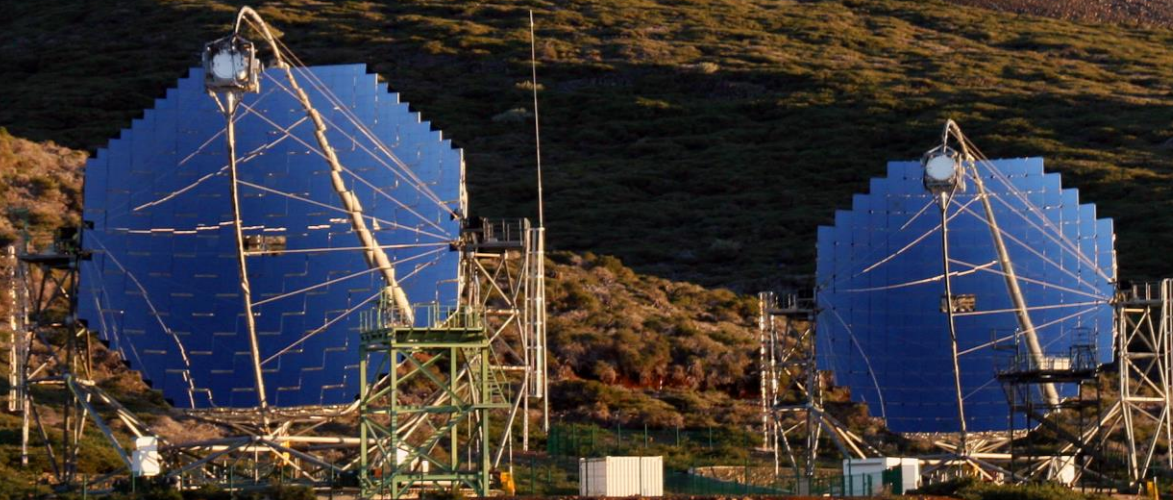


# *Croatian Teacher Programme*

# Uvod u astročestičnu fiziku

**Ivica Puljak**

**Sveučilište u Splitu - FESB**

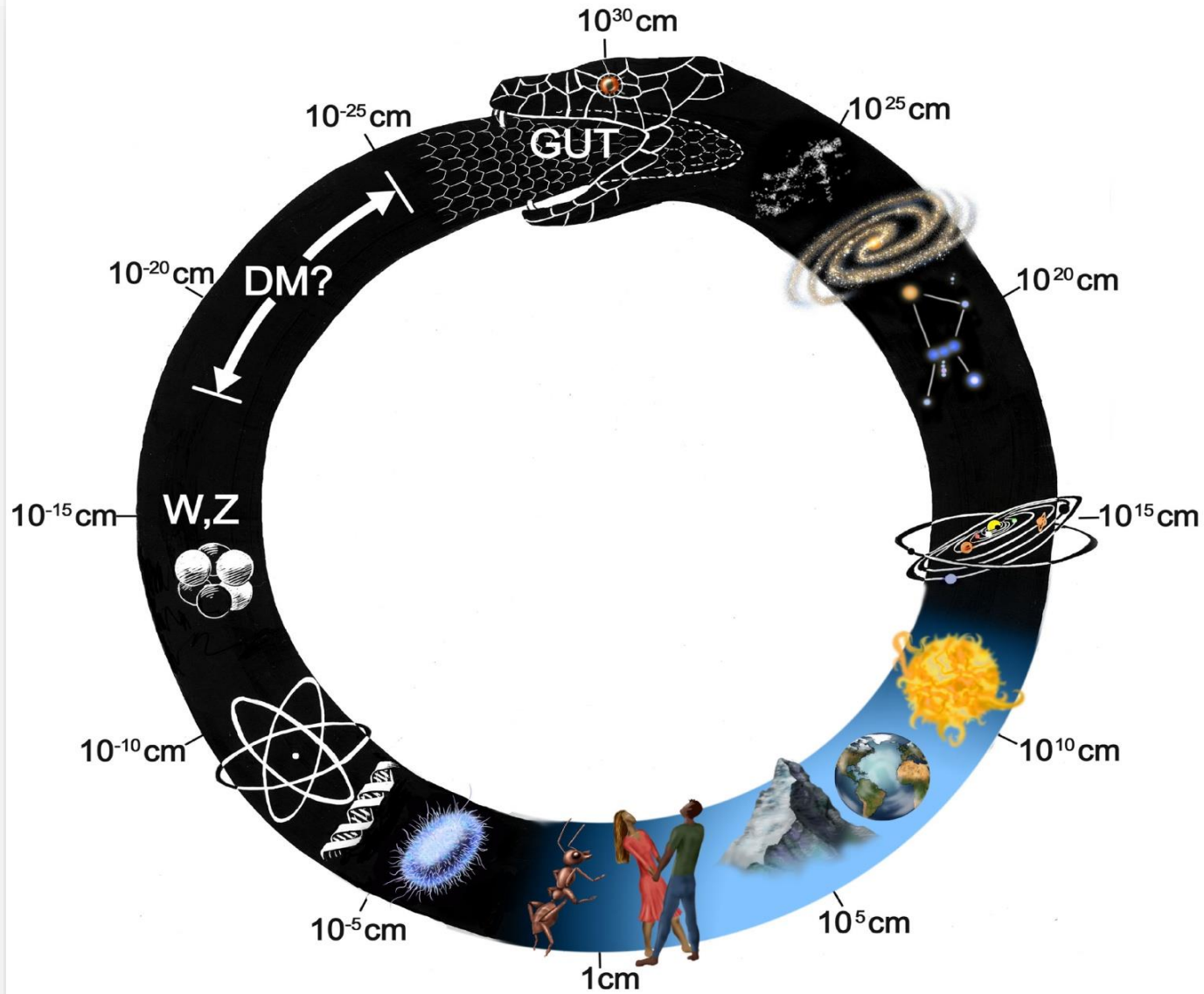


*Zahvaljujem kolegi Nikoli Godinoviću*

*CERN, 12. travnja*

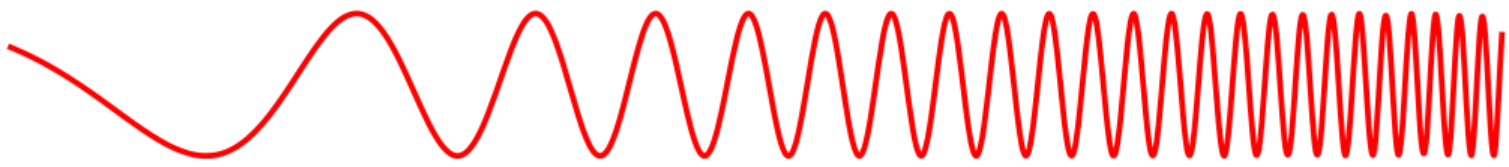
*2017.*

# Fizika velikog i malog



# Elektromagnetski spektar

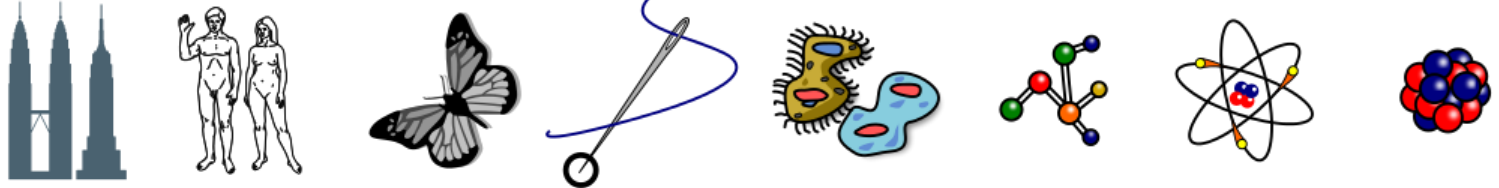
Penetrates Earth's Atmosphere?



Radiation Type  
Wavelength (m)

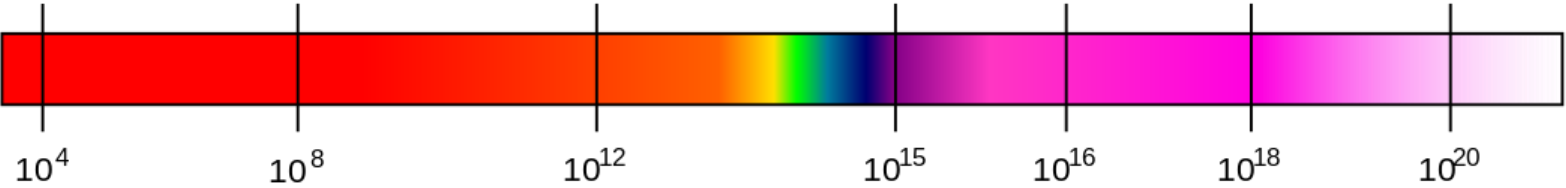
<b>Radio</b> $10^3$	<b>Microwave</b> $10^{-2}$	<b>Infrared</b> $10^{-5}$	<b>Visible</b> $0.5 \times 10^{-6}$	<b>Ultraviolet</b> $10^{-8}$	<b>X-ray</b> $10^{-10}$	<b>Gamma ray</b> $10^{-12}$
------------------------	-------------------------------	------------------------------	--	---------------------------------	----------------------------	--------------------------------

Approximate Scale of Wavelength

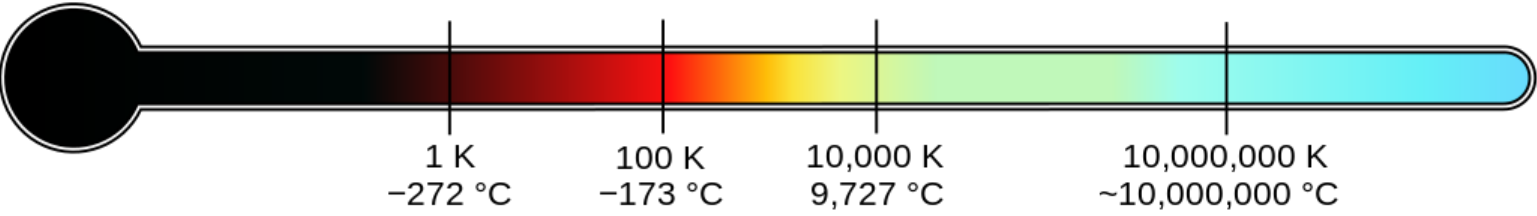


Buildings    Humans    Butterflies    Needle Point    Protozoans    Molecules    Atoms    Atomic Nuclei

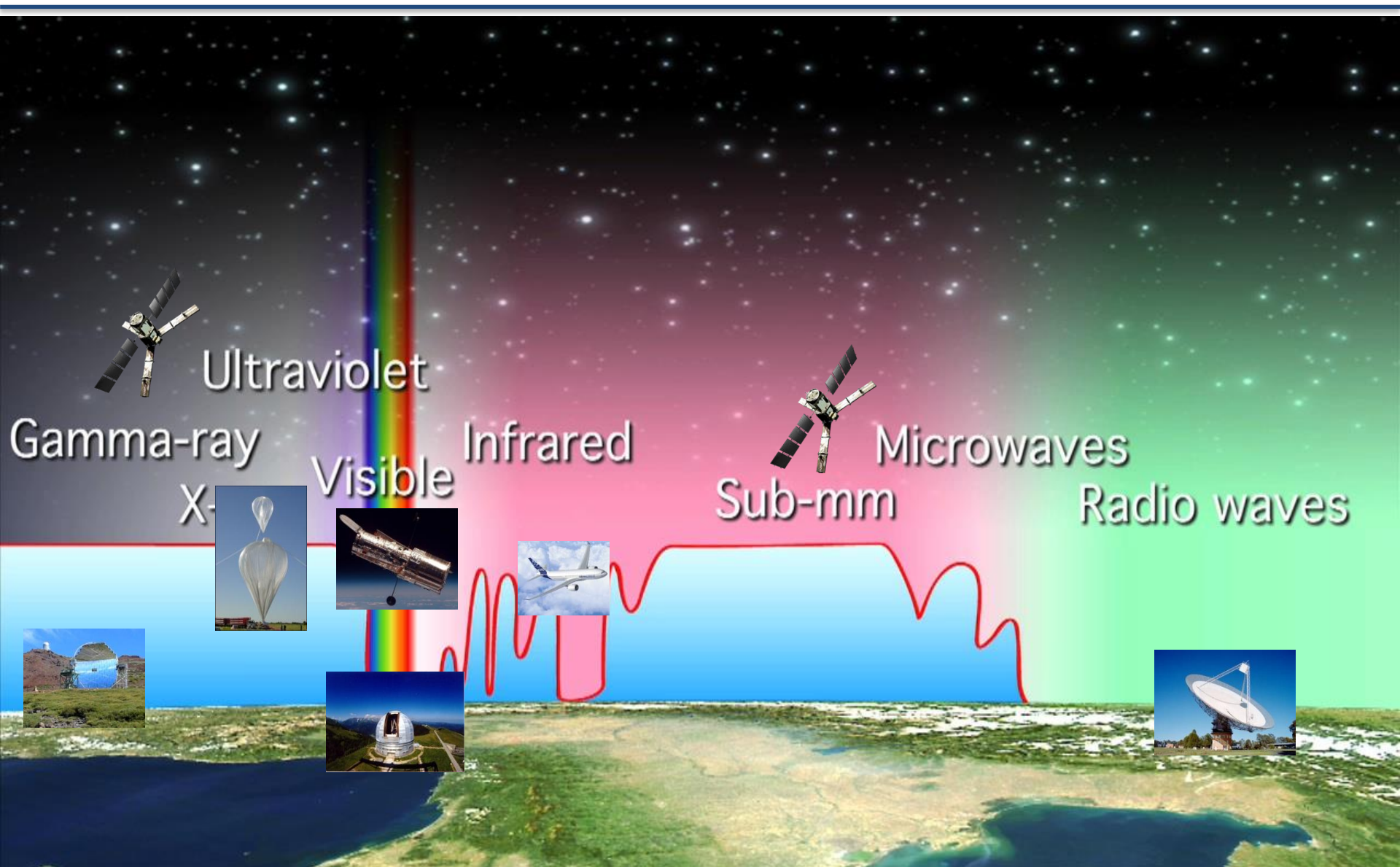
Frequency (Hz)



Temperature of objects at which this radiation is the most intense wavelength emitted







Ultraviolet

Gamma-ray

X-ray

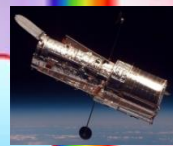
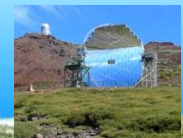
Visible

Infrared

Sub-mm

Microwaves

Radio waves

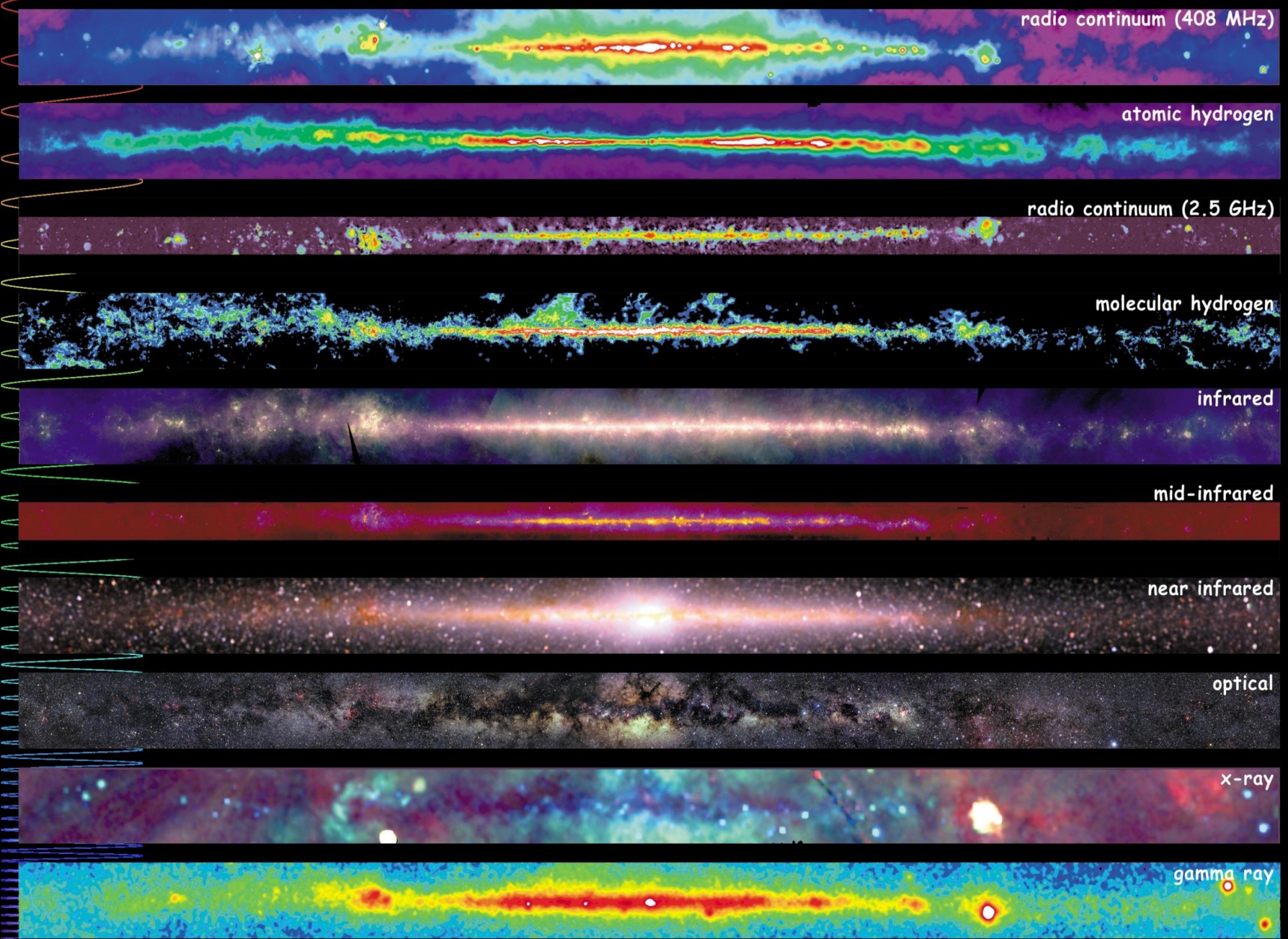




# Mliječna staza







<http://adc.gsfc.nasa.gov/mw>



# Multiwavelength Milky Way

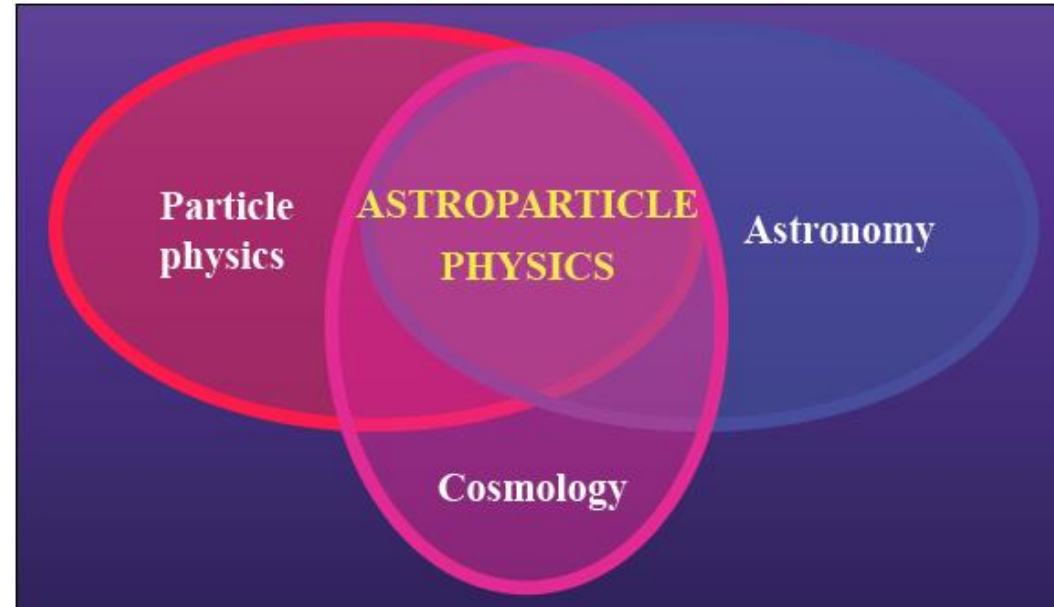
# Astročestična fizika

## ► Što istražuje

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

## ► Čime istražuje

- Teleskopi/detektor 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



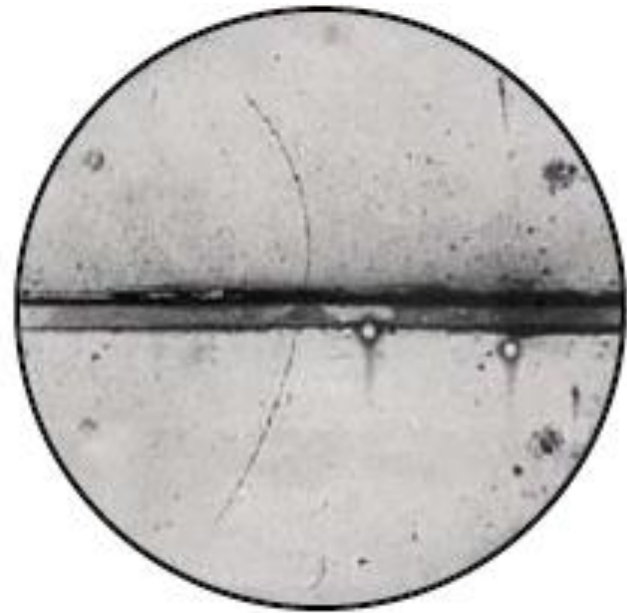
# Kozmičke zrake otkrivene 1912. godine



*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

<i>Godina</i>	<i>Otkriće</i>
1932	pozitron
1937	mion
1947	pion
1956	antineutrino

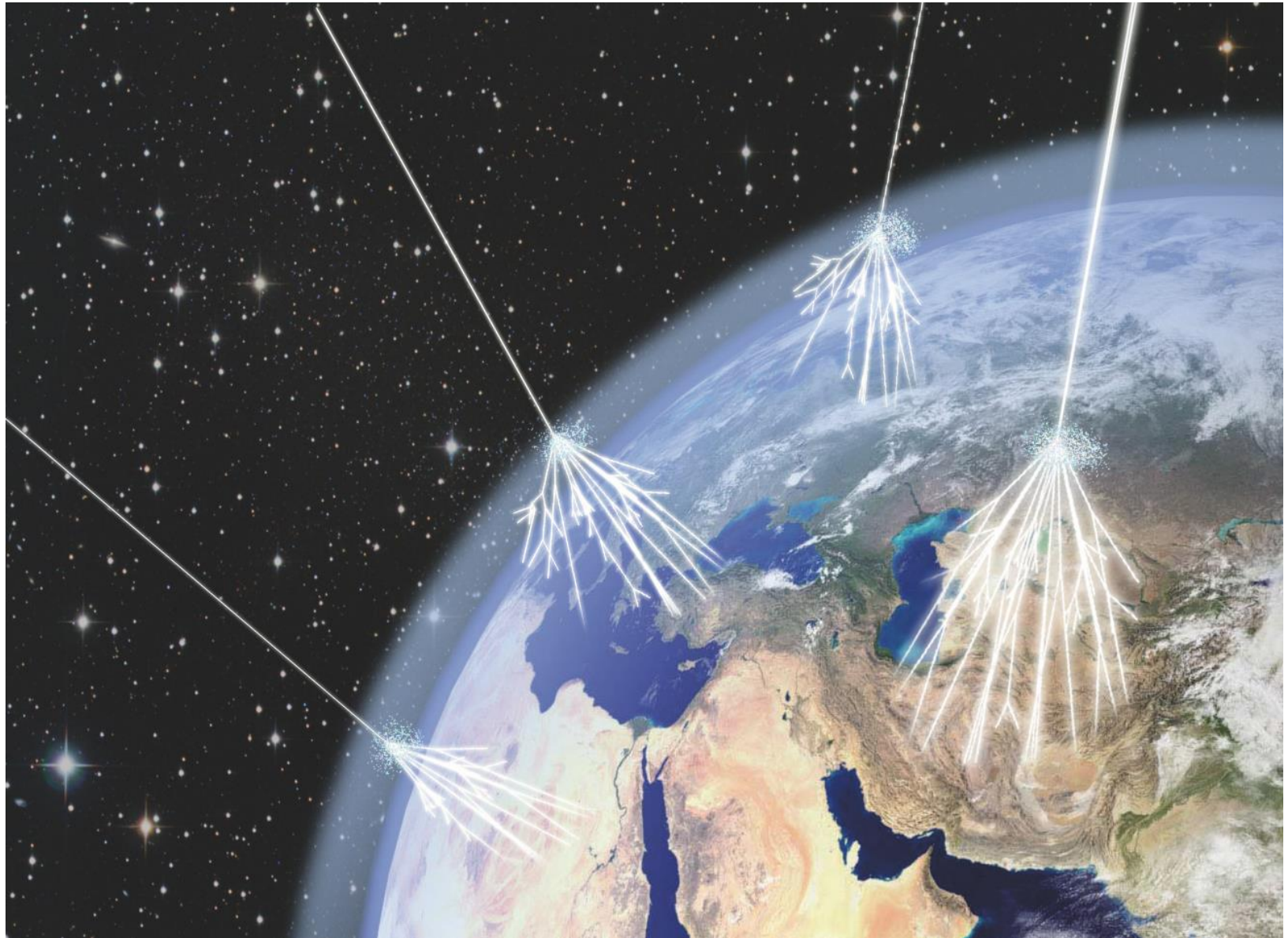


*One of the first positron tracks in a cloud chamber, recorded by Carl D. Anderson in 1932.*

# Važni datumi u astročestičnoj fizici

- ▶ **1912:** Victor Hess climbs to 5200 metres in a balloon and demonstrates the existence 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.

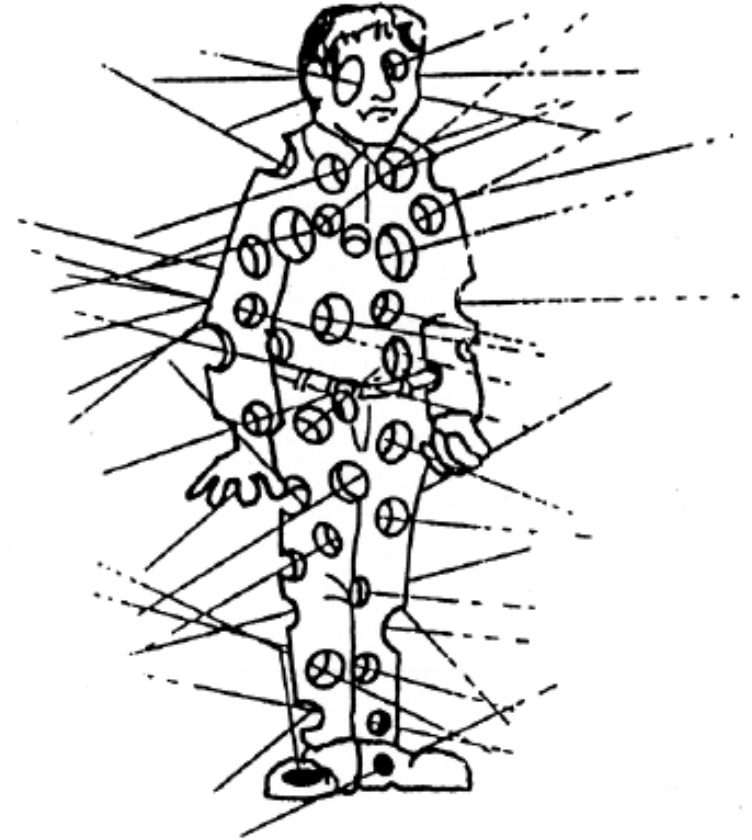
# Kozmičke zrake



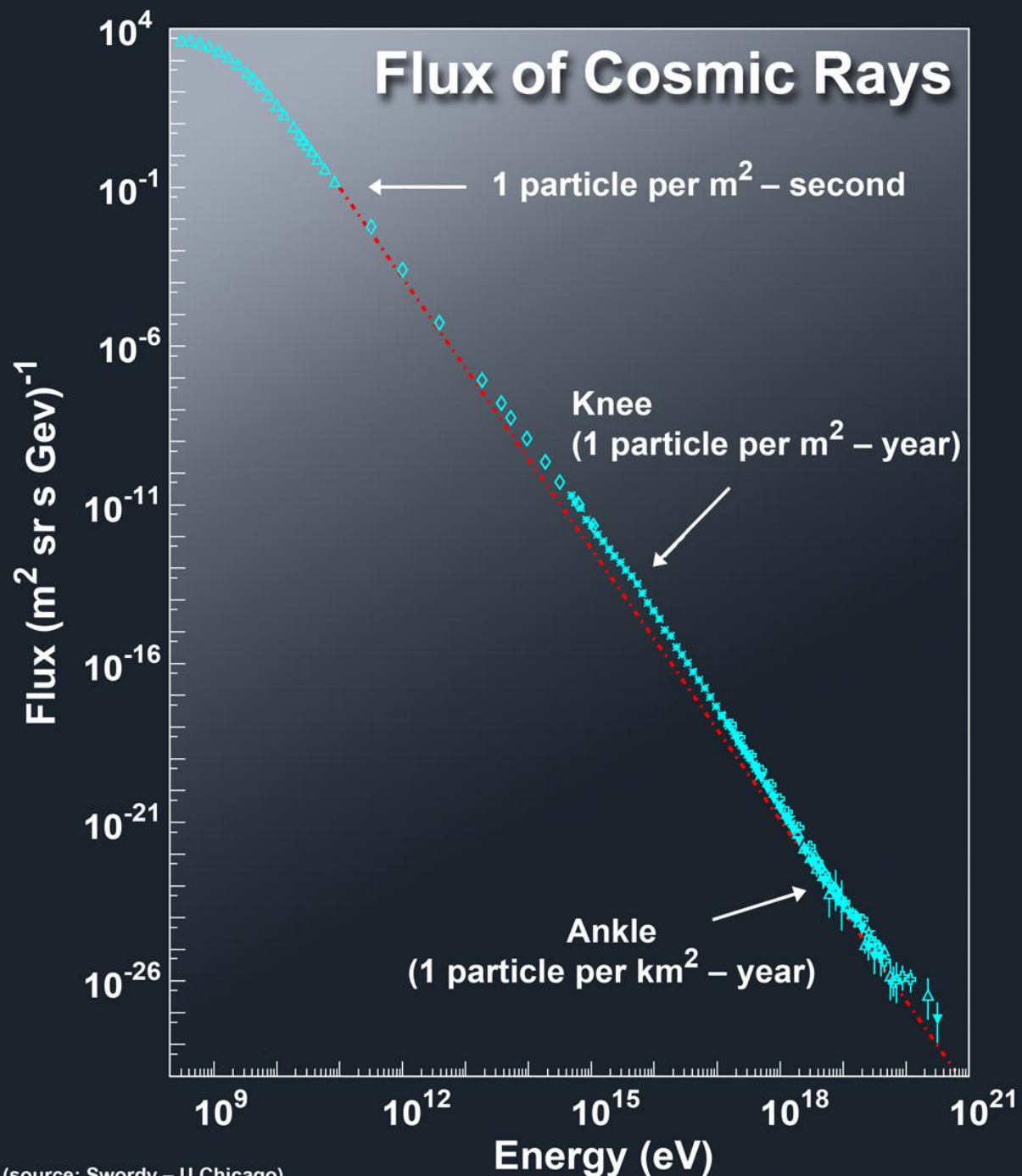


# Kozmičke zrake – Osnovni podaci

- ▶ 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

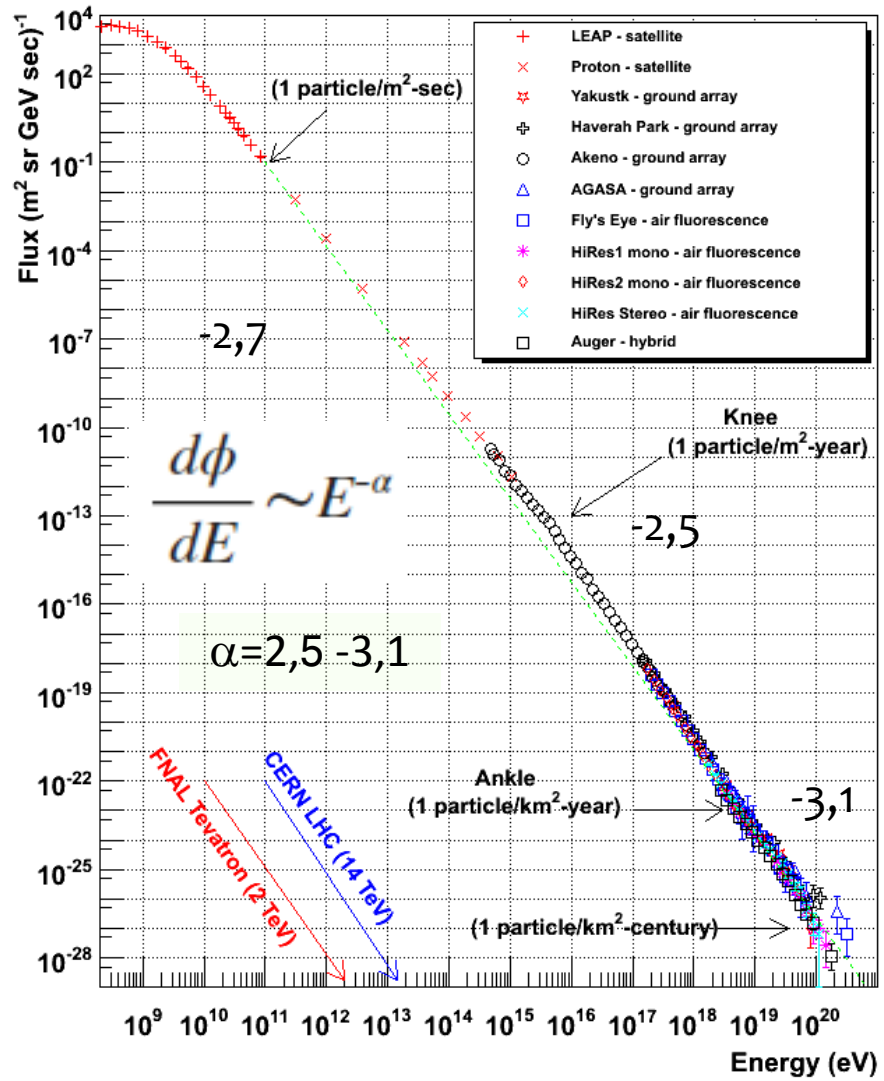


# Kozmičke zrake – Energijski spektar



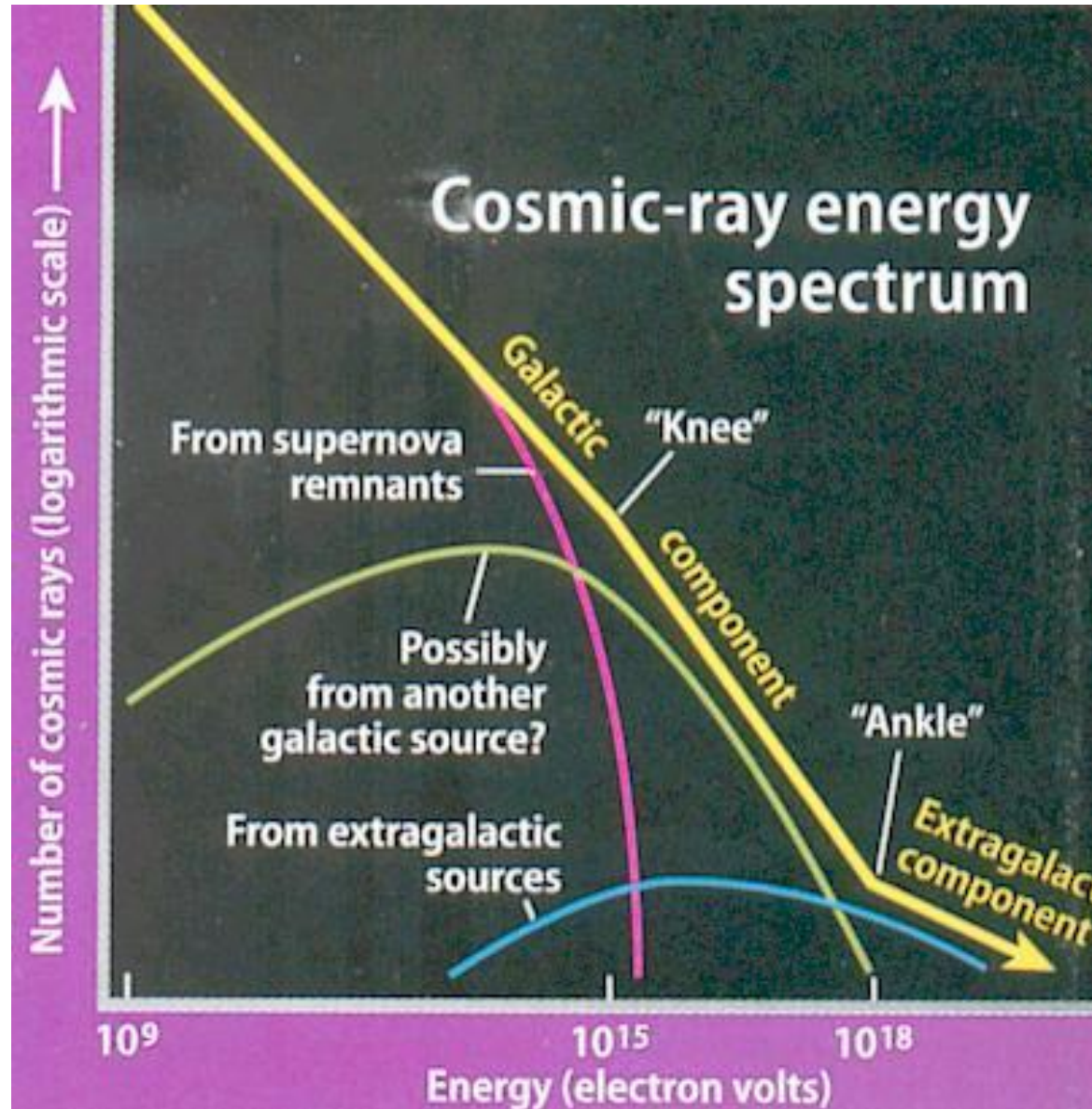
(source: Swordy – U.Chicago)

# Kozmičke zrake – Energijski spektar



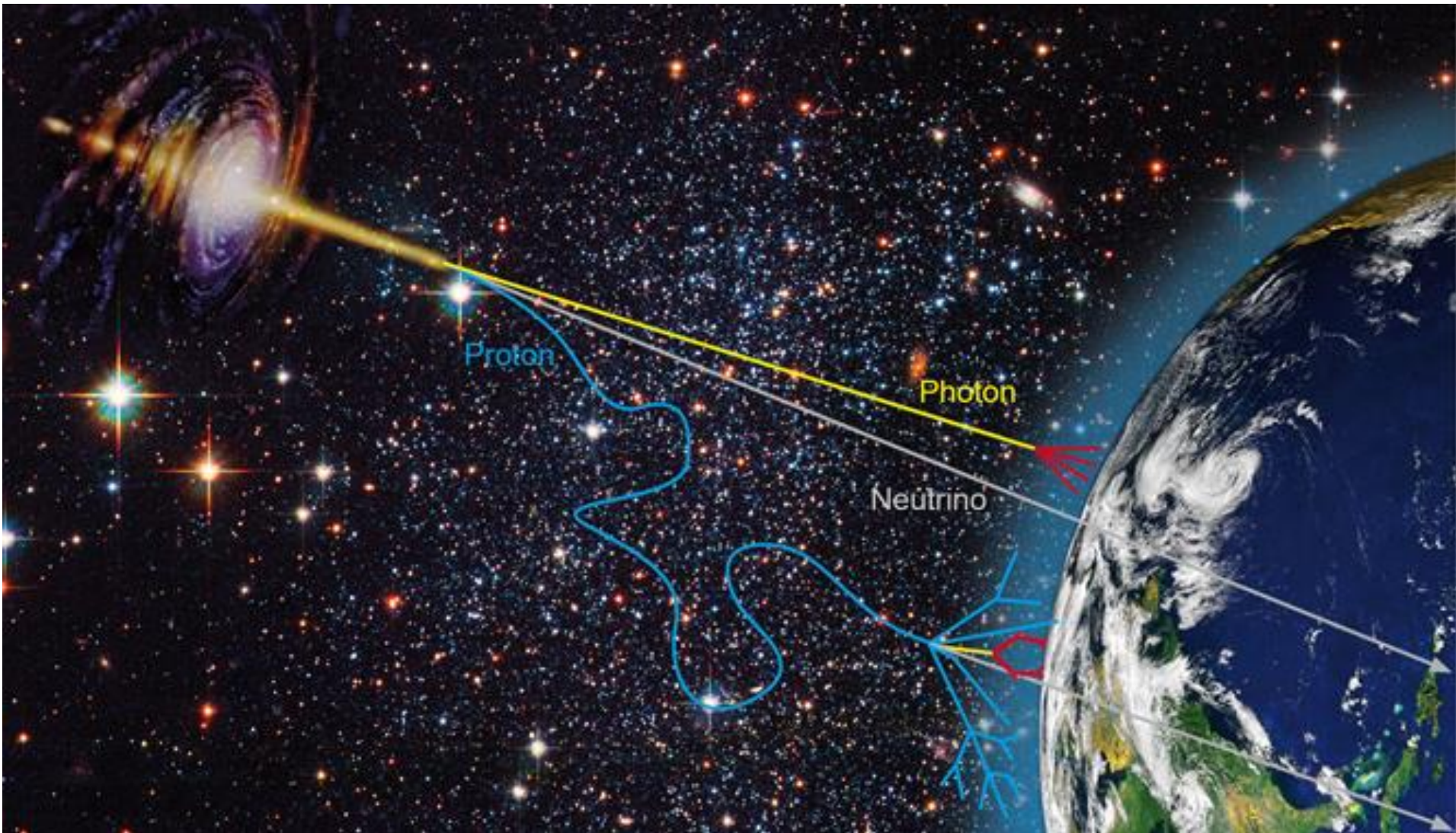


# Odakle dolaze kozmičke zrake?





# Kako se propagiraju kozmičke zrake?



# Neka od pitanja

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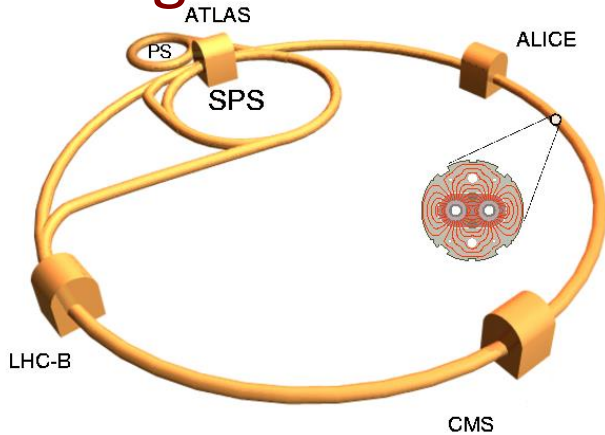
- ▶ Koji su izvori kozmičkih zraka?
- ▶ Gdje se nalazi izvori?
- ▶ Kako funkcioniraju kozmički akceleratori
- ▶ Kakav je spektar, priroda i smjer kozmičkih zraka?
- ▶ Koji su fizikalni mehanizmi produkcije kozmičkih zraka?
- ▶ Koja je maksimalna energija?



# Ubrzavanje čestica

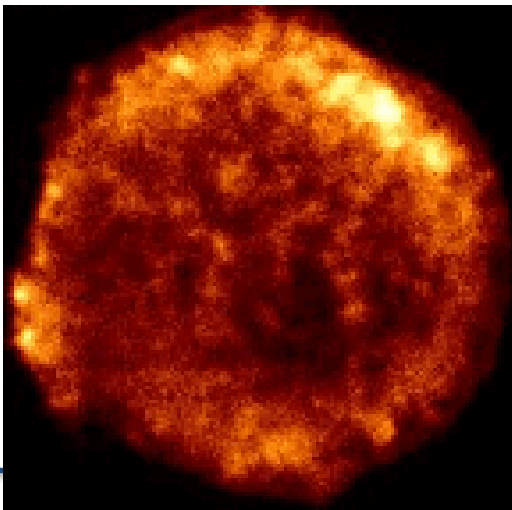
$$E \propto BR$$

## Large Hadron Collider



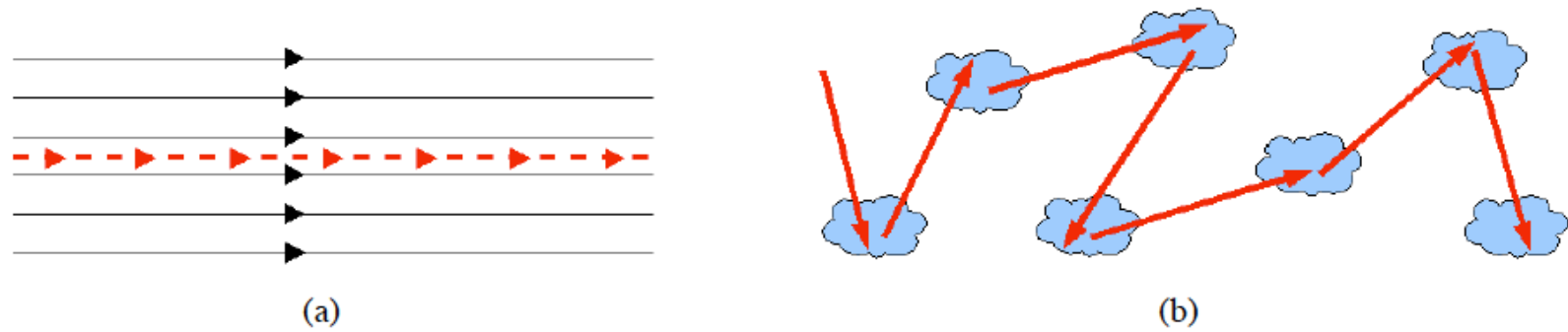
$$R \sim 10 \text{ km}, B \sim 10 \text{ T} \quad \Rightarrow \quad E \sim 10 \text{ TeV}$$

## Tycho SuperNova Remnant

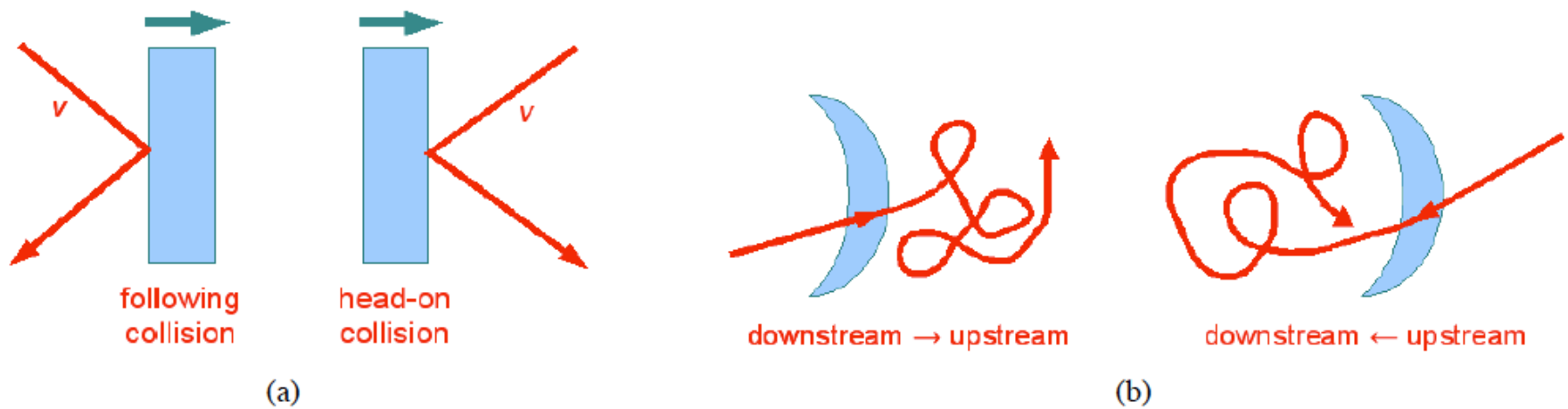


$$R \sim 10^{15} \text{ km}, B \sim 10^{-10} \text{ T} \quad \Rightarrow \quad E \sim 1000 \text{ TeV}$$

# 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

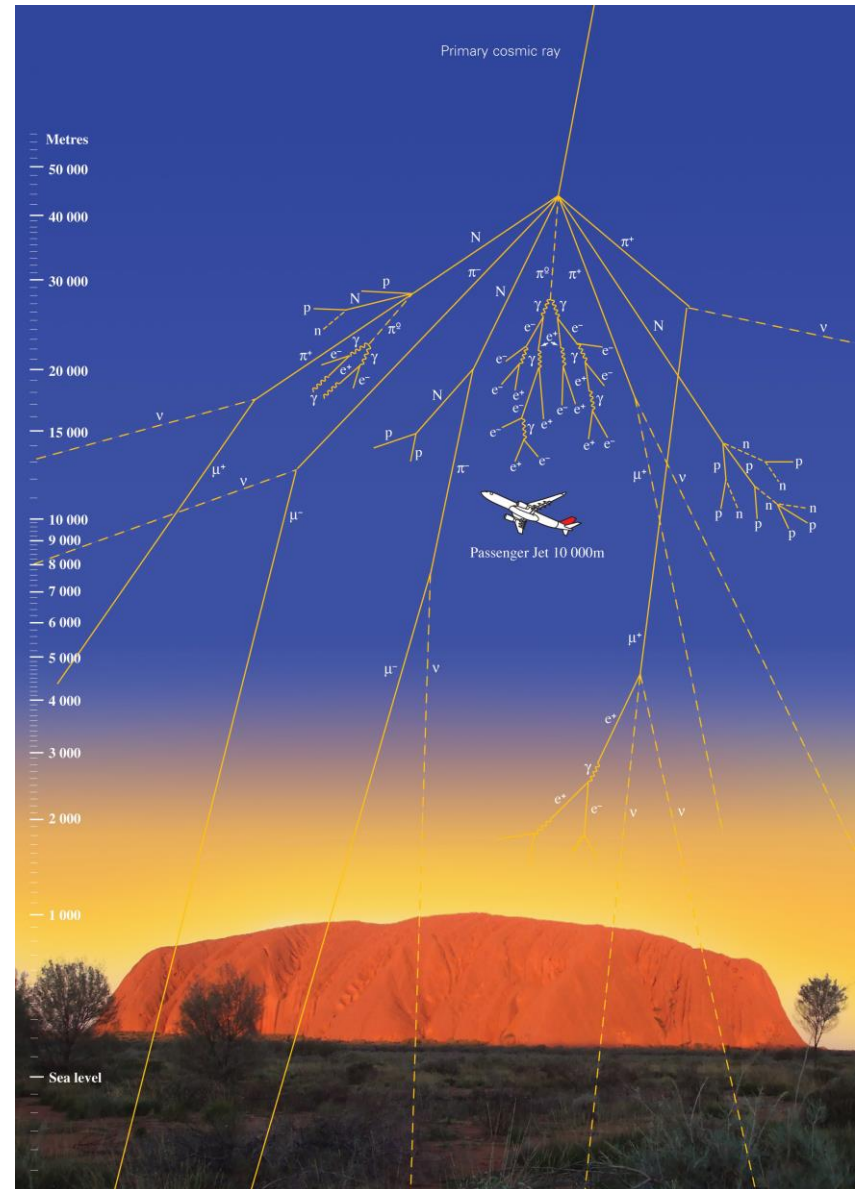
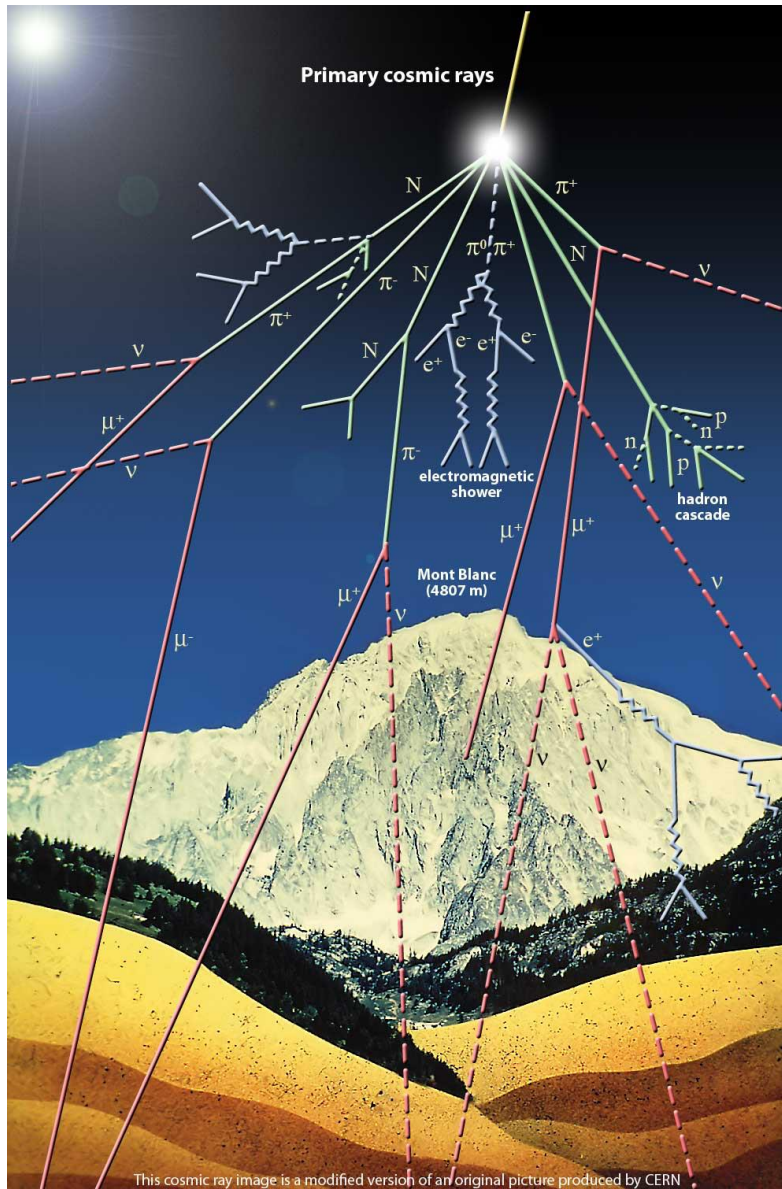
	<b>ENERGIJA</b>	<b>INSTRUMENTI</b>
LE	100 keV do 100 MeV	Sateliti
HE	100 MeV – 100 GeV	Sateliti: GLAST/Fermi
VHE	<b>100 GeV – 100 TeV</b>	<b>IACT</b> <b>MAGIC(HEGRA), HESS, VERITAS,</b> <b>CANGAROO III</b>
UHE	100 TeV – 100 PeV	AUGER
EHE	> 100 PeV	AUGER

# Kako detektiramo kozmičke zrake?

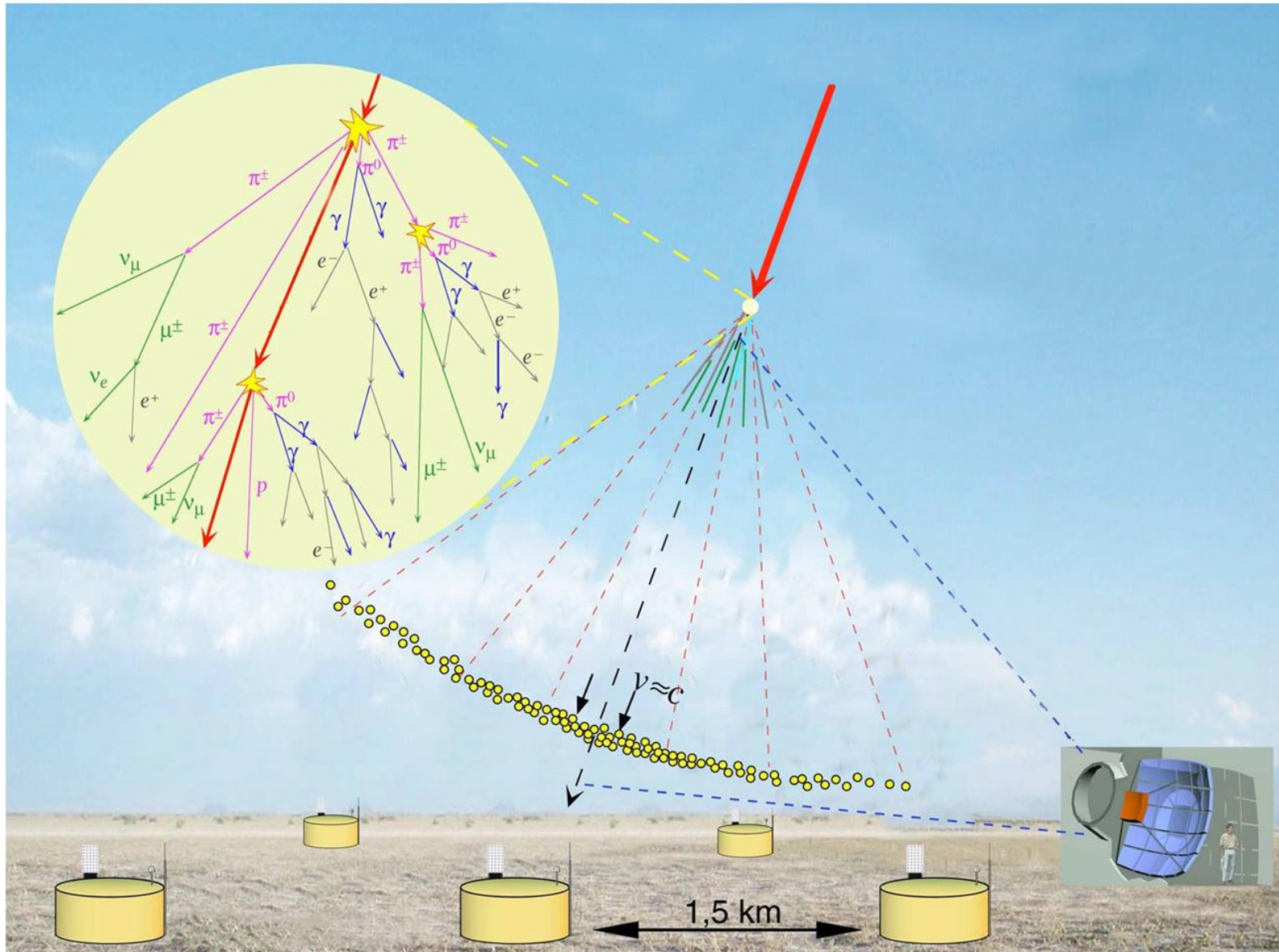




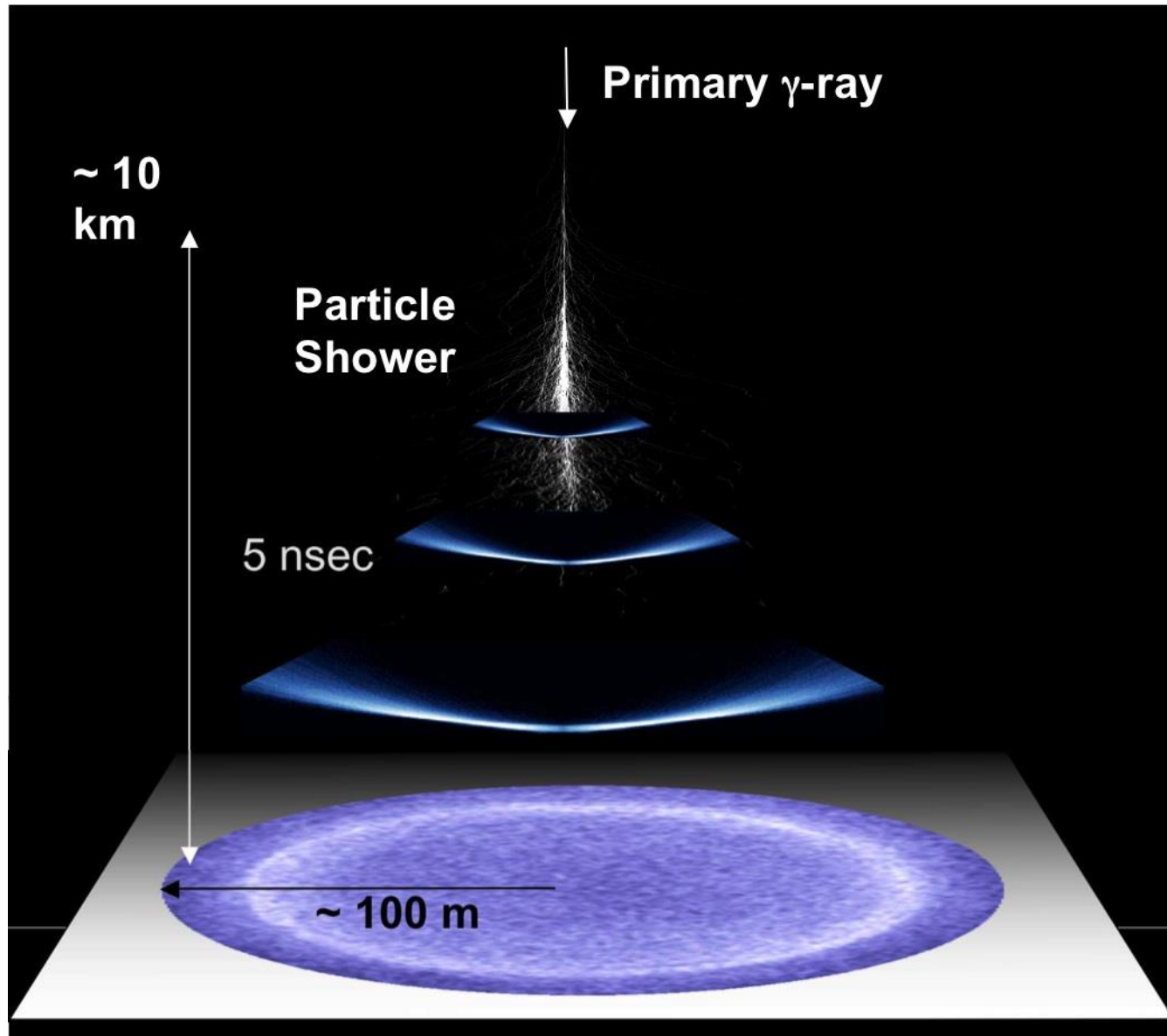
# Pljusak čestica



# Gama zrake



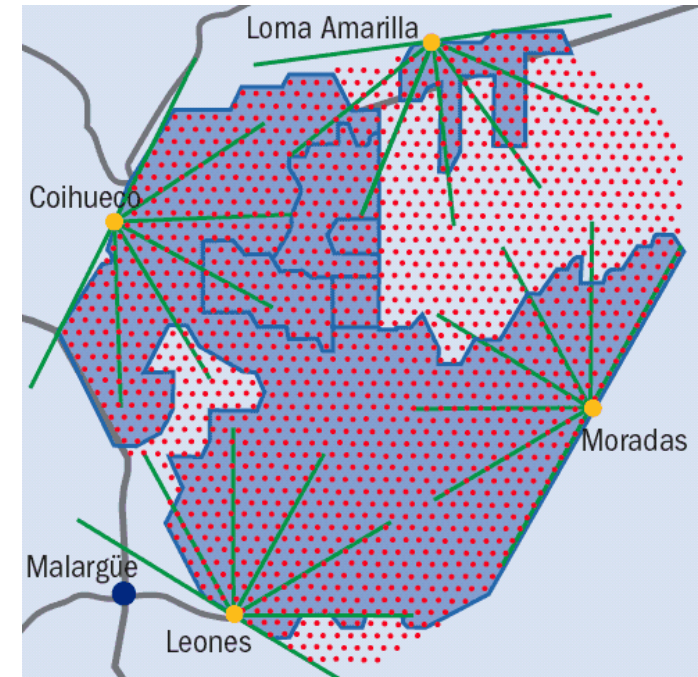
# Gama zrake





# Pierre Auger(PAO) Observatory (UHE-EHE)

- The world largest CR observatory, exposure area 40 000 km<sup>2</sup>, duty cycle about 100 %
- 1600 water ČD at a distance of 1,5 km distributed over the area of 3000 km<sup>2</sup> – 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<sup>16</sup> - 10<sup>20</sup>) eV



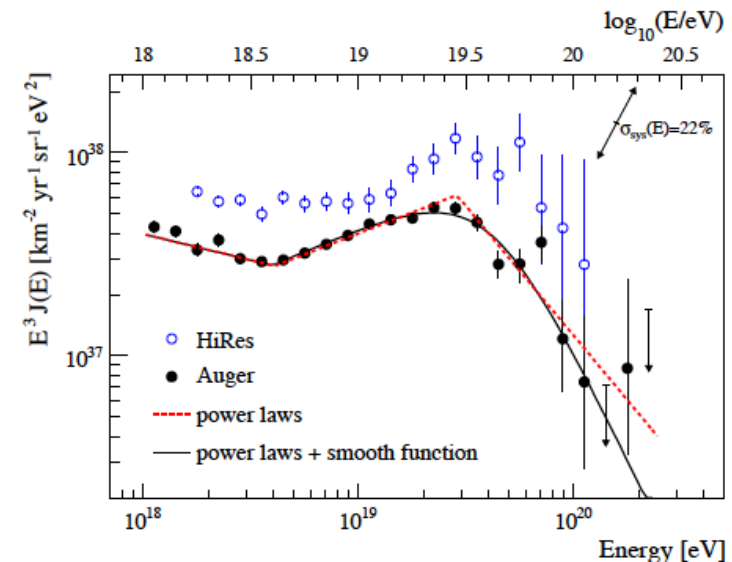
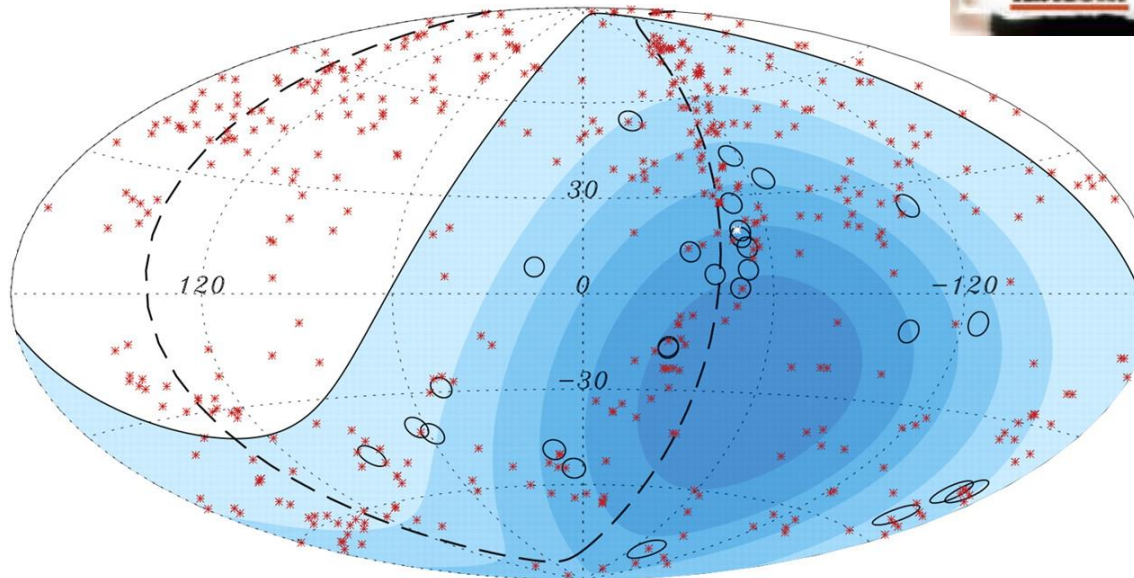


# EHE CR – P. Auger Observatory

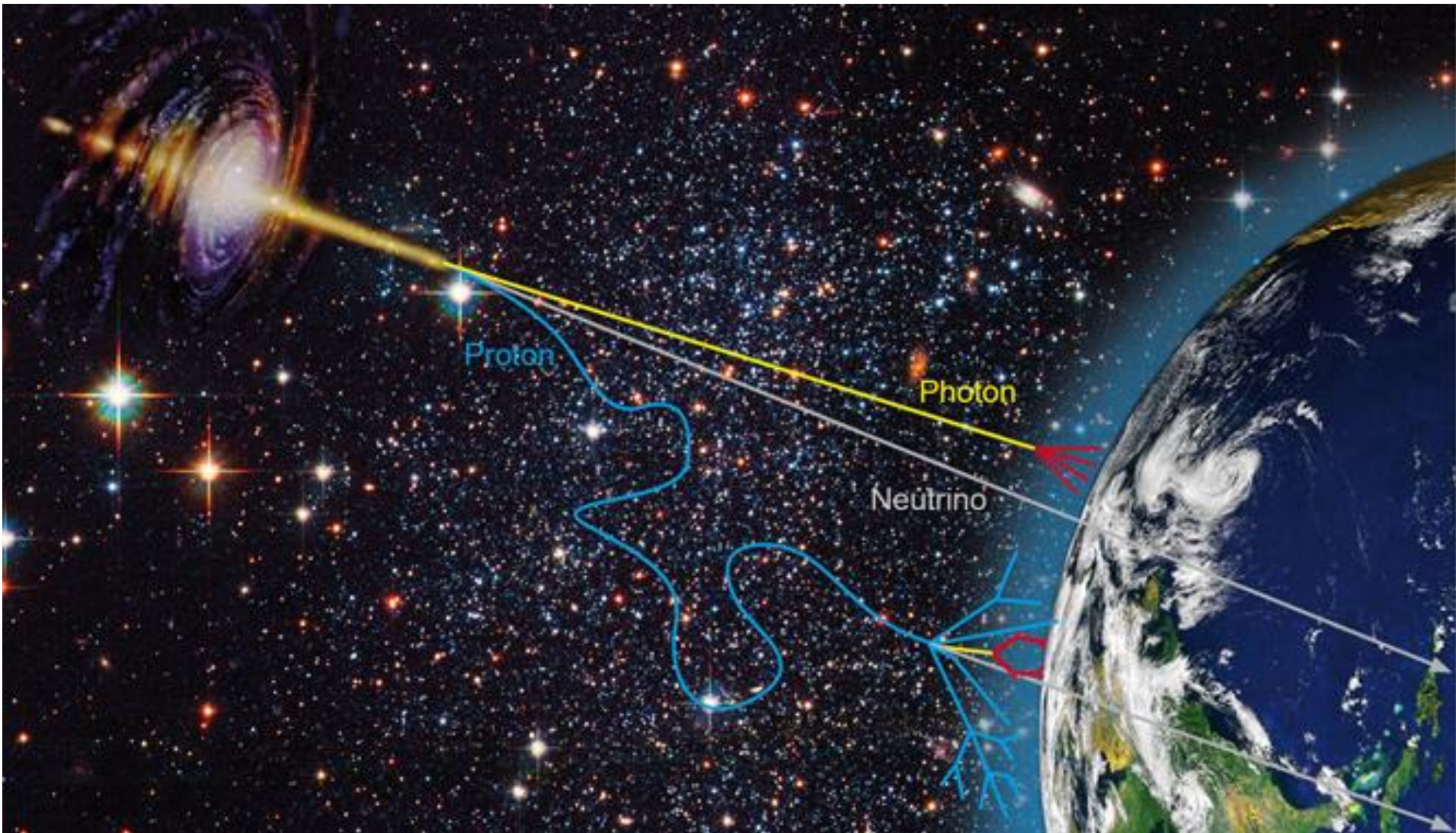
- ▶ PAO: AGN are sources of UHE (Science 318, 938 -943 (2007))
- ▶ UHE CR  $> 40 \text{ EeV}$  ( $4 \times 10^{19} \text{ eV}$ ) are slightly deflected by galactic and intergalactic magnetic field.

27 sources with  $E > 5.7 \times 10^{19} \text{ eV}$   
The highest energy event  $3.2 \times 10^{20}$

This note predicts that above  $10^{20} \text{ eV}$  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?



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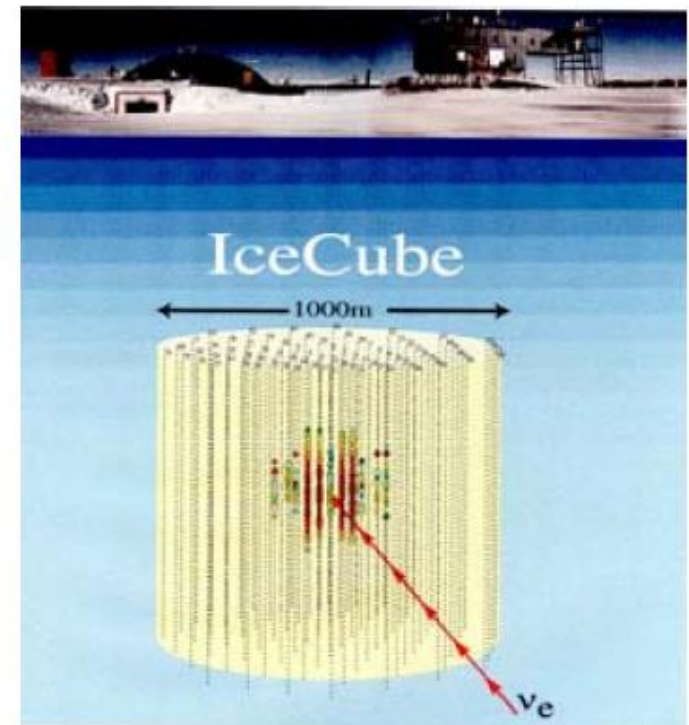
# Astronomija neutrinima

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# Astronomija neutrinima

- Neutrinos are elementary particles of very small mass (SuperKamiokande 1998).
- Intergalactic gas, dust and magnetic field 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 ( $400 \text{ neutrinos/m}^3$  at  $1.9 \text{ K}$ ) generated 2 seconds after Big Bang, passing through 50 l.y. thick lead.
- It will be wonderful to detect these neutrinos !?
- Neutrino detectors need a huge volume.
- Neutrino oscillation impose a lower limit on the heaviest neutrino mass of about  $0.05 \text{ eV}$ .
- Neutrino contribute at least  $0.1\%$  to cosmic matter

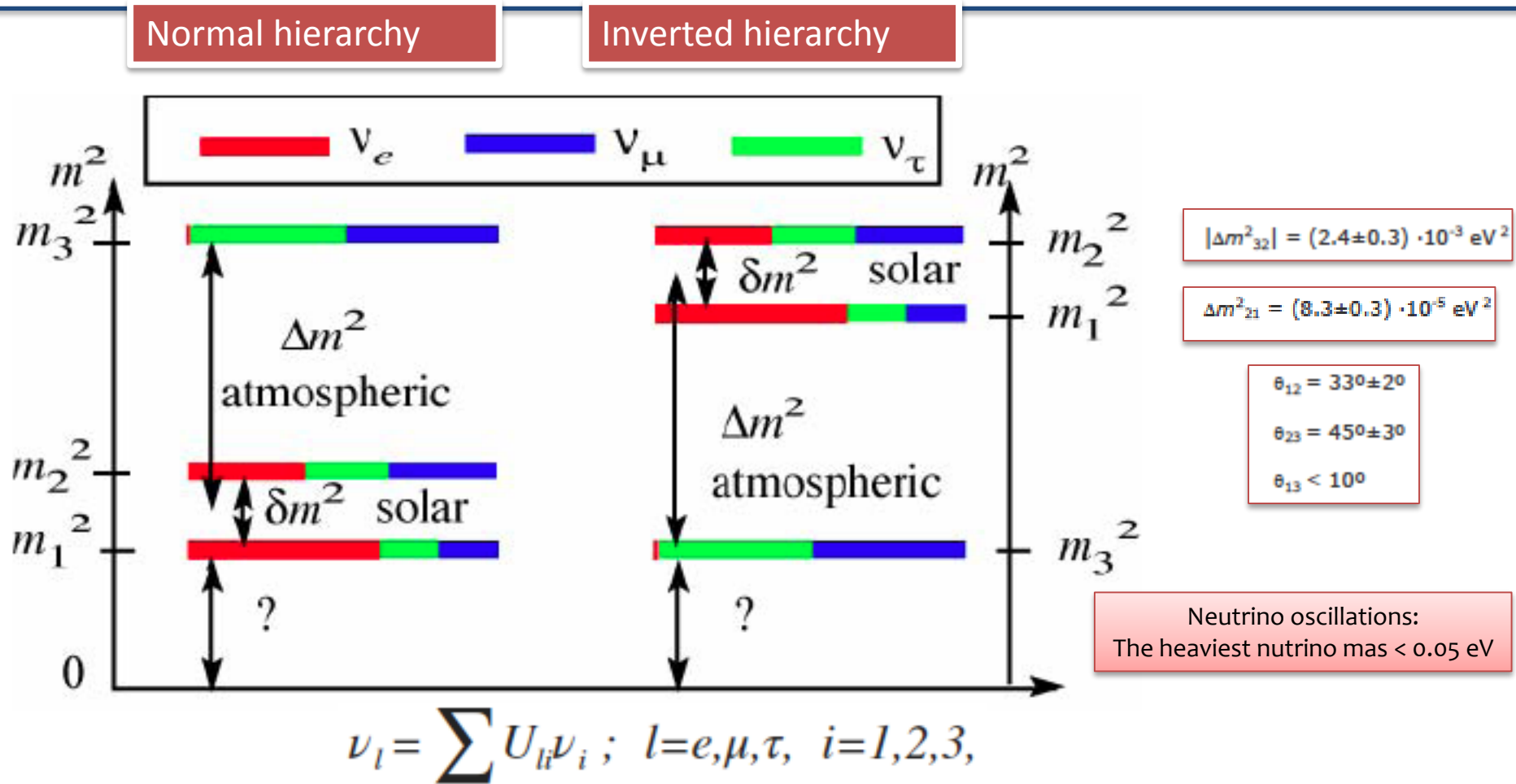


# Fundamental question in neutrino physics

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- ▶ 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 ( $e$ ,  $\mu$  and  $\tau$ ) 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  $m_4$  around 1 eV

# Neutrino masses – current knowledge

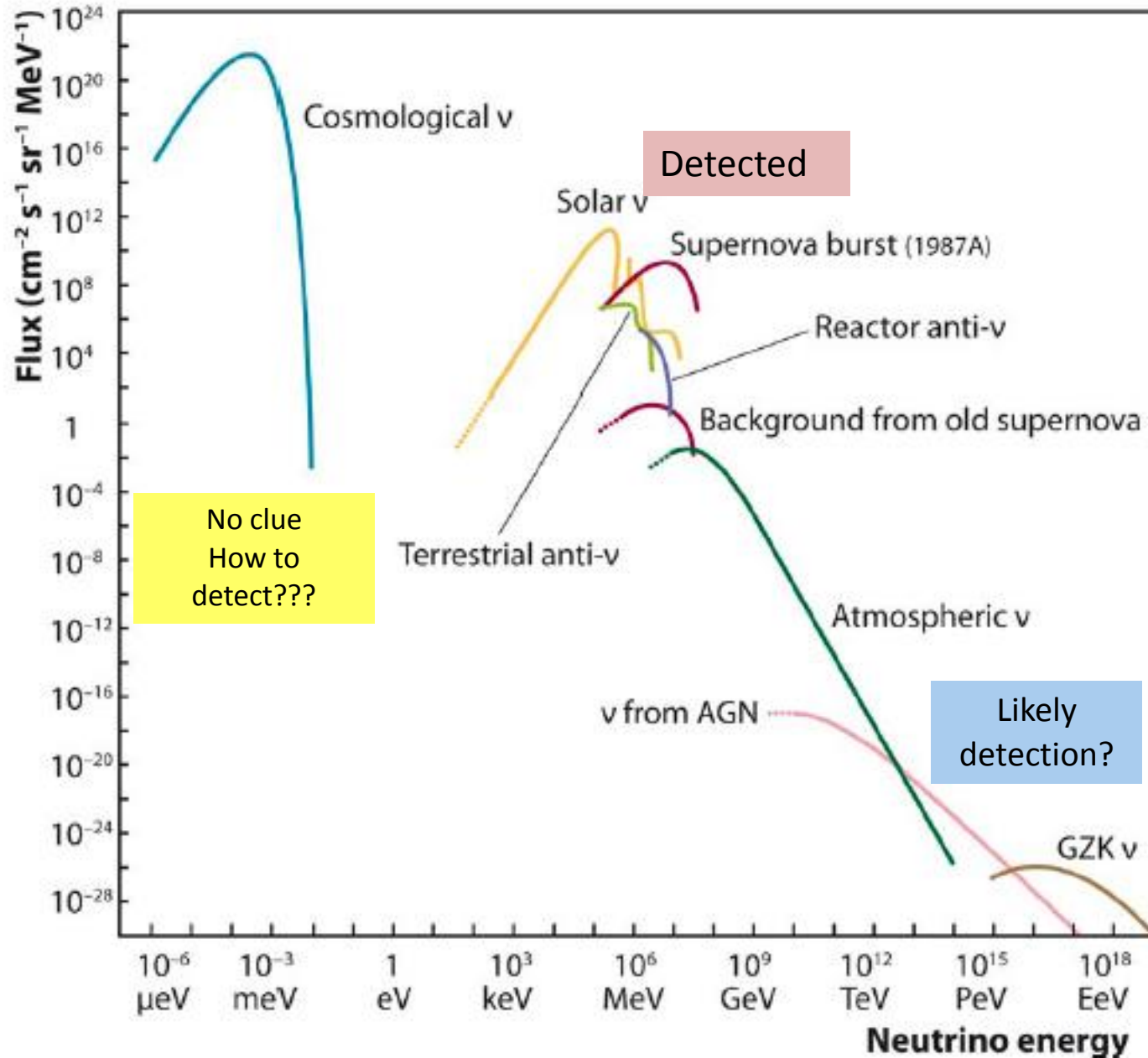


Weak eigenstate  $\neq$  mass eigenstate if neutrino have mass

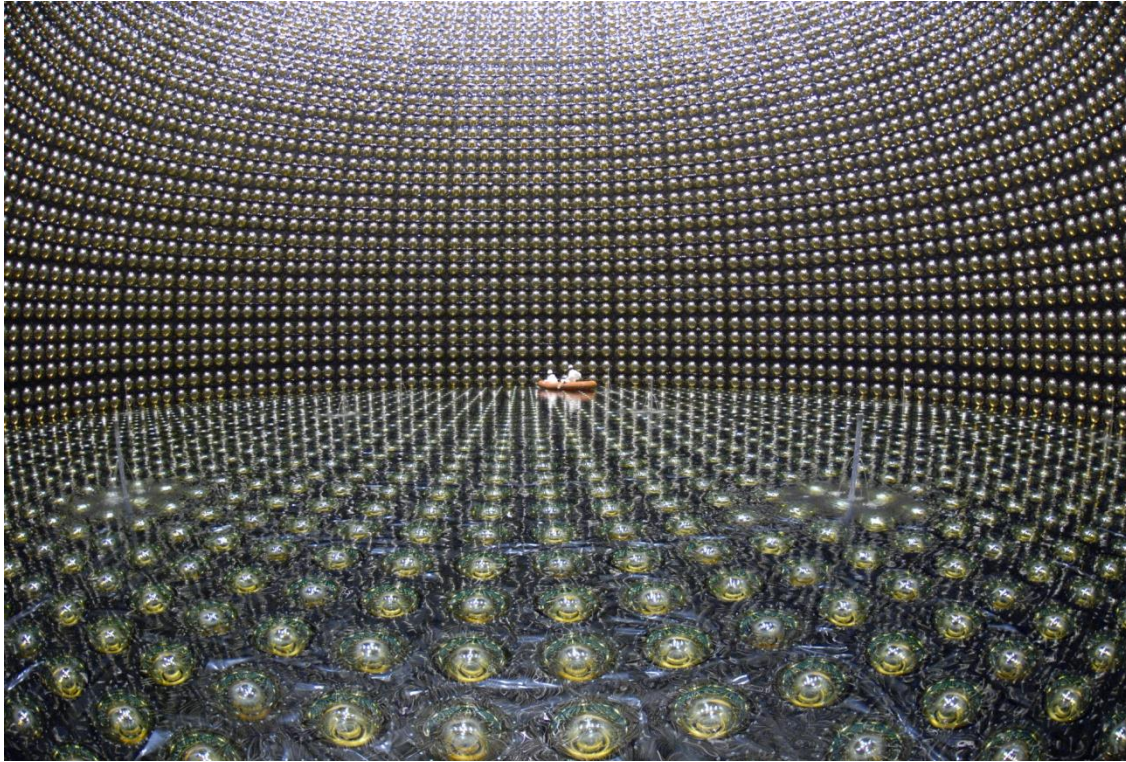
We do not know the sign of  $\Delta m^2_{32}$  so we do not know if  $m_3$  is heavier or lighter than  $m_1$  and  $m_2$ ,  
 We know:  $m_2 > m_1$ .



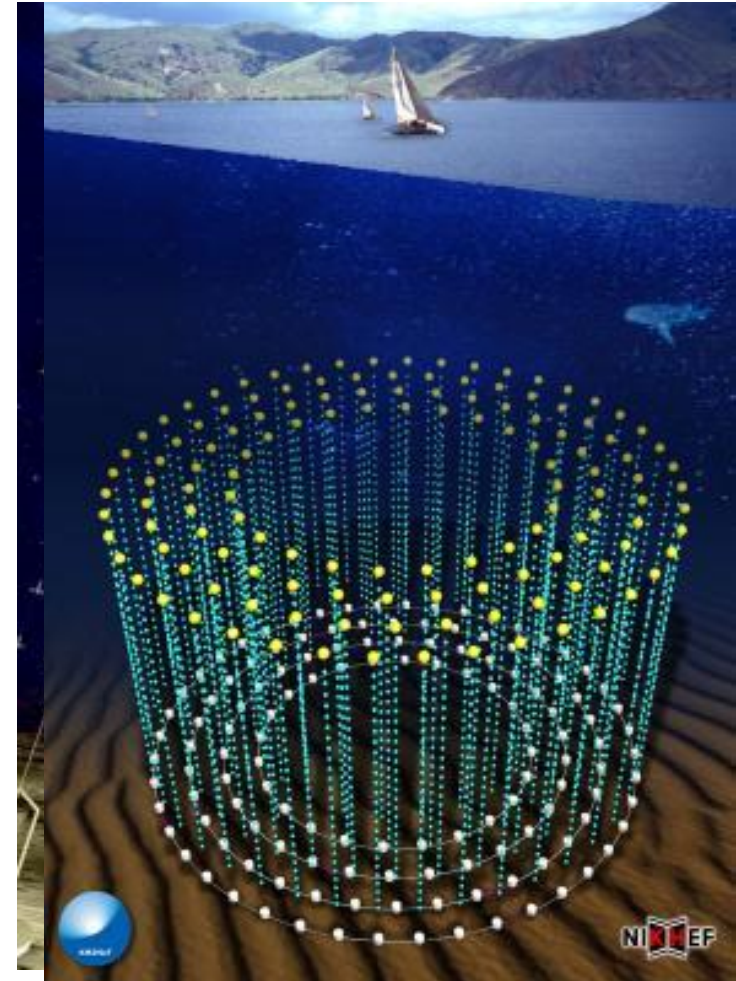
# Neutrino spectrum



# 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
- Baikal

## ► Under ice

- AMANDA
- IceCube

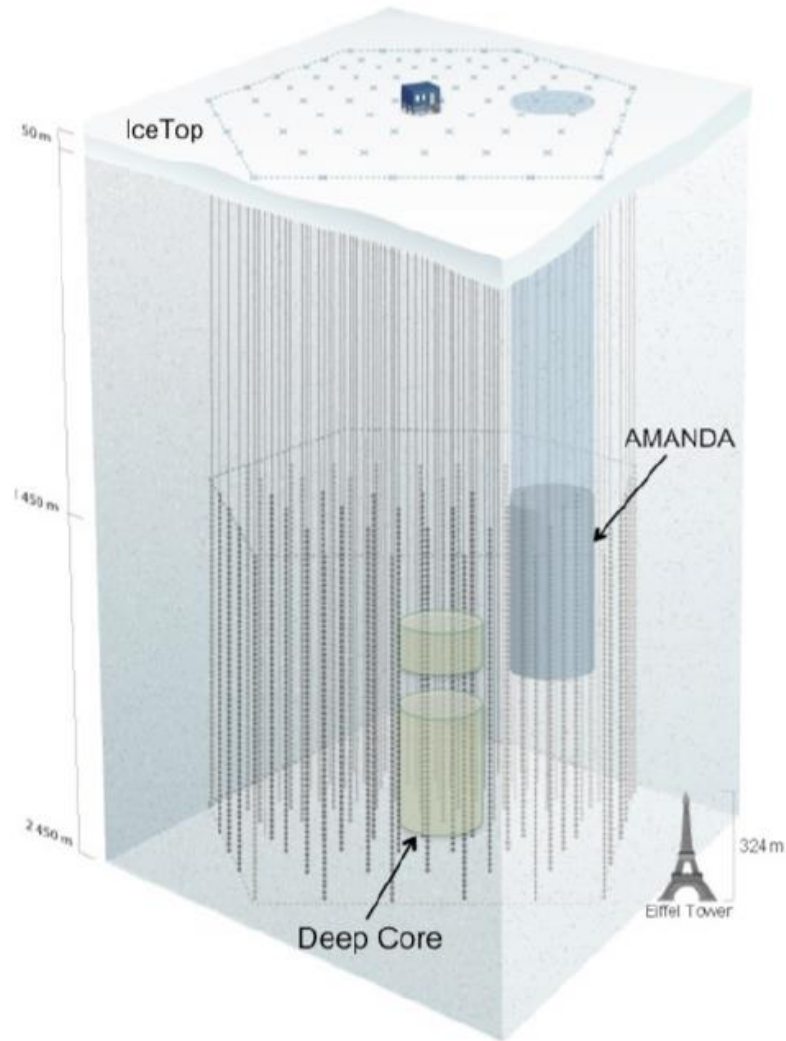


Figure 5: The IceCube Observatory, including the deep ice array, IceTop, AMANDA, and Deep Core. For comparing sizes the image of the Eiffel tower is also shown.



# Events in IceCube

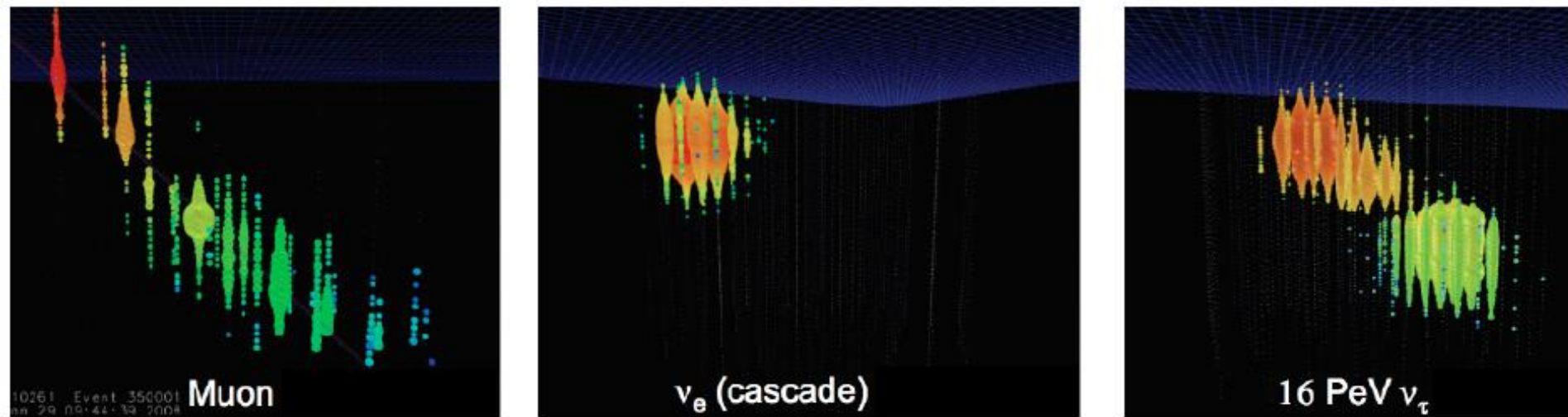
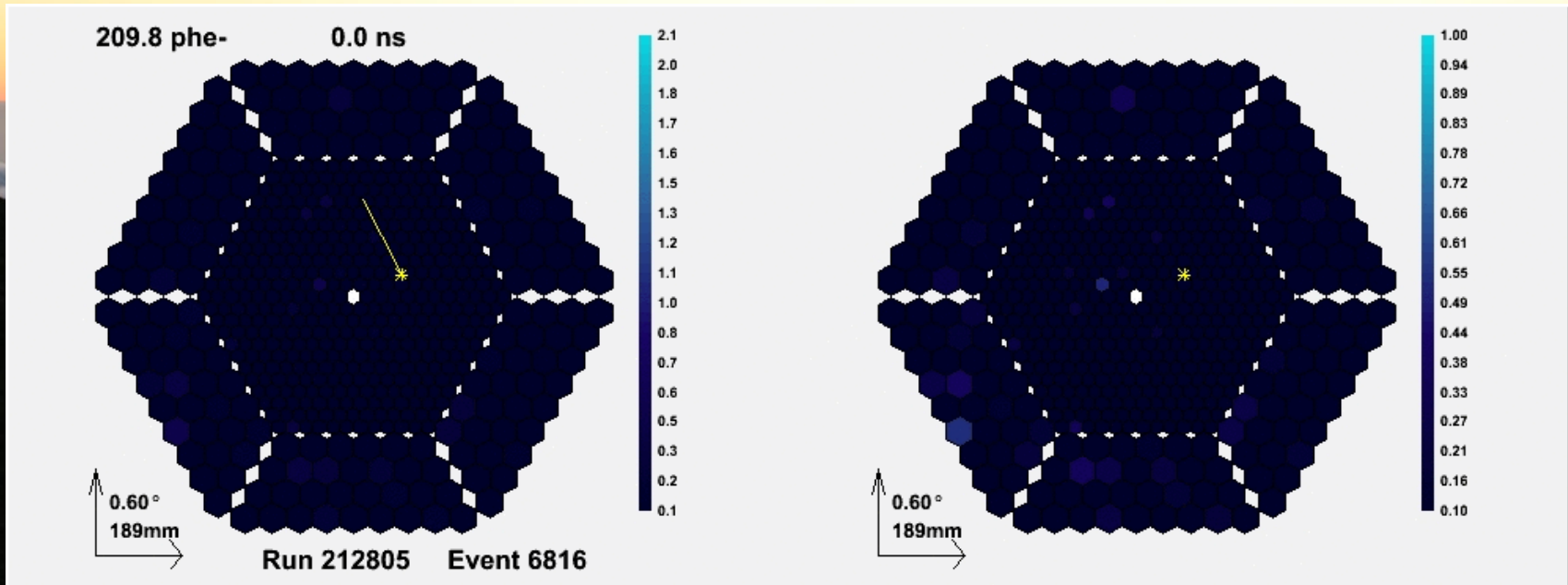


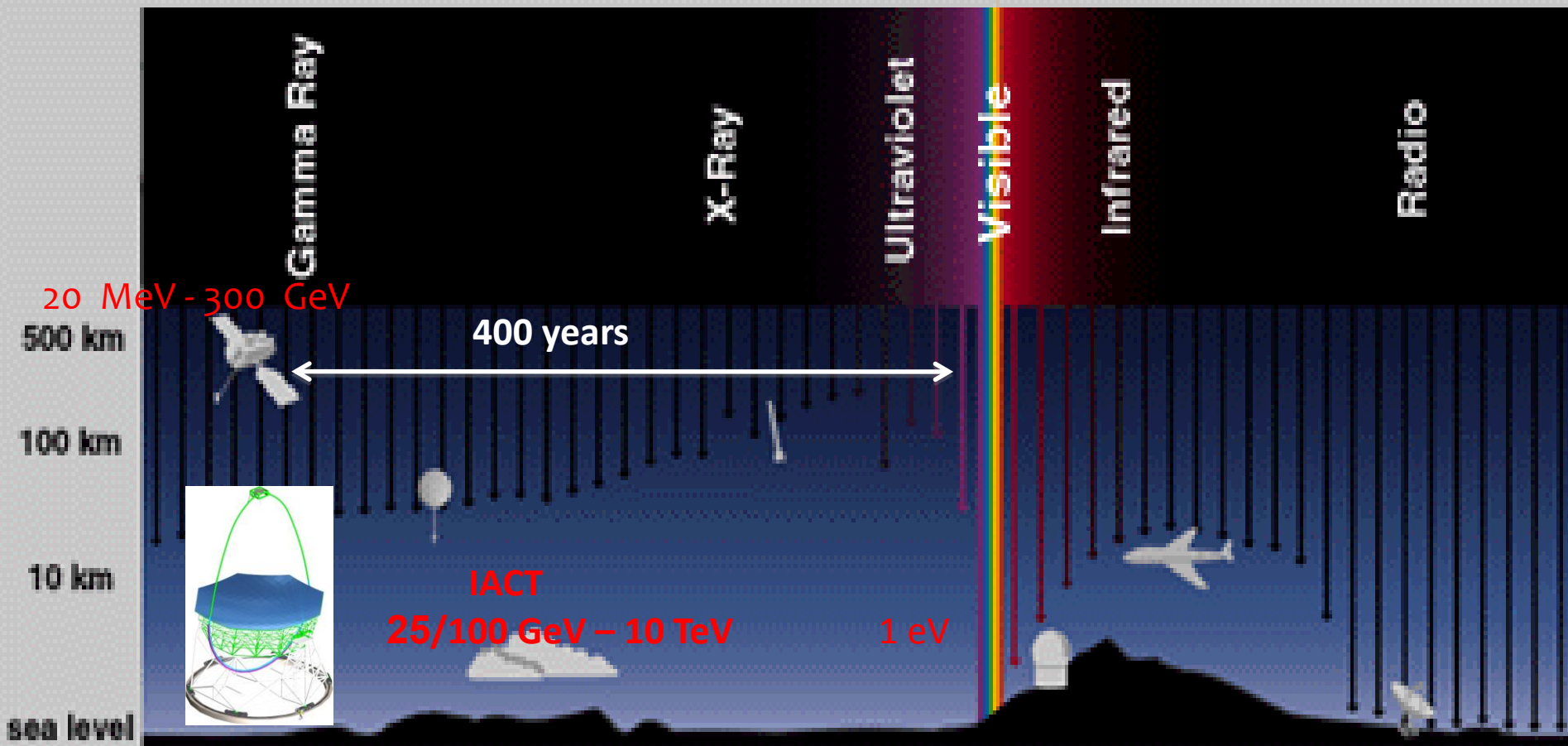
Figure 4: Simulated events in the IceCube detector, visualized using the IceCube event display, showing the 3 typical topologies discussed in Sec 3. The shading represents the time sequence of the hits. The size of the dots corresponds to the number of photoelectrons detected by the individual photomultipliers.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

# VHE gamma ray Astronomy



# VHE gamma-ray astronomy

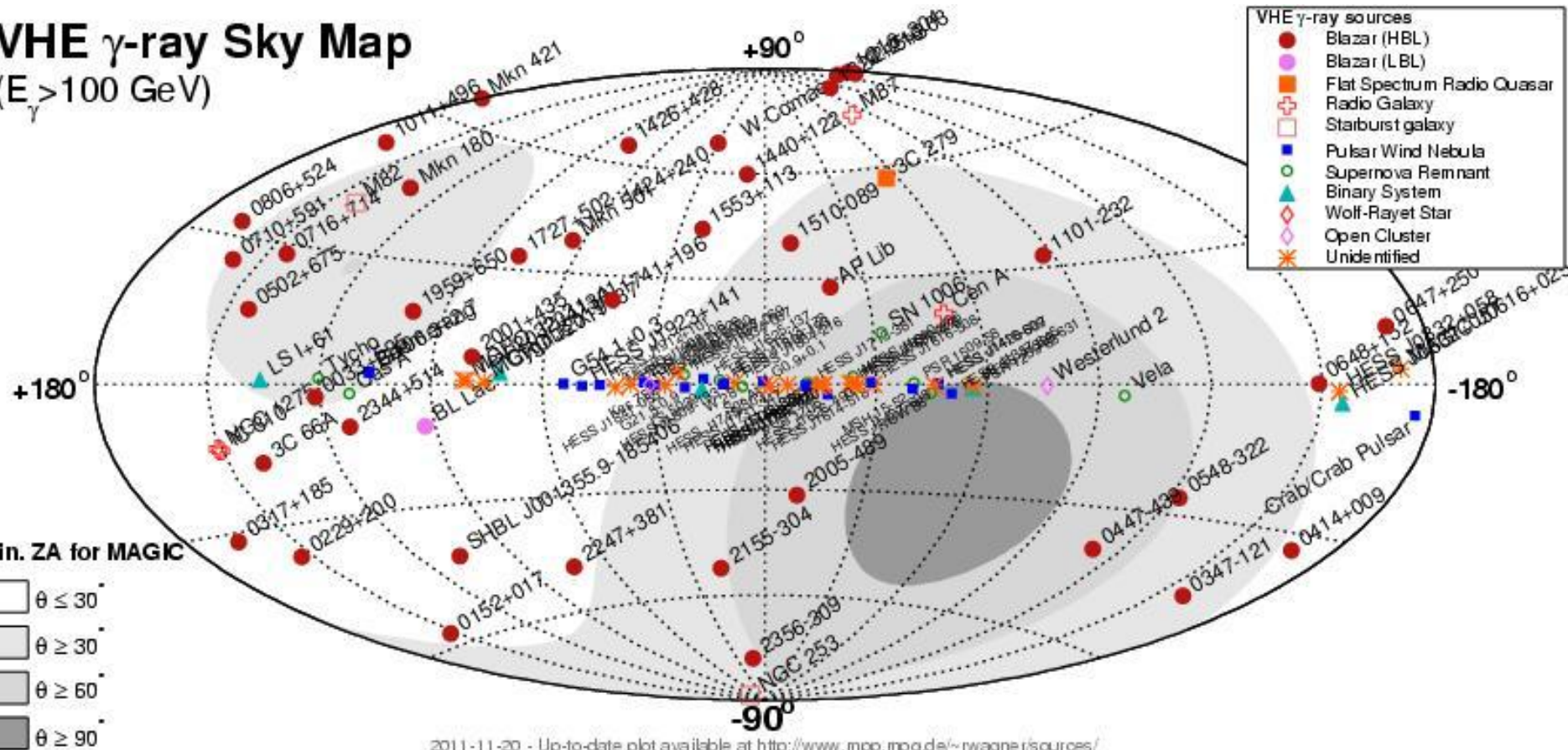
- ▶ American spy satellites detected accidentally 1967 high-energy gamma rays during the search for radiation generated by the explosion of atomic bombs
- ▶ 1989 Whipple Collaboration discovered 1<sup>th</sup> source of VHE gamma-ray
  - T. C. Weekes et. al., ApJ 342,(379-395) 1989
- ▶ Crab nebula, standard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

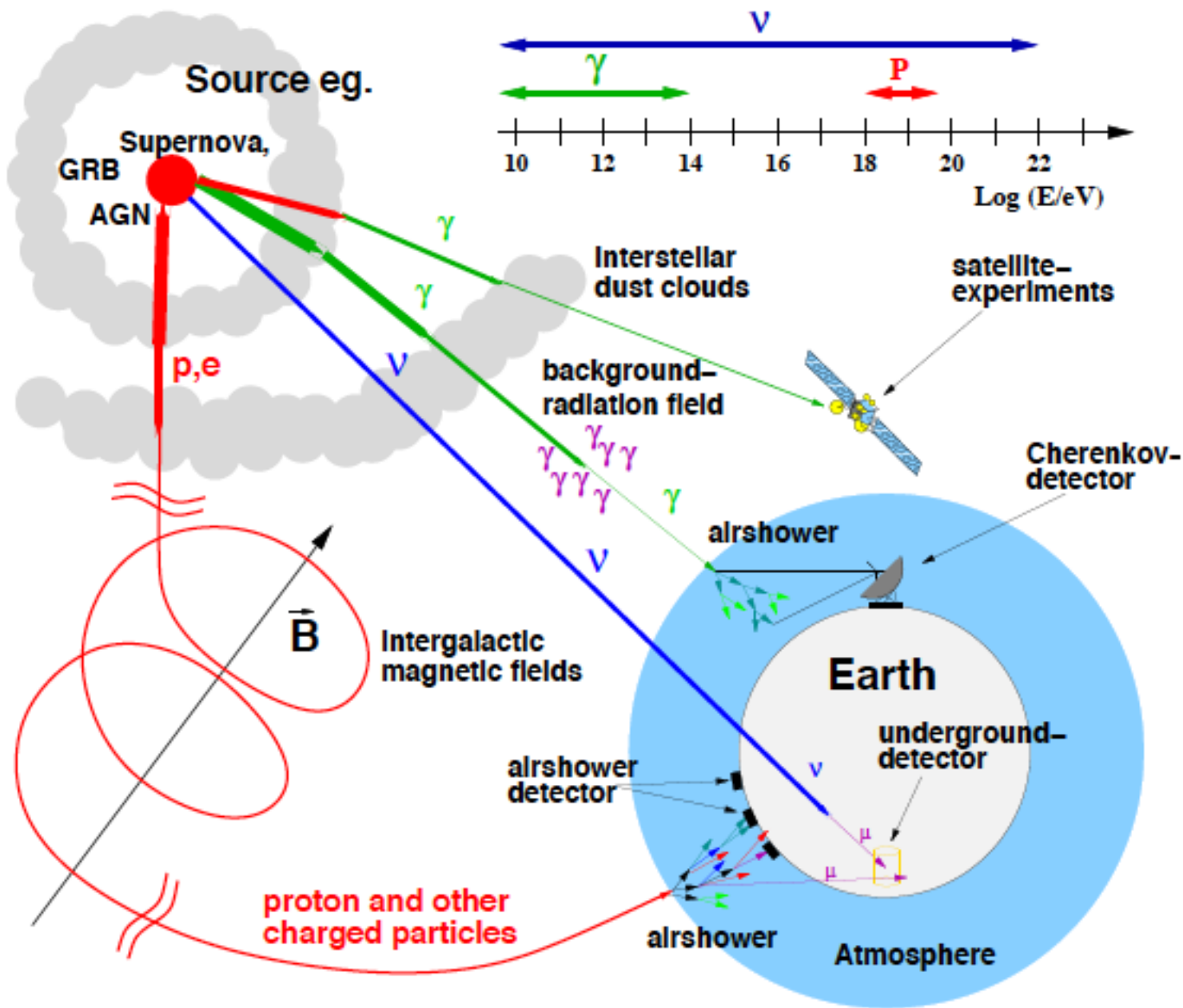




# VHE Gamma-ray Sky Map

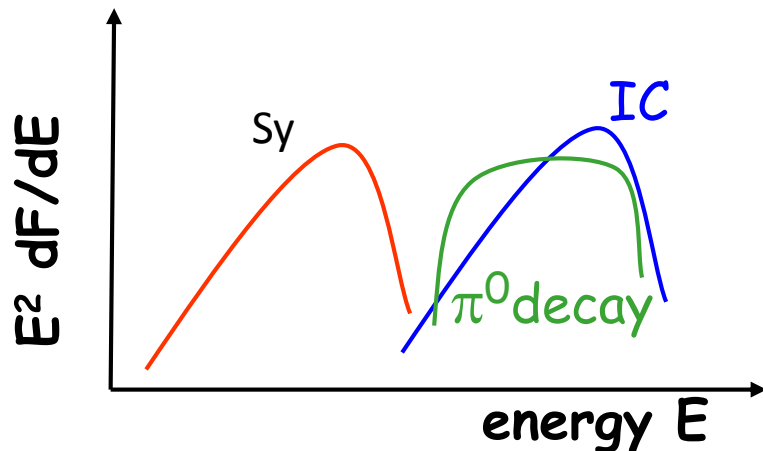
## VHE $\gamma$ -ray Sky Map ( $E_\gamma > 100$ GeV)





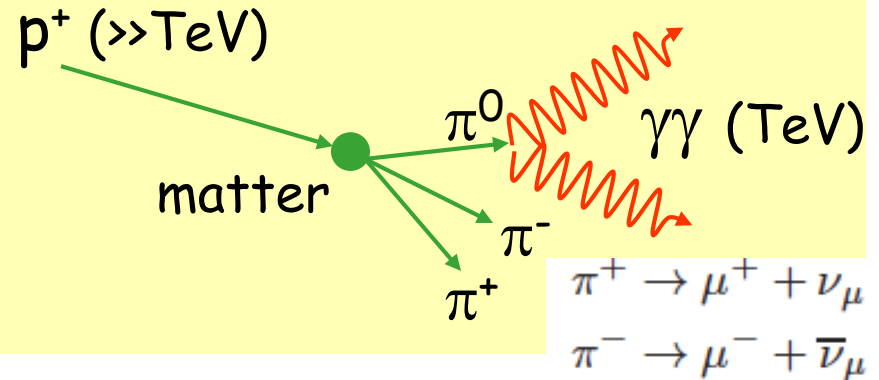
# Generation of VHE gamma ray

- Hadronic model of emission
  - Leptonic model of emission
- ▶ Disentangle hadronic from leptonic gamma ray origin  
=> shape of spectrum

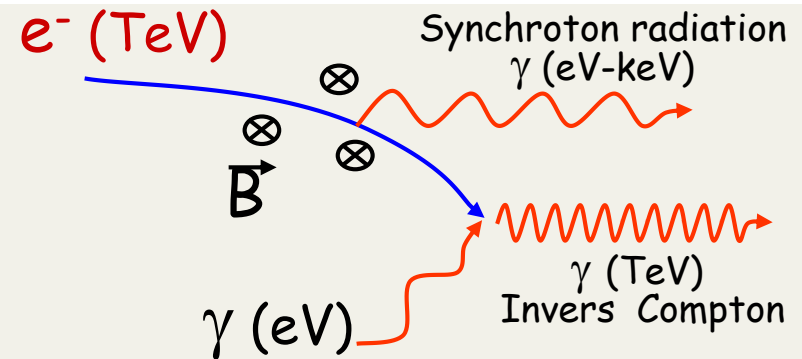


## Hadronic model of $\gamma$ emission

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

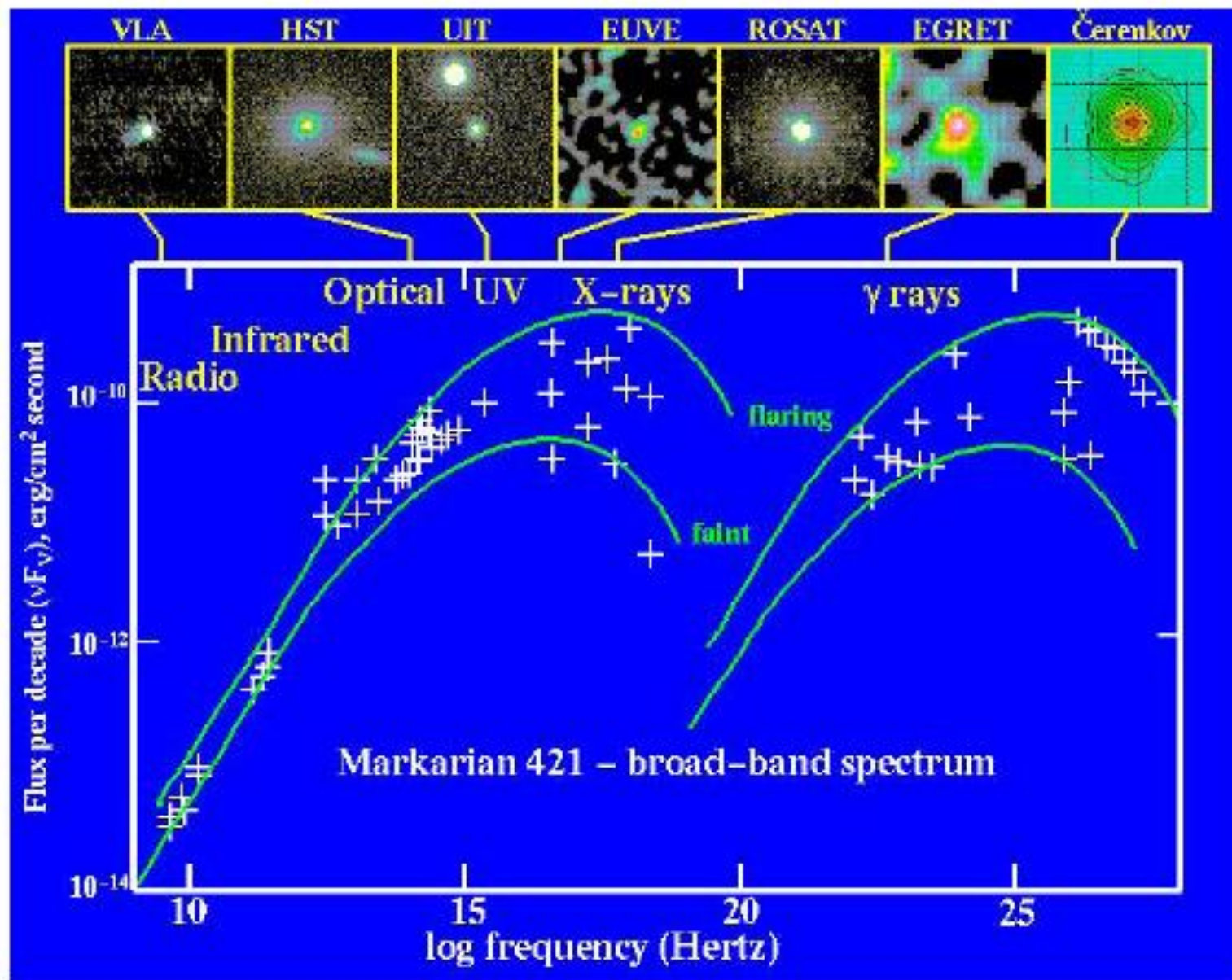


## Leptonic model $\gamma$ emission





# Active galactic nuclei – broad band spectra

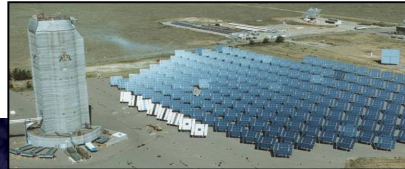


# VHE Gamma-ray telescopes (GeV-TeV)

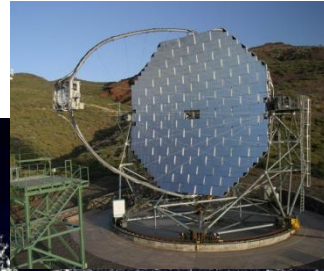
MILAGRO



STACEE



MAGIC



TIBET



MILAGRO

STACEE

MAGIC

TIBET  
ARGO-YBJ

TACTIC

PACT

GRAPES

VERITAS

VERITAS

TACTIC

HESS

CANGAROO III

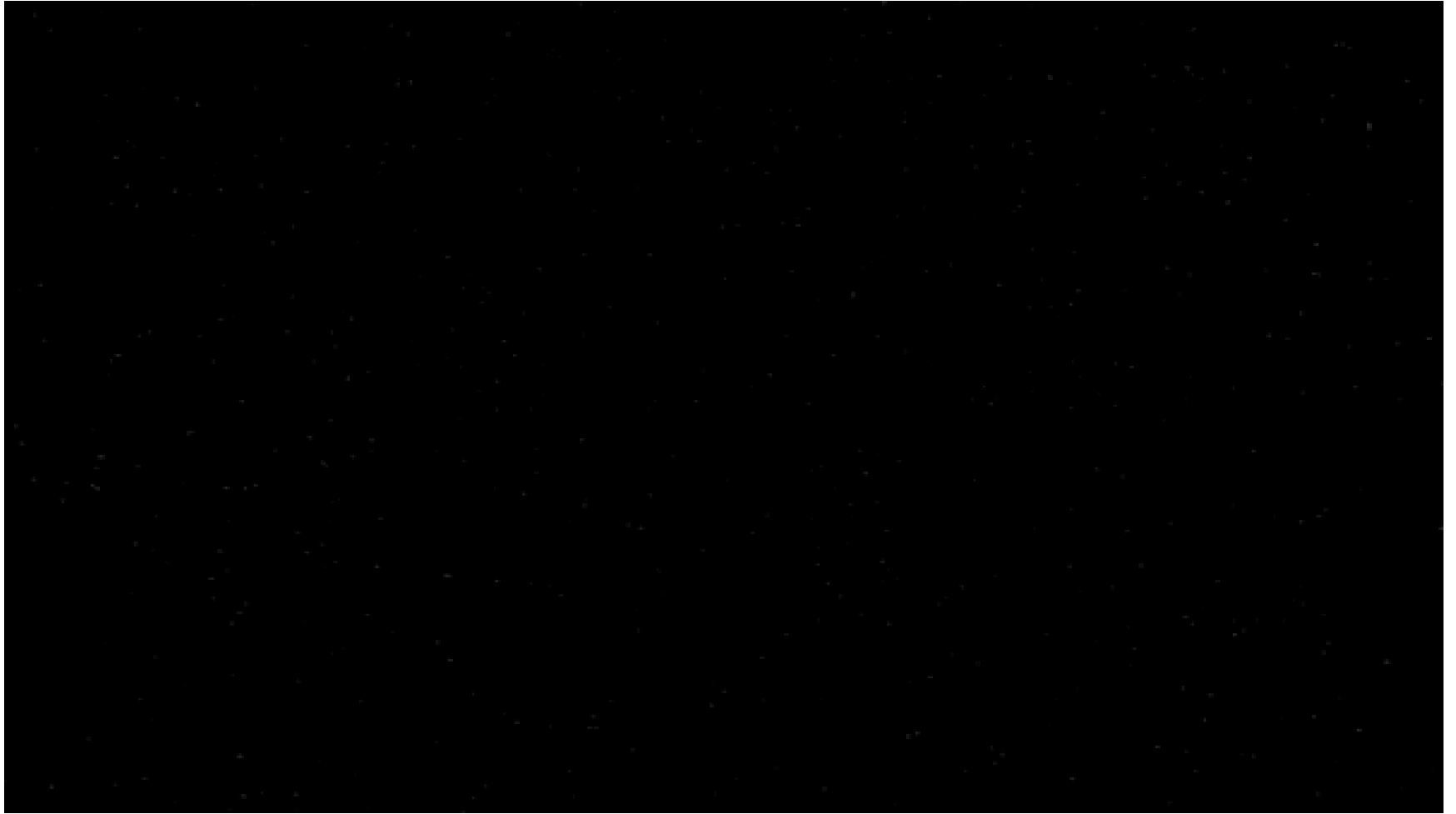
HESS

CANGAROO



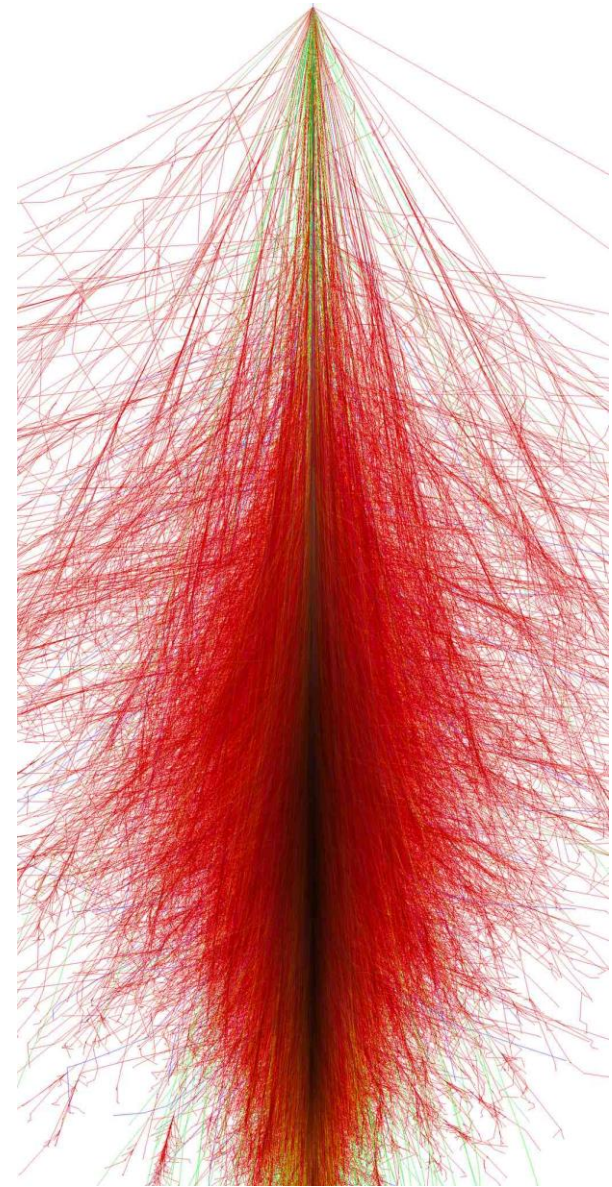
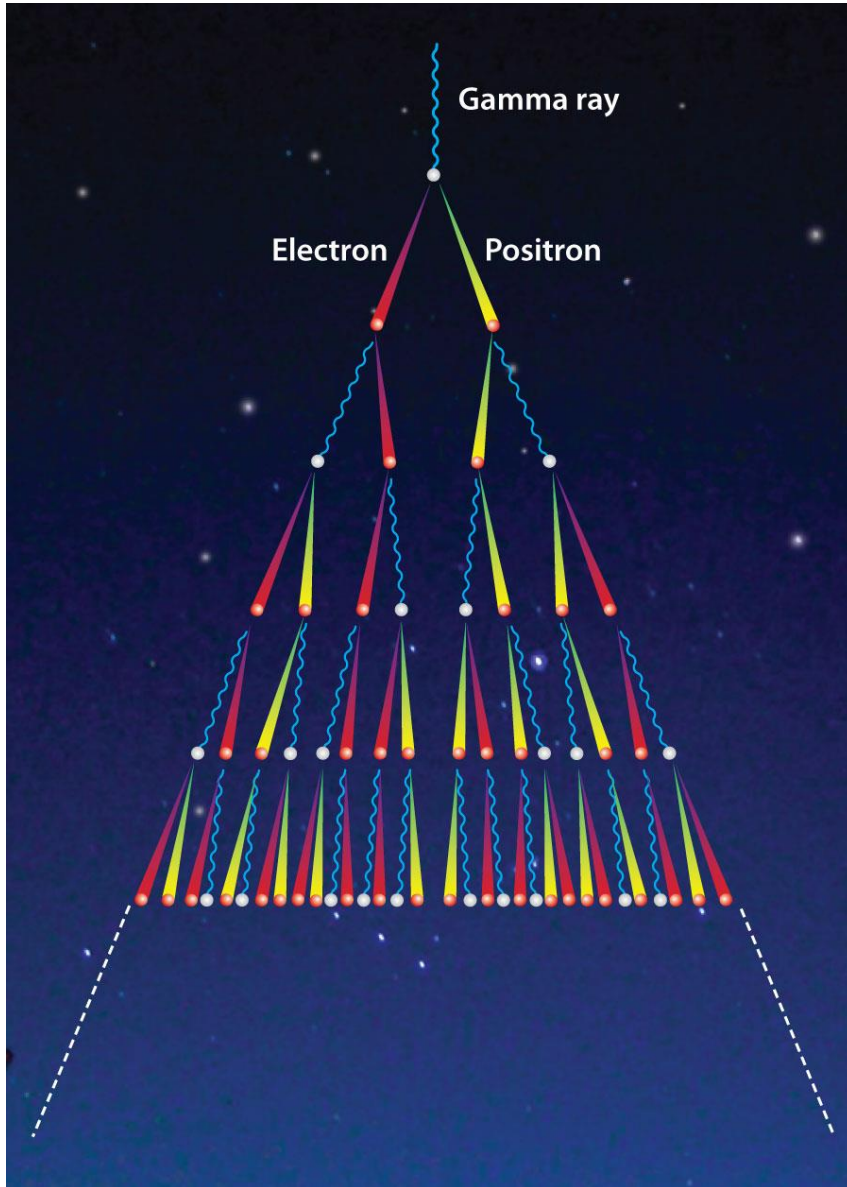
# Gama zrake u atmosferi

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# Pljusak čestica



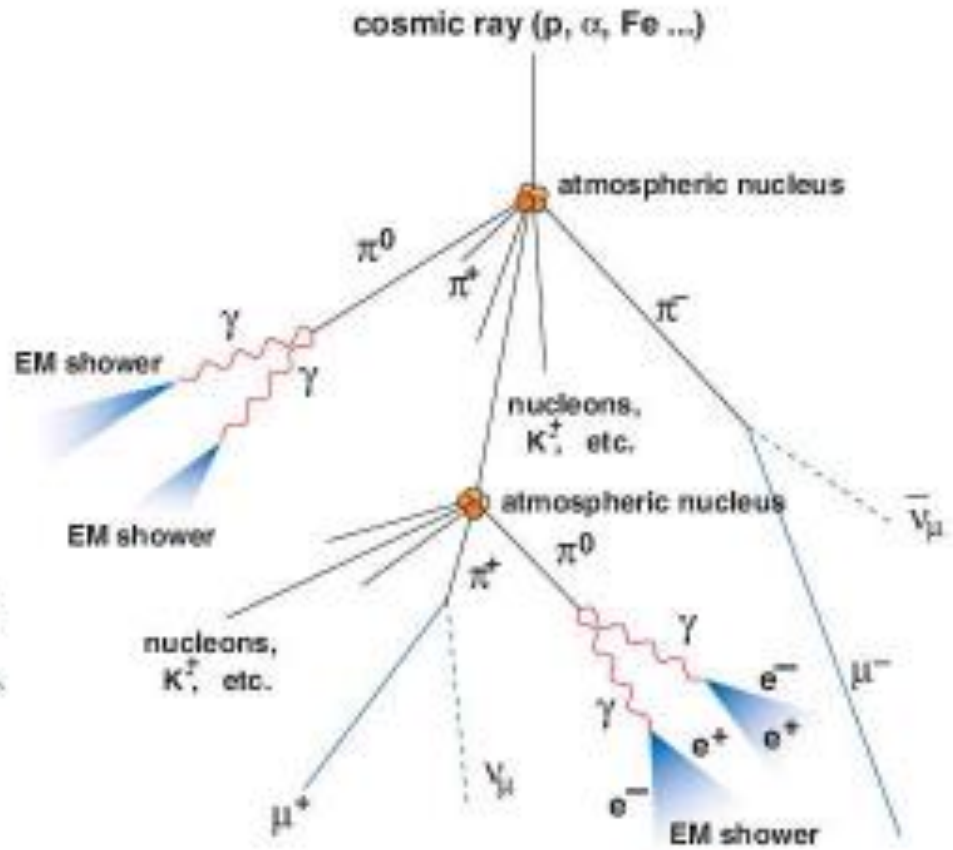
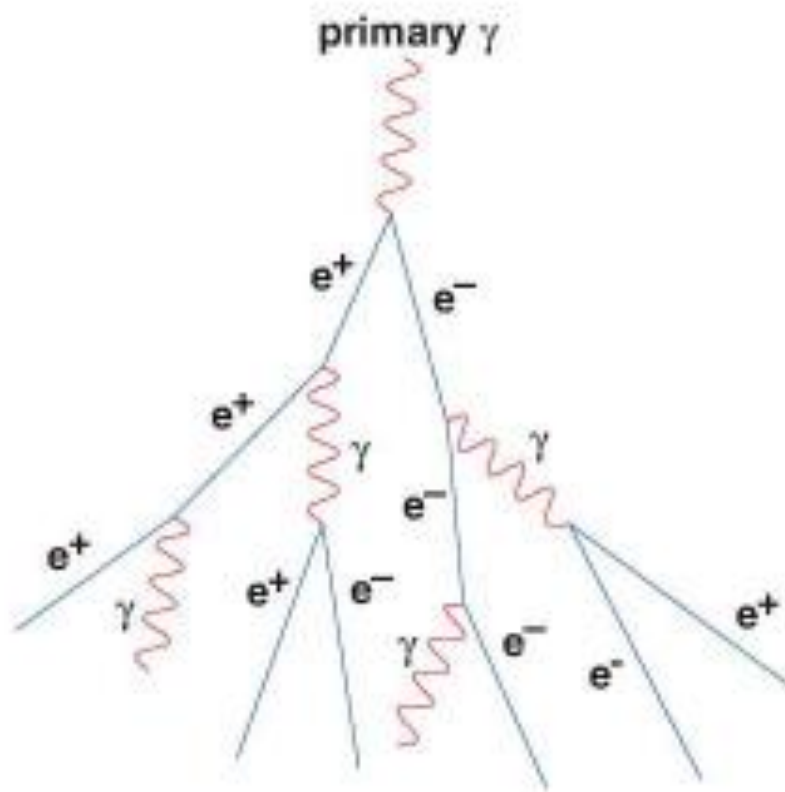
# Heitler model of em shower

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

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

(depends logarithmically on  $E_0$ )

# Pljusak čestica



1 gamma-ray in 10000 CR



# Čerenkovljevo svjetlo

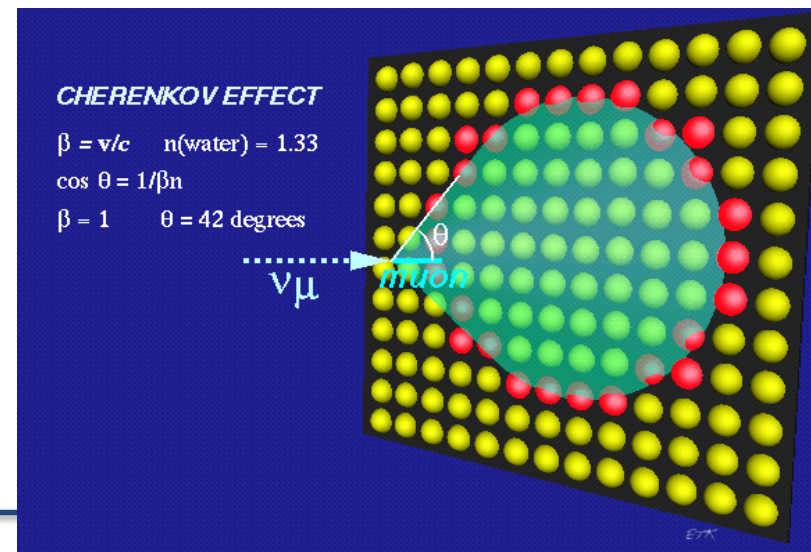
- ▶ Č light is produced by particles faster than light in air
- ▶ Limiting angle  $\cos \theta_c \sim 1/n$ 
  - $\theta_c \sim 1^\circ$  at sea level,  $1.3^\circ$  at 8 km asl
  - Threshold @ sea level : 21 MeV for e, 44 GeV for  $\mu$

Maximum of a 1 TeV  $\gamma$  shower  $\sim 8$  Km asl

200 photons/m<sup>2</sup> in the visible

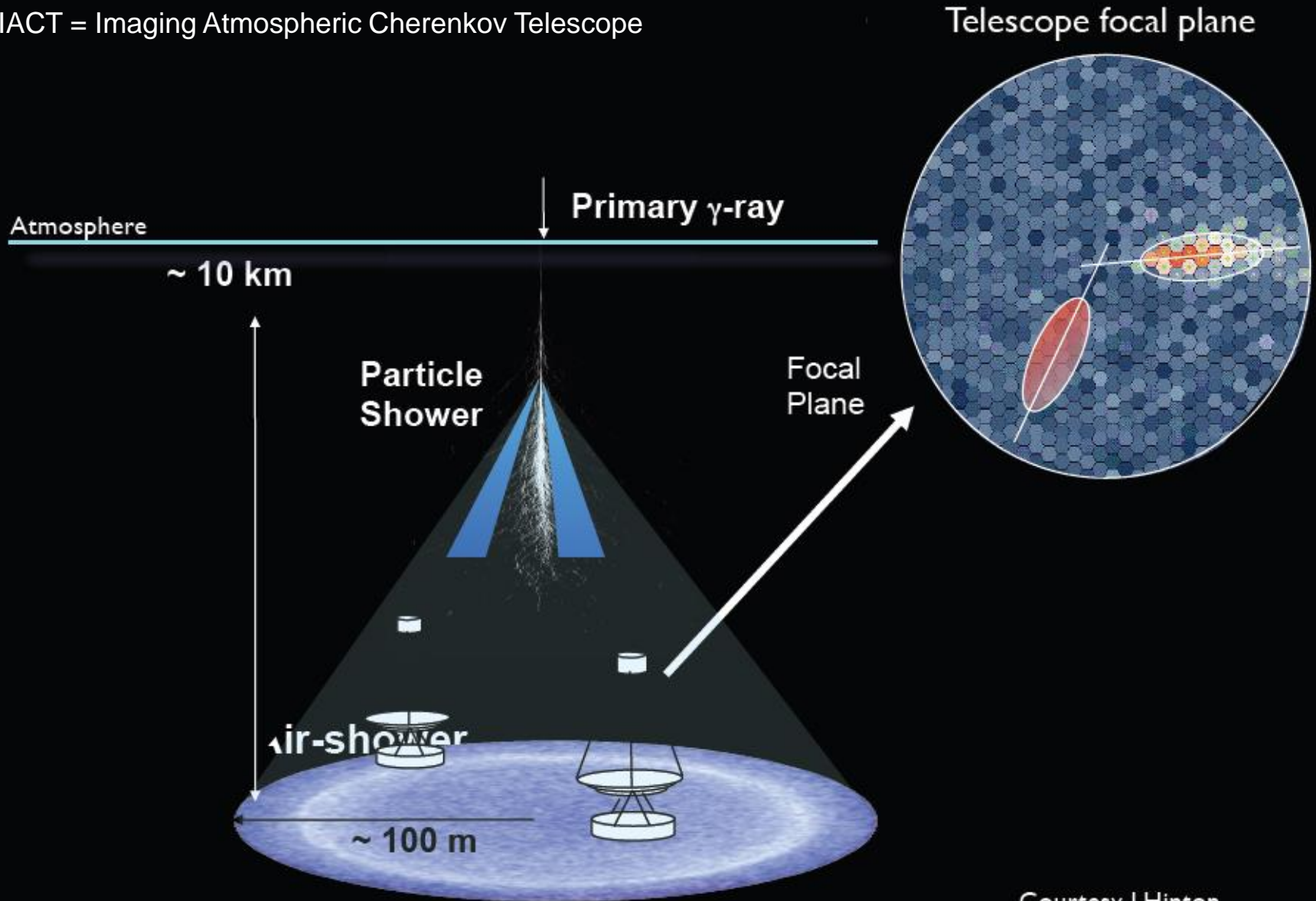
Duration  $\sim 2$  ns

Angular spread  $\sim 0.5^\circ$



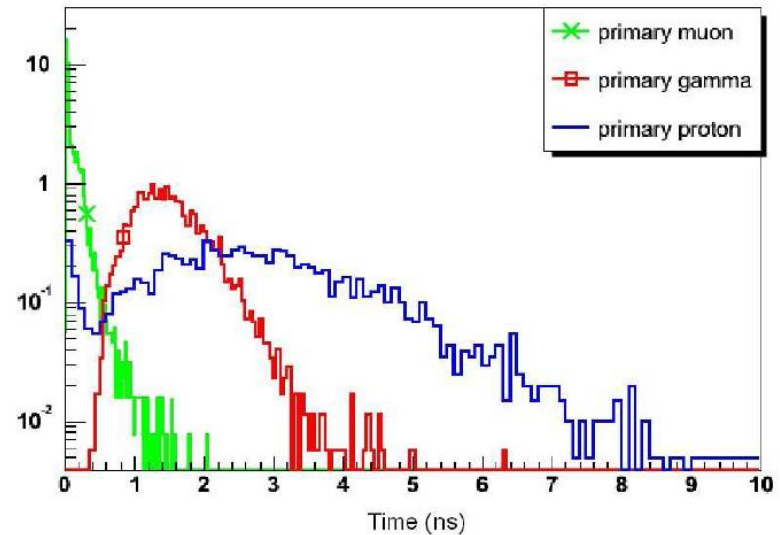
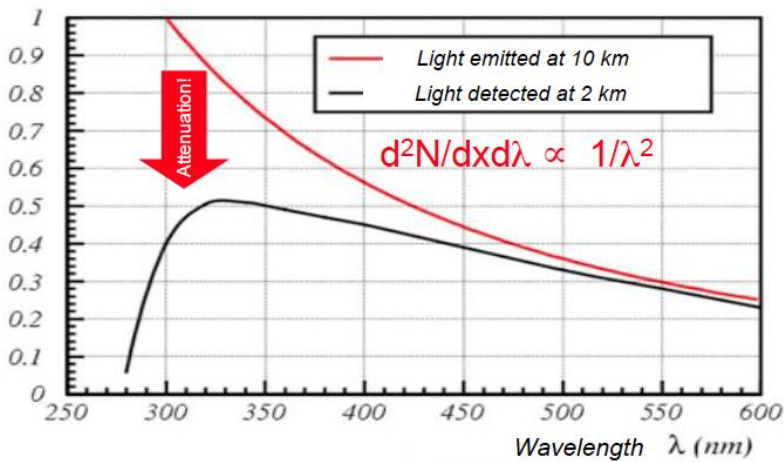
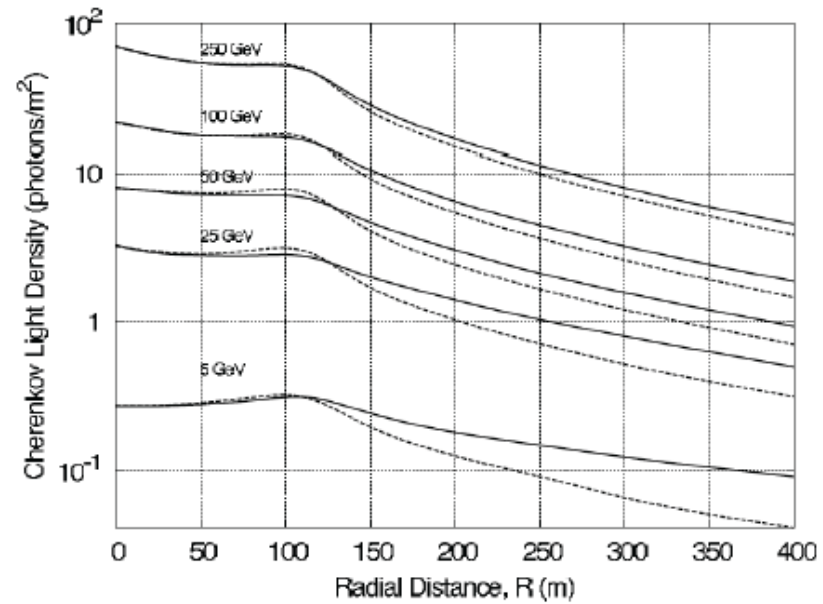
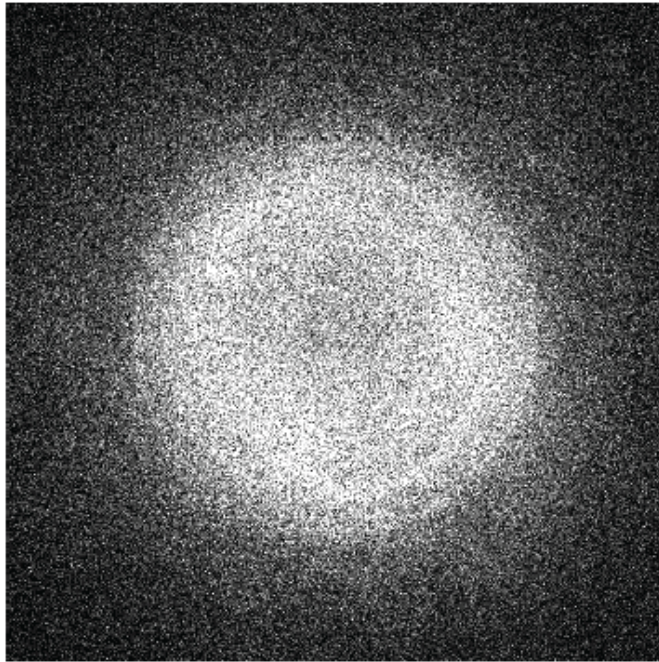
# IACT tehnika detekcije

IACT = Imaging Atmospheric Cherenkov Telescope



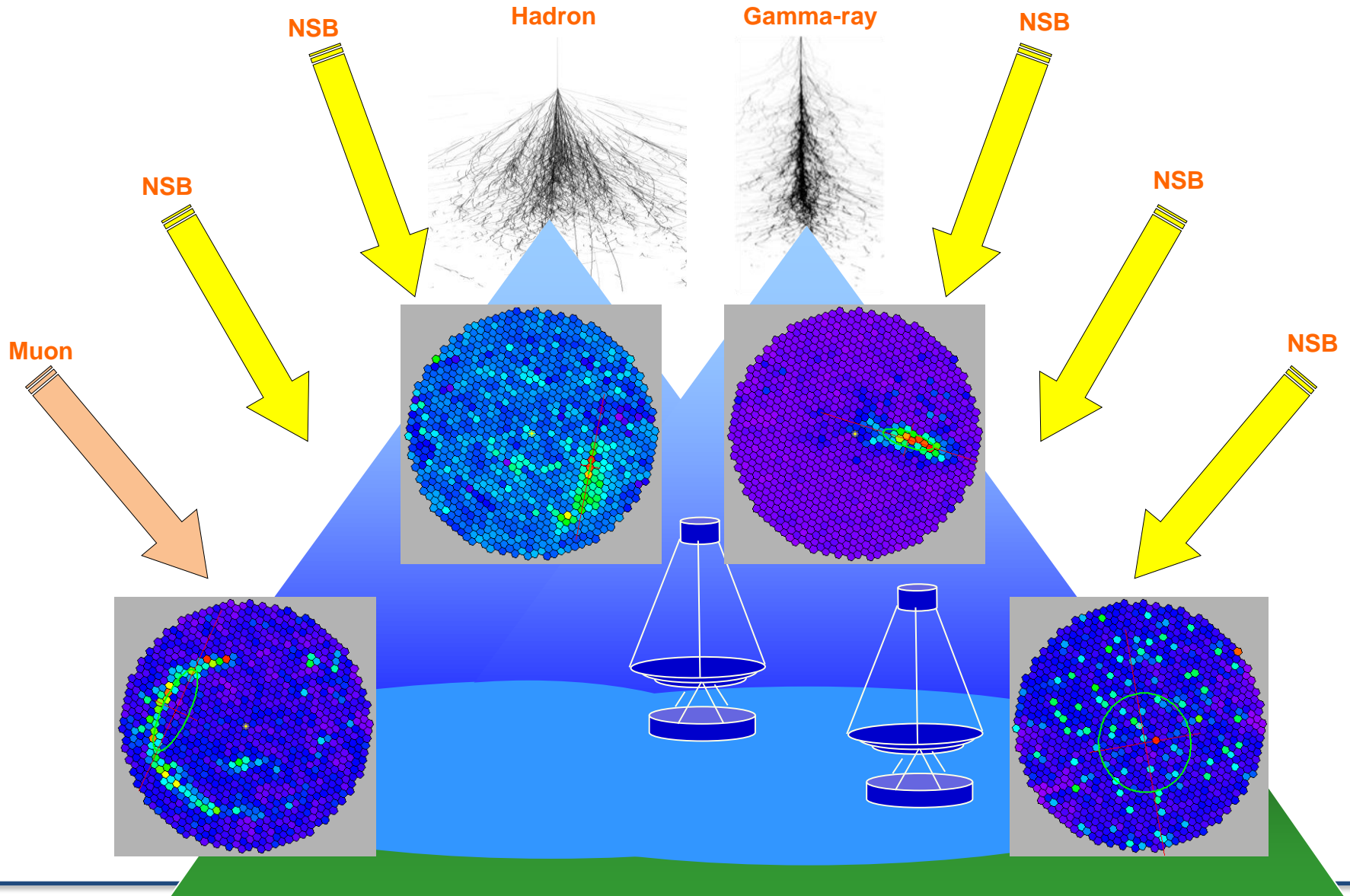
Courtesy J.Hinton

# Density of Cherenkov photons





# IACT tehnika detekcije



# Osjetljivost IACT tehnike detekcije

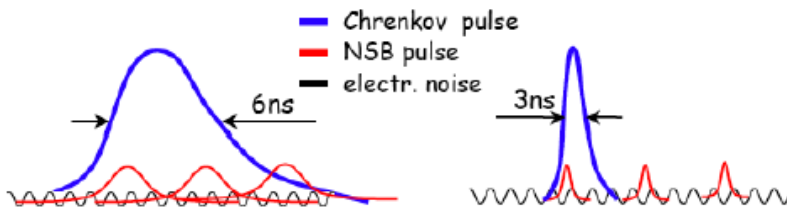
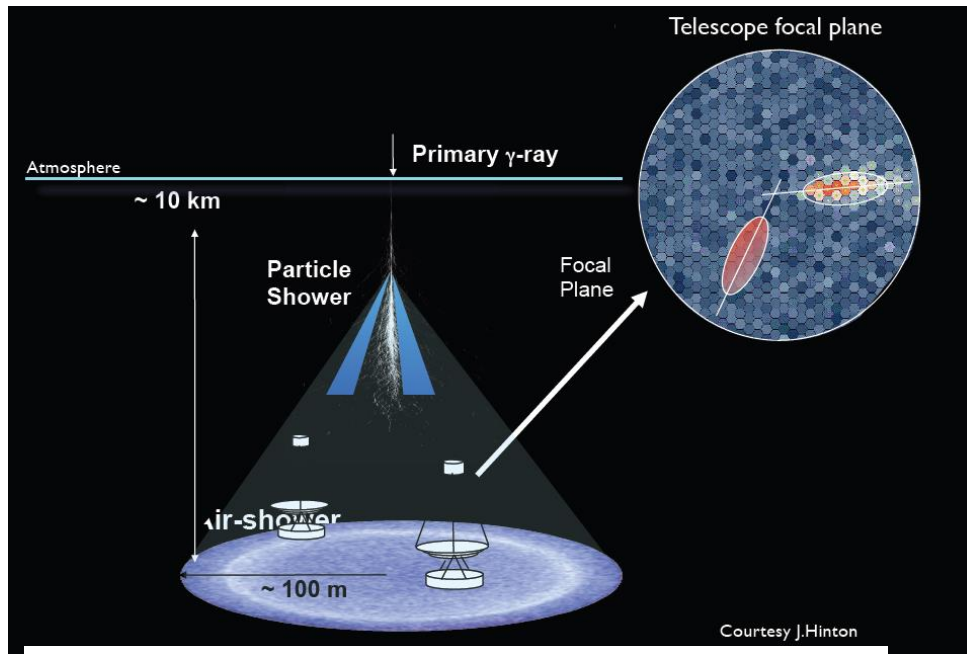
- ▶  $\Phi$  ( $\text{sr}^{-1}\text{s}^{-1}, \text{m}^{-2}$ ) – NSB flux
- ▶  $\Omega$  – solid angle viewed by detector
- ▶  $\tau$  – integration (exposure) time
- ▶  $F$  ( $\text{m}^{-2}$ ) – density of Cherenkov photons
- ▶  $A$  – light collection area
- ▶  $\varepsilon$  – light collection efficiency (reflectivity, QE, ...)
- ▶ Number of background photons
- ▶ Number of detected Cherenkov/signal photons

$$N_B = \phi \Omega A \varepsilon \pm \sqrt{\phi \Omega A \varepsilon}$$

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

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

# IACT tehnika detekcije



Signal  $\propto A$

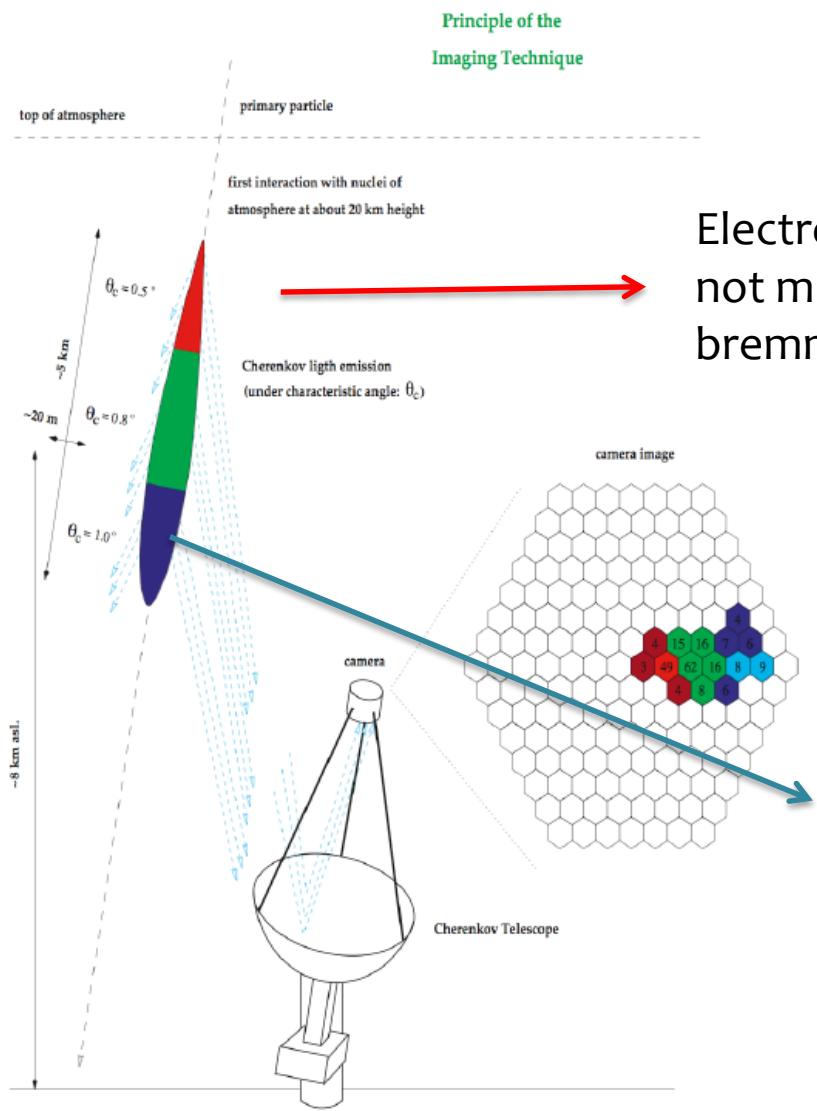
Fluctuations  $\sim (A\tau\Omega)^{1/2}$

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

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



# Razvoj pljuska čestica

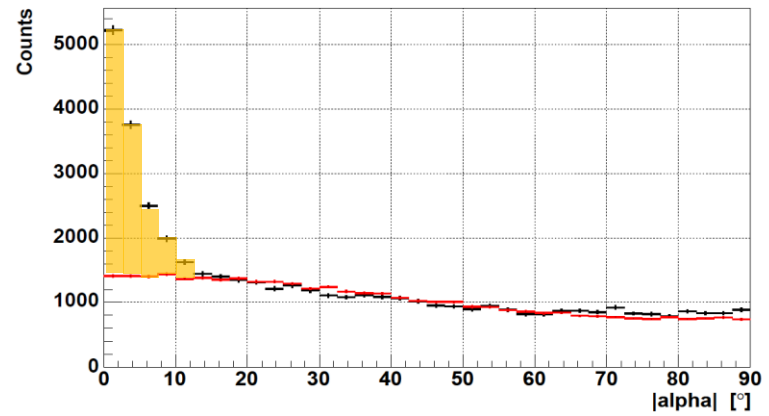
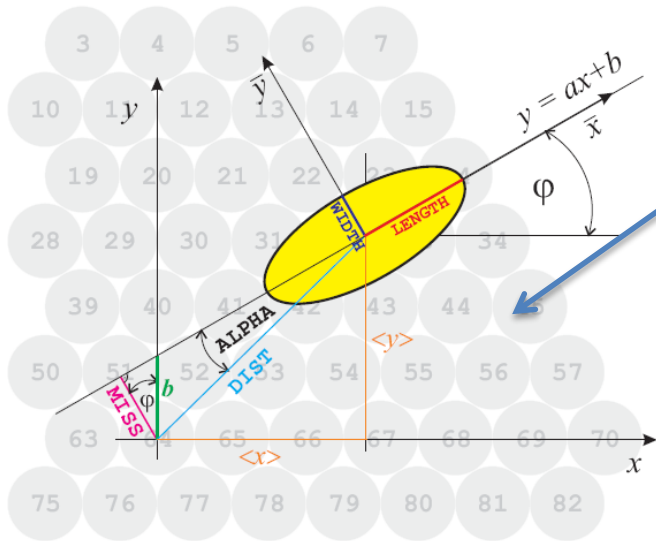
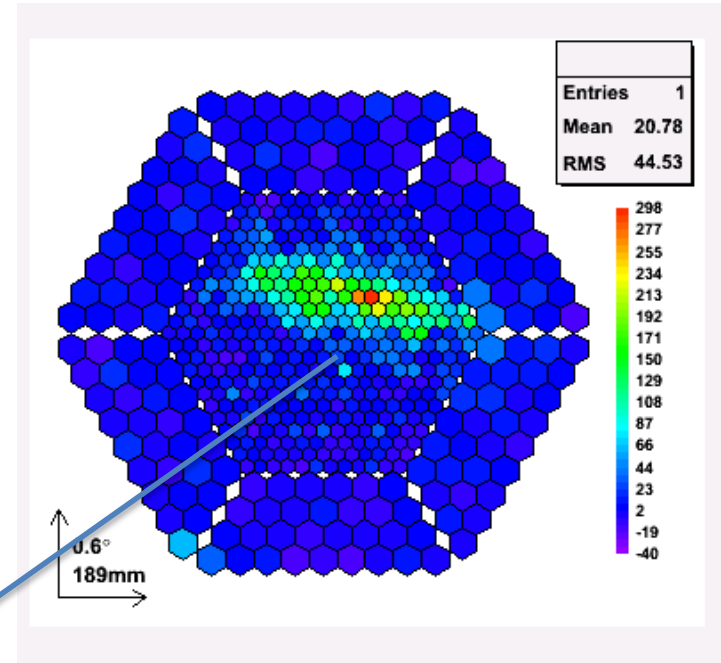


Electrons energetic and not much deflected by bremsstrahlung

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

Electrons less energetic deflected by bremsstrahlung  
Some photone deflected for 6 equivalent pixel away from the original trajectory

# Hillasovi parametri



# La Palma – Kanarski otoci



Data SIO, NOAA, U.S. Navy, NGA, GEBCO

©2009 Google

Image © 2010 GRAFCAN

28°40'02.67" S 17°50'29.37" Z podizanje 0 ft

Dobu mi slika: 31. prosinac 2008.

Visina pogleda 48.61 mi



# MAGIC telescopes

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



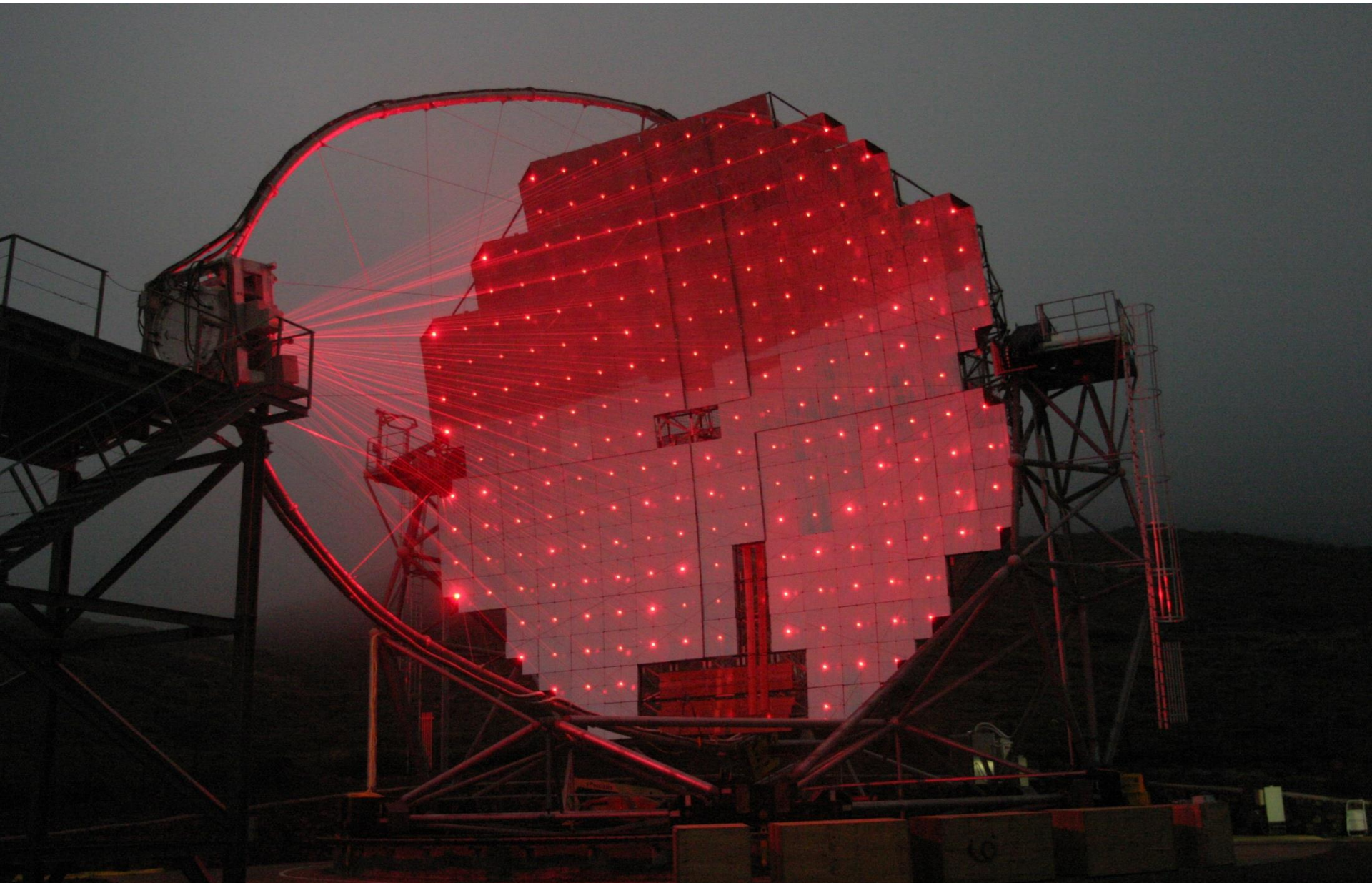
**MAGIC**

Major Atmospheric

Gamma Imaging

Cerenkov Telescope

# Kalibracija MAGIC-a

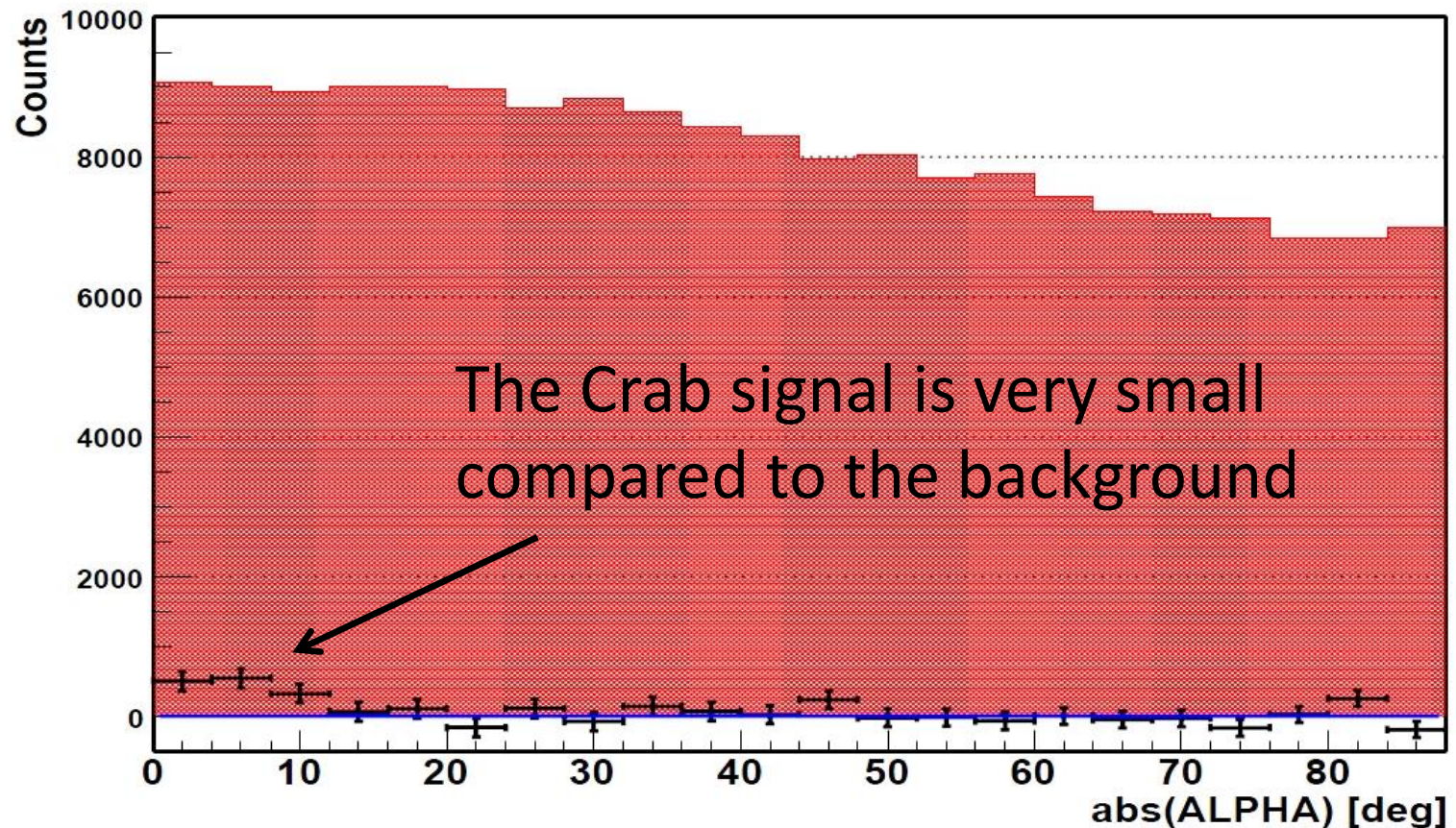




# MAGIC

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

ALPHA plot (analysis 3)

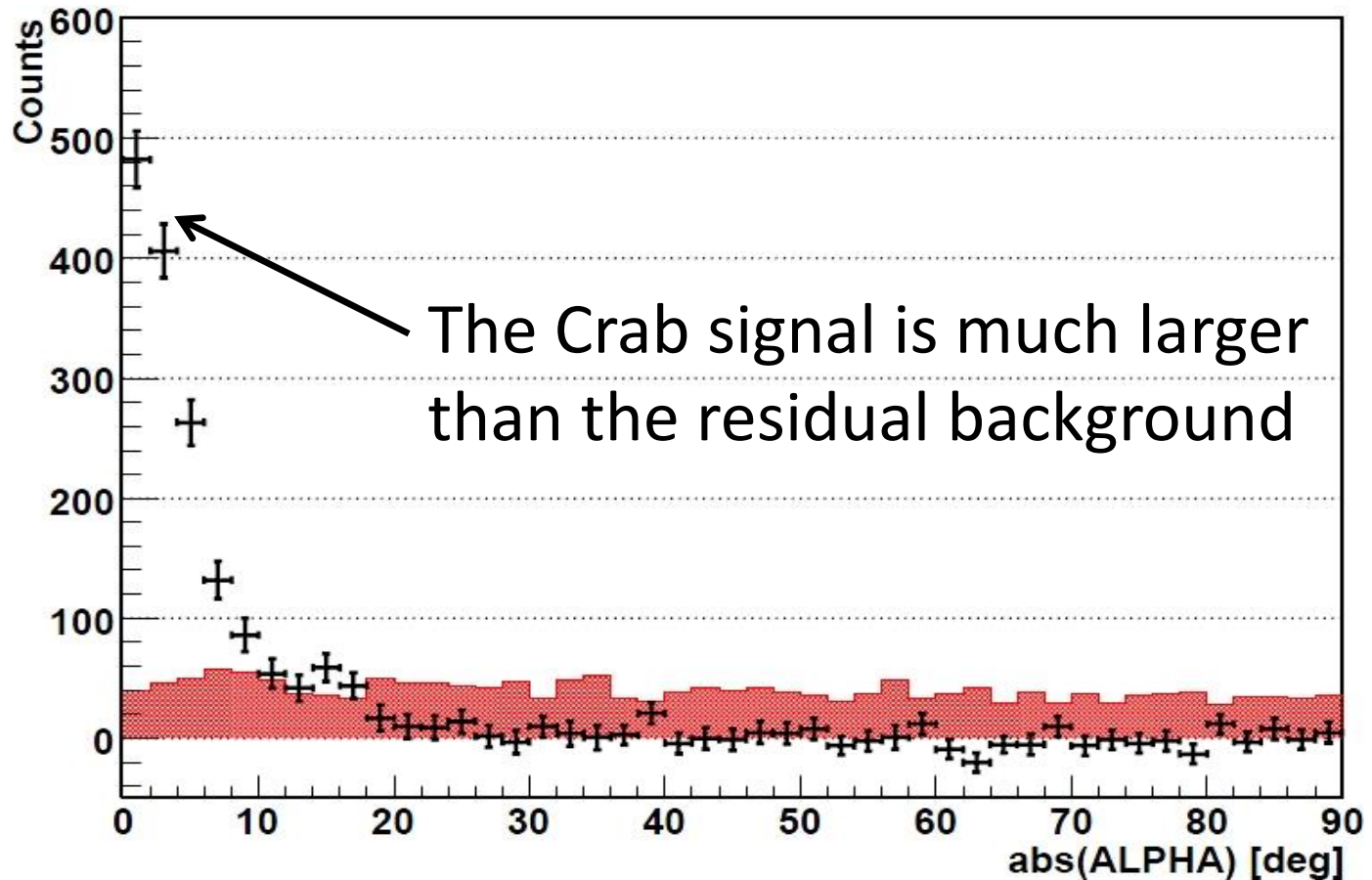




# MAGIC

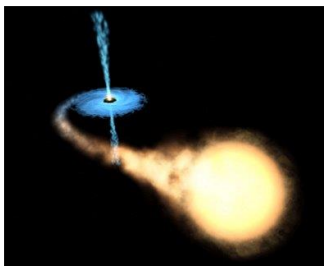
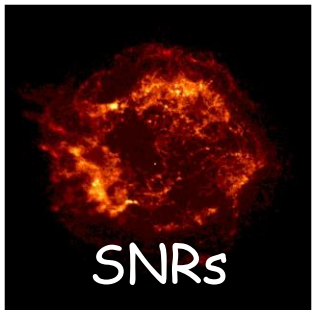
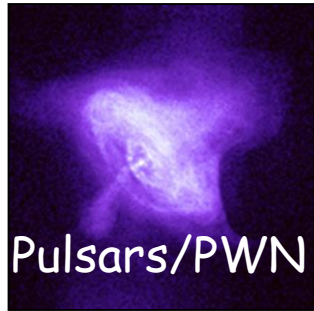
- For comparison: high energies ( $>250$  GeV)

ALPHA plot (analysis 3)

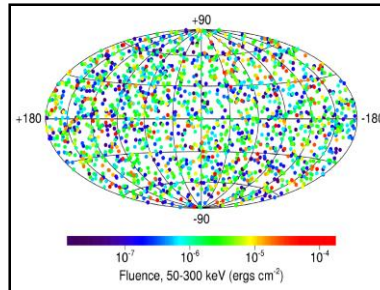
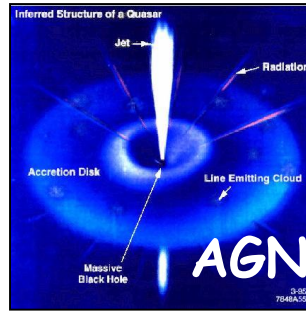


# Znanstveni ciljevi MAGIC-a

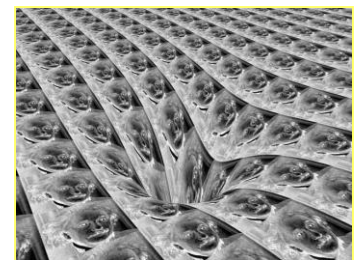
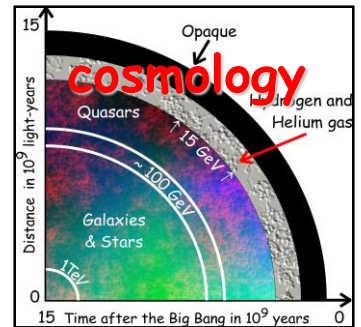
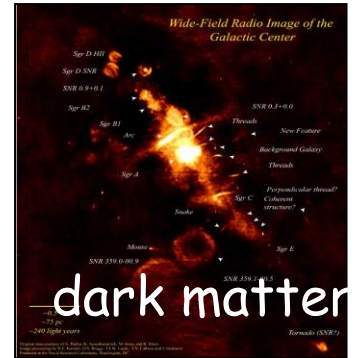
## Galactic



## Extragalactic



## Fundamental



# Rakova maglica – Crab nebula

## Crab Nebula



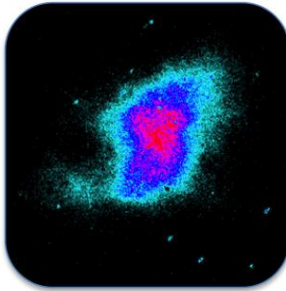
radio



infrared



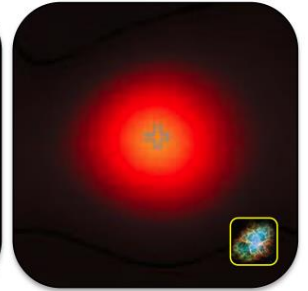
visible



ultraviolet



X-ray

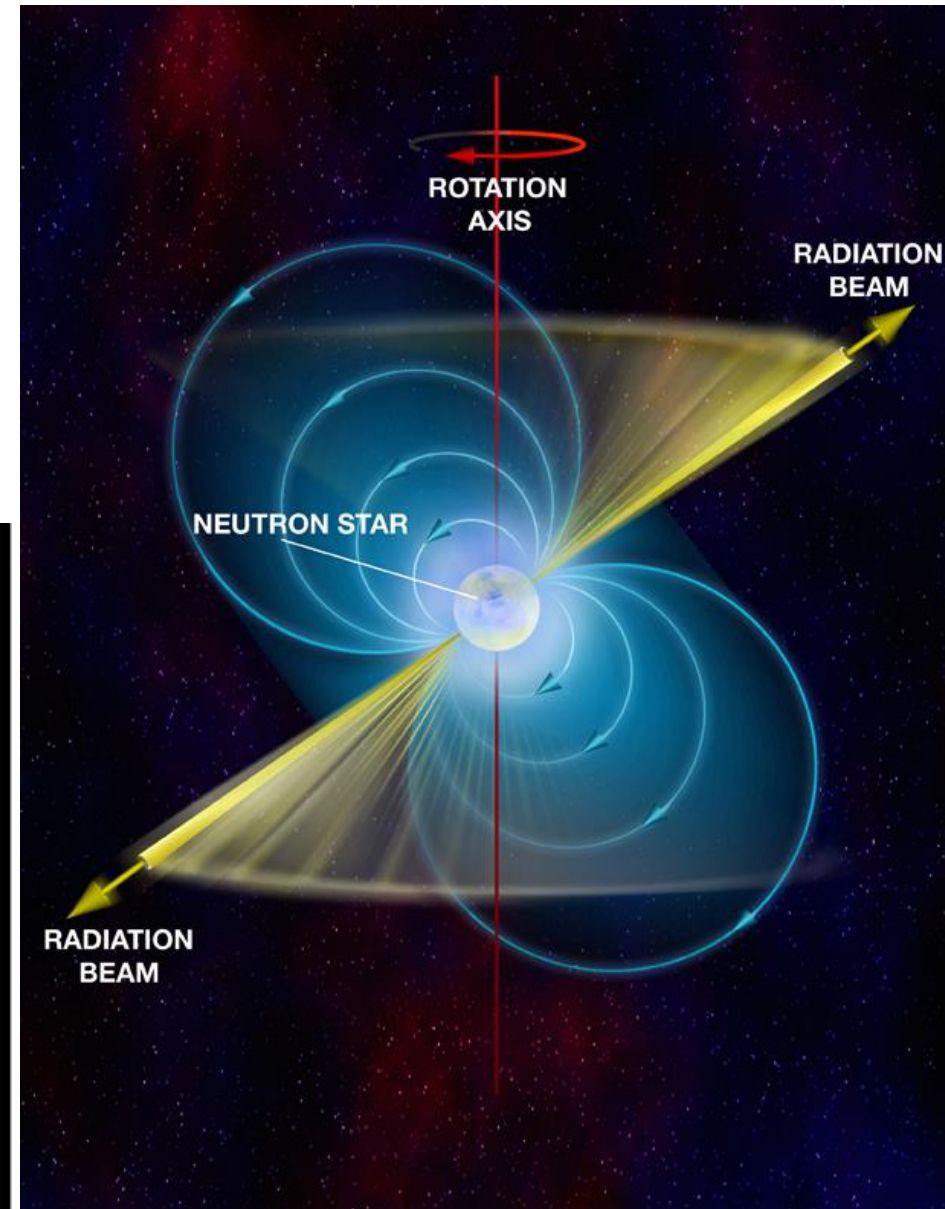
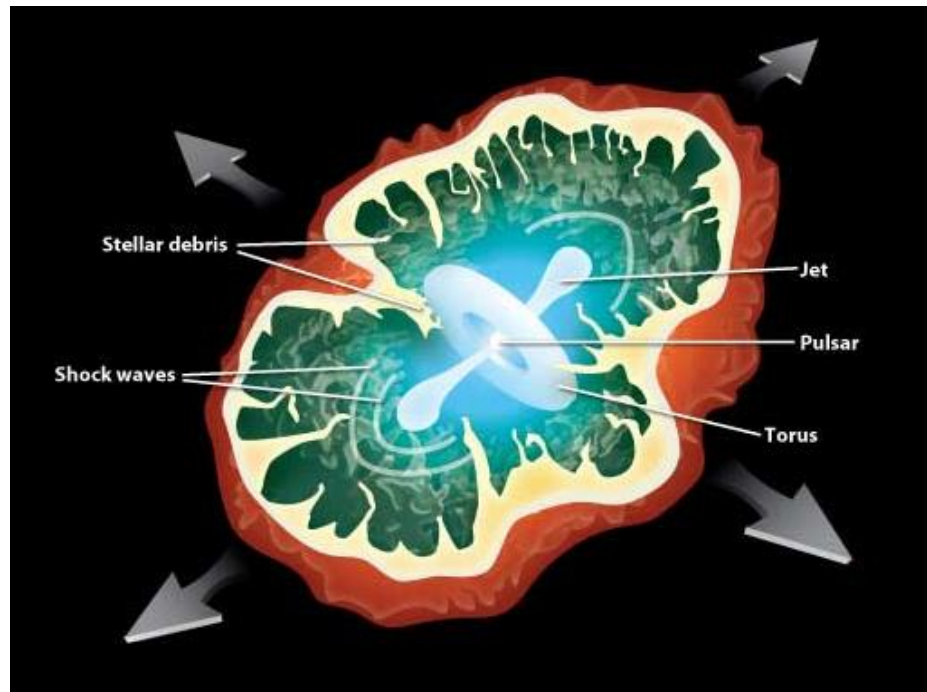


gamma ray

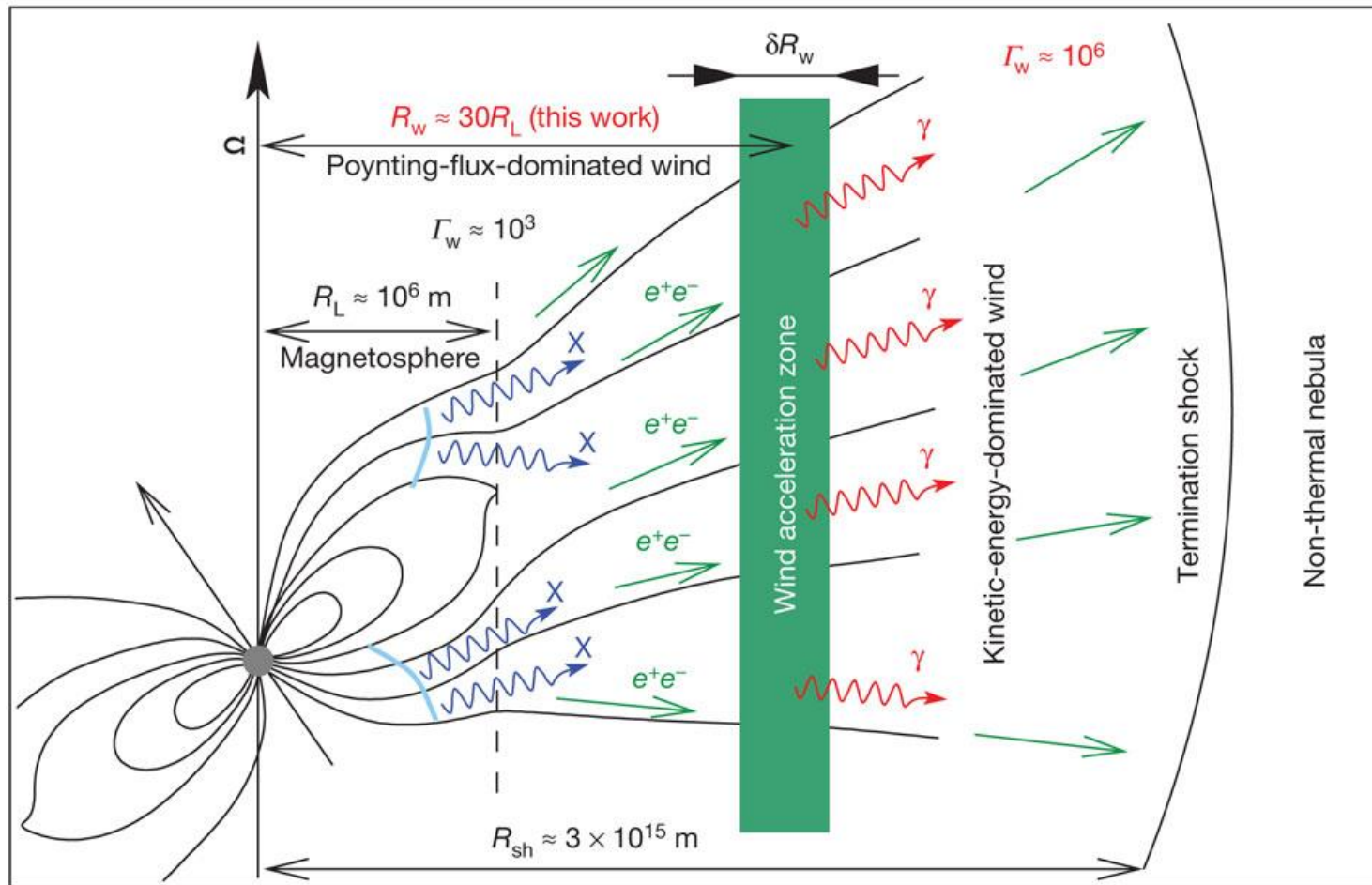


# Crab nebula

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



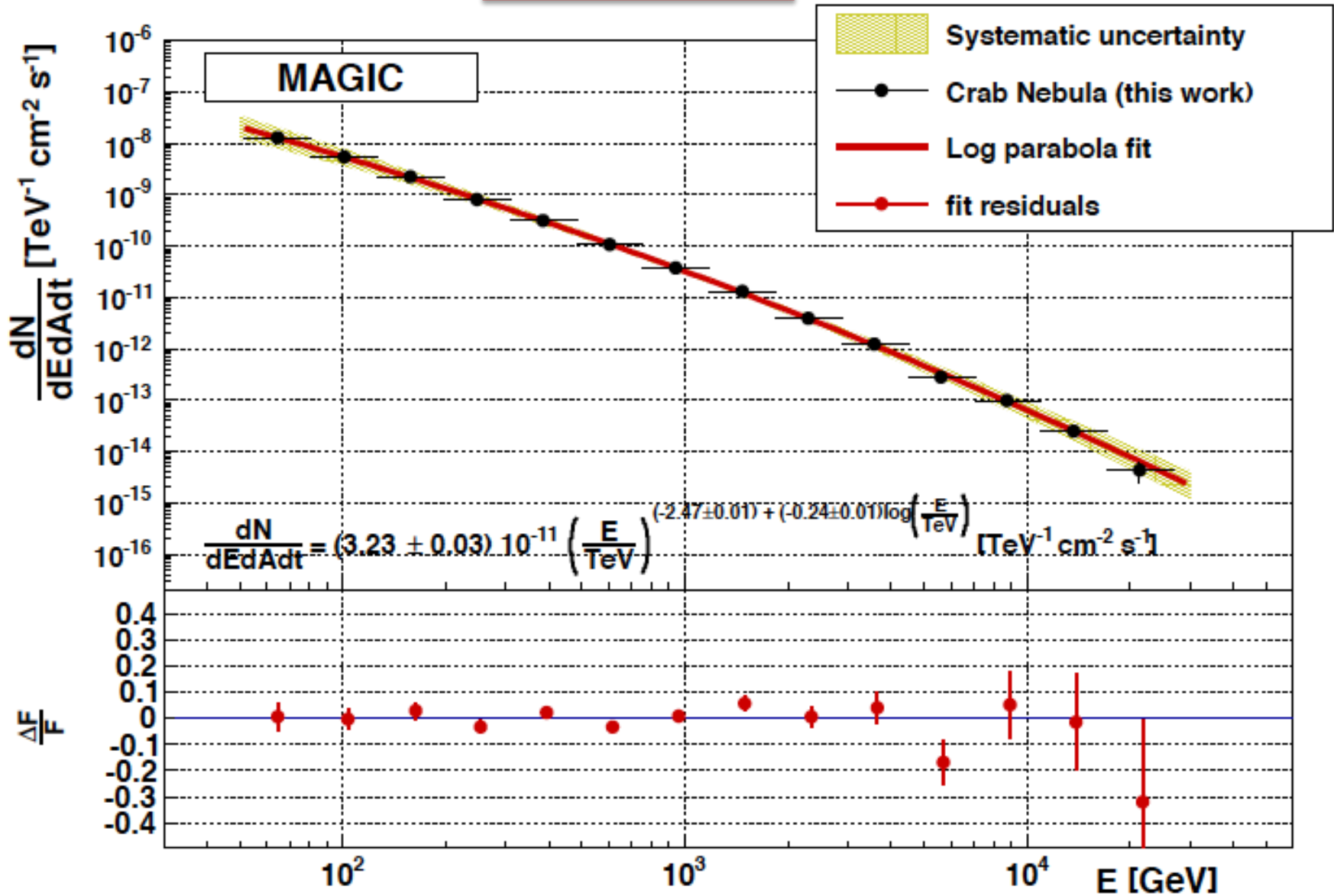
# Crab – standard candle for VHE $\gamma$



- 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,  $\dot{E}_{rot} = 5 \times 10^{31} \text{ J s}^{-1}$  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 least  $20 \Gamma_w \approx 10^4$ . 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 source<sup>2</sup>, the Crab nebula.

# Differential energy spectrum of Crab nebula

50 GeV – 30 TeV

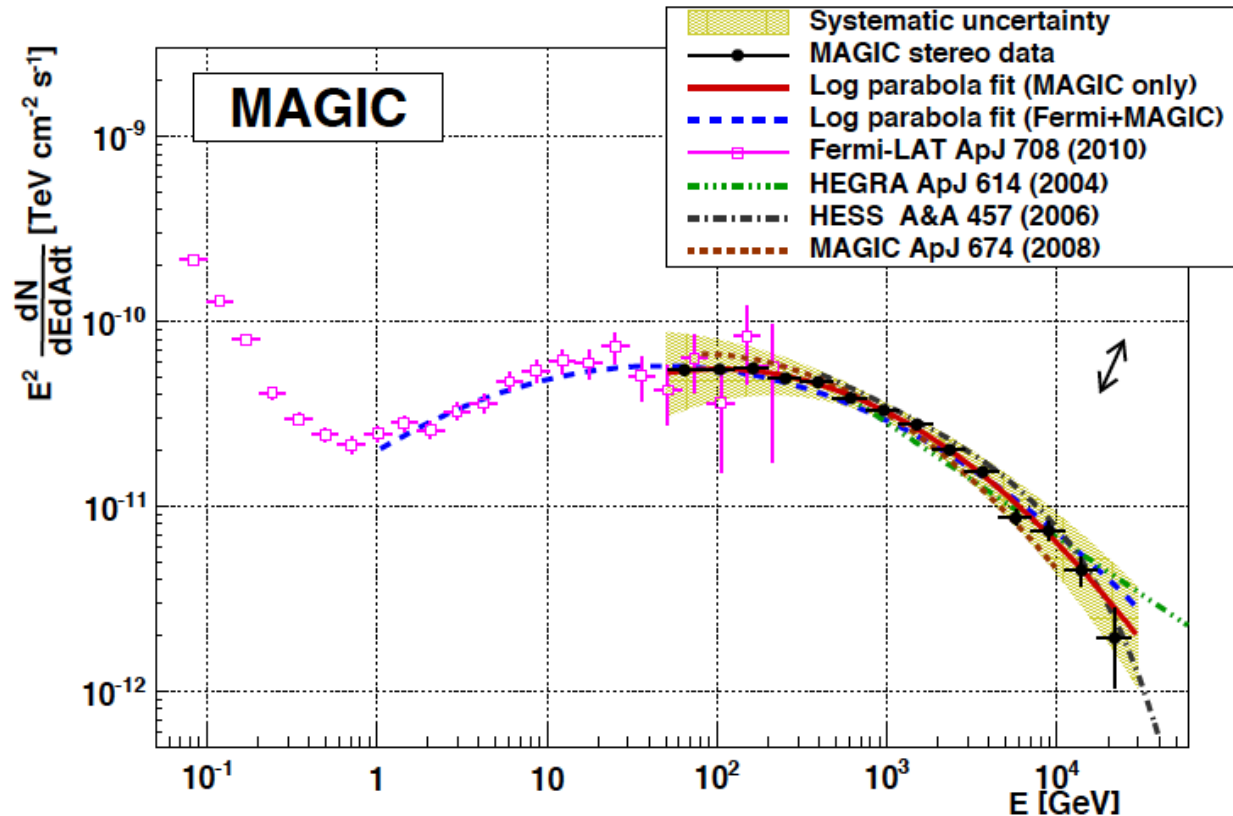




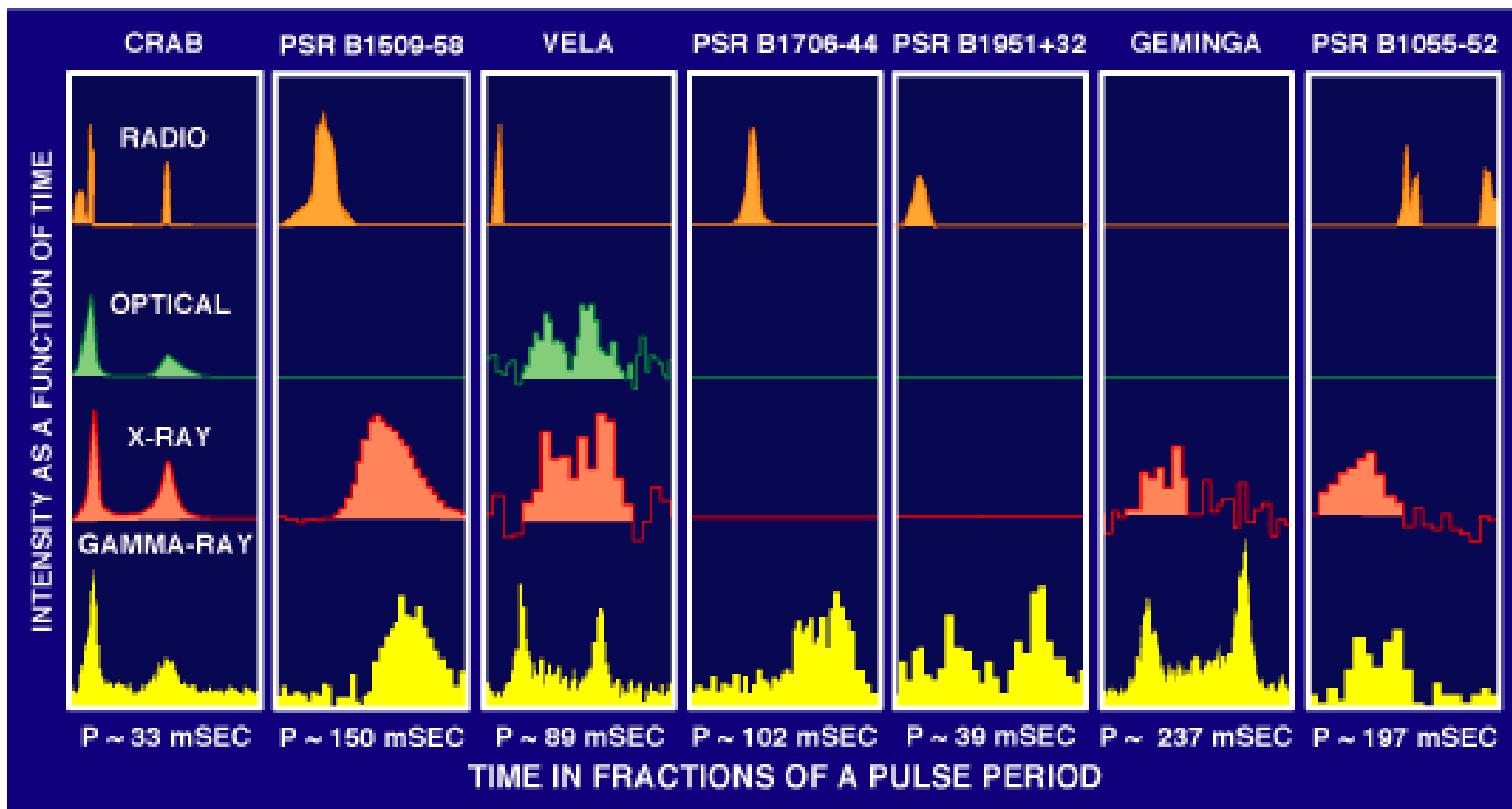
# Crab Nebula - Spectral Energy Distribution

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

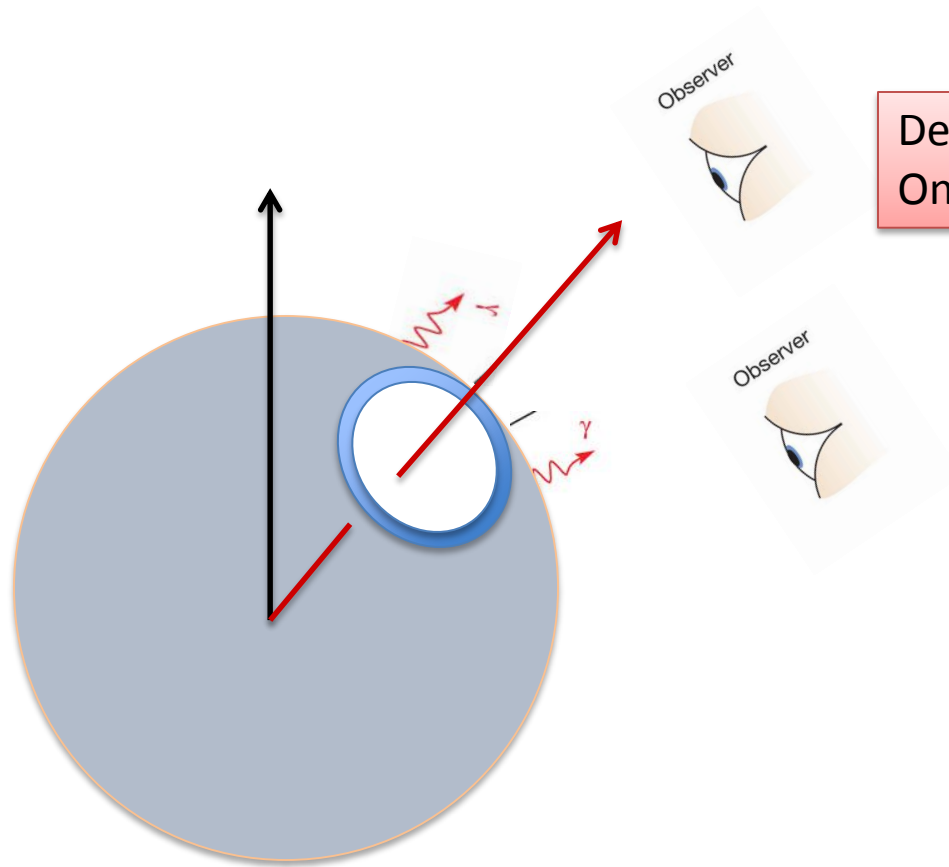
MOST PRECISE  
IC PEAK  
MEASUREMENT  
SO FAR



# Before Fermi, 6 EGRET Pulsars



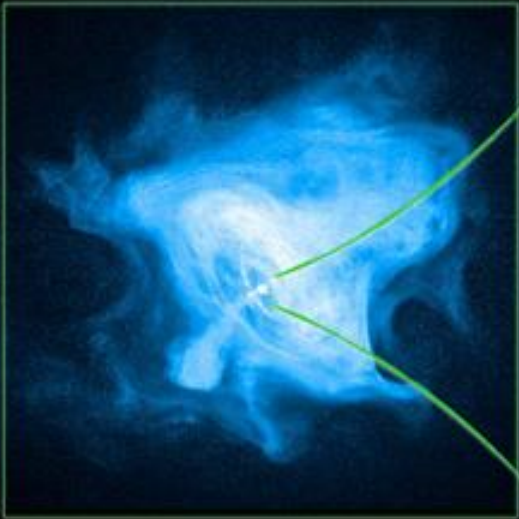
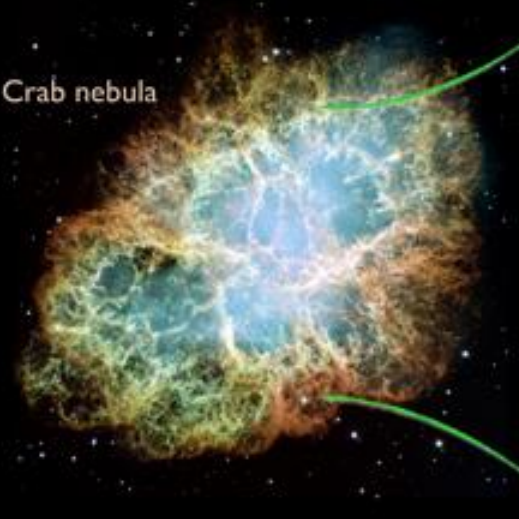
# Pulsed and bridge emission from pulsar



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

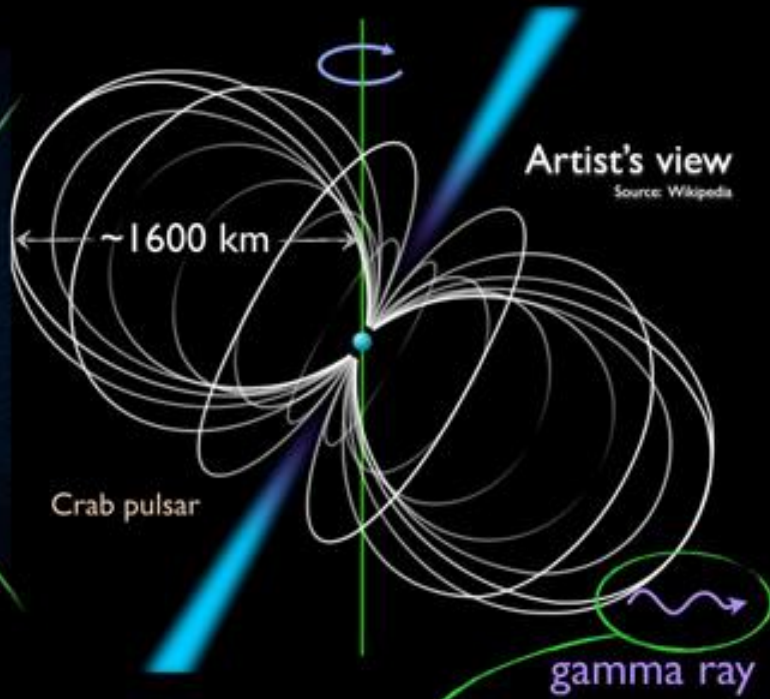


Crab nebula



Optical image  
Source: NASA/ESA

X-ray image  
Source: NASA/ESA

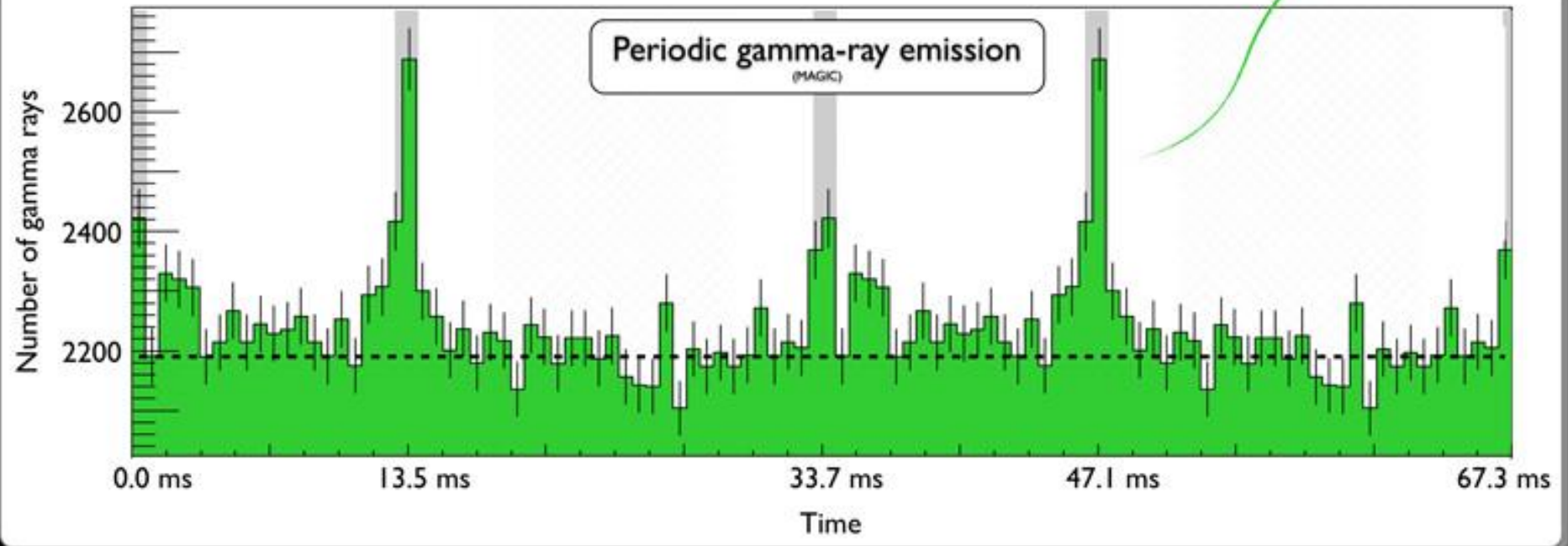


Artist's view  
Source: Wikipedia

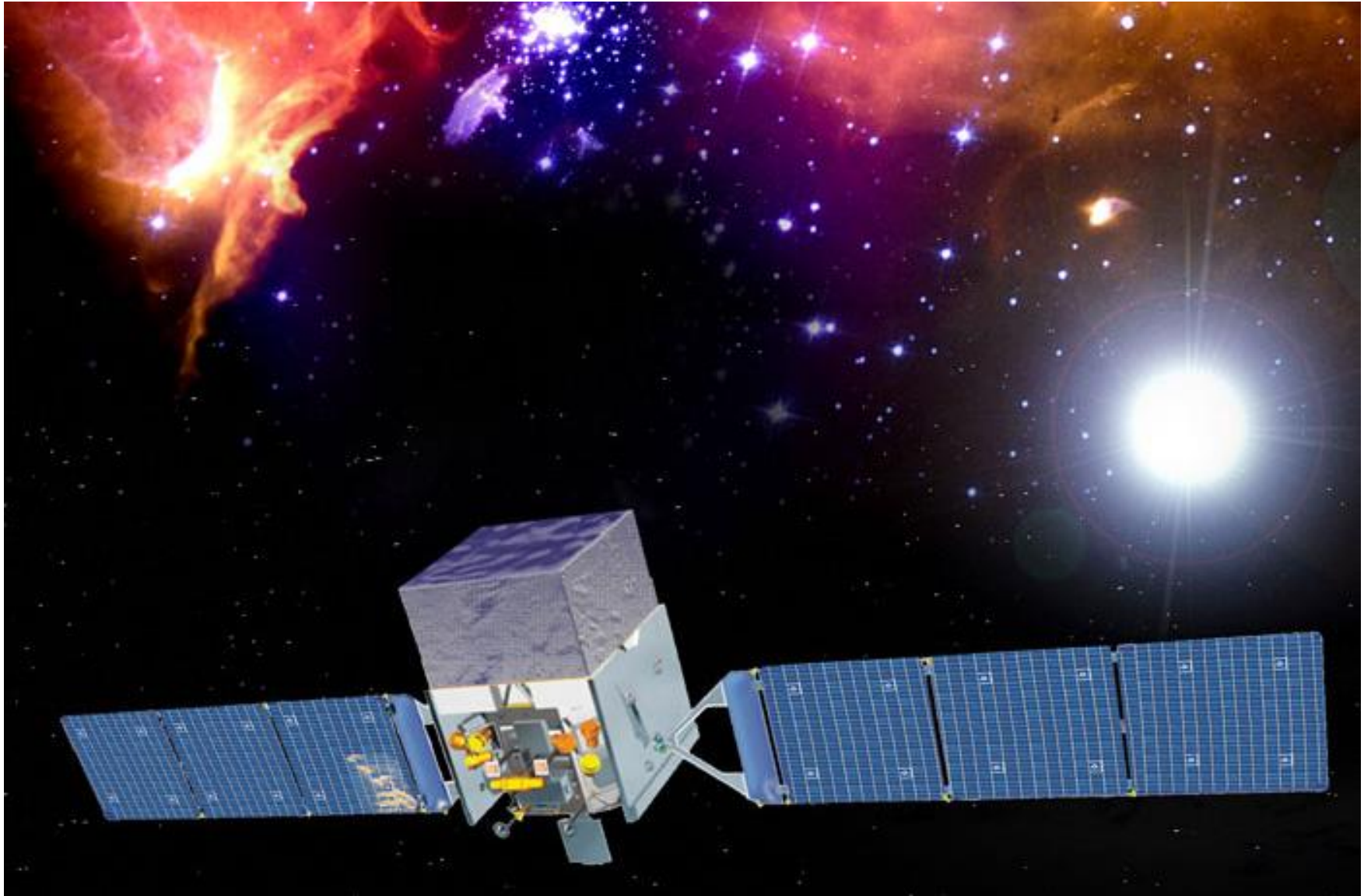
Crab pulsar

~1600 km

gamma ray



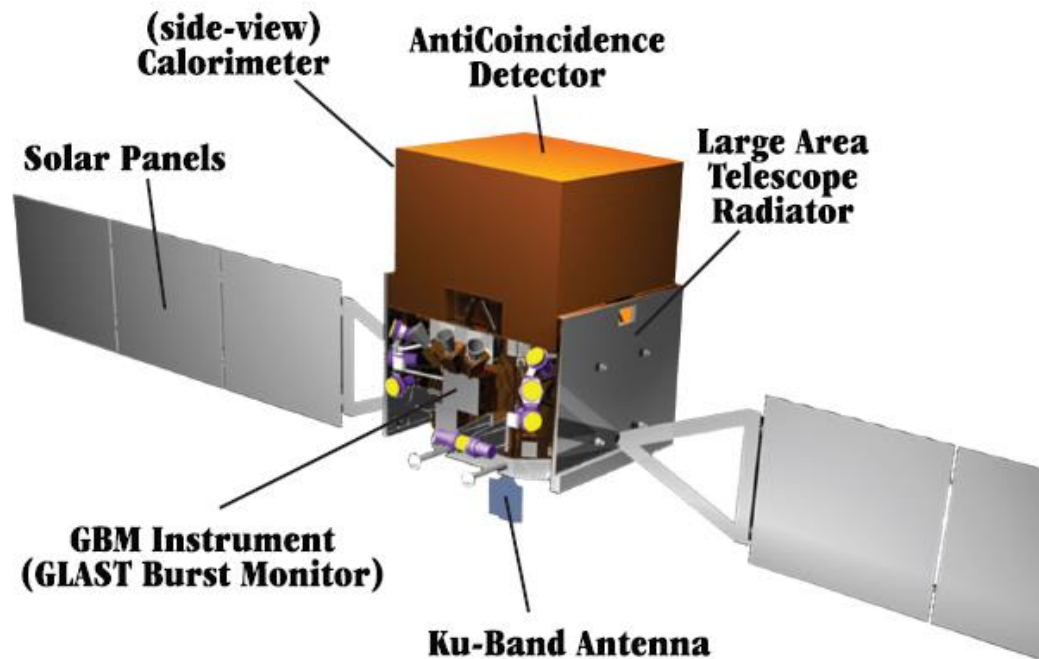
# Fermi teleskop



# FERMI – gamma telescope on board satellite

At the height 565 km

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





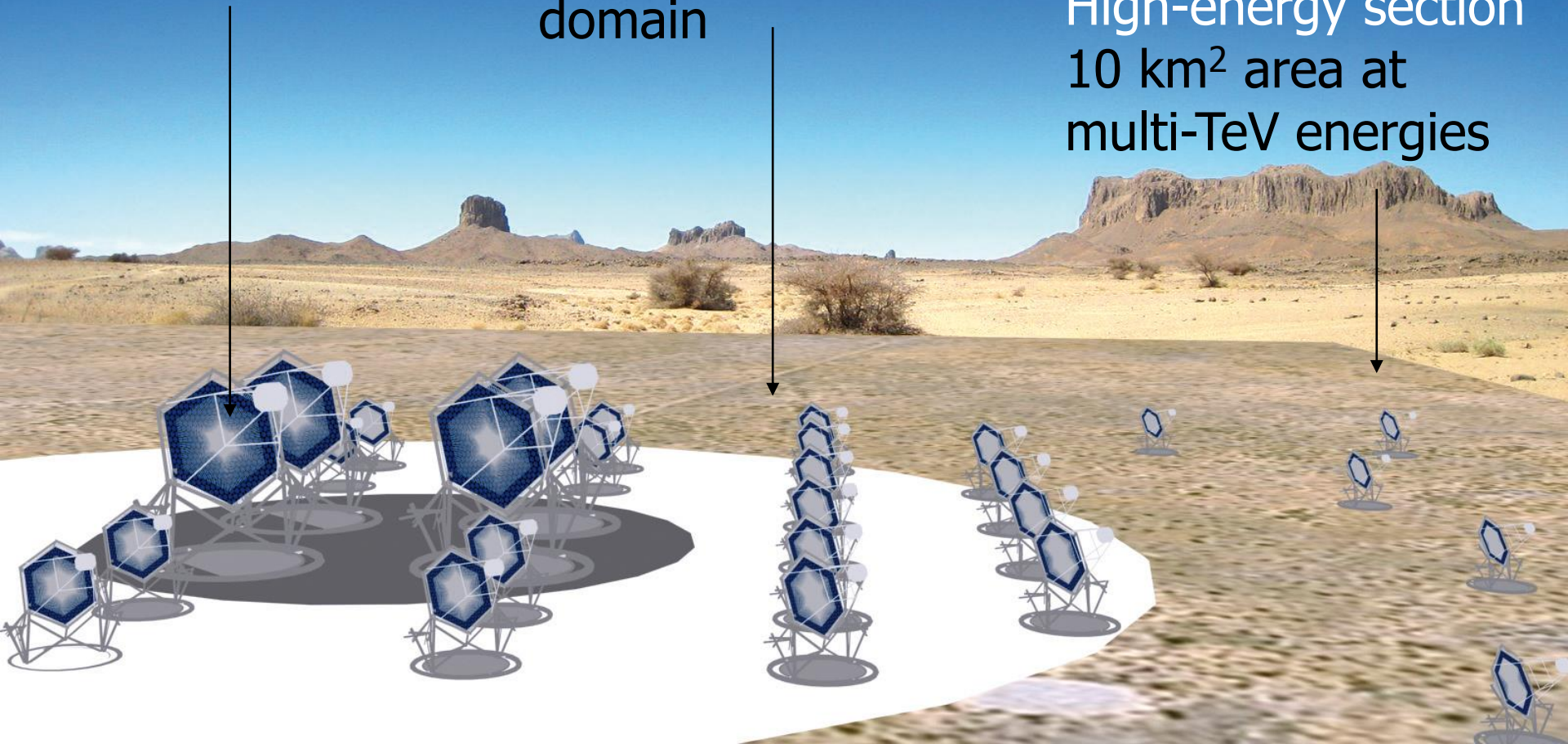
# Future: Cherenkov Telescope Array (CTA)

<http://www.cta-observatory.org>

Low-energy section  
energy threshold  
of some 10 GeV

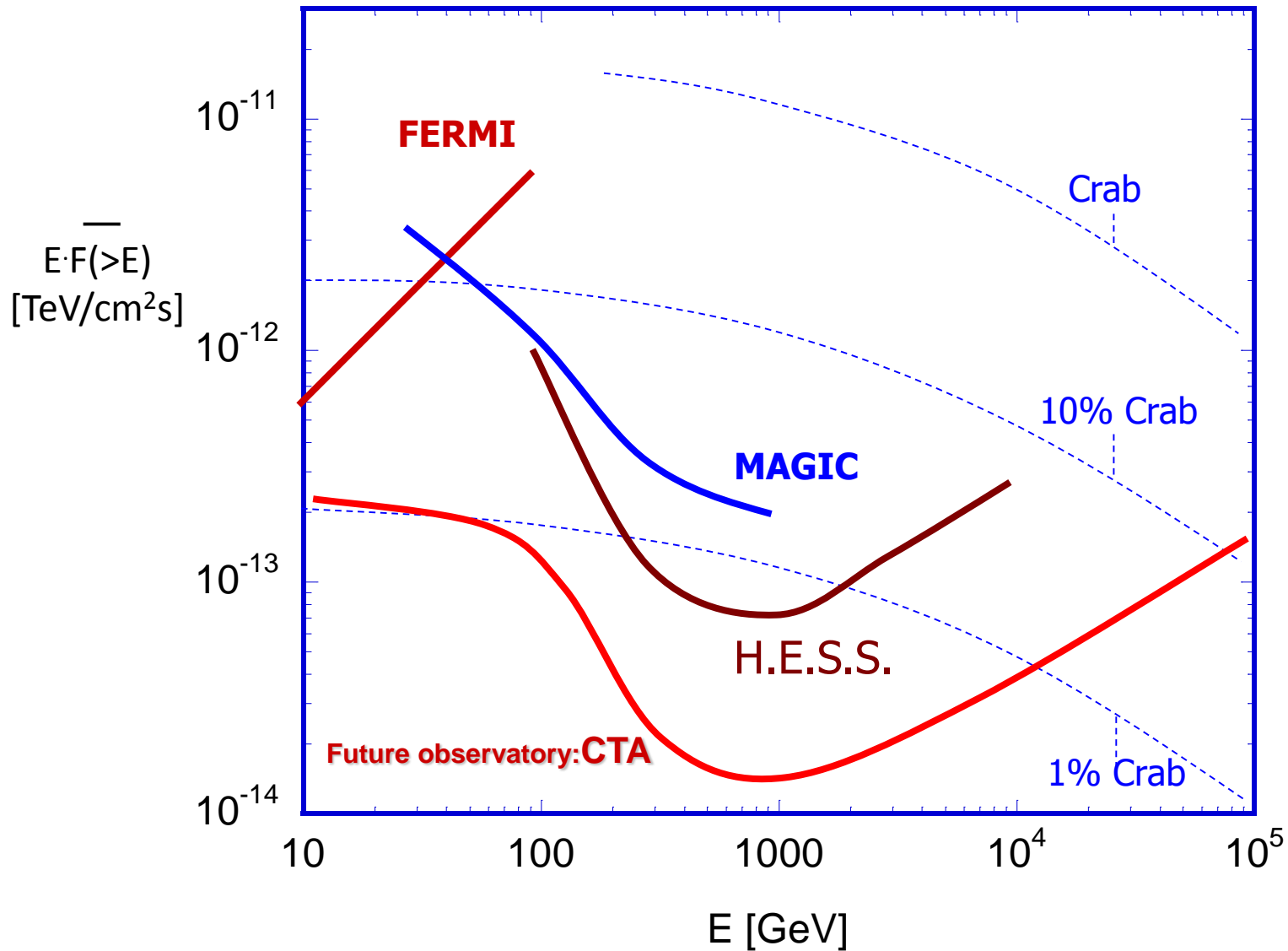
Core array:  
mCrab sensitivity  
in the 100 GeV–10 TeV  
domain

High-energy section  
10 km<sup>2</sup> area at  
multi-TeV energies





# Sensitivity of gamma ray telescopes



# Nekoliko zaključnih misli

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- ▶ 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