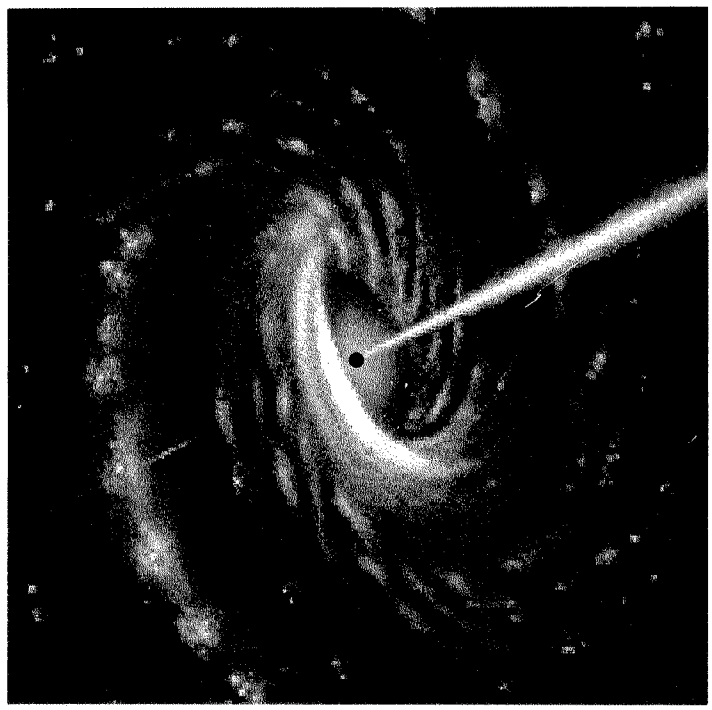
HIGH ENERGY PARTICLES FROM THE UNIVERSE



Lepton–Photon 99
Stanford, CA

Rene A. Ong
University of Chicago

OUTLINE

Broad overview

Three recent exciting results

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:

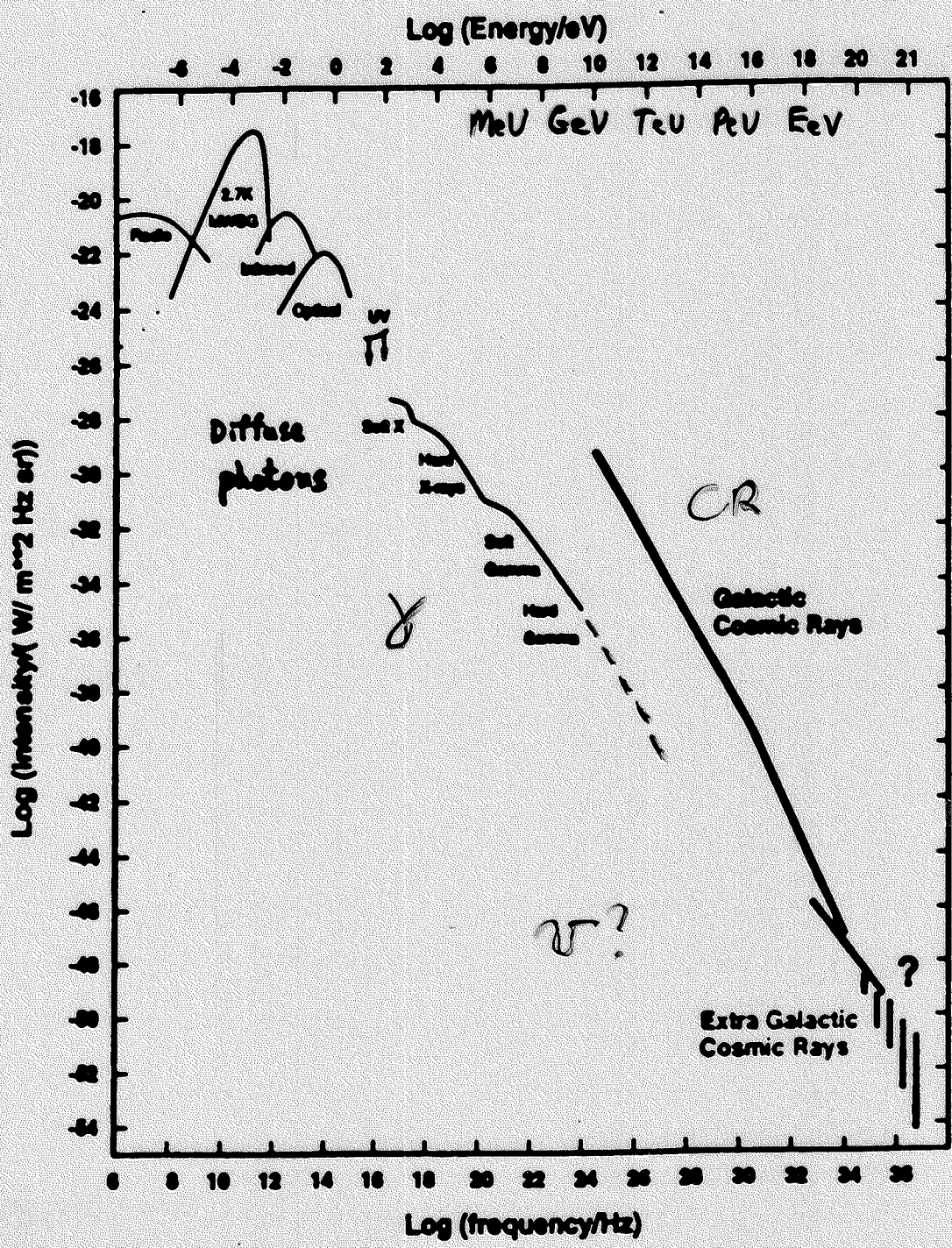
		strengthes	weaknesses
1. Light	γ	**neutral**	**absorption**
2. Cosmic Rays	**p, He ...**	**direct acceleration**	**charged**
3. Neutrinos	ν	**neutral**	**hard to detect**
4. Gravity Waves		**neutral**	**very hard to detect**

So far . . .

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

* This talk will summarize 1–3 at high energies

Grand Unified Spectrum



High energies:

power law spectra
enormous dynamic range
very low fluxes

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 windows 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 fluxes on < 1 hr timescales

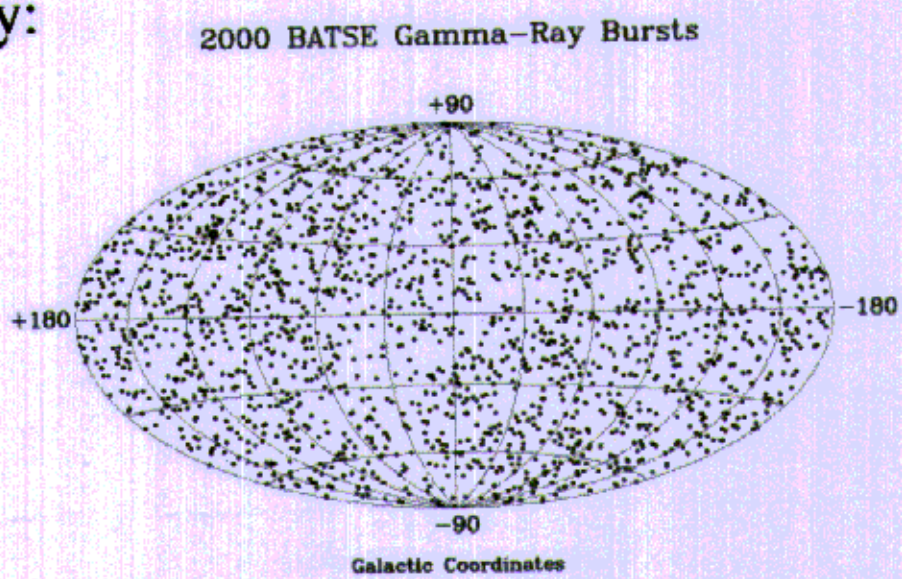
3. Highest energy cosmic rays

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

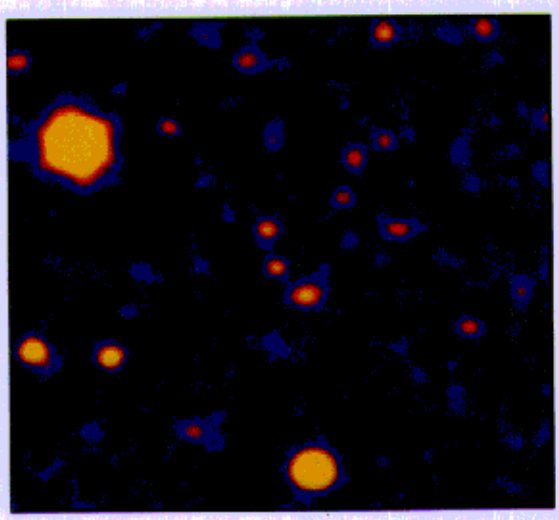
Gamma–ray Bursts (GRBs)

* 30 year old mystery

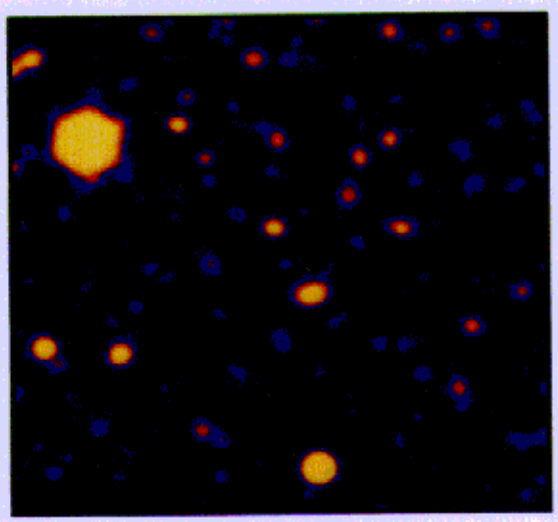
Isotropy:



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



Before



After

Keck
GRB 971214
z = 3.412

"Afterglows"

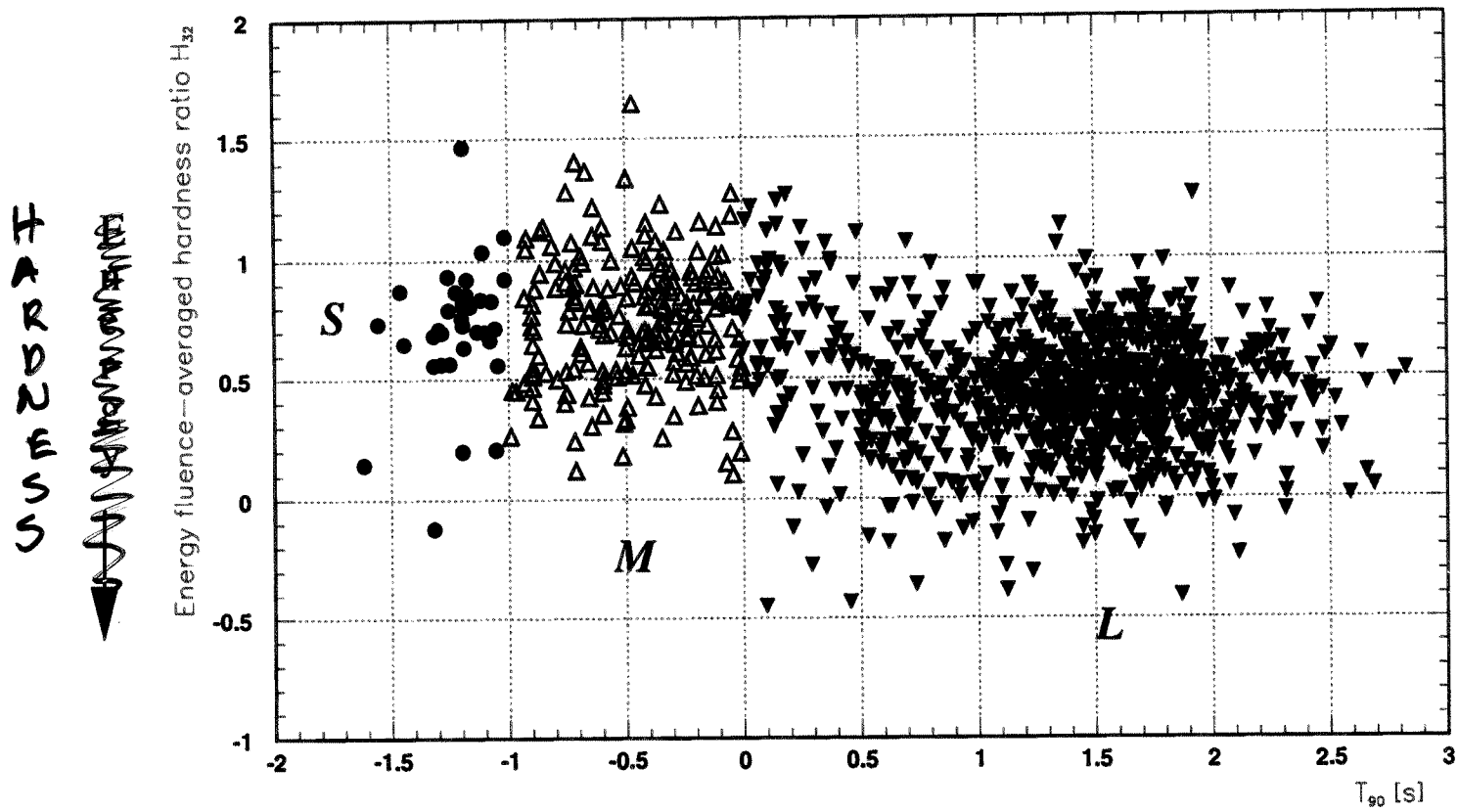
Gamma–ray Bursts (GRBs)

At least two classes or bursts:

* Counterparts detected only for long, energetic bursts

* Short bursts may be local!

Cline et al.
Tavani et al.



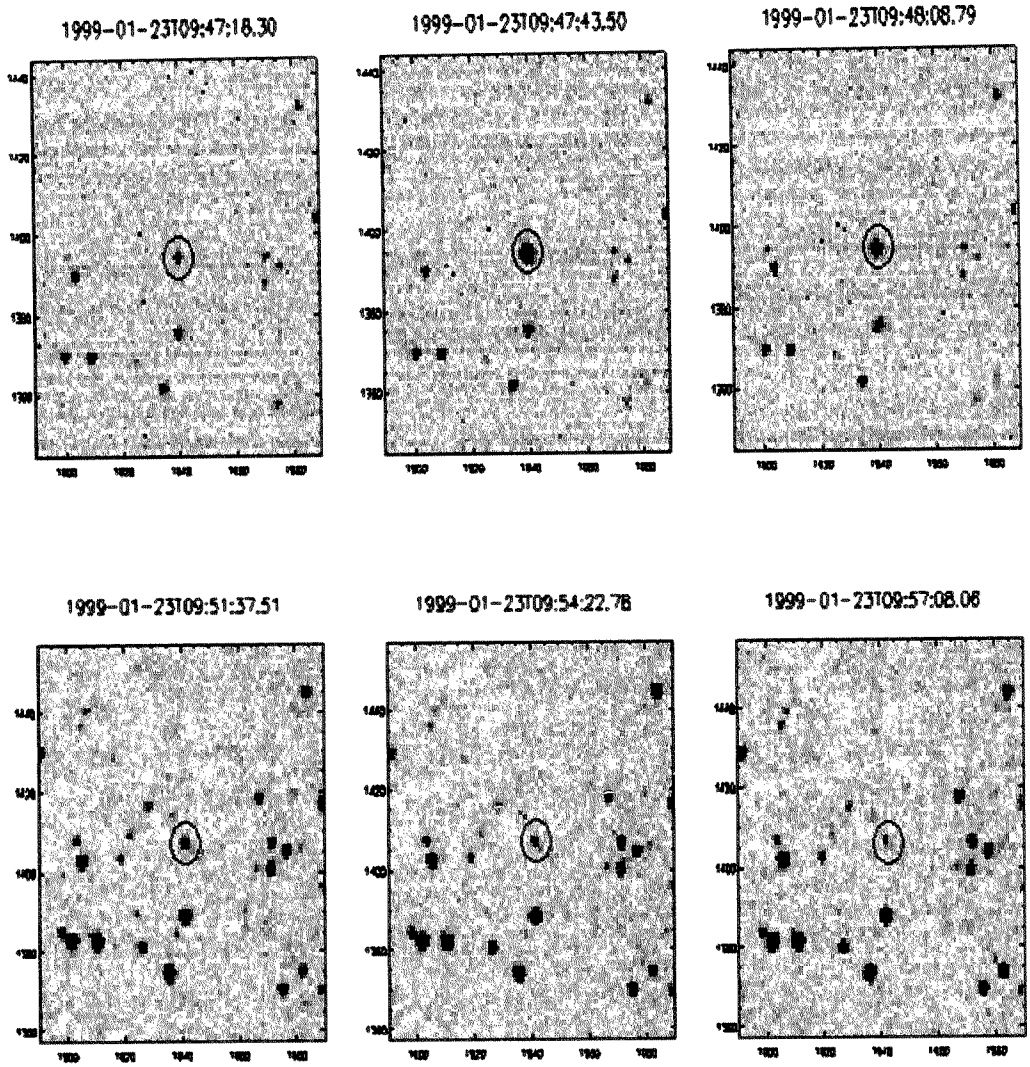
Time duration

GRB problem still not solved . . .

Gamma–ray Bursts (GRBs)

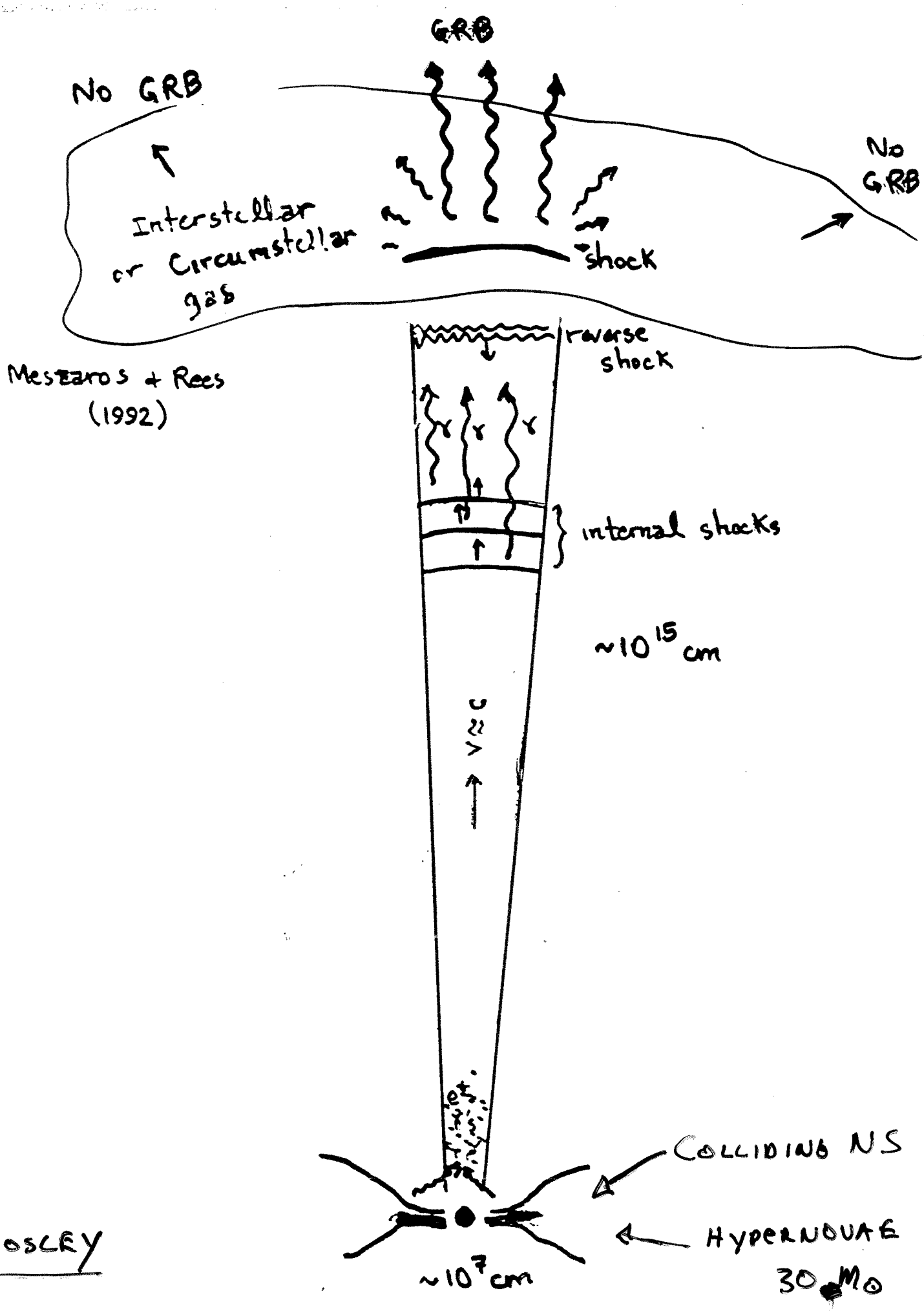
* Redshifts for ~ 20 afterglows now measured
  Cosmological distances

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!

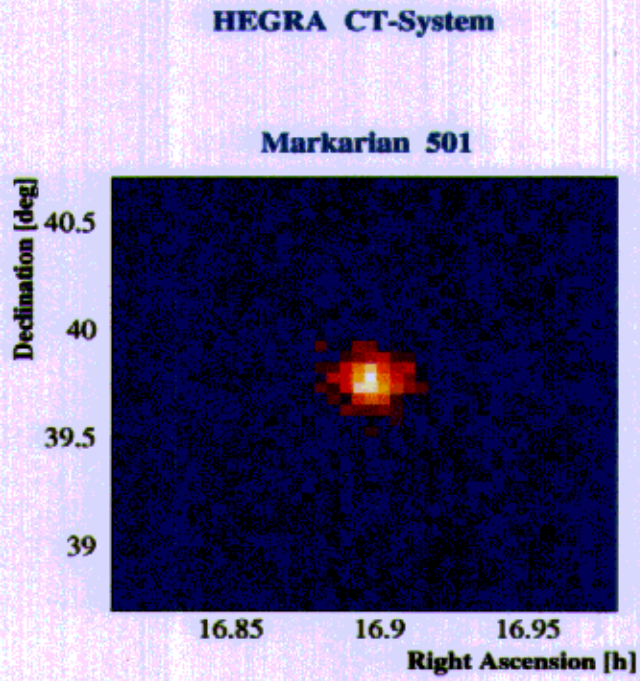


Meszaros + Rees (1992)

WOOSLEY

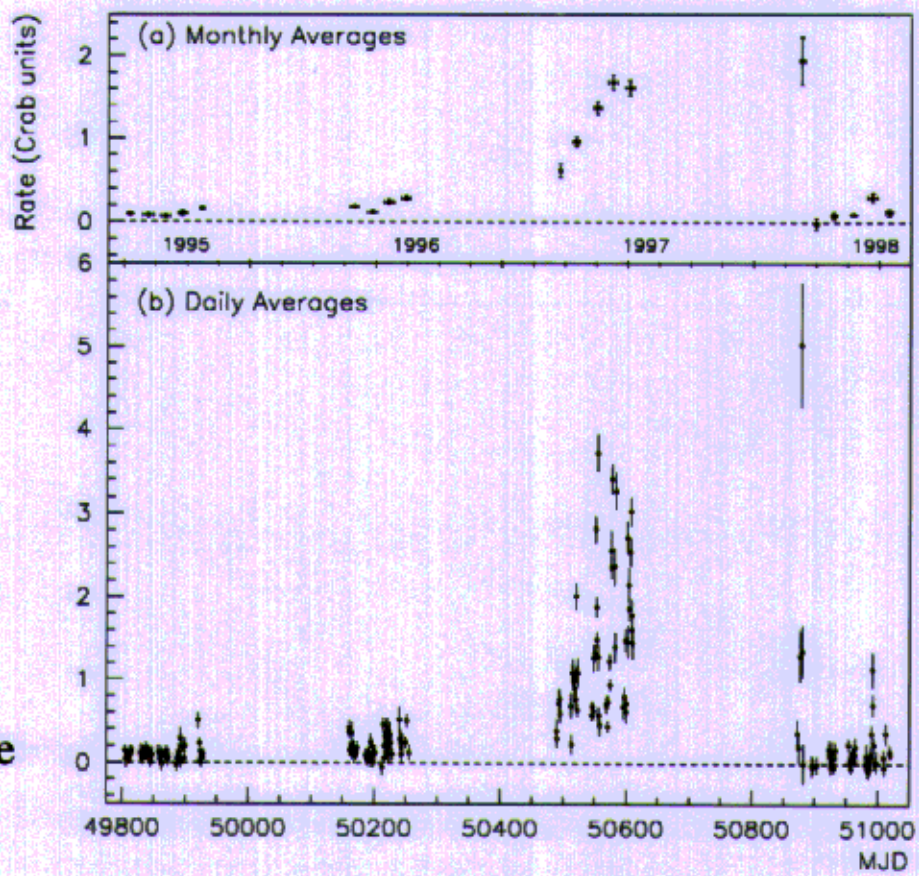
TeV γ–rays from Extragalactic Sources

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



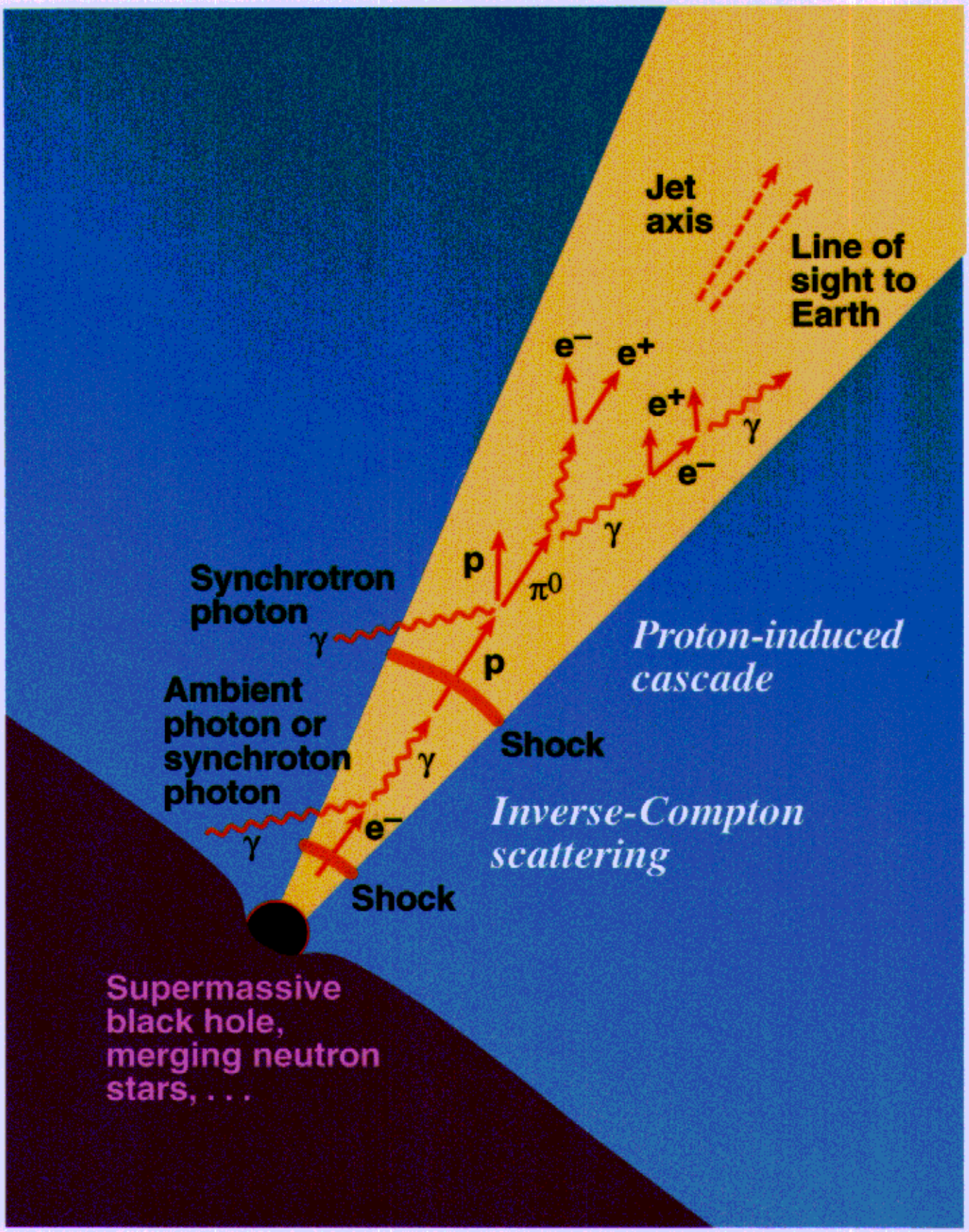
Hegra

Tremendous variability:



Whipple

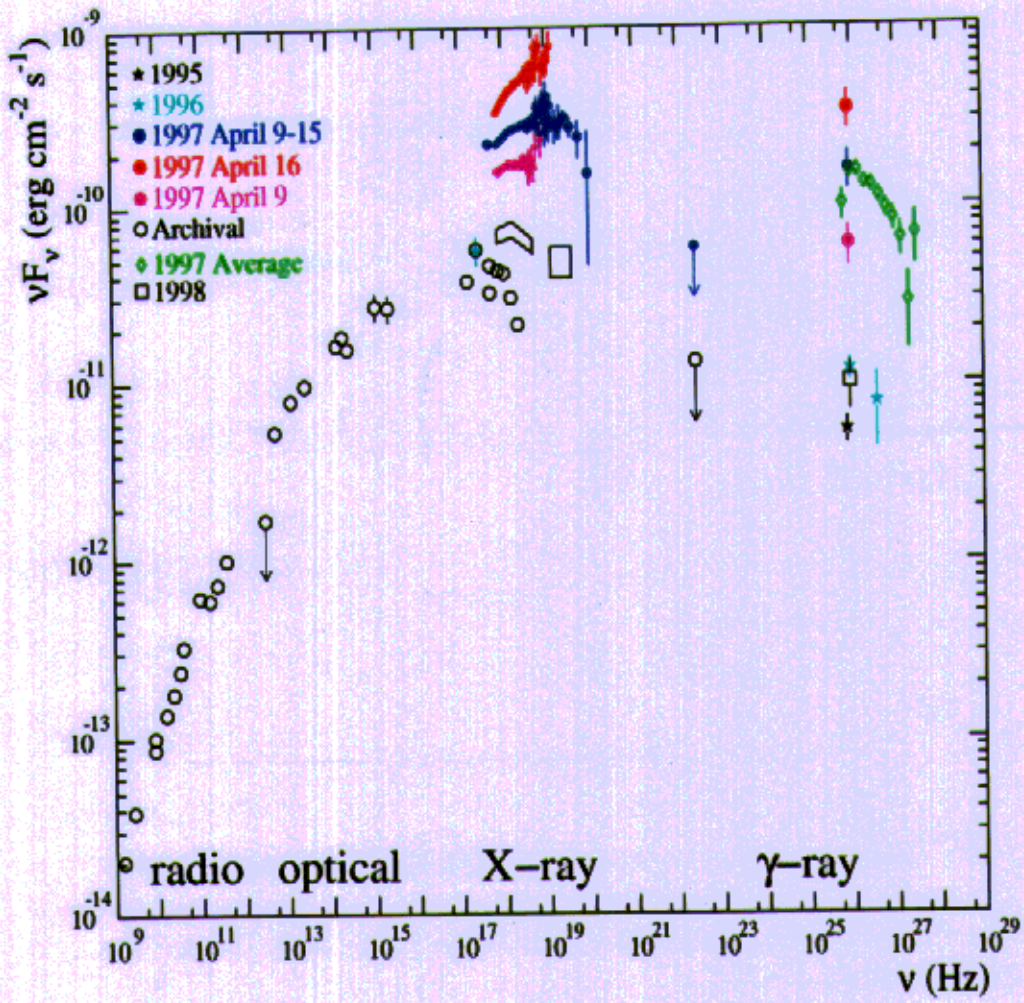
Model of AGN



F. Halzen

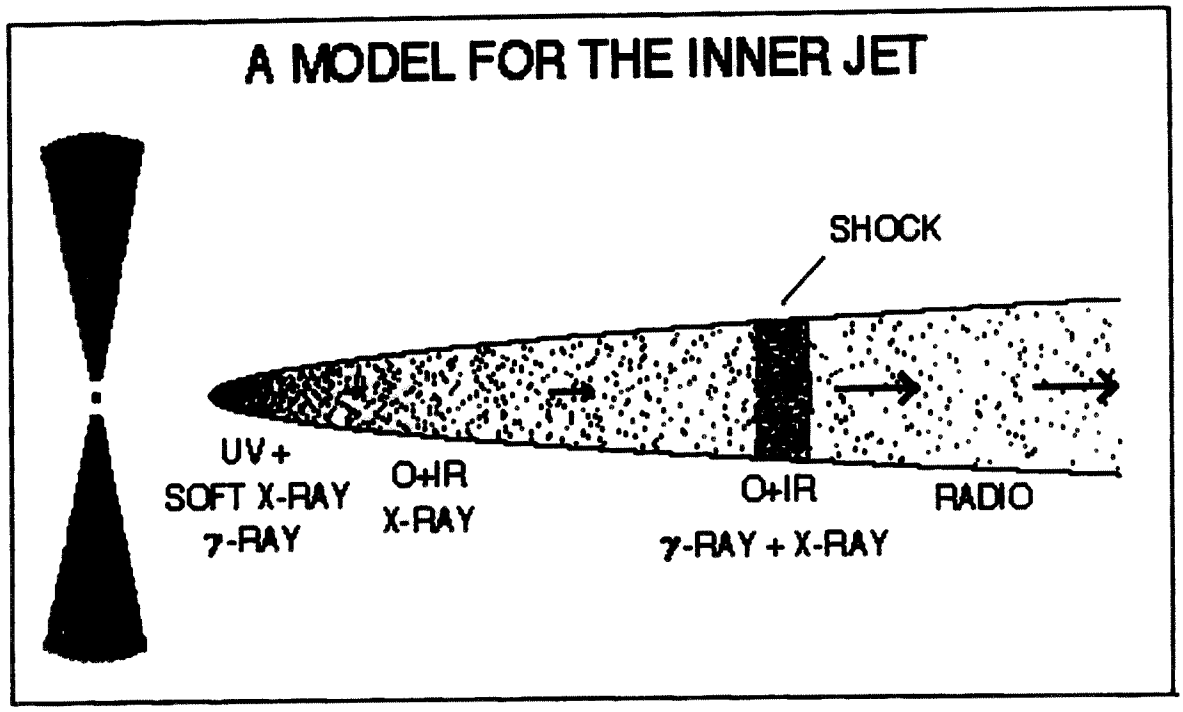
TeV γ–rays from Extragalactic Sources

Mrk 501 power spectrum:



* X–ray and γ–ray emission dominate power output

* Detailed measurements –>
  testing astrophysical models



A. Marscher

Many Questions:

Nature of beam particles

Acceleration process

Magnetic fields

Seed photons

Emission zone(s)

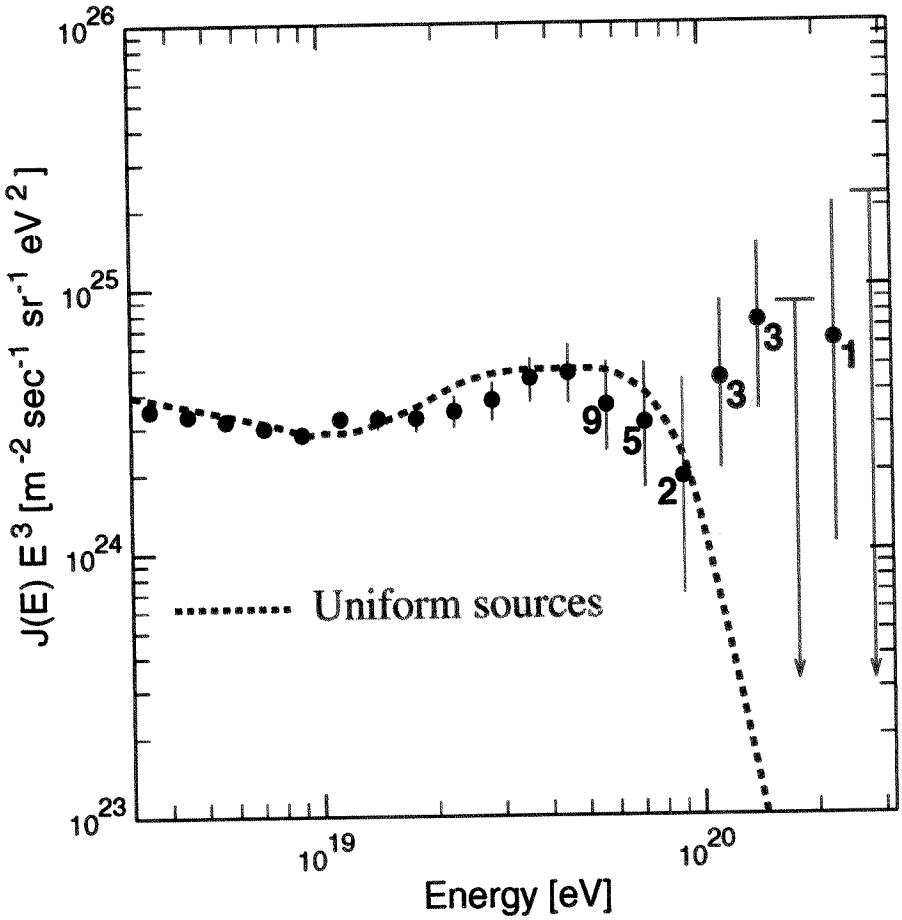
Variability

Beaming

.
.
.

Highest Energy Cosmic Rays

Latest spectrum from AGASA experiment:

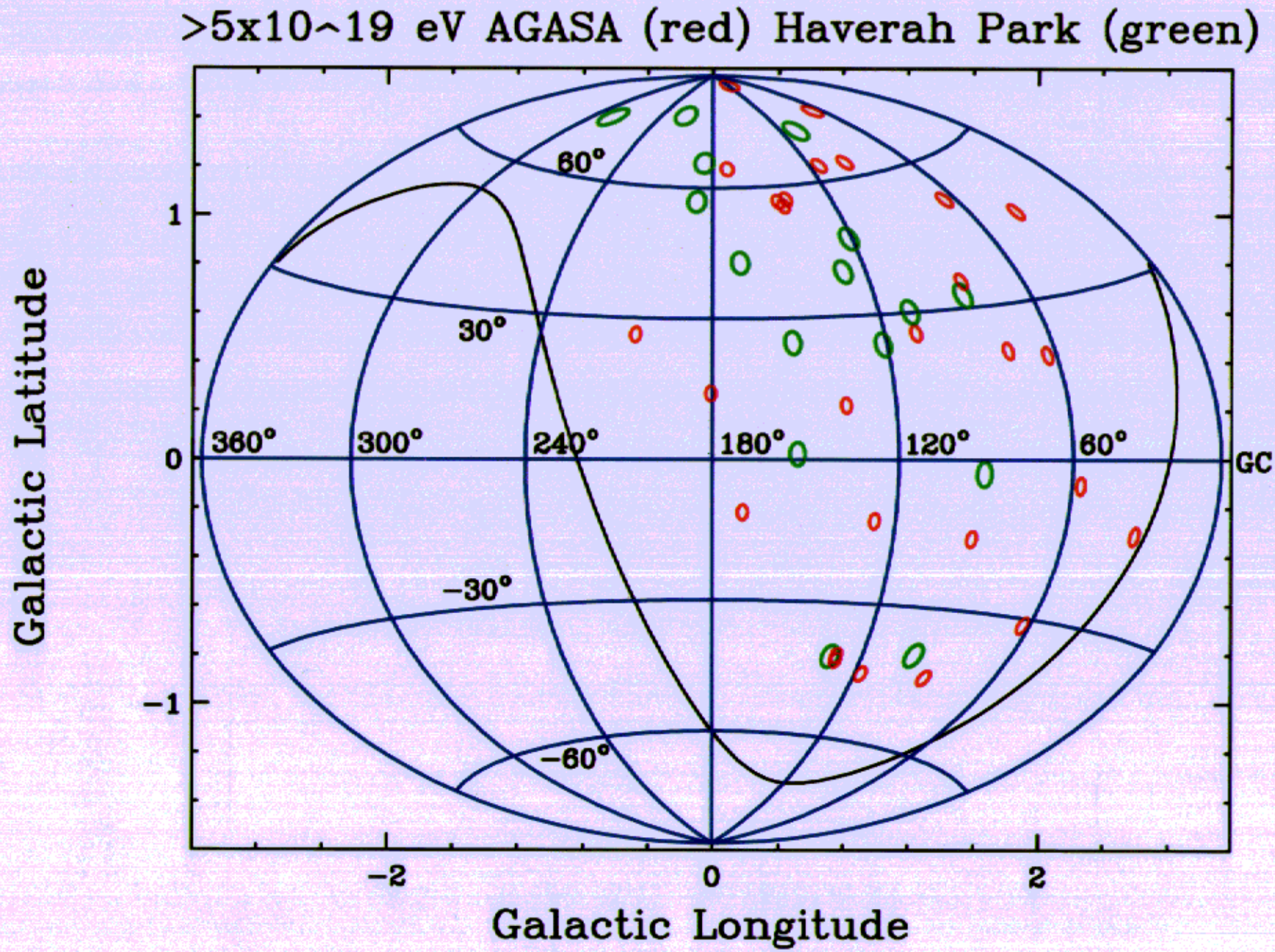


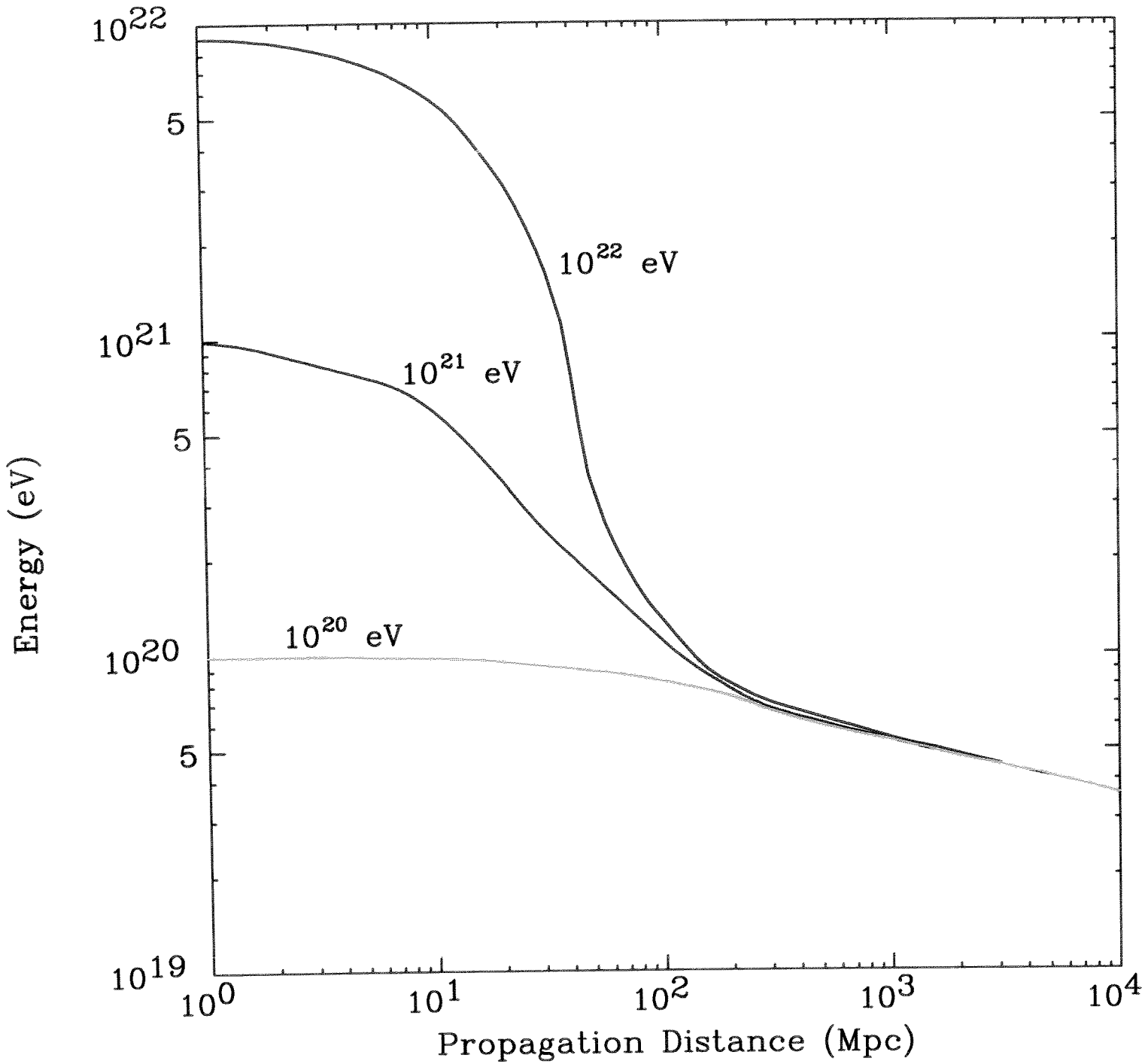
* 7 events above 10^{20} eV
  more events from FE I and HiRes

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

* Sources must be local, but <u>no</u> obvious choices

? ? ?


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

* All above objects have been detected at HE

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
	$\pi^o \rightarrow \gamma\,\gamma$	
	$\pi^+ \rightarrow \nu$	

   * CRs can interact

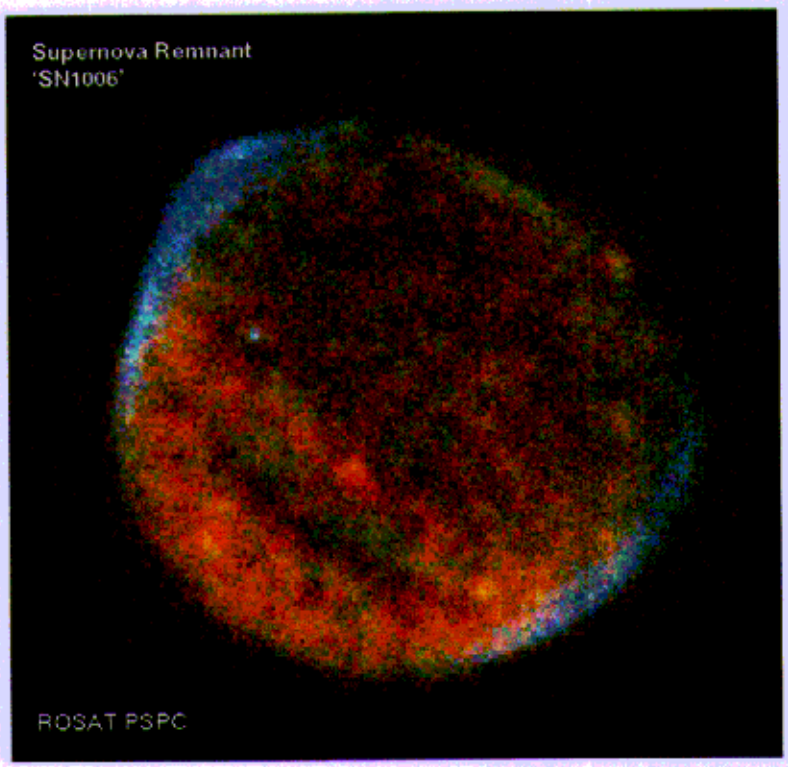
   * γ's can be absorbed

Extreme Astrophysics

Lick

Neutron star power:

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



ROSAT

Supernova Remnant:

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

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

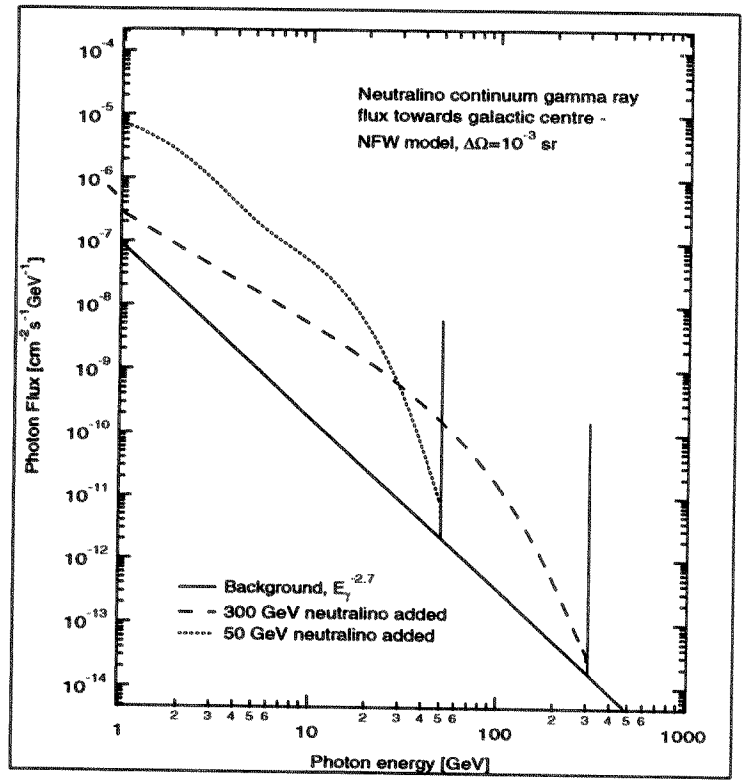
4. Supersymmetry

* LSP = galactic halo dark matter

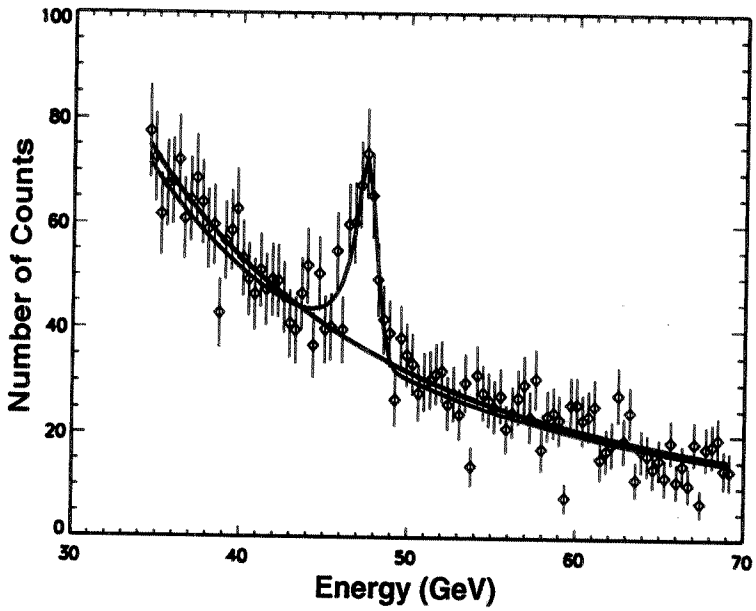
Neutralino annihilation in GC, Sun, Earth

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

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 <u>ground–based</u> instruments

Basic technique:

sampling calorimeter
measures particle's energy and direction

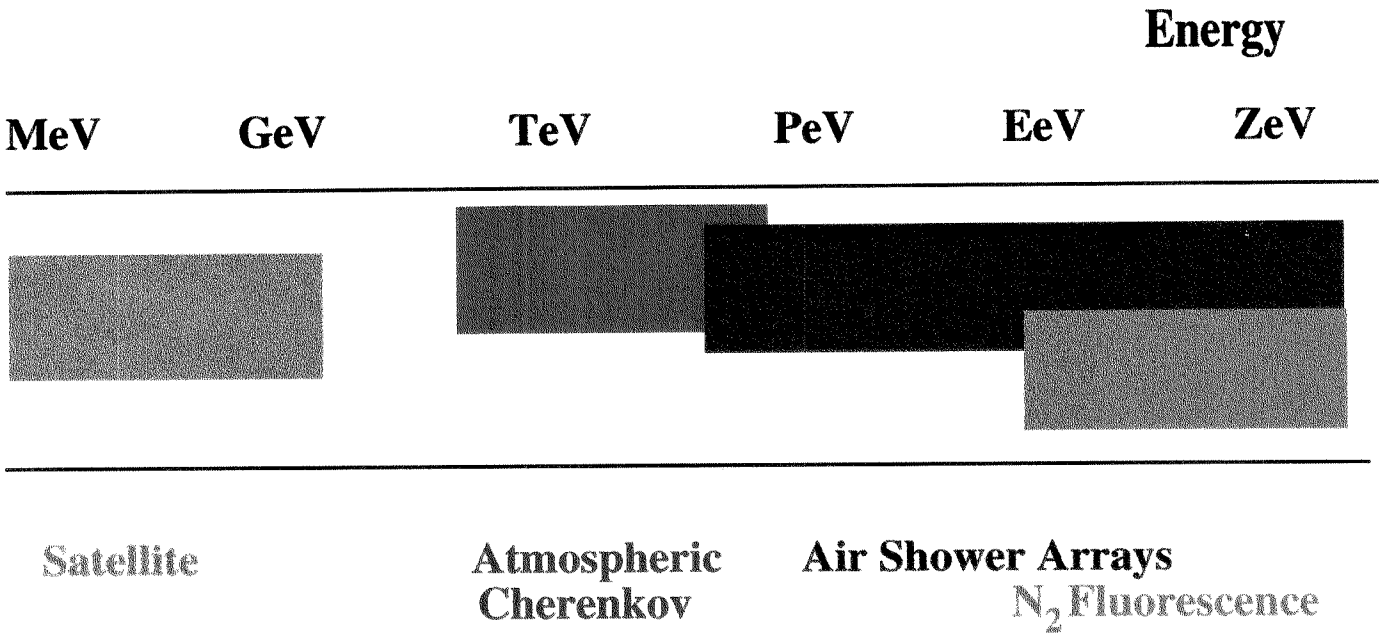
* calorimeter:
  Earth's atmosphere (γ, CR, ν)
  Earth's volume (ν)

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

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

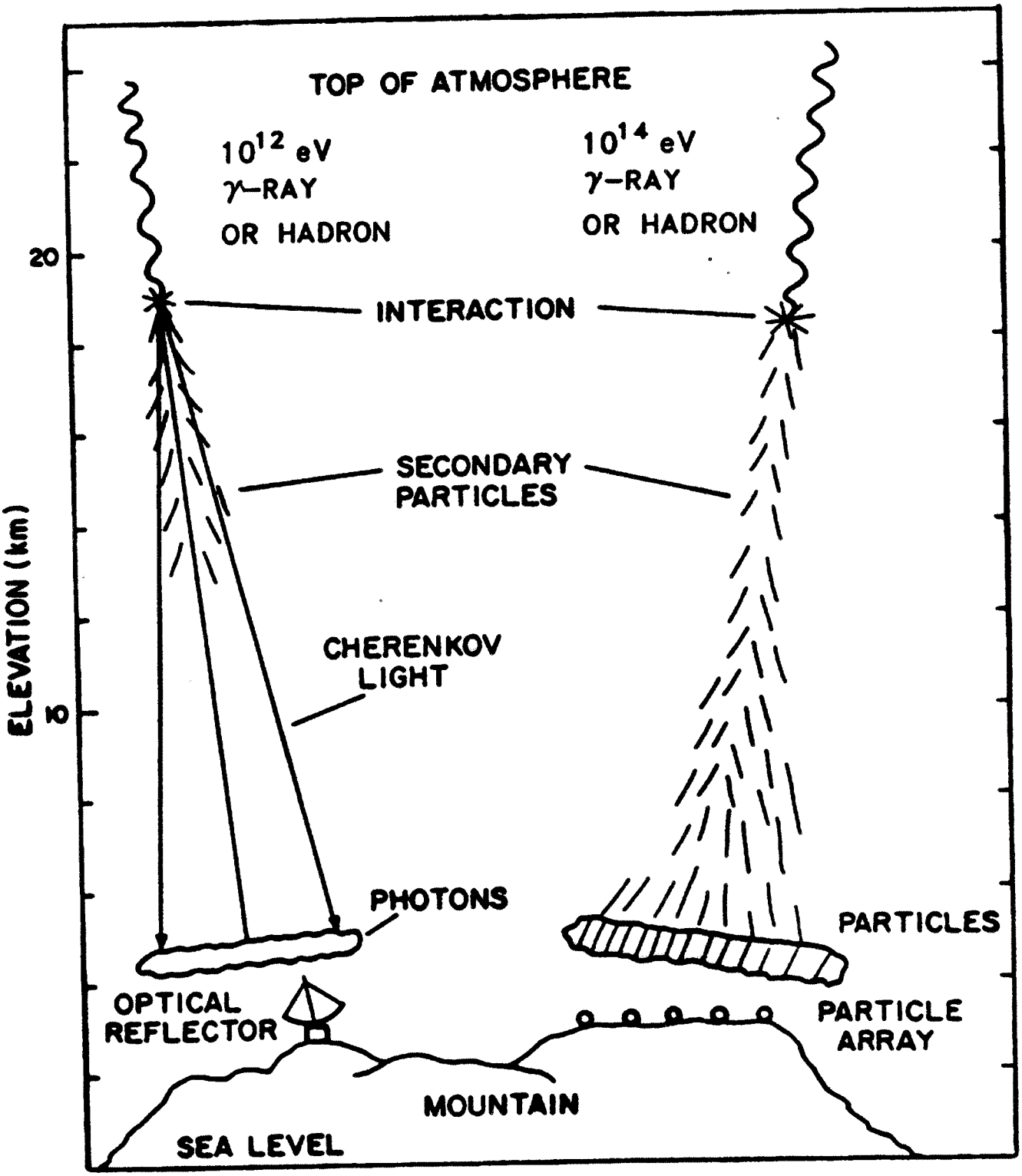
γ–ray and Cosmic ray Detection

* Wide energy range requires several techniques



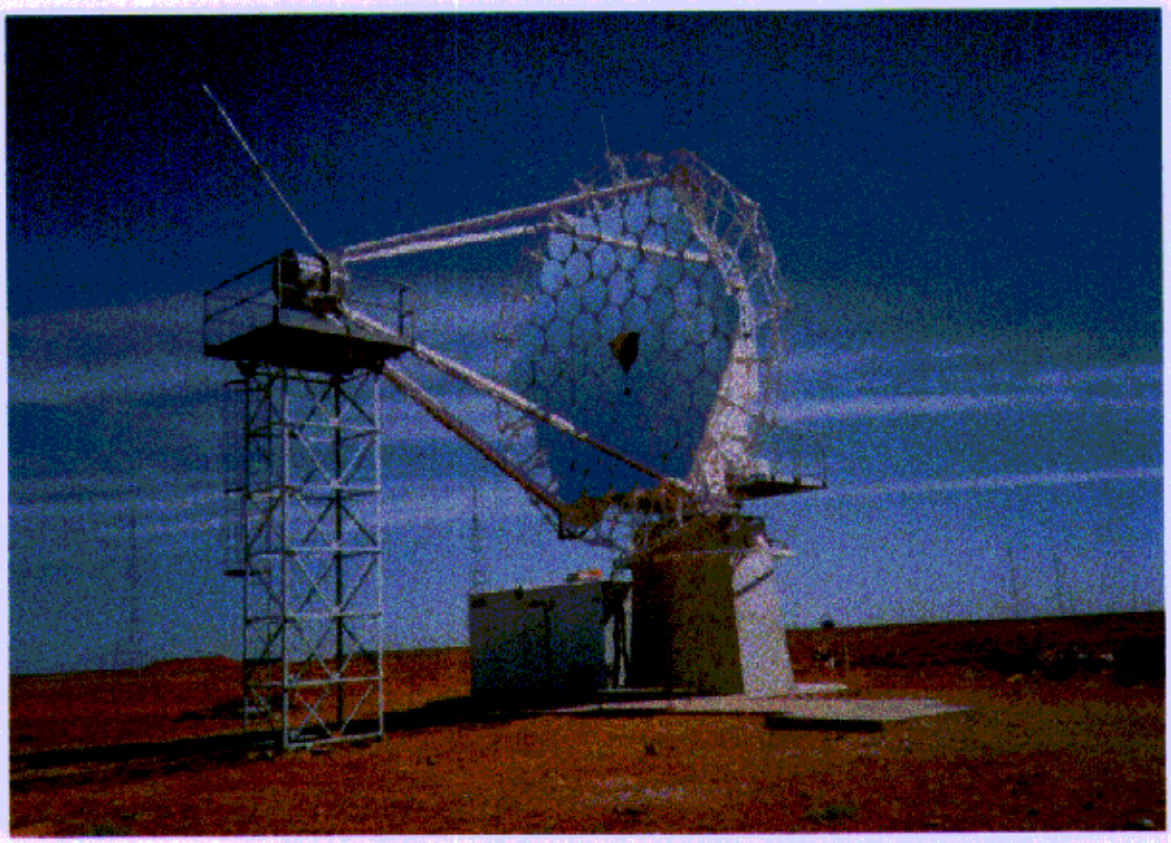
← γ–rays CRs →

γ–ray and CR techniques:

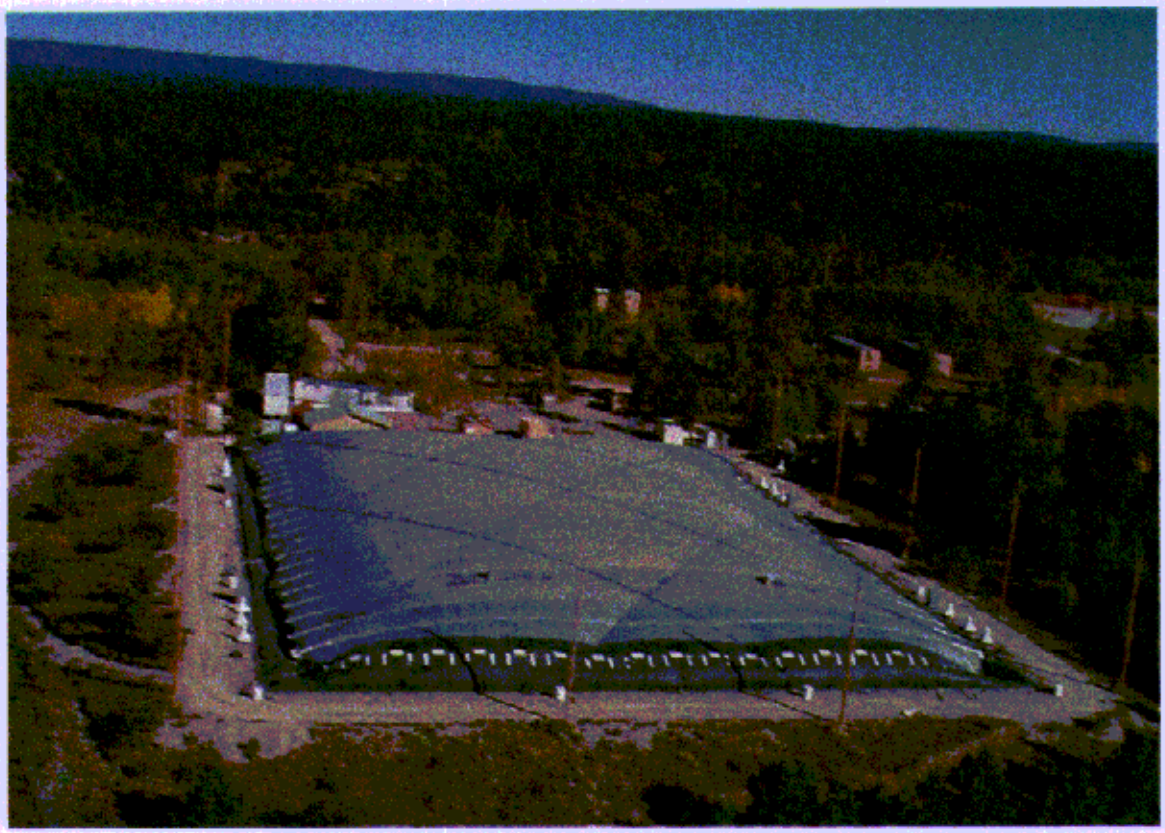


Cherenkov telescopes Air shower experiments

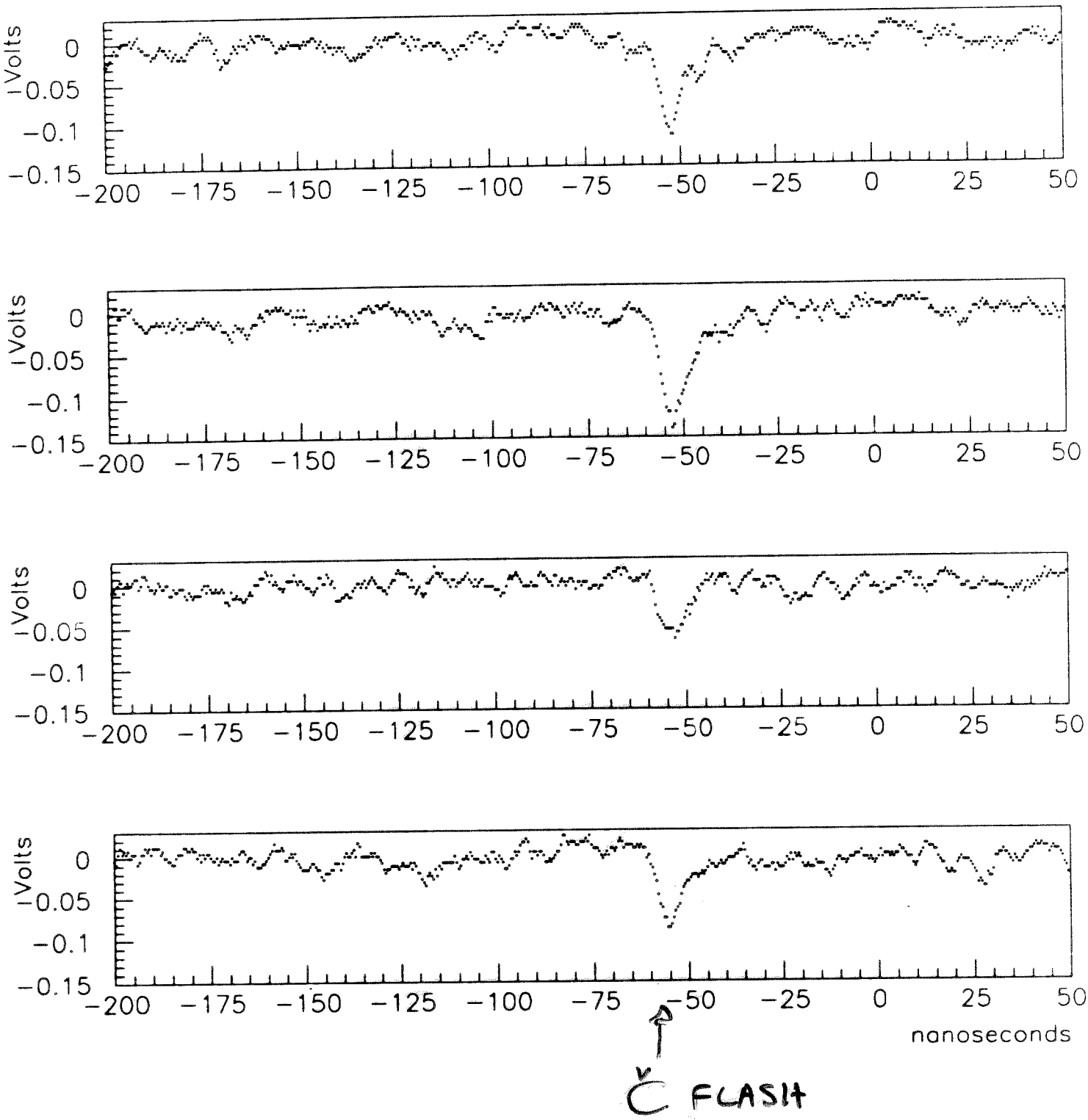
Cherenkov telescope: CANGAROO II



Air shower experiment: MILAGRO

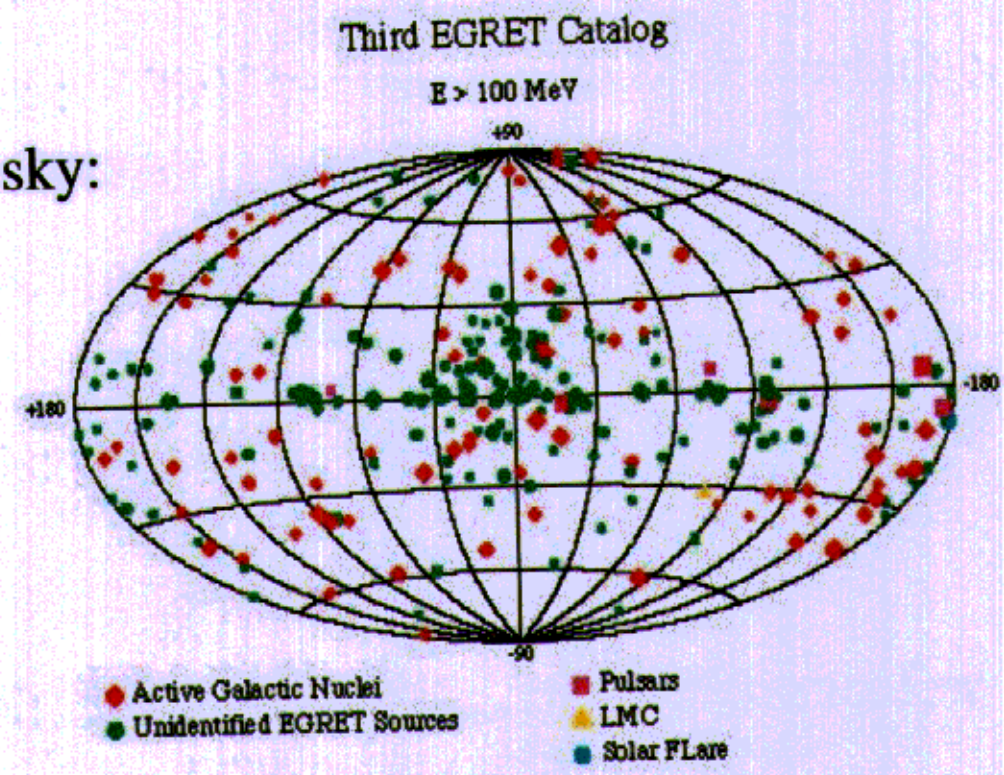


Digitized Cherenkov Pulses

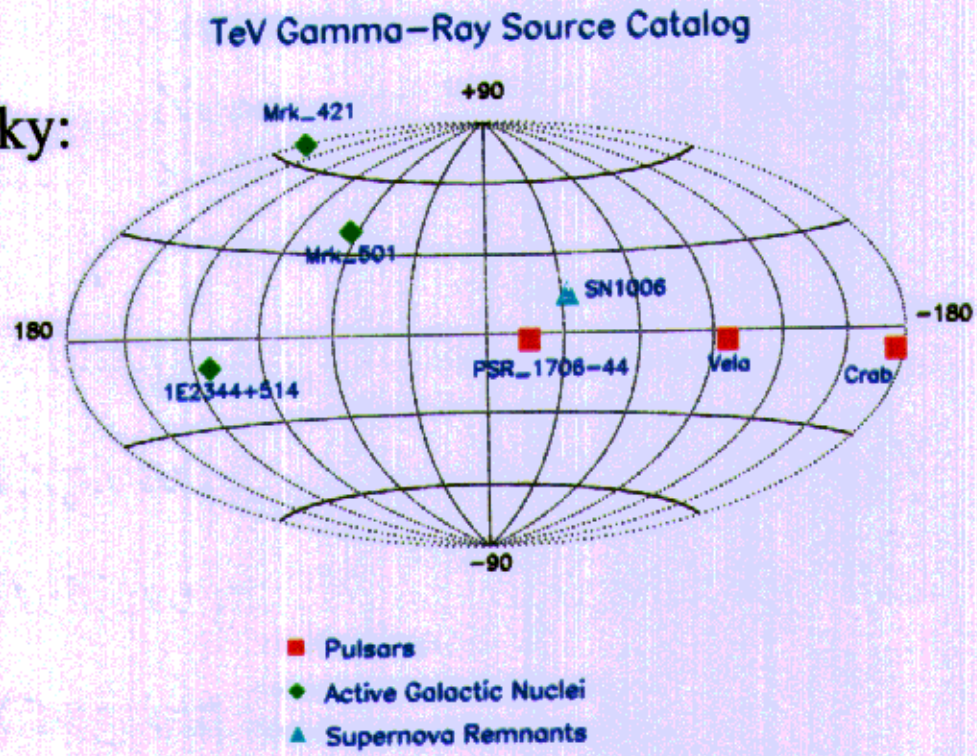


γ–RAY ASTROPHYSICS

GeV γ–ray sky:



TeV γ–ray sky:



γ–ray Astrophysics

Selected topics:

* Pulsars: TeV γ–rays detected from nebulae.
  No emission from pulsars?

* SNRs: Detected SN1006 – e acceleration.
  Origin of cosmic rays?

* GRBs: Some bursts are cosmological.
  What about others?
  What about HE component?

* AGN: 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:

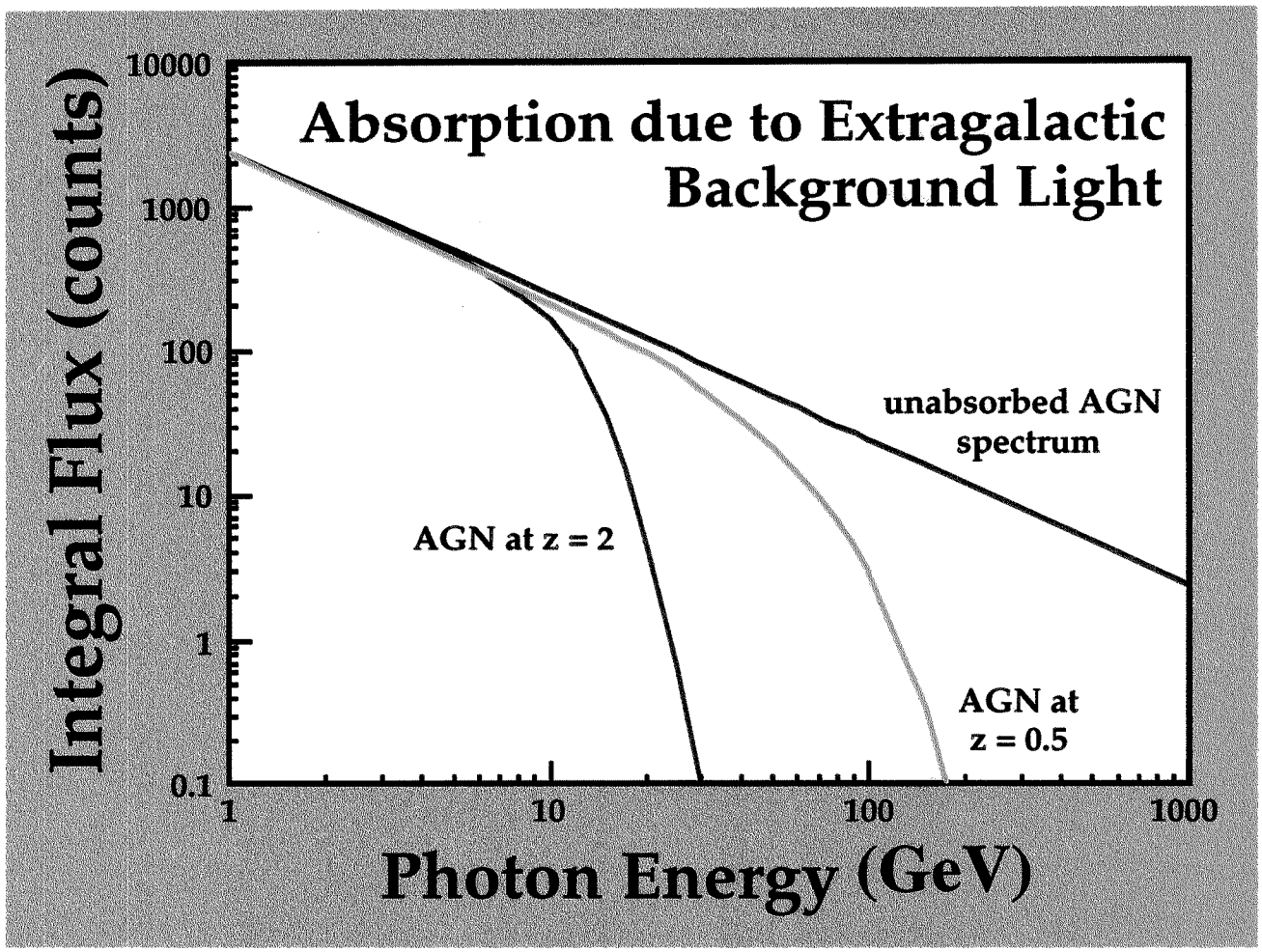
1. Explore region between 20 – 250 GeV
2. Achieve much greater sensitivity
3. Carry out all–sky surveys

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

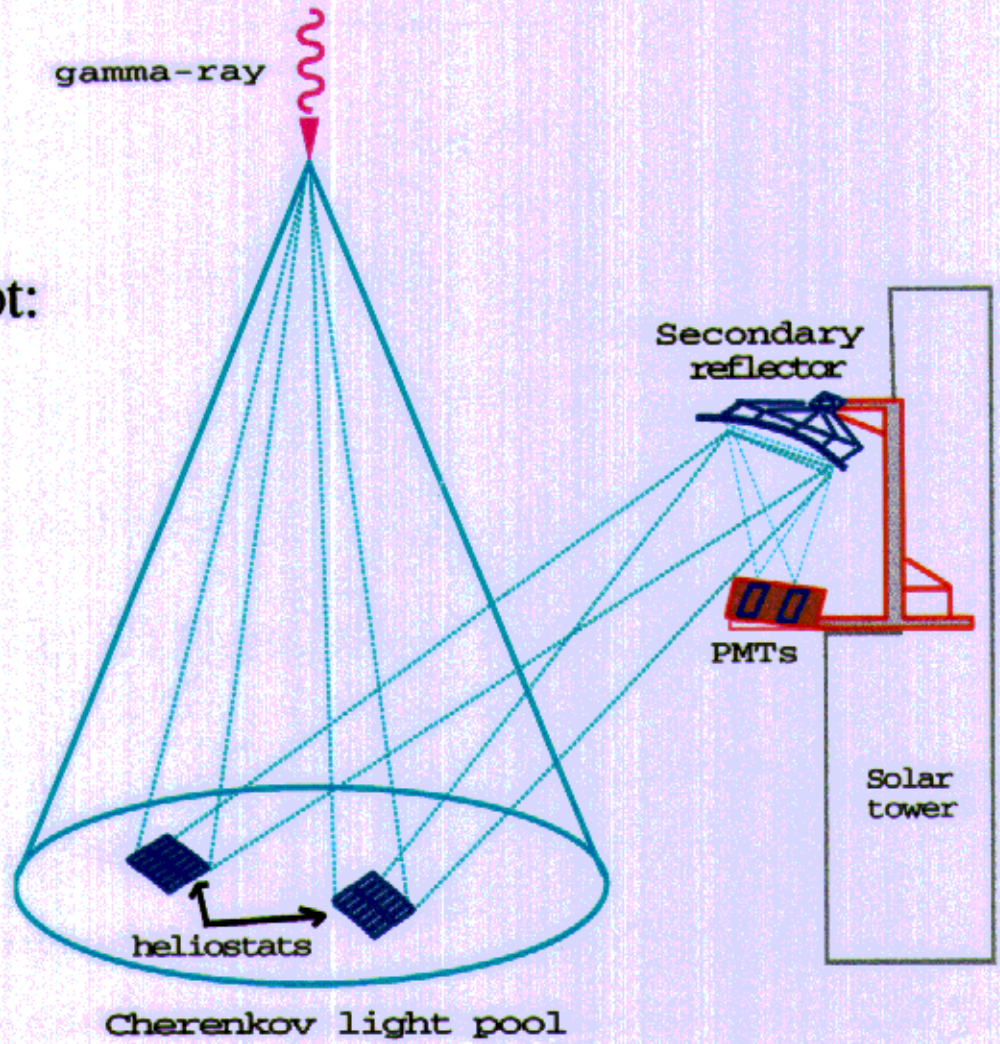
Two new experiments: STACEE, CELESTE

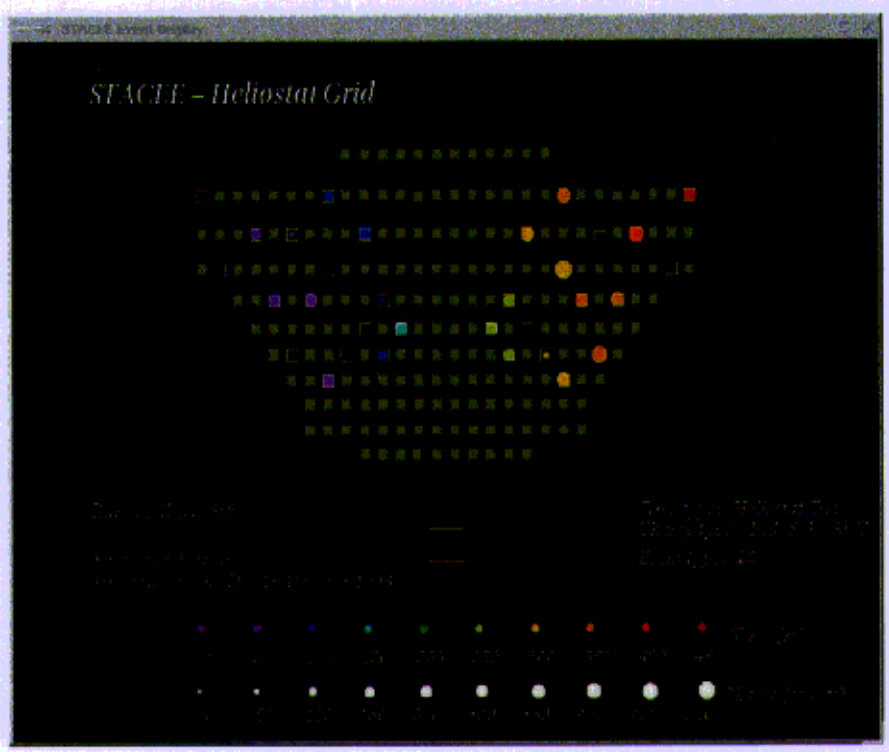
* Use solar mirror arrays to make very large Cherenkov detector
  –> low energy threshold

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

* 1999: both projects 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 started:

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

   Separated in latitude & longitude, with different emphasis. Operational in a few years.

2. New Satellite Experiment (GLAST)

   * Much greater sensitivity (factor of 30)

   * All–sky coverage

   * Uses state–of–the–art detectors/electronics pioneered by HEP

   * Collaboration of astrophysicists/particle phys.

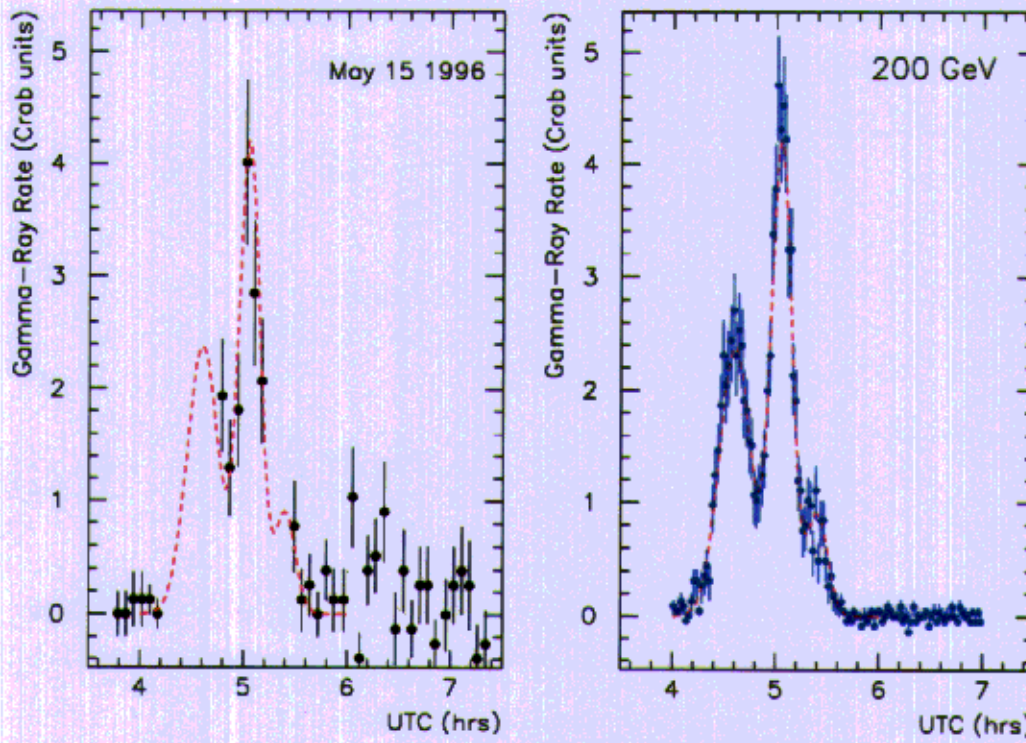
Launch > 2005

Cherenkov telescope array: example of VERITAS

Mt. Hopkins AZ

Response to AGN Flare:

Detailed structure resolved

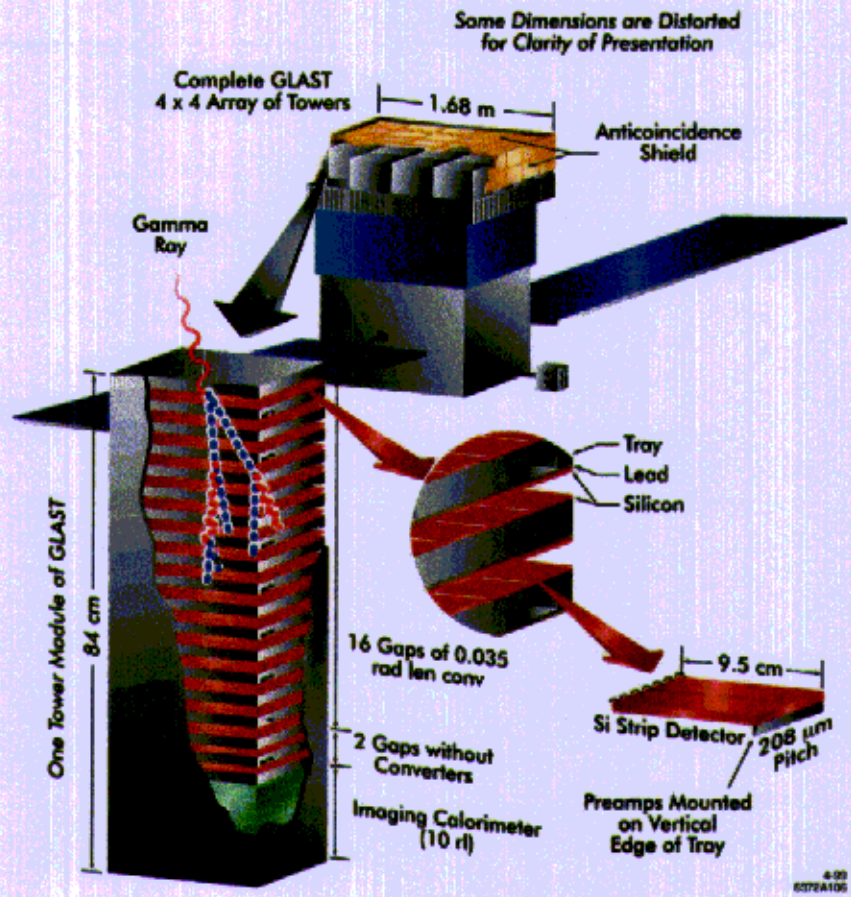


VERITAS

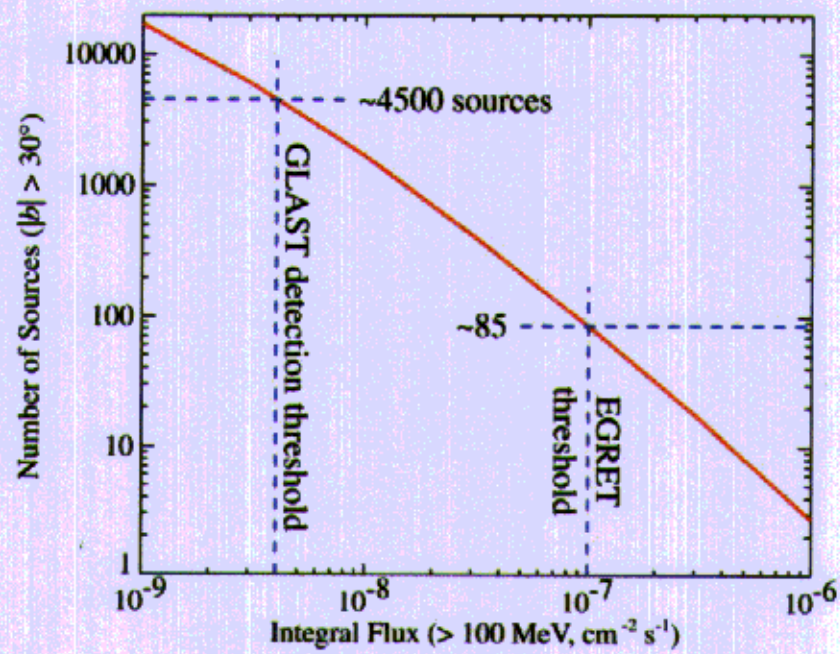
Gamma–ray Large Area Space Telescope (GLAST)

* Two possible technologies: Silicon, SciFi

Si–GLAST Option:



Greatly enlarge AGN sample:



COSMIC RAY ASTROPHYSICS

What we know:

* <u>Spectrum</u> measured up to 10^{20} eV : knee & ankle

* <u>Composition</u> measured up to 10^{14} eV (direct)
  10^{18} eV (indirect)
  consistent with mixture of heavy nuclei

* <u>Anisotropy</u> no clear picture

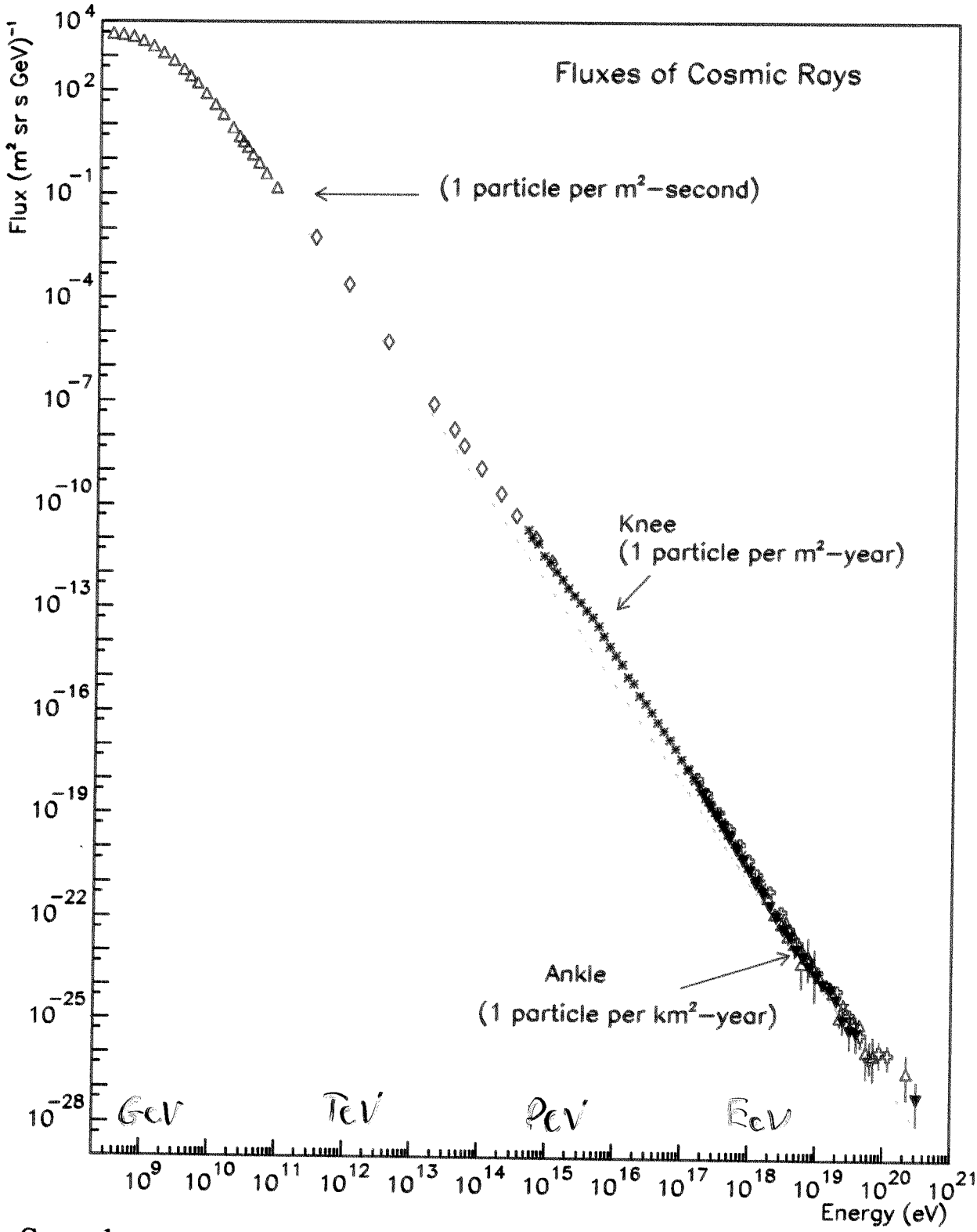
General picture:

$< 10^{15}$ 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?

Cosmic ray fluxes at Earth



S. Swordy

Highest Energy Cosmic Rays

Basic problem is one of statistics:

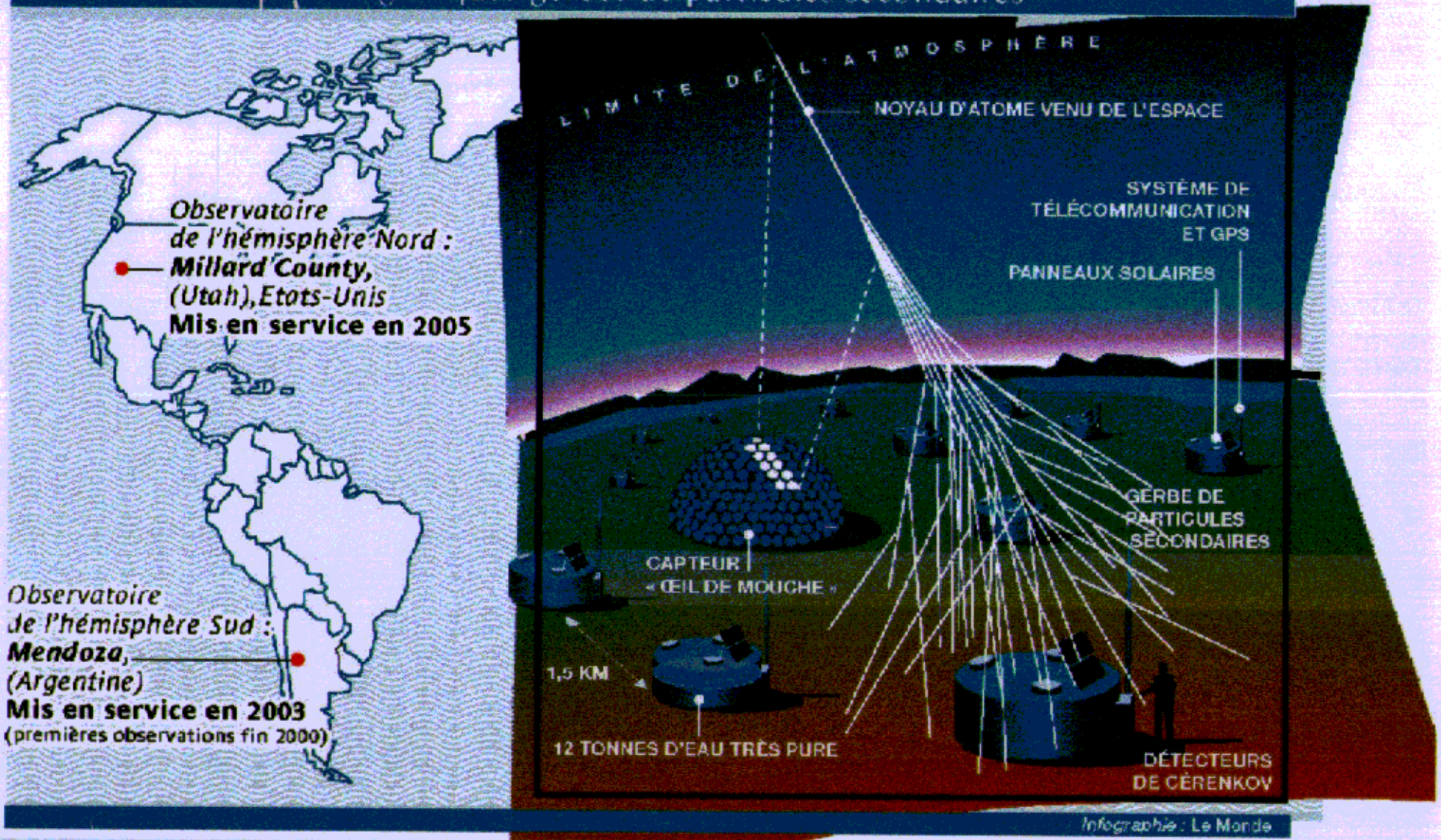
* Need largest aperture (km·sr) possible
* Measure particle energy, direction, composition as best as possible

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	~ 100 / year
Tel. Array	Utah ?	Proposed	~ 100 / year
OWL	Space	Proposed	> 1000 / year

We need to wait a few years . . .

De magnifiques gerbes de particules secondaires

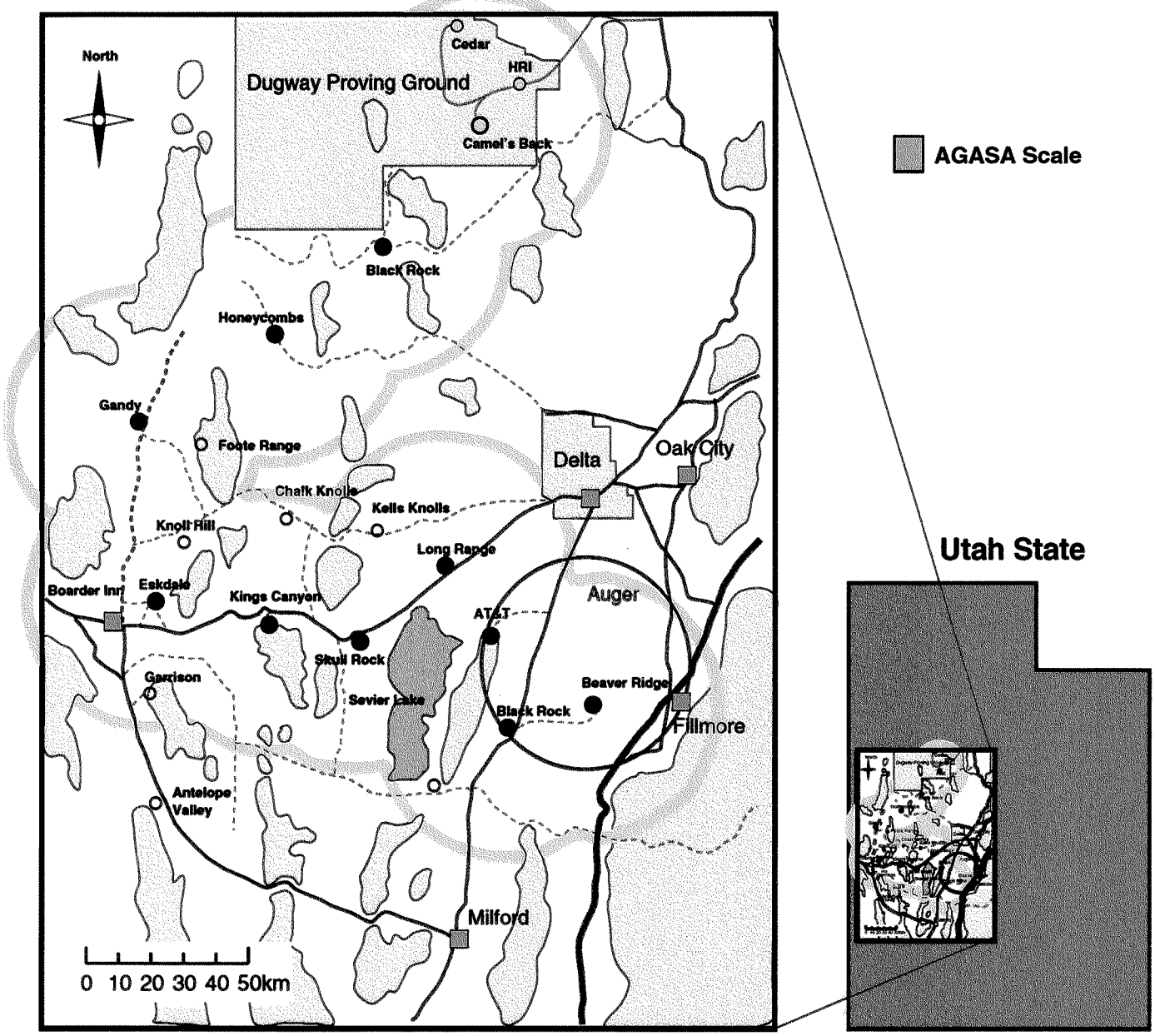


Infographie : Le Monde

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

Telescope Array Station arrangement, Utah USA

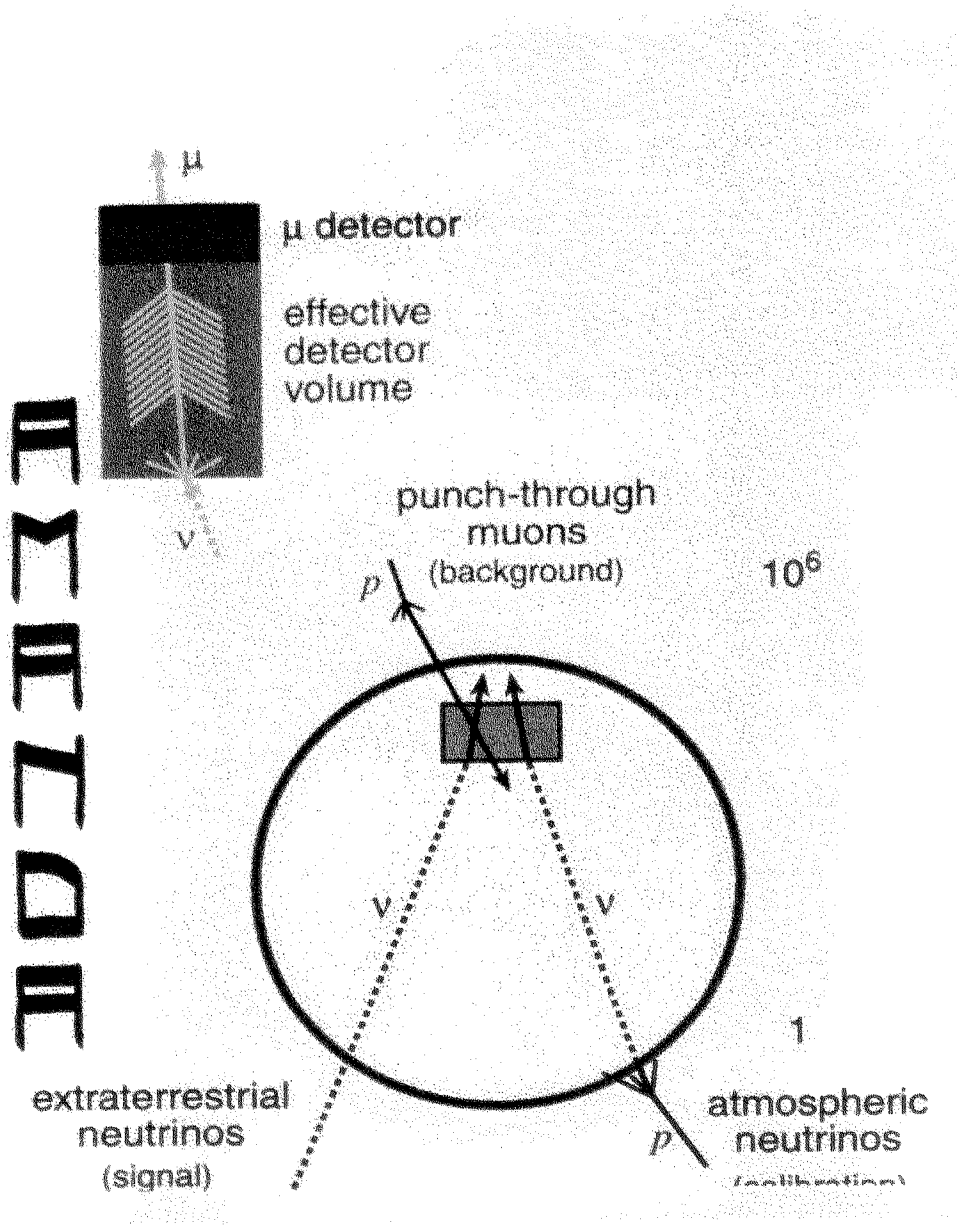


ν–ASTROPHYSICS

* Sources are 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

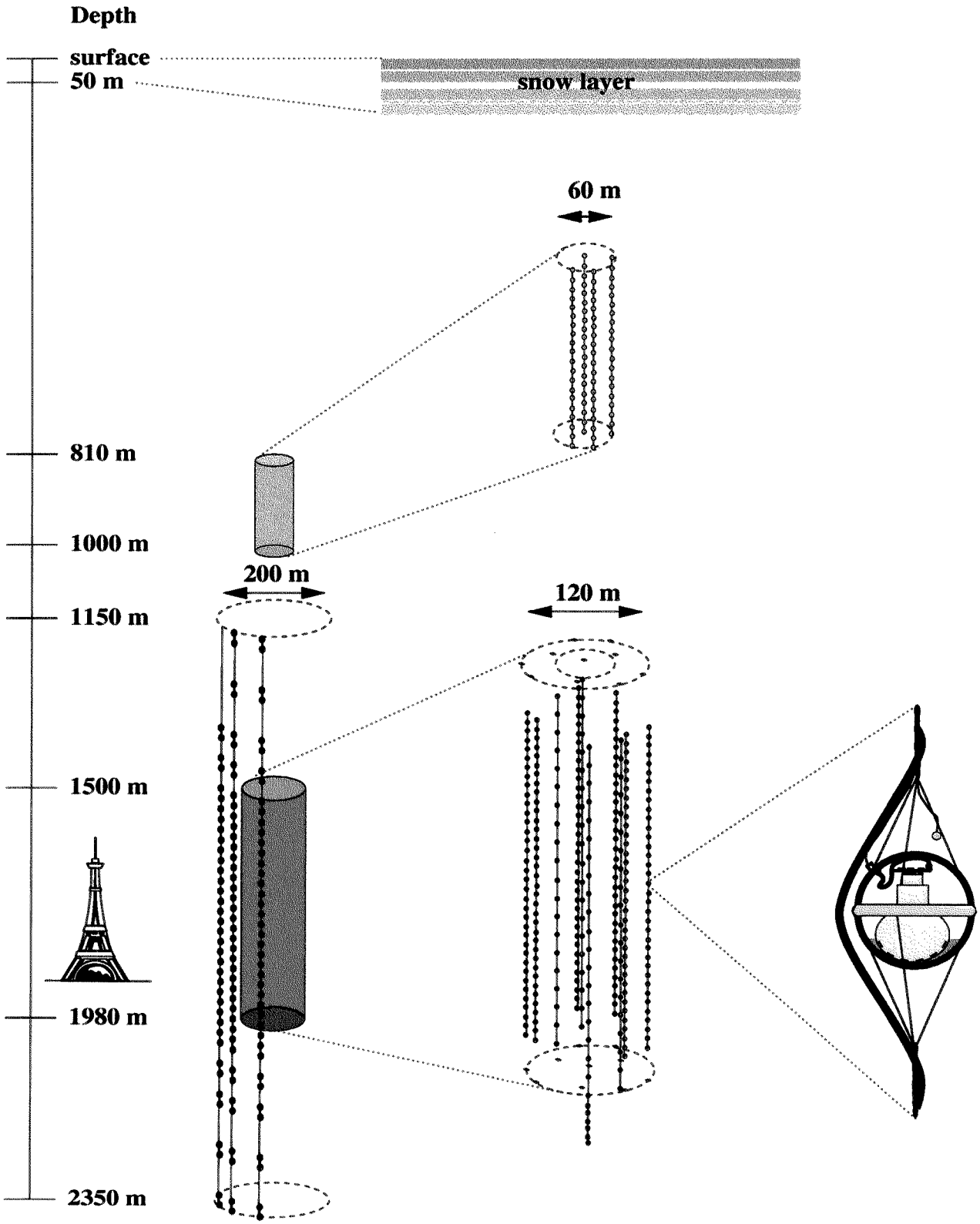
Incomplete List:

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

AMANDA is on scale ~ 0.05 km^2
ANTARES is on scale ~ 0.10 km^2
ICECUBE is on scale ~ 1.0 km^2

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

AMANDA Layout



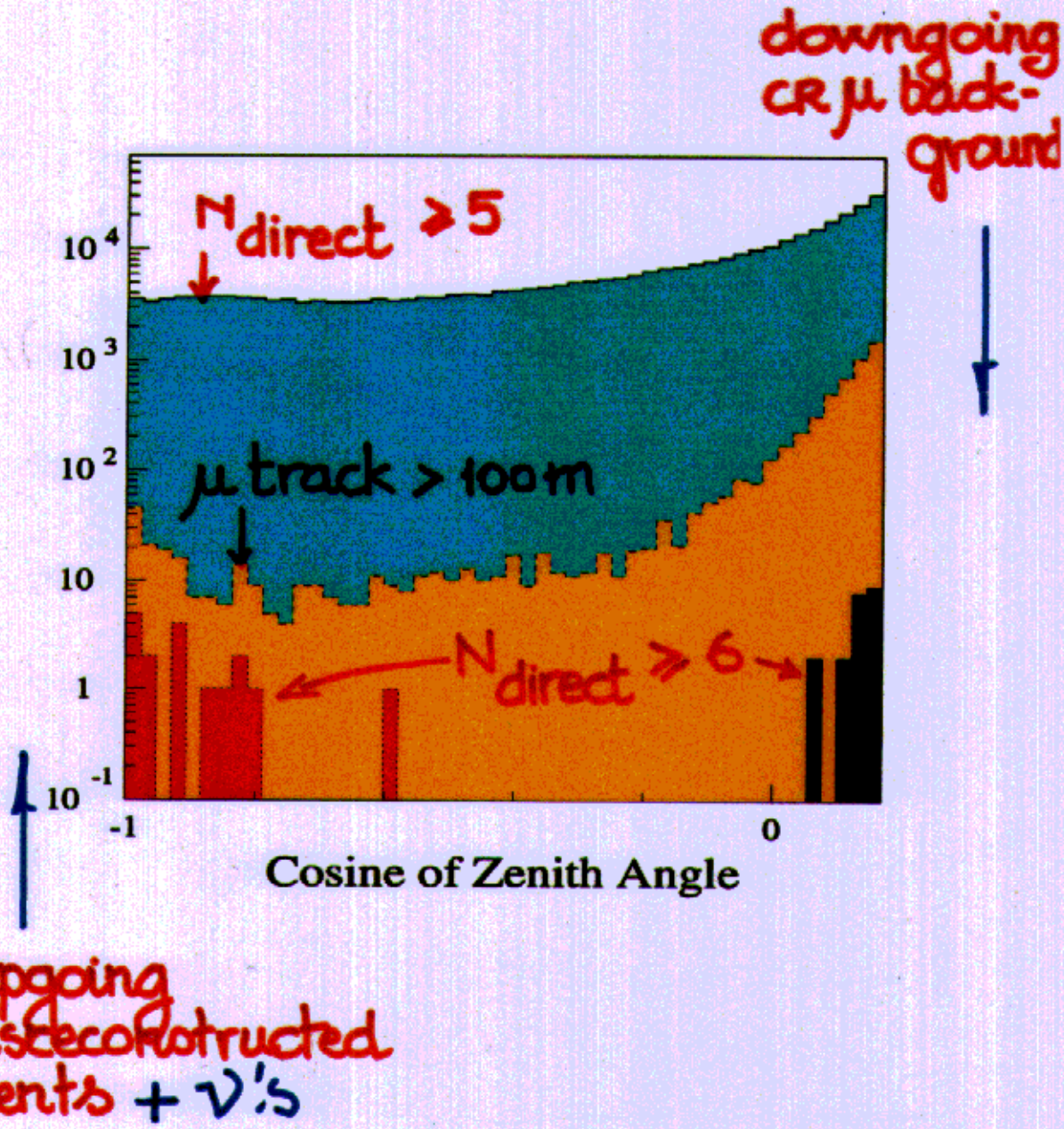
AMANDA as of 1998
Eiffel Tower as comparison
(true scaling)

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

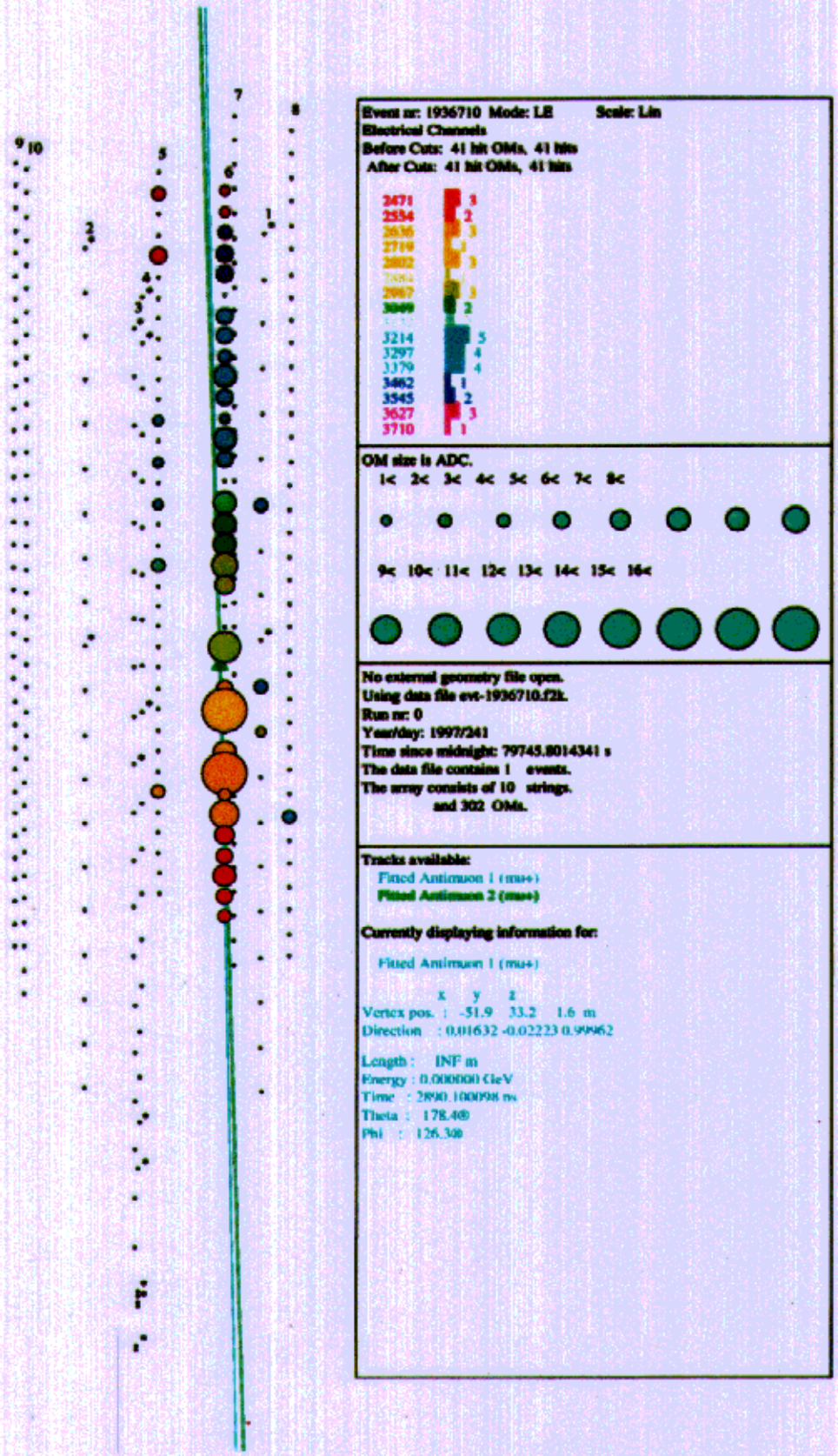
zoomed in on one
optical module (OM)

AMANDA Reconstruction

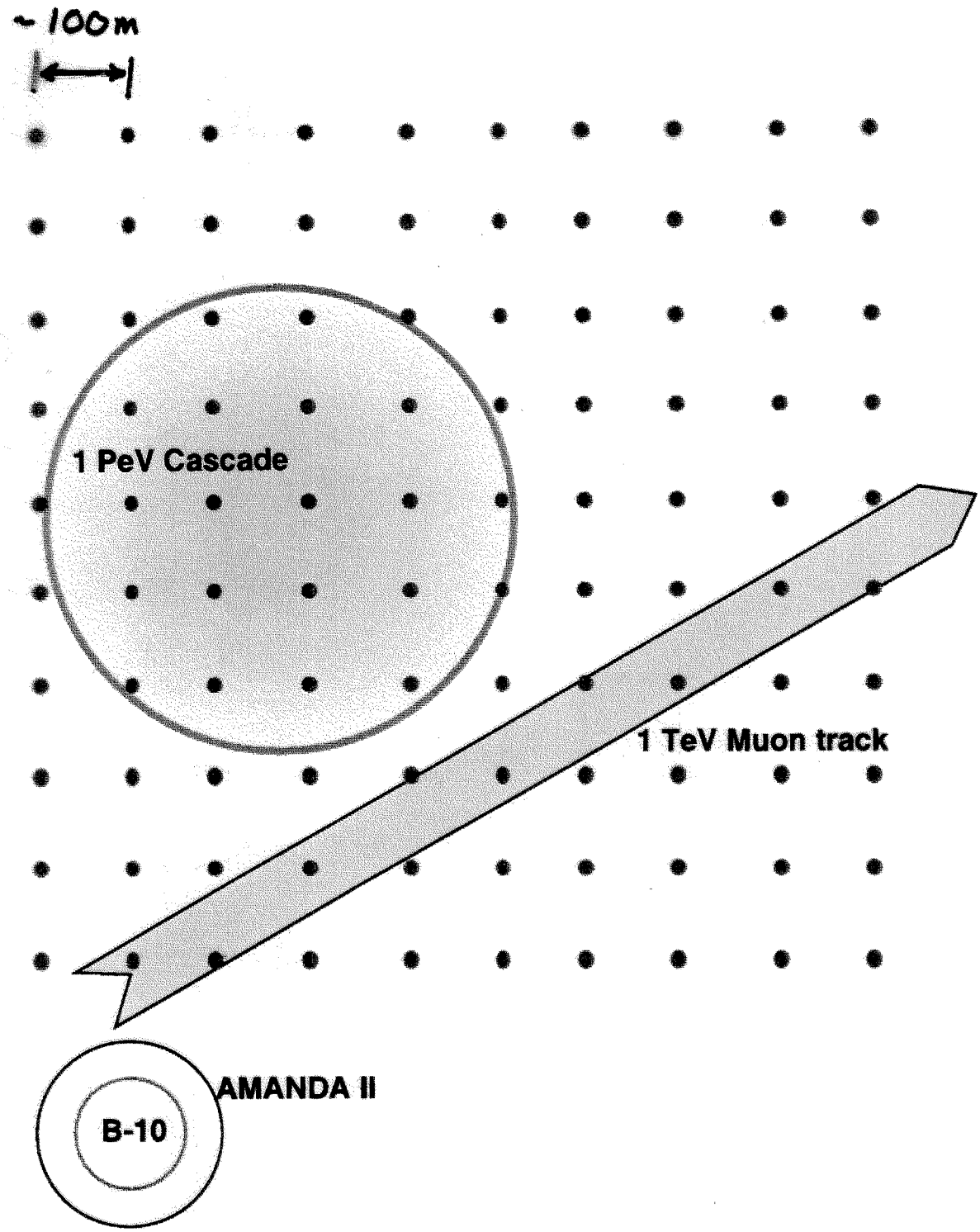
* Zenith distribution shows clean sample of upward going muons = atmospheric ν's



AMANDA Event (atmospheric ν)



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: V. large ground experiments

   ν's: Ice and water Cherenkov detectors

   * Hope: knowledge increases at similar pace !