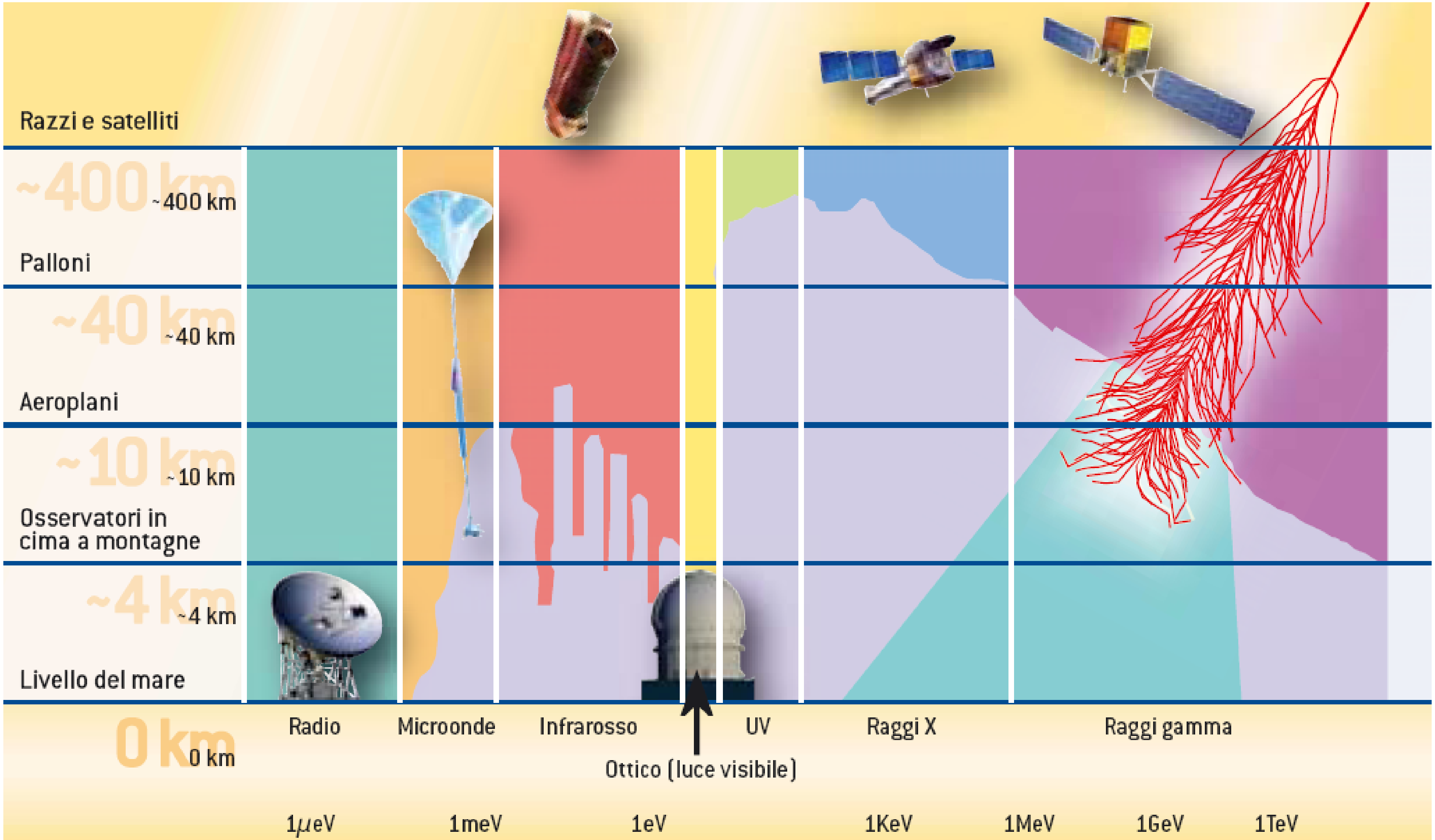
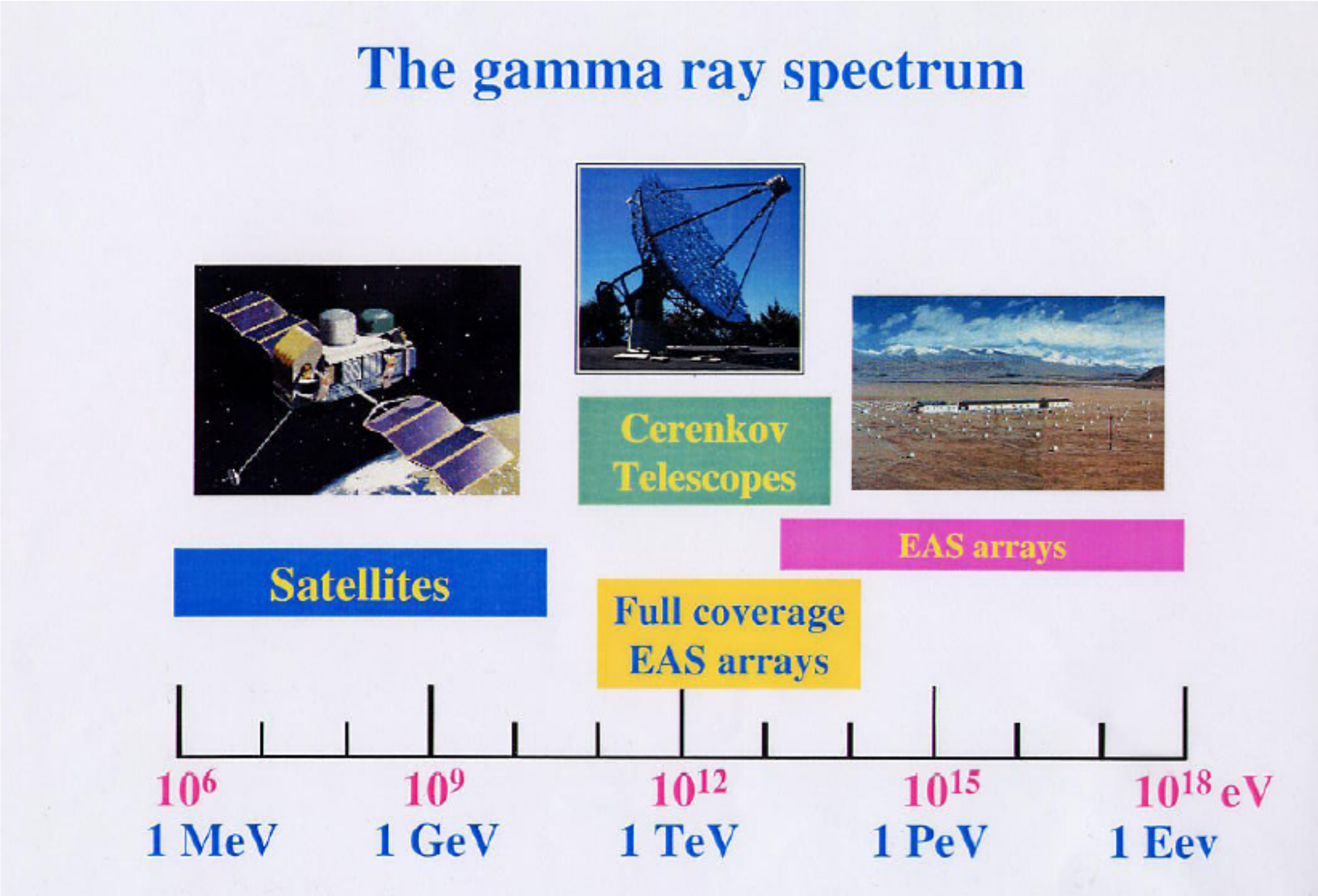
Astrofisica Nucleare e Subnucleare

Astrofisica al “TeV”

The opacity of the atmosphere

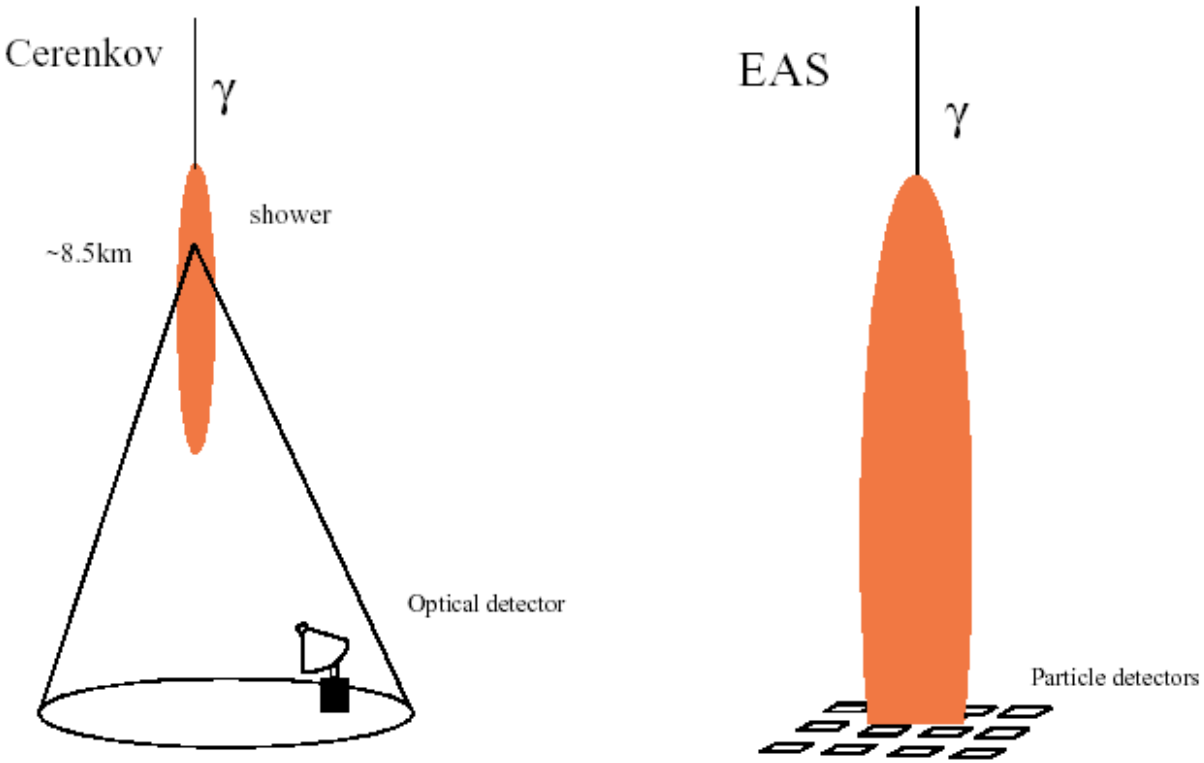


TeV detectors



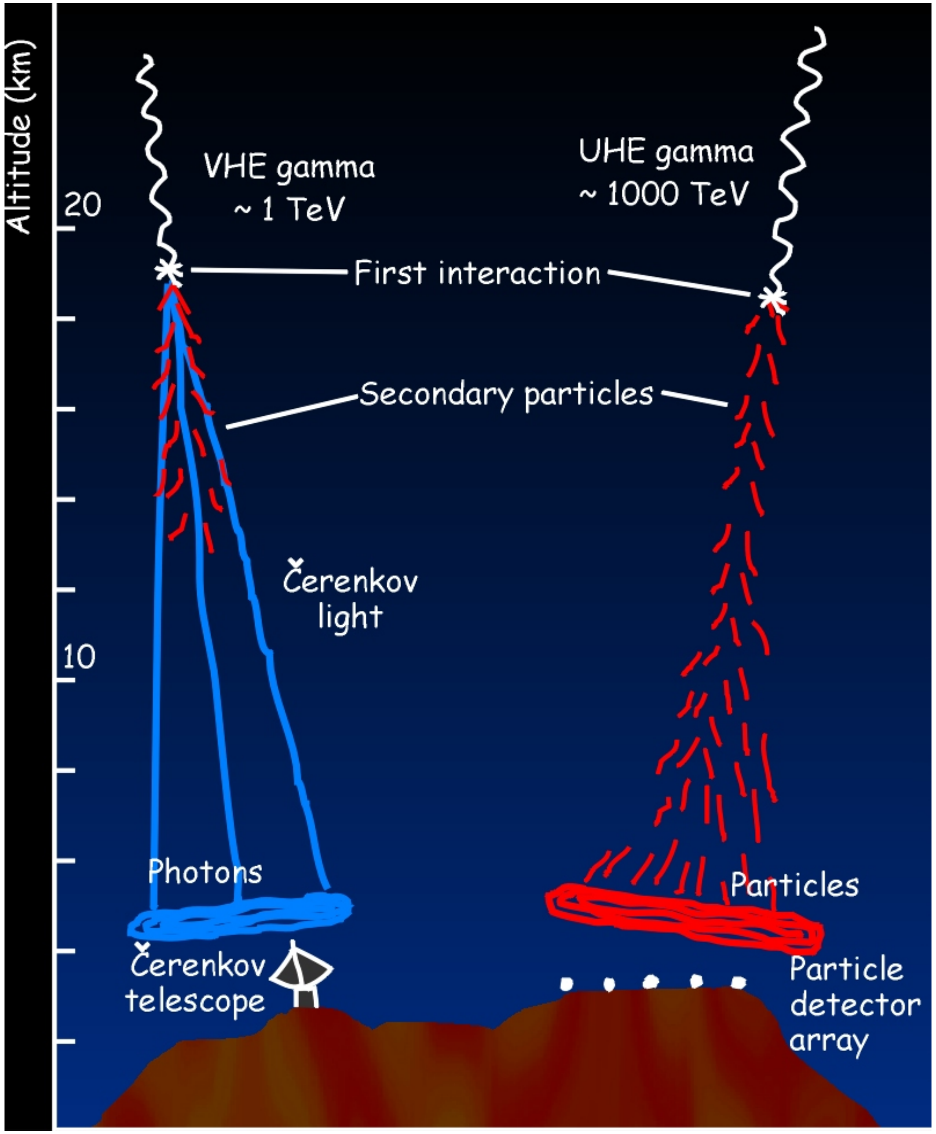
TeV detectors

Cerenkov and Extensive air shower (EAS) gamma ray telescope concepts



~ 40.000 m^2 , but no anticoincidence shield !

IACT & EAS experiments



- Cherenkov experiments consist of almost-optical telescopes devoted to detect Cherenkov light.
- EAS (Extensive Air Shower) experiments are huge arrays or carpets of particle detectors.
- Cherenkov experiments have lower energy thresholds, but also a lower duty-cycle as well as a smaller field of view.

Complementary Capabilities

Parameter	Ground-based		Space-based
	ACT	EAS	Pair
angular resolution	good	fair	good
duty cycle	low	high	high
area	large	large	small
field of view	small	large	large & can repoint
energy resolution	good	fair	good w/ smaller systematic uncertainties

The next generation of ground-based and space-based facilities are well matched!

EM Air Showers

Air shower development

- Pair production $I = I_0 \, e^{-x/\lambda}$

  λ = mean free path

- Bremsstrahlung $E = E_0 \, e^{-x/\chi_0}$

  χ_0 = radiation length

In the ultra-relativistic limit $\lambda \sim \chi_0 = 36.5 \text{ g/cm}^2$ in air

$R = \chi_0 \ln 2 \quad \Rightarrow$ After a distance nR:

$N_{e,\gamma} = 2^n \qquad E_{e,\gamma} \sim E_{pr} / 2^n$

EM Air Showers

The process continues until the electrons energy is $E > E_c$

E_c= critical energy = 83 MeV in air

Number of particles at the shower maximum:

$$N_{max} = 2^n = E_{pr} / E_c$$

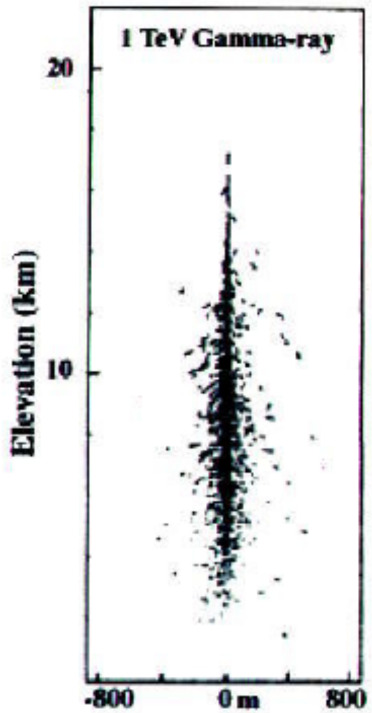
Depth of the maximum:

$$n_{max} = \ln (E_{pr} / E_c) / \ln 2$$

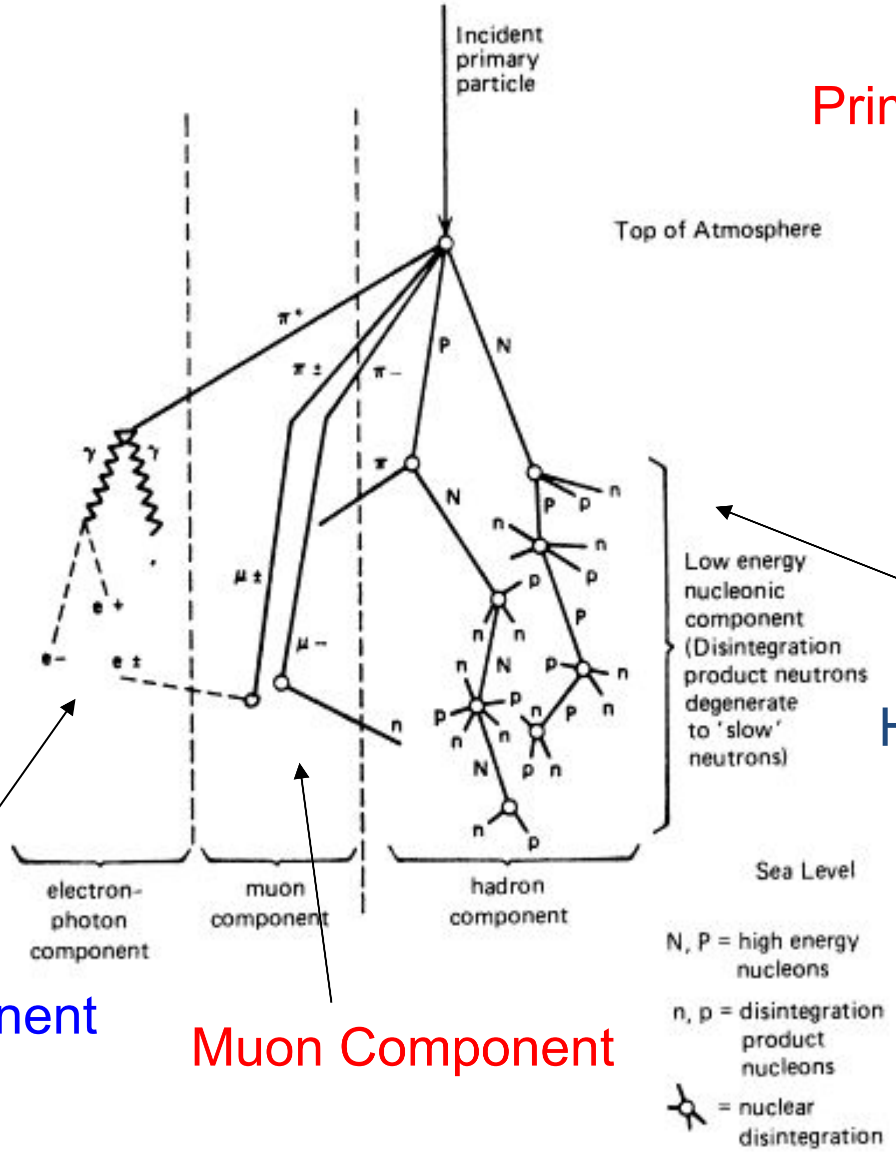
$$\Rightarrow X_{max} = n R = n \chi_0 \ln 2 = \chi_0 \ln (E_{pr} / E_c)$$

Example: $E_{pr} = 1$ TeV

$$\Rightarrow X_{max} = 340 \text{ g / cm}^2 \sim 8 \text{ Km}$$



CR interactions



Primary Interaction

Hadronic Component

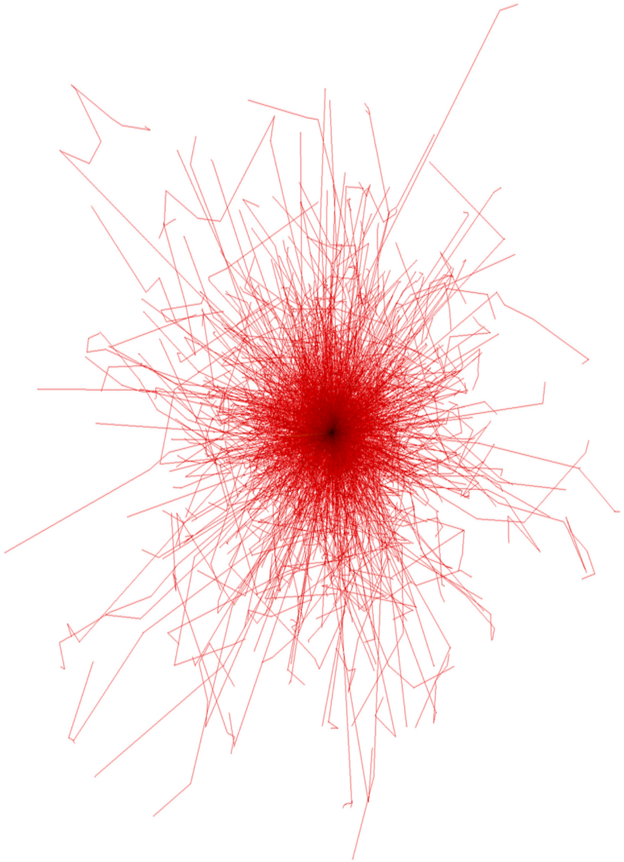
EM Component

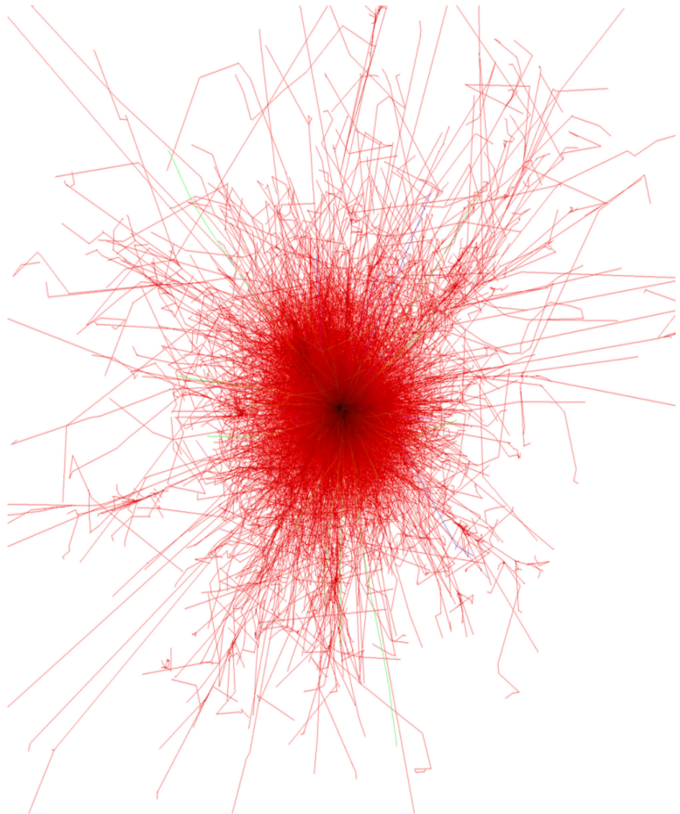
Muon Component

The importance of MC

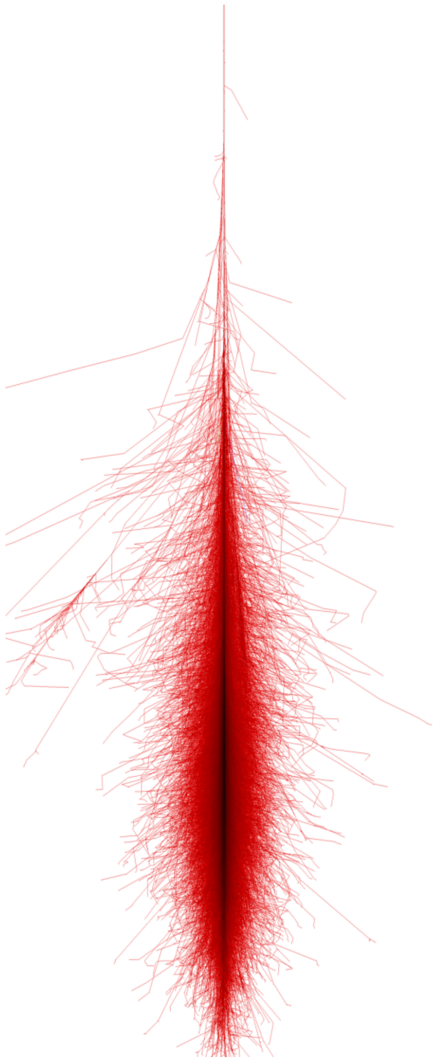
- CORSIKA (COsmic Ray SImulations for KAscade) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries.
- The particles are tracked through the atmosphere until they undergo reactions with the air nuclei or - in the case of instable secondaries - decay.
- The hadronic interactions at high energies may be described by six reaction models alternatively: The VENUS, QGSJET, and DPMJET models are based on the Gribov-Regge theory, while SIBYLL is a minijet model. HDPM is inspired by findings of the Dual Parton Model and tries to reproduce relevant kinematical distributions being measured at colliders. The neXus model extends far above a simple combination of QGSJET and VENUS routines.
- Hadronic interactions at lower energies are described either by the GHEISHA interaction routines, by a link to FLUKA, or by the UrQMD model.
- In particle decays all decay branches down to the 1 % level are taken into account.
- For electromagnetic interactions a taylor made version of the shower program EGS4 or the analytical NKG formulas may be used.
- Options for the generation of Cherenkov radiation and neutrinos exist.
- CORSIKA may be used up to and beyond the highest energies of 100 EeV.
- http://www-ik.fzk.de/corsika/

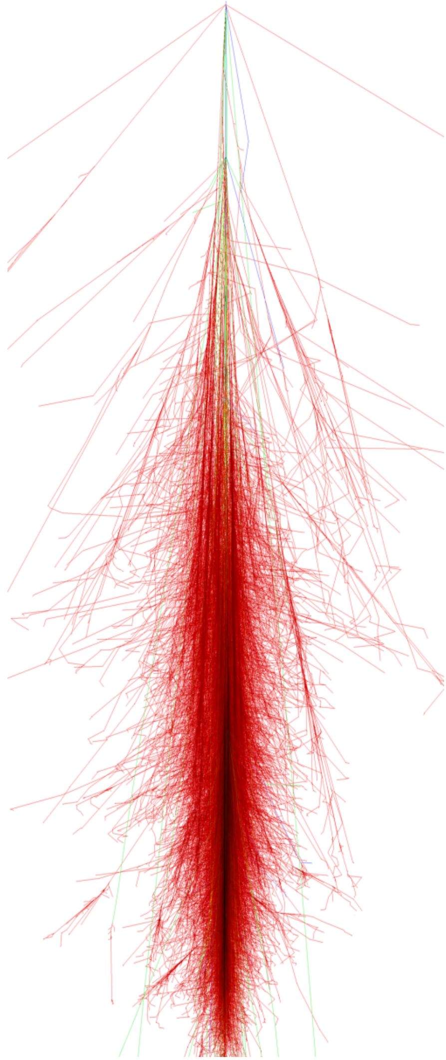
Shower Images



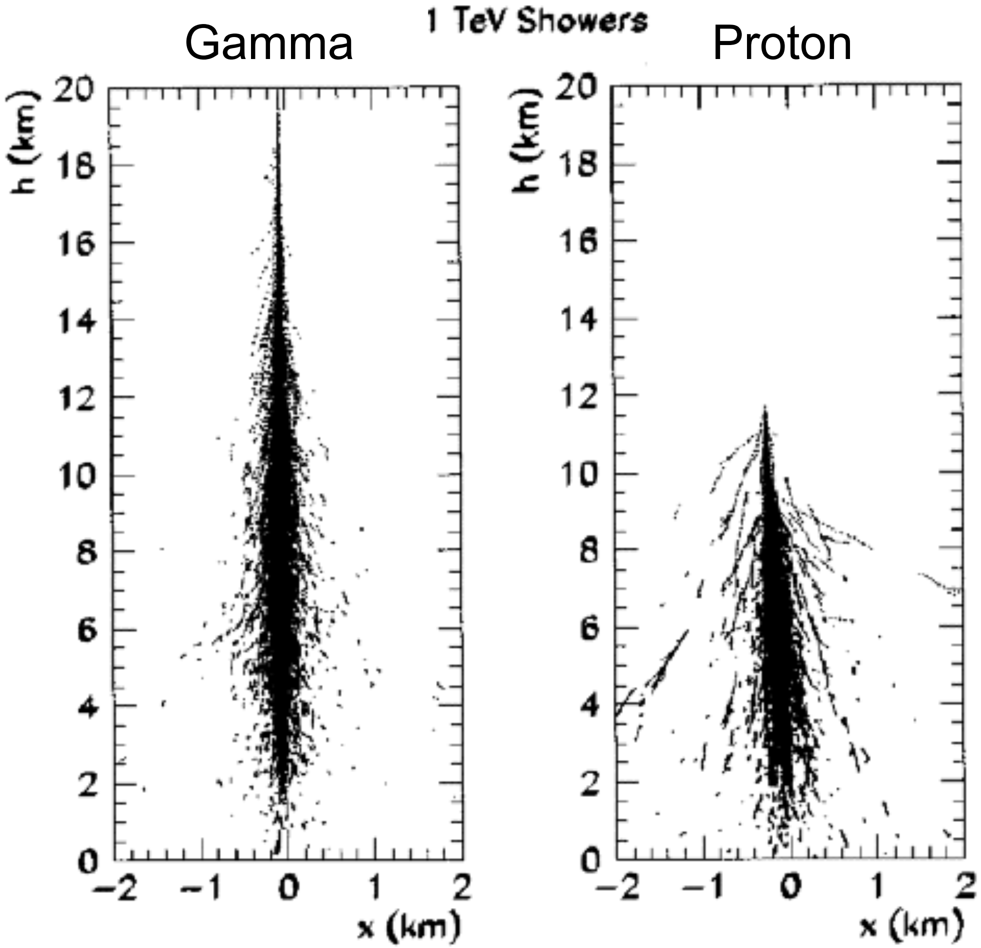


Shower Images



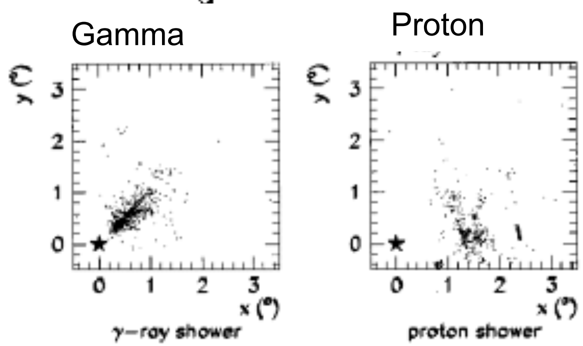


Development of vertical 1-TeV proton and γ-ray shower

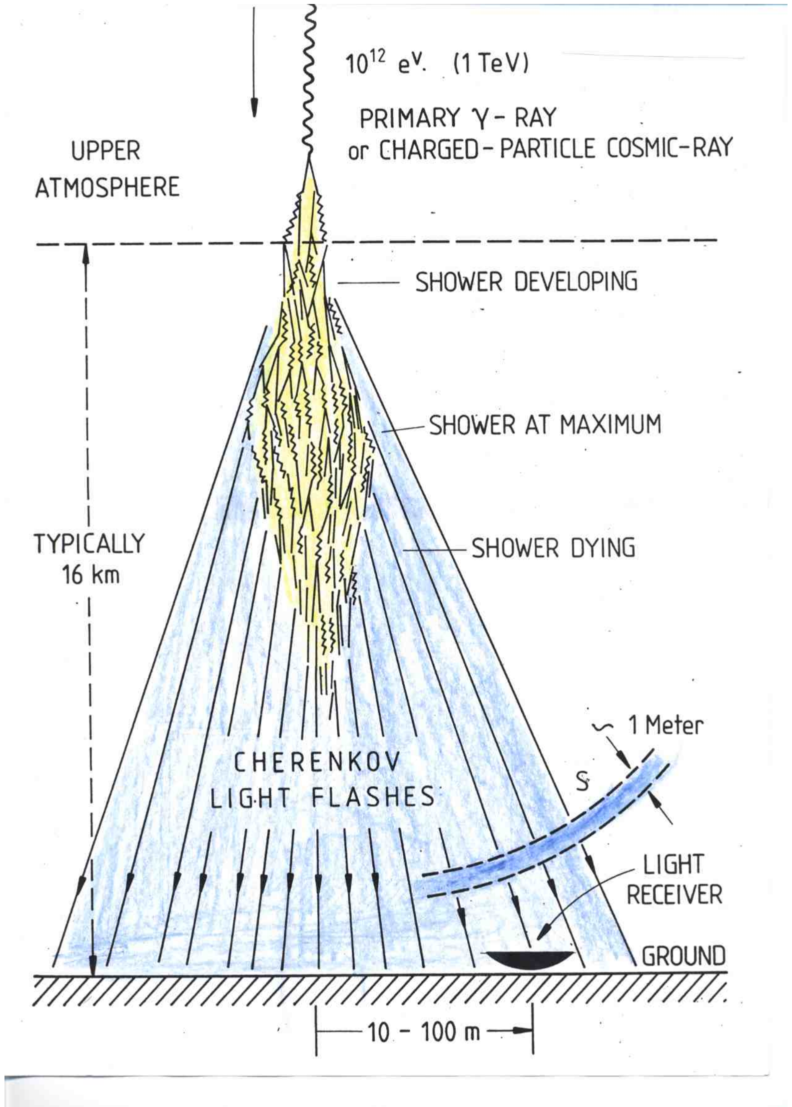


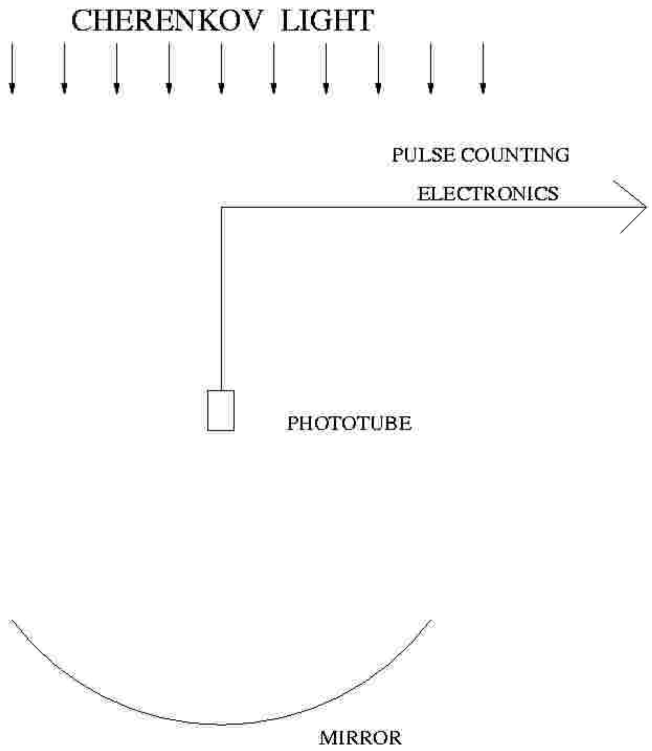
Positions in the atmosphere of all shower electrons above the Cerenkov threshold

Resulting Cerenkov images in the focal plane of a 10-m reflecting mirror .



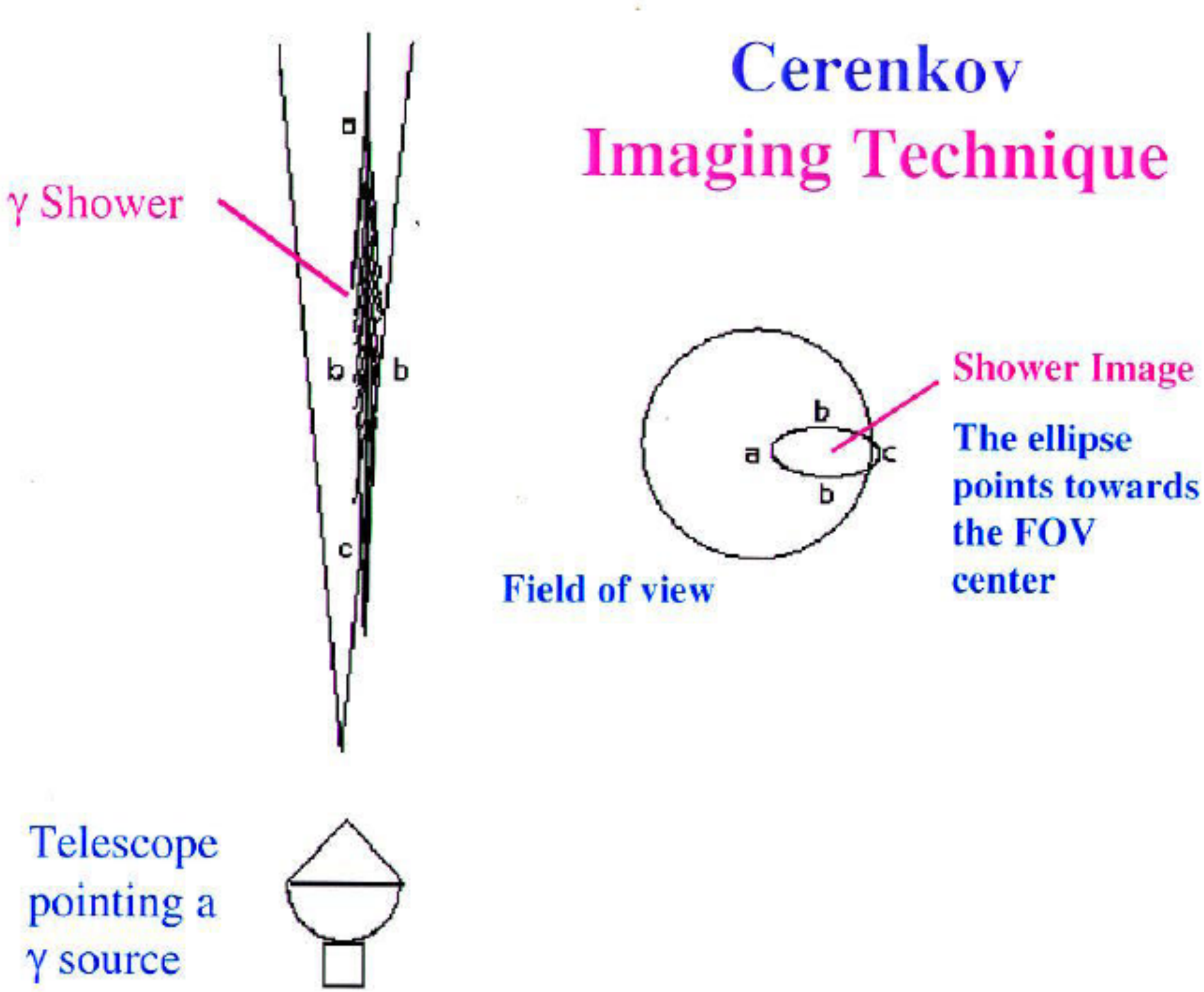
TeV detectors





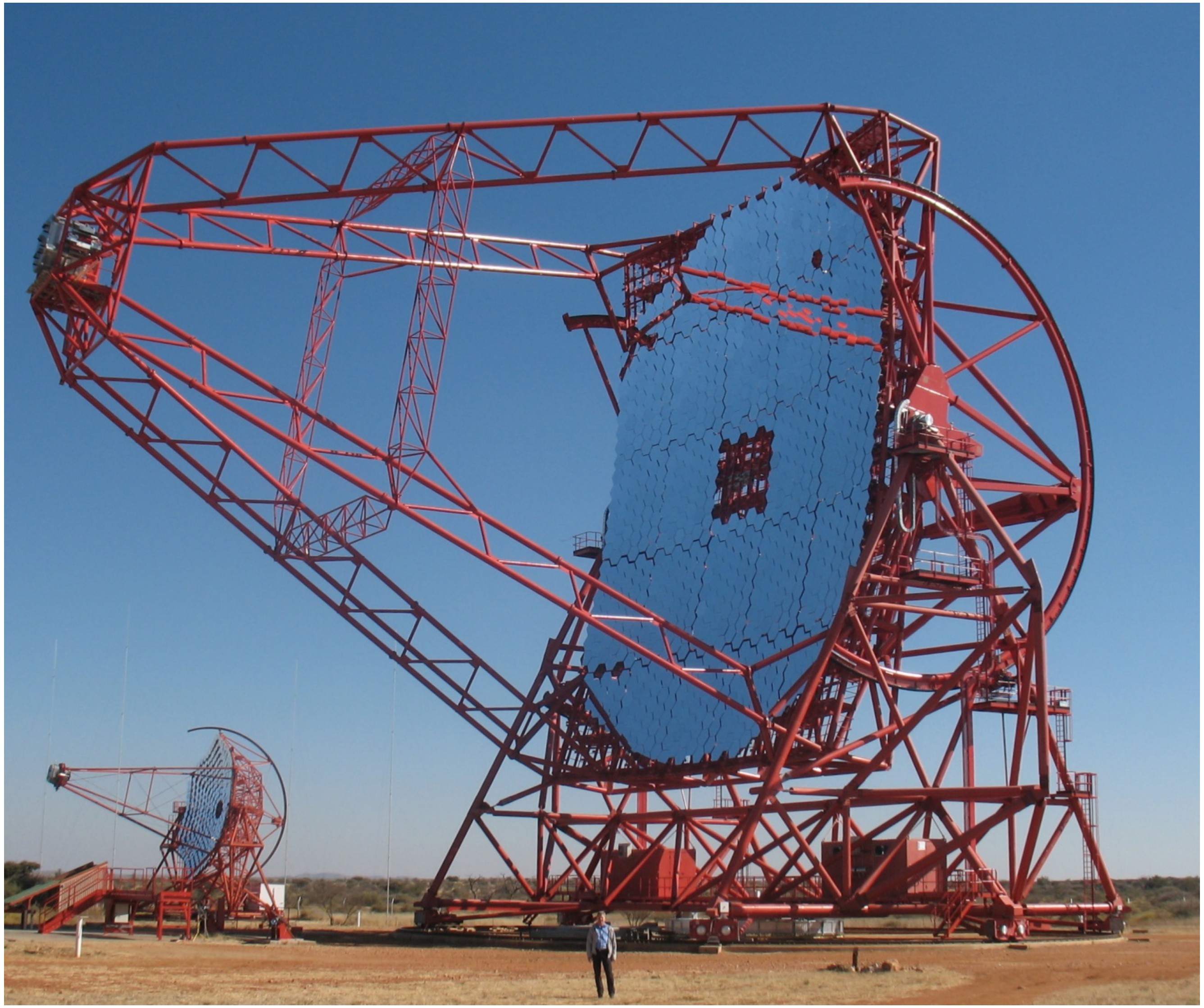
Direction ~ → arc-min
Energy Resolution ~ →10%
Background ~ →0

TeV detectors



HESS

HESS-II

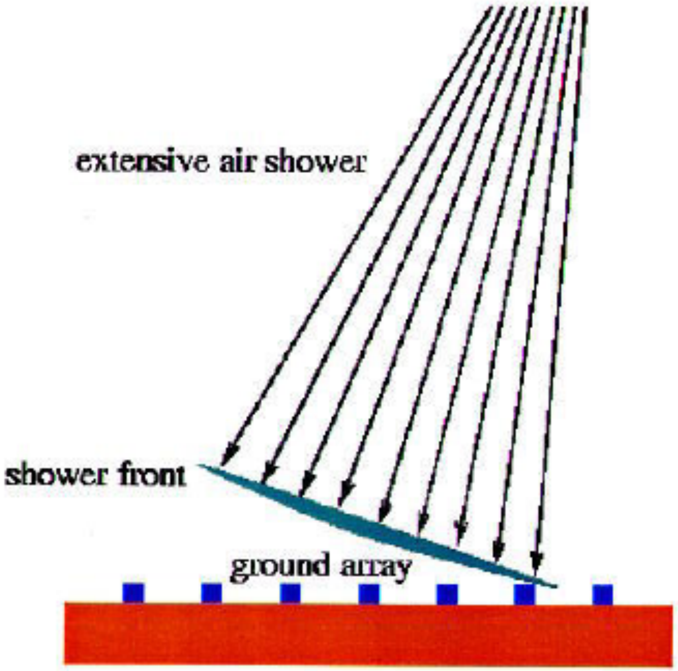


MAGIC telescopes

VERITAS

TeV detectors

Air Shower Arrays



Reconstruction of the γ direction with the particles arrival times

Large field of view: ~ π sr

Duty cycle ~ 100%

Gamma-hadrons discrimination:

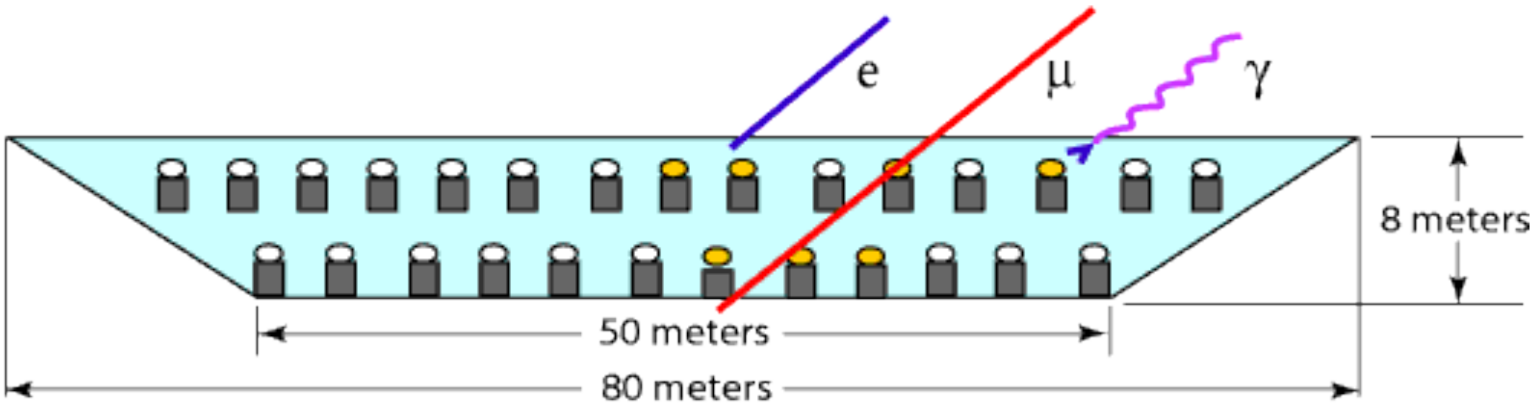
μ-poor showers

EAS technique

Charged particles produce Cherenkov photons in water
~1400 times more Cherenkov photons than in air per unit length track of charged particle
Cherenkov cone in water ~41° (in air: less than 1°)

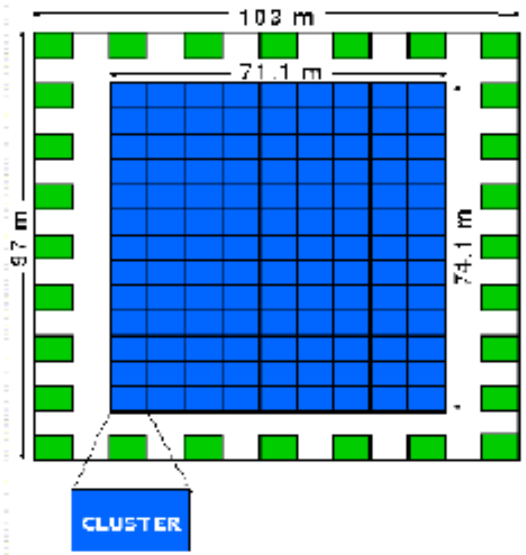
Uniform sky view with an array of PMTs

Direction reconstruction through PMTs signal times



ARGO

Area 5.200 m^2 (full coverage)
(10.000 m^2 with guard ring)
Field of view ~ 1 sr
E = 50 GeV - 50 TeV
Location: Tibet 4300m alt.

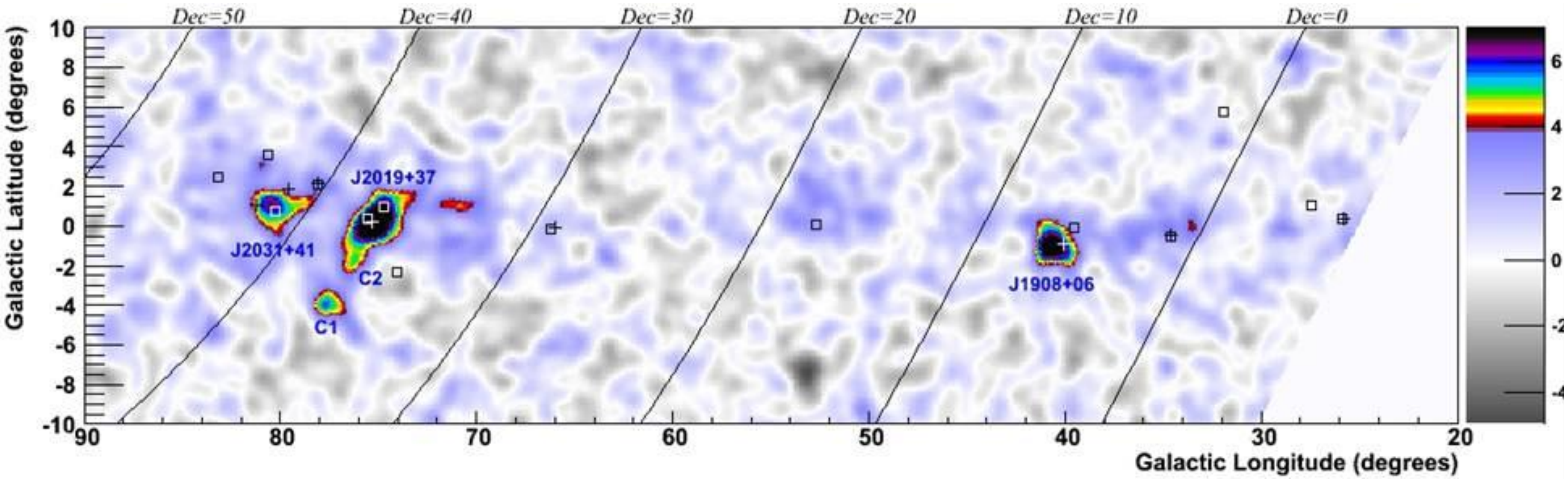


17400 Pads 56 by 60 cm^2 each of Resistive Plate Chamber (RPC).
Each pad subdivided in pick-up strips 6 cm wide for the space pattern inside the pad.
The CLUSTER is made of 12 RPCs Pads

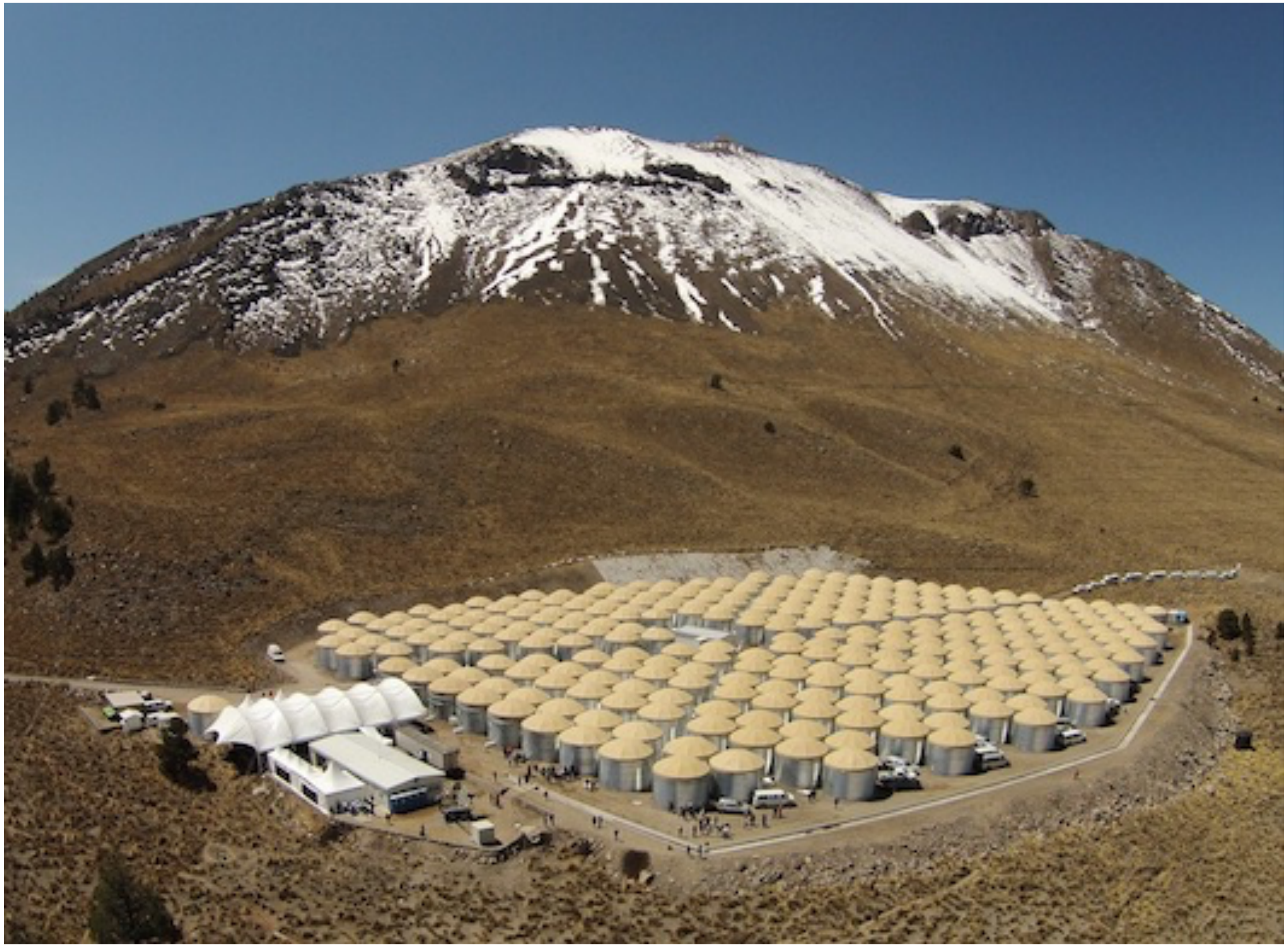
MILAGRO

Cherenkov in water, Arizona

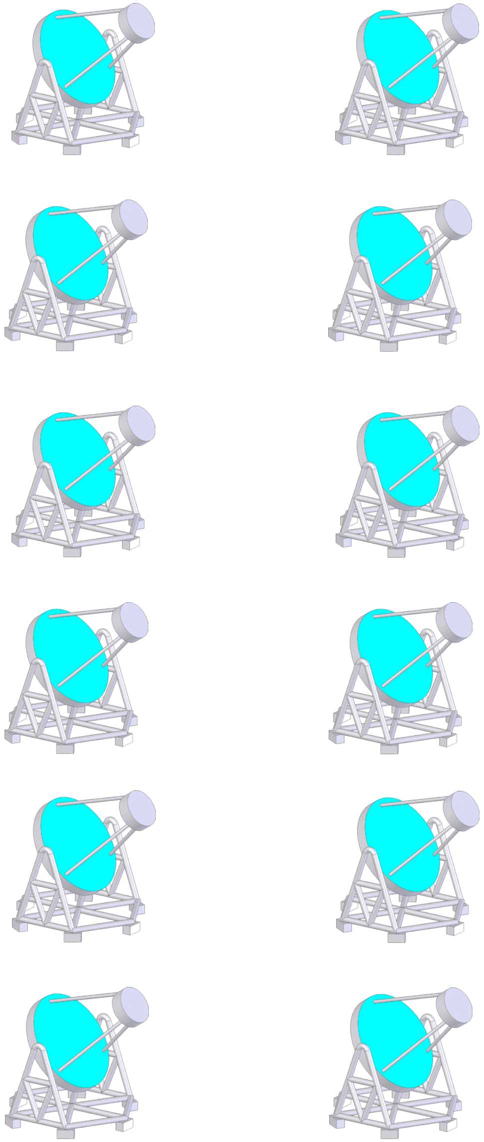
Crab:
~5σ in 100 days
Median energy ~20 TeV

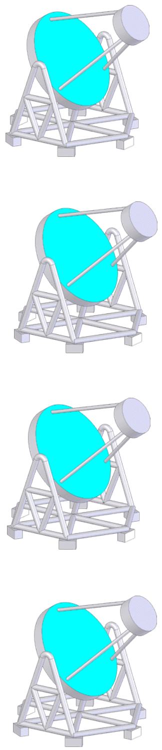


HAWC



Outlook: What next ?



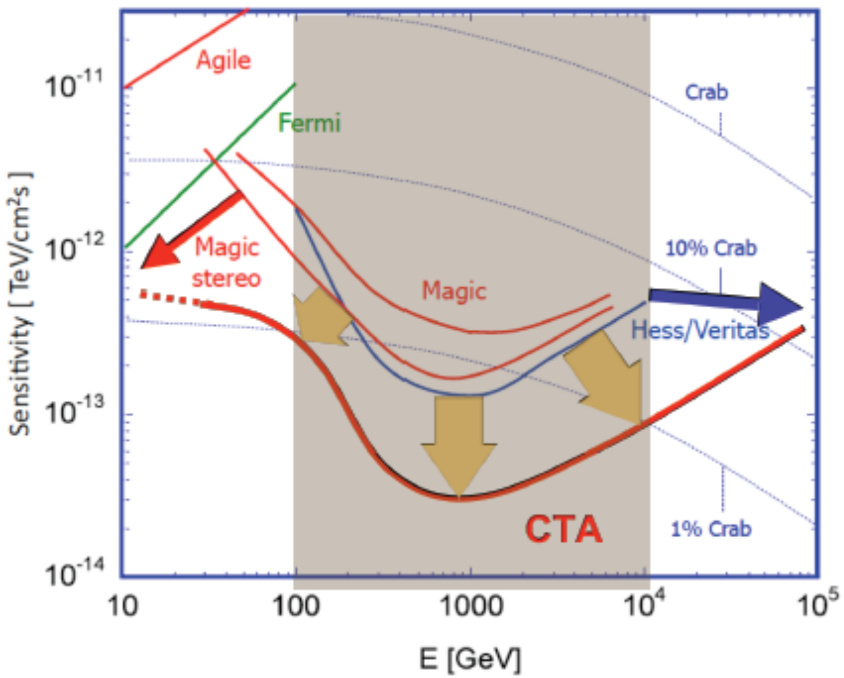


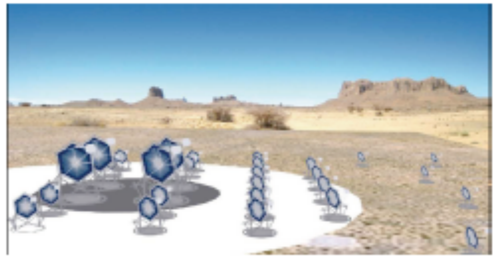
The Cherenkov Telescope Array (CTA)

- aims to explore the sky in the 10 GeV to 100 TeV energy range
- builds on demonstrated technologies
- combines guaranteed science with significant discovery potential
- is a cornerstone towards a multi-messenger exploration of the nonthermal universe

CTA

Improve sensitivity



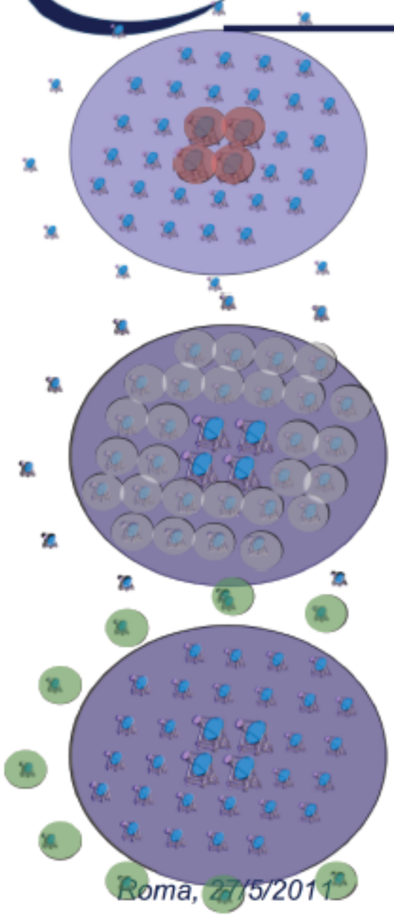


CTA will be about a factor of 10 more sensitive than any existing instrument in the 100 GeV-10 TeV energy band.

CTA will also extend the observed energy band reaching both the lower (10 GeV) and the higher (100 TeV) energies.

CTA

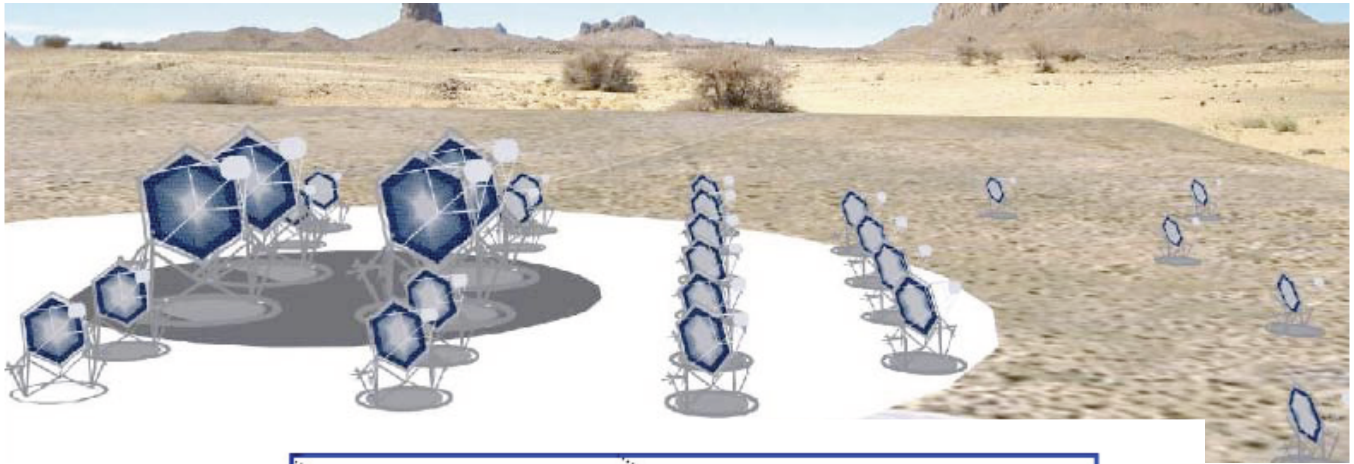
CTA concept

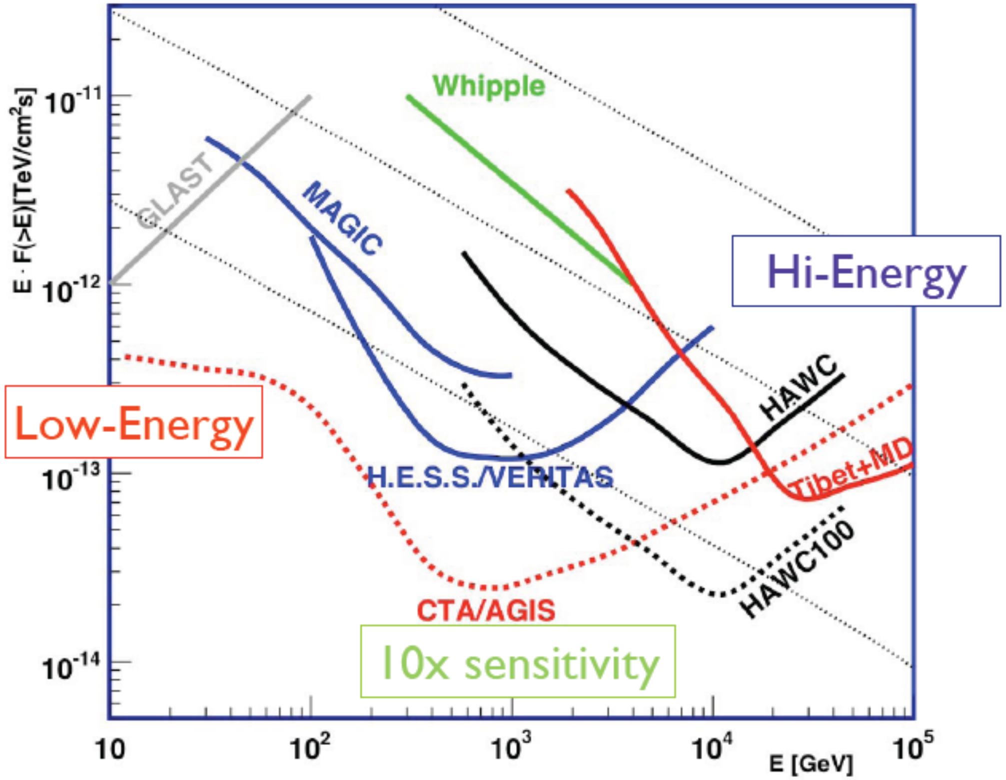


- Few Large Size Telescopes should catch the sub-100 GeV photons
  - Large reflective area
  - Parabolic profiles to maintain time-stamp
  - Contained FOV
- Several Medium Size Telescopes perform 100 GeV-50 TeV observation
- well-proven techniques (HESS, MAGIC)
- goal is to reduce costs and maintenance
- core of the array
- act as VETO for LSTs

- Several Small Size Telescopes perform ultra-50 TeV observation
- challenging design
- Large field-of-view (8°)
- New camera technology

CTA





Whipple
GLAST
MAGIC
Hi-Energy
HAWC
Low-Energy
H.E.S.S./VERITAS
Tibet+MD
HAWC100
CTA/AGIS
10x sensitivity
E · F(>E)[TeV/cm²s]
E [GeV]

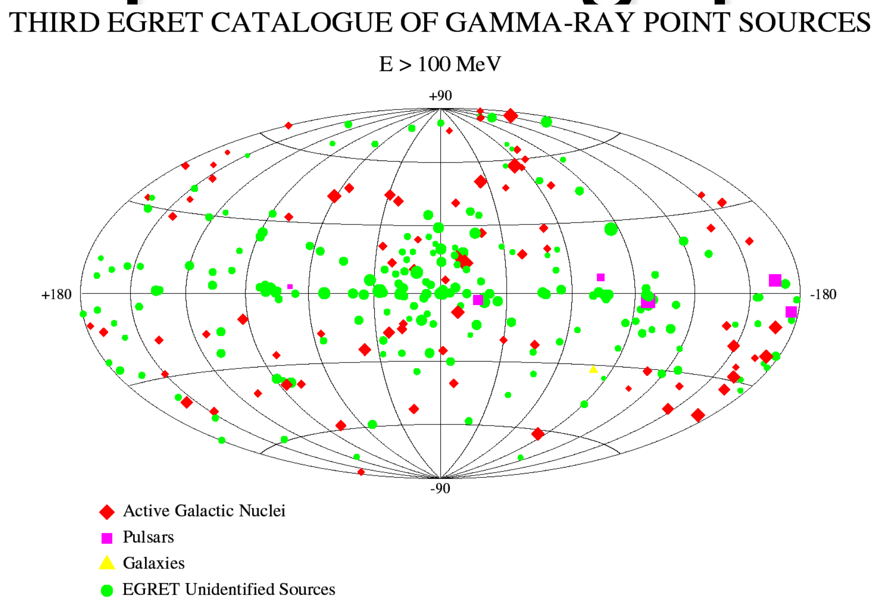
CTA

Astrofisica Nucleare e Subnucleare

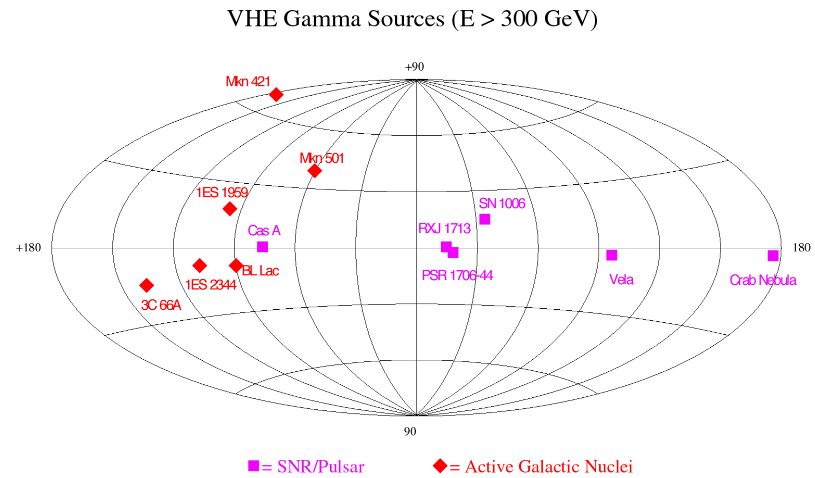
VHE Gamma Astrophysics

The unexplored spectrum gap

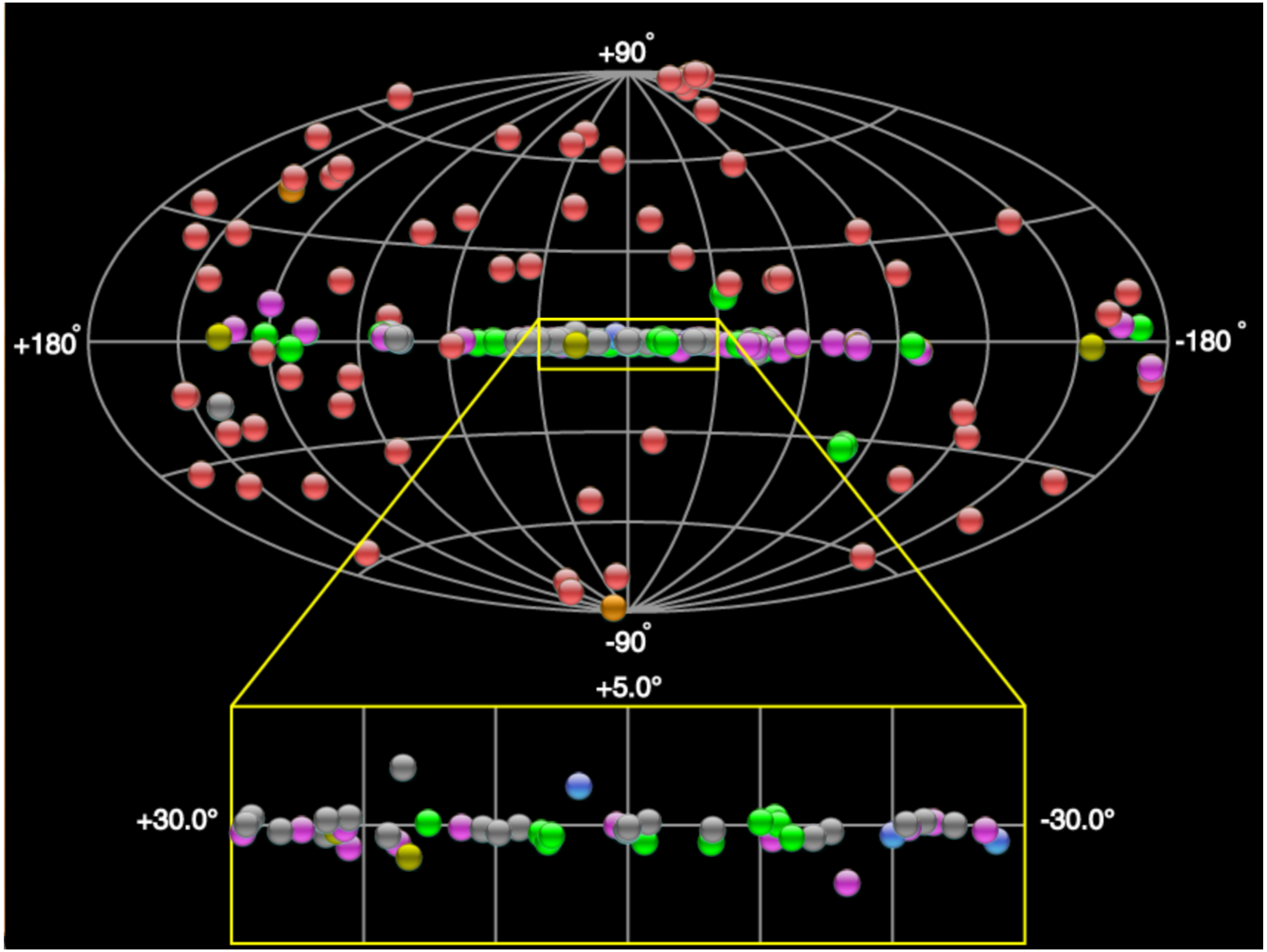
- Satellites give a nice crowded picture of energies up to 10 GeV.

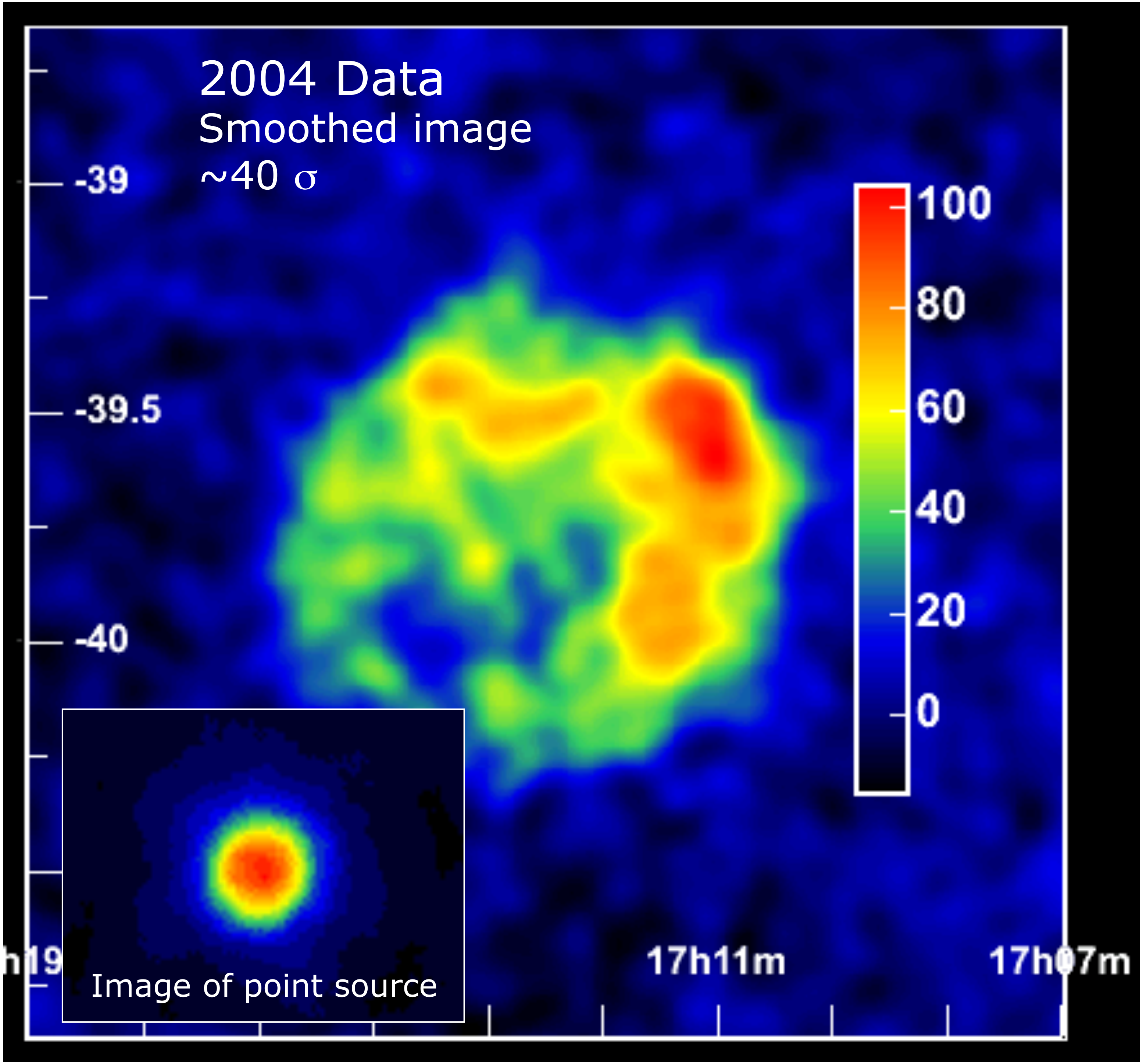


- **Ground based experiments show very few sources with energies > ~300 GeV.**



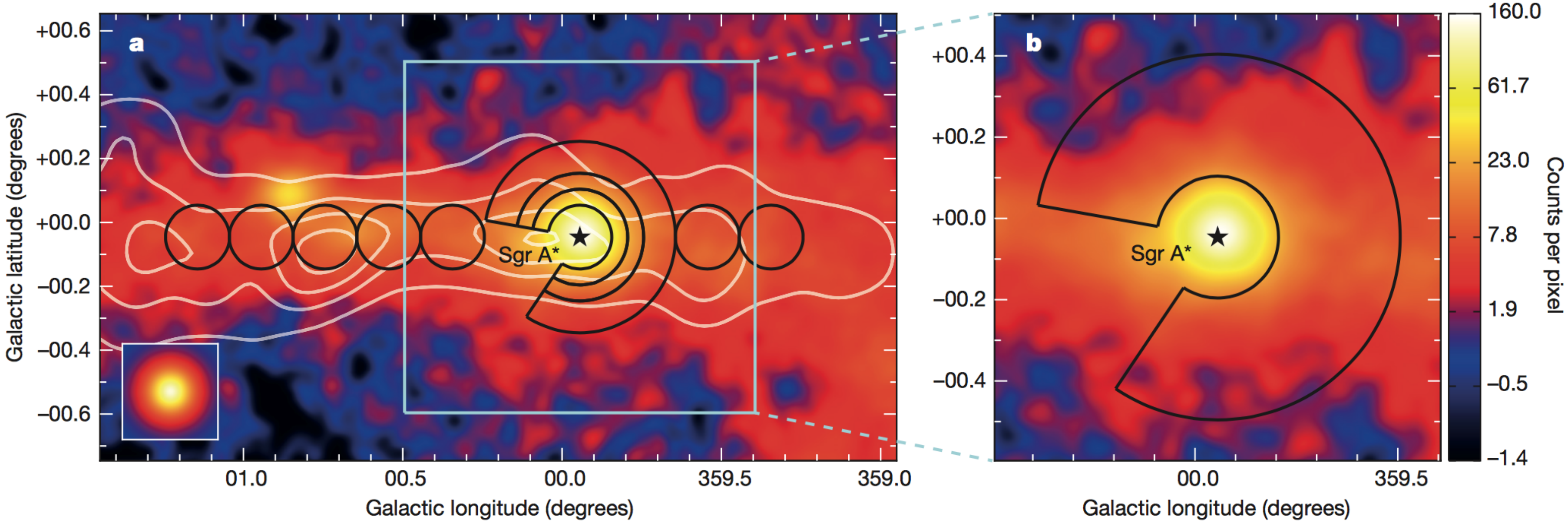
The TeV Catalog





2004 Data
Smoothed image
~40 σ
-39
-39.5
-40
100
80
60
40
20
0
17h11m
17h07m
Image of point source

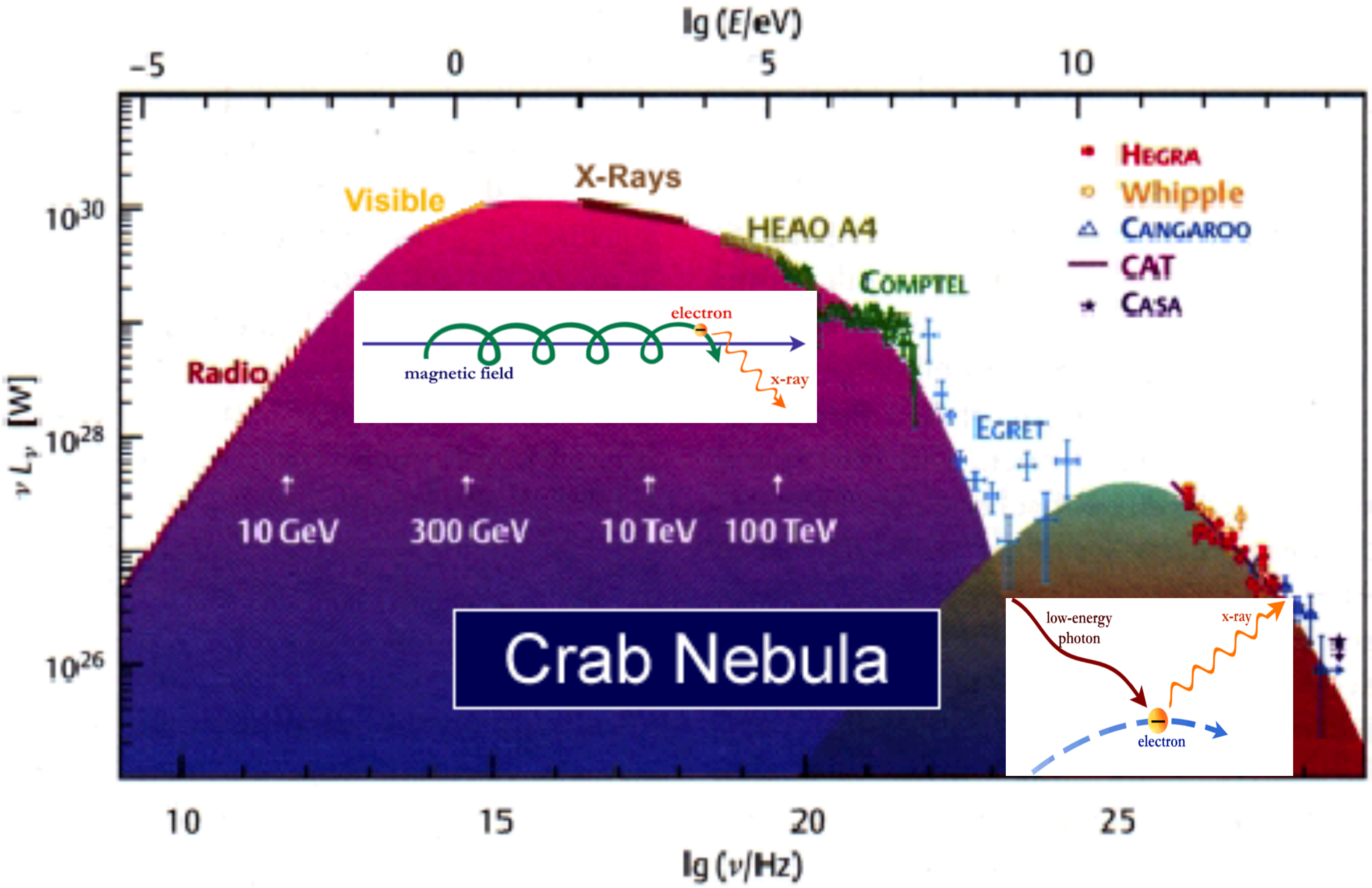
The "Pevatron"



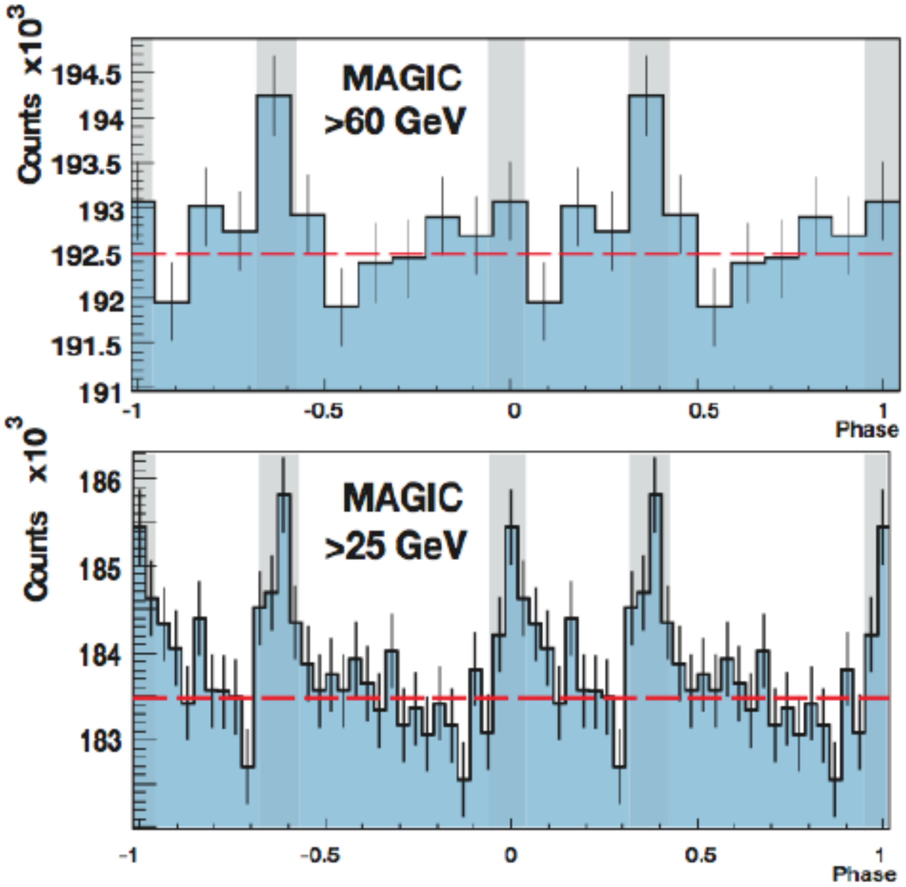
Abramovski et al. (2016)

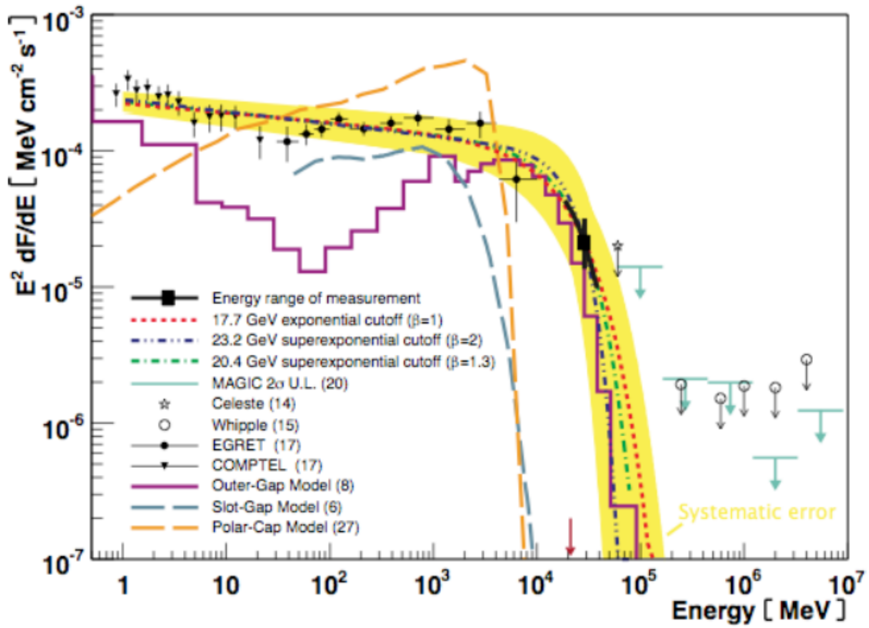
A (minimal) standard model: what do we expect?

Explains most of the observations, not necessarily the most interesting…



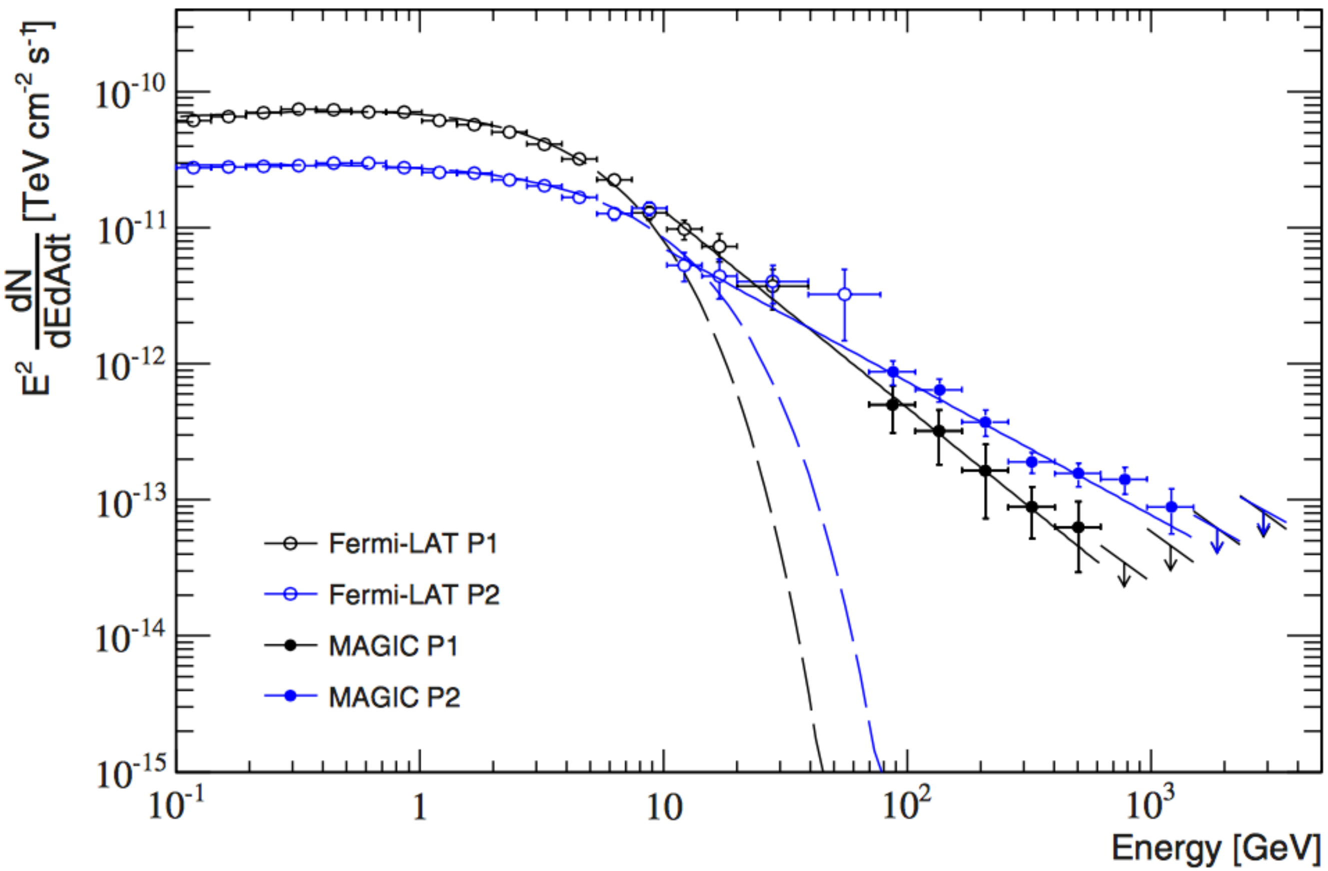
MAGIC – the Crab PSR





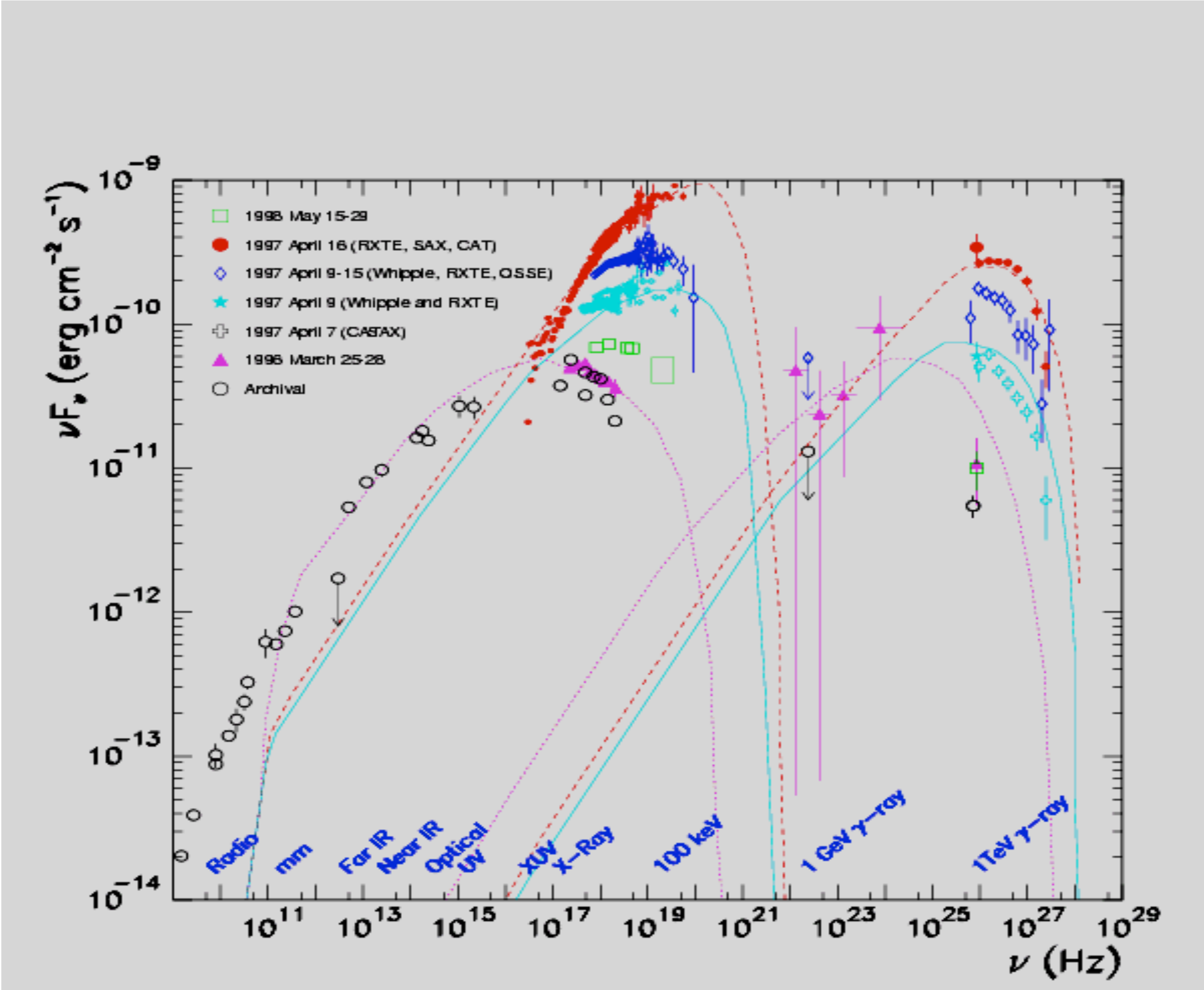
Albert et al. 2008

Crab PSR

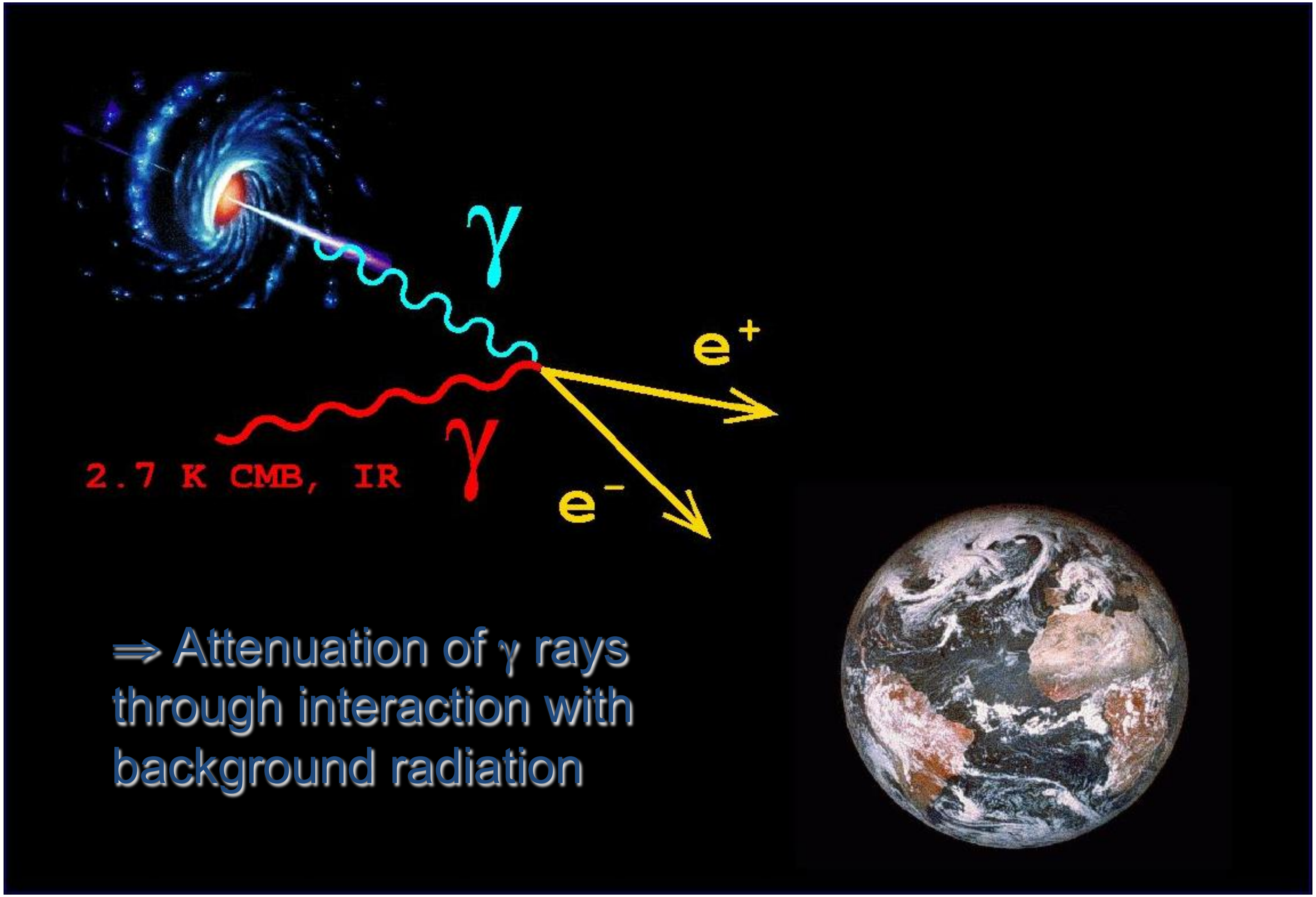


Ansoldi et al. (2016)

Active Galactic Nuclei



Photon Propagation Effects



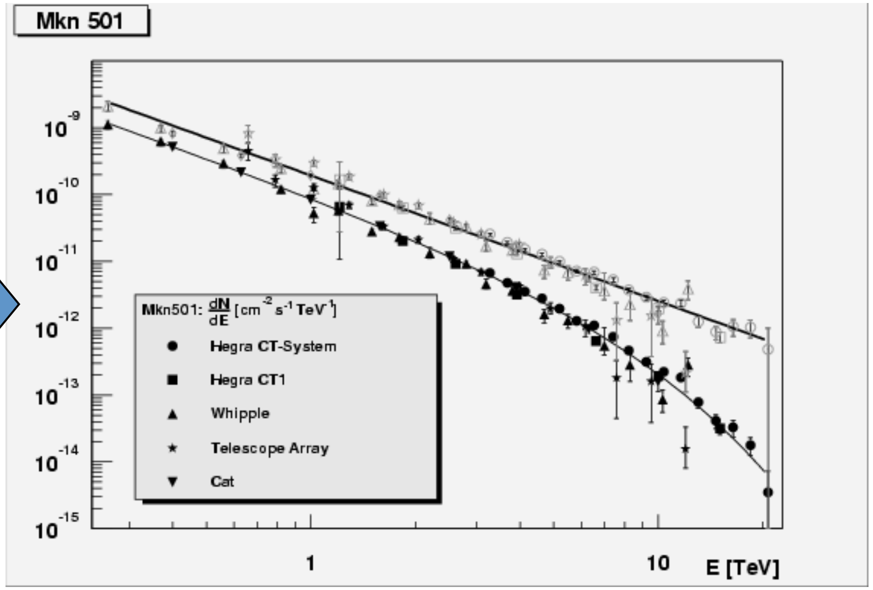
Gamma Ray Horizon

Any γ that crosses cosmological distances through the universe **interacts with the EBL**

$$\gamma_{HE}\,\gamma_{EBL} \rightarrow e^{+}\,e^{-} \quad \longrightarrow \quad E\varepsilon(1-\cos\theta) > 2\left(m_e c^2\right)^2$$

The absorption effect seen on a nearby blazar

Mkn 501 (z=0.034)

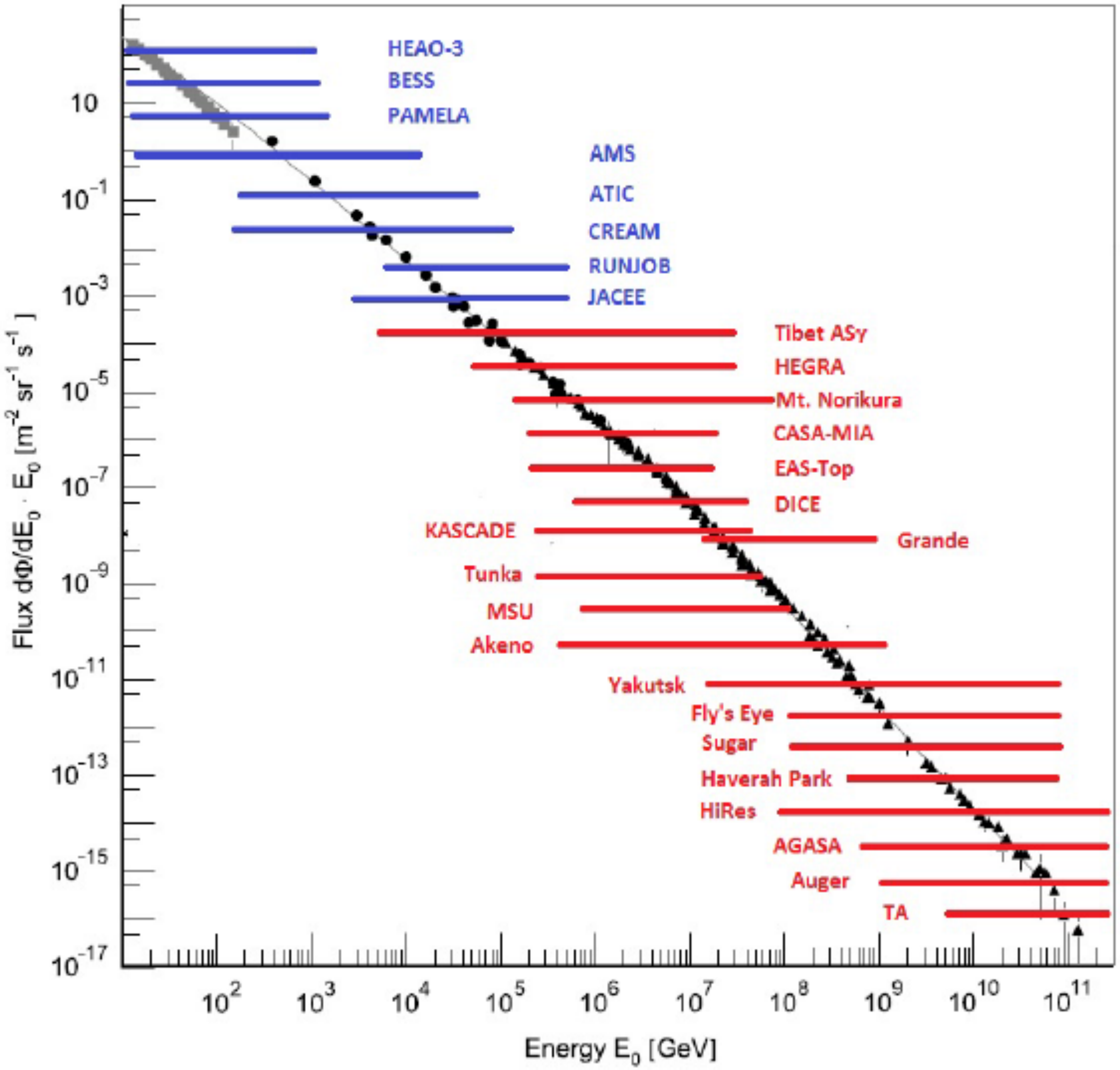


Astrofisica Nucleare e Subnucleare

UHECR

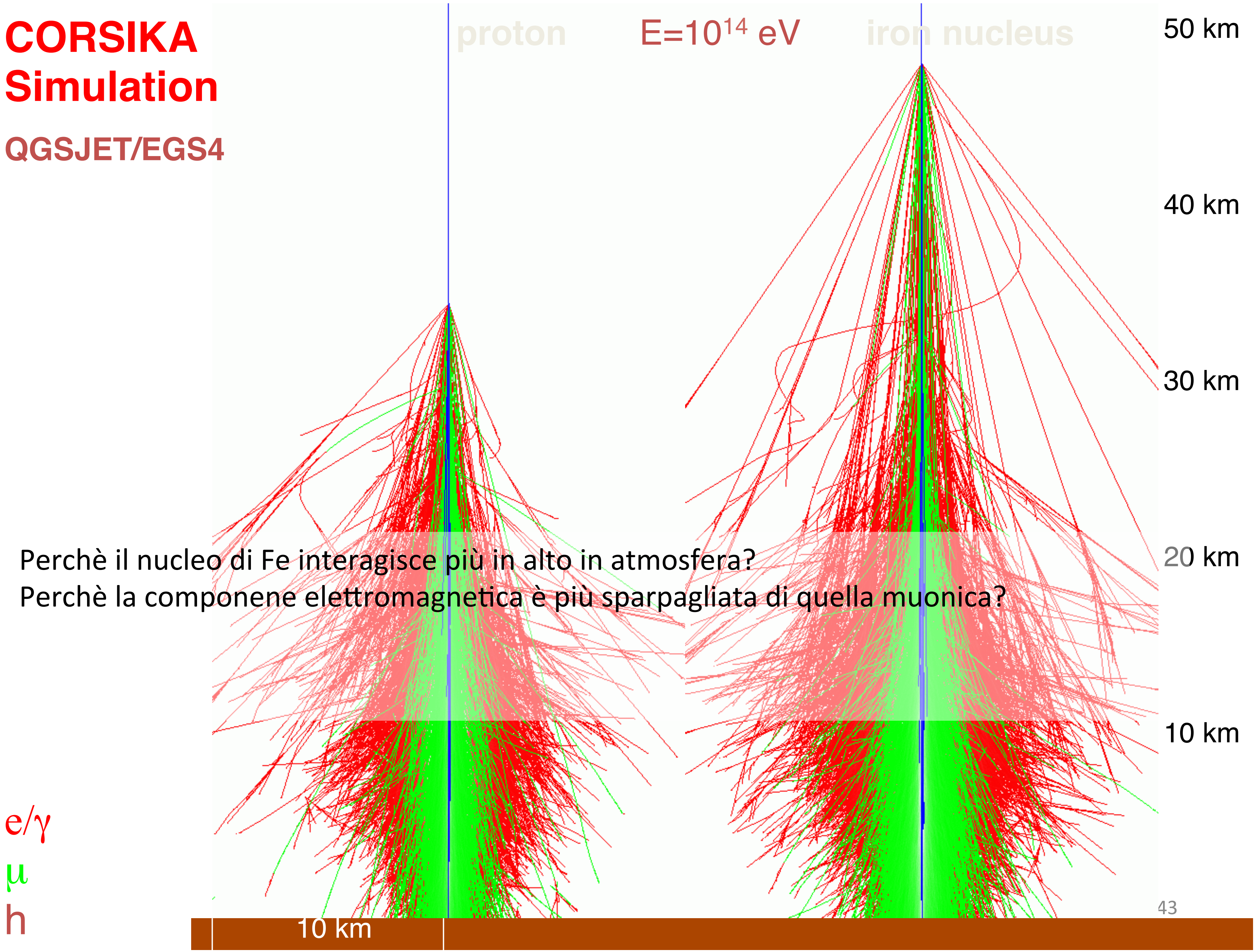
Metodi di misura dei raggi cosmici

Misure dirette
E<10^{14} eV
Misure indirette,
E>10^{14} eV



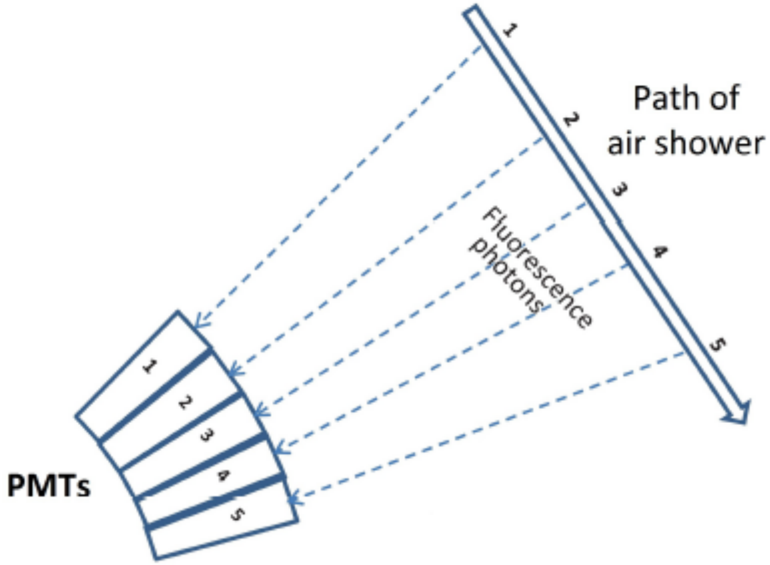
CORSIKA Simulation

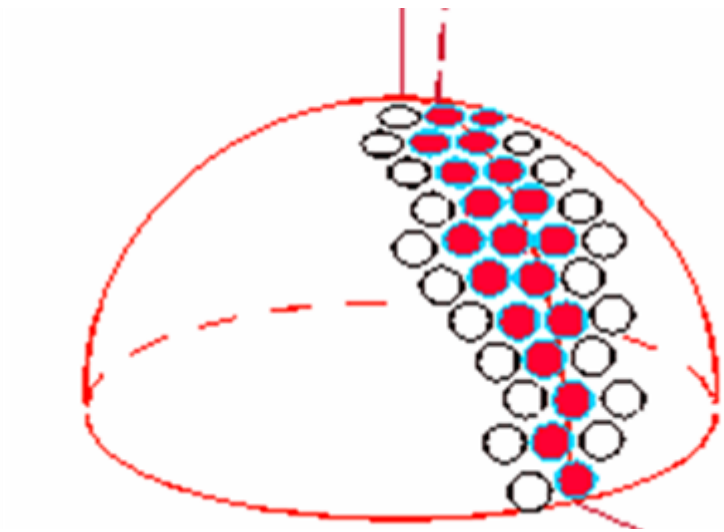
QGSJET/EGS4

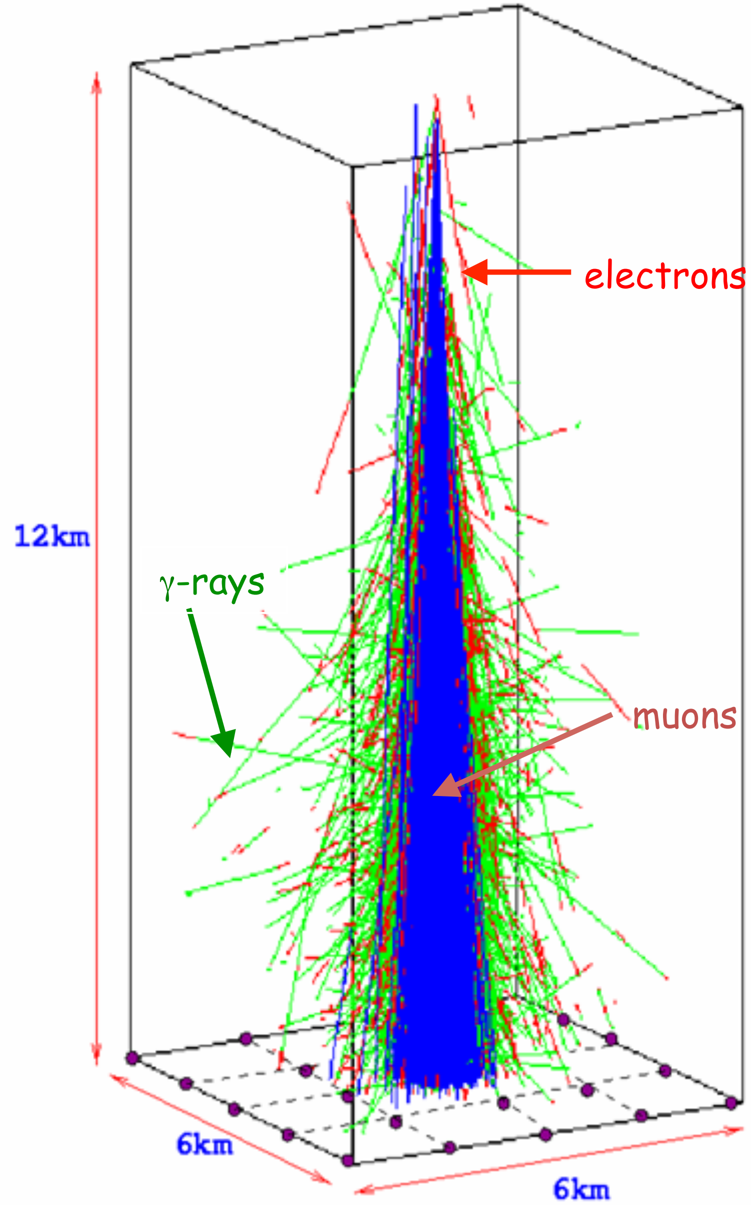


Perchè il nucleo di Fe interagisce più in alto in atmosfera?
Perchè la componene elettromagnetica è più sparpagliata di quella muonica?

Rivelatori di sciami di alta energia







AUGER: Un rivelatore ibrido

Rivelatore di sciami: 1600 taniche cilindriche (ciascuna di 10 m^2 ed alte 1.5 m) riempite di acqua, per rivelare gli sciami al suolo tramite la luce Cerenkov emessa dagli elettroni nell'acqua

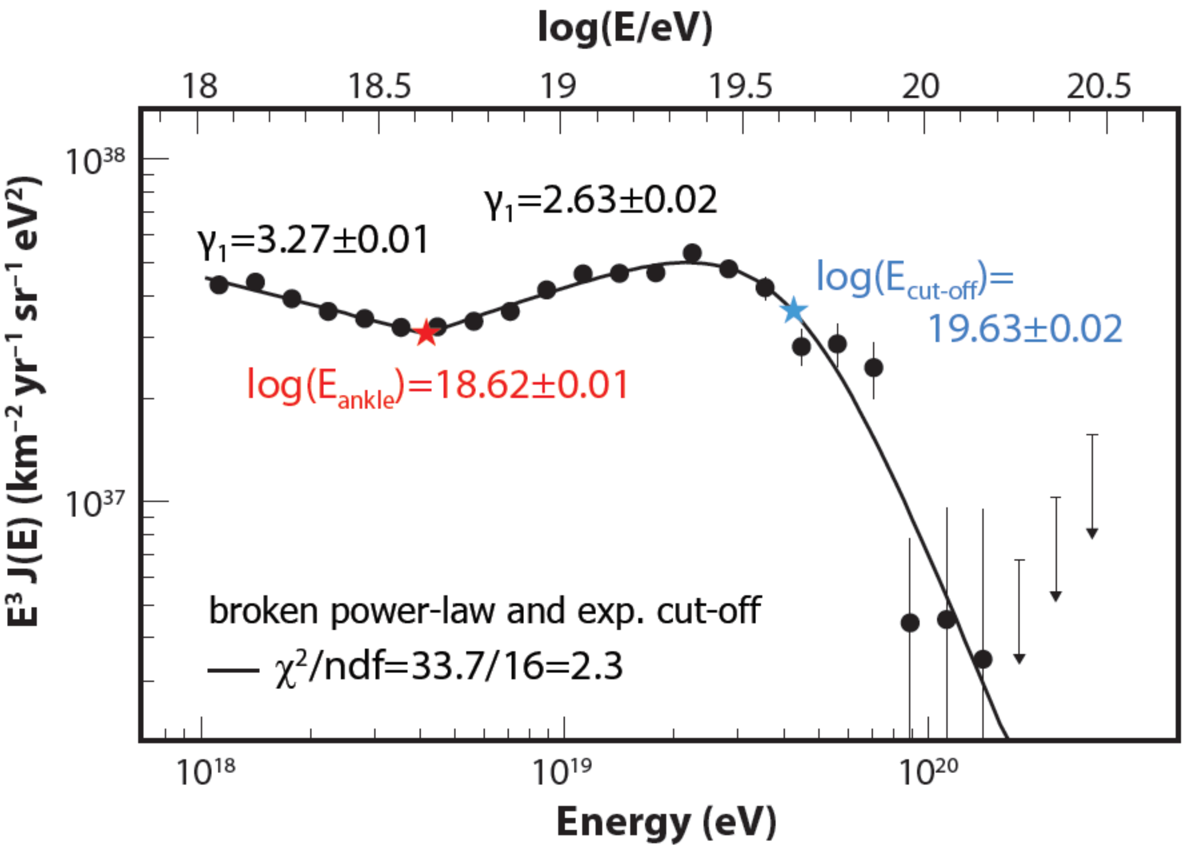
- Il rivelatore di sciami misura la distribuzione laterale e temporale dello sciame
- Distanza tra taniche: 1.5 km
- Area di forma esagonale, di 60×60 km^2
- Rivelatori di fluorescenza: 6 telescopi con ciascuno 4 "occhi" per determinare il profilo longitudinale dello sciame e l'altezza del suo massimo.

AUGER Energy spectrum

SD+Hybrid Combined Spectrum

#893: Salamida

#724: Dembinsky

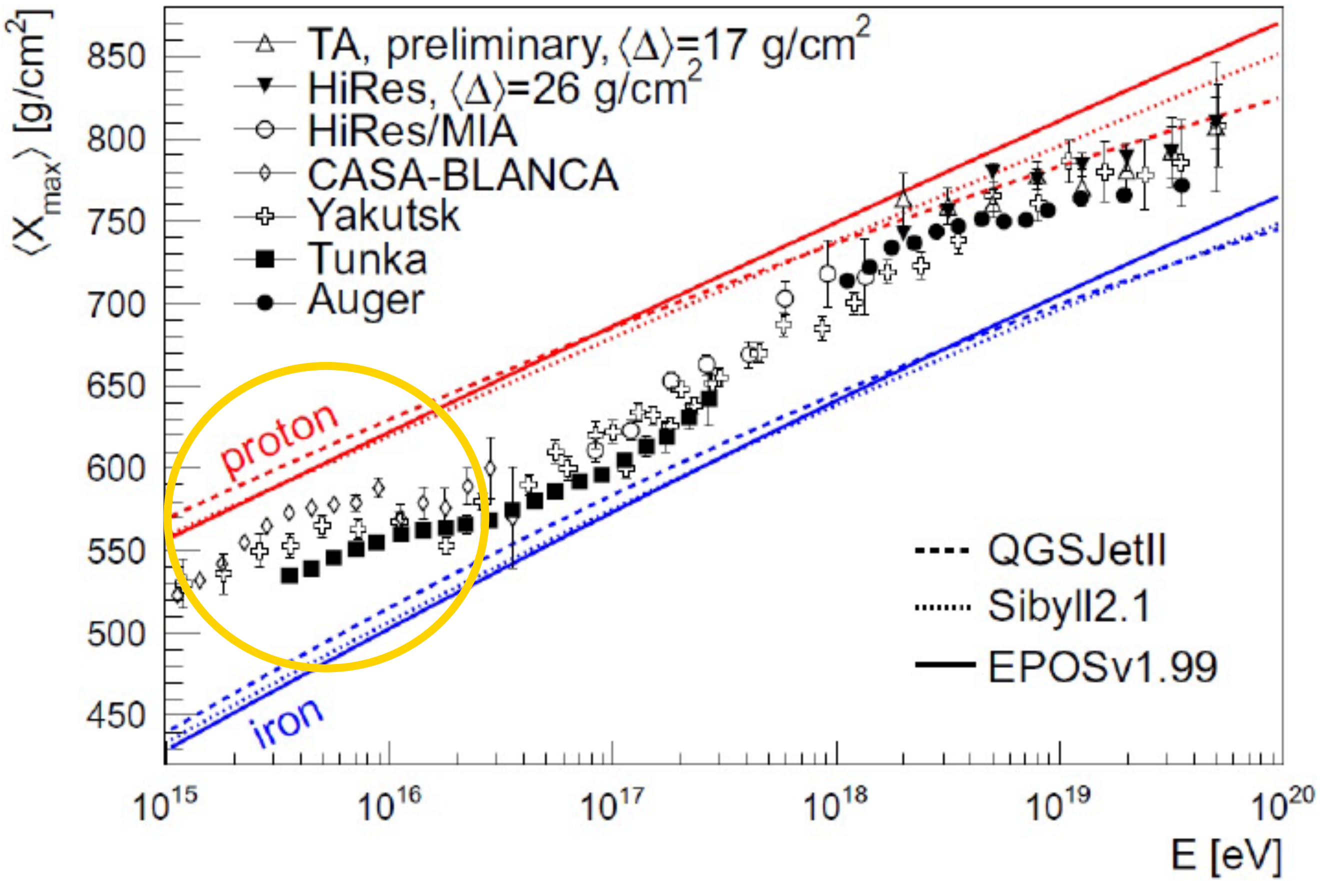


Exposure = 20905 km² sr yr (60% increase over PLB 685 (2010) 239)

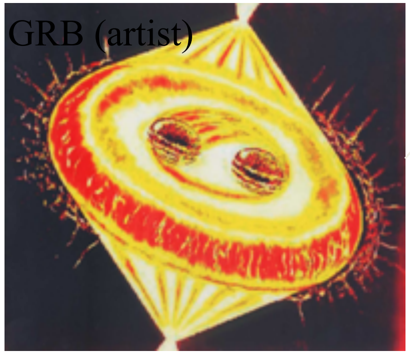
Inclined showers add another 5300 km² sr yr (→ #724)

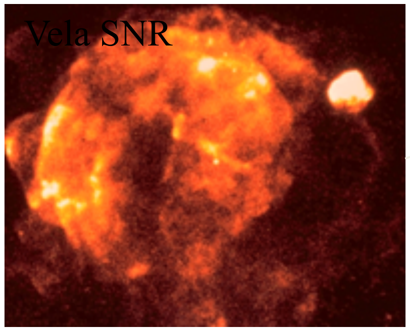
Composizione chimica dei RC nella regione degli EAS

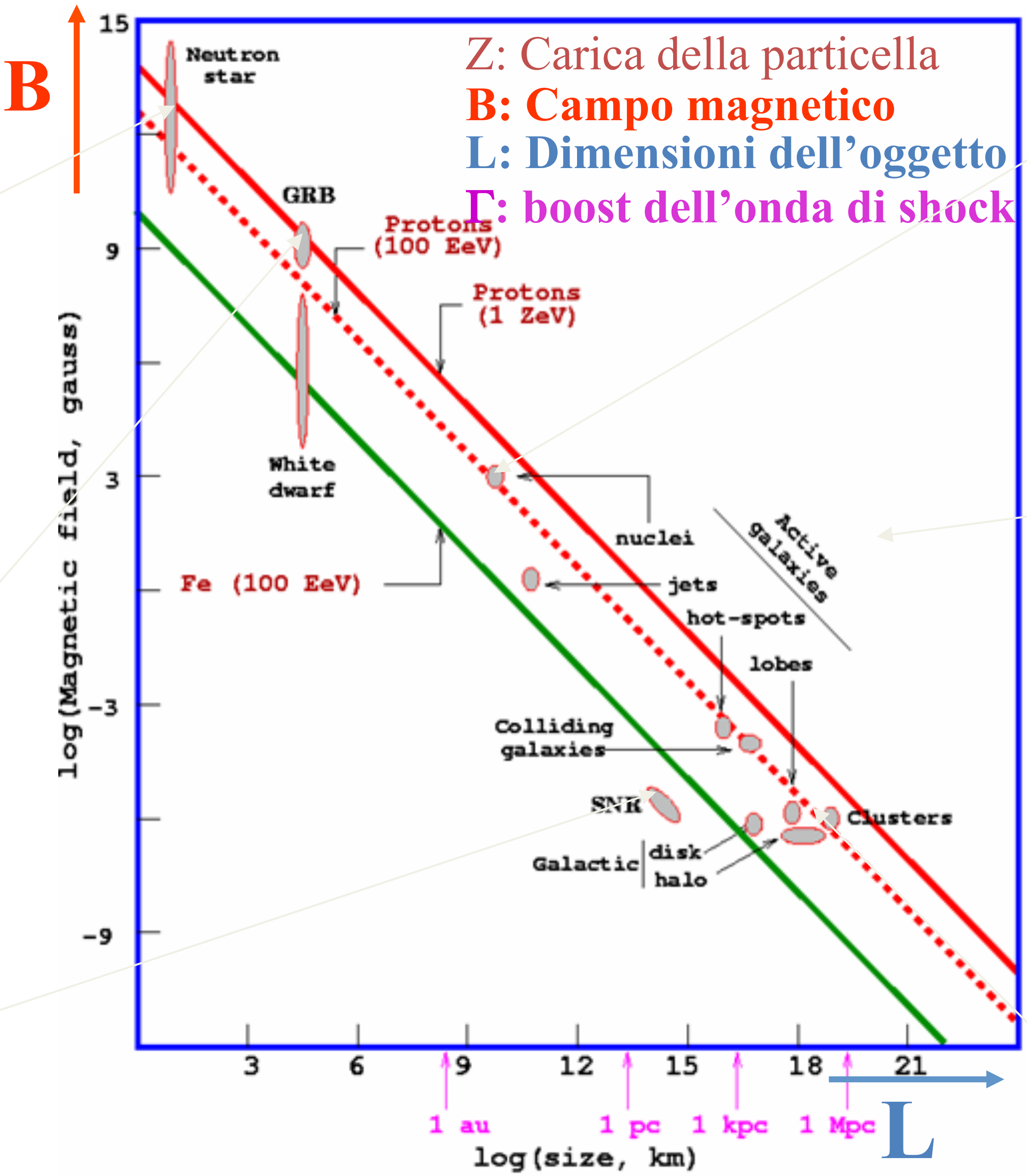
- Il modello del *leaky box* prevede un arricchimento di elementi pesanti nei RC sino al ginocchio.
- Gli EAS possono misurare <A> con difficoltà.
- Le misure possono essere poi confrontate con *modelli estremi* (solo p o Fe) via MC

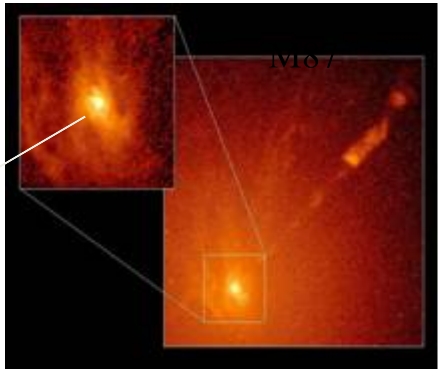


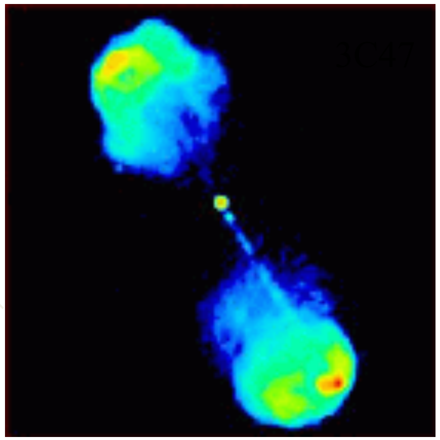
Possibili macchine acceleratrici







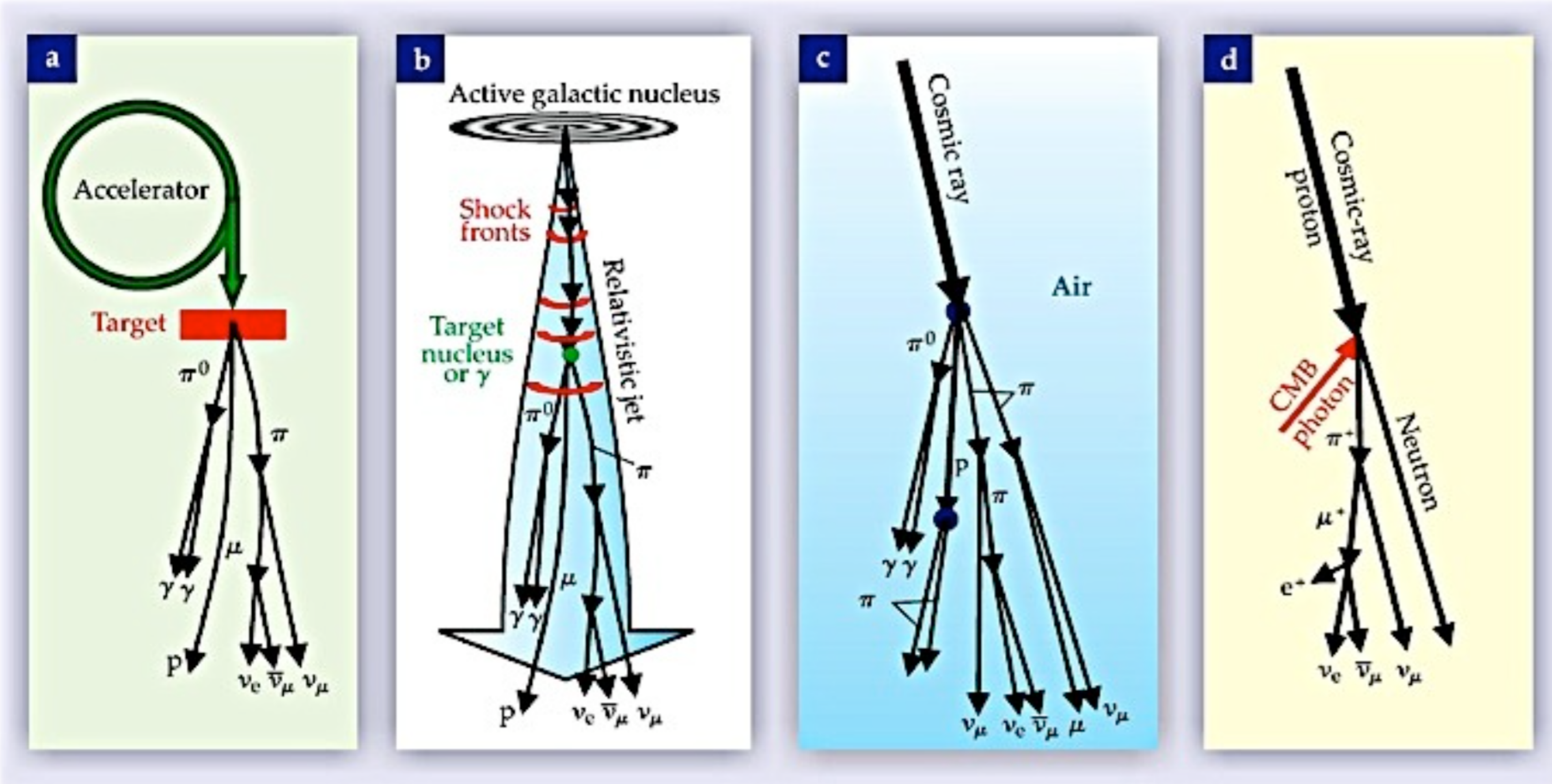




Astrofisica Nucleare e Subnucleare

Astrophysical Neutrinos

Summary of neutrino production modes



From Physics Today

THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

5160 PMTs

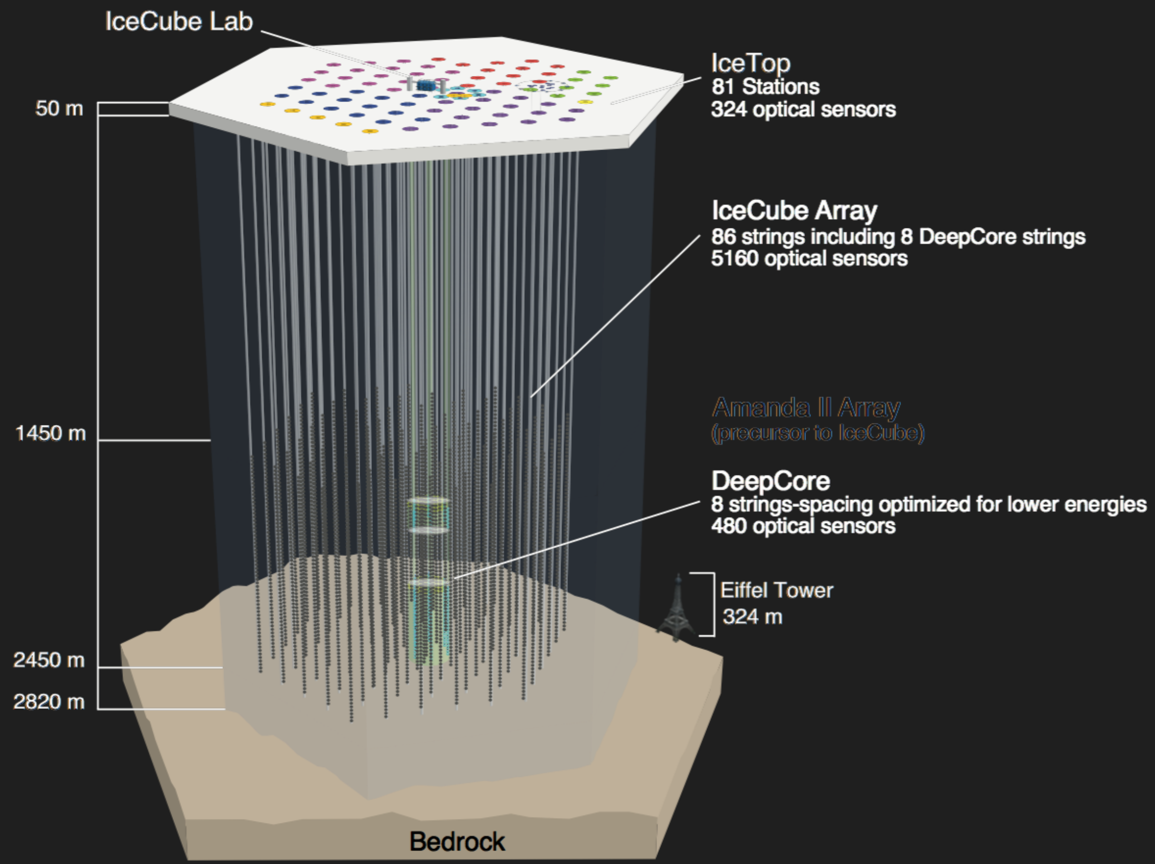
1 km³ volume

86 strings

17 m vertical spacing

125 m string spacing

Completed **2010**

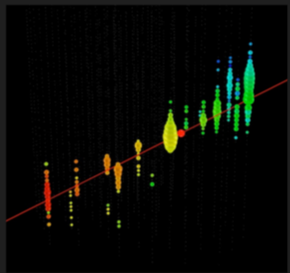


NEUTRINO EVENT SIGNATURES

Signatures of signal events

time

CC Muon Neutrino

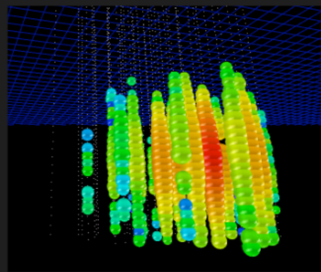


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino



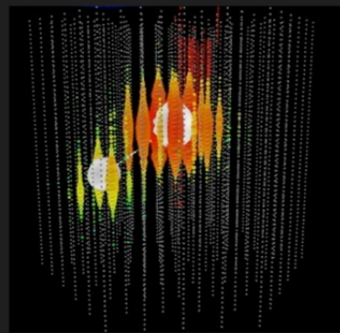
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

CC Tau Neutrino

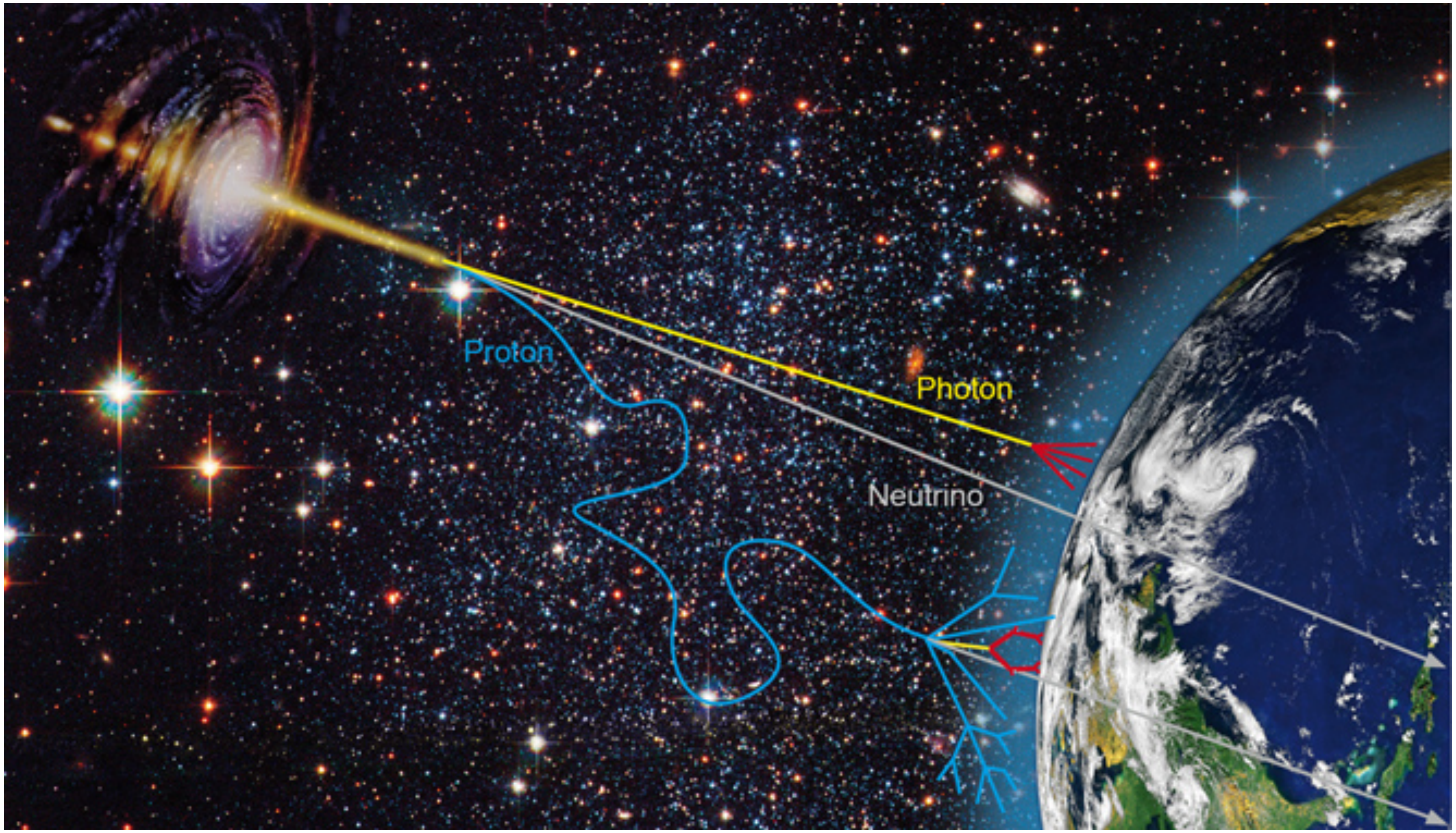


$$\nu_\tau + N \rightarrow \tau + X$$

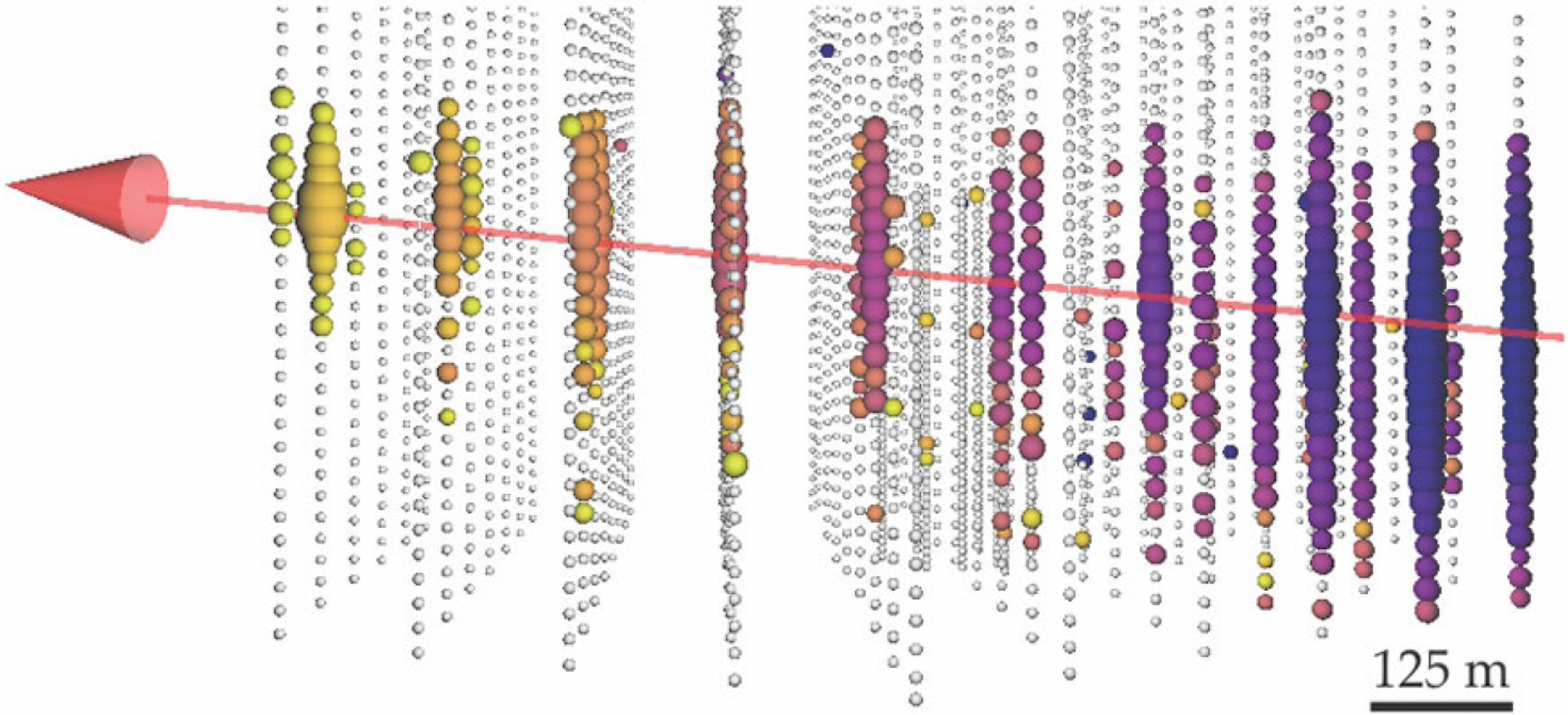
"double-bang" (≳10PeV) and other signatures (simulation)

(not observed yet: τ decay length is 50 m/PeV)

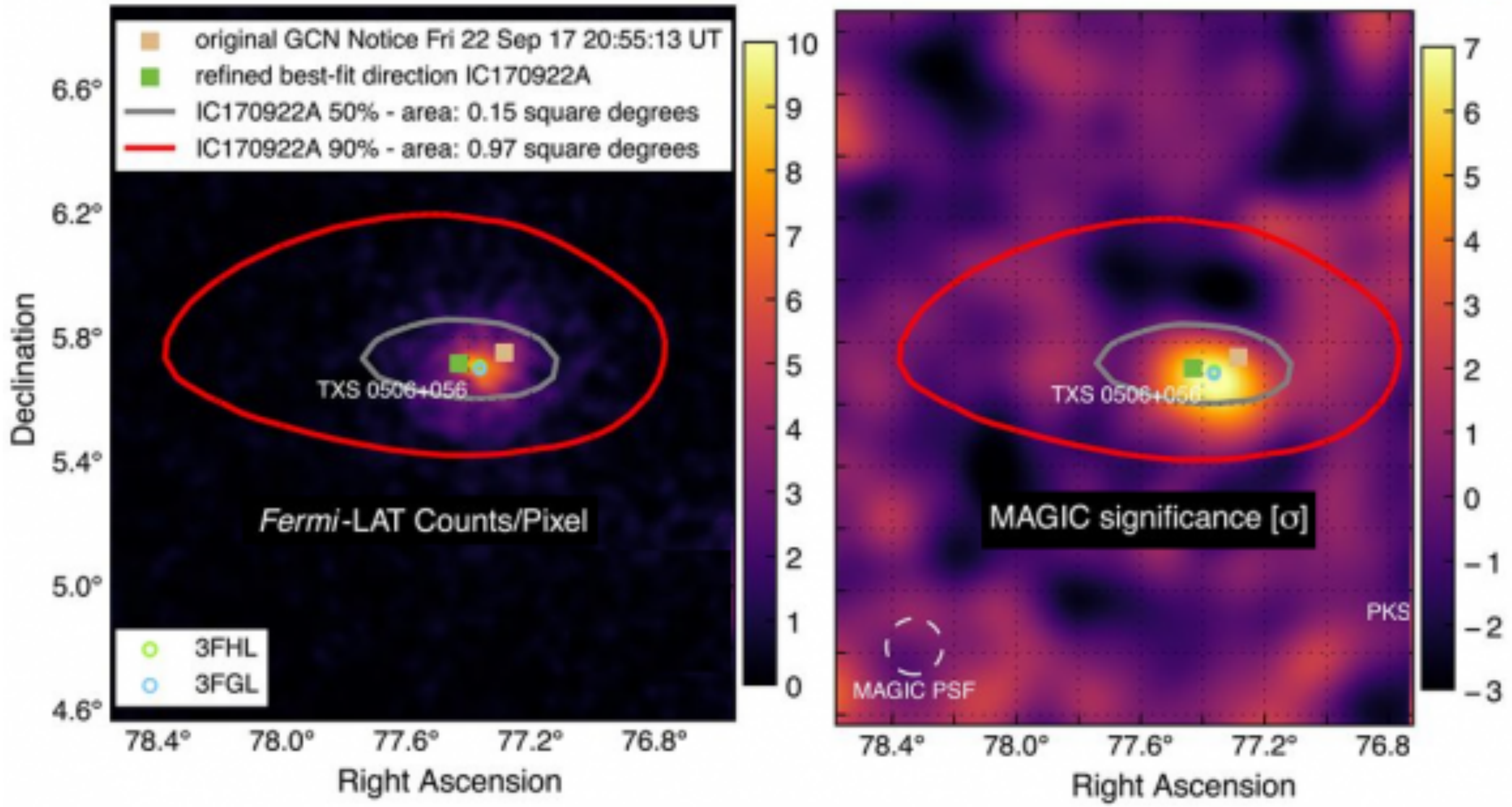
Astrophysical Neutrinos



“The” neutrino …

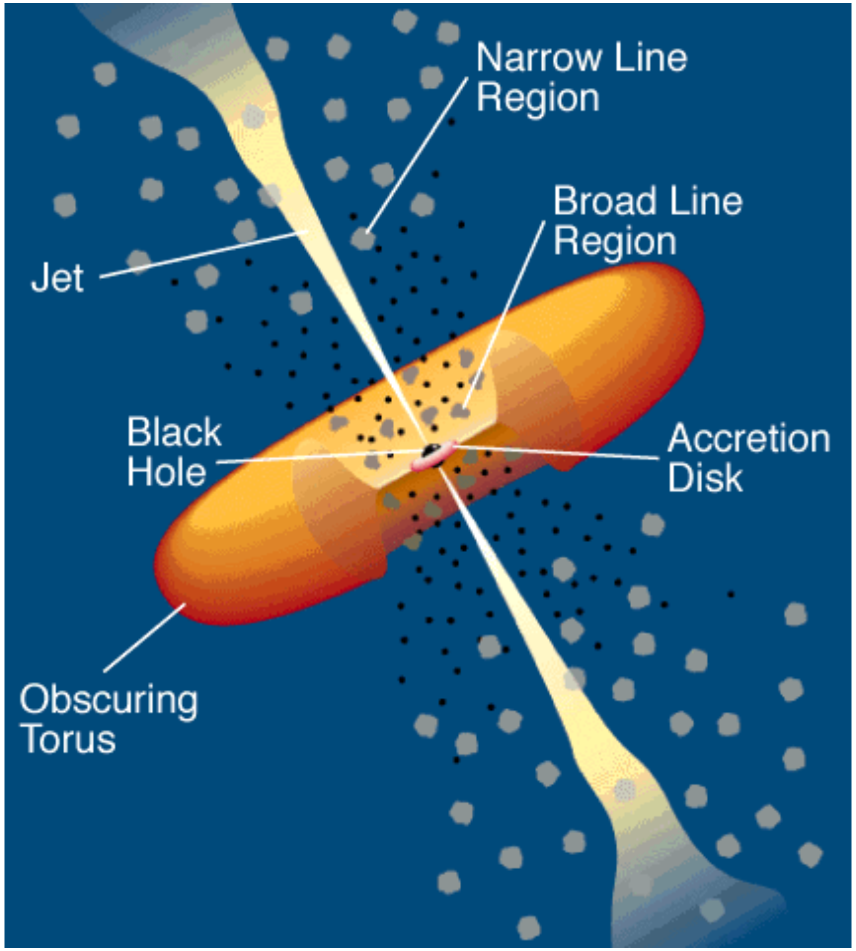


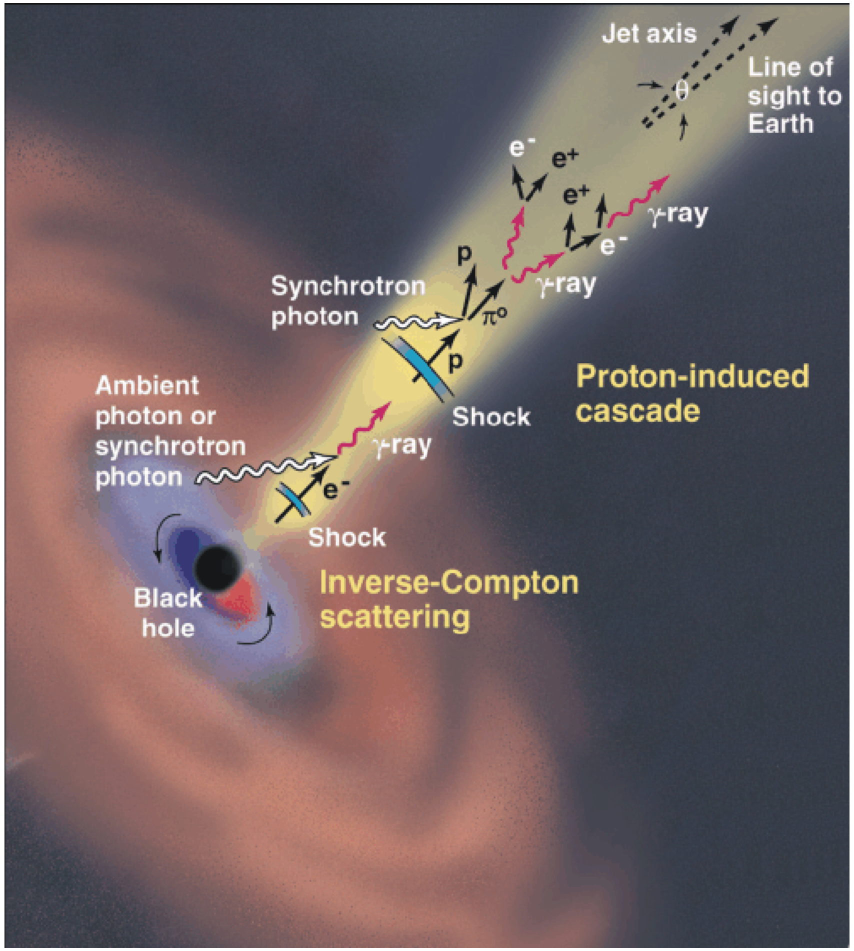
TXS 0506+056



original GCN Notice Fri 22 Sep 17 20:55:13 UT
refined best-fit direction IC170922A
IC170922A 50% - area: 0.15 square degrees
IC170922A 90% - area: 0.97 square degrees
6.6°
6.2°
5.8°
5.4°
5.0°
4.6°
Declination
TXS 0506+056
Fermi-LAT Counts/Pixel
3FHL
3FGL
78.4°
78.0°
77.6°
77.2°
76.8°
Right Ascension
10
9
8
7
6
5
4
3
2
1
0
TXS 0506+056
MAGIC significance [σ]
MAGIC PSF
PKS
78.4°
78.0°
77.6°
77.2°
76.8°
Right Ascension
7
6
5
4
3
2
1
0
−1
−2
−3

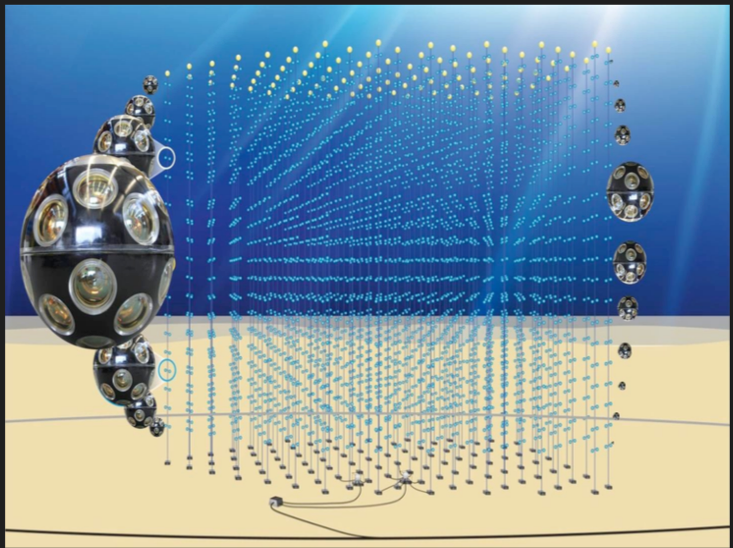
AGN model


Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus

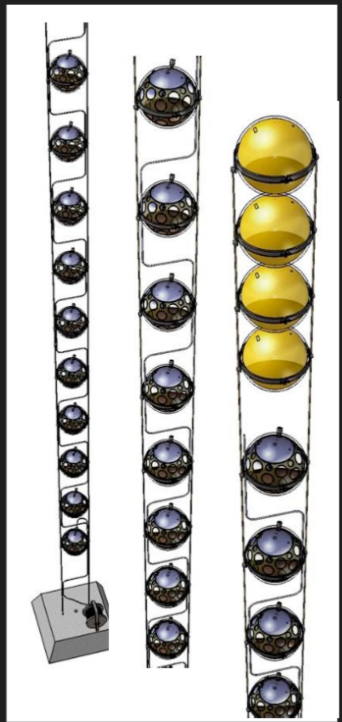

Jet axis
Line of sight to Earth
θ
e-
e+
e+
γ-ray
p
e-
γ-ray
Synchrotron photon
π°
p
Proton-induced cascade
Shock
Ambient photon or synchrotron photon
γ-ray
e-
Shock
Black hole
Inverse-Compton scattering

THE KM3NET NEUTRINO TELESCOPE

Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in "building blocks", started construction



KM3NeT "building block"



string with OMs

Multi-PMT digital optical module ("DOM")