Croatian Teacher Programme

Uvod u astročestičnu fiziku

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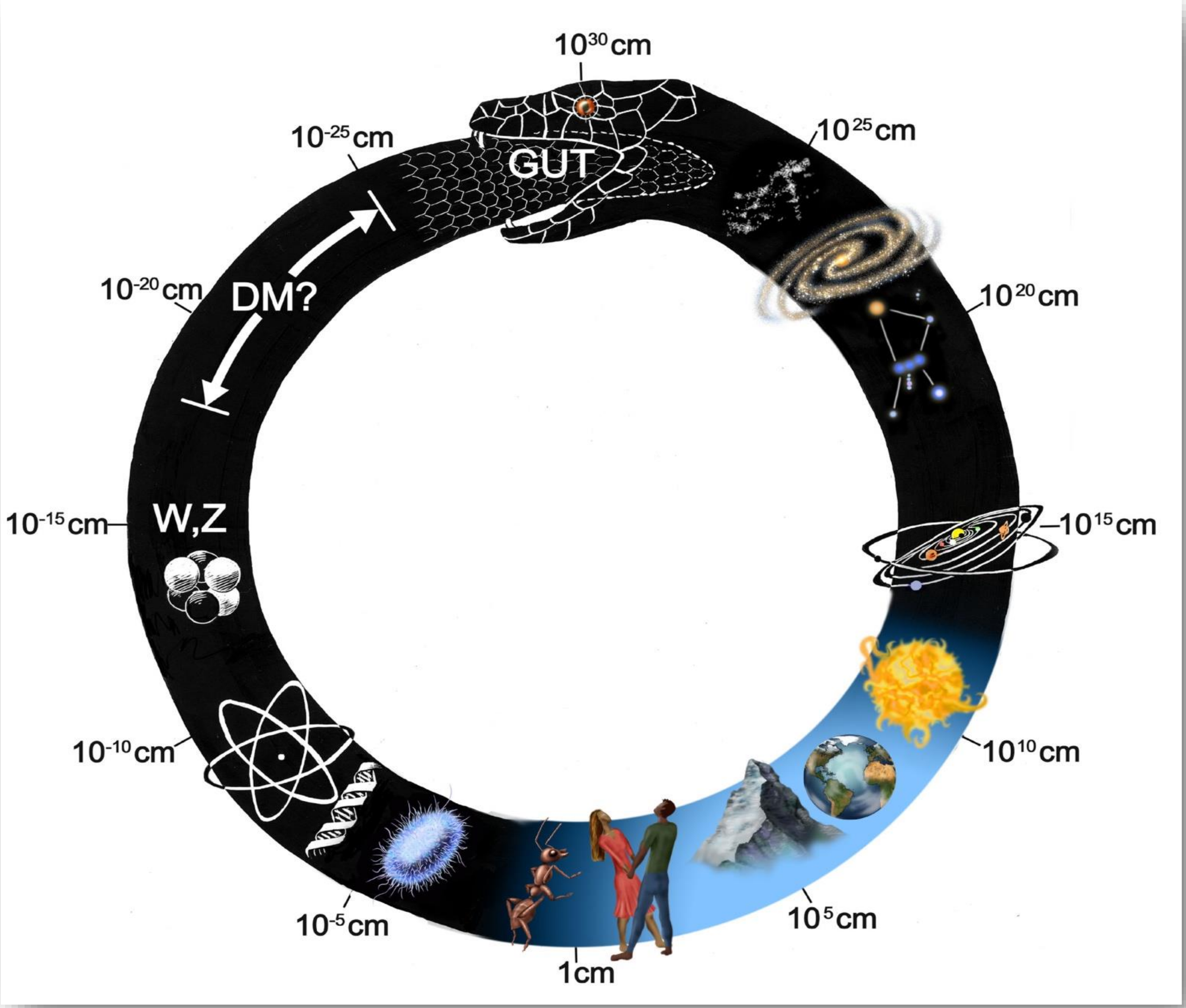
Sveučilište u Splitu - FESB

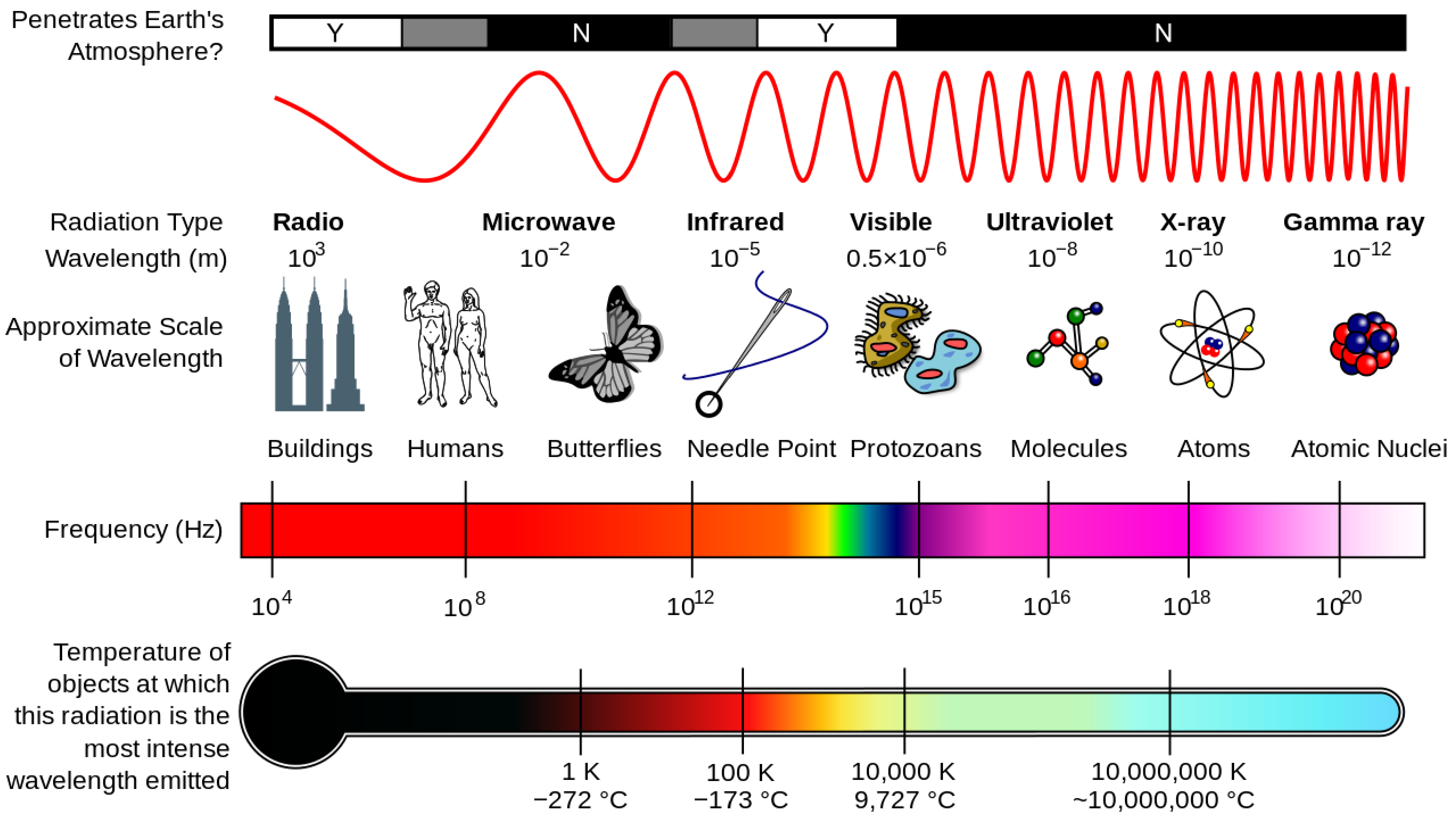
Zahvaljujem kolegi Nikoli Godinoviću

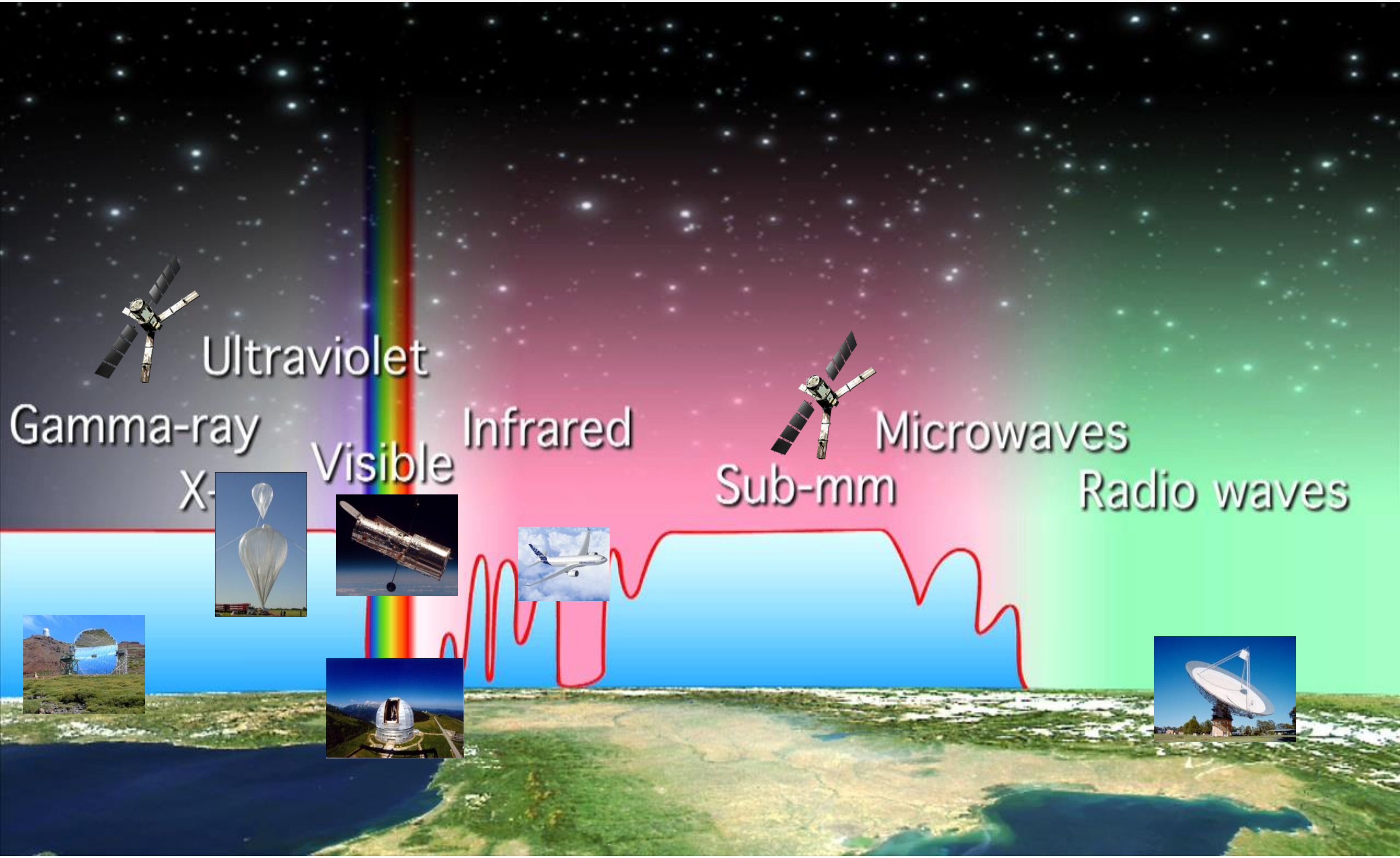
CERN, 18. travnja 2019.

Fizika velikog i malog

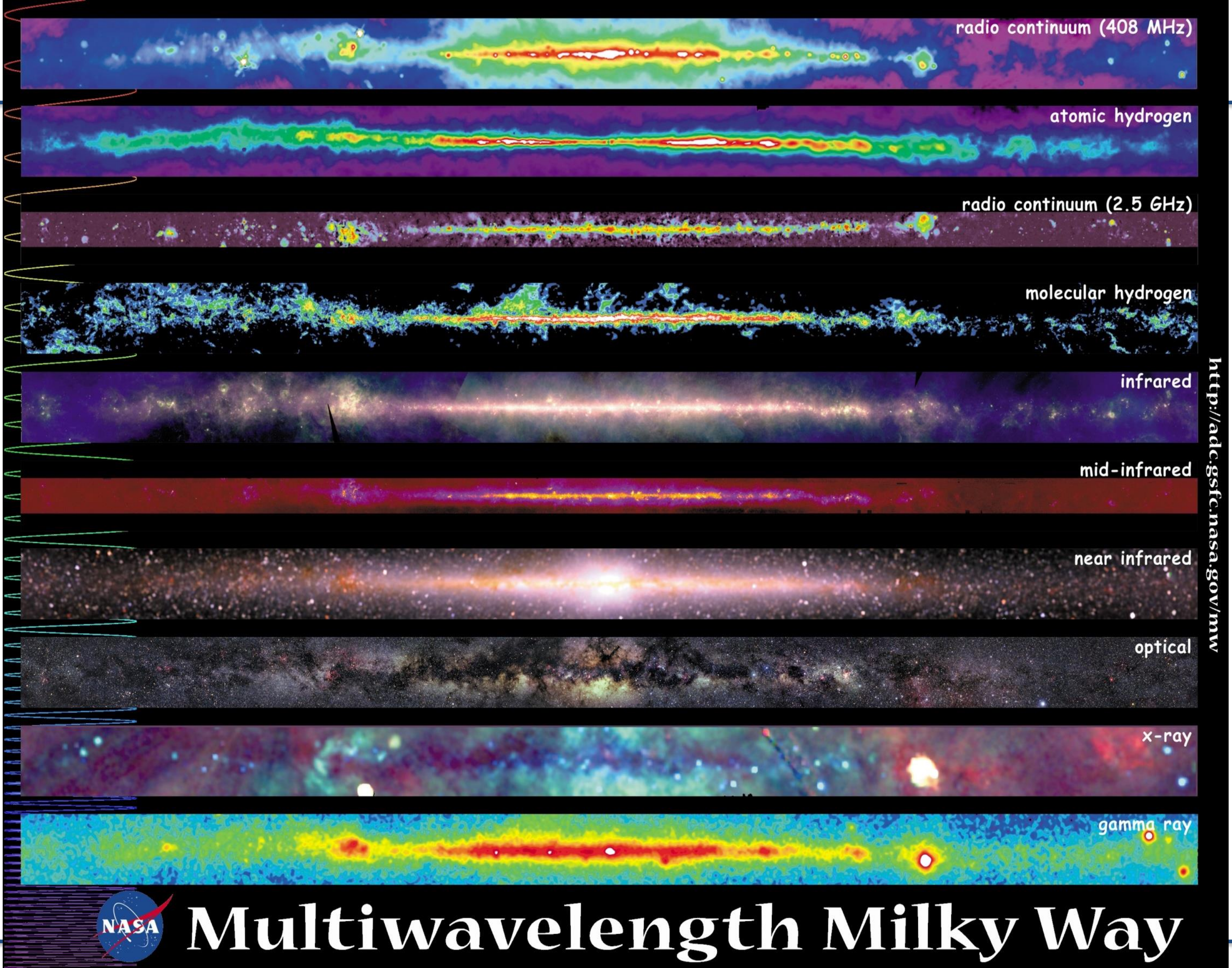


Elektromagnetski spektar



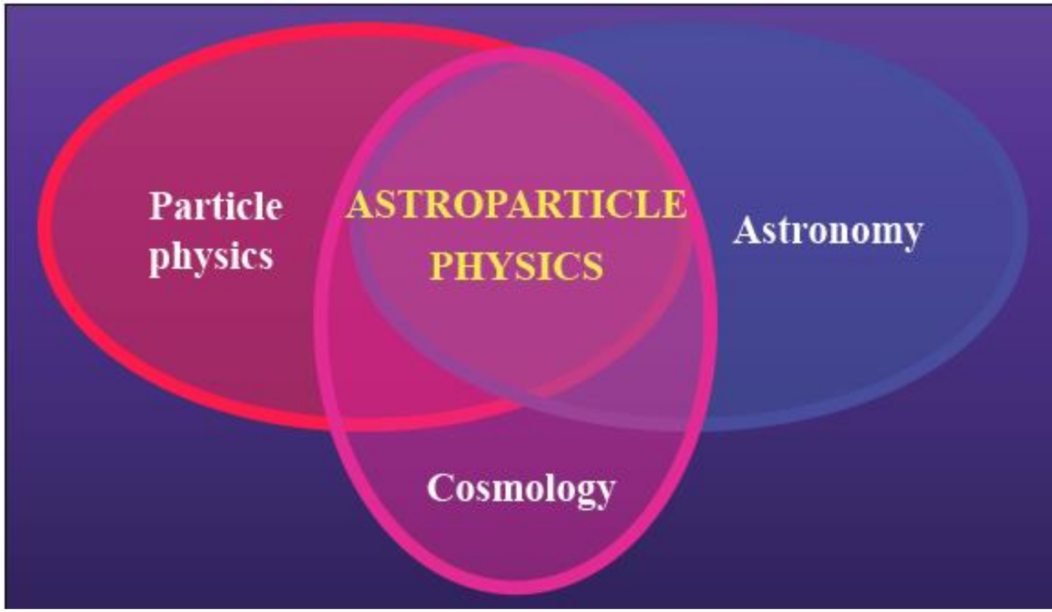

Ultraviolet
Gamma-ray
X-
Visible
Infrared
Microwaves
Sub-mm
Radio waves

Mliječna staza


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

Astročestična fizika

- **Što istražuje**
  - Najenergetskije procese u svemiru
  - Najranije periode razvoja svemira
  - “Nevidljive” dijelove svemira



- **Čime istražuje**
  - Teleskopi/detektori visokenergijskih kozmičkih i gama zraka
  - Detektori neutrina
  - Detektori gravitacijskih valova

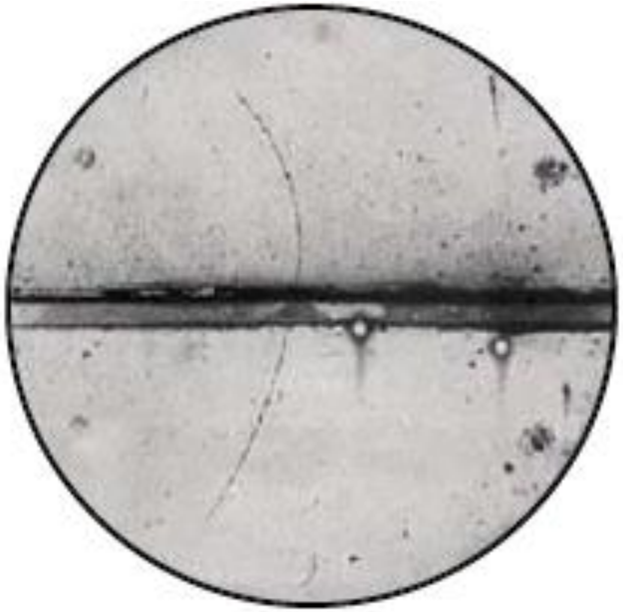
- Koristi tehnike iz fizike čestica, astrofizike, kozmologije, sve do napredne astronomije
- Koristi fiziku čestica za objašnjavanje svemira, i čestice iz vanjskih dijelova svemira za napredak fizike čestica

Kozmičke zrake otkrivene 1912. godine

August 1912: Victor Hess after his highest balloon flight. Hess' discovery of cosmic rays was acknowledged with the 1936 Nobel Prize in Physics.

Otkrića novih čestica u kozmičkim zrakama

Godina	***Otkriće***
1932.	pozitron
1937.	mion
1947	pion
1956.	antineutrino

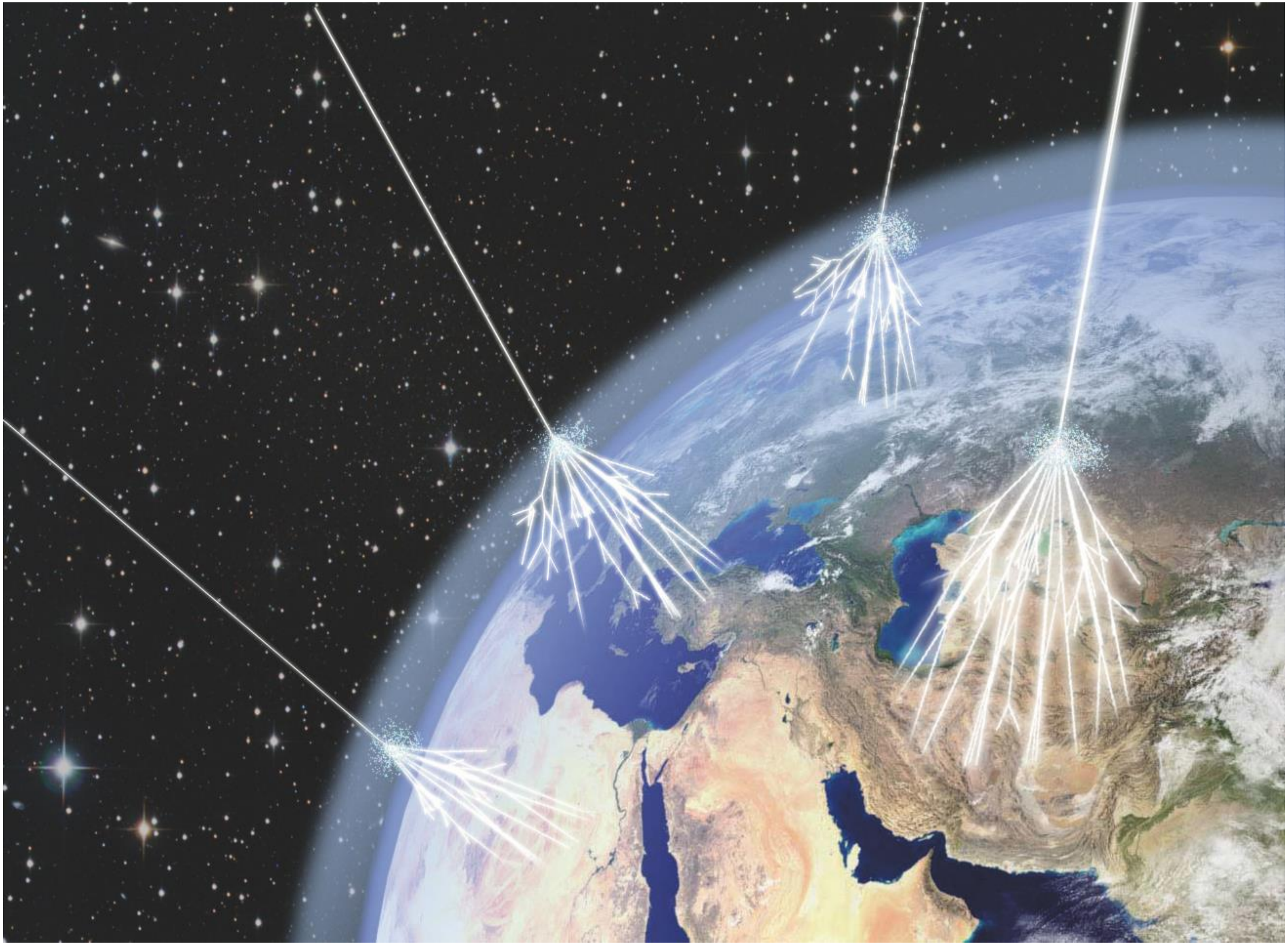


One of the first positron tracks in a cloud chamber, recorded by Carl D. Anderson in 1932.

Važni datumi u astročestičnoj fizici

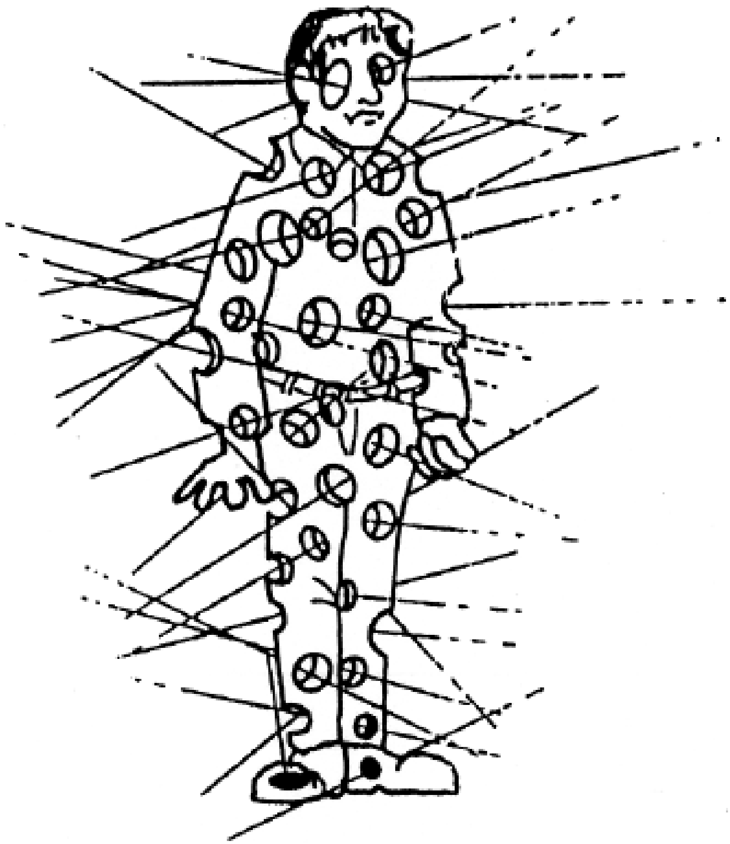
- **1912:** Victor Hess climbs to 5200 metres in a balloon and demonstrates the existen of radiation coming from the sky.
- **1930:** Pierre Auger discovers particle showers, which come from the collisions between cosmic rays and particles of the atmosphere.
- **1932:** Carl Anderson discovers the positron; the first antiparticle.
- **1937:** For the first time, muons are observed in the tracks of a particle shower in a bubble chamber.
- **1956:** Frederick Reines & Clyde Cowan bring the neutrinos to the fore.
- **1965:** Arno Penzias & Robert Wilson discover the Cosmic Microwave Background.
- **1987:** Neutrino emissions by Supernova SN 1987A confirm theories about the origin of elements.
- **1989:** The first source of high-energy gamma rays is discovered.
- **1992:** The COBE satellite discovers the anisotropy of the Cosmic Microwave Background.
- **1998:** Cosmic neutrinos reveal the oscillatory nature of these particles.

Kozmičke zrake

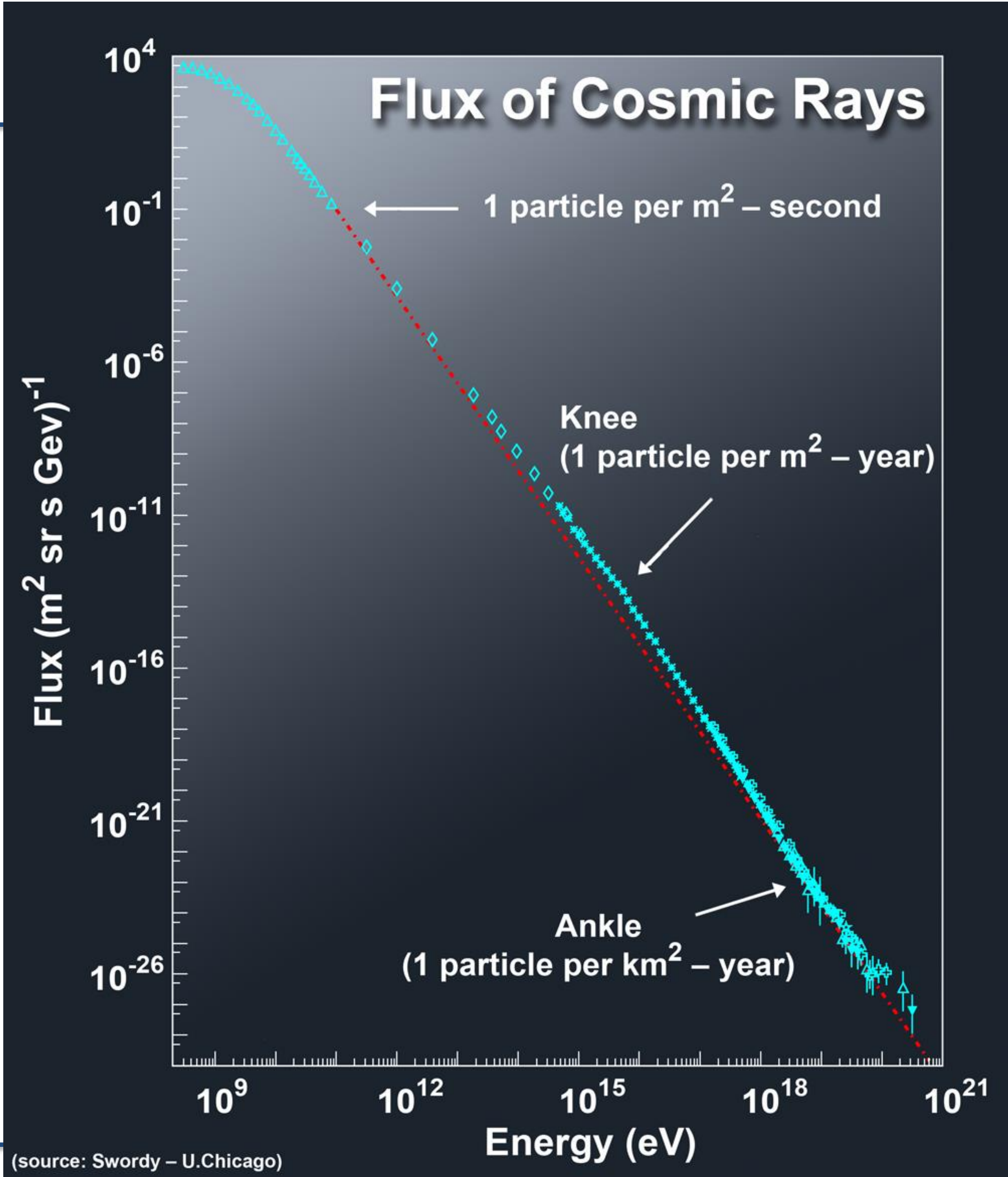


Kozmičke zrake – Osnovni podaci

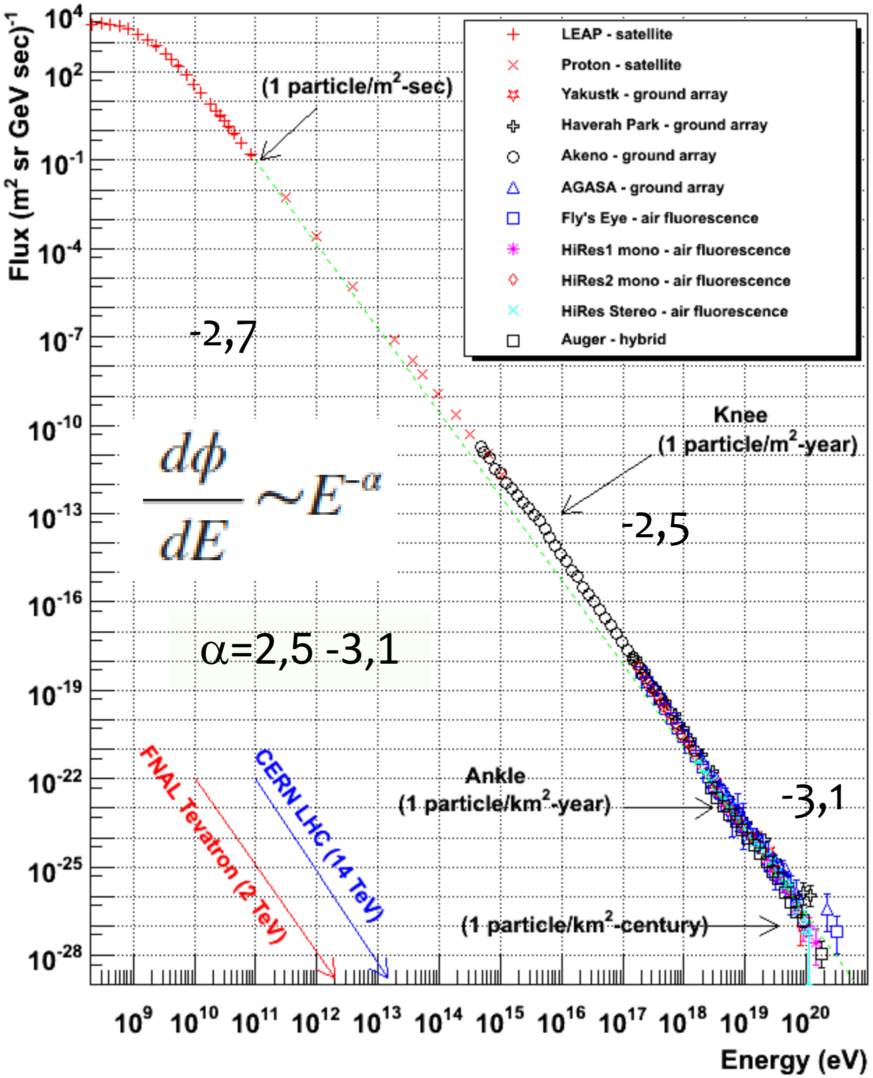
- Konstantno bombardiraju Zemlju
- Kroz vaše tijelo u sat vremena ih prođe oko 100 000
- Kada pogodi čip može promijeniti stanje memorije
- Može oštetiti živu stanicu
- Sastav
  - 89% protoni
  - 10% alfa čestice (jezgre He)
  - 1% ostale čestice



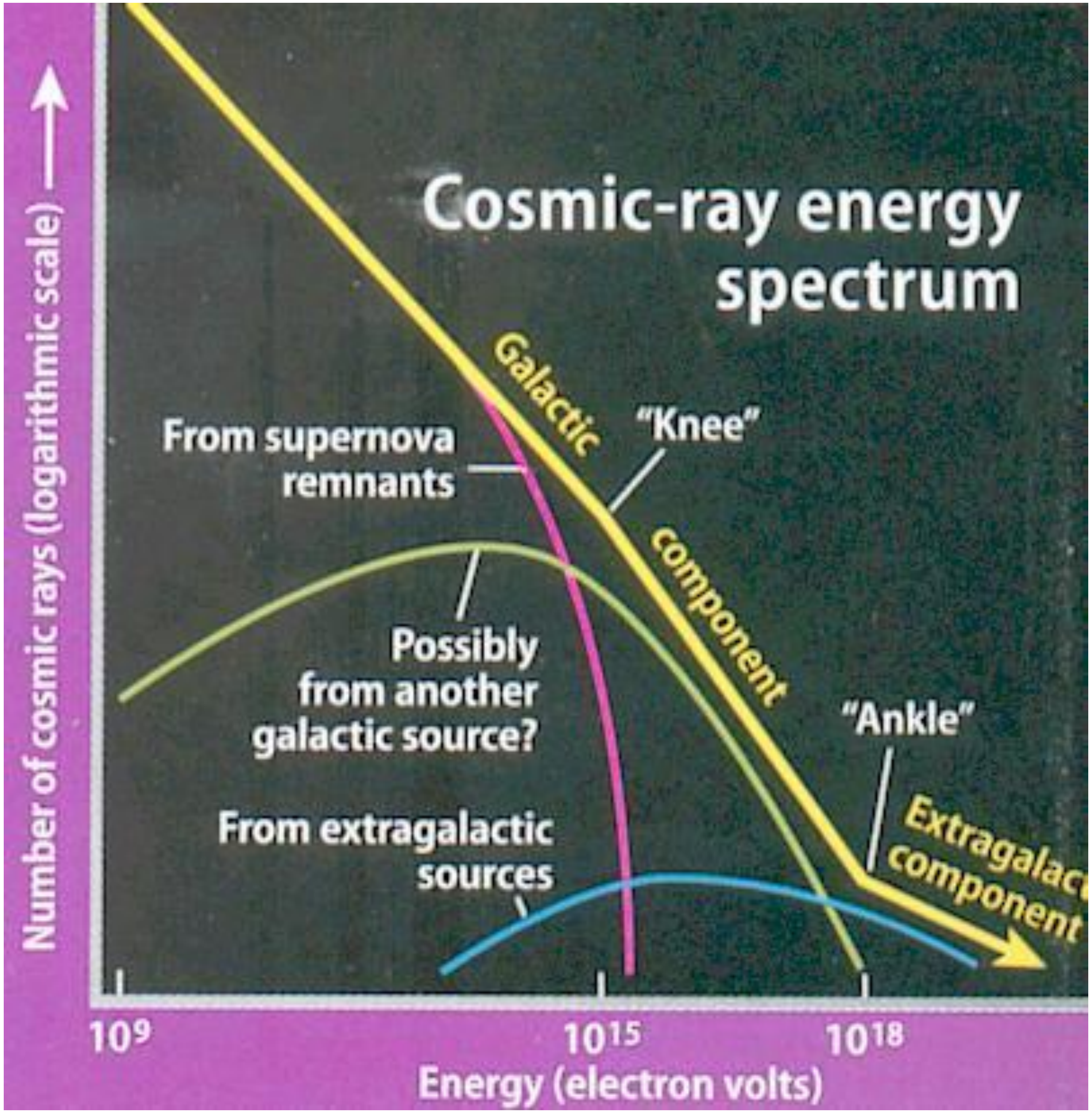
Kozmičke zrake – Energijski spektar



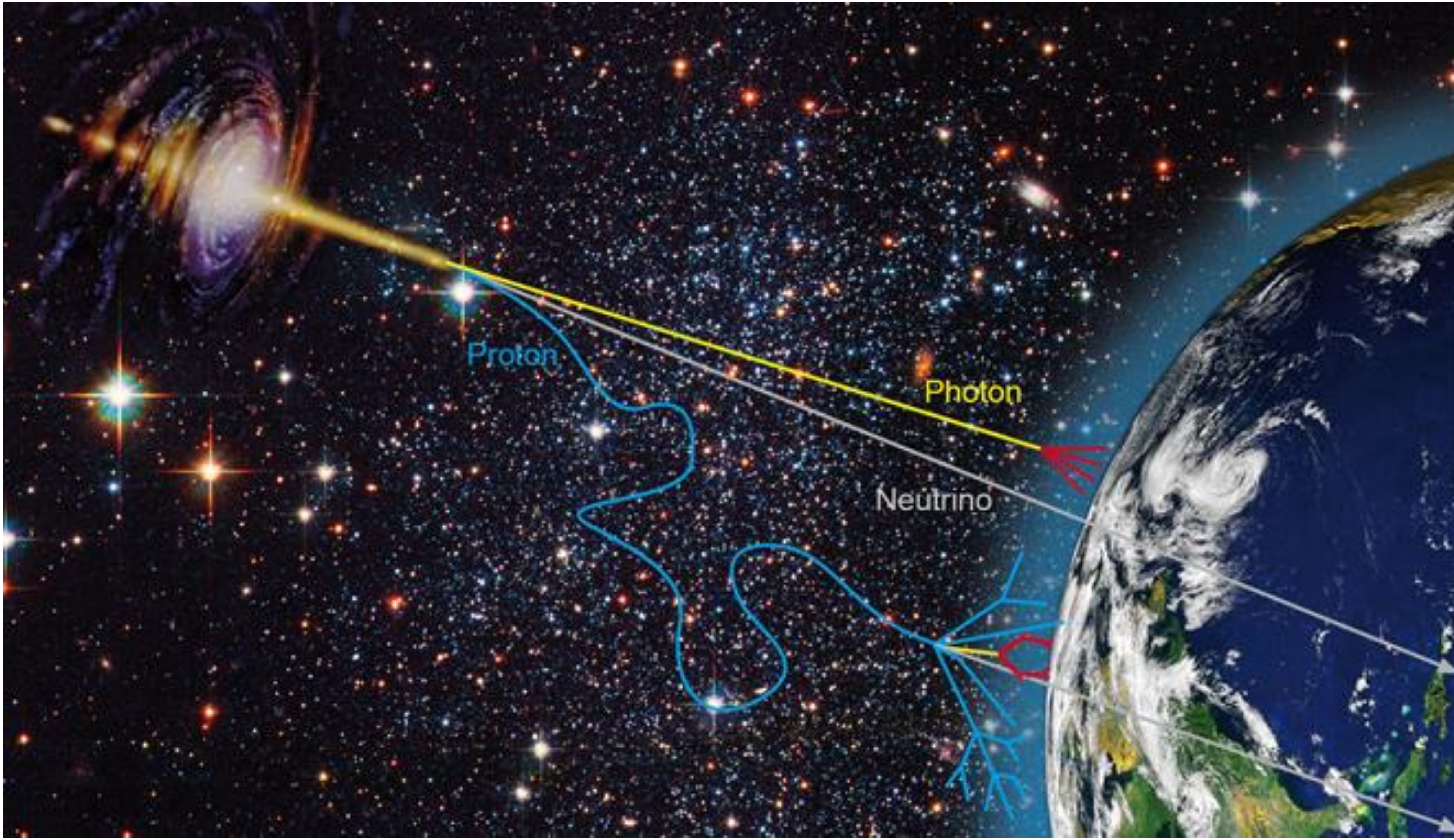
Kozmičke zrake – Energijski spektar



Odakle dolaze kozmičke zrake?



Kako se propagiraju kozmičke zrake?



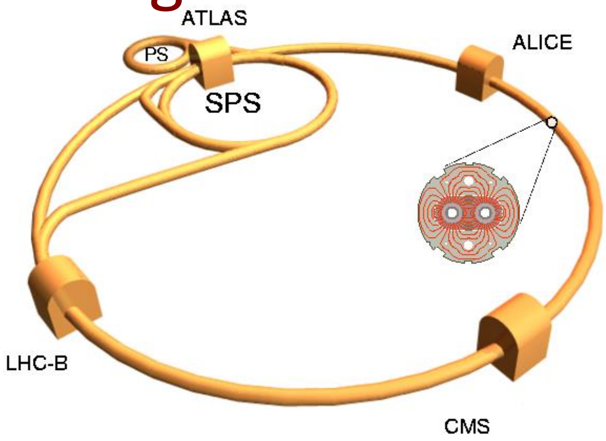
Neka od pitanja

- Koji su izvori kozmičkih zraka?
- Gdje se nalazi izvori?
- Kako funkcioniraju kozmički akceleratori
- Kakav je spektar, priroda i smjer kozmičkih zraka?
- Koji su fizikalni mehanizmi produkcije kozmičkih zraka?
- Koja je maksimalna energija?

Ubrzavanje čestica

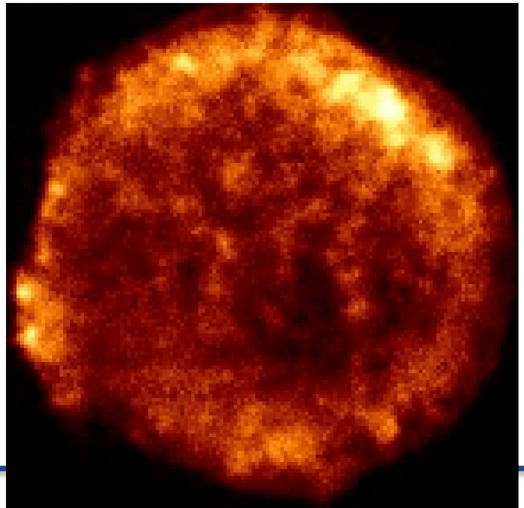
$$E \propto BR$$

Large Hadron Collider



$R \sim 10\,\text{km},\ B \sim 10\,\text{T} \quad \Rightarrow E \sim 10\ \text{TeV}$

Tycho SuperNova Remnant



$R \sim 10^{15}\,\text{km},\ B \sim 10^{-10}\,\text{T} \quad \Rightarrow E \sim 1000\ \text{TeV}$

Mehanizmi ubrzanja

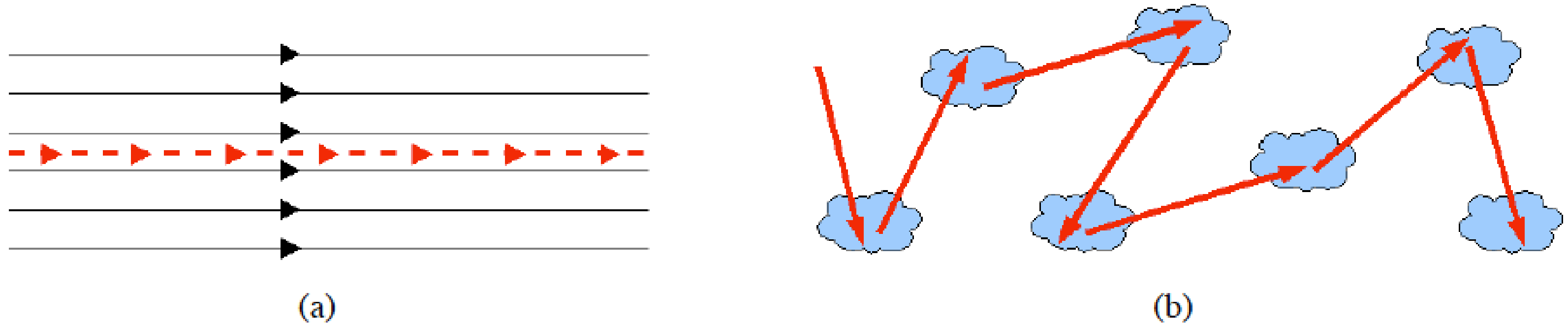


Fig. 4: (**a**) One-shot acceleration. (**b**) Diffusive shock acceleration

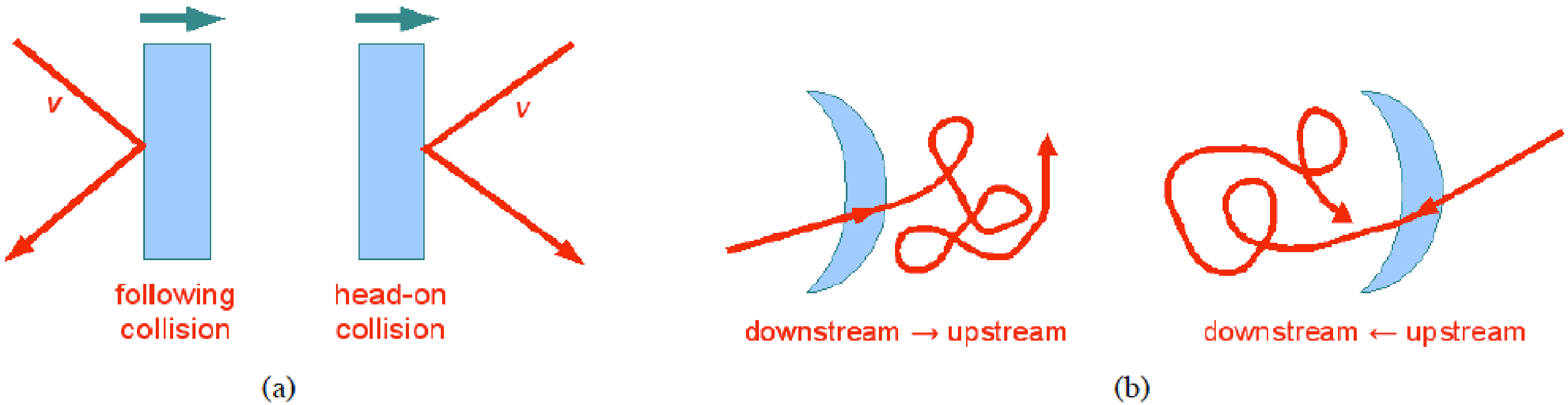
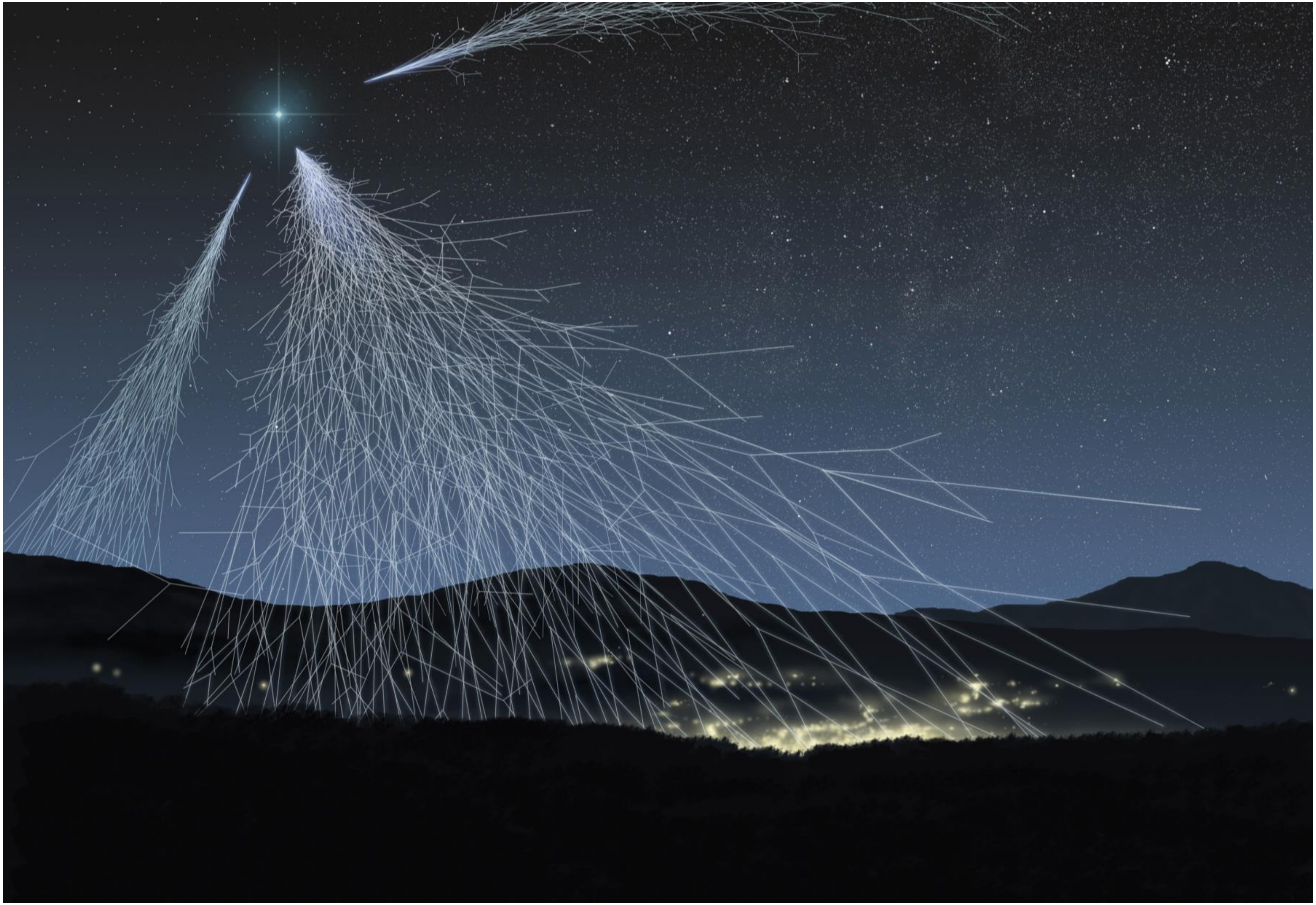


Fig. 5: (**a**) Second-order Fermi acceleration. (**b**) First-order Fermi acceleration.

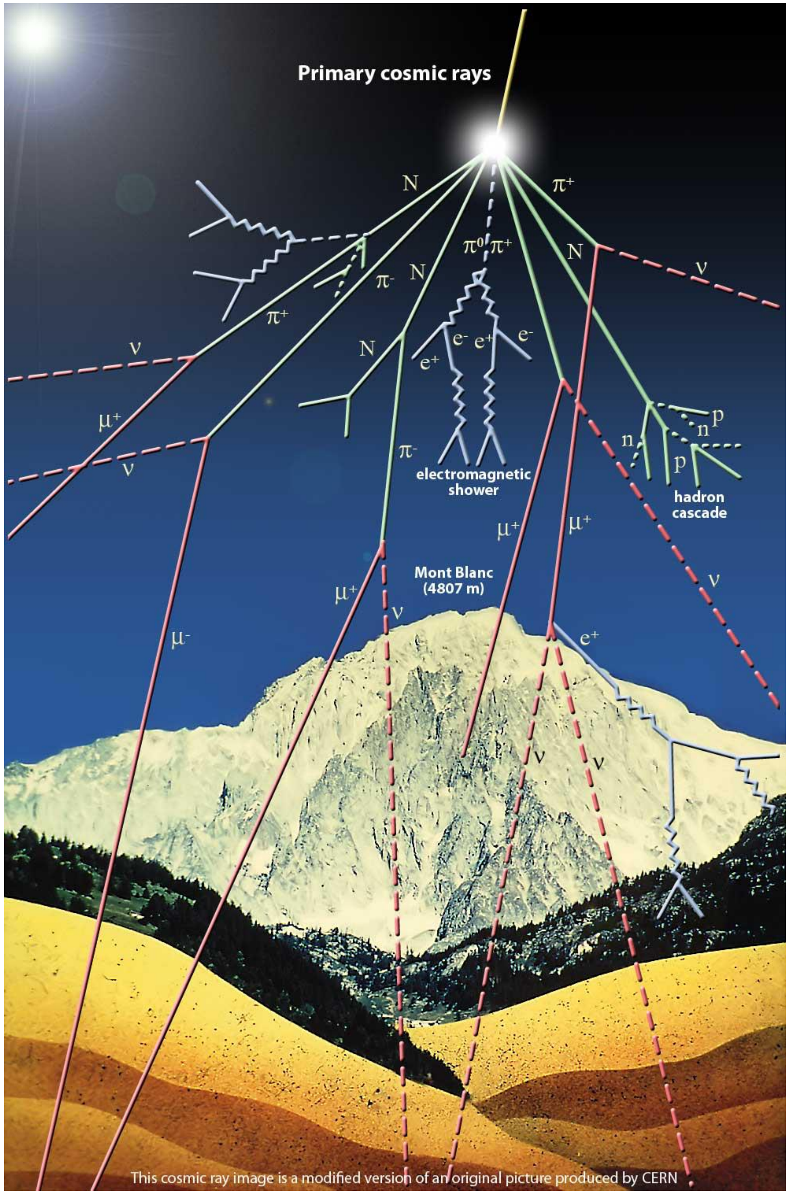
Astronomija kozmičkih zraka

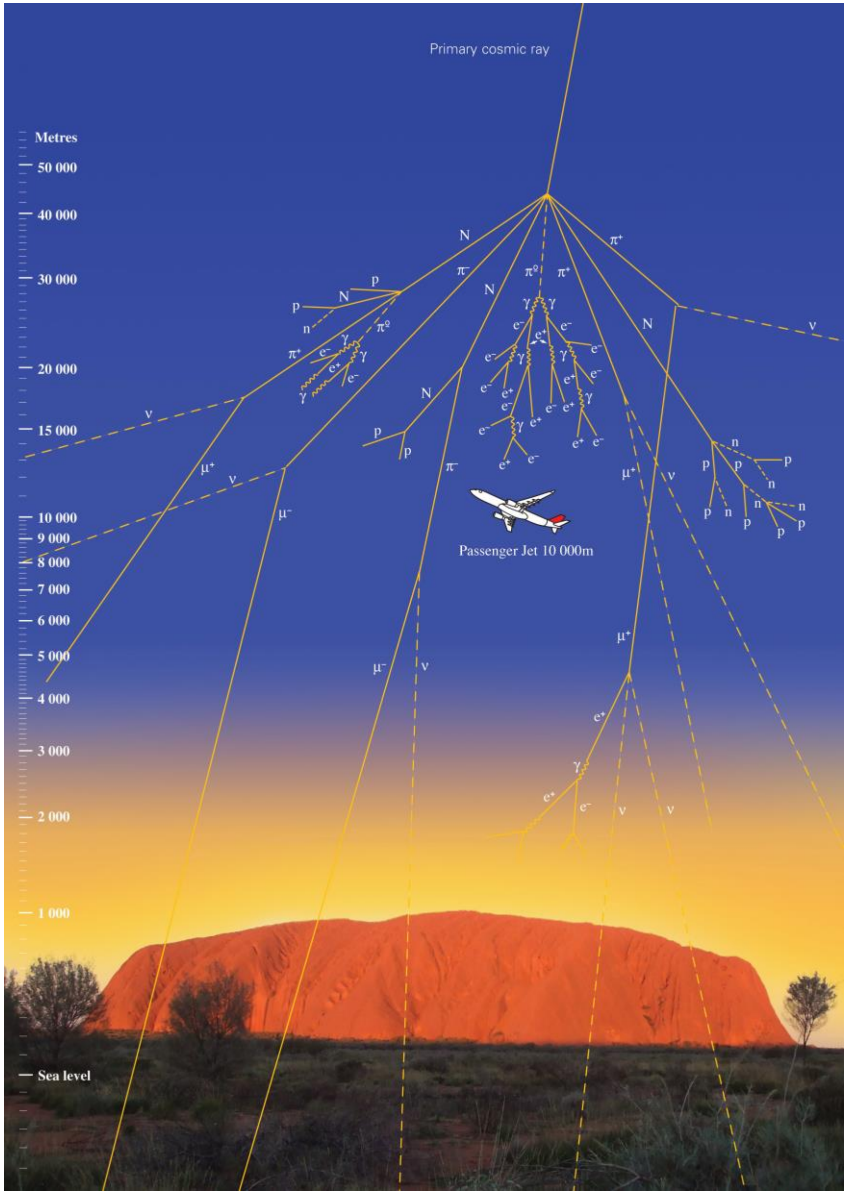
	ENERGIJA	INSTRUMENTI
LE	100 keV do 100 MeV	Sateliti
HE	100 MeV – 100 GeV	Sateliti: GLAST/Fermi
VHE	**100 GeV – 100 TeV**	**IACT** **MAGIC (HEGRA), HESS, VERITAS, CANGAROO III**
UHE	100 TeV – 100 PeV	AUGER
EHE	> 100 PeV	AUGER

Kako detektiramo kozmičke zrake?

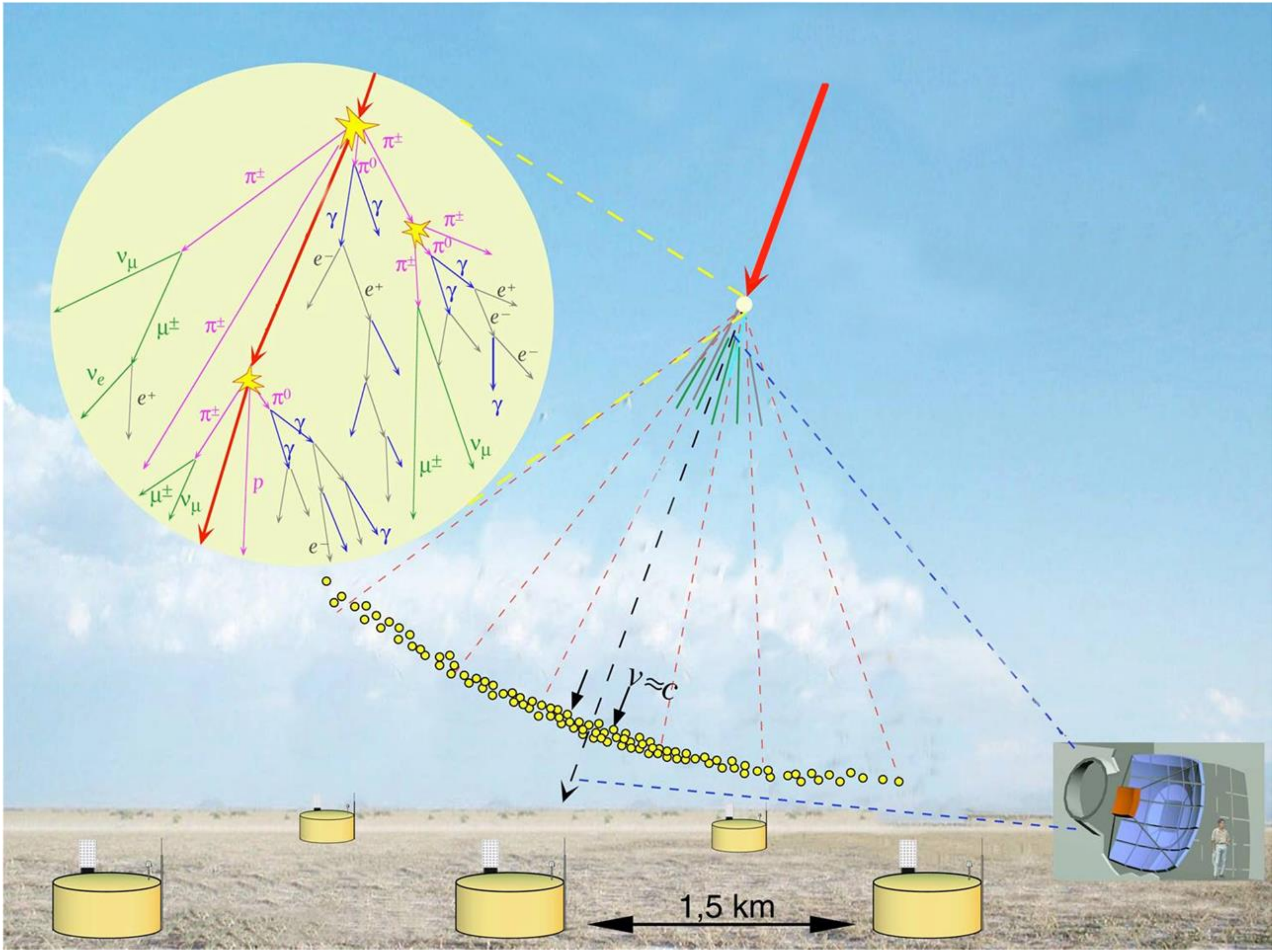


Pljusak čestica

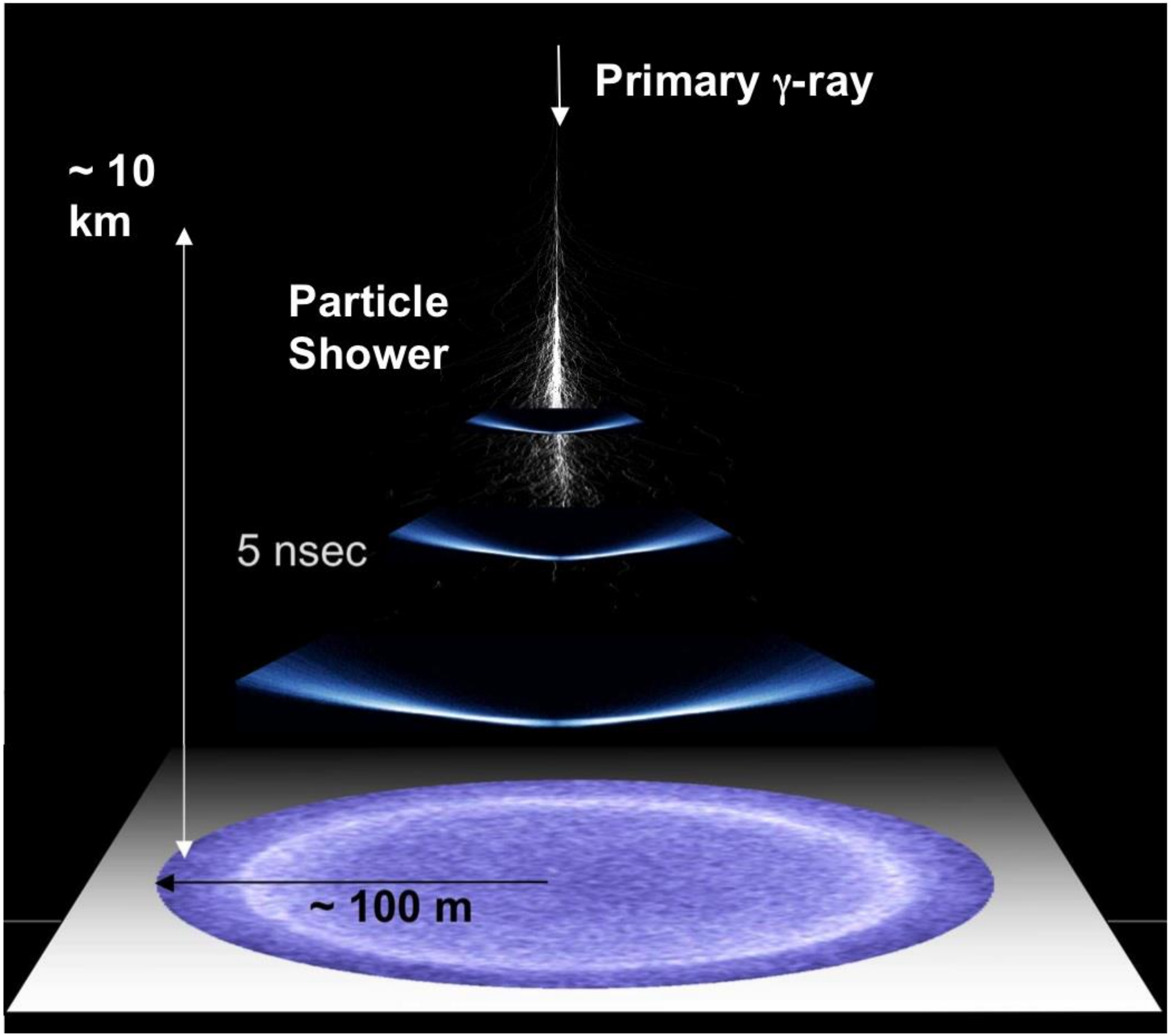




Gama zrake

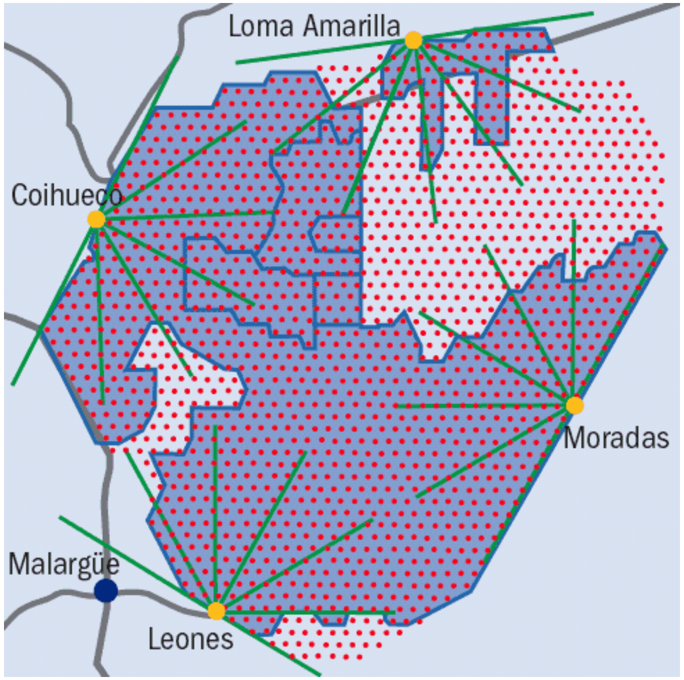


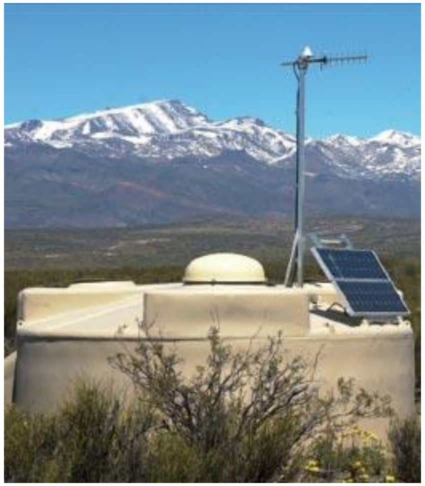
Gama zrake



Pierre Auger (PAO) Observatory (UHE-EHE)

- The world largest CR observatory, exposure area 40 000 km², duty cycle about 100 %
- 1600 water ČD at a distance of 1,5 km distributed over the area of 3000 km² – measure lateral profile EAS.
- 24 special telescopes record UV light (300-400 nm) emitted by excited nitrogen atoms in the atmosphere – measure longitudinal profile of EAS.
- PA energy range: (10^{16} - 10^{20}) eV

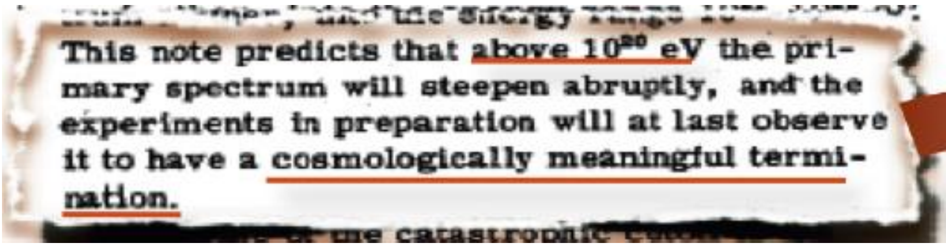




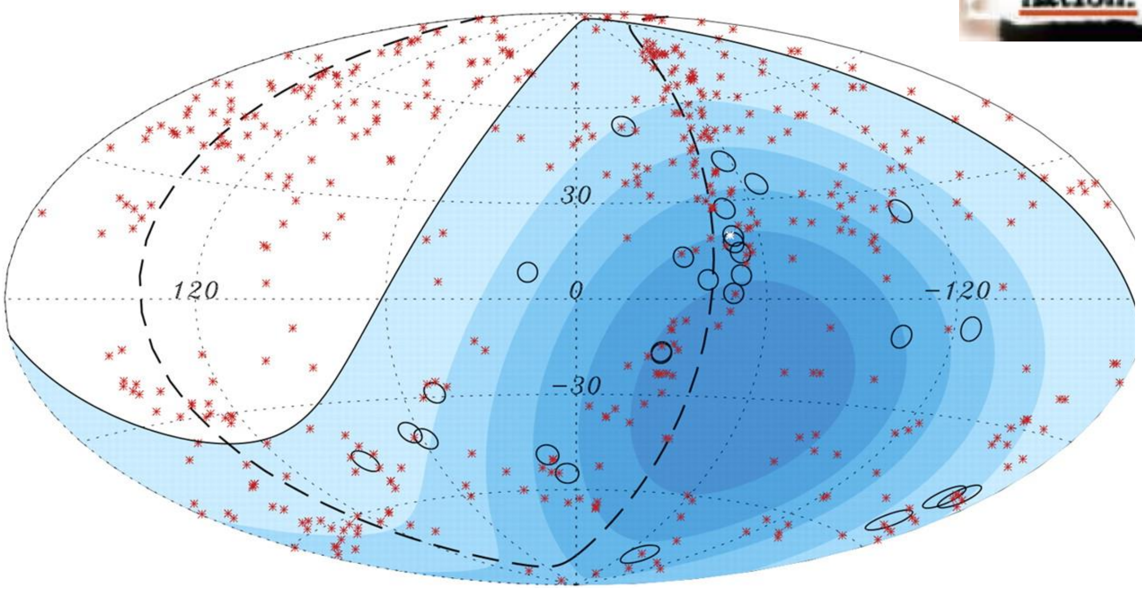
EHE CR – P. Auger Observatory

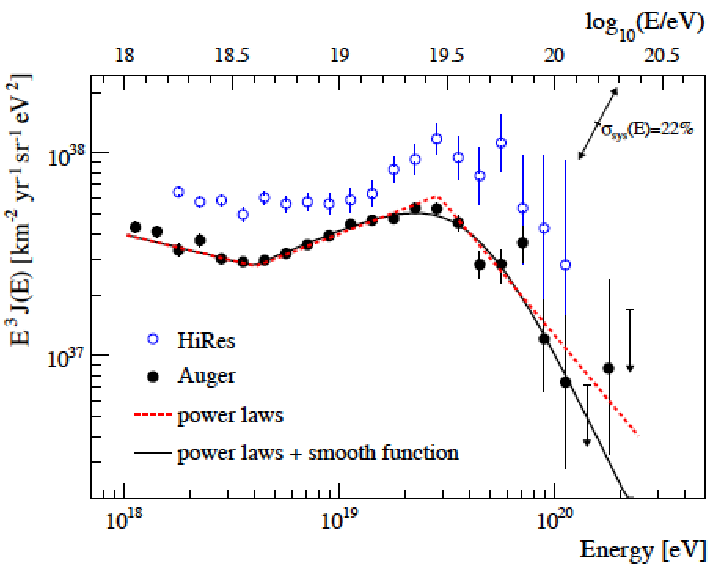
- PAO: AGN are sources of UHE (Science 318, 938 -943 (2007))
- UHE CR > 40 EeV ($4x10^{19}$ eV) are slightly deflected by galactic and intergalatic magnetic filed.

27 sources with E > $5,7x10^{19}$ eV
The highest energy event 3.2×10^{20} eV

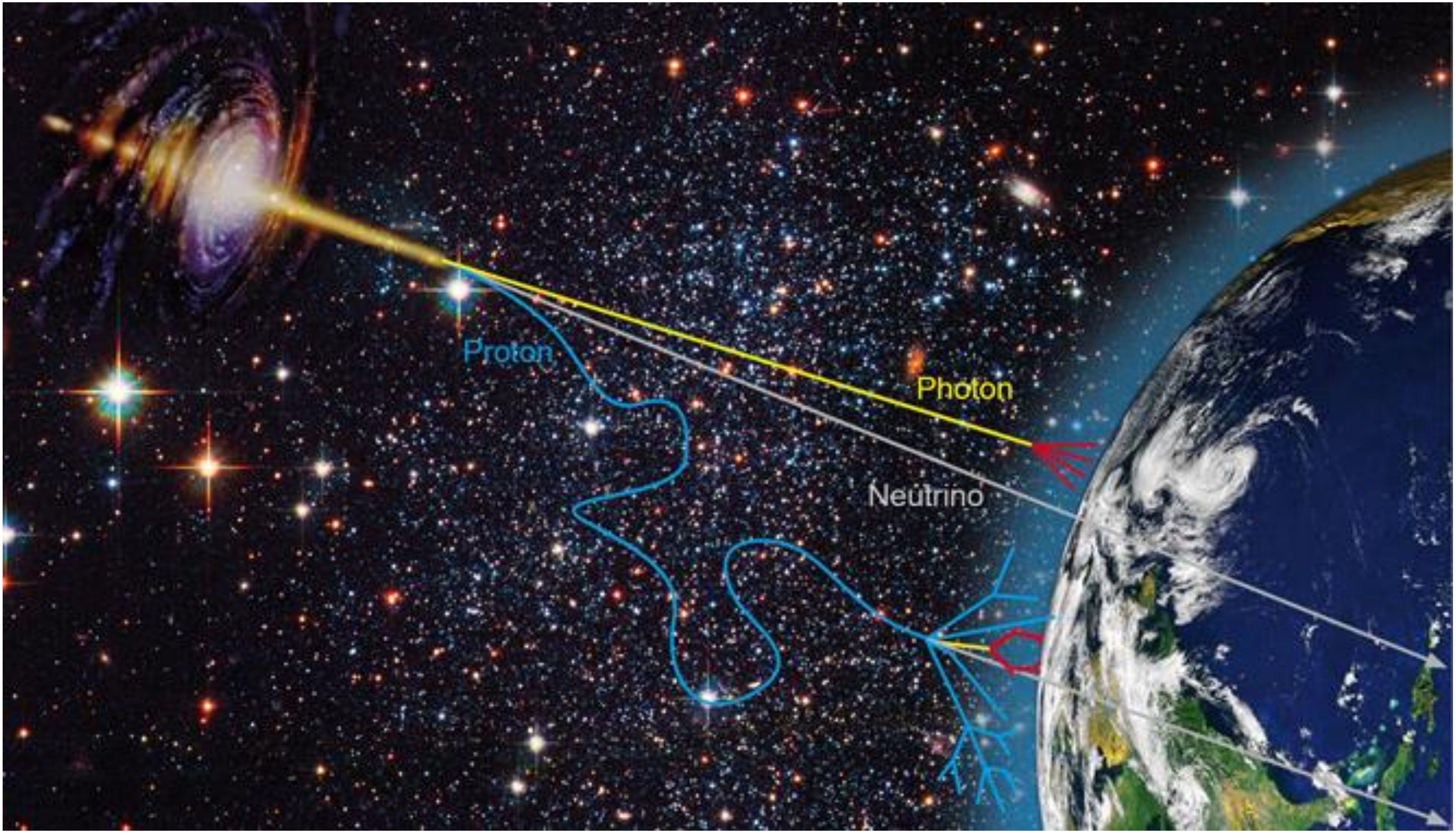


This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.





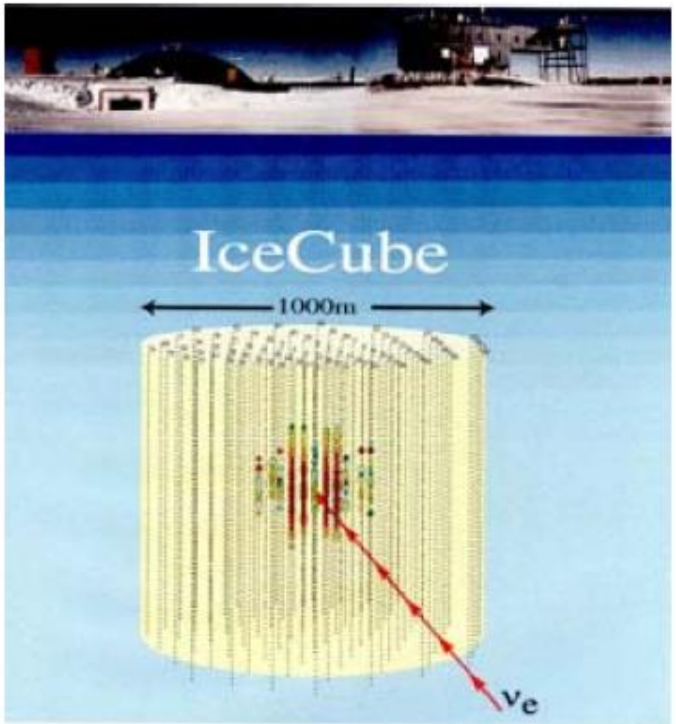
Kako se propagiraju kozmičke zrake?



Astronomija neutrinima

Astronomija neutrinima

- Neutrinos are elementary particles of very small mass (SuperKamiokande 1998).
- Intergalactic gas, dust and magnetic filed does not affect neutrinos.
- Neutrinos are ideal messenger from the region of the Universe unreachable by electromagnetic spectrum
- Universe is full of relic neutrinos of very low energy (400 neutrinos/m^3 at 1.9 K) generated 2 seconds after Bing Bang-a, passing through 50 l.y. thick lead.
- It will be wonderful to detect these neutrinos !?
- Neutrino detectors need a huge volume.
- Neutrino ocillation impose a lower limit on the heaviest neutrino mass of about 0.05 eV.
- Neutrino contribute at least 0.1% to cosmic matter



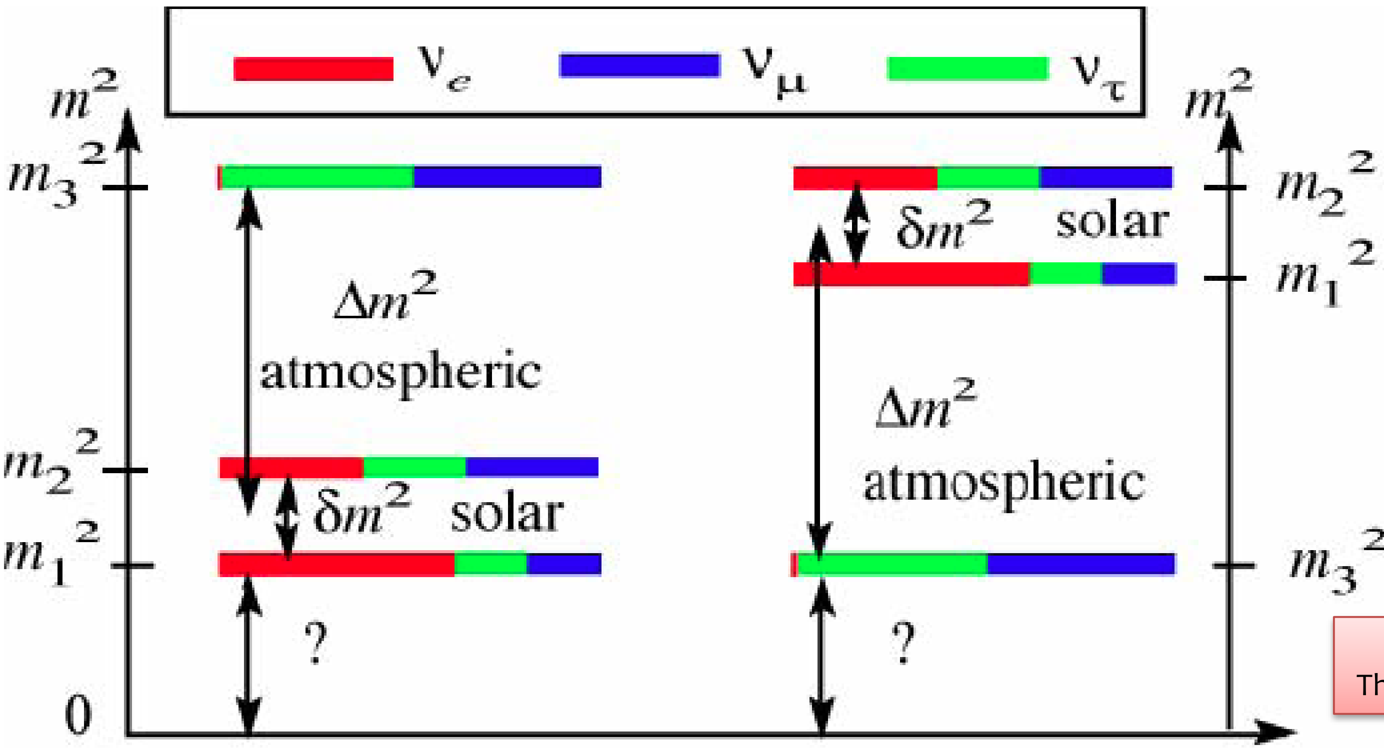
Fundamental question in neutrino physics

- Are neutrinos their own antiparticles (“Majorana particles”)?
- What are the masses of the neutrinos?
- How do different neutrinos mix?
- Are the CP, T and CPT symmetries broken by neutrinos?
- Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the Universe?
- Are there additional light (“sterile”) neutrino types beyond the three known (e, μ and τ) flavors?
  - “Strange/Puzzle” results of LSND experiment not confirmed by any other experiment
    - Muon antineutrino has been produced but detected a significant appearance of electron antineutrinos over 30 m distance
    - This results could not be accommodated with all the other results on oscillations
    - Expect by introducing a fourth neutrino mass te around 1 eV

Neutrino masses – current knowledge

Normal hierarchy

Inverted hierarchy



$|\Delta m^2_{32}| = (2.4 \pm 0.3) \cdot 10^{-3}\ eV^2$

$\Delta m^2_{21} = (8.3 \pm 0.3) \cdot 10^{-5}\ eV^2$

$\theta_{12} = 33^0 \pm 2^0$

$\theta_{23} = 45^0 \pm 3^0$

$\theta_{13} < 10^0$

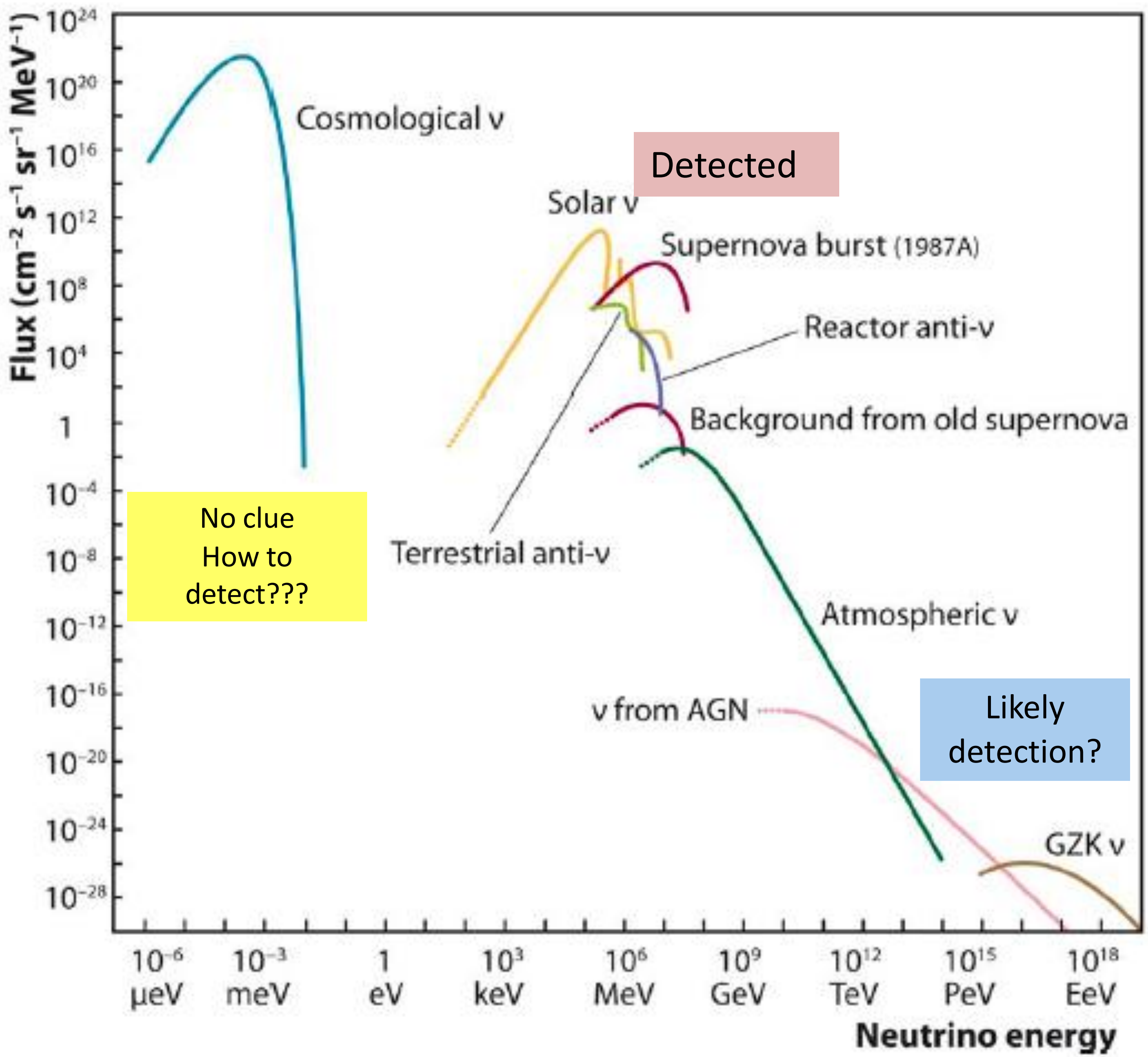
Neutrino oscillations:
The heaviest nutrino mas < 0.05 eV

$$\nu_l = \sum U_{li} \nu_i \ ; \ \ l = e, \mu, \tau, \ \ i = 1, 2, 3,$$

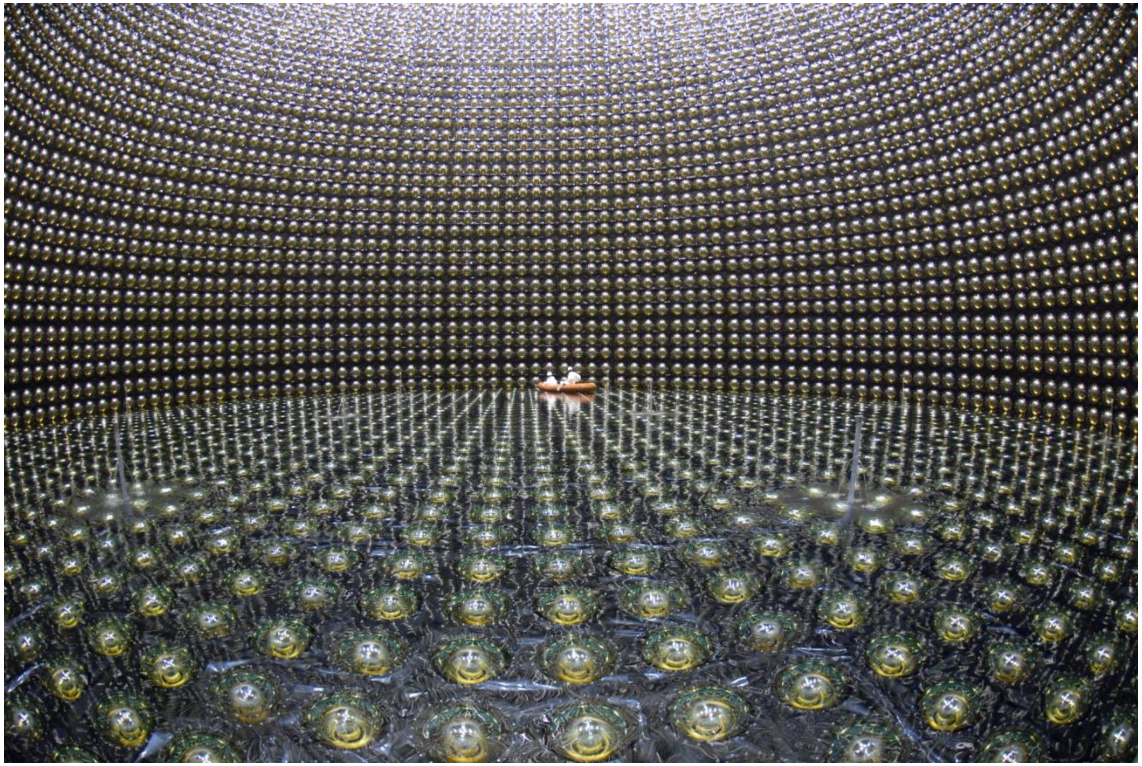
Weak eigensate ≠ mass eigenstate if neutrino have mass

We do not know the sign of Δm^2_{32} so we do not know if m_3 is heavier or lighter than m_1 and m_2,
We know: $m_2 > m_1$.

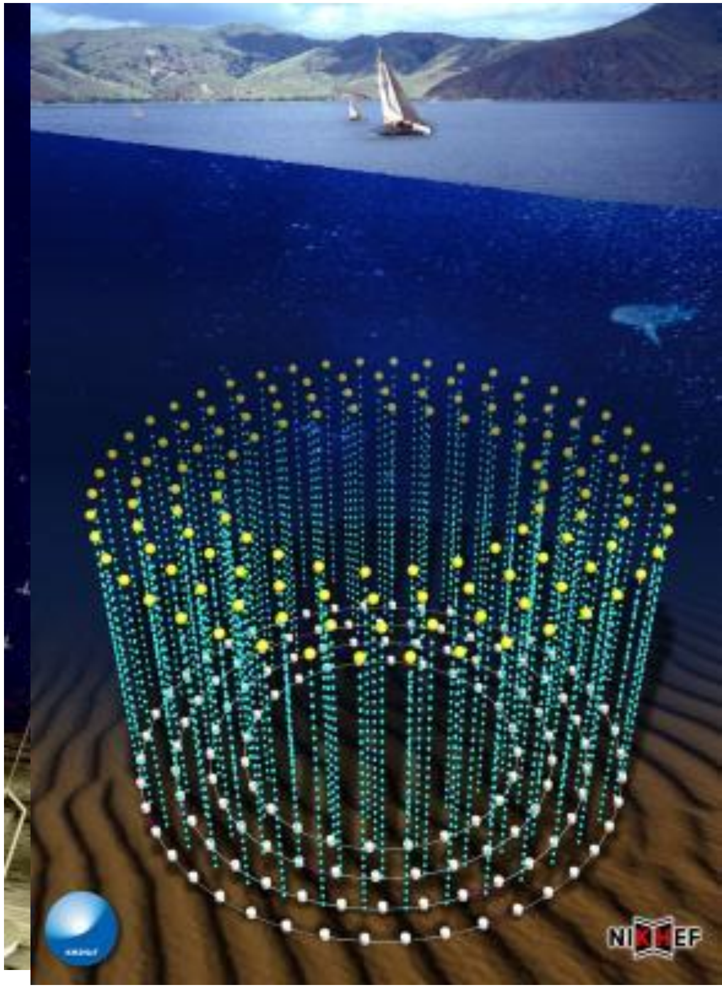
Neutrino spectrum



Neutrino astronomy



SuperKamiokande neutrino detector 600 m underground filled with 50 000 tons of ultra pure water equipped with 11 146 photomultiplier tubes of 50 cm in diameter



ANTARES – near Marseille

Neutrino observatories

- ► Under sea/water
  - ANTARES
  - NESTOR
  - DUMAN
  - Baikl

- ► Under ice
  - AMANDA
  - IceCube

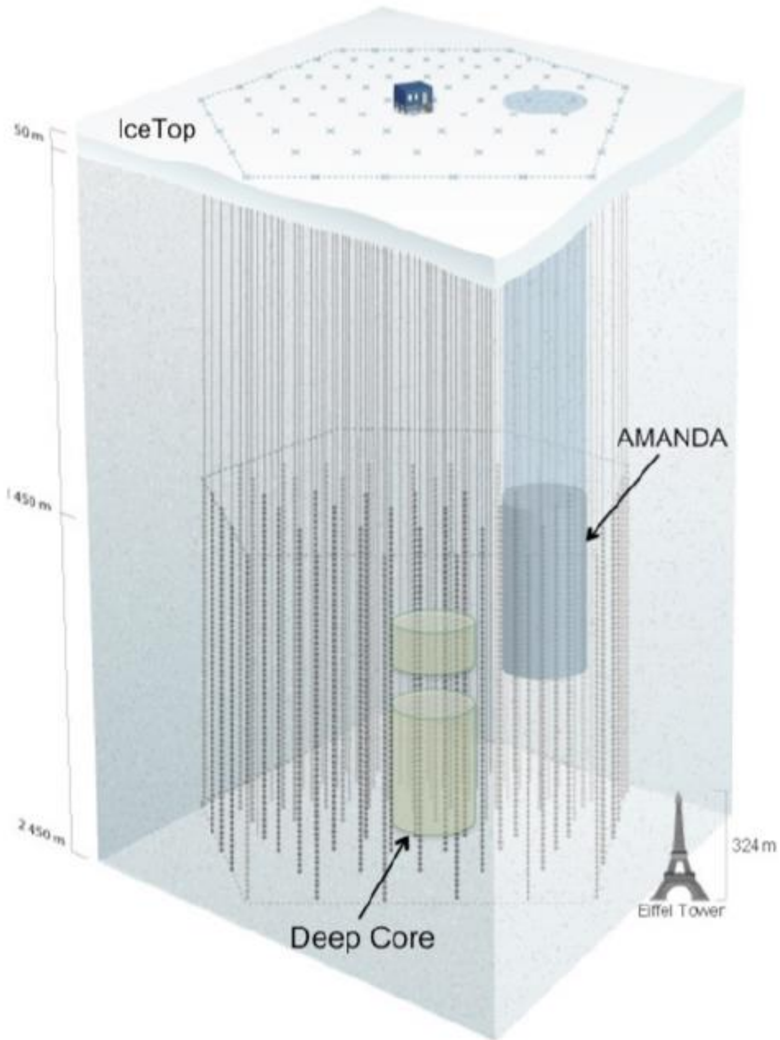


Figure 5: The IceCube Observtory, including the deep ice array, IceTop, AMANDA, and Deep Core. For comparing sizes the image of the Eiffel tower is also shown.

Events in IceCube

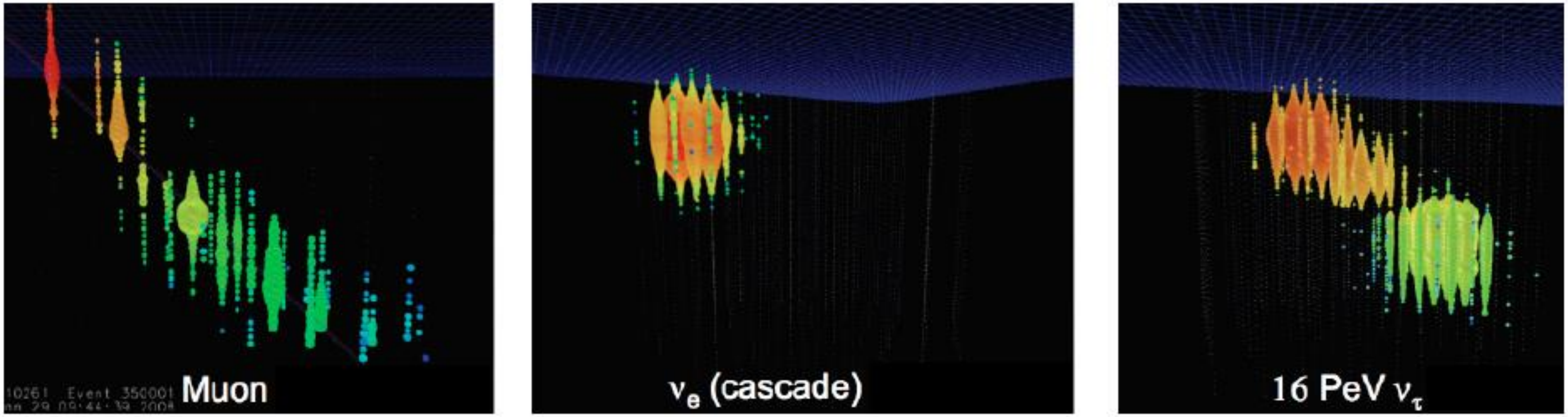
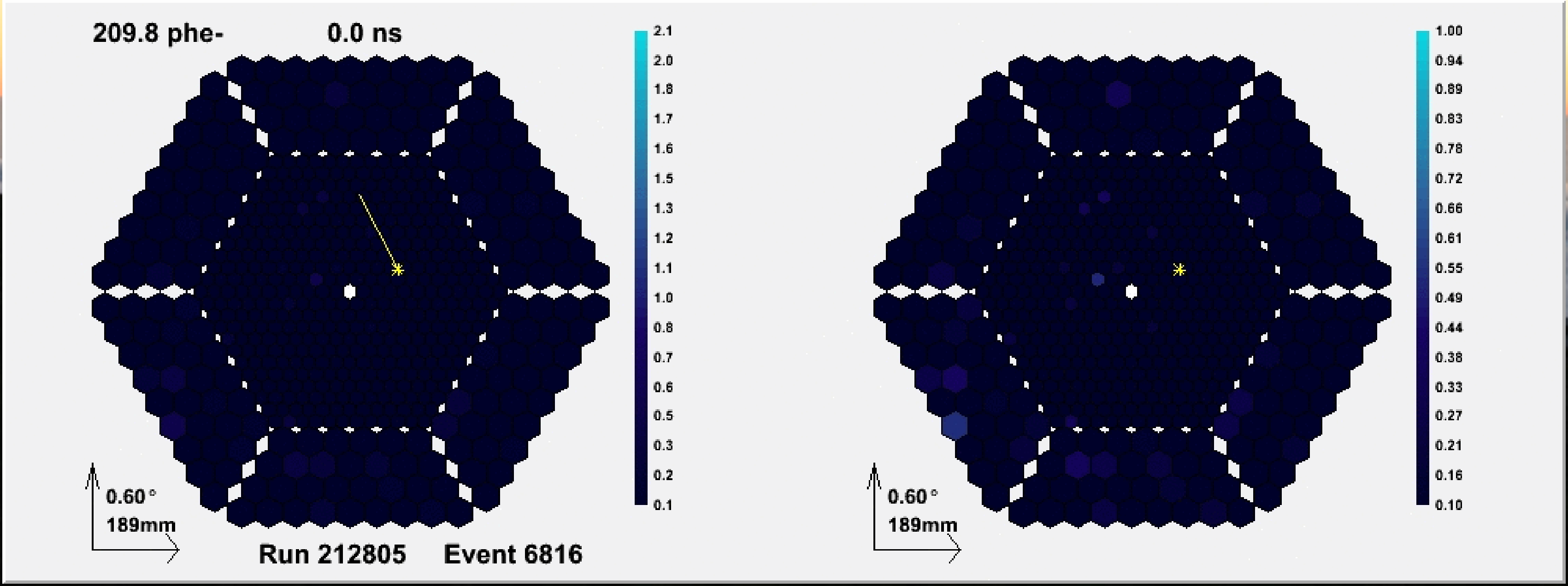


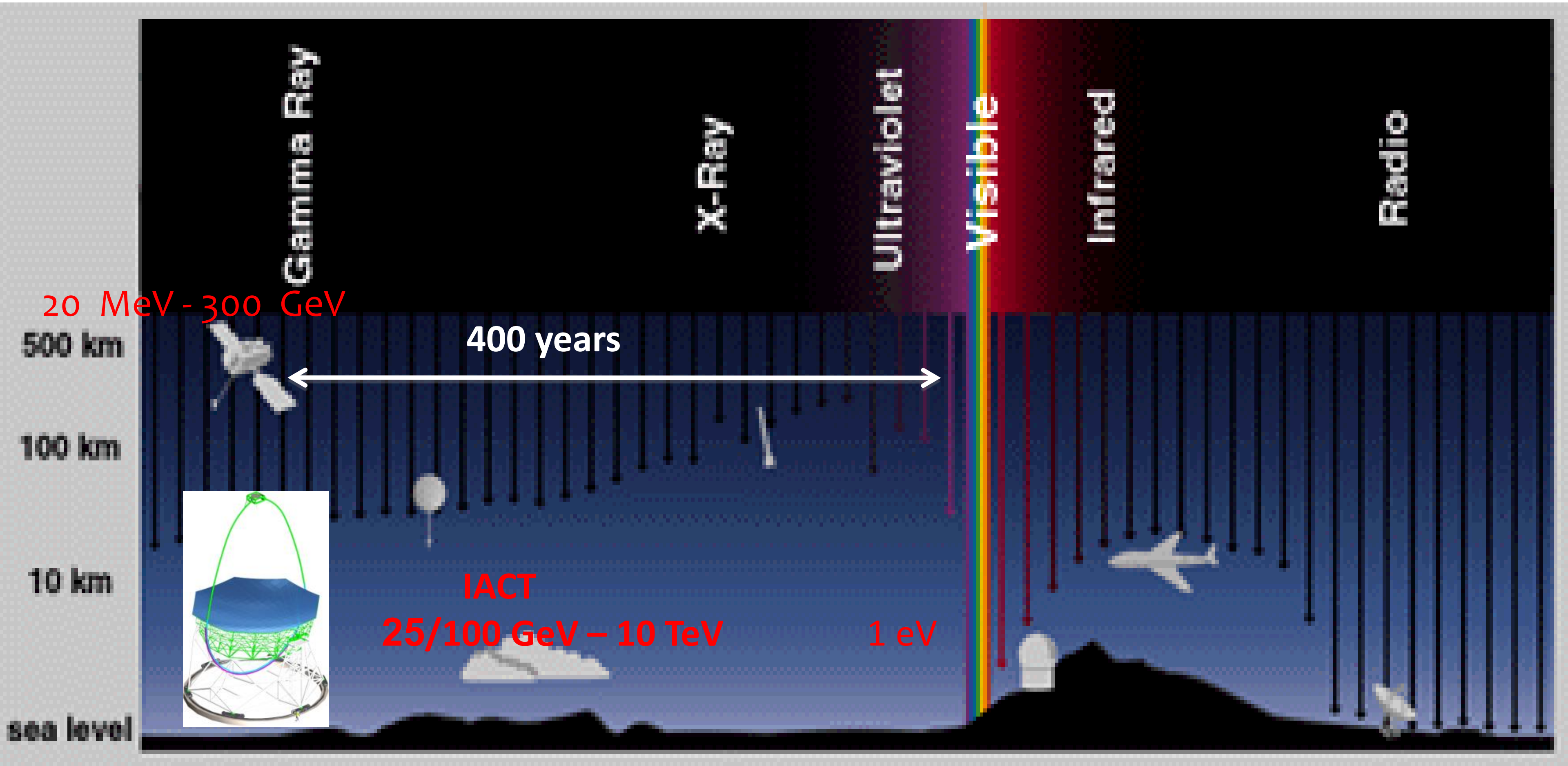
Figure 4: Simulated events in the IceCube detector, visualized using the IceCube event display, showing the 3 typical topologies discussed in Sec 3. The shading represents the time sequence of the hits. The size of the dots corresponds to the number of photoelectrons detected by the individual photomultipliers. From left to right: a muon event of 100 TeV, a cascade event induced by a 100 TeV ν_e, and a double bang event induced by a 16 PeV ν_τ.

VHE gamma ray Astronomy

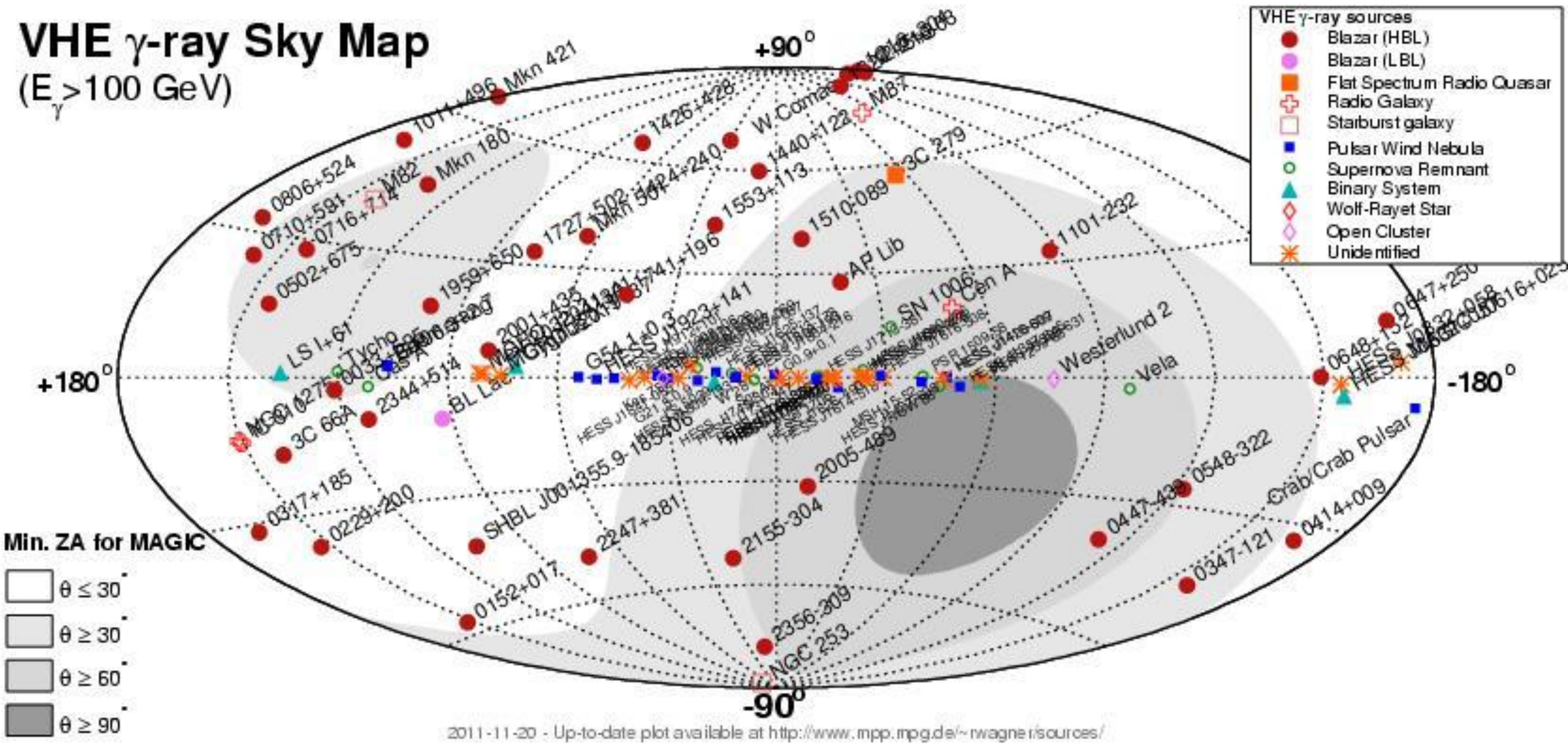


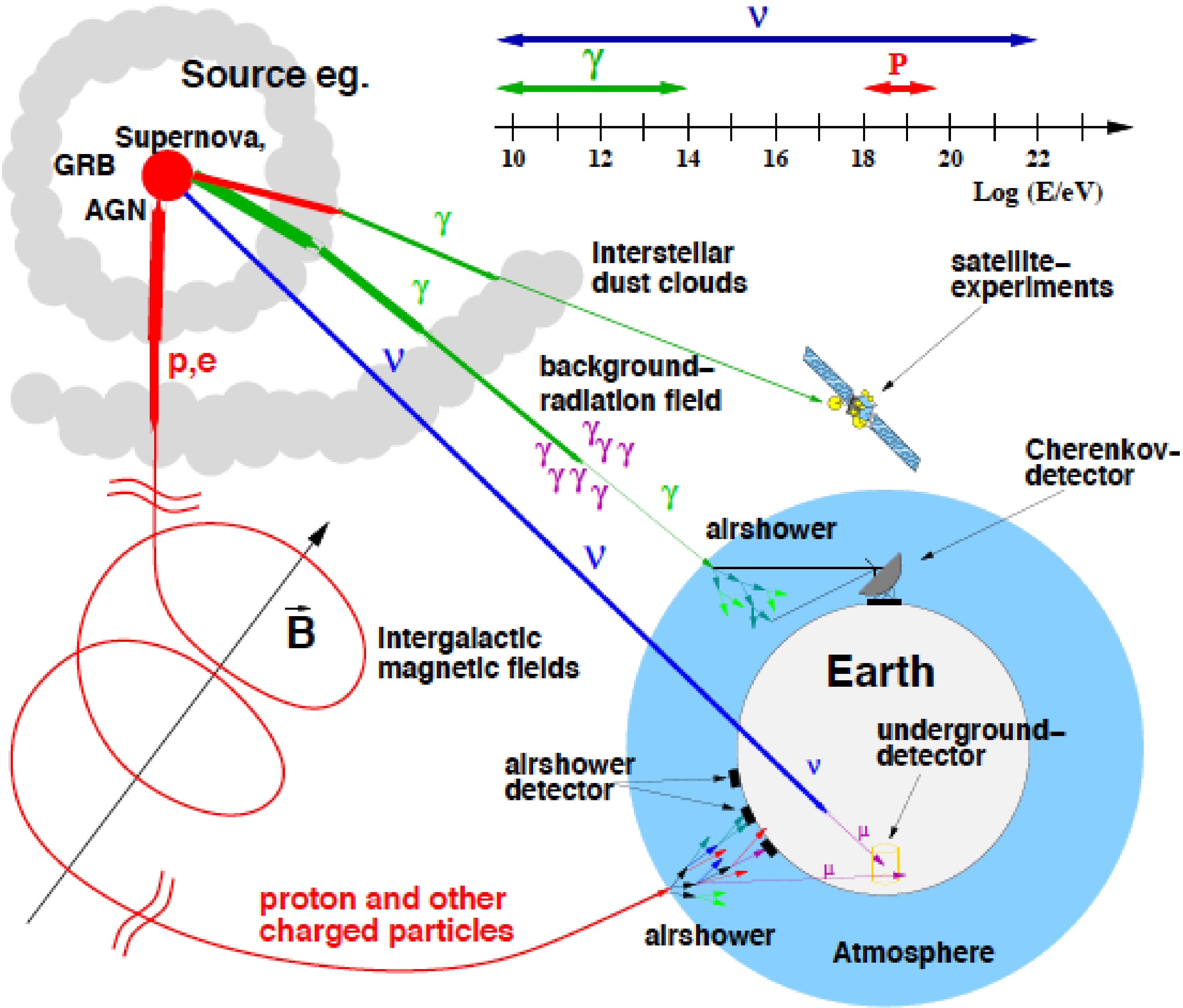
VHE gamma-ray astronomy

- American spy satellites detected accidentally 1967 high-energy gamma rays during the search for radiation generated by the explosion of atomic bombs
- 1989 Whipple Collaboration discovered 1th source of VHE gamma-ray
  - T. C.Weekes et. al., ApJ 342,(379-395) 1989
- Crab nebula, standard candle E > 1TeV, flux=2 × 10^{-7} m^{-2} s^{-1}



VHE Gamma-ray Sky Map

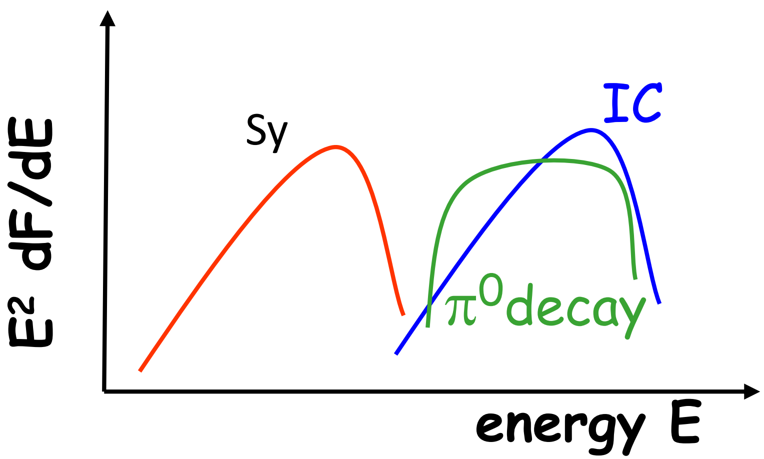



ν
γ
P
10
12
14
16
18
20
22
Log (E/eV)
Source eg.
Supernova,
GRB
AGN
γ
γ
Interstellar
dust clouds
satellite-
experiments
p,e
ν
background-
radiation field
Cherenkov-
detector
γ
ν
airshower
B
Intergalactic
magnetic fields
Earth
underground-
detector
ν
airshower
detector
μ
μ
proton and other
charged particles
airshower
Atmosphere

Generation of VHE gamma ray

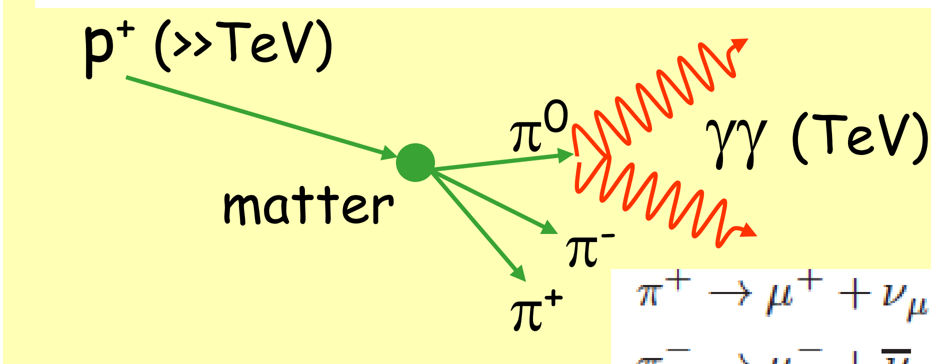
- Hadronic model of emission
- Leptonic model of emission

- Disentangle hadronic from leptonic gamma ray origin
  => shape of spectrum



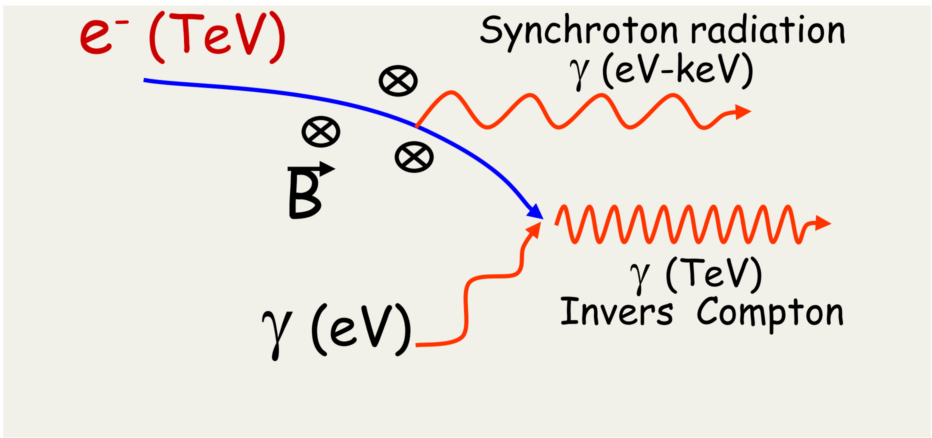
Hadronic model of γ emission

$$E^{max}_{min} = \frac{1}{2}(\gamma m_\pi \pm \beta\gamma m_\pi) = \frac{1}{2} E_\pi (1 \pm \beta)$$

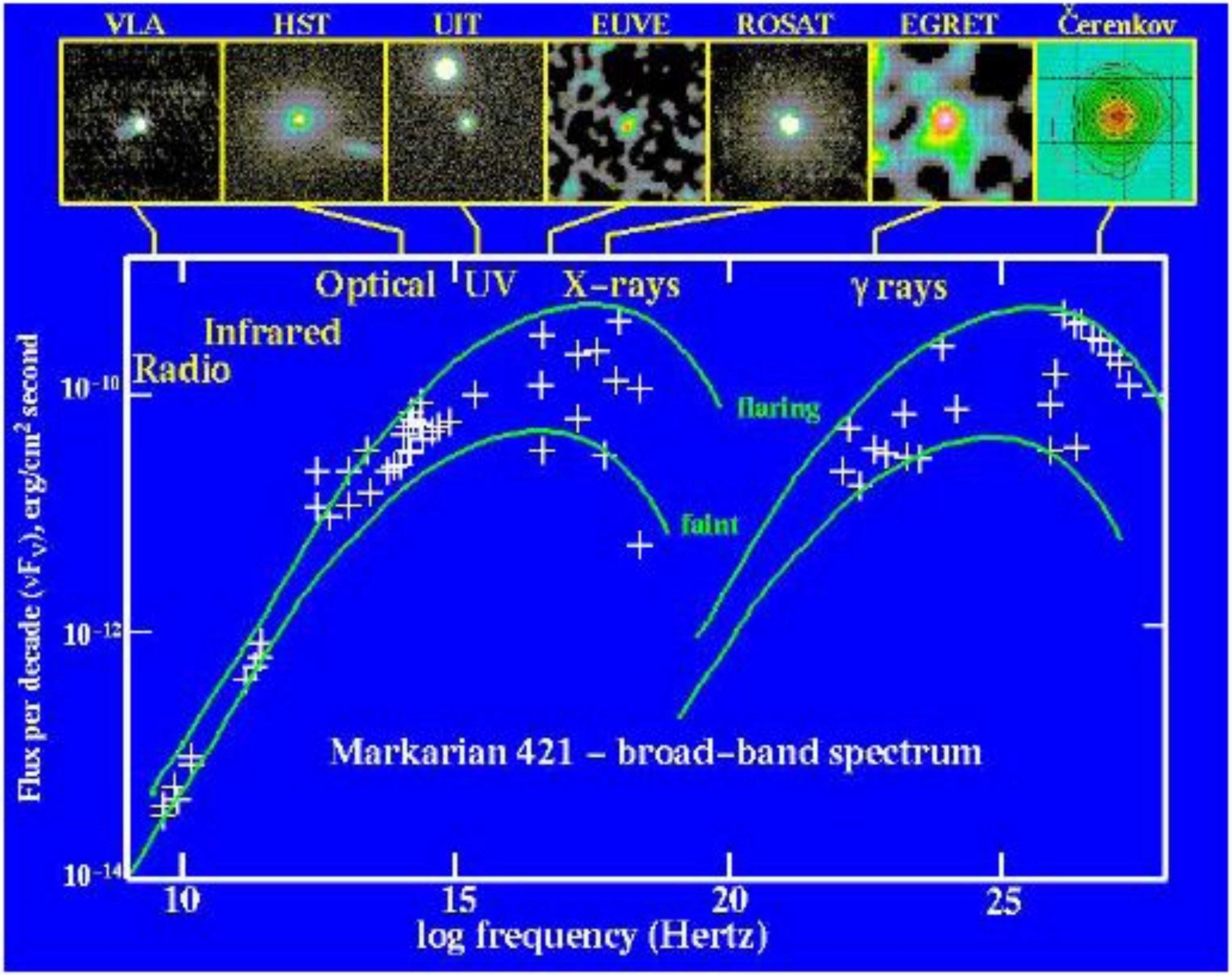


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

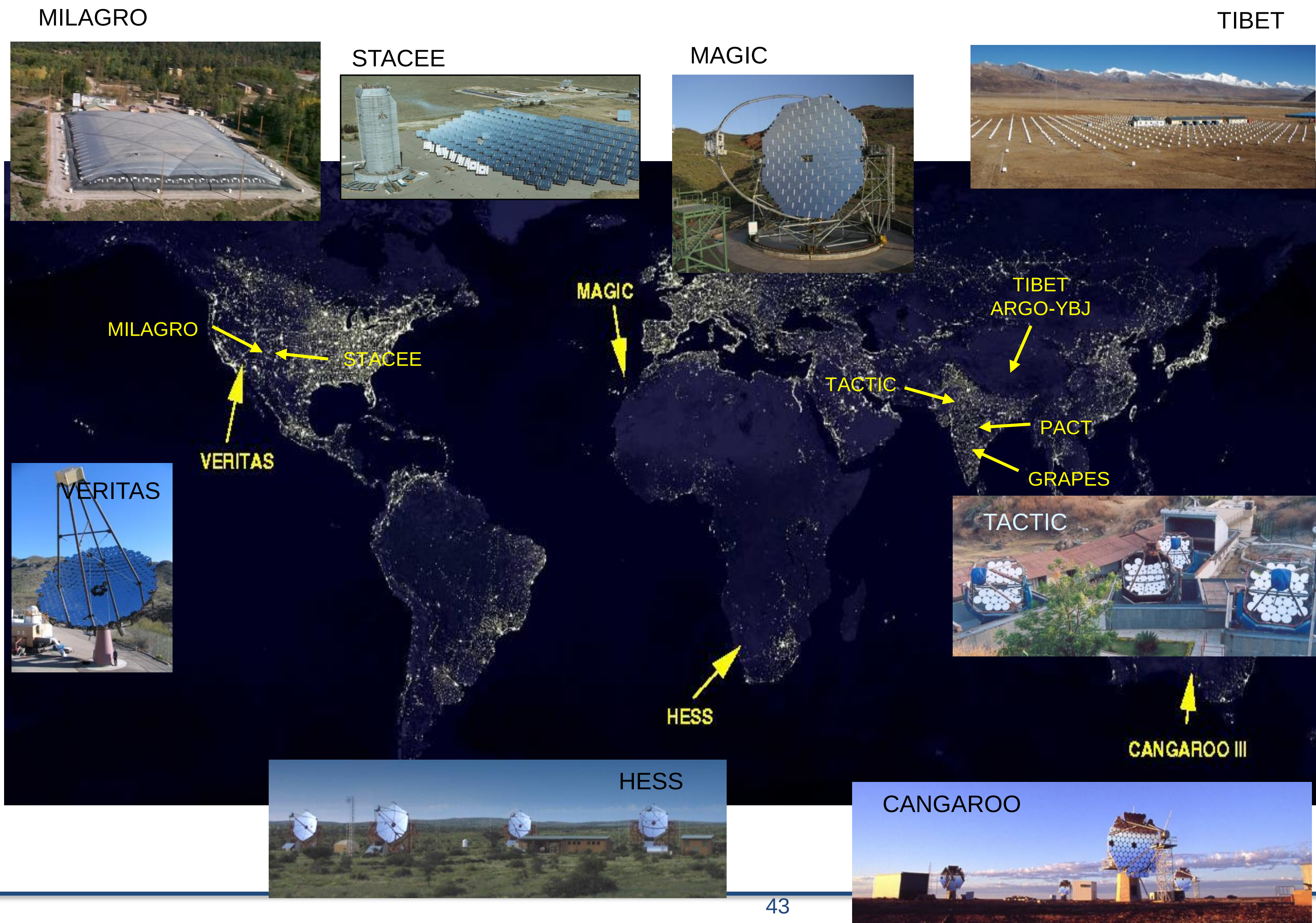
Leptonic model γ emission



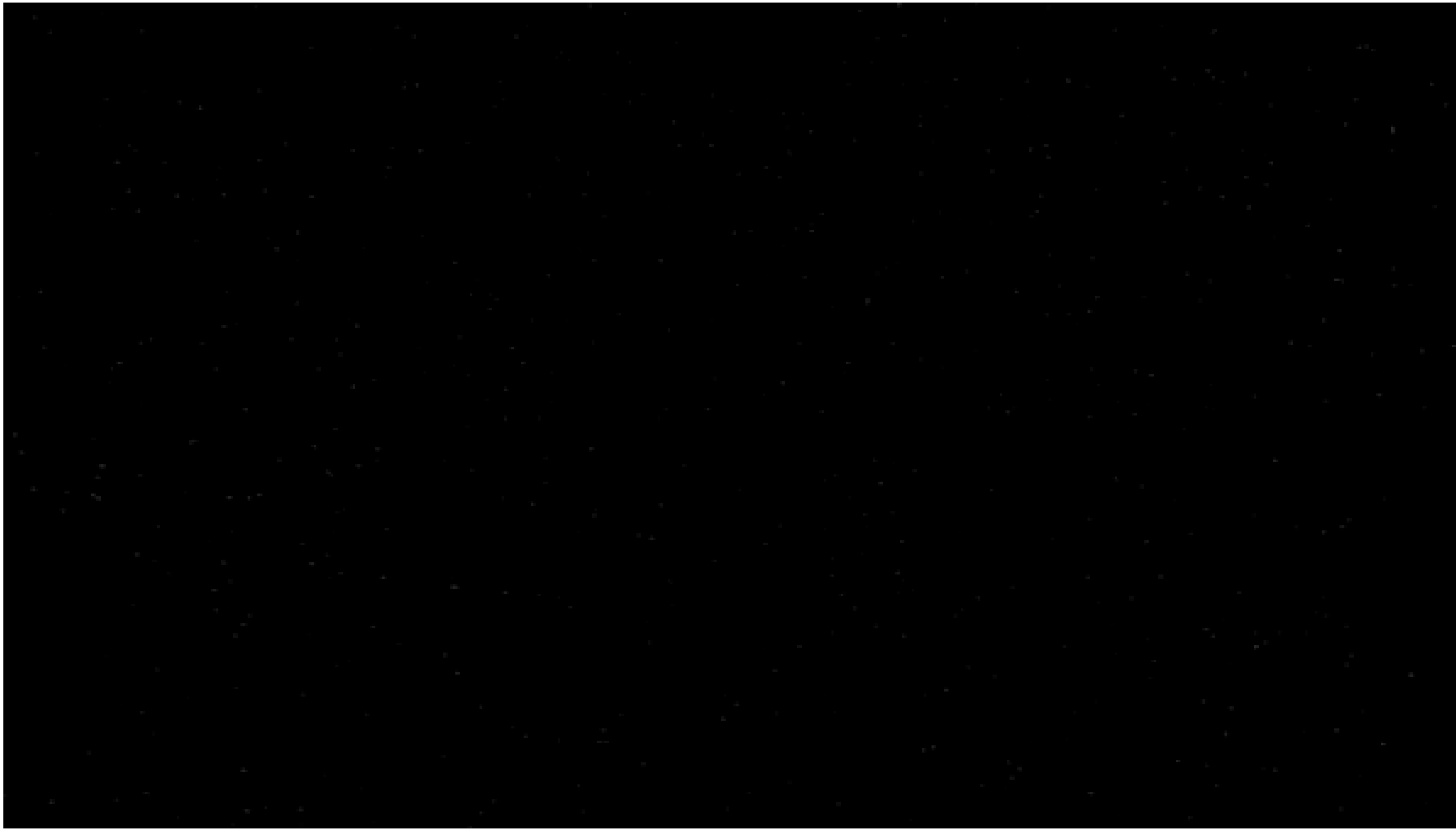
Active galactic nucleai – broad band spectra



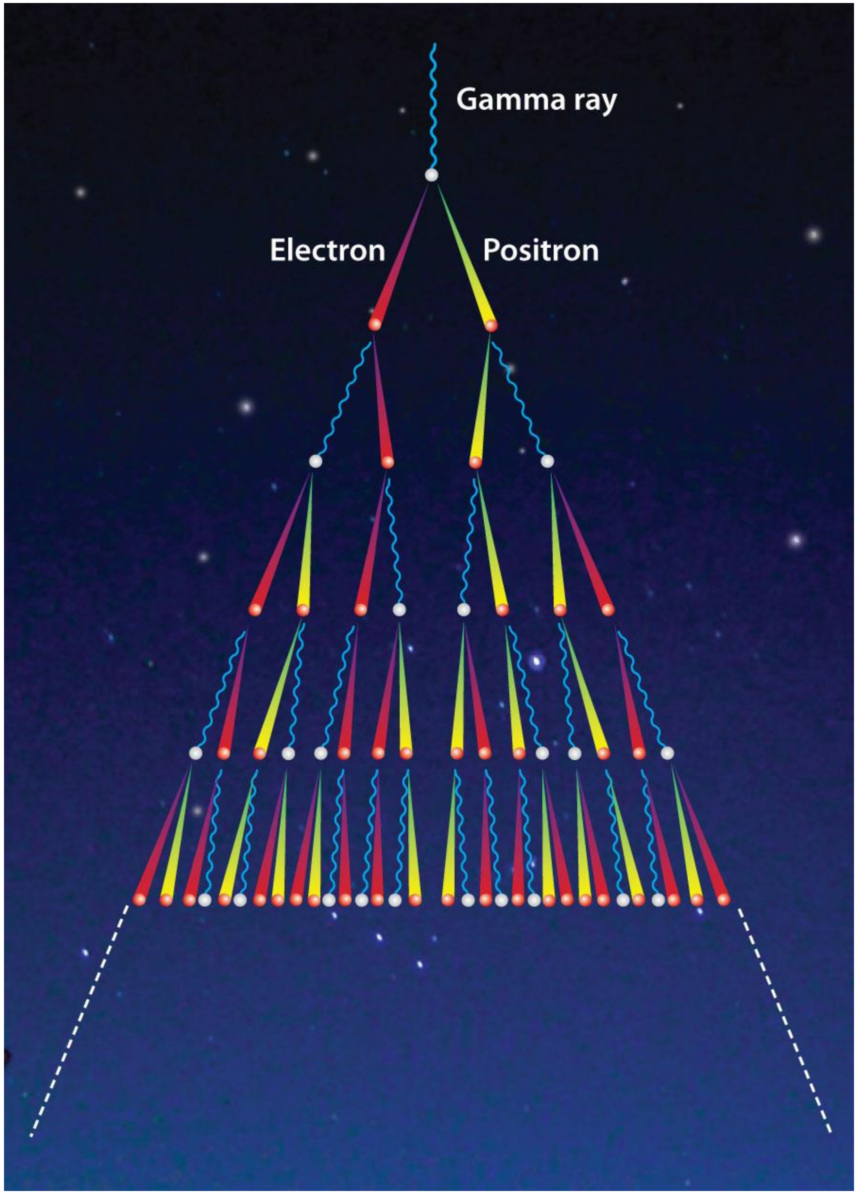
VHE Gamma-ray telescopies (GeV-TeV)

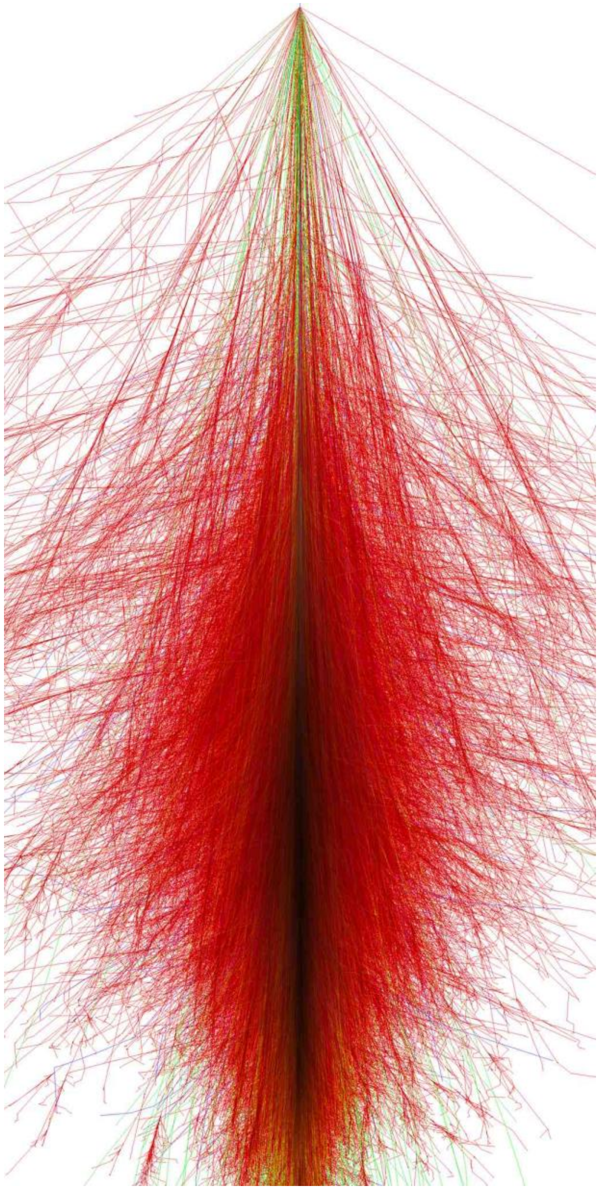


Gama zrake u atmosferi



Pljusak čestica





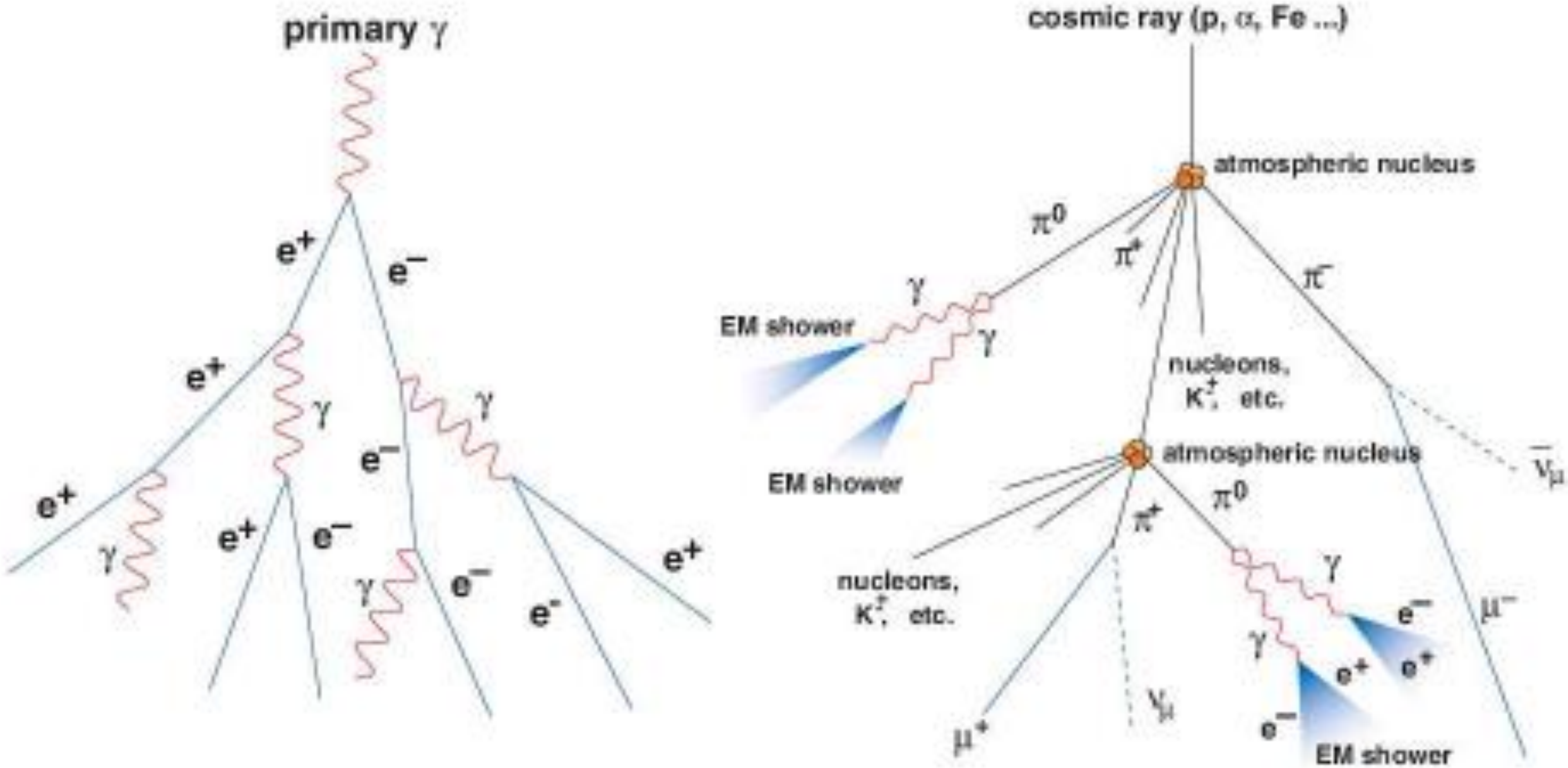
Heitler model of em shower

- In the n^{th} generation, 2^n particles ($e^\pm$ and γ) o energy $E_0 / 2^n$
- Shower maximum reached when E_c is reached, hence $E_0 / 2^{n_{max}} = E_c$
- Number of generations until shower maximum: $n_{max} = \ln (E_0 / E_c) / \ln(2)$
- Atmospheric depth of shower maximum:

$$X_{max} \cong n_{max} \cdot R = X_0 \ln (E_0 / E_c)$$

(depends logarithmically on E_0)

Pljusak čestica



1 gamma-ray in 10000 CR

Čerenkovljevo svjetlo

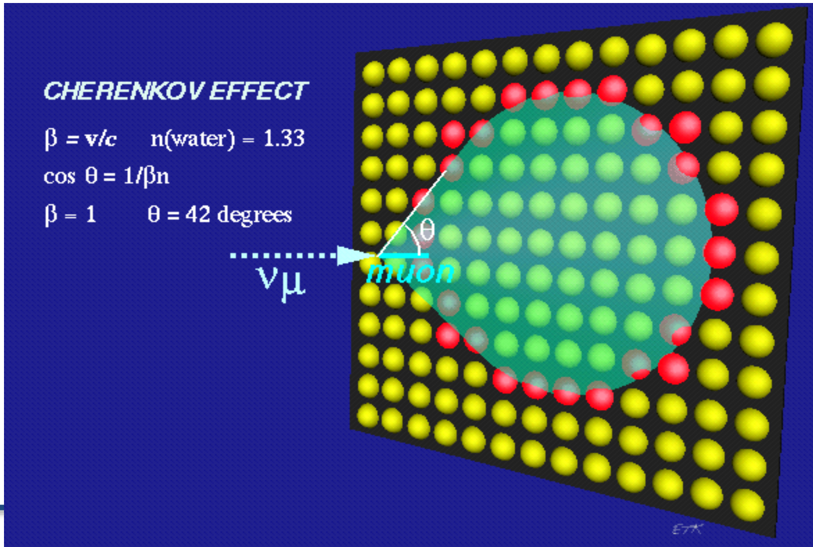
- Č light is produced by particles faster than light in air
- Limiting angle cos $\theta_c \sim 1/n$
  - $\theta_c \sim 1^o$ at sea level, 1.3^o at 8 km asl
  - Threshold @ sea level : 21 MeV for e, 44 GeV for μ

Maximum of a 1 TeV γ shower ~ 8 Km asl

200 photons/m^2 in the visible

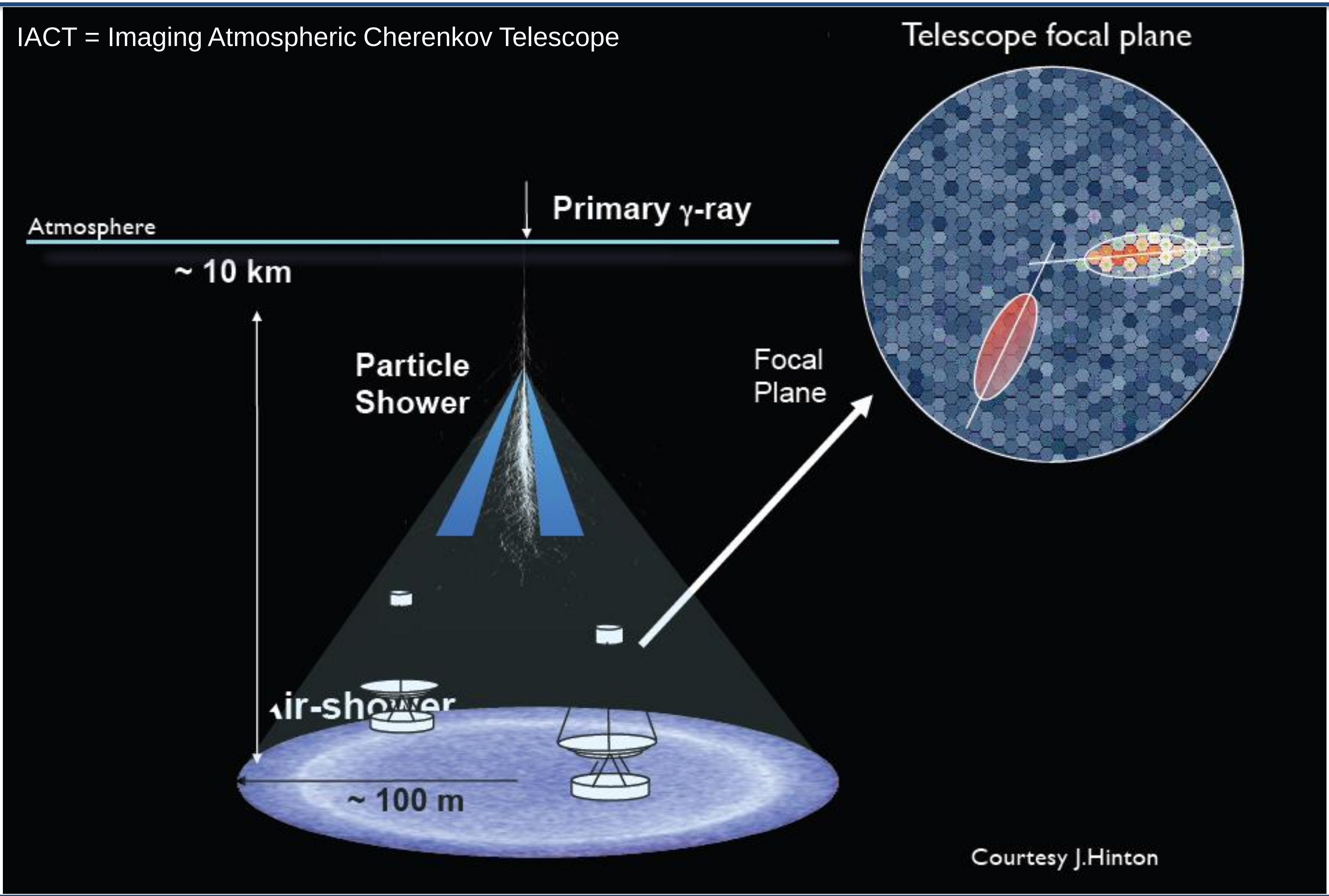
Duration ~ 2 ns

Angular spread ~ 0.5^o

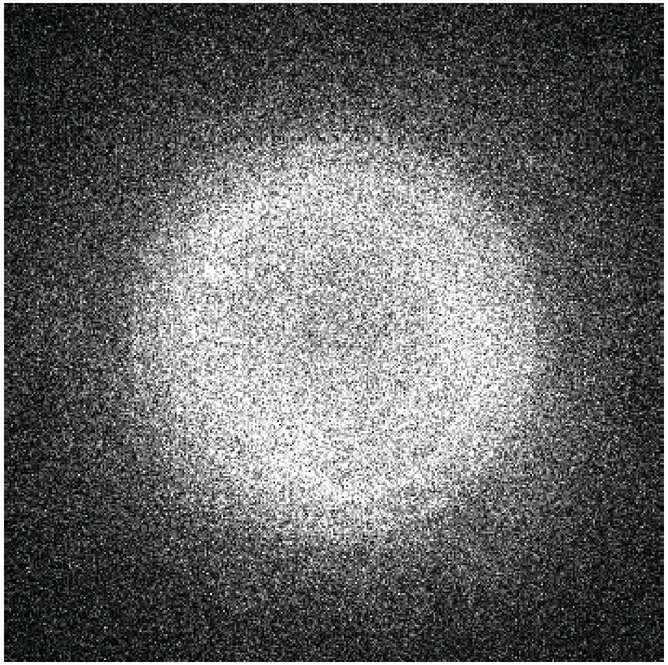


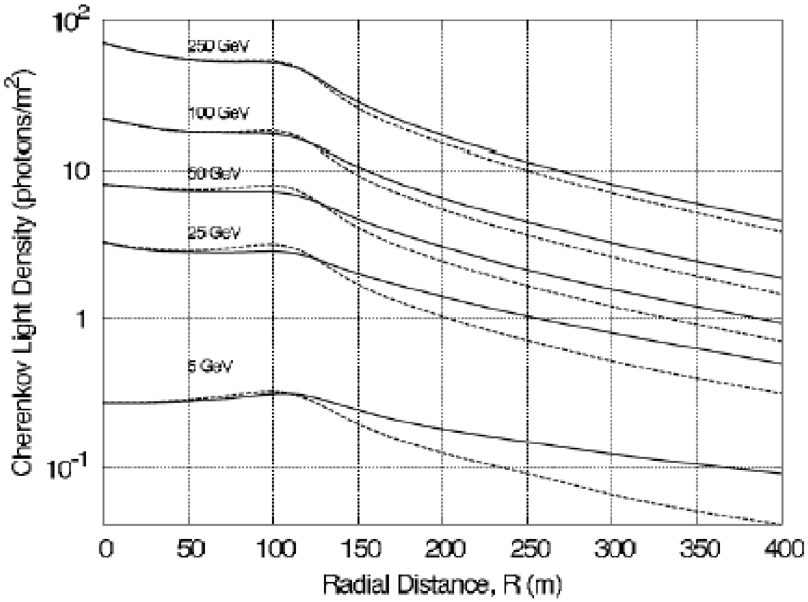
IACT tehnika detekcije

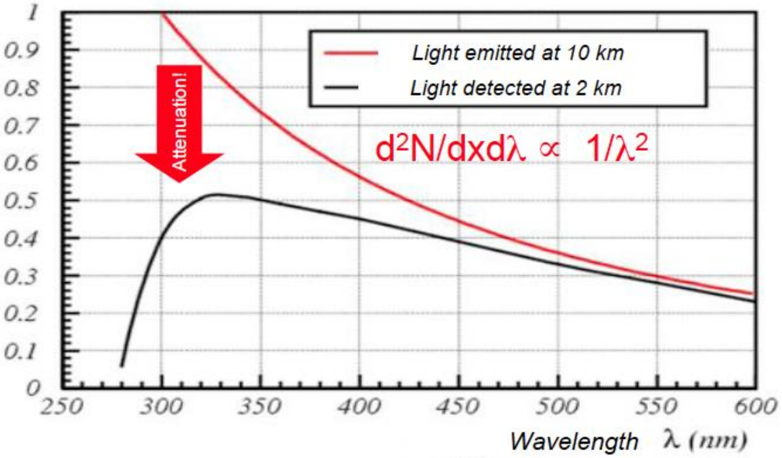
IACT = Imaging Atmospheric Cherenkov Telescope

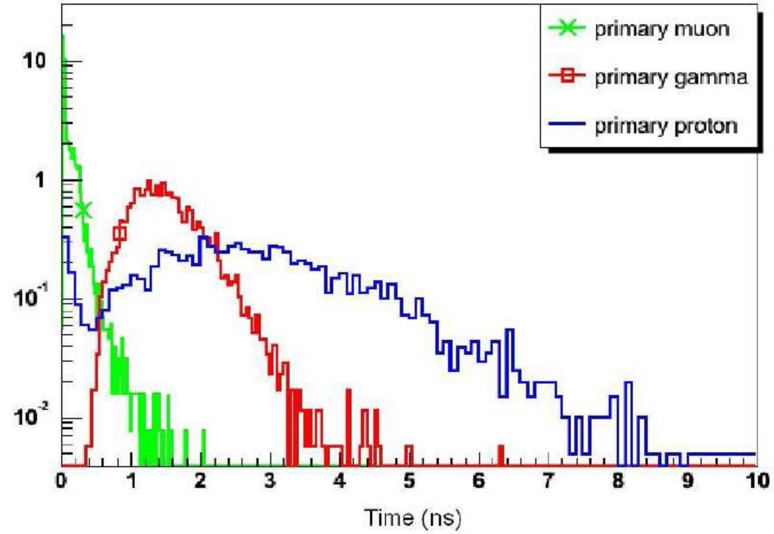


Density of Cherenkov photons

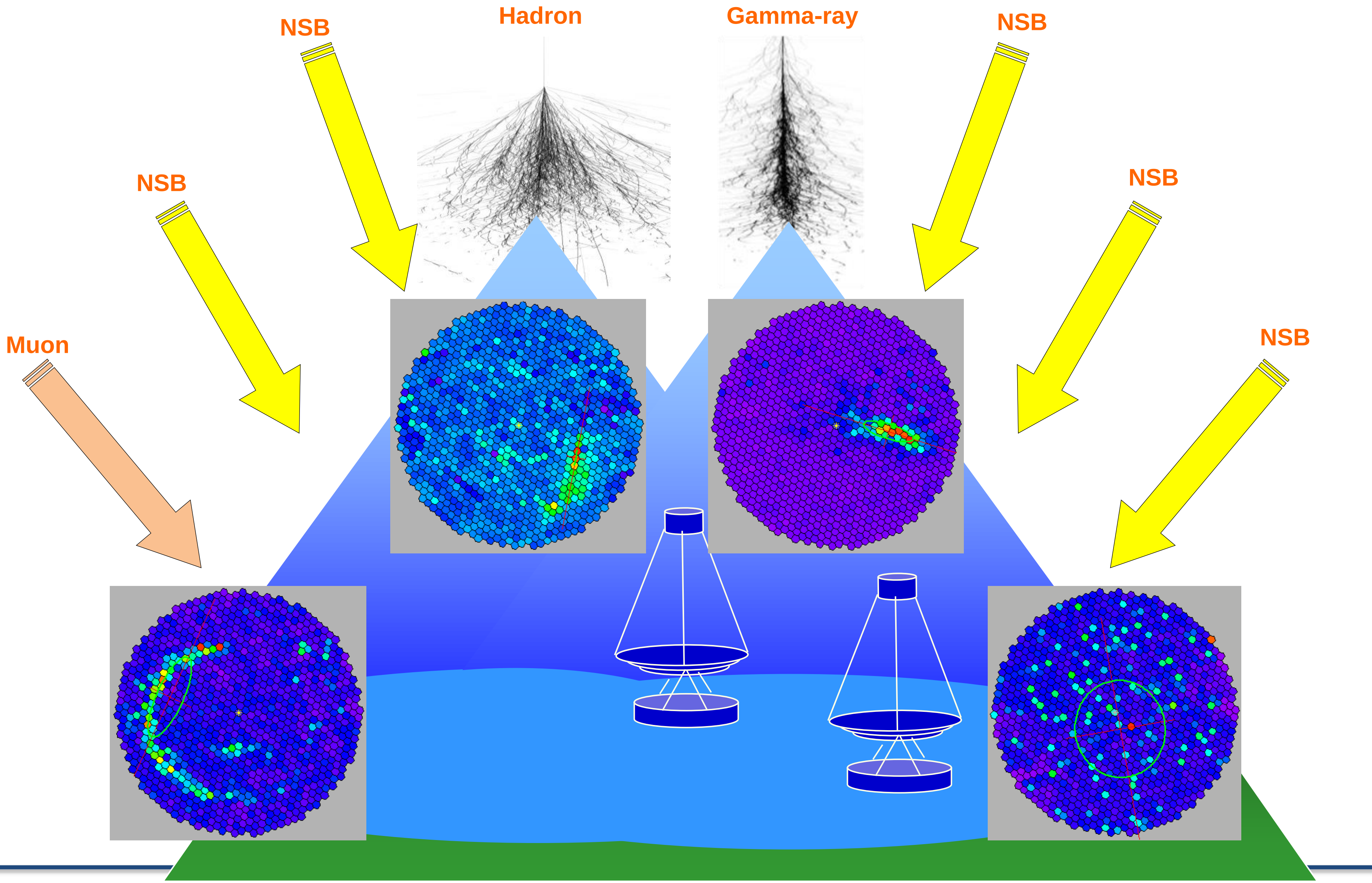








IACT tehnika detekcije



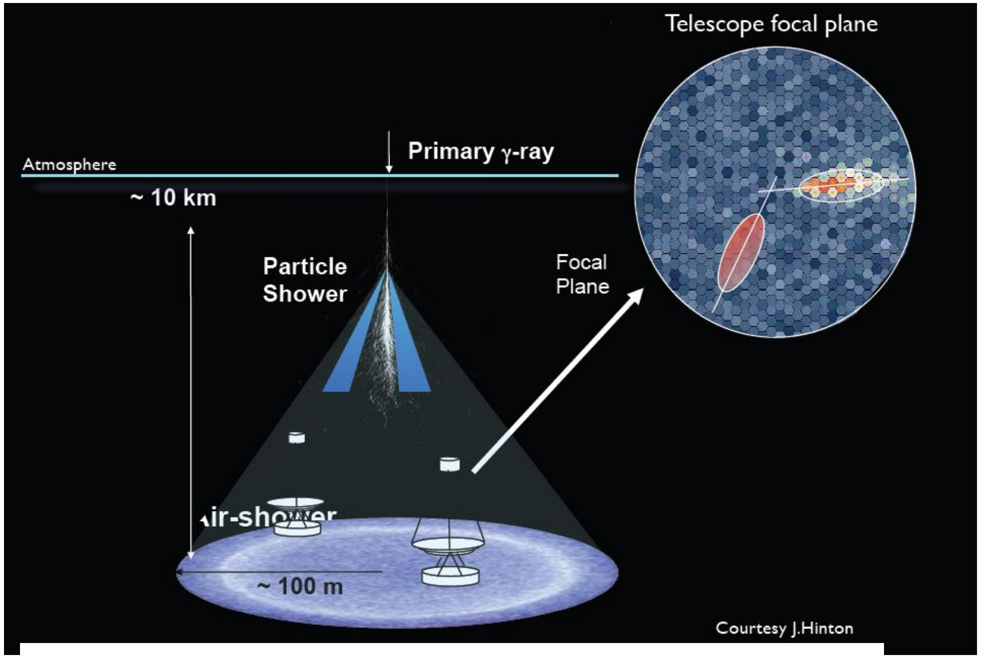
Osjetljivost IACT tehnike detekcije

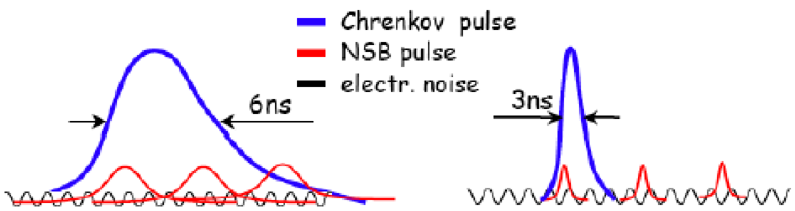
- Φ ($sr^{-1}s^{-1}, m^{-2}$) – NSB flux
- Ω – solid angle viewd by detector
- τ – integration (exposure) time
- F (m^{-2}) – density of Cherenkov photons
- A- light collection area
- ε – light collection efficiency (reflectivity,QE,...)
- Number of background photons $N_B = \phi\Omega A\varepsilon \pm \sqrt{\phi\Omega A\varepsilon}$
- Numer of detected Cherenkov/signal photons N=FεA

$$\frac{S}{B} \equiv \frac{N}{\sqrt{N_B}} \frac{FA\varepsilon}{\sqrt{\phi\Omega A\varepsilon\tau}} = \sqrt{\frac{F\varepsilon A}{\phi\Omega\tau}}$$

$$E_{th} \sim \sqrt{\frac{\phi\Omega\tau}{\varepsilon A}}$$

IACT tehnika detekcije





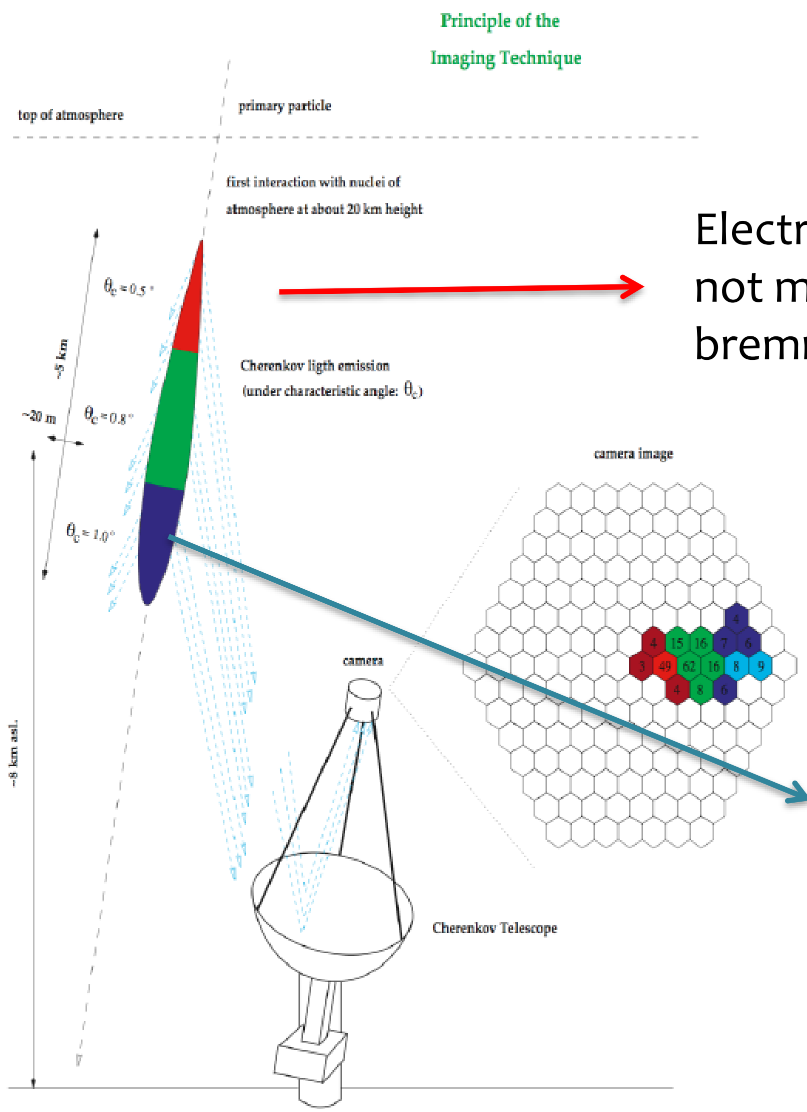
Signal ∝ A

Fluctuations ~ $(A\tau\Omega)^{1/2}$

=> $S/B^{1/2} \propto (A/\tau\Omega)^{1/2}$

- ►IACT – counting technique
- ►Signal & Background:
  - **Night sky background light, (NSB)**
  - **1 g-shower in ~ 10 000 h-showers**
  - **μ, $e^{\pm}$**
- ►NSB is controlled by small integration time
- ►Trigger logic & sophisticated analysis is needed to reduce h-shower
- ►Images parameterization (Hillas parameters)

Razvoj pljuska čestica

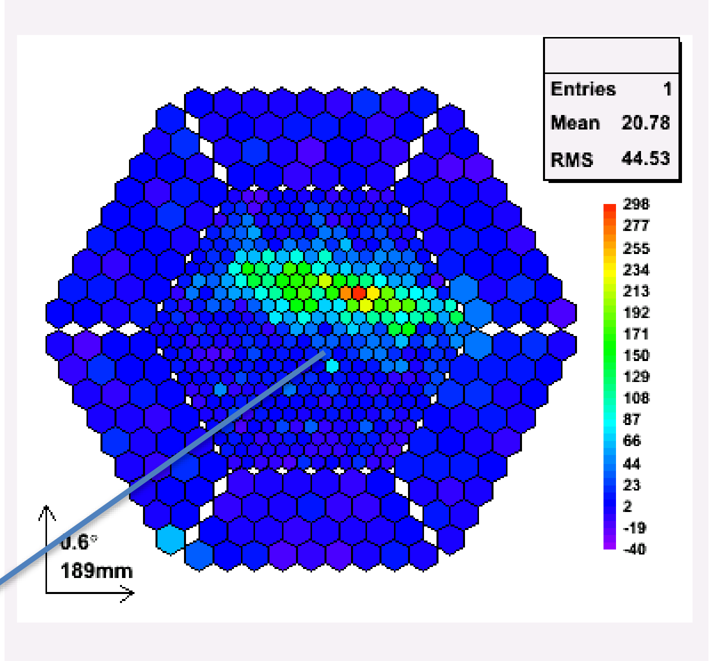


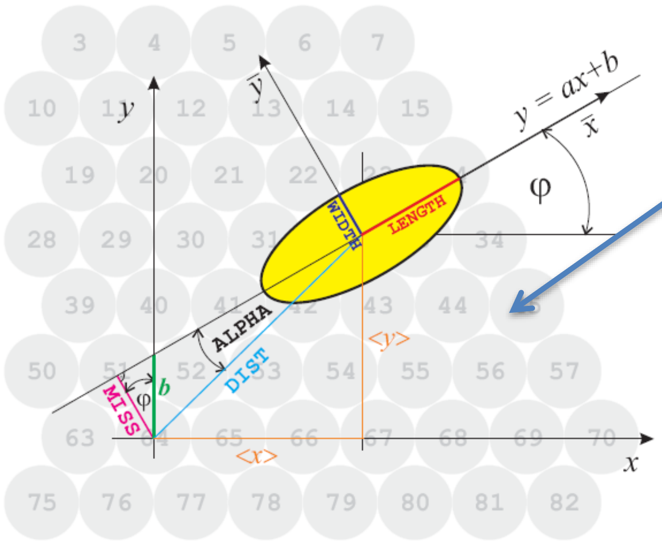
Electrons energetic and not much deflected by bremmstrahlung

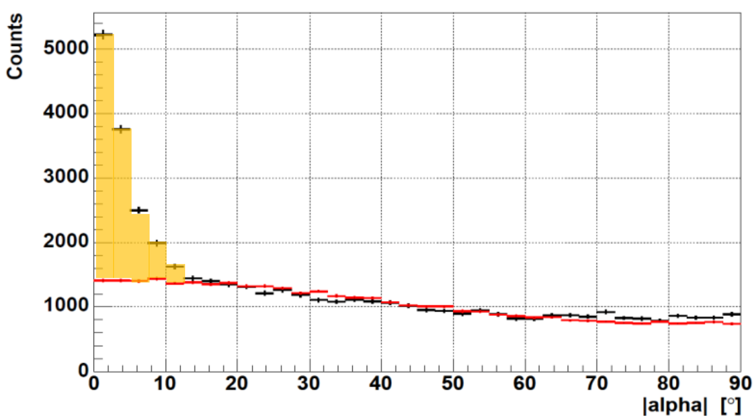
$$\alpha_{scattering}(n) \simeq \frac{1}{\gamma} = \frac{m_e c^2}{E(n)}$$

Electrons less energetic deflected by bremmstrahlung
Some photone deflected for 6 equivalent pixel away forn the original trajectory

Hillasovi parametri







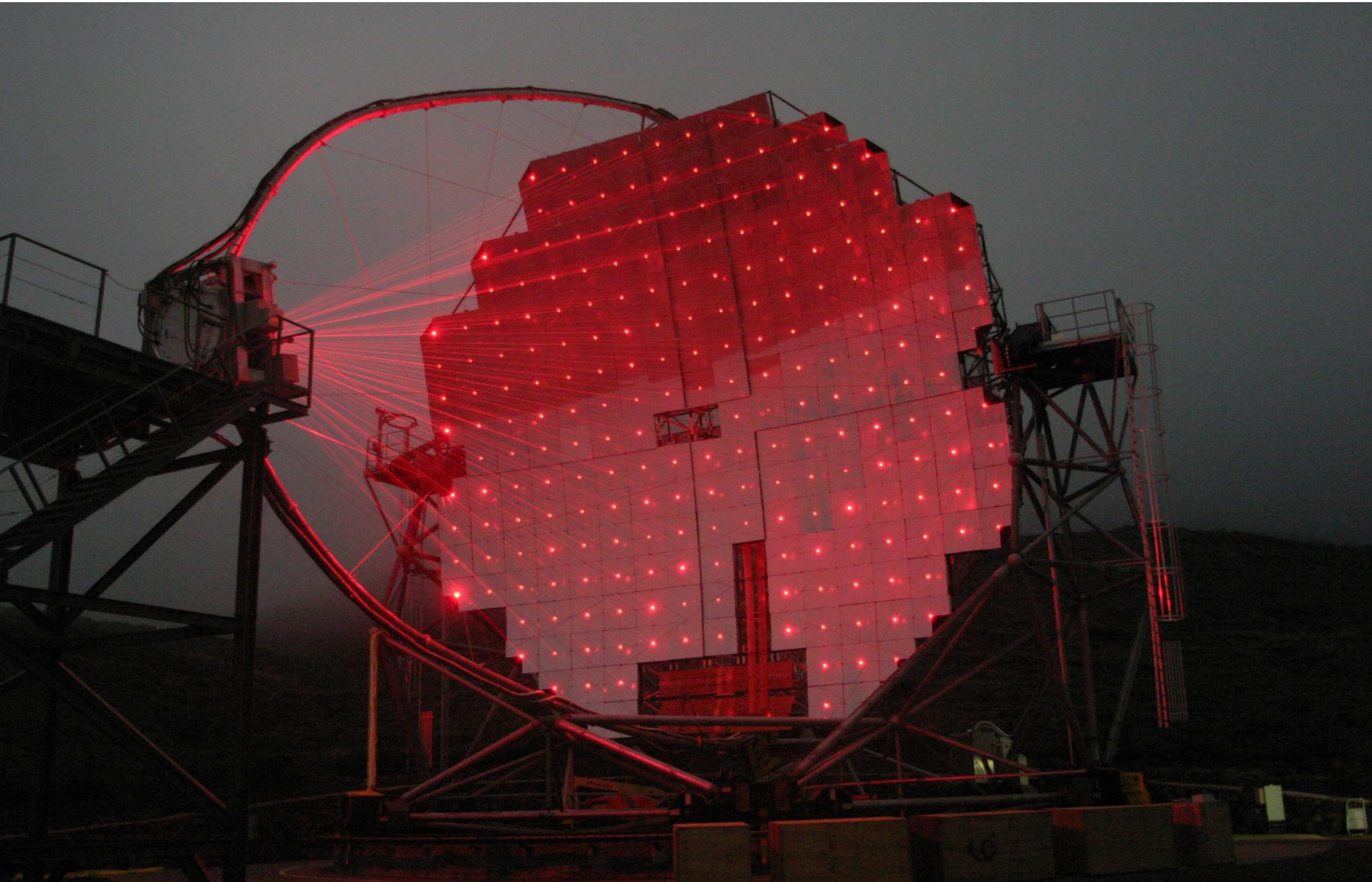
La Palma – Kanarski otoci

MAGIC telescops

- ►Telescope array: M1 & M2
- ►Largest CT, 17 m ø mirror dish
  M1: 236.0 m^2 reflector
  M2: 241.5 m^2 reflector
- ►3.5° FoV
  M1: 1039 coated PMT’s
  M2: 1039 enhanced QE PMTs
- ►Fast repositioning for GRBs:
  M1: 30 s for 180^0 Az
  M2: ~30 faster
- ►Trigger threshold
  M1: **50 - 60 GeV**
  (25 GeV sumtrigger)
  M2: not measured yet
- ►Sensitivity: 0.7 % Crab / 50 h
- ►γ-PSF: ~ 0.1°
- ►Energy resolution: 20 %

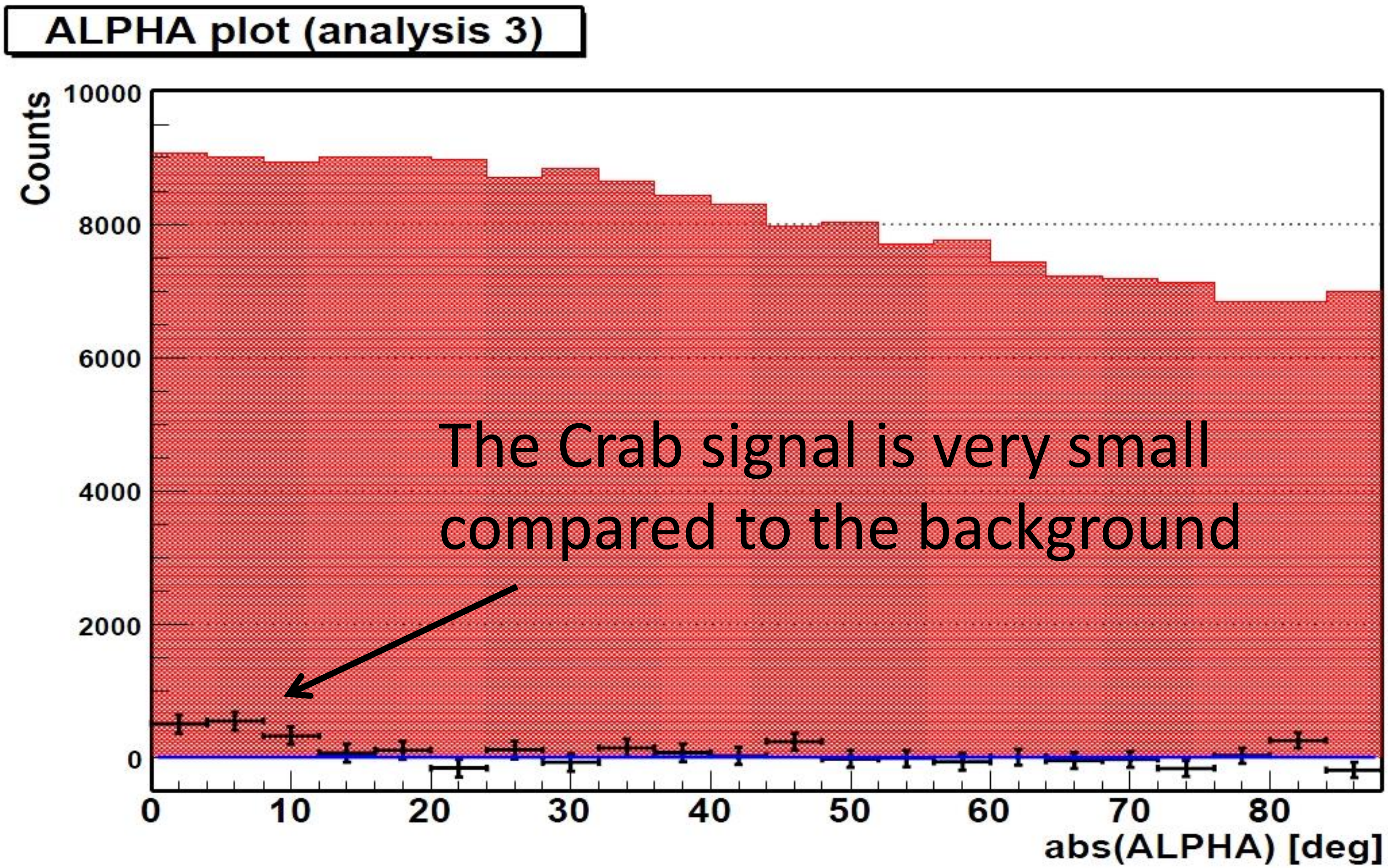
MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescope

Kalibracija MAGIC-a



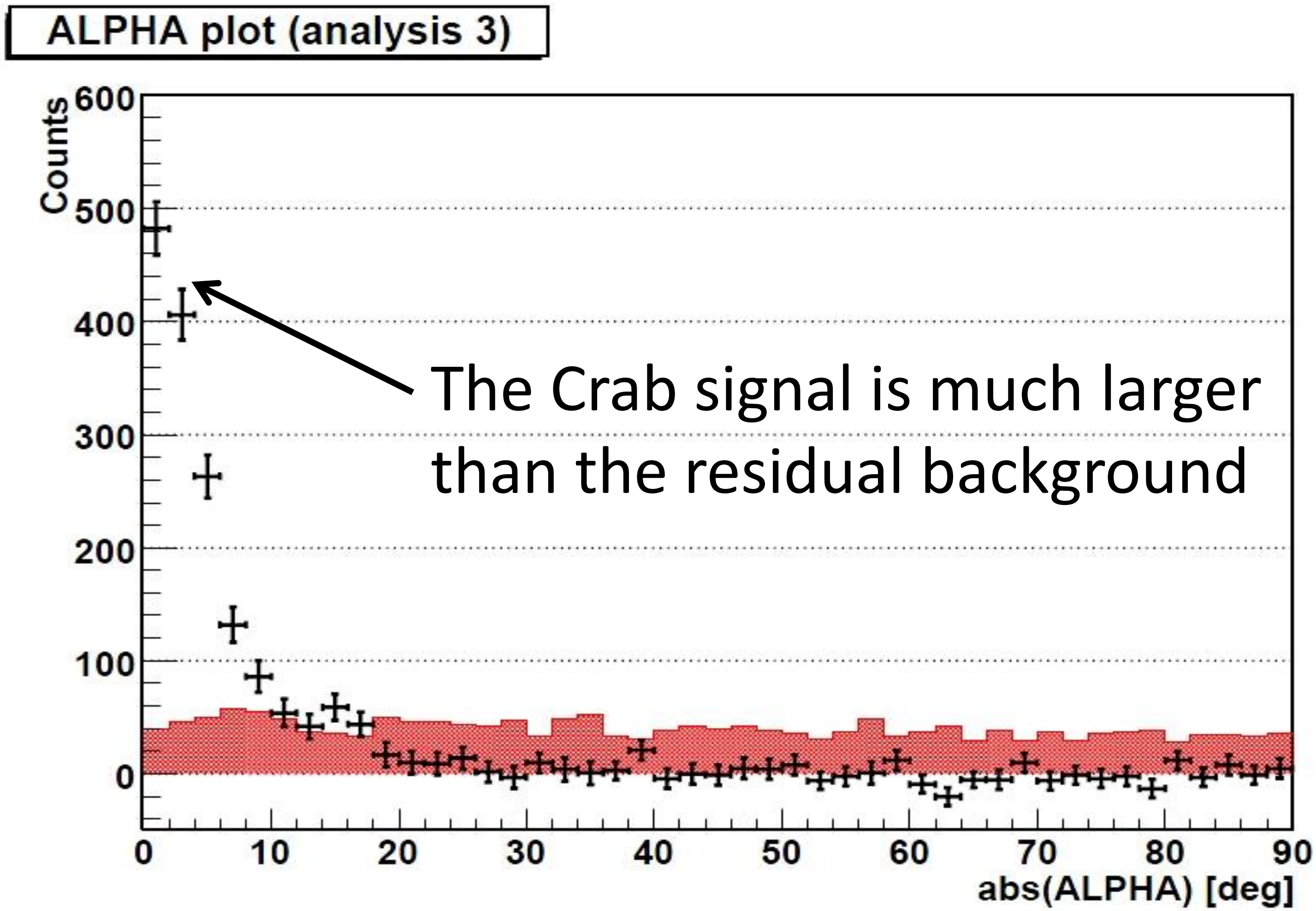
MAGIC

- Very low trigger threshold but background suppression <100 GeV very poor with single telescope (even with time information):



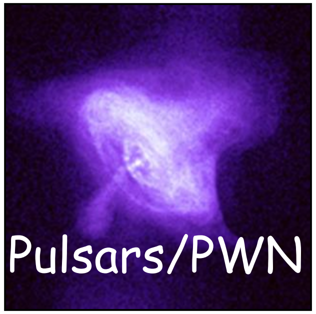
MAGIC

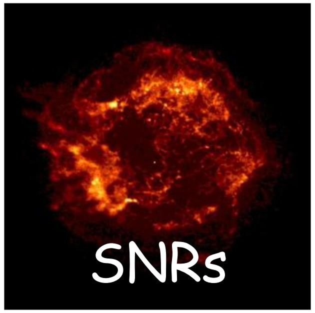
- For comparison: high energies (>250 GeV)

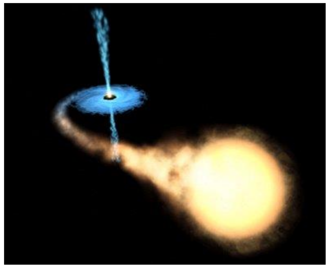


Znanstveni ciljevi MAGIC-a

Galactic

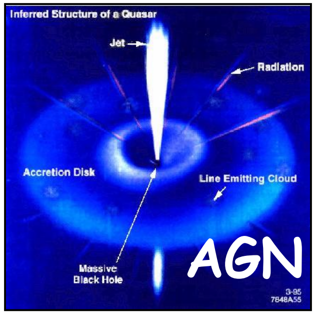


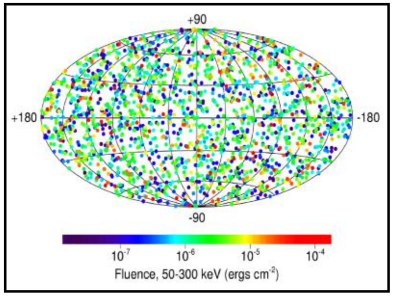




Binary systems

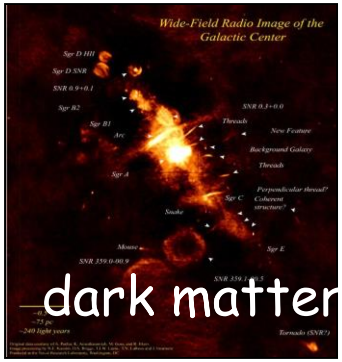
Extragalactic

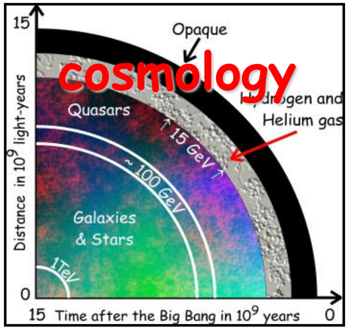


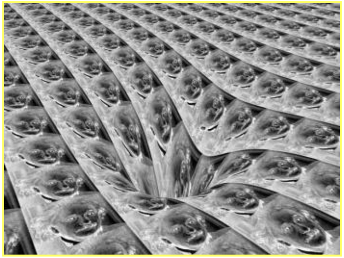


GRBs

Fundamental

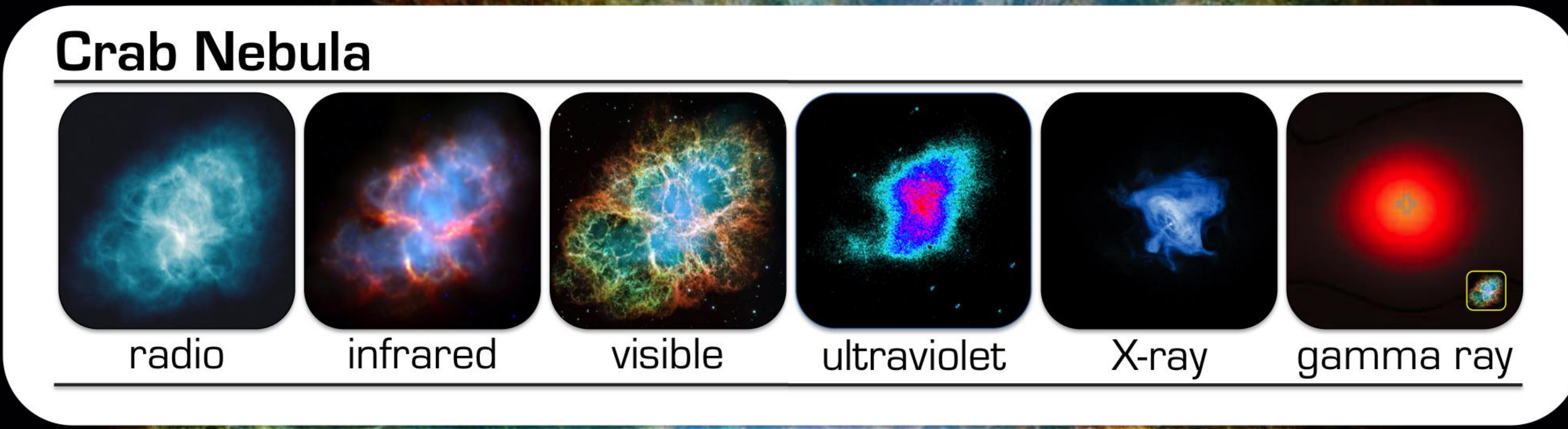






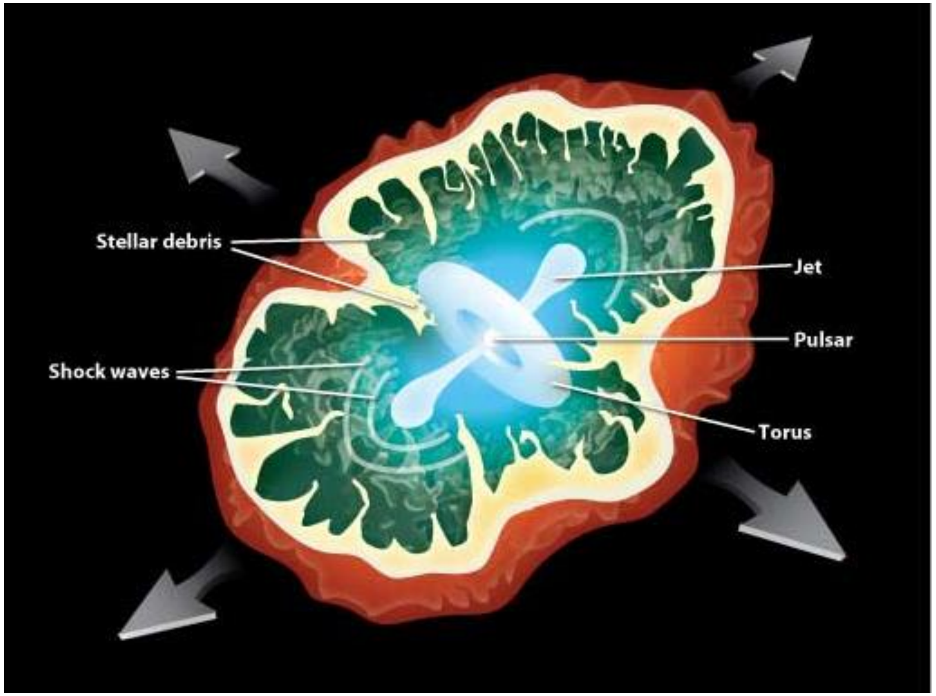
Qantum Gravity Effect

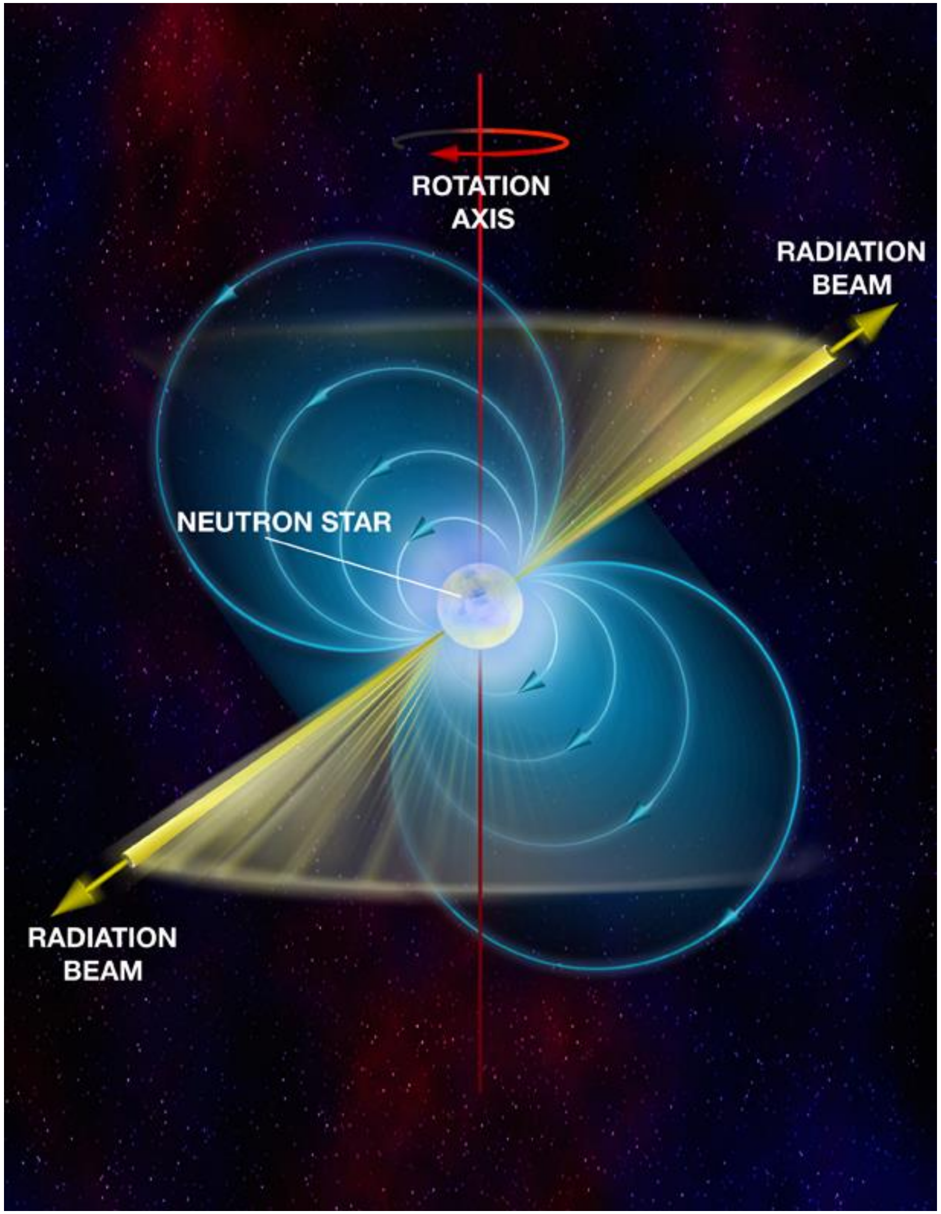
Rakova maglica – Crab nebula



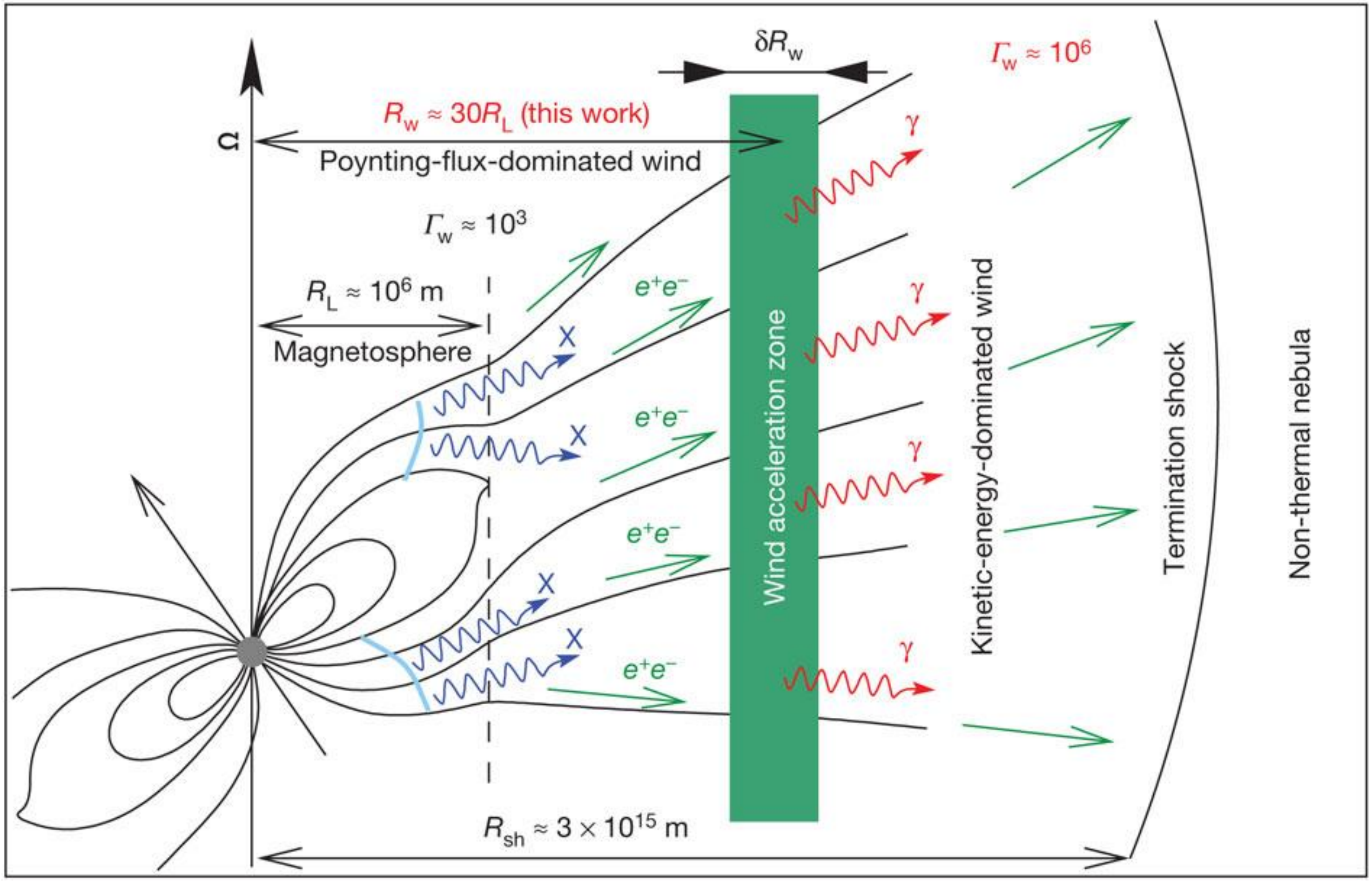
Crab nebula

- Supernove in 1054
- Neutron star - engine
- T=33 ms
- Radius: ~12 km
- Density: ~10^{14} x Sun
- Gravity: ~10^{11}x Earth
- B = 10^{12} x Earth
- Tempeture: 10^{12} K (initial)





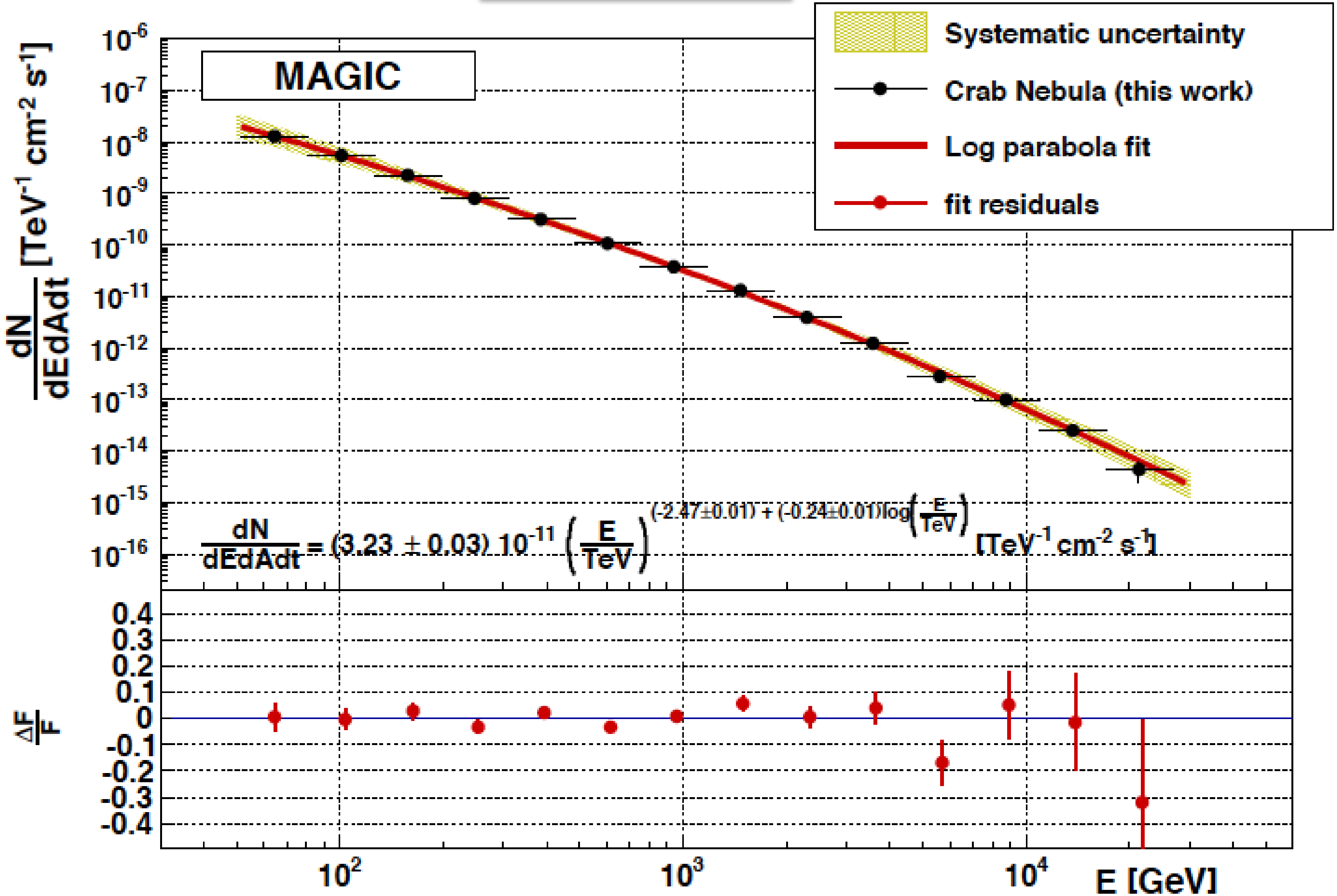
Crab – standard candle for VHE γ



- Dense electron (e−)–positron (e+) plasma produced in the pulsar magnetosphere by pair creation processes initiates an electron–positron wind at the light cylinder, which has radius $R_L \approx 10^6$ m. Initially, the rotational energy lost by the pulsar, $\dot{E}_{rot} = 5 \times 10^{31}\ \mathrm{J\ s^{-1}}$ is released mainly in the form of electromagnetic energy (Poynting flux) and the wind's Lorentz factor therefore cannot be very large. At a distance R_w, the Poynting flux is converted to the kinetic energy of bulk motion (green zone), leading to an increase in the bulk-motion Lorentz factor to at least20 $\Gamma w \approx 10^4$. The termination of the wind by a standing reverse shock at $R_{sh} \approx 3 \times 10^{15}$ m boosts the energy of the electrons to 10^{15} eV and randomizes their pitch angles. The radiative cooling of these electrons through the synchrotron and inverse-Compton processes results in an extended non-thermal source2, the Crab nebula.

Differential energy spectrum of Crab nebula

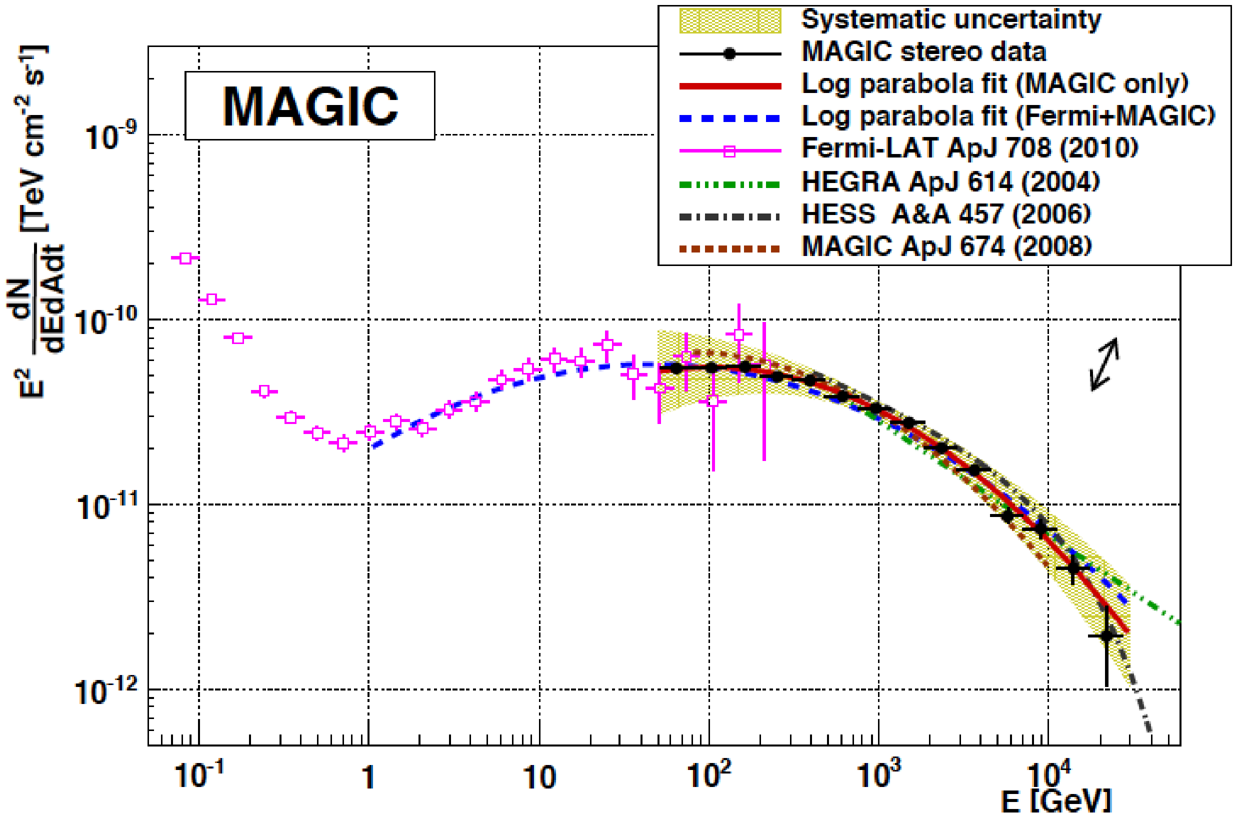
50 GeV – 30 TeV



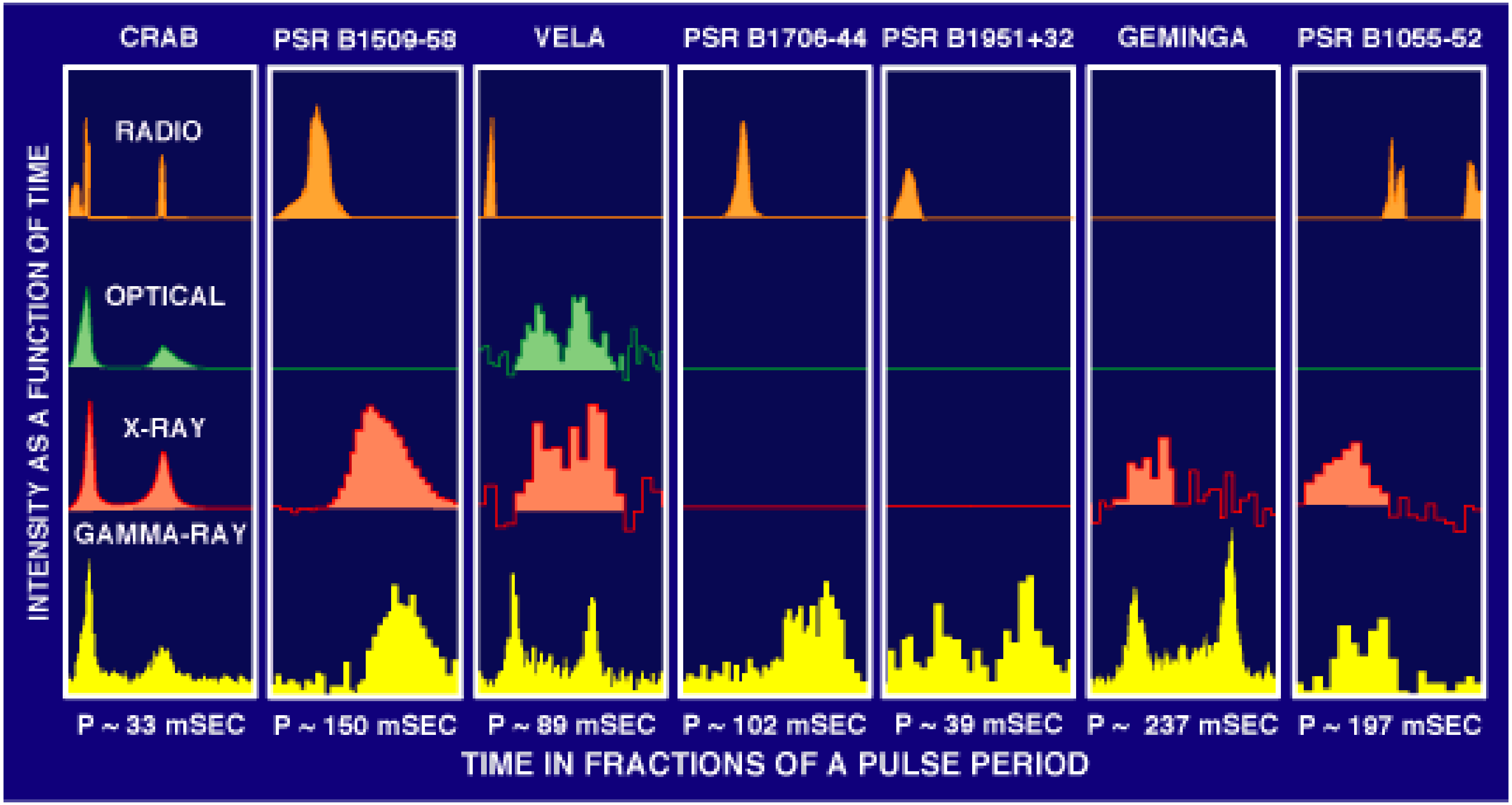
Crab Nebula -Spectral Energy Distribution

- Dominated by systematic uncertainties
- Given the systematic impossible to exclude the cutoff at E > 10 TeV
- Inverse Compton peak estimation (MAGIC + Fermi): **52.5 ± 2.6GeV** stat. err. only

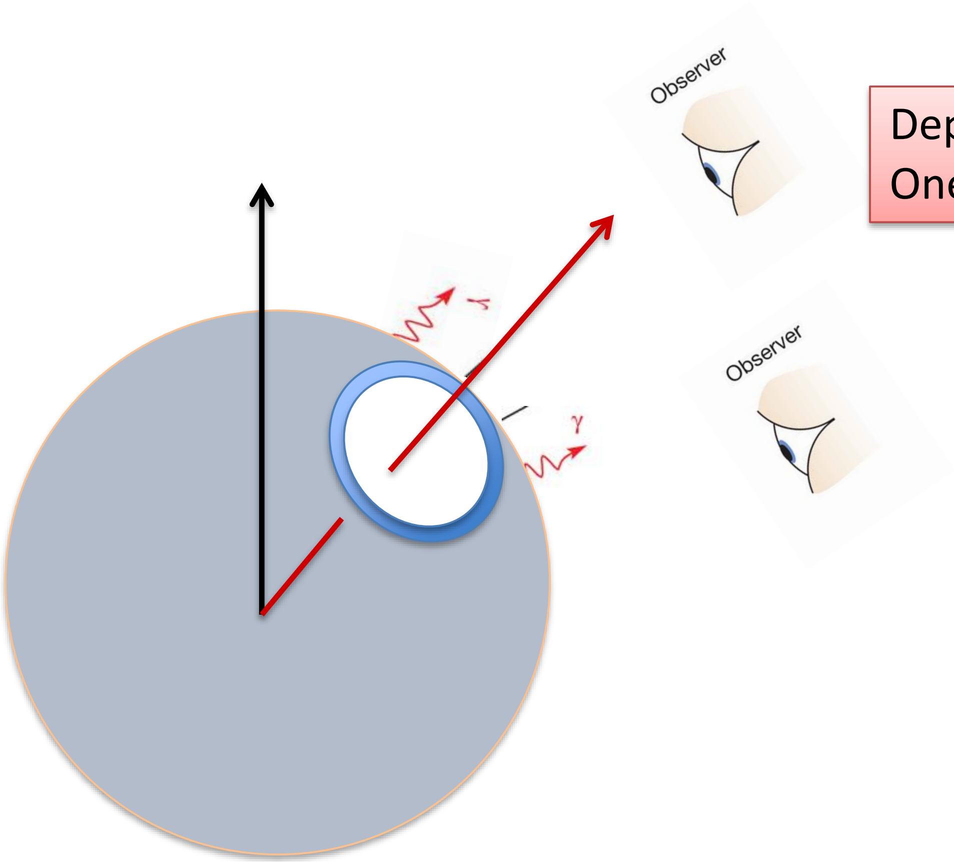
MOST PRECISE IC PEAK MEASUREMENT SO FAR



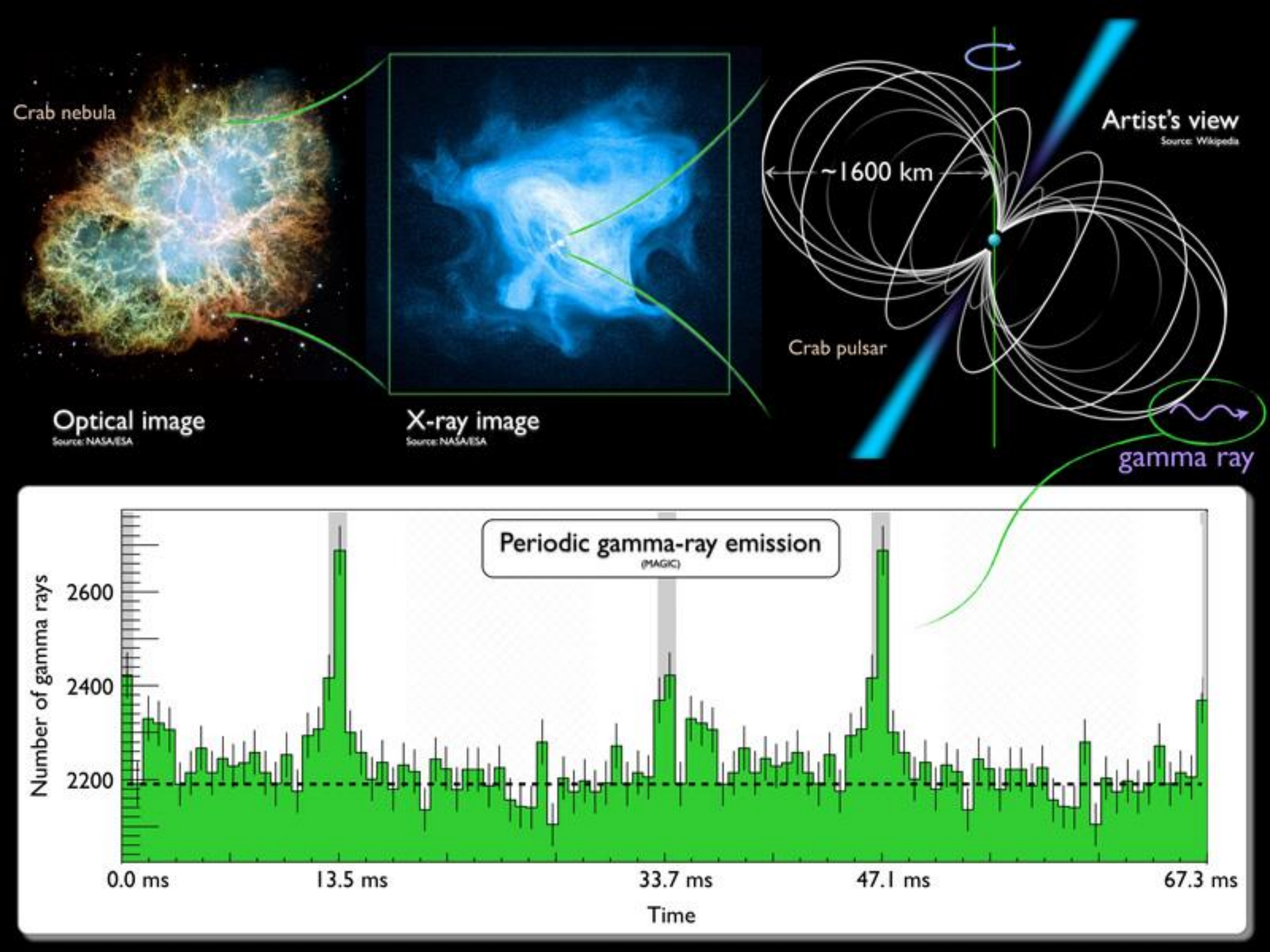
Before Fermi, 6 EGRET Pulsars



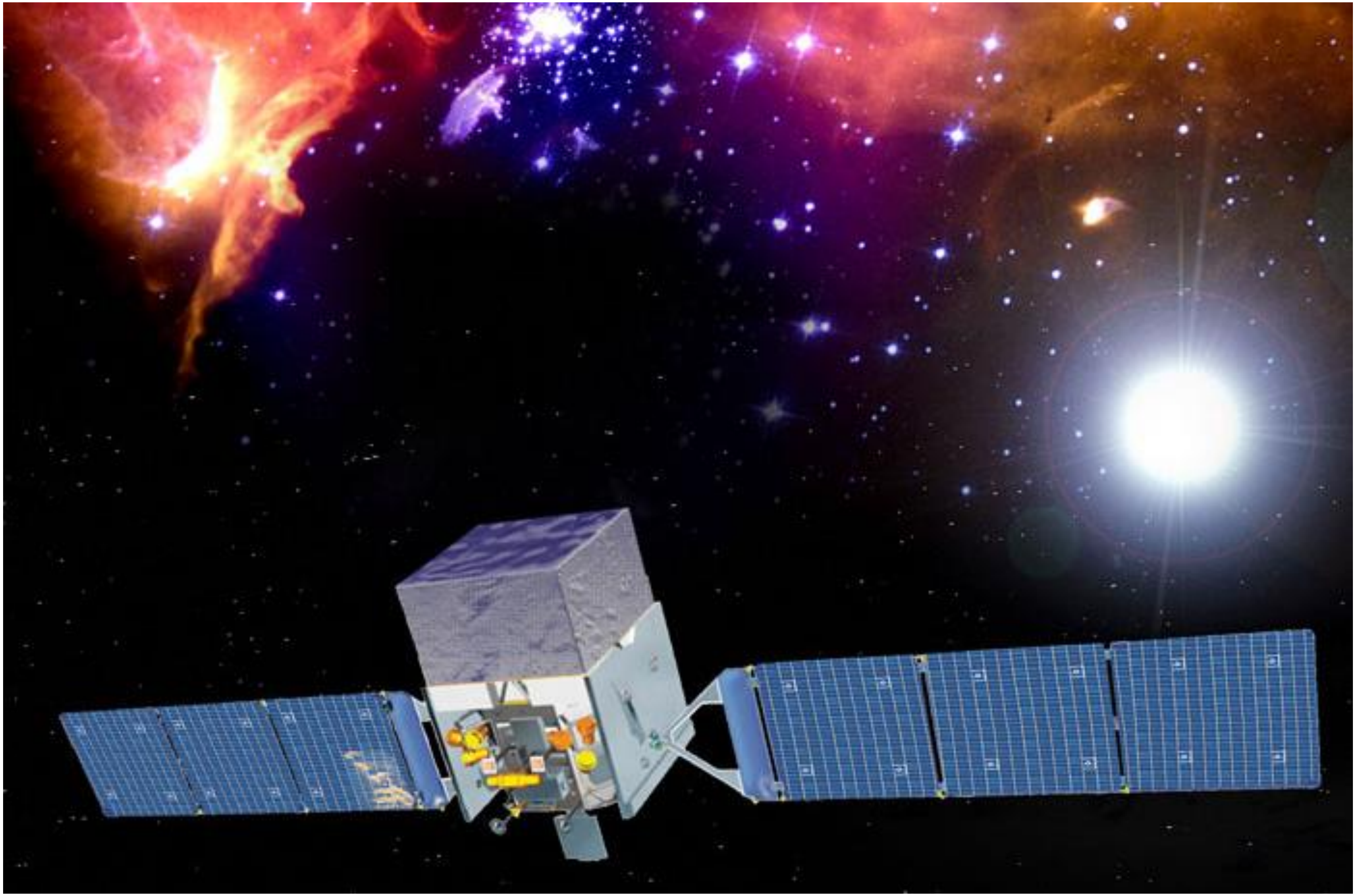
Pulsed and bridge emission from pulsar



Depending of the angle of view
One see two pulses or one puls


Crab nebula
Optical image
Source: NASA/ESA
X-ray image
Source: NASA/ESA
~1600 km
Artist's view
Source: Wikipedia
Crab pulsar
gamma ray
Periodic gamma-ray emission
(MAGIC)
Number of gamma rays
2600
2400
2200
0.0 ms
13.5 ms
33.7 ms
47.1 ms
67.3 ms
Time

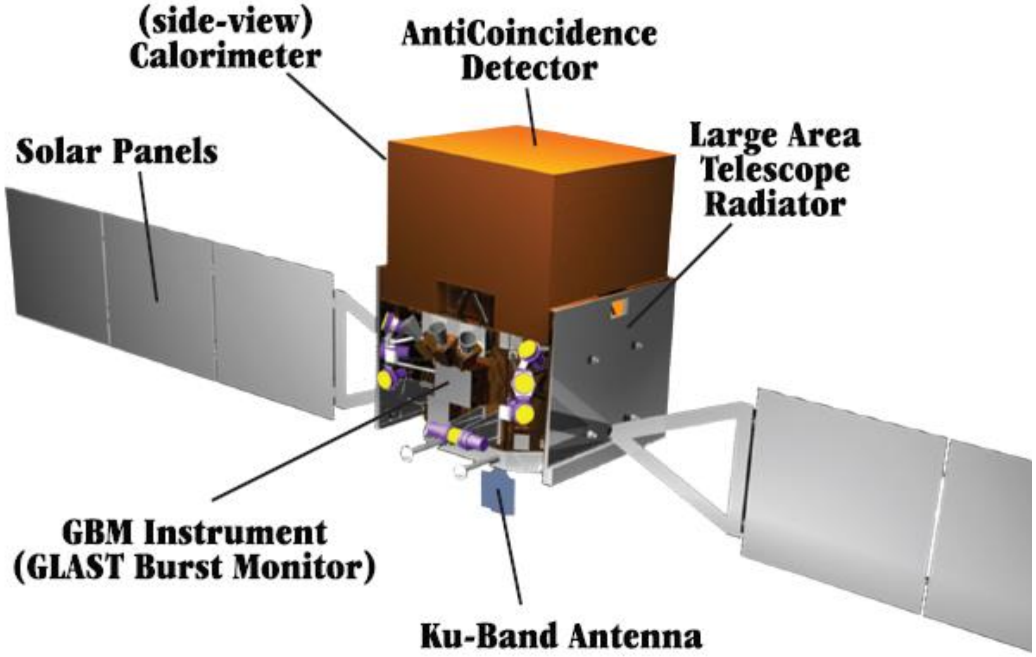
Fermi teleskop



FERMI – gamma telescope on board satelite

At the height 565 km

- ► Period 90 min
- ► Scan of whole sky in 3 hours
- ► Energy range:
  - **20 MeV – 300 GeV**



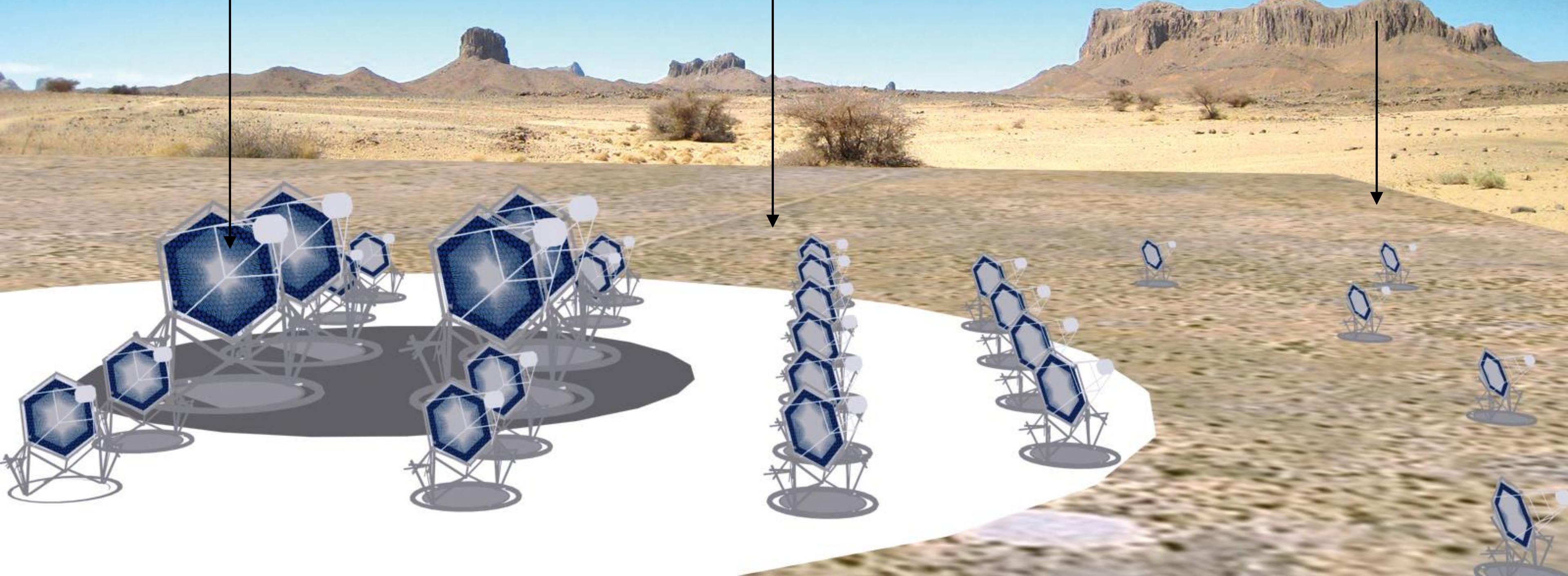
Future: Cherenkov Telescope Array (CTA)

http://www.cta-observatory.org

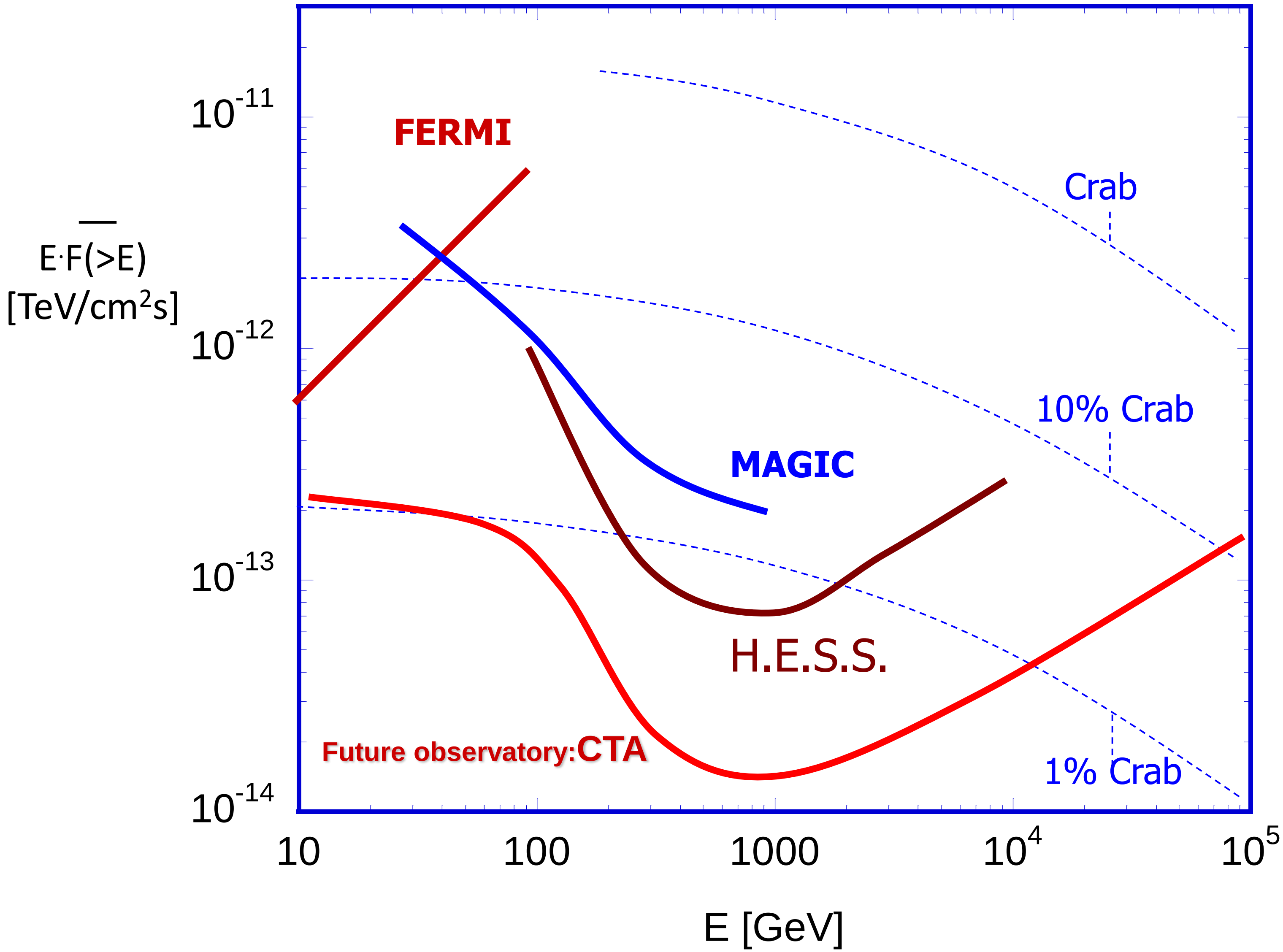
Low-energy section
energy threshold
of some 10 GeV

Core array:
mCrab sensitivity
in the 100 GeV–10 TeV
domain

High-energy section
10 km^2 area at
multi-TeV energies



Sensitivity of gamma ray telescopes



Nekoliko zaključnih misli

- Fizika čestica je započela kao astročestična fizika
  - Sada se stvari događaju u obrnutom redoslijedu
  - Ali isto tako astročestična fizika ponovo utječe na fiziku čestica
- Napredak u tehnologiji i razumijevanju fizike čestica nam je omogućio studiranje najekstremnijih procesa u svemiru
  - Koje nije bilo moguće mjeriti u laboratoriju
- IACT instrumenti na zemlji su relativno jeftini i postaju sve više tehnološki napredni
  - Za ispitivanje ne-termalnog svemir
  - I najekstremnijih procesa u svemiru