Astroparticle Physics

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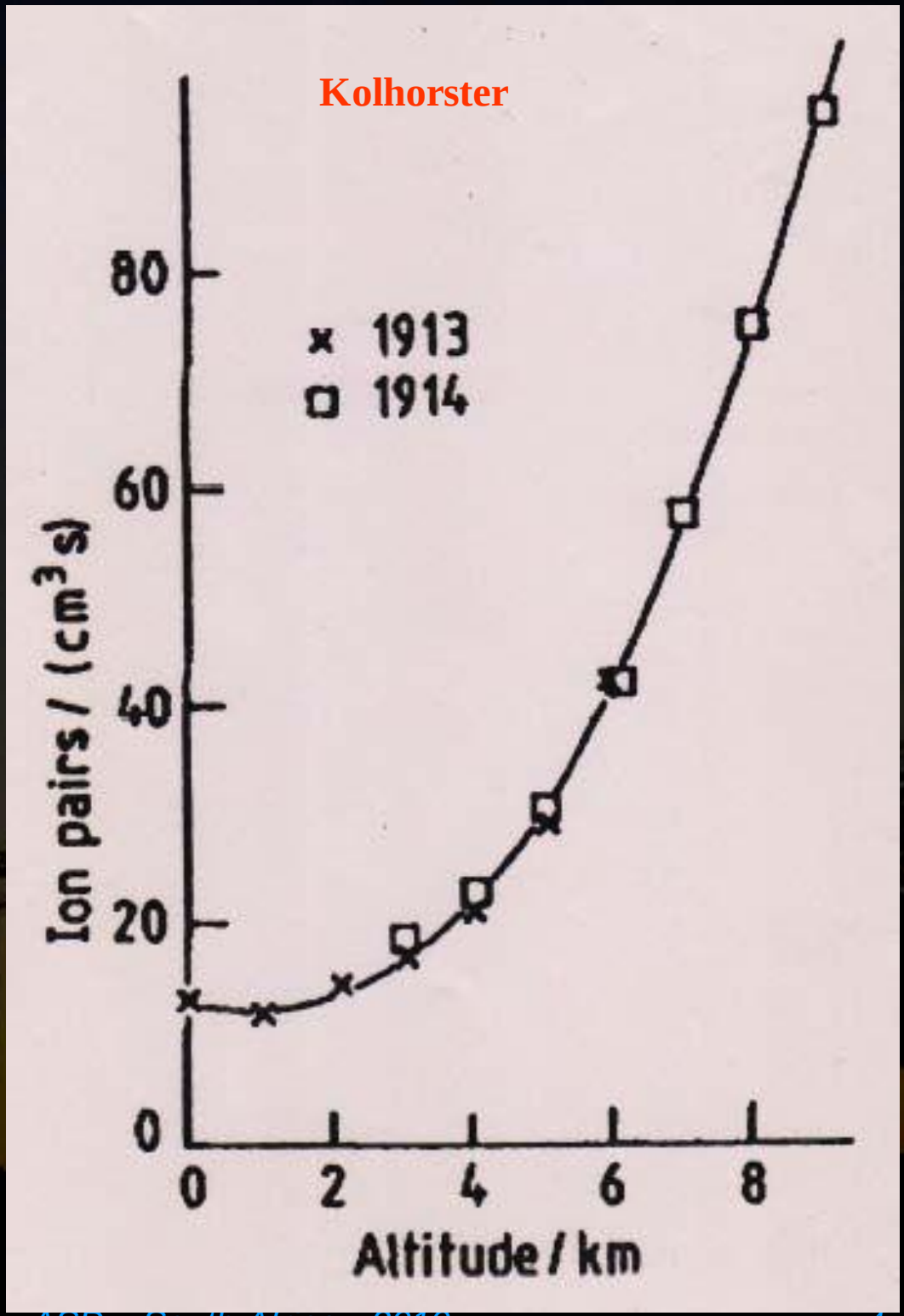
- Introduction: Some historical facts, general problematic
- Cosmic Rays from space and balloons
- (Very) High Energy Gamma ray astronomy
- Ultra High Energy Cosmic Rays
- High Energy Neutrinos
- (Gravitational Waves)
- ~~Direct Dark Matter Searches~~
- ~~CMB~~
- Future prospects and conclusion

SOME HISTORICAL FACTS

The Cosmic Ray Mystery

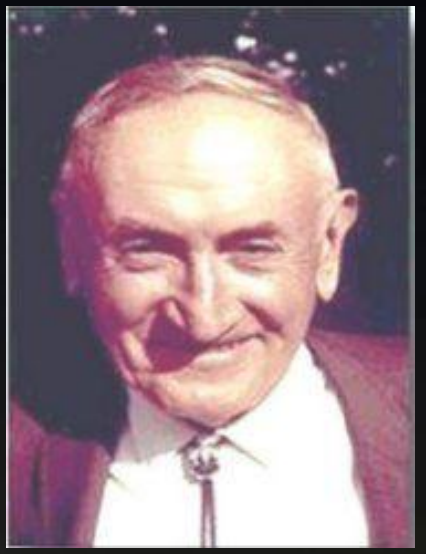
1912 : Discovery by Victor HESS (Nobel Prize 1936 with Anderson)

- 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



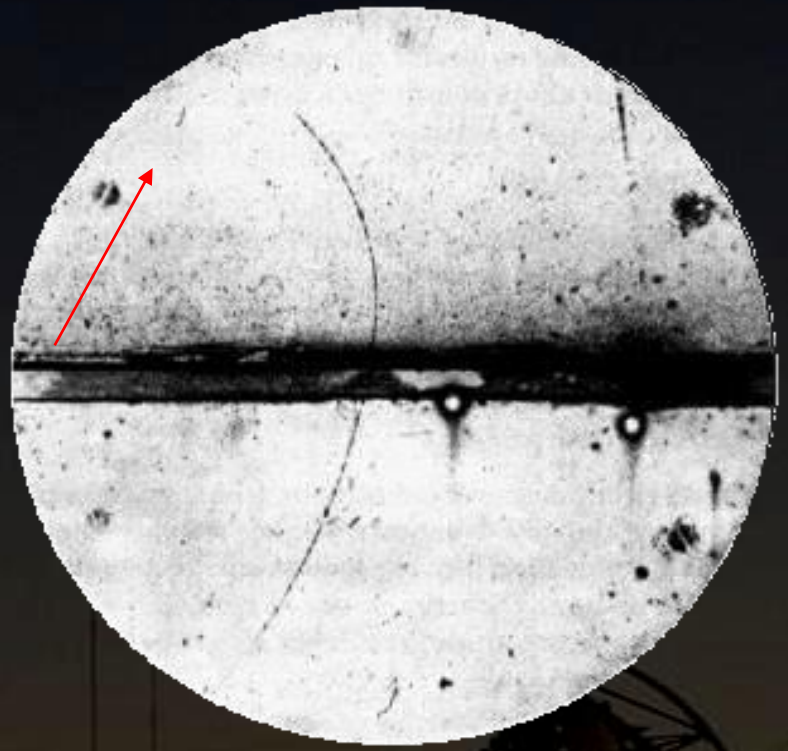
ON SUPER-NOVAE

By W. Baade and F. Zwicky

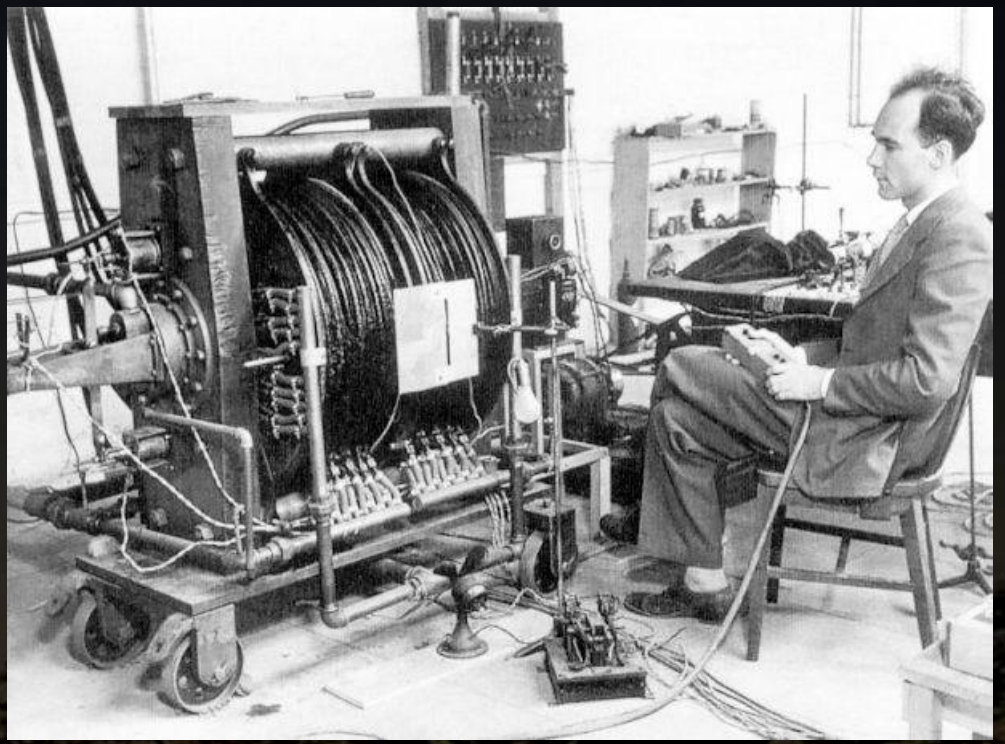
Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

Some major dates – con't



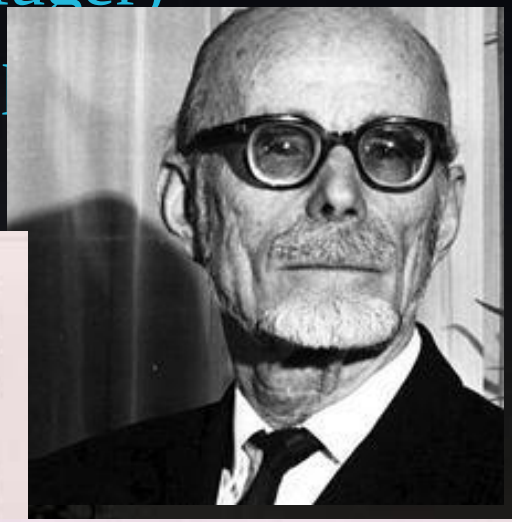
First positron
Anderson, Phys. Rev. (1933)



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

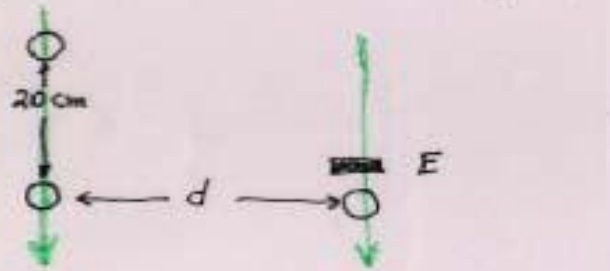
Discovery of giant showers

- 1939 : Discovery of giant showers (Pierre Auger) using coincidence between detectors 50 m a
- Up to 10^{15} eV (at least) !!



PHYSIQUE NUCLÉAIRE. — *Les grandes gerbes cosmiques de l'atmosphère.* Note (*) 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 éter
de plusieurs dizaines de mètres et
corpuscules de très haute énergie da



d.	E = 0,2.	3 com 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

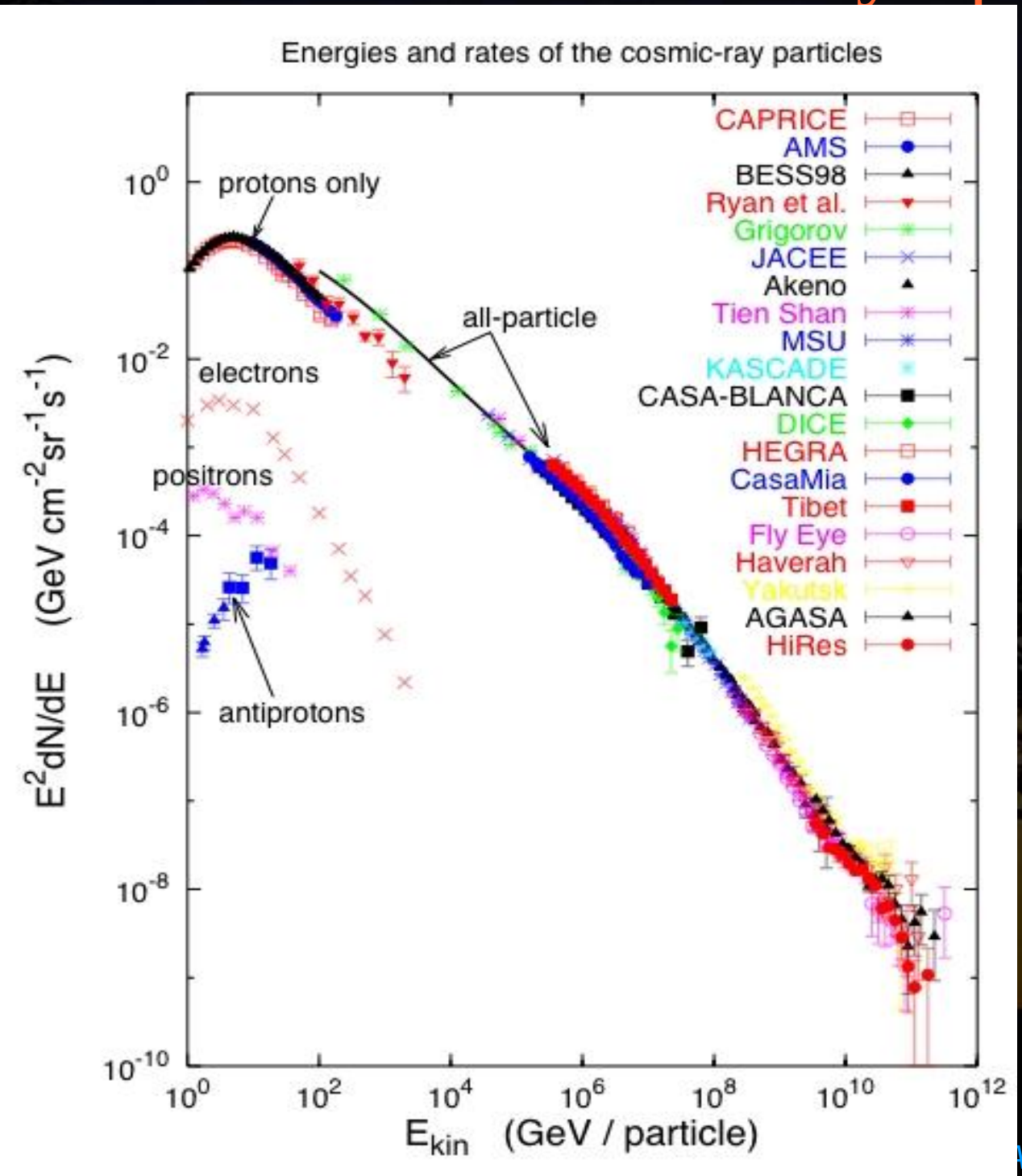
Pierre Auger
In collaboration with
P. Ehrenfest, R. Maze, J. Daudin, Robley, A. Fréon
Paris, France

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.

Cosmic Ray Conference University of Chicago July 1939

Cosmic Ray Spectrum

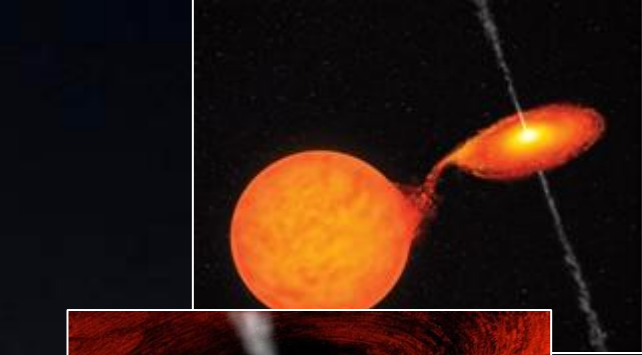
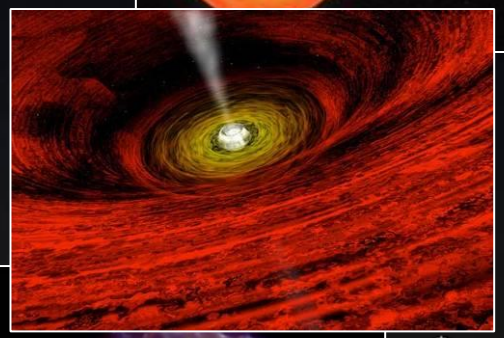
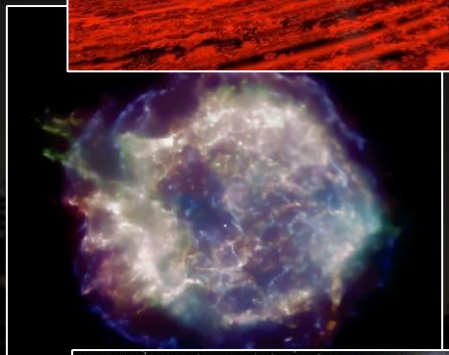


- One wonder of physics
- 12 orders of magnitude in energy, 32 orders in flux

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

Open questions

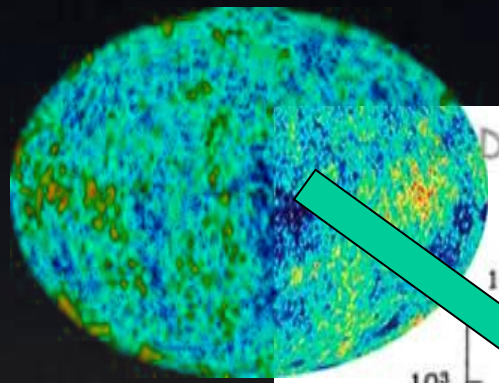
- What the sources of cosmic rays?
- What are the acceleration mechanisms, what are the accelerated particles?
- Is there new physics in there? (Dark Matter, ...)
- How do high energy particles propagate in Universe ? What can we learn from the propagation ?
- Link with cosmology: large structure formation,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

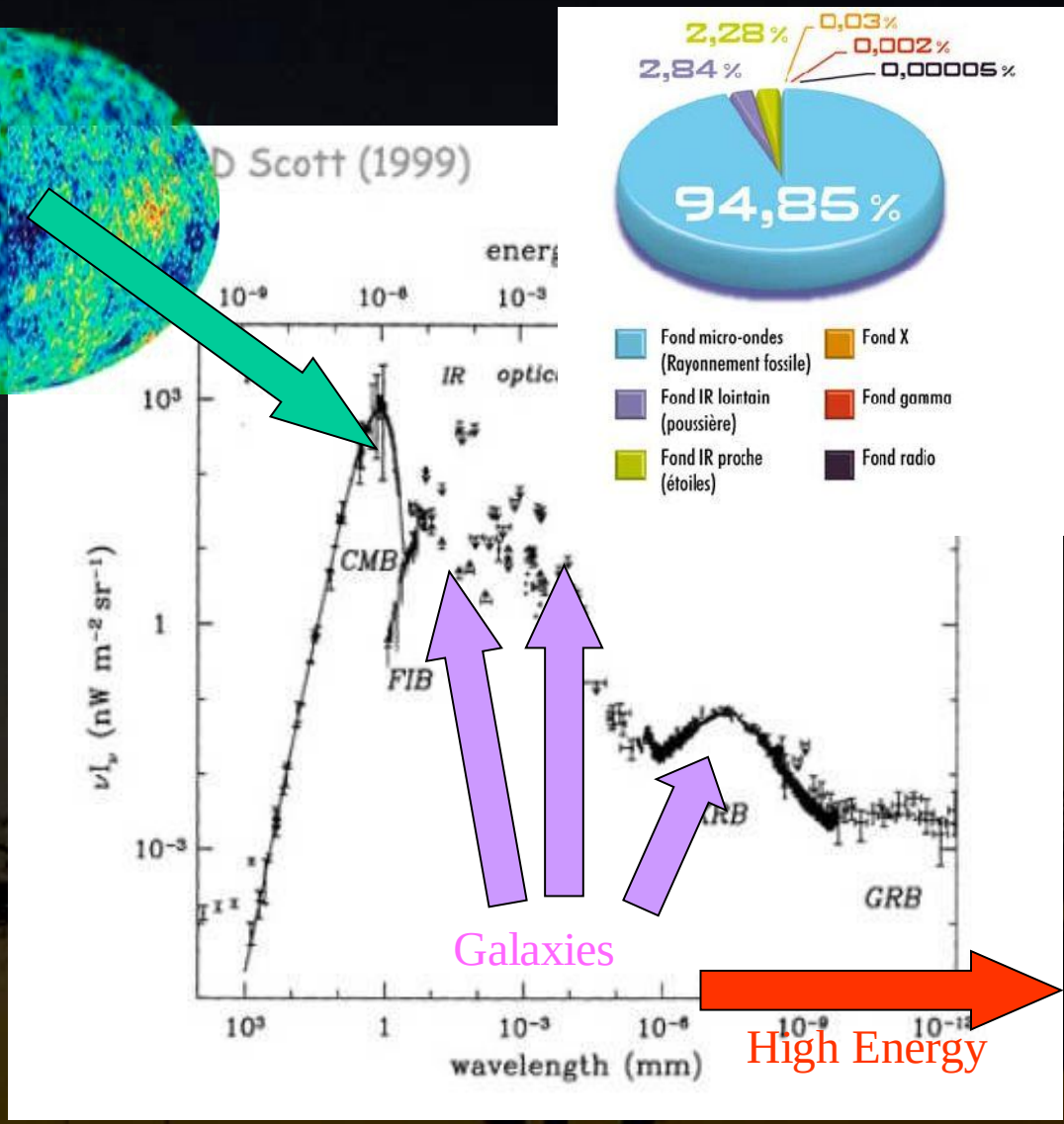





THE MAIN PROBLEMATICS

(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



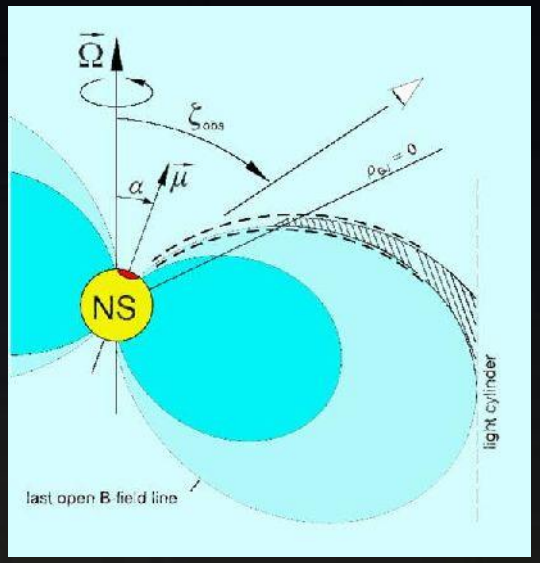


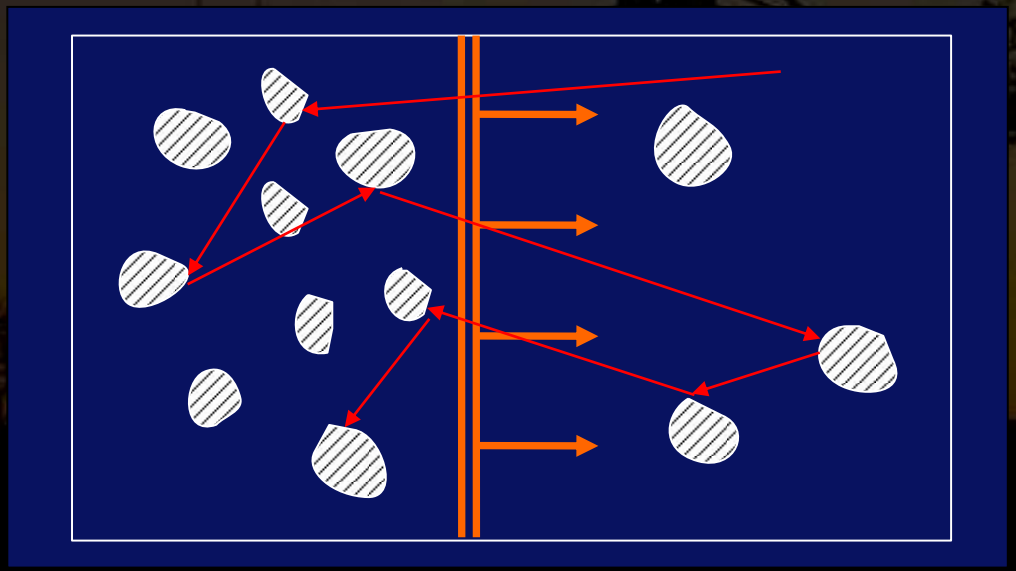
$\Rightarrow$ VHE Universe is Non-Thermal

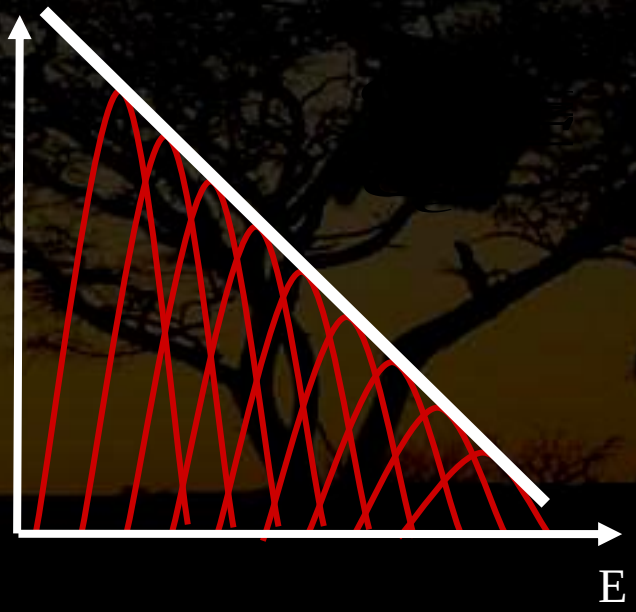
Astroparticle will mainly concern non-thermal Universe

Particle acceleration in a nutshell

- Strong electric :
  pulsars (Rotating Magnetized Neutron Star)
  ~ dynamo effect, V ~ 10^{12} V
- Astrophysical shocks : Diffusive shock acceleration (DSA)
  (Fermi mechanism)







Maximum Energy

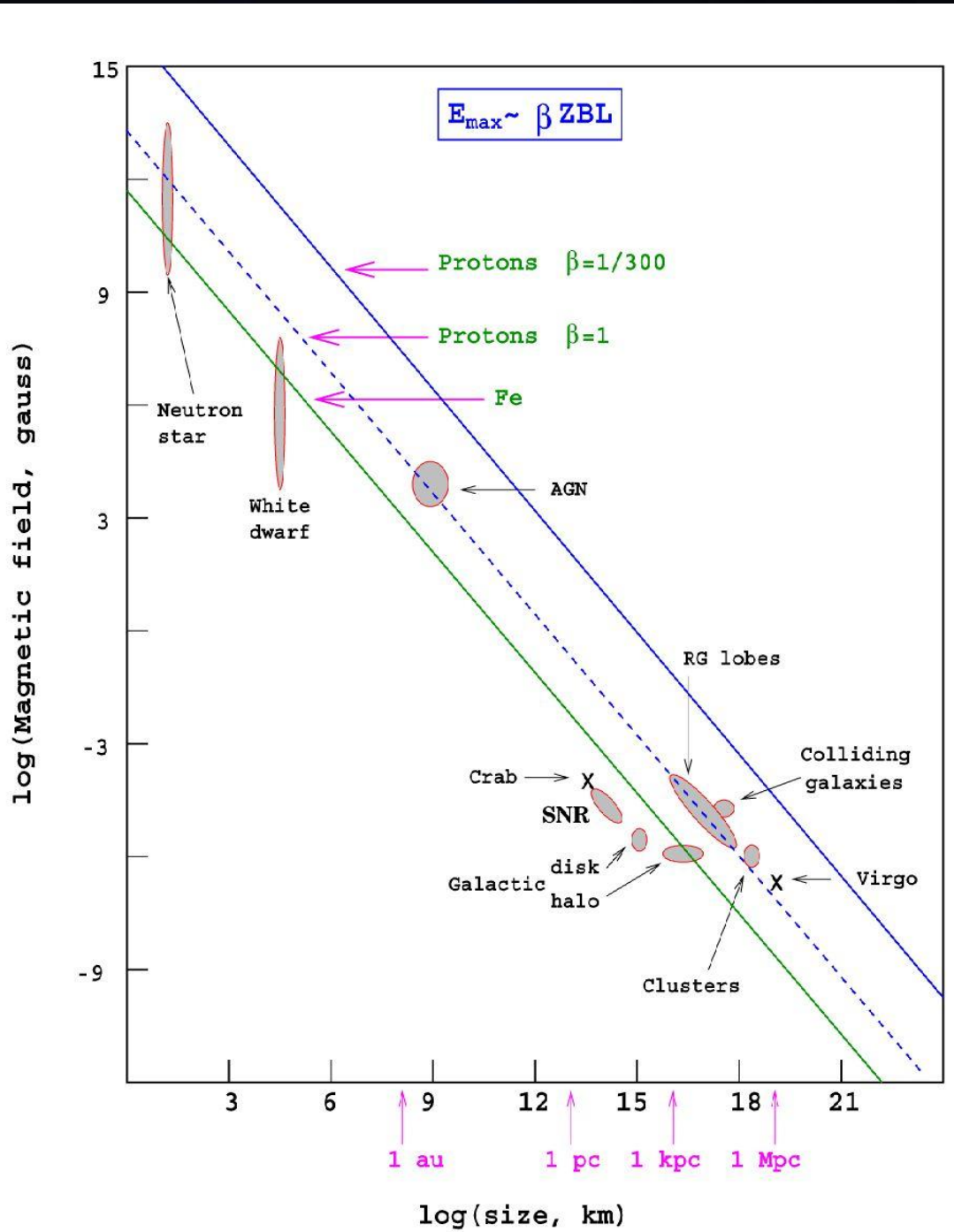
- Max energy limited by confinement size
- Larmor Radius

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

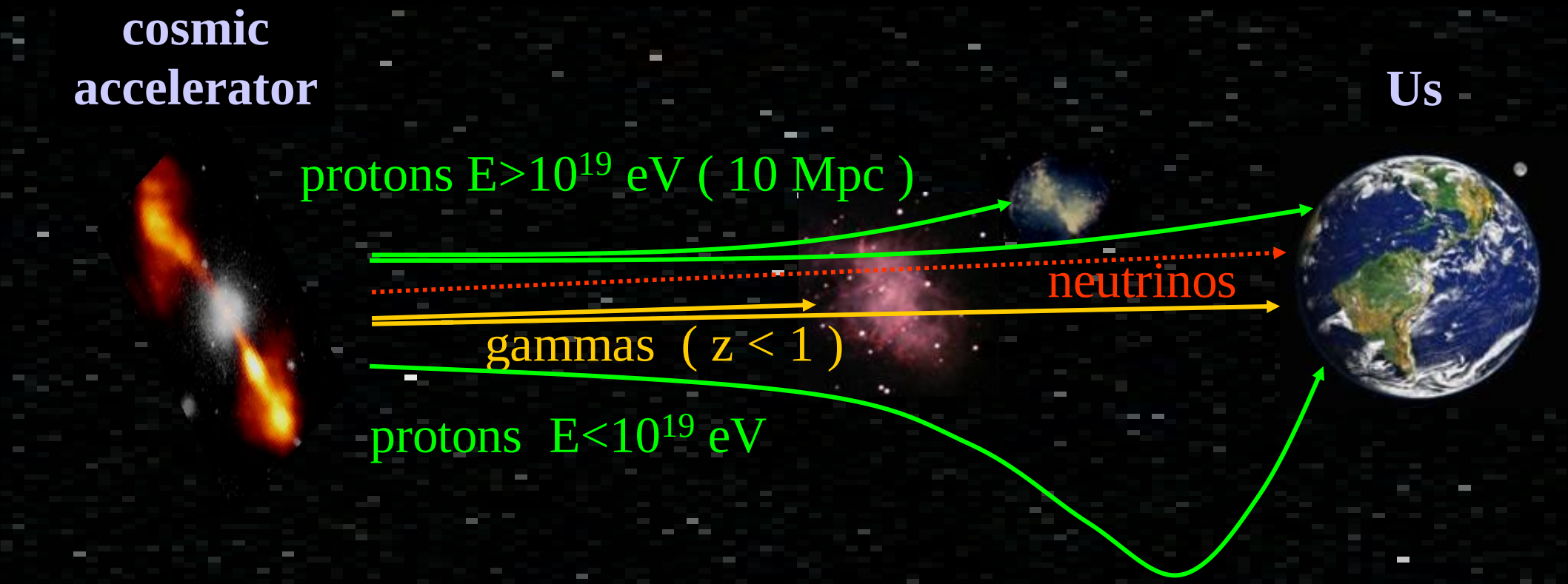
- Confinement: source size > R_L

$$E_{max} \approx qBcR$$

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



Multi-messenger observations of the Cosmos



protons/nuclei: Deviated by magnetic fields,
Absorbed by radiation field (GZK)

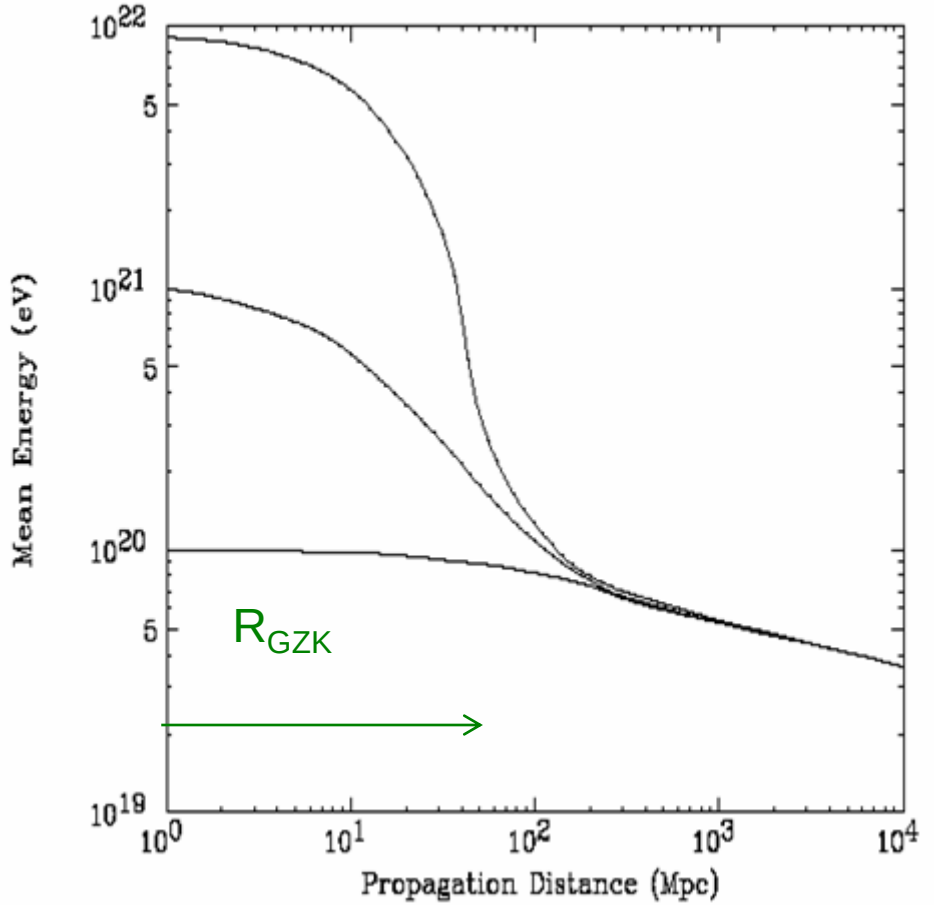
photons: Absorbed by dust & radiation field (CMB)

neutrinos: Difficult to detect

⇒ Three "astronomies" possible...

GZK effect

- Cosmic Microwave Background discovered in 1965 (Penzias & Wilson)
  $T_0 = 6 \times 10^{-4}$ eV (2.7 K) ,
  $N = 400$ cm^{-3}
- Inelastic collision of nuclei with CMB $\Rightarrow$ GZK effect (Greisen, Zatsepin et Kuzmin) (1965)



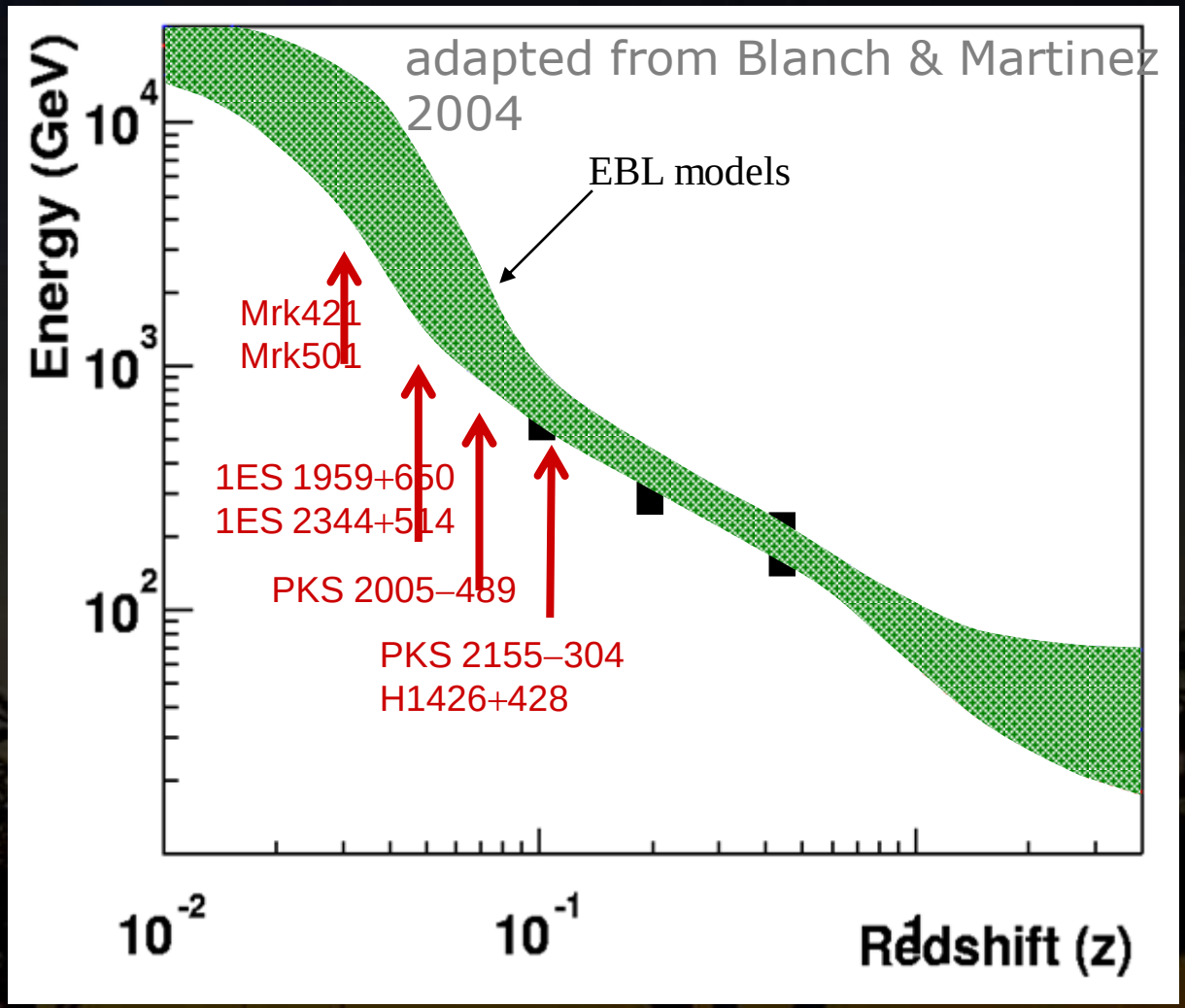
$$p + \gamma_{CMB} \rightarrow \Delta^{+} \begin{cases} \rightarrow p\ \pi^{0} \rightarrow p\ \gamma\gamma \\ \rightarrow n\pi^{+} \rightarrow n\nu_{\mu}\mu^{+} \rightarrow n\nu_{\mu}\bar{\nu}_{\mu}\nu_{e}e^{+} \end{cases}$$

γ-ray horizon

- Absorption of VHE γ by pair creation on CMB/IR photons:

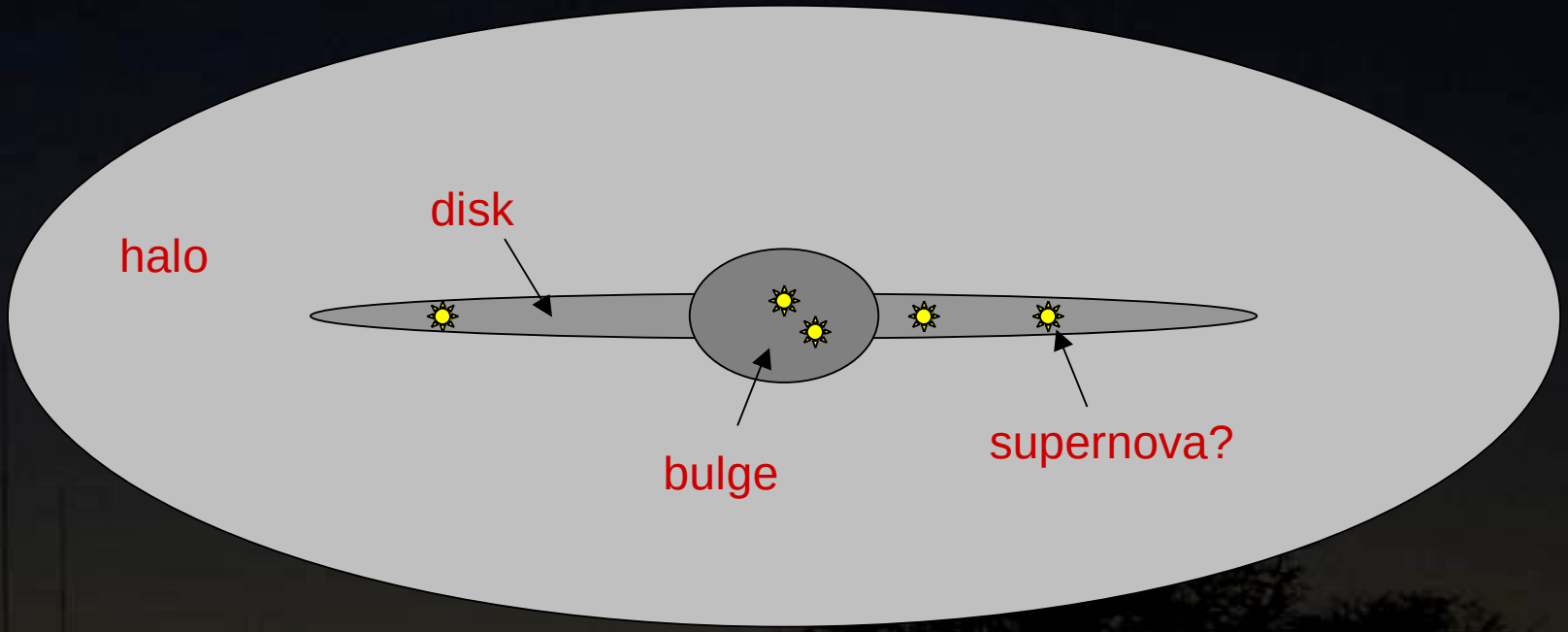
$$\gamma + \gamma_{CMB} \rightarrow e^+ e^-$$

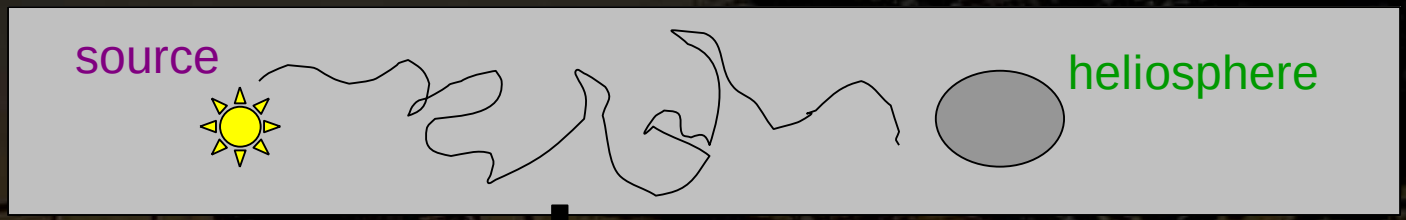
- Observable Universe:
  - z < 0.1 @ 500 GeV
  - z < 0.01 @ 2 TeV



- Observation of distant quasars ⇒ indirect measurement of star and dust background ⇒ "tomography" of Universe

Propagation



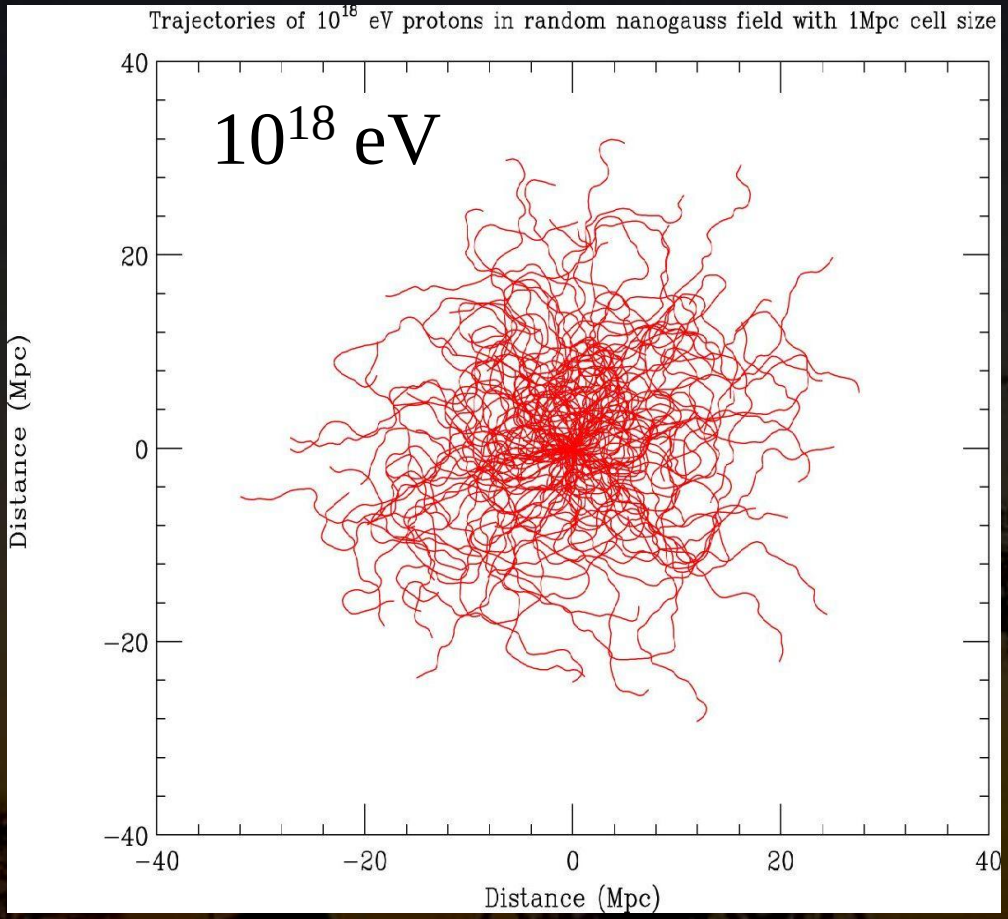


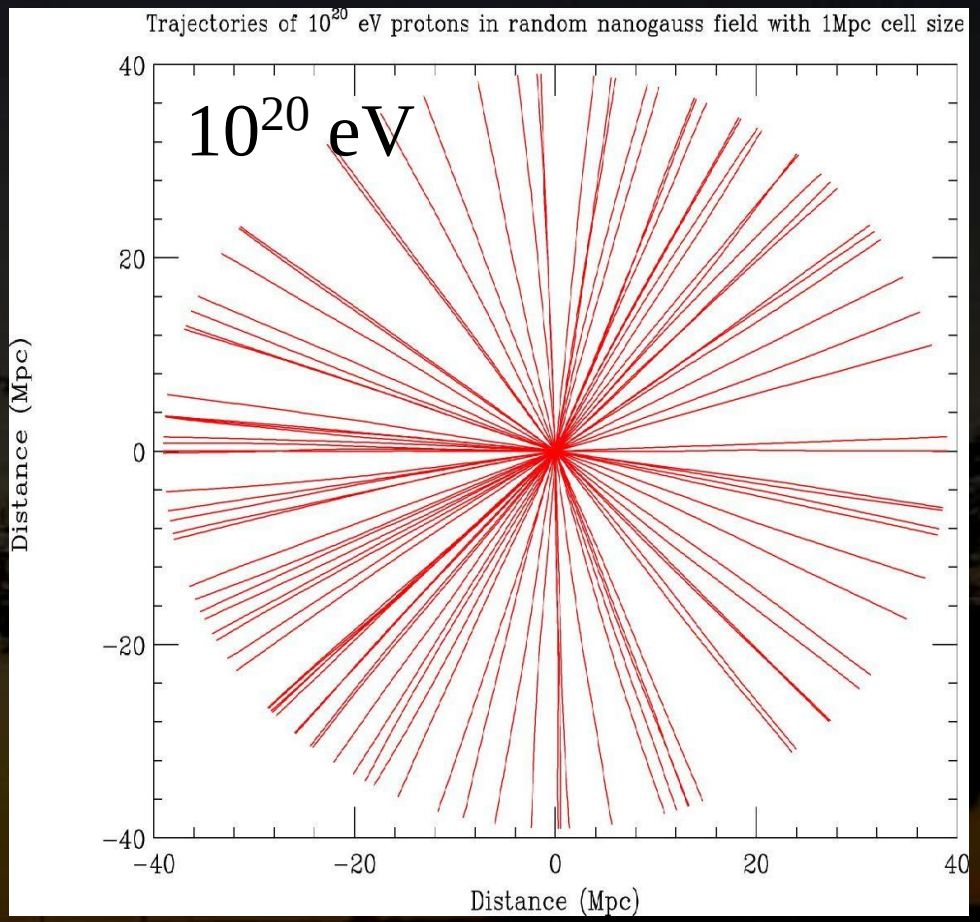
propagation effects:
energy losses, nuclear reactions (spallation, ...)

- Energy dependant diffusion ⇒ observed spectrum differs from primary spectrum
- Steeper spectrum (high energy CRs escape more easily)

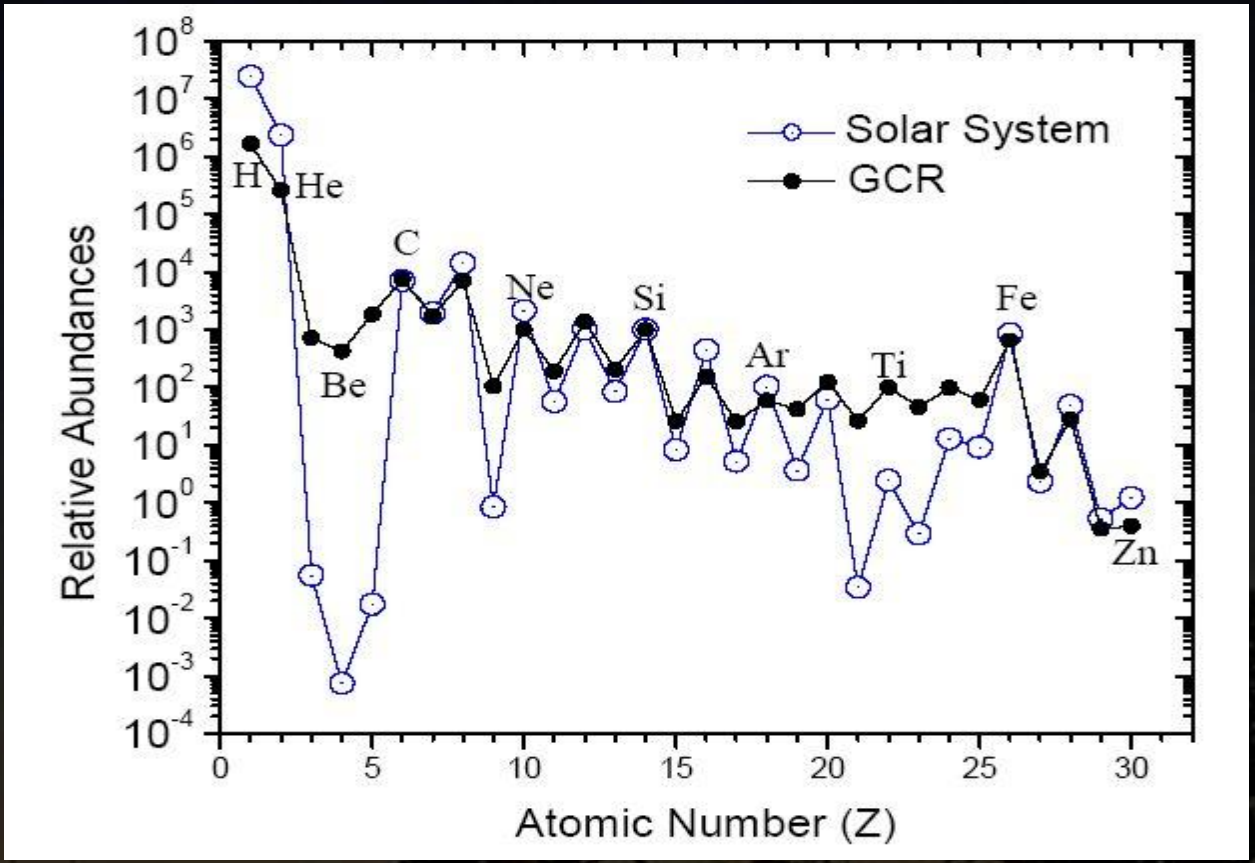
Propagation

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





Composition

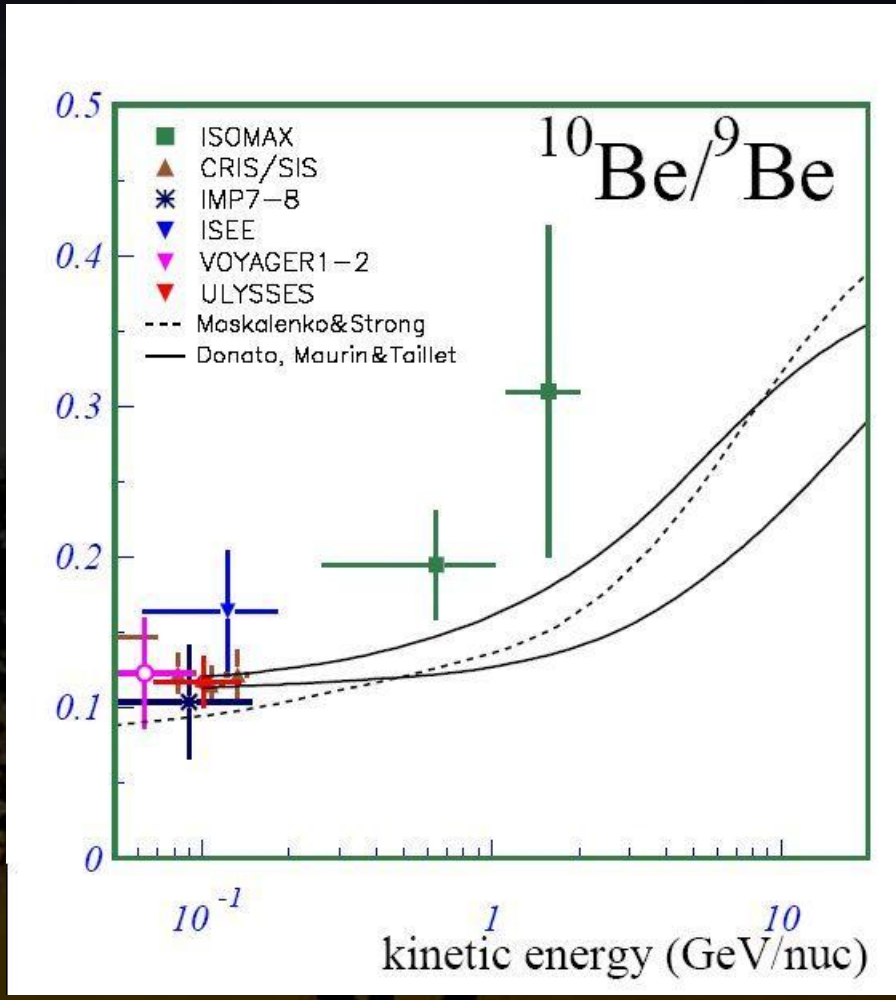


70 to 280 MeV/nucléon, Satellite

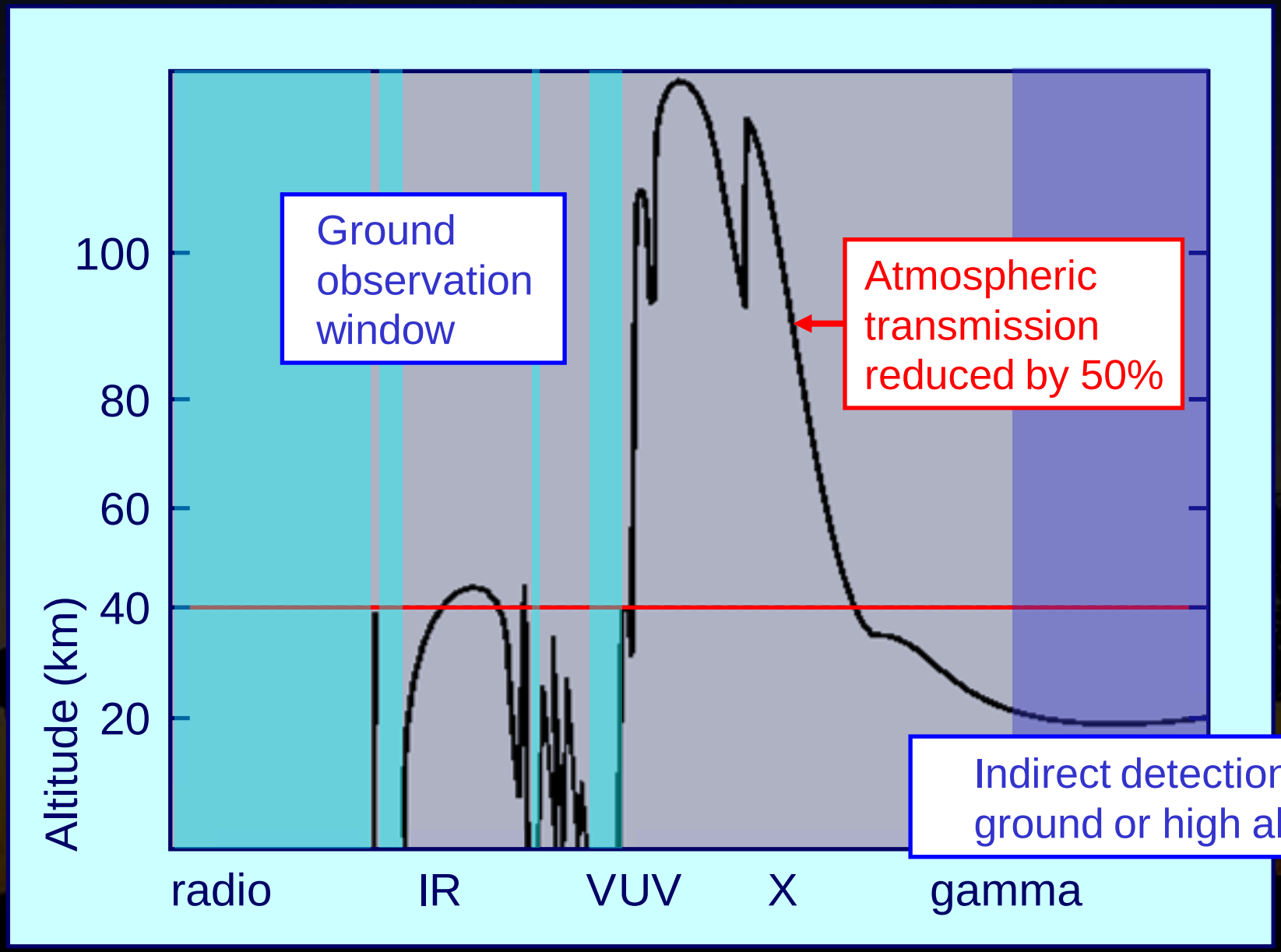
- CR abundances differs from local measurement
  - Excess of Li - Be - B et sub Fe
  - Secondary nucleus created by spallation ⇒ constraints on propagation
  - Primary nuclei (CNO, Fe,.) accelerated in sources
  - Other particles are produced in propagation (γ, ν, antiparticles). Excess w/o prediction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

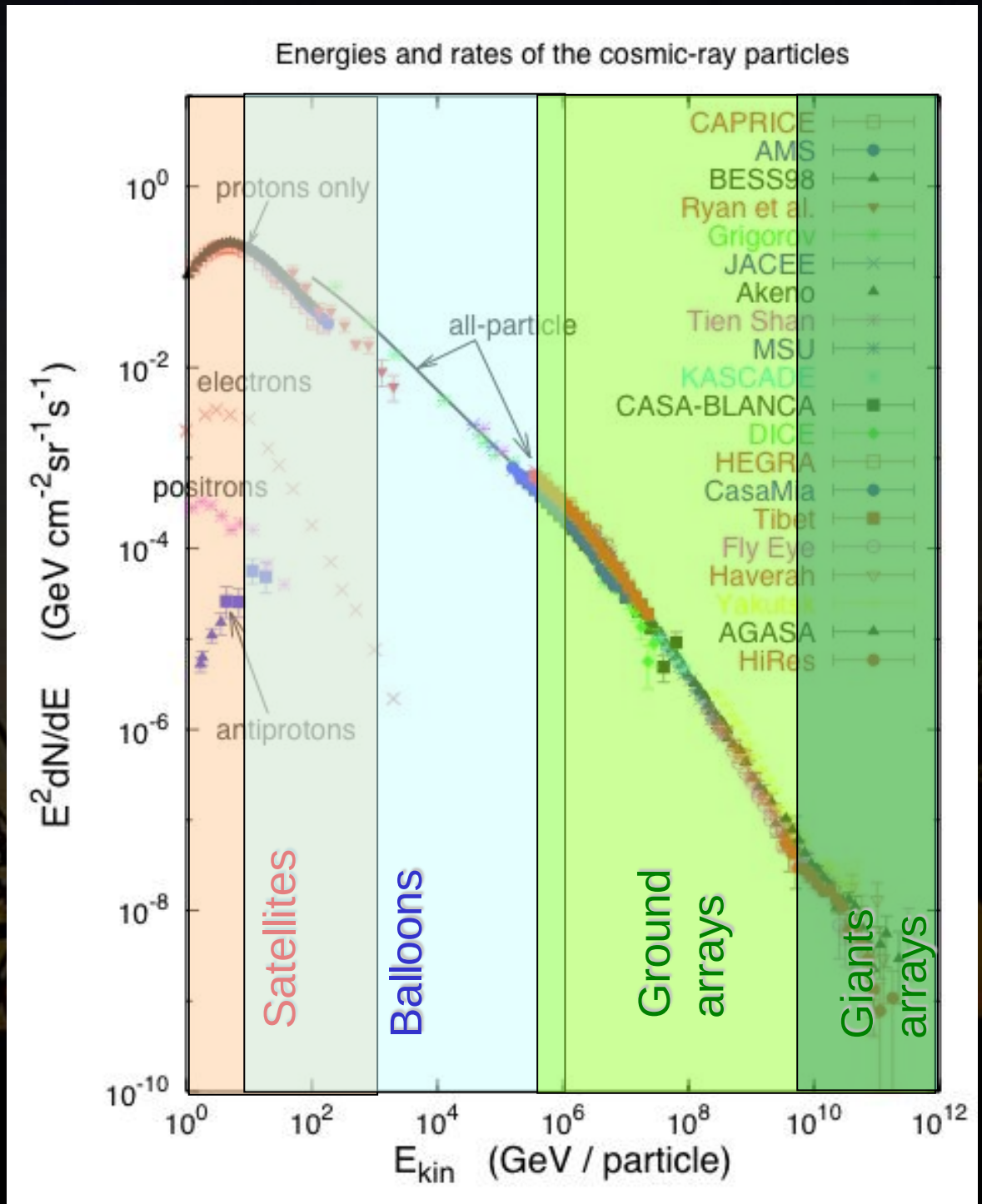


Atmospheric Transparency



Acceptance & fluxes

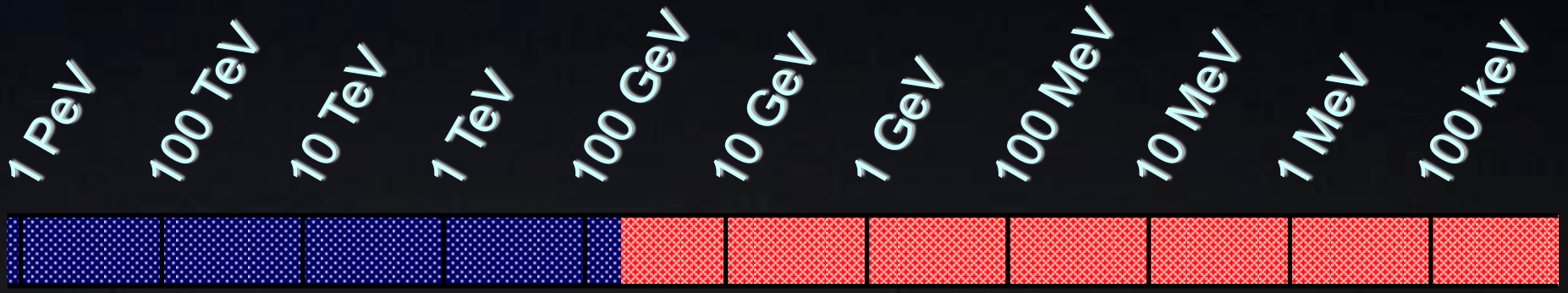
- The higher the energy, the biggest the needed acceptance:
  - 10 GeV : 1 CR/m^2/s
    $\Rightarrow$1 m^2 (satellite or balloon)
  - Knee: 1 CR/m^2/an
    $\Rightarrow$ 1 km^2 (ground array)
  - Ankle: 1 CR/km^2/century
    $\Rightarrow$ 1000 km^2 (giant array)



Challenges

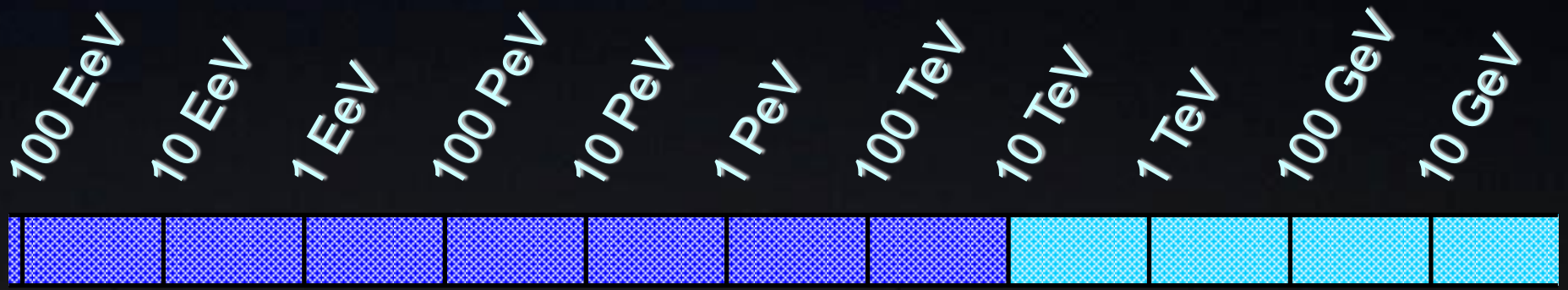
- Atmosphere opaque to cosmic rays
  ⇒ Stratospheric balloons or indirect detection
- Flux decreases rapidly with energy
  ⇒ Need for very large effective area (1000 km^2 at the knee)
- Composition (and isotopic composition) is very rich
  ⇒ Need for precise mass measurement
- Specificities related to primary particles:
  - Neutrinos : very low interaction probability ⇒ need for huge detection volumes
  - Gammas : very large hadronic and electronic background
    ⇒ large rejection factors needed

Photons



From Ground From Space

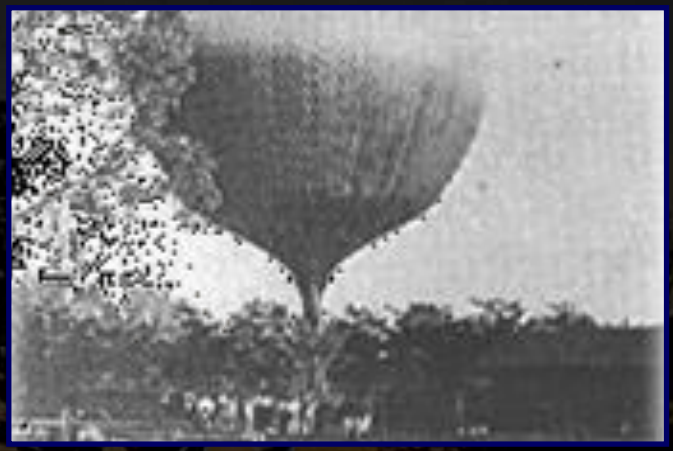
Charged Particles



Giant showers – from ground

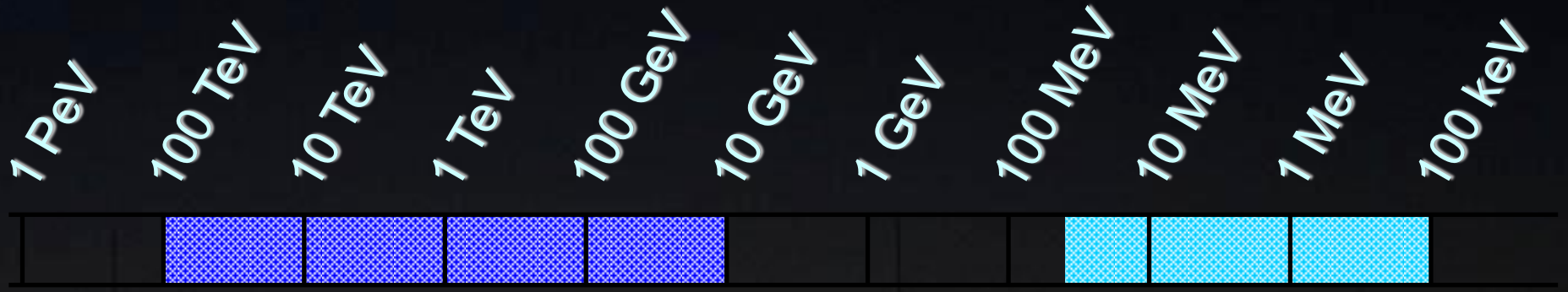
Direct detection

Balloons



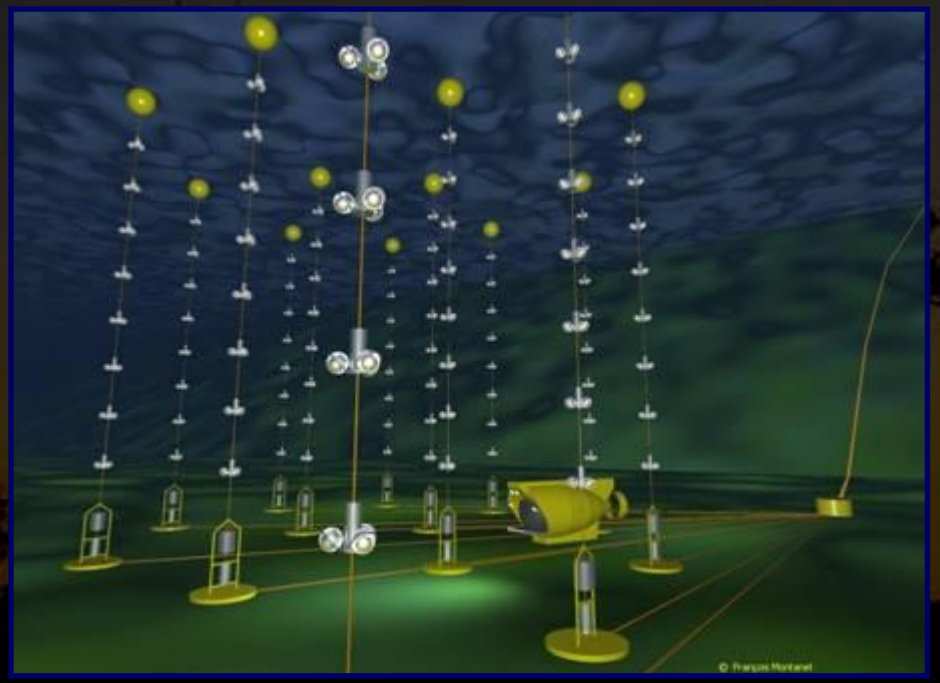
Space

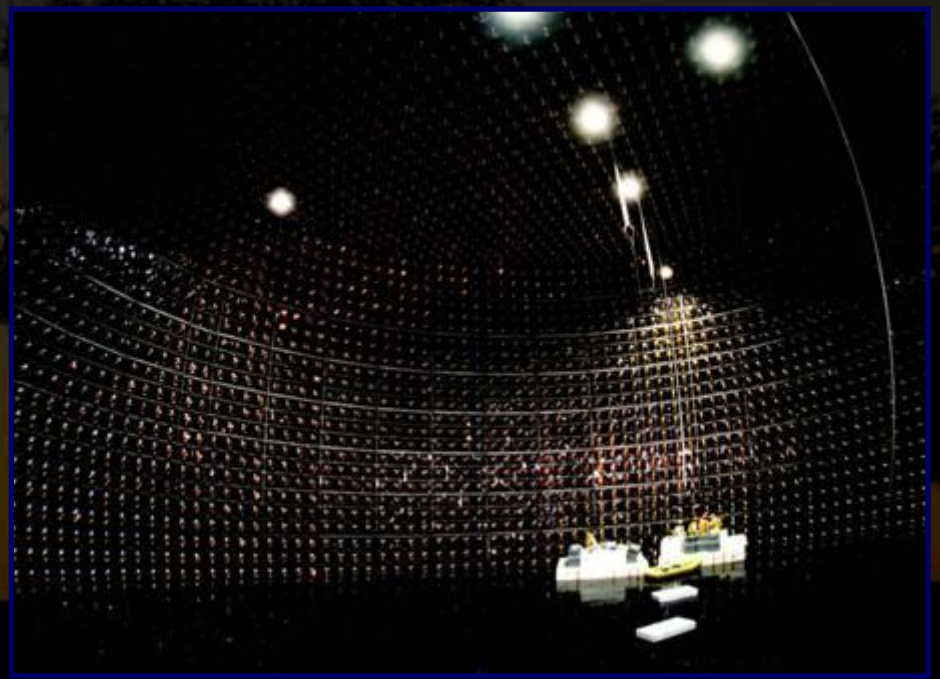
Neutrinos



See or deep ice

Underground

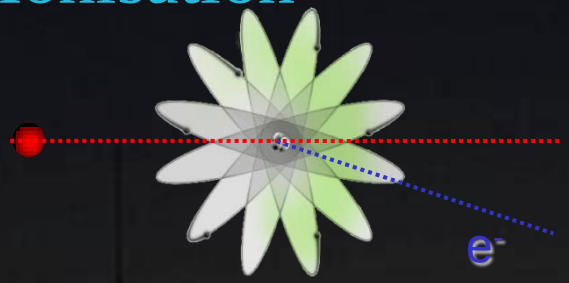




ELEMENTARY PROCESSES

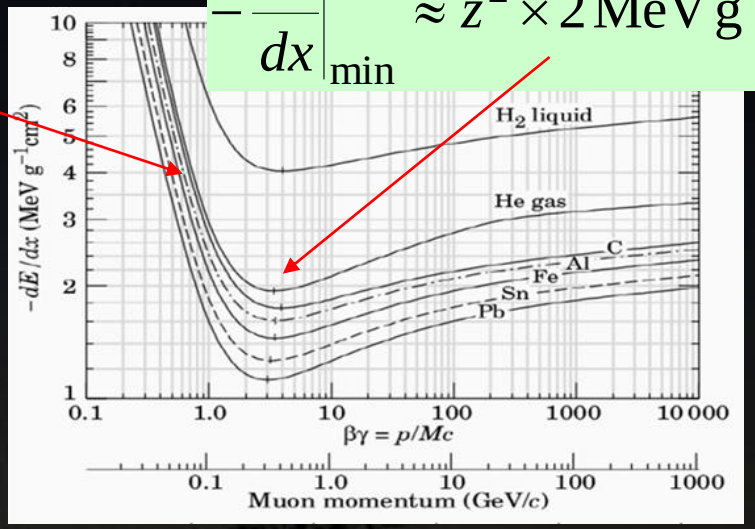
Charged particles

- Ionisation

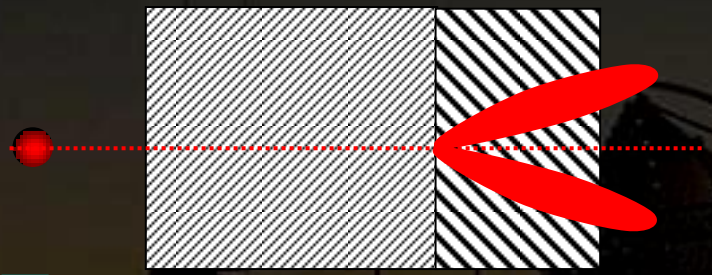


$$-\frac{dE}{dx} \propto \frac{Z}{A}\frac{z^2}{\beta^2}$$

$$-\left.\frac{dE}{dx}\right|_{\min} \approx z^2 \times 2\,\mathrm{MeV\,g^{-1}\,cm^2}$$

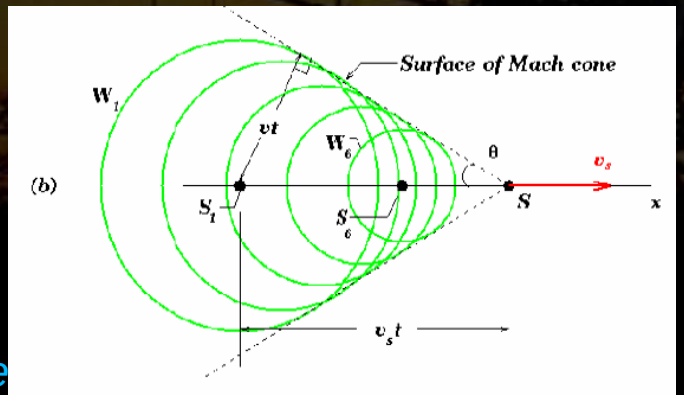


- Transition Radiation



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

- Cherenkov Radiation



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

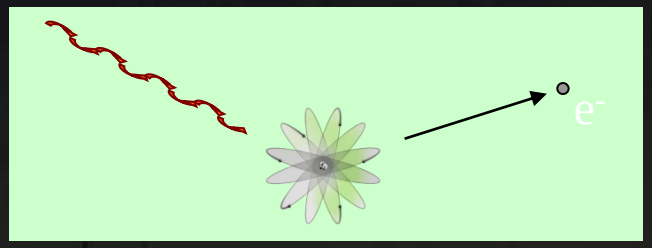
$$\frac{d^2N}{d\lambda\,dl} = \frac{2\pi\alpha}{\lambda^2} \times z^2 \sin^2\theta$$

Detectors and observables

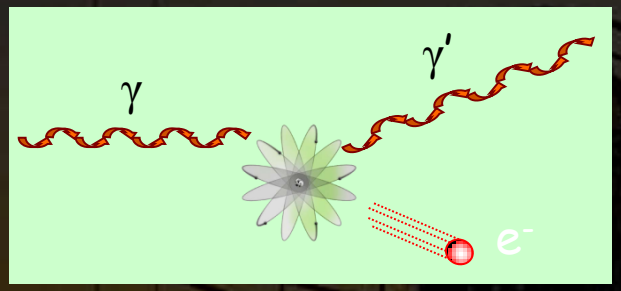
Detector	Observable	Link with primary particle
Tracker	Rigidity and sign of charge	pc / ze
Time of flight	Speed	β
Proportional Counters Scintillators Ionisation Chambers	Ionisation	$dE/dx = z^2 f(\beta)$
Cherenkov	Density of Cherenkov photons	$dN/dx = z^2 g(\beta)$
Transition Radiation Detector	X-Ray photons	$N = z^2 h(\gamma)$
Calorimeter	Deposited Energy	$mc^2(\gamma-1)$

Detection of photons

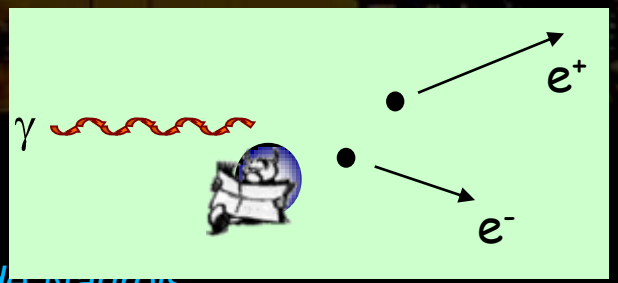
- Photons cannot be directly detected:
  ⇒ Production of charged particles
  - Photoelectric effect



  - Compton Scattering



  - Pair creation



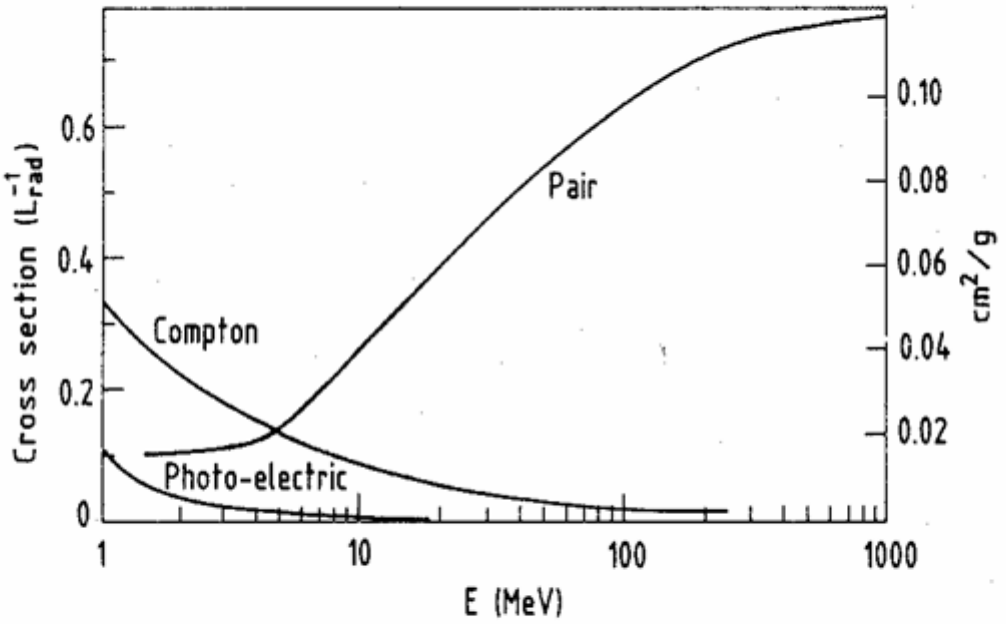


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

CHARGED COSMIC RAYS

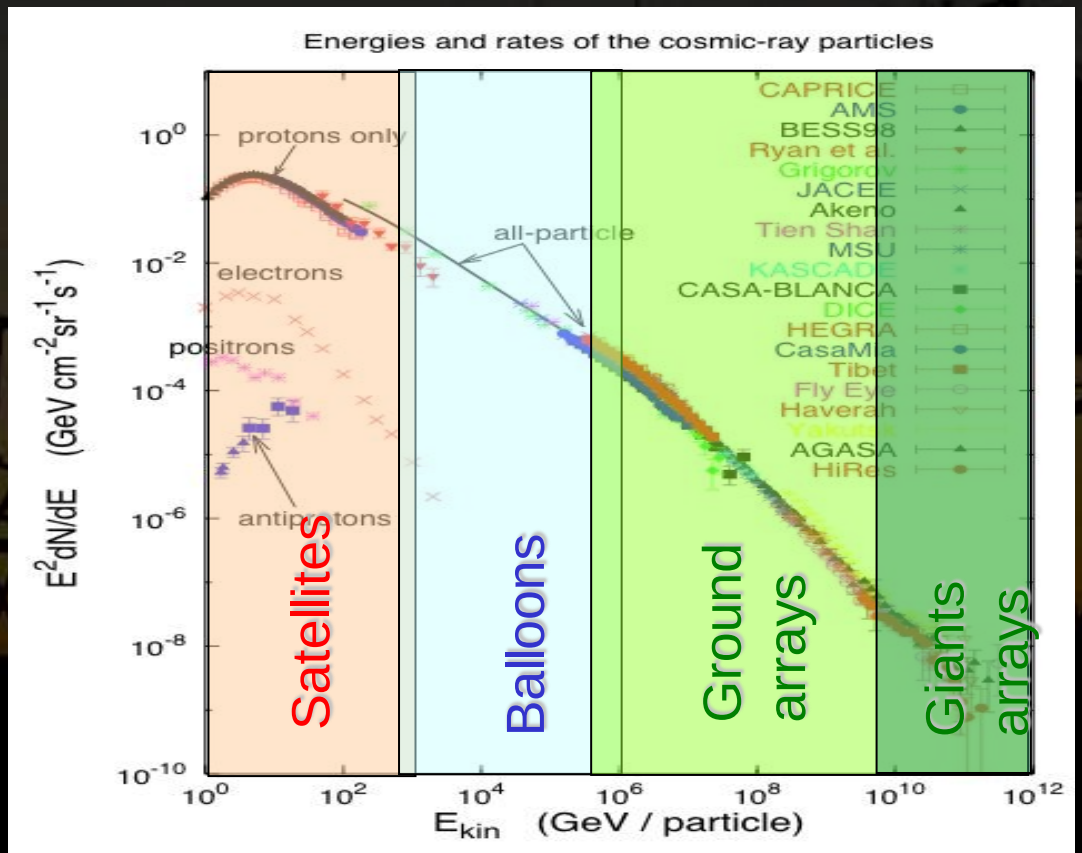
Current experiments

Balloons	Satellites	Ground Arrays

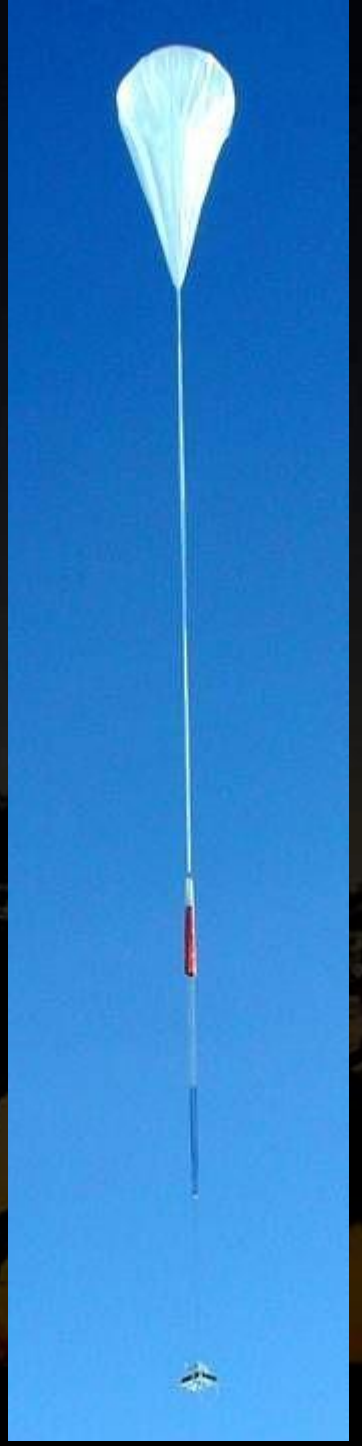
- CREAM
- ATIC
- Tracer
- TIGER
- BESS-Polar
- PPB-BETS
- .....

- Pamela
- AMS

- HESS
- Tibet Array
- Kaskade

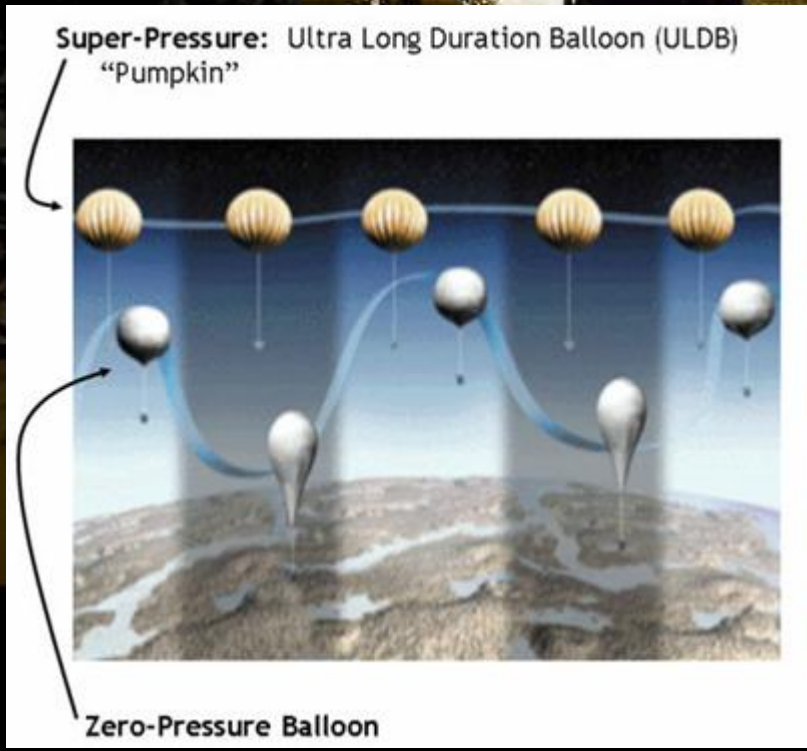


Stratospheric Balloons



Why Balloons?

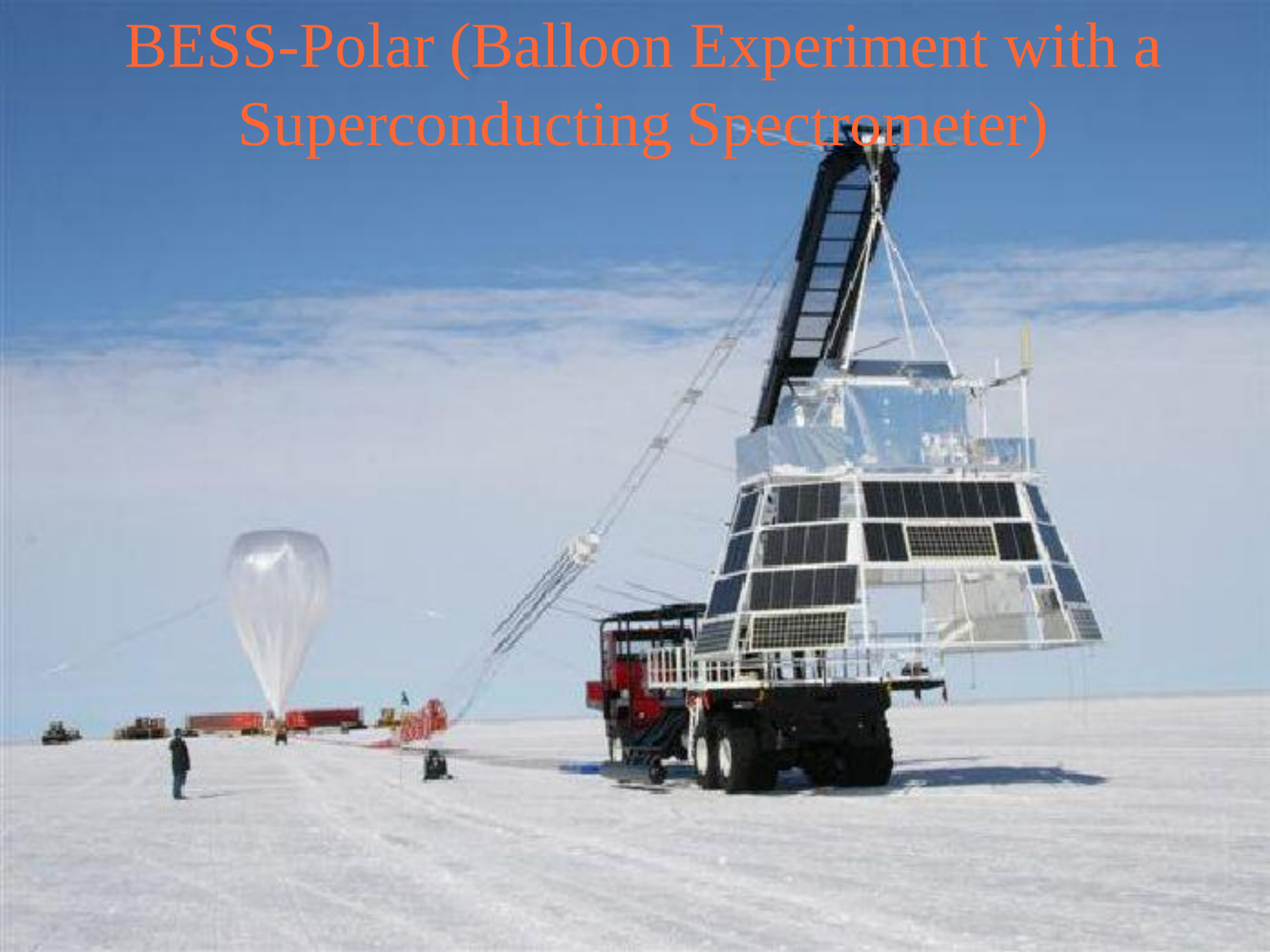
- Short time scale: ~6 months
- Cost << satellite
- Supply recovery
- Ultra Long Duration Ballooning Program:
  - A few tons
  - Several Months
  - Better controlled altitude



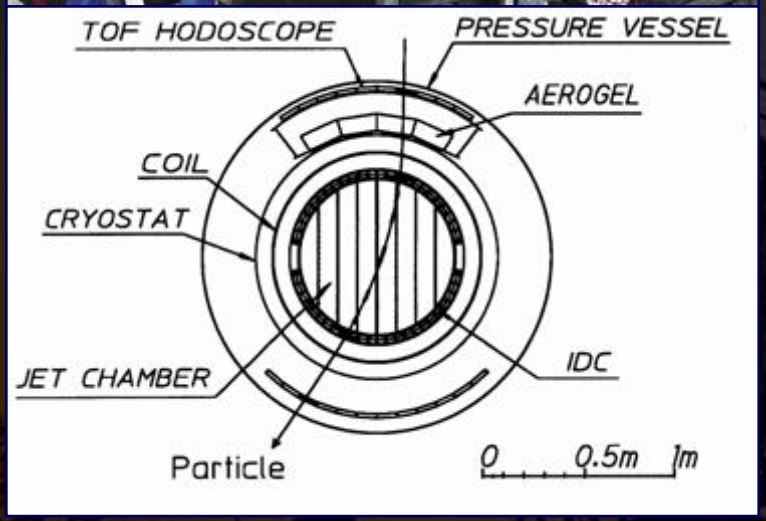
Easy detector recovery...

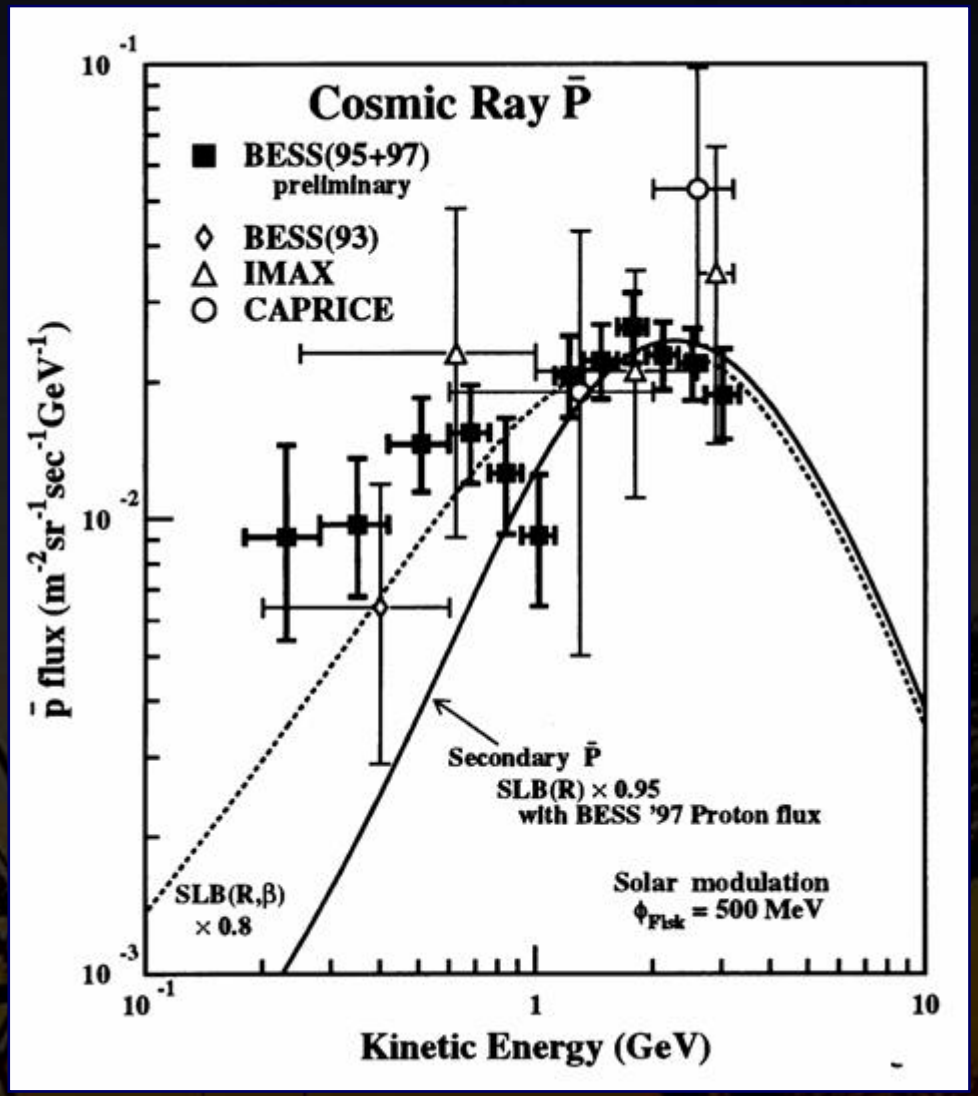
Less easy...

BESS-Polar (Balloon Experiment with a Superconducting Spectrometer)



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





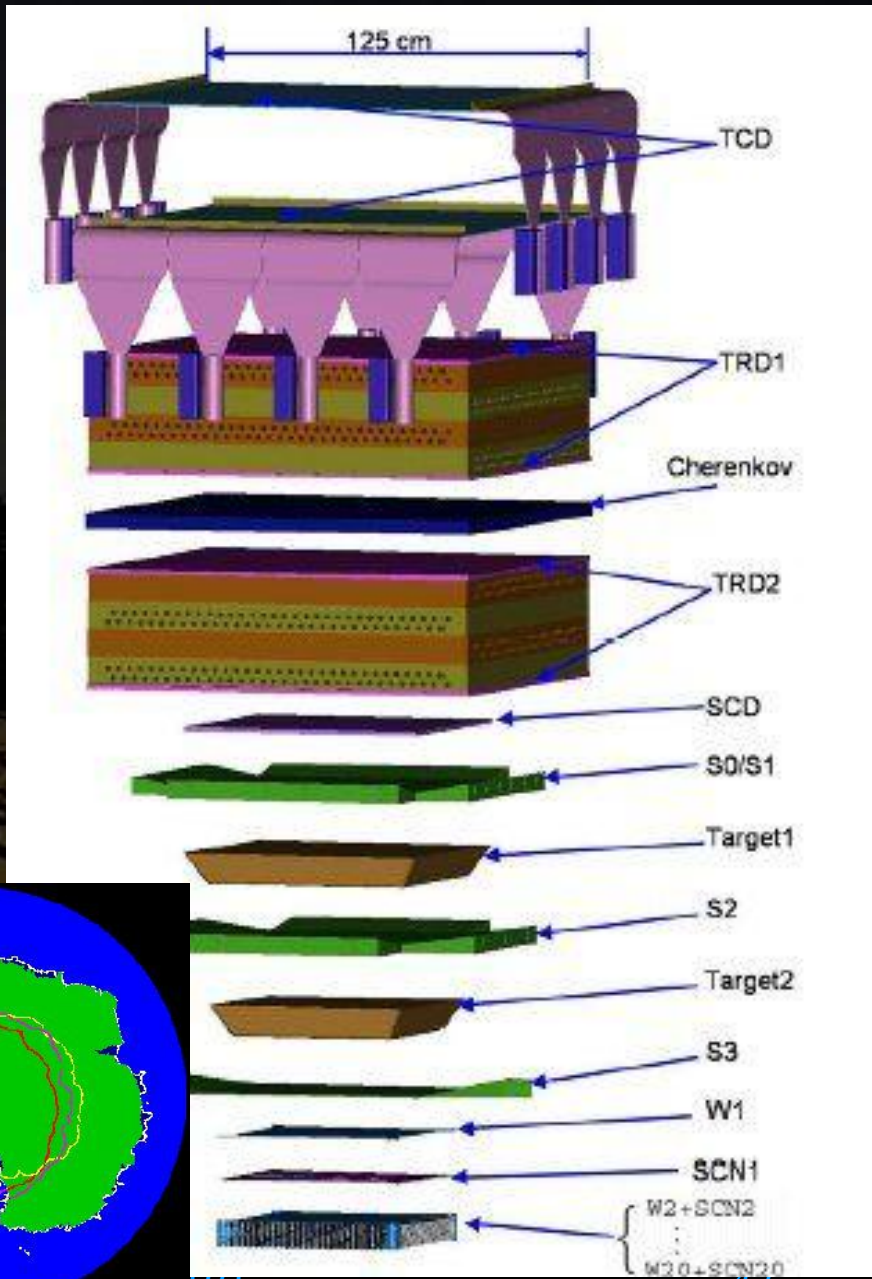
- Search for antimatter (antiprotons, antihelium) and measurement of light isotopes

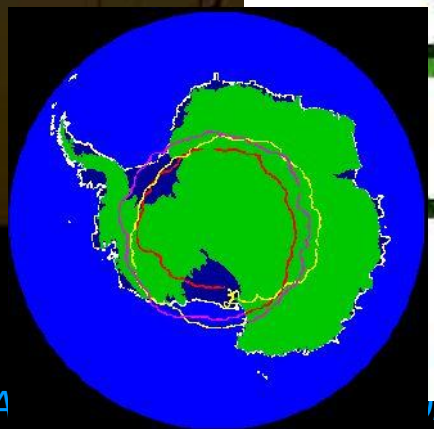
CREAM , long duration flights
E: 10^{12} to 5×10^{14} eV , 2004, 2005, 2007

CREAM

Cosmic Ray Energetics and Mass

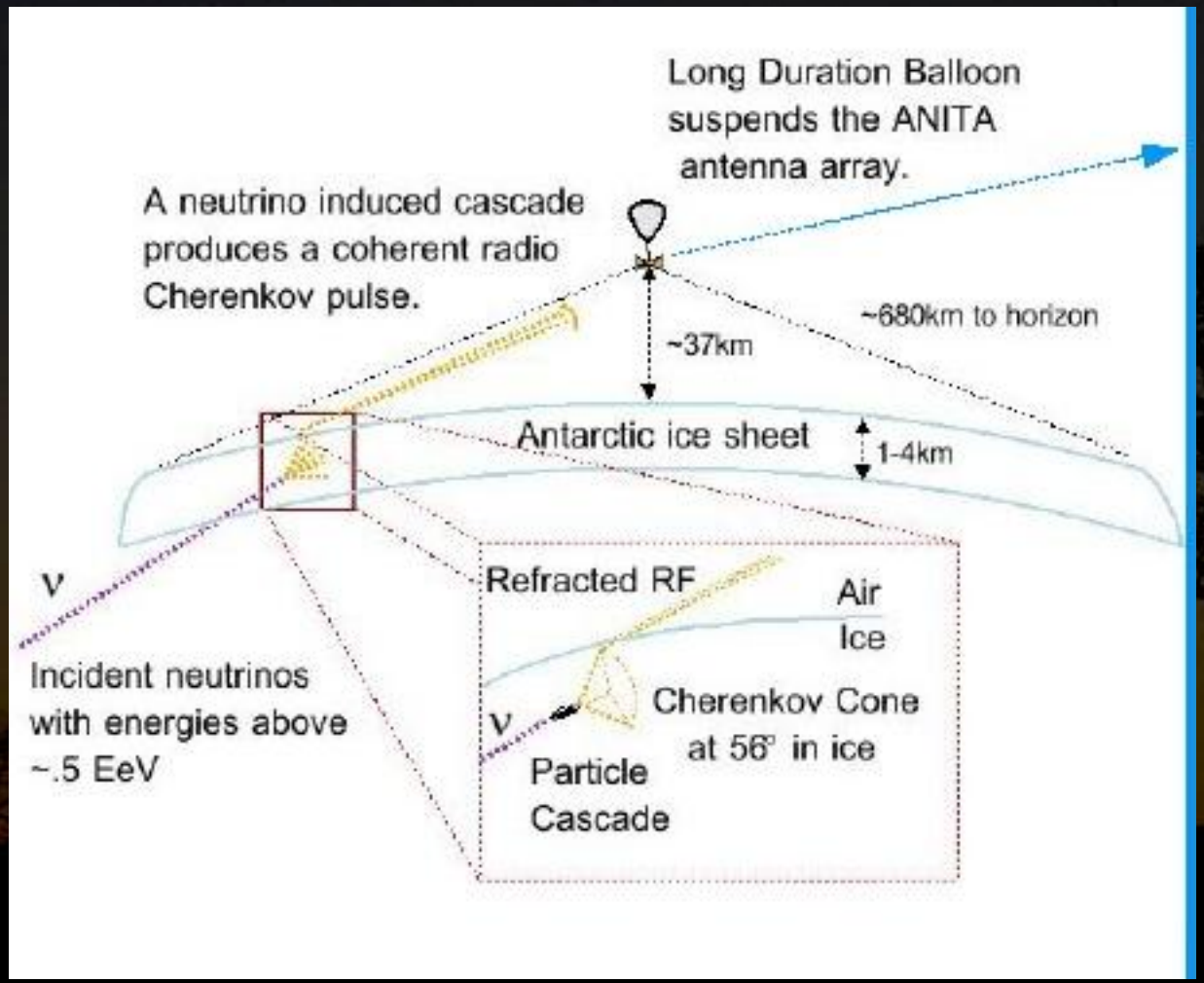
- Composition and spectrum of high energy cosmic rays (TeV to ~500 TeV)
- Acceptance : 2,2 m^2 sr
- Energy measurement :
  - Thick calorimeter 20 X_0 (W + fibres)
  - Transition radiation detectors
- Identification :
  - Transition radiation detectors
  - Ring Imaging Cherenkov « CHERCAM » similar to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



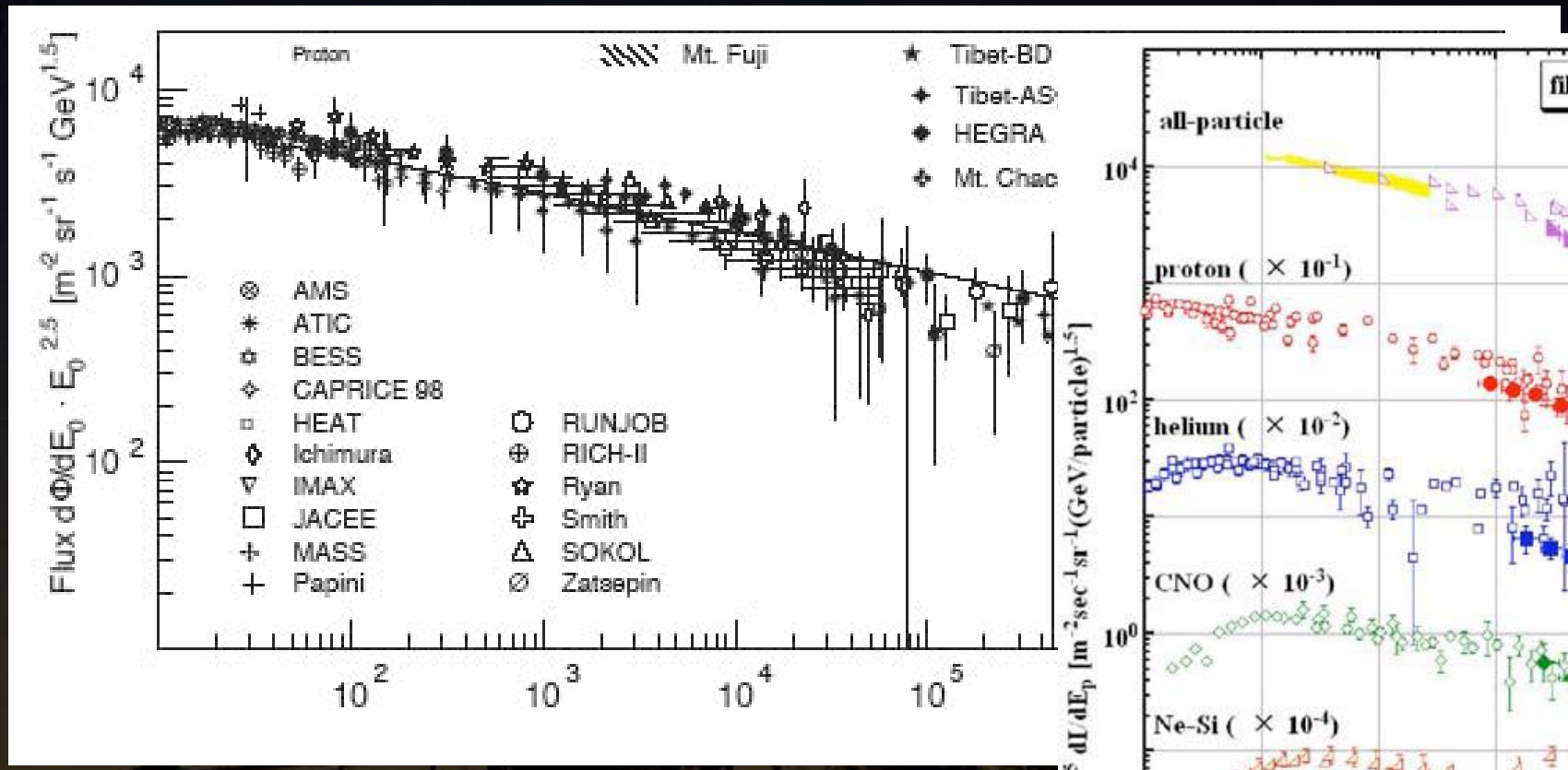


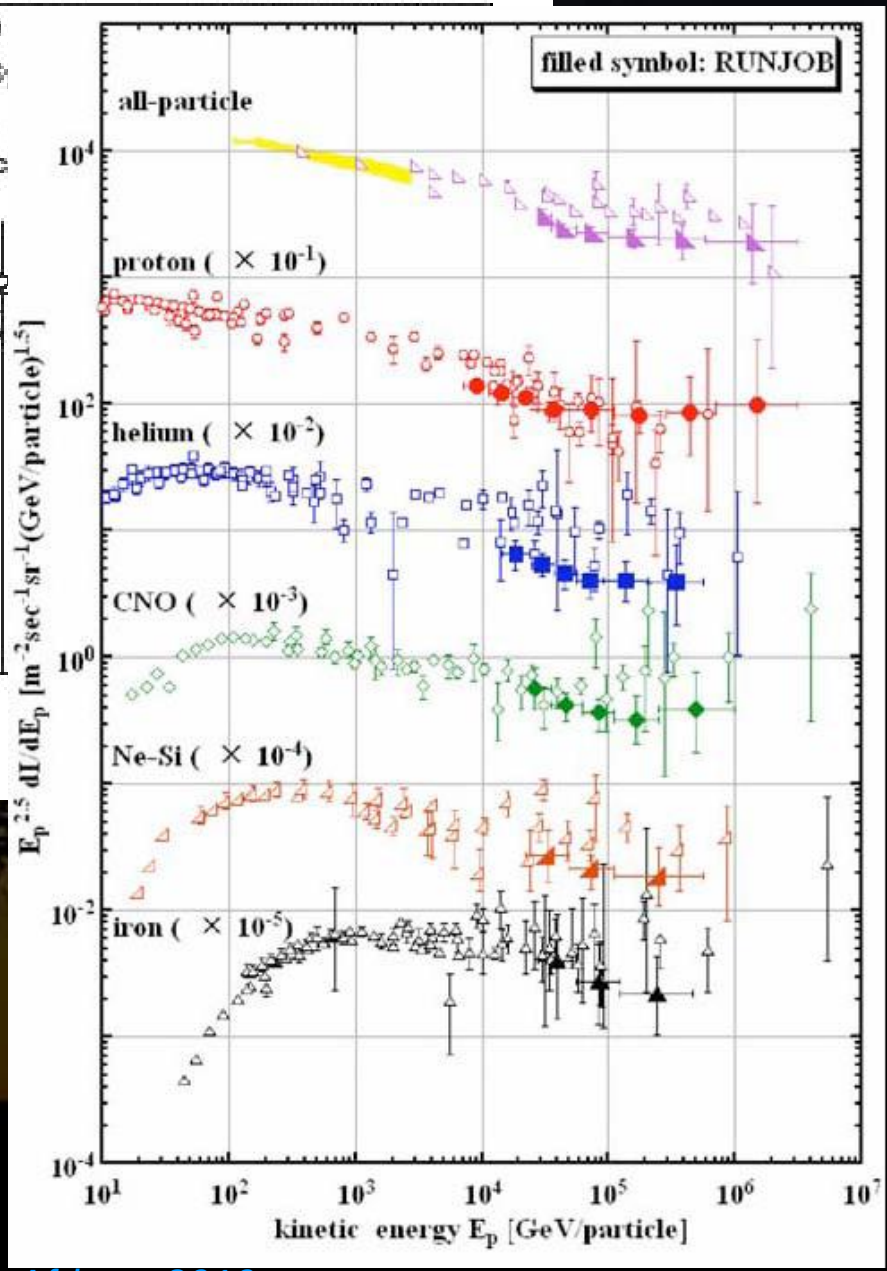
ANITA

- Radio detection of earth skimming neutrinos...



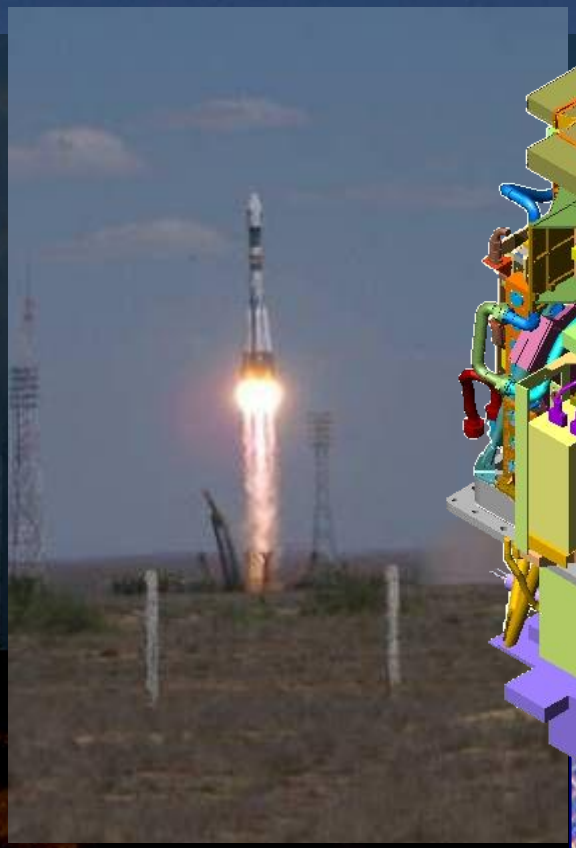
Balloon experiment results

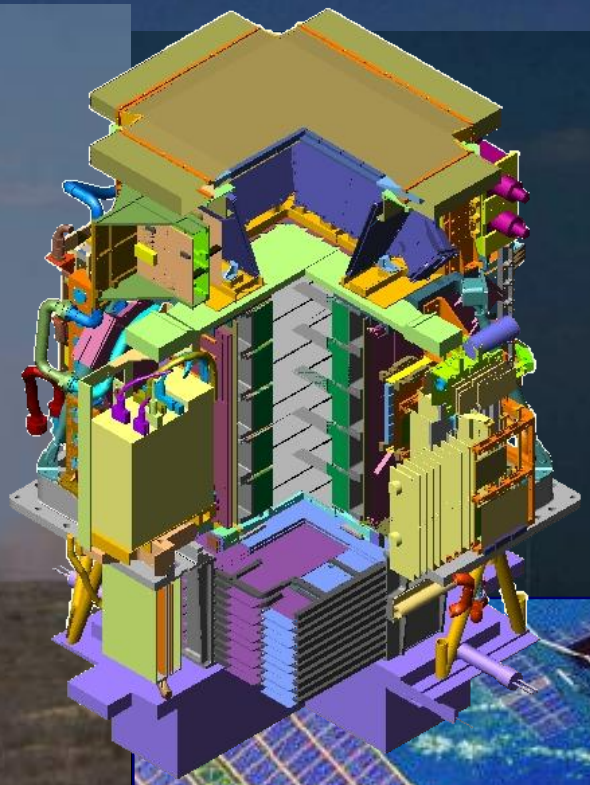


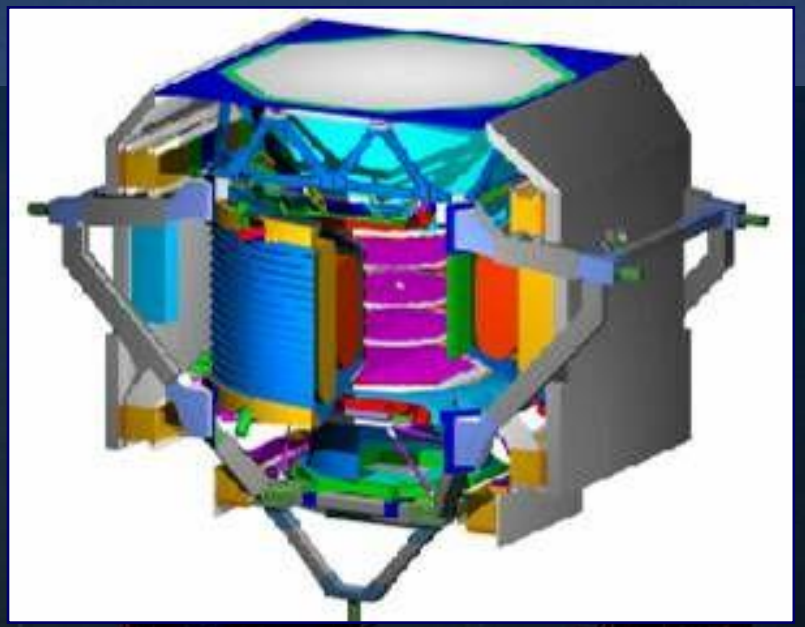


- All particle spectra
- Composition resolved spectra

Satellites



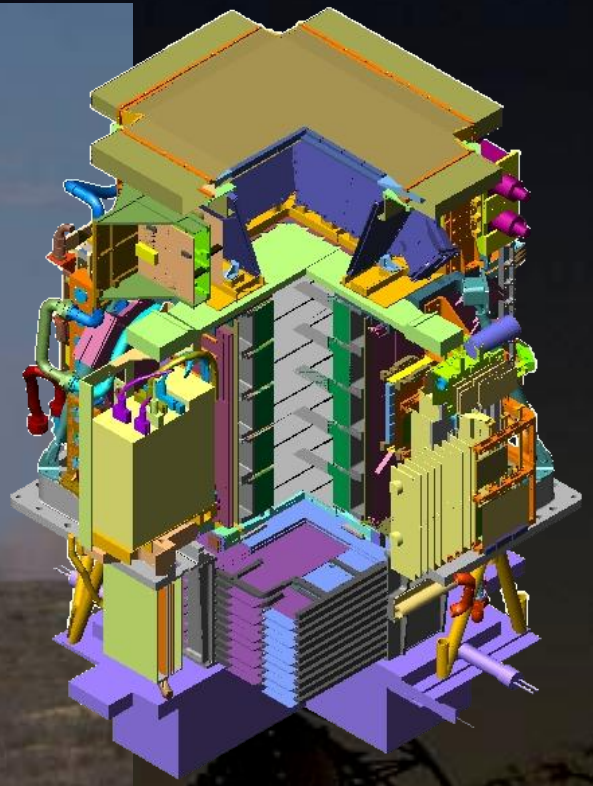


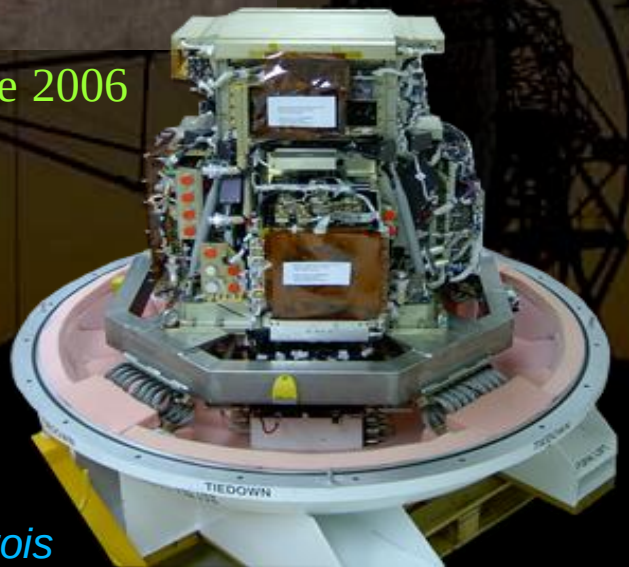


PAMELA

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

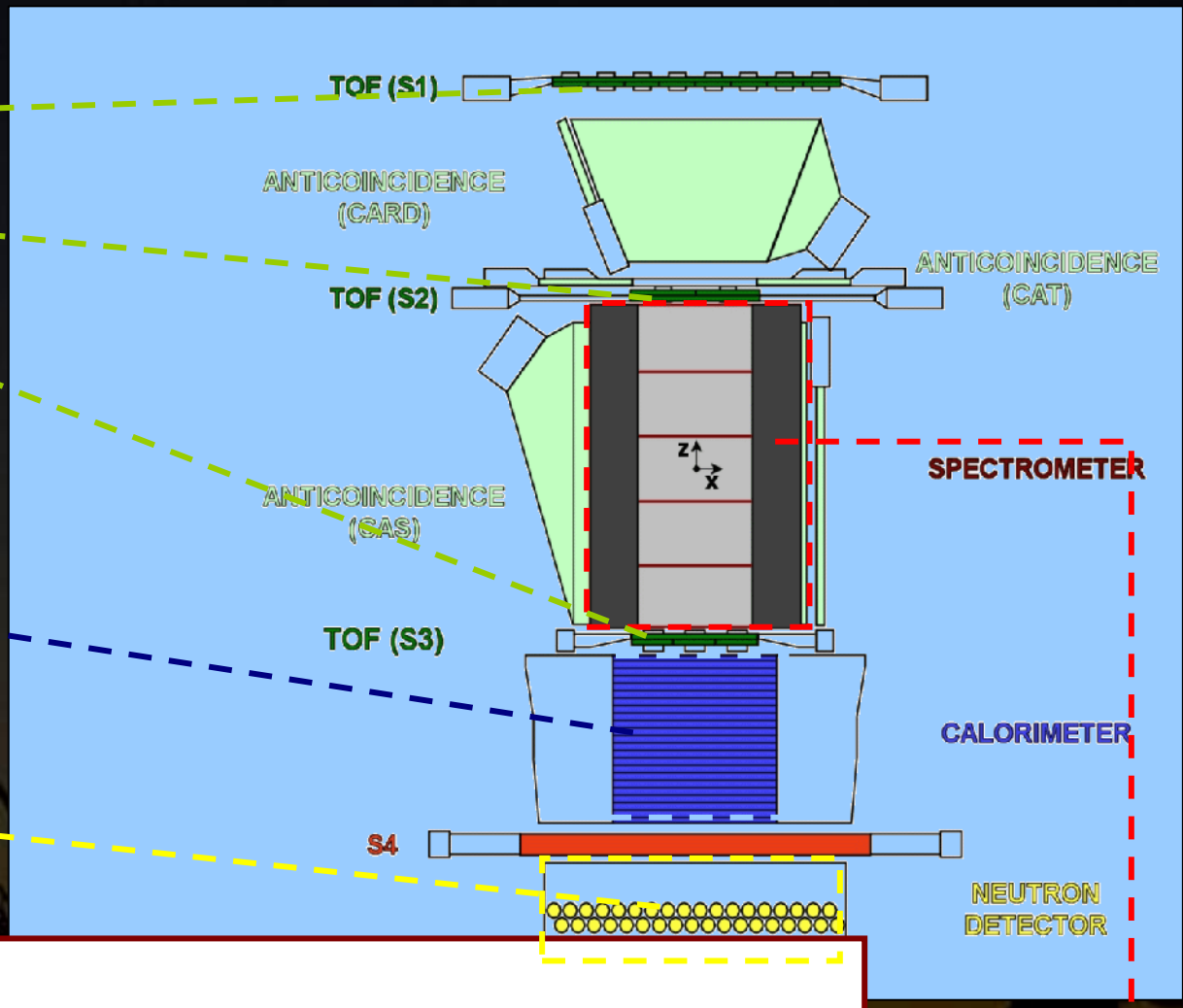
Particle	Energy	Particle	Energy
p	< 1 TeV	e^-	< 800 GeV
Antiprotons	< 100 GeV	e^+	< 100 GeV
D, ^{3}He	<1GeV/nuc	Elements Z≤6	<500 GeV/nuc

PAMELA

Time-Of-Flight (TOF)
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

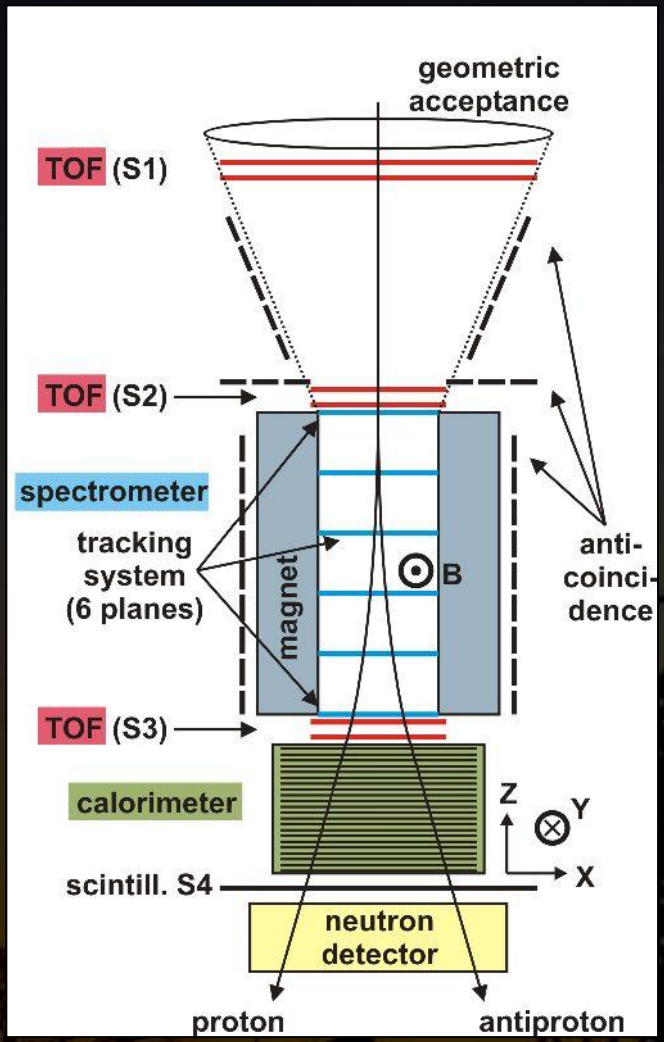


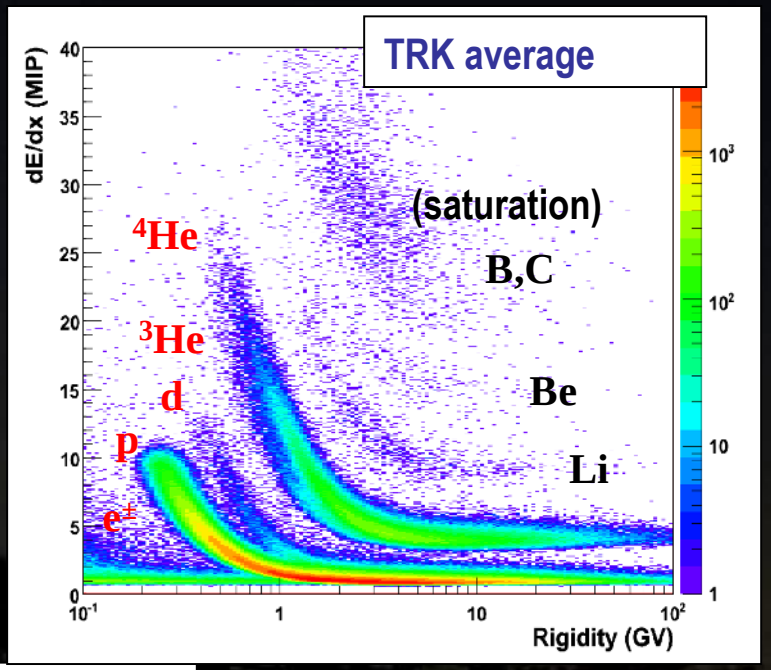
Spectrometer
microstrip Si tracking system (TRK) + permanent magnet
6 planes
- Charge sign (particle/antiparticle discrimination)
- Momentum
- Charge value from dE/dL
- 6 planes of double-sided (X-Y) microstrip Si sensors.
- Spatial resolution: 3÷4 mm.

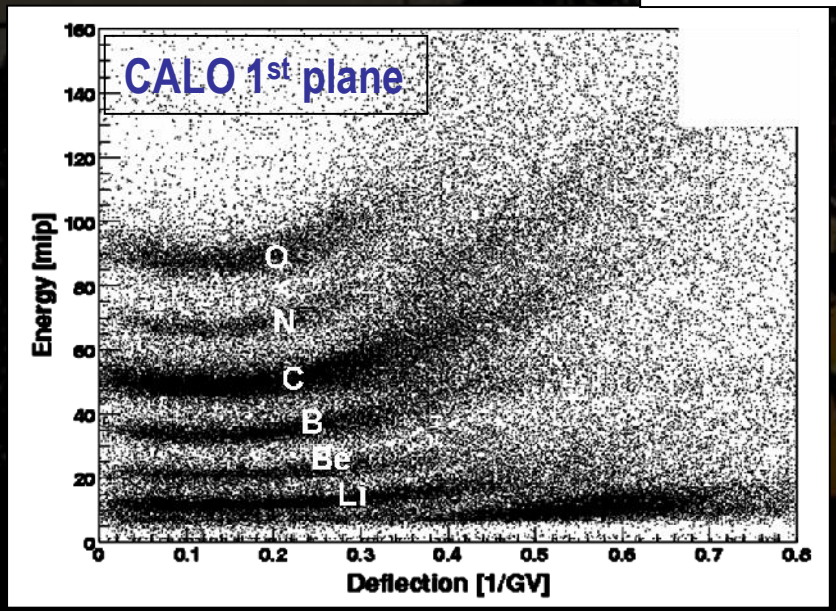
Acceptance: 21.6 cm^2 sr
Masse: 470 kg
Size: 130 · 70 · 70 cm^3
Consommation: 360 W

Particle Identification

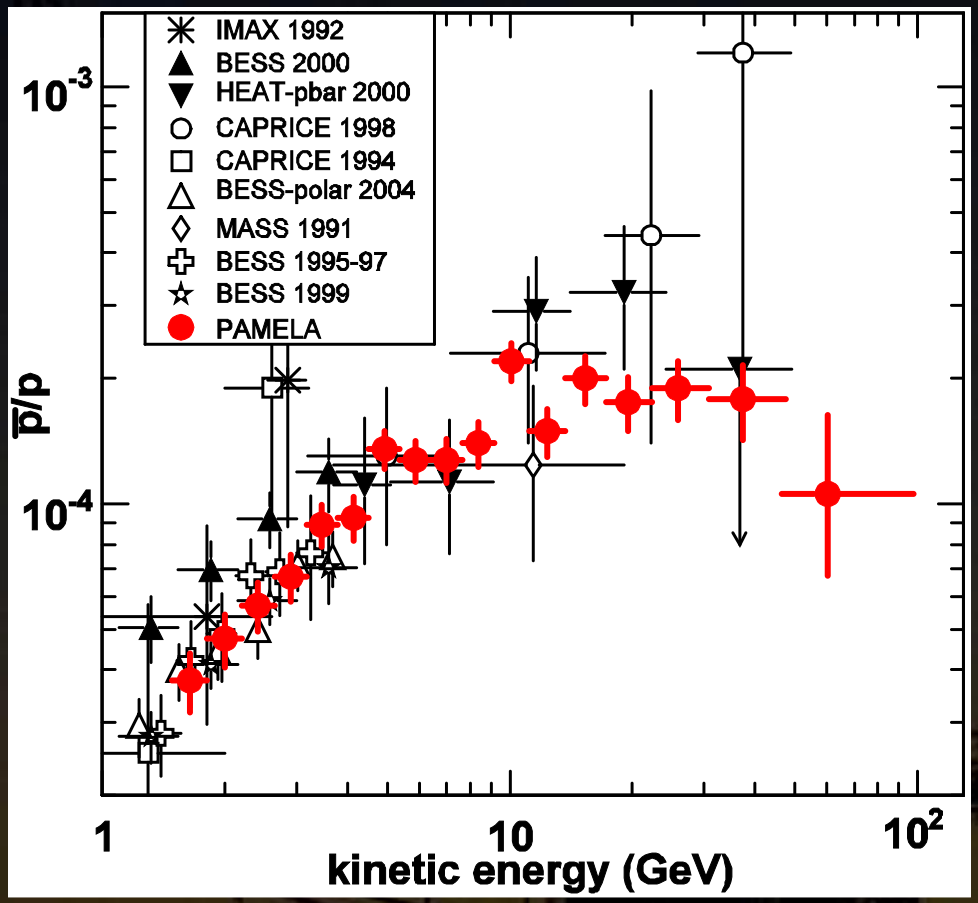
- Rigidity (p/Ze) from tracker
- dE/dx or E from time-of-flight or calorimeter
- Redundancy

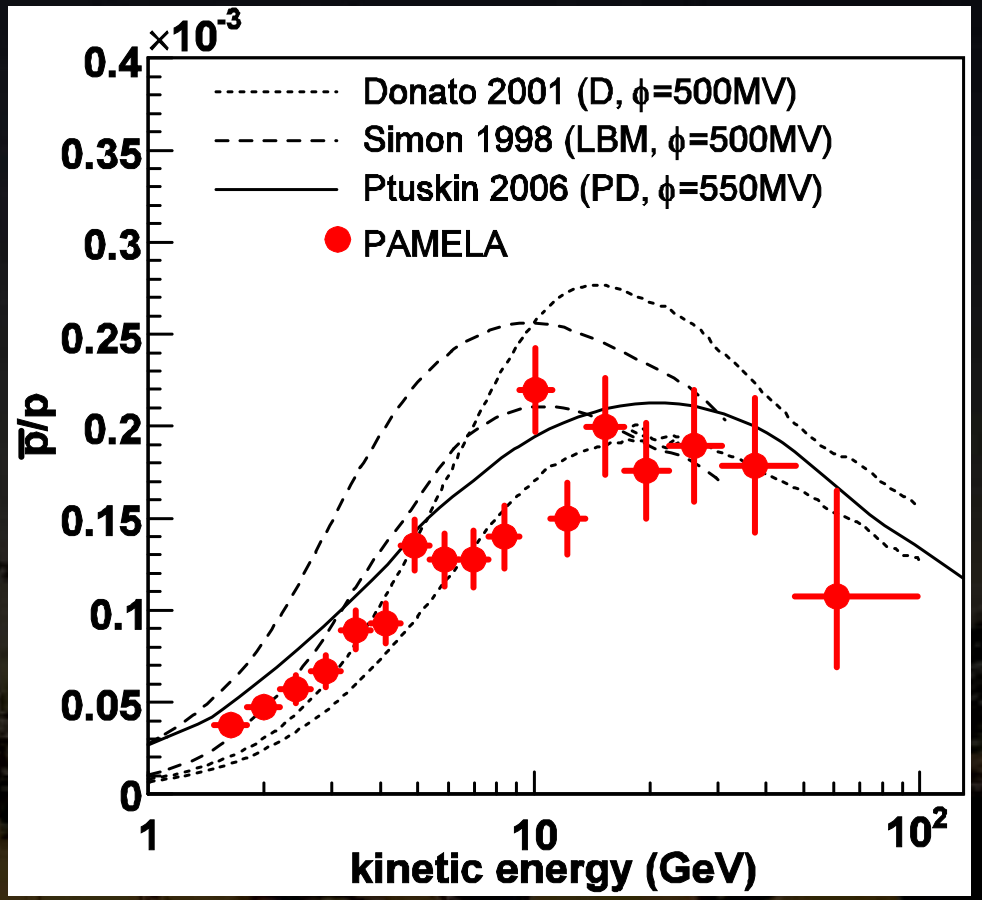






Antiprotons/protons (PRL 102, 2009)

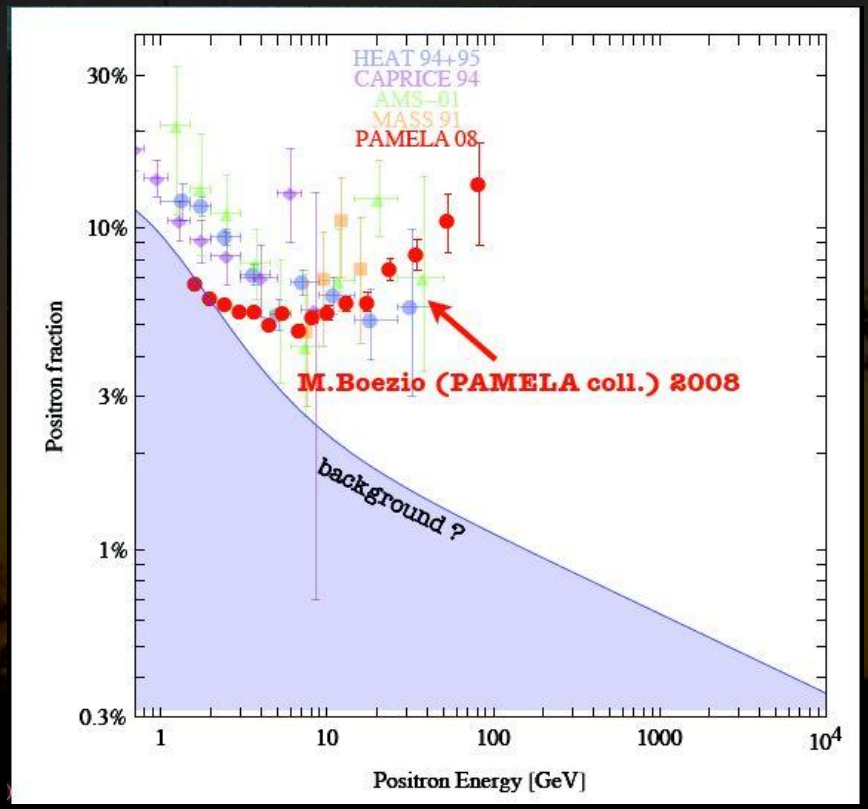


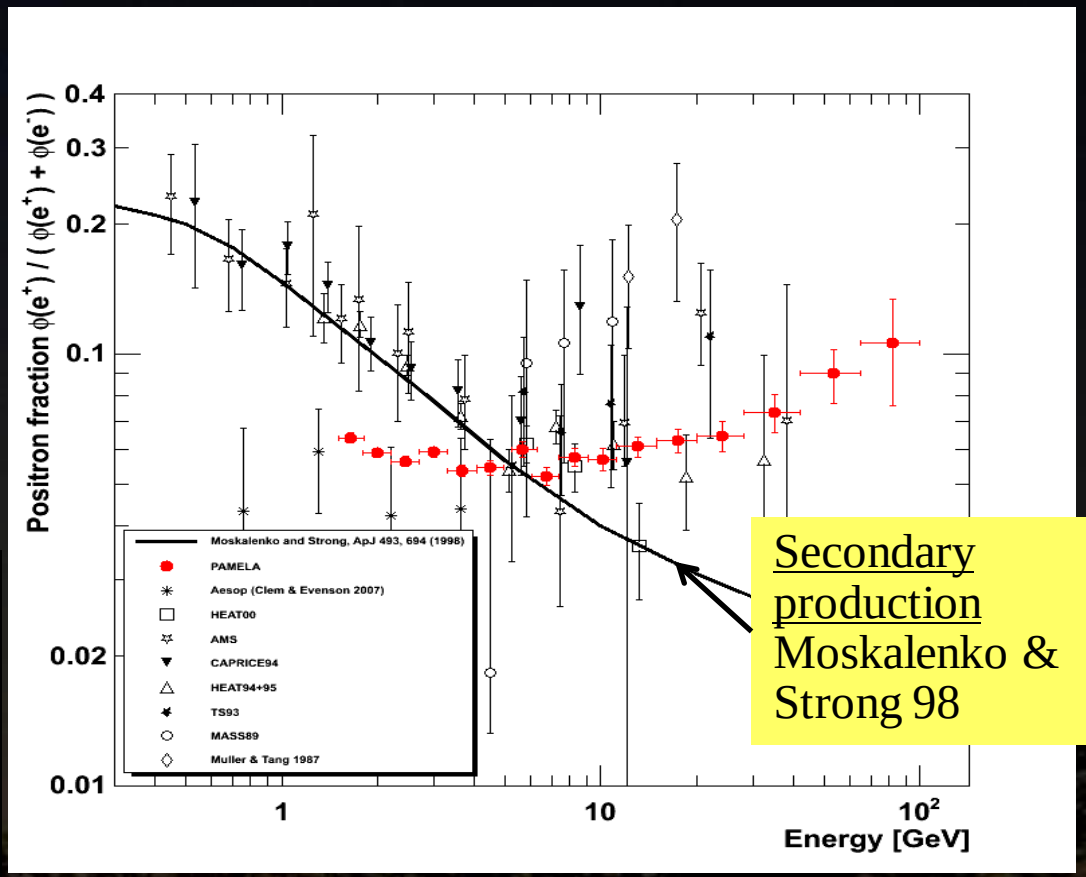


- Ration changes with energy
- Precision of measure greatly improved
- Constraints on dark matter models

Positrons fraction (very hot topic)

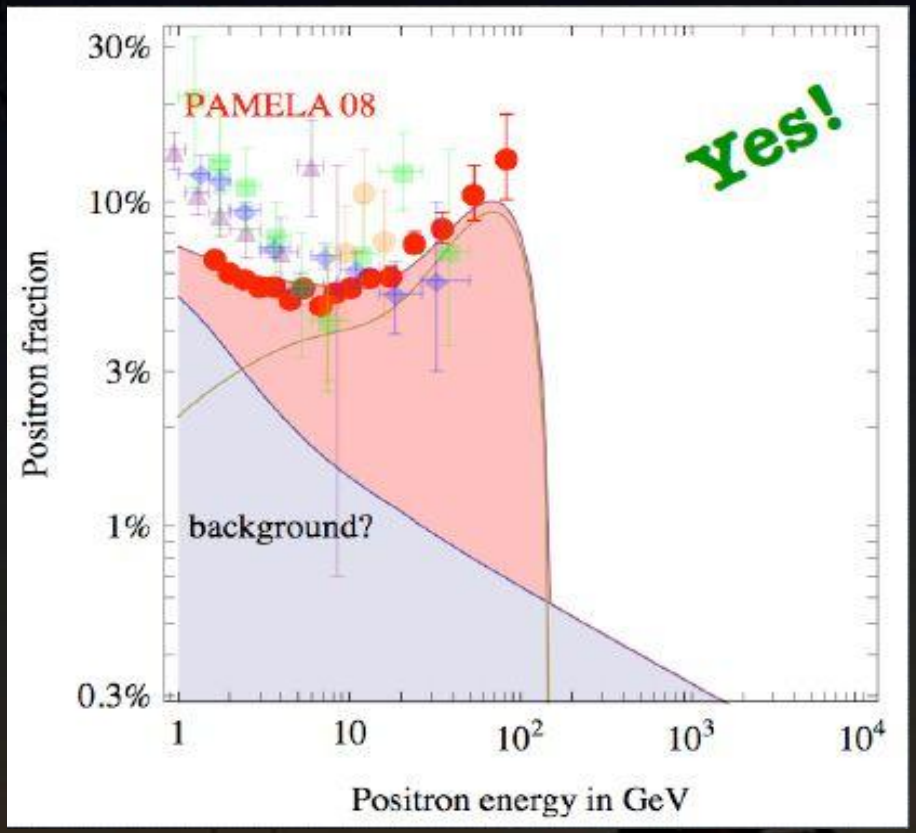
- ~ 10 000 e+
  - Improvement of uncertainties compared to previous exeriments.
  - Up to 100 GeV

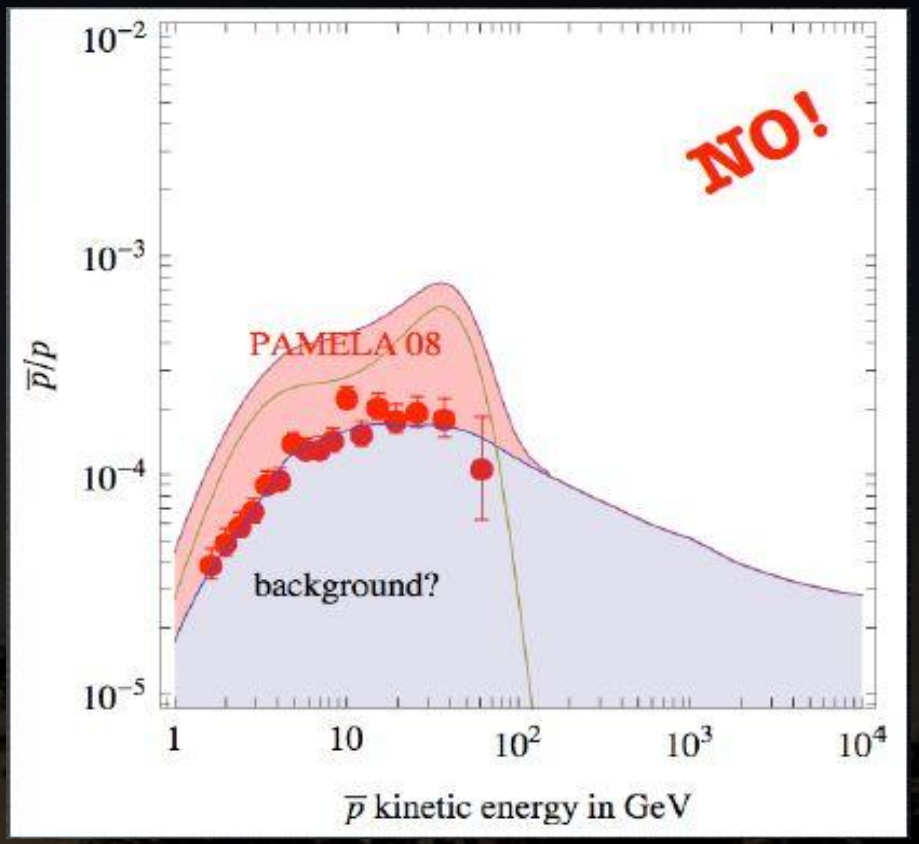




- Above expected background (secondary e+)
- Nearby source (pulsar)?
- Dark Matter?
- Or unknown propagation effect?

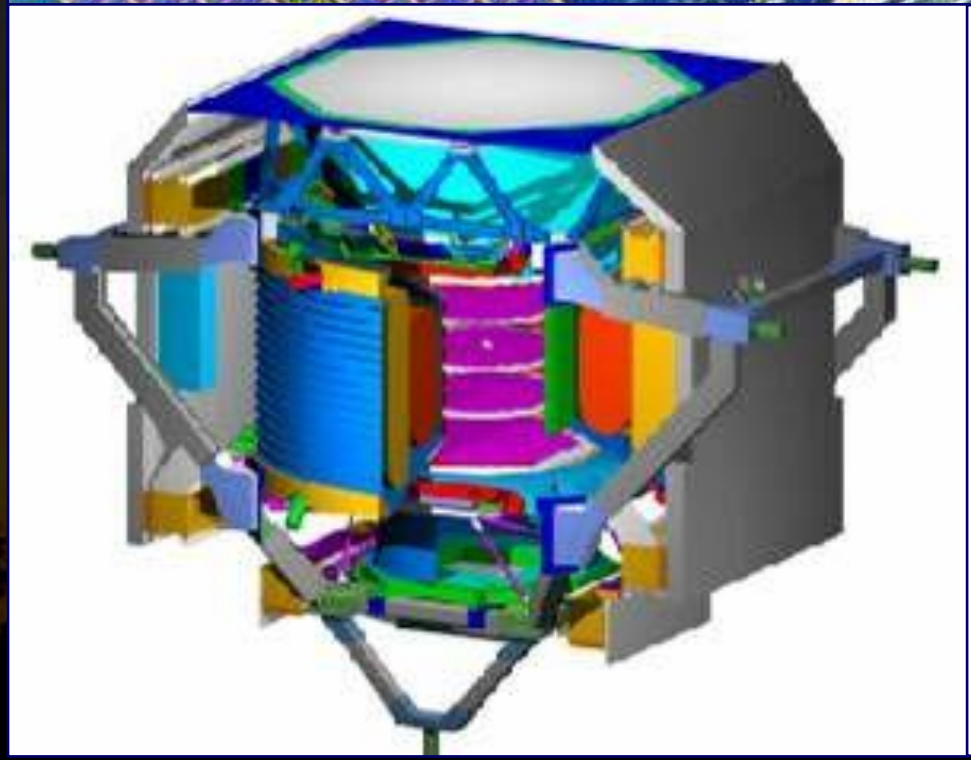
Dark Matter ?

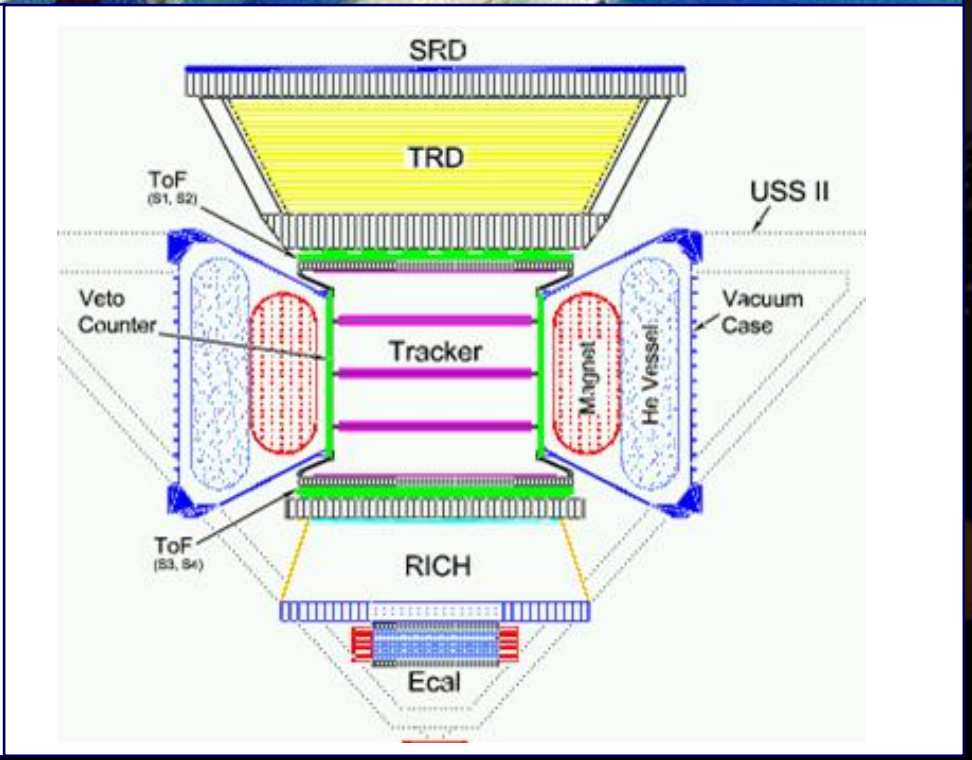




- Positron excess compared to diffusion models, antiprotons shows no excess
- A wino ($\omega\ \omega \rightarrow W^+\ W^-$) at 150 GeV is consistent with positrons excess, but not with anti-protons
- A much higher mass (10 TeV) could fit the data, but conflicts with relic density (factor 1000)
- Possible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

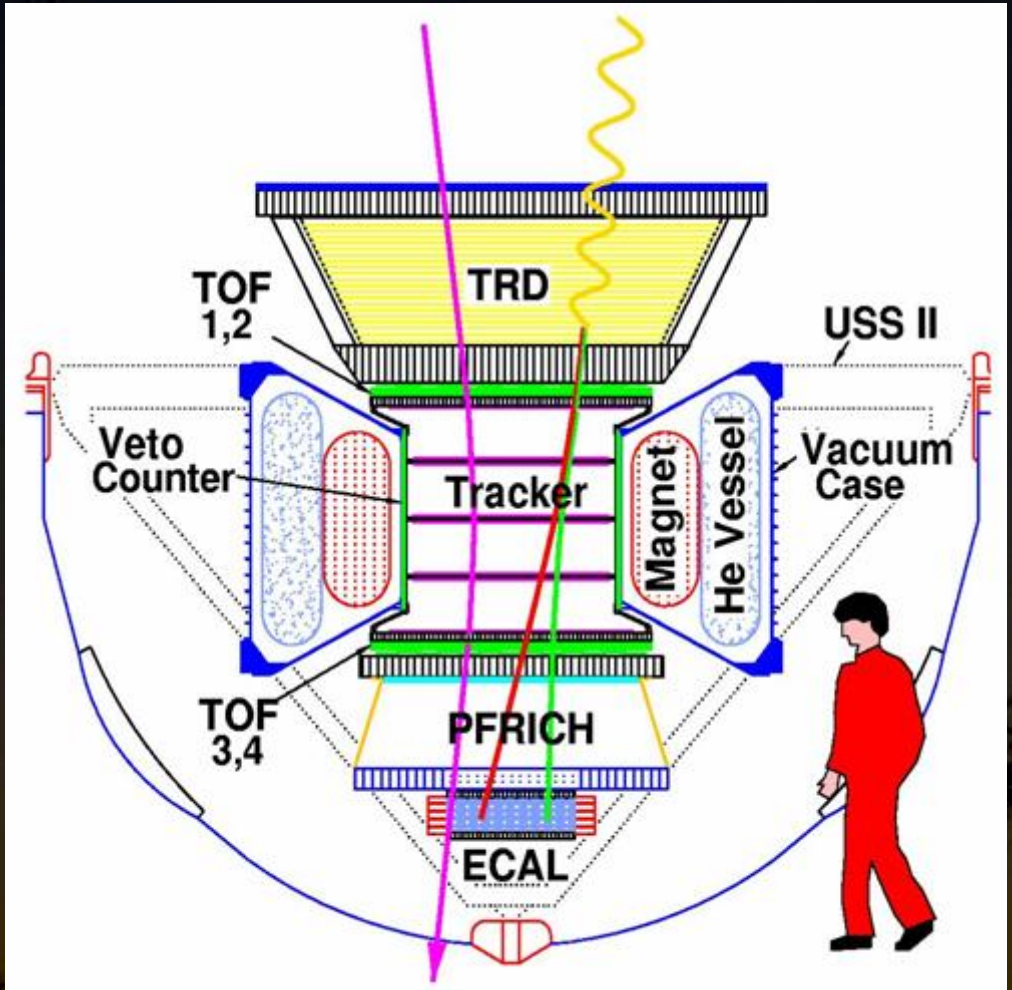
AMS - Alpha Magnetic Spectrometer





53

AMS



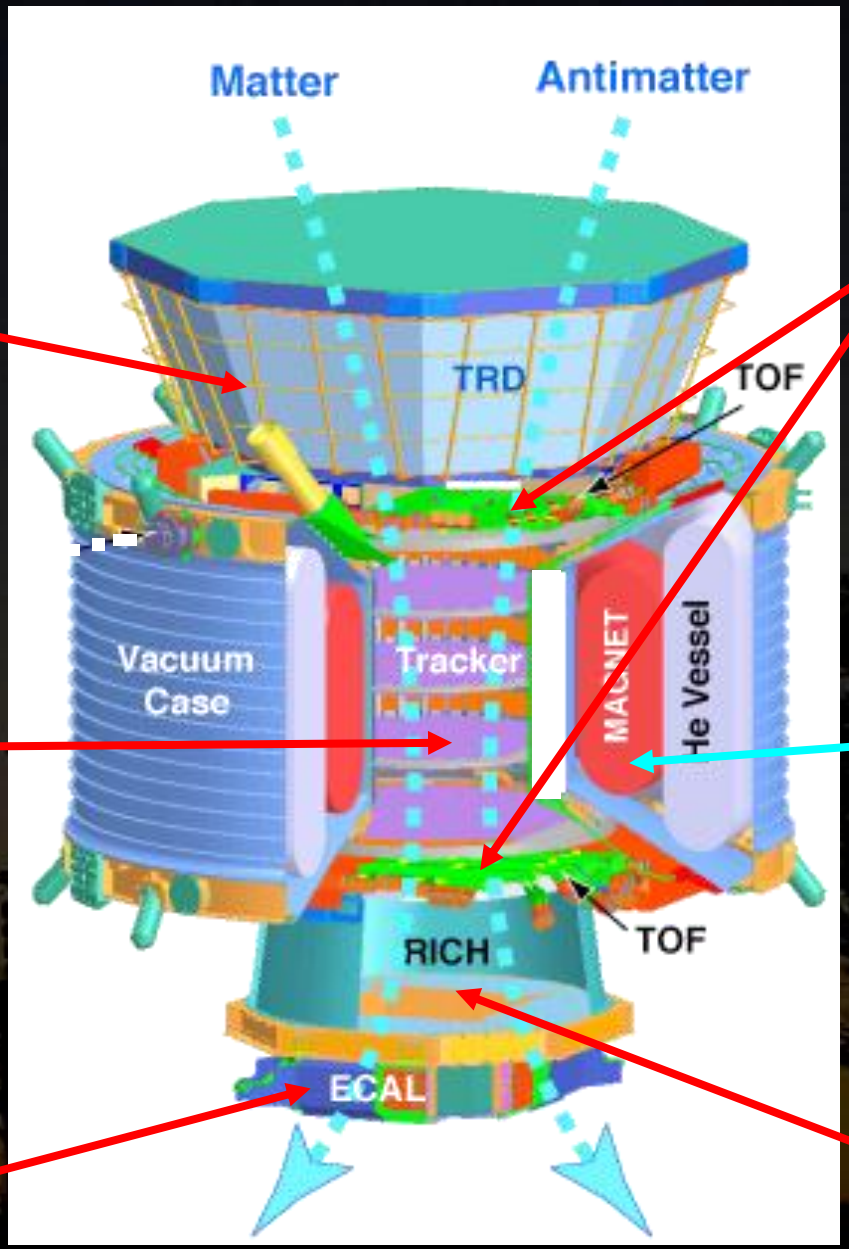
- A real (small scale) particle physics detector
- Spectrum & composition of charged particles from 500 MeV & a few TeV
  - Direct antimatter search (antihelium)
  - Indirect search of dark matter (e^+/e^-)
- Planned to be launch on the ISS in February 2011 (last shuttle flight)

AMS detector

TRD
Discrimination e/p

Tracker
Z,R

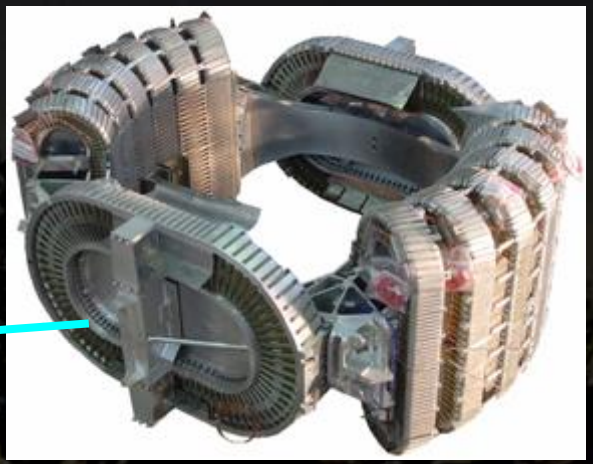
Electromagnetic Calorimeter
Discrimination e/p , E



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

Time of flight
β, Z

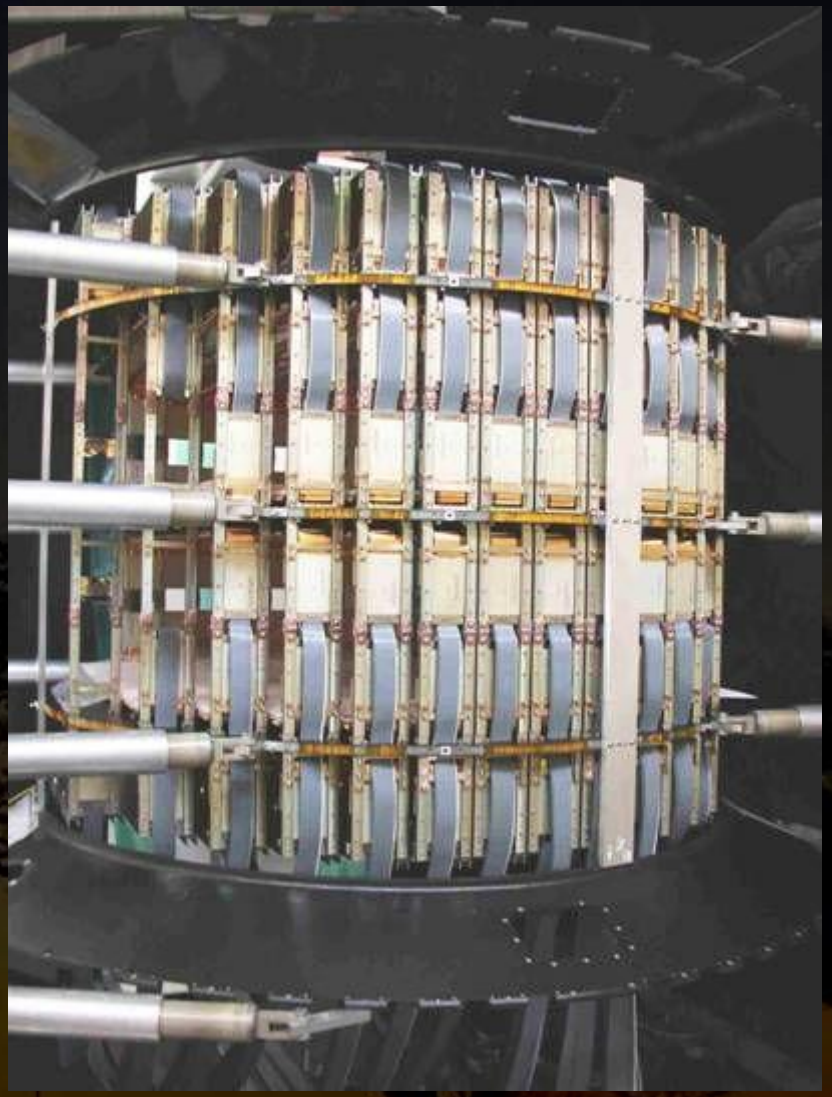
Permanent Magnet

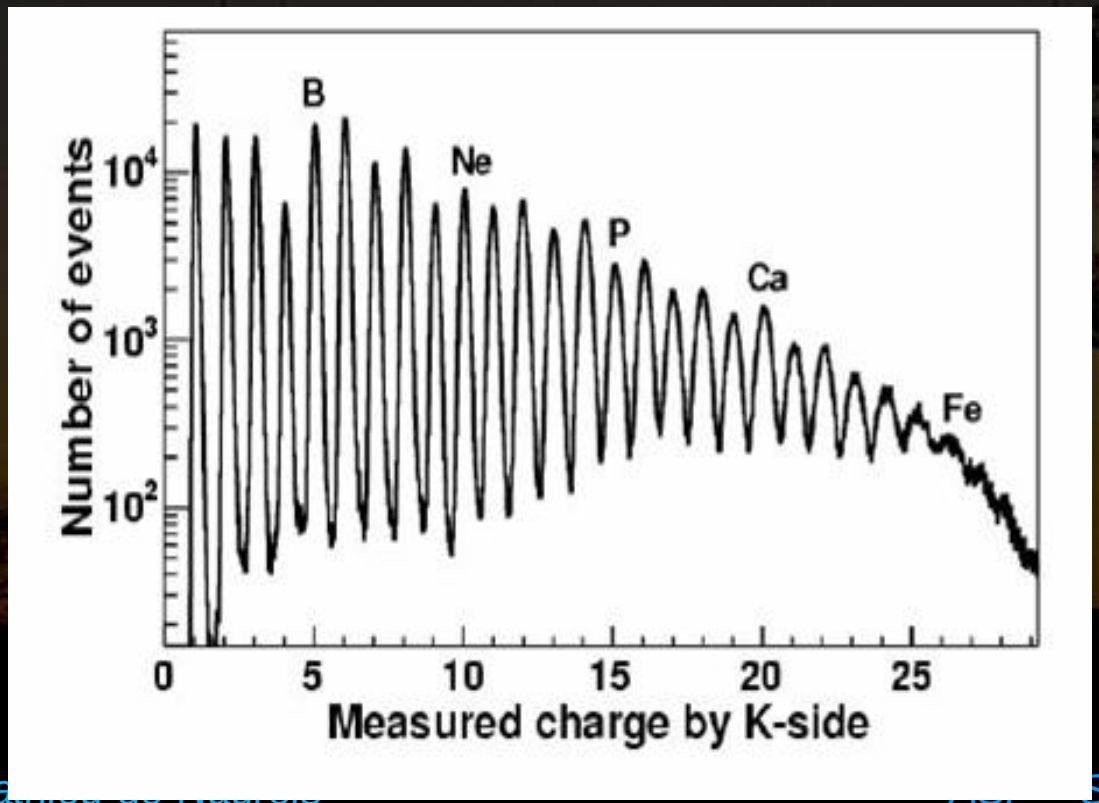


RICH
β, Z

Tracker

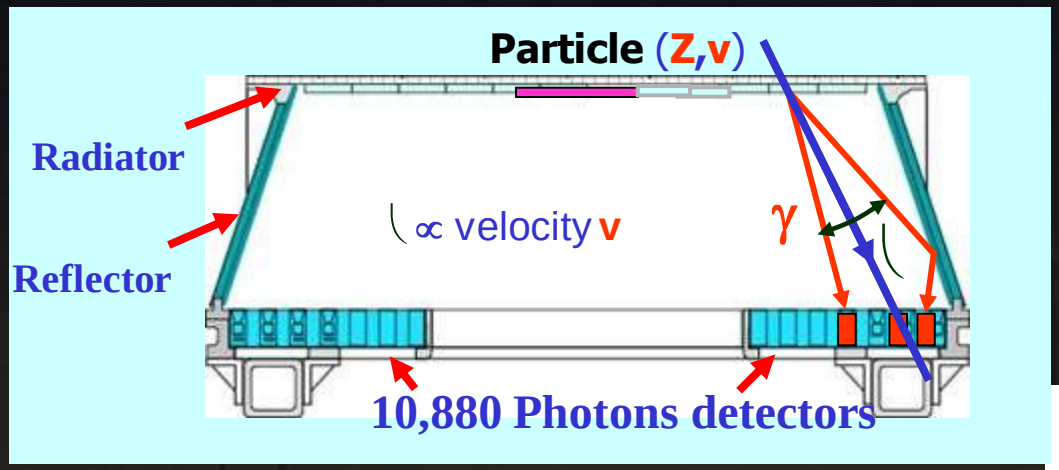
- Silicium strips (similar to FERMI)
  - 8 layers
  - Resolution 10/30 μm varying with orientation w/o B
  - Charge (Z) from dE/dx
  - Identification of elements ⇒ Fe

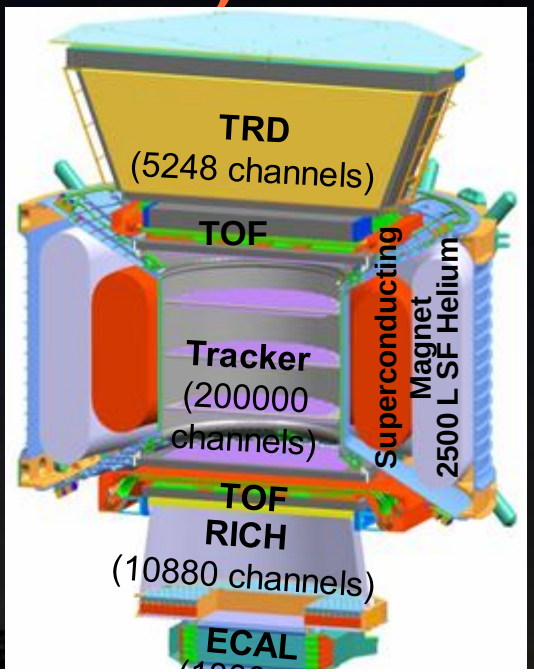




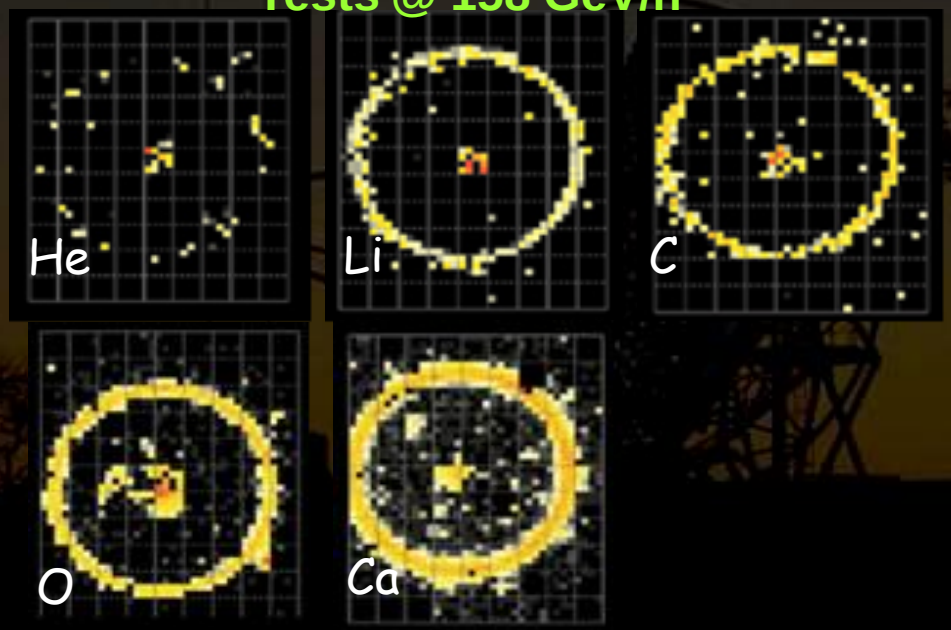
Ring Imaging Cerenkov (RICH)

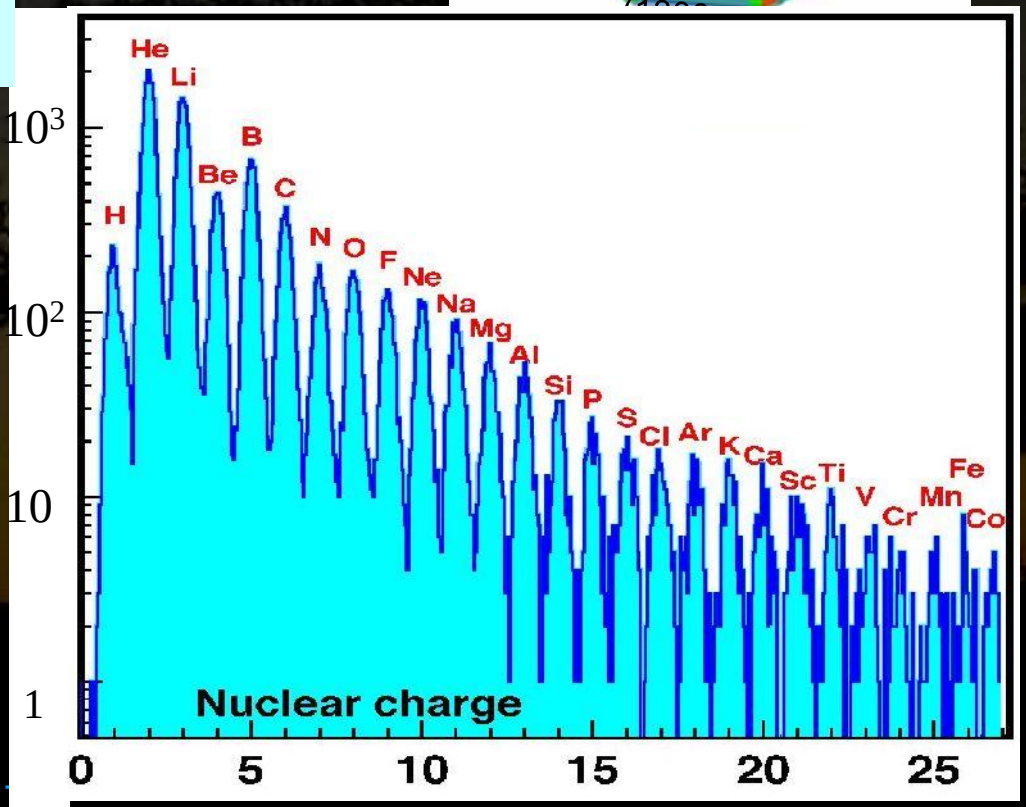
- Charge measurement ($\sigma(Z) = 0.3$) from photons density





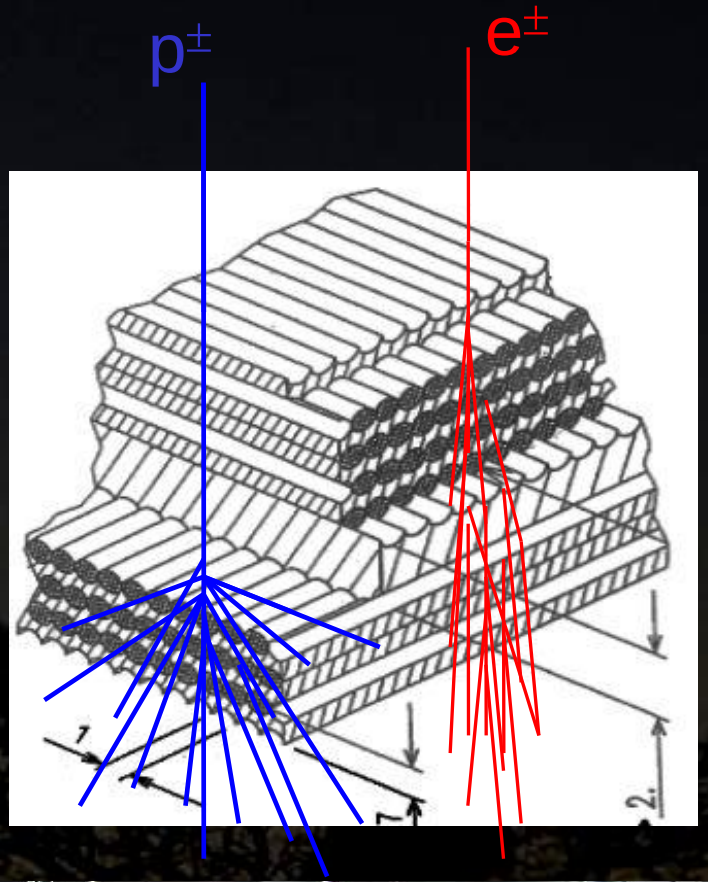
Tests @ 158 GeV/n

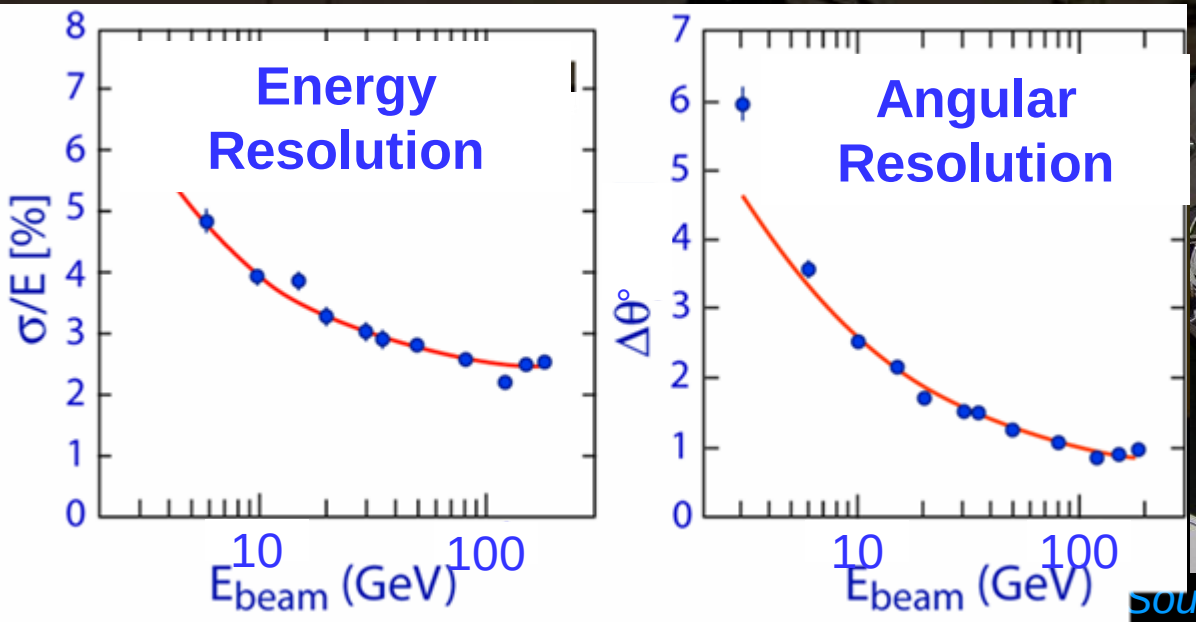




Electromagnetic Calorimeter

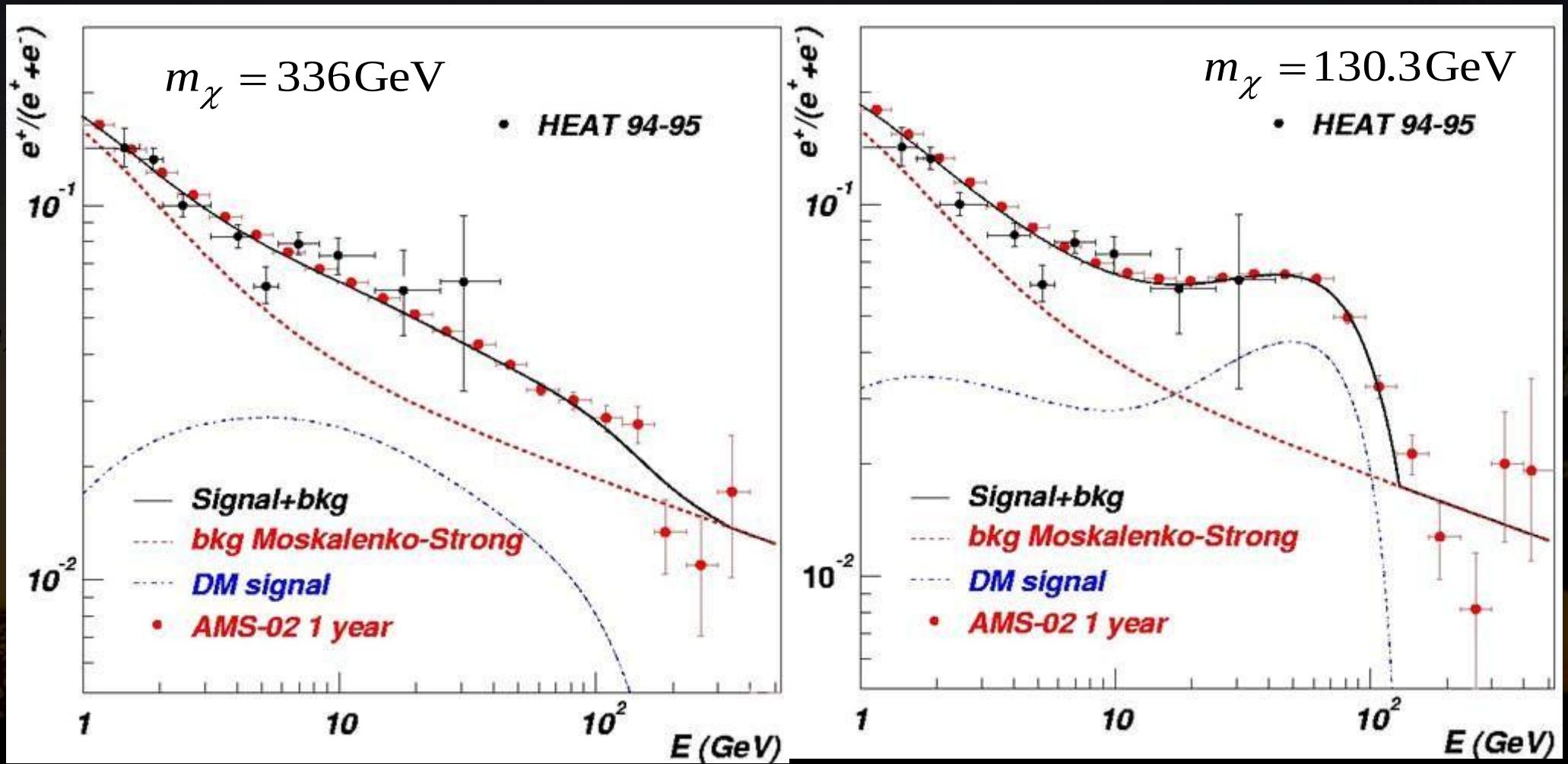
- 3D hodoscopic calorimeter
  - 9 super layers of 10 lead/fibres layers
  - Fibres alternated in X/Y
  - PMT readout
  - 16.4 X_0 total thickness
  - Energy Resolution: a few %
  - Angular resolution (0.5° – 1°)
  - Rejection p /e r=10^{-3} with 95% efficiency (using shower profile)





AMS-02: Expected SUSY signal

- Much improved precision expected



VERY HIGH ENERGY Γ–RAY ASTRONOMY

Pair Creation Telescopes

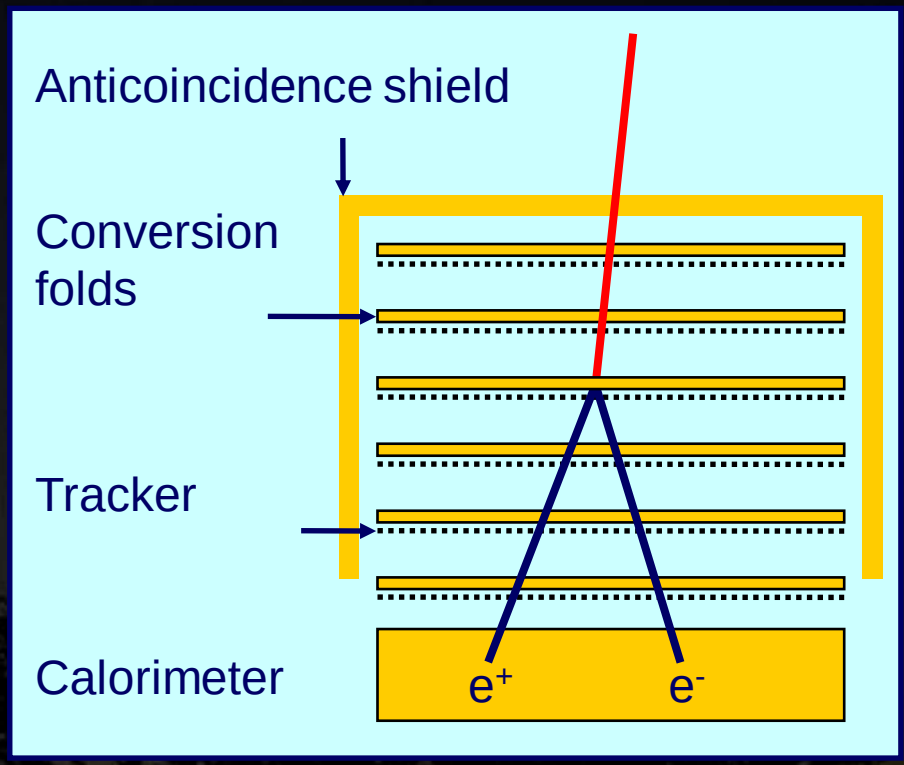
- Conversion of γ into pair e^+ e^-
  - Threshold $E_\gamma > 2m_e c^2$ (1.022 MeV)
  - Pair opening angle

$$\theta \approx \frac{1.6\,\text{rad}}{E\,[\text{MeV}]} \approx 1^\circ \text{ at } 100\,\text{MeV}$$

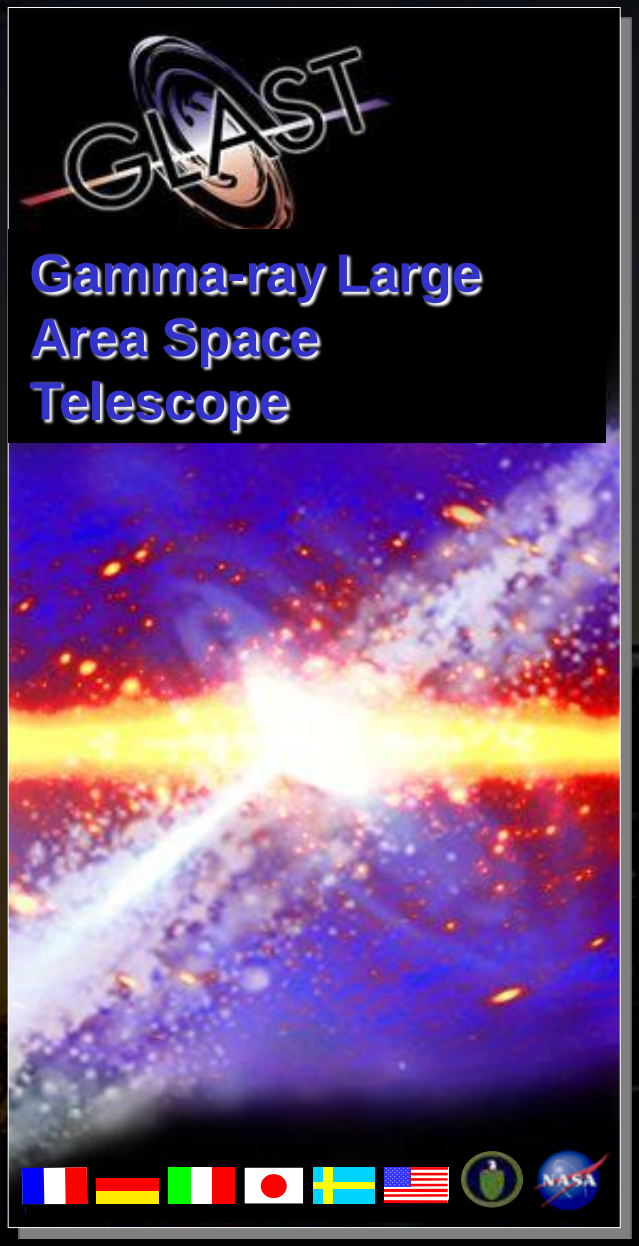
  - Average deviation: (Multiple scattering)

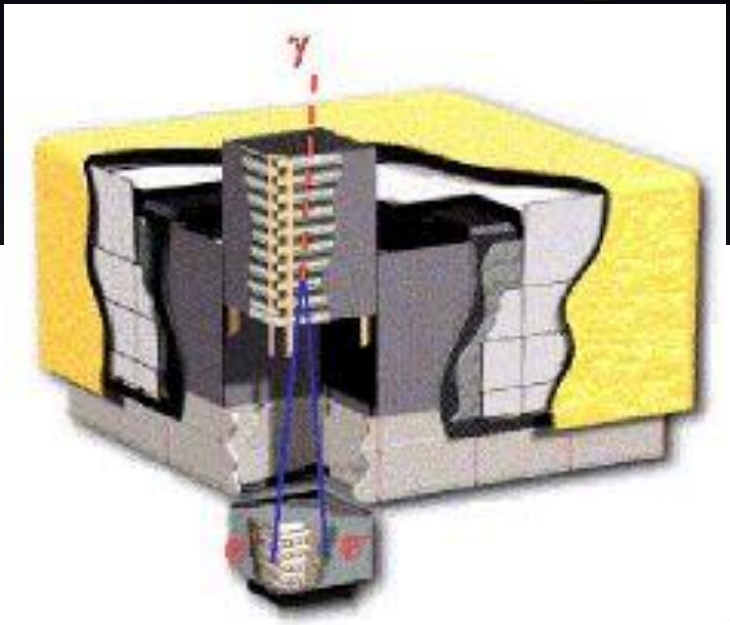
$$\sqrt{\langle \theta^2 \rangle} = q(E_\gamma, E_e, Z)\sqrt{\frac{m_e c^2}{E}}\ln\left(\frac{E}{m_e c^2}\right)$$

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

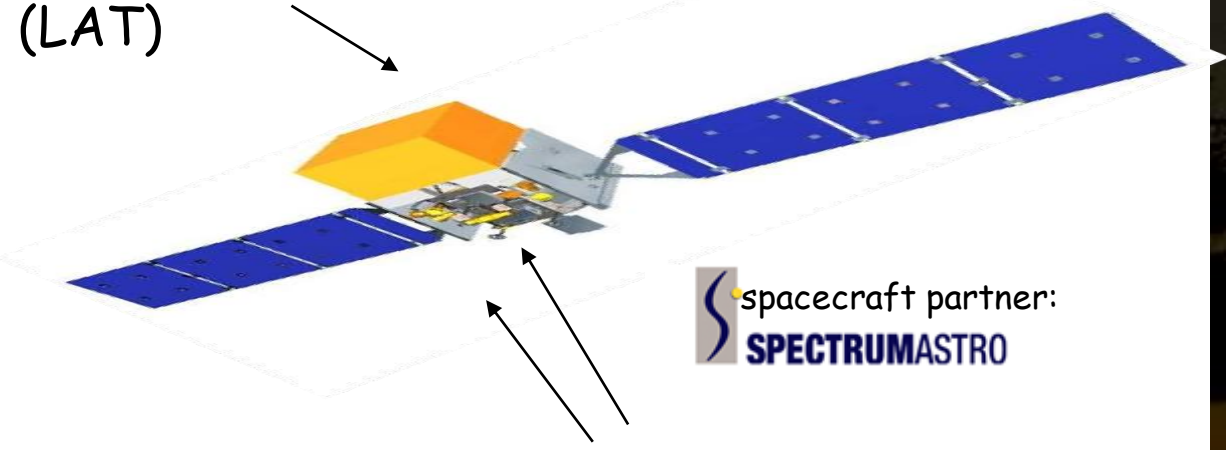


FERMI Large Area Telescope





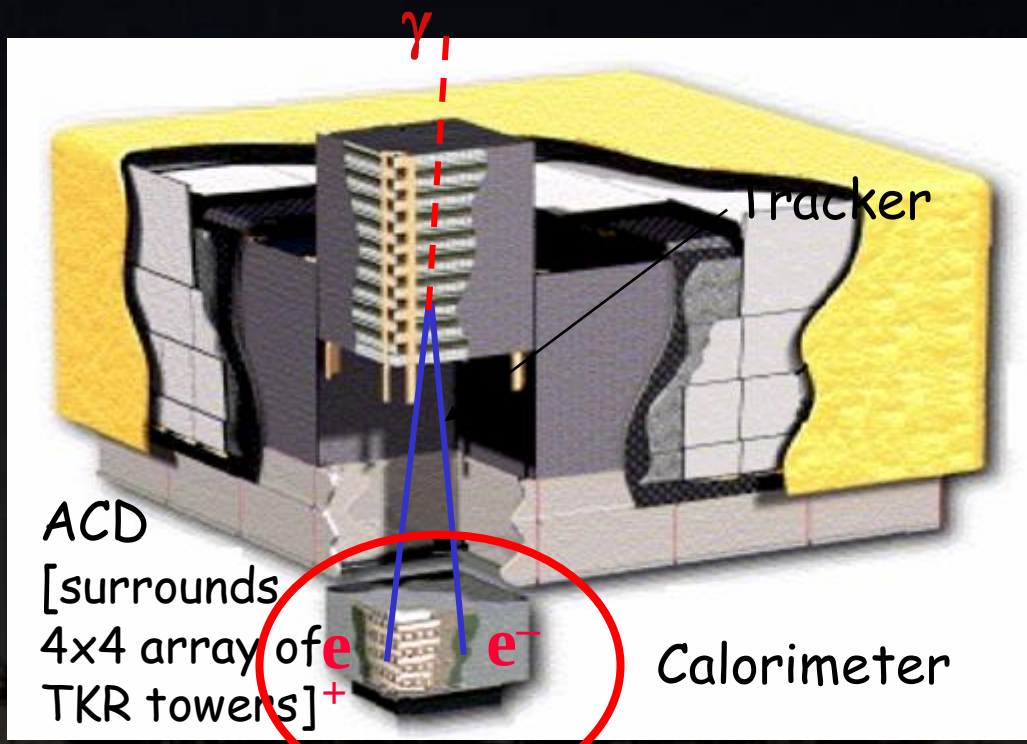
Large Area Telescope (LAT)

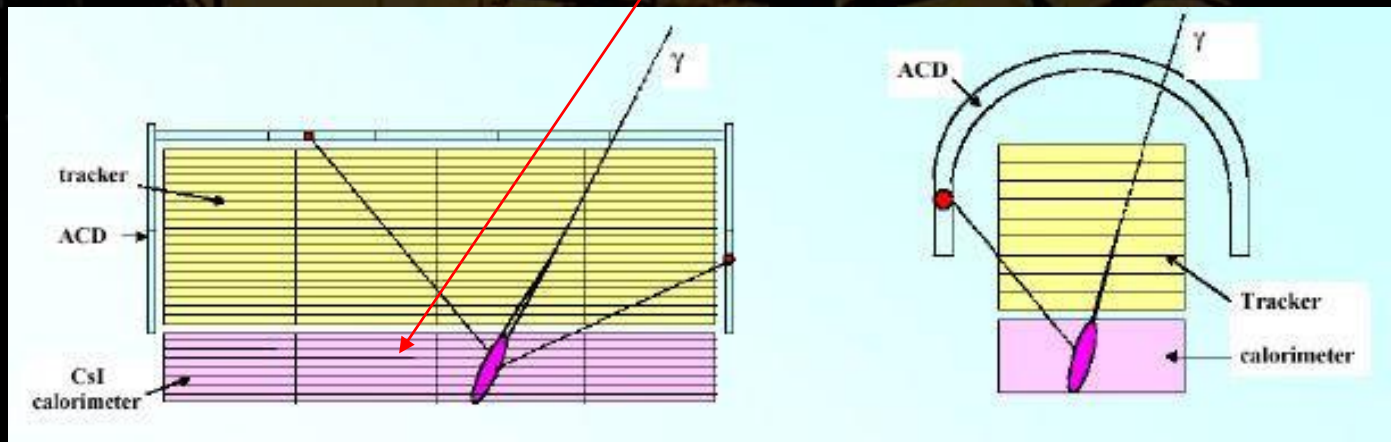


FERMI Burst Monitor (GBM)

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



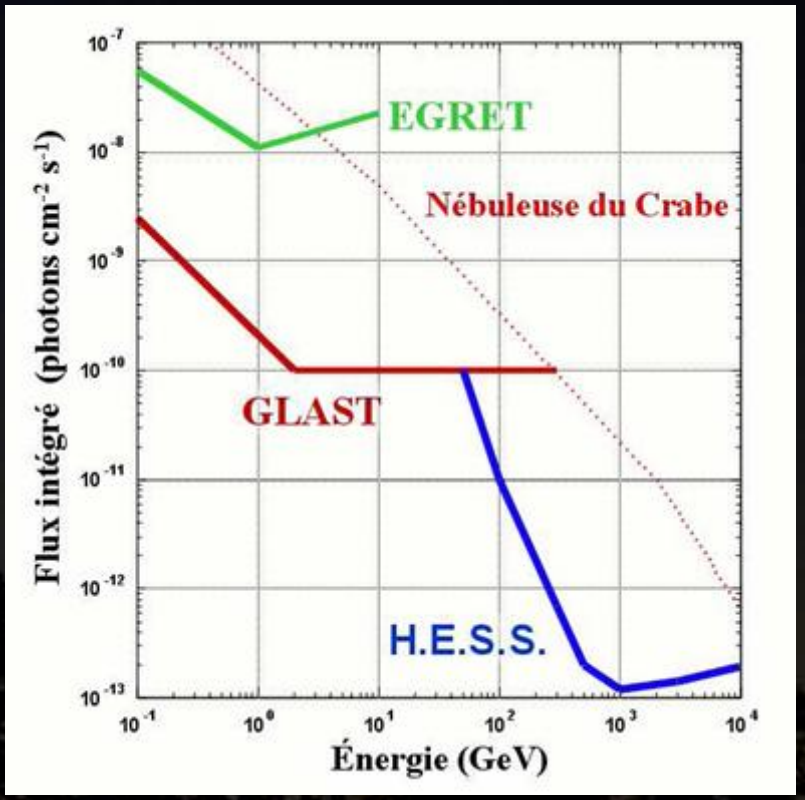


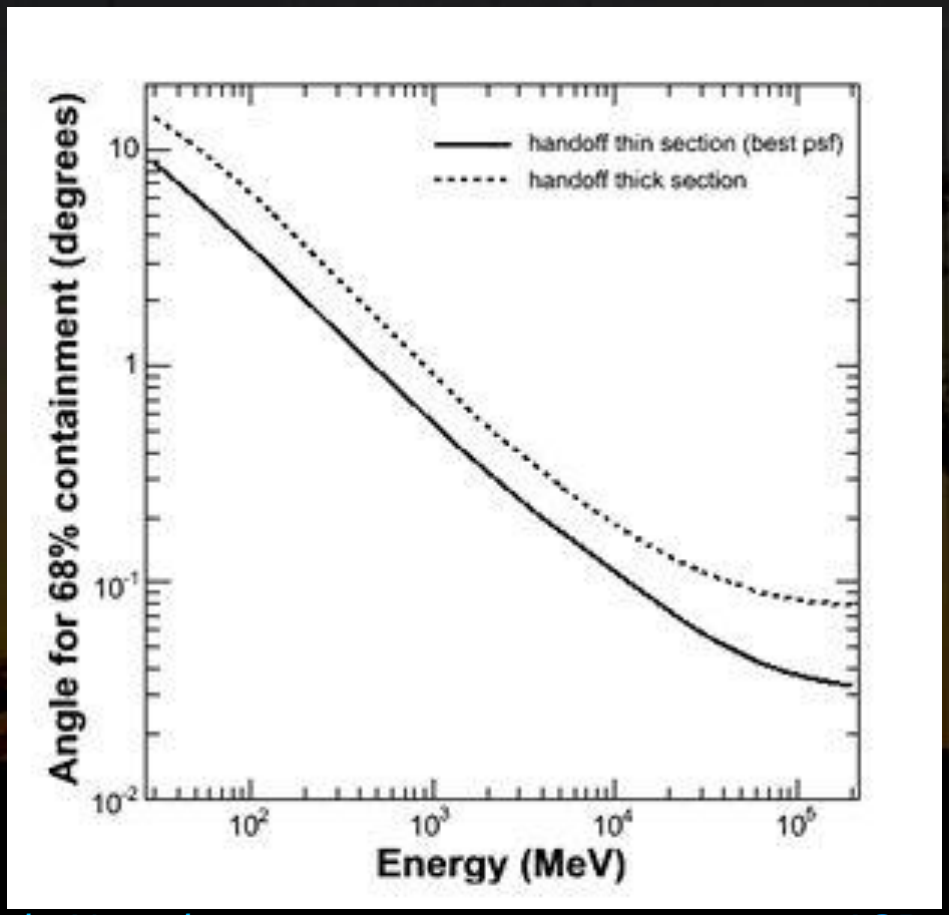
FERMI

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

Performances

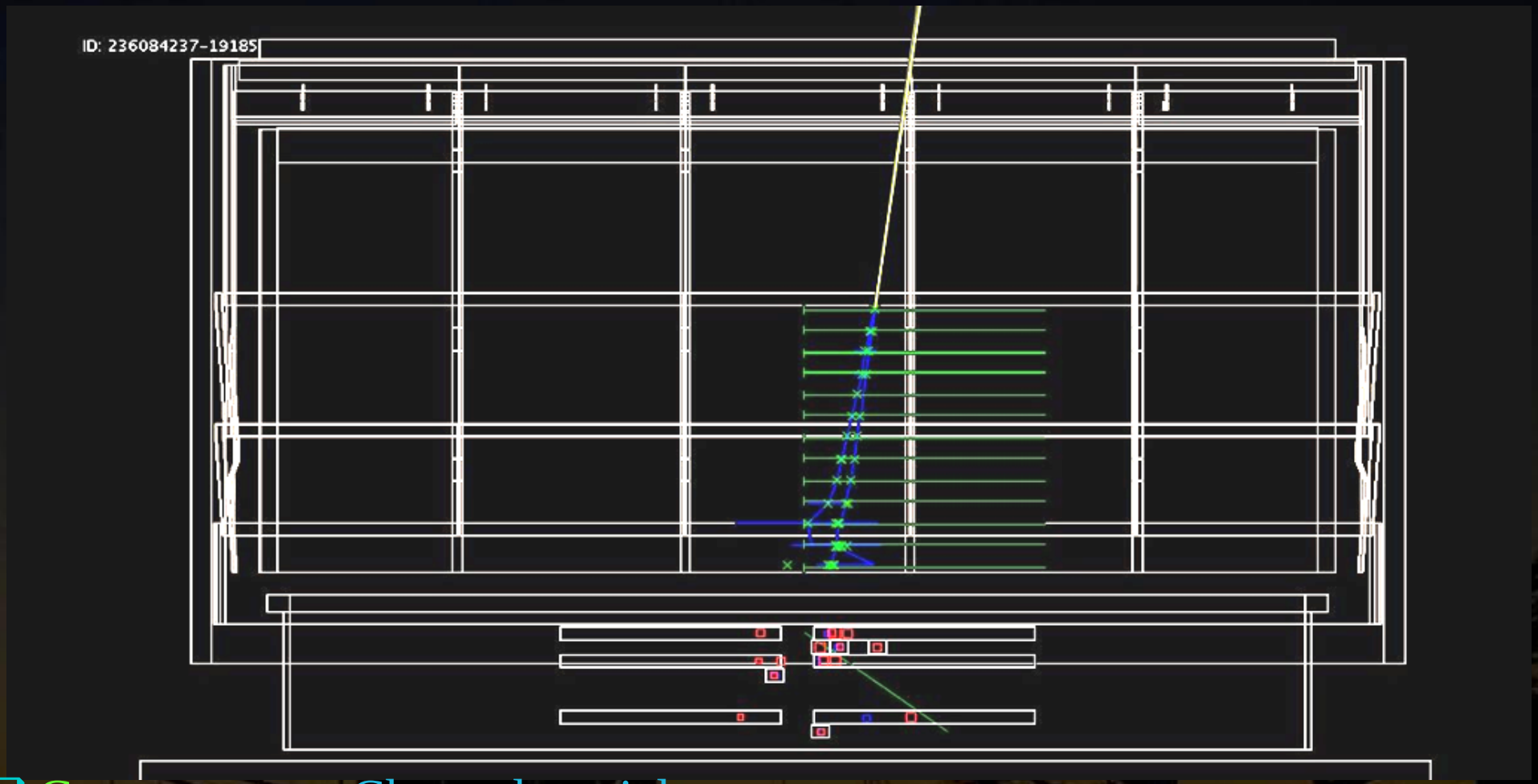
- 25 × more sensitive than EGRET
  100 × at high energy
- Angular resolution
  4° @ 100 MeV ⇒ 0.1° @ 10 GeV





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

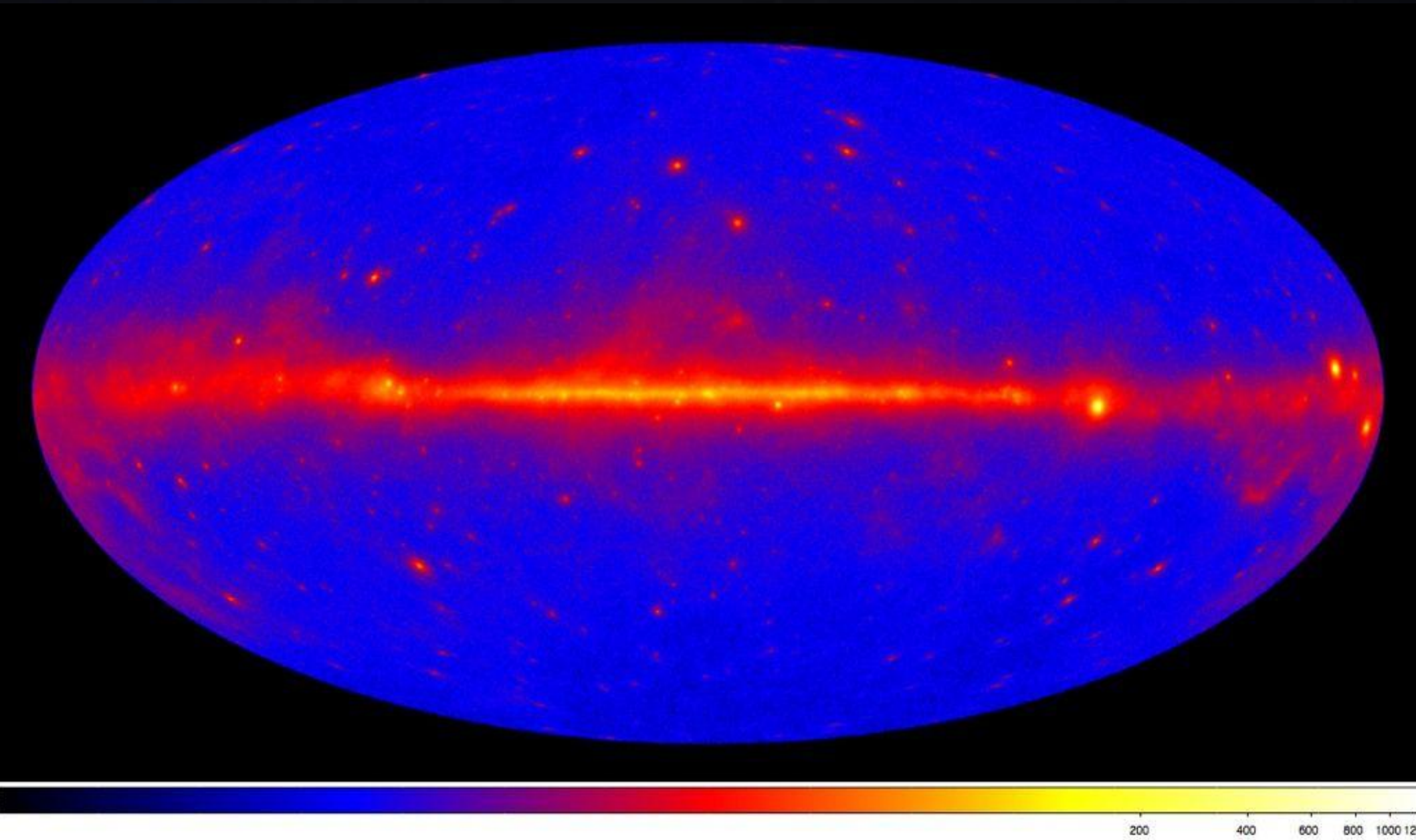
Gamma-Ray candidate



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

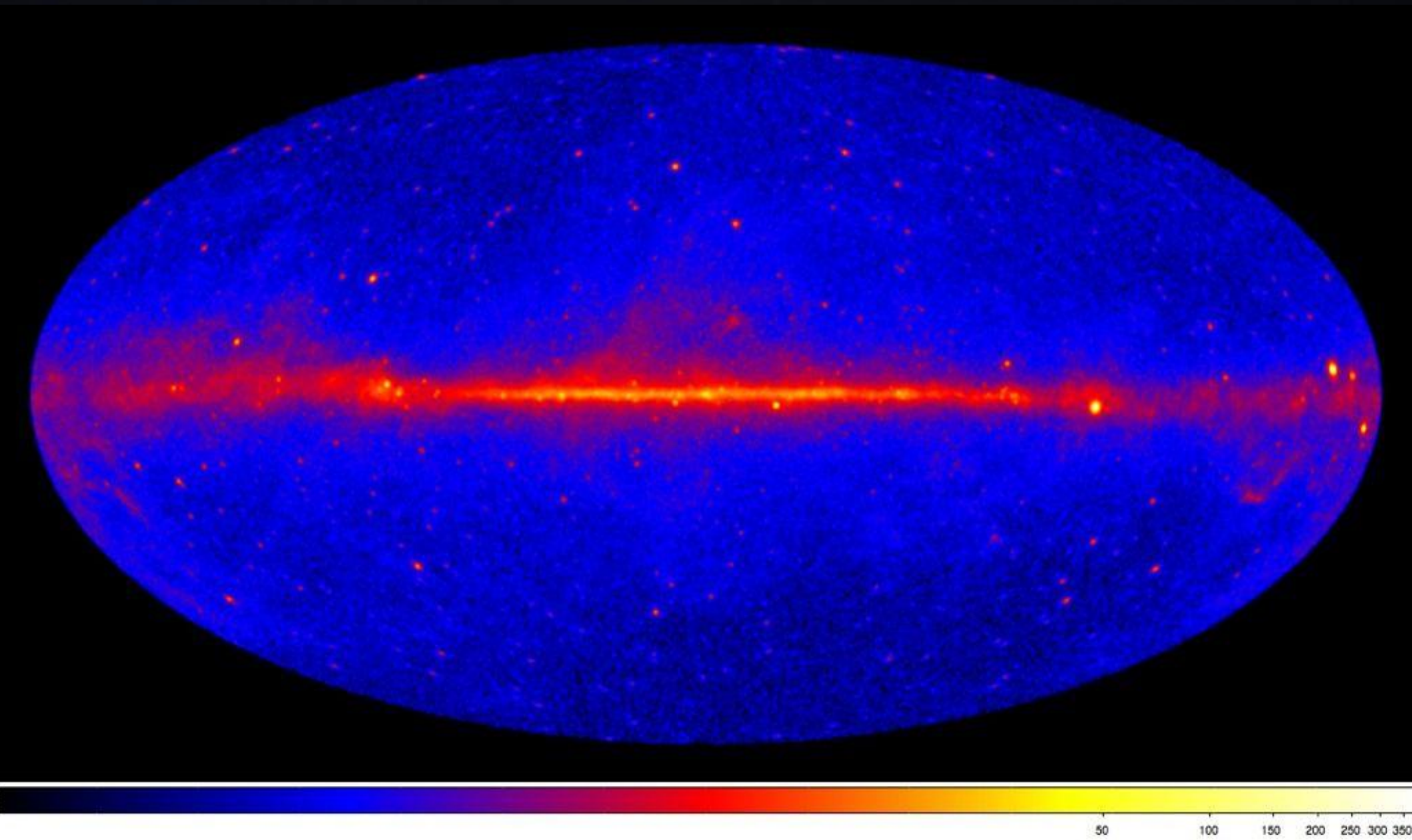
Fermi LAT > 100 MeV

- 3×10^7 photons, <E> = 800 MeV, $\Delta E/E = 100$ %



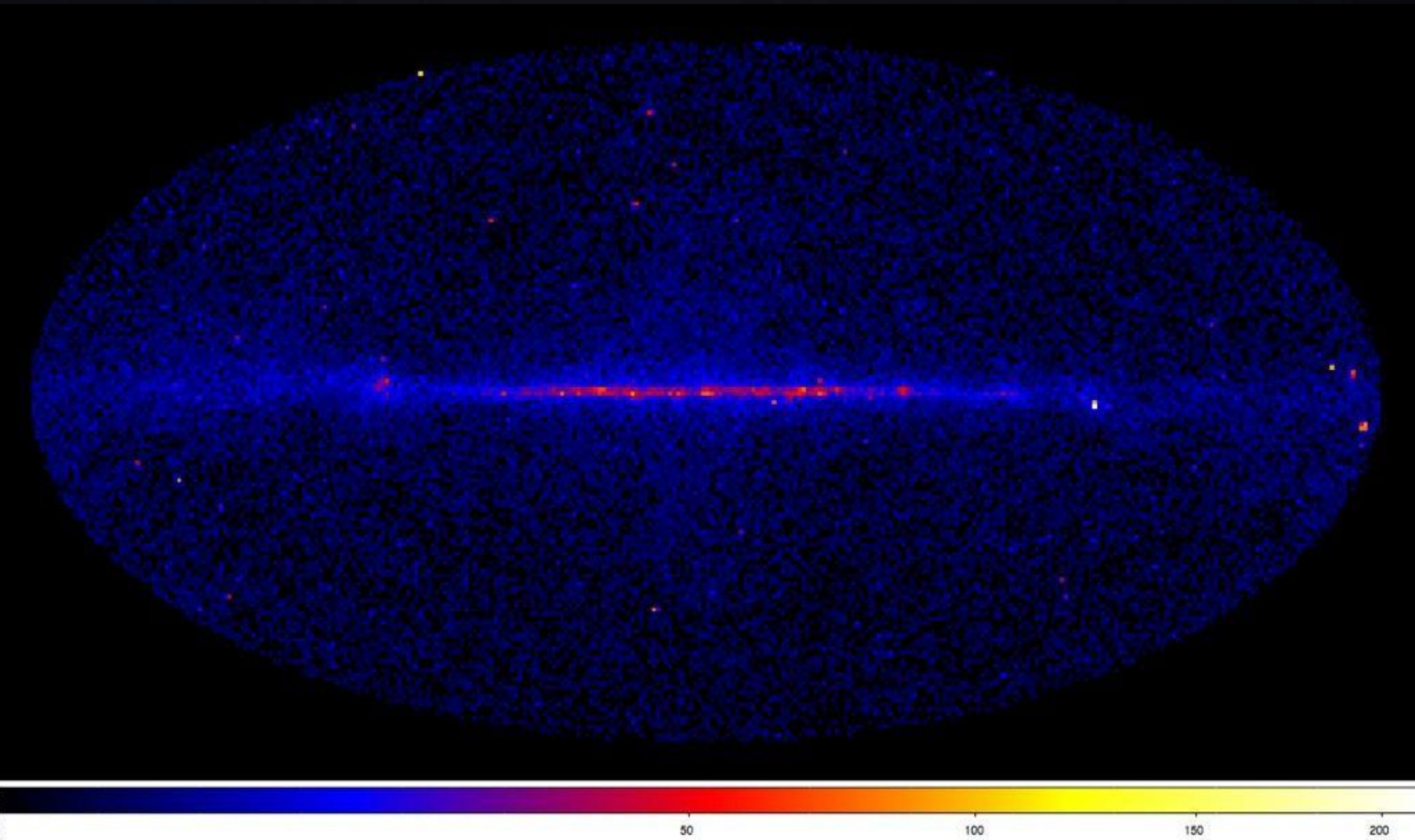
Fermi LAT > 1 GeV

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



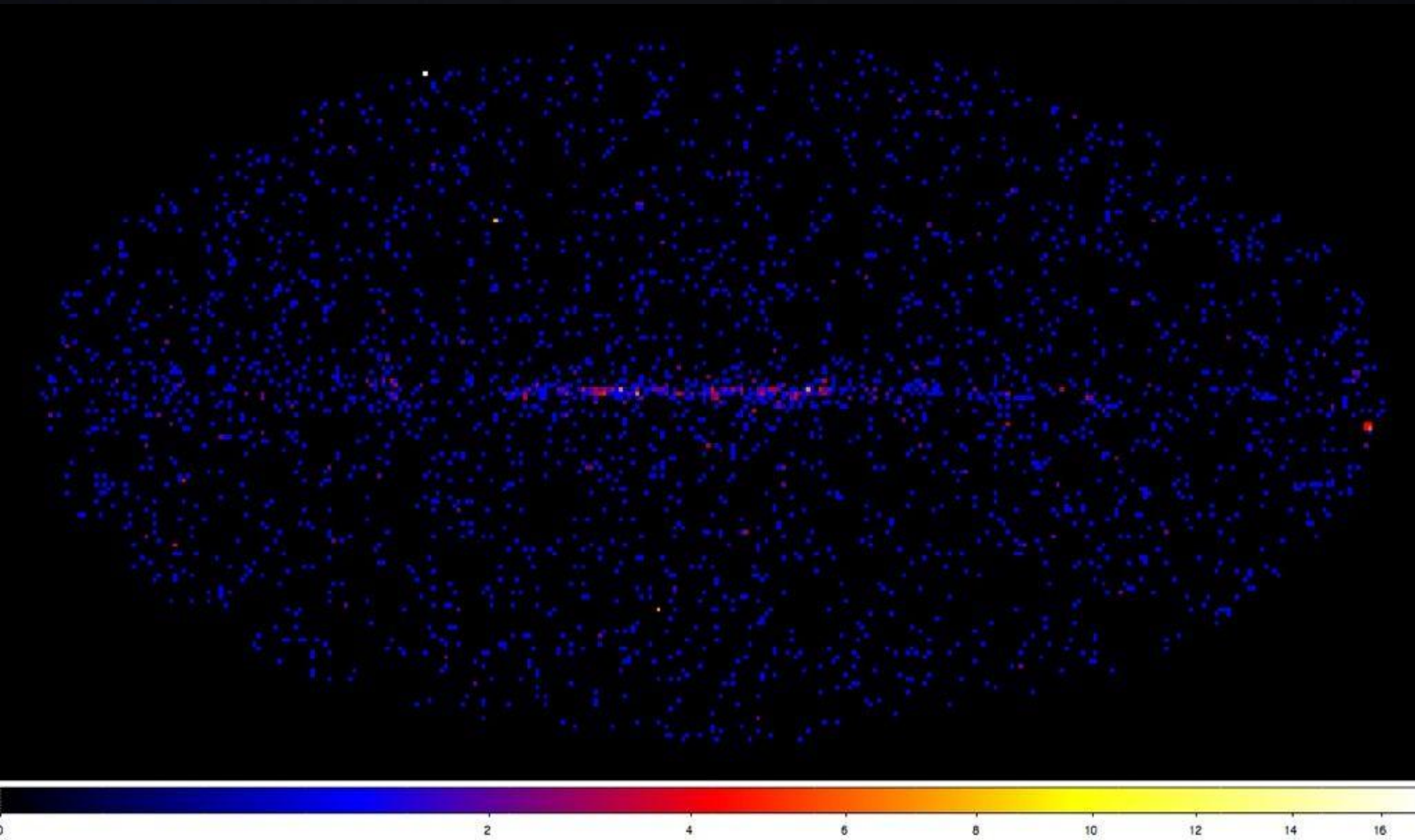
Fermi LAT > 10 GeV

- 7×10^4 photons, $\langle E \rangle = 30$ GeV, $\Delta E/E = 0{,}6$ %



Fermi LAT > 100 GeV

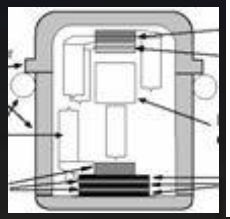
- 3×10^3 photons, $\langle E \rangle = 150$ GeV, $\Delta E/E = 0{,}02$ %



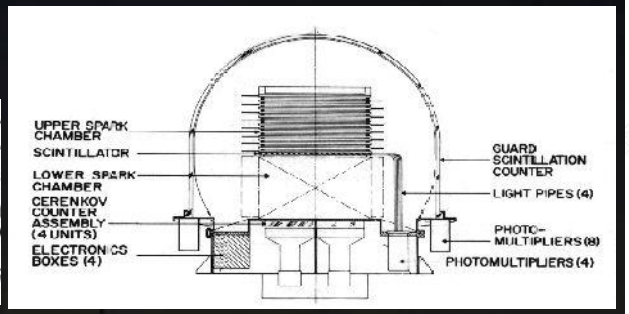
History of pair creation telescopes

- **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 × 10^6 γ, 271 sources**
- **2007-**, AGILE
- **2008-**, FERMI

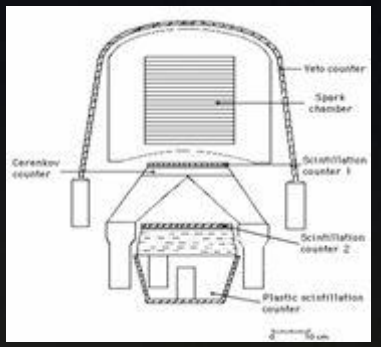
OSO-3



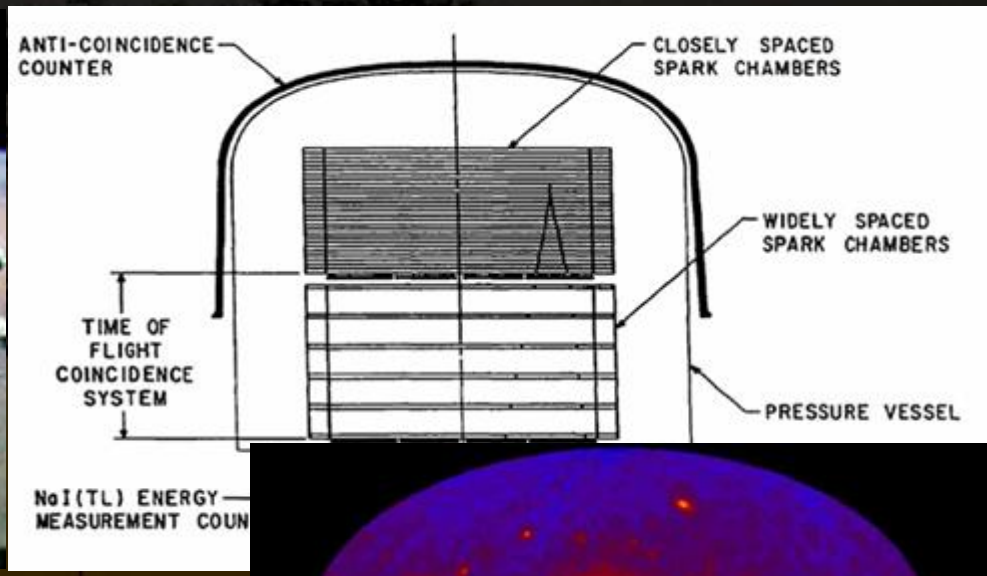
SAS-2

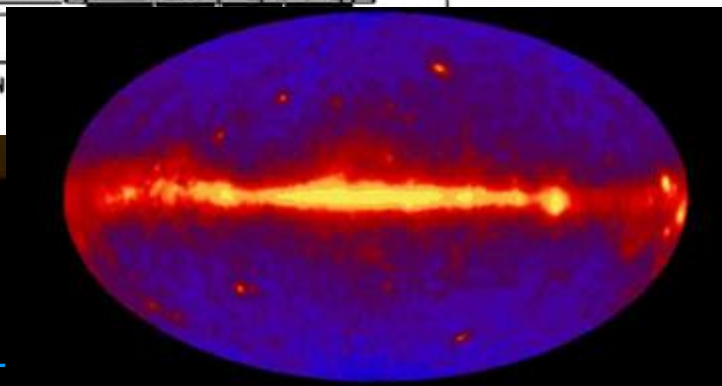


COS-B

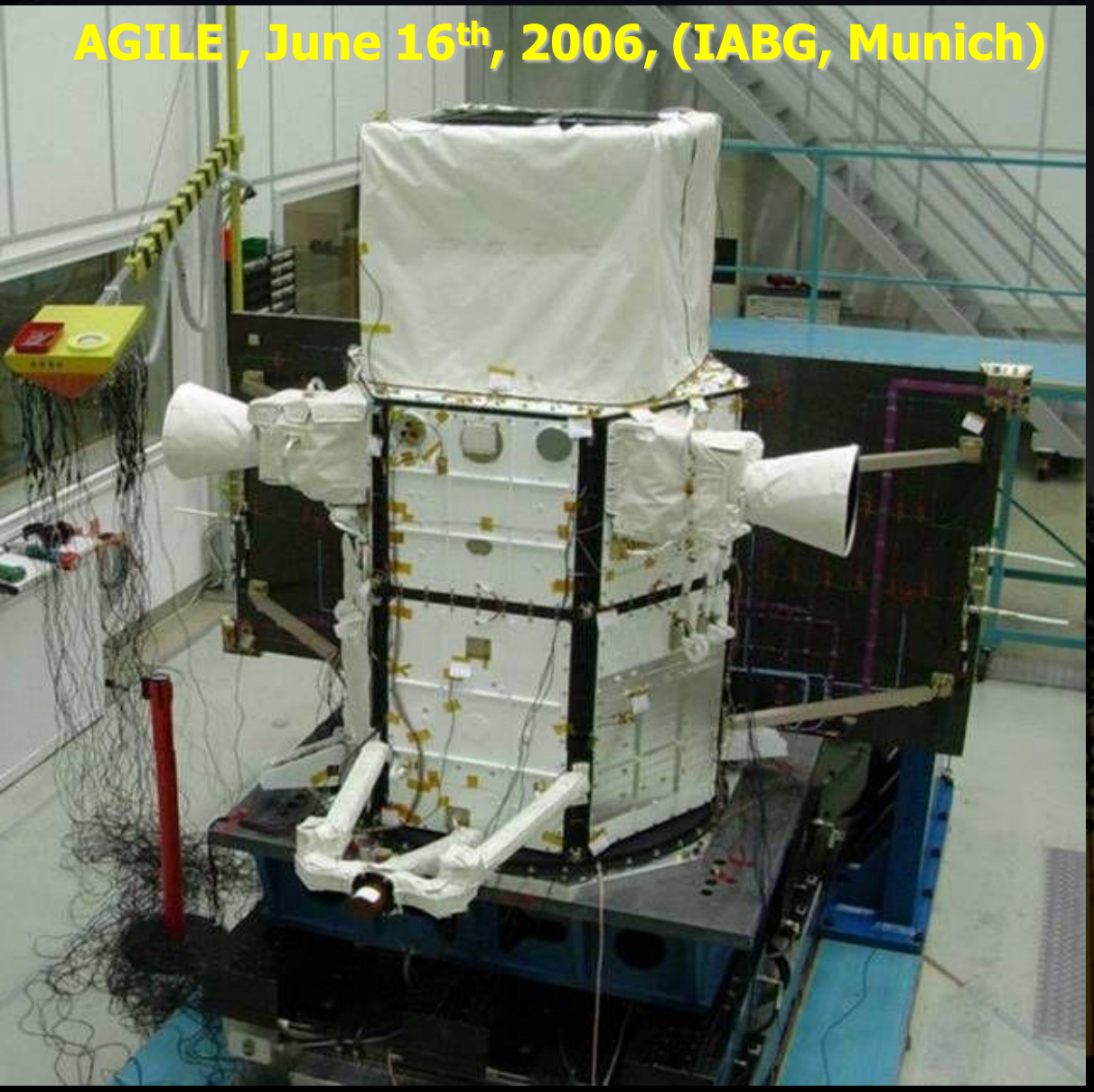


EGRET





AGILE

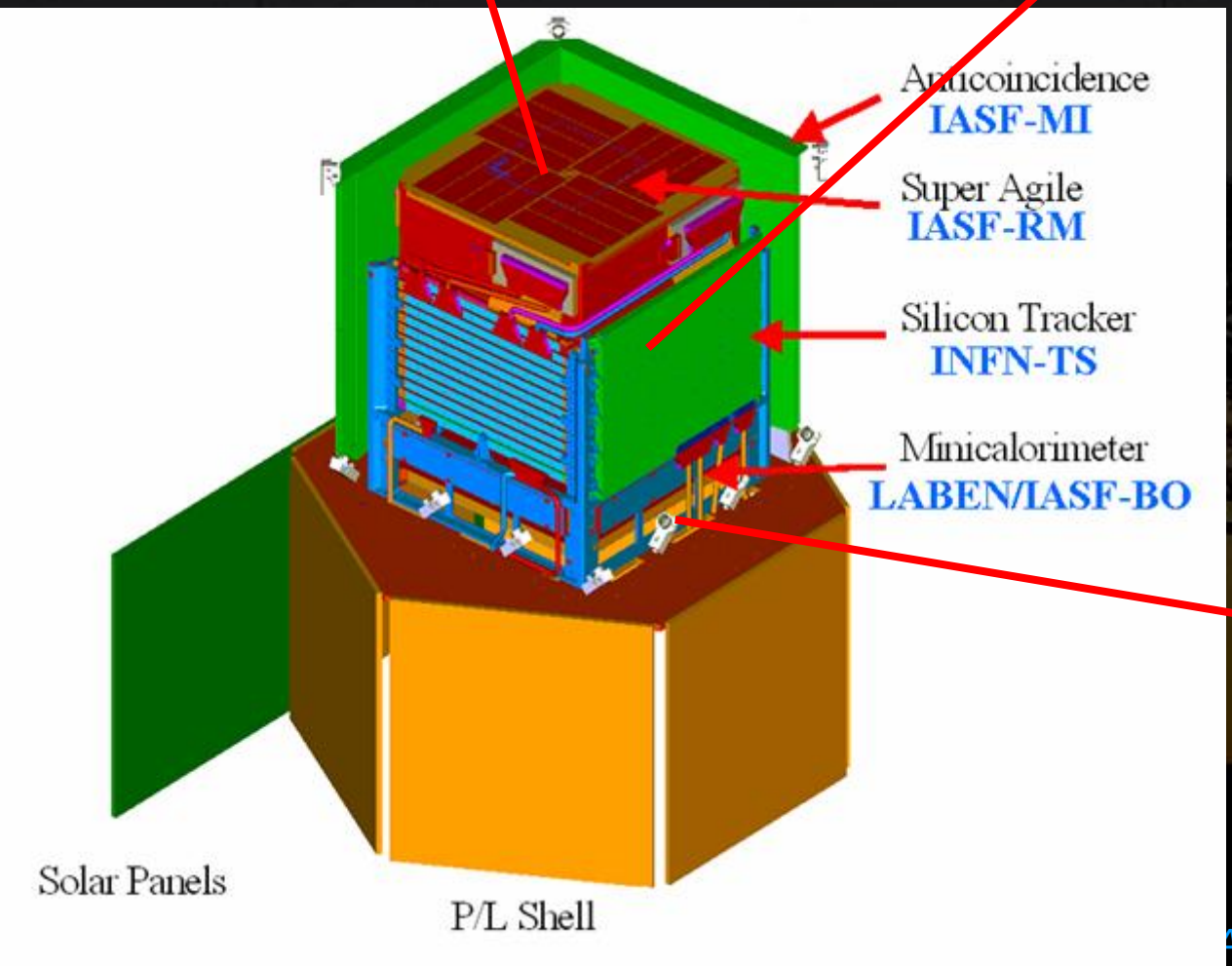


- Light instrument (instrument 120 kg, 350 kg incl. vessel)
  ⇒ Correct imaging capabilities, poor spectroscopy
- Pair creation telescope: 30 MeV – 30 GeV
- Hard X-ray aligned imager (coded mask, 1-60 keV)
- Launched on april 23th 2007 from India
- Mini-calorimeter (1.5 X_0)

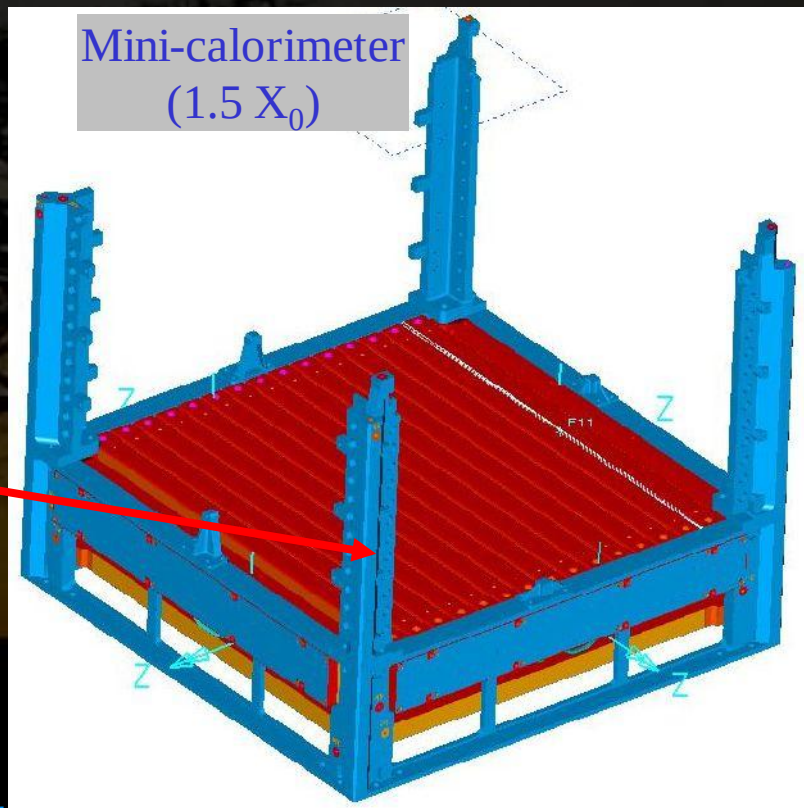
AGILE

X Imager (coded mask)

Tracker



Mini-calorimeter
(1.5 X_0)



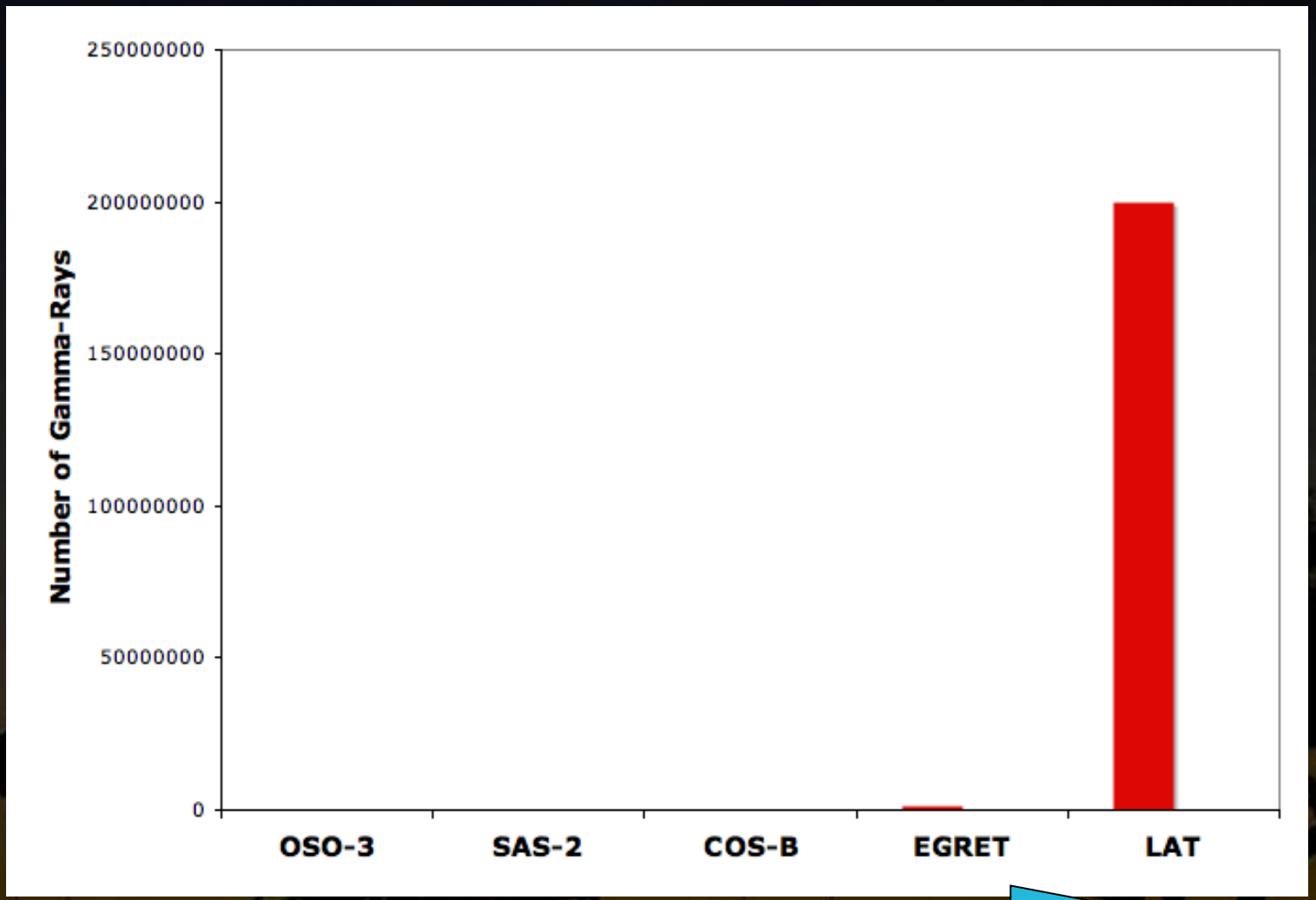
From EGRET to AGILE & FERMI

Instrument	EGRET	AGILE	FERMI
Launch	1991	April 2007	February 2008
Energy	2 MeV-30 GeV	30 MeV-50 GeV	10 MeV-300 GeV
Tracker	Spark Chamber	Si Strips + W (14 pl.)	Si 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	2 MeV-30 GeV	30 MeV-50 GeV	10 MeV-300 GeV
FOV	0.20 sr	2 sr	2.4 sr
Angular resolution	1.5 @ 1 GeV	0.6	0.12 @ 10 GeV 4 @ 100 MeV
Source determination accuracy	5' à 10 '	30 ' @ 300 MeV	0.4 '
ΔE/E	10 %	100 %	10 %
Dead time	0.1 s	< 100 μs	< 100 μs

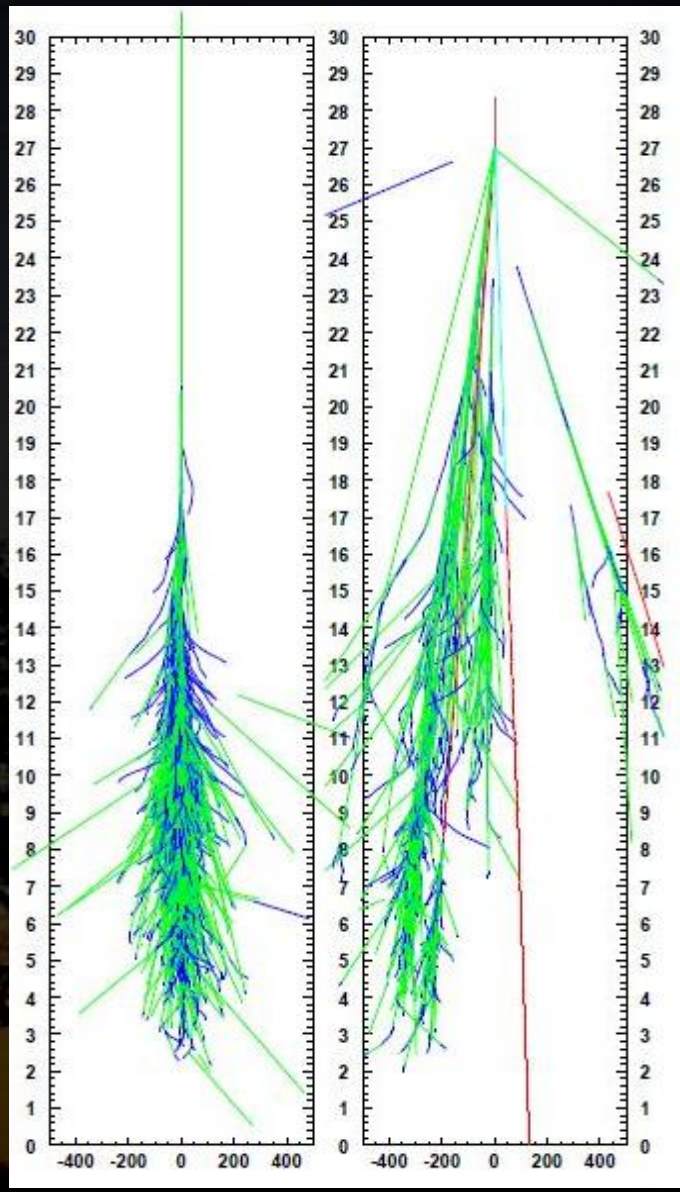
Gamma-ray counts



VERY HIGH ENERGY Γ–RAY ASTRONOMY

Atmospheric Showers

- Primary interaction in the high atmosphere
  - Shower of secondary particles, detectable up to a few 100m
  - 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

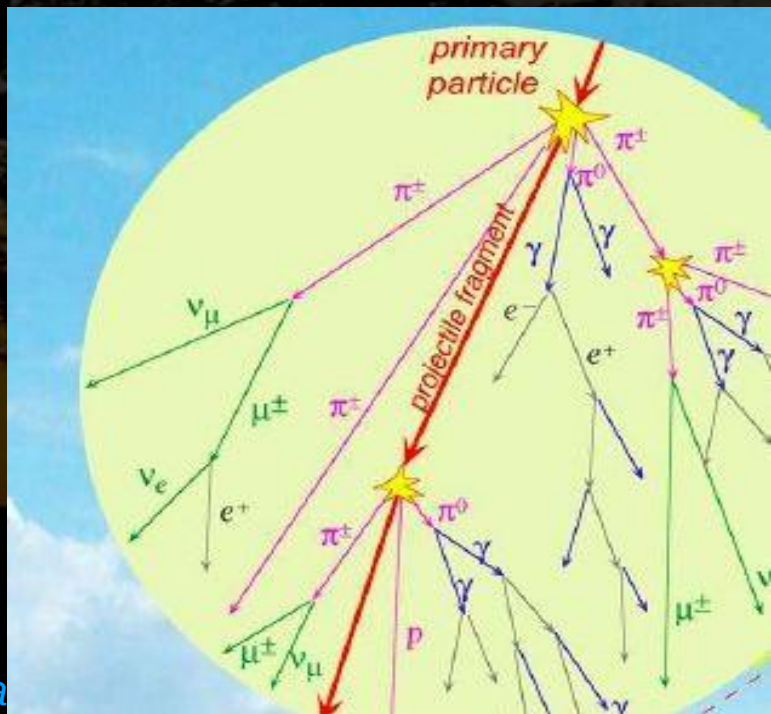
- bremsstrahlung of e±
- Conversion of high energy γ's into e^+e^- pairs
- Multiple scattering

} In the Coulombian field of nuclei

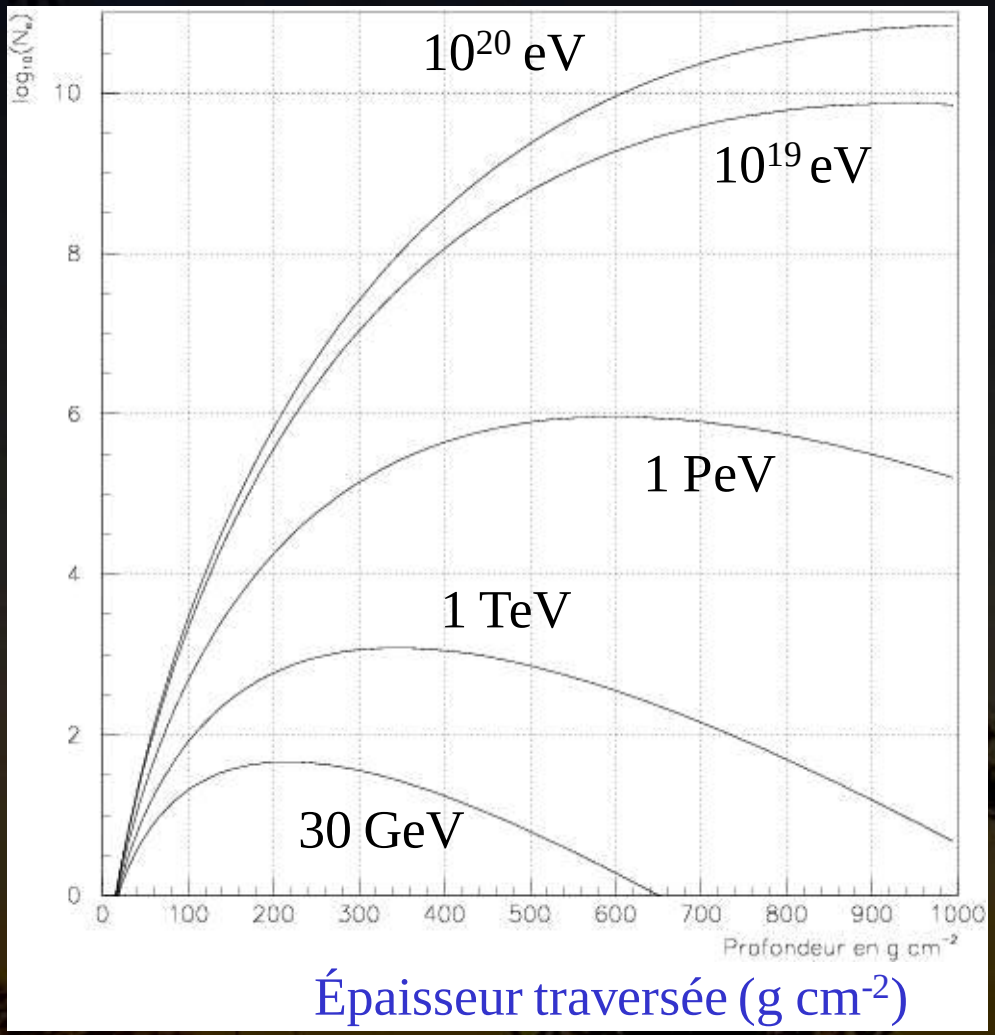
- Energy loss by ionisation or excitation

⇒ 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)



Épaisseur traversée (g cm^{-2})

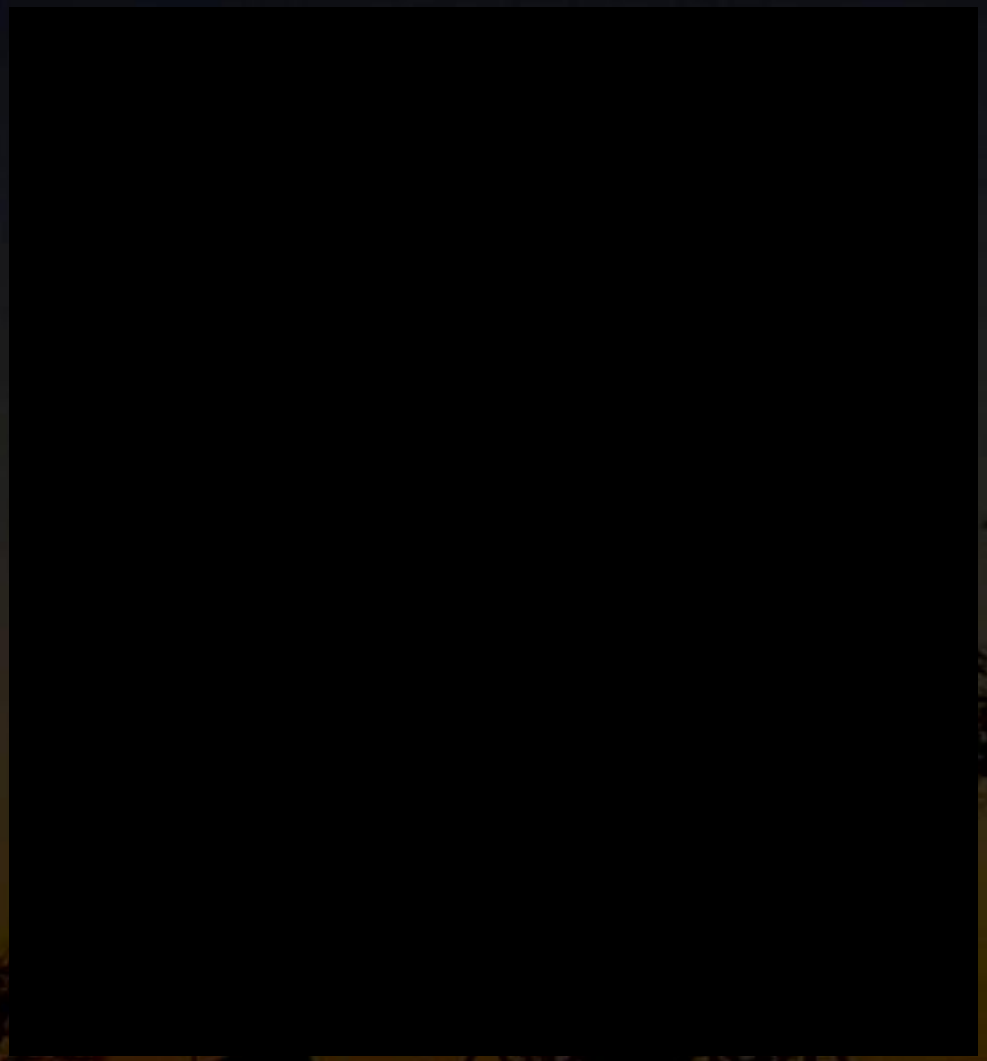
Orders of magnitude

E_0	T_{max} (g cm^{-2})	Altitude (m)	N_e (t_{max})
30 GeV	216	12000	50
1 TeV	345	8000	1200
1000 TeV	600	4400	0,9 10^6
10^{19} eV	936	1200	7,4 10^9
10^{20} eV	1021	0	7,0 10^{10}

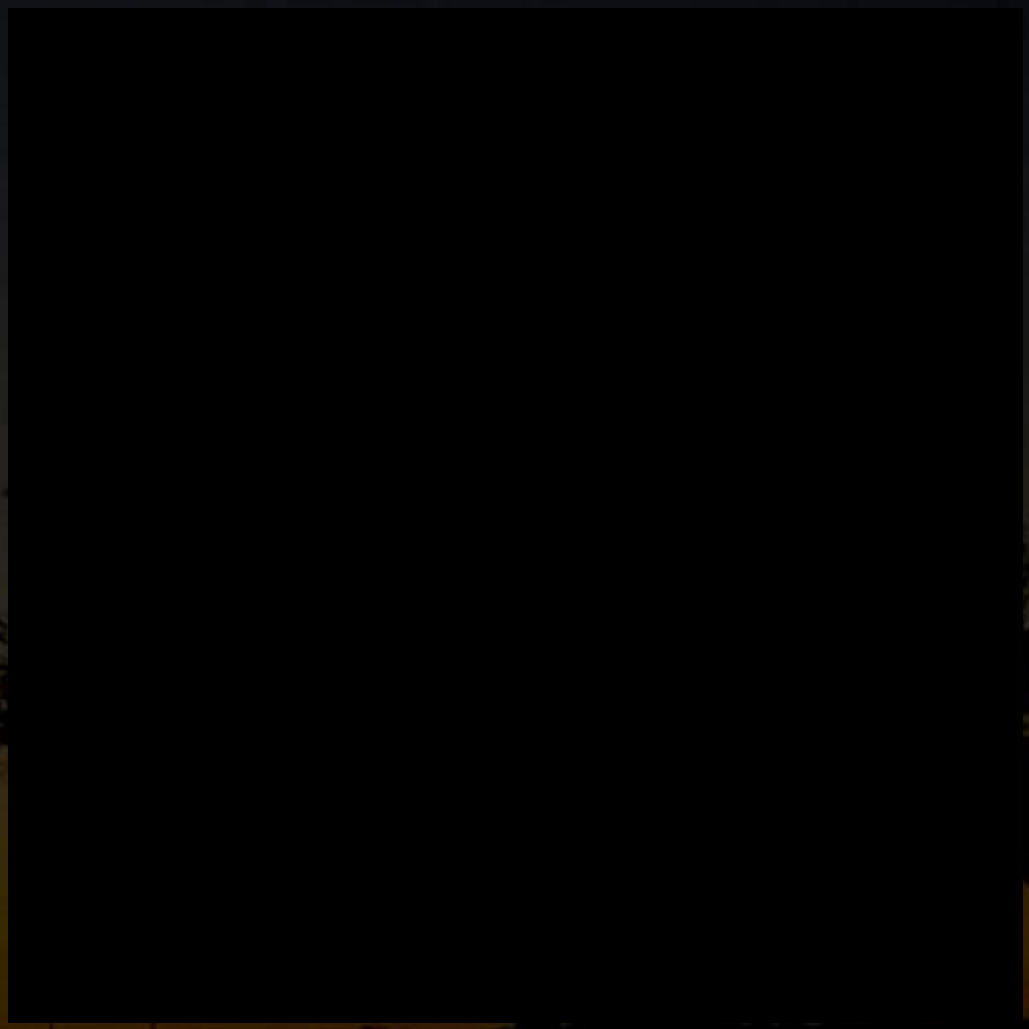
An electromagnetic shower (1 TeV)

- Cerenkov Light

From below



~ 10 km

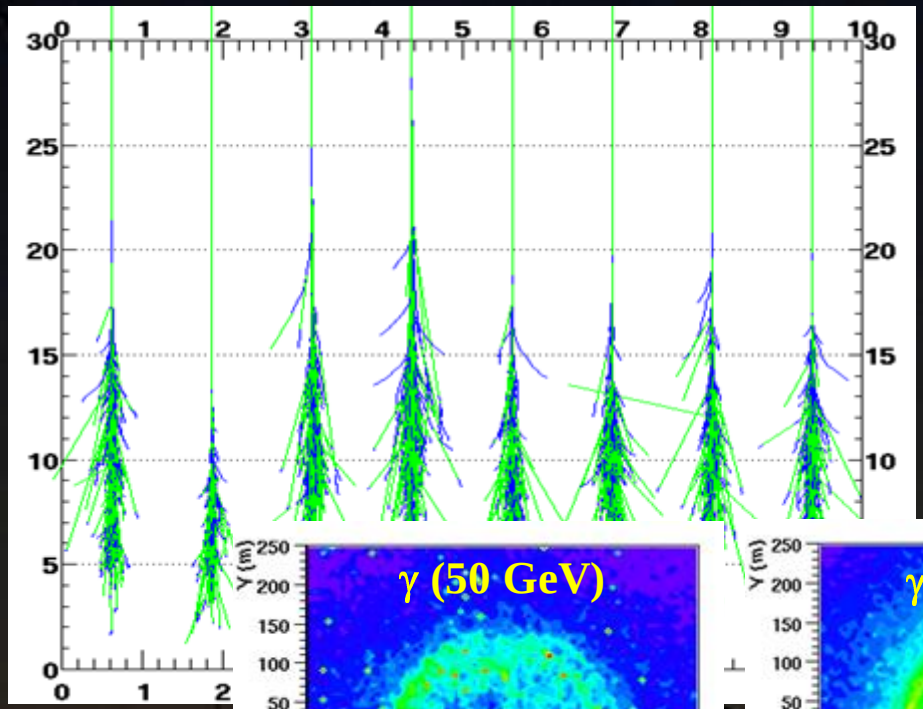


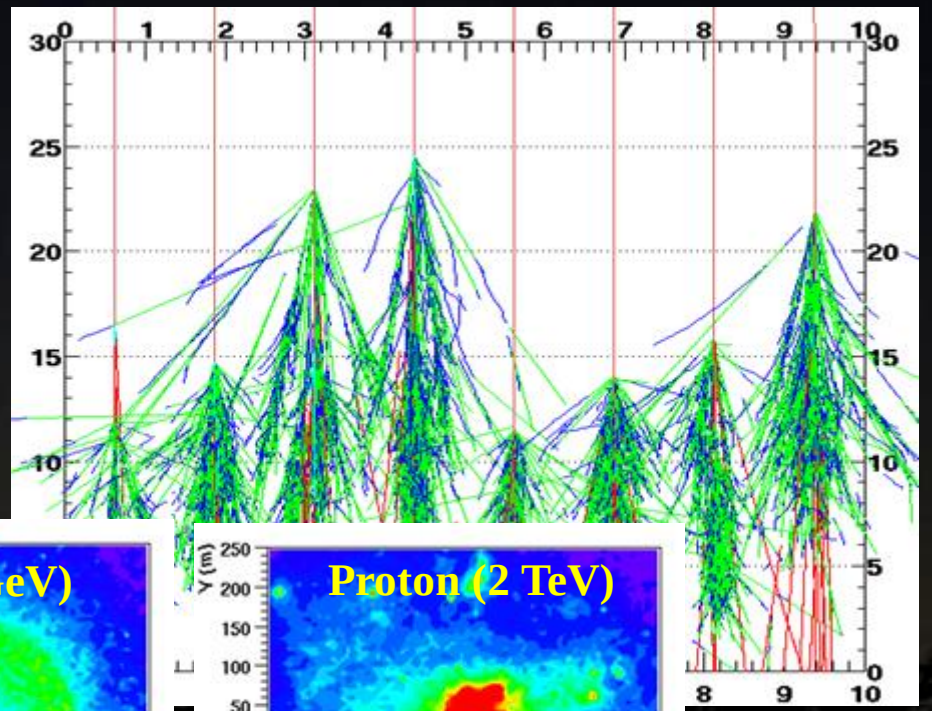
~ 300 m

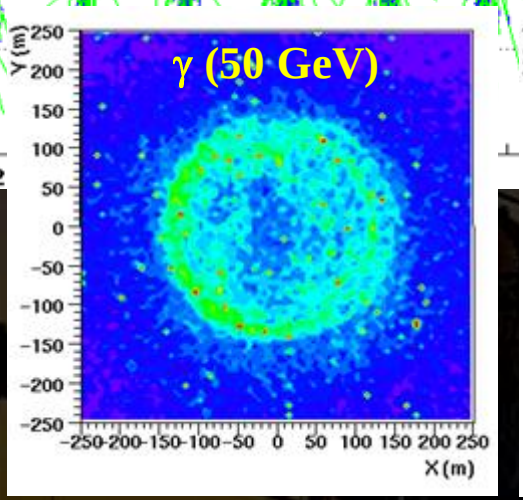
Shower variability

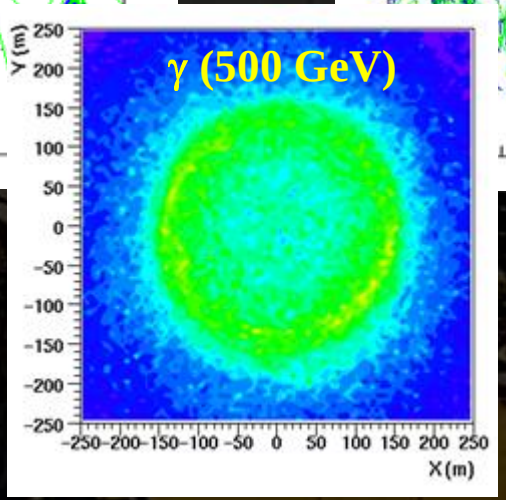
γ, 100 GeV

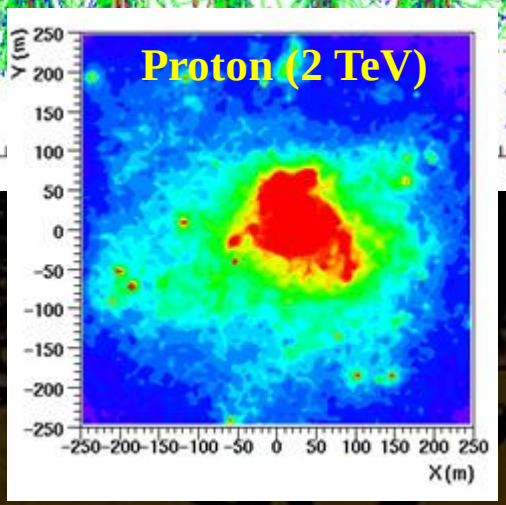
Protons, 500 GeV











- Hadronic shower more fluctuating
- Contain muons

Experimental techniques
(E > 10 GeV)

TIBET

Scintillator or Water

Primary (γ,hadron)

Shower

μ

Hadrons Detector

MILAGRO

Primary (γ,hadron)

Shower

Cherenkov Emission

Cherenkov Telescope

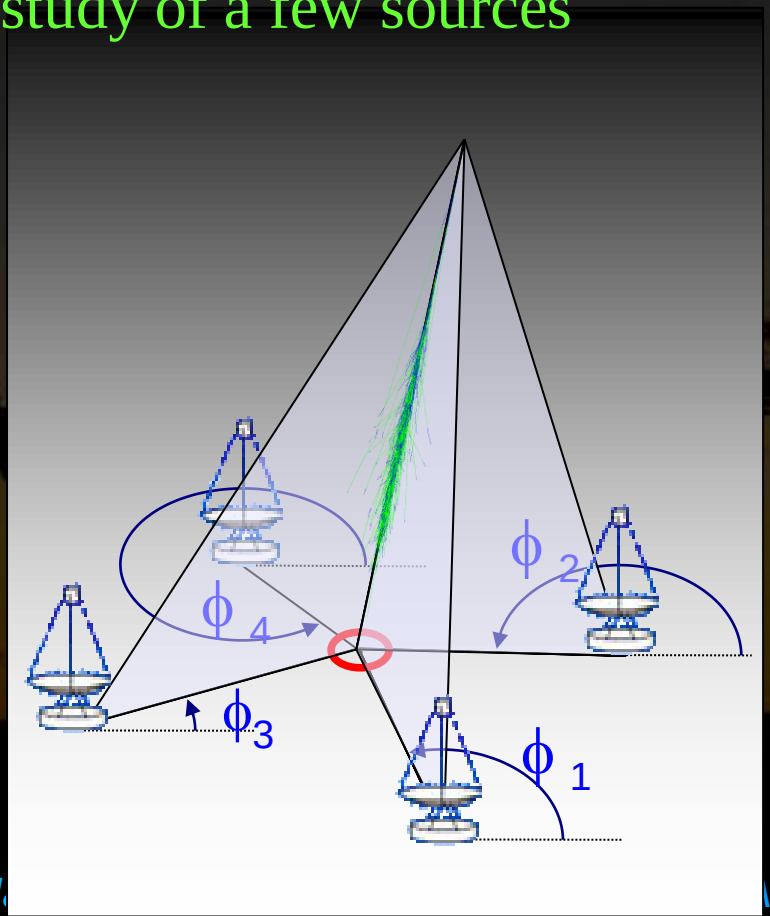
HESS, VERITAS, MAGIC, CANGAROO

STACEE, CELESTE, SOLAR II, GRAAL

2 Complementary Techniques

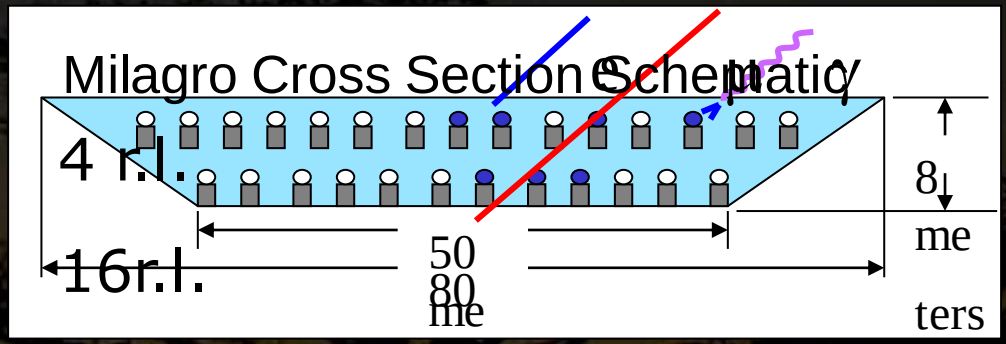
- Atmospheric Cherenkov Telescopes:
  - Small F.O.V.
  - Low duty cycle
  - High rejection
  - High resolution

Detailed study of a few sources



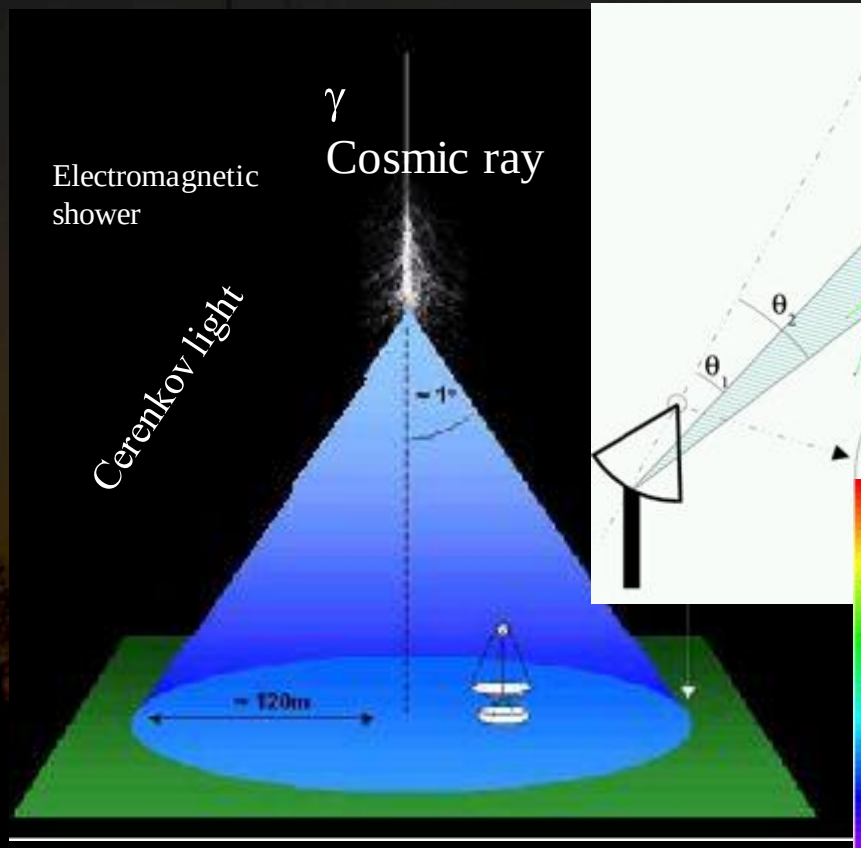
- Sampling experiments (Water Cerenkov, Particle Arrays,…)
  - Large F.O.V.
  - High duty cycle
  - Poor rejection
  - Poor resolution

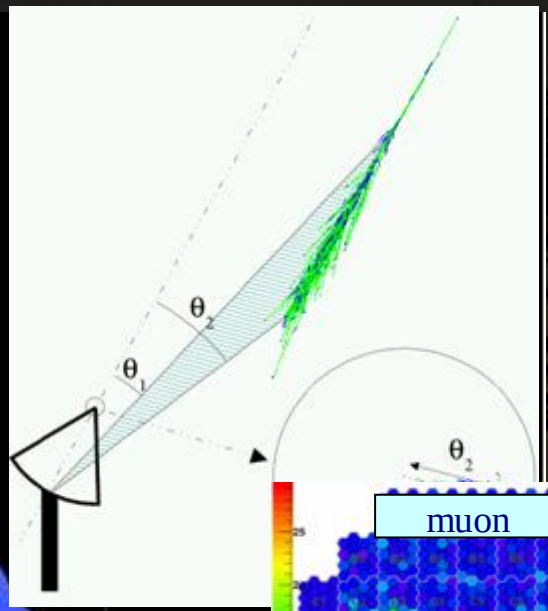
Long term survey instruments



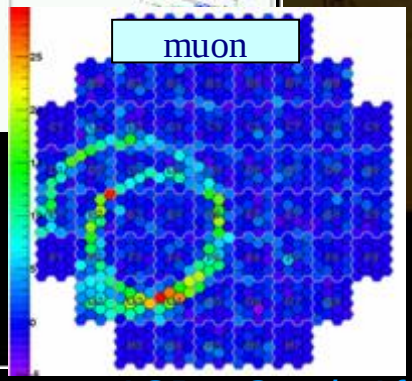
Atmospheric Cerenkov Imaging

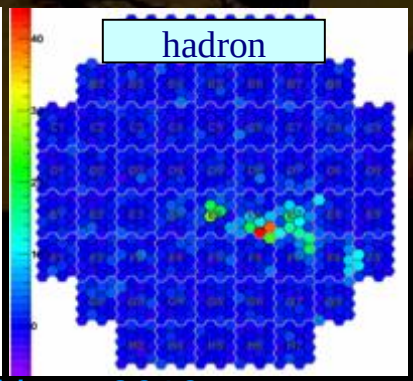
- Cerenkov light pool R ~120 m
- Image of the shower on a fast ($\Delta T \sim 2ns$)
- Large effective area (10^5 m^2) even with modest size reflector

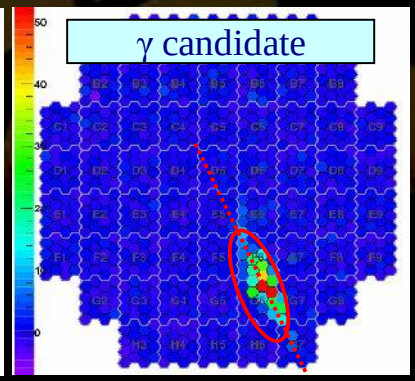




- Key parameter: speed (< 10ns)
- Image shape used in γ/hadron separation

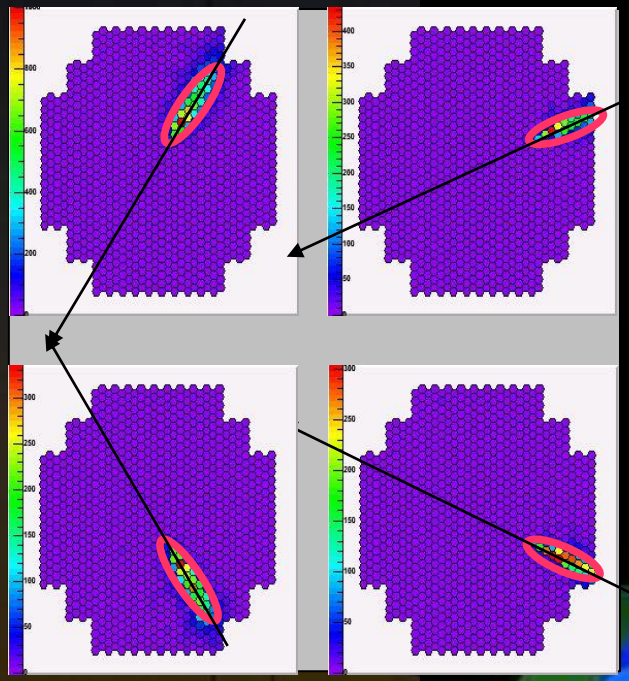


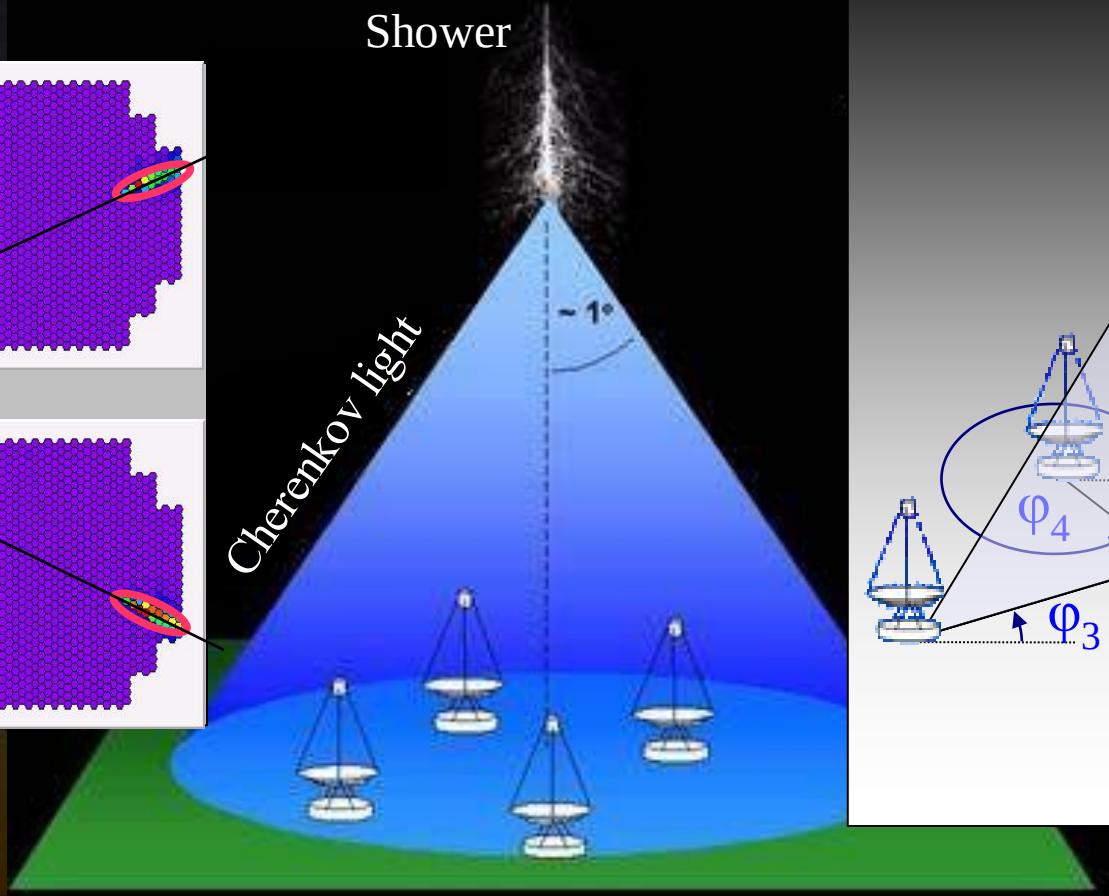


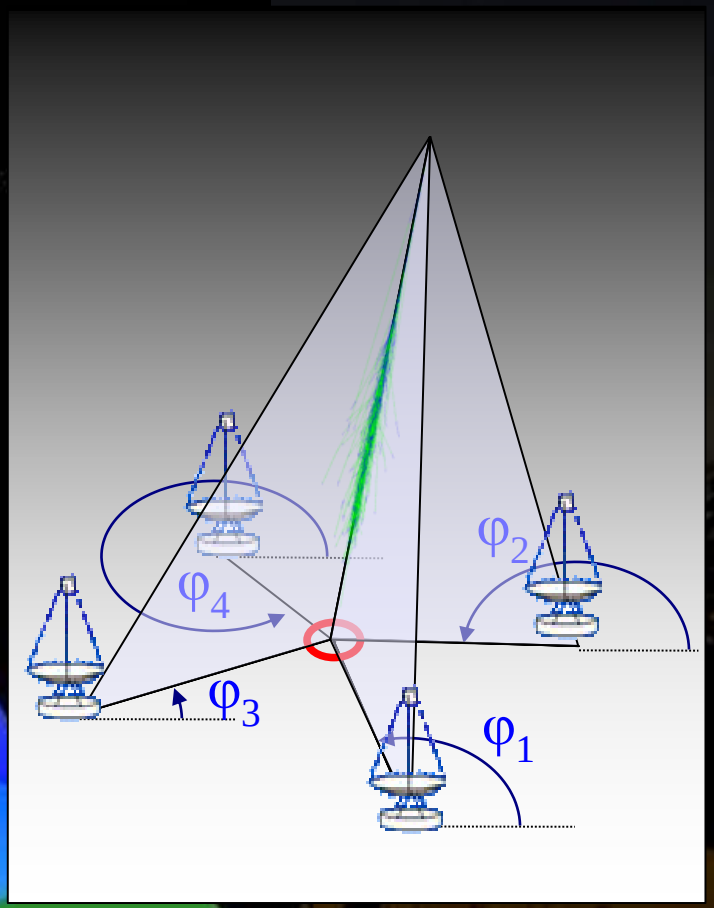


Stereoscopy

- Geometrical reconstruction of direction from intersection of major axis (angular space)
- Impact reconstruction from intersection of planes (Telescope, φ_i) on ground





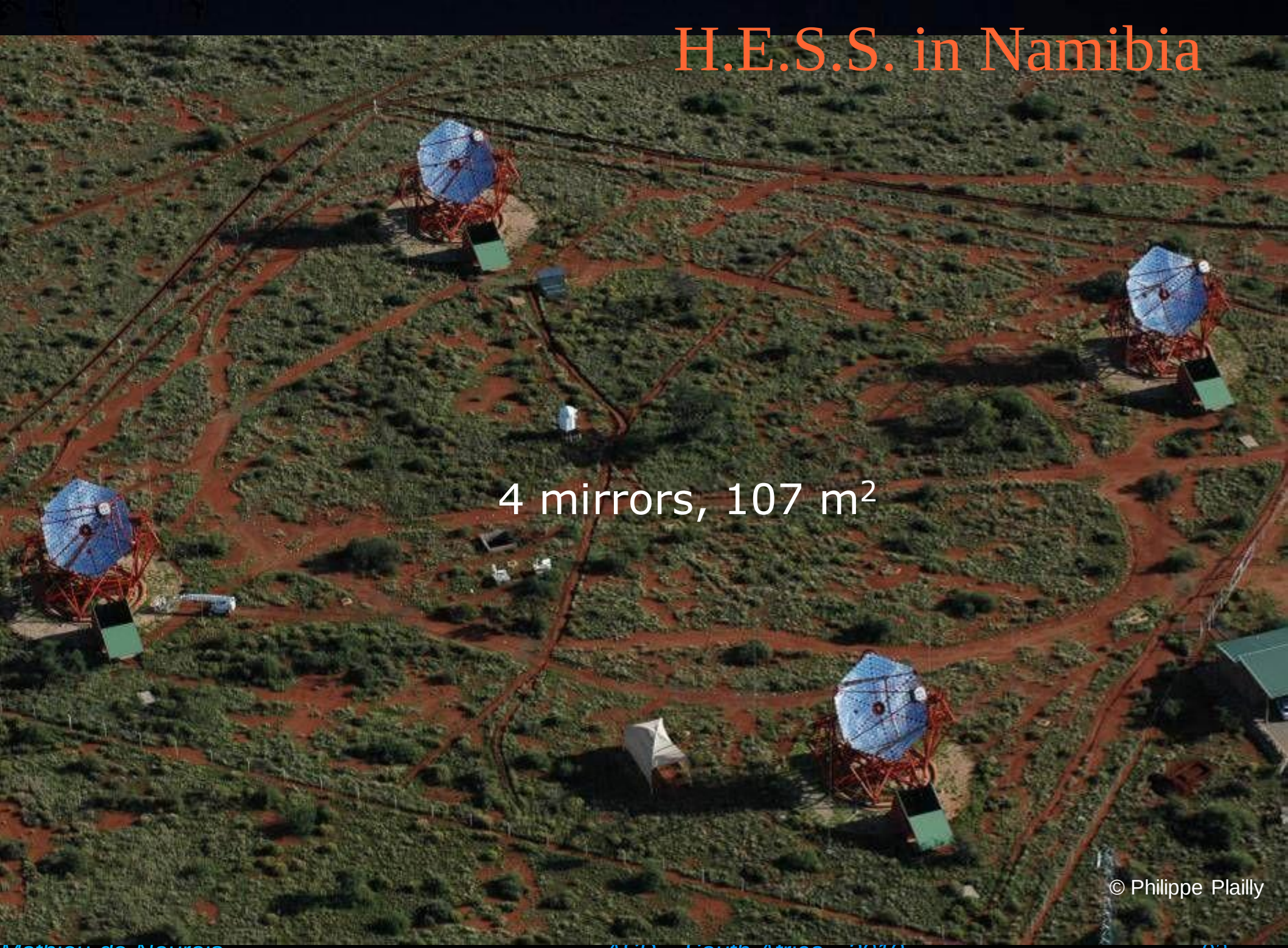


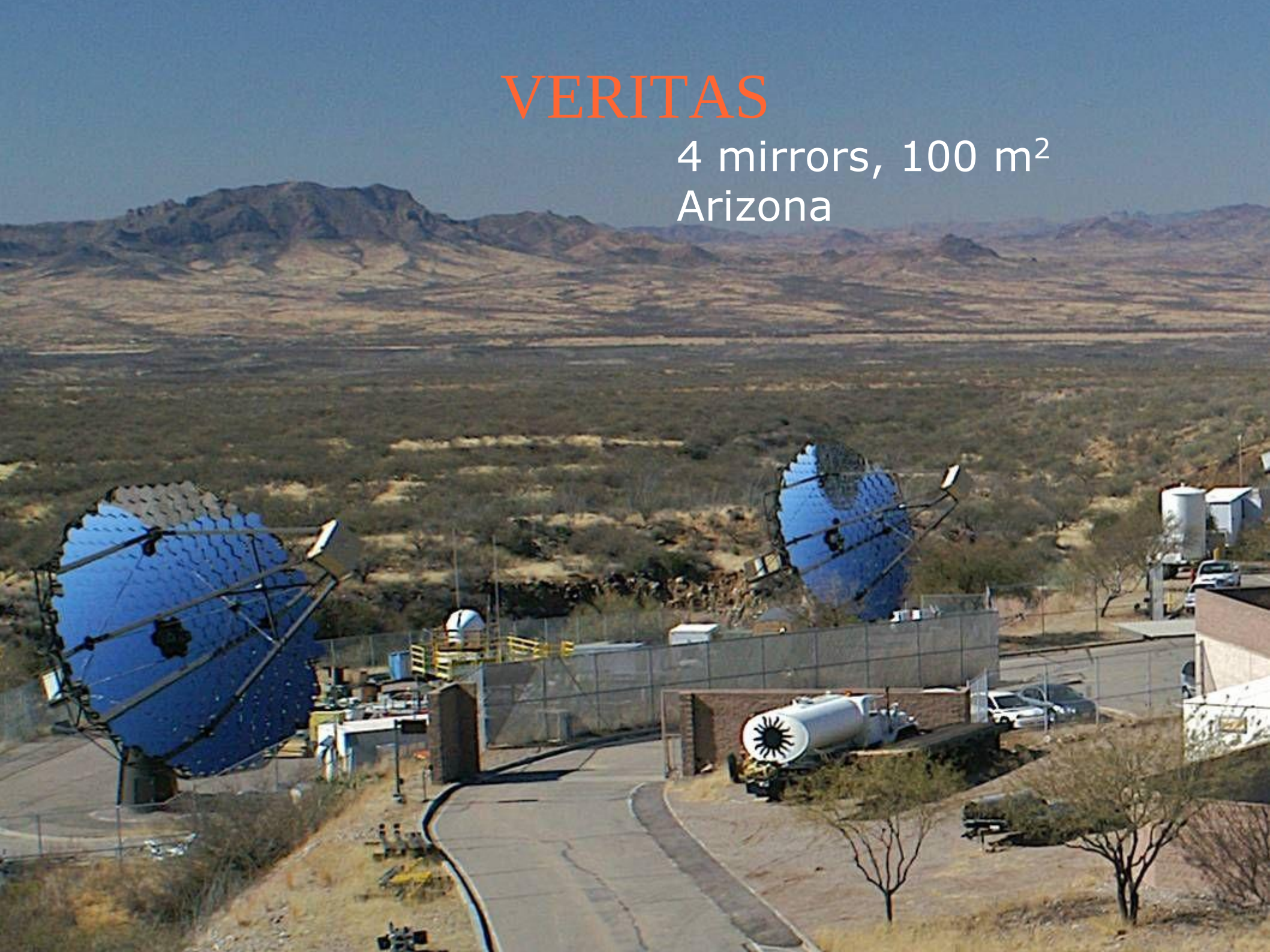
- Energy from comparison of image intensity with simulations
- Discrimination from image shape (width)

VHE γ-Ray world

MAGIC @ La Palma

H.E.S.S. in Namibia




VERITAS
4 mirrors, 100 m^2
Arizona

MAGIC II – Canary Island (commissioning)

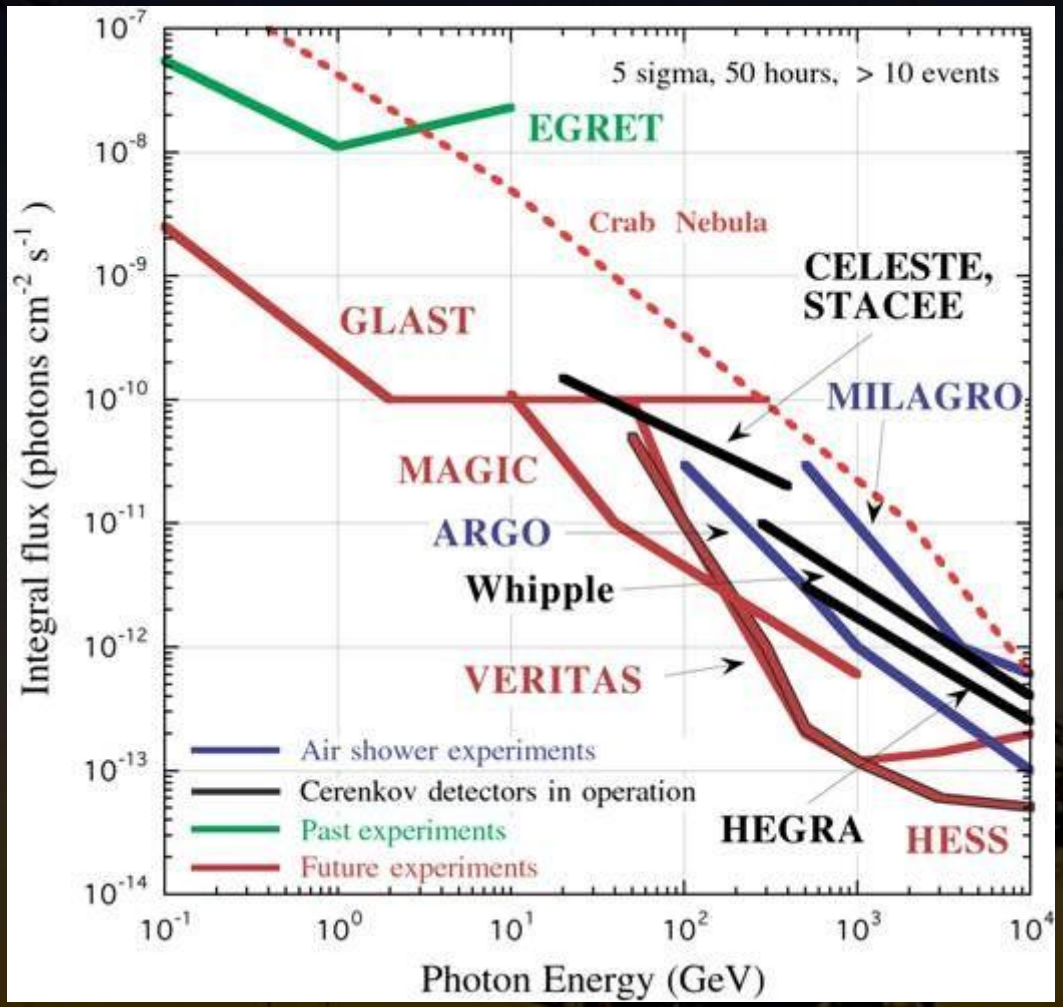
H.E.S.S. Phase II

One additional 600 m^2, early 2011

Imaging telescopes

Experiment	# Telescopes	Mirror size (m)	Site
CANGAROO III	4	10	Australia
HESS I	4	12	Namibia
MAGIC	1→2	17	Canary Islands
VERITAS	4	12	Arizona
HESS II (2011)	4 (HESS I)+1	28	Namibia

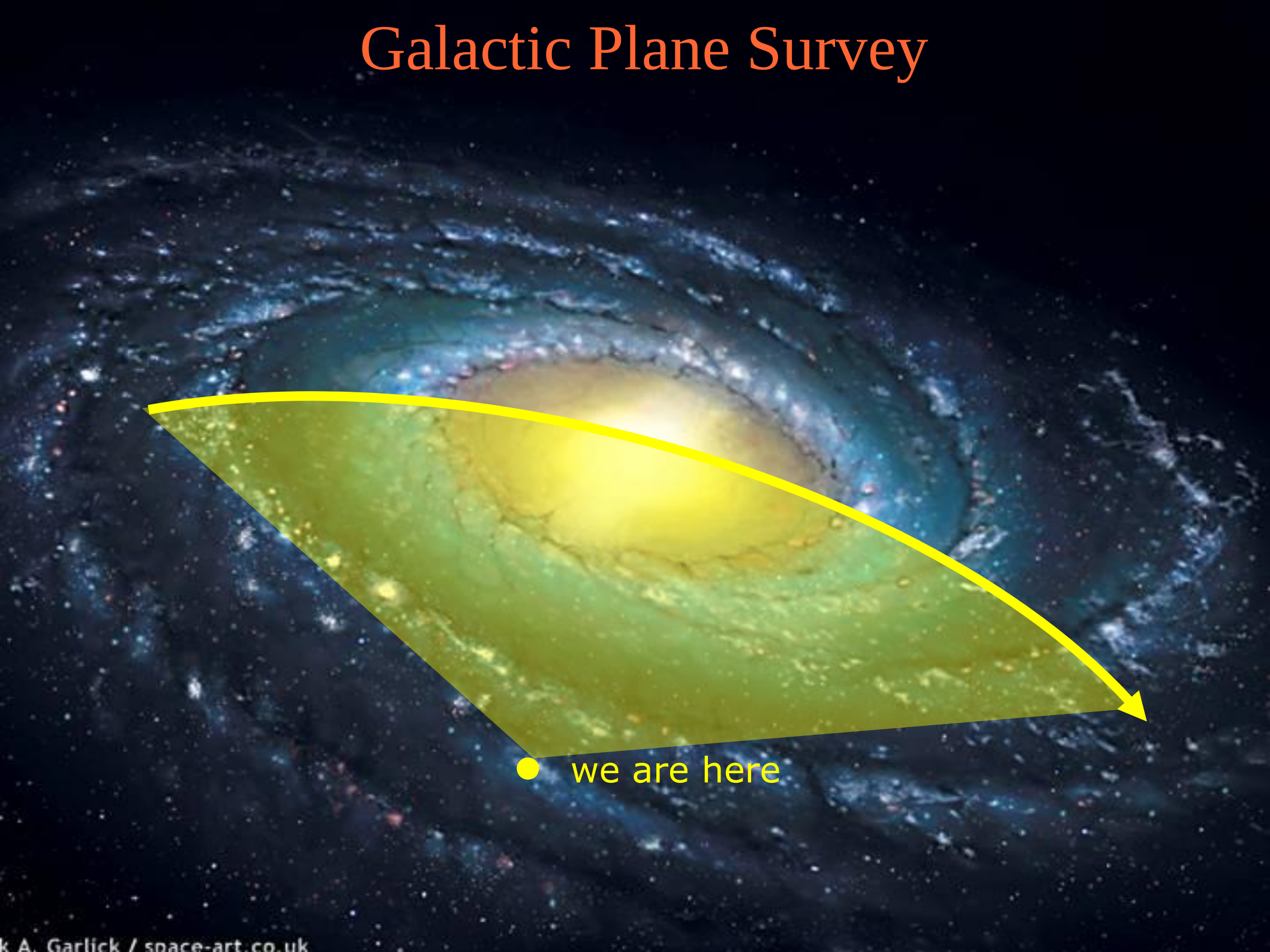
Comparison with Satellites



	Ground	Space
Angular Resolution	~ 0.1	1 $\Rightarrow$ 0.1
Energy Resolution	~15%	~10%
Effective Area	10^5 m^2	~ 1m^2
FOV	a few deg.	Half sky
Rejection	~ 10^2, limiting factor	Excellent

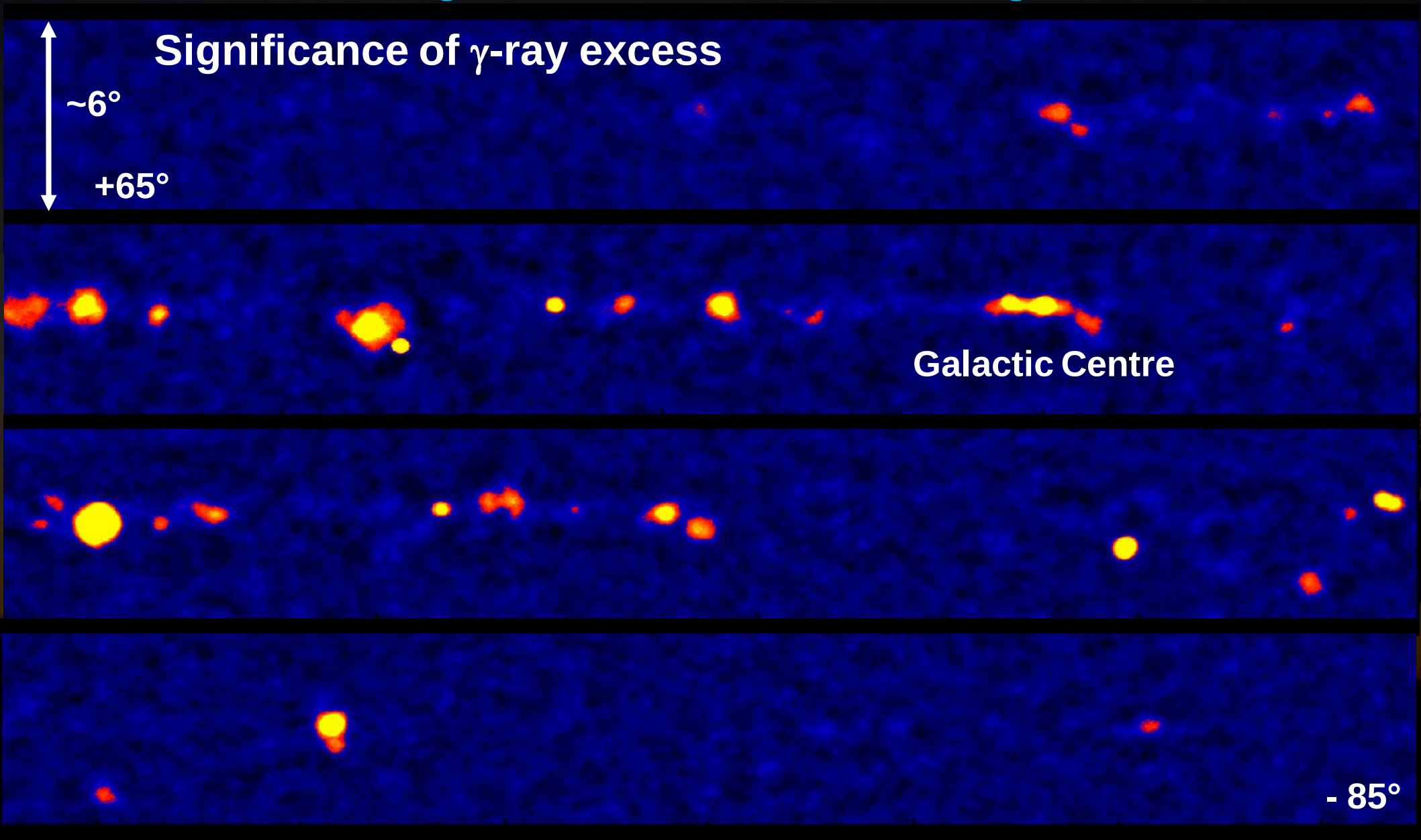
- Two techniques are very complementary

Galactic Plane Survey



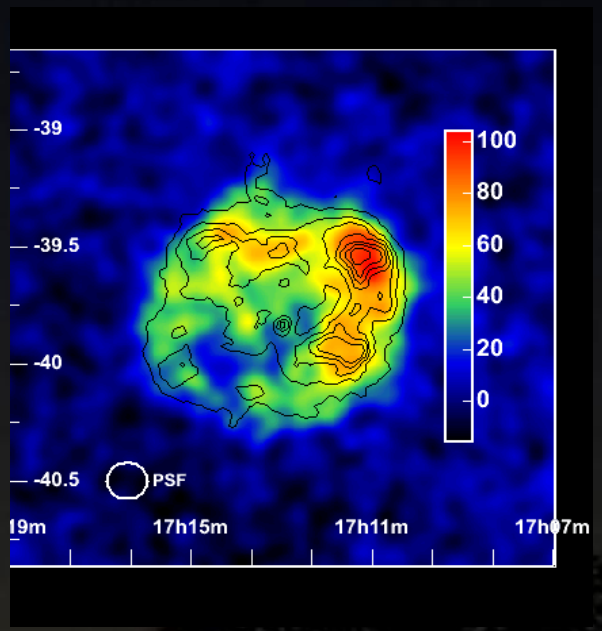
HESS Galactic Plane Survey

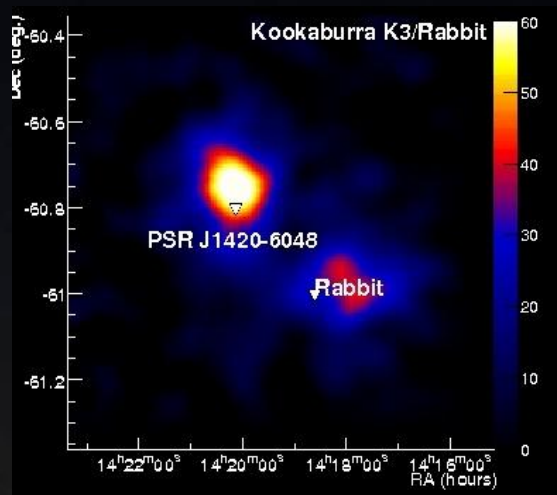
- 52 TeV sources, mostly extended
- Vertical Scale : 0.3 deg RMS ~ Molecular Gaz ⇒ Young sources

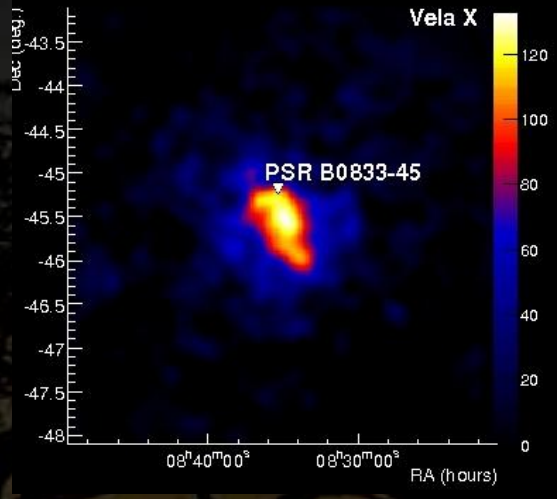


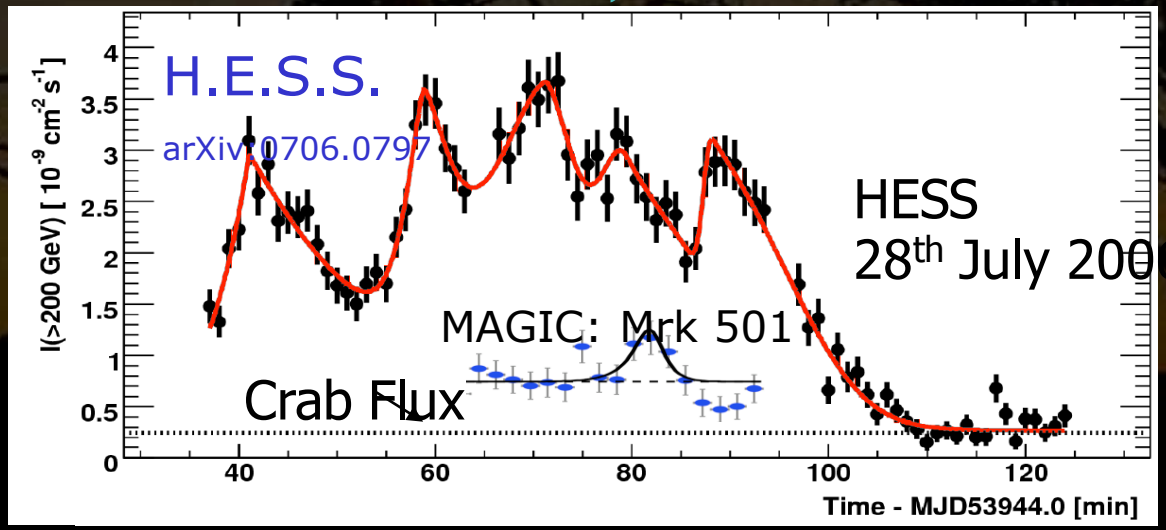
Results

- 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,
  - ....



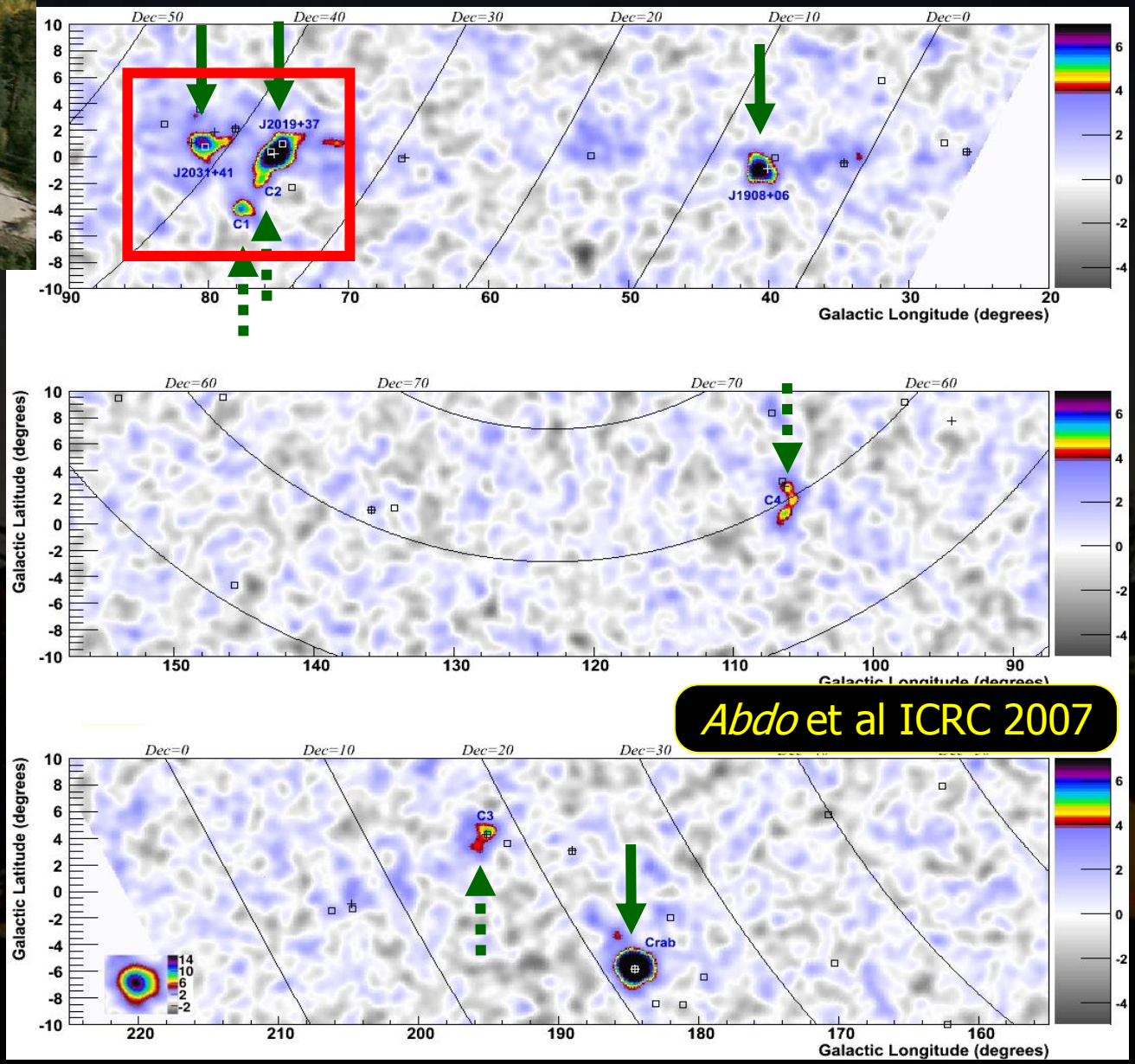






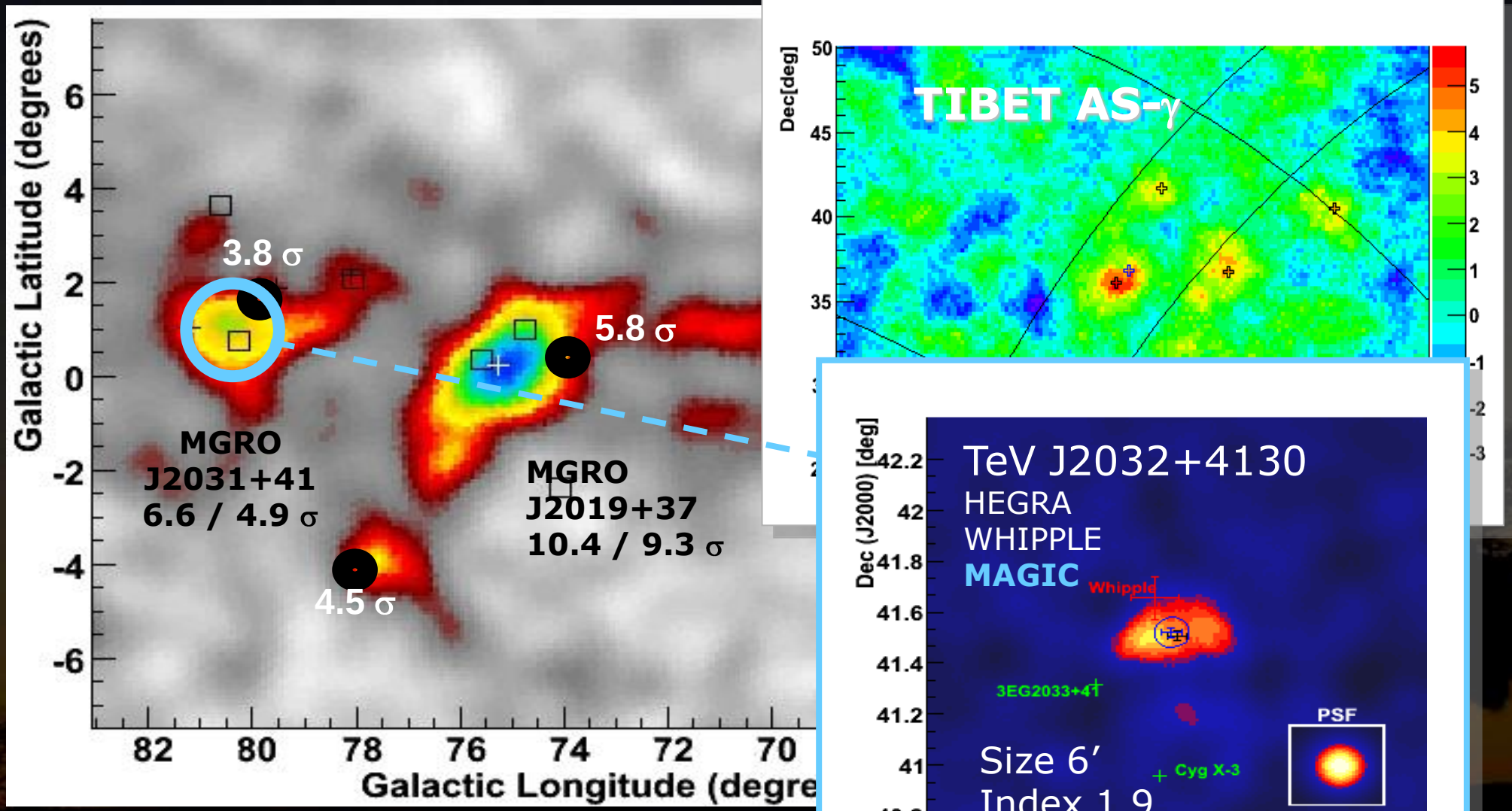
Milagro Northern Sky Survey

- 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



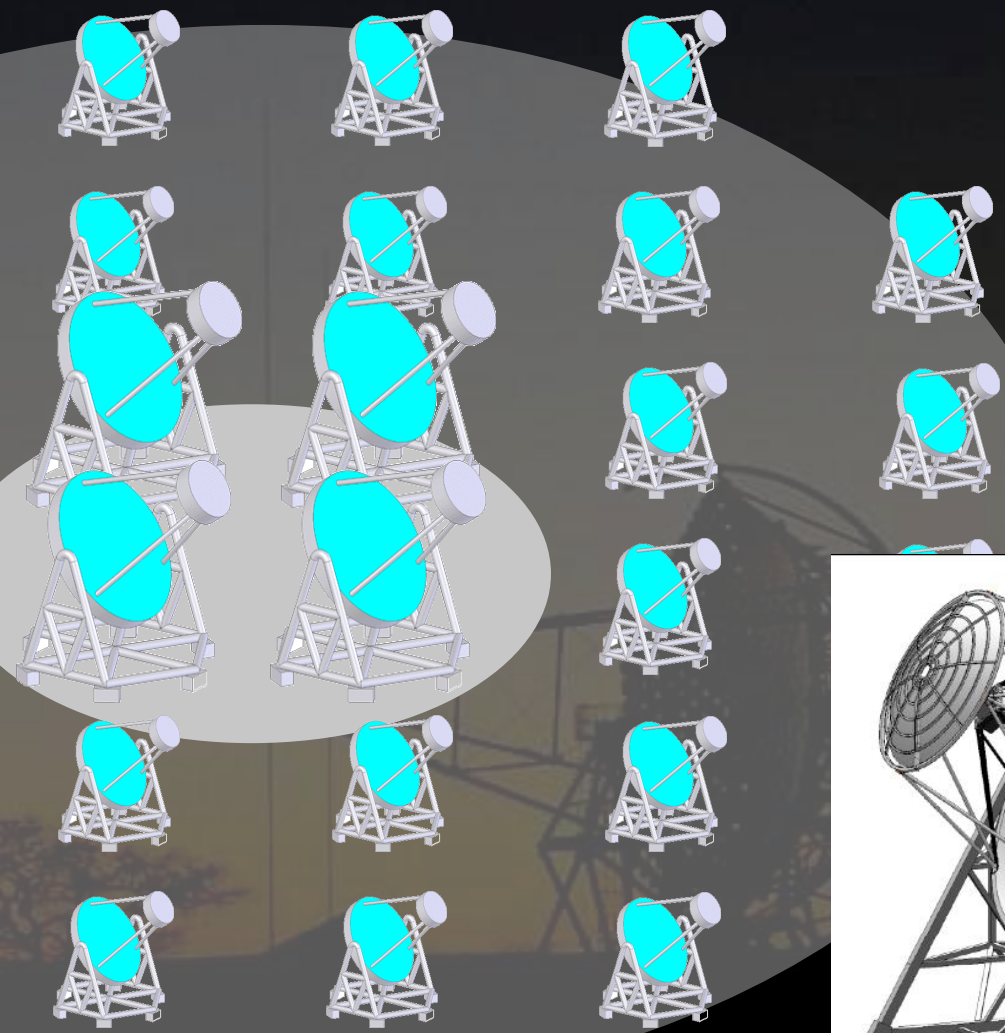
The Cygnus region

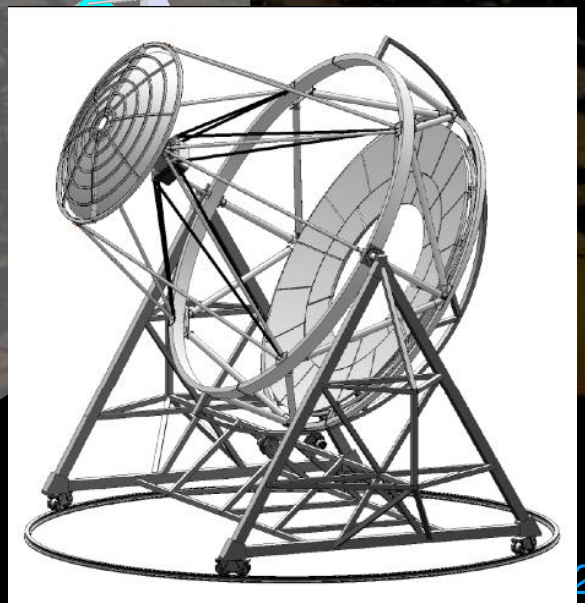
- Convergence of several techniques

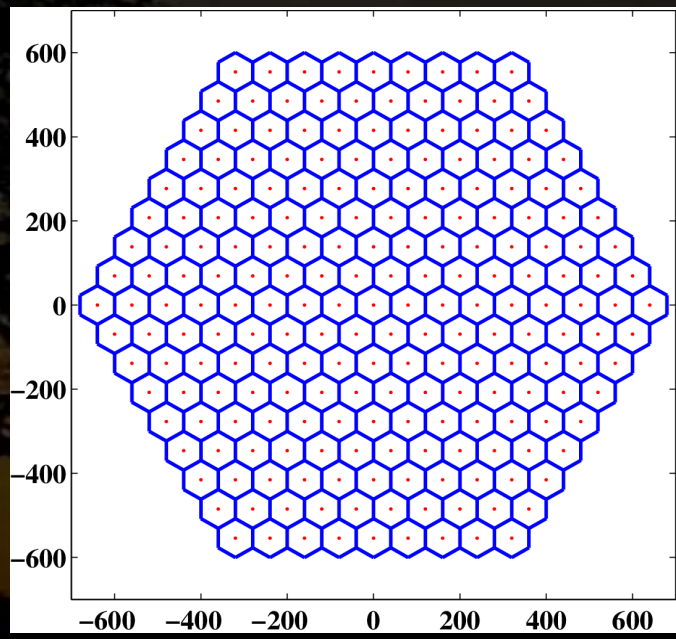


Longer term perspective (I)

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

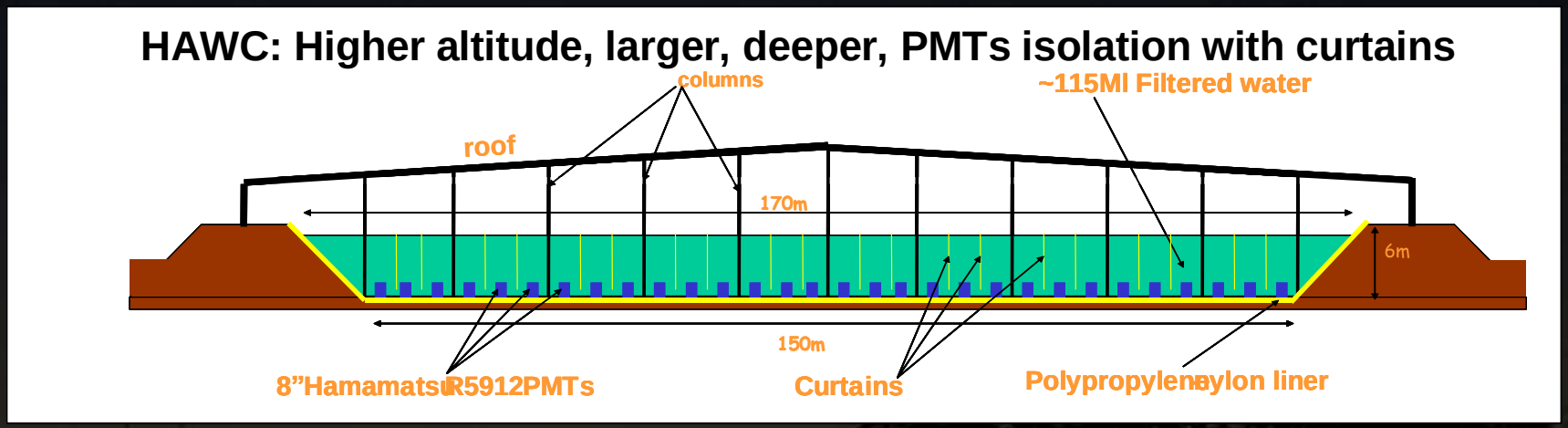




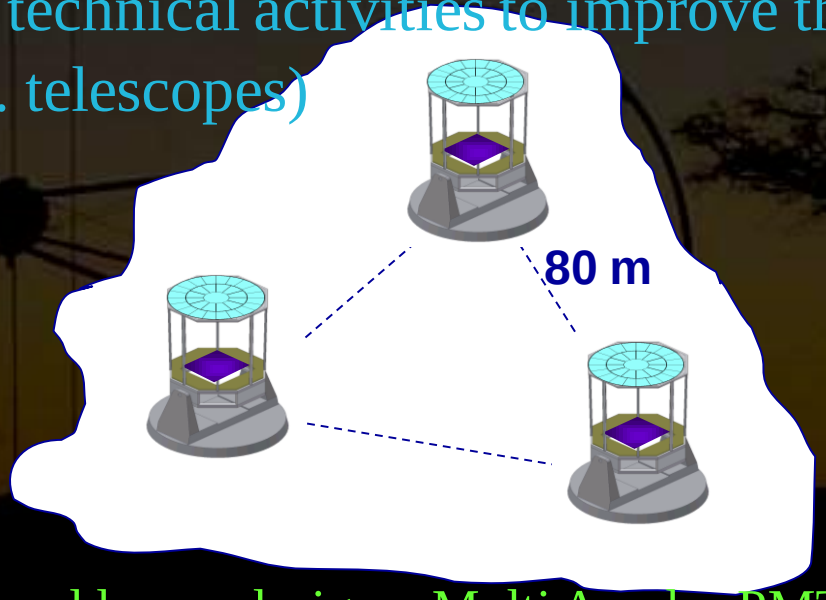


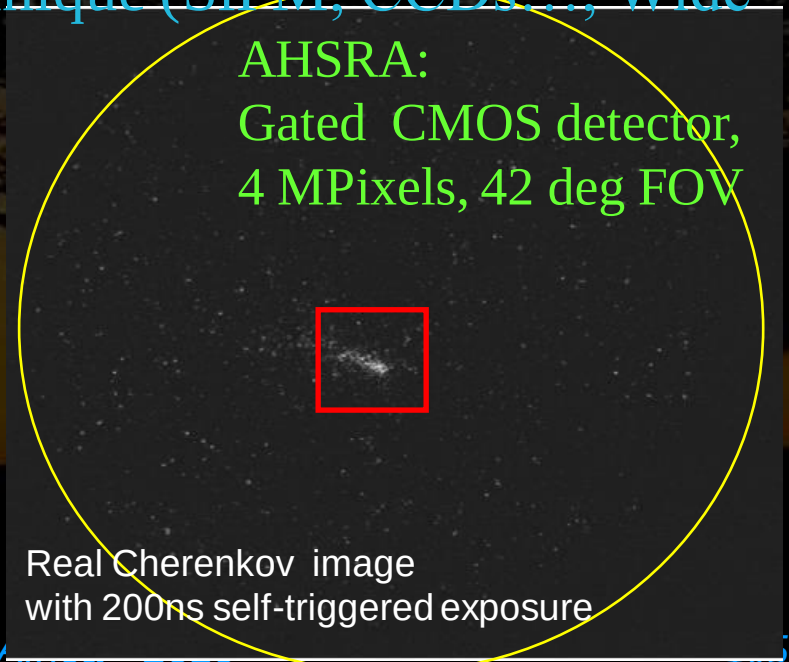
Longer term perspective (II)

- 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)

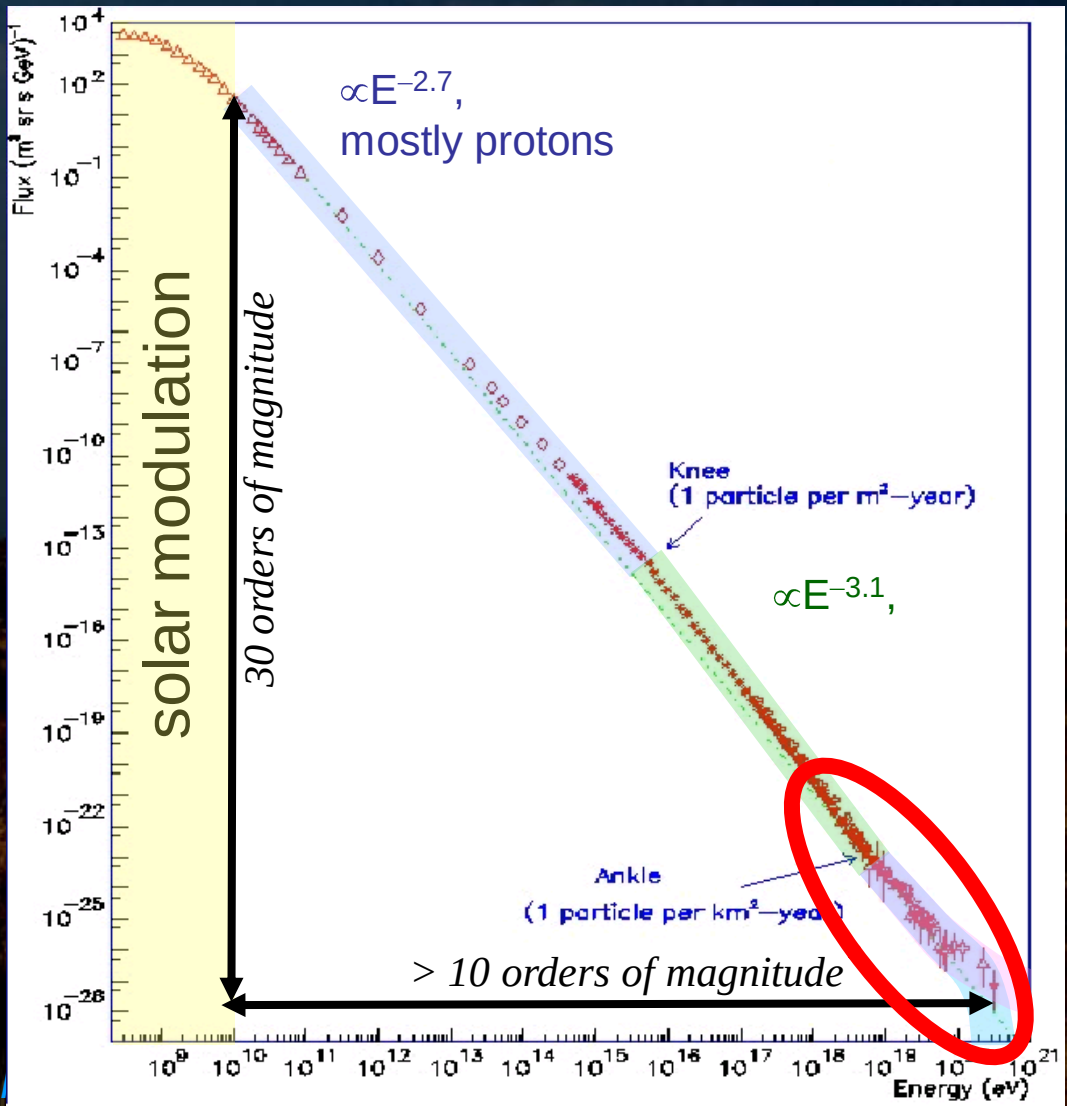




GAW : Fresnel lenses design – Multi Anodes PMTS

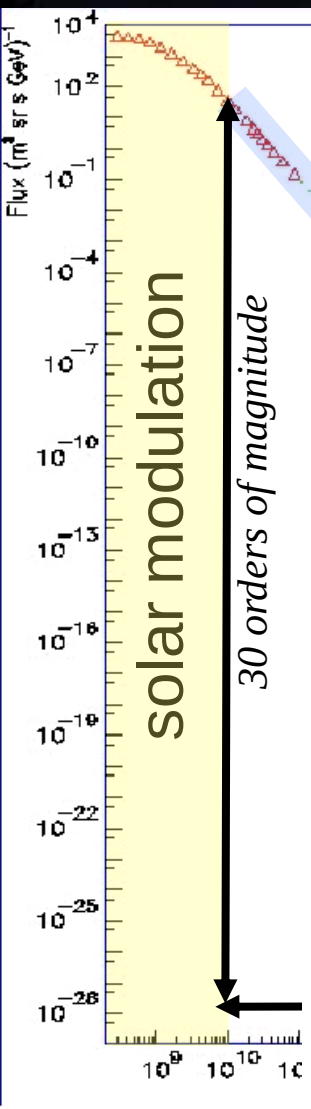
ULTRA HIGH ENERGY COSMIC RAYS (UHECR)

- Energy spectrum
- Composition
- Direction

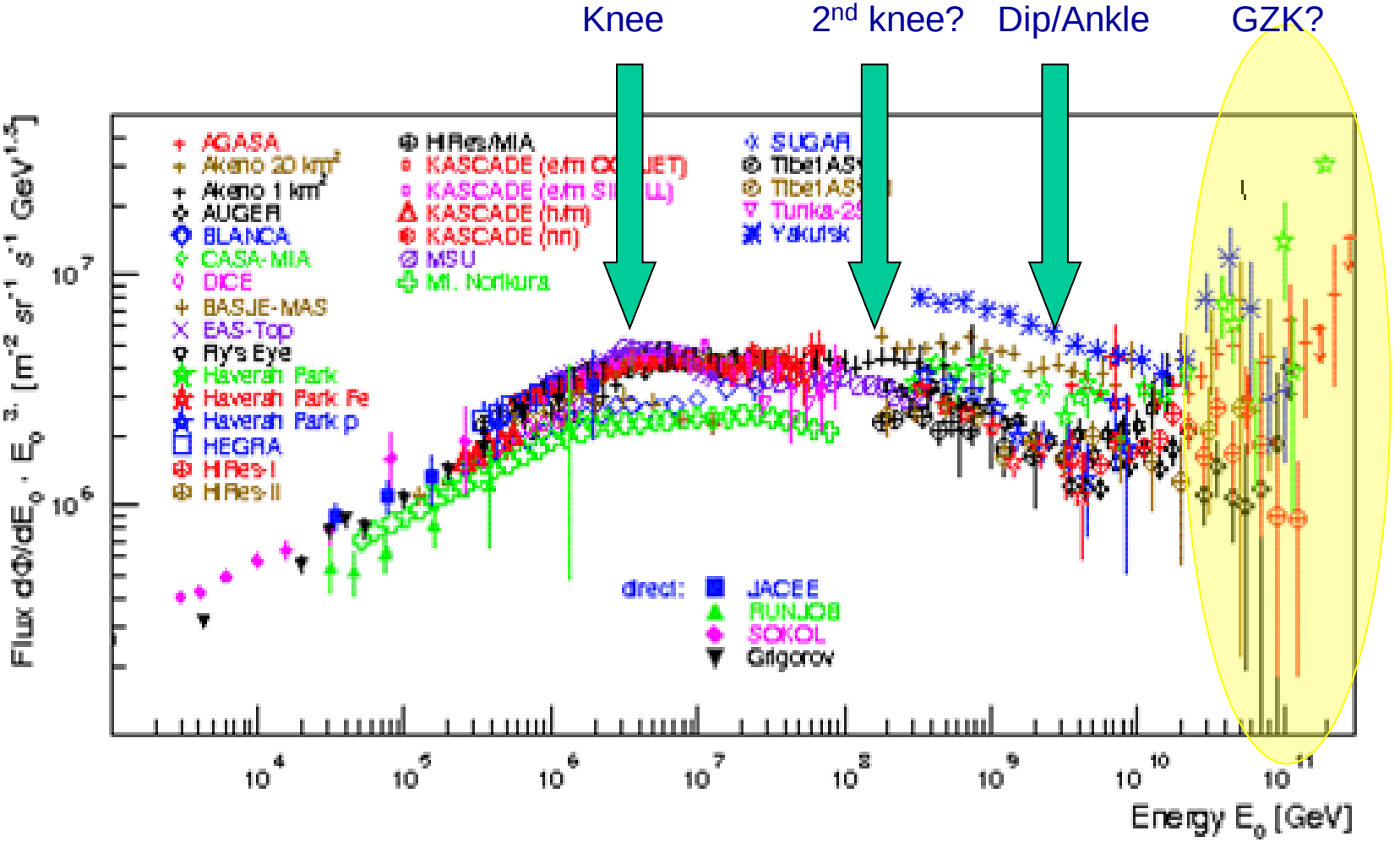


Structures in the CR spectrum

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



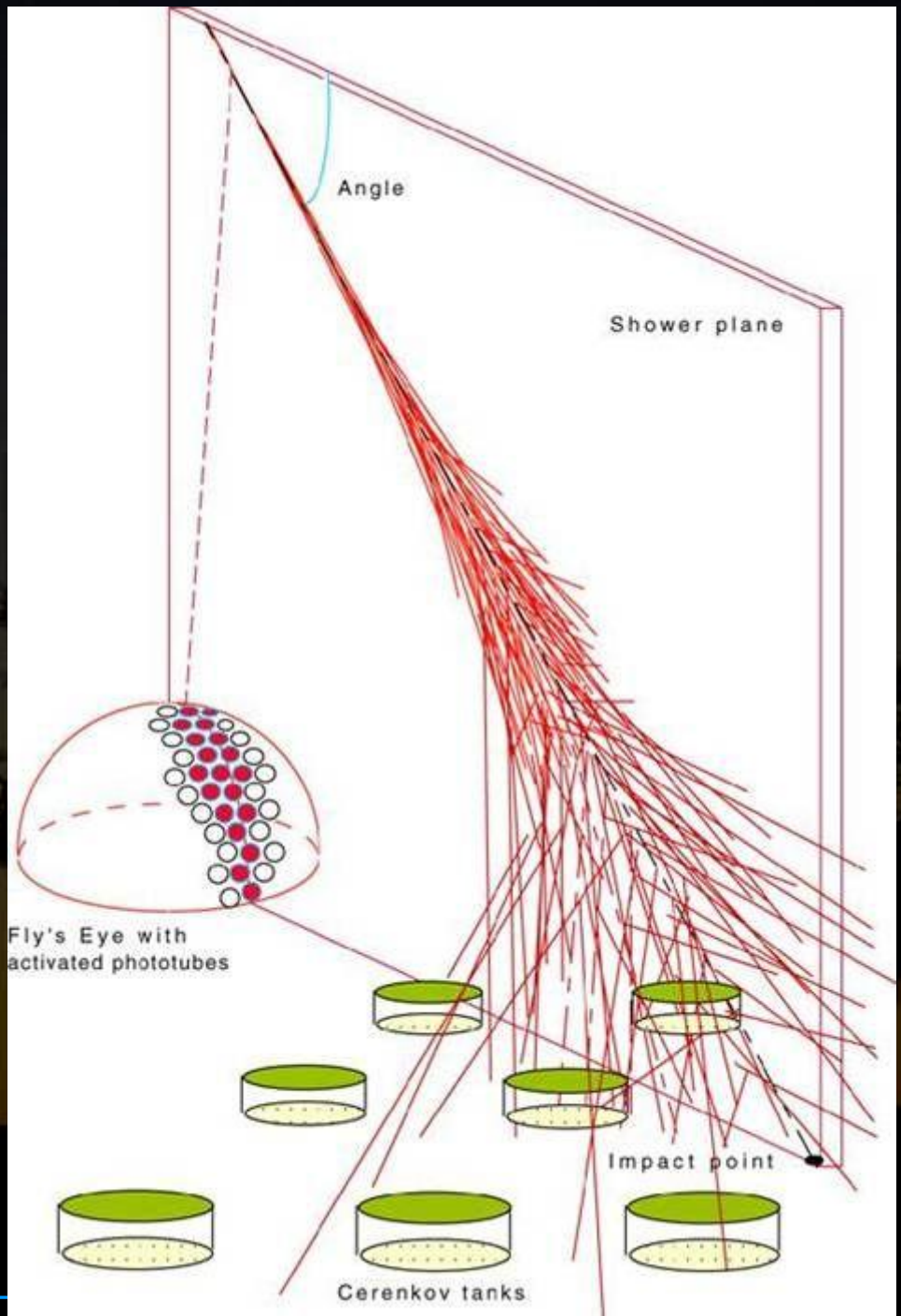
$\propto E^{-2.7}$,
mostly protons



Detection for giant showers

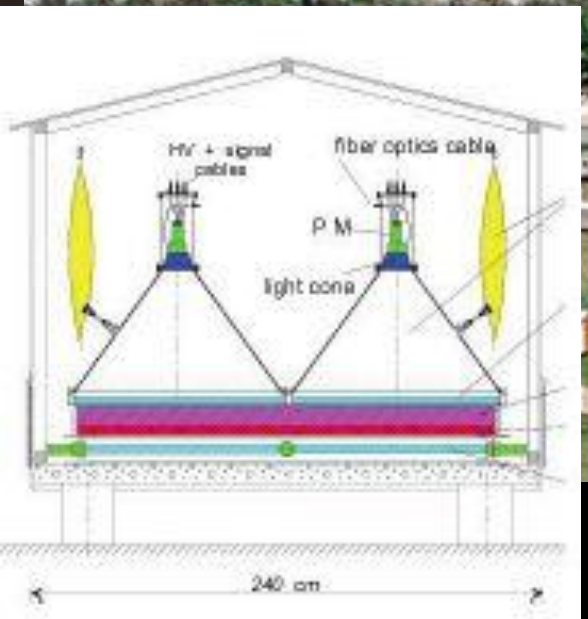
- 2 complementary techniques:

- SD: Detection of charged particles reaching the ground
  - ☑ 24h/24 duty cycle
  - ☒ Shower tail measurement (degraded information)
- FD: Detection of fluorescence light emitted by nitrogen excitation
  - ☑ Direct development measure
  - ☒ Night without moon (10%)



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

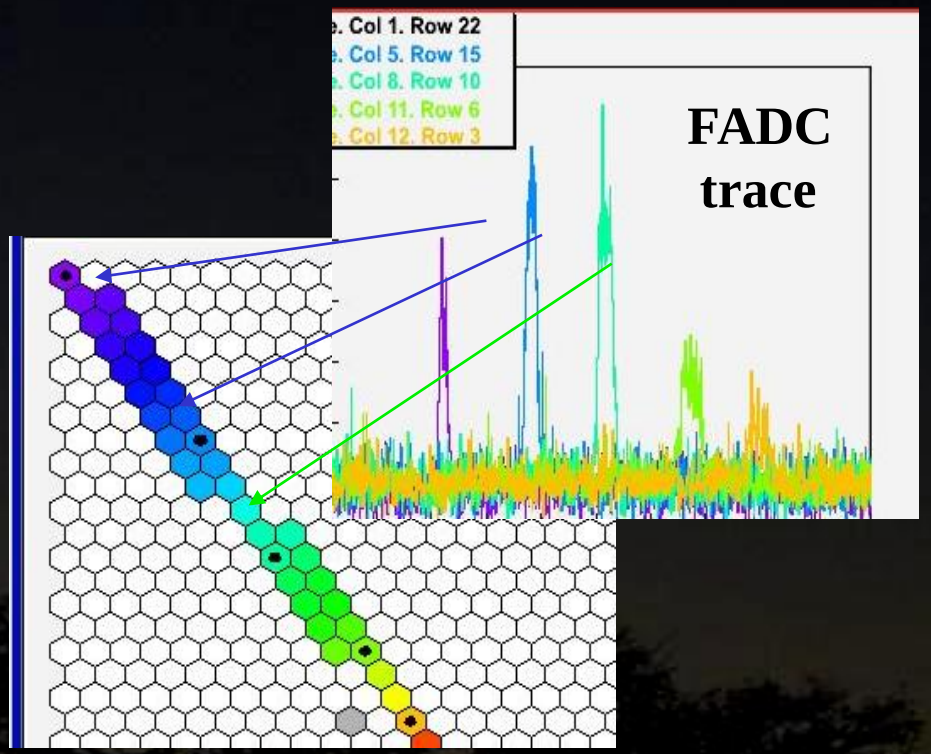


- Reconstruction relies on simulation
  - Hadronic Models
  - Detector geometry

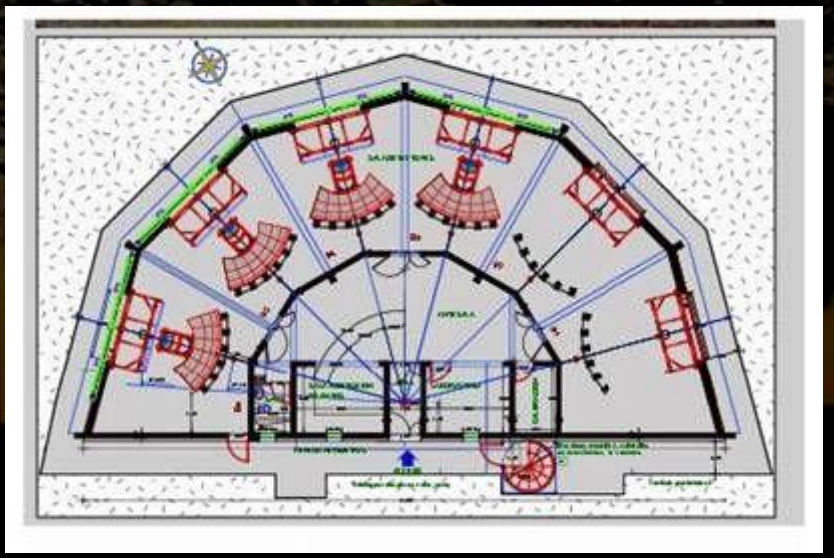
⇒ Poorly controlled systematics

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



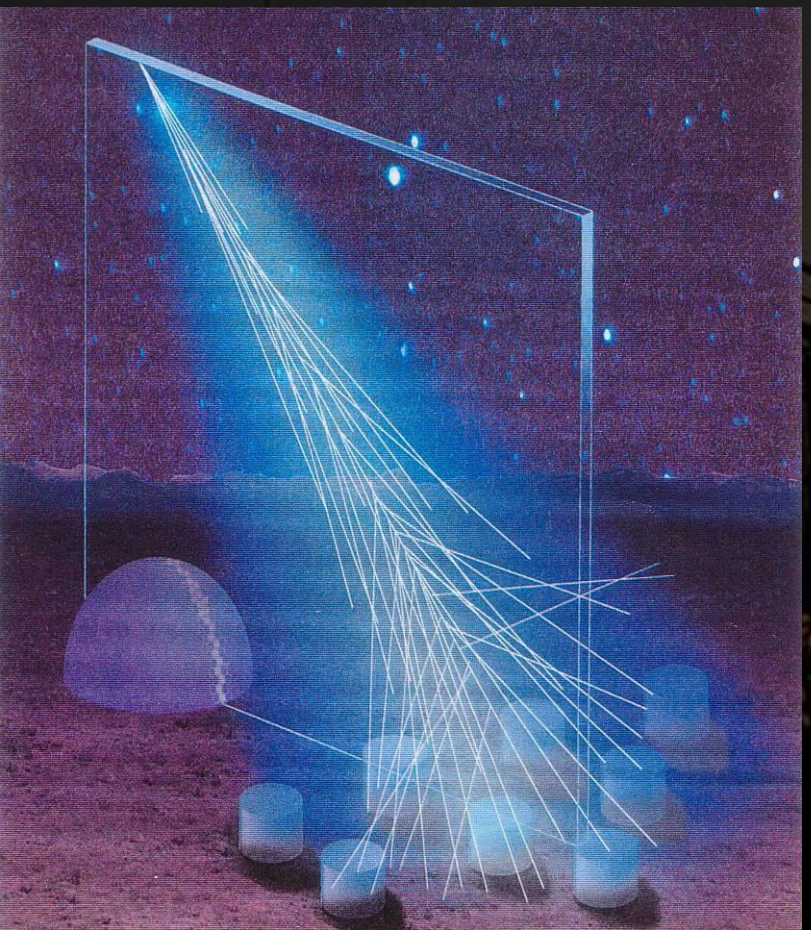
- Stereoscopy ⇒ simple geometric reconstruction. Time sequence also usable
- Problems:
  - Fluorescence light yield poorly known. Depends on composition, humidity, ...
  - Atmospheric transparency
  - Need to subtract forward Cherenkov

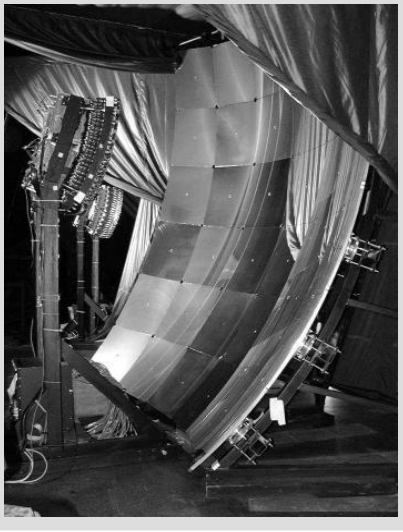


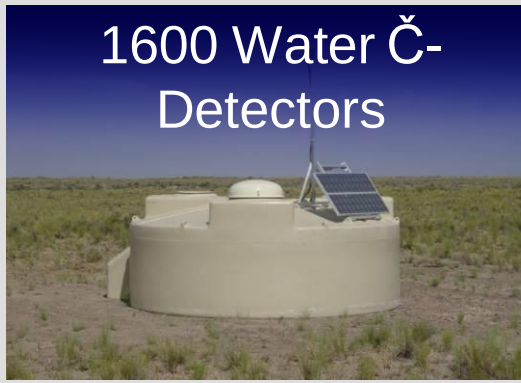
Experiments

Auger

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

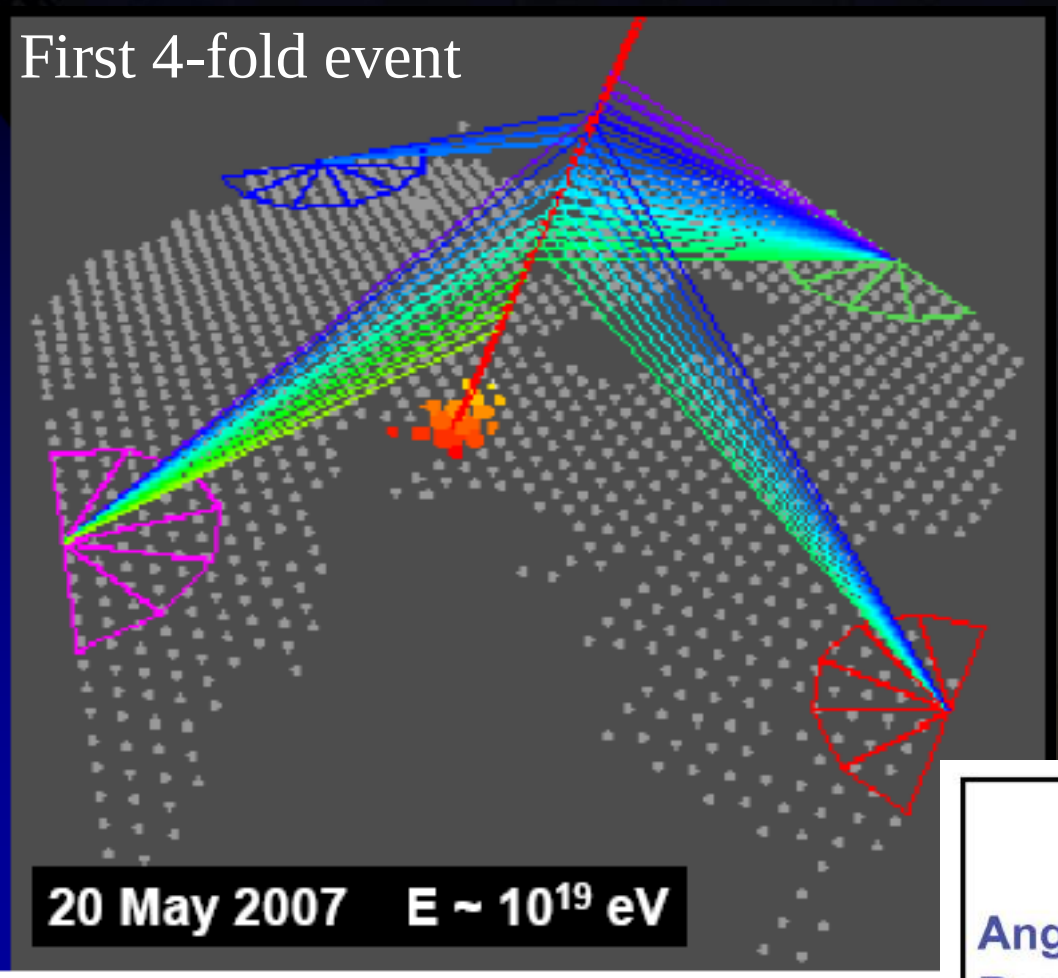


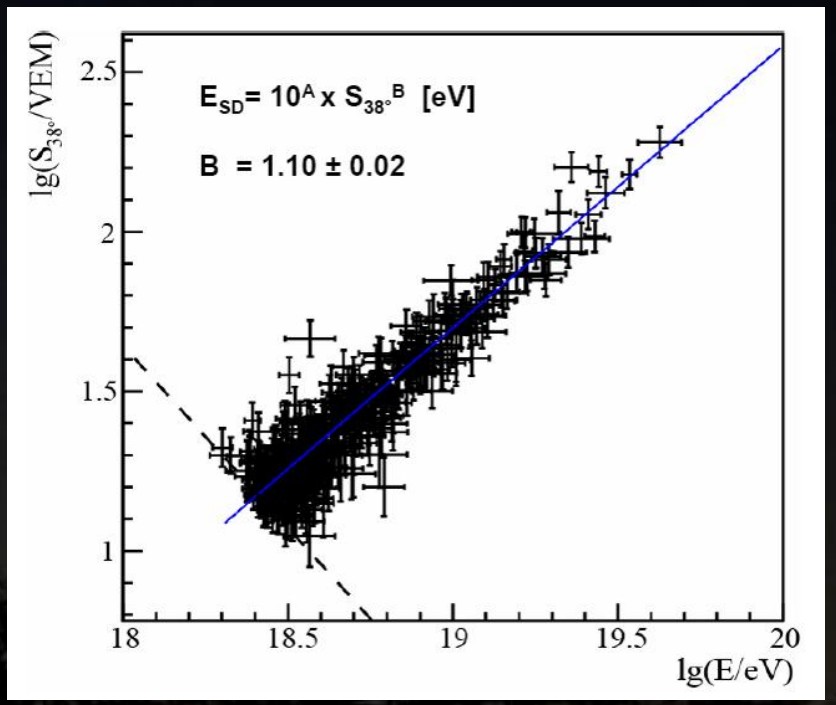




frica - 20

Hybrid Era



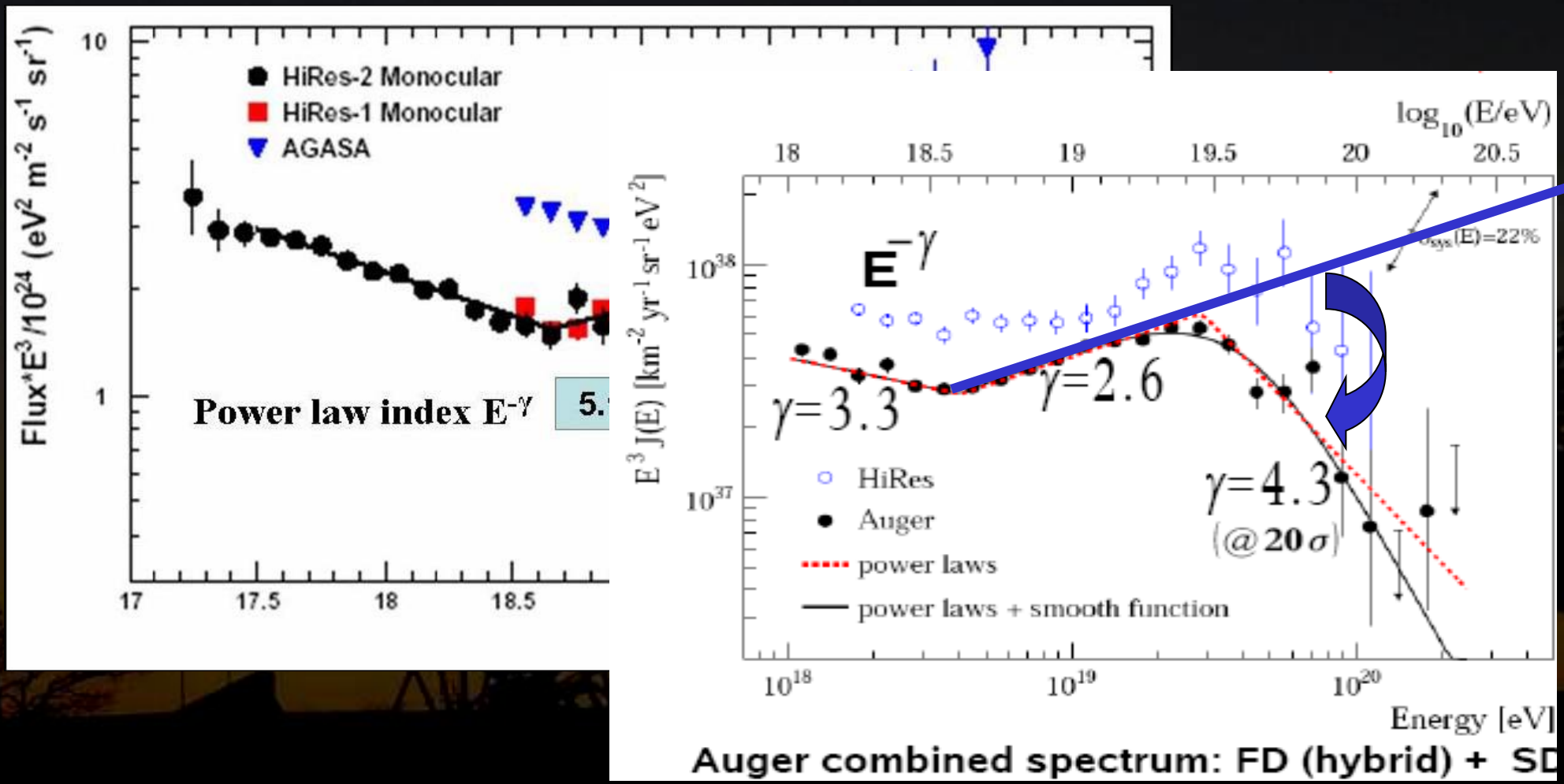


	Hybrid	SD-only	FD-only mono (stereo – low N)
Angular Resolution	~ 0.2°	~ 1 - 2°	~ 3 - 5°
Aperture	Flat with energy AND mass and model (M) free		E, A, spectral slope and M dependent
Energy	A and M free	A and M dependent	A and M free

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

Energy Spectrum

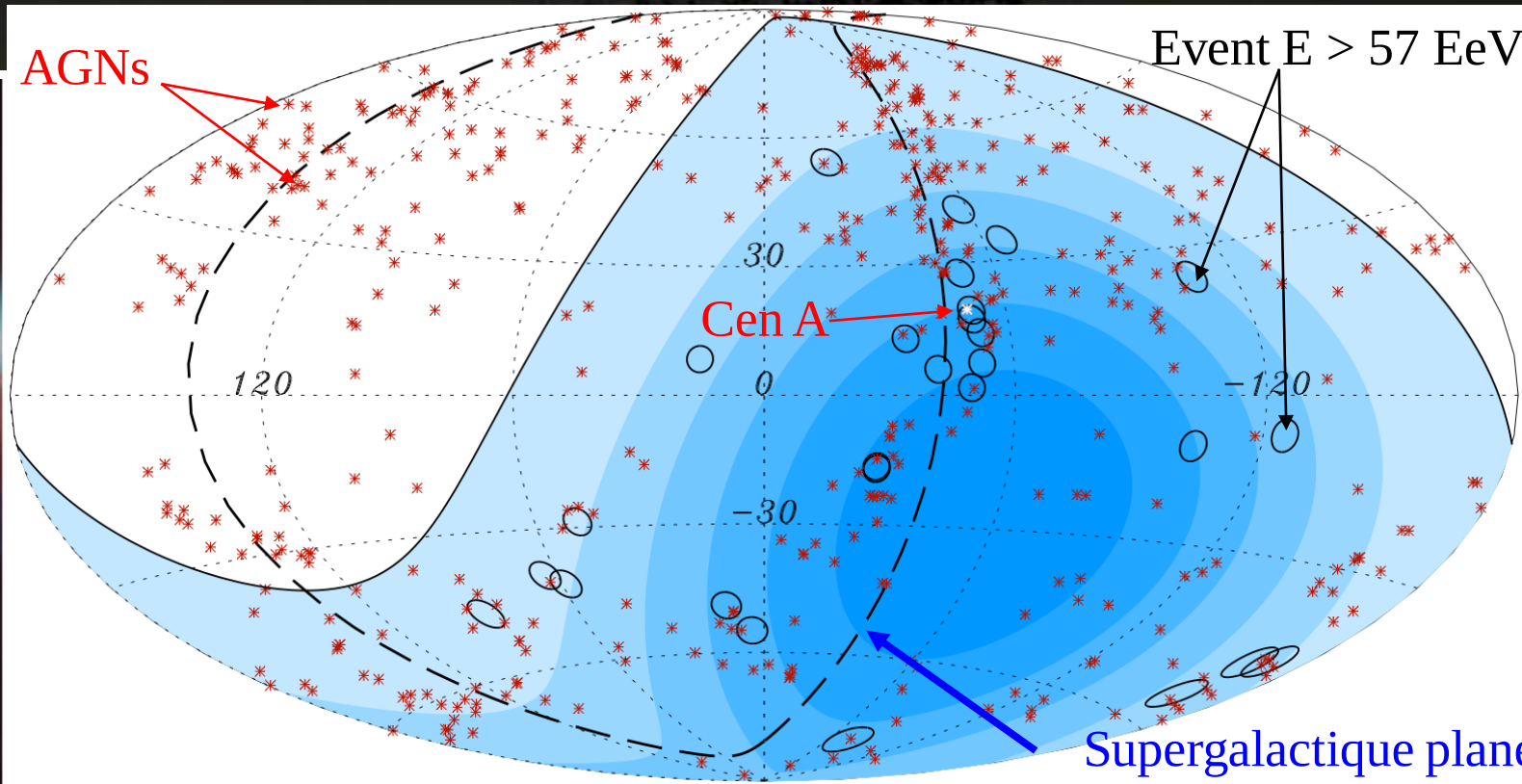
- Situation before Auger unclear
- FD / SD intercalibration on hybrid events
- Confirmation of a cutoff @ $10^{19.7}$ eV (20 σ effect)



Did we find the sources of UHECRs ?

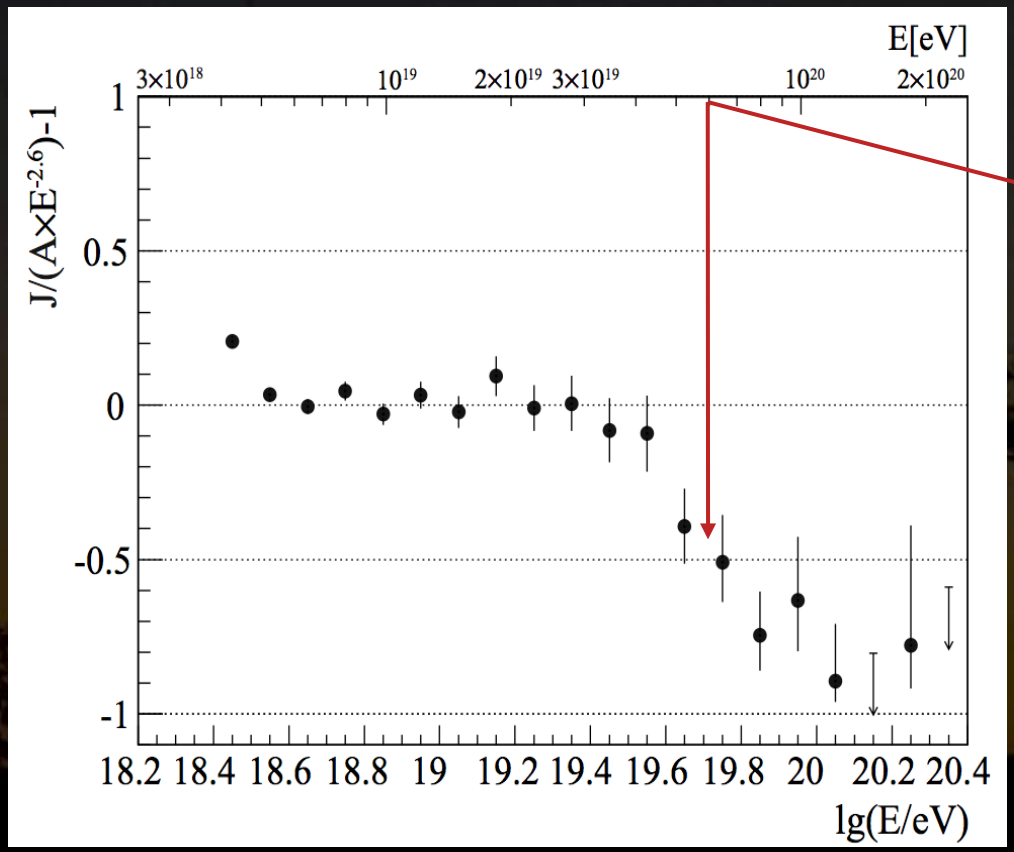
- Data set 2004 - 08/2007
  - > 10^6 events above 0.2 EeV.
  - 81 events > 40 EeV, $\theta < 60$
  - P = 10^{-5} incl. trials
- Correlation with supergalactic plane (nearby AGNs)
- Controversy on more recent data...

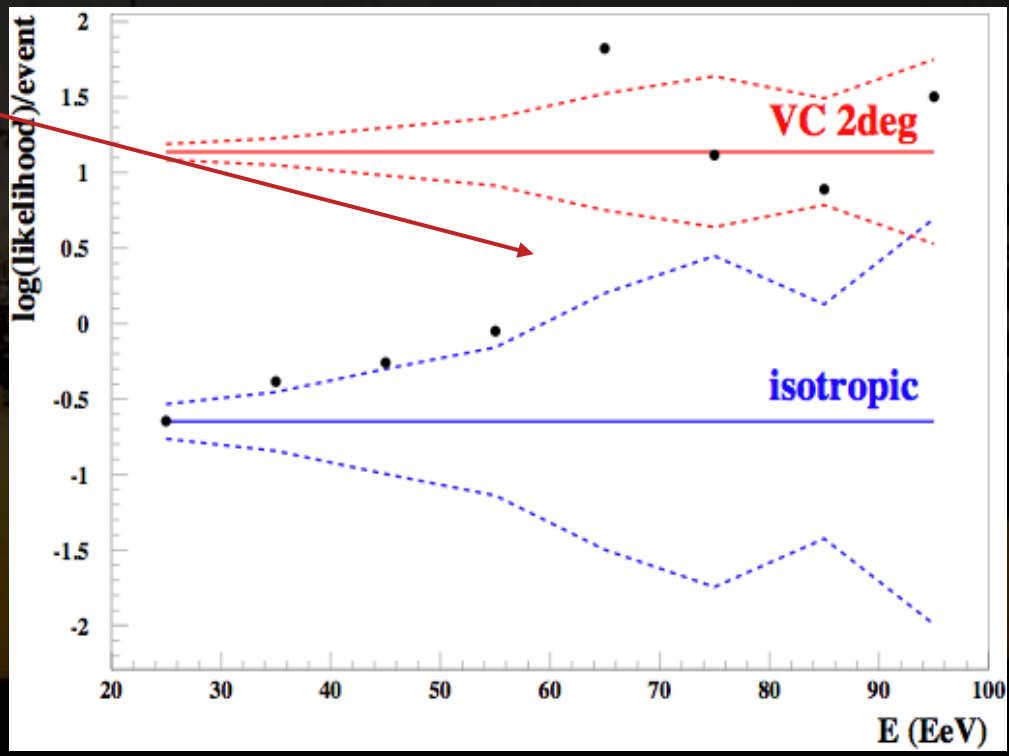
Science (Nov. 2007)



GZK Cutoff ?

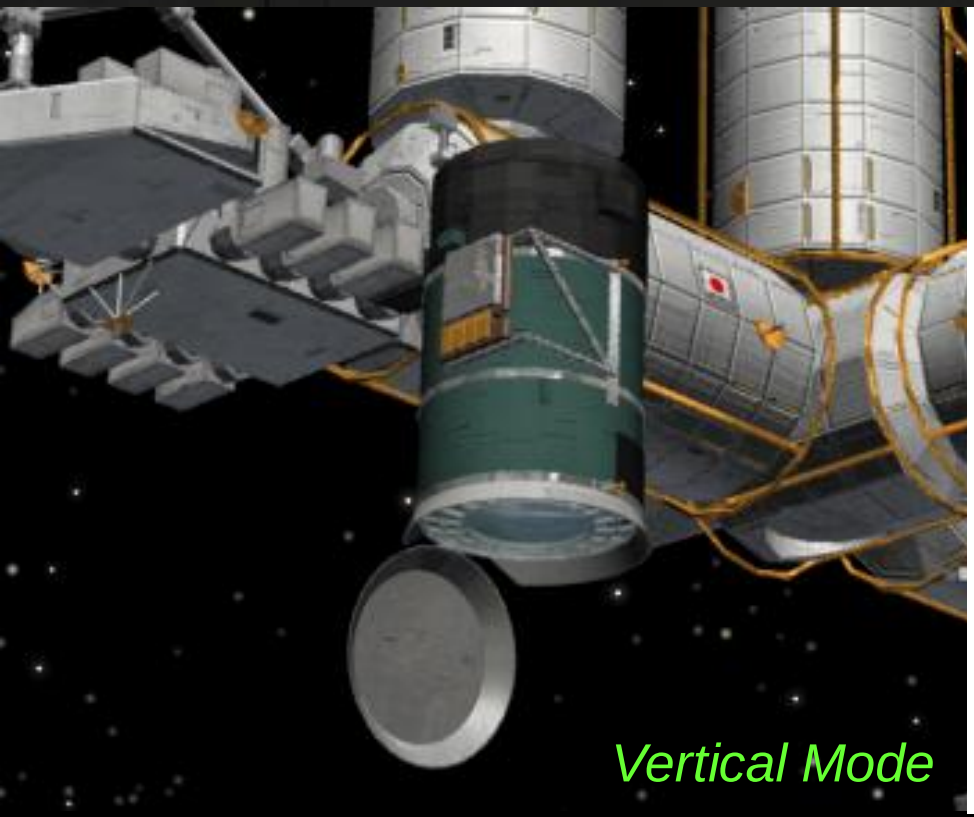
- Energy cutoff @ $10^{19.7}$ eV
- At the same energy, appearance of anisotropies (Anisotropy signal maximum where flux divided by two)
- Naturally leads to GZK interpretation
- Alernate explanation: exhausted sources

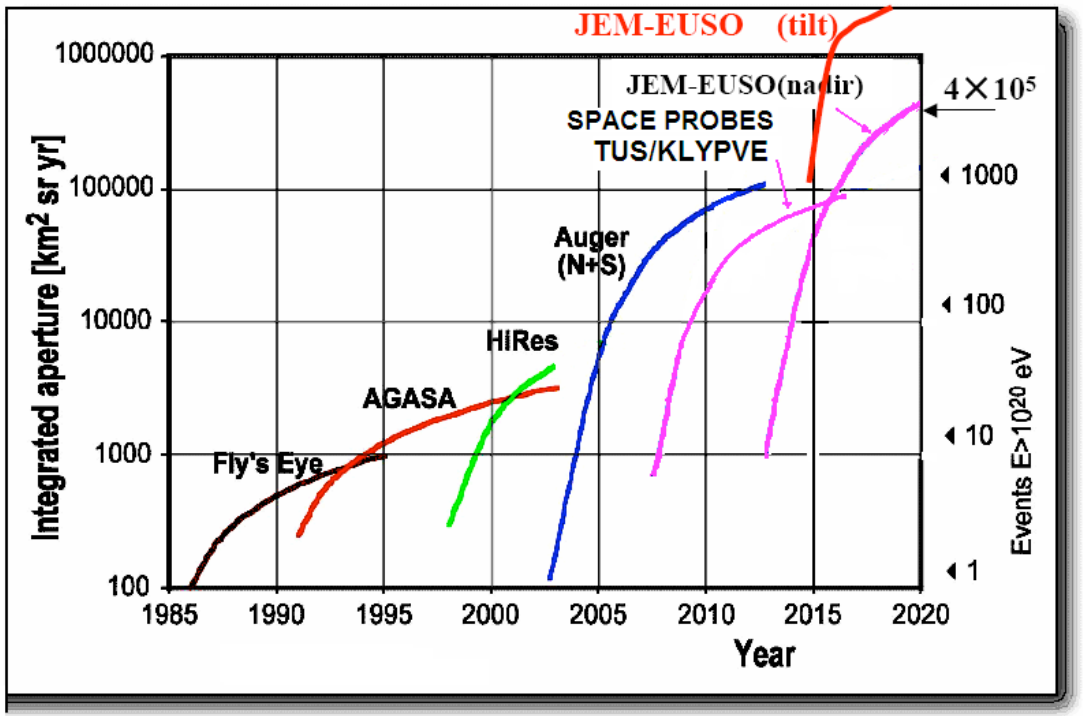




Perspectives (I)

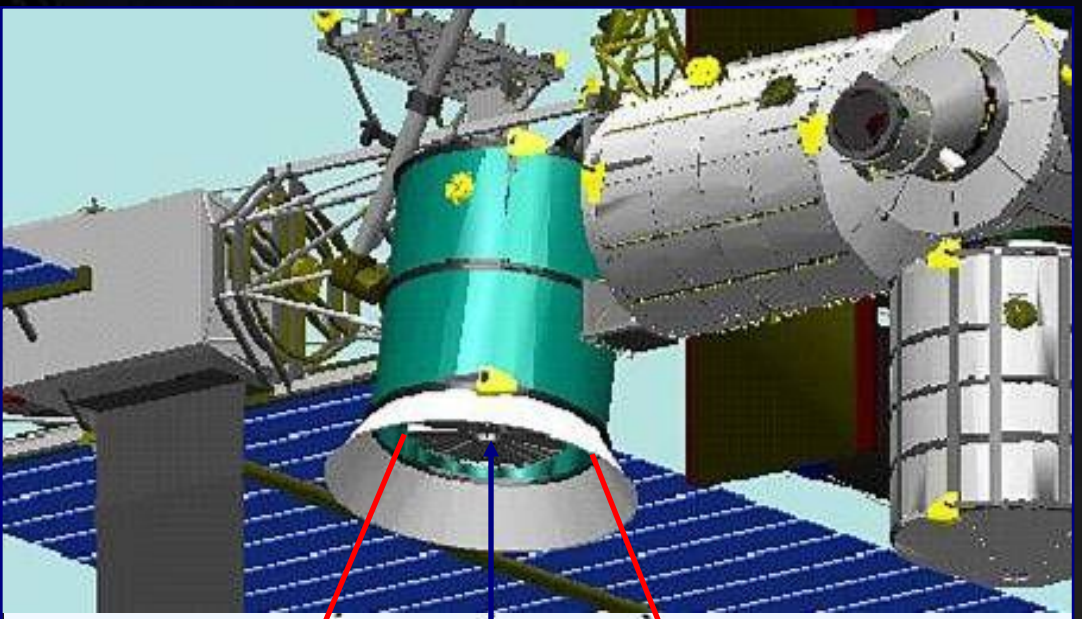
- Larger network for investigating the highest energies: Auger North + JEM-EUSO Telescope on ISS (2013)
- Upgrade of existing networks (HEAT, AMIGA…)
- Low energy extensions toward the knee (Tel. Array)
- A lot of R&D in other detection techniques (Radio!)

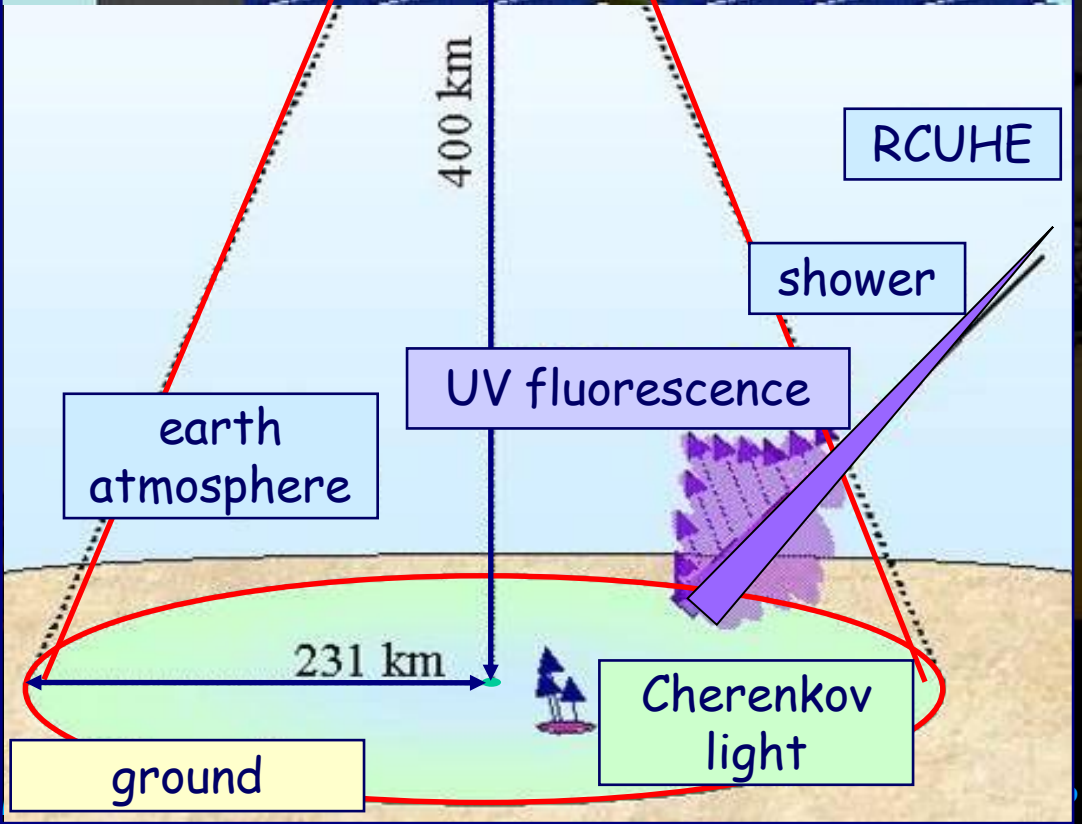




by Boris Khrenov 2006

JEM - EUSO

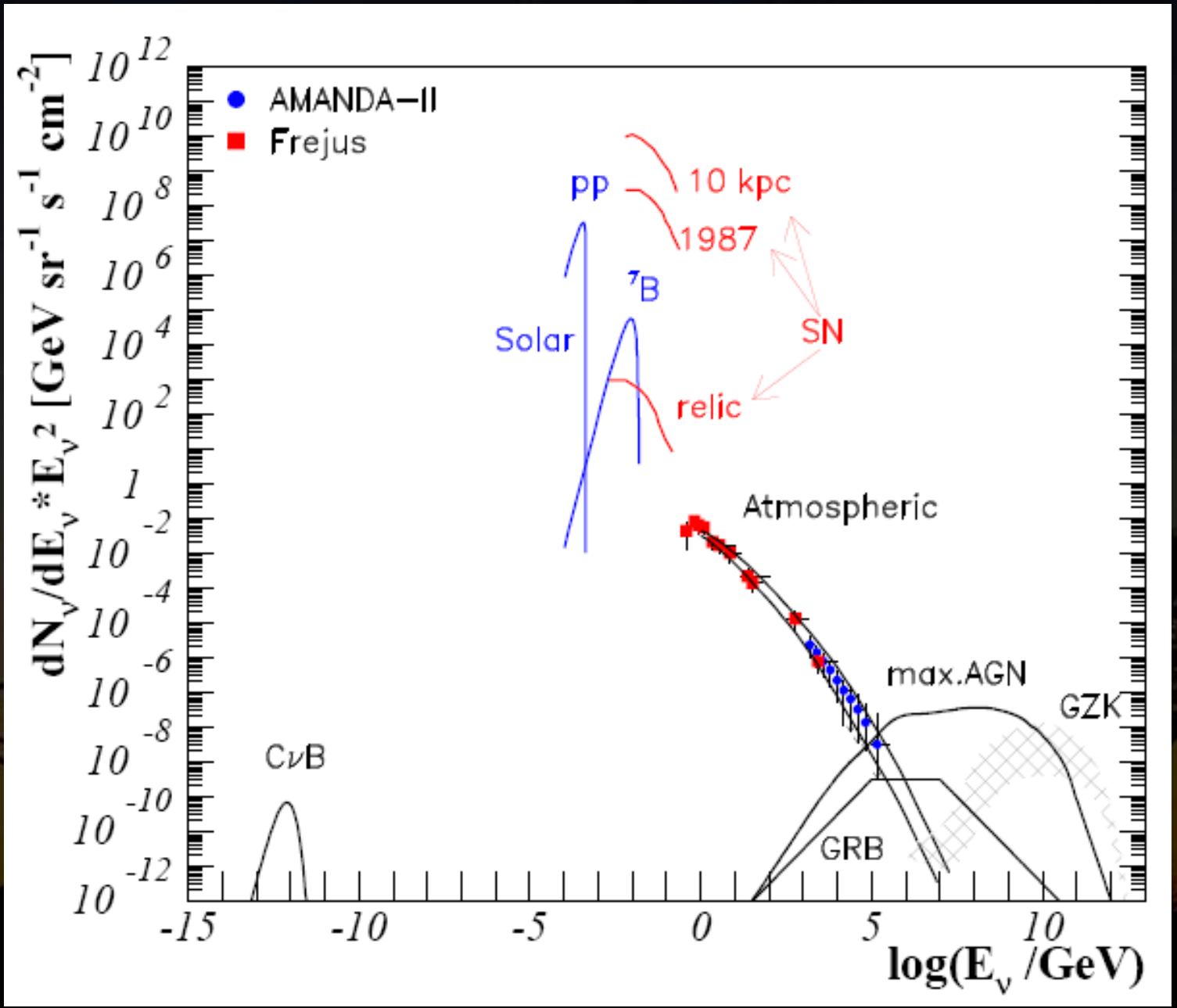




- Acceptance : 10^6 km^2 sr
- Target air mass : 10^{13} T
- Full sky coverage in one year
- 1000 events per year with $E>10^{20}$ eV
- Launch foreseen in 2013

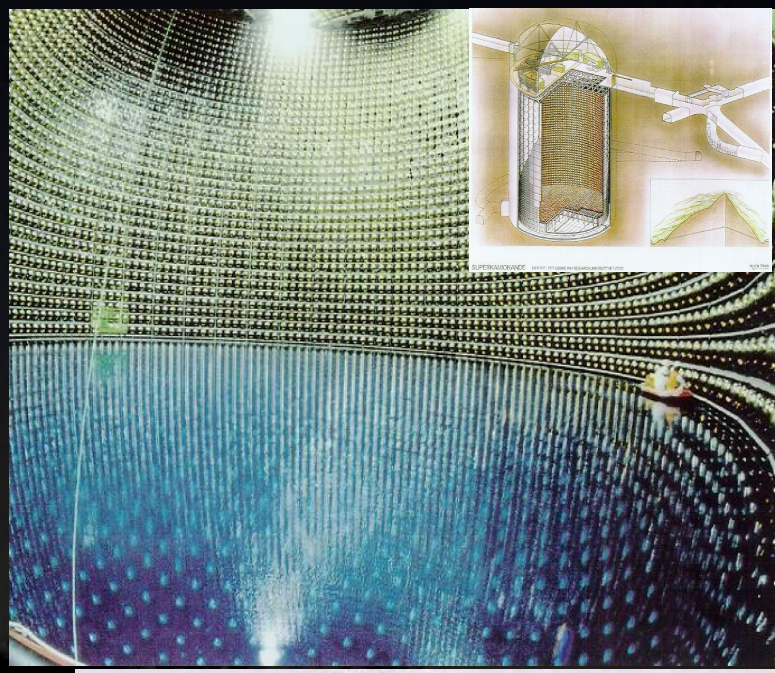
NEUTRINOS

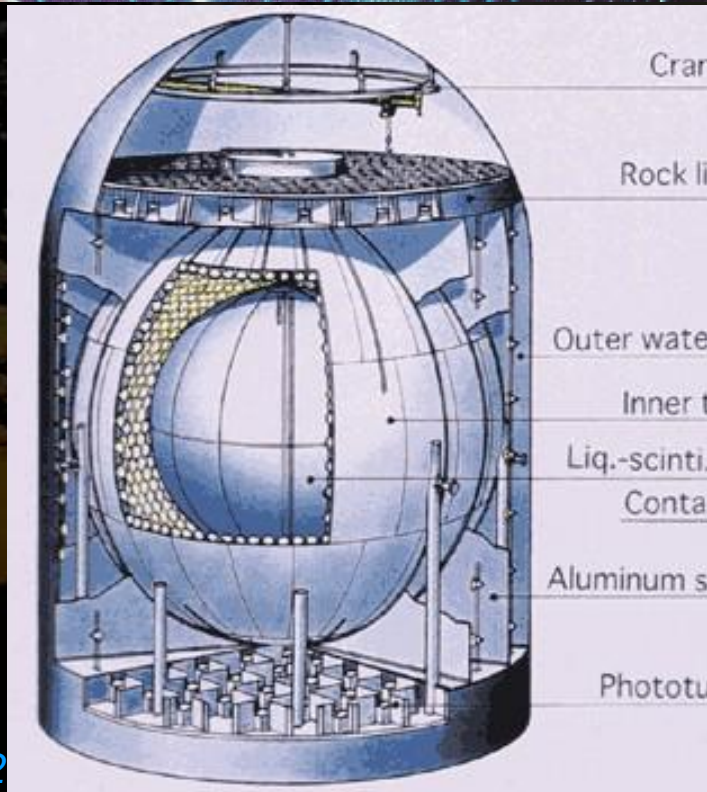
Neutrino spectrum



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....



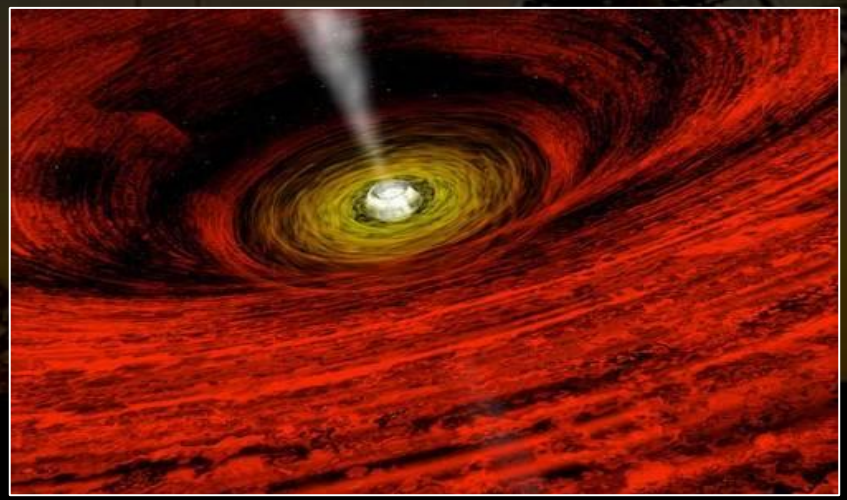


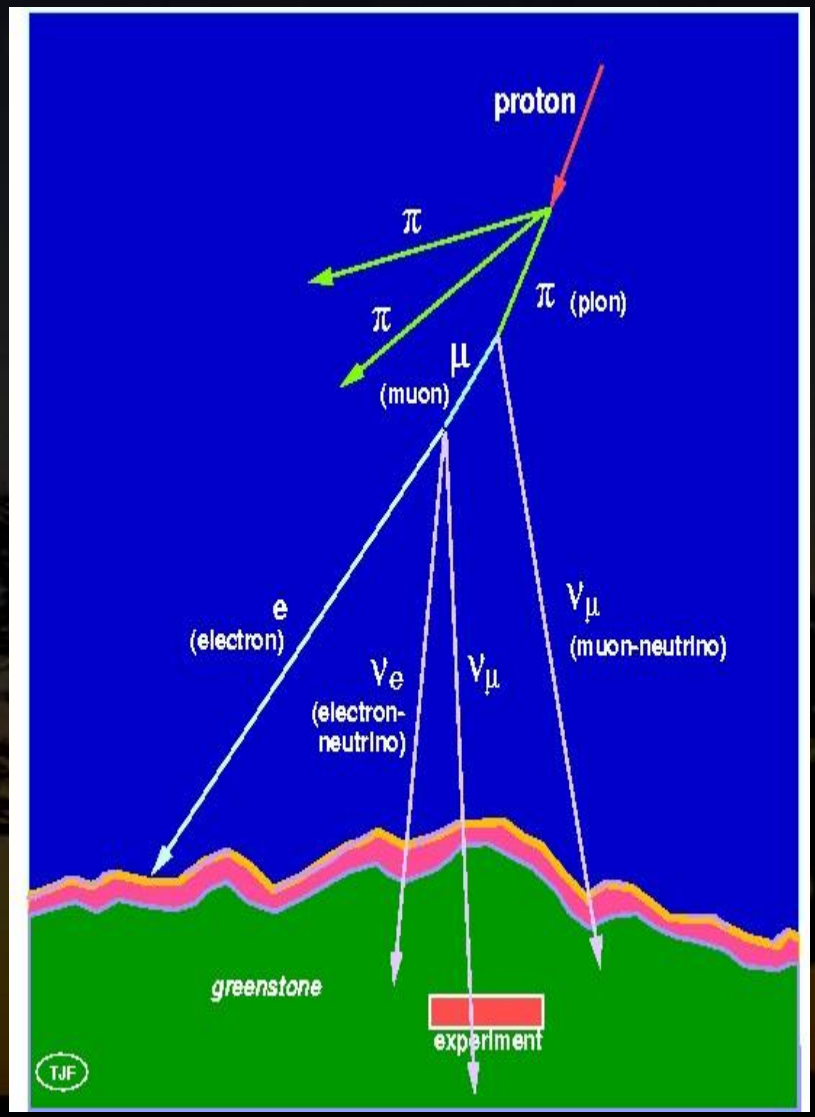
High Energy Neutrinos

- Atmospheric neutrinos
  - Neutrinos produced in hadronic showers

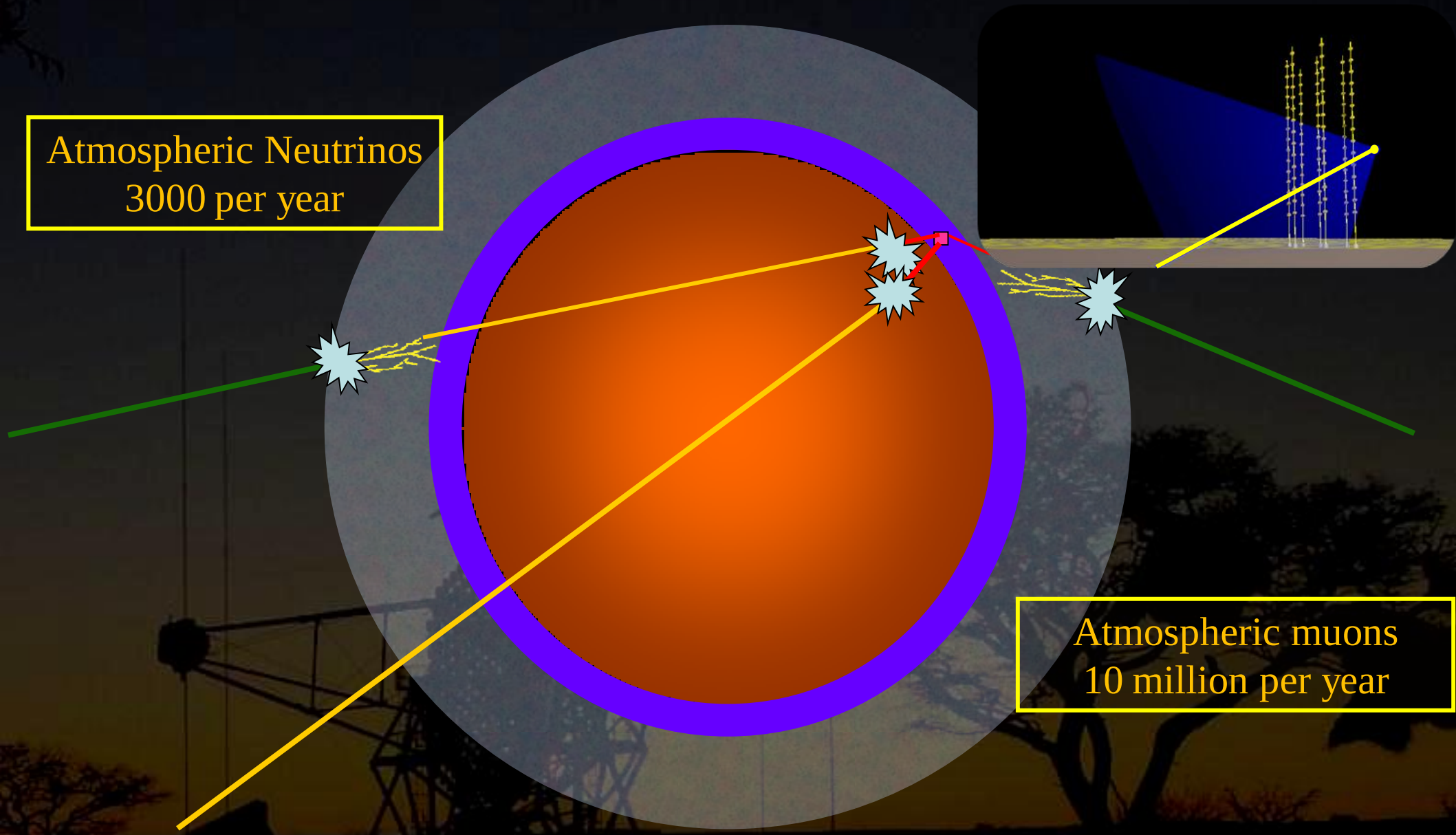
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$

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



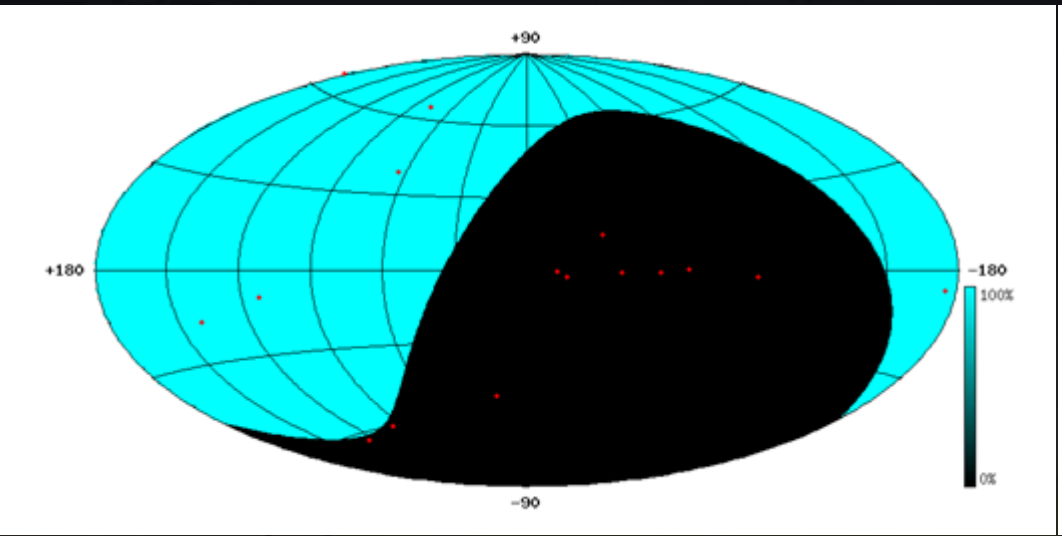


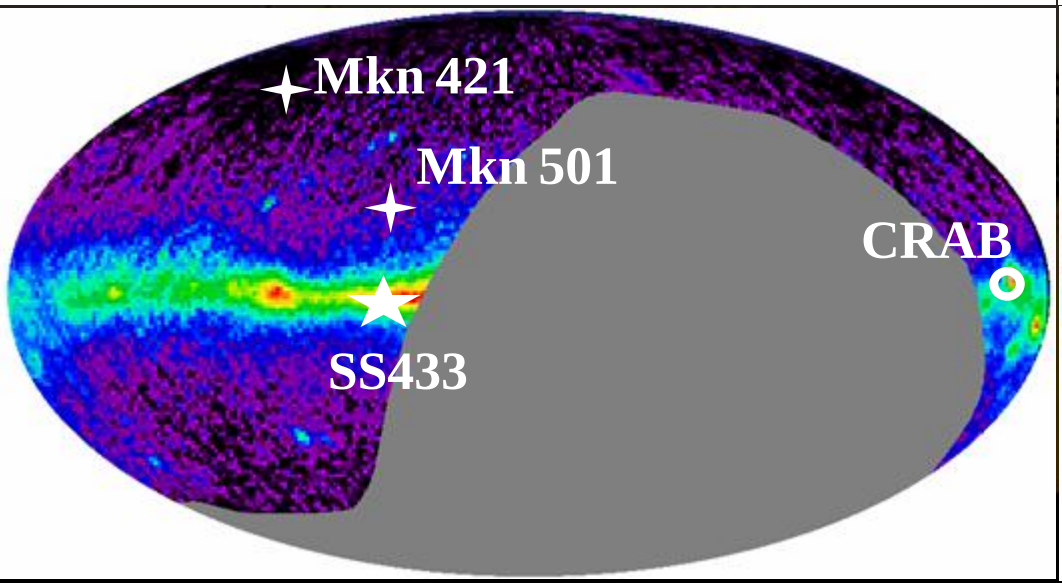
Detection principle



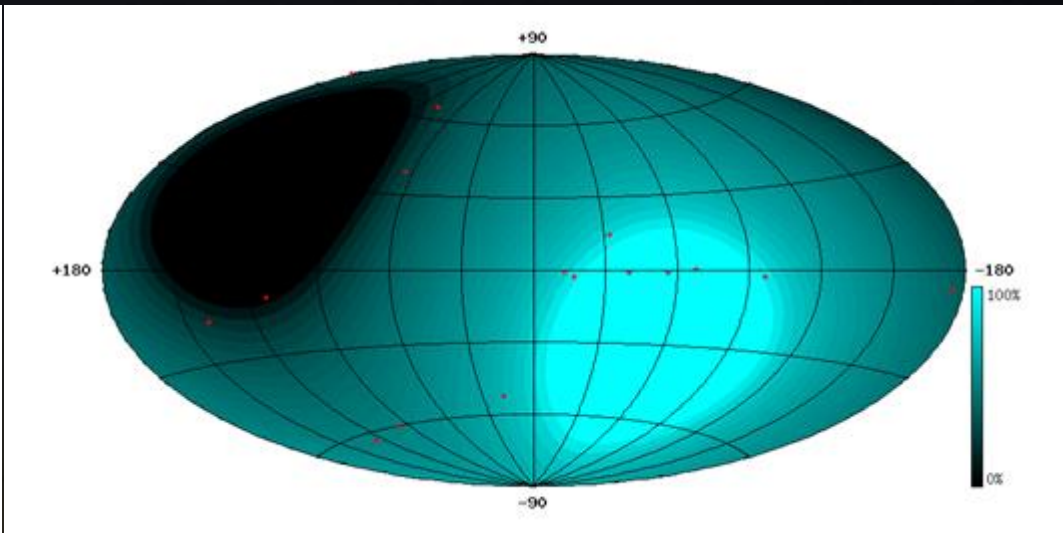
High Energy Neutrino Sky

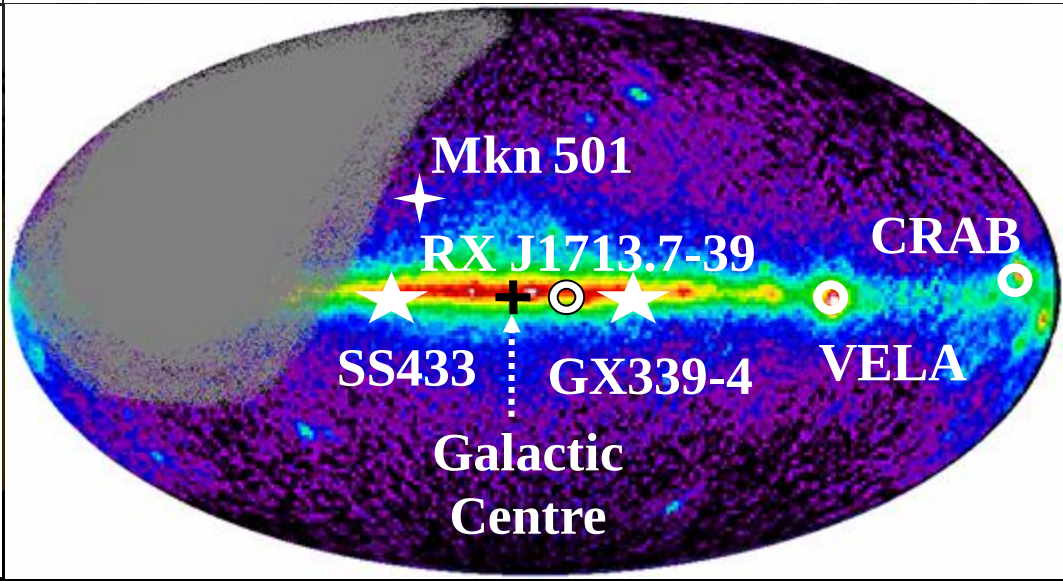
AMANDA (South Pole)





ANTARES (43° North)





+ Baikal, Nemo, Nestor

Comparison of media

ICE

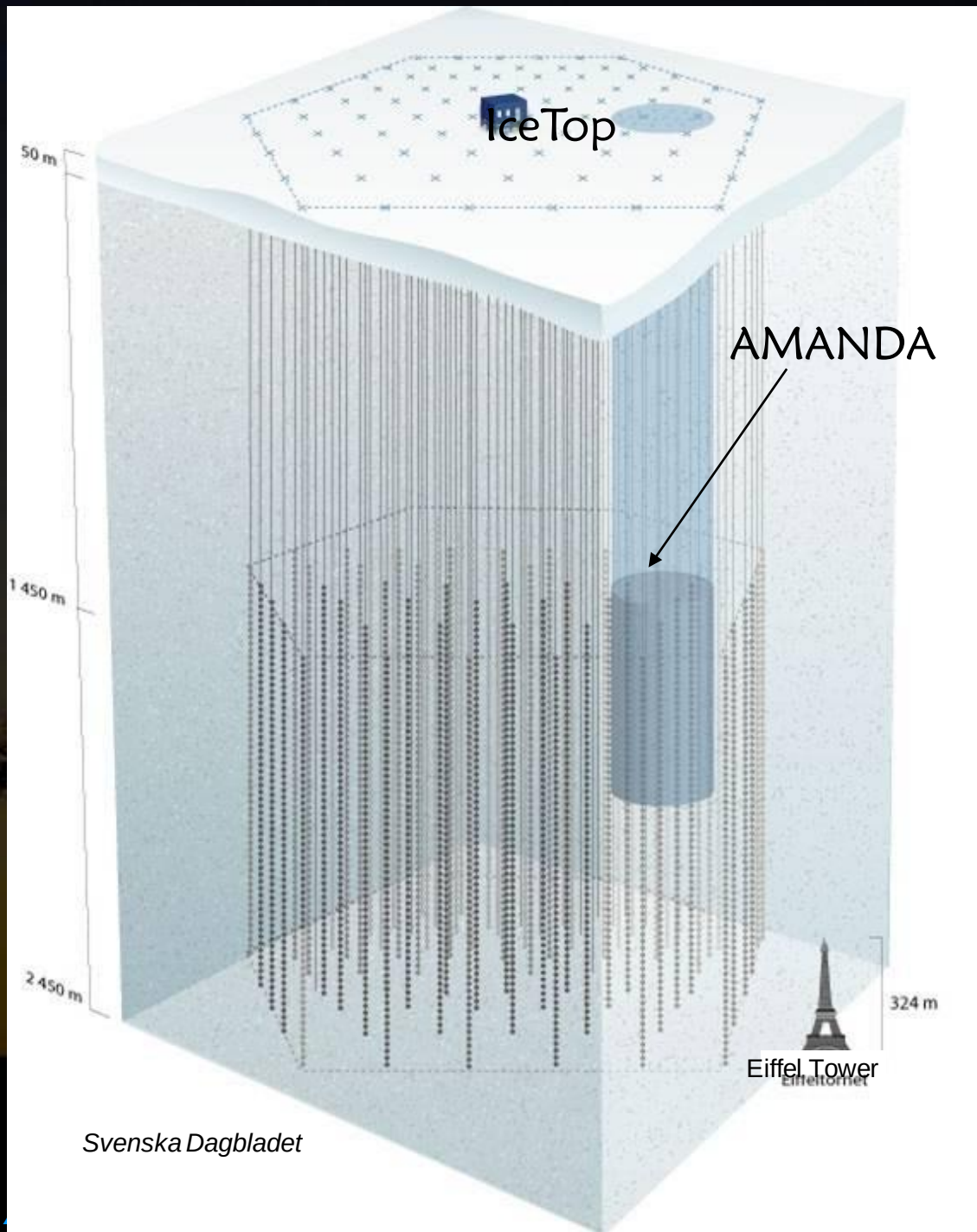
- Stable, easy drilling
- ~350 Hz noise (^{40}K), sterile
- Large absorption length ~100 m
- Low diffusion length 20-25 m (degraded angular resolution)
- Max Depth 2500 m

WATER

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

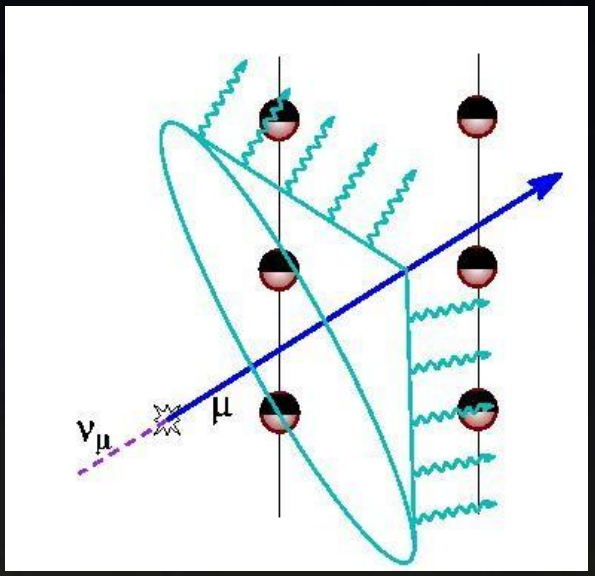
IceCube

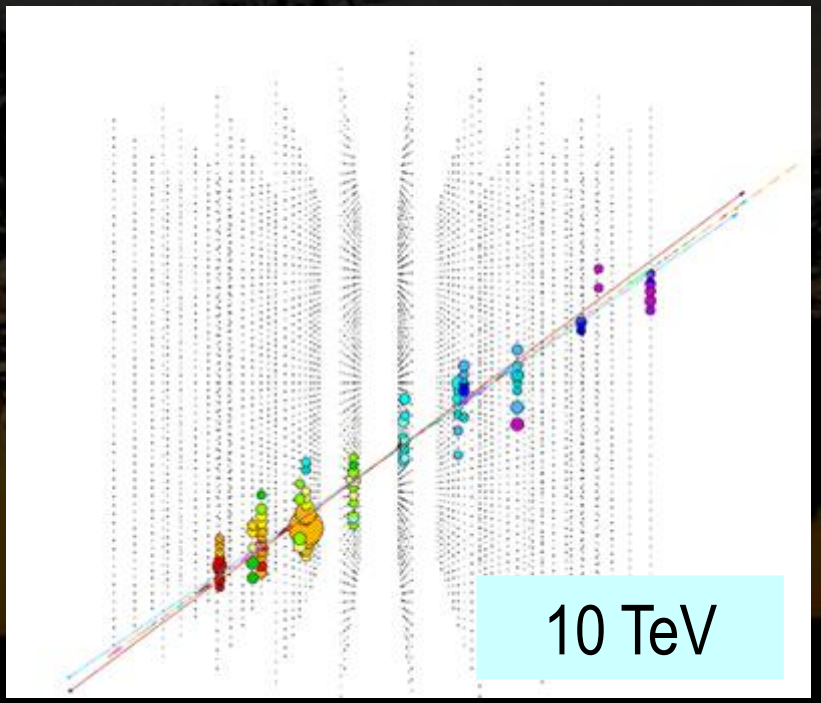
- Deployment:
  - 2005 : 1 line installed
  - 2009 : 59 lines installed
  - 2010 : 79 lines (4790 DOM)
  - final : 86 lines (5160 DOM)
- Estimated lifetime: 15 years
- Performances:
  - O(100) ν per day
  - O(10^8) μ per day
  - 0.4-1° angular resolution
  - 10 GeV threshold
- Radio detection activities (ARIANNA)
- Surface array: IceTop



Signatures – Neutrino μ

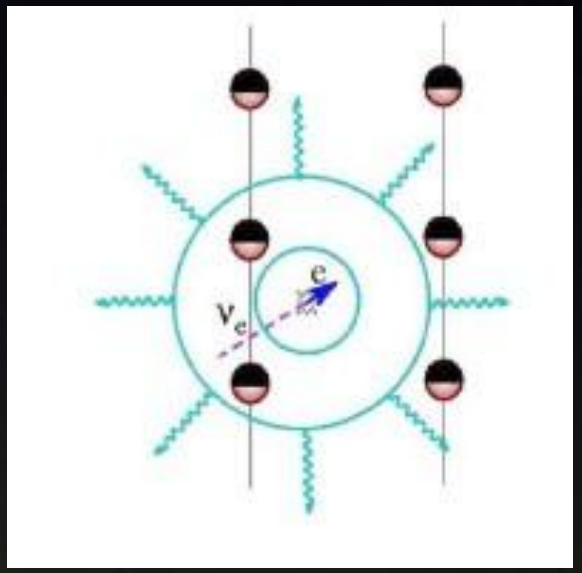
- Long, linear track
- linear « image » aligned with muon track

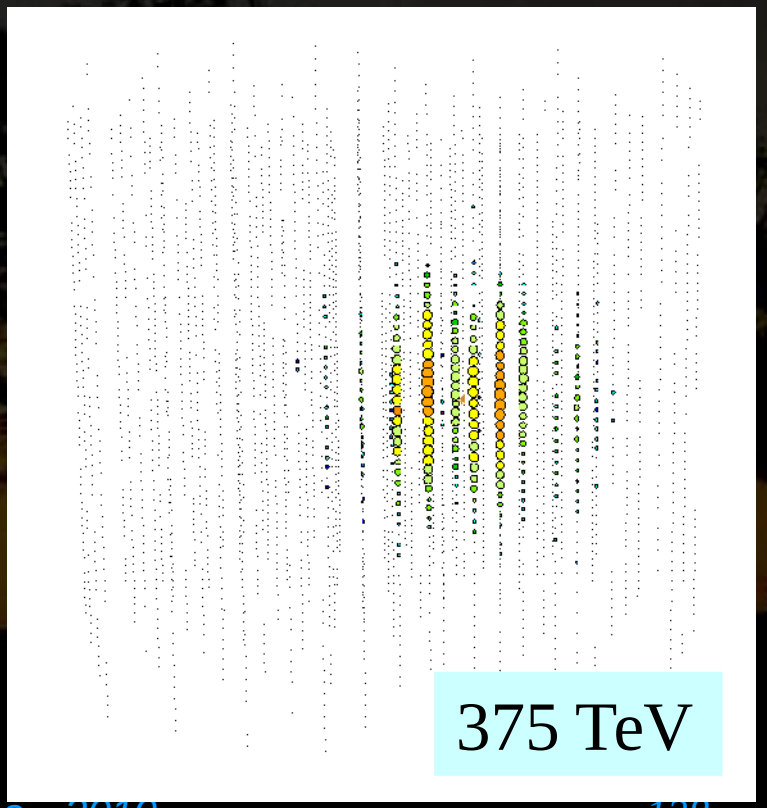




Signatures – Neutrino e

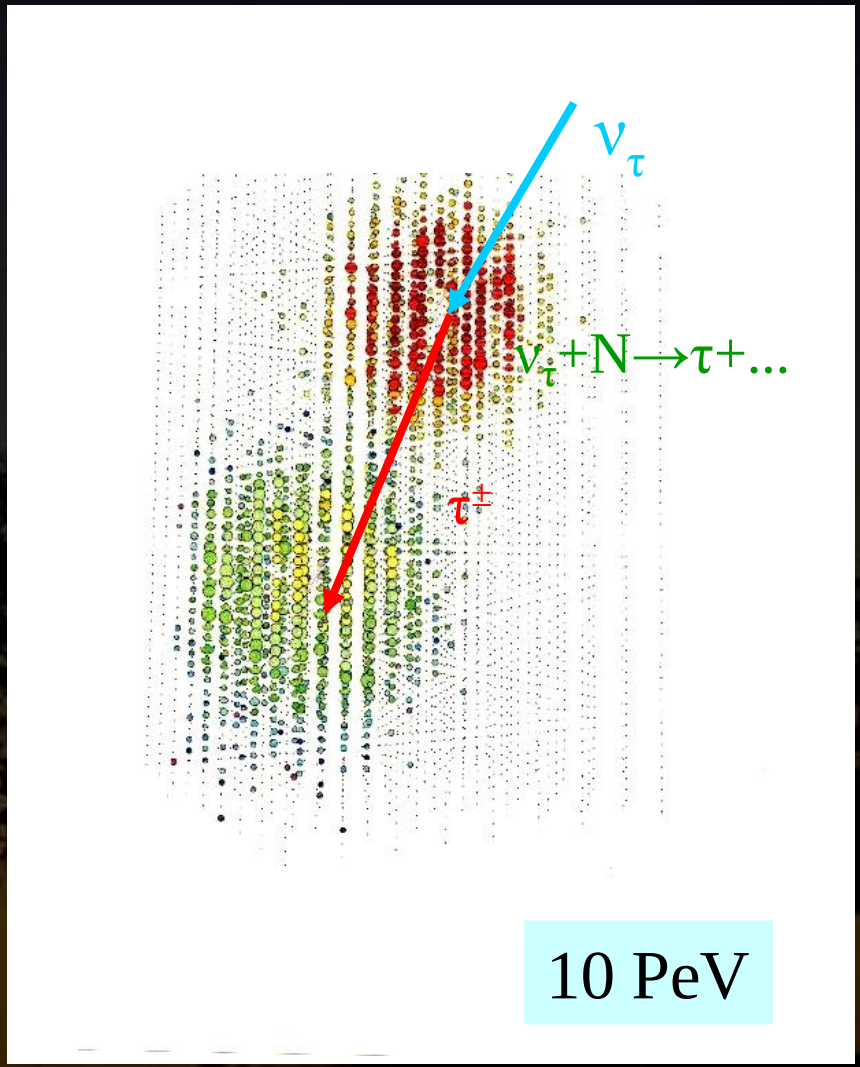
- Short track (ionisation/bremsstrahlung losses), shower, multiple scattering
- Concentrated « Image »



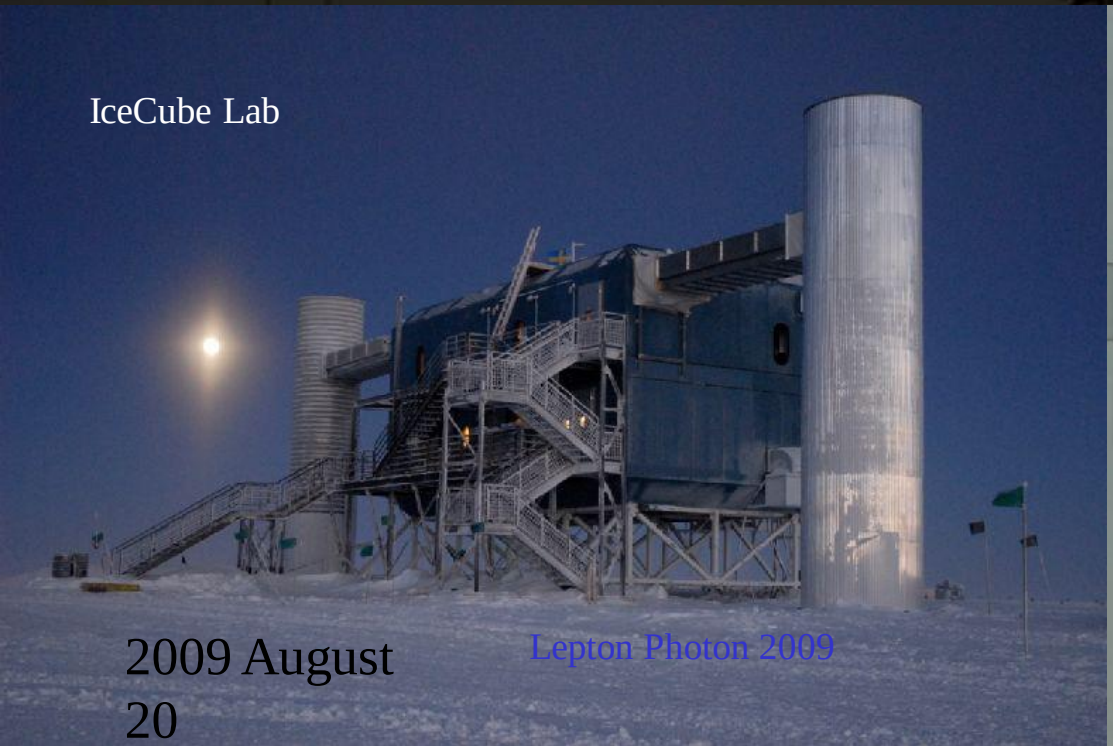


Signatures – Neutrino τ

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

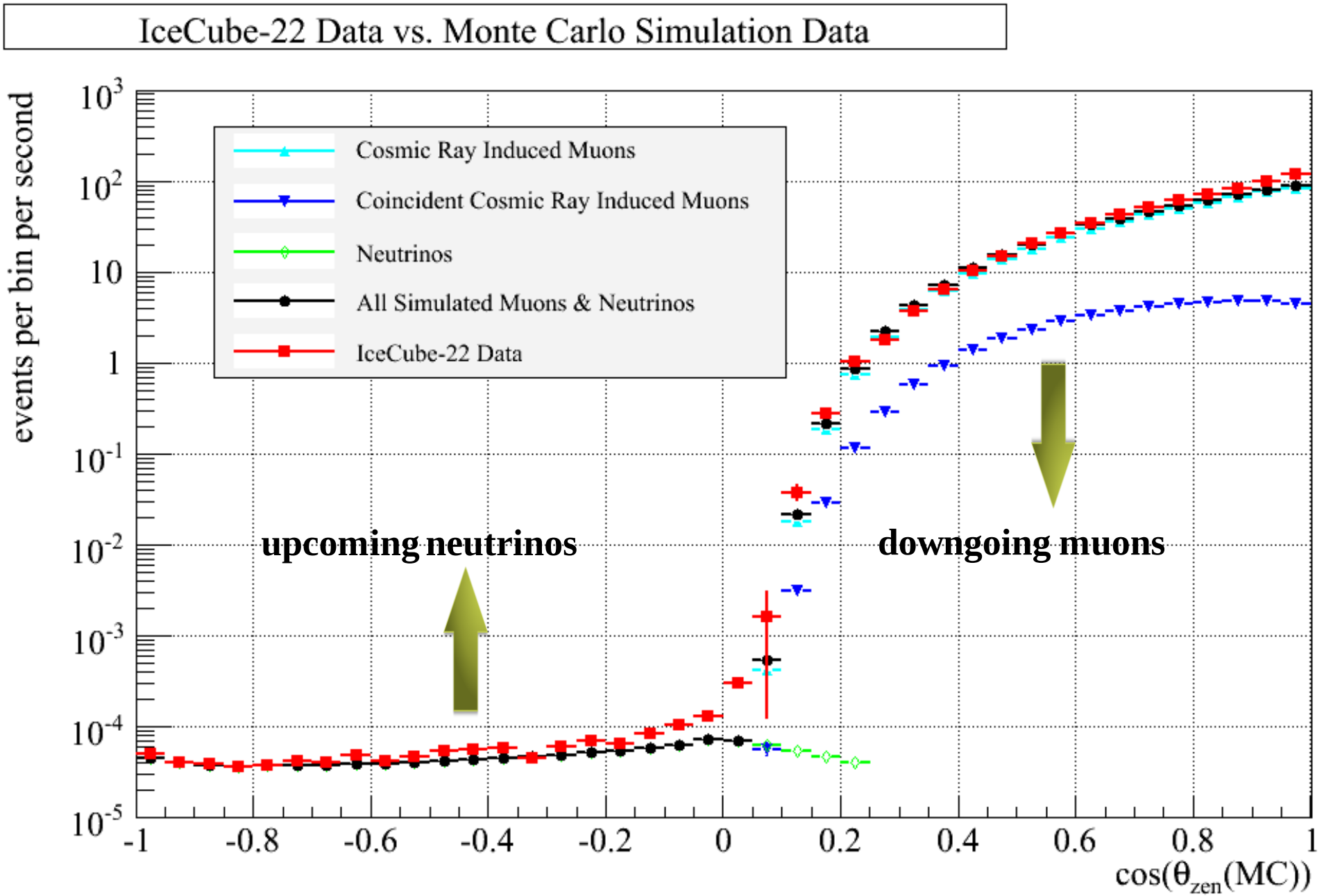


IceCube Lab

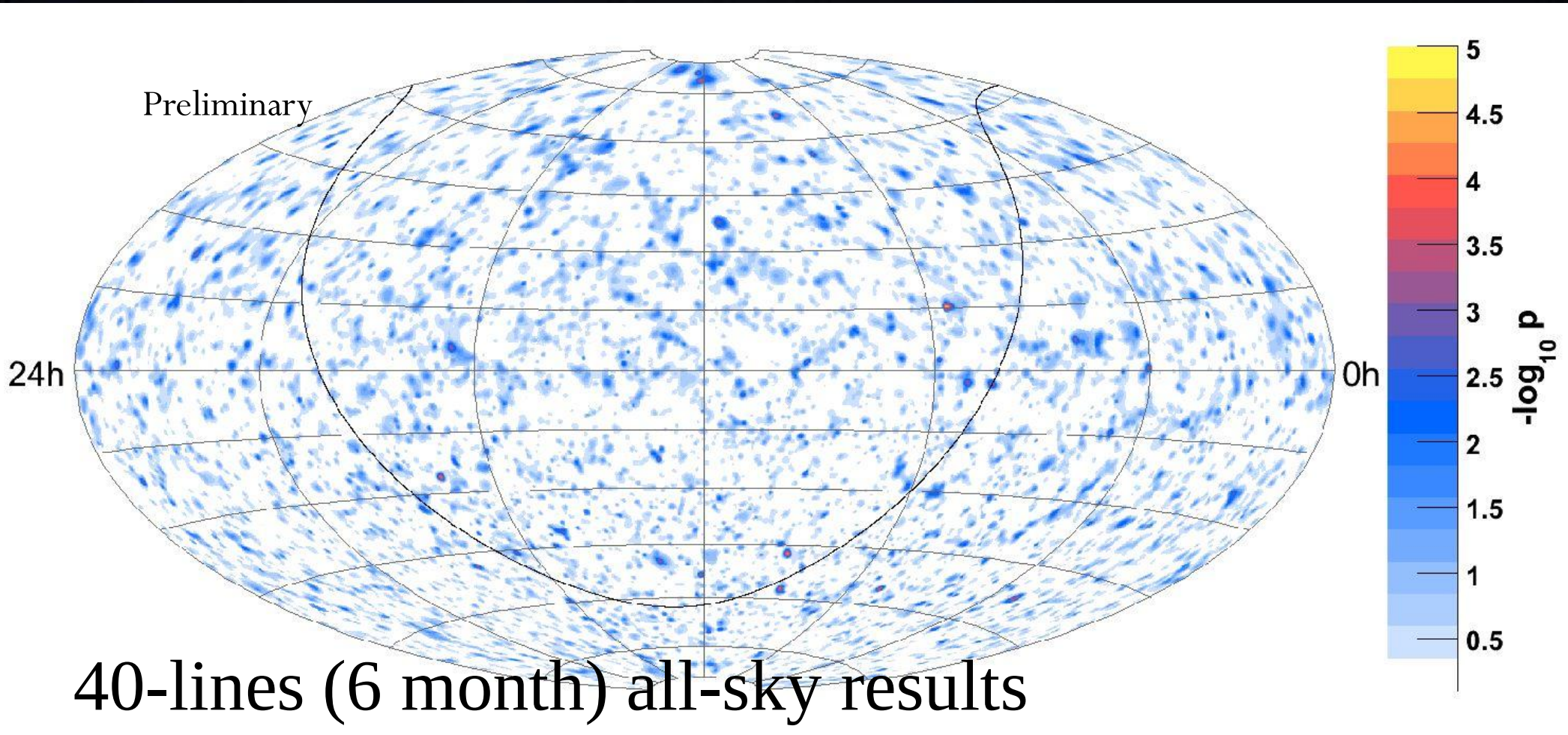


South Pole and Christmas tree

Angular distribution



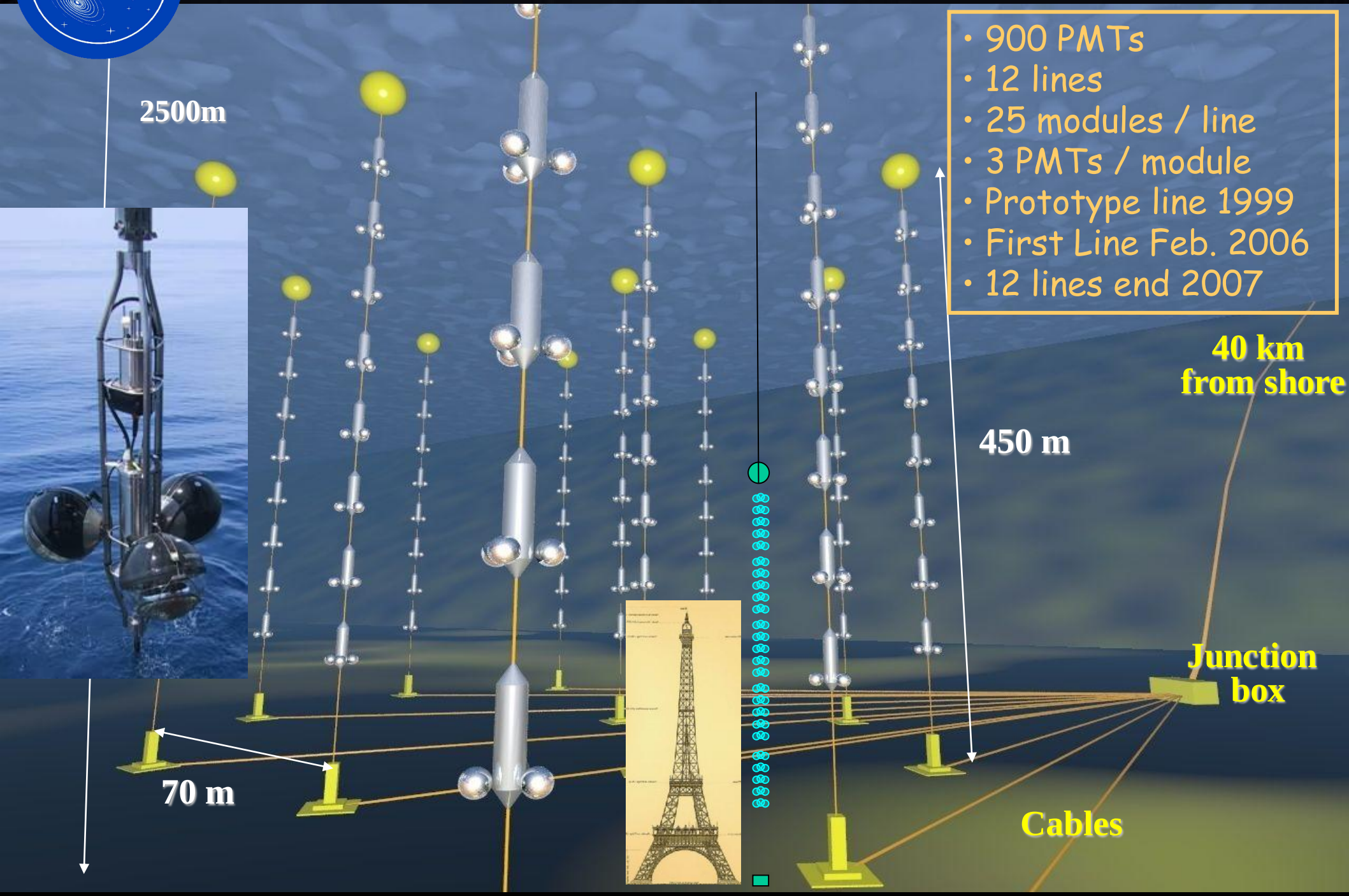
Search for point like sources



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

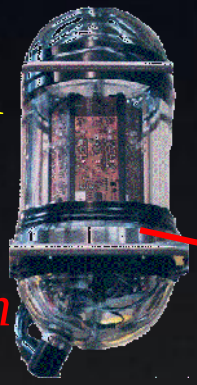
Antares


2500m
• 900 PMTs
• 12 lines
• 25 modules / line
• 3 PMTs / module
• Prototype line 1999
• First Line Feb. 2006
• 12 lines end 2007
40 km
from shore
450 m
Junction
box
70 m
Cables

Base Module

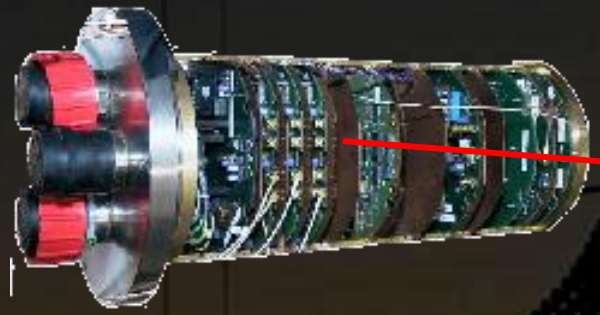
titanium frame: *support structure*

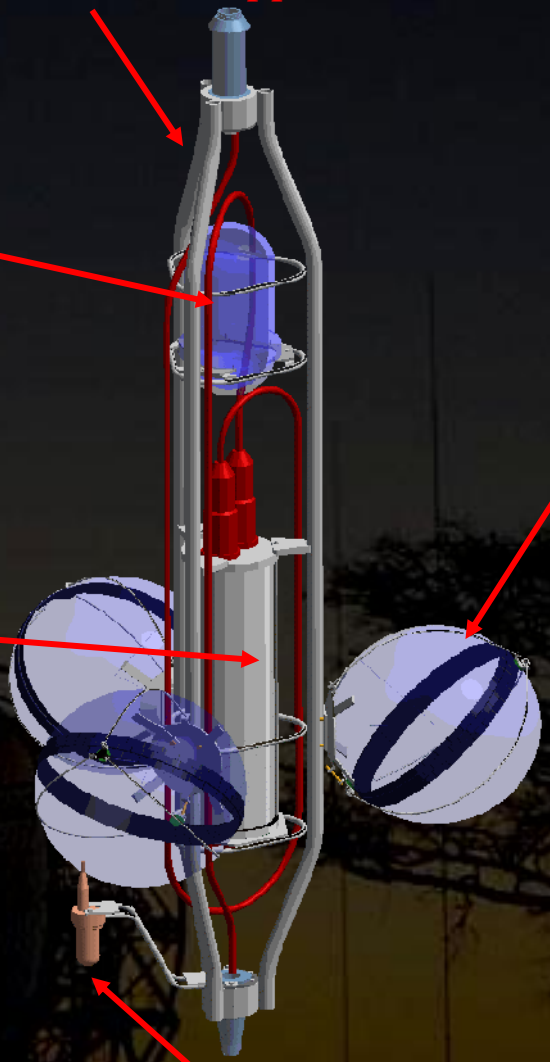
Optical Beacon with blue LEDs: *time calibration*



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

Photon detection

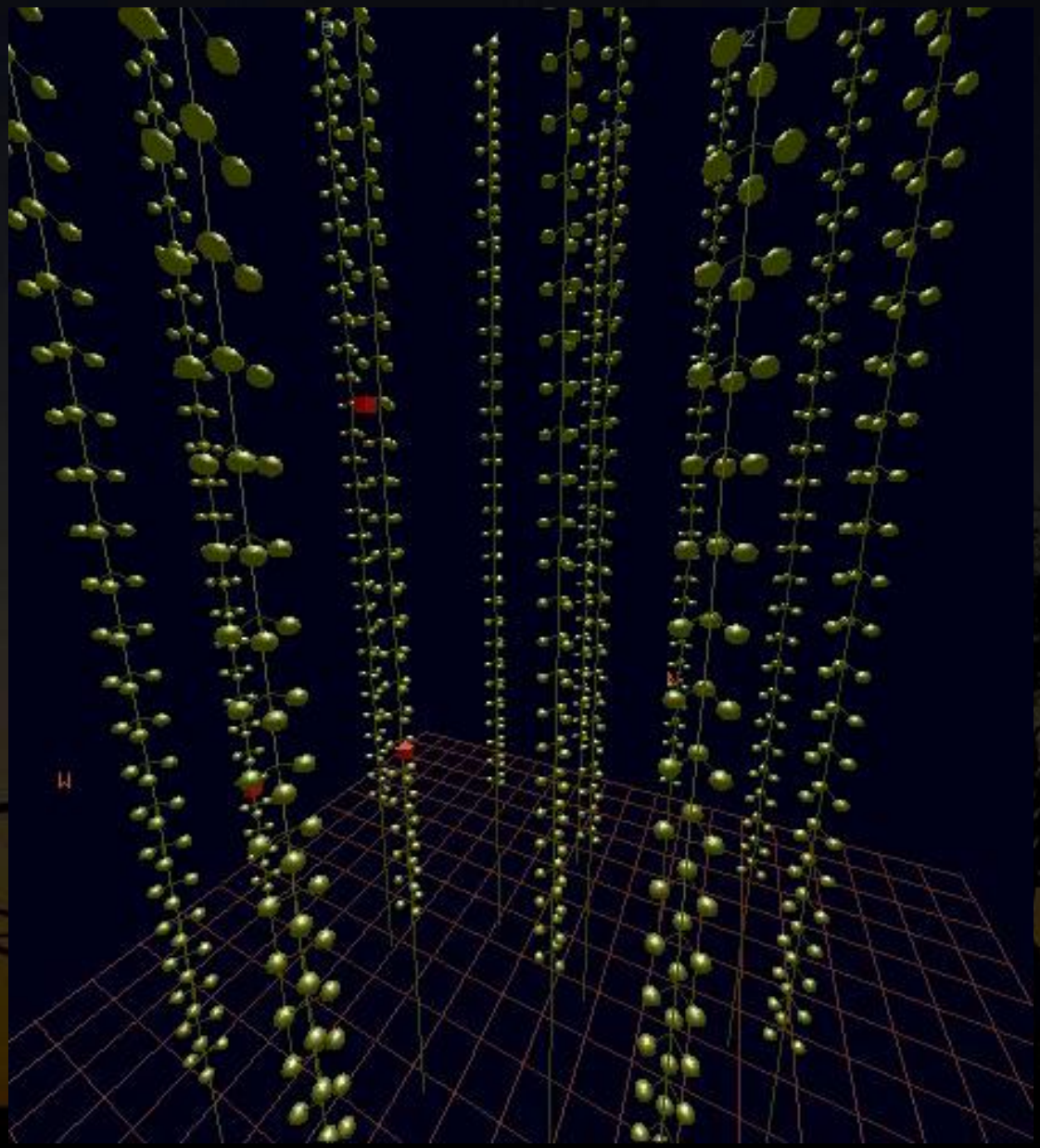




Local Control Module (Ti cylinder): *Front-end ASIC, DAQ/SC, DWDM, Clock, tilt/compass, power distribution…*

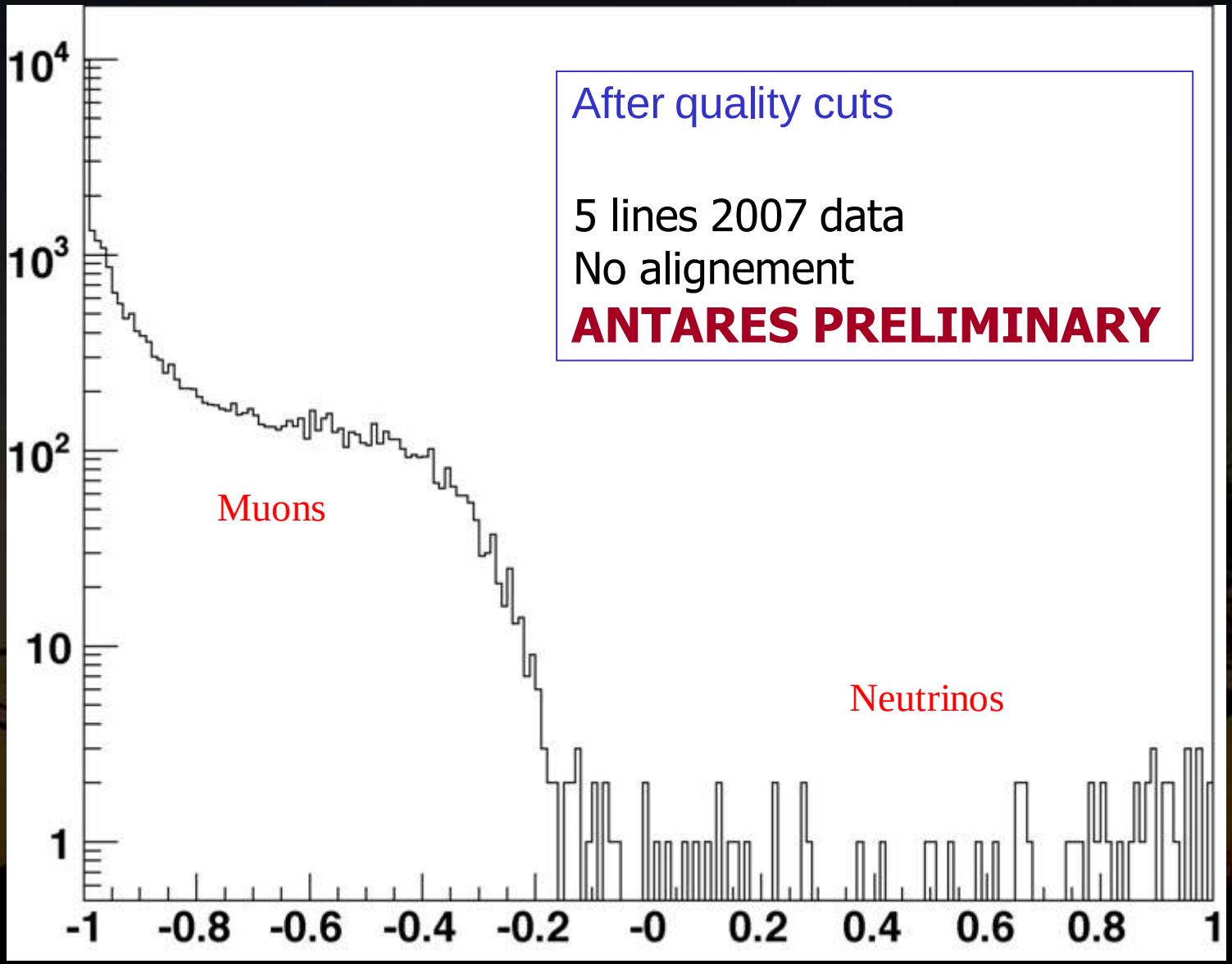
Hydrophone: *acoustic positionning*

Antares Simulation



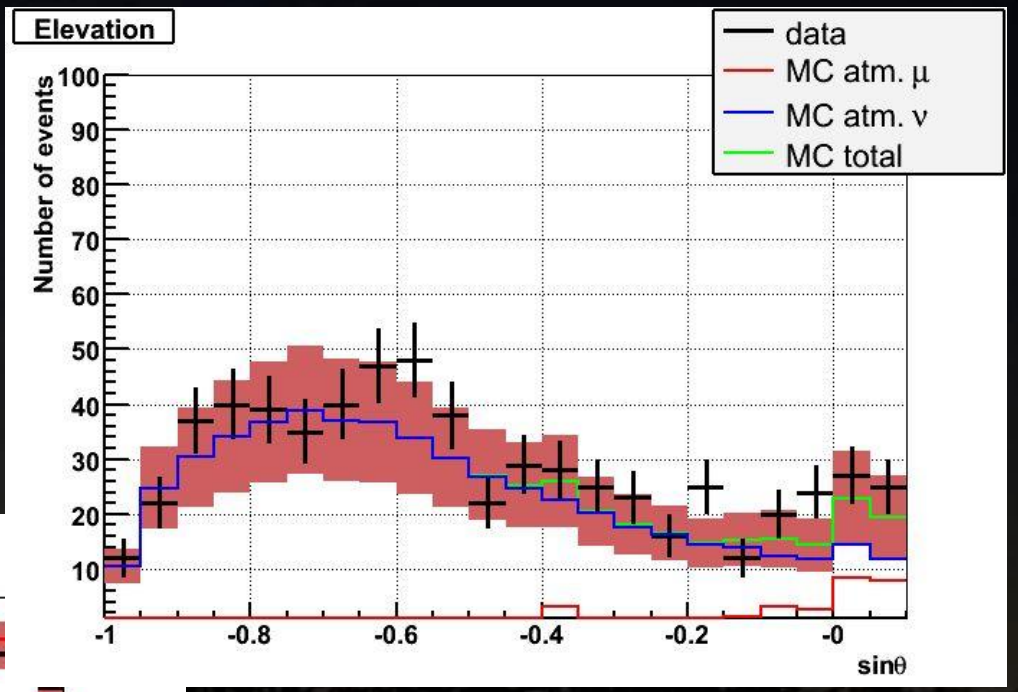
Muon 1 TeV

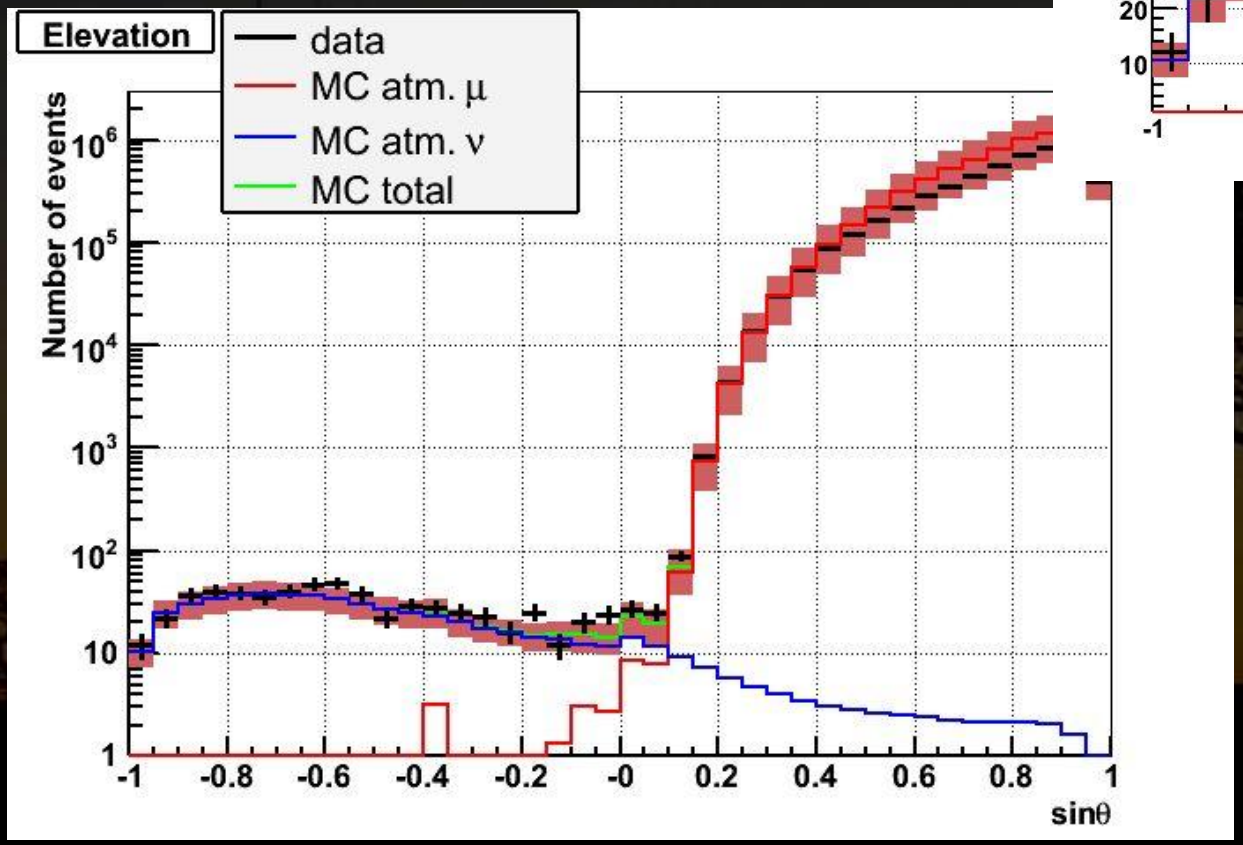
Angular distribution of events



2008 data

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

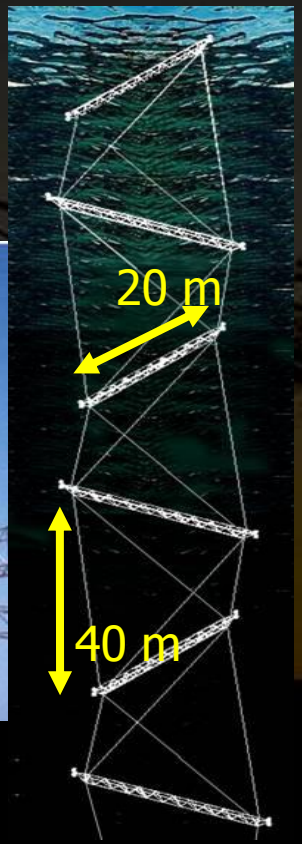


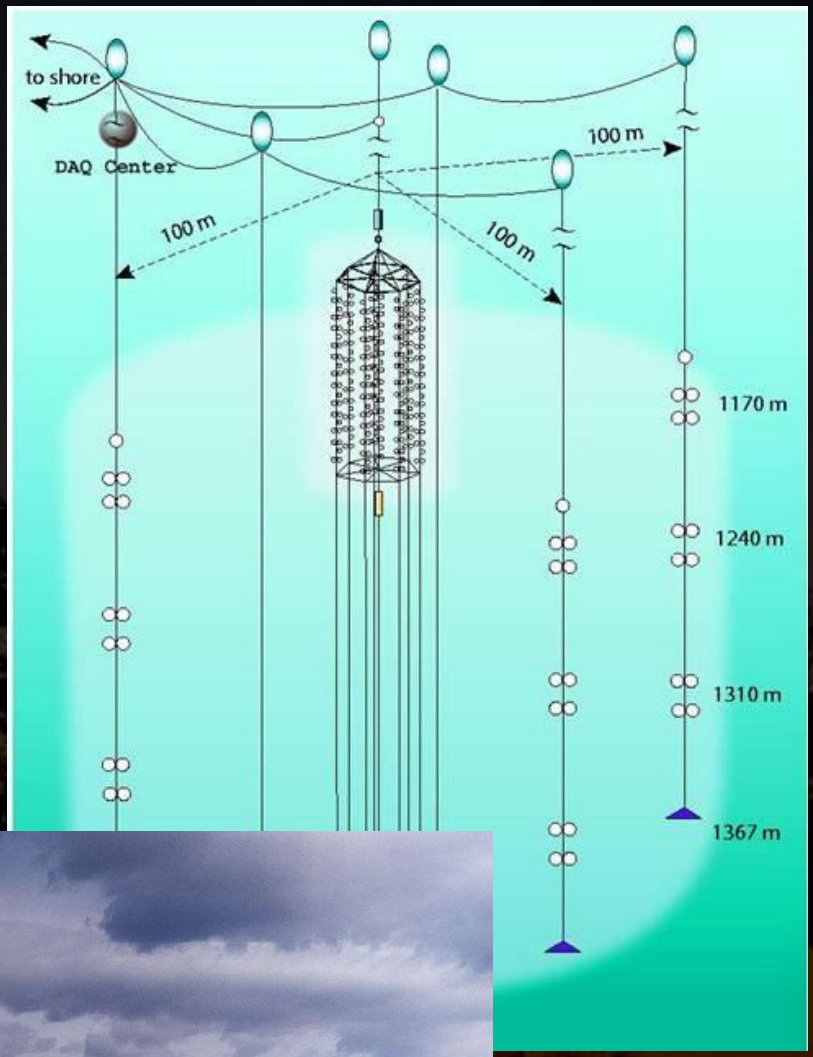


174 days
582 upgoing candidates
(multi-line fit)

Other Neutrino Telescopes

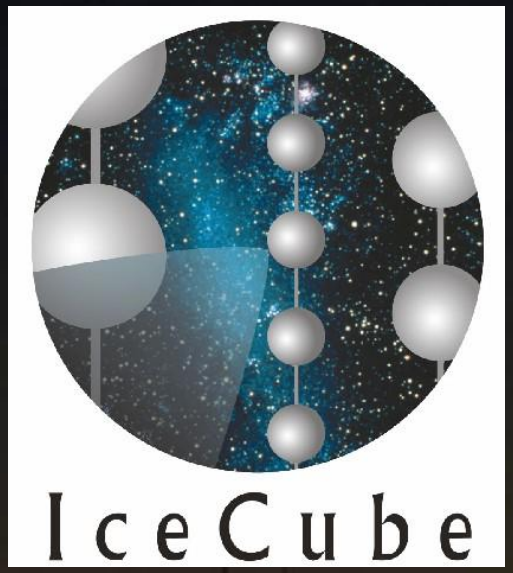
- Baikal NT-200+:
  - First operational neutrino telescope NT-36 in 1993, NT-200 in 1998
  - Expanded with 3 outlying strings for PeV events (2005)
- In Mediterranean sea:
  - Nemo (Italy)
  - Nestor (Greece)





Next generation: toward km^3

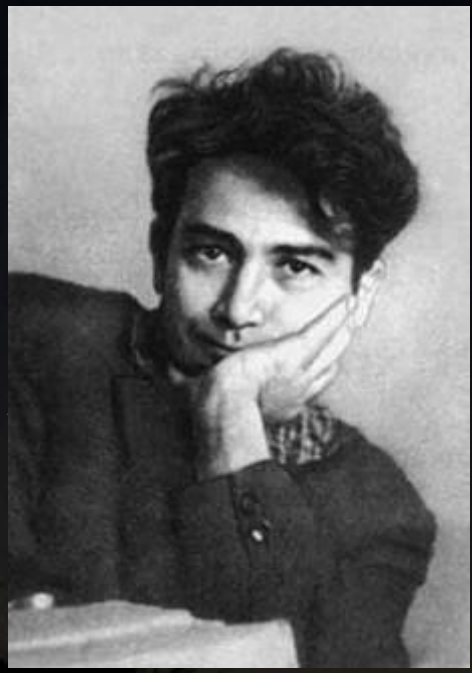
- In FP7…



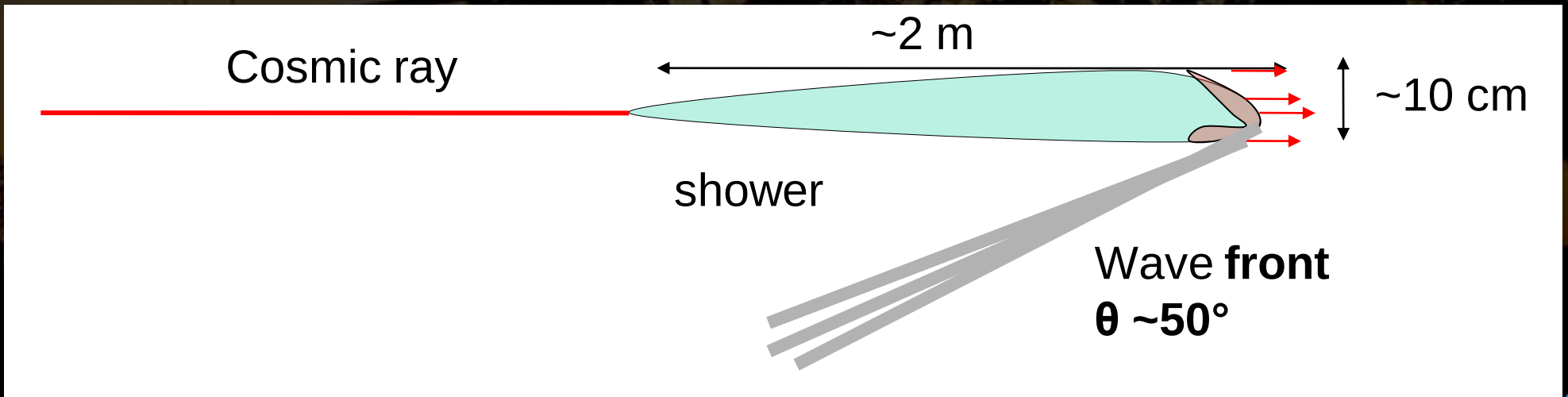
KM3NeT

RADIO DETECTION

Askaryan Effet (1928-1997)



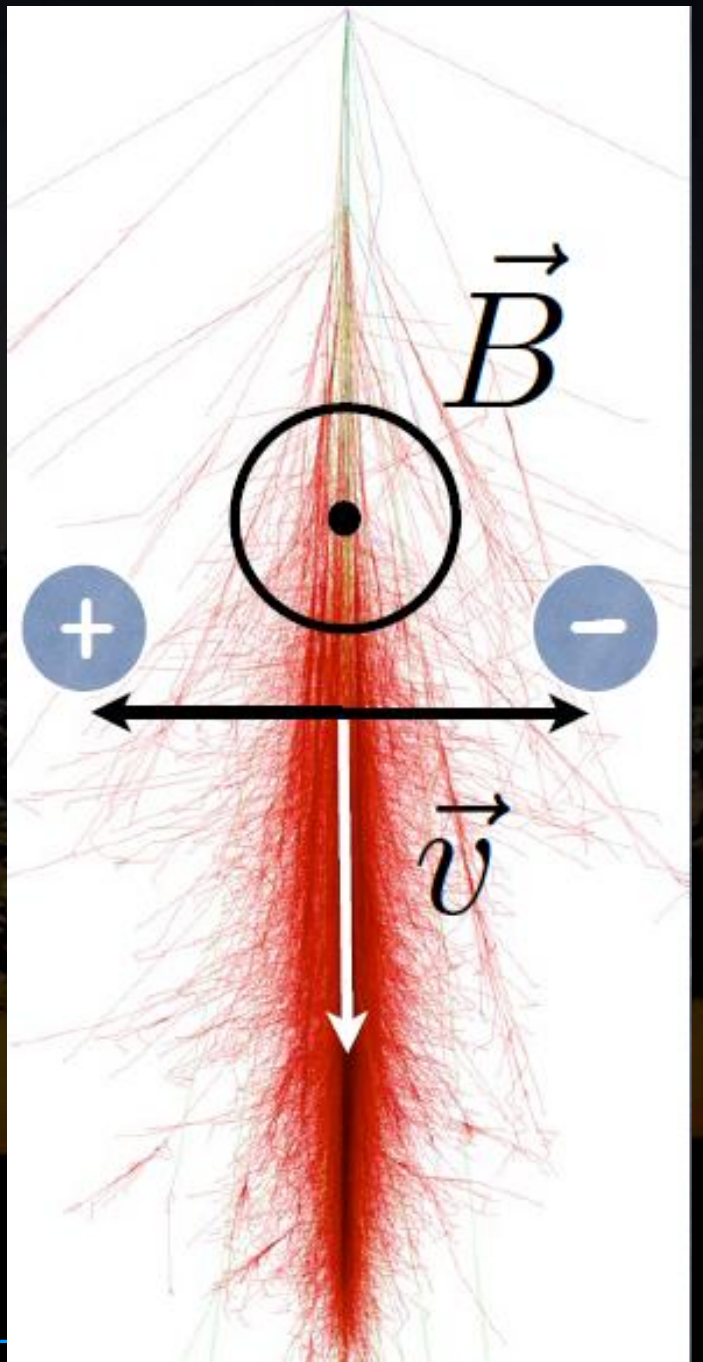
- Small e^+/e^- asymmetry in showers:
  - Positron Annihilation
  - Compton scattering
- Coherent Cherenkov forward emission, (2~5 GHz), emitted in matter (ice, salt, rocks) showers
- Confirmed in 2000 at SLAC
- Well adapted for neutrinos (emerging shower)
- Many experiments: FORTE, RICE, SALSA, GLUE



Other sources of radio emission

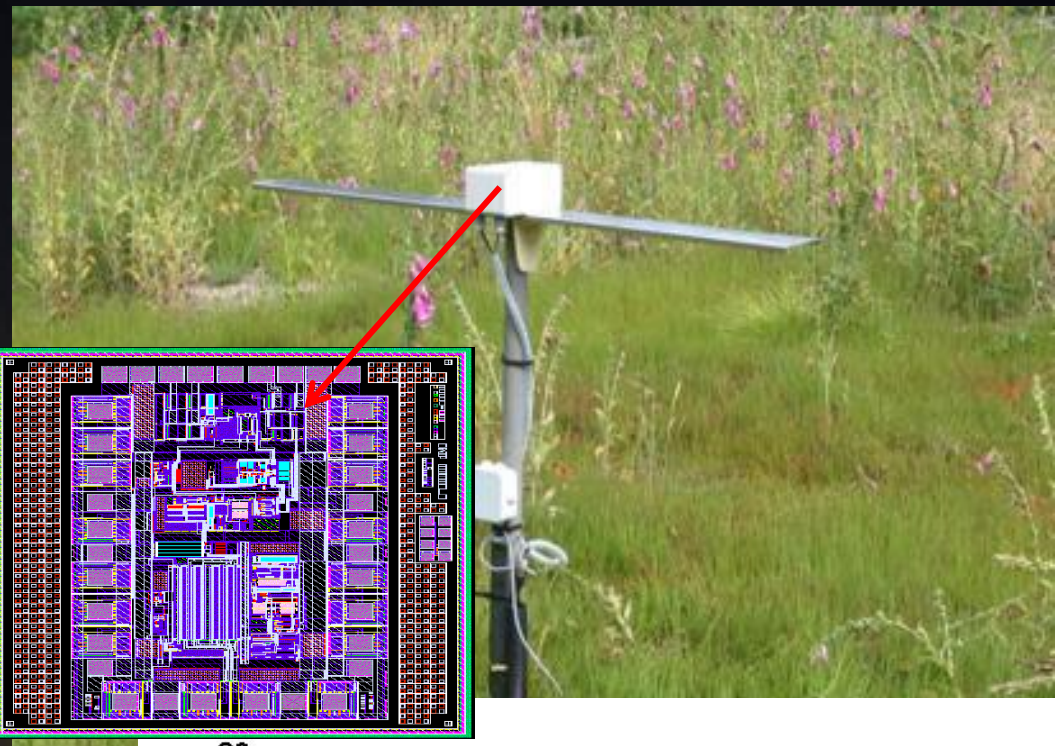
- Geomagnetic effect:
  - Earth magnetic fields separates electrons and positrons apart
  - Dipole in relativistic motion...
- Synchrotron emission of electrons
- Emission from the current
- ...

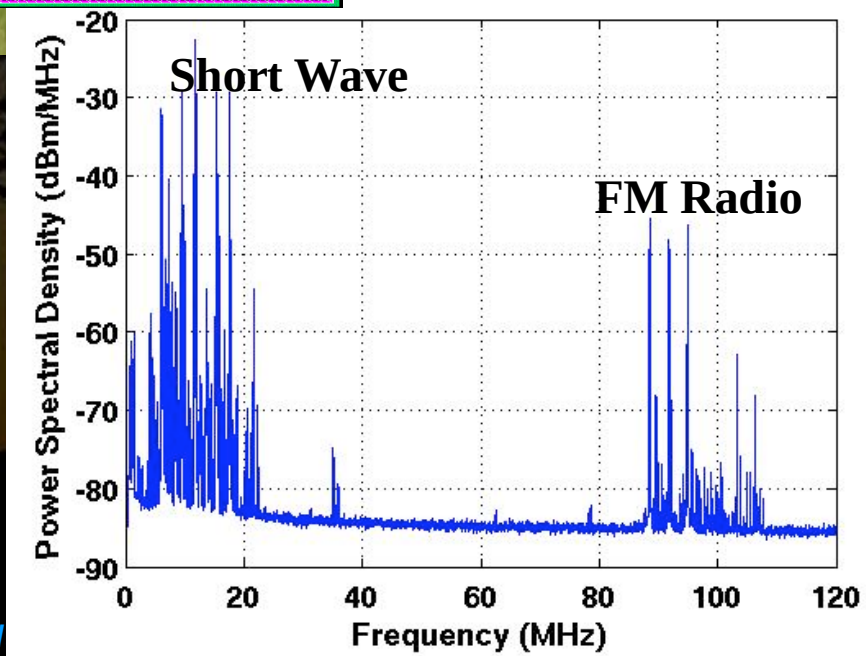
- Frequency band [1-200] MHz
- Monopolar signal
- Dependancy v × B



Why is radio interesting ?

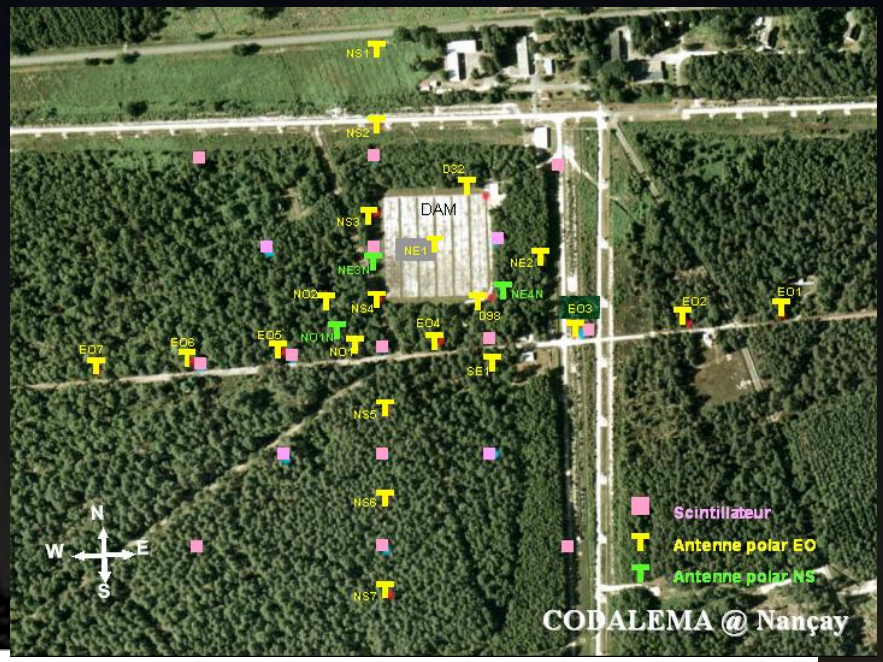
- Pretty inexpensive equipment
  - Active Dipolar antenna
    ~1 m × 10 cm
    Frequency band [1-200] MHz
  - Low noise amplifier (ASIC)
  - Fast ADC (300 MHz)
  - Cost ~ 4000 Euros
- Duty cycle ~100 %
- Efficiency ~100 %
- Calorimetric Measurement
- Timing and lateral distribution allow reconstruction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

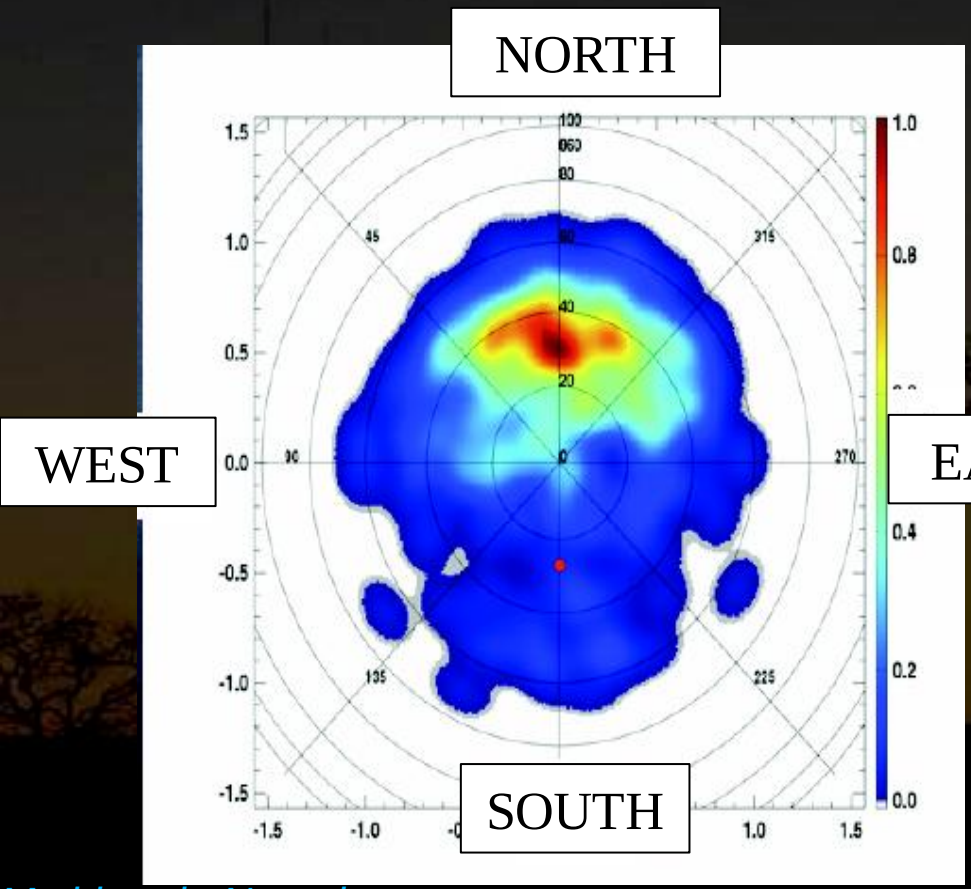


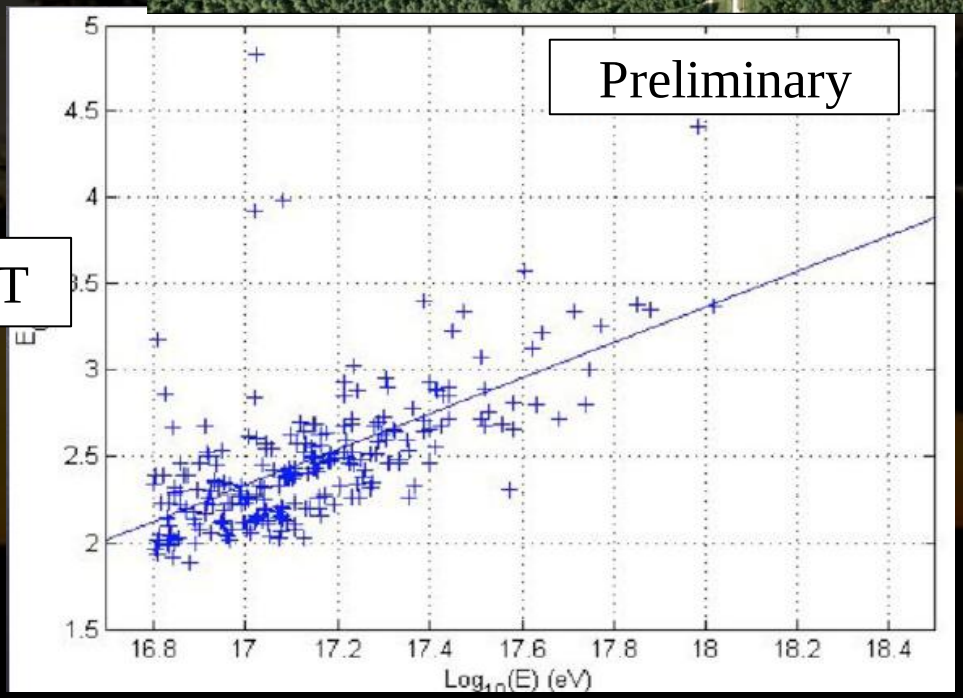


Radio detection of showers: CODALEMA

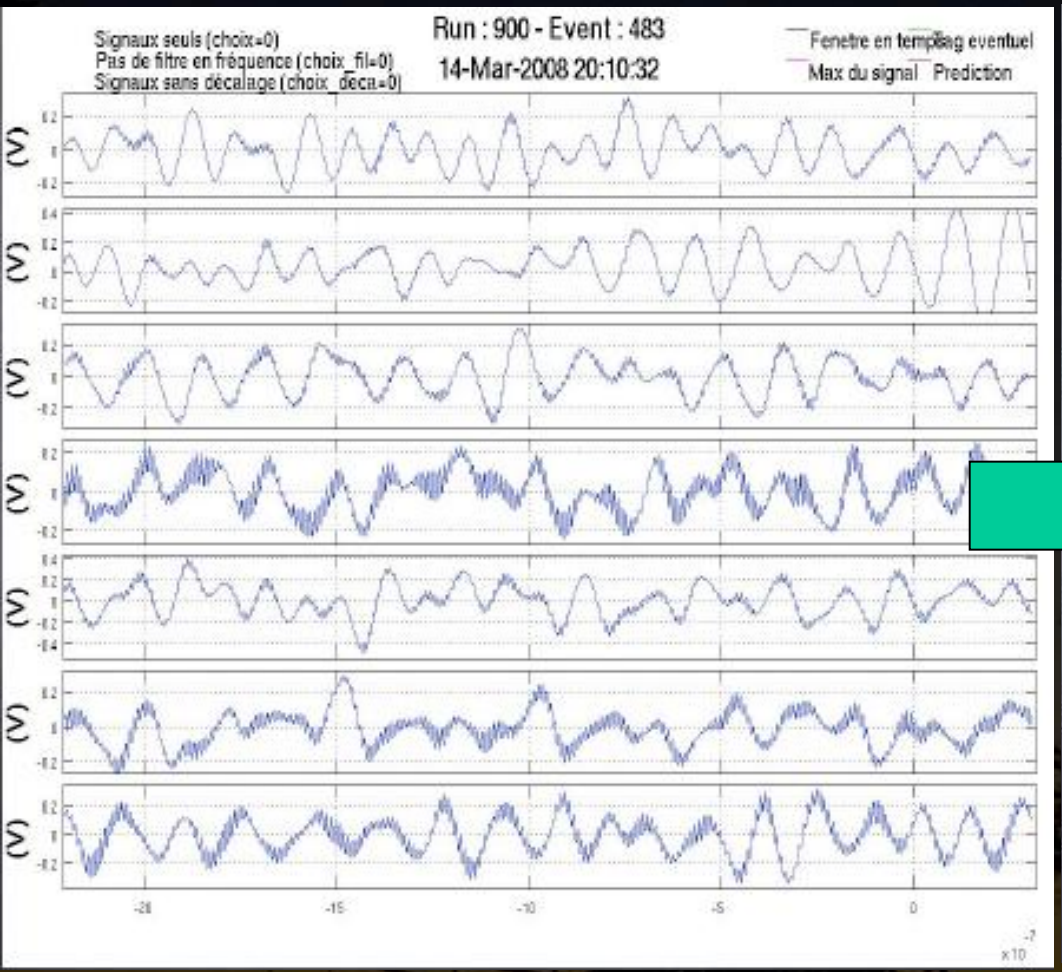
- Clear asymmetry in arrival directions
- Unambiguous proof for geomagnetic effect
- Electric field amplitude proportional to energy ⇒ calorimetric measurement?

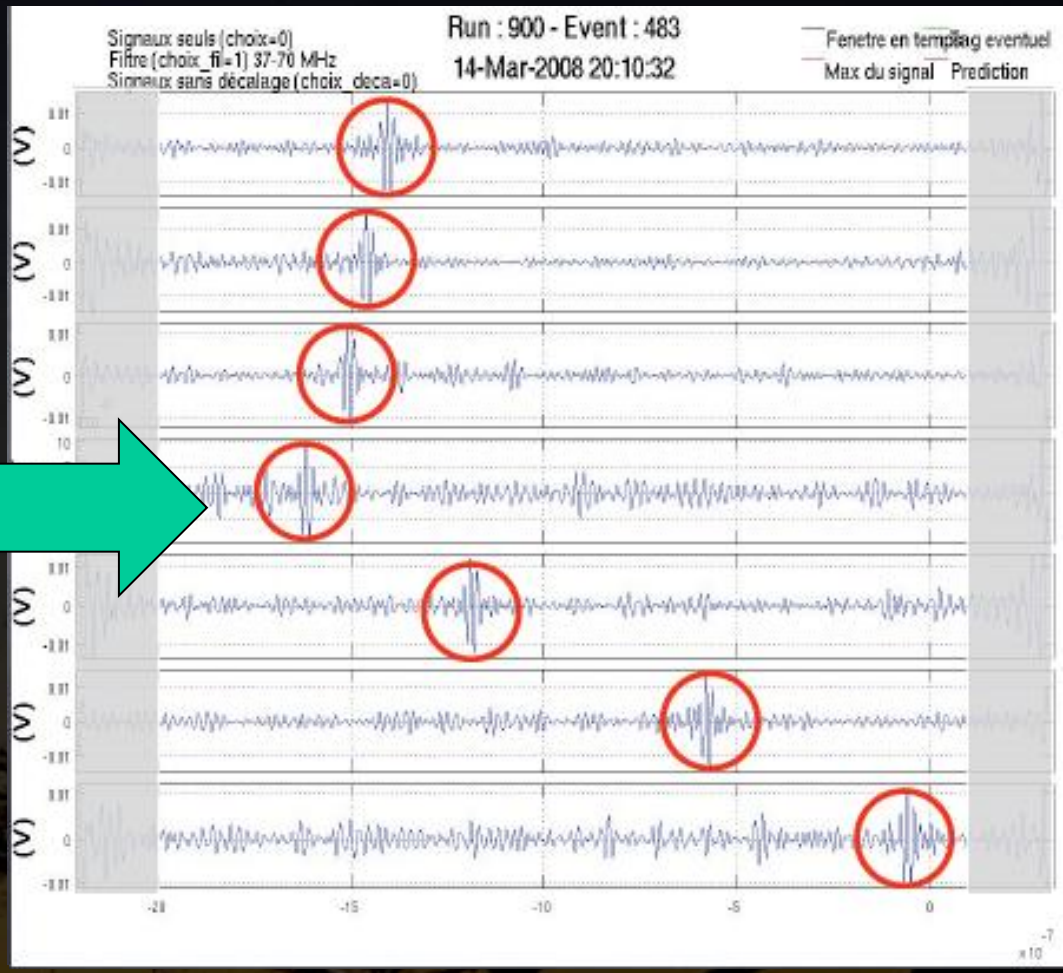






Signal Processing



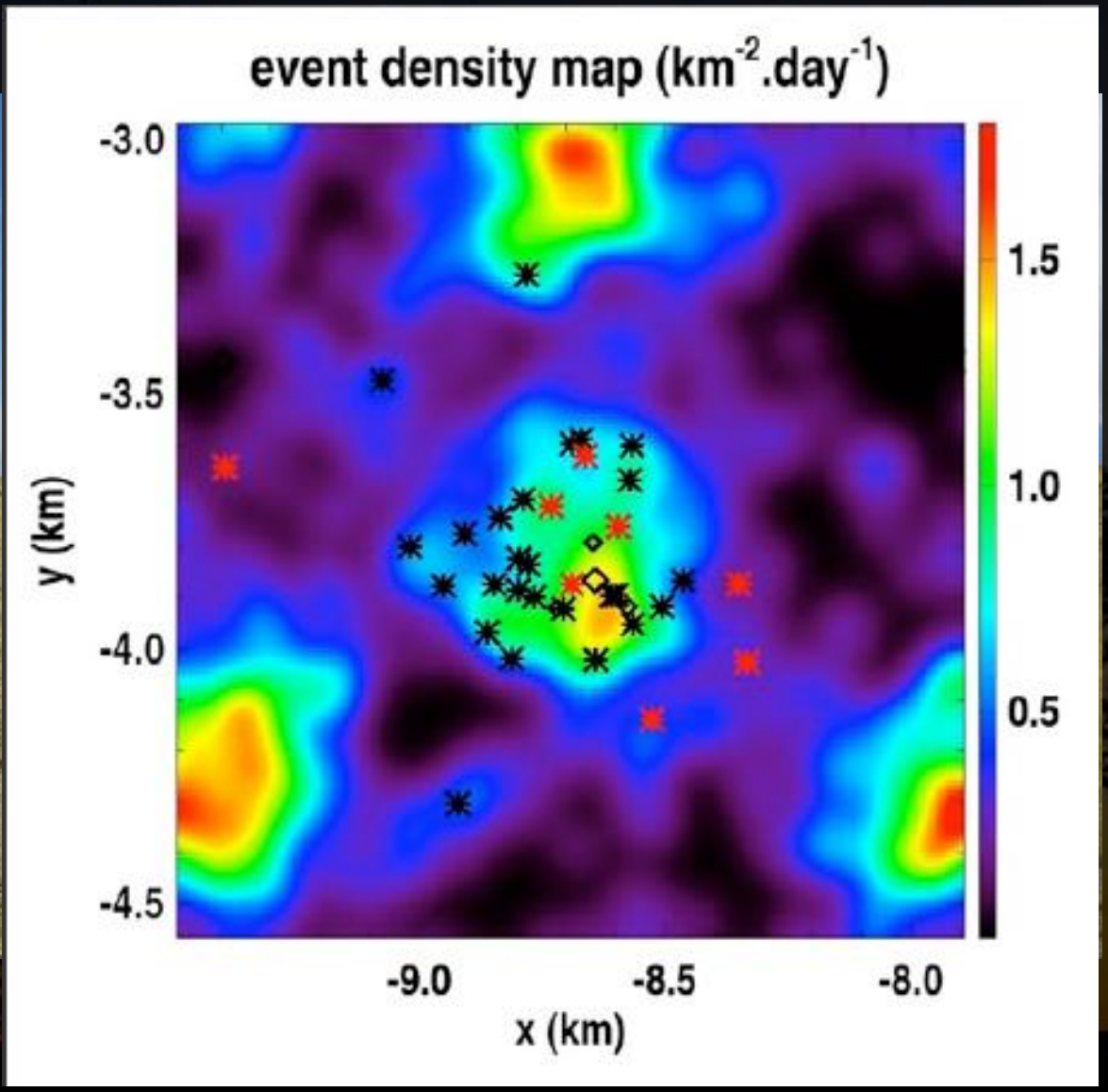


Raw signal, SD trigger, 1Gs/s

23-82 MHz filtering

- Timing measurement is possible
- Simple trigonometric reconstruction

Radio Detection @ Auger

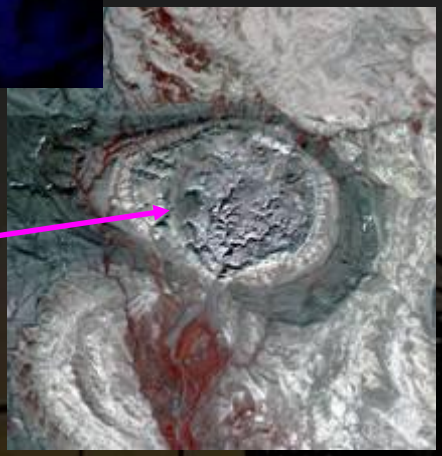


- Autonomous prototype installed @ AUGER
- First detection: July 2007
- 39 events in coincidence with Auger SD (SD trigger)
- First self-trigger announced recently
- Radio detection seems to work up to 1 km away from antennas
- Radio detection seems to work for horizontal showers

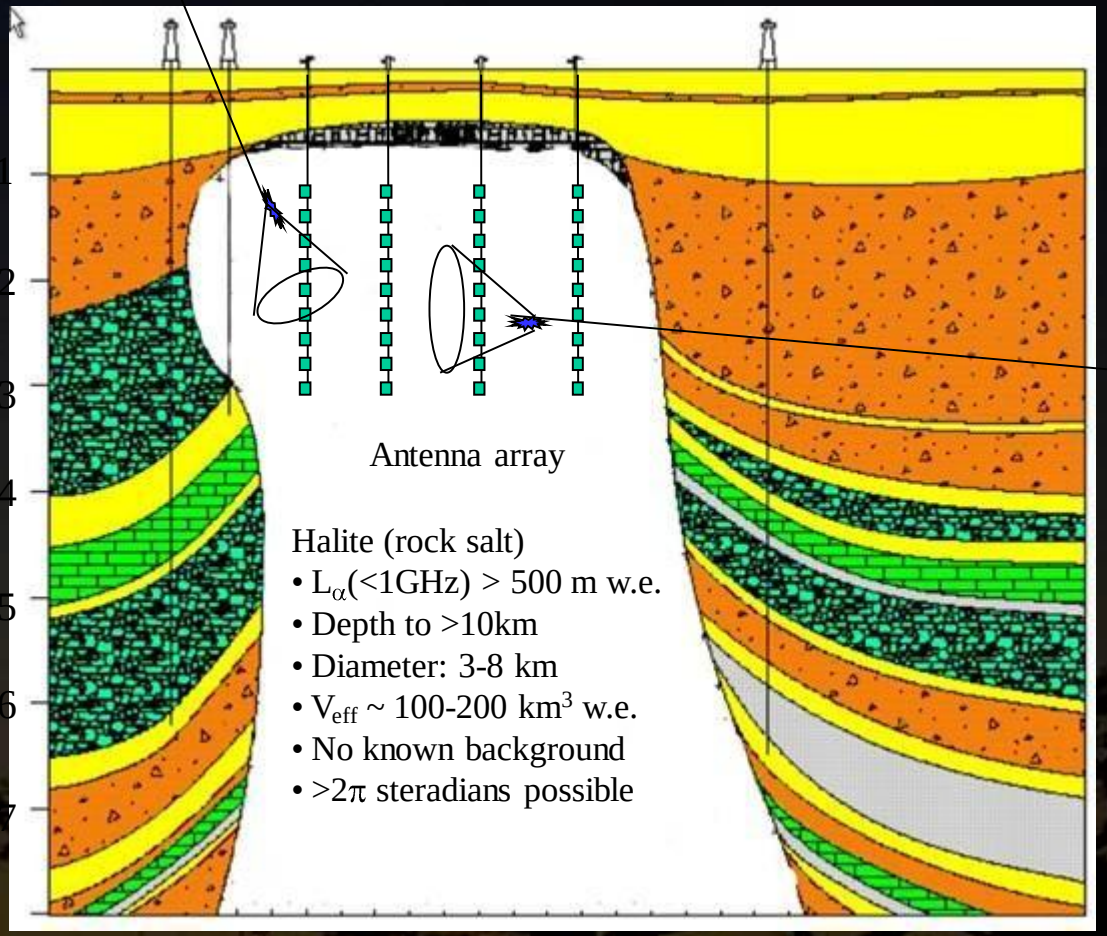
Saltdome Shower Array (SalSA)

Salt domes: found throughout the world

Qeshm Island, Hormuz strait, Iran, 7km diameter



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

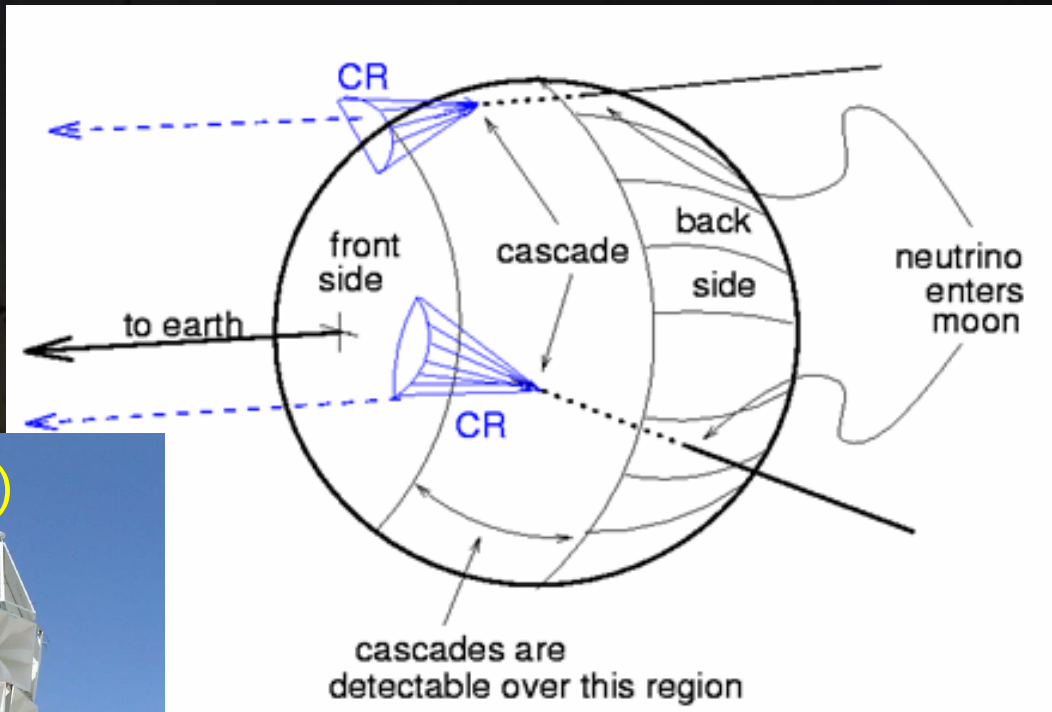


- Domes de sel transparents aux radio fréquences, pas d'eau
- Volumes de 50-100 km^3

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)

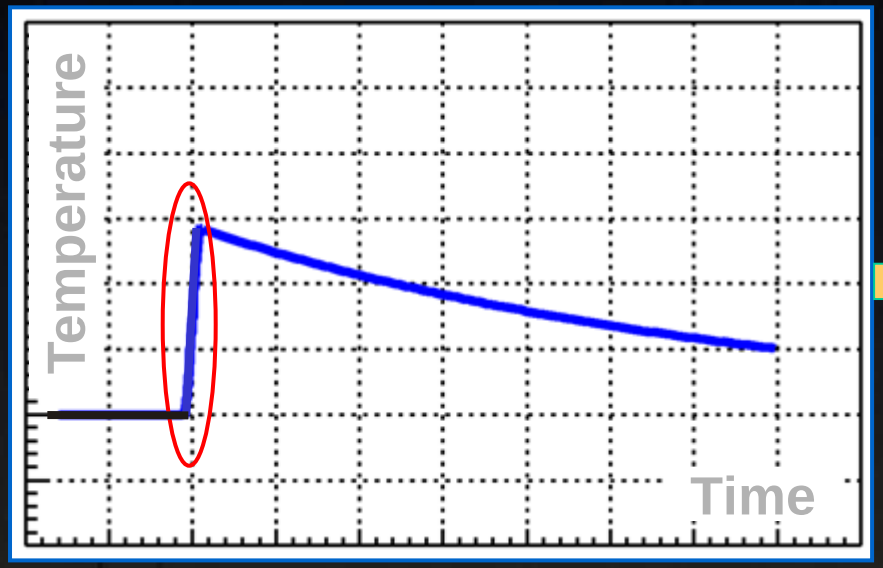
radio from neutrinos hitting the moon

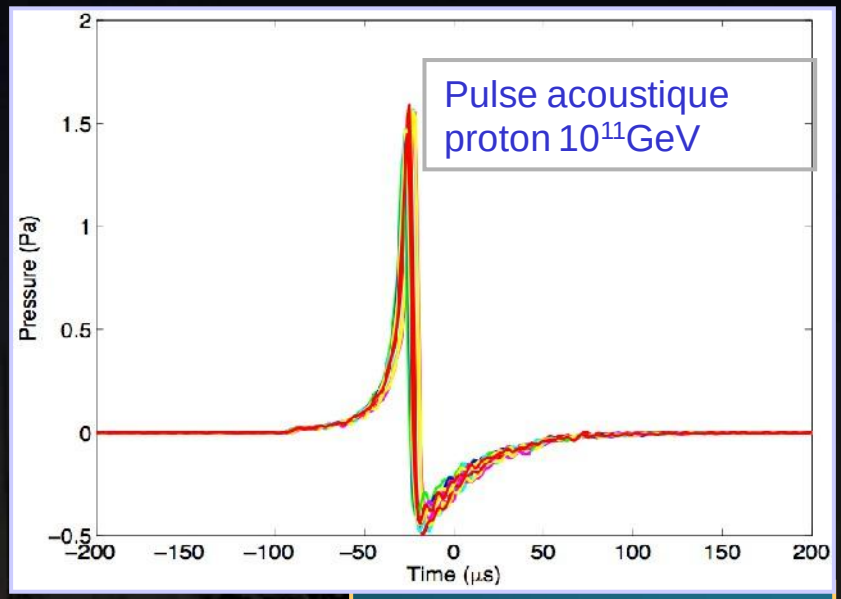


NuMOON @ Westerbork

ANITA (lite)

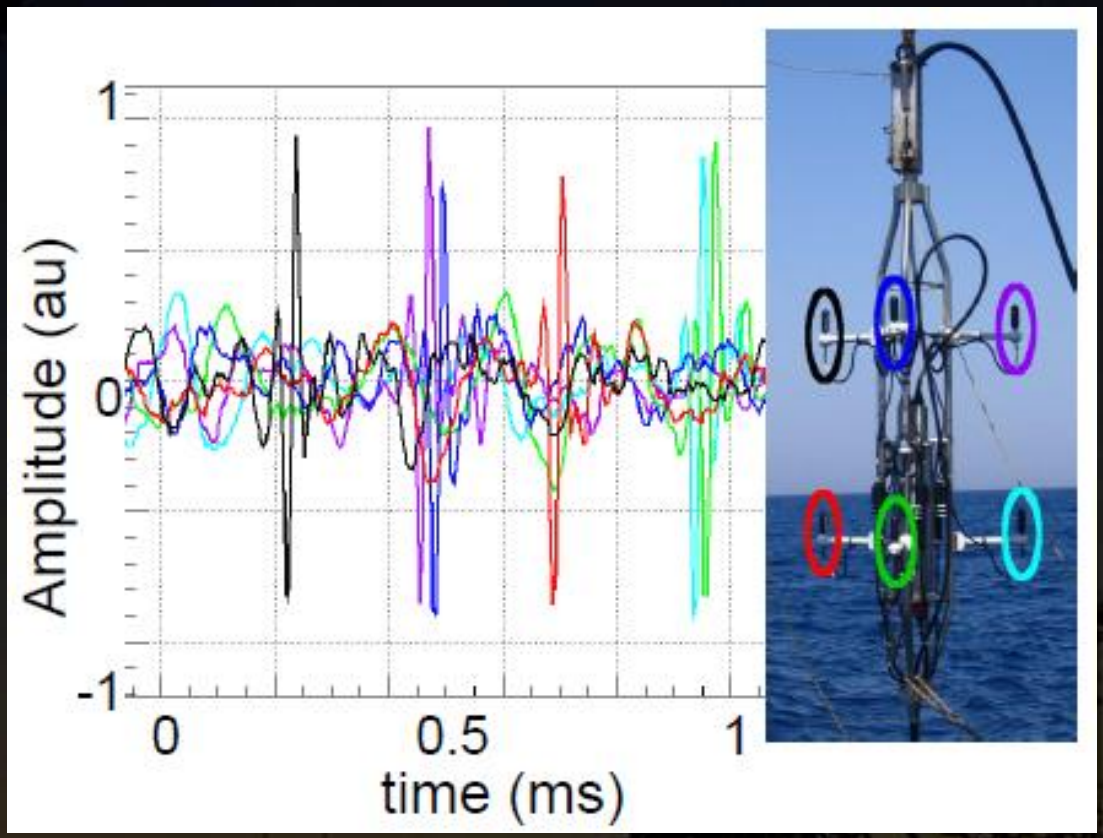
Acoustic Detection

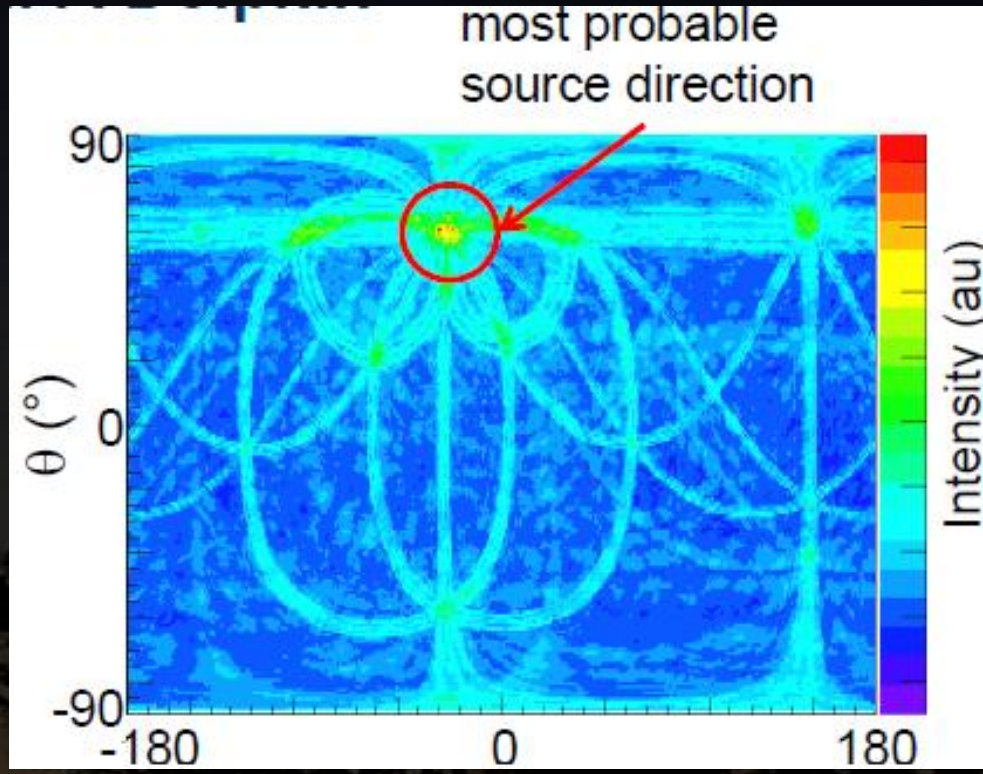




- Acoustic wave triggered by shower
  - quasi-instantaneous energy deposit
  - water dilatation ⇒ dipolar acoustic signal
  - Ongoing R&D in several sites (Baikal, Antares, IceCube, …)
- Challenges : background noise (waves, whales, dolphins, ships, …)

Direct reconstruction – A dolphin



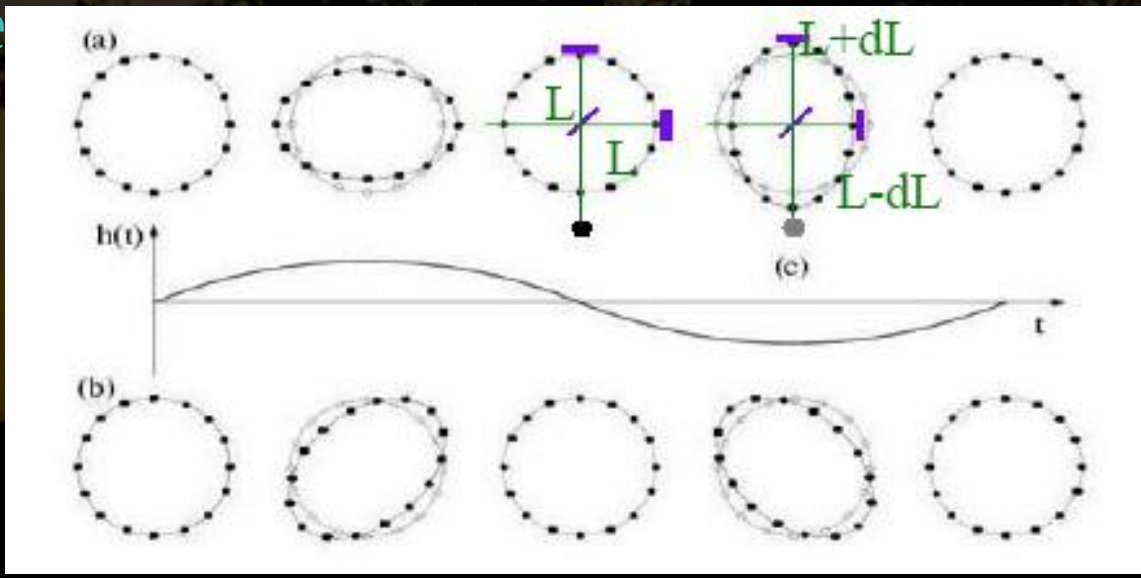


- Acoustic signal amplitude on several hydrophones
- Beam forming algorithm leads to angular resolution < 1°

GRAVITATIONAL WAVES

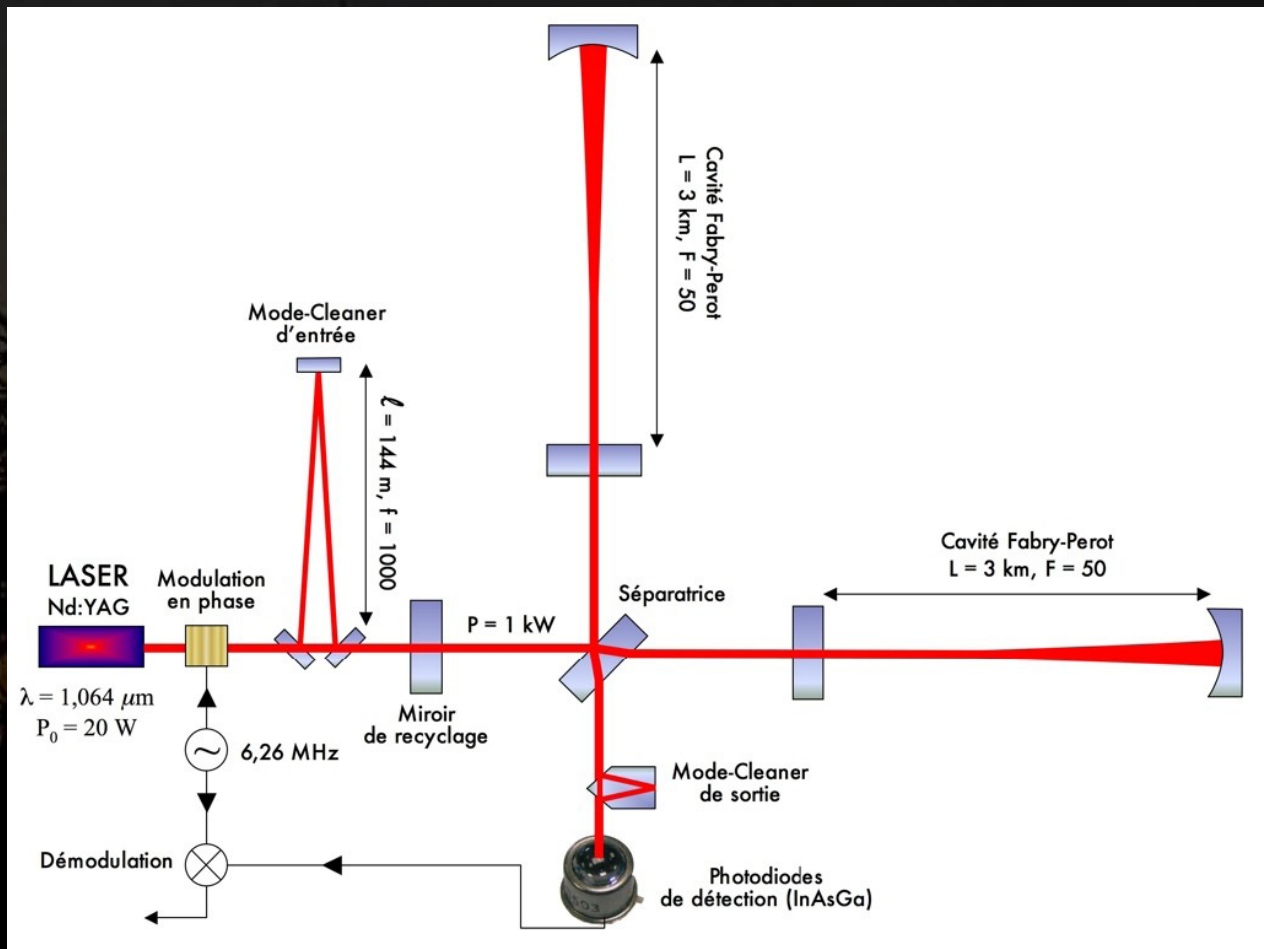
Gravitational waves

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

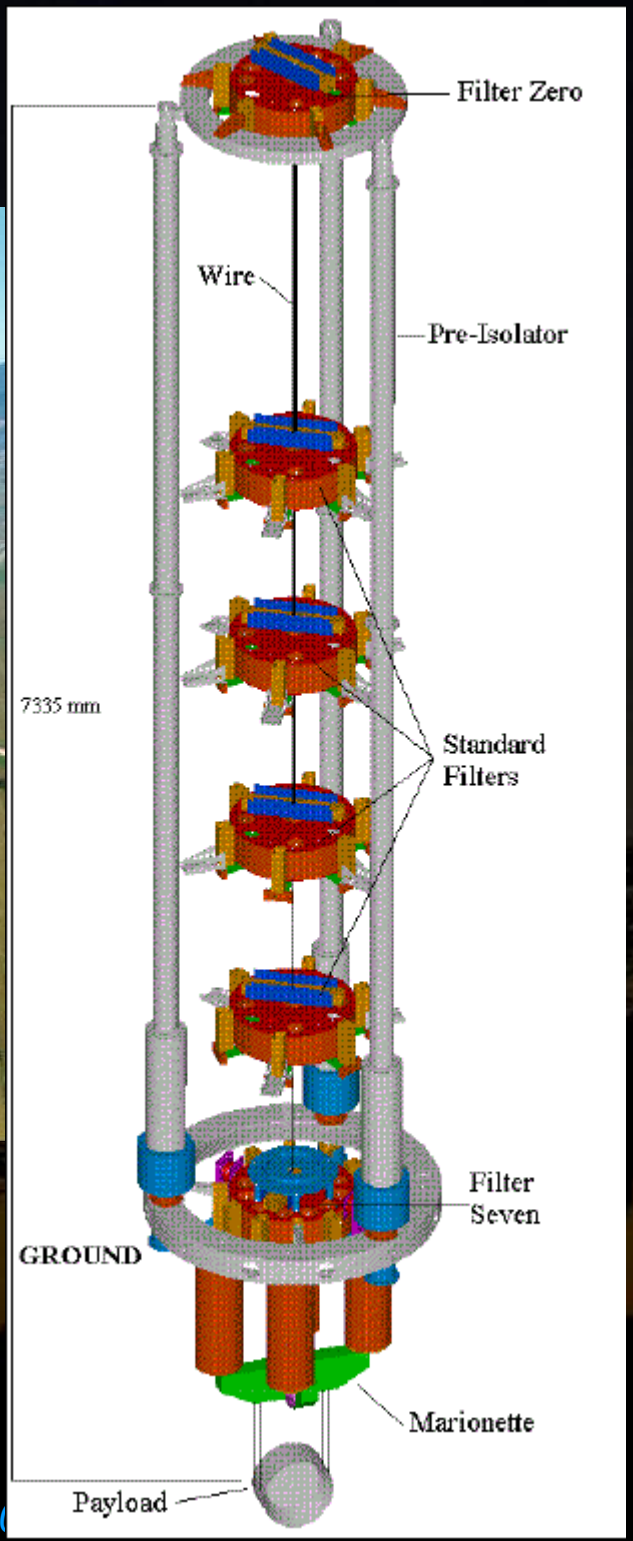


Detection Principles

- 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

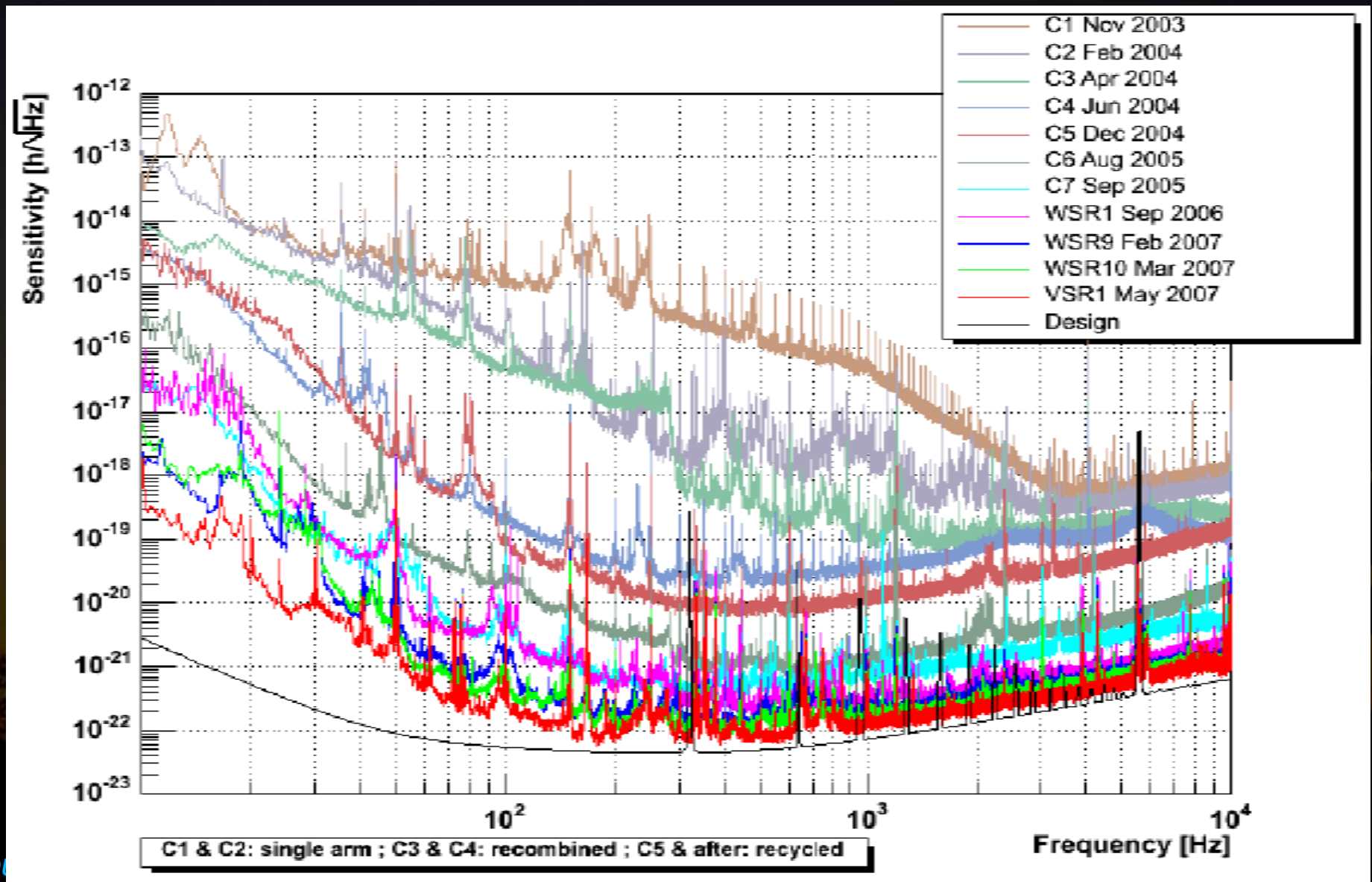


VIRGO


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



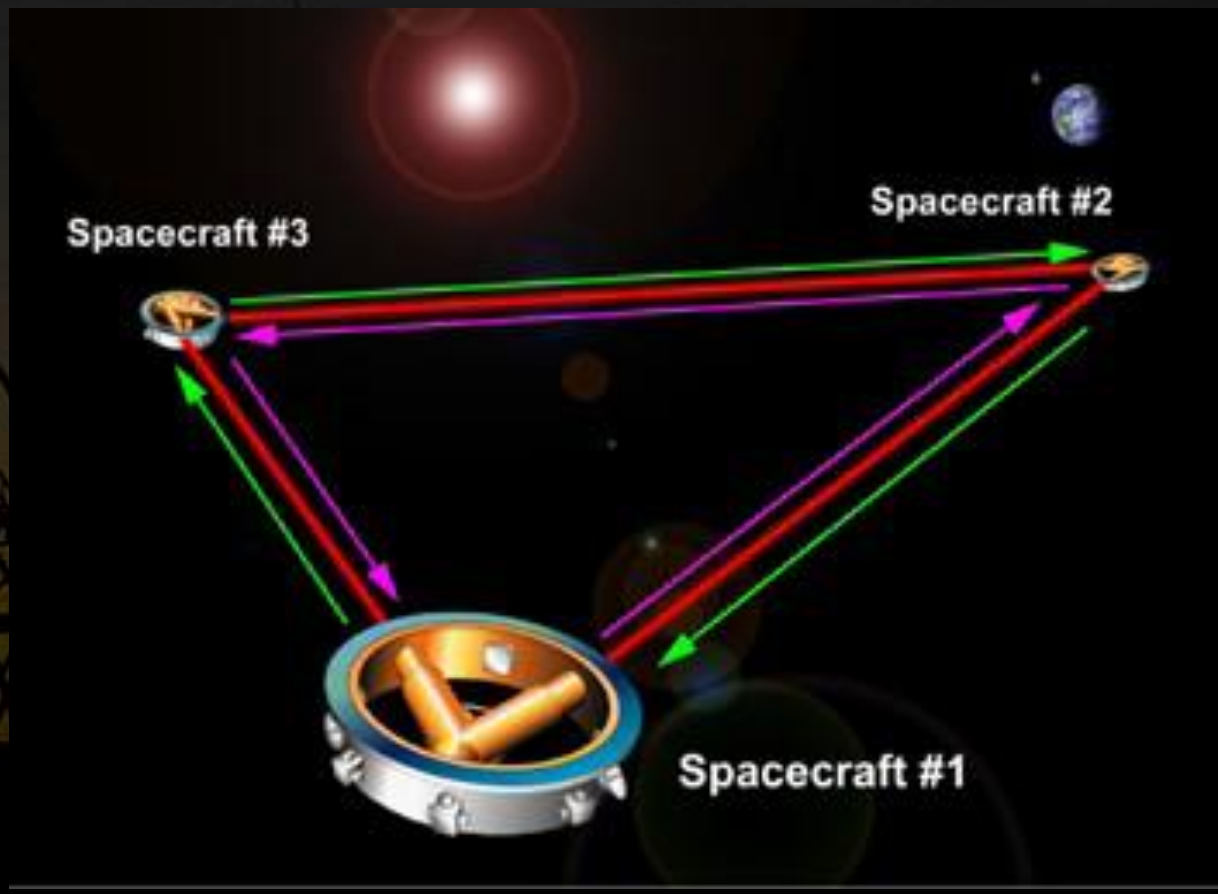
LIGO

- 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)

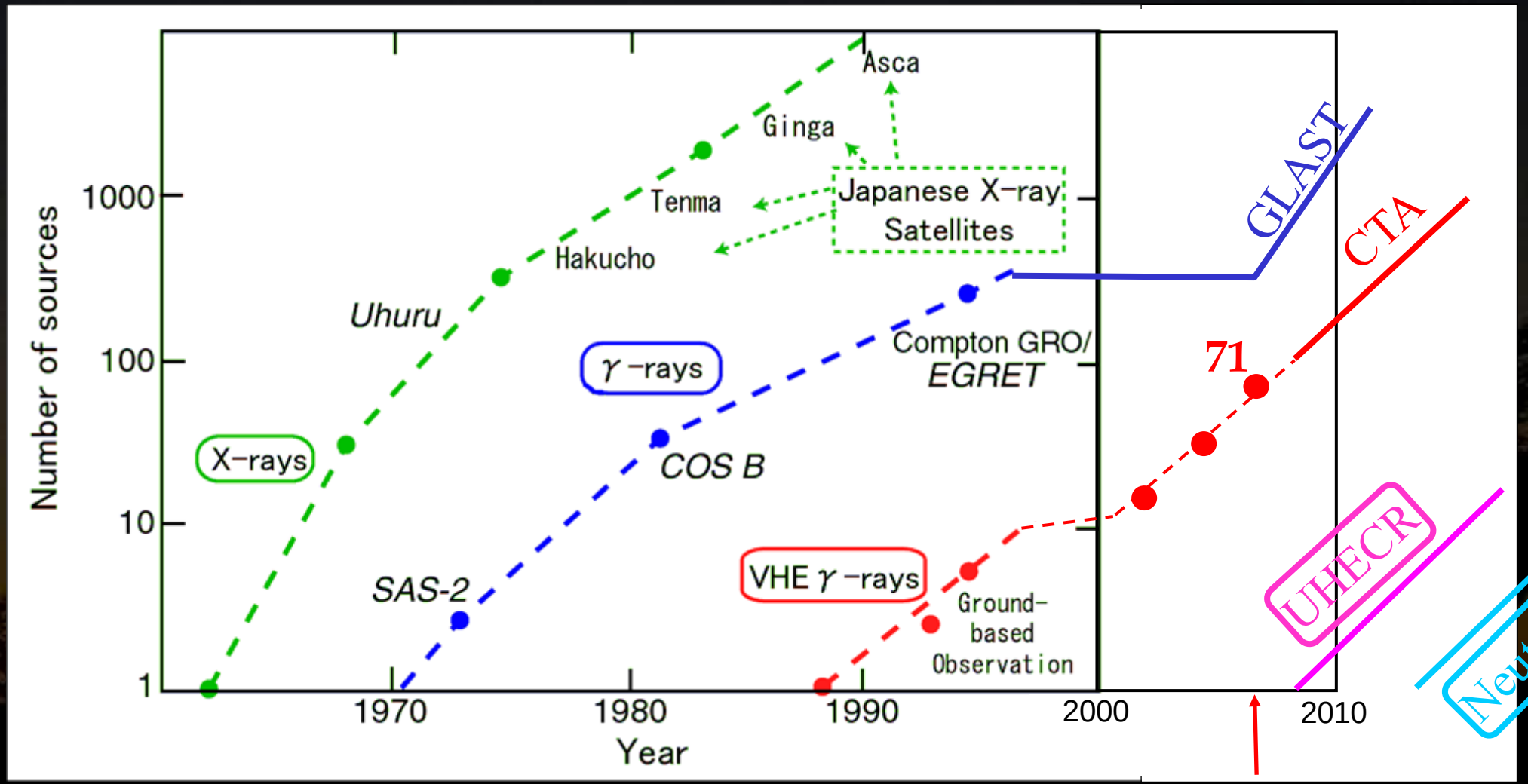
- The γ-ray sky in surprisingly full of sources
  - High spin-down pulsars
  - Supernovae remnant are able to accelerate particles to E > 100 TeV, most probably protons (e^- disfavored as they required low B fields)
  - Interaction of CR with ambient matter (molecular gaz) strongly support hadron production 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




Backup

GENERAL ASPECTS

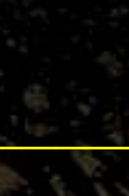
The Electromagnetic spectrum

keV MeV GeV TeV PeV EeV

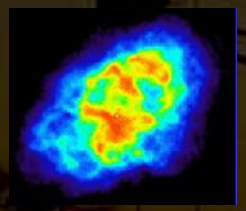
10^{-6} 10^{-3} 10^{0} 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} E (eV)

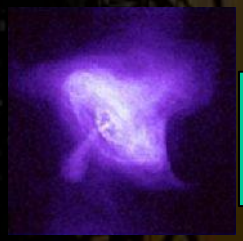
1 10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15} 10^{-18} 10^{-21} 10^{-24} λ (m)

10^{8} 10^{11} 10^{14} 10^{17} 10^{20} 10^{23} 10^{26} 10^{29} 10^{32} ν (Hz)



Radio *IR* *Visible* *UV* *X-Rays* *γ-Rays* *VHE* *(Very High Energy)* *UHE* *(Ultra High Energy)*





Astroparticles

Cold objects (10K), Dust,... Synchrotron emission of electrons

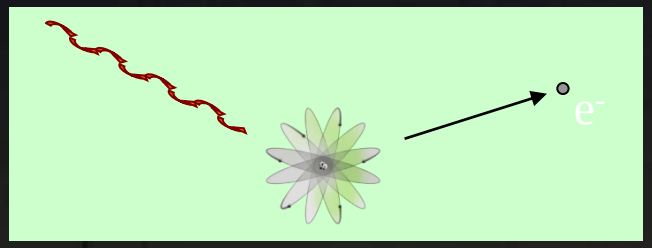
Hot objects (~2000K), Sun, Nebulae

Very hot compact objects (~10^{6}K), pulsars, black holes... Size ~km

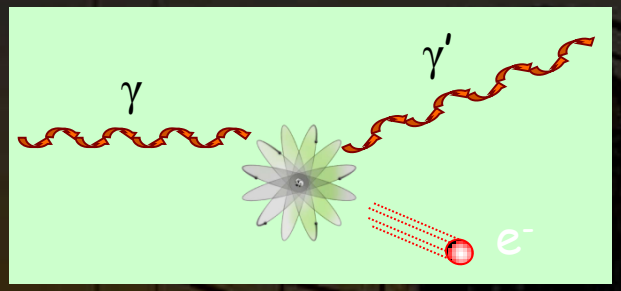
Exteme objects. Non-thermal processes (Particle Acceleration in astrophysical) Inverse Compton, Bremstrahlung, Annihilation, Pions Disintegration

Detection of photons

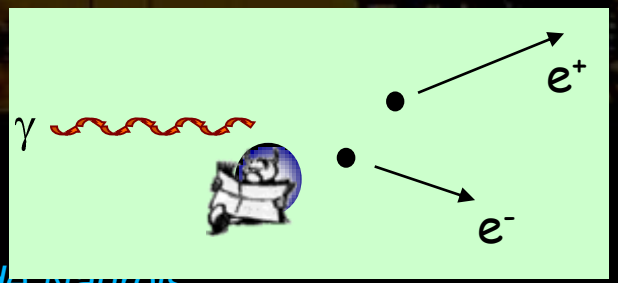
- Photons cannot be directly detected:
  ⇒ Production of charged particles
  - Photoelectric effect



  - Compton Scattering



  - Pair creation



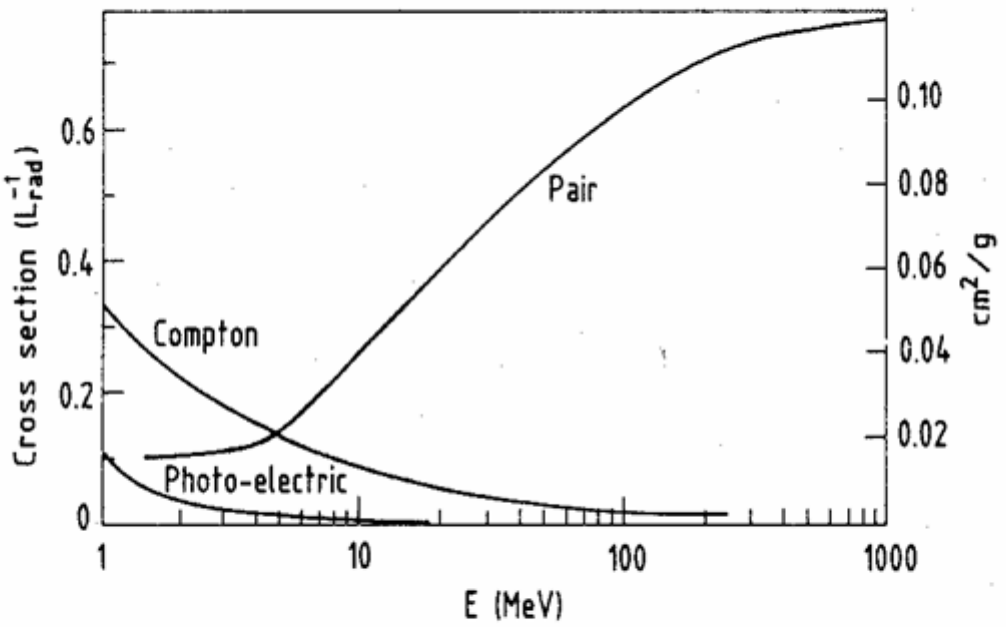
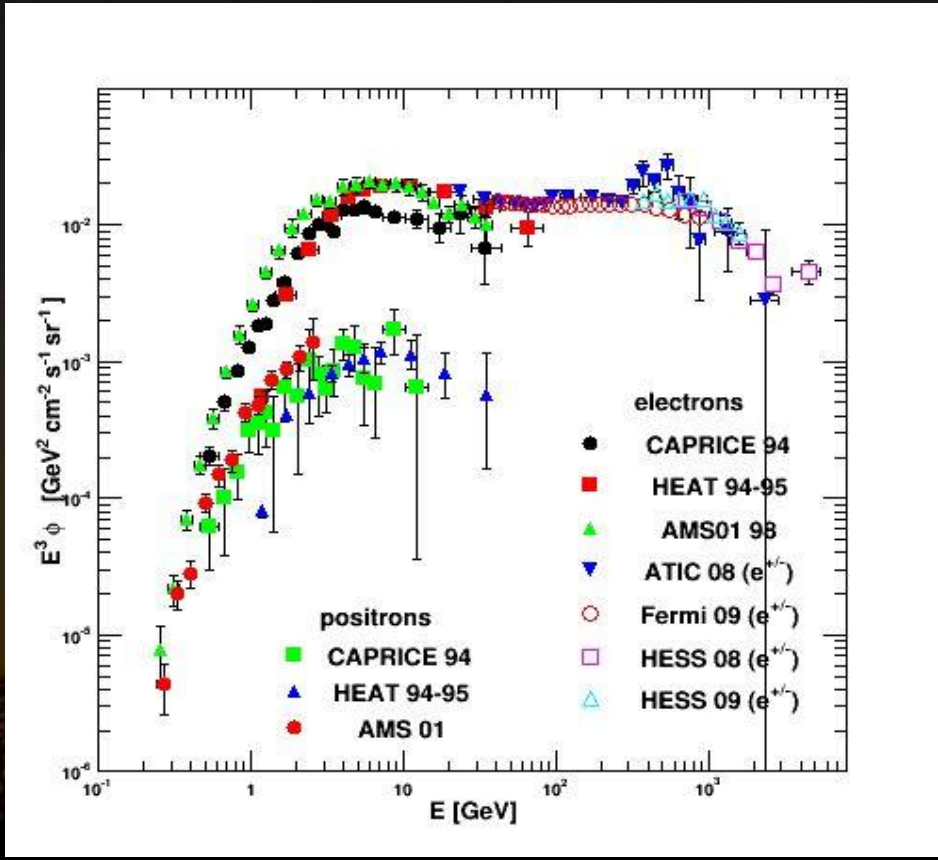


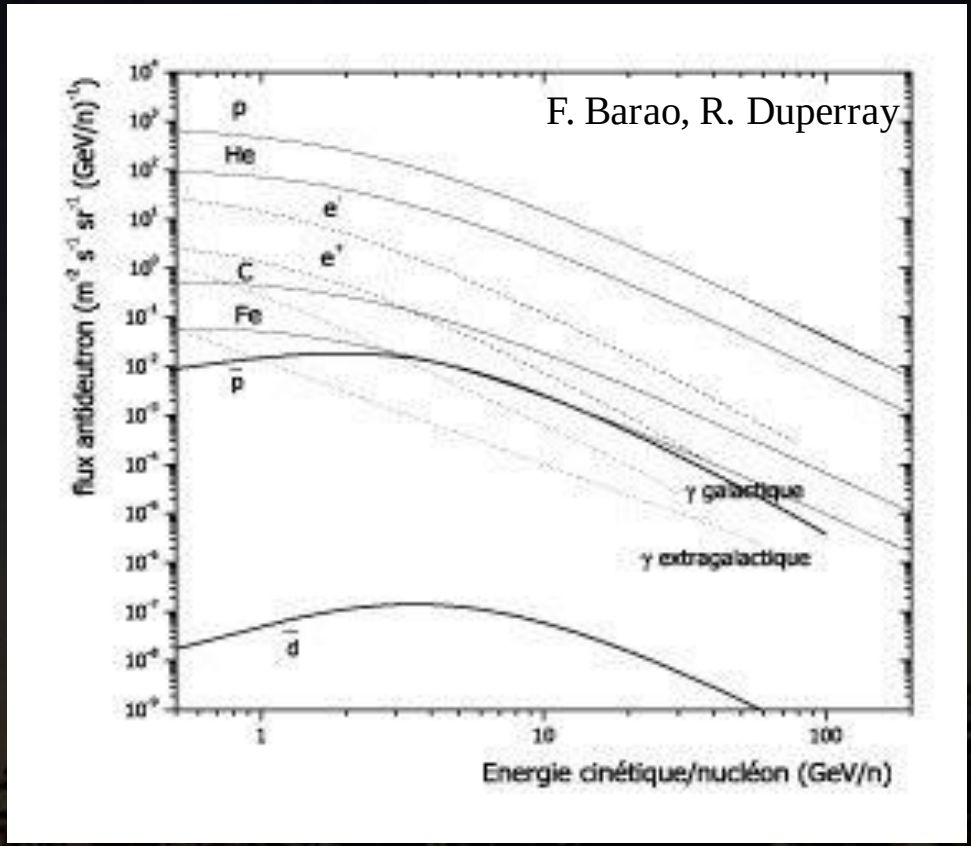
Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

CHARGED COSMIC RAYS

Composition – II

- Other species:
  γ, ν, antiparticles





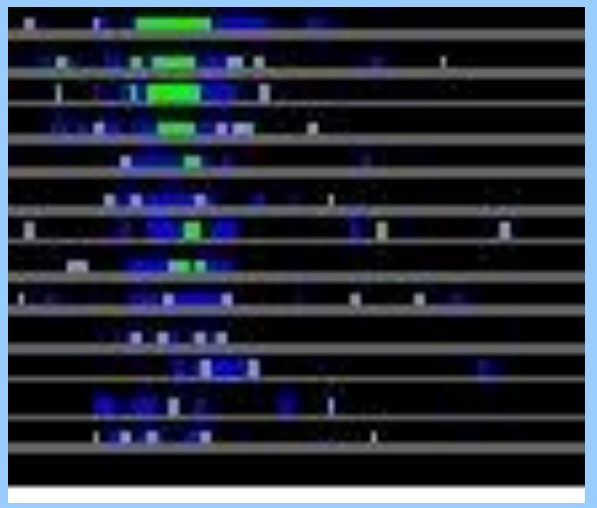
Secondary/primary depends on propagation history

Excess with respect to predictions can be a signature of new physics

PAMELA Calorimeter

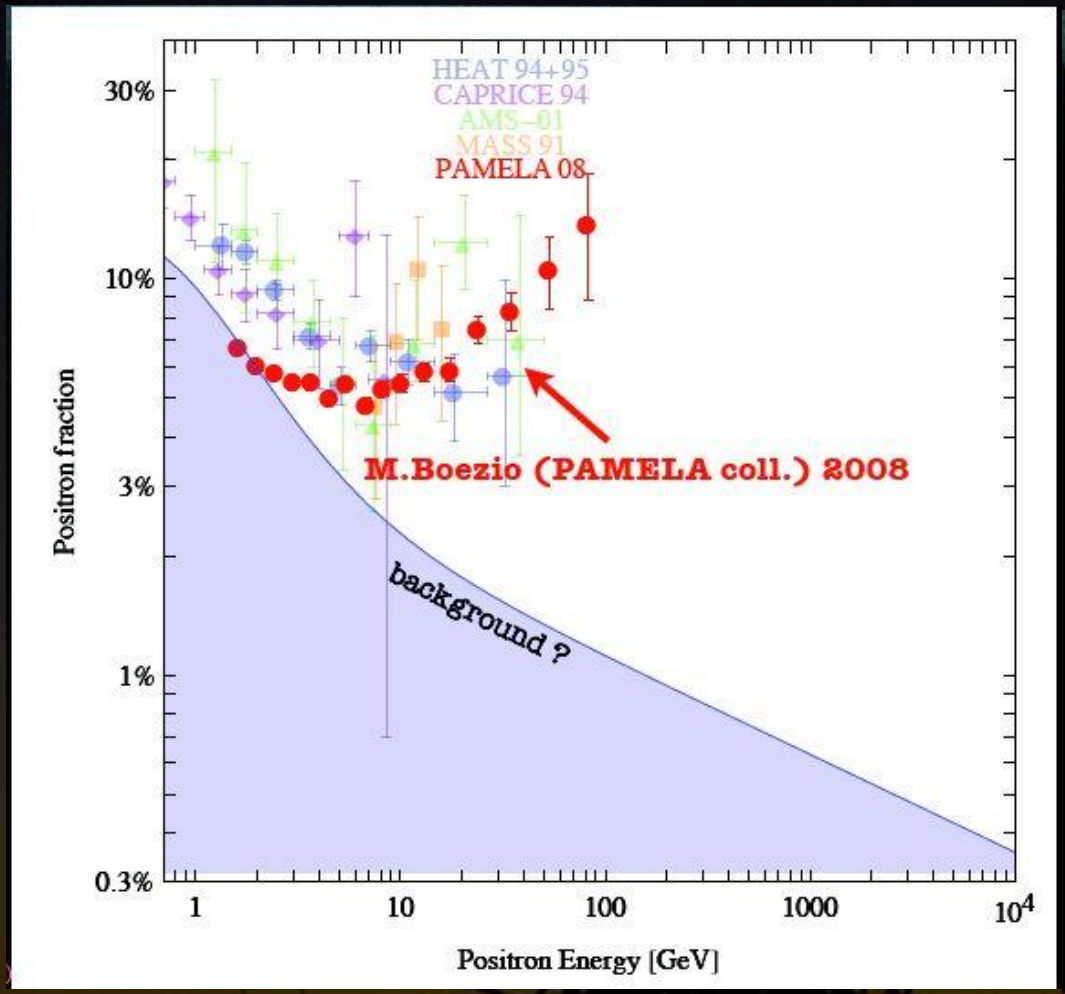
hadron (R=19GV/c)

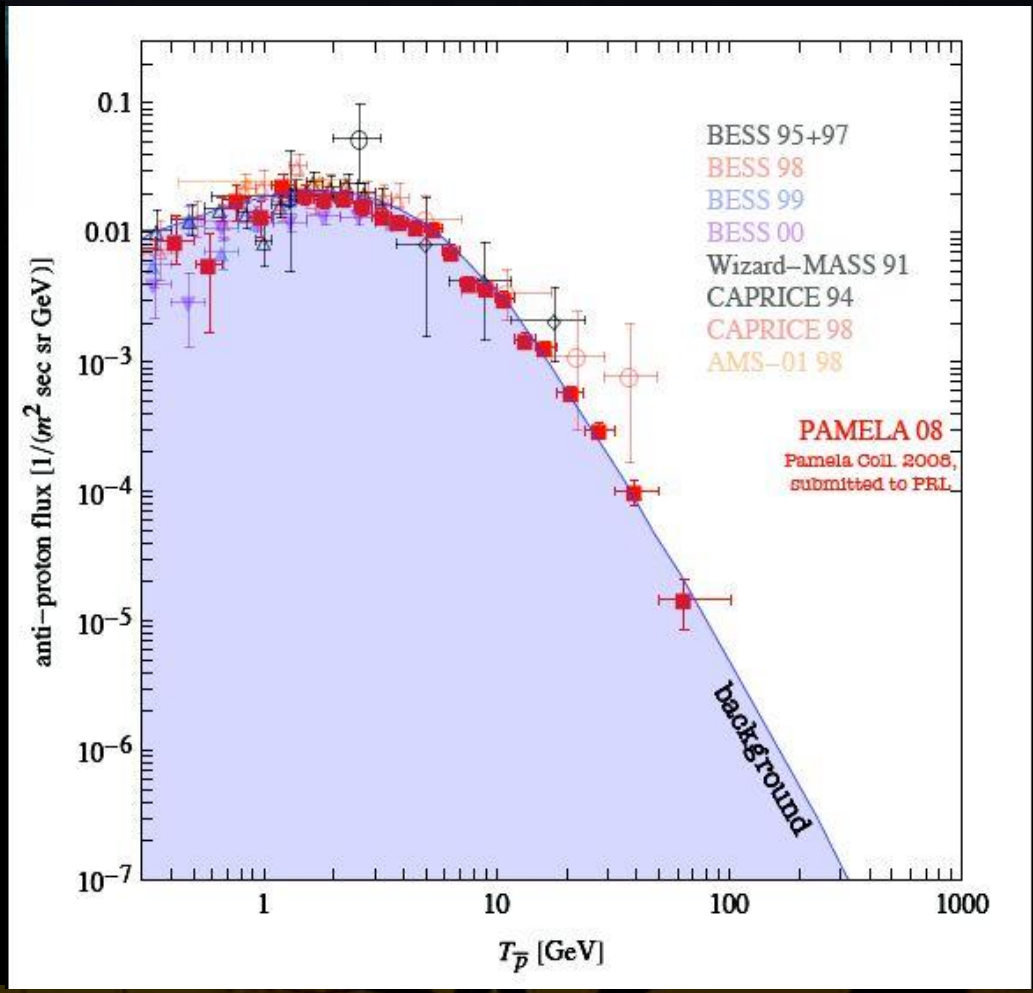
electron (R=17GV/c)



- 22 modules, crossed Si planes with tungstene layers
- Total length 16,3 X_0, direct measure of dE/dx on the planes
- Neutron detector improves rejection

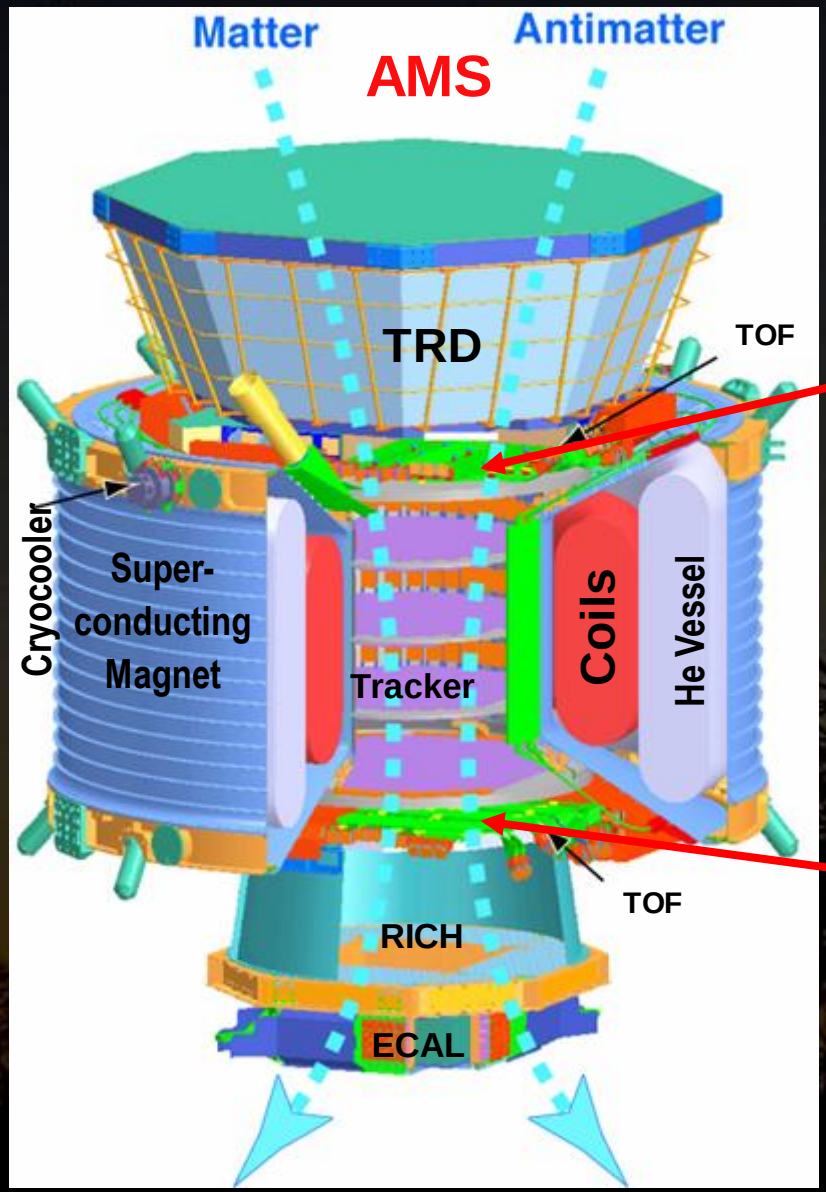
positrons and antiprotons

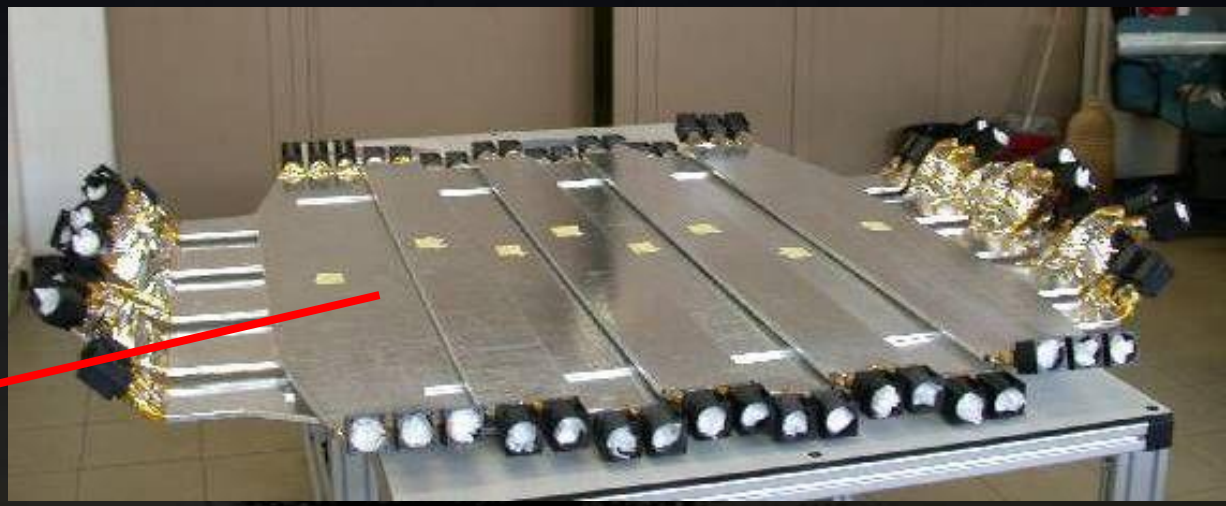




Time of flight

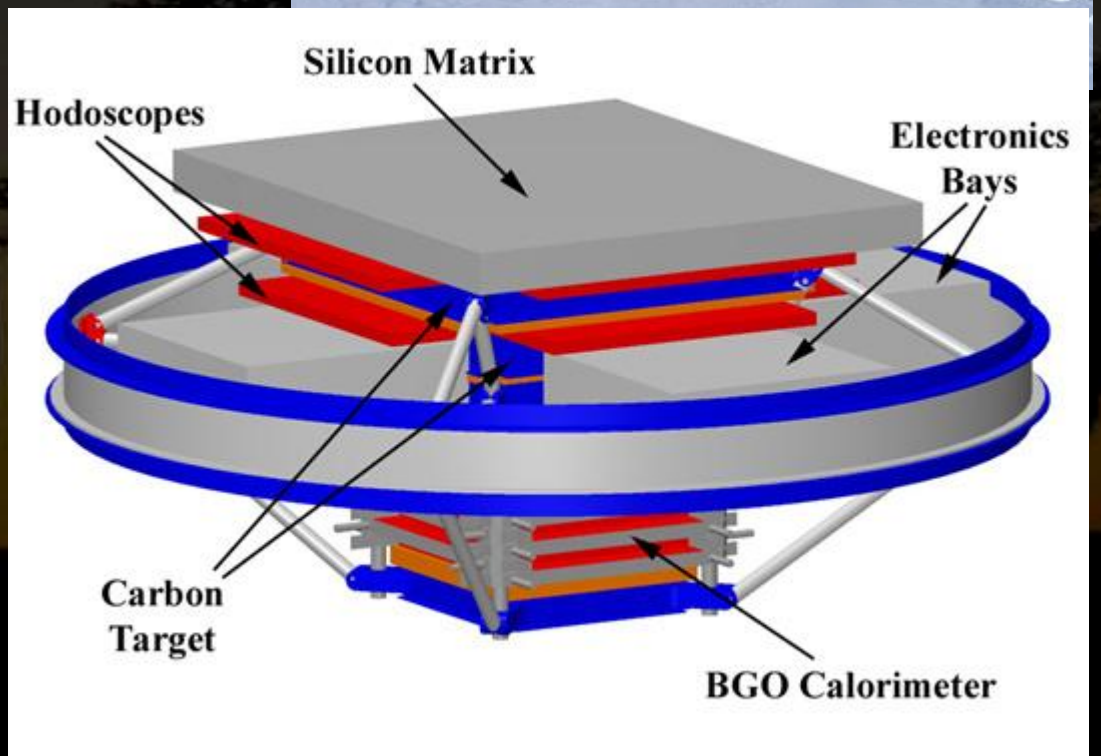
Time of light measurement with precision ~ 100 picoseconds





ATIC

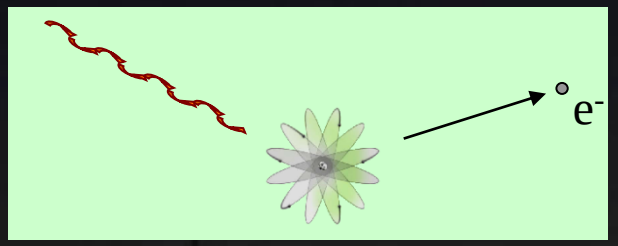
- Ionization calorimeter
  - 10 layers of Bismuth Germanate (BGO)
- Si matrix detector on top (charge measurement)
- Excess of cosmic ray electrons at energies of 300–800 GeV
  - nearby source?
  - Dark matter signal?



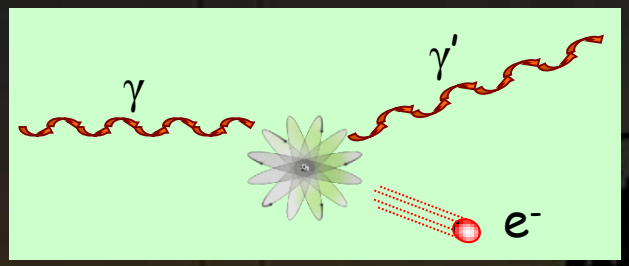
VERY HIGH ENERGY GAMMA-RAYS

Detection of photons

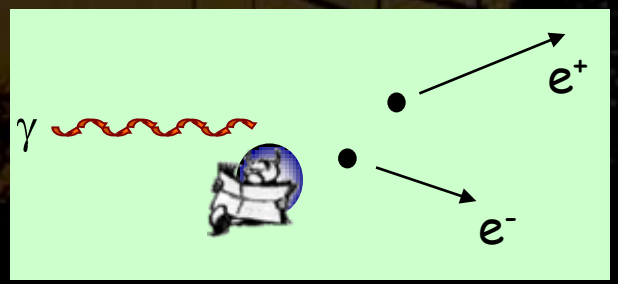
- Produced photons
  - Photoelectric effect

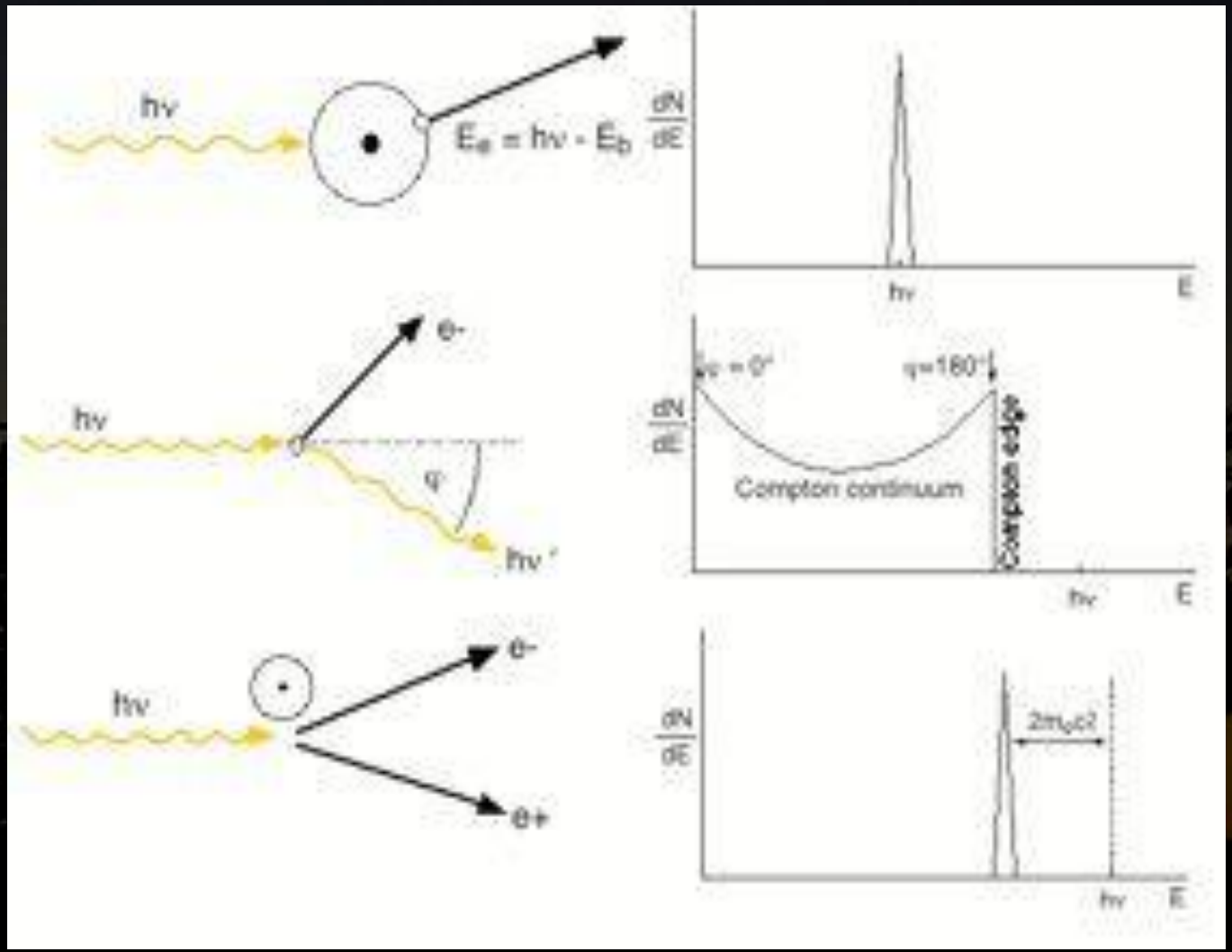


  - Compton



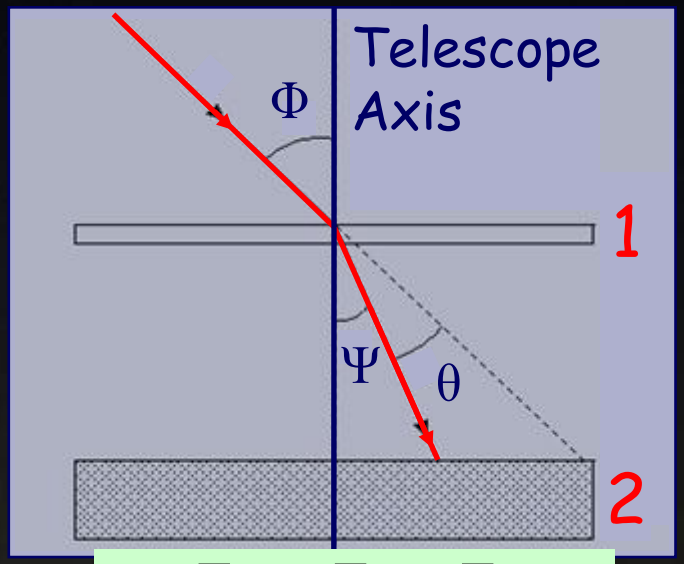
  - Pair creation





Compton Telescopes

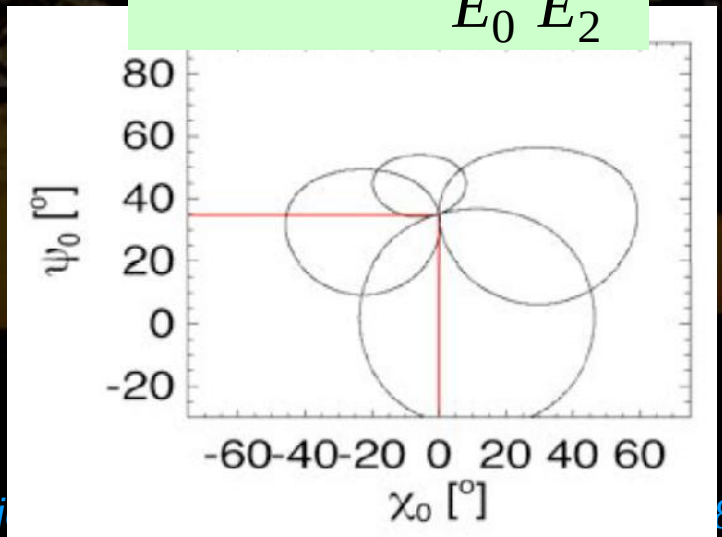
- Two detection planes
  - Plane 1: Low Z material, scatters the photon
  - Plane 2: High Z material, absorbs scattered photons
- Incidence angle Φ & Energy E_0 obtained from deposited energies E_1 & E_2 in the two layers and Ψ angle of scattered photon
- Degeneracy $\Rightarrow$ probabilistic reconstruction using all photons
- MeV energy domain (Comptel)



$$E_0 = E_1 + E_2$$

$$\Phi = \psi + \theta$$

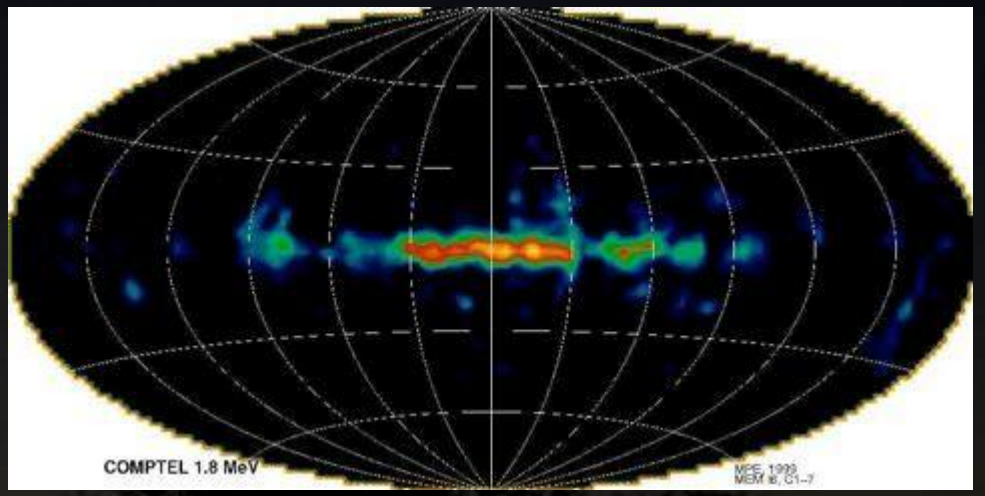
$$\cos\theta = 1 - \frac{E_1\, m_e\, c^2}{E_0\, E_2}$$

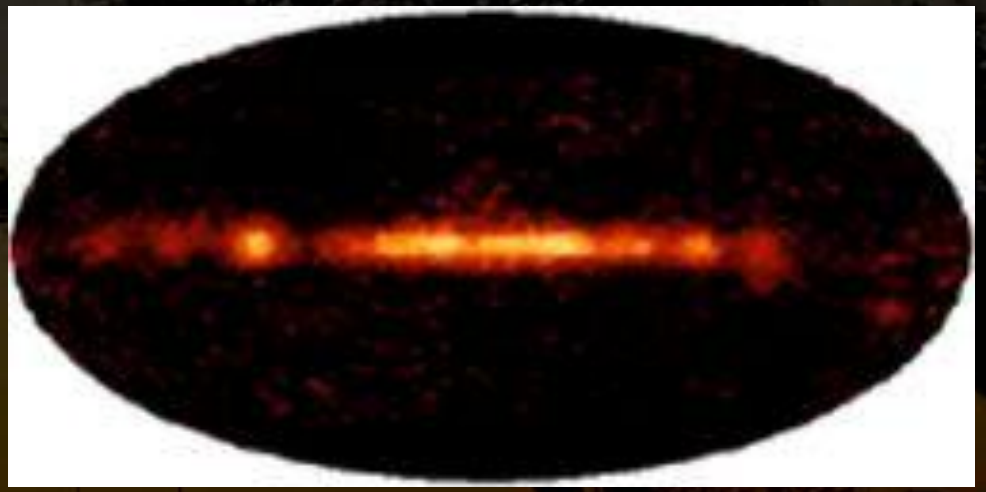


Comptel

- Onboard CGRO (1991-2000)
  - 1-30 MeV
  - Resolution 0,5 – 1°
  - FOV 60°
- ^{26}Al line map
  - 1.809 MeV,half life 10^6 years,
  - nucleosynthesis tracer (stellar winds,...)
- Correlated with bremsstrahlung emission
  - winds from massive star

Carte de ^{26}Al





Bremsstrahlung Emission

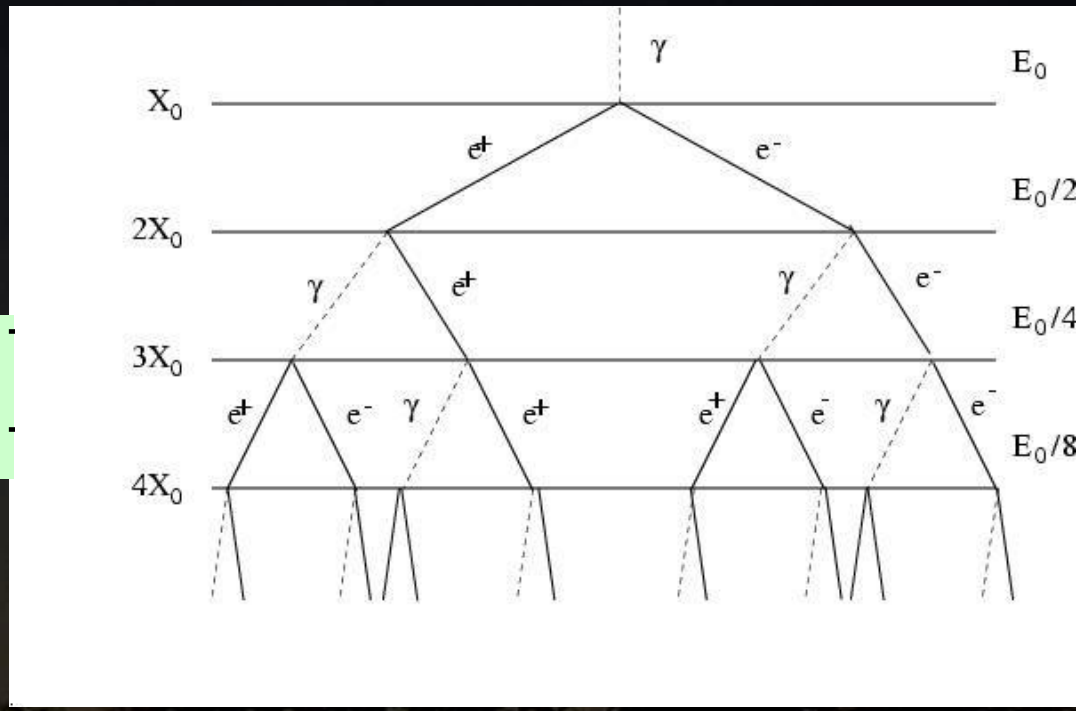
Heitler Model

- Above critial energy (84.2 MeV), ionisation losses ignored.

  ⇒ Bremsstrahlung & pair creation depend on radiation length :

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} Z^2 \ln\left(183 Z^{-1/3}\right) \quad \text{cm}^{-2}$$

(X_0 = 36.7 g.cm^{-2} in air)



- Bremsstrahlung:

$$\frac{\mathrm{d}\overline{E}}{\mathrm{d}t} = -\left(b+1\right)\frac{E}{X_0}$$

$$b = \frac{1}{18\ln\left(183/Z^{1/3}\right)} = 0{,}0122 \quad \text{(air)}$$

- Pair Creation probability

$$X_0 \frac{\mathrm{d}P}{\mathrm{d}X} = \sigma_0 = \frac{7}{9} - \frac{b}{3} = 0{,}774 \quad \text{(air)}$$

Integral Bethe-Heitler equations

Heitler Model – II

- Bremsstrahlung
  - Average Loss

$$E(t) = E_0 \exp\left(\frac{-t}{X_0}(+b)\right)$$

$$E = \frac{E_0}{2} \text{ pour } t = X_0 \ln 2$$

- Pair creation integrated probability

$$P(t) = 1 - \exp\left(\frac{-t}{X_0}\left(\frac{7}{9} - \frac{b}{3}\right)\right)$$

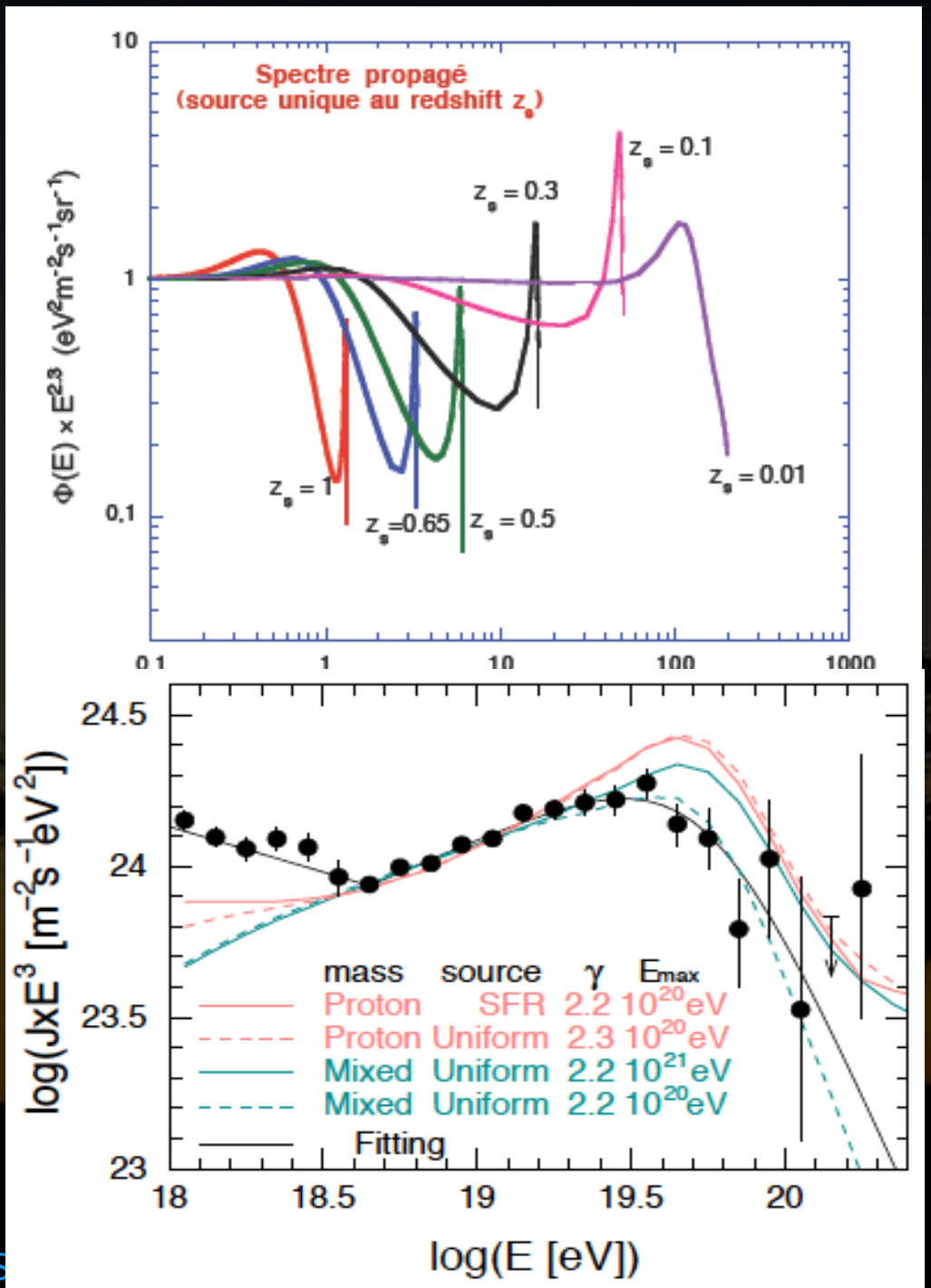
$$P = \frac{1}{2} \text{ for } t = \frac{9}{7} X_0 \ln 2 \approx X_0 \ln 2$$

- Number of particles growing exponentially with depth, energy decreasing in inverse
- Below critical energy, rapid death of shower by ionisation

UHECRS

Do we understand GZK ?

- Ankle can be explained by accumulation of sources at different distances
- Propagation effects can change composition below GZK
- Transition Galactic / Extragalactic
- Depends on evolution scheme and composition
- Depending on the primary mass, the observable universe could be large (500 Mpc for p/Fe) or much smaller (80 Mpc for light nuclei)
- Need more data

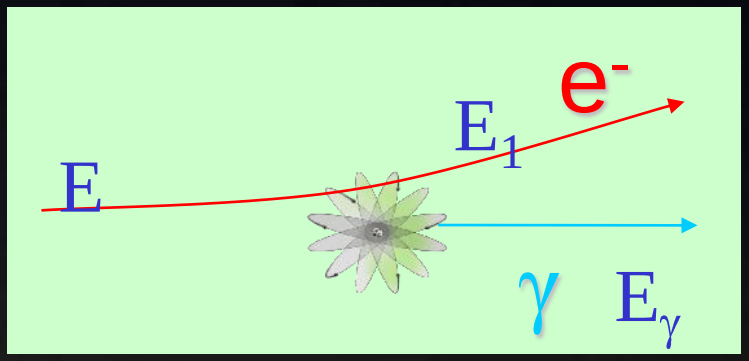


High Energy Effects
I – Landau-Pomerantchuk-Migdal (LPM)

- Bremsstrahlung
  - Impulsion exchange

$$\hbar k \times c = \sqrt{E^2 - \left(m_e c^2\right)^2} - \sqrt{E'^2 - \left(m_e c^2\right)^2} - E_\gamma$$

$$\approx \frac{1}{2}\left(\frac{m_e c^2}{E}\right)^2 E_\gamma \text{ for } E_\gamma \ll E$$



  - Heisenberg uncertainty principle gives formation length:

$$\Delta x \propto \frac{\hbar}{\Delta p} = 2\left(\frac{E}{m_e c^2}\right)^2 \frac{\hbar c}{E_\gamma} \propto 2\,\gamma^2\,\frac{\hbar c}{E_\gamma}$$

  - Alternate explanation: in electron frame:

$$\Delta\tau = \frac{\hbar}{\Delta E} = \frac{\hbar}{E'_\gamma} \text{ (proper formation time)}$$

$$\Delta x = c \cdot \Delta t = \gamma\, c\, \Delta\tau = \frac{\gamma\, c\, \hbar}{E'_\gamma} = \gamma^2 \frac{\hbar c}{E_\gamma}$$

LPM effect

- Formation length becoming similar to interaction distance: interferences between scattering centres:
  ⇒ coherent bremsstrahlung and multiple scattering in a single process. Coherent pair creation.
- Destructive interferences when multiple scattering distance smaller than formation distance
  - Bremsstrahlung & pair creation heavily suppressed
  - Deeper shower…, atypical profiles (2 maxima,…)
- Destructive interferences condition reads:

$$E_\gamma < \frac{E_e^2}{E_{\mathrm{LPM}}} \text{ with } E_{\mathrm{LPM}} = \frac{\alpha\, X_0 \left(m_e c^2\right)^2 X_0}{4\pi\, \hbar c\, \rho} = 770\ \mathrm{TeV\ cm^{-1}} \times \left(\frac{X_0}{\rho}\right)$$

- In air (20°C, 1 atm.) : E_{LPM} = 116 PeV = 1,16 10^{17} eV
- Higher at high altitude (1/ρ)

High Energy Effects II – Pré-gerbes

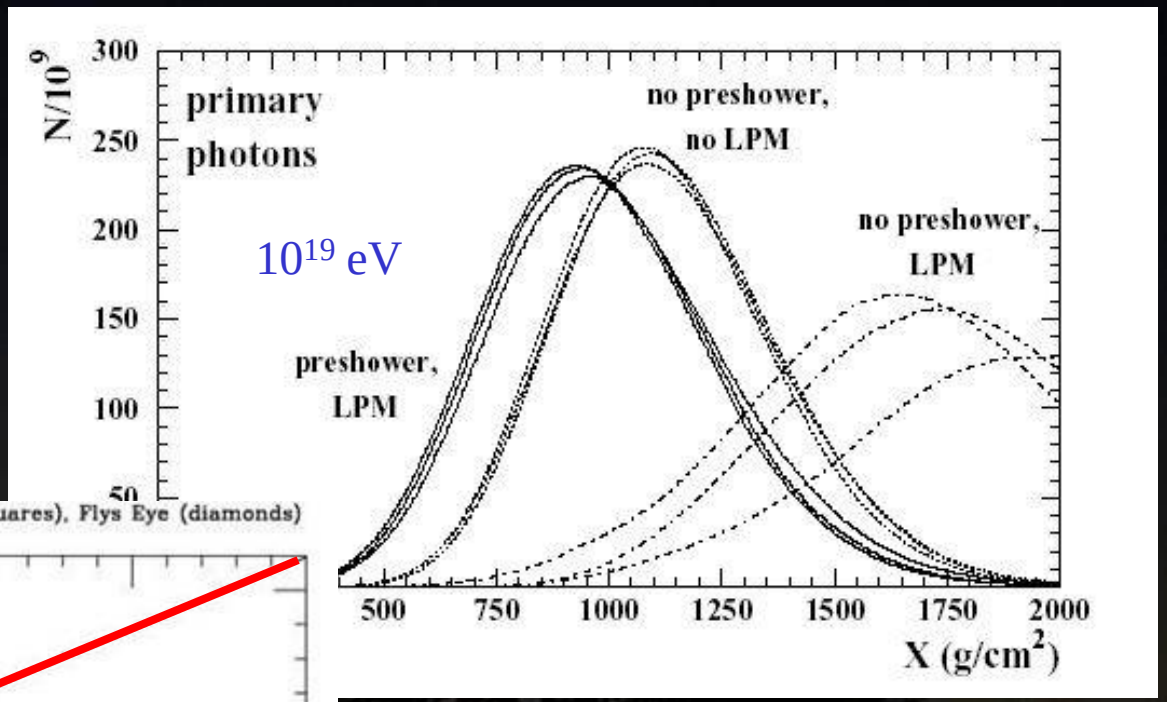
- Pair creation between high energy γ ray and earth magnetic field:

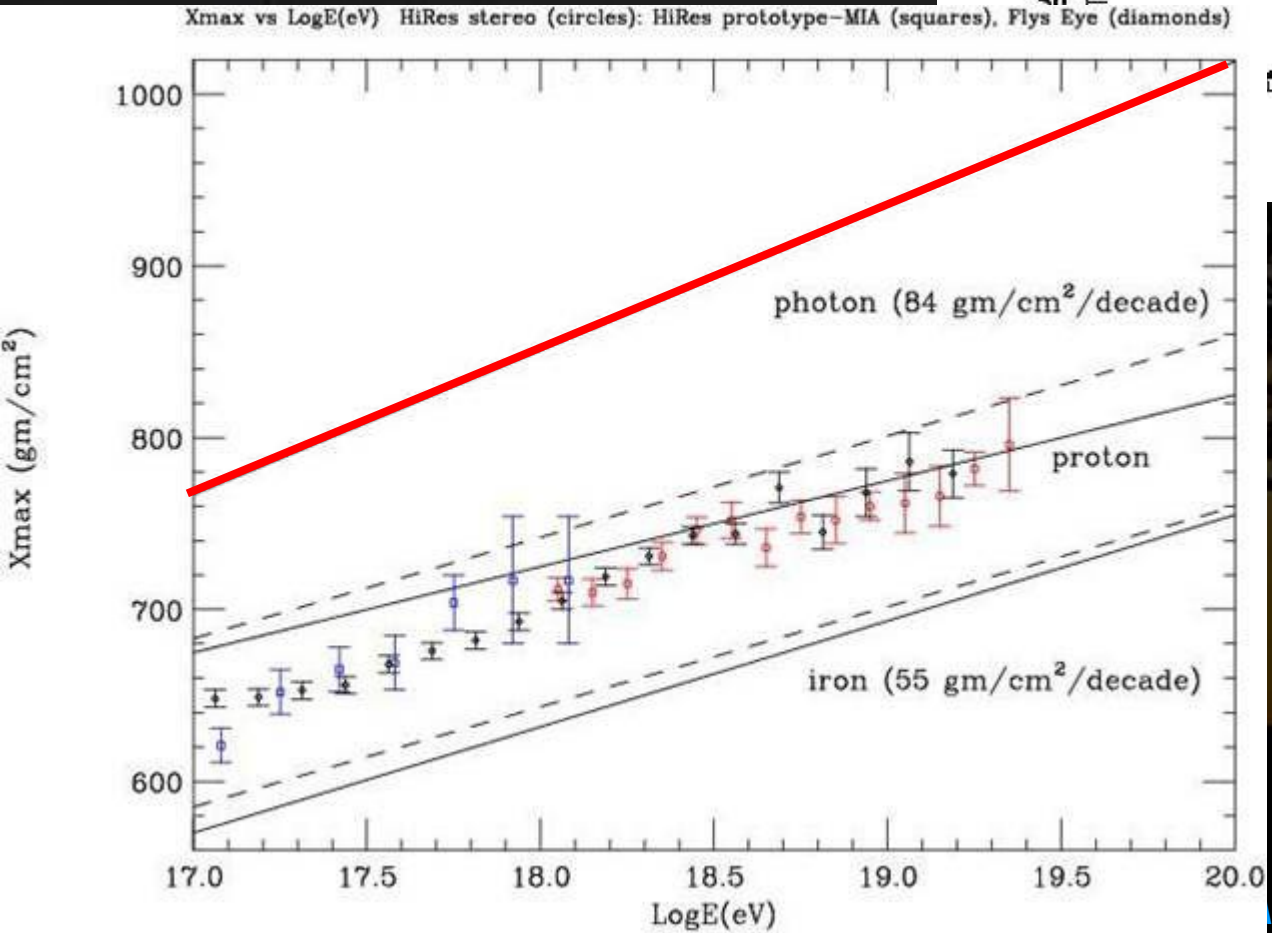
$$E_\gamma > \frac{m_e c^2}{\mu_B B_\perp} \approx 10^{19}\,\text{eV} \text{ where } \mu_B = \frac{e\hbar}{2m_e} \text{ (Bohr magneton)}$$

- Synchrotron emission in earth magnetic field
- Shower develops before atmosphere!
- Goes into opposite direction to LPM

Ultra High Energy Photons

- LPM & pre-shower affect shower development

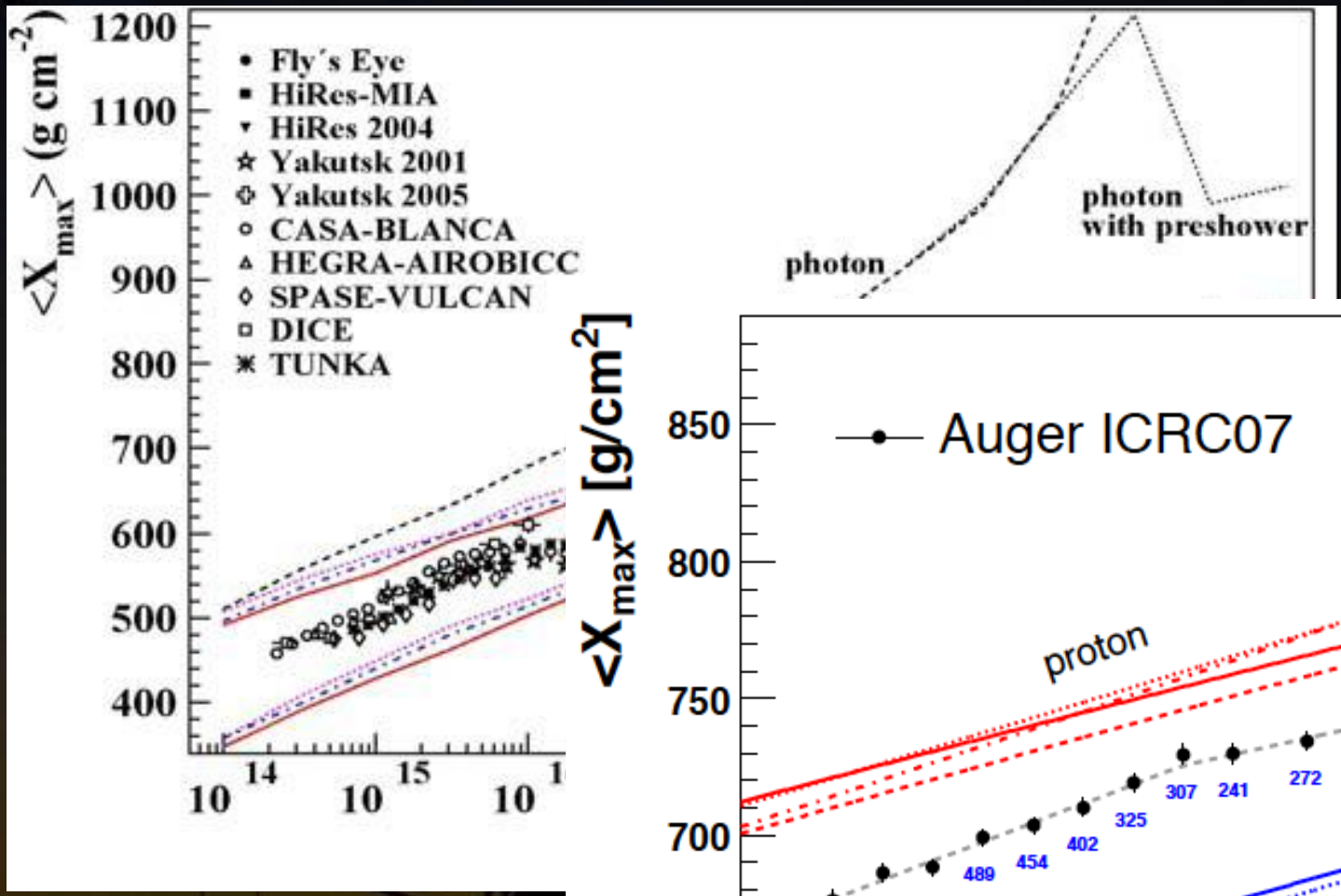


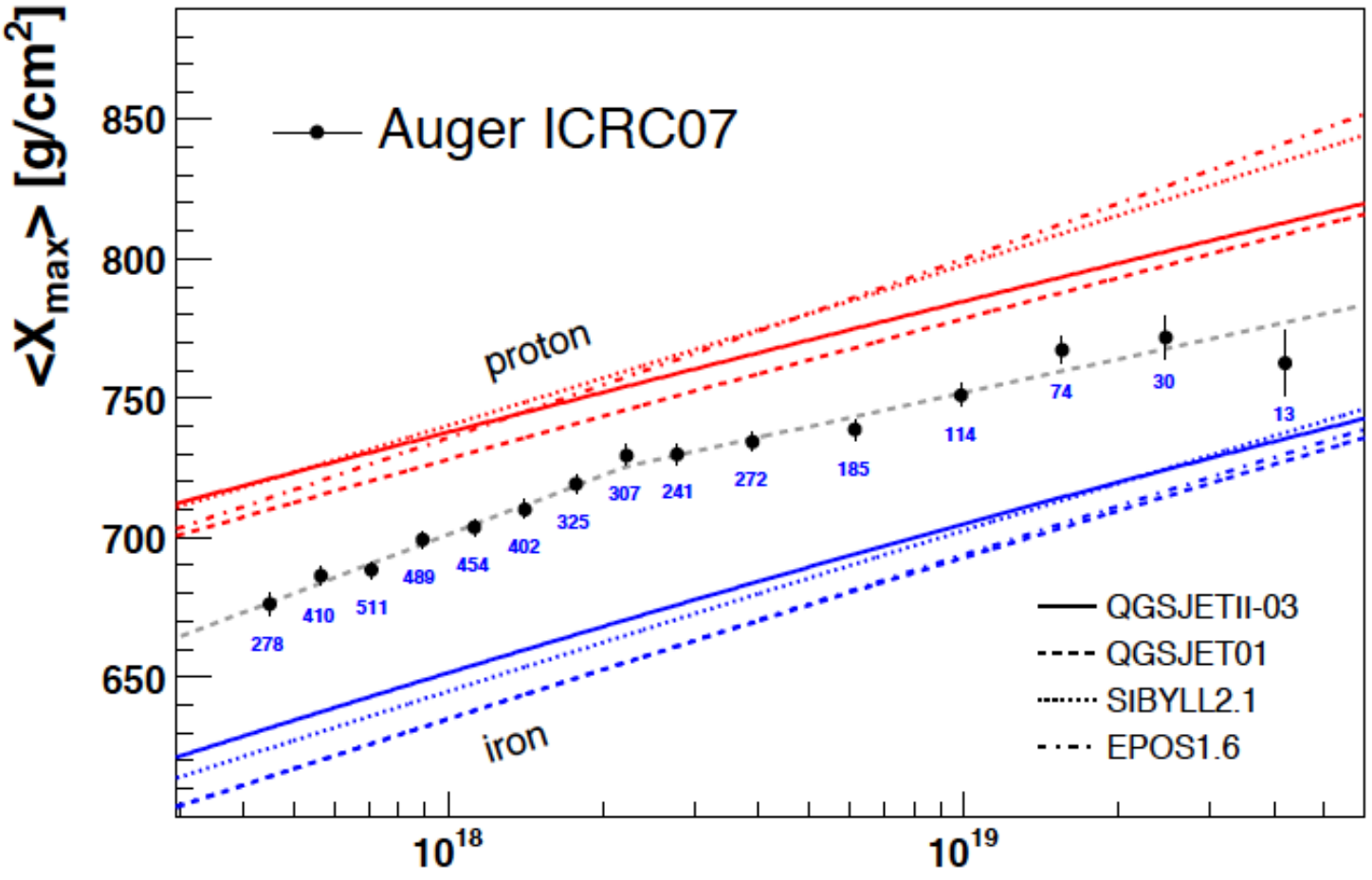


- X_{max} (E) is different for photons and nuclei
  $\Rightarrow$ constraints on photon fraction

Latest Auger composition results

- Mixed composition at all E
- Becoming heavier at highest E?

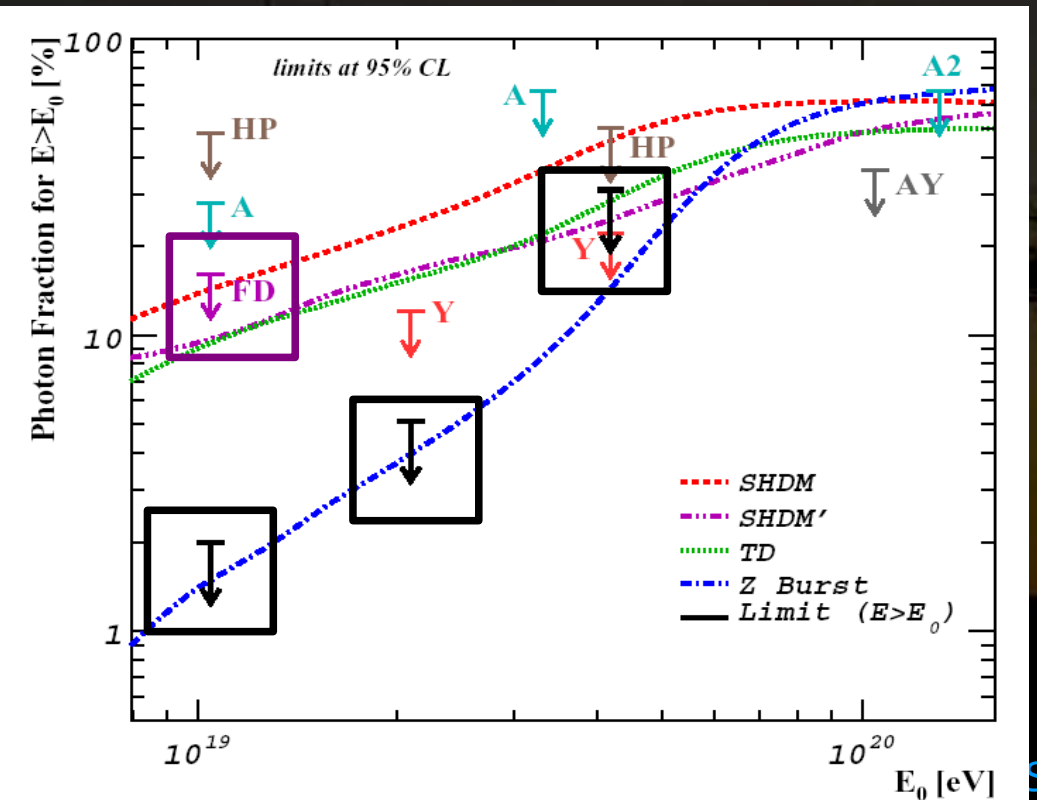


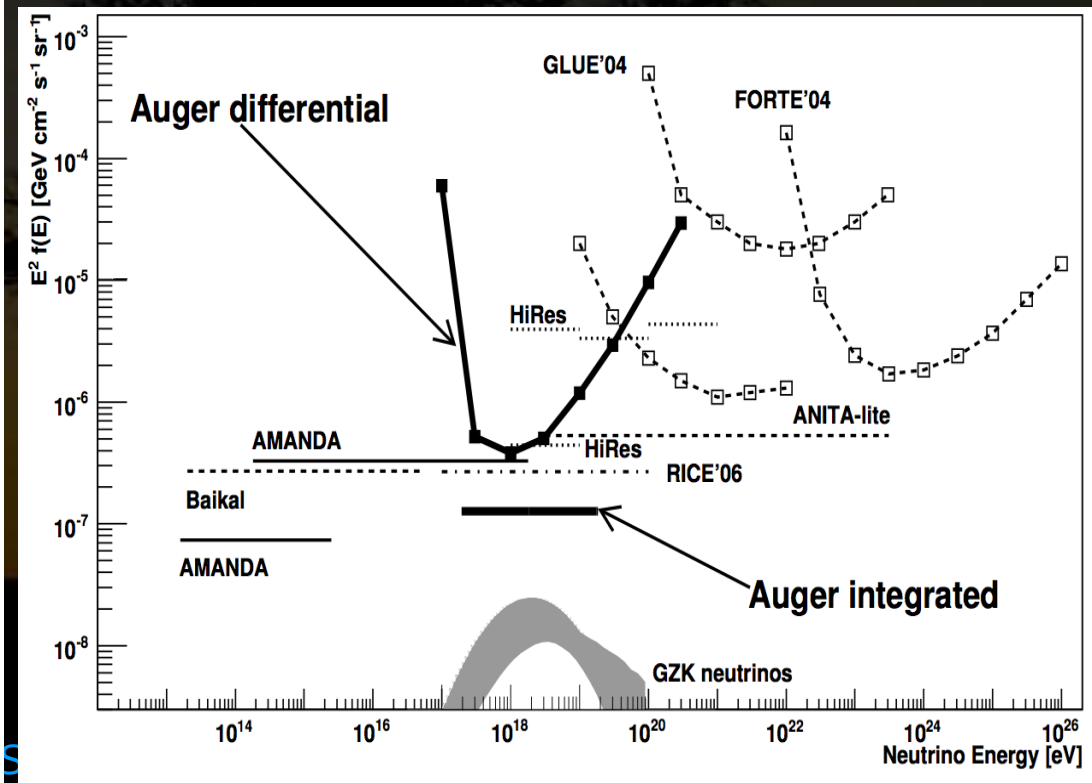


arXiv: 0706.1495

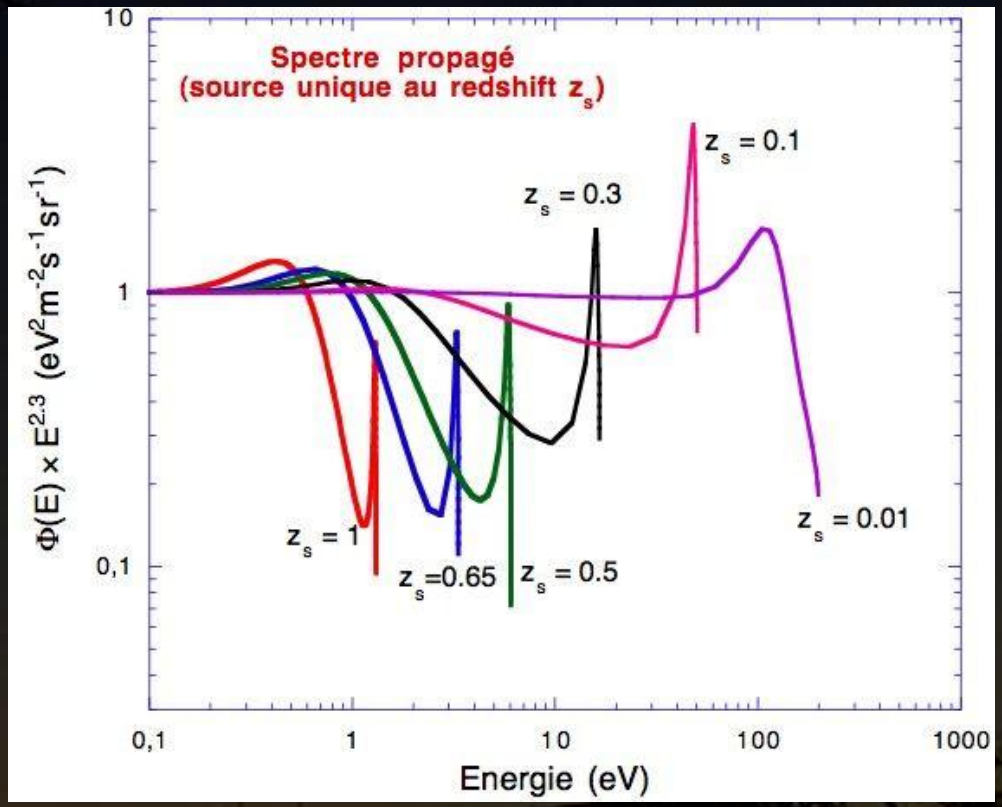
Photon and Neutrinos fractions

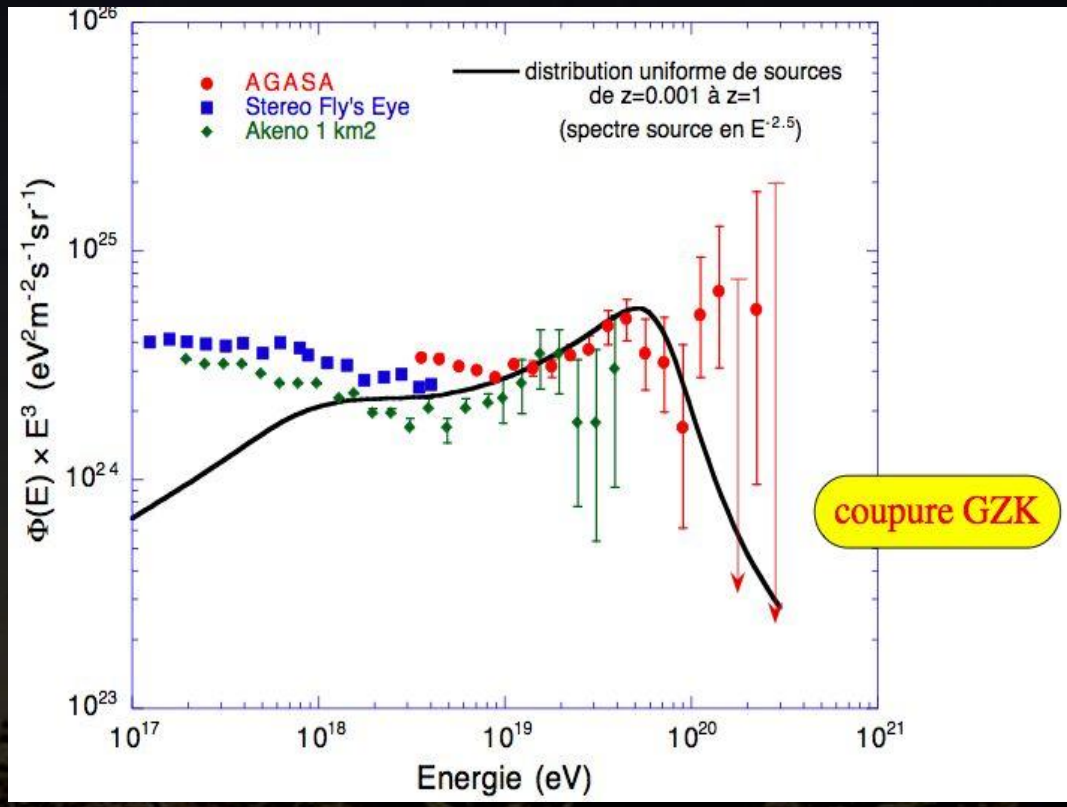
- High Energy Photons expected in many Top-Down Scenario
- Neutrinos sign hadronic processes,
  + Calorimetric measure of UHECRs (through GZK interaction)
- Current limits strongly disfavor top-down models
- GZK neutrinos need bigger detectors (or > 20 y Auger)





Propagation effects

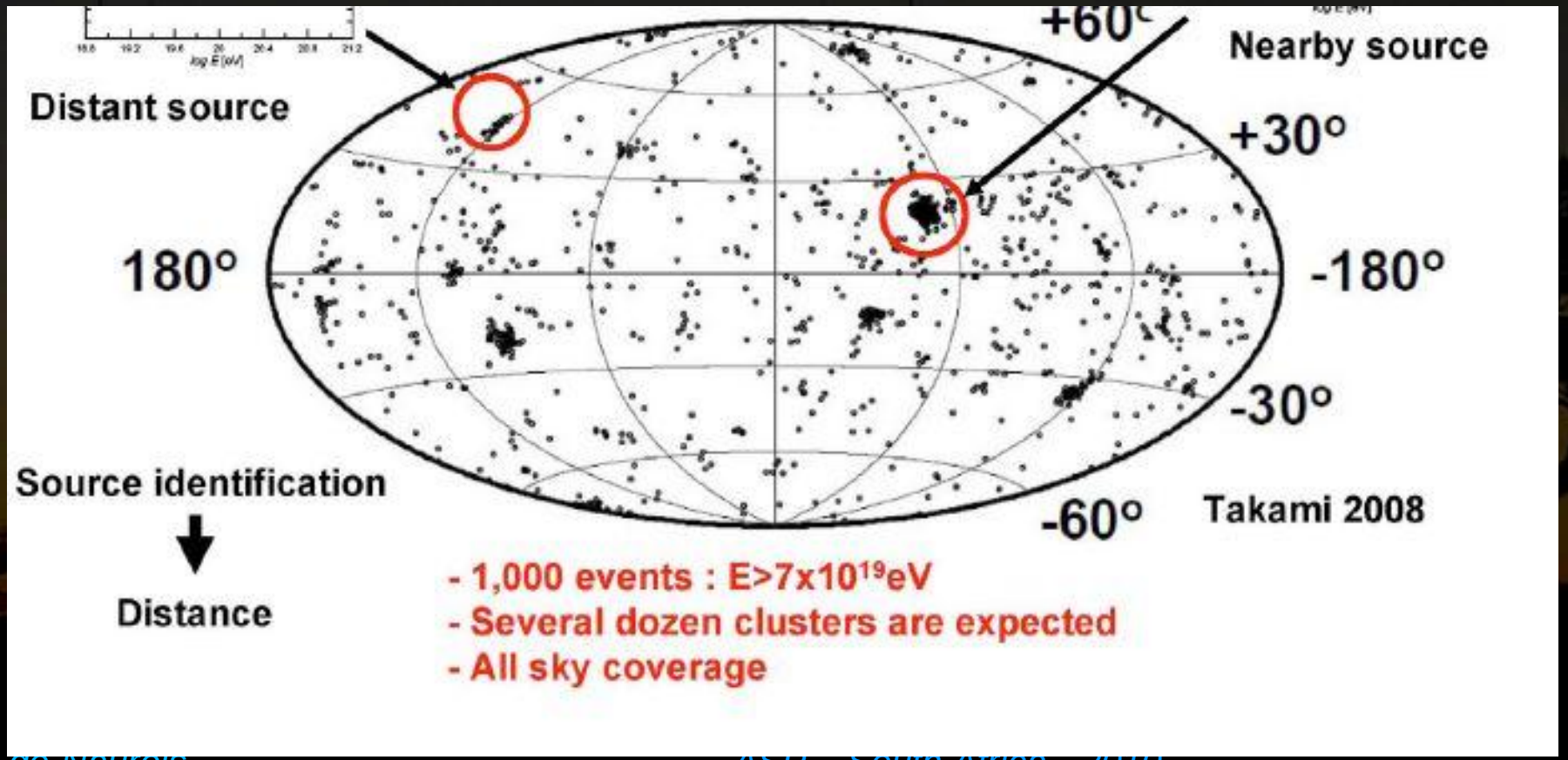




- Propagation effects and spatial distribution of sources affect spectrum shape
- Precise tests still out of reach

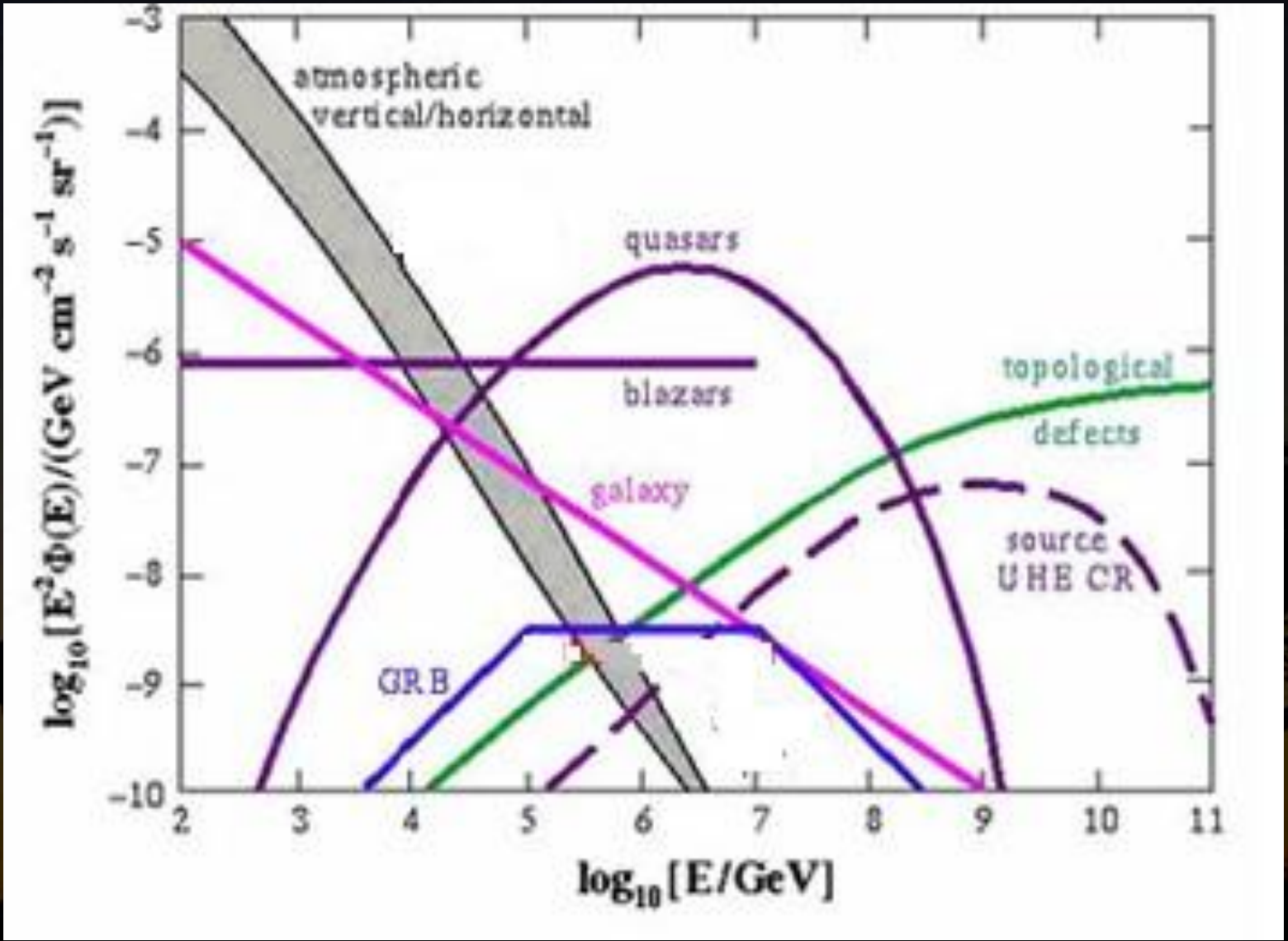
JEM-EUSO performances

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

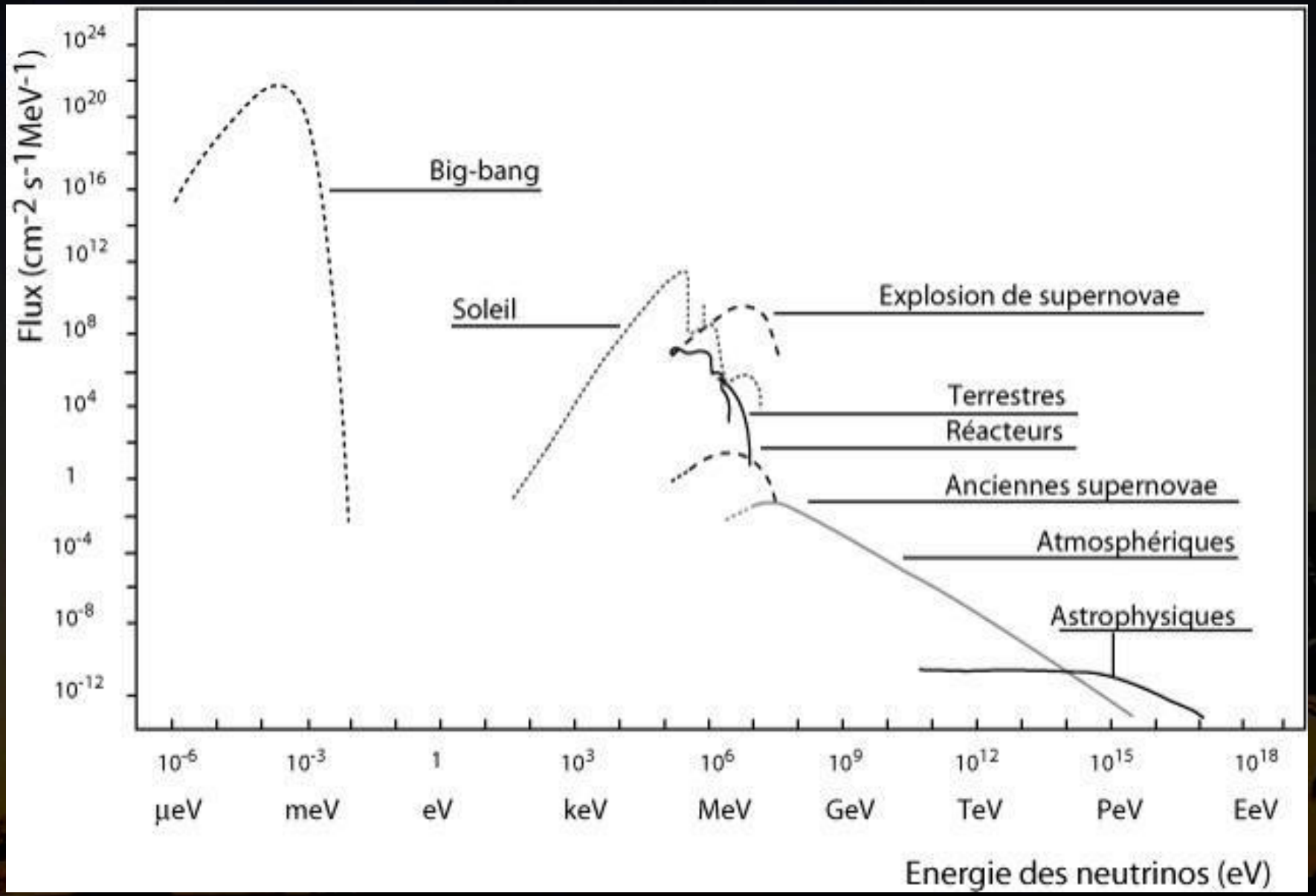


NEUTRINOS

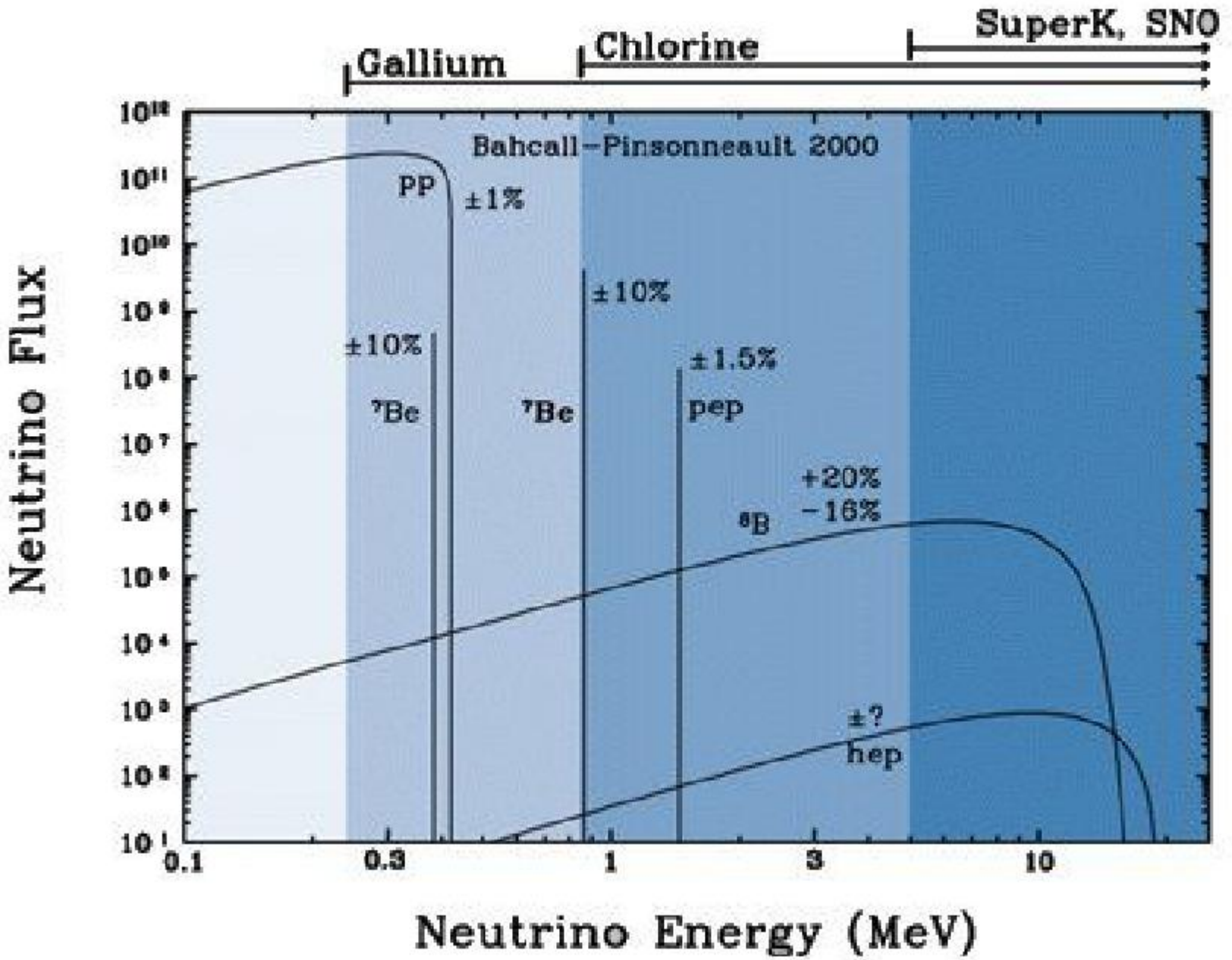
Astrophysical sources



Cosmic Neutrino fluxes



Solar Neutrinos



Cross Section

- Elastic Neutrino – Electrons scattering

$$\sigma_{\nu_e e^- \to \nu_e e^-} \approx 9.5 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$$

- Charge current : $\nu_X + n \rightarrow p + e^-$ (E < 1 GeV)

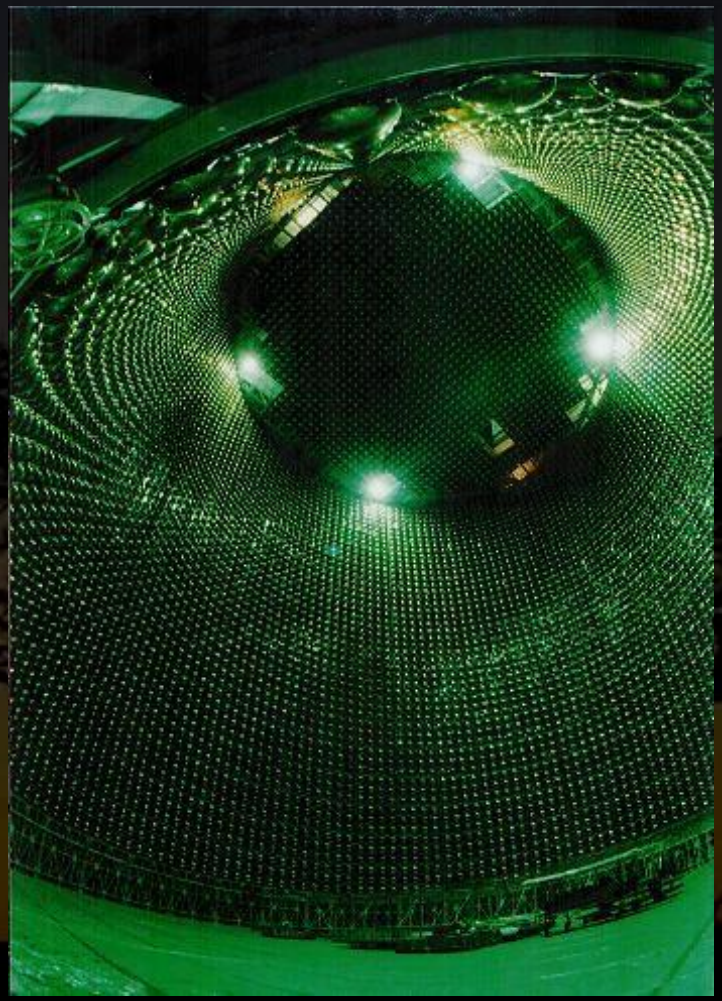
$$\sigma_{\nu_e n \to e^- p} = 9.3 \cdot 10^{-48}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2$$

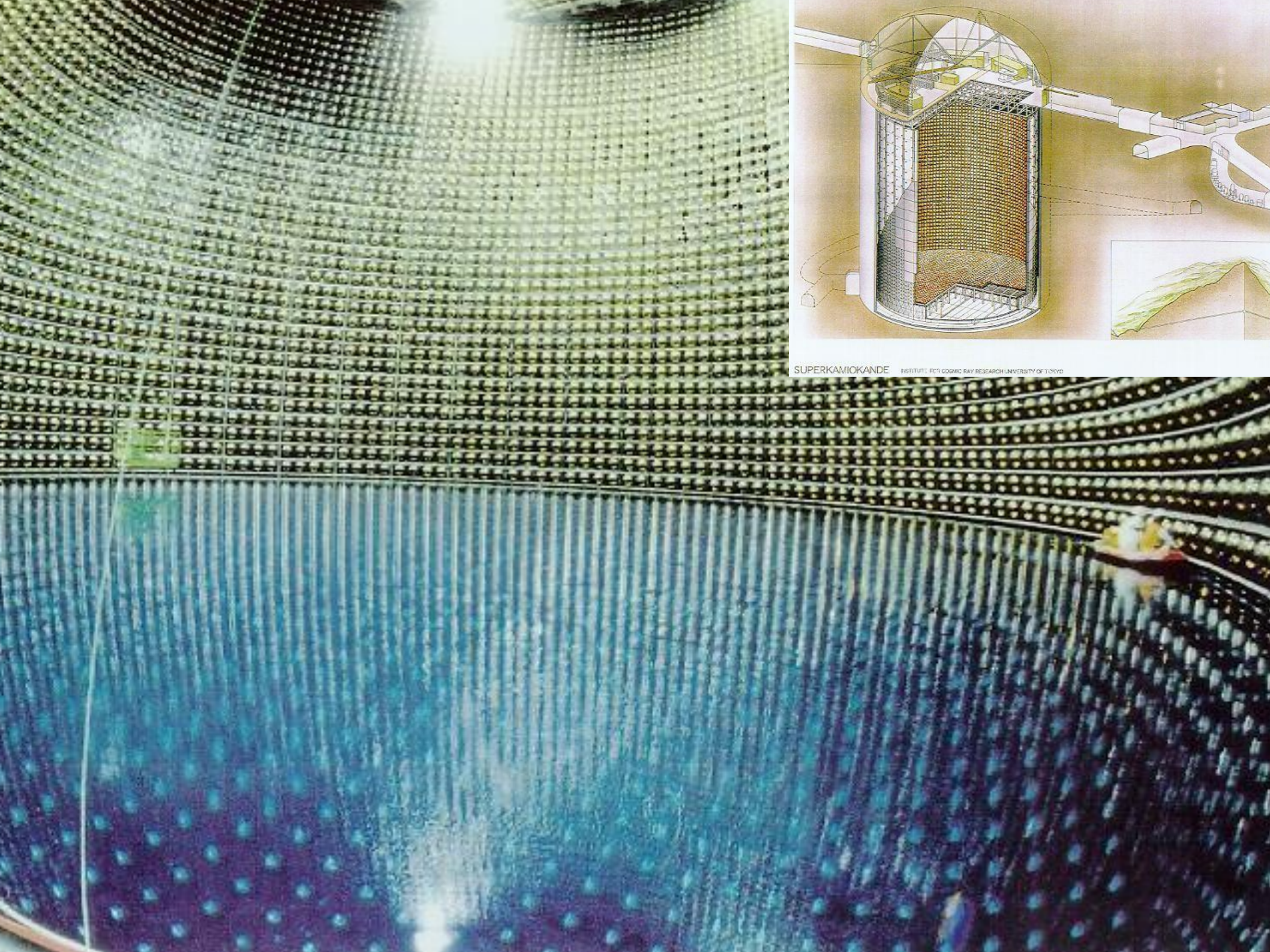
- Neutral courant on deuterium : $\nu_X + d \rightarrow p + n + \nu_X$
- Charged current on nuclei (50 GeV < E < 250 GeV)

$$\sigma_{\nu_e N \to e^- X} \approx 6.7 \cdot 10^{-43} \left(\frac{E}{\mathrm{GeV}}\right) \mathrm{m}^2$$

Atmospheric Neutrinos: SuperKamiokande

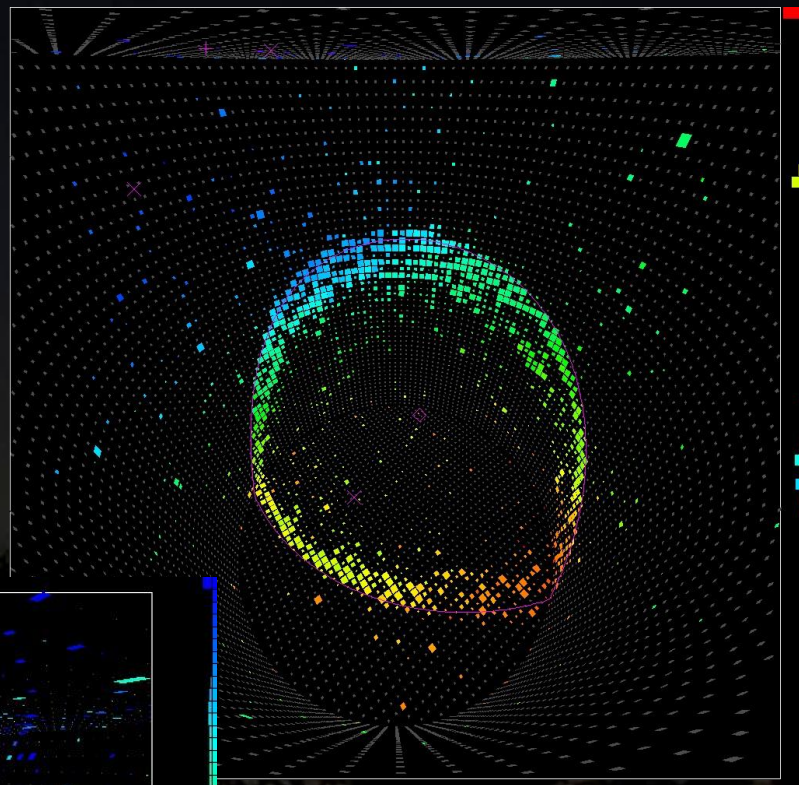
- Water Cherenkov detectors
  - 50 000 tons pure water
  - 41.4m (h) × 39.3m (Ø)
  - 1000 m depth (2700 m water equivalent)
  - ~ 11000 PMTs (20')
- Threshold:
  - $e^{+/-}$: 0.768 MeV
  - $\mu^{+/-}$: 158.7 MeV
  - $\pi^{+/-}$: 209.7 MeV

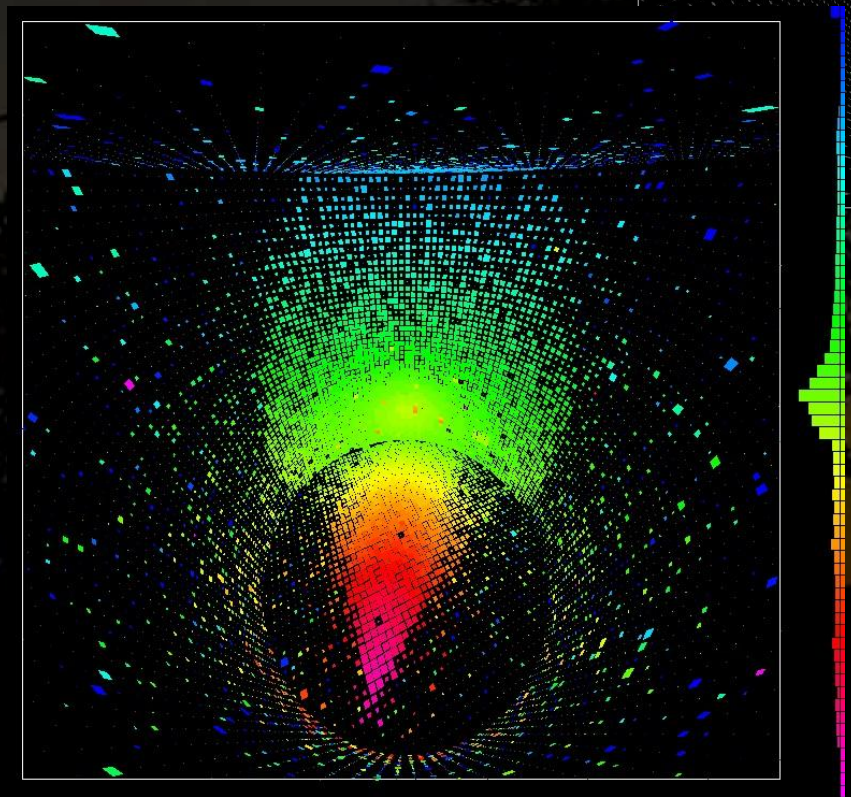



SUPERKAMIOKANDE
INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

Muon Neutrino

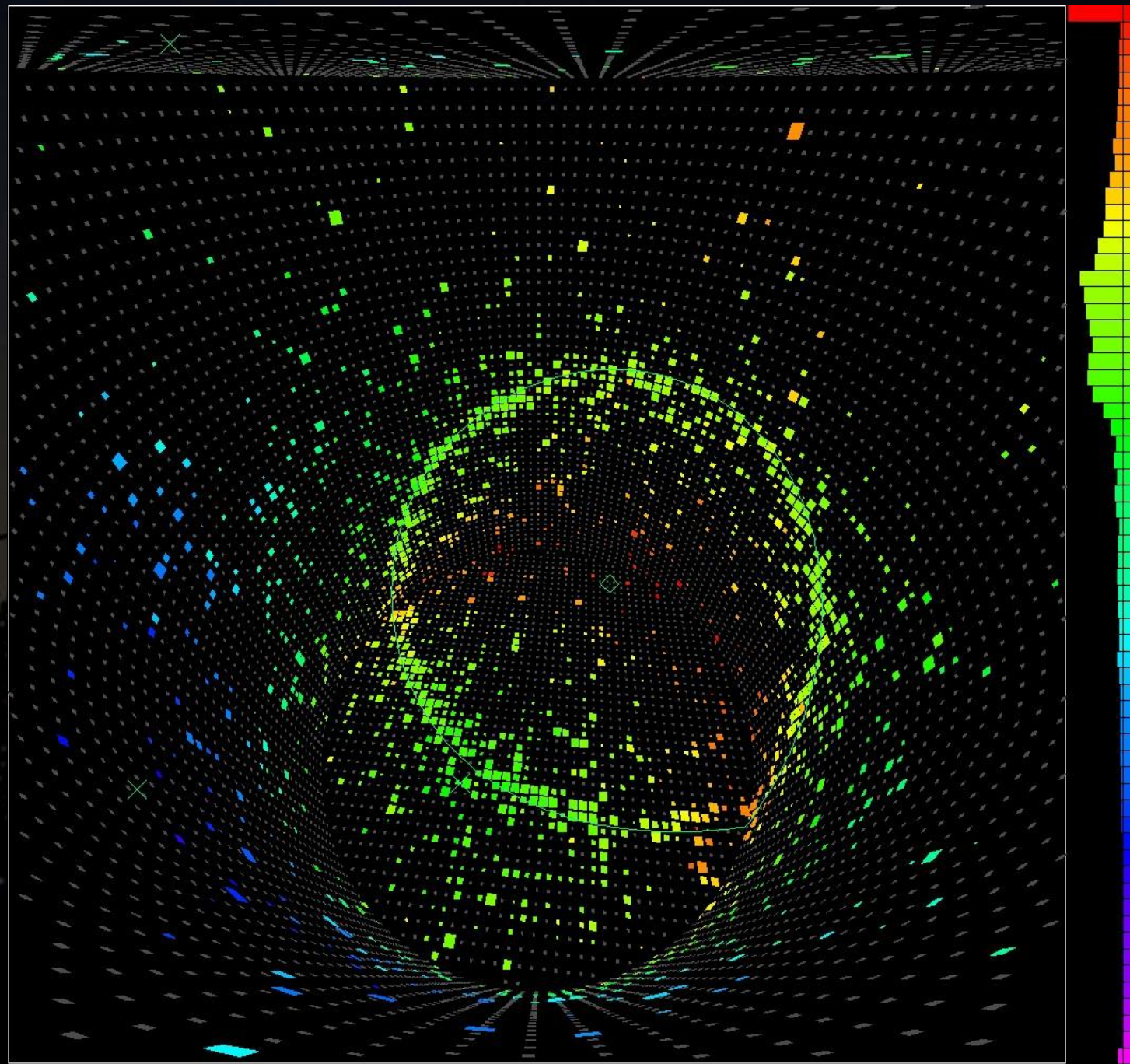
- Well defined ring
- Sometimes followed by a secondary event (disintegration)
- Colour coding: arrival time
- Here: 603 MeV, duration 162 ns
- Second case: Muon going through the detector





An electron neutrino

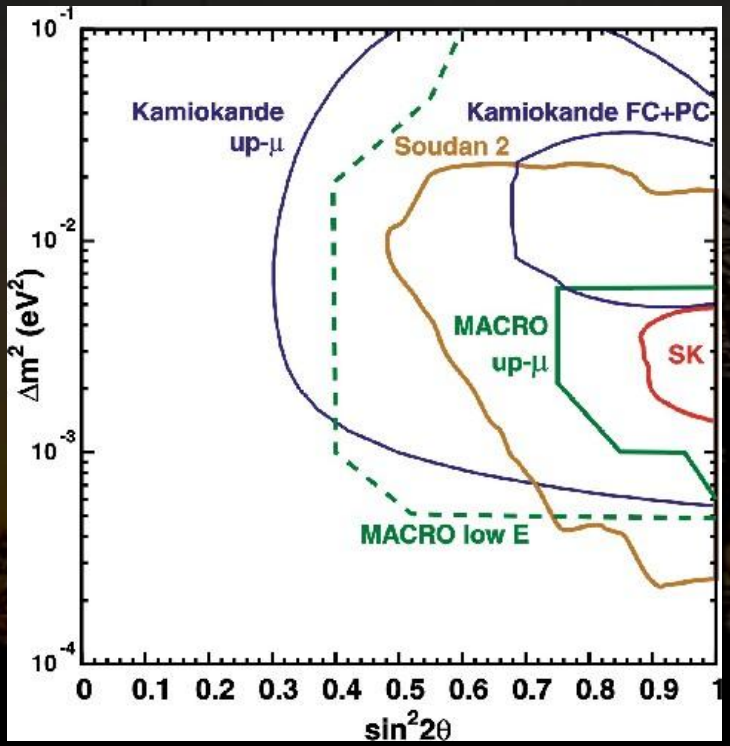
- More diffuse ring (multiple scattering, shower)
- Here 492 MeV, duration 130 ns

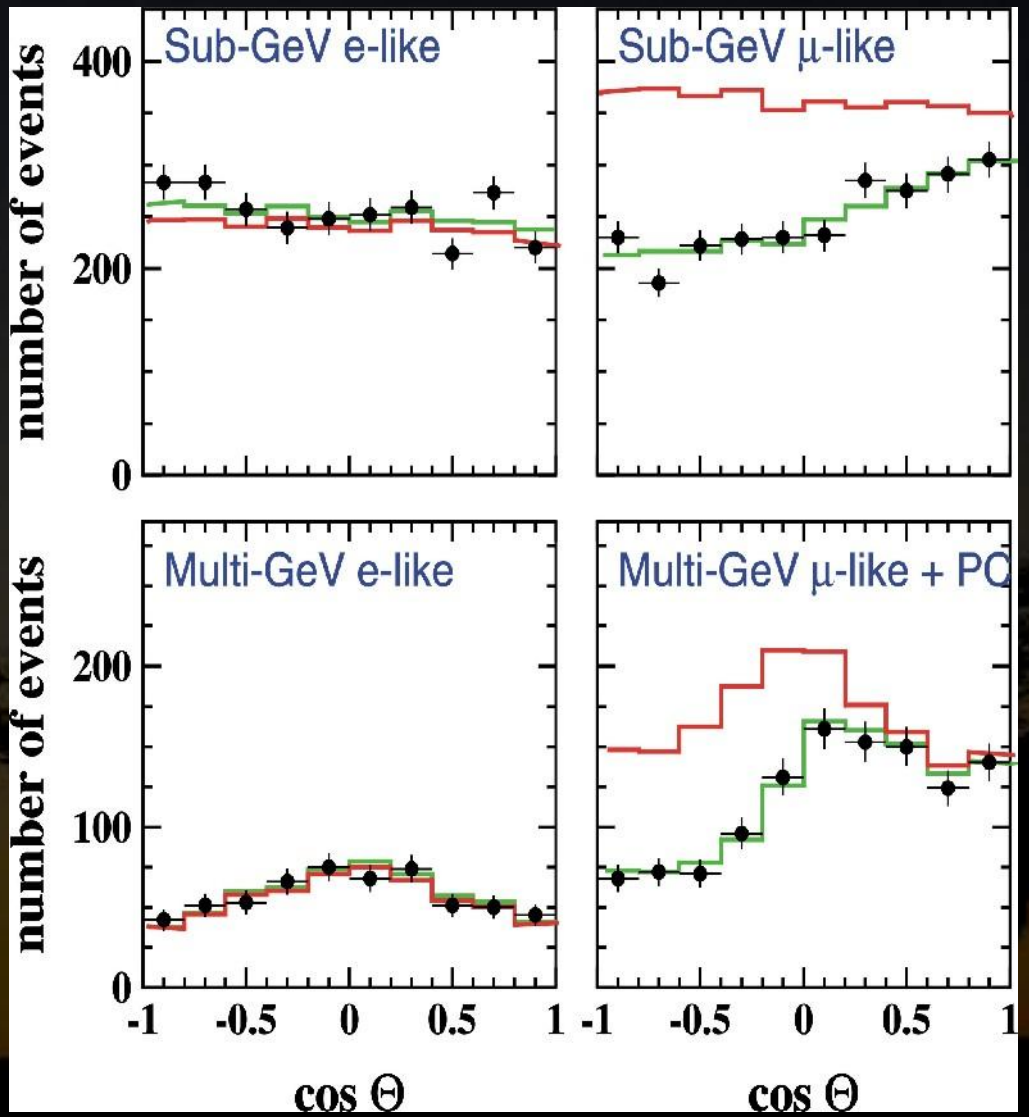


Atmospheric Neutrinos

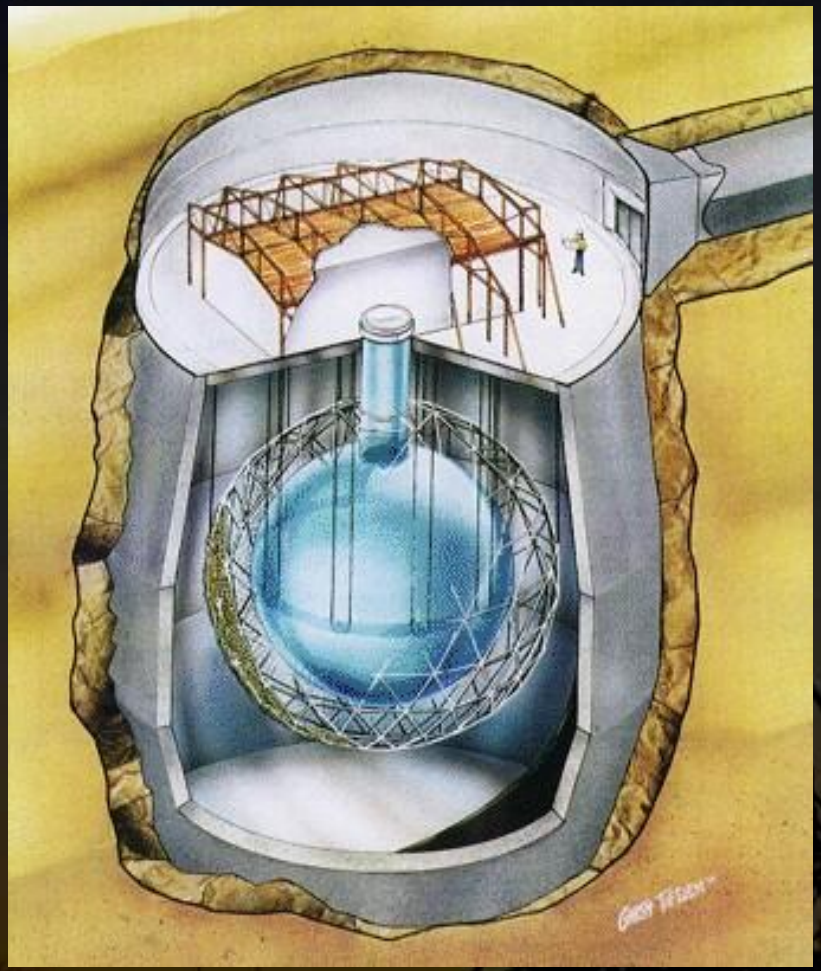
- Disappearing of ν_μ neutrinos due to oscillation in earth:

  $\nu_\mu \leftrightarrow \nu_\tau$





Neutrinos Detection – Low Energy



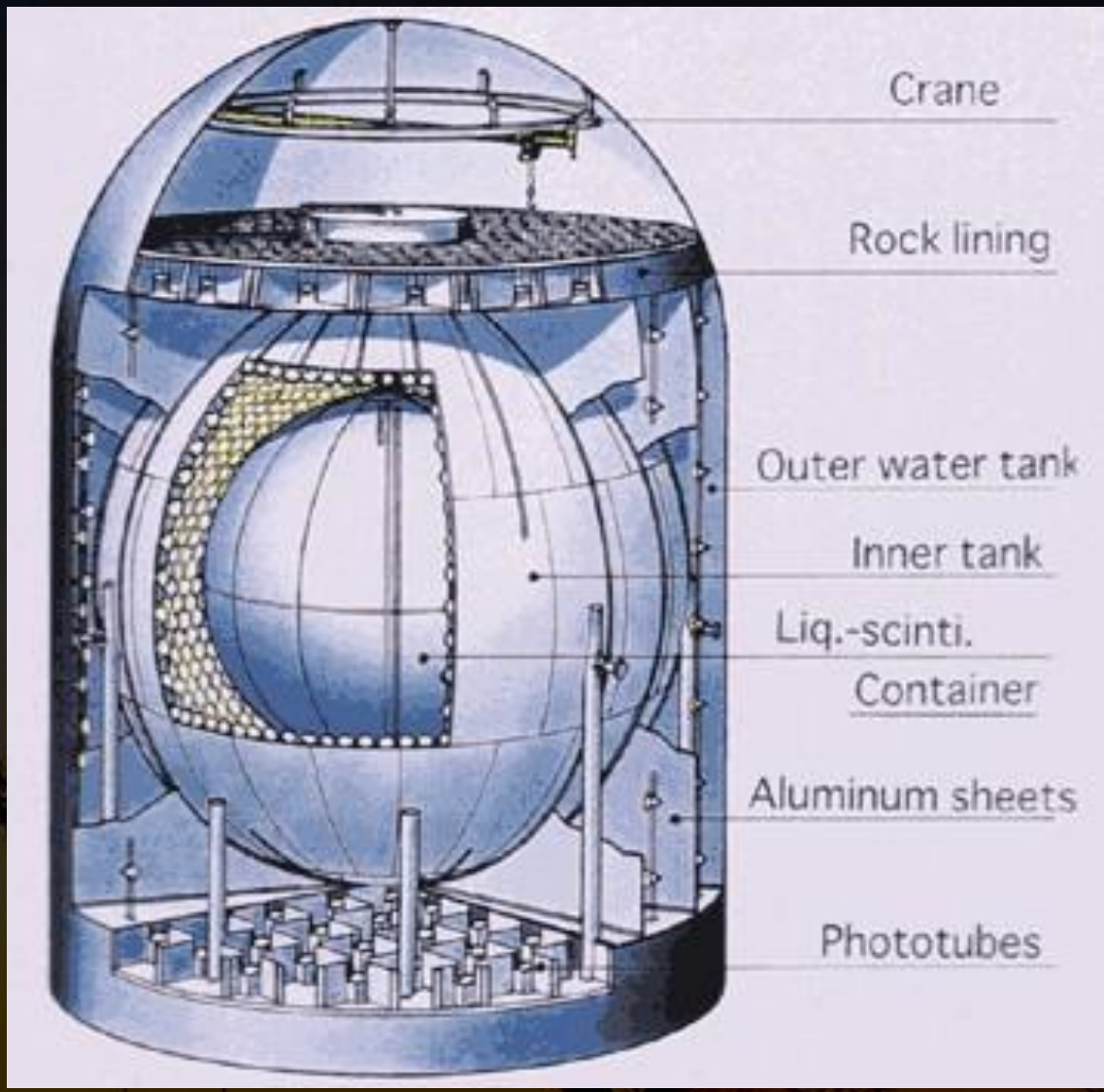
- SNO : acrylic sphere (12m) containing 1000 tons of heavy water D_2O (neutral current)
- 9500 photomultipliers
- Outer detector filled with pure water
- 2 km depth we (water equivalent)
- Electron detection (CC- CN) (Cherenkov) and neutron detection (capture)

- Solar neutrinos, oscillations

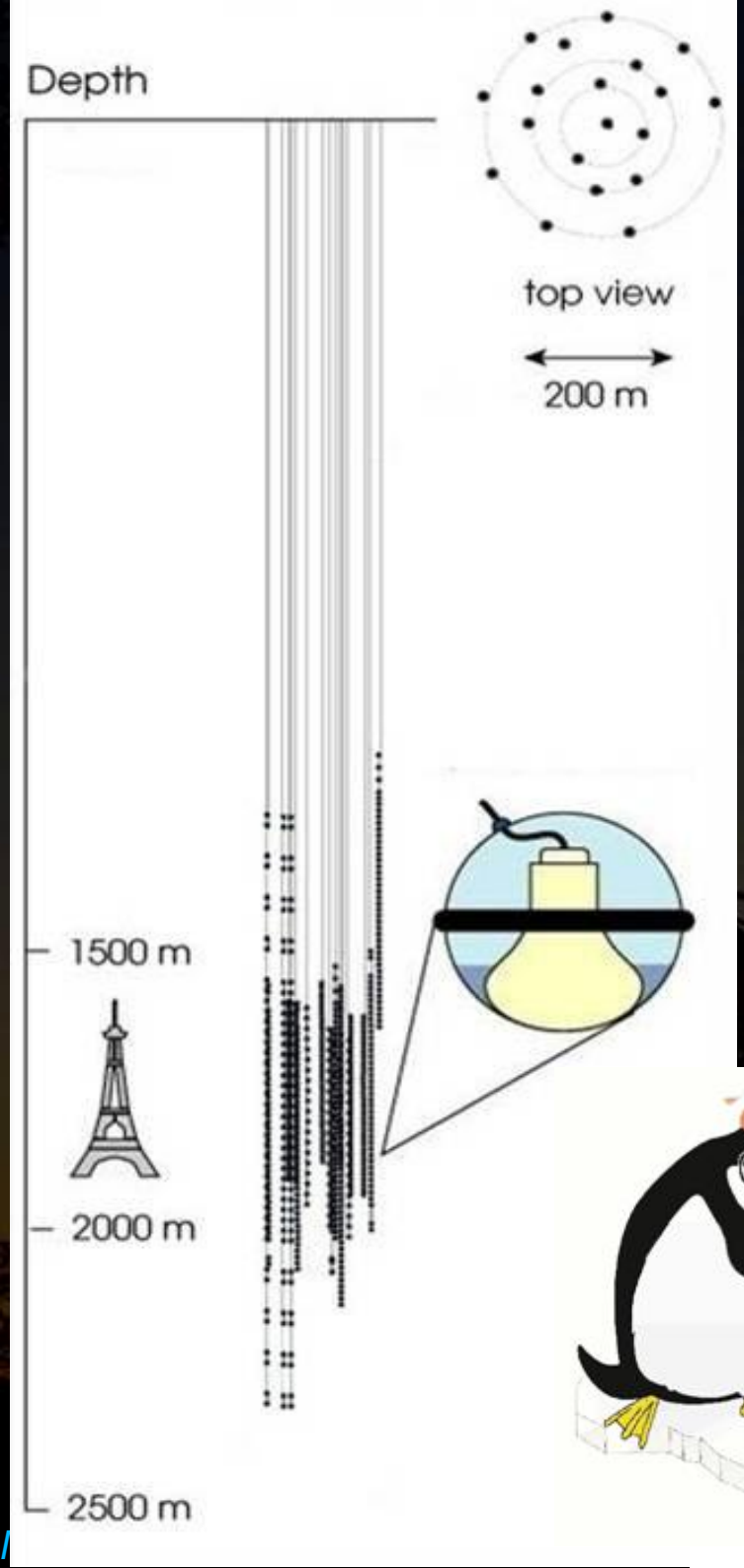
KamLAND

- 1 kton liquid scintillator
  - 1300 17” fast PMTs
  - 700 20” PMTs
  - 30% covering
- H_2O veto
- Zero dead time electronics
- Neutrinos from Japan Nuclear reactors (~160 km)

- Sensitive to ν_e only (CC)
- Oscillations (sensitivity to $\Delta m^2 \sim 7 \times 10^{-6} eV^2$),
- Solar Neutrinos

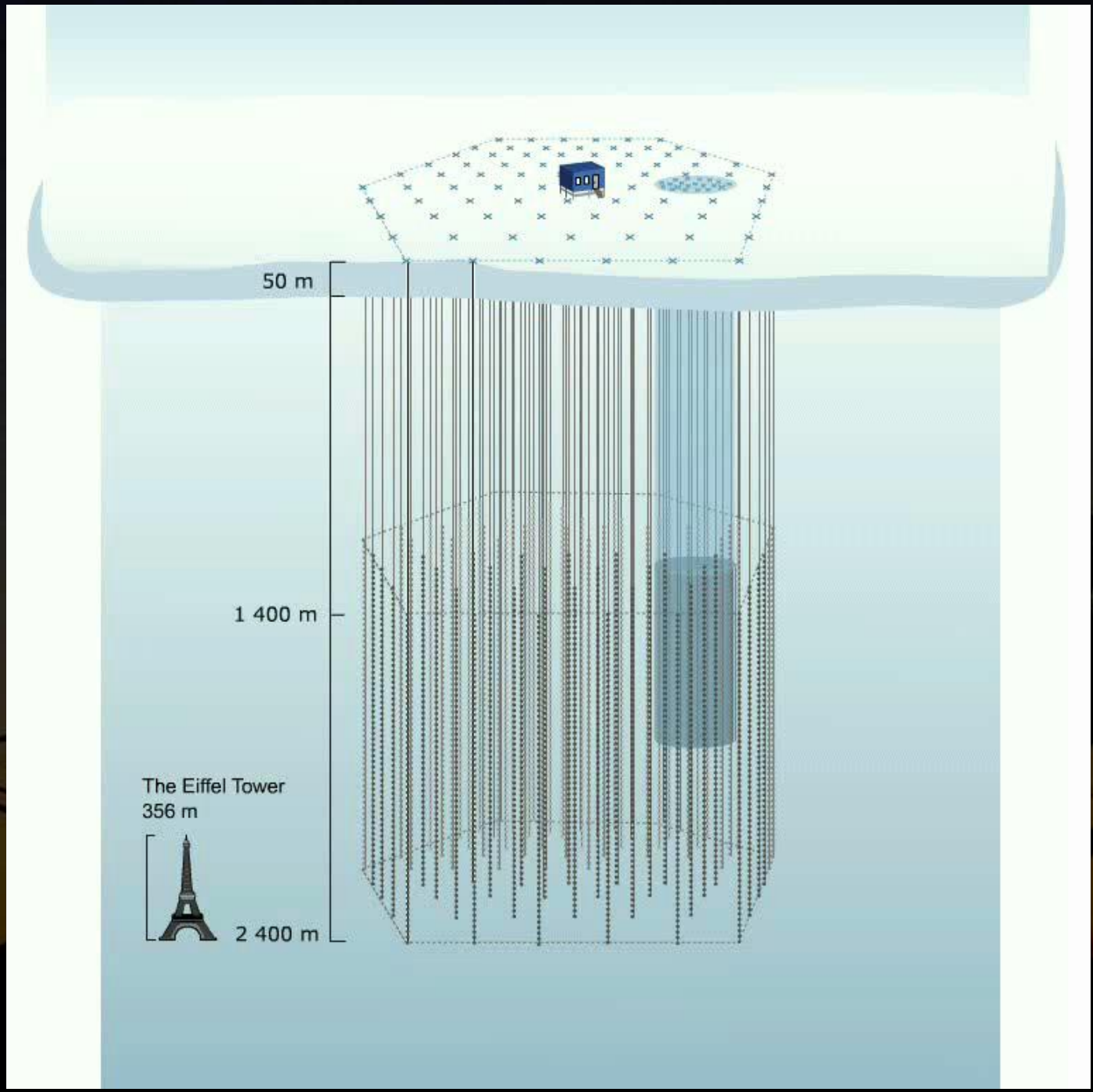


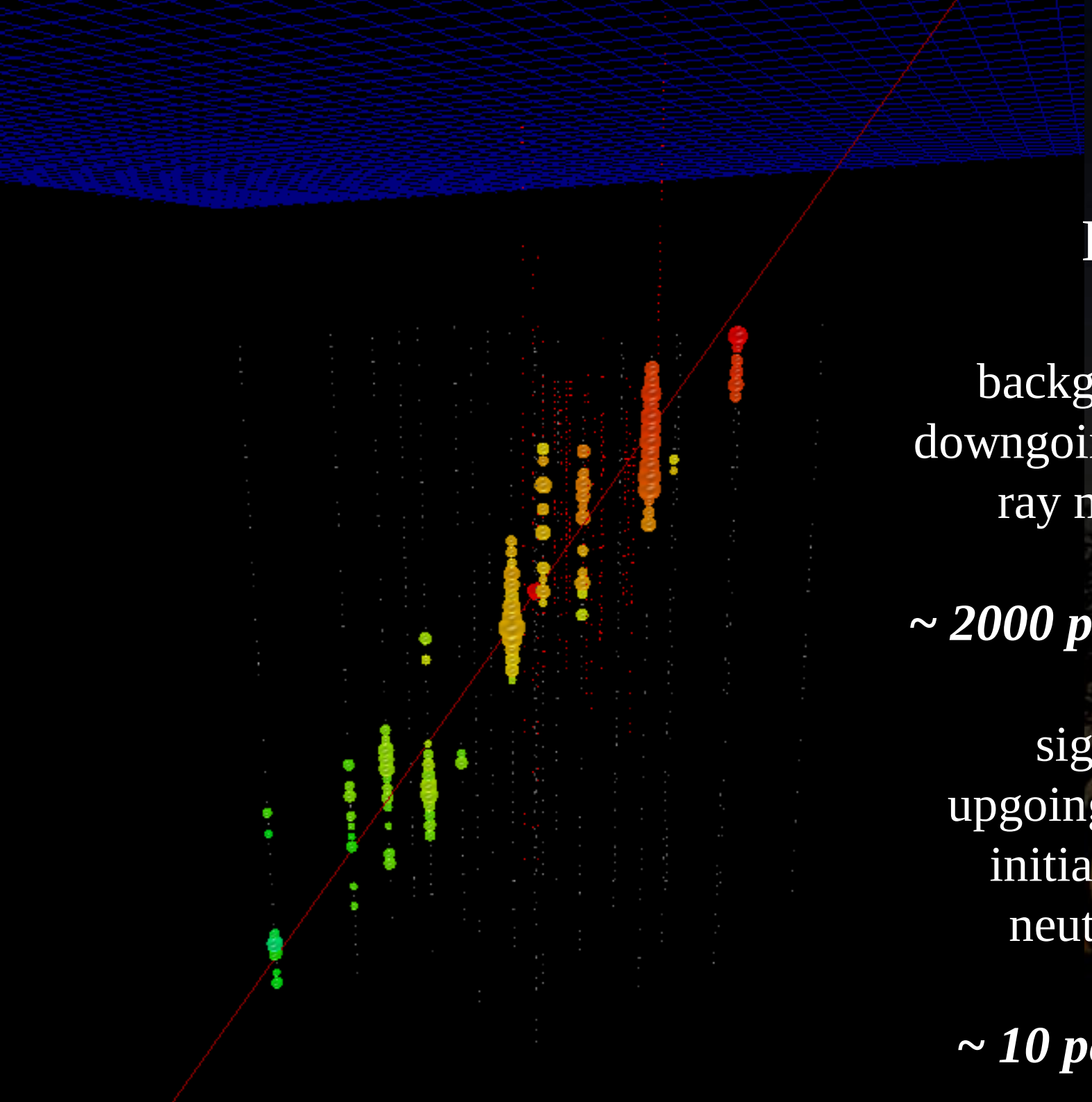
AMANDA-II



- AMANDA started in 1996
- 19-lines in 2000
- R&D for a km^3 detector (IceCube)
- Some results on atmospheric neutrino
- No neutrino source found

IceCube, ~2000 modules





IceCube

background:
downgoing cosmic
ray muons

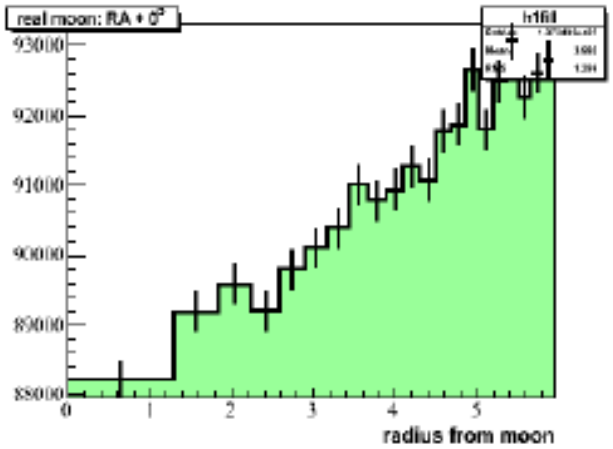
~ 2000 per second

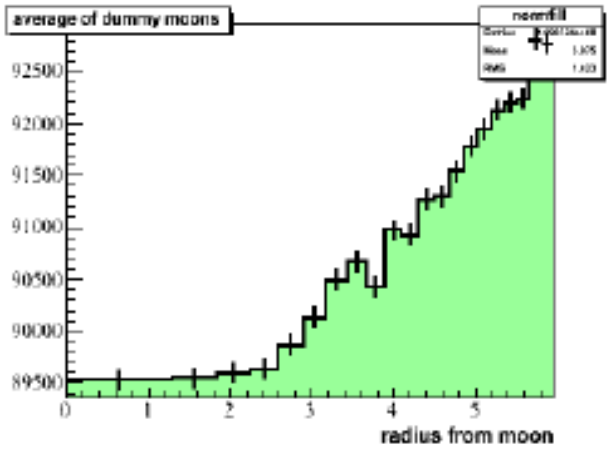
signal:
upgoing muons
initiated by
neutrinos

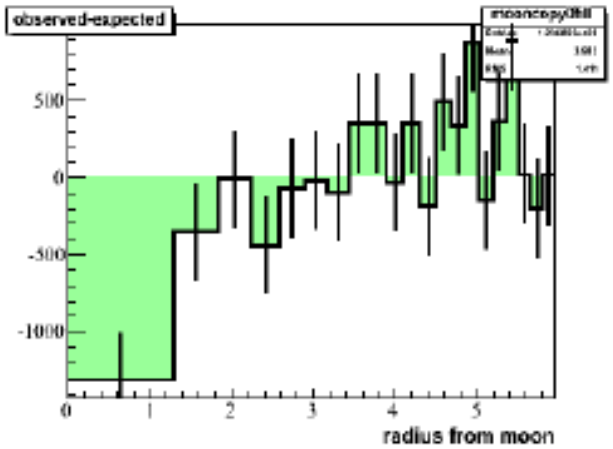
~ 10 per hour

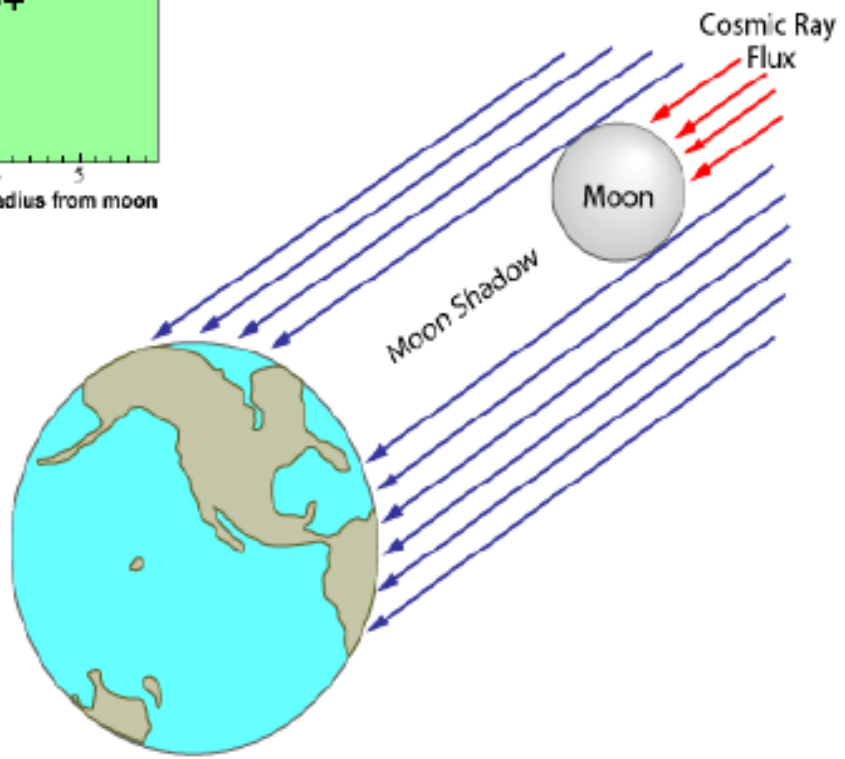
Moon Shadow

- 4.2 σ deficit of events fromp direction of moon in the IceCube 40-string detector.
- Confirms pointing accuracy

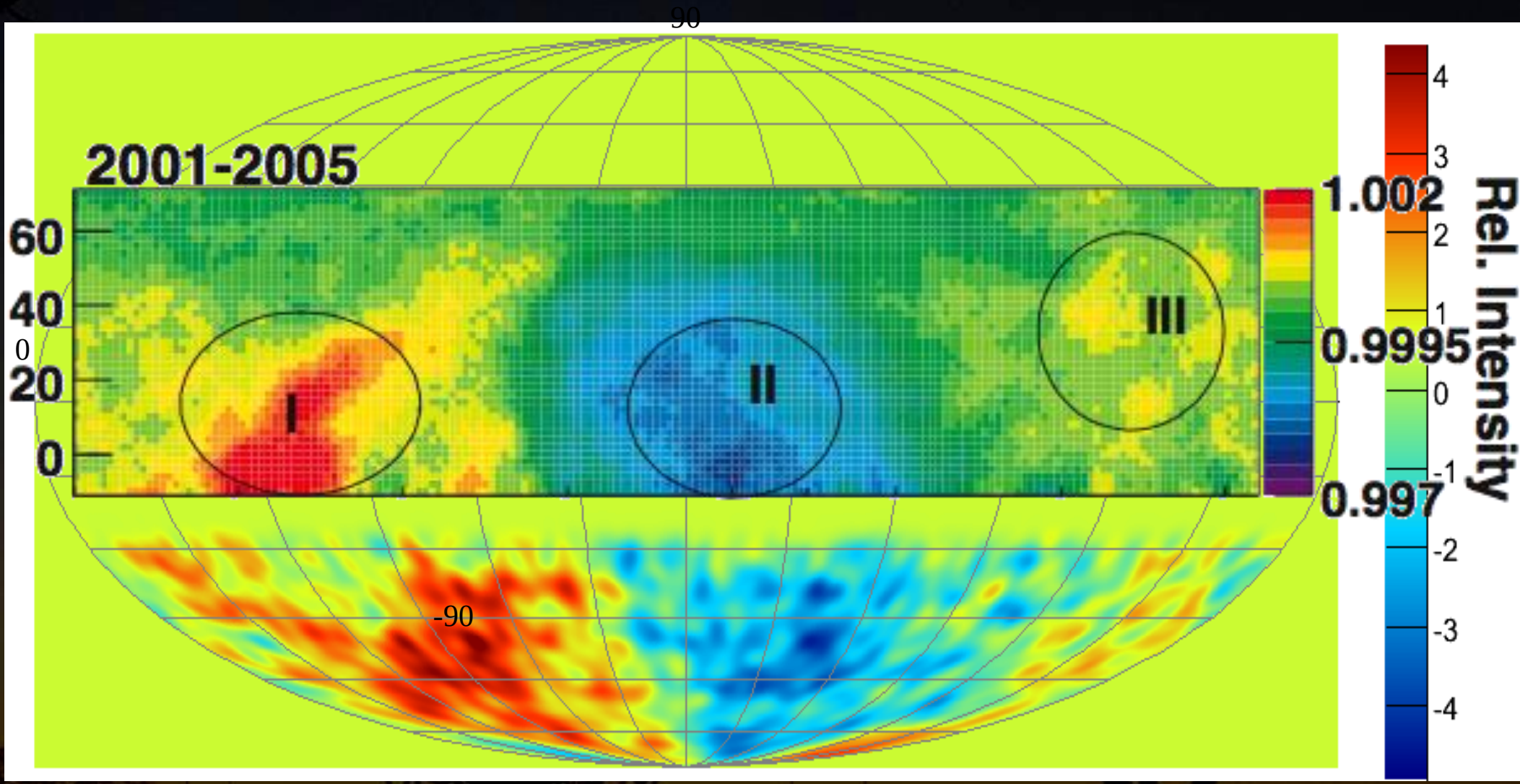








Muon Background in TeV

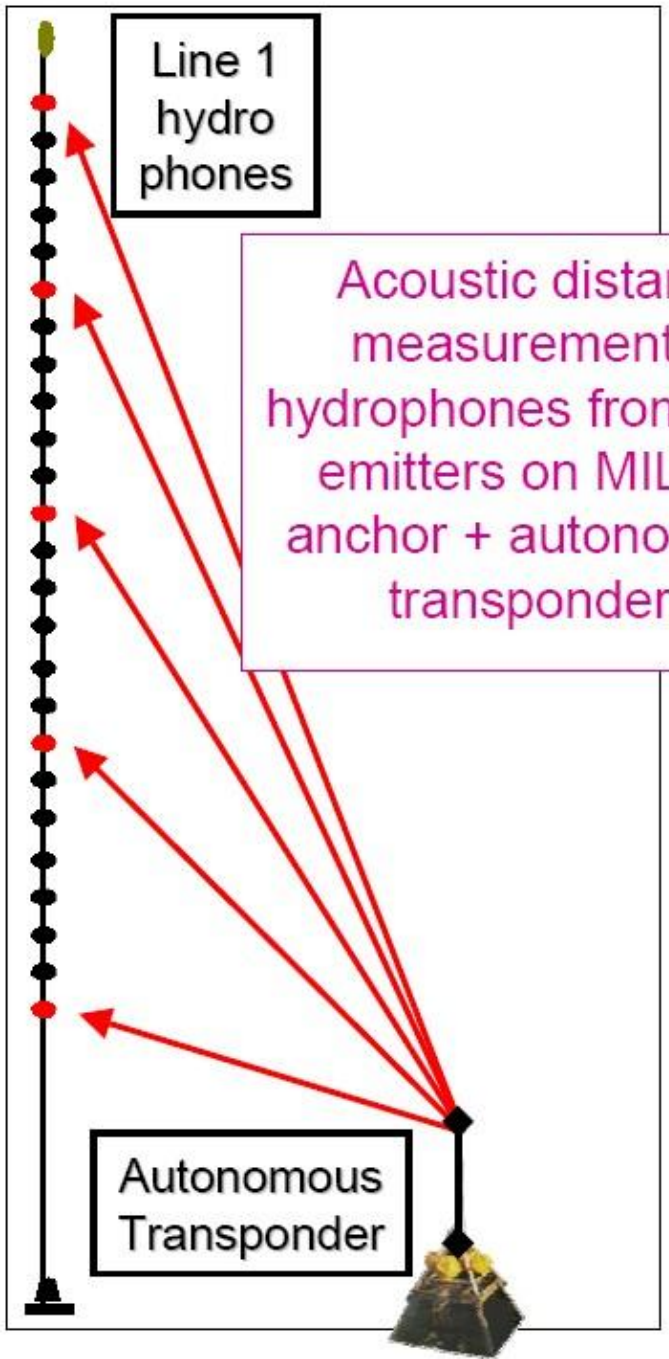


- Muon Background slightly inhomogeneous (10^{-3})
- Seen also by Tibet Array

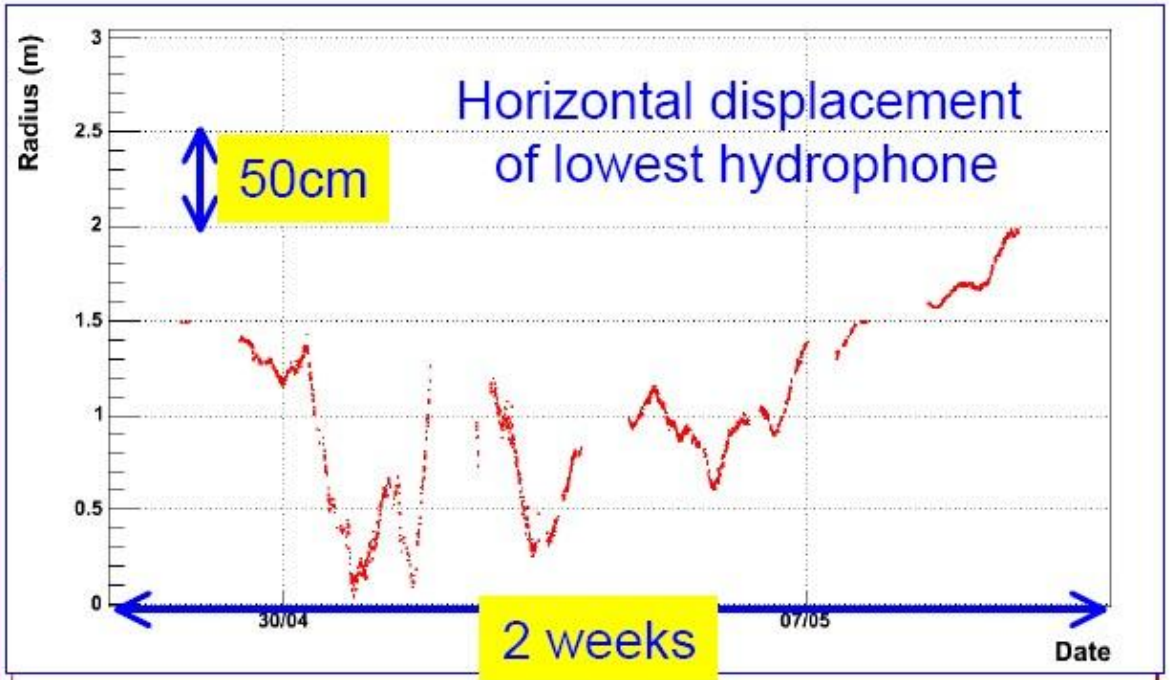
Deployment

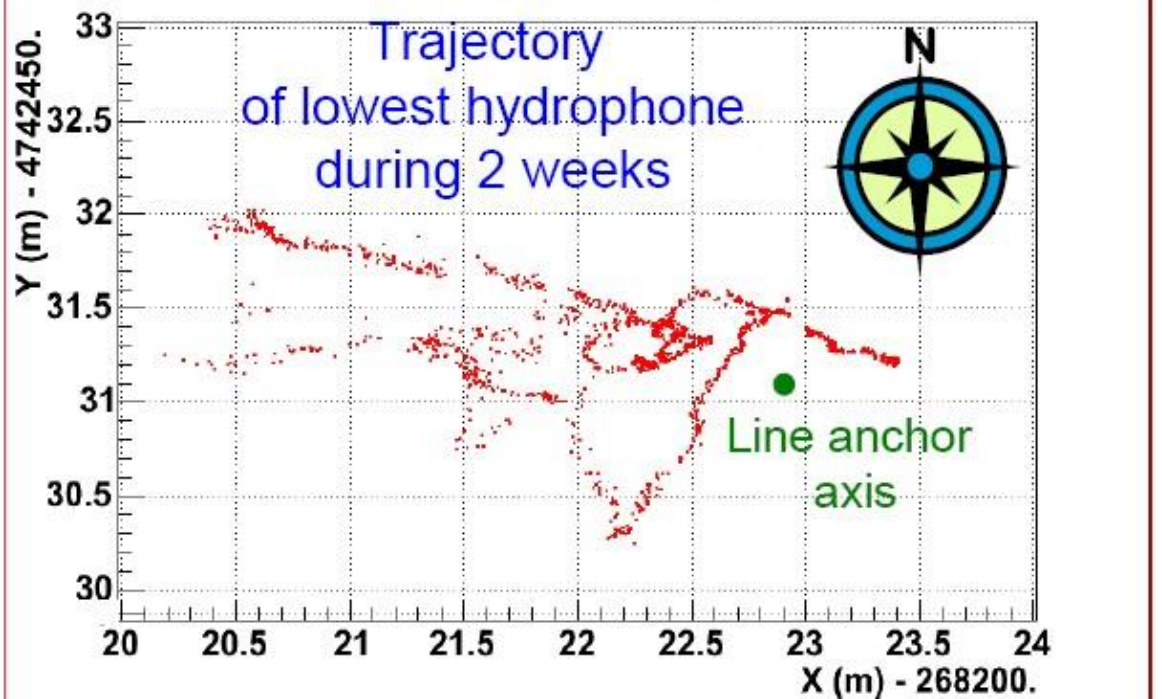
- 2003-2005 Lignes prototypes
- 2006 Lignes 1, 2
- 2007 Lignes 3, 4, 5, 6, 7, 8, 9,10
- 2008 Lignes 11, 12

Acoustic triangulation of Line 1 hydrophone



Acoustic distance measurement of hydrophones from fixed emitters on MILOM anchor + autonomous transponders

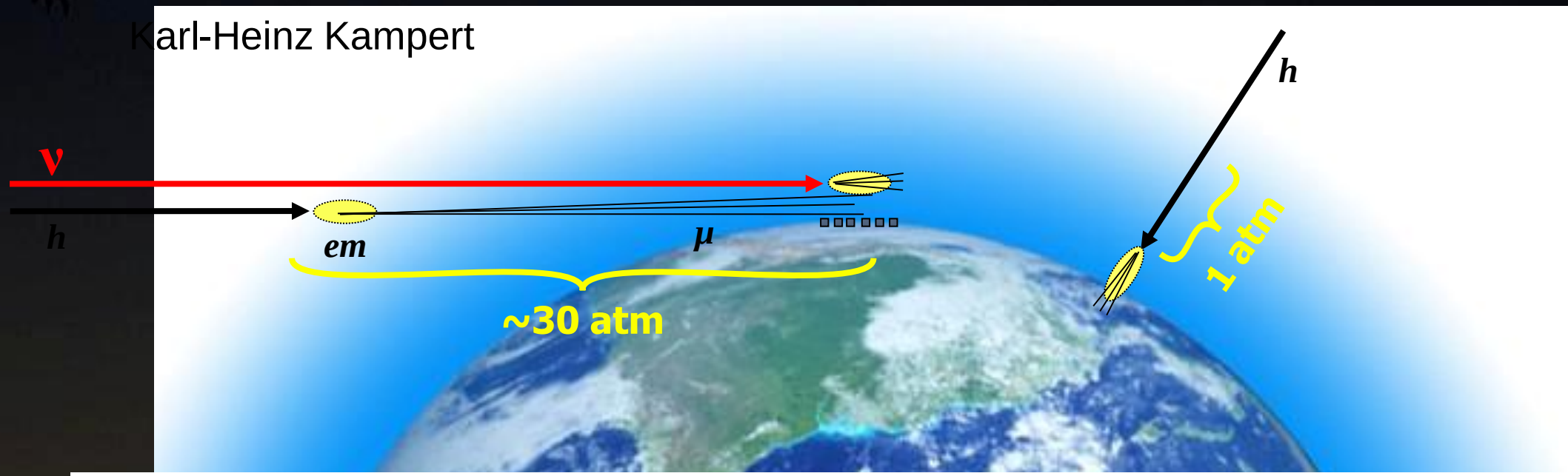


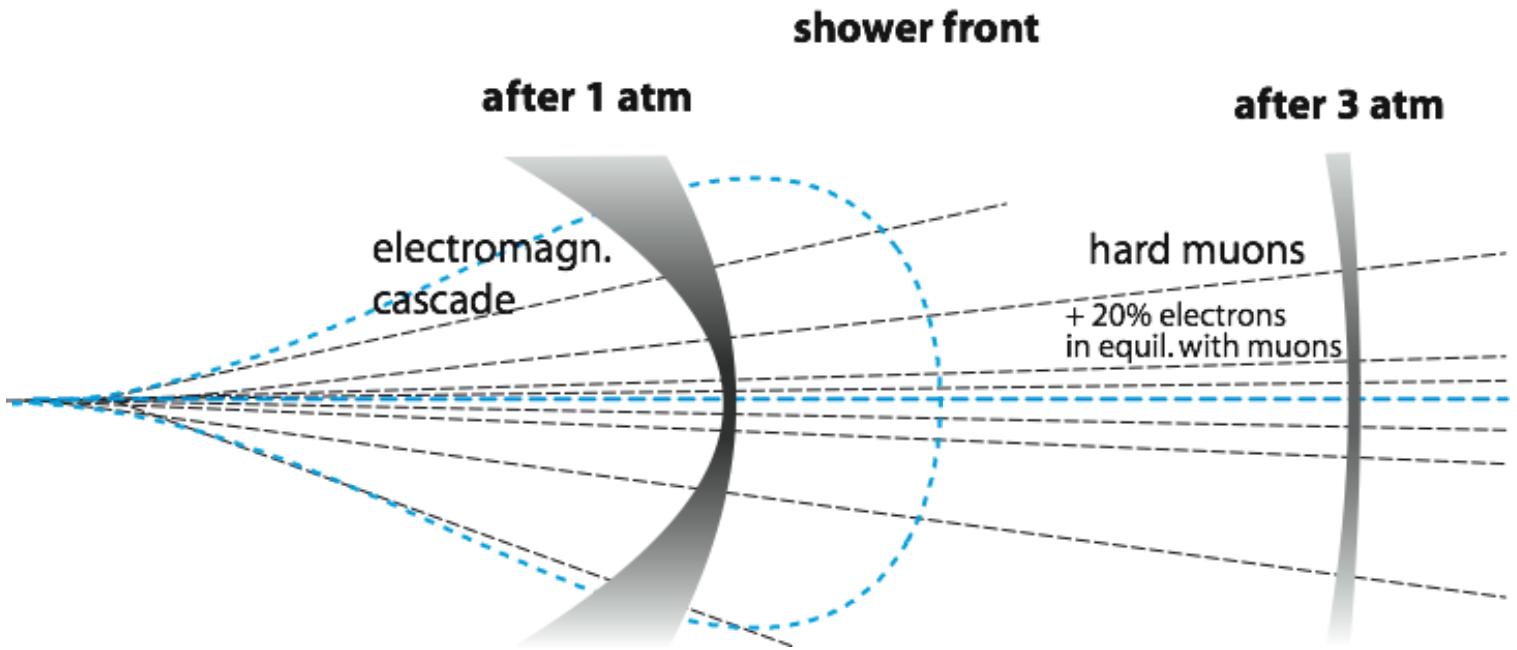


Neutrinos: important bi-product in Auger

A neutrino can induce a young horizontal shower !

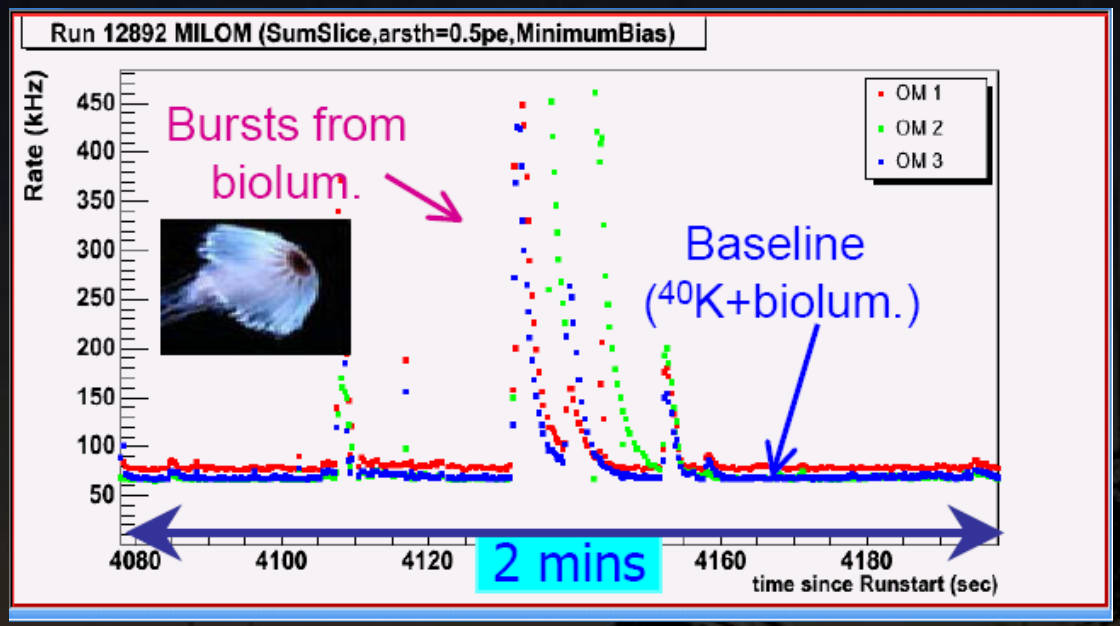
Karl-Heinz Kampert



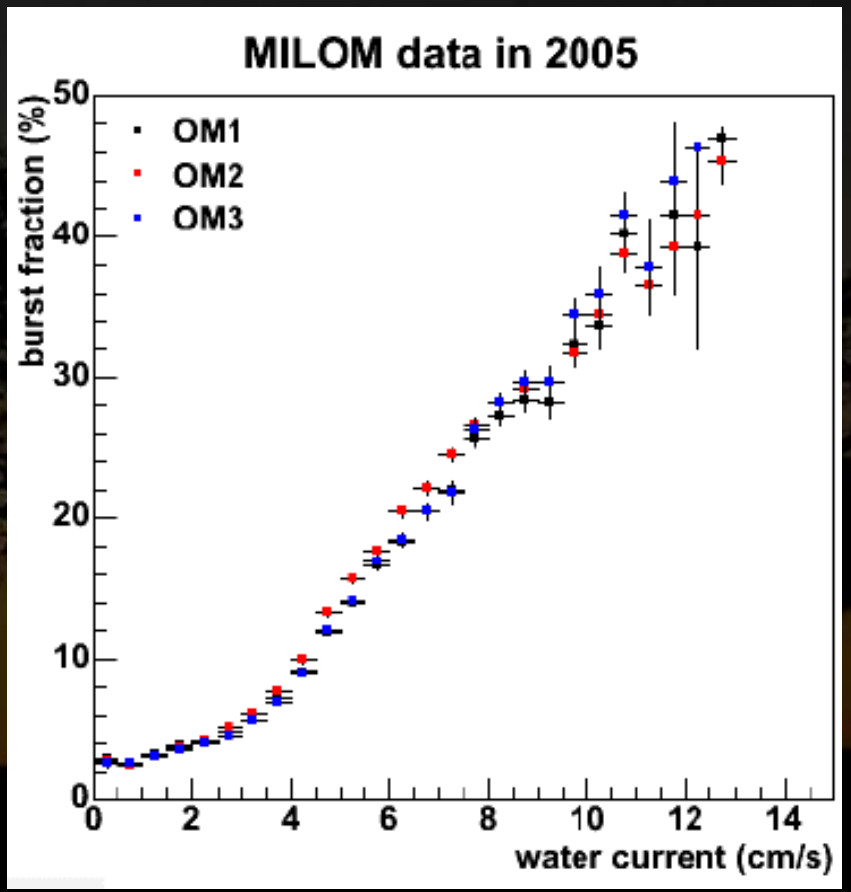


Bioluminescence

- Bioluminescence Activity



- Correlated with marine current

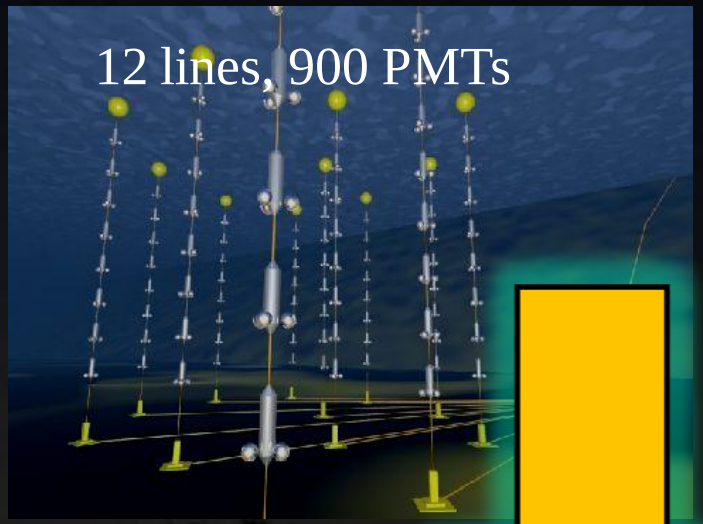


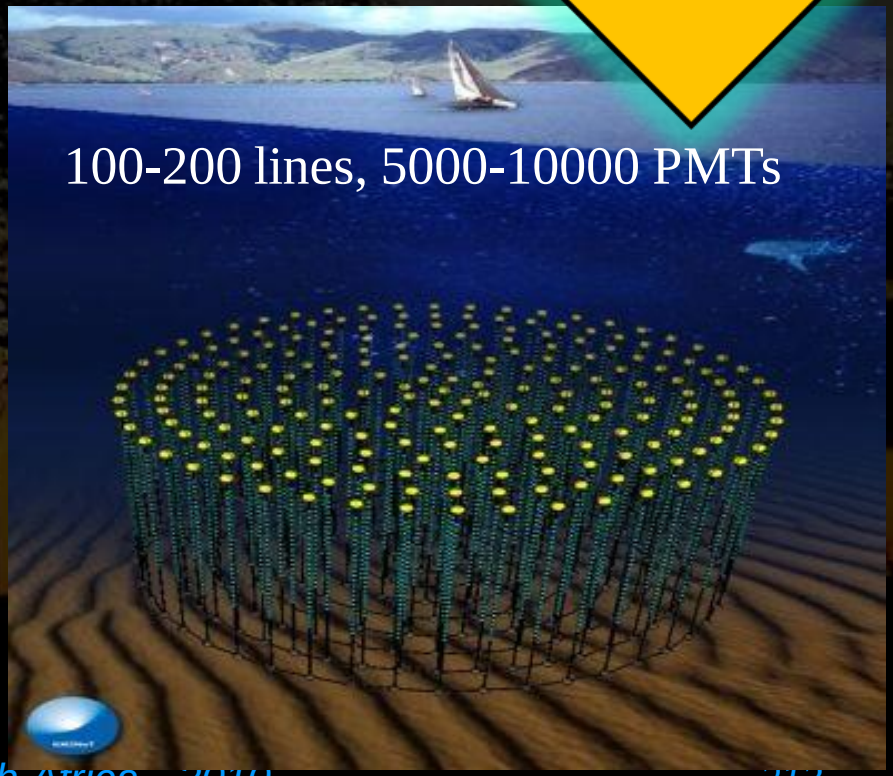
Challenges

- Maximise physics potential
  - Substantial improvement over ICECUBE
  - Instrumented volume >1km3
  - 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
  - …

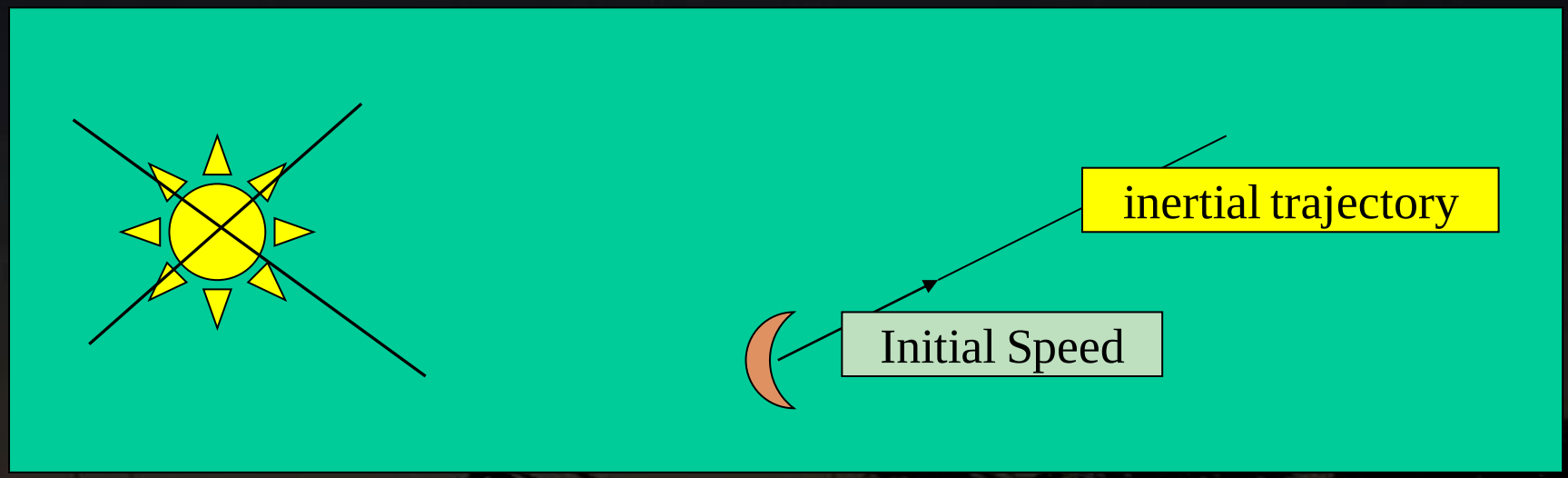


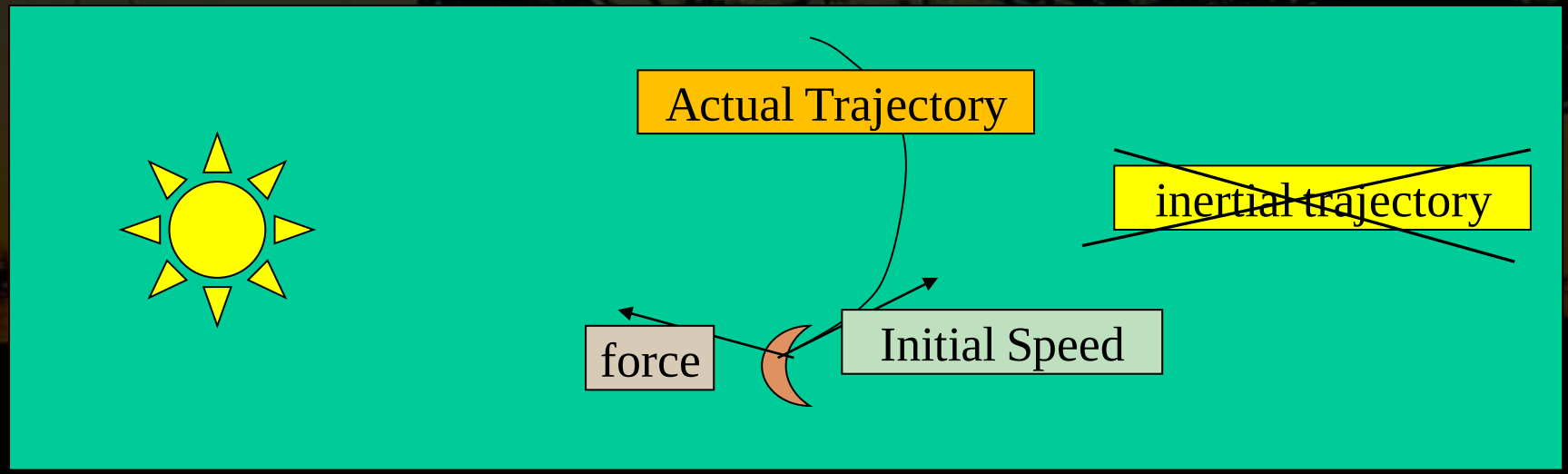


GRAVITATIONAL WAVES

Newtonian Gravity

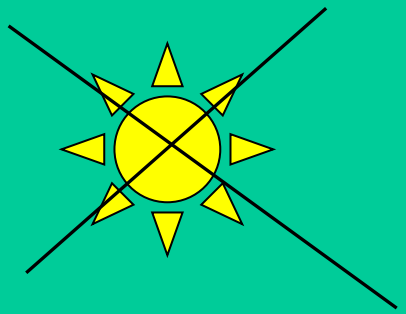
- Flat Space-time



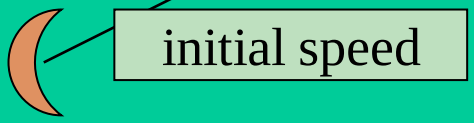


General Relativity

flat space time

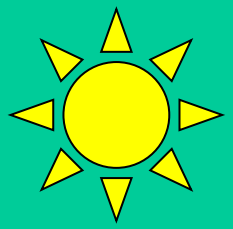


inertial trajectory = straight uniform

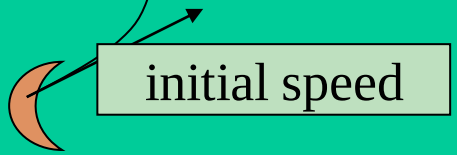


initial speed

non-flat space time



actual trajectory = intertial trajectory ~~straight uniform~~



initial speed