Introduction to Astrophysics

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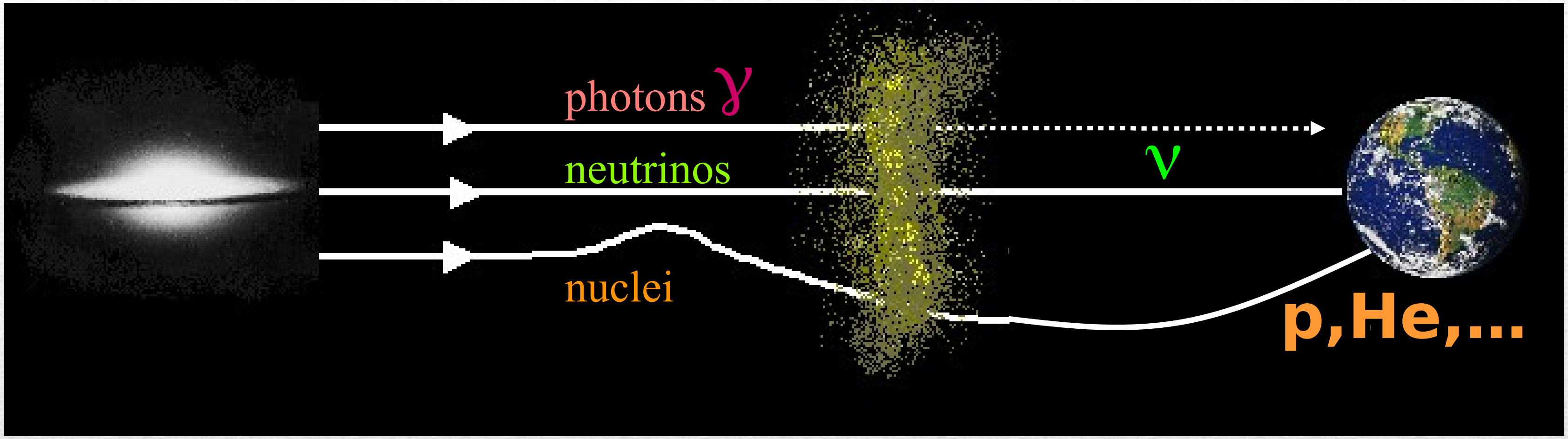
Outline

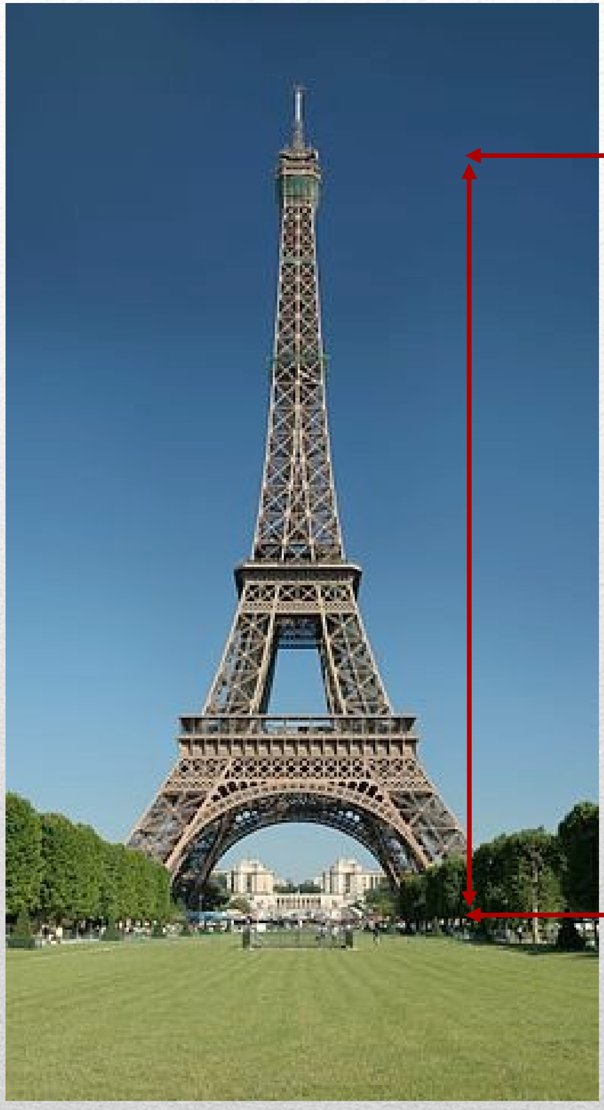
- The beginning of astroparticle physics: the discovery of Cosmic Rays
- Cosmic rays flux
- Direct detection of Cosmic Rays
- Cosmic ray showers in the atmosphere and their detection
- Gamma rays: direct and indirect detection
- Astrophysical neutrinos
- Gravitational waves

Which are the messengers?



- The nuclei can interact with the interstellar medium (ISM) ,cosmic microwave background (CMB) and can be deviated bu magnetic fields (galactic and intergalactic)
- Photons can be absorbed by the ISM and CMB
- Neutrinos are not absorbed and deviated
- Gravitational Waves!

A bit of history: first evidence of CR



3.5 ions/cm^3

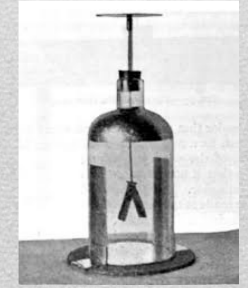
300 meters: flux/15
→ 0.4 ions/cm^3

6 ions/cm^3

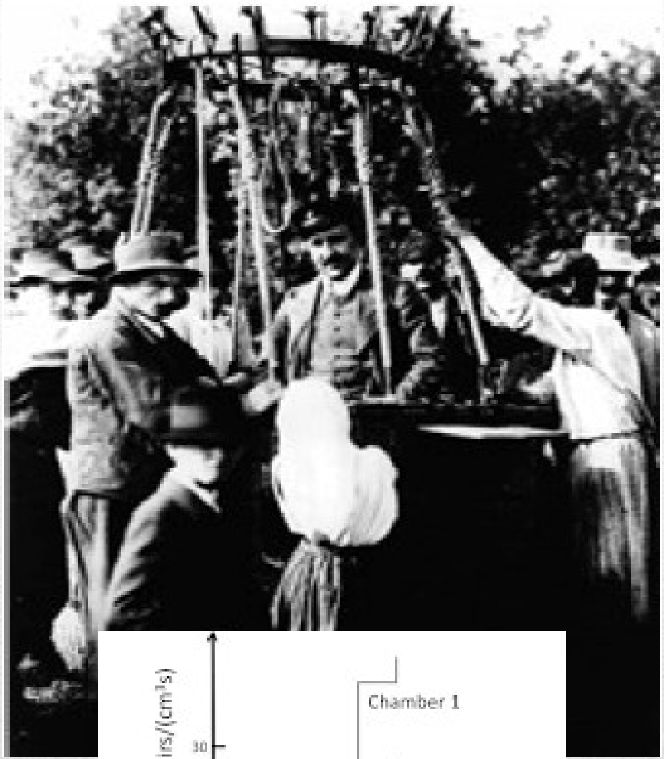
1910:

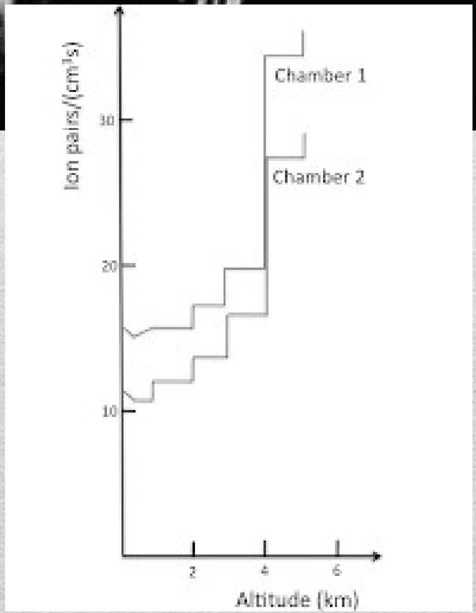
- ***Theodor Wulf*** measured air ionisation as a function of altitude.
- The ionisation is slower than expected if the cause is coming only from radioactivity of the ground

electroscope



A bit of history: the discovery of CR

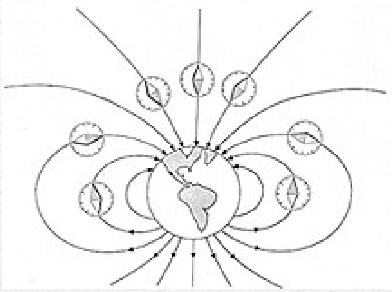




1912:

- ***Victor Hess*** repeated ionisation measurement (using an electroscope) on board a balloon until an altitude of 5200 m
- the radiation decreased slowly until 700 m and then increased considerably with height
- He concluded that the increase of the ionisation with height was originated by radiation coming from space
- Results were confirmed by W. Kolhorster in flights up to 9200 m
- Victor Hess was awarded the Nobel Prize in 1936 for the discovery of cosmic rays

A bit of history:The nature of CR



- Long debate on the nature of extraterrestrial radiation:
  - **R.A. Millikan** and others believed Cosmic Rays (CR) were photons.
  - 1927: **J. Clay** finds evidence of CR intensity variation with latitude
  - 1930: **Bruno Rossi** predicts the "*East-West effect*": CR are charged positive particles which are deviated by the geomagnetic field → the intensity of CR should be different if they are coming from East or West
  - 1932: **Compton** verifies Rossi's prediction with a world-wide campaign

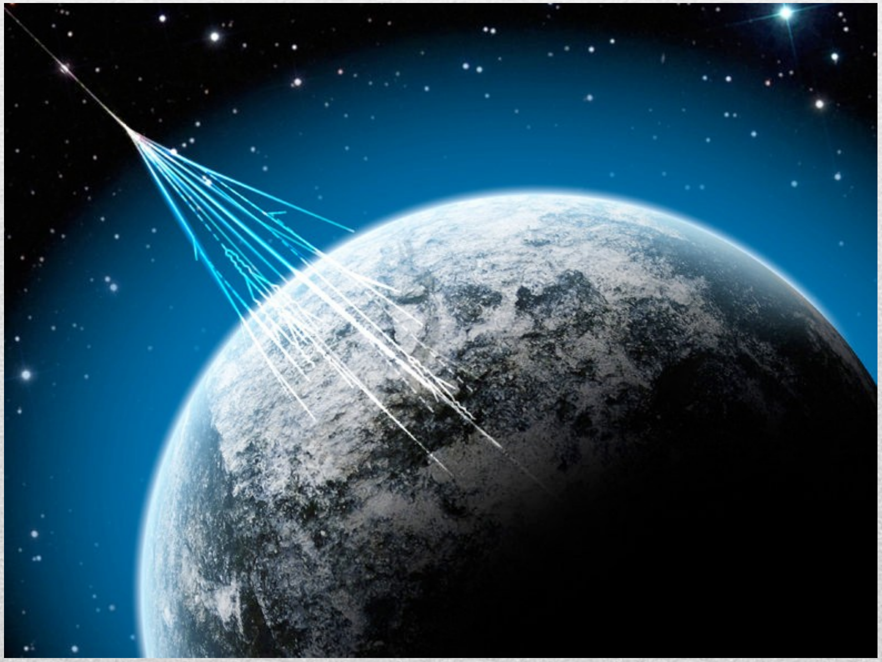
↓

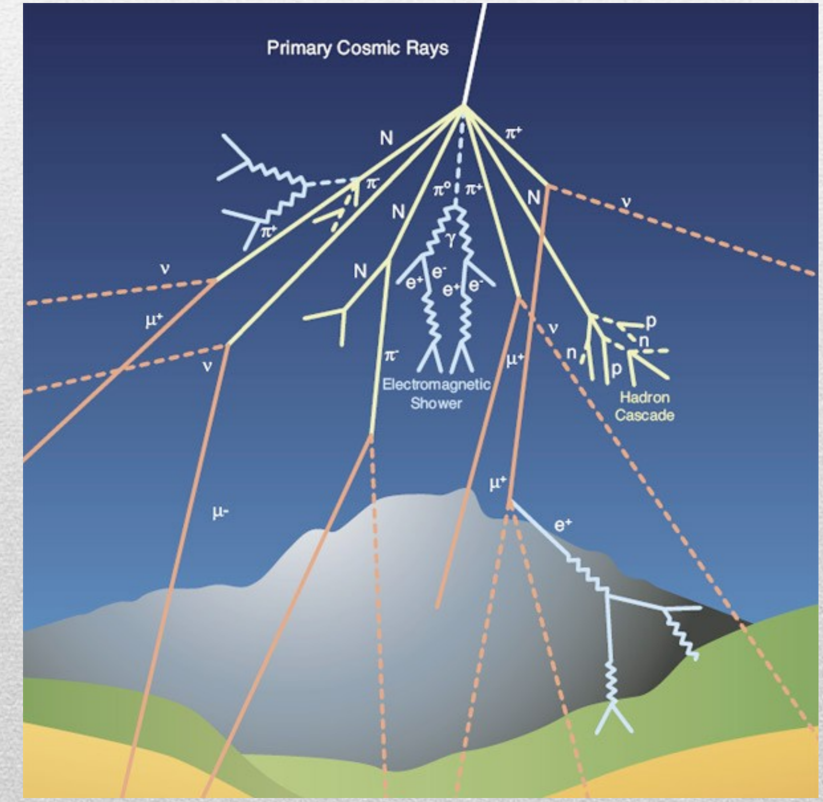
Cosmic Rays are charged particles !

A bit of history: Auger experiment

- 1938: **Pierre Auger** demonstrated that group of particles arrive in time coincidence on detectors separated by distances as large as 200 m:
  - this demonstrated that the particles arriving at the Earth surface are "**secondary**" particles produced by a common "**primary**" particle that interacts in the high atmosphere, producing a shower of particles.

Pierre Auger (1899-1993)





A bit of history: particle physics with CR

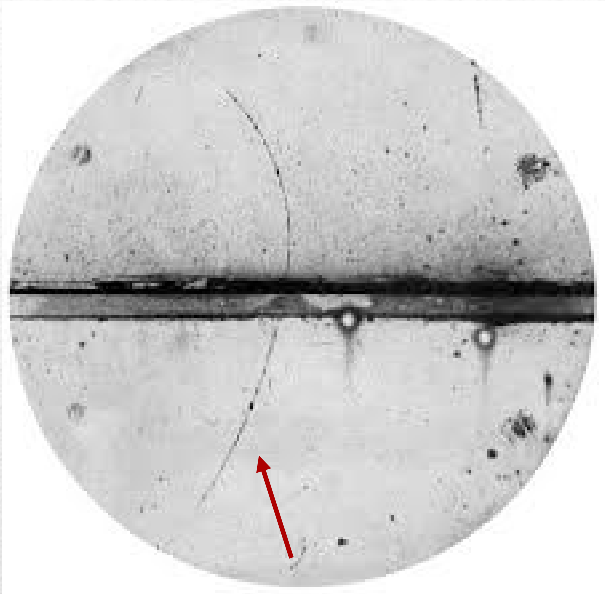
- Since 1930s experimental techniques for detection and measurement of electric charge, mass, lifetime of particles become more refined.

- **New particles** are discovered in CR:

  - 1932: **C. Anderson** discovers the **positron** in a cloud chamber (Nobel Laureate in 1936)

  - 1937: **C. Anderson** and **S. Neddermeyer** discover the **muon**

  - 1947: **C. Lattes, G. Occhialini** and **C. Powell** discover the **pion** using nuclear emulsions



First image of a positron obtained by Anderson

First discoveries in particle in physics using Cosmic Rays!

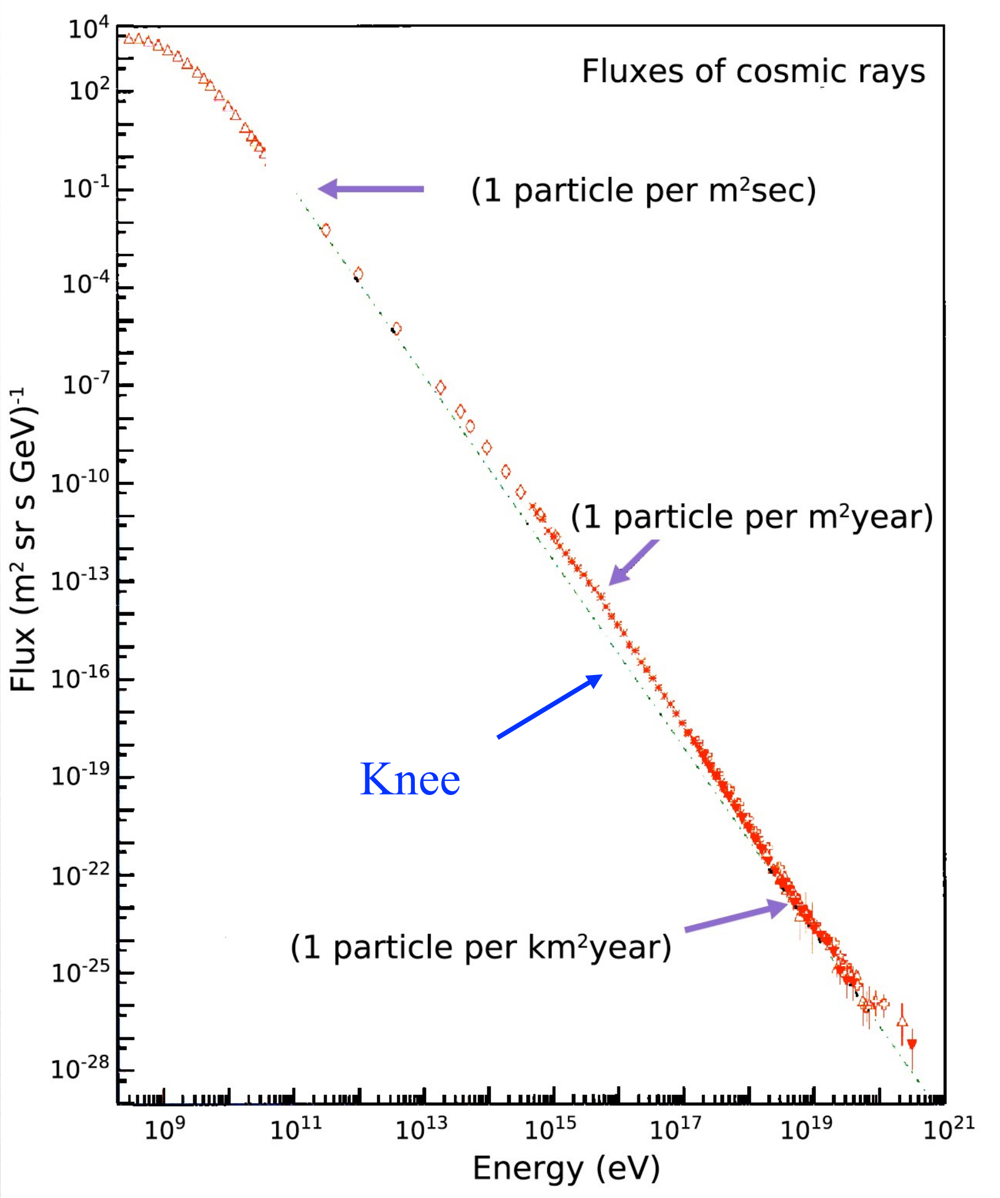
Charged Cosmic rays

Primary charged cosmic rays composition:

99 % nuclei
- 89% protons
- 10% helium nuclei
- 1% heavier nuclei

1% electrons

0.15% photons



Power-law (PL)

$$\Phi(E) = \Phi_0 . \left(\frac{E}{E_0}\right)^{-\gamma}$$

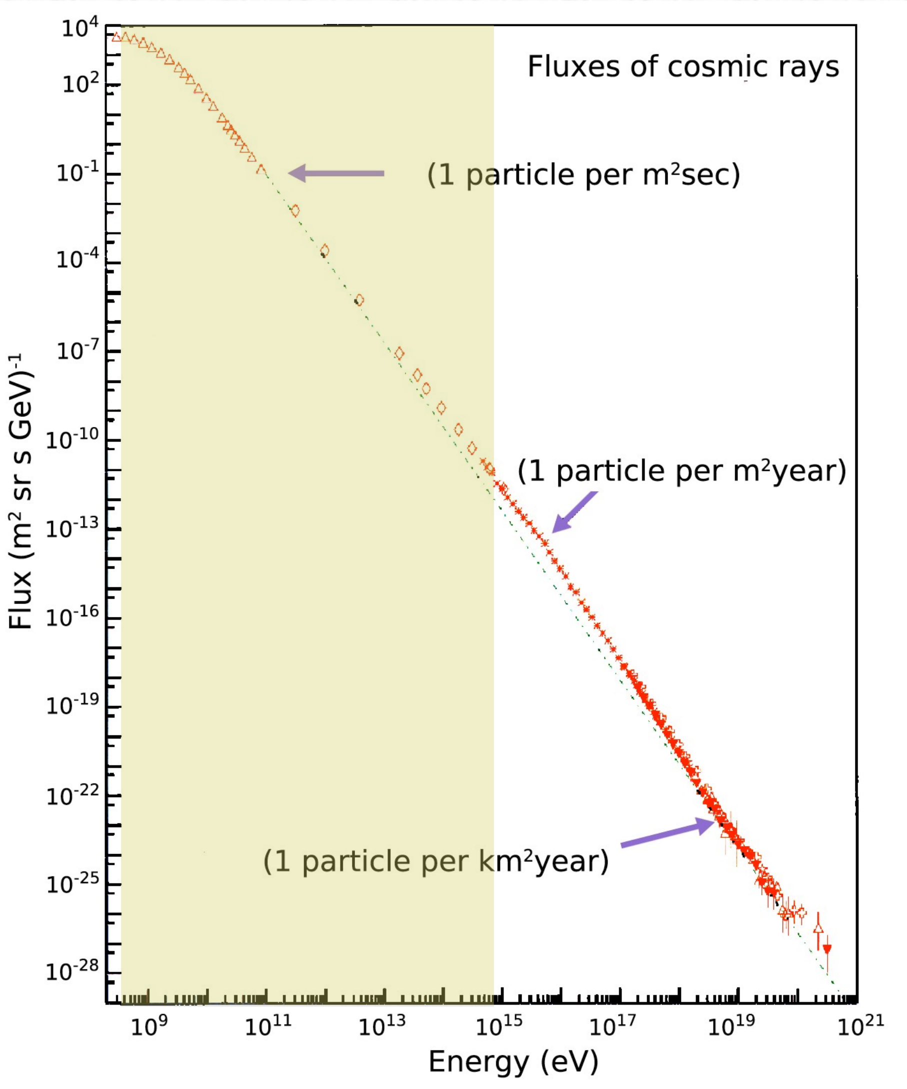
Exponential cutoff PL

$$\Phi(E) = \Phi_0 . \left(\frac{E}{E_0}\right)^{-\gamma} . \exp - \left(\frac{E}{E_c}\right)$$

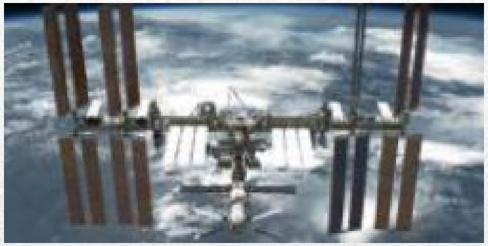
Flux is ~ $E^{-2.7}$ for $E<10^{15}$ eV (PeV)
Flux is ~ $E^{-3.0}$ for $E>10^{15}$ eV (PeV)

How can we detect CR?

Direct detection



($E<10^{15}$ eV)
Stratospheric balloons, satellites



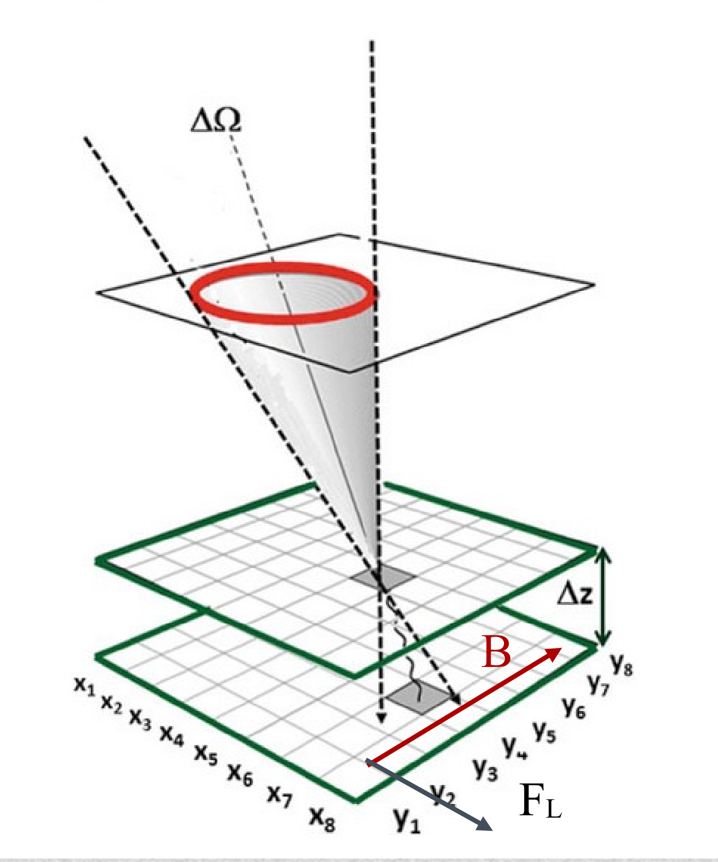
- Important to determine the flux and energy of protons, helium and heavier nuclei

- The detector must:

1-) Identify particles (what they are ?)
2-) Measure the flux (how many ?)
3-) Measure their energies

Direct detection

- **A Toy Telescope for primary Cosmic Rays:**
  - 2 layers of counters separated by a distance (Δz)
  - each layer measures position (x,y,z), time of crossing the layer (t) and intensity of the signal (I)
  - trigger logic: coincidence between two layers: to decrease probability of fake signals on the layers
  - to distinguish between upward ($t_2-t_1>0$) and downward ($t_2-t_1<0$) going CR, timing resolution of layers must be of the order of ns (or better) (relativistic particles cover 1 m in 3.3 ns): *time-of-flight* measurement
  - A uniform magnetic field can be added between the two layers to allow particle momentum (if |Ze| is known) and sign of the charge measurement.
  - Detectors with good spatial resolution (*tracking systems*) are required the measure particle deflection due to B: combination of the magnetic field and tracking detectors form a *magnetic spectrometer*

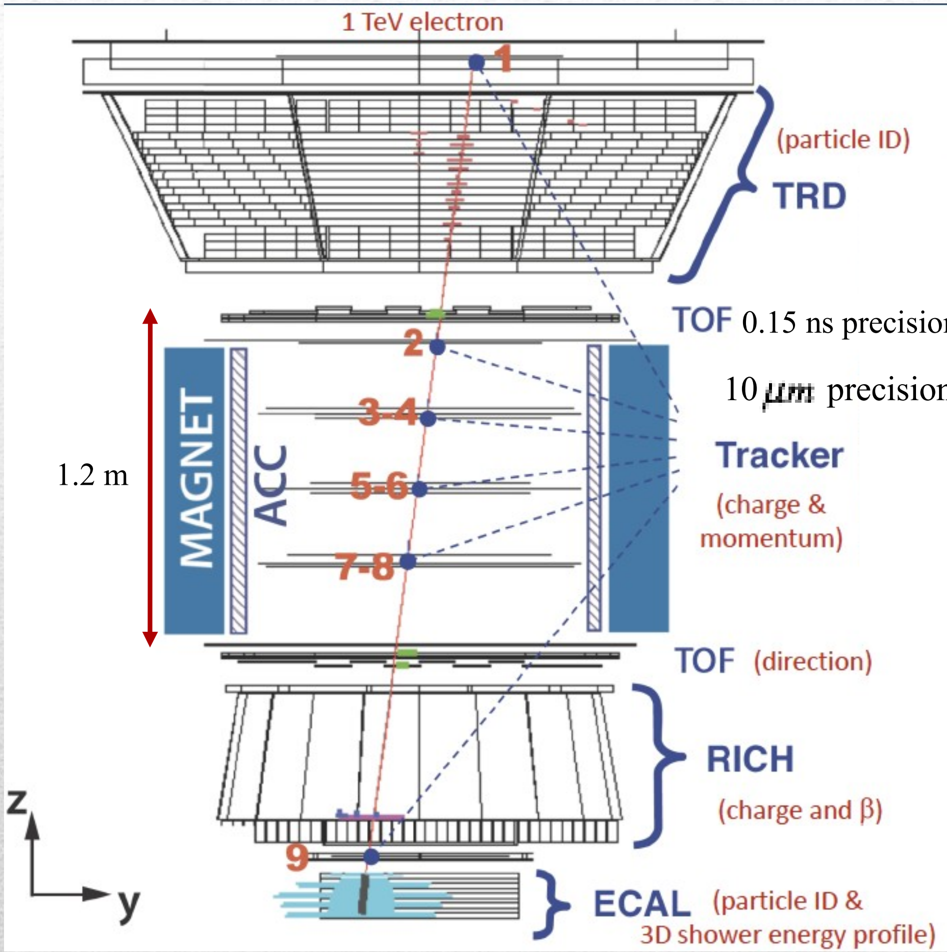


Direct detection: satellites

L. Accardo et al. PRL 113, 121101 (2014)

AMS–02

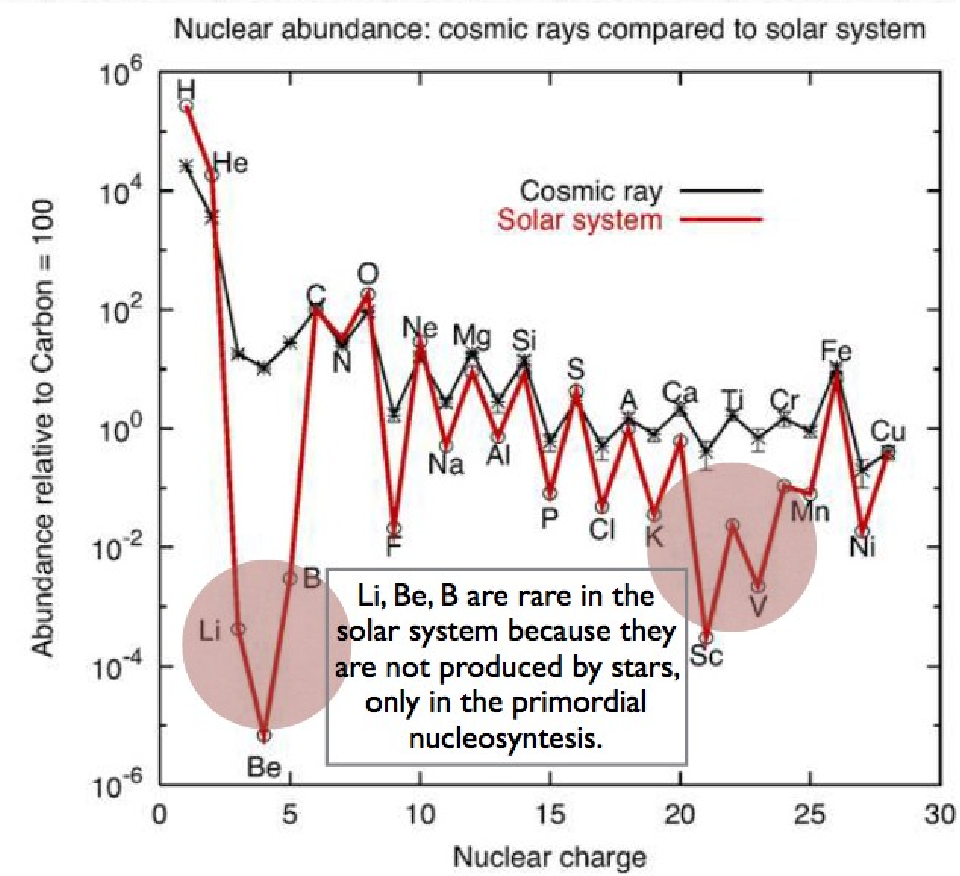
Alpha Magnetic Spectrometer

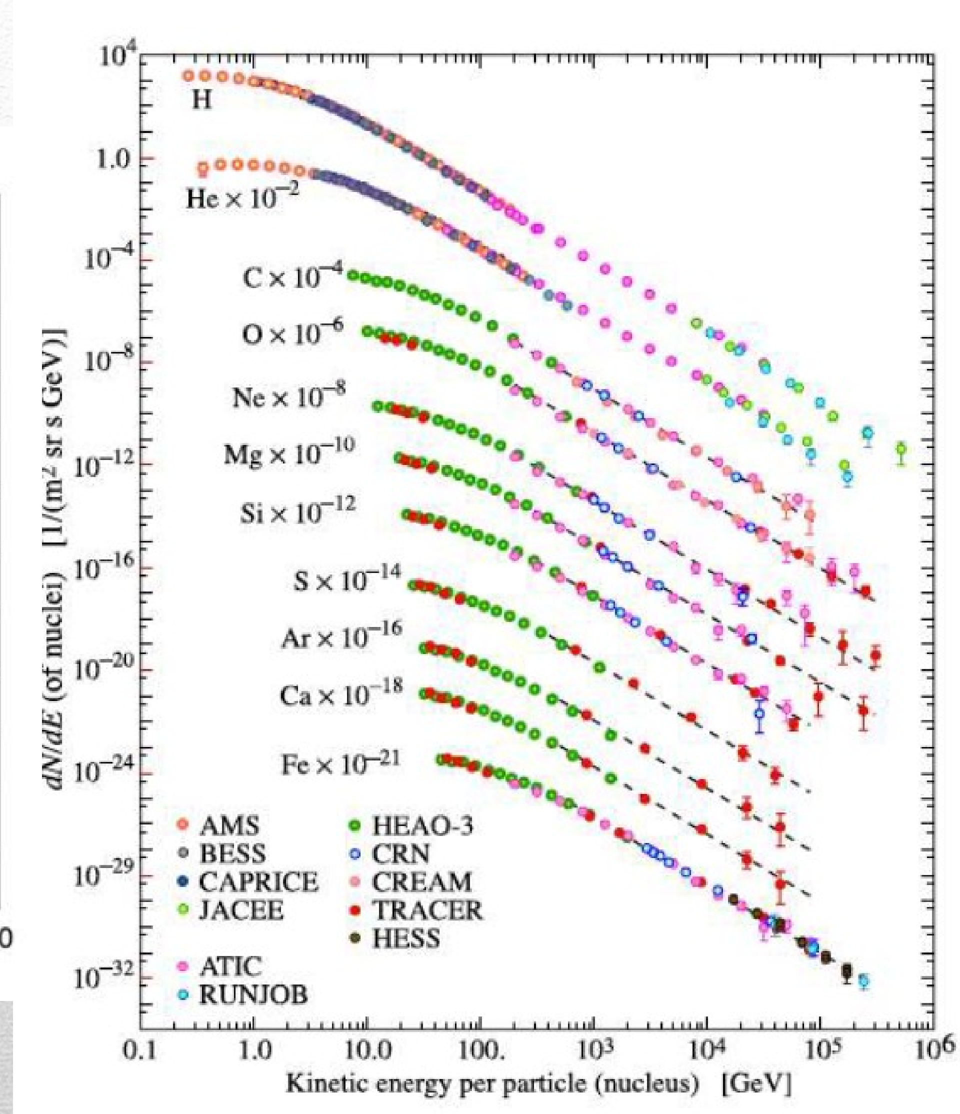


- Since 2011 : 90 billions of primary CR have been detected
- Energy between 0.5-500 GeV

Cosmic rays composition

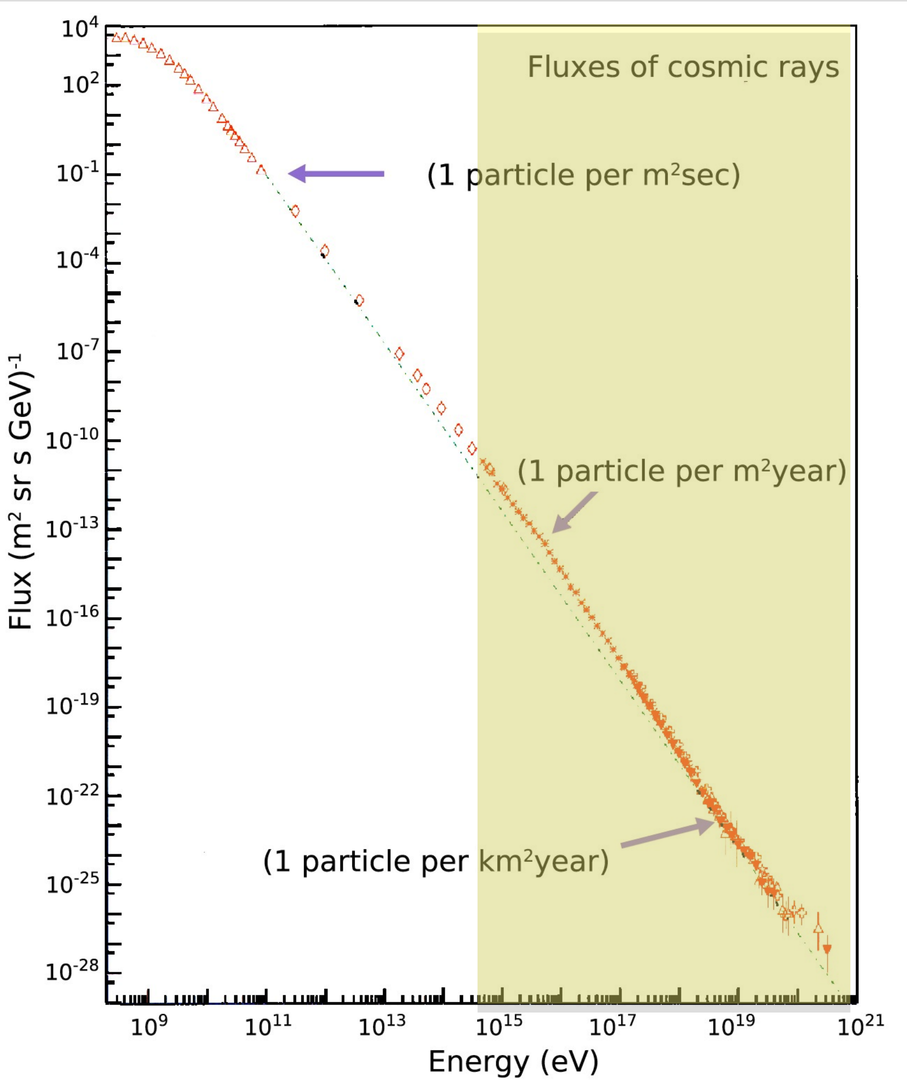
CR composition similar to Solar one





Li, Be, B are secondary components produced by fragmentation reactions of the heavier C,N and O during the journey of CR in ISM

Indirect detection

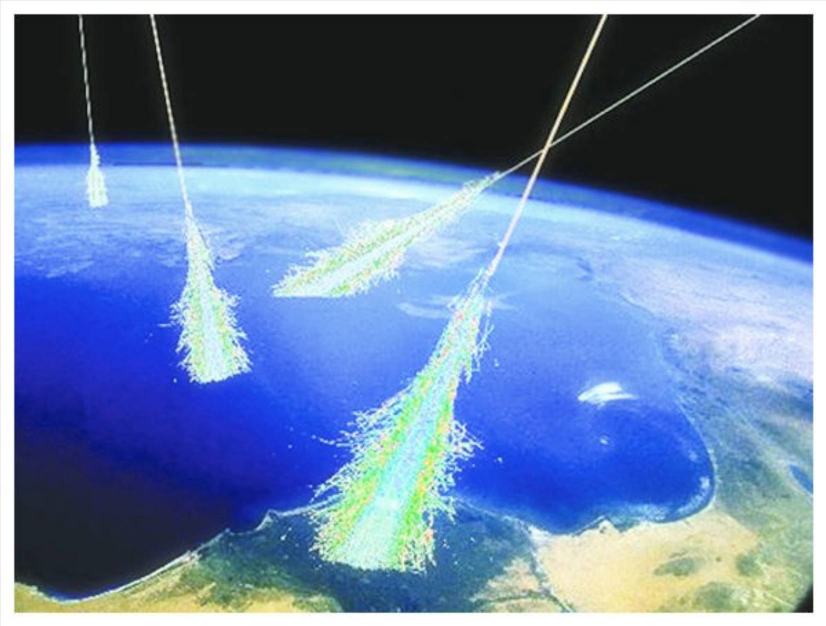


($E > 10^{15}$ eV)

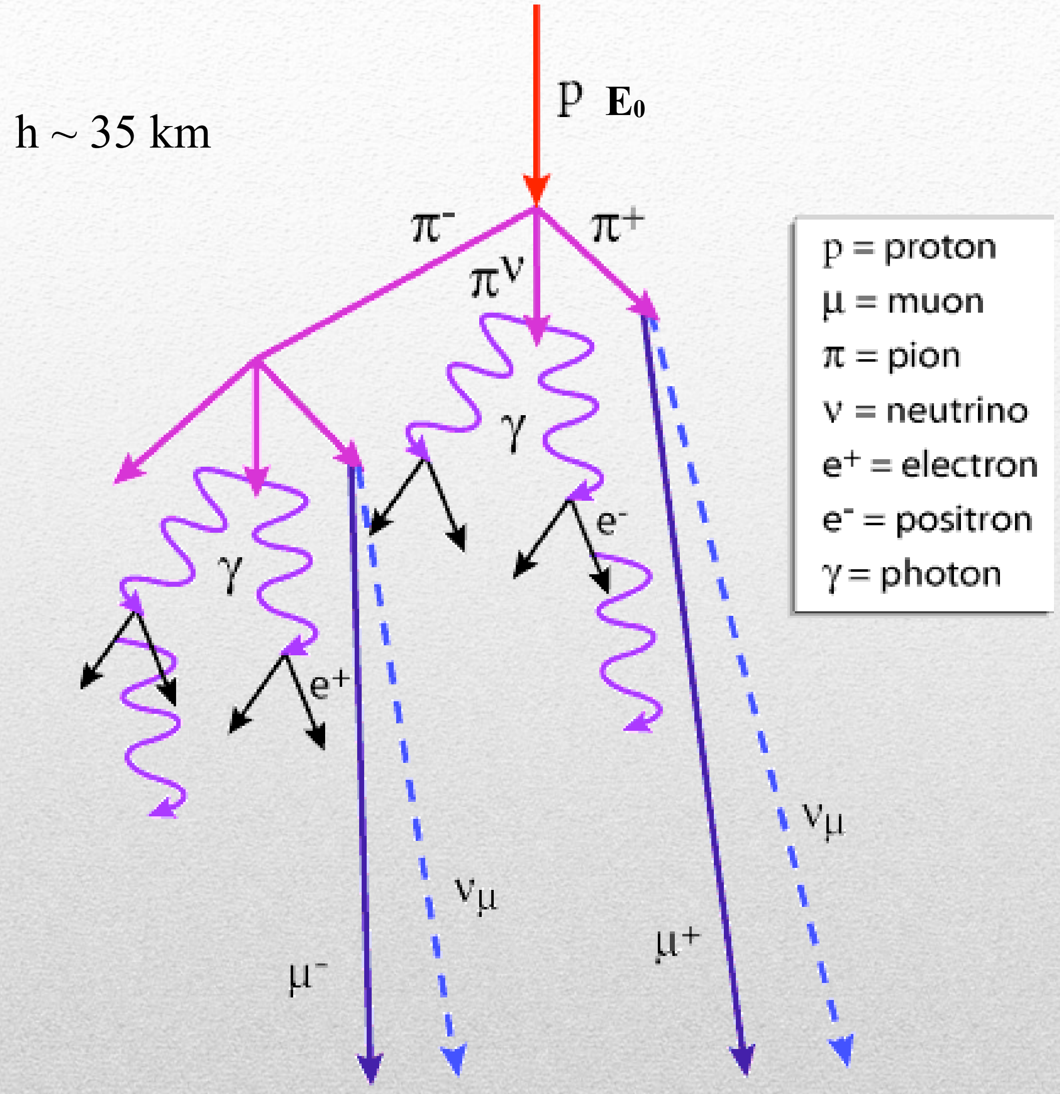
Detectors on ground

- to detect high energy CR, larger detectors are needed (no enough space on satellites or balloons)

- CR entering in the atmosphere create showers → by detecting the showers on ground it's possible to measure direction and energy of CR



Extensive Air Shower

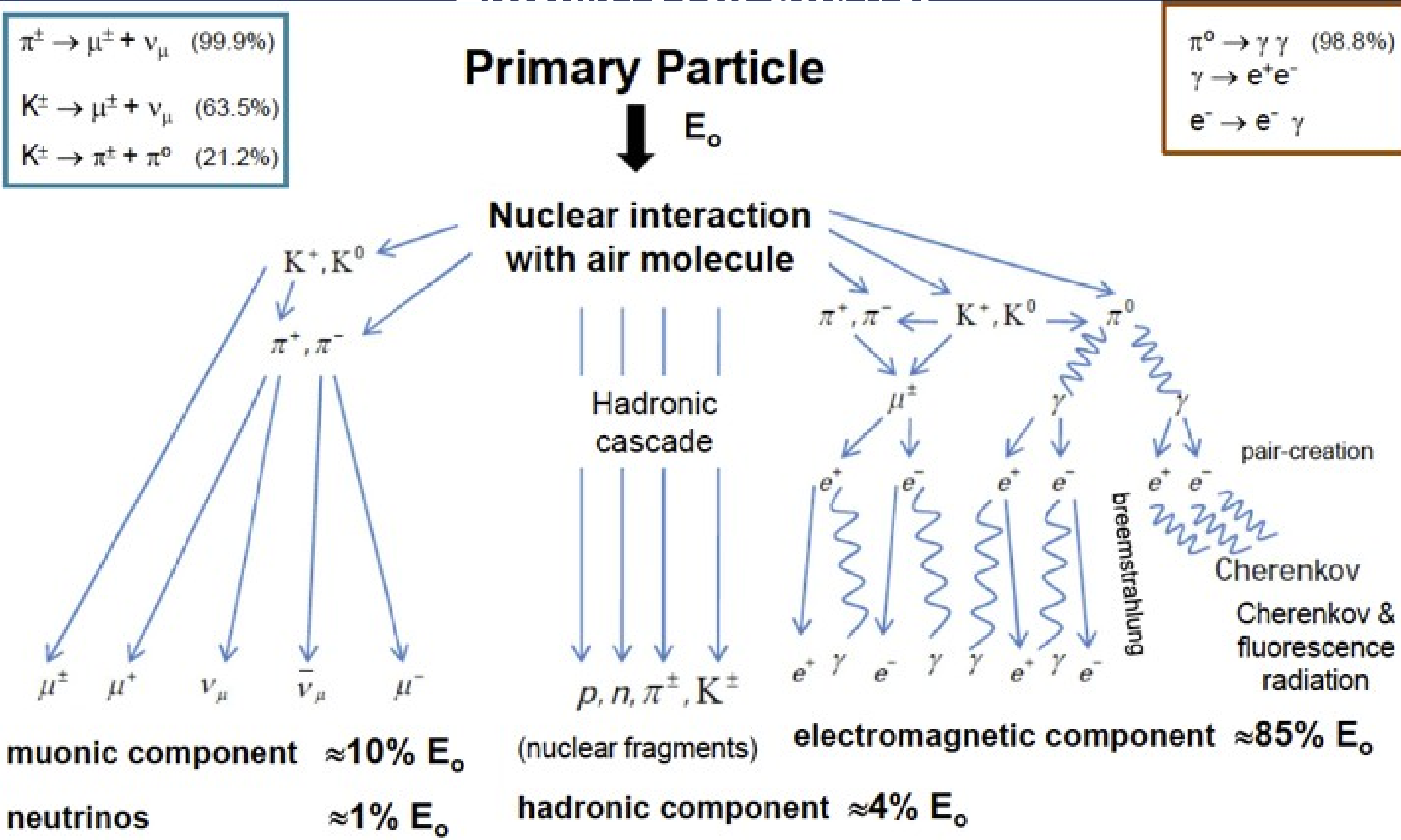


- **gamma , e^-, e^+ ~ 85% E_0**
- **muons ~ 10% E_0**
- **hadrons ~ 4% E_0**
- **neutrinos ~ 1 % E_0**

$E_0 = 10^{18}$eV → 10^{10} particles (some km²)

$E_0 = 10^{15}$eV → 10^6 particles (10^4 m²)

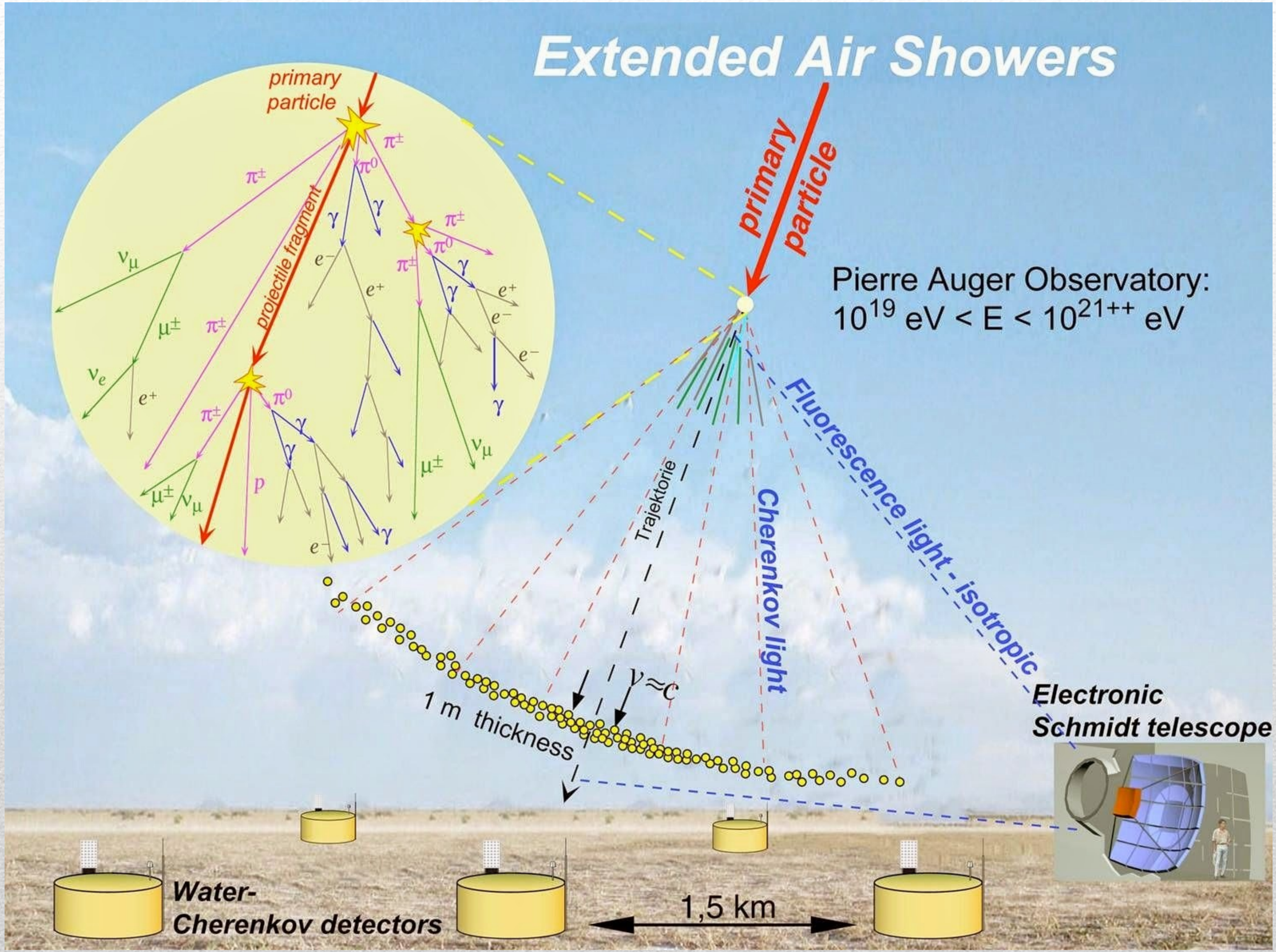
Extensive Air Shower



$E_0 = 10^{18}$eV → 10^{10} particles on a surface of few km^2

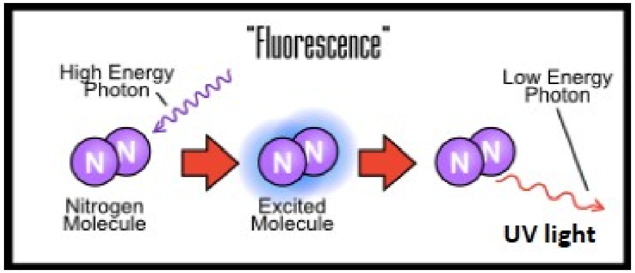
$E_0 = 10^{15}$eV → 10^{4} particles on a surface of about km^2

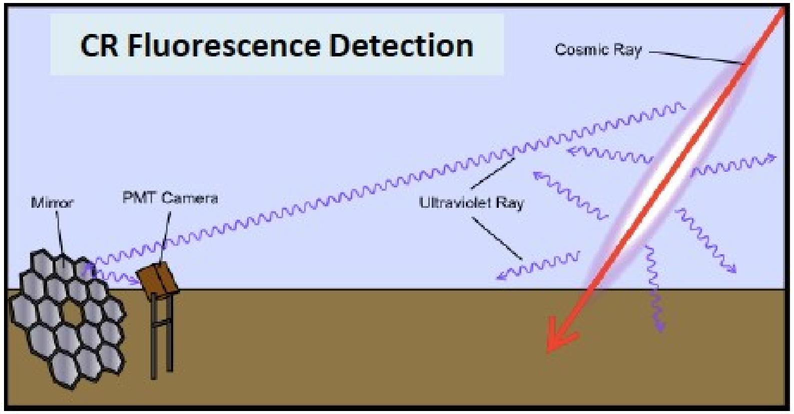
Detection of Air Shower

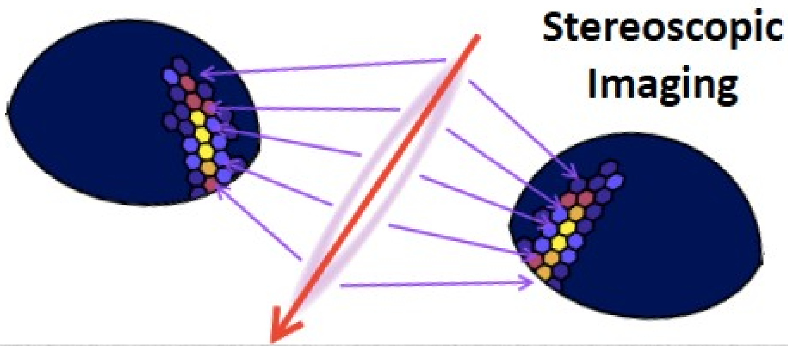


Detection techniques

Shower Longitudinal Profile

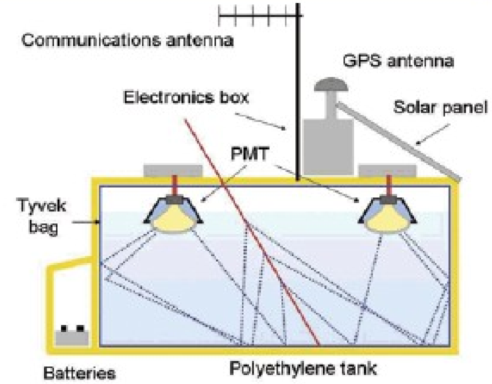






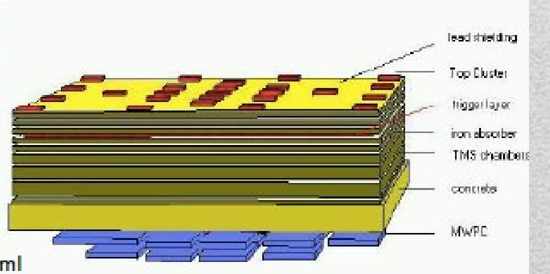
Lateral Distribution of Particles at Ground

Water Cherenkov stations



Scintillators

e/γ detector: liquid scintillator + light collector + PMT
Muon detector: plastic scintillator shielded (iron) + PMT

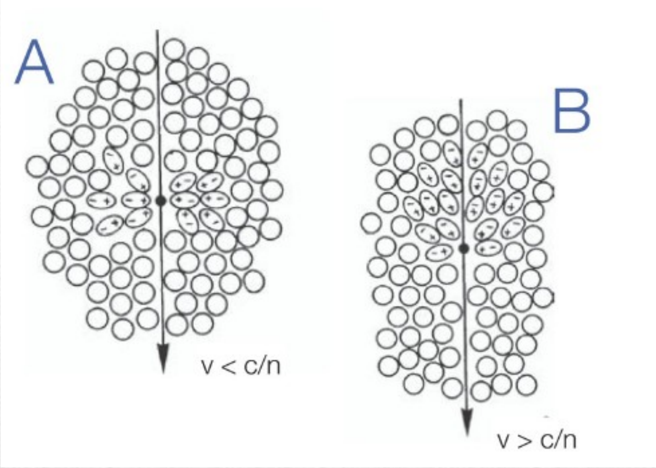


https://web.ikp.kit.edu/KASCADE/welcome.html

The Cherenkov effect

Cherenkov radiation is emitted when a charged particle passes through a dielectric medium at a speed faster than the speed of light in that medium.

When a charged particle passes an insulator, the particle's charge disturbs the local electromagnetic fields of the atoms. The electrons in the atoms are displaced which causes polarization. This stimulated state restores itself back to equilibrium state after the particle has passed, the Cherenkov photons are emitted.



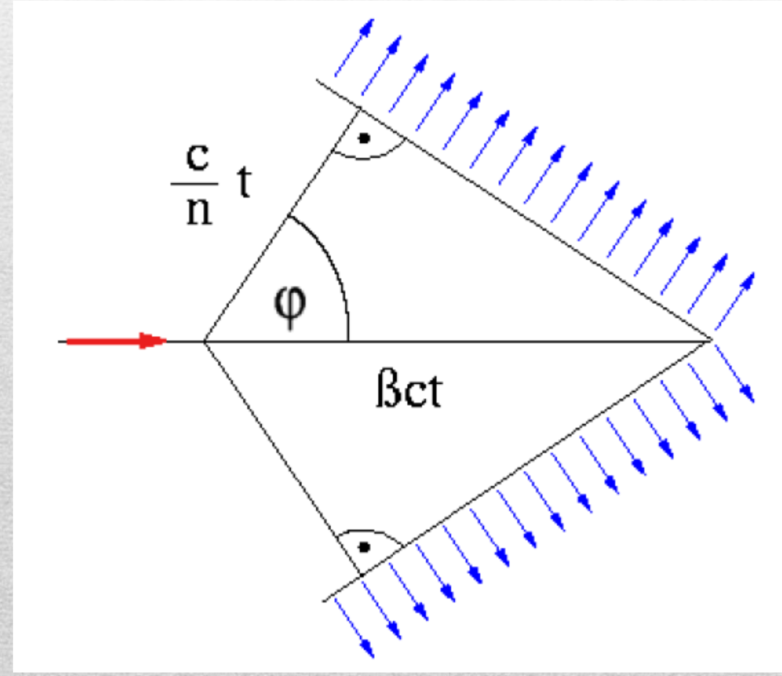
$$\cos(\varphi) = \frac{1}{\beta n(\lambda)}$$

$\beta = v/c$

speed of the particle

Case A (v < c/n) : The produced Cherenkov photons destructively interfere with each other, therefore no radiation can be detected.

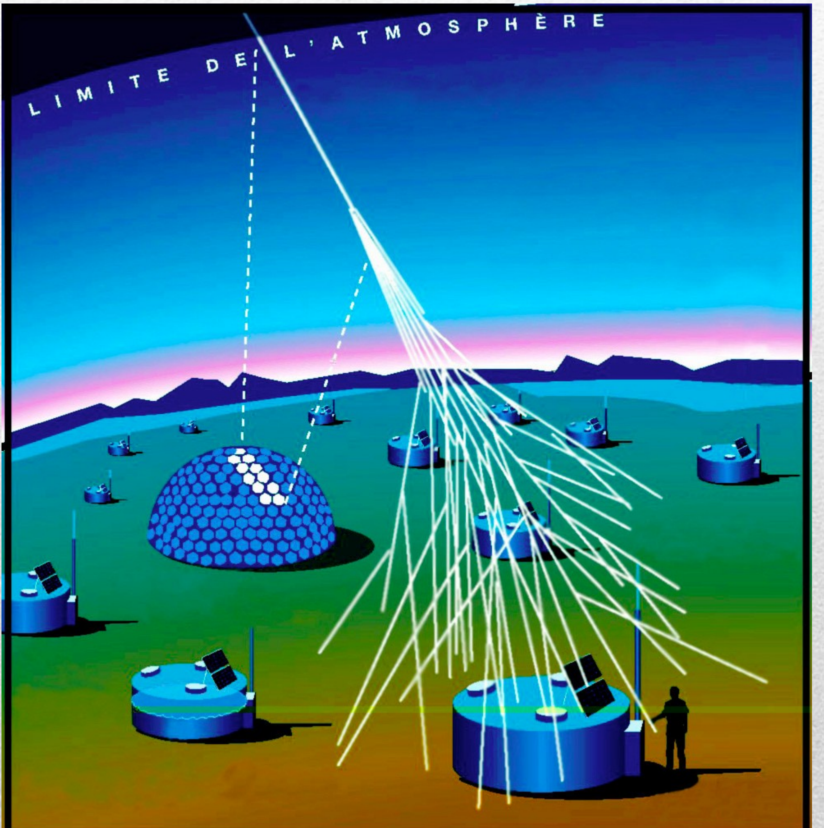
Case B (v > c/n) : The produced Cherenkov photons constructively interfere with each other, therefore the Cherenkov radiation becomes observable.

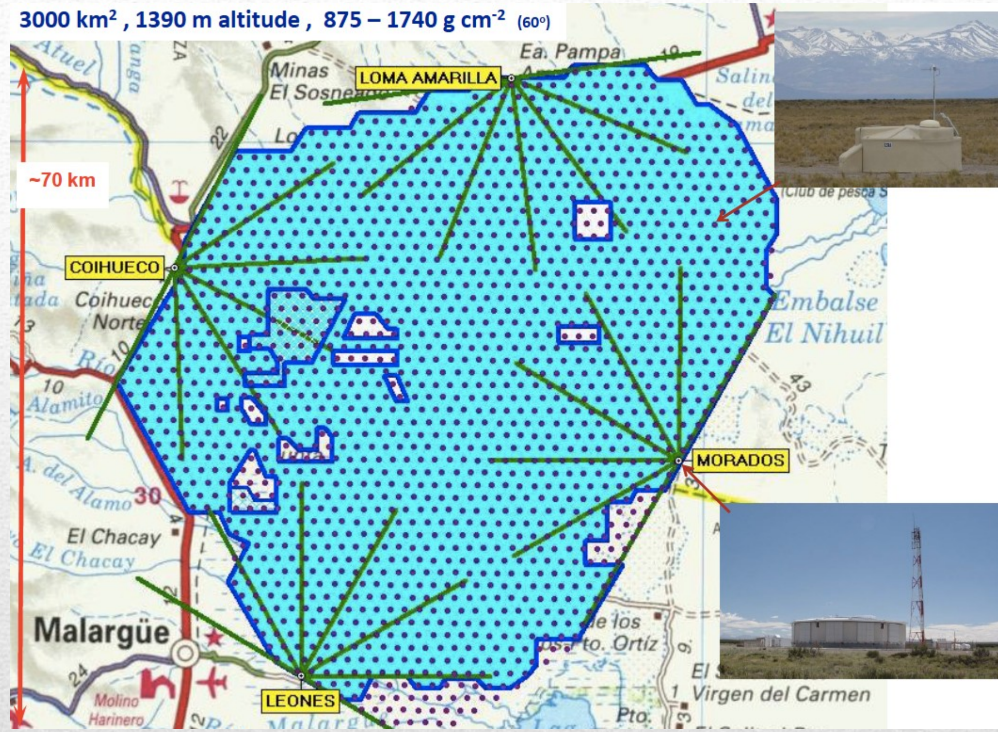


Pierre Auger Observatory

Hybrid observatory:

- surface detectors
- fluorescence detectors

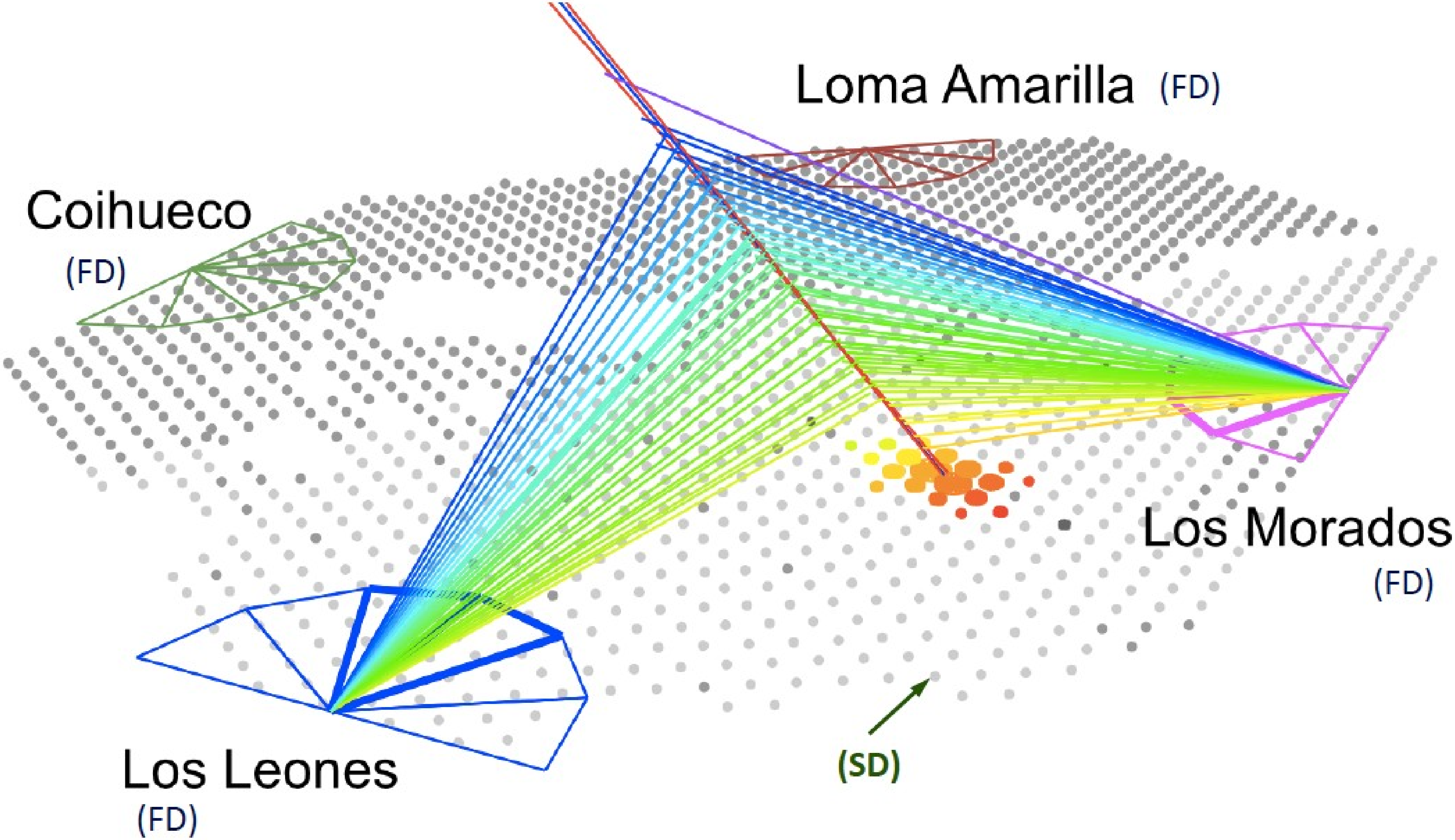




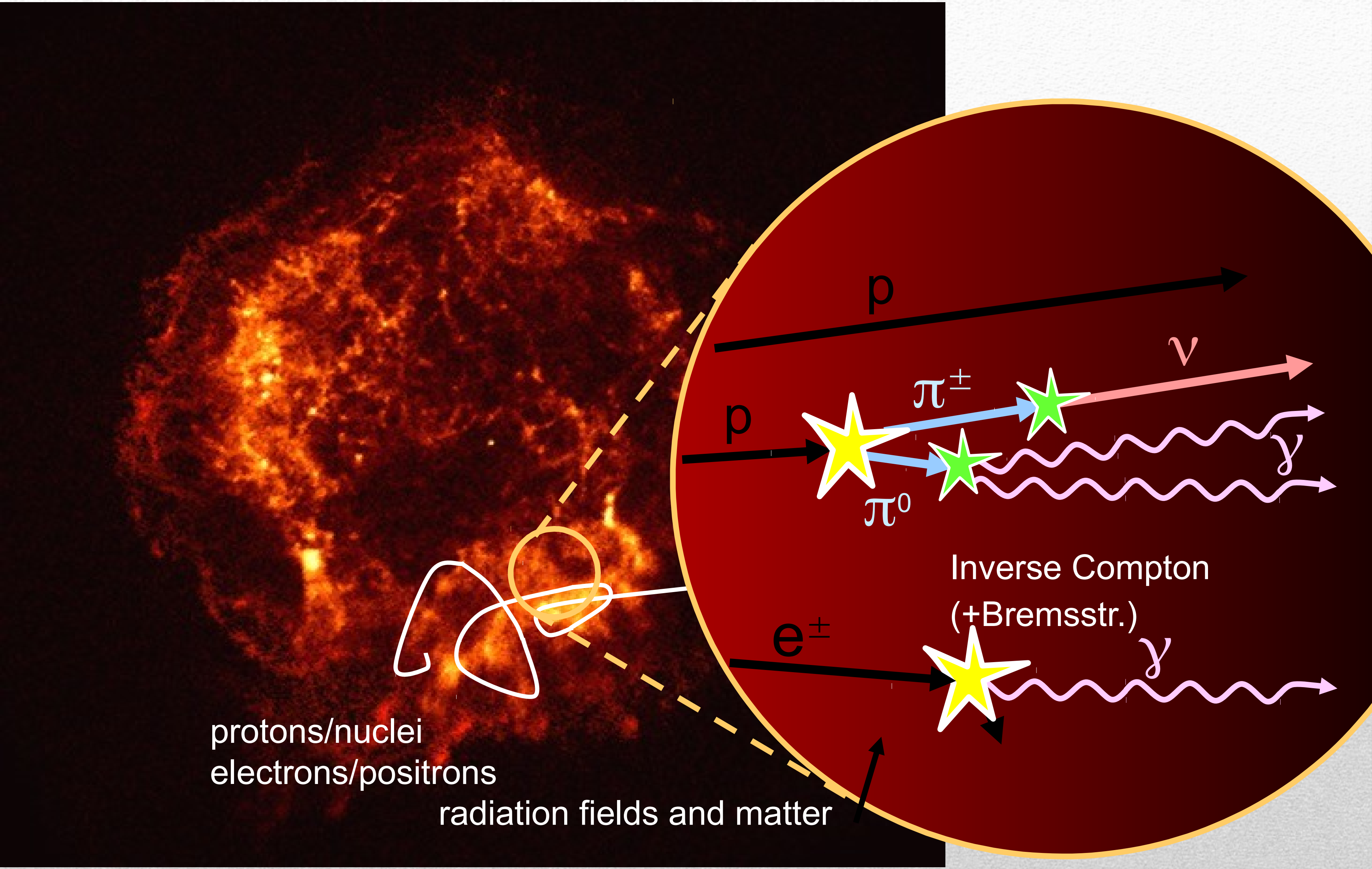
- 1600 water tanks at 1.5 km distance of 1.5 km
- 12 tons of purified water

- 4 sites for fluorescence detectors
- Field of View: 30 deg x 30 deg

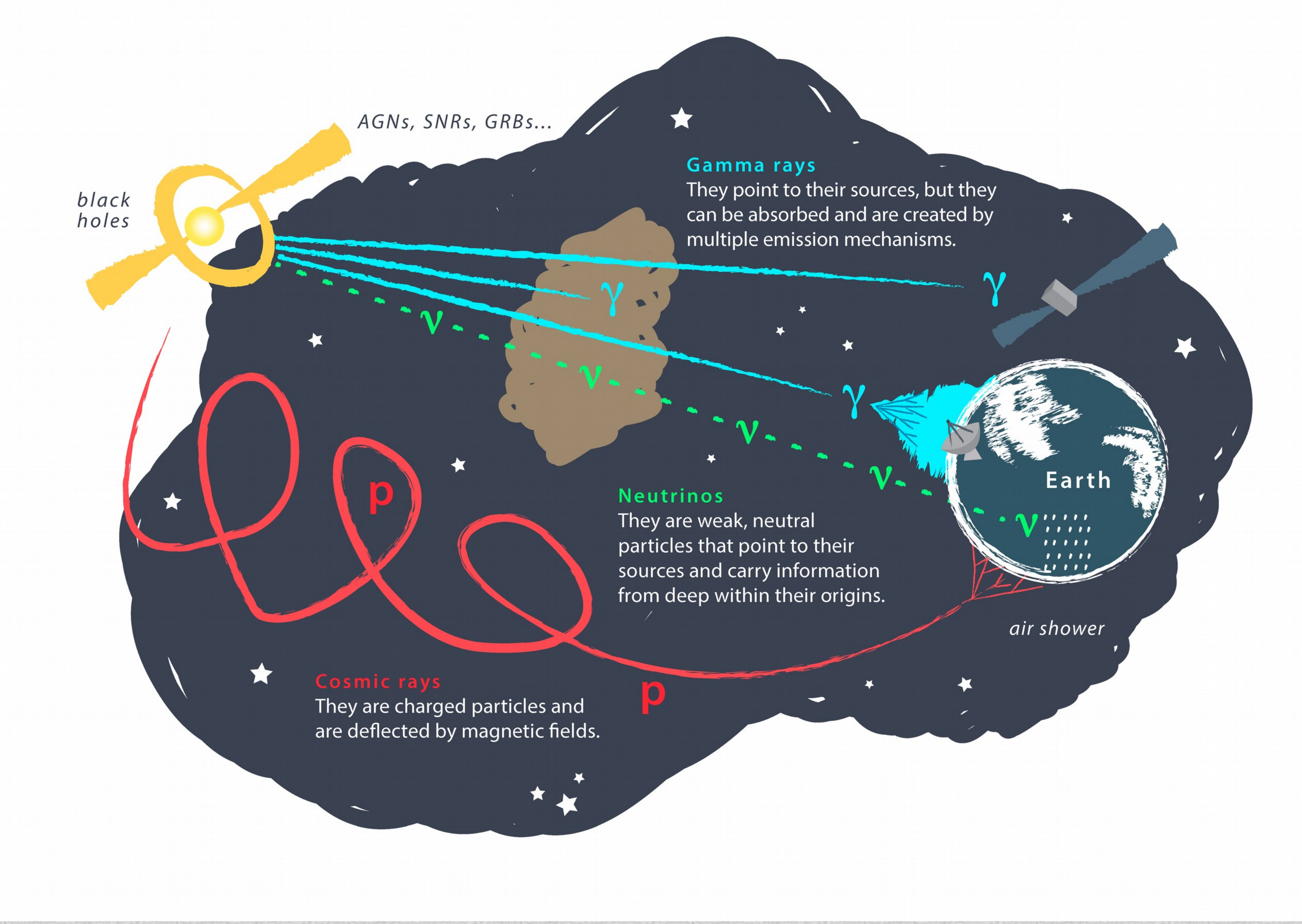
Example of an hybrid event



Connection CR-gamma-neutrino

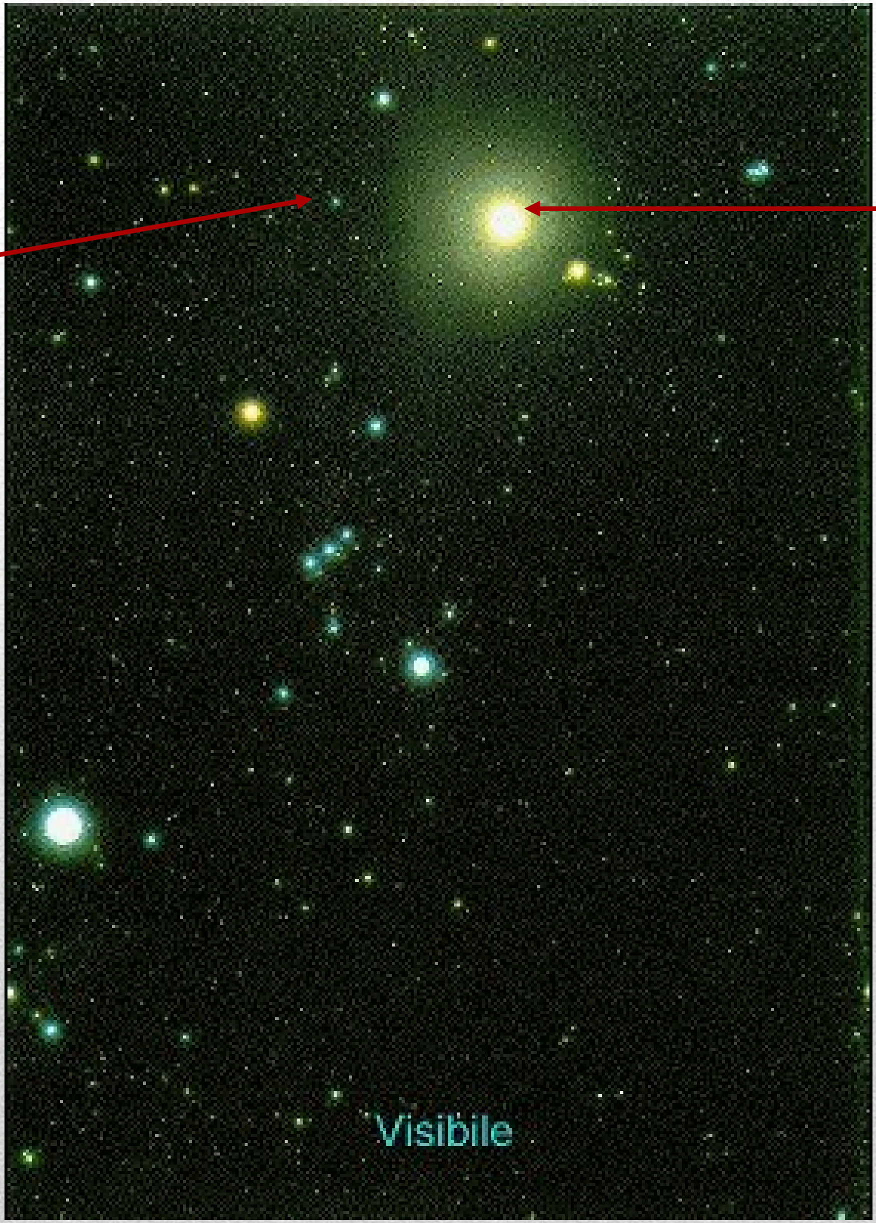


Connection CR-gamma-neutrino

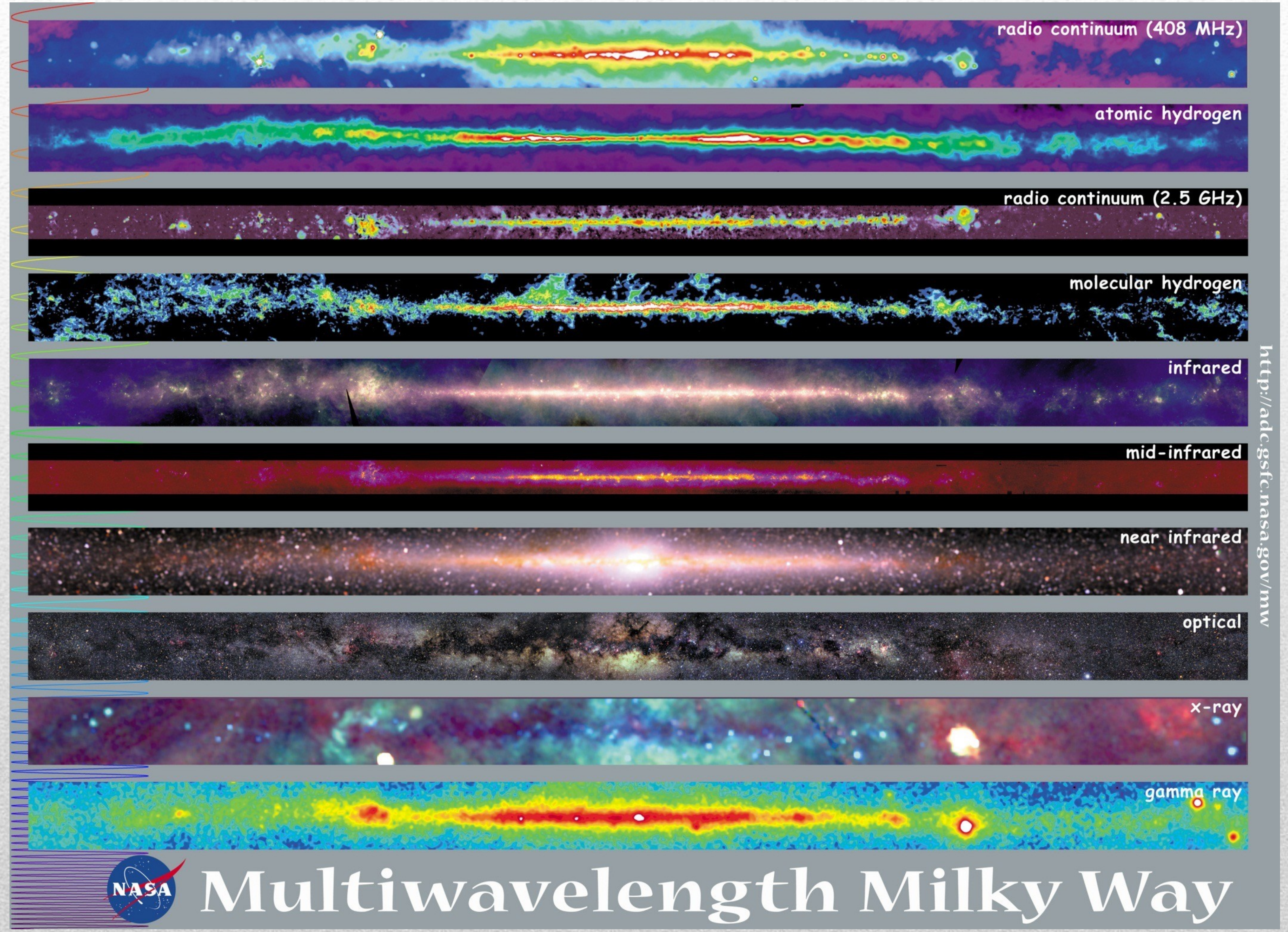


The sky in different wavelengths

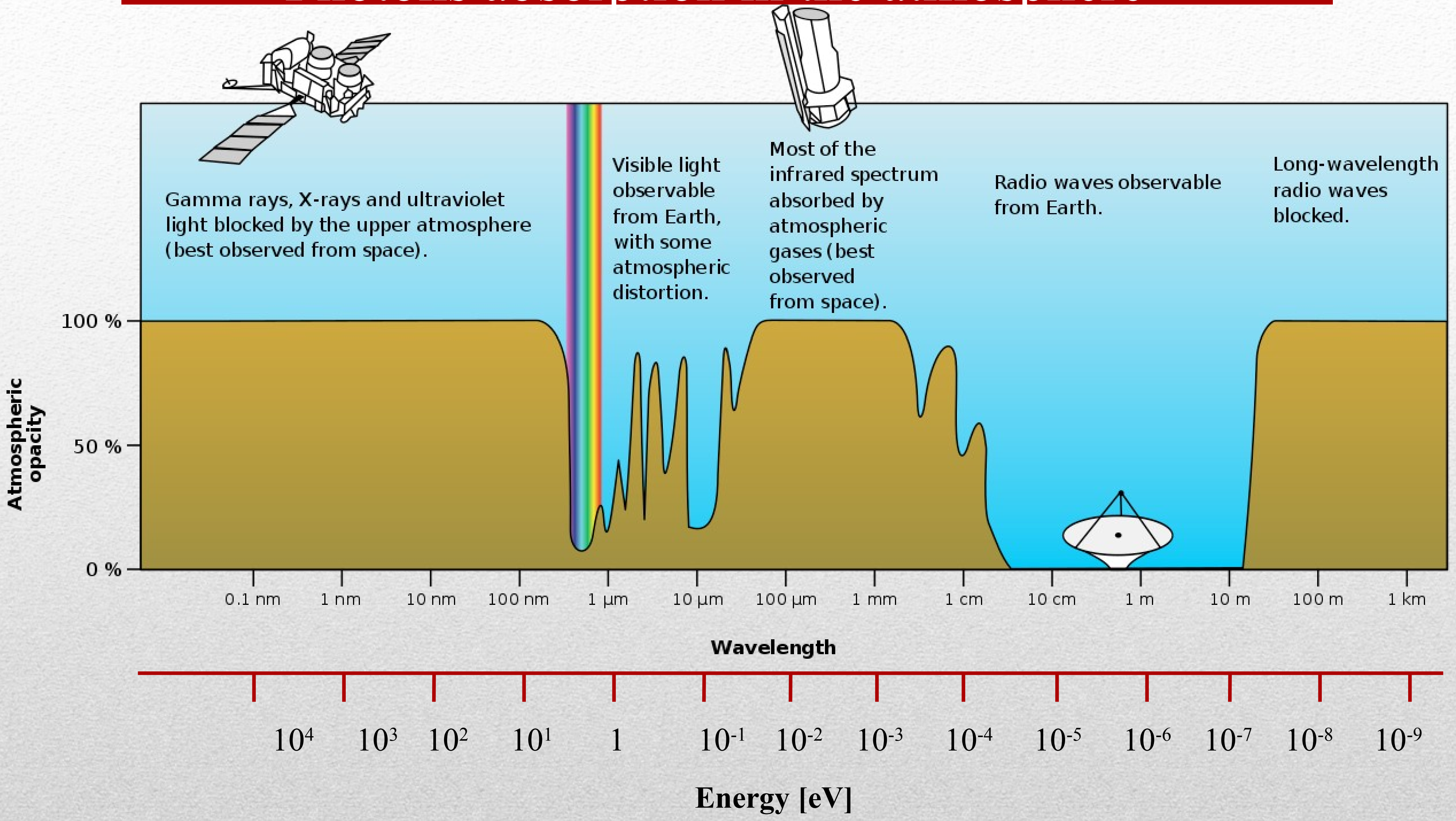
Crab



Moon


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

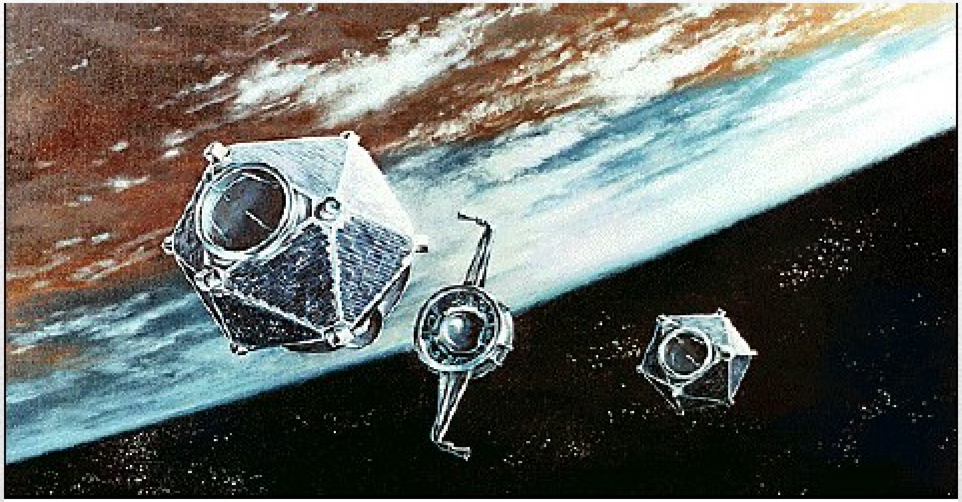
Photons absorption in the atmosphere

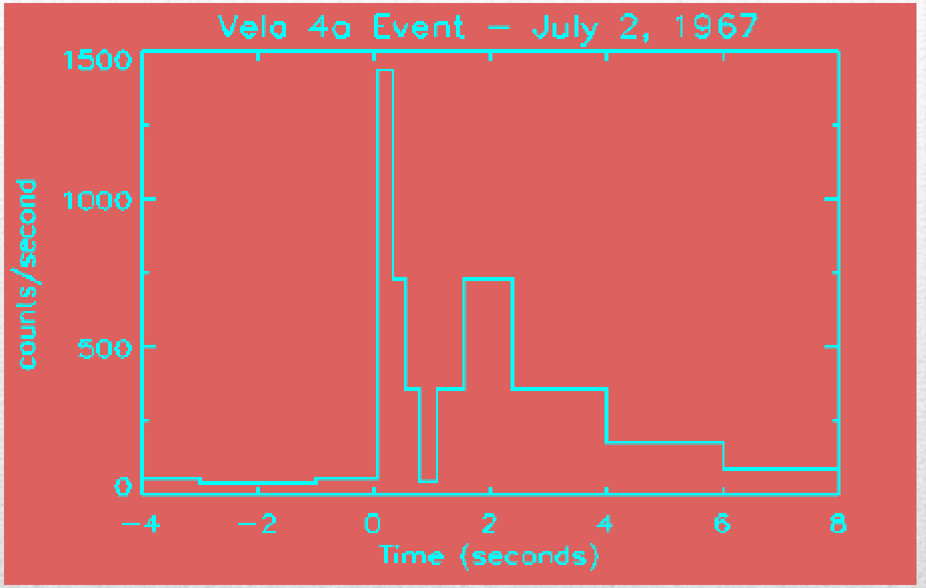


Discovery of cosmic gamma rays

First detection : VELA

3 pairs of satellites launched on 1963-1964-1965
Goal: gamma survey of nuclear bomb tests





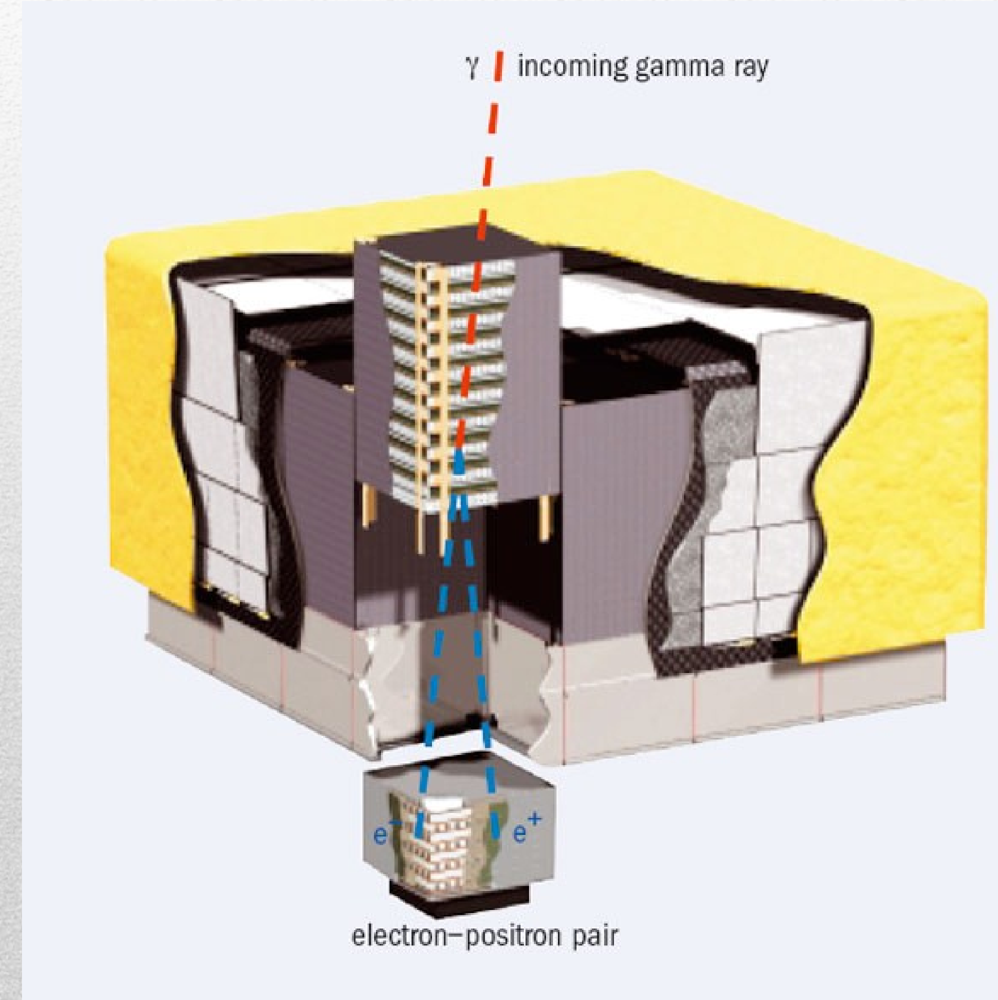
1967: detection of a gamma ray burst

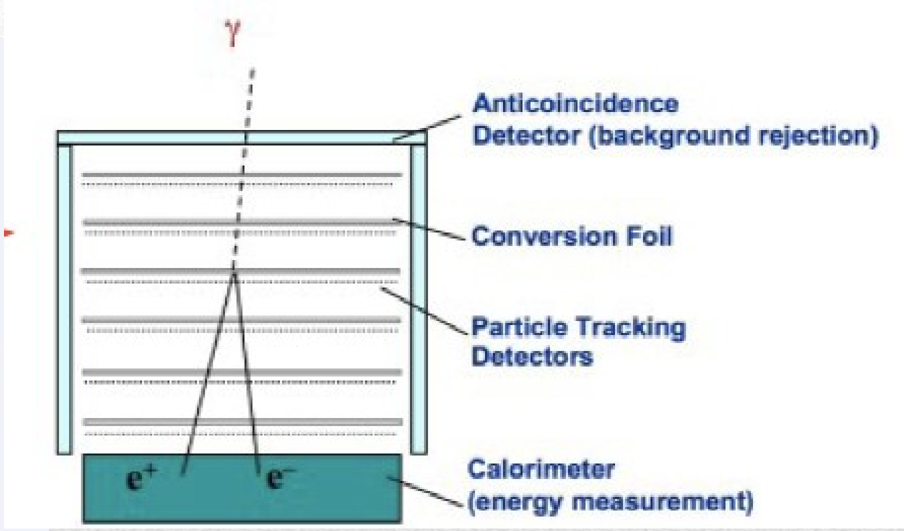
Detected energy: 0-10 MeV

Gamma Direct detection: satellite

For **energies below 100 GeV** gamma flux can be measured on satellites

FERMI Large Area Telescope: 20 MeV-300 GeV

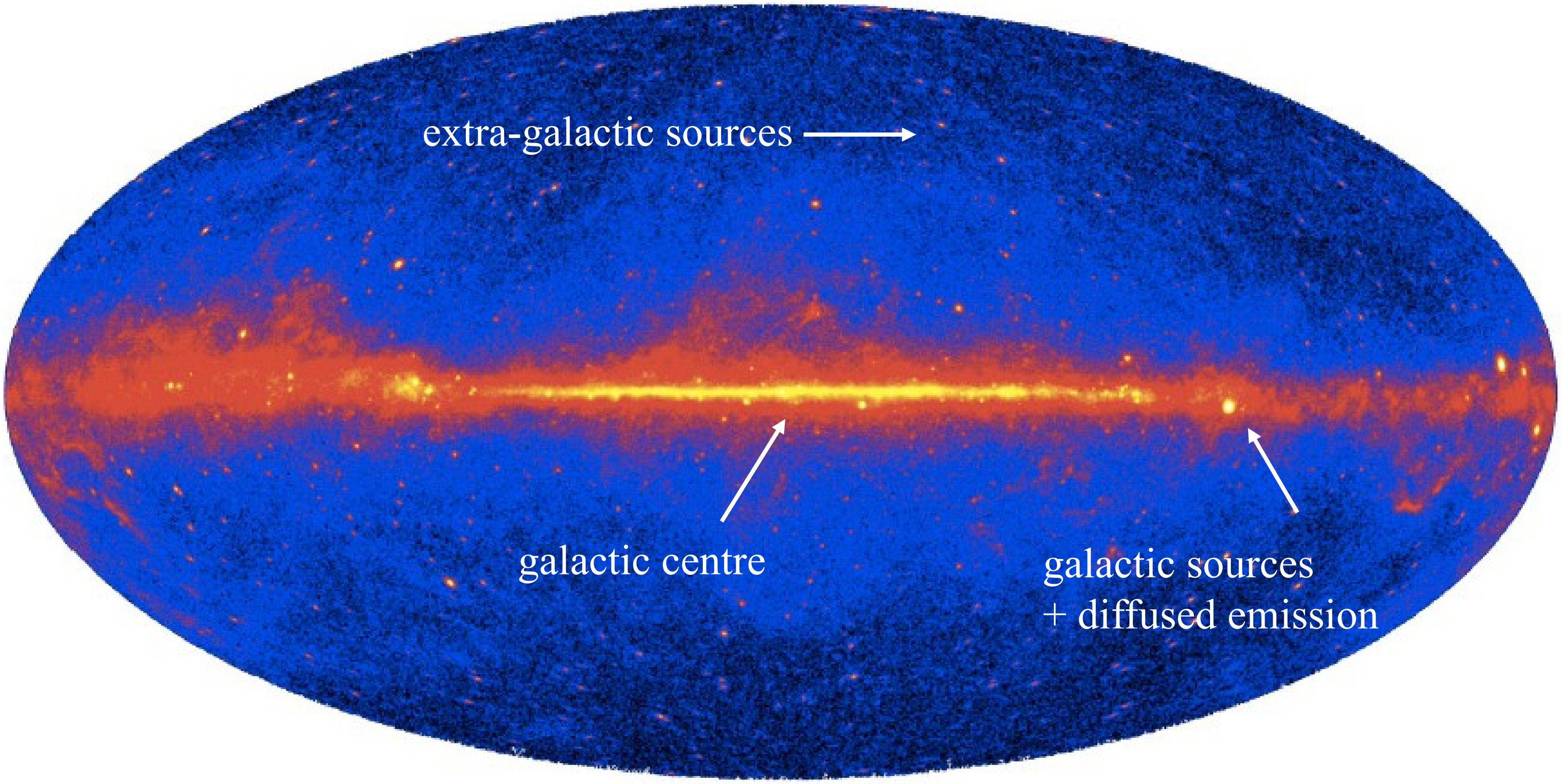




Gamma Astronomy at GeV

1800 sources have been detected: a lot of extragalactic sources

> Fermi 2FGL catalog



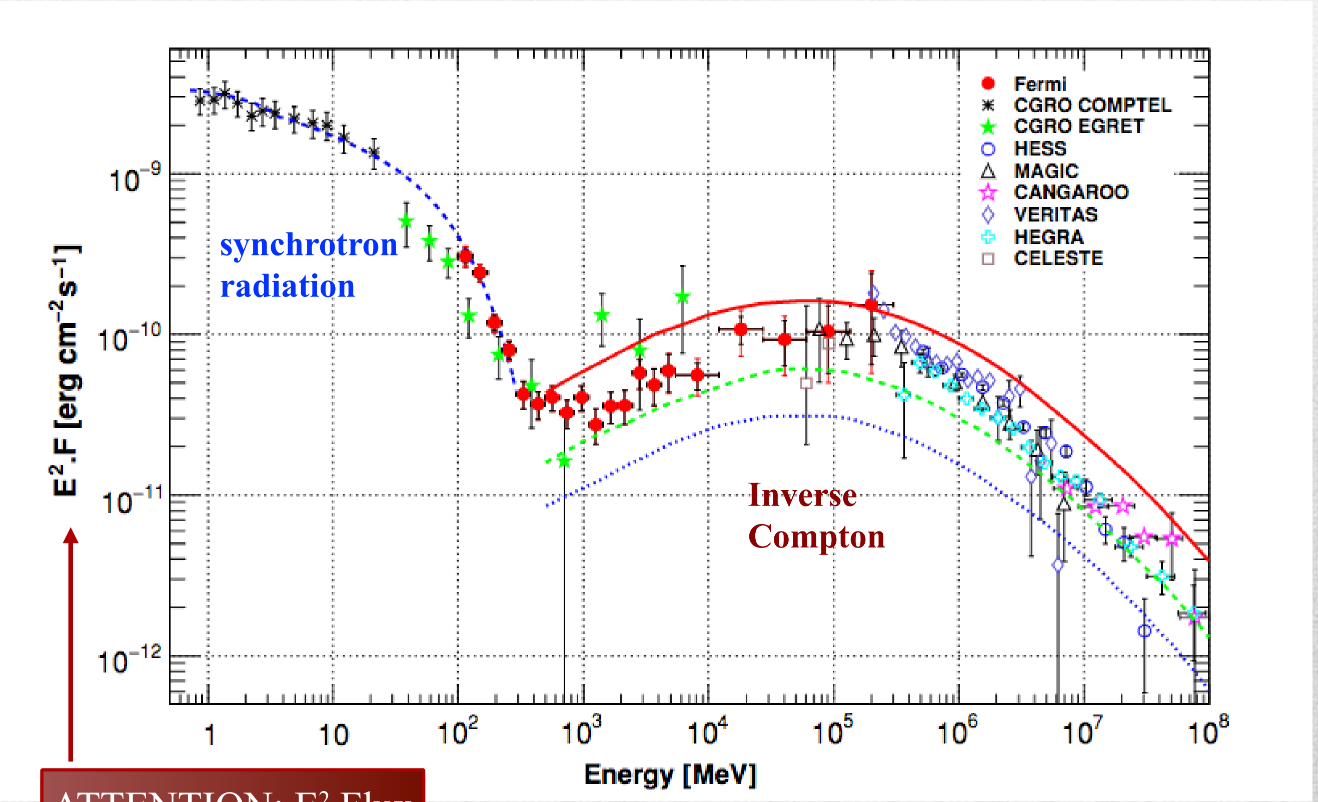
Gamma sources: The Crab nebula: a reference

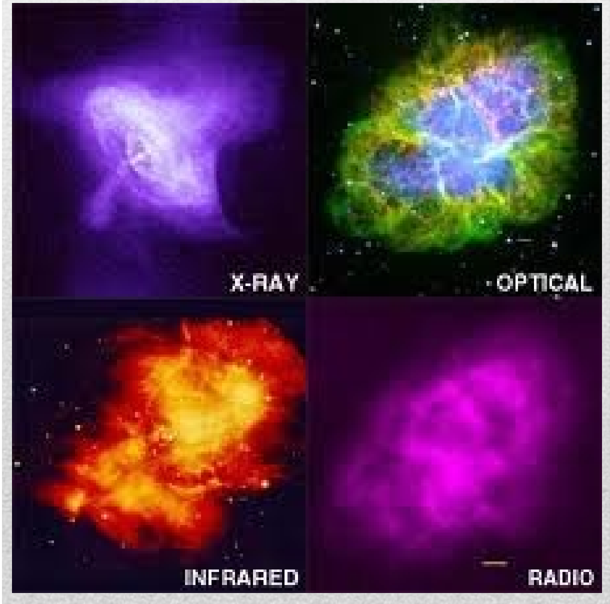
It is the remnant of a supernova observed in 1054, that was visible during the day for 6 weeks.

A fast rotating neutron star (PULSAR) is what remains of this supernova explosion : diameter of 20 km and rotation period of 30 tours/s.

The x-rays images show the acceleration regions (synchrotron radiation)

Particles are the reaccelerated in the shockwaves with the surrounding gas, producing TeV gamma rays (Inverse Compton mechanism)

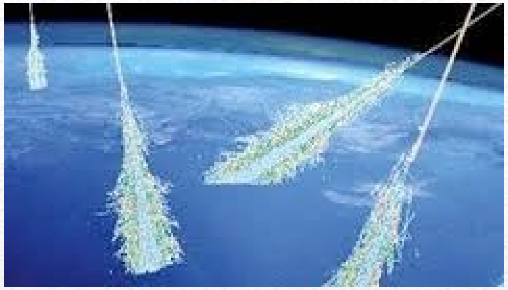


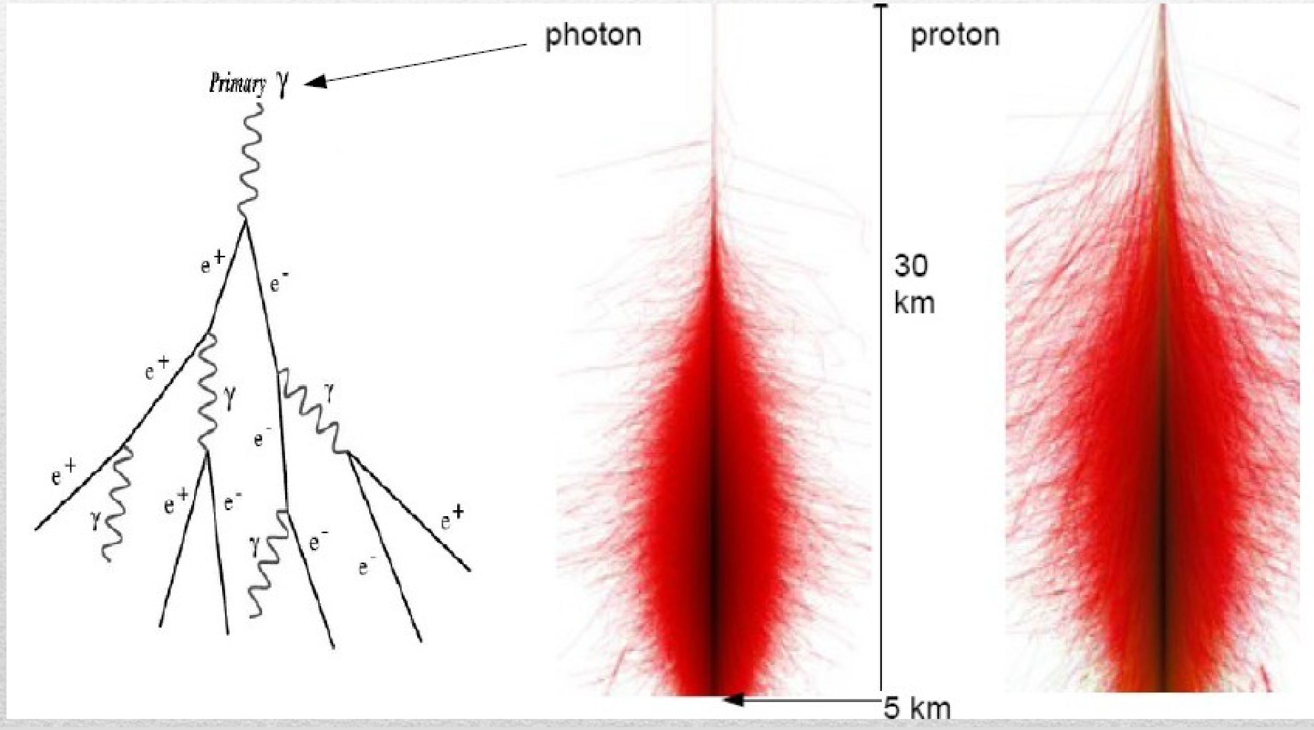


ATTENTION: E^2 Flux

Gamma Indirect detection

For E > 100 GeV gammas are detected through the electromagnetic showers created in the atmosphere



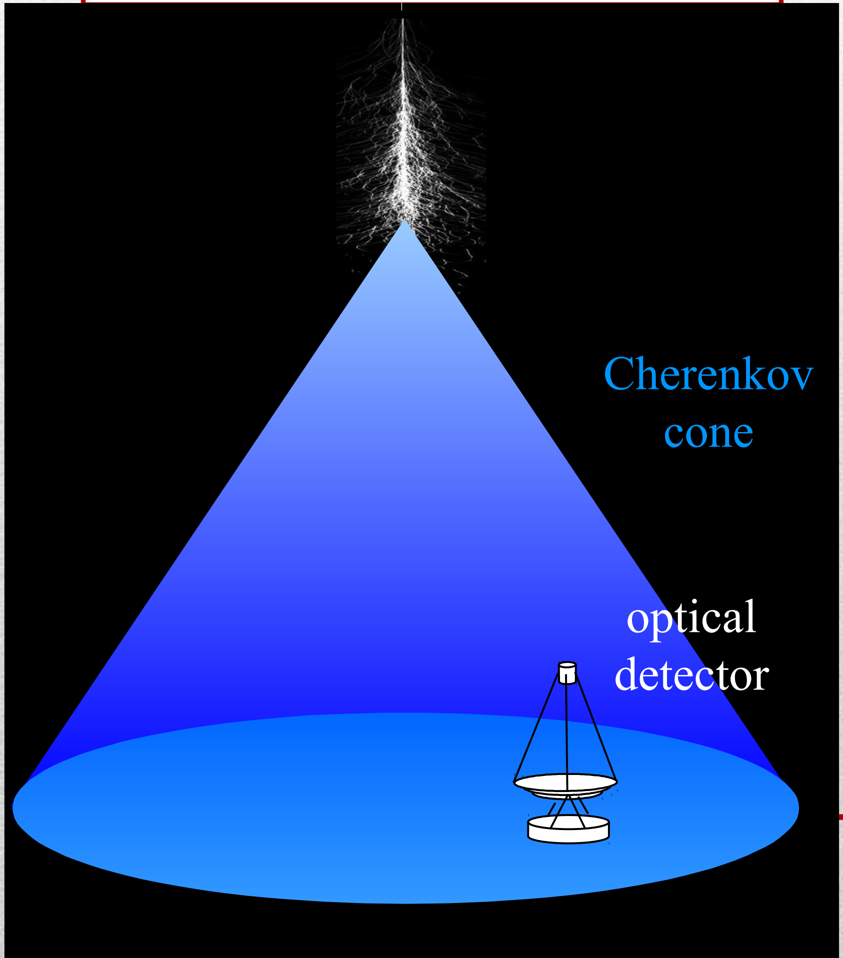


Showers produced by **gammas** are **much more symmetric and thin** in respect to showers produced by protons. This characteristics is used to differentiate gammas from protons.

Gamma Indirect detection

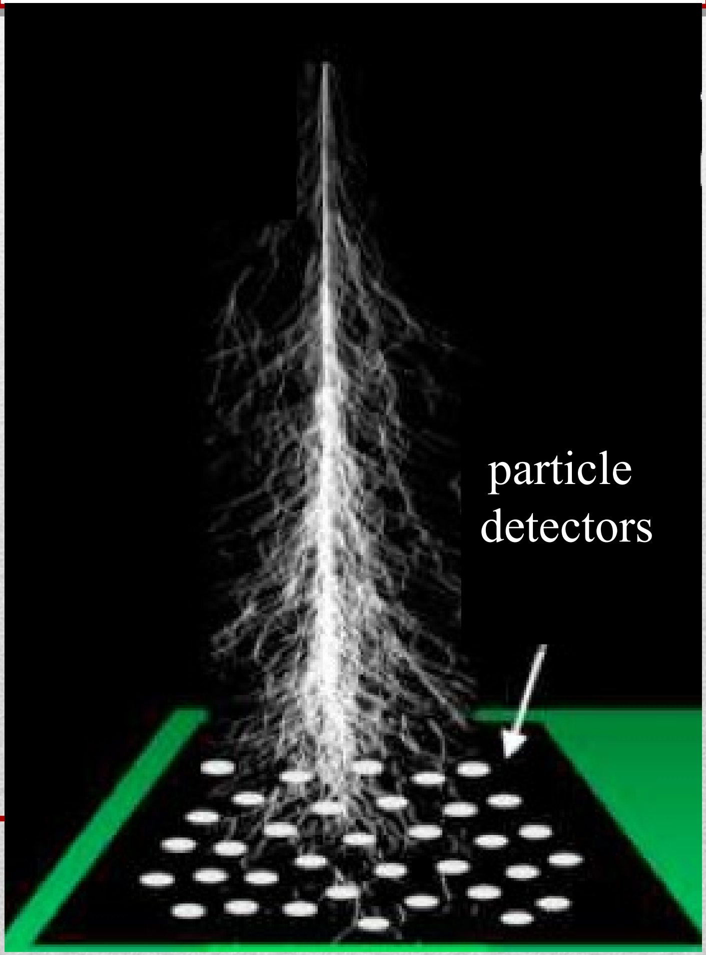
Imaging Air Cherenkov Telescopes

- high efficiency at E ~ 1-10 TeV
- angular resolution ~ 0.1°
- hadronic rejection power (>99%)
- small Field of View
- observations during clear nights



Air Shower arrays

- high efficiency at E > 100 TeV
- angular resolution ~ 0.2° -1°
- hadronic rejection power (~ 50%)
- large Field of View
- permanent observation

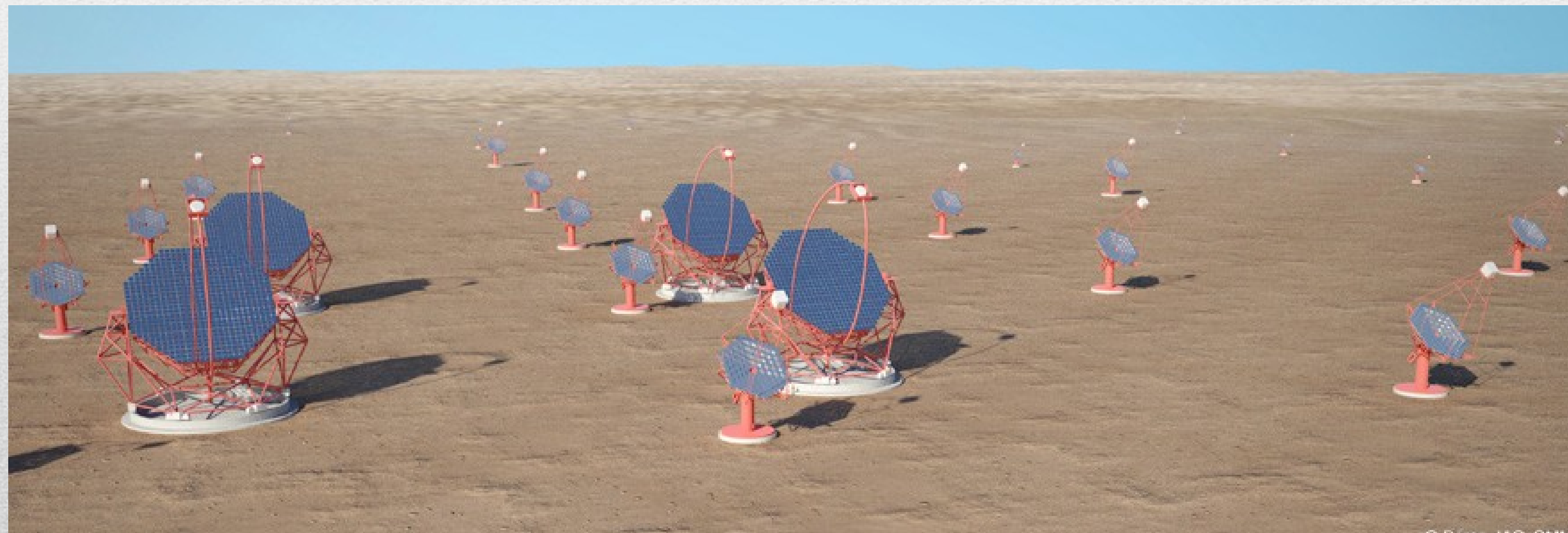


Gamma Indirect detection

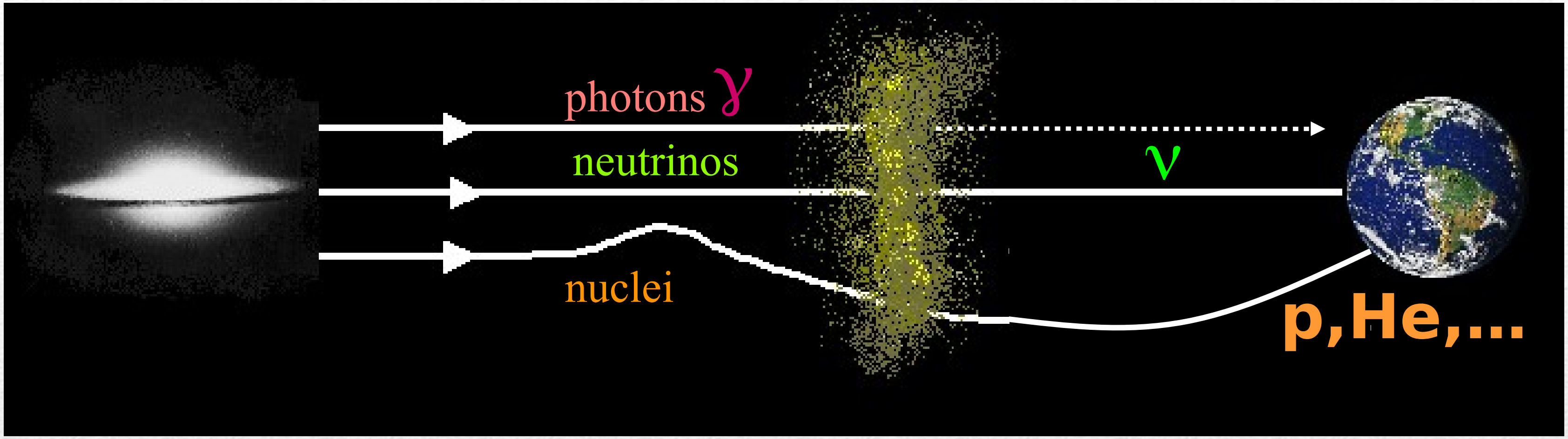
Imaging Air Cherenkov Telescopes (IACT)

cta
cherenkov telescope array

See Lecture about CTA this afternoon!



Which are the messengers?



$$p/A + p/\gamma \rightarrow \pi^0 + \pi^\pm + \ldots$$

$$\pi^0 \rightarrow \gamma\ \gamma \qquad \pi^\pm \rightarrow \nu_\mu\ \mu, \quad \mu \rightarrow \nu_\mu\ \nu_e\ e$$

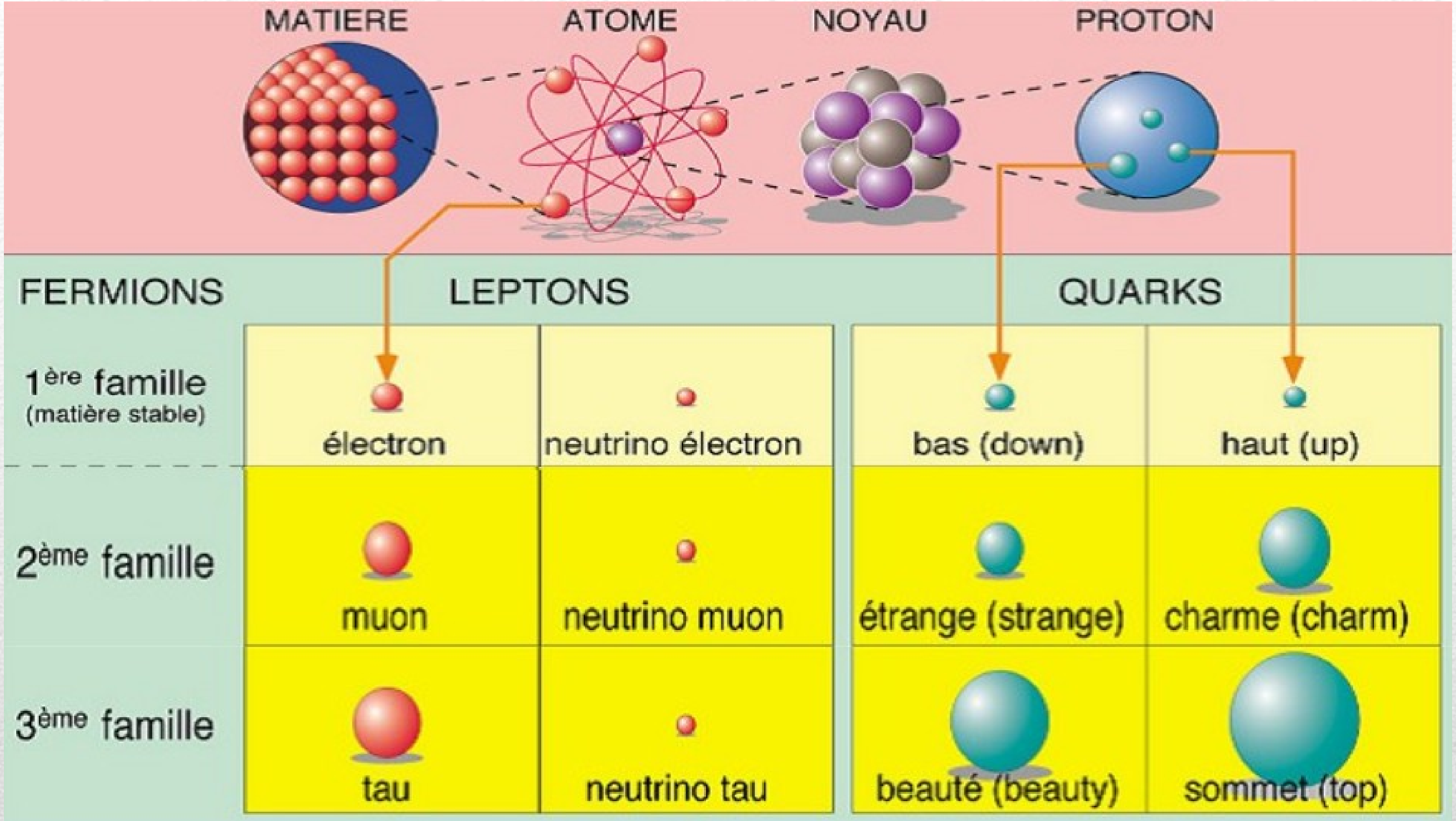
As TeV gammas, neutrinos are produced by hadronic interaction of high energy nuclei and protons in astrophysical sources

If astrophysical neutrinos are detected coming from a source, surely this source has produced cosmic rays (protons, nuclei)

BUT interaction probability in detectors is extremely small → We need HUGE detectors!

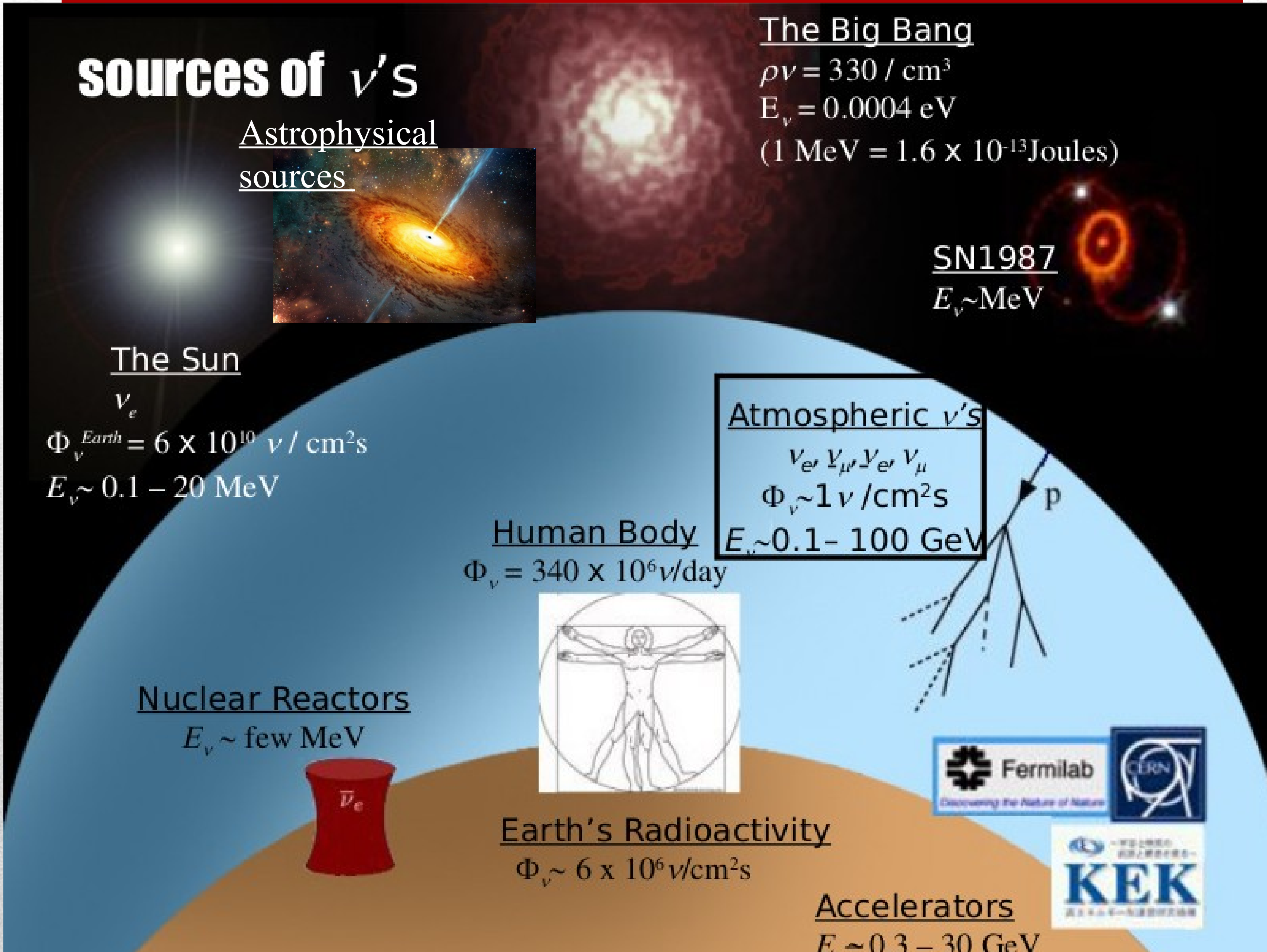
Only 1 neutrino over 10 bilions of neutrinos coming from the Sun and traversing the Earth, will interact!!

What are neutrinos?



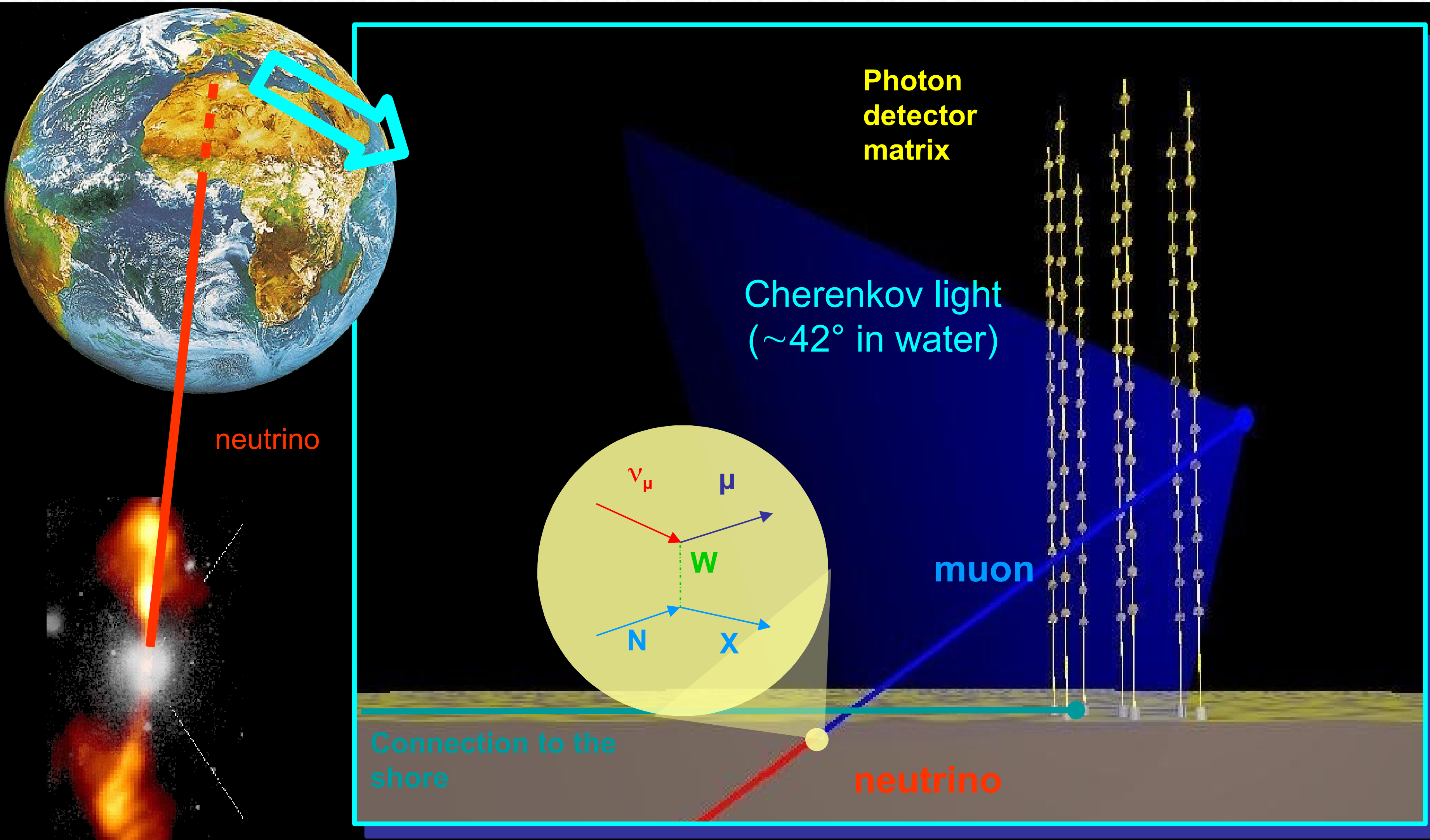
For details on research on neutrino properties see Lecture on:

- ***ORCA***
- ***SuperNEMO***


sources of ν's
Astrophysical sources
The Big Bang
$\rho\nu = 330$ / cm^3
$E_\nu = 0.0004$ eV
(1 MeV = 1.6 x 10^{-13}Joules)
SN1987
E_ν~MeV
The Sun
ν_e
$\Phi_\nu^{Earth} = 6 \times 10^{10}$ ν / cm^{2}s
E_ν~ 0.1 – 20 MeV
Atmospheric ν's
$\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$
Φ_ν~1 ν /cm^{2}s
E_ν~0.1- 100 GeV
p
Human Body
$\Phi_\nu = 340 \times 10^6 \nu$/day
Nuclear Reactors
E_ν ~ few MeV
$\bar{\nu}_e$
Earth's Radioactivity
Φ_ν~ 6 x 10^6 ν/cm^{2}s
Fermilab
CERN
KEK
Accelerators
E_ν~ 0.3 – 30 GeV

How to detect astrophysical neutrinos?

Use the Earth as detector!!



principal interaction channel: ν_μ interacts with matter creating a relativistic muon

Neutrino telescopes in the World

ANTARES & KM3NeT

BAIKAL

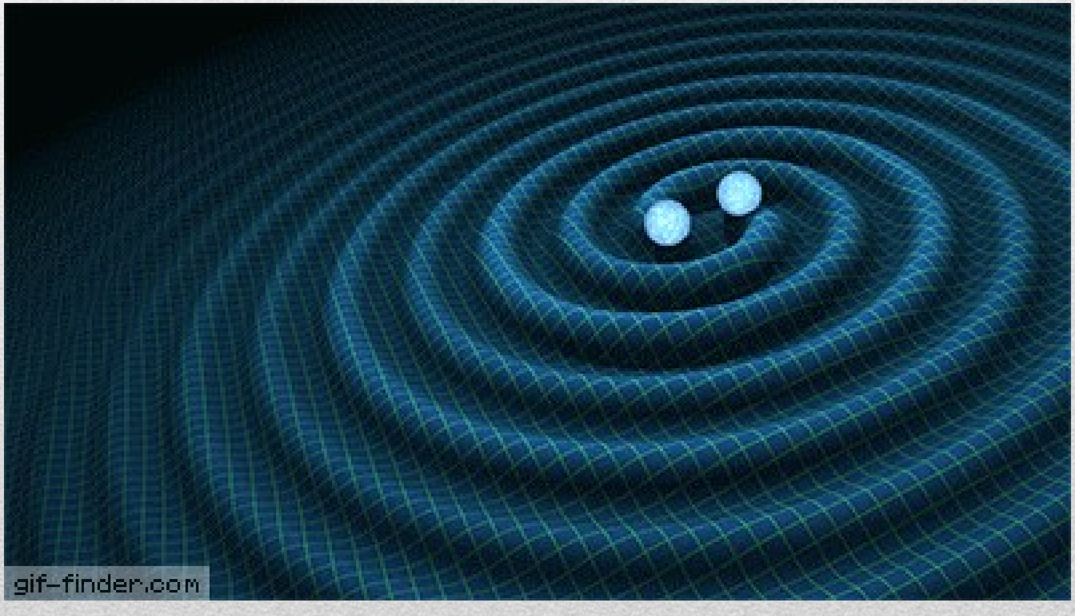
See Lecture on ANTARES and KM3Net this afternoon!

IceCube

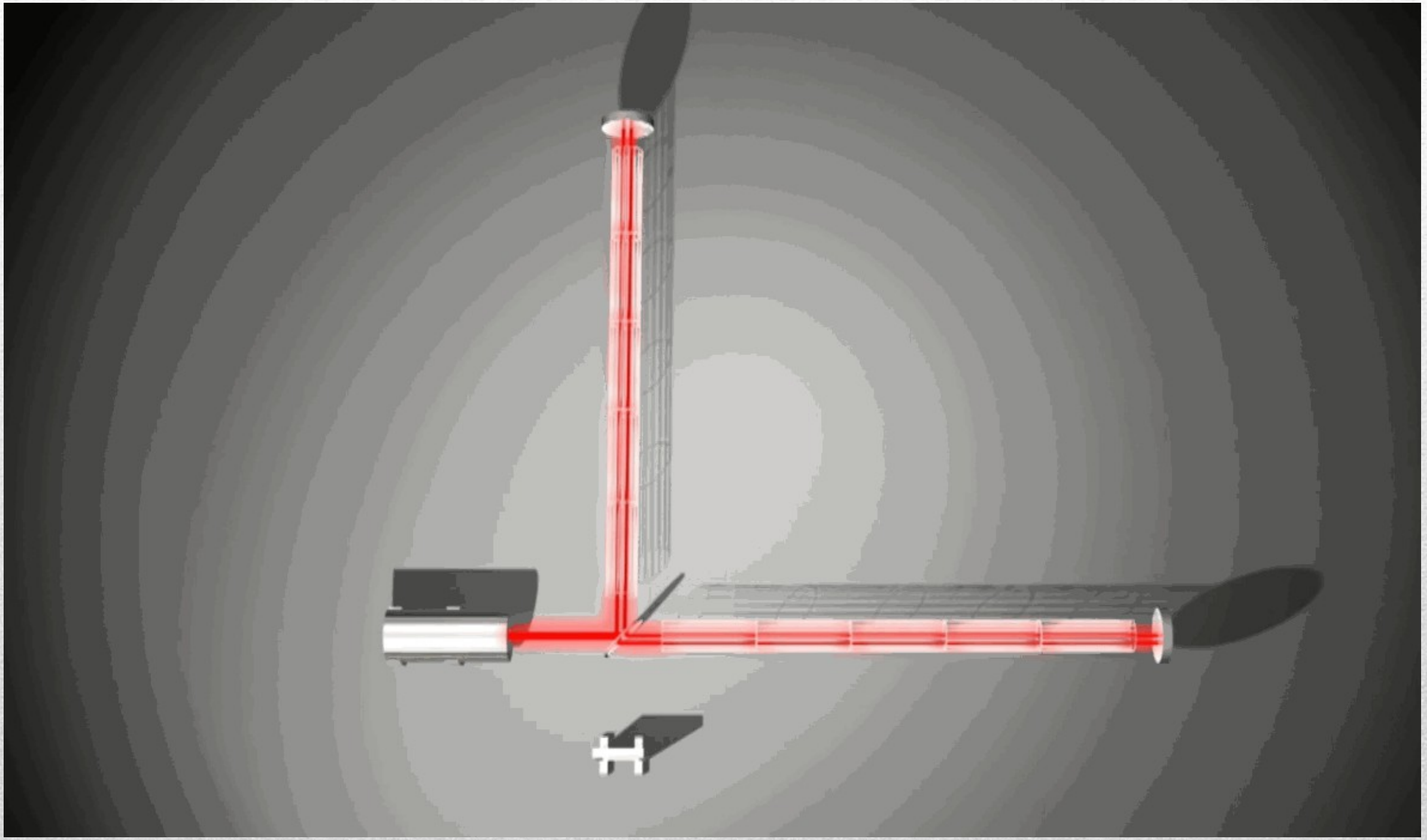
Are there other cosmic messengers?

Gravitational waves

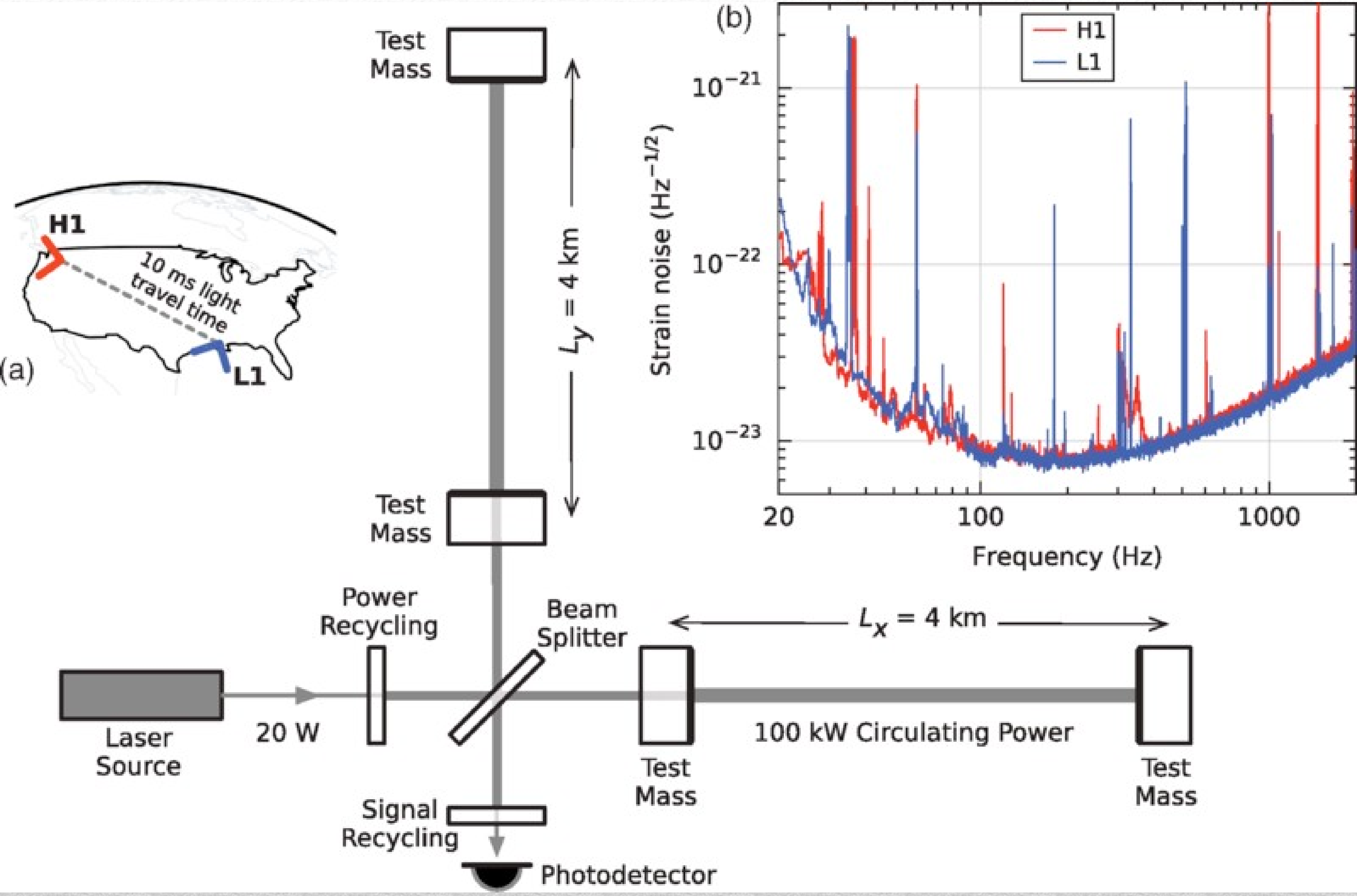
- 'ripples' in the fabric of space-time caused by energetic processes in the Universe (collision of black holes, neutron stars etc.)
- Albert Einstein predicted the existence of gravitational waves in 1916 in his general theory of relativity.



How can we detect GW?



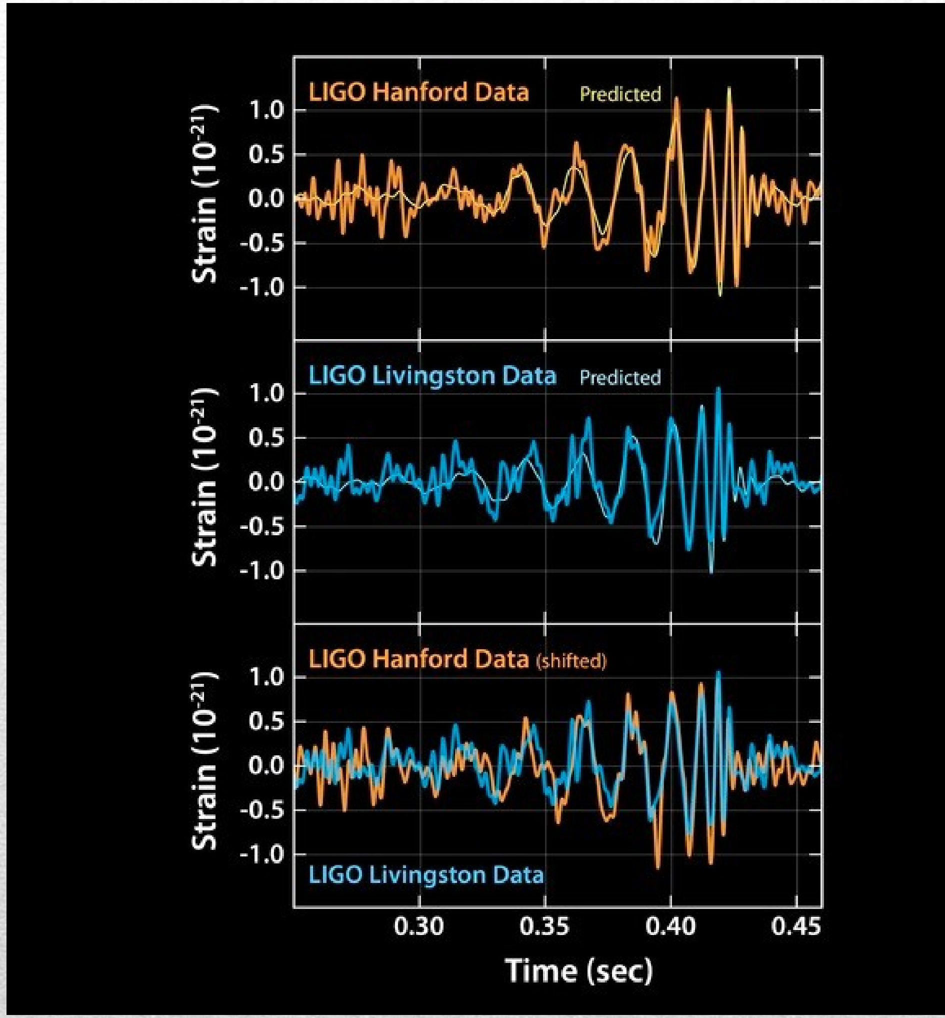
LIGO interferometer



Discovery of gravitational waves

September 14, 2015

LIGO interferometer for the first time senses distortions in spacetime itself caused by passing gravitational waves generated by **two colliding black holes** nearly **1.3 billion light years away**!



Conclusions

- **Astroparticle physics is an exiting field between Astrophysics and Particle Physics**
- **we want understand the origin and the role of cosmic relativistic particles**
- **we want to explore the most extreme and energetic events in our universe**
- **using different and new probes we can open new windows on the universe allowing new discoveries and better understanding of the universe**