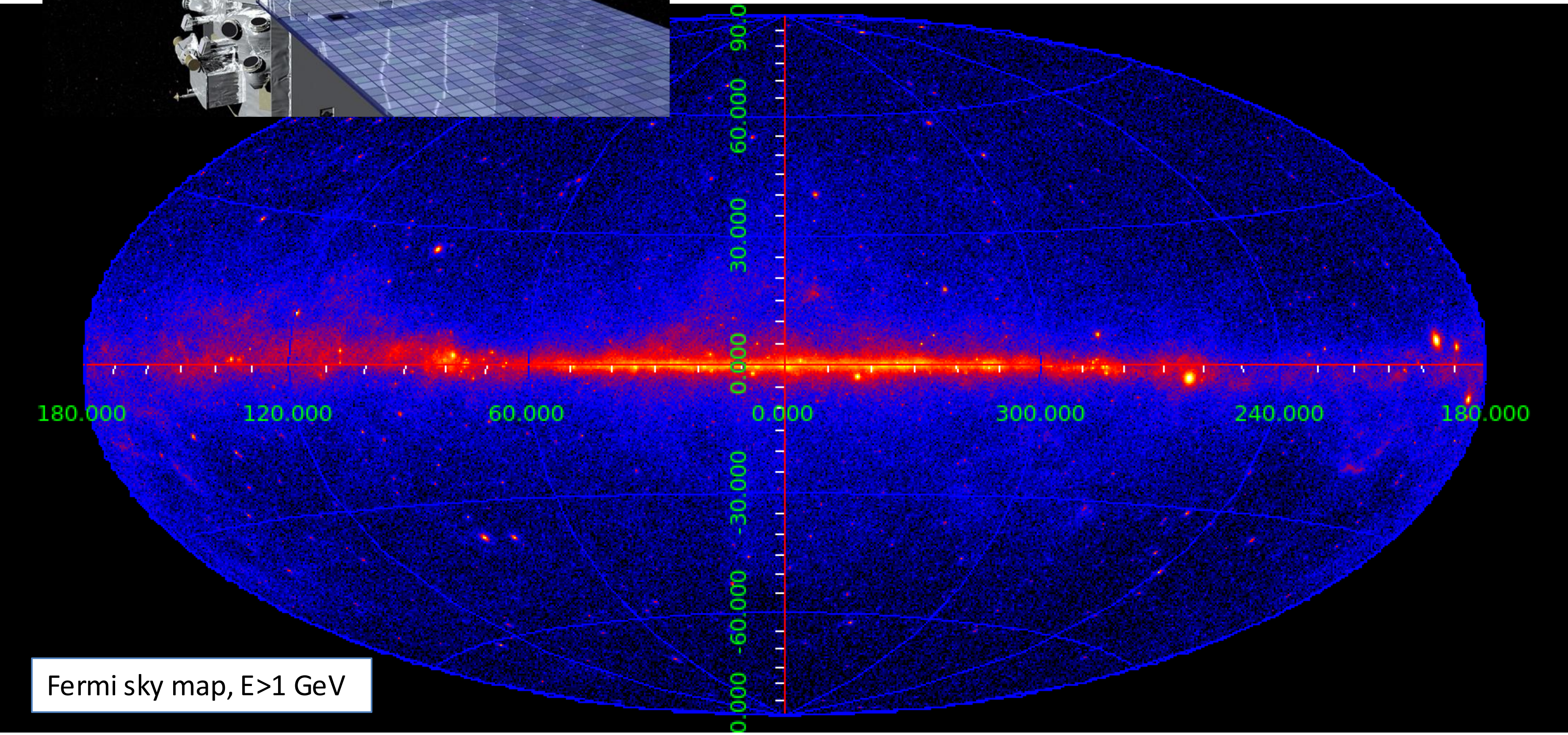
XMM-Newton telescope, in orbit since 1999

Conventional matter that has not been visible to Zwicky (e.g. gas heated to millions of Kelvin in trapped in the galaxy clusters) is now detectable with X-ray telescopes. It is possible that the dark matter interactions produce detectable electromagnetic signal… in yet unexplored energy range (?)

Dark matter



Cosmic ray and gamma-ray detectors can detect dark matter indirectly, looking at the products of interactions of dark matter particles residing in the Milky Way dark matter halo.



Fermi sky map, E>1 GeV

Astroparticle physics topics

Cosmic ray physics

... direct continuation of
research started by V.Hess

Gamma-ray astronomy

.... application of particle physics
methods in astronomy

Gravitational waves

Neutrino physics

* neutrino oscillations
* high-energy neutrino astronomy

Dark matter physics

... direct continuation of
research started by F.Zwicky

Particle physics in the Early Universe

... direct continuation of research started by Gamow

Exercise 1

Natural system of units. Classical vs. quantum physics.

Within natural system of units some constants are set to one:

$$\hbar = 6.6 \times 10^{-16}\ \mathrm{eV\ s}$$
$$c = 3 \times 10^{10}\ \mathrm{cm/s}$$
$$k_B = 8.6 \times 10^{-5}\ \mathrm{eV/K}$$

This suggests that one talk interchangingly of energy or frequency, or inverse of the distance scale (think about photons, for which it is enough to specify either wavelength or frequency or energy).

1) Find the units and the value of the Gravitational constant G_N in this system of units

2) Construct a "gravitational distance scale" associated to a body of the of a mass M , that involves the Gravitational constant, along with the mass (and speed of light $c \equiv 1$)
3) Construct a "quantum distance scale" that involves the mass M (along with $c \equiv 1$ and $\equiv \hbar \equiv 1$).
4) Find the value of mass at which the two scale of equal. Relate the gravitational constant to this characteristic mass ("Planck mass").
5) What is the "quantum=gravitational" distance scale associated to the Planck mass scale ("Planck length")?

Exercise 2

Natural system of units. Classical vs. quantum physics.

Within natural system of units some constants are set to one:

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This suggests that one talk interchangingly of energy or frequency, or inverse of the distance scale (think about photons, for which it is enough to specify either wavelength or frequency or energy).

1) What are the units of measurement of magnetic field within the Natural System of units?

2) Recall the expression for the gyroradius of a charged particle (electron) in magnetic field, using classical Newtonian mechanics.

3) Find the value of magnetic field at which the gyroradius becomes equal to the “quantum distance scale”.

Planck's constant:	$h = 6.6261 \times 10^{-27}\mathrm{cm}^2\,\mathrm{g}\,\mathrm{sec}^{-1}$
	$\hbar = 1.0546 \times 10^{-27}\mathrm{cm}^2\,\mathrm{g}\,\mathrm{sec}^{-1}$
Speed of light:	$c = 2.9979 \times 10^{10}\mathrm{cm}\,\mathrm{sec}^{-1}$
Boltzmann's constant:	$k_B = 1.3807 \times 10^{-16}\mathrm{erg}\ \mathrm{K}^{-1}$
Electron charge (MKS):	$\mathrm{e}' = 1.6022 \times 10^{-19}\mathrm{Coulomb} = 0.085425$
Fermi constant:	$G_F = 1.1664 \times 10^{-5}\mathrm{GeV}^{-2}$
	$= (292.80\ \mathrm{GeV})^{-2}$
Newton's constant:	$G = 6.6720 \times 10^{-8}\mathrm{cm}^3\,\mathrm{g}^{-1}\mathrm{sec}^{-2} \equiv m_{Pl}^{-2}$
Planck energy:	$m_{Pl} \equiv (\hbar c^5/G)^{1/2} = 1.2211 \times 10^{19}\mathrm{GeV}$
Fine-structure const:	$\alpha_{\mathrm{EM}} = 1/137.036 \qquad \equiv \mathrm{e}'^2$
Electron mass:	$m_e = 0.5110$ MeV
Neutron mass:	$m_n = 939.566$ MeV
Proton mass:	$m_p = 938.272$ MeV

in CGS EM units, $\alpha_{EM} = e'^2$, the magnitude of the charge of the electron is $e' = \alpha_{EM}^{1/2} = 0.085425$, and the Lagrangian density for the free Maxwell field is $\mathcal{L} = -(1/16\pi)F^{\mu\nu}F_{\mu\nu}$. In this system, magnetic field strength is measured in Gauss, the EM energy density is $(T^0_{\ 0})_{EM} = (\vec{\mathbf{E}}^2 + \vec{\mathbf{B}}^2)/8\pi$, and the potential due to a point charge q is $\phi = q/r$.]