Experiments in astroparticle physics

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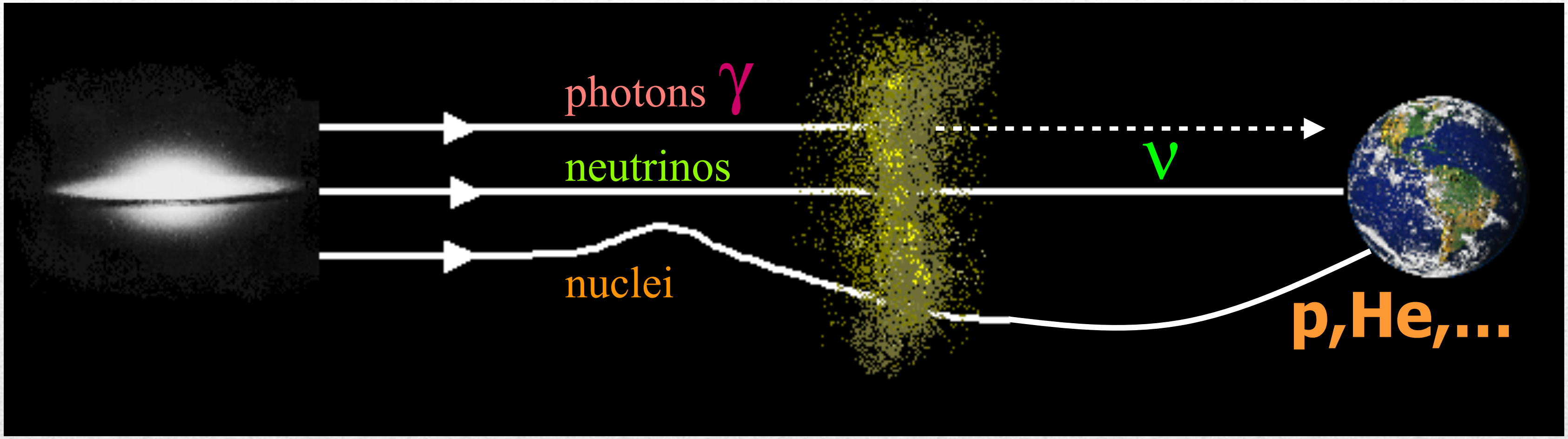
Which are the messengers?

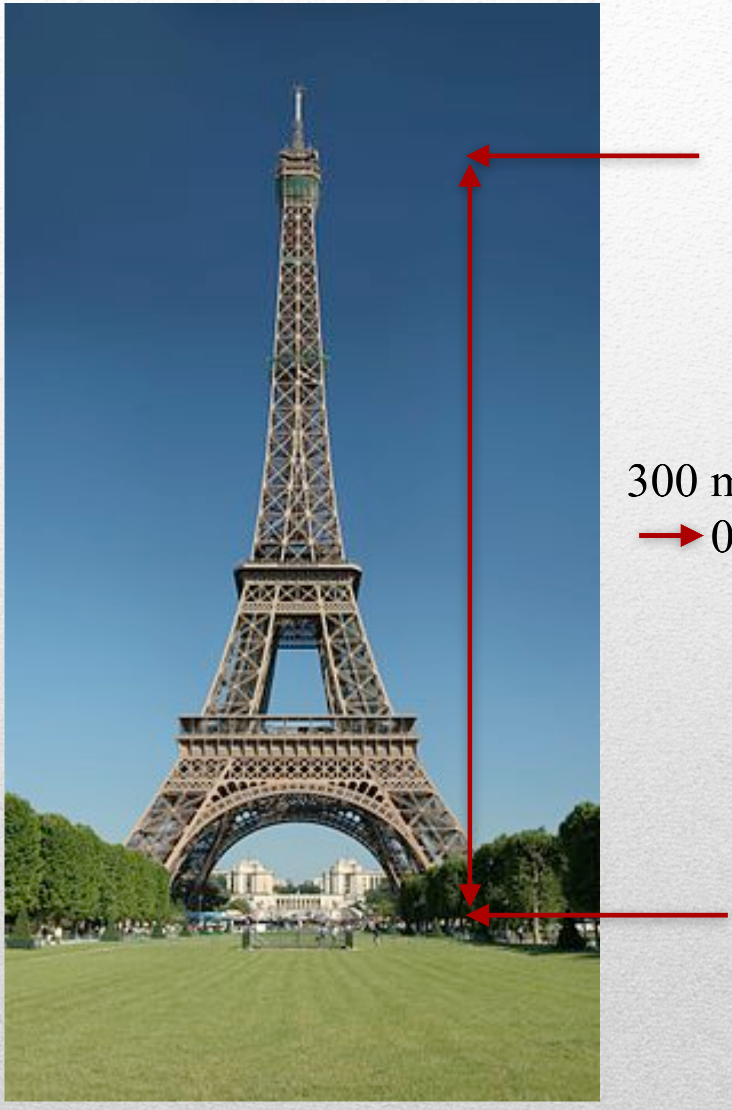


- The nuclei can interact with the interstellar medium (ISM) ,cosmic microwave background (CMB) and can be deviated but magnetic fields (galactic and intergalactic)
- Photons can be absorbed by the ISM and CMB
- Neutrinos are not absorbed and deviated
- Gravitational Waves!

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 **see also this afternoon lecture by O. Angüner**
- Astrophysical neutrinos **see also this afternoon lecture by M. Lincetto**
- Gravitational waves

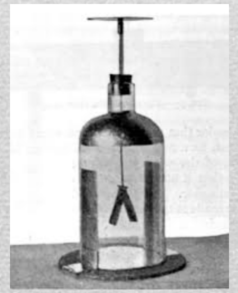
A bit of history: first evidence of CR



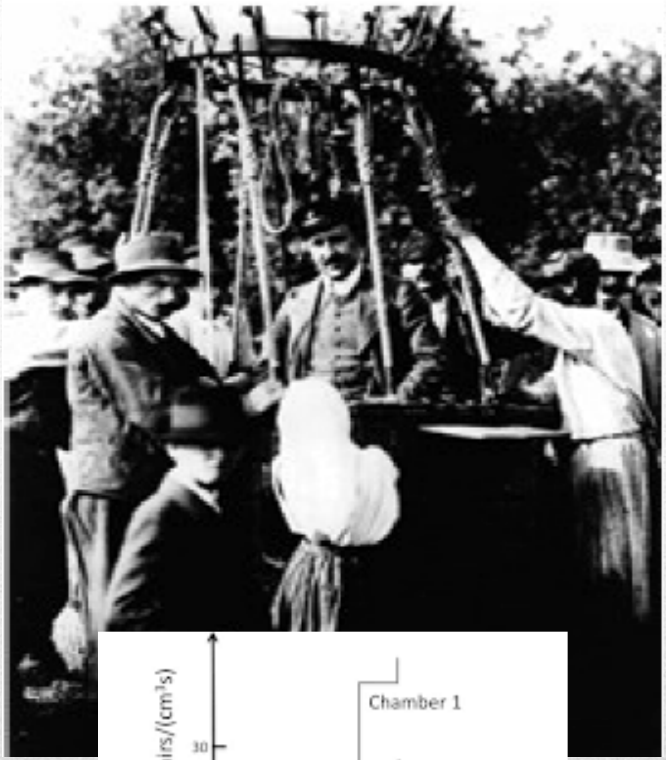
1910:

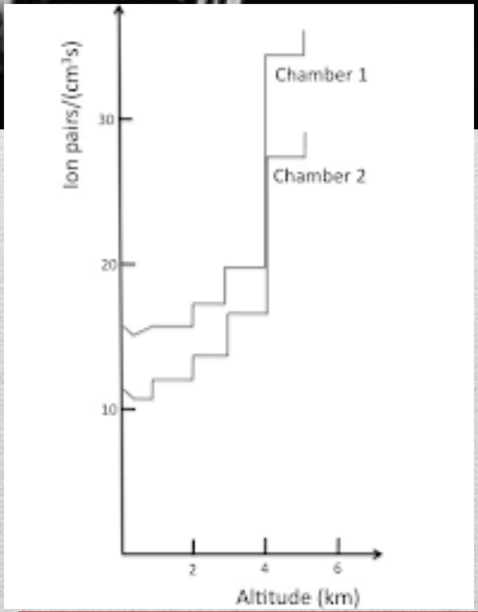
- ***Theodor Wulf*** measured air ionisation as a function of altitude.
- The ionisation decreases slower as a function of altitude than expected if the cause is coming only from radioactivity of the ground

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

- V.H. 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 $\rightarrow$ 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

↓

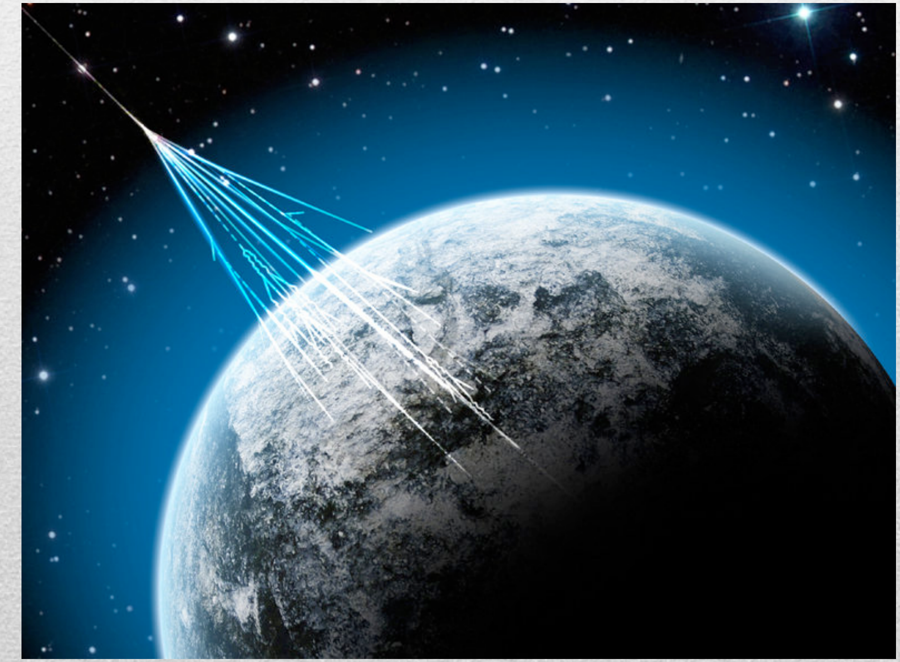
Cosmic Rays are charged particles !

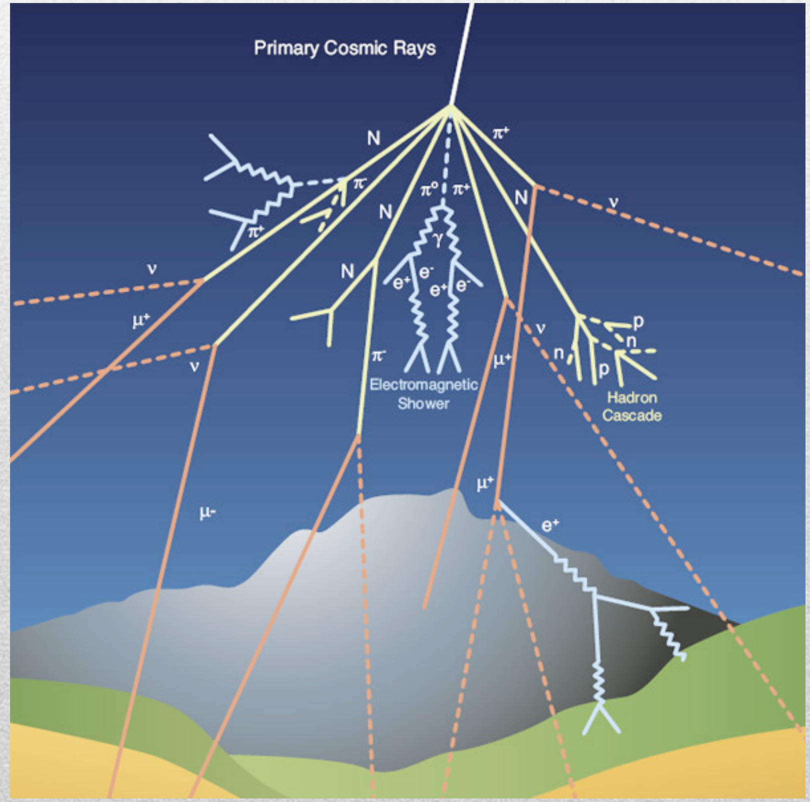
Research project on CRs angular distribution

A bit of history: Auger experiment


Pierre Auger (1899-1993)

- 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.

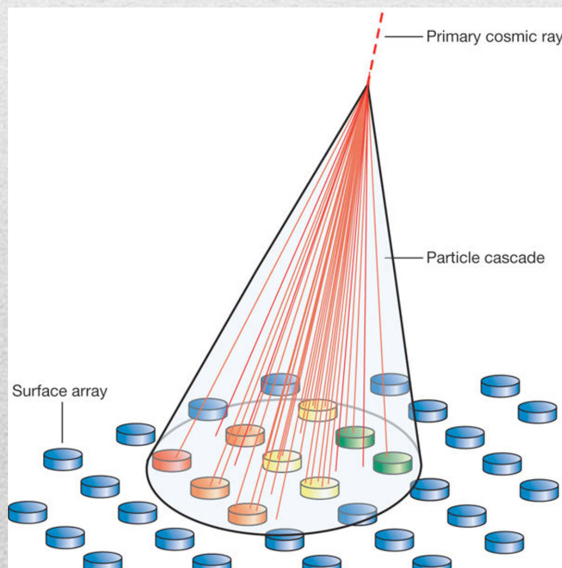




A bit of history: Auger experiment

ACADÉMIE DES SCIENCES - SÉANCE DU 8 JUIN 1938

	1ère partie			2ème partie		3ème partie			
Nombre de compteurs	3	3	3	2	3	2	2	2	2
Distance extrême en mètres	0,20	2	5	1,3	1,3	2	2	2	2
Ecran de plomb (cm)	-	-	-	-	-	0	5	10	15
Coïncidences par heure (fortuites déduites)	6,7	2,1	0,7	3,4	1,5	4	0,7	0,5	<0,2



$$\frac{dE}{dx}(Pb) = 30\ \ MeV / cm \rightarrow in\ 15cm\ \Delta E = 450\ \ MeV$$

S(detector)=150 cm^2
efficiency counter= 0.003/cm^2 → E_primary_min ~100 GeV
Total surface covered = $2x10^5$ cm^2

Research project on Auger experiment

A bit of history: particle physics with CR

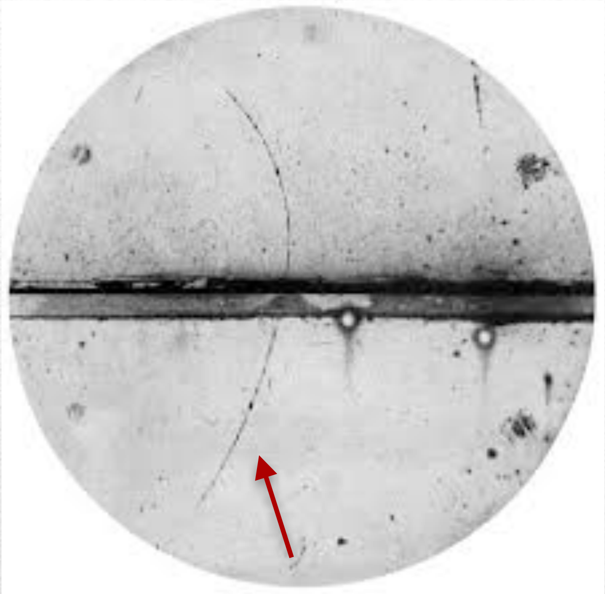
- Since 1930s experimental techniques for detection and measurement of electric charge, mass, lifetime of particles become more refined.

- **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

Research project on cloud chamber

First discoveries in particle in physics using Cosmic Rays!

Charged Cosmic rays

Primary charged cosmic rays composition:

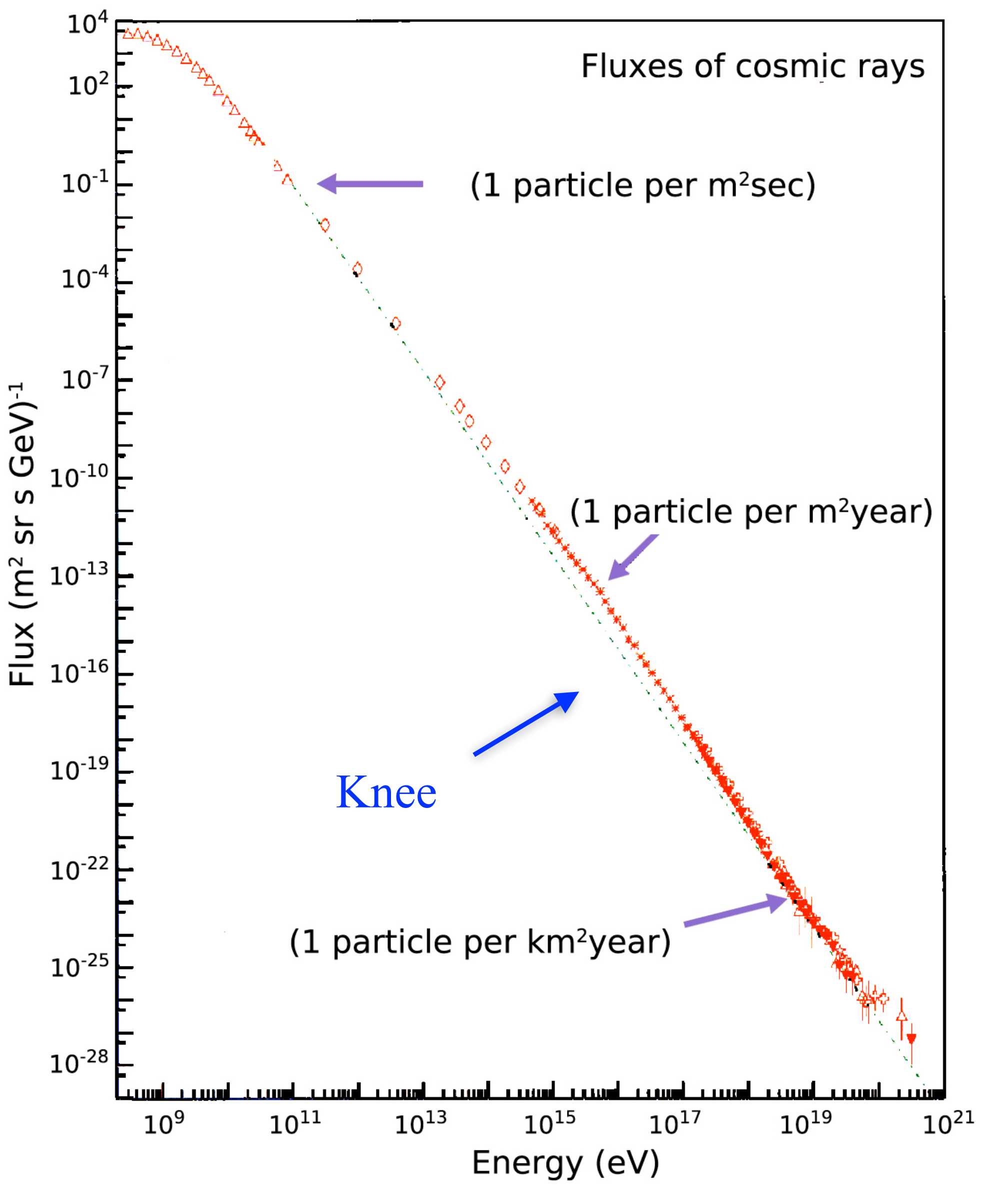
99 % nuclei
- 89% protons
- 10% helium nuclei
- 1% heavier nuclei

1% electrons

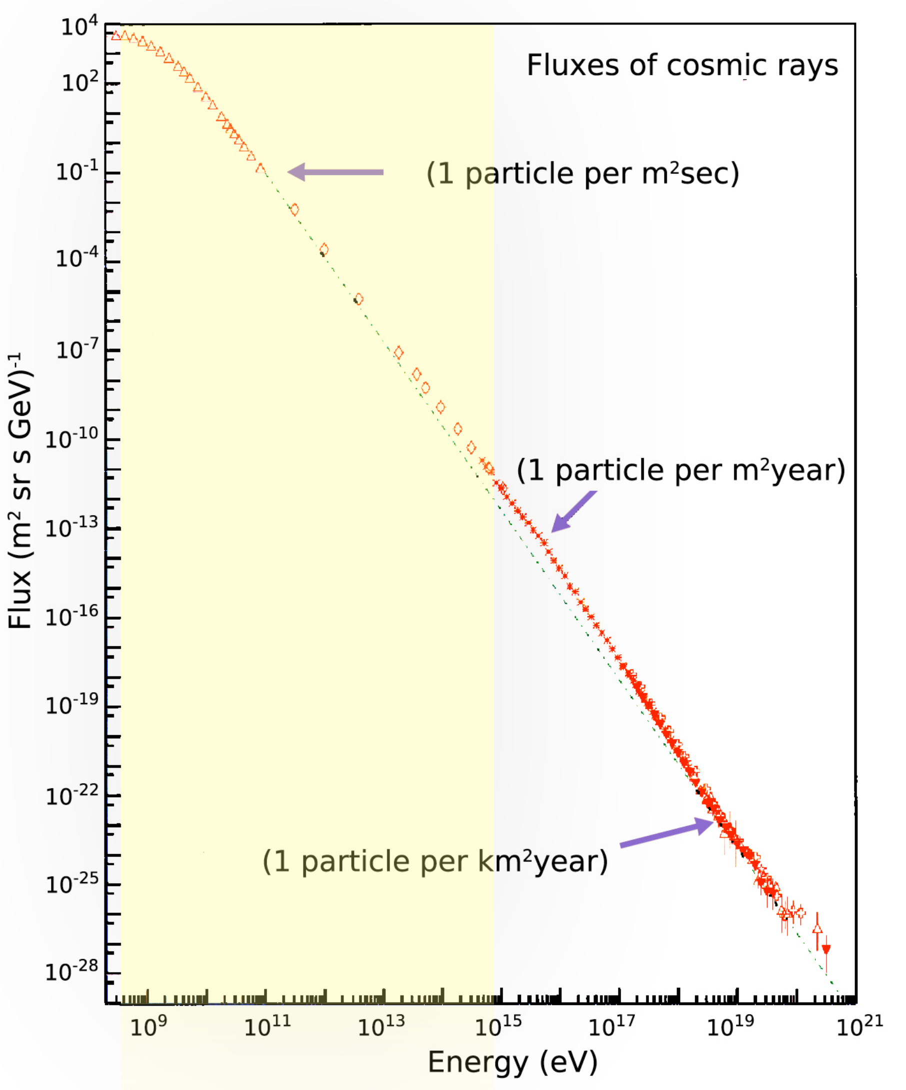
0.15% photons

Flux proportional to $E^{-2.7}$ pour $E<10^{15}$ eV

How can we detect CR?



Direct detection

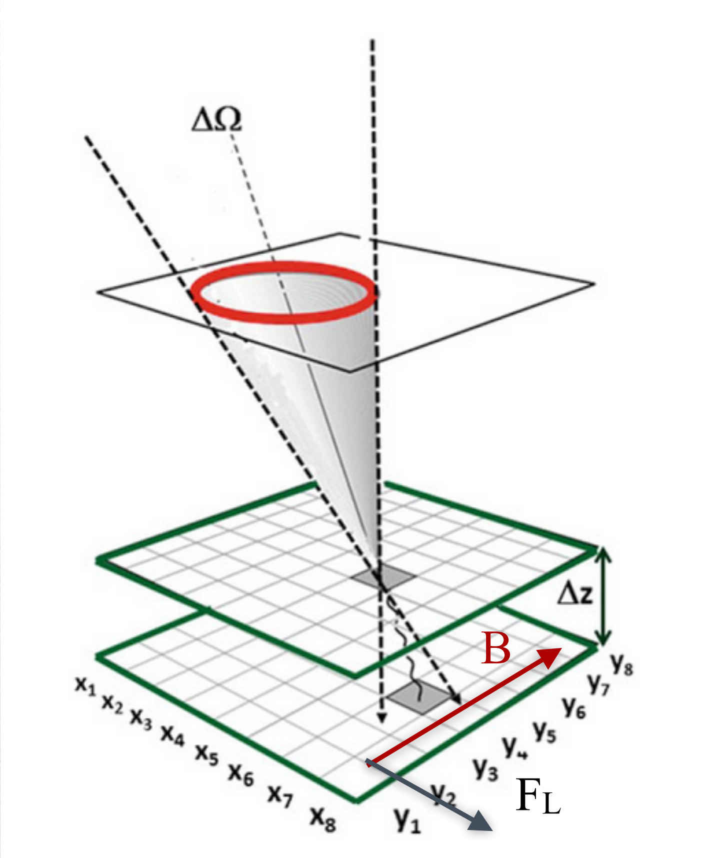


($E<10^{15}$ eV)
Stratospheric balloons, satellites

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

- the detector must:
  - measure the flux
  - identify particles
  - measure their energies

- **A Toy Telescope for primary Cosmic Rays:**
  - 2 layers of counters separated by 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: $|t_1 - t_2| \leq T$ 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*) in x are required to measure particle deflection due to B: combination of the magnetic field and tracking detectors form a *magnetic spectrometer*

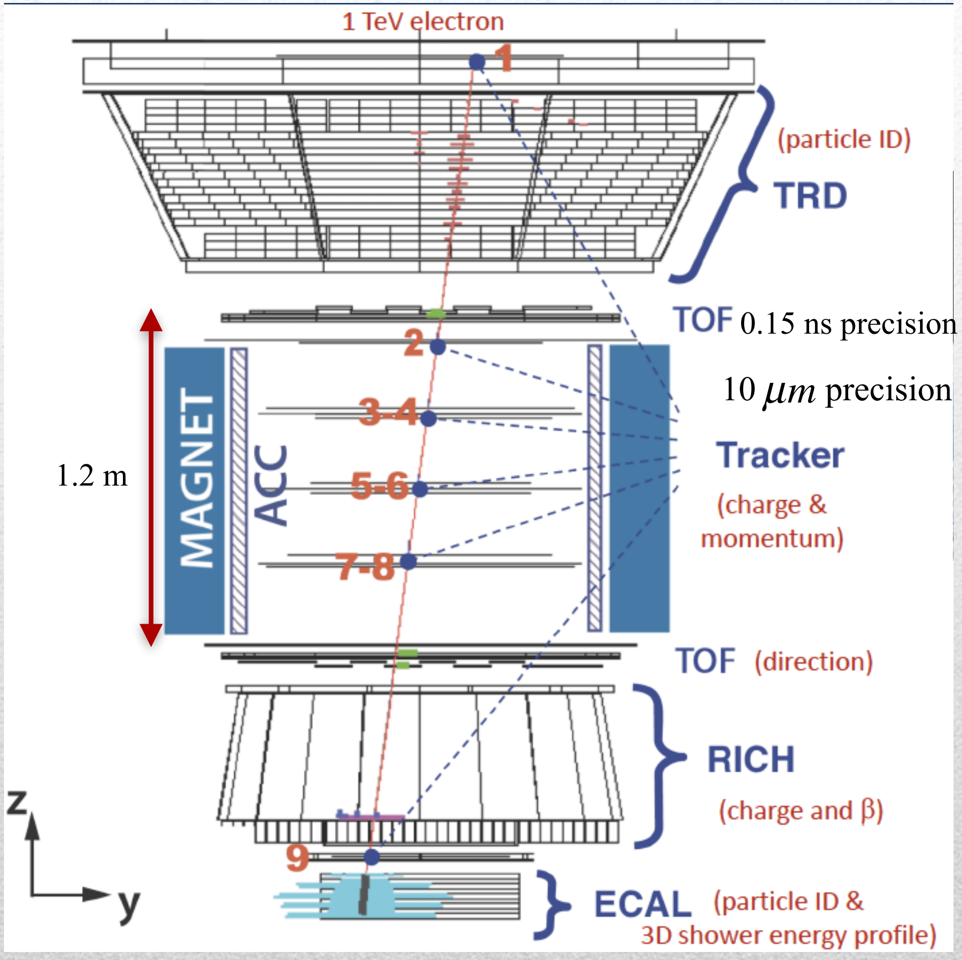


Direct detection: satellites

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

AMS-02

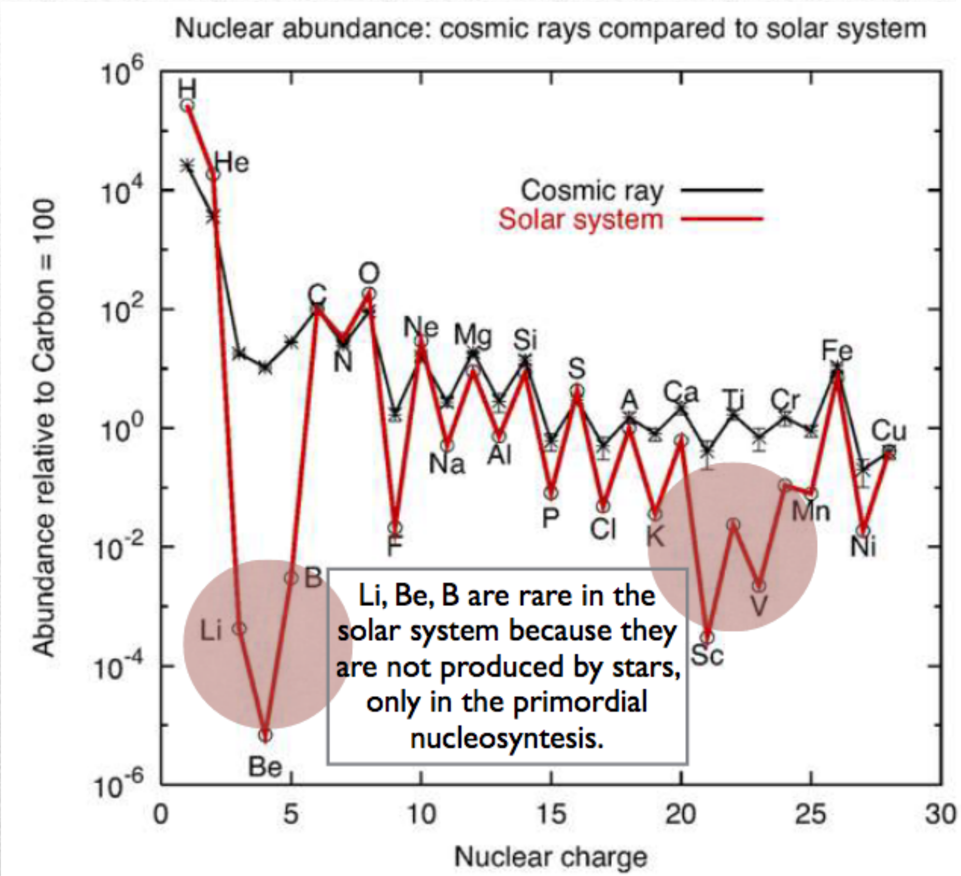
Alpha Magnetic Spectrometer

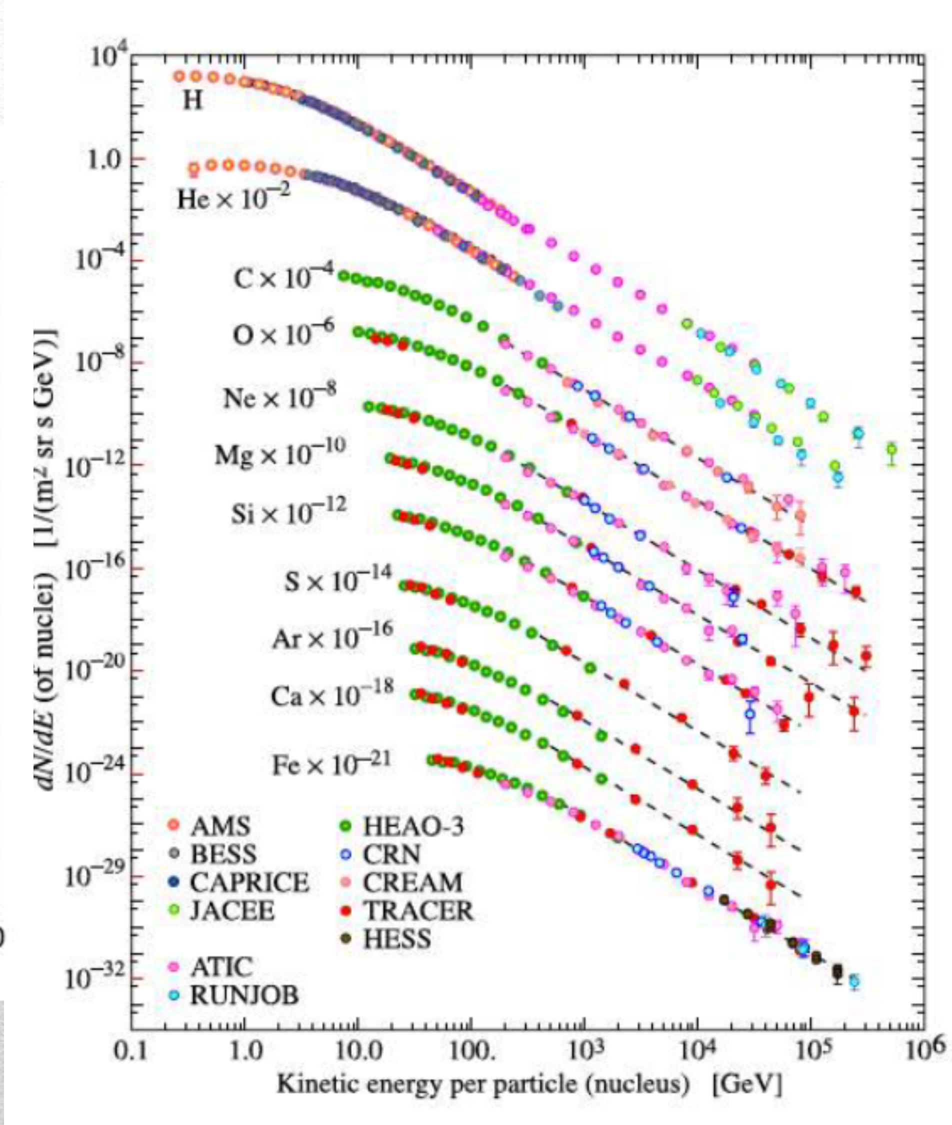


- since 2011 : 90 billions of primary CR have been detected
- Energy between 0.5-500 GeV

Cosmic rays composition

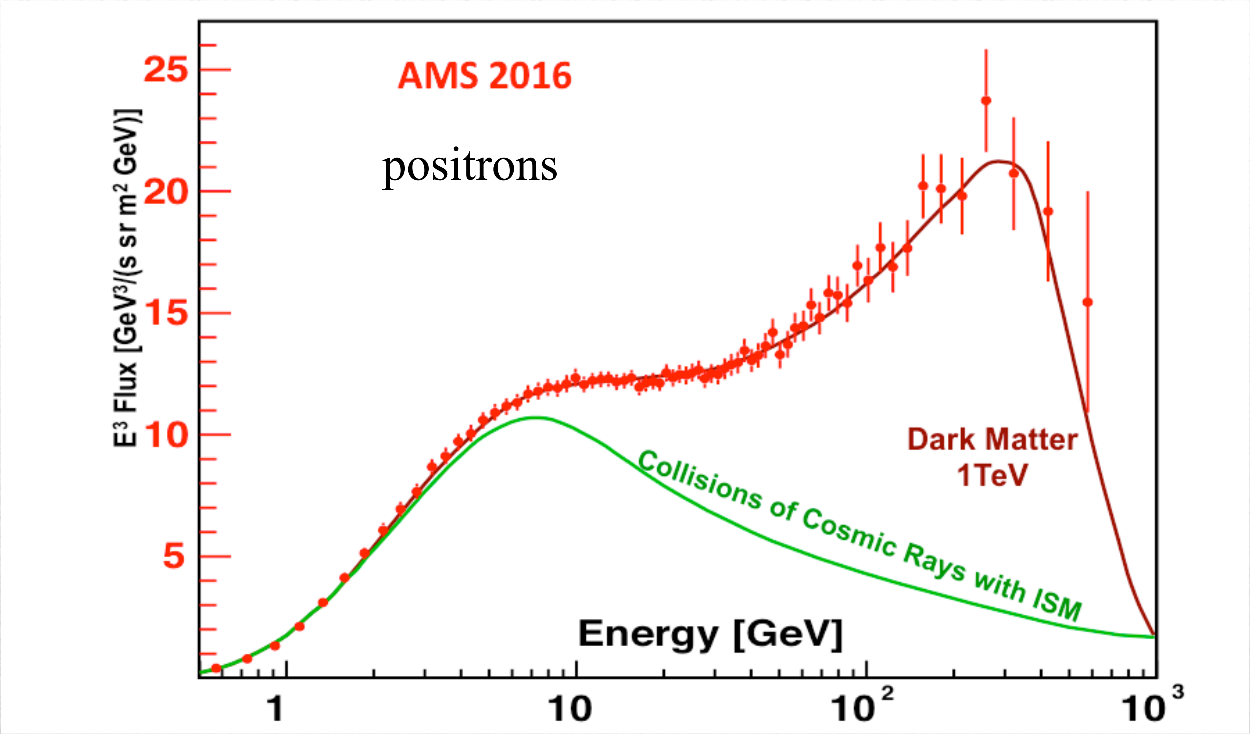
CR composition similar to Solar one





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

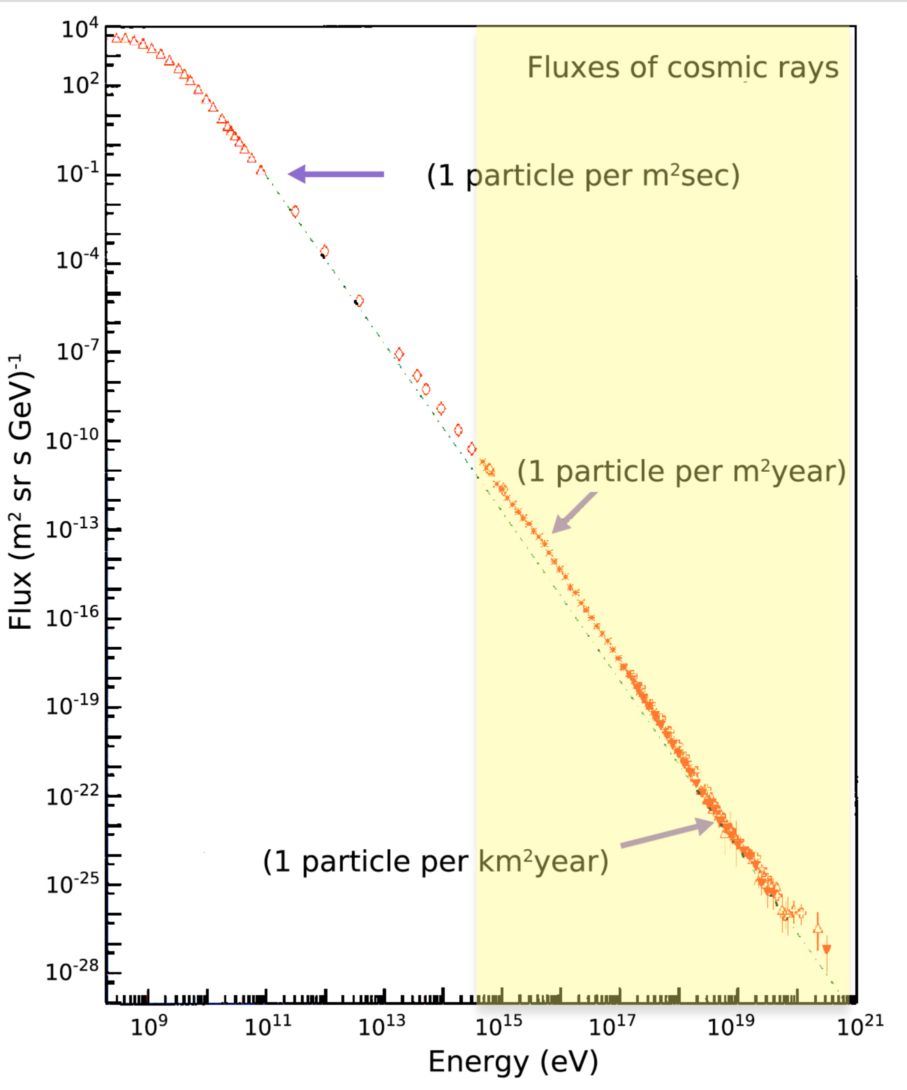
Antimatter measurements by AMS-02



Possible explanations:

- Dark Matter annihilation (Wimp with mass ~ 1 TeV)
- positrons created in pulsar wind (nearby pulsars)

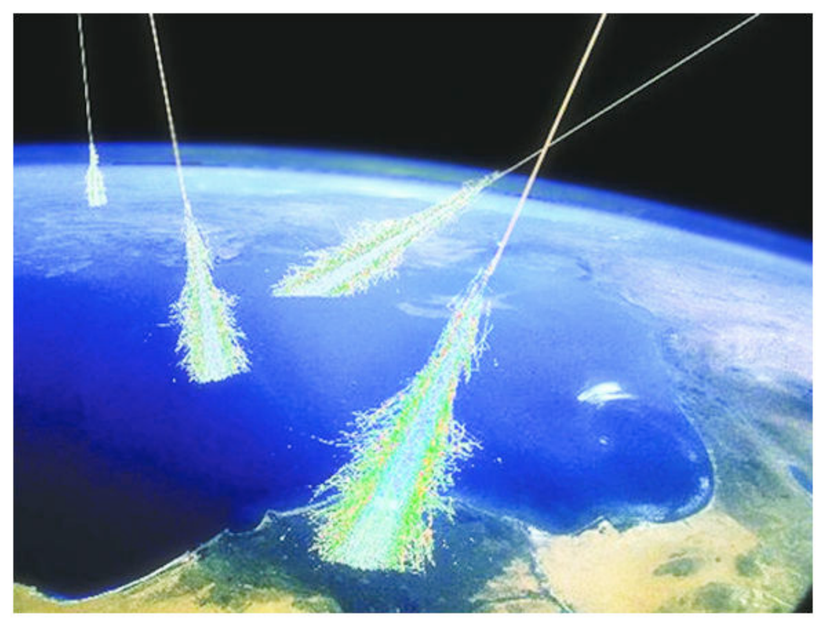
Indirect detection



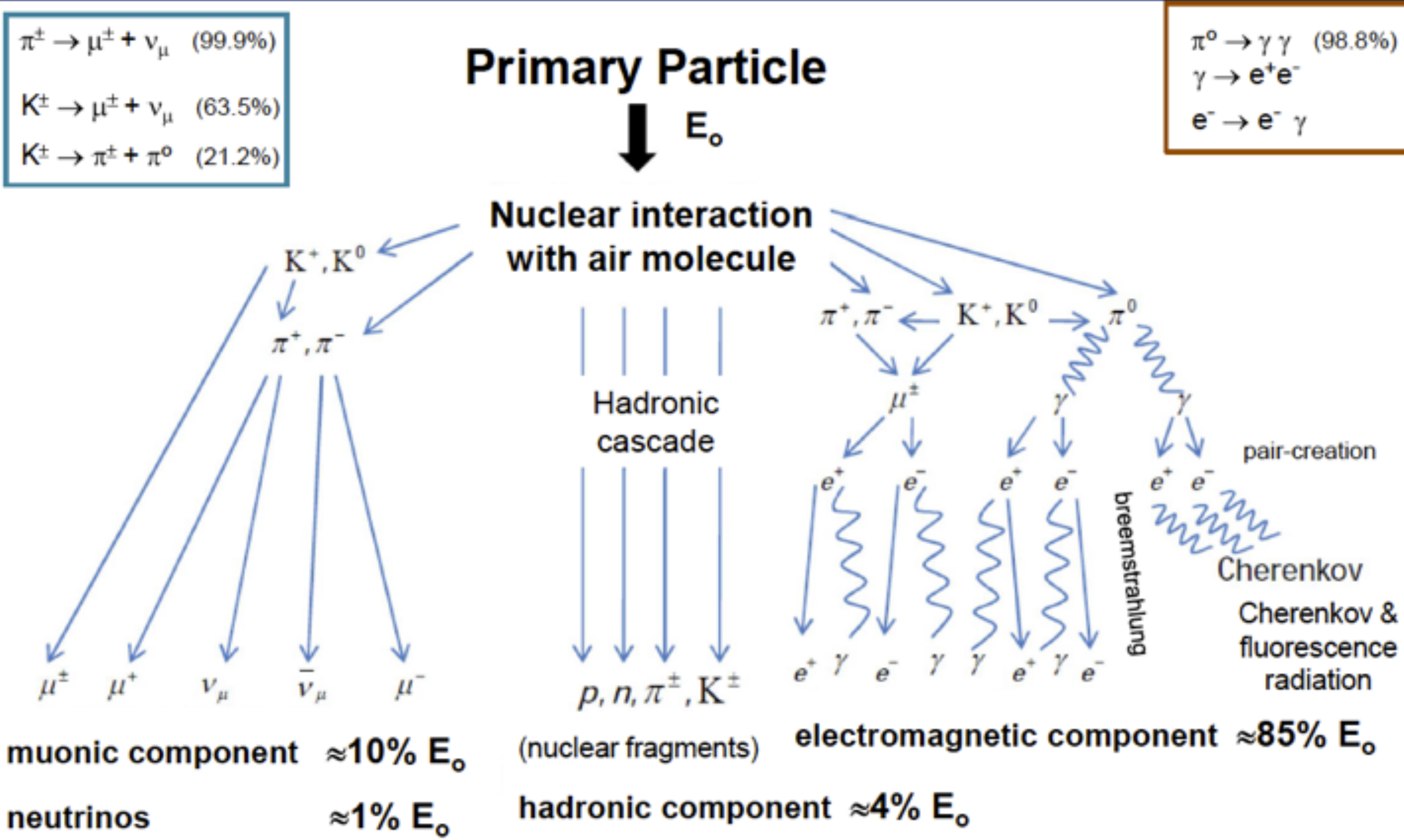
($E>10^{15}$ eV)
Detectors on ground

- to detect higher 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



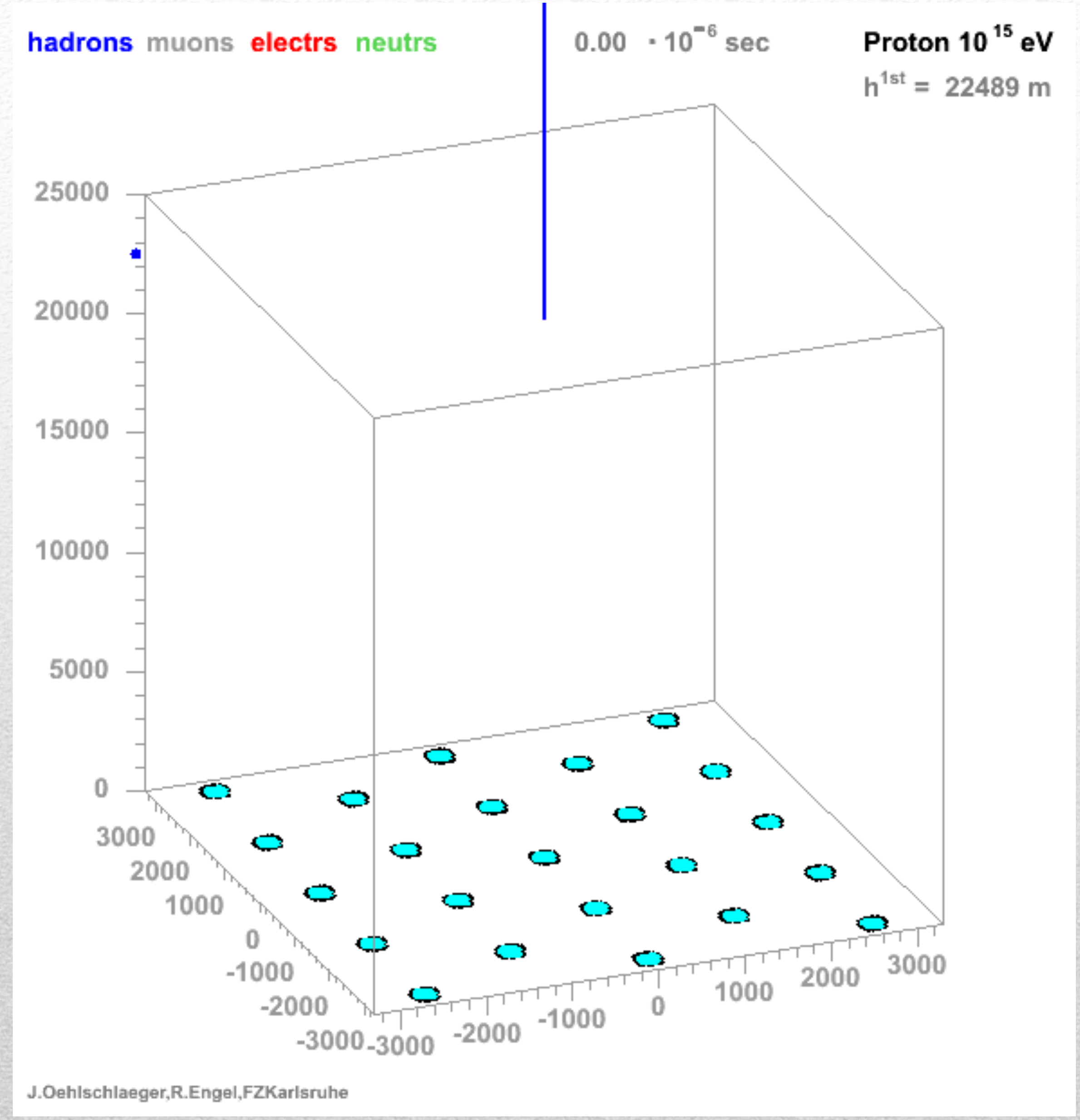
Extensive Air Shower



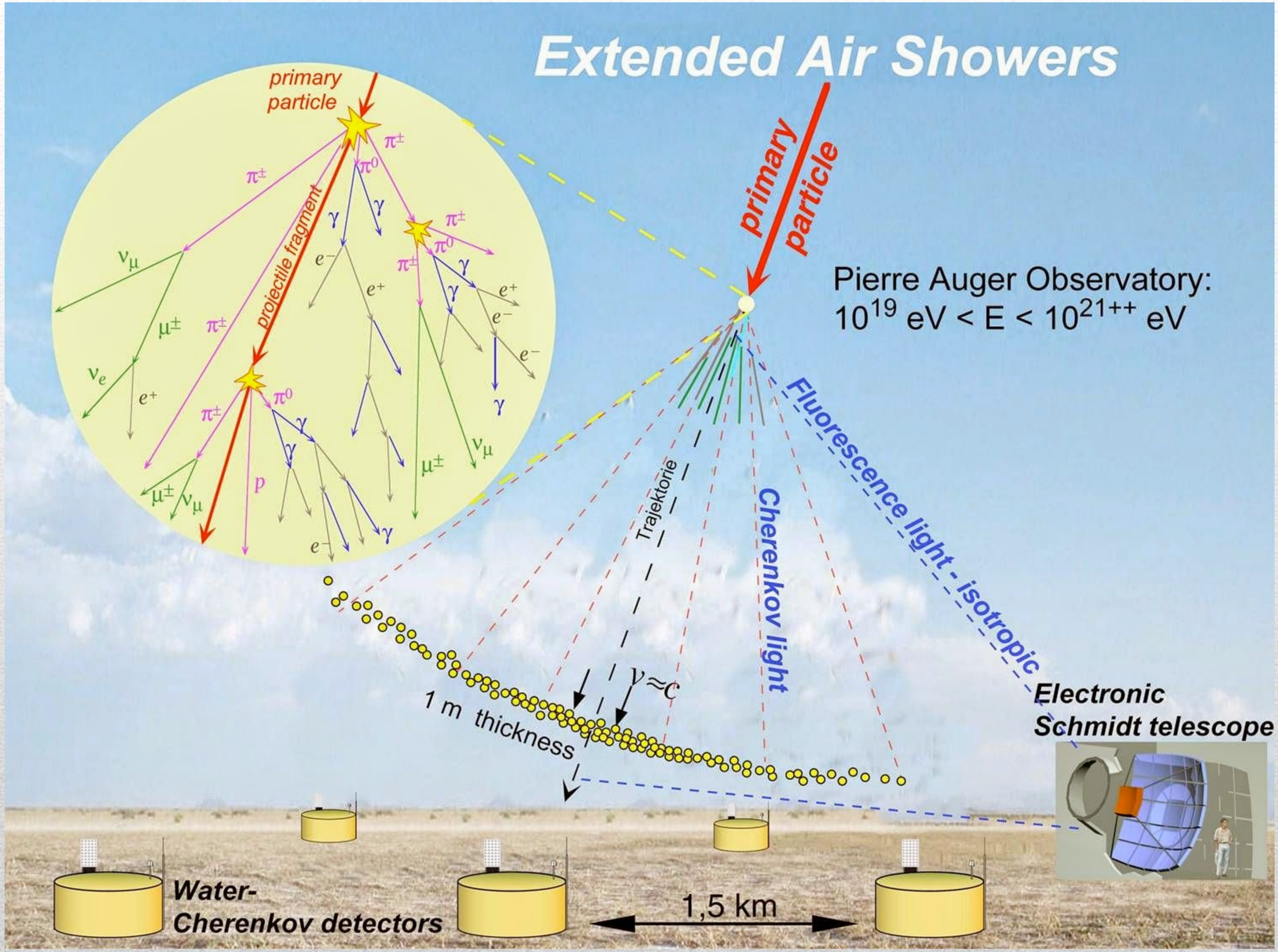
$E_0 = 10^{18}$eV → 10^{10} particles on a surface of few km^2

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

Extensive Air Shower

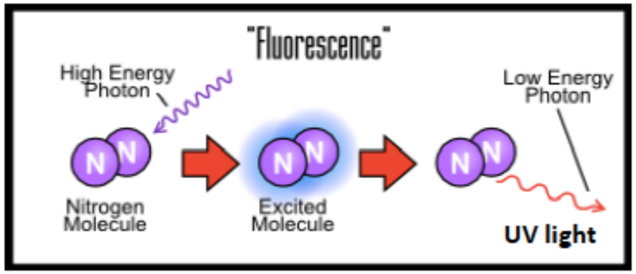


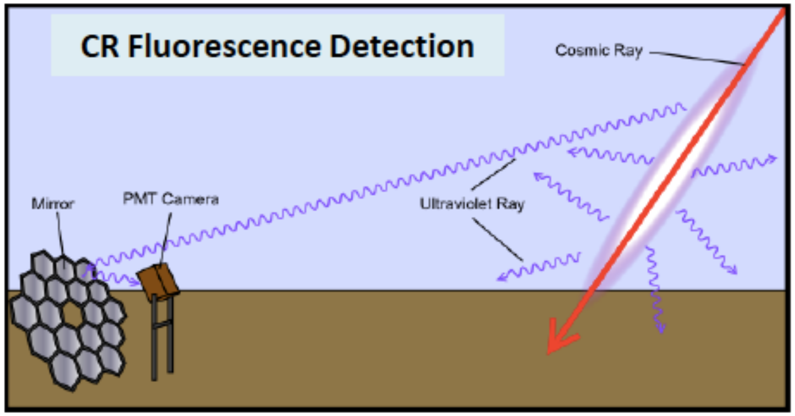
Detection of Air Shower

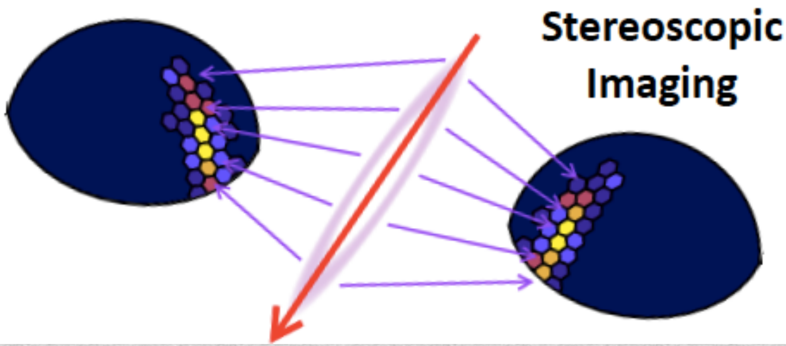


Detection techniques

Shower Longitudinal Profile

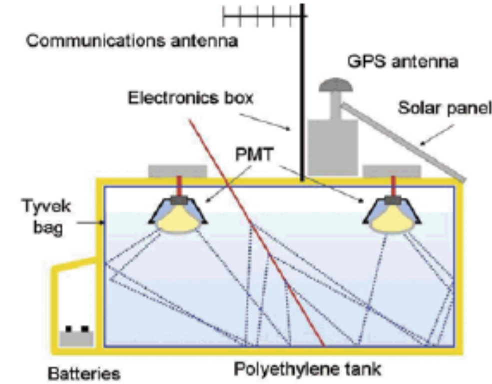






Lateral Distribution of Particles at Ground

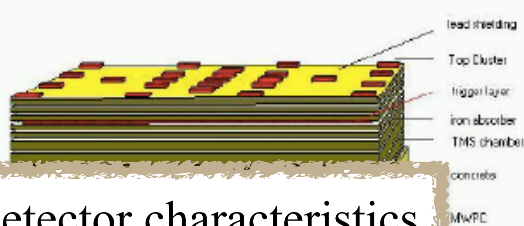
Water Cherenkov stations



Scintillators

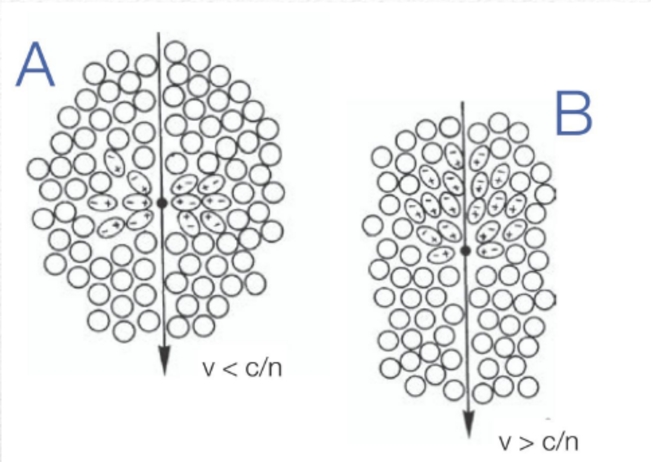
e/γ detector: liquid scintillator + light collector + PMT

Muon detector: plastic scintillator shielded (iron) + PMT



Research project on detector characteristics

Cherenkov effect



The Cherenkov effect is happening when a charged particle moves at a speed higher than the speed of light in the medium.

v>c/n

n =refractive index

$$\cos\vartheta_C = \frac{1}{\beta n}$$

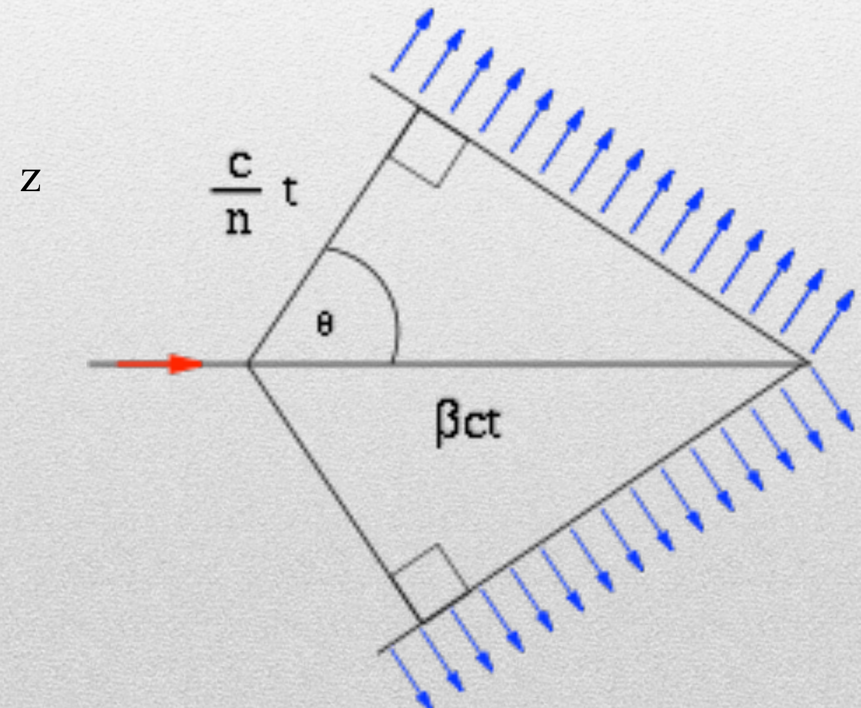
$$\beta = \frac{v}{c}$$

A: v < c/n

Induced dipoles symmetrically arranged around particle path; no net dipole moment; no Cherenkov radiation

B: v > c/n

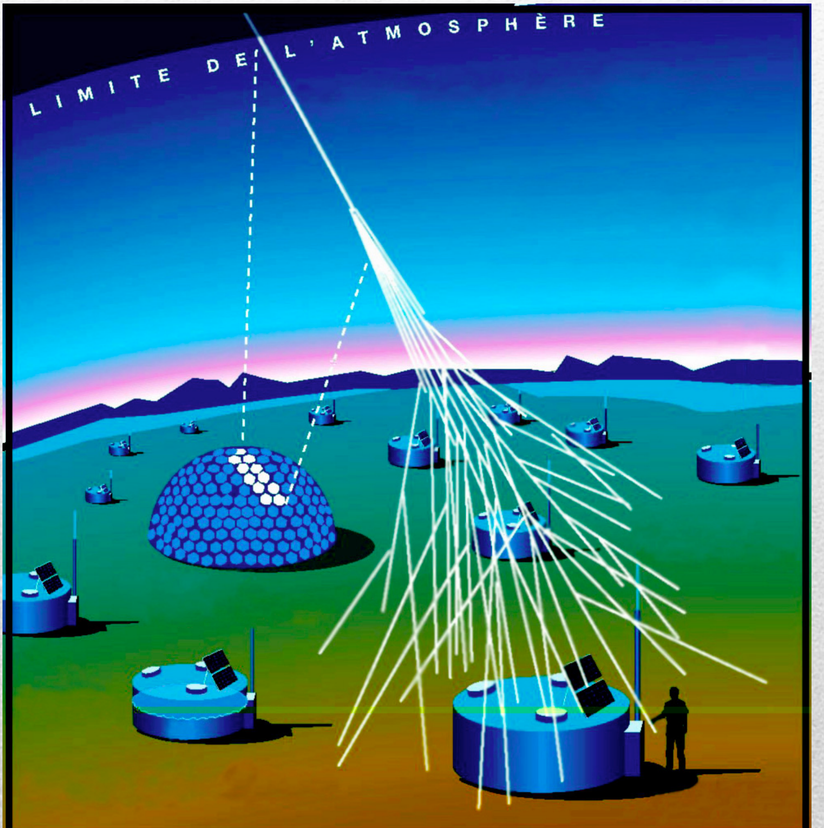
Symmetry is broken as particle faster the electromagnetic waves; non-vanishing dipole moment; radiation of Cherenkov photons

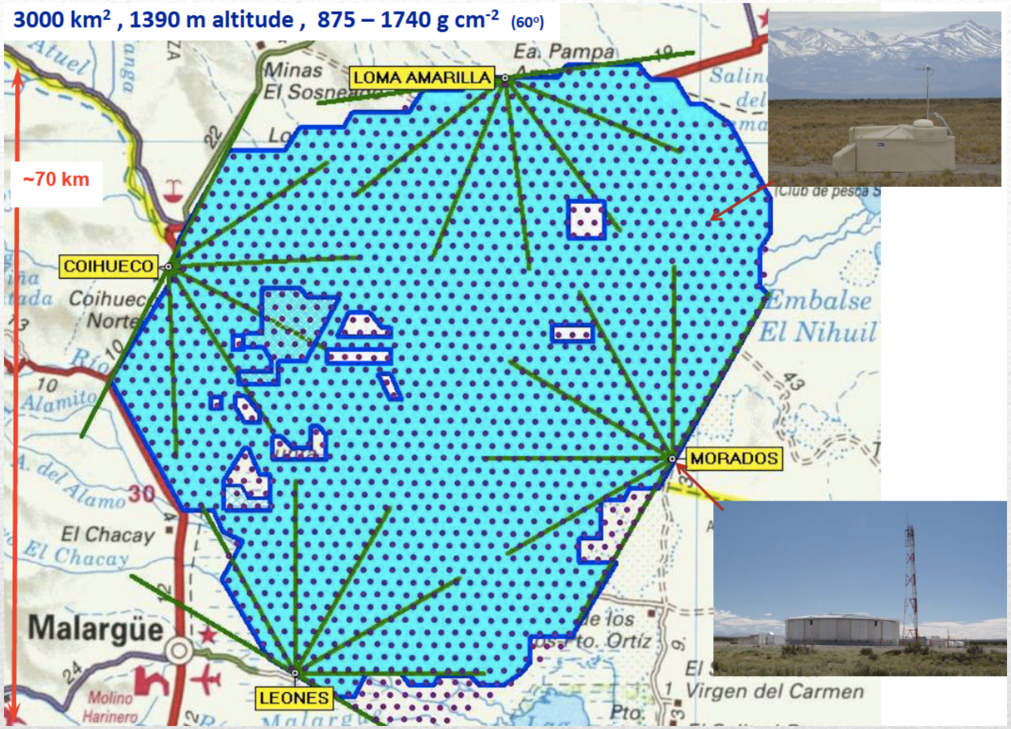


Pierre Auger Observatory

Hybrid observatory:

- surface detectors
- fluorescence detectors

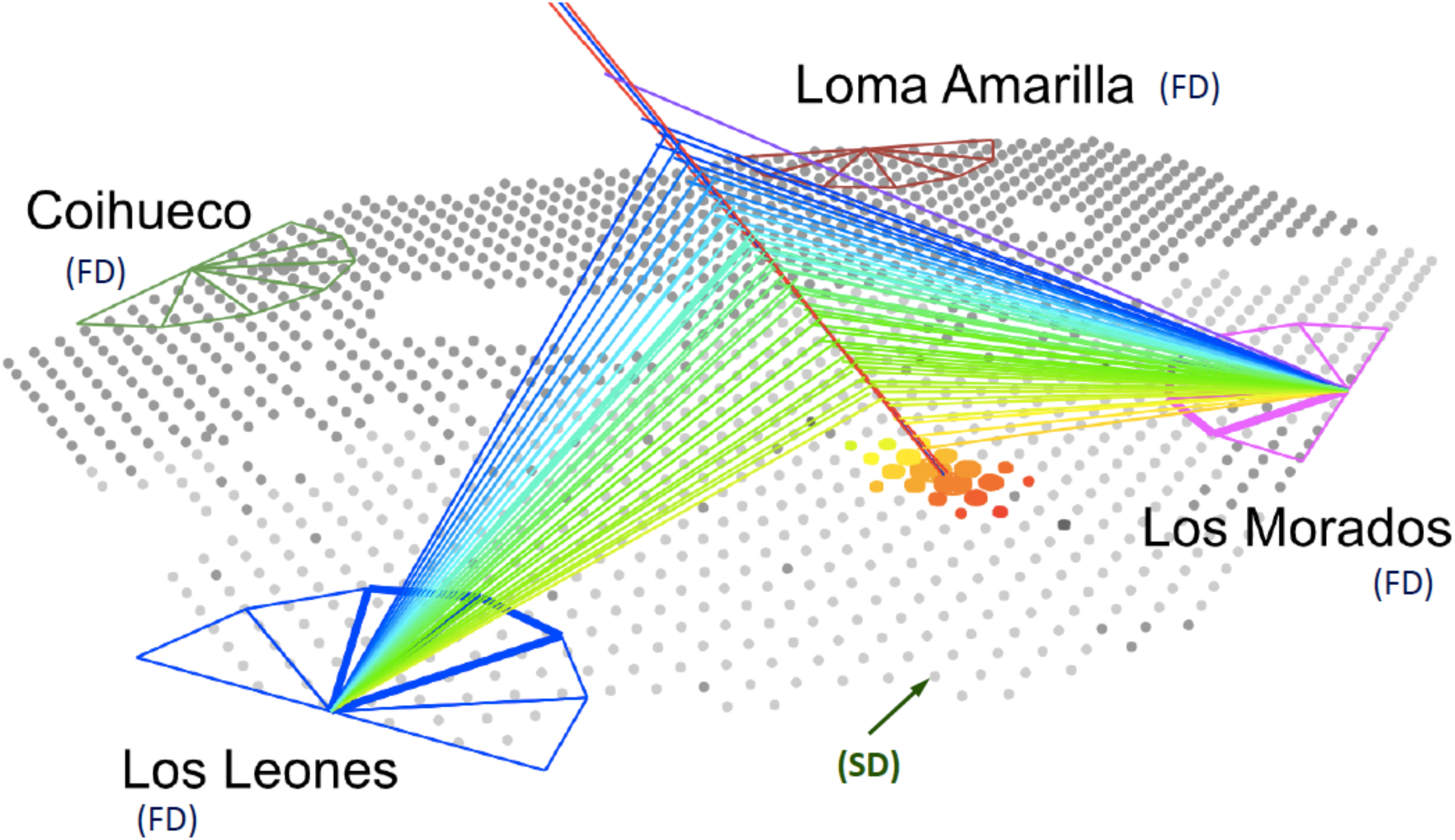




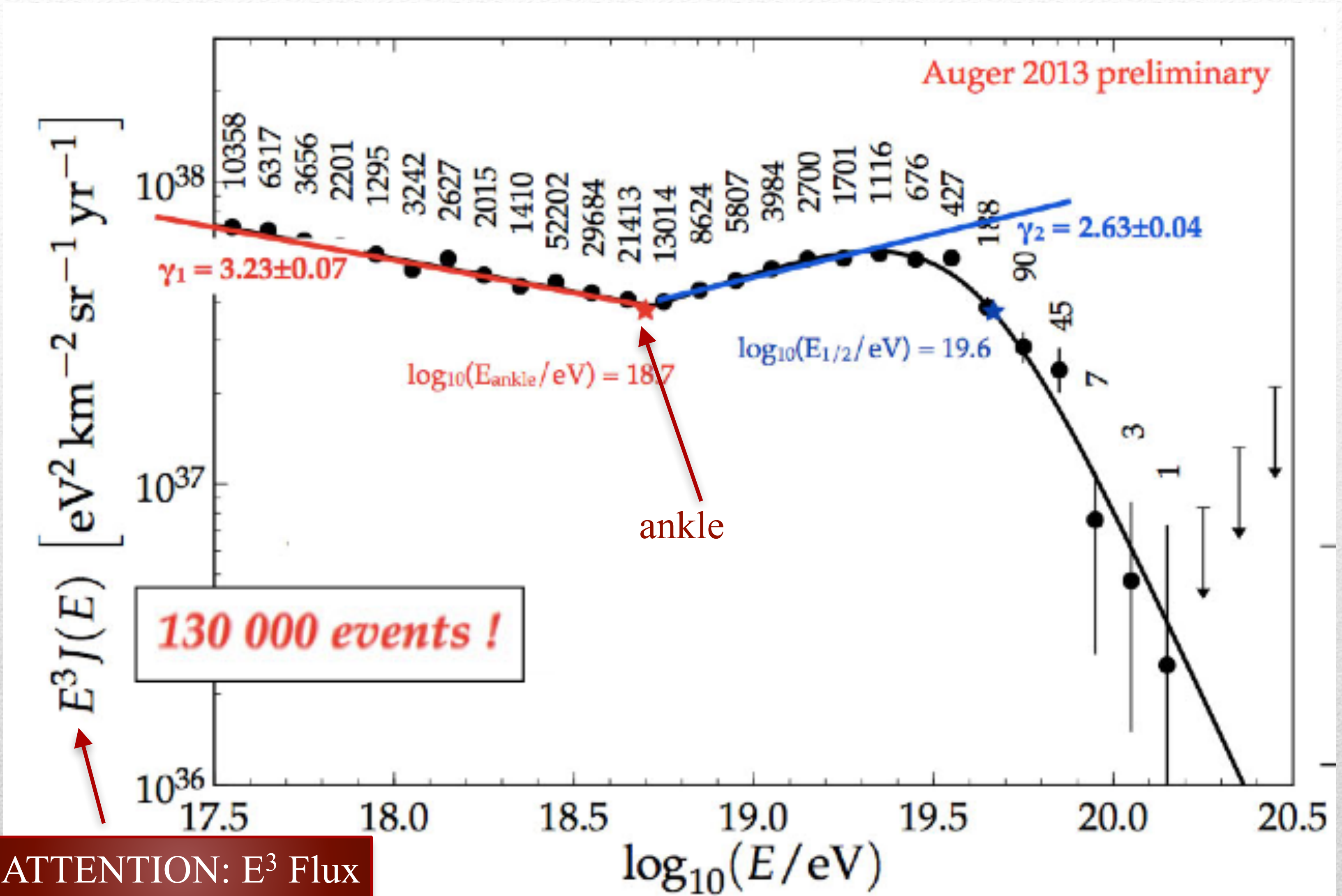
- 1600 water tanks at 1.5 km distance de 1.5 km
- 12 tons of purified water

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

Example of an hybrid event



Spectrum of UHECR



ATTENTION: E^3 Flux

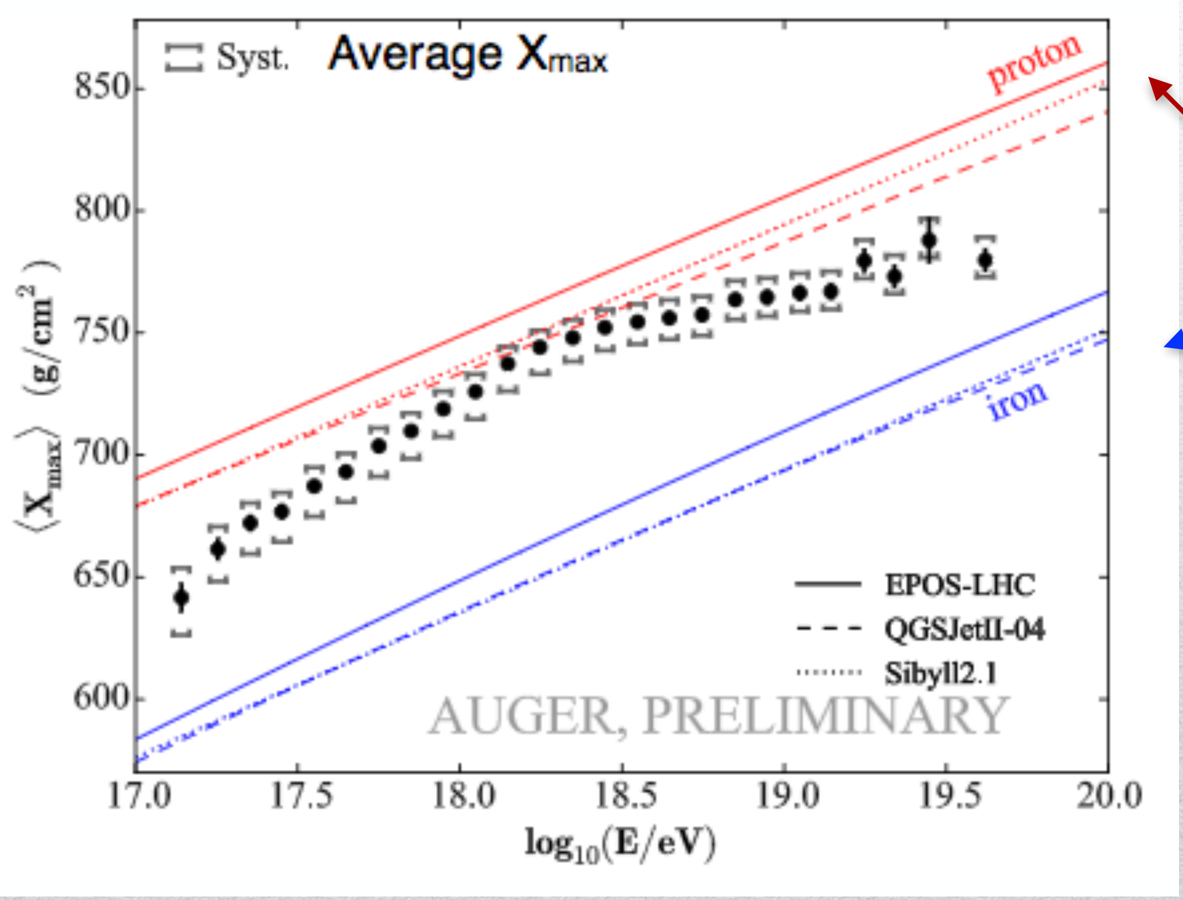
A cut is visible !!!

what is the nature of this cut?
interaction with CMB?
Maximum acceleration energy in sources?

Composition of UHECR

Xmax= depth at which the energy deposit reaches its maximum.

X max is proportional to the logarithm of the mass A of the primary particle.



simulations using proton and Iron primary particles

CR anisotropy

J. Abraham et al. / Astroparticle Physics 29 (2008) 188–204

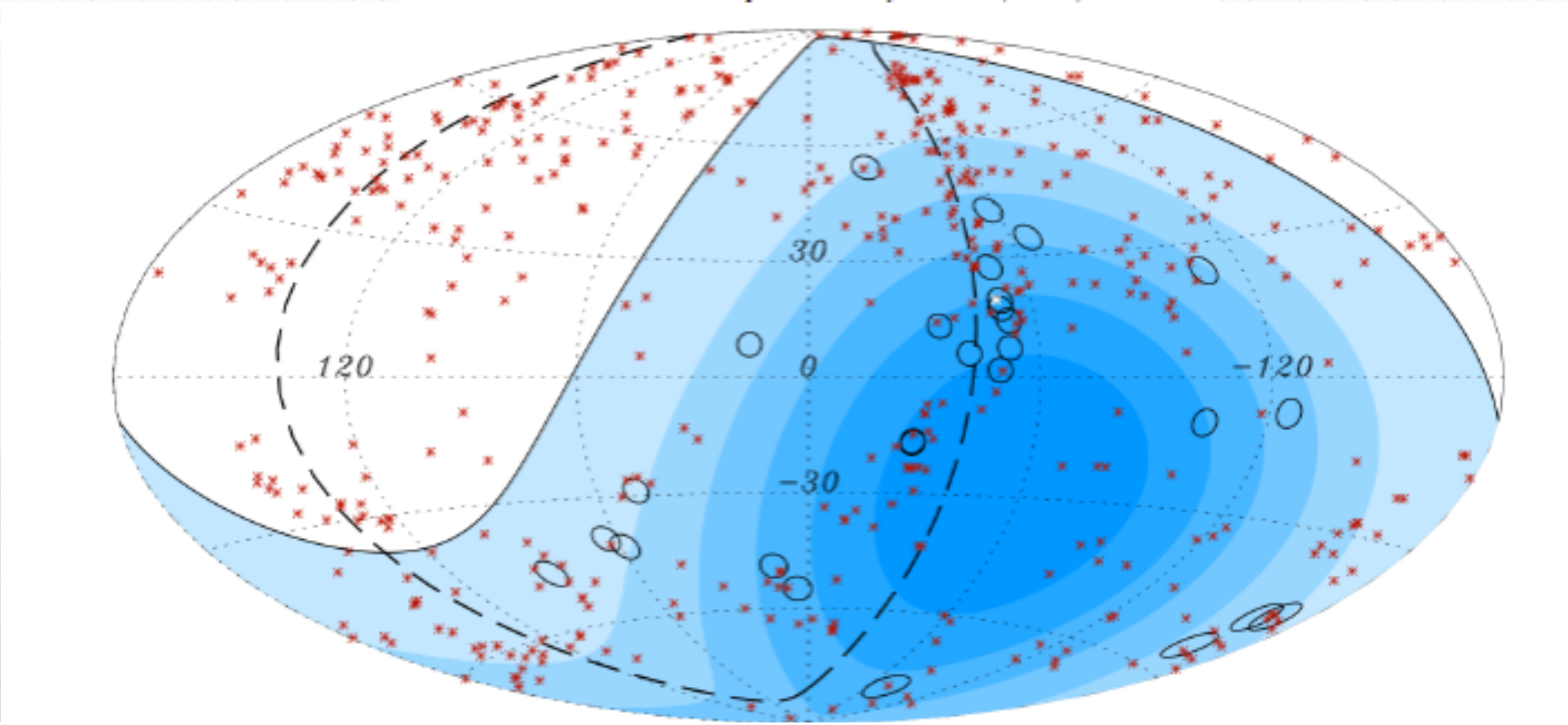
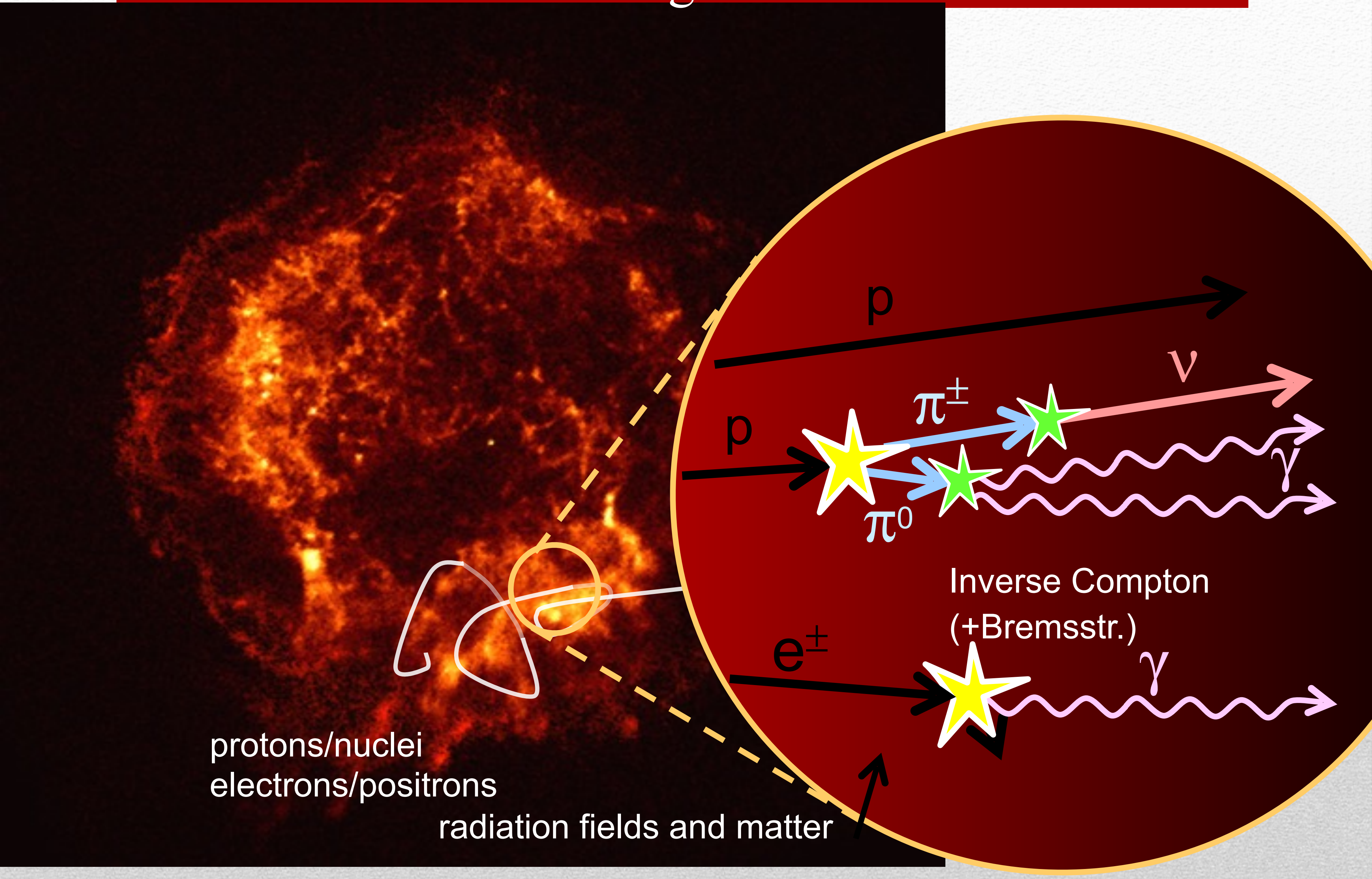


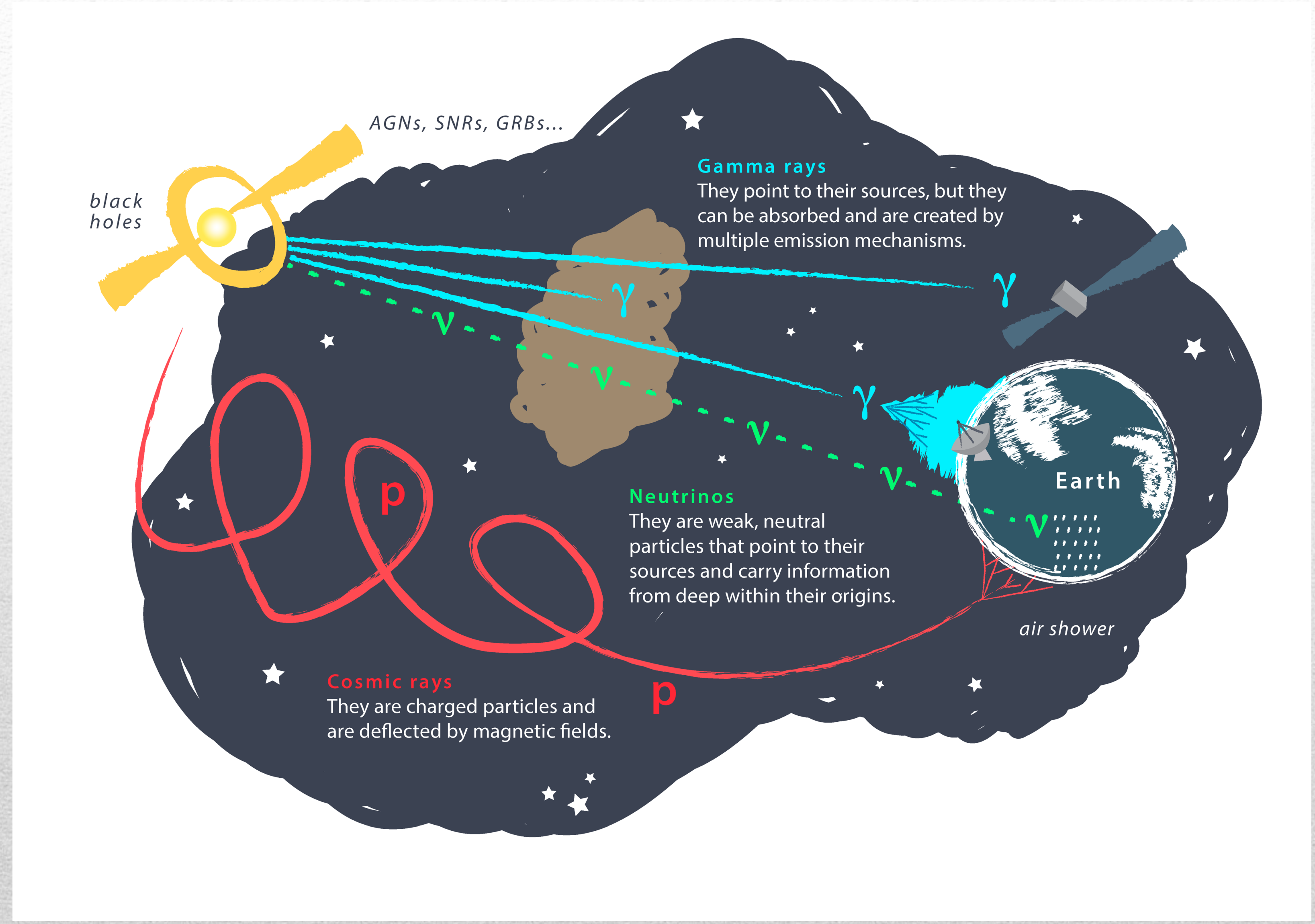
Fig. 2. Aitoff projection of the celestial sphere in galactic coordinates with circles of 3.2° centred at the arrival directions of 27 cosmic rays detected by the Pierre Auger Observatory with reconstructed energies $E > 57$ EeV. The positions of the 442 AGN (292 within the field of view of the Observatory) with redshift $z \leqslant 0.017$ ($D < 71$ Mpc) from the 12th edition of the catalogue of quasars and active nuclei [11] are indicated by asterisks. The solid line draws the border of the field of view for the southern site of the Observatory (with zenith angles smaller than 60°). The dashed line is, for reference, the super-galactic plane. Darker colour indicates larger relative exposure. Each coloured band has equal integrated exposure. Centaurus A, one of the closest AGN, is marked in white.

NOW: no evidence for correlation between AGNs positions and 27 UHECR (E>57EeV)

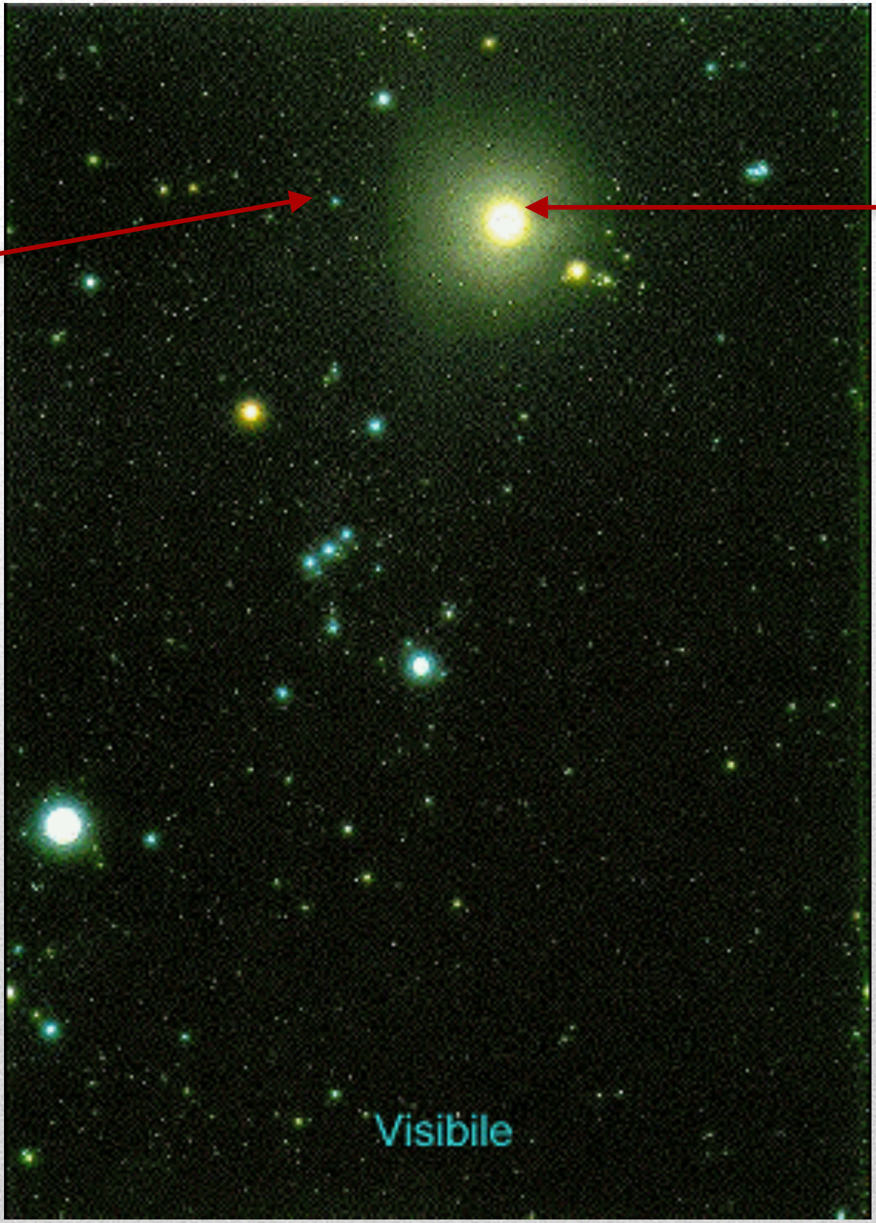
Connection CR-gamma-neutrino



Connection CR-gamma-neutrino

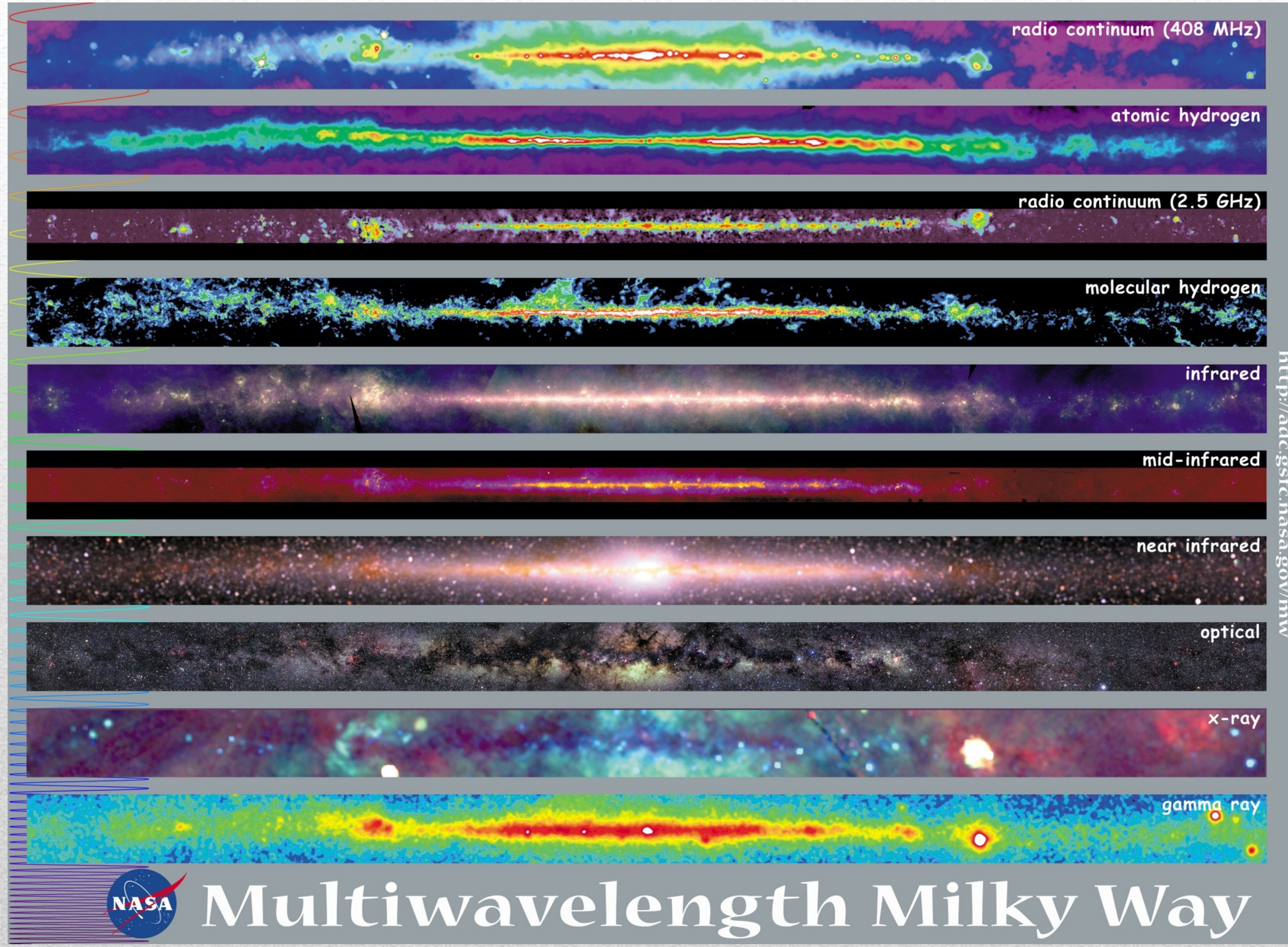


The sky in different wavelengths



Crab

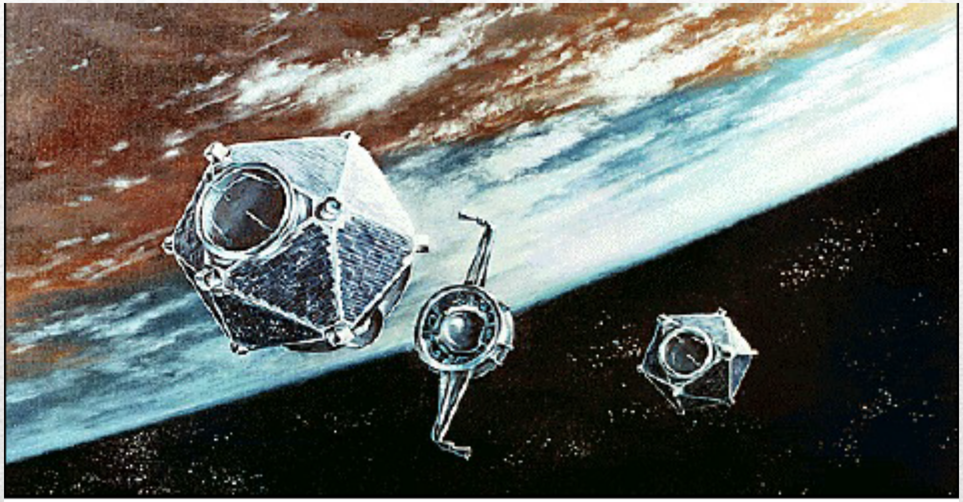
Moon

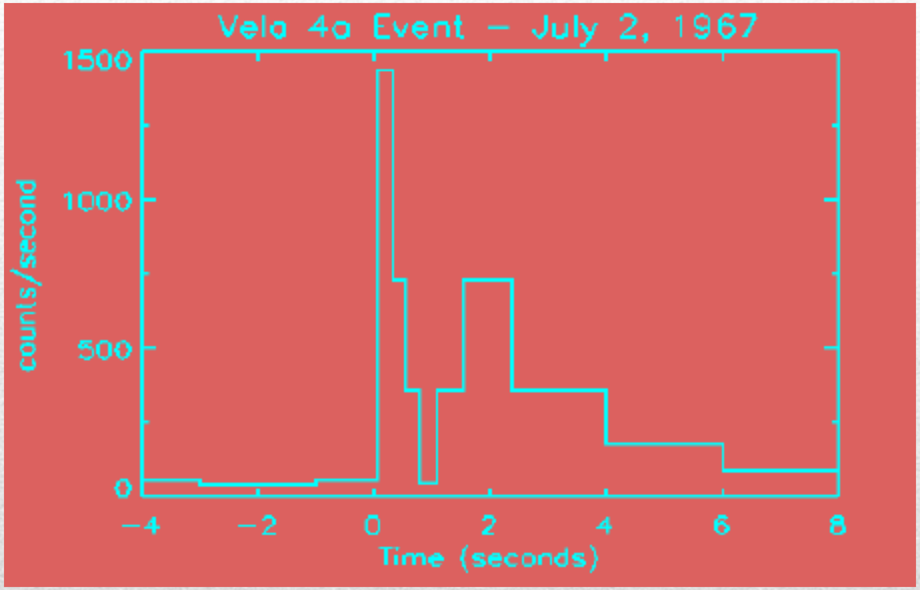

radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

Discovery of cosmic gamma rays

First detection : VELA

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

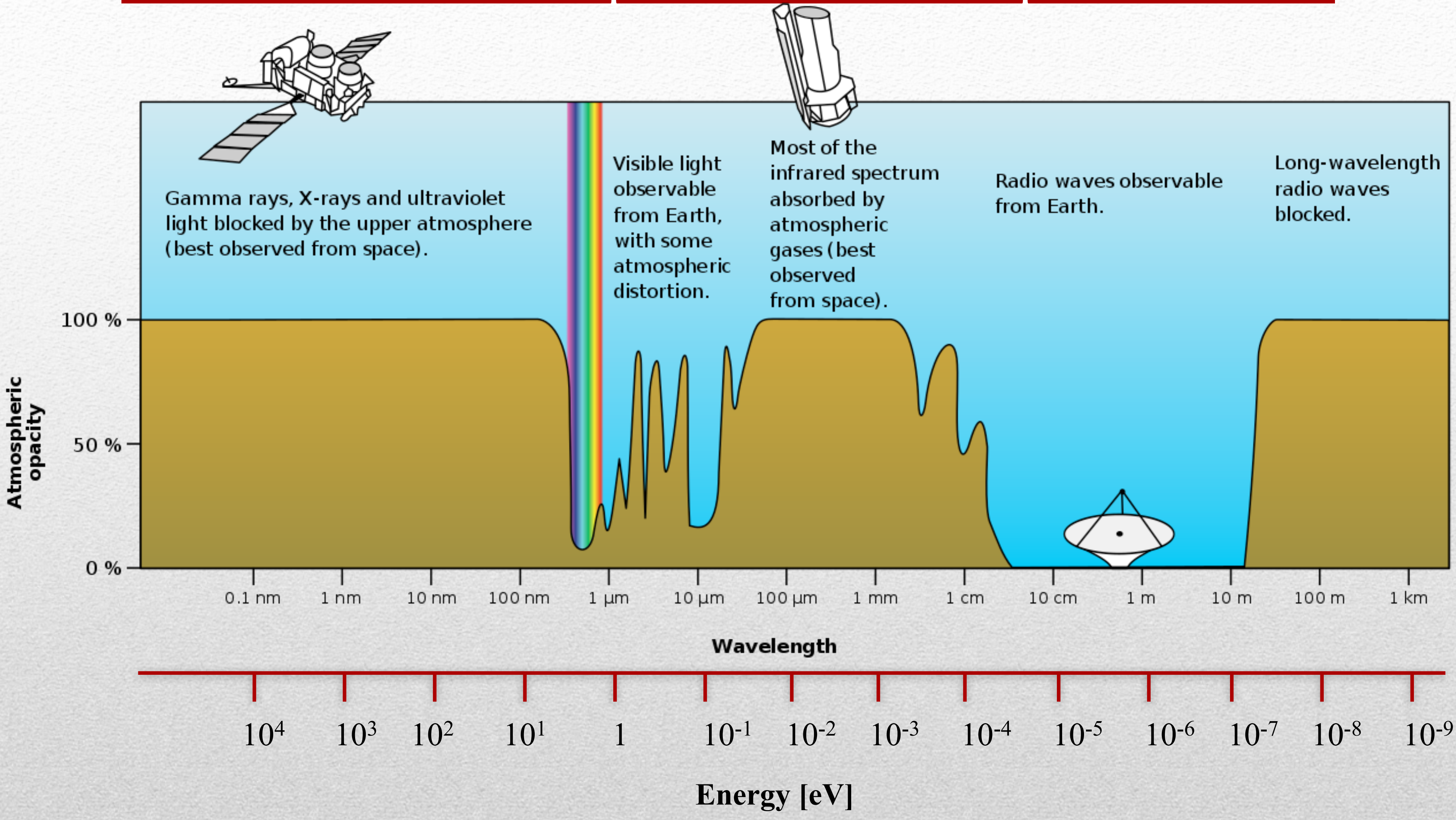




1967: detection of a gamma ray burst

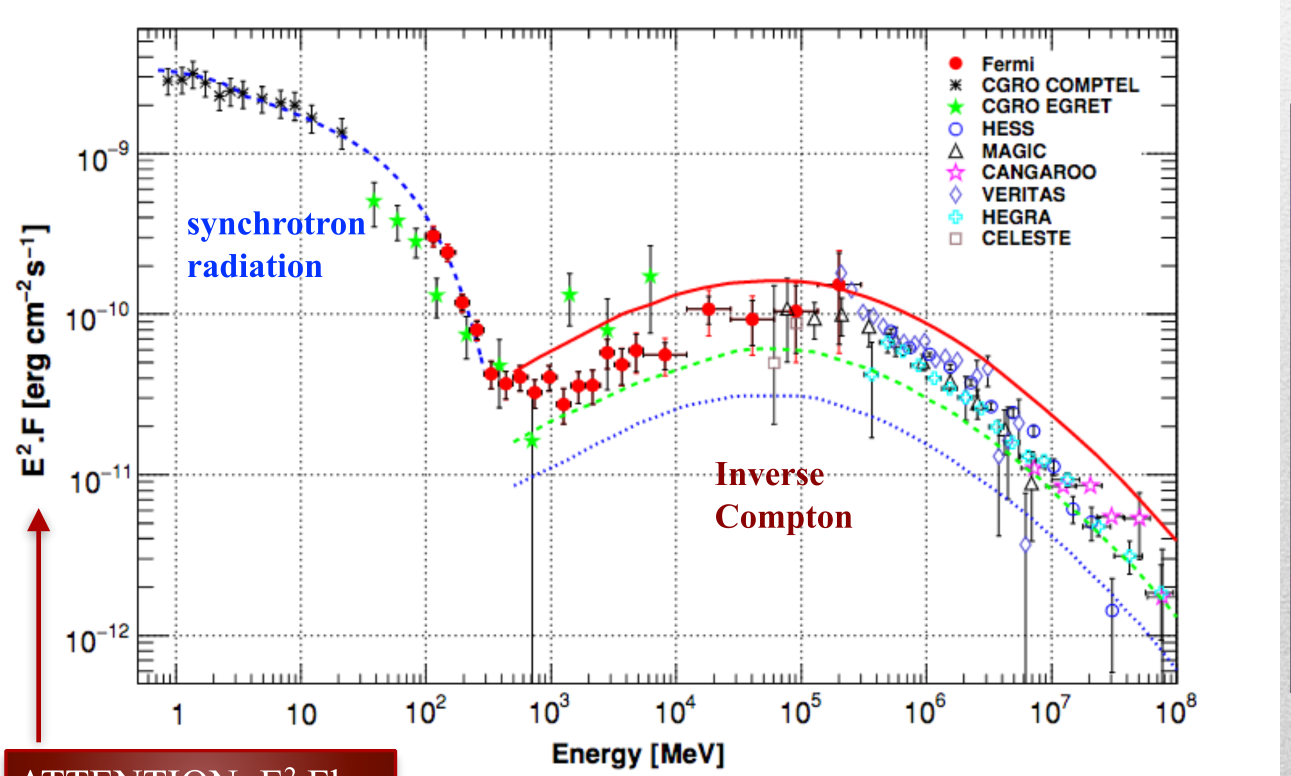
Detected energy: 0-10 MeV

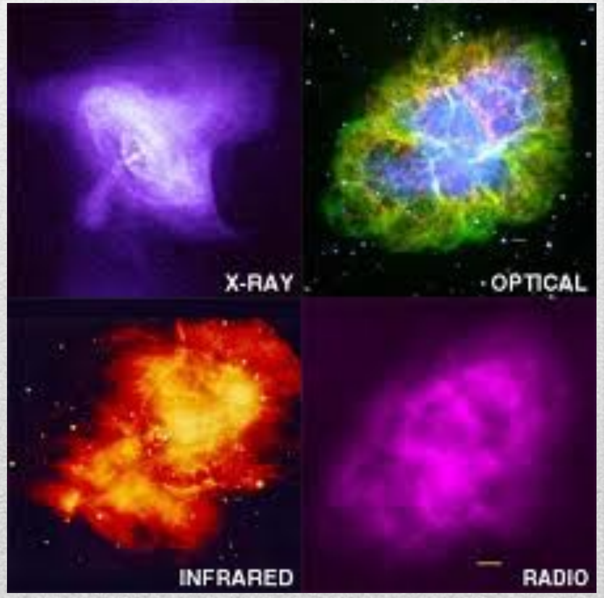
Photons absorption in the atmosphere



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)



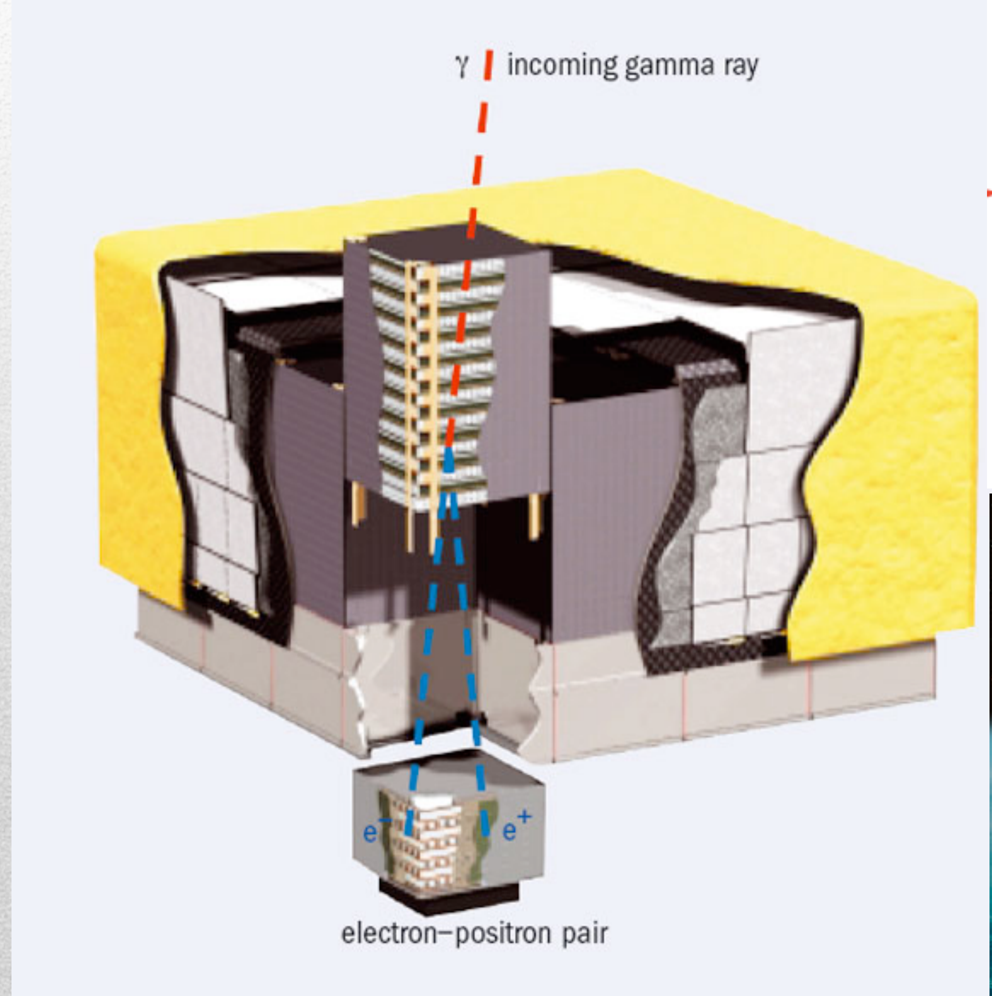


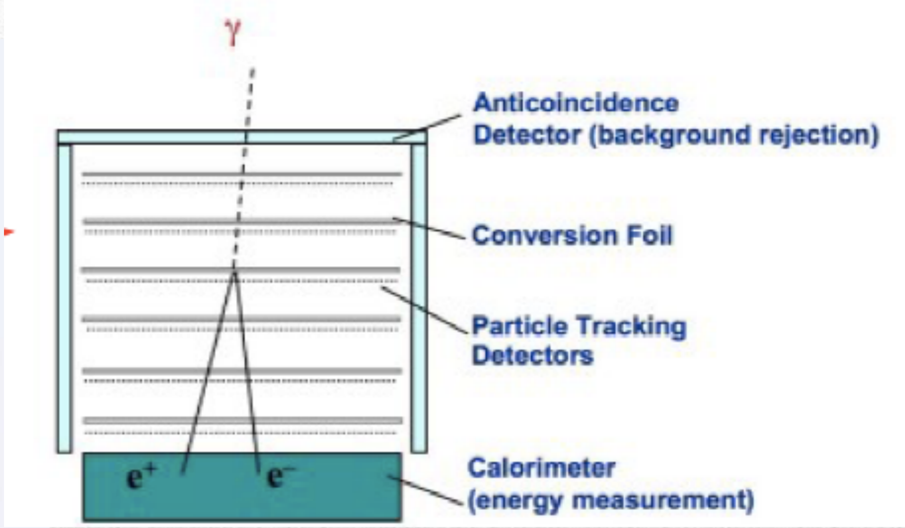
ATTENTION: E^2 Flux

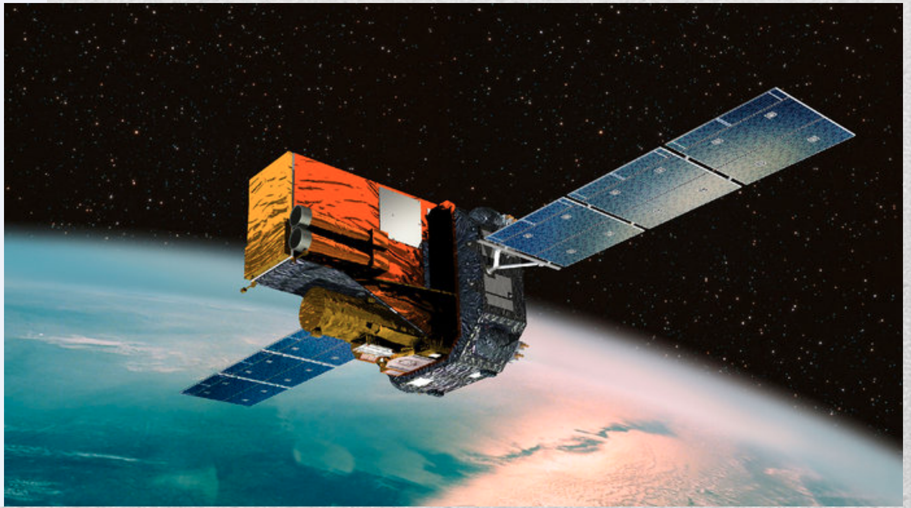
Gamma Direct detection: satellite

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

FERMI Large Area Telescope: 20 MeV-300 GeV



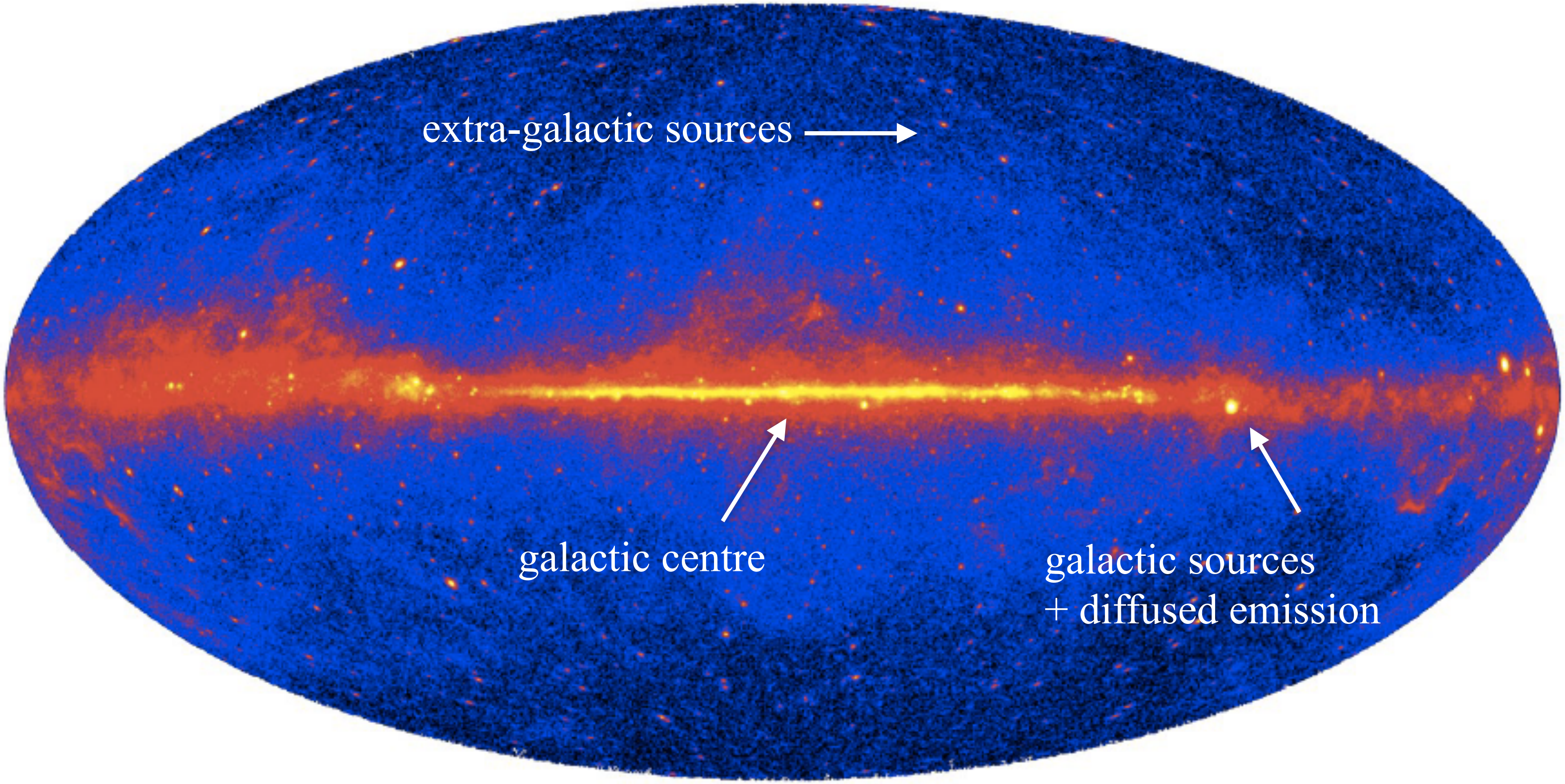




Gamma Astronomy at GeV

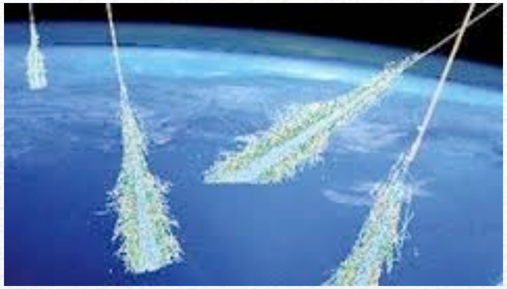
1800 sources have been detected: a lot of extragalactic sources

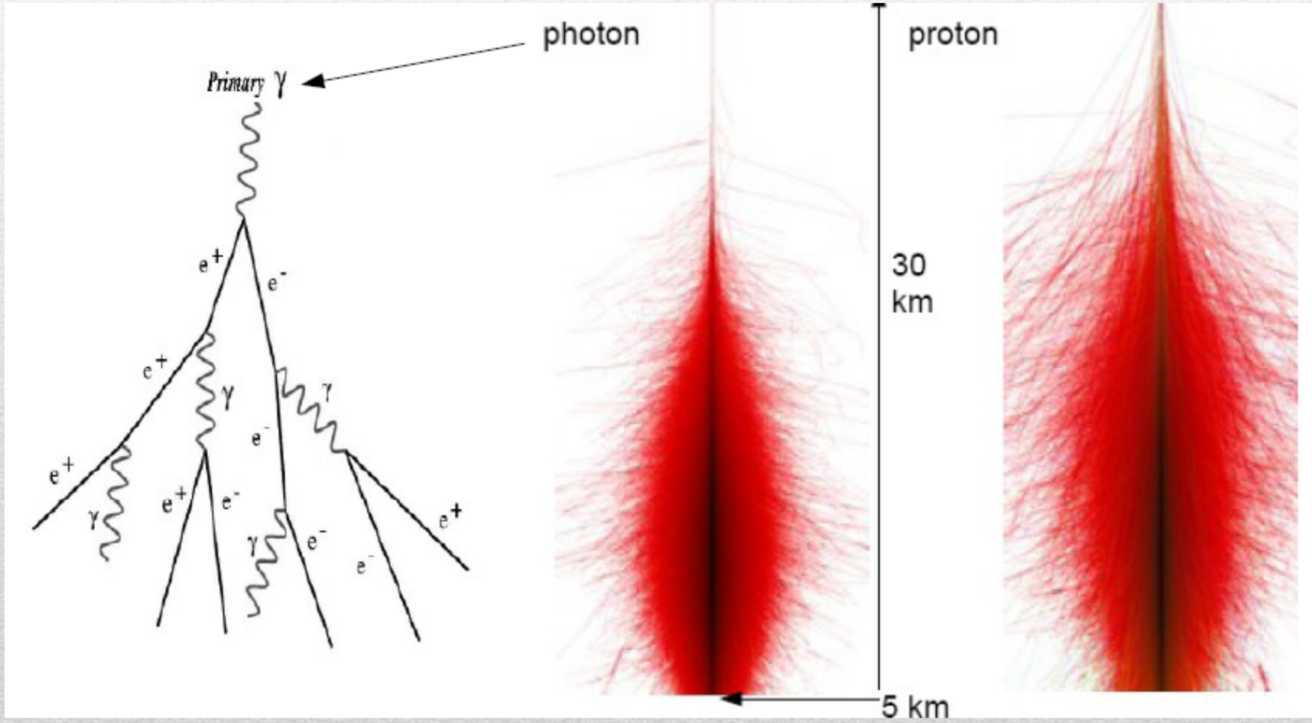
> Fermi 2FGL catalog



Gamma Indirect detection

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



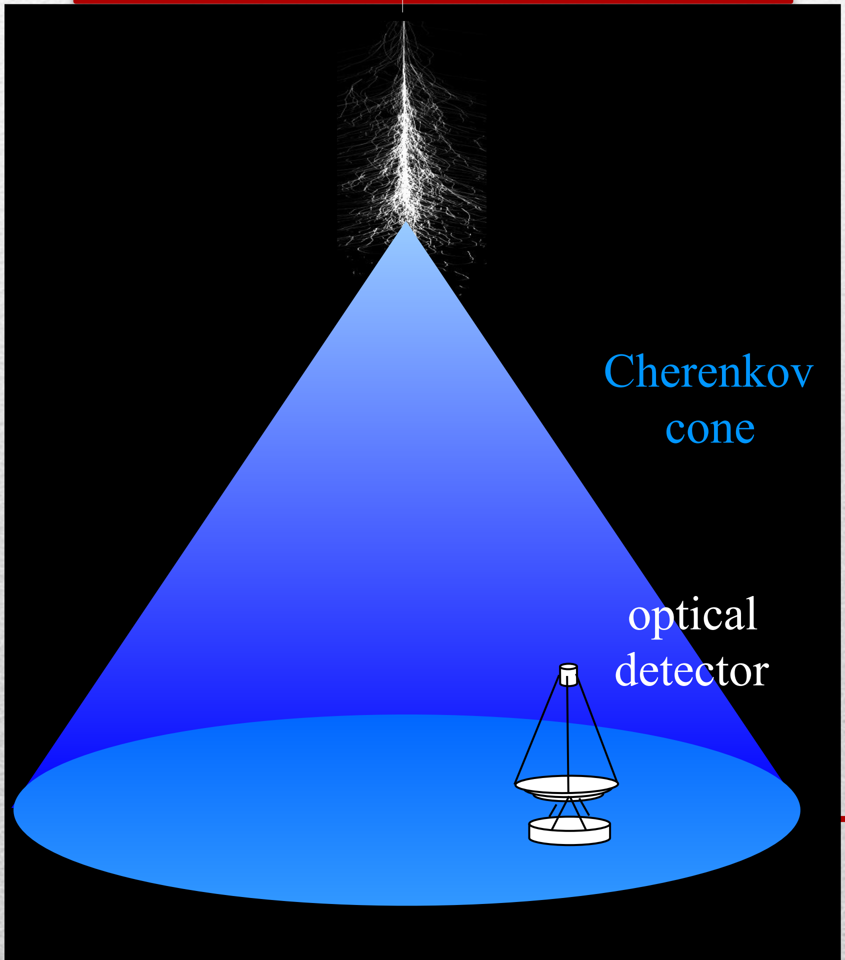


Showers produced by **gammas** are **much more symmetric and thin** in respect to showers produced by protons. This characteristics is used to differentiate gammas from protons.

Gamma Indirect detection

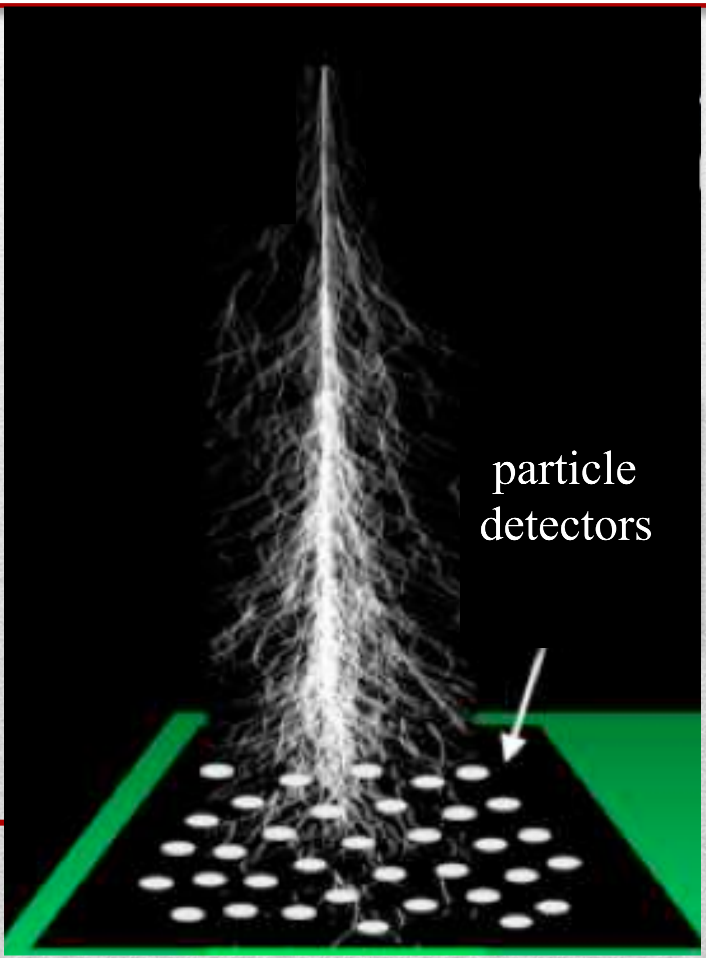
Imaging Air Cherenkov Telescopes

- 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



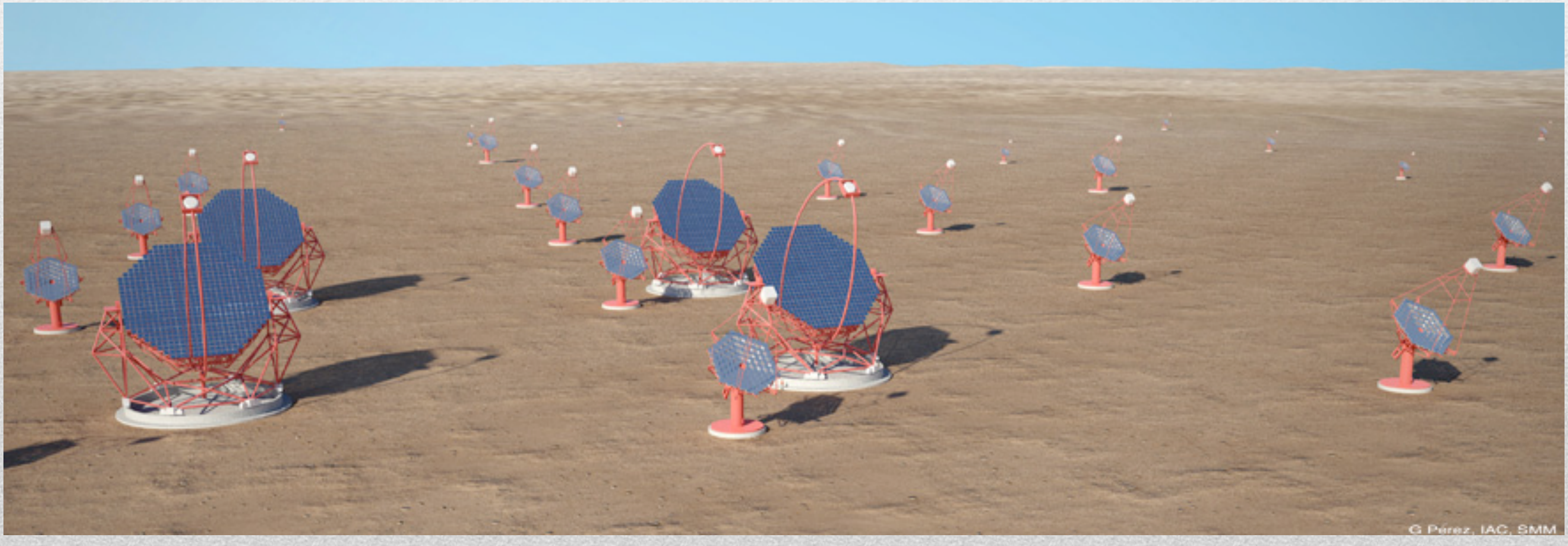
Gamma Indirect detection

Imaging Air Cherenkov Telescopes (IACT)

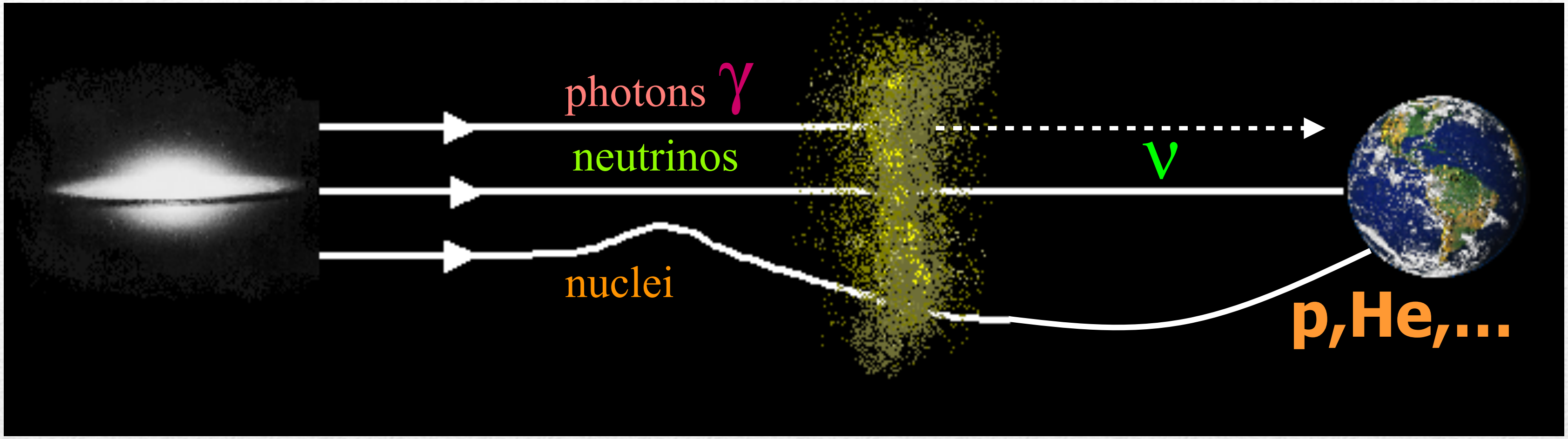
H.E.S.S.

See Lecture about HESS/CTA this afternoon!

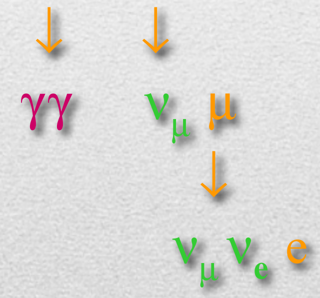
cta cherenkov telescope array



Which are the messengers?



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



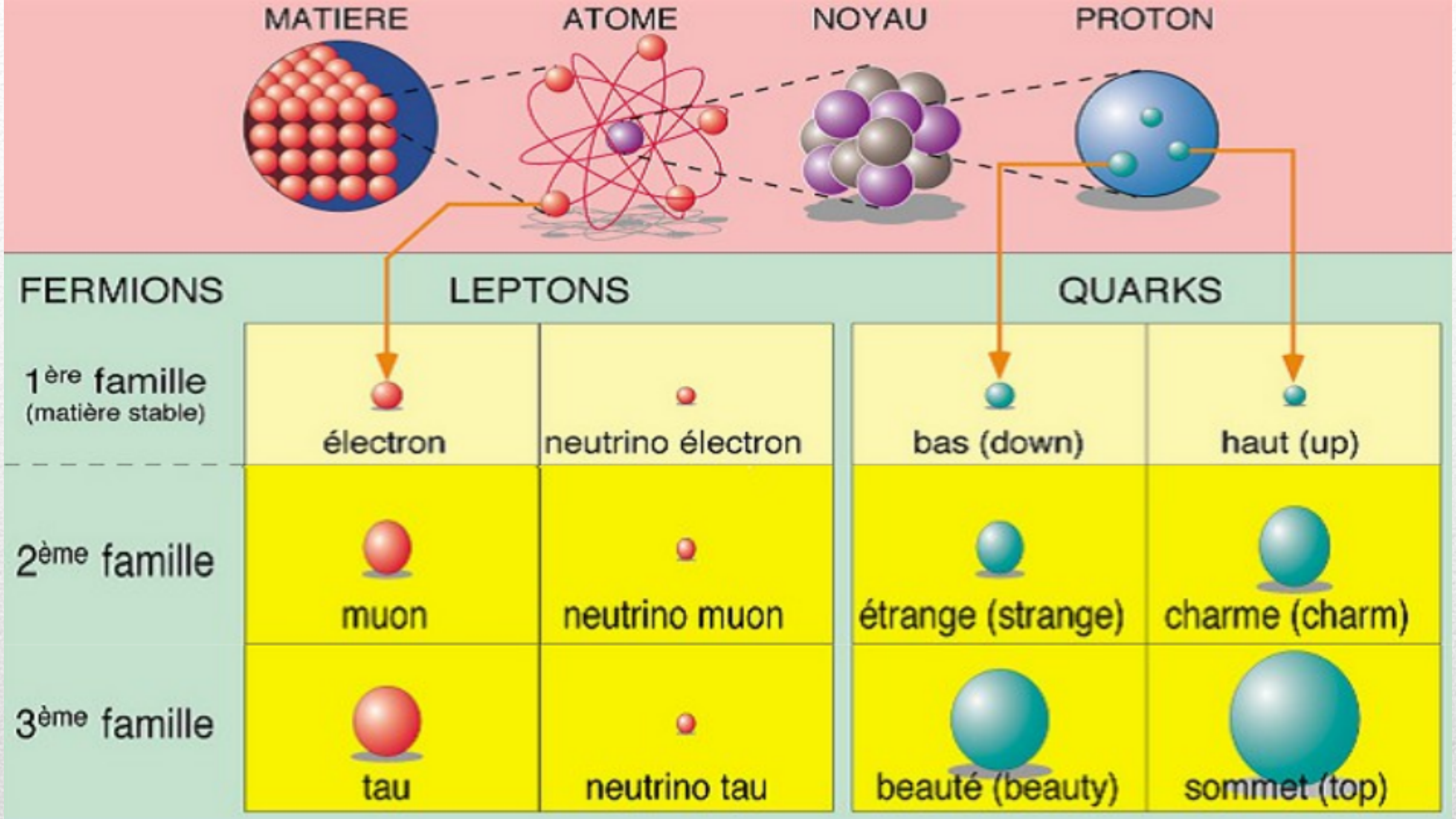
As TeV gammas, neutrinos are produced by hadronic interaction of high energy nuclei and protons in astrophysical sources

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!

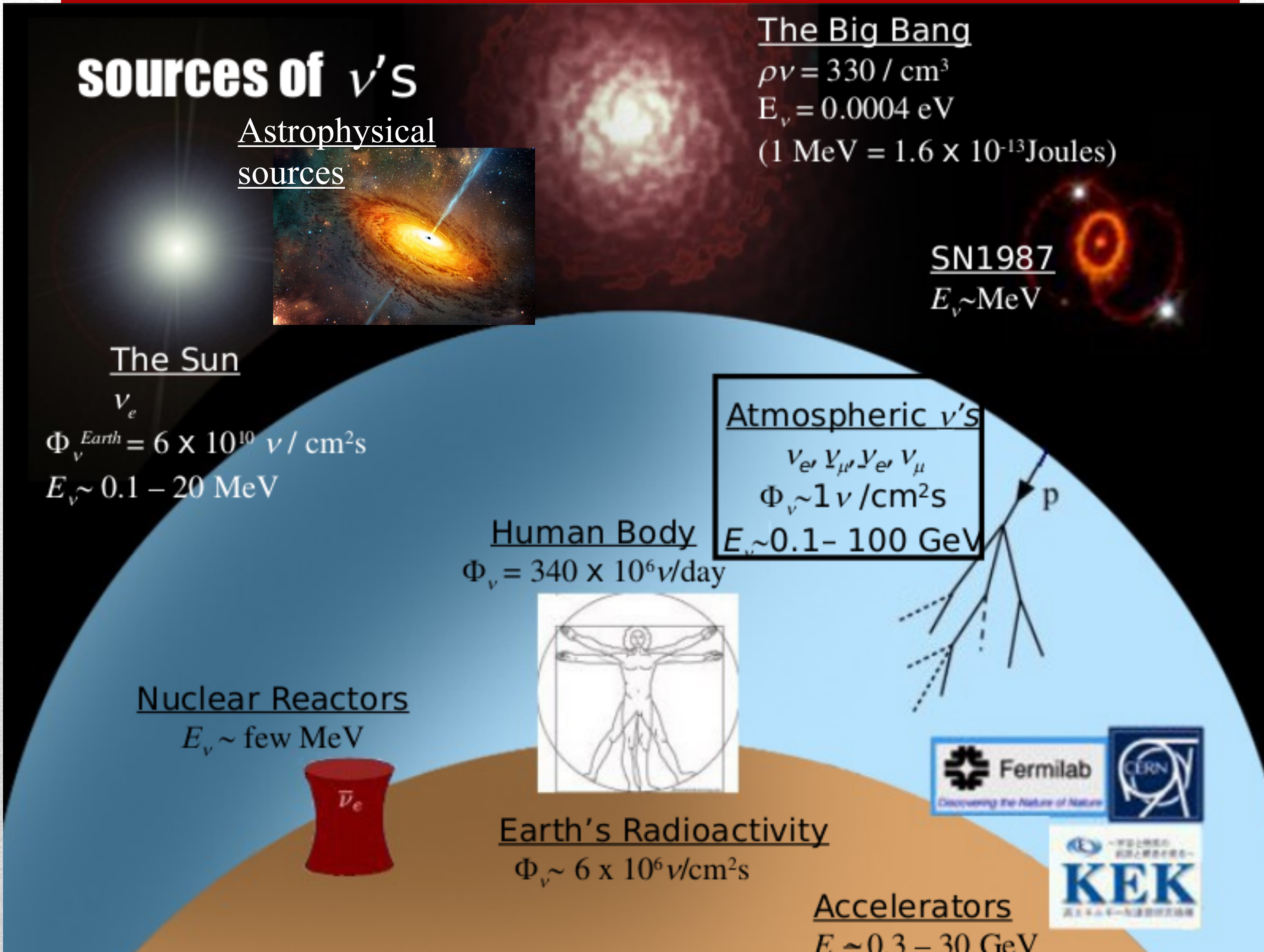
Only 1 neutrino over 10 bilions of neutrinos coming from the Sun and traversing the Earth, will interact!!

What are neutrinos?



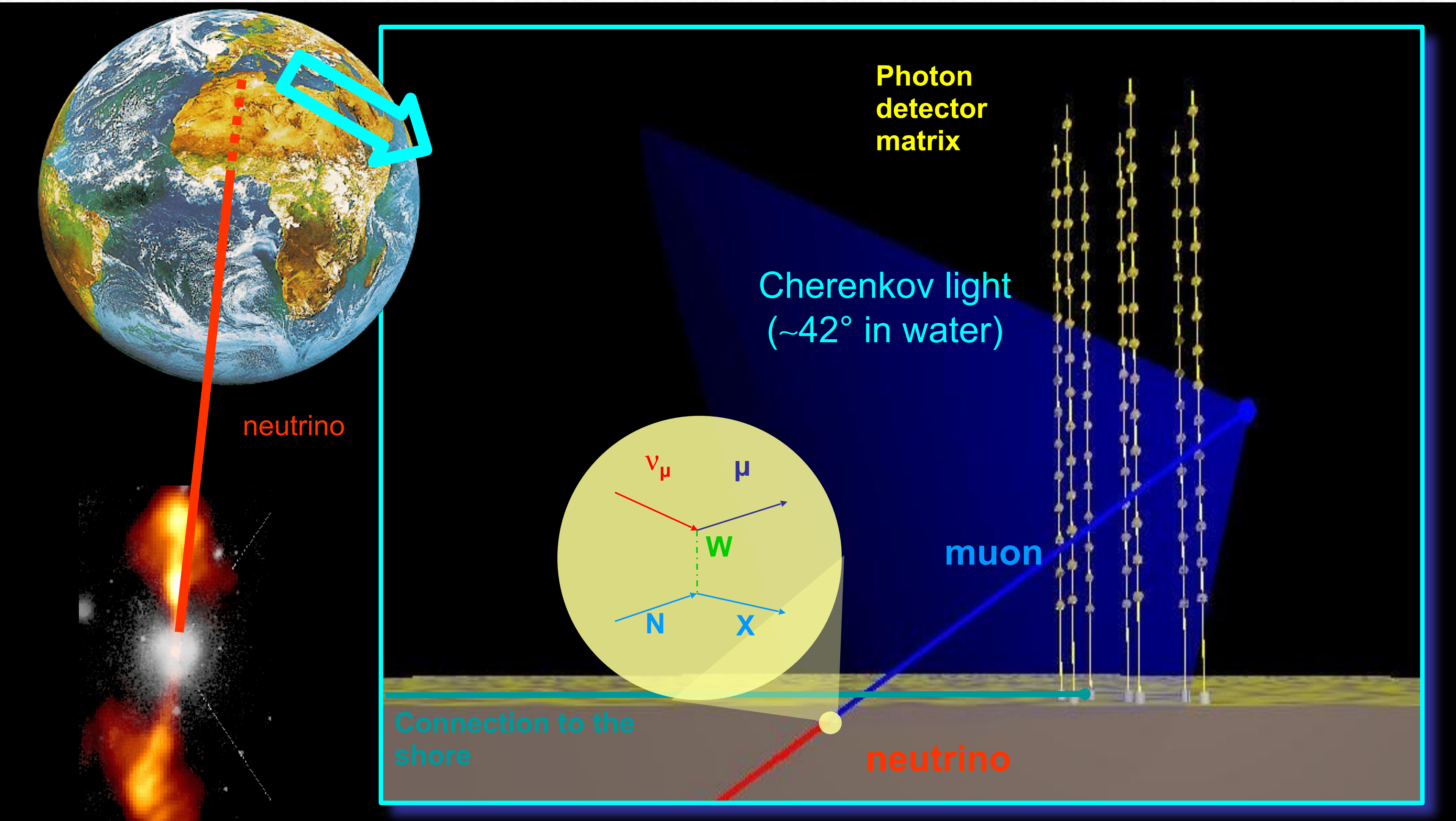
For details on research on neutrino properties see Lecture on:

- ***ORCA (this afternoon)***
- ***SuperNEMO (Saturday morning)***


sources of ν's
Astrophysical sources
The Big Bang
ρν = 330 / cm³
E_ν = 0.0004 eV
(1 MeV = 1.6 x 10⁻¹³ Joules)
SN1987
E_ν~MeV
The Sun
ν_e
Φ_ν^Earth = 6 x 10¹⁰ ν / cm²s
E_ν~ 0.1 – 20 MeV
Atmospheric ν's
ν_e, ν_μ, ν_e, ν_μ
Φ_ν~1 ν /cm²s
E_ν~0.1– 100 GeV
p
Human Body
Φ_ν = 340 x 10⁶ ν/day
Nuclear Reactors
E_ν ~ few MeV
ν̄_e
Earth's Radioactivity
Φ_ν~ 6 x 10⁶ ν/cm²s
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

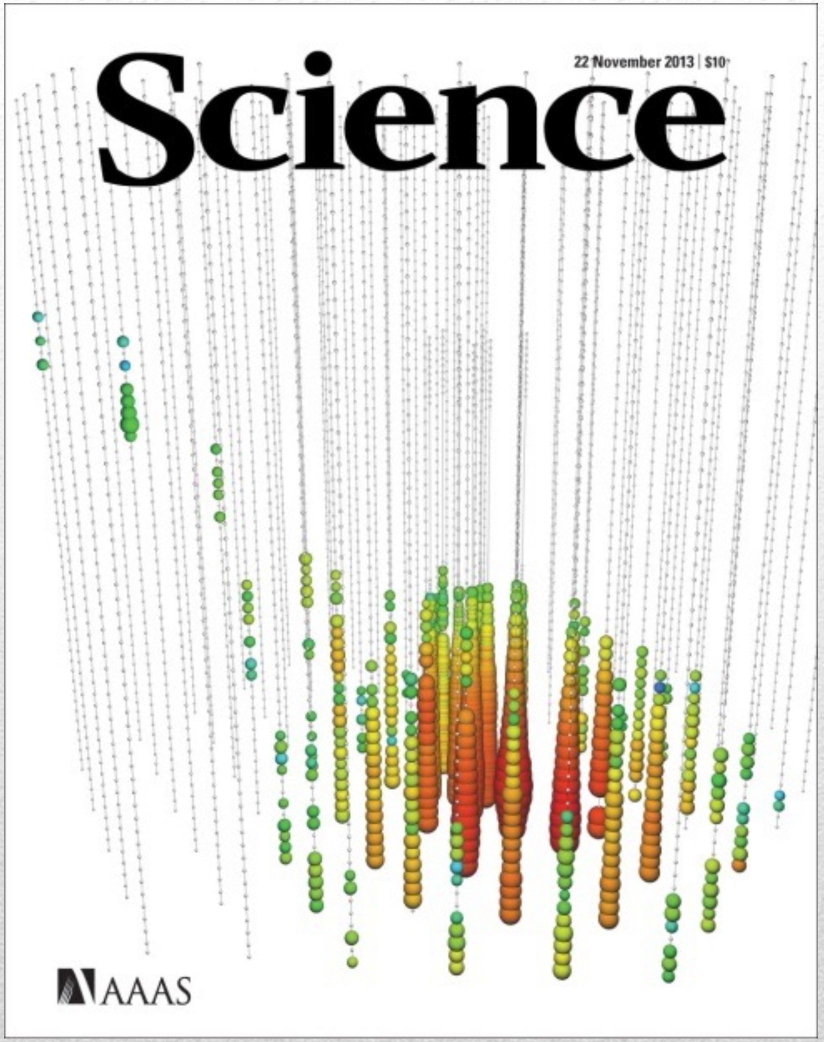
ANTARES & KM3NeT

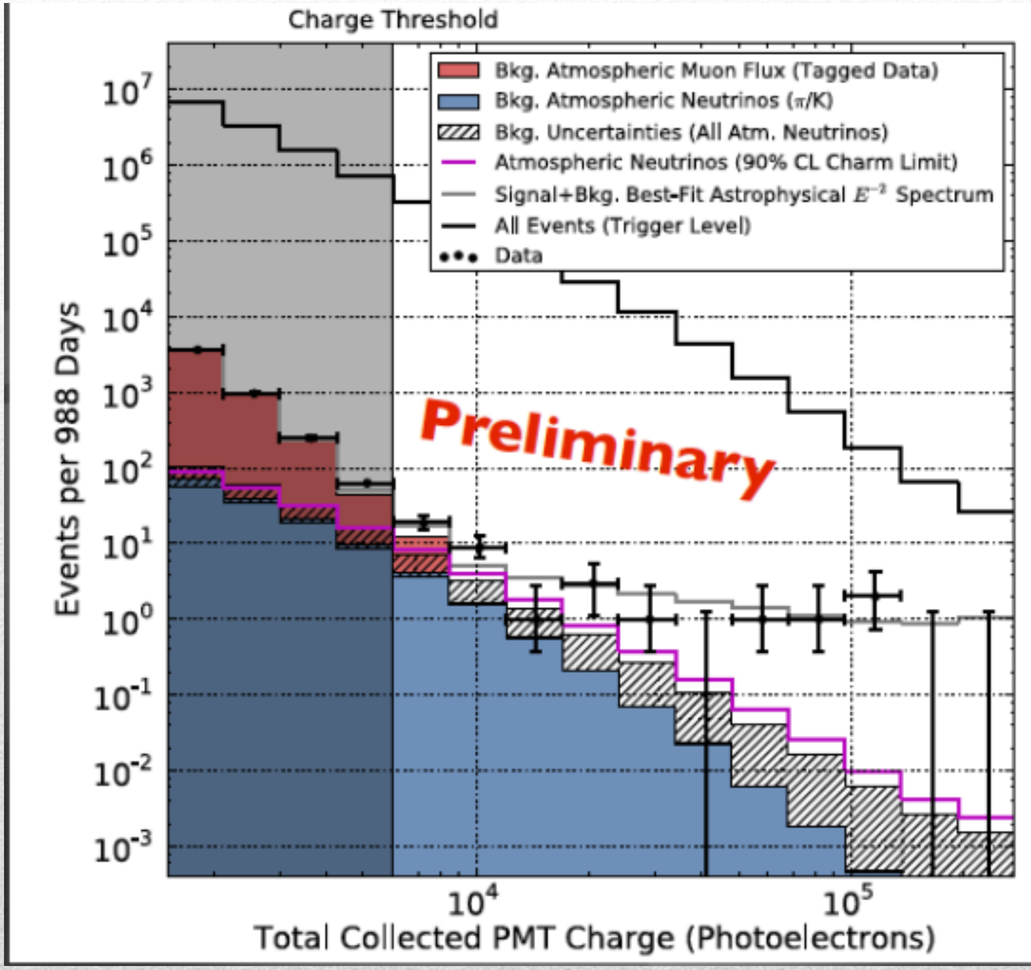
BAIKAL

See Lecture on ANTARES and KM3Net this afternoon!

IceCube

Astrophysical neutrinos exist!





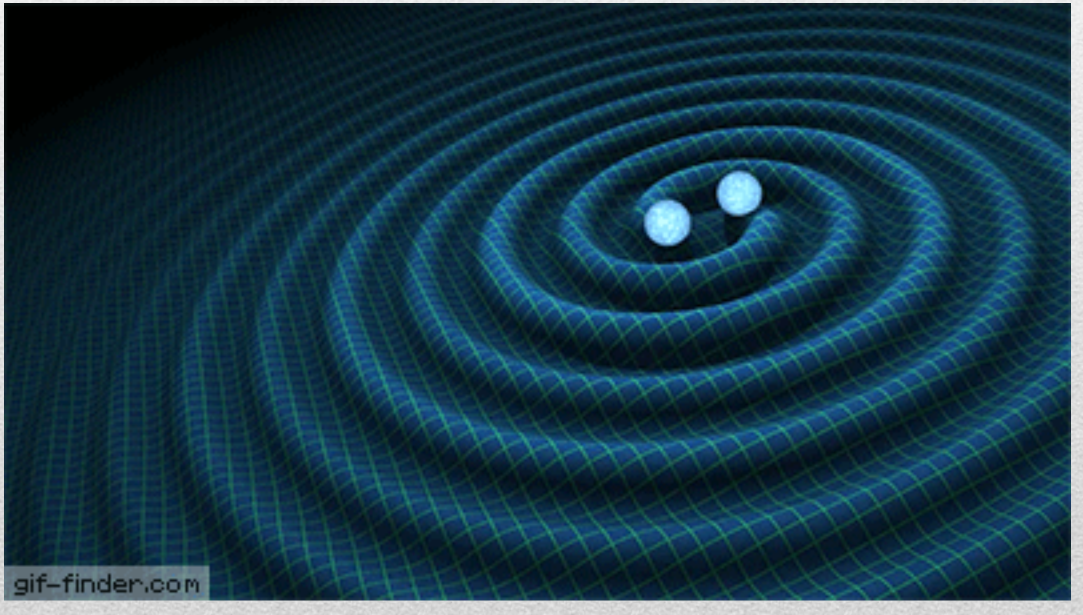
3 yr data: 988 days
Observed : 37 events

Significance 5.7 σ

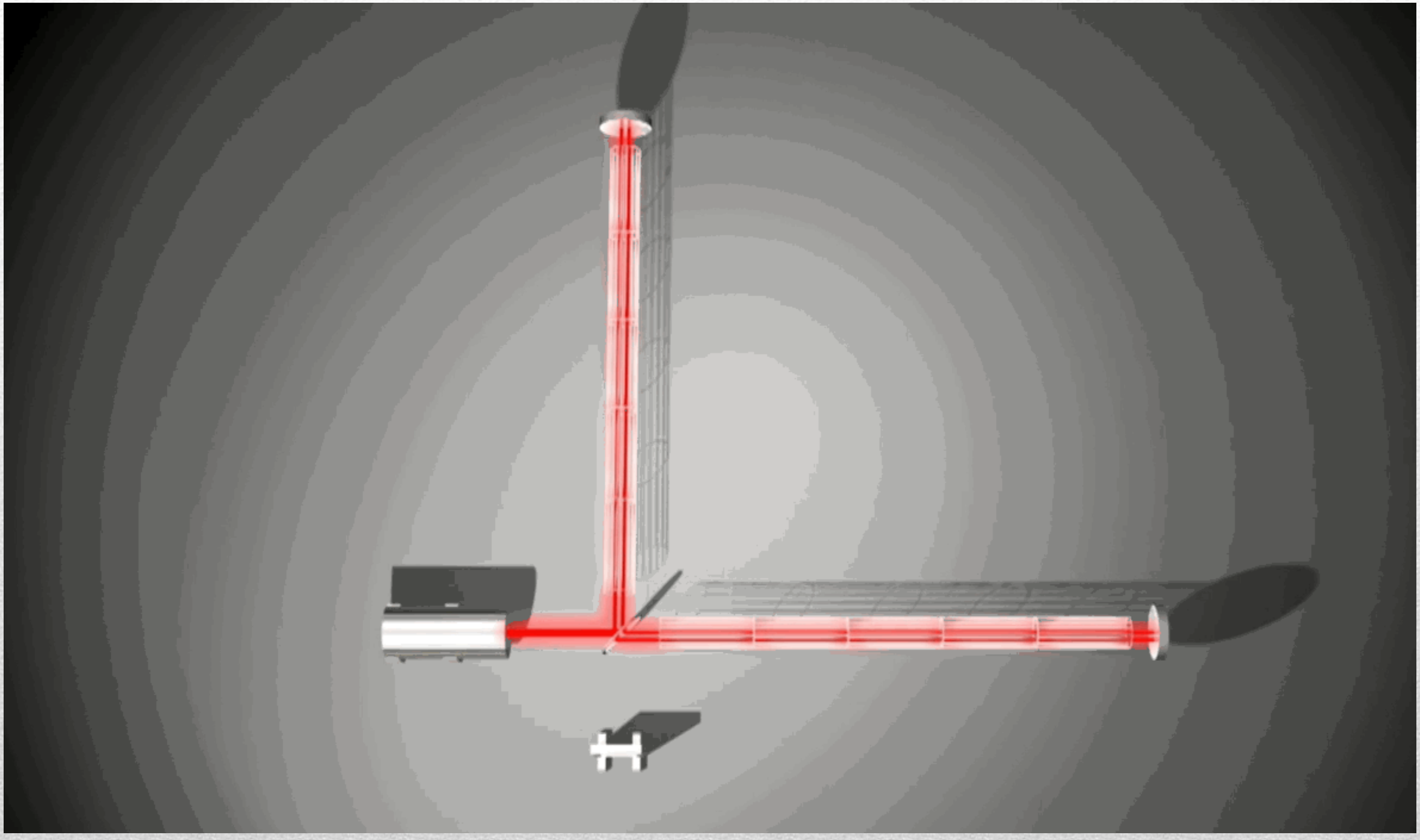
Are there other cosmic messengers?

Gravitational waves

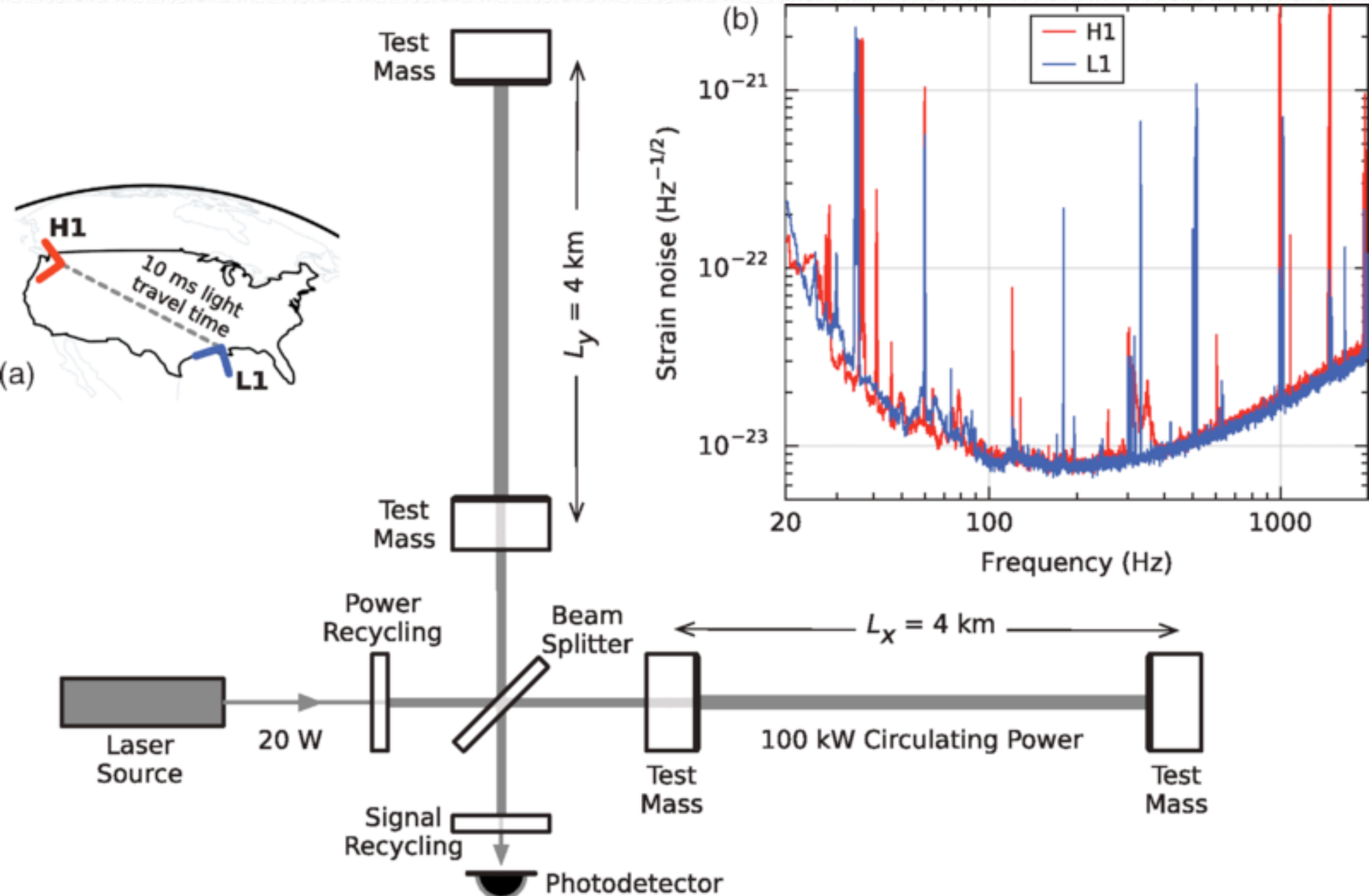
- 'ripples' in the fabric of space-time caused by energetic processes in the Universe (collision of black holes, neutron stars etc.)
- Albert Einstein predicted the existence of gravitational waves in 1916 in his general theory of relativity.



How can we detect GW?



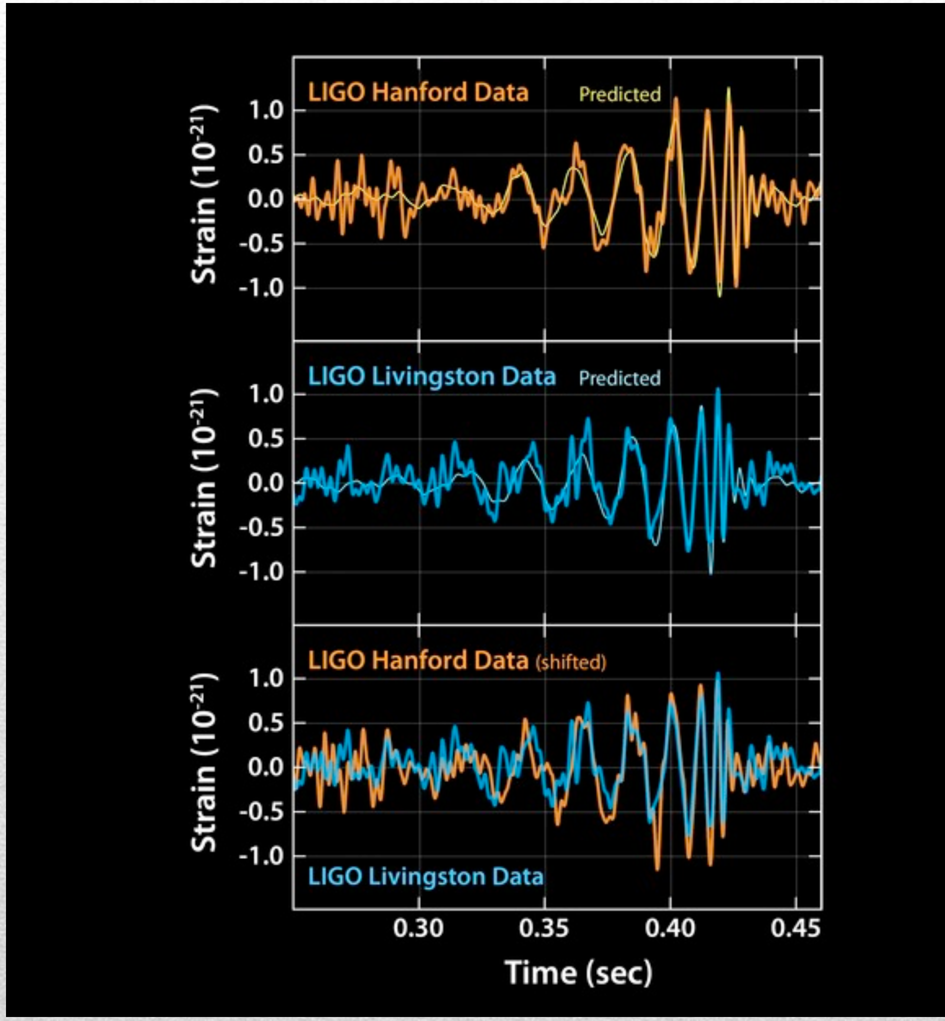
LIGO interferometer



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**!

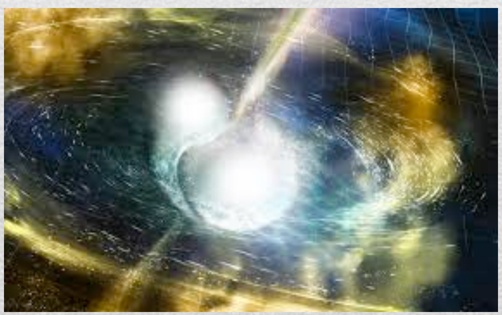


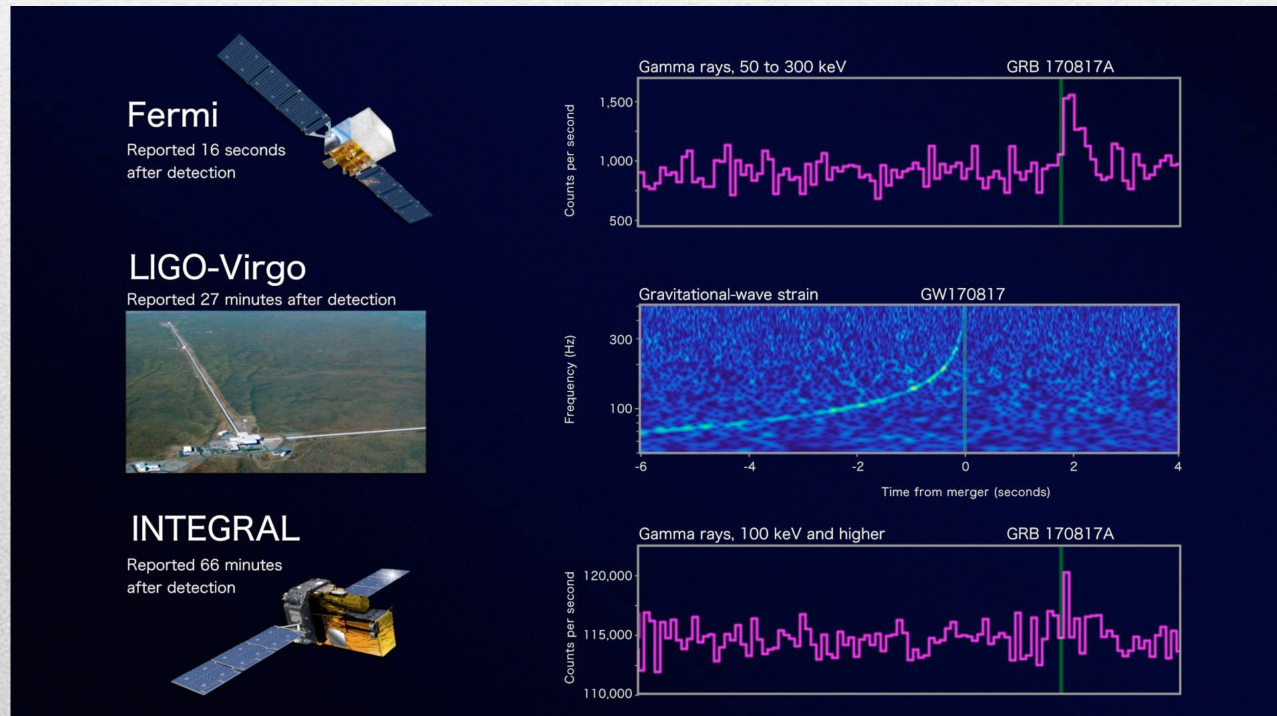
First electromagnetic counterpart of GW

August 17, 2017

LIGO and **Virgo** make first detection of gravitational waves produced by **colliding neutron stars**

Discovery marks first cosmic event observed in **both gravitational waves and light.**





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**