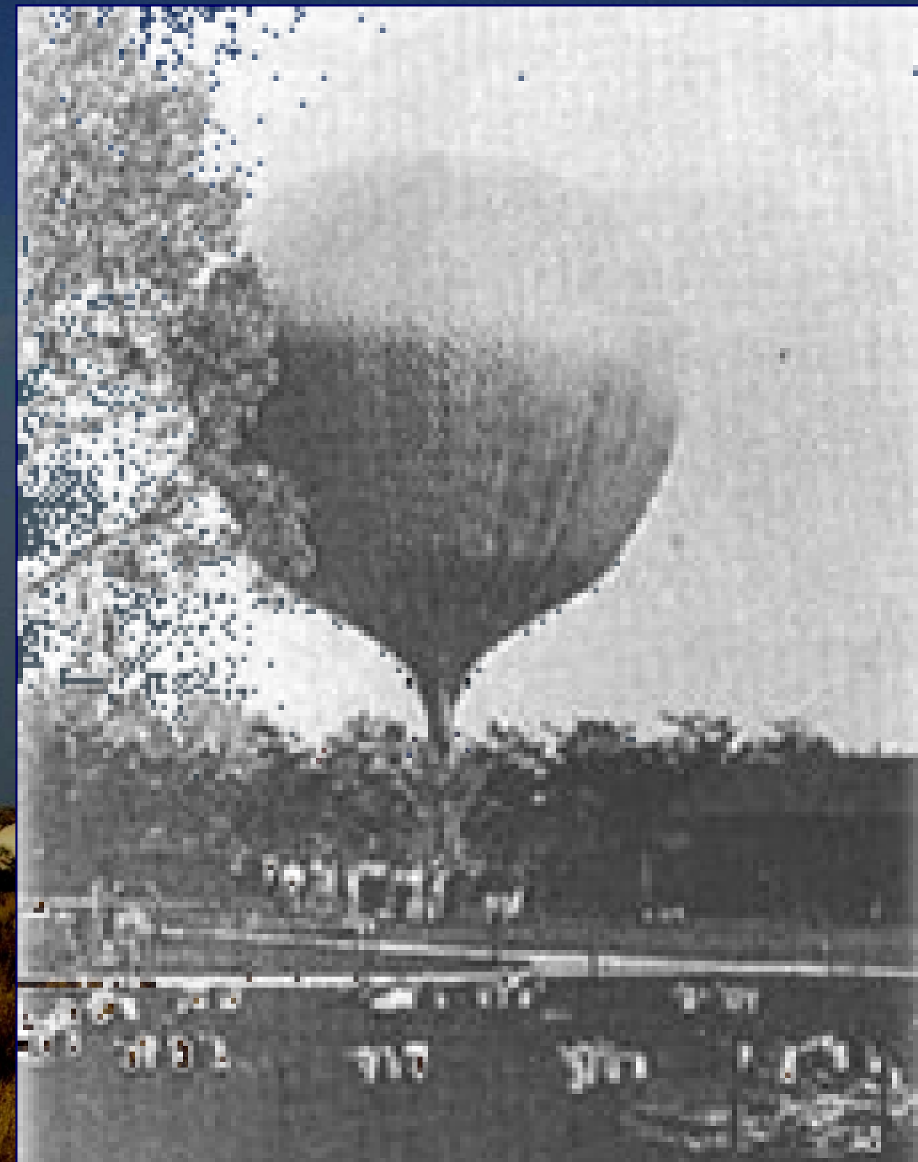
Astroparticle Physics

Mathieu de Naurois
LLR- *In2p3/CNRS – Ecole Polytechnique*
denauroi@in2p3.fr

- Introduction: Some historical facts, general problematic
- Cosmic Rays from space and balloons
- (Very) High Energy Gamma ray astronomy
- Ultra High Energy Cosmic Rays
- High Energy Neutrinos
- (Gravitational Waves)
- ~~Direct Dark Matter Searches~~
- Future prospects and conclusion

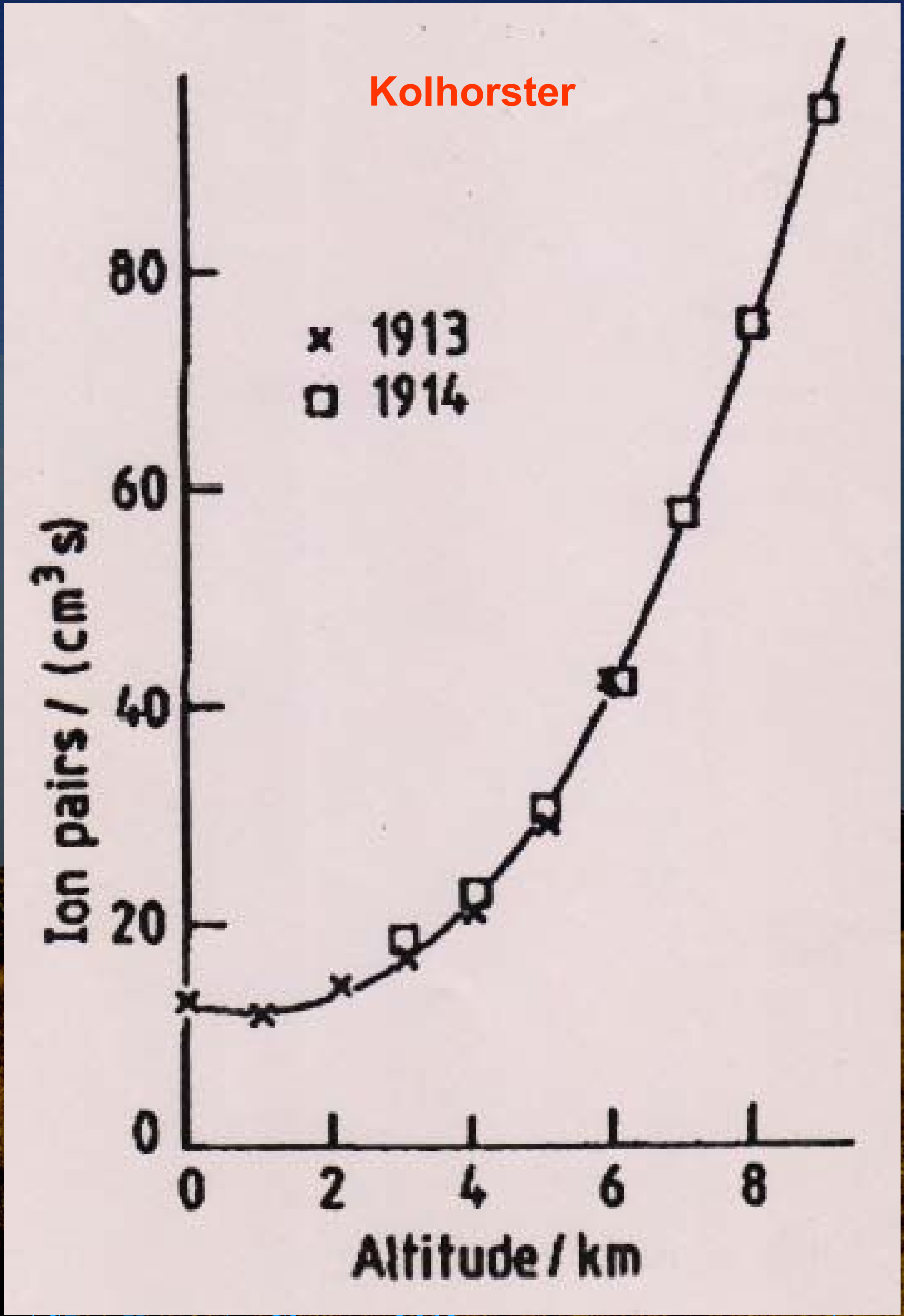
Some historical facts

The Cosmic Ray Mystery



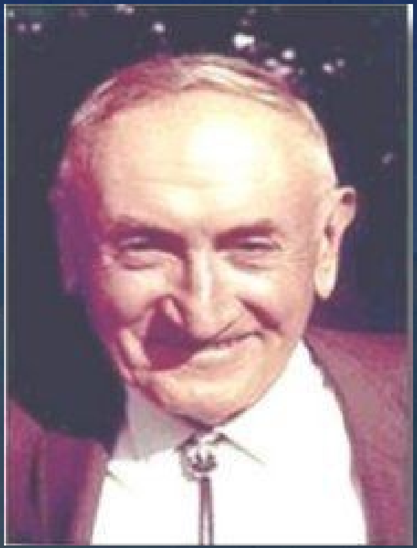
1912 : Discovery by Victor HESS (Nobel Prize 1936 with Anderson)

- 1913-1814: Werner Kolhörster repeats and confirms findings of Victor Hess ⇒ 9 km
- 1928-1929: uses Geiger counters: ⇒ Charged cosmic rays are most probably charged (Science, 1930)



Some major dates – con't

- 1934 : Supernovas proposed as putative sources of CRs. (Baade & Zwicky)
- 1938: Neutron star collapse can be used as cosmological standard candle ⇒ cosmology



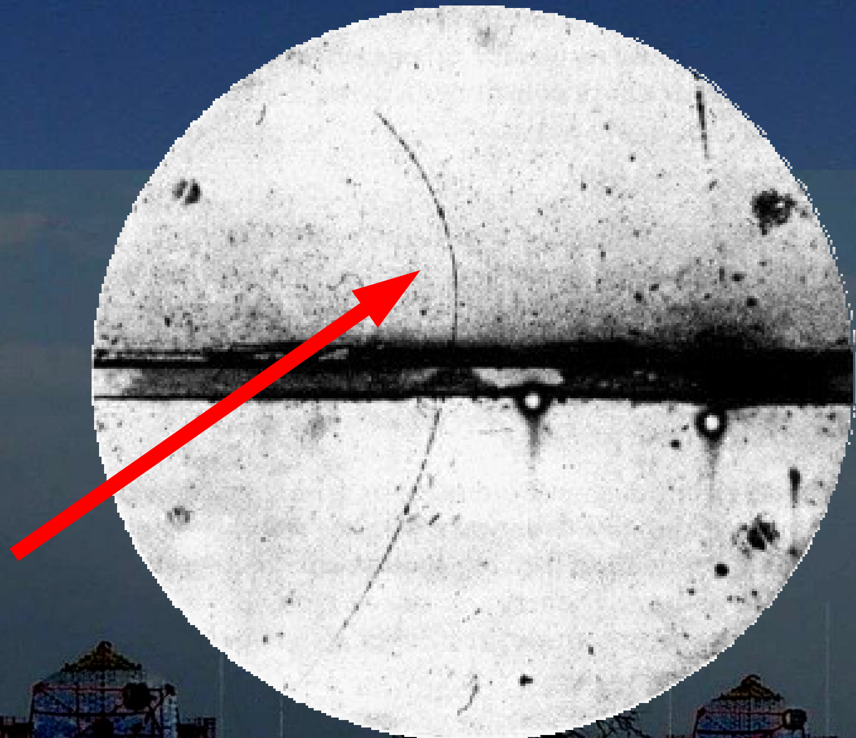
ON SUPER-NOVAE

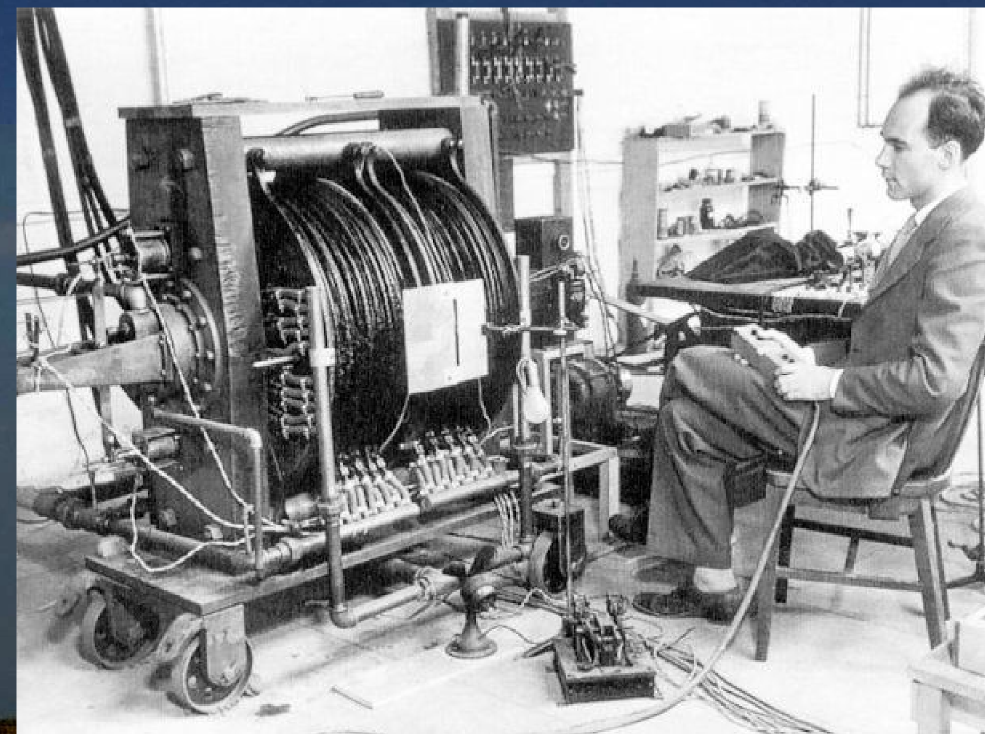
BY W. BAADE AND F. ZWICKY

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

Some major dates – con't



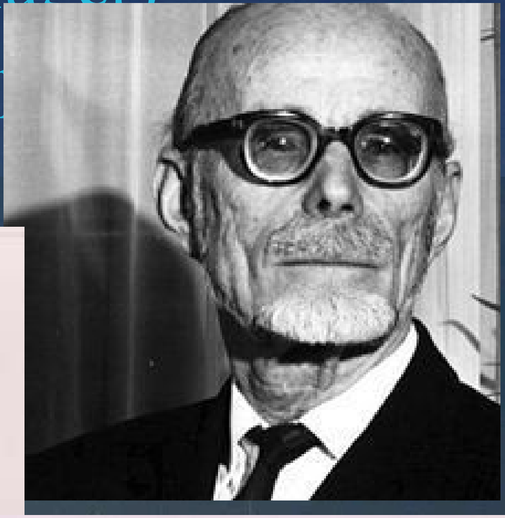


First positron
Anderson, Phys. Rev. (1933)

- 1933: Discovery of positron (e+) in the cosmic rays
- ⇒ Strong relation with particle physics (μ± (1936), π± (1947), Strange particles (1947), ...)

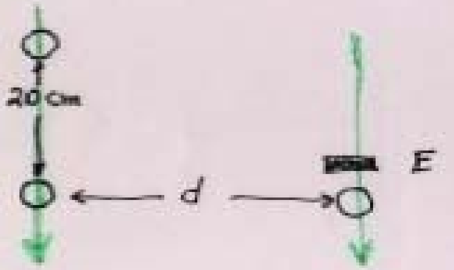
Discovery of giant showers

- 1939 : Discovery of giant showers (Pierre Auger) using coincidence between detectors 50 m a
- Up to 1015 eV (at least) !!



PHYSIQUE NUCLÉAIRE. — *Les grandes gerbes cosmiques de l'atmosphère.* Note (1) de MM. Pierre Auger et Roland Maze, présentée par M. Jean Perrin.

1. Nous avons montré (2) l'existence de gerbes de rayons cosmiques produites dans l'atmosphère et dont l
plusieurs mètres. Nous avons pu éten
de plusieurs dizaines de mètres et
corpuscules de très haute énergie da



3 com

d.	E = 0,2.	5.
2m	1,7	0,86
5m	1,4	0,7
20m	0,9	0,4

JULY-OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

Extensive Cosmic-Ray Showers

Pierre Auger
In collaboration with
P. Ehrenfest, R. Maze, J. Daudin, Robley, A. Fréon
Paris, France

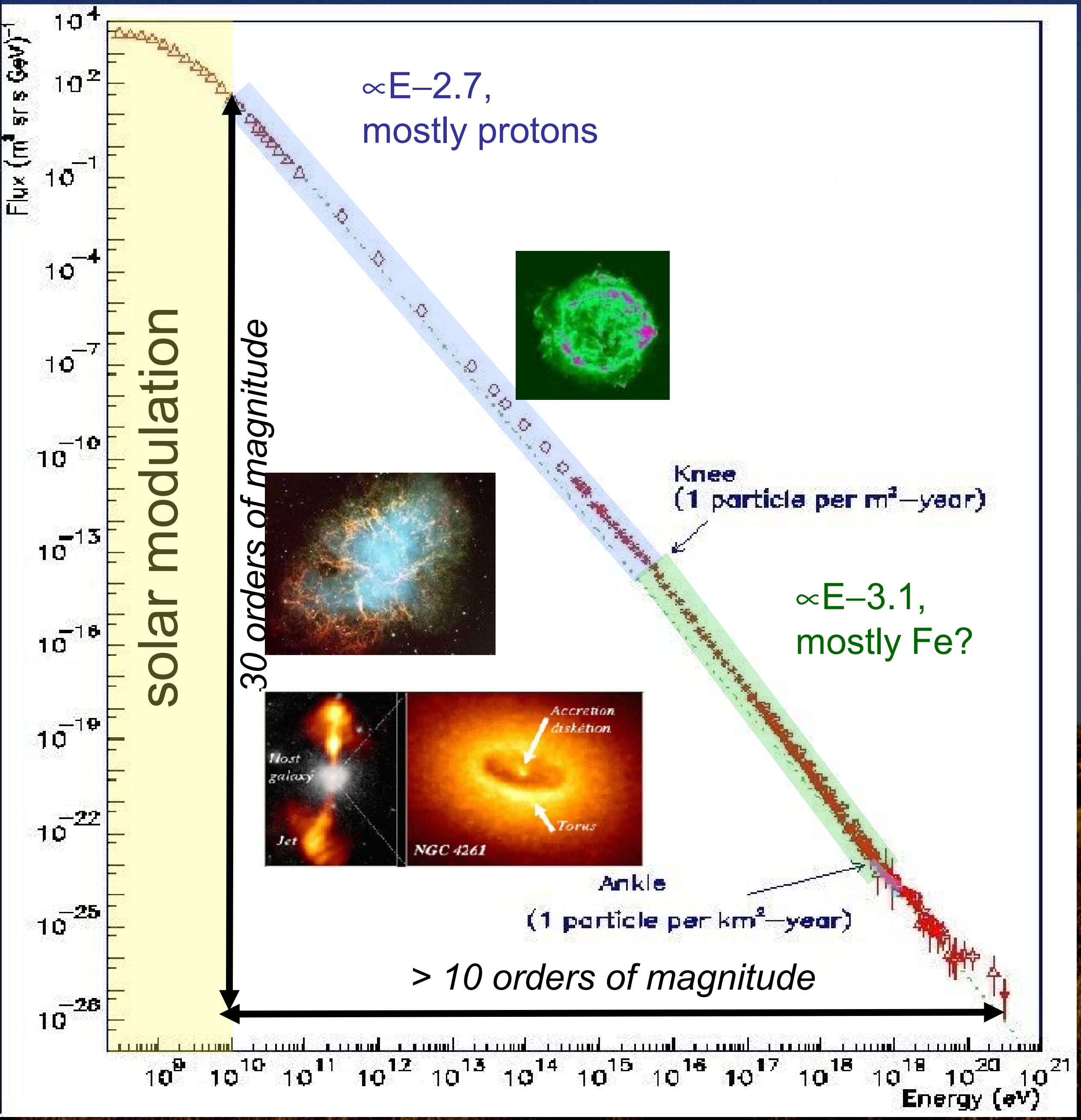
Conclusion

One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy. It seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension.

Mathieu de Naurois

Cosmic Ray Conference University of Chicago July 1939

Cosmic Ray Spectrum



- One wonder of physics
- 12 orders of magnitude in energy, 32 orders in flux

  ⇒ various detection techniques
- Very low spectra at high energy ⇒ huge area needed (>1000 km^2)
- Sources unknown
- Isotropic (above 10 GeV)

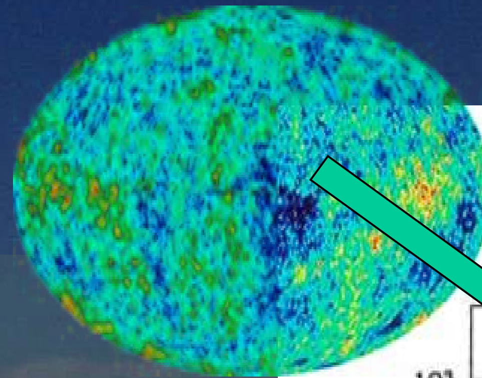
Open questions

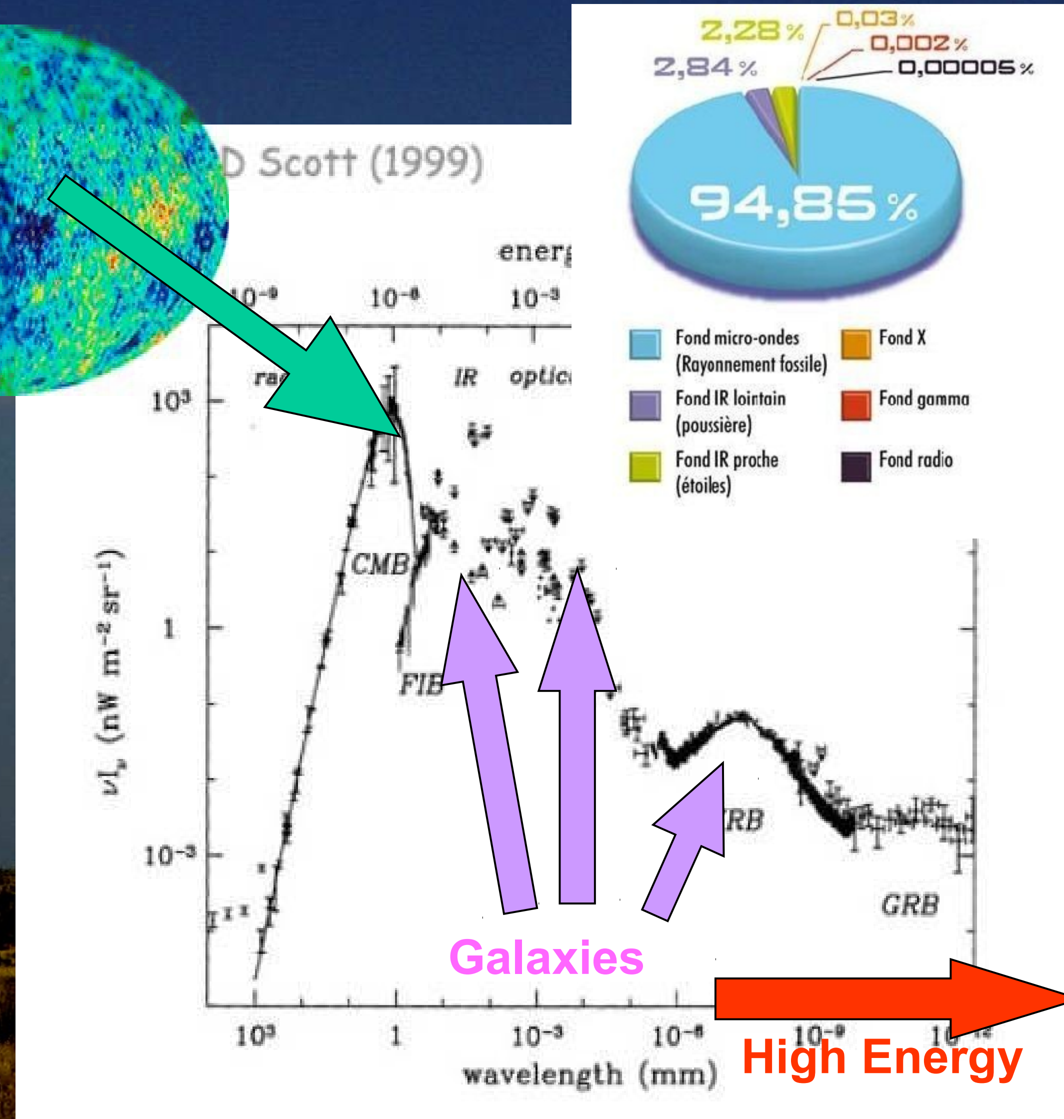
- What the sources of cosmic rays?
- What are the acceleration mechanisms, what are the accelerated particles?
- Is there new physics in there? (Dark Matter, ...)
- How do high energy particles propagate in Universe ? What can we learn from the propagation ?
- Link with cosmology: large structure formation, tomography of Universe

The main problematic

(Photon) Energy distribution in Universe

- Photon Energy Distribution
  - CMB 3K
  - Galaxies (Star light and dust)
  - Compacts objects (X)
- Emitting Power
  - $P = \sigma \times T^4 \times R^2$ (Stefan)
    $\Rightarrow$ Same power emitted by an object $10 \times$ hotter and $100 \times$ smaller
  - X-Rays (10 keV) : ~ 1km (Neutron Star) $\Leftrightarrow$ Sun
  - VHE (1 GeV): 0.2 nm $\Leftrightarrow$ Sun



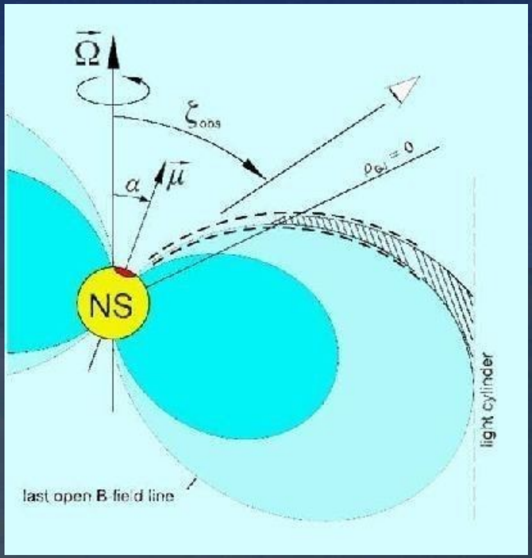


$\Rightarrow$ VHE Universe is Non-Thermal

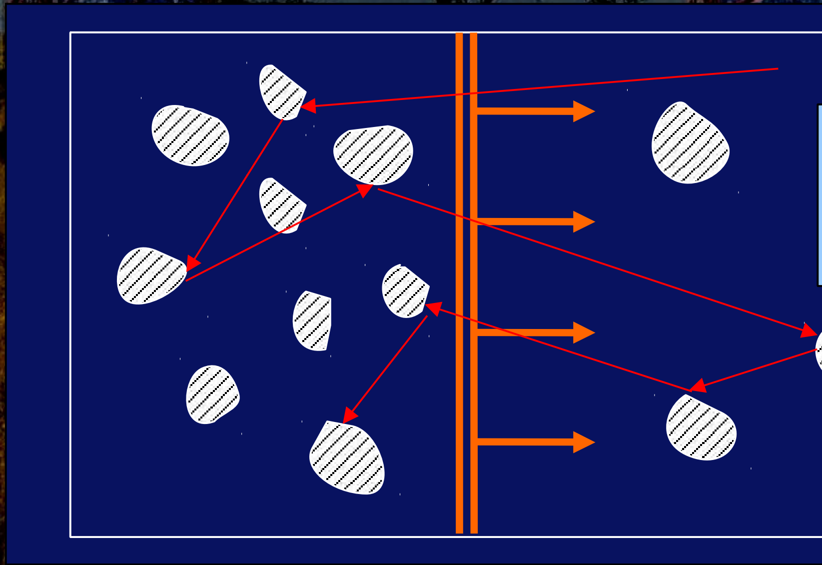
Astroparticle will mainly concern non-thermal Universe

Particle Acceleration

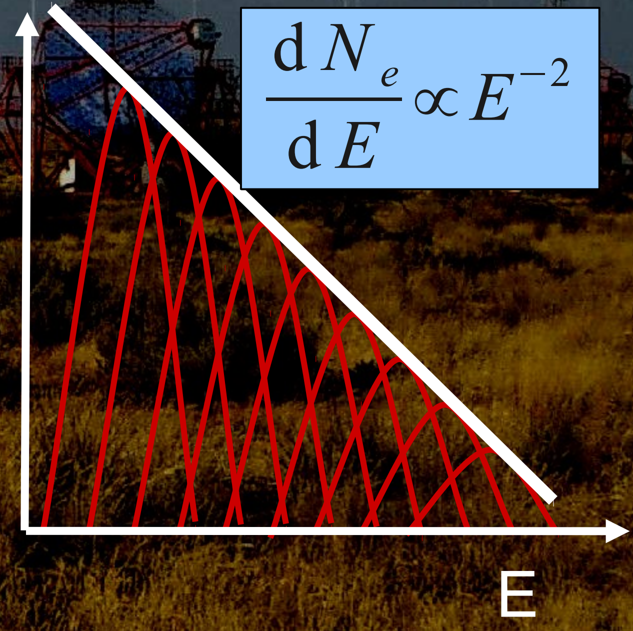
- Intense electromagnetic fields: pulsars (magnetized compact stars in fast rotation)
  ~ dynamo effect, V ~ 10^{12} V



- Astrophysical shocks: « ping-pong » particle accelerated at each shock crossing, retro diffused by B
  (First order Fermi)
- Diffusive acceleration



$$\frac{\Delta E}{E} = -2\frac{\vec{v}\,\vec{V}}{c^2}$$



$$\frac{\mathrm{d}N_e}{\mathrm{d}E} \propto E^{-2}$$

Maximum Energy

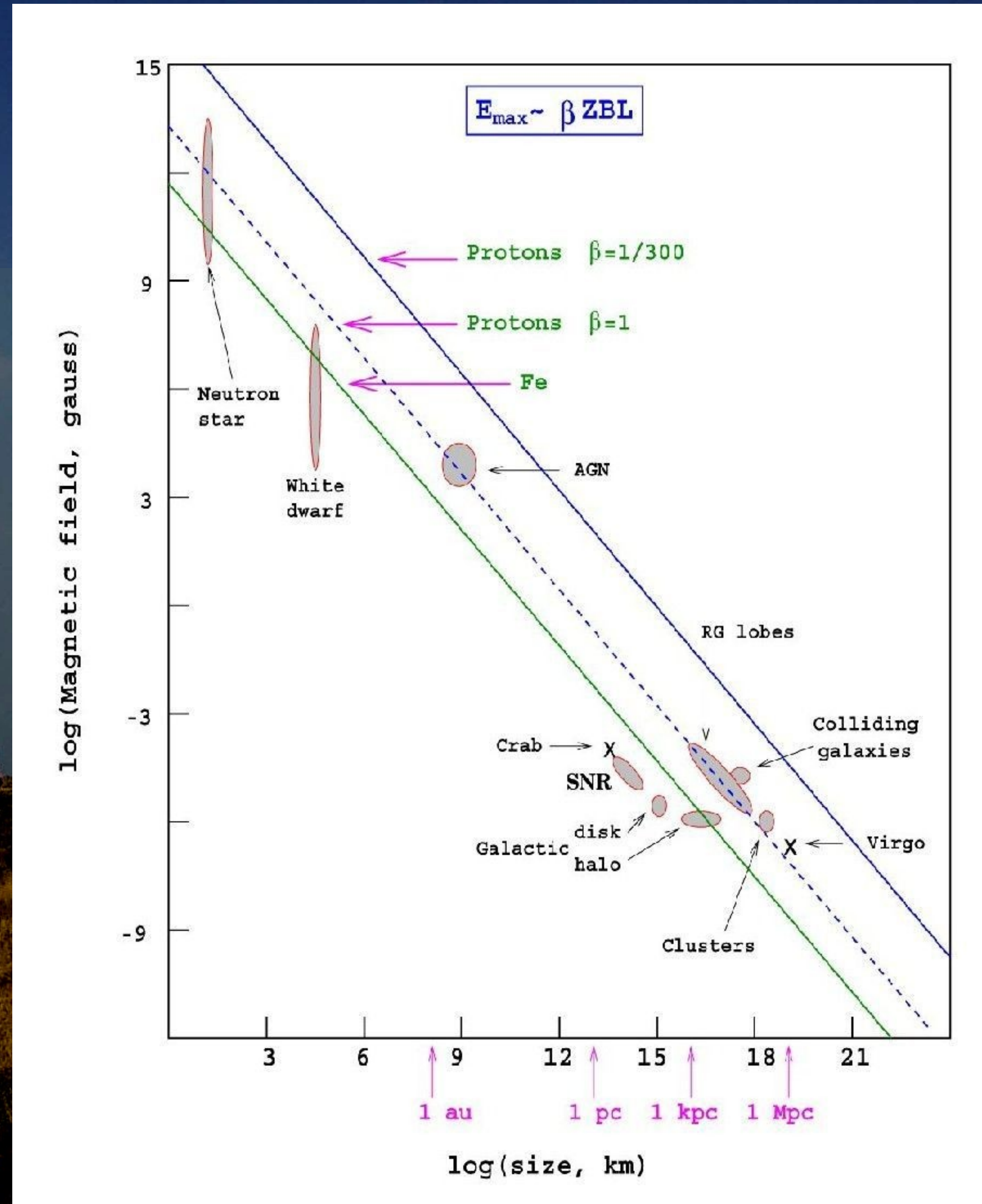
- Max energy limited by confinement size
- Larmor Radius

$$R_L = \frac{P}{qB} \approx \frac{E}{qBc}$$

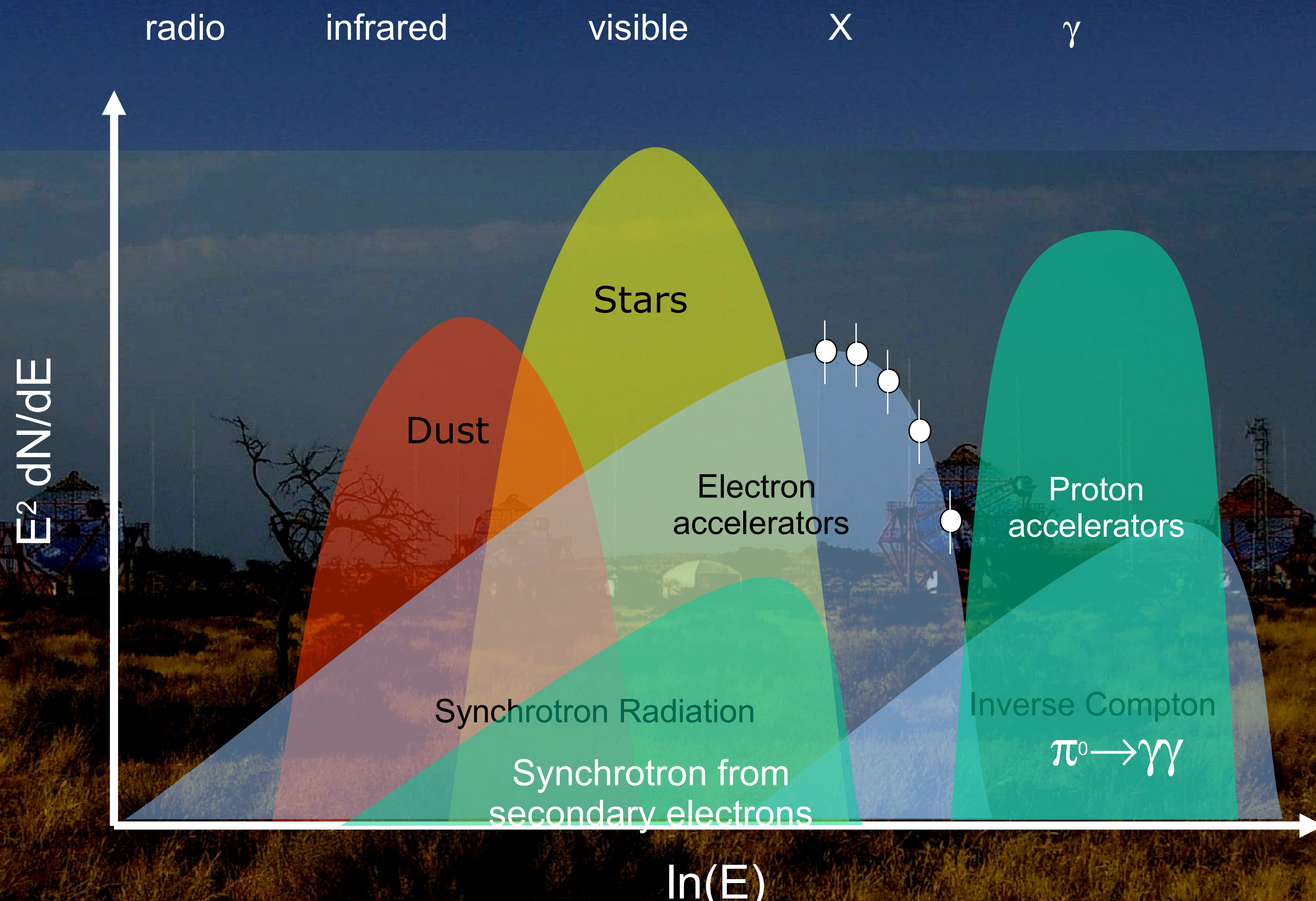
- Confinement: source size > RL

$$E_{max} \approx qBcR$$

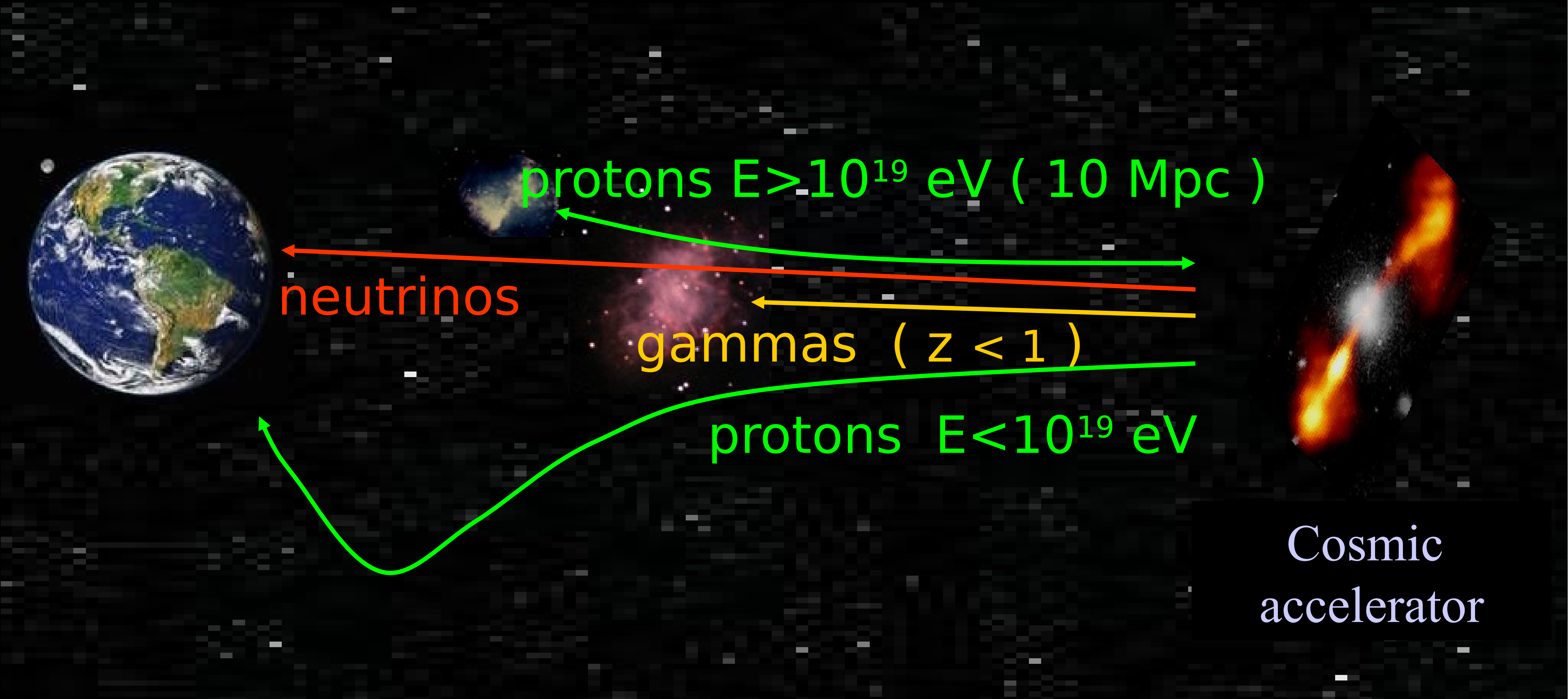
- Line of slope -1 in log(R) - log(B) (Hillas Criteria)



Multi-wavelength aspects



Multi-messenger observations of the Cosmos

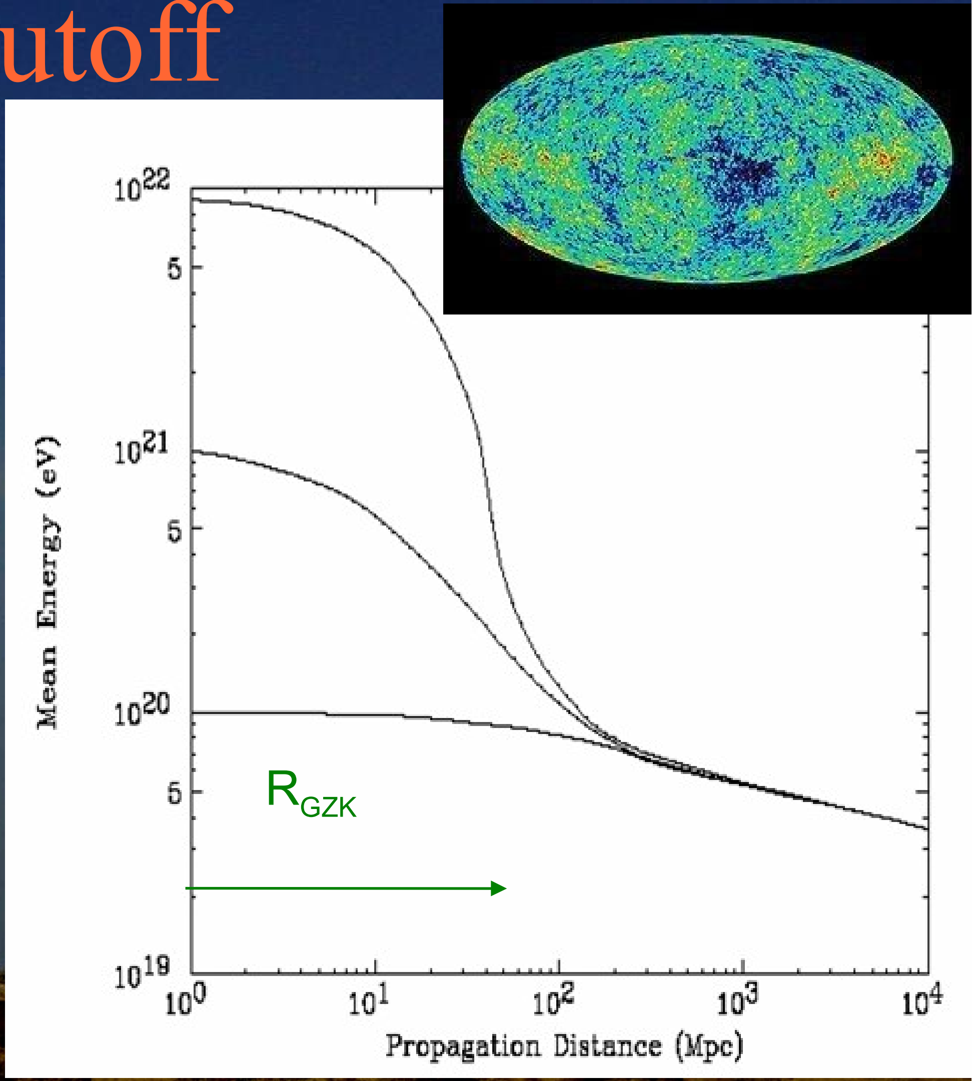


- **photons:** Absorbed by dust and radiation (pair creation on CMB)
- **protons/nuclei:** Deviated by B field, absorbed by CMB (GZK effect)
- **neutrinos:** Difficult to detect

⇒ Three "astronomies" possible...

GZK cutoff

- 1965: discovery of cosmological background by Penzias & Wilson (CMB)
  T°= 6 10^{-4} eV (2.7 Kelvin) ,
  N = 400 cm^{-3}
- Interaction of nuclei with CMB photons ⇒ effet GZK (Greisen, Zatsepin et Kuzmin) (1965)
  particle degraded to lower energies:
  10^{22} down to 10^{20} after 100 Mpc



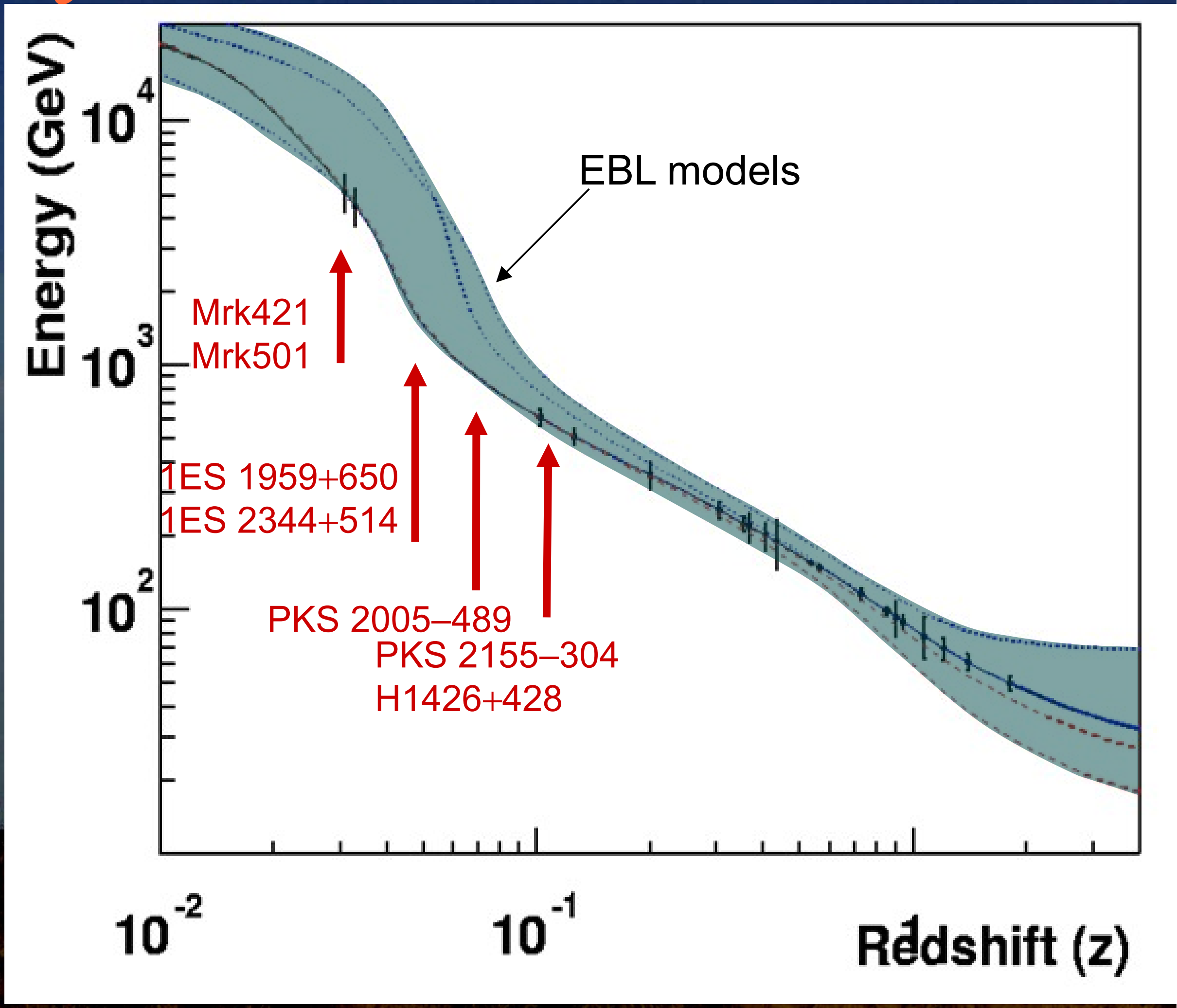
$$p+\gamma_{CMB}\rightarrow\Delta^{+}\begin{cases}\rightarrow p\pi^{0}\rightarrow p\gamma\gamma\\ \rightarrow n\pi^{+}\rightarrow n\nu_{\mu}\mu^{+}\rightarrow n\nu_{\mu}\mu^{+}\bar{\nu}_{\mu}\nu_{e}e^{+}\end{cases}$$

γ - ray Horizon

- γ –rays absorbed by pair creation on infrared background:

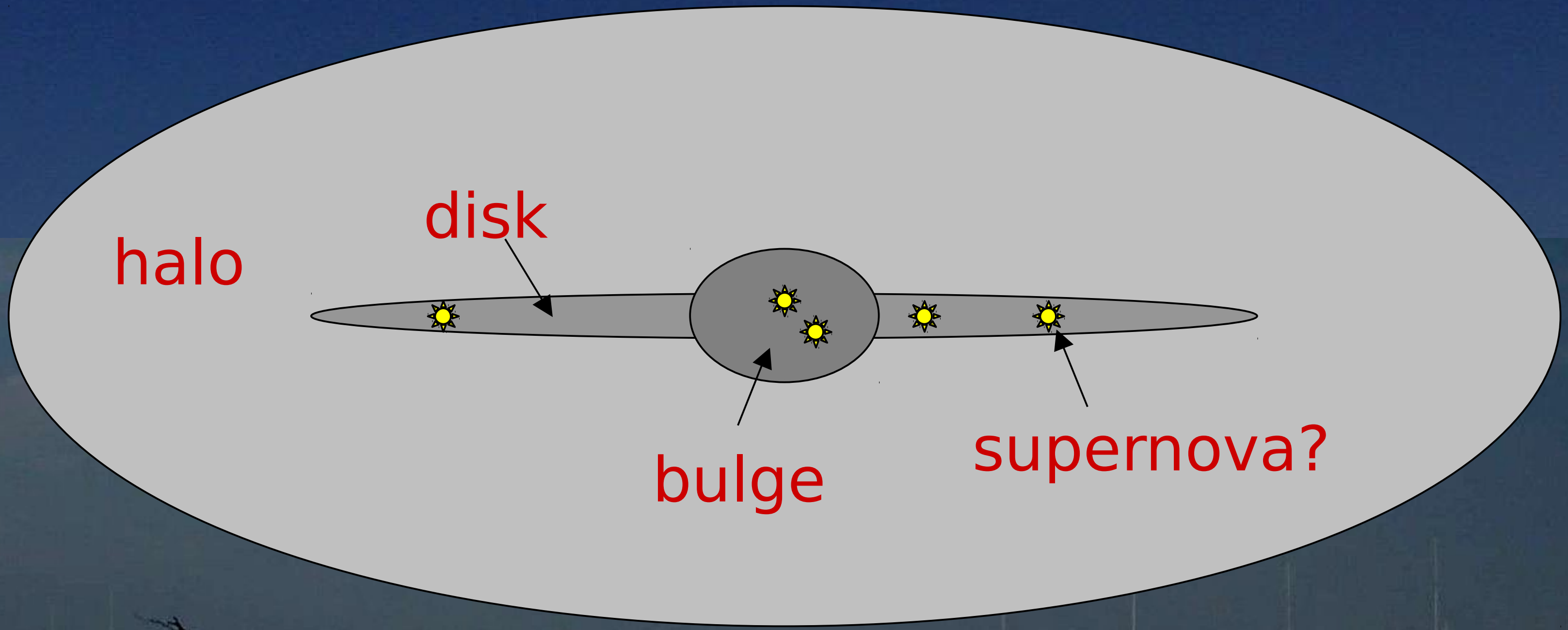
$$\gamma + \gamma_{CMB} \rightarrow e^{+} e^{-}$$

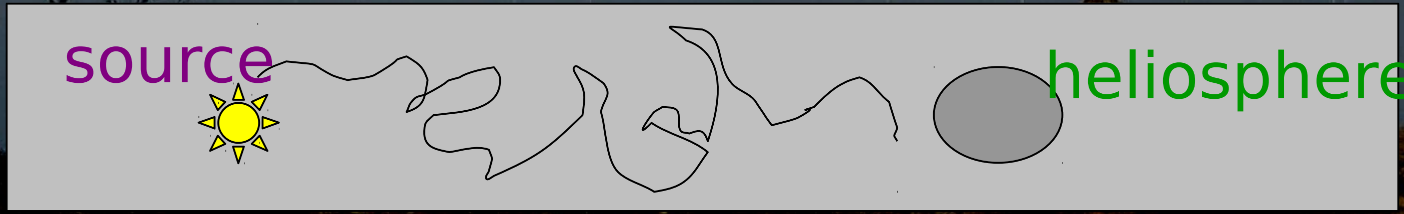
- Limits the size of observable Universe:
  - z < 0.1 @ 500 GeV
  - z < 0.01 @ 2 TeV



- Indirect measurement of dust & star background through tomography (energy spectrum vs distance) ⇒ link with cosmology

Propagation in Galaxy

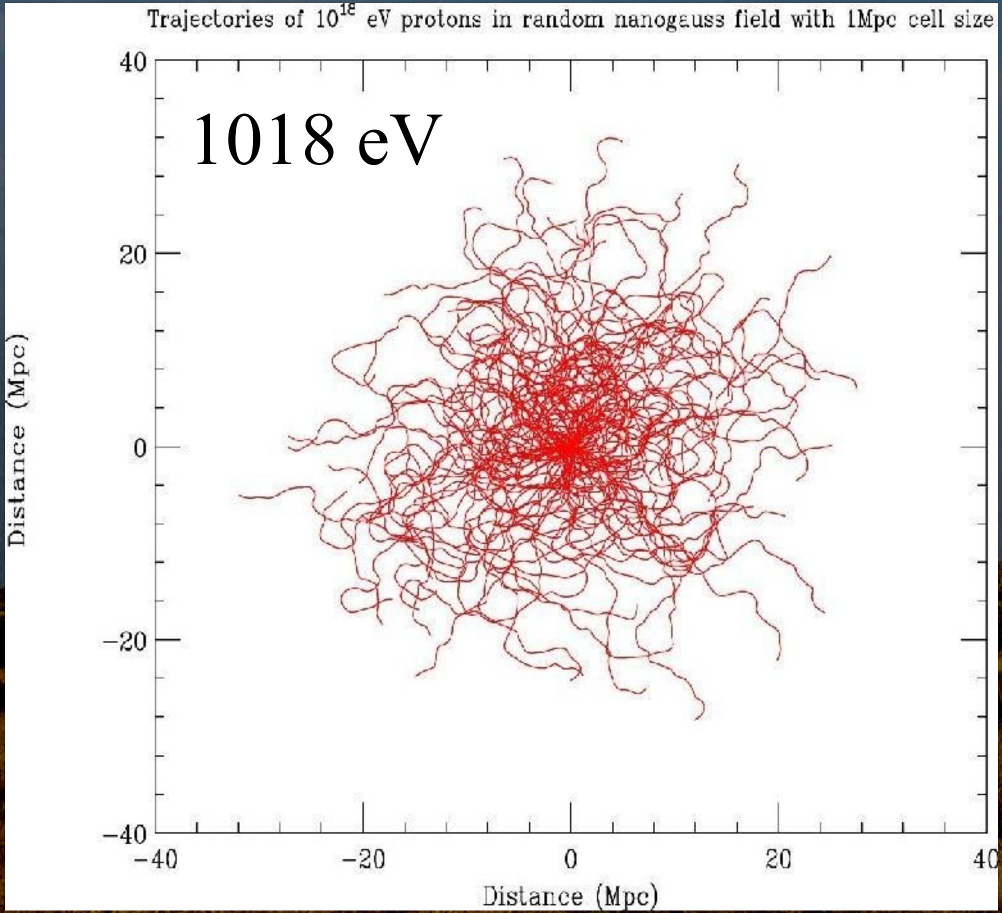


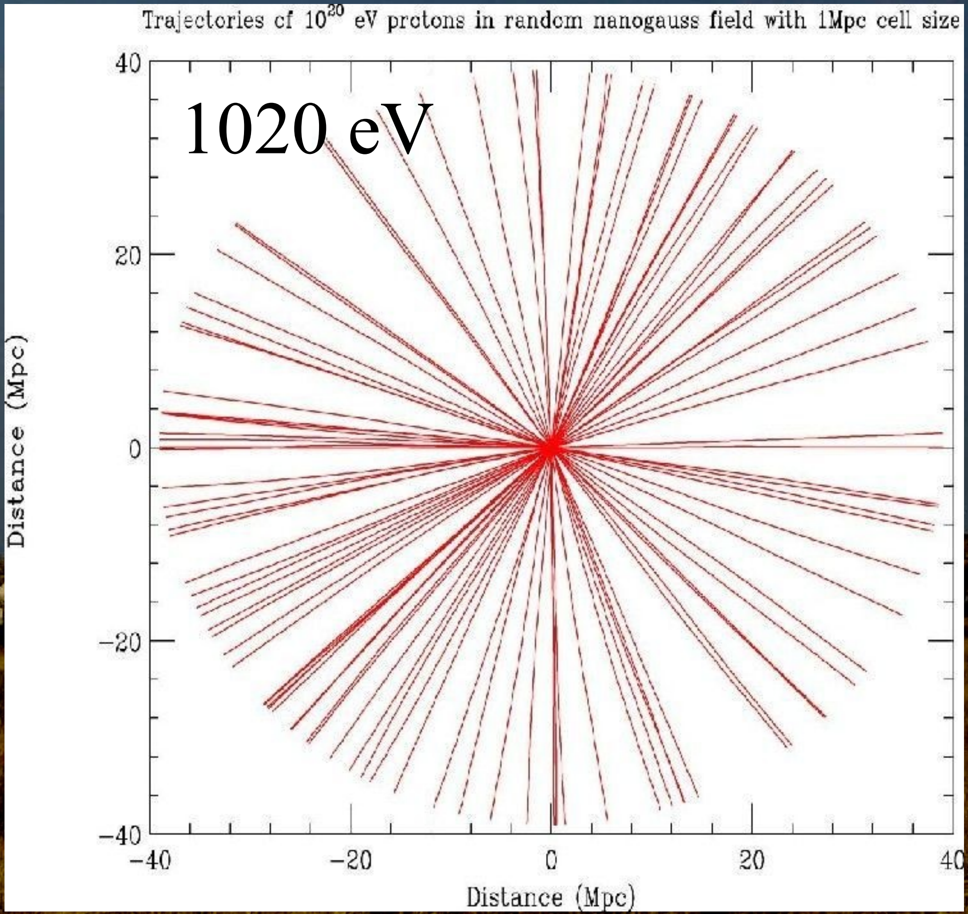


- Diffusion of particles: high energy particle escape first ⇒ Observed spectrum steeper than source spectrum. e.g. $E^{-2.7}$ at earth vs $E^{-2.0}$ at galactic center.
- Composition change: spallation (nuclear reaction)

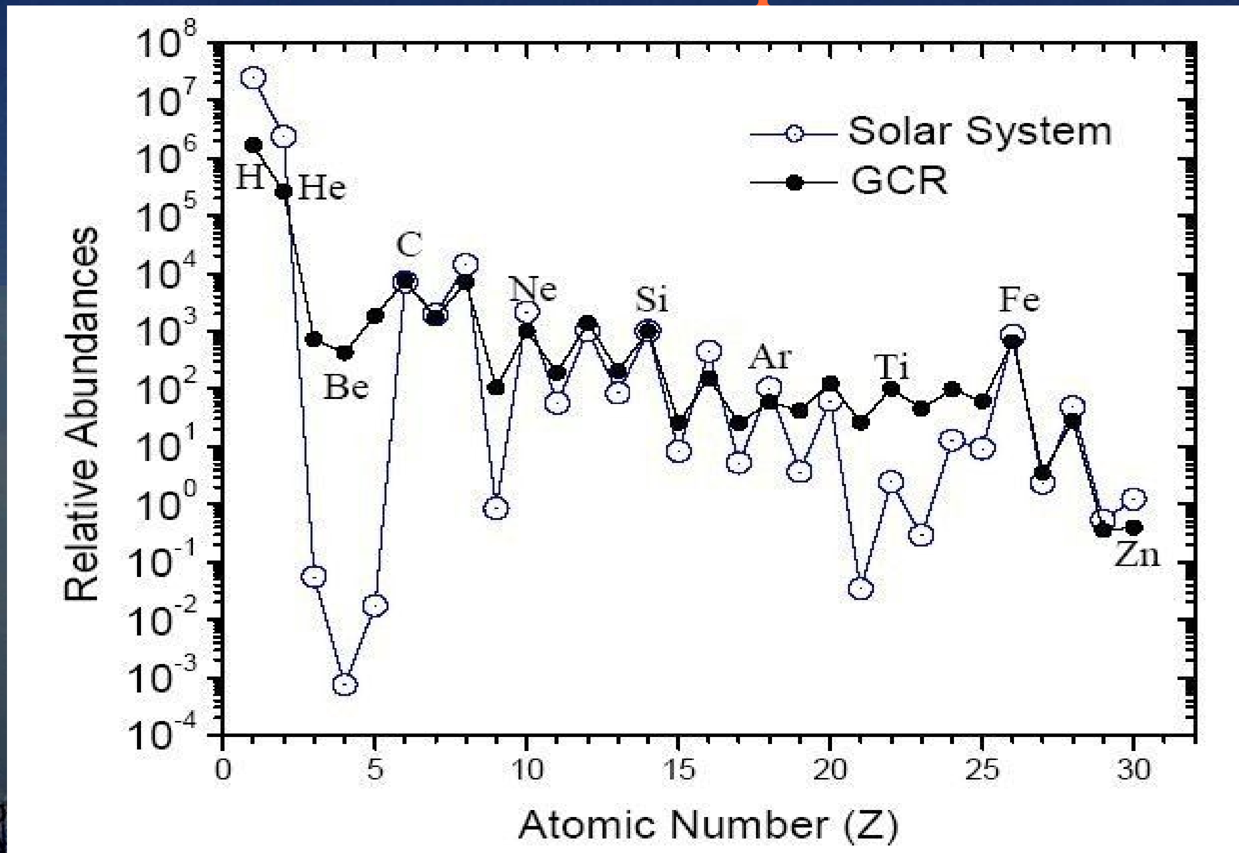
Propagation

- Above 10^{20} eV a proton astronomy becomes possible





Composition

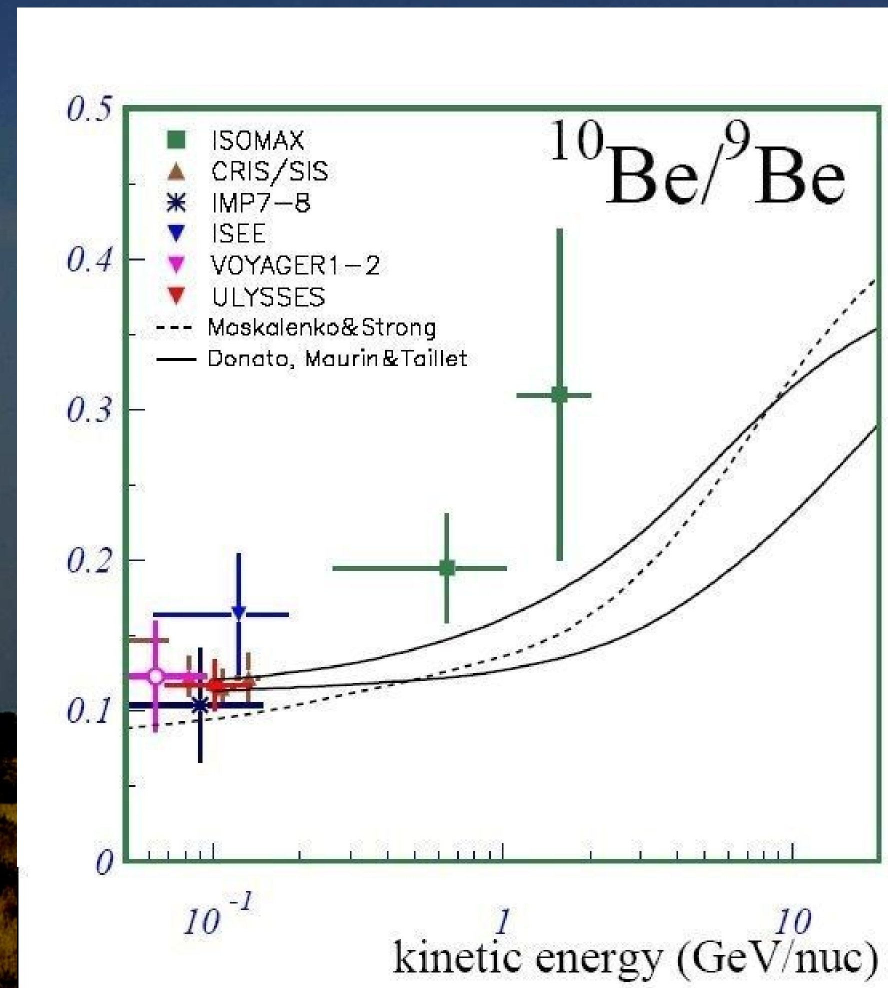


70 to 280 MeV/nucléon,
Satellite

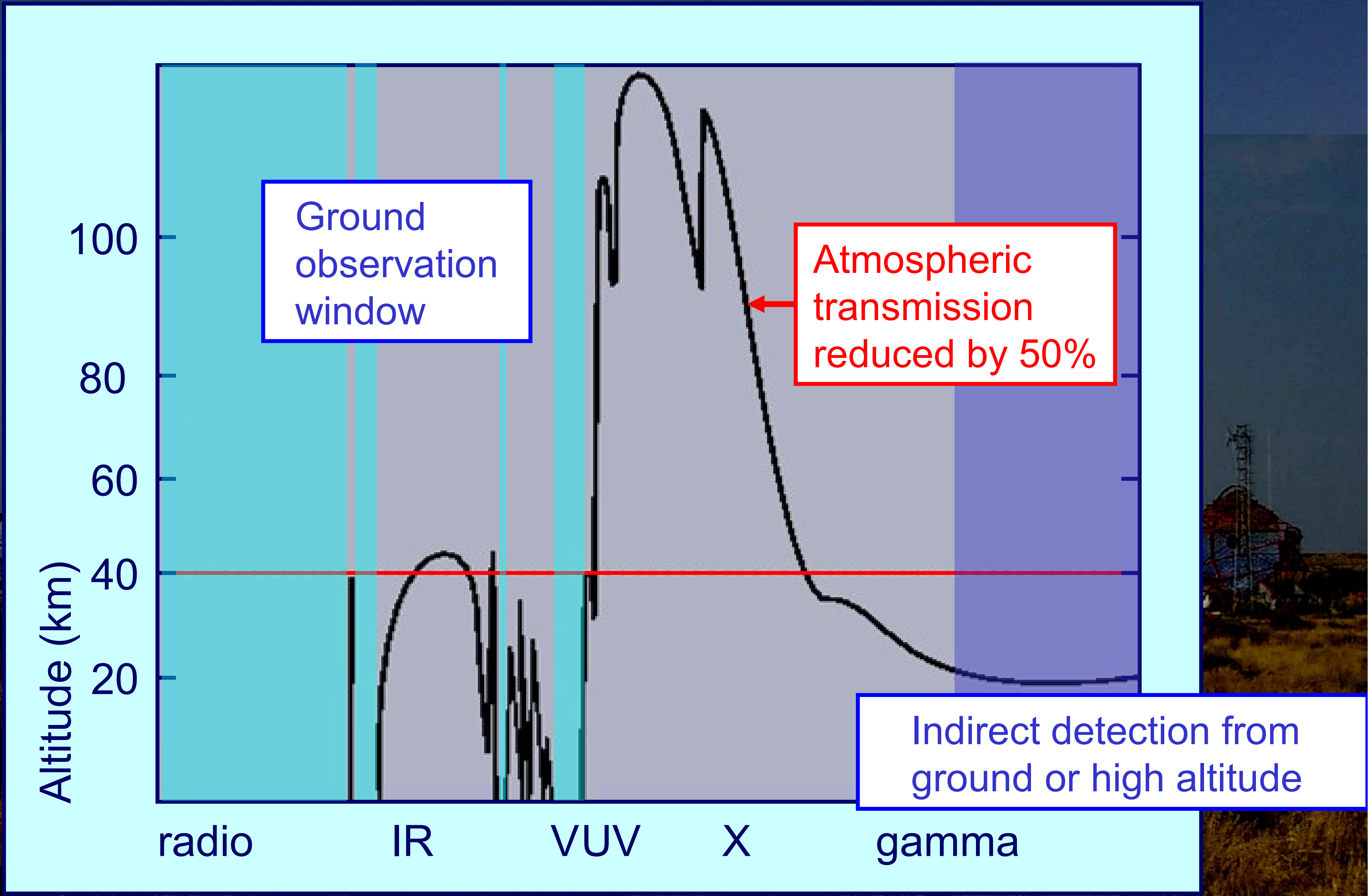
- CR abundances differs from local measurement
  - Excess of Li - Be - B et sub Fe
  - Secondary nucleus created by spallation ⇒ constraints on propagation
  - Primary nuclei (CNO, Fe,.) accelerated in sources
  - Other particles are produced in propagation (γ, ν, antiparticles). Excess w/o prediction can be the sign of new physics

Composition – II – Isotopic Measurement

- Secondary Nuclei:
  - CNO spallation → Li, Be, B
  - Constraints on CR propagation in the galaxy
- Radioactive Nuclei: Cosmic Ray clocks.
  - ^{10}Be ($t_{1/2}$~1.5 10^6 year)
  - ^{10}Be/^{9}Be give information about confinement time in the Galaxy
  - ^{26}Al line (1.809 MeV,half life ~ 10^6 years): nucleosynthesis tracer (stellar winds,...)
- Current isotopic measurement:
  - Low statistics, low energy only

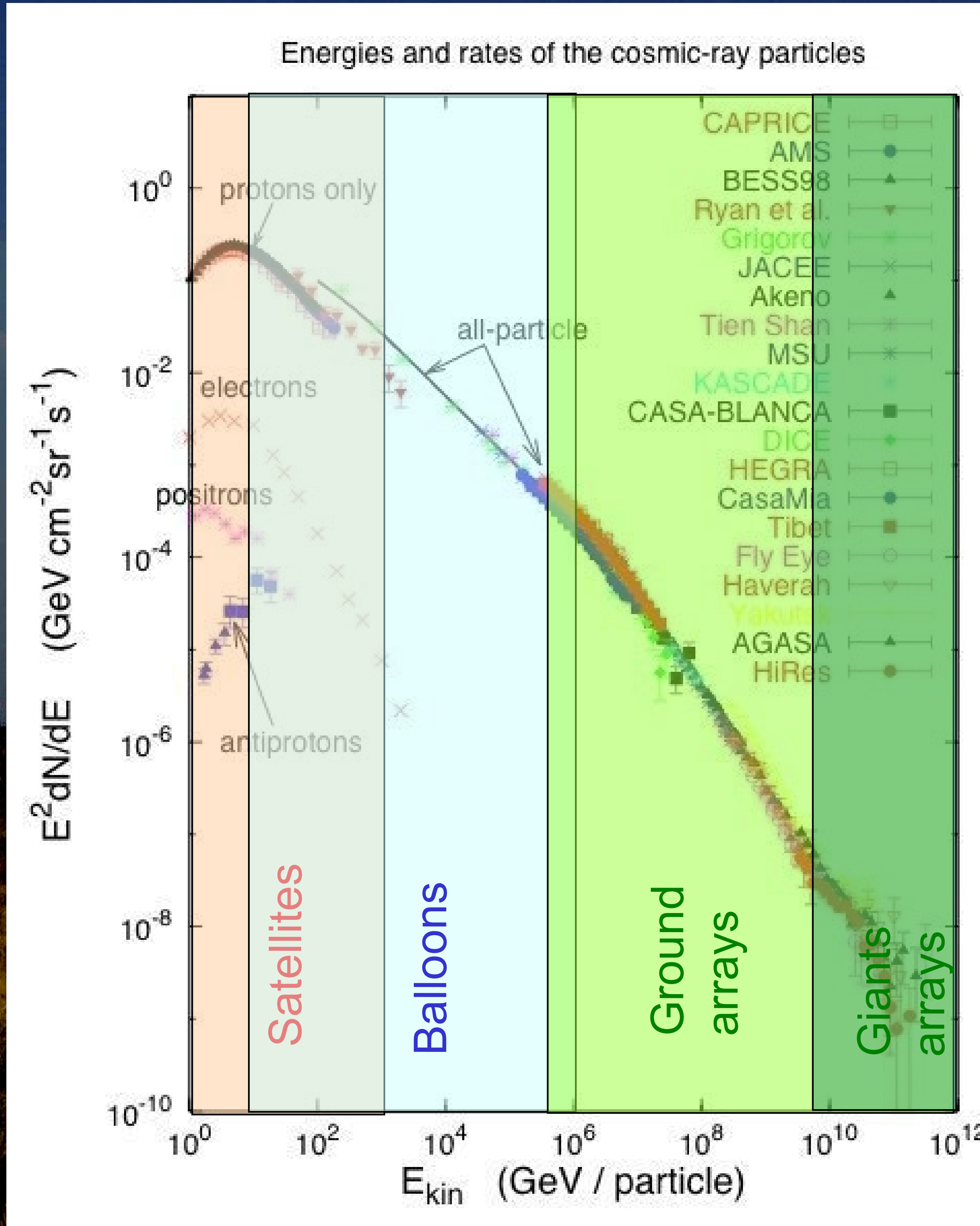


Atmospheric Transparency



Acceptance & fluxes

- The higher the energy, the biggest the needed acceptance:
  - 10 GeV : 1 CR/m^2/s
    $\Rightarrow$1 m^2 (satellite or balloon)
  - Knee: 1 CR/m^2/an
    $\Rightarrow$ 1 km^2 (ground array)
  - Ankle: 1 CR/km^2/century
    $\Rightarrow$ 1000 km^2 (giant array)



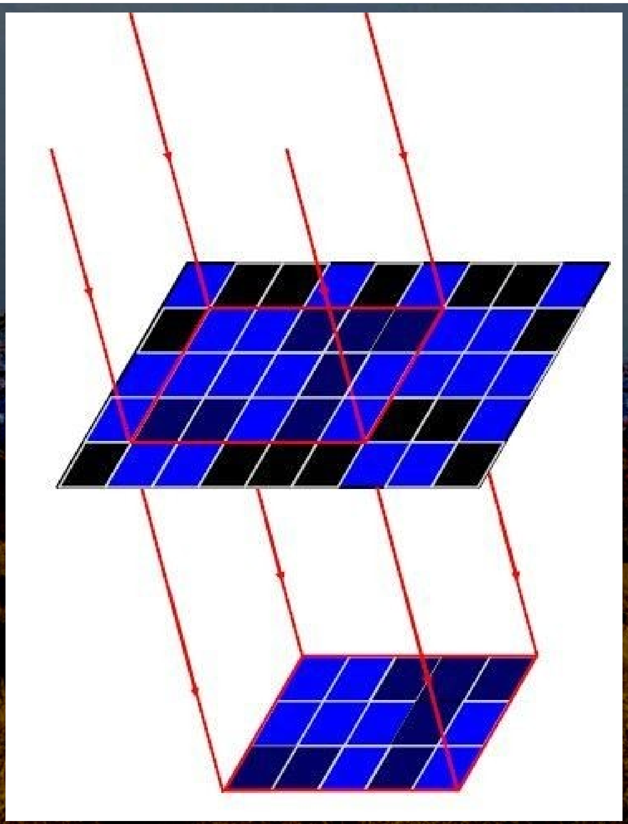
Mathieu de Naurois

Challenges

- Atmosphere opaque to cosmic rays
  ⇒ Stratospheric balloons or indirect detection
- Flux decreases rapidly with energy
  ⇒ Need for very large effective area (1000 km2 at the knee)
- Composition (and isotopic composition) is very rich
  ⇒ Need for precise mass measurement
- Specificities related to primary particles:
  - Neutrinos : very low interaction probability ⇒ need for huge detection volumes
  - Gammas : very large hadronic and electronic background
    ⇒ large rejection factors needed

Photons

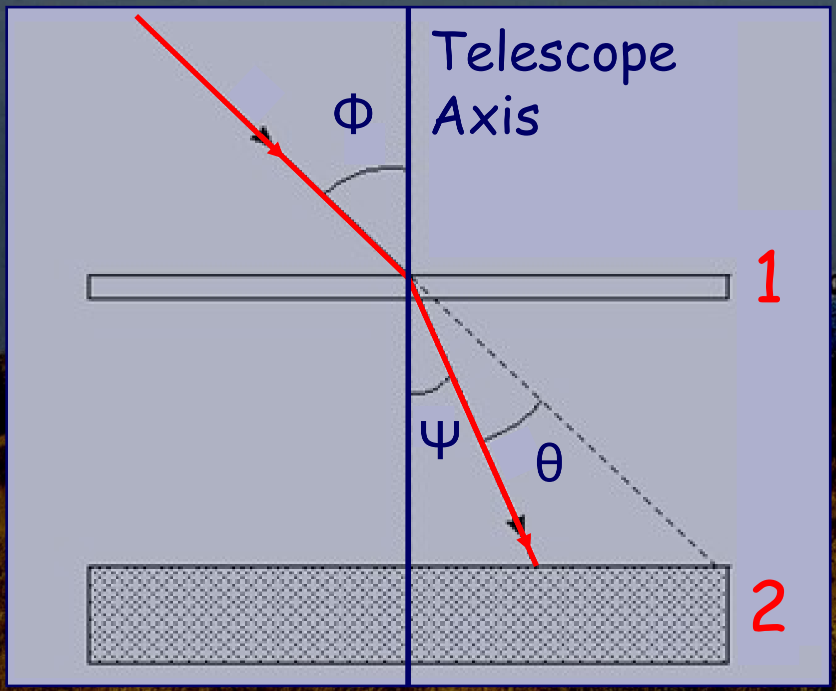
Space



Coded mask telescope

Photons

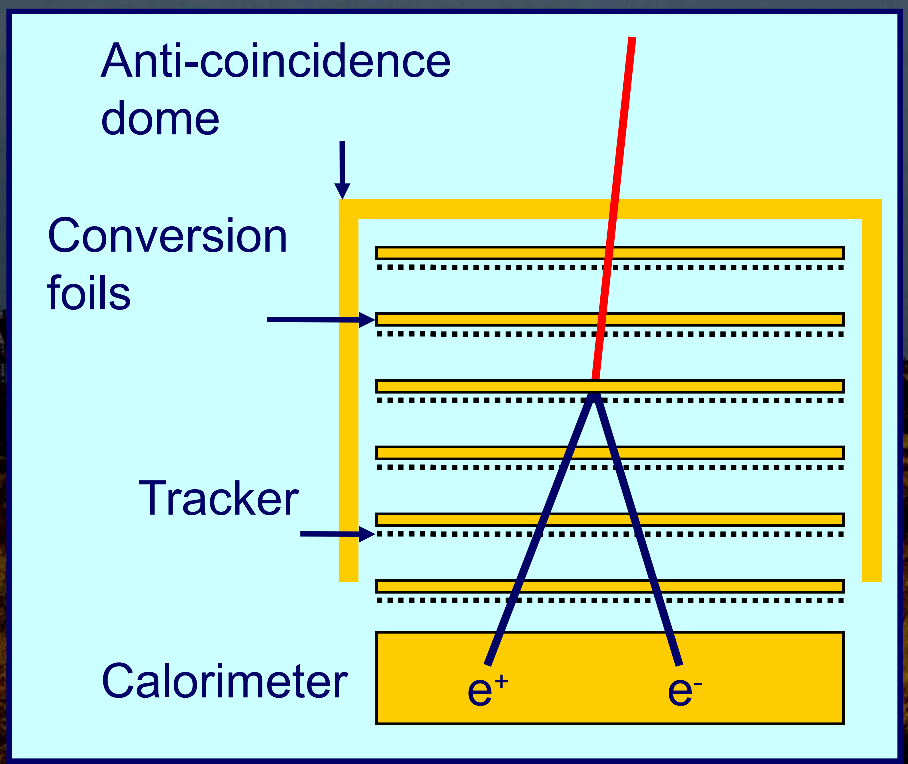
Space



Compton Telescope

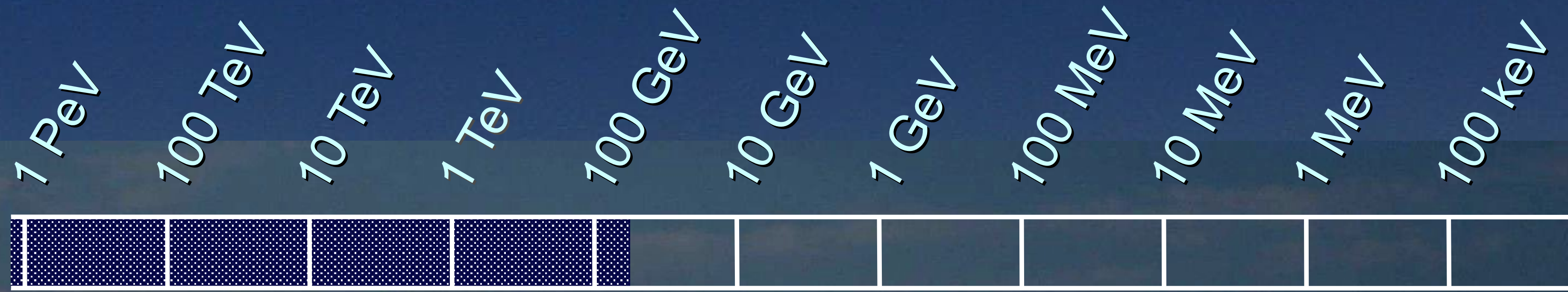
High Energy Photons

Space

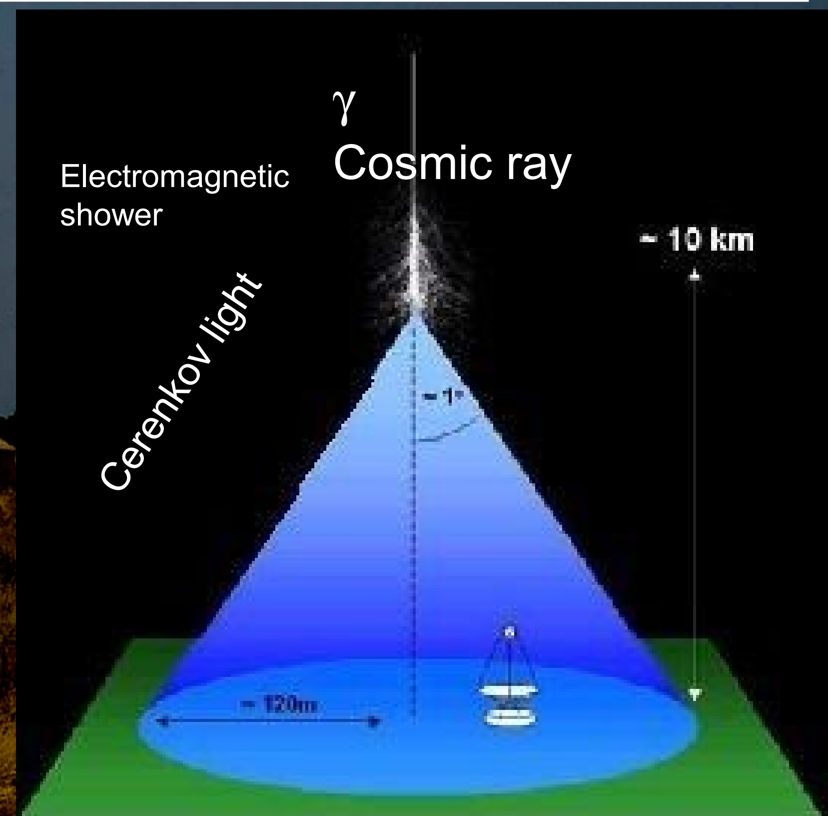


Pair creation telescope

Very High Energy Photons



From ground



Atmospheric Cerenkov Telescopes

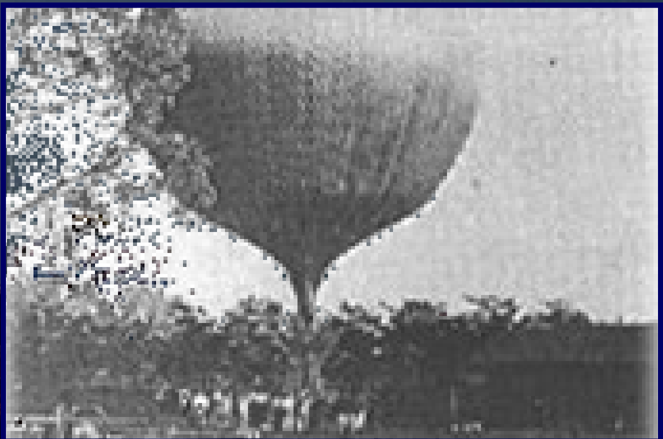
Charged Particles

100 EeV | 10 EeV | 1 EeV | 100 PeV | 10 PeV | 1 PeV | 100 TeV | 10 TeV | 1 TeV | 100 GeV | 10 GeV

Direct detection

Extended air showers – from ground

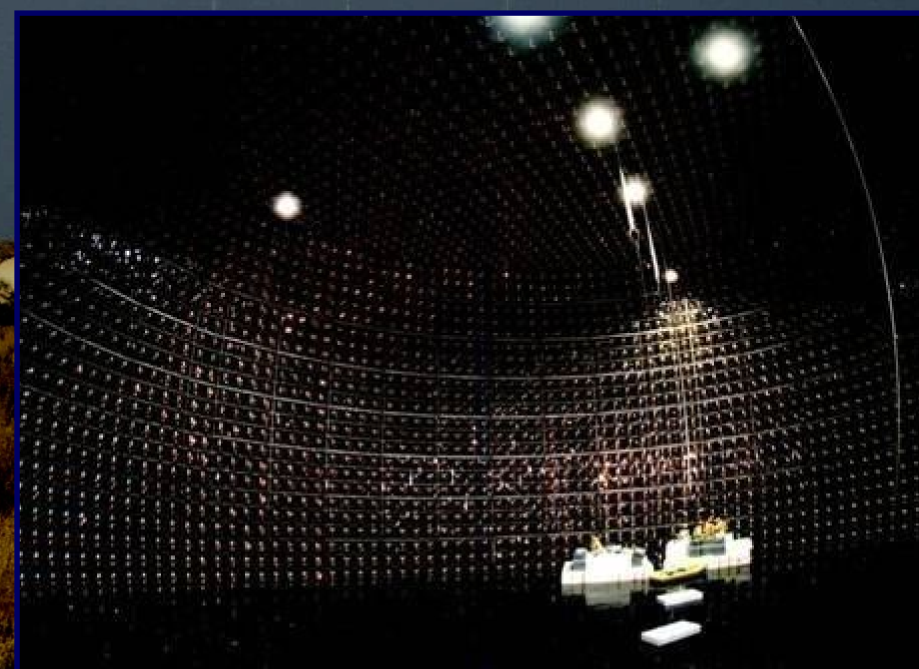
Ballons



Space

Neutrinos

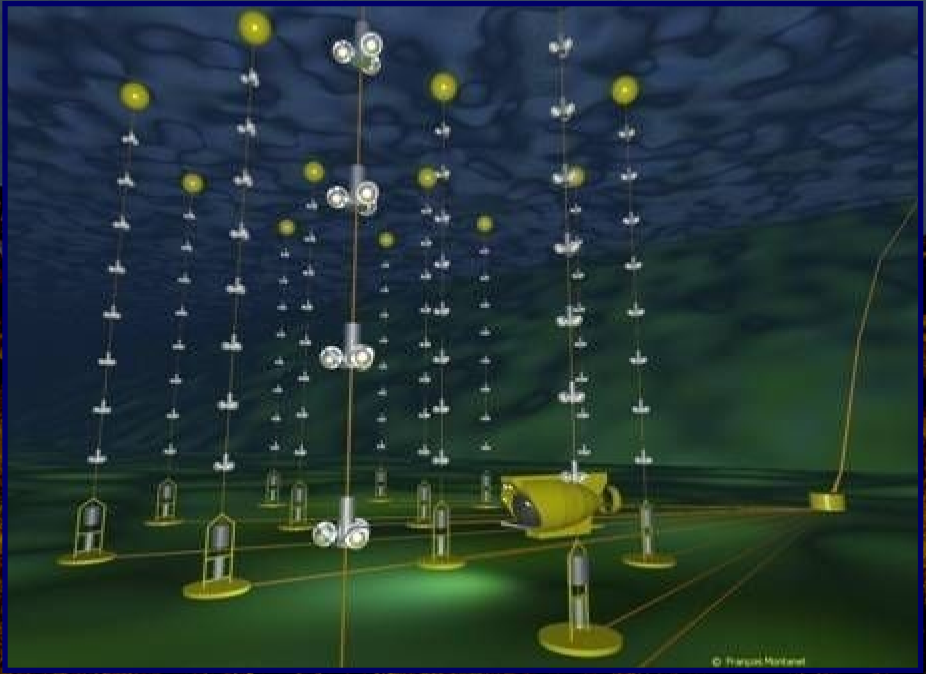
- Neutrino Scattering off one electron
- Cherenkov emission of the electron in water

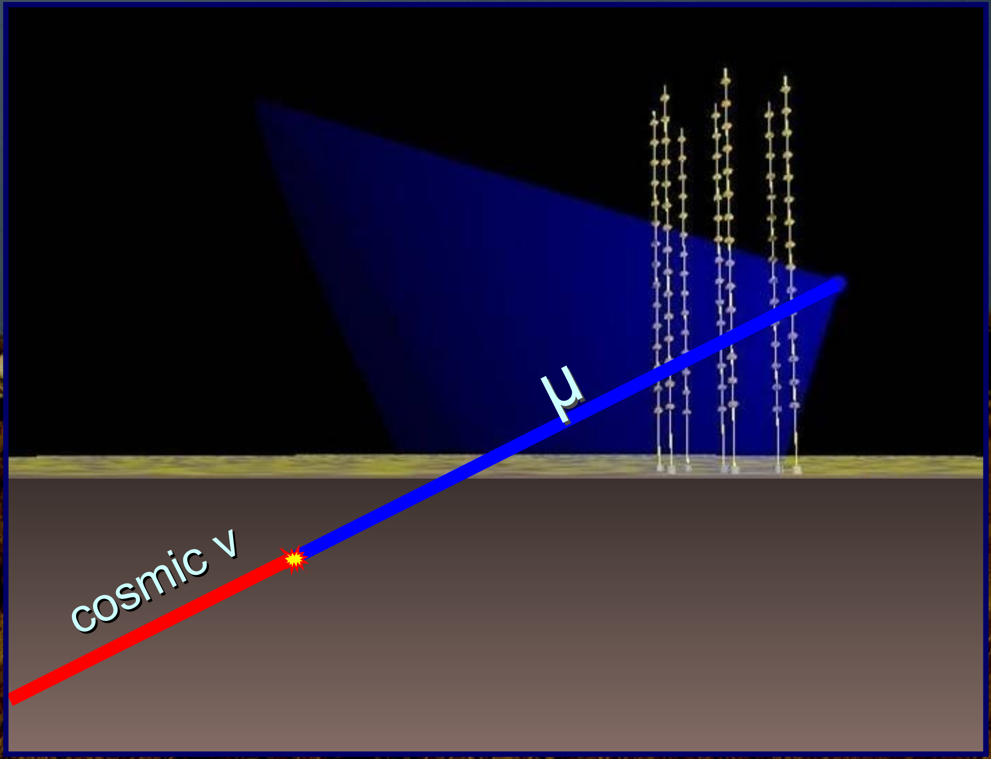


Neutrinos

1 PeV | 100 TeV | 10 TeV | 1 TeV | 100 GeV | 10 GeV | 1 GeV | 100 MeV | 10 MeV | 1 MeV | 100 keV

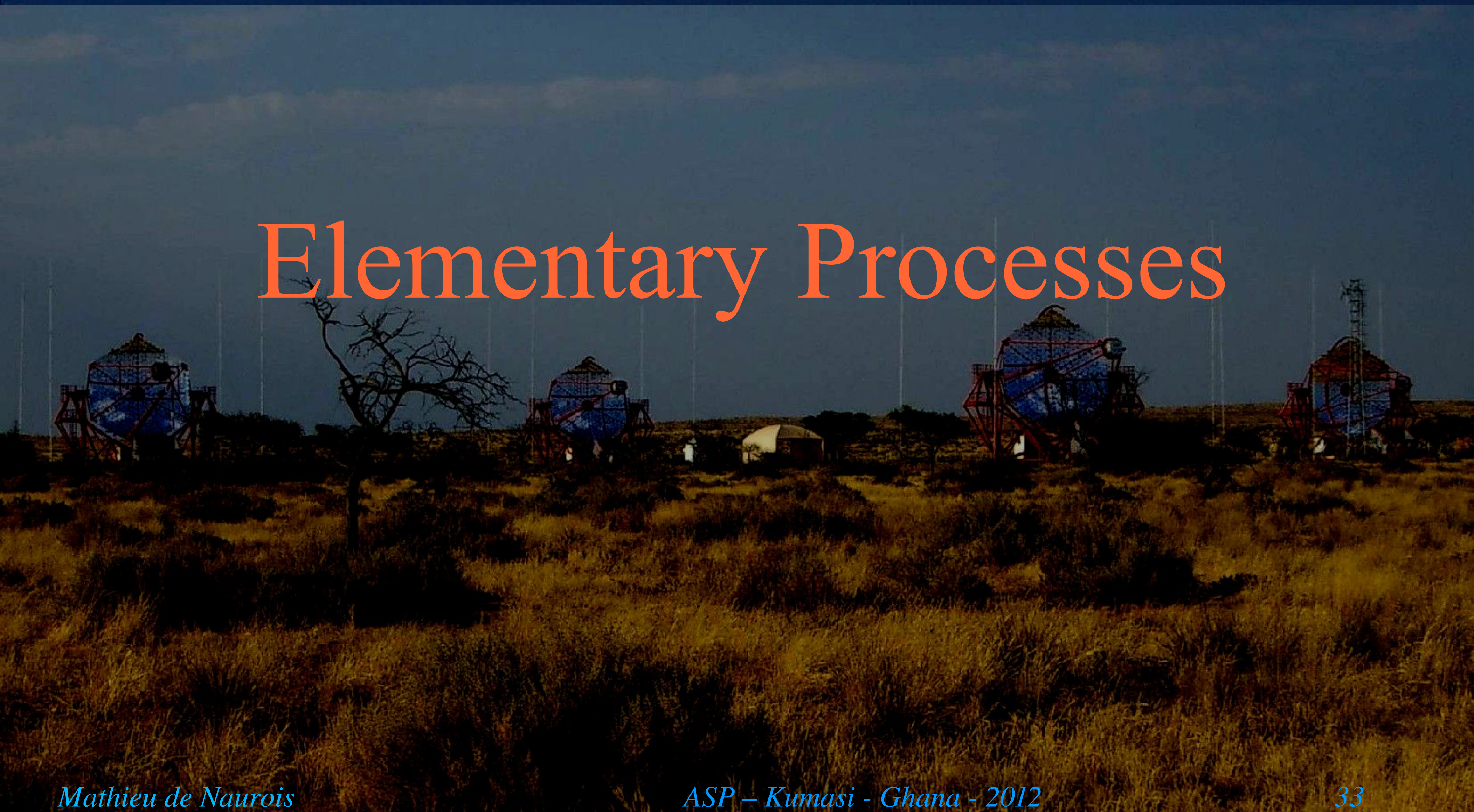
Deep water or ice





Cherenkov Detector

Elementary Processes



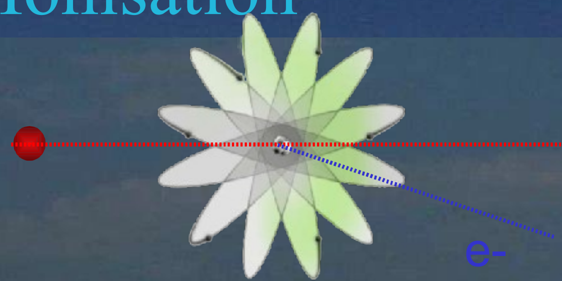
Characterization of primary particles

Mass	m	$[GeV/c^2]$
Electric Charge	$Z\,e$	$[e]$
Speed	$v = \beta c$	$[c]$
Lorentz factor	$\gamma = E/(mc^2)$	
Momentum	$p = mc\,\beta\gamma$	$[GeV/c]$
Rigidity	$R = p\,/\,Ze$	$[GV/c]$
Kinetic Energy	$T=mc^2(\gamma-1)$	$[GeV]$

$R_L = R/B$

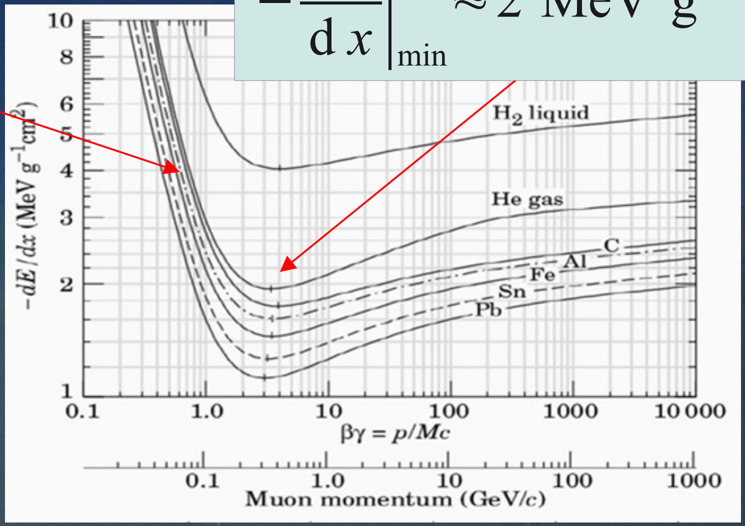
Charged particles

- Ionisation

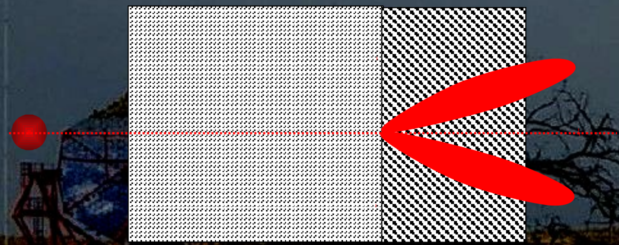


$$-\frac{\mathrm{d}E}{\mathrm{d}x} \propto \frac{z^2}{\beta^2}$$

$$-\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\min} \approx 2 \text{ MeV g}^{-1}\text{ cm}^2$$

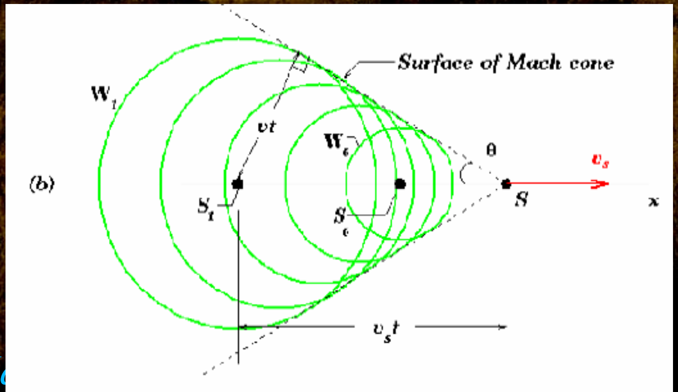


- Transition Radiation



$$W = z^2\gamma\,\frac{\alpha\,\hbar}{3} \times \frac{\left(\omega_{p,1} - \omega_{p,2}\right)^2}{\omega_{p,1} + \omega_{p,2}}$$

- Cherenkov Radiation



$$\cos\theta_c = \frac{1}{\beta\; n}$$

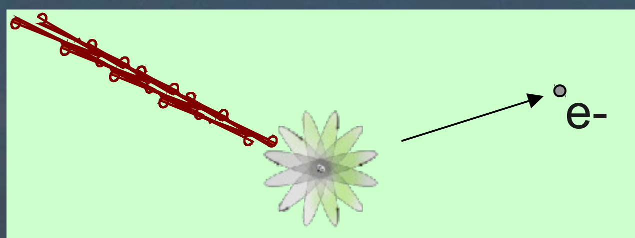
$$\frac{\mathrm{d}^2 N}{\mathrm{d}\lambda\,\mathrm{d}l} = \frac{2\pi\,\alpha}{\lambda^2} \times Z^2 \sin^2\theta$$

Detectors and observables

Detector	Observable	Link with particle
Magnetic Spectrometer	Rigidity and charge sign	pc / ze
Time Of Flight (TOF)	Speed/c	β
Proportional counters Scintillators Ionization Chambers	Ionisation	$dE/dx = z^2 f(\beta)$
Cherenkov Detector	Density of Cherenkov photons	$dN/dx = z^2 g(\beta)$
Transition Radiation	X-ray photons density	$N = z^2 h(\gamma)$
Calorimeter	Deposited Energy	$mc^2(\gamma-1)$

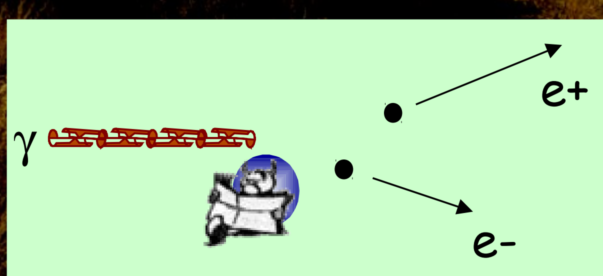
Detection of photons

- Photons cannot be directly detected:
  $\Rightarrow$ Production of charged particles
  - Photoelectric effect



  - Compton Scattering

  - Pair creation



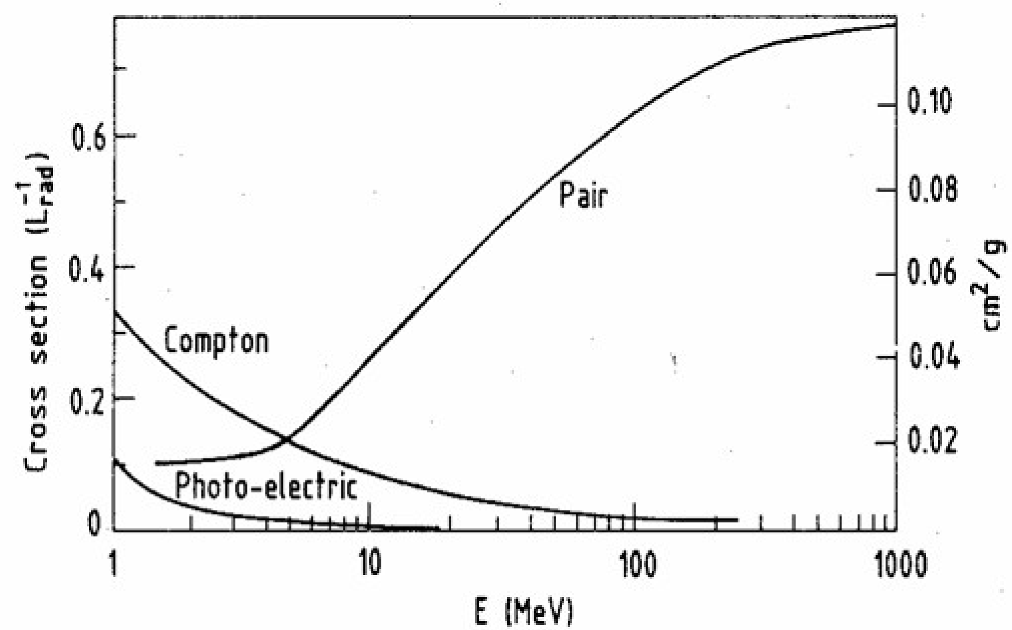


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

Charged Cosmic Rays

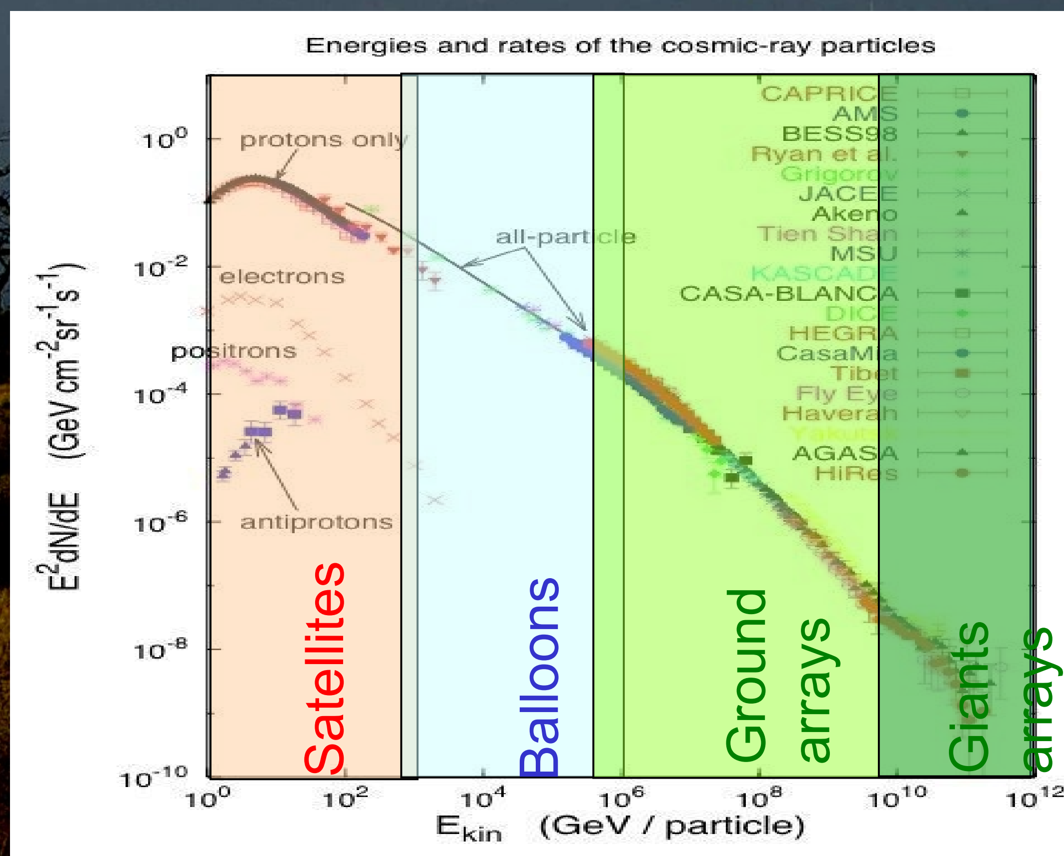
Current experiments

Balloons	Satellites	Ground Arrays

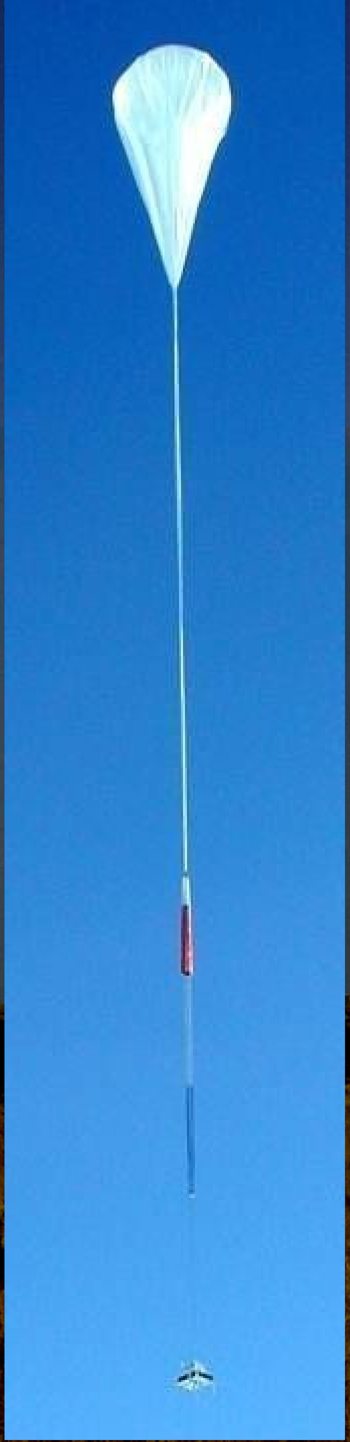
- CREAM
- ATIC
- Tracer
- TIGER
- BESS-Polar
- PPB-BETS
- …..

- Pamela
- AMS

- HESS
- Tibet Array
- Kaskade

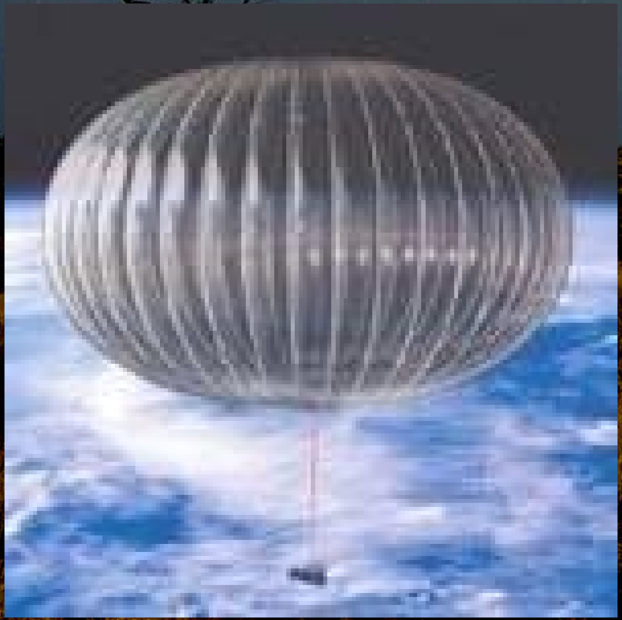


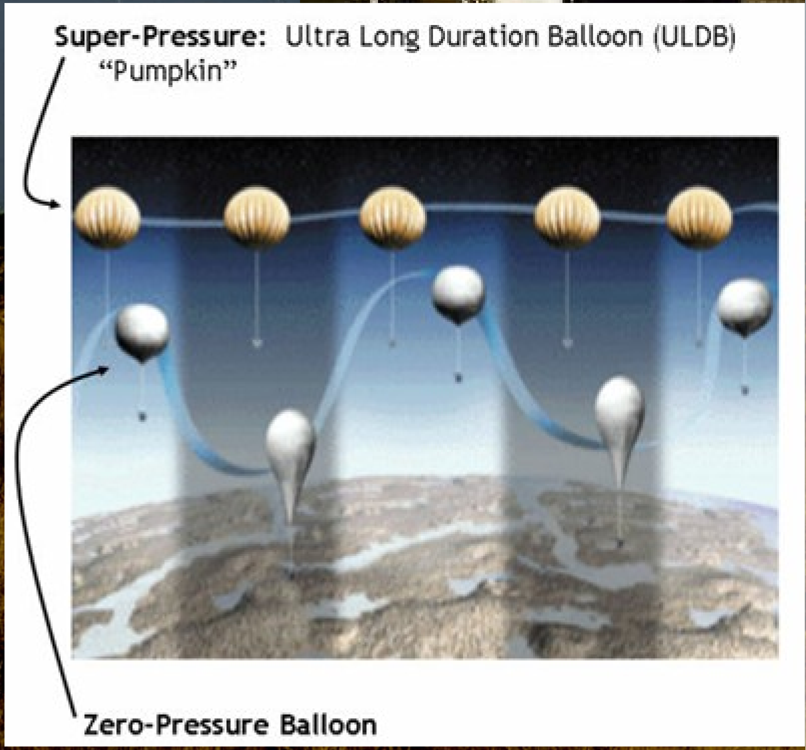
Stratospheric Balloons



Why Balloons?

- Short time scale: ~6 months
- Cost << satellite
- Supply recovery
- Ultra Long Duration Ballooning Program:
  - A few tons
  - Several Months
  - Better controlled altitude

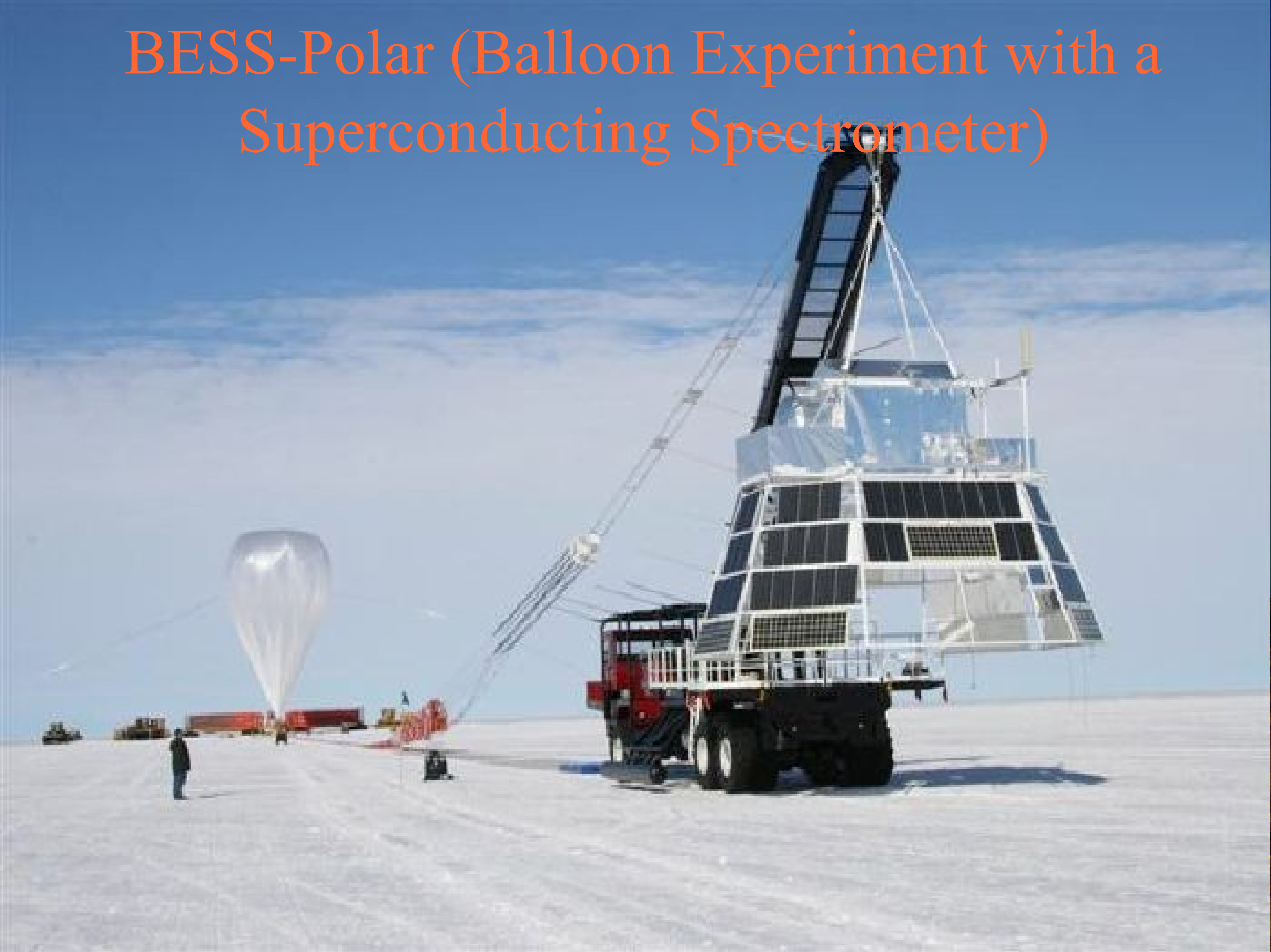




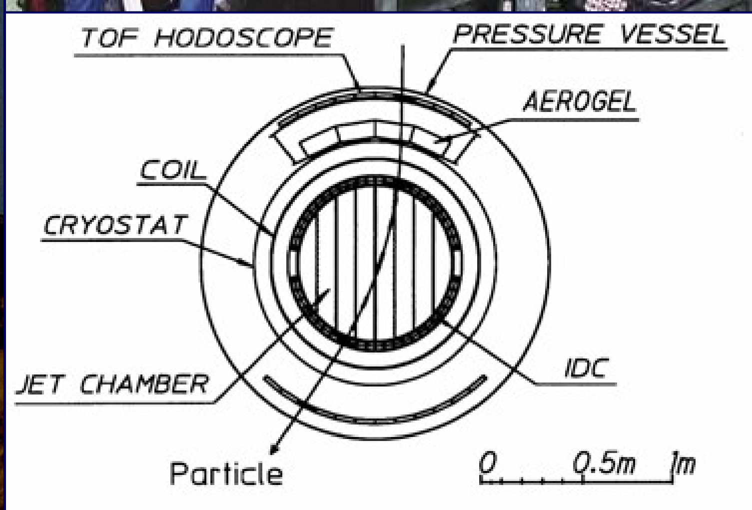
Easy detector recovery...

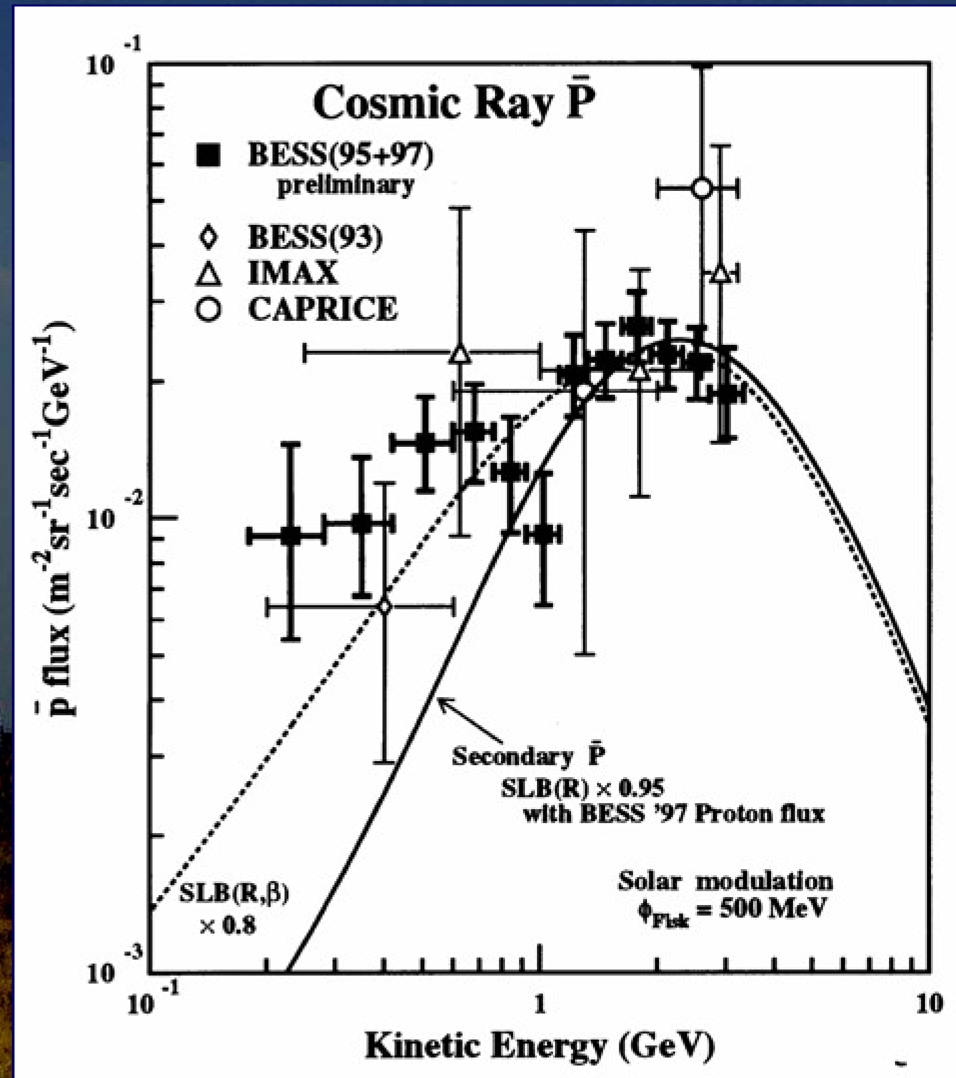
Or less easy...

BESS-Polar (Balloon Experiment with a Superconducting Spectrometer)



BESS (the Balloon-borne Experiment with a Superconducting Solenoidal magnet)





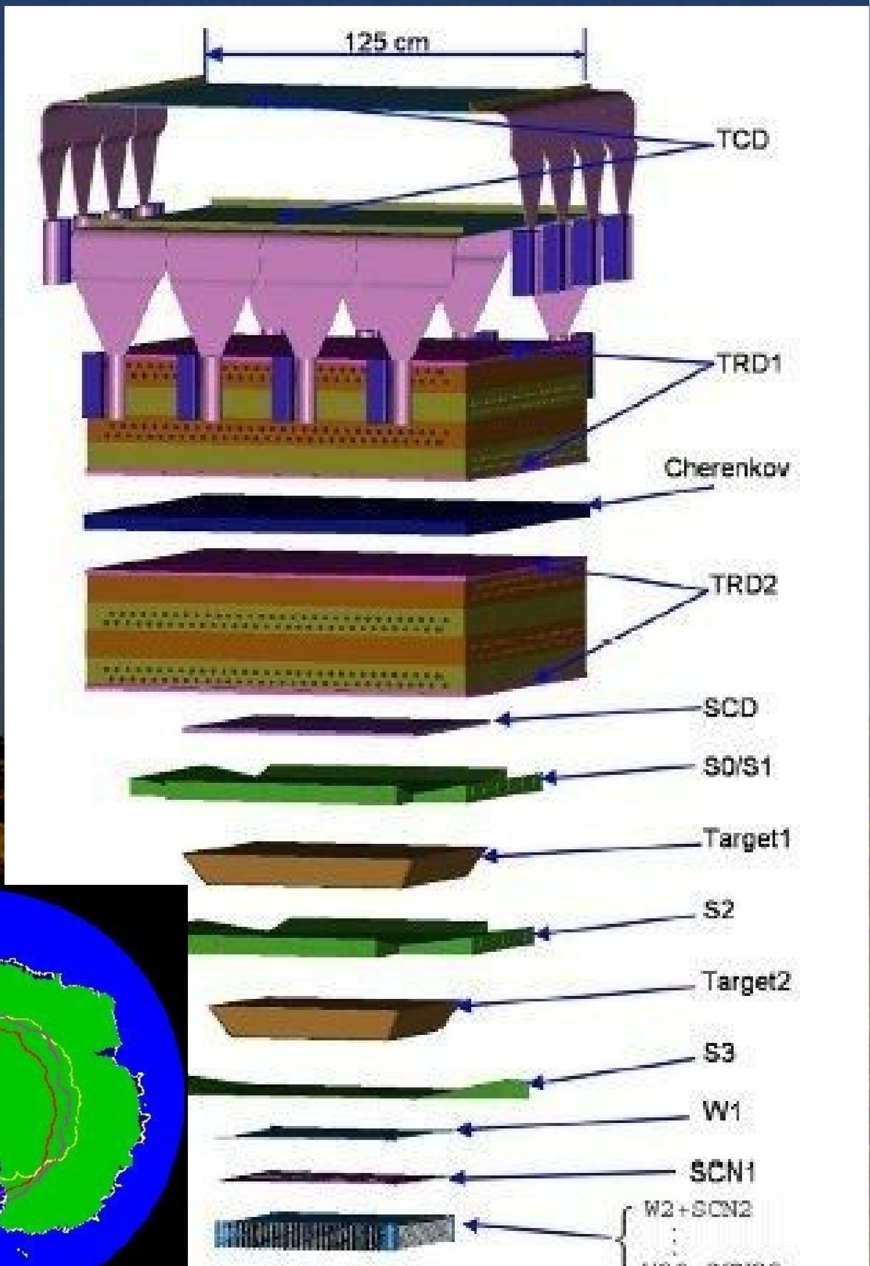
- Search for antimatter (antiprotons, antihelium) and measurement of light isotopes

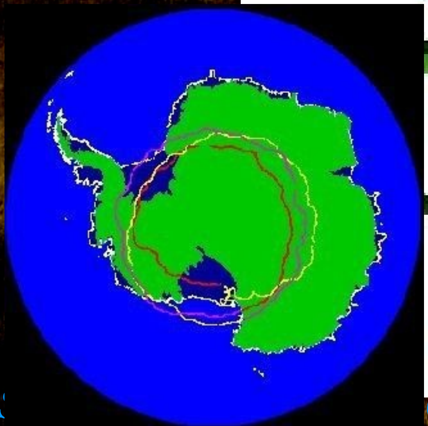
CREAM , long duration flights
E: 10^{12} to 5×10^{14} eV , 2004, 2005, 2007

CREAM

Cosmic Ray Energetics and Mass

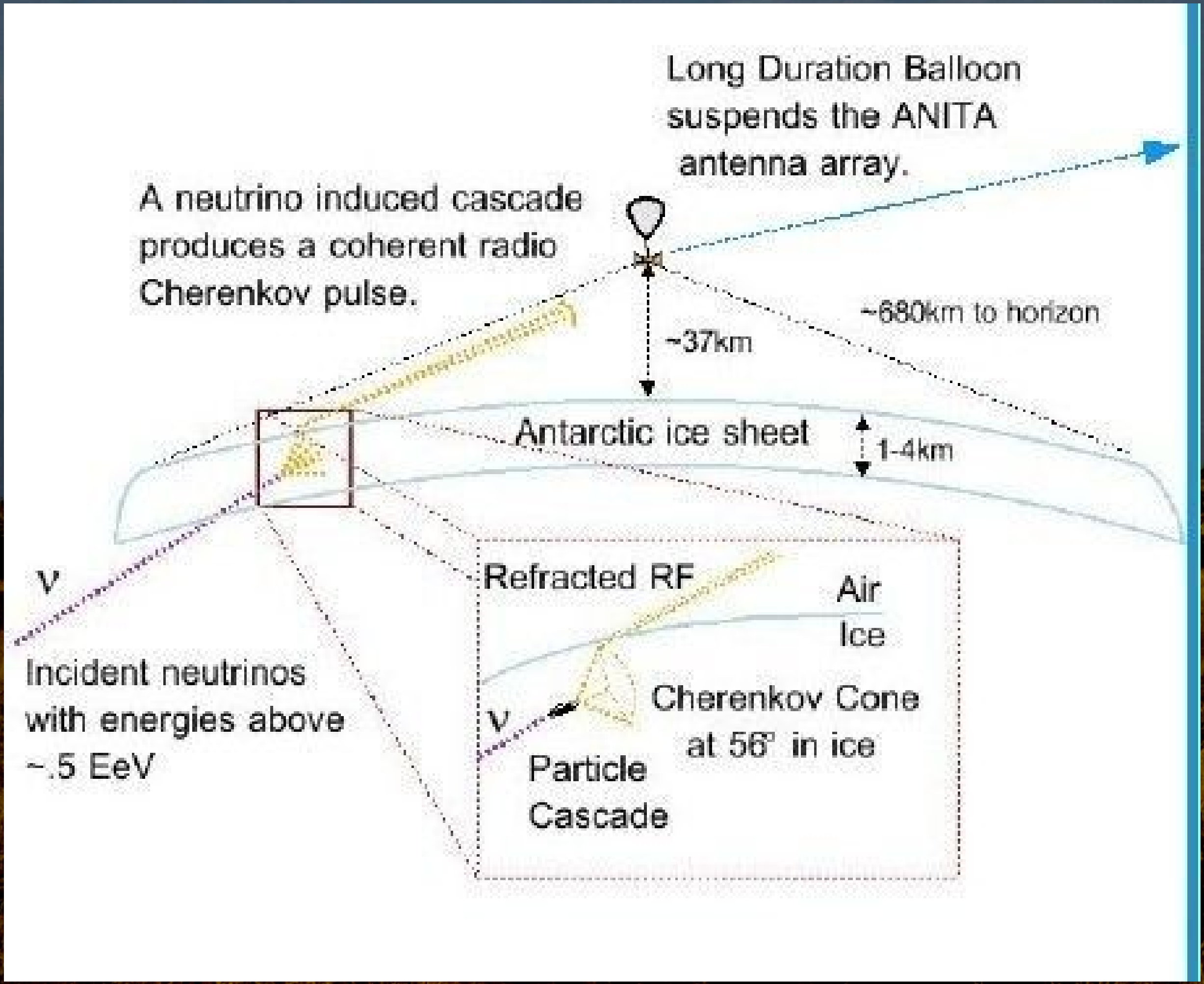
- Composition and spectrum of high energy cosmic rays (TeV to ~500 TeV)
- Acceptance : 2,2 m^2 sr
- Energy measurement :
  - Thick calorimeter 20 X_0 (W + fibres)
  - Transition radiation detectors
- Identification :
  - Transition radiation detectors
  - Ring Imaging Cherenkov « CHERCAM » similar to AMS-2
- Flight V: 12/01/2009 ⇒ 01/06/2010



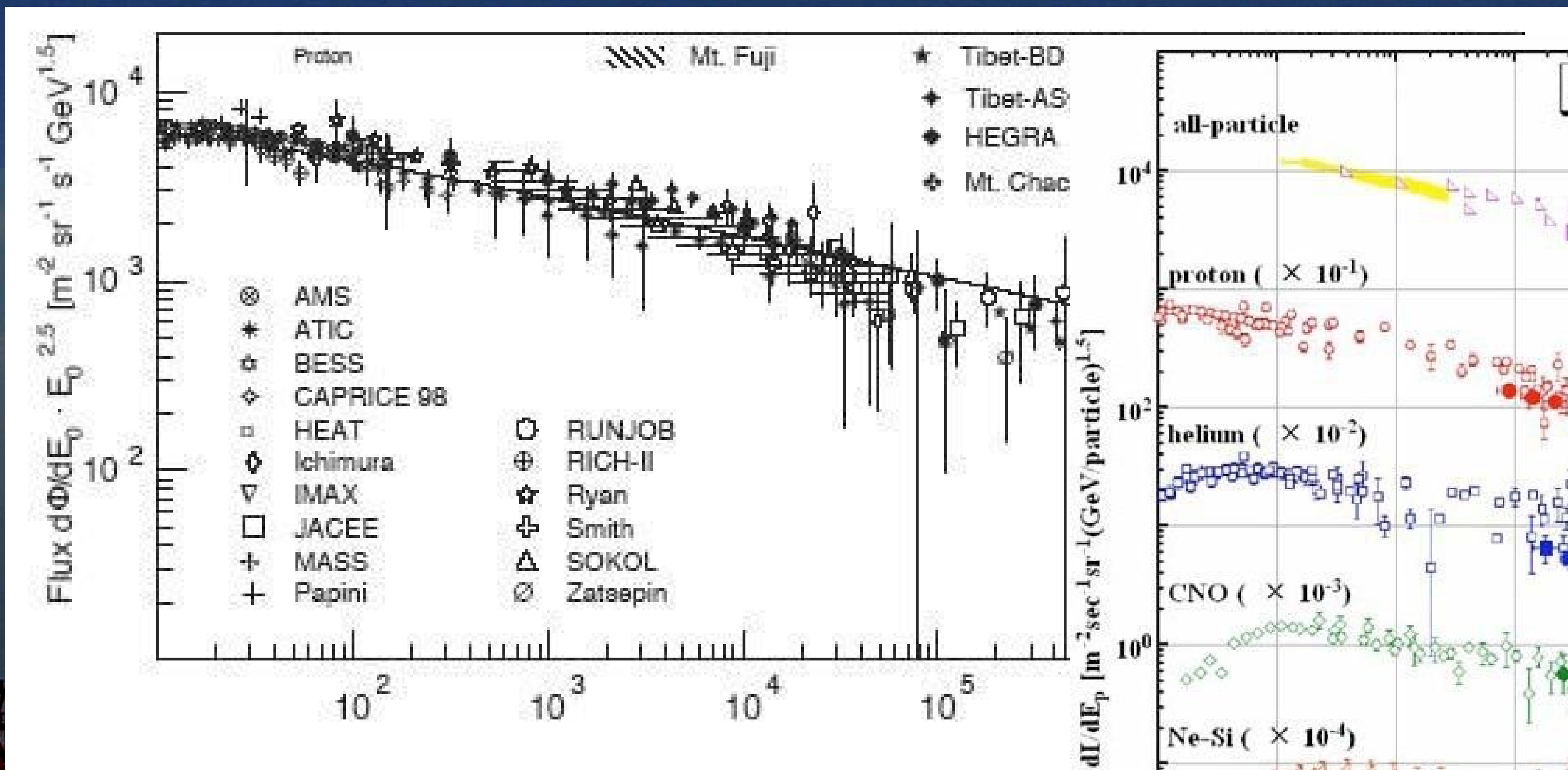


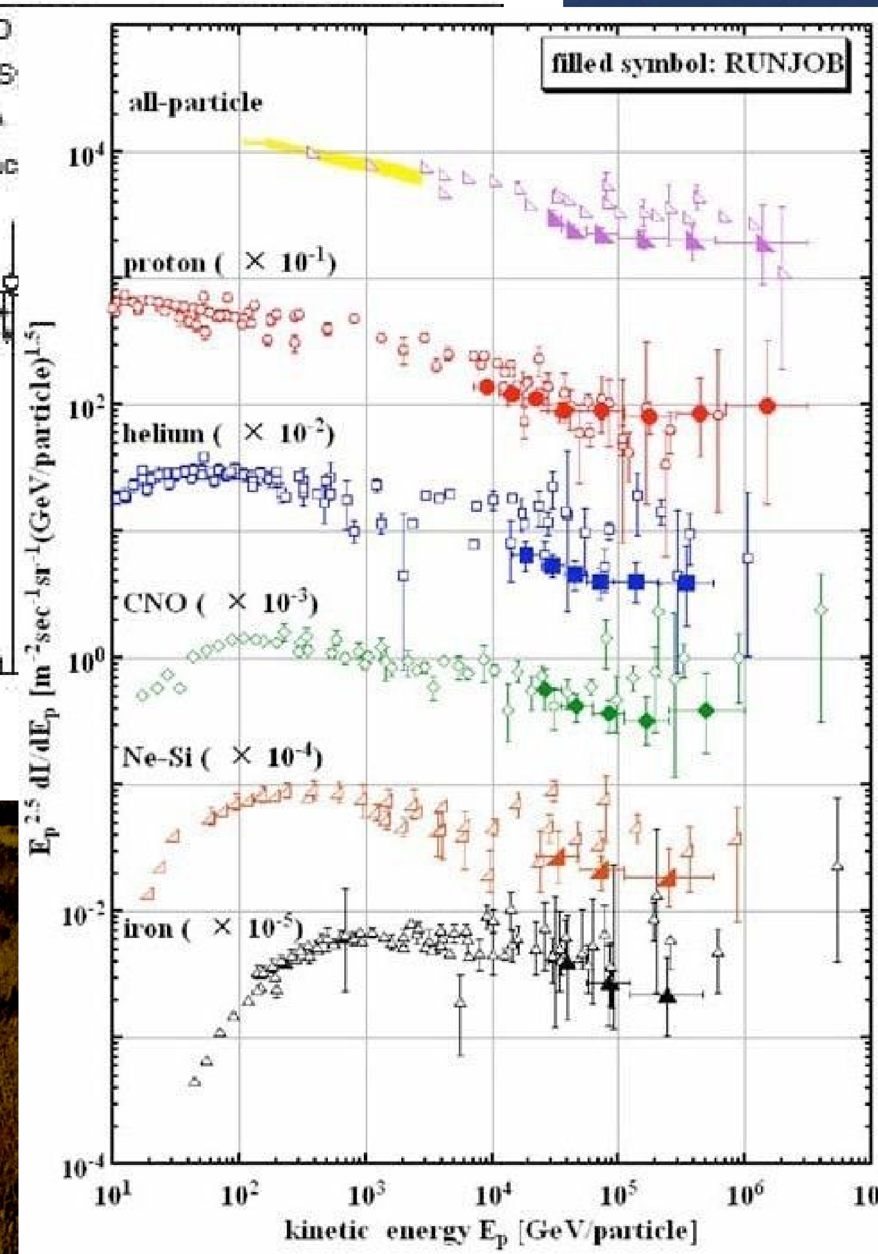
ANITA

- Radio detection of earth skimming neutrinos...



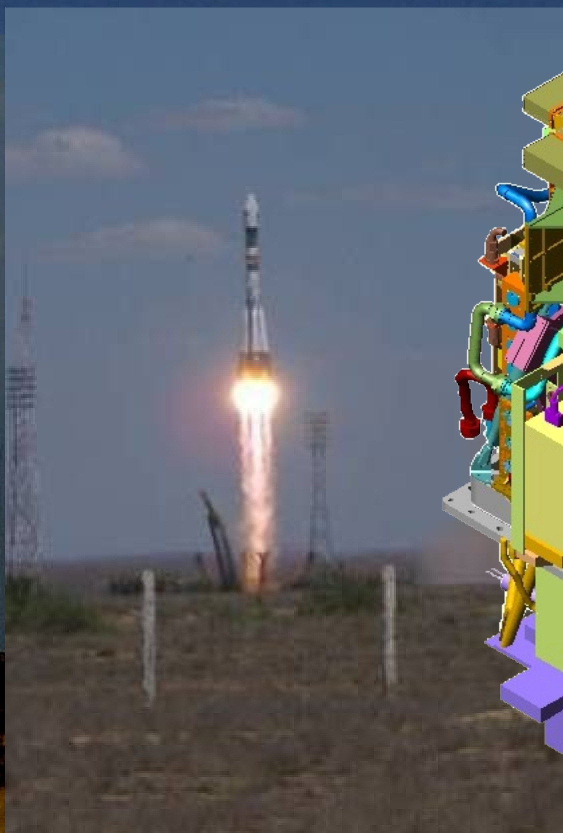
Balloon experiment results

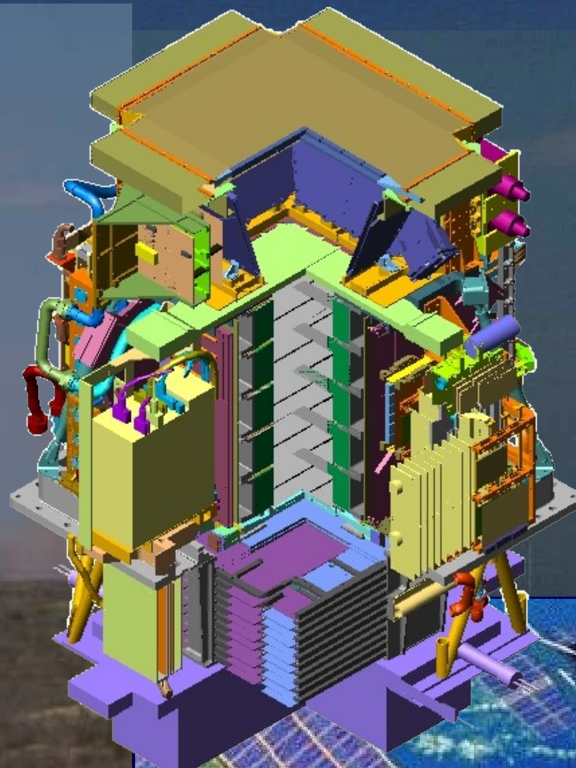


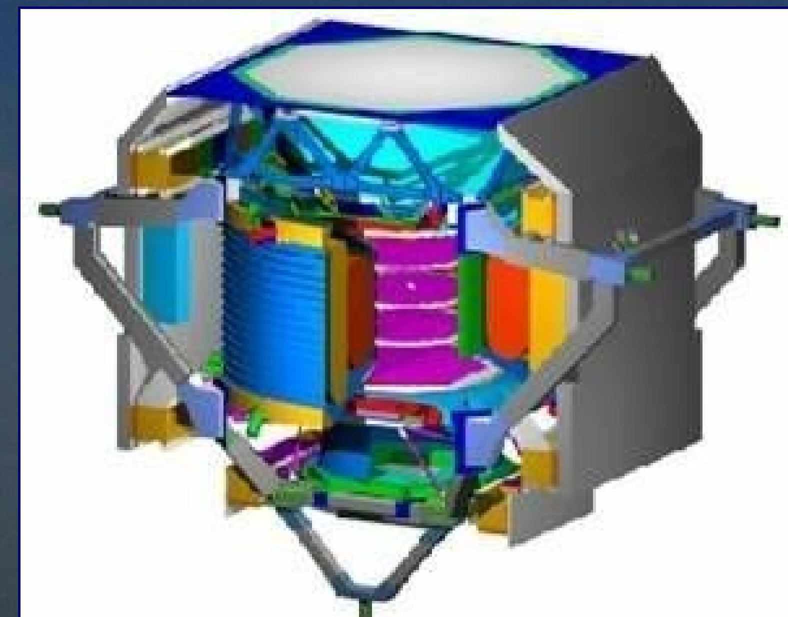


- All particle spectra
- Composition resolved spectra

Satellites

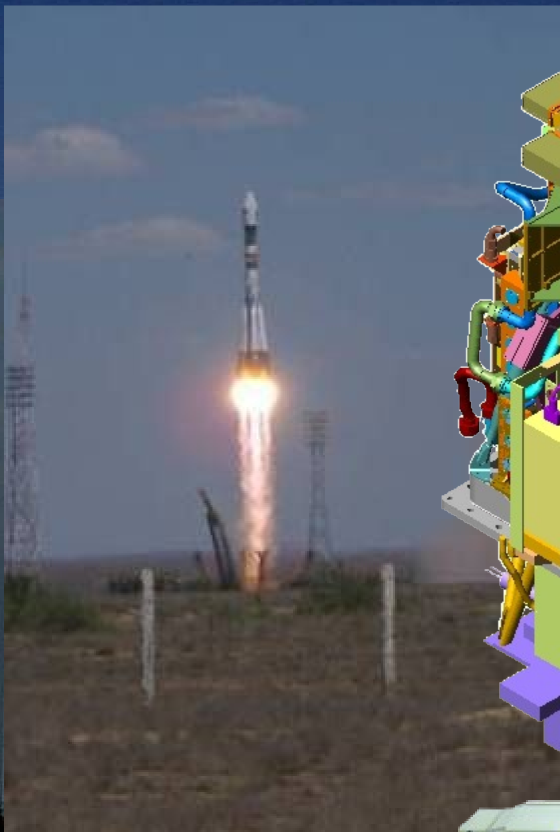




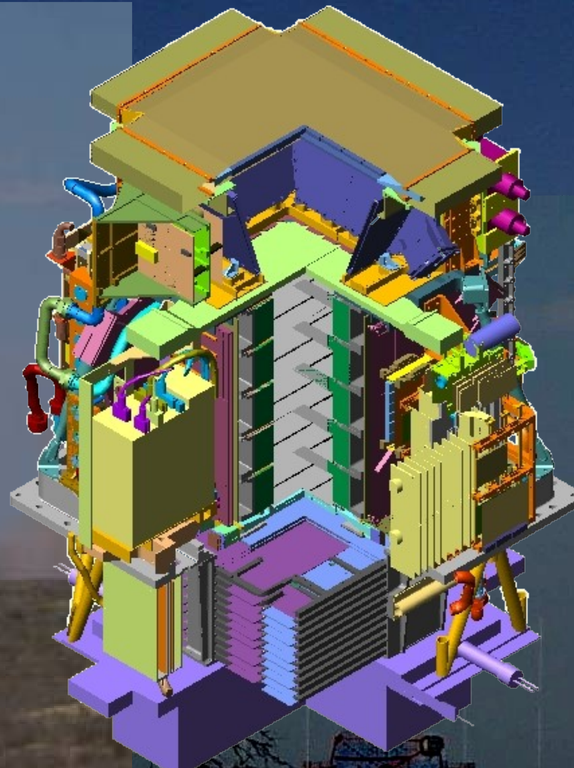


PAMELA

Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics



15th June 2006



- Search for:
  - antimatter in cosmic rays
  - Dark matter annihilation signatures (e+ & antiprotons spectra)
  - Primary anti helium
- Composition & spectrum of cosmic rays, propagation studies
- Sun & Earth magnetospheres

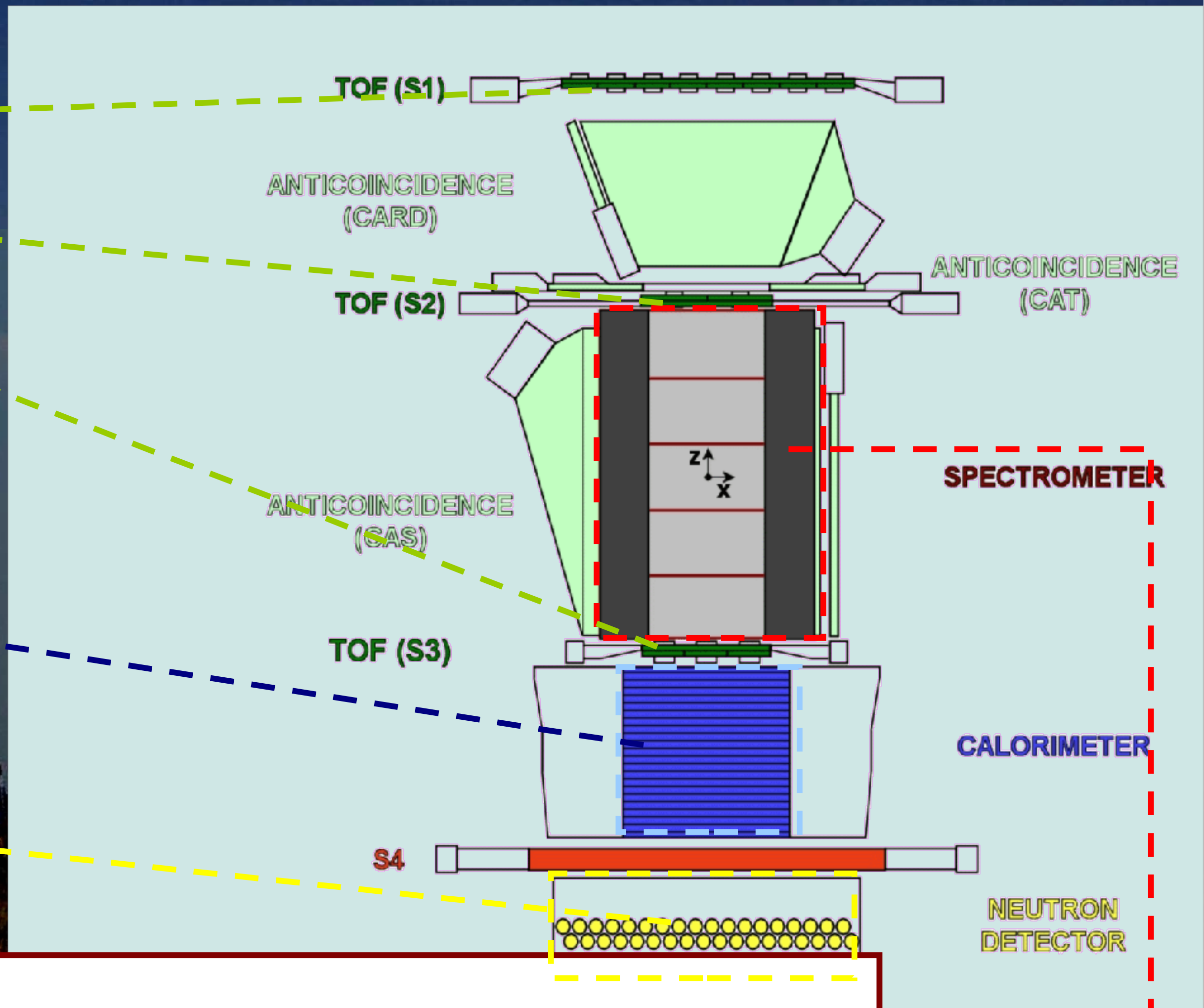
Particle	Energy	Particle	Energy
p	< 1 TeV	e-	< 800 GeV
Antiprotons	< 100 GeV	e+	< 100 GeV
D,3He	<1GeV/nuc	Elements Z≤6	<500 GeV/nuc

PAMELA

<u>Time-Of-Flight (TOF)</u>
plastic scintillators + PMT:
- Trigger
- Upward-going rejection
- Mass identification up to 1 GeV
- Charge value from dE/dL

Electromagnetic calorimeter
W/Si sampling (16.3 X_0, 0.6 λ_I)
- Discrimination e^+ / p, p-bar / e^- (shower topology)
- Direct E measurement for e^-/e^+

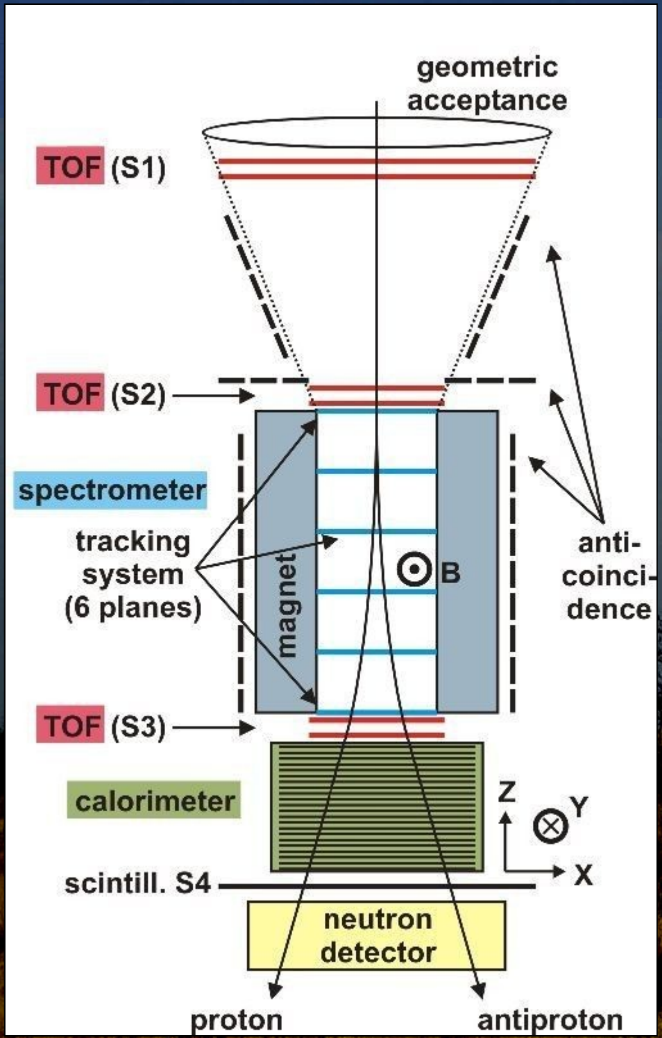
Neutron detector
polyethylene + ^{3}He counters:
- High-energy e/h discrimination



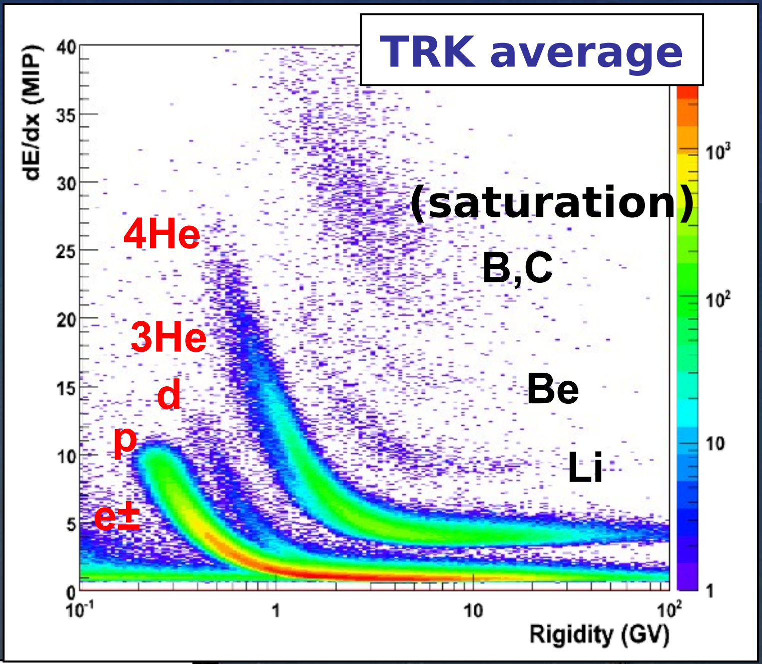
GF: 21.6 cm² sr
Masse: 470 kg
Taille: 130 · 70 · 70 cm³
Consommation: 360 W

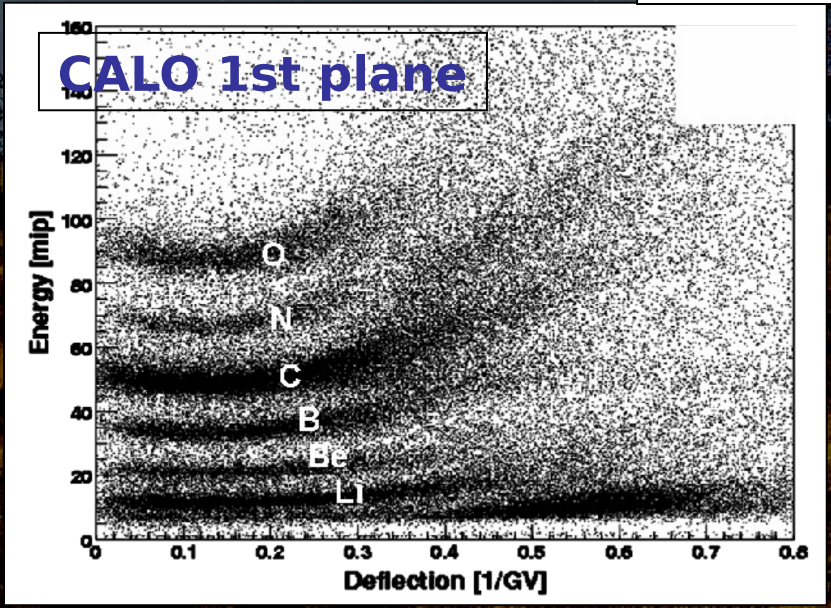
Spectrometer
microstrip Si tracking system (TRK) + permanent magnet
6 plans
- Charge sign (particle/antiparticle discrimination)
- Momentum
- Charge value from dE/dL
- 6 planes of double-sided (X-Y) microstrip Si sensors.
- Spatial resolution: 3÷4 mm.

Particle Identification



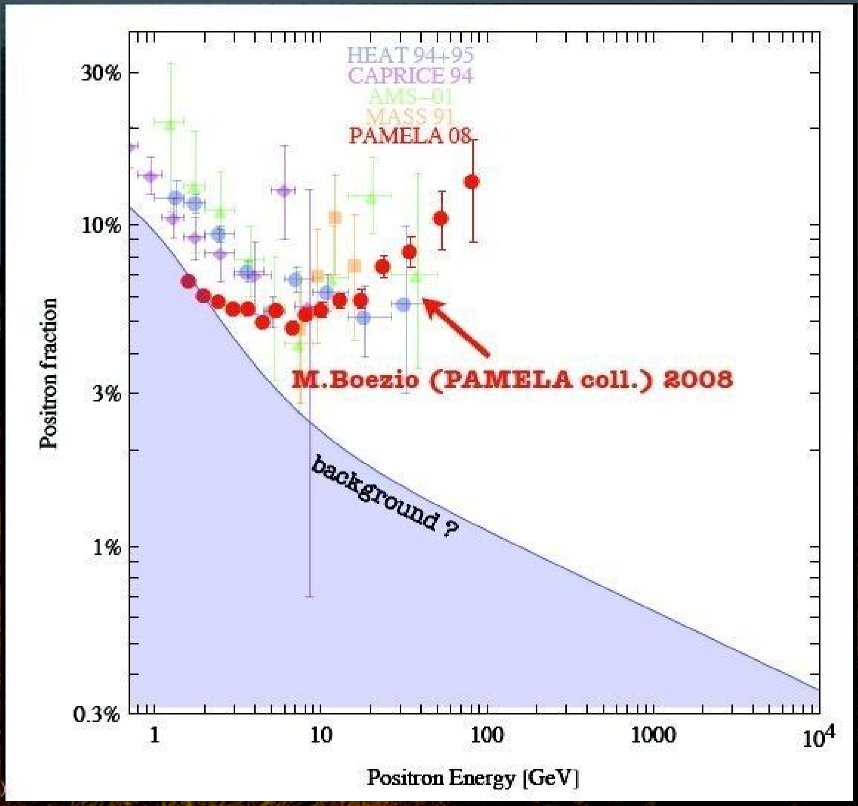
- Rigidity (p/Ze) from tracker
- dE/dx or E from time-of-flight or calorimeter
- Redundancy

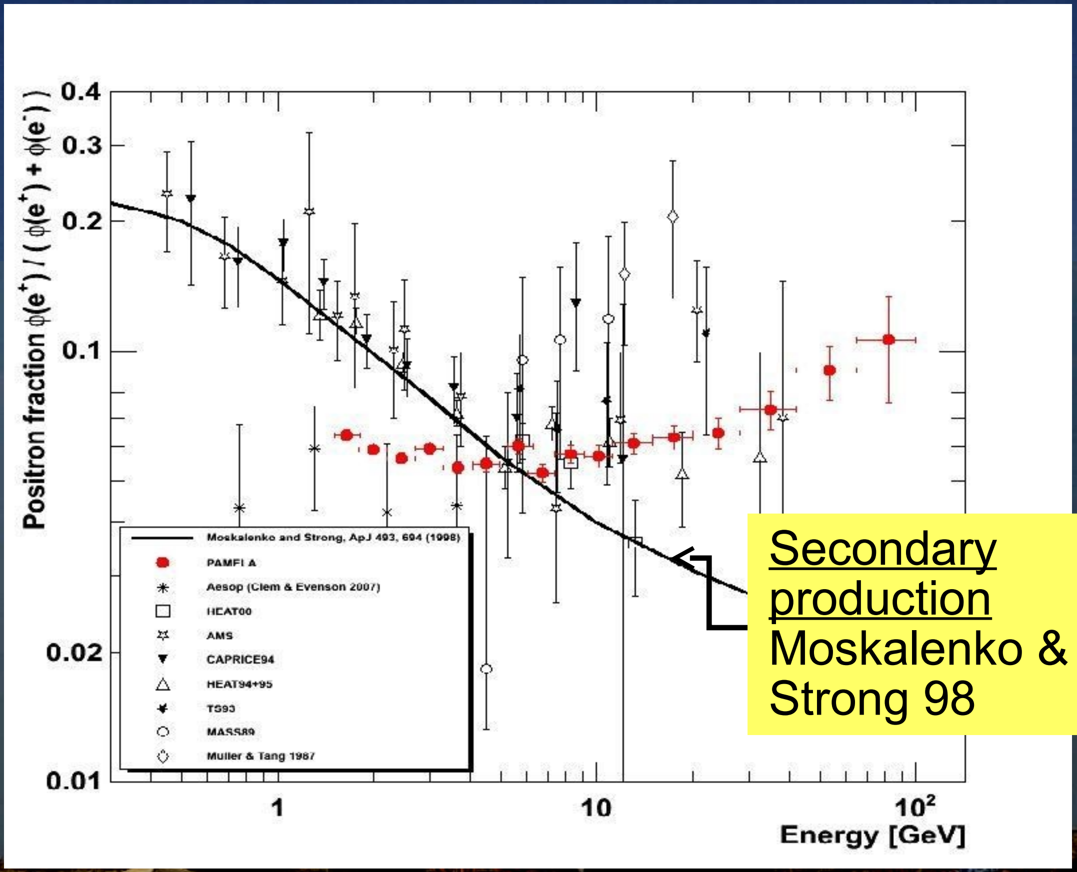




Positrons fraction (very hot topic)

- ~ 10 000 e+
  - Improvement of uncertainties compared to previous exeriments.
  - Up to 100 GeV

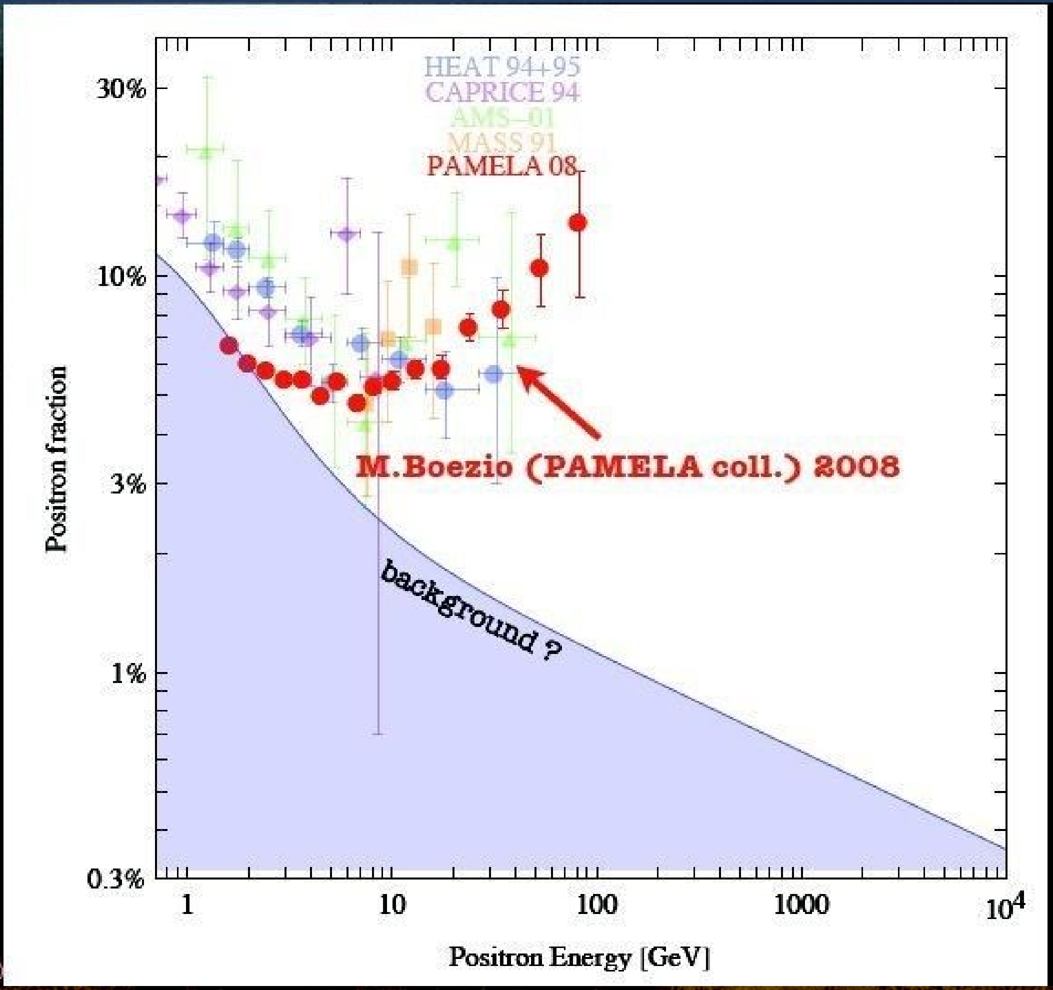


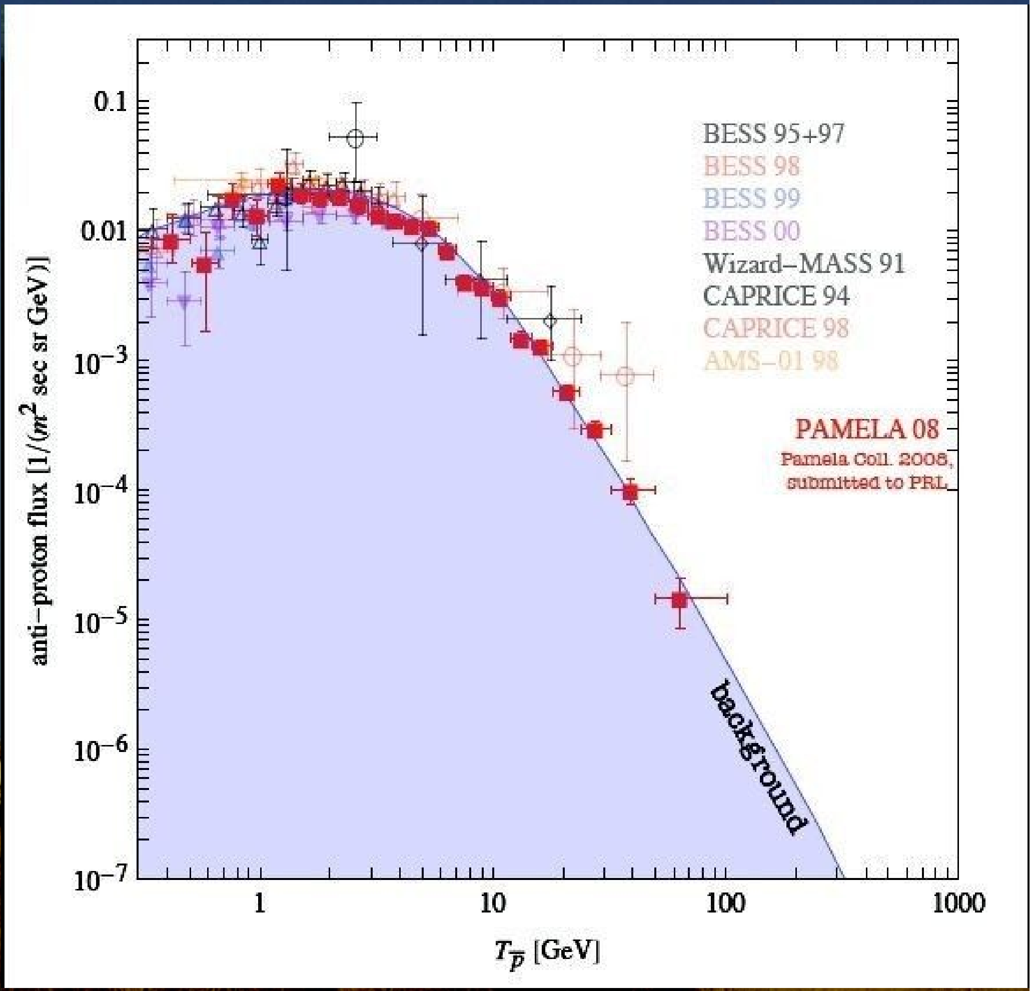


Secondary production Moskalenko & Strong 98

- Above expected background (secondary e+)
- Nearby source (pulsar)?
- Dark Matter?
- Or unknown propagation effect?

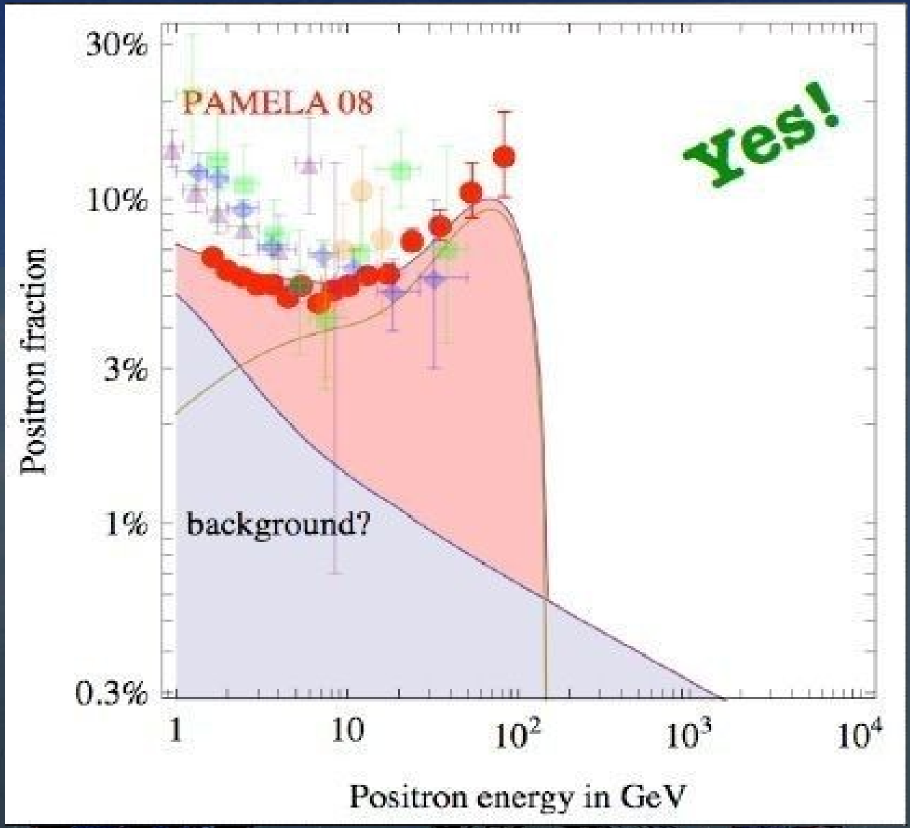
positrons & antiprotons

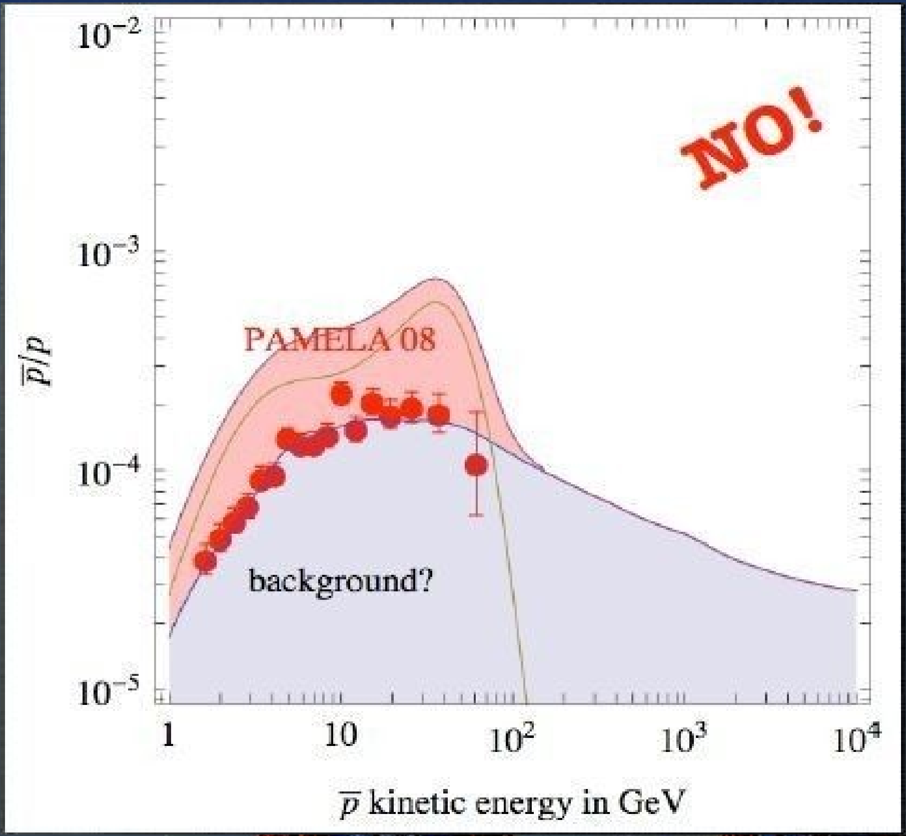




- Antiprotons flux compatible with propagation model
- Positron fraction is not

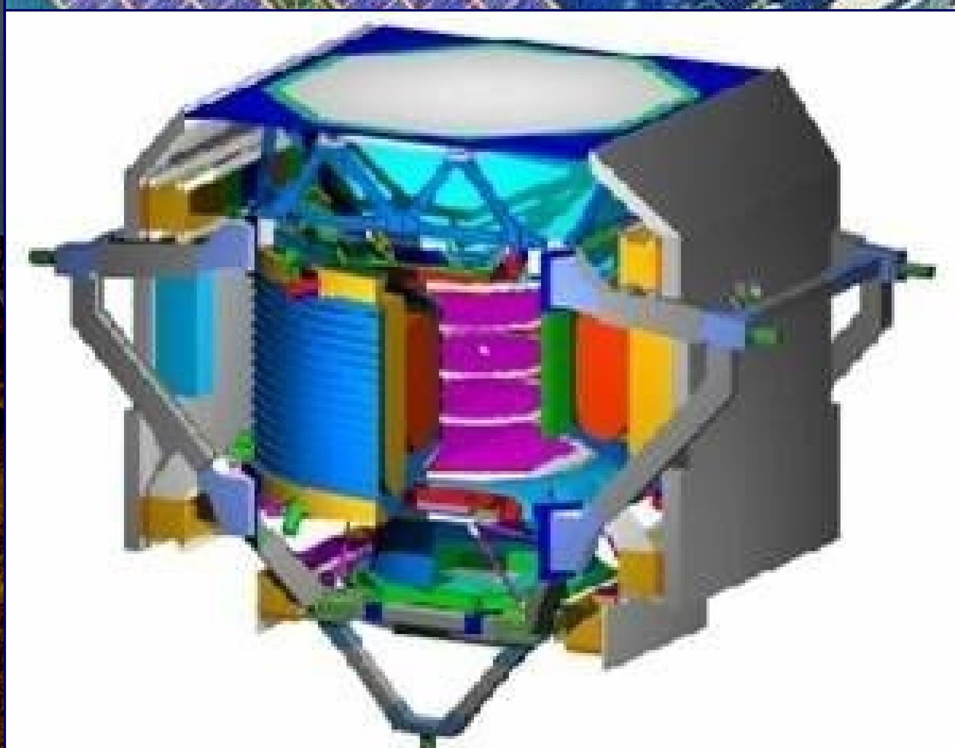
Dark Matter ?

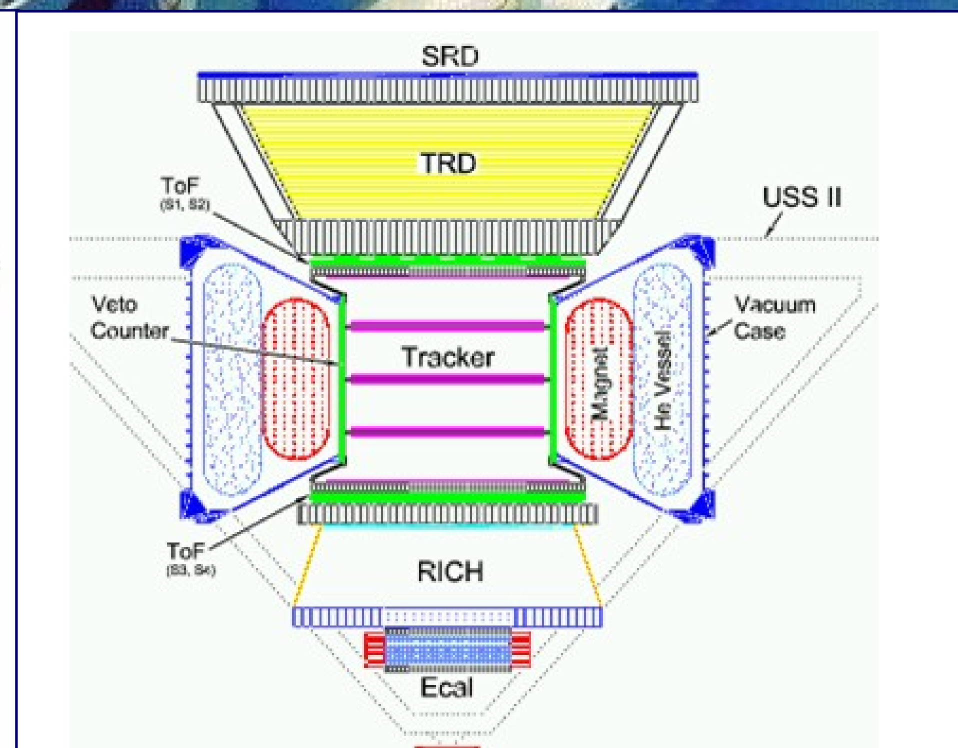




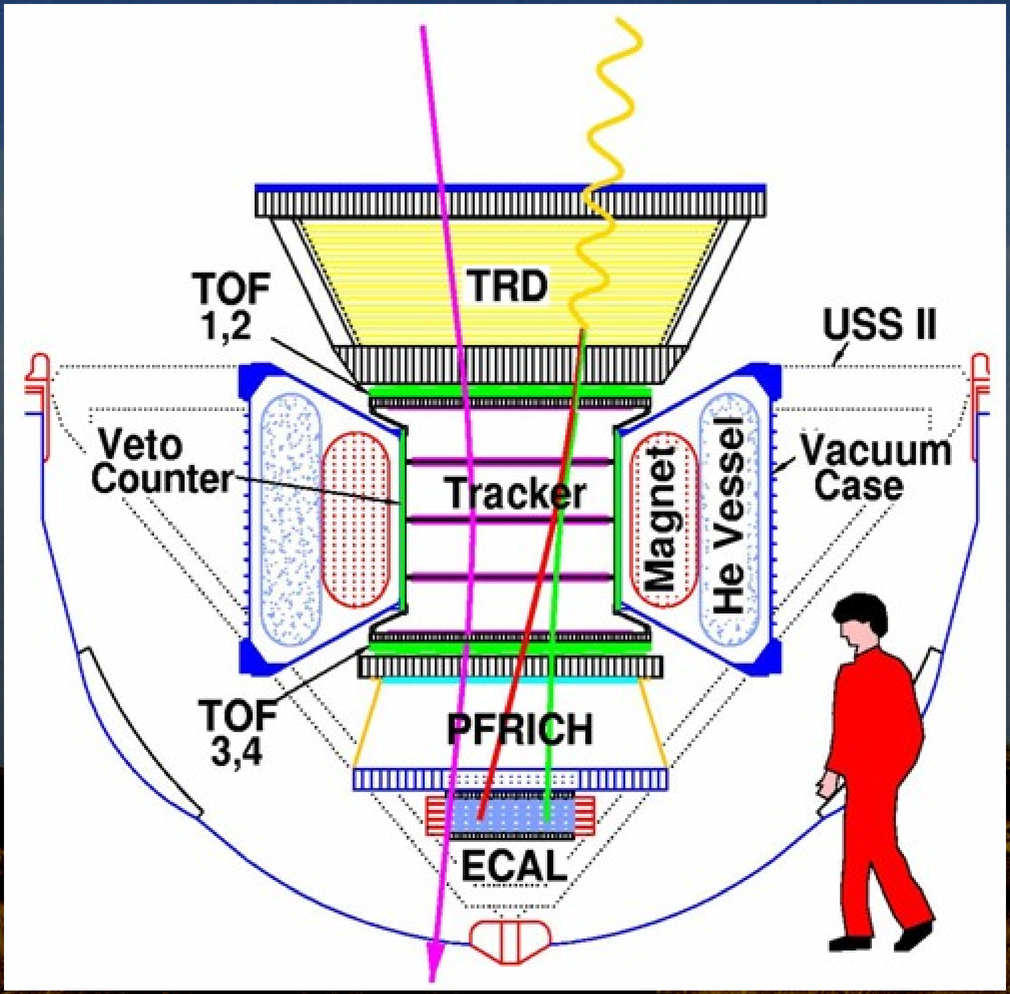
- Positron excess compared to diffusion models, antiprotons shows no excess
- A wino (ω ω → W+ W-) at 150 GeV is consistent with positrons excess, but not with anti-protons
- A much higher mass (10 TeV) could fit the data, but conflicts with relic density (factor 1000)
- Possible exotic solution: annihilation into leptons (μ+ μ-), ... many papers

AMS - Alpha Magnetic Spectrometer





AMS



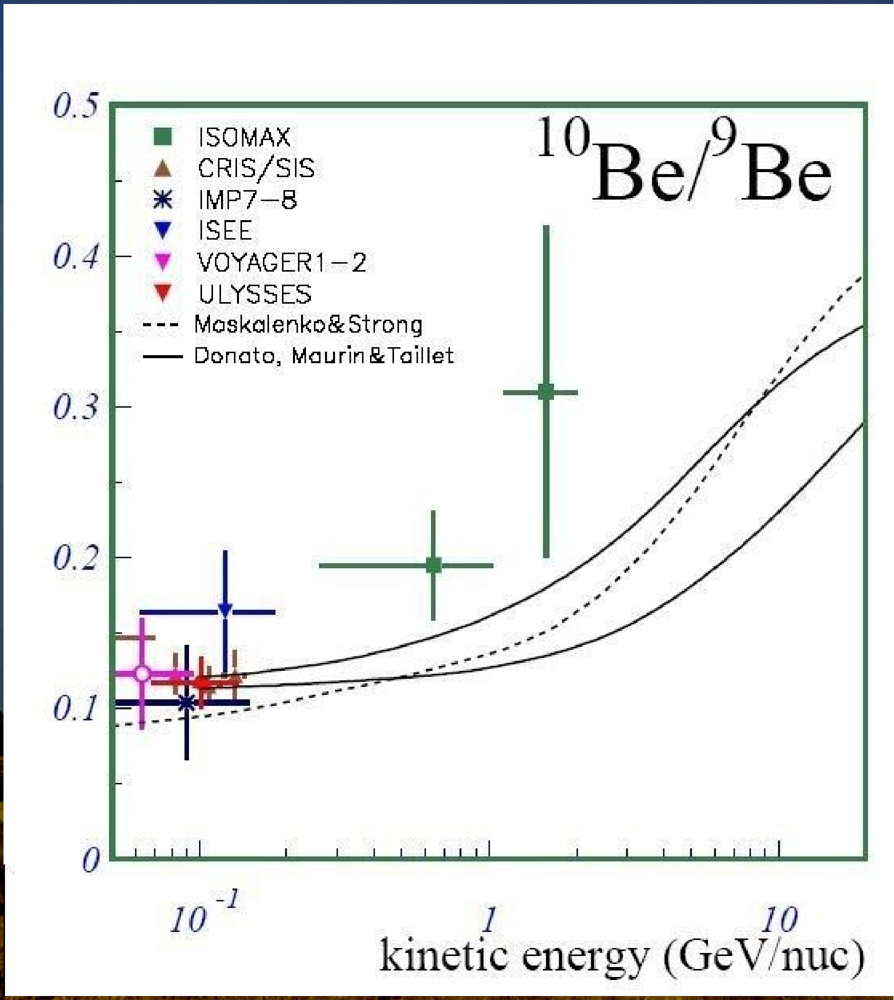
- A real (small scale) particle physics detector
- Spectrum & composition of charged particles from 500 MeV & a few TeV
  - Direct antimatter search (antihelium)
  - Indirect search of dark matter (e+/e-)
- Installed on the ISS in May 2011 (last shuttle flight)

Goals

- Dark-matter (cf Pamela), e^+, $\bar{p}$
- Secondary nuclei:
  - CNO spallation → Li, Be, B
  - Propagation of cosmic rays in the Galaxy
- Cosmic ray clocks – isotopic composition:

  ^{10}Be ($t_{1/2}$~1.5 10^6 ans)

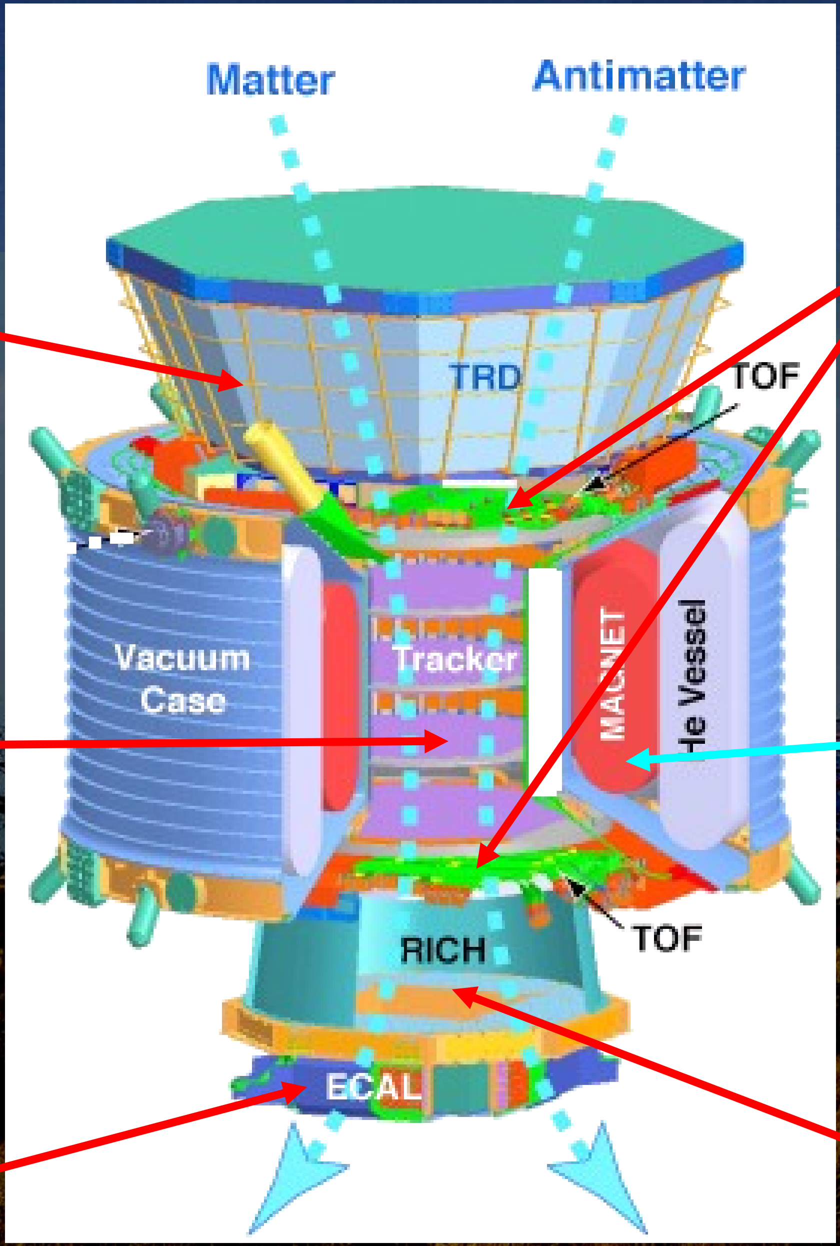
  ^{10}Be/^{9}Be ratio is a measure of time of propagation in the Galaxy
- Current isotopic measurements:
  - Low statistics
  - Only at low energy



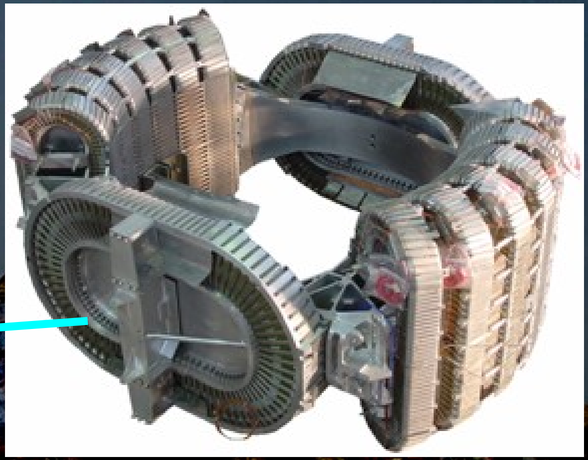
AMS detector

TRD
Discrimination e/p

Time of flight
β, Z



Permanent Magnet



Tracker
Z,R

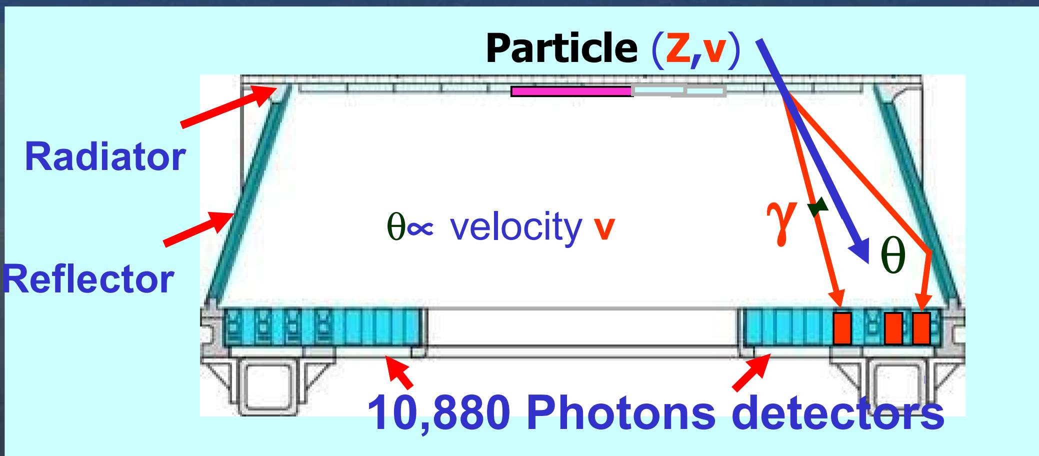
Electromagnetic Calorimeter
Discrimination e/p , E

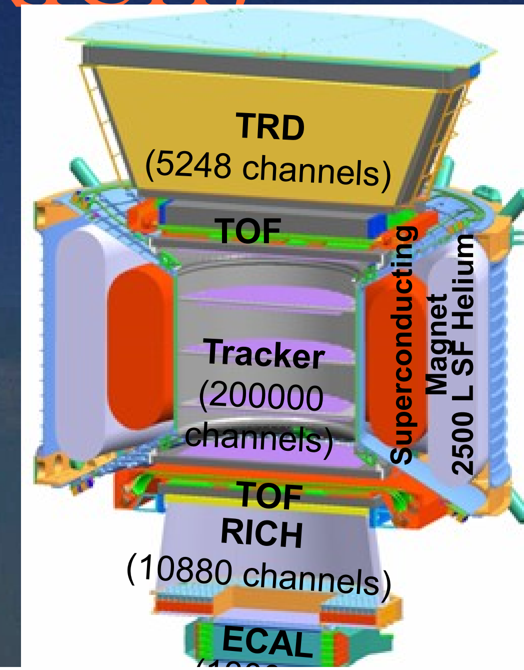
RICH
β, Z

Size: 3m x 3m x 3m
Weight: 7 tons

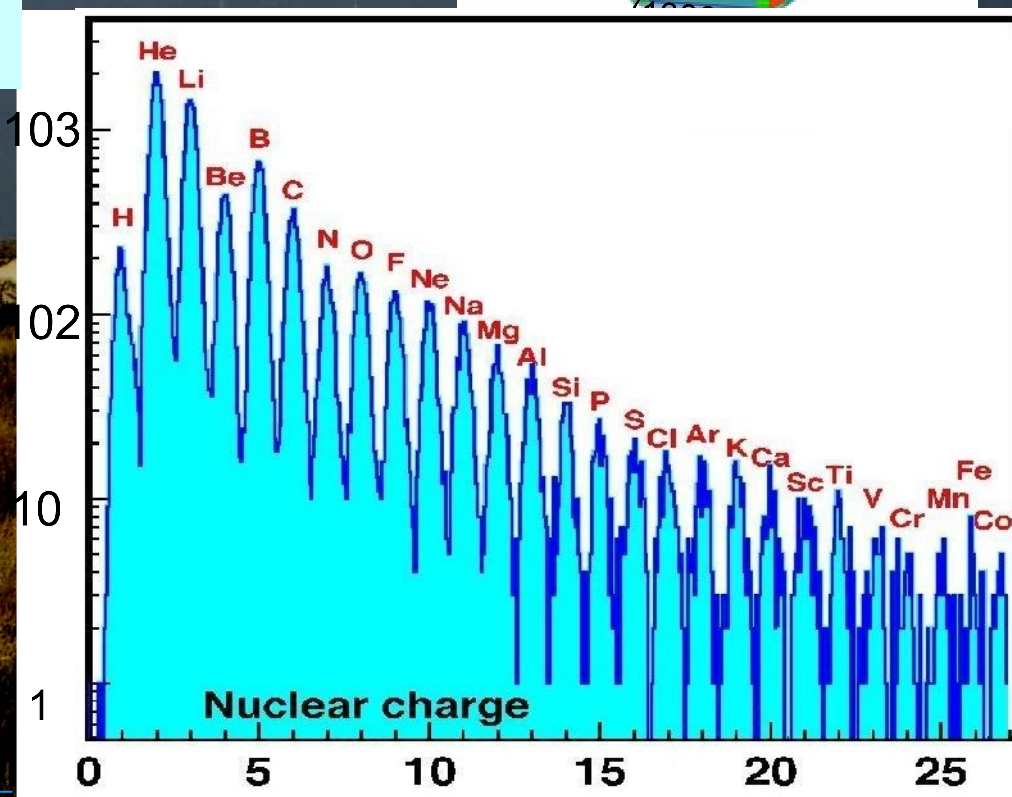
Ring Imaging Cerenkov (RICH)

- Charge measurement ($\sigma(Z) = 0.3$) from photons density



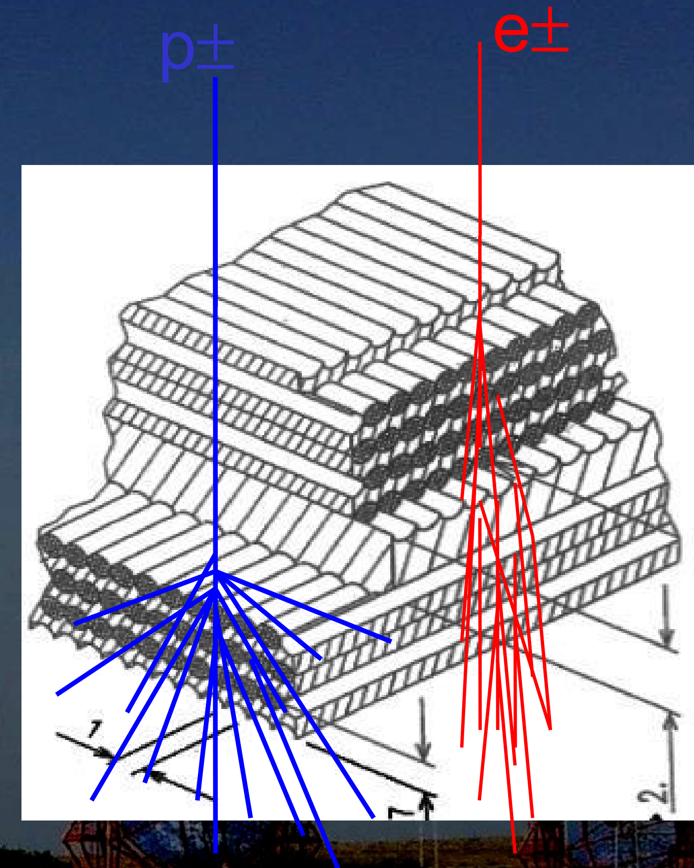


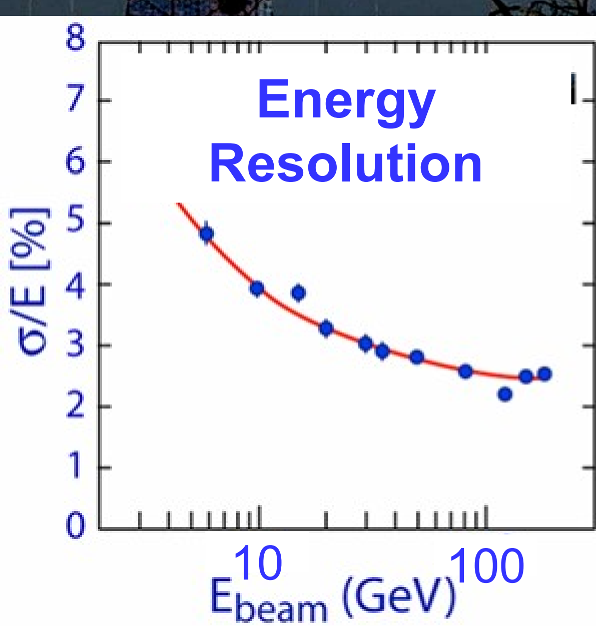
Tests @ 158 GeV/n

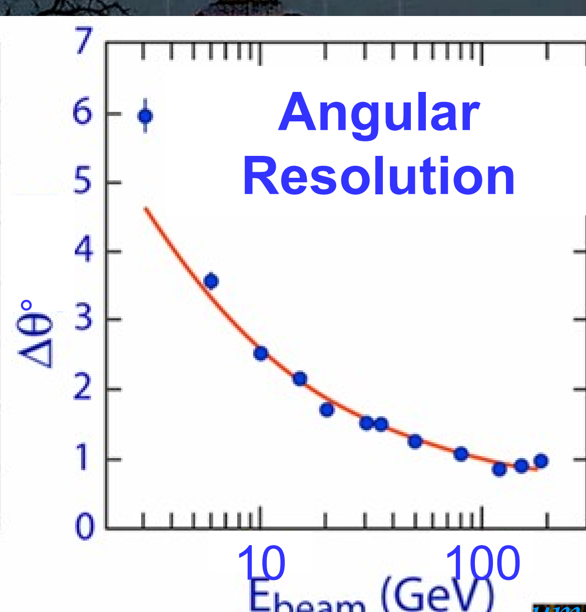


Electromagnetic Calorimeter

- 3D hodoscopic calorimeter
  - 9 super layers of 10 lead/fibres layers
  - Fibres alternated in X/Y
  - PMT readout
  - 16.4 X0 total thickness
  - Energy Resolution: a few %
  - Angular resolution (0.5° – 1°)
  - Rejection p±/e± r=10-3 with 95% efficiency (using shower profile)

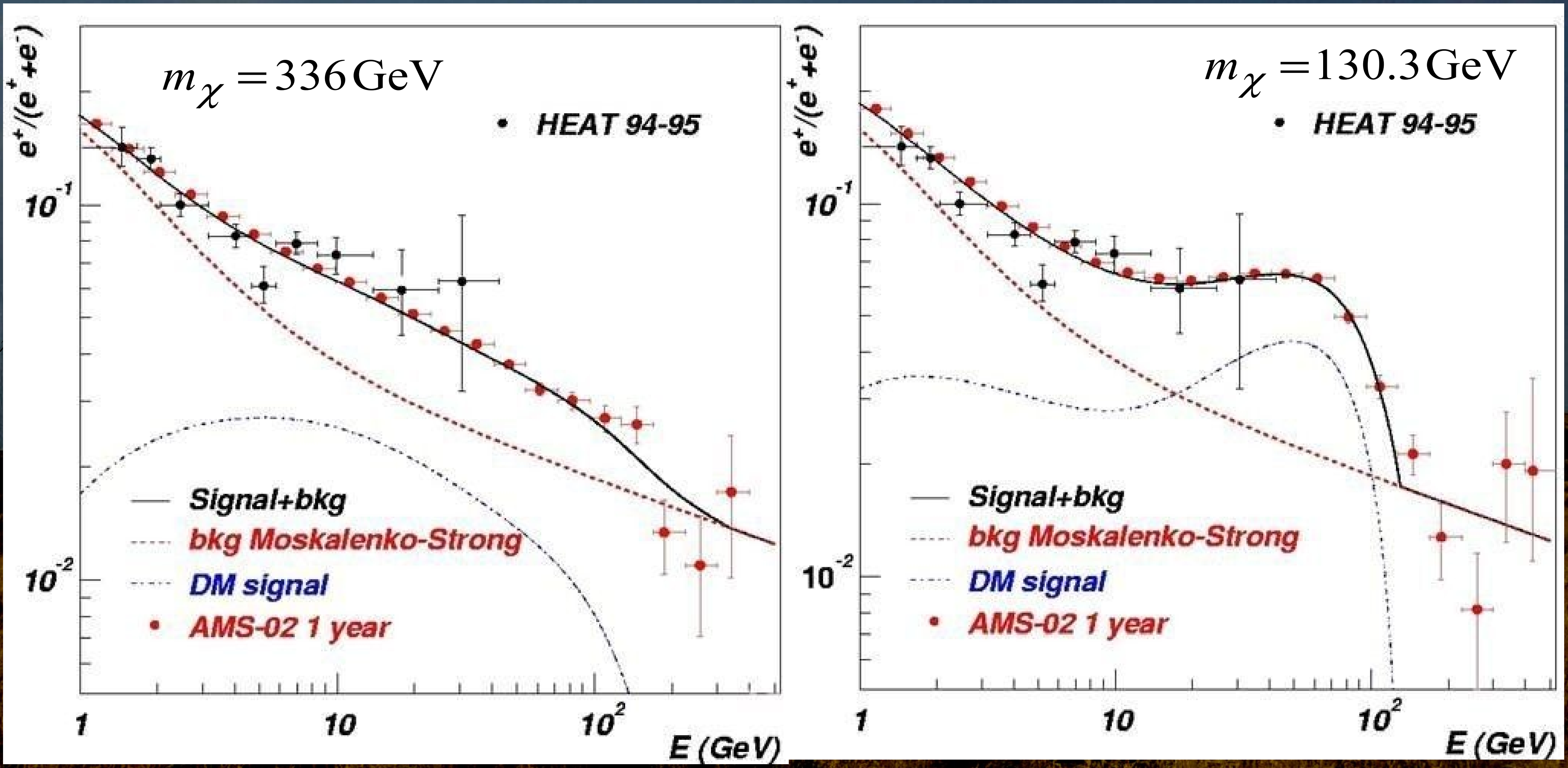


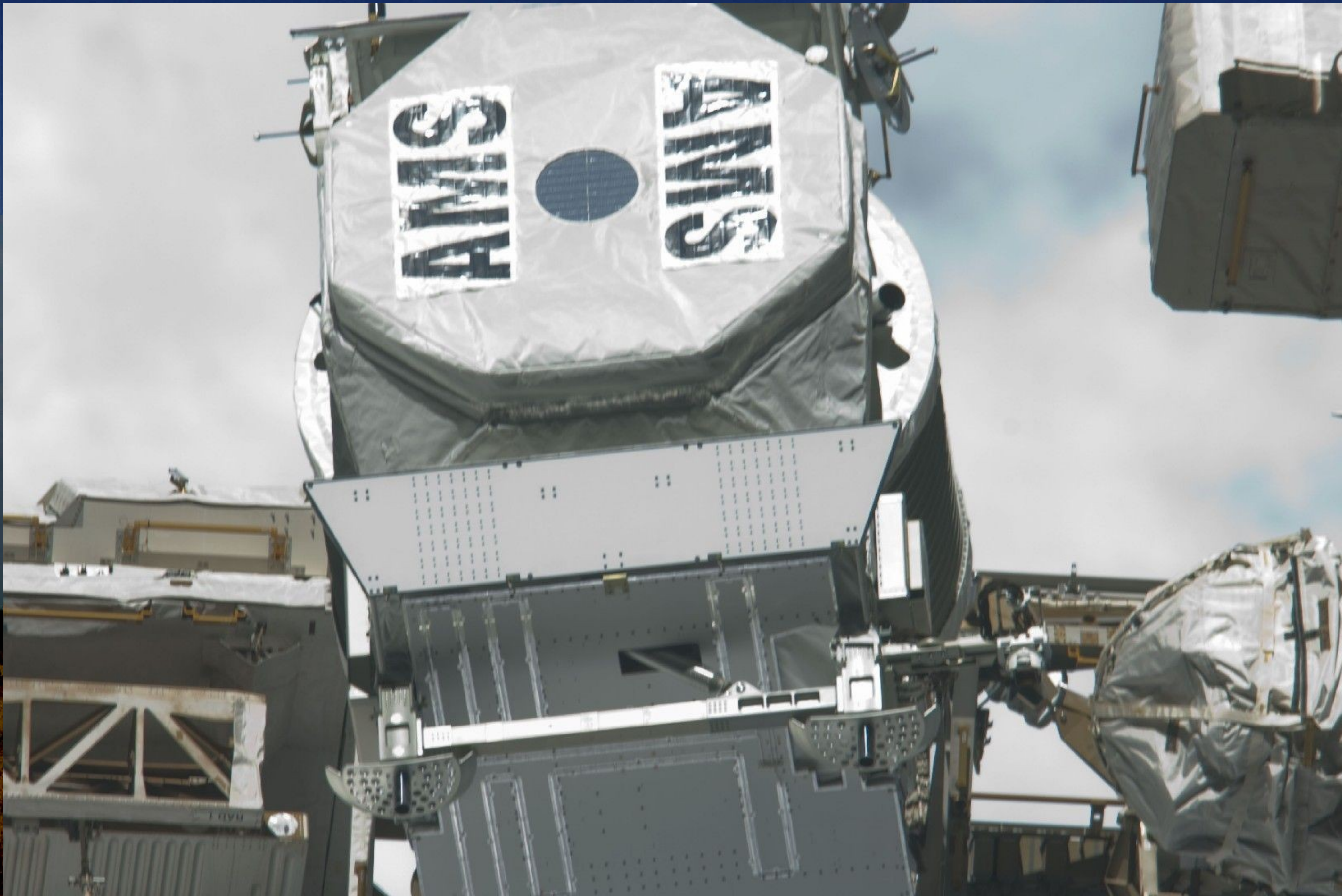




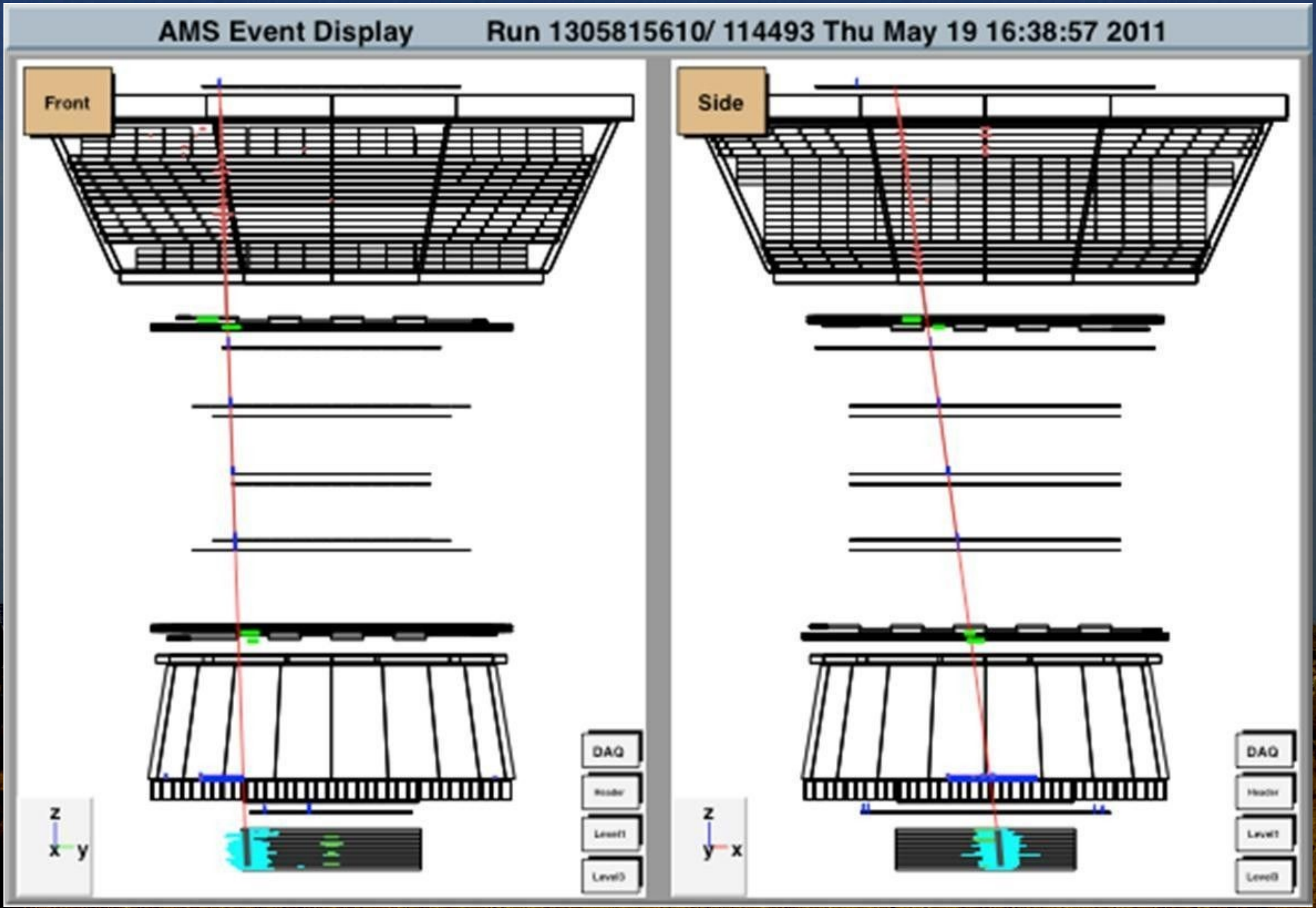
AMS-02: Expected SUSY signal

- Much improved precision expected

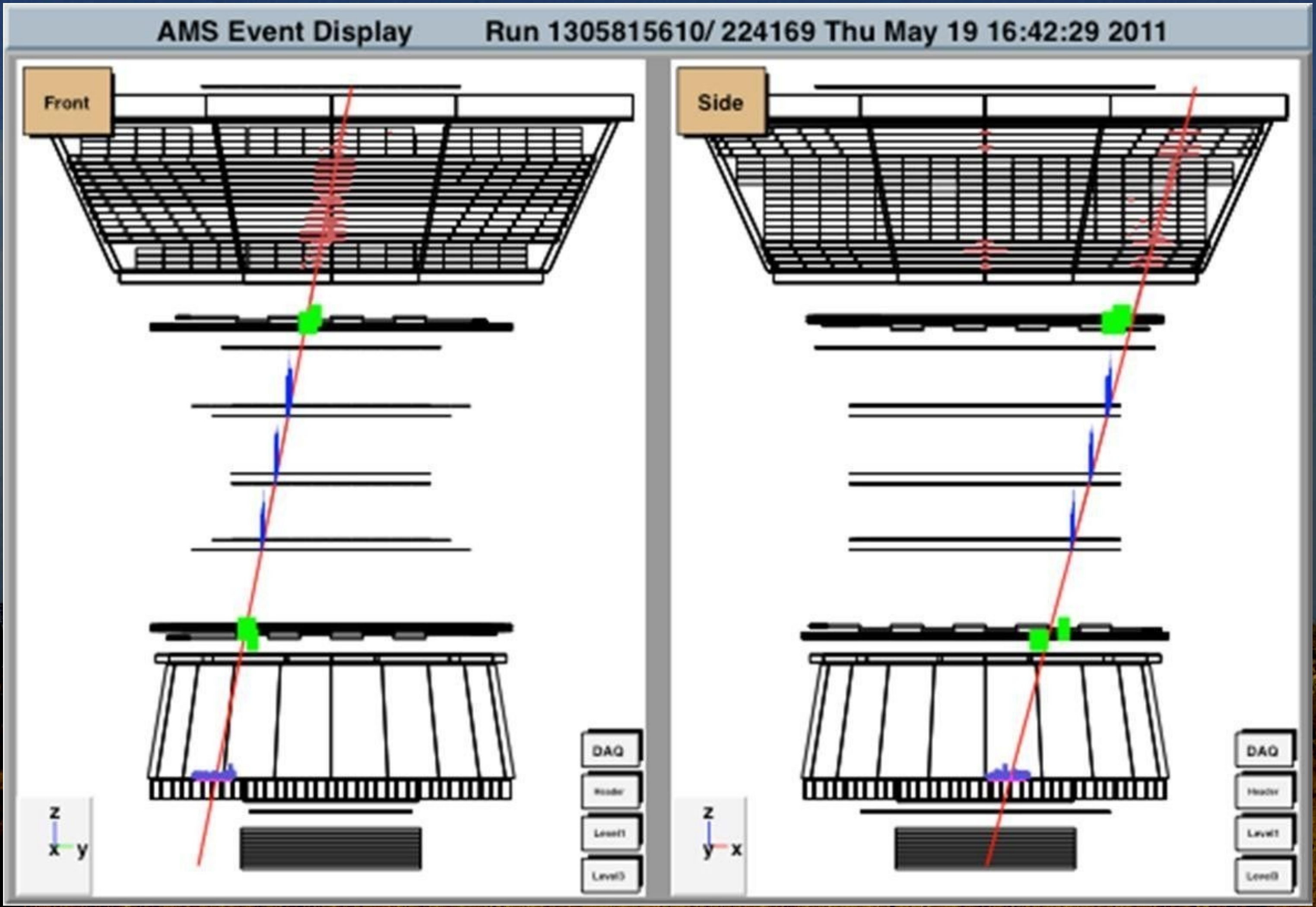



AMS
AMS

20 GeV Electron



40 GeV Carbon nuclei



First results to be announced in summer 2012.....

High Energy γ–ray Astronomy

Pair Creation Telescopes

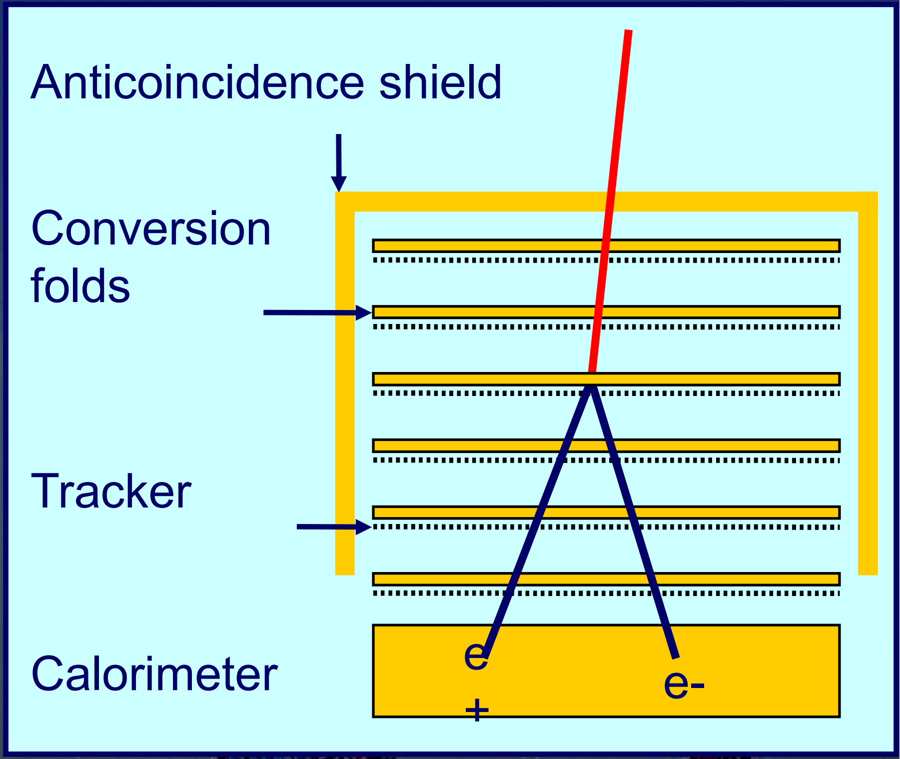
- Conversion of γ into pair e+ e-
  - Threshold $E_\gamma > 2\, m_e c^2$ (1.022 MeV)
  - Pair opening angle

$$\theta \approx \frac{1.6\,\mathrm{rad}}{E[\mathrm{MeV}]} \approx 1\,° @\ 100\ \mathrm{MeV}$$

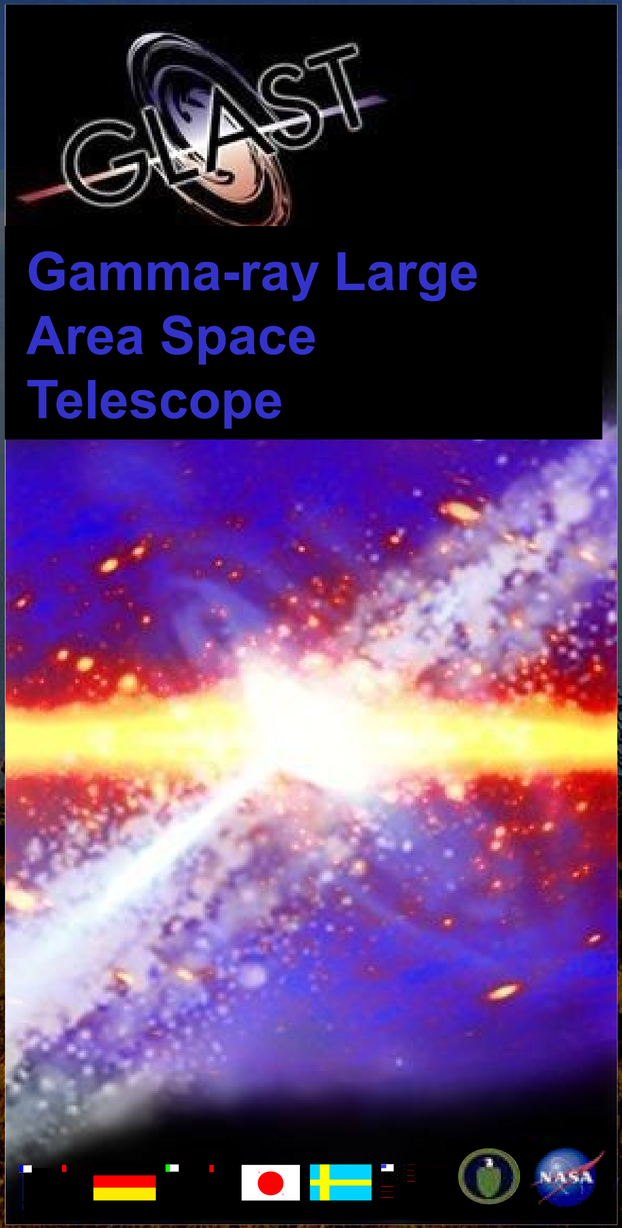
  - Average deviation: (Multiple scattering)

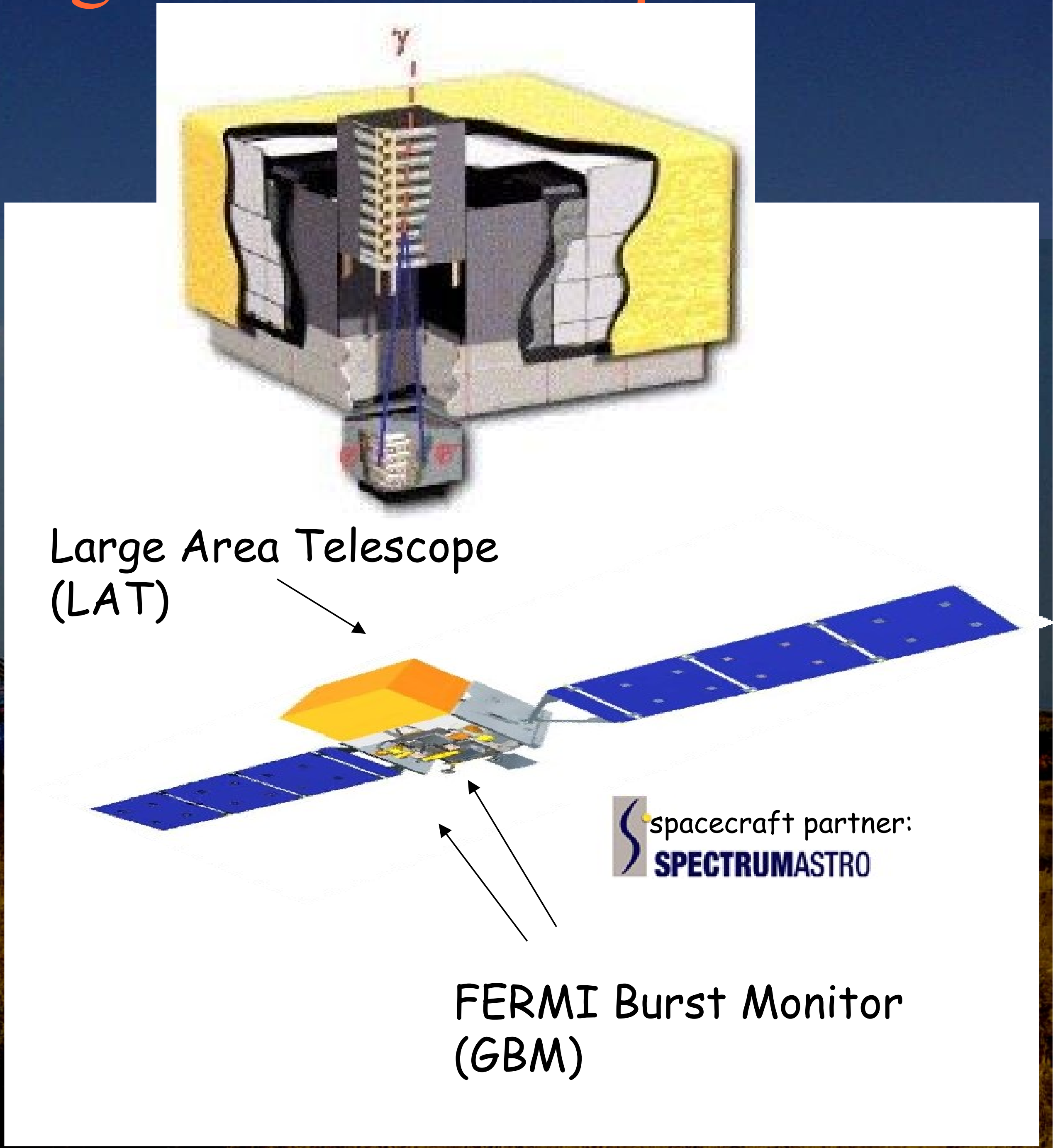
$$\sqrt{\langle \theta^2 \rangle} = q(E_\gamma, E_e, Z) \frac{m_e c^2}{E} \ln\left(\frac{E}{m_e c^2}\right)$$

  - Almost no deviation for $E\gamma \gg 2\, m_e c^2$, @ 100 MeV: $\theta \sim 1.5°$
- e+ e- reconstructed in a tracker ⇒ incident γ ray
- Anti-coincidence shield against charged cosmic rays



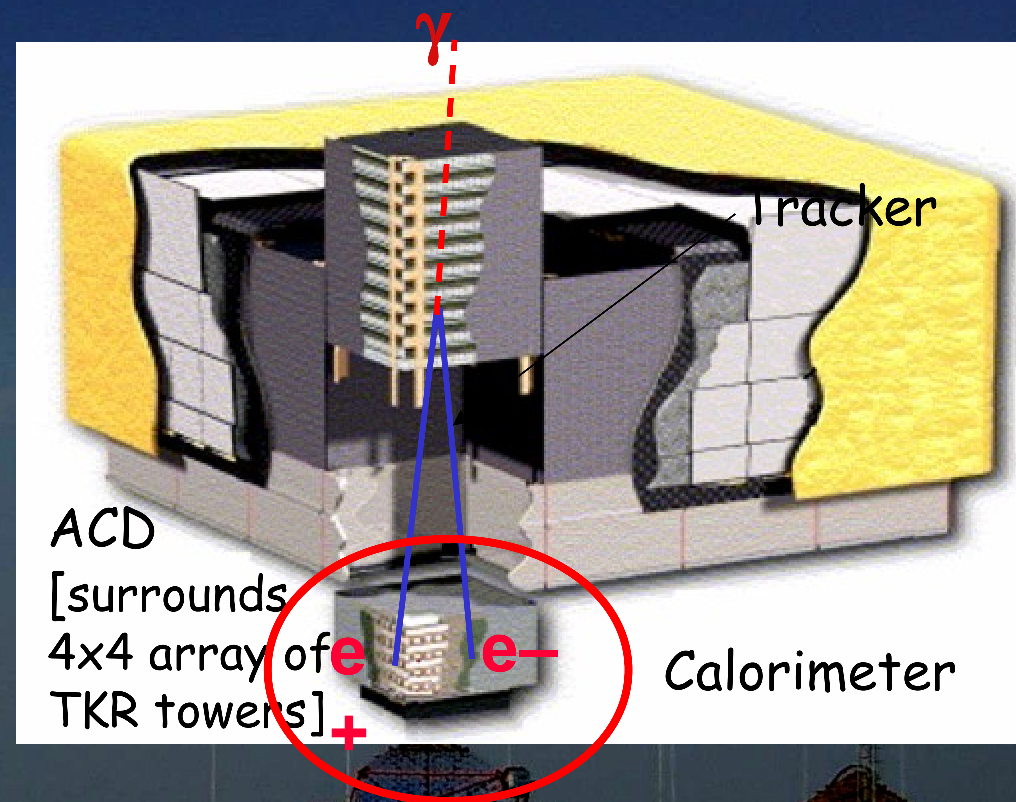
FERMI Large Area Telescope

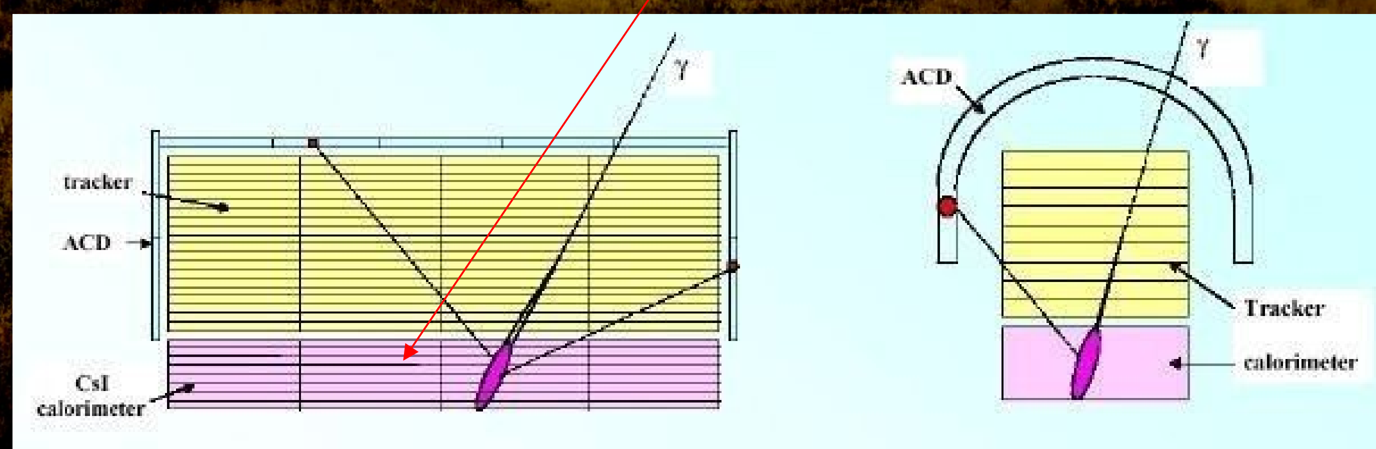




FERMI - LAT

- High precision tracker
  - 18 X/Y planes, Si strips (228 µm)
  - 900 000 channels
  - Triggers on 3 X/Y planes
- Hodoscopic Calorimeter
  - 1536 CsI(Tl) cristals(8 layers)
  - Shower imaging capabilities
- Anti-coïncidence shield
  - Segmented to avoid self-veto,
  - 89 folds





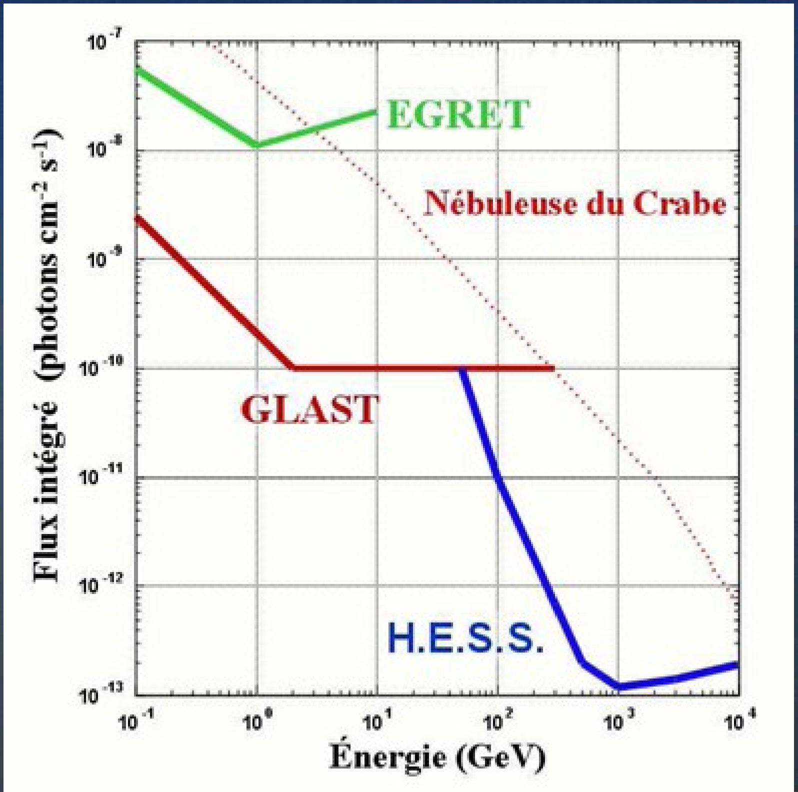
Mathieu de Naurois

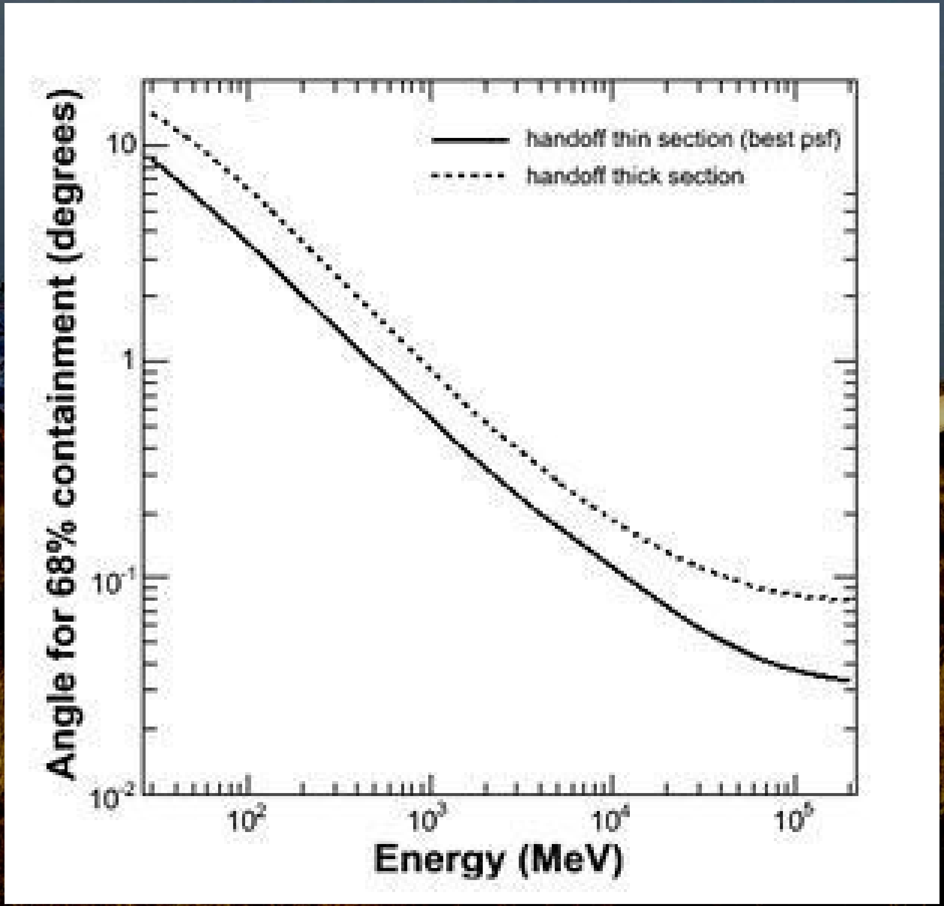
FERMI

- Launch: June 11th, 2008 (Delta rocket)
- Circular orbit @ 565 km (96 mn period), inclination 26°

Performances

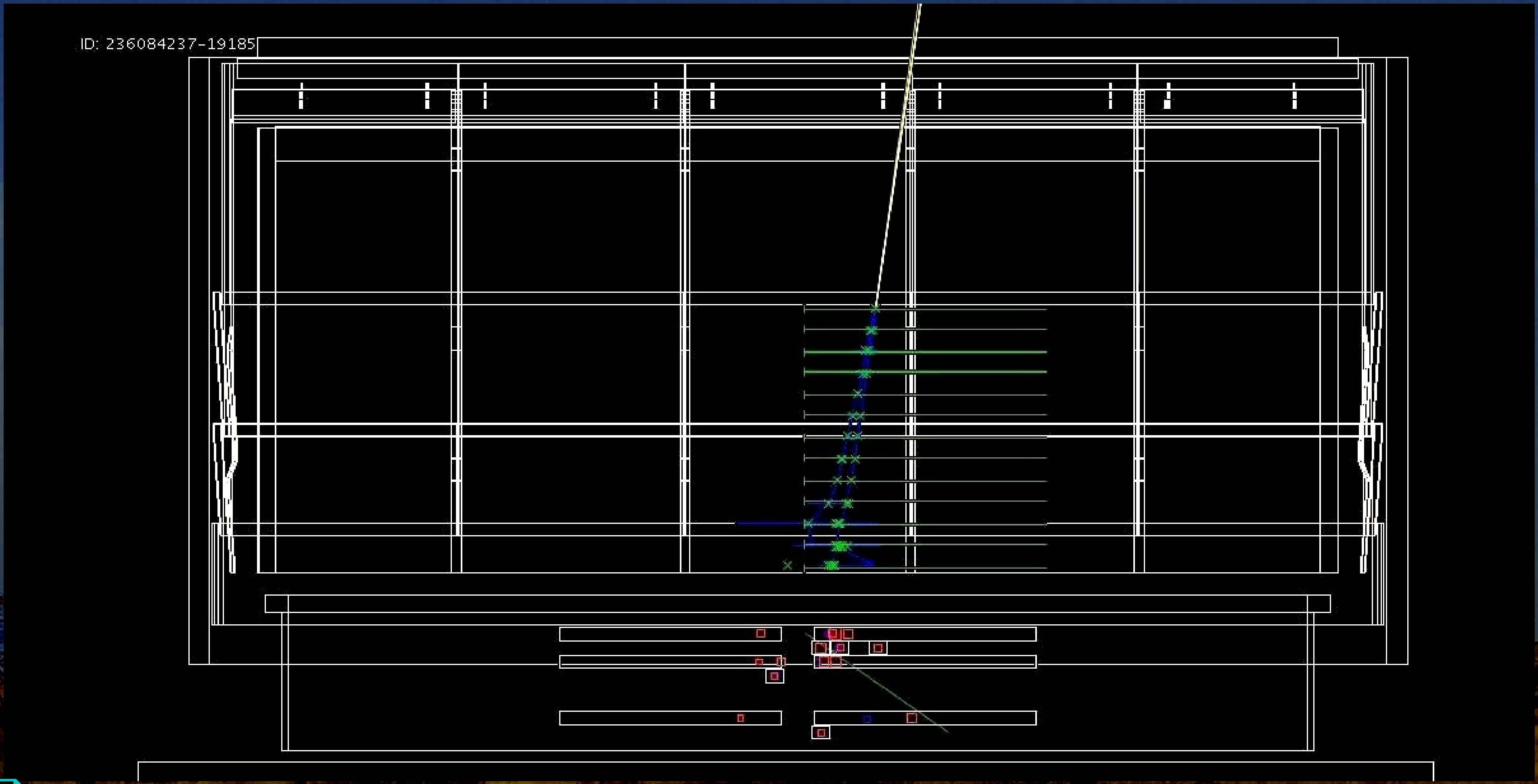
- 25 × more sensitive than EGRET
  100 × at high energy
- Angular resolution
  4° @ 100 MeV ⇒ 0.1° @ 10 GeV





- Energy Resolution ~ 10%
- 20% of sky seen at a given time
- 30 mn on each position every 3h
- 10 MeV – 100 GeV : 7 decades

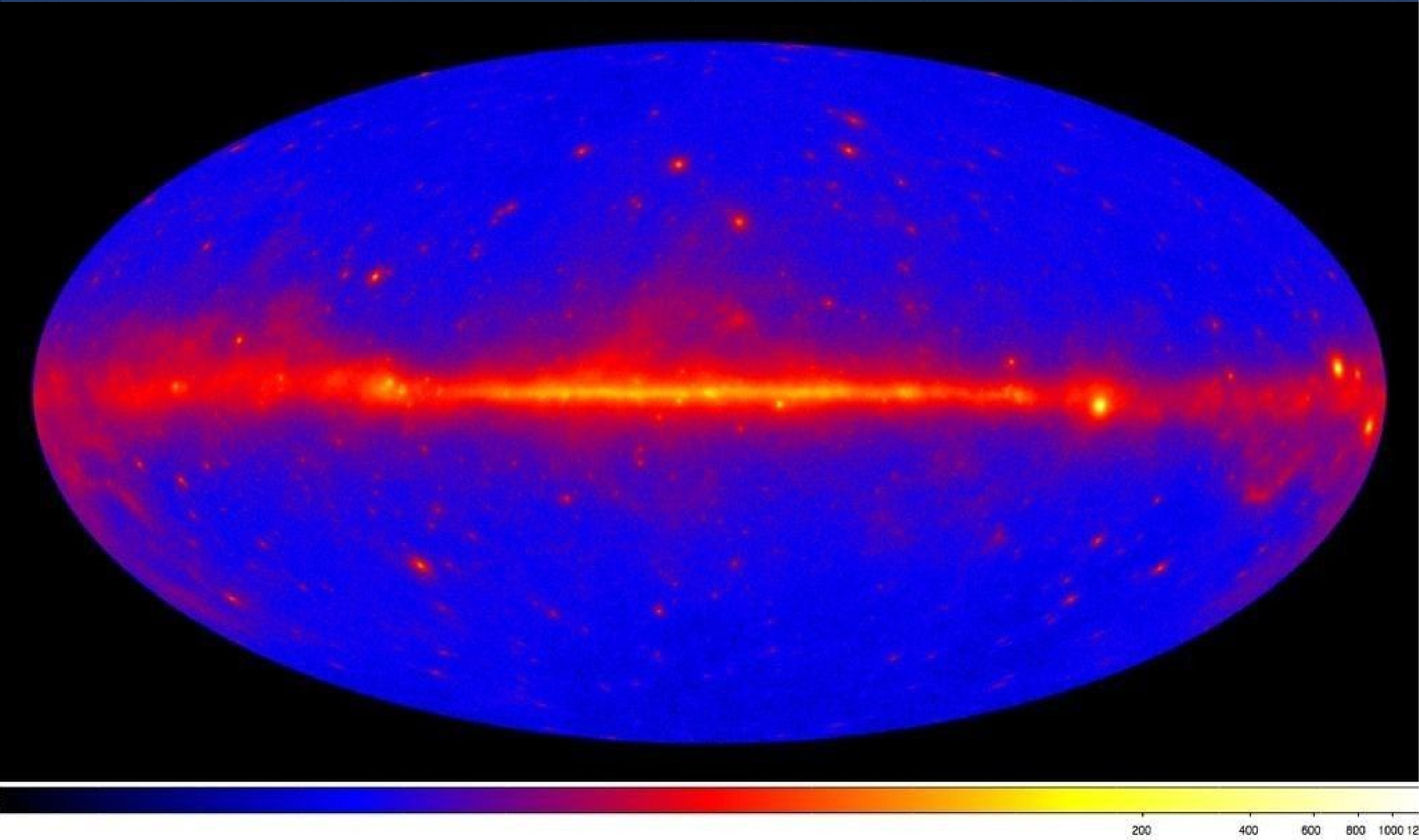
Gamma-Ray candidate



- Green crosses: Charged particles
- Blue lines: Reconstructed tracks
- Yellow: Reconstructed direction of primary γ
- Red: Energy deposit in calorimeter

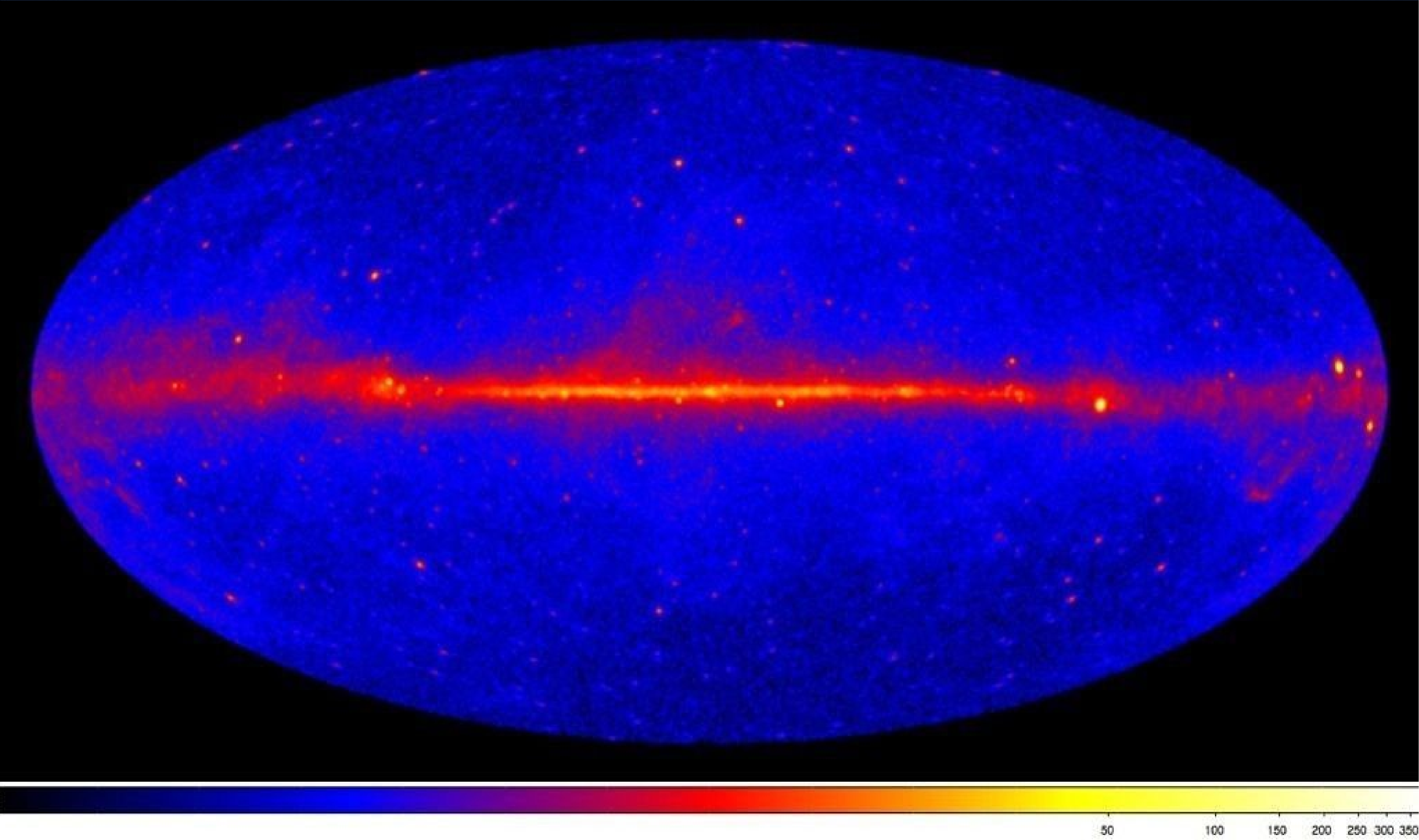
Fermi LAT > 100 MeV

- 3×10^{7} photons, <E> = 800 MeV, ΔE/E = 100 %



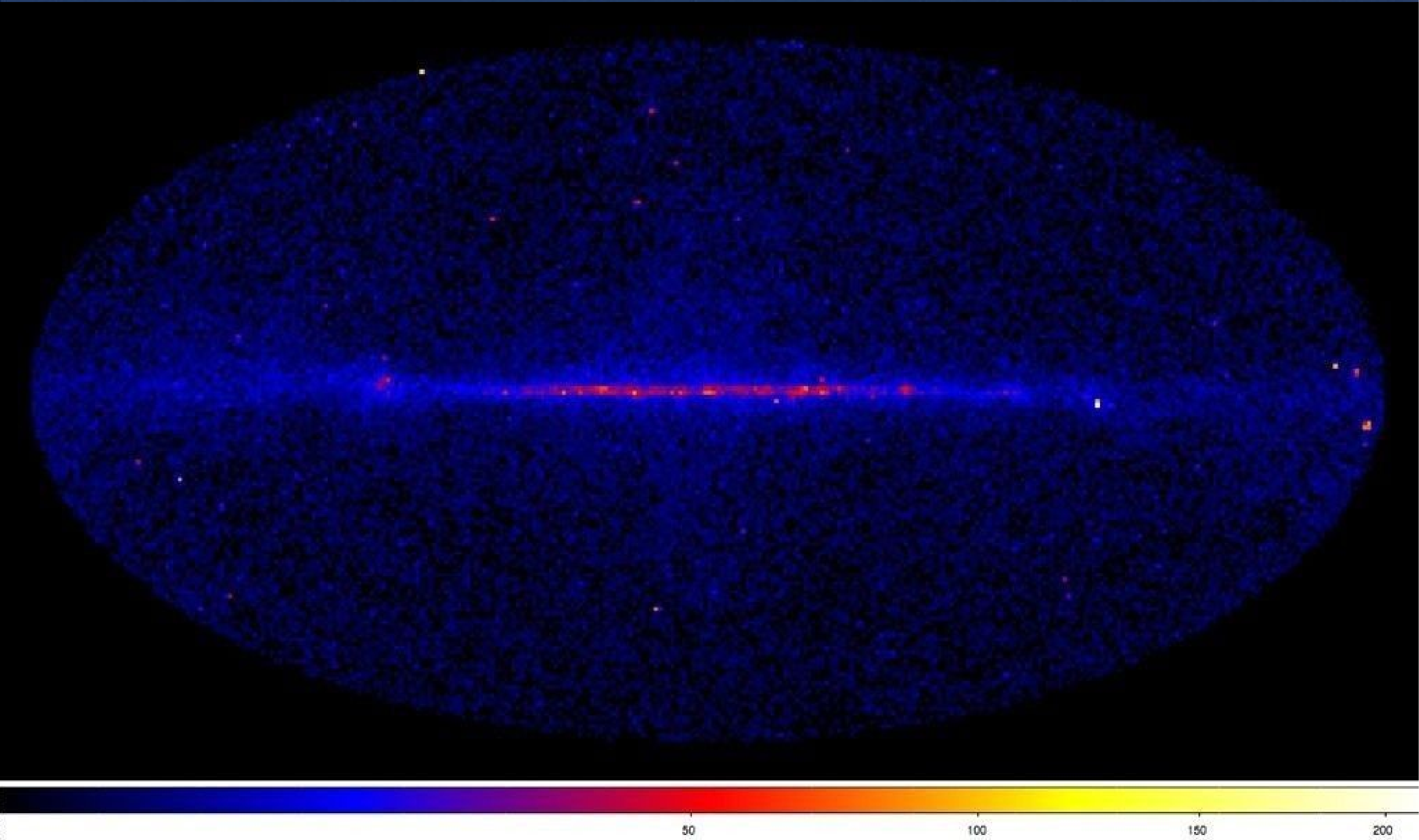
Fermi LAT > 1 GeV

- 2×10^6 photons, <E> = 3 GeV, ΔE/E = 17 %



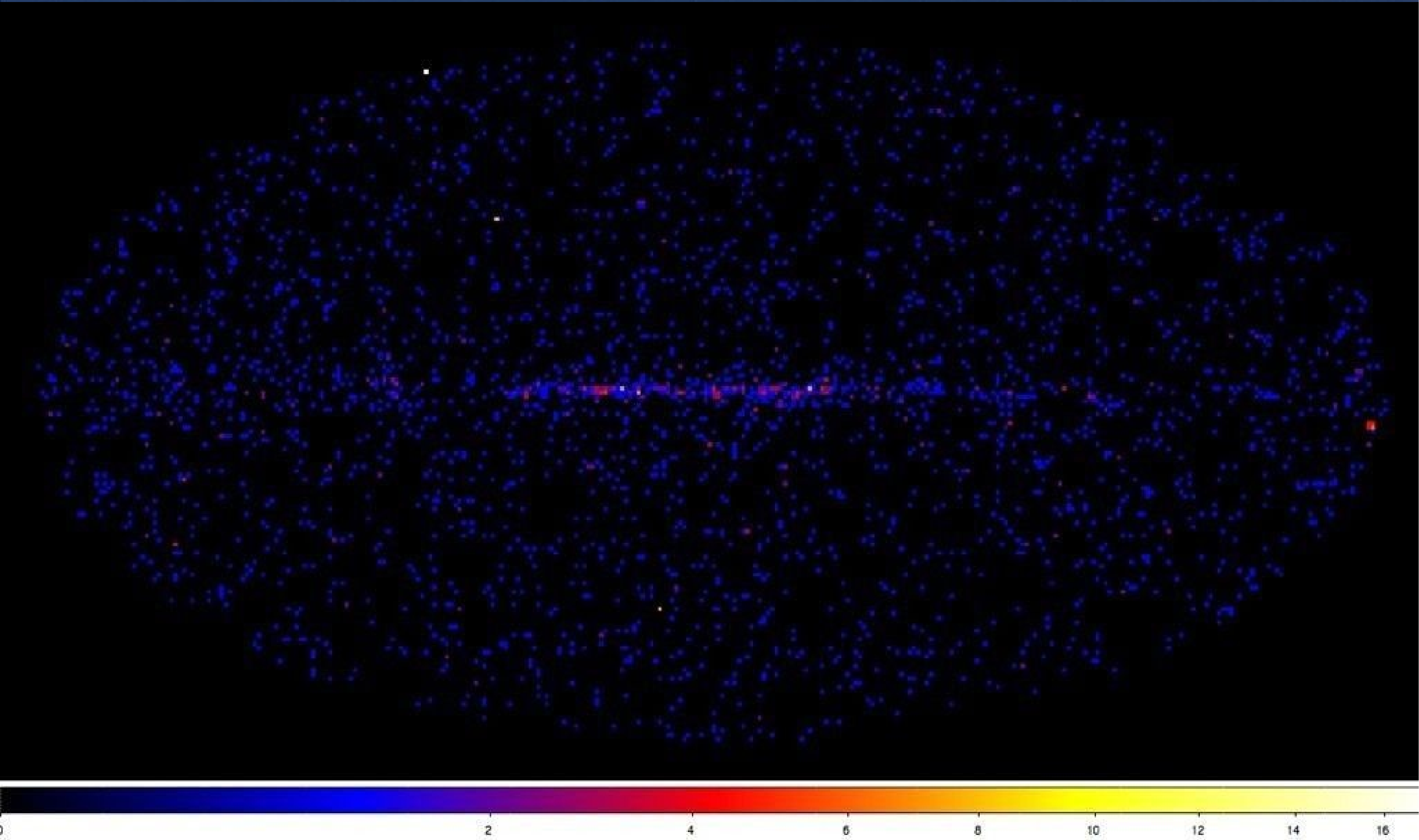
Fermi LAT > 10 GeV

- 7×10^4 photons, <E> = 30 GeV, $\Delta E/E$ = 0,6 %



Fermi LAT > 100 GeV

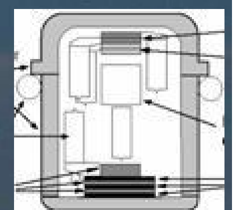
- 3×10^3 photons, <E> = 150 GeV, ΔE/E = 0,02 %



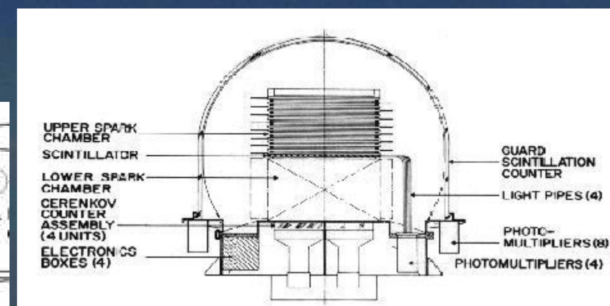
History of pair creation telescopes

- 1967-1968, OSO-3
- 621 γ, Galactic Plane
- 1972-1973, SAS-2,
- ~8,000 γ, 3 sources
- 1975-1982, COS-B
- ~200,000 γ, 25 sources (3C 273)
- 1991-2000, EGRET
- $>1.4 \times 10^6$ γ, 271 sources
- 2007- AGILE
- 2008- FERMI

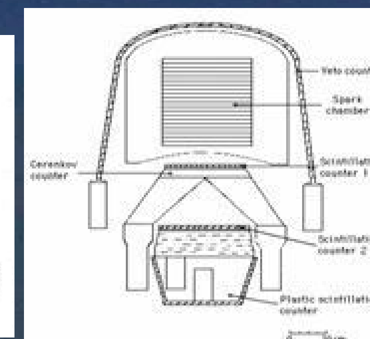
OSO-3



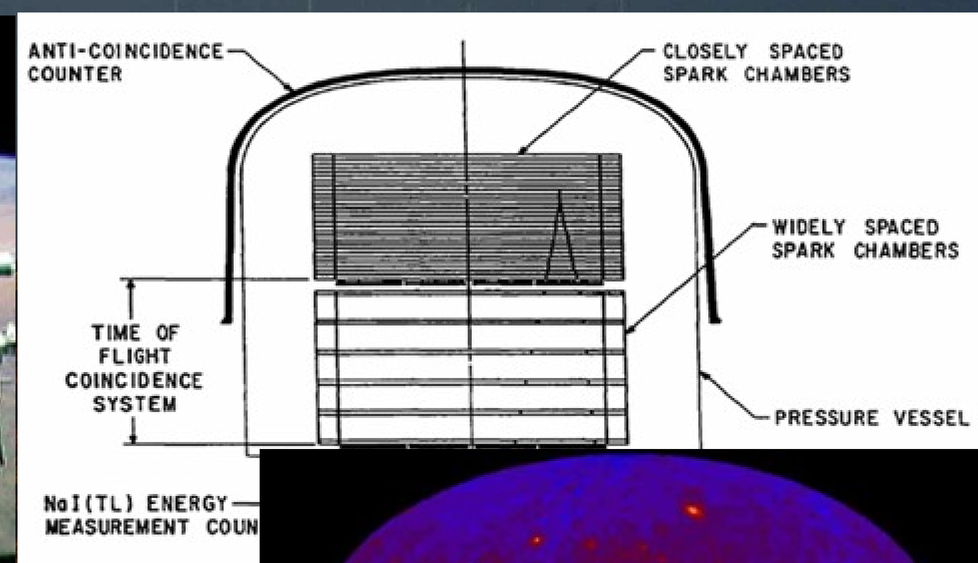
SAS-2

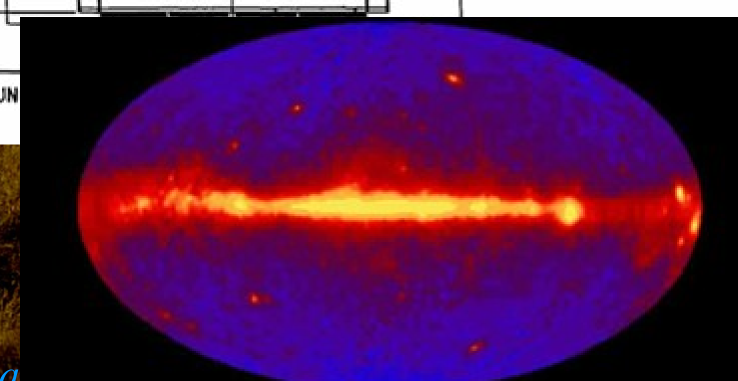


COS-B



EGRET





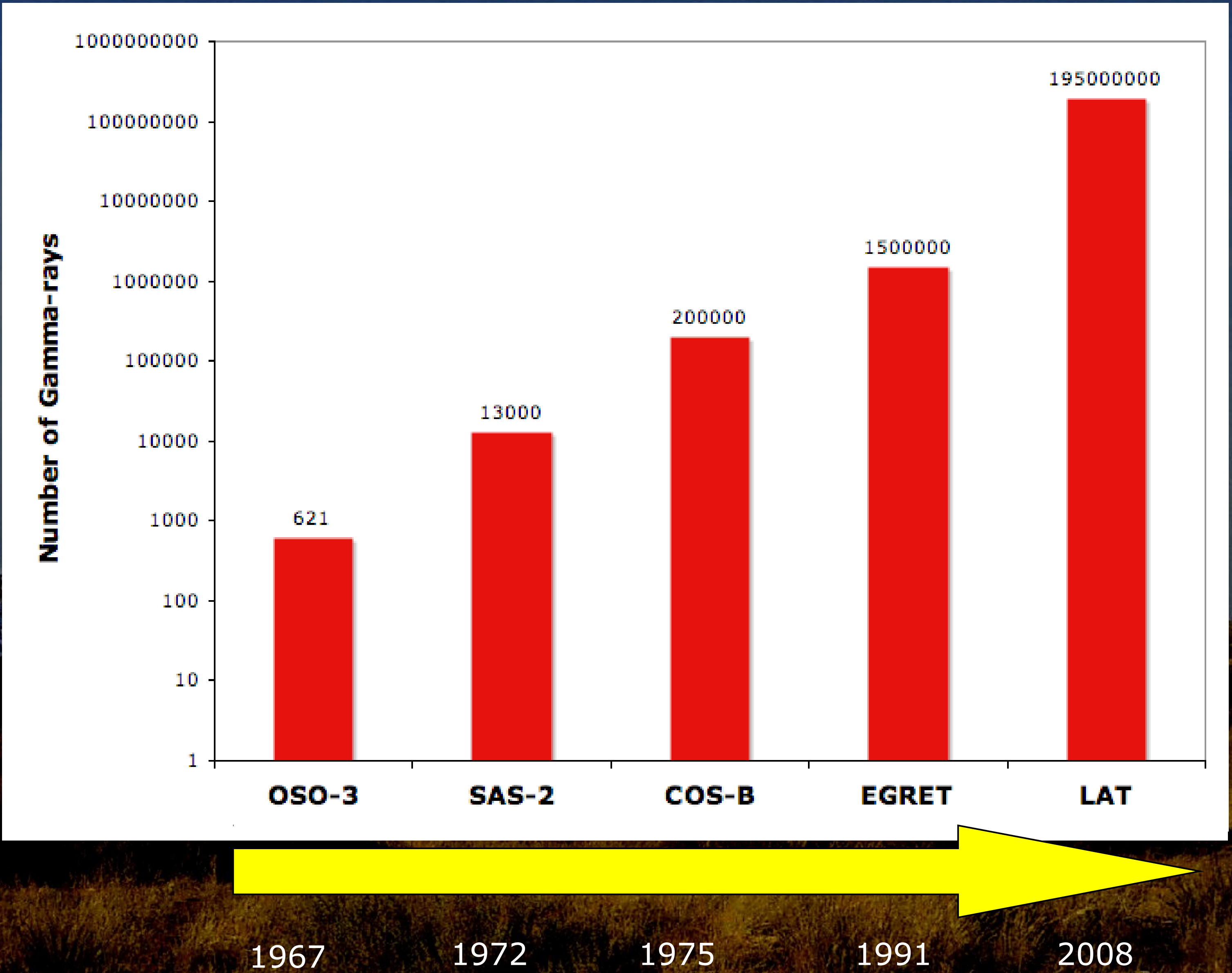
From EGRET to AGILE & Fermi

Instrument	EGRET	AGILE	FERMI
Launch	1991	April 2007	Februar 2008
Energy domain	2 MeV-30 GeV	30 MeV-50 GeV	10 MeV-300 GeV
Tracker	Sparck chamber	silicium strips + W (14 pl.)	silicium strips + Pb (18 pl.)
Calorimeter	NaI (Tl) 8.5 X_0	CsI (Tl) 1.5 X_0	CsI (Tl) 10 X_0
Effective Area	1200 cm^2 @ 1 GeV	700 cm^2 @ 1 GeV	10 000 cm^2 @ 10 GeV

From EGRET to AGILE & Fermi

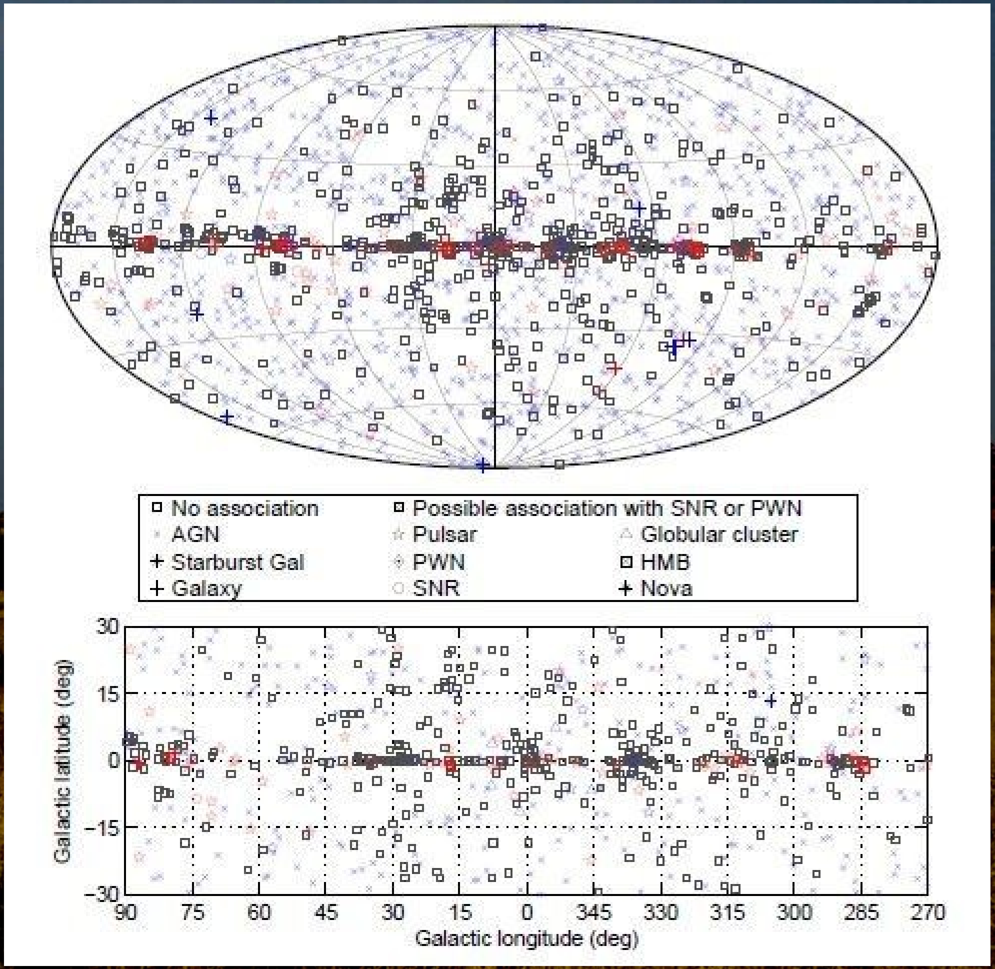
Instrument	EGRET	AGILE	FERMI
Energy Domain	2 MeV-30 GeV	30 MeV-50 GeV	10 MeV-300 GeV
Field of view	0.20 sr.	2 sr.	2.4 sr.
Angular resolution	1.5° @ 1 GeV	0.6°	0.12° @ 10 GeV 4° @ 100 MeV
Localization accuracy	5' to 10 '	30 ' @ 300 MeV	0.4 '
ΔE/E	10 %	100 %	10 %
Dead time	0.1 s	< 100 μs	< 100 μs

Gamma-ray count



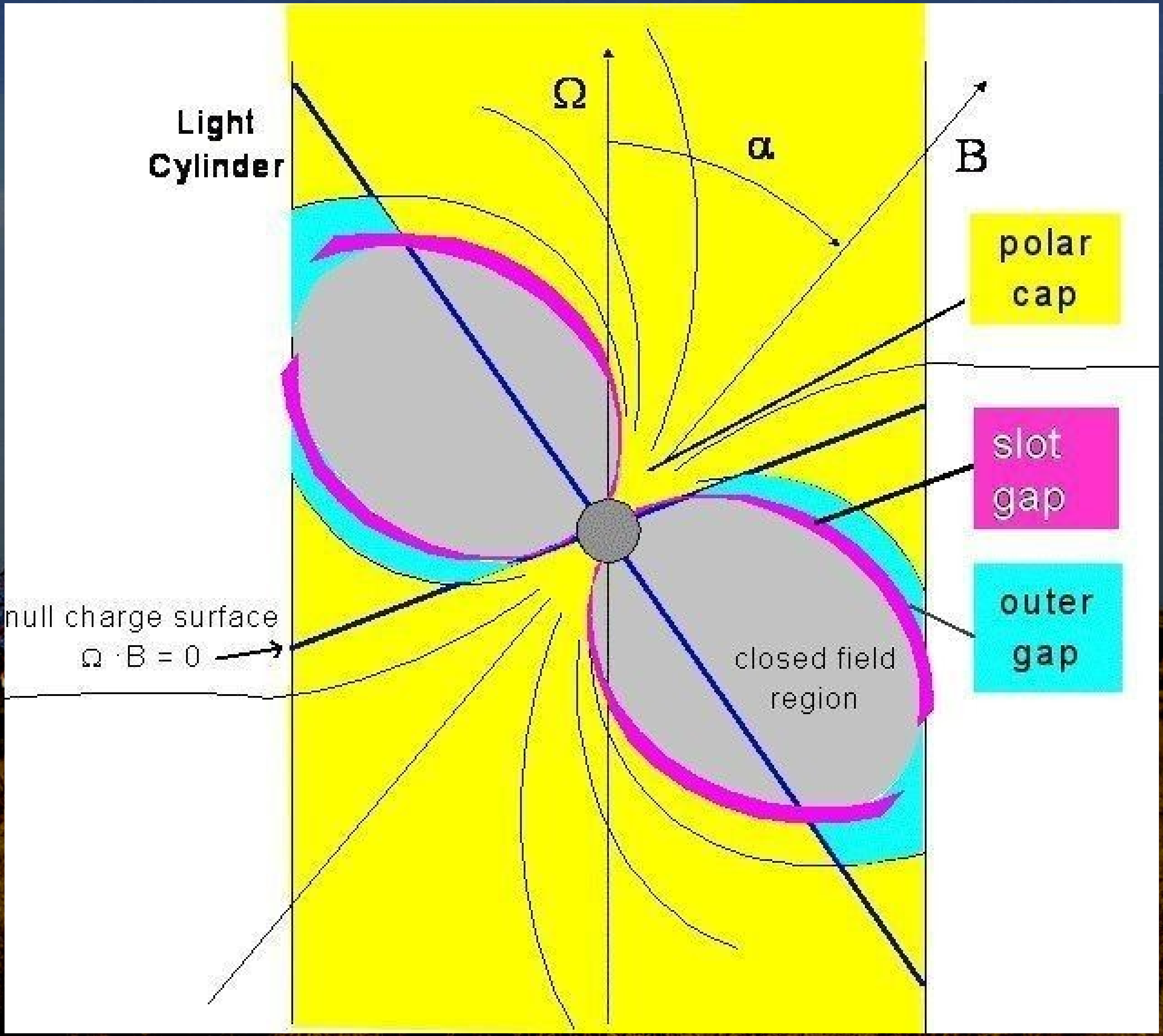
2 FGL Catalog

- December 2011
  http://arxiv.org/abs/1108.1435
- Galactic Sources:
  - 83 pulsars with measured P
  - 58 PWN/SNR associations
  - 25 pulsars without γ period
  - 11 globular clusters
  - 10 SNRs
  - 4 binary systems
  - 3 isolated PWN
  - 1 nova



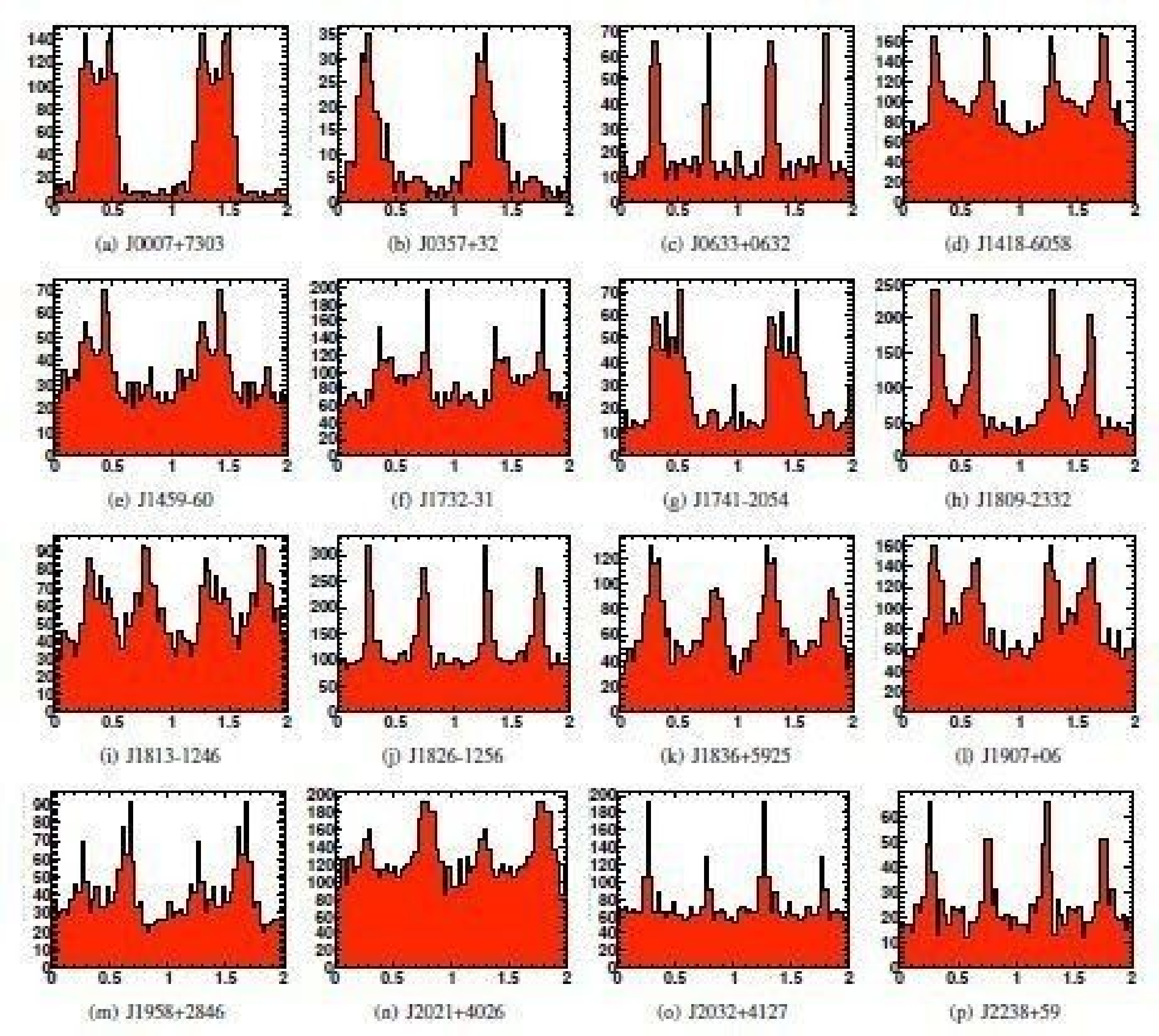
Pulsars

- Compact object (neutron star) highly magnetized, rapidly rotating:
  - R ~ 10 km
  - M ~ 1.4 $M_\odot$
  - Period ms ⇒ s
- Several possible acceleration regions

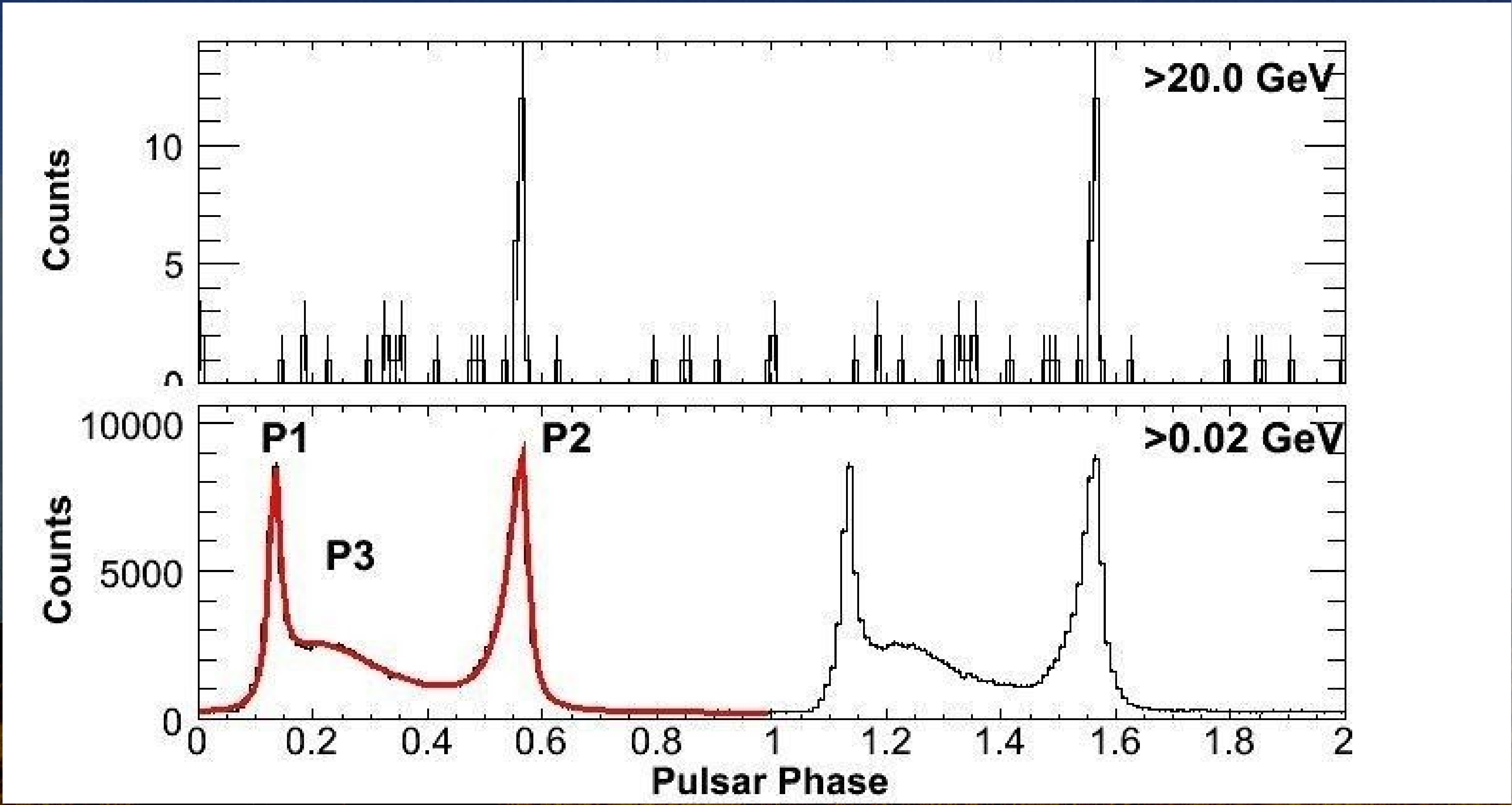


Gamma-ray pulsars

- Gamma-ray pulsar: seen only in GeV.
- EGRET: A single gamma-ray pulsar (Geminga) out of 8 pulsars
- Fermi: discovery of a full population (16 in 6 month)
- Strong constraints on the geometry of emission zone (cone opening angle vs energy)



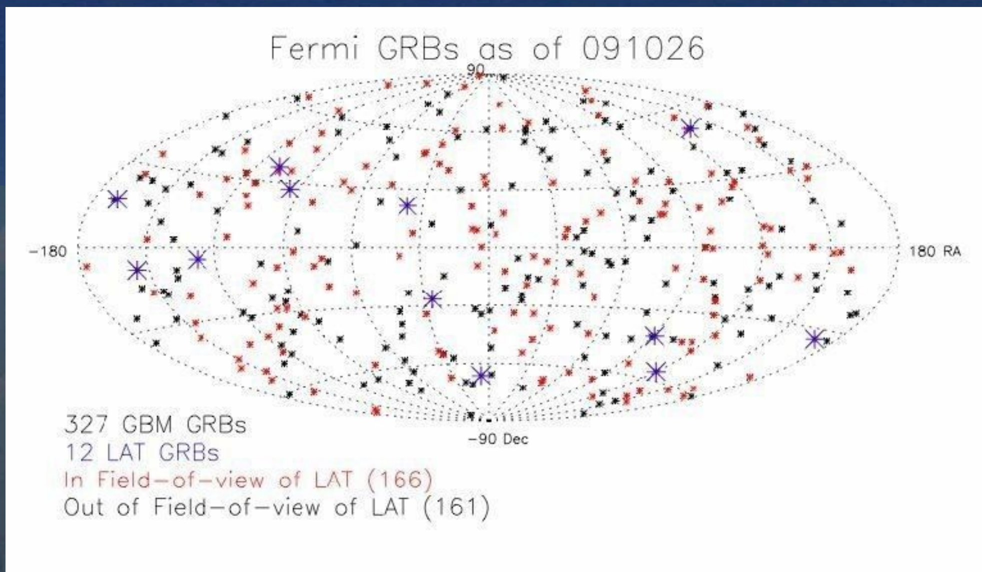
Vela at high energy

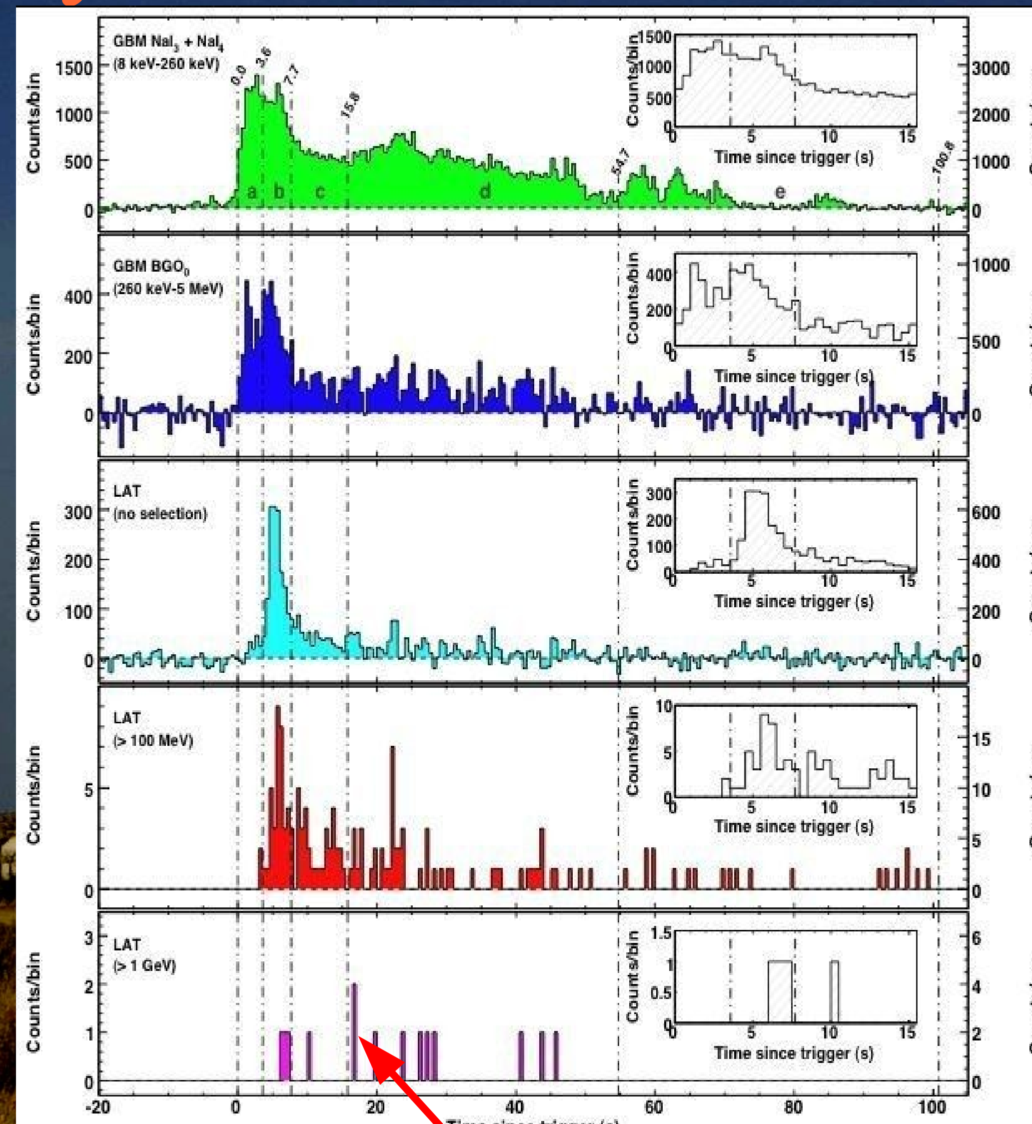


Preliminary   Abdo et al submitted

- High energy emission concentrated at one phase
  ⇒ constraints on acceleration models

Gamma-ray bursts



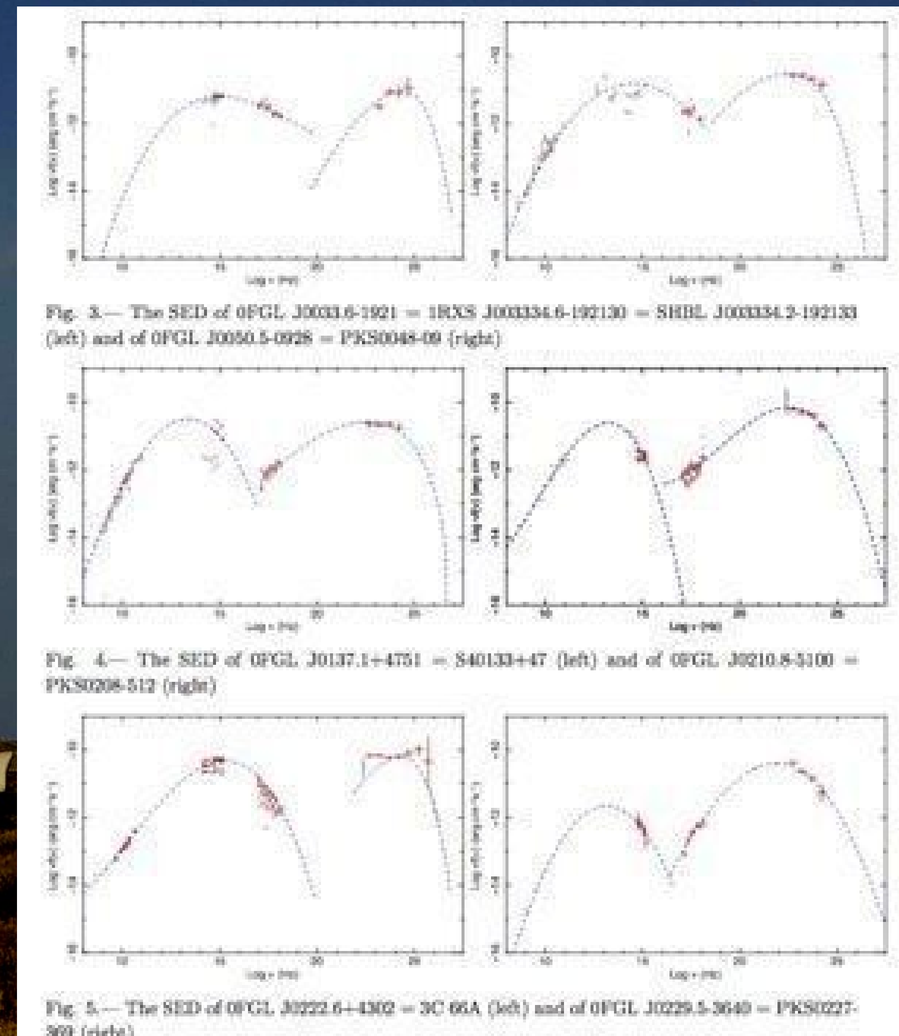


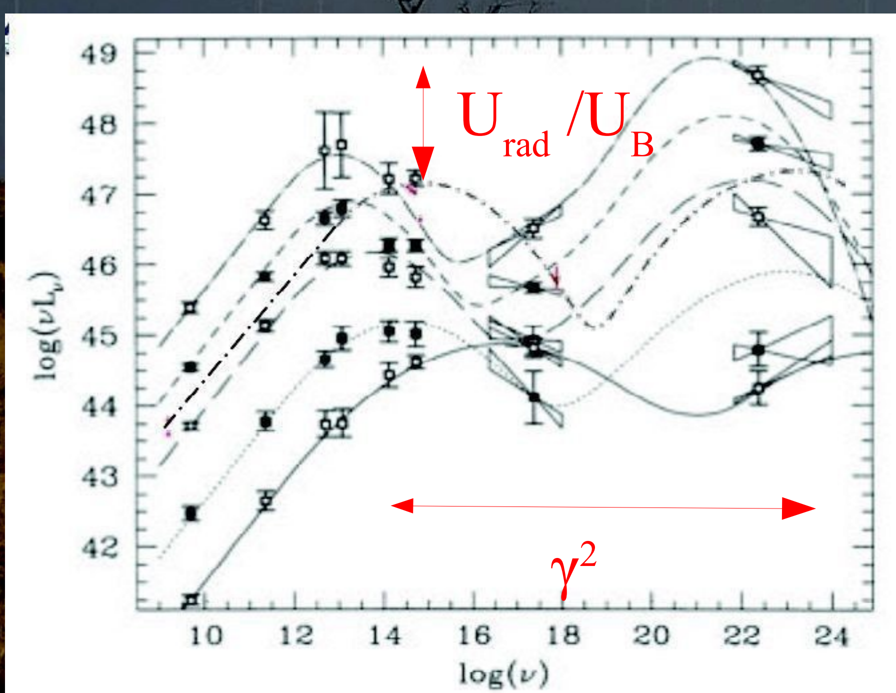
13.6 GeV

- Several hundreds of GRB
- A dozen seen in LAT
- Time resolved spectra
  - Prompt emission
- > 10 GeV

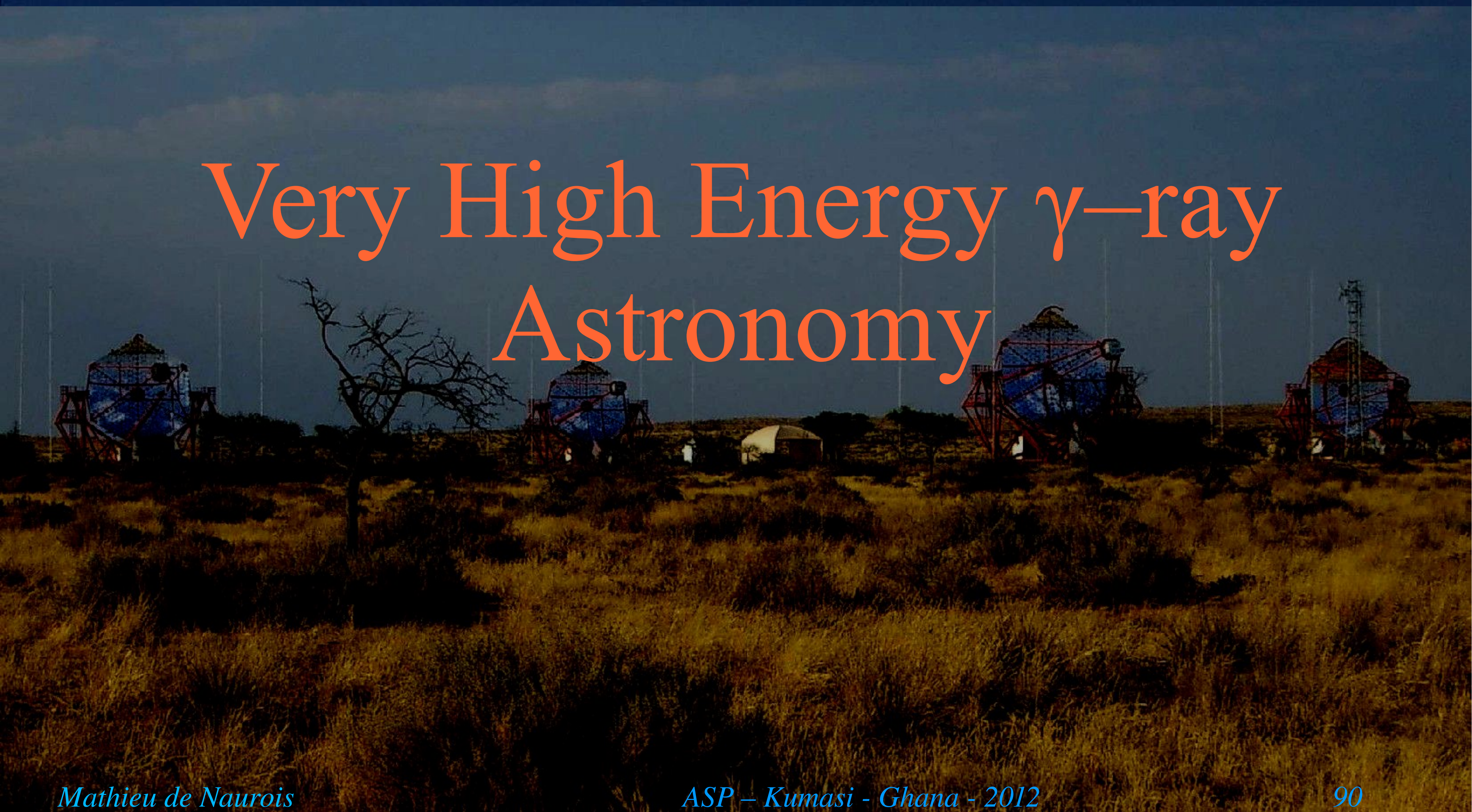
Blazars

- Good quality MWL data
- Sequence of blazars emerging
- Population studies
- Tests of models (correlations X/γ,...)



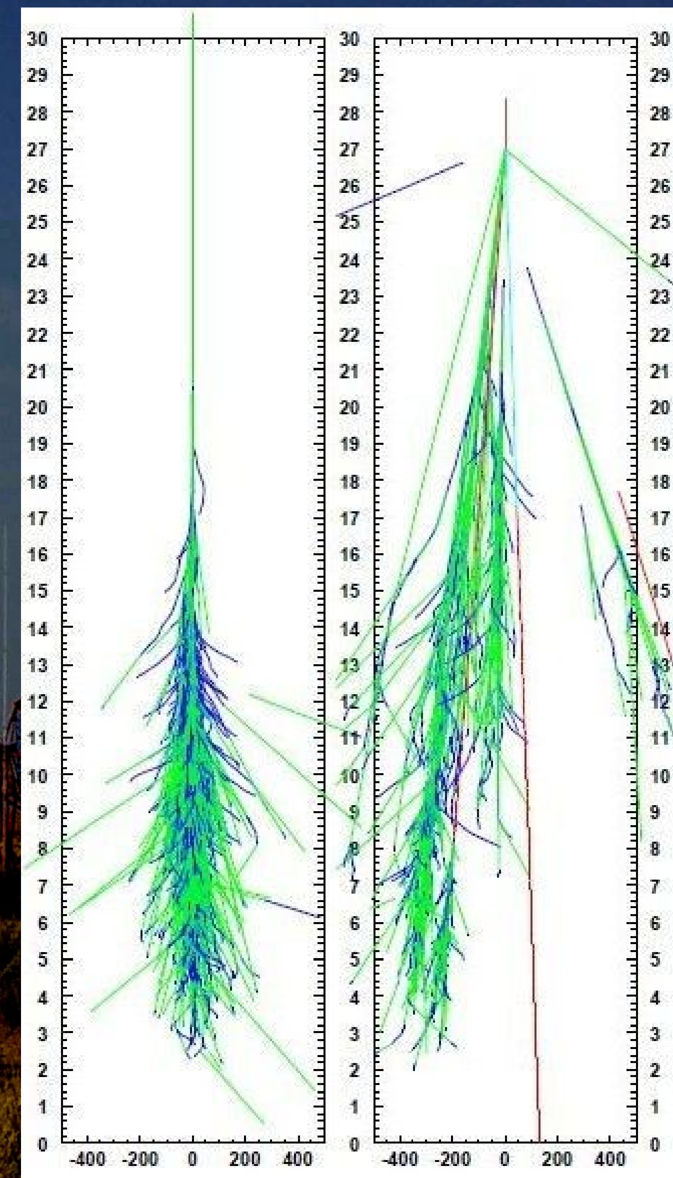


Very High Energy γ–ray Astronomy



Atmospheric Showers

- Primary interaction in the high atmosphere
  - Shower of secondary particles, detectable up to a few 100 m
  - Large effective areas (>10^5 m^2, increasing with energy)
  - ⇒ High energies (≥ 1000 TeV)
- Atmosphere used as an inhomogeneous calorimeter.
- Observables: charged particles, Cerenkov light, fluorescence light, radio emission
- Reconstruction: Energy, direction, impact, nature of primary particle (γ-hadron ; light (p, He) – heavy nuclei (Fe))



Elementary processes

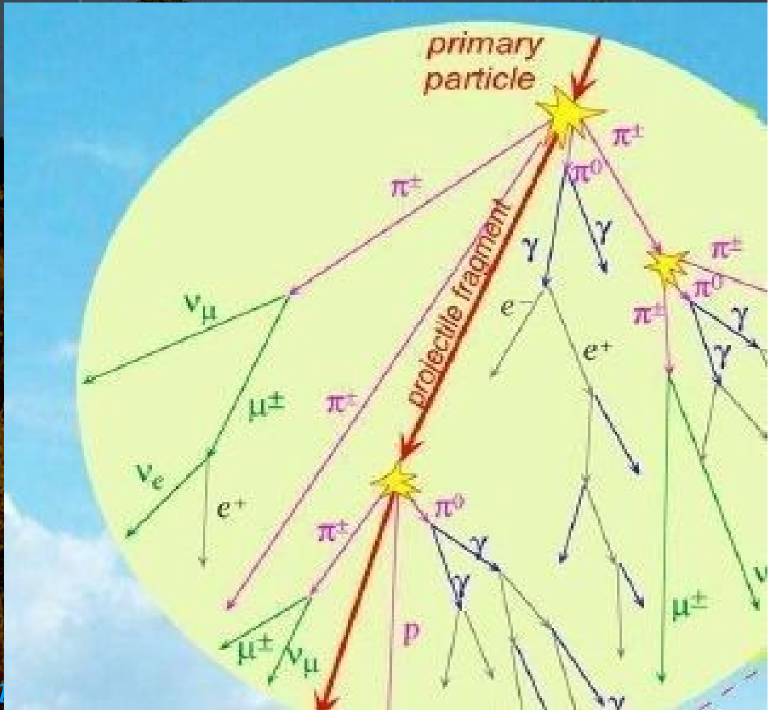
- bremsstrahlung of e±
- Conversion of high energy γ's into e+e- pairs
- Multiple scattering

In the Coulombian field of nuclei

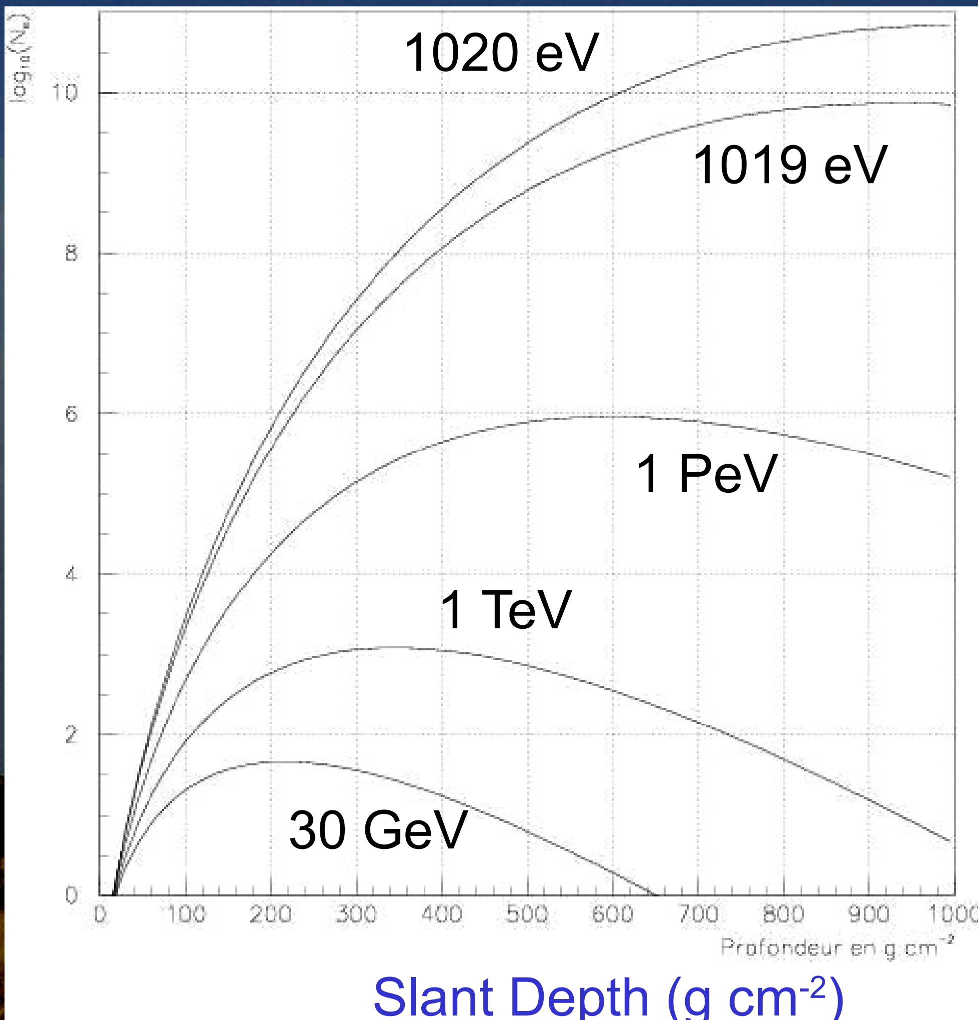
- Energy loss by ionisation or excitation

⇒ Rapid extinction below critial energy (84.2 MeV)

- Hadronic showers:
  - Nuclear fragments, π & K, mesons, ...
  - Muonic component
  - Neutrinos from π± K± and μ± disintegrations
  - Electromagnetic component from $\pi^0 \rightarrow \gamma\gamma$



Shower profiles (electromagnetic)

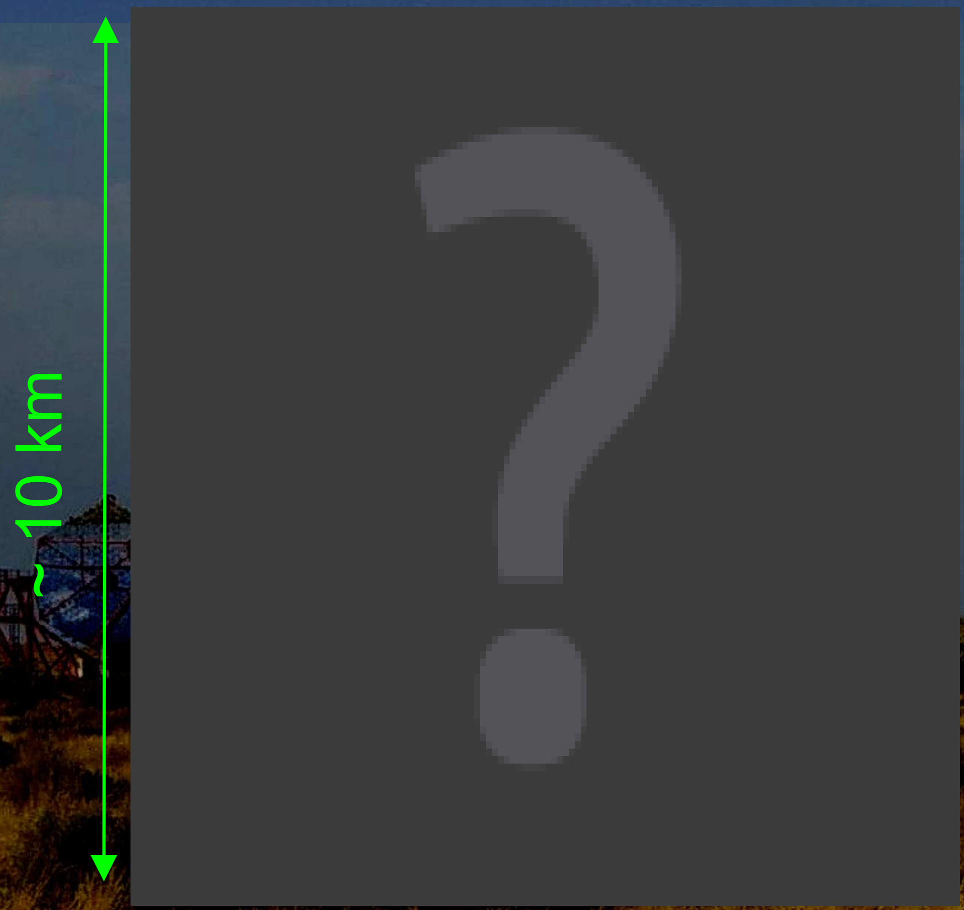


Orders of magnitude

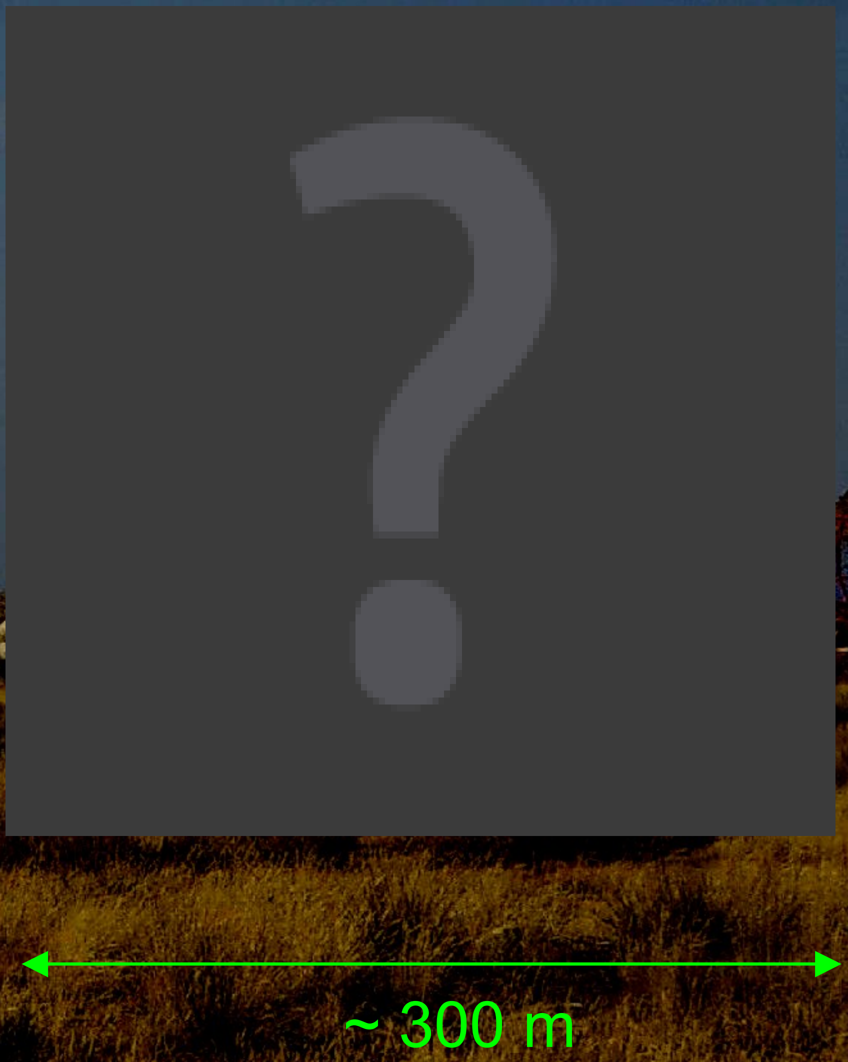
E0	Tmax (g cm^{-2})	Altitude (m)	Ne (tmax)
30 GeV	216	12000	50
1 TeV	345	8000	1200
1000 TeV	600	4400	$0{,}9 \times 10^6$
10^{19} eV	936	1200	$7{,}4 \times 10^9$
10^{20} eV	1021	0	$7{,}0 \times 10^{10}$

An electromagnetic shower

- Simulation of a γ induced shower

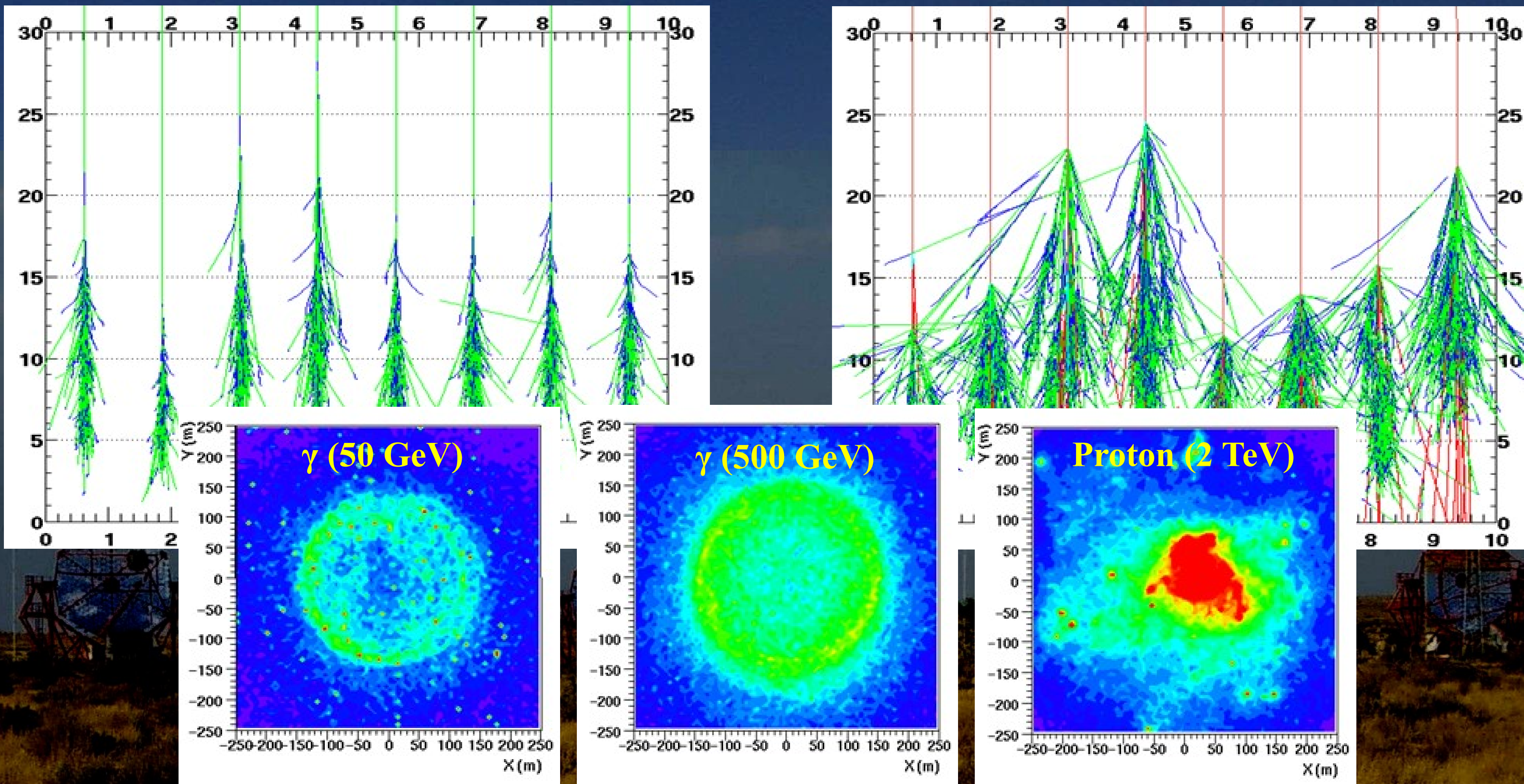


From below

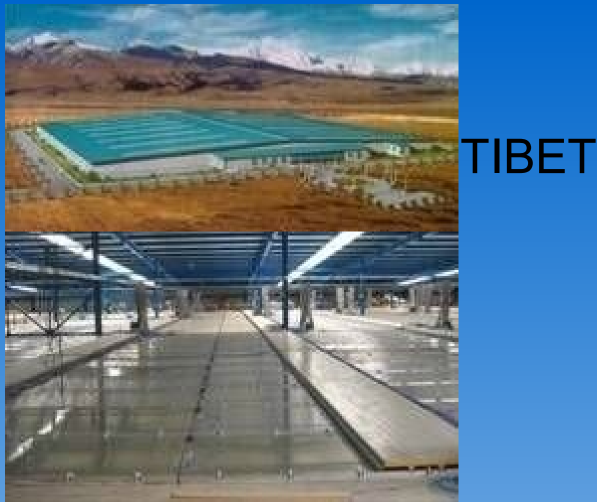


Shower variability

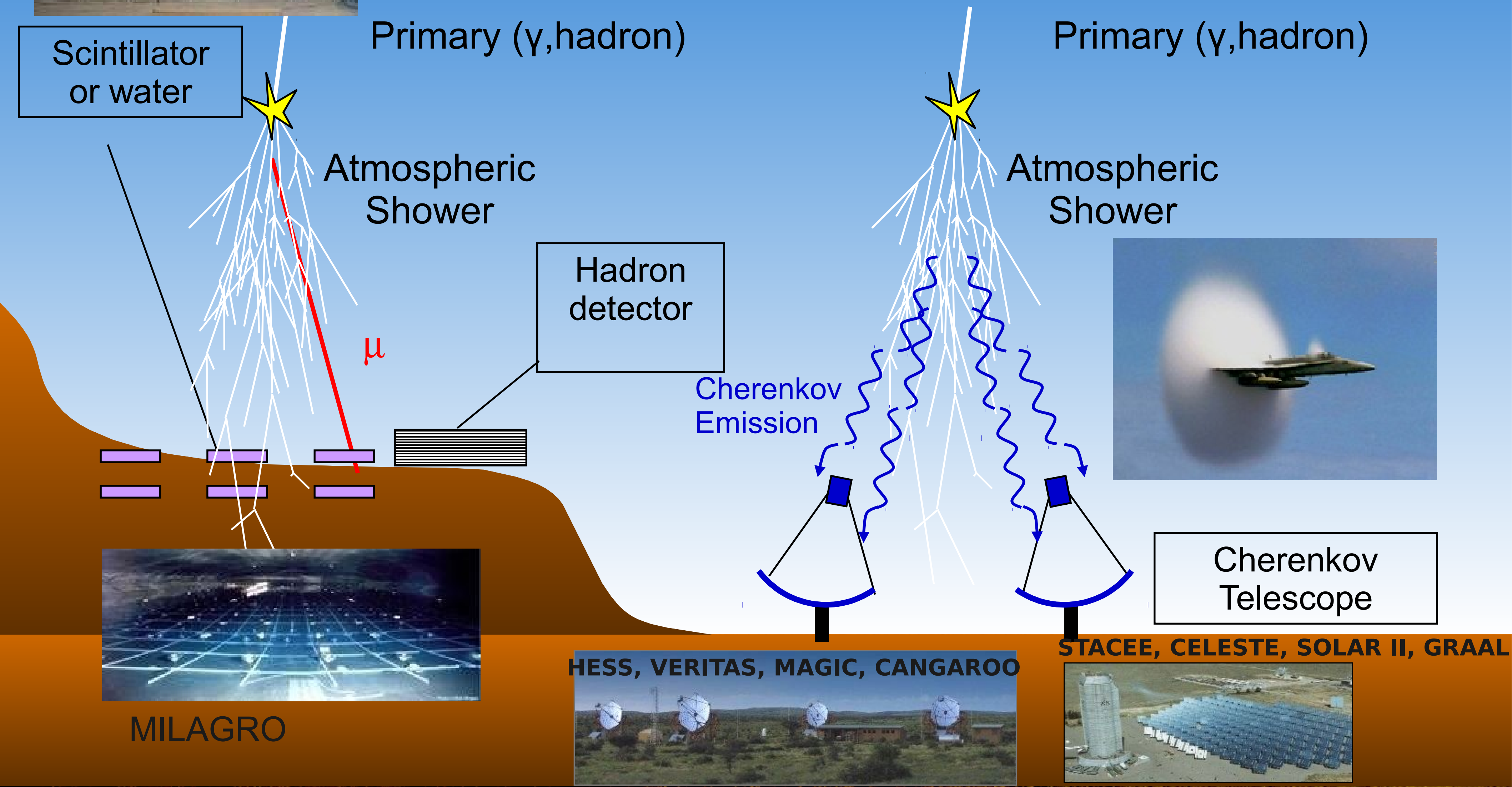
γ, 100 GeV *Protons, 500 GeV*



- Hadronic shower more fluctuating
- Contain muons



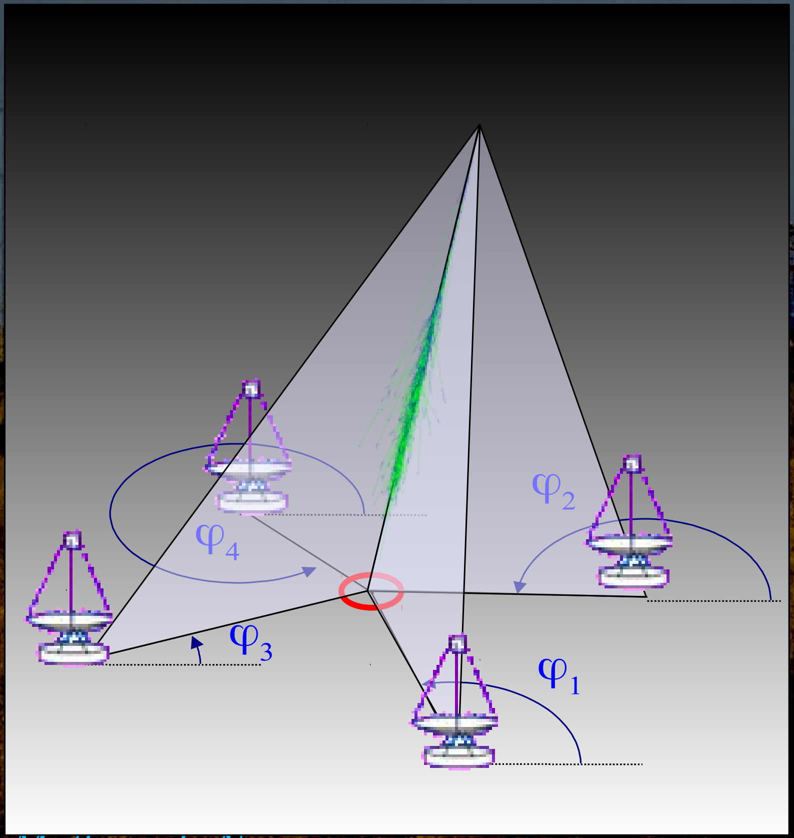
Observables and experimental techniques (E > 10 GeV)



2 Complementary Techniques

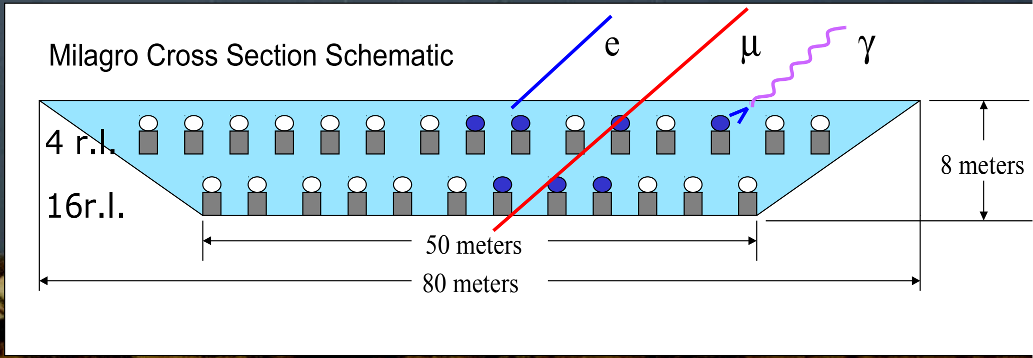
- Atmospheric Cherenkov Telescopes:
  - Small F.O.V.
  - Low duty cycle
  - High rejection
  - High resolution

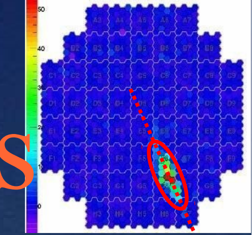
Detailed study of a few sources



- Sampling experiments (Water Cerenkov, Particle Arrays,…)
  - Large F.O.V.
  - High duty cycle
  - Poor rejection
  - Poor resolution

Long term survey instruments

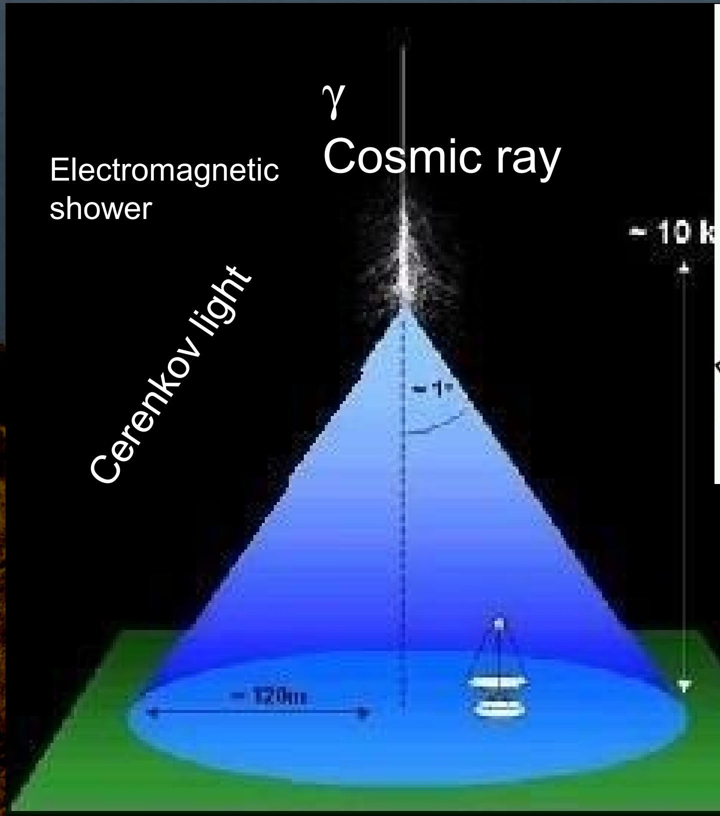


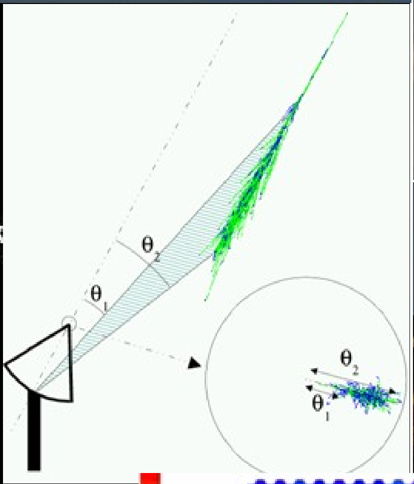


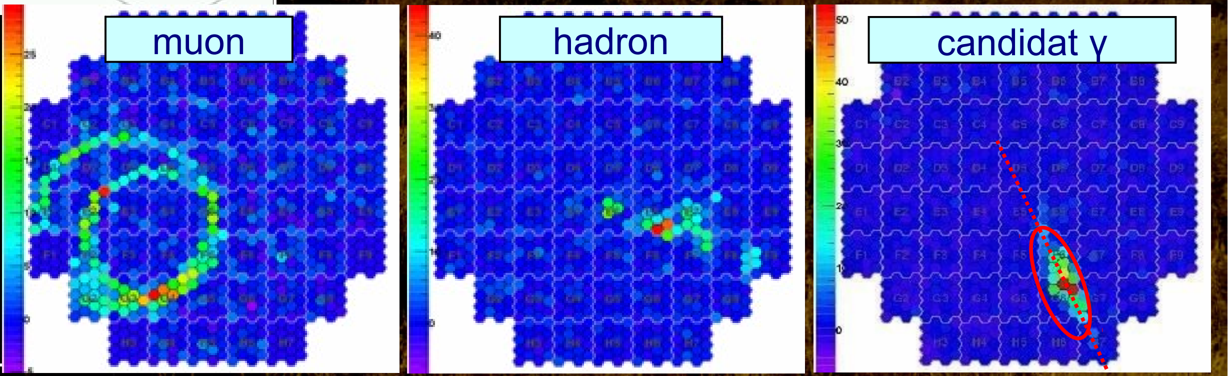
Atmospheric Cherenkov Telescopes

- Cherenkov light-pool ~ 120 m
- Image the shower on a fact camera (ΔT ~ 2ns)
- Large effective area (10^5 m^2) even with modest reflector

- Key parameter : speed (< 10 ns)
- Image shape used in discrimination

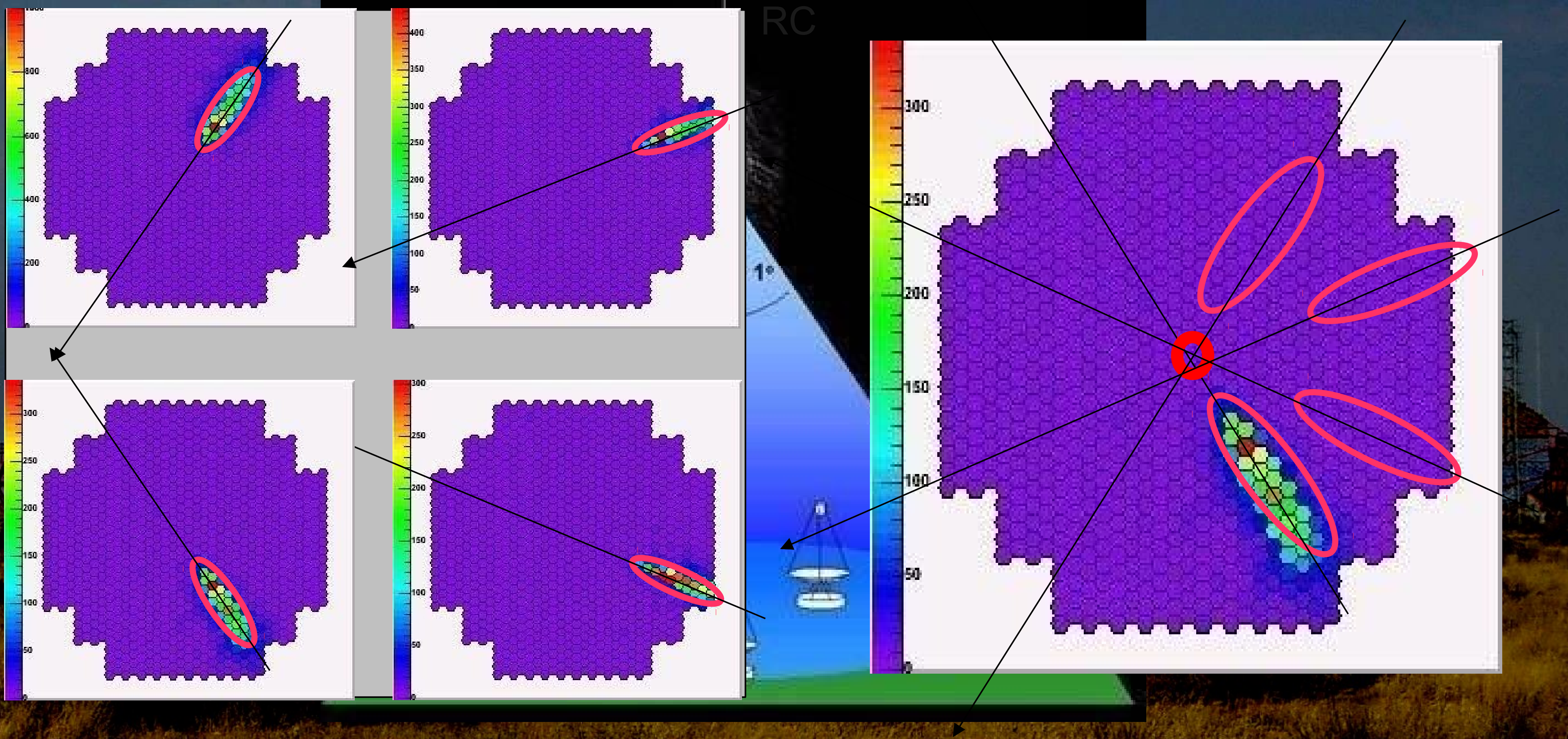






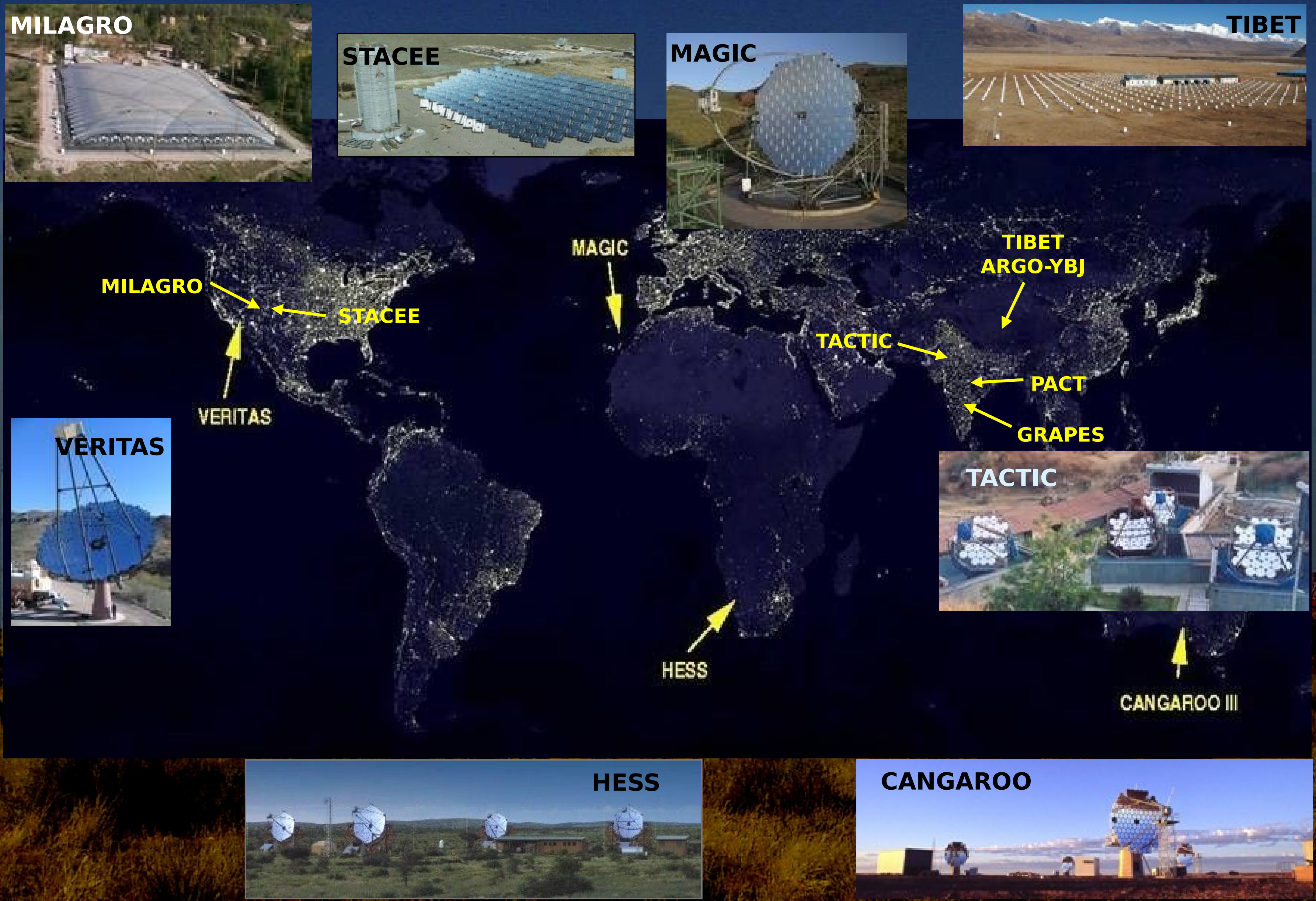
Stereoscopic technique (Hillas)

- Direction reconstruction by geometrical intersection of image main axes (in reciprocal space)



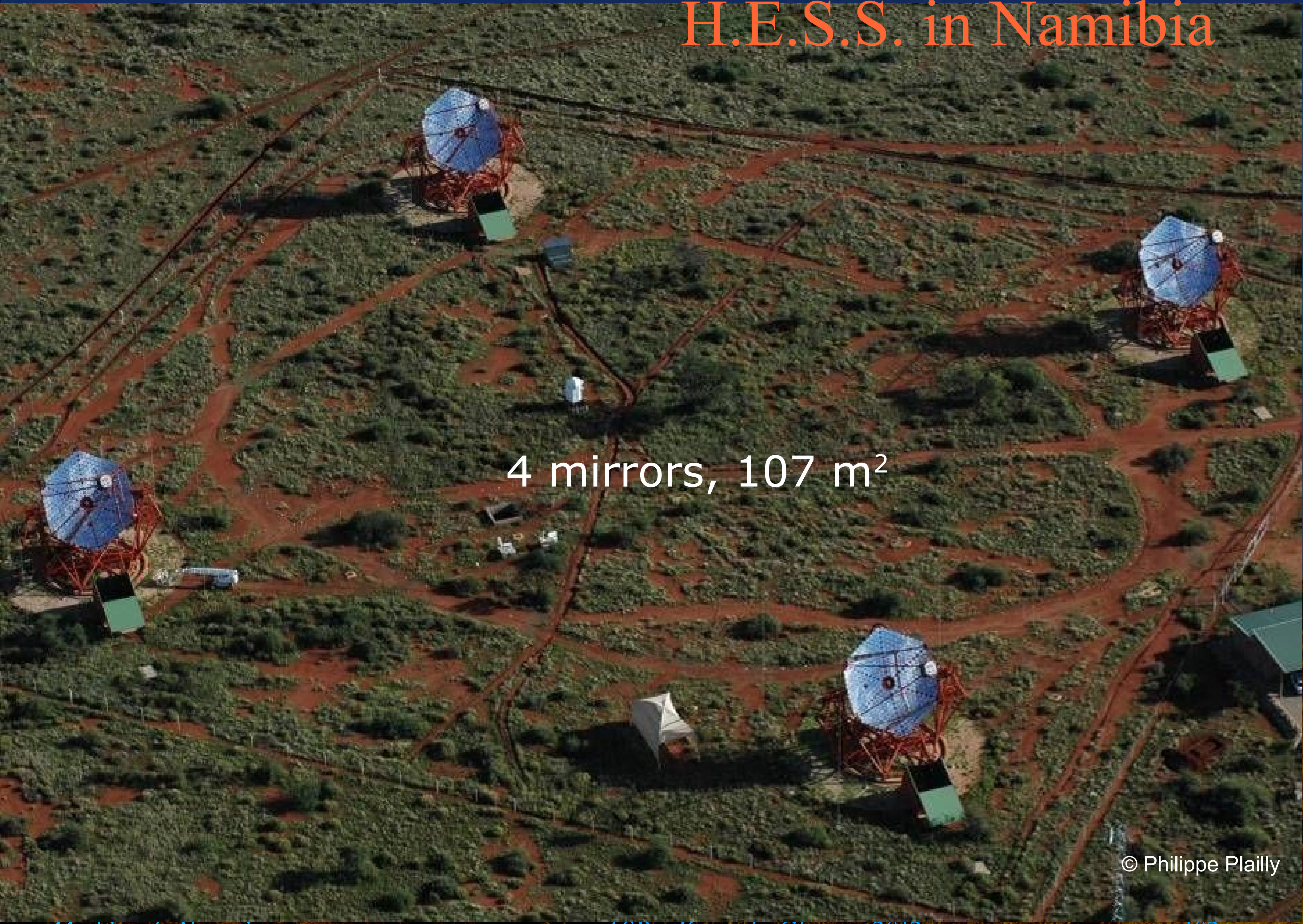
- Energy from comparison of image intensity with simulations
- Discrimination from image shape (width)

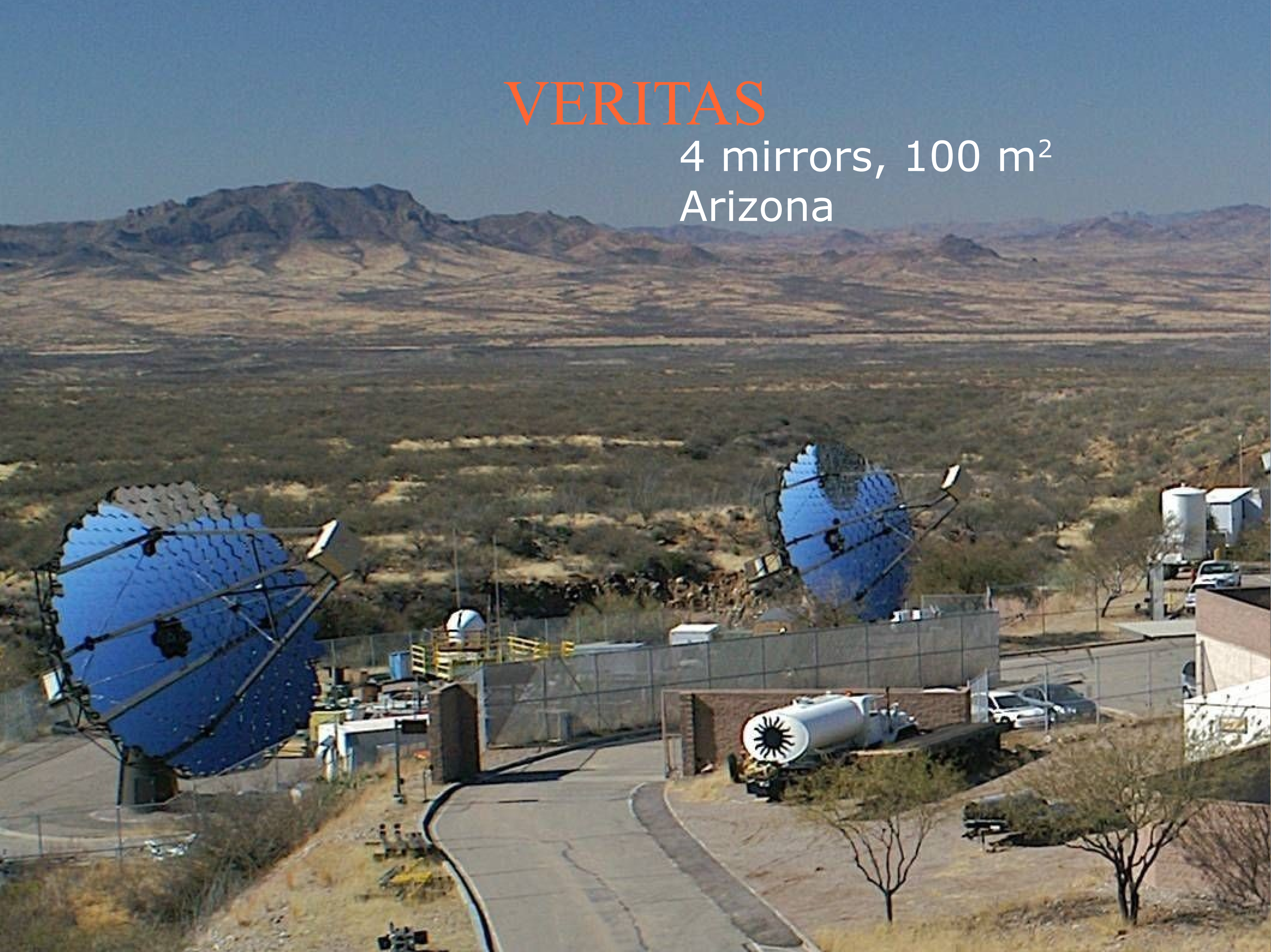
VHE γ-Ray world




MAGIC @ La Palma
mirror 240 m²

H.E.S.S. in Namibia




VERITAS
4 mirrors, 100 m²
Arizona

MAGIC II – Canary Island (commissioning)

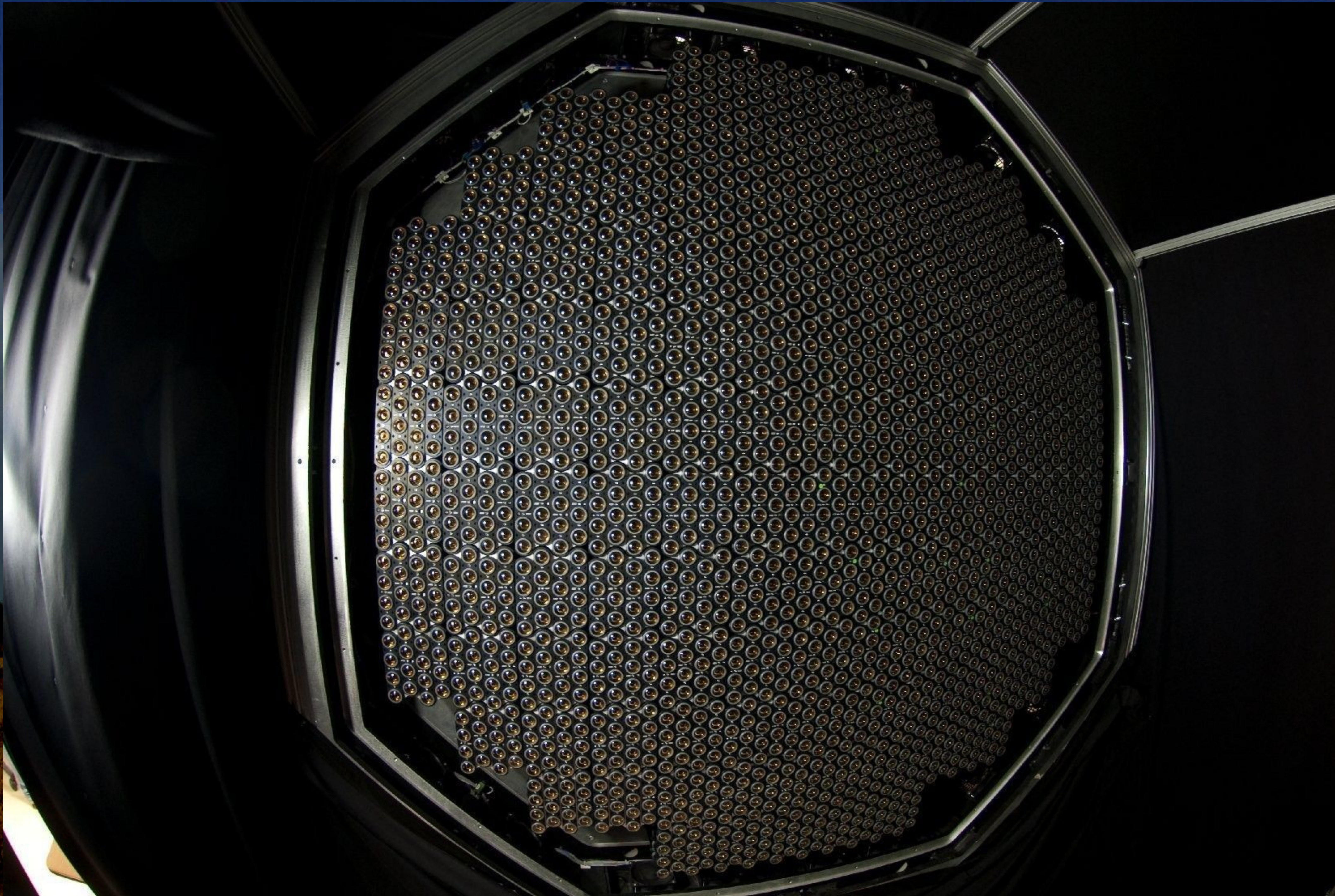
H.E.S.S. Phase II

One additional 600 m², 2012

September 2009

HESS – II

HESS-II First light: July 10th 2012



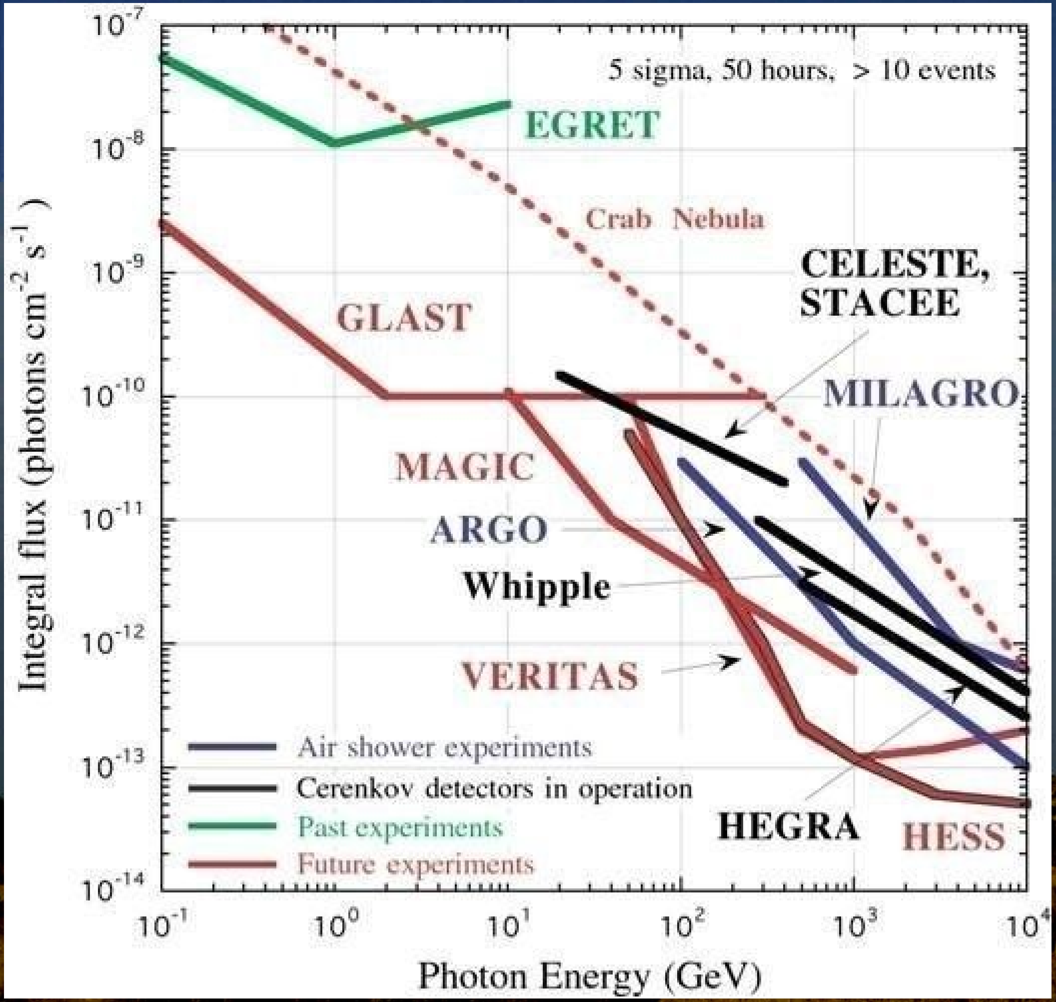
Imaging Telescope

Experiment	Number of Telescopes	Reflector size	Site
CANGAROO III	4	10	Australia
HESS I	4	12	Namibia
MAGIC	1→2	17	Canaries
VERITAS	2→ 4	12	Arizona
HESS II (2012)	4 (HESS I) +1	28	Namibia

Imaging Telescopes

Experiment	Number of pixels	Pixel size	Field of view (Ø)
CANGAROO III	552	0.115°	3°
HESS I	960	0.16°	5°
MAGIC	396+180	0.08°-0.12°	4°
VERITAS	499	0.15°	3.5°
HESS II	2048	0.1°	3°

Complementarity with satellites



	Ground	Space
Angular Resolution	~ 0.1°	1° ⇒ 0.1°
Energy Resolution	~15%	~10%
Effective Area	10^5 m^2	~ 1m^2
Field of View	a few °	~ 2 π sr
Rejection	~ 10^2, limiting factor	Excellent

- Two techniques are very complementary

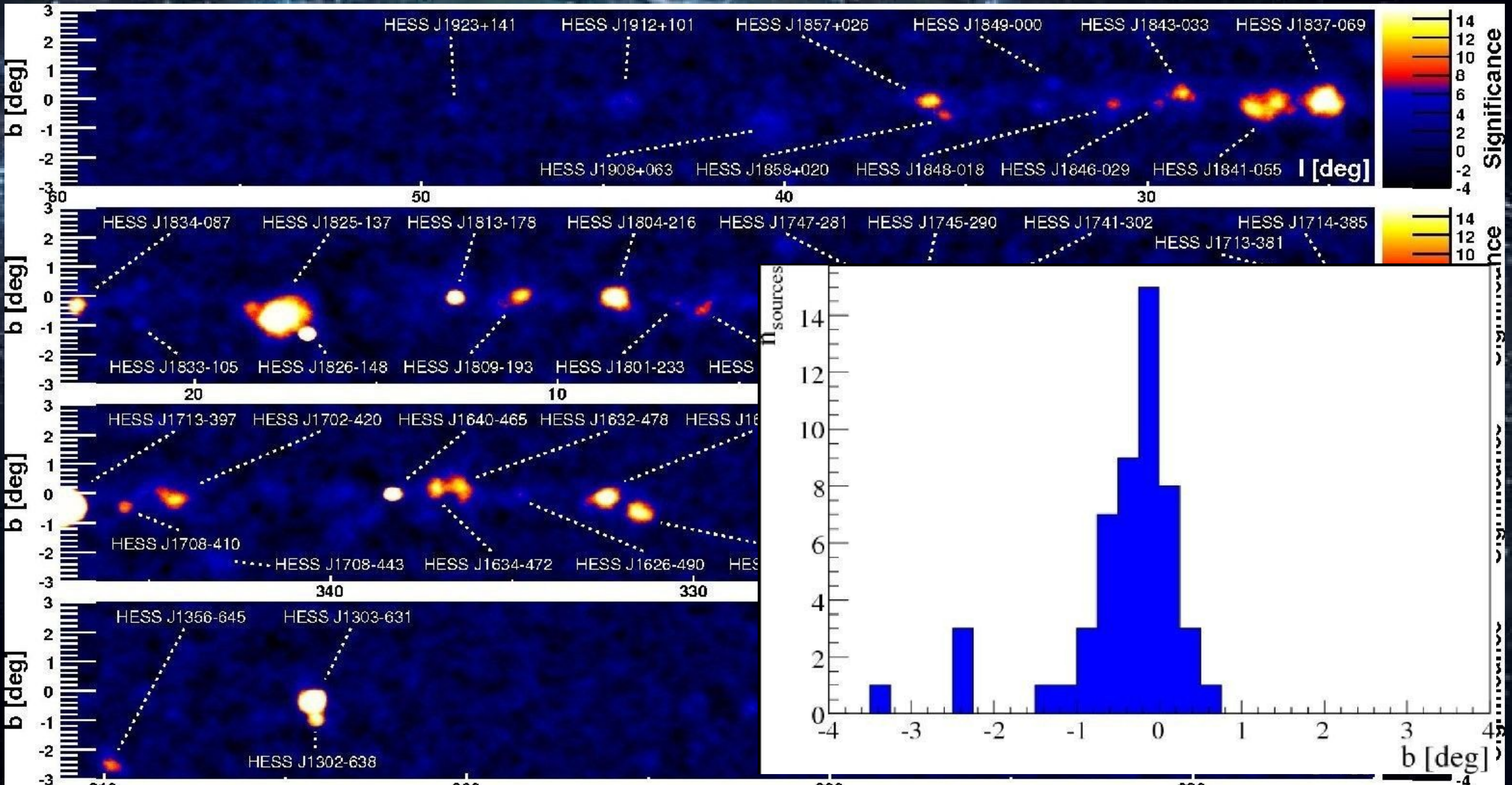
H.E.S.S. Galactic Plane Survey

Inner part of the Galaxy: |b|<3°, -80 < l < 60°, 1400 h of data + dedicated pointing

56 sources, very narrow distribution (RMS(b) ~0.3°)

⇒ Molecular gaz scale, young sources

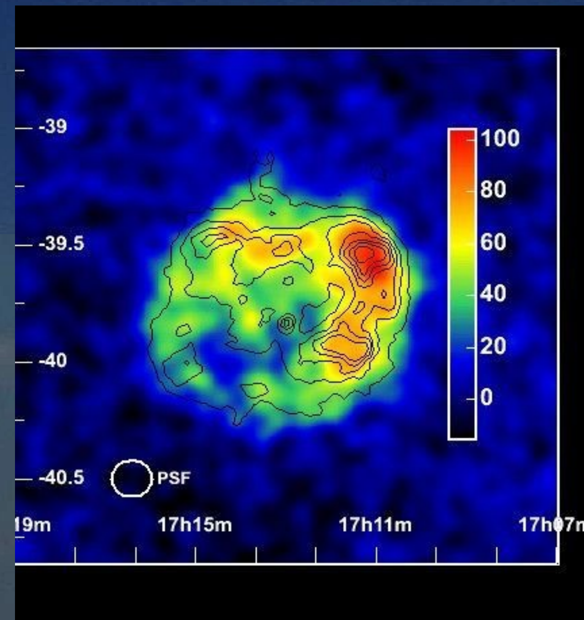
Population: PWN (29), SNRs (9), Binary systems (3), Dark sources, Interacting stellar winds,...

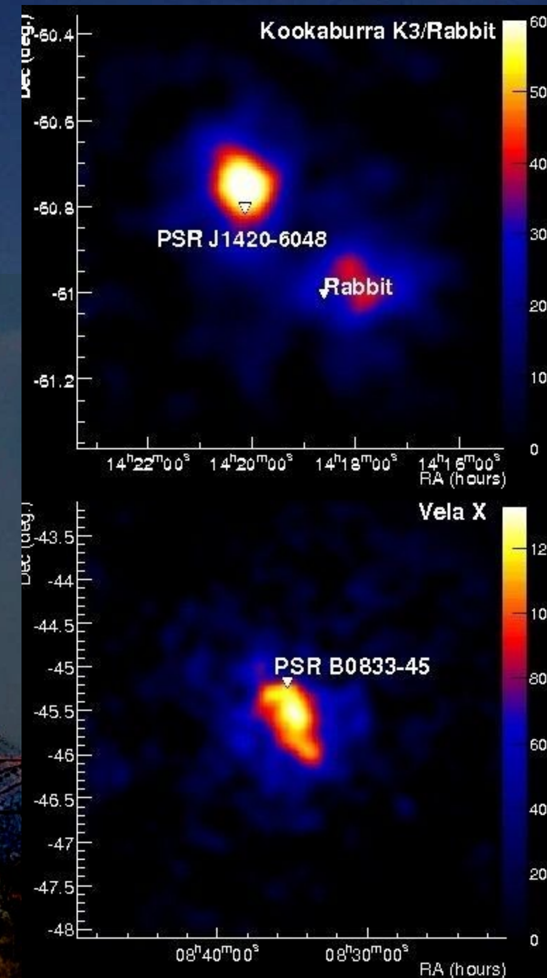


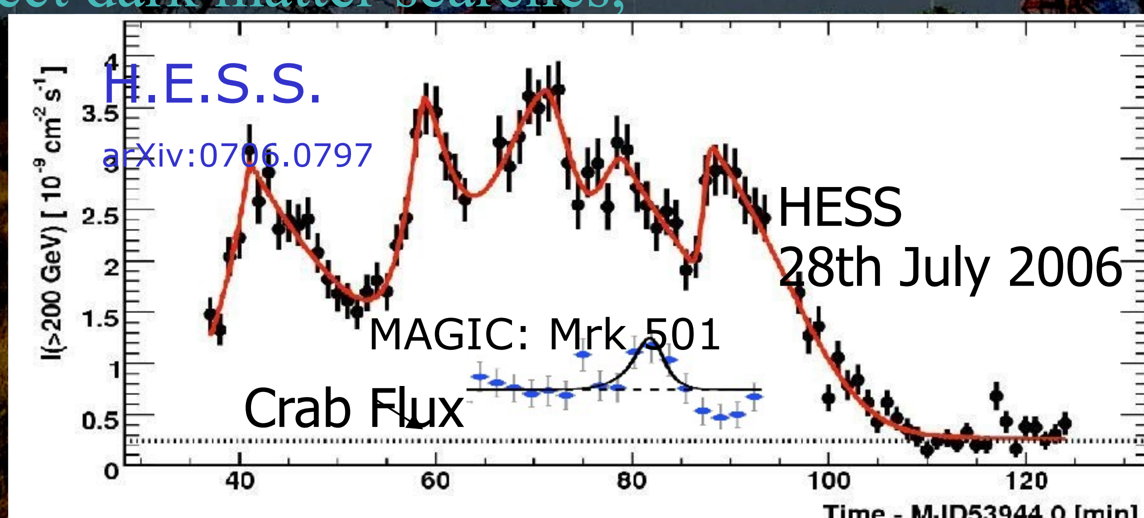
k A. Garlick / space-art.co.uk

Results

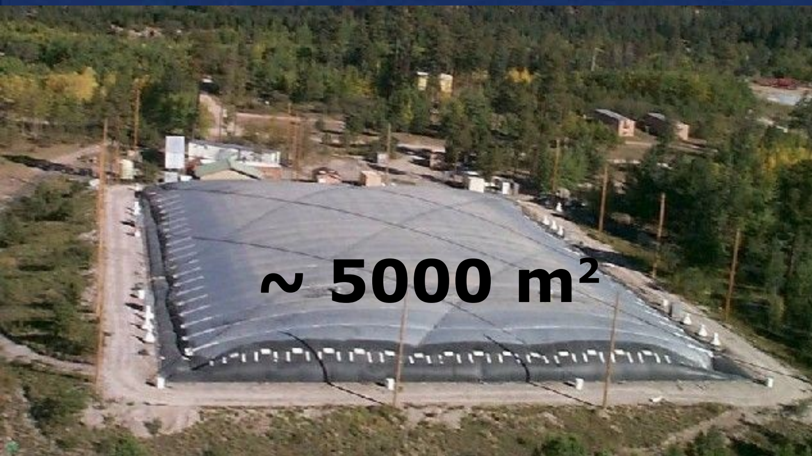
- Wealth of results:
  - Supernova remnants
  - Plerions
  - Galactic Center
  - Binary Systems
  - Interacting Stellar Winds
  - Starburst galaxies
  - Huge flares from blasars, Tests of Lorentz Invariance
  - Indirect dark matter searches,
  - ….

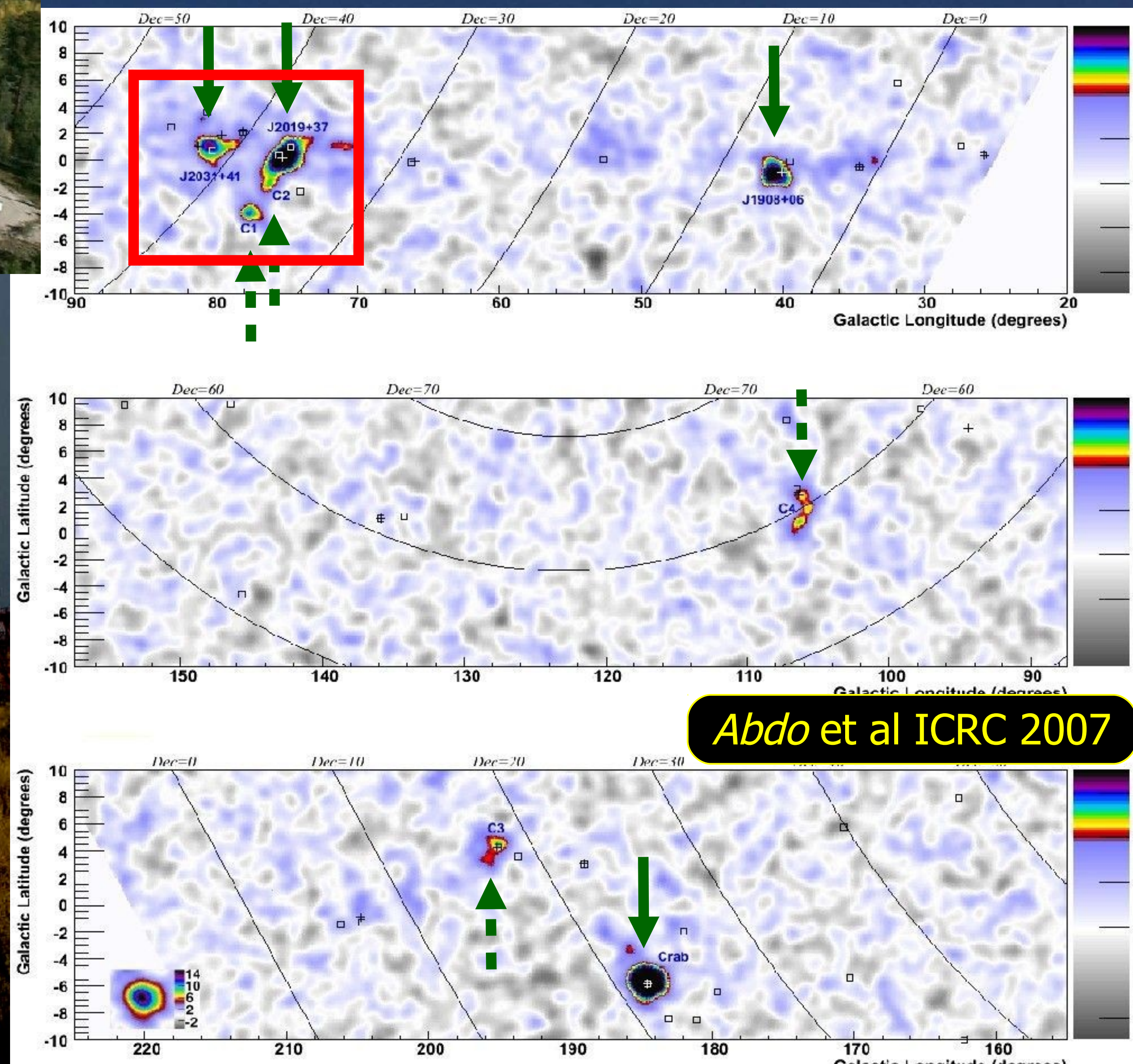






Milagro Northern Sky Survey



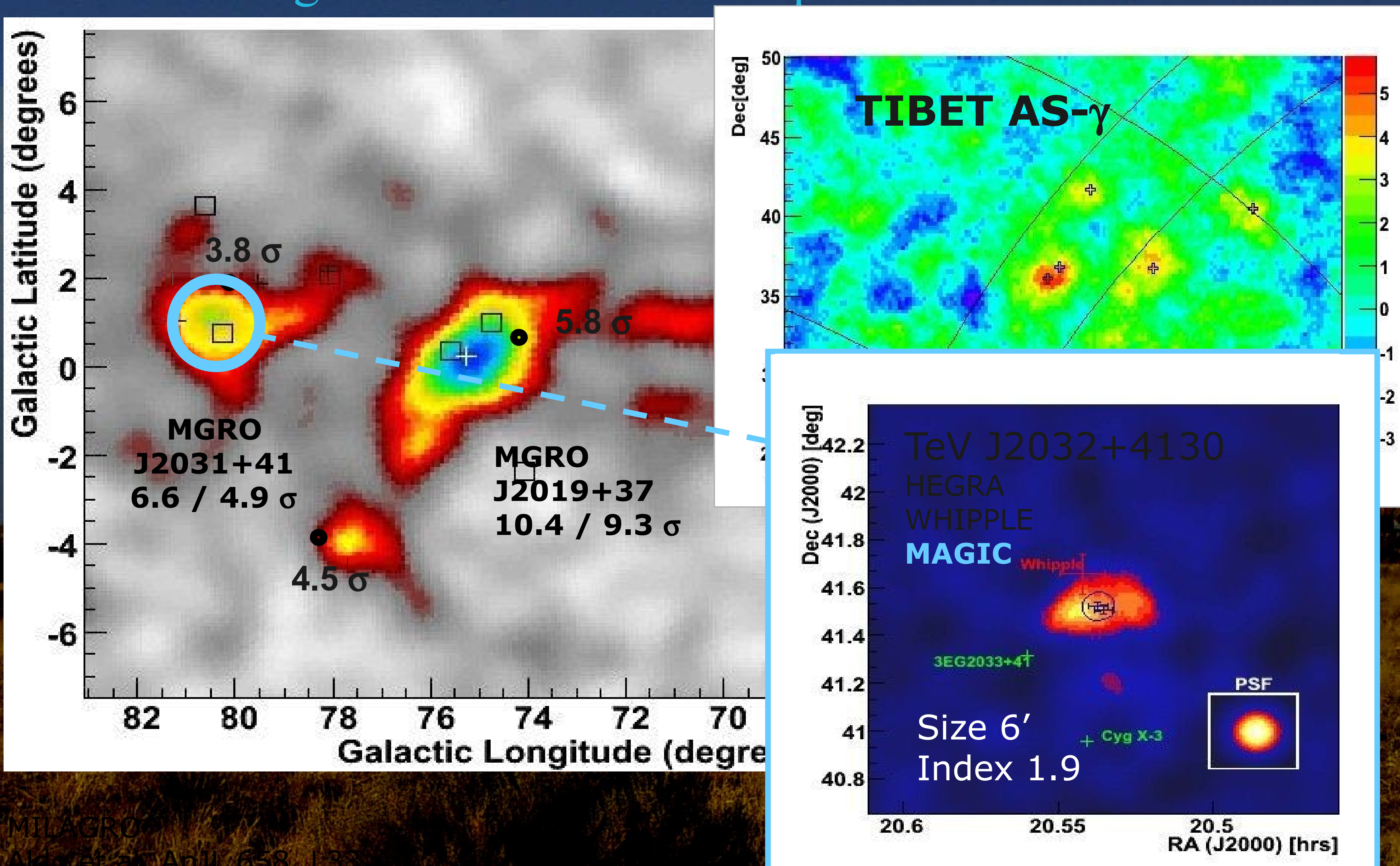


Abdo et al ICRC 2007

- Survey instruments start producing results
  - 7 year exposure
  - ~20 TeV median energy
  - 0.5° angular resolution
  - ~0.5 Crab sensitivity
- 3 significant new sources (all on galactic plane),
  - One with HESS counterparts
  - 4 interesting hotspots

The Cygnus region

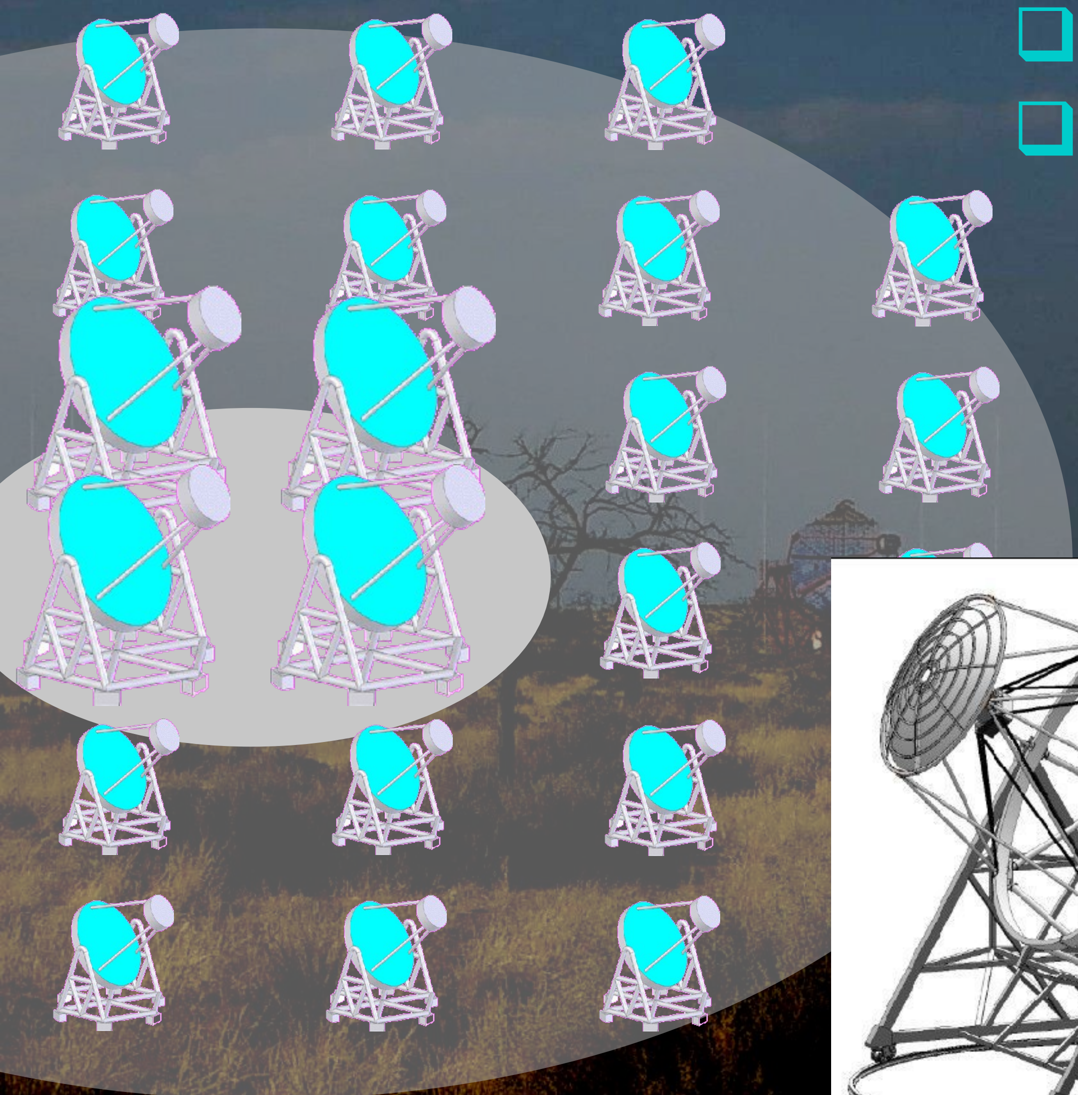
- Convergence of several techniques

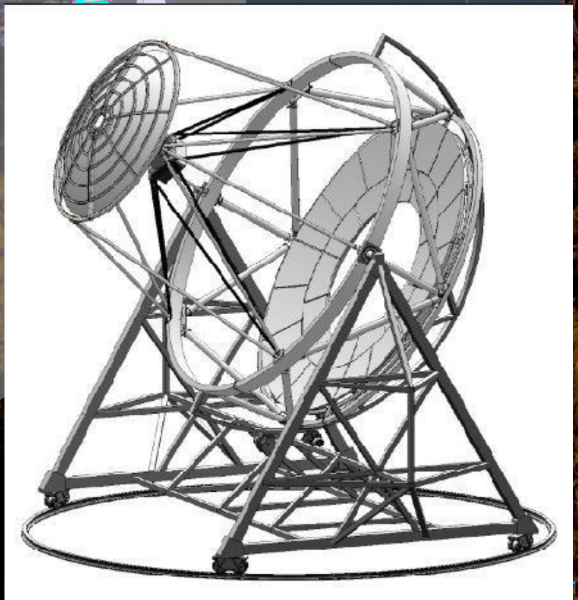


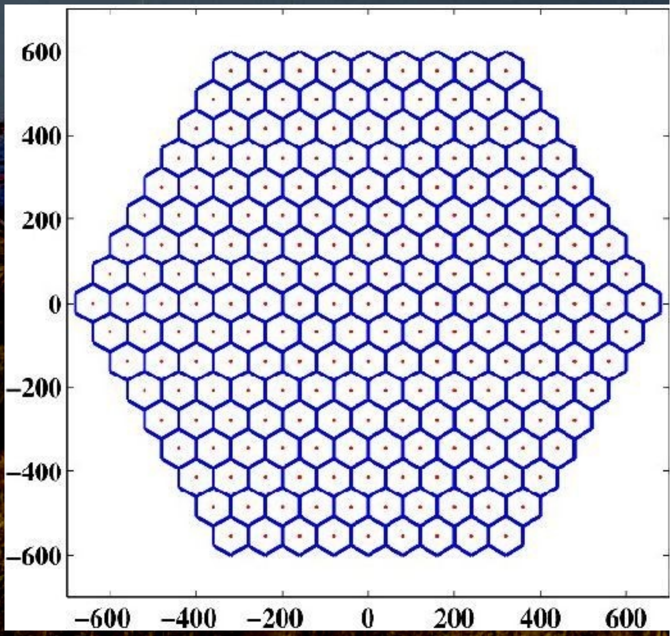
MILAGRO
Abdo et al. ApJL 658, L33

Longer term perspective (I)

- Large observatories (CTA, AGIS)
  - > 50 telescopes
  - Factor 10 in performances
  - Increased energy coverage

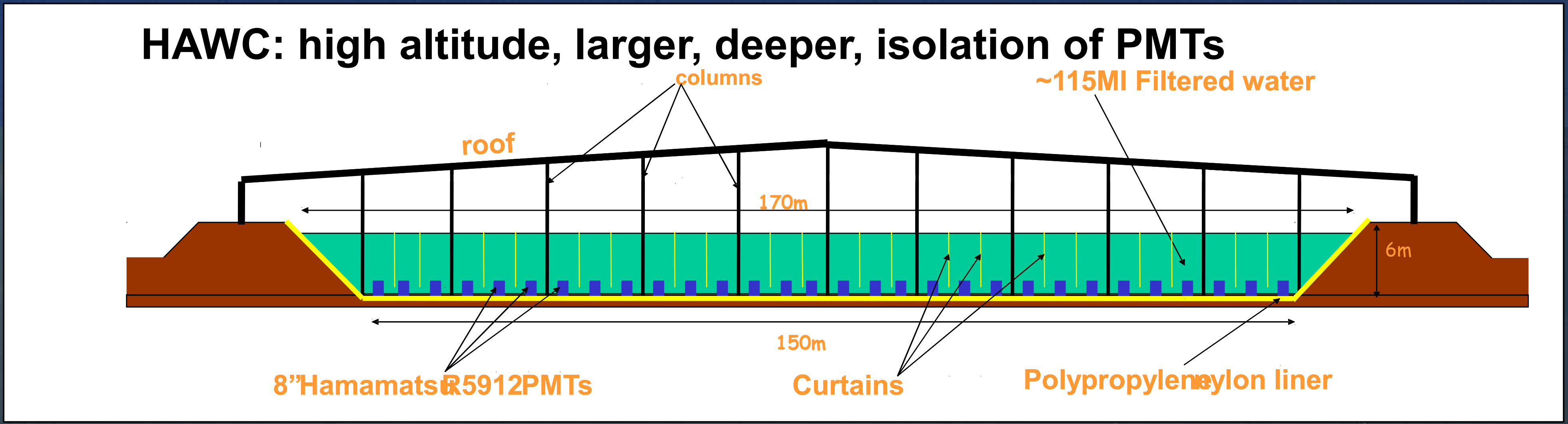




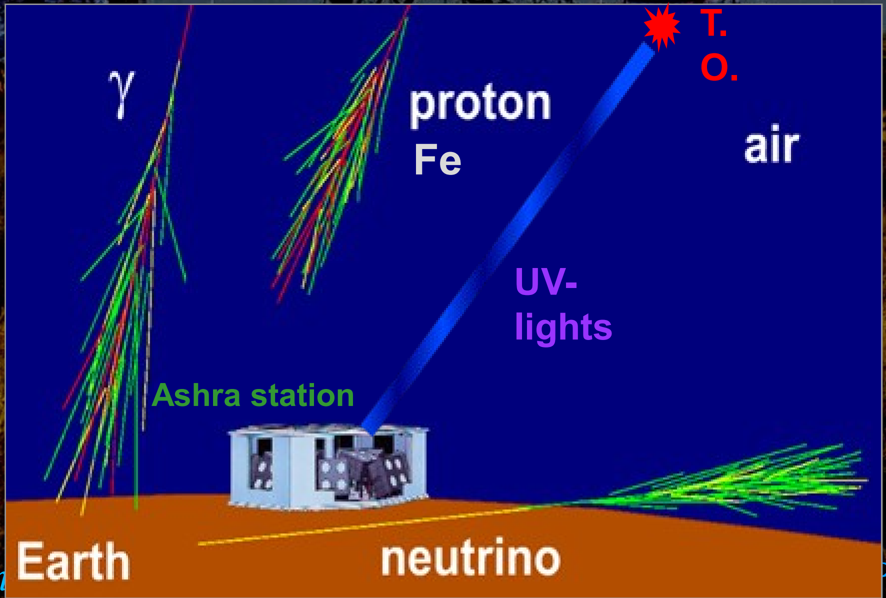


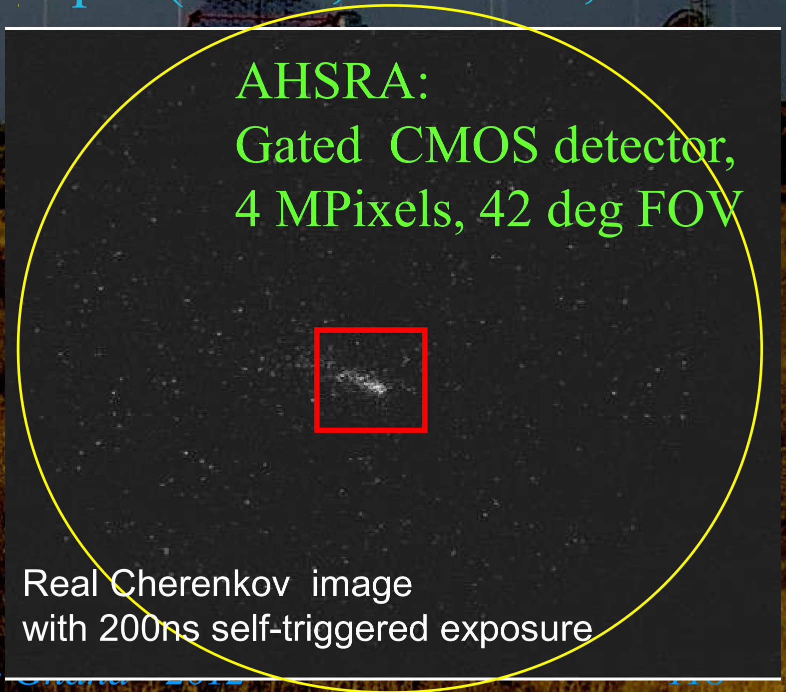
Longer term perspective (II)

- Large survey instruments (HAWC) should achieve a factor 15 in sensitivity



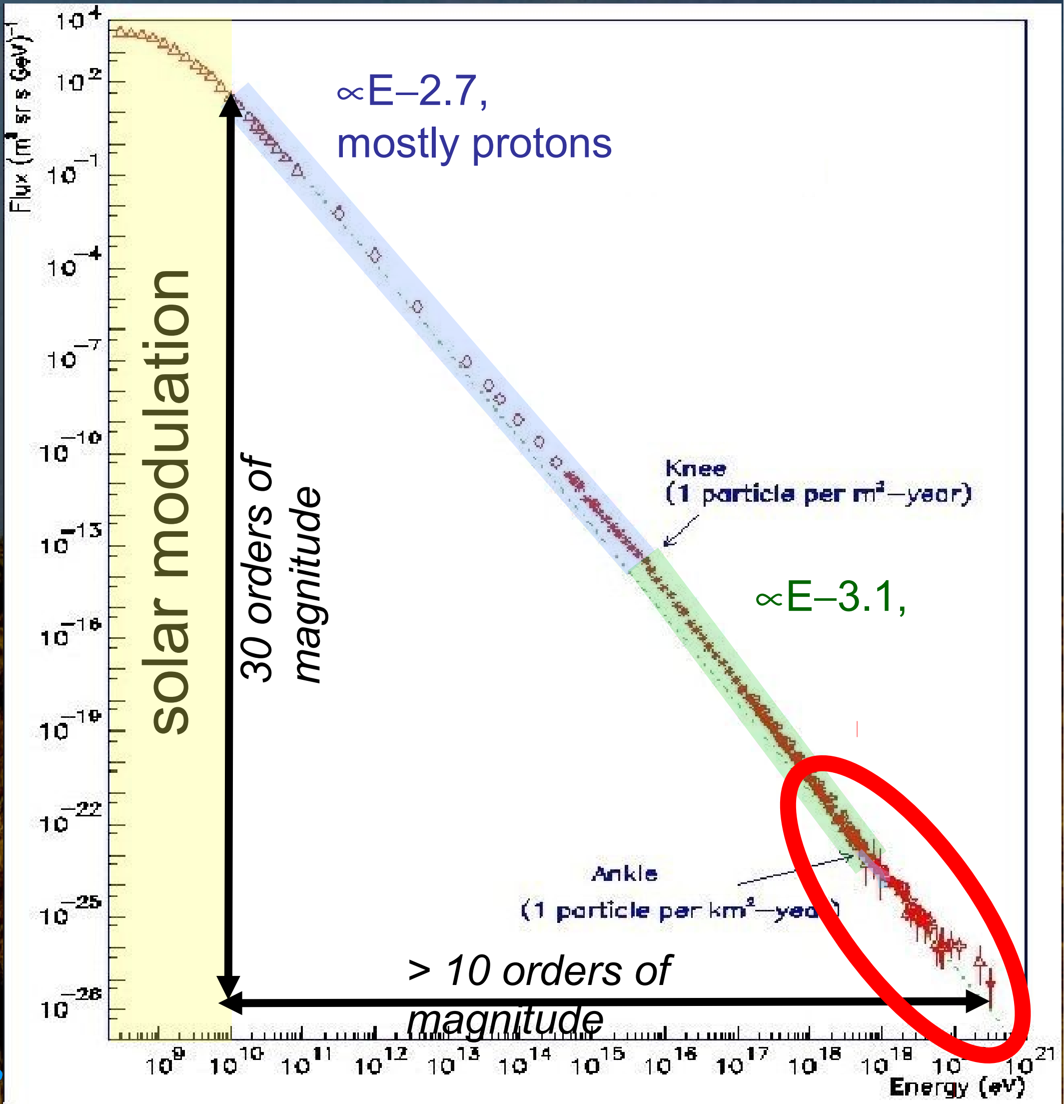
- Lot of technical activities to improve the technique (SiPM, CCDs…, Wide F.O.V. telescopes)





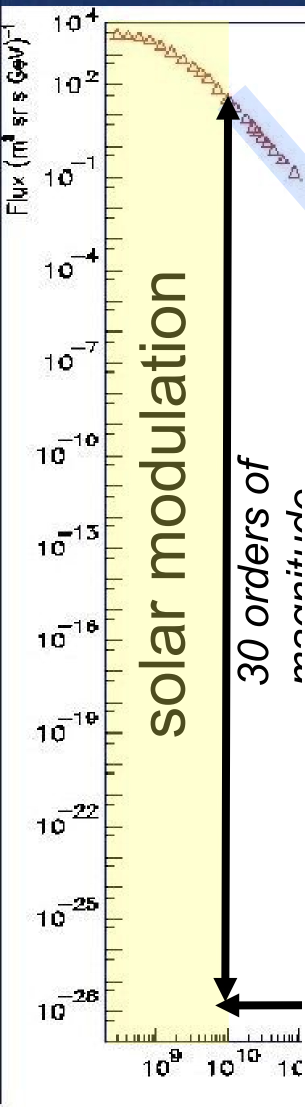
Ultra High Energy Cosmic Rays (UHECR)

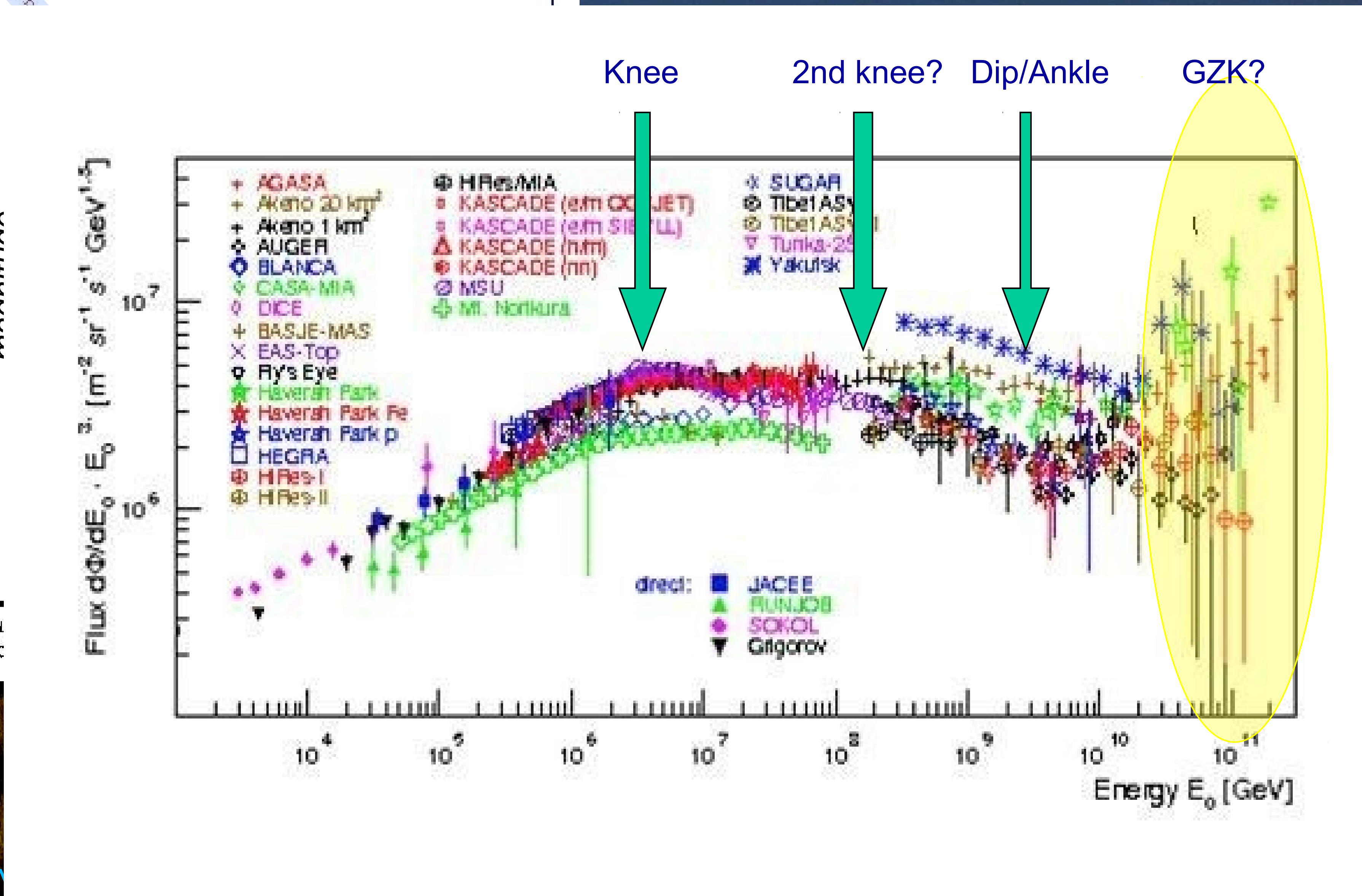
- Energy spectrum
- Composition
- Direction



Structures in the CR spectrum

- Somewhat messy picture
- Different experiments/techniques
- Many things to understand!

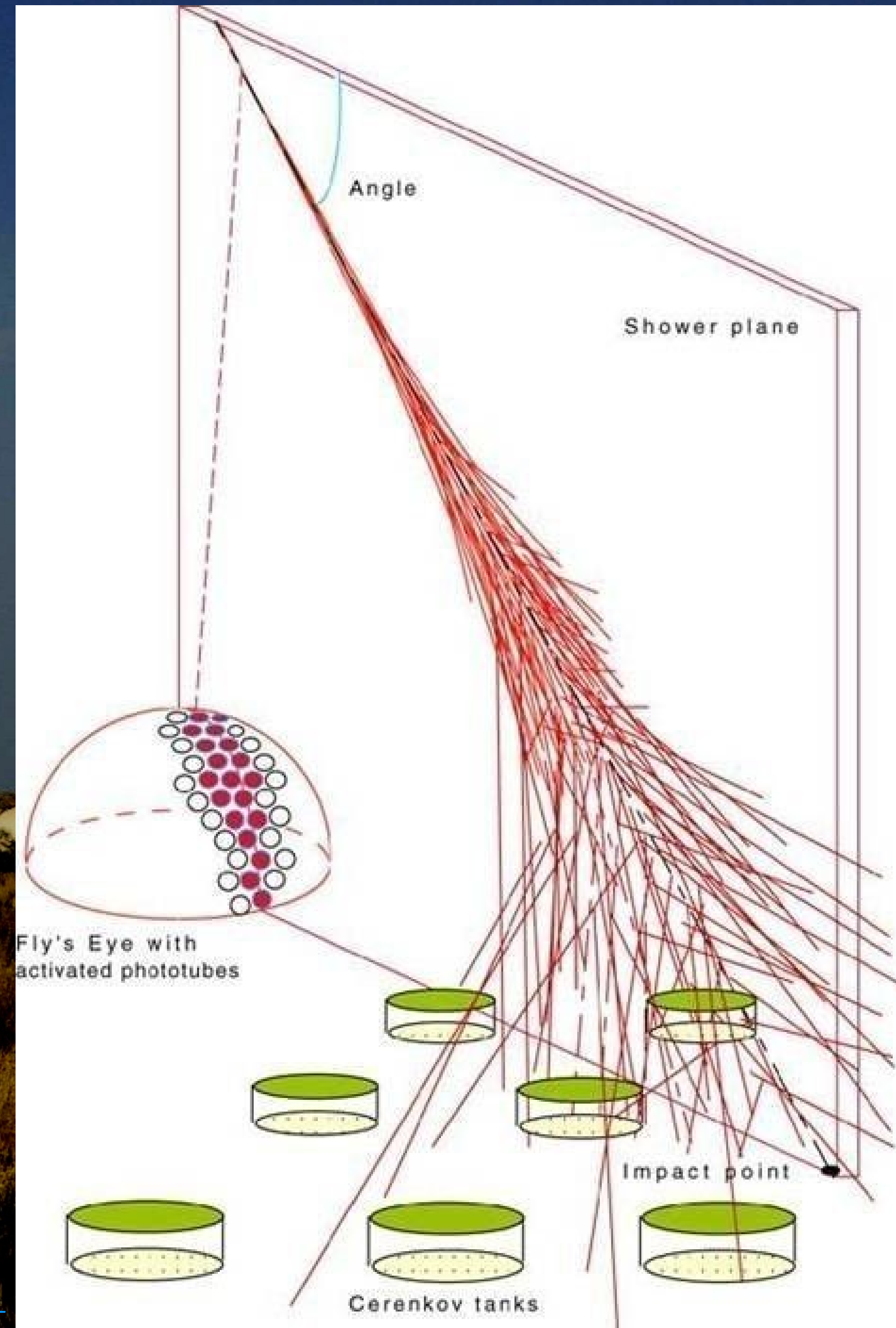




Detection of extended shower

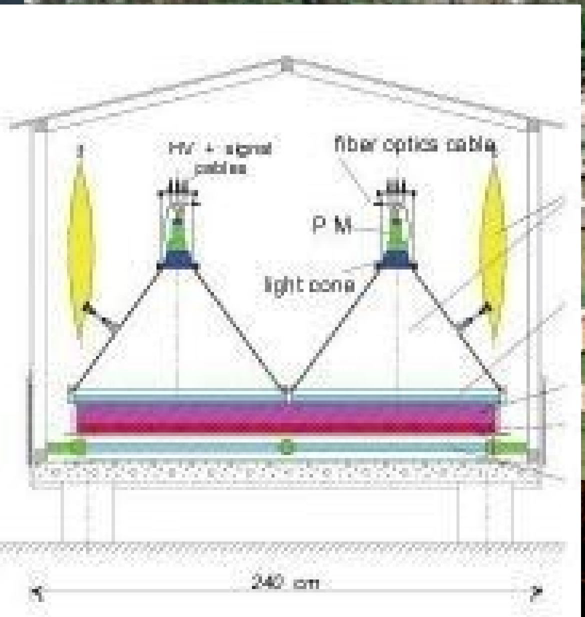
2 complementary techniques

- ❑ Detection of charged particles on the ground
  - ☑ 24h/24h duty cycle
  - ☒ Degraded information (shower tails)
- ❑ Detection of nitrogen fluorescence
  - ☑ Direct measure of shower development profile
  - ☒ 10% duty cycle (dark nights)



Surface Detector

- Charged particles in shower tail (e± & μ±)
  - Water Cherenkov tanks (e± & μ±) : AUGER
  - Scintillator arrays. Absorber $(20\ X_0)$ can be used to separately measure e±/μ± components



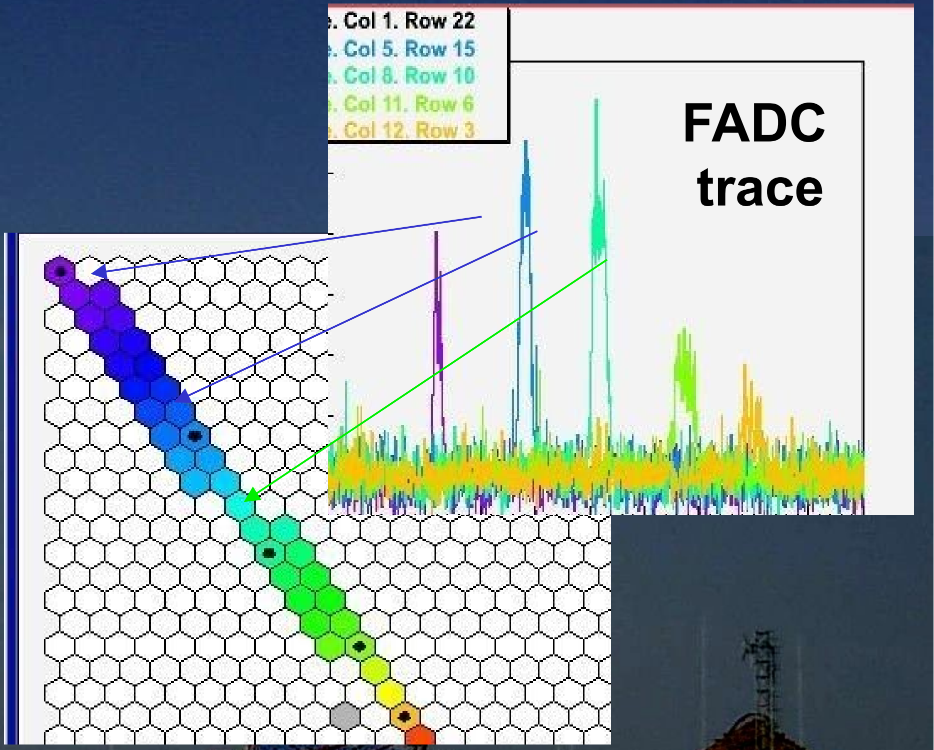
- Reconstruction relies on simulation
  - Hadronic Models
  - Detector geometry

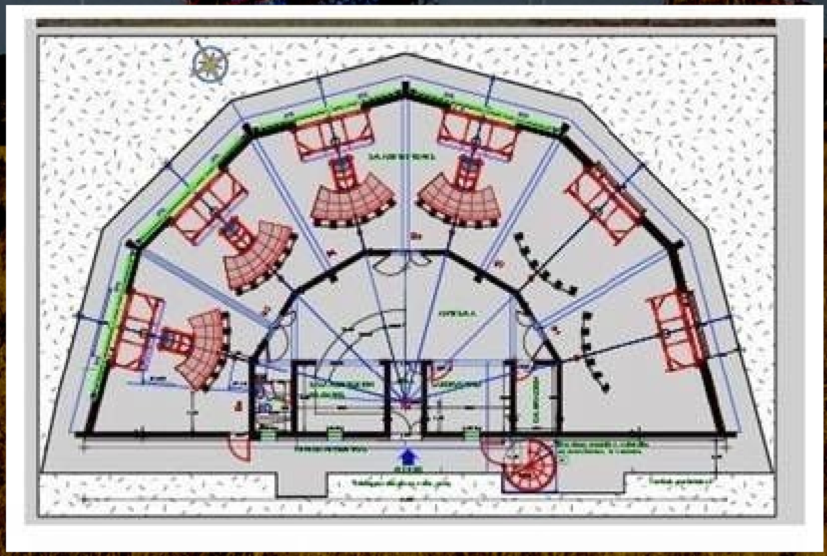
⇒ Poorly controlled systematics

Fluorescence Detector

- Nitrogen excitation, Molecular lines emission (2P from N^2, 1N from N^{2+}), proportional to ionization
- Isotropic emission (310-400 nm)
  ⇒ can be detected up to several 10 km
- Direct calorimetric measure
  ⇒ Longitudinal profile

- Stereoscopy ⇒ simple geometric reconstruction. Time sequence also usable
- Problems:
  - Fluorescence light yield poorly known. Depends on composition, humidity, ...
  - Atmospheric transparency
  - Need to subtract forward Cherenkov

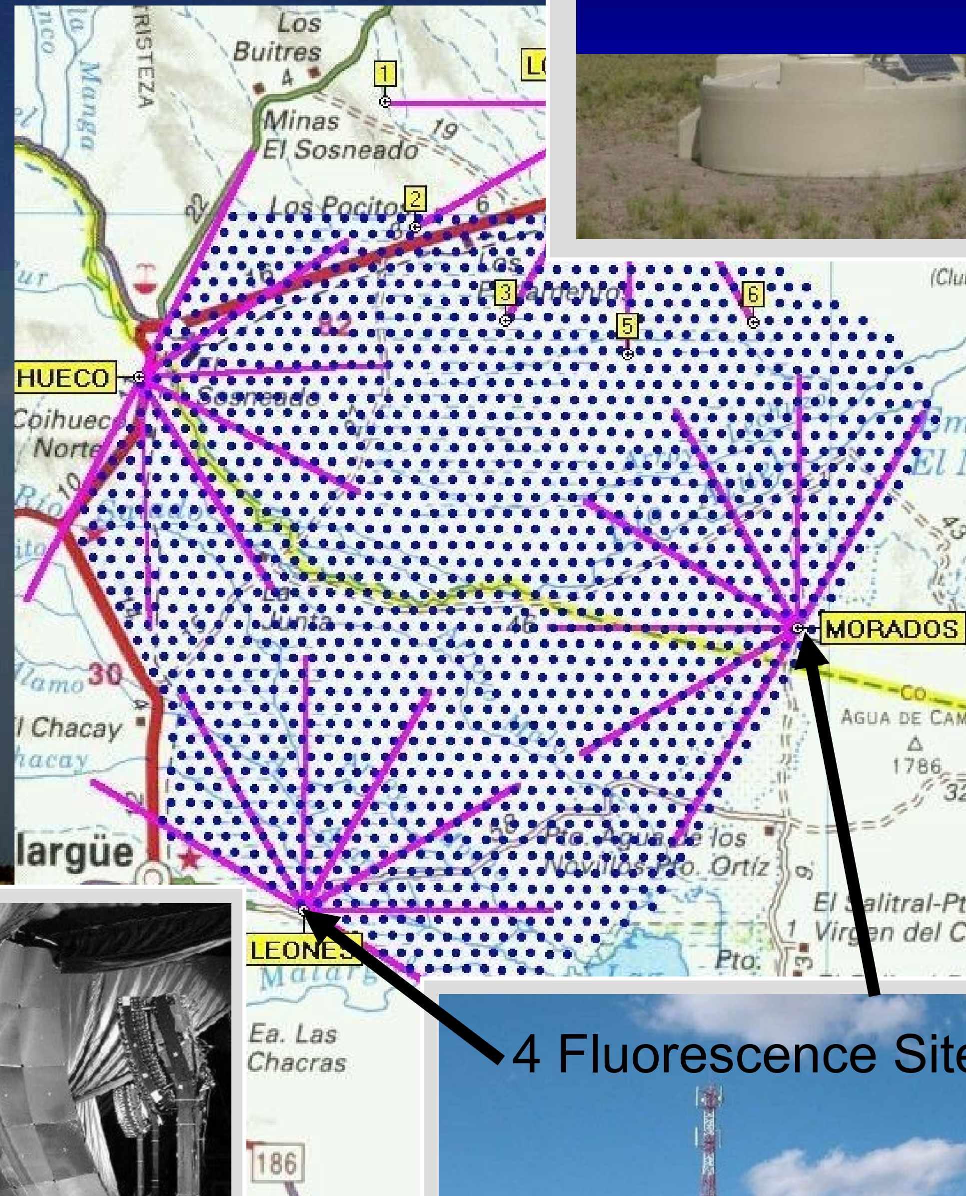


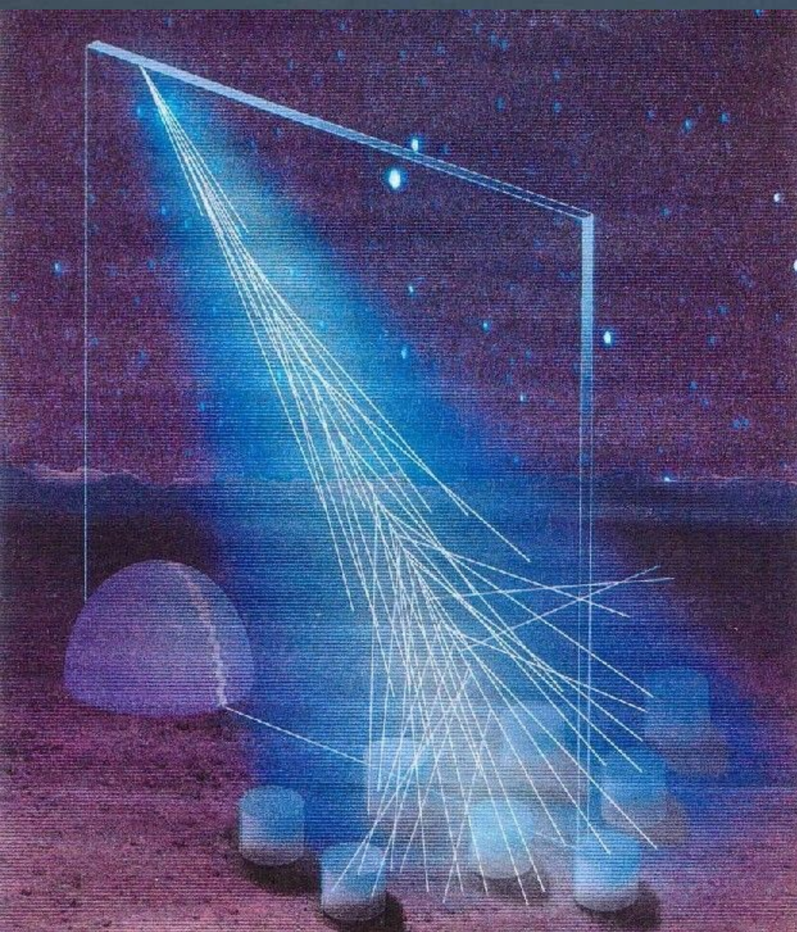


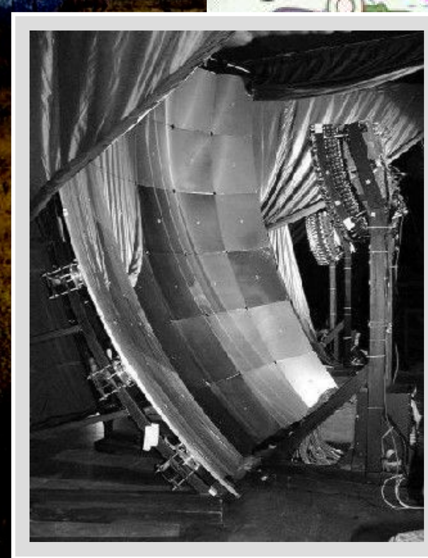
Experiments

Auger

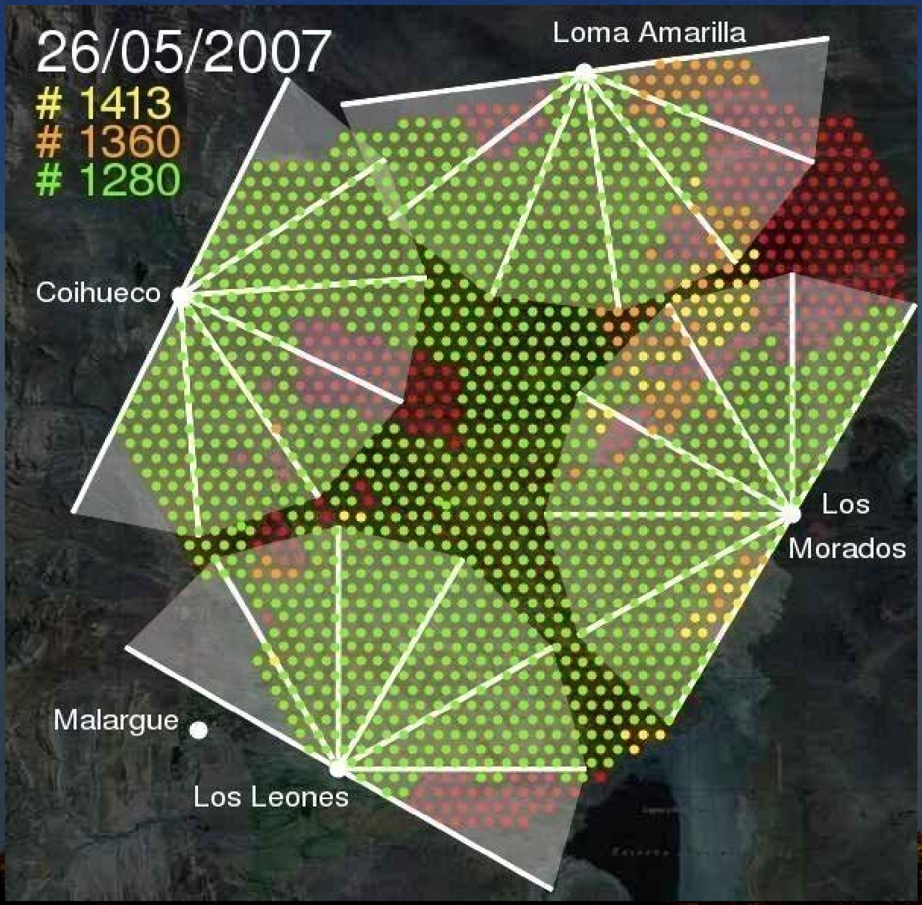
- Hybrid detector
  - 1600 tanks over 1000 km^2
  - 4 fluorescence detectors with 6 telescopes each

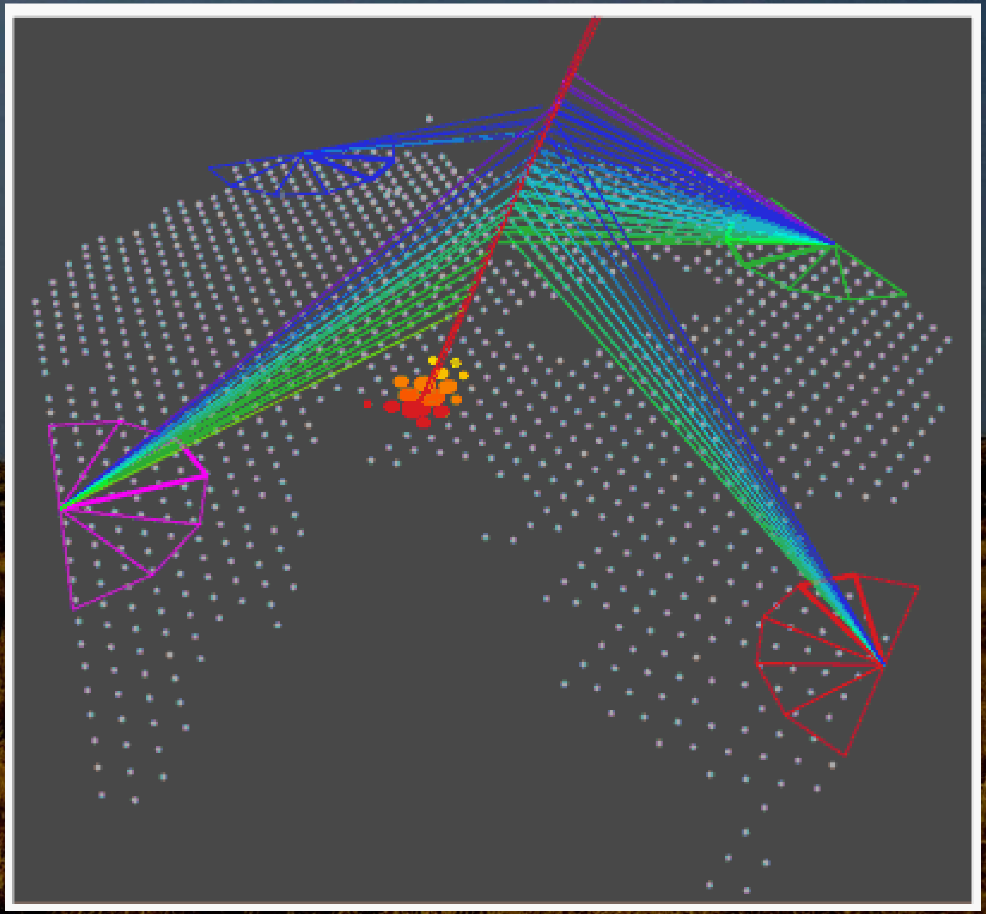




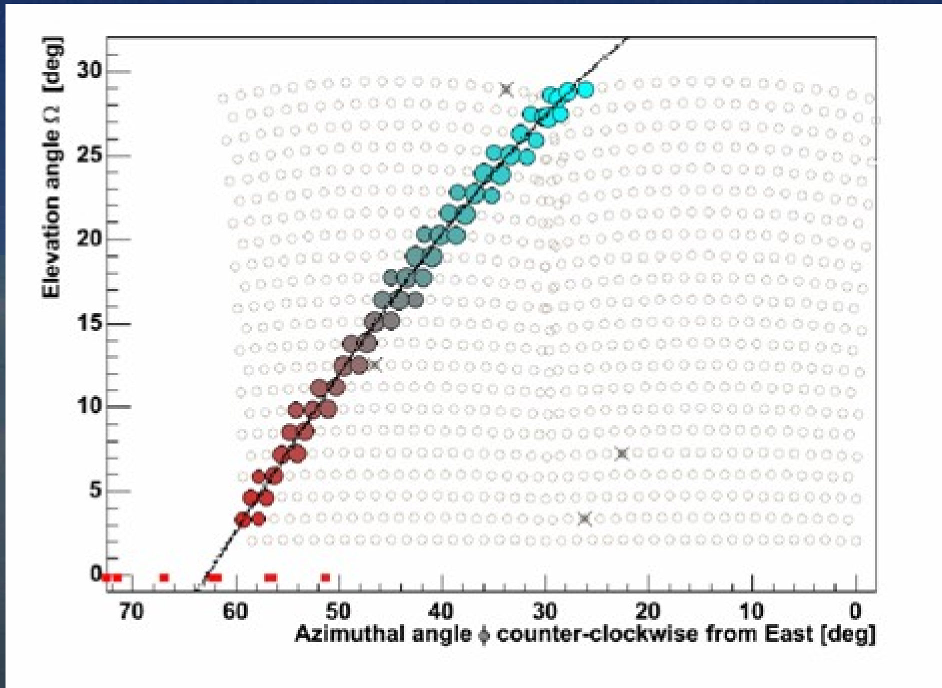


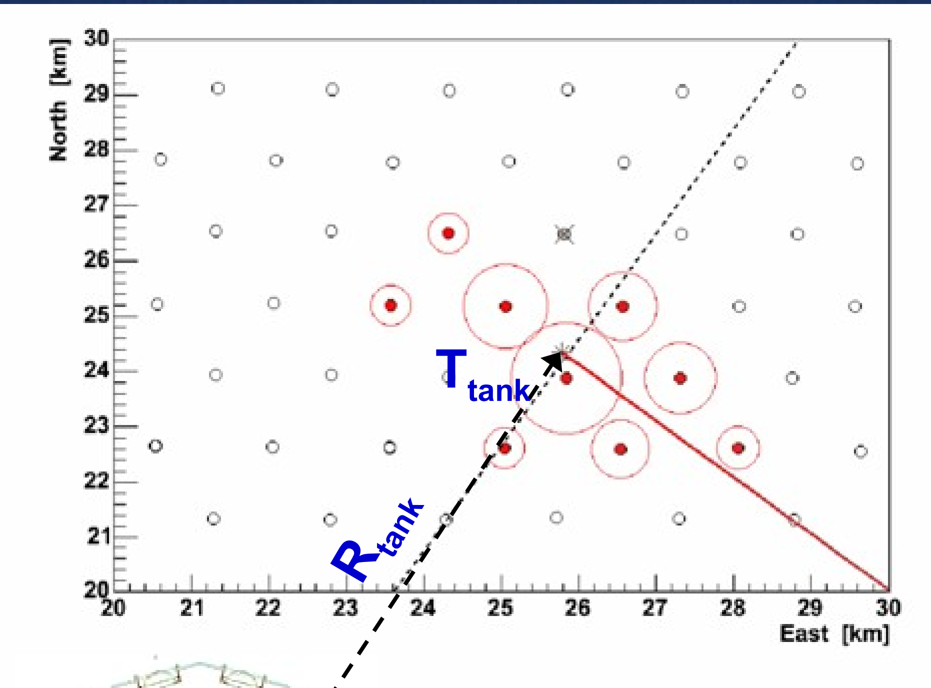
Quadruple Fluorescence Event

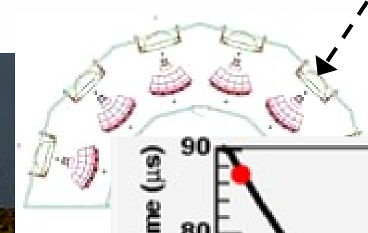


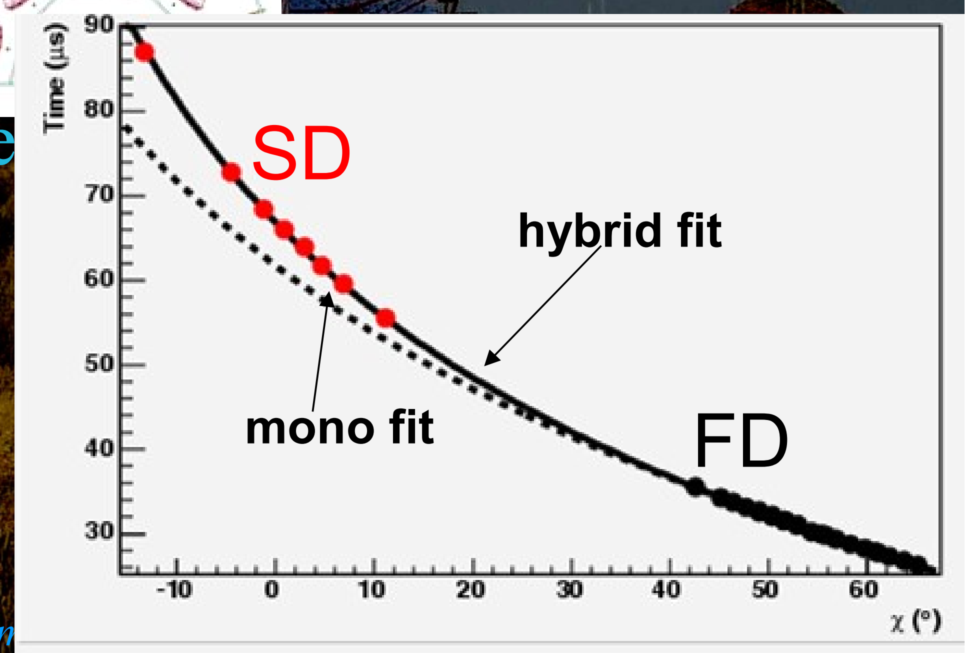


Hybrid Events



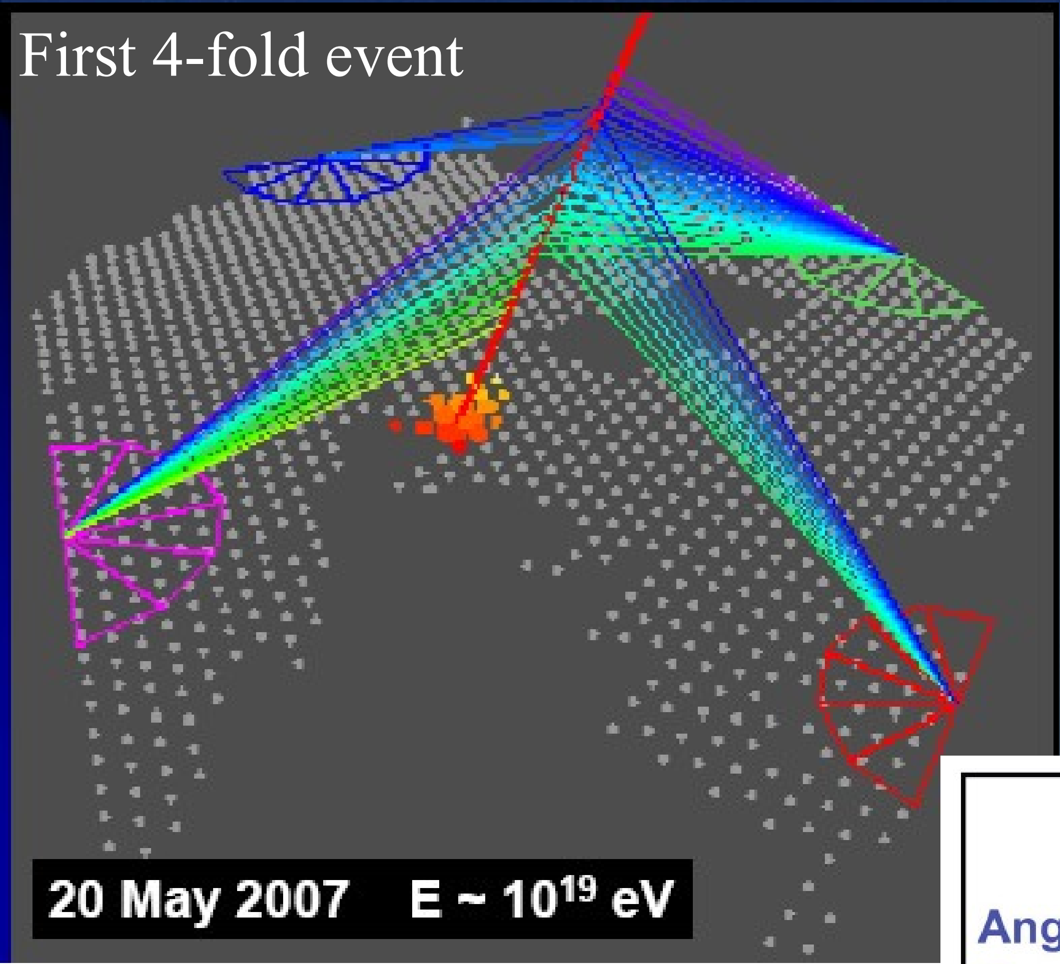


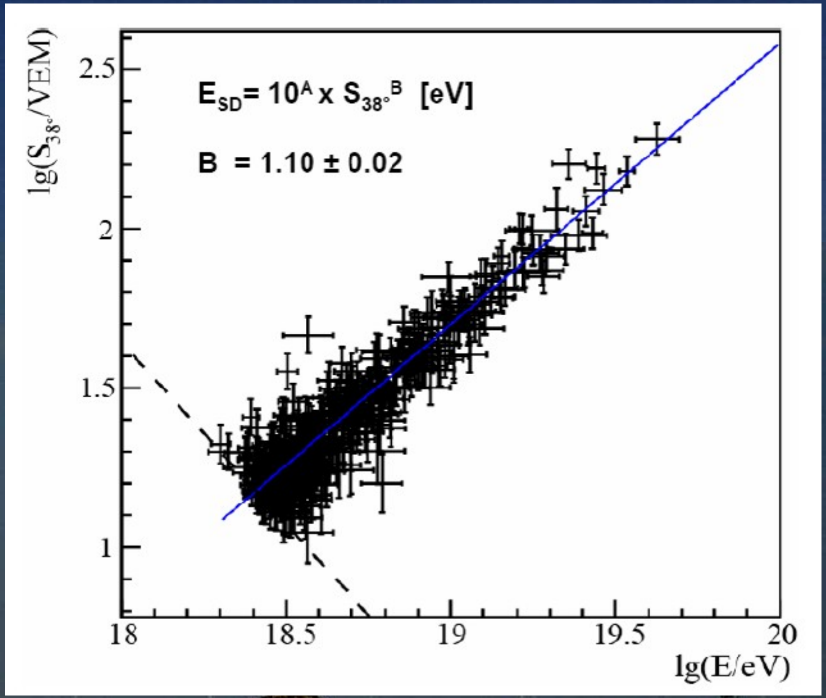




- FD: principal axis and time profile
- SD: measurement of time on the ground
- Combined fit improves core reconstruction

Hybrid Era





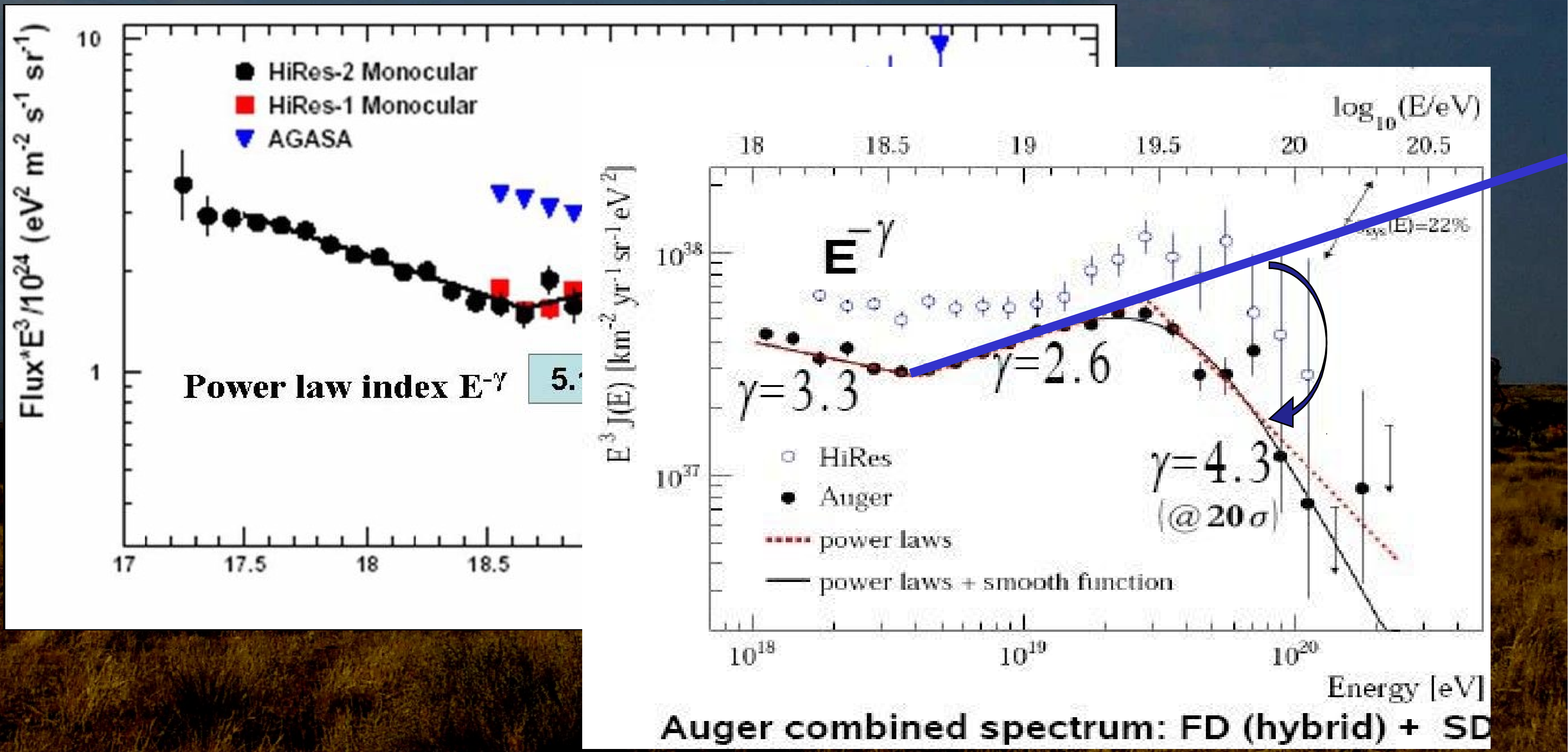
	Hybrid	SD-only	FD-only mono (stereo – low N)
Angular Resolution	~ 0.2°	~ 1 - 2°	~ 3 - 5°
Aperture	Flat with energy AND mass and model (M) free		E, A, spectral slope and M dependent
Energy	A and M free	A and M dependent	A and M free

- Cross-calibration SD-FD
- Improved resolutions
- Less model dependency
- Control on systematics

Mathieu de Naurois

Energy Spectrum

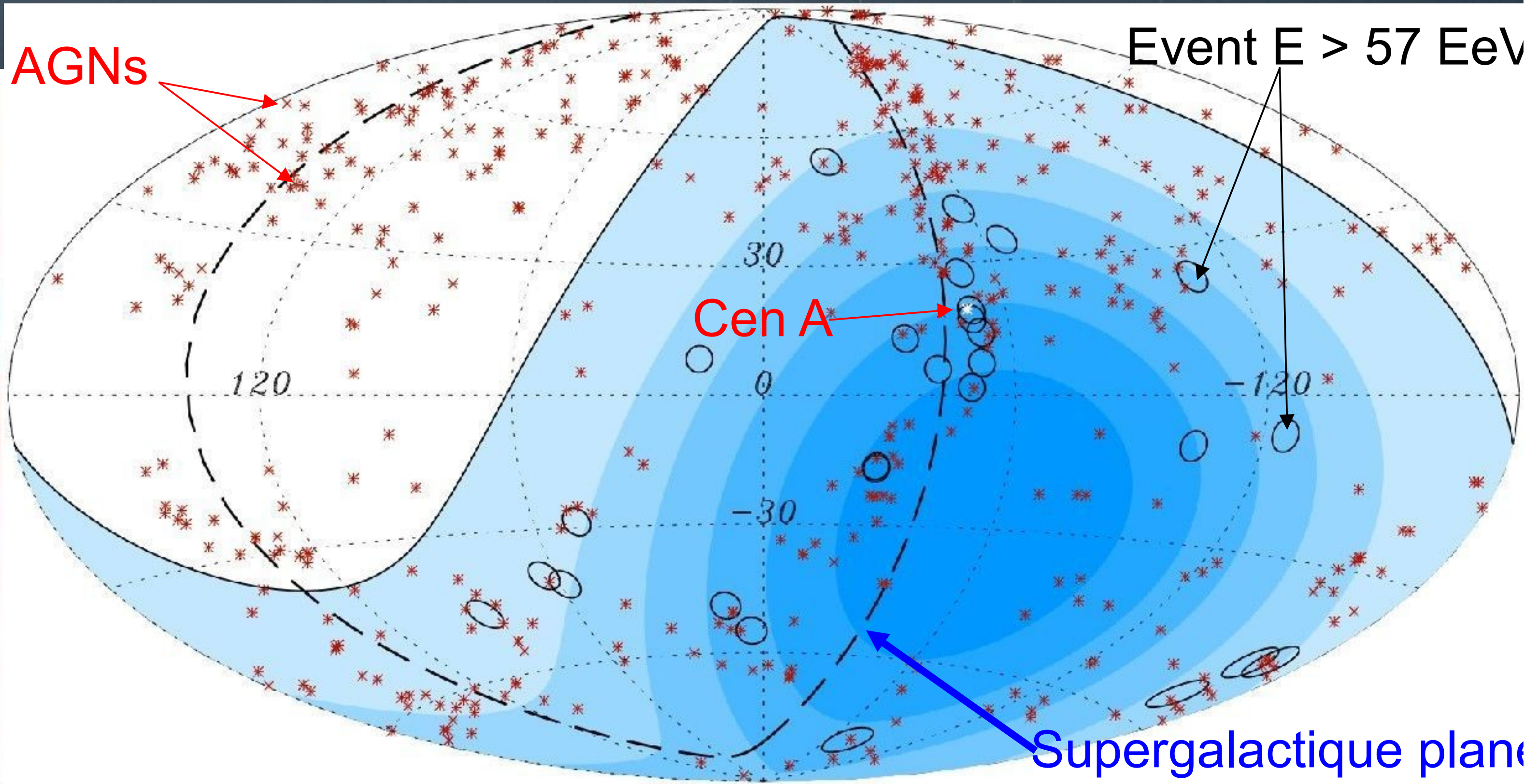
- Situation before Auger unclear
- FD / SD intercalibration on hybrid events
- Confirmation of a cutoff @ $10^{19.7}$ eV (20 σ effect)



Did we find the sources of UHECRs ?

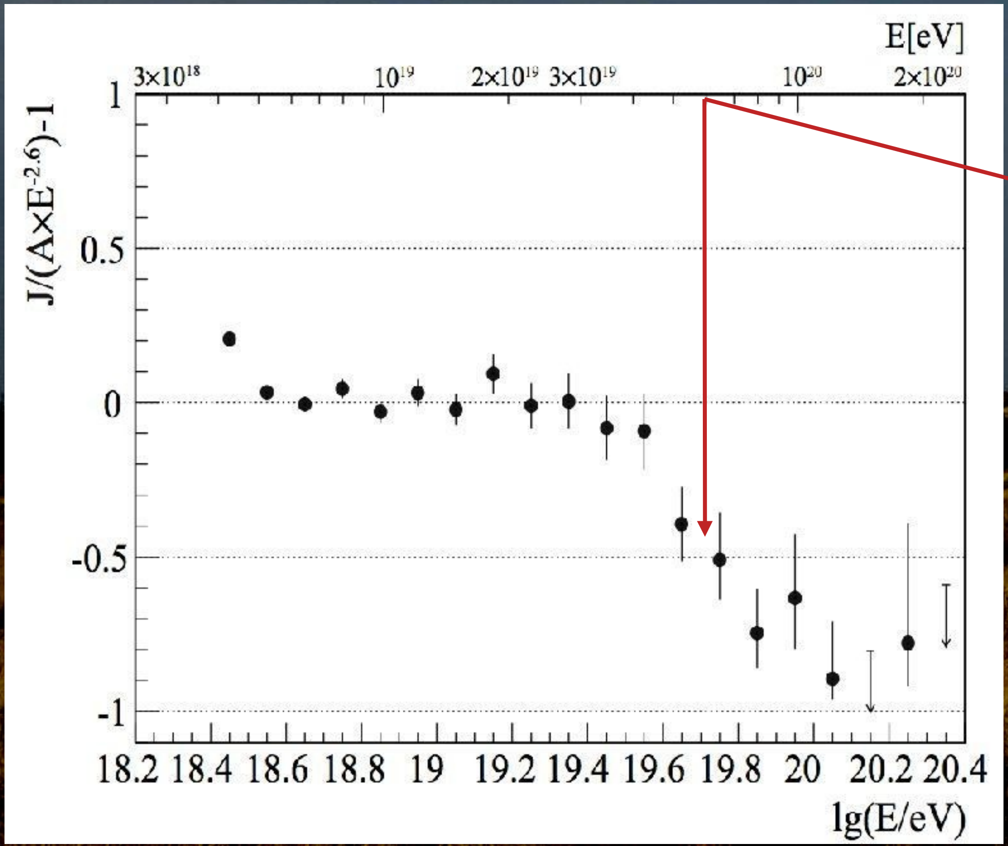
- Data set 2004 - 08/2007
  - > 10^6 events above 0.2 EeV.
  - 81 events > 40 EeV, $\theta < 60°$
  - $P = 10^{-5}$ incl. trials
- Correlation with supergalactic plane (nearby AGNs)
- Controversy on more recent data...

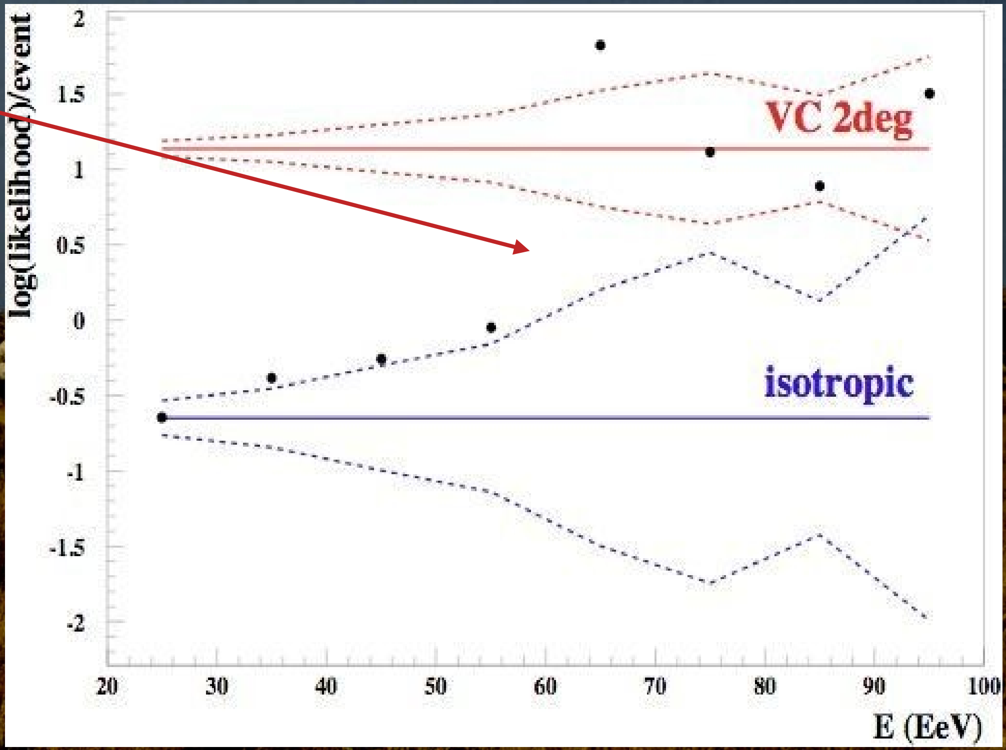
Science (Nov. 2007)



GZK Cutoff ?

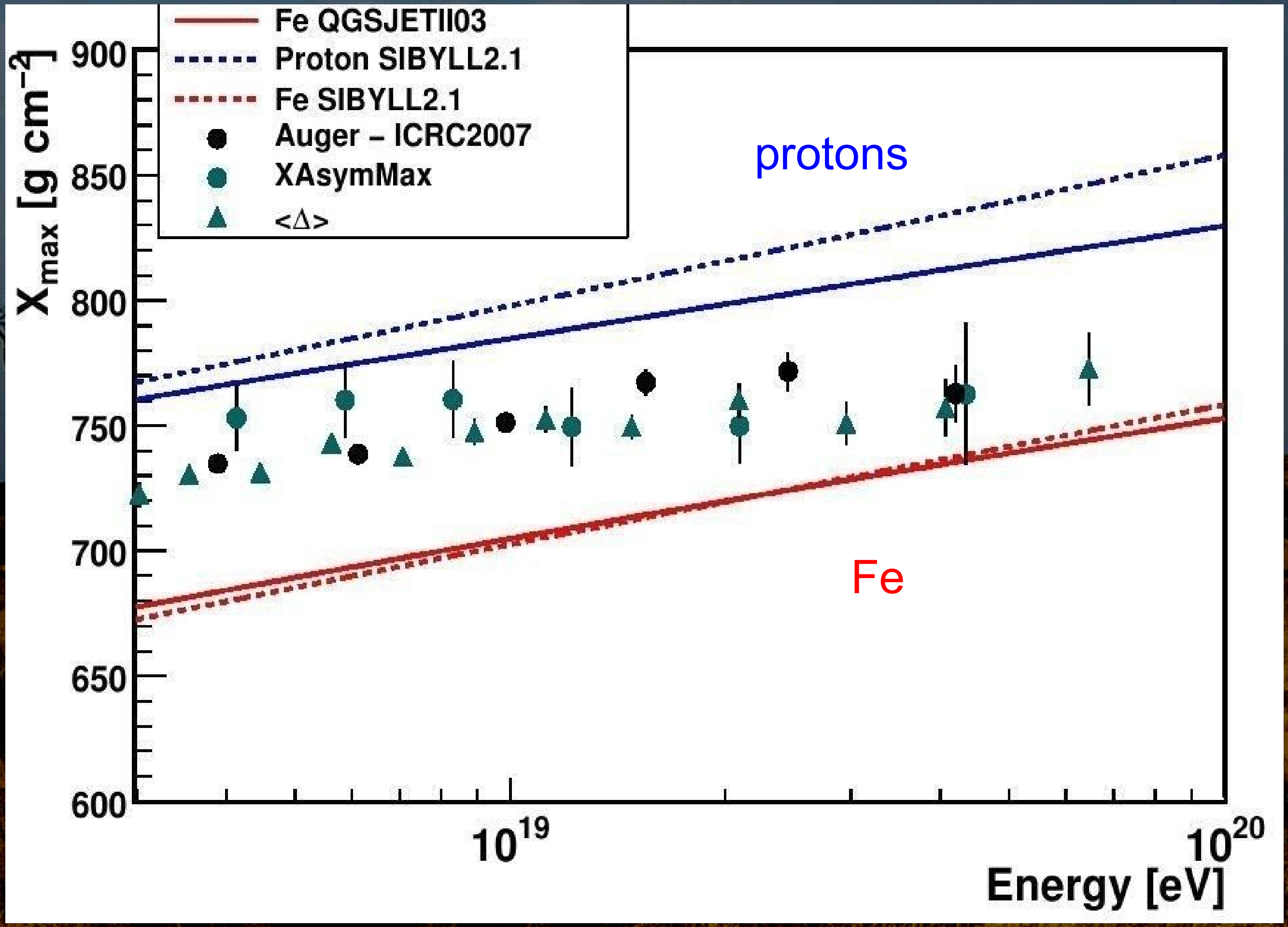
- Energy cutoff @ $10^{19.7}$ eV
- At the same energy, appearance of anisotropies (Anisotropy signal maximum where flux divided by two)
- Naturally leads to GZK interpretation
- Alernate explanation: exhausted sources





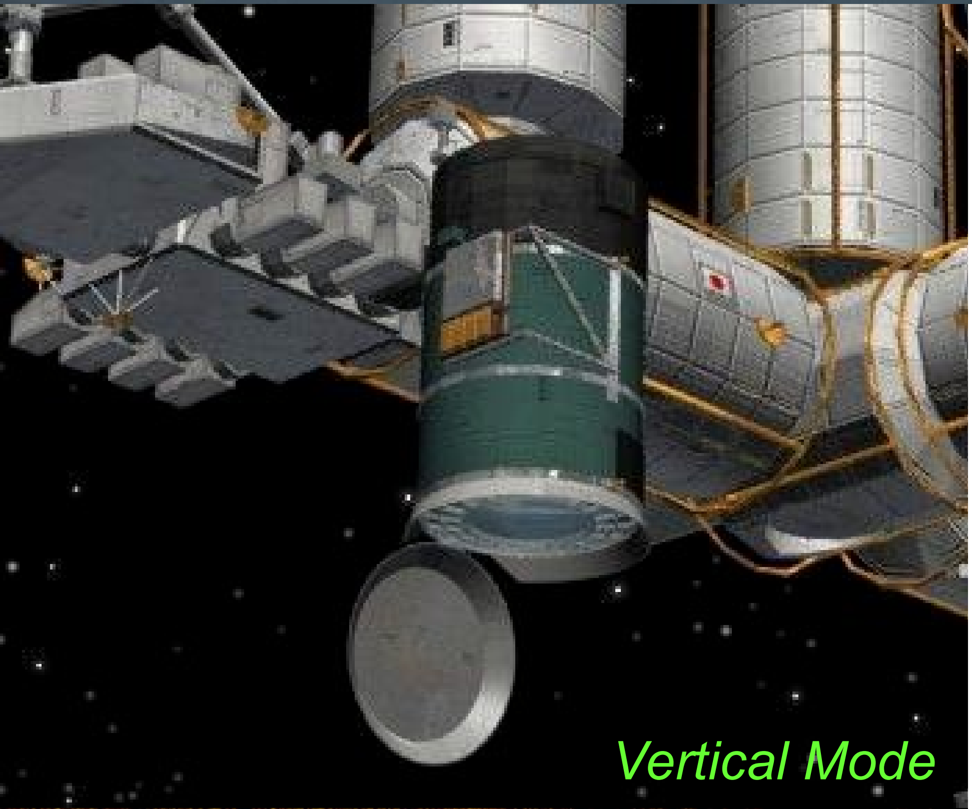
Composition

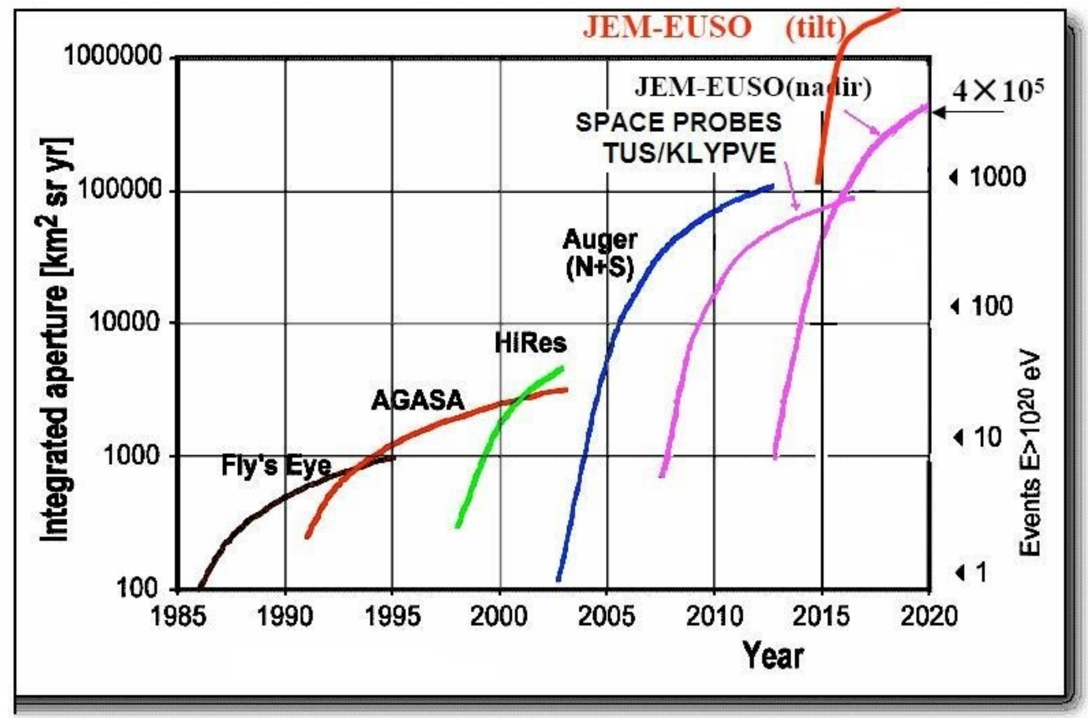
- Several different measurement agree pretty well
- Hint toward heaver composition at high energy



Perspectives (I)

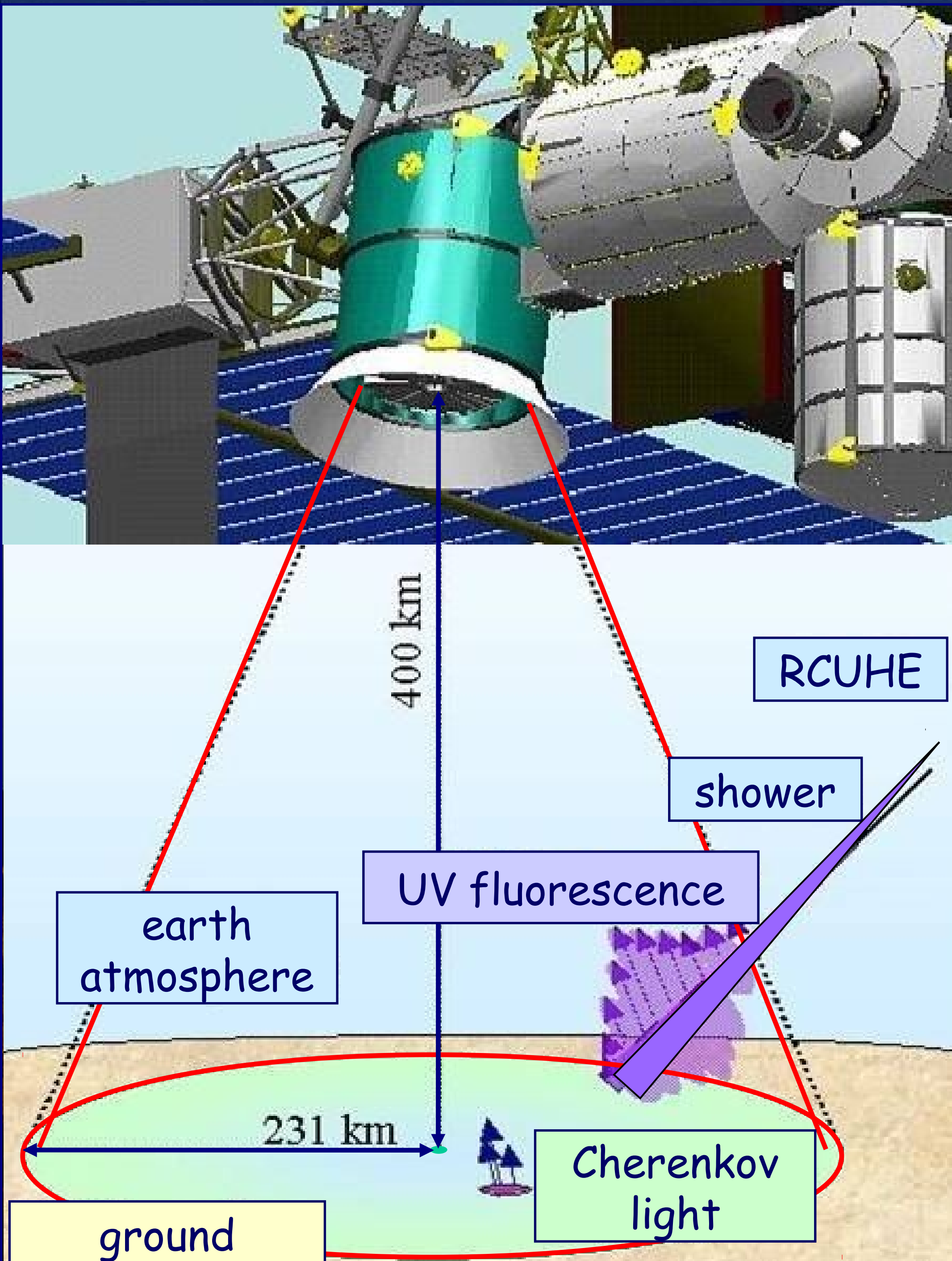
- Larger network for investigating the highest energies: Auger North + JEM-EUSO Telescope on ISS (2013)
- Upgrade of existing networks (HEAT, AMIGA…)
- Low energy extensions toward the knee (Tel. Array)
- A lot of R&D in other detection techniques (Radio!)





by Boris Khrenov 2006

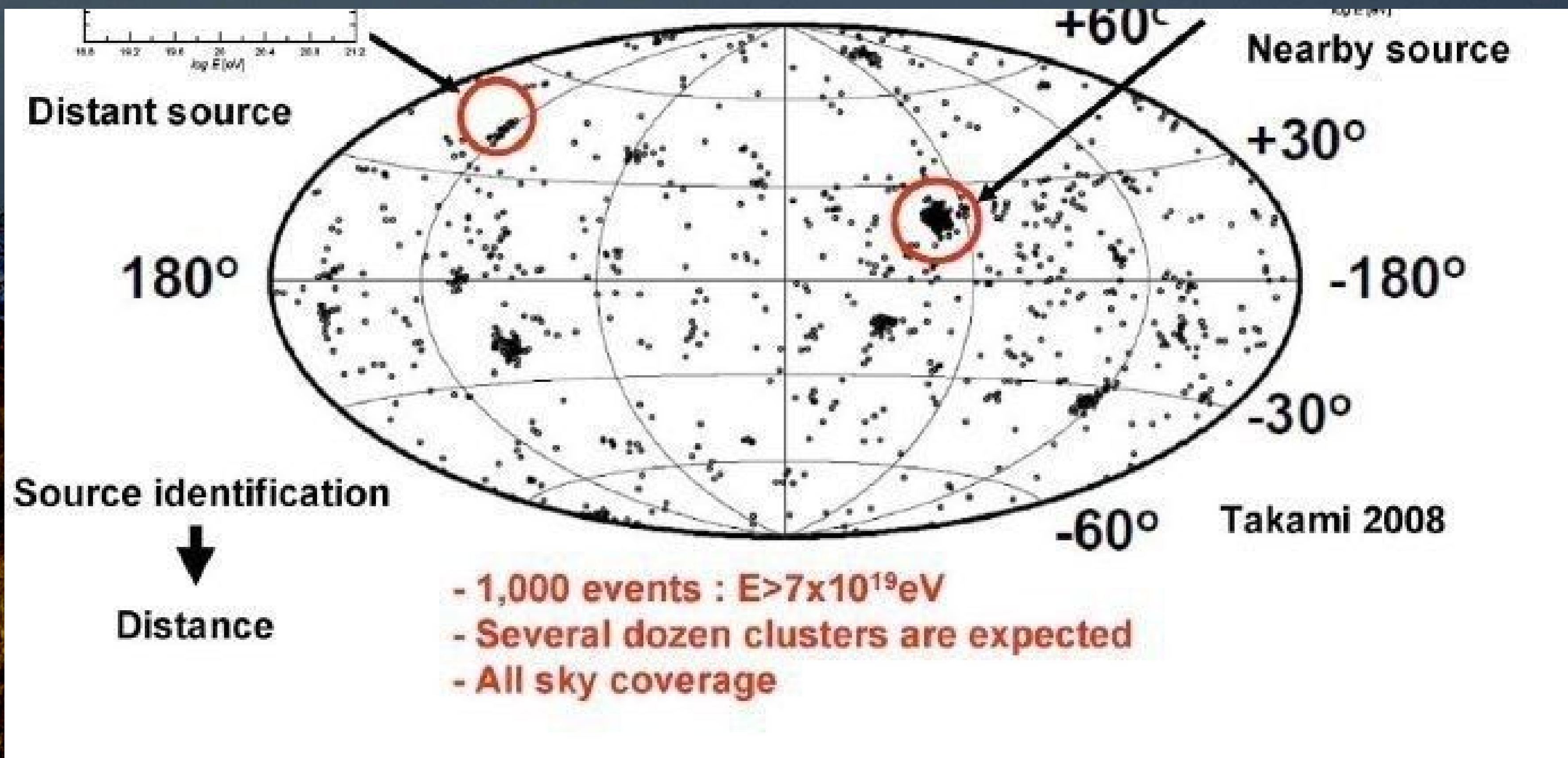
JEM - EUSO



- Acceptance : 10^6 km^2 sr
- Target air mass : 10^{13} T
- Full sky coverage in one year
- 1000 events per year with E>10^{20} eV
- Launch foreseen in 2013 => 2015?

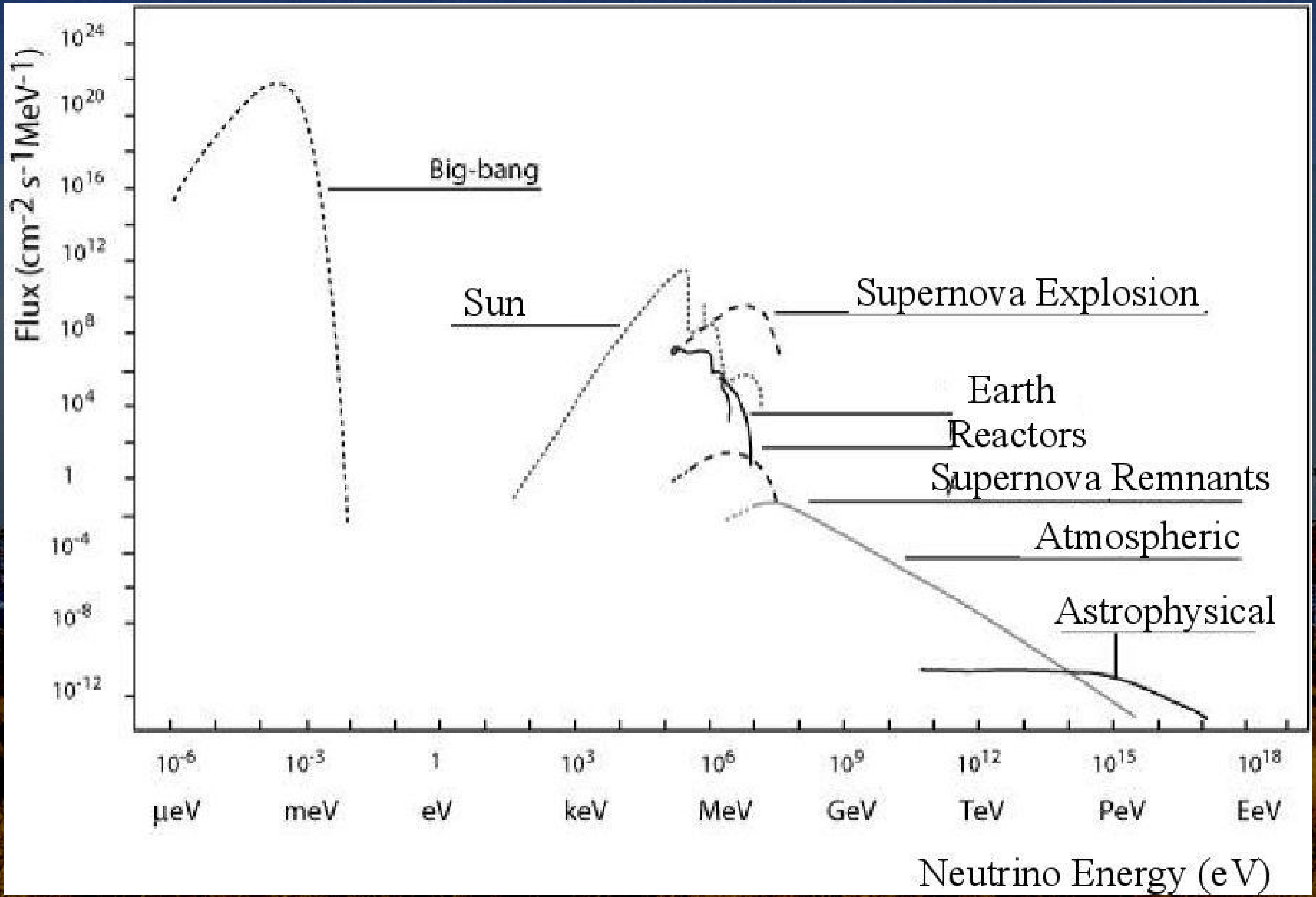
Needed performances

- > 1000 events E > 7 10^{19} eV
- Angular resolution < 2.5°
- Energy resolution < 30%
- X_{max} resolution < 120 g / cm^2

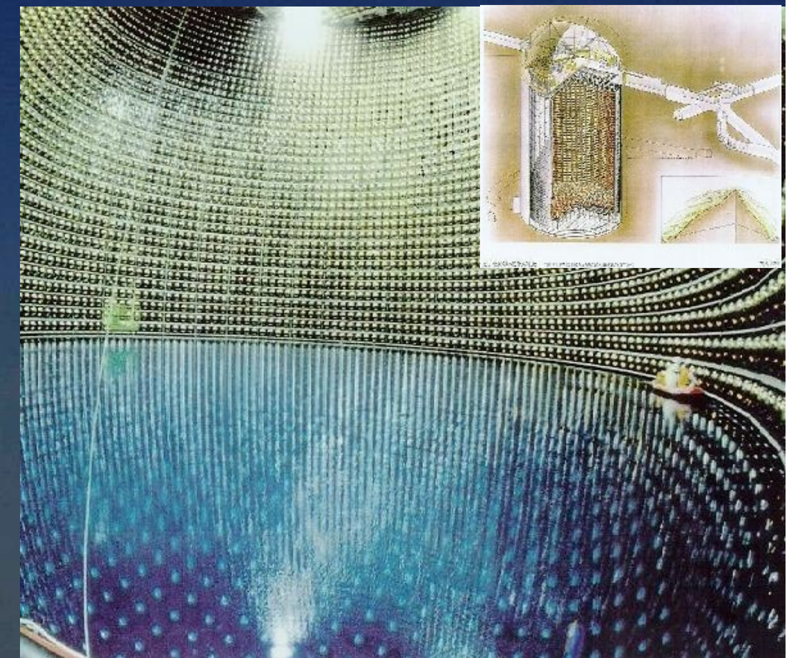


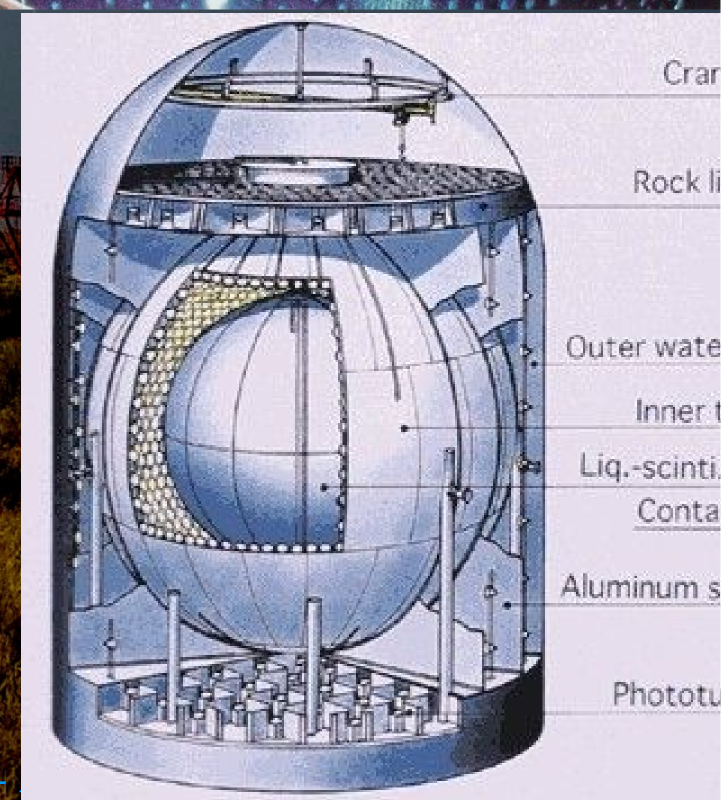
Neutrinos

Flux of cosmic neutrinos



Low Energy Neutrinos





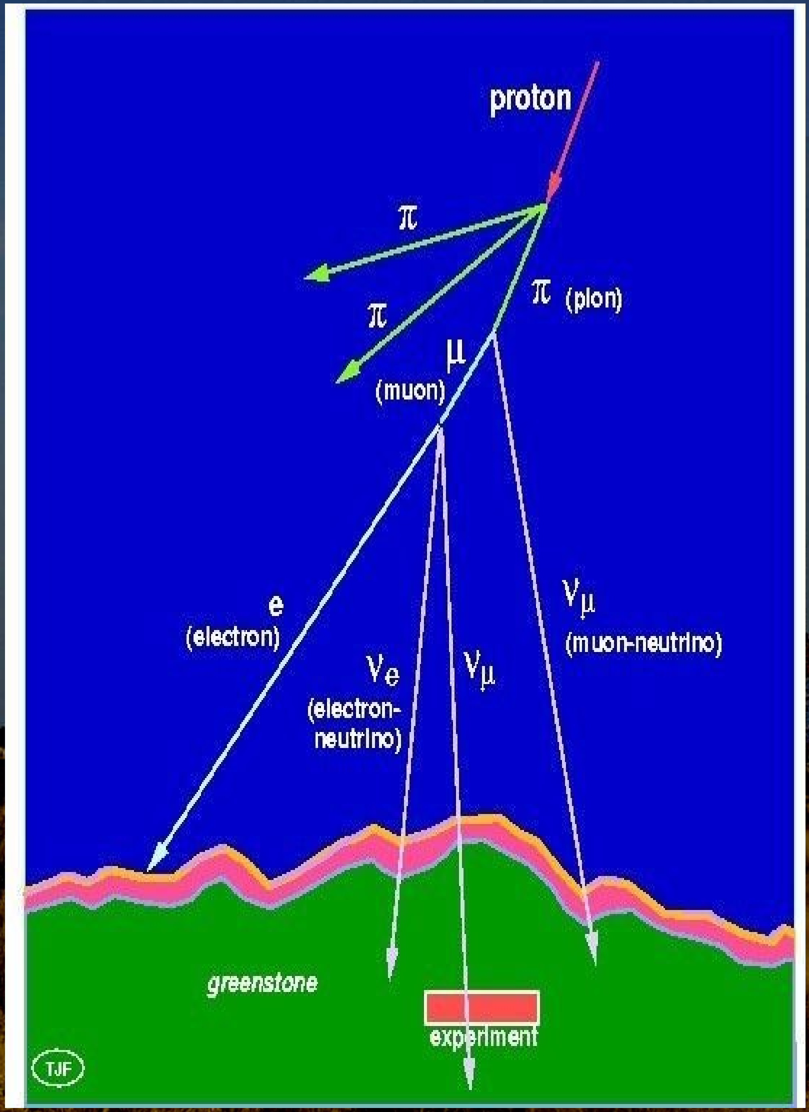
- Solar Neutrinos physics (oscillation,...) in the MeV domain
- Supernovae Neutrinos (SN 1987A)
- Underground Water Cherenkov detectors (KamLAND, SuperKamiokande, ...)
- Using heavy water (SNO) for detection of all flavours (ν_μ appearance)
- Liquid Scintillator (LSND)
- Chemical reaction detector (Gallex, Homestake,...)
- Many experiments....

High Energy Neutrinos

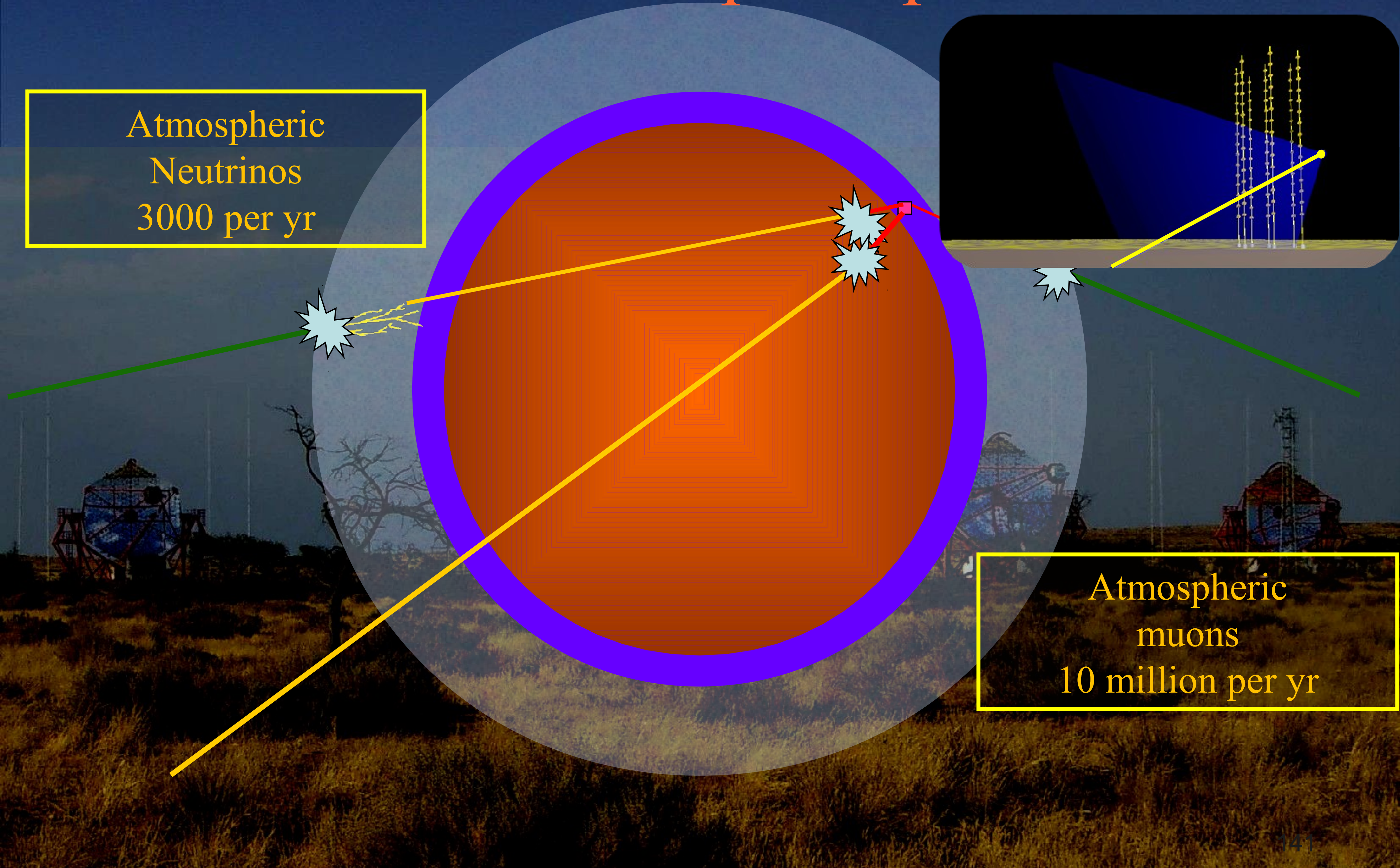
- Atmospheric neutrinos
  - Neutrinos produced in hadronic showers

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$

  - Ratio $\nu_\mu/\nu_e \sim 2$
- Astrophysical neutrinos (AGN, GRB, SNRs, ...)

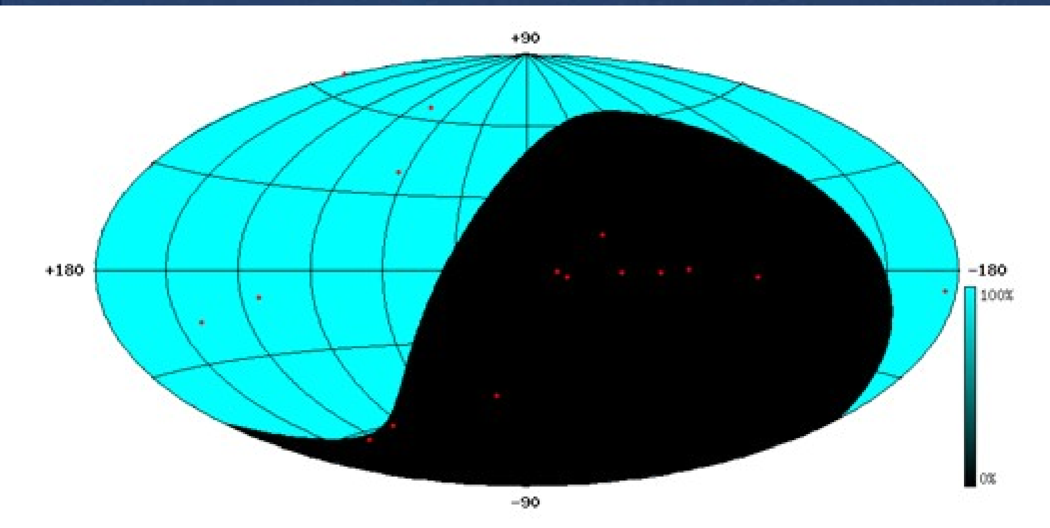


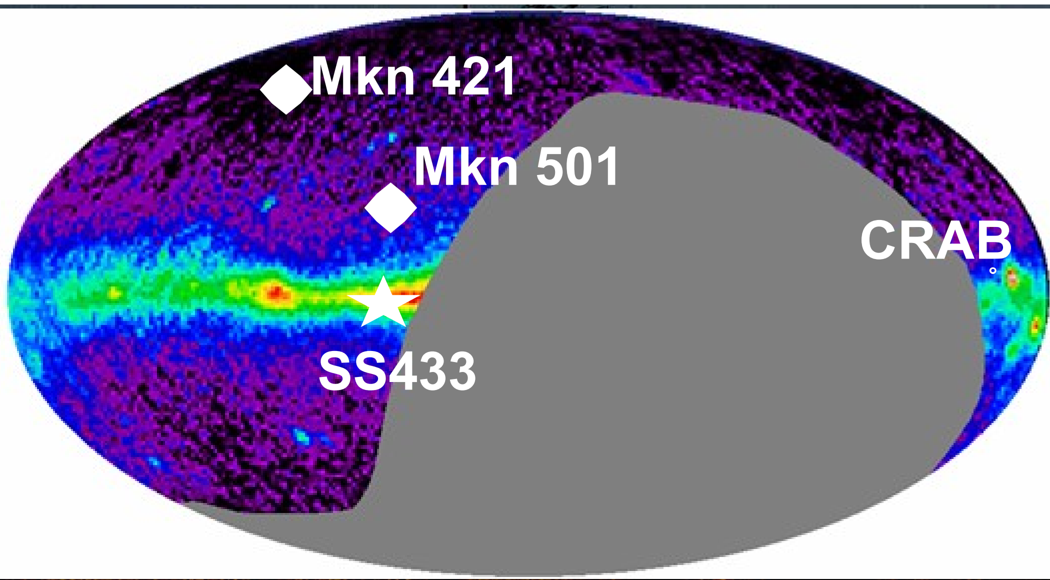
Detection principle



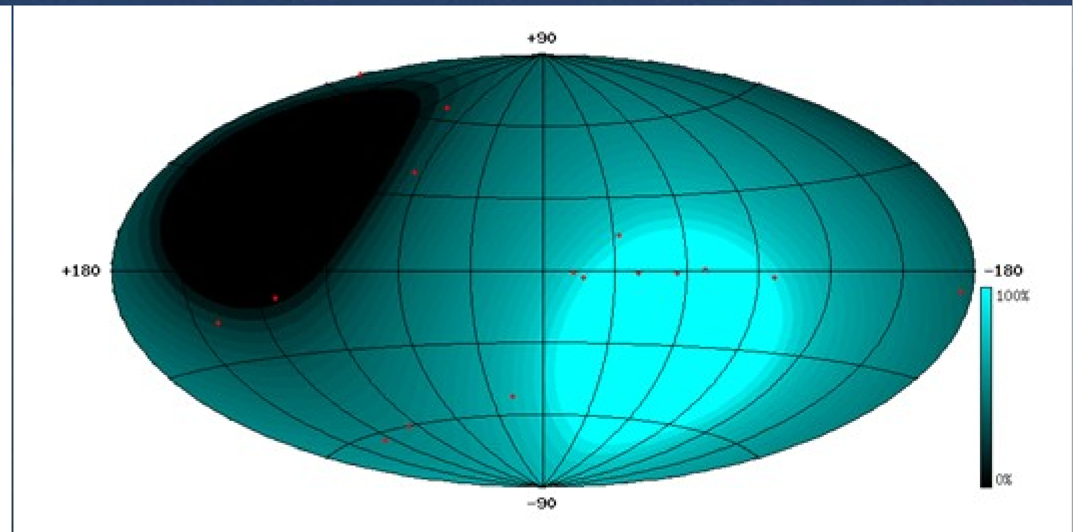
High Energy Neutrino Sky

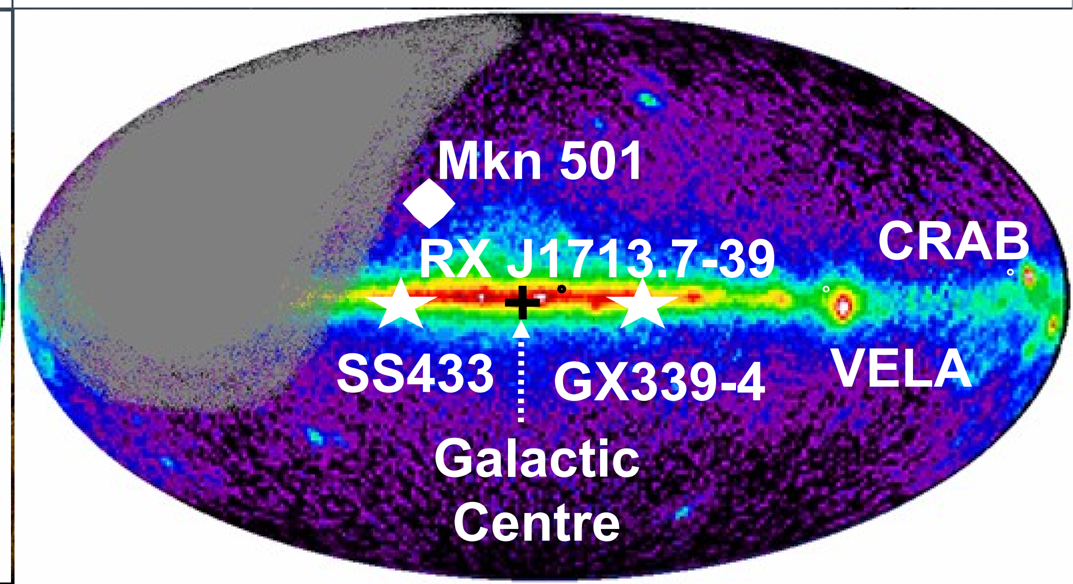
AMANDA (South Pole)





ANTARES (43° North)





+ Baikal, Nemo, Nestor

Comparison of media

ICE

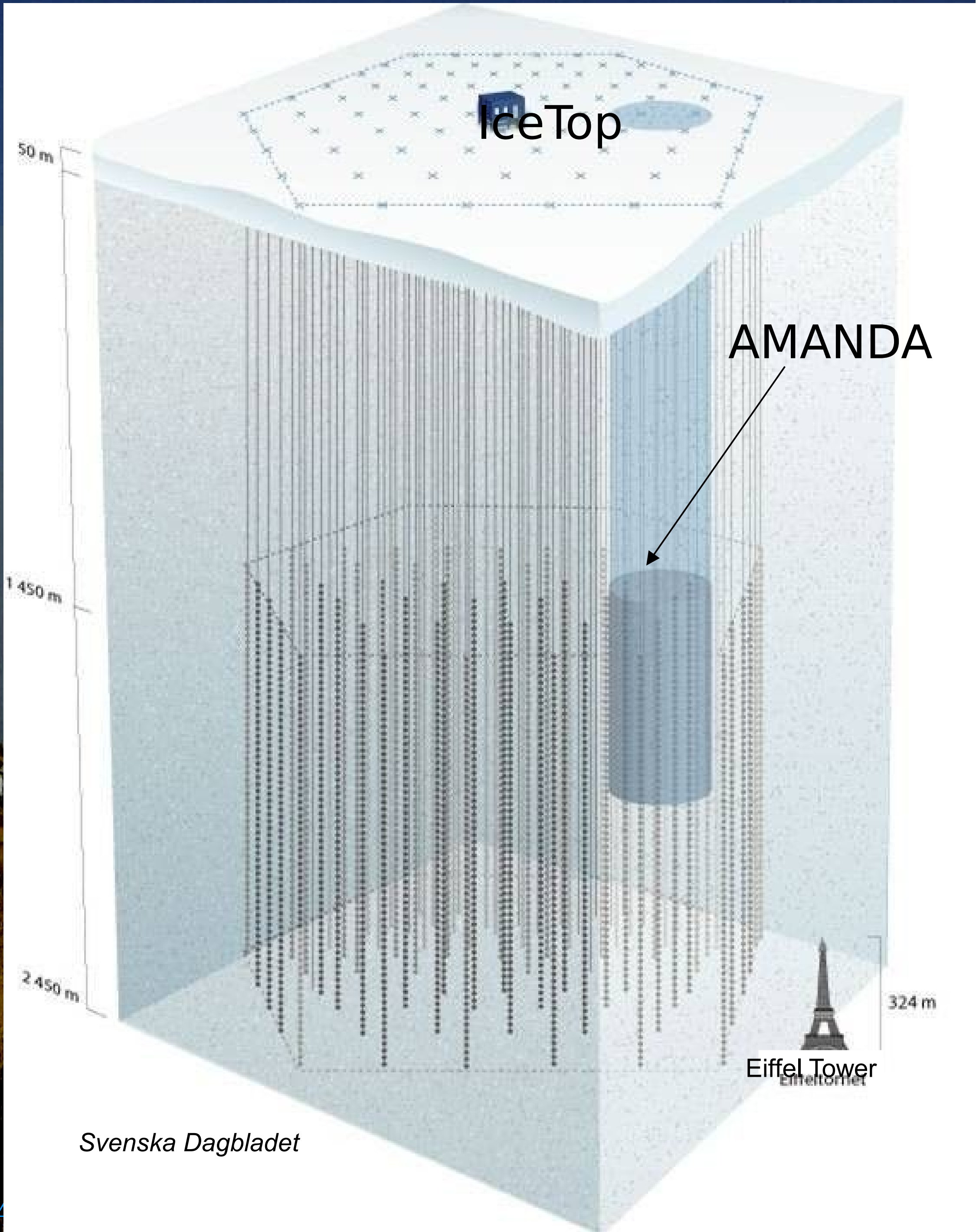
- Stable, easy drilling
- ~350 Hz noise (40K), sterile
- Large absorption length ~100 m
- Low diffusion length 20-25 m (degraded angular resolution)
- Max Depth 2500 m

WATER

- High pressure, corroding
- 30-60 kHz noise, bioluminescence
- Low absorption length 25-60 m
- Large diffusion length >100 m
- Max Depth 3800 m

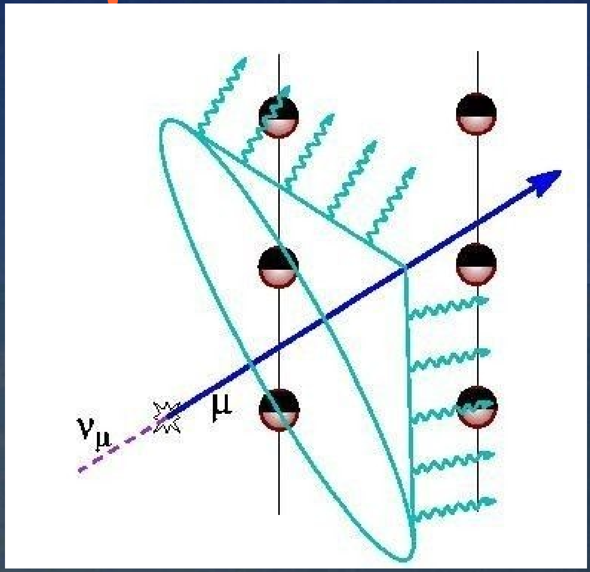
IceCube

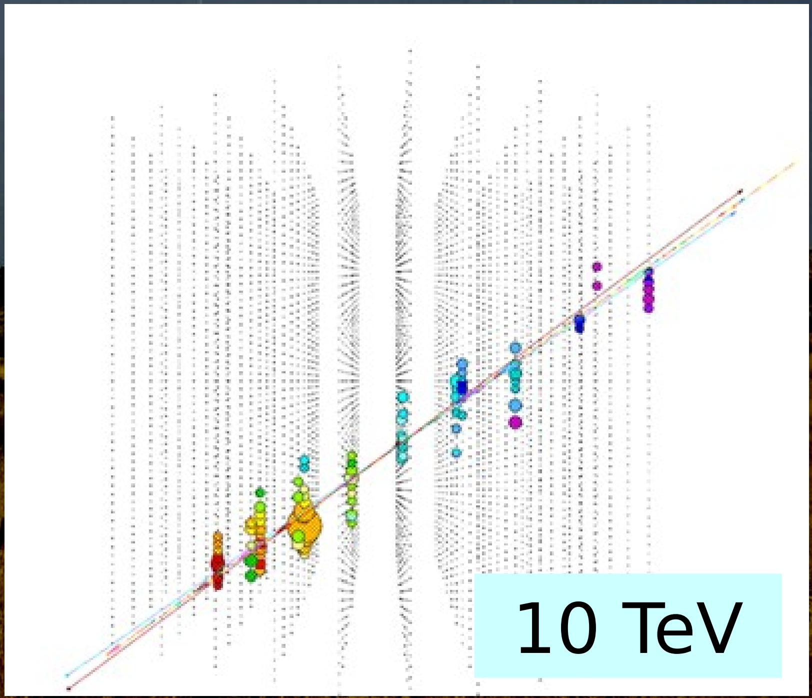
- Deployment:
  - 2005 : 1 line installed
  - 2009 : 59 lines installed
  - 2010 : 79 lines (4790 DOM)
  - final : 86 lines (5160 DOM)
- Estimated lifetime: 15 years
- Performances:
  - $O(10^0)$ ν per day
  - $O(10^8)$ μ per day
  - 0.4-1° angular resolution
  - 10 GeV threshold
- Radio detection activities (ARIANNA)
- Surface array: IceTop



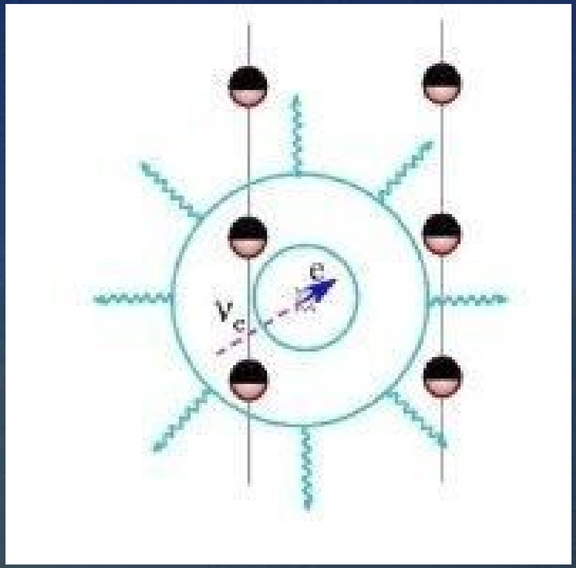
Signatures – Neutrino μ

- Long, linear track
- linear « image » aligned with muon track

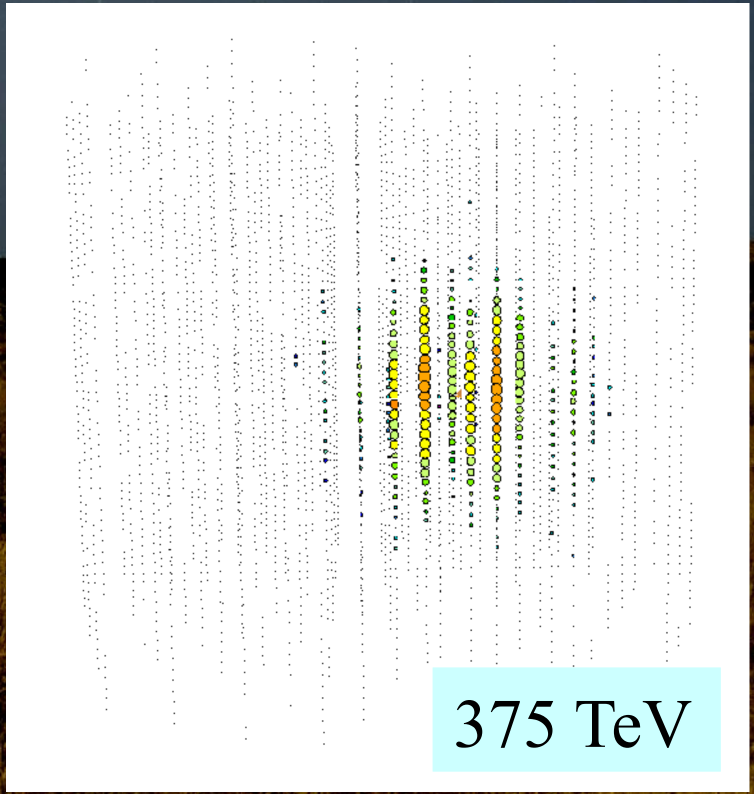




Signatures – Neutrino e

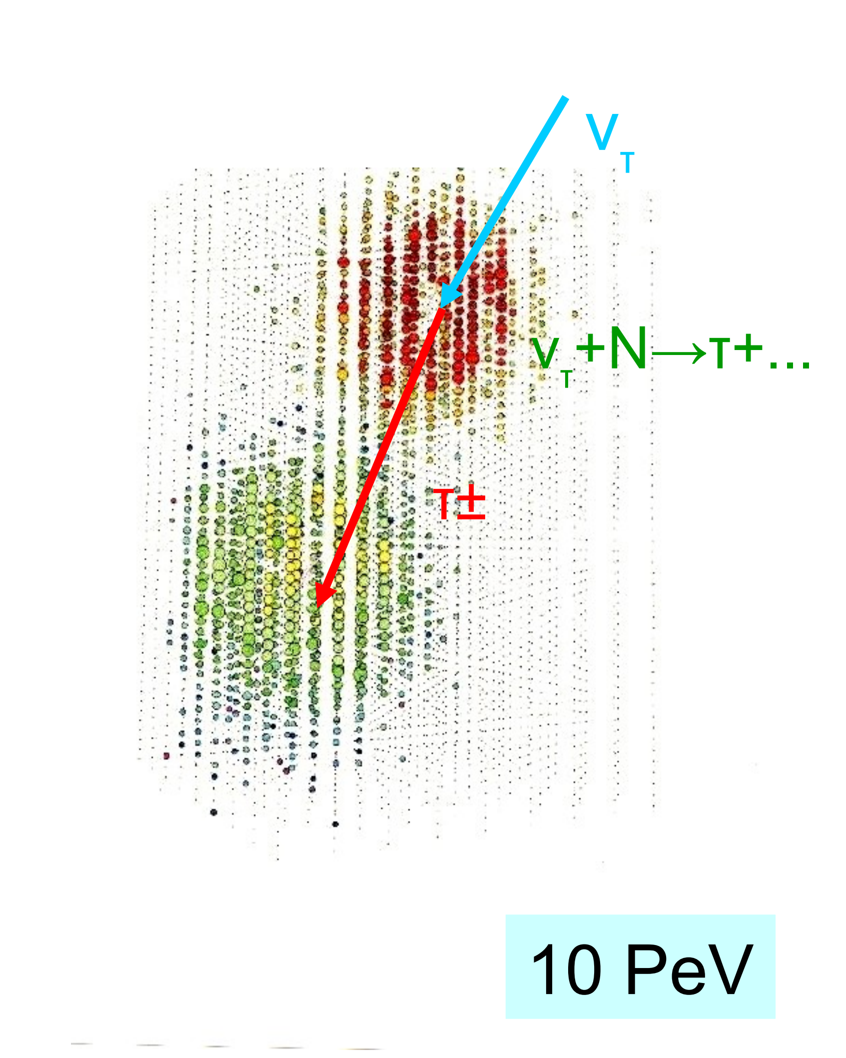


- Short track (ionisation/bremsstrahlung losses), shower, multiple scattering
- Concentrated « Image »



Signatures – Neutrino τ

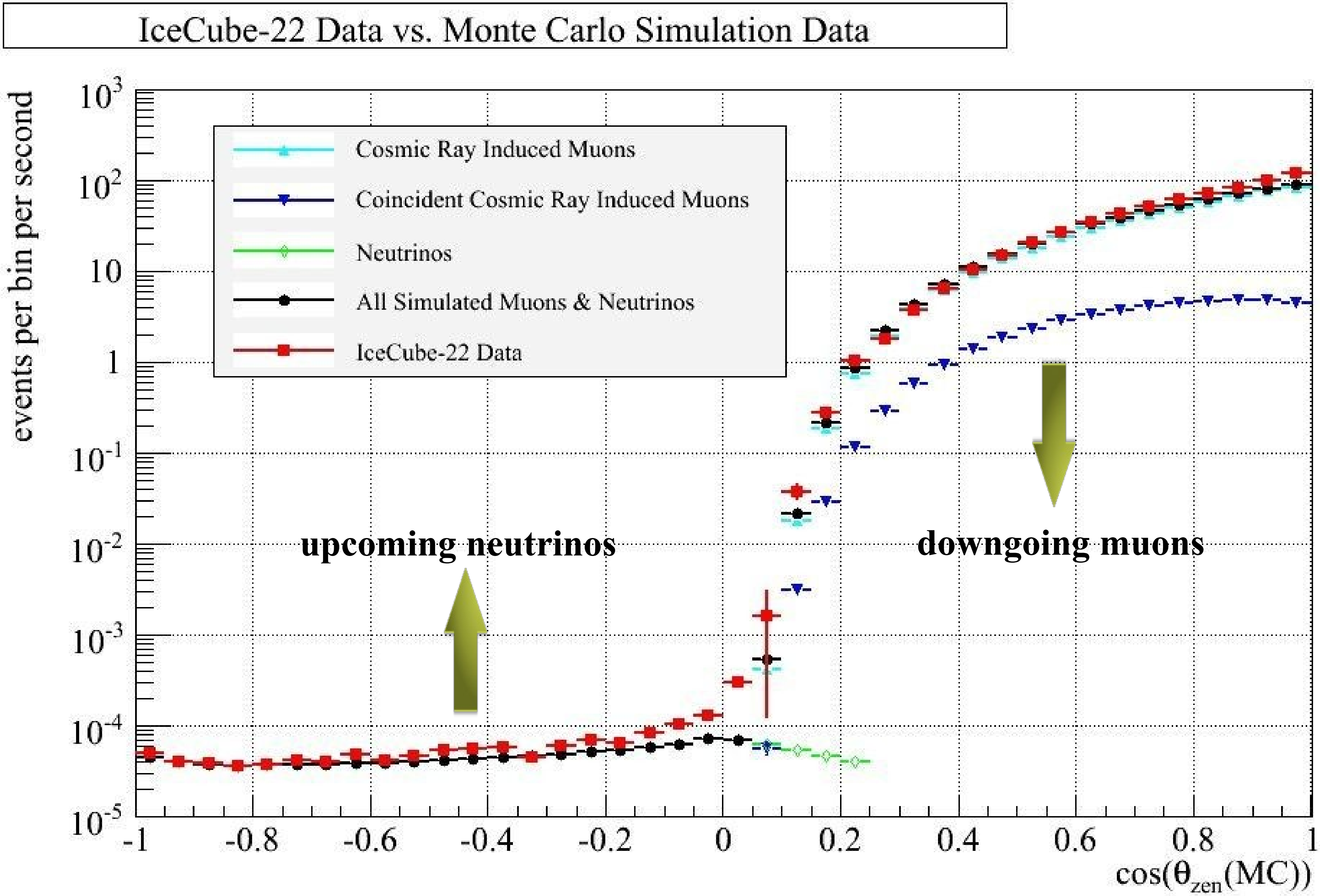
- « Double bang »:
  - Neutrino disintegration with secondary hadrons
  - Further away, tau disintegration into electron



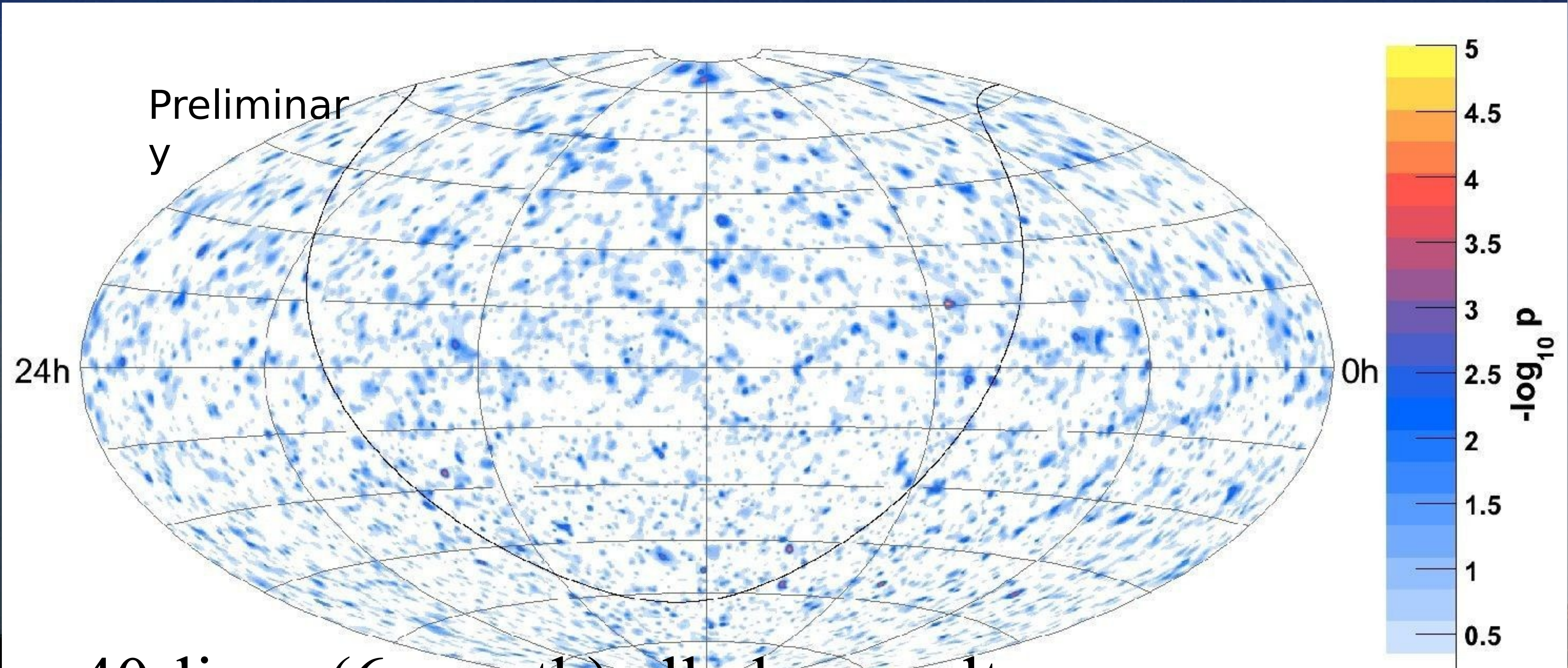
IceCube Lab

South Pole and Christmas tree

Angular distribution



Search for point like sources

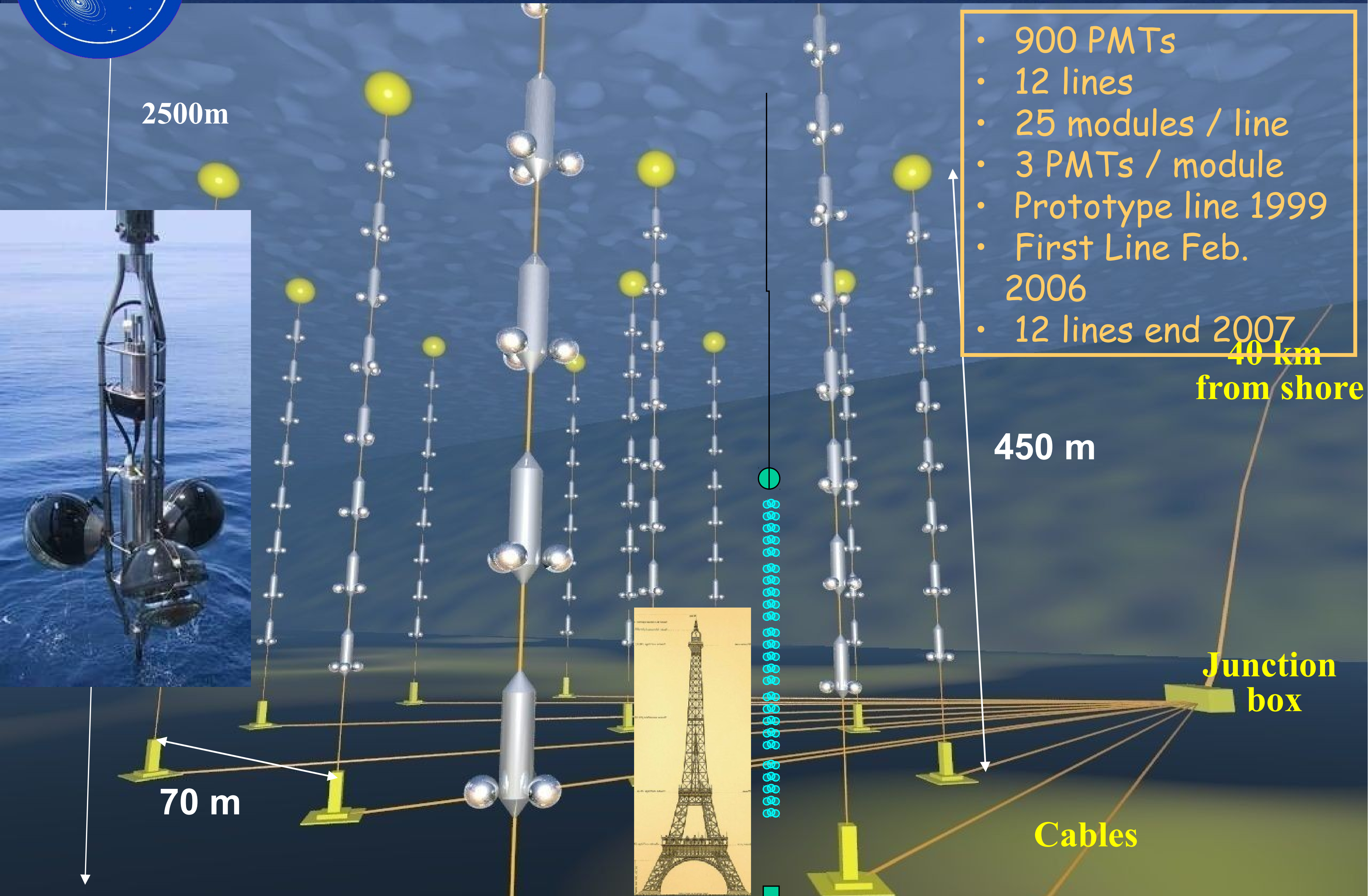


40-lines (6 month) all-sky results

- 175.5 days livetime,
- 17777 events: 6796 up-going, 10981 down-going
- No point like source sofar
- Sensitivity getting closer to potential sources

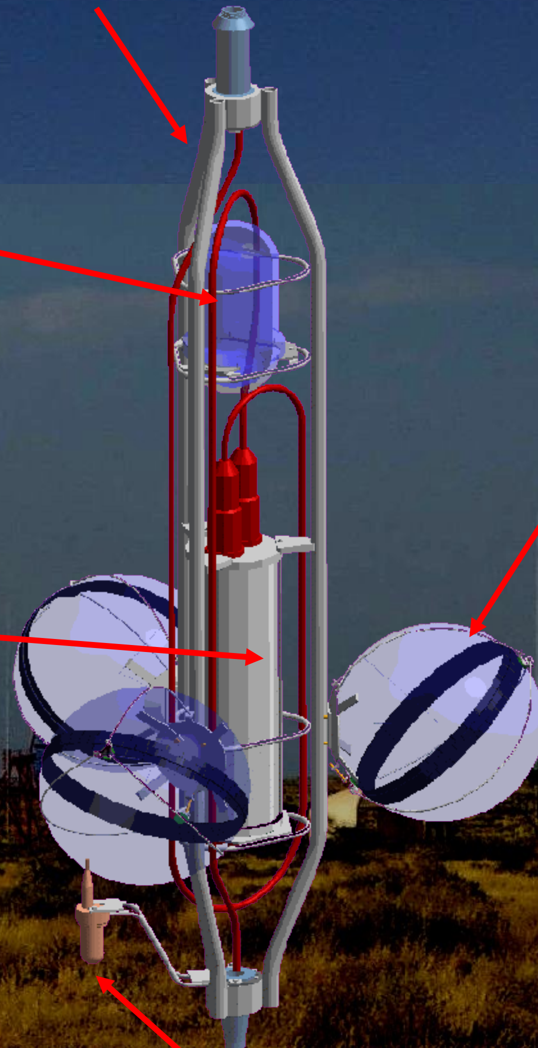
Antares

- 900 PMTs
- 12 lines
- 25 modules / line
- 3 PMTs / module
- Prototype line 1999
- First Line Feb. 2006
- 12 lines end 2007



Base Module

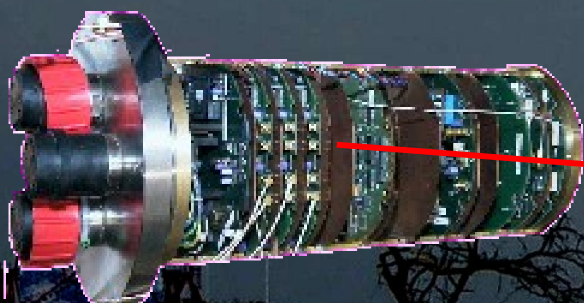
titanium frame: *support structure*



Optical Beacon with blue LEDs: *time calibration*

Optical module: 10” Hamamatsu PMT in 17” glass sphere (σ_{TTS} ~ 1.3 ns) *Photon detection*

Local Control Module (Ti cylinder): *Front-end ASIC, DAQ/SC, DWDM, Clock, tilt/compass, power distribution…*



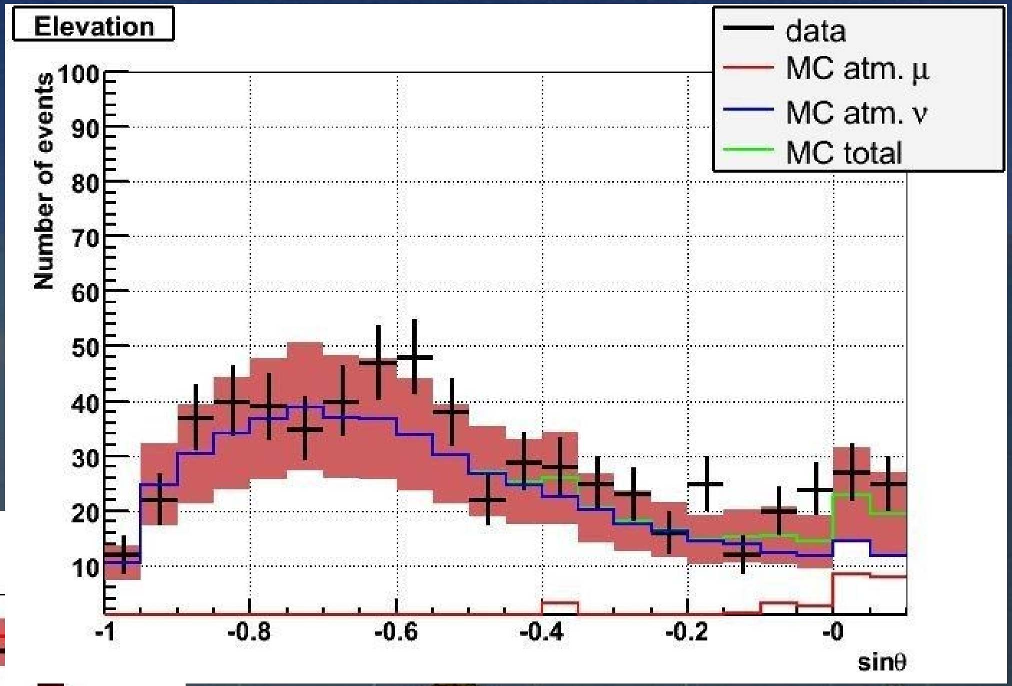
Hydrophone: *acoustic positionning*

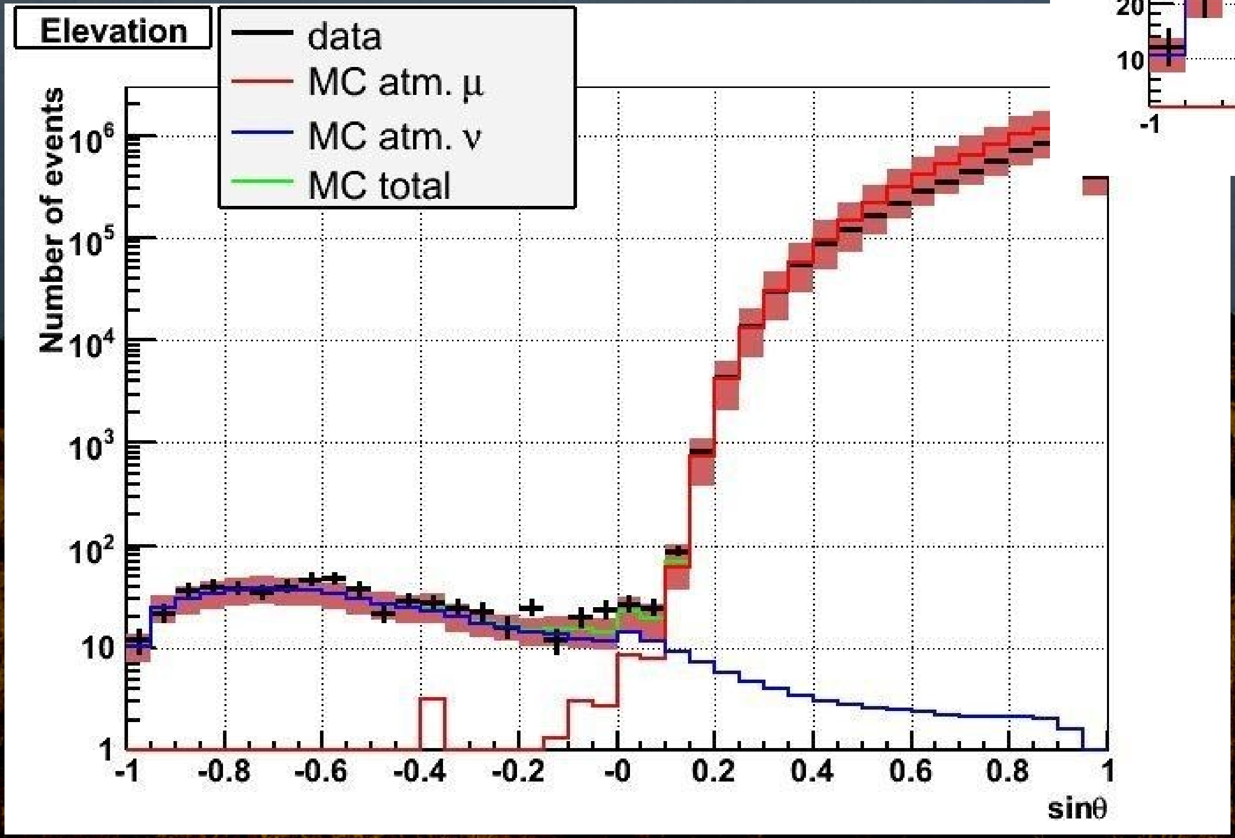
Antares Simulation

Muon 1 TeV

Angular distribution of events

- Data well reproduced by simulation including atmospheric neutrinos
- No astronomical neutrino sofar.

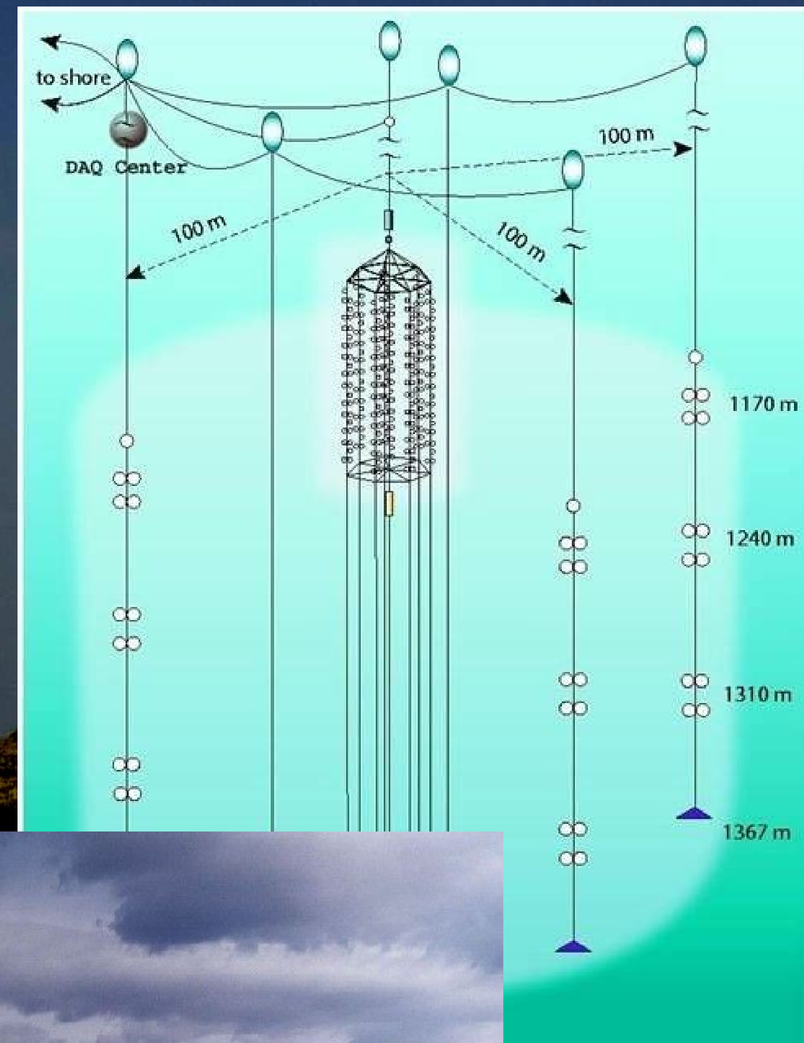


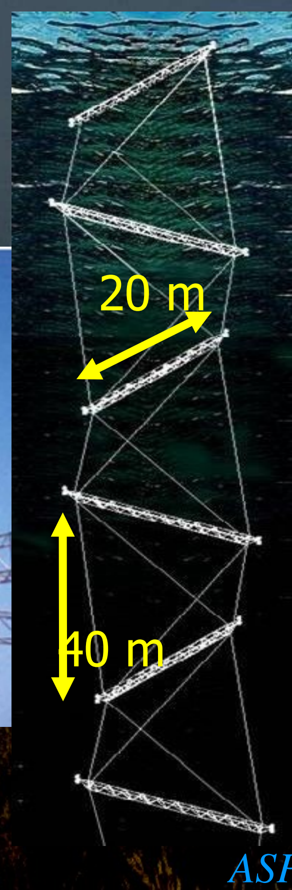


174 days
582 upgoing candidates
(multi-line fit)

Other Neutrino Telescopes

- Baikal NT-200+:
  - First operational neutrino telescope NT-36 in 1993, NT-200 in 1998
  - Expanded with 3 outlying strings for PeV events (2005)
- In Mediterranean sea:
  - Nemo (Italy)
  - Nestor (Greece)



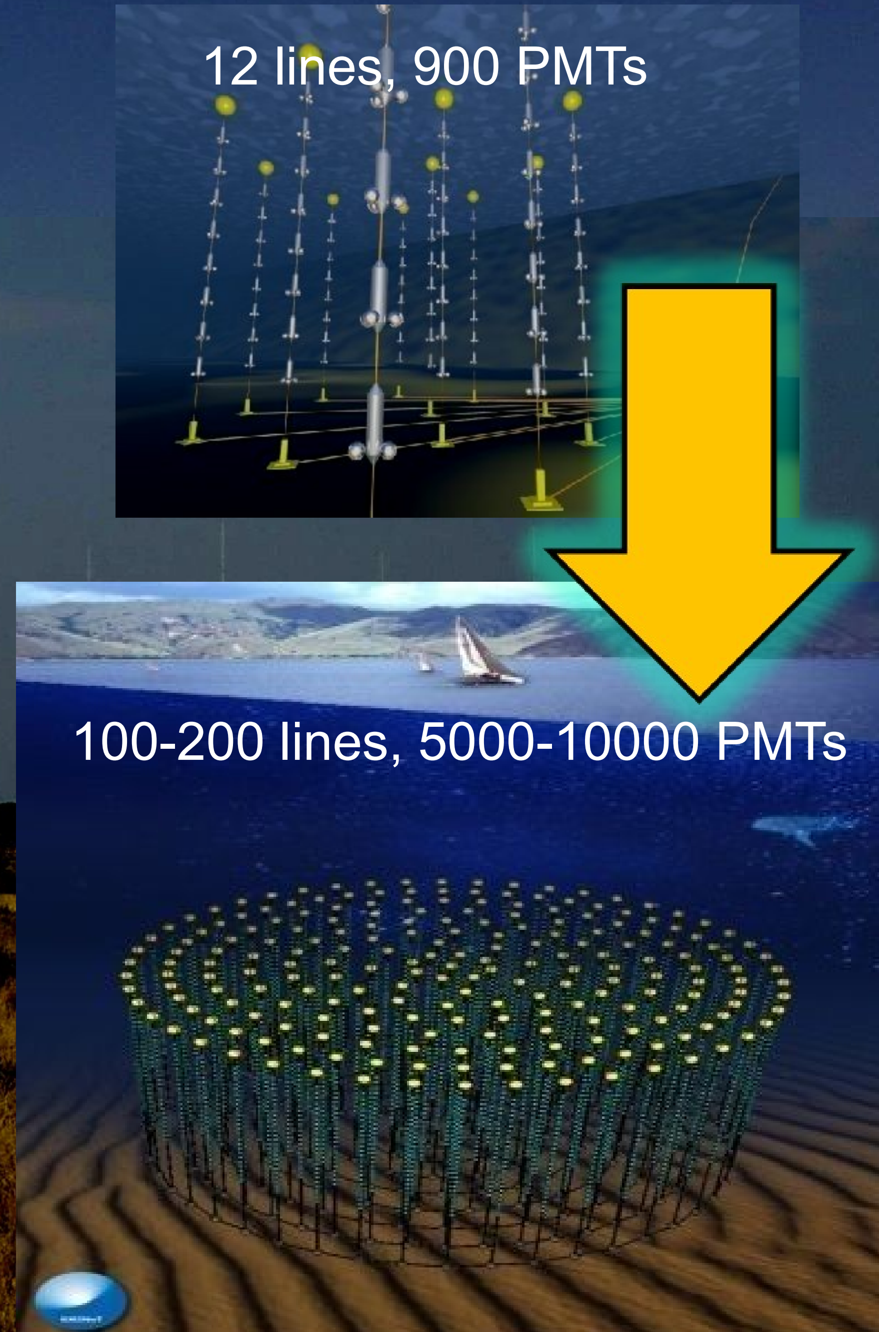


Next generation: toward km3

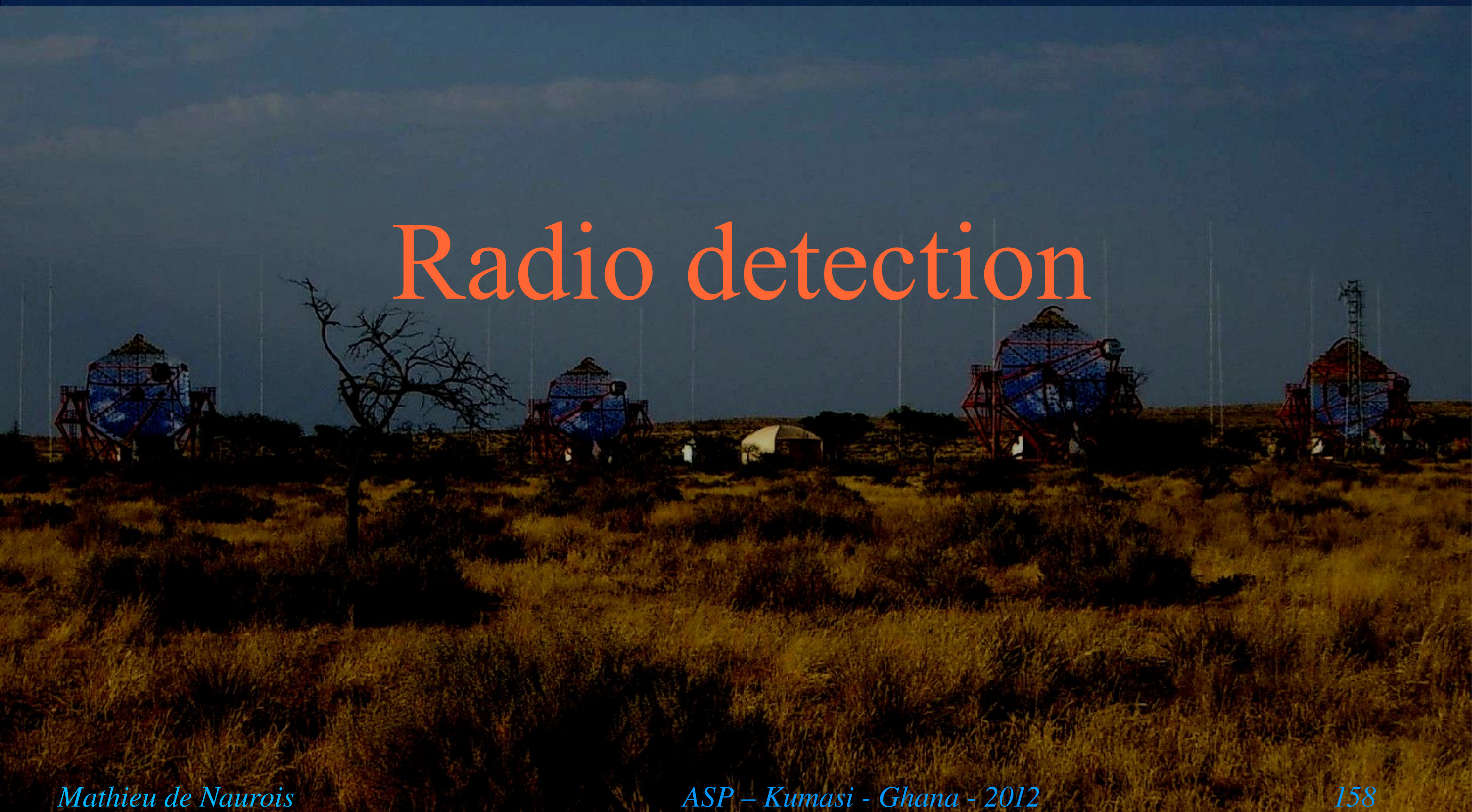
- In FP7…

Challenges

- Maximise physics potential
  - Substantial improvement over ICECUBE
  - Instrumented volume >1 km^3
  - Angular resolution ~0.1 degrees (E>10 TeV)
  - Expandable
- Build in a reasonable time ~ 4 years
  - New deployment techniques
  - Speed-up integration time
  - Sub contract part of the production
  - …
- At a reduced cost
  - Factor 2 reduction cf ANTARES
  - Simplified architecture
  - Reduced maintenance
  - Multi-line deployments
  - …

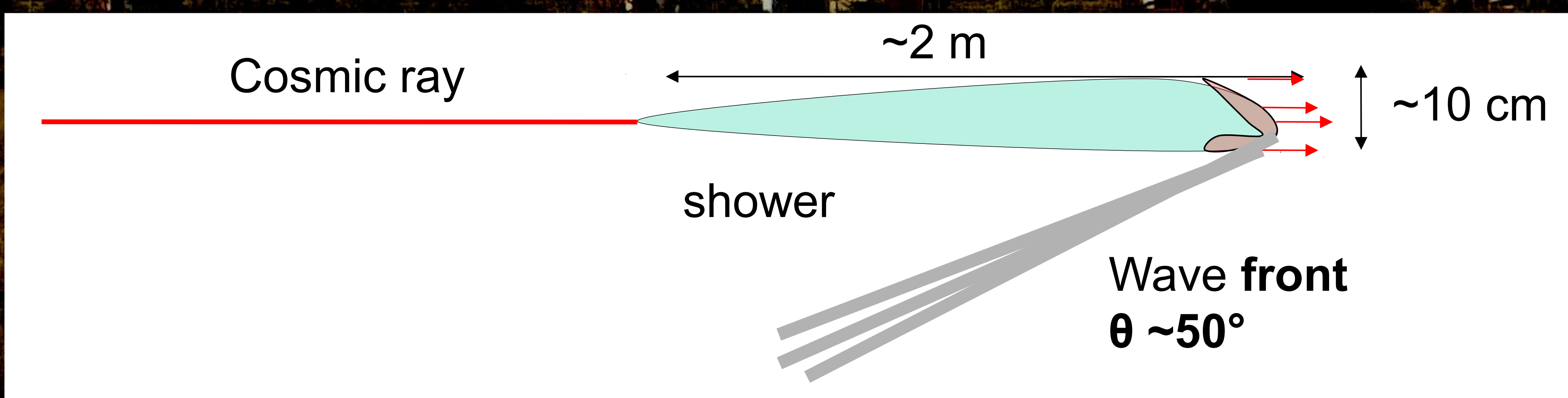


Radio detection



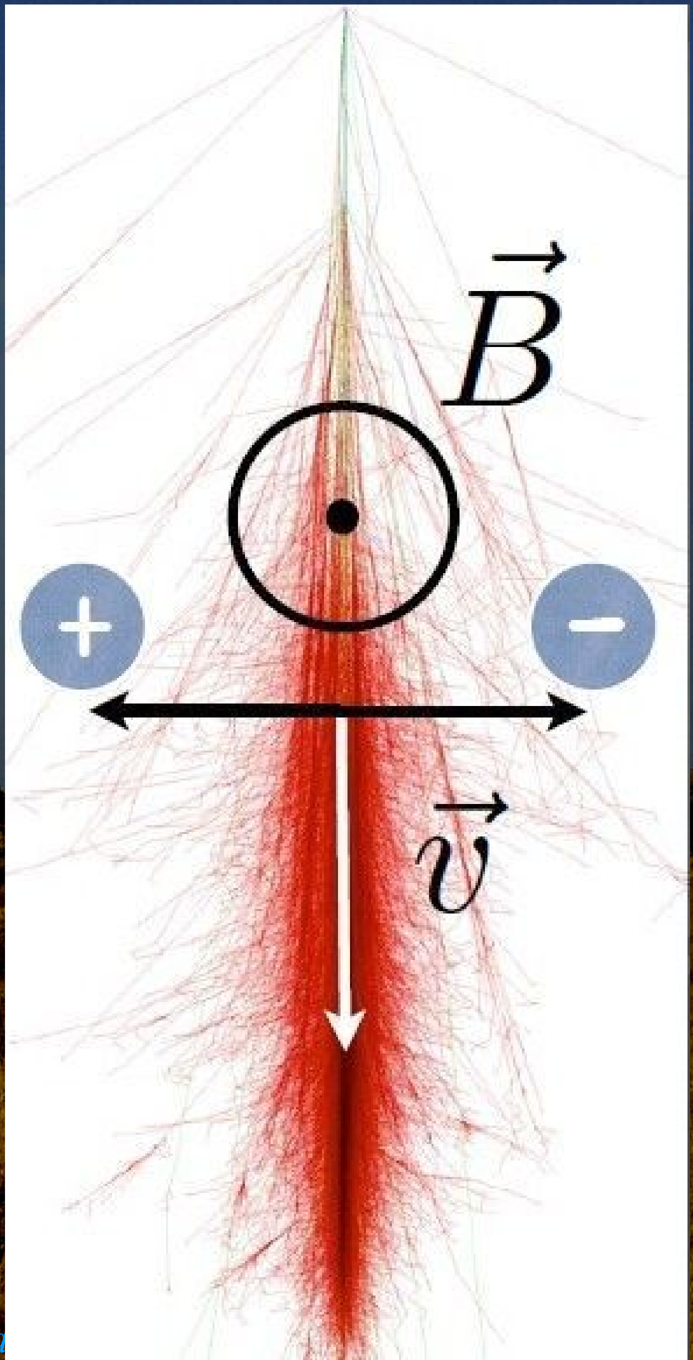
Askaryan Effet (1928-1997)

- Small e+/e- asymmetry in showers:
  - Positron Annihilation
  - Compton scattering
- Coherent Cherenkov forward emission, (2~5 GHz), emitted in matter (ice, salt, rocks) showers
- Confirmed in 2000 at SLAC
- Well adapted for neutrinos (emerging shower)
- Many experiments: FORTE, RICE, SALSA, GLUE



Other sources of radio emission

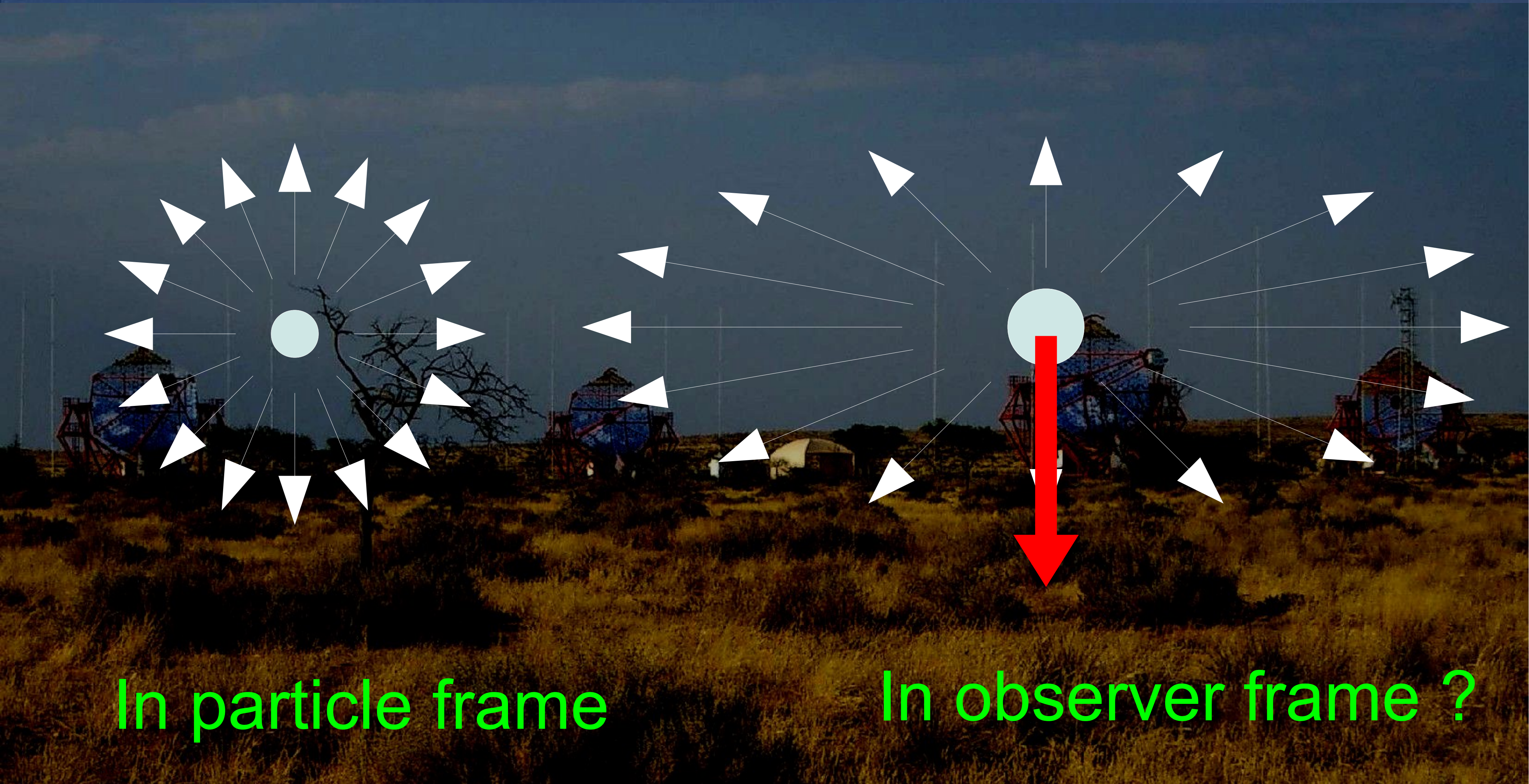
- Geomagnetic effect:
  - Earth magnetic fields separates electrons and positrons apart
  - Dipole in relativistic motion...
- Synchrotron emission of electrons
- Emission from the current
- ...



- Frequency band [1-200] MHz
- Monopolar signal
- Dependancy v × B

Coulomb field

- Field radiated by a particle in relativistic motion



Coulomb field

- Transverse field

$$\vec{E}_{\perp} = \frac{\gamma q b}{4\pi\epsilon_0 \left(\gamma^2 \beta^2 c^2 t^2 + b^2\right)^{3/2}}$$

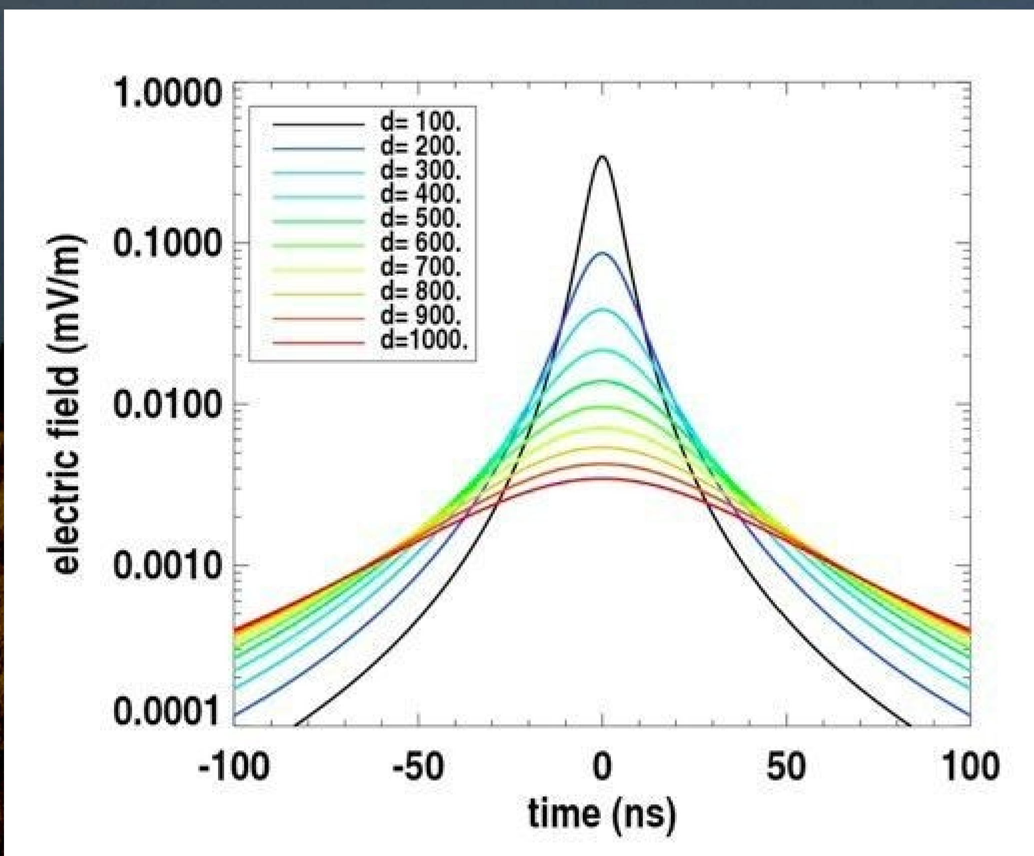
- Transverse field is proportional to number of particles in the shower, thus to energy
- Short, monopolar pulse (longer at large impact parameters)
- Longitudinal field is bipolar and fainter (by γ)
- Field strength ~ 10^{-4} V/m at 100 m for E ~ 10^{17} eV

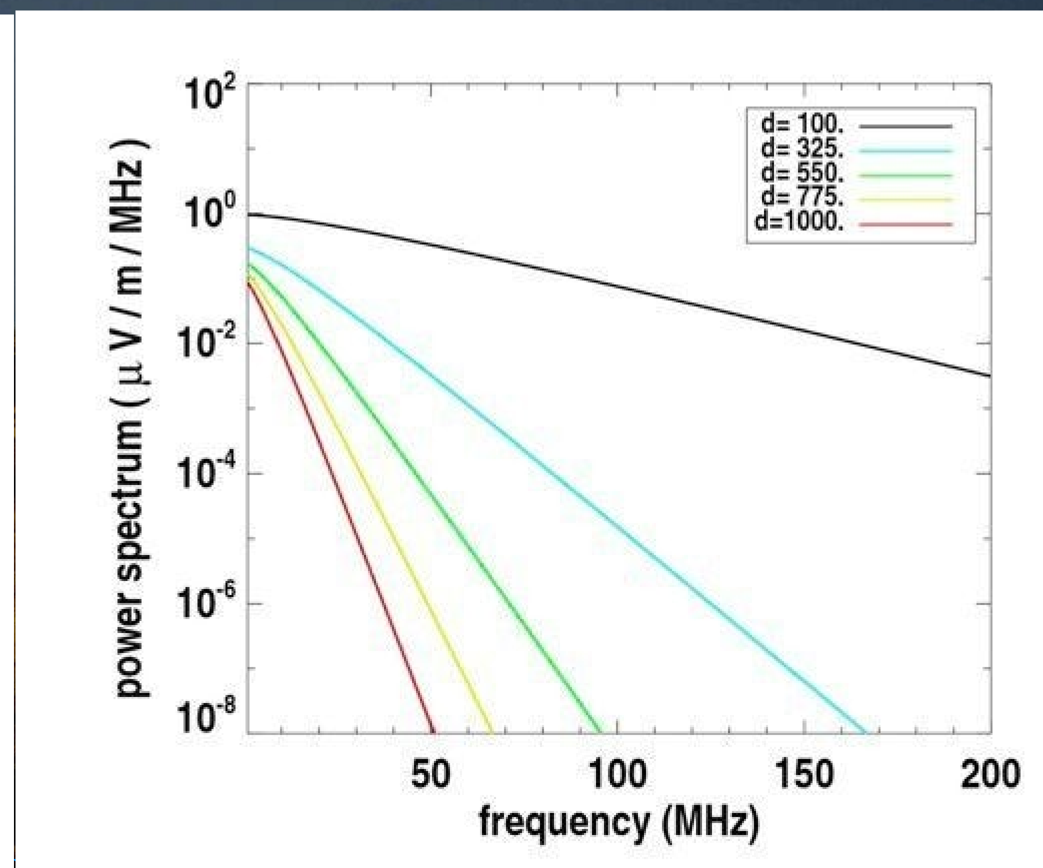
$$\vec{E}_{max} = \frac{\gamma q}{4\pi\epsilon_0 b^2}$$

$$\Delta t = \frac{b}{\gamma c}$$

Coulomb field

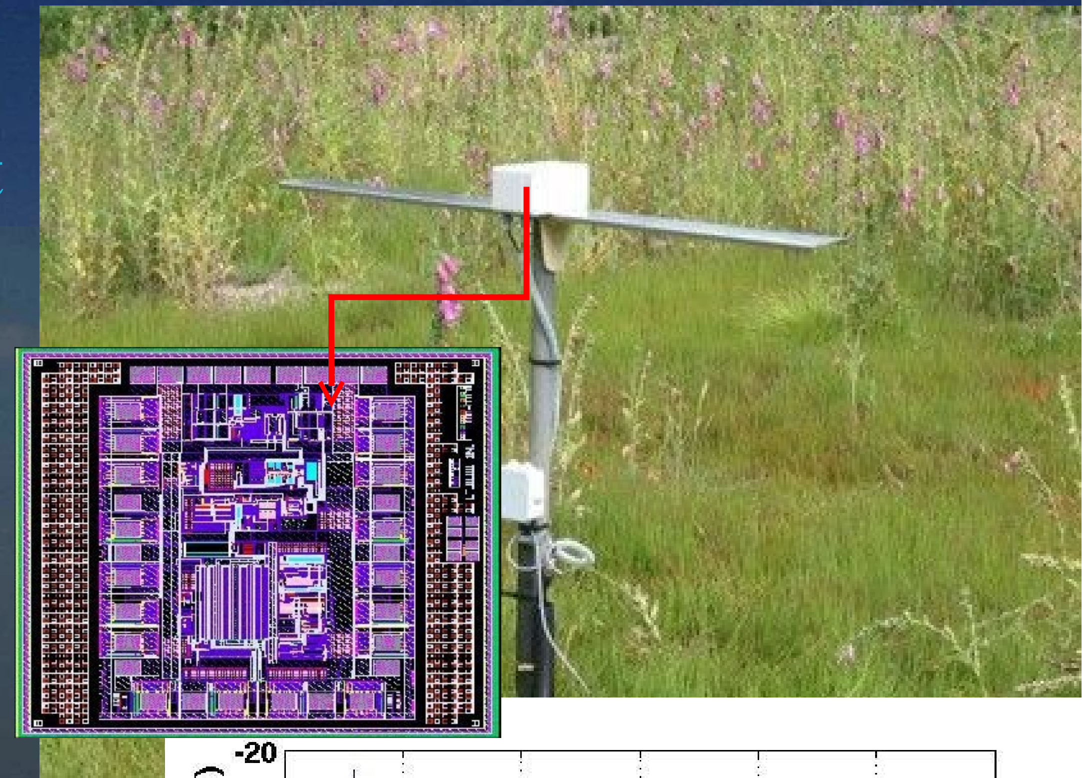
- In the range ~ 1 - 200 MHz
- Wide band antennas needed
- Lower frequencies required to be able to see distant showers
- Scales as γ/b^2

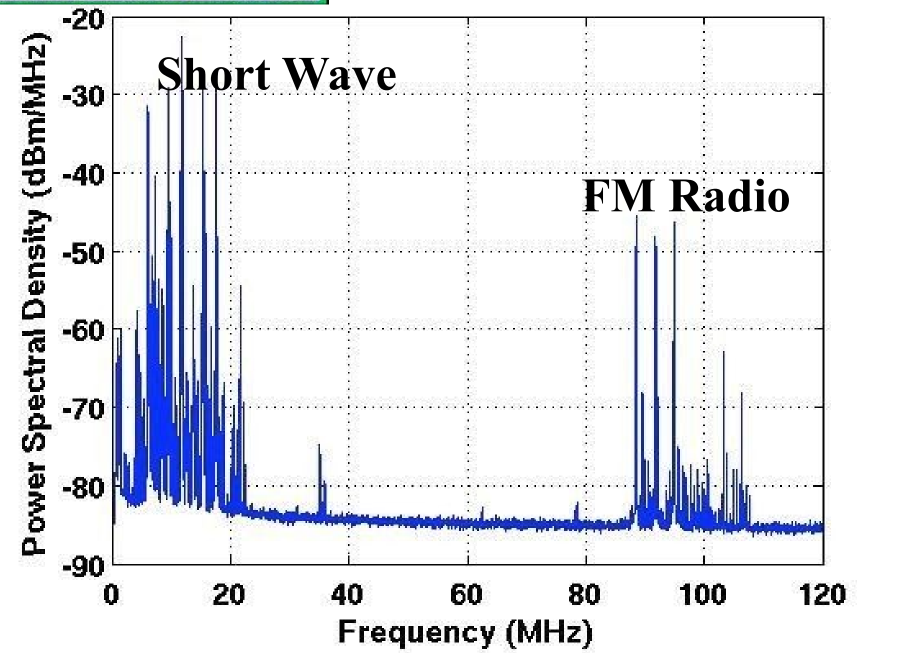




Why is radio interesting ?

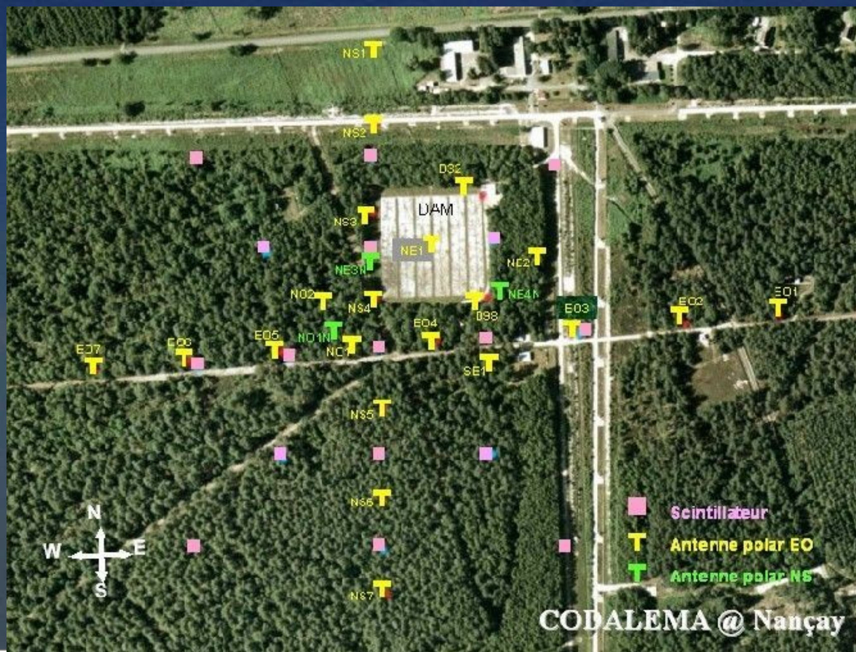
- Pretty inexpensive equipment
  - Active Dipolar antenna
    ~1 m × 10 cm
    Frequency band [1-200] MHz
  - Low noise amplifier (ASIC)
  - Fast ADC (300 MHz)
  - Cost ~ 4000 Euros
- Duty cycle ~100 %
- Efficiency ~100 %
- Calorimetric Measurement
- Timing and lateral distribution allow reconstruction of shower
- 25 – 85 MHz region pretty empty

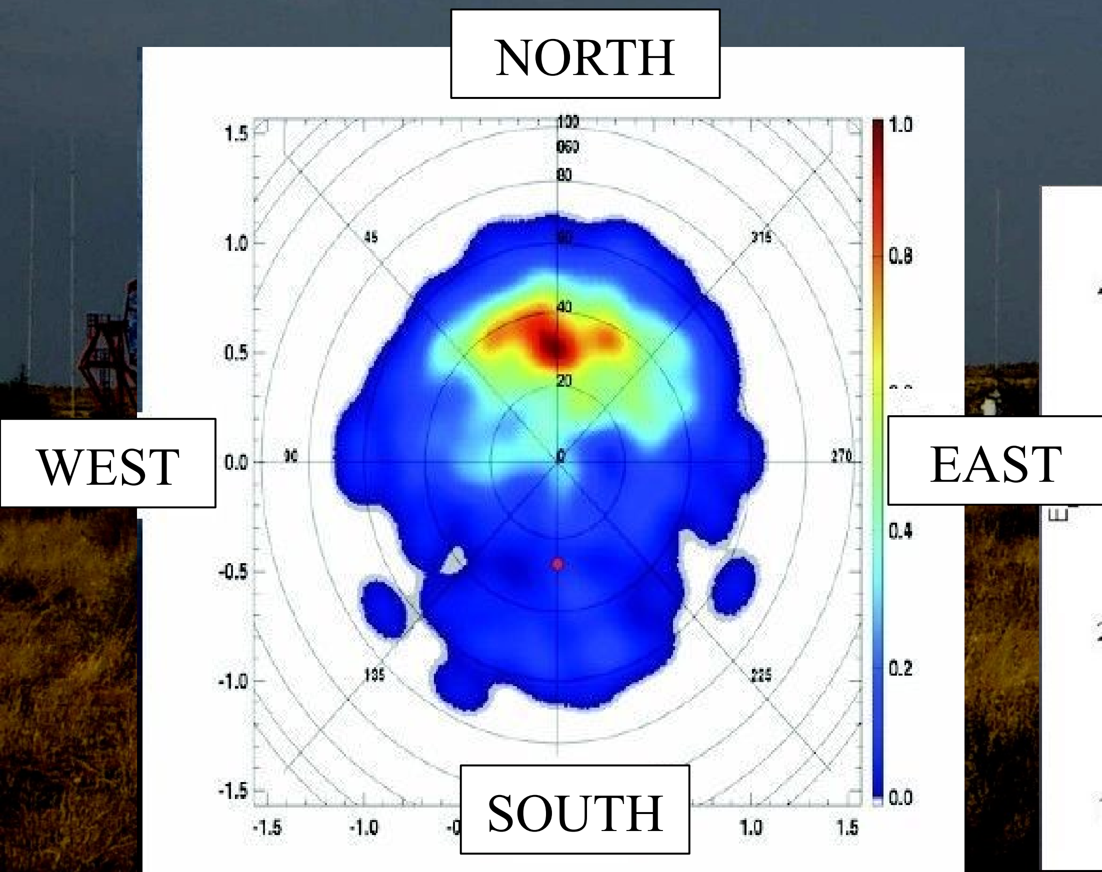


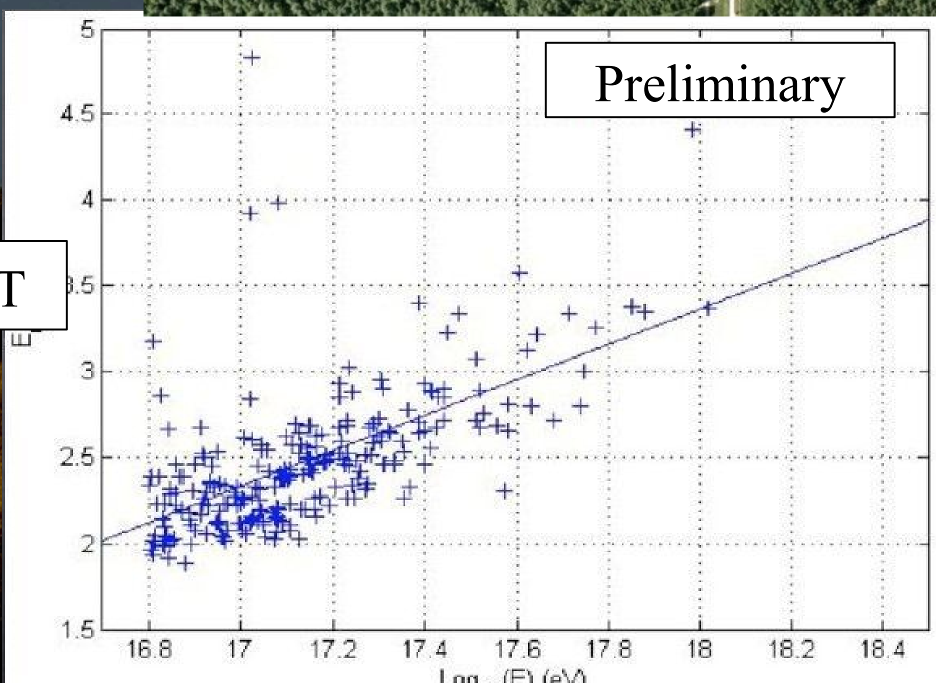


Radio detection of showers: CODALEMA

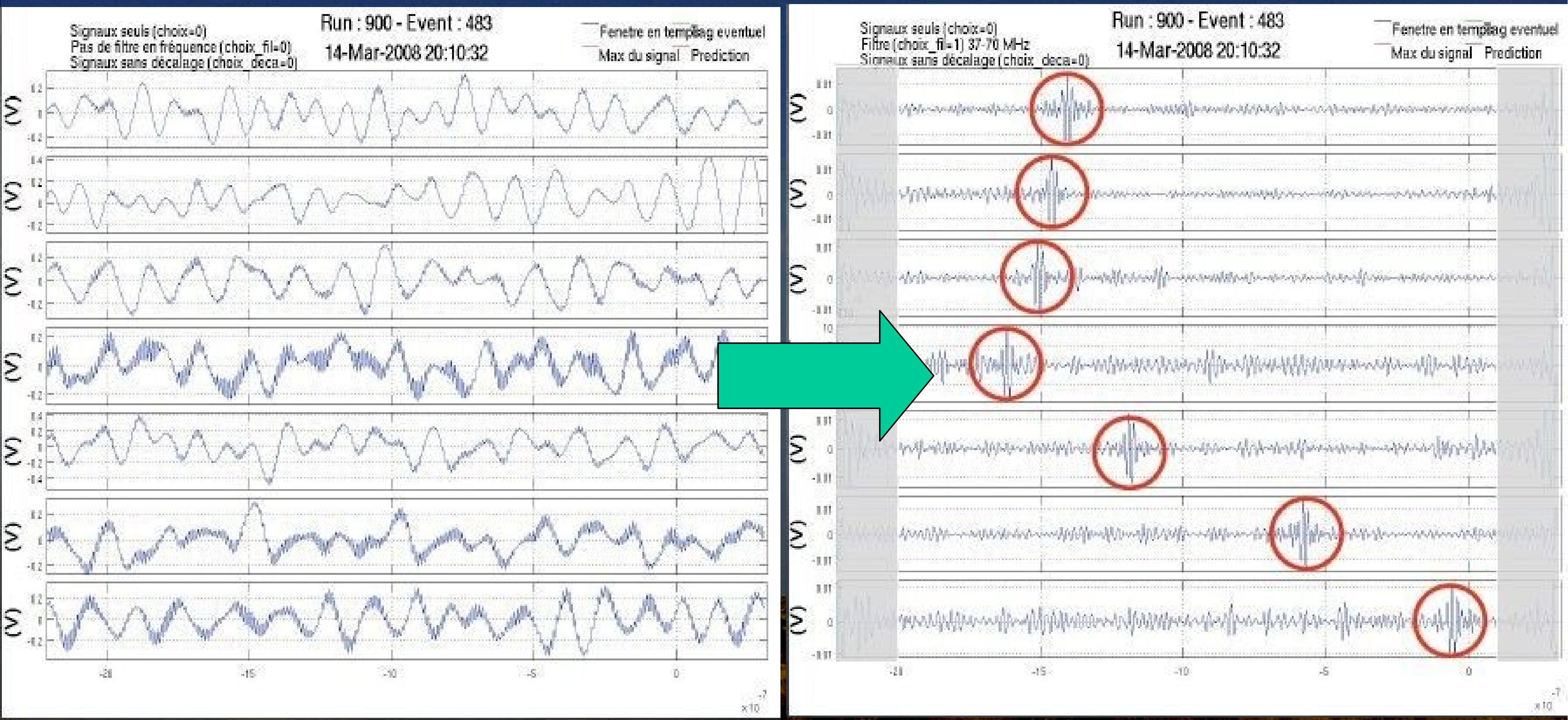
- Clear asymmetry in arrival directions
- Unambiguous proof for geomagnetic effect
- Electric field amplitude proportional to energy ⇒ calorimetric measurement?







Signal Processing

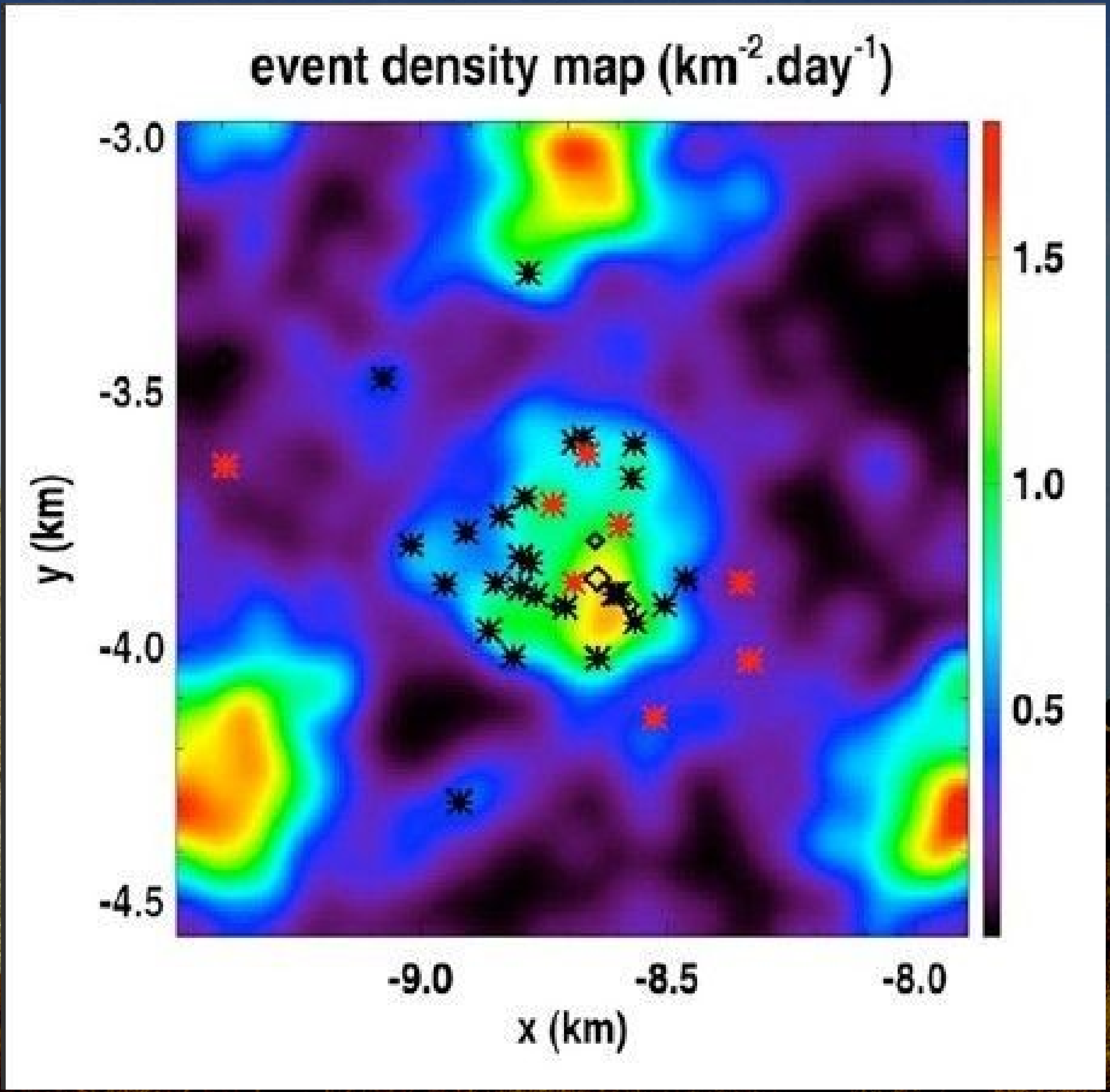


Raw signal, SD trigger, 1Gs/s

23-82 MHz filtering

- Timing measurement is possible
- Simple trigonometric reconstruction

Radio Detection @ Auger



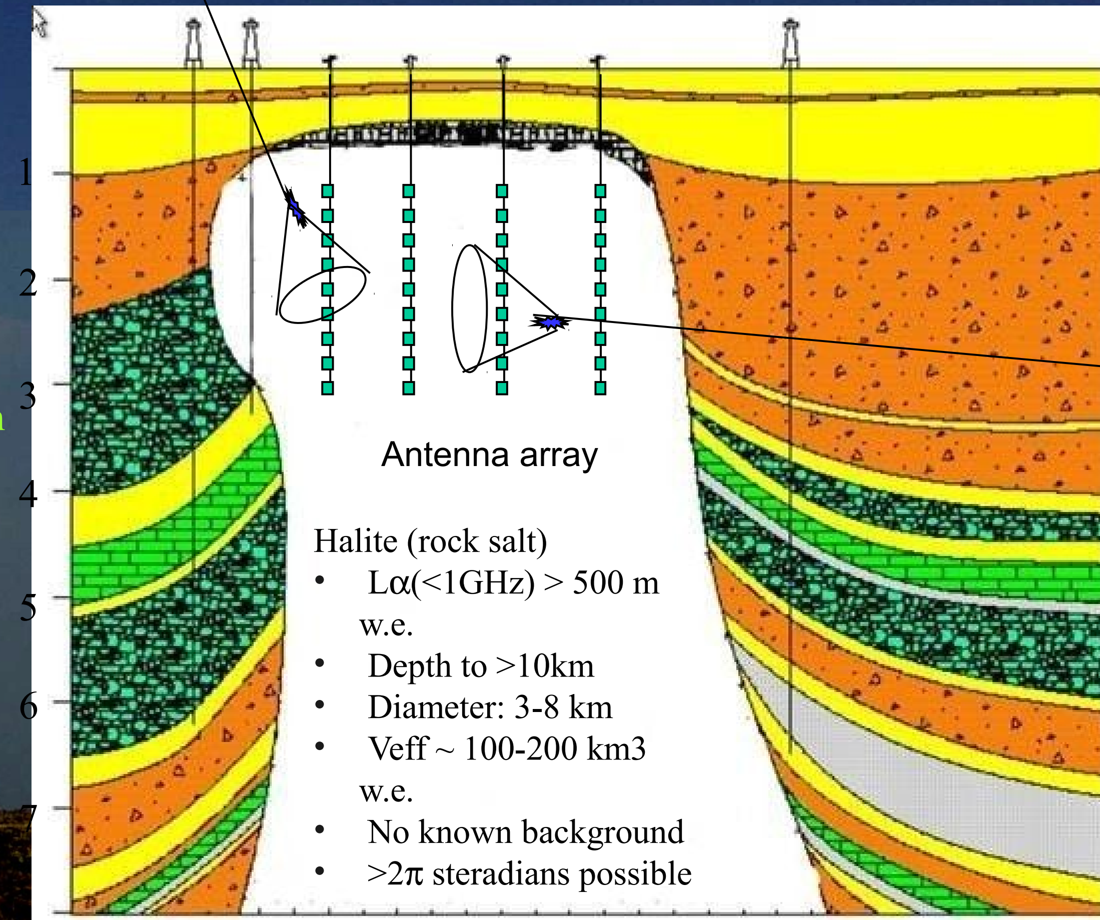
- Autonomous prototype installed @ AUGER
- First detection: July 2007
- 39 events in coincidence with Auger SD (SD trigger)
- First self-trigger announced recently
- Radio detection seems to work up to 1 km away from antennas
- Radio detection seems to work for horizontal showers

Saltdome Shower Array (SalSA)

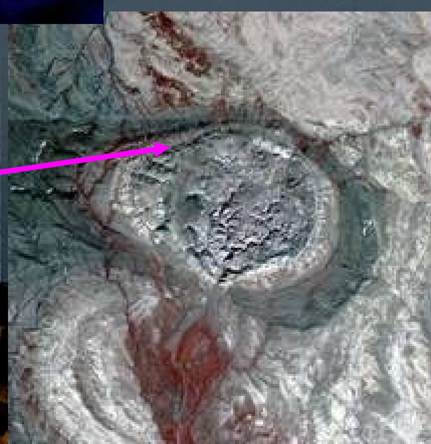
Salt domes: found throughout the world

Qeshm Island, Hormuz strait, Iran, 7km diameter

Depth (km)



Isacksen salt dome, Elf Ringnes Island, Canada 8 by 5km

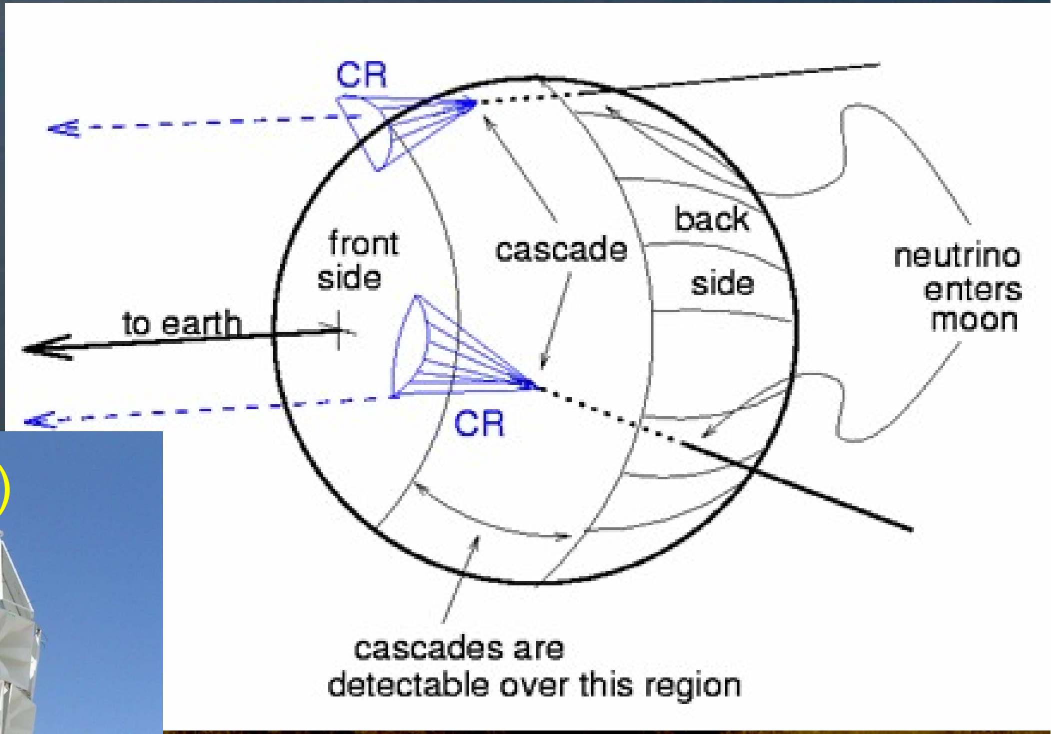


- ❑ Salt domes are transparent to radio frequencies (no water)
- ❑ Huge volumes 50-100 km^3

Using the moon

- Radio emission in moon surface
- Largest and cleanest detector for high energy
- Well suitable to neutrinos (skimming)
- GHz emission
- Current projects
  - GLUE
  - FORTE
  - NuMOON
- Or use the ice (ANITA @ IceCube)

radio from
neutrinos hitting the moon

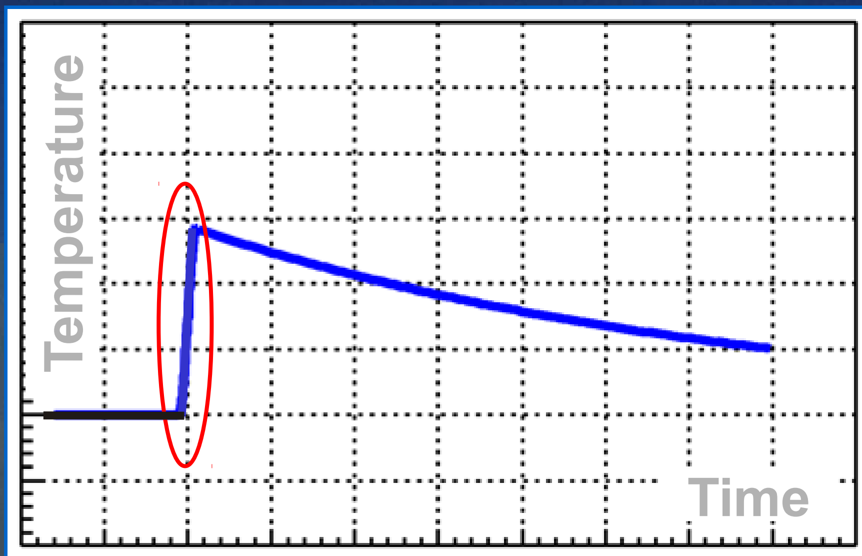


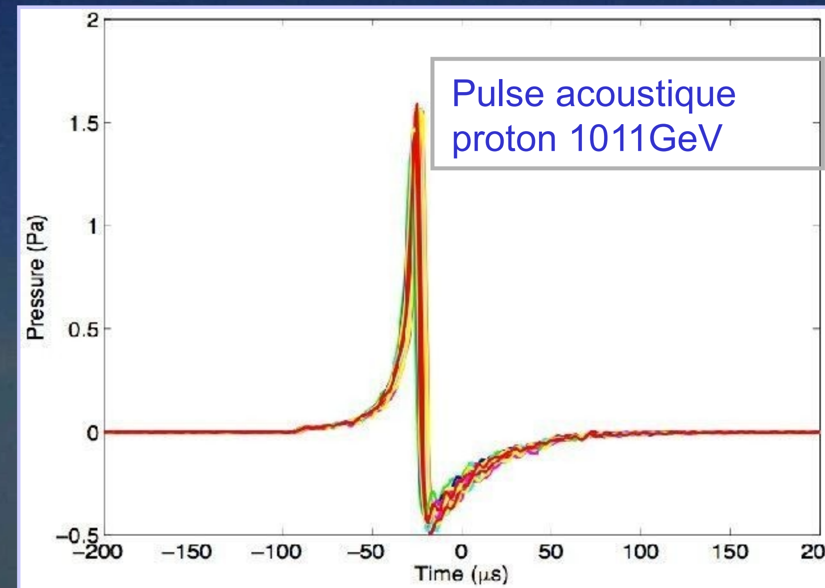
NuMOON @ Westerbork

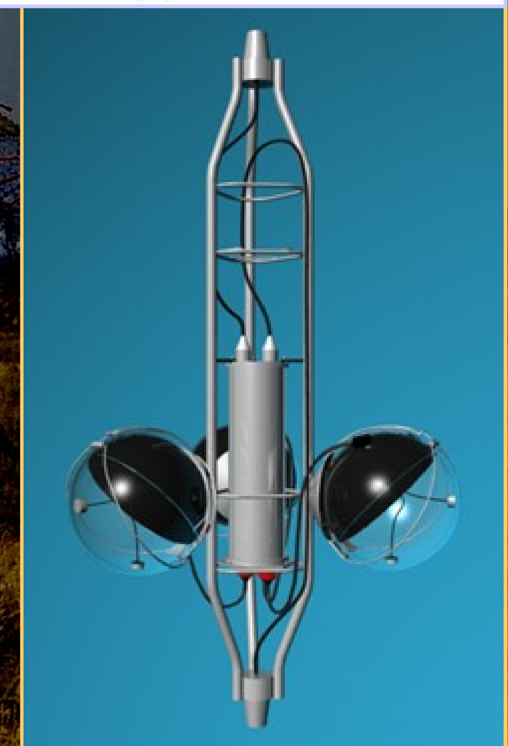
ANITA (lite)

from Gorham et al. (2000)

Acoustic Detection

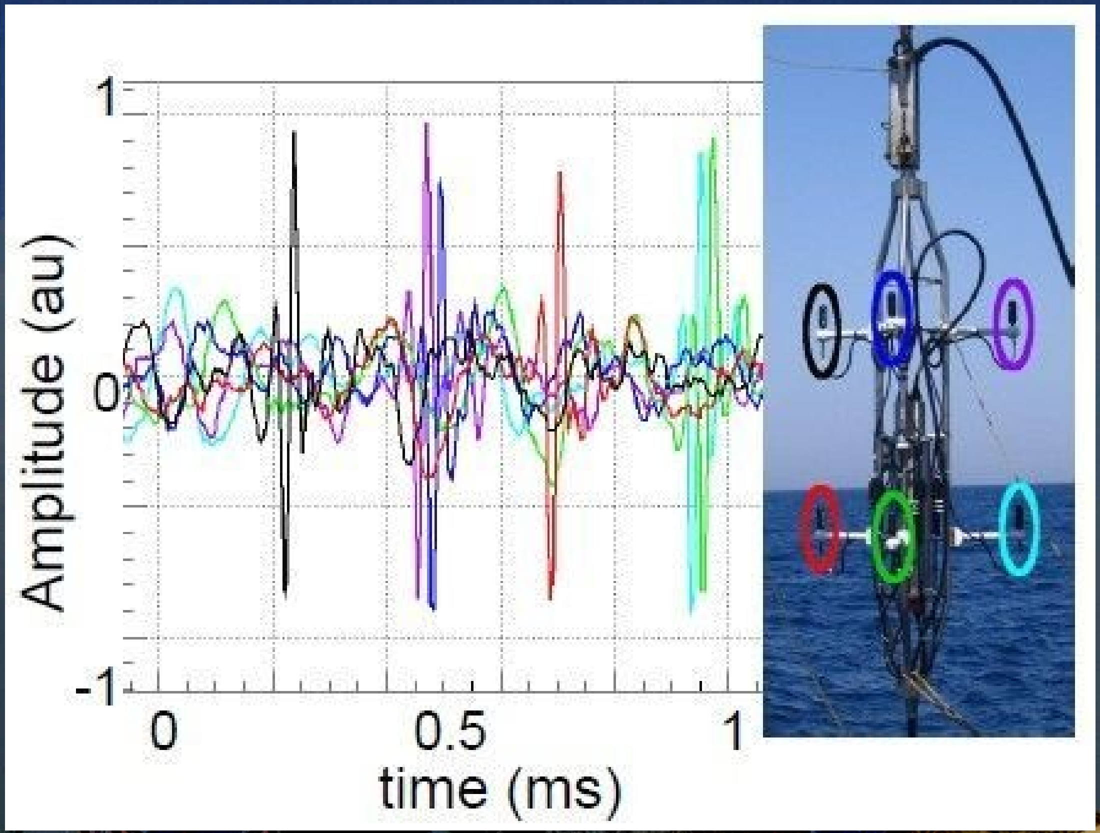


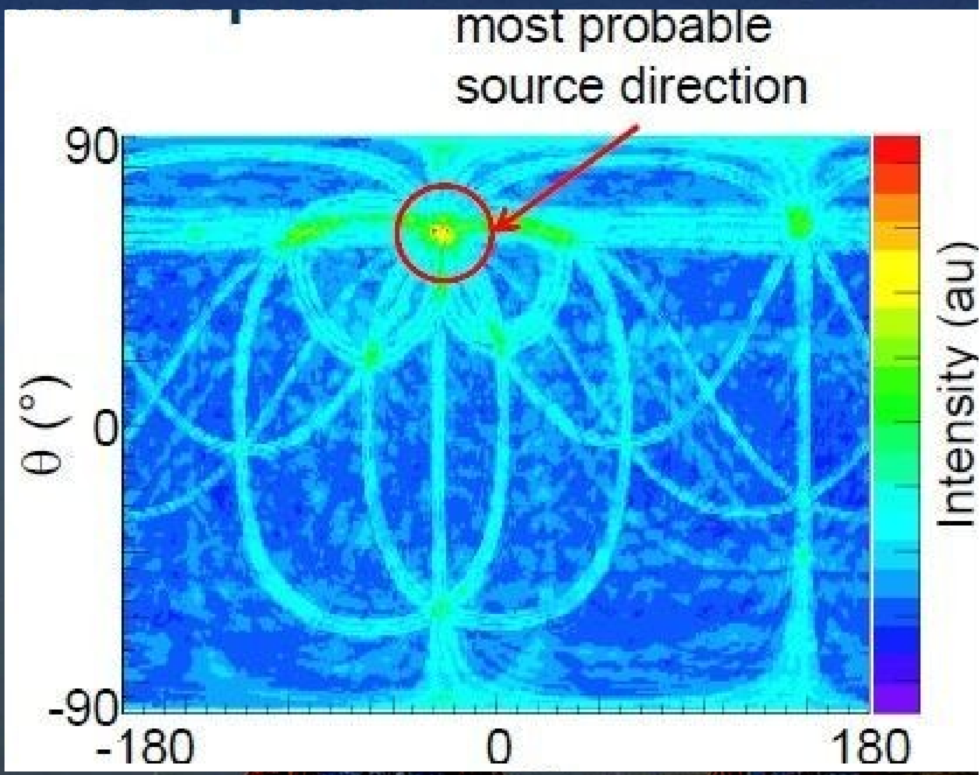




- Acoustic wave triggered by shower
  - quasi-instantaneous energy deposit
  - water dilatation ⇒ dipolar acoustic signal
  - Ongoing R&D in several sites (Baikal, Antares, IceCube, …)
- Challenges : background noise (waves, whales, dolphins, ships, …)

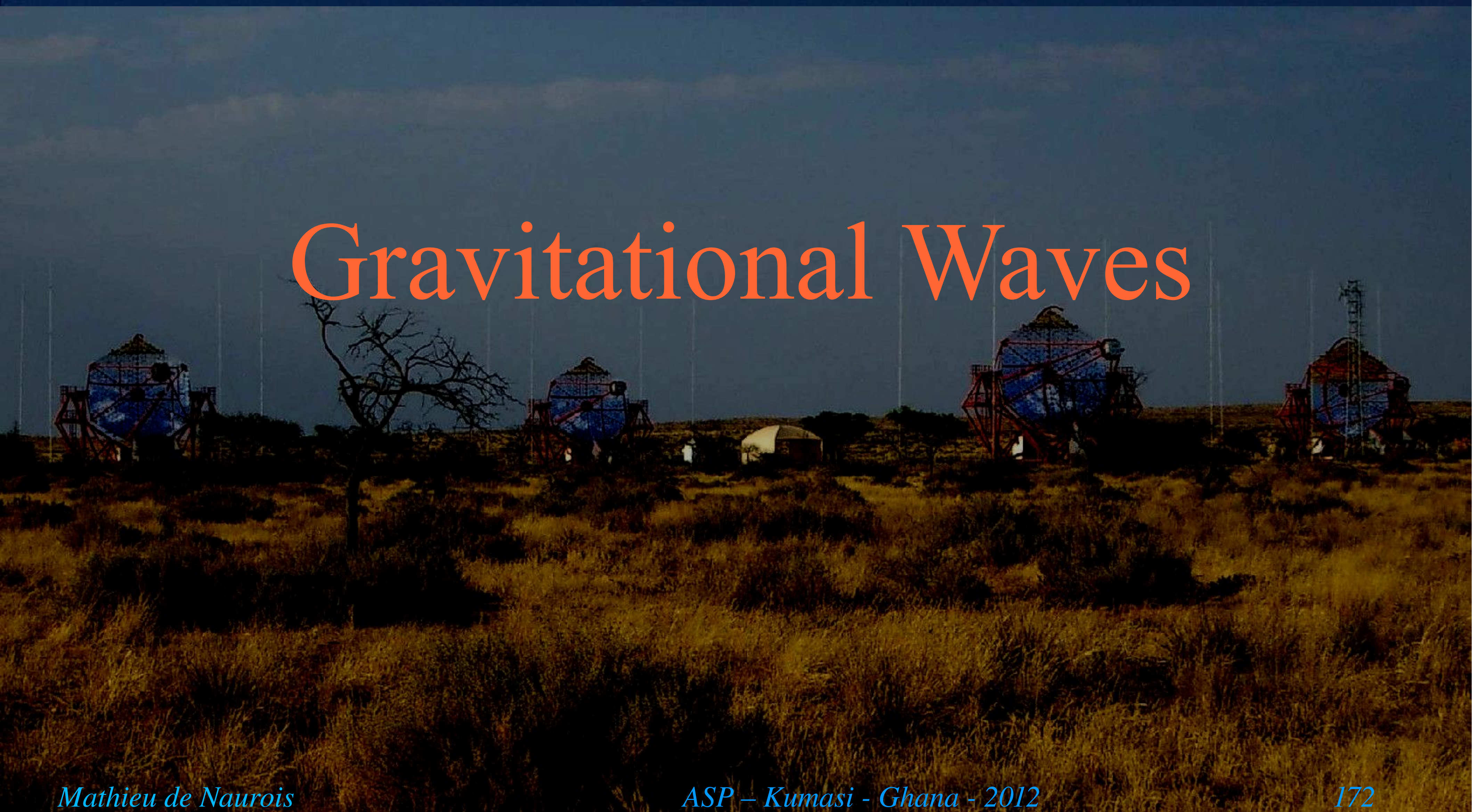
Direct reconstruction – A dolphin





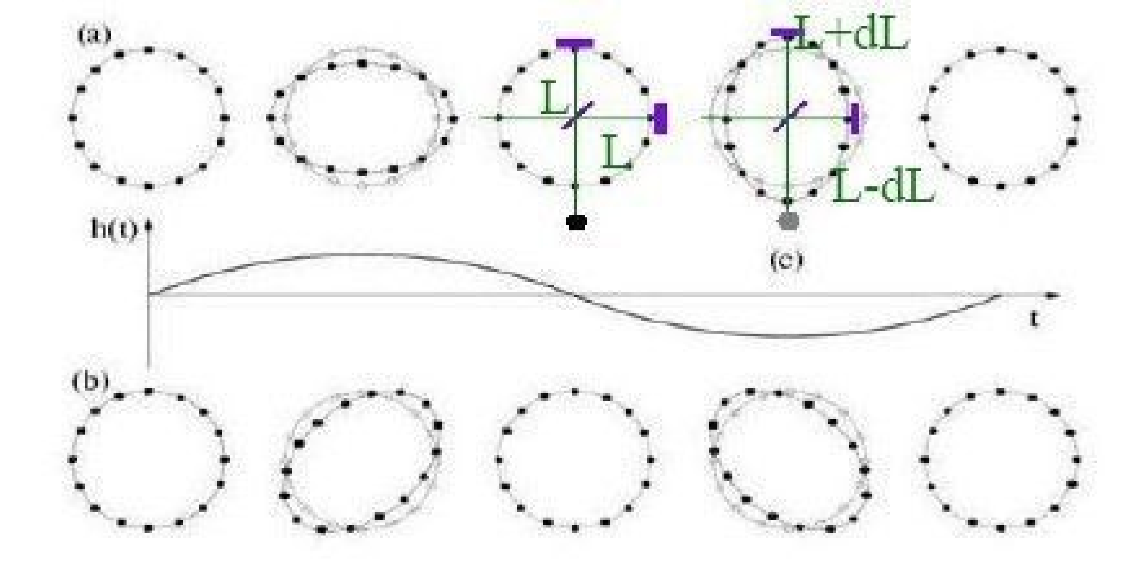
- Acoustic signal amplitude on several hydrophones
- Beam forming algorithm leads to angular resolution < 1°

Gravitational Waves



Gravitational waves

- General Relativity predicts propagation gravitational waves (deformation of space-time)
- Bursts
  - Supernovae
  - Black Holes disexcitation
- Spiralling binary systems
  - Neutron stars, black holes
- Periodic sources
  - Pulsars
- Other? (new physics)

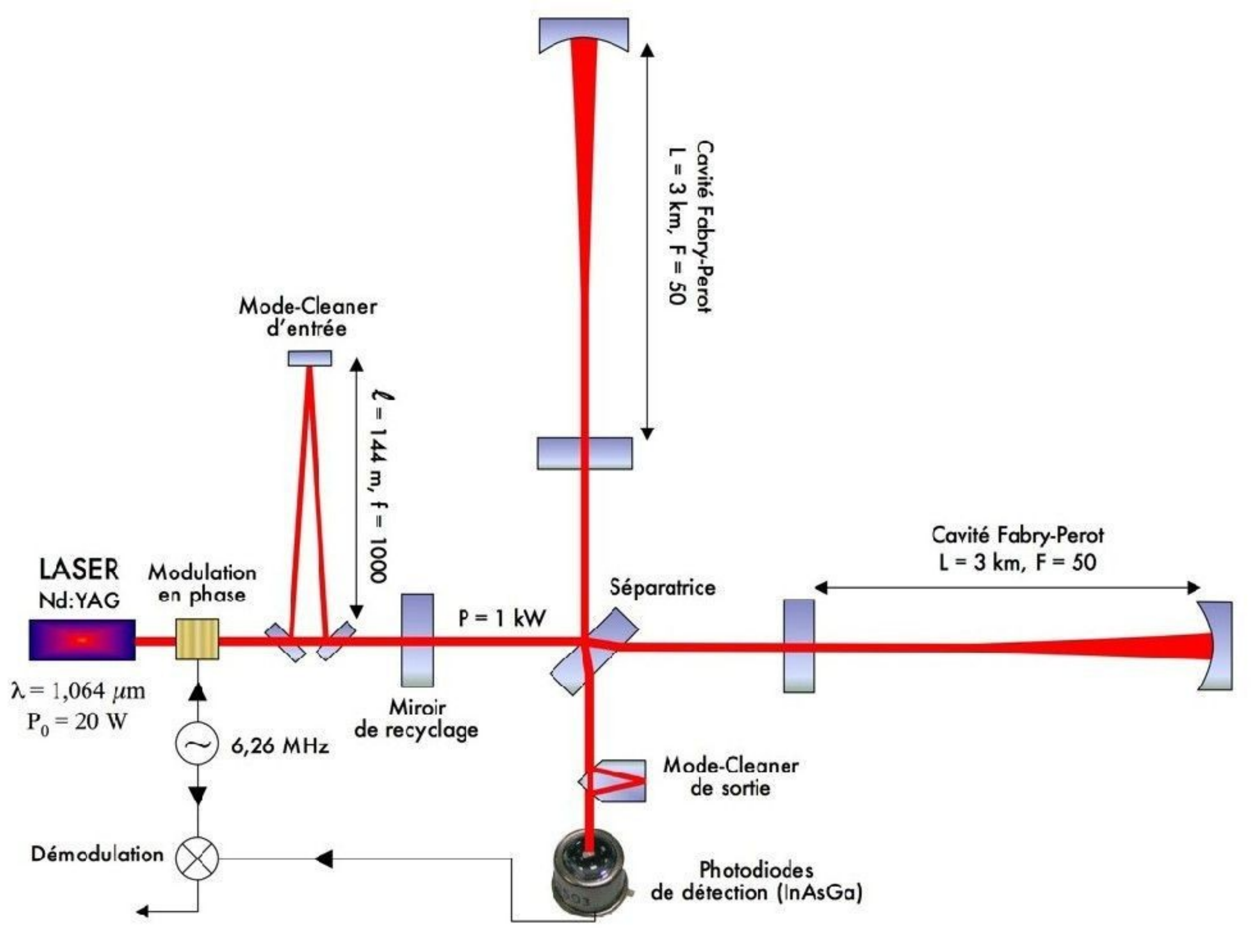


Detection Principles

- Basic idea: giant interferometer
- Frabry Perrot cavities in each arms multiply path length and increases sensitivity
- Challenges:
  - Typical amplitude: $\Delta L/L \sim 10^{-21}$
  - Mechanic Noise (vibrations, …)

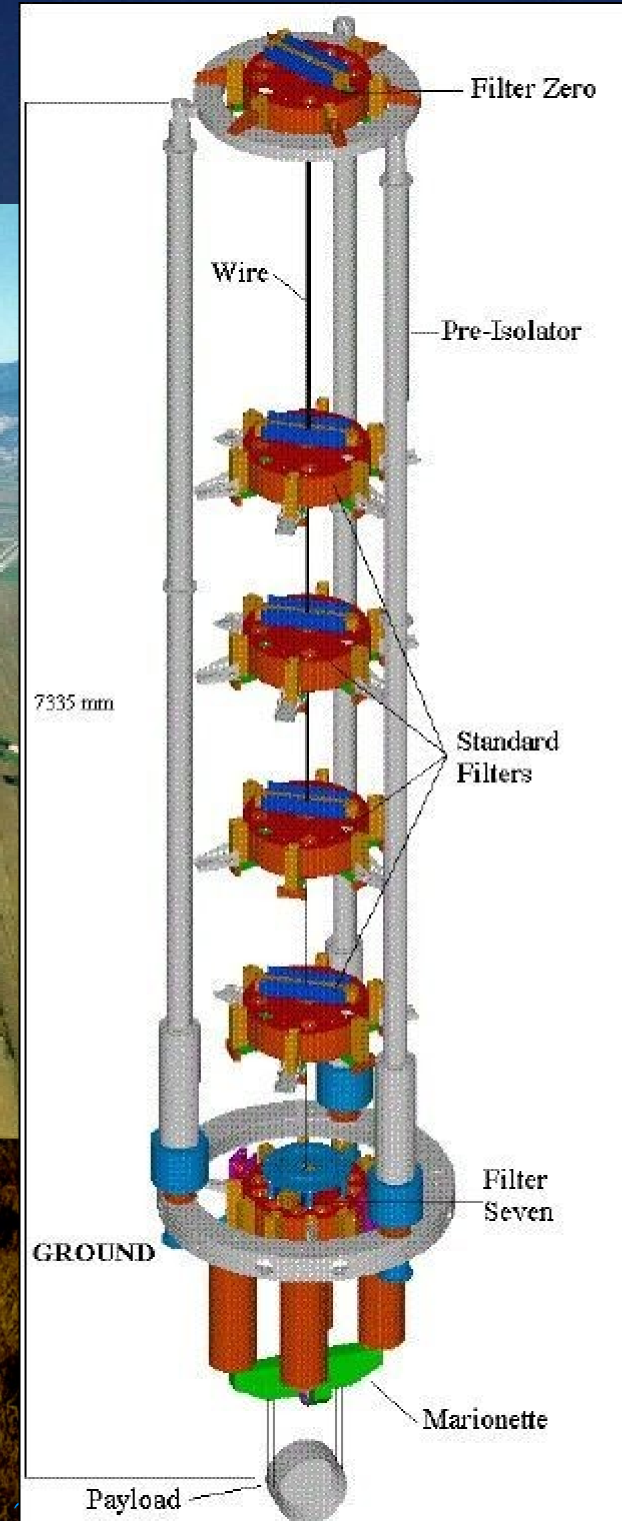
  $\Rightarrow$ Multistage filters
  - Quantum Noise

    $\Rightarrow$ High laser intensity



Mathieu de Naurois

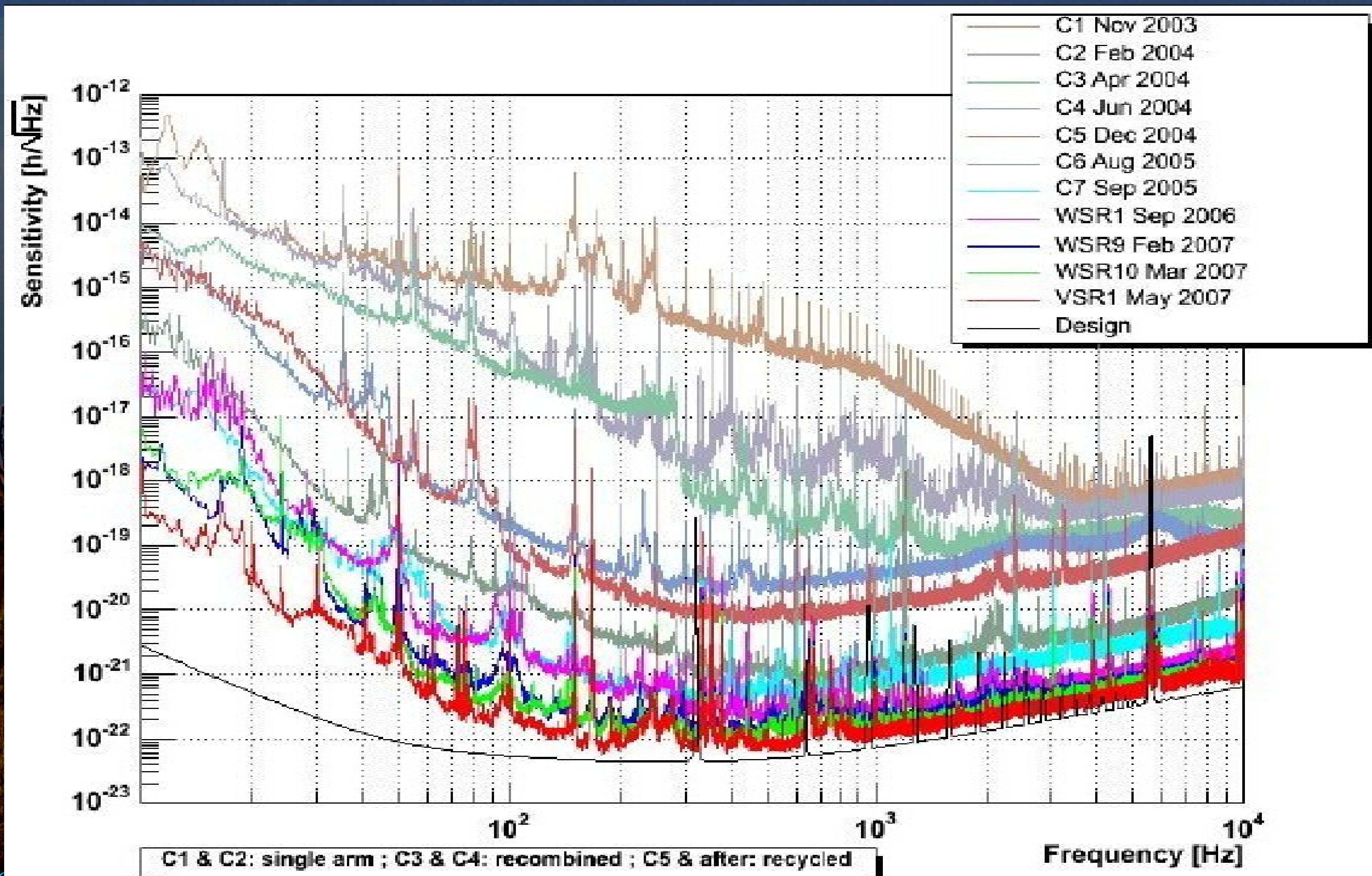
VIRGO



Filter Zero
Wire
Pre-Isolator
7335 mm
Standard Filters
Filter Seven
GROUND
Marionette
Payload

Sensitivity

- Nominal sensitivity almost reached after several years of intense efforts



LIGO

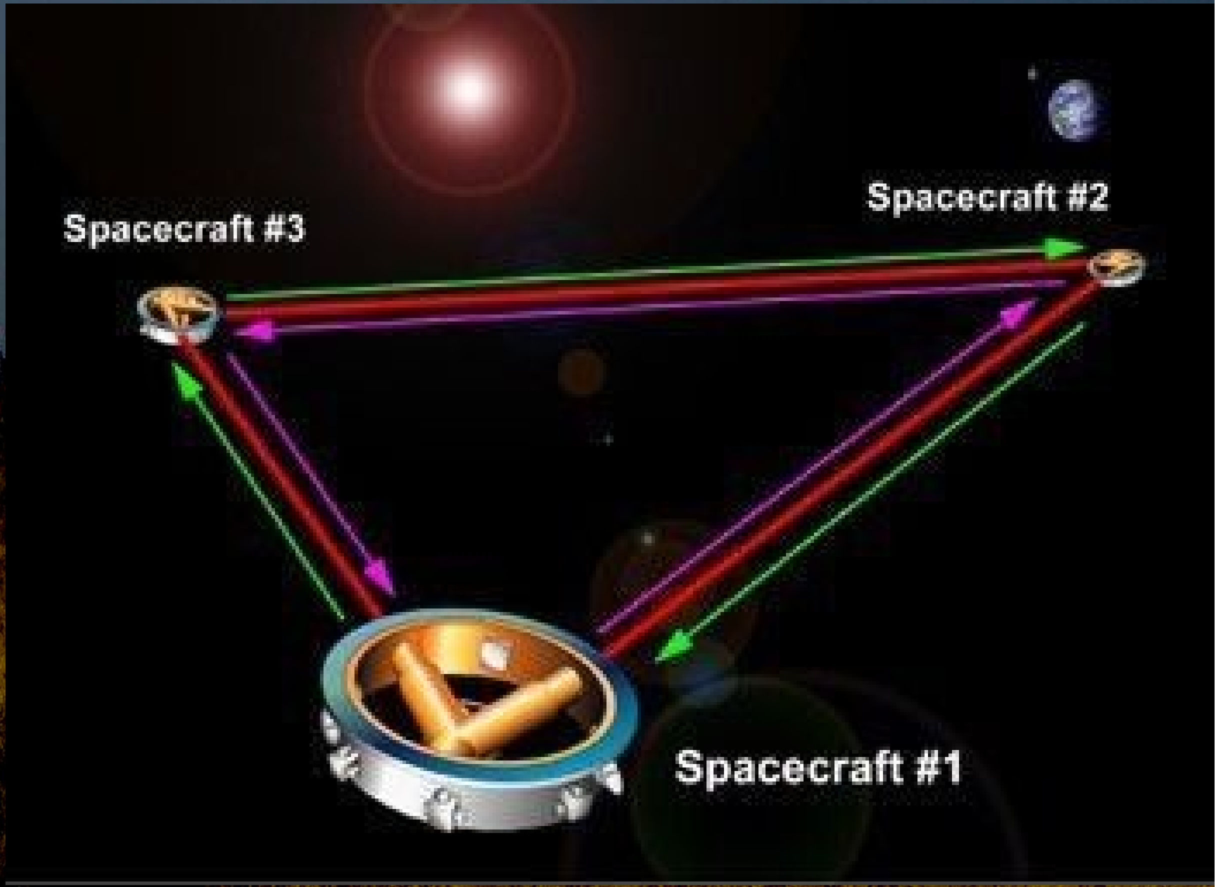
- Laser Interferometer Gravitational wave Observatory
- 2 sites 3030 km away
- Taking data
- Close cooperation with VIRGO (data exchange)

Hanford (Washington): 2 interferometers

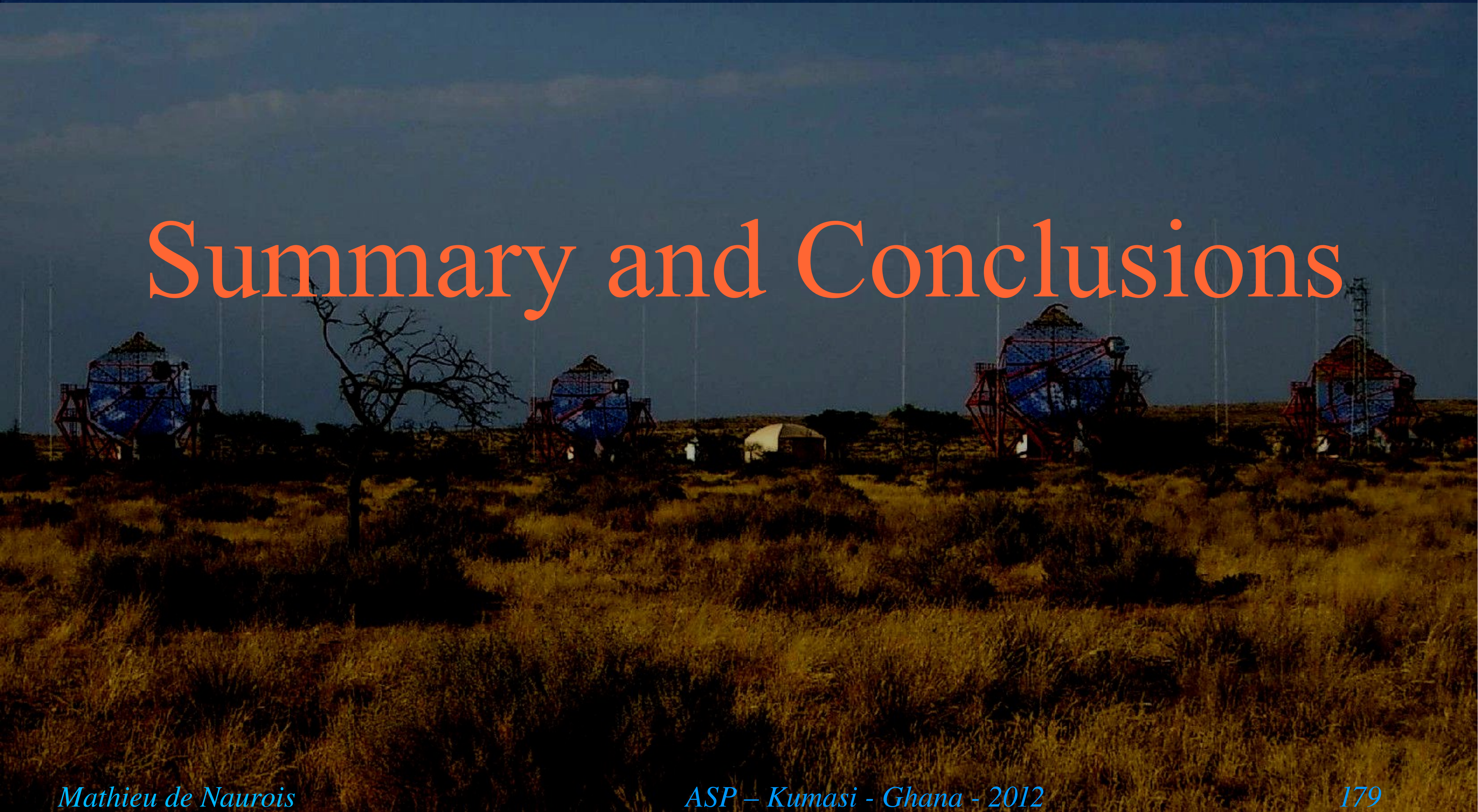
Livingston (Louisiane) : 1 interferometer (4 km)

Future projects: LISA

- 3 satellites, formation flight
- 5 Mkm levelarm
- lower frequency range: $[10^{-4},10^{-1}]$ Hz, vs $[10^{1},10^{4}]$
- Launch around 2018 ?



Summary and Conclusions



Astroparticles...

- Is a very various field:
- Multimessenger:
  - Cosmic rays
  - Gamma-rays
  - Neutrinos
  - Gravitational Waves
- Multiwavelength: from 10^6 to 10^{20} eV: 14 decades in energy!
- Great variety of technologies and instruments
  - satellites, balloon, ground based, underground , ...
  - particle physics detector, radio detection, acoustic, ...
- Great variety of physics subjects: phenomenology of cosmic rays, astronomy, cosmology (structure formation), dark matter search, fundamental physics (Lorents invariance, ...)
- Exciting future, many projects (AMS, Auger North, Radio detection, Neutrinos, CTA, Virgo+, ET, LISA, ...)

What have we learned ? (I)

- Cosmic ray phenomenology is rich
  - Constraints on magnetic fields and propagation
  - Large amount of data, increasing in quality
  - 4 spectral dimensions:
    - Composition (Isotopic),
    - Energy Spectrum,
    - Directions, isotropy
    - Time variability
  - Link with cosmology (formation of structures)
  - Link with dark matter (annihilation)

What have we learned ? (II)

- The γ-ray sky in surprisingly full of sources
  - High spin-down pulsars
  - Supernovae remnant are able to accelerate particles to E > 100 TeV, most probably protons (e- disfavored as they required low B fields)
  - Interaction of CR with ambient matter (molecular gaz) strongly support hadron production mechanisms, around Galactic Center and SNRs
  - Regions of star formation
  - Huge flares from active galactic nuclei can tell us about photon propagation in Universe
  - The Universe is more transparent to γ-rays than expected (low EBL)
  - New, unexpected, mysterious sources

What have we learned ? (II)

- Ultra high energies:
  - GZK cutoff is there
  - A UHECR Astronomy is possible, UHECRs are correlated with nearby matter (AGN, GRB?)
  - Top-Down models are strongly disfavored
  - A mixed composition is favored by data around the ankle
  - More data is needed to go further

Conclusions

- A lot of experimental activities
- Convergence of several techniques