HIGH ENERGY PARTICLES

FROM THE UNIVERSE

Lepton−Photon 99
Stanford, CA

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University of Chicago

OUTLINE

Broad overview

Recent exciting results: 3 examples

Theoretical considerations:

- **Extreme astrophysics**
- **Physics beyond Standard Model**

Review of HE Astronomy using γ−rays, cosmic rays, and ν's

- **Experimental techniques**
- **Results**
- **Future experiments**

Summary

Rene A. Ong
University of Chicago

OVERVIEW

We learn about the Universe outside the Solar System from four messengers:

		strengths	weaknesses
1. Light	γ	**neutral**	**absorption**
2. Cosmic Rays	**p, He ...**	**direct acceleration**	**charged**
3. Neutrinos	ν	**neutral**	**hard to detect**
4. Gravity Waves		**neutral**	**very hard to detect**

So far . . .

1. has been the cornerstone of Astronomy
2. provides important information about the Galaxy
3. one serendipitous detection (SN1987A)
4. field is just beginning

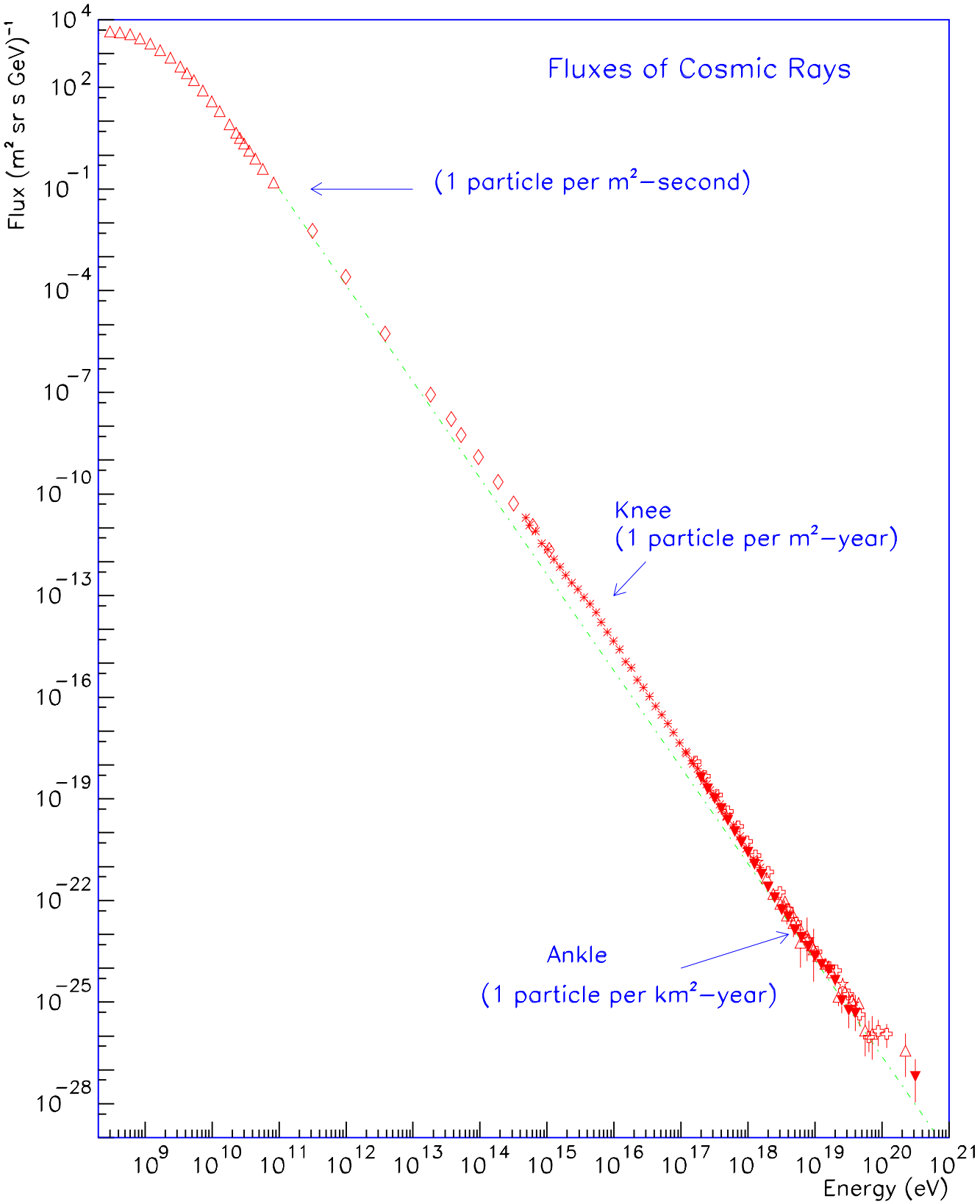
* This talk will summarize 1−3 at high energies

Grand Unified Spectrum

Inserted here is a figure of the diffuse photon/cosmic ray spectrum at all energies.

High energies: power law spectra
enormous dynamic range
very low fluxes

Cosmic ray fluxes at Earth



S. Swordy

Scientific Motivation

Physics motivations:

* Studying astrophysics at extreme conditions of magnetic field, gravitational potential

* "Cosmic accelerators" reach beam energy scale not (yet) attainable on Earth

  Possibility of new particle/interaction

* In some cases, may be able to probe particle physics

Astronomical motivation:

* Opening new window in:

  energy
  particle type (e.g. ν)

No theoretical picture on par with Standard Model !

THREE RECENT EXCITING RESULTS

1. Gamma−ray bursts (GRBs)

   * Optical counterparts identified
     Cosmological distances!

   * At least two classes recognized

2. TeV γ−rays

   * Extragalactic AGN sources
     change output on < 1 hr timescales

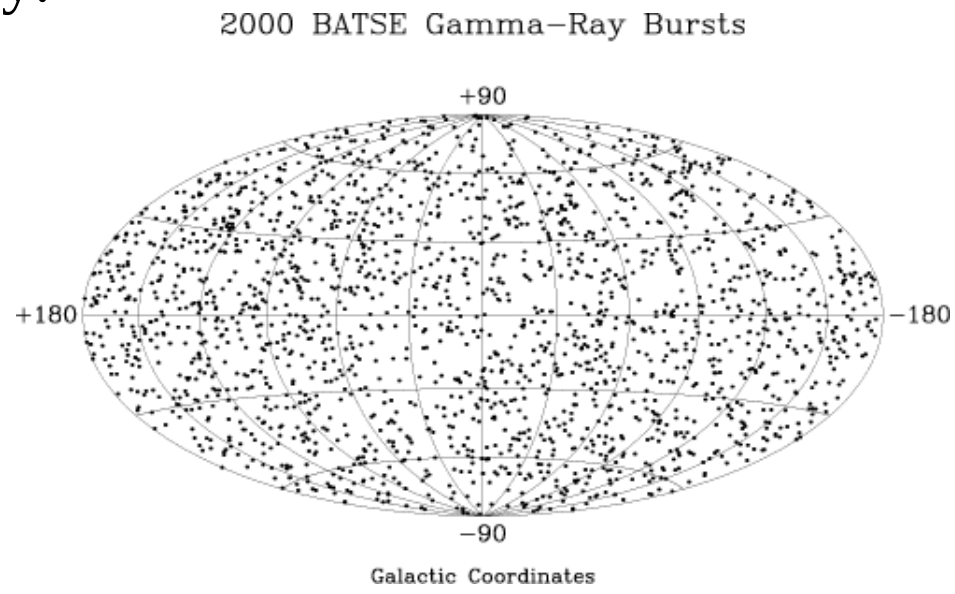
3. Highest energy cosmic rays

   * Clear evidence for particles
     above 10^{20} eV

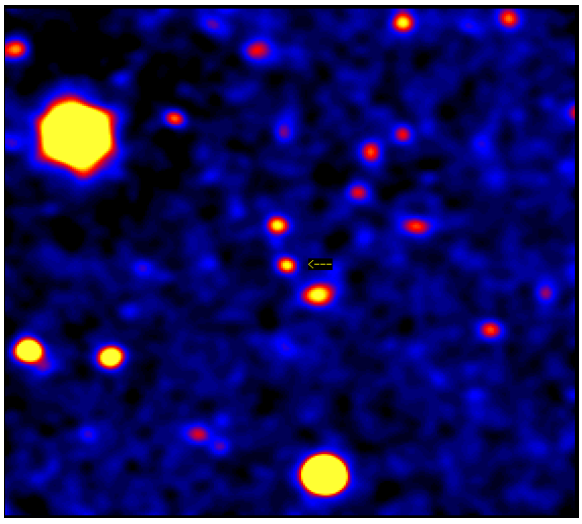
Gamma−ray Bursts (GRBs)

* **30 year old mystery**

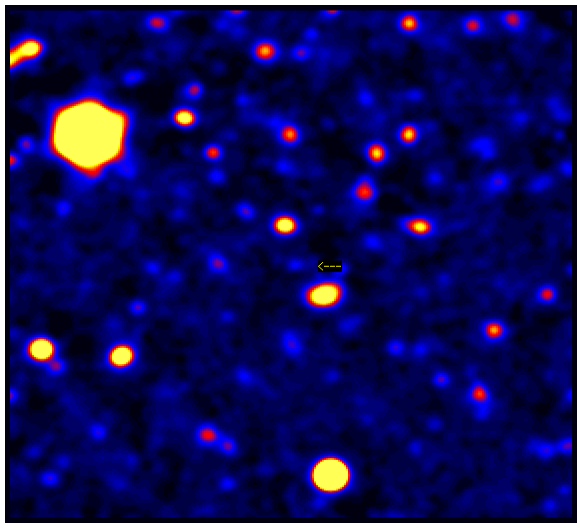
Isotropy:



1997: Major breakthrough (Beppo/SAX):
X−ray and optical counterparts found



Before



After

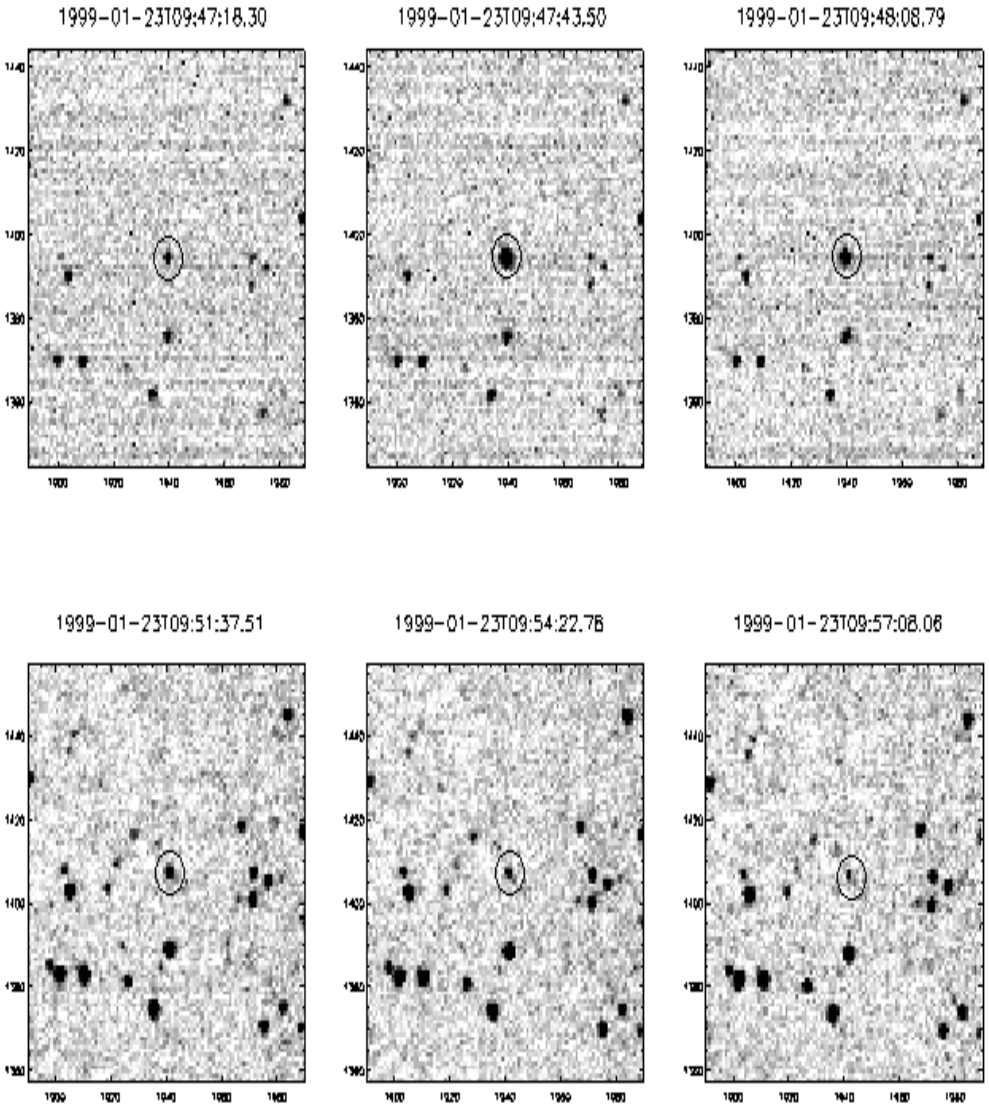
Keck
GRB 971214
z = 3.412

"Afterglows"

Gamma−ray Bursts (GRBs)

* Redshifts for ~ 20 afterglows now measured
  Cosmological distances

1999: Detection by ROTSE of a GRB in process (optical)



GRB 990123
z = 1.600
Mag = 8.95

* Energy release ~ 10^{54} ergs (isotropy)
  Largest explosion since Big−Bang!

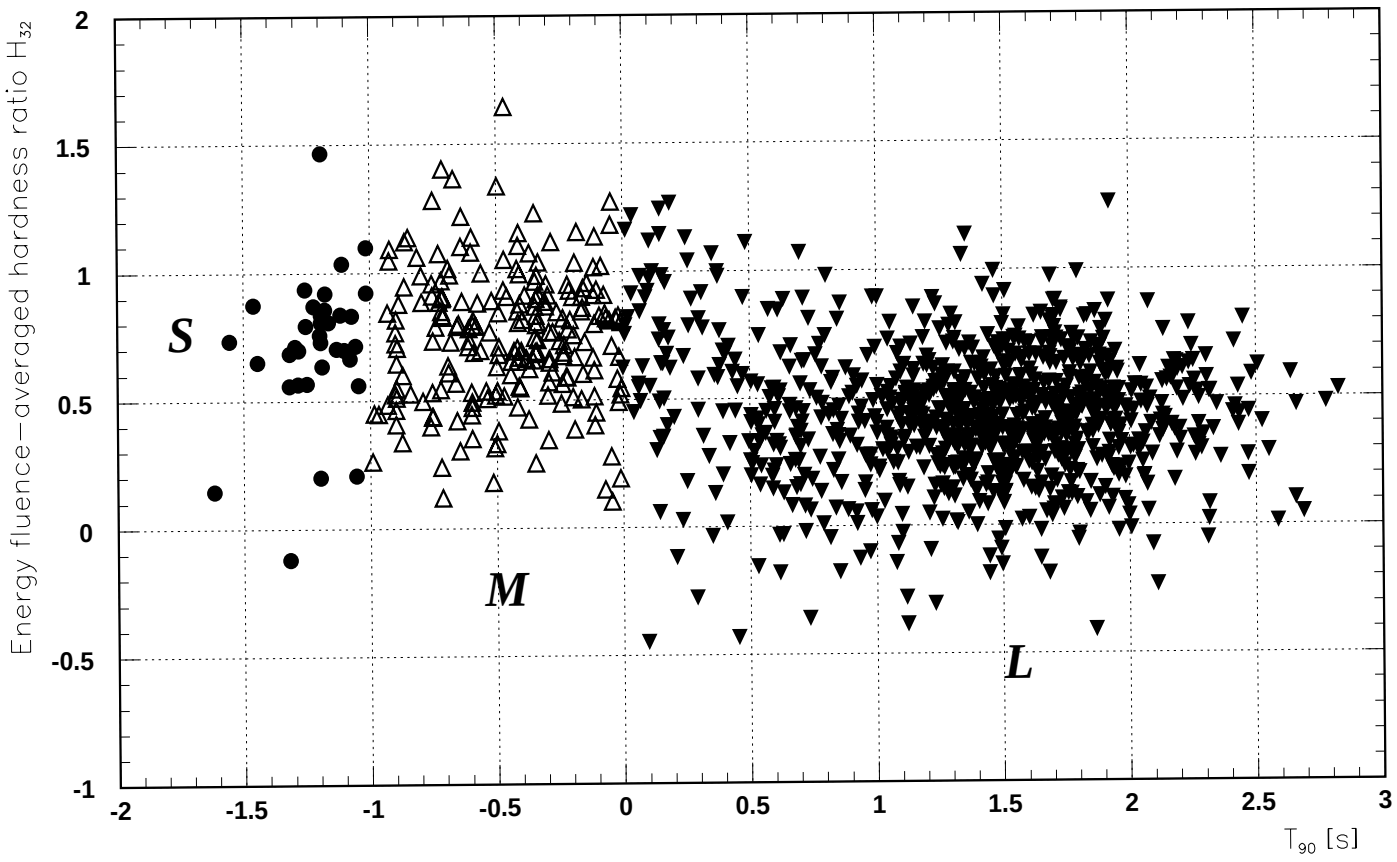
Gamma−ray Bursts (GRBs)

At least two classes or bursts:

* Counterparts detected only for long, energetic bursts

* Short bursts may be local!

Cline et al.
Tavani et al.



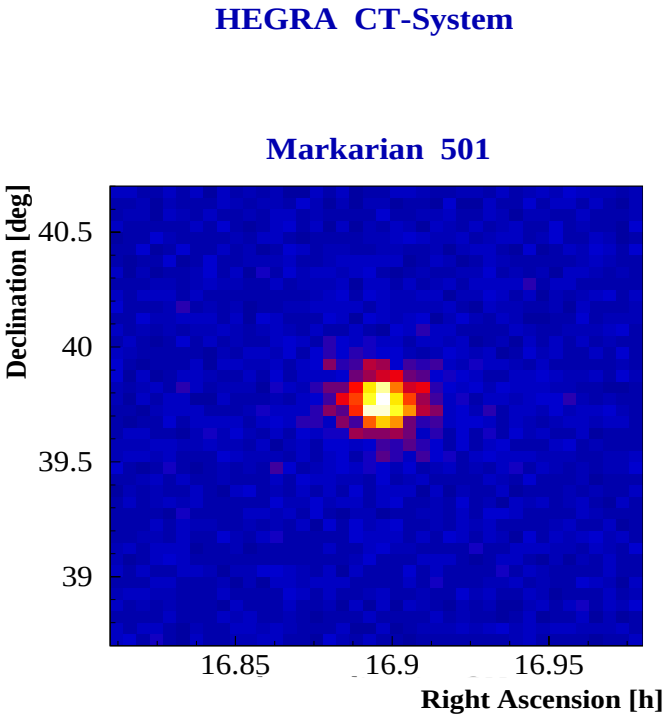
Hardness

Time duration

GRB problem still not solved . . .

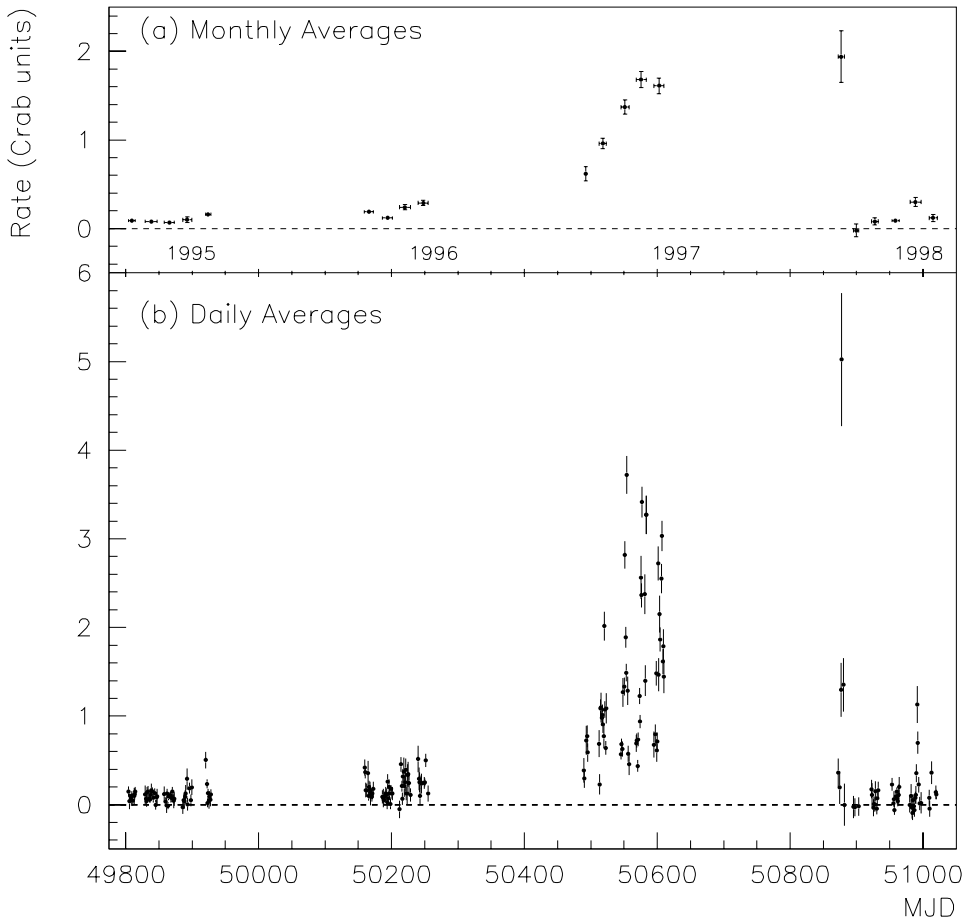
TeV γ−rays from Extragalactic Sources

* Mrk 501:
  AGN of blazar class
* 150 Mpc away
* γ−rays up to 20 TeV
* 10^{11} γ / sec at Earth



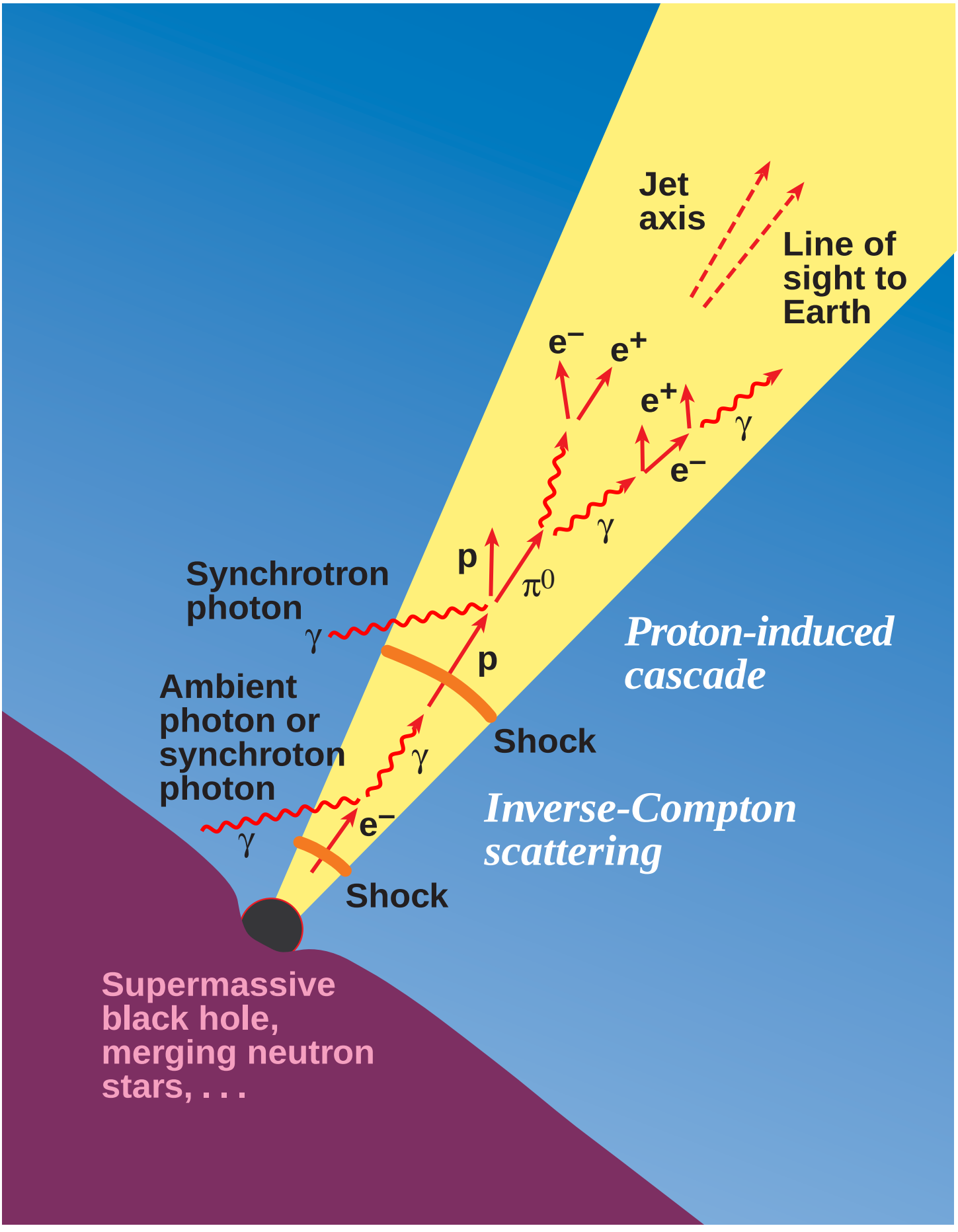
Tremendous variability:

Hegra



Whipple

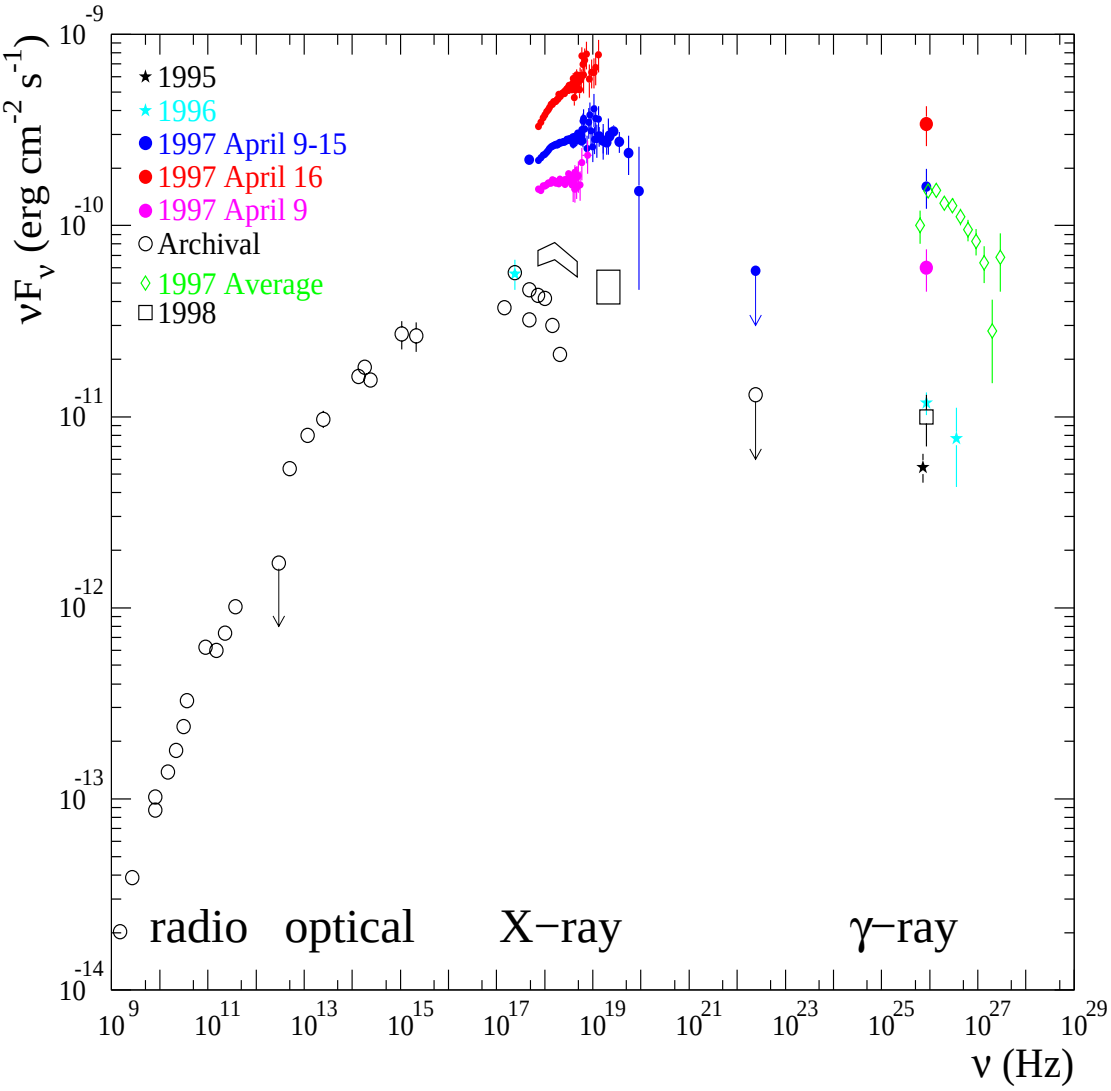
Model of AGN



F. Halzen

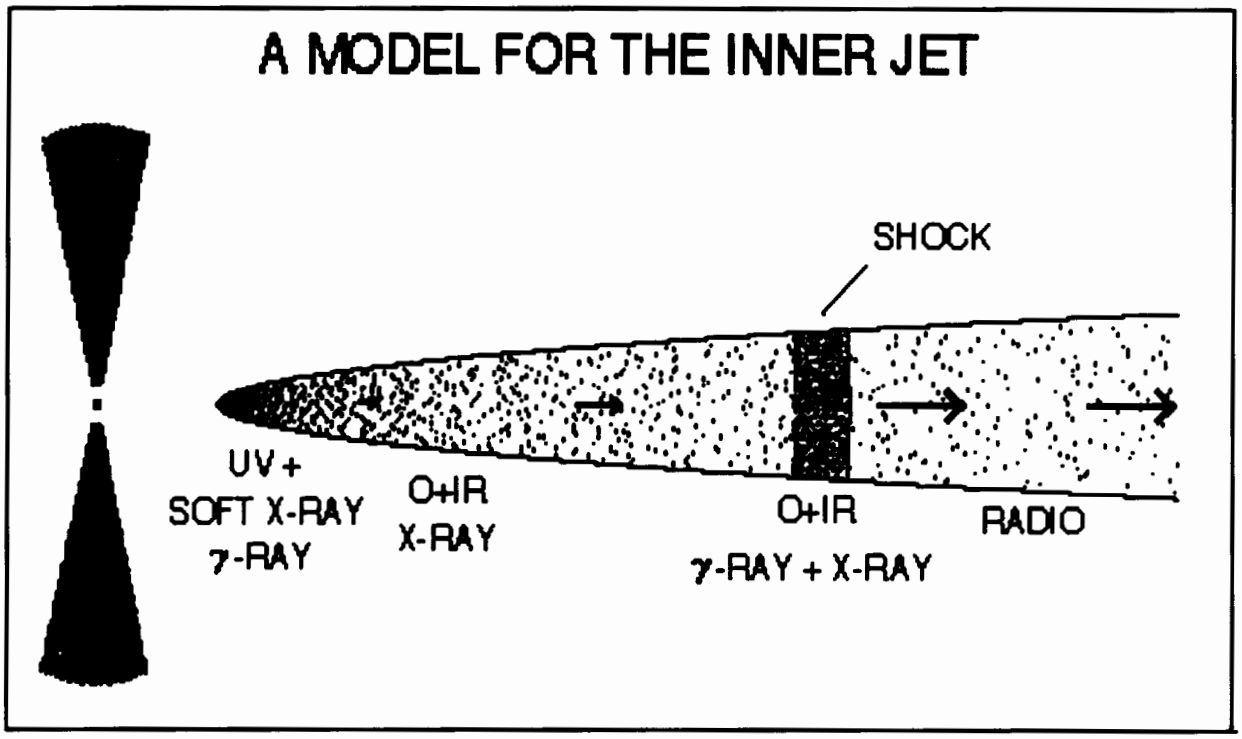
TeV γ−rays from Extragalactic Sources

Mrk 501 power spectrum:



* X−ray and γ−ray emission dominate output

* Detailed measurements −>
  testing astrophysical models



A. Marscher

Many Questions:

Nature of beam particles

Acceleration process

Magnetic fields

Seed photons

Emission zone(s)

Variability

Beaming

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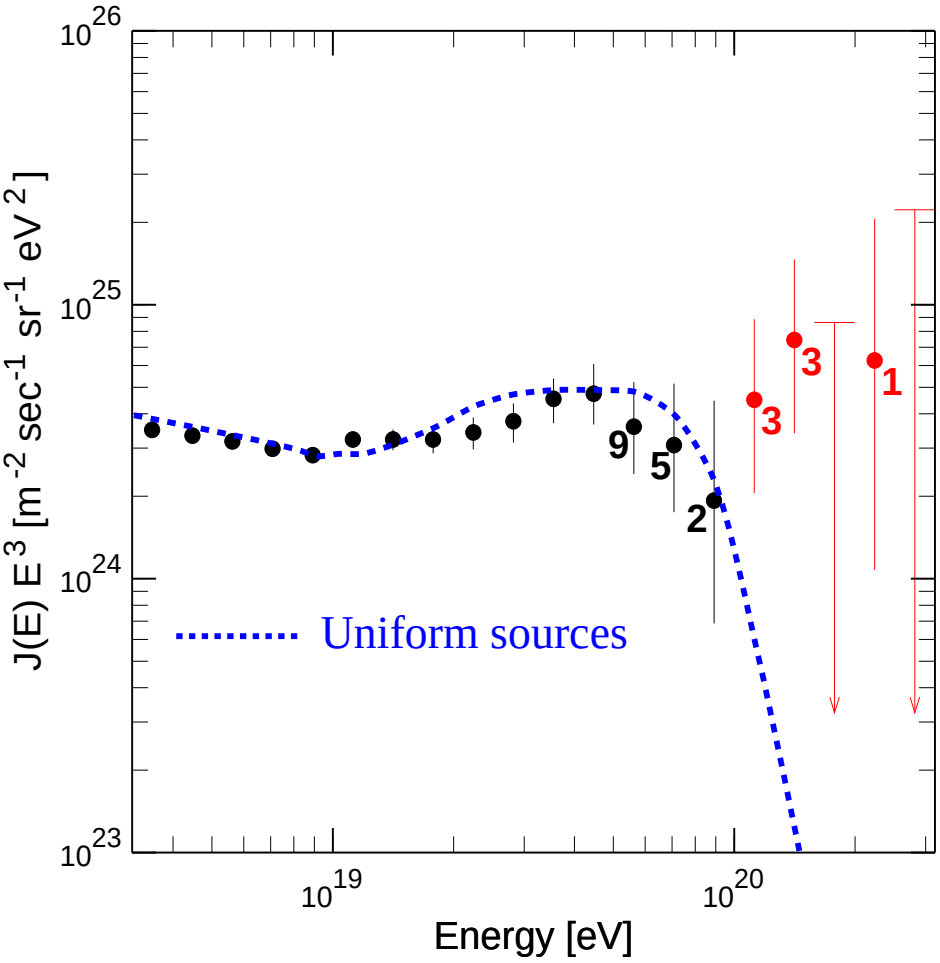
Highest Energy Cosmic Rays

Latest spectrum from AGASA experiment:

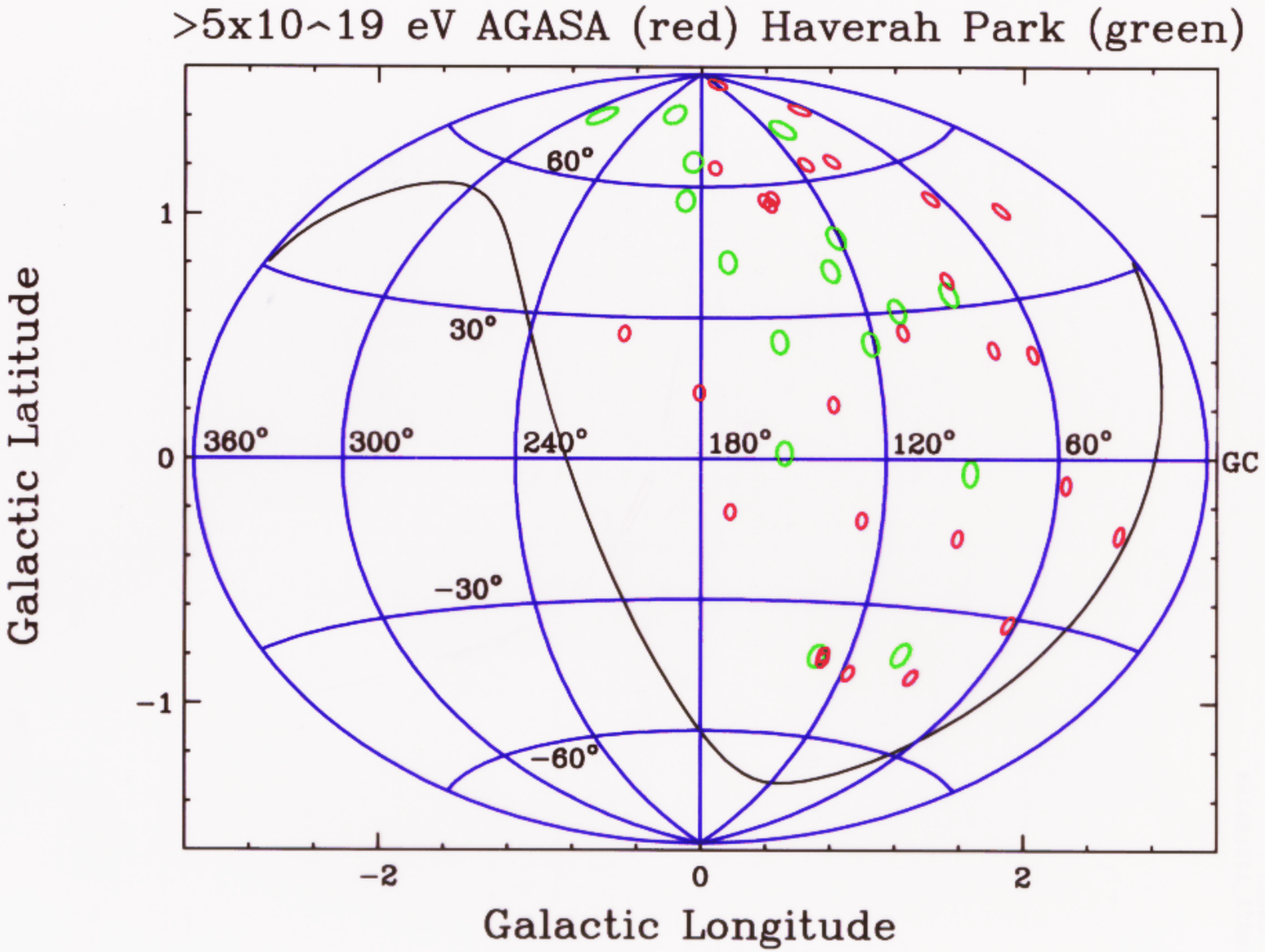


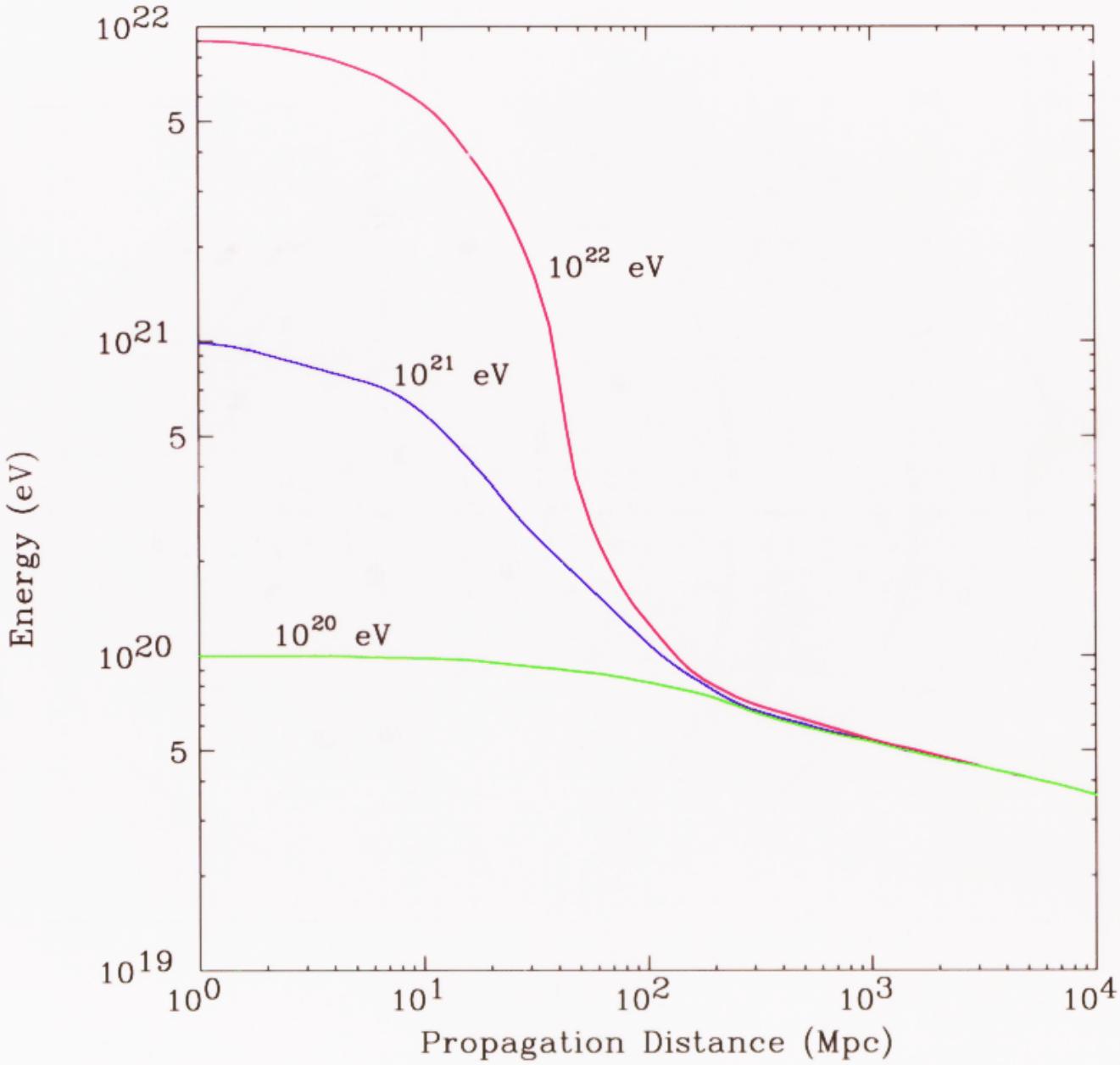
* 7 events above 10^{20} eV
  more events from FE I and HiRes

* Beyond Greisen cutoff: $p\,\gamma \rightarrow \Delta^{+} \rightarrow \pi$'s

* Sources must be local, but no obvious choices

? ? ?


>5x10^19 eV AGASA (red) Haverah Park (green)
Galactic Latitude
Galactic Longitude
60°
30°
360°
300°
240°
180°
120°
60°
GC
−30°
−60°
1
0
−1
−2
0
2


10^{22}
5
10^{21}
5
10^{20}
5
10^{19}
Energy (eV)
10^{22} eV
10^{21} eV
10^{20} eV
10^0
10^1
10^2
10^3
10^4
Propagation Distance (Mpc)

THEORETICAL CONSIDERATIONS

"Extreme Astrophysics"

1. Power source: E & M, Gravity

Process	Object
NS rotation	pulsar
accretion	active galactic nuclei (AGN)
star collapse	SN, SNR
collisions of massive objects	GRB

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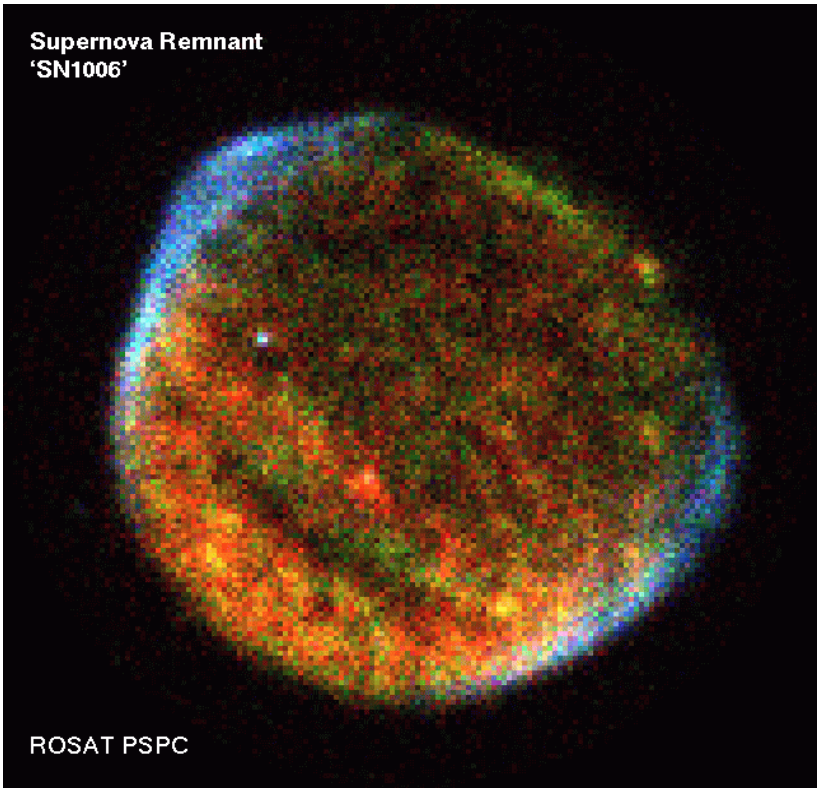
* All of these objects have been detected at HE

"Extreme" Astrophysics

Neutron star power:

* Crab pulsar/nebula
* γ−rays to 50 TeV

Lick



ROSAT

Supernova Remnant:

* SN 1006
* TeV γ−rays from shell (upper left)

"Extreme" Astrophysics

2. Acceleration: charged particles

   * injection

   * shock acceleration (e.g. Fermi 1949)
     bulk motion at large Γ factor

   * beam particles:
     leptonic (e) or hadronic (p)

3. Emission

leptonic	$e \rightarrow e\,\gamma$	bremsstrahlung
	$e\,\gamma \rightarrow e\,\gamma$	inverse−Compton
hadronic	n, p, He	CR production

$$\pi_o \rightarrow \gamma\gamma$$

$$\pi_+ \rightarrow \nu$$

4. Propagation

   * CRs can interact, deflect

   * γ's can be absorbed

Physics beyond Standard Model

Relic particles/structures from early Universe

Higher mass scale: "top down" theories

Examples:

1. Topological defects
   (Hill 1983, Hill & Schramm 1987...)
   cosmic strings, monopoles, etc.

   * decay to GUT−scale particles (X) −> CR

2. Primordial black holes
   (Page & Hawking 1976)

   * evaporate to produce a spectrum of particles on < 1 sec timescale −> GRB

3. Heavy neutrinos
   (Berezinsky and Blasi 1997)

   * decay −> γ , CR

Physics beyond Standard Model

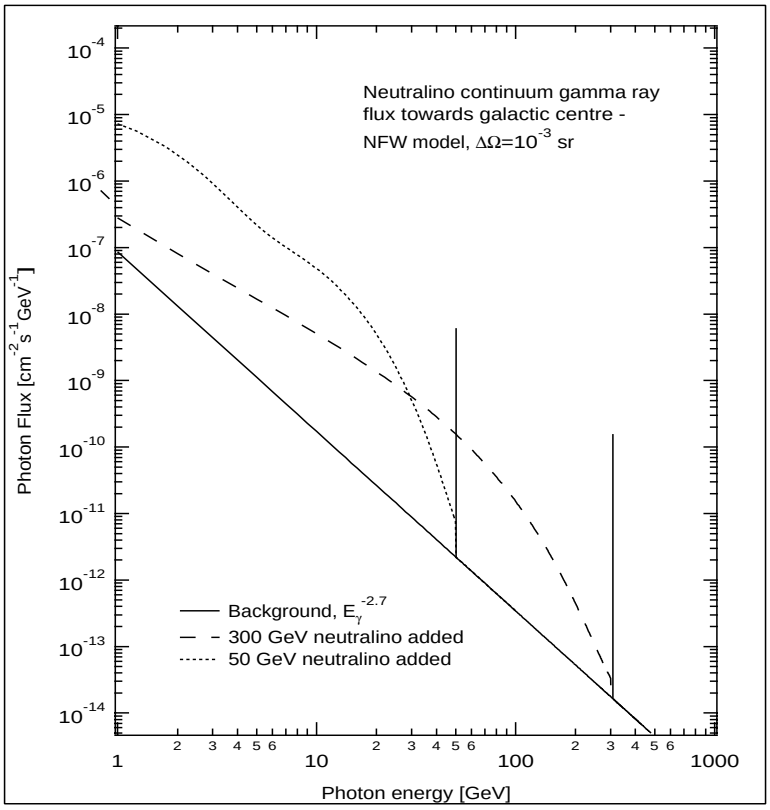
4. Supersymmetry

* LSP = galactic halo dark matter

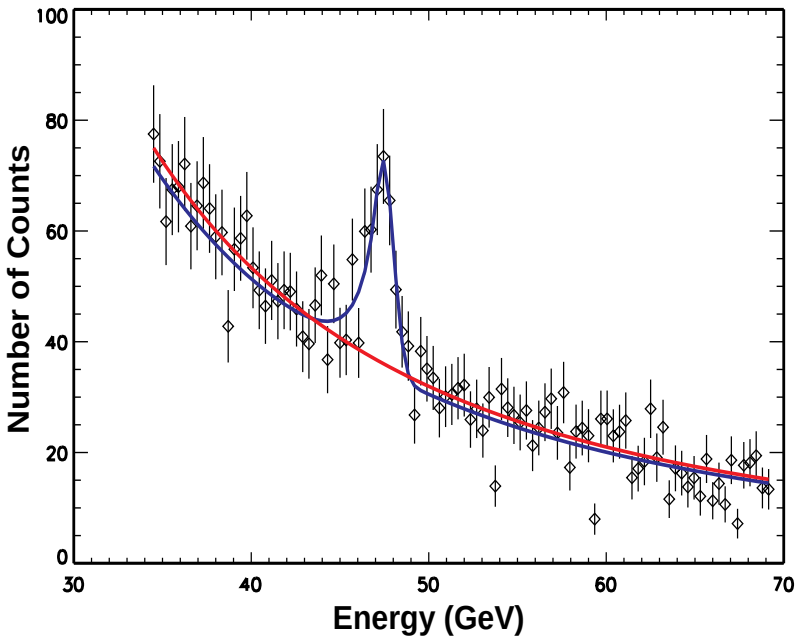
Neutralino annihilation in GC, Sun, Earth

$\tilde{X}^0 \tilde{X}^0 \rightarrow \gamma\gamma$
$\nu\nu$

γ−ray spectrum from Galactic center



Bergstrom et al.



Line detection by GLAST

* "smoking gun"
* measure mass

EXPERIMENTAL TECHNIQUES

Can detect HE particles in space: flux limited

Here, concentrate on ground−based instruments

Basic technique:
sampling calorimeter
measures particle's energy and direction

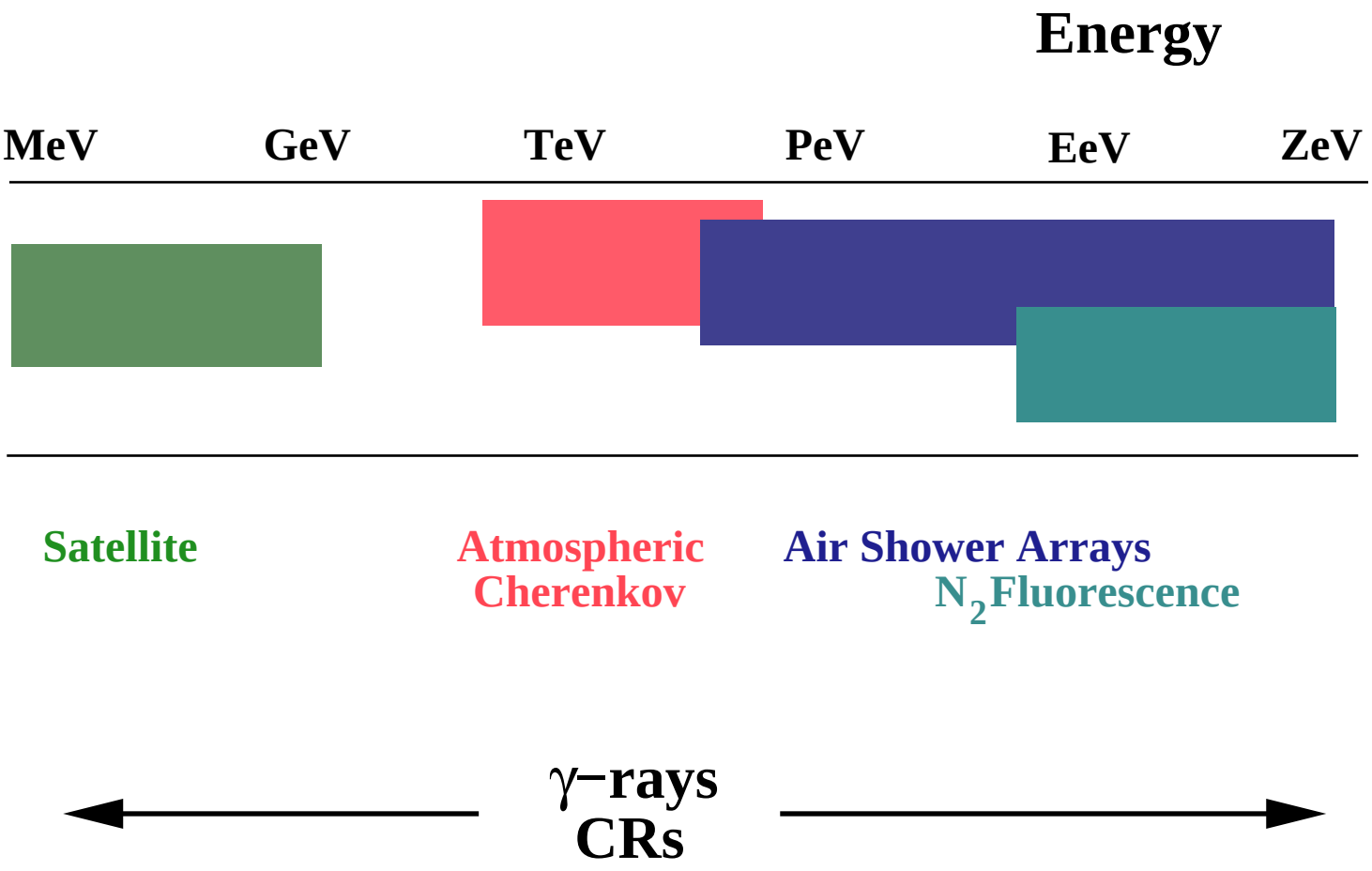
* calorimeter:
  Earth's atmosphere (γ, CR, ν)
  Earth's volume (ν)

* detection method:
  Cherenkov radiation (atm., water, ice)
  ionization
  N_2 fluorescence

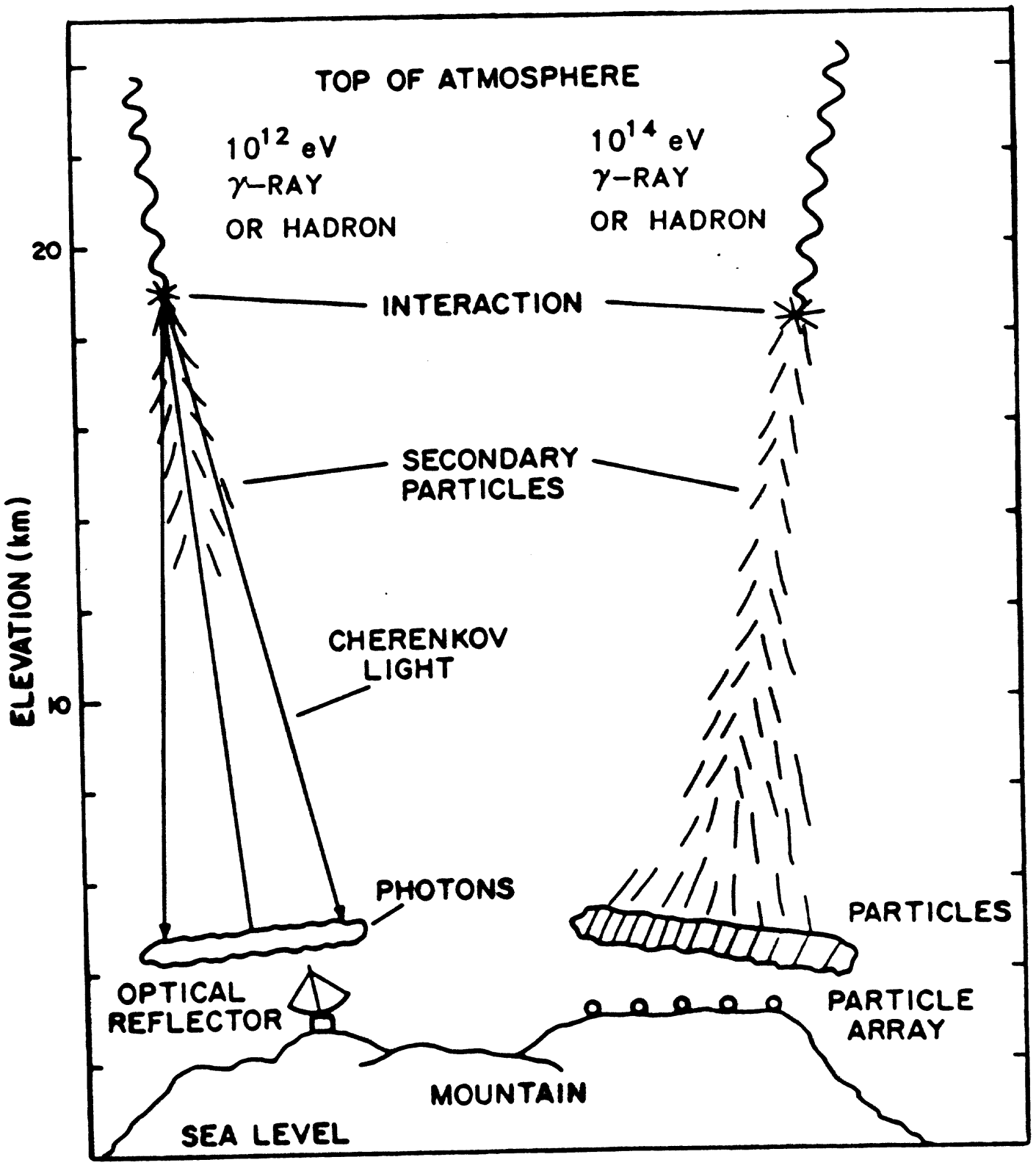
* technology:
  fast charged particle of photo−detectors
  fast electronics

γ−ray and Cosmic ray Detection

* Wide energy range requires several techniques

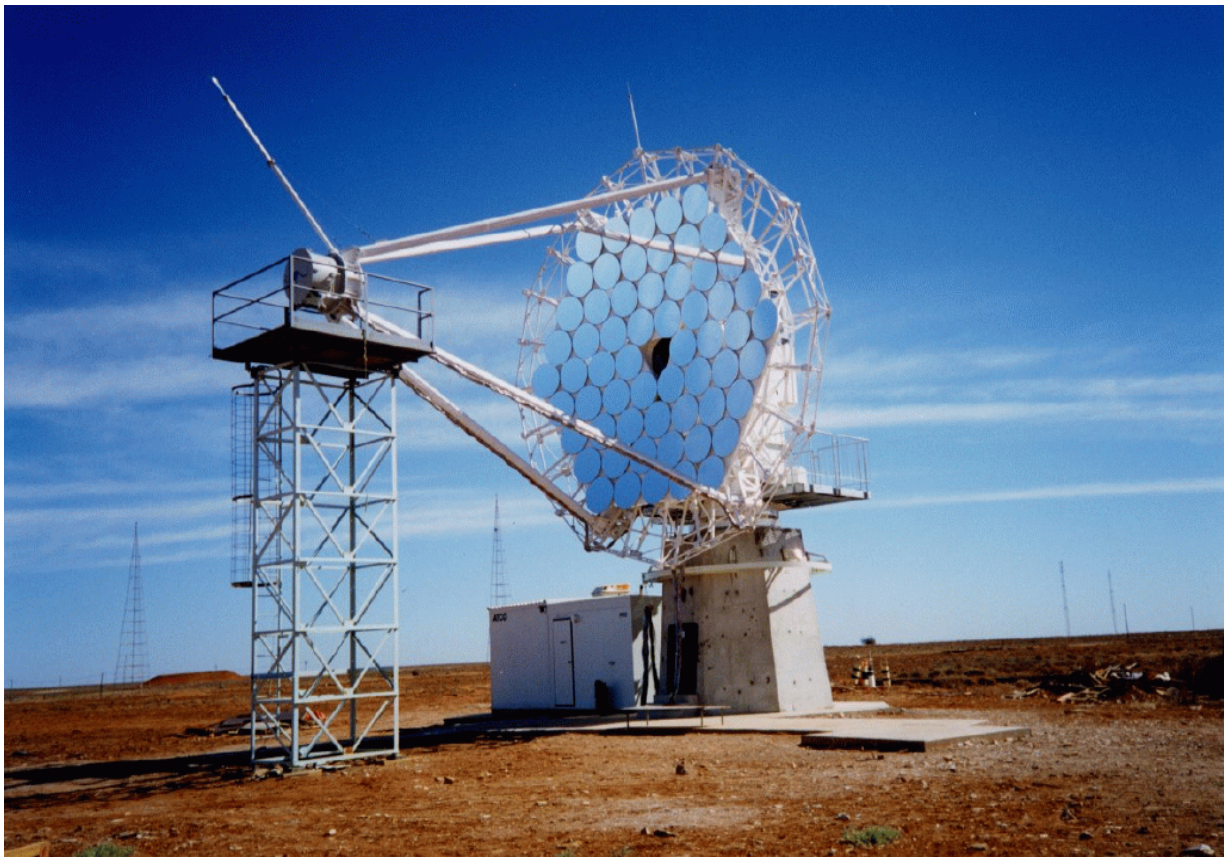


γ–ray and CR techniques:



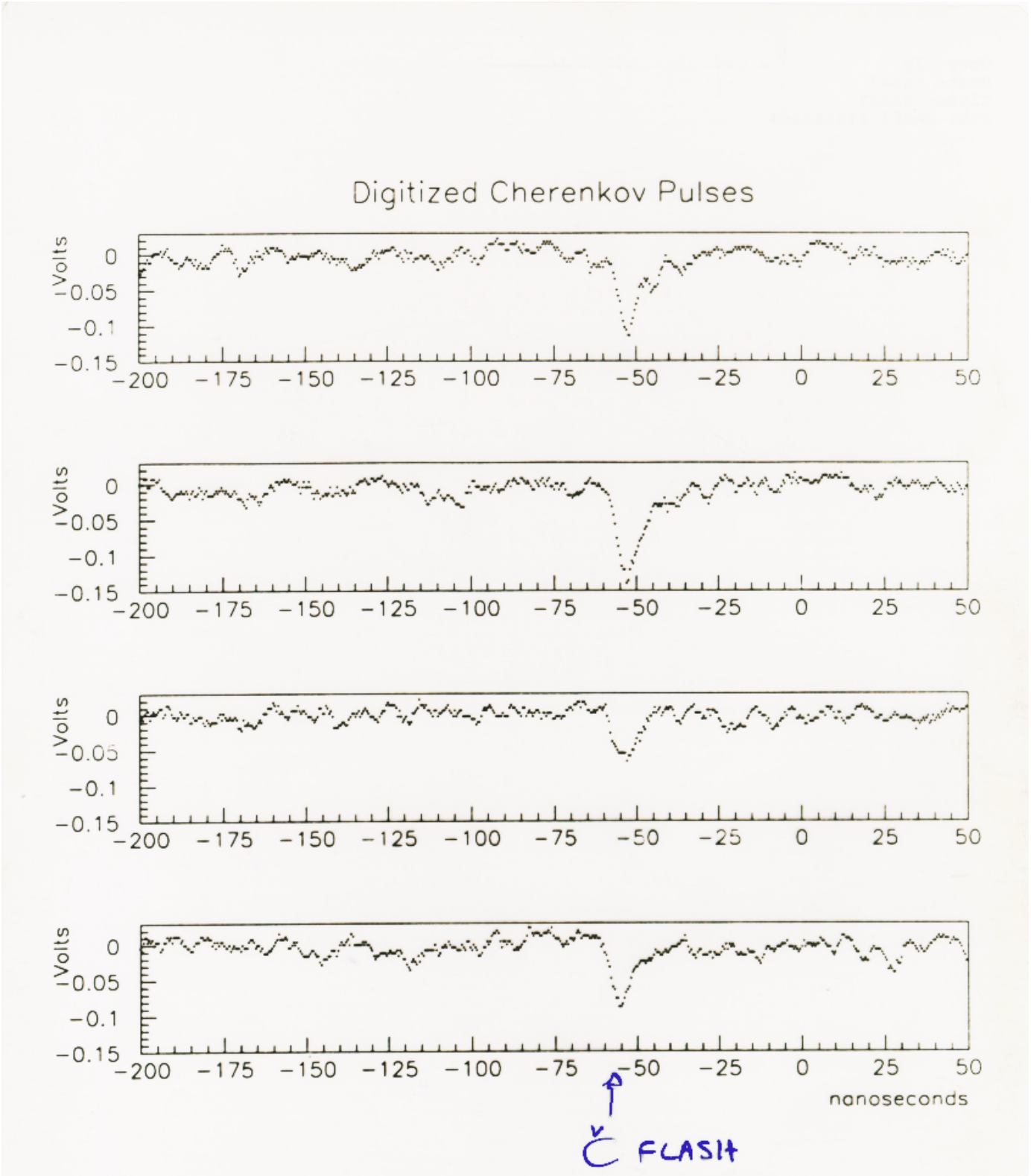
Cherenkov telescopes **Air shower experiments**

Cherenkov telescope: CANGAROO II



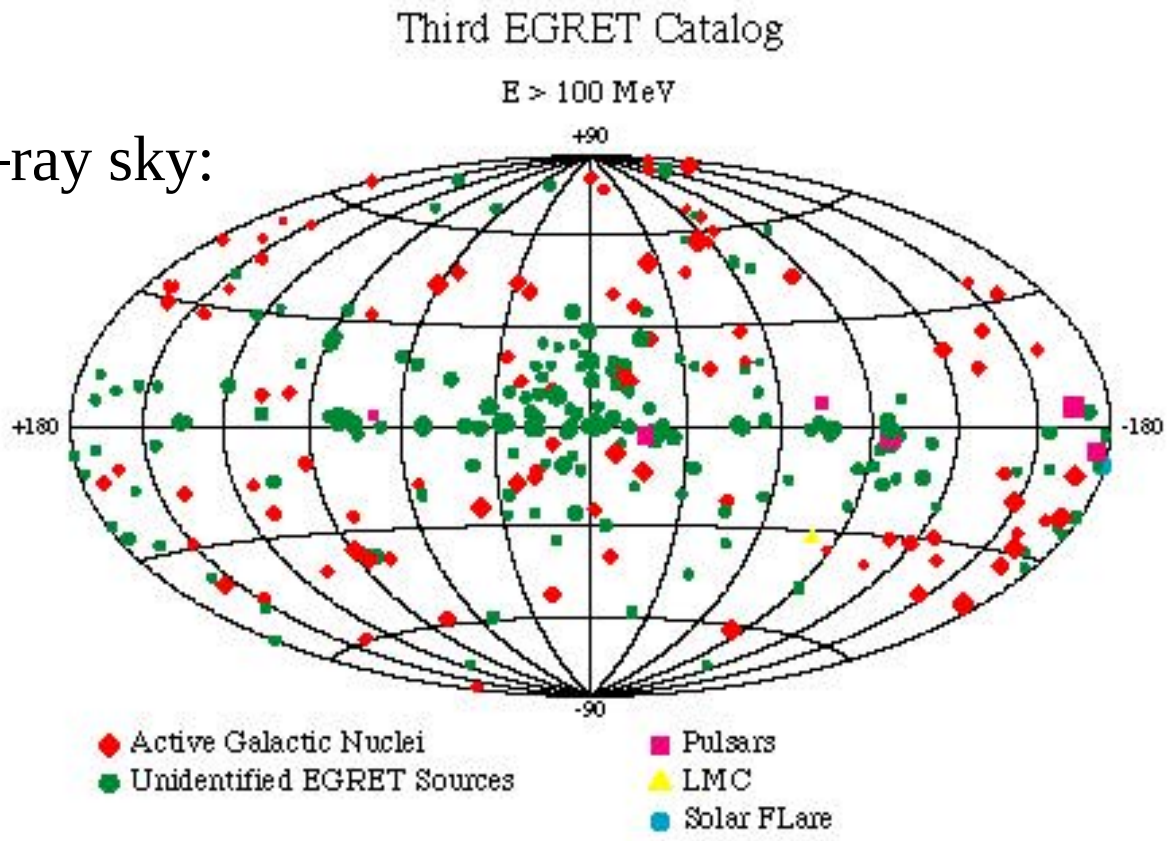
Air shower experiment: MILAGRO

Atmospheric Cherenkov pulses

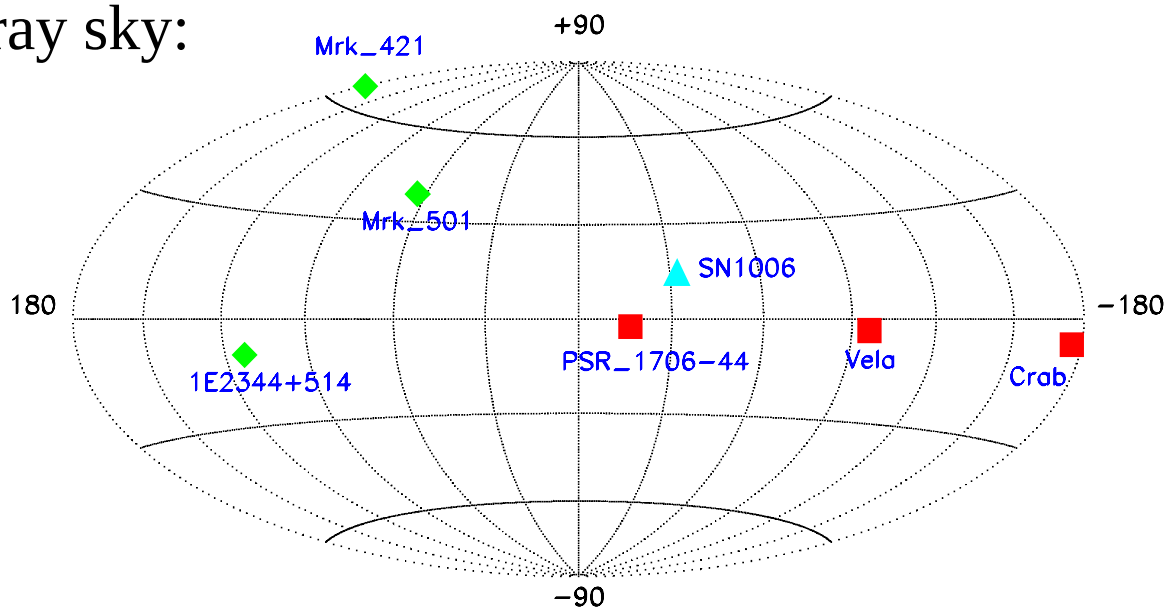


γ– RAY ASTROPHYSICS

GeV γ–ray sky:



TeV γ–ray sky:



γ−ray Astrophysics

Selected topics:

* Pulsars: TeV γ−rays detected from nebulae.
  No emission from pulsar?
* SNRs: Detected SN1006: e acceleration
  Origin of cosmic rays?
* GRBs: Some bursts are cosmological.
  What about other bursts?
  What about HE component?
* AGNs: Remarkable emission from a few nearby blazars.
  How do they work?
  What about many other AGN?
* Dark matter: Need to carry out astrophysical searches.

New instruments required to:

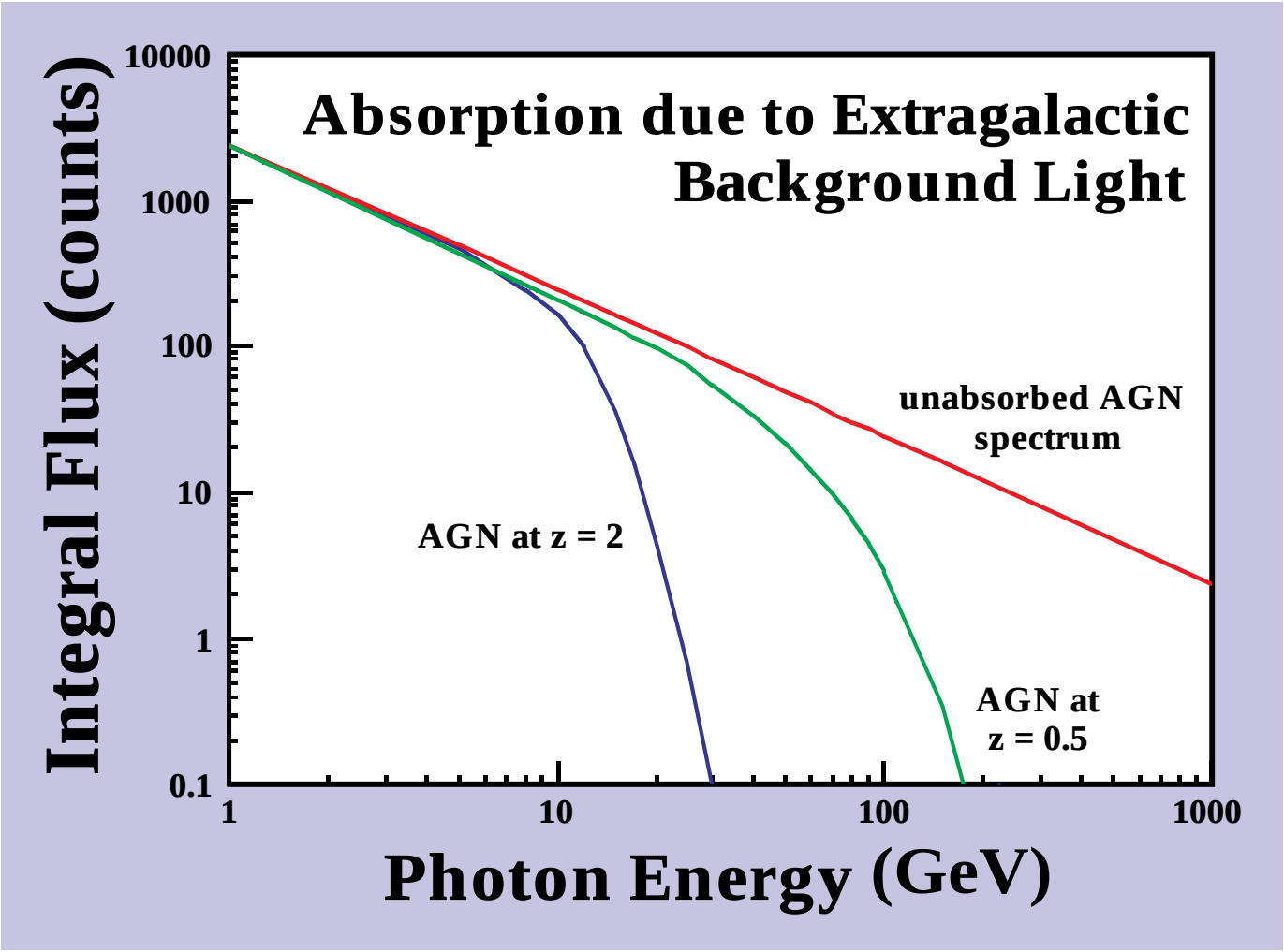
1. Explore region between 20 − 250 GeV
2. Achieve much greater sensitivity
3. Carry out all−sky surveys

IR Absorption of γ−rays

* Many AGN seen at GeV energies, but only a few nearby ones at TeV energies

* HE γ−rays from distant obects will interact with diffuse light in interstellar space:

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



* γ−rays can probe the Cosmic IR field sensitive to its density, and evolution

Two new experiments: STACEE, CELESTE

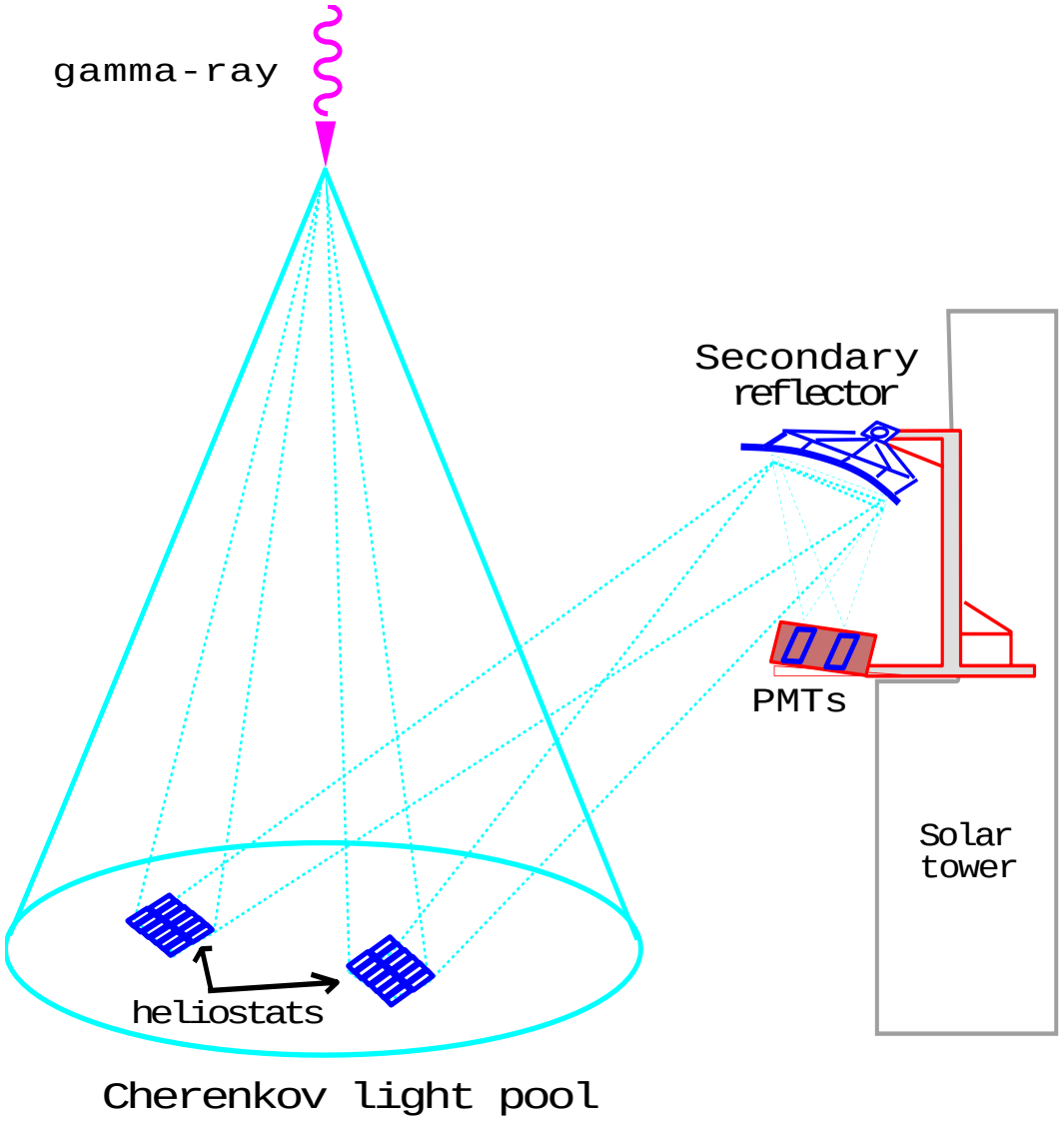
* Use solar mirror arrays to make a very large Cherenkov detector −> low E threshold

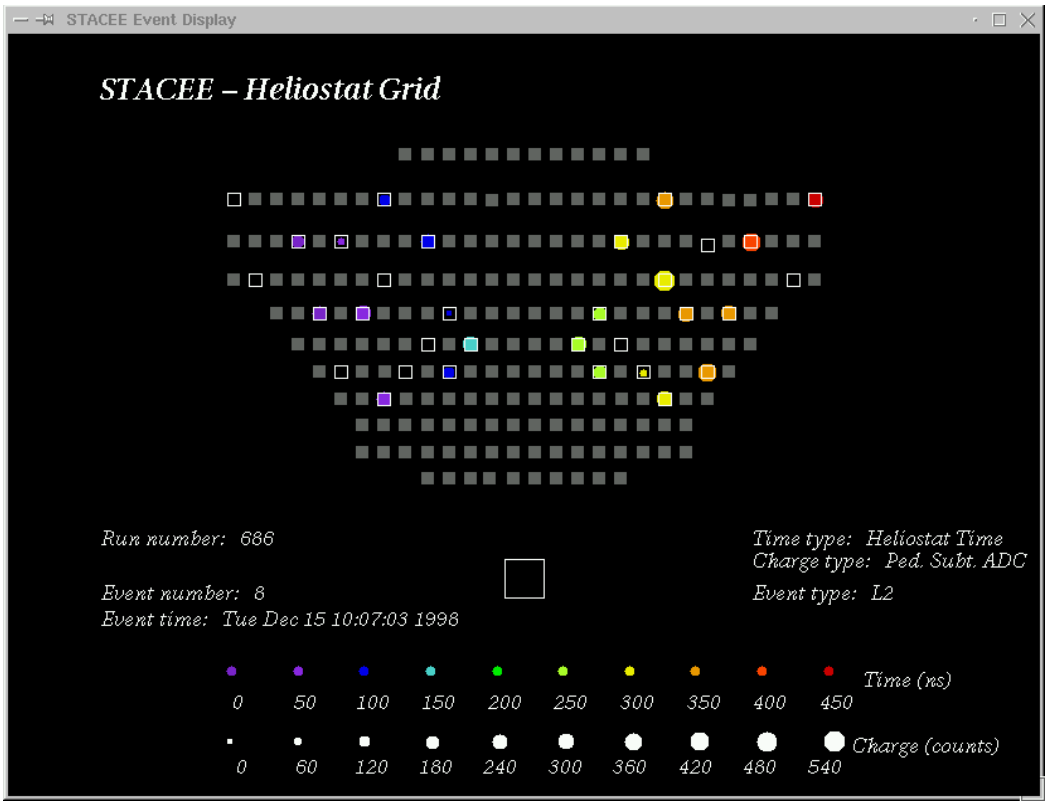
Sandia

* STACEE (Sandia) and CELESTE (Pyrenees) should thresholds as low as 40 GeV

* 1999: both experiments reporting first results

Concept:





STACEE Event

Future γ−ray Detectors

1. Cherenkov Telescopes

   * Improve sensitivity by factor of 10

   * Cover energy range 50 GeV − 10 TeV

   * Four new projects starts:

CANGAROO III	(Australia)
HESS	(Namibia)
MAGIC	(La Palma)
VERITAS	(Arizona)

   Separated in latitude & longitude
   Operational in several years

2. New Satellite Experiment (GLAST)

   * Much greater sensitivity (factor of 30)

   * All−sky coverage

   * Uses state−of−the−art detector/electronics pioneered by HEP

   * Collaboration of astrophysicists/particle phys.

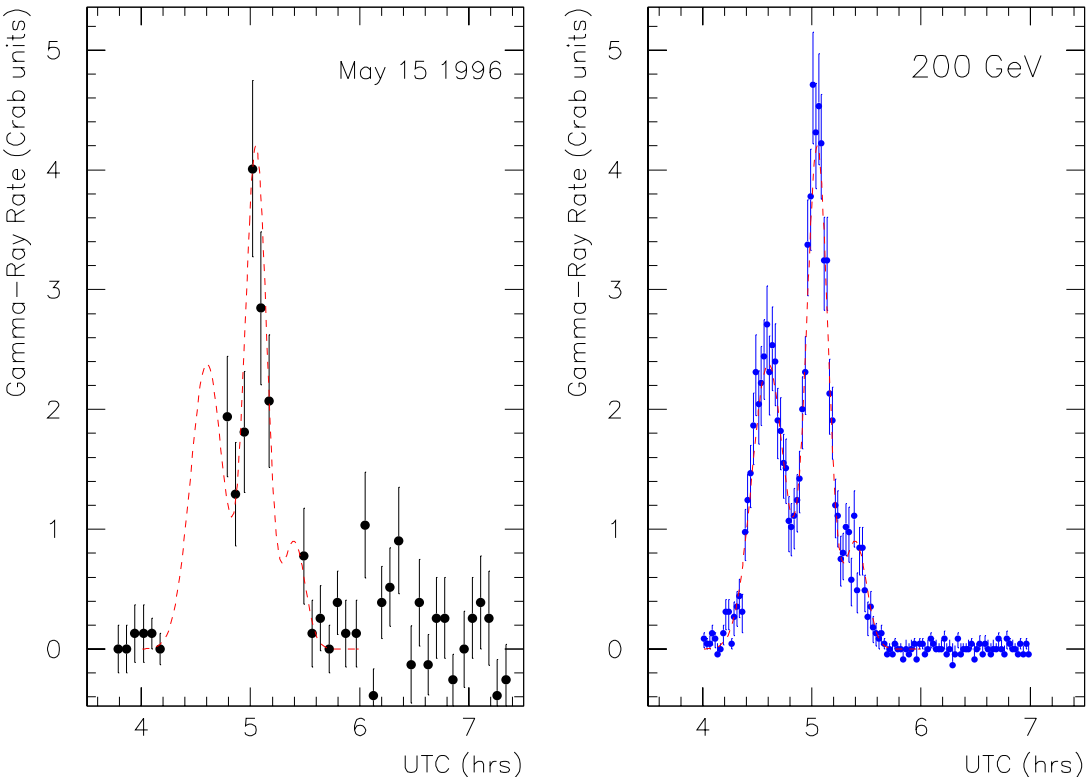
Launch > 2005

Cherenkov telescrope array: example of VERITAS

Mt. Hopkins AZ

Response to AGN Flare:

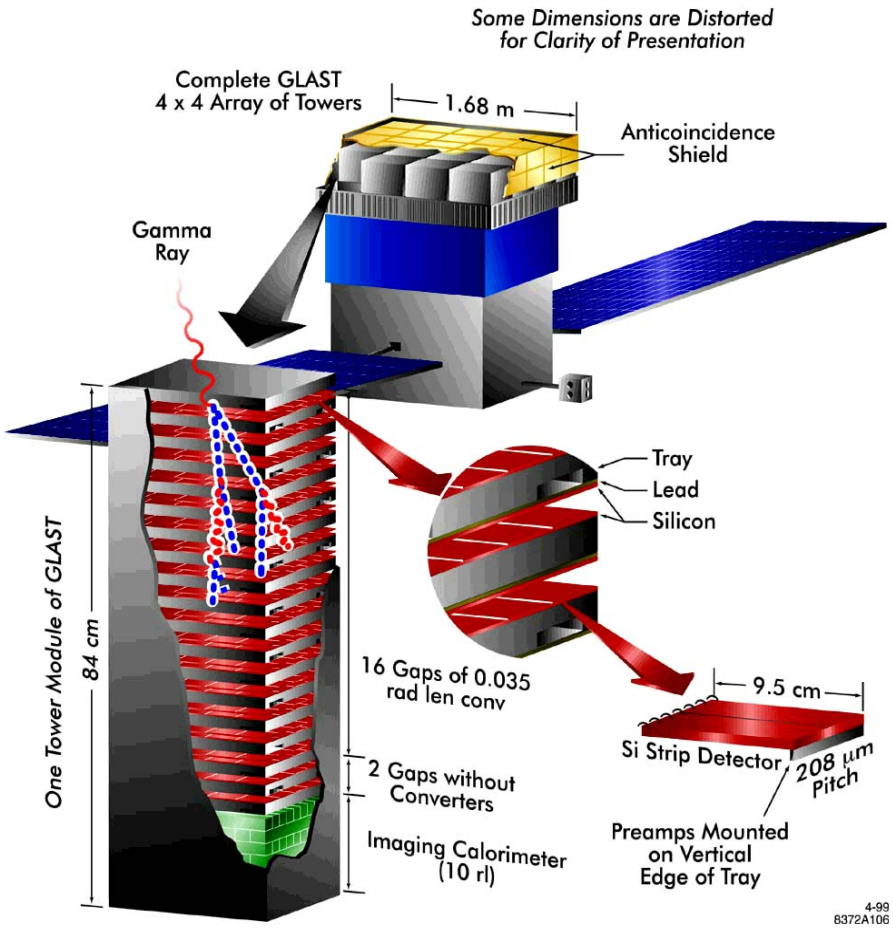
Detailed structure resolved.



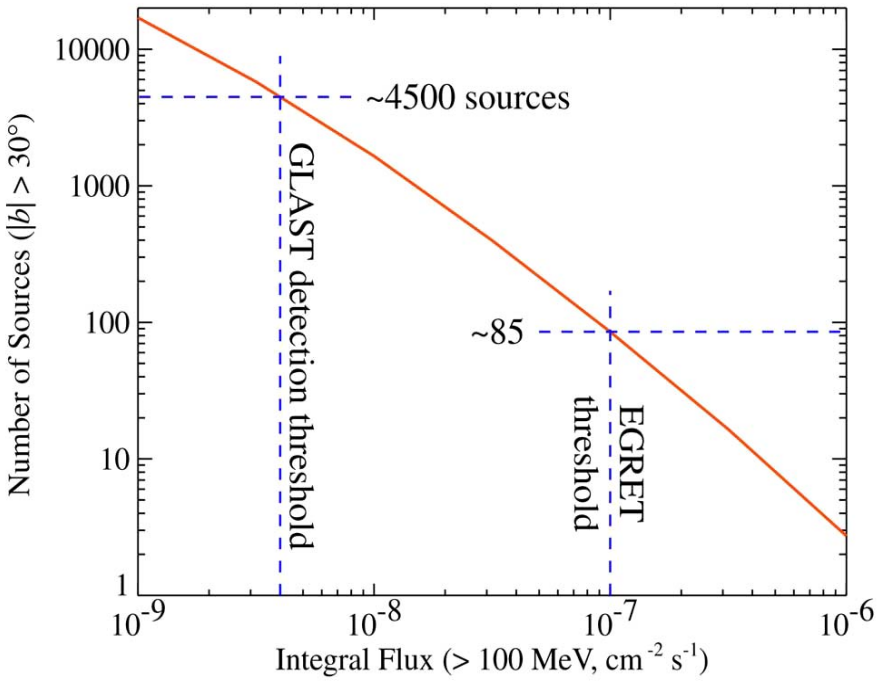
Gamma−ray Large Area Space Telescope (GLAST)

* Two possible technologies: Silicon, SciFi

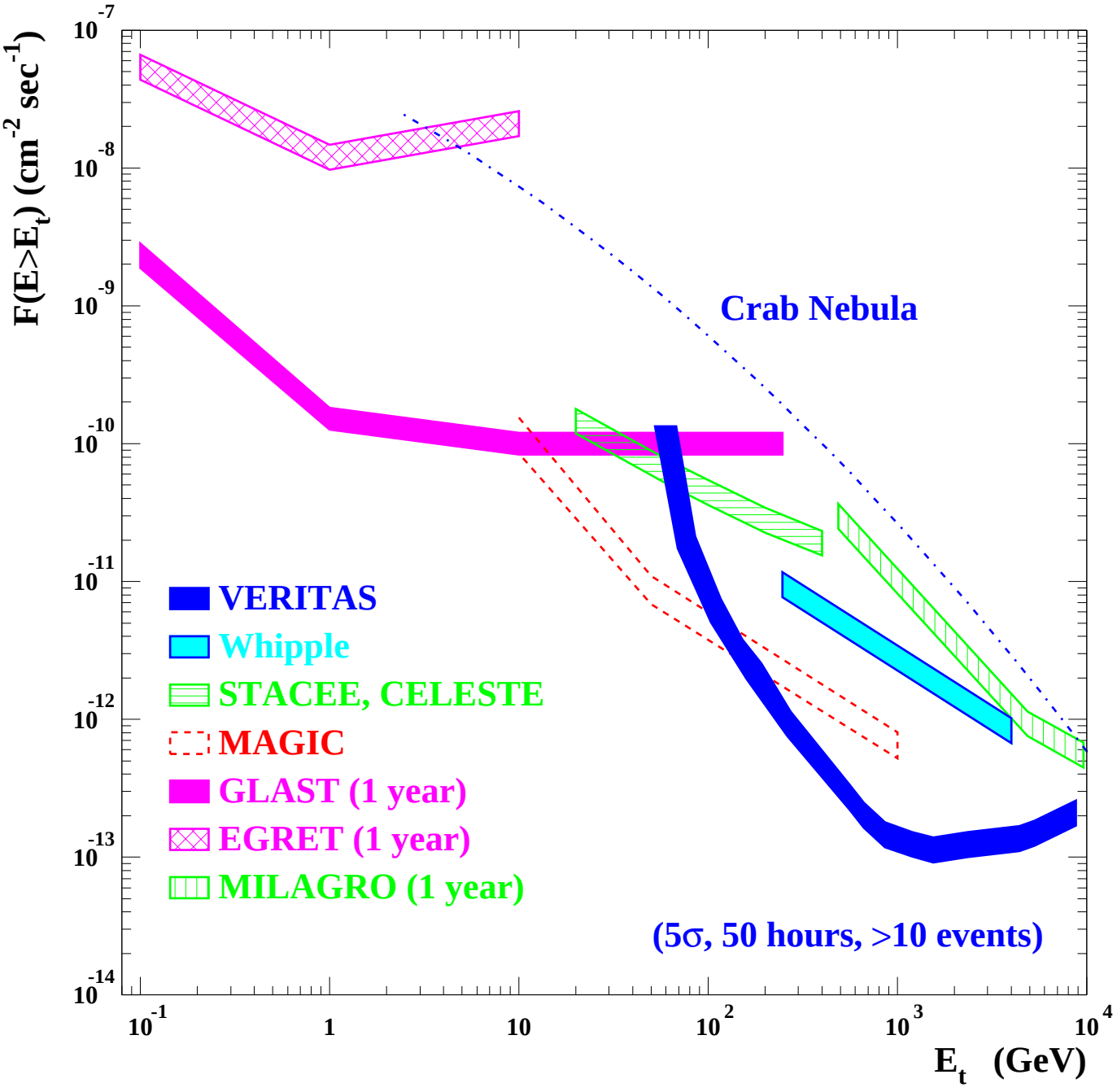
Si−GLAST Option:



Greatly enlarge AGN sample:



Sensitivities of future γ−ray experiments:



COSMIC RAY ASTROPHYSICS

What we know:

* Spectrum measured up to 10^{20} eV

* Composition measured up to 10^{14}eV (space)
  10^{18}eV (air showers)

  consistent with mixture of heavy nuclei

* Anisotropy no clear picture

General picture:

$< 10^{15}$eV Galactic origin SNR
$> 10^{15}$eV Extragalactic ?

What we don't know:

1. Is there any primordial antimatter? (AMS)
2. What happens at knee? What is origin $> 10^{15}$ eV?
3. What is happening at highest energies $> 10^{20}$ eV?

AMS Experiment on Space Shuttle

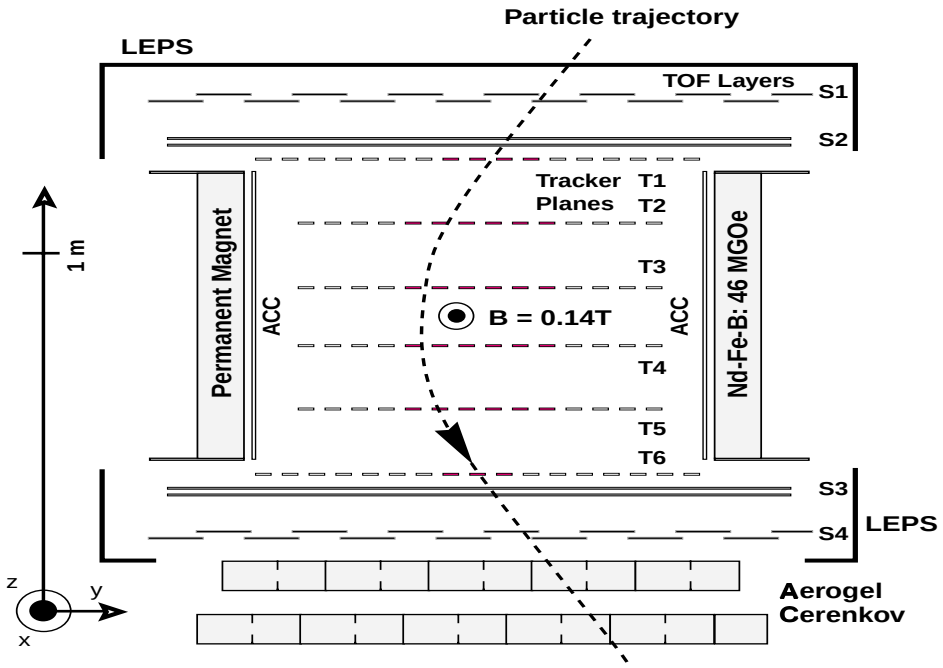


Figure 1: Schematic view of AMS as flown on STS–91 showing the cylindrical permanent magnet, the silicon microstrip tracker planes T1 to T6, the time of flight (TOF) hodoscope layers S1 to S4, the aerogel cerenkov counter, the anticoincidence counters (ACC) and low energy particle shields (LEPS).

First result

$\overline{\text{He}} < 10^{-6}\,\text{He}$

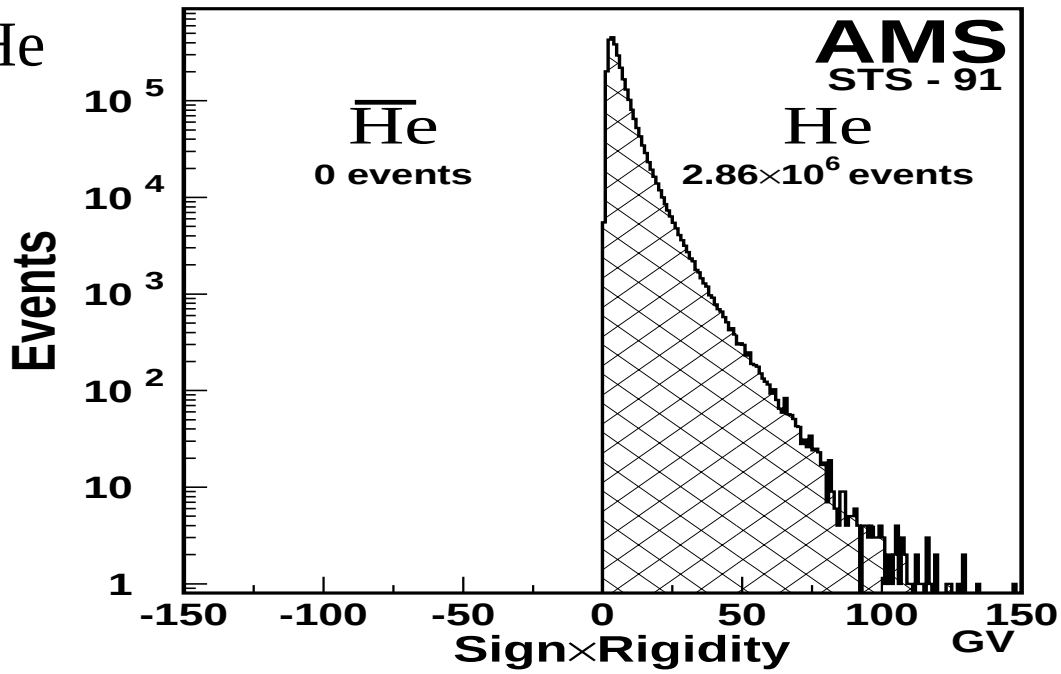
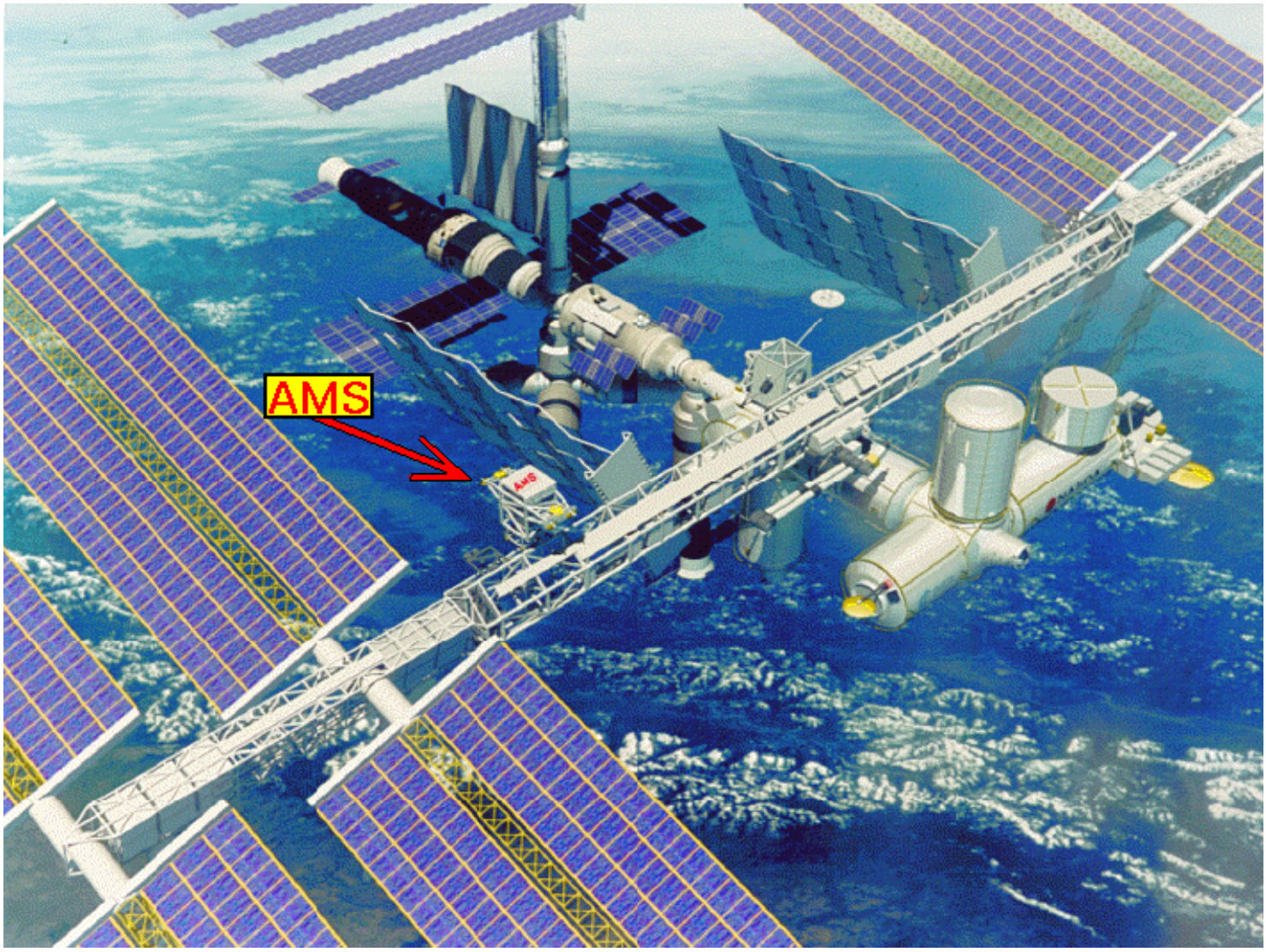


Figure 8: Measured rigidity times the charge sign for selected $|Z| = 2$ events.

AMS Experiment on ISS



Highest Energy Cosmic Rays

Basic problem is one of statistics:

* Need largest aperture (km^2 sr) possible

* Measure particle energy, direction, composition as best as possible

Table of Expts:

Expt	Location	Status	Yield (> 10^{20} eV)
FE 1&2	Utah	Complete	1
AGASA	Japan	Operating	7
FE HiRes	Utah	Begun	~ 15 / year
AUGER S	Argentina	2003	~ 100 / year
N	Utah	Proposed	" "
Tel. Array	Utah ?	Proposed	~ 100 / year
OWL	Space	Proposed	> 1000 / year

We need to wait a few years . . .

The Highest Energy Particle (Fly's Eye)

3×10^{20}eV (50 J)

Profile:

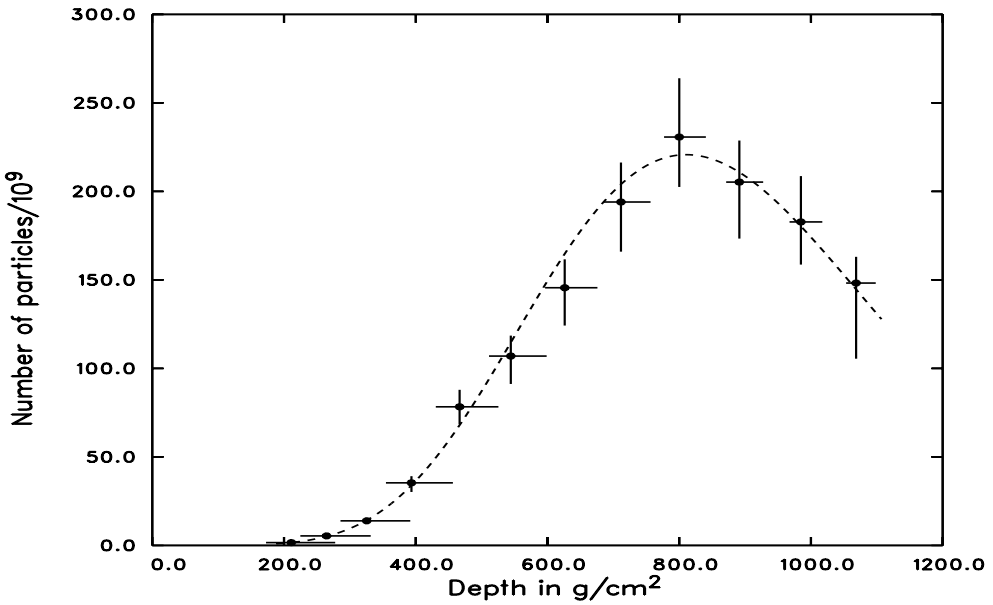
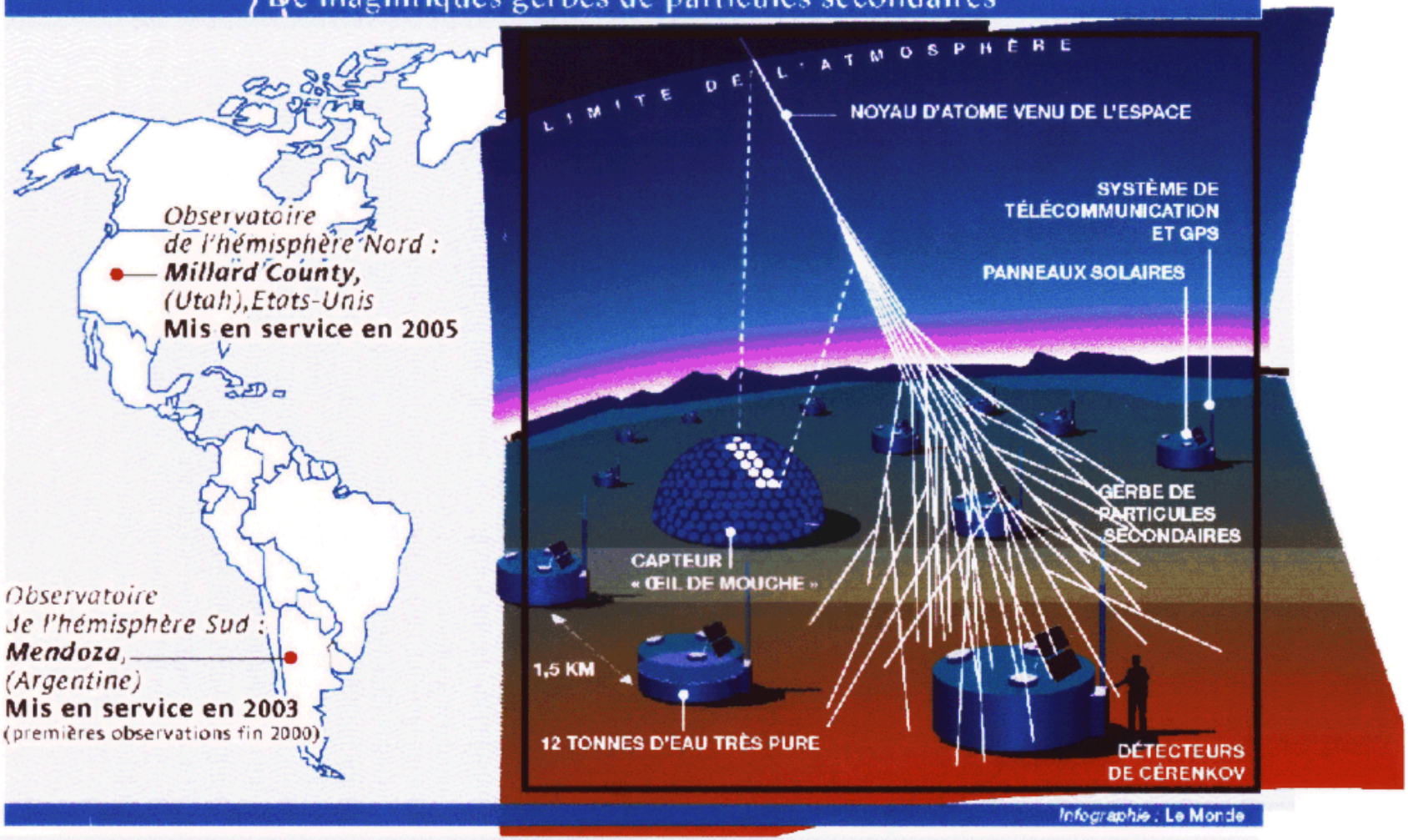


Figure 3: The 3-parameter best-fit shower profile is shown along with points obtained from the data in 5-degree intervals. The size at maximum is greater than 200 billion particles.

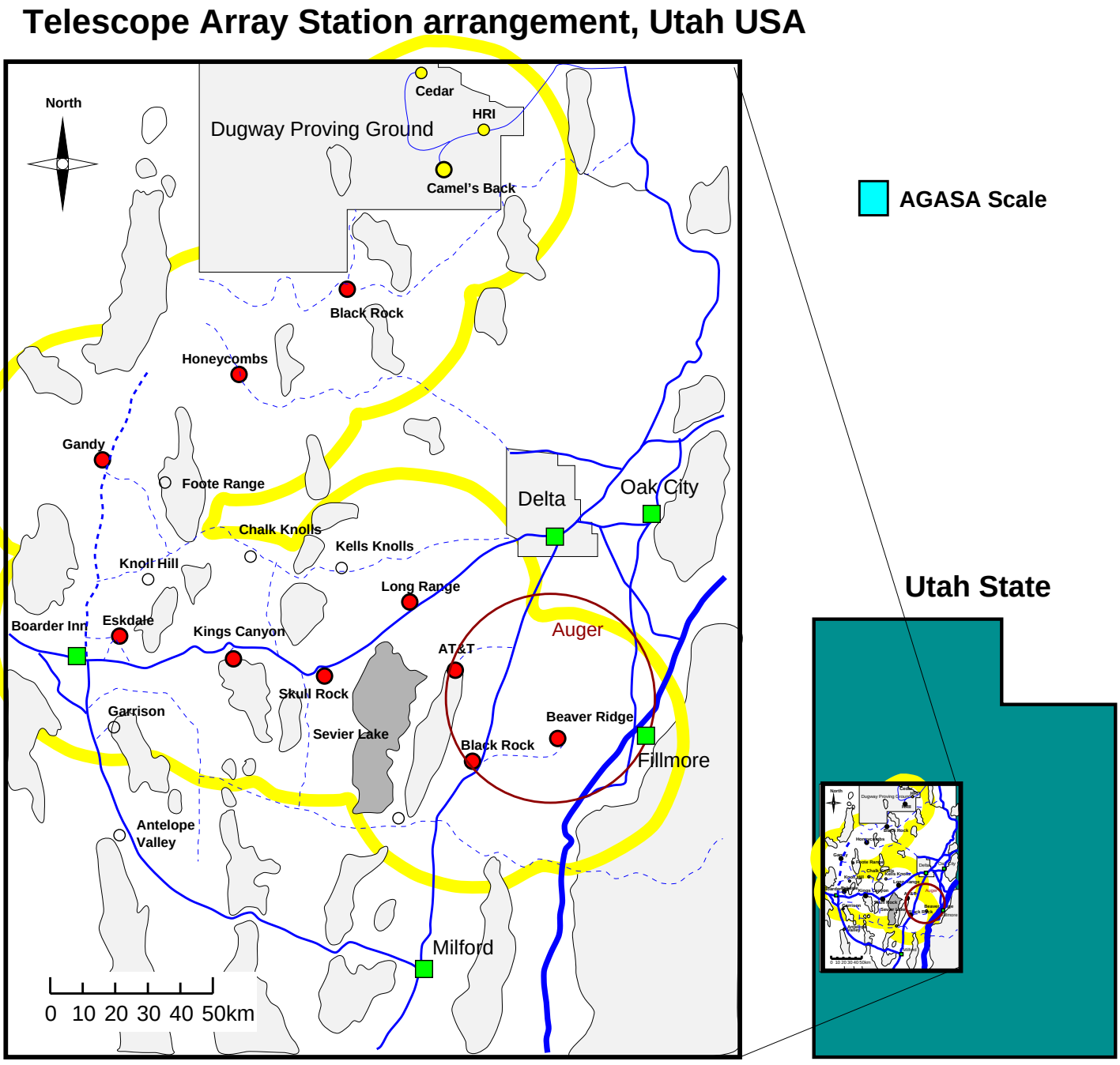
De magnifiques gerbes de particules secondaires



Infographie : Le Monde

Une pluie continue de particules venues de l'espace percute chaque seconde l'atmosphère. L'énergie de certaines d'entre elles défie l'imagination. En trente-cinq ans, seules une dizaine ont été observées. Trop peu. C'est la raison pour laquelle dix-neuf pays ont décidé de construire deux observatoires géants de 3 000 km^2 constitués chacun de trois capteurs « œil de mouche » pour suivre leurs traces en altitude et de 1 600 autres à effet Cérenkov pour détecter leur impact au sol.

Telescope Array: Possible Site Selection

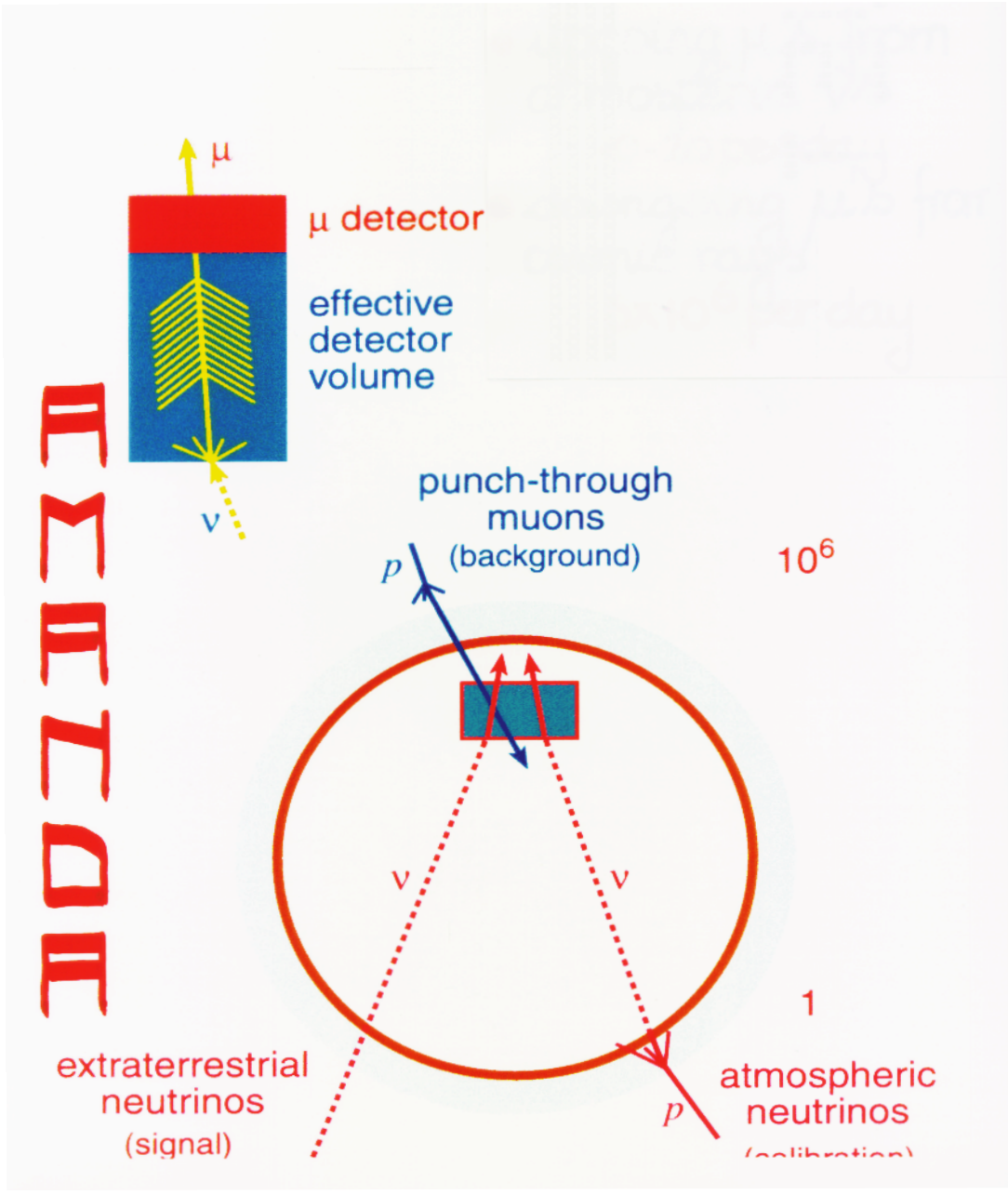


ν–ASTROPHYSICS

* Sources similar to γ–rays
* ν's can come from central engines
* sensitive to ν particle physics (e.g. mass)

Basic technique:

Use water/ice as Cherenkov medium for HE muons



ν Telescopes Around the World

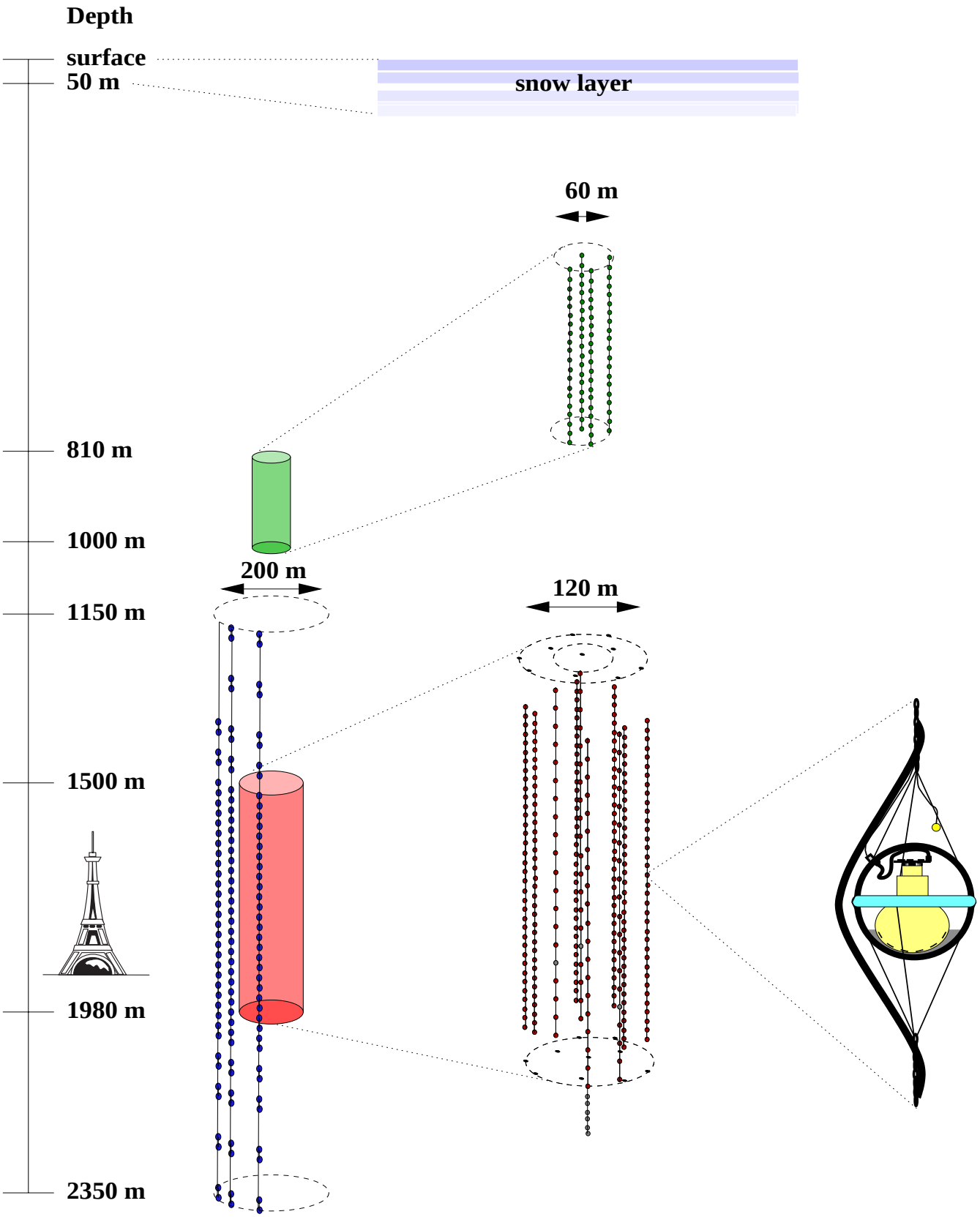
* Variety of projects underway
* Expts. have different designs/challenges

Incomplete List:

Experiment	Location	Optical Modules	Status
BAIKAL	Siberia	200	Operating
AMANDA I	South Pole	300	Operating
II		400	Construction
ANTARES	Near Toulon	1000	Starting
NESTOR	Near Pylos	?	Proposed
NEMO	Near Sicily	?	Proposed
ICECUBE	South Pole	5000	Proposed

The AMANDA project is taking data; use it as an example . . .

AMANDA Layout



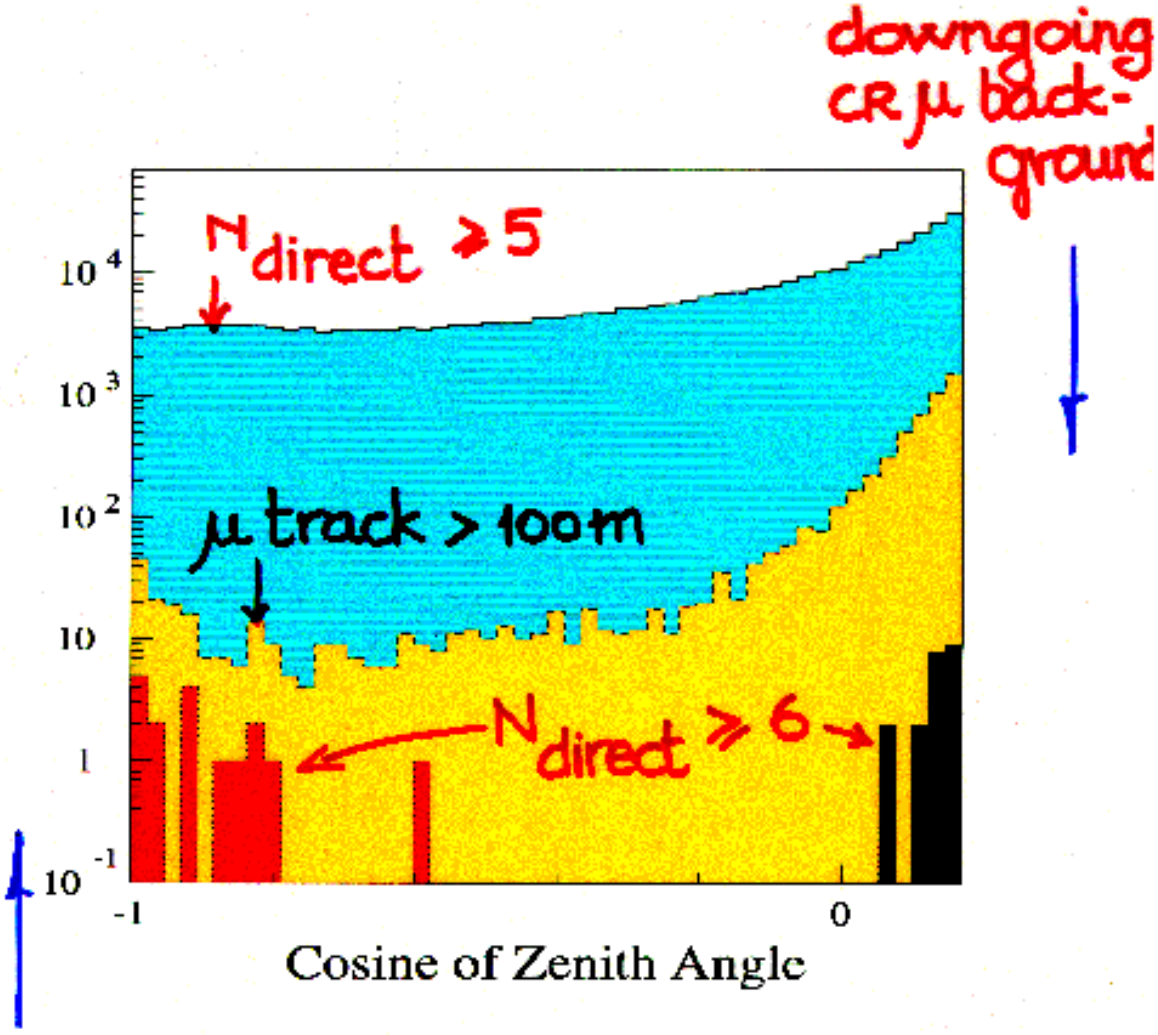
AMANDA as of 1998
Eiffel Tower as comparison
(true scaling)

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

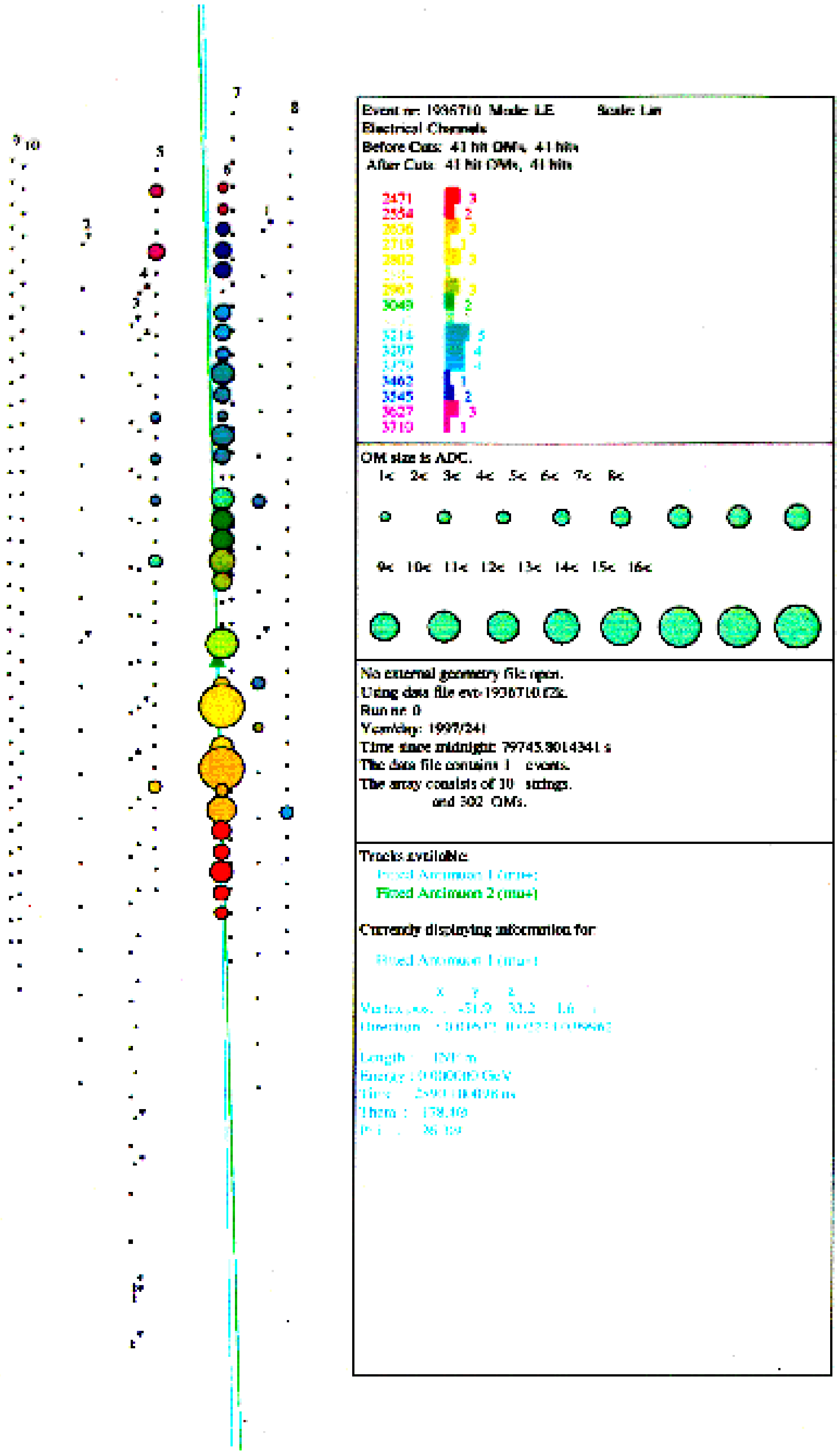
zoomed in on one
optical module (OM)

AMANDA Reconstruction

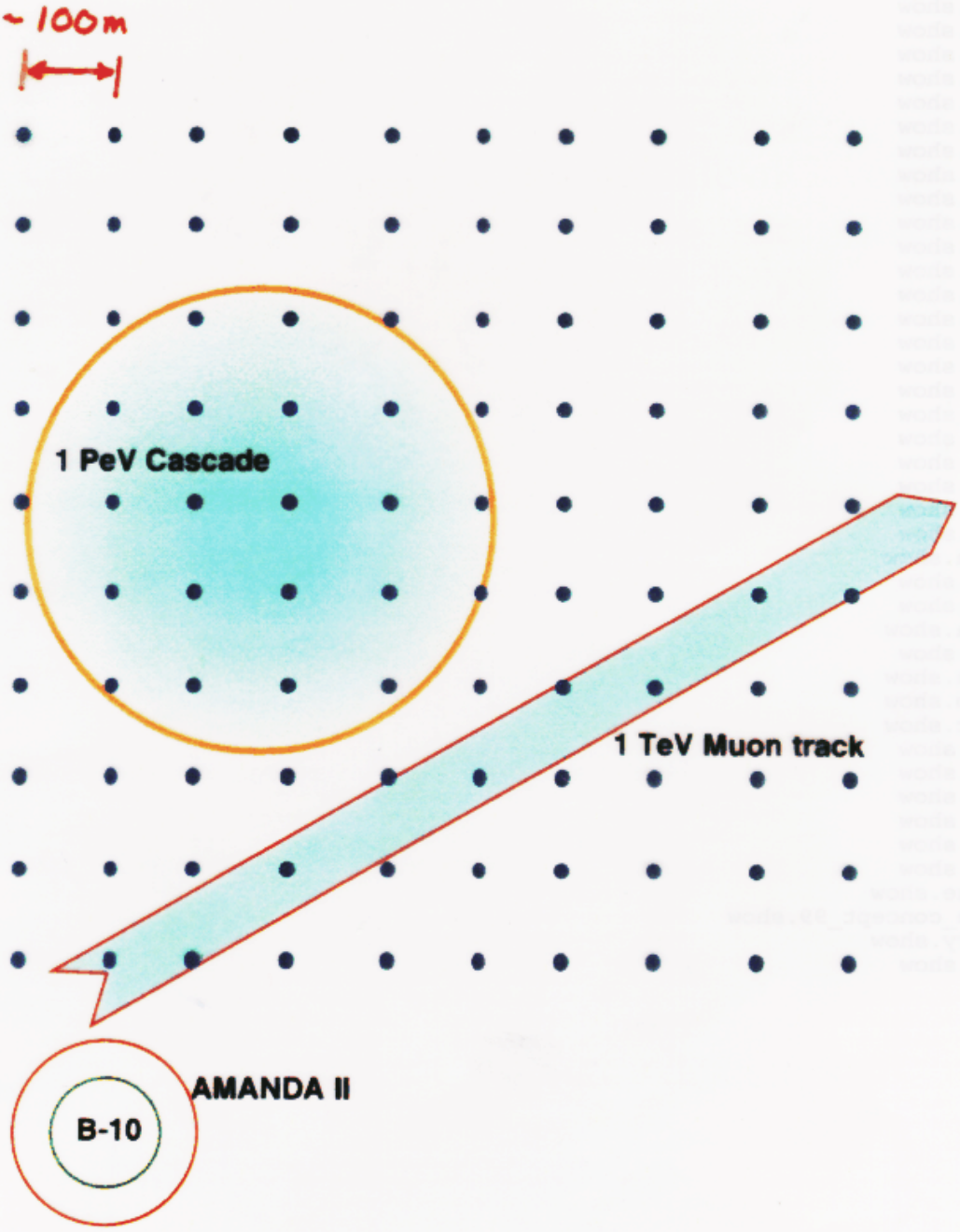
* Zenith distribution shows clean sample of upward going muons = atmospheric ν's



AMANDA Event



ICECUBE



SUMMARY

Outlook is extremely good:

1. Significant scientific progress, timescale of 2 years

   γ−rays: growing catalog of sources, types
   fantastic phenomena GRB, AGN

   CR's: clear mystery at highest energies

* Real challenge for theory.

* Discoveries raise as many questions as they answer !

2. Ever expanding panoply of experiments

   γ−rays: Cherenkov telescopes, GLAST

   CR's: Very large ground−based instruments

   ν's: Ice and water Cherenkov detectors

* Hope: knowledge increases at similar pace !

THANKS

K. Arisaka
S. Barwick
M. Catanese
J. Cronin
F. Halzen
T. Kifune
P. Leonard
E. Lorenz
J. Matthews
M. Mori
G. Sinnis
D. Smith
S. Swordy
S. Ritz
P. Sokolsky
M. Takeda
T. Weekes
H. Voelk

and

J. Jaros