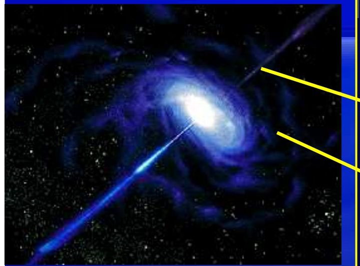
High Energy Astroparticle Physics: Study of the Extreme Universe

Valencia, June 26, 2006

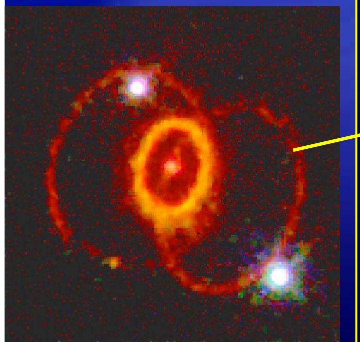
Tiina Suomijärvi
IPN-Orsay
University of Paris South - Orsay

High Energy Cosmic Phenomena

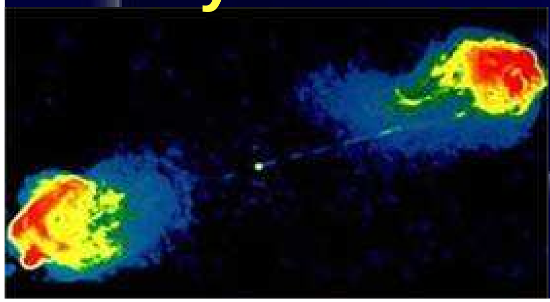
AGN

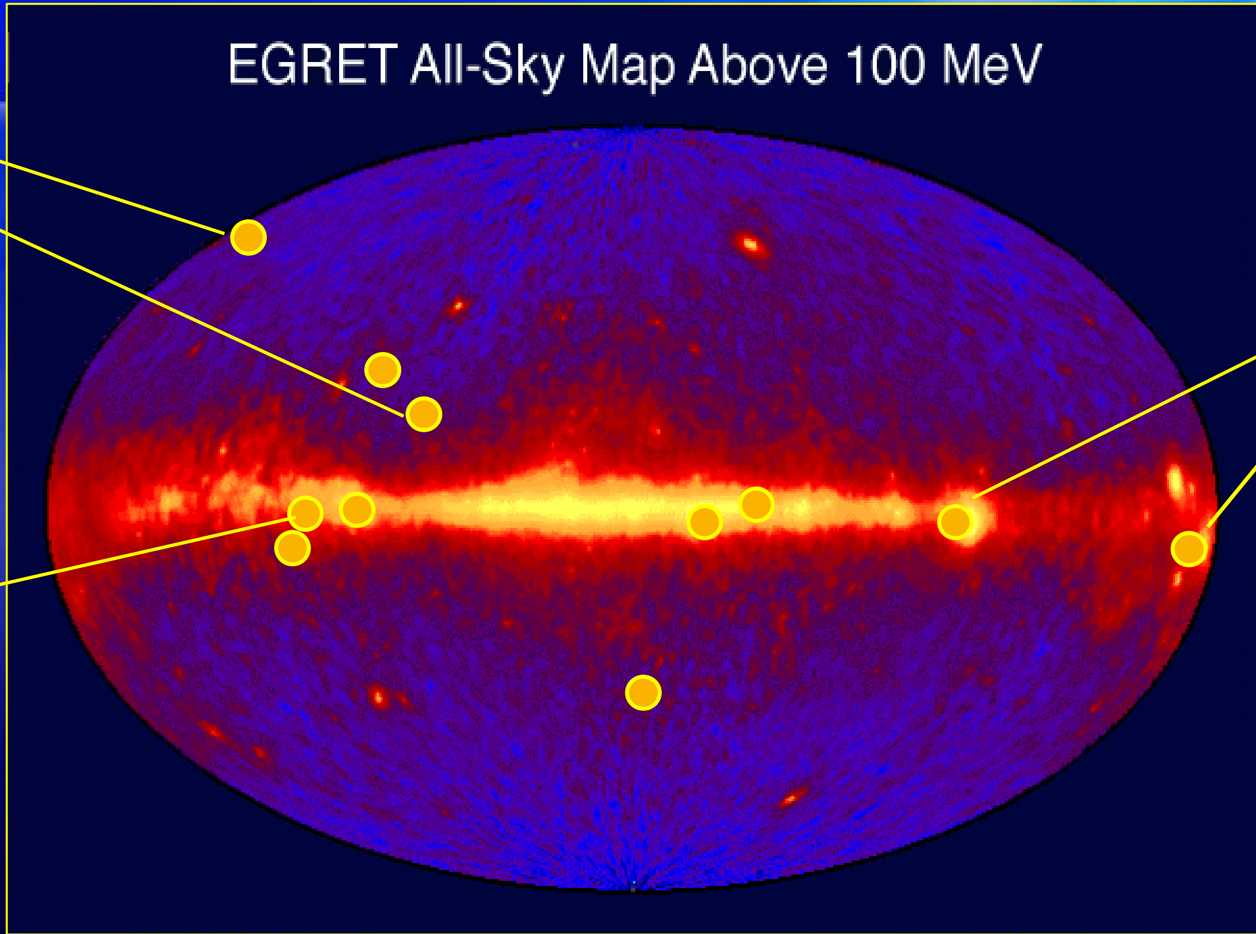


SNR



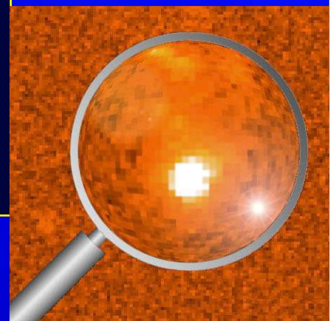
Radio Galaxy





Pulsar

GRB



Colliding galaxies

Supernovae

- Supernova occur at the end of a star's lifetime, when its nuclear fuel is exhausted and it is no longer supported by the release of nuclear energy.
- The result of the collapse may be a rapidly rotating neutron star that can be observed many years later as a radio pulsar.

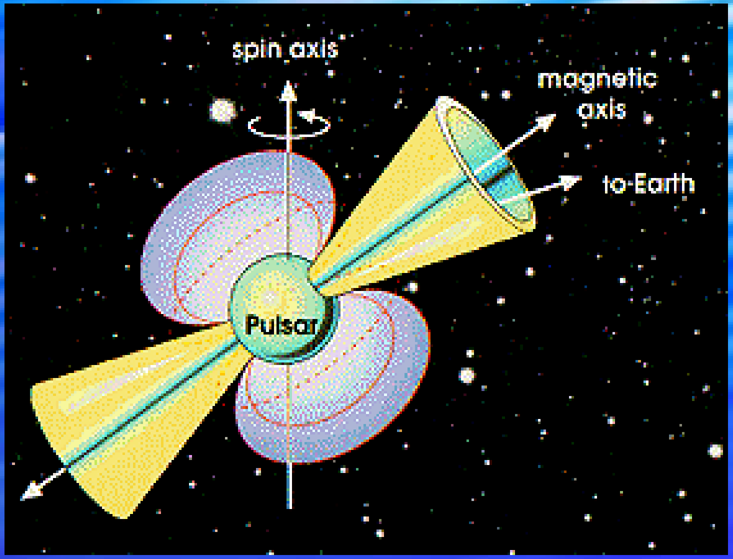
QuickTime™ et un
décompresseur Sorenson Video 3
sont requis pour visionner cette image.

Illustration of he events following the supernova 1987A outburst (Large Magellanic Cloud). The blue ring is previously observed material ejected from the star thousands of years ago. The expanding orange and yellow shell is multimillion degree, X-ray emitting gas produced by the explosion. Portions of the blue ring light up when struck by the X-ray shell.

Supernovae are rare events in our galaxy.
There are many remnants of Supernovae explosions in our galaxy, that are seen as X-ray shell like structures caused by the shock propagating out into the interstellar medium.

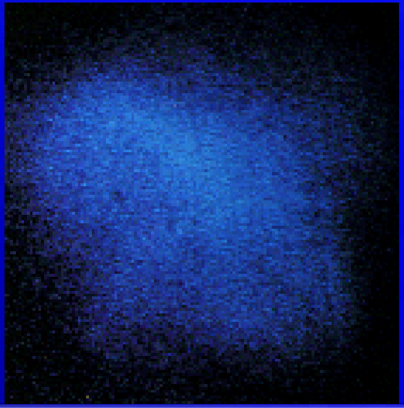
Pulsars

Pulsars are isolated, rotating, magnetised neutron stars.
They have jets of particles moving almost at the speed of light streaming out above their magnetic poles.



A famous remnant is **the Crab Nebula** which exploded in 1054: pulsar which rotates 30 times a second and emits a rotating beam of X-rays (like a lighthouse).

Crab Nebula:
Figures show the diffuse emission of the Crab Nebula surrounding the bright pulsar in both the "on" and "off" states, i.e. when the magnetic pole is "in" and "out" of the line-of-sight from Earth.
The period is 33 ms.



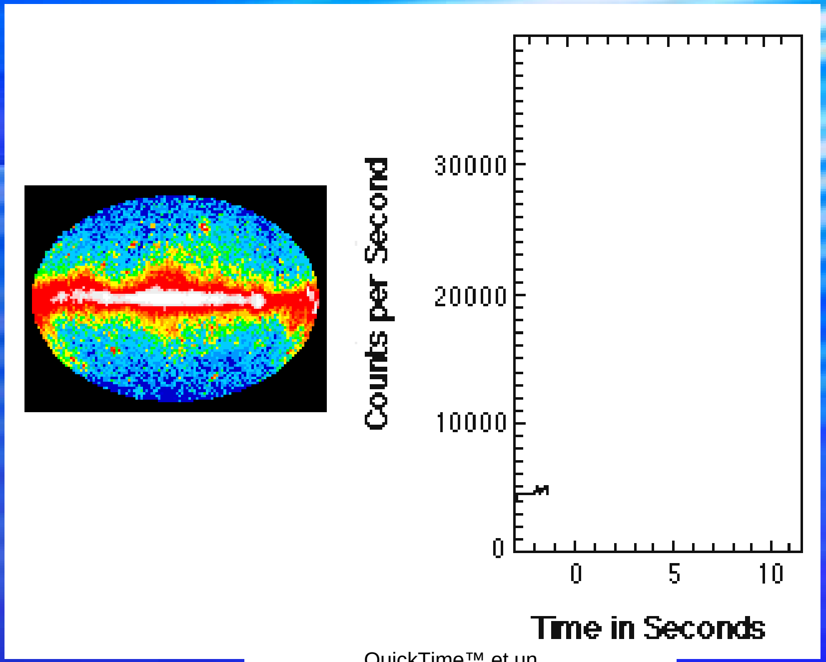
Gamma Ray Bursts

Gamma-ray bursts are short-lived bursts of gamma-ray photons.
At least some of them are associated with a special type of supernovae.

Lasting anywhere from a few milliseconds to several minutes, gamma-ray bursts (GRBs) shine hundreds of times brighter than a typical supernova.

GRBs are detected roughly once per day from wholly random directions of the sky.

The star -- containing about 10 solar masses worth of helium, oxygen and heavier elements -- has depleted its nuclear fuel. This has triggered a Type Ic supernova / gamma-ray burst event.
The core of the star has collapsed, without the star's outer part knowing. A black hole forms inside surrounded by a disk of accreting matter, and, within a few seconds, launched a jet of matter away from the black hole that ultimately made the gamma-ray burst.

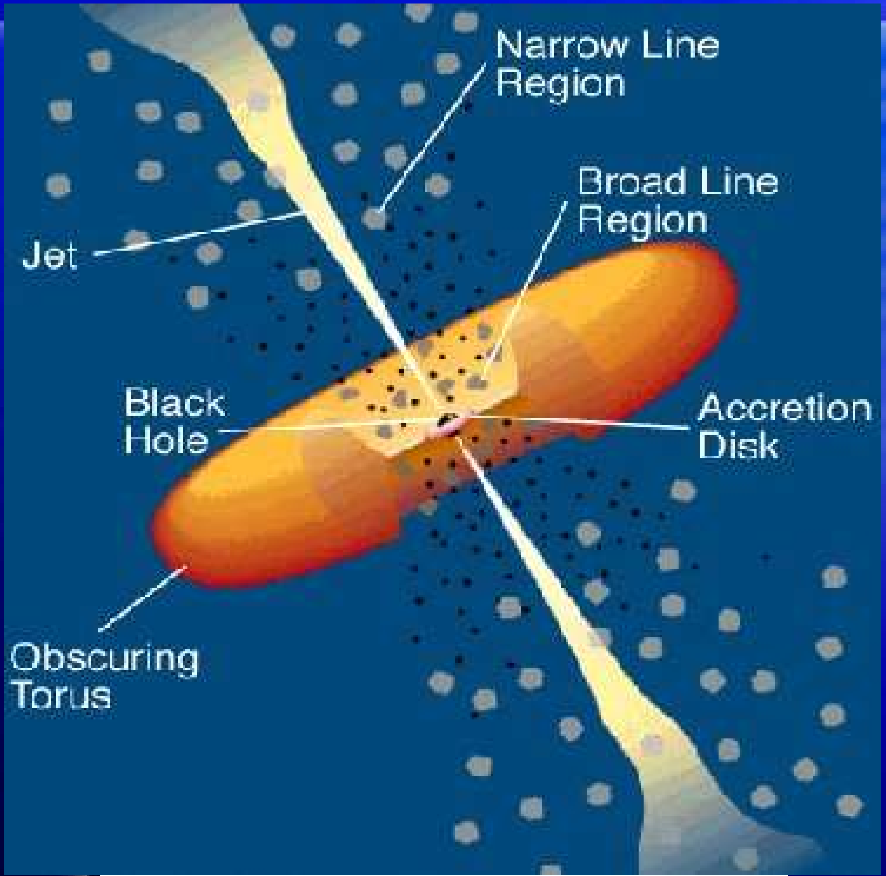


QuickTime™ et un
décompresseur TIFF (LZW)
sont requis pour visionner cette image.

QuickTime™ et un
décompresseur Photo
sont requis pour visionner cette image.

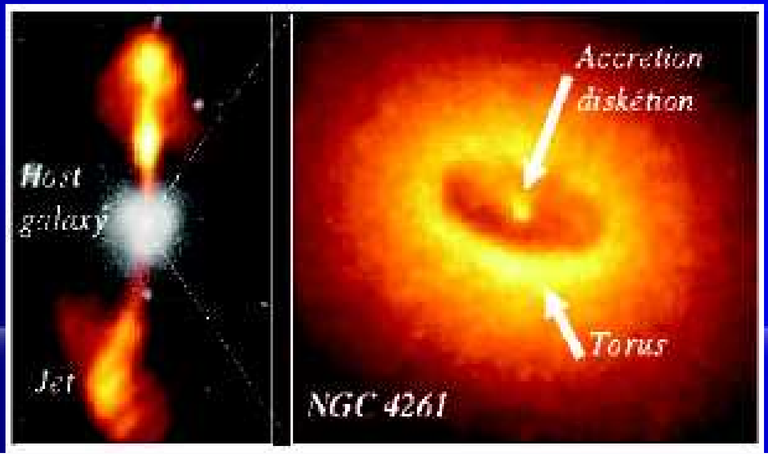
Active Galactic Nuclei

Model for generating energy in AGNs

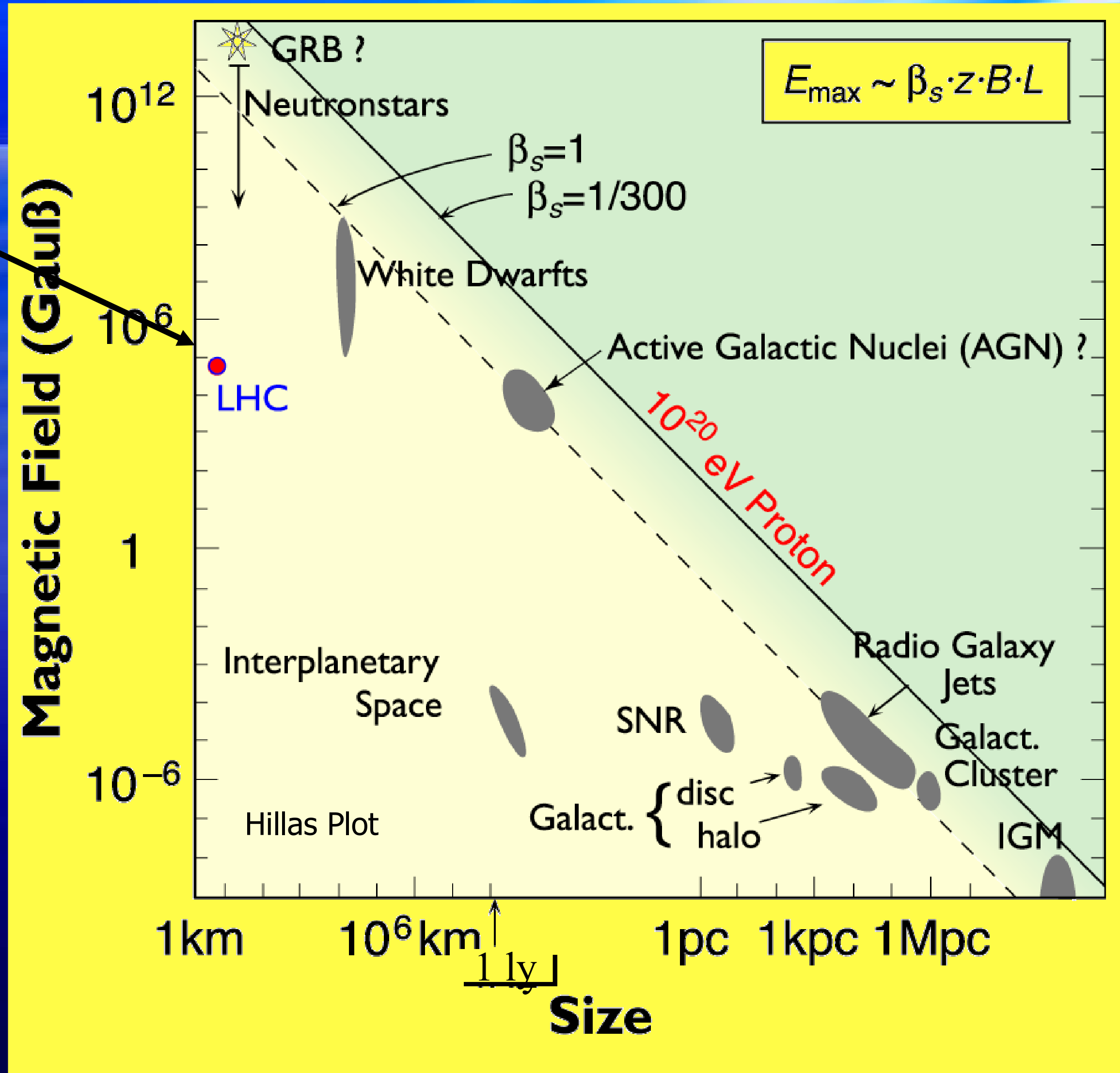


QuickTime™ et un
décompresseur TIFF (LZW)
sont requis pour visionner cette image.

- Radio galaxies
  - Sources of vast fluxes of high energy particles and magnetic fields
- Quasars
  - Look like star but has a luminosity much greater than galaxies.
- Blazars, radio quiet quasars
- BL Lacertae er BL-Lac objects, the most extreme examples of active galactic nuclei
  - Similar to quasars but luminosity vary rapidly (days): compact objects.



Cosmic Accelerators



Stochastic acceleration in magnetic turbulences

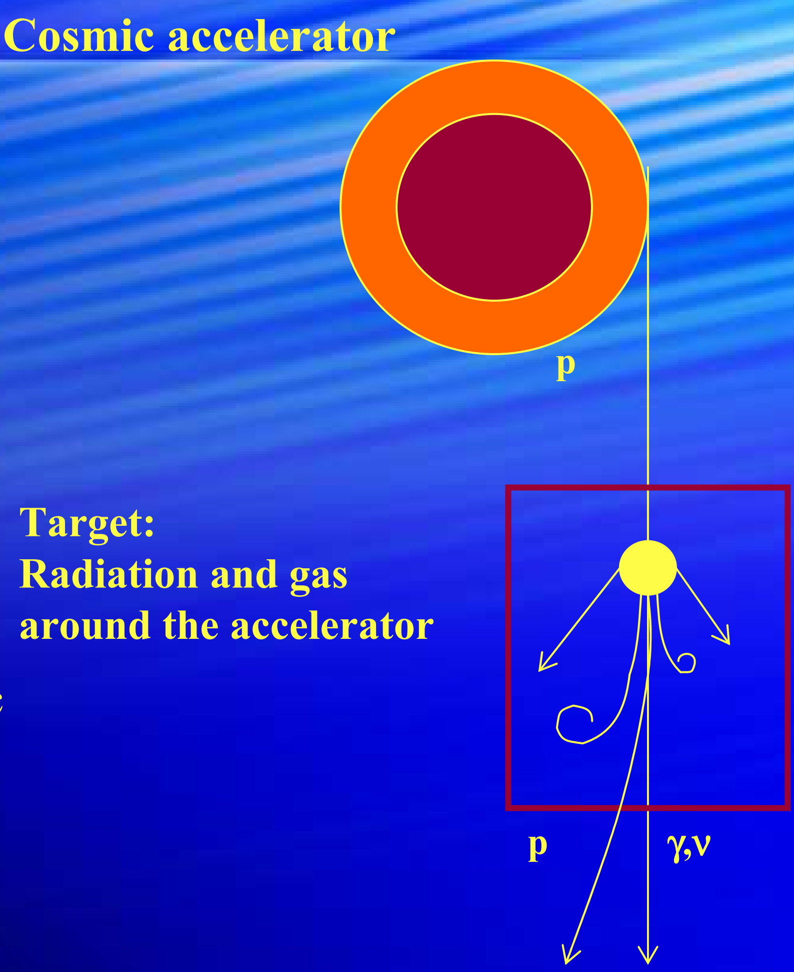
Maximum energy is obtained when particles are confined in the acceleration site => large dimension necessary (1 Mpc), weak radiation around the site required : the jets of the radiogalaxies ?

Electrostatic acceleration in magnetized, rapidly rotating objects

Young neutron starts ?

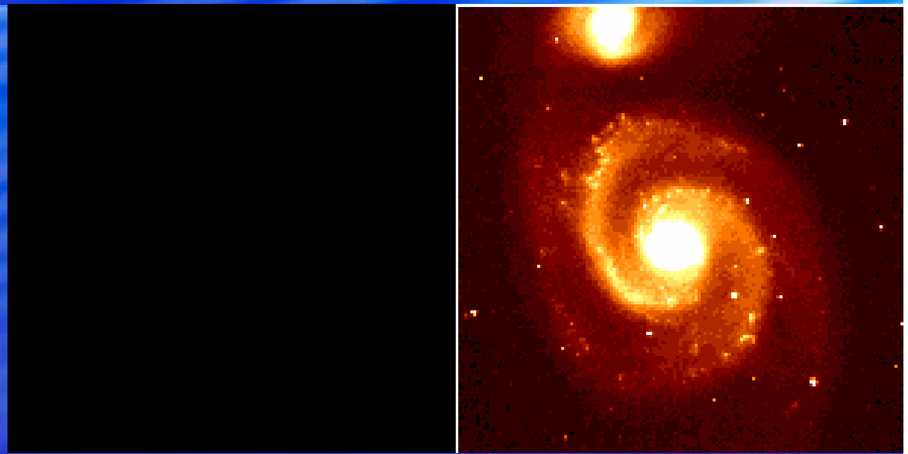
Production of Radiation and Particles

- Primary particles accelerated are charged particles.
- Neutrinos and gammas are created as secondary products.
- A power law energy spectrum: $dN(E) \propto E^{-x} dE$ where x is about 2.2-3.
- The acceleration of cosmic rays to energies of about 10^{20} eV.
- The acceleration mechanism should result in chemical abundances of cosmic rays which are similar to cosmic abundances of the elements.



Dark matter ?

Velocity measurements -> the amount of inferred mass is much more than can be explained by the luminous stuff -> Dark Matter



Dark matter makes up about 25% of the energy budget of the Universe !

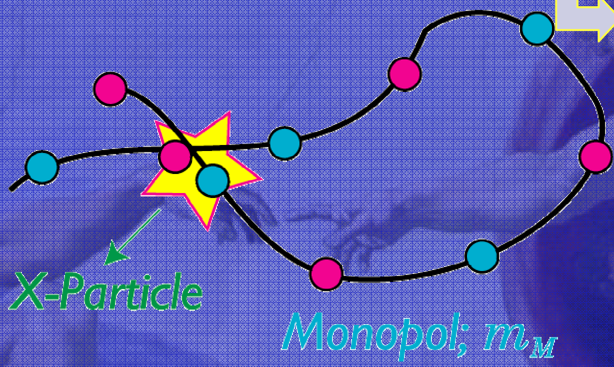
The leading candidate for this "dark matter" is the **neutralino**, the lightest supersymmetric particle.

Collisions of neutralinos with ordinary matter are believed to slow them down. The scattered neutralinos, may then be gravitationally trapped by objects such as the Sun, Earth, and the black hole at the center of the Milky Way galaxy, where they can accumulate over cosmic time scales.

Exotic Particles ?

Cosmic rays produced by decay of topological defects

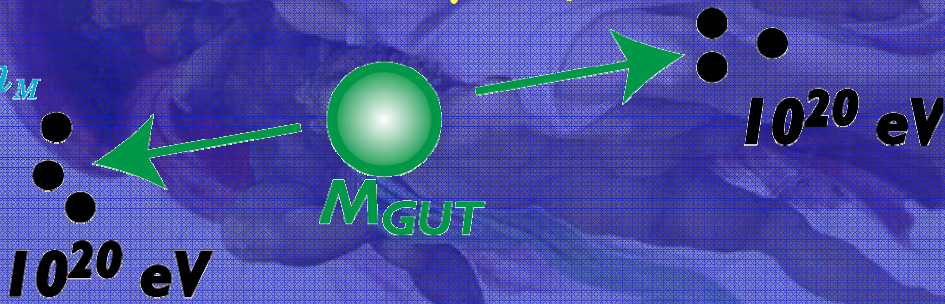
• super heavy relic particles from Big-Bang



↳ X-particles (m ≈ 10^{21}-10^{25} eV)

↳ W,Z bosons

↳ γ, ν, p…

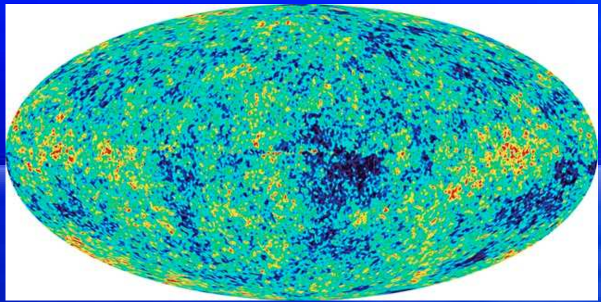


• long living X-particles

Clustering im galactic halo, Dark Matter candidate

see e.g. Bhattacharjee, Sigl: Phys. Rep. 327 (2000) 109

Propagation of Charged Particles



The Wilkinson Microwave Anisotropy Probe (WMAP) team has made the first detailed full-sky map of the oldest light in the universe.

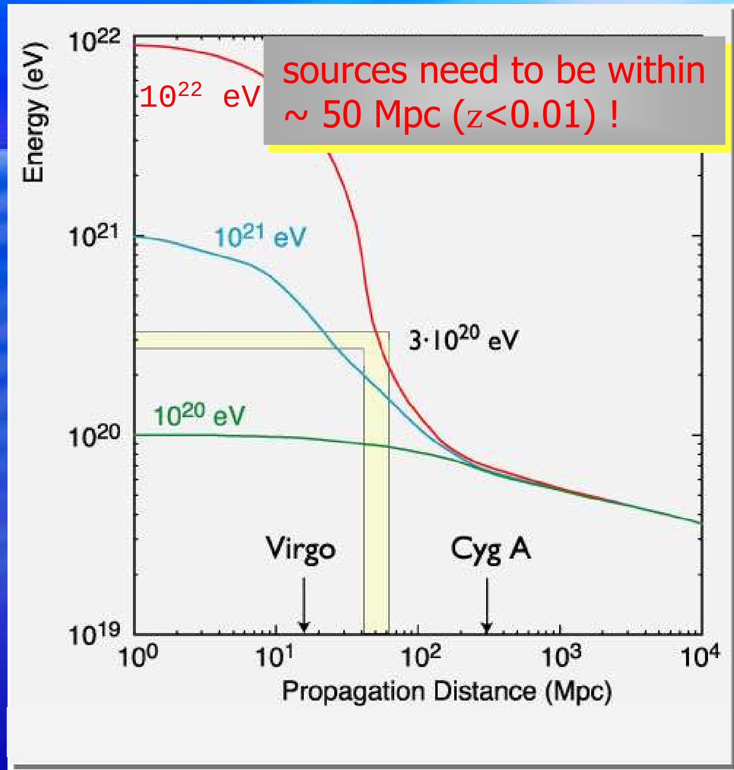
Pion production with CMB

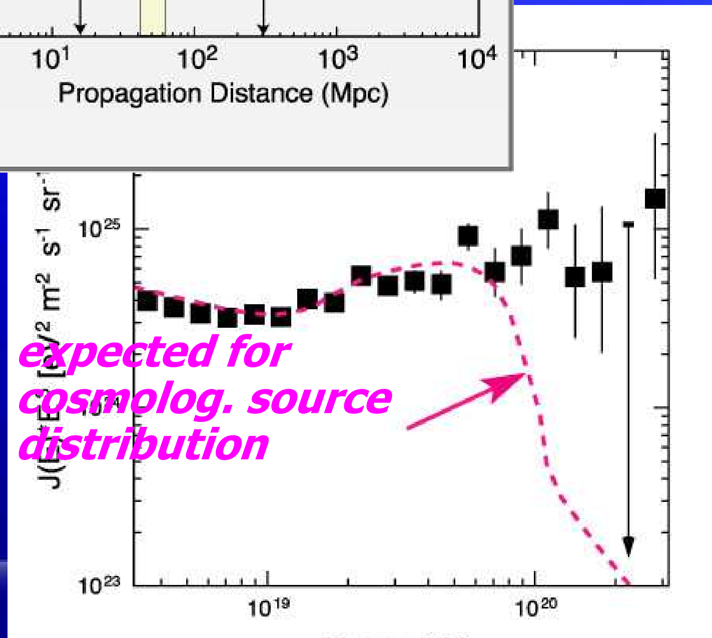
$$p + \gamma_{3K} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \; ; n + \pi^{+}$$

threshold: $E_p E_\gamma > (m_\Delta^2 - m_p^2)$

$\Rightarrow E_{GZK} \approx 6 \cdot 10^{19}$ eV

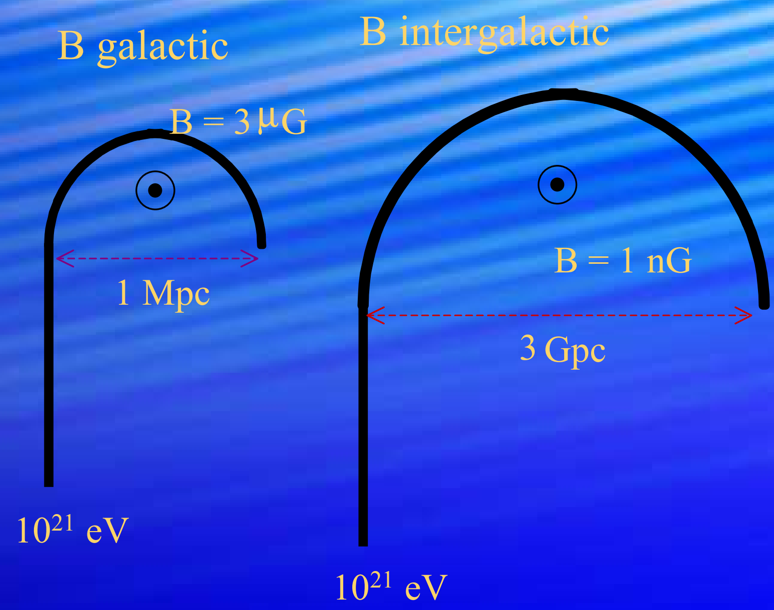
GZK-Effect:
Protons with
E **greater than** $6 \cdot 10^{19}$ eV scatter with CMB
(Greisen - Zatsepin - Kuzmin)

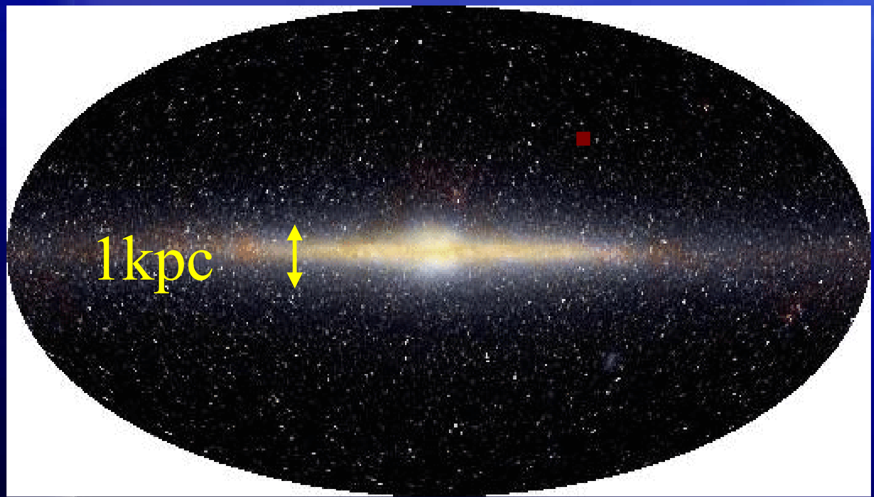




AGASA, PRL 2001

Effects of Magnetic Field





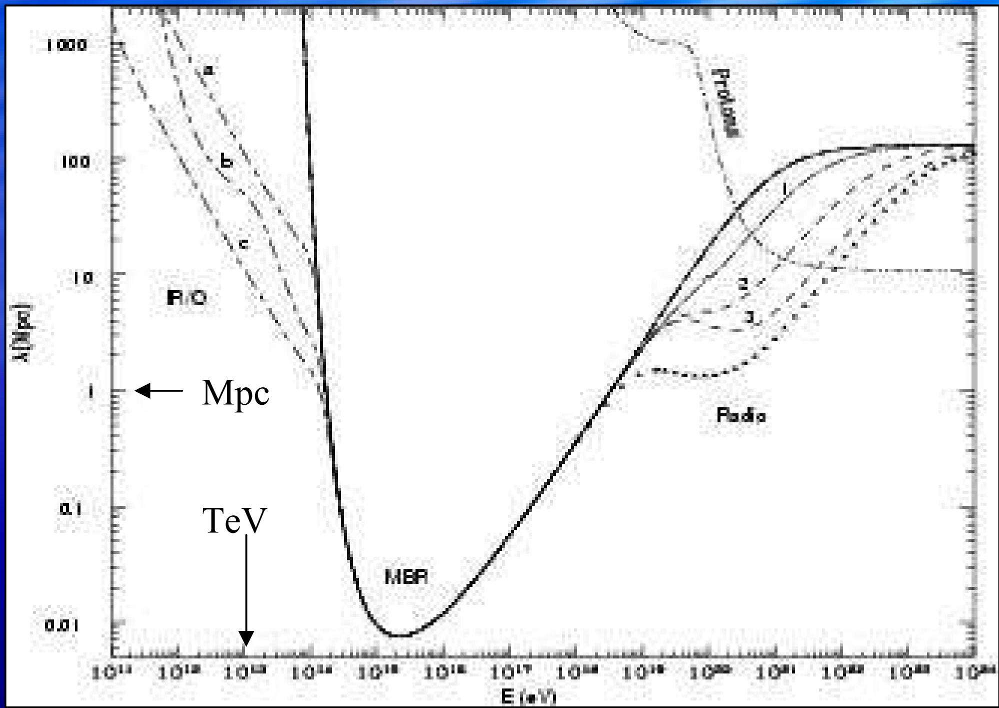
Ultra-high energy cosmic rays point to sources.
They are not confined to our galaxy: extra-galactic visibility.

Attenuation of Gamma Rays

Pair production ->
•TeV photons are abserbed on infrared light
•PeV photons on the CMB
•EeV photons on radio-waves

Origin of infrared light: light emitted by galaxies since their formation, re-processed by dust and redshifted due to the expansion of the Universe

γ-ray absorption length vs. γ -ray energy



Only neutrinos propagate without attenuation !

Study of Extreme Universe

- Understand relativistic winds, shock acceleration, jet formation, extreme electrodynamics
- Understand cosmic ray origin and propagation
- Learn more about cosmic magnetic fields
- Search for antimatter
- Indirect detection of dark matter
- Search for exotic particles

Cosmic Laboratory

Extreme conditions:
- Magnetic field
- Temperature
- Density
- Gravitation

Unique opportunity to test the limits of our conception of Physics

Possibility to discover new Physics laws non-accessible in the laboratories on the Earth

Potential for major discoveries !

Detection Methods

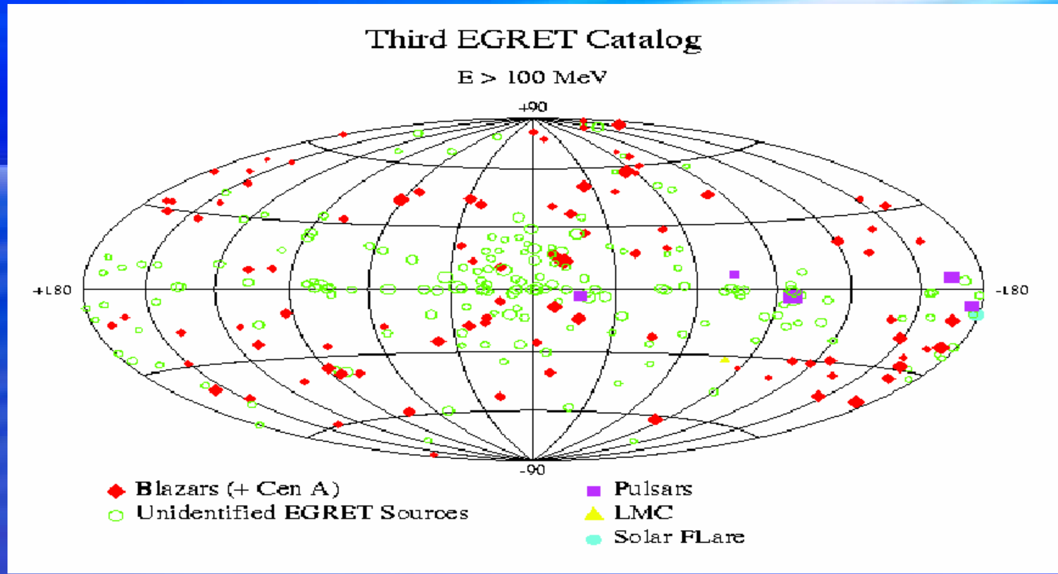
- High energy cosmic messengers are rare and difficult to detect, the technique employed requires deployment of large area detectors and use of large volume natural detector media (atmosphere, sea water, ice, salt-mines, etc.).
  - High-energy gamma rays: telescopes by measuring the Cherenkov light induced in the Earth's atmosphere
  - High-energy neutrinos: large-volume telescopes deployed in deep sea or in deep ice, measuring the Cherenkov light from secondary muons
  - Very high-energy cosmic rays: fluorescence telescopes measuring light induced by the cosmic shower in the Earth's atmosphere or by sampling the particle shower on the ground with huge detector arrays.

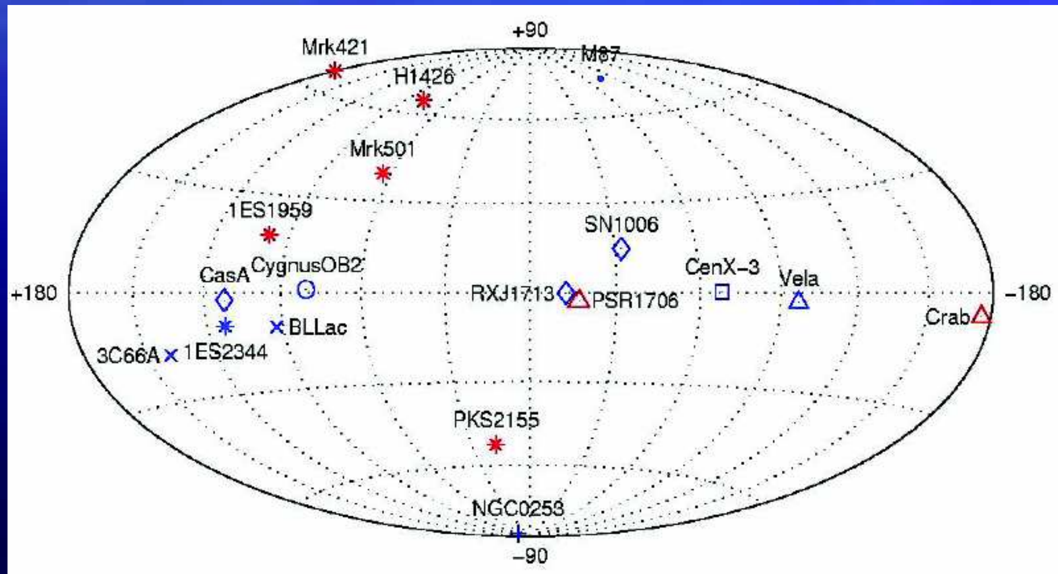
High Energy Gamma Sources

Discovery of the extragalactic γ-ray sky (about 60 sources) by EGRET (NASA, within Compton Gamma-Ray Observatory, CGRO) 1991-2000

3rd EGRET catalogue: about 300 sources

The sky map filling up with high energy sources



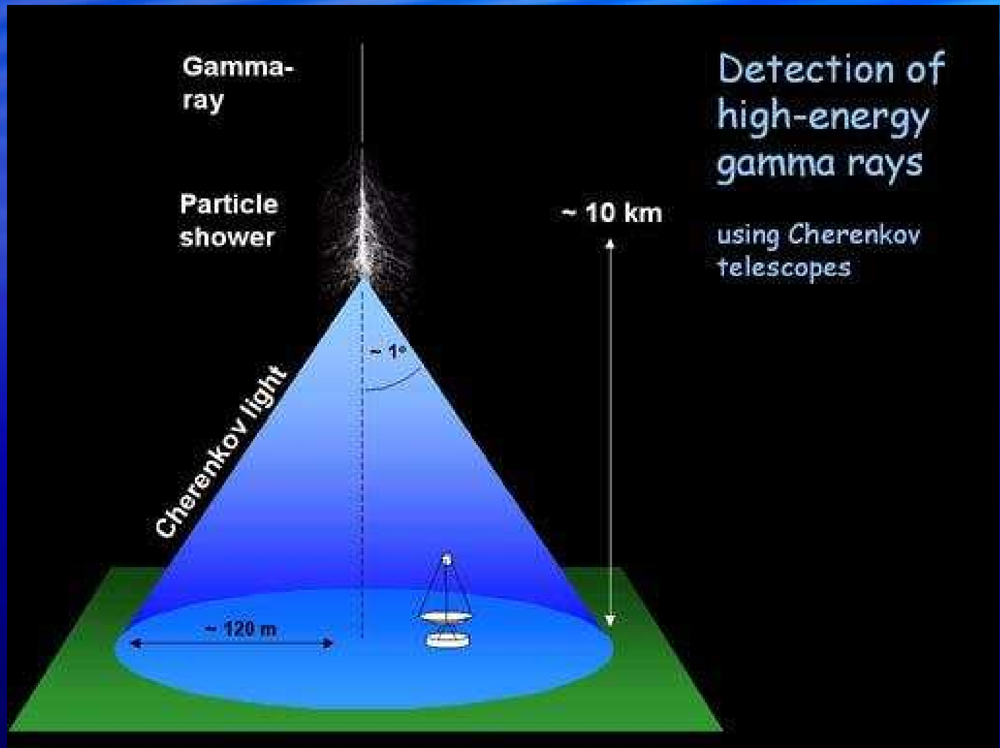


TeV sources early 2004

Detection of High Energy Gammas

Cherenkov telescopes between 50 GeV and 50 TeV

- Very low fluxes:
  e.g. Crab nebula: flux(E > 1 TeV) = 2 x 10^{-11} cm^{-2} s^{-1}
  Large effective detection areas (>30 000 m^2) needed
  -> Back to the ground
- Use the atmosphere as a huge calorimeter and detect γ-ray induced atmospheric showers through Cherenkov light



Atmospheric Cherenkov Technique

- Only working by clear moonless nights

  -> Duty cycle ≈ 10 % or less
- Detection area ≈ size of the Cherenkov light pool on the ground
  - Cherenkov angle ≈ 1° at ground level
  - Light pool diameter ≈ 300 m at 2000 m a.s.l.
- Cherenkov light peaks at short wavelength (blue/UV)
- Very brief flash of Cherenkov light (a few nanoseconds) -> need fast photodetectors
- Limited field of view (a few degrees) -> *tracking instrument*

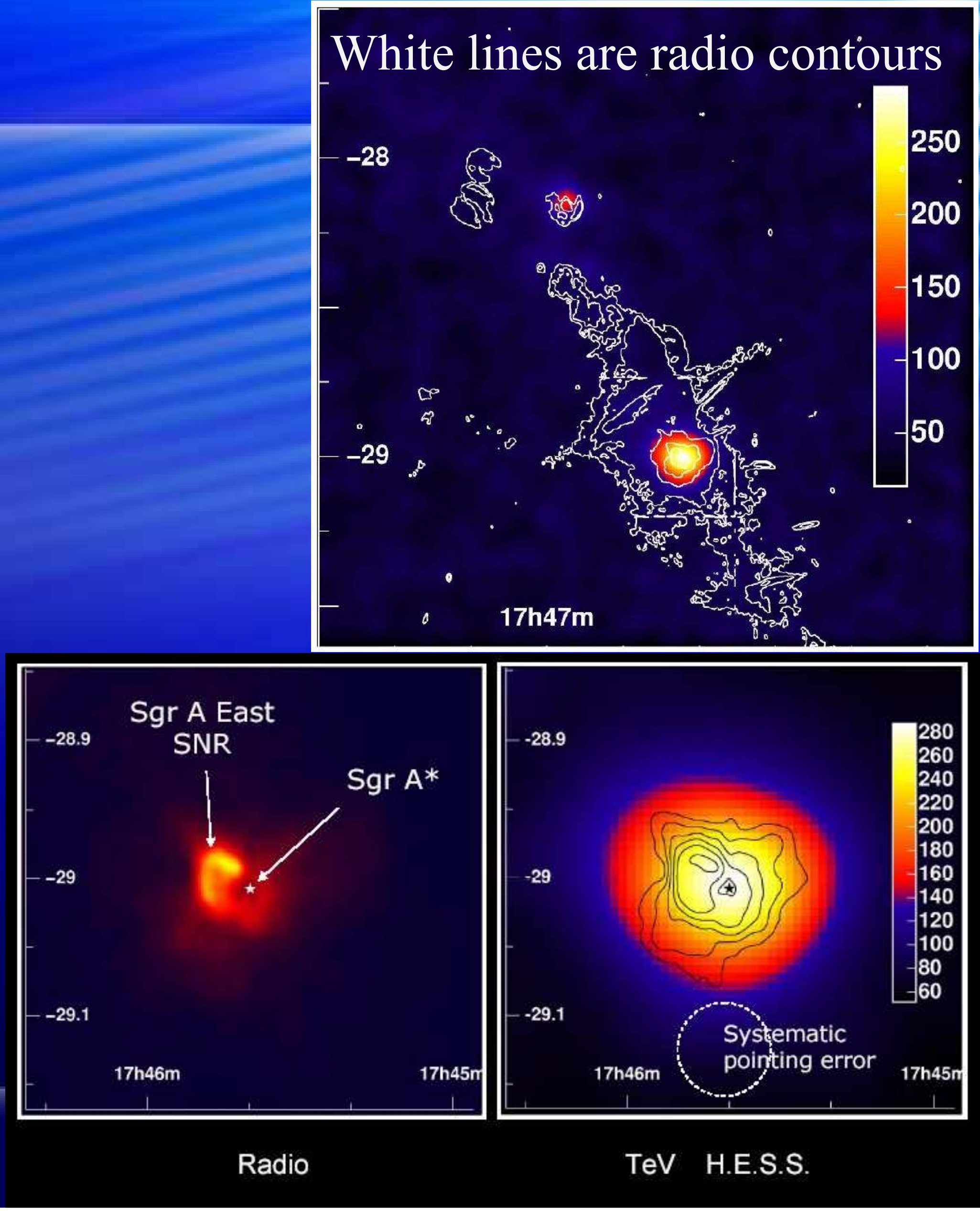
Main European Telescopes

MAGIC in Canarian Islands

HESS in Namibia

Results from the Galactic Centre

- Central region of the Galaxy showing the HESS signal compatible with SgrA*
- Black hole SgrA*
  $M = 2.6 \times 10^6 M_{sol}$
- Supernova remnant
  SgrA East
- Radioastronomy measurements are nicely reproduced !

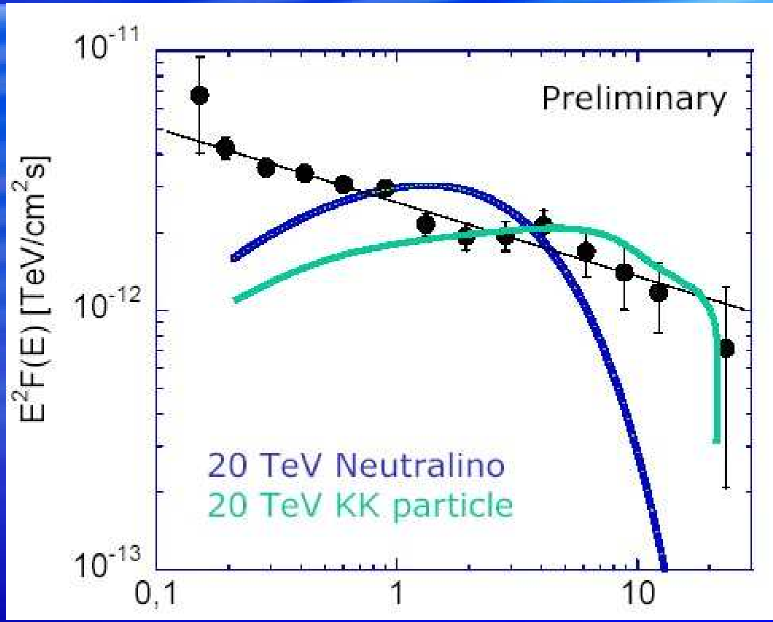


Dark Matter in the Galactic Centre ?

- Power-law spectrum from 25 GeV to 20 TeV
- No evidence for a cutoff

  E_{cut} > 6 TeV (95%CL)
- Energy spectrum cannot be reconciled with a pure dark matter spectrum with neutralino mass below

  12 TeV (90% CL)



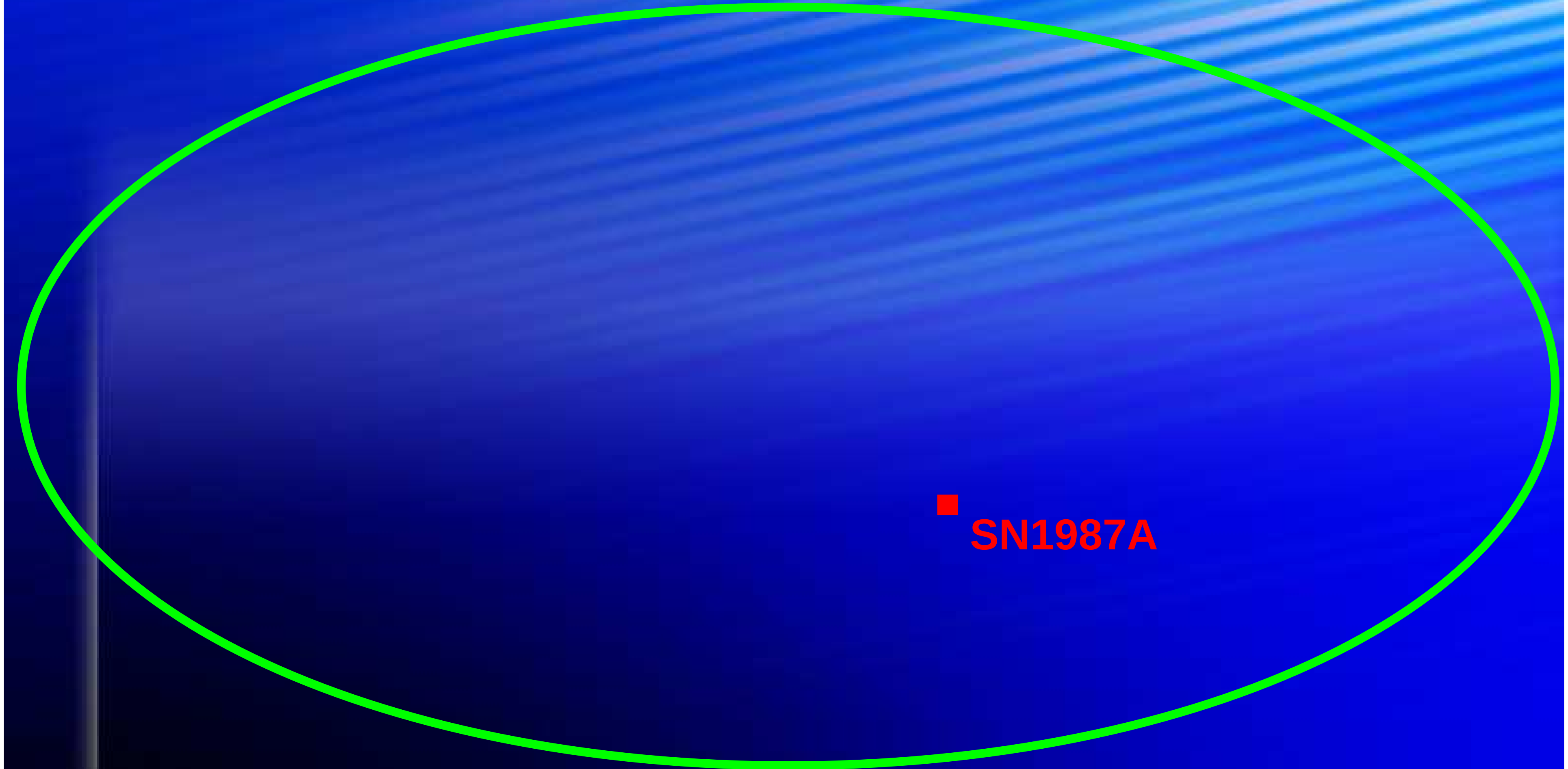
No real constraints on SUSY models

Why Neutrino Astronomy ?

- Neutrinos traverse space without being deflected or attenuated
  - They point back to their sources
  - They allow to view into dense environments
  - They allow to investigate the Universe over cosmological distances
- Neutrinos are produced in high energy hadronic processes
  - They can allow distinction between hadronic and leptonic acceleration mechanisms
- Neutrinos could be produced in Dark Matter (neutralinos) annihilation

Astronomy as we know it becomes blind at ~100 TeV
Photons absorbed by pair production on IR & CMB
Particles scattered by B-fields or GZK

High Energy Neutrinos



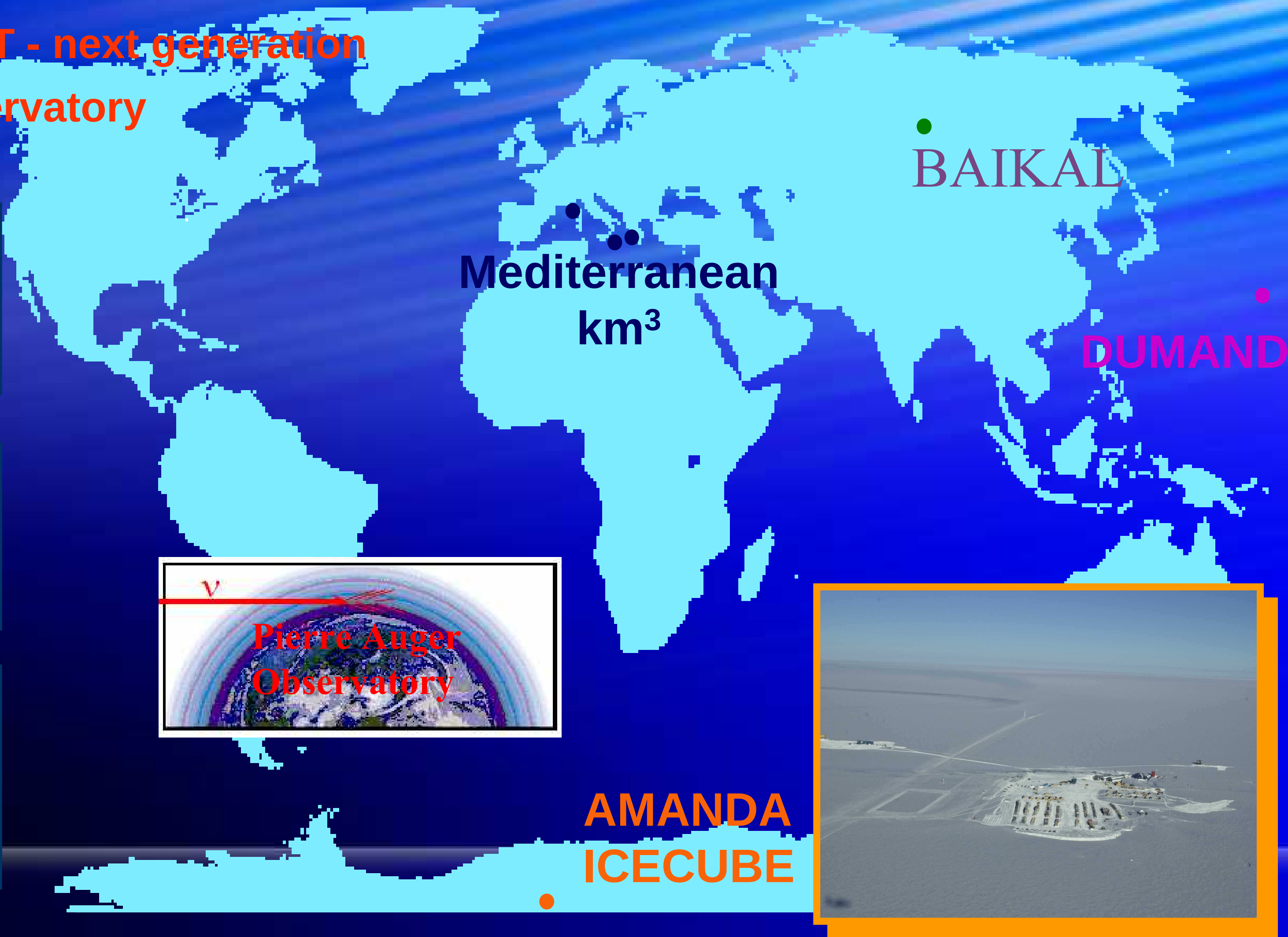
Main Neutrino Detectors

AMANDA - taking data

ANTARES, NEMO, NESTOR - under construction / first data

ICECUBE, KM3NeT - next generation

Pierre Auger Observatory



Principles of Neutrino Telescopes

Earth screens all particles except neutrinos.
Atmosphere source of background neutrinos.

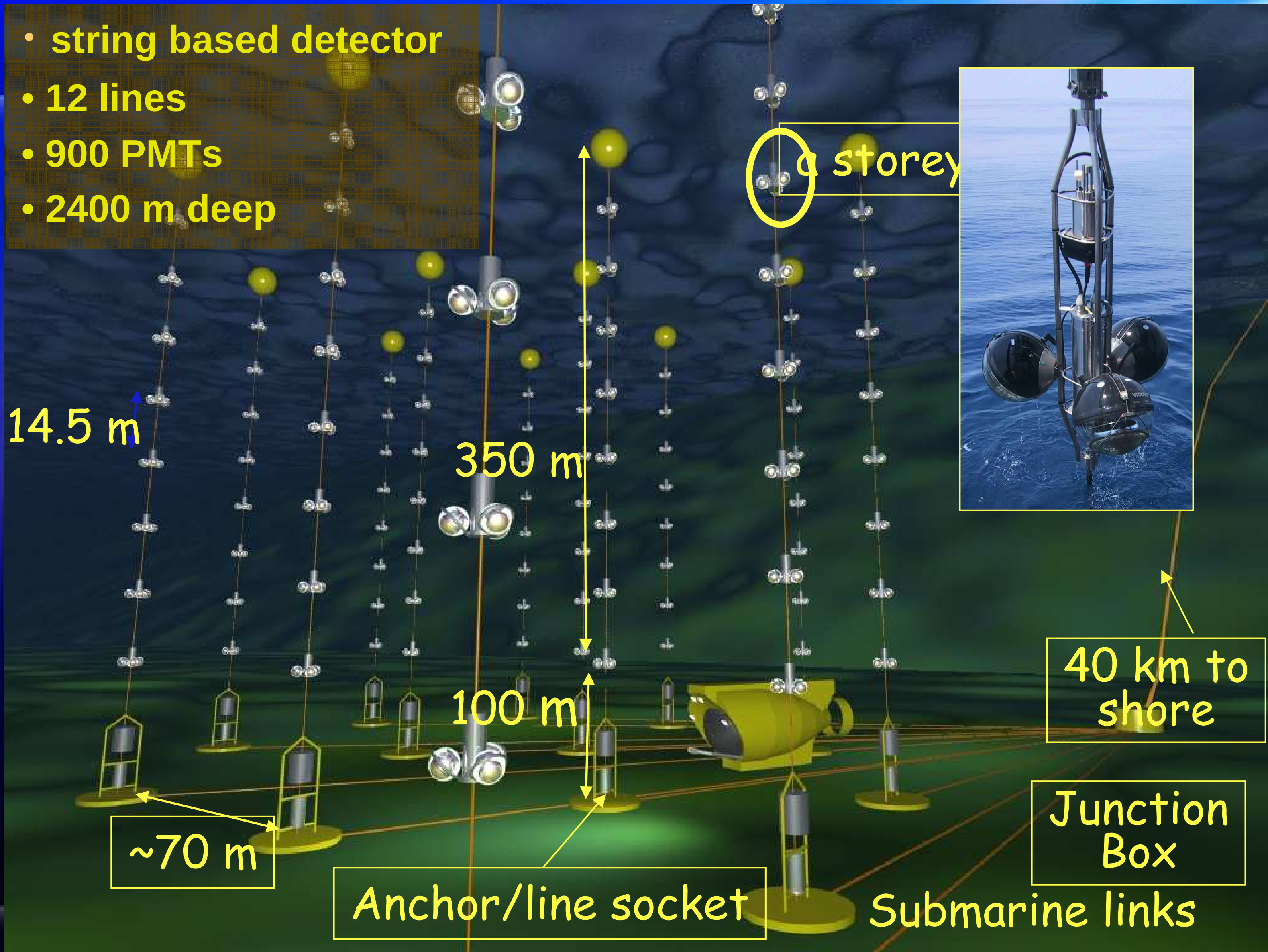
Cherenkov light produced by muons with $\theta_C = 43°$
Spectral range 350-500 nm

QuickTime™ et un
décompresseur TIFF (LZW)
sont requis pour visionner cette image.

The downgoing atmospheric μ flux overcomes by several orders of magnitude the expected μ fluxes induced by ν interactions.

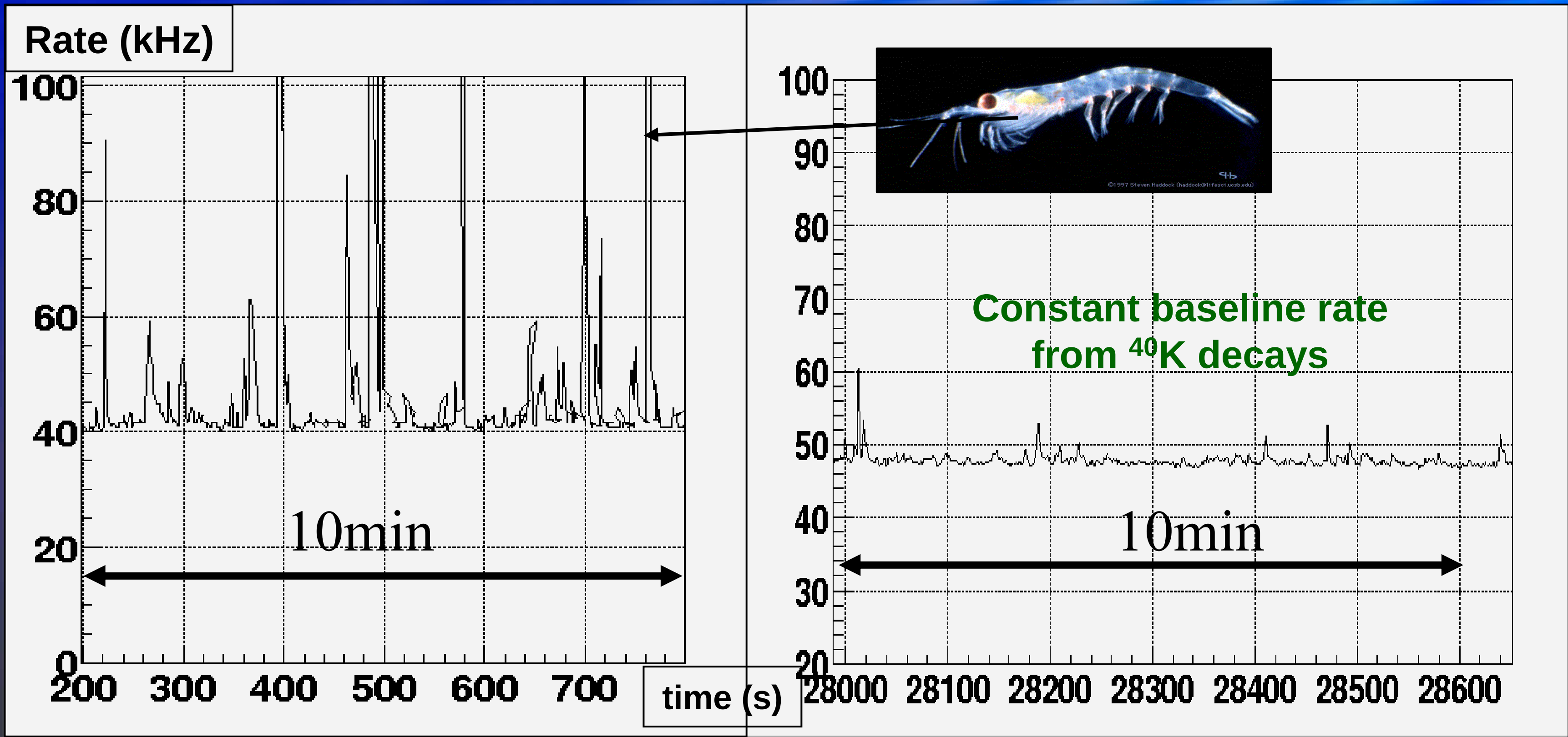
ANTARES

- string based detector
- 12 lines
- 900 PMTs
- 2400 m deep



ANTARES: First Deep Sea Data

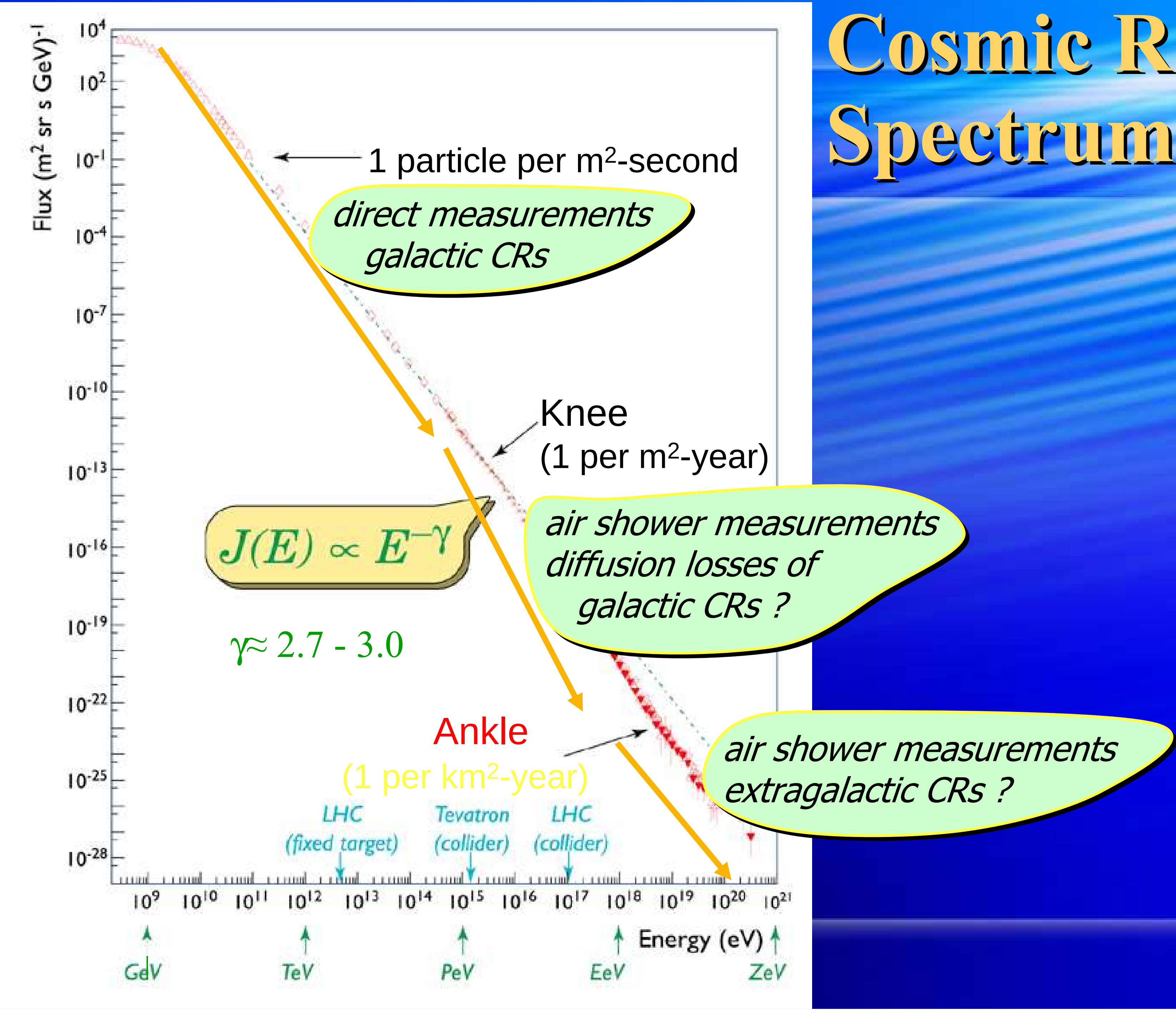
- Rate measurements: Strong fluctuation of bioluminescence background observed



Main Instruments for High Energy Charged Particles


Pierre Auger Observatory

Cosmic Ray Spectrum



Current Situation

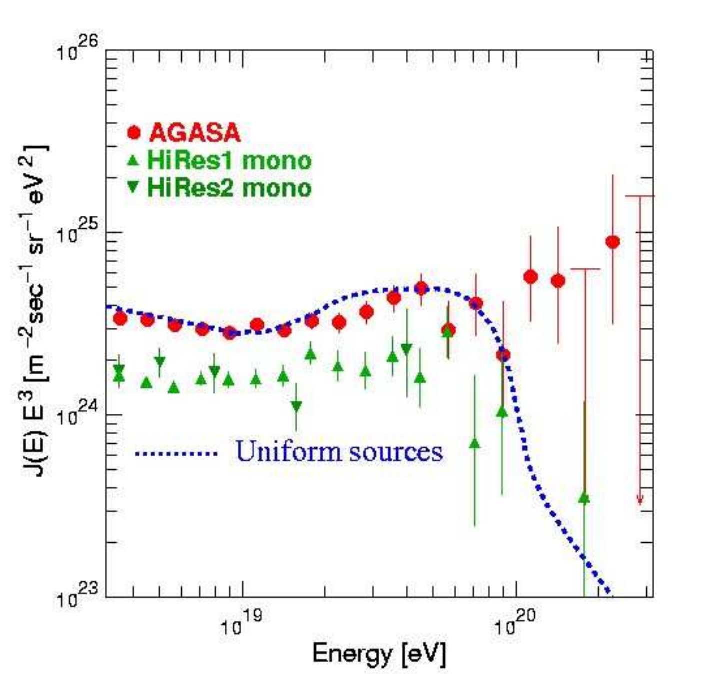
There are evens above 10^{20} eV (AGASA, Fly's Eye and HiRes)

- but the flux is uncertain

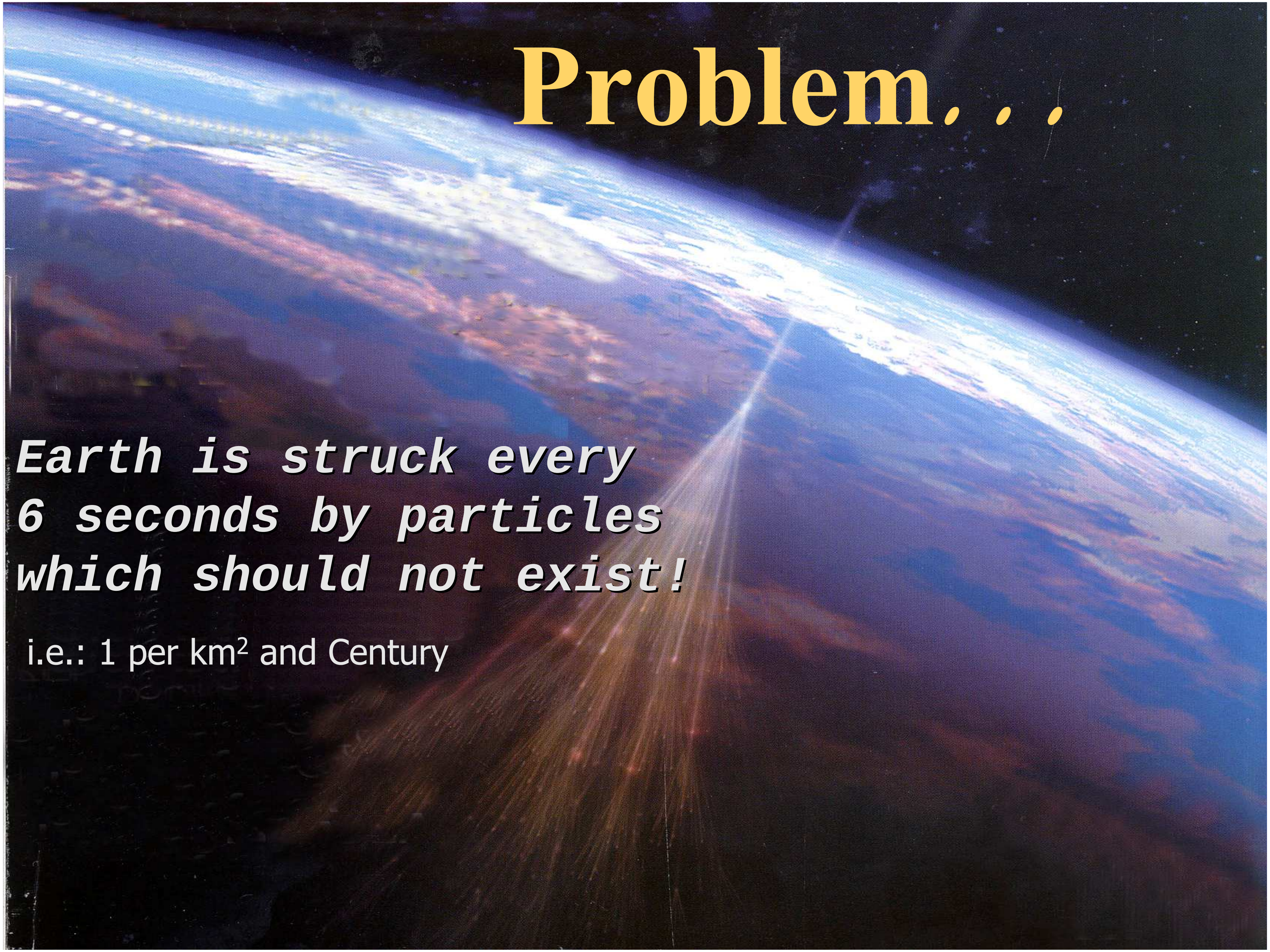
Arrival direction seems to be isotropic

- but there are probably clusters
- a possible anisotropy at 10^{18} eV (AGASA)

Composition seems to be compatible with protons



Problem...



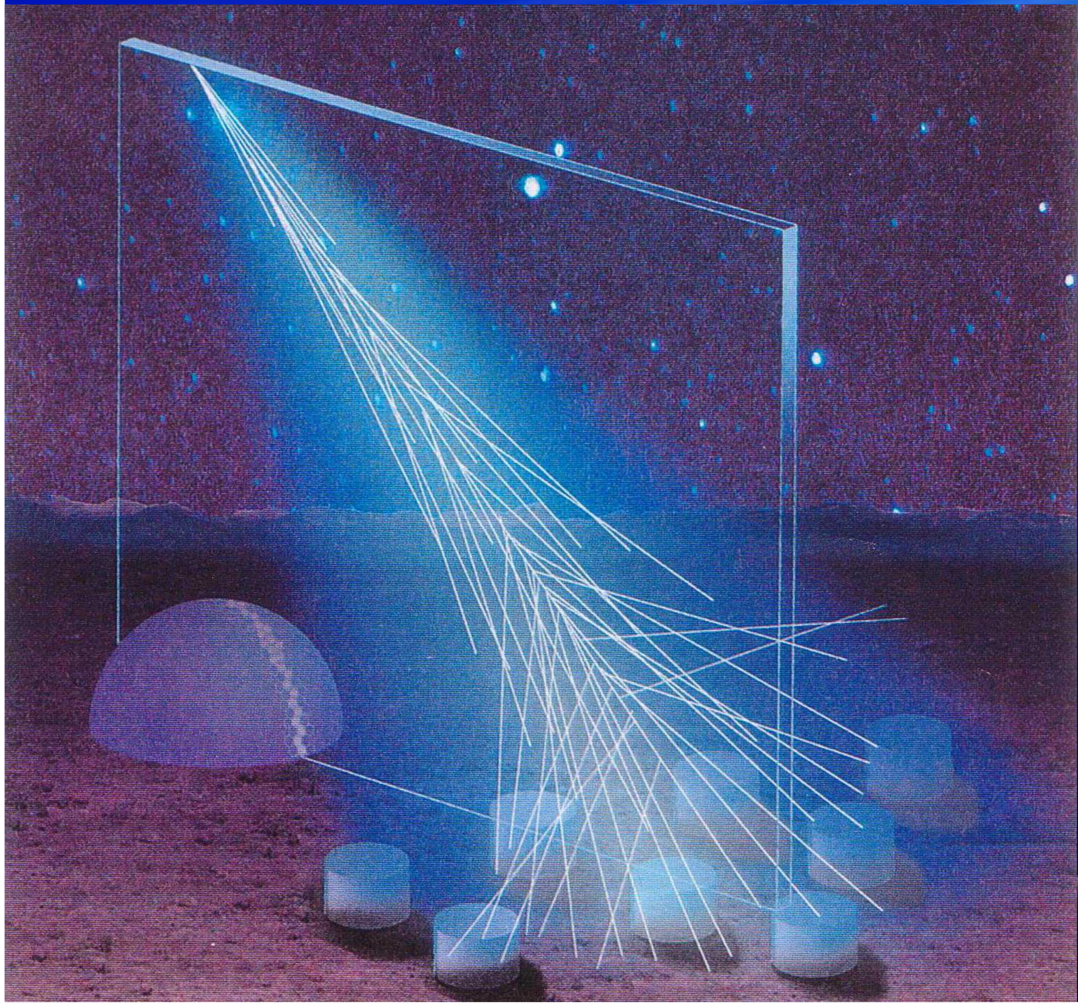
Earth is struck every 6 seconds by particles which should not exist!

i.e.: 1 per km^2 and Century

The Hybrid Design of Pierre Auger Observatory

Surface detector array + Air fluorescence detectors

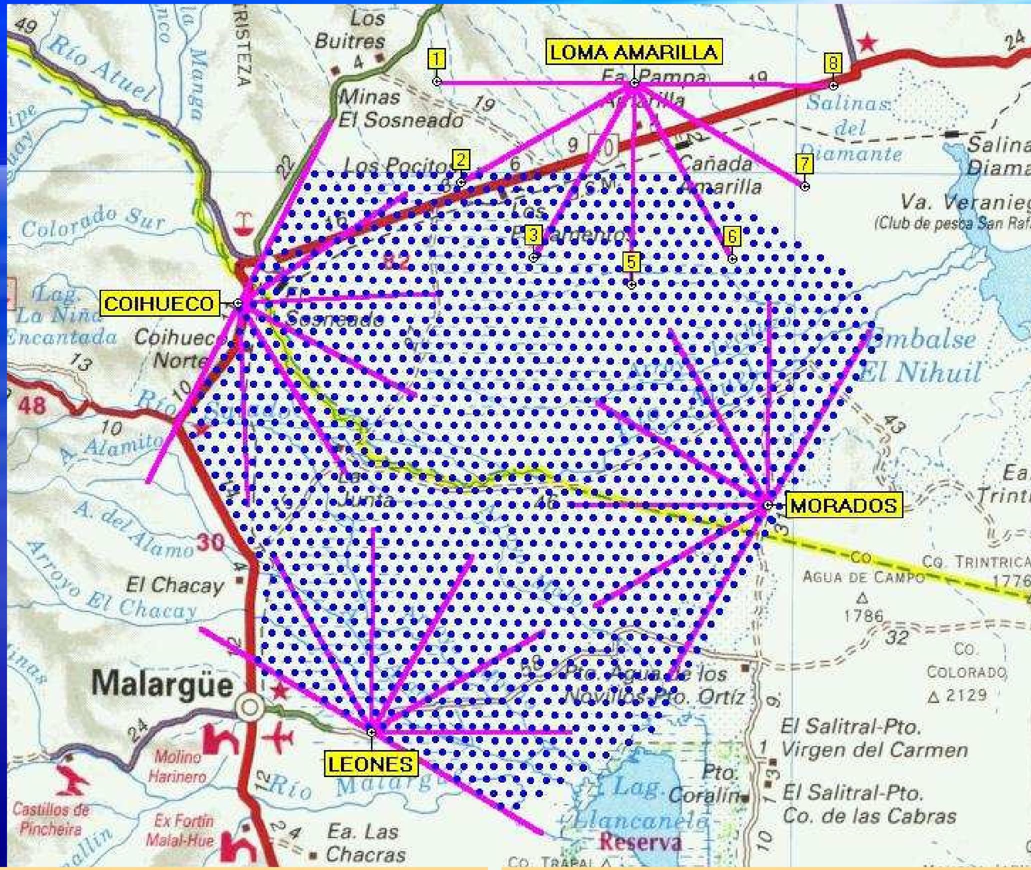
A unique and powerful design



- Nearly calorimetric energy calibration of the fluorescence detector transferred to the event gathering power of the surface array.
- A complementary set of mass sensitive shower parameters.
- Different measurement techniques force understanding of systematic uncertainties
- Determination of the angular and core position resolutions

Pierre Auger Observatory

Argentina



Surface Array

1600 detector stations

1.5 Km spacing

3000 Km²

Fluorescence Detectors

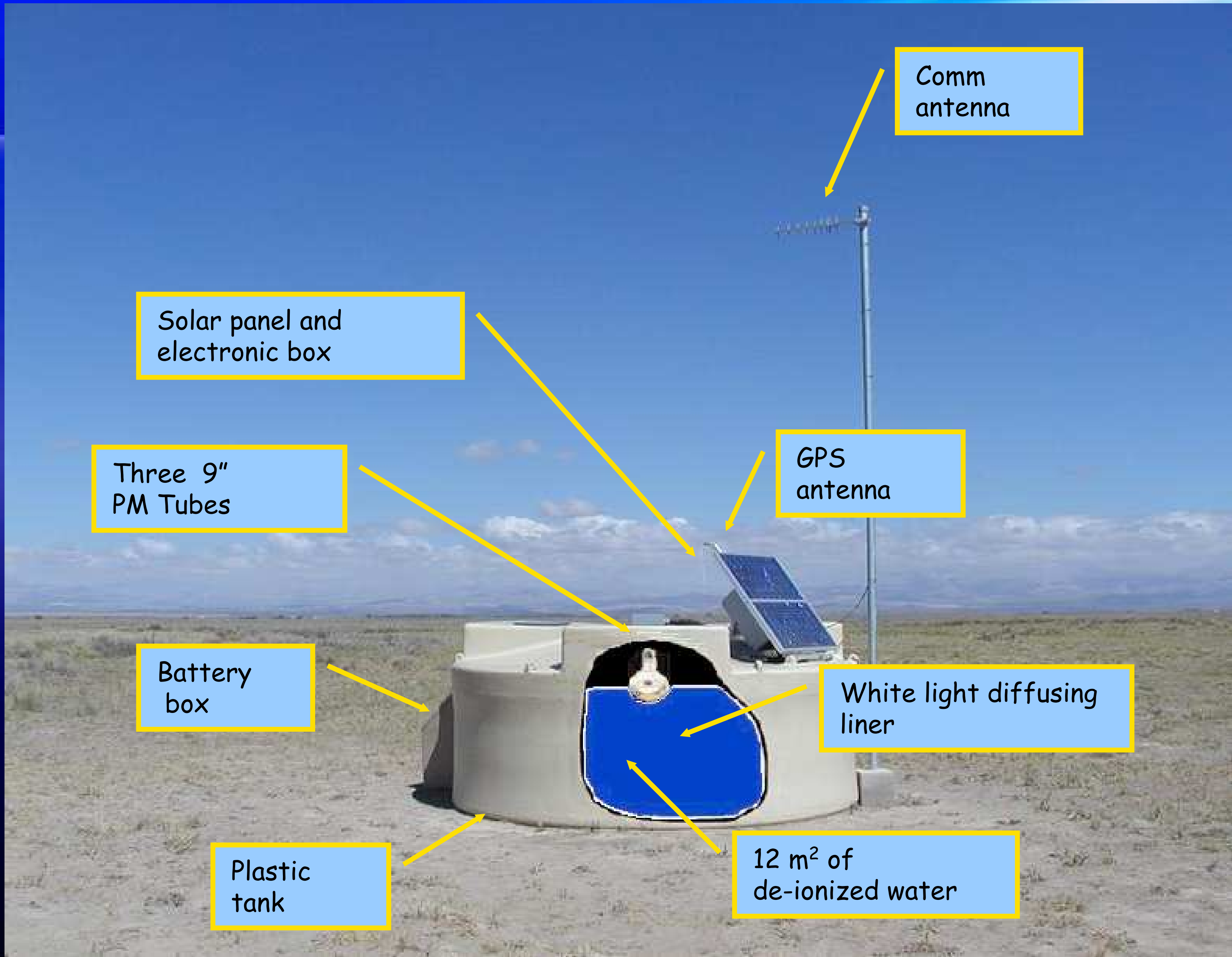
4 Telescope enclosures

6 Telescopes per enclosure

24 Telescopes total

Campus

Water Cherenkov Detector (WCD)



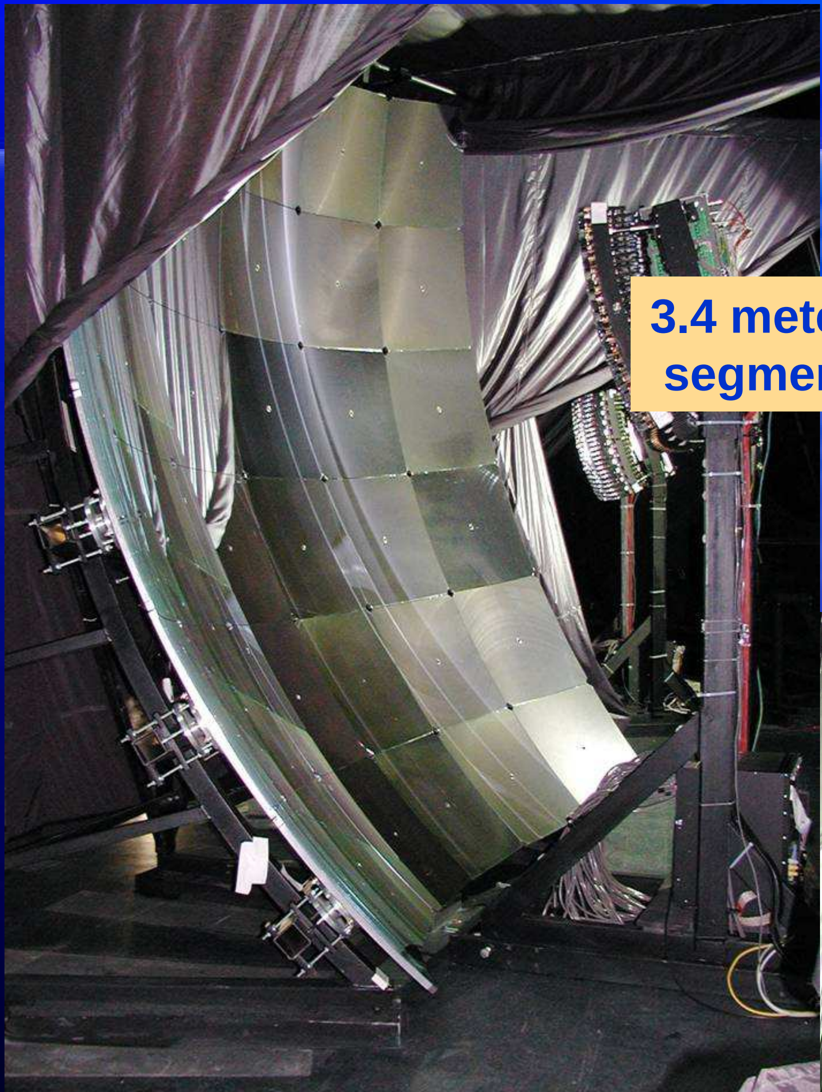
Tanks Aligned seen from Los Leones

Difficult Environnement

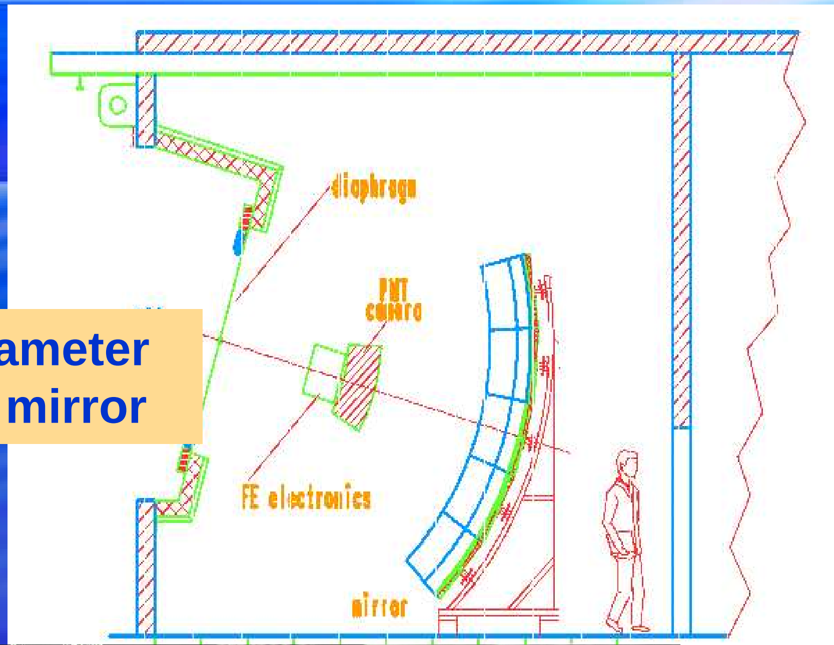
Non-qualified Drivers

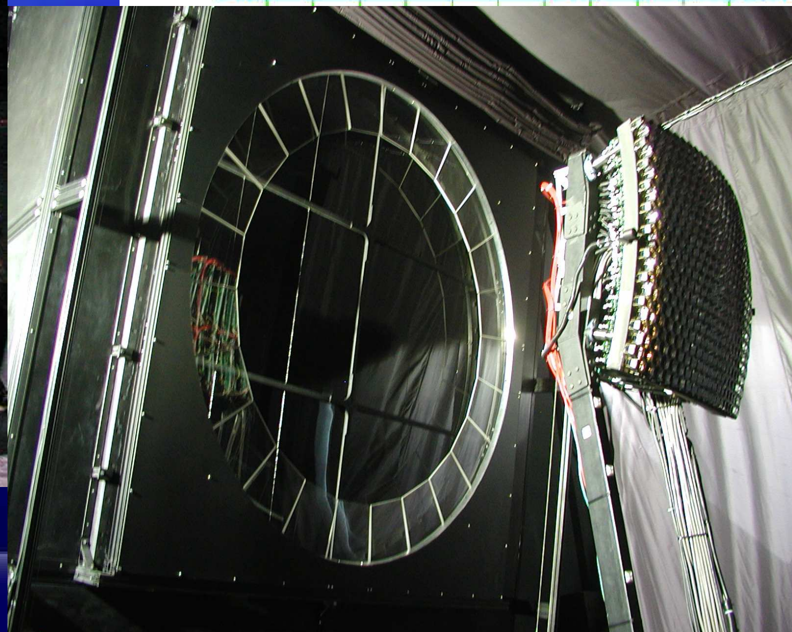
Frequent Visitors

The Fluorescence Detector



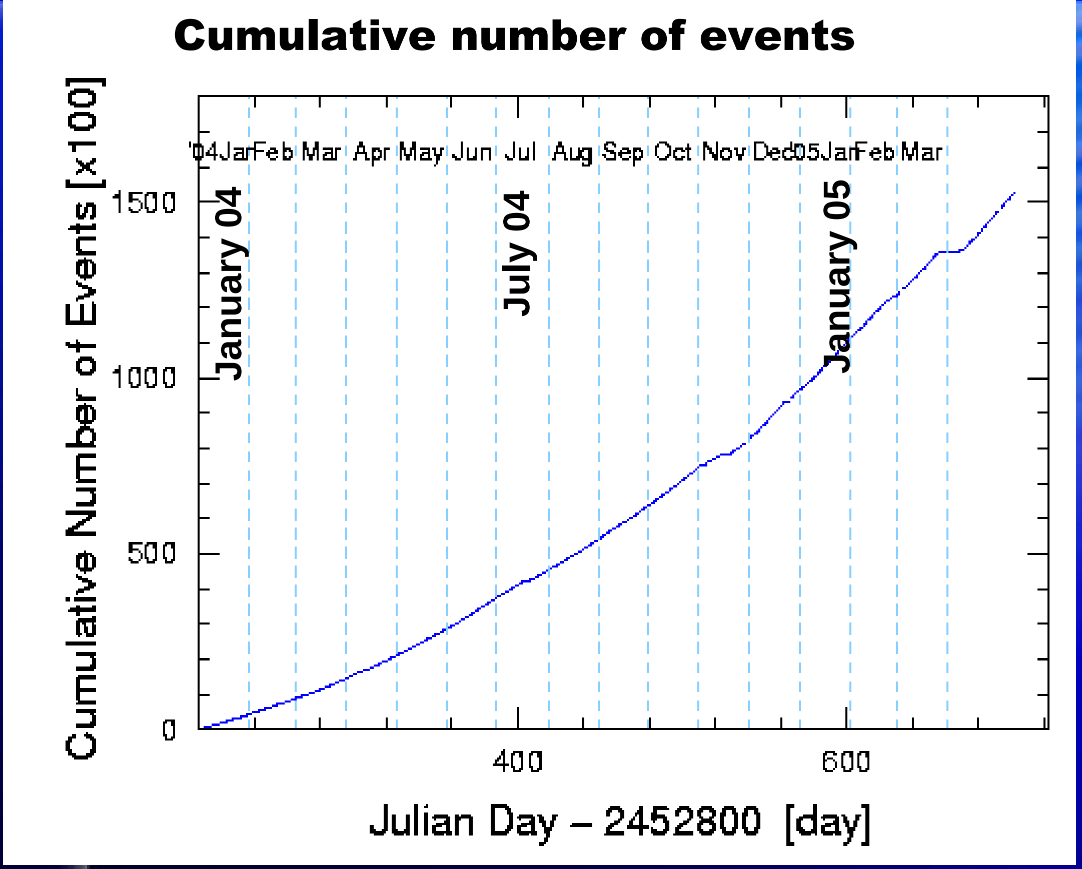
3.4 meter diameter segmented mirror





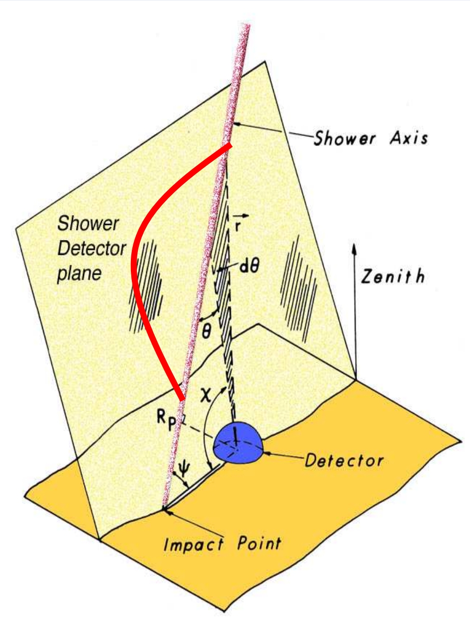
View of Los Leones FD

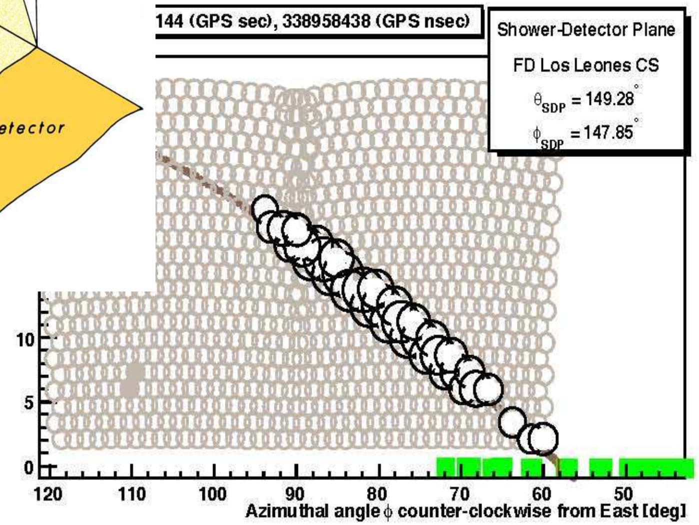
The First Data Set

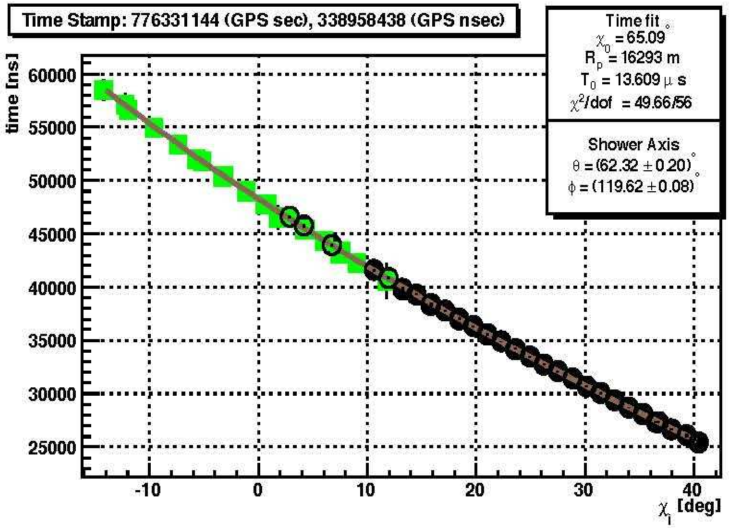


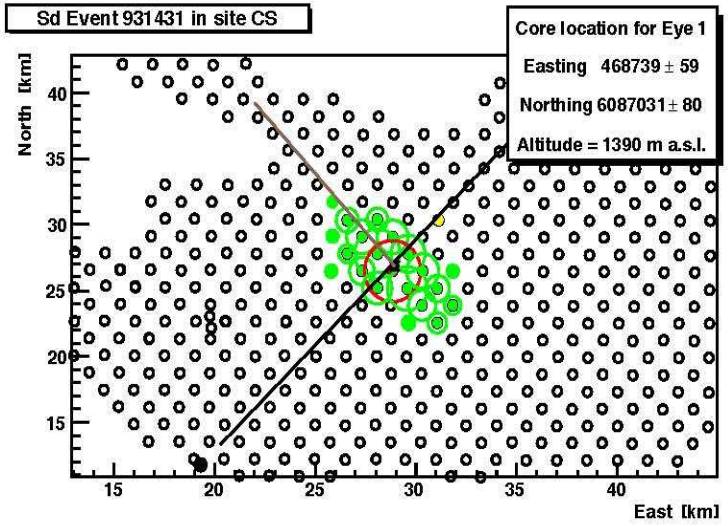
- Collection period – 1 January 2004 to 5 June 2005
- Zenith angles - 0 - 60º
- Total acceptance – 1750km² sr yr (~ AGASA)
- Surface array events (after quality cuts)
  - Current rate - 18,000 / month
  - Total -~180,000
- Hybrid events (after quality cuts)
  - Current rate – 1800 / month
  - Total ~ 18000

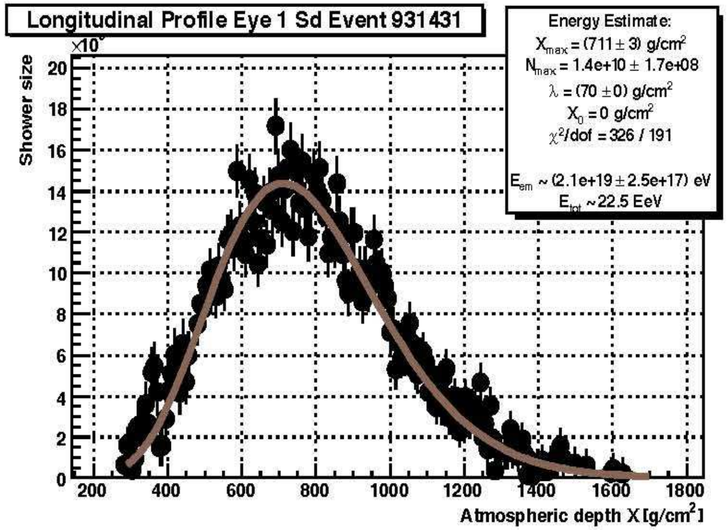
Hybrid Event



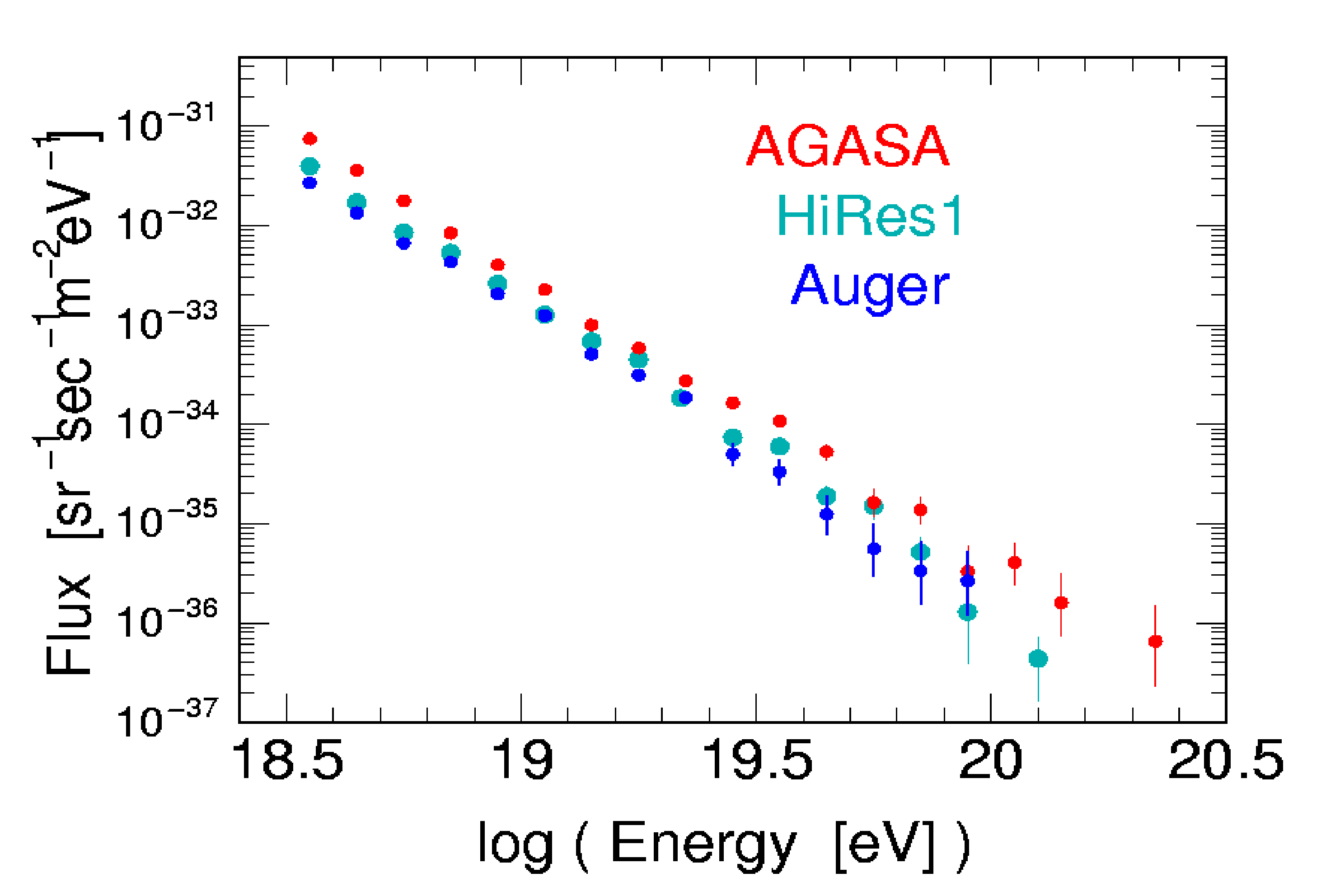




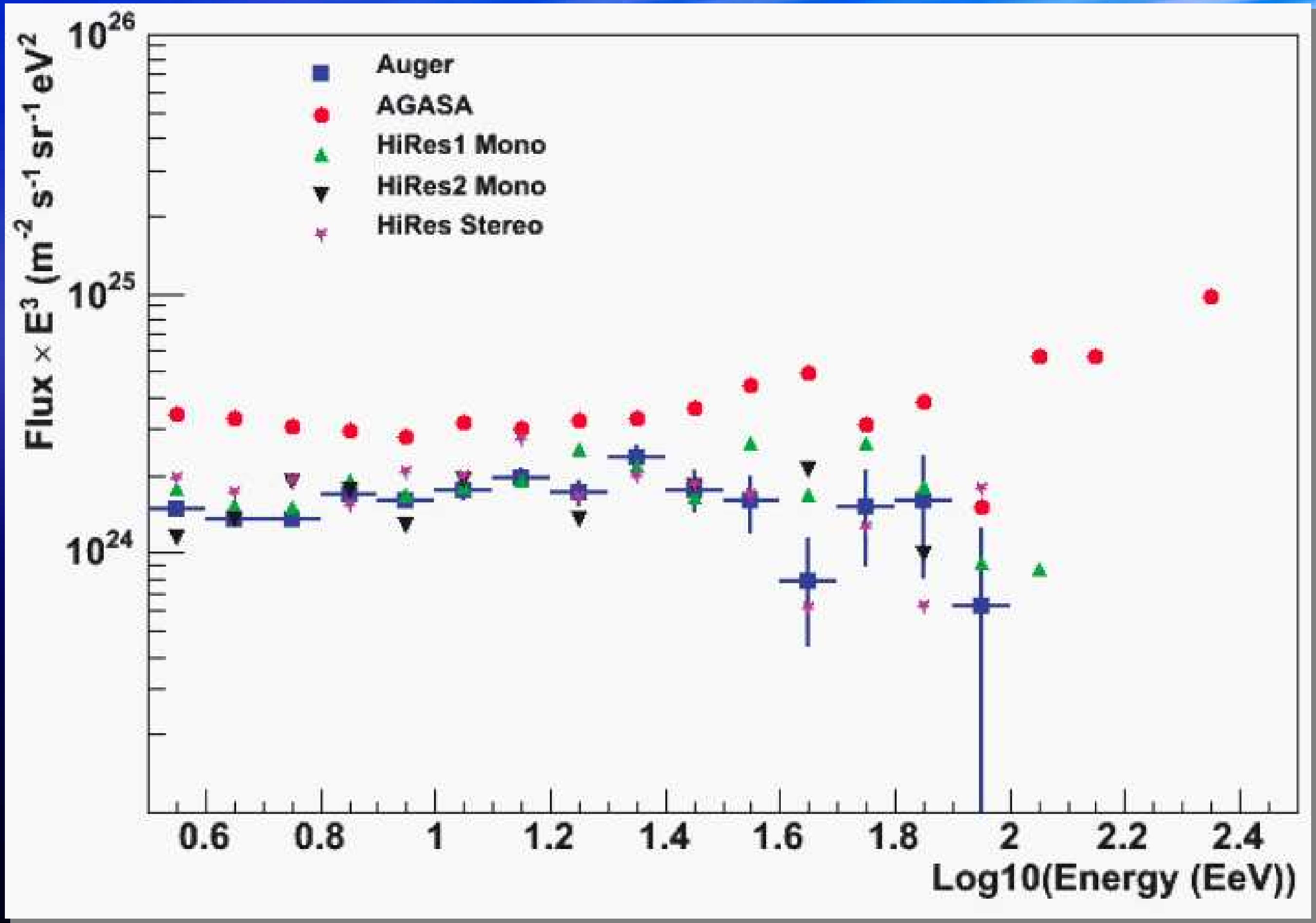




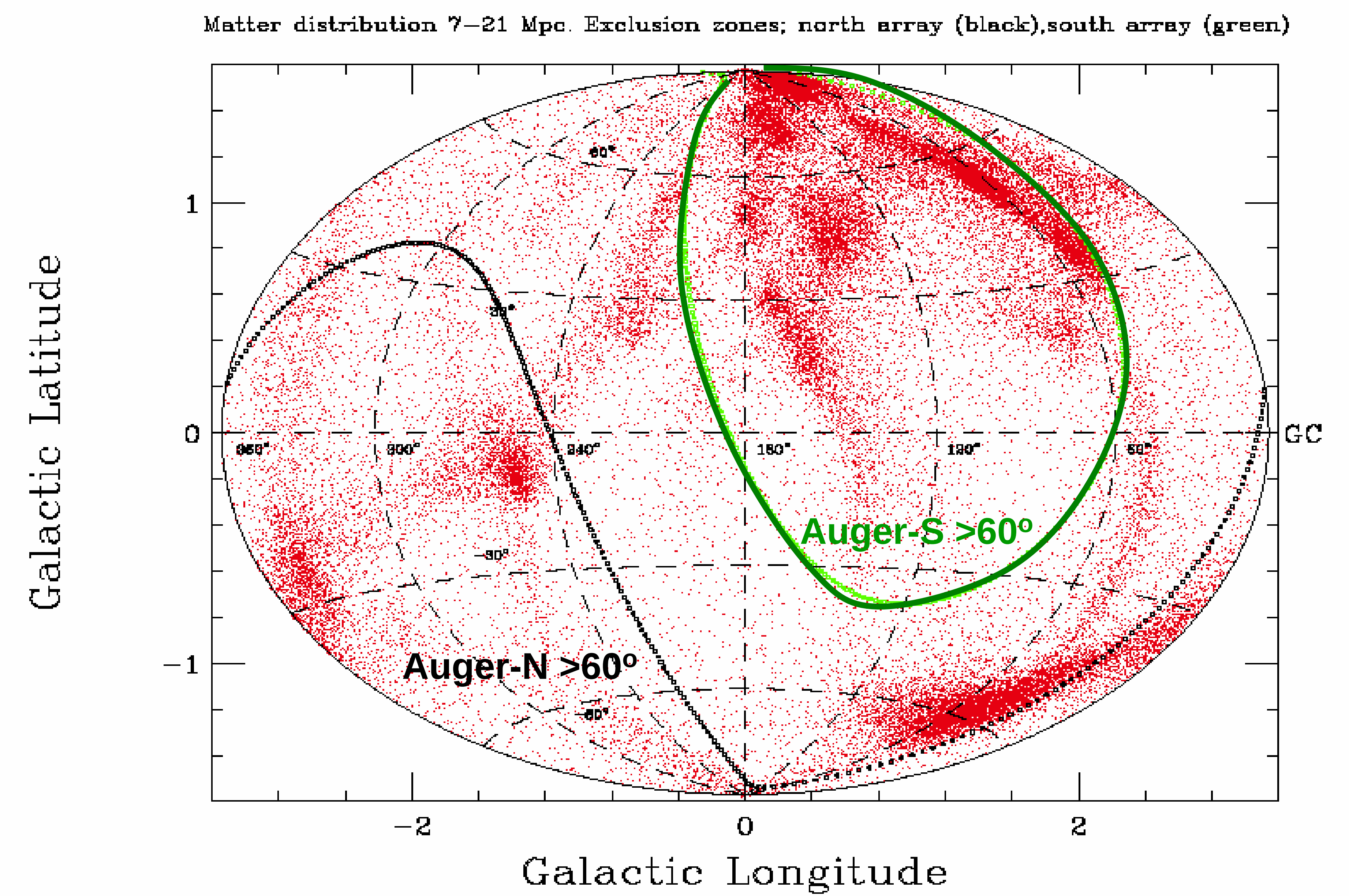
Auger Spectrum



Spectrum: Flux x E^3



North ≠ South



Cronin, astro-ph/0402487

Auger North

Site: Colorado (Lamar)

High Energy Astroparticle Physics Conclusions

Roadmap

Detecting rare events

Deploying detectors in remote, exotic places

Discovering new, unexpected Physics !

Long but not winding road….