Astroparticle Physics and Hadronic Multiparticle Dynamics

Particle Physics ⇄ High Energy Astrophysics

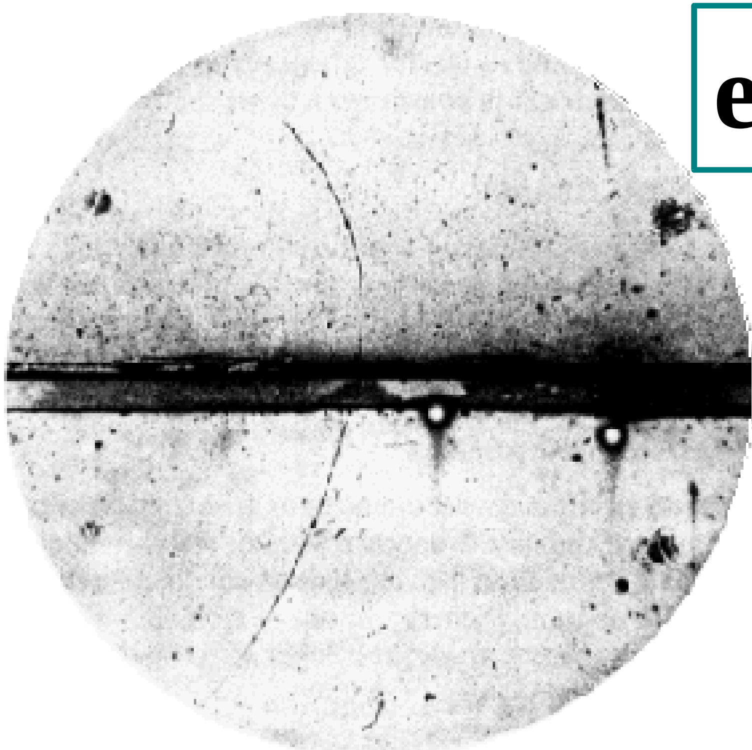
Paolo Lipari
ISMD
Krakow 6-11 september 2003

Victor Hess
before the balloon fligh of 1912

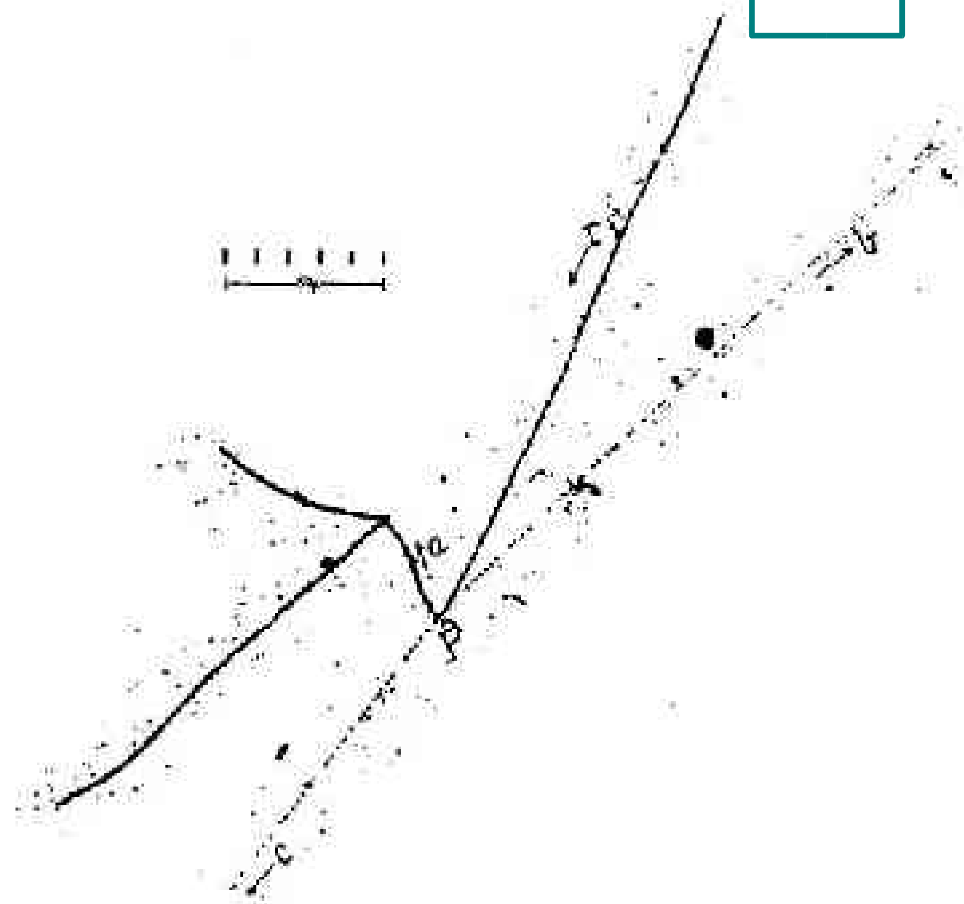
Discovery of Cosmic Rays
Beginning of
High Energy Astrophysics

Intense Connection
between the fields of
Cosmic Rays and
Particle Physics

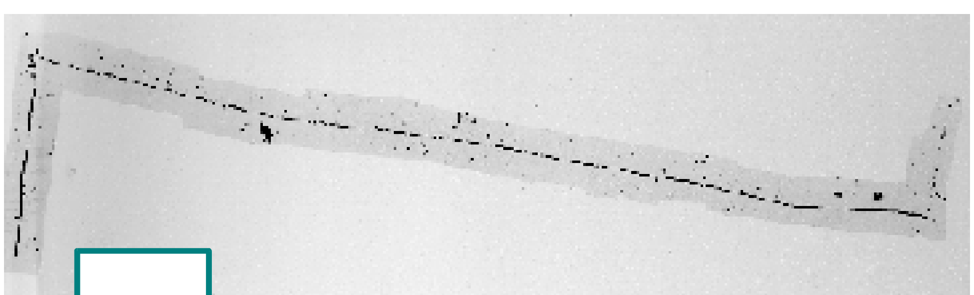
Particle Physics ← Cosmic Ray Physics



e^+



$K^\pm$



$\pi^\pm$

Particle Physics → Cosmic Ray Physics

Understanding of Shower Development
Interpretation of Indirect Measurements
of High Energy Cosmic Rays

Fixed Target Programs
ISR
SppS
TEVATRON

FUTURE ?

Particle Physics

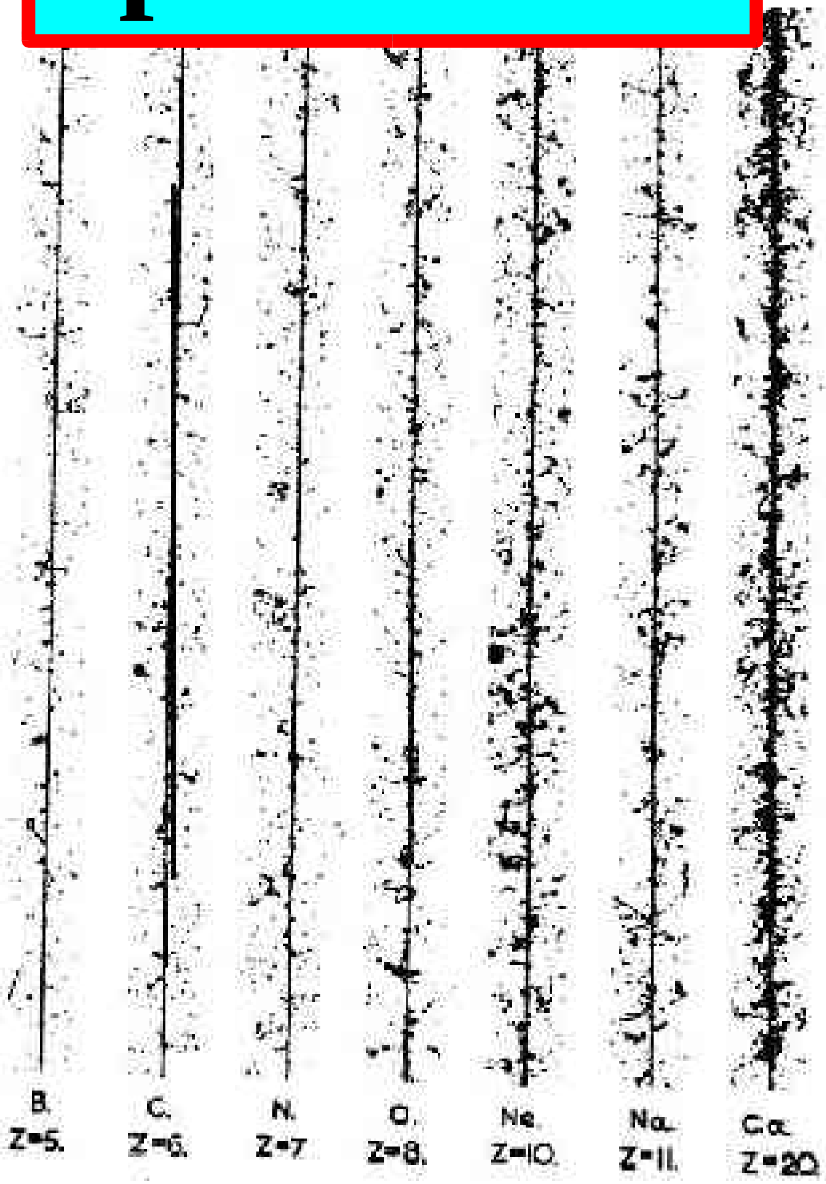
Cosmic Ray Physics

Both "flows" of information are possible

Very important input
of hadronic physcs
for the terpretation of c.r.

Highest energy interactions
observed with
Cosmic Rays

Cosmic Ray Spectrum



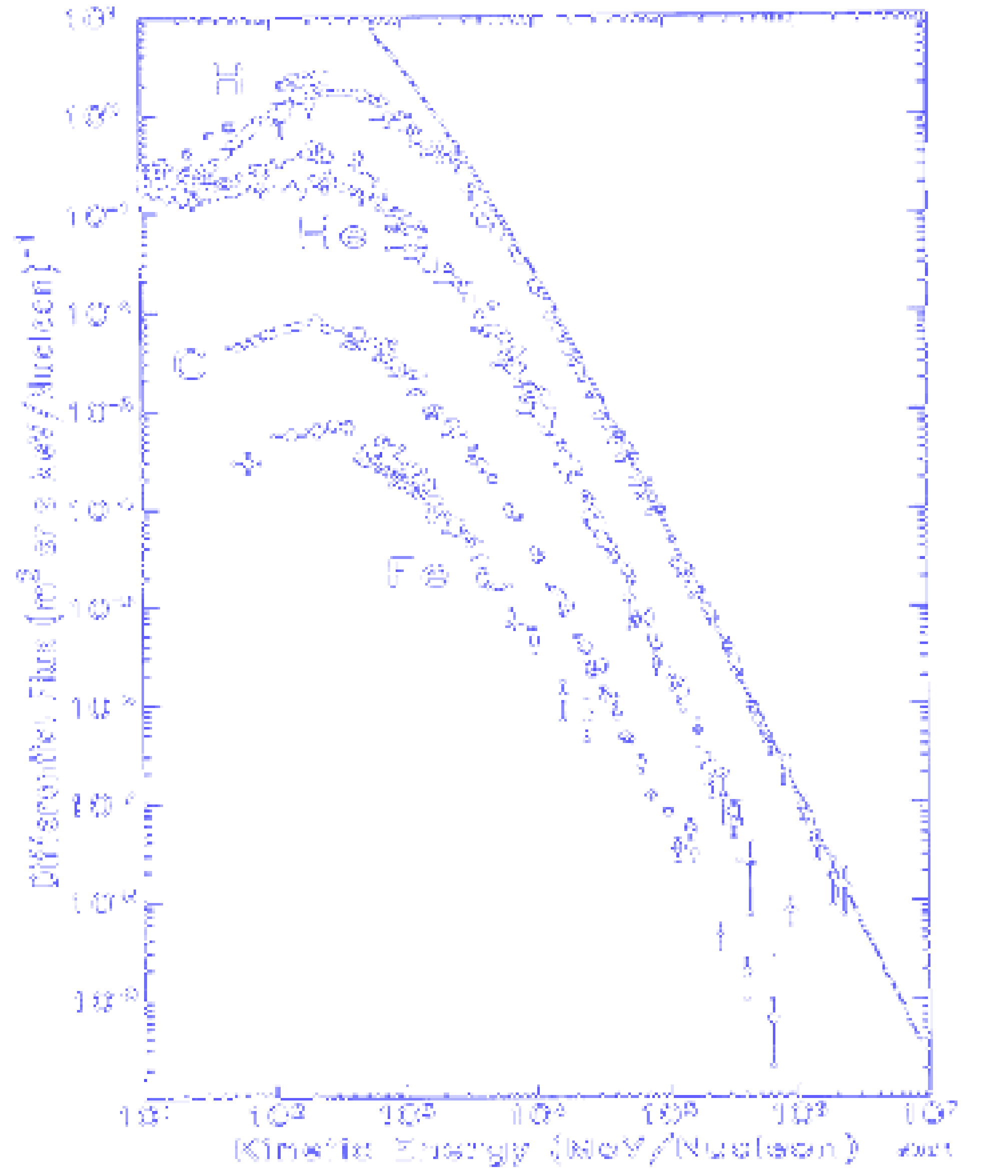
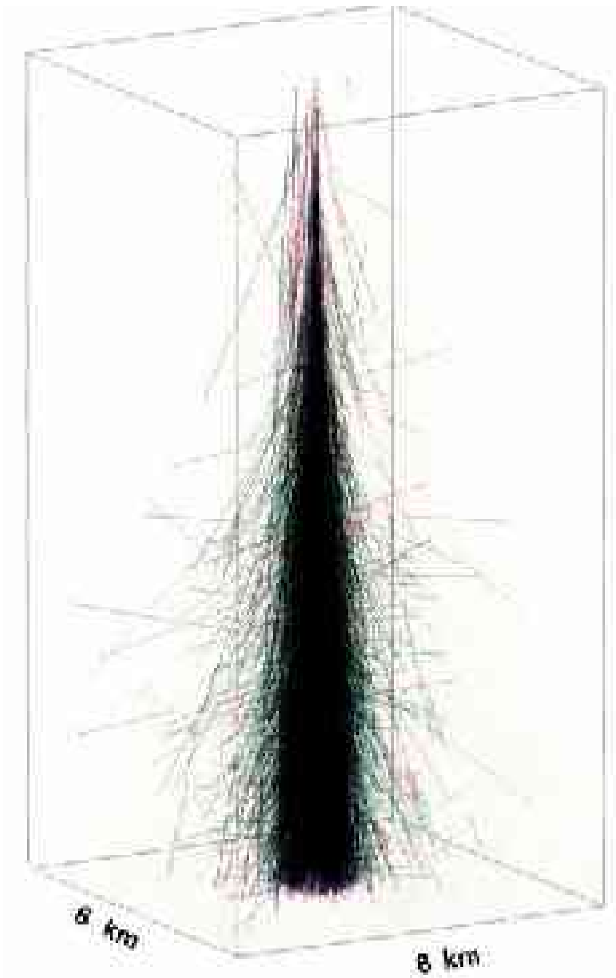
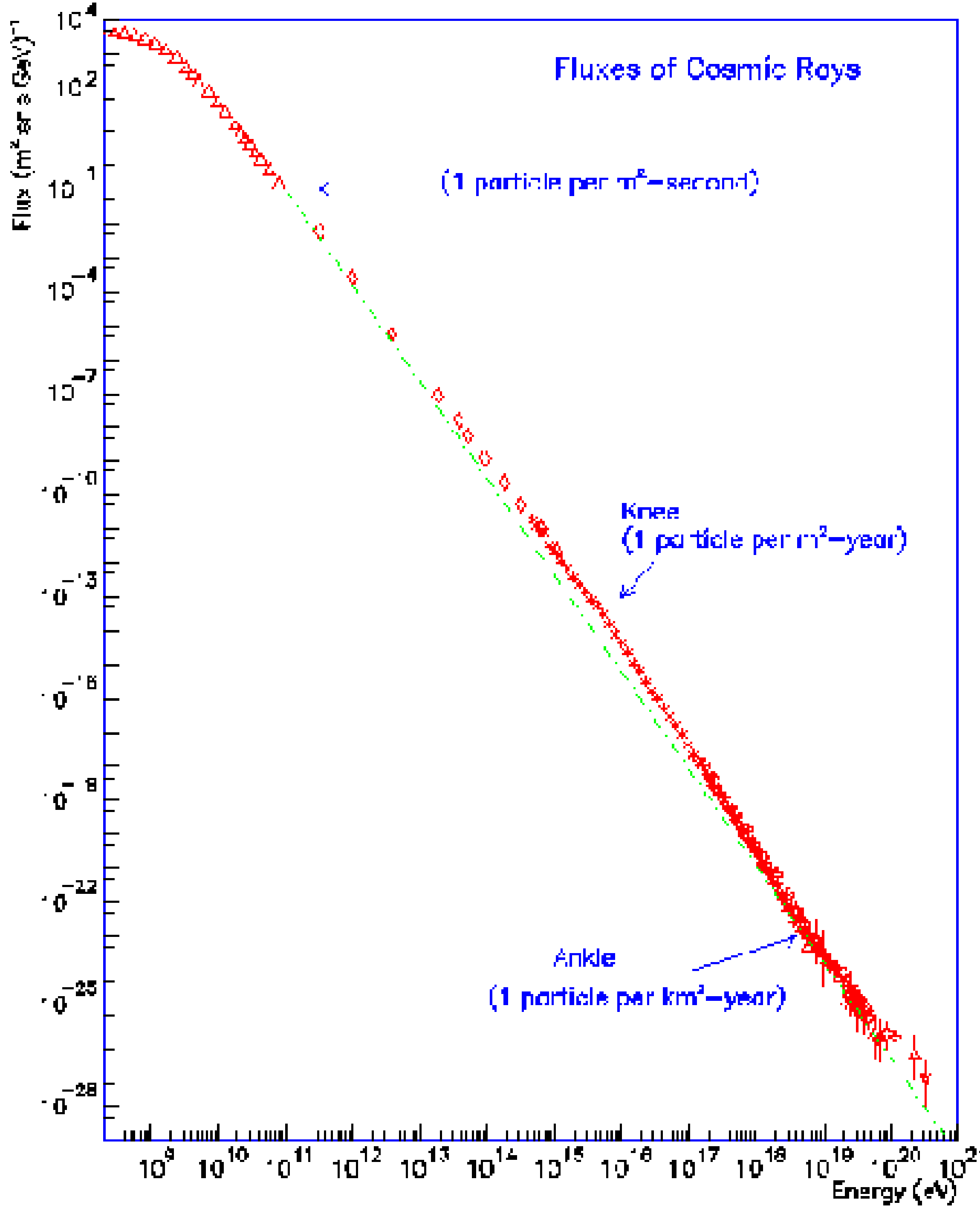


Figure 5. The differential energy spectra of the primary cosmic ray H, He, C, and Fe at Earth. [Reproduced with permission from J. A. Simpson (1983). Ann. Rev. Nucl. Part. Sci. 33 by Annual Reviews, Inc.]

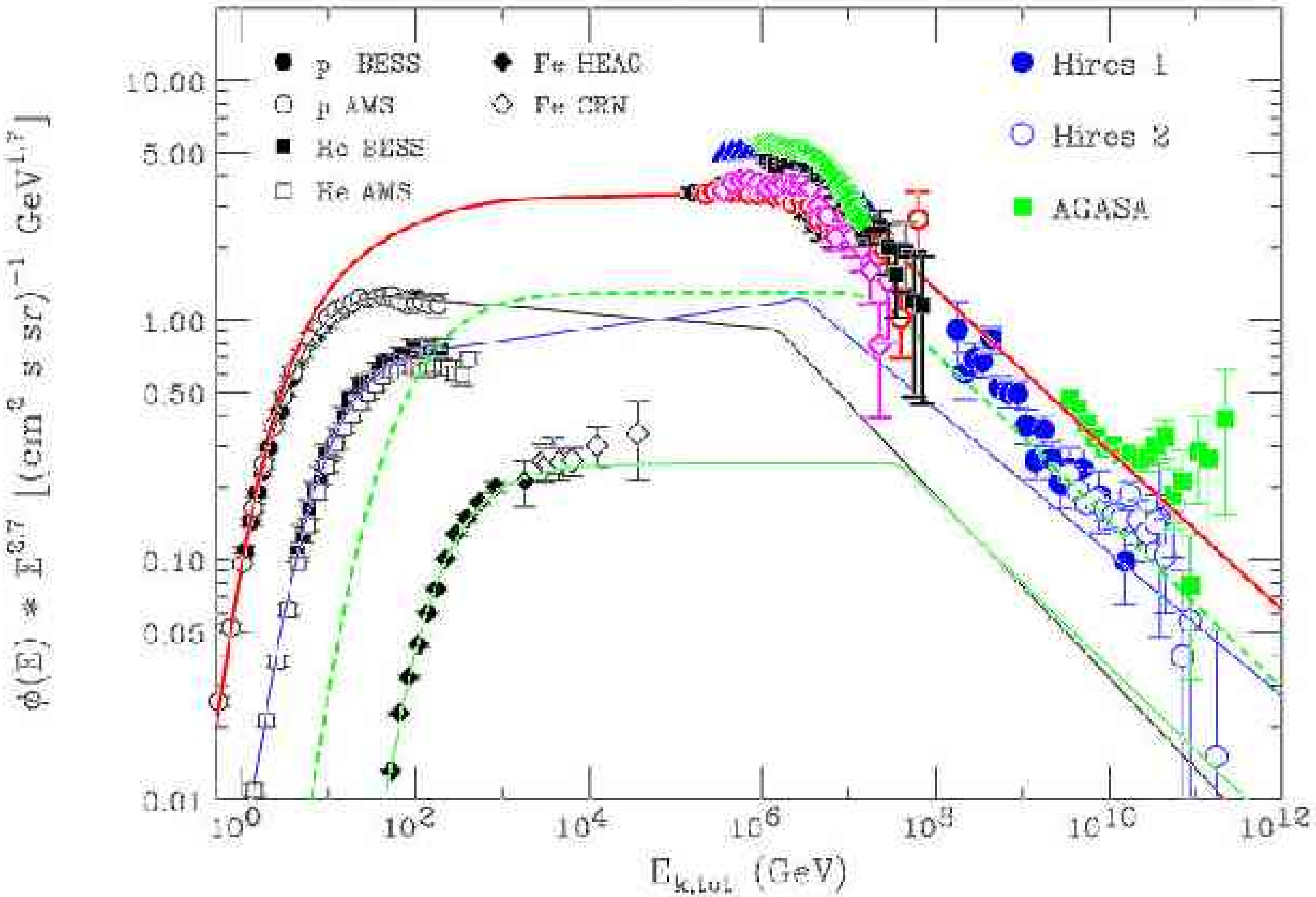
Cosmic Ray Spectrum

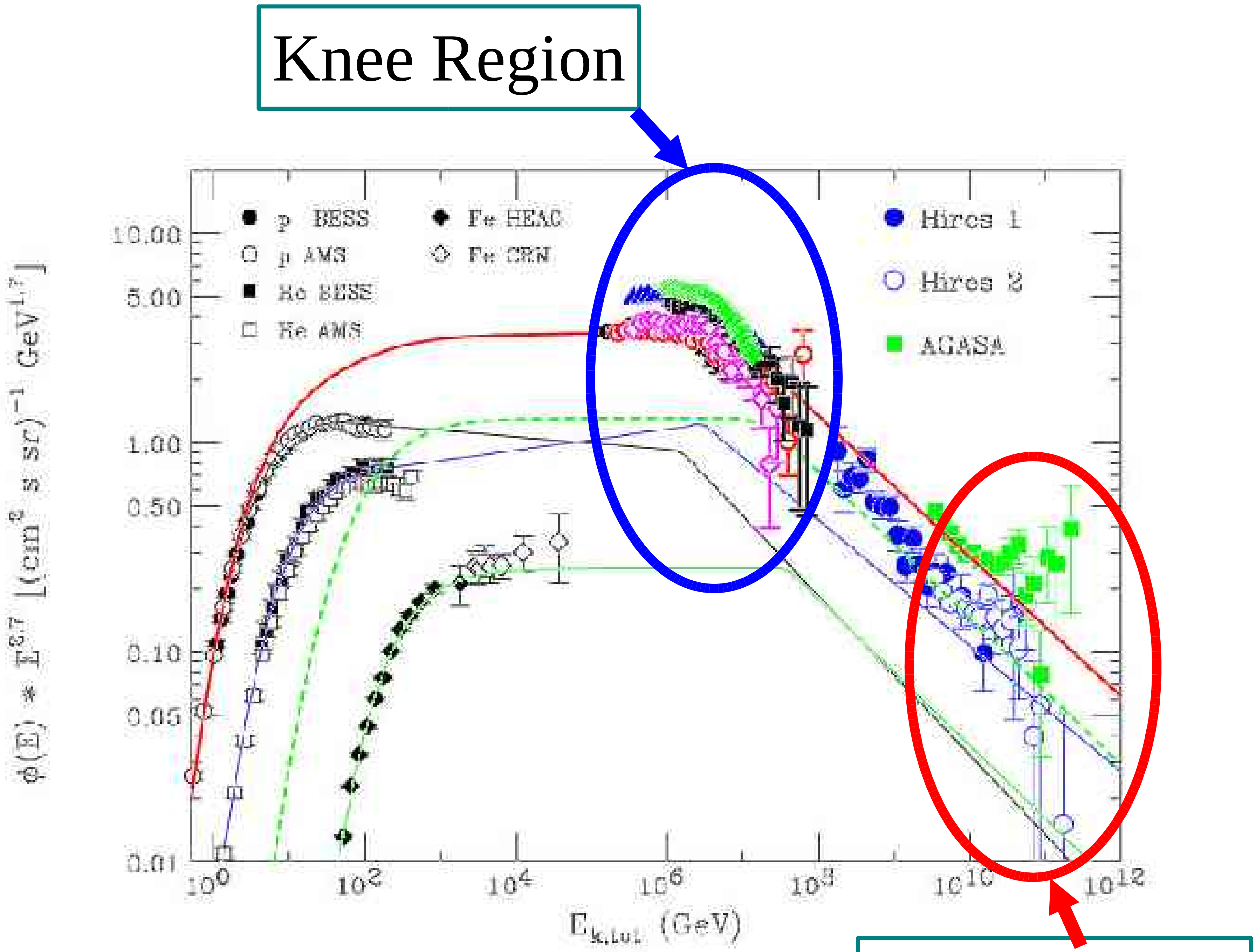


E = 10^{19} eV



Spectrum * $E^{2.7}$





$$p + \gamma_{(2.7\,\mathrm{K})} \rightarrow p(n) + \pi + \ldots$$

$$E_{\mathrm{knee}} \sim 3 \times 10^{15}\ \mathrm{eV}$$

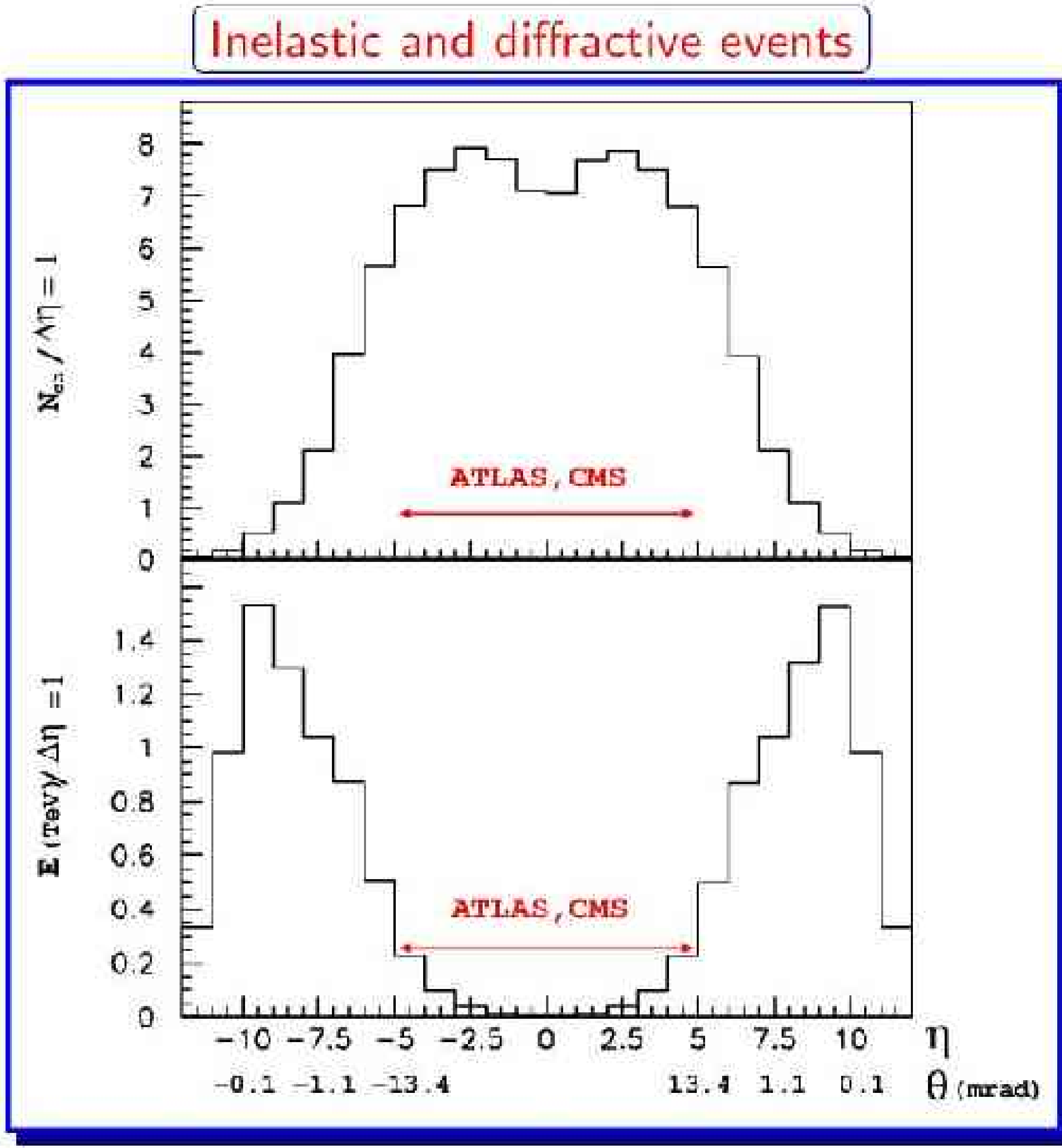
$$E_{\mathrm{GZK}} \sim 10^{20}\ \mathrm{eV}$$

$$(\sqrt{s_{NN}})_{\mathrm{knee}} \sim \frac{2.5}{\sqrt{A}}\ \mathrm{TeV}$$

$$(\sqrt{s_{NN}})_{\mathrm{GZK}} \sim \frac{400}{\sqrt{A}}\ \mathrm{TeV}$$

LHC

14 TeV


Inelastic and diffractive events
ATLAS, CMS
ATLAS, CMS
η
θ (mrad)
-0.1 -1.1 -13.4
13.4 1.1 0.1
-10 -7.5 -5 -2.5 0 2.5 5 7.5 10

Indirect Measurements of Cosmic Rays

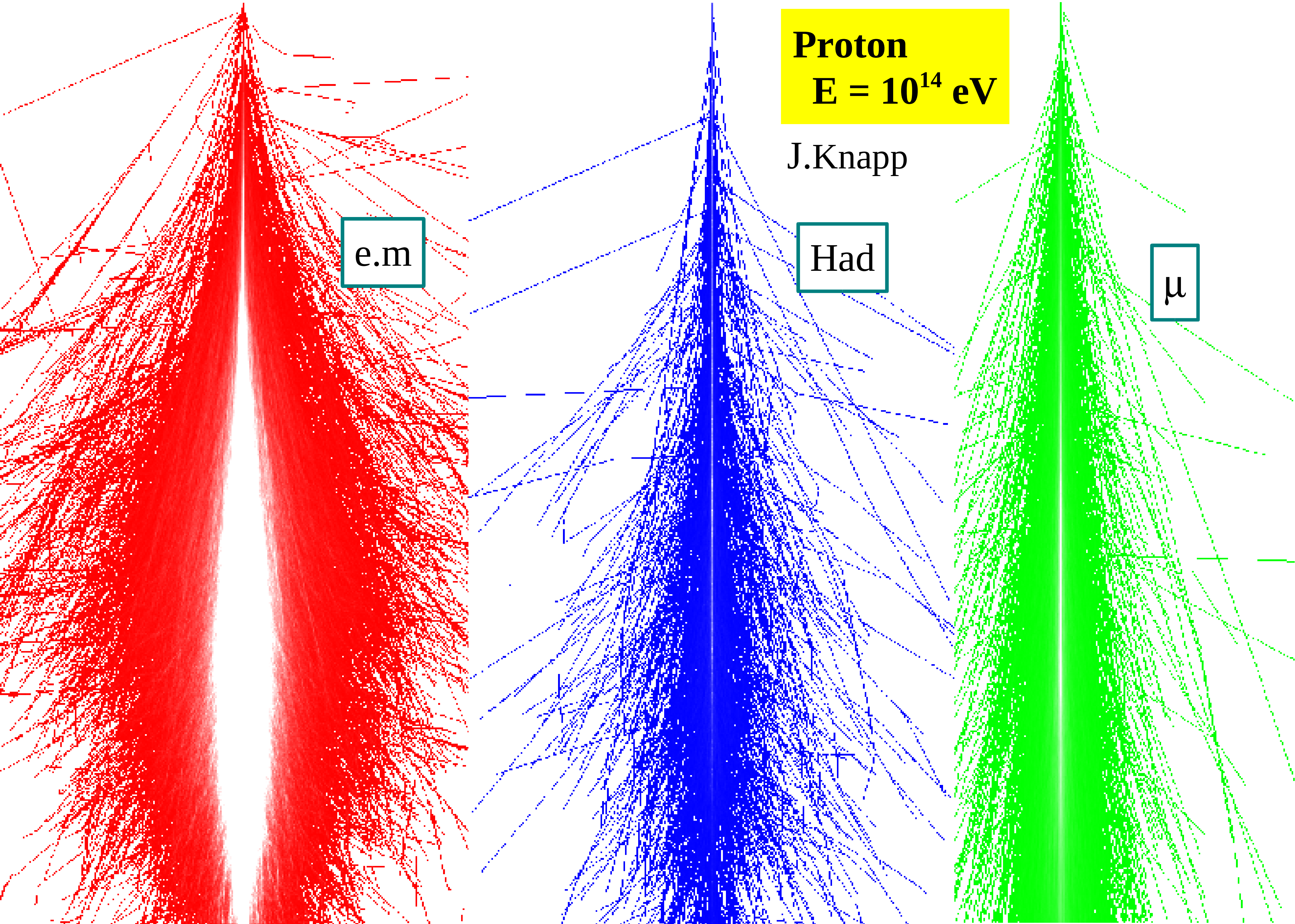
$E > 10^{14}$ eV

Extensive Air Showers

Multi-Component measurements

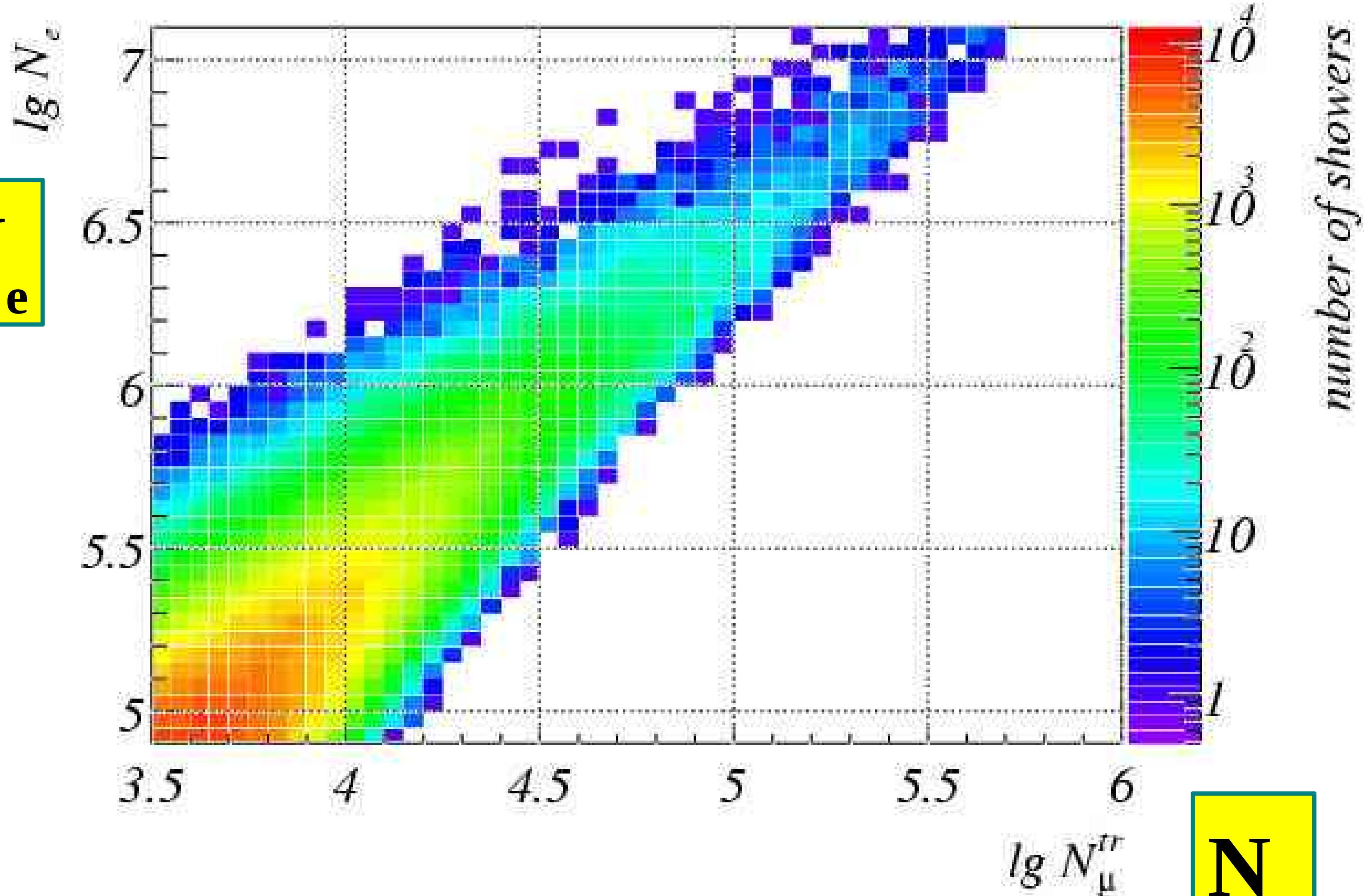
e.m. ($e^{\pm}$, γ), μ, hadrons.

Tibet ASγ detector



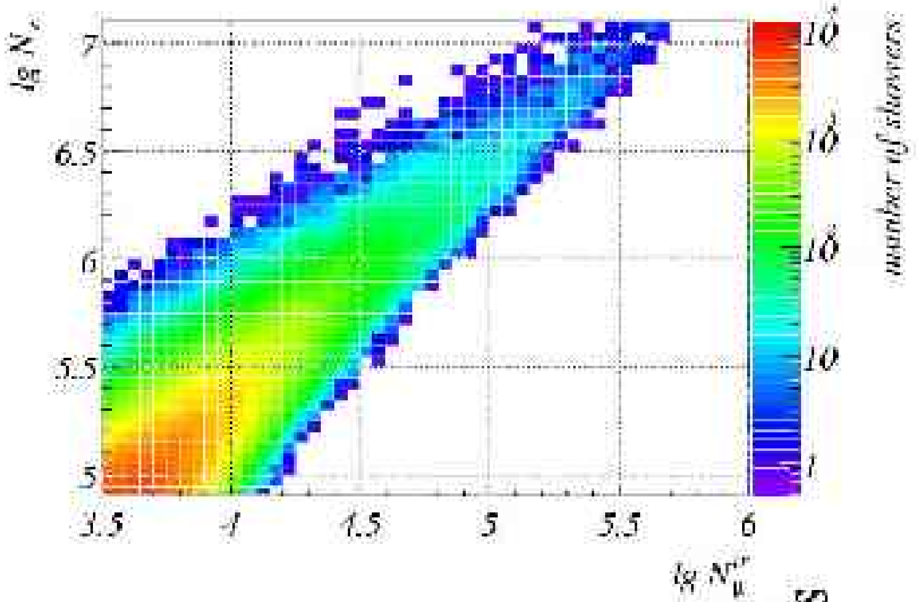
Proton
E = 10^{14} eV
J.Knapp
e.m
Had
μ

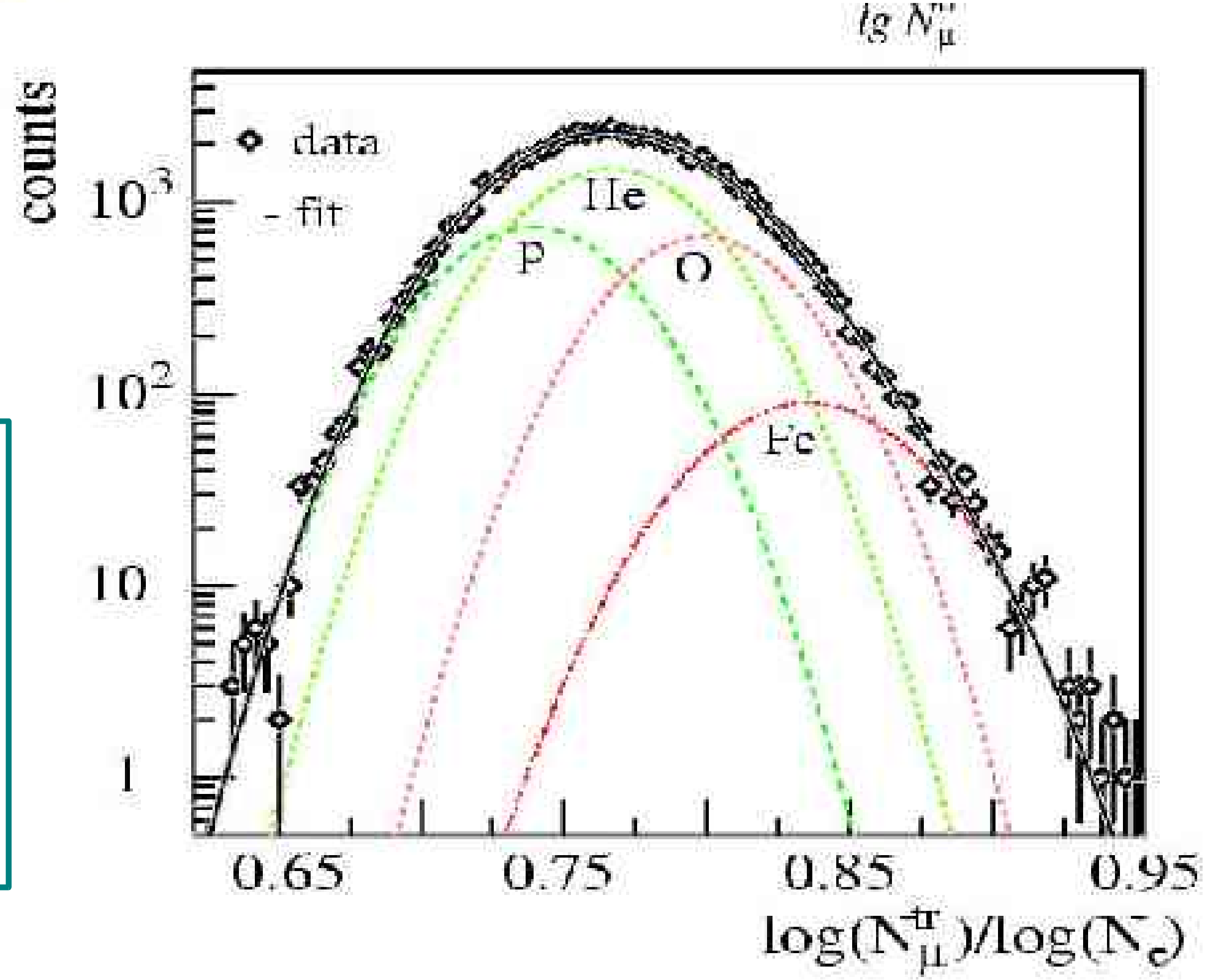
Kascade



N_e

N_μ

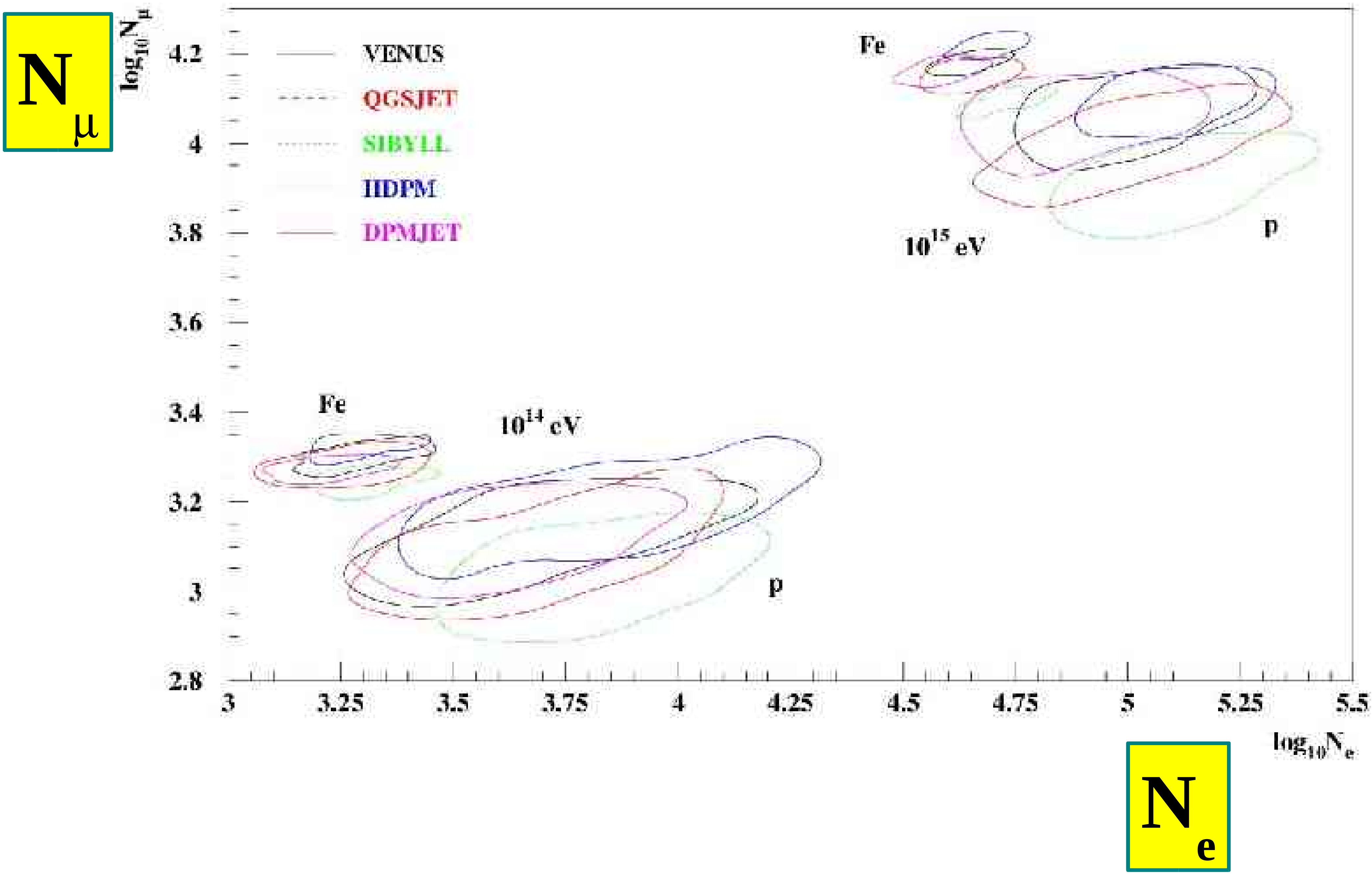


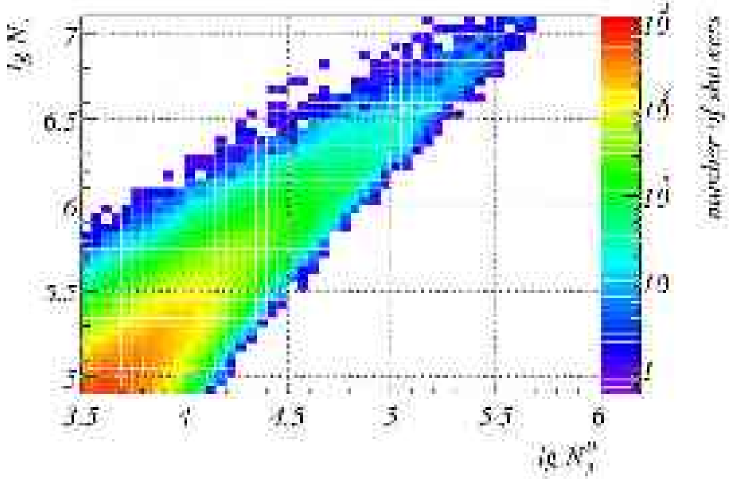


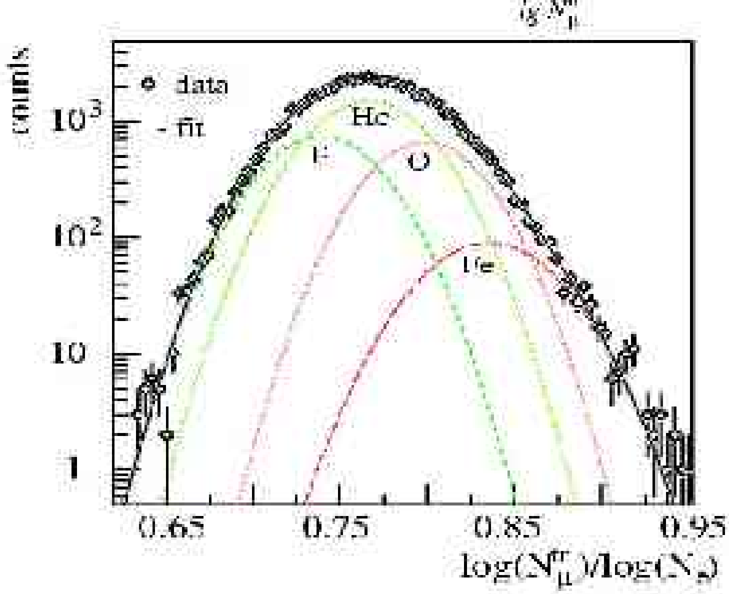
Components
not Resolved:

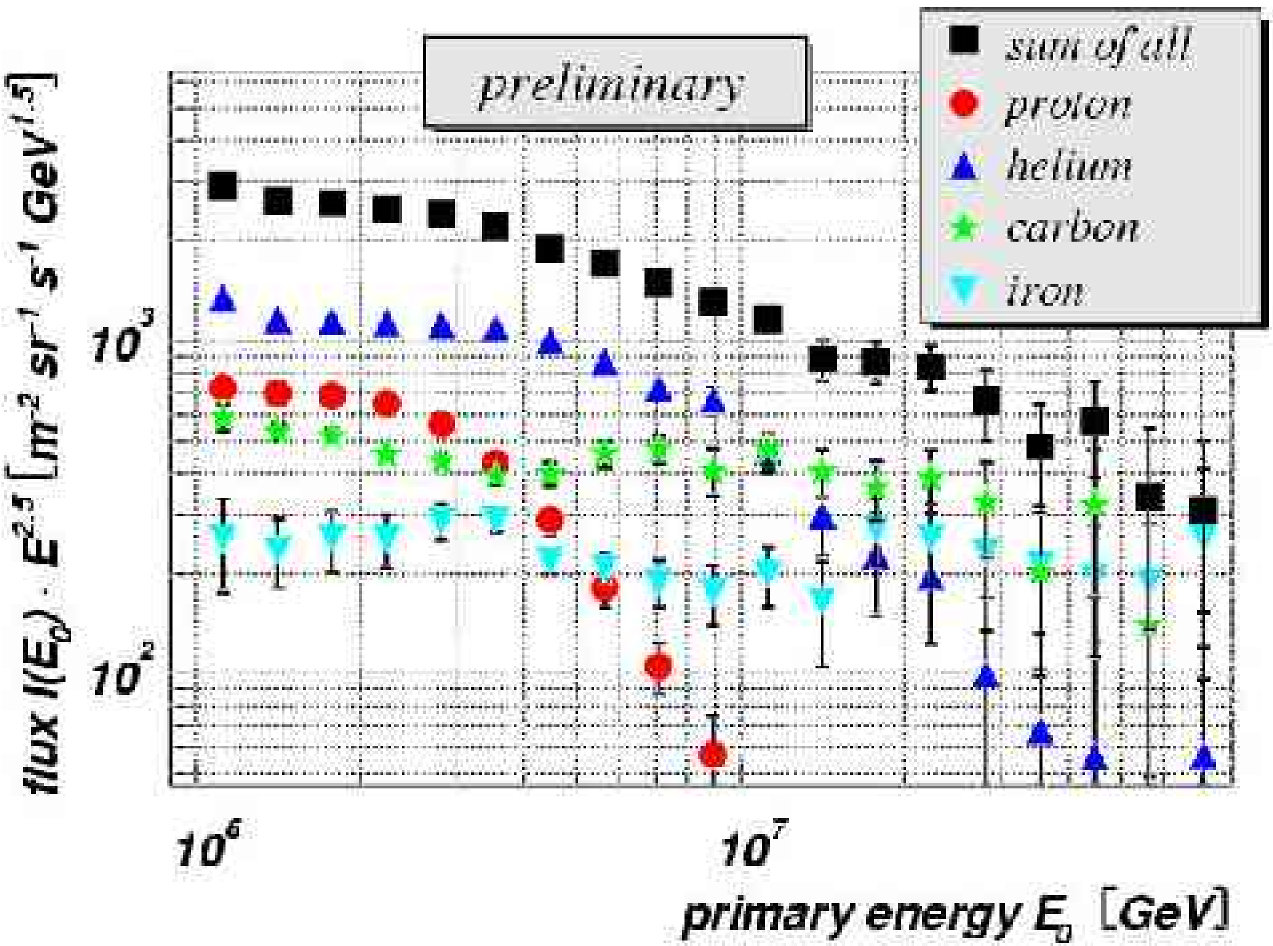
Model Dependence

Measurement of two or more Components



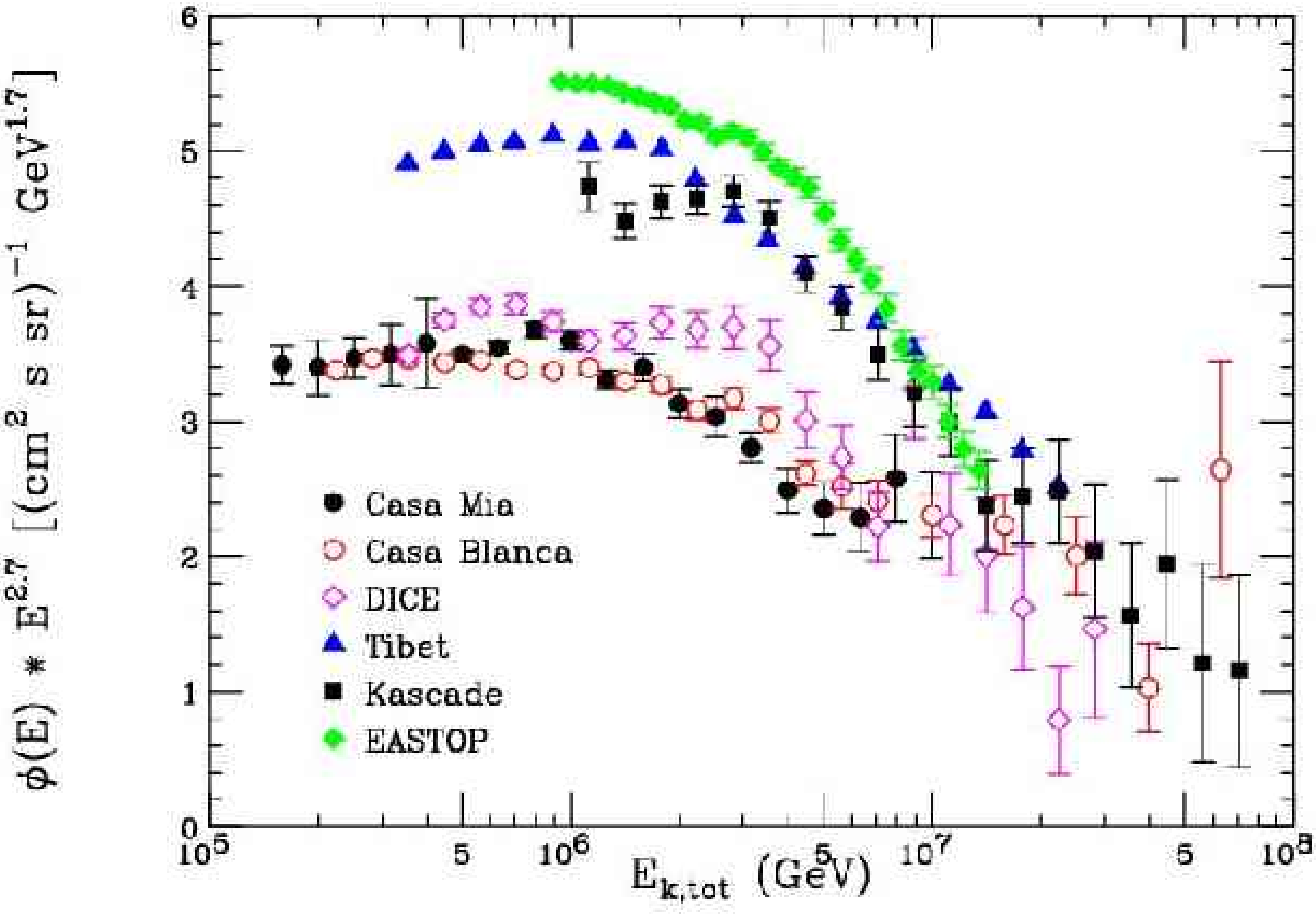

number of showers
3.5
4
4.5
5
5.5
6
6.5
7


counts
data
fit
He
O
Fe
10^3
10^2
10
1
0.65
0.75
0.85
0.95
$\log(N_\mu^{tr})/\log(N_e)$


preliminary
sum of all
proton
helium
carbon
iron
10^3
10^2
10^6
10^7
flux $I(E_0) \cdot E^{2.5}$ [m^{-2} sr^{-1} s^{-1} $GeV^{1.5}$]
primary energy E_0 [GeV]

The **KNEE**

Different Experiments



Ultra High Energy Cosmic Rays (E > 10^{19} eV)

AGASA

HIRES (High Resolution Fly's Eye)

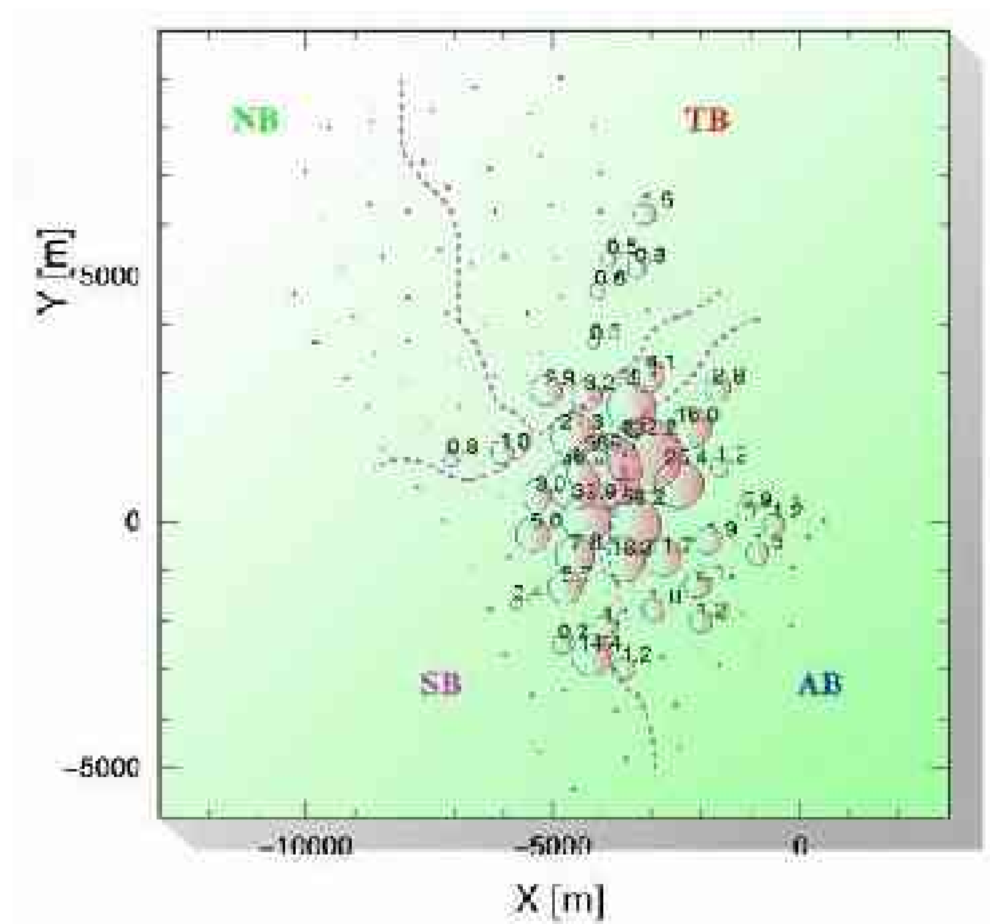
AUGER

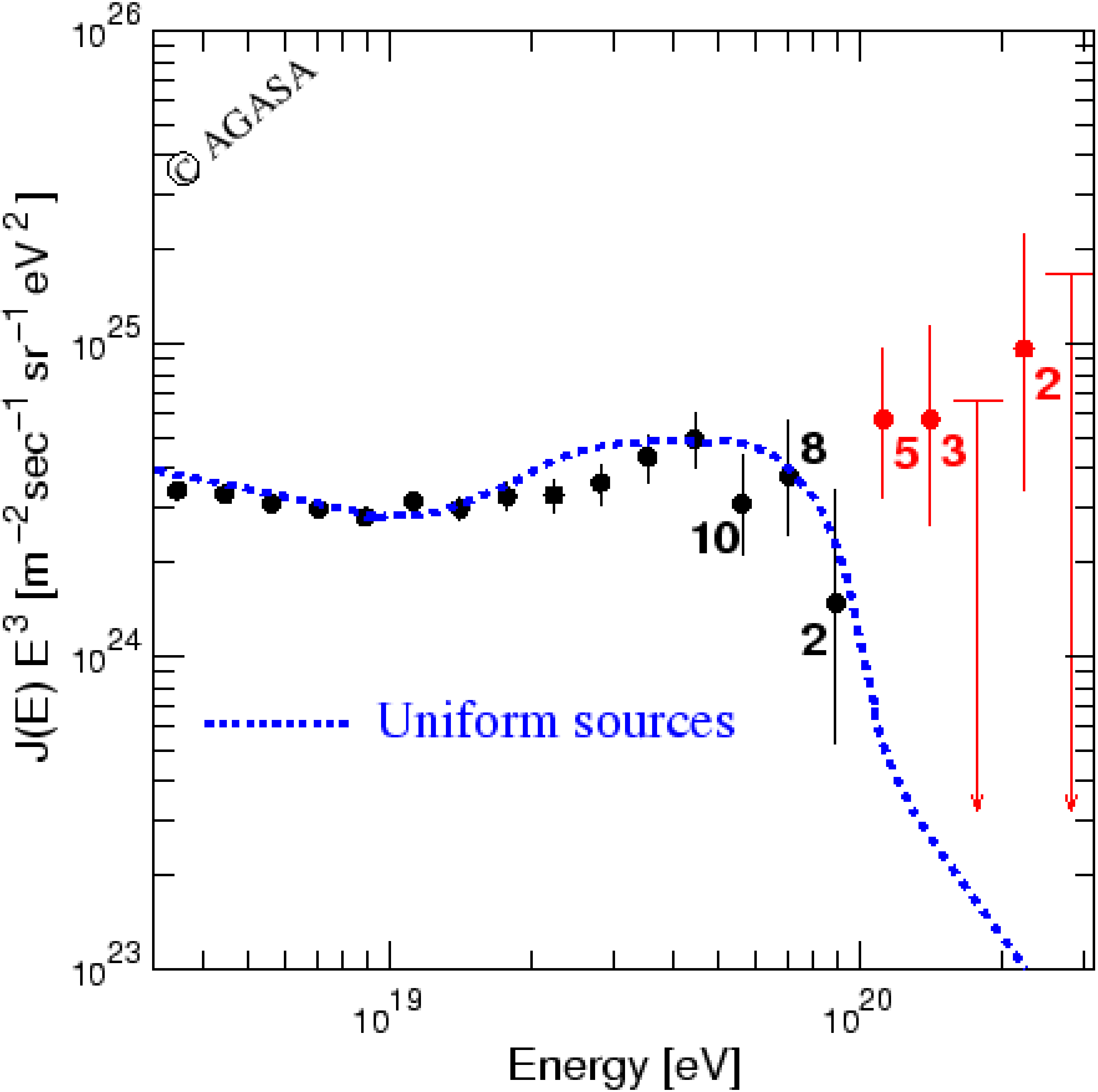
EUSO

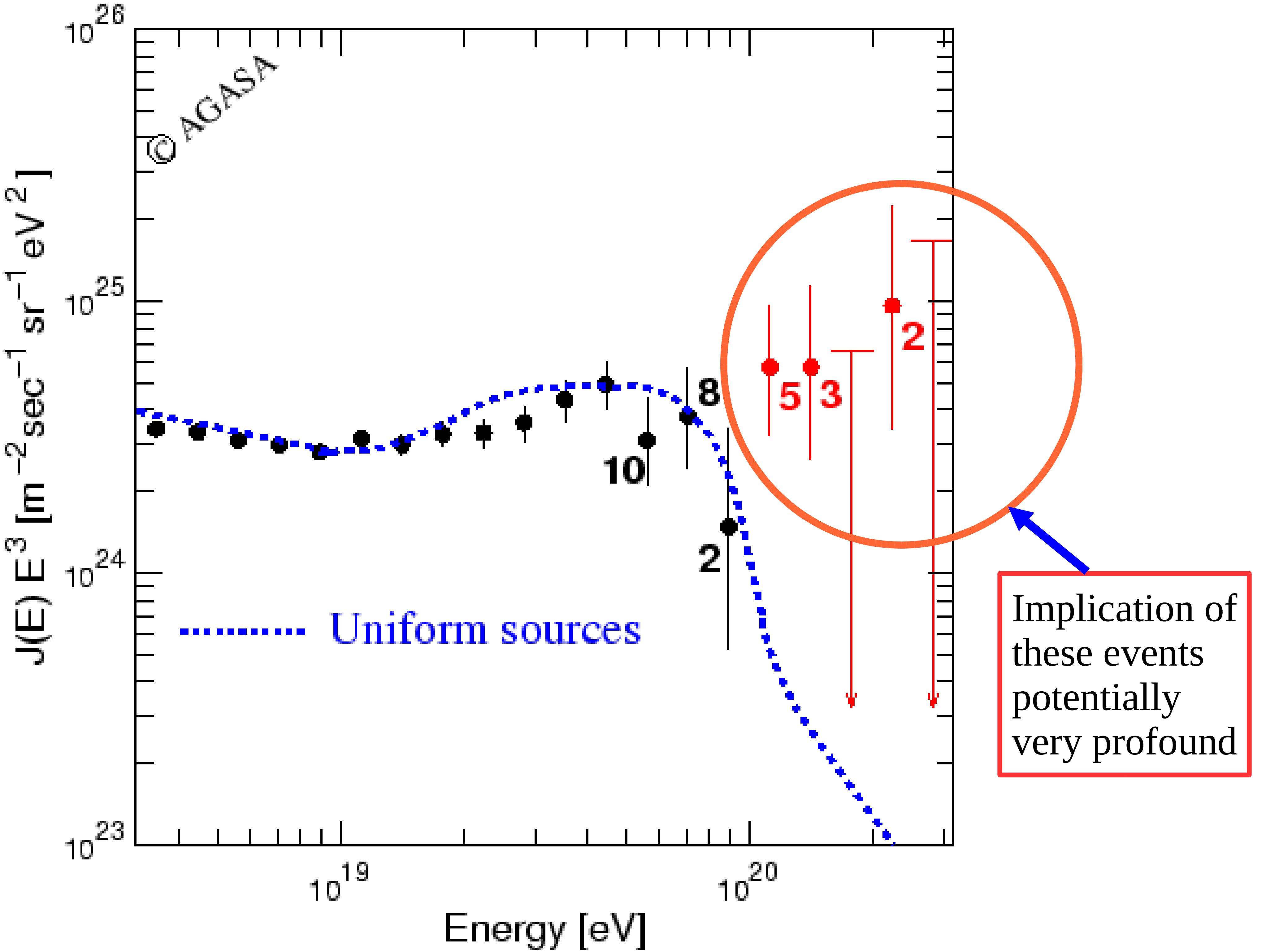
AGASA detector

(Japan)

Area = 100 Km^2



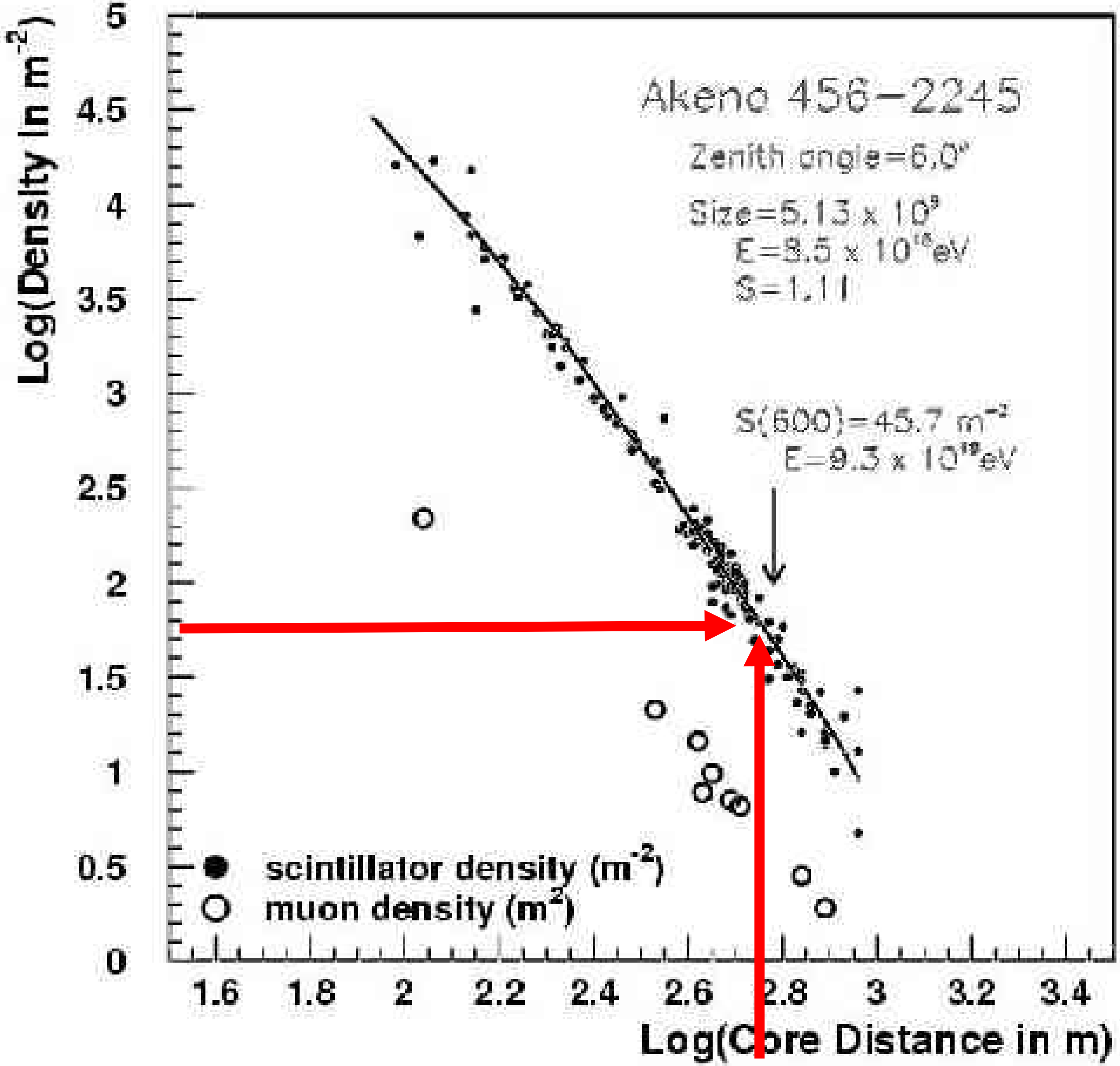

© AGASA
J(E) E^3 [m^-2 sec^-1 sr^-1 eV^2]
Energy [eV]
Uniform sources
10
8
2
5
3
2

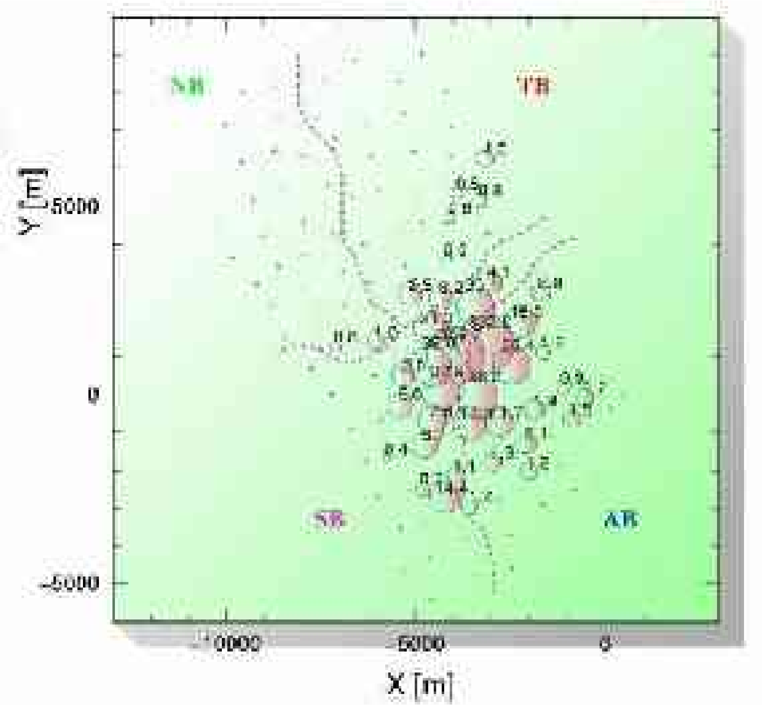


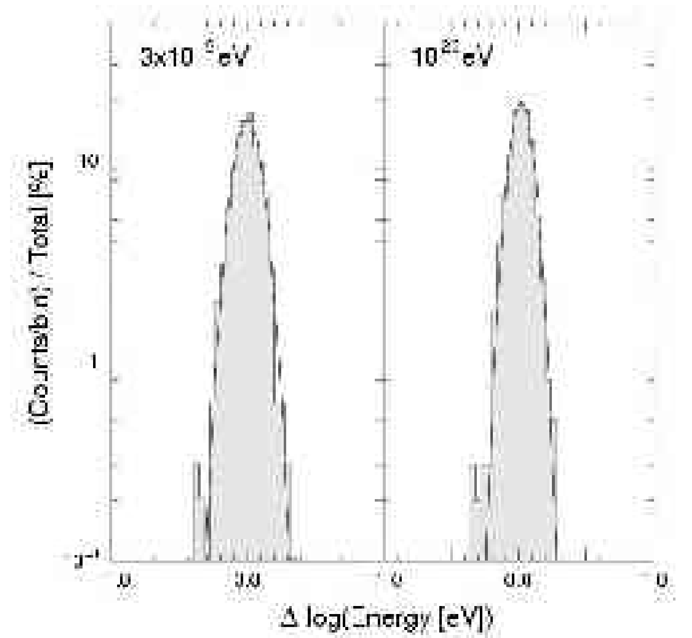
© AGASA
10^{26}
10^{25}
10^{24}
10^{23}
10^{19}
10^{20}
J(E) E^3 [m^{-2}sec^{-1} sr^{-1} eV^2]
Energy [eV]
Uniform sources
10
8
2
5
3
2
Implication of these events potentially very profound

AGASA Energy determination

$$E = 2.03 \times 10^{17} \cdot S_0(600) \quad \text{eV}$$







Energy Determination

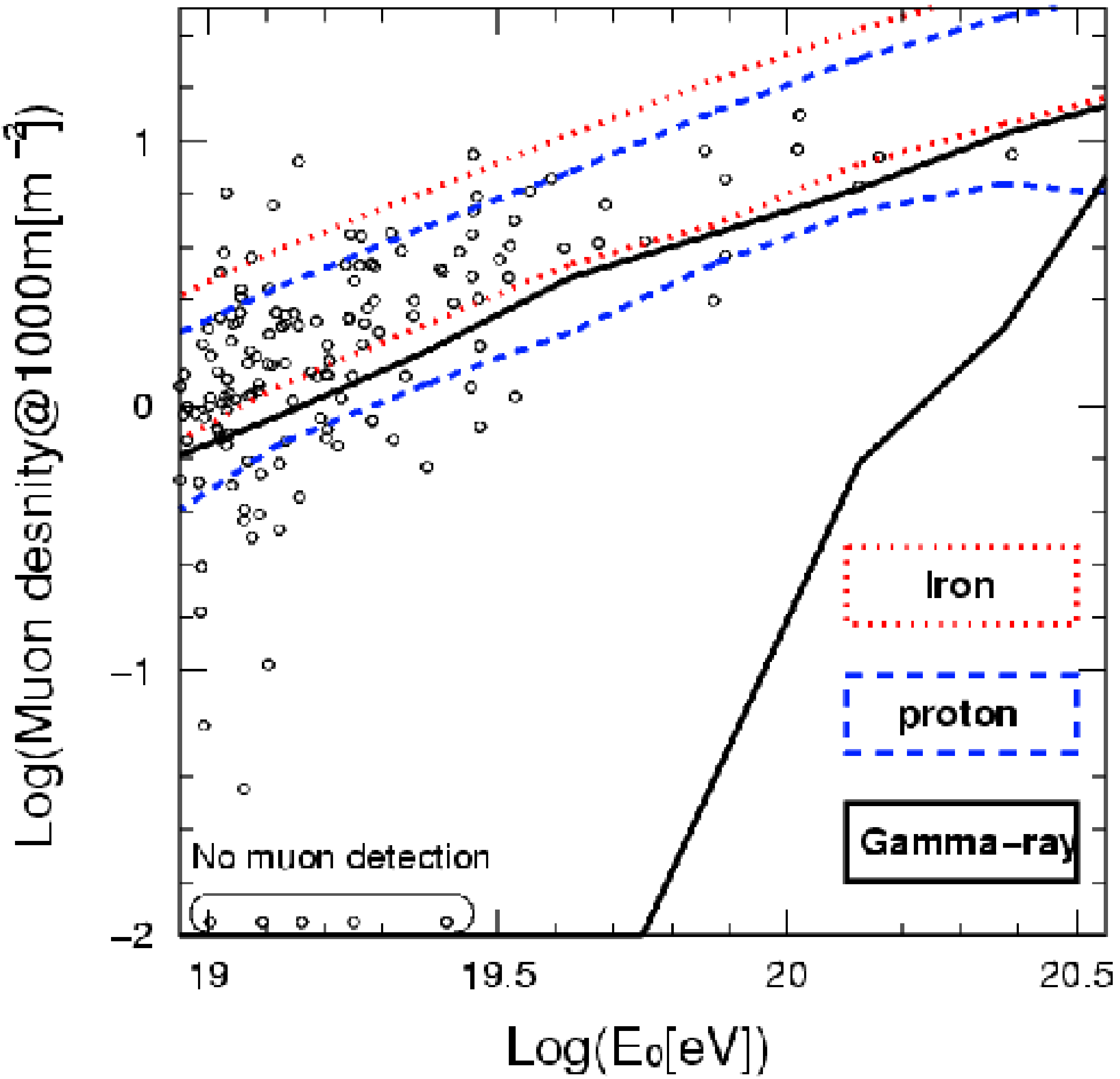
Major systematics of AGASA.

Detector:	
detector absolute gain	$\pm$ 0.7%
detector linearity	$\pm$ 7%
detector response (box, housing, ...)	$\pm$ 5%
Air shower phenomenology:	
lateral distribution function	$\pm$ 7%
$S(600)$ attenuation	$\pm$ 5%
shower front structure	$-$ 5% $\pm$ 5%
delayed particles	$-$ 5% $\pm$ 5%
Energy estimator $S(600)$:	
interaction models, chemical compositions (p/Fe), simulation codes, height correction, $S(600)$ fluctuation	+10% $\pm$12%
Total	18 %

Energy conversion from $S(600)$. The column "Single Particle" describes the definition of "a single particle" used in the evaluation of $S(600)$. Each formula is evaluated at the altitude given in the column "Altitude".

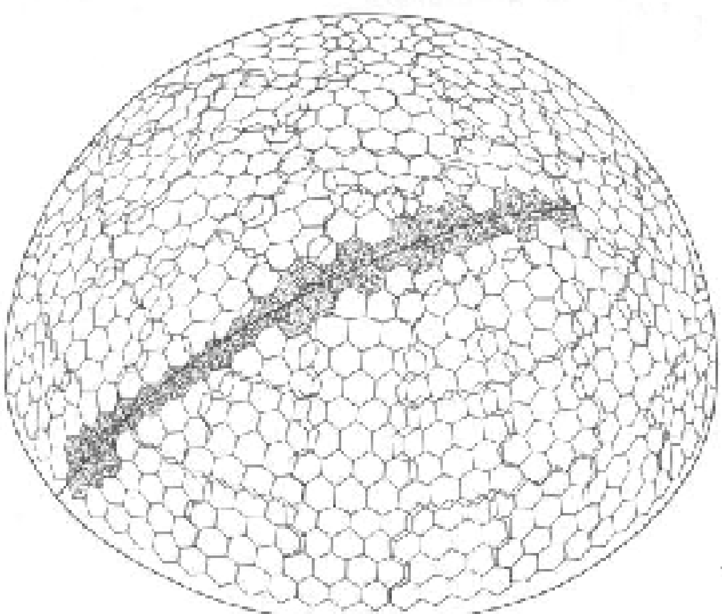
Simulation Code	Single Particle	Altitude	Interaction Model	Primary Composition	$E = a \times 10^{17} \cdot S_0(600)^b$ a	b
COSMOS	"electrons"	900m	QCDJET	p	2.03	1.02
CORSIKA (v5.623)	PH^0_{peak}	900m	QGSJET98	p	2.07	1.03
				Fe	2.24	1.00
			SIBYLL1.6	p	2.30	1.03
				Fe	2.19	1.01
AIRES (v2.2.1)	PW^θ_{peak}	667m	QGSJET98	p	2.17	1.03
				Fe	2.15	1.01
			SIBYLL1.6	p	2.34	1.04
				Fe	2.24	1.02

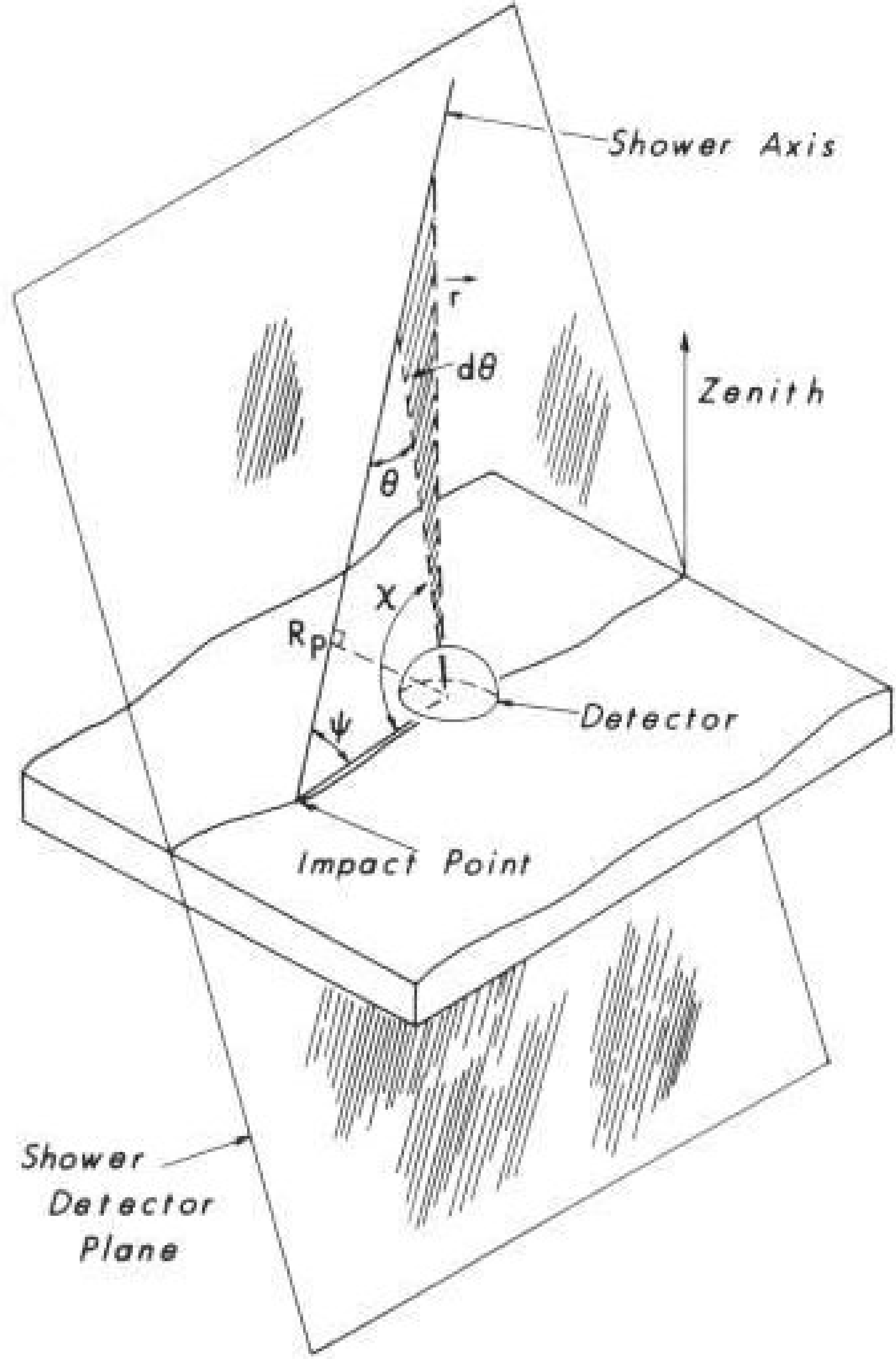
Composition Analysis

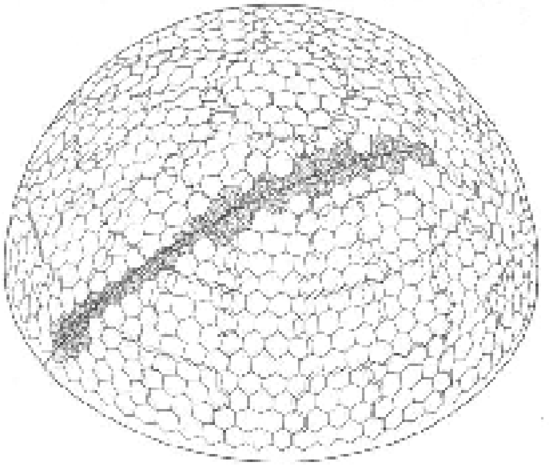


AGASA

The **Fly's Eye** Detector concept

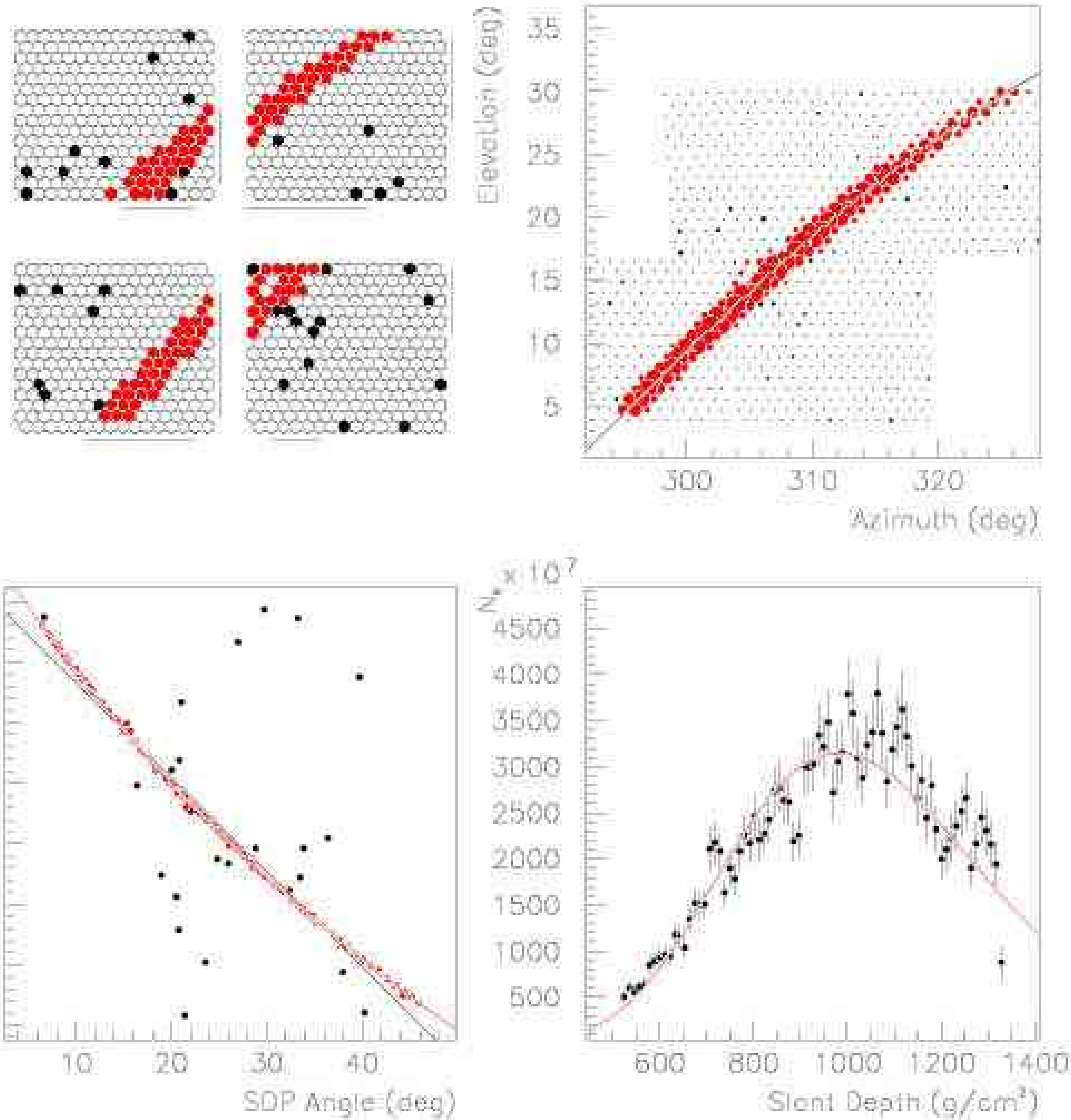






The Fly's Eye
detector (Utah) 1990 -1998

The High Resolution Fly's Eye (HIRES)


Elevation (deg)
35
30
25
20
15
10
5
300
310
320
Azimuth (deg)
Time (100 ns)
600
550
500
450
400
350
300
250
10
20
30
40
SDP Angle (deg)
$N_e \times 10^7$
4500
4000
3500
3000
2500
2000
1500
1000
500
600
800
1000
1200
1400
Slant Depth (g/cm²)

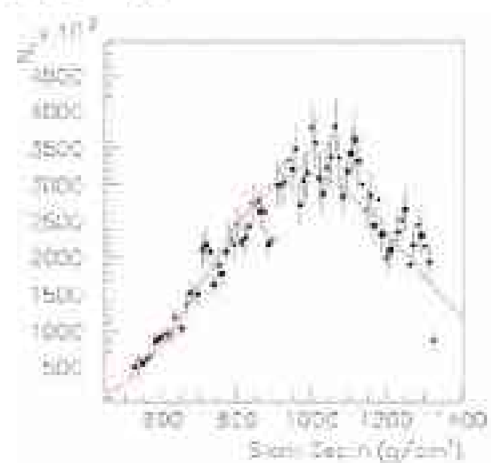
Absorption corrected

$$\frac{dN_{\mathrm{fluo}}}{dX} = N_c(X) \left\langle -\frac{dE}{dX} \right\rangle \frac{dY_{\mathrm{fluo}}}{dE}(X)$$

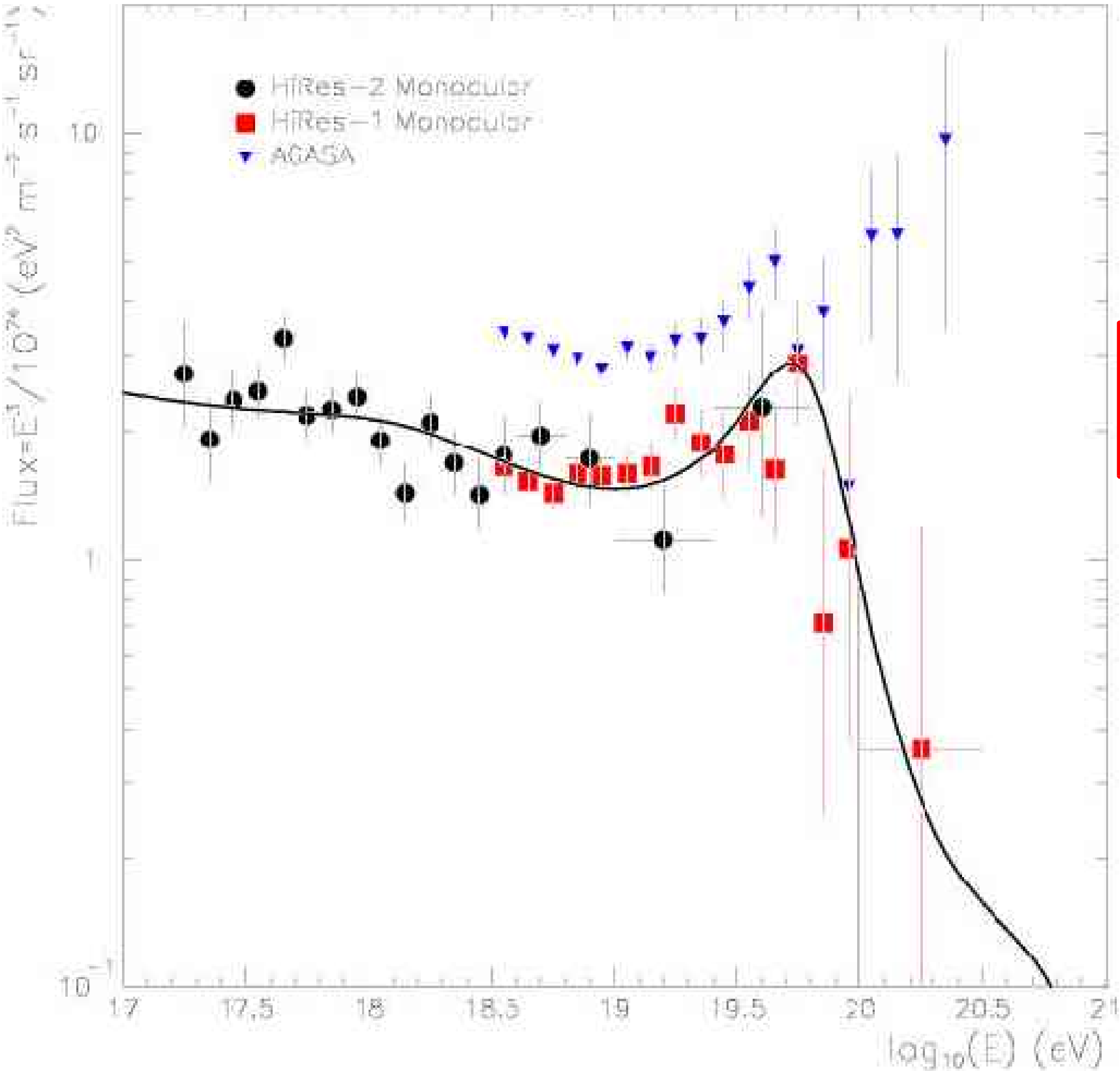
$$E_{\mathrm{ionization}} = \int dX \; N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

$$E_{\mathrm{tot}} = E_{\mathrm{ionization}} + E_\nu + E_\mu + E_{\mathrm{ground}}$$

In principle less Model Dependence
in the Energy Determination



Energy Spectrum of the Highest Energy Cosmic Rays



Hires results:
astro-ph/
0208243
0208301

GZK Cutoff
(Greisen-Zatsepin-Kuzmin)

$$p + \gamma_{2.7^\circ} \rightarrow p + \pi^\circ$$

$$E_p \gtrsim 10^{20}\ \text{eV}$$

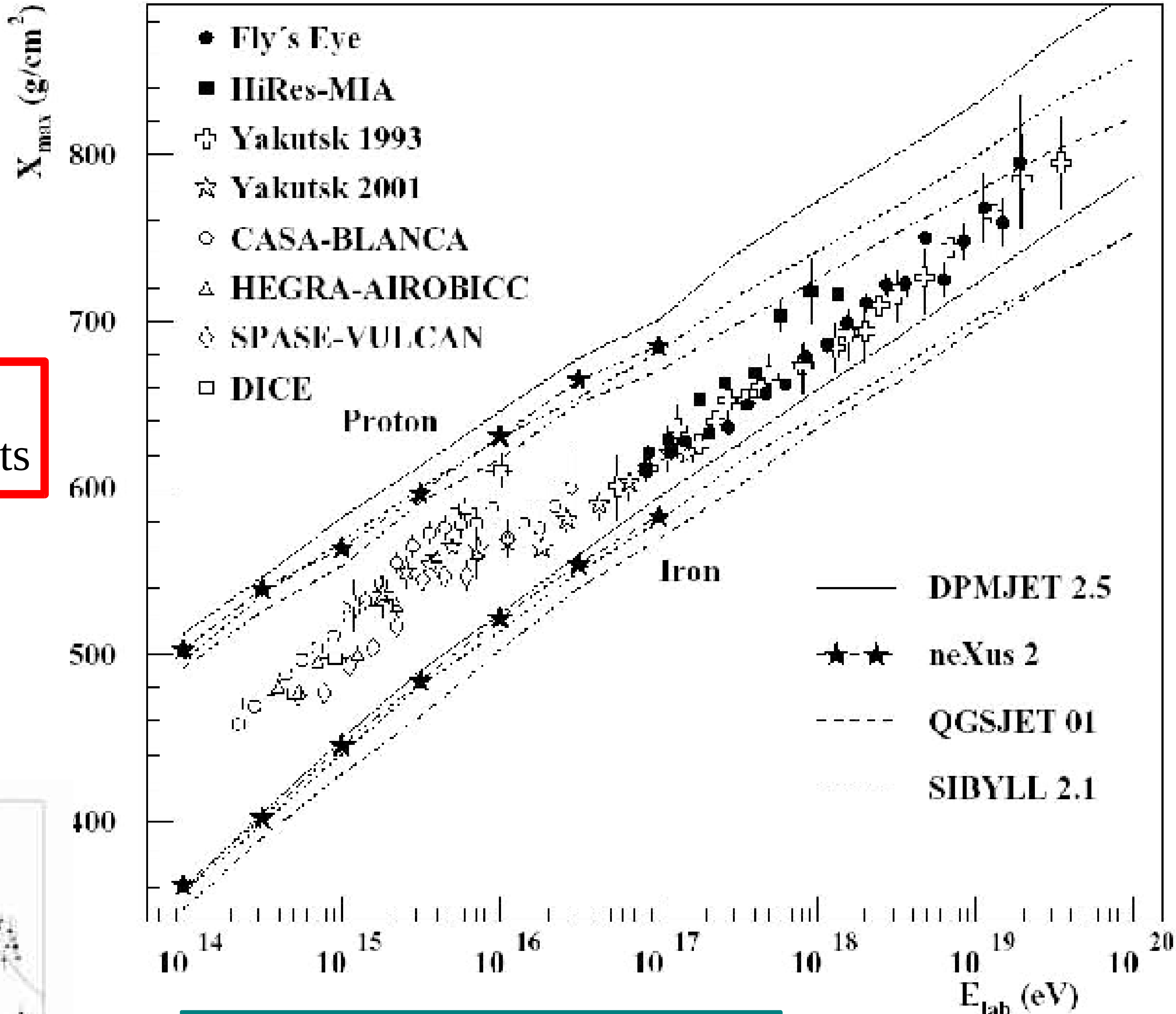
Controversy

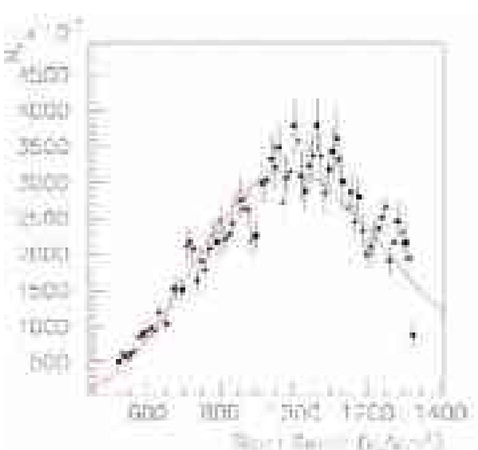
QUESTION:

Has the Discrepancy between
AGASA and HIRES
anything to do with
the behaviour of
Hadronic Interactions
at High Energy **?**

Composition Measurements

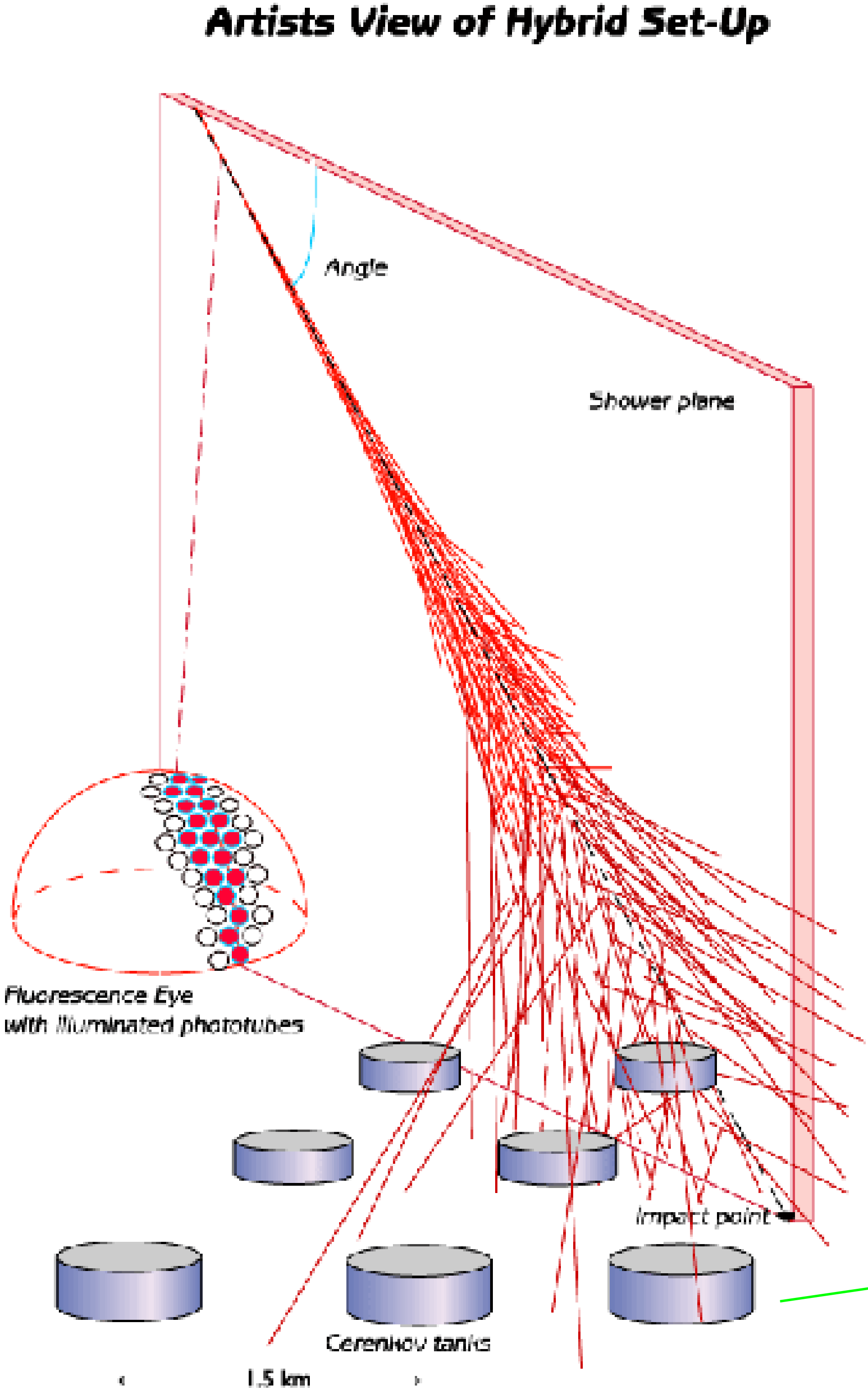
X_{max}





Significant Model dependence

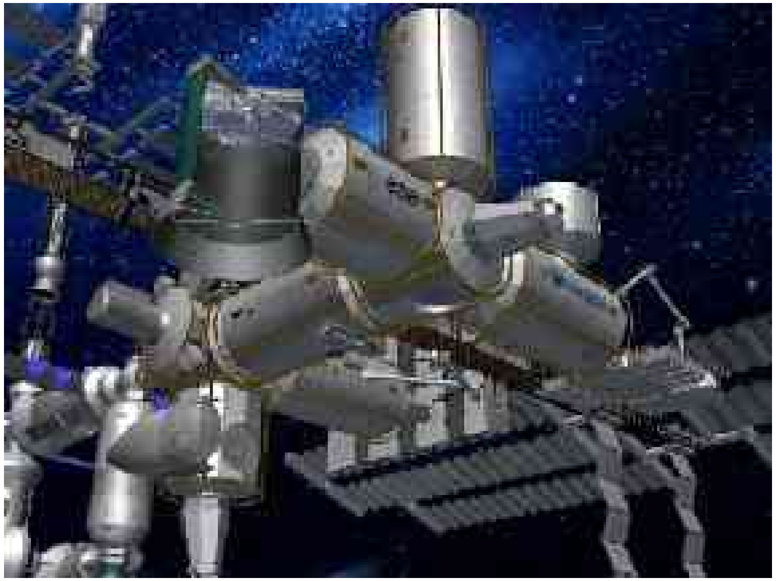
AUGER detector



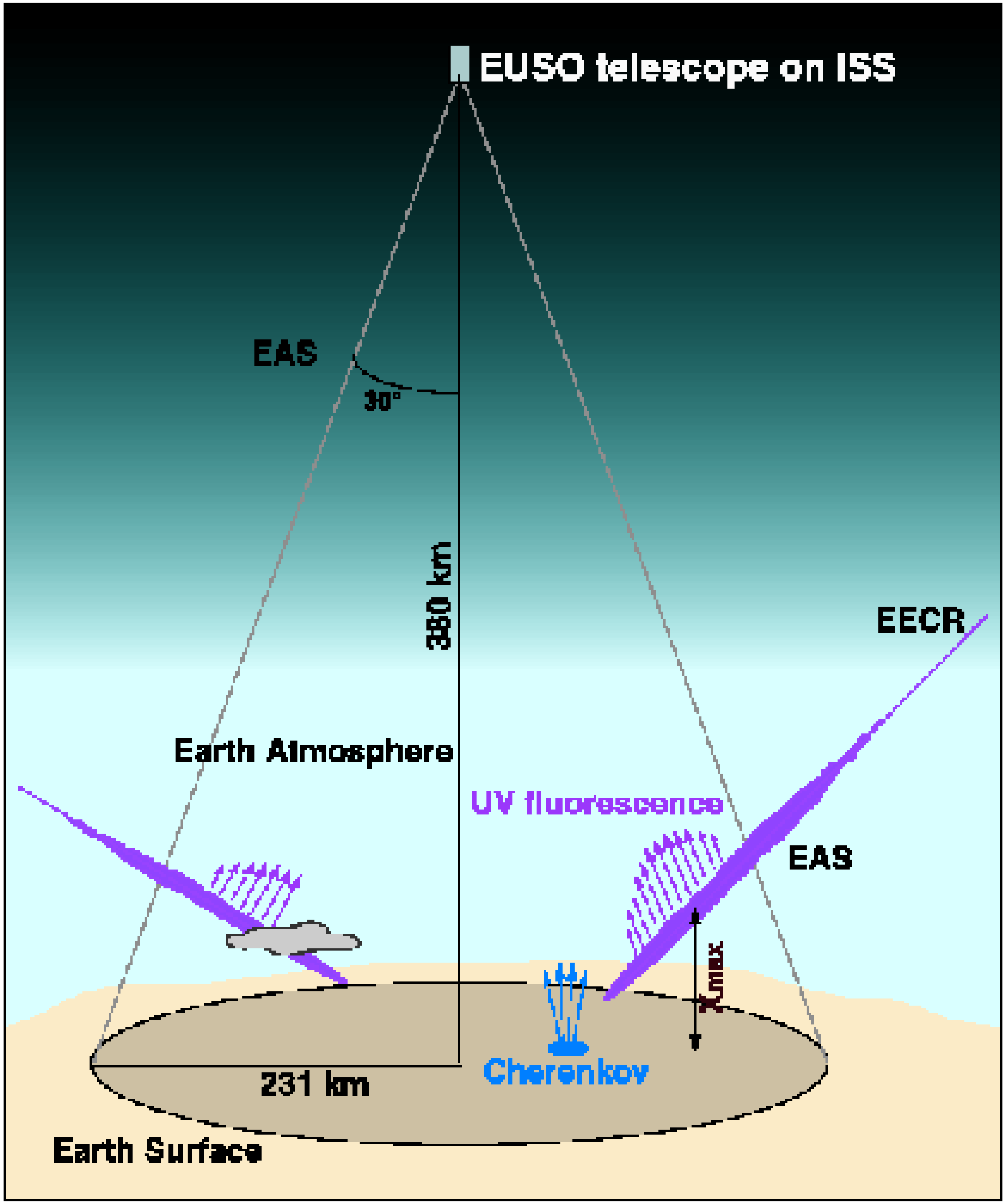
3000 Km^2

Hybrid
system

EUSO



Planned for
the ISS



COSMIC RAY PHYSICS

Has matured
to become a subfield of

HIGH ENERGY ASTROPHYSICS

γ Astronomy
ν Astronomy
Gravitational waves

Astrophysical Observations with Four Messengers

- Photons
- Neutrinos
- Cosmic Rays (p, e^-, $\bar{p}$, e^+, ...)
- Gravitational Waves

Astrophysical Observations with Four Messengers

- Photons ←

> Nearly all the information that we have about the Universe obtained with Photons
>
> History of Astrophysics
> Extension of the range
> of observed wavelength.

- Neutrinos
- Cosmic Rays (p, e^-, $\bar{p}, e^+, \ldots$)
- Gravitational Waves

Astrophysical Observations with Four Messengers

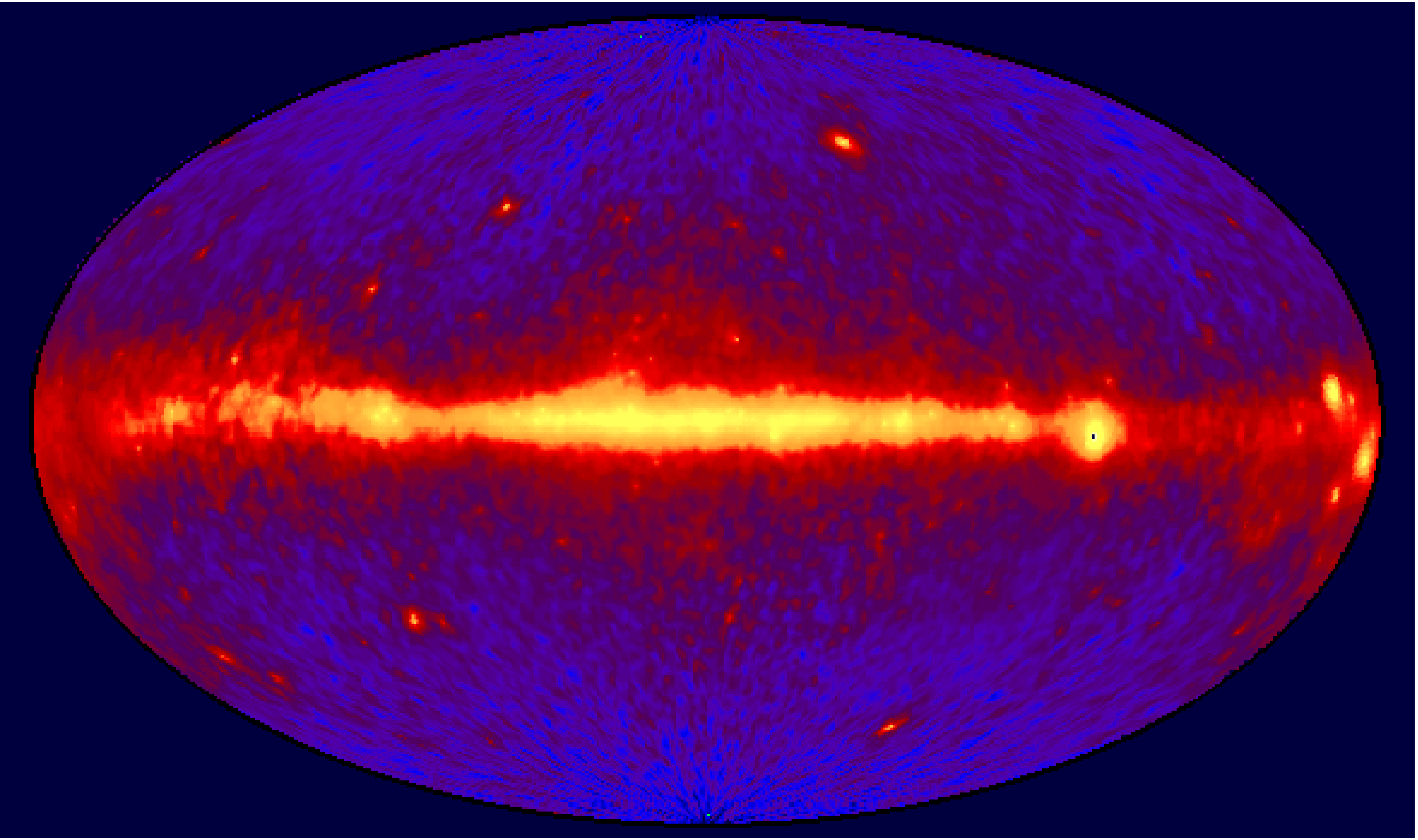
- Photons
- Neutrinos
- Cosmic Rays $(p, e^-, \bar{p}, e^+, \ldots)$
- Gravitational Waves

Messenger Properties are a "Fundamental Physics" problem

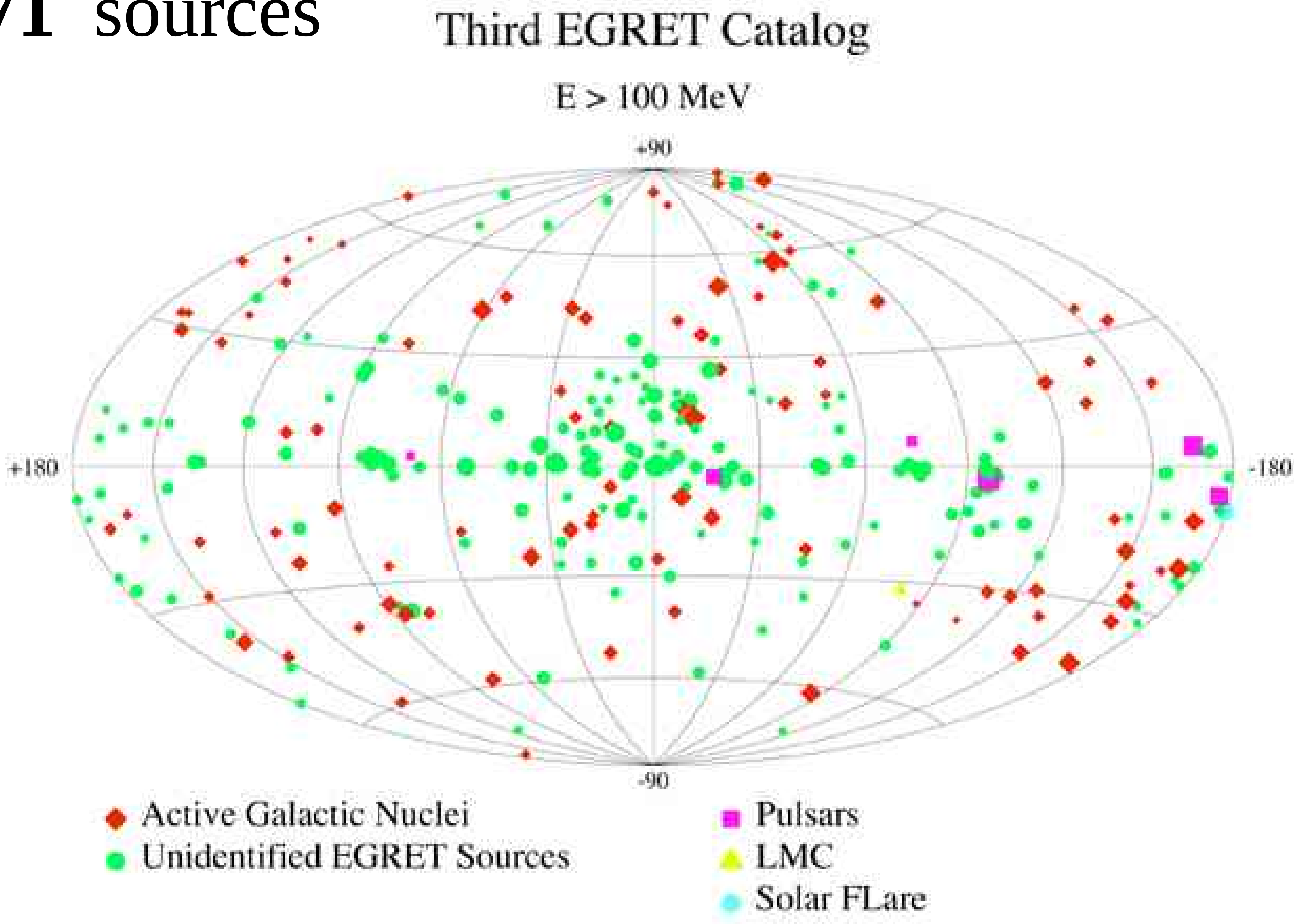
Compton Gamma Ray Observatory

1991-2000

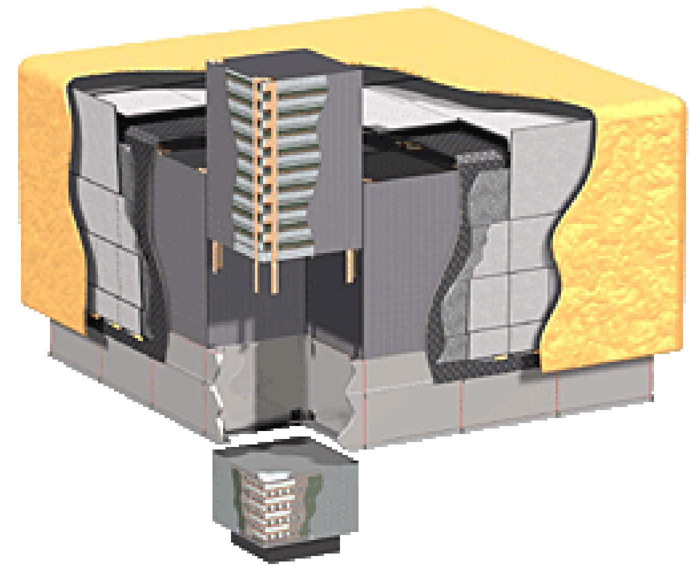
EGRET all Sky Map



271 sources

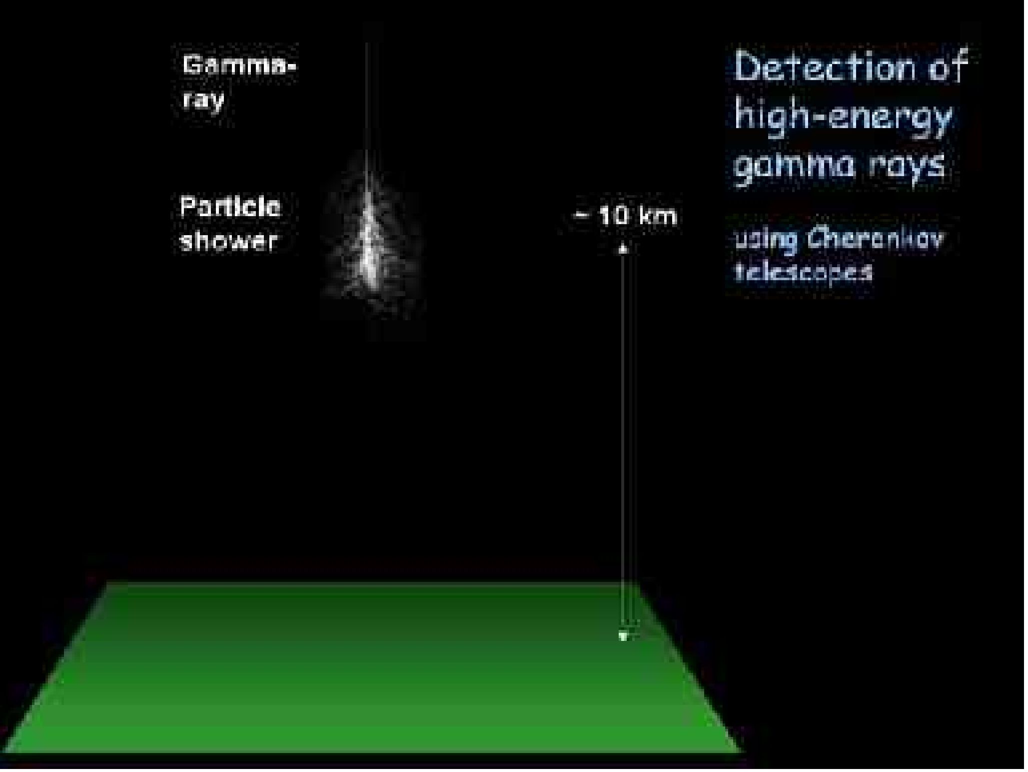

Third EGRET Catalog
E > 100 MeV
+90
+180
-180
-90
Active Galactic Nuclei
Unidentified EGRET Sources
Pulsars
LMC
Solar FLare

GLAST

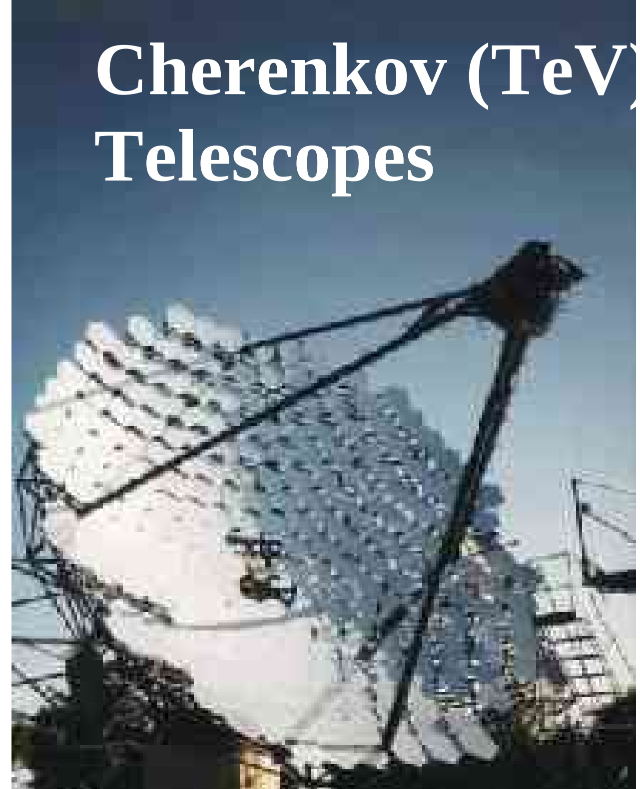


Launch 2007

Order of magnitude improvement over EGRET

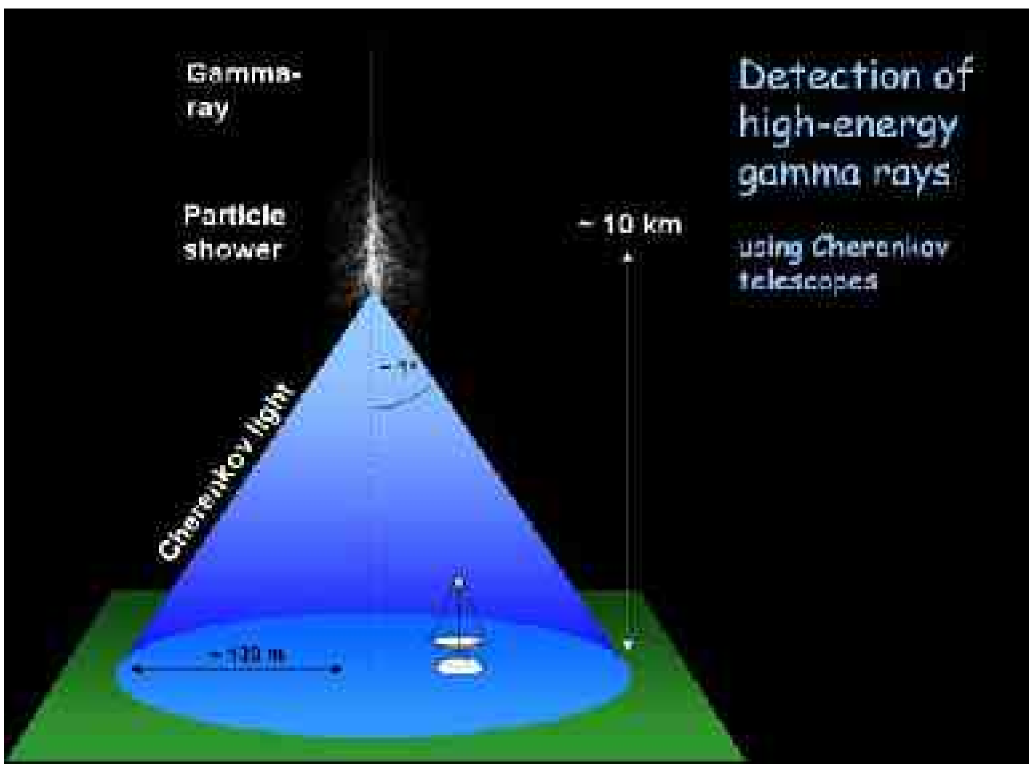


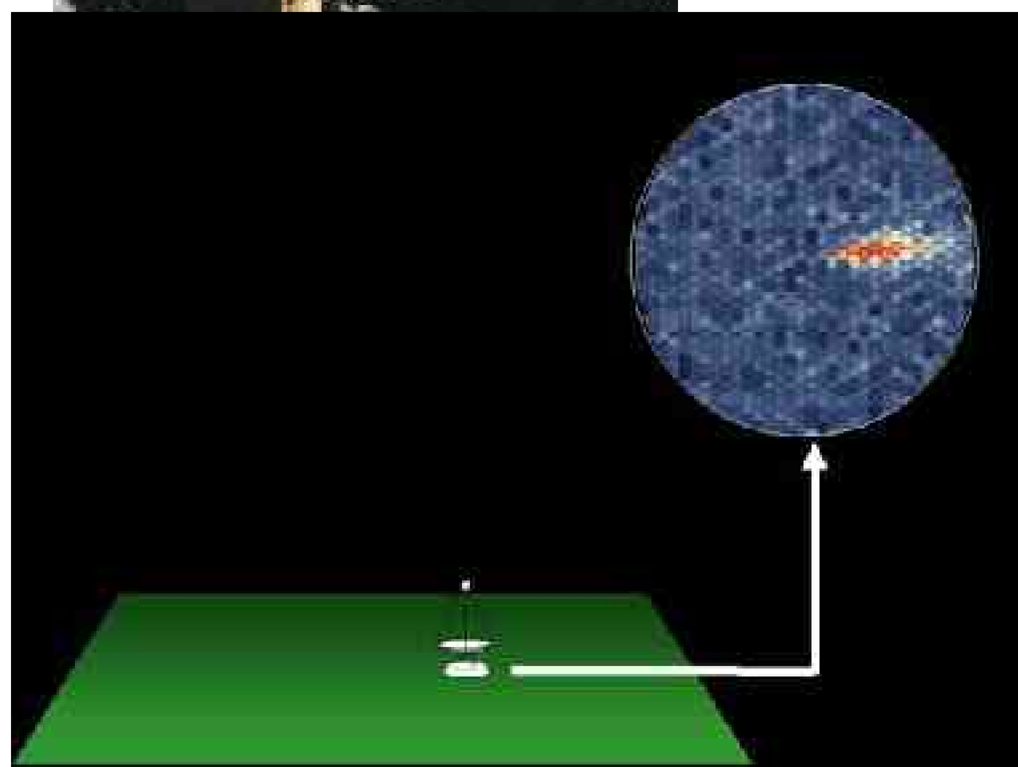
Cherenkov (TeV) Telescopes



Whipple
HEGRA
CAT
Cangaroo

MAGIC
HESS
VERITAS





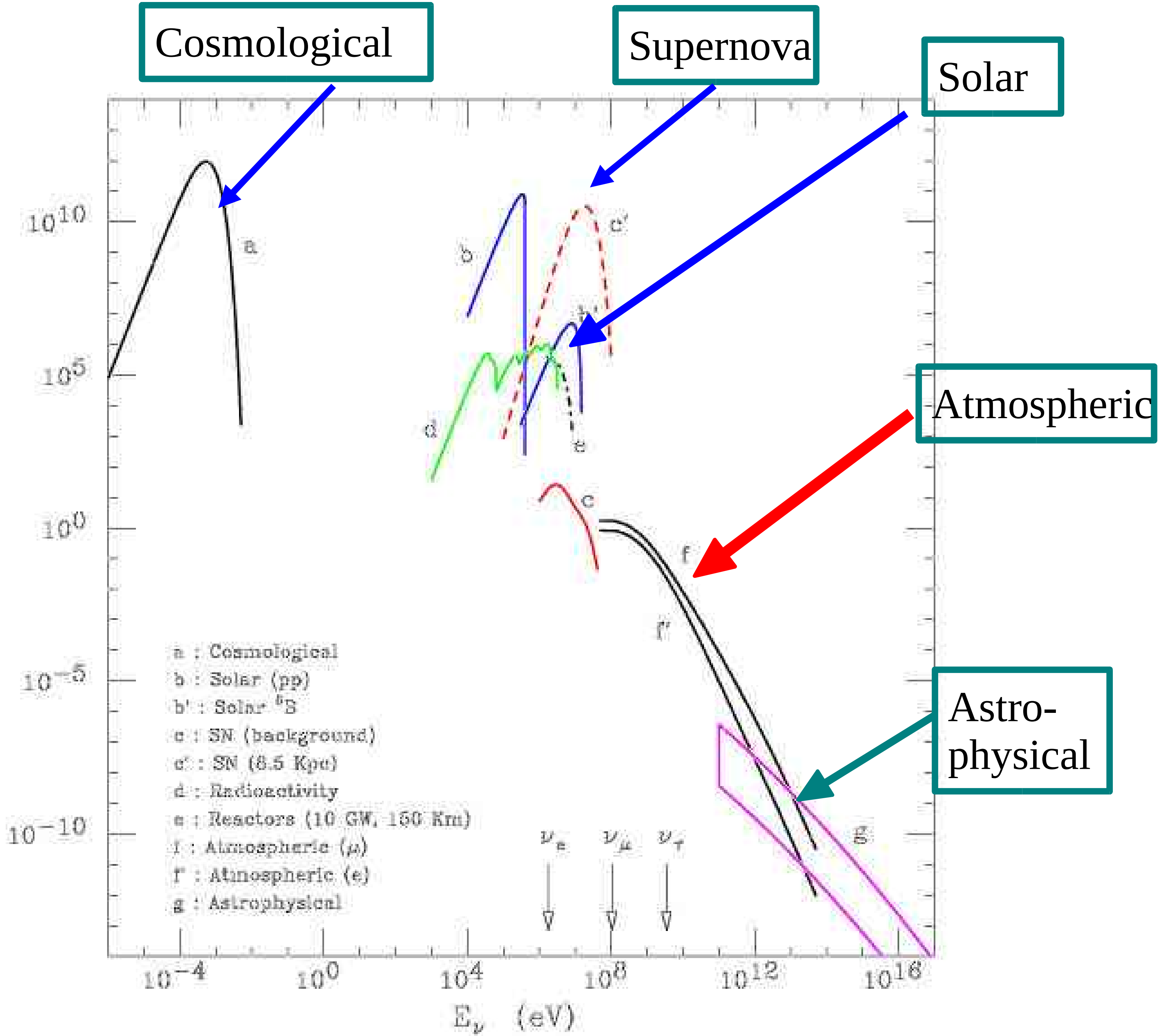
Discovery of several classes of
Astrophysical Objects (or Events)
Where particles (electrons and/or positrons)
are accelerated to UltraRelativistic Energy

AGN
GRB
SuperNova Remnants
MicroQuasars

NEUTRINO PHYSICS

- Particle Properties
- Astrophysics with Neutrinos

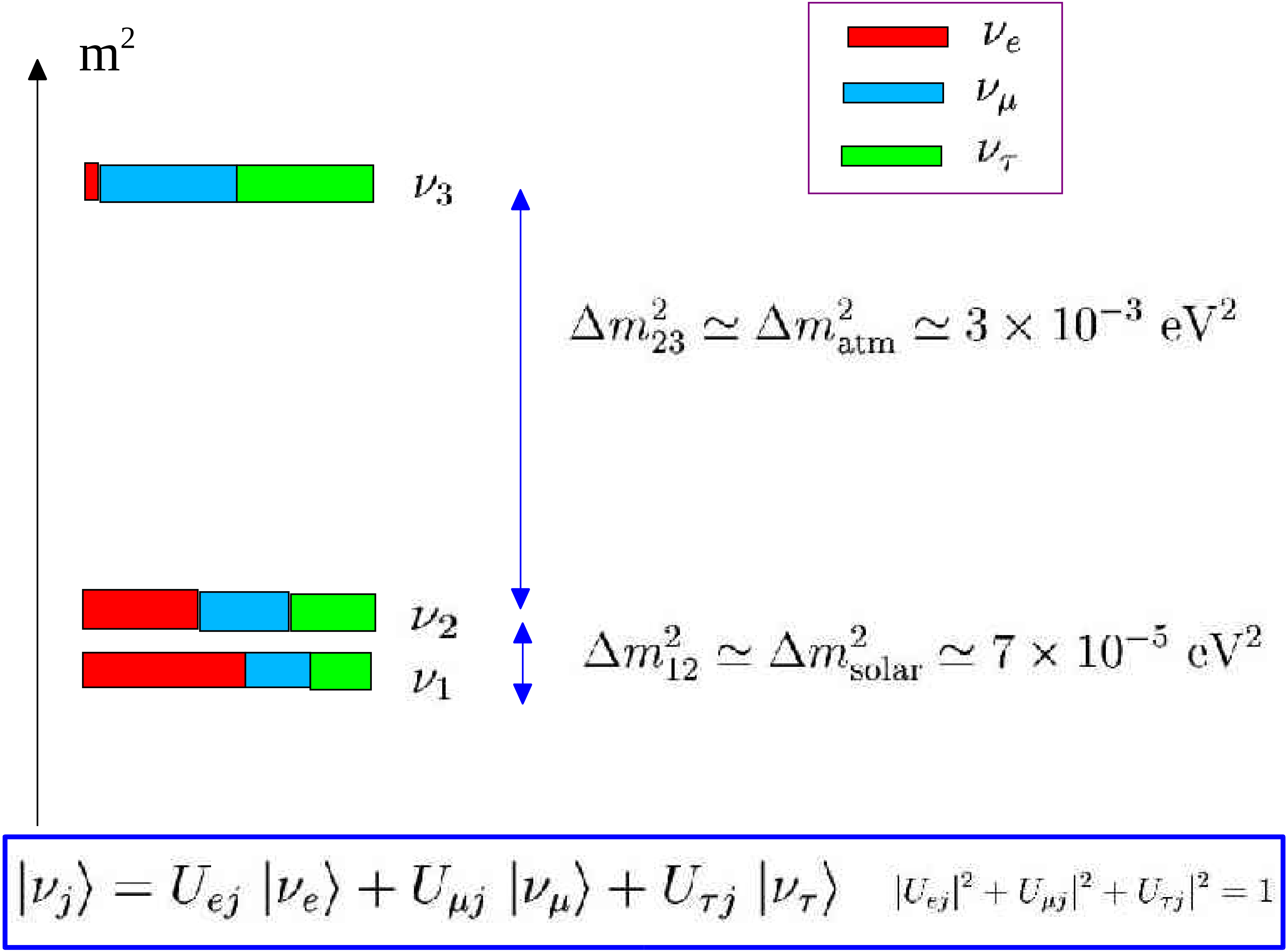
Natural ν Fluxes



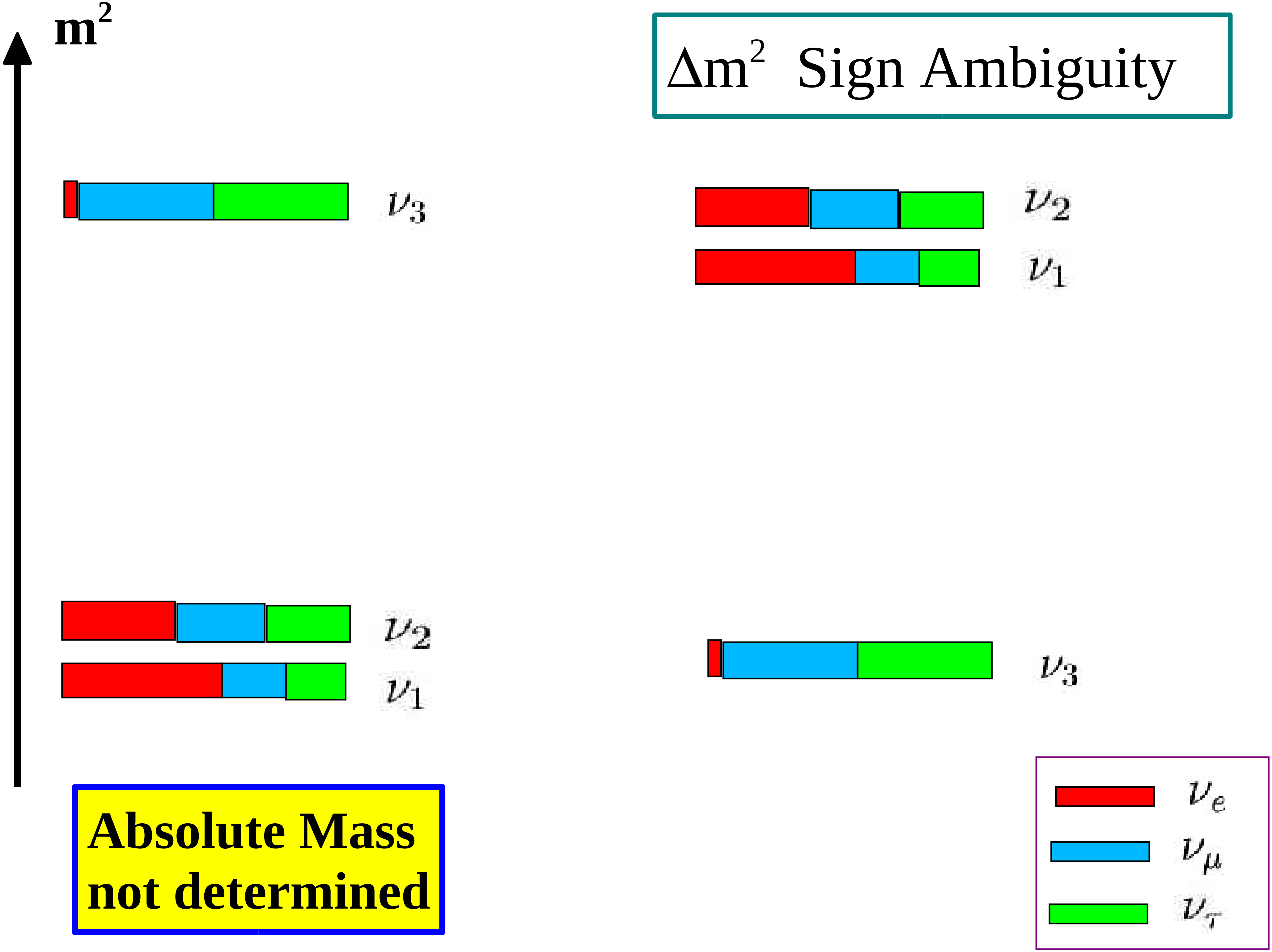
3 type (FLAVORs) of Neutrinos

ν_e ν_μ ν_τ

$\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$



m^2
ν_e
ν_μ
ν_τ
ν_3
ν_2
ν_1
$\Delta m^2_{23} \simeq \Delta m^2_{\rm atm} \simeq 3 \times 10^{-3}\ {\rm eV}^2$
$\Delta m^2_{12} \simeq \Delta m^2_{\rm solar} \simeq 7 \times 10^{-5}\ {\rm eV}^2$
$|\nu_j\rangle = U_{ej}\ |\nu_e\rangle + U_{\mu j}\ |\nu_\mu\rangle + U_{\tau j}\ |\nu_\tau\rangle$
$|U_{ej}|^2 + |U_{\mu j}|^2 + |U_{\tau j}|^2 = 1$



Δm^2 Sign Ambiguity
m^2
ν_3
ν_2
ν_1
ν_2
ν_1
ν_3
Absolute Mass not determined
ν_e
ν_μ
ν_τ

Dirac Particle

e^-_L e^-_R

e^+_L e^+_R

ν_L ν_R

$\overline{\nu}_L$ $\overline{\nu}_R$

Majorana Particle

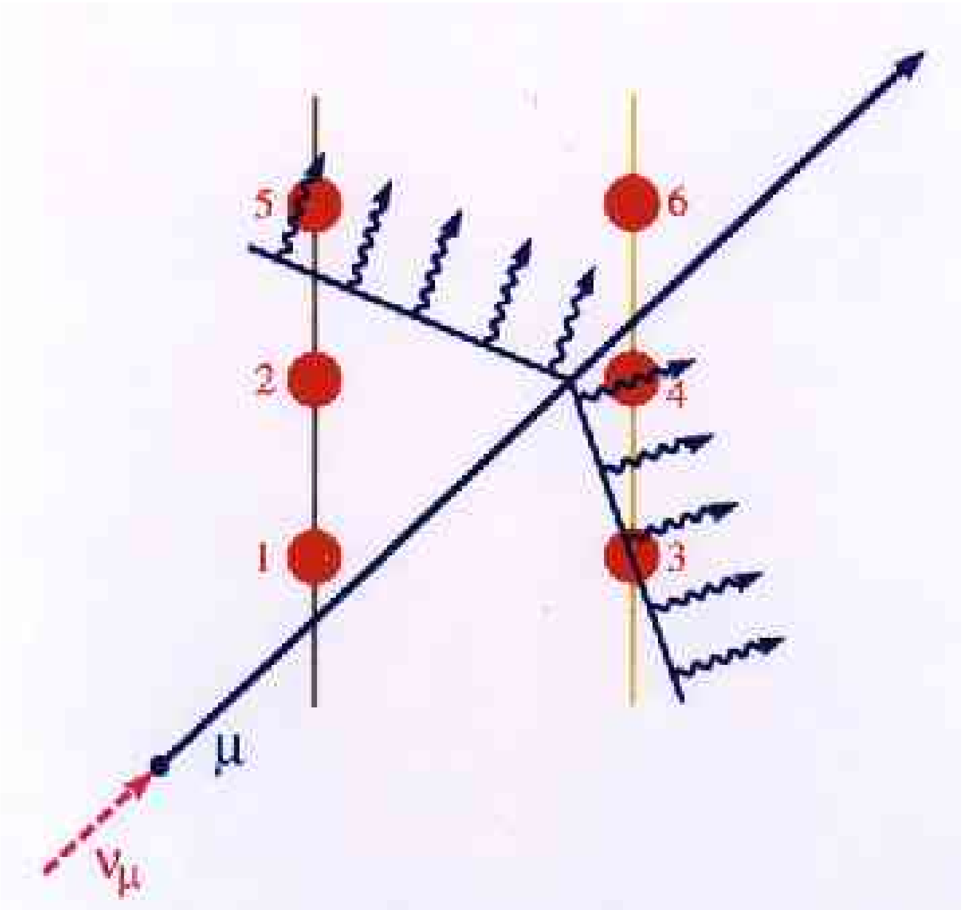
ν_L

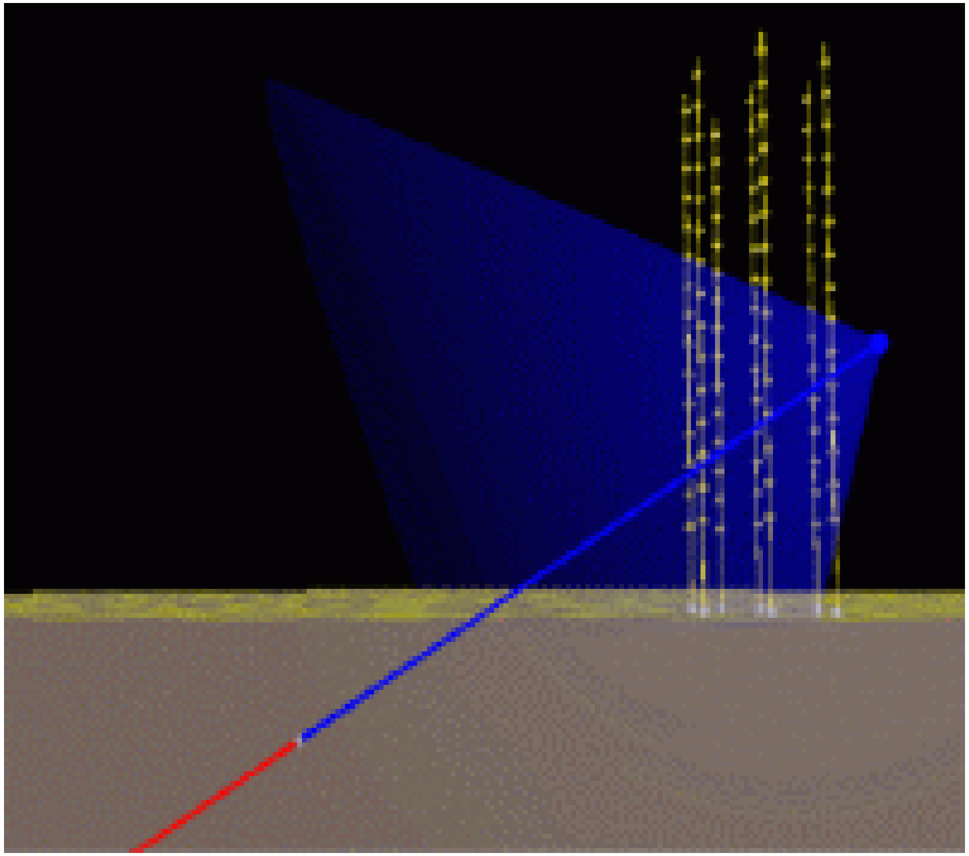
$\overline{\nu}_R$

Neutrino Telescopes

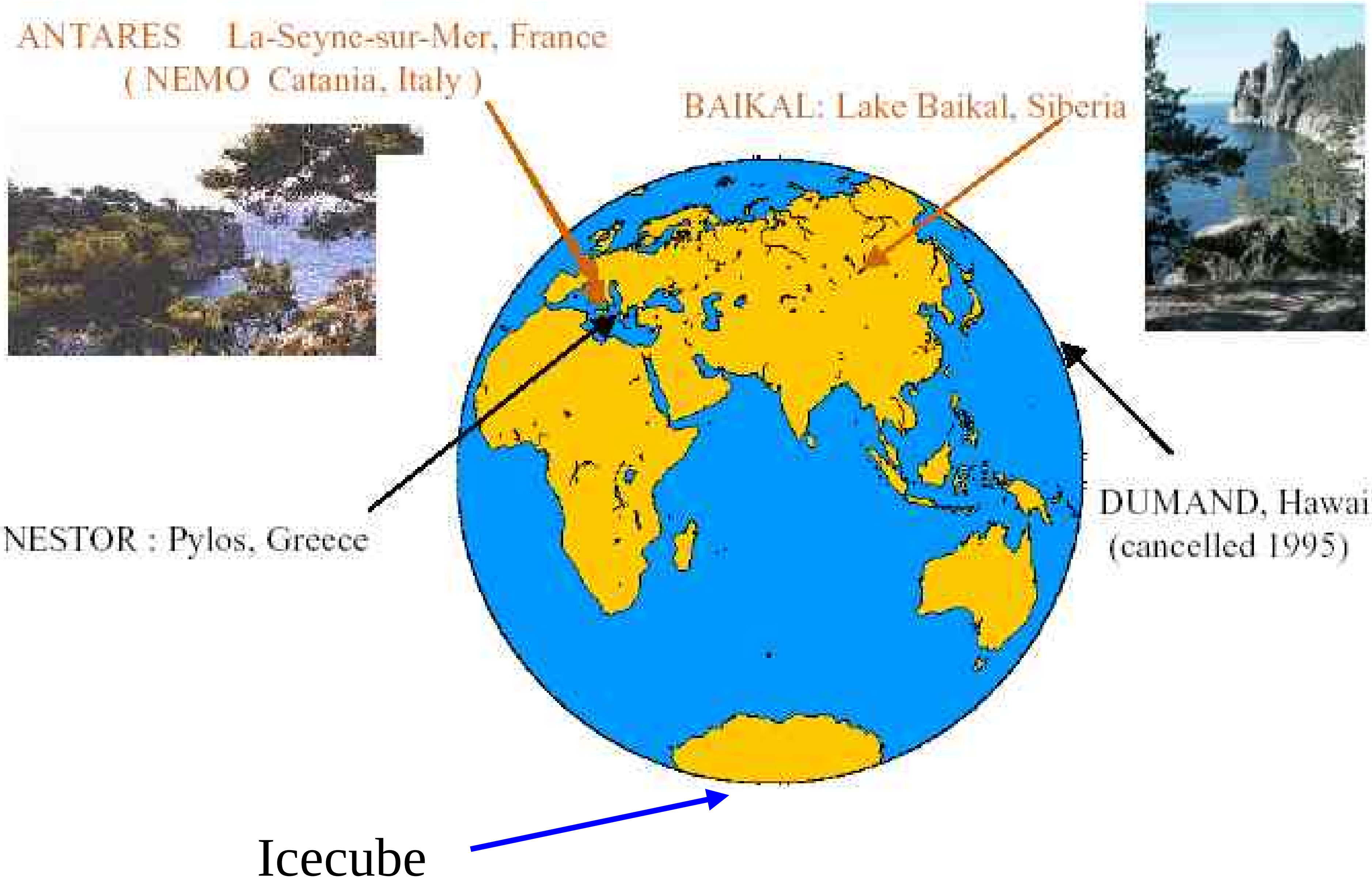
Antares, Nemo, Nestor
Amanda, Ice-cube

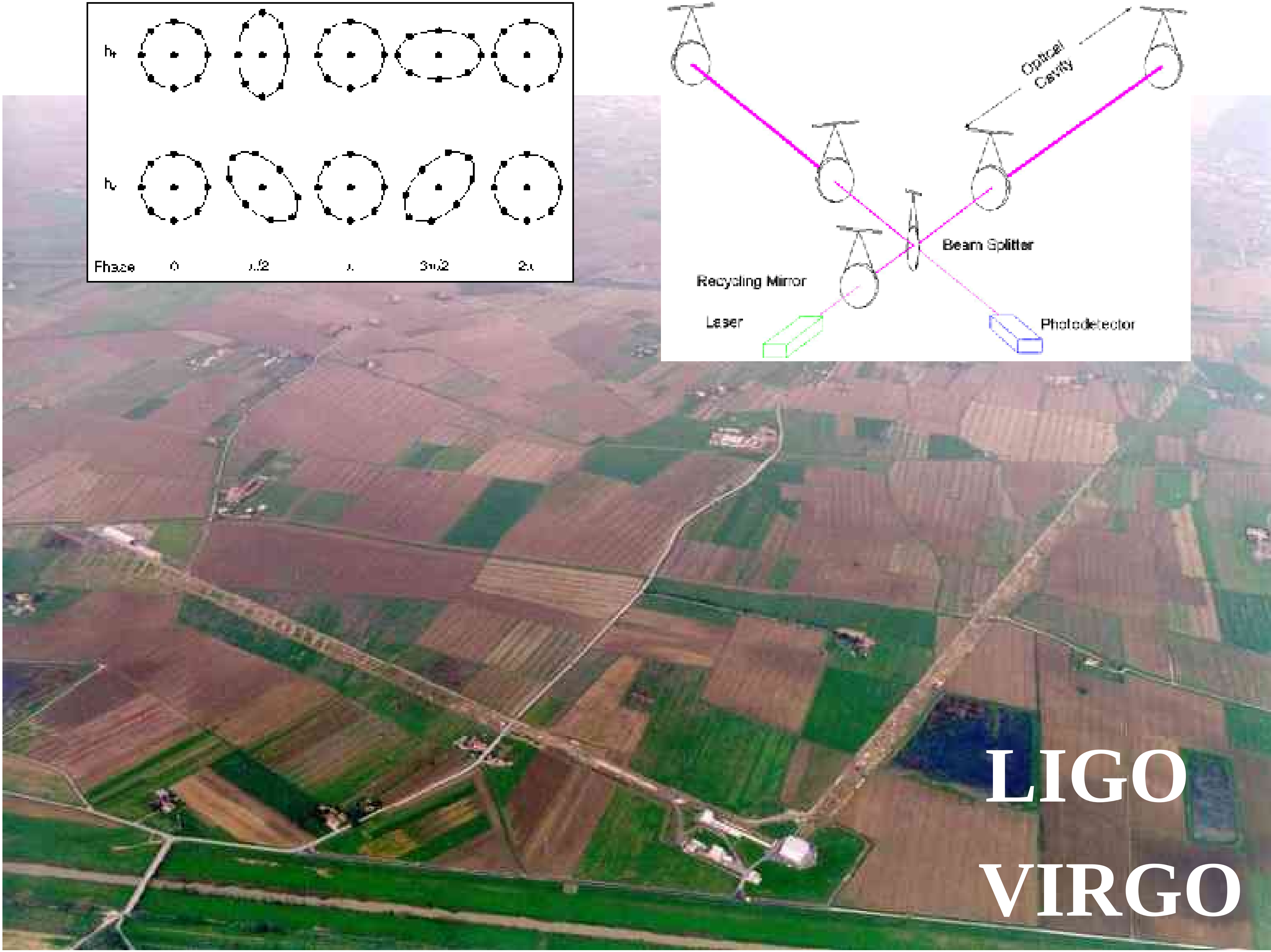
Detection concept





Neutrino Telescopes




h+
h×
Phase 0 π/2 π 3π/2 2π
Optical Cavity
Beam Splitter
Recycling Mirror
Laser
Photodetector
LIGO
VIRGO

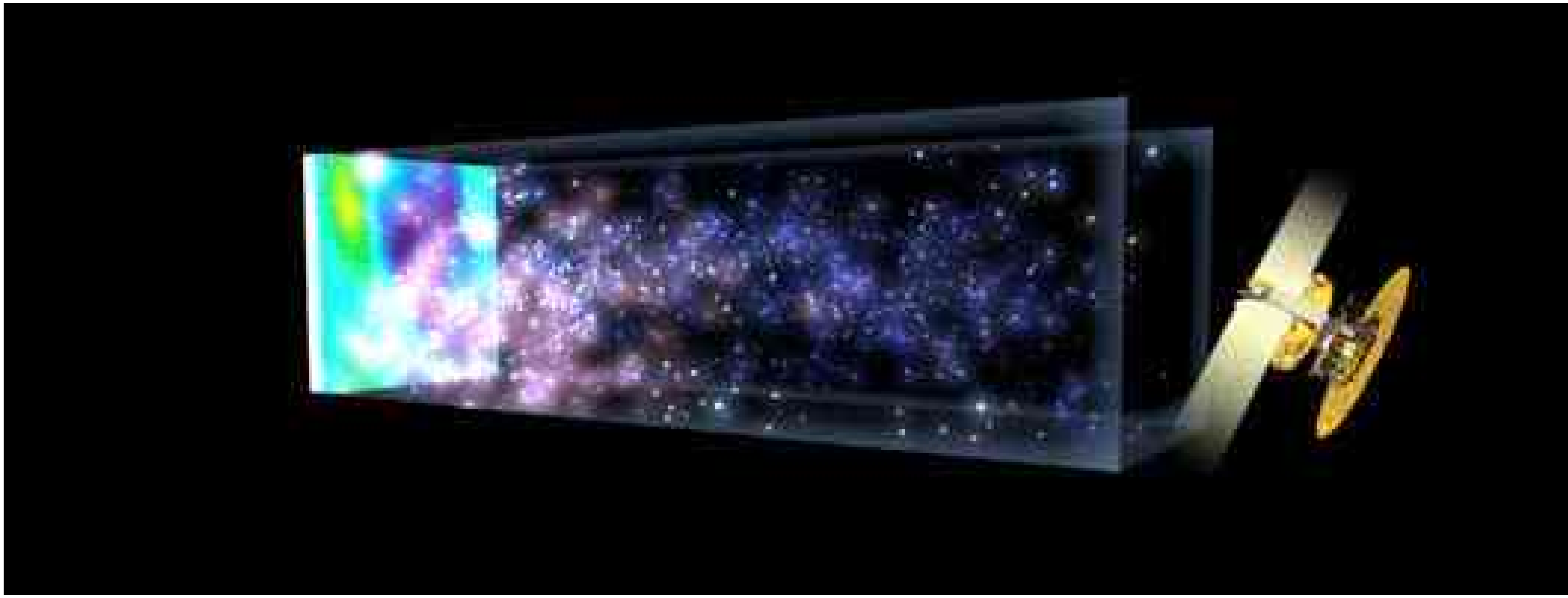
LISA - Interferometer in Space

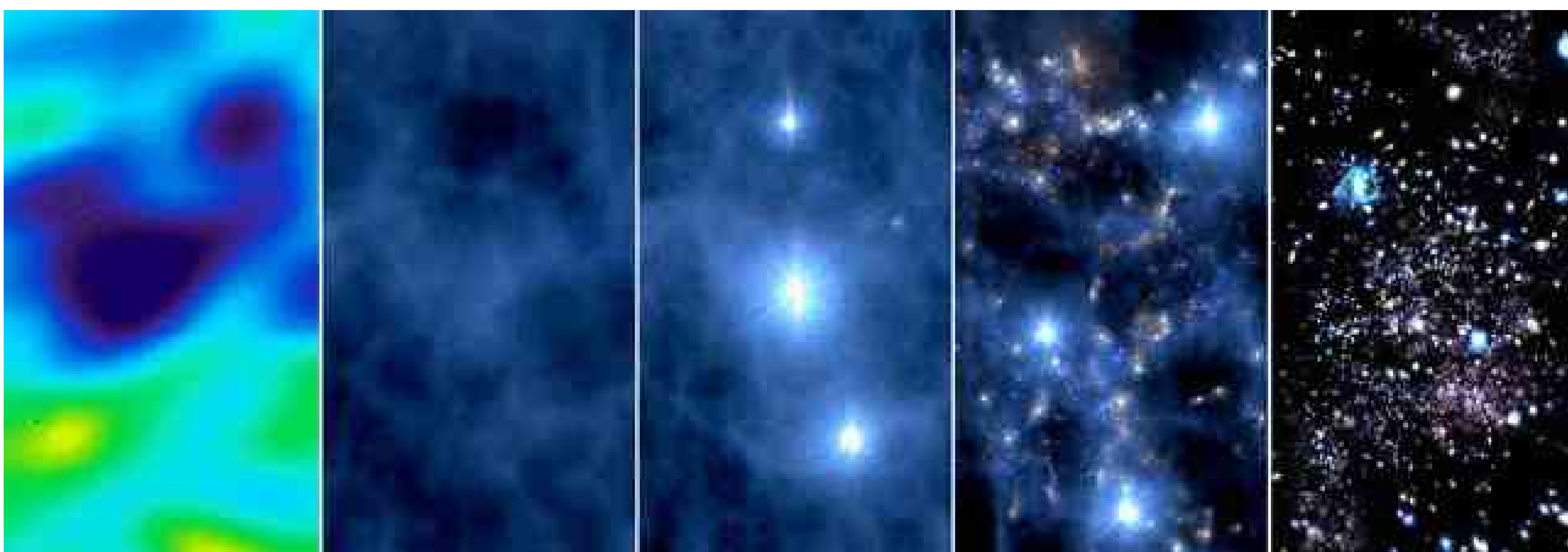
Resonant ANTENNAE

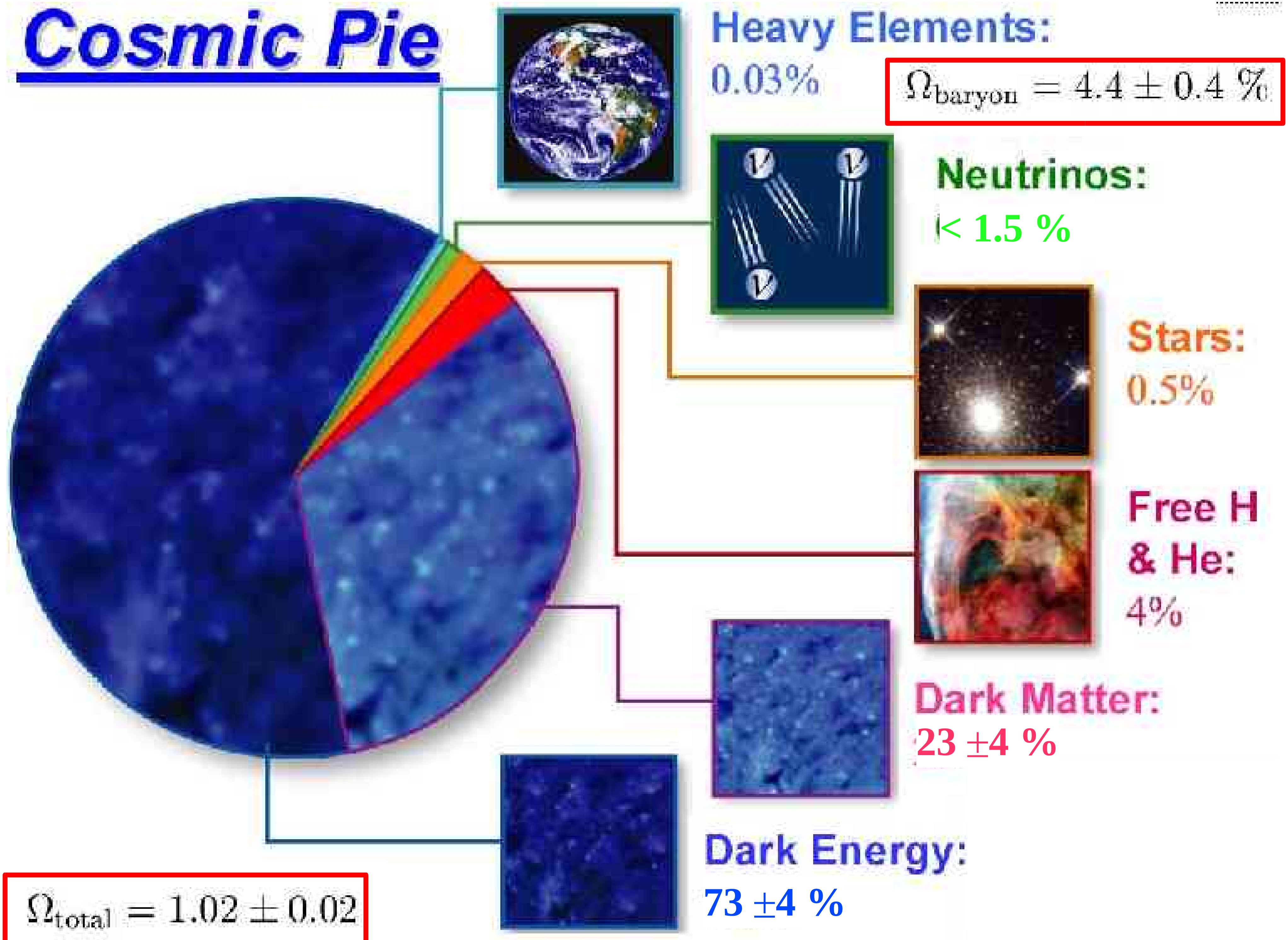
NAUTILUS (CERN):
Aluminum cylinder,
M = 2300 kg,

T = 0.1 K
Resonance frequencies:
908 and 924 Hz

COSMOLOGY






Cosmic Pie
Heavy Elements:
0.03%
$\Omega_{\text{baryon}} = 4.4 \pm 0.4$ %
Neutrinos:
< 1.5 %
Stars:
0.5%
Free H
& He:
4%
Dark Matter:
23 ±4 %
Dark Energy:
73 ±4 %
$\Omega_{\text{total}} = 1.02 \pm 0.02$

DARK ENERGY

DARK MATTER

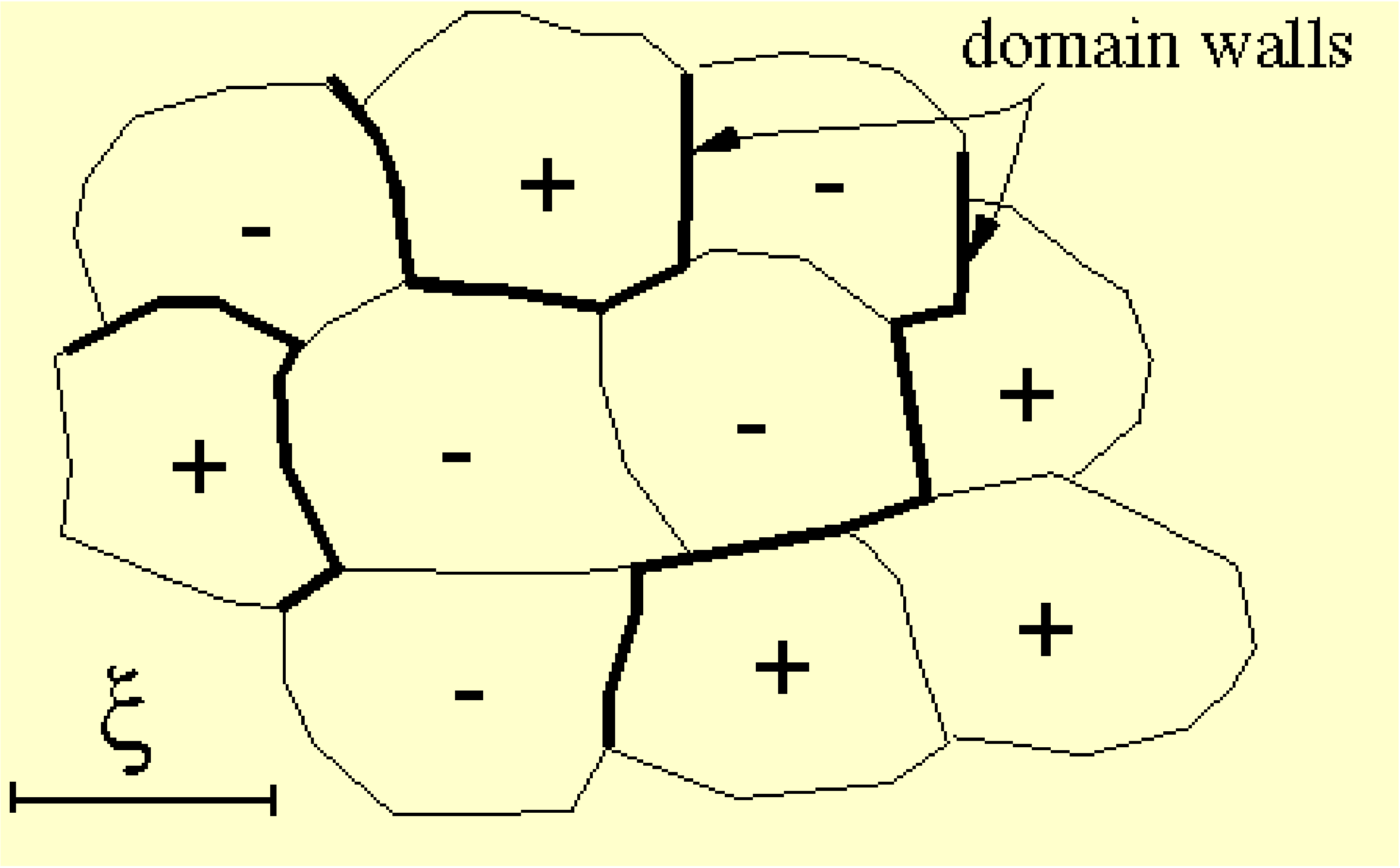
IMPLICATIONS of the EXISTENCE of COSMIC RAYS above 10^{20} eV

Possibly Very Profound

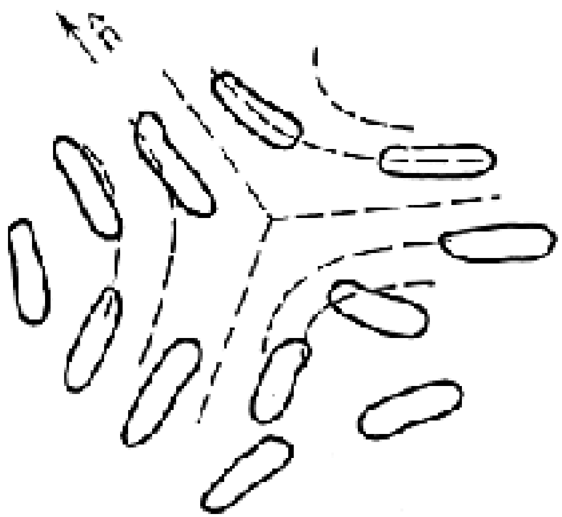
TOP - DOWN Models

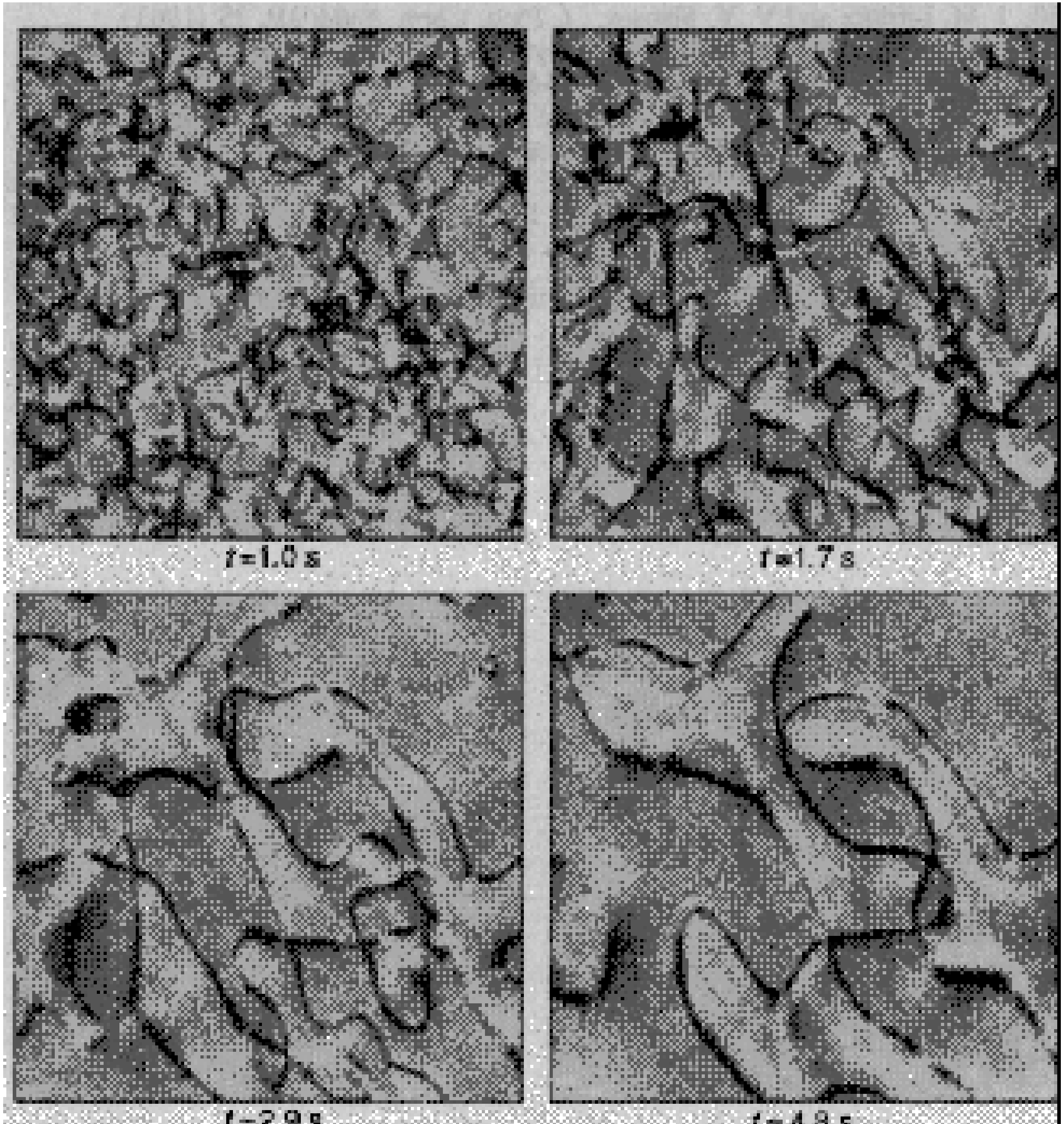
High Energy Cosmic Rays as DECAY products of
Massive "Exotic" Objects (Relics of the Early Universe)

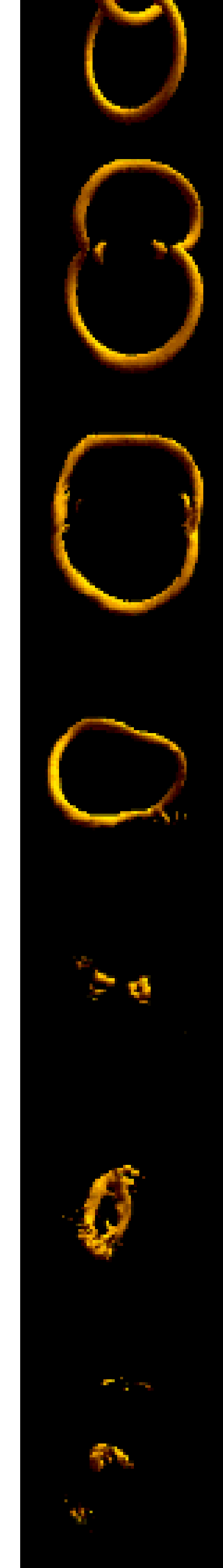
Topological Defects. SuperMassive Particles



Nematic Liquid Crystals

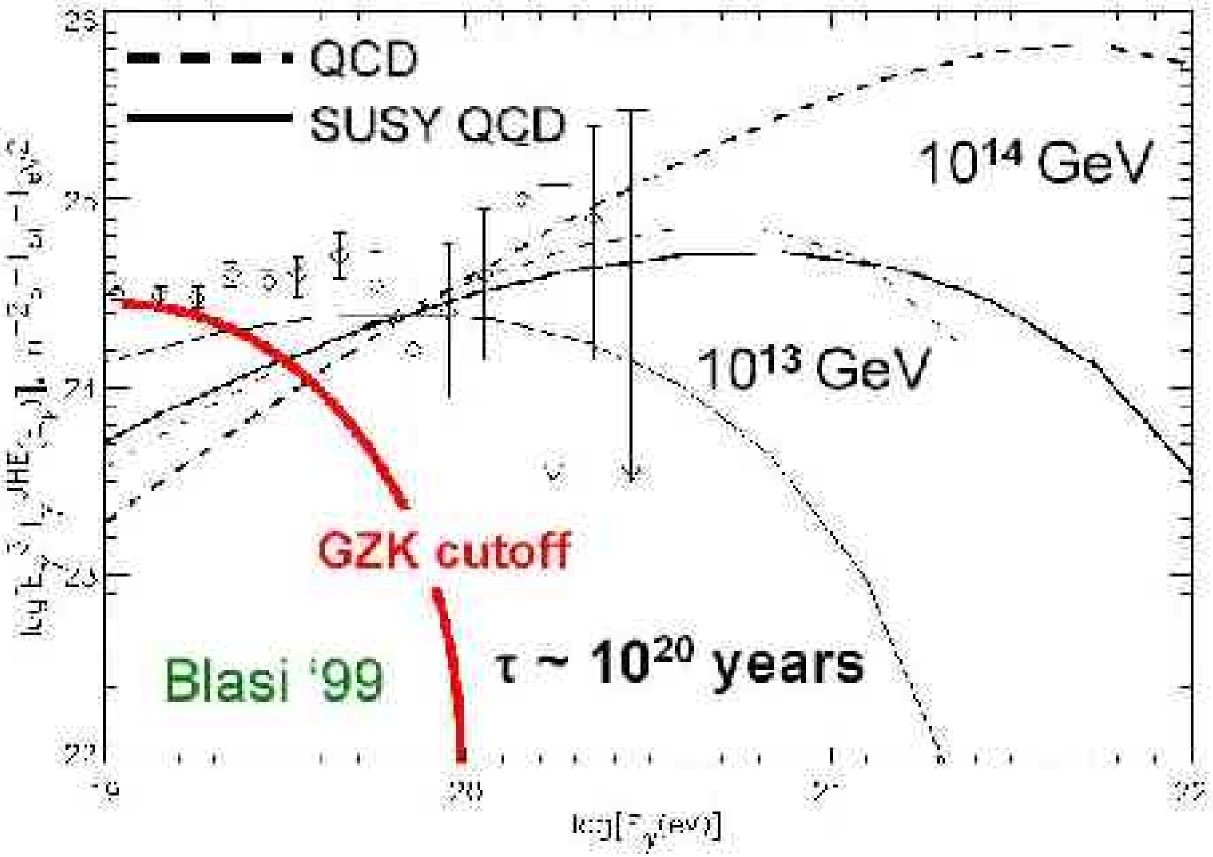



t=1.0 s
t=1.7 s
t=2.9 s
t=4.8 s

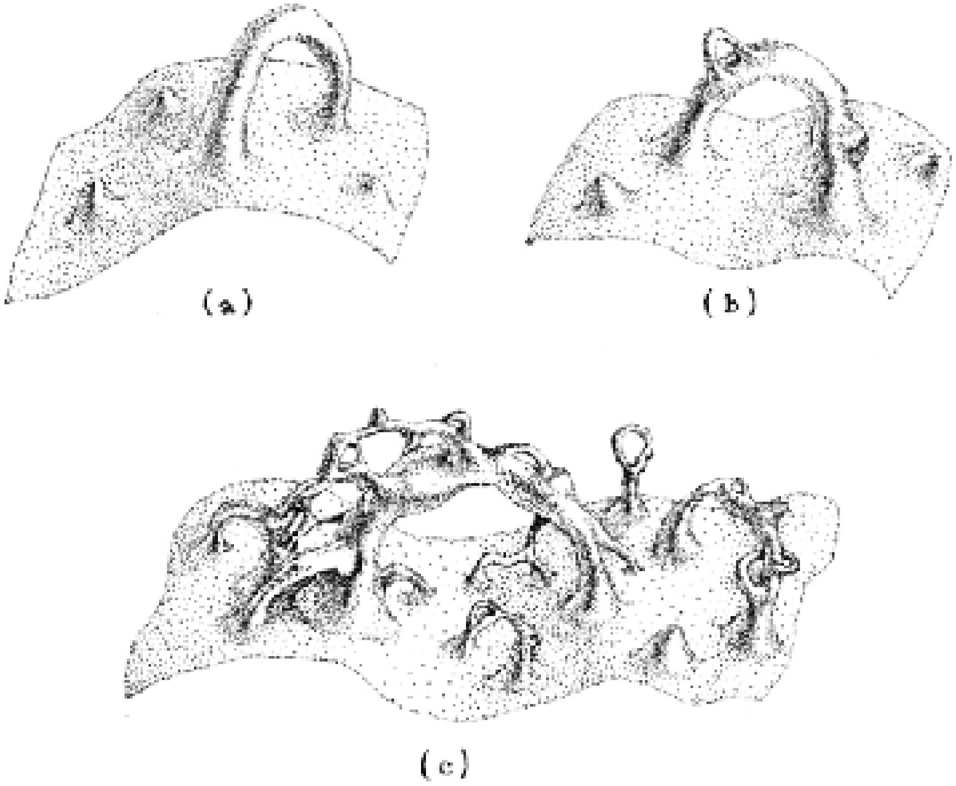


WIMPZILLA's

M = 10^9 - 10^{19} GeV



Phenomenology of QUANTUM GRAVITY ?!



Effective speed of photons in quantum space foam

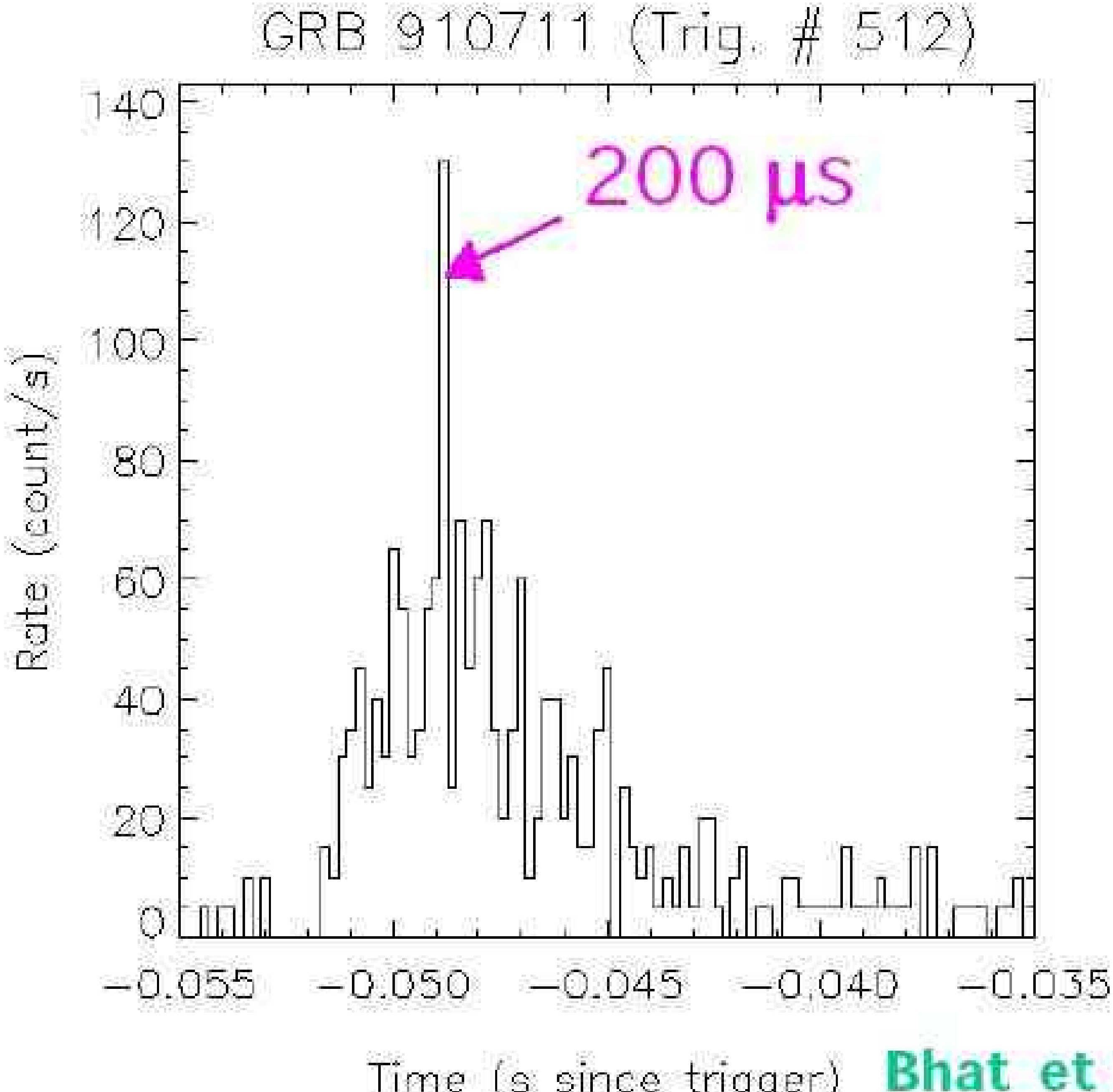
$$c(E) = c \times \left(1 - \xi \frac{E}{M_{\rm Planck}} + \ldots\right)$$

$$\Delta t \simeq \xi \; \frac{E}{M_{\rm Planck}} \; \frac{L}{c}$$

$$\Delta t \simeq 0.06 \; \xi \; E_{\rm GeV} \;\; z \; {\rm sec}$$

High Energy Photons delayed

SHORTEST GRB: ~6 ms



Bhat et al. 1992

Modifications of Reaction Thresholds

$$p + \gamma \rightarrow p + \pi^{\circ}$$

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

$$E \times \varepsilon = m_e^2$$

$$E \times \varepsilon - \xi' \frac{E^3}{M_{\mathrm{Planck}}} = m_e^2$$

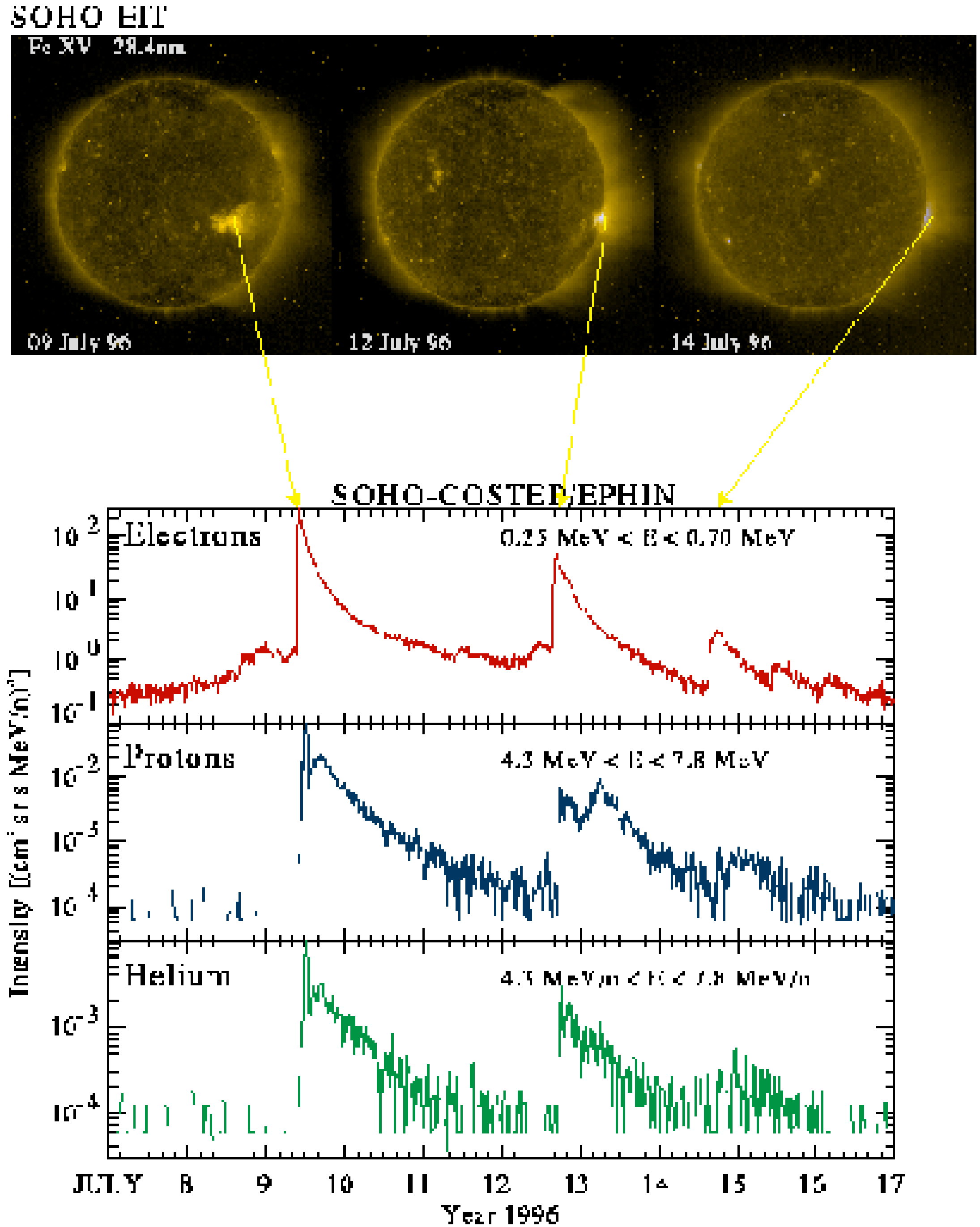
The "BORING" Conservative Solution:

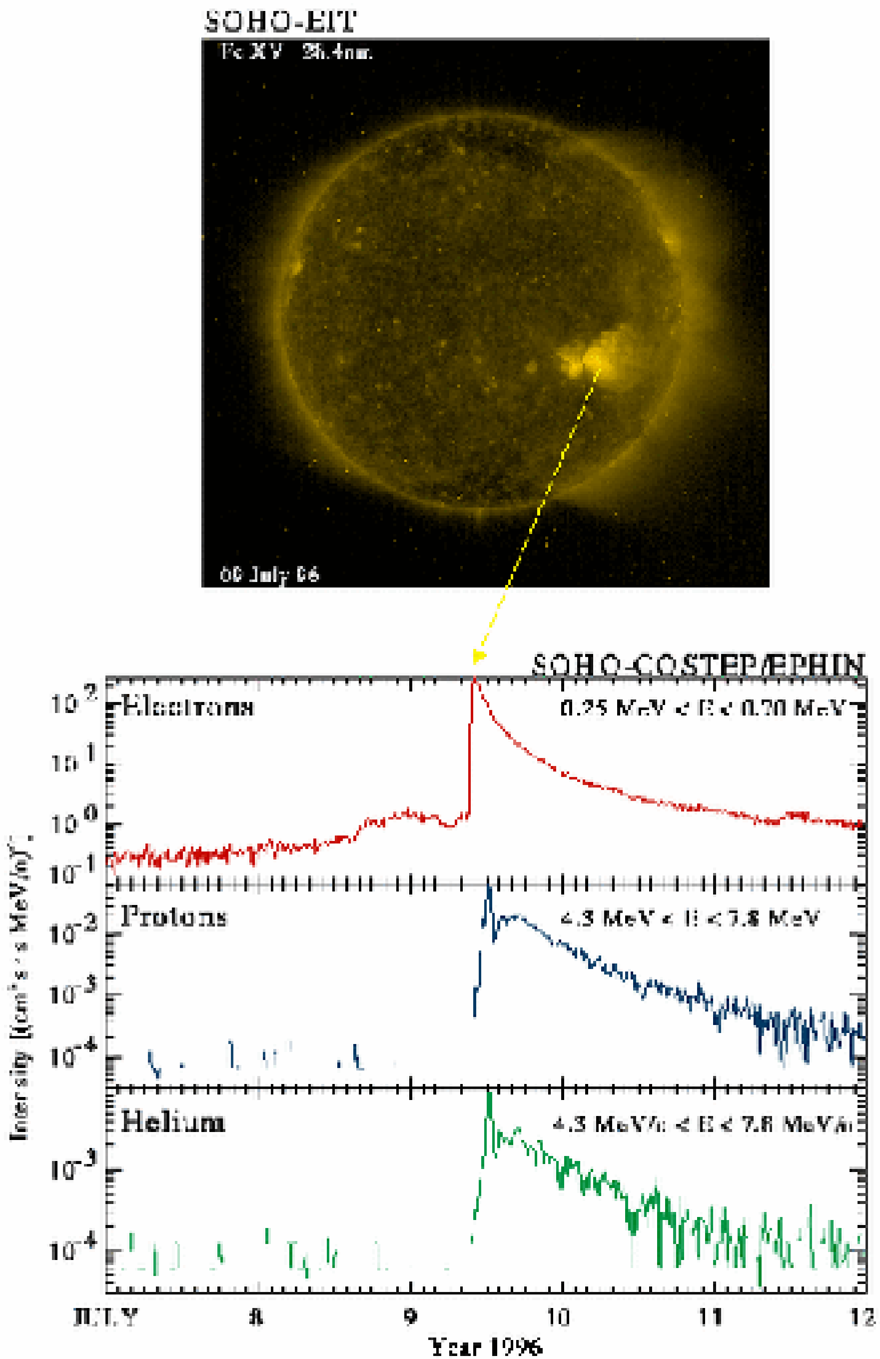
Cosmic Ray are Accelerated

The GZK cutoff exists

is NOT "boring" at ALL !!

Shock Acceleration of Cosmic Rays in the sun





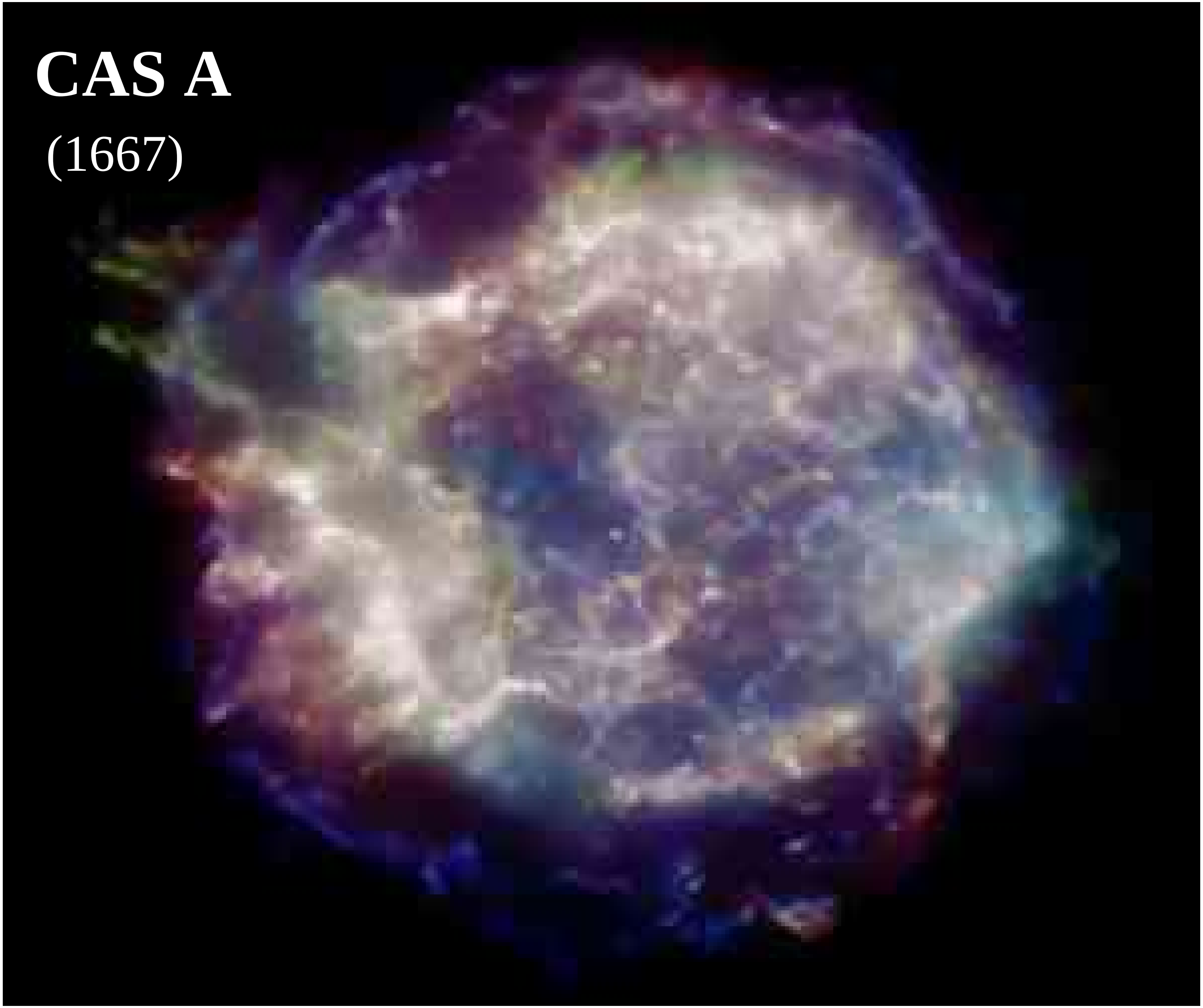
Mechanism
reproduced at

MUCH LARGER SCALE
(size, magnetic field.
Velocity of plasma flows)

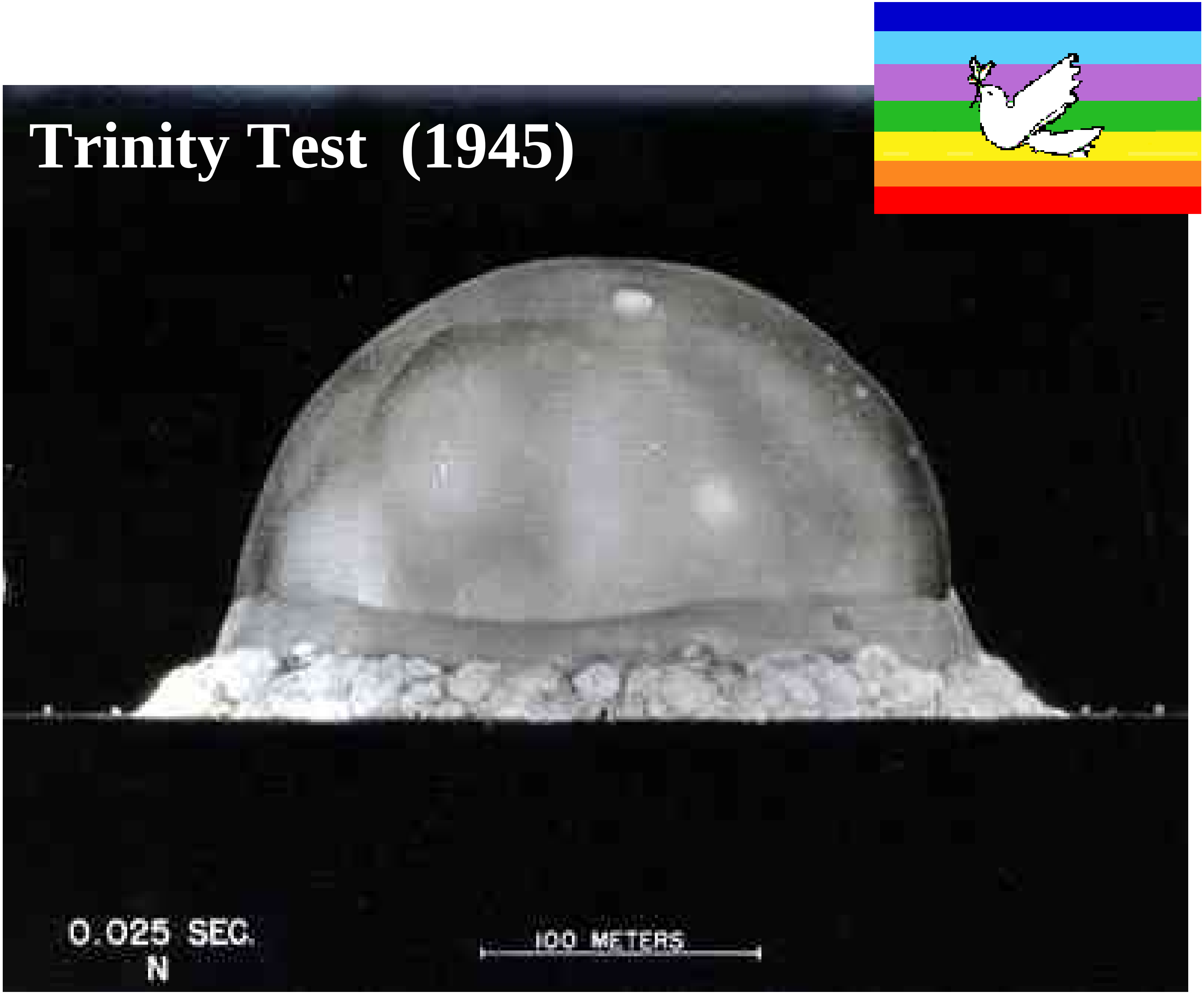
to produce the cosmic rays
up to the highest energy

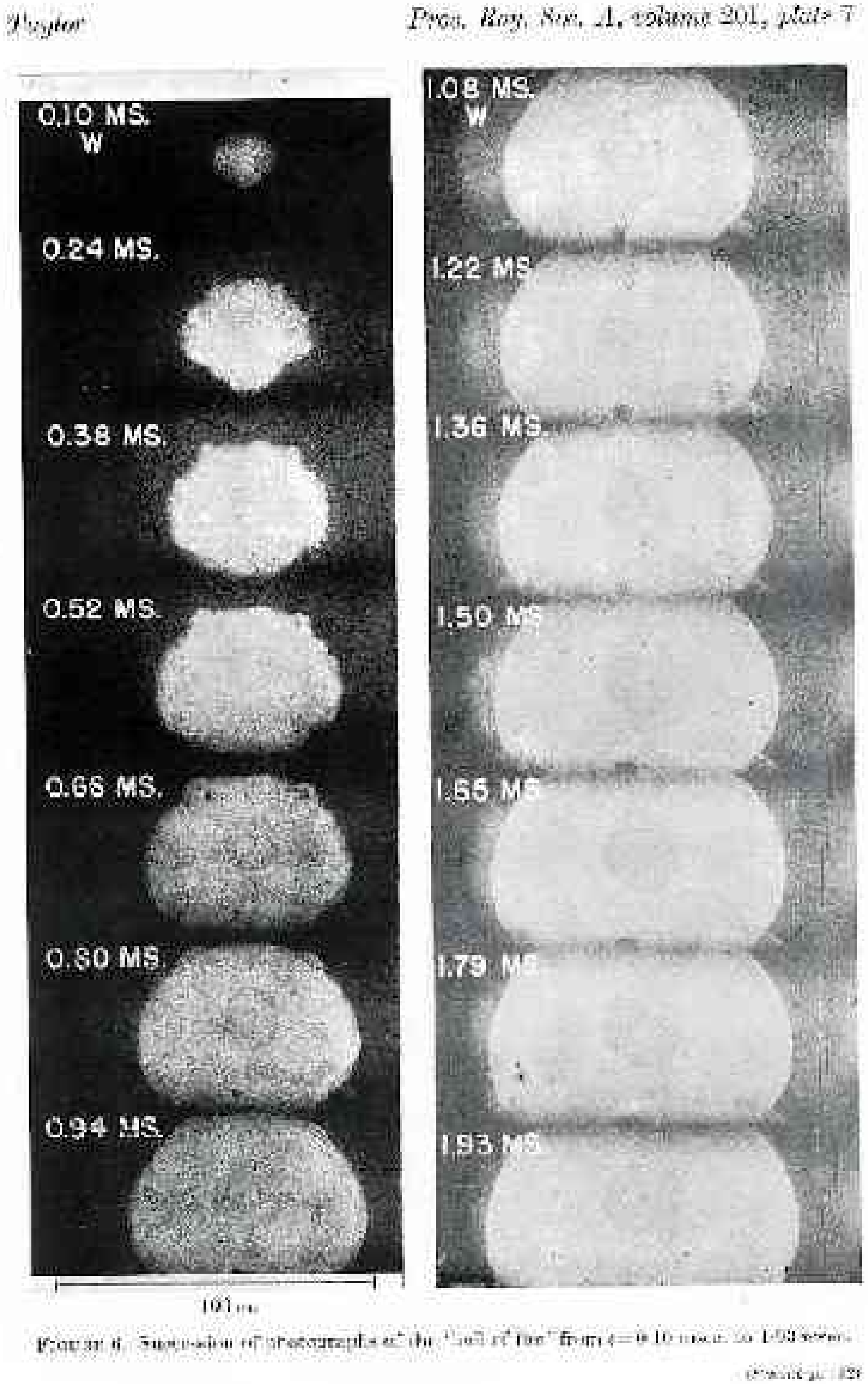
The Most Extraordinary BEASTS in the COSMOS

- Supernovae
- Gamma Ray Bursts
- AGN
- Microquasars


CAS A
(1667)

Trinity Test (1945)





Sedov-Taylor expansion

$R(t) = t^{5/2}$

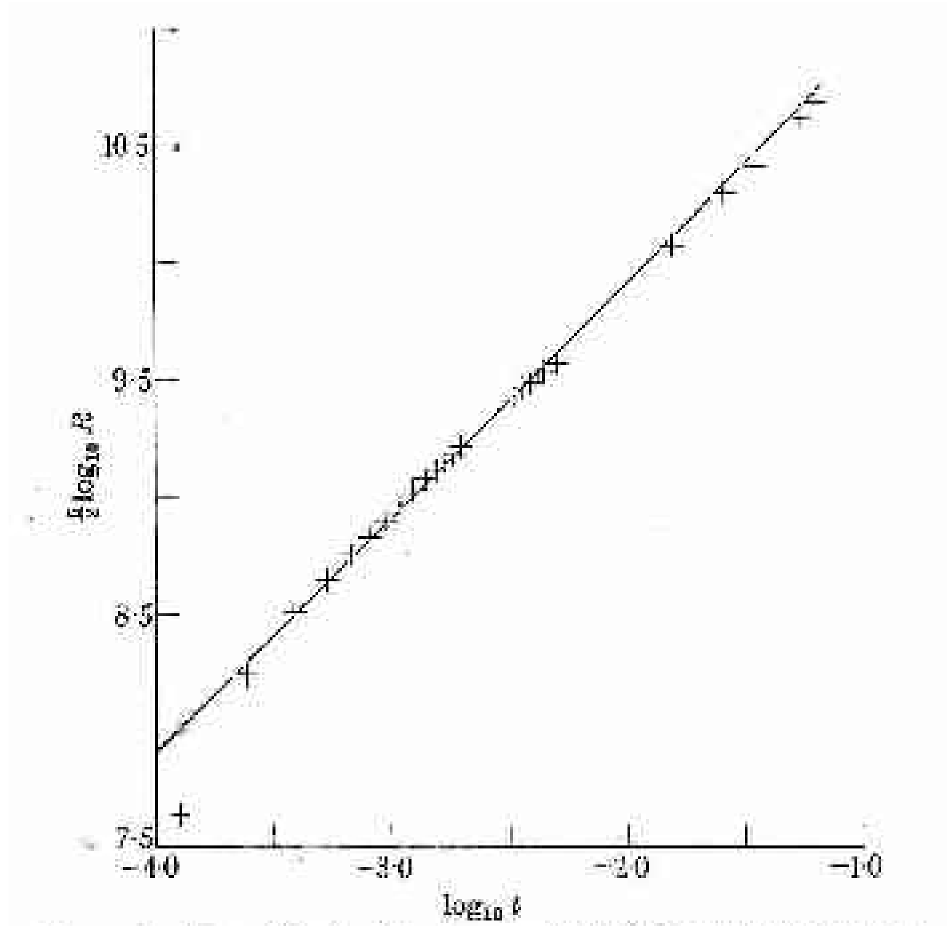


FIGURE 1. Logarithmic plot showing that $R^{5/2}$ is proportional to t.

The formation of a blast wave by a very intense explosion

I. Theoretical discussion

By Sir Geoffrey Taylor, F.R.S.

(*Received* 6 *October* 1949)

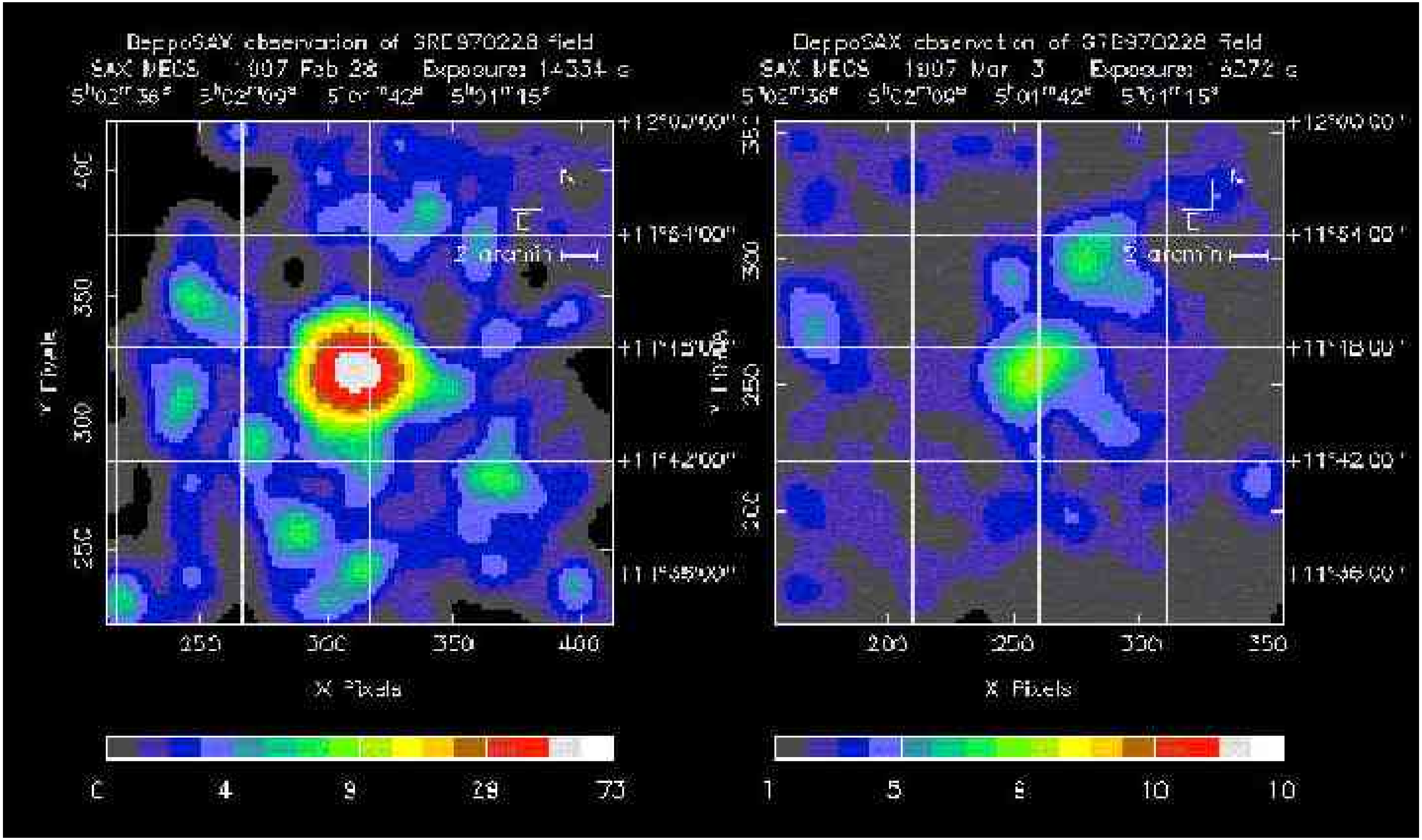
Summary and introduction

This paper was written early in 1941 and circulated to the Civil Defence Research Committee of the Ministry of Home Security in June of that year. The present writer had been told that it might be possible to produce a bomb in which a very large amount of energy would be released by nuclear fission—the name atomic bomb had not then been used—and the work here described represents his first attempt to form an idea of what mechanical effects might be expected if such an explosion could occur. In the then common explosive bomb mechanical effects were produced by the sudden generation of a large amount of gas at a high temperature in a confined space. The practical question which required an answer was: Would similar effects be produced if energy could be released in a highly concentrated form unaccompanied by the generation of gas? This paper has now been declassified, and though it has been superseded by more complete calculations, it seems appropriate to publish it as it was first written, without alteration, except for the omission of a few lines, the addition of this summary, and a comparison with some more recent experimental work, so that the writings of later workers in this field may be appreciated.

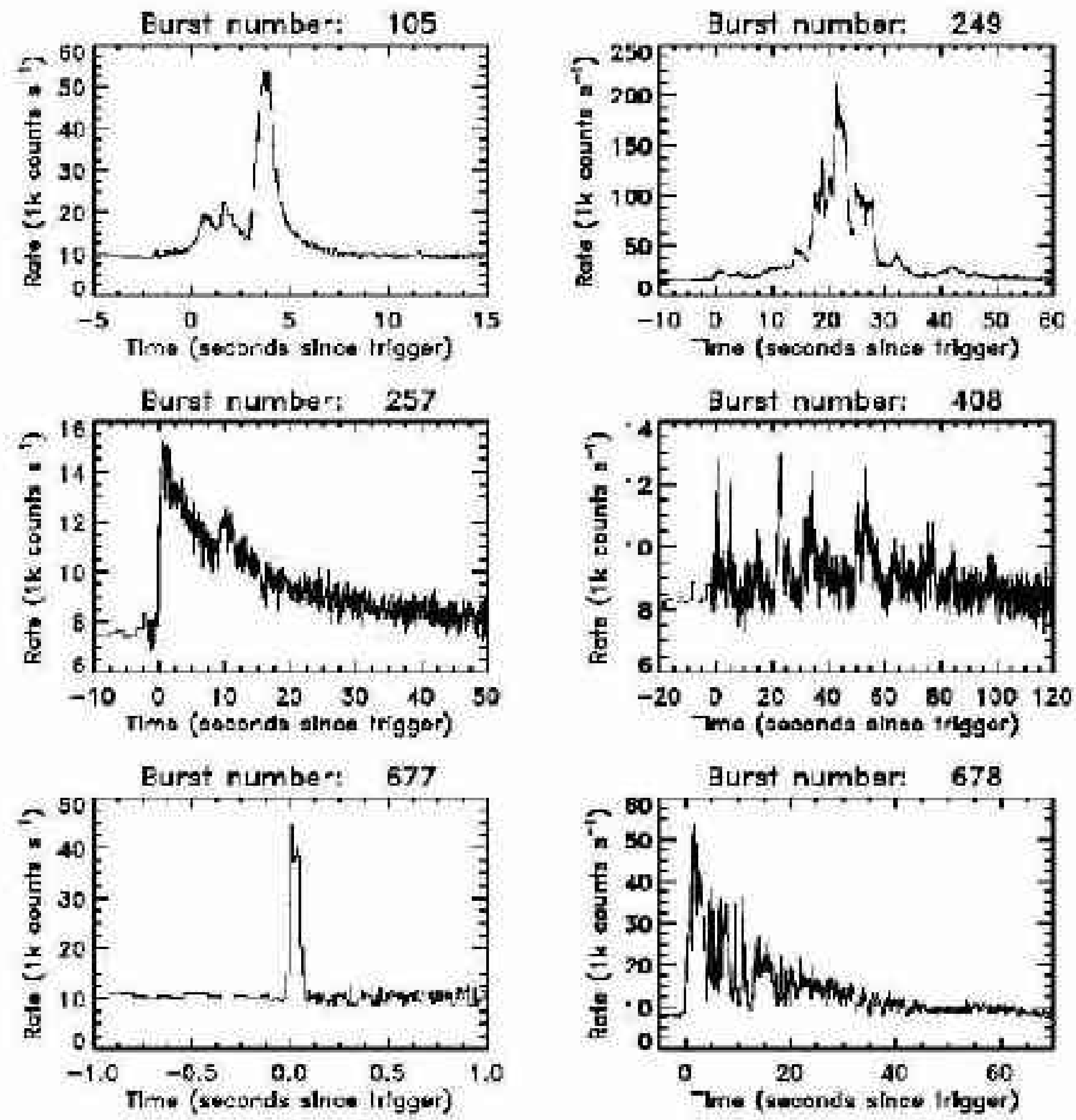
GRB 970228

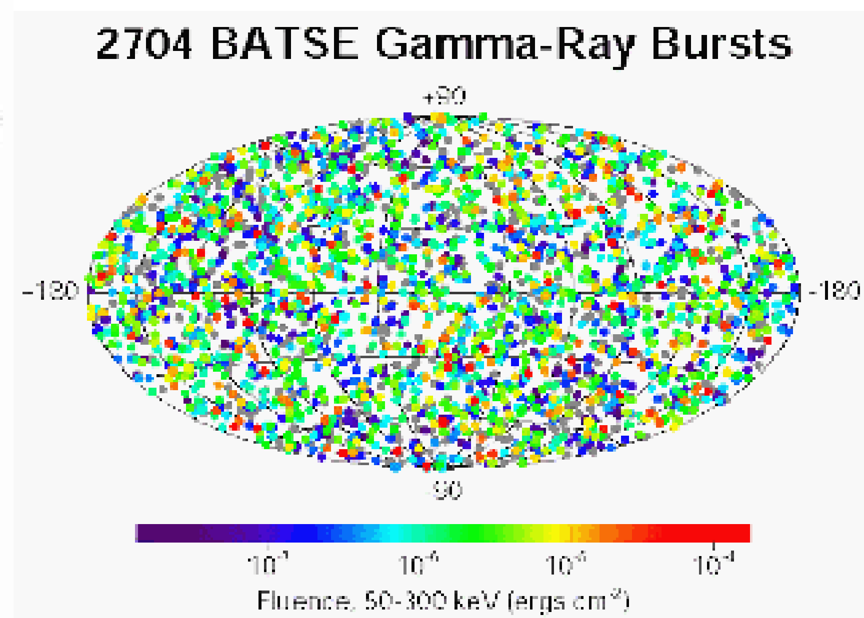
28 february 1997

Beppo SAX

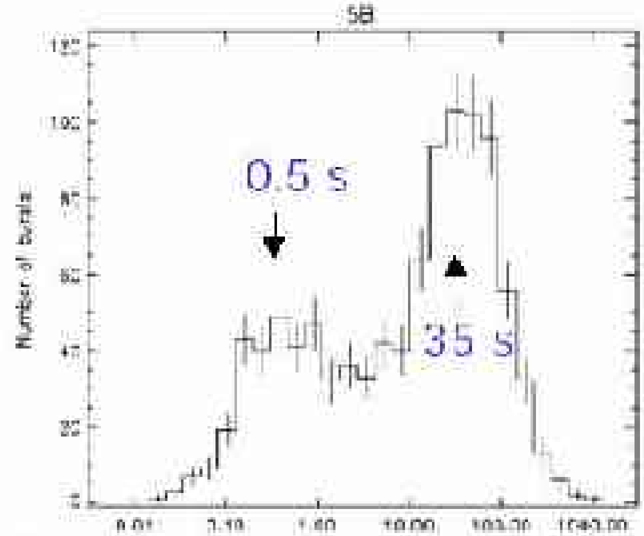


GAMMA RAY BURSTS (GRB's)





GRB Durations

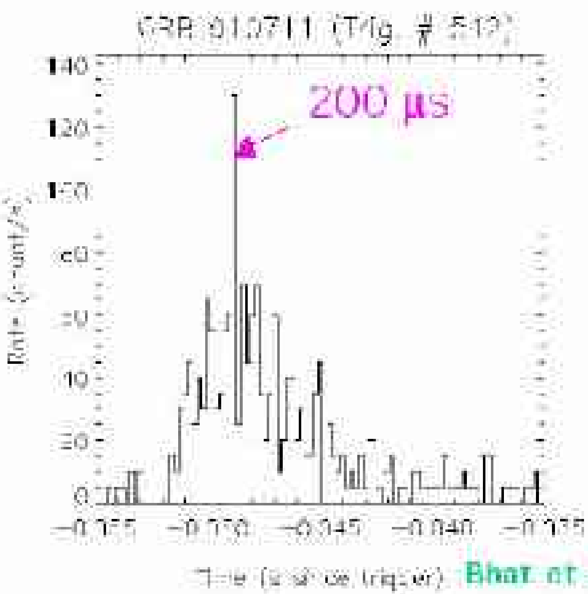


Briggs et al. 2002

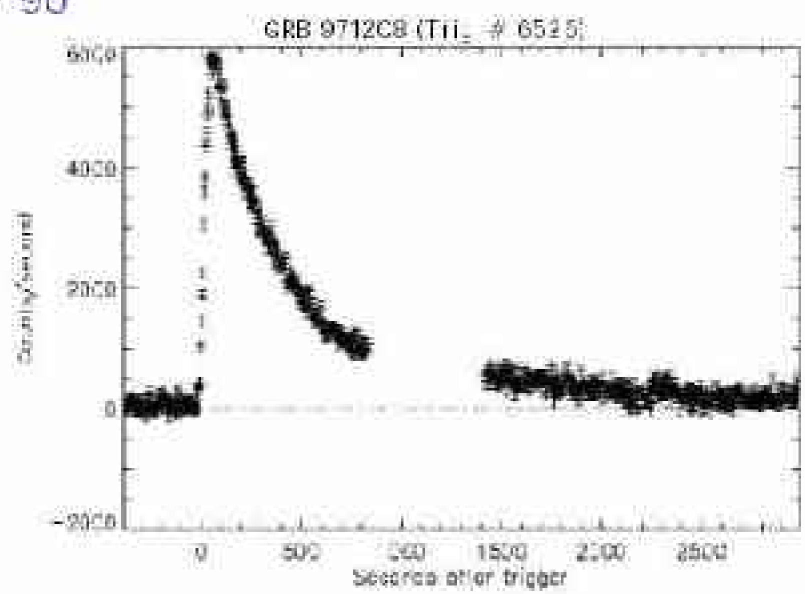
SHORTEST GRB: ~6 ms

T_{90}

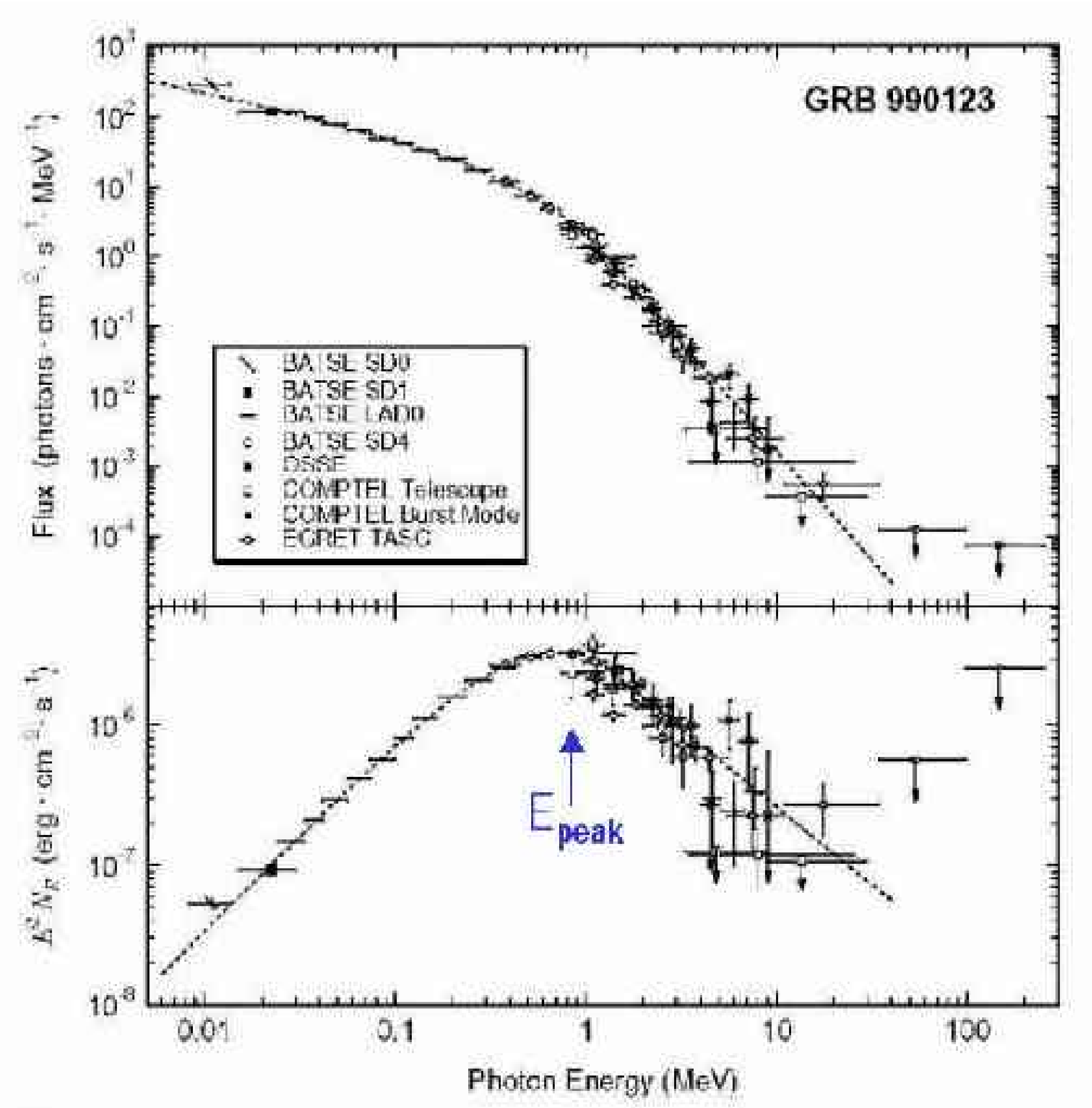
LONGEST GRB: ~2000 s



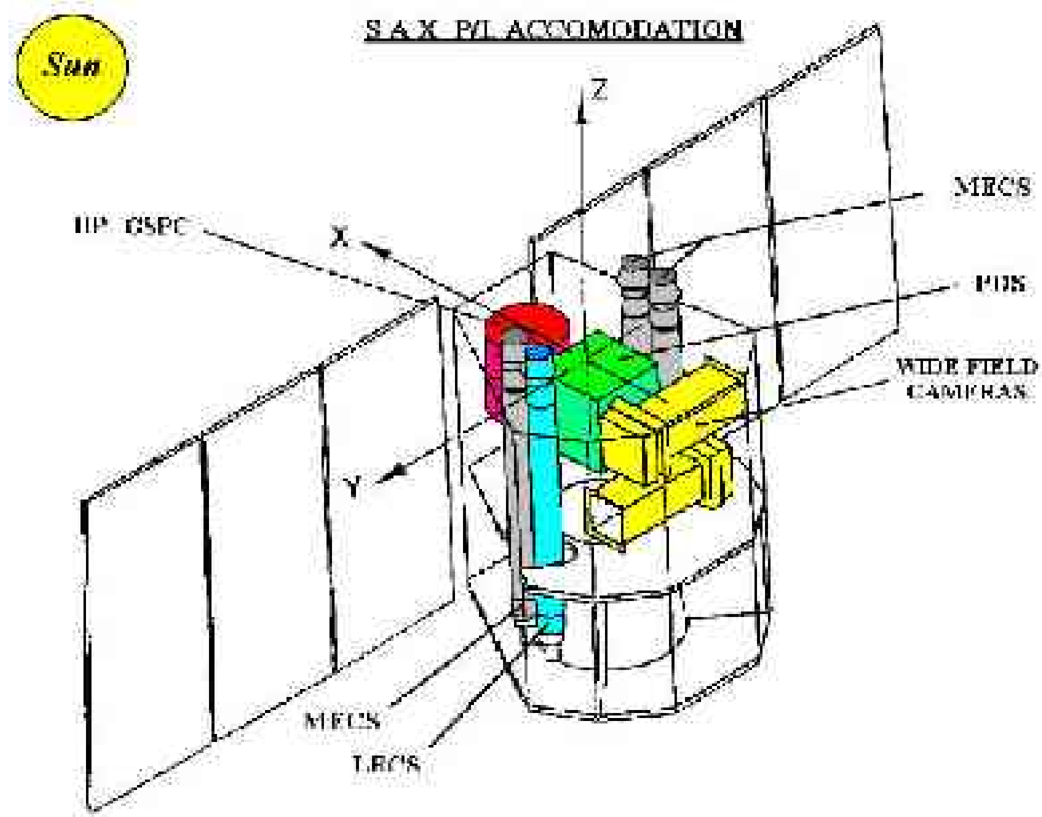
Bhat et al. 1992



Energy Spectrum

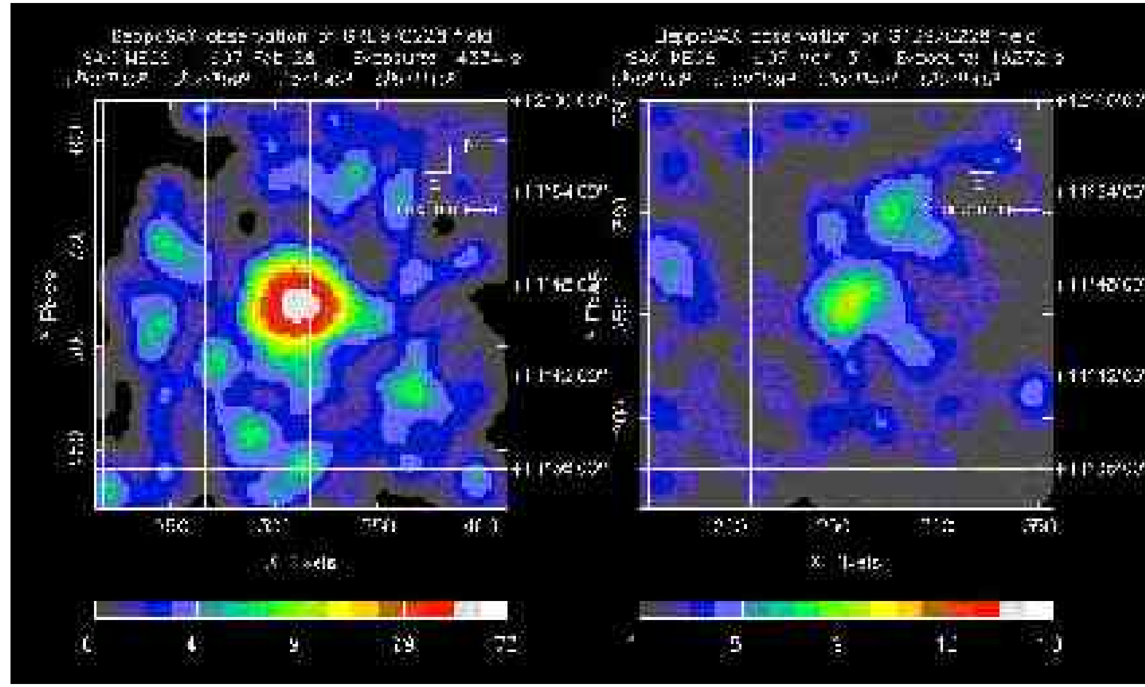


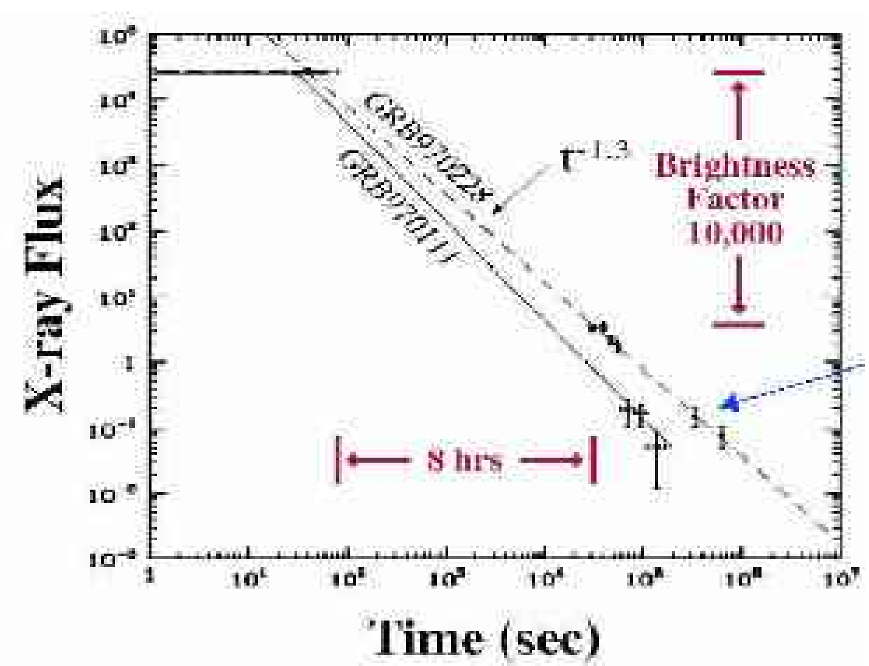
BEPPO SAX   X-ray satellite

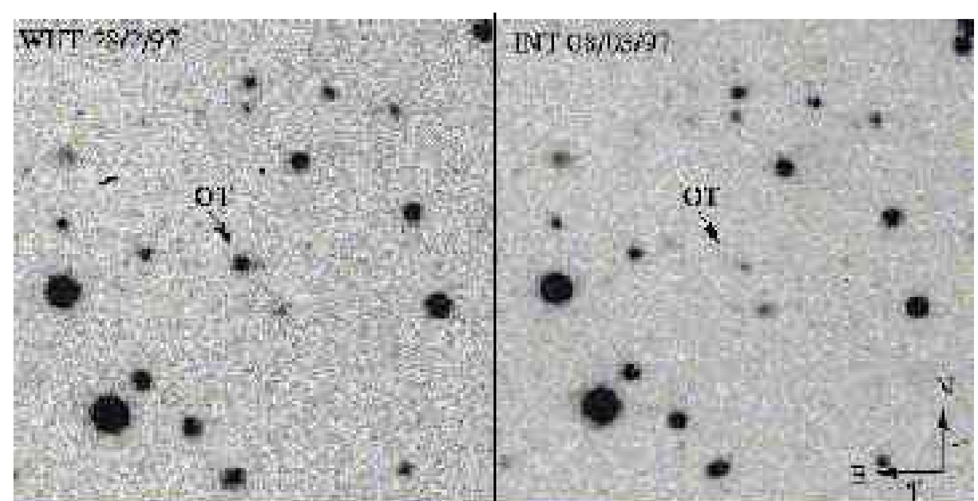


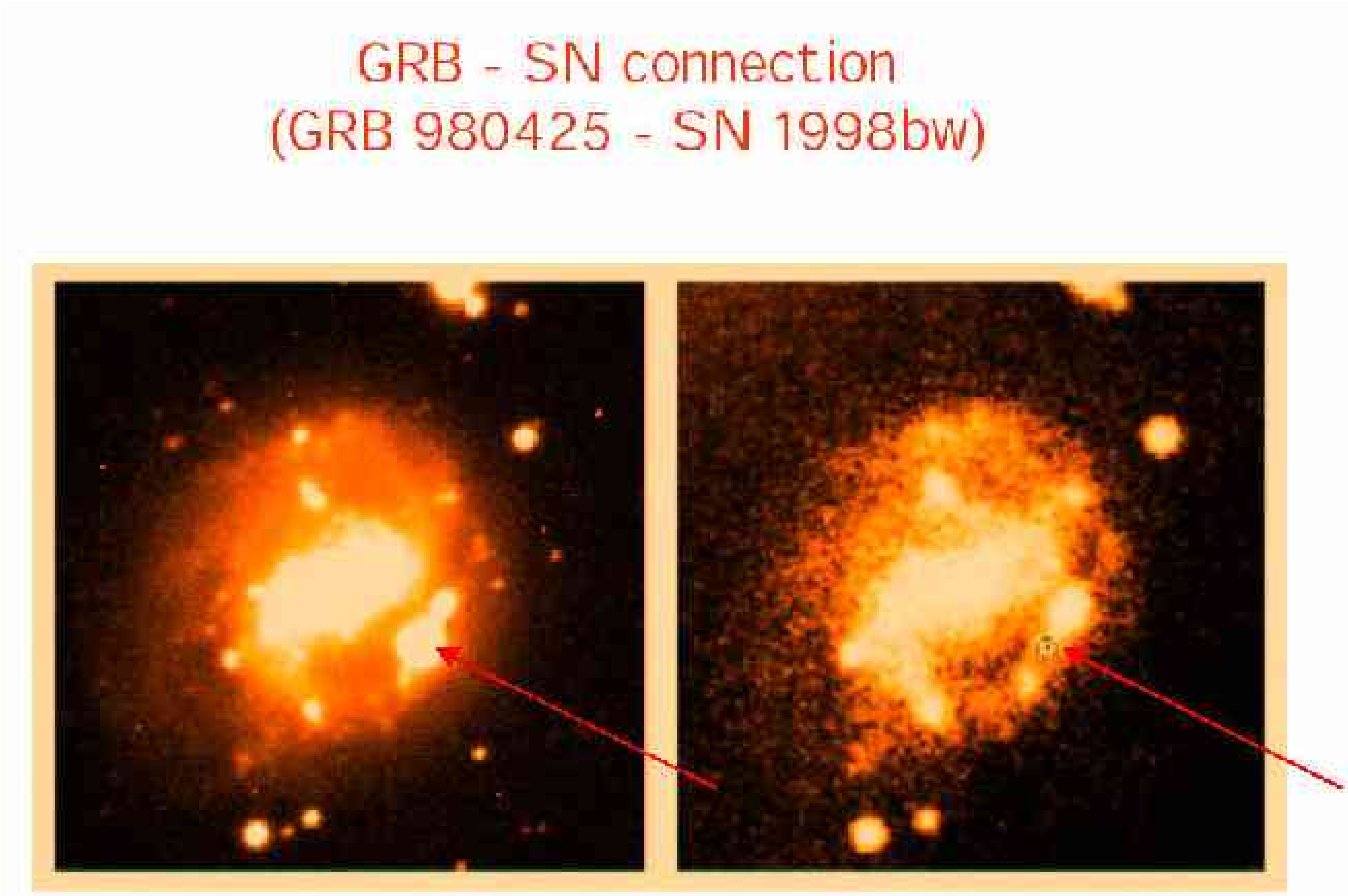
GRB 970228

28 february 1997

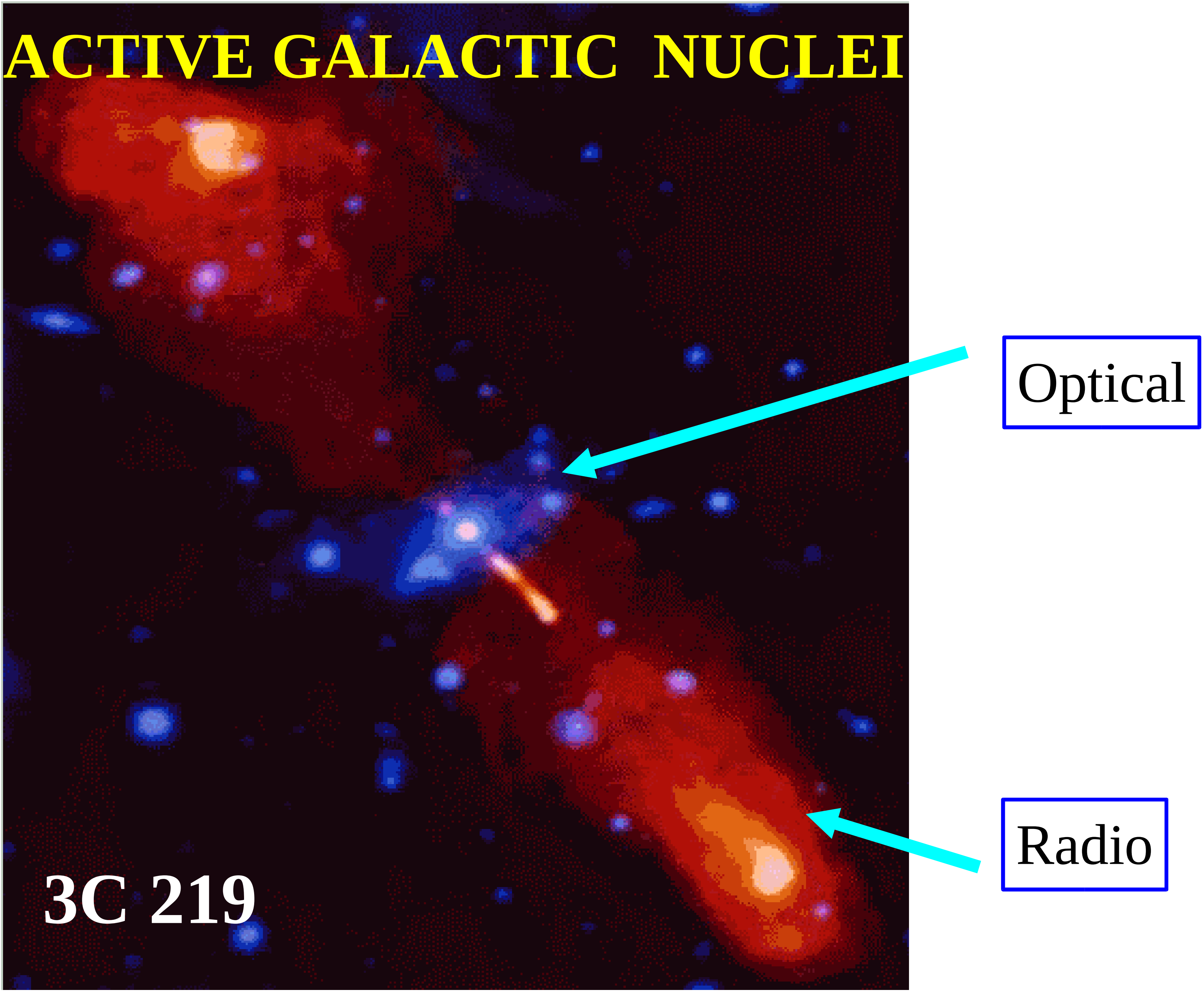




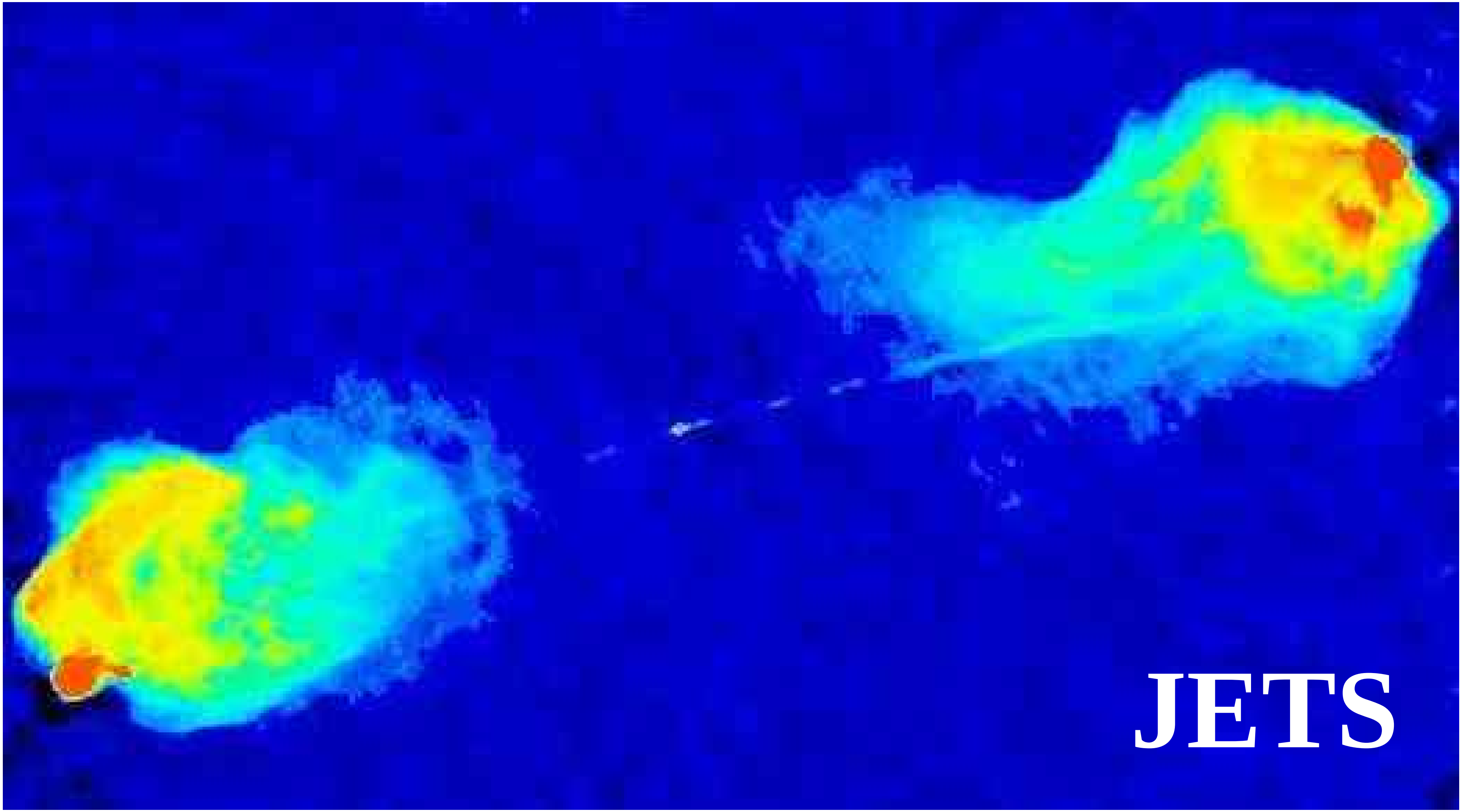




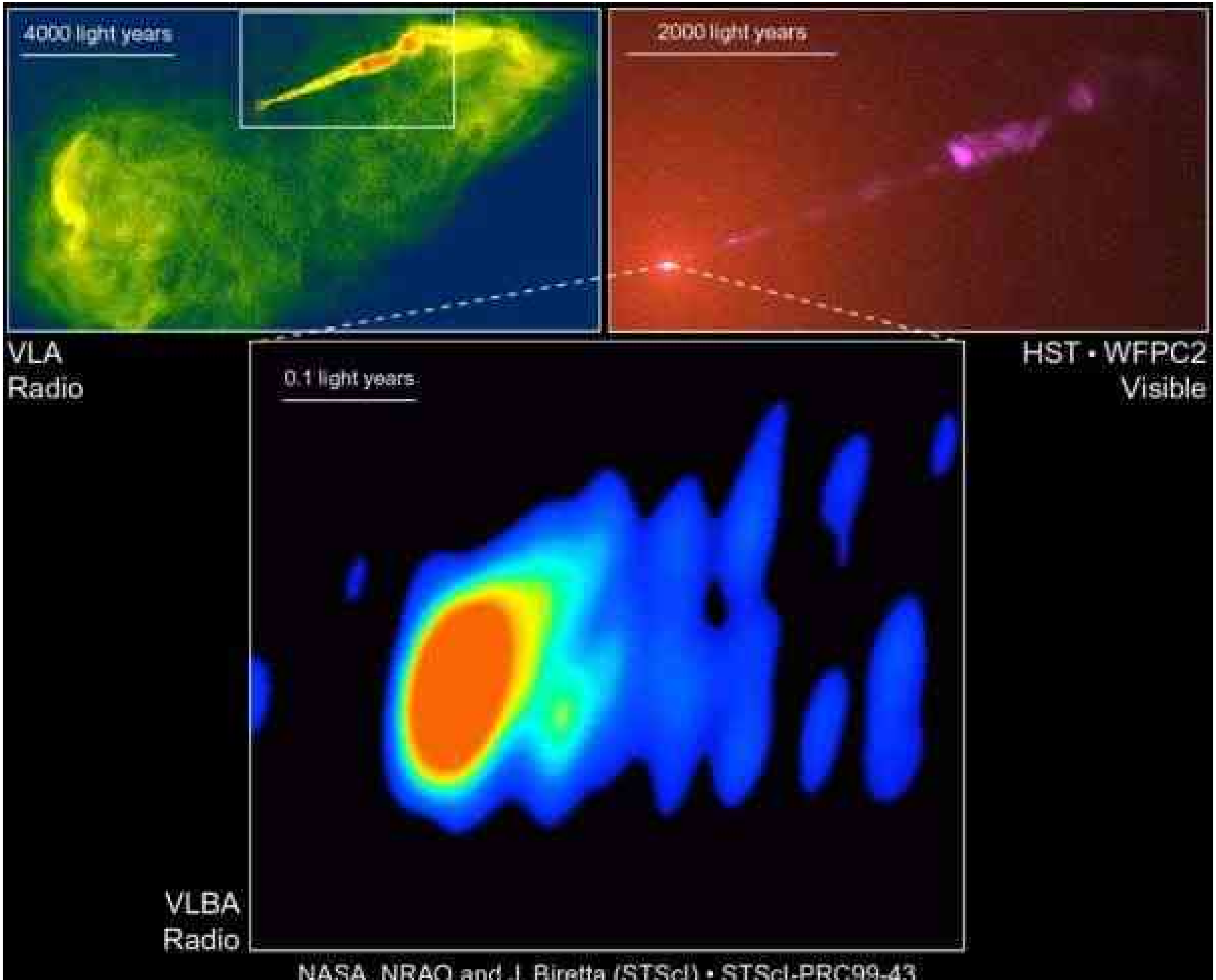
GRB030329

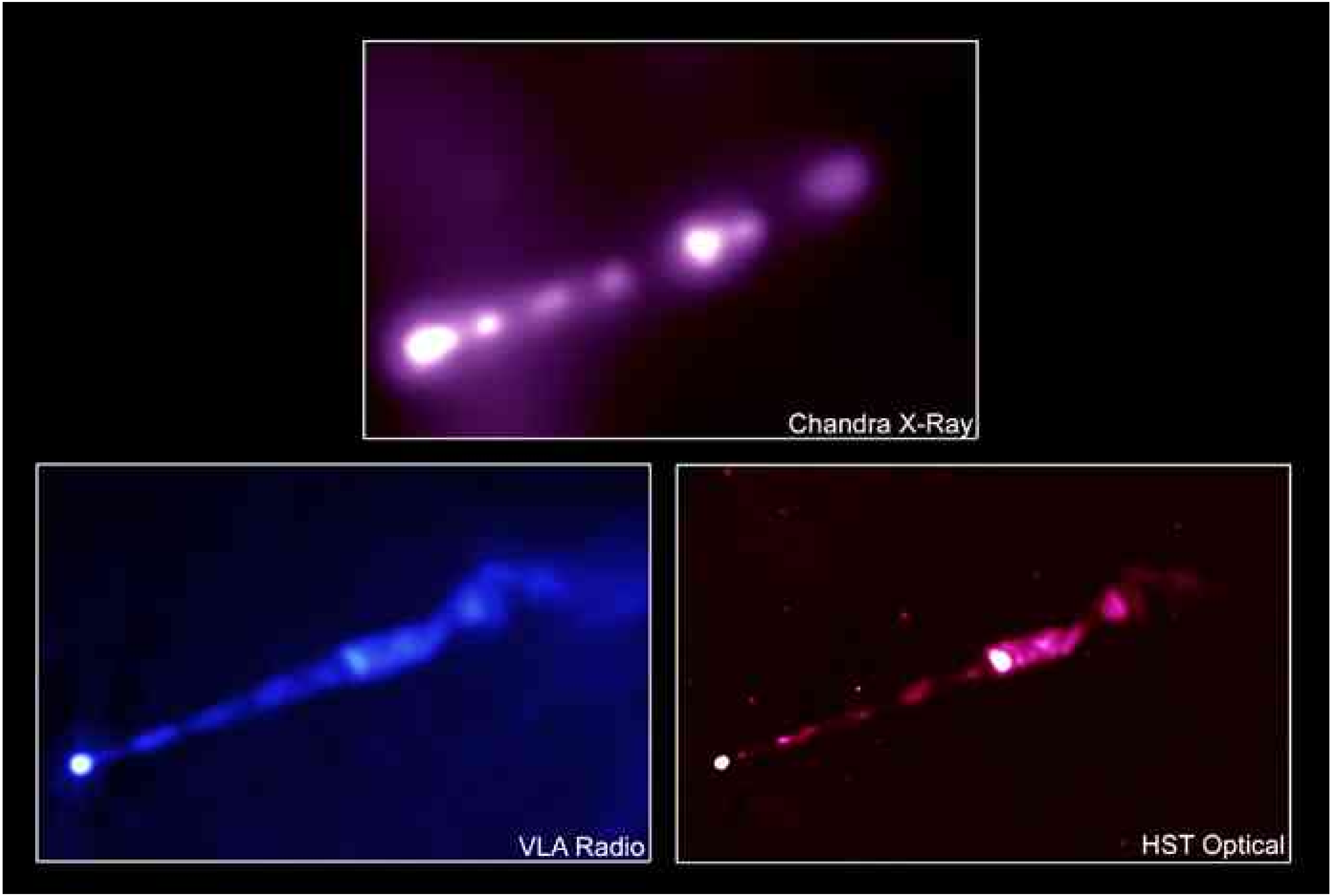

ACTIVE GALACTIC NUCLEI
Optical
Radio
3C 219

CYGNUS-A



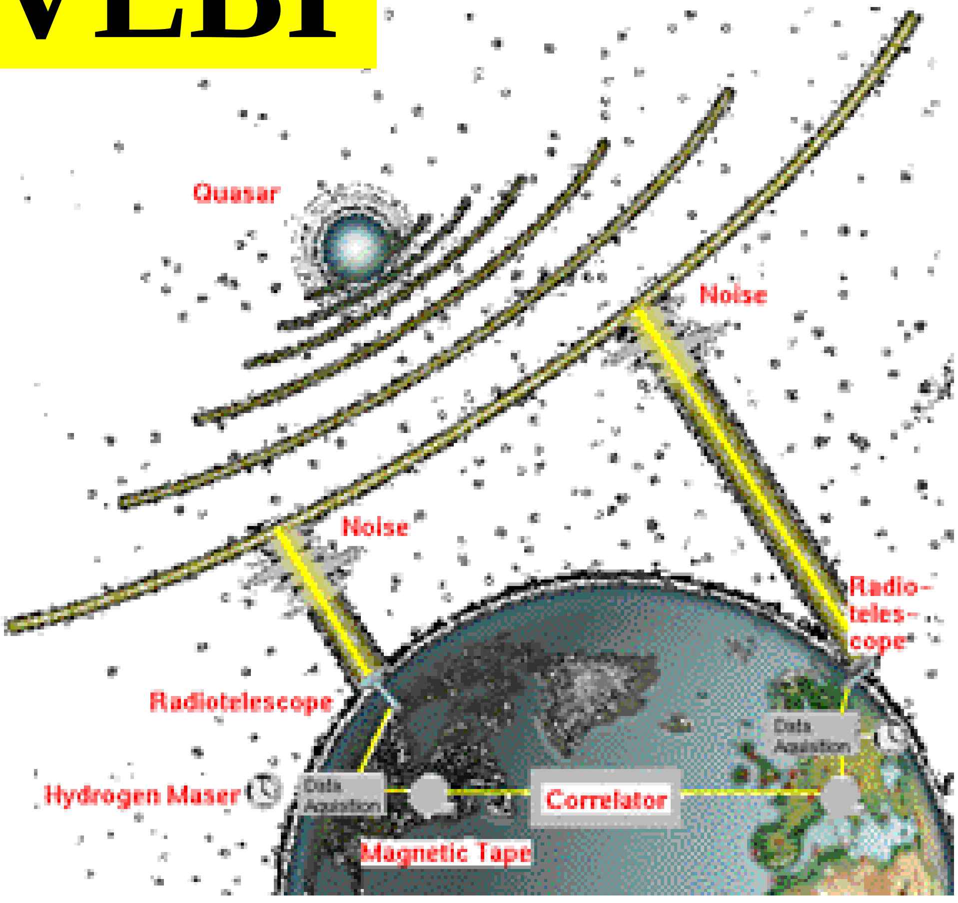
VLA radio image

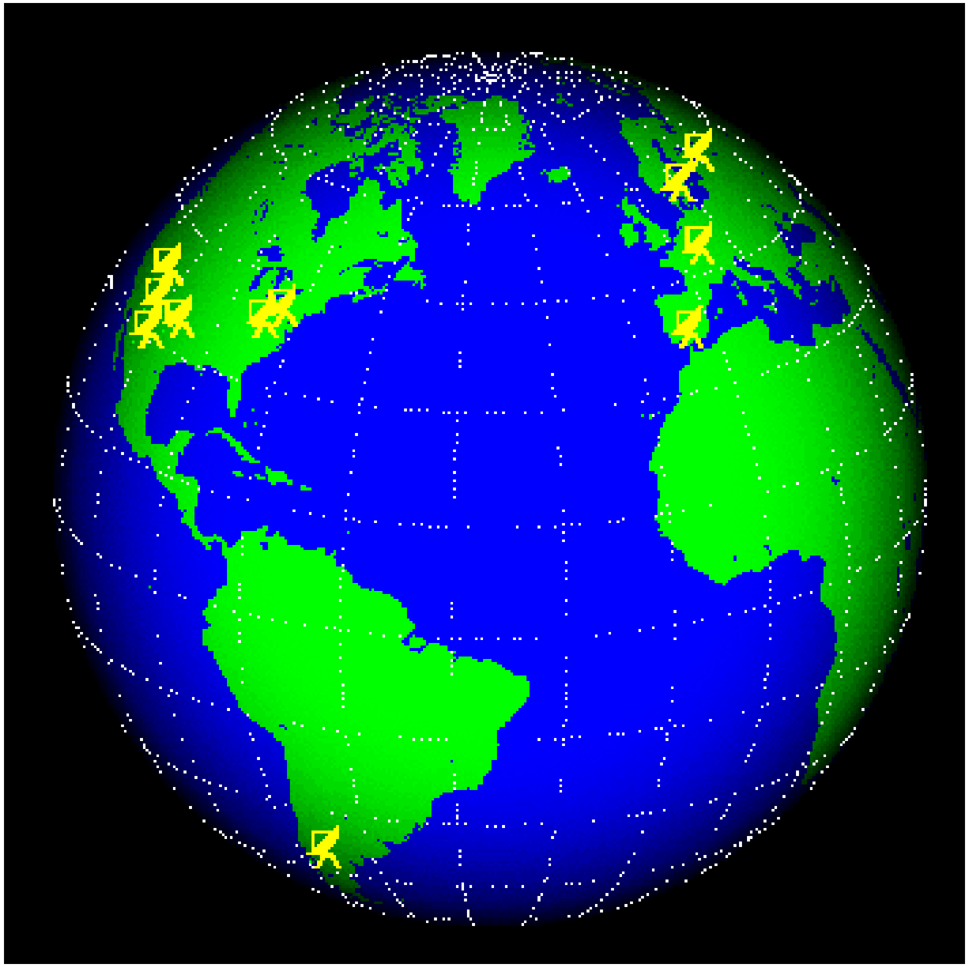

4000 light years
2000 light years
VLA
Radio
HST • WFPC2
Visible
0.1 light years
VLBA
Radio
NASA, NRAO and J. Biretta (STScI) • STScI-PRC99-43


Chandra X-Ray
VLA Radio
HST Optical

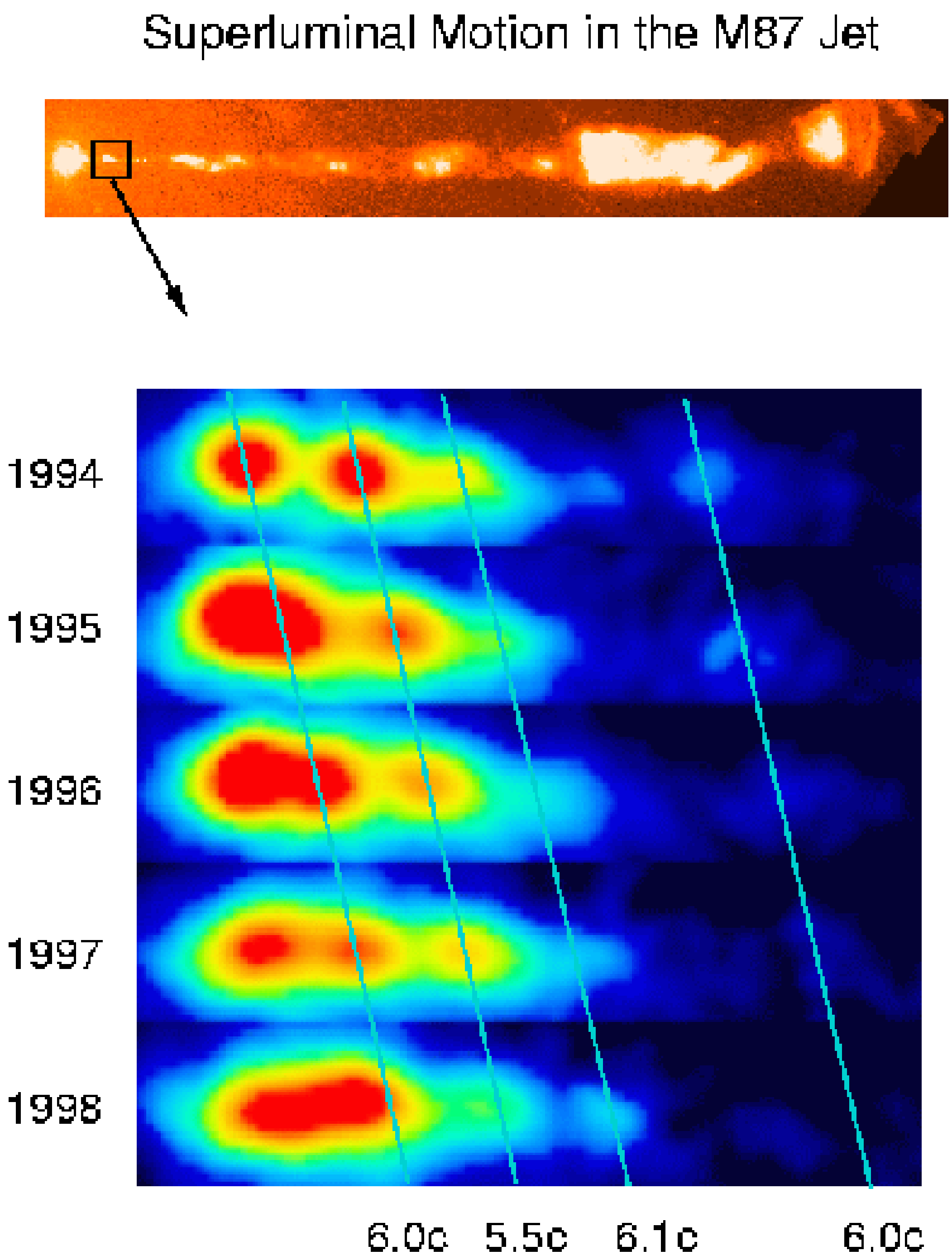
VLA

VLBI

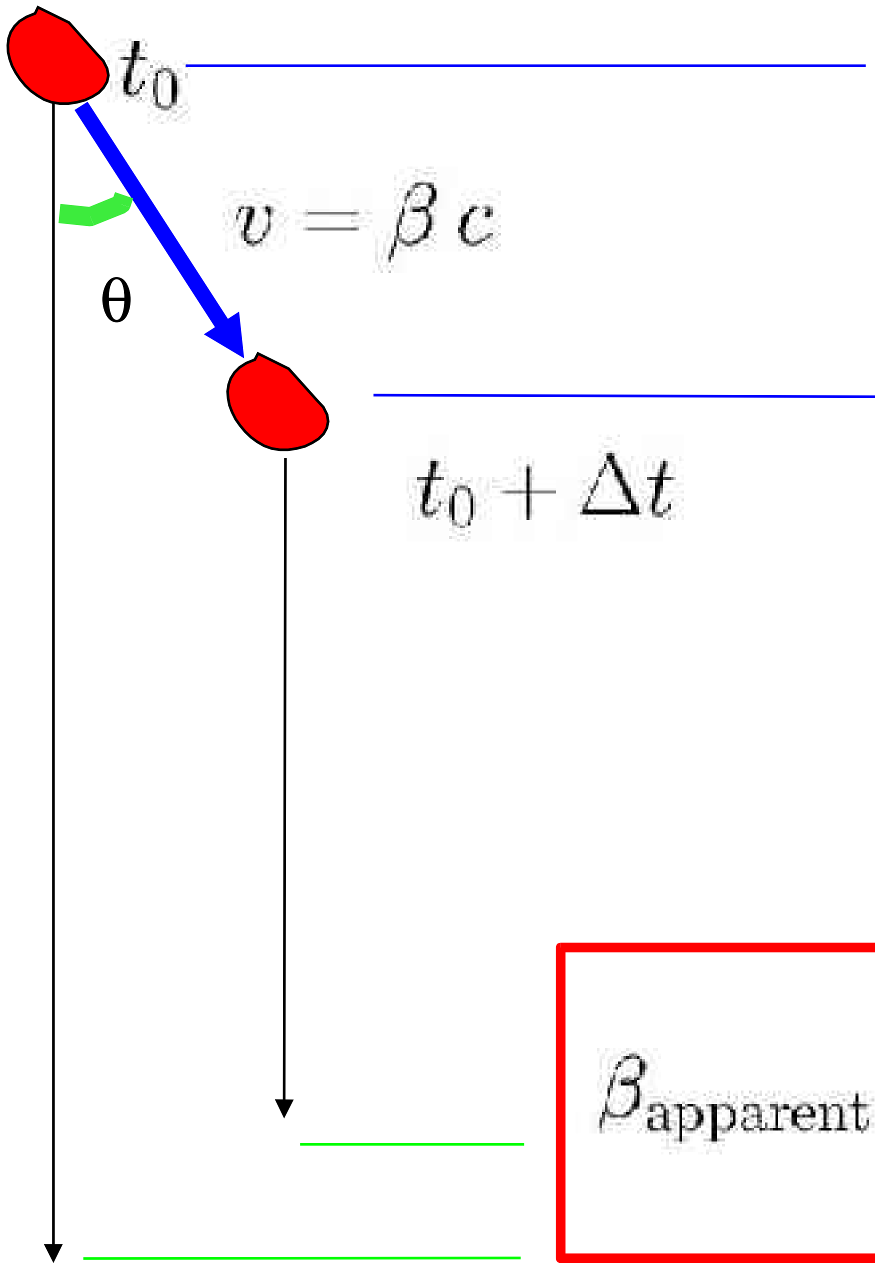

Quasar
Noise
Noise
Radio-
teles-
cope
Radiotelescope
Hydrogen Maser
Data Aquisition
Correlator
Data Aquisition
Magnetic Tape



Superluminal Motion



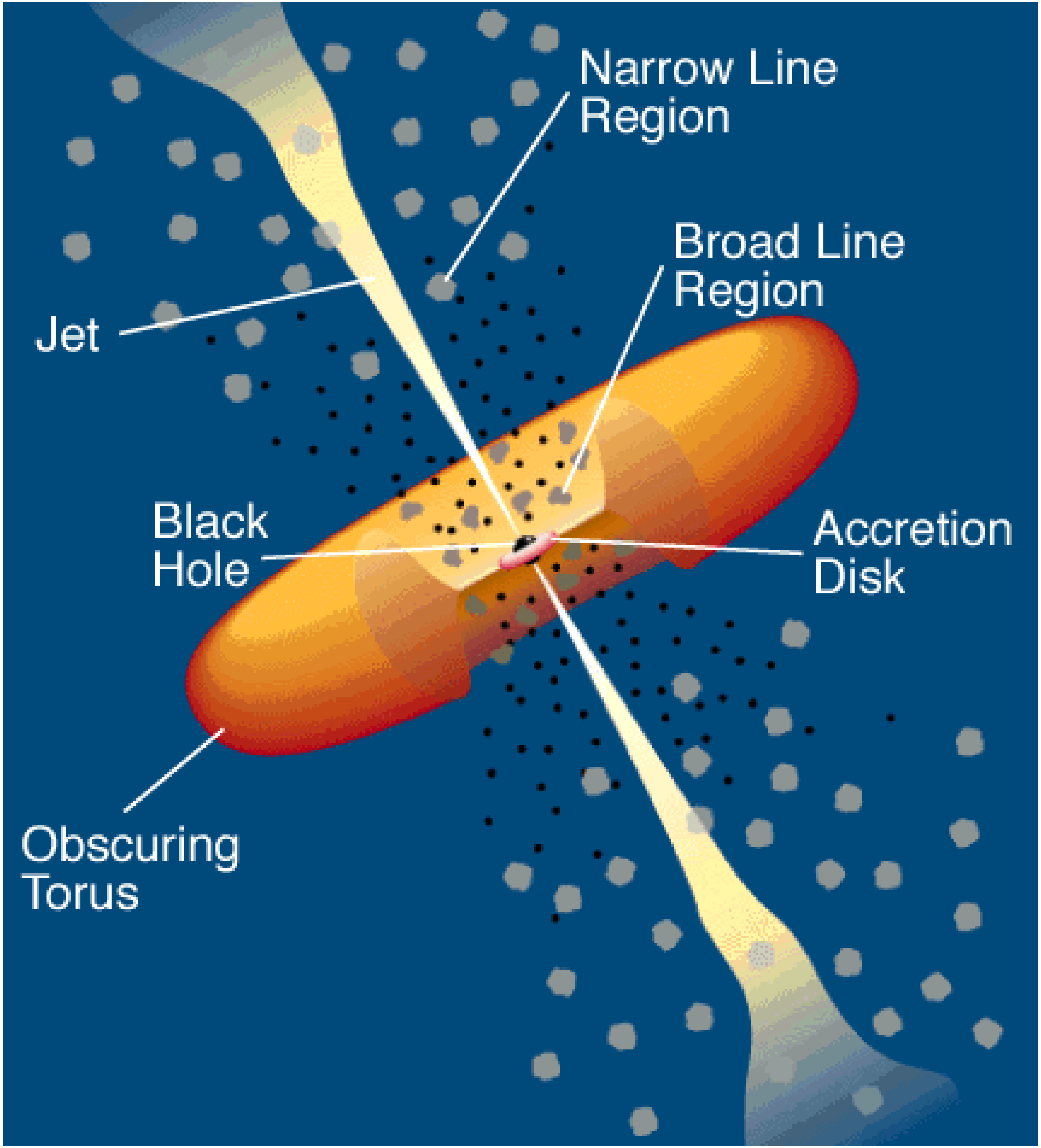
$$v_{\text{apparent}} = d \times \dot{\Omega}$$



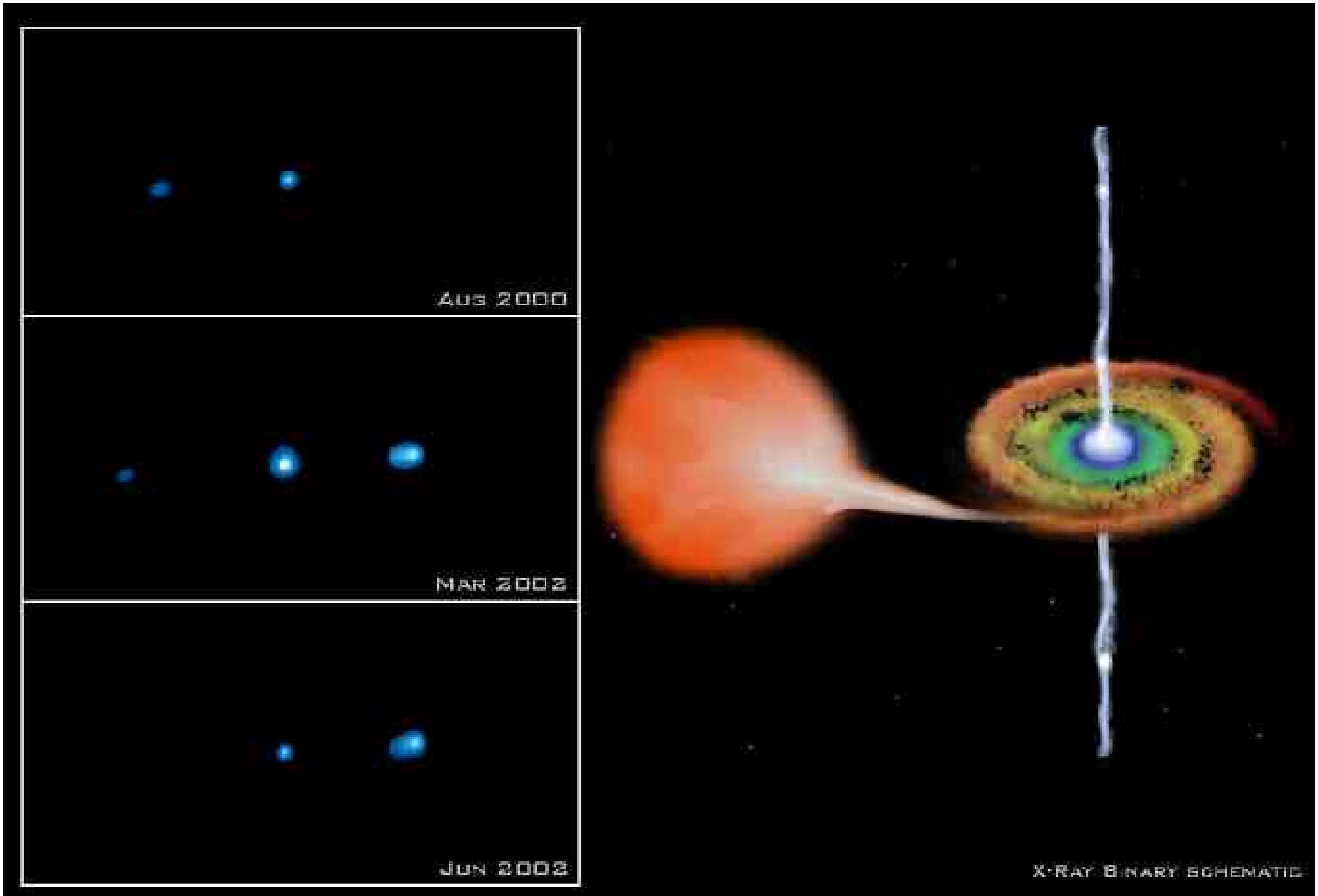
$$\Delta\Omega = \frac{v \, \sin\theta}{r} \, \Delta t$$

$$\begin{aligned} \Delta t_{\text{obs}} &= \Delta t - \frac{1}{c} \Delta t \, v \, \cos\theta \\ &= \Delta t \, [1 - \beta \, \cos\theta] \end{aligned}$$

$$\beta_{\text{apparent}} = \frac{r}{c} \, \frac{\Delta\Omega}{\Delta t_{\text{obs}}} = \frac{\beta \, \sin\theta}{[1 - \beta \, \cos\theta]}$$


Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus

Micro-Quasars



HIGH ENERGY ASTROPHYSICS

A rich and Rapidly developing Field

Prospects for the FUTURE
of the HIGHEST INTEREST

Communication between different Communities
is ESSENTIAL

Multi-Messenger Studies
Photons, Neutrinos, Cosmic Rays, Gravitational Waves

Particle Physicists
Astrophysicists

The Cosmic Ray VICIOUS CIRCLE

Need good knowledge of
Hadronic Interactions to interpret
the Cosmic Ray Data
Energy Spectrum - Composition

Not knowing
the **Energy Spectrum and Composition**
one cannot use the c.r. data
to extract information about
Hadronic Interactions

Two Approaches to break the "Vicious Circle"

Baron of Munchausen
finding himself in a swamp
got himself out .... pulling his own hair

Baron of Munchausen (Bootstrap) Method

Redundant Measurements of Cosmic Rays
allow a determination of the
Energy Spectrum and Chemical Composition
together with a determination of the most relevant properties of the Hadronic Interactions

Cosmic Ray TOMOGRAPHY

Brain
X-ray Tomography

Second Approach to break the "Vicious Circle"

Build a Stair

Jack and the Beanstalk Method
(building a stair)

with experimental and
theoretical studies

NEEDS

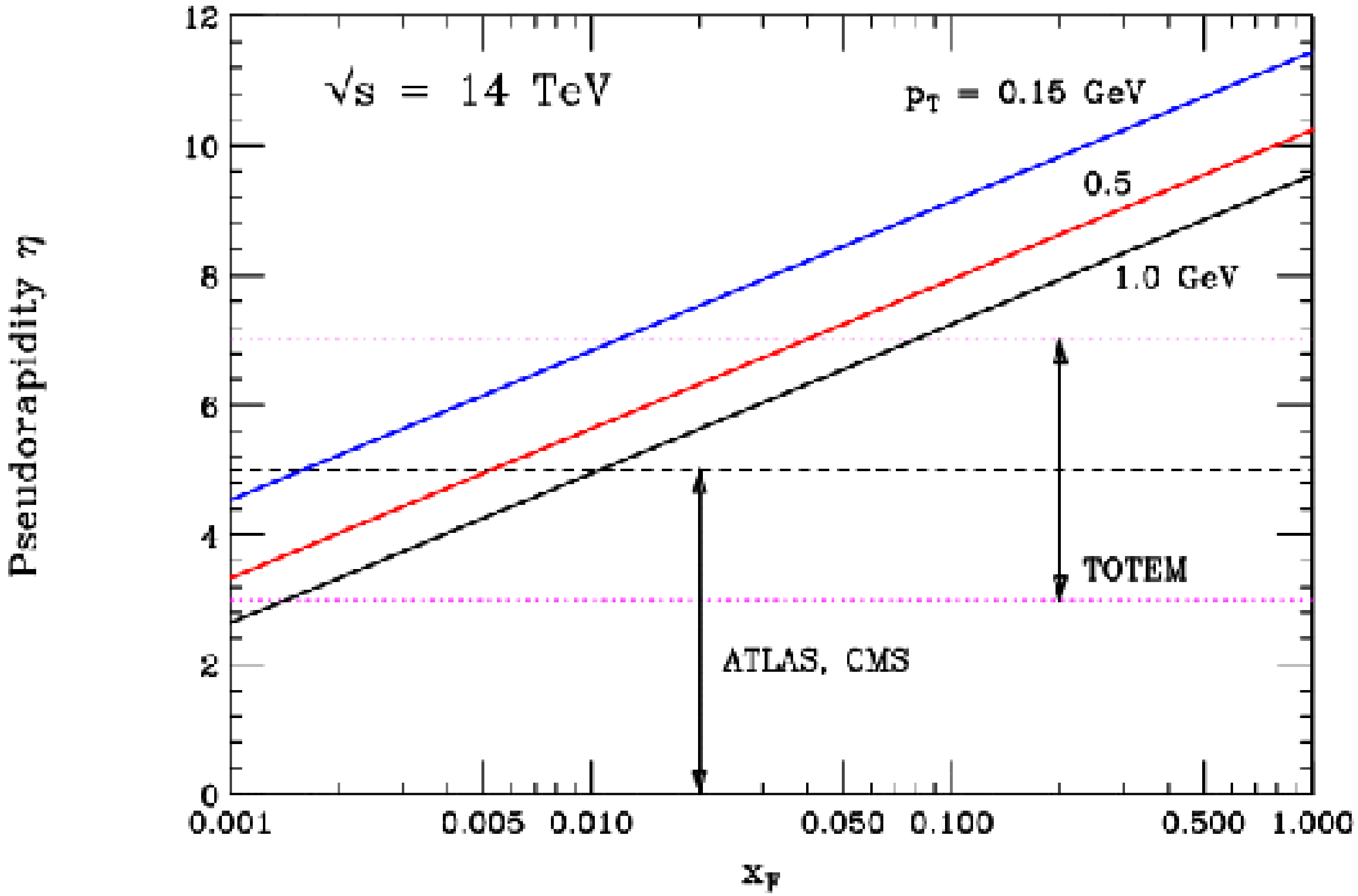
(i) Precise measurements of σ_{tot} and σ_{inel}.

(ii) Measurements of the ratio $\sigma_{\text{diff}}/\sigma_{\text{inel}}$.

(iii) Energy distribution of the leading nucleon in the final state.

(iv) Inclusive π spectra in the fragmentation region $x_F \gtrsim 0.1$.

FORWARD PHYSICS



LHC

Very little infomation of the region $x_F > 0.1$

QUESTIONS

(i) What is the importance of our knowledge of hadronic interactions in the determination of the c.r. flux and composition in the knee region?

(ii) What is the importance of uncertainties of hadronic interactions in the determination of energy scale and composition for UHE ($E \geq 10^{19}$ eV) Cosmic Rays?

(iii) What impact can have present and future experiments in reducing these uncertanties ?

(iv) Can Theoretical work help in reducing these uncertainties?

(v) Can Experimental Cosmic Ray Studies give valuable information on High Energy Hadronic Interaction?