Experimental Astroparticle Physics
(a short introduction)

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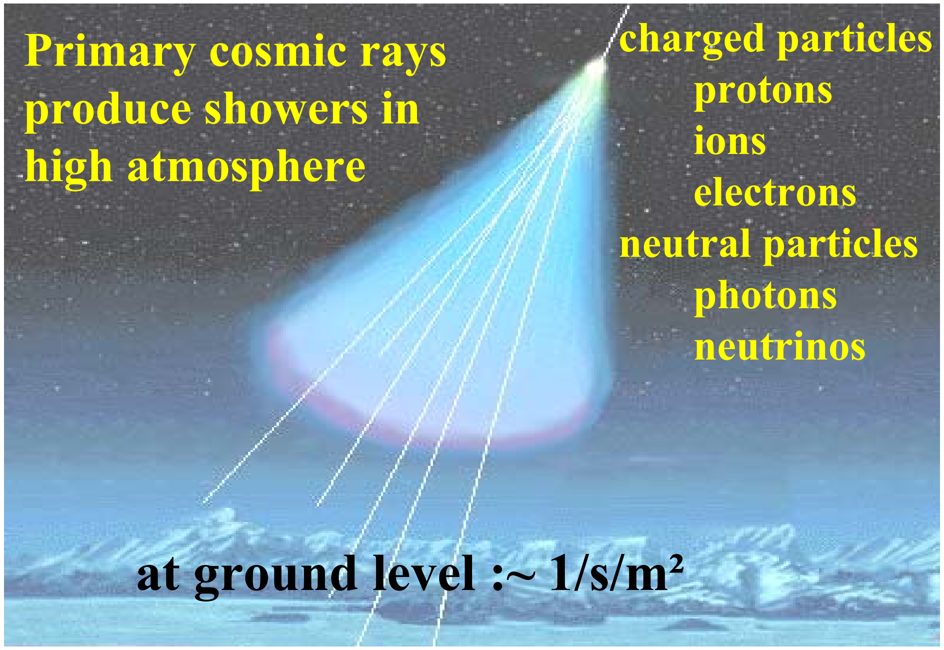
Lectures 3 & 4

III

High Energy Particles from space

Cosmic Rays

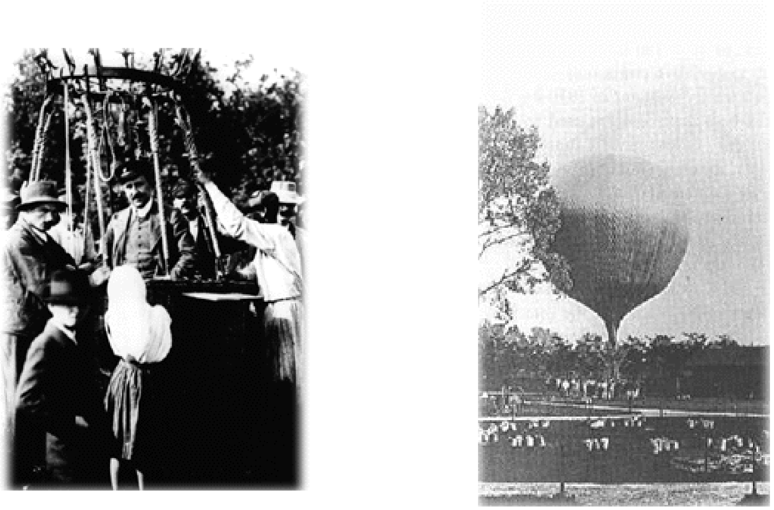


Primary cosmic rays produce showers in high atmosphere

charged particles
- **protons**
- **ions**
- **electrons**

neutral particles
- **photons**
- **neutrinos**

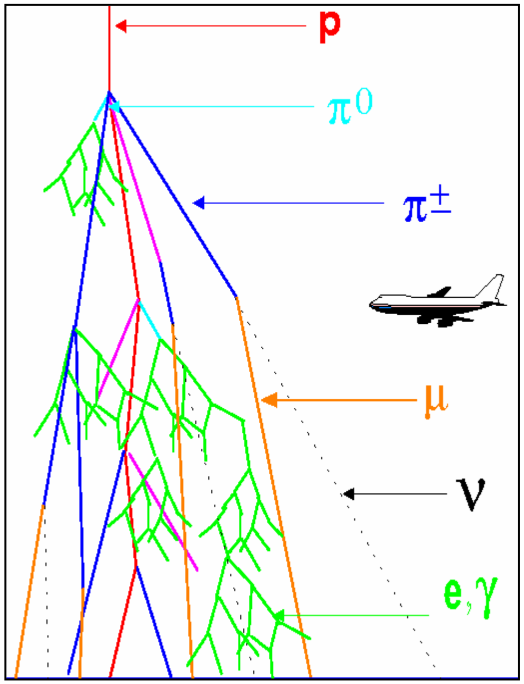
at ground level :~ 1/s/m²



100 years after discovery by Hess origin still uncertain

Primary:

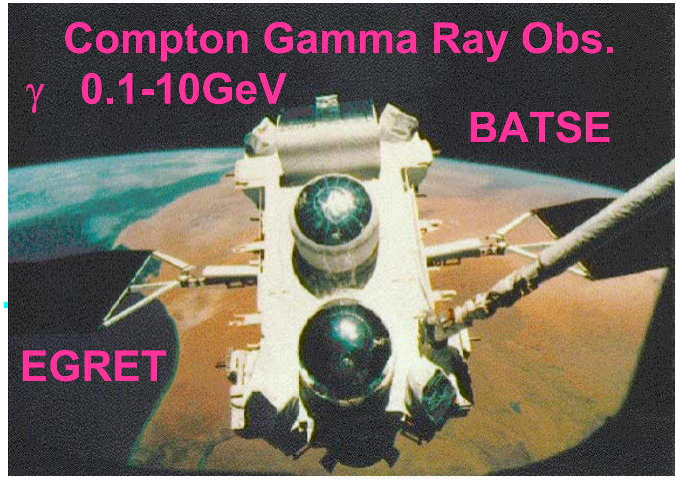
p 80 %, α 9 %, n 8 %
e 2 %, heavy nuclei 1 %
γ 0.1 %, ν 0.1 % ?

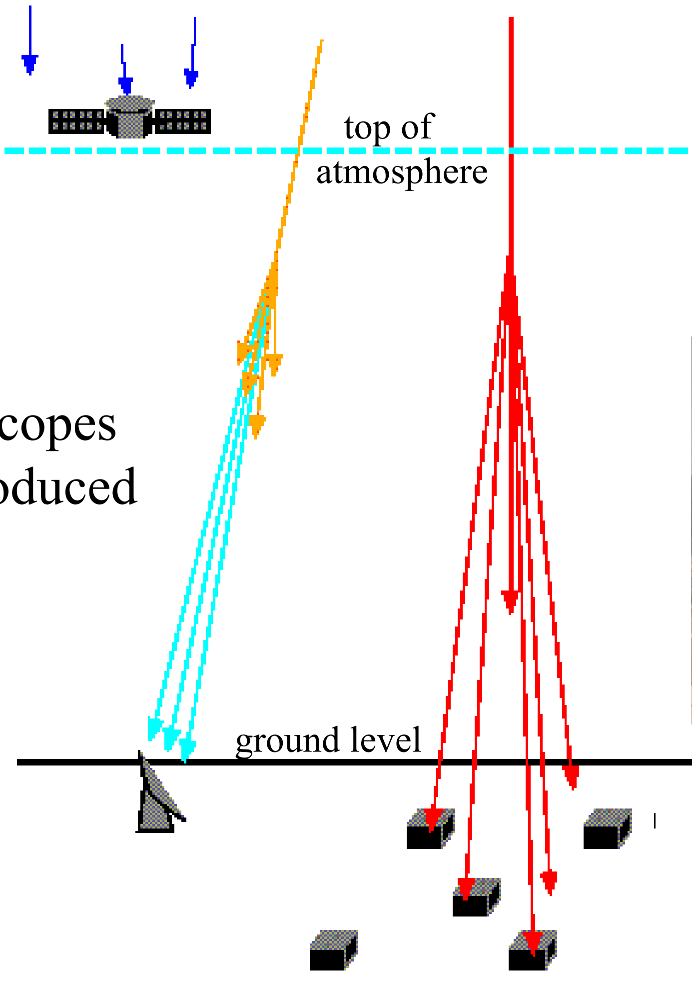


Secondary at ground level:

ν 68 %
μ 30 %
p, n, ... 2 %

Types of Cosmic Ray Detectors





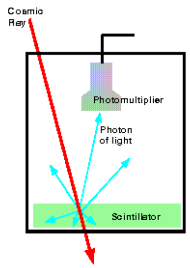
Satellites

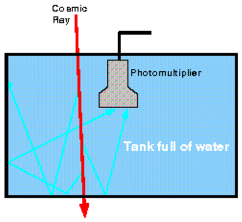
top of atmosphere

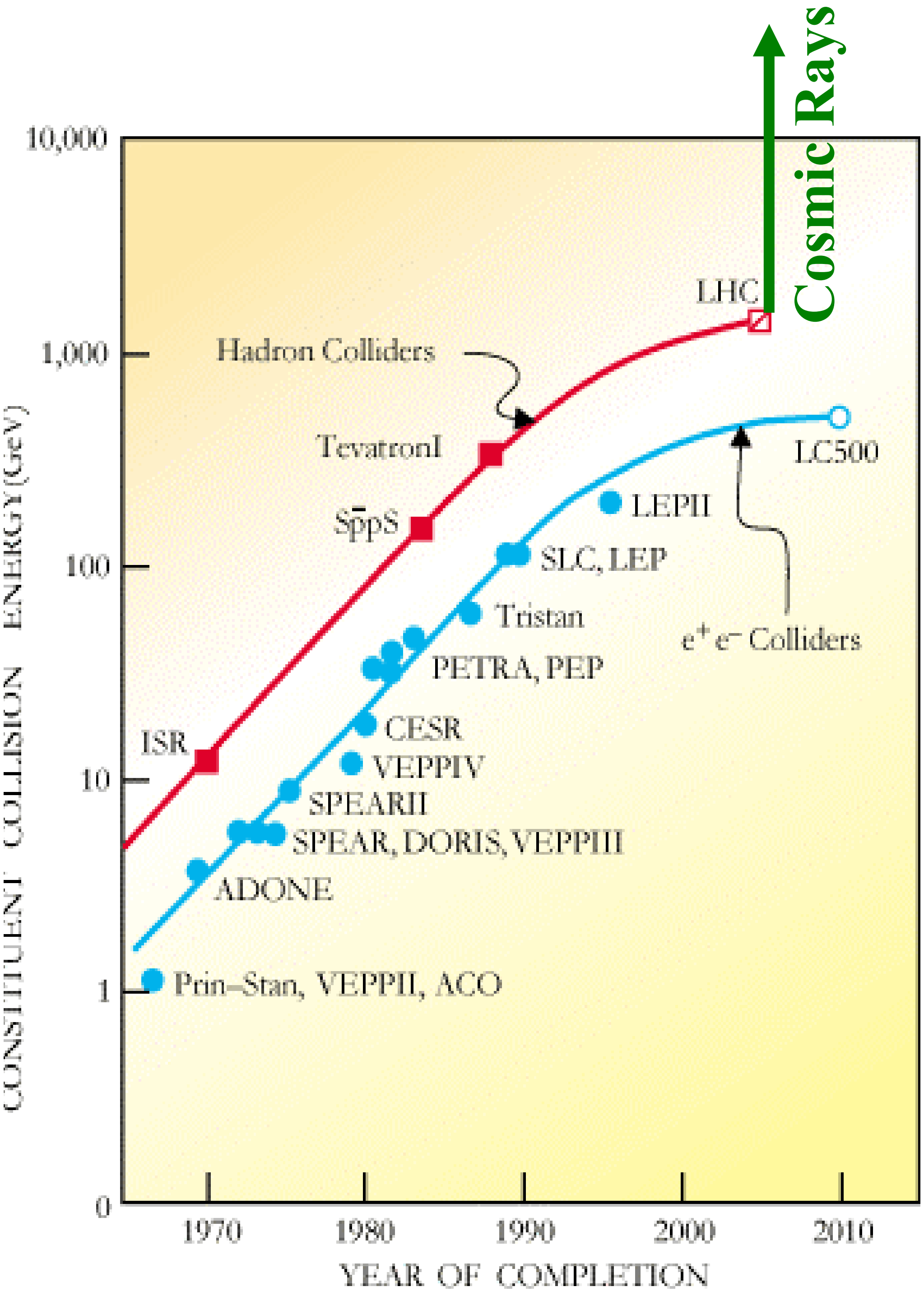
Ground based telescopes looking at light produced in atmosphere

ground level

Arrays of particle detectors







The future of HEP?

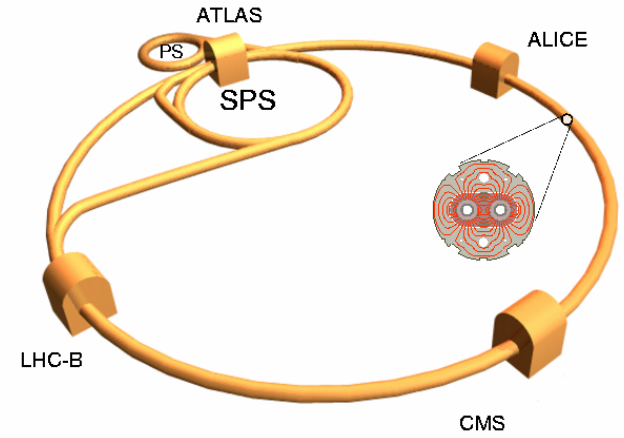
- Higher energies are not the full story…

  Also small x (lost in the beam pipes for collider detectors)

Particle Acceleration

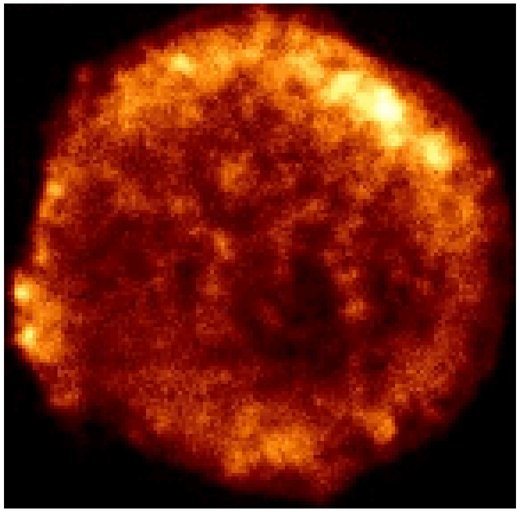
$$E \propto BR$$

Large Hadron Collider



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

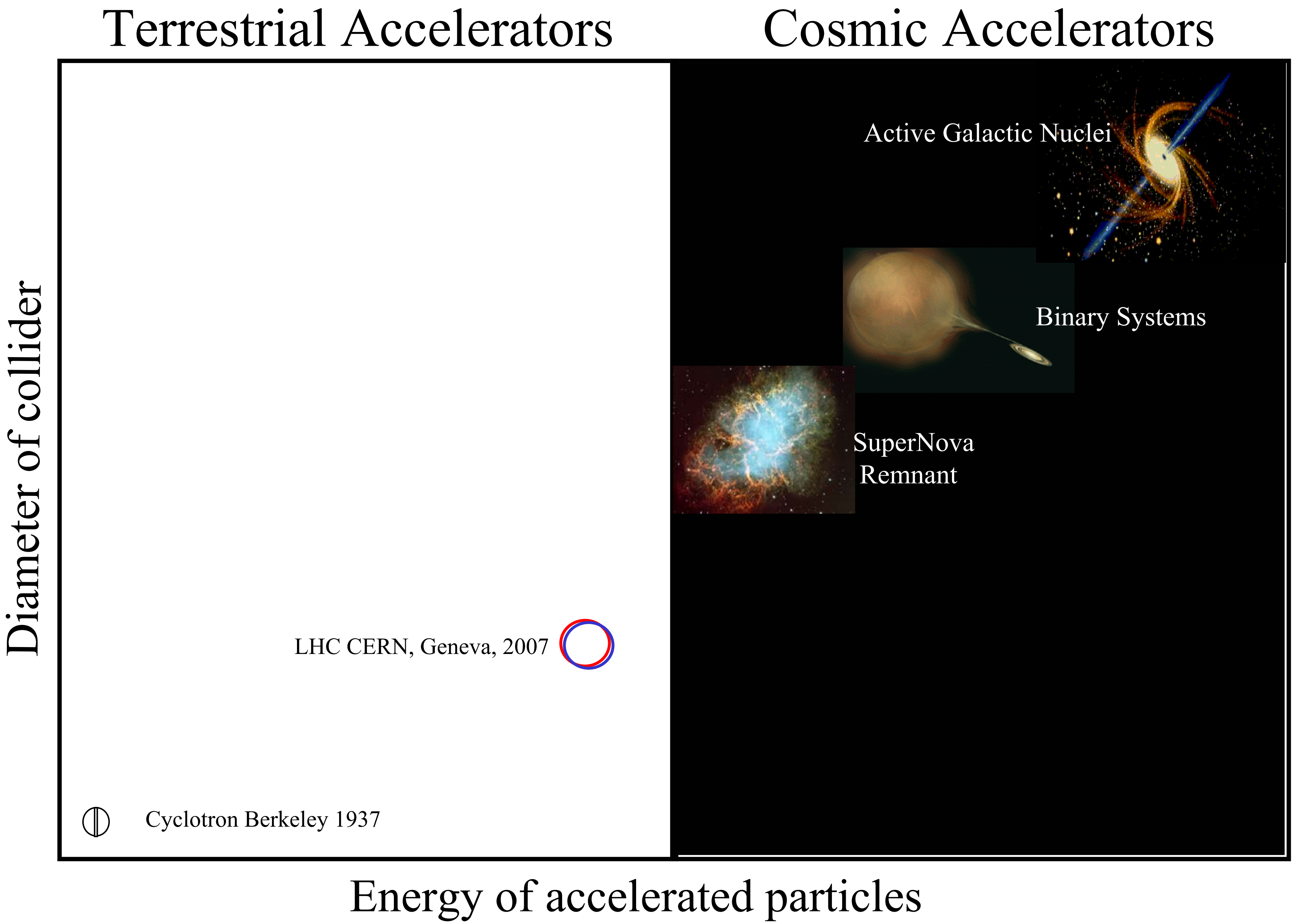
Tycho SuperNova Remnant



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

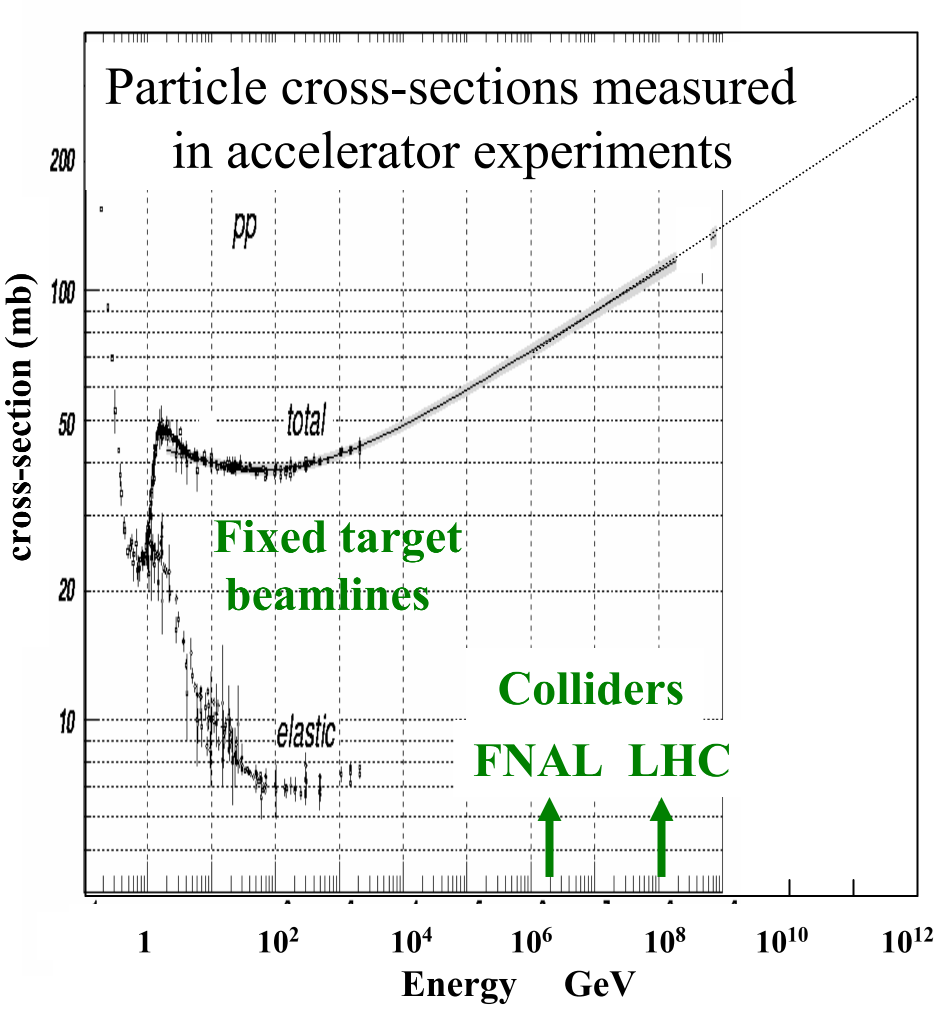
(NB. $E \propto Z \rightarrow$ Pb/Fe higher energy)

Particle Physics ⇒ Particle Astrophysics

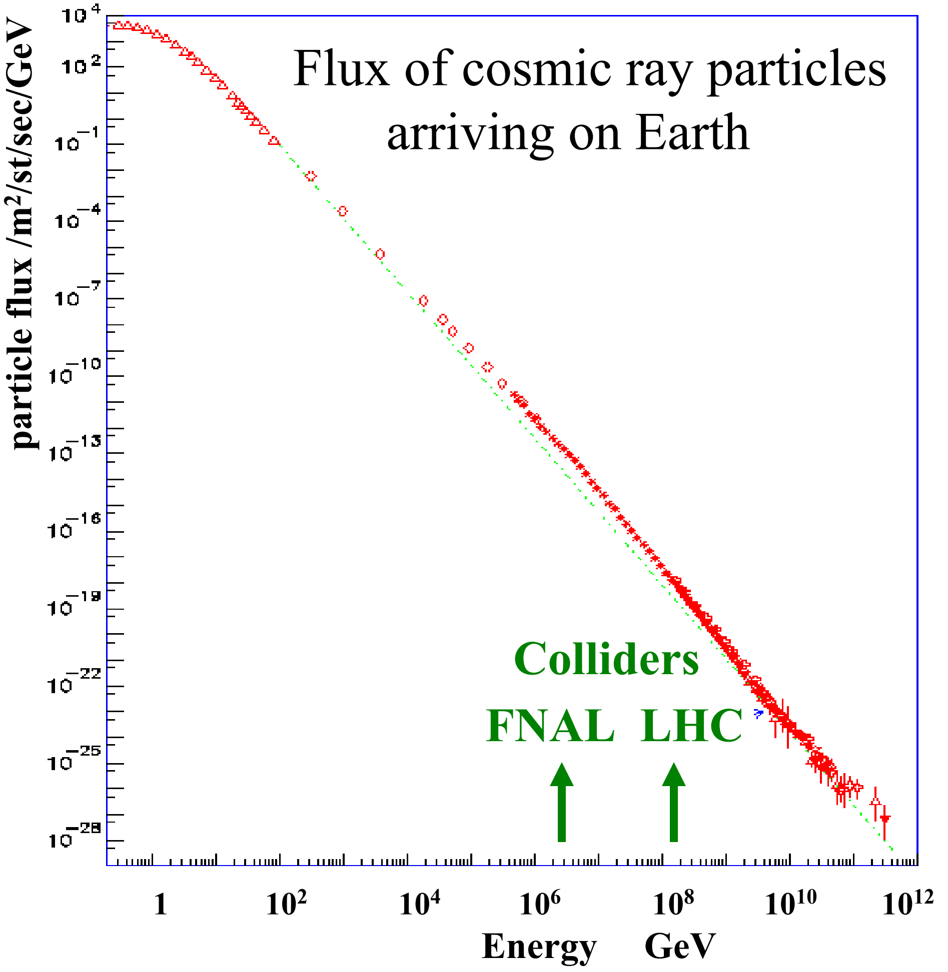


Ultra High Energy from Cosmic Rays

From laboratory accelerators

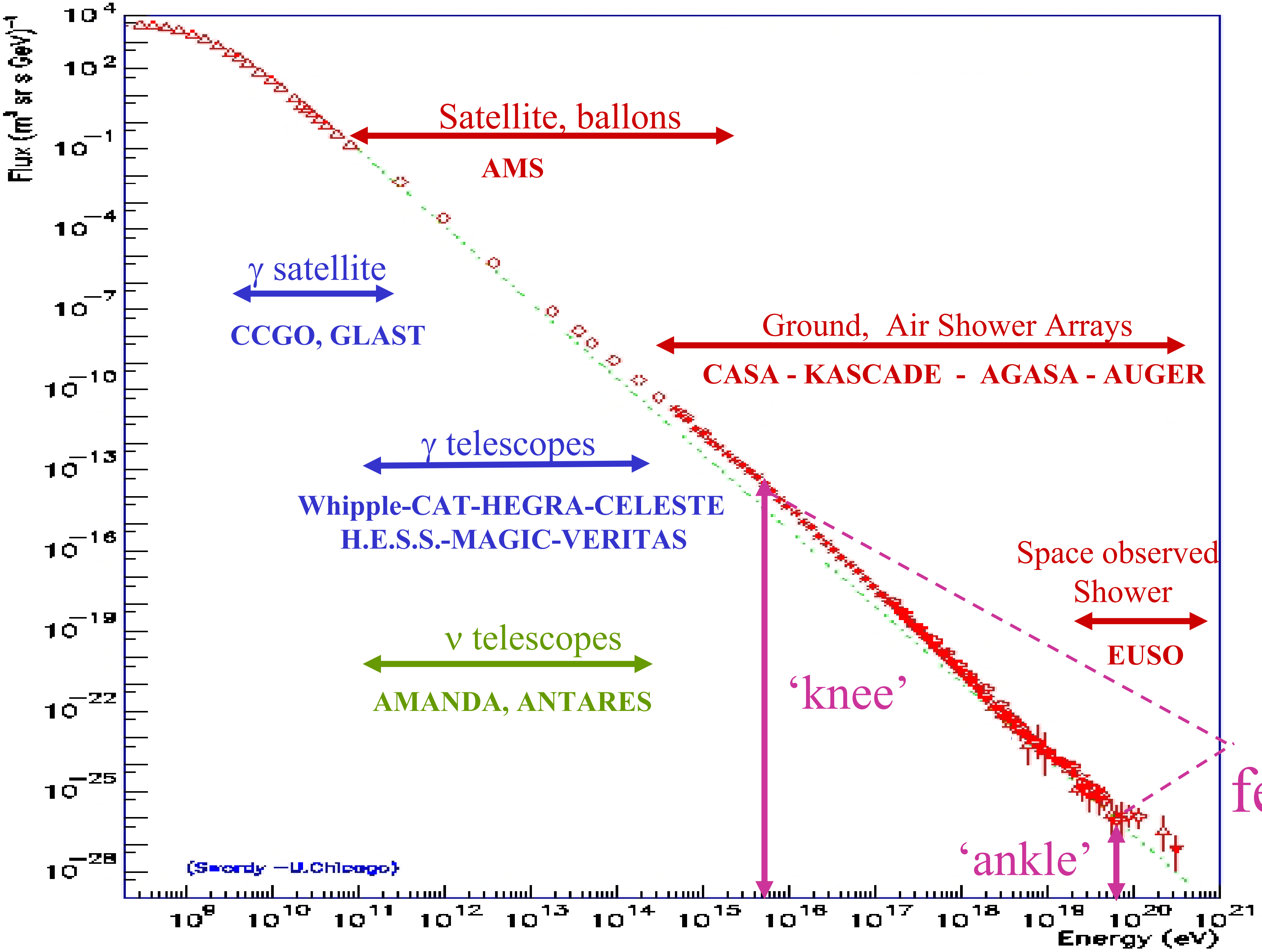


From cosmic accelerators



Ultra High Energy Particles arrive from space for free: make use of them

Charged Cosmic Ray Energy Spectrum



Satellite, ballons

AMS

γ satellite

CCGO, GLAST

Ground, Air Shower Arrays

CASA - KASCADE - AGASA - AUGER

γ telescopes

Whipple-CAT-HEGRA-CELESTE
H.E.S.S.-MAGIC-VERITAS

Space observed
Shower

EUSO

ν telescopes

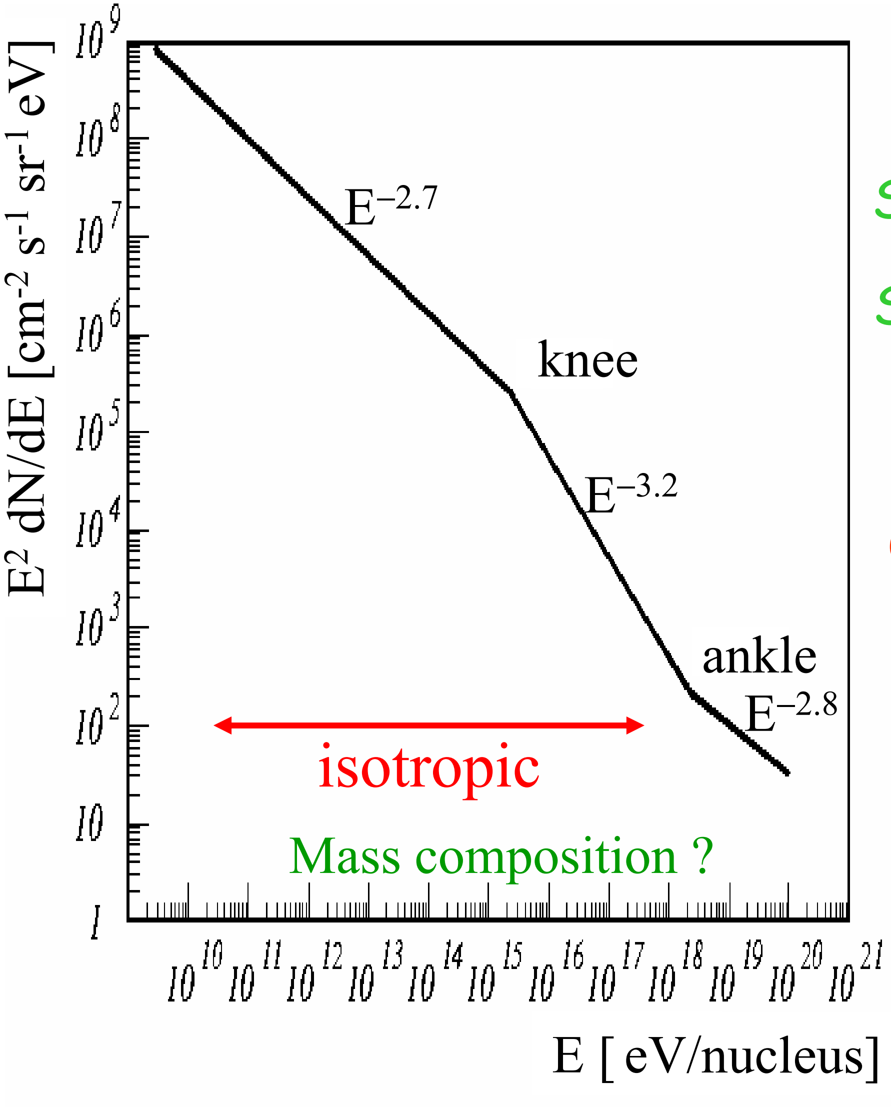
AMANDA, ANTARES

‘knee’

‘ankle’

Why
these
features
?

Features of Cosmic Ray Spectrum



Ingredients of models:

source propagation

$$dN/dE \sim E^{\alpha\ +\ \delta}$$

Source acceleration: $\alpha = -2.0$ to -2.2,..

Source cut-off $E < 10^{18}\, Z \left[\frac{R}{\mathrm{kpc}}\right]\left[\frac{B}{\mu G}\right] \mathrm{eV}$

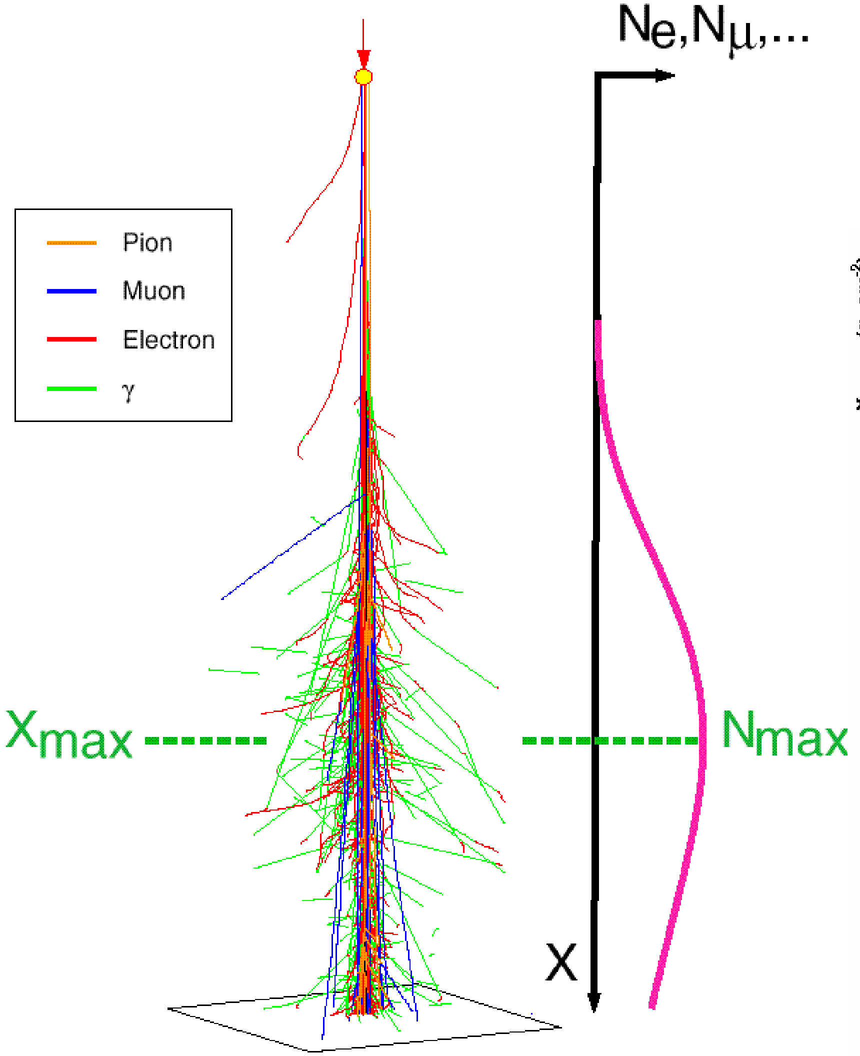
Diffusion models $\delta = -0.3$ to -0.6

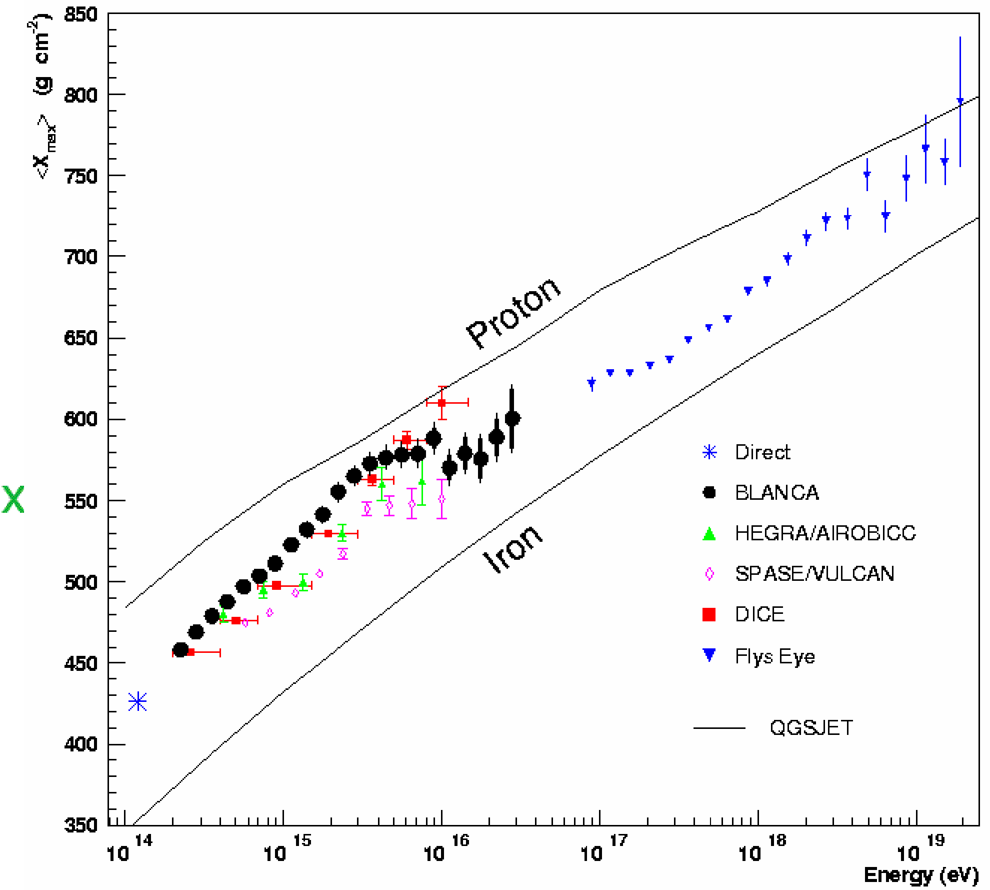
GZK cut-off on CMB γ $E \approx 7\ 10^{19}$ eV

'Conventional Wisdom':

Galactic SNR	$E < 3\ 10^{18}$ eV
Galactic losses	$E > 4\ 10^{14}$ eV
Extragalactic	$E > 3\ 10^{18}$ eV
exotic	$E > 7\ 10^{19}$ eV

Mass composition from shower depth



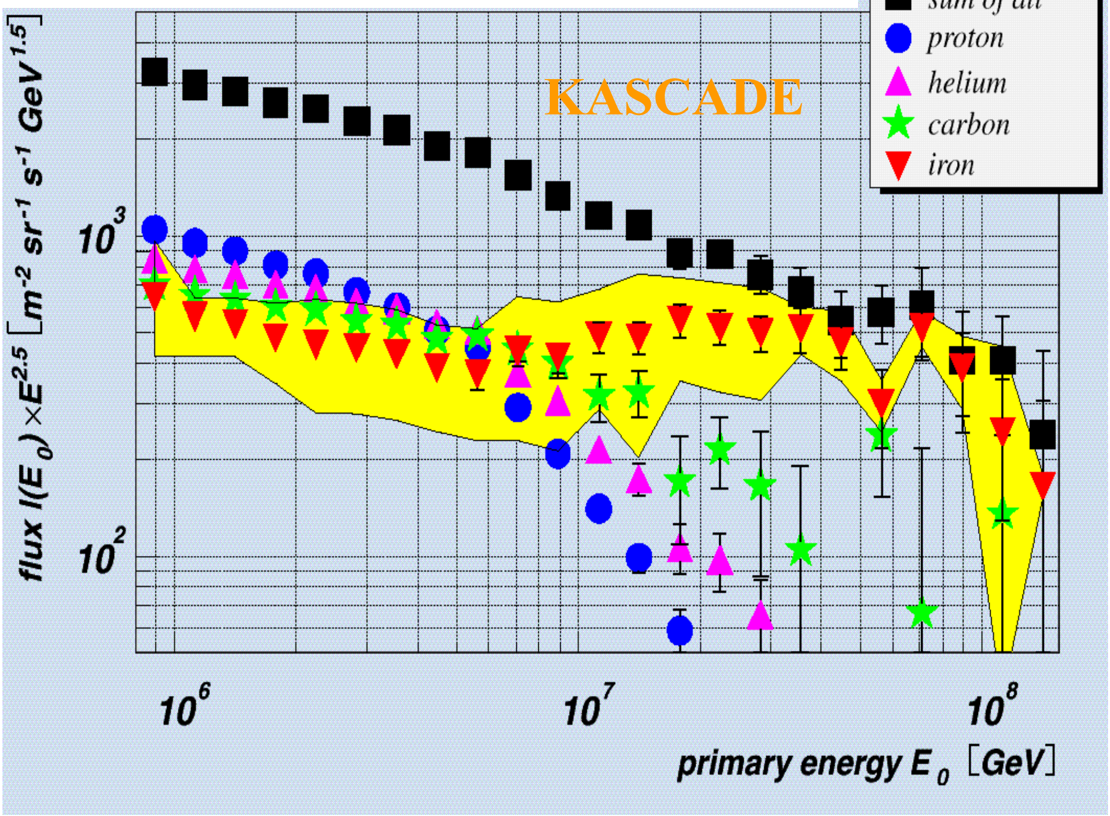


Mass composition at knee

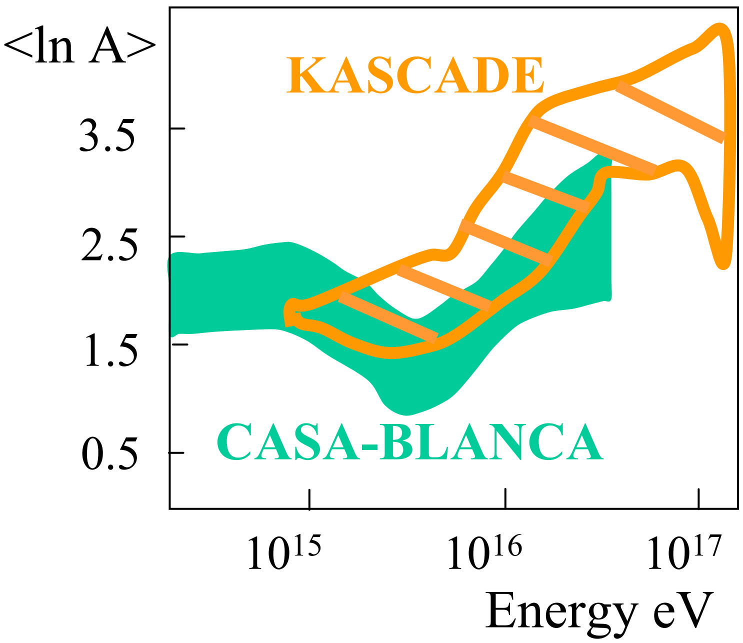
Average shower depth and ratio N_μ / N_e sensitive to primary mass

(NB. Mass composition extracted is very sensitive to Monte Carlo simulation)

Flux × $E^{2.5}$



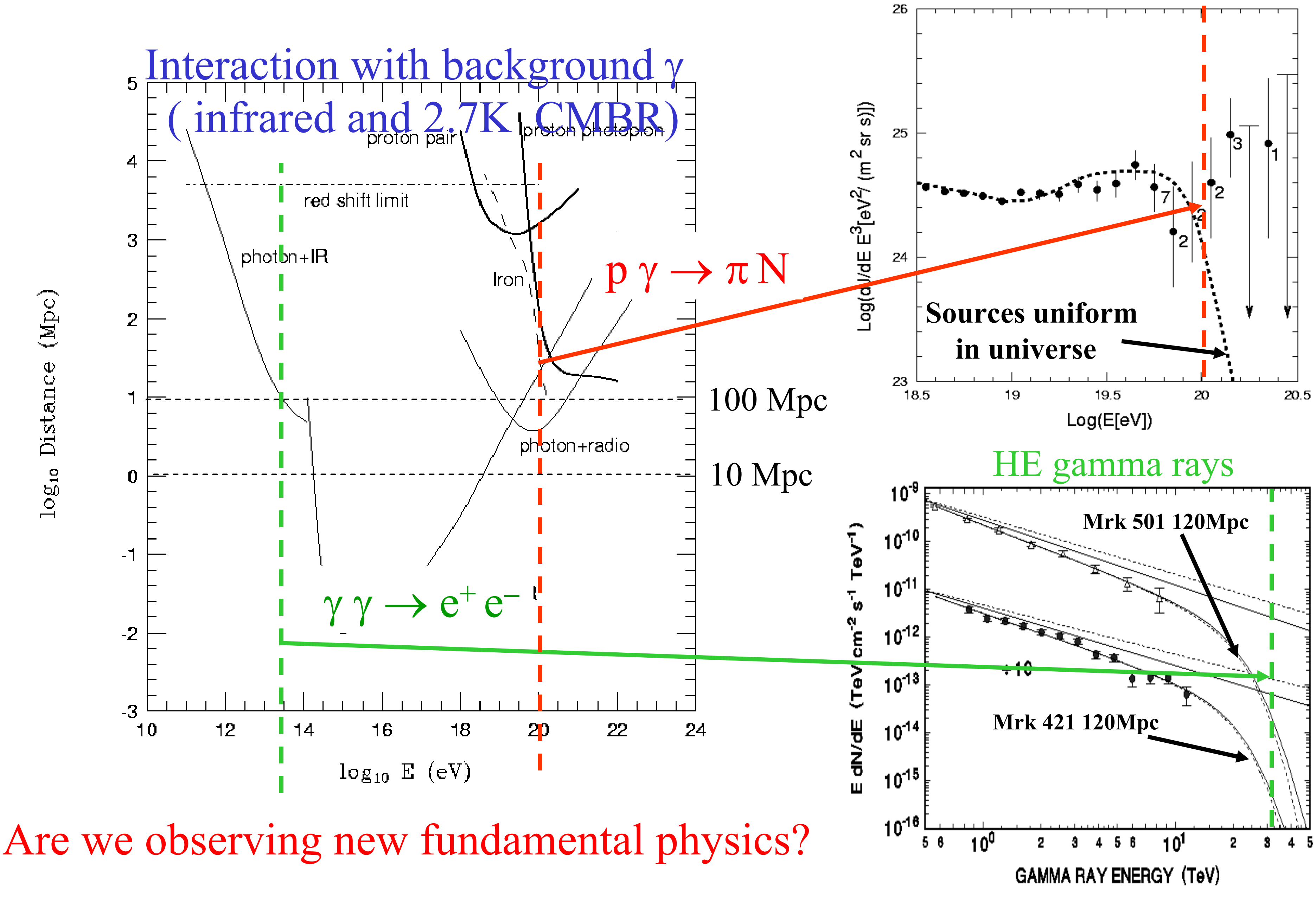
Mean ln(A)



KASCADE ⇒ series of knees at different energies: p,He,..,C,..,Fe.

E(Knee) ∝ Z ⇒ knee due to source confinement cut-off ?

‘GZK cutoff ’



Interaction with background γ
(infrared and 2.7K CMBR)

$p\,\gamma \rightarrow \pi\,N$

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

100 Mpc

10 Mpc

HE cosmic rays

Sources uniform in universe

HE gamma rays

Mrk 501 120Mpc

Mrk 421 120Mpc

Are we observing new fundamental physics?

Explanations of Ankle/ E > 10^{20} eV events

Astronomy type explanations

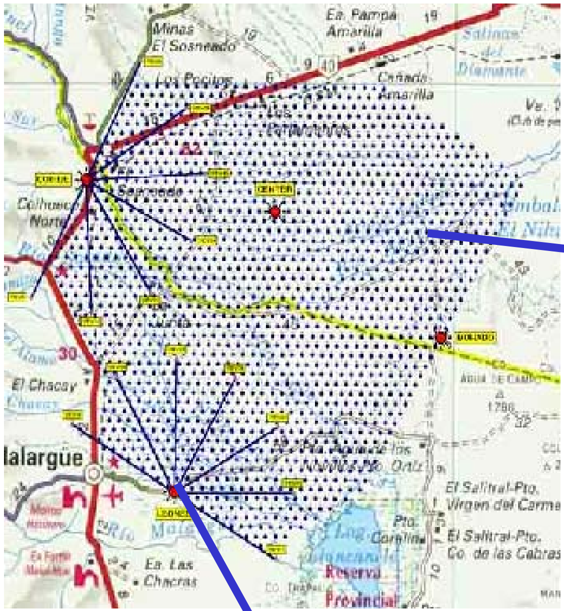
- ‘Bottom-Up’ : acceleration
  - pulsars in galaxy,
  - radio lobes of AGN (proximity a problem due to GZK, also should see source)

Particle Physics type explanations

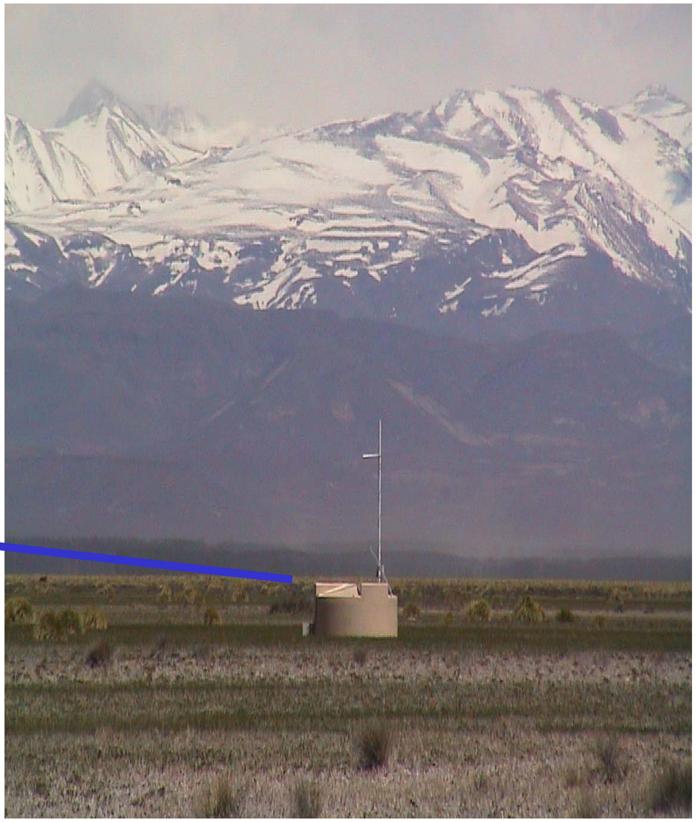
- ‘Top-Down’ : decay of massive particles
  - GUT X particles with mass > 10^{20} eV and long lifetimes
  - Topological defects
- New Physics (Lorentz violation)

AUGER experiment

2 sites each 3000km^2, E > 5.10^{18}eV

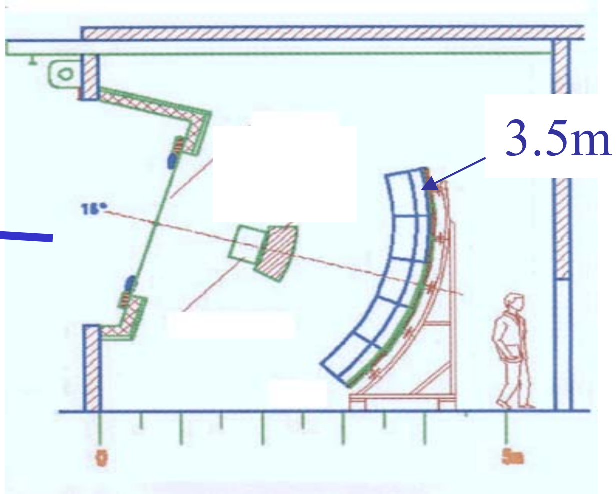


Southern site,
Mendoza Province,
Argentina



Water Cherenkov
Tanks
(1600 each 10m^2)

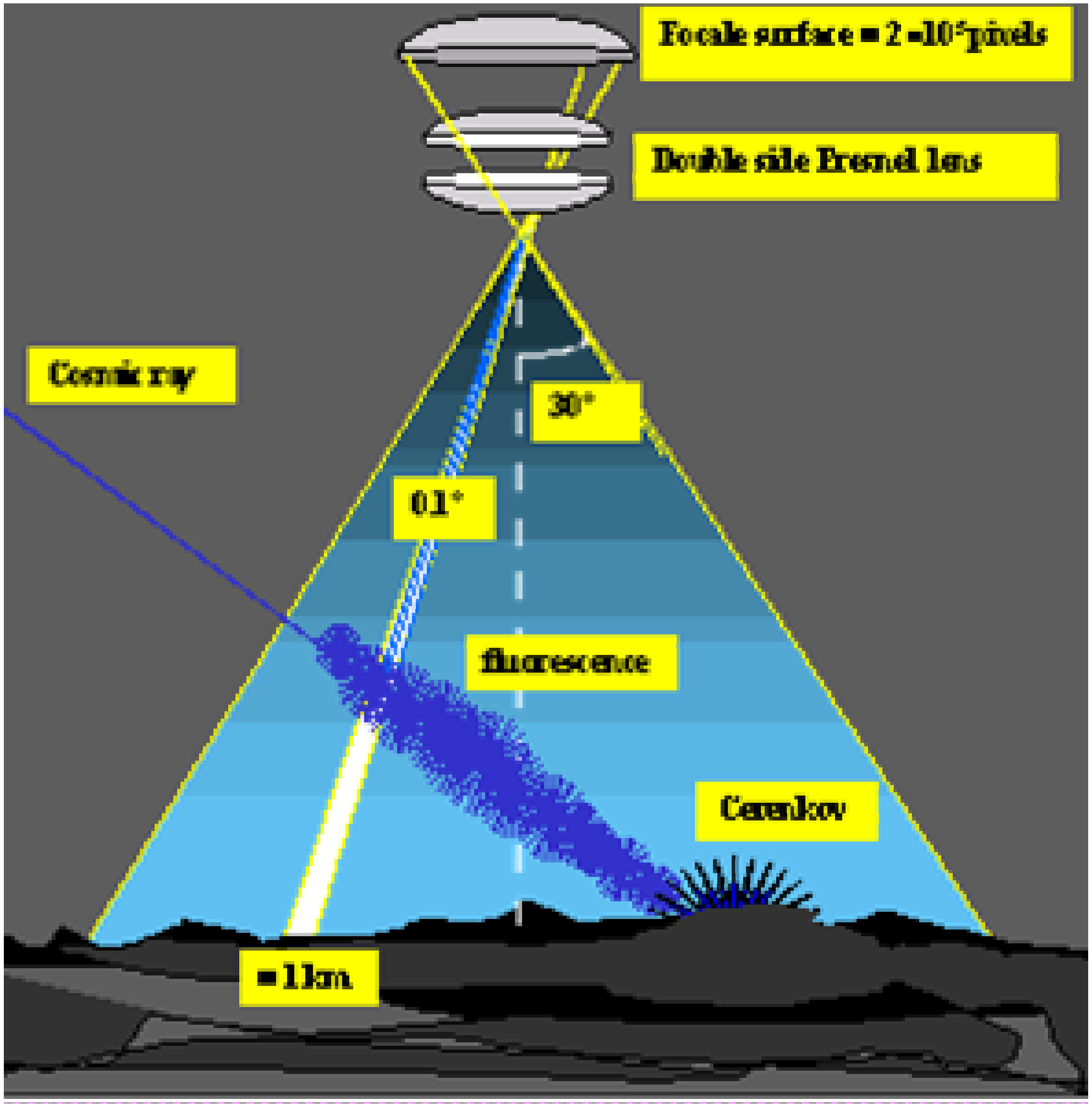
Fluorescence Telescopes (6 telescopes each 30° ×30° at 4 sites)



3.5m mirrors

A new concept: EUSO (and OWL)

- The Earth atmosphere is the ideal detector for the Extreme Energy Cosmic Rays and the companion Cosmic Neutrinos. The new idea of EUSO (2010?-) is to watch the fluorescence produced by them from the top

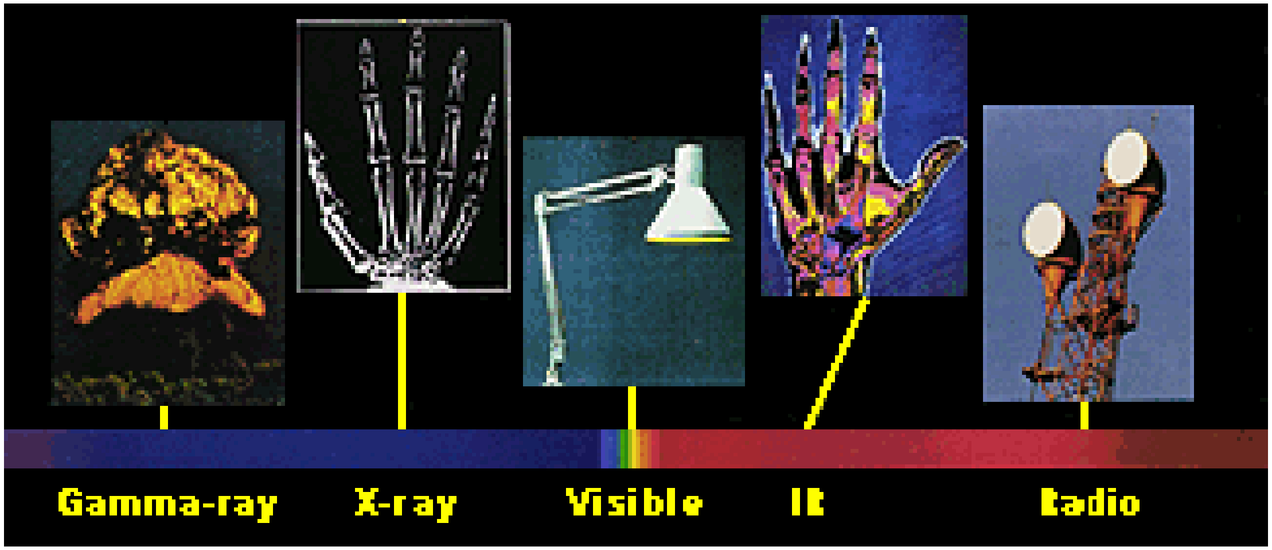


IV

Detectors for multimessanger astrophysics

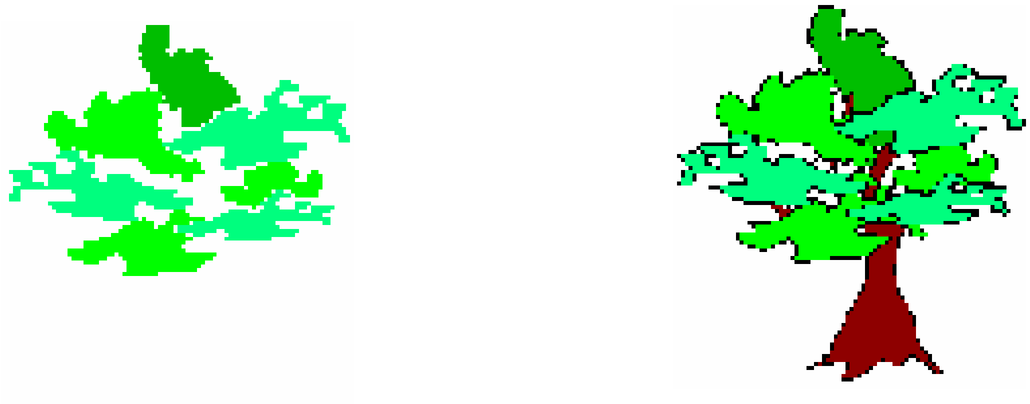
We see only partly what surrounds us

- We see only a narrow band of colors, from red to purple in the rainbow
- Also the colors we don’t see have names familiar to us: we listen to the radio, we heat food in the microwave, we take pictures of our bones through X-rays…



What about the rest ?

- What could happen if we would see only, say, green color?



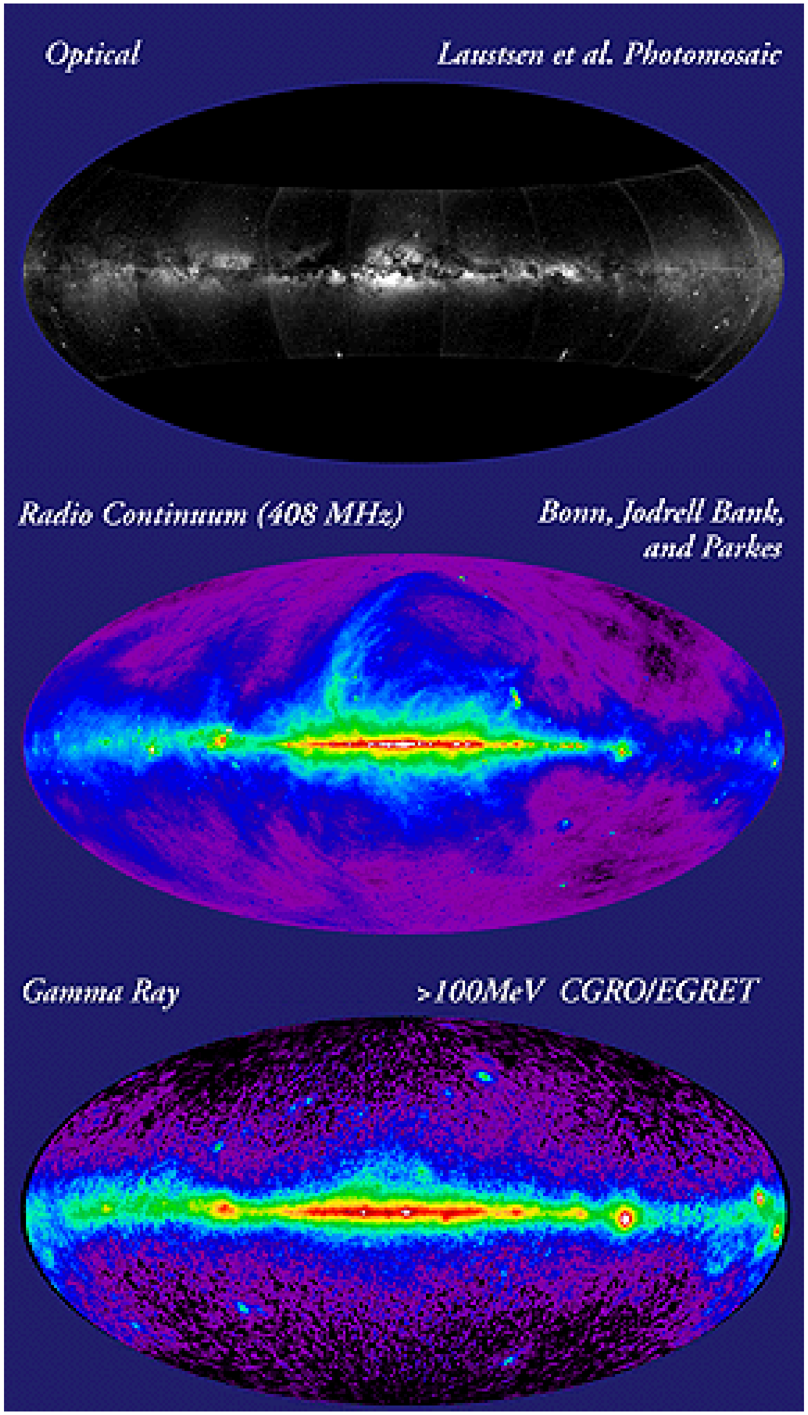
The universe we don’t see

- When we take a picture we capture light

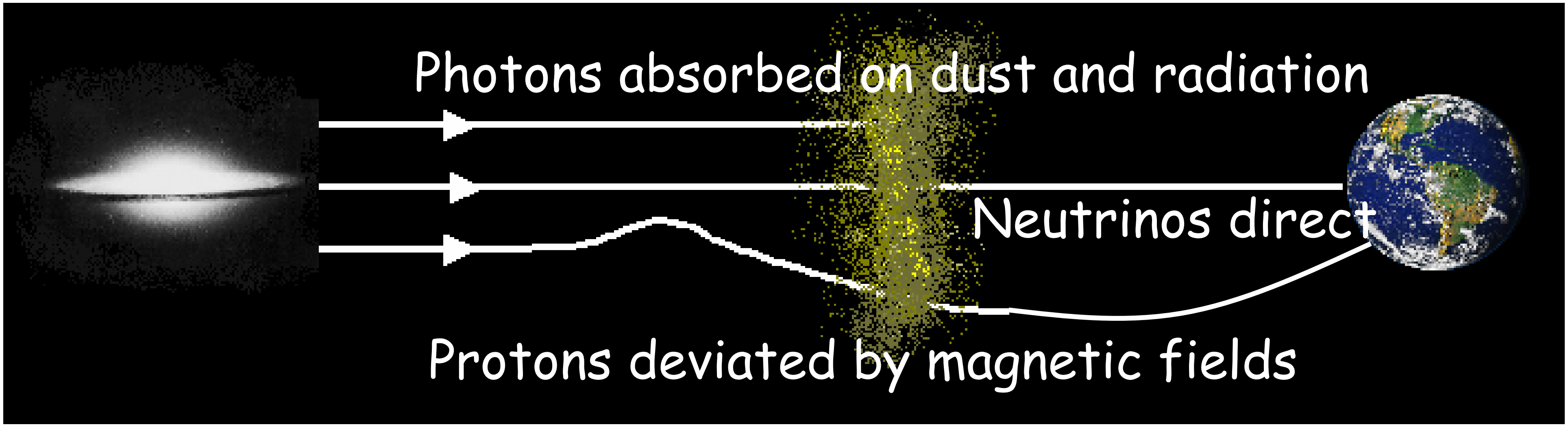
  (a telescope image comes as well from visible light)

- In the same way we can map into false colors the image from a “X-ray telescope”

- Elaborating the information is crucial



But also…



- Neutrino astrophysics
- *Graviton (?) astrophysics*

Surprises in history of astrophysics

New instruments often give unexpected results:

Telescope	**User**	**date**	**Intended Use**	**Actual use**
Optical	**Galileo**	**1608**	**Navigation**	**Moons of Jupiter**
Optical	**Hubble**	**1929**	**Nebulae**	**Expanding Universe**
Radio	**Jansky**	**1932**	**Noise**	**Radio galaxies**
Micro-wave	**Penzias, Wilson**	**1965**	**Radio-galaxies, noise**	**3K cosmic background**
X-ray	**Giacconi …**	**1965**	**Sun, moon**	**neutron stars accreating binaires**
Radio	**Hewish,Bell**	**1967**	**Ionosphere**	**Pulsars**
γ-rays	**military**	**1960?**	**Thermonuclear explosions**	**Gamma ray bursts**

With future new detector can again hope for completely new discoveries

The high-energy γ spectrum

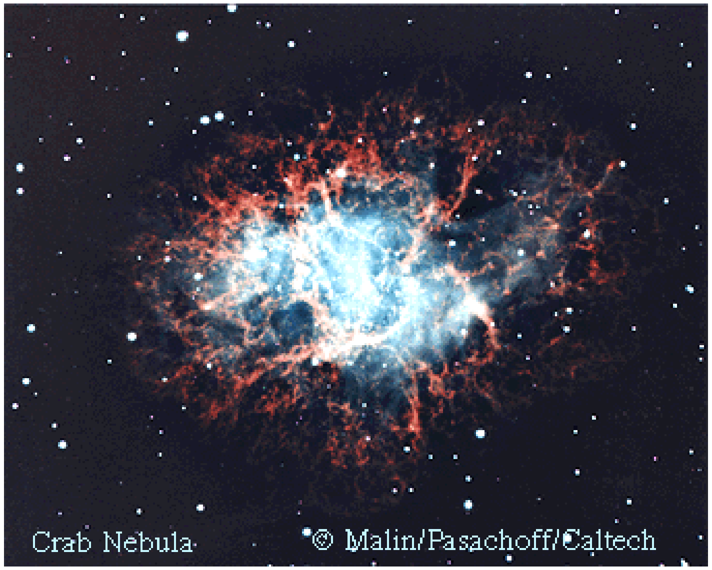
$E_\gamma > 30$ keV ($\lambda \sim 0.4$ A, $\nu \sim 7\ 10^9$ GHz)

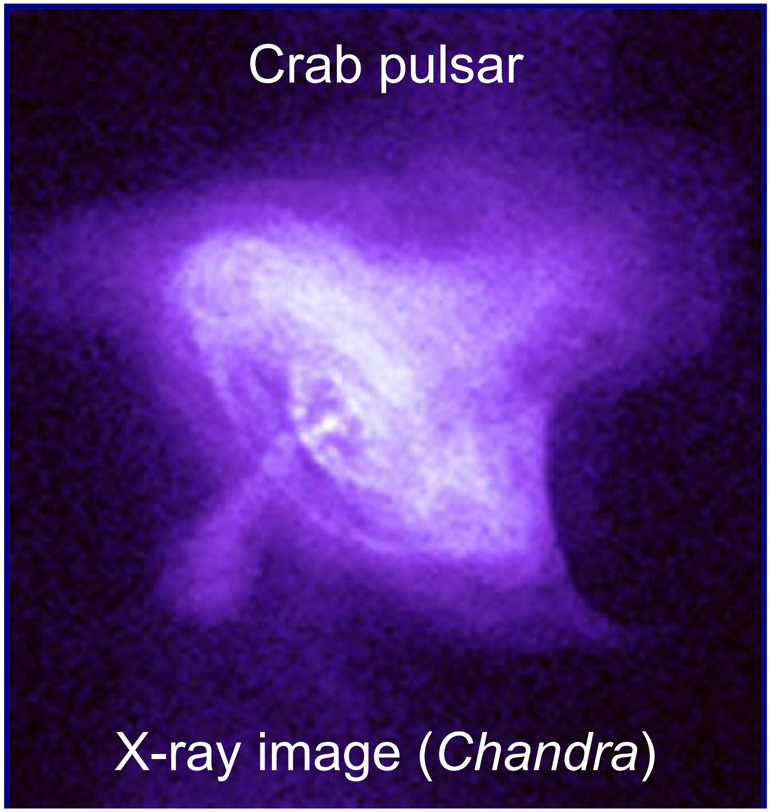
Although arbitrary, this limit reflects astrophysical and experimental facts:

- Thermal emission -> nonthermal emission
- Problems to concentrate photons (-> telescopes radically different from larger wavelengths)
- Large background from cosmic particles

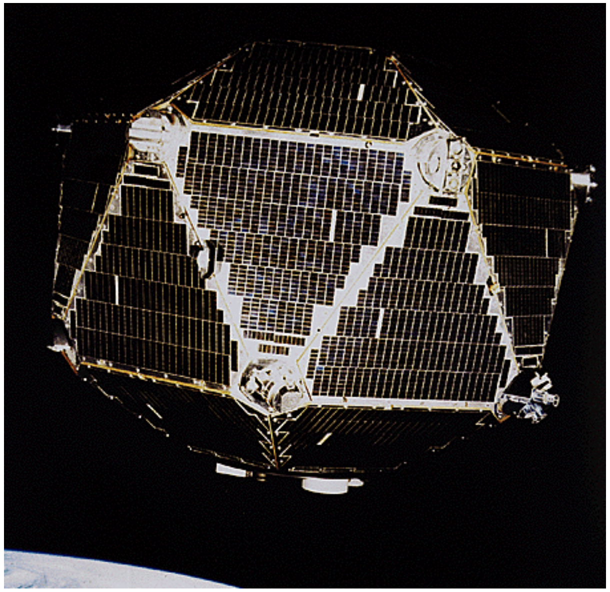
Exotic objects: Pulsars

- Rapidly rotating neutron stars with
  - T between ~1ms and ~1s
  - Strong magnetic fields (~100 MT)
  - Mass ~ 3 solar masses
  - R ~ 10 Km (densest stable object known)
- For the pulsars emitting TeV gammas, such an emission is unpulsed





Study of exotic objects: γ-ray bursts (History, I)



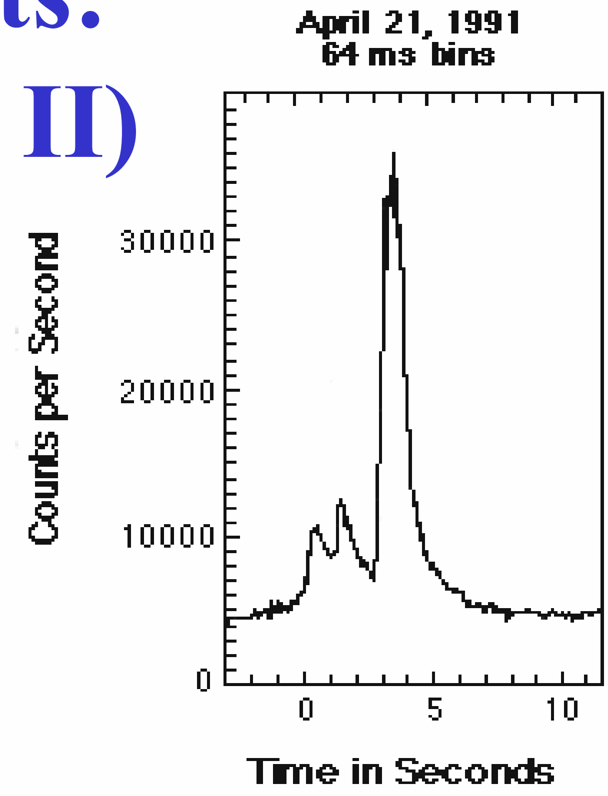
- An intriguing puzzle of today's astronomy… A brief history
  - Beginning of the '60s: Soviets are ahead in the space war
    - 1959: USSR sends a satellite to impact on the moon
    - 1961: USSR sends in space the 27-years old Yuri Gagarin
  - 1963: the US Air Force launches the 2 Vela satellites to spy if the Soviets are doing nuclear tests in space or on the moon
    - Equipped with NaI (Tl) scintillators

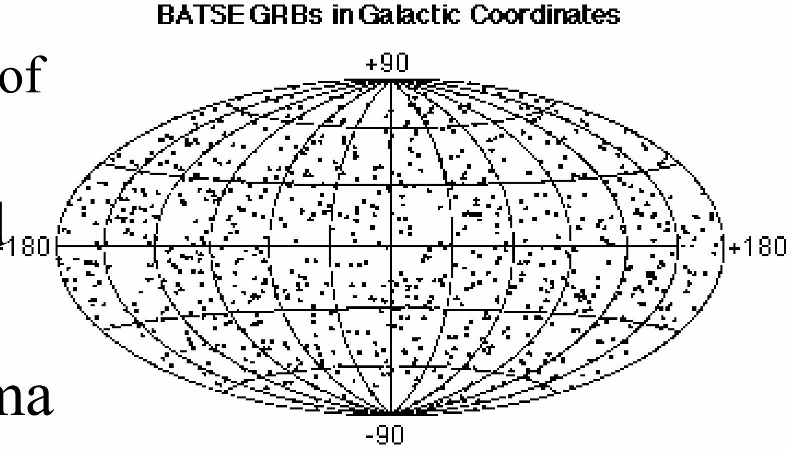
Study of exotic objects: γ-ray bursts (History, II)

- 1967 : an anomalous emission of X and γ rays is observed. For a few seconds, it outshines all the γ sources in the Universe put together. Then it disappears completely. Another in 1969...

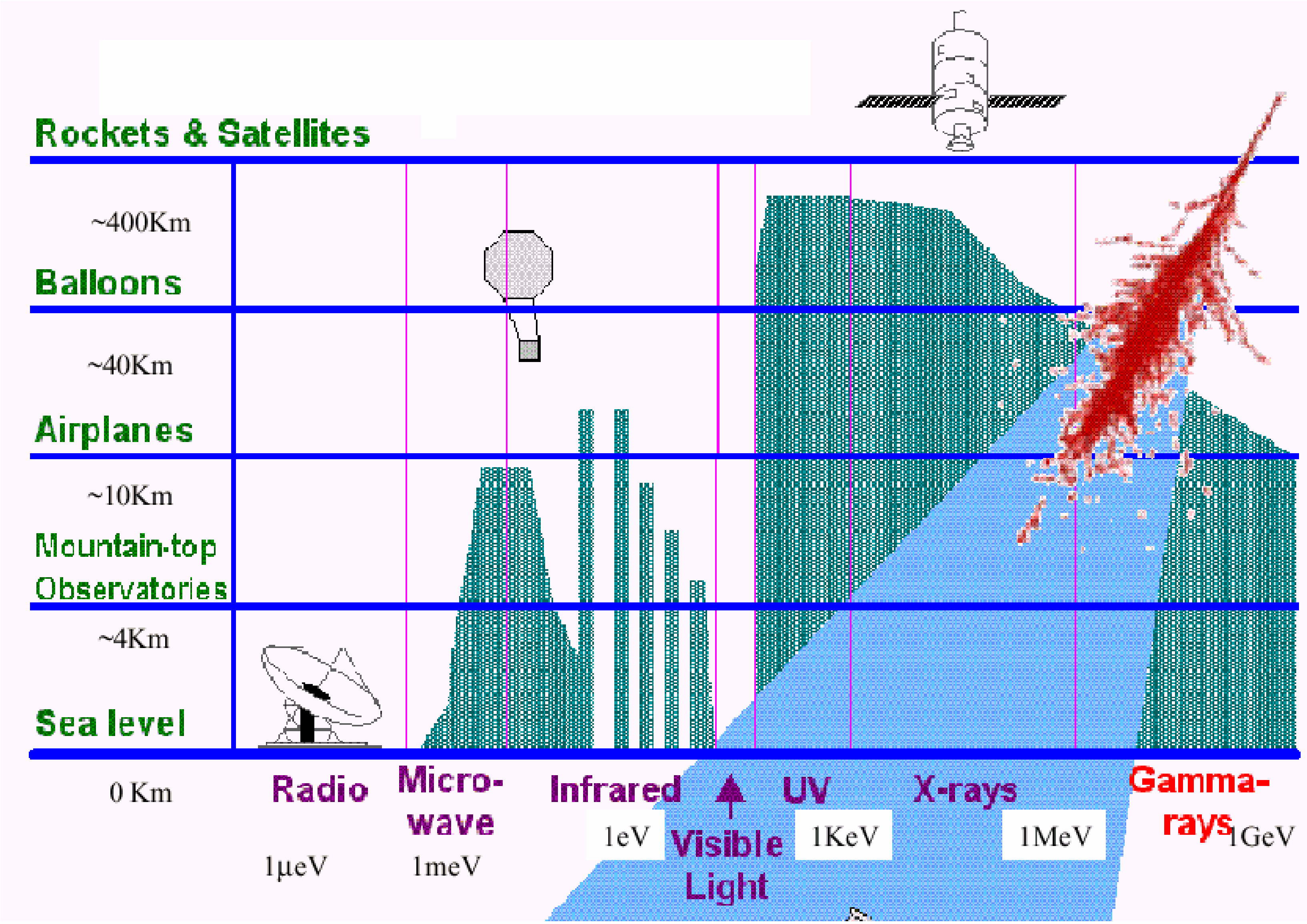
  After careful studies (!), origination from Soviet experiments is ruled out

  - The bursts don't come from the vicinity of the Earth
- 1973 (!) : The observation is reported to the world
- Now we have seen hundreds of gamma ray bursts...



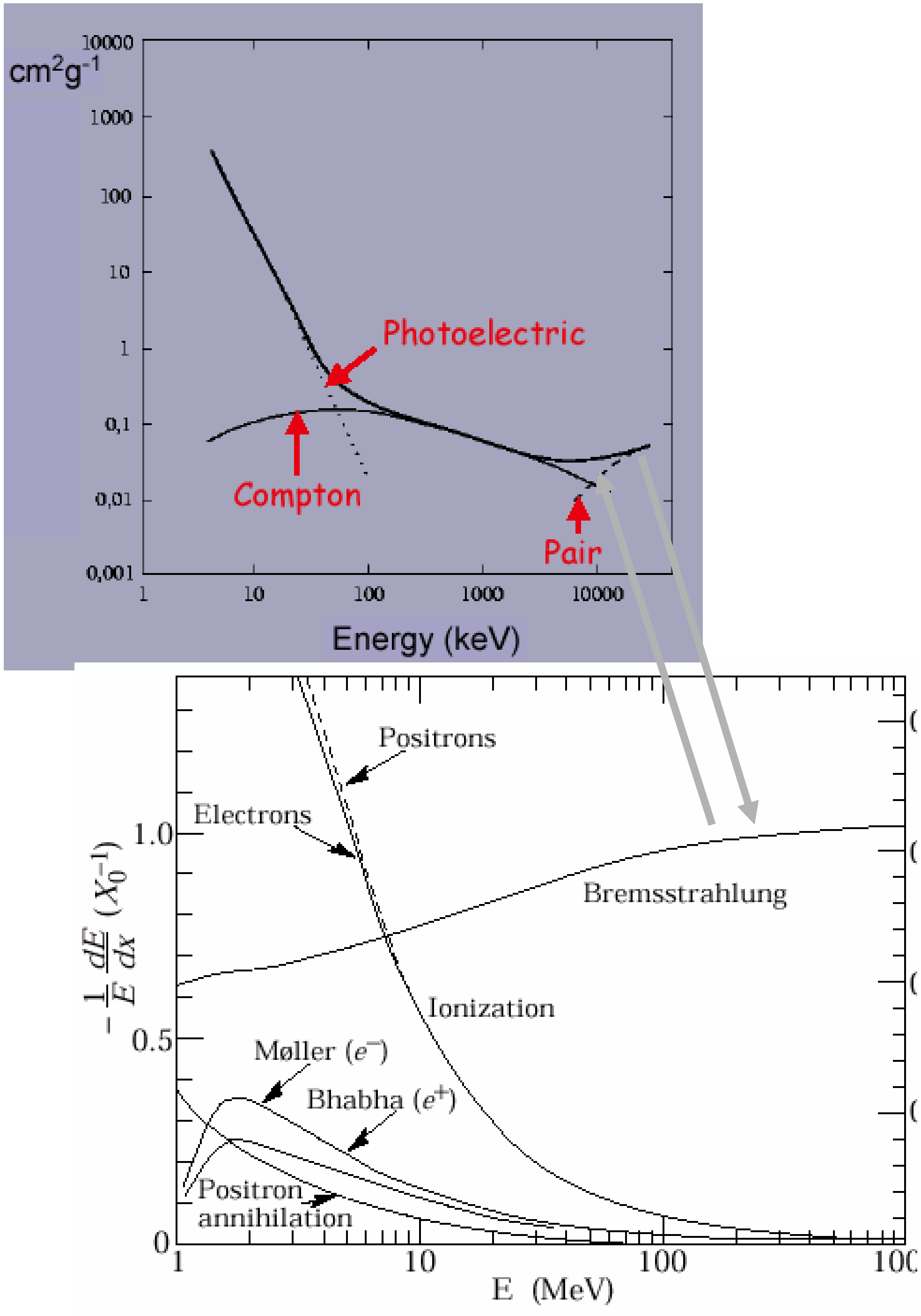


Transparency of the atmosphere

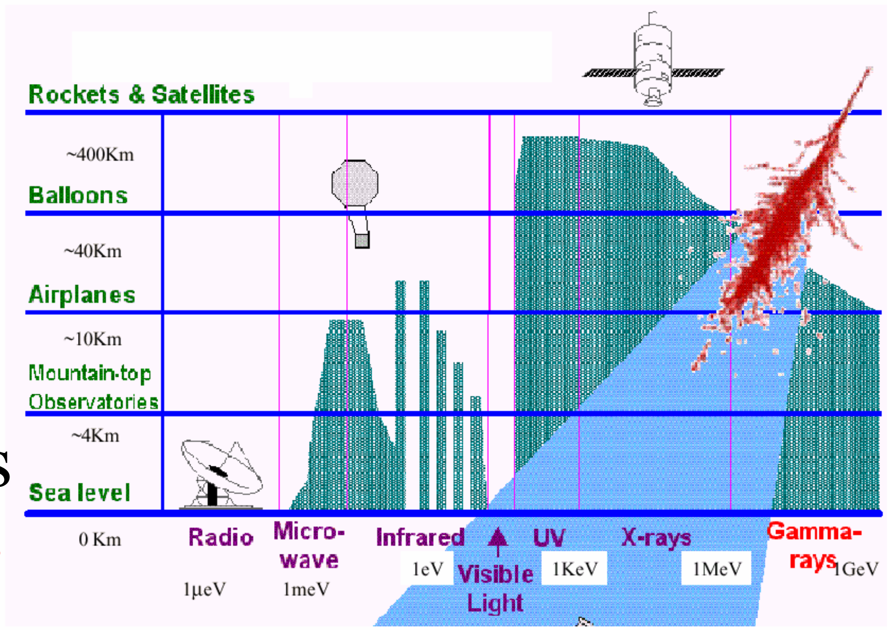


Detection of a high E photon

- Above the UV and below "50 GeV", shielding from the atmosphere
  - Below the e+e- threshold + some phase space ("10 MeV"), Compton/scintillation
  - Above "10 MeV", pair production
- Above "50 GeV", atmospheric showers
  - Pair <-> Brem



Consequences on the techniques

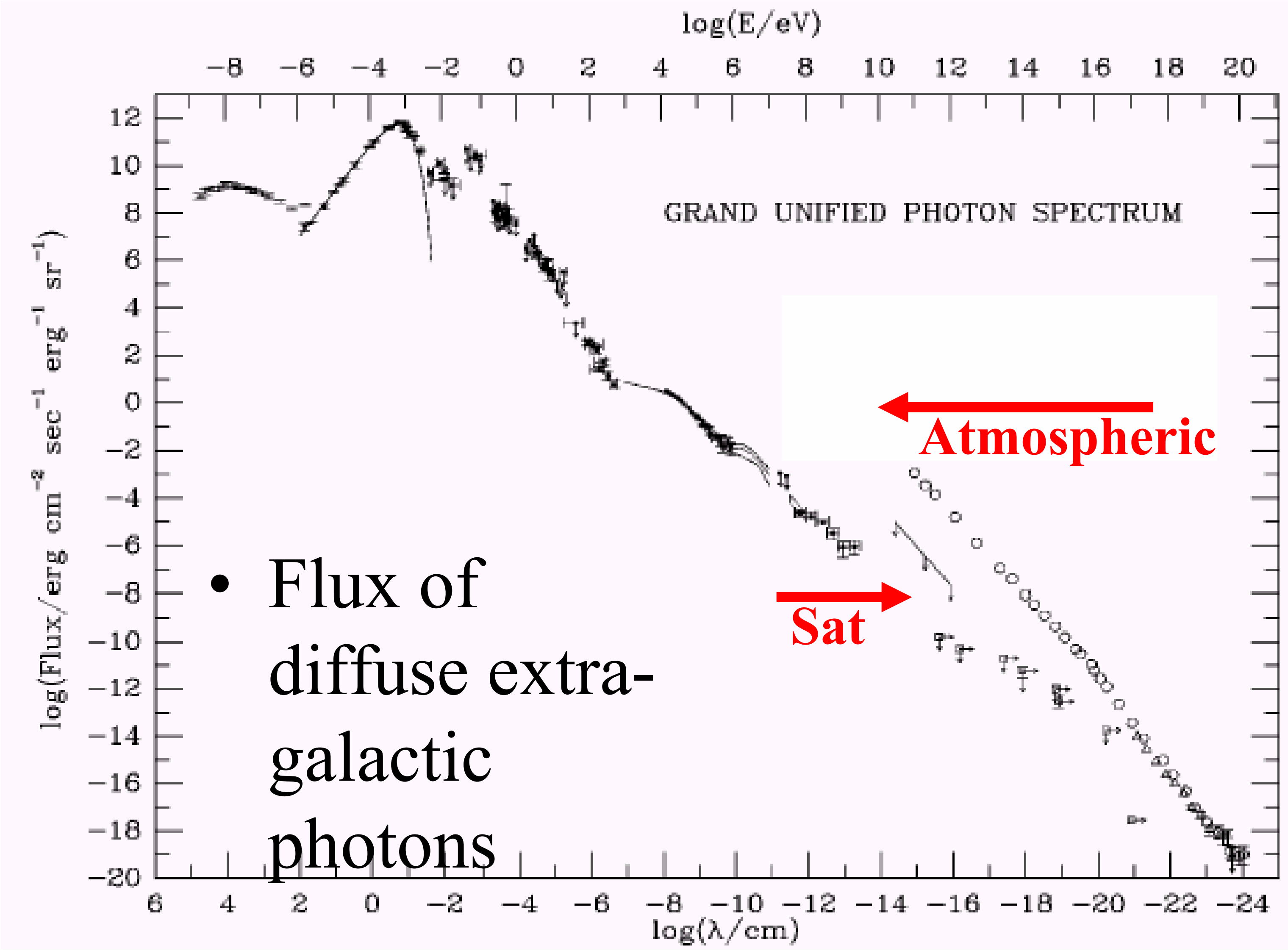


- The earth atmosphere (28 X_0 at sea level) is opaque to X/γ Thus **only a satellite-based detector can detect primary X/γ**
- The fluxes of h.e. γ are low and decrease rapidly with energy
  - Vela, the strongest γ source in the sky, has a flux above 100 MeV of 1.3 10^{-5} photons/(cm^2s), falling with $E^{-1.89}$ => a 1m^2 detector would detect only 1 photon/2h above 10 GeV

=> **with the present space technology, VHE and UHE gammas can be detected only from atmospheric showers**

  - Earth-based detectors, atmospheric shower satellites
- The flux from high energy cosmic rays is much larger

Satellite-based and atmospheric: complementary, w/ moving boundaries



- Flux of diffuse extra-galactic photons

Satellite-based detectors: figures of merit

- Effective area, or equivalent area for the detection of γ

  $$A_{eff}(E) = A \times eff.$$

- Angular resolution is important for identifying the γ sources and for reducing the diffuse background

- Energy resolution

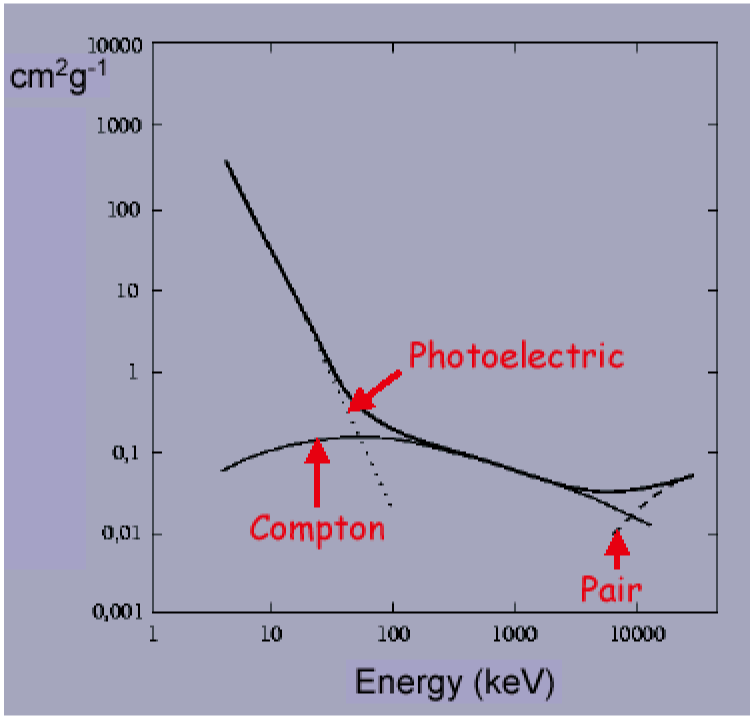
- Time resolution

X detectors

- The electrons ejected or created by the incident gamma rays lose energy mainly in ionizing the surrounding atoms; secondary electrons may in turn ionize the material, producing an amplification effect
- Most space X- ray telescopes consist of detection materials which take advantage of ionization process but the way to measure the total ionization loss differ with the nature of the material

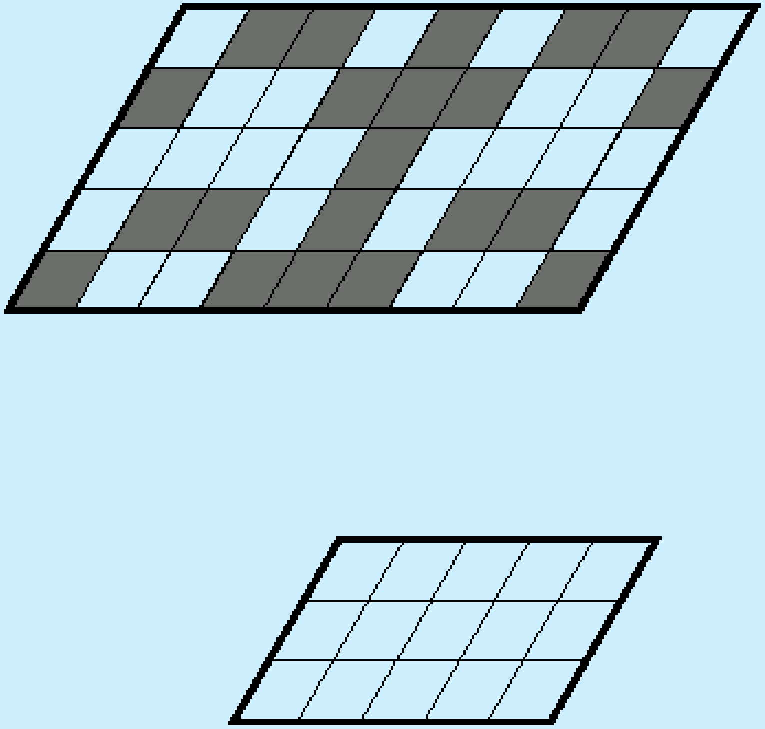
Commonly used detection devices are...

  - gas detectors
  - scintillation counters
  - semiconductor detectors



X detection (direction-sensitive)

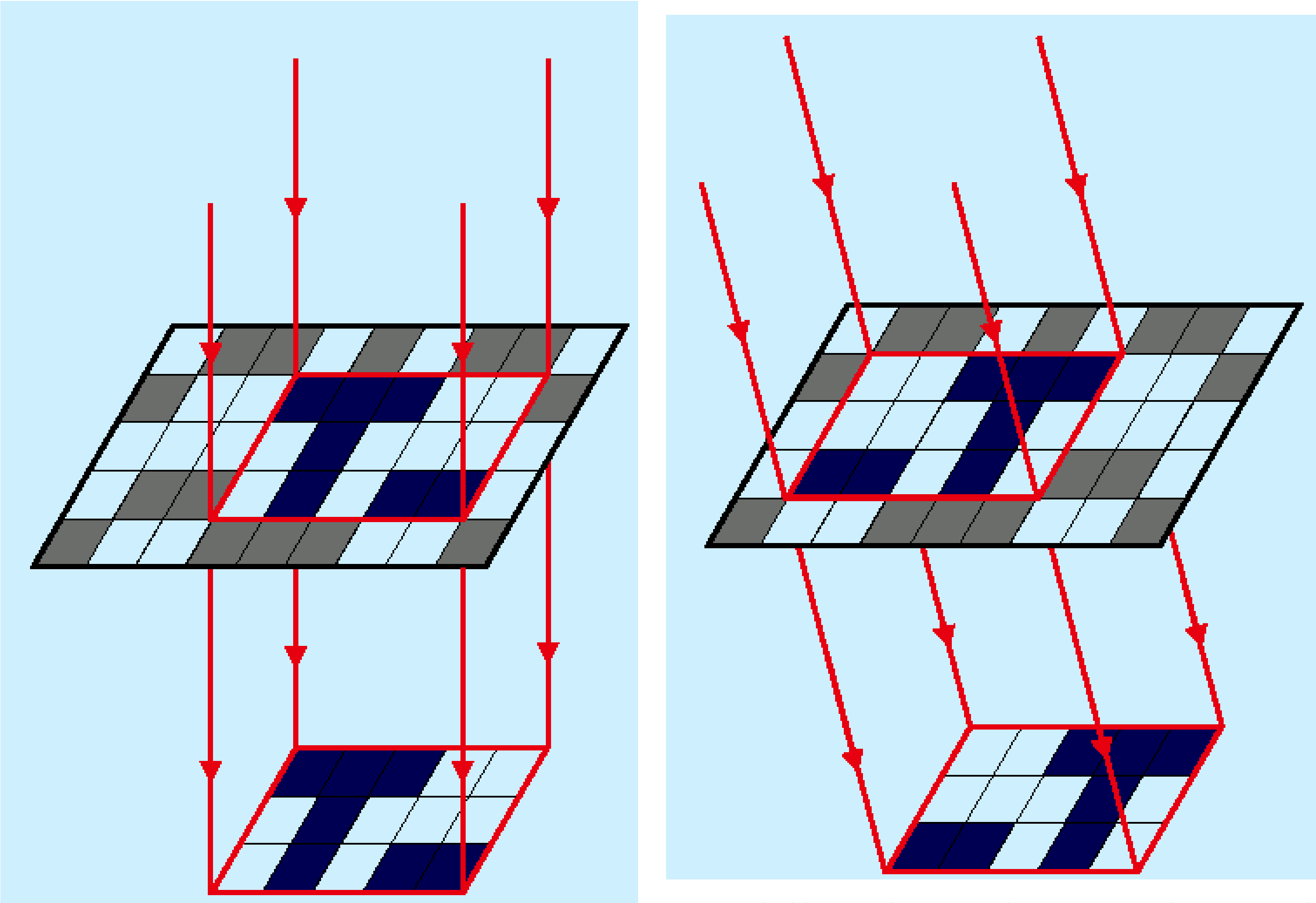
A coded mask (array of opaque blocks) is disposed so that a point source at infinity projects on a position sensitive detector a pattern characteristic of the source direction



Coded mask

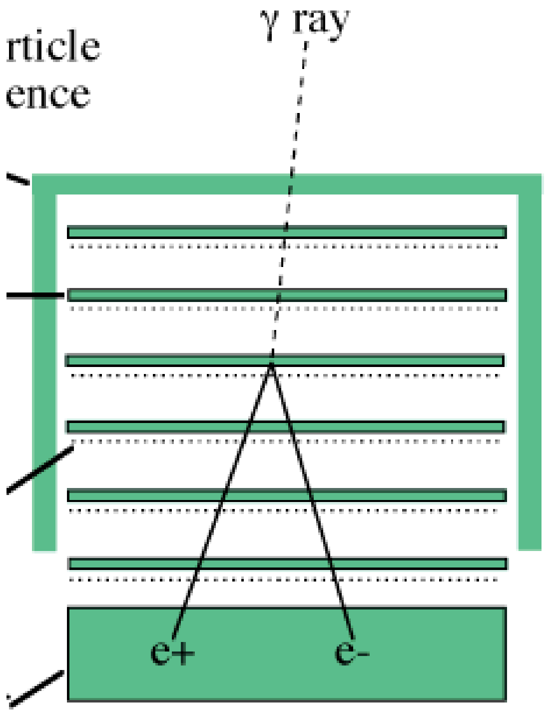
Position sensitive detector

X detection (direction-sensitive)



Unfolding is a nice mathematical problem !

γ satellite-based detectors: engineering



- Techniques taken from particle physics

☐ γ direction is mostly determined by e+e- conversion

  - Veto against charged particles by an ACD
  - Angular resolution given by
    - Opening angle of the pair $m/E \ln(E/m)$
    - Multiple scattering $(20/p\beta)\ (L/X_0)^{1/2}$ (dominant)

  => large number of thin converters, but the # of channel increases

  (power consumption << 1 kW)

- If possible, a calorimeter in the bottom to get E resolution, but watch the weight (leakage => deteriorated resolution)

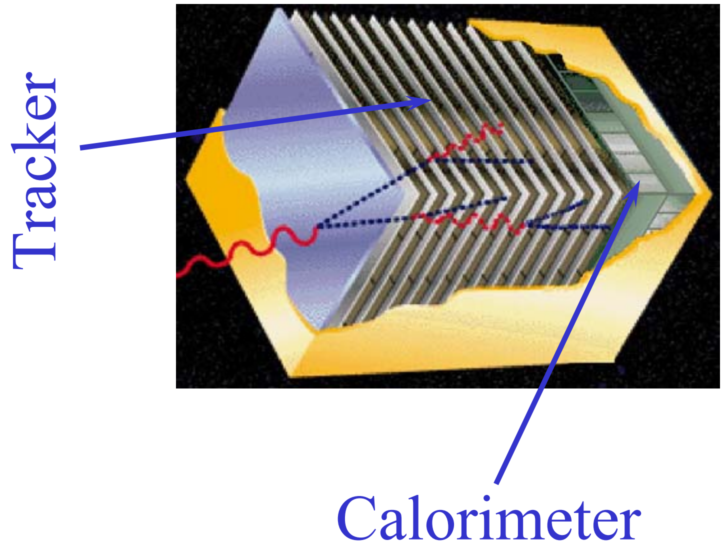
  Smart techniques to measure E w/o calorimeters (AGILE)

INTEGRAL/CHANDRA

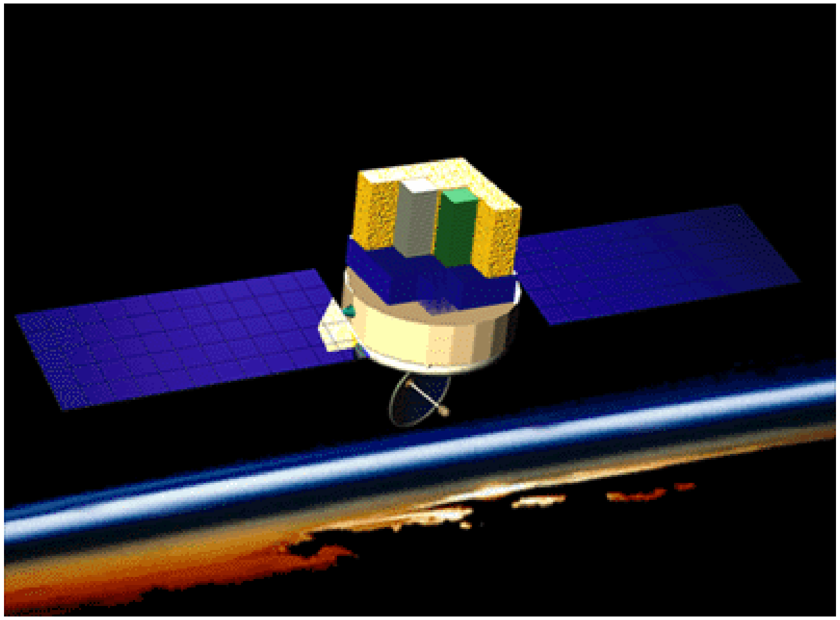
- INTEGRAL, the International Gamma-Ray Astrophysics Laboratory is an ESA medium-size (M2) science mission
- Energy range 15 keV to 10 MeV plus simultaneous X-ray (3-35 keV) and optical (550 nm) monitoring
- Fine spectroscopy ($\Delta E/E \sim 1\%$) and fine imaging (angular resolution of 5')
- Two main -ray instruments: SPI (spectroscopy) and IBIS (imager)

- Chandra, from NASA, has a similar performance

GLAST

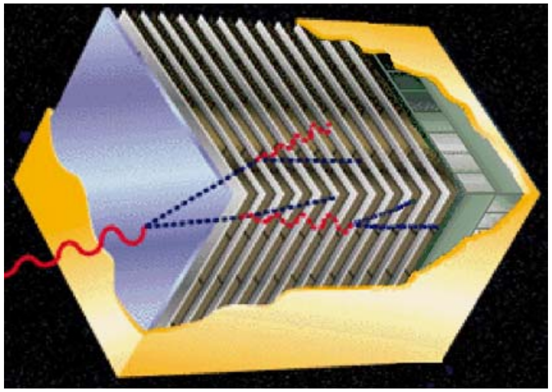


- □ γ telescope on satellite for the range 20 MeV-300 GeV
  - hybrid tracker + calorimeter
- International collaboration US-France-Italy-Japan-Sweden
  - Broad experience in high-energy astrophysics and particle physics (science + instrumentation)
- Timescale: 2006-2010 (->2015)



A HEP / astrophysics partnership

GLAST: the instrument

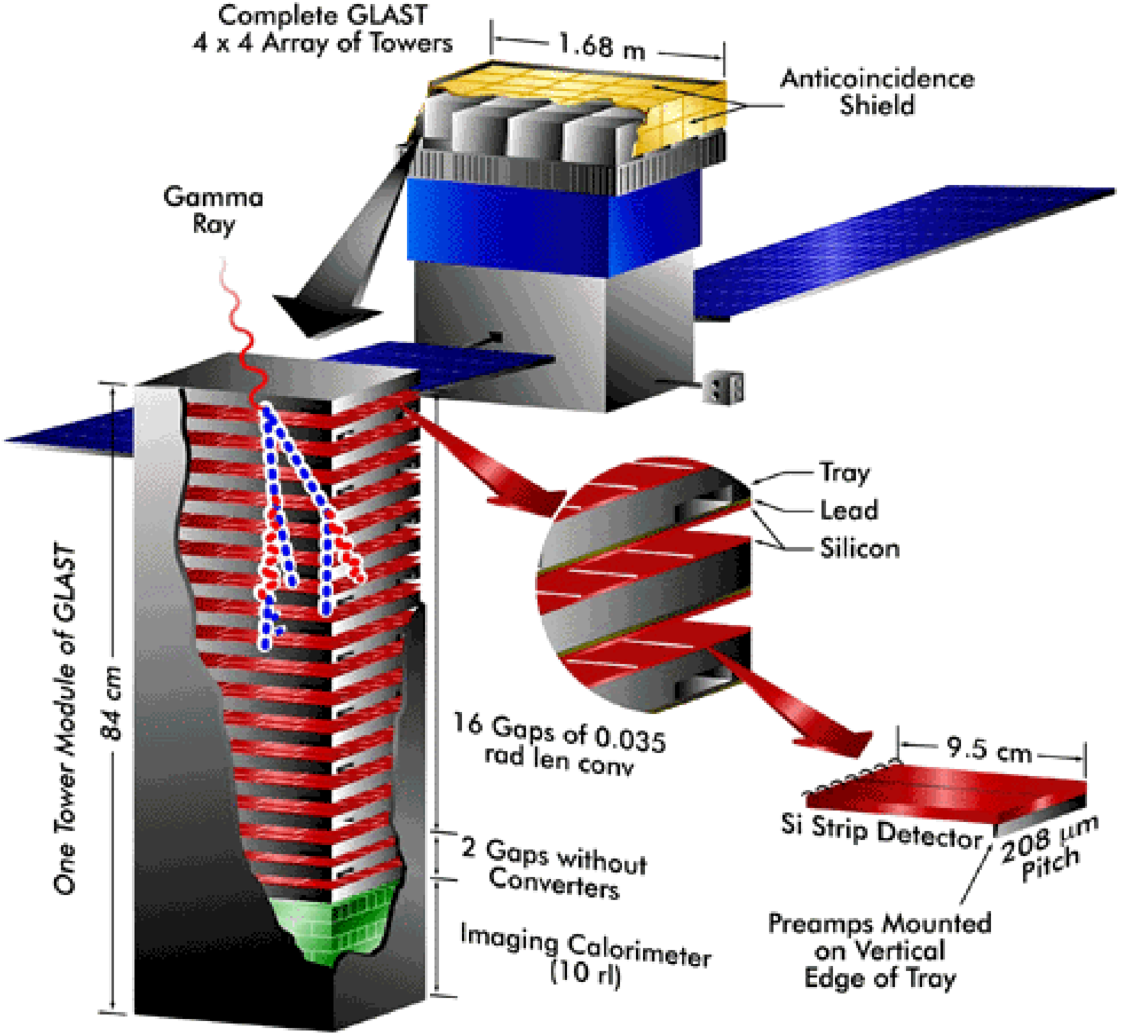


- Tracker
  Si strips + converter

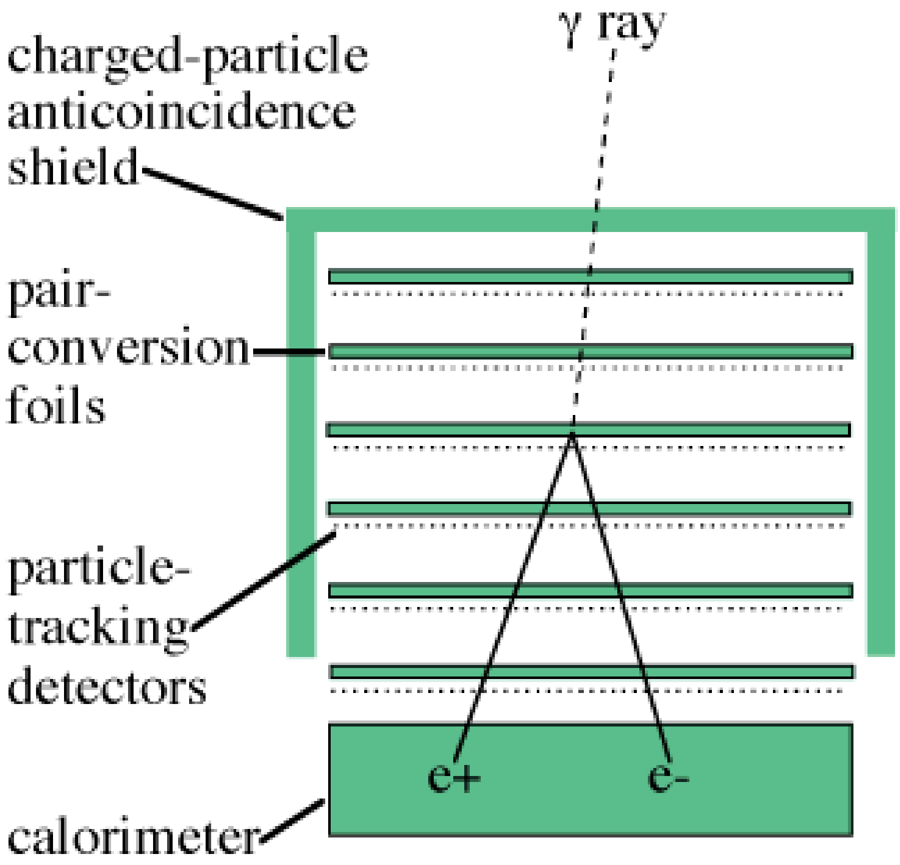
- Calorimeter
  CsI with diode readout

(a classic for HEP)

- 1.7 x 1.7 m^2 x 0.8 m
  height/width = 0.4 ⇒
  large field of view
- 16 towers ⇒ modularity



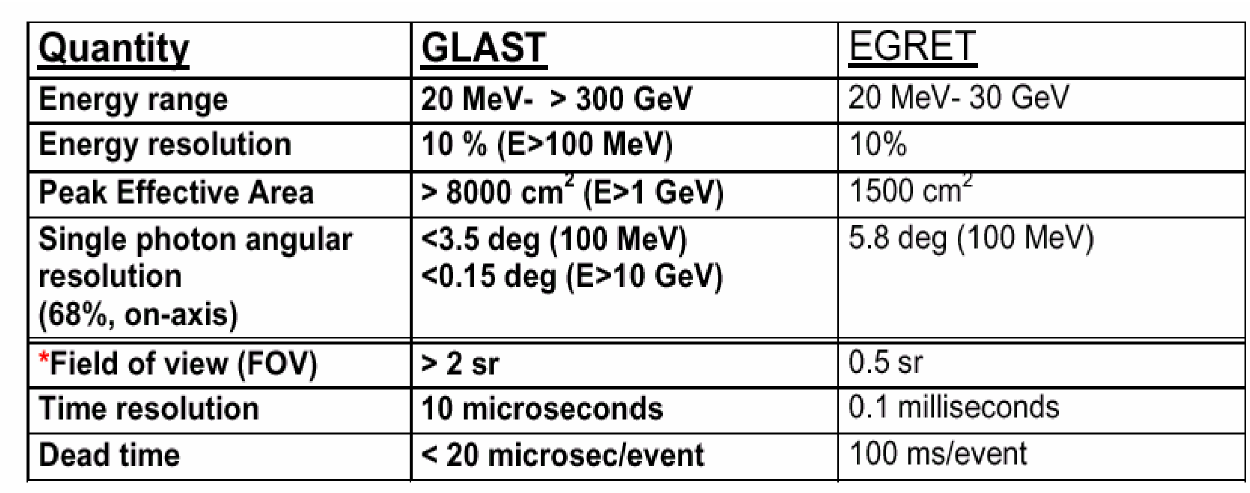
GLAST: the tracker



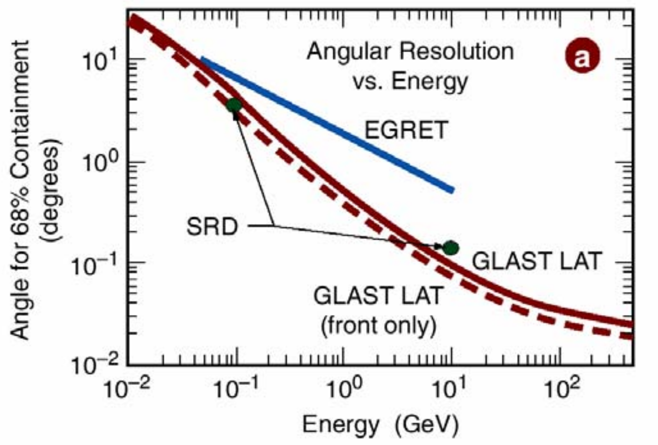
Si strips + converter
  - High signal/noise
  - Rad-hard
  - Low power

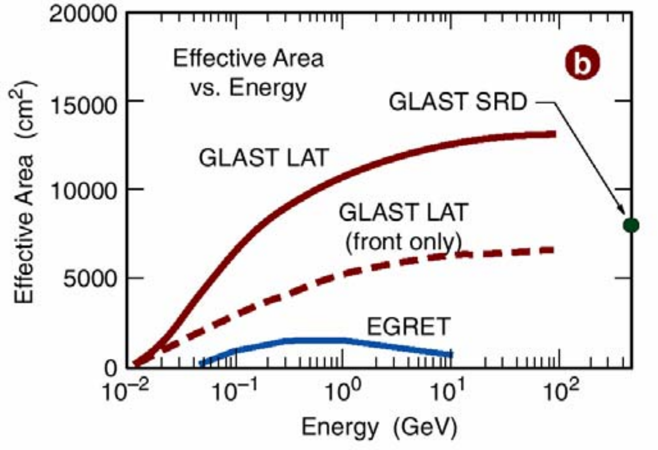
- 4x4 towers, of 37 cm × 37 cm of Si
- 18 *x,y* planes per tower
  - 19 “tray” structures
    - 12 with 2.5% Pb on bottom
    - 4 with 25% Pb on bottom
    - 2 with no converter
- Electronics on the sides of trays
  - Minimize gap between towers
- Carbon-fiber walls to provide stiffness

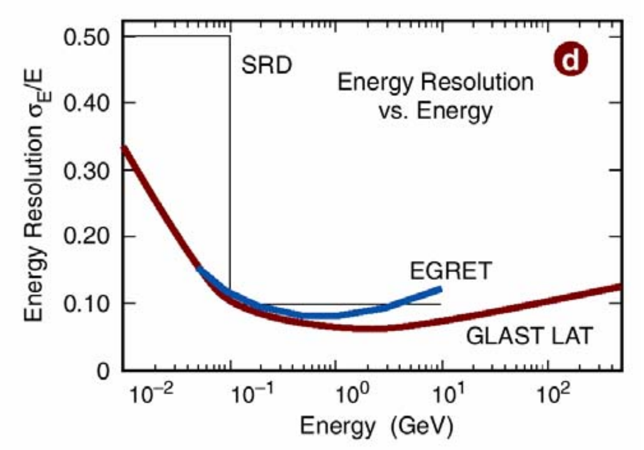
GLAST performance (compared to EGRET)



Quantity	GLAST	EGRET
Energy range	20 MeV- > 300 GeV	20 MeV- 30 GeV
Energy resolution	10 % (E>100 MeV)	10%
Peak Effective Area	> 8000 cm^2 (E>1 GeV)	1500 cm^2
Single photon angular resolution (68%, on-axis)	<3.5 deg (100 MeV) <0.15 deg (E>10 GeV)	5.8 deg (100 MeV)
*Field of view (FOV)	> 2 sr	0.5 sr
Time resolution	10 microseconds	0.1 milliseconds
Dead time	< 20 microsec/event	100 ms/event

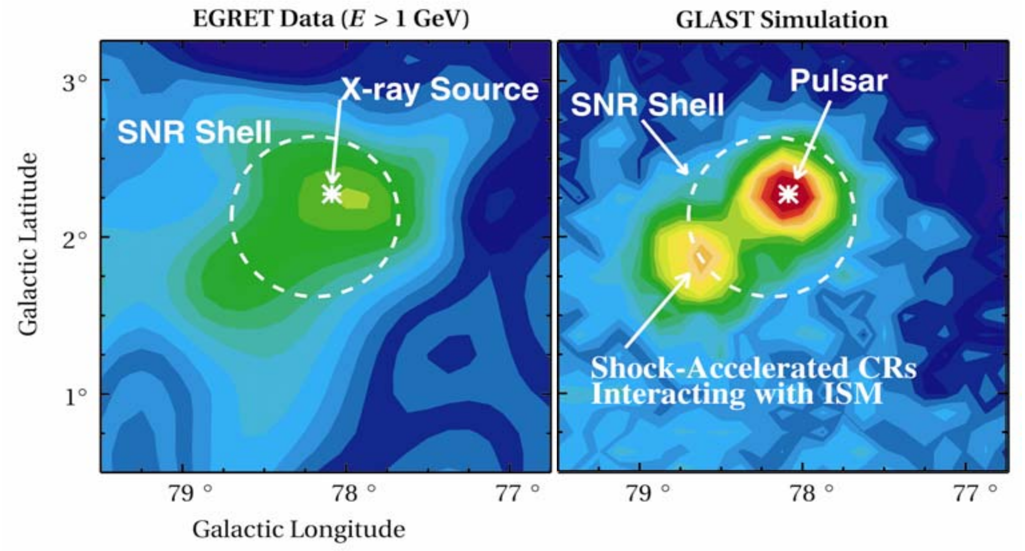




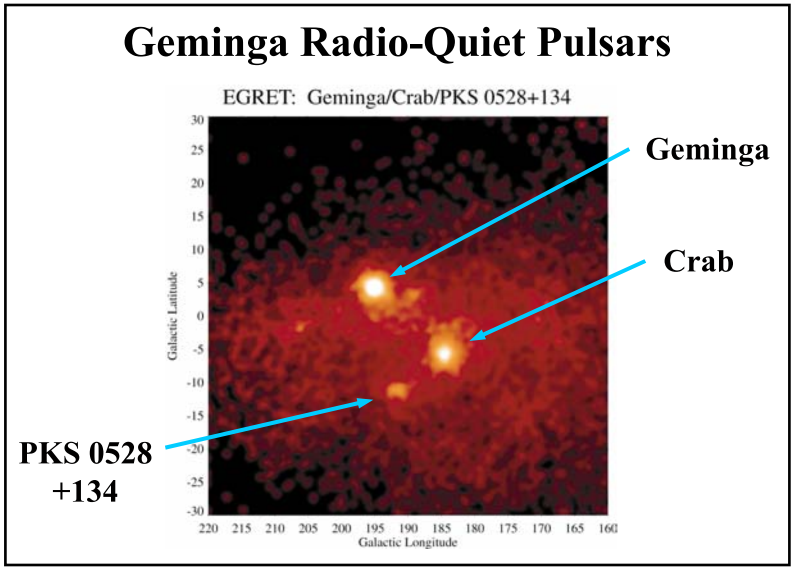


GLAST performance
two examples of application

- Cosmic ray production



- Facilitate searches for pulsations from millisecond pulsars

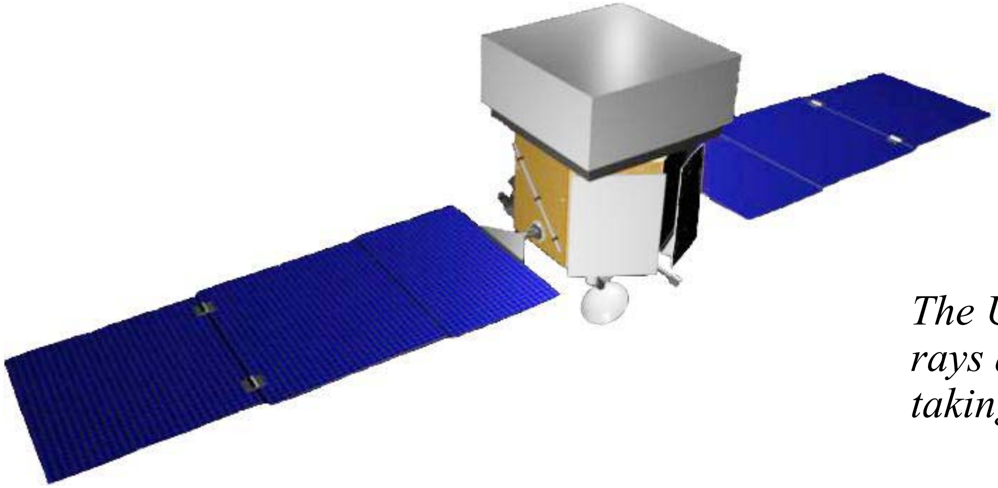


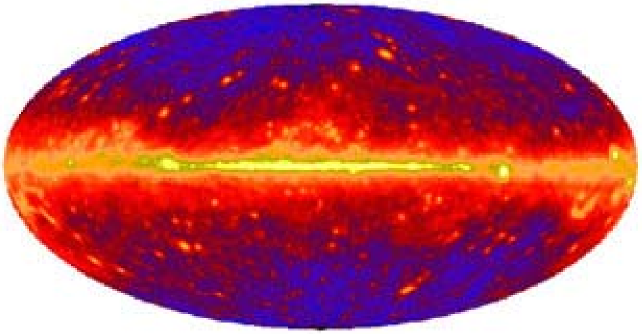
The Gamma-ray Large Area Space Telescope

GLAST will be sent in space in 2007

A collaboration USA-Japan-France-Italy-Sweden

Large part of the software is written in Udine... So come and help !

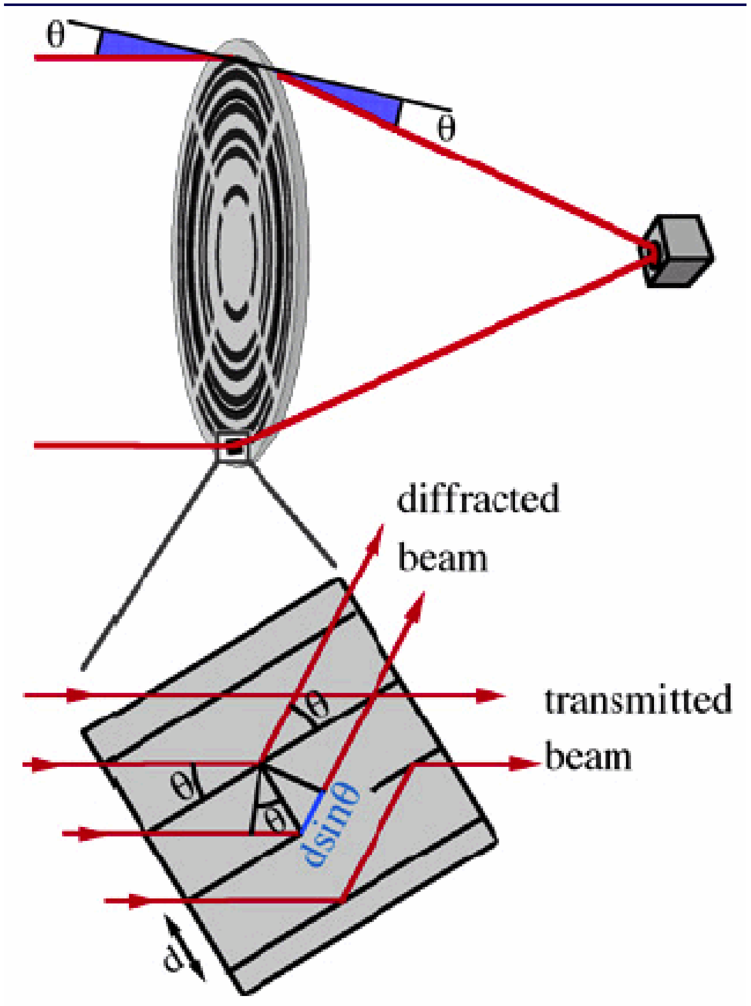




The Universe in the gamma rays after one year of data taking. Center: our galaxy

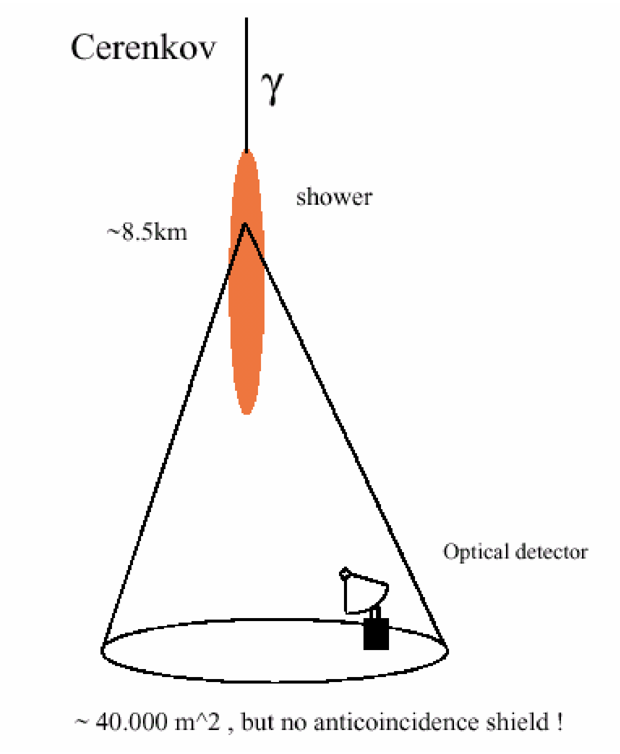
But despite the progress in satellites…

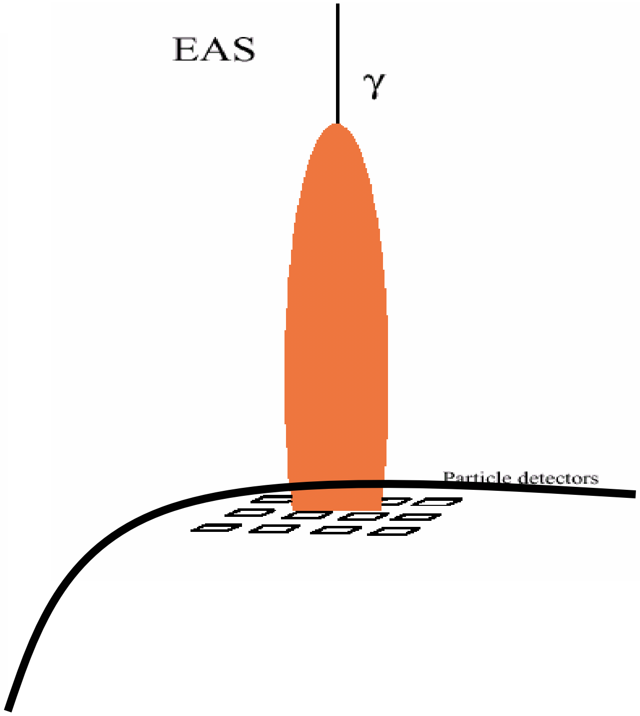
- The problem of the flux (~1 photon/day/km2 @ ~30 PeV) cannot be overcome
  - Photon concentrators work only at low energy
  - The key for VHE gamma astrophysics and above is in ground-based detectors
  - Also for dark matter detection…



Ground-based detectors

- An Extensive Air Shower can be detected
  - From the shower particles directly (EAS Particle Detector Arrays)
  - By the Cherenkov light emitted by the charged particles in the shower (Cherenkov detectors)

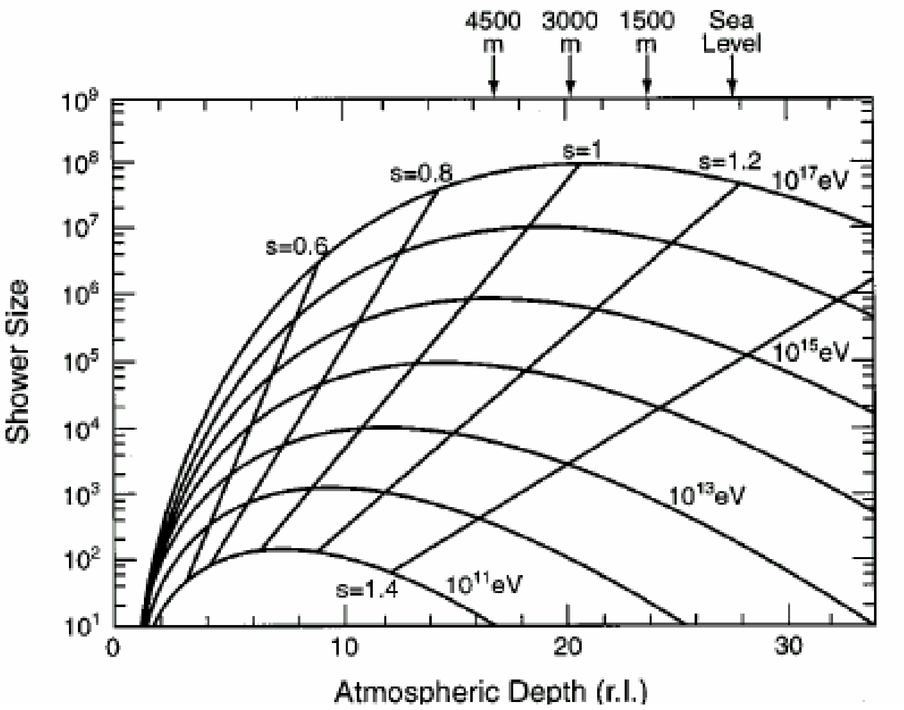




Earth-based detectors
Properties of Extensive Air Showers

- We **believe** we know well the γ physics up to EHE…

  Predominant interactions e.m.
  - e+e- pair production dominates
  - electrons loose energy via brem
  - Rossi approximation B is valid
    - Maximum at $z/X_0 \approx \ln(E/\varepsilon_0)$; ε_0 is the critical energy ~80 MeV in air; X_0 ~ 300 m at stp
    - Cascades ~ a few km thick
    - Lateral width dominated by Compton scattering ~ Moliere radius (~80m for air at STP)



- Note: λ_{had} ~ 400 m for air

  hadronic showers have 20x more muons and are less regular than em

Cherenkov (Č) detectors
Cherenkov light from γ showers

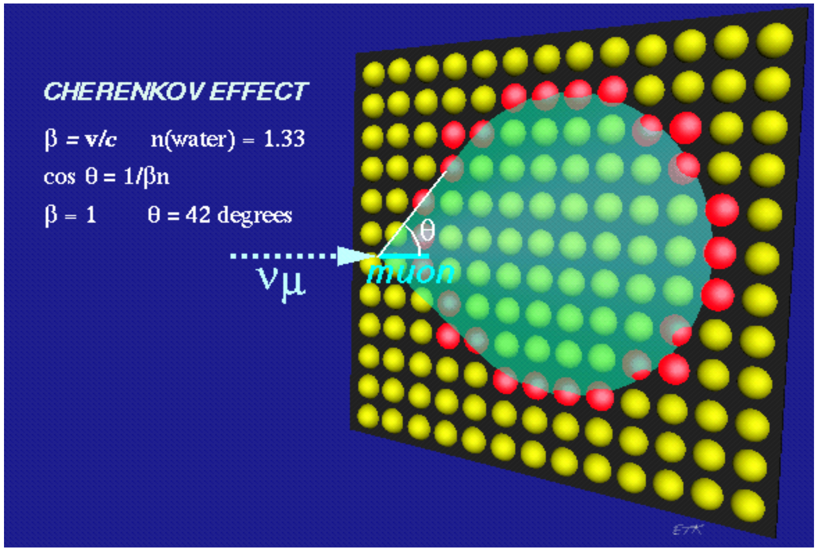
- Č light is produced by particles faster than light in air
- Limiting angle $\cos \theta_c \sim 1/n$
  - □ $\theta_c \sim 1^o$ at sea level, 1.3^o at 8 Km asl
  - – Threshold @ sea level : 21 MeV for e, 44 GeV for μ

Maximum of a 1 TeV γ shower ~ 8 Km asl

200 photons/m^2 in the visible

Duration ~ 2 ns

Angular spread ~ 0.5^o



Cherenkov detectors
Principles of operation

- Cherenkov light is detected by means of mirrors which concentrate the photons into fast optical detectors
- Often heliostats operated during night
  - Problem: night sky background

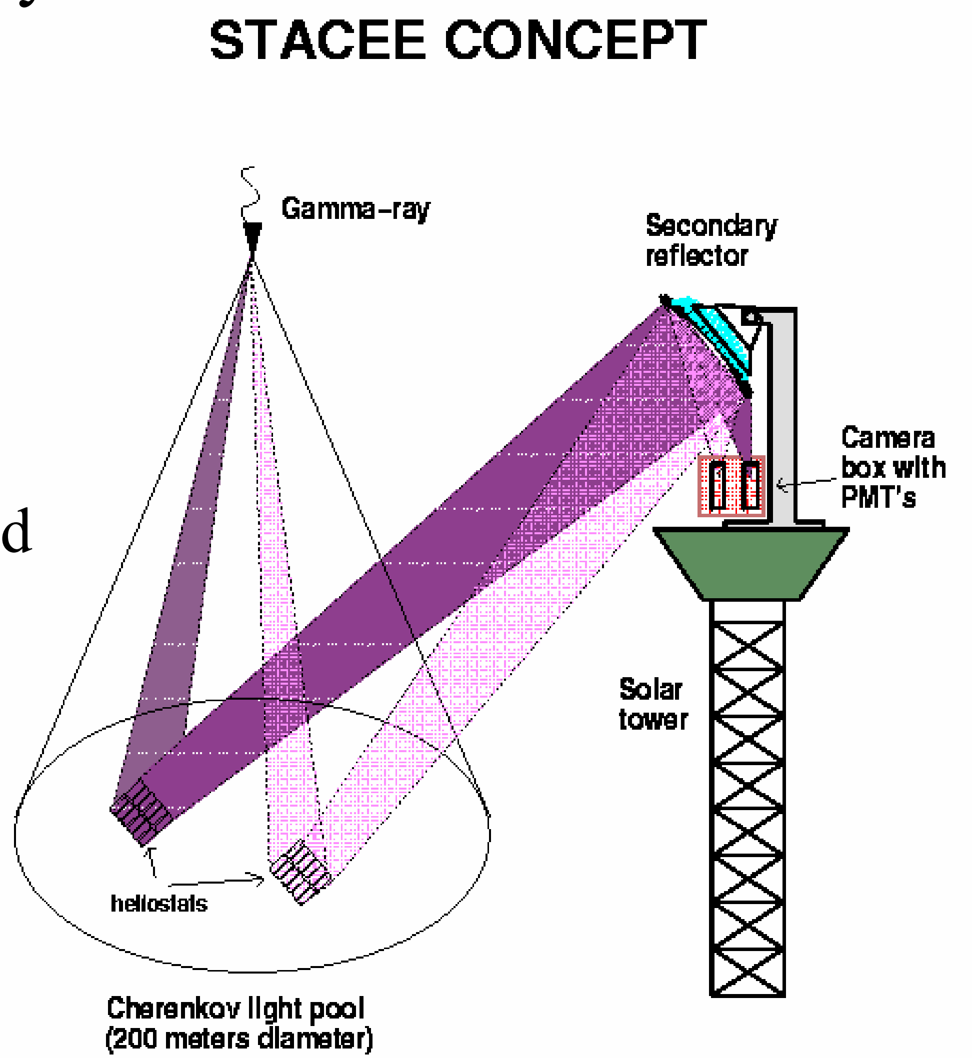
    On a moonless night

    ~ 0.1 photons/(m^2 ns deg)

Signal $\propto$ A

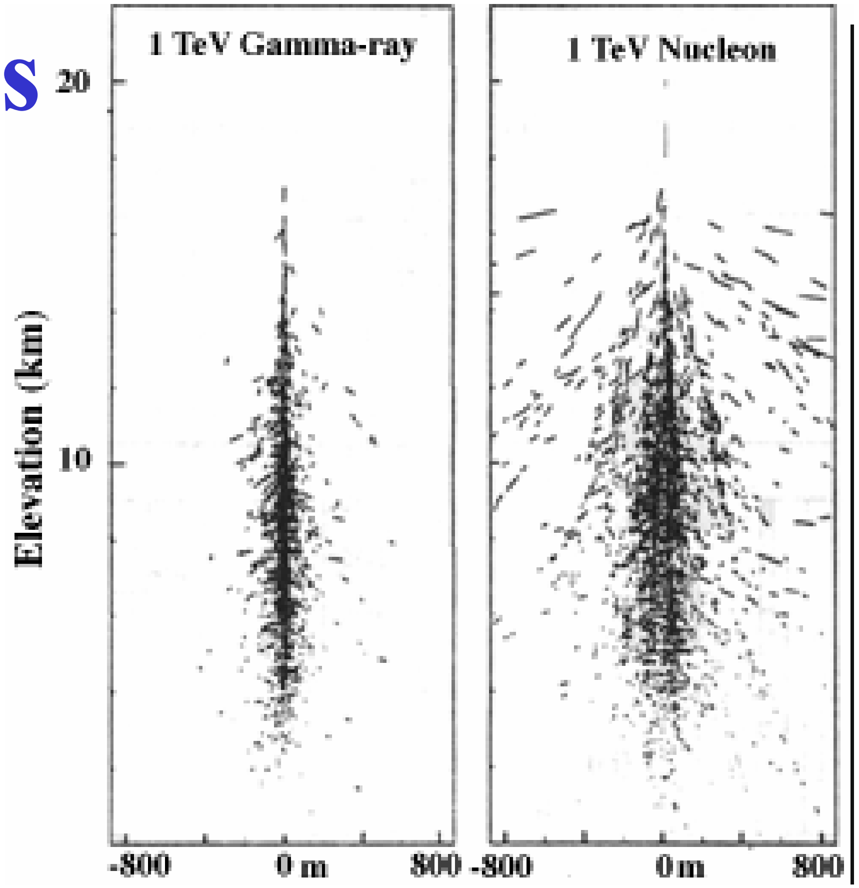
fluctuations $\sim (A\tau\Omega)^{1/2}$

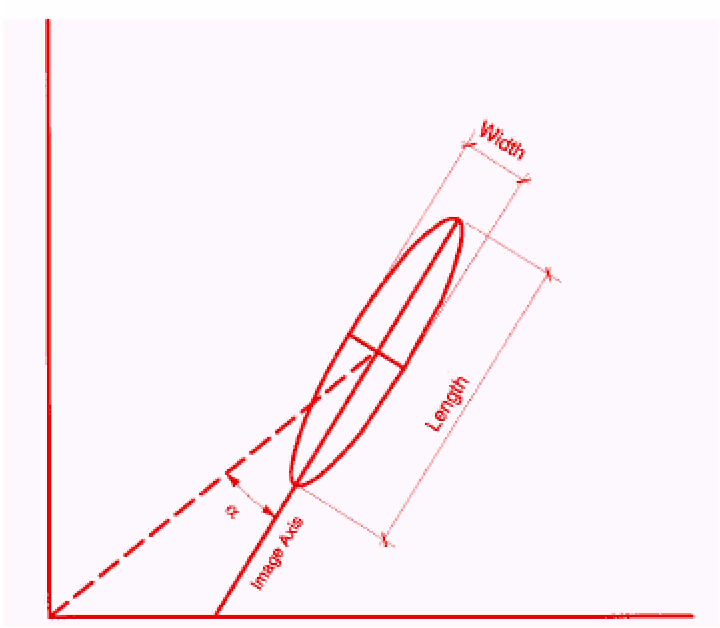
$\Rightarrow S/B^{1/2} \propto (A/\tau\Omega)^{1/2}$

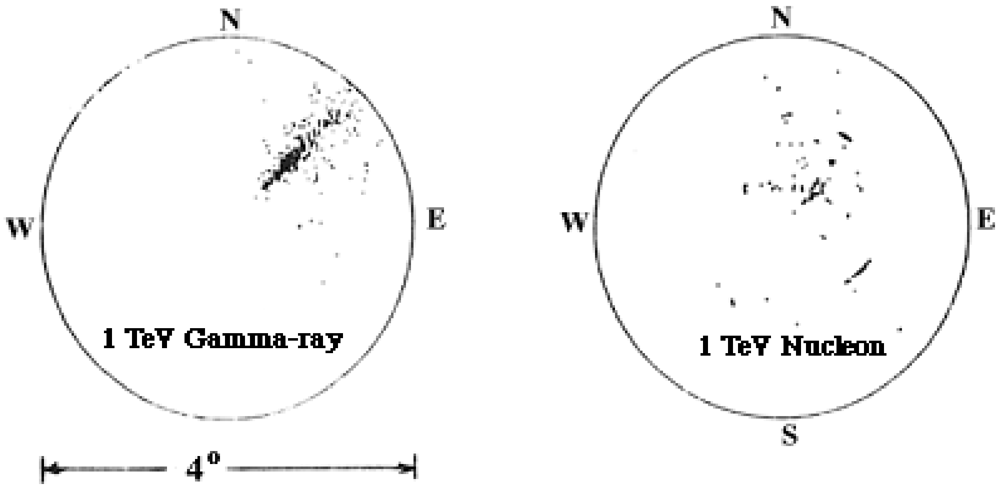


IACT Analysis features

- Rejection of cosmic ray background: from shape or associated muon detectors
- Wavefront timing: allows rejection and fitting the primary direction as well

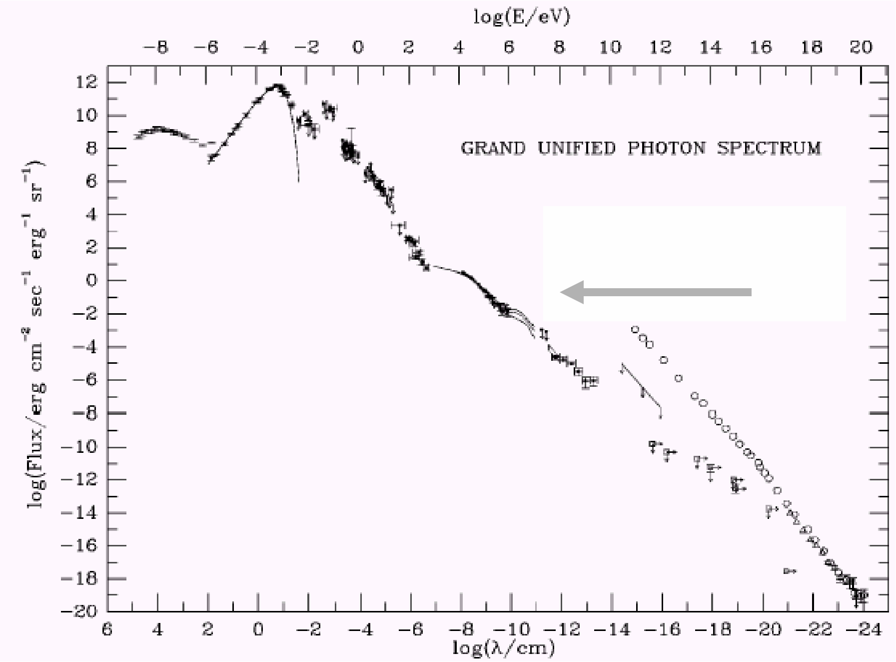






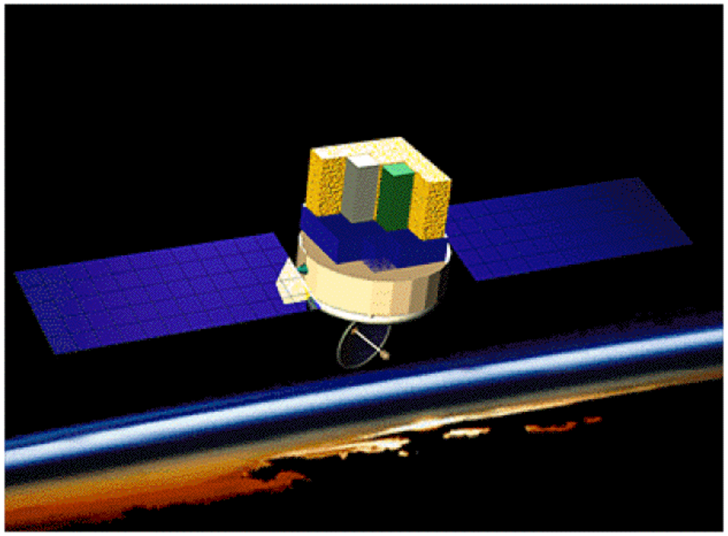
Ground-based detectors
Improvements in atmospheric Č

- Improving flux sensitivity
  - Detect weaker sources, study larger sky regions $S/B^{1/2} \propto (A/\tau\Omega)^{1/2}$
    - Smaller integration time
    - Improve photon collection, improve quantum efficiency of PMs
    - Use several telescopes
- Lowering the energy threshold
  - Close the gap ~ 100 GeV betwee satellite-based & ground-based instruments



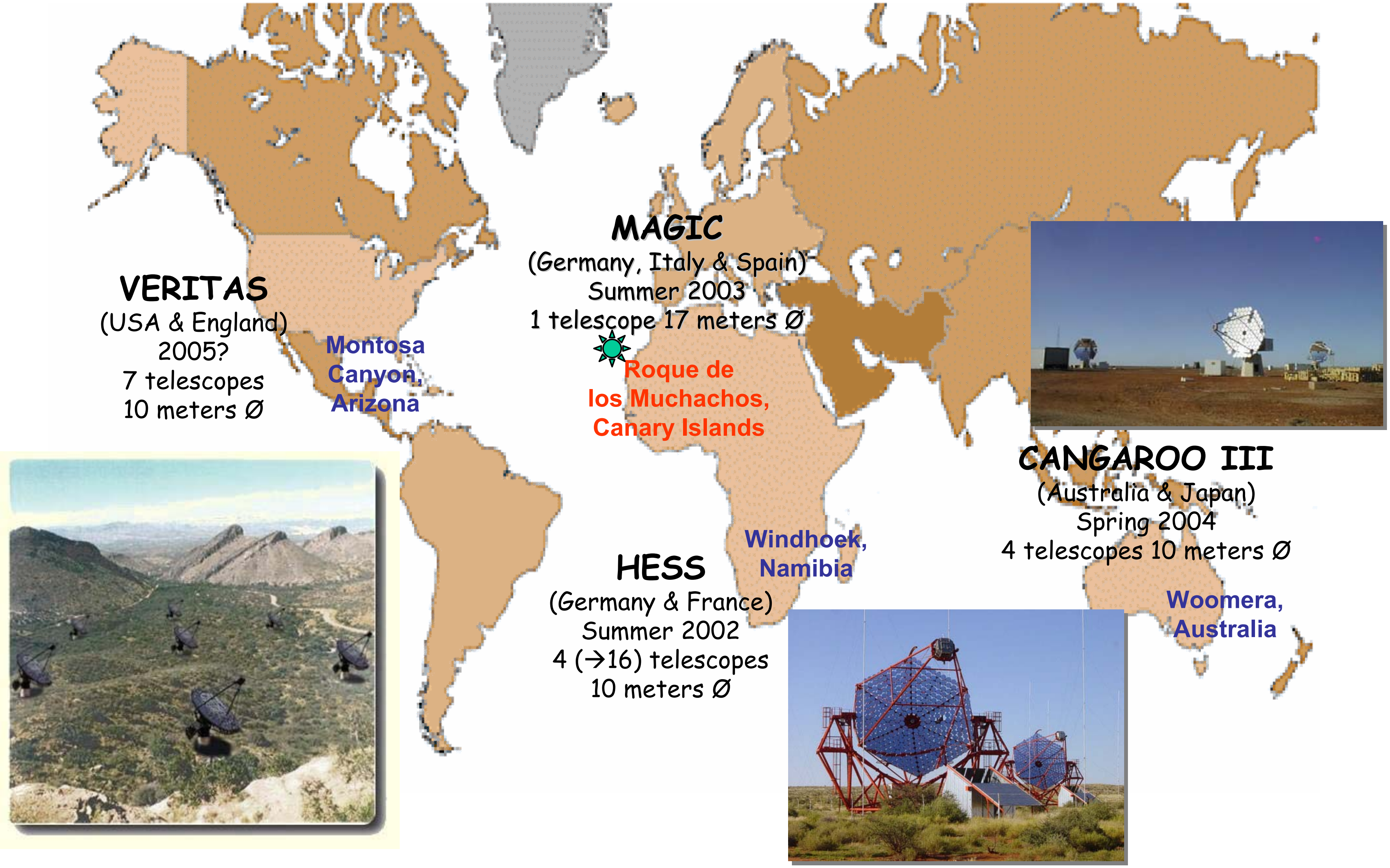
IACT vs Satellite

- Satellite :
  - primary detection
  - small effective area ~1m^2
    - lower sensitivity
  - large angular opening
    - search
  - large duty-cycle
  - large cost
  - lower energy
  - low bkg



- IACT/ground based
  - secondary detection
  - huge effective area ~10^4 m^2
    - Higher sensitivity
  - small angular opening
    - Serendipity search
  - small duty-cycle
  - low cost
  - high energy
  - high bkg

New generation IACT telescopes



VERITAS
(USA & England)
2005?
7 telescopes
10 meters Ø

Montosa Canyon, Arizona

MAGIC
(Germany, Italy & Spain)
Summer 2003
1 telescope 17 meters Ø

Roque de los Muchachos, Canary Islands

CANGAROO III
(Australia & Japan)
Spring 2004
4 telescopes 10 meters Ø

Woomera, Australia

HESS
(Germany & France)
Summer 2002
4 (→16) telescopes
10 meters Ø

Windhoek, Namibia

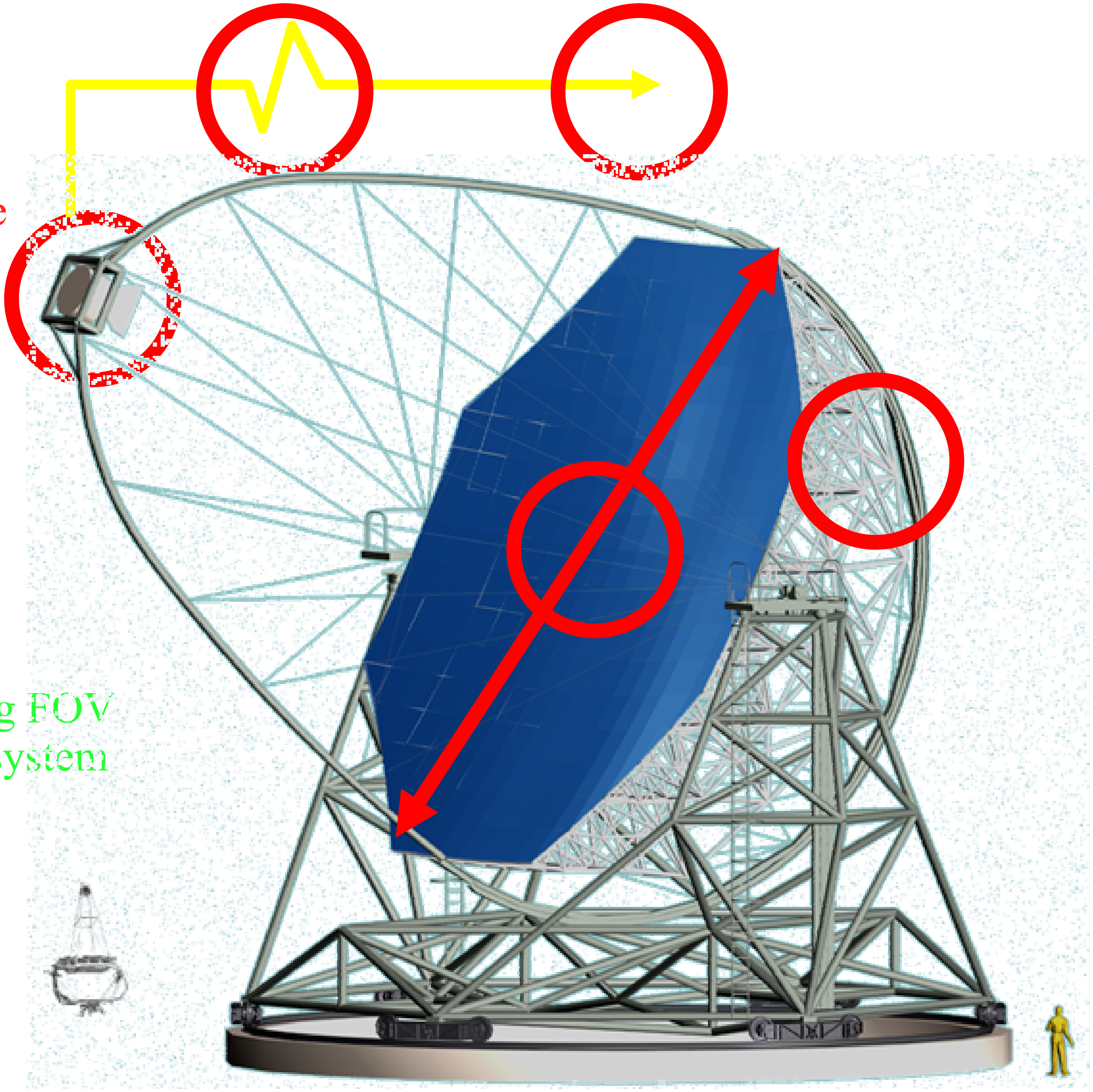
The MAGIC Collaboration

Major Atmospheric Gamma-Ray Imaging Cherenkov Telescope

Barcelona IFAE, Barcelona UAB, Crimean Observatory, U.C. Davis, U. Lodz, UCM Madrid, INR Moscow, MPI Munich, INFN/ U. Padua, INFN/ U. Siena U. Siegen, Tuorla Observatory, Yerevan Phys. Institute, INFN/U. Udine , U. Wuerzburg, ETH Zurich

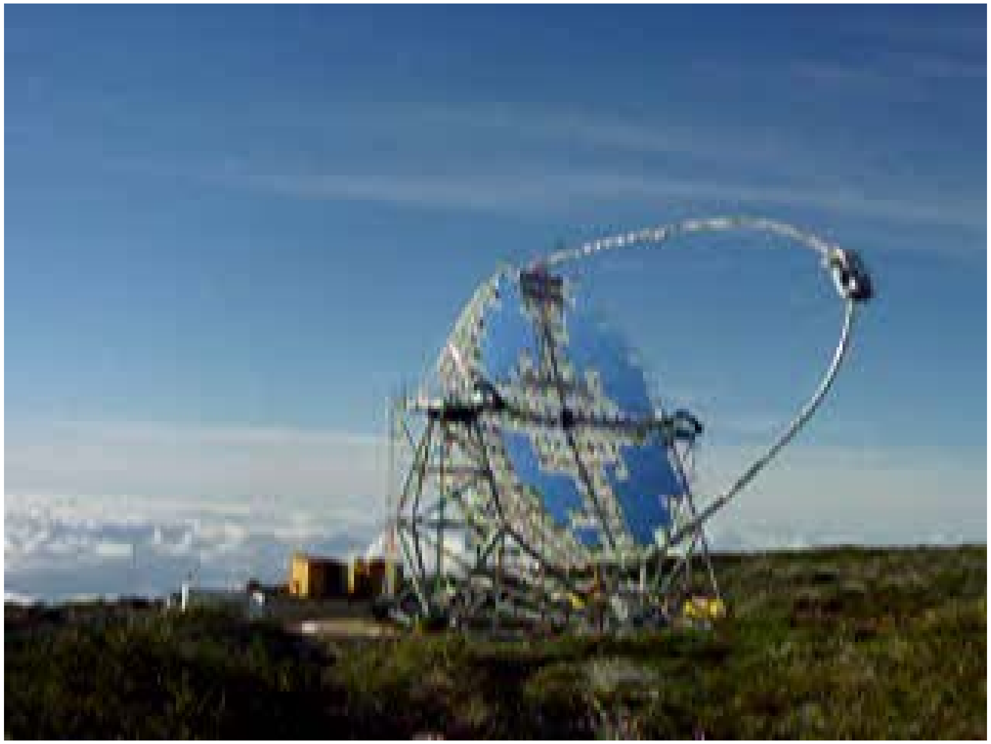
- The MAGIC Project is an international collaboration building a 17 m Cherenkov Telescope for the observation of HE cosmic γ–rays.
- Main aim: to detect γ–ray sources in the unexplored energy range: 30 *(10)->* 250 GeV
- MAGIC needs a challenging design to decrease the energy threshold, pushing the affordable technology in terms of **mirror size**, **trigger**, **mechanical stability**, **camera and electronics development.**
- **Lowest energy threshold** ever obtained with a Cherenkov telescope!!!

Key elements of the MAGIC detector

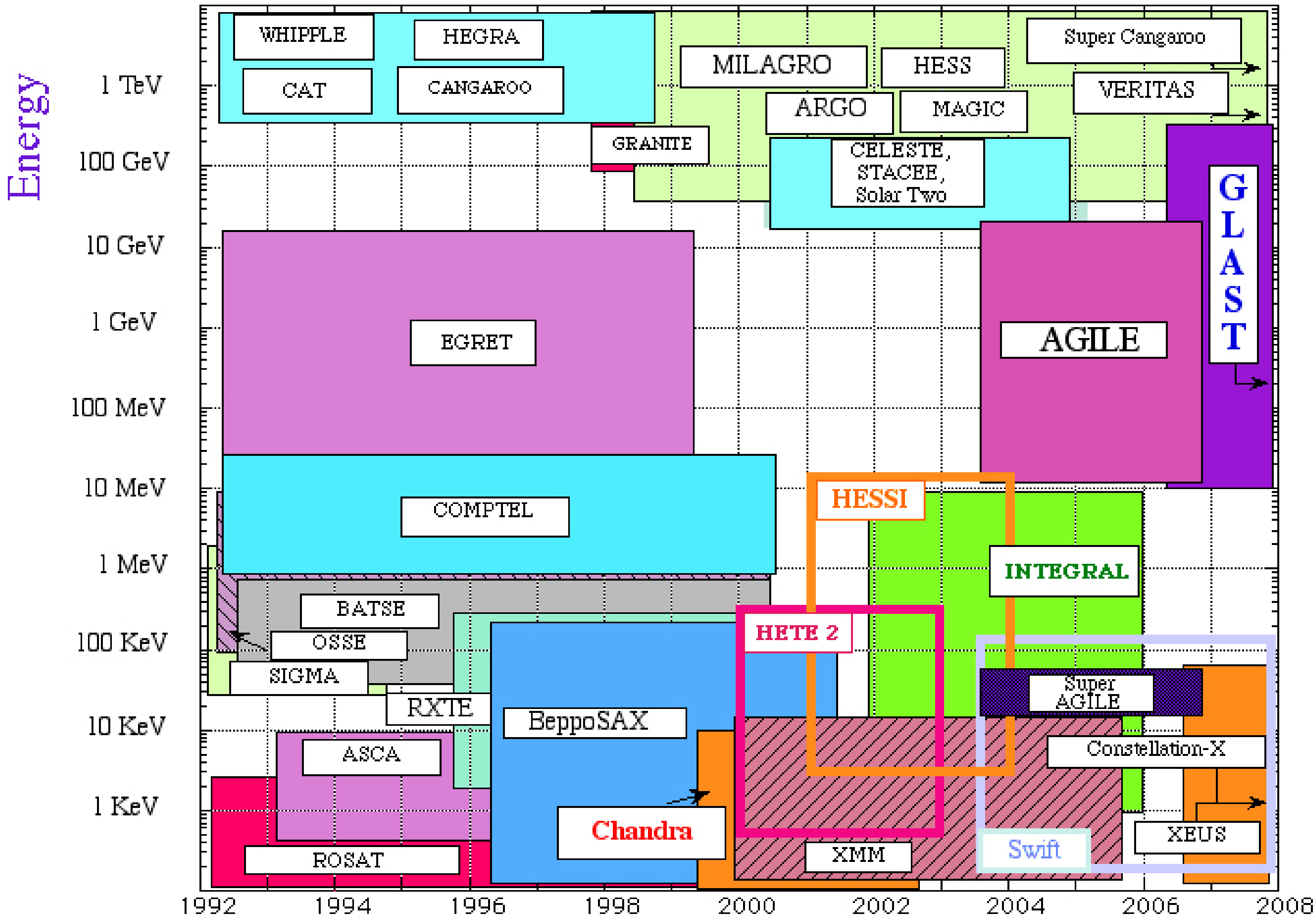


- 17 m diameter reflecting surface (240 m^2)
- Light weight carbon fiber frame
- Active mirror control
- 577 pixels enhanced QE, 3.9 deg FOV camera + advanced calibration system
- Analog optical signal transport
- 2-level trigger system

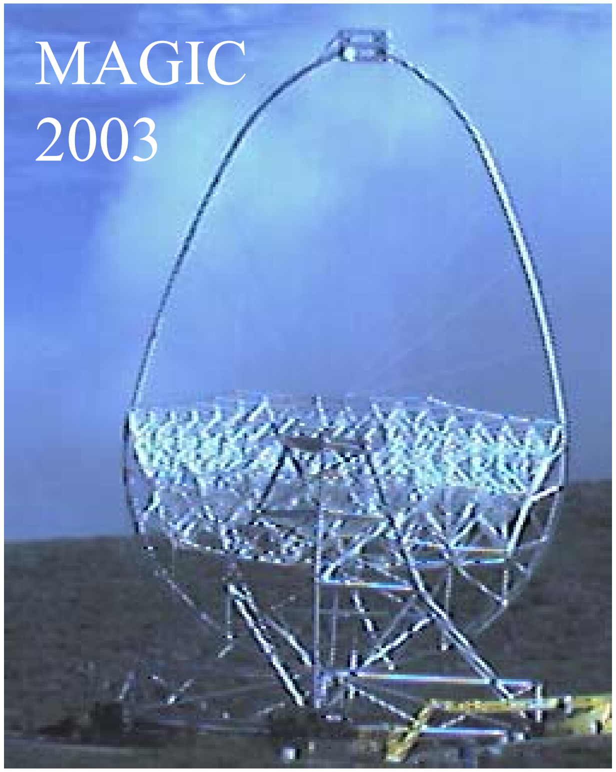
Last but not least, can point to surces…

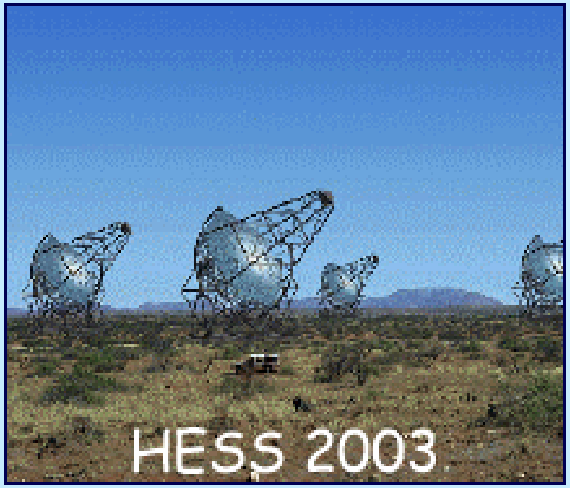


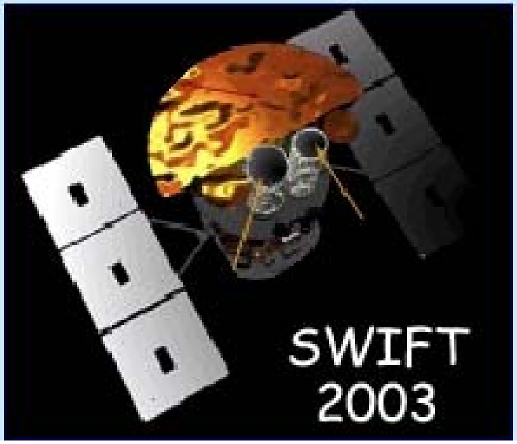
An armada of detectors at different energy ranges



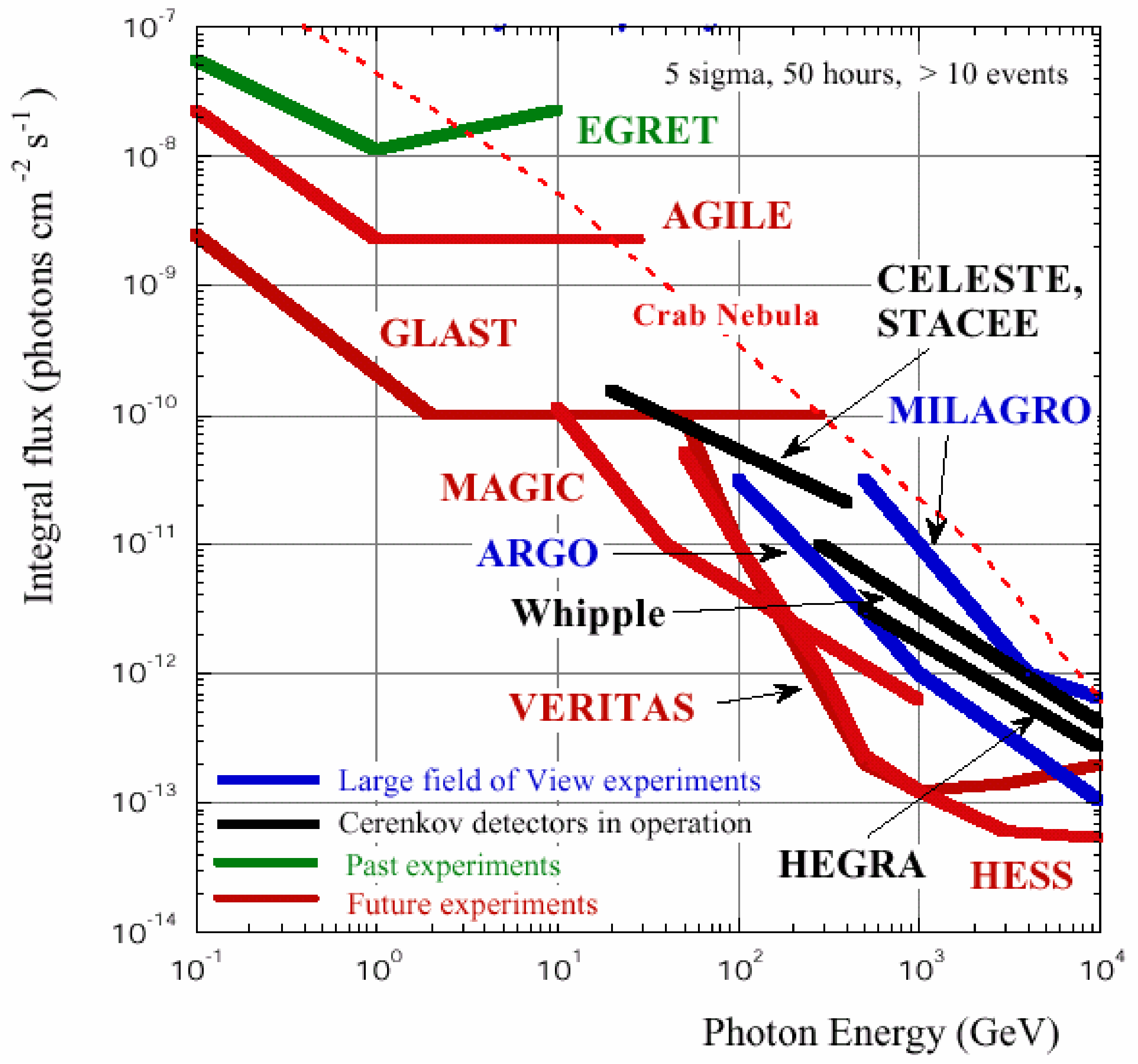
…some are coming now





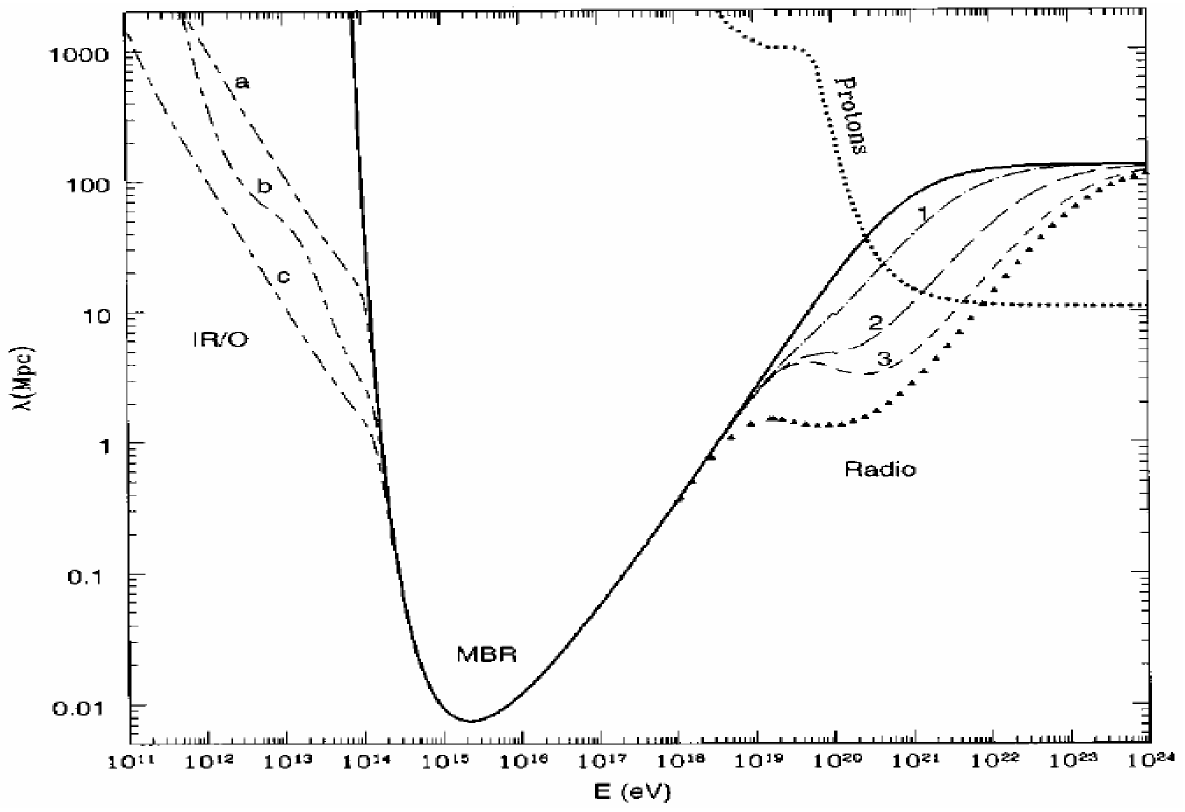


Sensitivity

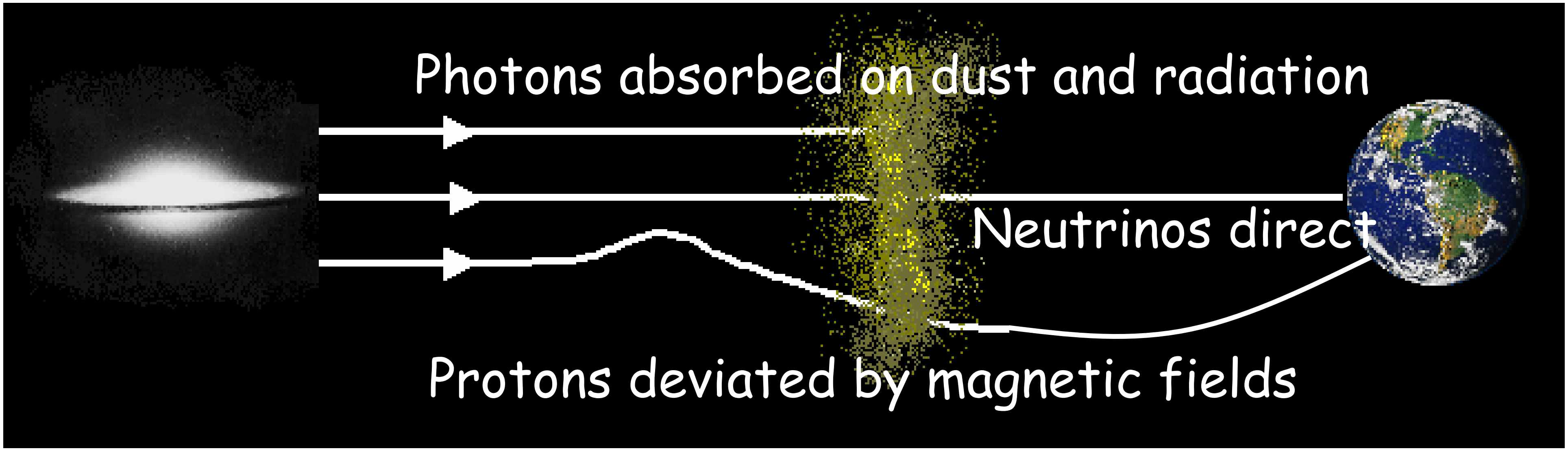


All sensitivities are at 5σ.
Cerenkov telescopes sensitivities (Veritas, MAGIC, Whipple, Hess, Celeste, Stacee, Hegra) are for 50 hours of observations.
Large field of view detectors sensitivities (AGILE, GLAST, Milagro,ARGO are for 1 year of observation.

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



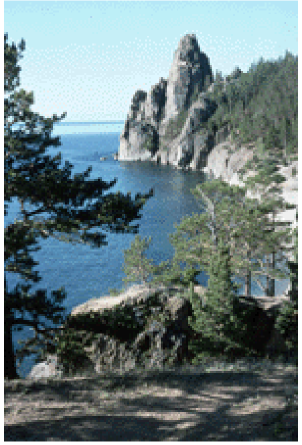
In the 100 TeV - 100 PeV region…

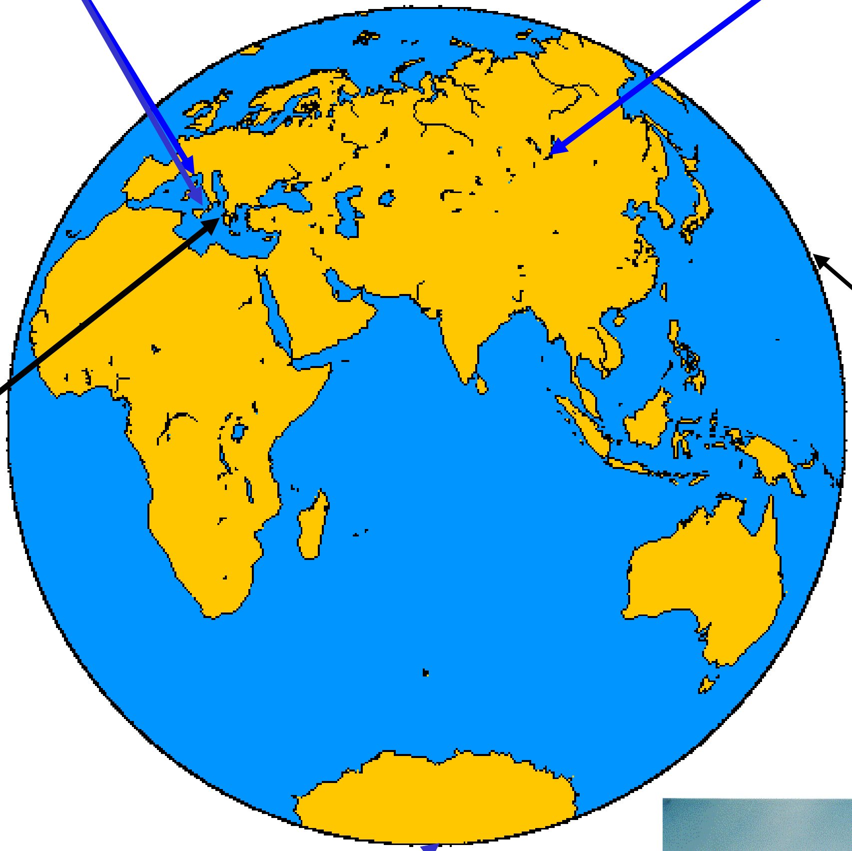


Neutrino Telescope Projects

ANTARES La-Seyne-sur-Mer, France
(NEMO Catania, Italy)

BAIKAL: Lake Baikal, Siberia





NESTOR : Pylos, Greece

DUMAND, Hawaii
(cancelled 1995)

AMANDA, South Pole, Antarctica

AMANDA

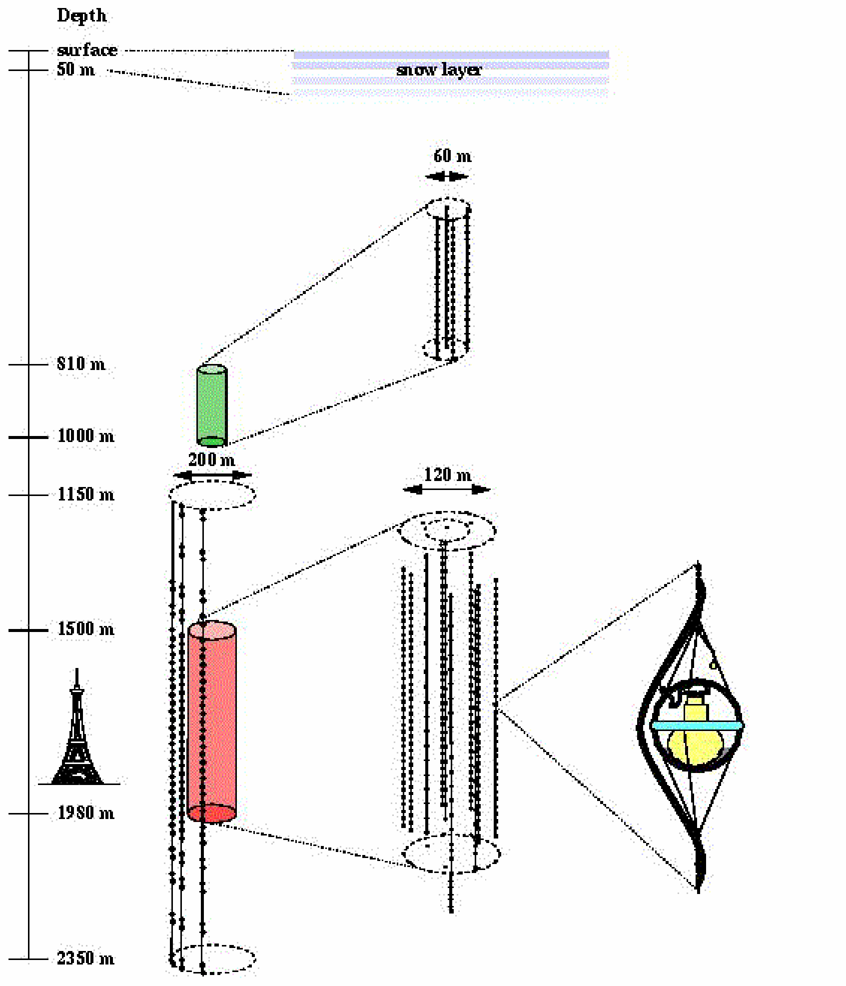
South Pole: glacial ice

1993 First strings AMANDA A
1998 AMANDA B10 ~ 300 Optical Modules

2000 ~ 700 Optical Modules

→ ICECUBE 8000 Optical Modules


AMANDA
ν > 50GeV



AMANDA as of 1998
Eiffel Tower as comparison
(true scaling)

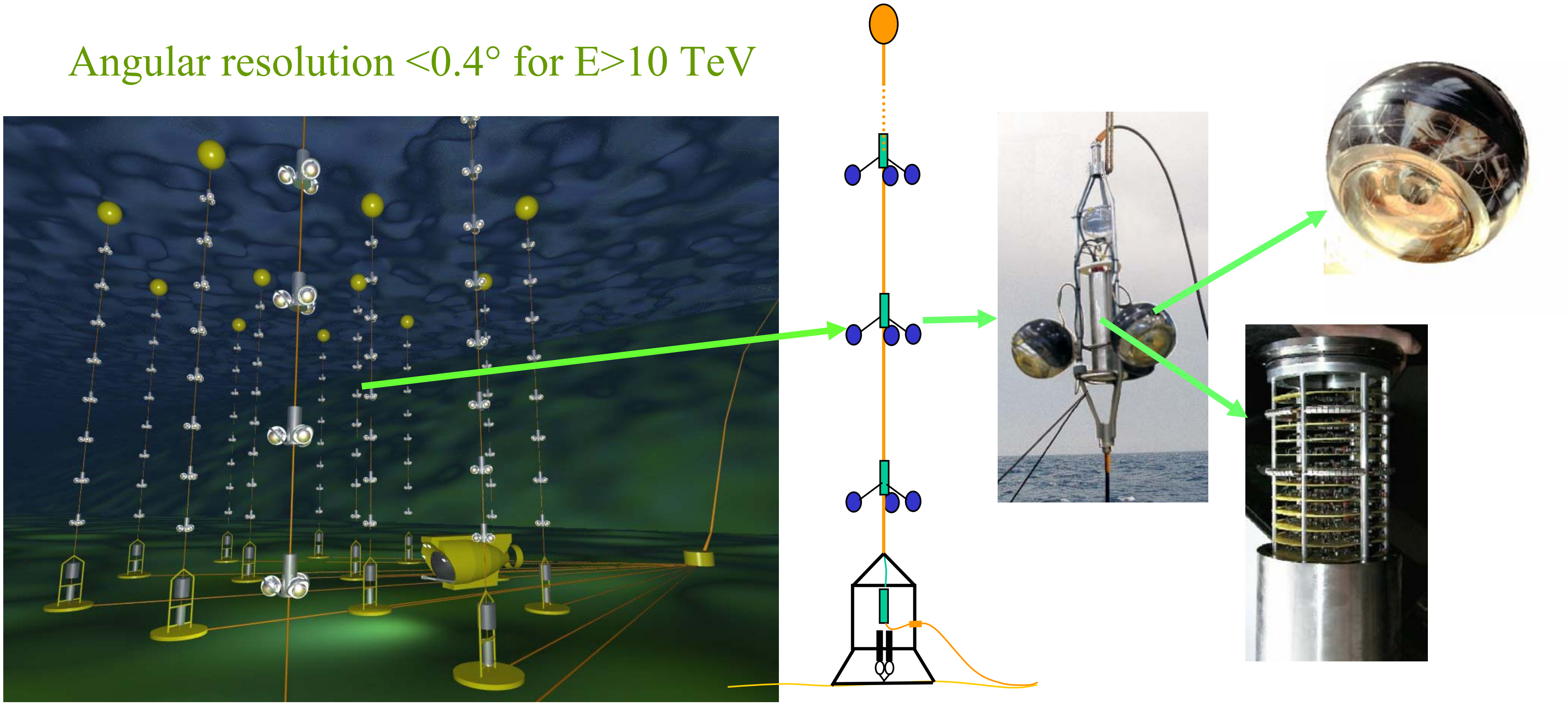
zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

Future in ν telescopes: ANTARES

1996	Started
1996 - 2000	Site exploration and demonstrator line
2001 - 2004	Construction of 10 line detector, area ~0.1km^2 on Toulon site
future	1 km^3 in Mediterranean

Angular resolution <0.4° for E>10 TeV



To know more…

- Not to ingenerate confusion, just a book
  - It's swedish, and it connects well to Martin & Shaw:

    Bengström & Goobar, Cosmology and Particle Astrophysics, Wiley 1999

- But careful: the field is in fast evolution…

  So if you are interested, talk to a teach' (to me if you pass by) and have a chat about a school