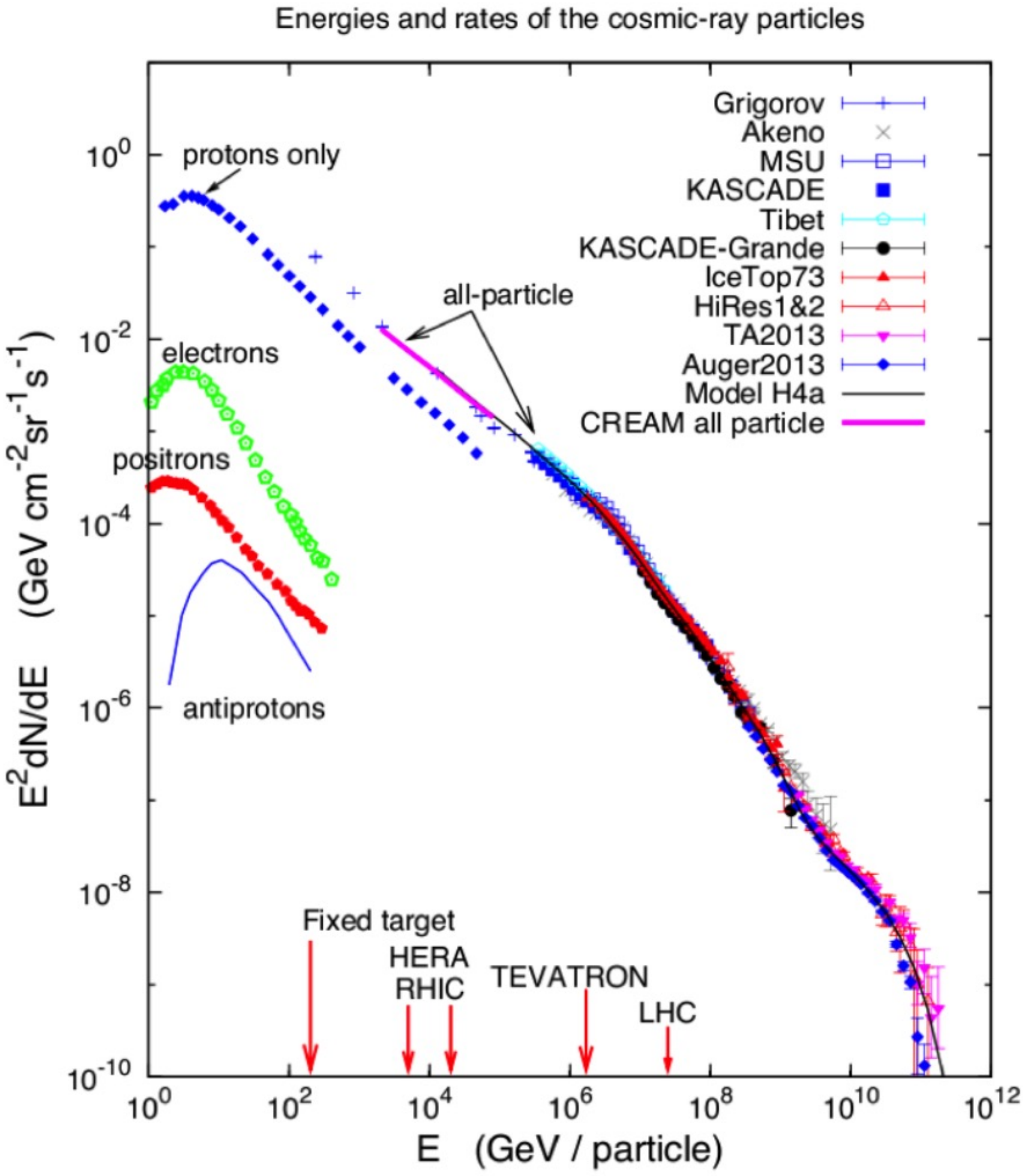
High Energy Neutrino Astrophysics– A. A. 2020-21

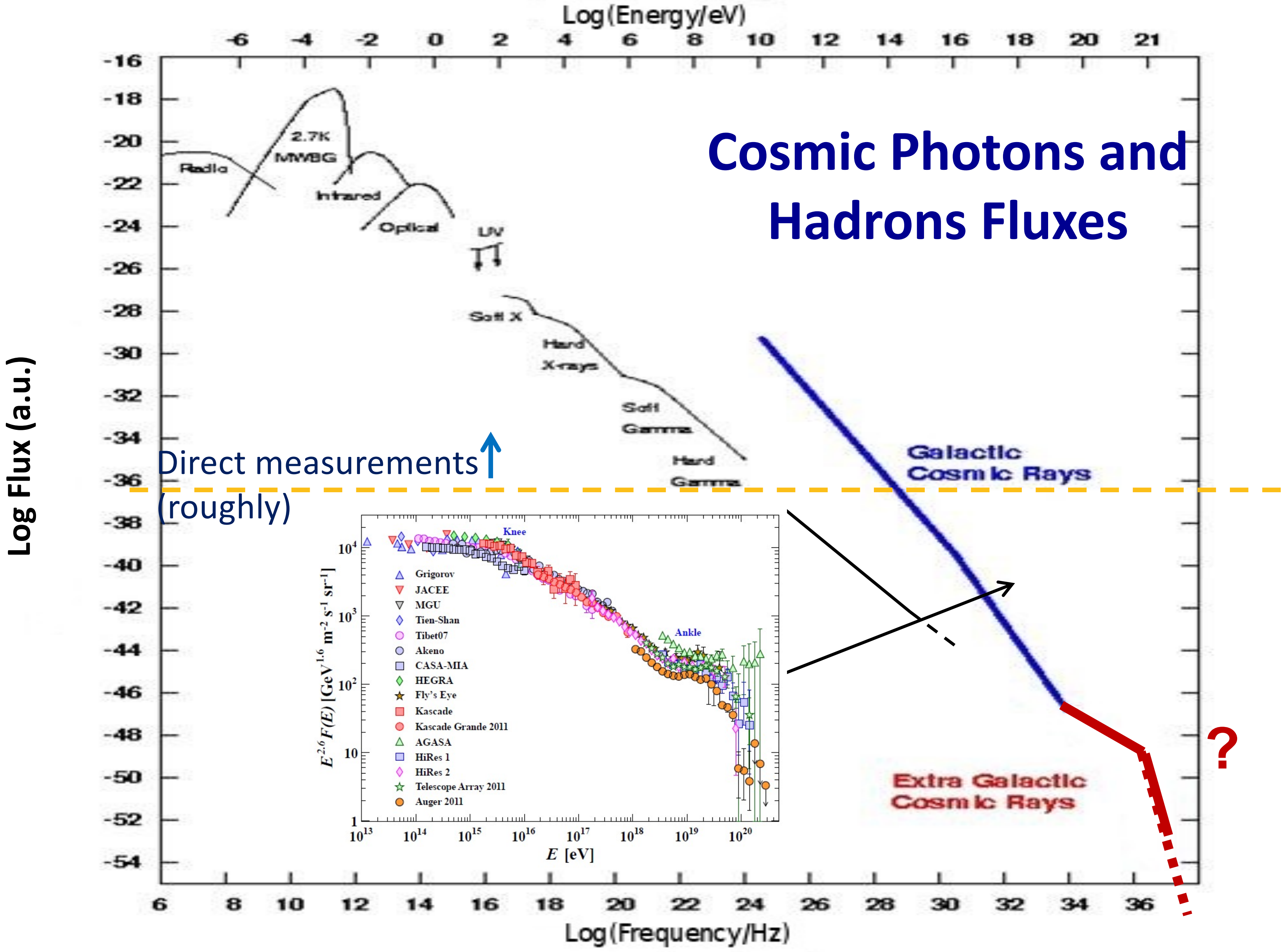
Lessons 5 and 6

- Measurement of the C.R. electromagnetic component: primary photons and electrons: how to detect photons and electrons ?
- Detection of primary cosmic rays with E < few 100 GeV.
- ”FERMI”: the detector and the obtained results.
- The Alpha Magnetic Spectrometer (AMS) detector on the International Space Station: experimental capabilities, resolutions, results obtained for: fraction $e^+/(e^+ + e^-)$ and antiproton/proton ratio.
- Indirect detection of photons with 50 GeV < E_g < 100 TeV.
- Characteristics of Extensive Atmospheric Showers (EAS), measurable quantities (energy, nature and direction of the primary, X_{max}, etc.) with detectors "at ground".
- Detection of EAS: detection of the Cherenkov and "fluorescence" radiations.
- Cherenkov Telescopes, basic working principle and characteristics: "effective area", angular and energy resolutions, threshold in energy, sensitivity.
- "Cherenkov Imaging” telescopes: the mono and stereo images of the EAS.
- Detection of VHE g induced events: the background due to charged C.R. events, the signal-background separation.
- HEGRA, MAGIC, HESS, Veritas: detectors and main results

Let's recall …


Energies and rates of the cosmic-ray particles
Grigorov
Akeno
MSU
KASCADE
Tibet
KASCADE-Grande
IceTop73
HiRes1&2
TA2013
Auger2013
Model H4a
CREAM all particle
protons only
all-particle
electrons
positrons
antiprotons
Fixed target
HERA
RHIC
TEVATRON
LHC
$E^2 dN/dE$ (GeV cm^{-2}sr^{-1}s^{-1})
E (GeV / particle)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}

Photons are also present in C.R.



Cosmic Photons and Hadrons Fluxes

Direct measurements (roughly)

INTErnational Gamma-Ray Astrophysics Laboratory

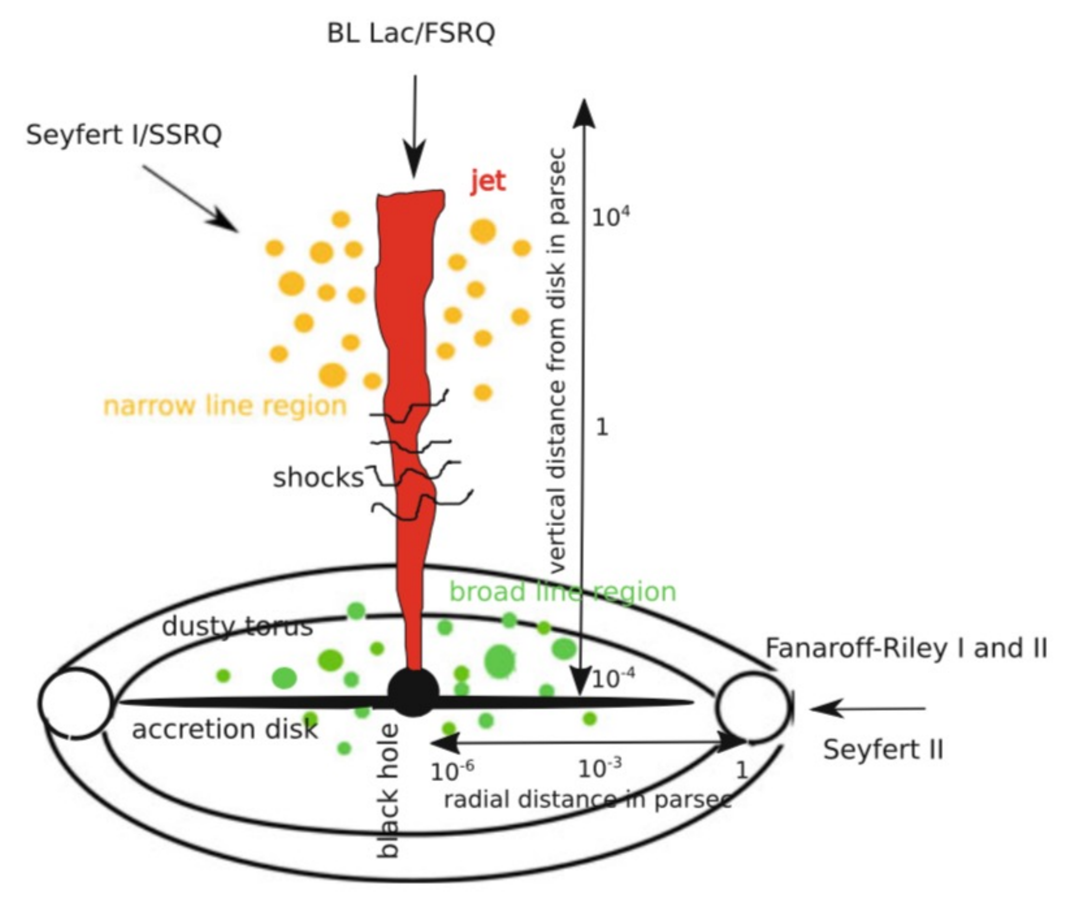
From BeppoSAX increasing the energy range in the last 20 years → XMM → INTEGRAL → AGILE → and near future ATHENA and CTA to exploit high energy gamma ray science

Italy-Europe has a four decades worldwide record of success in the field of high energy astrophysics

Astrophysical gamma rays sources

The extragalactic high energy sources most relevant for us are active galactic nuclei (AGNs) and Gamma Ray Bursts (GRBs). All AGNs are believed to be powered by a supermassive black hole at the center of a galaxy. The supermassive black hole will accrete gas in a disk-like configuration.

Sketch of the typical geometry of an AGN on a logarithmic length scale. Depending on the viewing direction, the AGN appears as a BL Lac object or flat spectrum radio quasar (FSRQ), a Seyfert-I galaxy or steep spectrum radio quasar (SSRQ), or as an high luminosity Faranoff Riley-II (FR-II) galaxy, a low luminosity Faranoff Riley-I (FR-I) galaxy or a Seyfert-II galaxy, respectively, as indicated.

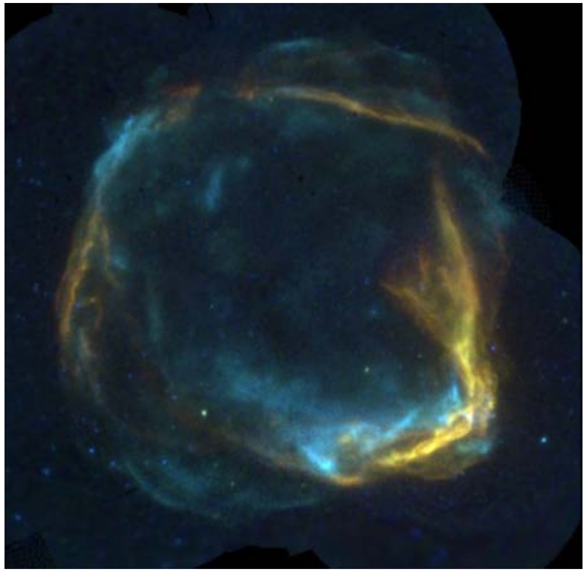


Perpendicular to the accretion disk two jets are emitted that consist of relativistic matter and magnetic fields and whose formation is probably related to MHD effects. Immersed in these jets are shocks that form knots and hot spots in which particles can be accelerated to very high energies. Particle acceleration can also occur in the immediate environment of the supermassive black hole but due to the intense radiation fields there the maximal energies achieved are expected to be lower.

Cosmic Accelerators: Supernova Remnants

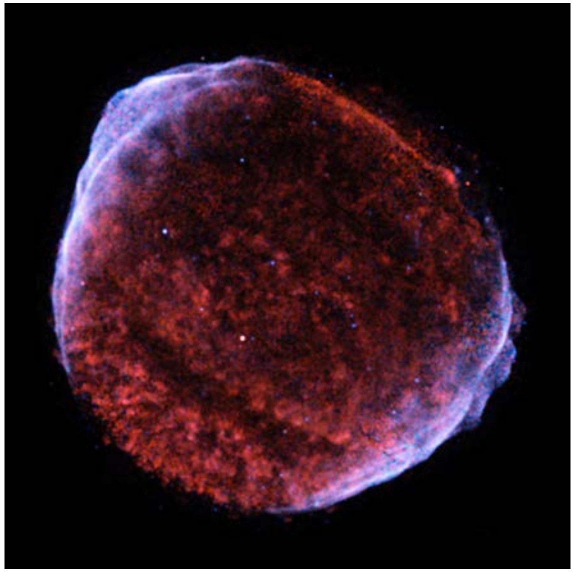
Credit: NASA

Cosmic Accelerators: Supernova Remnants



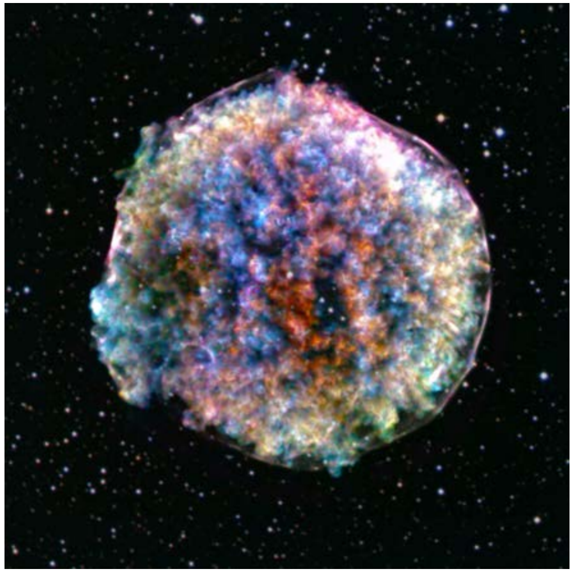
RCW 86 – X rays signals

Associated to 185 AD explosion, distance 7500 l.y.; diameter 90 l.y.



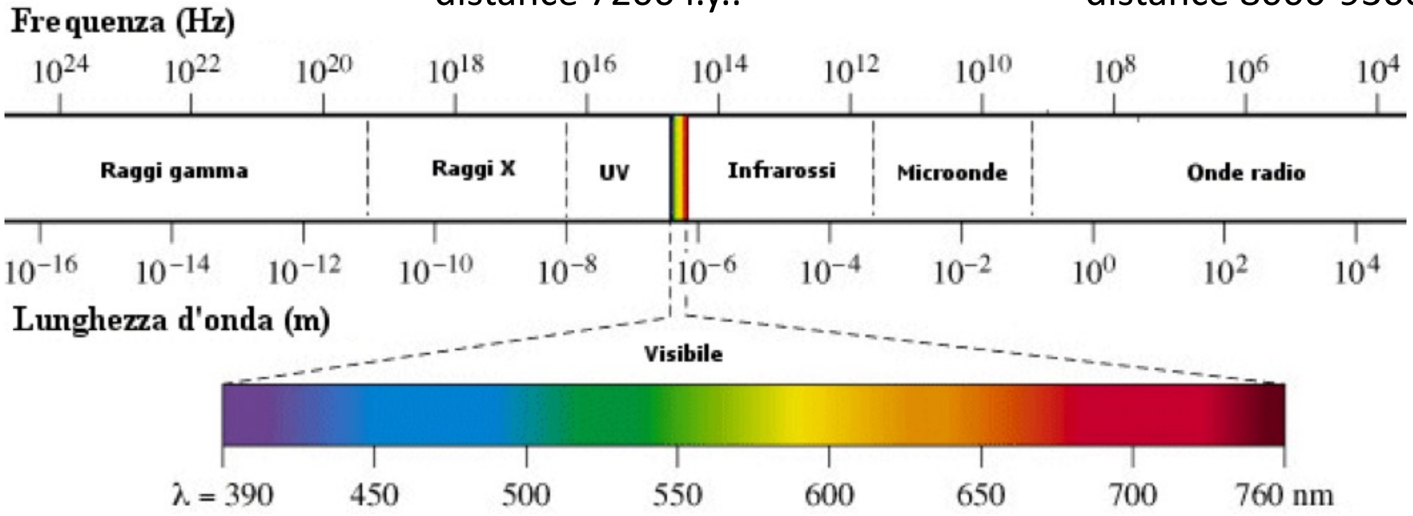
SN 1006 – X rays (blu), radio (red), visible (yellow)

Associated to 1006 AD explosion, distance 7200 l.y..

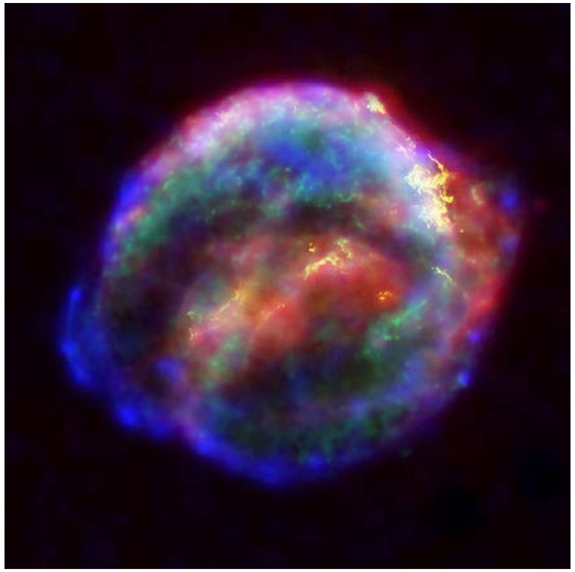


Tycho 86 – X rays (blu) radio (red), visible (yellow)

Associated to 1572 AD explosion, distance 8000-9300 l.y.

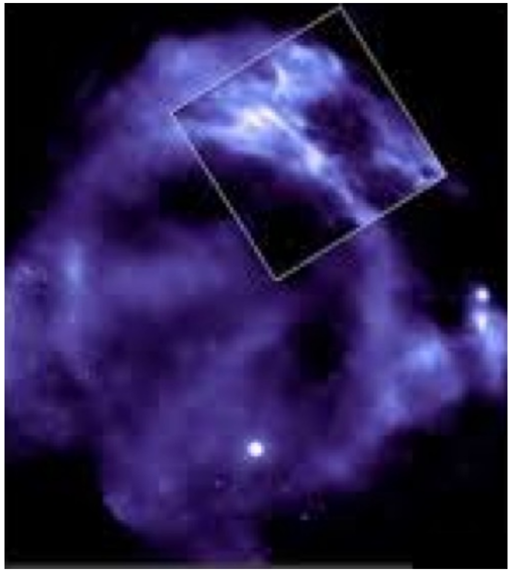


Cosmic Accelerators: Supernova Remnants

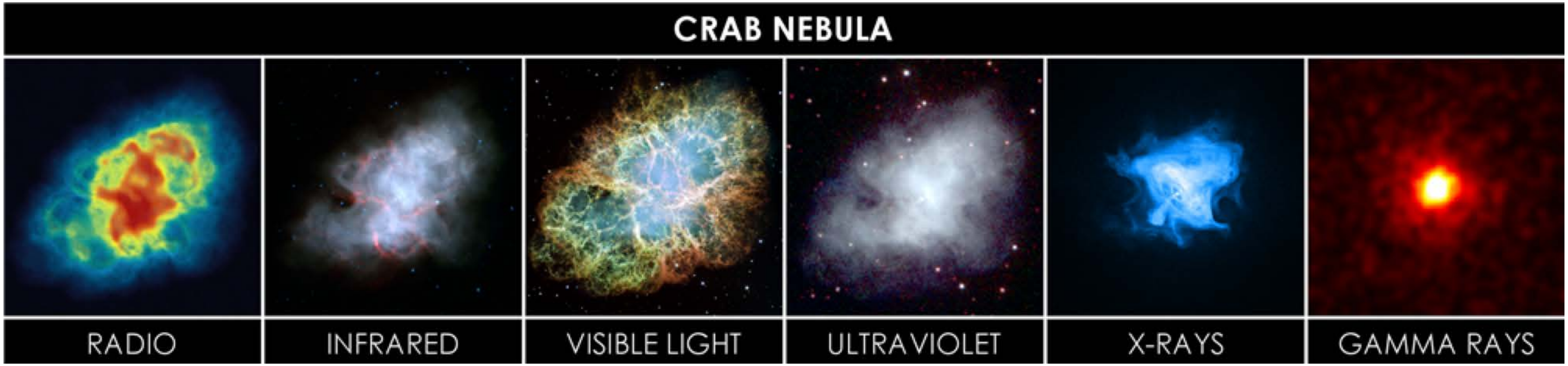


Kepler – X rays (blu), infra-red (red), visible (yellow)
Associated to 1604 AD explosion, distance 20000 l.y.

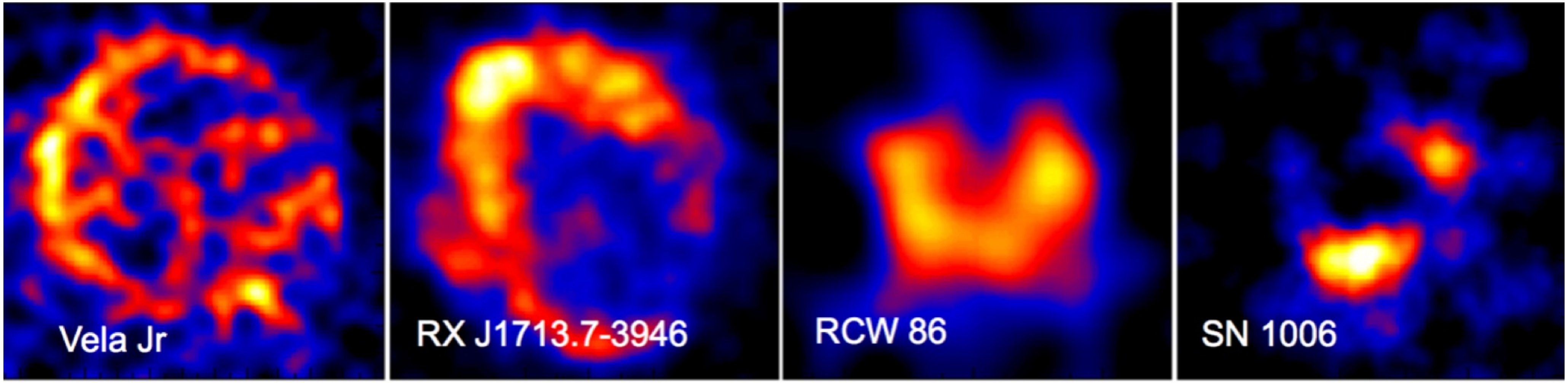
CasA 1006 – X rays (blu), radio (red), visible (yellow)
Probably associated to 344 AD explosion, distance 11000 l.y..



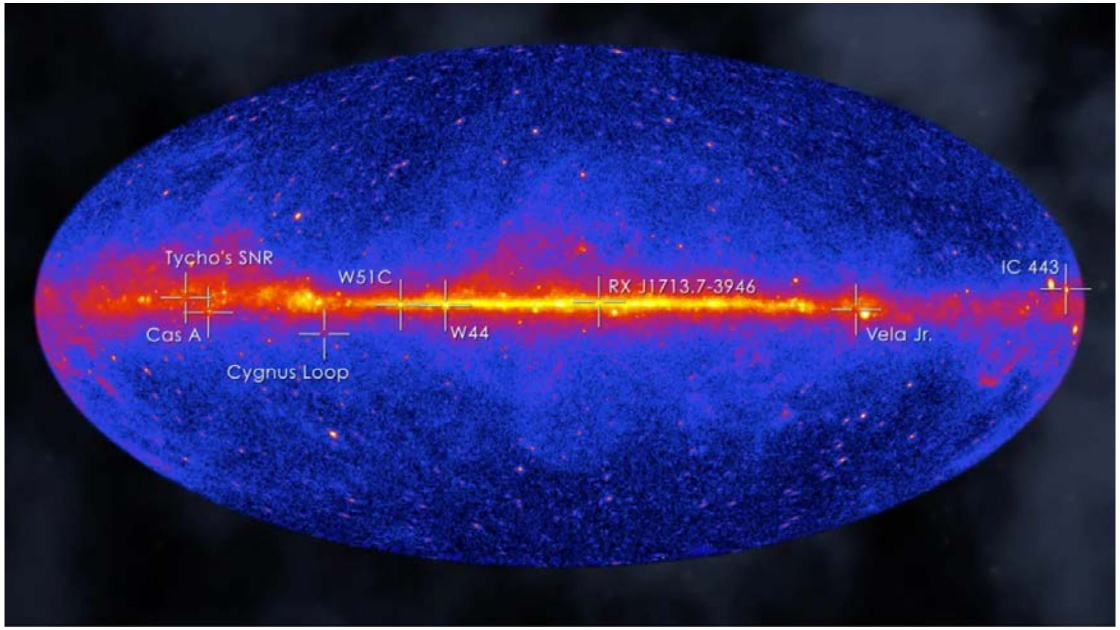
RXJ1713.7-3946 – X rays
probably ssociated to 393 AD explosion, distance 4200 l.y.



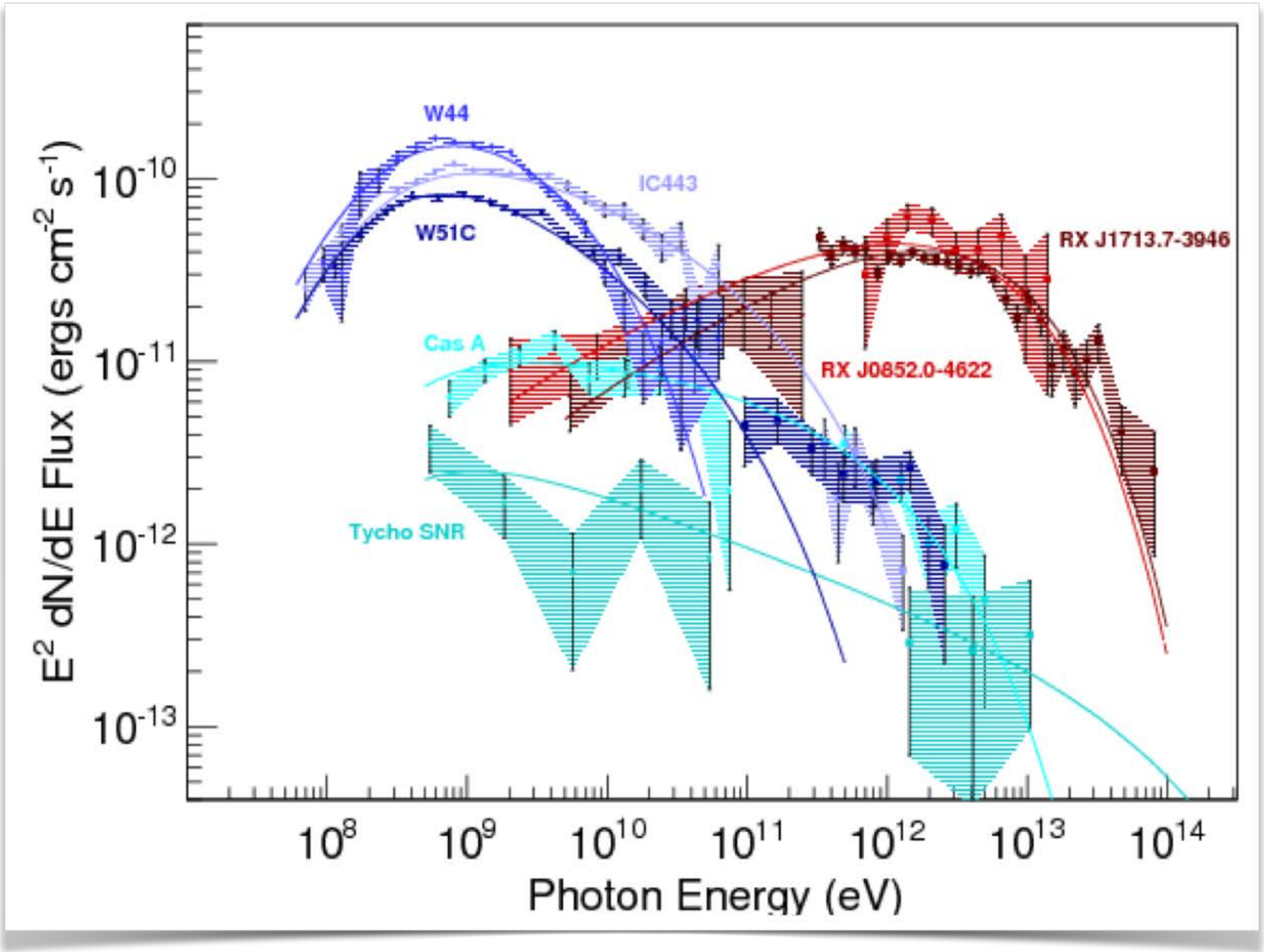
Cosmic Accelerators: Supernova Remnants



Several S.N.R. observed with gamma rays !!!



Gamma rays from SNRs



Temporal evolution of sources

Middle-aged SNRs (20000 yrs)

- hadronic emission
- steep spectra
- E_{max} < 1 TeV

Young SNRs (2000 yrs)

- hadronic/leptonic ?
- hard spectra
- E_{max} = 10 - 100 TeV

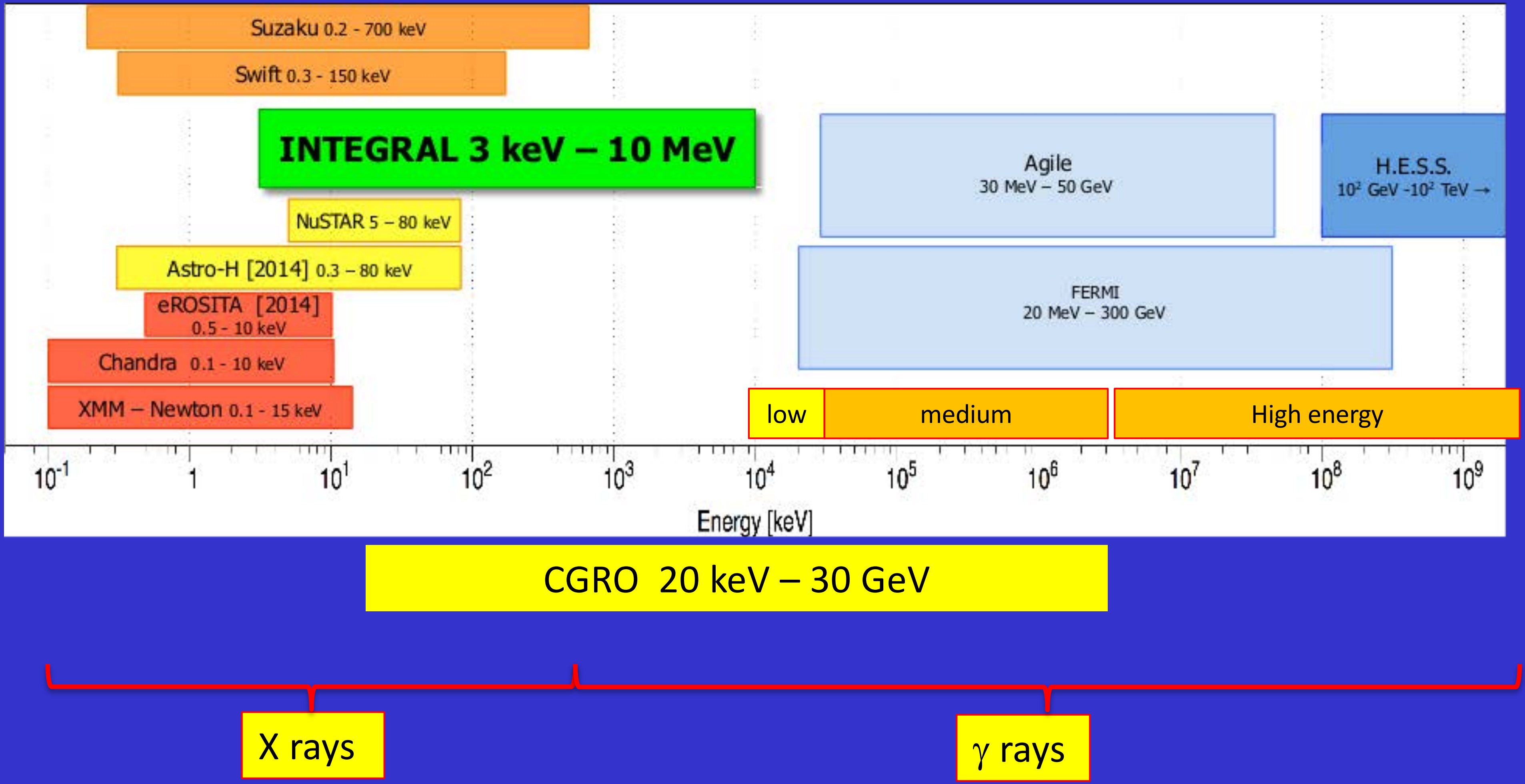
Very young SNRs (300 yrs)

- hadronic ?
- steep spectra $E^{-2.3}$
- E_{max} = 10 - 100 TeV

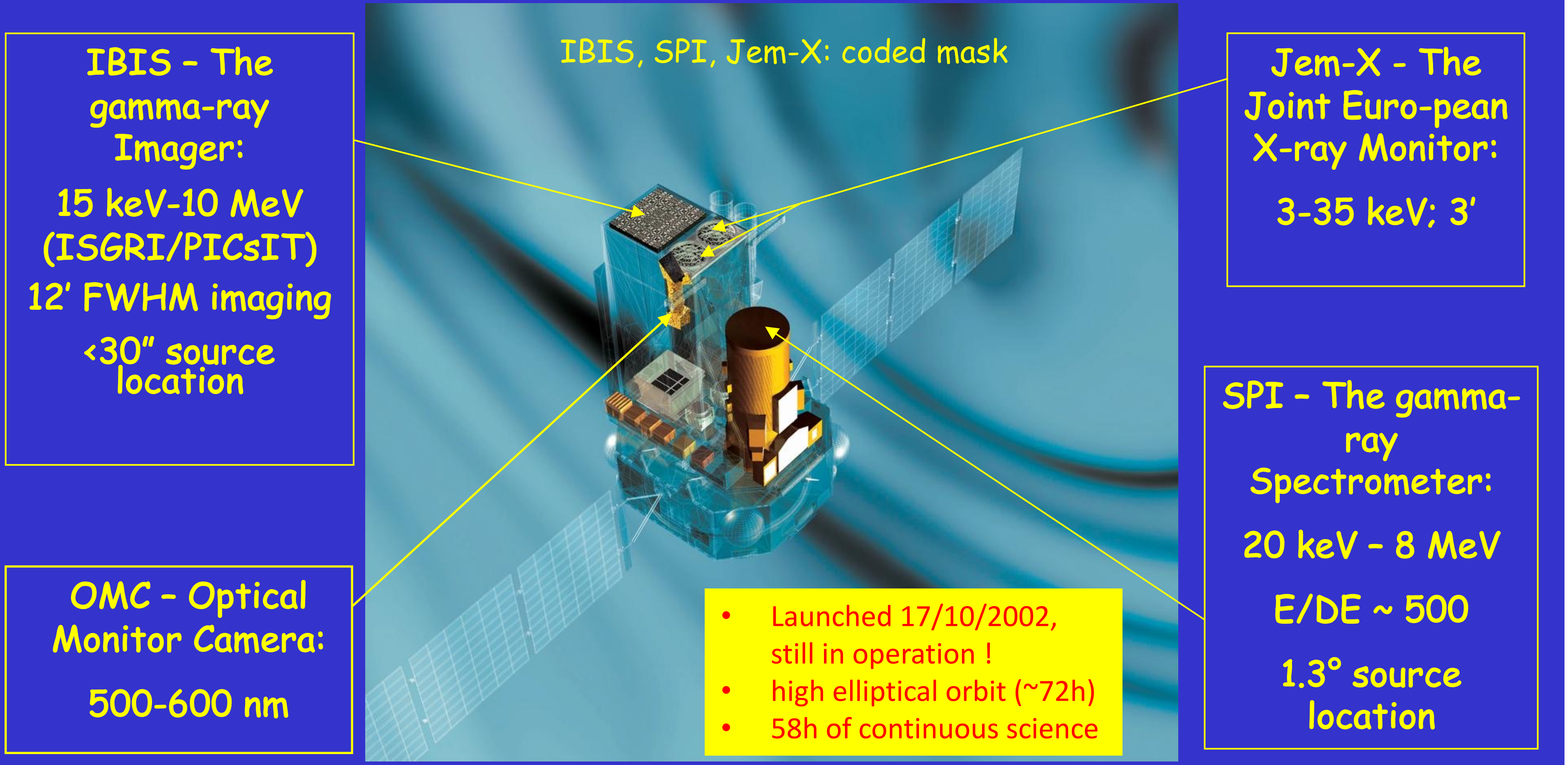
Searching for astrophysical EM radiation

Soft X-ray to high-energy gamma-ray observatories in operation

The list below is not complete !!!



The **INTEGRAL** Gamma Ray Observatory



IBIS, SPI, Jem-X: coded mask

IBIS – The gamma-ray Imager:

15 keV-10 MeV (ISGRI/PICsIT)

12′ FWHM imaging

<30″ source location

OMC – Optical Monitor Camera:

500-600 nm

Jem-X - The Joint Euro-pean X-ray Monitor:

3-35 keV; 3′

SPI – The gamma-ray Spectrometer:

20 keV – 8 MeV

E/DE ~ 500

1.3° source location

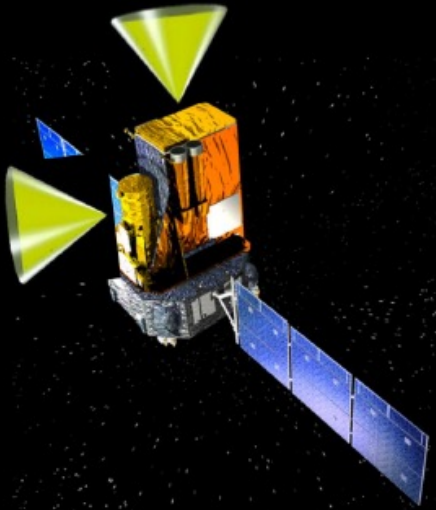
- Launched 17/10/2002, still in operation !
- high elliptical orbit (~72h)
- 58h of continuous science

- Is the link between soft X-ray and high energy γ-ray science
- High Sensitivity for photons 3 keV < E_γ <10 MeV
- Wide Field Of View ~ 100 – 1000 deg^2
- All-Sky monitor capability for 80 keV < E_γ <2.5 MeV
- Real time transmission of “transient” to Earth laboratory

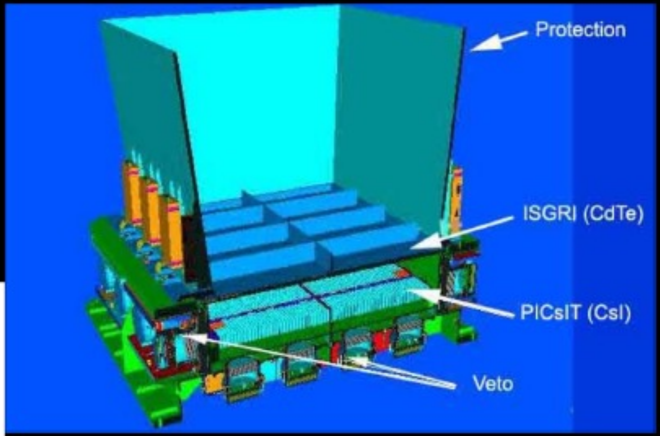
INTEGRAL an instrument to hunt γ-ray transients

The SPI/ACS detectors view ~4π solid angle of the sky.
E>75 keV, Tres=50ms
Effective area: up to $1\,m^2$

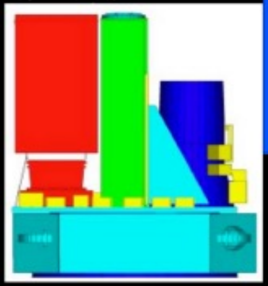
The IBIS detectors ISGRI and PICsIT have max sensitivity to directions normal to SPI/ACS factor of 5 at least



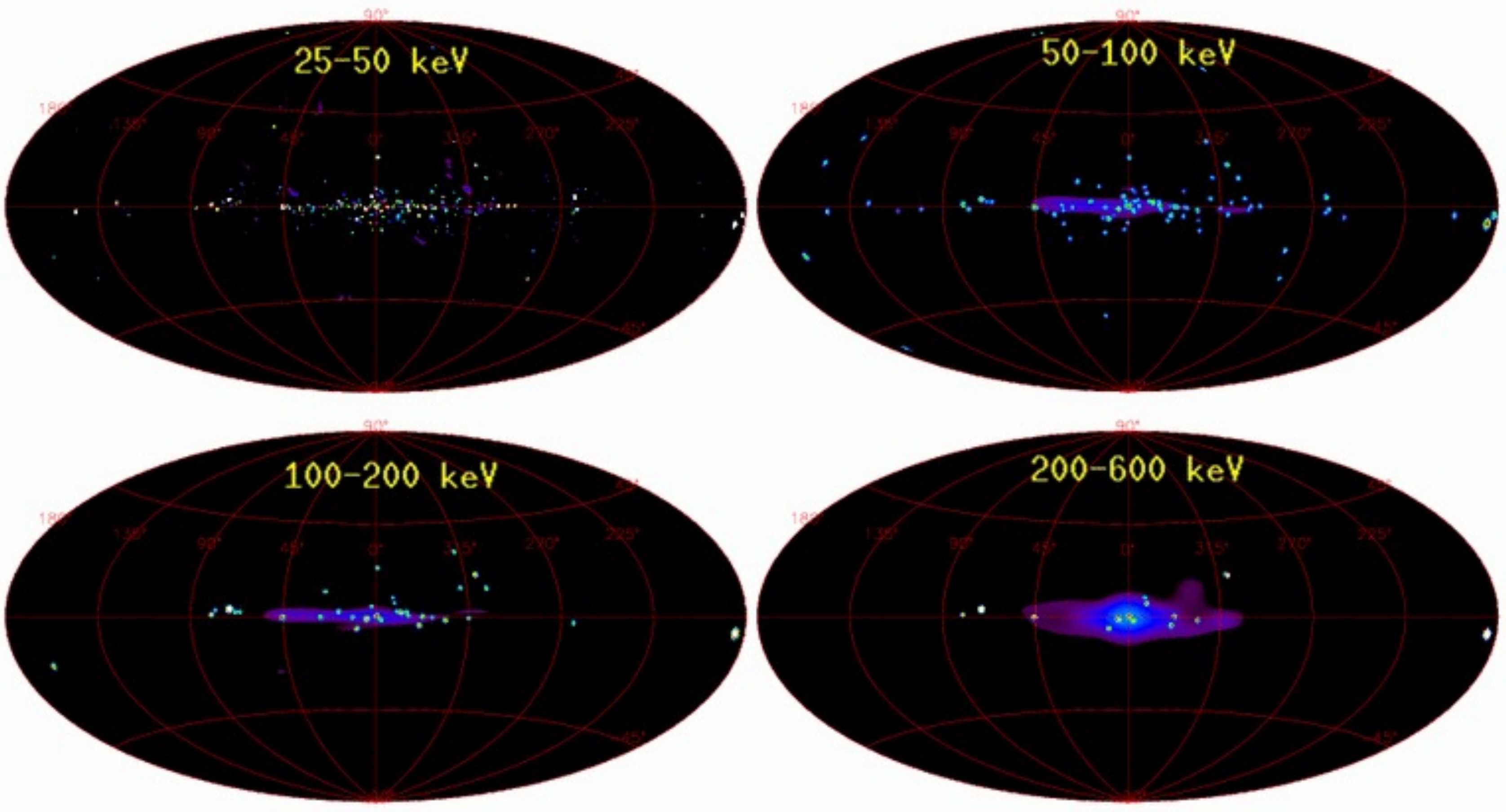
Outside the IBIS FOV (~30x30 deg^2) the ISGRI and PICsIT detectors also view ~4π up to 2.6 MeV.
PICsIT: T_res=15.6ms
Effective area up to $\sim 900\,cm^2$



The sensitivity to a gamma-ray transient depends on sky position and its evaluation must take into account the payload and satellite masses distribution

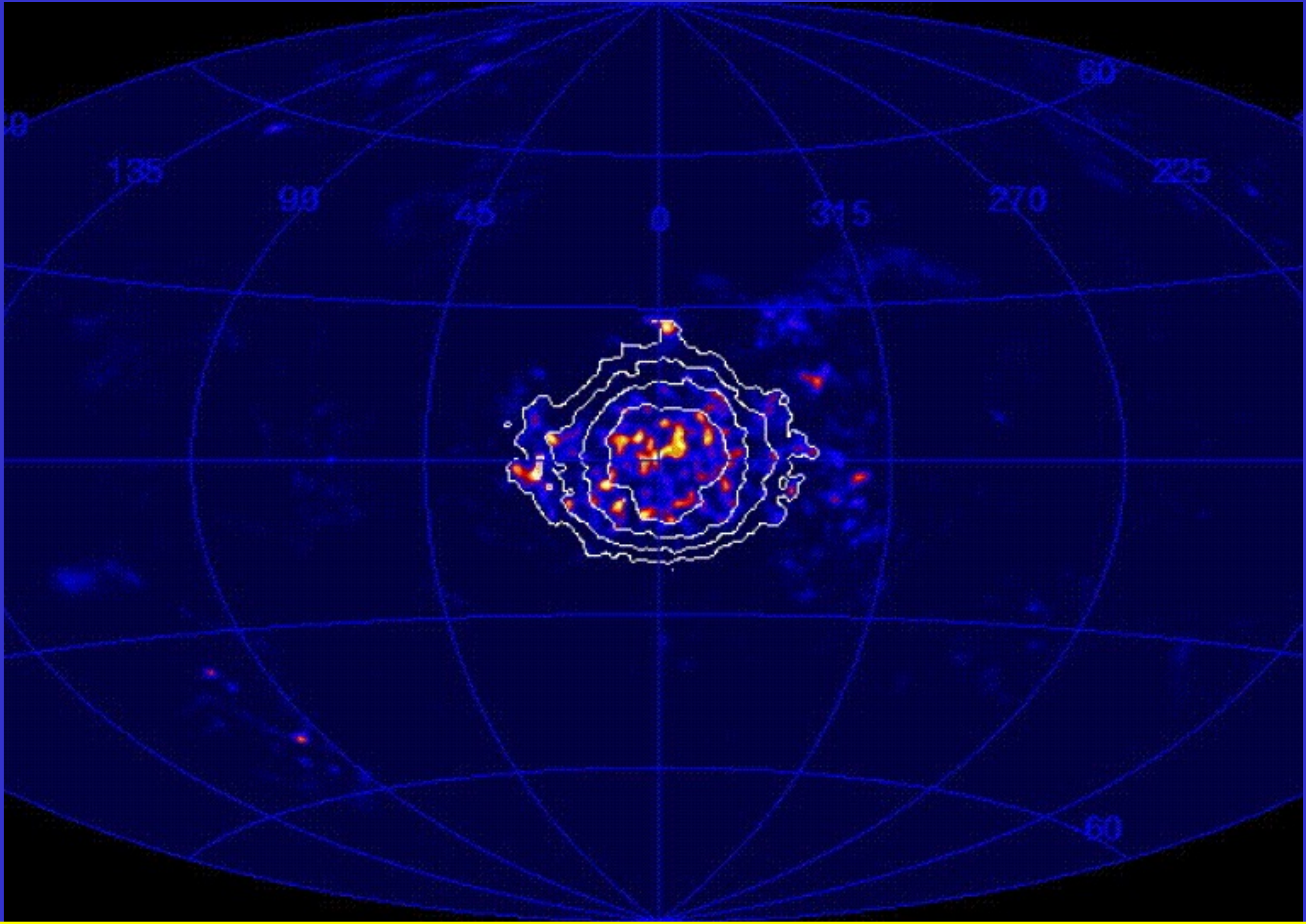


INTEGRAL: some results



THE GALAXY IN HARD-X/SOFT GAMMA-RAYS

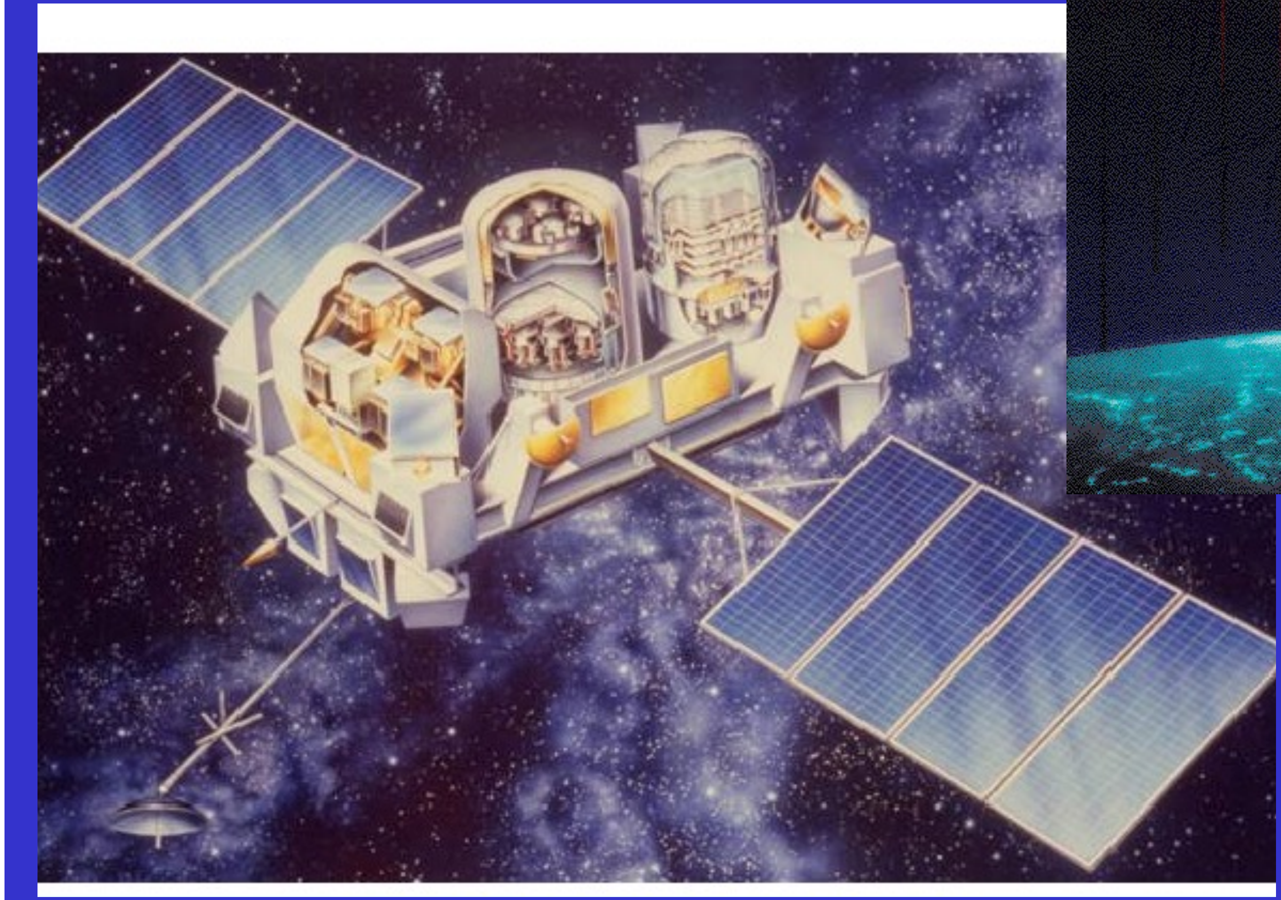
INTEGRAL: ANNIHILATION IN THE GALAXY

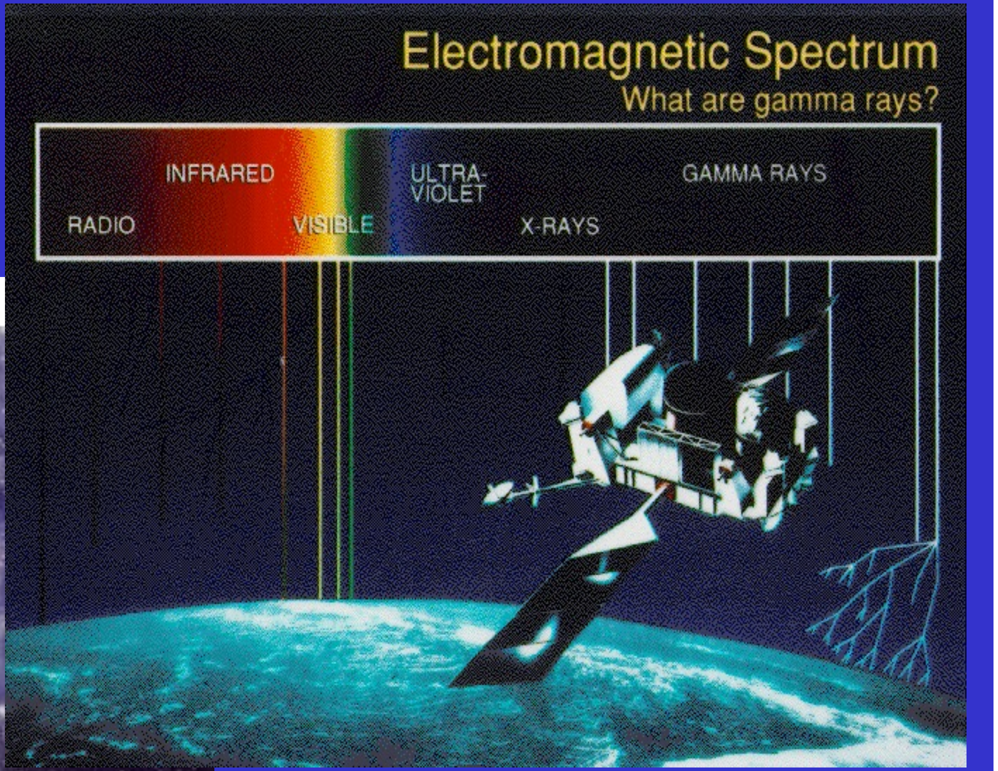


The SPI instrument onboard INTEGRAL has performed a search for 511 keV emission (resulting from positron-electron annihilation) all over the sky.

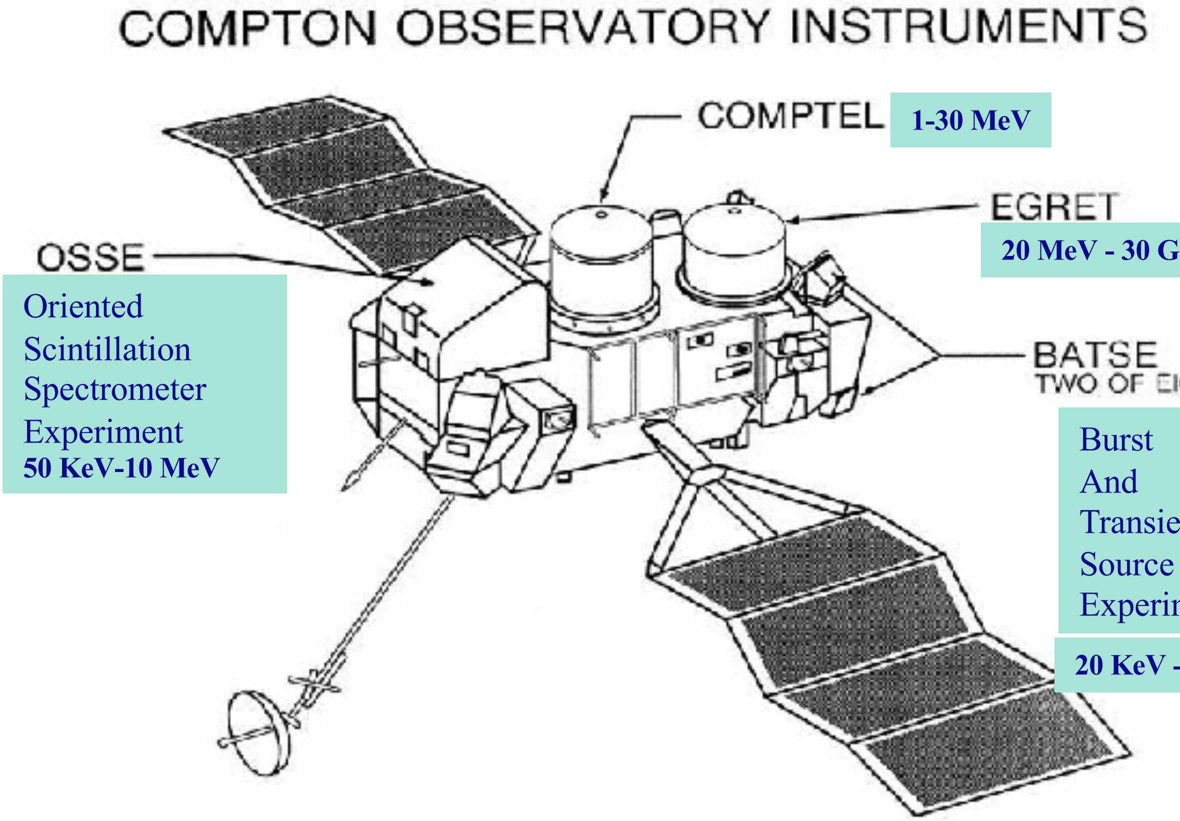
Compton Gamma Ray Observatory

CGRO (1991- 2000)





Compton Gamma Ray Observatory



1-30 MeV

20 MeV - 30 GeV

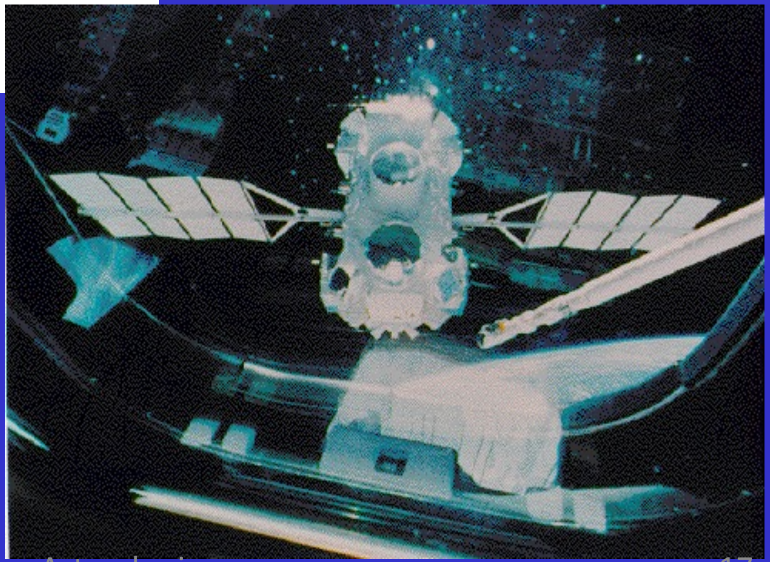
Oriented Scintillation Spectrometer Experiment
50 KeV-10 MeV

Burst And Transient Source Experiment

20 KeV - 1 MeV

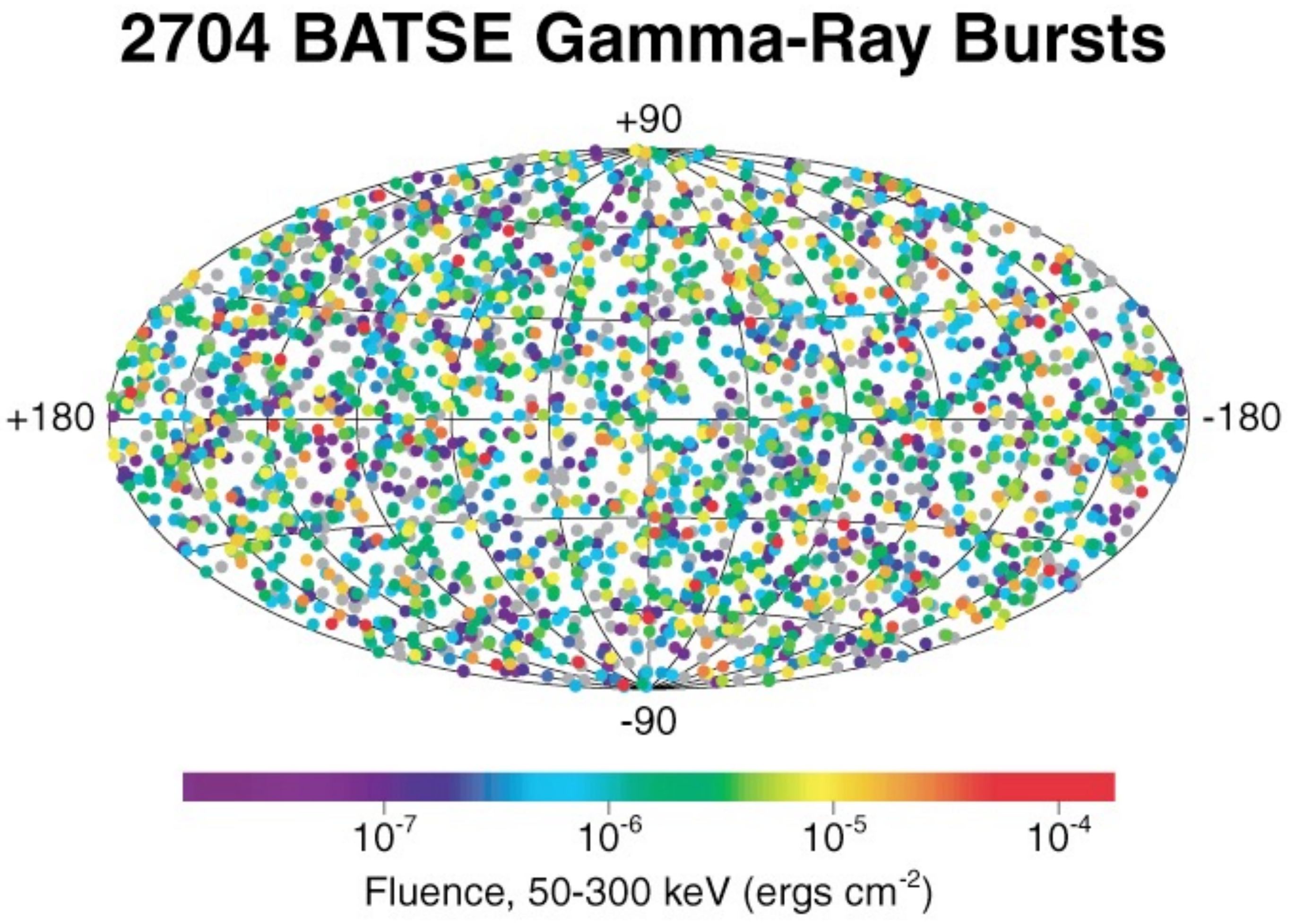
These four instruments are much larger and more sensitive than any gamma-ray telescopes previously flown in space. The large size is necessary because the number of gamma-ray interactions that can be recorded is directly related to the mass of the detector.

Since the number of gamma-ray photons from celestial sources is very small compared to the number of optical photons, large instruments are needed to detect a significant number of gamma rays in a reasonable amount of time. The combination of these instruments can detect photon energies from 20 thousand electron volts (20 keV) to more than 30 billion electron volts (30 GeV).



BATSE main results

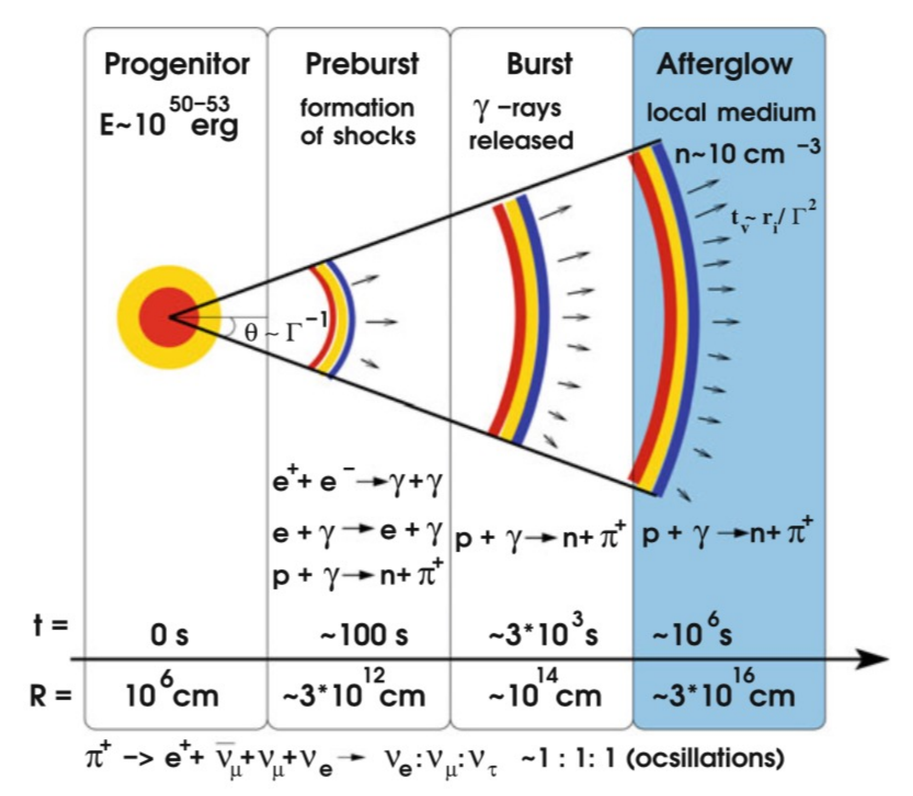
The bursts are isotropically distributed on the sky: no significant quadrupole moment or dipole moment is found. The nature of the sources remains unknown. At the same time, a deficiency has been detected in the number of faint bursts, interpreted as an indication that the spatial extent of the burst distribution is limited and that BATSE has seen the limit or edge of the distribution.



The Gamma Ray Bursts isotropic distribution on the sky along with the deficiency of faint bursts can be naturally explained if the bursts are located at cosmological distances (far beyond the Milky Way).

A source of Gamma Ray Burst (in brief)

Sketch of the typical geometry of a GRB in the fireball model. Apart from the distance from the centre also plotted are the emission timescales of the various stages of the explosion are plotted along the horizontal axis. Also listed are the most relevant electromagnetic and photo-hadronic processes. If photons are emitted roughly isotropically in the comoving plasma rest frame, in the observer frame the emission appears to be beamed into a cone with opening angle $\theta \sim 1/\Gamma$ with Γ the Lorentz factor of the plasma in the observer frame. GRBs were first discovered in the late 1960s by the Vela satellites and were originally thought to be linked to nuclear testing. However, it soon became clear that these objects have an extra-terrestrial origin.



In the following 20 years it was thought that GRBs are originated as explosions at the surfaces of neutron stars within our own Galaxy.

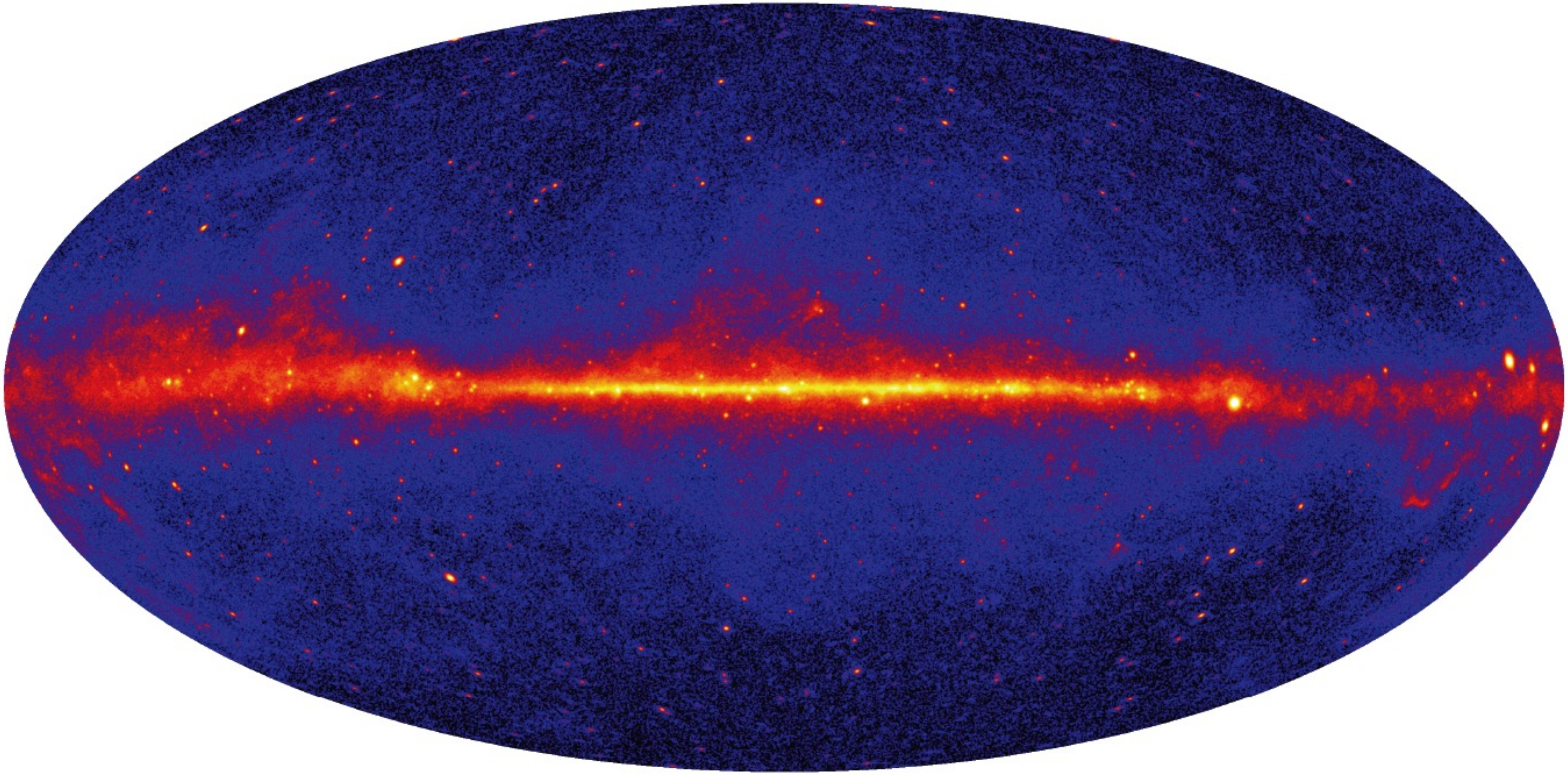
There are two types of GRBs, the *short GRBs* with a duration <~2 s and a higher than average peak energy, and the *long GRBs* with a duration >~2 s that are observed up to higher redshifts. The catastrophic event linked to the former is believed to be the merger of two neutron stars or of a neutron star and a black hole, whereas the latter are thought to be triggered by the collapse of a very massive star.

The "today" γ telescope in the space: FERMI

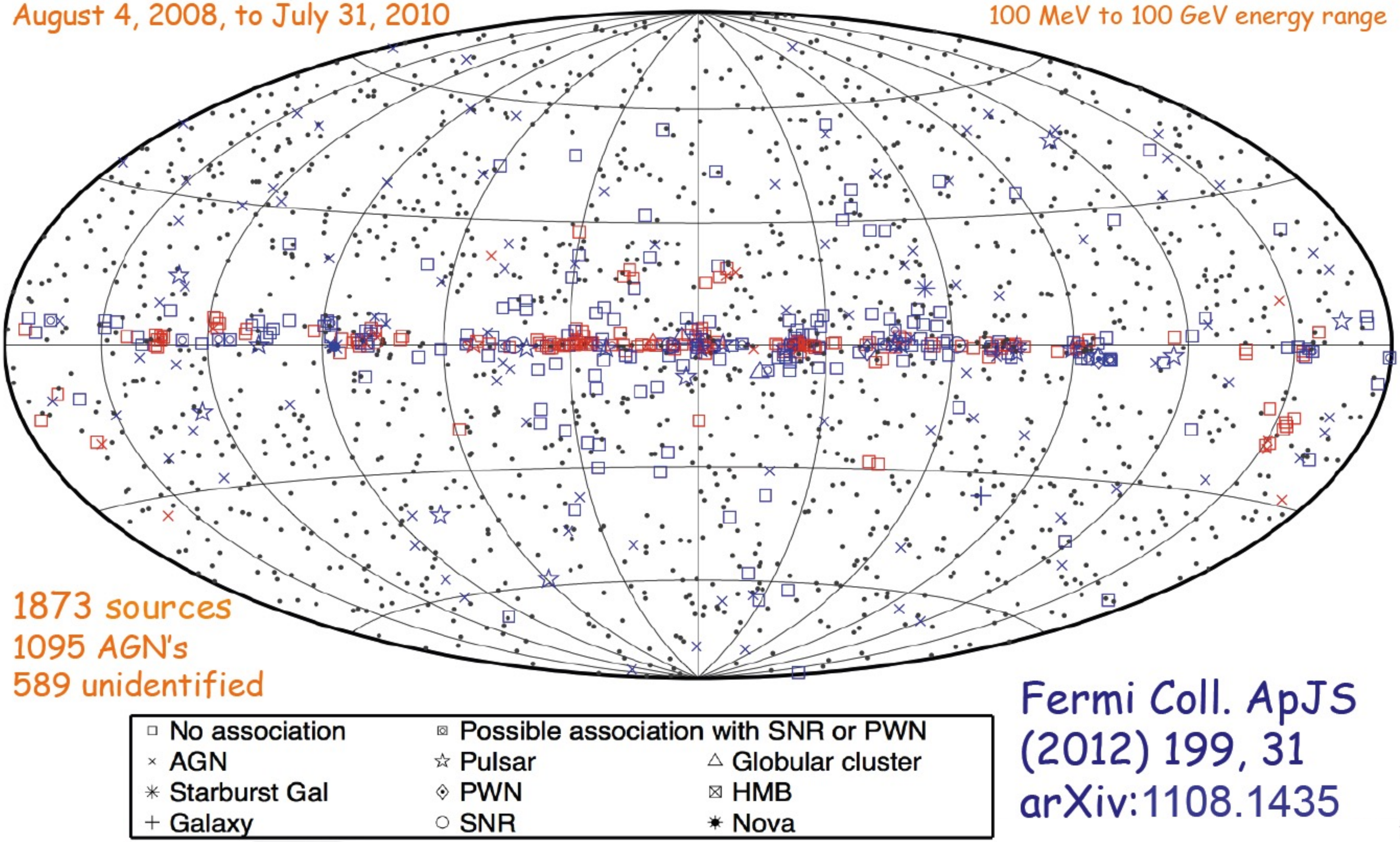
fermi
Gamma-ray
Space Telescope

Fermi LAT Gamma-ray Sky

4 year all sky map (E > 1 GeV)



The "today" γ telescope in the space: Fermi



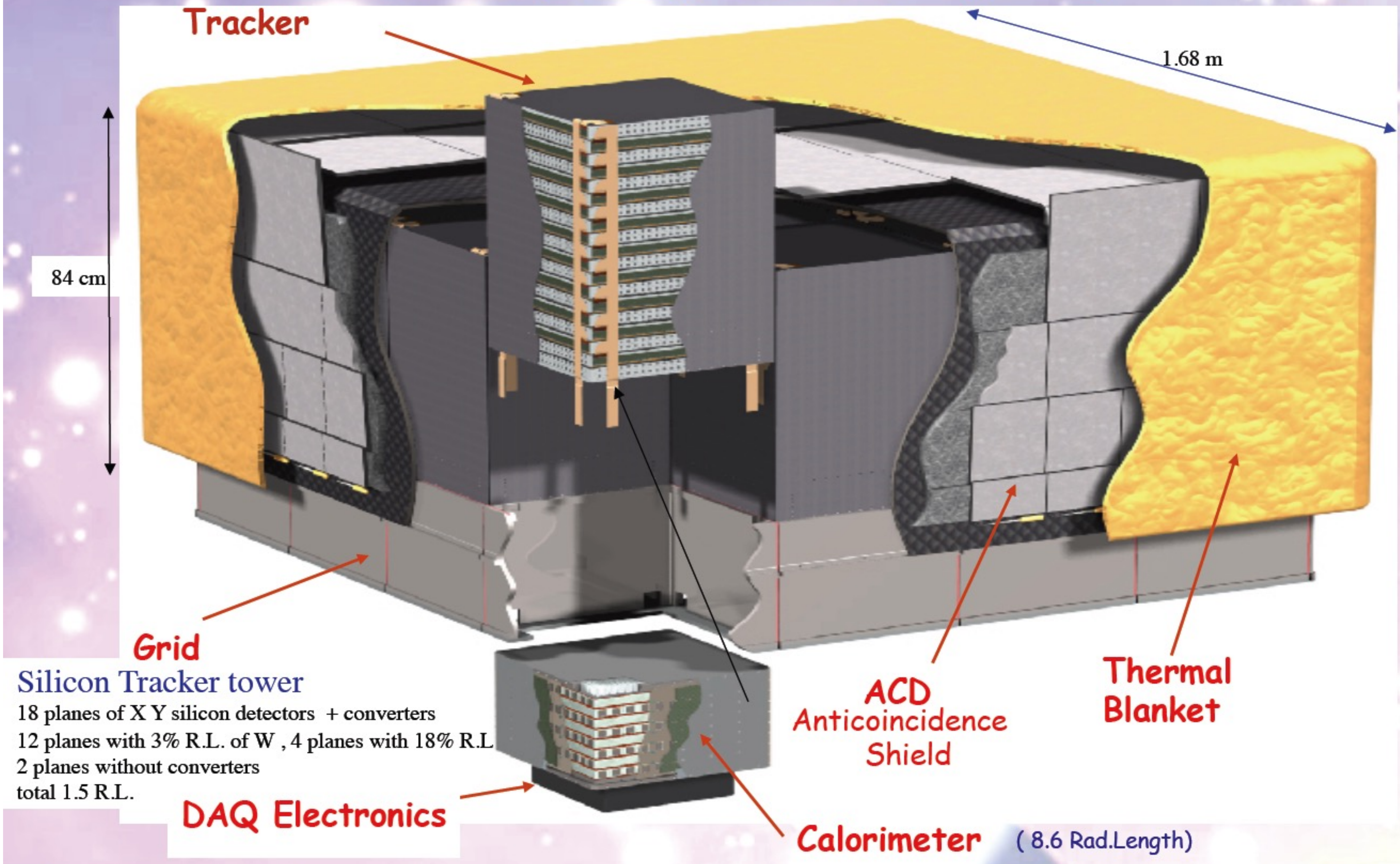
August 4, 2008, to July 31, 2010

100 MeV to 100 GeV energy range

1873 sources
1095 AGN's
589 unidentified

Fermi Coll. ApJS (2012) 199, 31
arXiv:1108.1435

Fermi Gamma-Ray Large Area Space Telescope



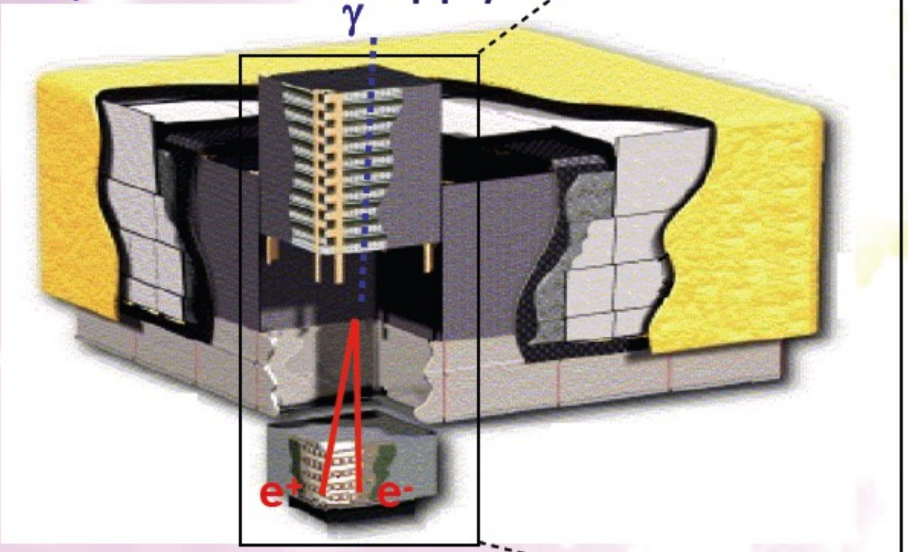
Silicon Tracker tower

18 planes of X Y silicon detectors + converters
12 planes with 3% R.L. of W , 4 planes with 18% R.L
2 planes without converters
total 1.5 R.L.

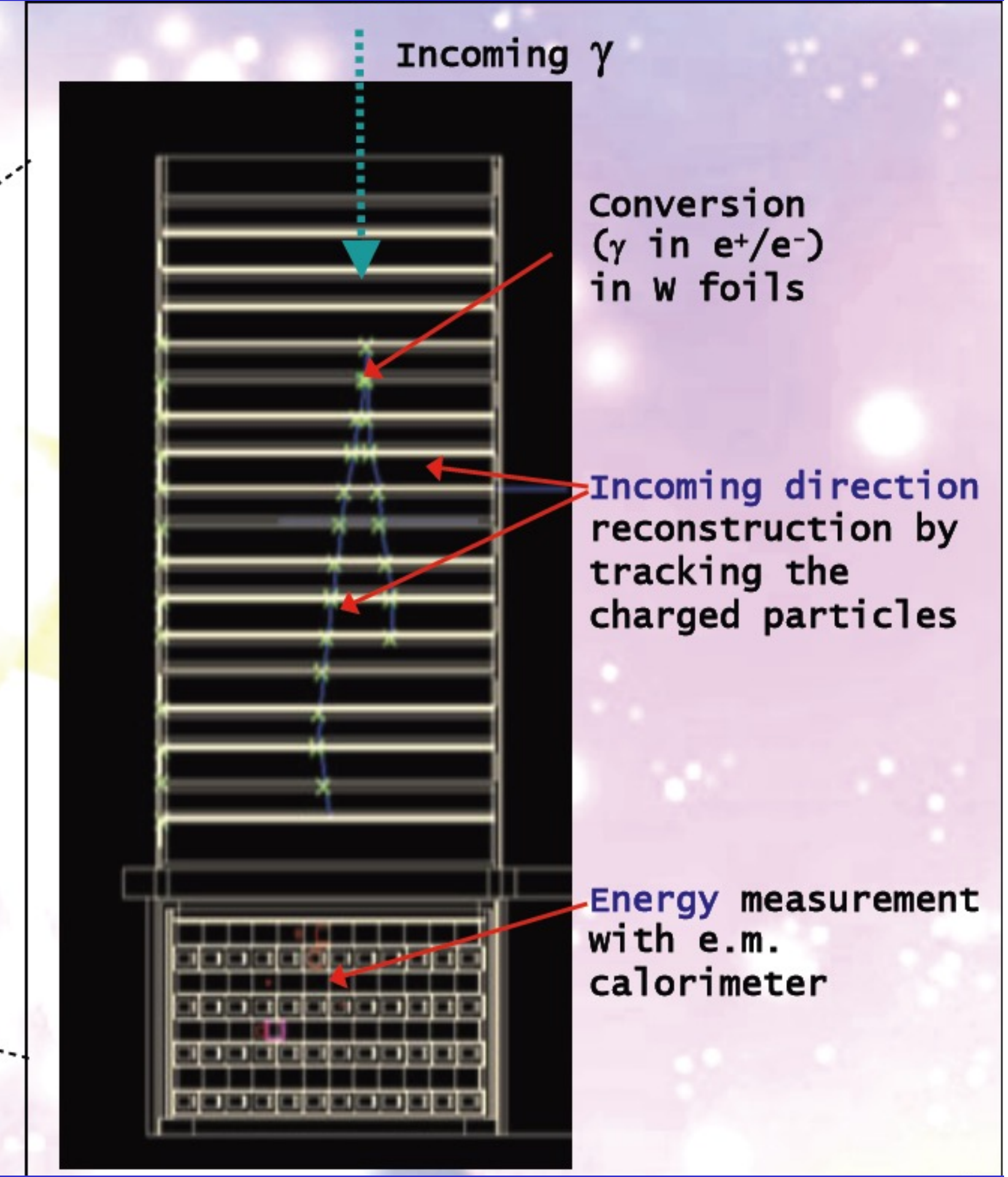
How Fermi LAT detects gamma rays

4 x 4 array of identical towers with:

- Precision Si-strip tracker (TKR)
    - With W converter foils
- Hodoscopic CsI calorimeter (CAL)
- DAQ and Power supply box



An anticoincidence detector around the telescope distinguishes gamma-rays from charged particles



Incoming γ

Conversion
(γ in e^+/e^-)
in W foils

Incoming direction
reconstruction by
tracking the
charged particles

Energy measurement
with e.m.
calorimeter

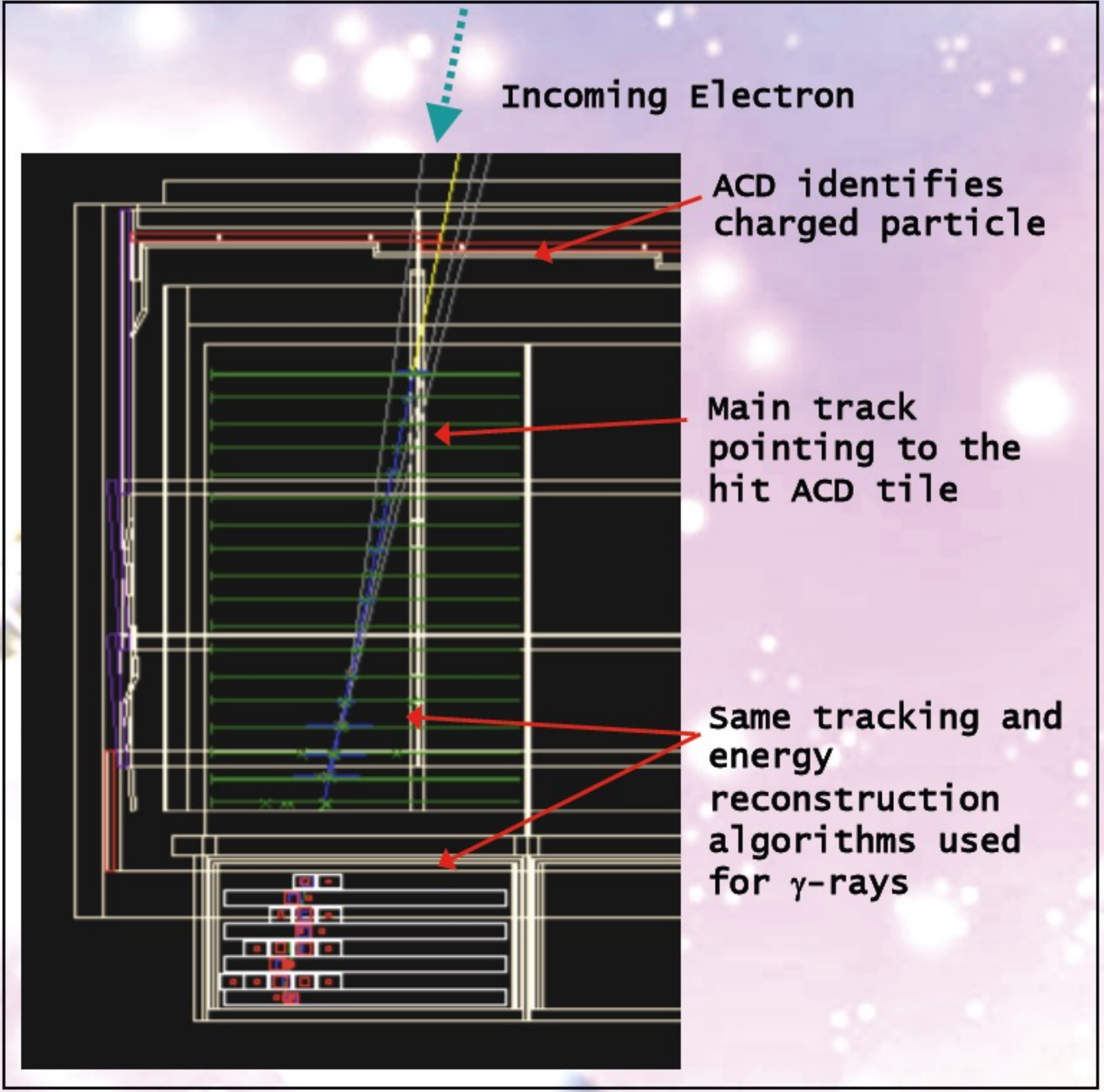
How Fermi LAT detects electrons

Trigger and downlink

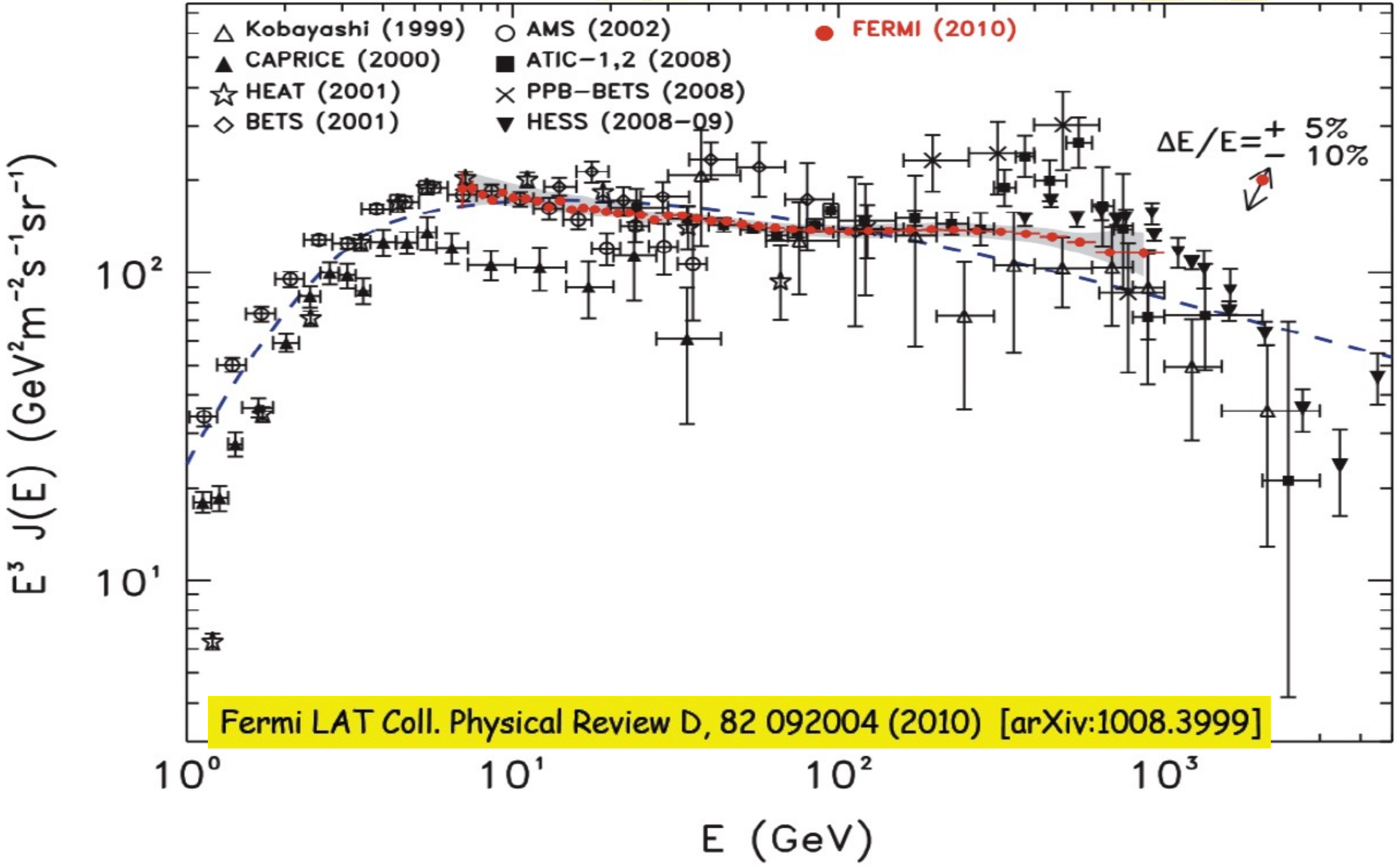
- LAT triggers on (almost) every particle that crosses the LAT
  - ~ 2.2 kHz trigger rate
- On board processing removes many charged particles events
  - But keeps events with more that 20 GeV of deposited energy in the CAL
  - ~ 400 Hz downlink rate
- Only ~1 Hz are good γ-rays

Electron identification

- The challenge is identifying the good electrons among the proton background
  - Rejection power of 10^3 - 10^4 required
  - Can not separate electrons from positrons



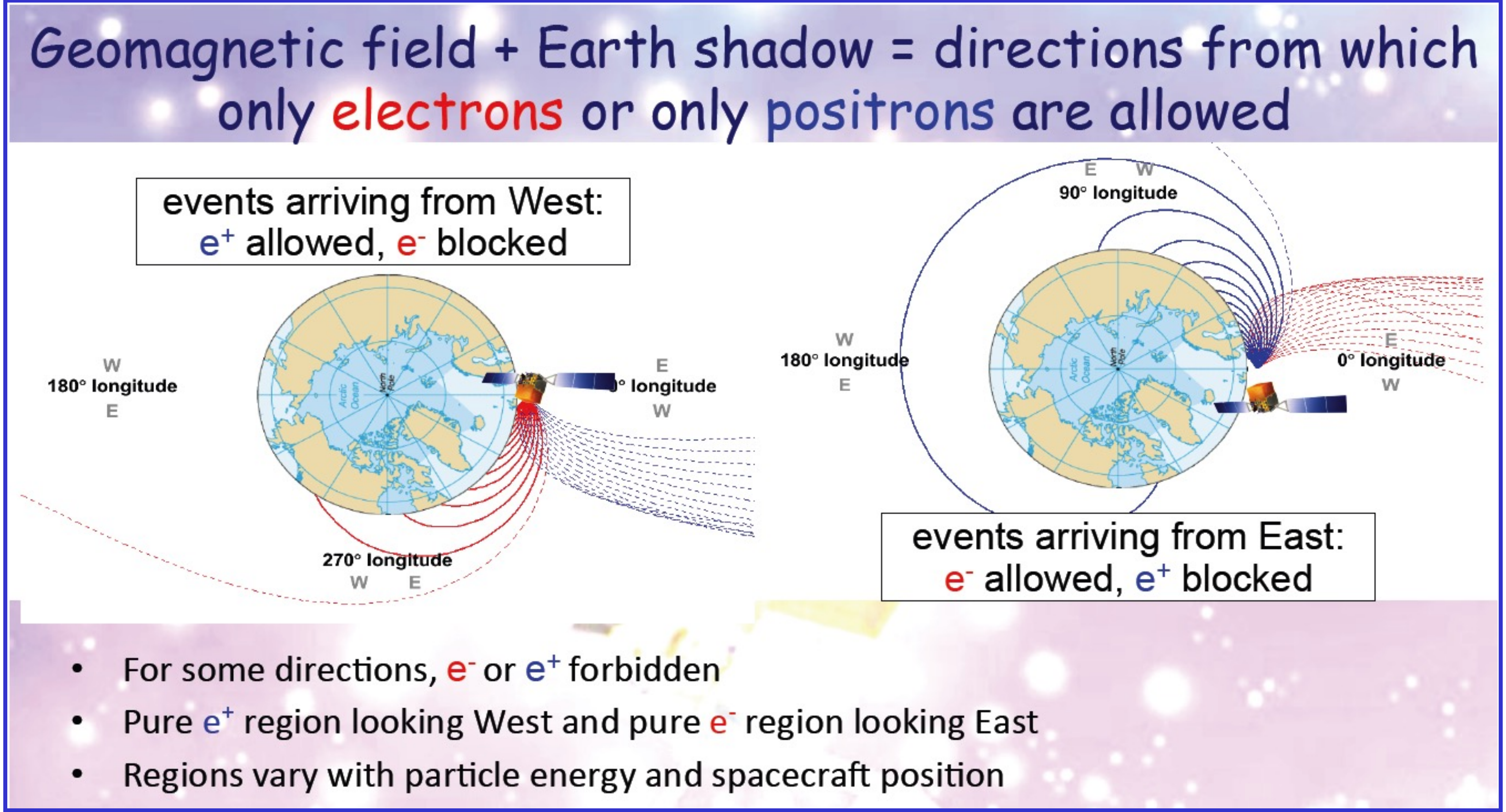
Fermi Electron + Positron Spectrum



Fermi LAT Coll. Physical Review D, 82 092004 (2010) [arXiv:1008.3999]

Extended Energy Range (7 GeV – 1 TeV) One year statistics (8M evts)

FERMI has no magnetic field: can FERMI distinguish e^+ from e^- ??



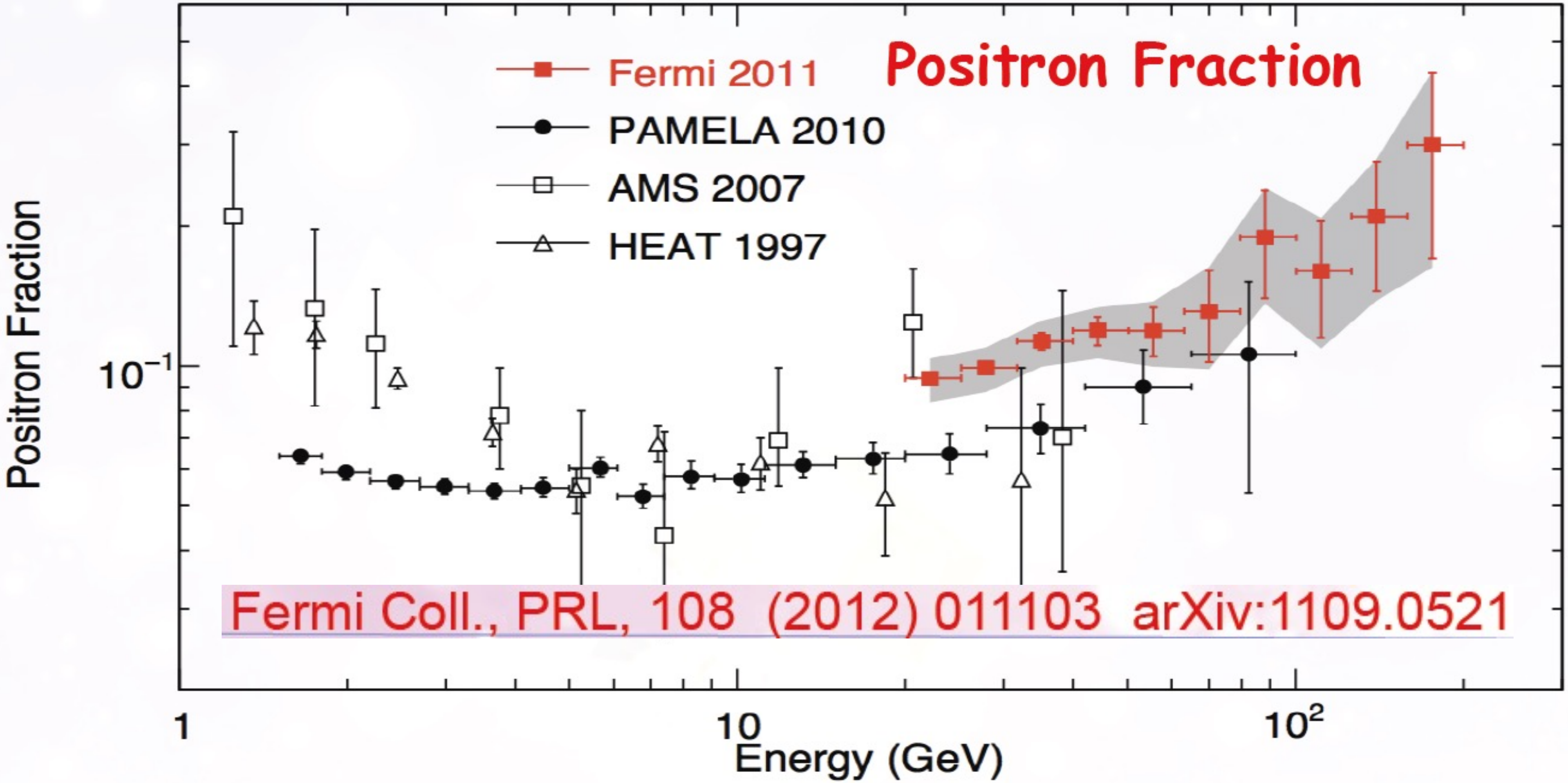
Geomagnetic field + Earth shadow = directions from which only electrons or only positrons are allowed

events arriving from West:
e^+ allowed, e^- blocked

events arriving from East:
e^- allowed, e^+ blocked

- For some directions, e^- or e^+ forbidden
- Pure e^+ region looking West and pure e^- region looking East
- Regions vary with particle energy and spacecraft position

Fermi, an estimate of positrons flux



Fermi Coll., PRL, 108 (2012) 011103 arXiv:1109.0521

The Fermi-LAT has measured the cosmic-ray positron and electron spectra separately, between 20 and 130 GeV, using the Earth's magnetic field as a charge discriminator

- **Two independent methods of background subtraction produce consistent results**
- **The observed positron fraction is consistent with the one measured by PAMELA**

Differences between different experiments below few GeV's probably due to charge-sign-dependent modulation but still under study

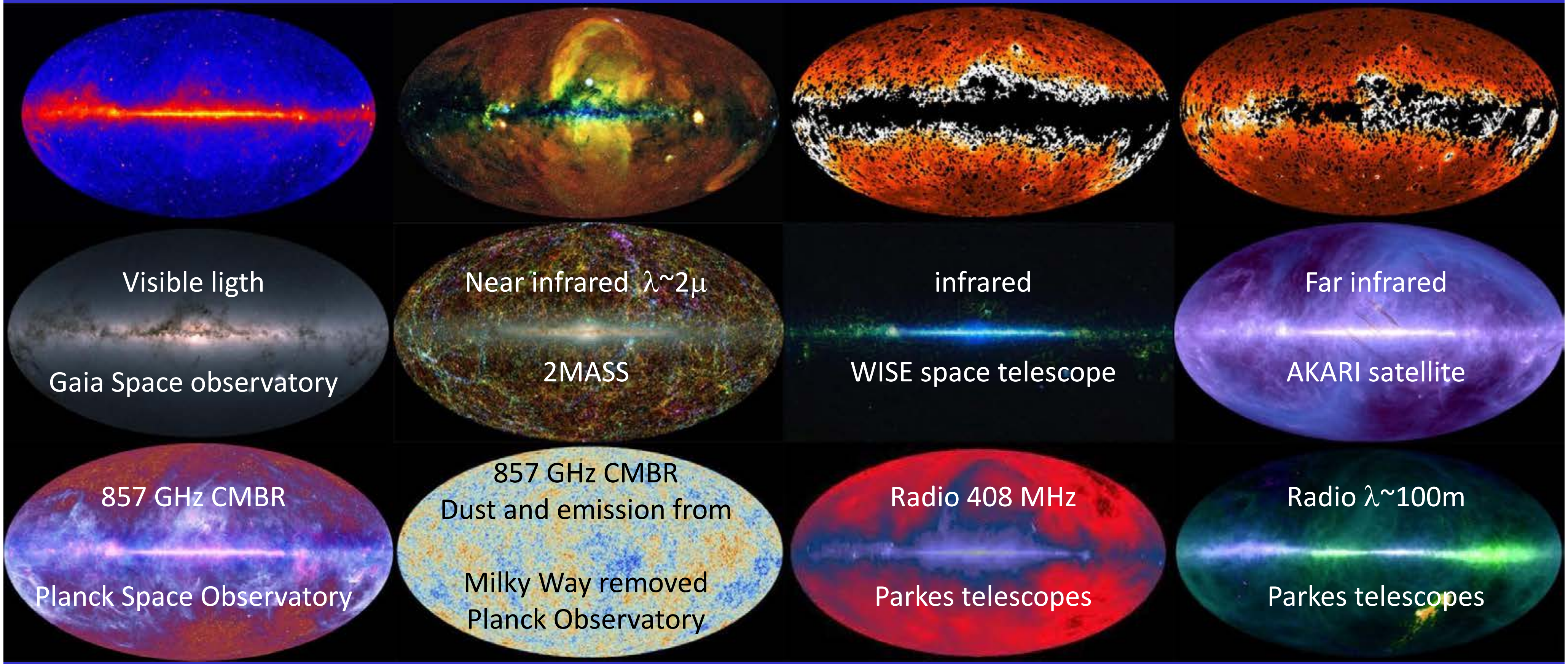
Multiwavelength sky-map representation

Fermi
E_{γ}>1GeV

eRosita
X-Rays

GALEX
Far Ultraviolet

GALEX
Near Ultraviolet



Visible ligth
Gaia Space observatory

Near infrared λ~2μ
2MASS

infrared
WISE space telescope

Far infrared
AKARI satellite

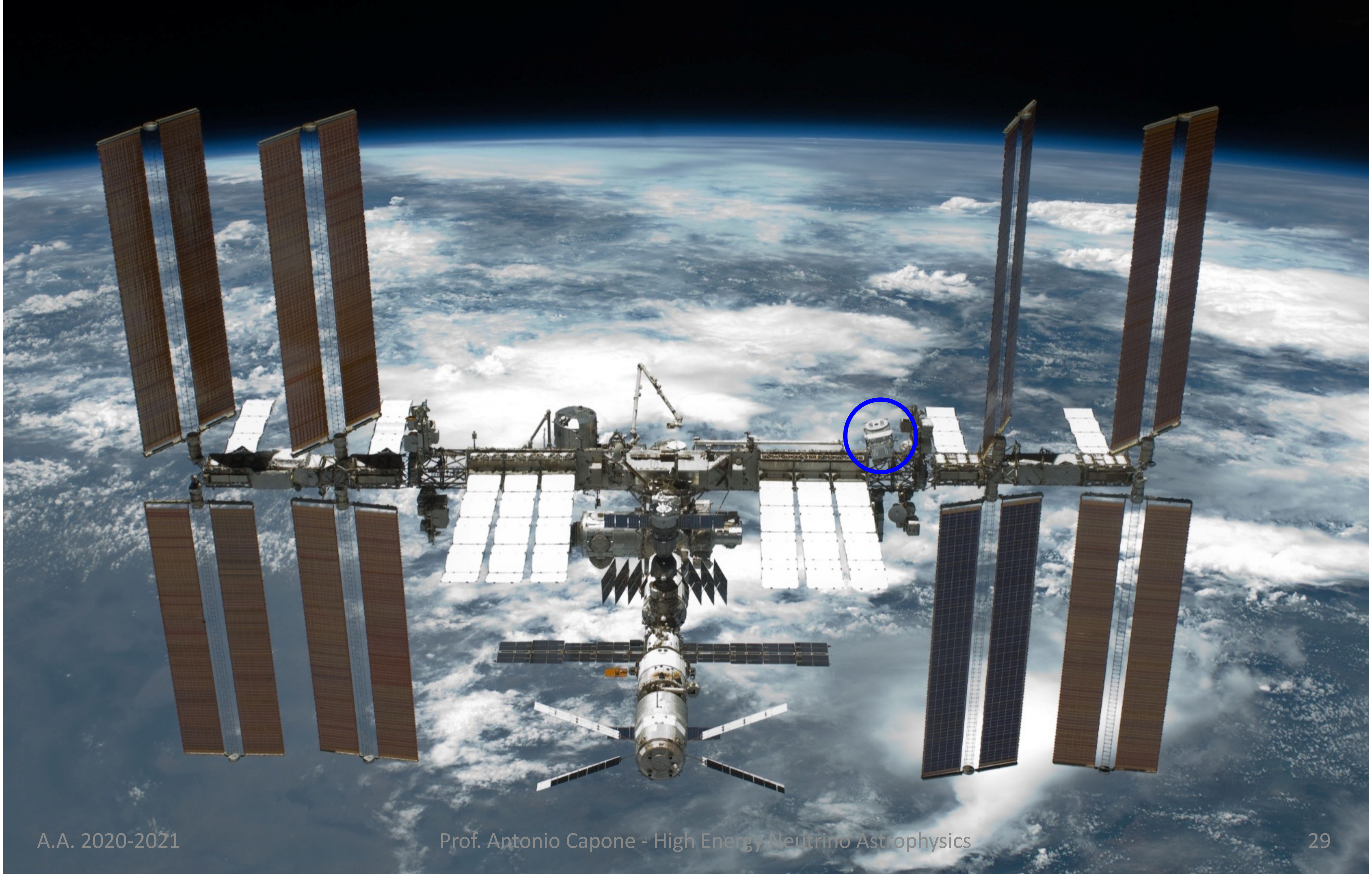
857 GHz CMBR
Planck Space Observatory

857 GHz CMBR
Dust and emission from
Milky Way removed
Planck Observatory

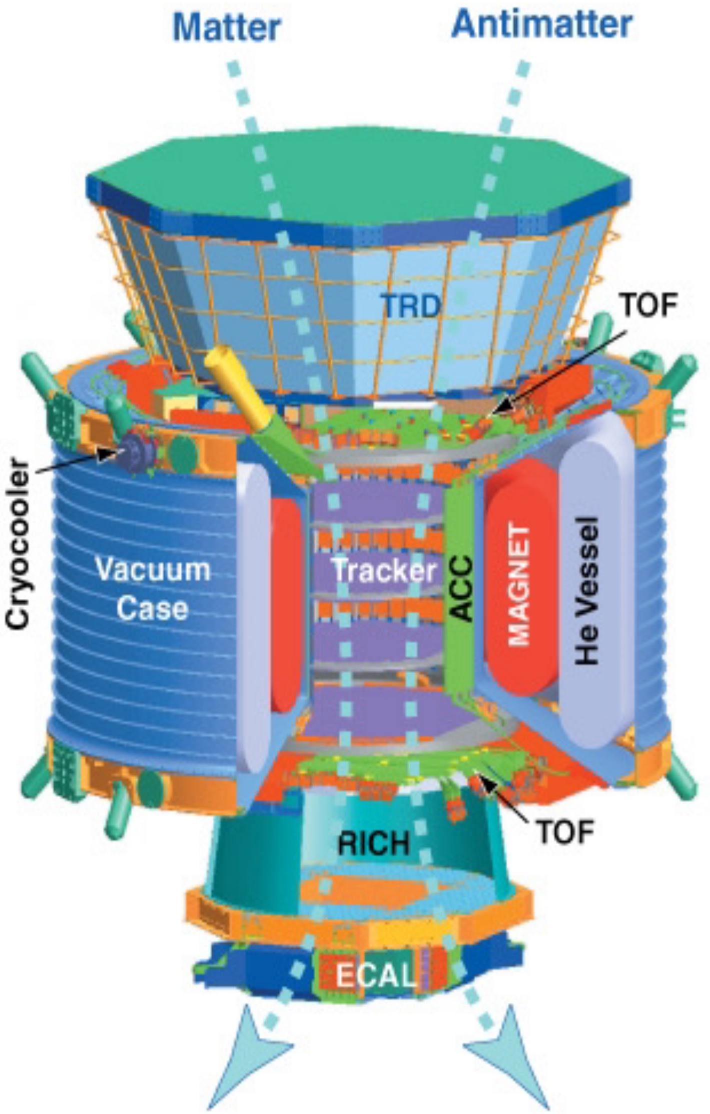
Radio 408 MHz
Parkes telescopes

Radio λ~100m
Parkes telescopes

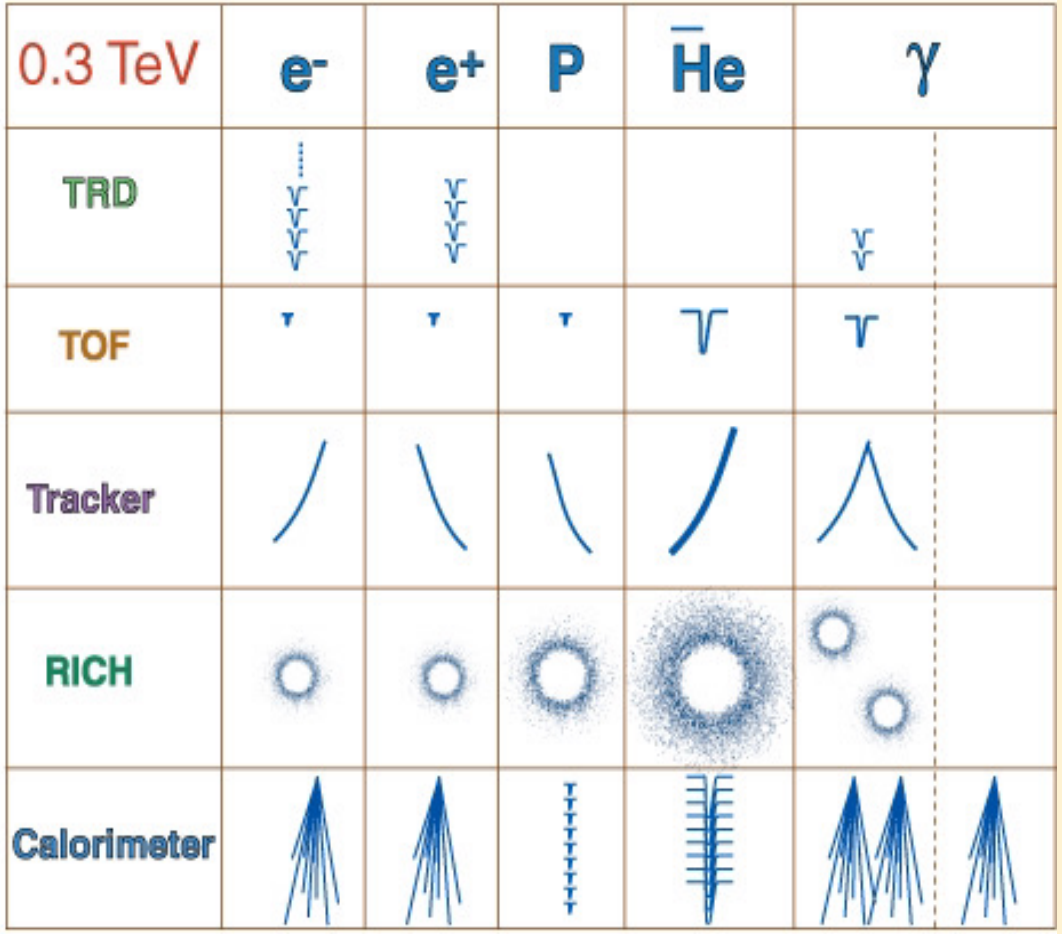
The Alpha Magnetic Spectrometer (AMS) Experiment *on the International Space Station.*



The AMS Cosmic ray detector



300,000 channels of electronics Δt = 100 ps, Δx = 10μ



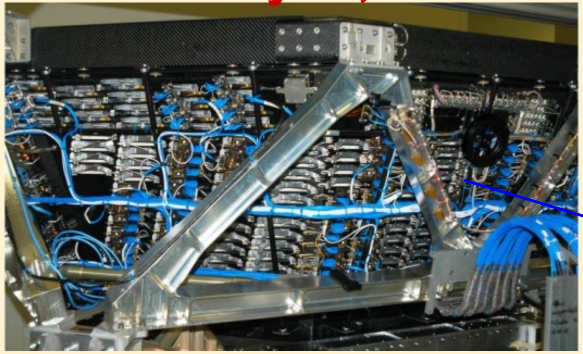
0.3 TeV	e^-	e^+	P	$\overline{\mathrm{He}}$	γ
TRD					
TOF					
Tracker					
RICH					
Calorimeter					

AMS: A TeV precision, multipurpose spectrometer

Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

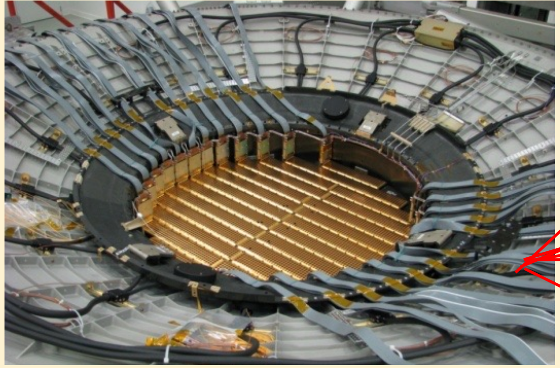
TRD

Identify e⁺, e⁻



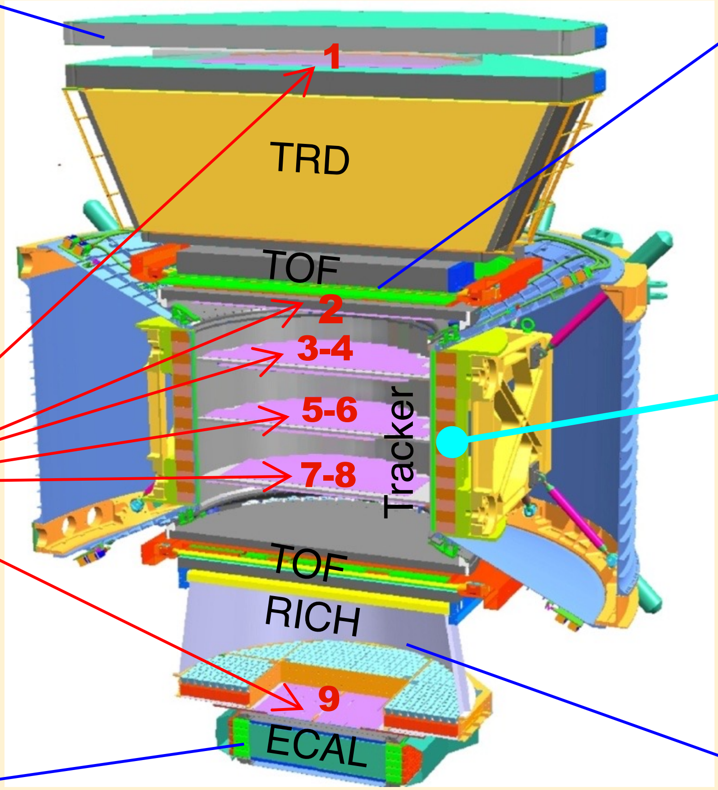
Silicon Tracker

Z, P



ECAL

E of e⁺, e⁻, γ

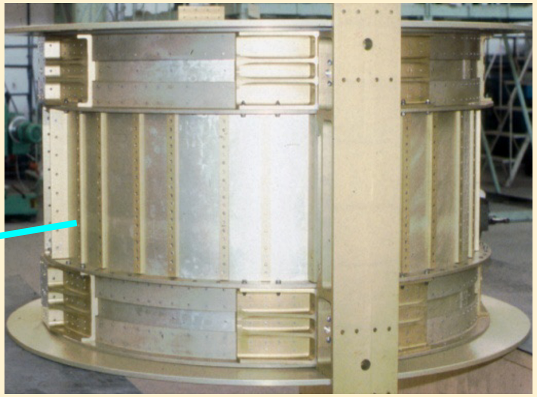


TOF

Z, E

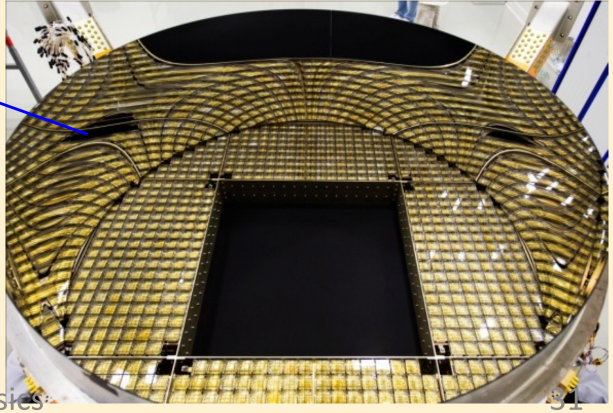
Magnet

±Z



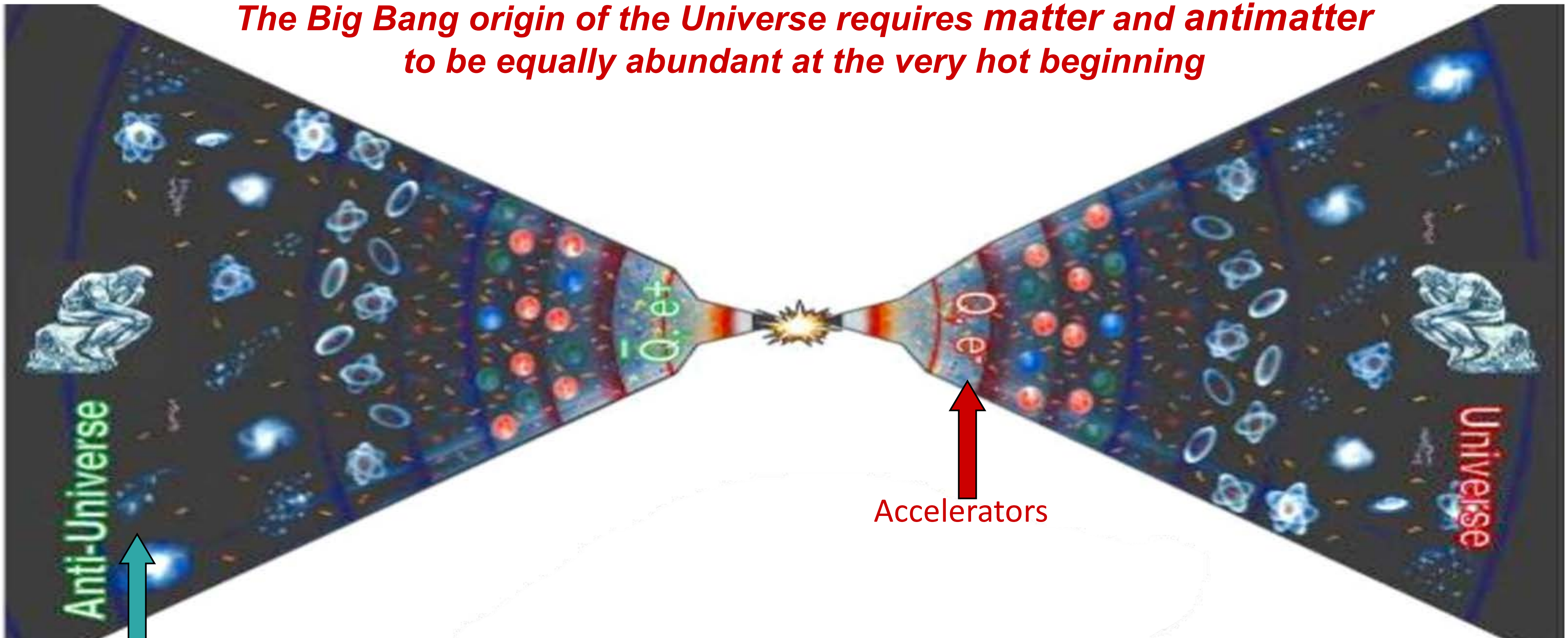
RICH

Z, E



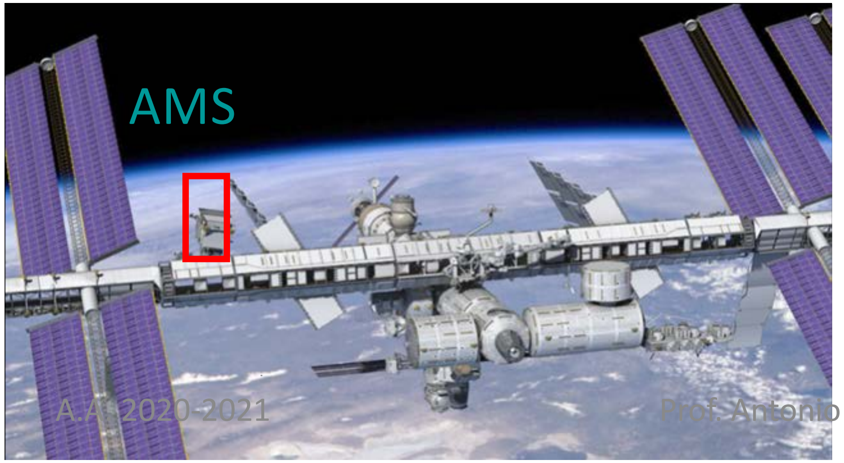
Z, P are measured independently by the Tracker, RICH, TOF and ECAL

Search for antimatter: One of the AMS Physics objectives

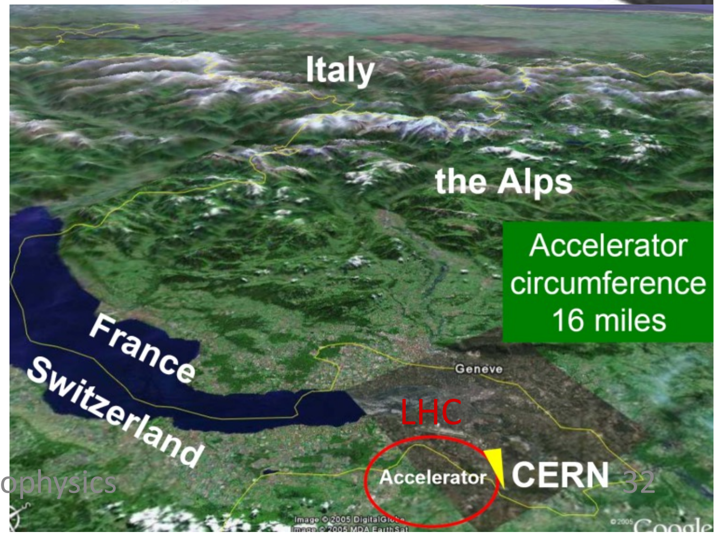


The Big Bang origin of the Universe requires matter and antimatter to be equally abundant at the very hot beginning

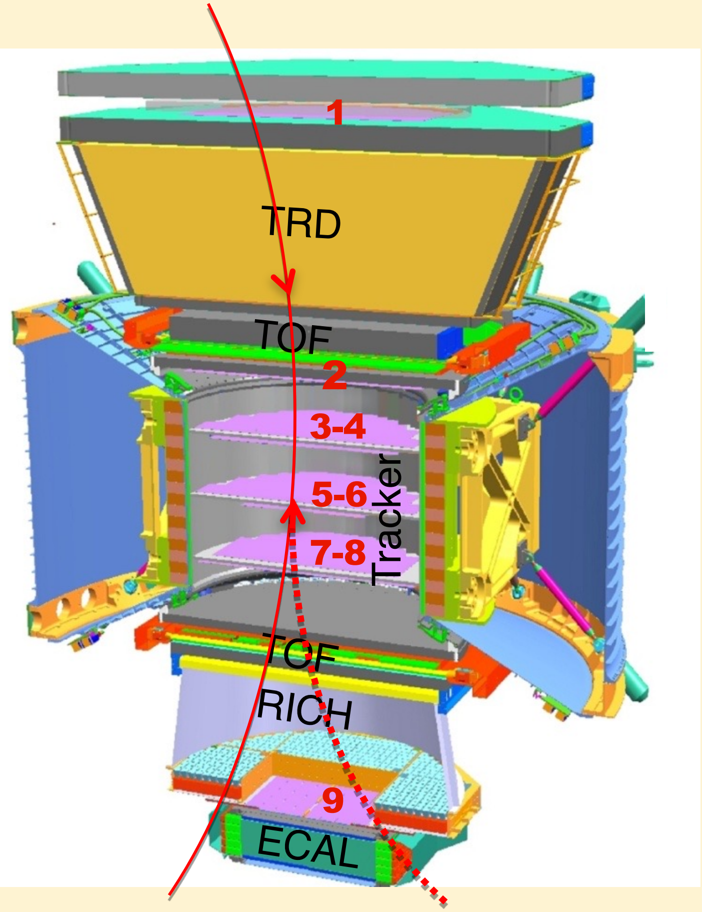
AMS in Space



AMS on the Space Station for 10-20 years will search for the existence of antimatter to the edge of the universe



Sensitive Search for Antimatter with $He/\overline{He} > 10^{10}$



a) Minimal material in the detector

So that the detector does not become a source of large angle scattering

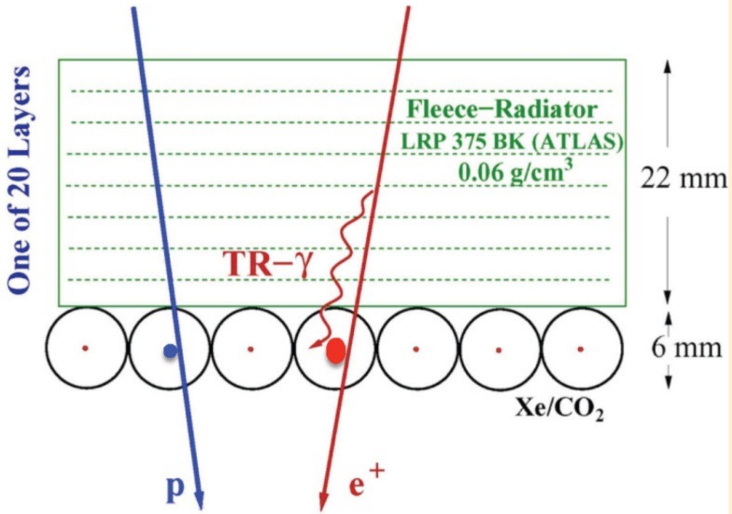
b) Repetitive measurements of momentum

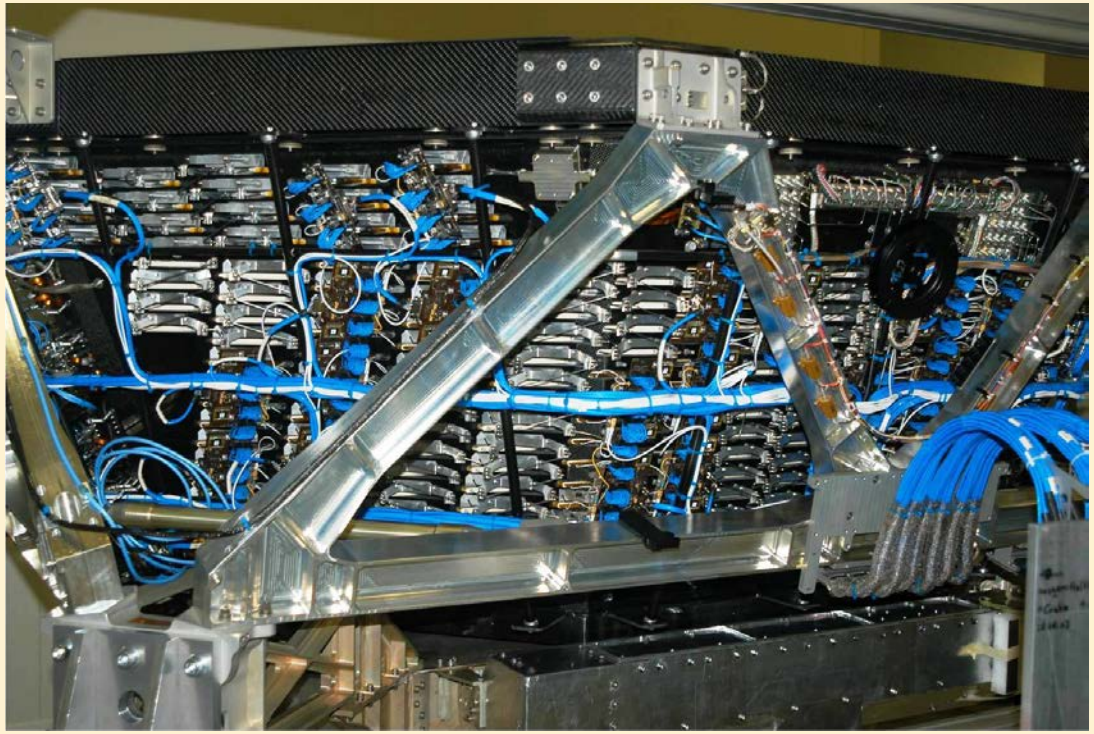
To ensure that particles which had large angle scattering are not confused with the signal.

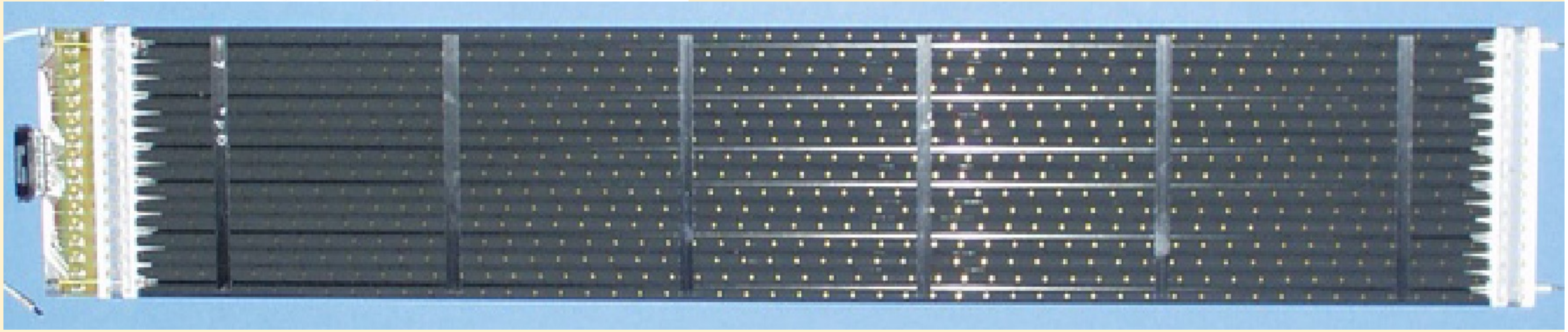
The Transition Radiation Detector (TRD)

20 Layers each consisting of:

- **22 mm fibre fleece**
- **Ø 6 mm straw tubes filled with Xe/CO_2 80%/20%**

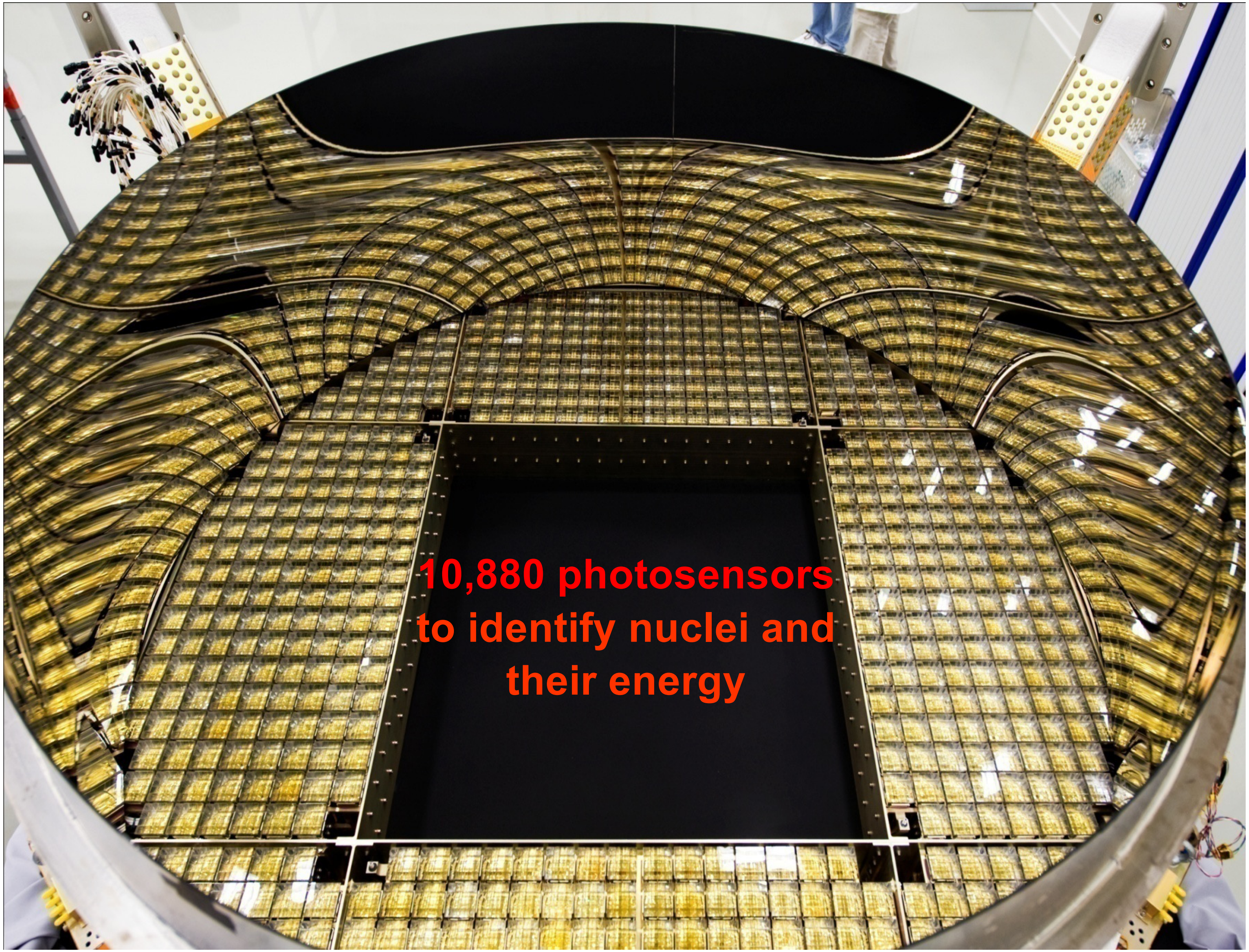






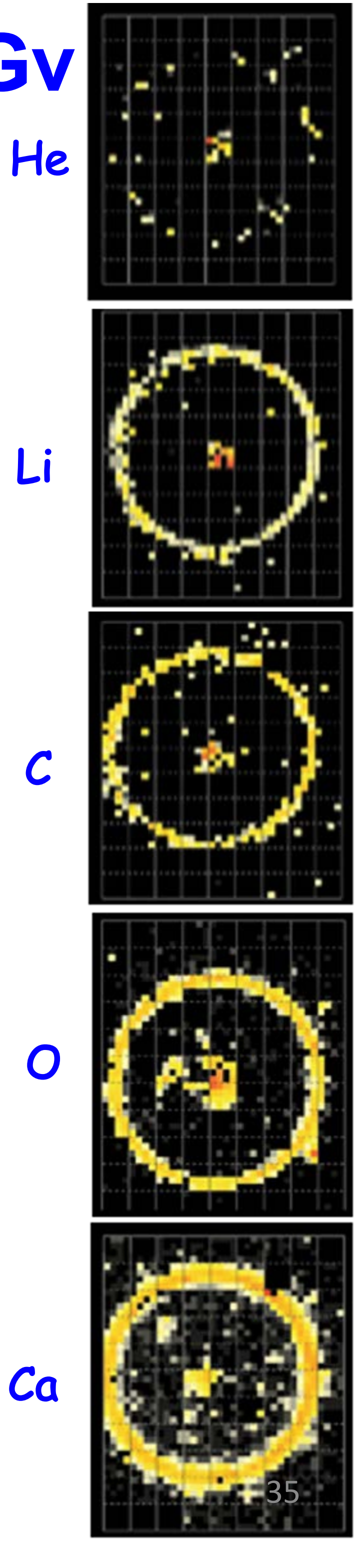
5,248 tubes selected from 9,000, 2 m length centered to 100μm, verified by CAT scanner

Ring Imaging CHerenkov (RICH)

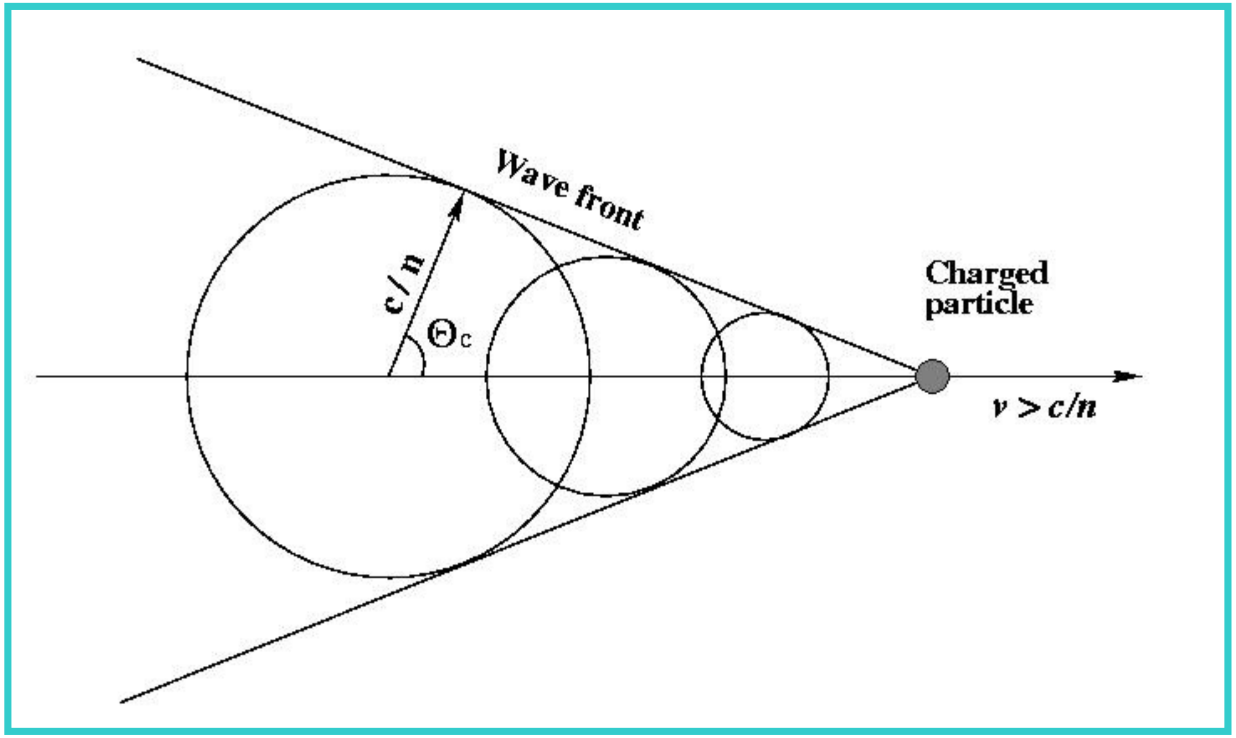


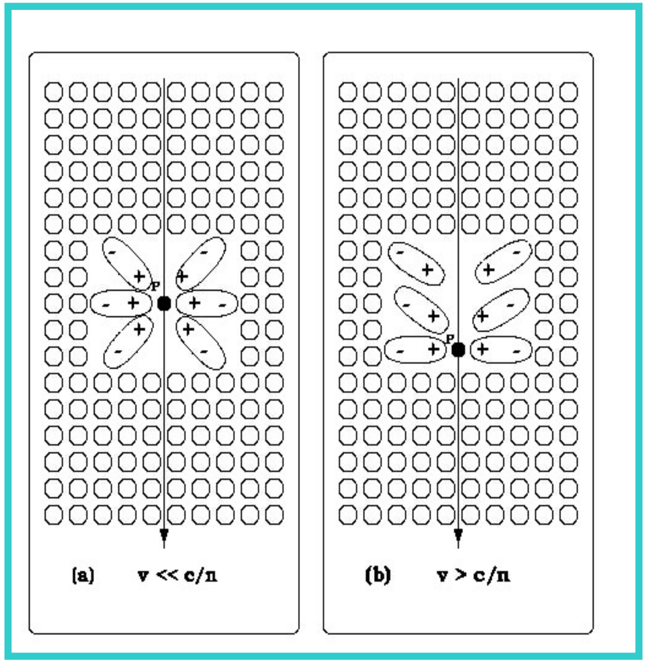
10,880 photosensors to identify nuclei and their energy

160 Gv



Cherenkov light detector



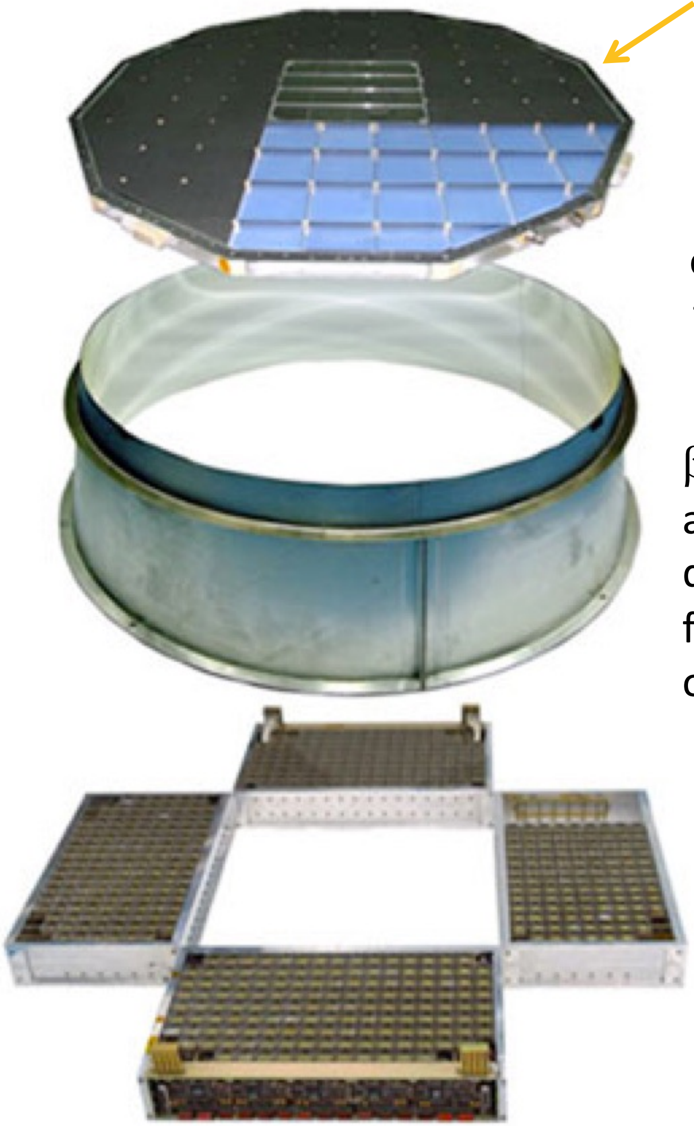


- Cerenkov radiation emitted when a charged particle travels with *v>c/n* in the medium

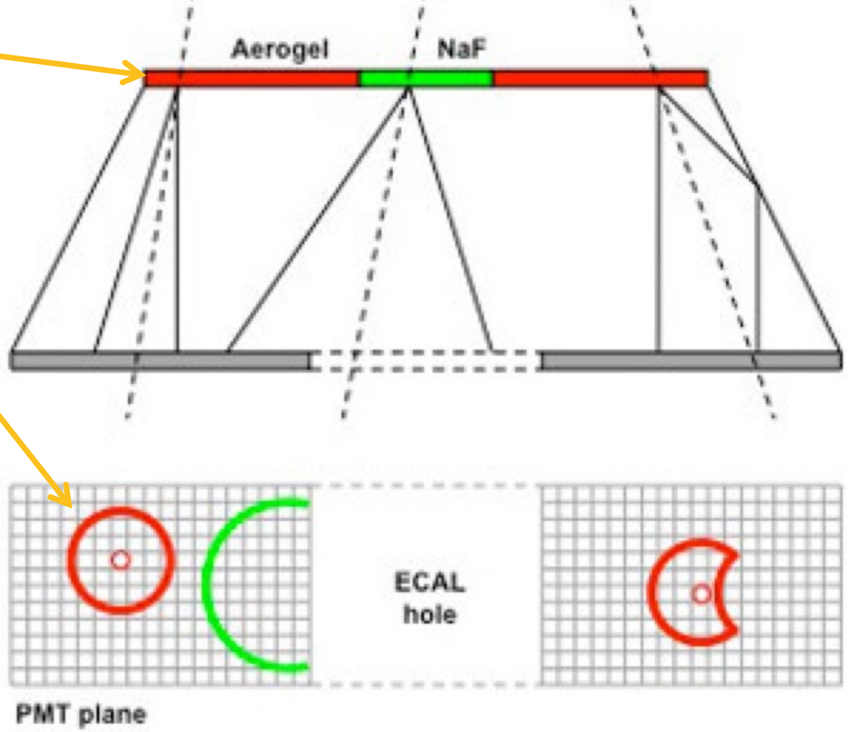
$$\beta > \frac{1}{n} \quad ; \quad \cos\Theta_c = \frac{1}{\beta n} \quad ; \quad \frac{d^2N}{dx\,d\lambda} \propto \frac{1}{\lambda^2}$$

- Mostly "blue" photons.

The Ring Imaging Cherenkov Detector (RICH)



Thin radiator in which Cherenkov light is produced



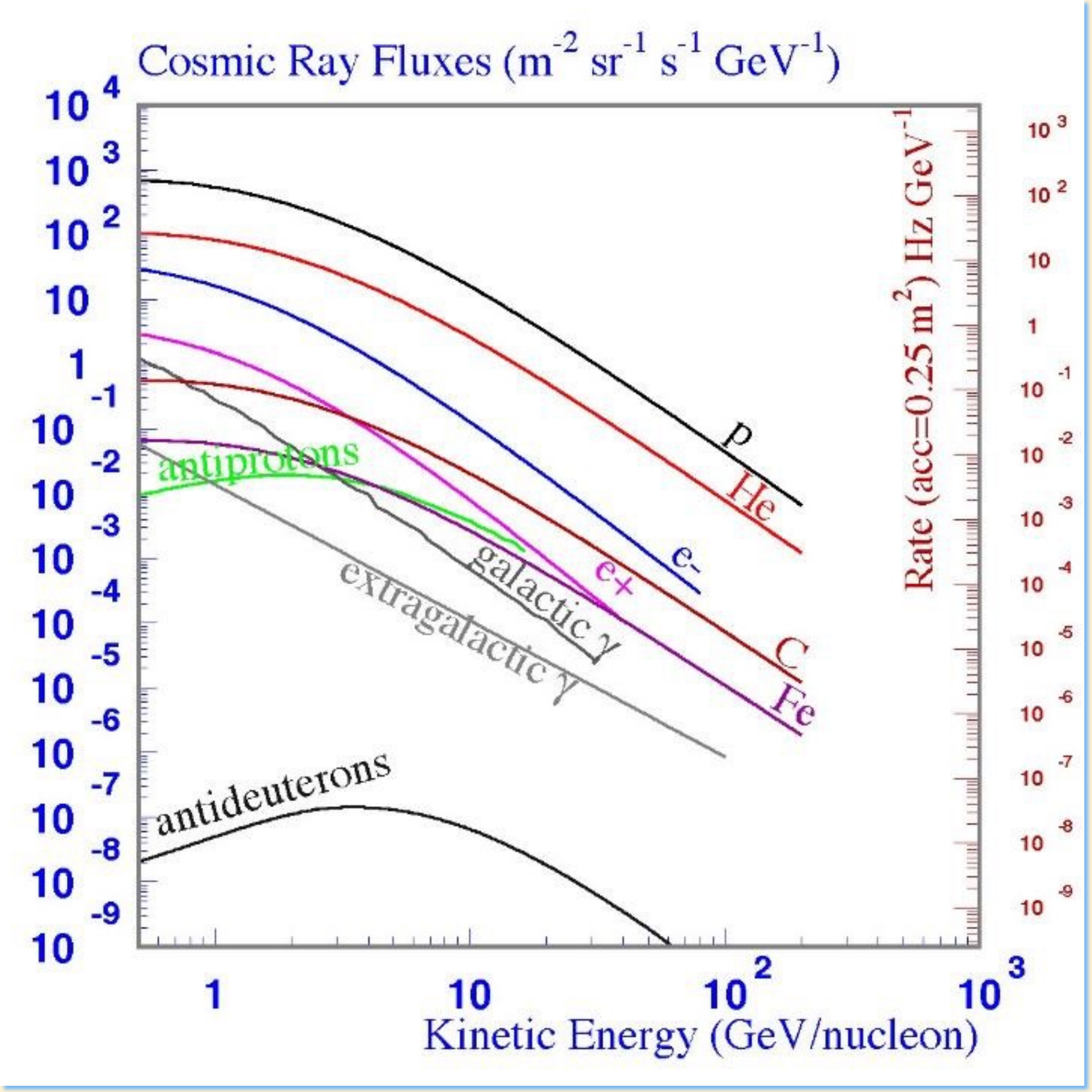
Circle, ellipse or
other depending on
the angle / position

β calculated
according to the
dimensions of the
figure on the plane
of the PMT

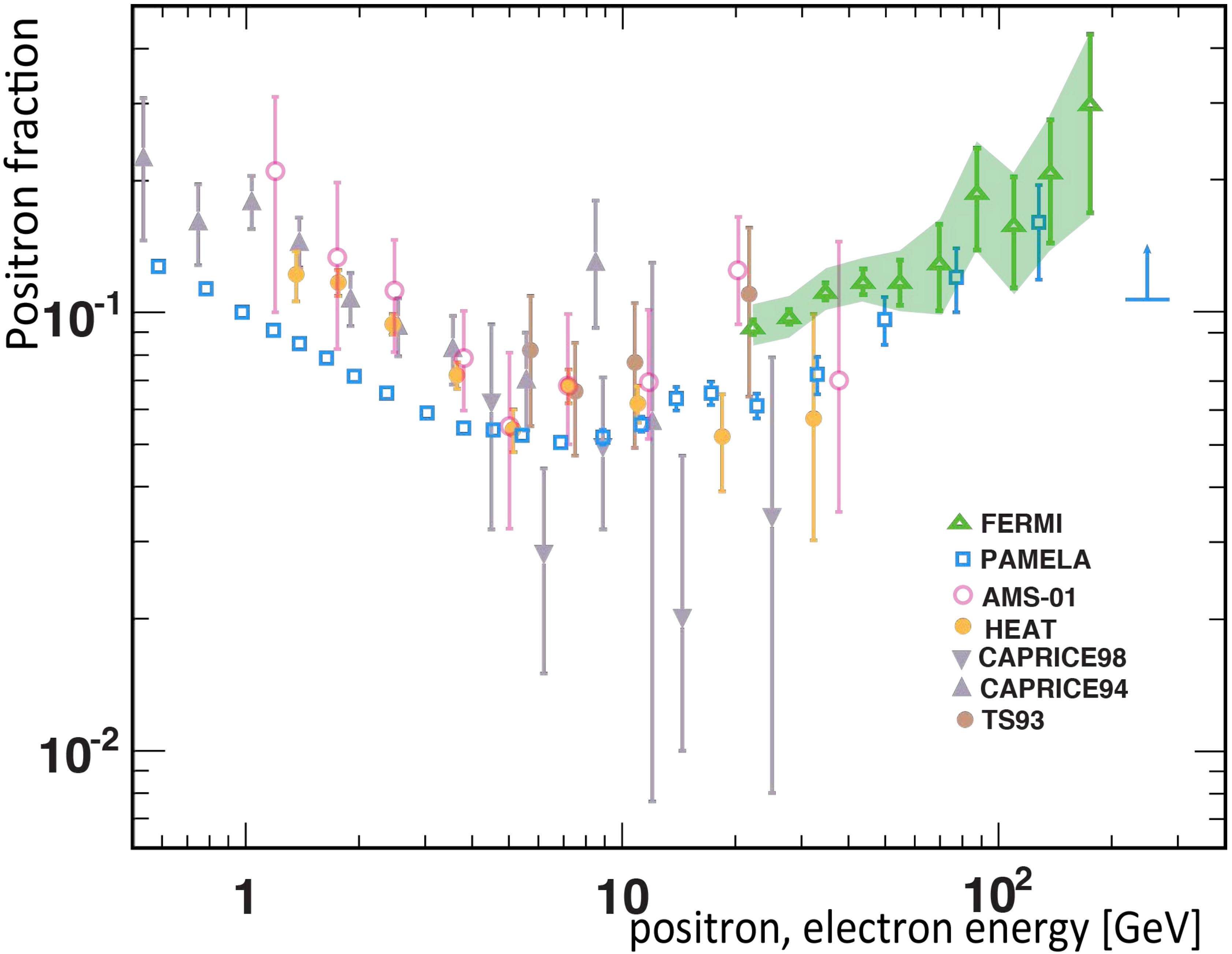
Used to distinguish particles of different masses
R = Rigidity (measured by the tracker)
Z = charge measured by tracker, TOF and RICH
b = measured by the RICH

$$m = RZ\frac{\sqrt{1-\beta^2}}{\beta}$$

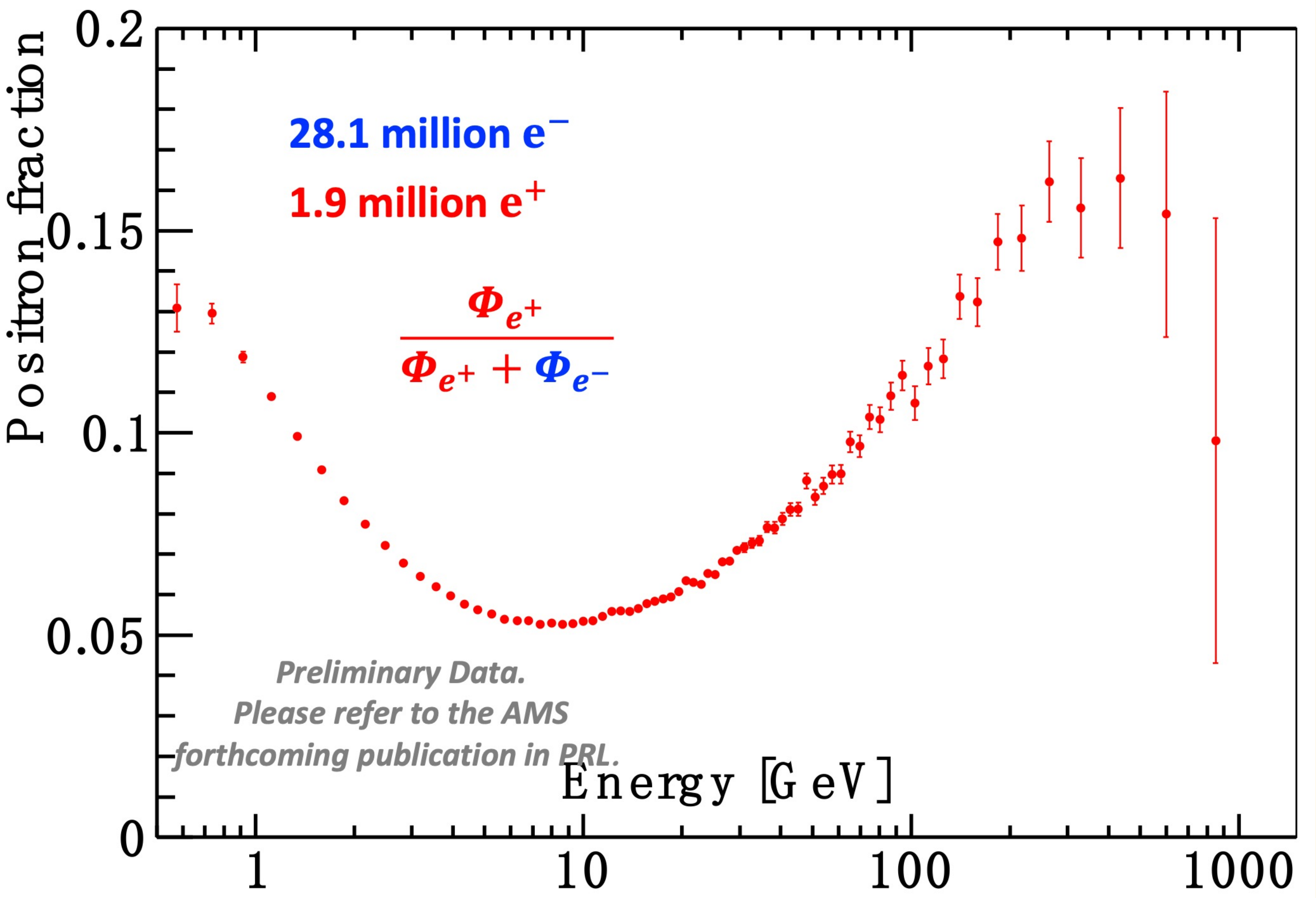
AMS results: fluxes of nuclei



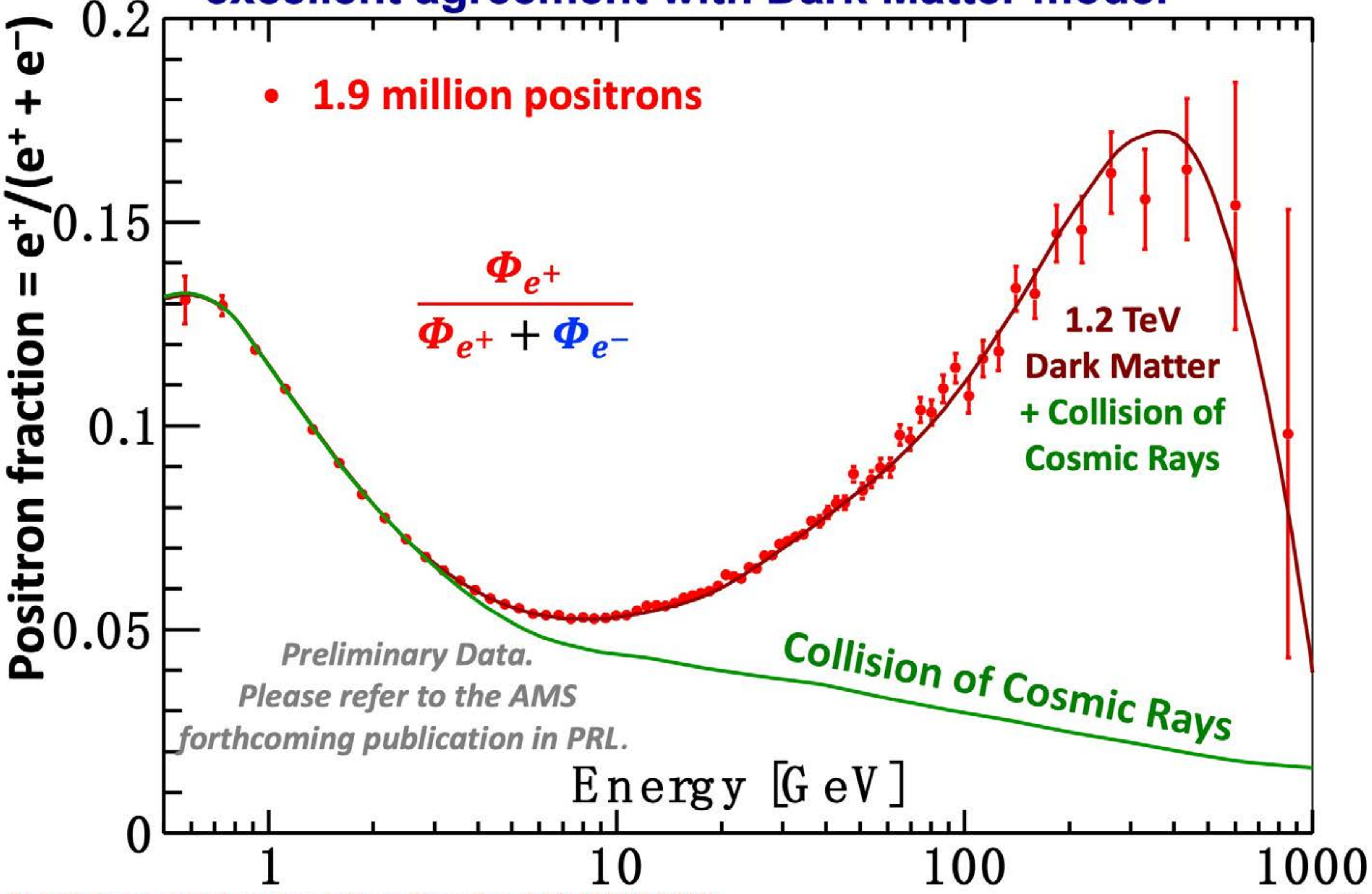
The $e^+/(e^++e^-)$ ratio before the AMS result



AMS positron fraction

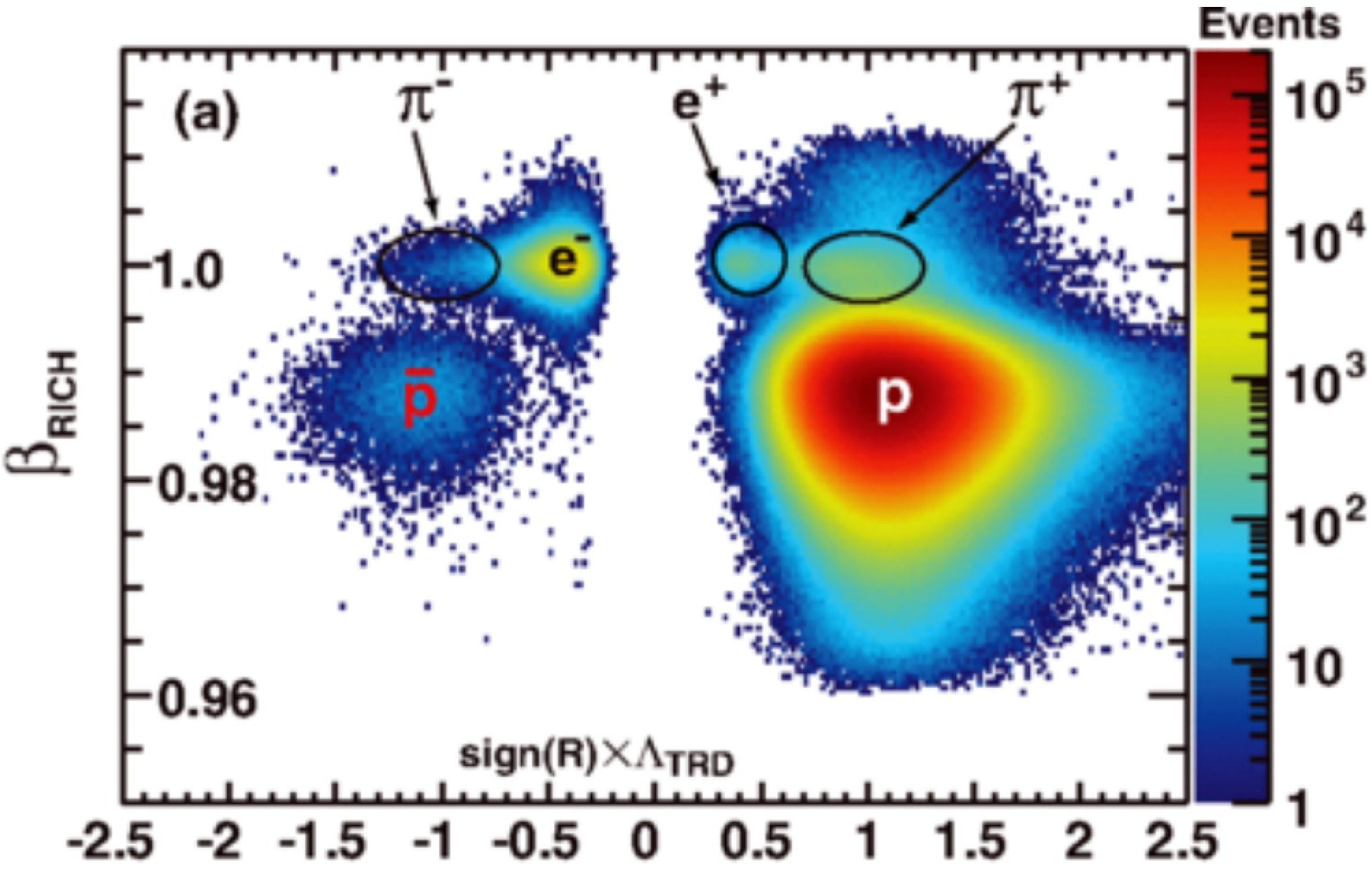


Latest AMS Positron fraction results appears to be in excellent agreement with Dark Matter model



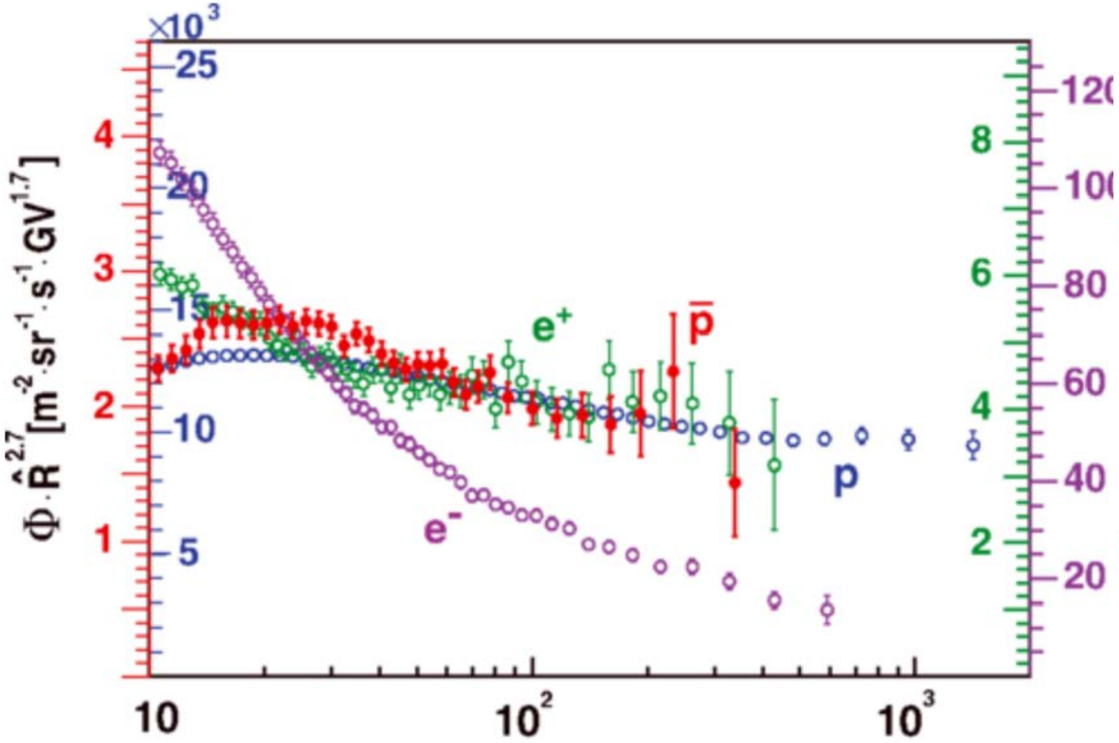
Dark Matter model is based on J. Kopp, Phys. Rev. D 88, 076013 (2013).

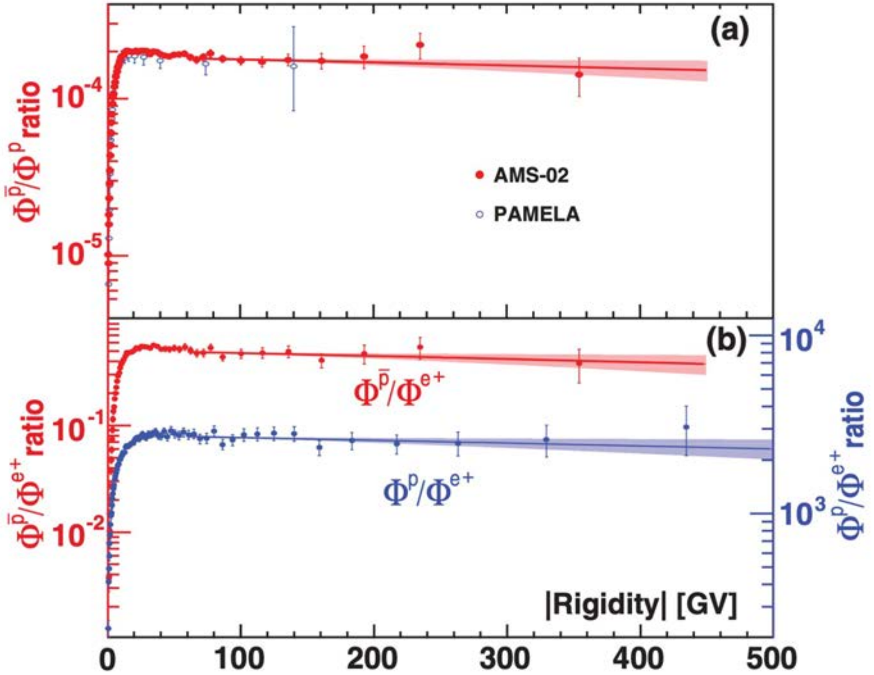
AMS – primary antiprotons/protons measurement
PRL 117, 091103 (2016)



Particle Identification with the AMS detector !

AMS – primary antiprotons/protons measurement
PRL 117, 091103 (2016)

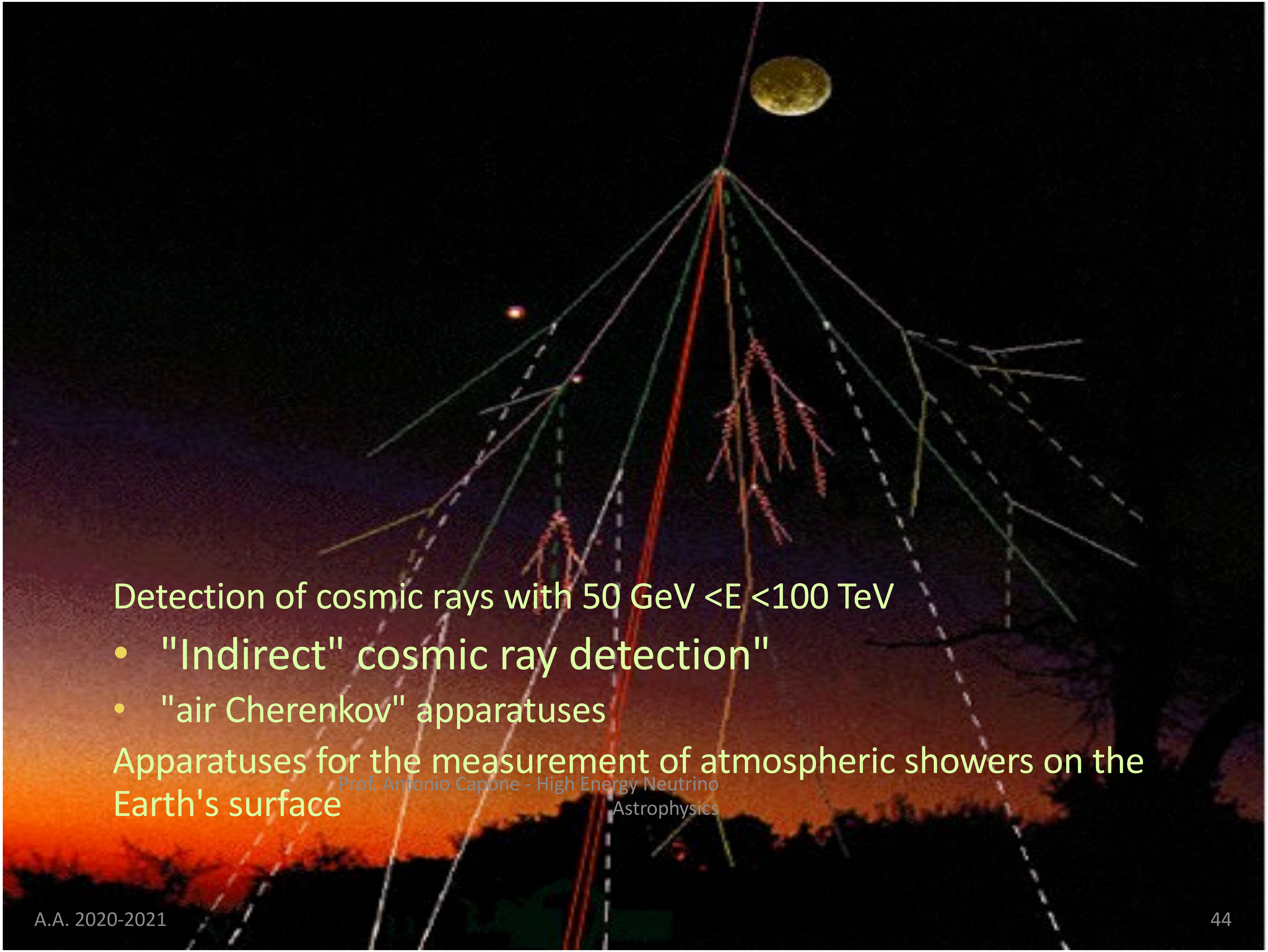




AMS paper conclusions:

“In the absolute rigidity range ∼60 to ∼500 GV, the antiproton, proton and positron fluxes are found to have nearly identical rigidity dependence. The electron flux exhibits a different rigidity dependence. …

These are new observations of the properties of elementary particles in the cosmos“

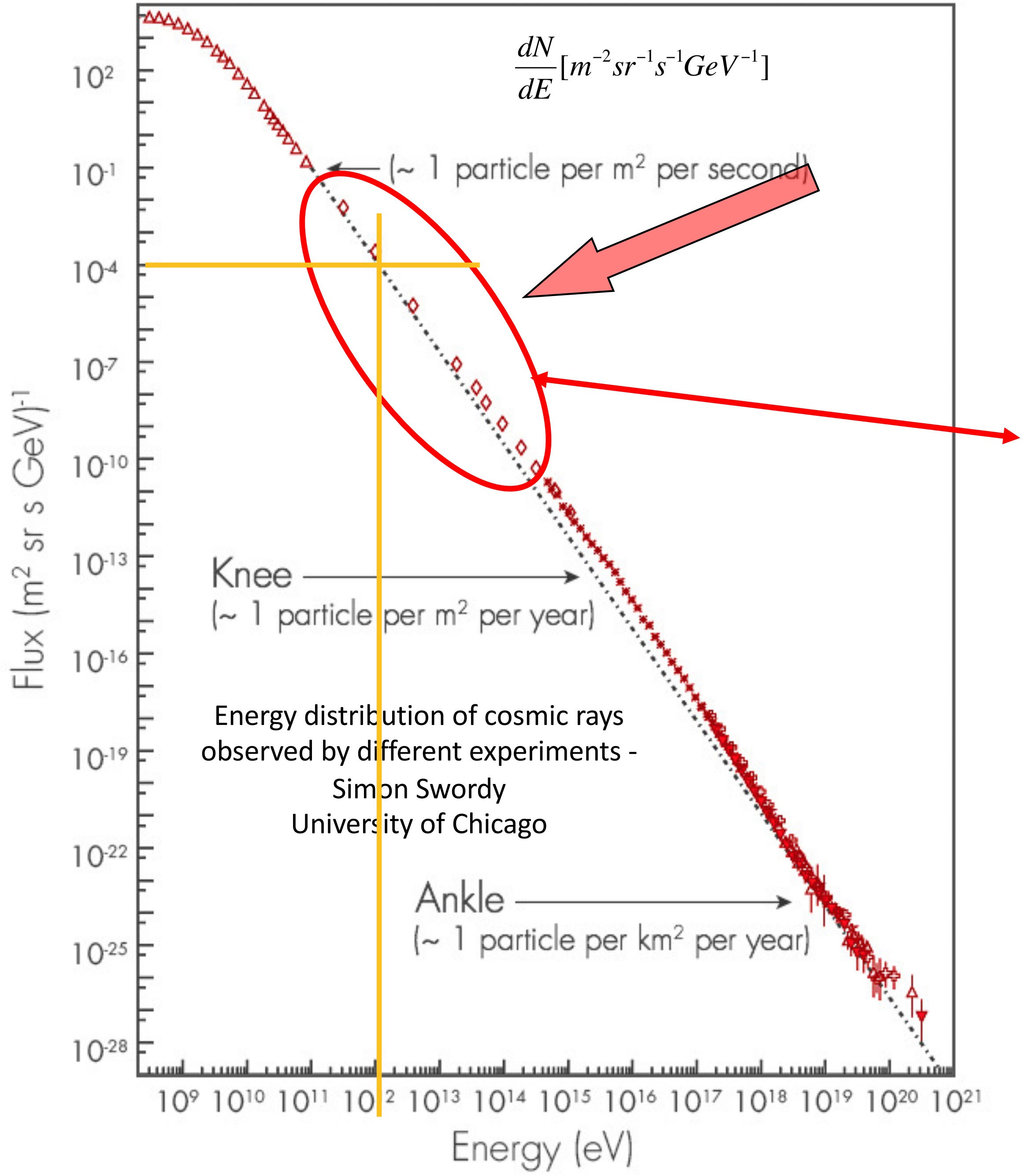


Detection of cosmic rays with 50 GeV <E <100 TeV

- "Indirect" cosmic ray detection
- "air Cherenkov" apparatuses

Apparatuses for the measurement of atmospheric showers on the Earth's surface

Cosmic Rays with energy > 50-100 GeV



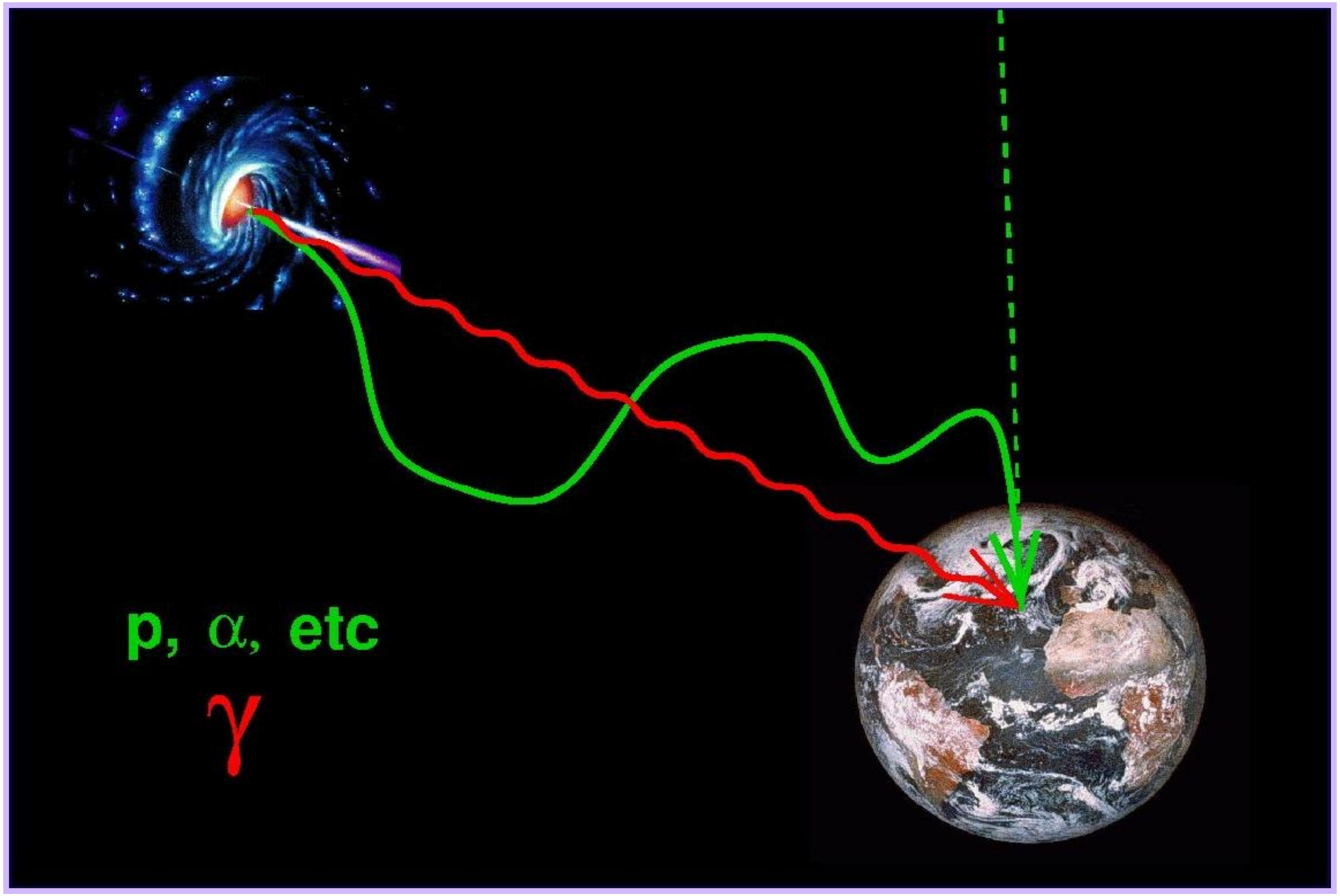
$\frac{dN}{dE}[m^{-2}sr^{-1}s^{-1}GeV^{-1}]$

Energy distribution of cosmic rays observed by different experiments - Simon Swordy University of Chicago

Indirect measurements

- extensive showers
- Cherenkov signals with Earth based detectors
- Underground detectors

- **γ's reach Earth undeflected from B-fields.**
- **Info on the accelerator (at least up to a certain distance.)**



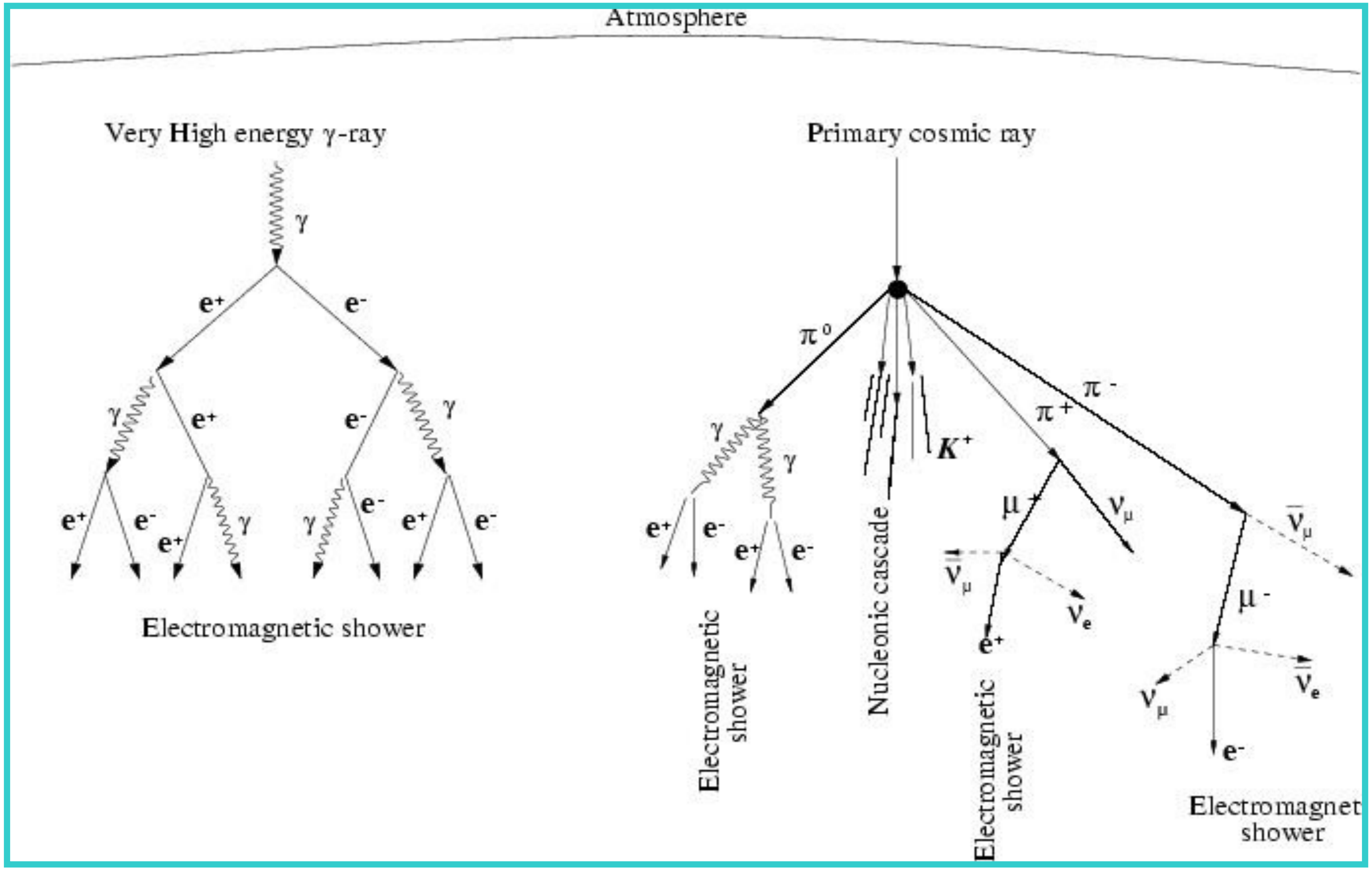
How to reveal the VHE (*) photons?

- Detectors large enough to measure the direction and estimate the initial energy of the photon
- It is not possible the use of anti-coincidences!
- Primary gammas from sources are rare ($<10^{-4}$ of the CR flux)
- Large Detectors ($10^3 m^2$) are required
- Showers detectors (EAS) - In competition with primary charged C.R. measurements

(*) 30 Gev - 30 TeV

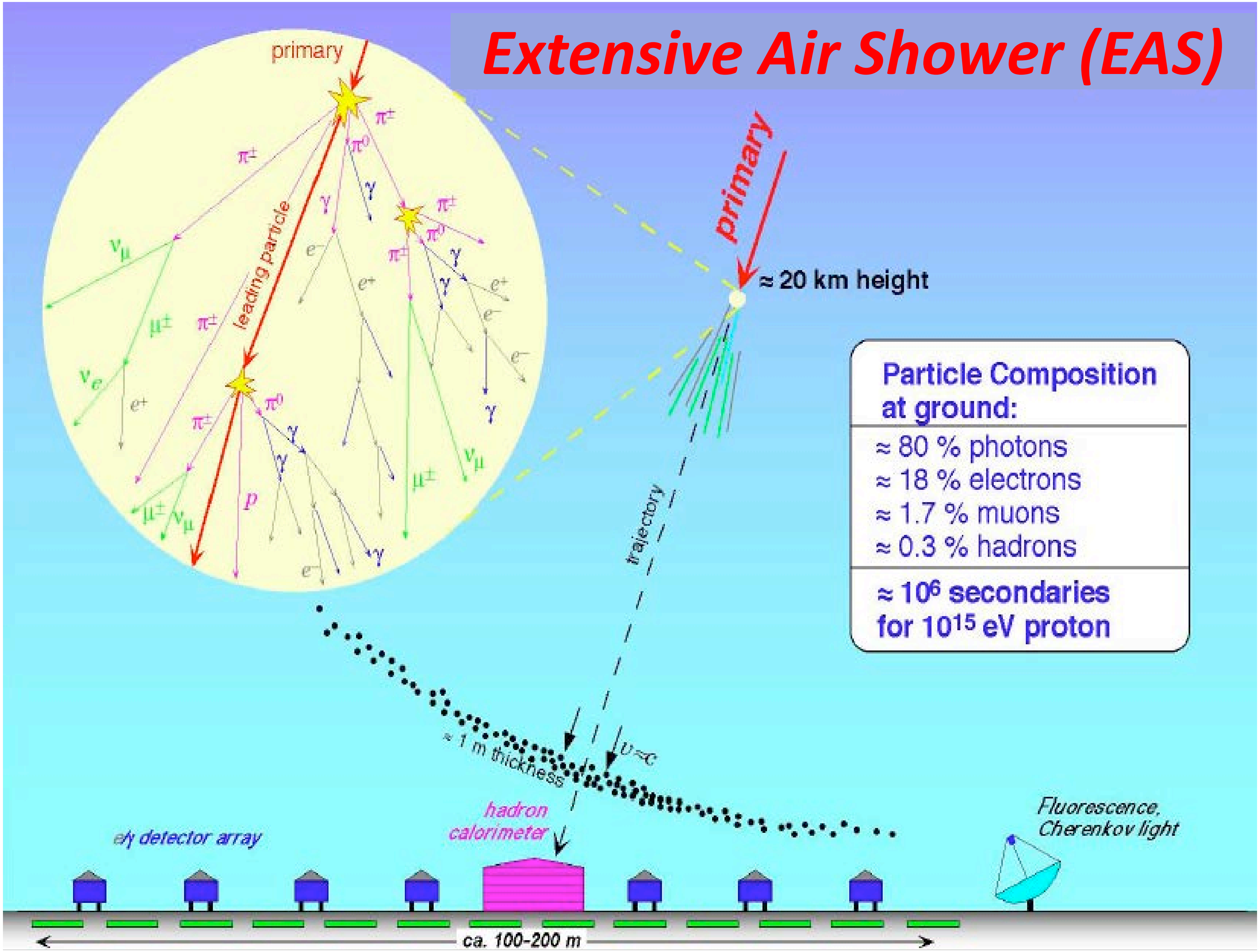
- VHE γ-rays induce elect. showers in the atmosphere.
- Charged CR also induce air showers.

Extensive air showers



Hadronic showers. The same principle as those e.m.
Production of charged pions ($\pi^{\pm}$ from which μ and ν) and neutral (π^{0} hence the γ)
On the ground arrive e^{+} e^{-}, photons (as in the e.m. electromagnetic) but also μ^{+}, μ^{-} and neutrinos
Apart from the content of $\mu^{+}\mu^{-}$ the hadronic and the electromagnetic showers are very similar

Extensive Air Shower (EAS)

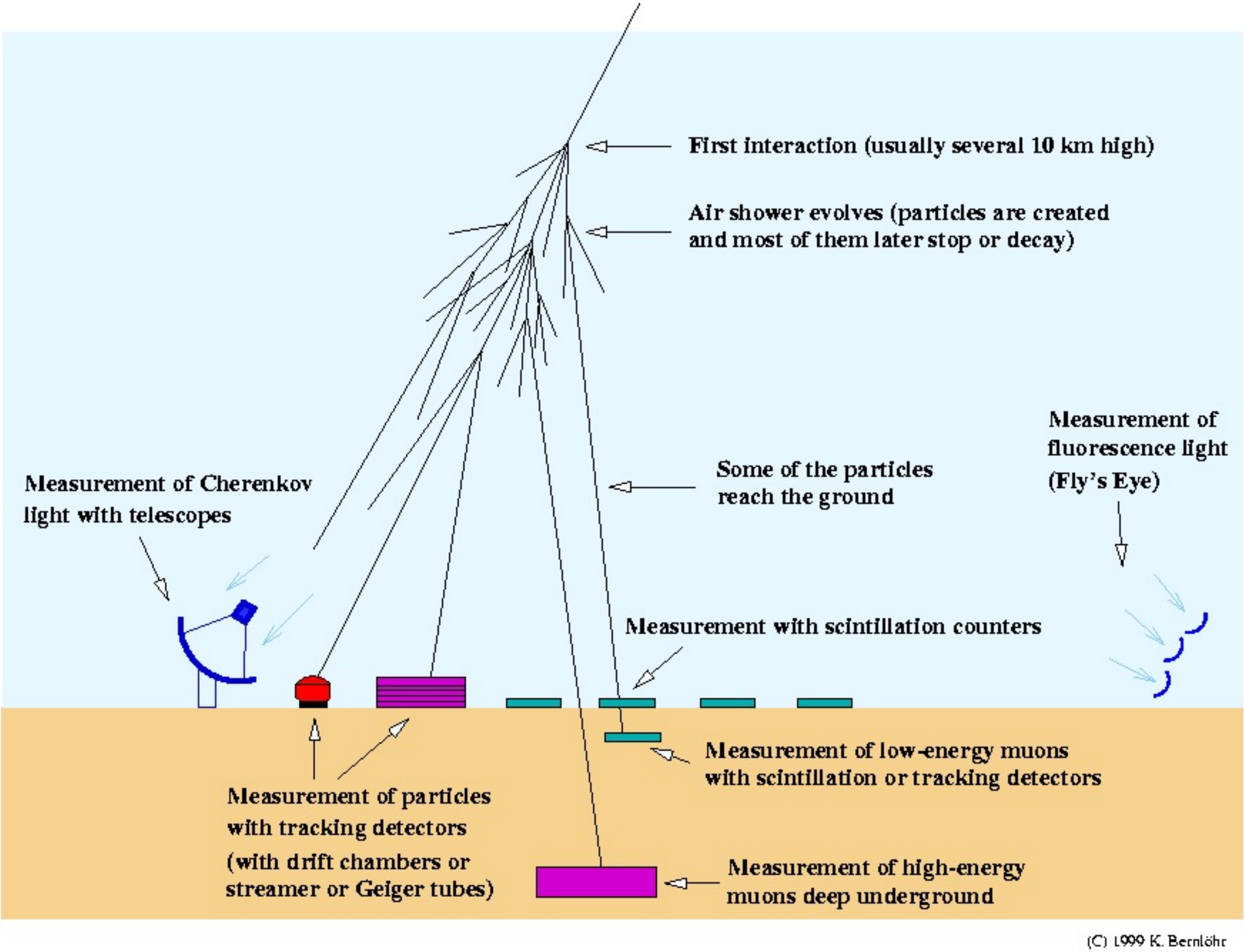


Particle Composition at ground:

- ≈ 80 % photons
- ≈ 18 % electrons
- ≈ 1.7 % muons
- ≈ 0.3 % hadrons

≈ 10^6 secondaries for 10^{15} eV proton

Measuring cosmic-ray and gamma-ray air showers


First interaction (usually several 10 km high)

Air shower evolves (particles are created and most of them later stop or decay)

Some of the particles reach the ground

Measurement of fluorescence light (Fly's Eye)

Measurement of Cherenkov light with telescopes

Measurement with scintillation counters

Measurement of low-energy muons with scintillation or tracking detectors

Measurement of particles with tracking detectors (with drift chambers or streamer or Geiger tubes)

Measurement of high-energy muons deep underground

(C) 1999 K. Bernlöhr

Simplified scheme for an EM shower development

”Toy Model” to describe an e.m. shower development

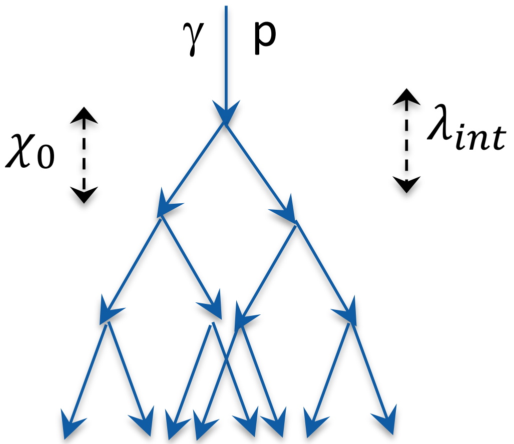
In each interaction:

- $e \rightarrow e'\gamma$
- $\gamma \rightarrow e^+e^-$

the number of particles doubles and the energy of each particles is ½ of the energy of the parent.

In each “step” t the N(t) increases and E(t) decreases:

$$N(0) = 1, \qquad E(0) = E_0$$
$$N(1) = 2, \qquad E(1) = \frac{E_0}{2}$$
$$N(2) = 4, \qquad E(2) = \frac{E_0}{4}$$
$$N(3) = 8, \qquad E(3) = \frac{E_0}{8}$$
$$N(t) = 2^t, \qquad E(t) = \frac{E_0}{2^t}$$



the multiplication of particles continue until the energy of electrons and gammas are sufficient to give the interactions **(1)** , i.e. until when the energy E(t)=E$_{critical}$. After that point the number of particles in the shower does not increase any more: the shower has reached the maximum development: we have: $N_{max} = N(t_{max})$

particles with energy $\boldsymbol{E(t_{max}) = \frac{E_0}{2^{t_{max}}} = E_{critical}}$ at a distance $\boldsymbol{X_{max} = \chi_0 \cdot t_{max}}$

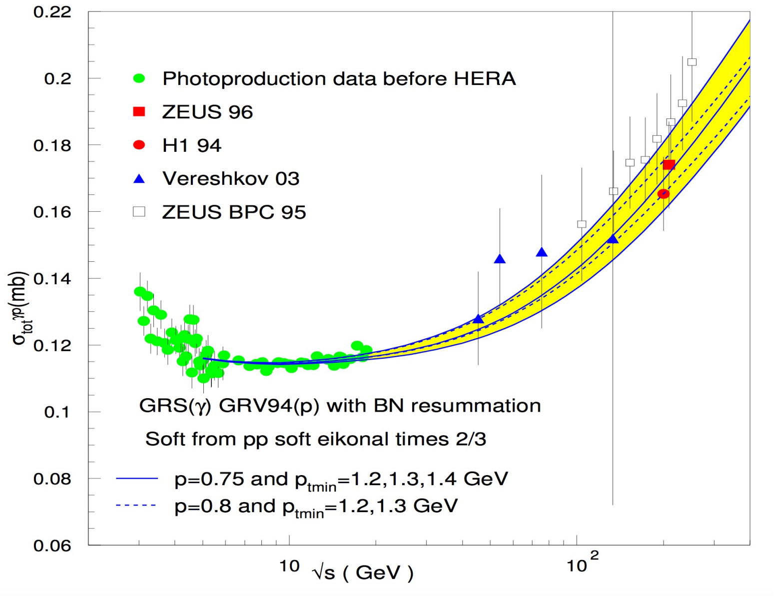
We can then write the relation $\boldsymbol{t_{max} = \frac{1}{\ln(2)} \ln(\frac{E_0}{E_{critical}})}$

Extensive Air Shower (EAS)

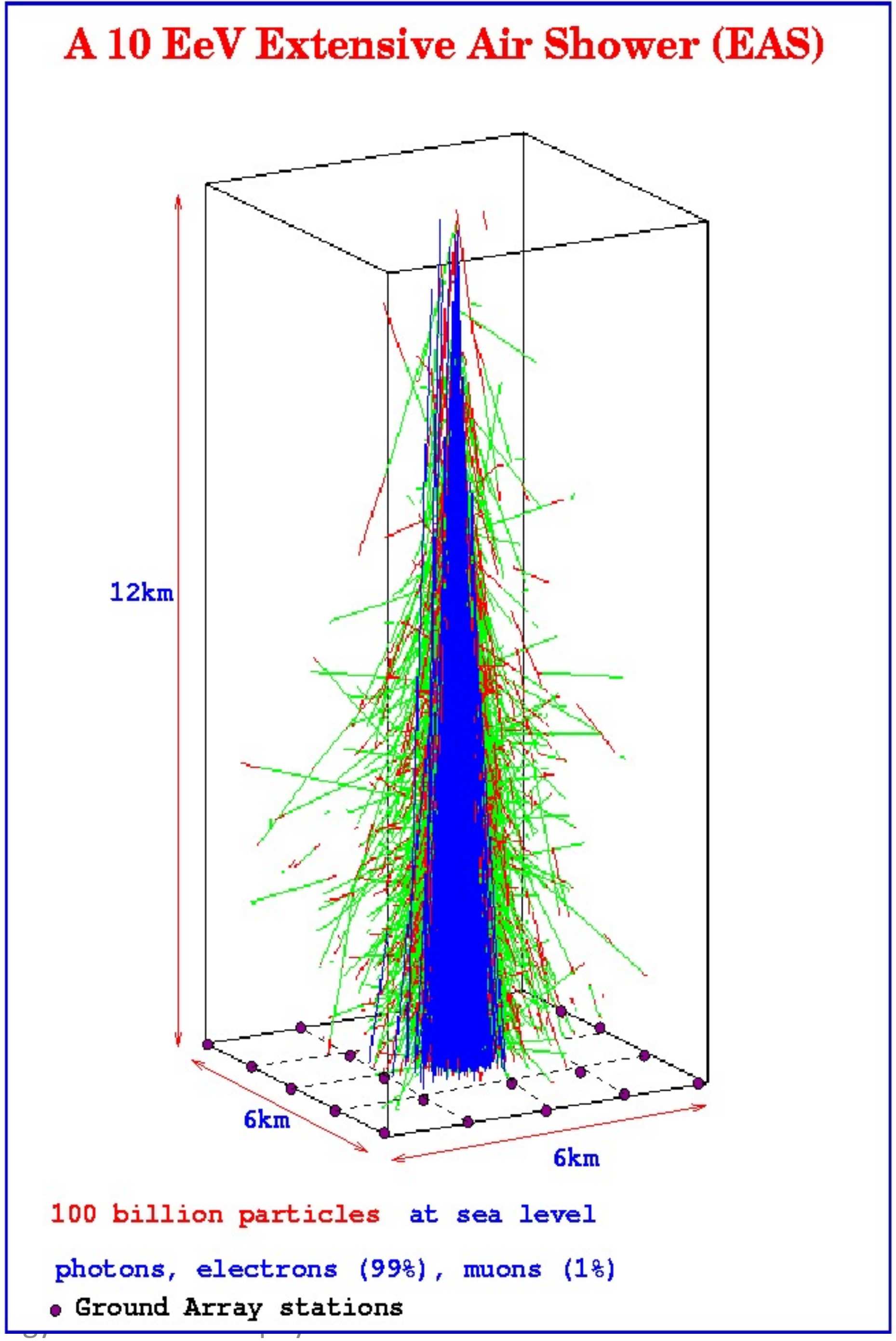
The VHE photons interact with atoms in the atmosphere. The products of these interactions are revealed at ground.
The cross-section γ-p was measured up to energies E_γ = 20 TeV. The extrapolations necessary are considered reliable.

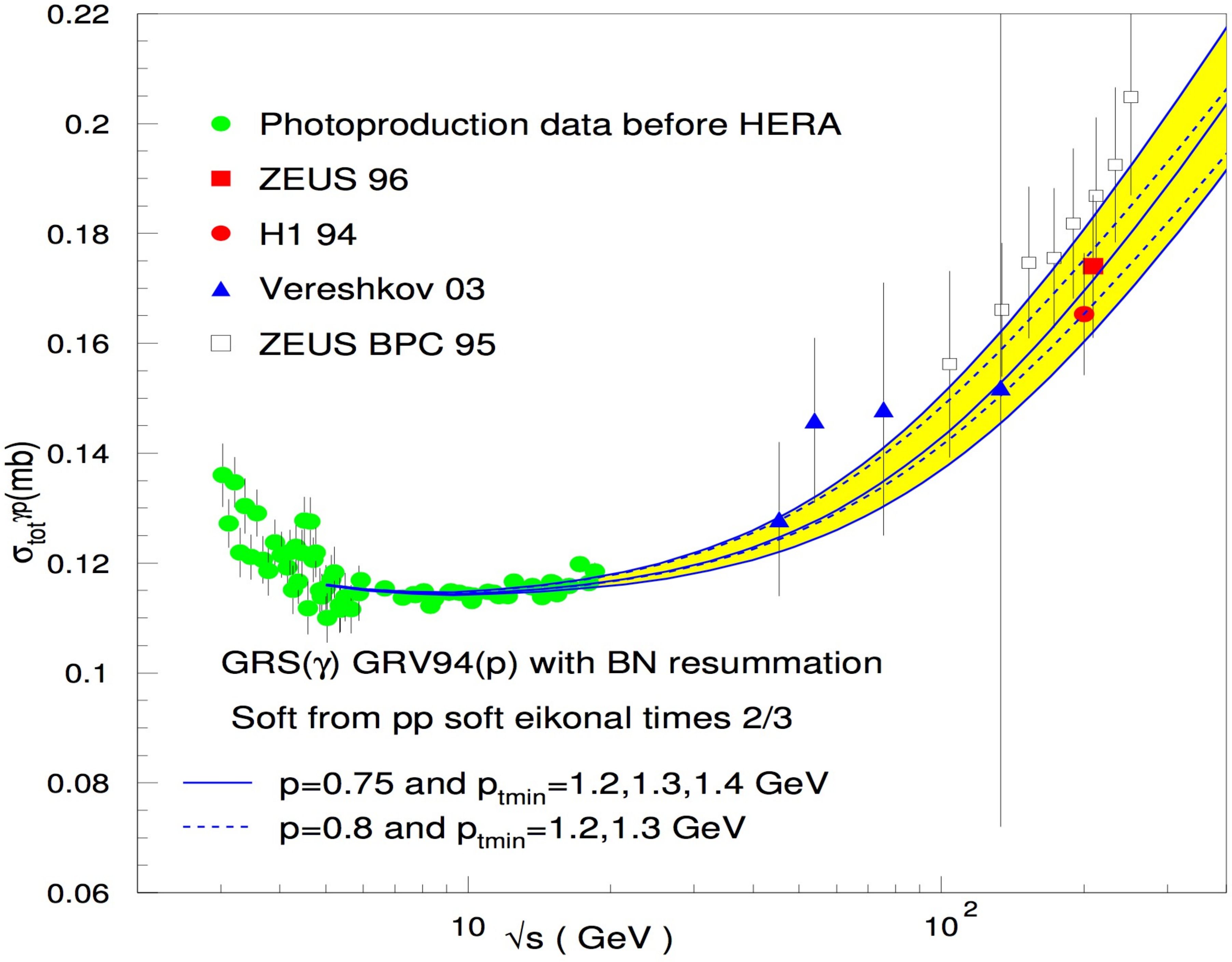
The "centre of mass" for γ+p is

$$\sqrt{s} \approx \sqrt{2E_\gamma m_p} = \sqrt{2 \cdot 20000 \cdot 1} = 200GeV$$



Shower development characterized by the "critical energy": E_c=80MeV




0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
$\sigma_{tot}{}^{\gamma p}$(mb)
Photoproduction data before HERA
ZEUS 96
H1 94
Vereshkov 03
ZEUS BPC 95
GRS(γ) GRV94(p) with BN resummation
Soft from pp soft eikonal times 2/3
p=0.75 and p_{tmin}=1.2,1.3,1.4 GeV
p=0.8 and p_{tmin}=1.2,1.3 GeV
10
10^2
√s (GeV)

EM showers characteristics

- ***longitudinal distribution***

$$\frac{dE}{dt} \propto t^{\alpha} e^{-\beta t}$$

- ***Position of shower maximum***

$$t_{max} = 1.4 \ell n \frac{E_0}{E_c}$$

- ***Longitudinal containment***

$$t_{95\%} = t_{max} + 0.08Z + 9.6$$

- ***Lateral containment dominated by multiple scattering (+ photon propagation)***

$$\langle \theta_M \rangle = \frac{21}{p\beta}\sqrt{t}$$

$$r_{95\%} = 2R_M$$

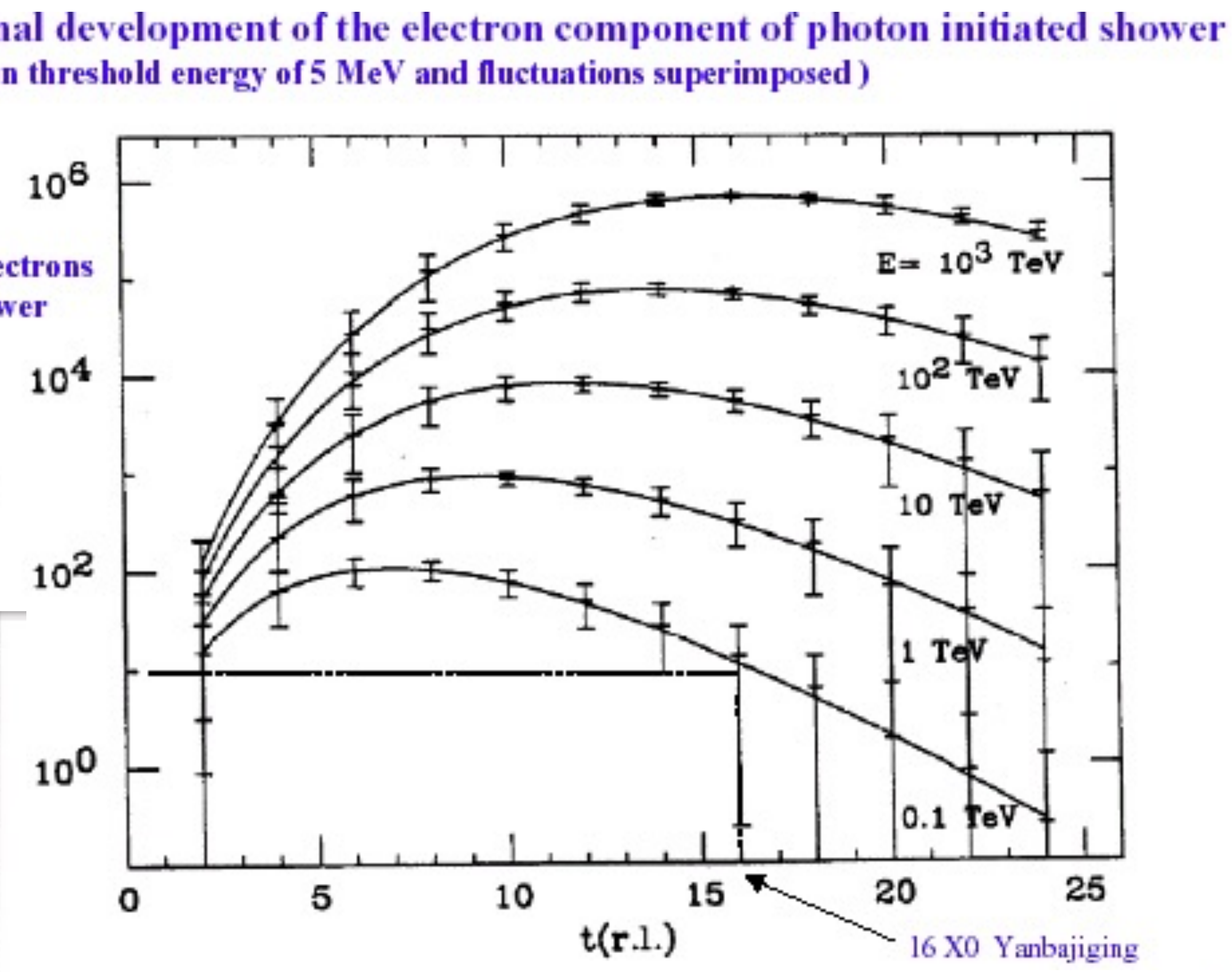
$$R_M = \frac{21MeV}{E_c} X_0 \quad g/cm^2$$ ***Molière radius***

$$R_M \propto \frac{X_0}{E_c} \propto \frac{A}{Z} \text{ per } Z >> 1$$

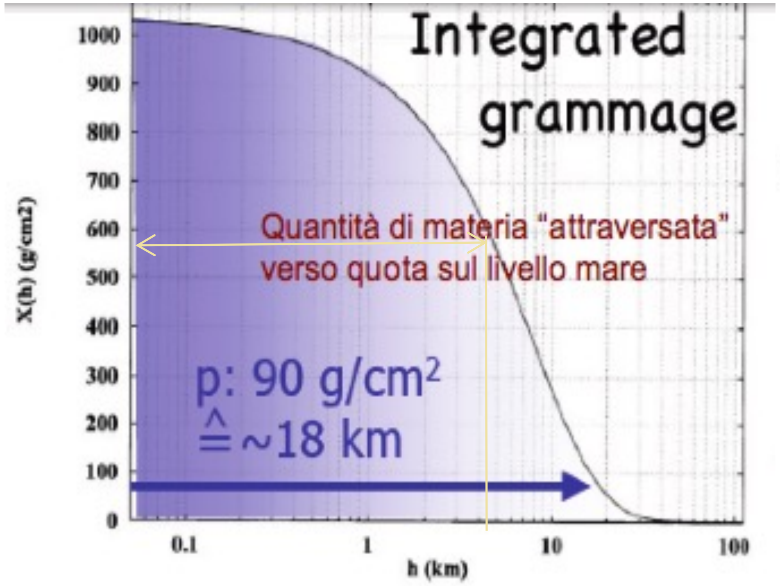
The electromagnetic component in a γ induced shower

Extended shower by γ measurements with high-altitude equipment: why ???

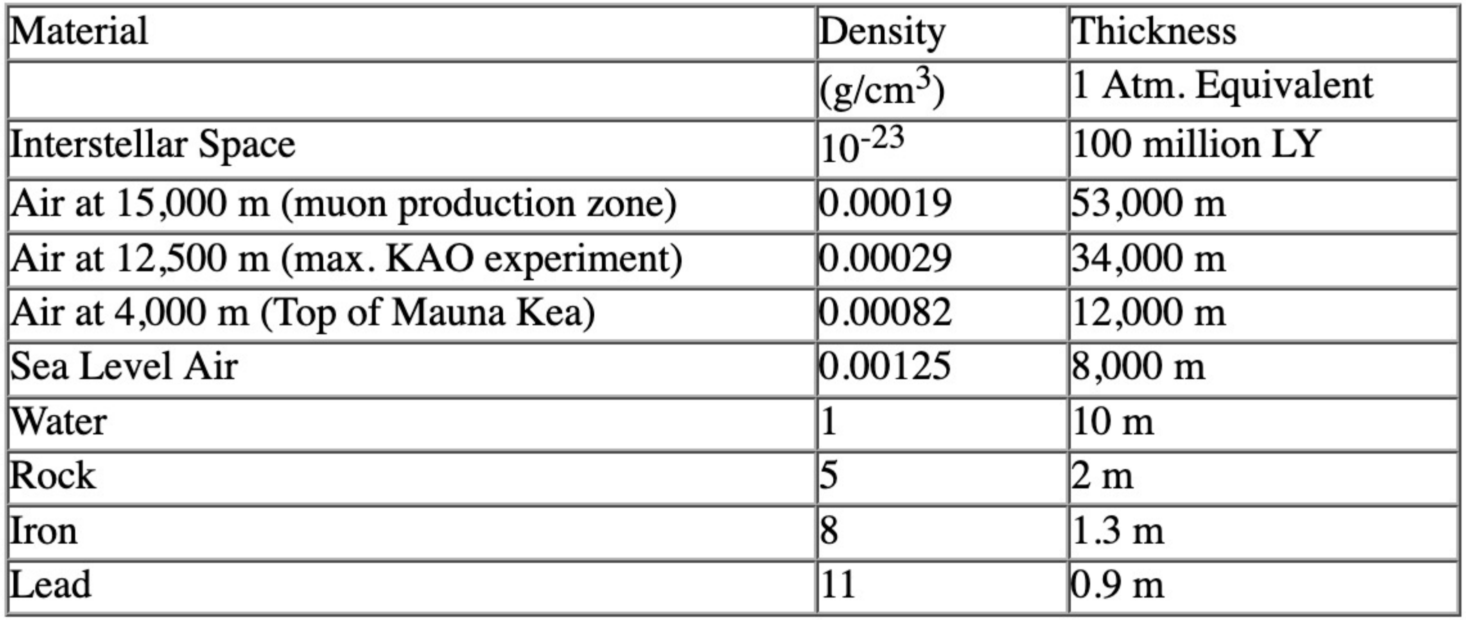
In air X_0 ~ 36.6g/cm^2 .
At 4300m s.l.m. a photon has crossed about 16 X_0



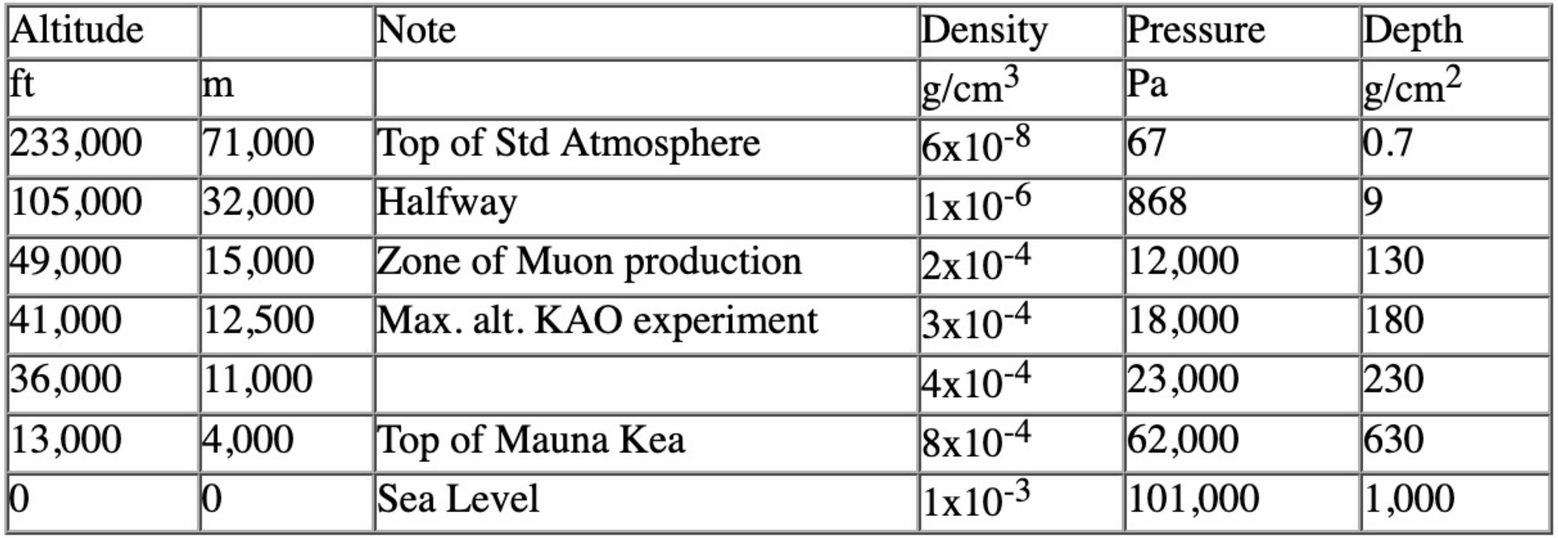
Shower depth as a function of radiation lenght



Some useful values



Material	Density	Thickness
	(g/cm^3)	1 Atm. Equivalent
Interstellar Space	10^{-23}	100 million LY
Air at 15,000 m (muon production zone)	0.00019	53,000 m
Air at 12,500 m (max. KAO experiment)	0.00029	34,000 m
Air at 4,000 m (Top of Mauna Kea)	0.00082	12,000 m
Sea Level Air	0.00125	8,000 m
Water	1	10 m
Rock	5	2 m
Iron	8	1.3 m
Lead	11	0.9 m



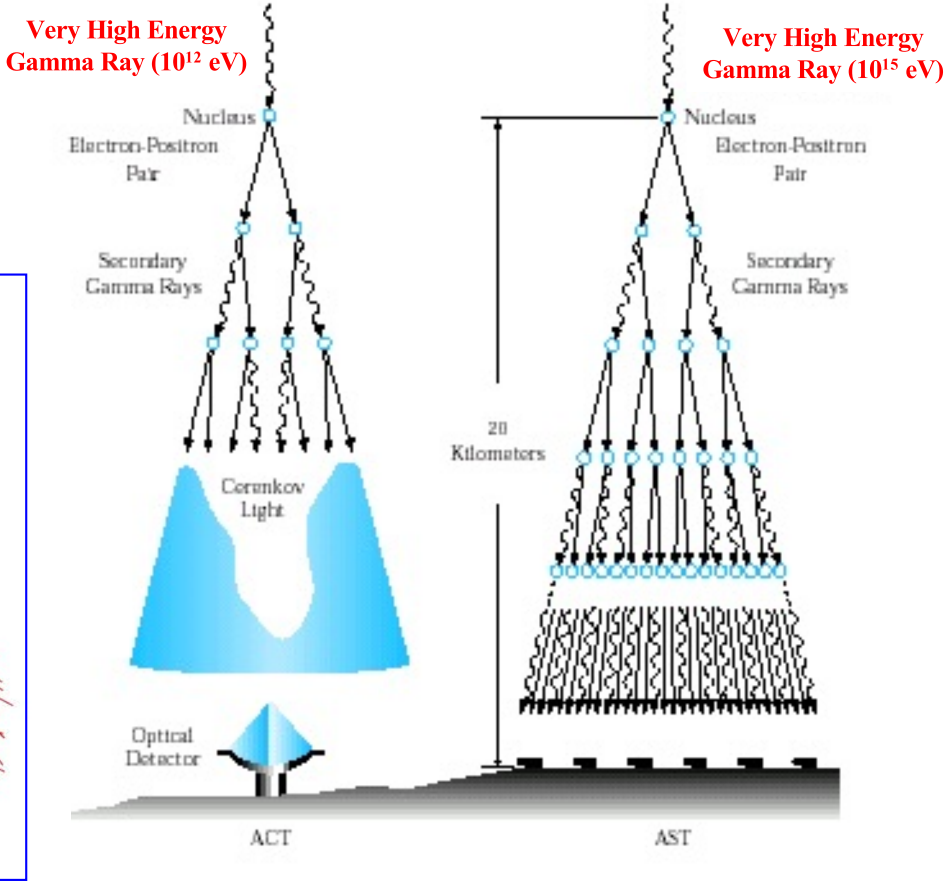
Altitude		Note	Density	Pressure	Depth
ft	m		g/cm^3	Pa	g/cm^2
233,000	71,000	Top of Std Atmosphere	$6\text{x}10^{-8}$	67	0.7
105,000	32,000	Halfway	$1\text{x}10^{-6}$	868	9
49,000	15,000	Zone of Muon production	$2\text{x}10^{-4}$	12,000	130
41,000	12,500	Max. alt. KAO experiment	$3\text{x}10^{-4}$	18,000	180
36,000	11,000		$4\text{x}10^{-4}$	23,000	230
13,000	4,000	Top of Mauna Kea	$8\text{x}10^{-4}$	62,000	630
0	0	Sea Level	$1\text{x}10^{-3}$	101,000	1,000

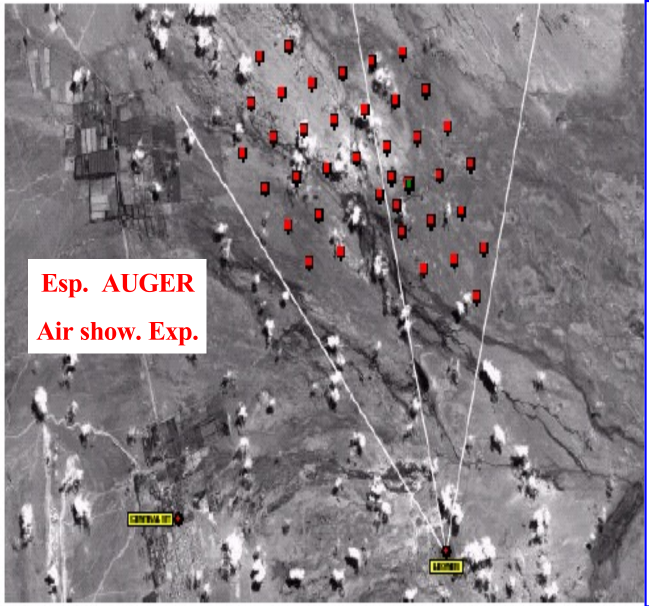
Experiments for the detection of showers in the air

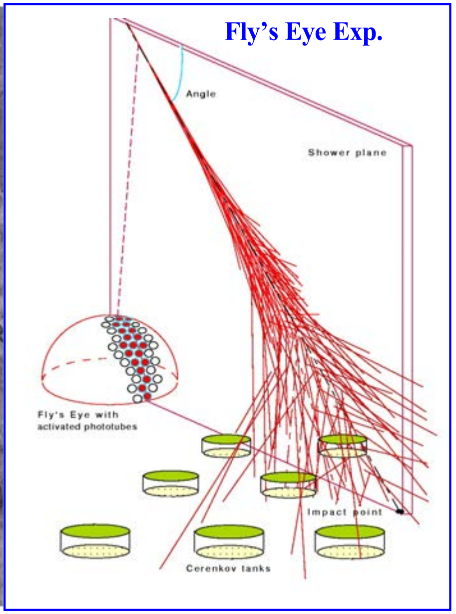
- **E_0 ~ 30GeV – 1TeV (Very High Energy)** the detection of showers in the air can be carried out with "optical" telescopes capable of detecting the Cherenkov light produced by relativistic charged particles in the upper atmosphere (the maximum amount of light located where the shower development is maximum) **- Air Cherenkov experiments**

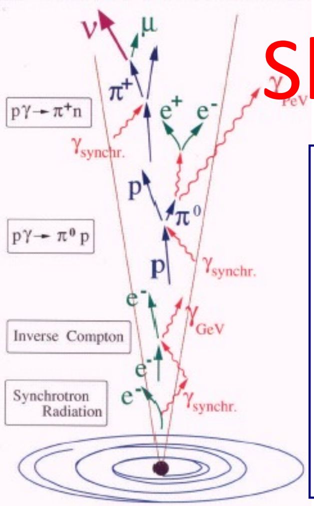
- **E_0 ~ 100 GeV - 1000 TeV (Ultra High Energy)** a detector placed in the mountains and made with large surface apparatuses is crossed by a sufficient number of particles to be "triggered" - **Classic Air shower experiments**

- **E_0 > 1000 TeV (Extreme UHE)** even a detector at sea level can be sensitive to extensive showers. - Detection of "fluorescence" radiation with apparatuses **Fly's Eye experiments**









Showers development in the atmosphere

γ , nucleons VHE o UHE interactions in high atm. ➡ Extensive Showers in Air (EAS)

In the shower: -3 components: electromagnetic, hadronic, muons

- **at the beginning $N_{e,p,\gamma,\mu}$ increases and ➡ $E_{e,p,\gamma,\mu}$ decreases**
- **when $E_{e,p,\gamma,\mu} > E_{critical}$ the number of particles grows**
- **when $E_{e,p,\gamma,\mu} \sim E_{critical}$ the number of particles reached the max value** ⬅ **N_{max}**
- **when $E_{e,p,\gamma,\mu} < E_{critical}$ no new particles generated, the shower goes to end**

Hadrons -> production π^0, π^+,π^-

For each hadronic interaction → ~1/3 of the energy goes into the electromagnetic component

π^0, $\eta \rightarrow \gamma\ \gamma \rightarrow e^+ e^- \rightarrow$ electromagnetic shower

$e^+ e^-$ after the shower maximum decrease in number since $E_{e+\ e-} < E_{critical}$ (~80MeV) and ionization processes predominate on production of pairs and irradiation

π^+, π^-, κ^+, $\kappa^- \rightarrow$ μ^+, μ^- "penetrants"

muons in air shower initiated by π, κ have bigger probability for "low energy mesons"-

$e^+ e^-$ they are the most numerous particles in the shower in the air, most of the E_0 energy of the R.C. primary is dissipated in ionization energy by e + e-, a part F (E_0) is transported by neutrinos.

The energy dissipated in ionization can be measured by integrating on the development of the shower $(1-F)\cdot E_0 \sim \alpha \cdot \int_0^\infty N(X)dX$ **where N (X) is the number of charged particles at depth X and at is the energy lost per unit of path in the atmosphere**

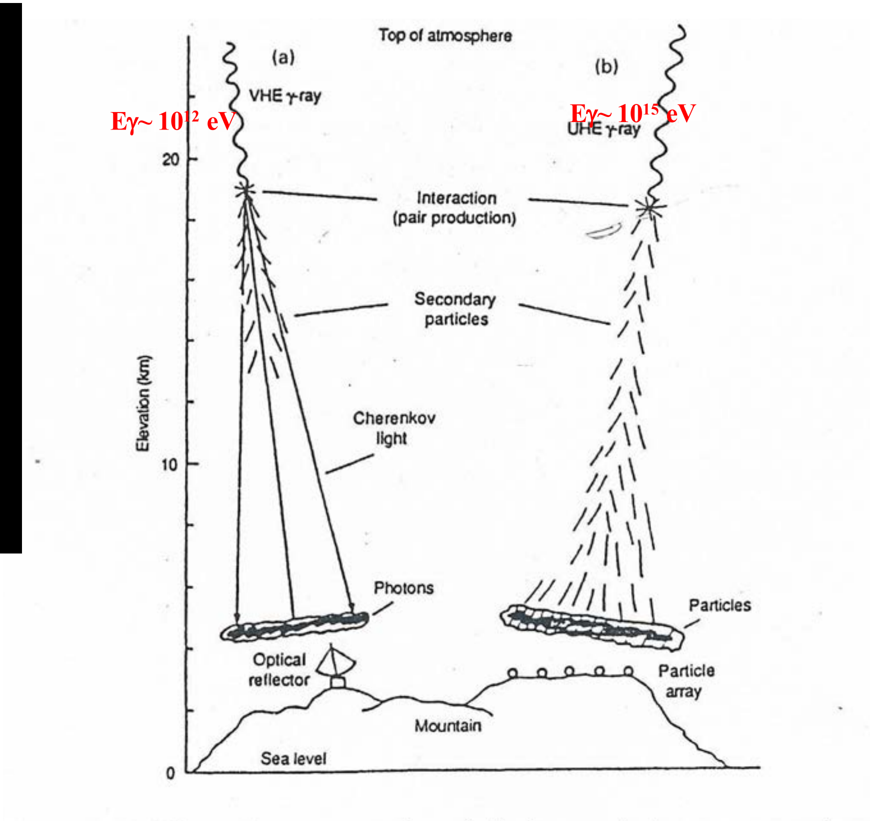
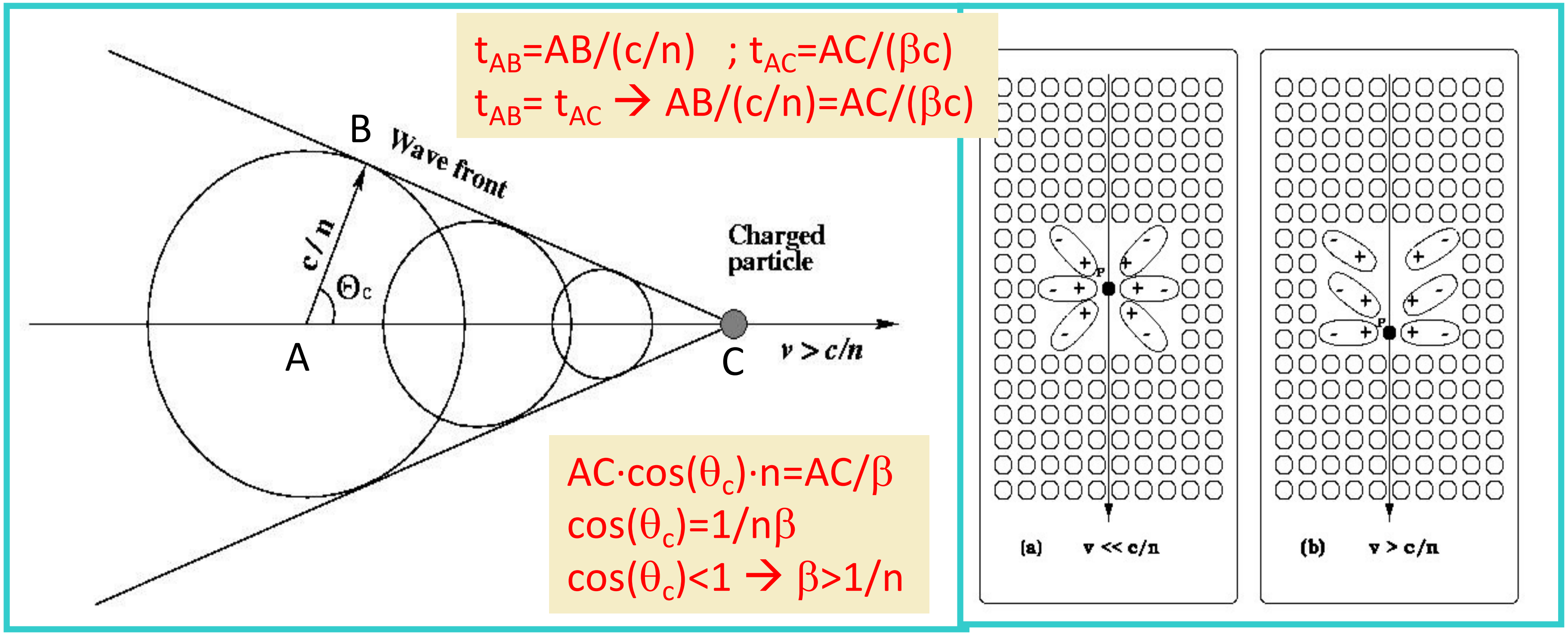


Figure 14.1: Schematic representation of air showers in two energy regions and the corresponding detectors: (a), $E \sim 1$ TeV, air Cherenkov telescope; (b) $E \sim 1$ PeV, air shower array. (From Lamb & Weekes 1987. © 1987 by AAAS.)

Cerenkov effect (I)



$t_{AB}=AB/(c/n)$; $t_{AC}=AC/(\beta c)$

$t_{AB}=t_{AC} \rightarrow AB/(c/n)=AC/(\beta c)$

$AC\cdot\cos(\theta_c)\cdot n=AC/\beta$

$\cos(\theta_c)=1/n\beta$

$\cos(\theta_c)<1 \rightarrow \beta>1/n$

- Cerenkov radiation emitted when a charged particle travels with *v>c/n* in the medium

$$\beta > \frac{1}{n} \quad ; \quad \cos\Theta_c = \frac{1}{\beta n} \quad ; \quad \frac{d^2N}{dx\,d\lambda} \propto \frac{1}{\lambda^2}$$

- Mostly “blue” photons.

Cherenkov light production in the air

At sea level, the air refractive index is $n=1.00029$.

For a relativistic particle with $\beta=0,9999$ we have Cherenkov light production; the angle of light propagation is given by:

$$\cos(\theta_{Cherenkov}) = 1/(\beta n) \Longrightarrow \theta_{Cherenkov} \sim 23 \text{ mrad} \sim 1.3^\circ$$

The threshold condition for the Cherenkov effect $(\cos(\theta_{Cherenkov}) \leq 1)$ implies the following conditions for electrons and muons:

$$E_{thr} \text{ for production of light Cherenkov in the air} < \begin{cases} \text{electrons} & E_e \geq 21 \text{ MeV} \\ \text{muons} & E_\mu \geq 4.4 \text{ GeV} \end{cases}$$

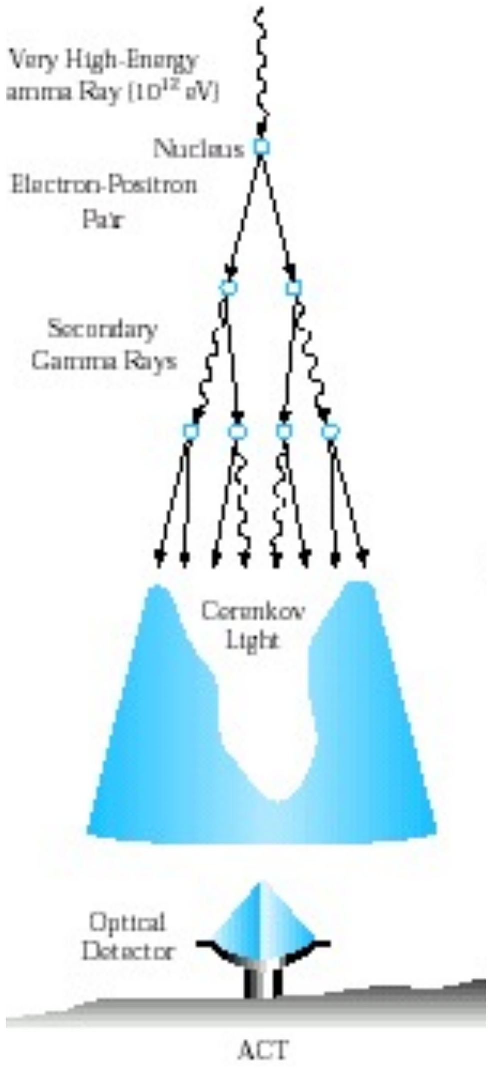
The maximum development of the shower (therefore the maximum production of light Cherenkov) is at ~ 10 km in height.

This implies that the area illuminated on the ground has a circular/elliptical shape (depending on the inclination of the primary RC) and has a:

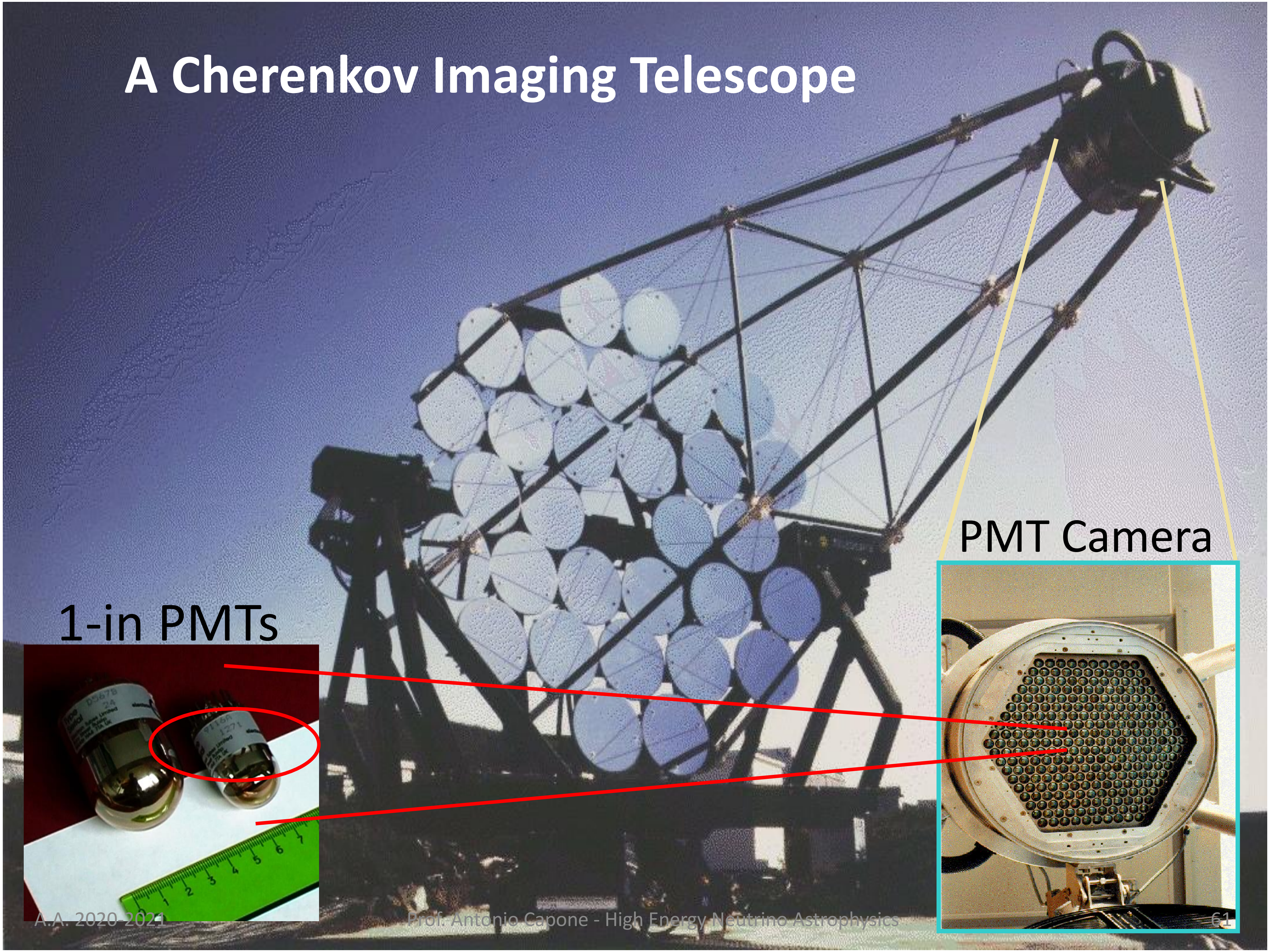
radius ~ 10000*0.023 = 230m.

The illuminated surface therefore has a size of 1.6×10^5 m^2. Likewise we can say that an observer (an instrument) on the ground can receive light from any point of a surface of 1.6×10^5 m^2 placed at 10 km of height.

We can easily calculate the n. of Cherenkov photons emitted as a function of the wavelength. For the "visible" radiation ($350 < \lambda < 500$ nm) we expect, in an "electromagnetic" shower started by 1 photon of 1 TeV, about $N_\gamma \sim 8.2 \cdot 10^3$ photons/λ, this leads to the ground a photons flux ~ 30-50 photons/m^2 in an area within 100m of the shower axis.



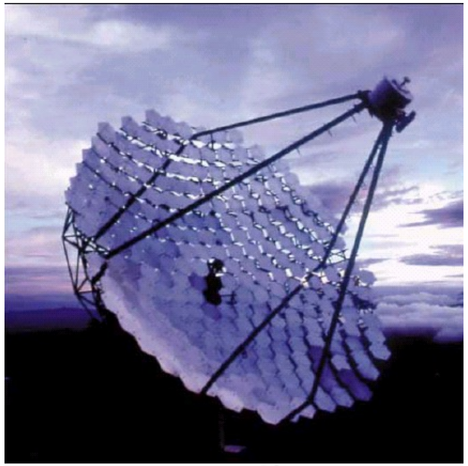
A Cherenkov Imaging Telescope

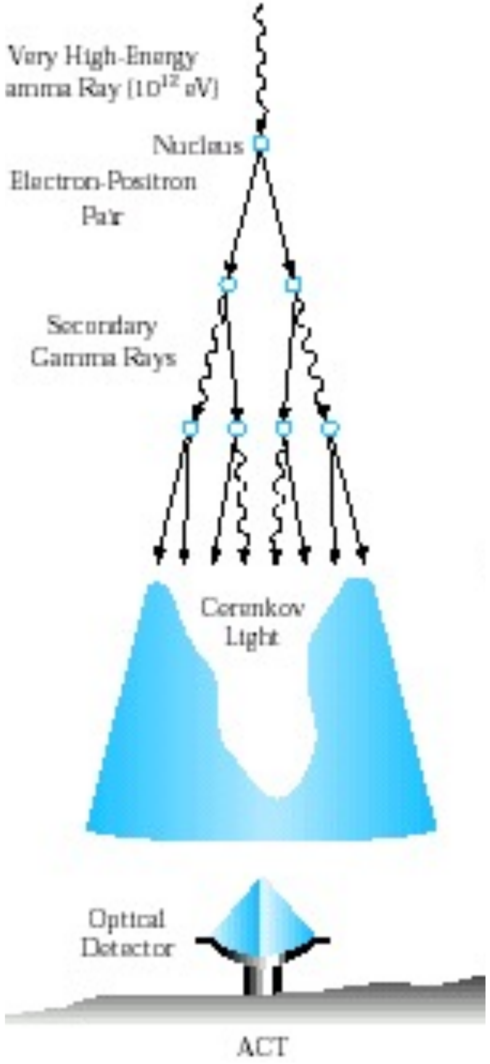


1-in PMTs

PMT Camera

Air Cherenkov experiments





The shower direction is determined by the directionality of the emitted Cherenkov light (at an angle ~ 0 with respect to the direction of the primary particle).

The maximum of the shower is typically at ~ 10km, the observed angular range is ~ 1 degree → the observed area is ~ 10^5 m^2 .

- They can collect data only during moonless nights and with good visibility (10% of the time).
- point sources can be studied only if above the horizon (duty cycle 10-20%)

What is the expected background ???? We want to reveal "photons" with $E_\gamma >$ TeV, the background consists of showers initiated by charged C.R. much more frequent than γ,

Flux of C.R. with E>TeV ~ 10^{-5} cm^{-2} sr^{-1} s^{-1} → 10^{-1} m^{-2} sr^{-1} s^{-1}

- If the effective collection area ~10^5 m^2 in an angular interval of 1° → ~ $A_{eff} F_{>1TeV} \Delta\Omega = 10^5 \cdot 10^{-1} \cdot 1.2 \cdot 10^{-3} \sim 10$ showers/s (due to C.R.)
- Then collecting data, for any astronomical coordinates, for a time equal to 30 h (10^5 s) → 10^6 background events (do to C.R.).

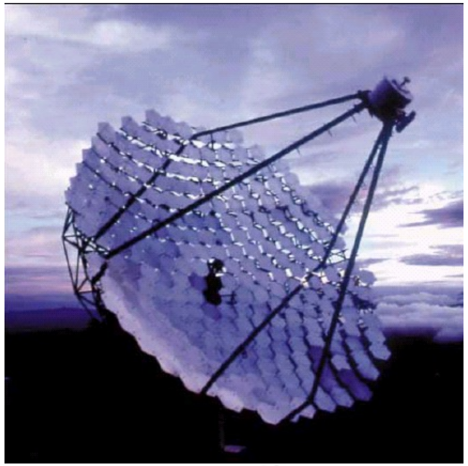
A possible point source could be visible only if it will give rise to a number of events statistically superior to the “fluctuation of the background”:

$$N_{\text{minimum signal}} > 3 * (10^6)^{0.5} = 3000$$

this corresponds to a flux of photons from the source equal to

$$3000 / (10^5 \text{ s} \cdot 10^9 \text{ cm}^2) = 3 \cdot 10^{-11} \text{ photons/ s} \cdot \text{cm}^2$$

Air Cherenkov experiments

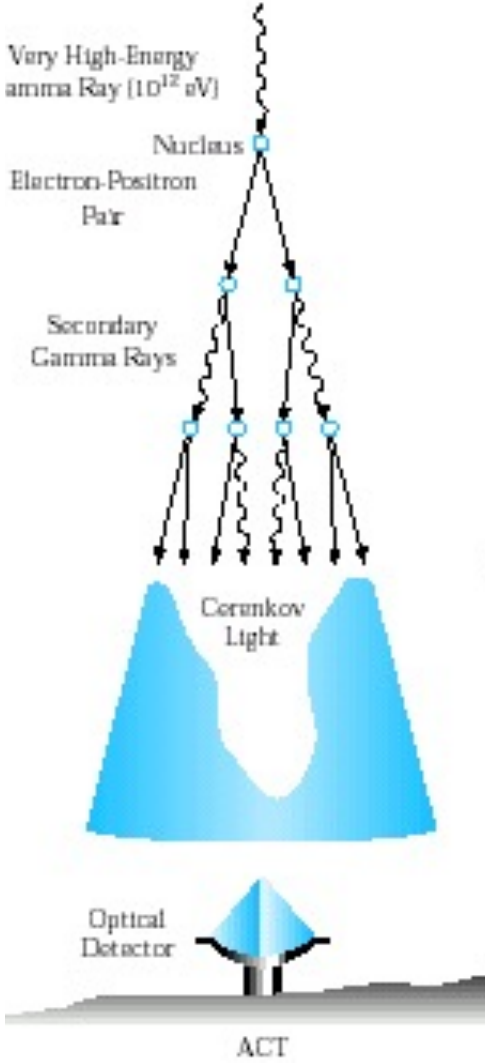


We can reconstruct the energy of the "primary photon" from the total amplitude of the signals on the PMT that collect the light from the reflector (experimental determination that requires a calibration)

calibration:

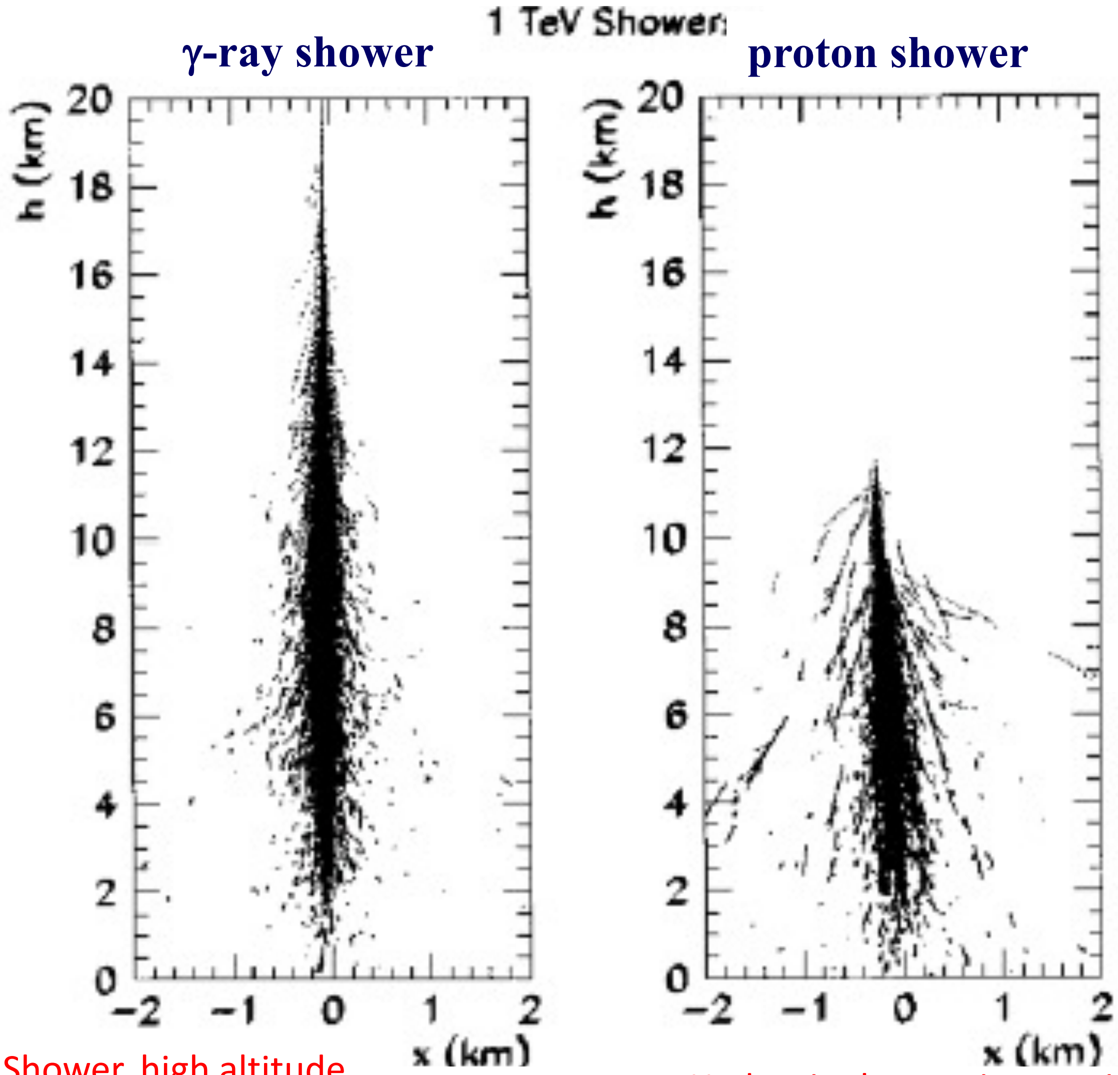
- **first one estimate the acceptance of the telescope (area * solid angle) then one compare the integral of the C.R. spectrum with the frequency of events observed as a function of the threshold in energy (ie of the signal on the PMTs)**
- **The above information are than compared with other detectors**

We can distinguish the nature of primary C.R. (photon or charged C.R.) from the "shape" of the shower ...



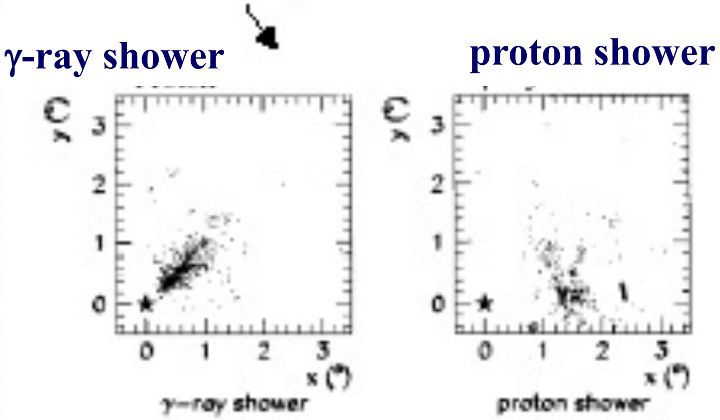
Development of vertical air showers originated from 1 TeV γ or p

In a "Cherenkov telescope" it is possible to distinguish the "leptonic" or "hadronic" nature of the "primary" thanks to the different properties of the showers produced by them.



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

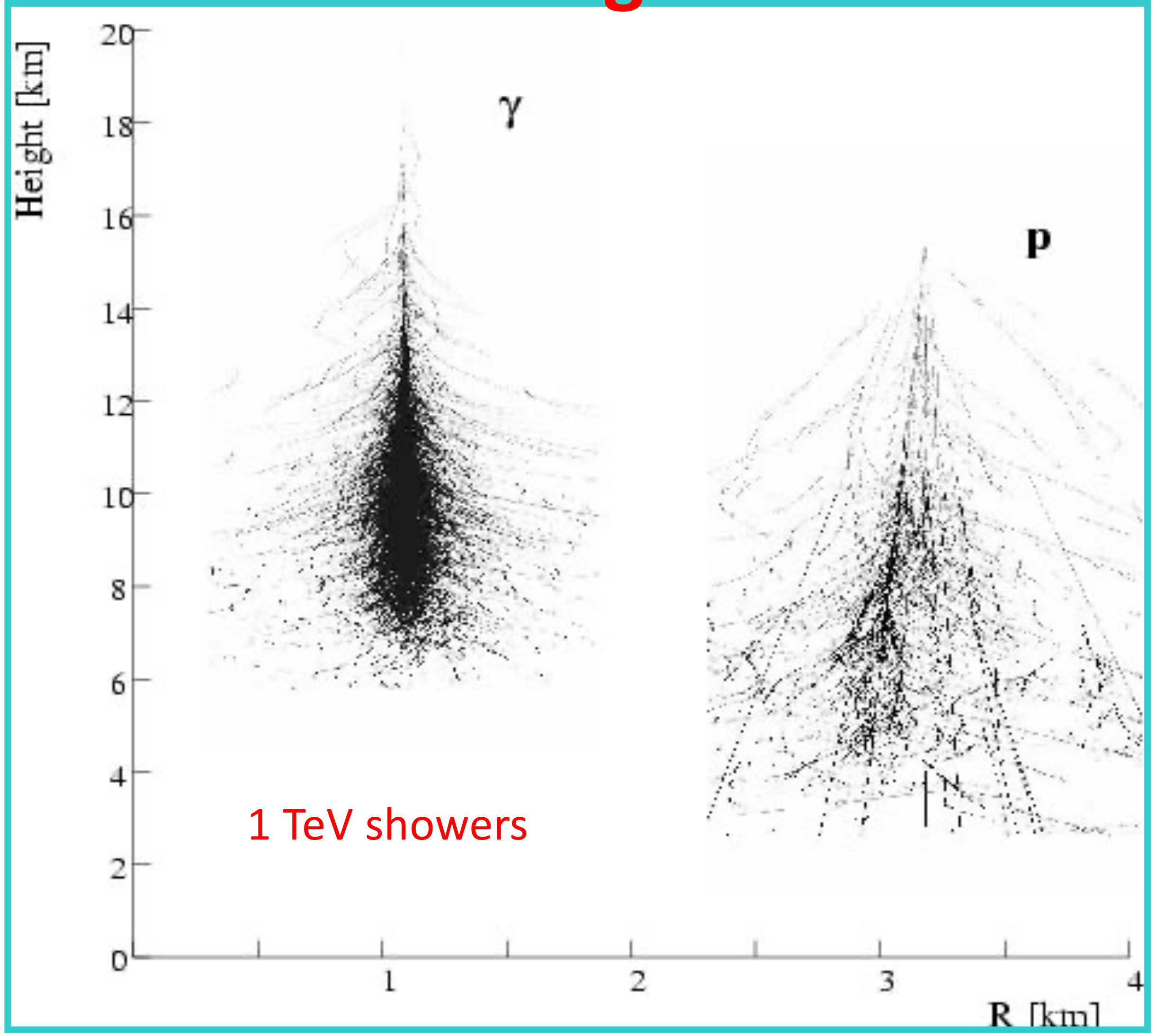
Resulting Cerenkov images in the focal plane of a 10-m reflecting mirror.



E.M. Shower, high altitude interaction, "regular" longitudinal and lateral development

Hadronic shower, interaction after a longer path, more "irregular" longitudinal and lateral development

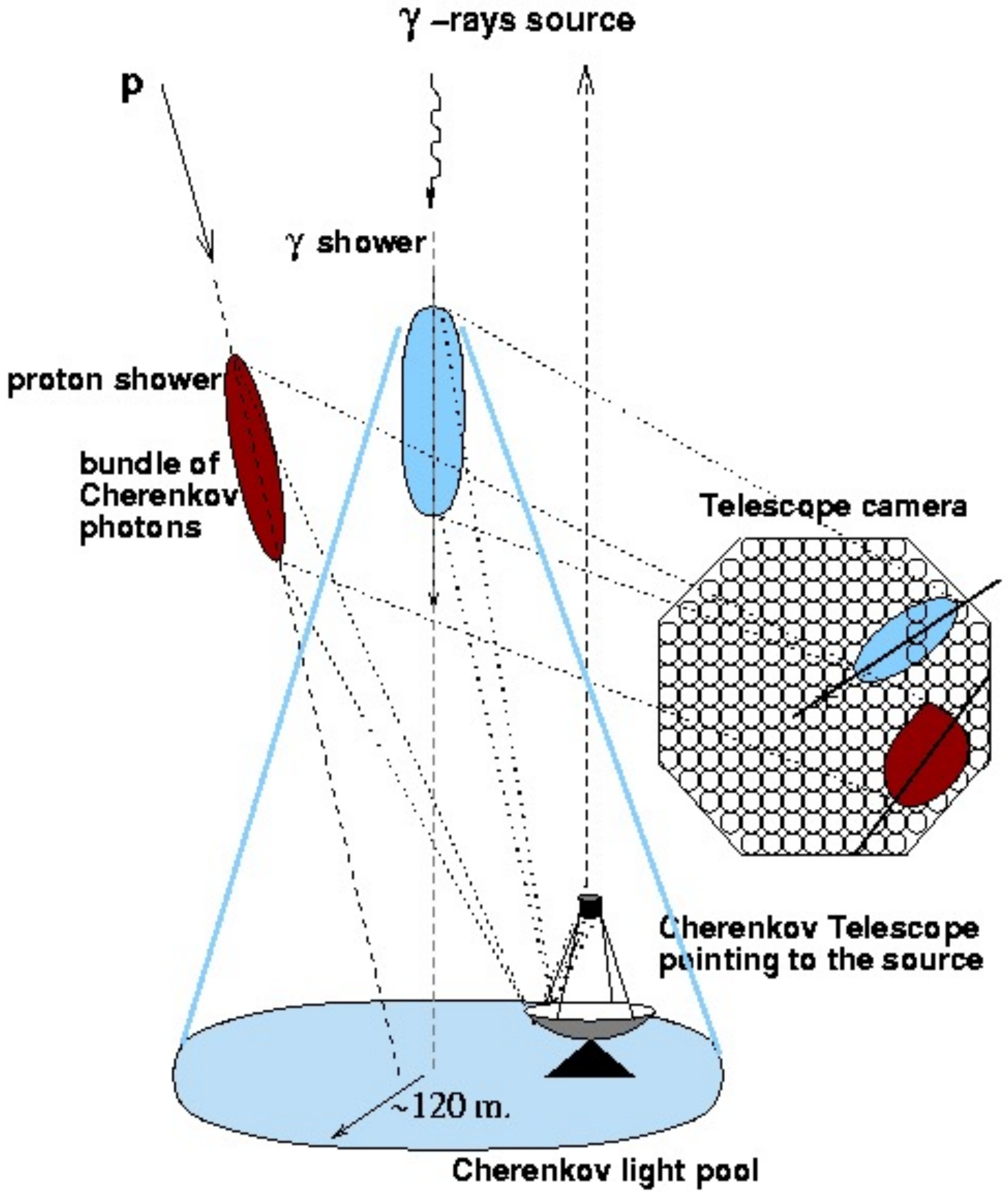
Recognizing the hadronic showers allows to reduce the backgound!



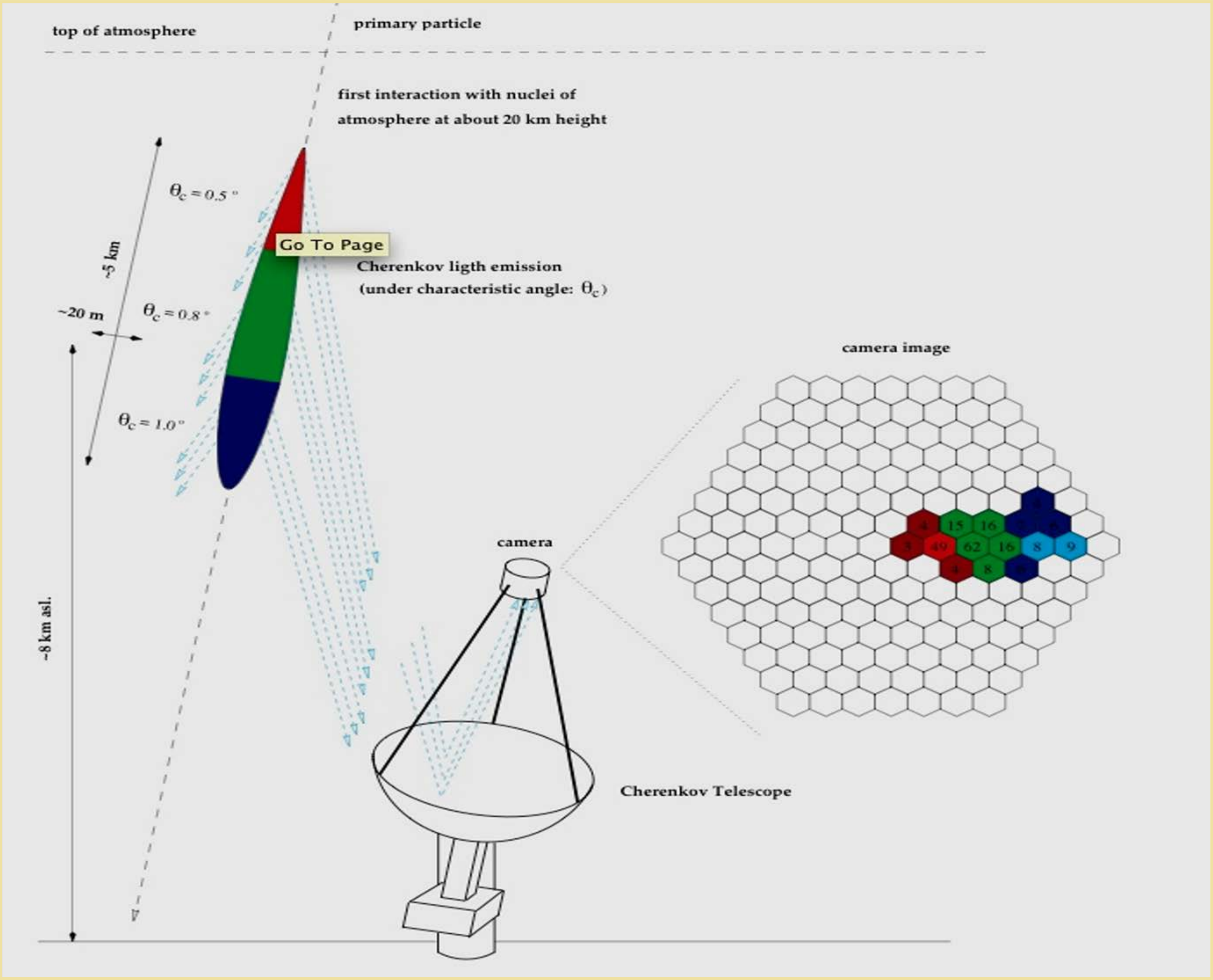
γ-rays/protons=1/10^4 ==> enormous source of background!

The Imaging Atmospheric Cherenkov technique

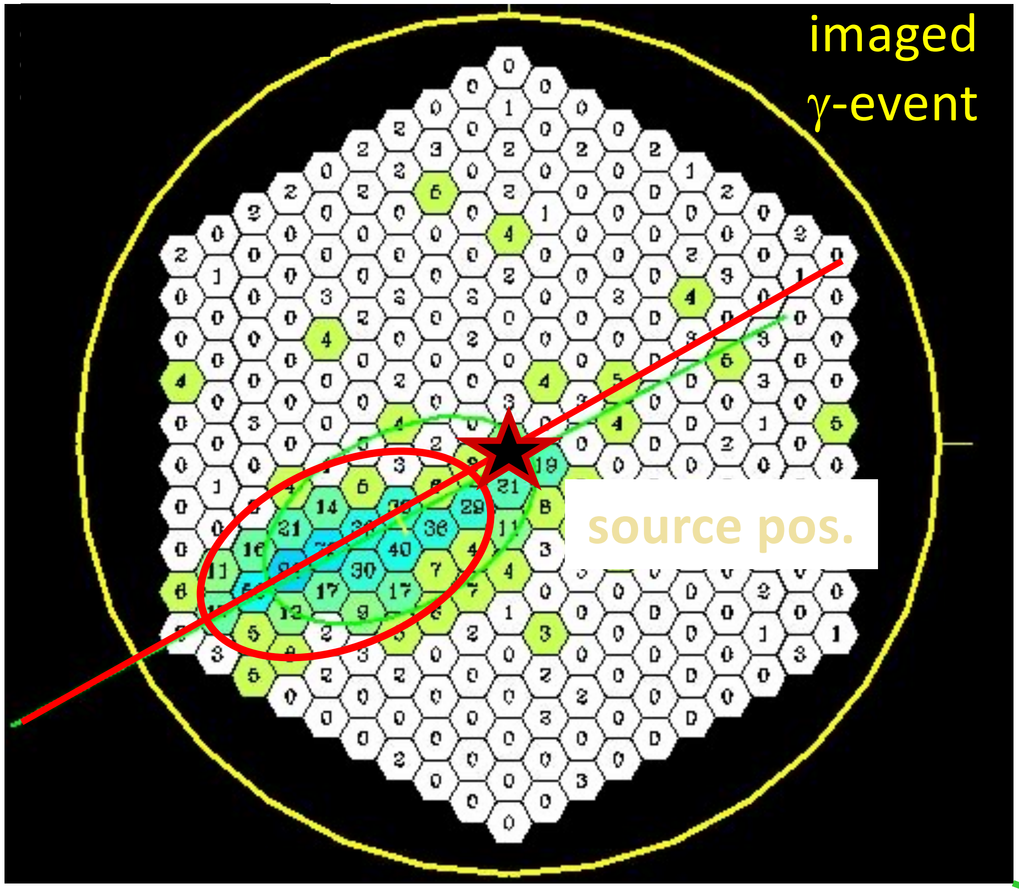
- Cherenkov radiation due to secondary particles with speed $v > c/n$.
- Short flashes (5-20 ns).
- Cherenkov photons collected by large ground reflectors and focused onto a camera with fast PMTs.
- The shower is “imaged” by the Cerenkov telescope.



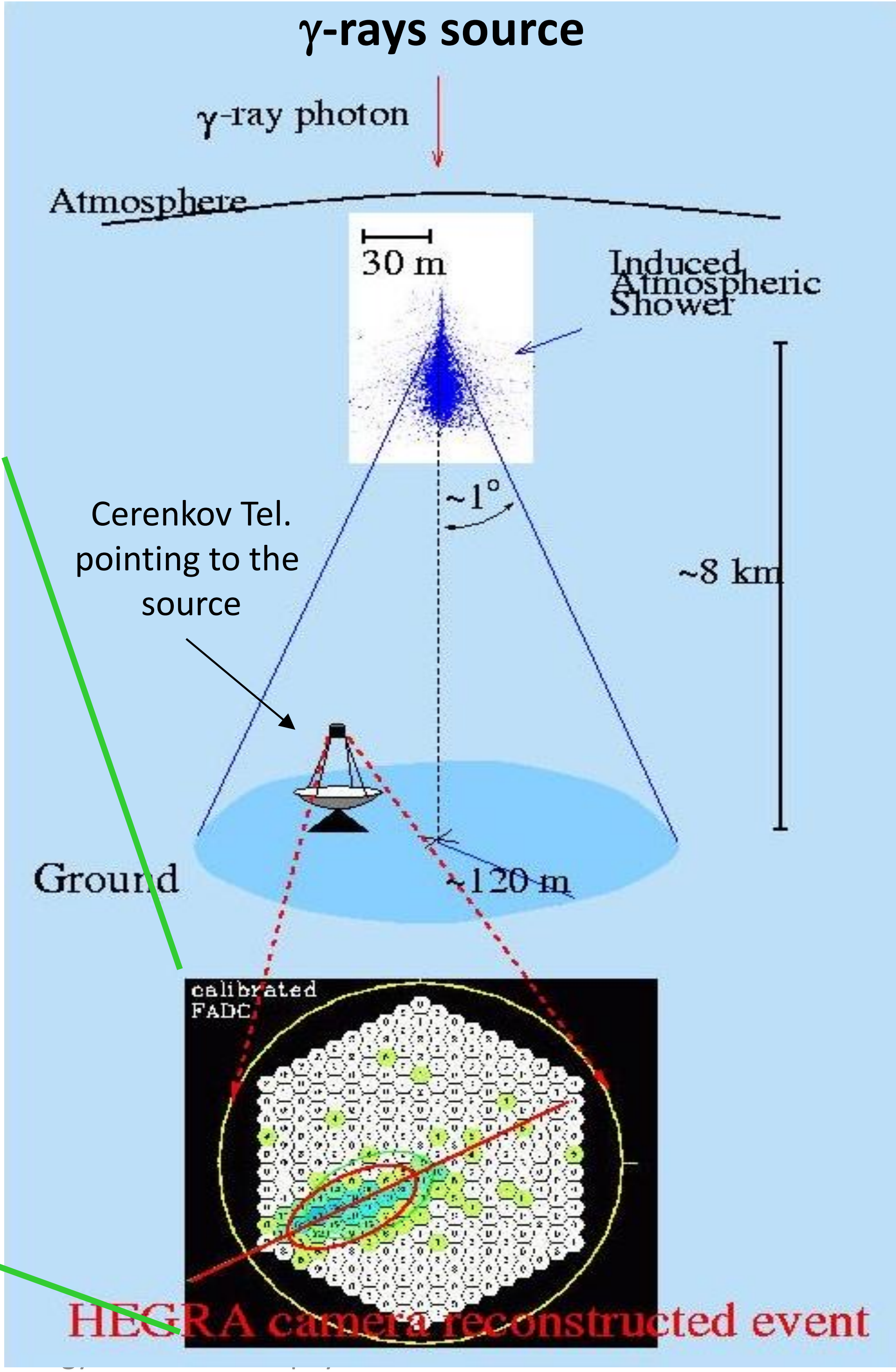
How the image is built-up on the central camera



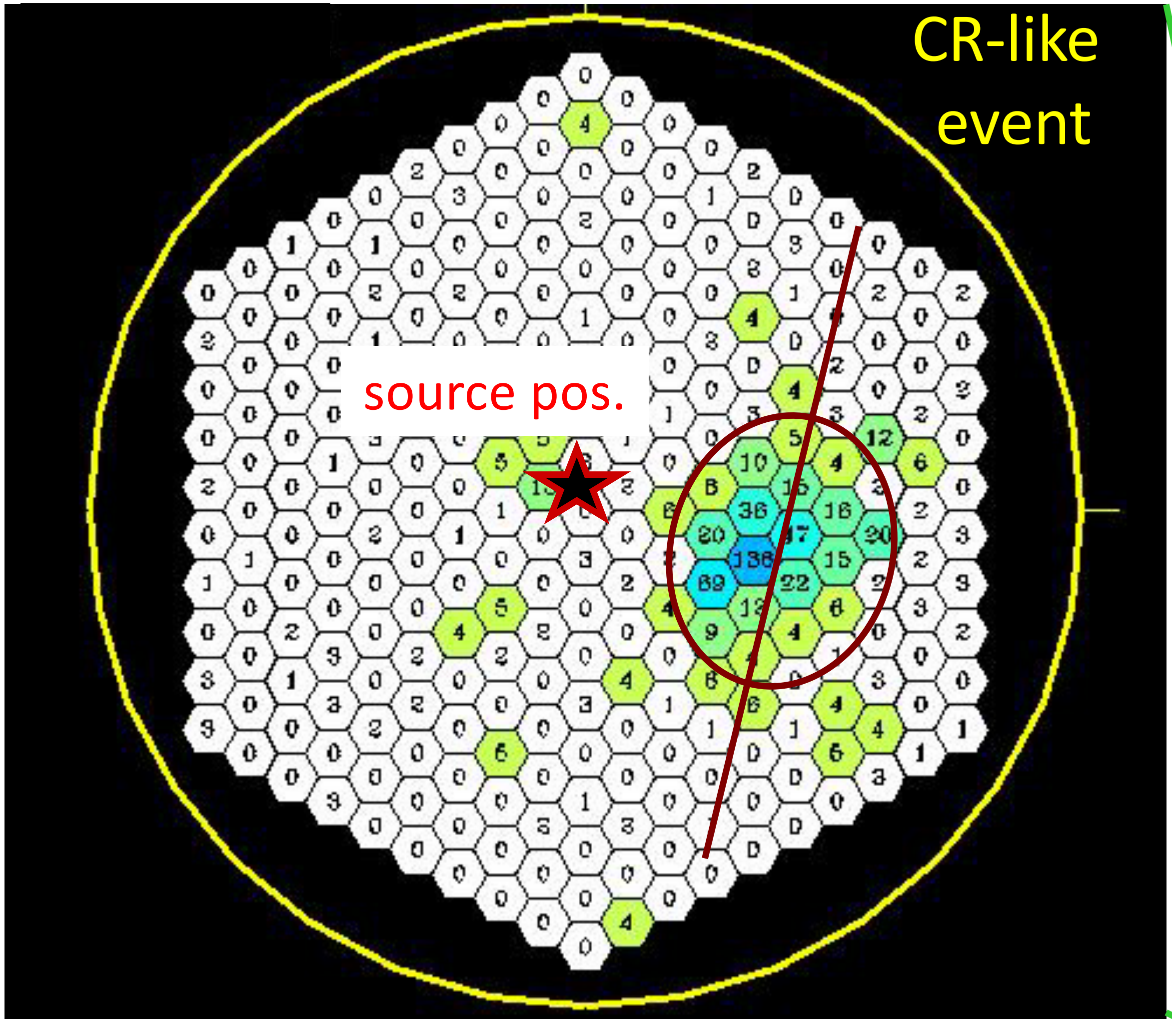
A γ-ray “image” obtained when the telescope points to the source

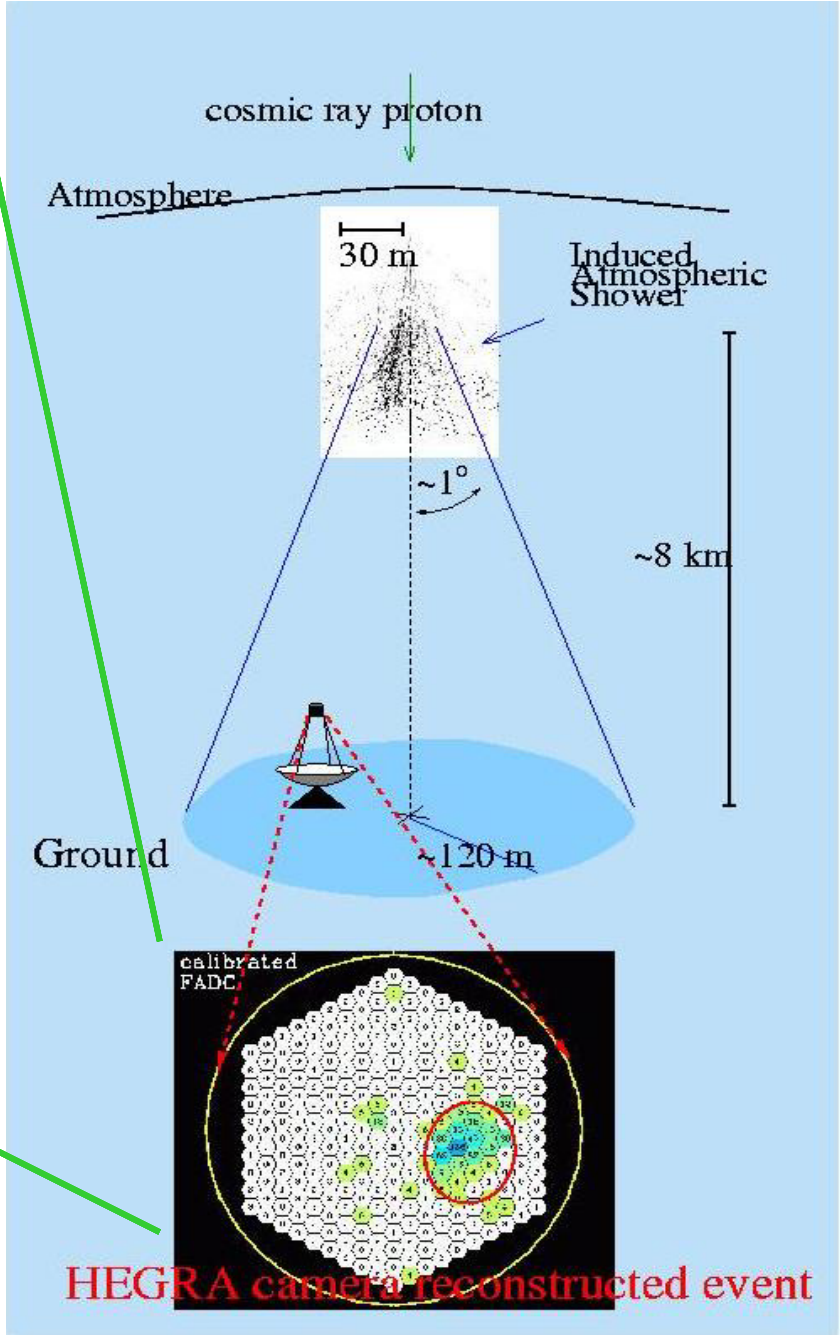


the source is placed at the camera center



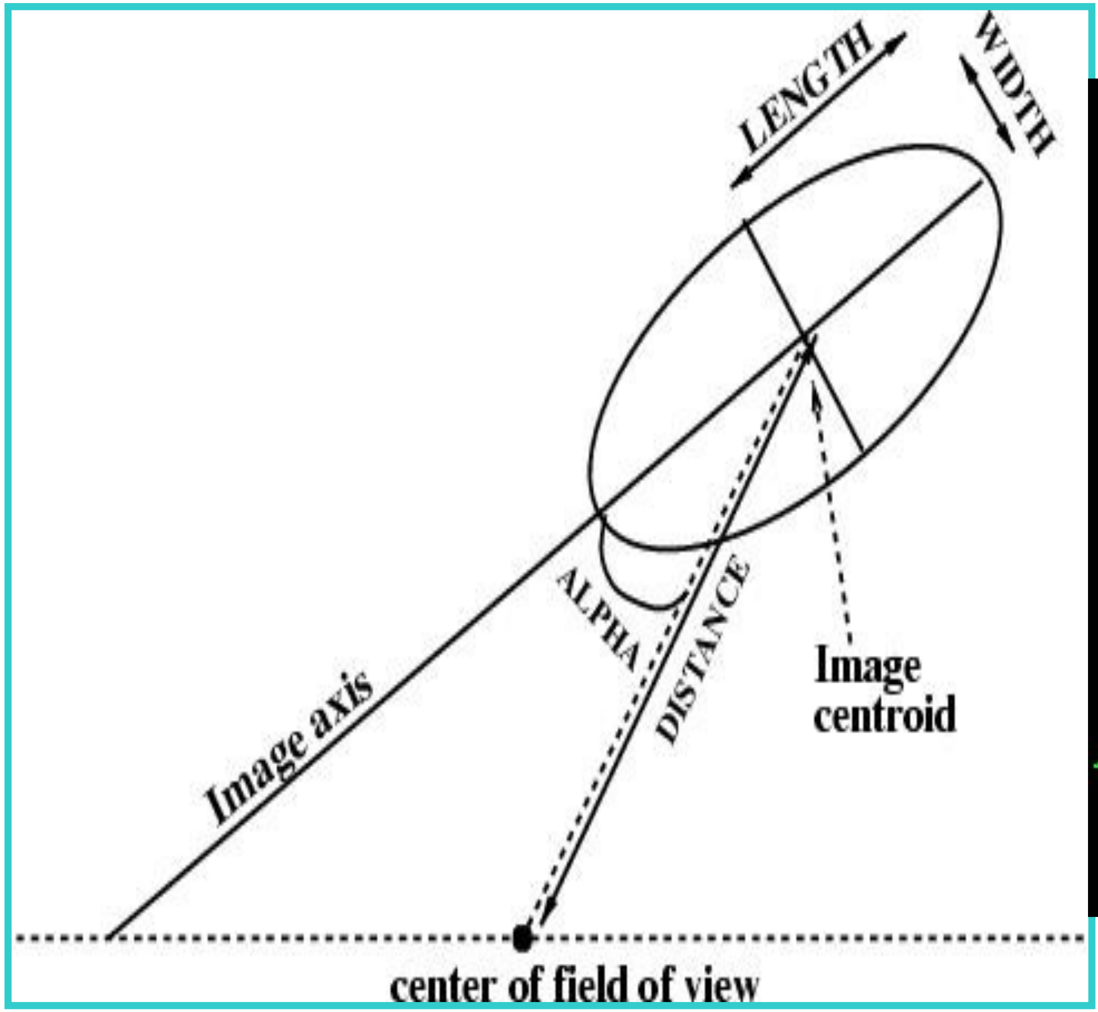
Charged Cosmic Ray “image”

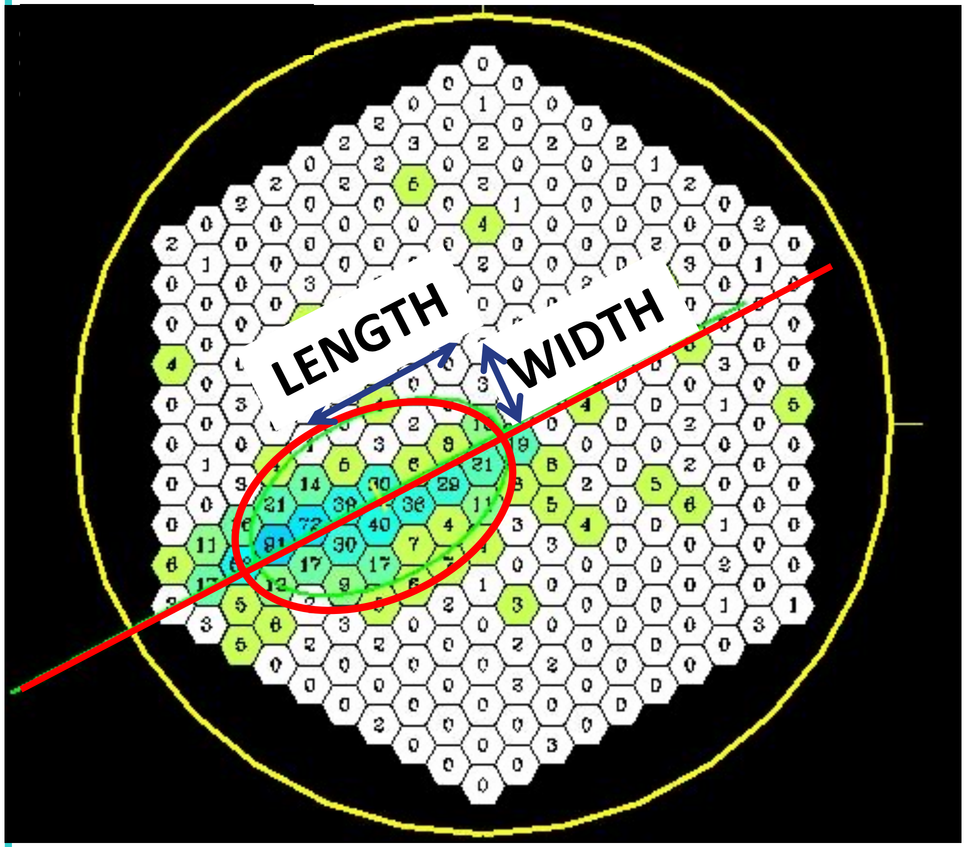




CR-images are randomly distributed so they don't point to the source !!

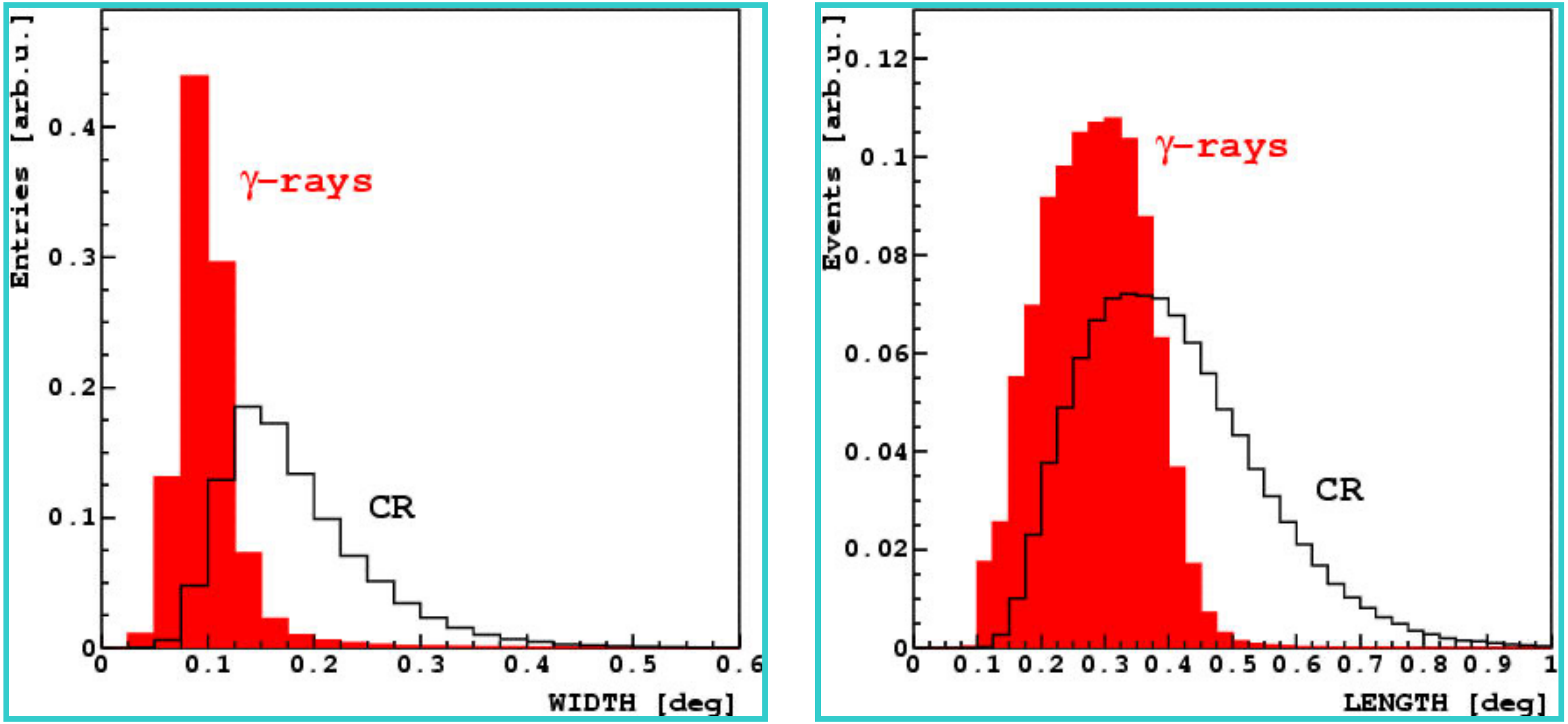
Cerenkov image parameterization





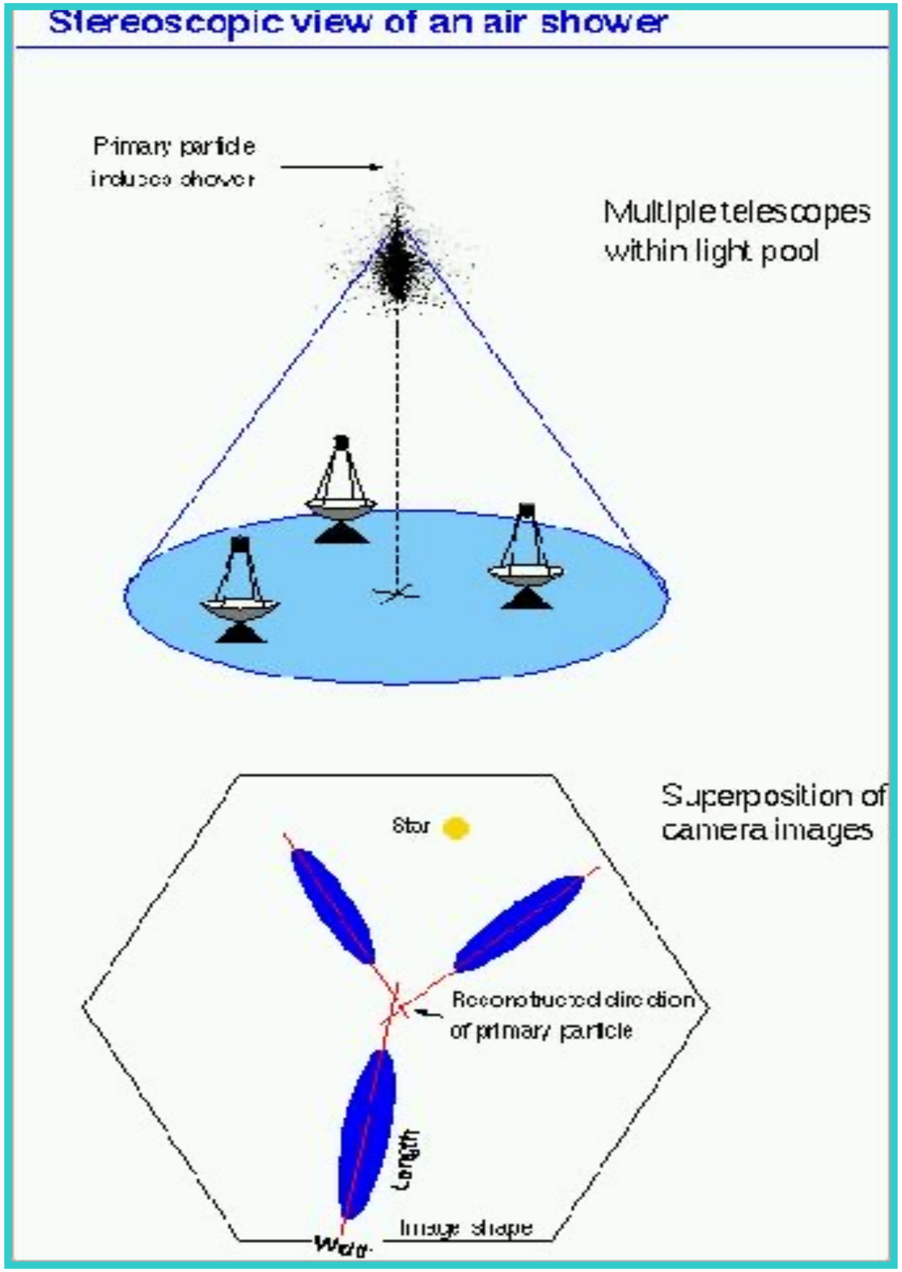
γ/hadron separation

- Based on the different Cerenkov image shapes.

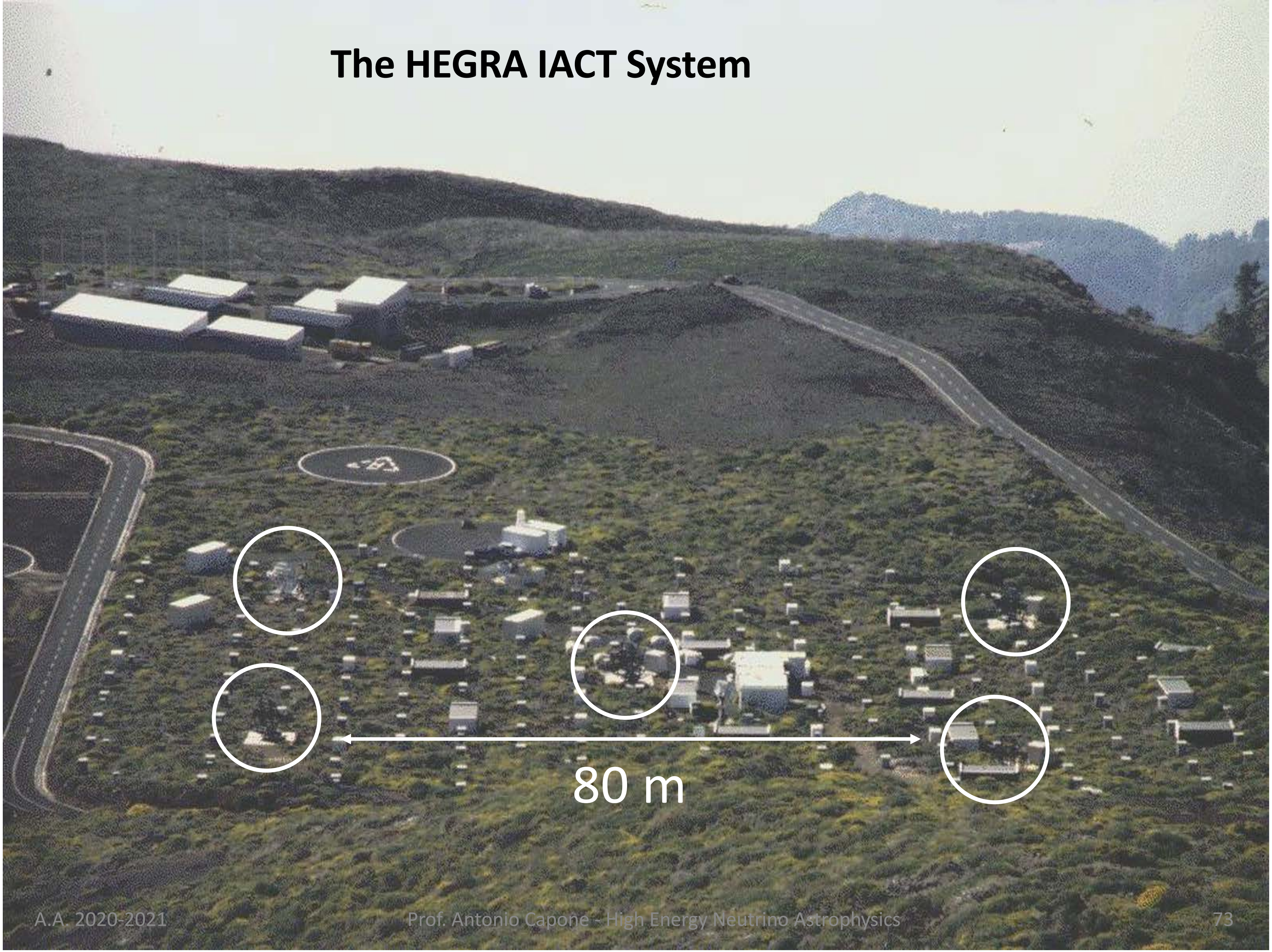


The Image Air Cherenkov, IAC, Stereoscopic technique

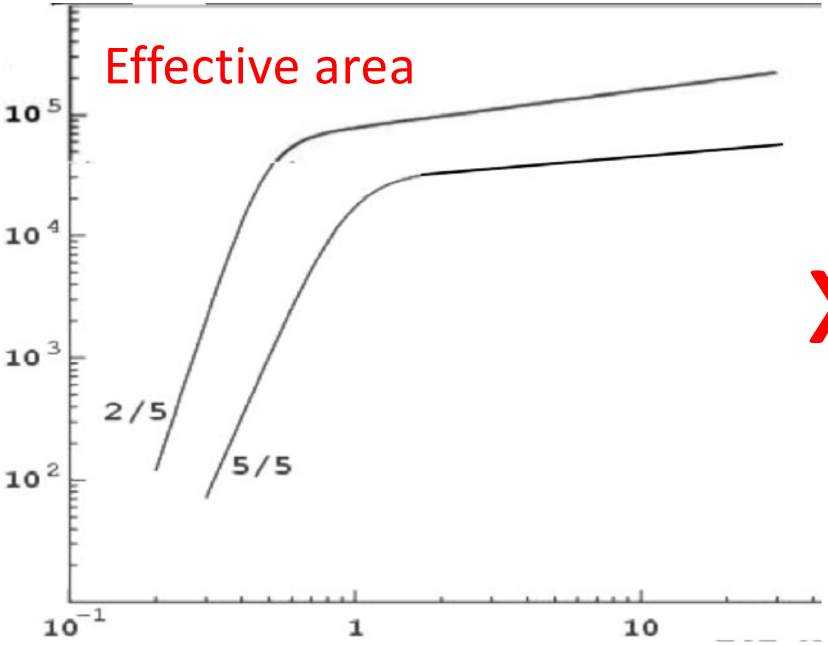
- View of the atmospheric shower from different angles (*stereoscopic*).
- 3D-reconstruction of the shower geometry (event-by-event).
- High background rejection.
- High energy resolution.
- Angular res.: <0.1°



The HEGRA IACT System

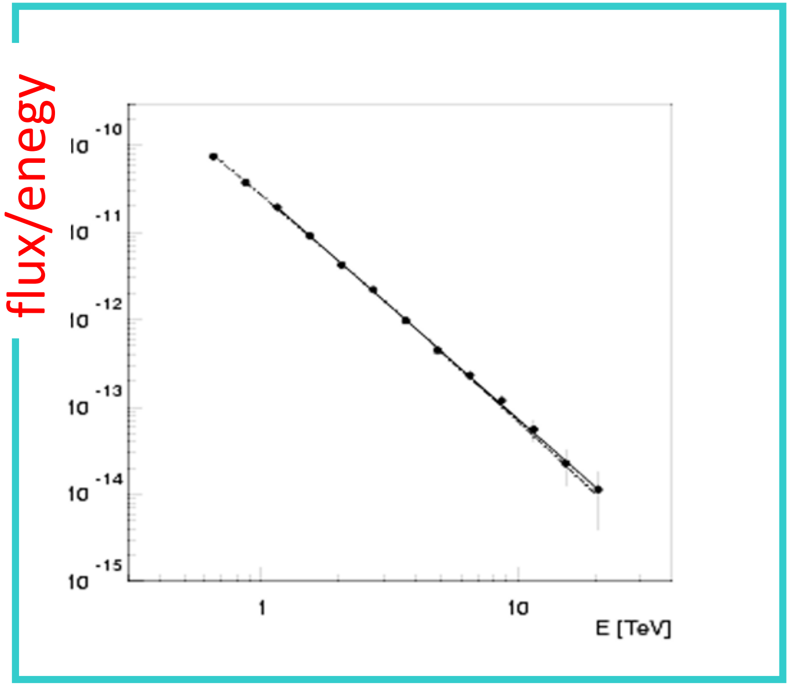


Event Rate = Effective area x flux



X

Crab differential energy spectrum



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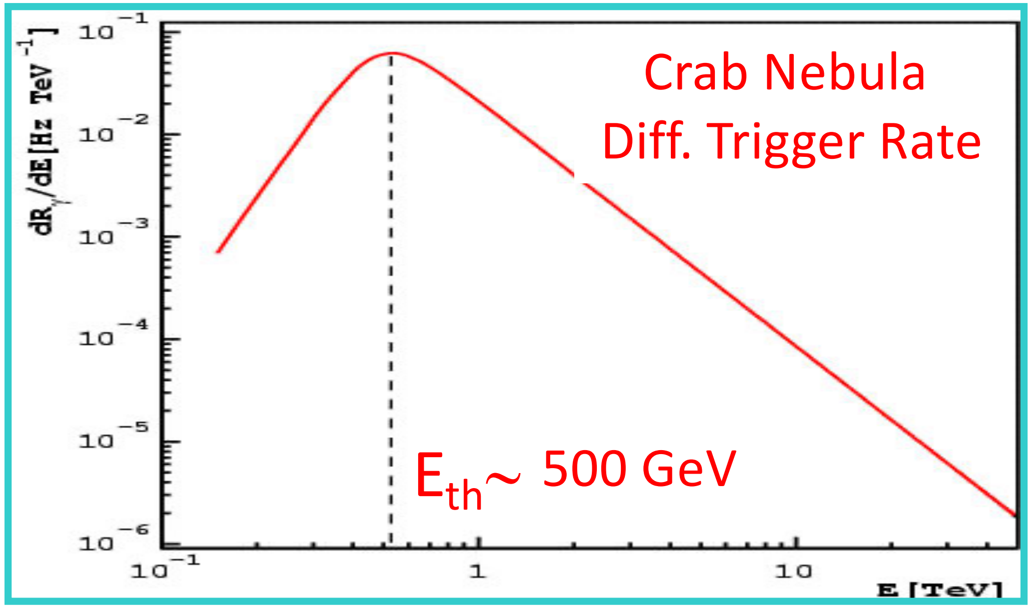
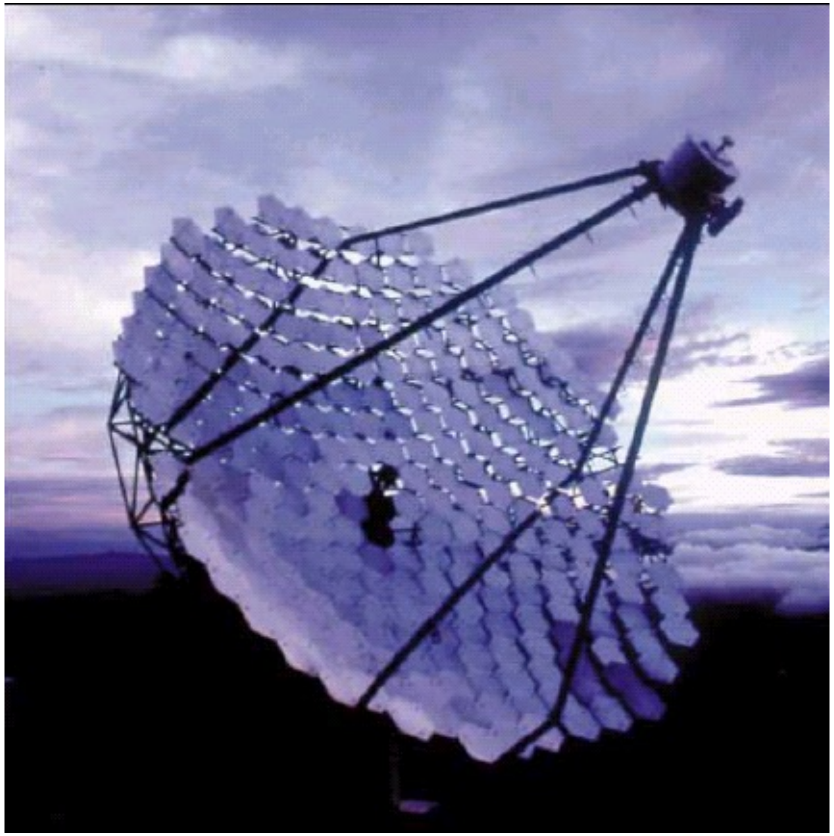


The Whipple Telescope

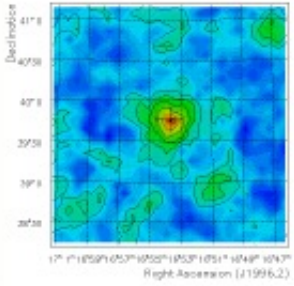
A review of Cherenkov imaging telescopes is available at the web site:
http://icrhp9.icrr.u-tokyo.ac.jp/c-experiments.html

HESS : Very high energy Gamma-ray astrophysics above 100 GeV

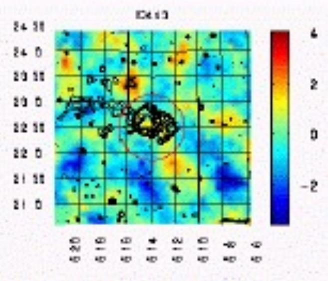


Whipple: diameter=10m, E > 350 GeV

The Whipple collaboration, which pioneered the Imaging Atmospheric Cherenkov Technique for the detection of very high energy (VHE) gamma rays, was based at the Fred Lawrence Whipple Observatory in Southern Arizona, in the United States. **The primary emphasis of the collaboration's research effort was the search for and study of celestial sources of gamma-rays in the energy range of 100 GeV - 10 TeV.**



MHK 501



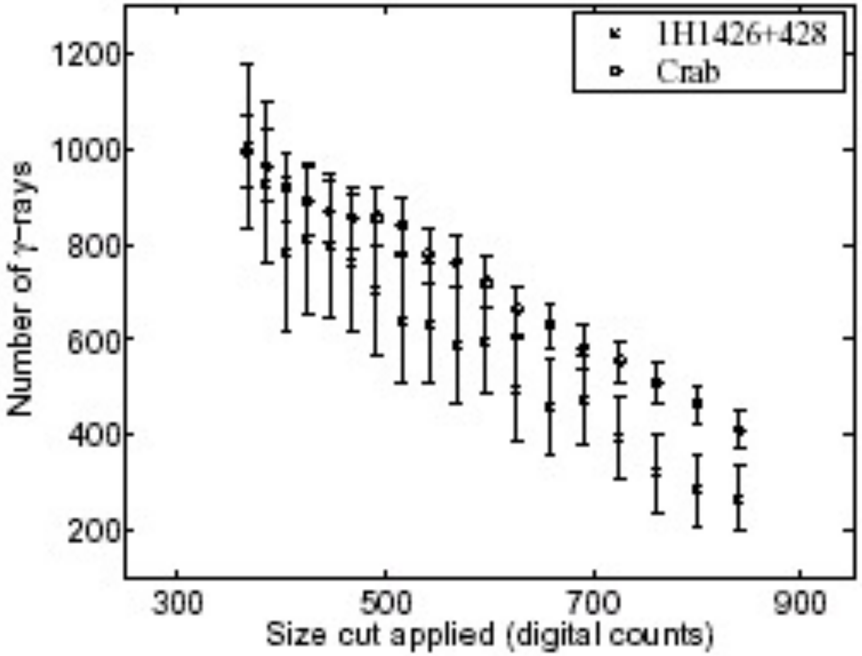


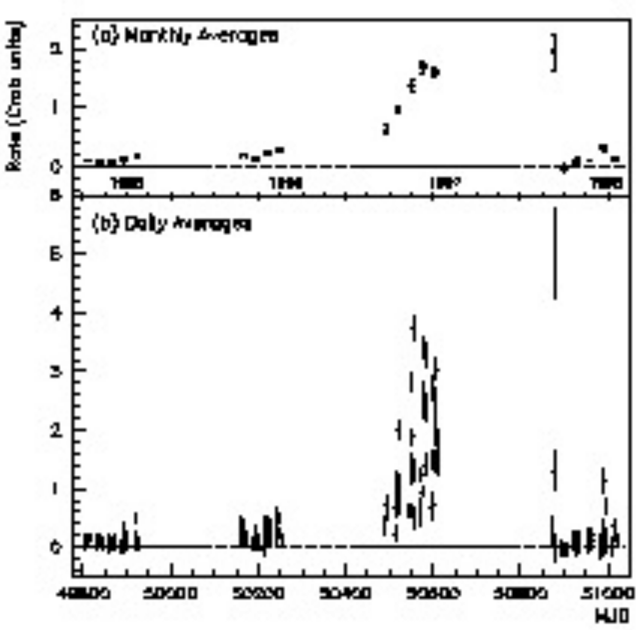
Fig. 4.— Integral excess events observed by the Whipple telescope from the directions of 1H1426+428 (crosses) and the Crab Nebula (open circles) during 2001 as a function of integrated Čerenkov light in the shower image. Exposure on the Crab Nebula was adjusted to match the total excess of 1H1426+428 at the lowest size cut applied, 366 digital counts. One photoelectron corresponds to ~ 3.6 digital counts.

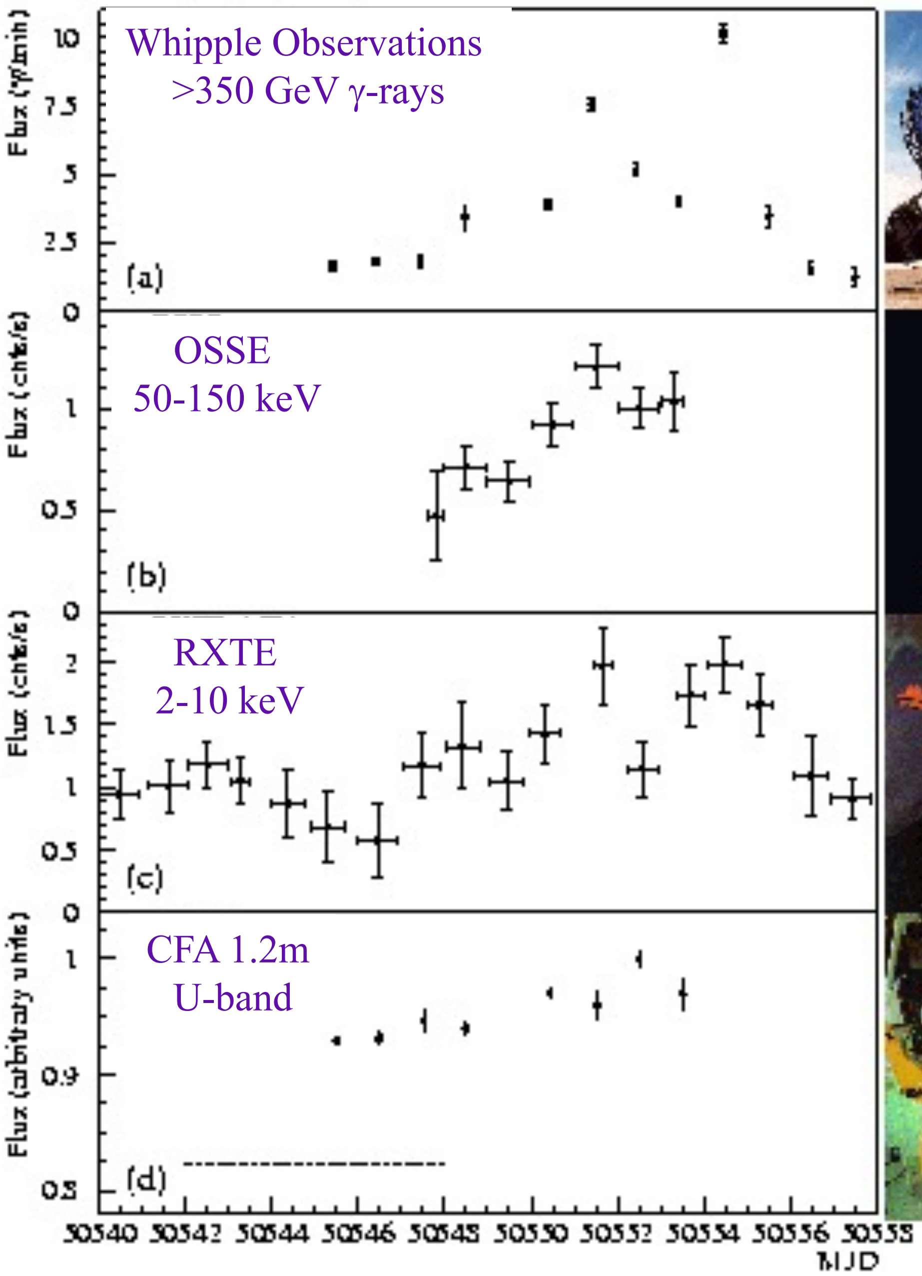
Markarian 501

An example of "multiwavelength observation"

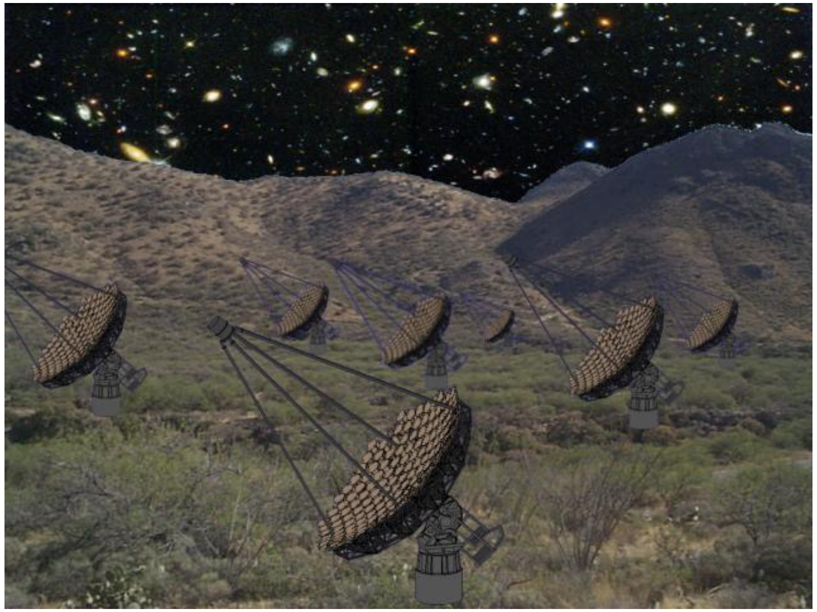
Whipple:

observation of Mrk501 in the years 1995-1998. In 1997 the flux of high energy γ from Mrk501 (up to 20 TeV energies) increased to ~ 10^{11} VHE γ/s (brighter than Crab Nebula).





VERITAS

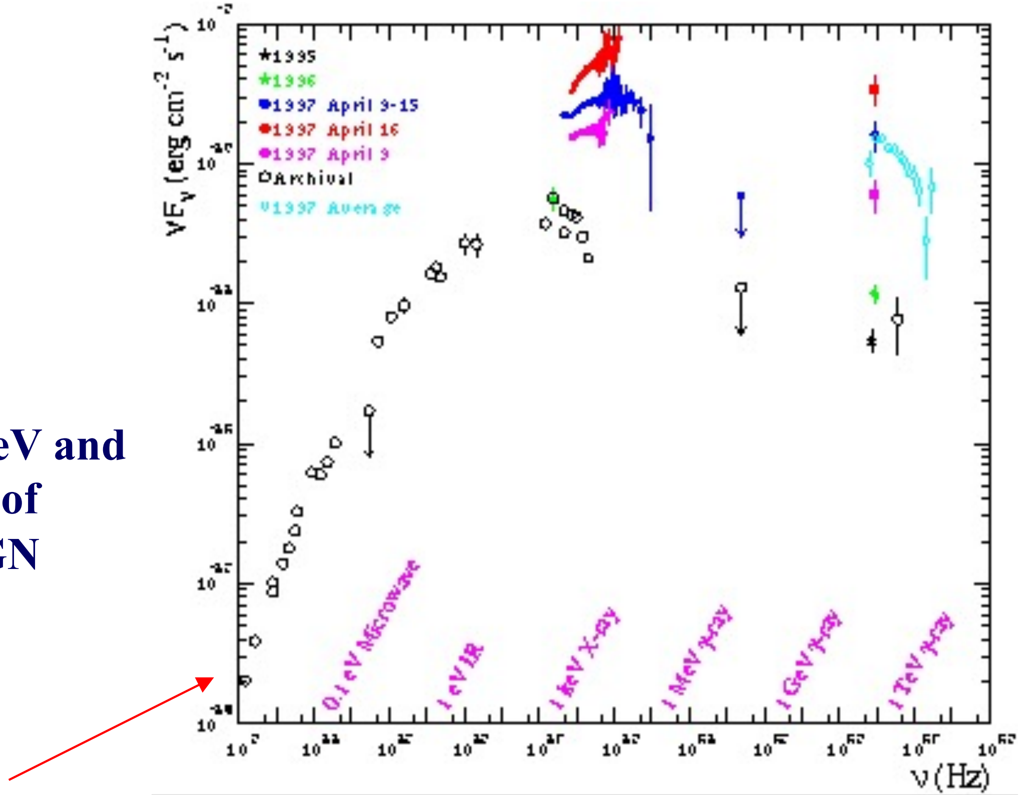


Very Energetic Radiation Imaging Telescope Array System a ground-based gamma-ray observatory with an array of **seven 10m optical reflectors** (like Whipple) for gamma-ray astronomy in the energy range of **50 GeV - 50 TeV** (with maximum sensitivity from 100 GeV to 10 TeV). In this band critical measurements of SNRs and AGNs have been made.

Scientific objectives:

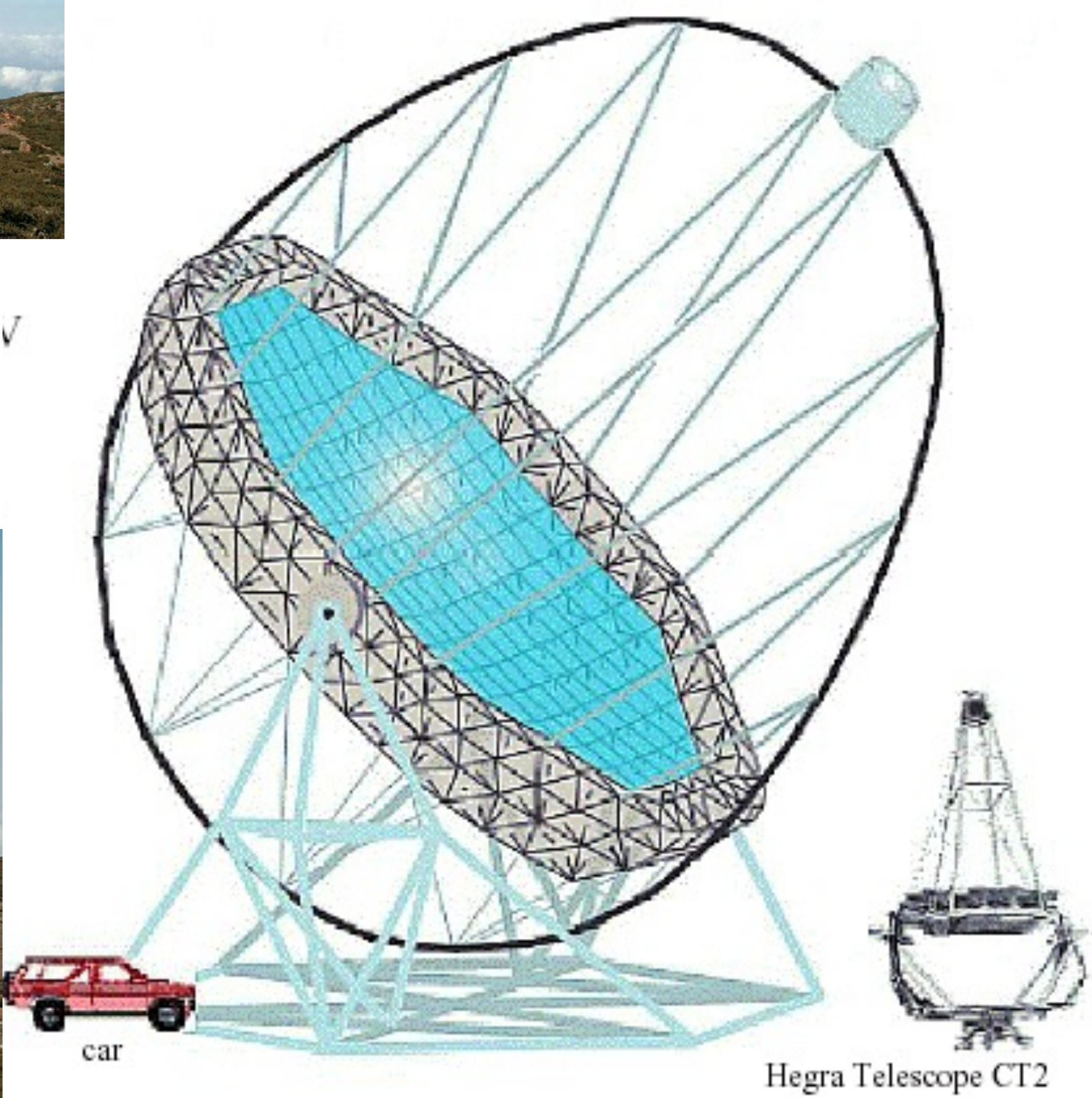
- **Supernova remnants**
- **Gamma-ray pulsars**
- **Active galactic nuclei**
- **Gamma-ray bursts**
- **EGRET unidentified sources**
- **Diffuse emission**

The correlation between the observation at the TeV and at lower energies allows to investigate the nature of some sources of R.C. of very high energy: e.g. AGN



MAGIC

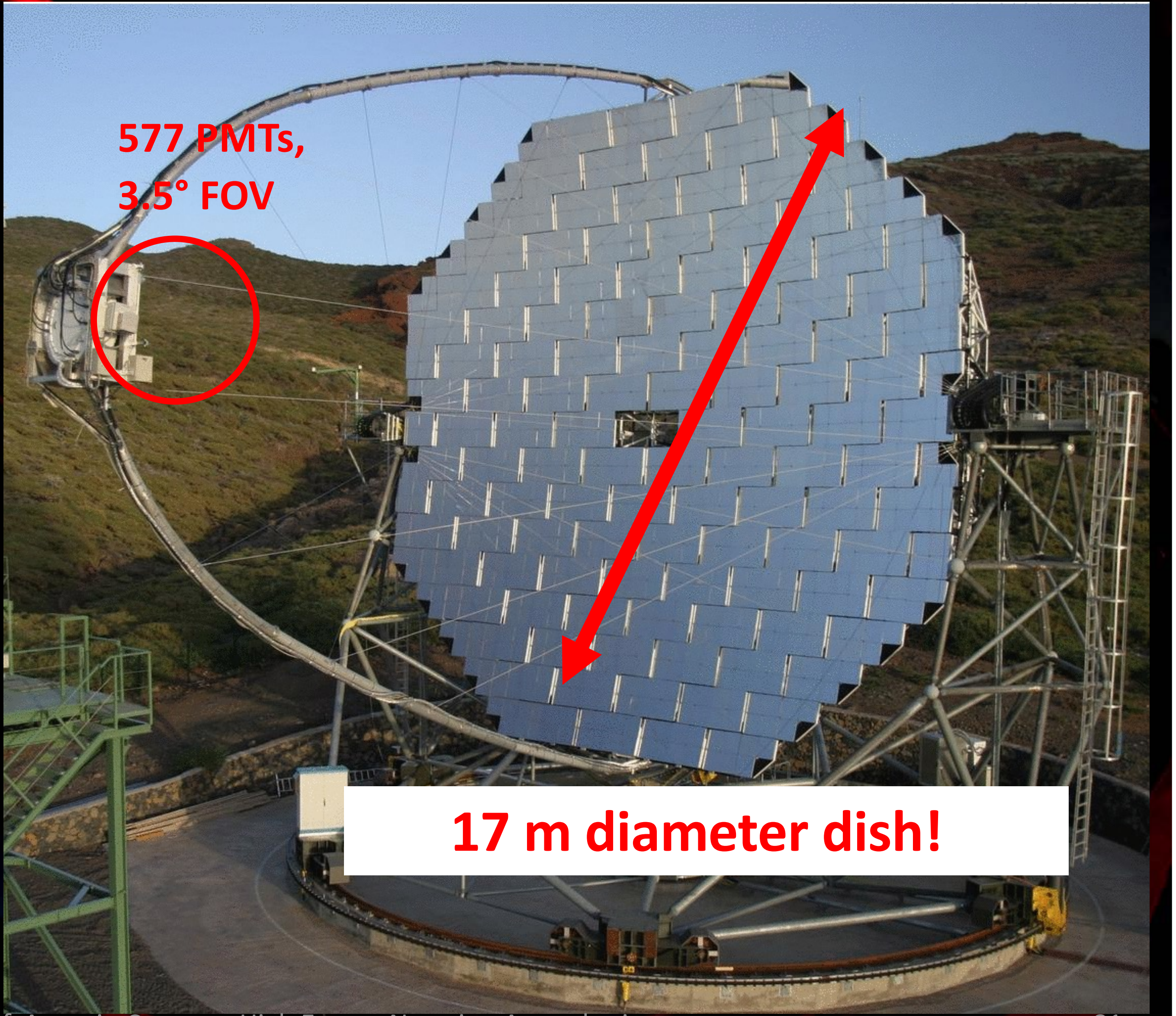
220 m^2 mirror area
E_γ = 10 GeV- 300 TeV
Location: La Palma
(Canary Islands)
Started June 2001



The MAGIC Telescope

- Located at 2220m at La Palma (Canary islands)

- Characteristics:
  - **Energy resolution: 25-30%**
  - **Energy threshold: 50 GeV**



HESS

H.E.S.S. was the second-generation system of Imaging Atmospheric Cherenkov Telescopes for the investigation of cosmic gamma rays in the 100 GeV energy range. The name H.E.S.S. stands for **High Energy Stereoscopic System**, and should also remind of **Victor Hess, who received in 1936 the Nobel Prize in Physics for his discovery of cosmic radiation**. The acronym also emphasizes two main features of the proposed installation, namely the **simultaneous observation of air showers with several (3 to 4) telescopes, under different viewing angles**, and the **combination of multiple (up to 16) telescopes to a large system to increase the effective detection area for gamma rays**.
With telescopes of over 100 m^2 mirror area, the system provides a:

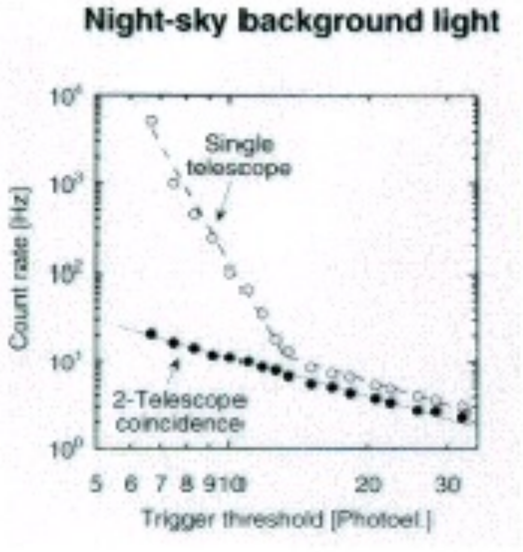
- **detection threshold of about 40 GeV,**
- **full spectroscopic capability above 100 GeV, an**
- **angular resolution for individual showers of 0.1 degrees**
- **energy resolution of about 20%.**

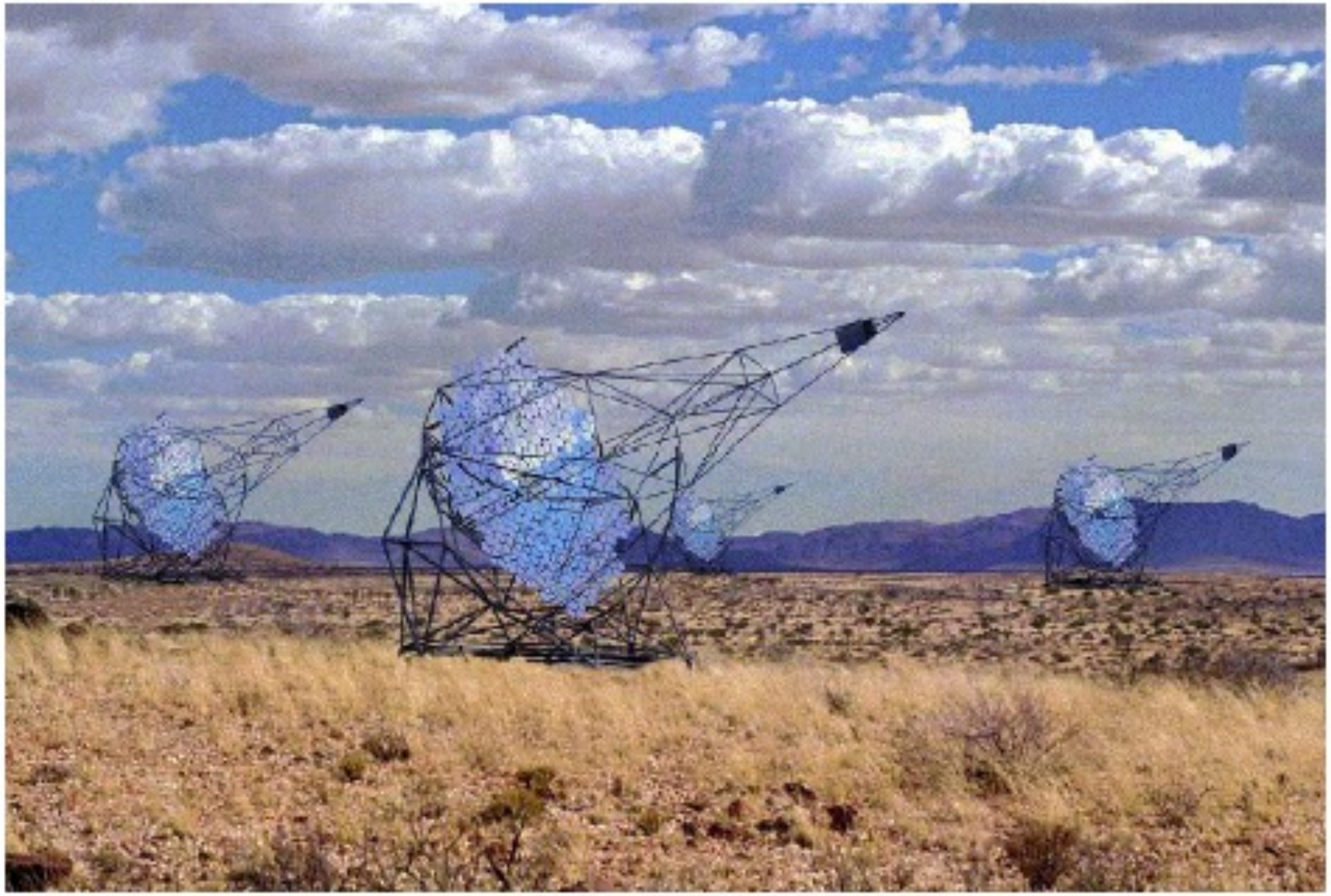
It allows to explore gamma-ray sources with intensities at a level of a few thousandth parts of the flux of the Crab nebula. H.E.S.S. is located in Namibia, near the Gamsberg, an area well known for its excellent optical quality.

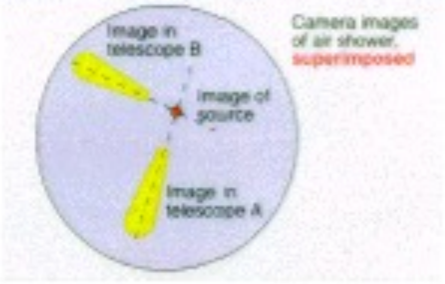
HESS phase 2

HESS Phase 2

four 110m² telescopes
Field of view 5 deg
Detection capability
at E > 40 GeV
Spectroscopy at E > 100 GeV
Location: Namibia







(artistic composition)
(not yet real !)

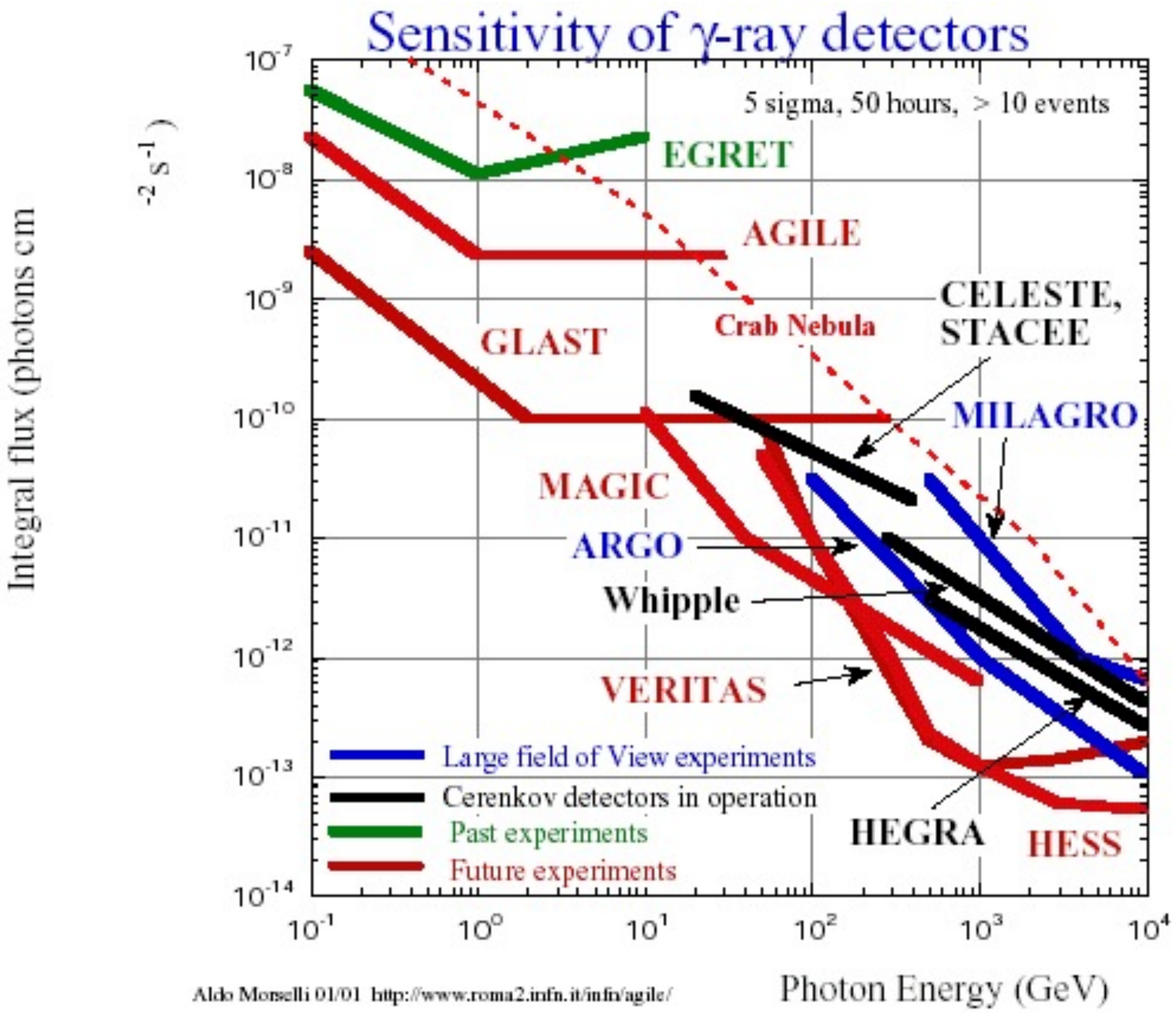
HESS stereoscopic system


13m diameter dish

960 PMTs camera

- Energy range: 100 GeV -100TeV
- Energy resolution: 15-20%
- Angular resolution: 3-6 arcmin
- Sensitivity: **1% Crab in 25 h**
- 5° FoV

Experiments for γ astronomy

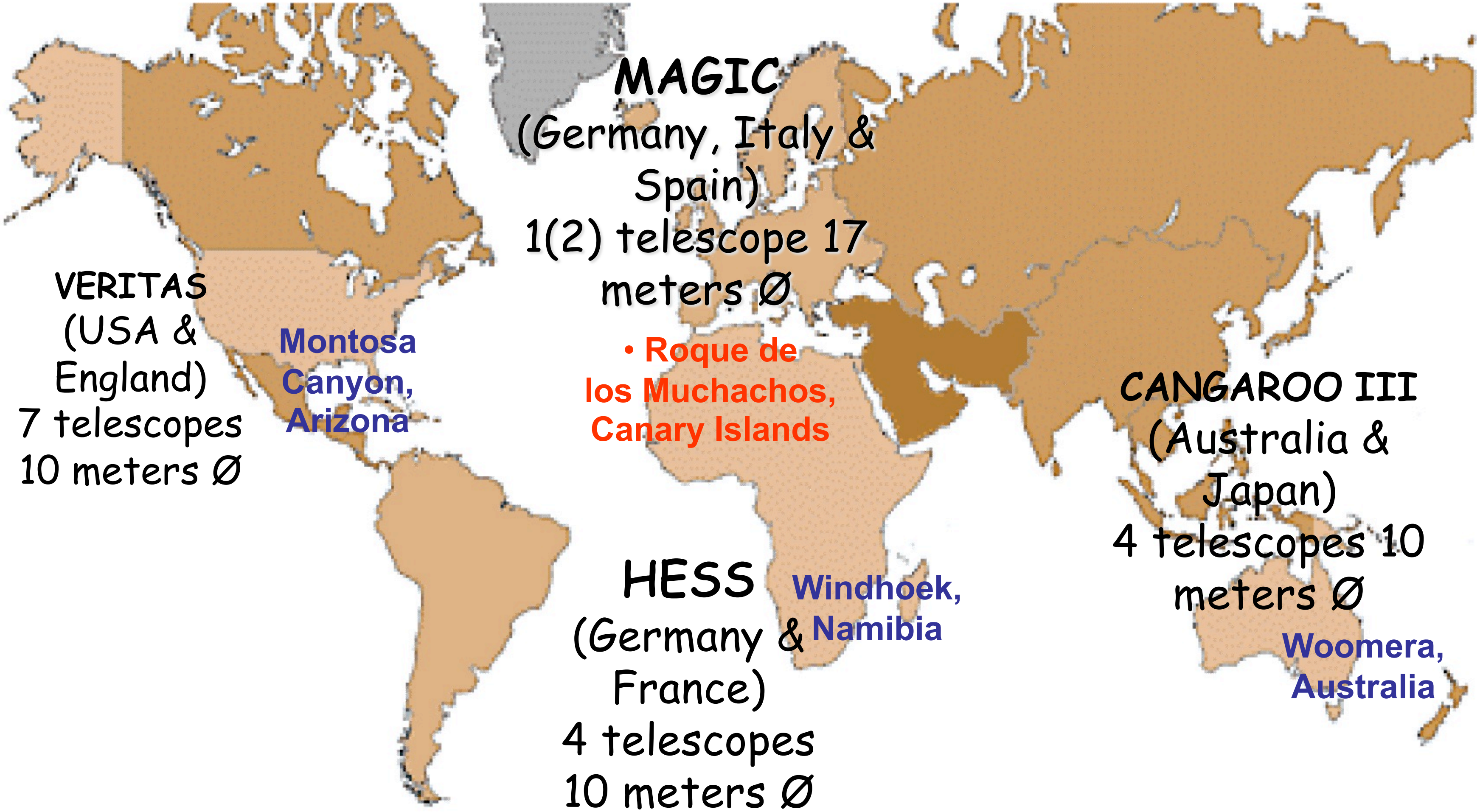


Aldo Morselli 01/01 http://www.roma2.infn.it/infn/agile/

All sensitivities are at 5σ.
Cerenkov telescopes sensitivities (Veritas, MAGIC, Whipple, Hess, Celeste, Stacee, Hegra) are for 50 hours of observations.
Large field of view detectors sensitivities (AGILE, GLAST, Milagro, ARGO are for 1 year of observation.

MAGIC sensitivity based on the availability of high efficiency PMT's

Operating Cherenkov telescopes



MAGIC
(Germany, Italy & Spain)
1(2) telescope 17 meters Ø

- Roque de los Muchachos, Canary Islands

VERITAS
(USA & England)
7 telescopes
10 meters Ø

Montosa Canyon, Arizona

CANGAROO III
(Australia & Japan)
4 telescopes 10 meters Ø

Woomera, Australia

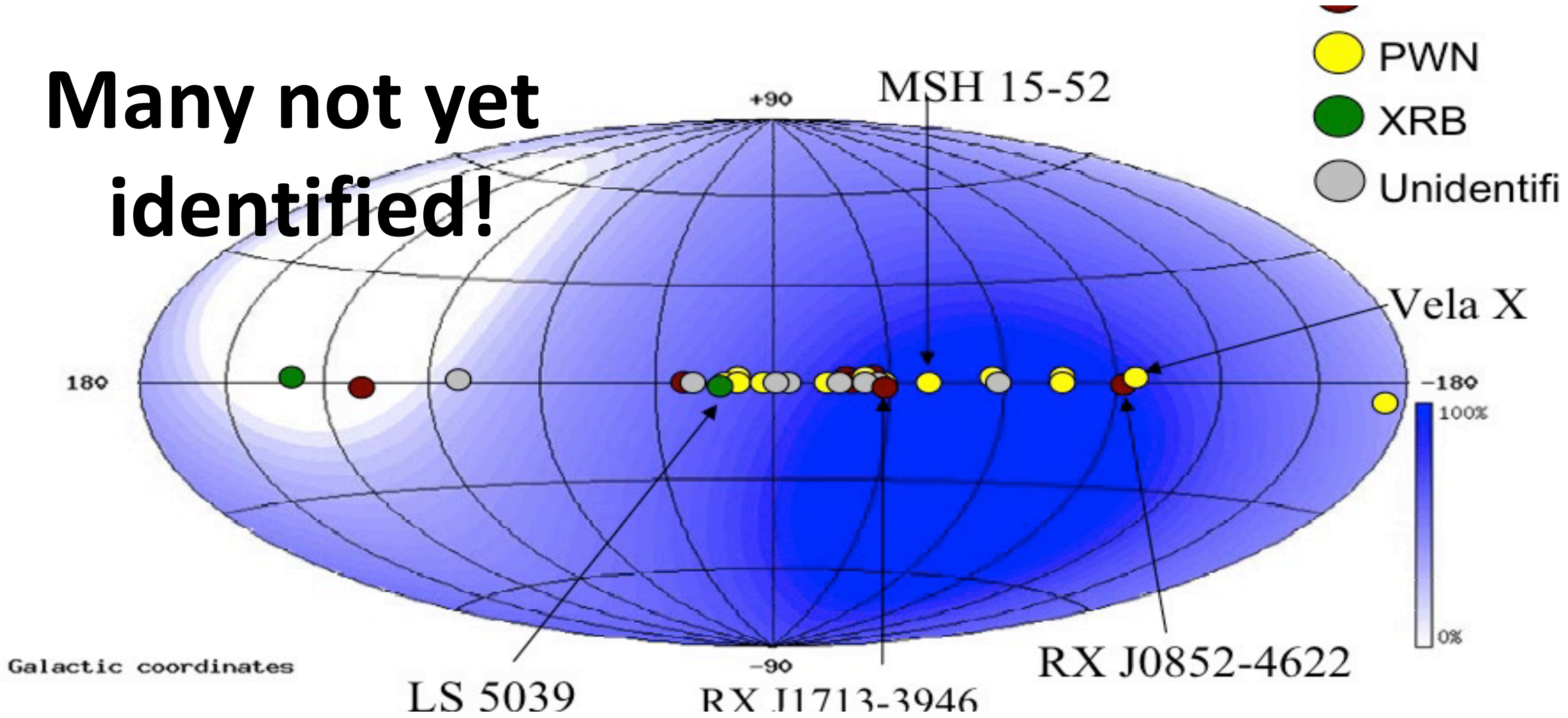
HESS
(Germany & France)
4 telescopes
10 meters Ø

Windhoek, Namibia

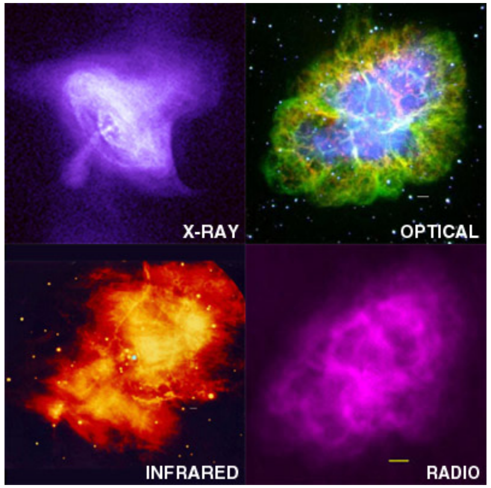
Galactic TeV gamma-ray Sources

- at least 4 source classes:
  - Shell-type SNR
  - Pulsar Wind Nebulae (PWN)
  - X-ray binaries (binary pulsar and microquasars)
  - Molecular Clouds plus SMBH in GC (Sgr A*)?

Many not yet identified!



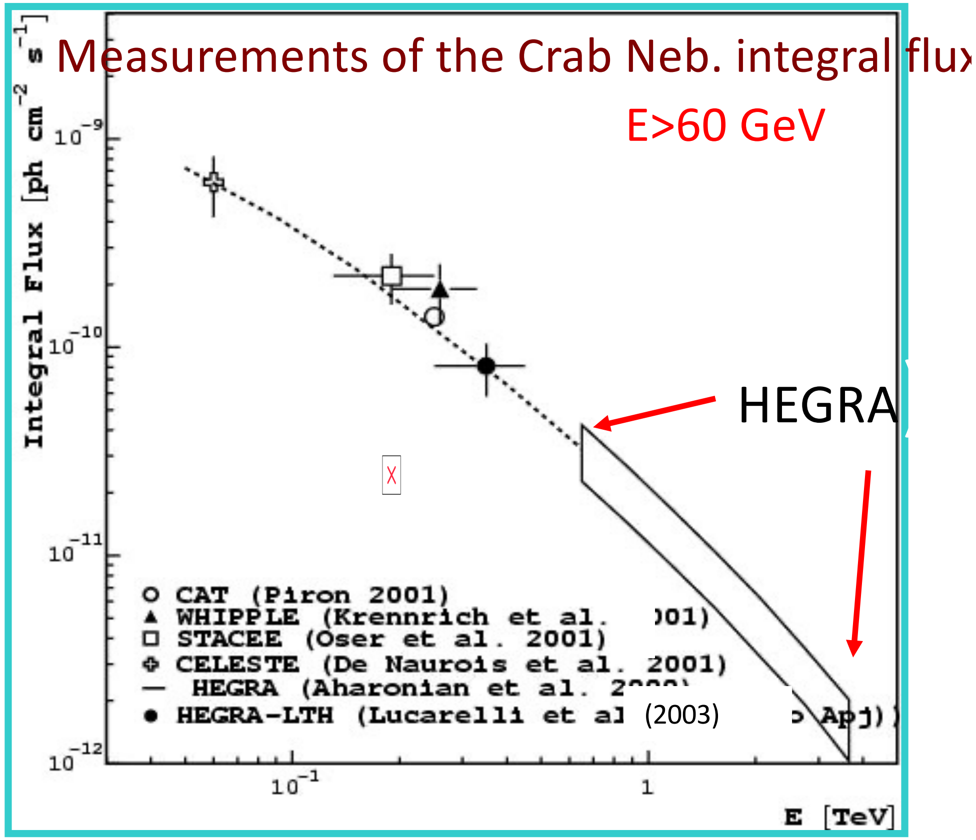
Crab Nebula: the standard candle (I)



- Remnant of a supernova explosion, occurred in 1054.
- Pulsar injecting relativistic electrons into the nebula.
- Emission predominantly by non-thermal processes, covering a huge energy range (radio to TeV).
- First TeV source (Whipple Telescope, 1989).
- Steady HE γ-ray emission

  → *standard candle*

- Φ (E>1 TeV) = $1.6 \cdot 10^{-11}$ ph cm^{-2} s^{-1}


Measurements of the Crab Neb. integral flux

E>60 GeV

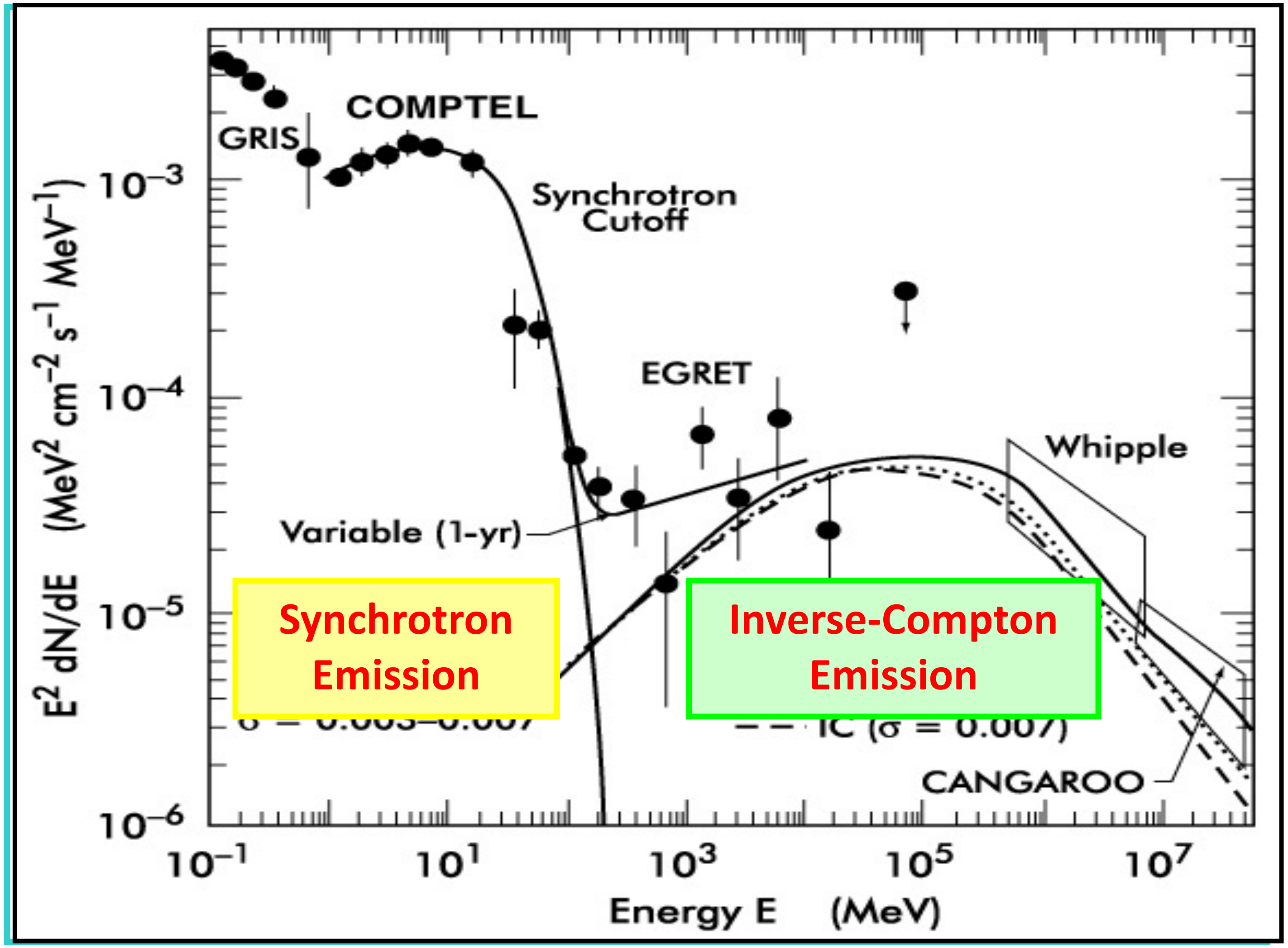
HEGRA

Crab Nebula: the standard candle (II)

☞ **TeV emission from up-scattering of low energy photons (synchrotron, MWB, IR) by electrons in the pulsar wind.**

- **Synchrotron Self-Comtpon** (SSC) model fits the observed spectrum.
- Inverse Compton peak expected below 100 GeV.

No pulsed emission detected
so far for E>0.01 TeV

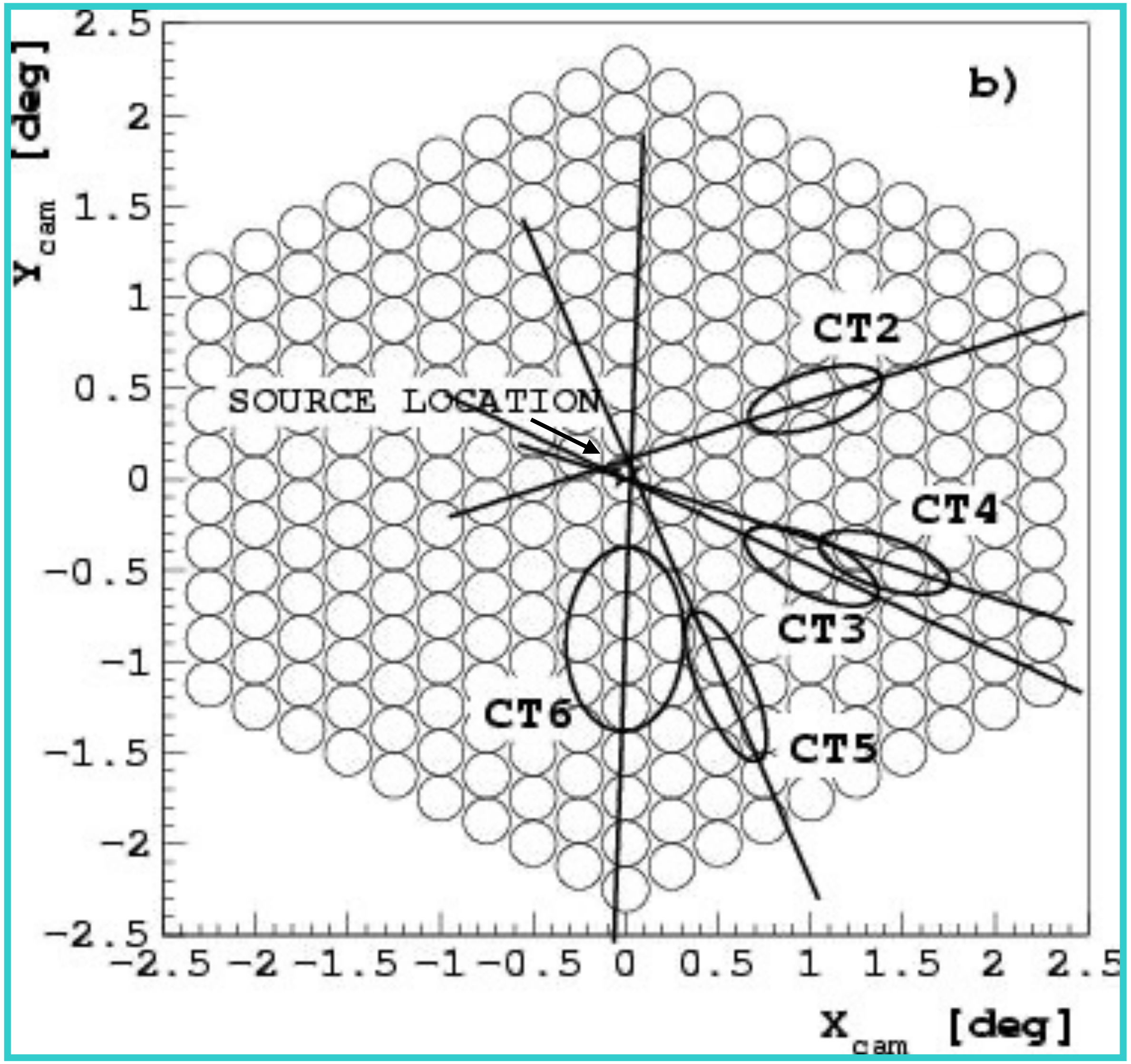


END

…for the moment…

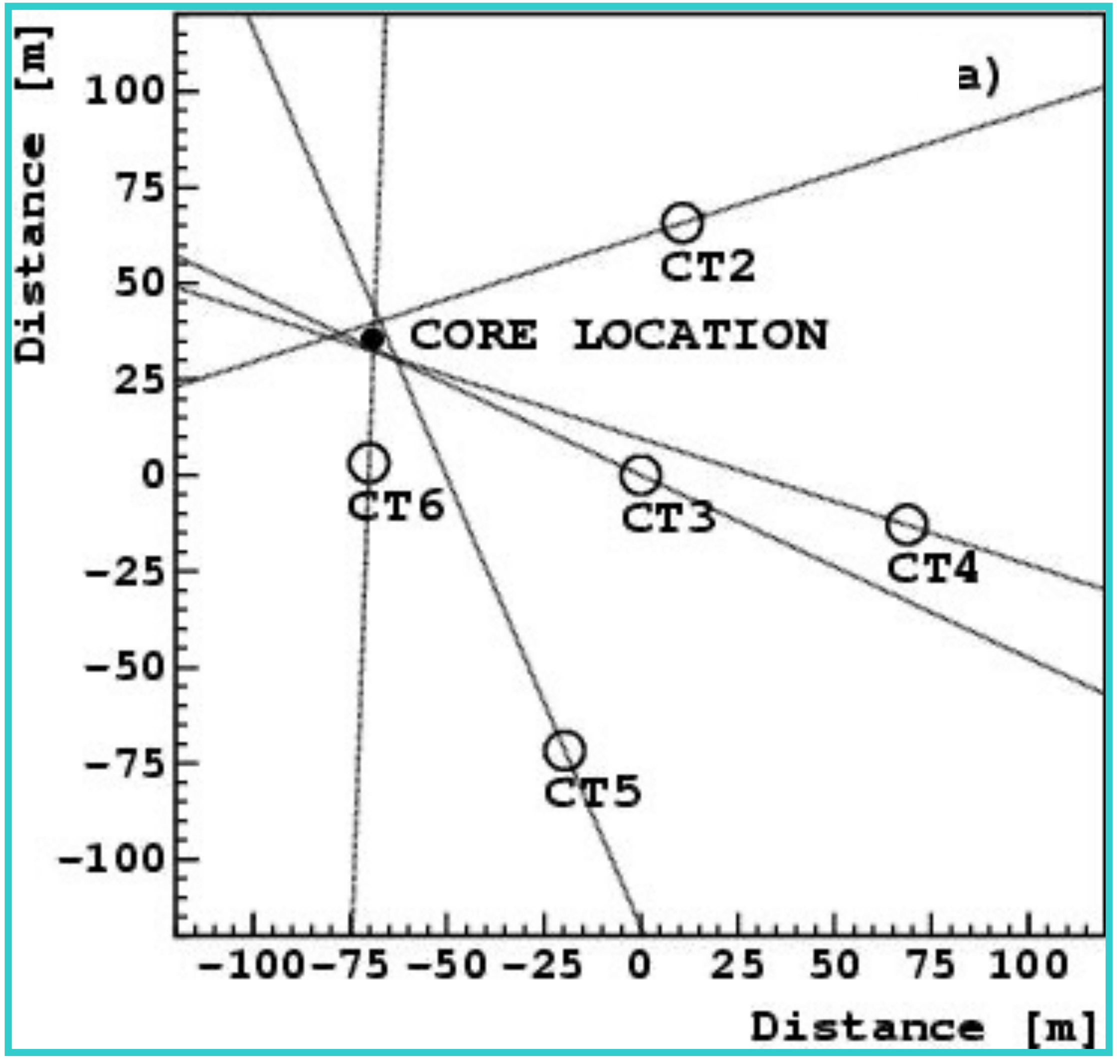
Shower geometry reconstruction (I)

Reconstruction of the shower arrival direction.



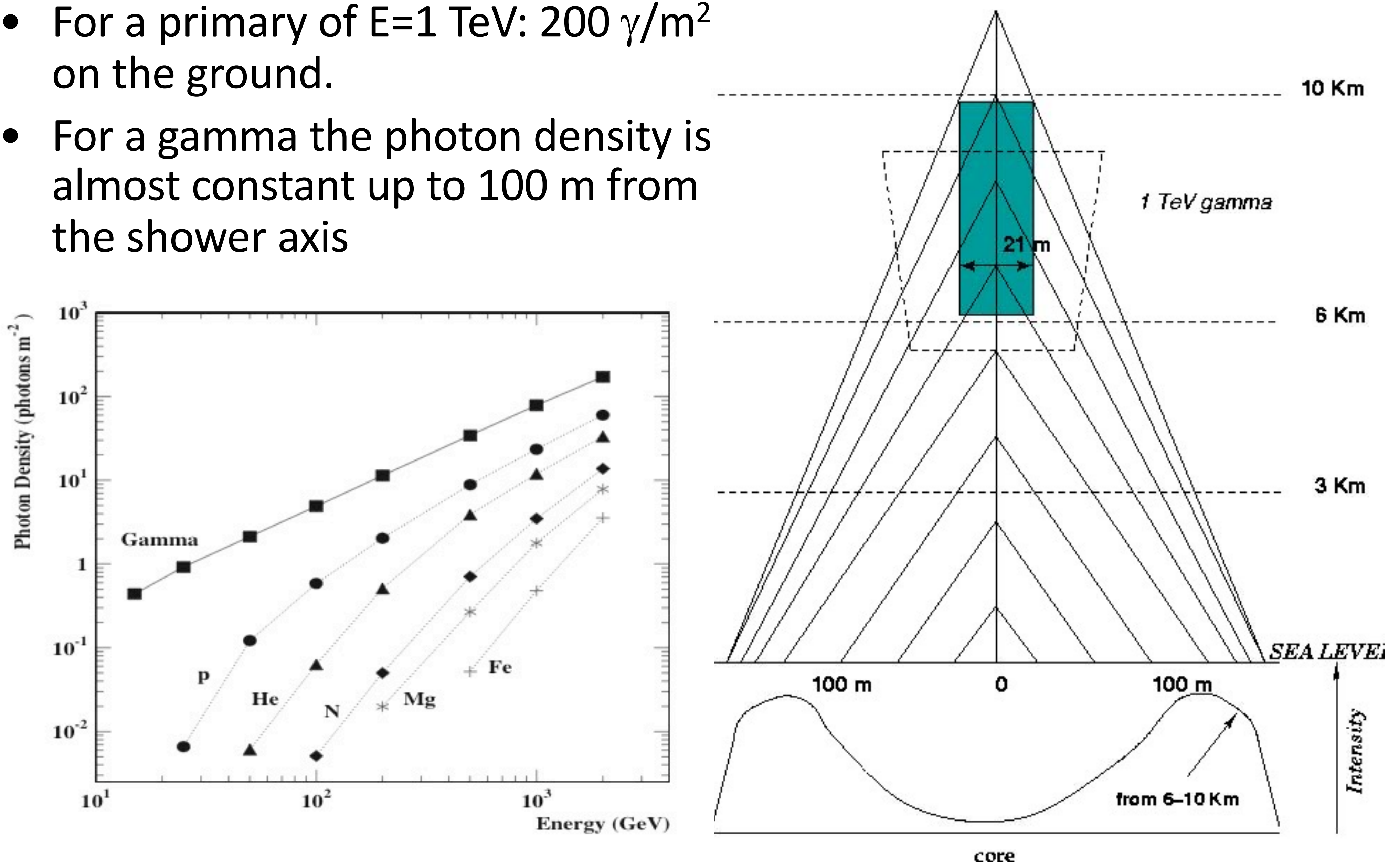
Shower geometry reconstruction (II)

Reconstruction of the impact point (*core*) on the ground with $\Delta R \approx 10\text{-}20$ m.



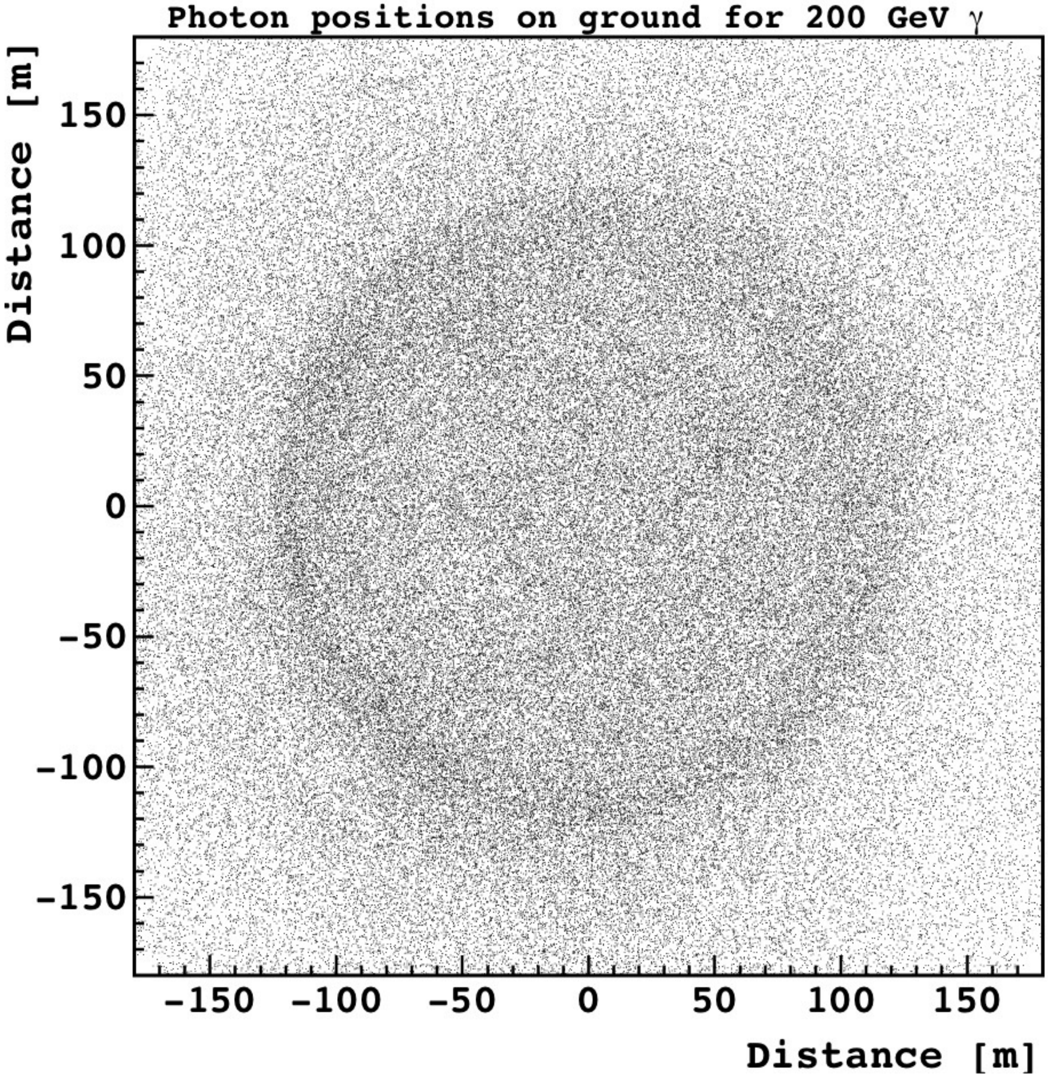
The Cherenkov light pool

- For a primary of E=1 TeV: 200 γ/m^2 on the ground.
- For a gamma the photon density is almost constant up to 100 m from the shower axis

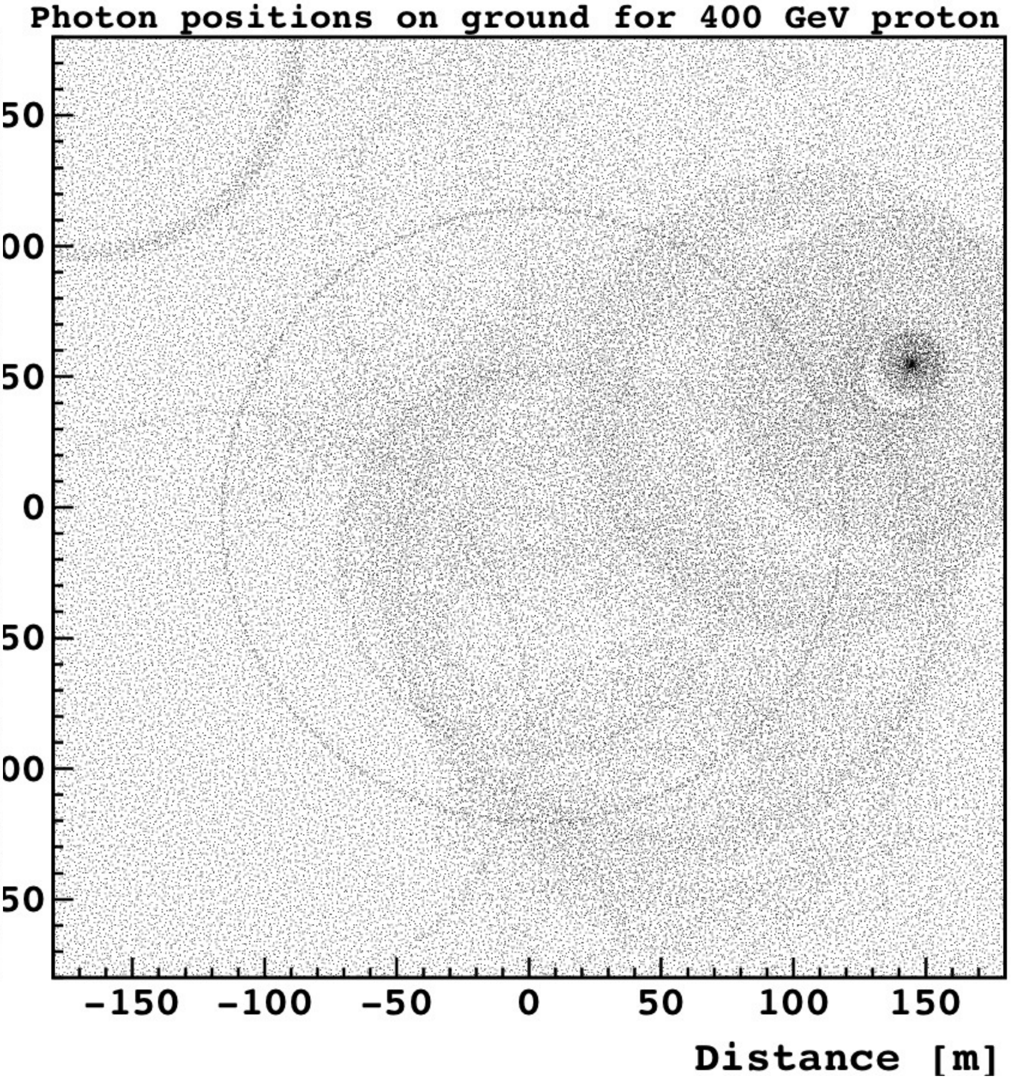


Distribution of Cherenkov photons to the ground

Shower induced by a photon E_γ ~ 200 GeV



Shower induced by a proton E_p ~ 400 GeV



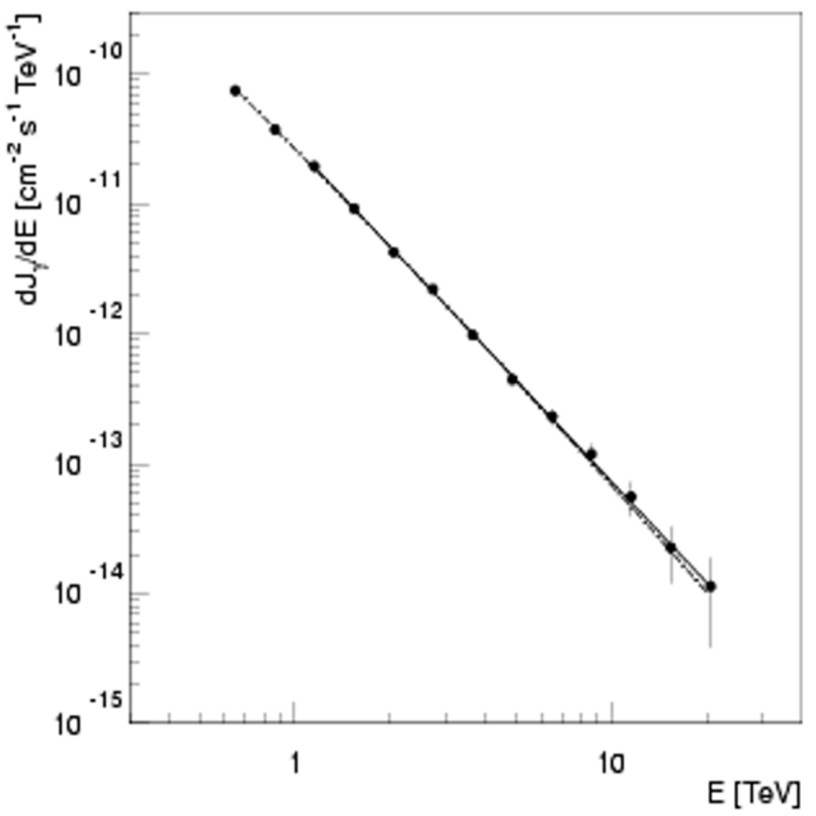
Shower energy determination

- Density of Cerenkov photons versus Energy of the primary particle
- E = F(SIZE, core_pos)

The stereoscopic system of IAC telescopes allow to reach energy resolution

$\Delta E/E \sim$ 10-20 % @ 1 TeV

Crab differential energy spectrum



θ_{zenith} dependence of collection area and energy threshold

Both increase with θ due to increasing distance to shower (less light on larger area)