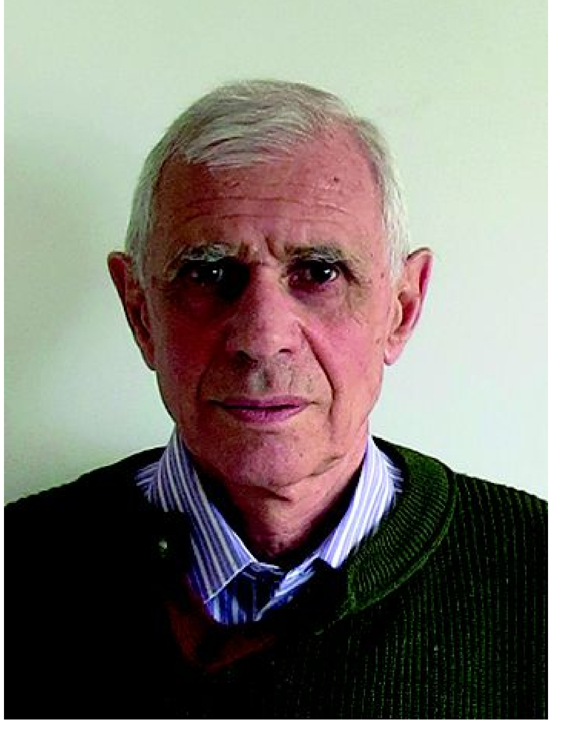
The Rise of Multi-Messenger Astrophysics

From Cygnus X3 and SN1987A to the present

and the role of
Veniamin Berezinsky

[1934 - 2023]



Paolo Lipari INFN Roma

Conference in memory of
Veniamin Berezinsky
GSSI, 1st October 2024

A personal recollection :

In 1986 I returned to Roma (after 6 years away from Italy)
with a temporary Post Doc position with INFN,
with the program to work in the experiment MACRO
approved for construction in the newly created
"Laboratorio Nazionale del Gran Sasso" [LNGS]

A new, rich field of research
was opening up for me: *"Non accelerator Physics"*

- Neutrino physics
- Cosmic Rays
- High energy astrophysics

...

I was fascinated ...and soon deeply "fell in love" ....

Nearly 40 years have passed ... and ....
the scientific progress in the field has been
nothing short of extraordinary
(and the field continues to be vibrant and exciting)

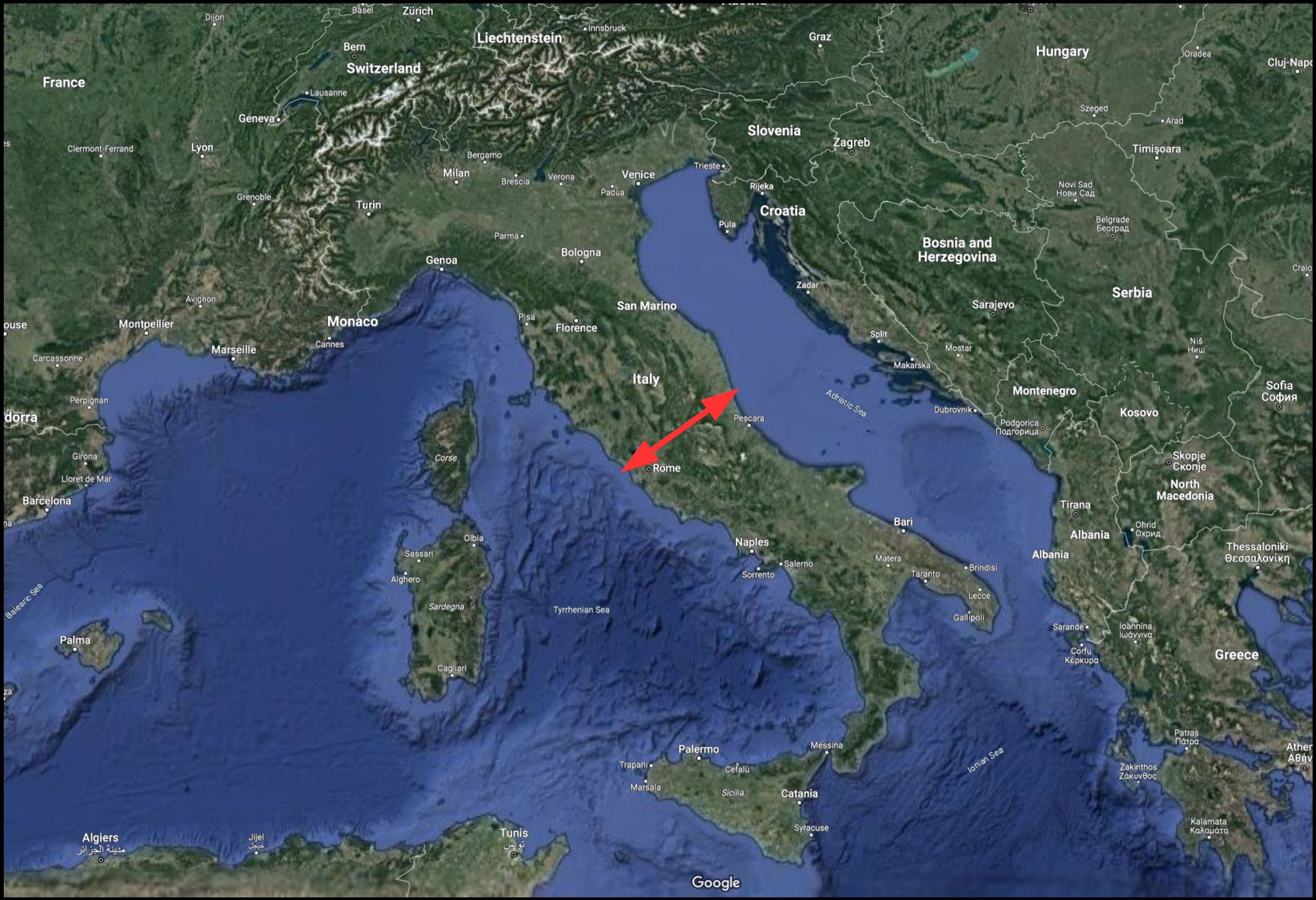
I met Venya for the first time in 1988
during a brief visit he made in Roma
(I think to discuss with Giulio Auriemma and Luciano Maiani)

I has a much better chance to know Venya
next year,when I spent 7 months at
the Bartol Research Center (USA) invited by
Tom Gaisser and Todor Stanev.

Venya was making an extensive visit to the US
and spent some time at the Bartol Research Institute,
time sufficient for extensive discussions about many topics.

(and not only about physics, but also about
the extraordinary developments unfolding
in the Soviet Union of Mikhail Gorbachev and in Eastern Europe).

For the next 30 years lively discussions with Venya
(that soon in 1991 arrived to lead the theory group
at LNGS) were of great importance for my research.



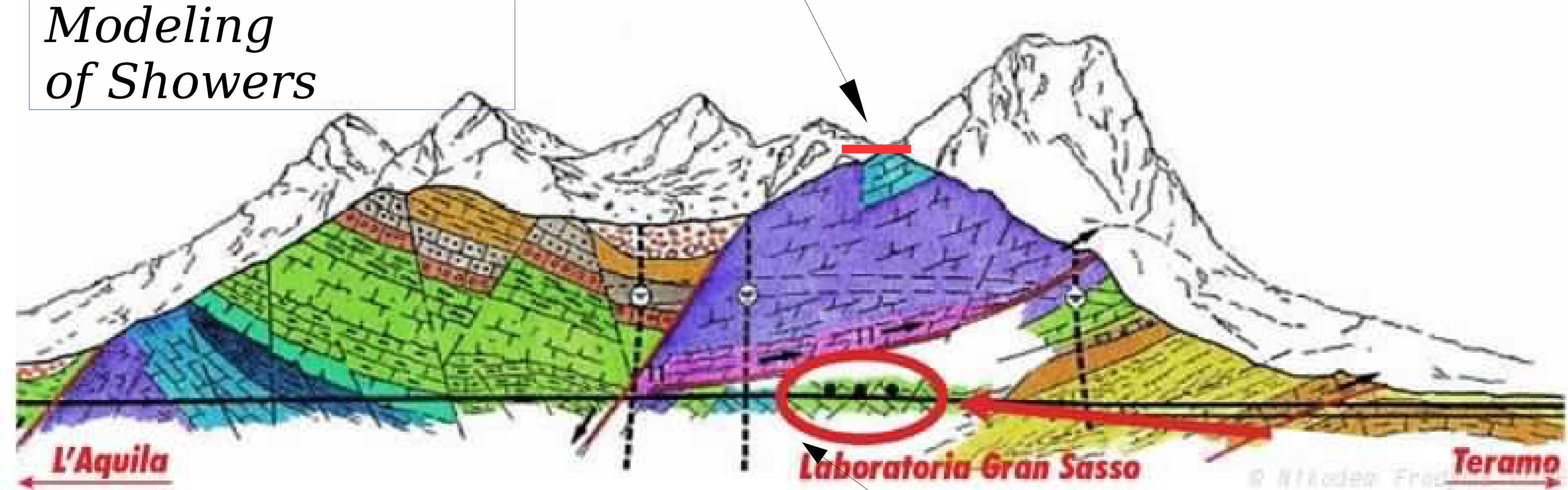
Construction of a Highway for rapid communication
Need a tunnel to traverse the Appennini mountains
opened officialy in Dec. 1984.

The Tunnel under the Gran Sasso Mountain
arriving from Teramo today

Coincident
detections
deep underground
+ surface

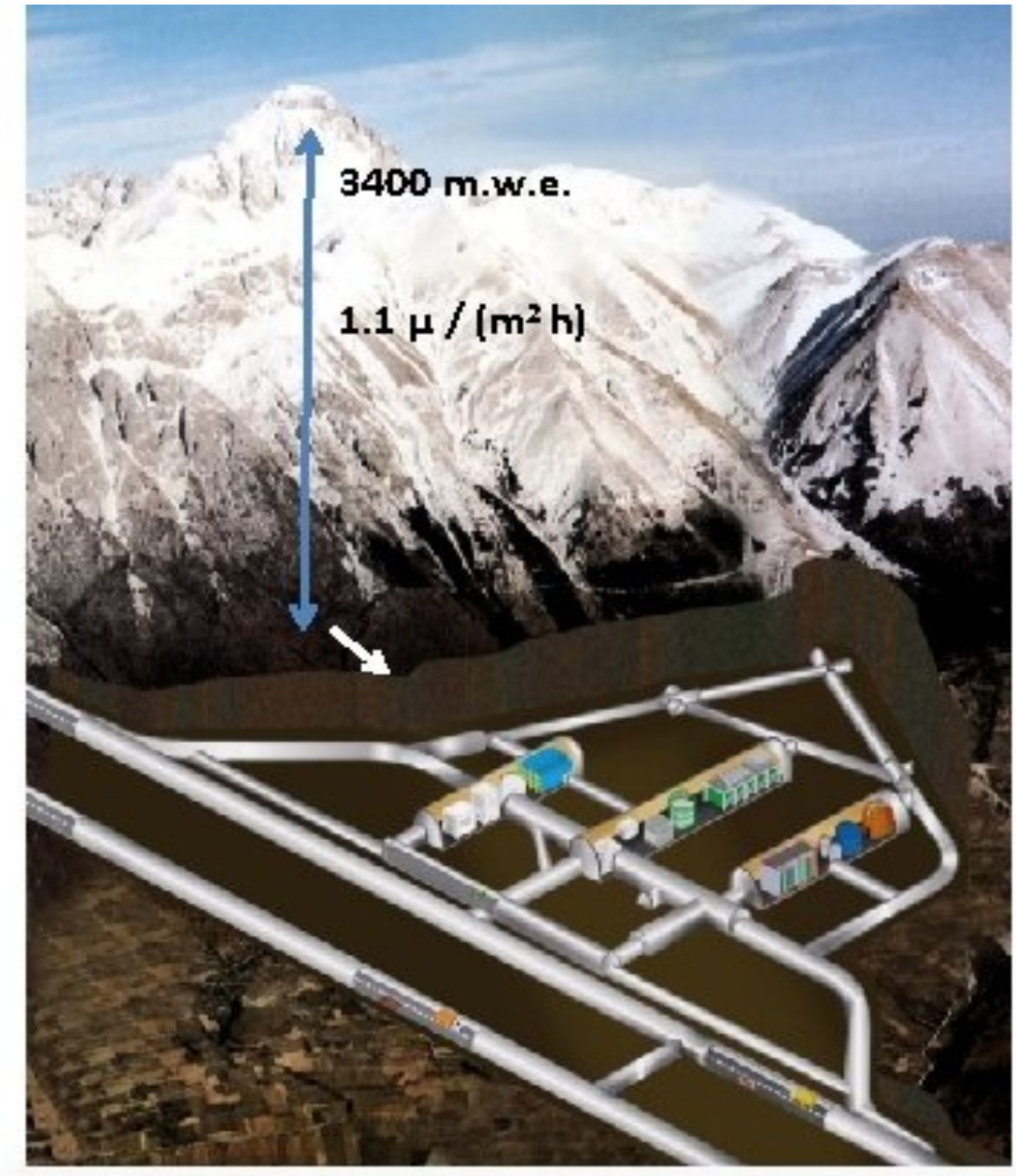
Modeling
of Showers

Surface detector



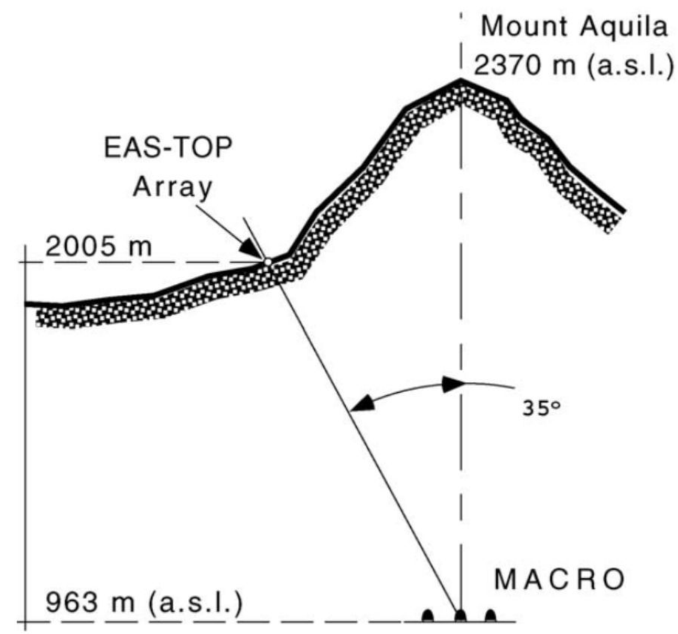
Underground
Laboratory
(3 Halls)

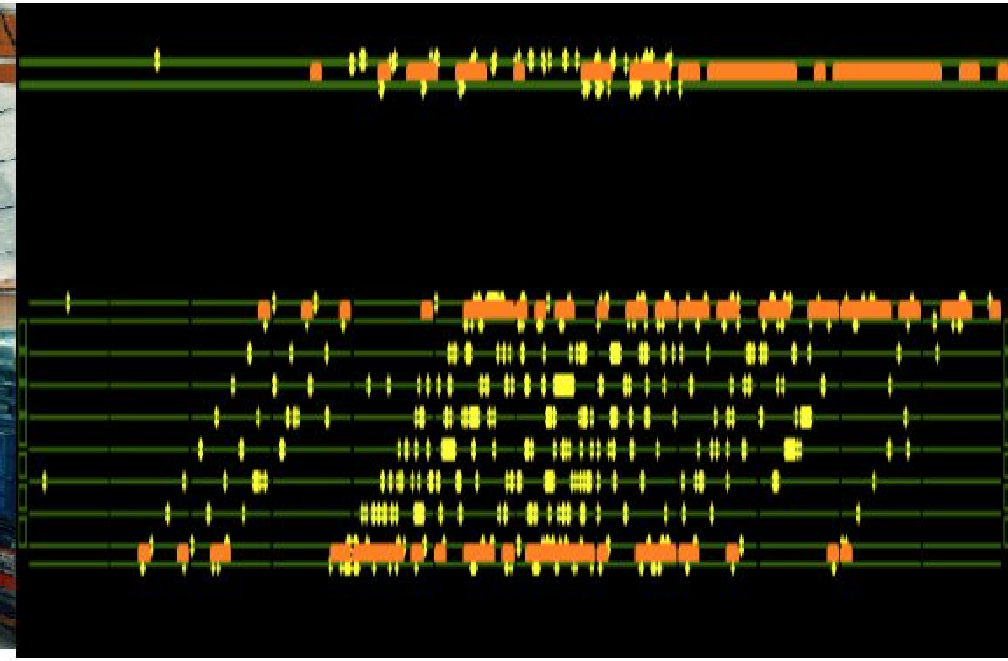
Idea of constructing an
underground laboratory
announced publicly in 1982

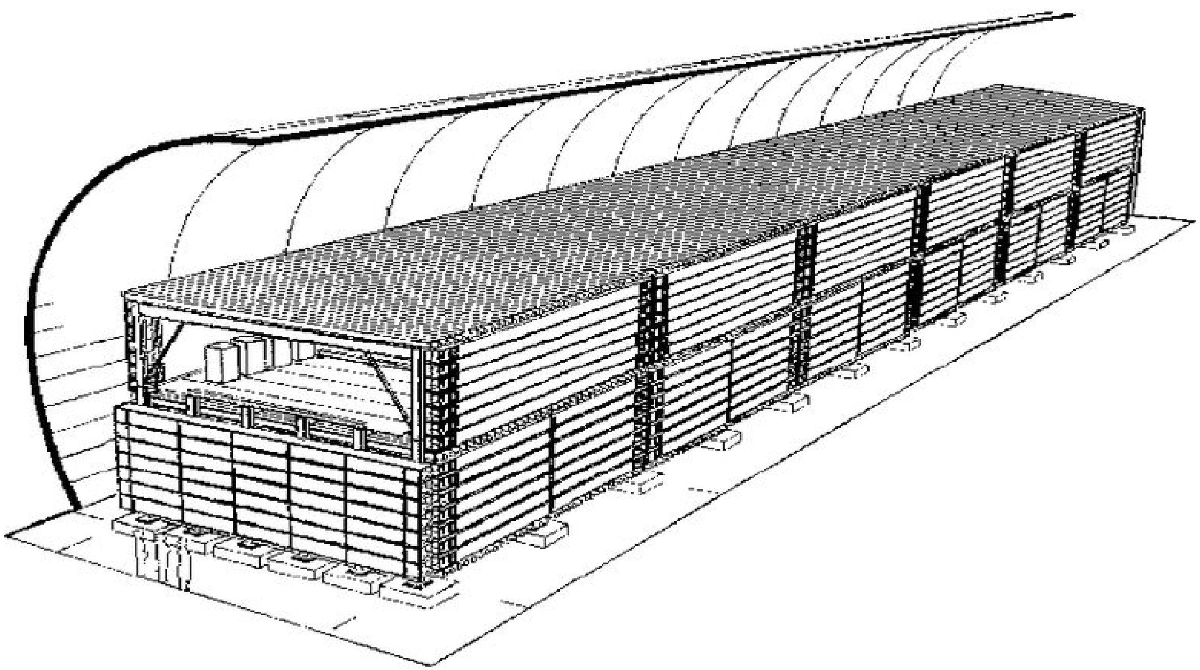


Three large
experiments halls
A, B, C

with a broad program
of experimental studies





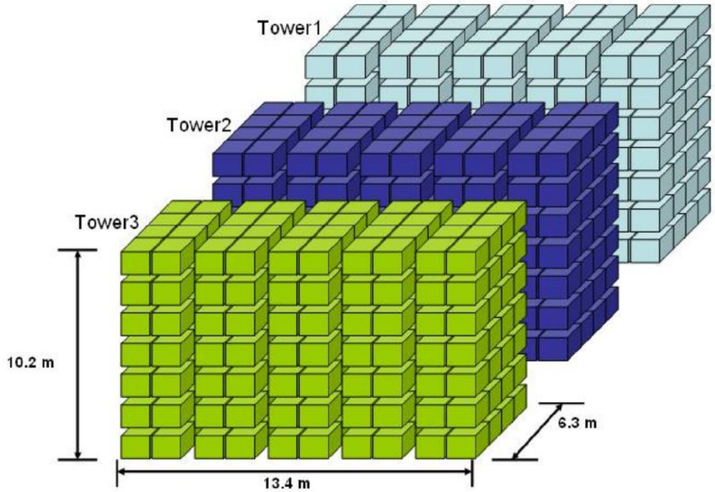


In Hall B:

The MACRO detector

In hall A
Large Volume Detector (LVD)
still in operation

840 counters of 1 m3)
(1000 tons of scintillators)



Venya has been a co-author
with the LVD Collaboration
from 1986 (proposal) to 2003
[More than 40 papers that cover
a broad range of topics]

neutrino physics
Cosmic ray showers
.....

Topics in Astroparticle Physics in 1987

Proton Decay

Solar neutrinos

Atmospheric Neutrinos
(Background for p decay
... but also probe for oscillations)

High Energy Sources
Gamma Astronomy
Neutrino Astronomy

Cosmic Rays Origin

Air Showers
(“surface detectors + fluorescence)
(Muons deep underground)

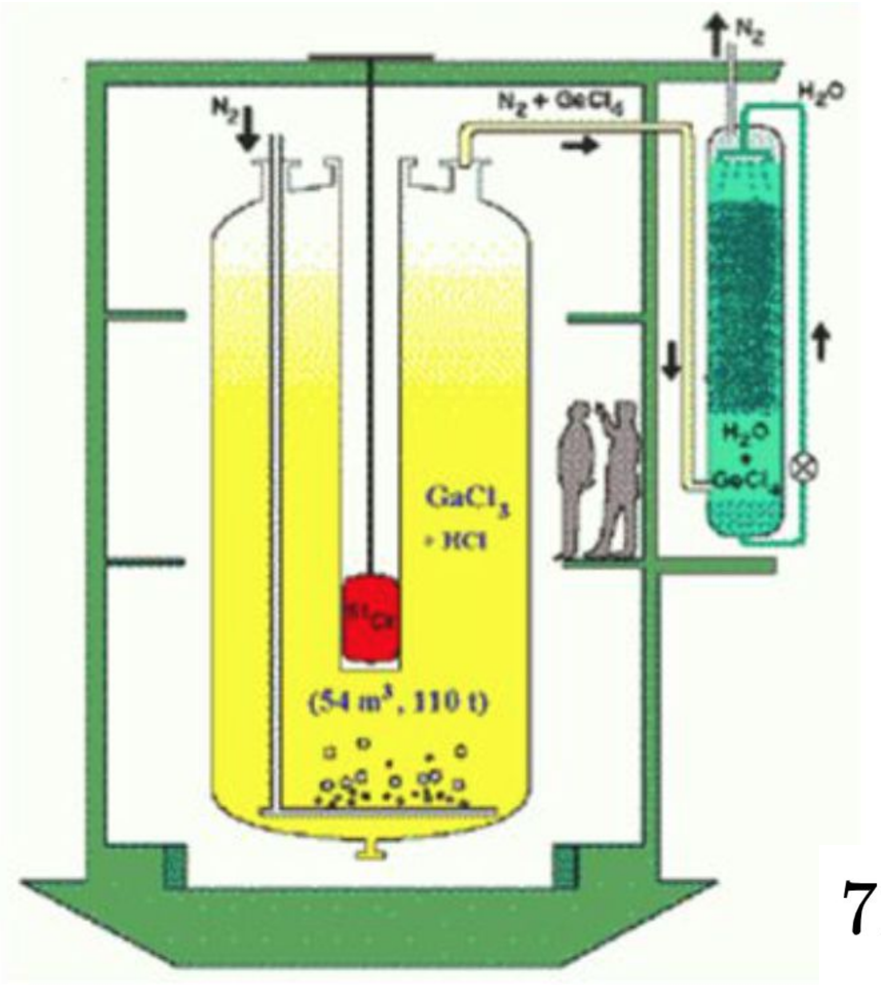
Hadronic Interactions

Venya was at the time
one the physicists
who was better at mastering
the ensemble of these topics.

The following 40 years
have see what can
certainly be seen as
extraordinary progress
[mostly thanks to the observers]

Venya kept a role as
a sort of one of the
“intellectual guides” in
this journey of understanding

Solar Neutrinos

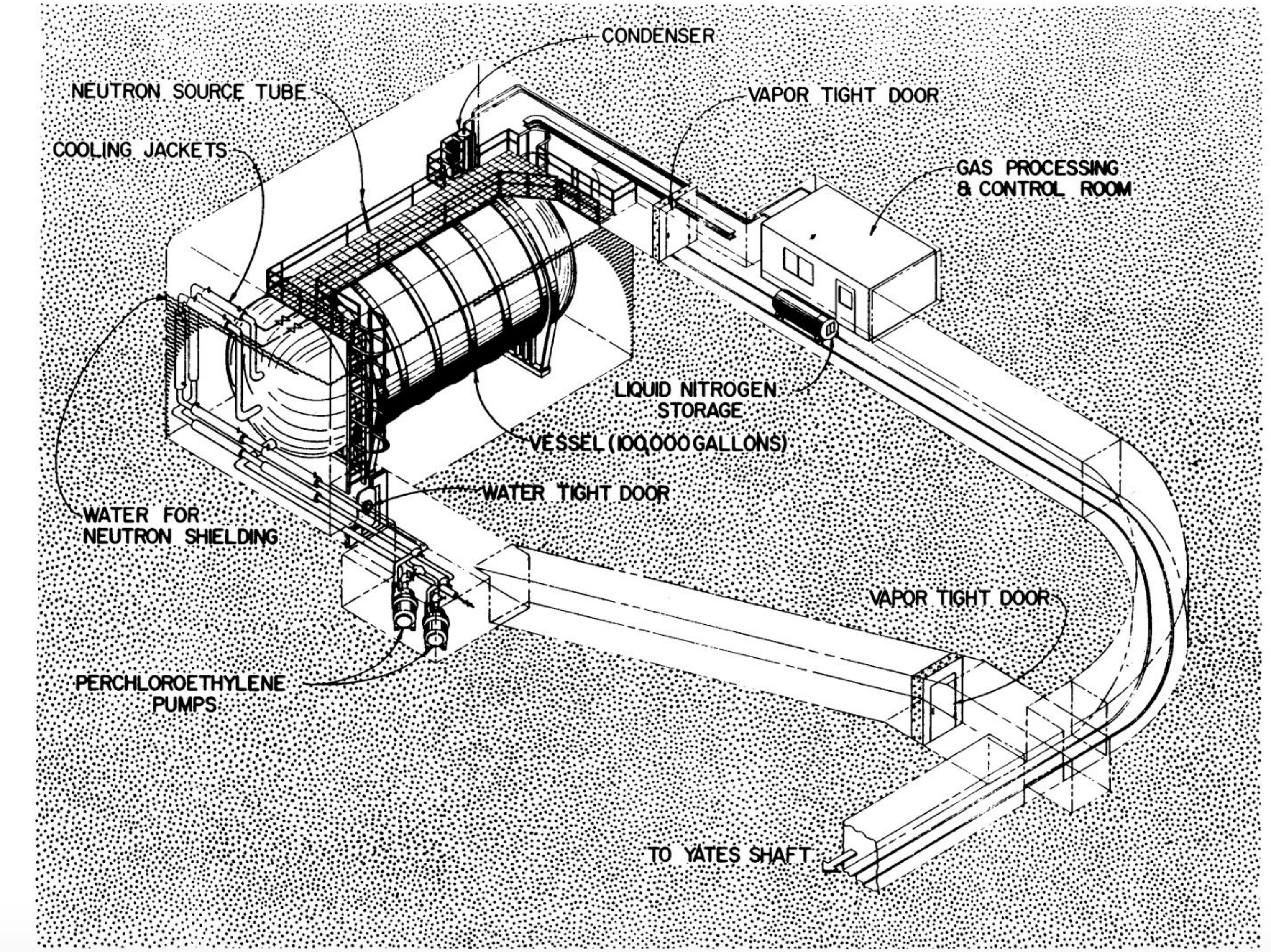


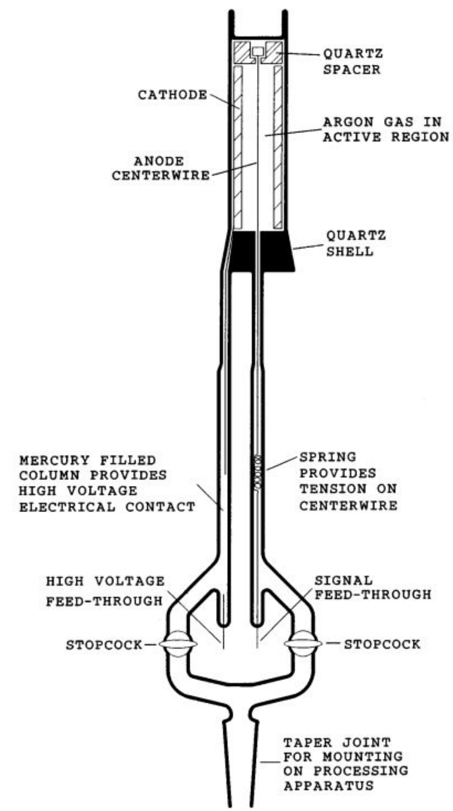
In Hall A there was to be built the GALLEX experiment to measure solar neutrinos

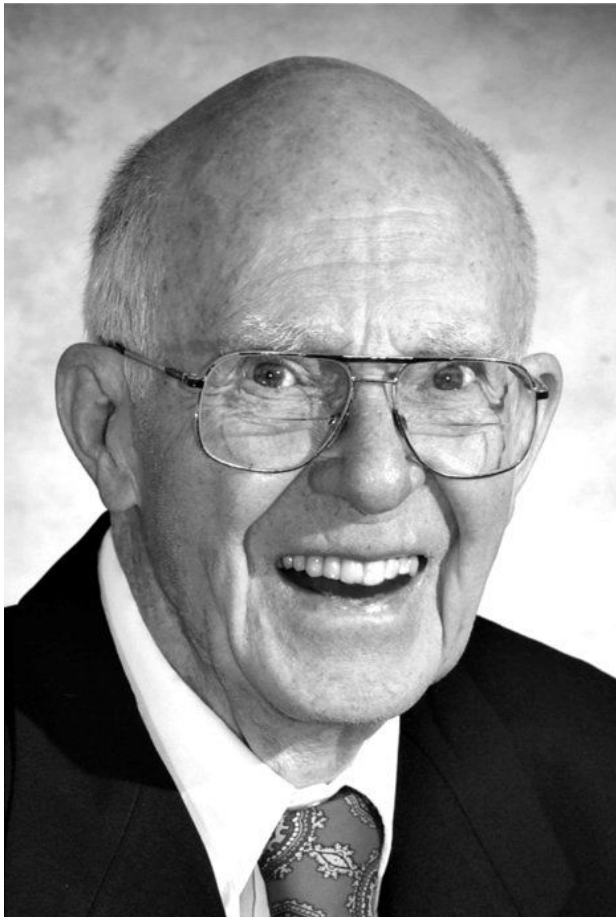
$$^{71}\mathrm{Ga} + \nu_e \rightarrow e^- + {}^{71}\mathrm{Ge}$$

The "Solar neutrino Problem" in 1986

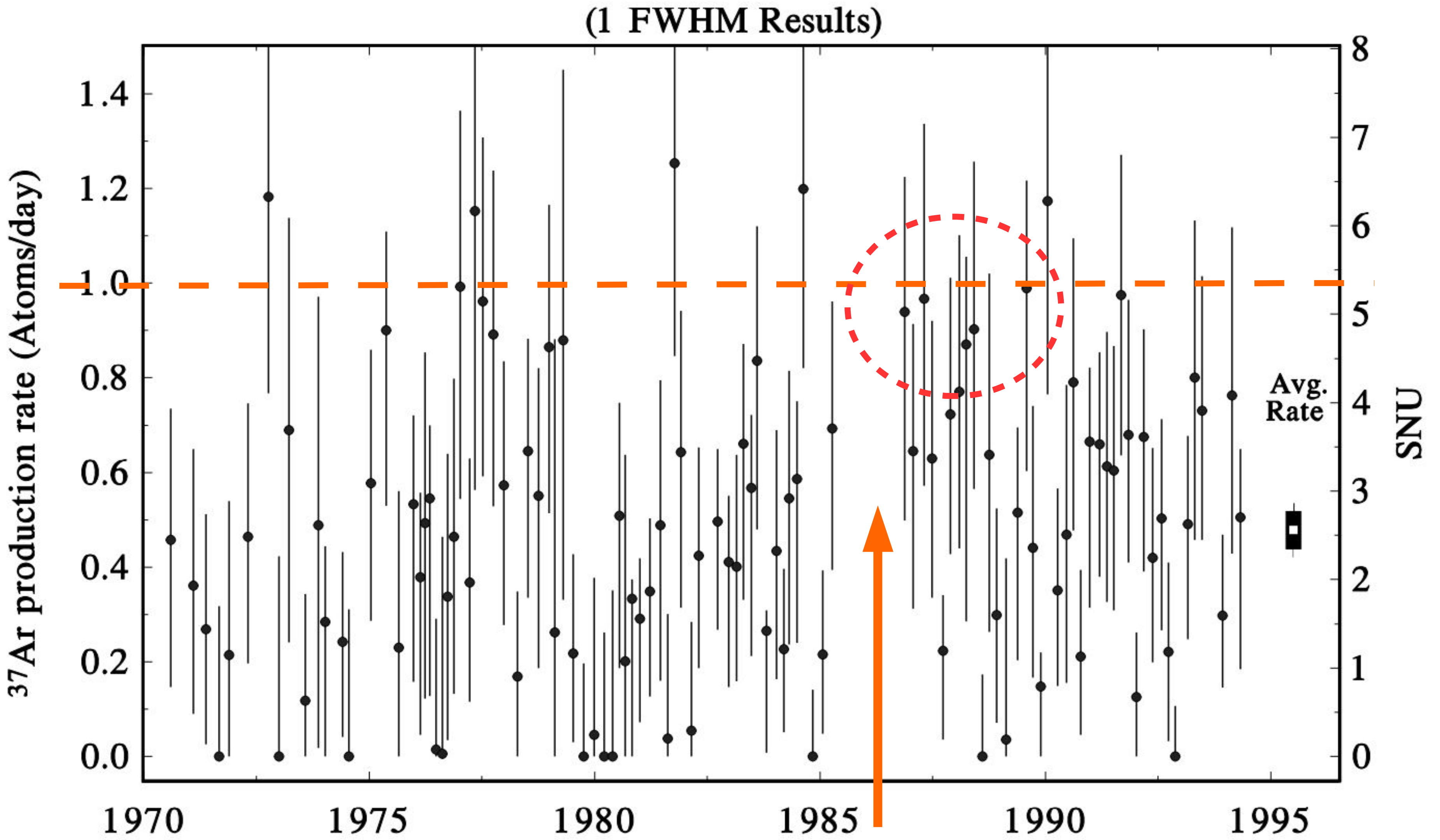
Homestake Solar Neutrino Experiment





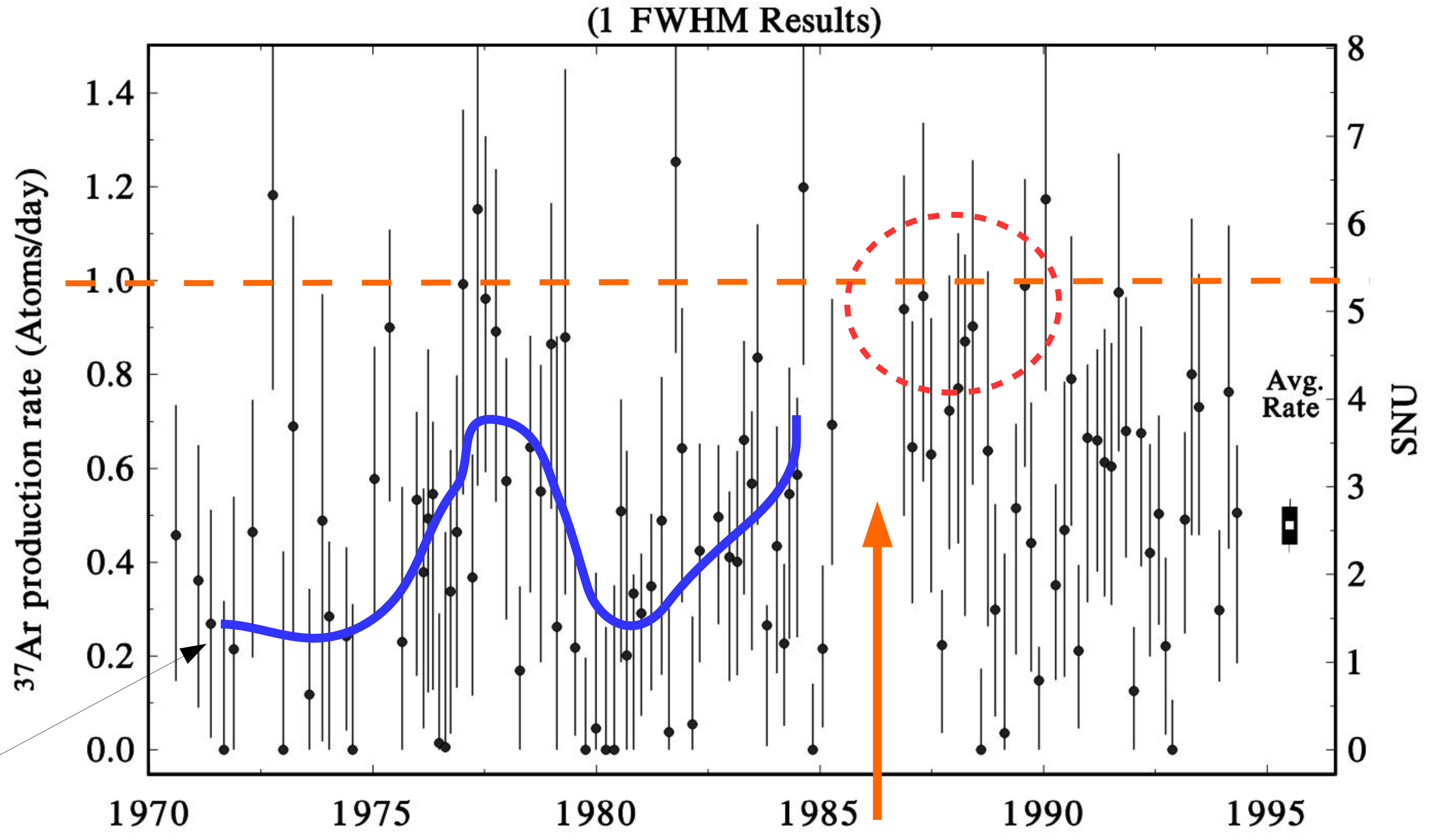



108 Measurements of the solar neutrino signal in the Homestake experiment



Gap in the data
[May 1985 October 1986]

108 Measurements of the solar neutrino signal in the Homestake experiment



time dependence ?!

Gap in the data
[May 1985 October 1986]

A lot of skepticism among the physicists
(at least those I discussed with ....)

Arriving in Roma a colleague back from a conference

“.. two russians have (perhaps) understood something important about neutrino oscillations, and this could explain the Davis experiment ! “

S. P. Mikheyev and A. Y. Smirnov,
“Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos”
Sov. J. Nucl. Phys. **42**, 913-917 (1985)

I remember reading these papers:

L. Wolfenstein,
"Neutrino Oscillations in Matter"
Phys. Rev. D **17**, 2369-2374 (1978)

H. A. Bethe,
"A Possible Explanation of the Solar Neutrino Puzzle"
Phys. Rev. Lett. **56**, 1305 (1986)

finding it was wonderful physics ! and thinking

"... it would be nice if this is relevant to the real world and observable... but it is not very likely ...."

[but started working on the implications for atmosphericneutrinos]

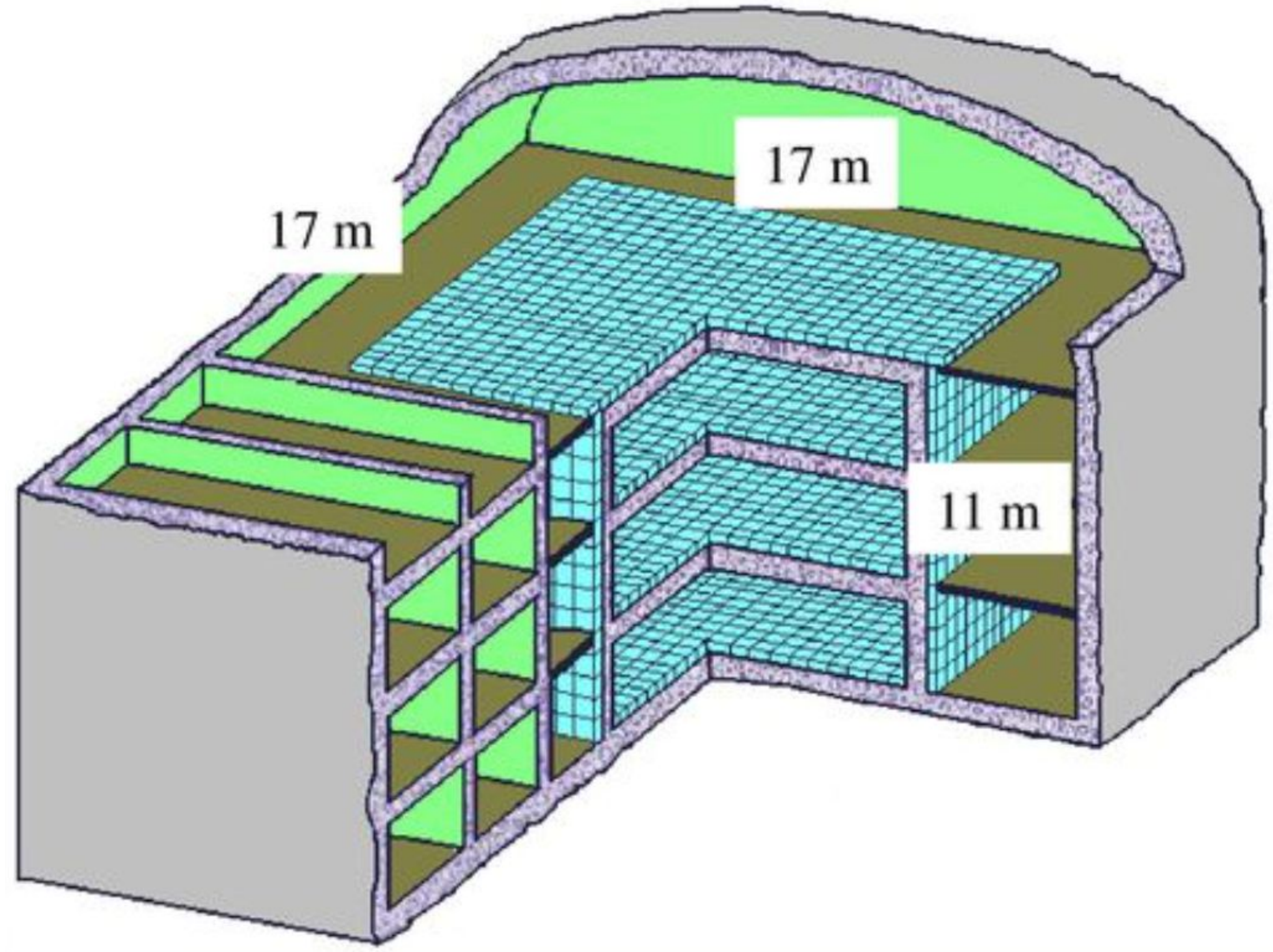
Станислав Павлович Михеев

Stanislav Pavlovich Mikheyev

1940 – 2011

From 1991 – 1998 was part of the MACRO Collaboration

Baksan Neutrino Telescope
(observations started in 1977)



Baxsan Neutrino telescope


(c)Danila85

“Underground Physics” starts very early
during the “heroic times” of cosmic ray physics.

Cecil Frank Powell
(Nobel prize 1950 for the discovery of charged pions)
`` *... a whole new world had been revealed ...*
It was as if, suddenly, we had broken into a walled orchard,
where protected trees had flourished and all kinds of exotic fruits
had ripened in great profusion.''

$$e^{+}$$

$$\mu^{\mp}$$

$$\pi^{\mp} \qquad \pi^{\circ}$$

$$K^{\pm} \qquad K^{\circ} \qquad \overline{K}_{0} \qquad ....$$

Cosmic Ray Showers in the Earth Atmosphere

$$p + \text{Air} \to p\ n, \quad \pi^+\ \pi^-\ \pi^\circ\ \ K^+\ K^-\ K^\circ\ \overline{K}^\circ\ \ \ldots$$

$$\pi^+ \to \mu^+\ \nu_\mu$$

$$\hookrightarrow \overline{\nu}_\mu\ e^+\ \nu_e$$

In modern notation
(neutrinos of different flavors)

Two decays in chain
1st : One invisible particle
2nd At least (exactly) two invisible particles

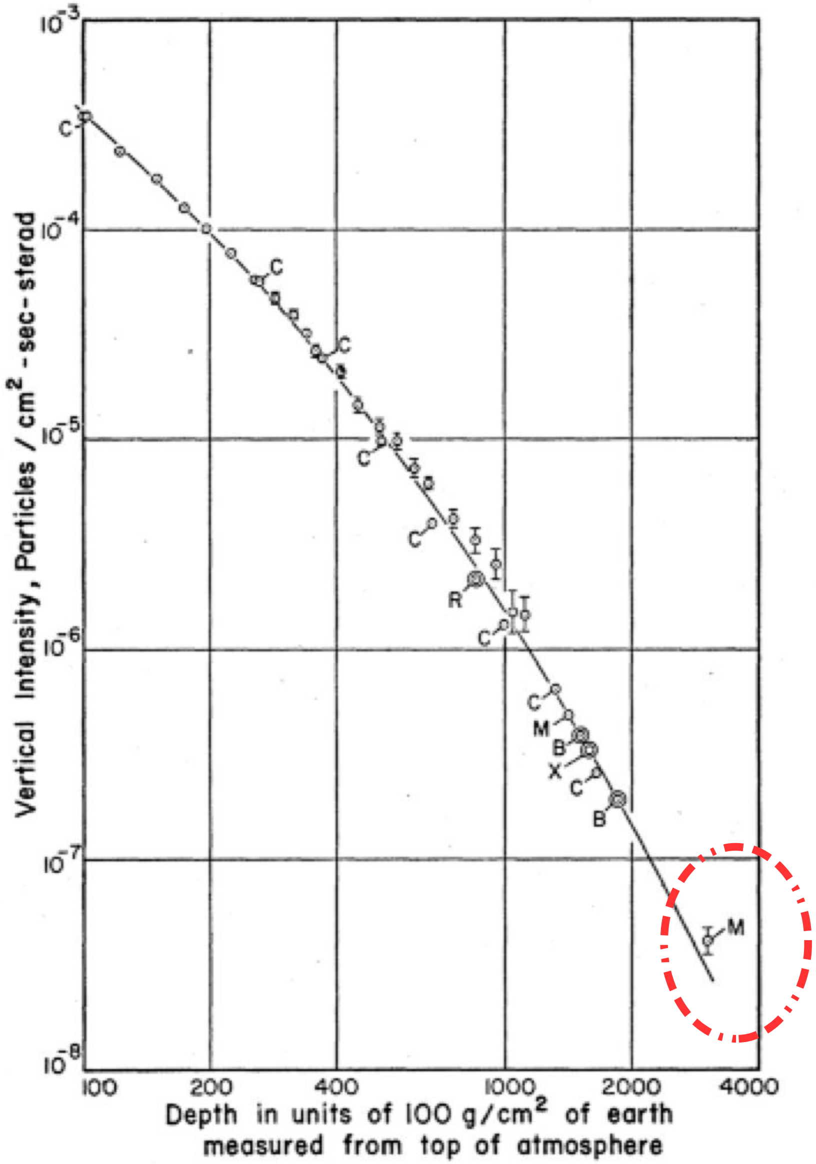
Cosmic Ray Showers in the Earth Atmosphere

$$p + \mathrm{Air} \to p\ n, \quad \pi^+\ \pi^-\ \pi^\circ\ \ K^+\ K^-\ K^\circ\ \overline{K}^\circ \quad \ldots$$

$$\pi^+ \to \mu^+\ \nu_\mu$$

$$\hookrightarrow \overline{\nu}_\mu\ e^+\ \nu_e$$

Very penetrating particle
Spectrum at high energy can be studied
going deep underground



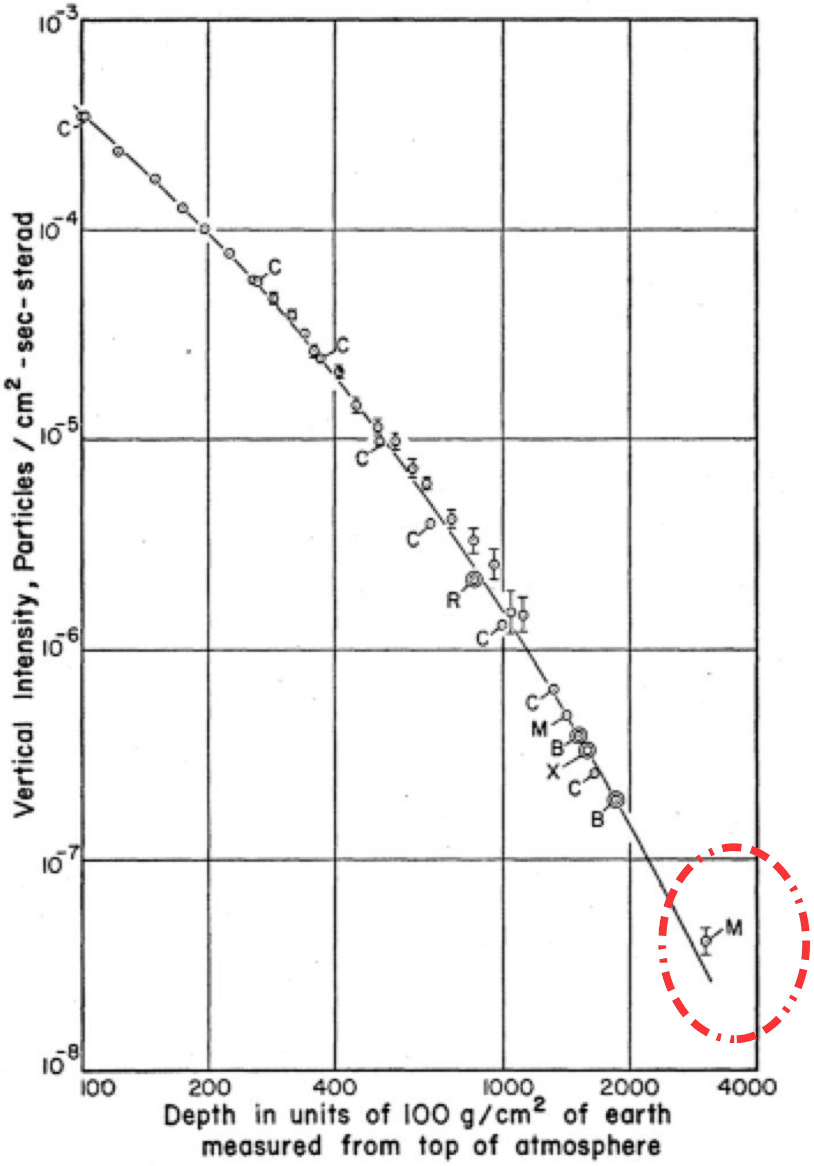
Review of 1952

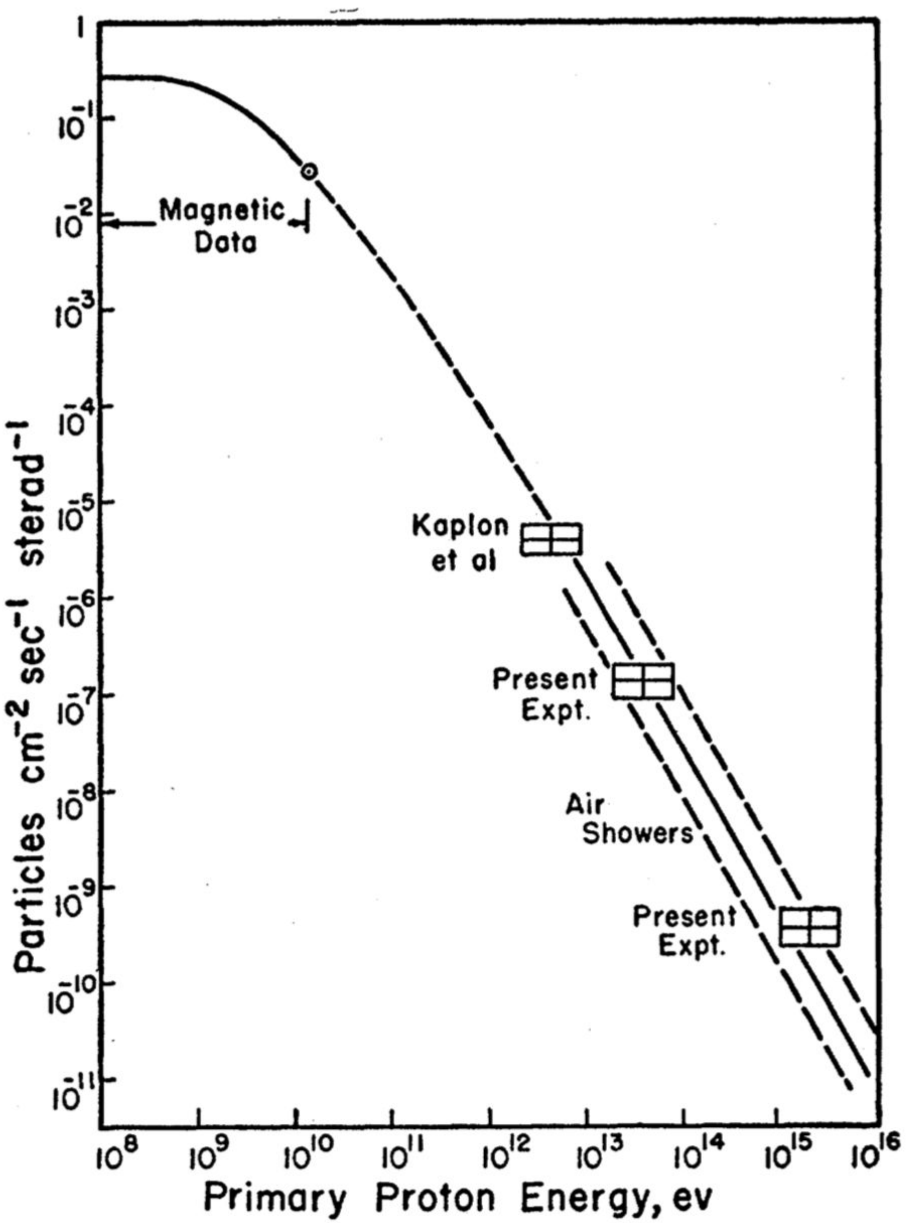
Measurements of the
muon flux
deep underground

Exponential suppression

3000 m.w.e.
(meters water equivalent)
the LNGS depth

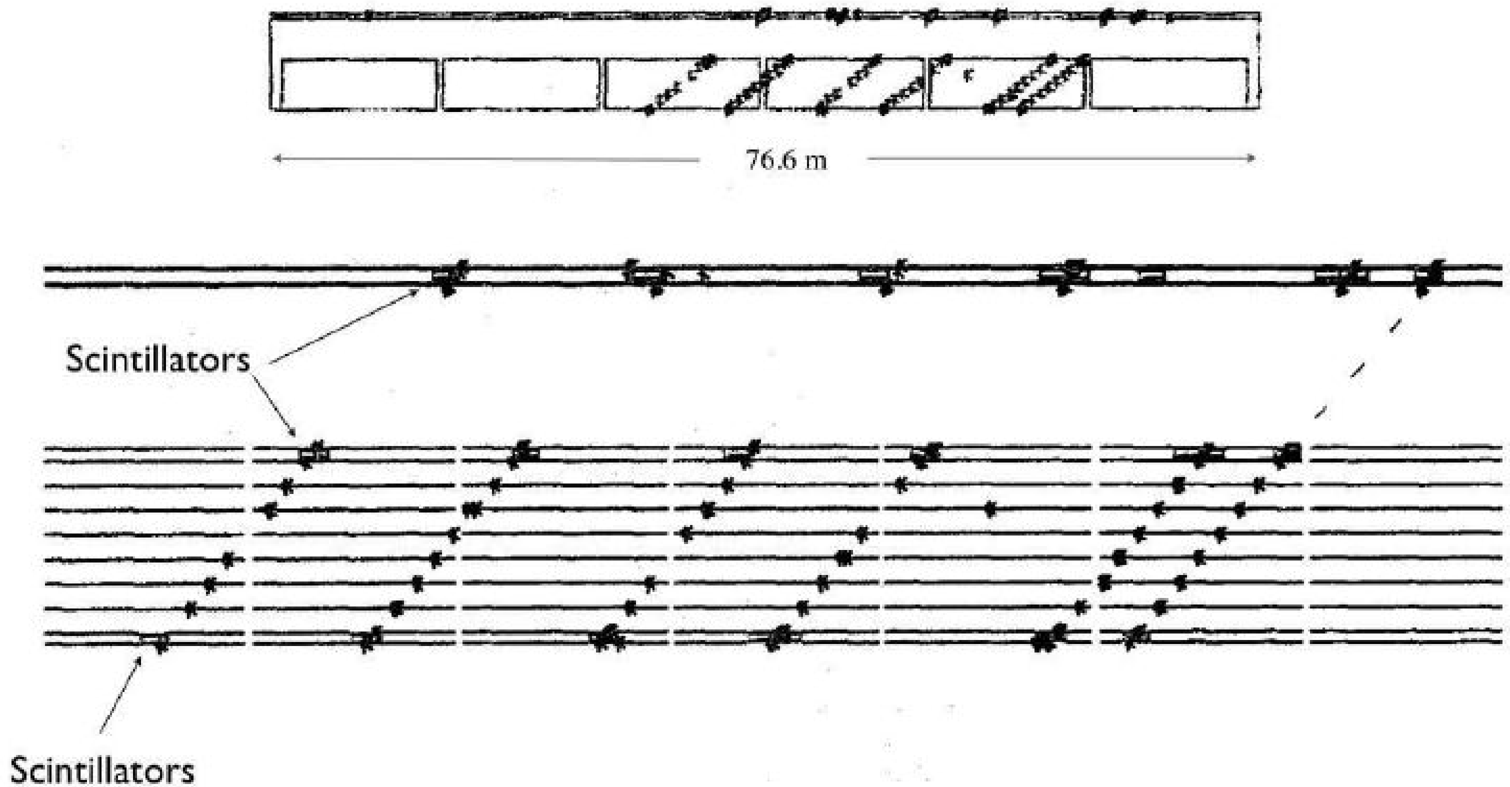
P. H. Barrett, L. M. Bollinger, G. Cocconi,
Y. Eisenberg and K. Greisen,
"Interpretation of Cosmic-Ray Measurements Far Underground"
Rev. Mod. Phys. **24**, no.3, 133-178 (1952)





Interpretation in terms of
energy spectrum of the primary cosmic ray radiation
[up to energy 10^{15} eV]

The Gran Sasso laboratory
offered the possibility to perform much more profound studies of this type, and not only with “single muon”, but also with
“muon bundles”
created in the shower of a single primary particle



one event in the MACRO detector

Cosmic Ray Showers in the Earth Atmosphere

$$p + \mathrm{Air} \to p\ n, \quad \pi^+\ \pi^-\ \pi^\circ\ \ K^+\ K^-\ K^\circ\ \overline{K}^\circ \quad \ldots$$

$$\pi^+ \to \mu^+\ \nu_\mu$$

$$\mu^+ \to \overline{\nu}_\mu\ e^+\ \nu_e$$

There must be an abundant flux
of *"Atmospheric neutrinos"*
[Generated in the showers of primary cosmic rays
in the Earth's atmosphere]

The existence of *Atmospheric neutrinos*
was immediately understood,

The possibility of detecting these high energy
neutrinos was clearly extremely difficult
but very interesting

[for example : *Measure the neutrino cross sections !*]

Another fantastic idea was also
very soon expressed:

Astrophysical Neutrinos

Cosmic rays are created somewhere,
and also "there" there will be some target, and
neutrinos are produced.....
... and they travel along straight lines .....

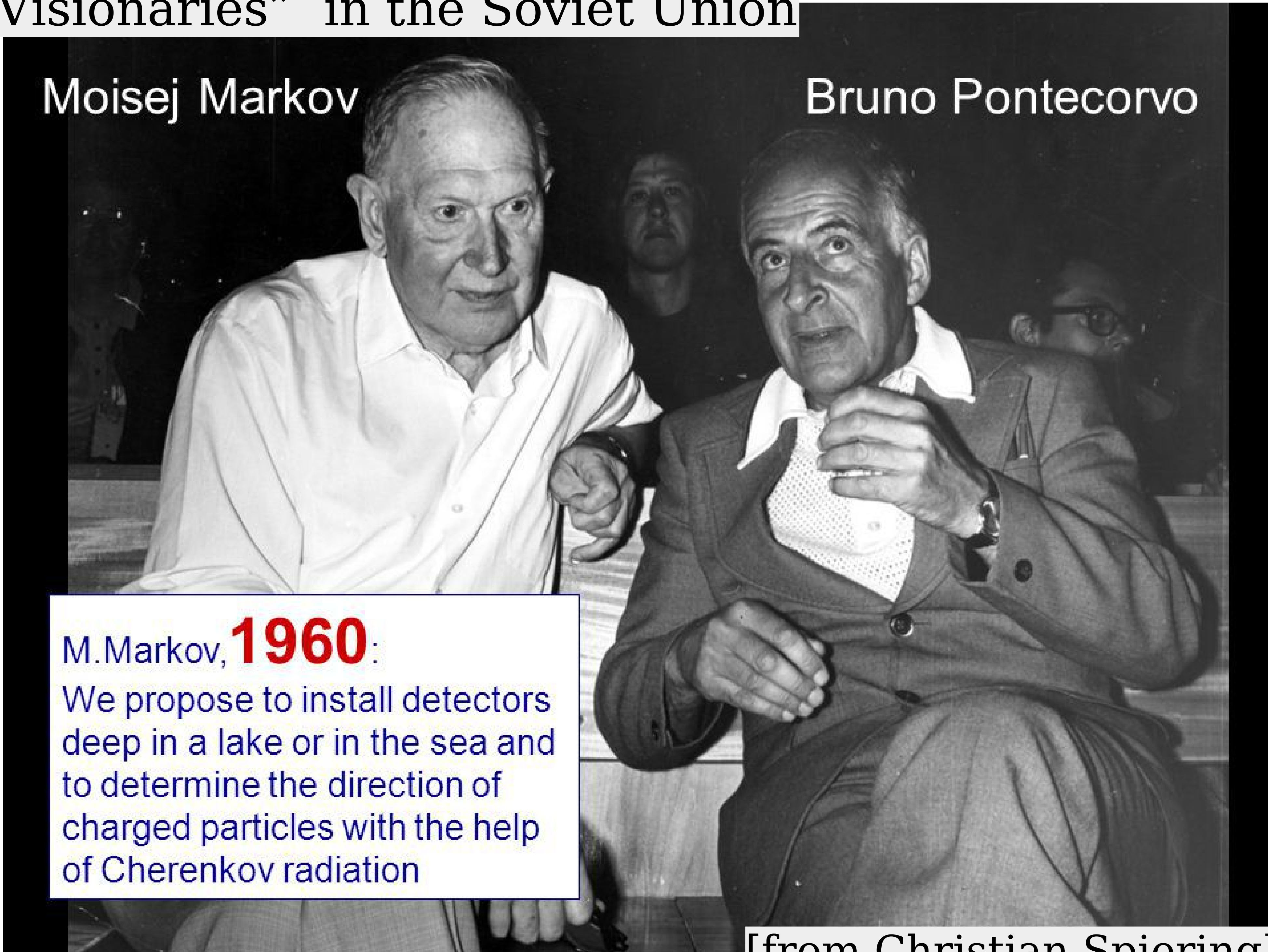
There *must be* a flux of
"cosmic neutrinos"
[atmospheric neutrinos]

Is it detectable ?

Are there (high energy) neutrinos
Generated from astrophysical Sources ?

Is Neutrino Astronomy Possible ?

“Visionaries” in the Soviet Union



[from Christian Spiering]

“Visionaries” in the Soviet Union

M. A. Markov and I. M. Zheleznykh,
“On high energy neutrino physics in cosmic rays,”
Nucl. Phys. **27**, 385 (1961).

B. Pontecorvo and Y. Smorodinsky,
“The neutrino and the density of matter in the universe,”
Zh. Eksp. Teor. Fiz. **41**, 239 (1961).

B. Pontecorvo and A. E. Chudakov,
“Neutrinos and the cosmic ray intensity at great depths,”
11th International Conference on High-energy Physics (ICHEP 62)
4-11 Jul 1962. Geneva, Switzerland

Fascinating review by a key participant:

I. Zheleznykh,
"Early years of high-energy neutrino physics in cosmic rays and neutrino astronomy (1957-1962),"
Int. J. Mod. Phys. A **21S1**, 1 (2006).

Idea also discussed in

K. Greisen, "Cosmic ray showers,"
Ann. Rev. Nucl. Part. Sci. **10**, 63 (1960).

While the experimentalist were
discussing (extremely) bold solutions for detection,

Berezinsky and Zatsepin made a *prediction*
of great importance about a flux of
astrophysical neutrinos at ultra high energy

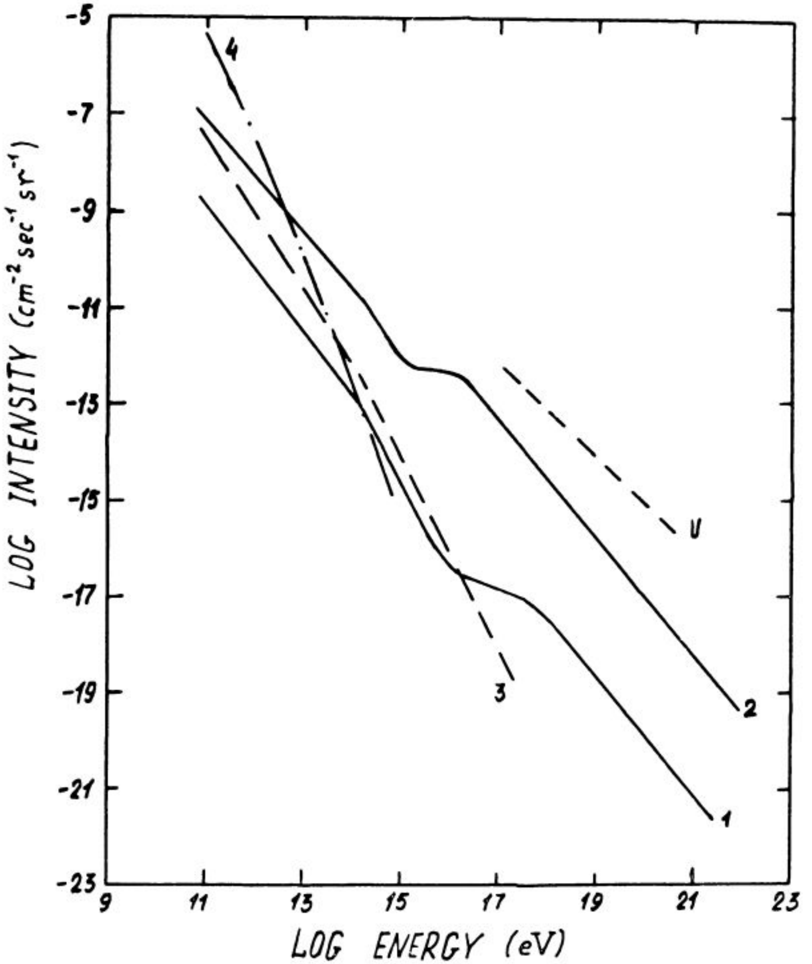
V. S. Berezinsky and G. T. Zatsepin,
"Cosmic rays at ultrahigh-energies (neutrino?)"
Phys. Lett. B **28**, 423-424 (1969)

Abstract:

The neutrino spectrum produced by protons on microwave photons is calculated. A spectrum of extensive air shower primaries can have no cut-off at an energy $E > 3 \times 10^{19}$ eV, if the neutrino-nucleon total cross-section rises up to the geometrical one of a nucleon.

Developing these ideas (with additional theoretical possibilities)

V. S. Berezinsky and A. Y. Smirnov,
"Cosmic neutrinos of ultra-high energies and detection possibility"
Astrophys. Space Sci. **32**, 461-482 (1975)



COSMIC NEUTRINOS OF ULTRA-HIGH ENERGIES AND DETECTION POSSIBILITY

V. S. BEREZINSKY and A. YU. SMIRNOV
Institute for Nuclear Study, U.S.S.R. Academy of Sciences, Moscow, U.S.S.R.

Abstract. The fluxes and spectra of galactic and extragalactic neutrinos at energy 10^{11}–10^{19} eV are calculated. In particular, the neutrino flux from the normal galaxies is calculated taking into account the spectral index distribution. The only assumption that seriously affects the calculated neutrino flux at $E_\nu \gtrsim 10^{17}$ eV is the power-like generation spectrum of protons in the entire considered energy region.

The normal galaxies with the accepted parameters generate the metagalactic equivalent electron component (electrons + their radiation) with energy density $\omega_e \approx 8.5 \times 10^{-7}$ eV cm^{-3}, while the density of the observed diffuse X-ray radiation alone is 100 times higher. This requires the existence of other neutrino sources and we found the minimized neutrino flux under two limitations: (1) the power-law generation spectrum of protons and (2) production of the observed energy density of the diffuse X- an γ-radiation. These requirements are met in the evolutionary model of origin of the metagalactic cosmic rays with modern energy density $\omega_{\mathrm{Mg}} \approx 3.6 \times 10^{-3}$ eV cm^{-3}.

The possibility of experiments with cosmic neutrinos of energy $E_\nu \gtrsim 3 \times 10^{17}$ eV is discussed. The upper bound on neutrino-nucleon cross-section $\sigma < 2.2 \times 10^{-29}$ cm^2 is obtained in evolutionary model from the observed zenith angular distribution of extensive air showers.

In Appendix 2 the diffuse X- and γ-ray flux arising together with neutrino flux is calculated. It agrees with observed flux in the entire energy range from 1 keV up to 100 MeV.

Very important idea

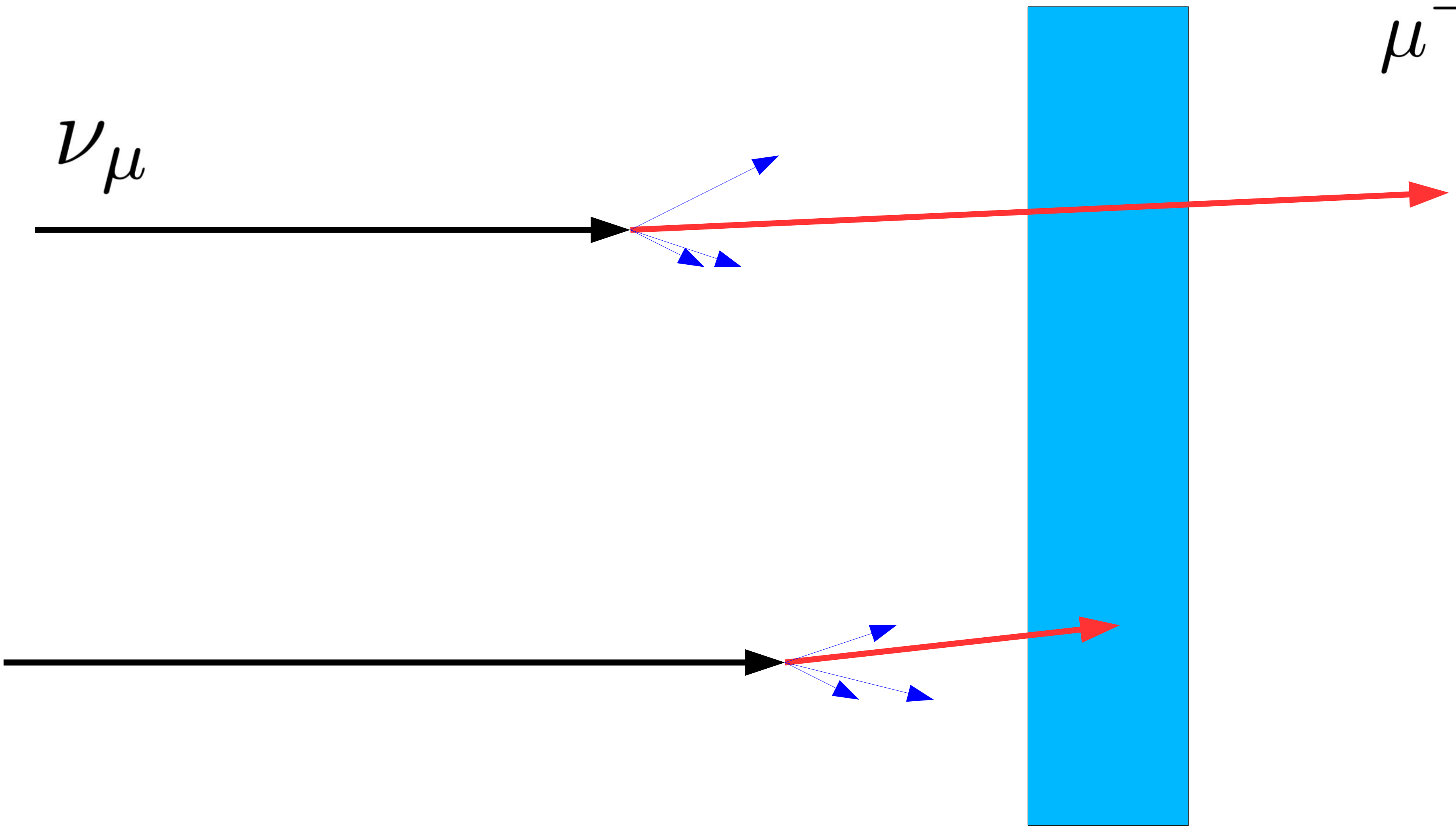
In Section 2 we have found the rigorous upper bound for high energy neutrino flux at $E \geqslant 10^{17}$ eV based on the observed intensity of diffuse X- and γ-radiation:

The high energy neutrino production (through $\pi^{\pm}$-production) is accompanied by high energy γ-rays (through π^0-production). These photons colliding with background radio and microwave photons give a start to the electromagnetic cascade, whose almost entire energy transfers to the observable X- and γ-ray band ($E_\gamma \lesssim 100$ MeV).

Neutrino Induced Muons

$$\nu_\mu + N \to \mu^- + \ldots$$

$$\overline{\nu}_\mu + N \to \mu^+ + \ldots$$

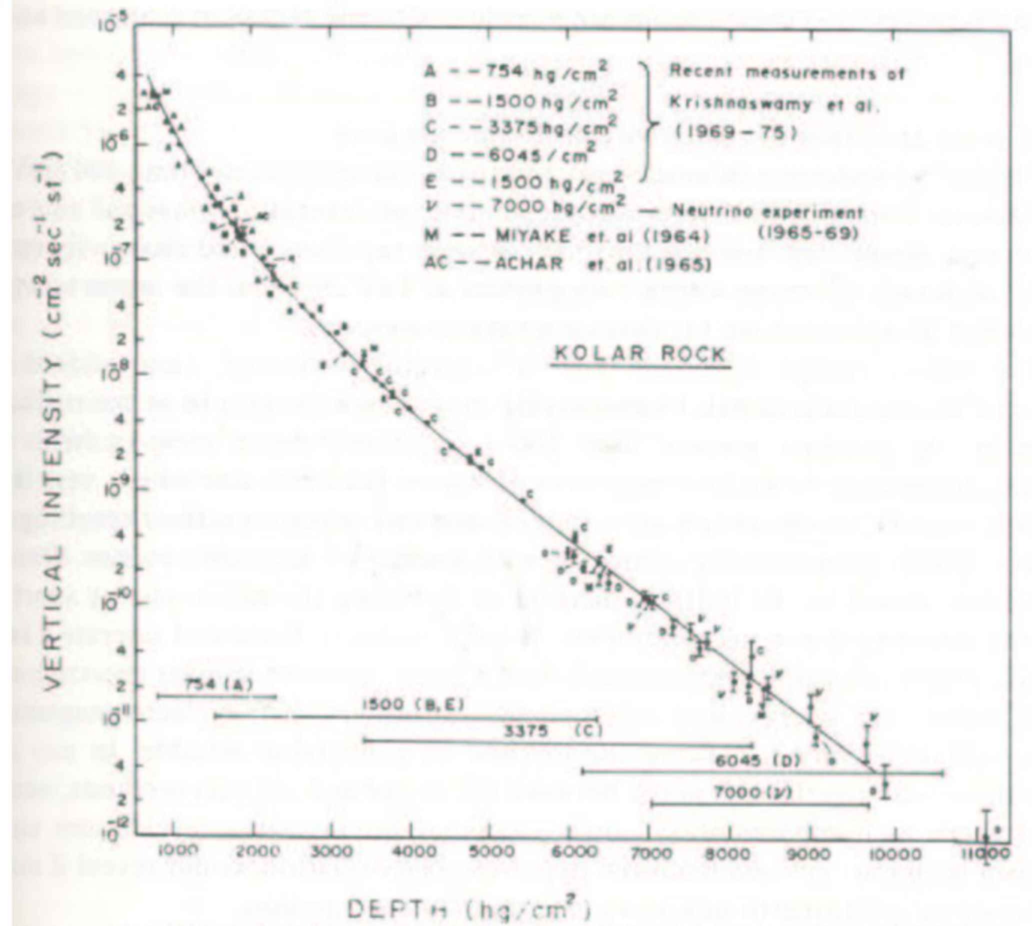


The first observations of Atmospheric Neutrinos

C. V. Achar *et al.*,
"Detection of muons produced by cosmic ray neutrinos deep underground,"
Phys. Lett. **18**, 196 (1965).

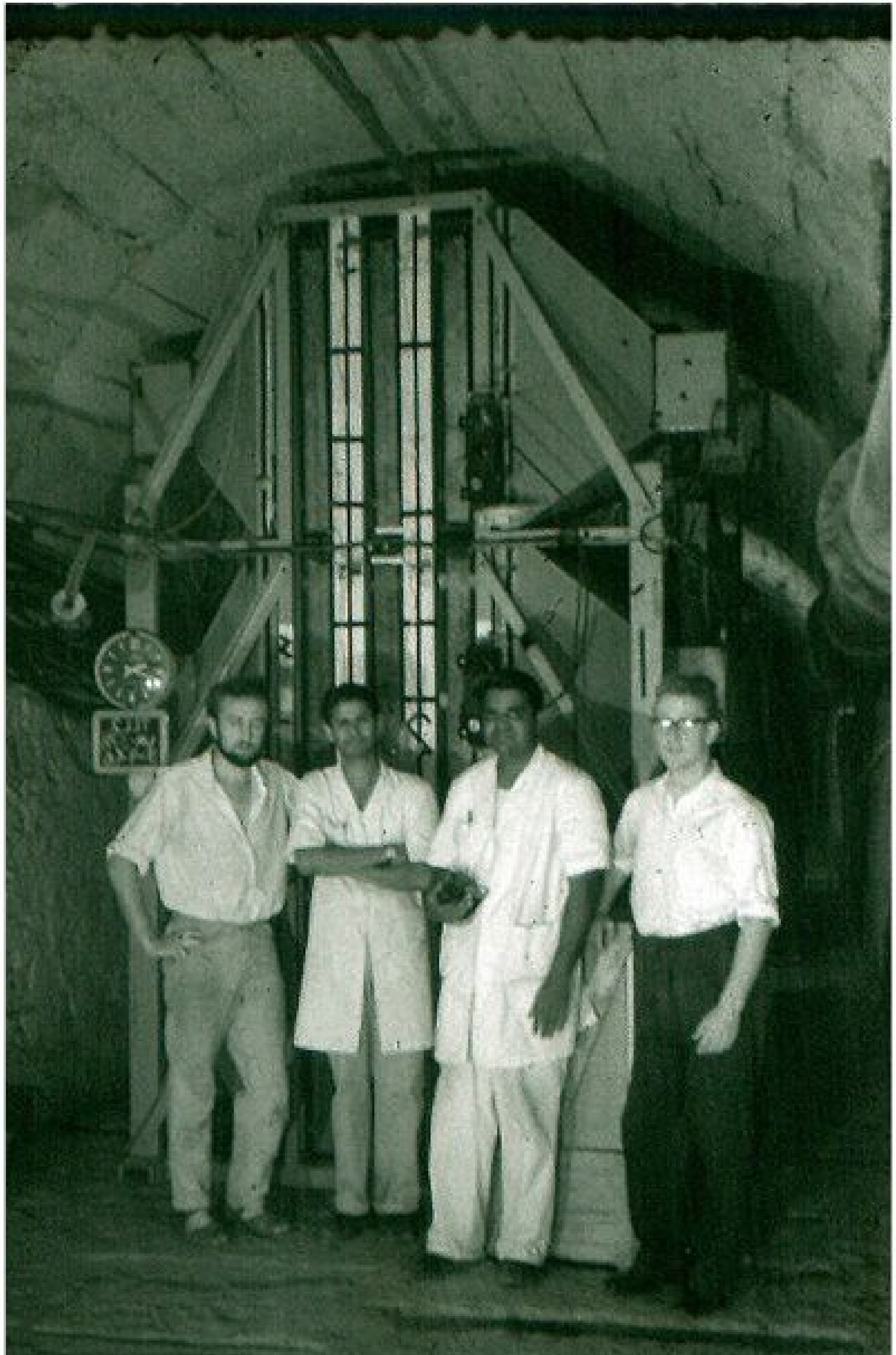
F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, G. R. Smith, J. P. F. Sellschop and B. Meyer,
"Evidence for high-energy cosmic ray neutrino interactions,"
Phys. Rev. Lett. **15**, 429 (1965).

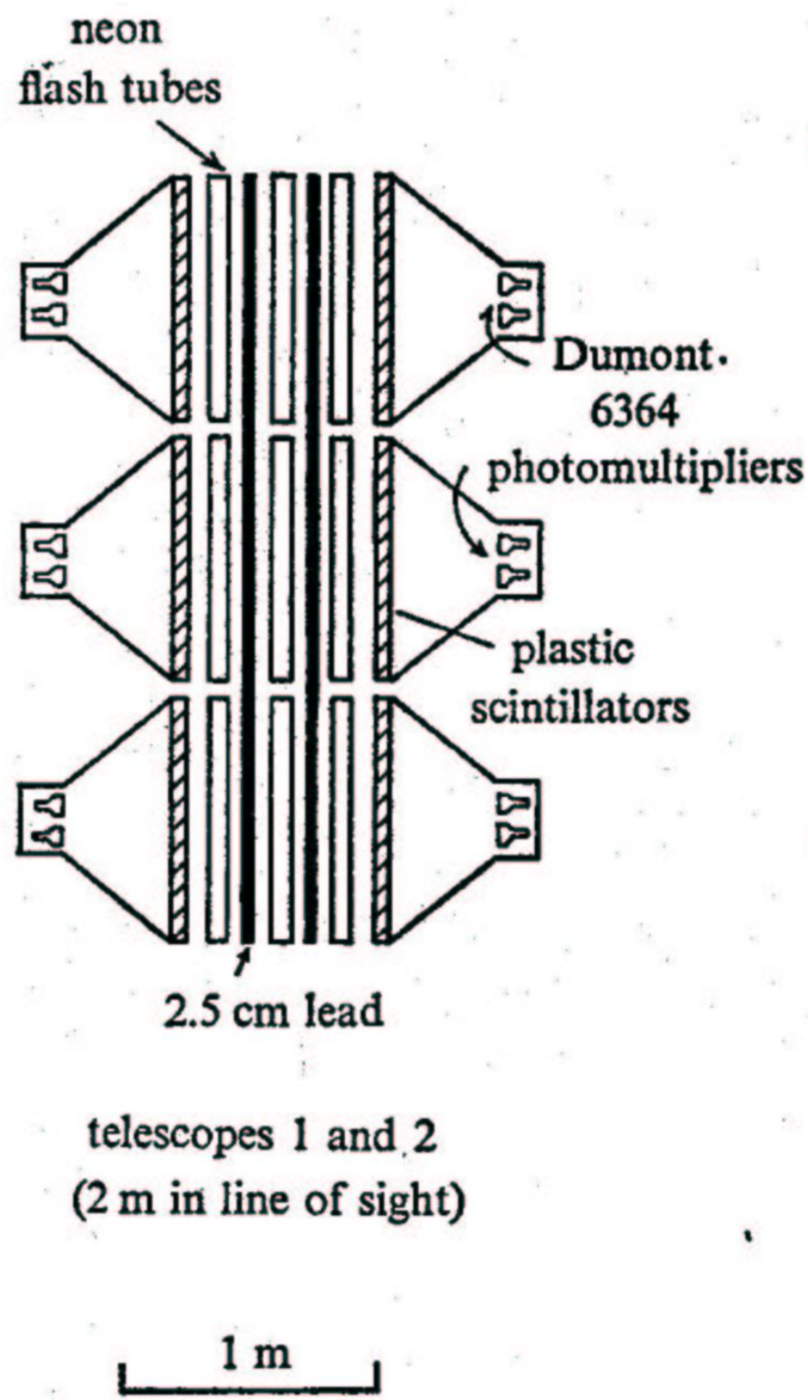
Kolar Gold Field Mine in India

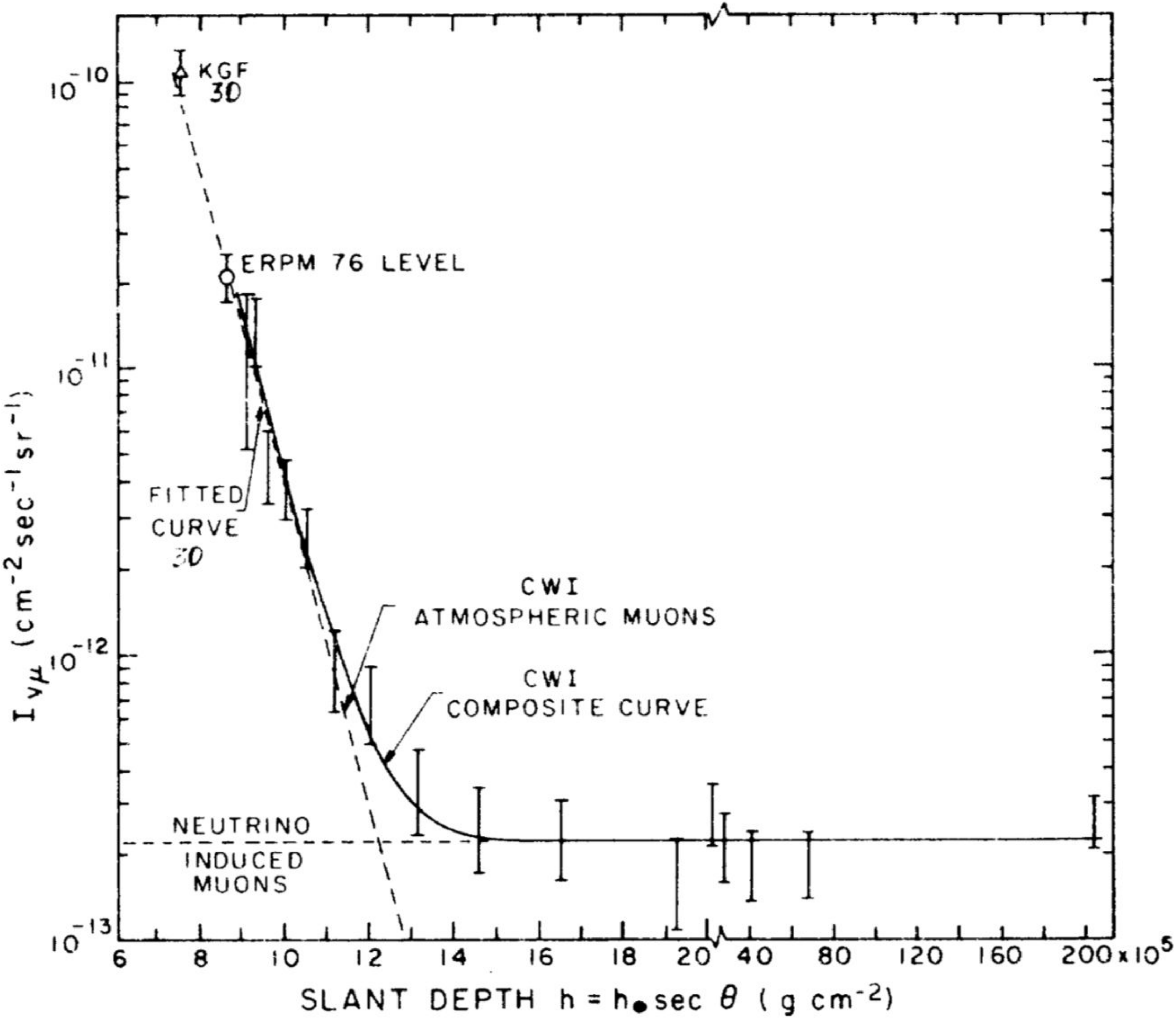


THE CONSOLIDATED DEPTH-INTENSITY RELATION FROM ALL WORKS DONE UNDER KOLAR ROCK

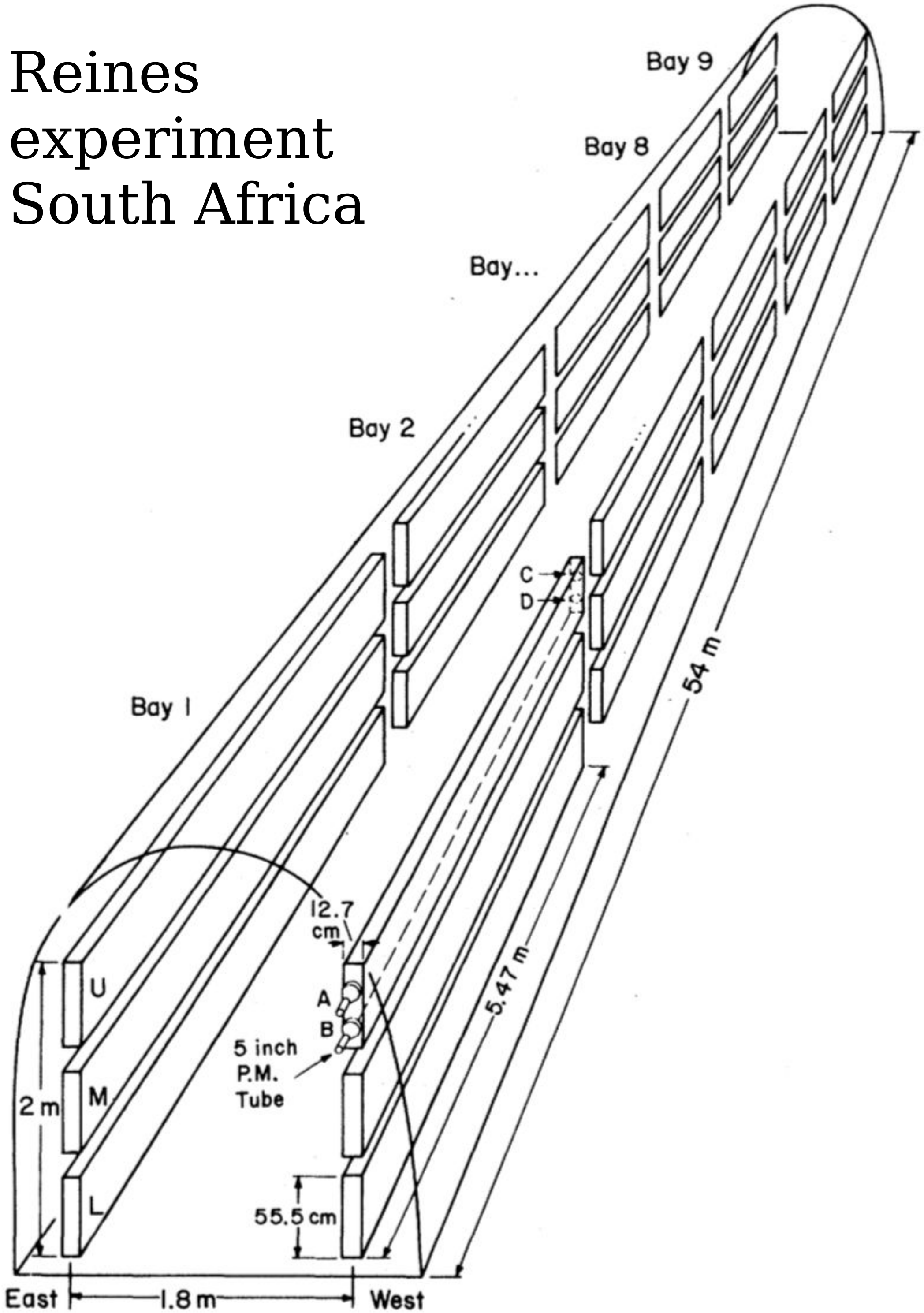
M. G. K. Menon, P. V. Ramana Murthy, B. V. Sreekantan and S. Miyake,
"Cosmic-ray intensity at great depths and neutrino experiments,"
Nuovo Cim. **30**, 1208 (1963).



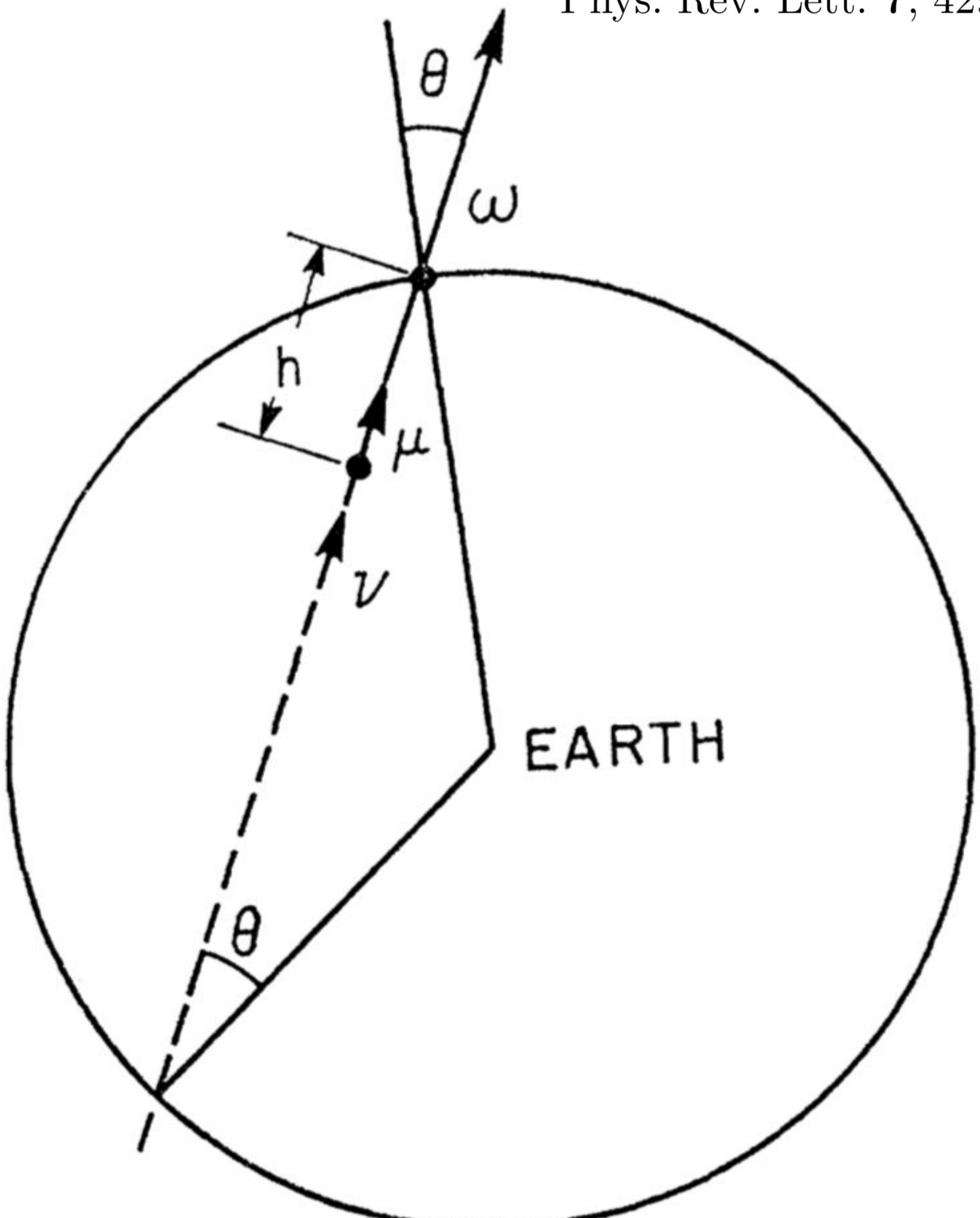

neon
flash tubes
Dumont
6364
photomultipliers
plastic
scintillators
2.5 cm lead
telescopes 1 and 2
(2 m in line of sight)
1 m


KGF
30
ERPM 76 LEVEL
FITTED
CURVE
30
CWI
ATMOSPHERIC MUONS
CWI
COMPOSITE CURVE
NEUTRINO
INDUCED
MUONS
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$I_{\nu\mu}$ ($cm^{-2} sec^{-1} sr^{-1}$)
6 8 10 12 14 16 18 20 40 80 120 160 200 x 10^5
SLANT DEPTH $h = h_\bullet \sec\theta$ (g cm^{-2})

Reines
experiment
South Africa



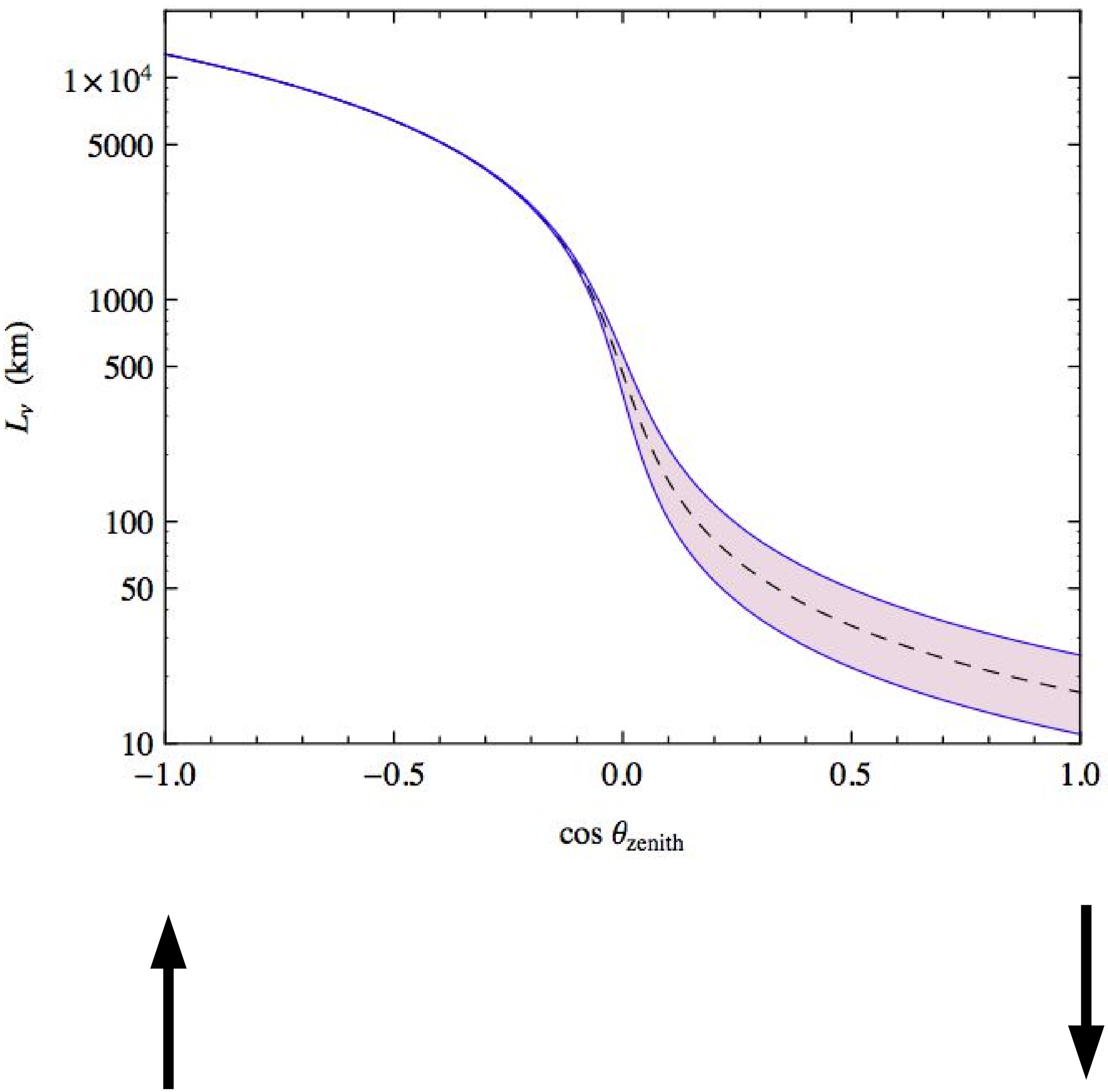
T. D. Lee, C. N. Yang and P. Markstein,
"Production Cross-section of Intermediate Bosons by Neutrinos in the Coulomb Field of Protons and Iron,"
Phys. Rev. Lett. **7**, 429 (1961).



$$\nu_\mu + Z \rightarrow \mu^- + W^+ + Z$$

$$L = -R_\oplus \cos\theta_z + \sqrt{R_\oplus^2 \cos^2\theta_z + 2hR_\oplus + h^2}$$

$\langle h \rangle \simeq 20$ Km



$$L = 2R_\oplus |\cos\theta_z| \simeq 12{,}700\, |\cos\theta_z| \text{ km}$$

$\cos\theta_z < 1$

$$L = \sqrt{2hR_\oplus} \simeq 500 \text{ Km}$$

$\cos\theta \approx 0$

$$L = \frac{h}{\cos\theta_z} \approx \frac{20 \text{ Km}}{\cos\theta_z}$$

$\cos\theta_z > 1$

Strong motivation for Underground experiments:

the prediction of *Proton Decay*

J. C. Pati and A. Salam,
“Is Baryon Number Conserved?,”
Phys. Rev. Lett. **31**, 661 (1973).

Georgi and Glashow,
"Unity of All Elementary Particle Forces",
Phys.Rev.Lett. 32 438 (1974).

Georgi, Quinn and Weinberg,
"Hierarchy of Interactions in Unified Gauge Theories",
Phys. Rev. Lett. 33, 451 (1974).

Physical Review 96, 1157 (1954)

Conservation of the Number of Nucleons*

F. Reines and C. L. Cowan, Jr., *University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

AND

M. Goldhaber, *Brookhaven National Laboratory, Upton, New York*

(Received September 27, 1954)

It has often been surmised that there exists a conservation law of nucleons, i.e., that they neither decay spontaneously nor are destroyed or created singly in nuclear collisions.[1] In view of the fundamental nature of such an assumption, it seemed of interest to investigate the extent to which the stability of nucleons could be experimentally demonstrated.[2]

To investigate the possible decay of a free proton, the large scintillation detector developed for the neutrino search[3] was employed. The detector was partially shielded from cosmic rays by placing it in an underground room with about 100 feet of rock above.

First limit: 10^{21} yr

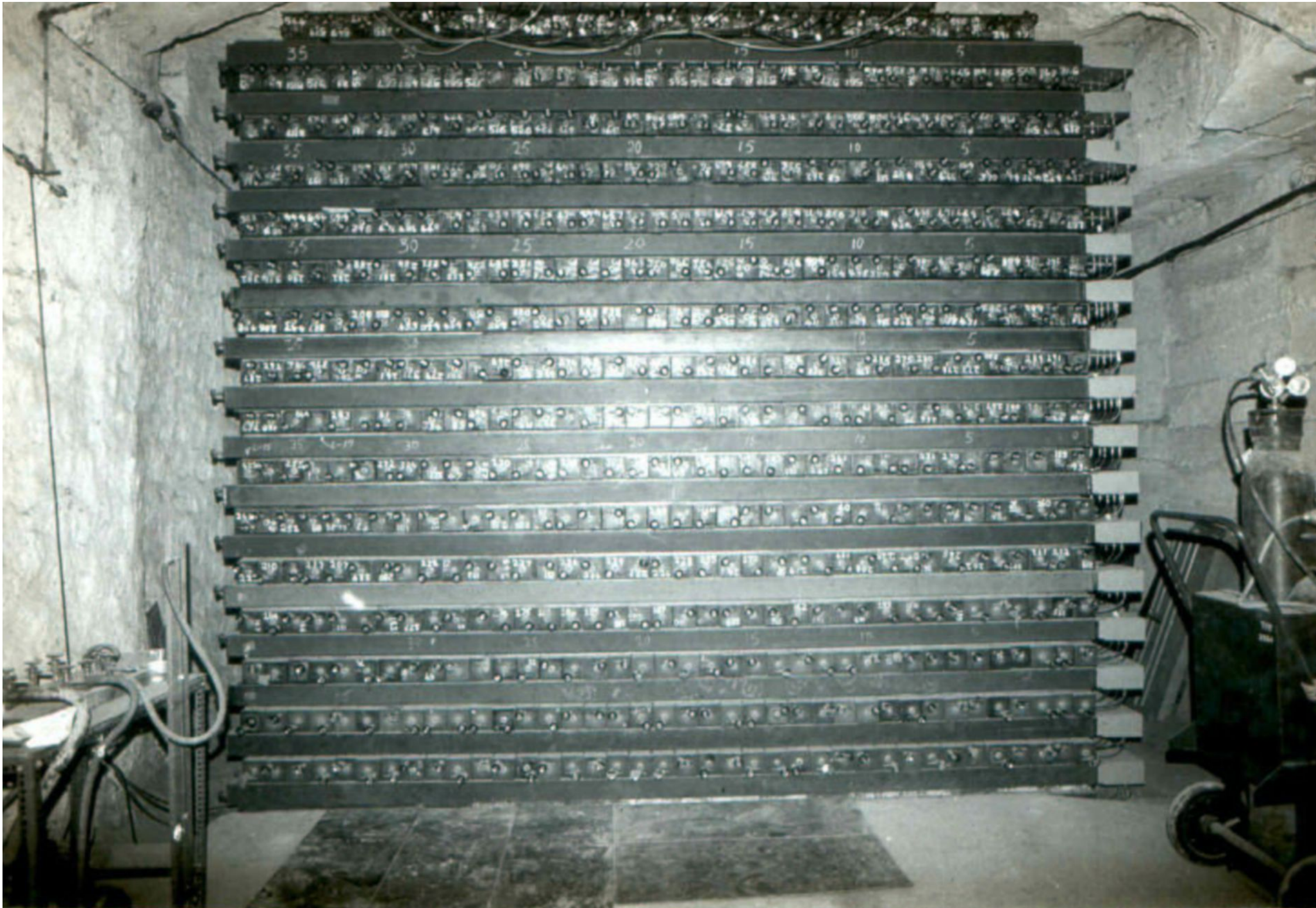
H. S. Gurr, W. R. Kropp, F. Reines and B. Meyer,
"Experimental test of baryon conservation,"
Phys. Rev. **158**, 1321 (1967).

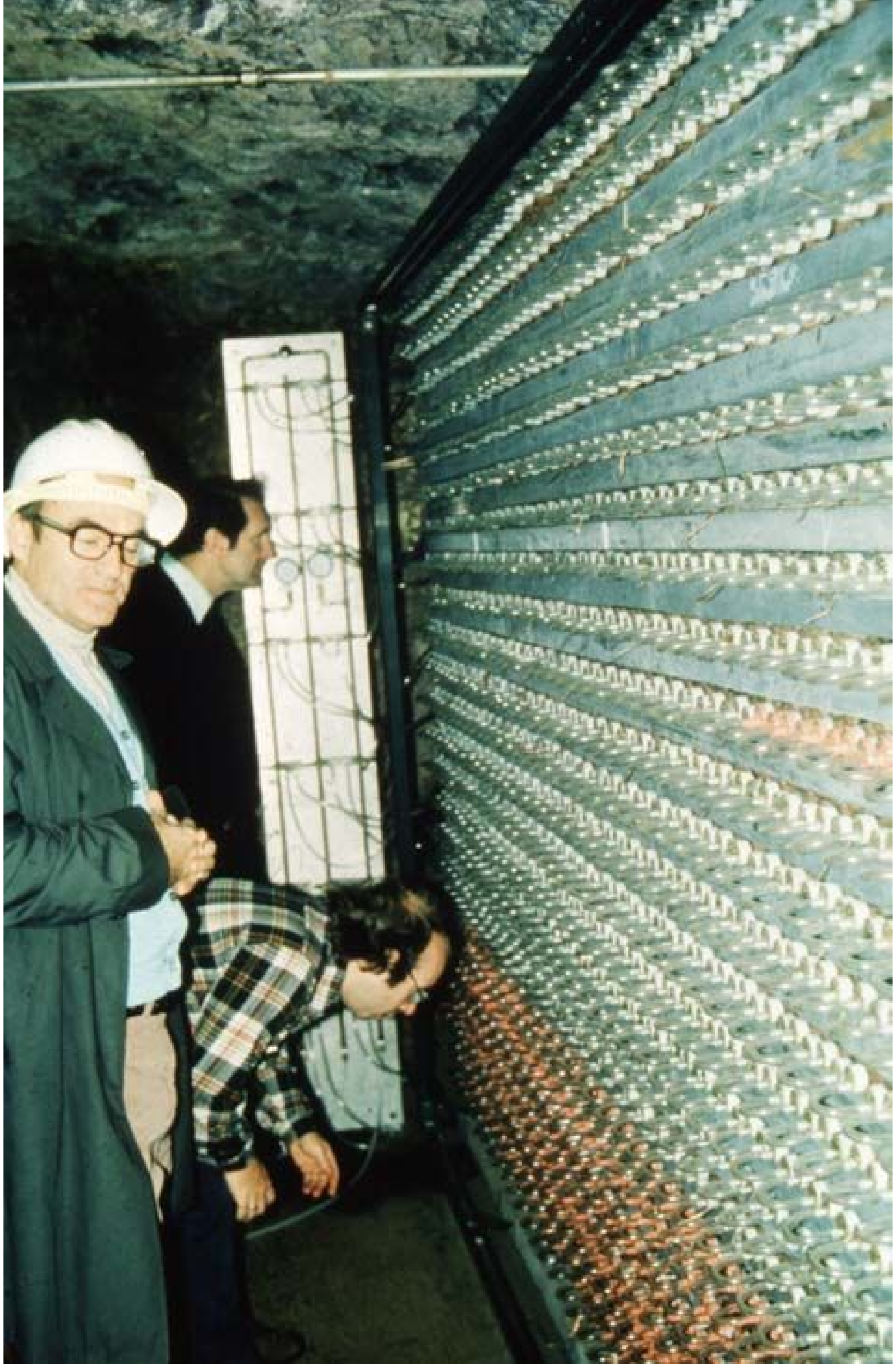
The data give no evidence for the existence of nucleon decay. Lower limits on the half-life of the nucleon from 2×10^{28} to 8×10^{29} yr depending on the assumed decay mode are established. It is seen that the atmospheric muon neutrino serves as the major source of background in the present experiment. If it were possible to positively identify all muon neutrino events, improved half-life limits could be established.

Lower Limit pushed up

2×10^{28} to 8×10^{29} yr

depending on the assumed decay mode

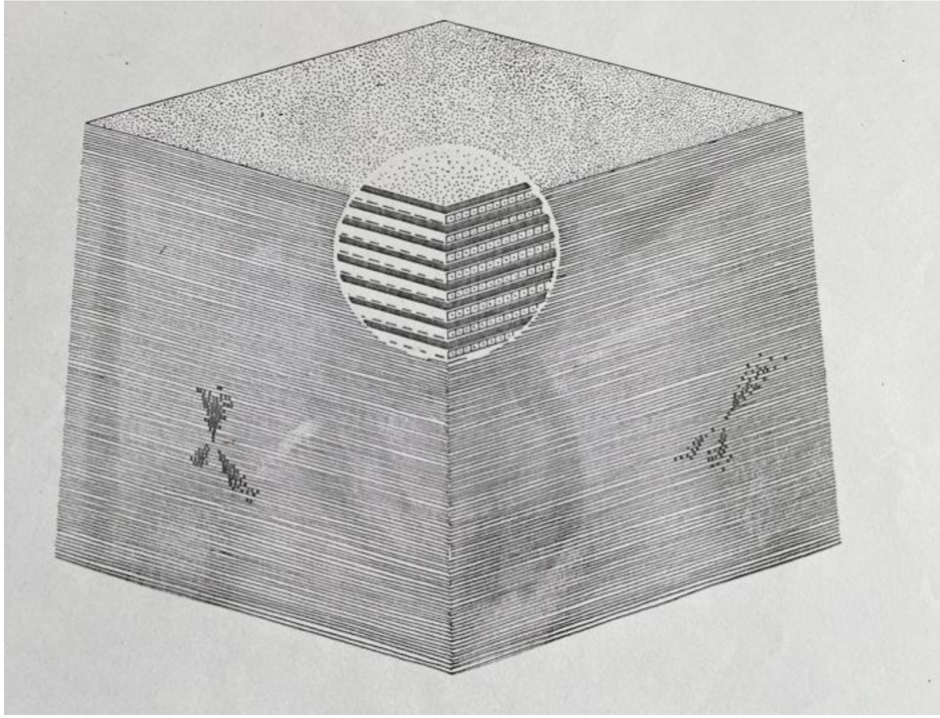




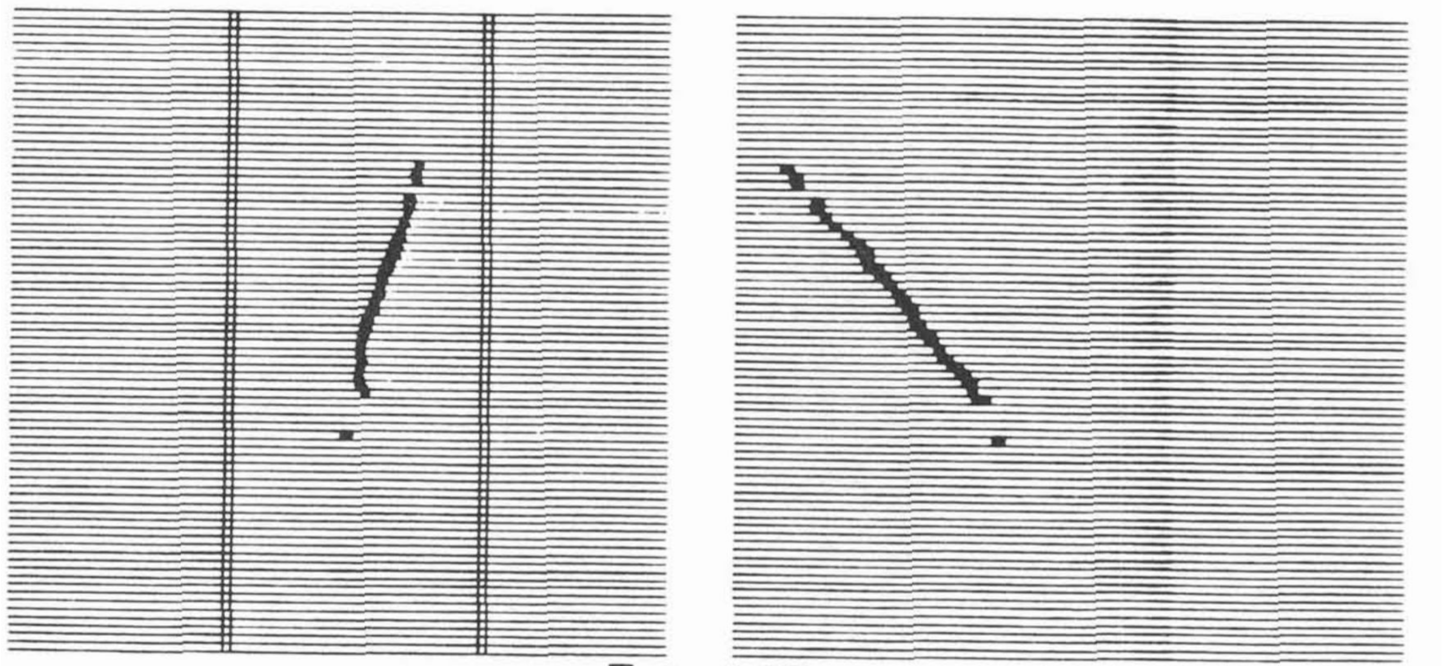
Soudan 1
detector

Nucleon Stability Experiment (NUSEX)

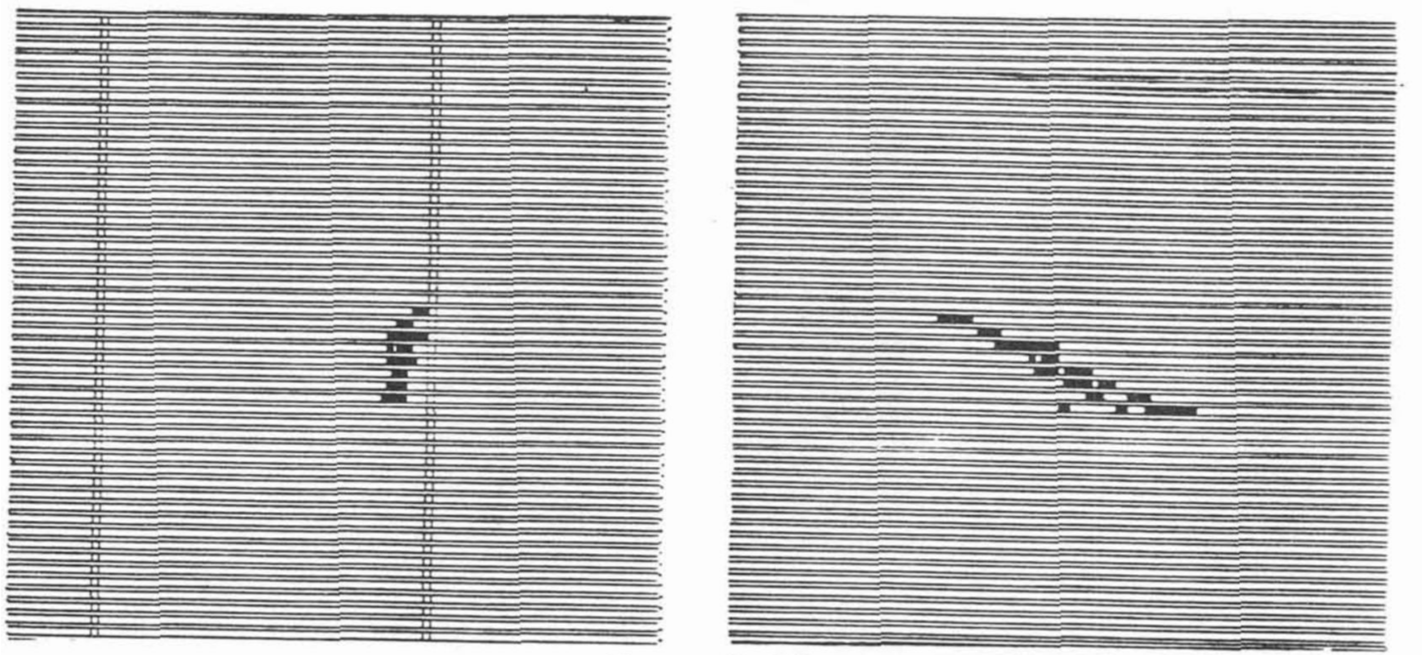
Mont Blanc



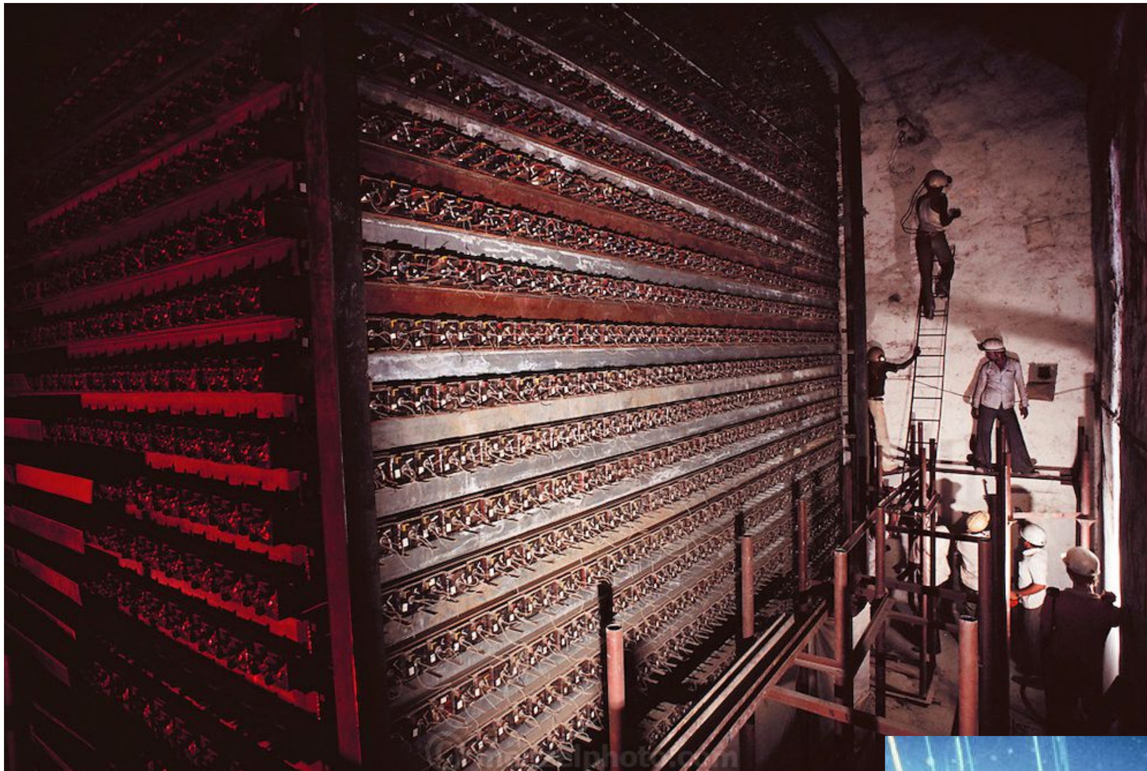
NUSEX: contained events



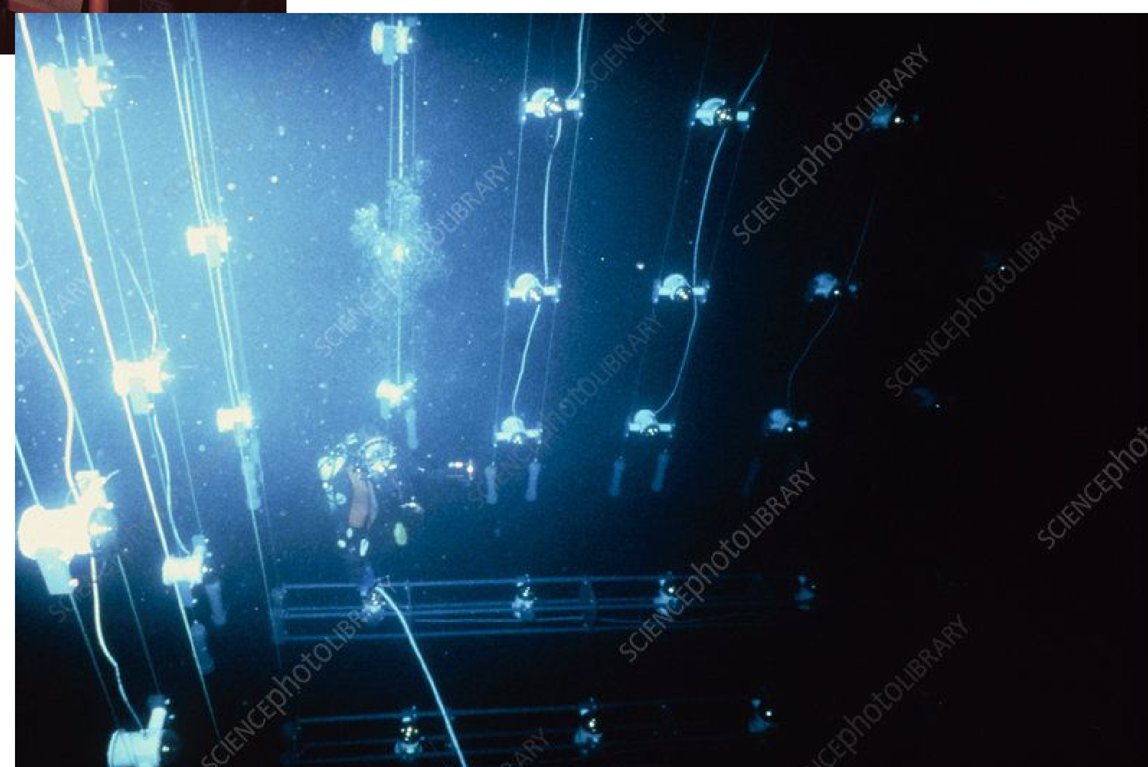
Event 15



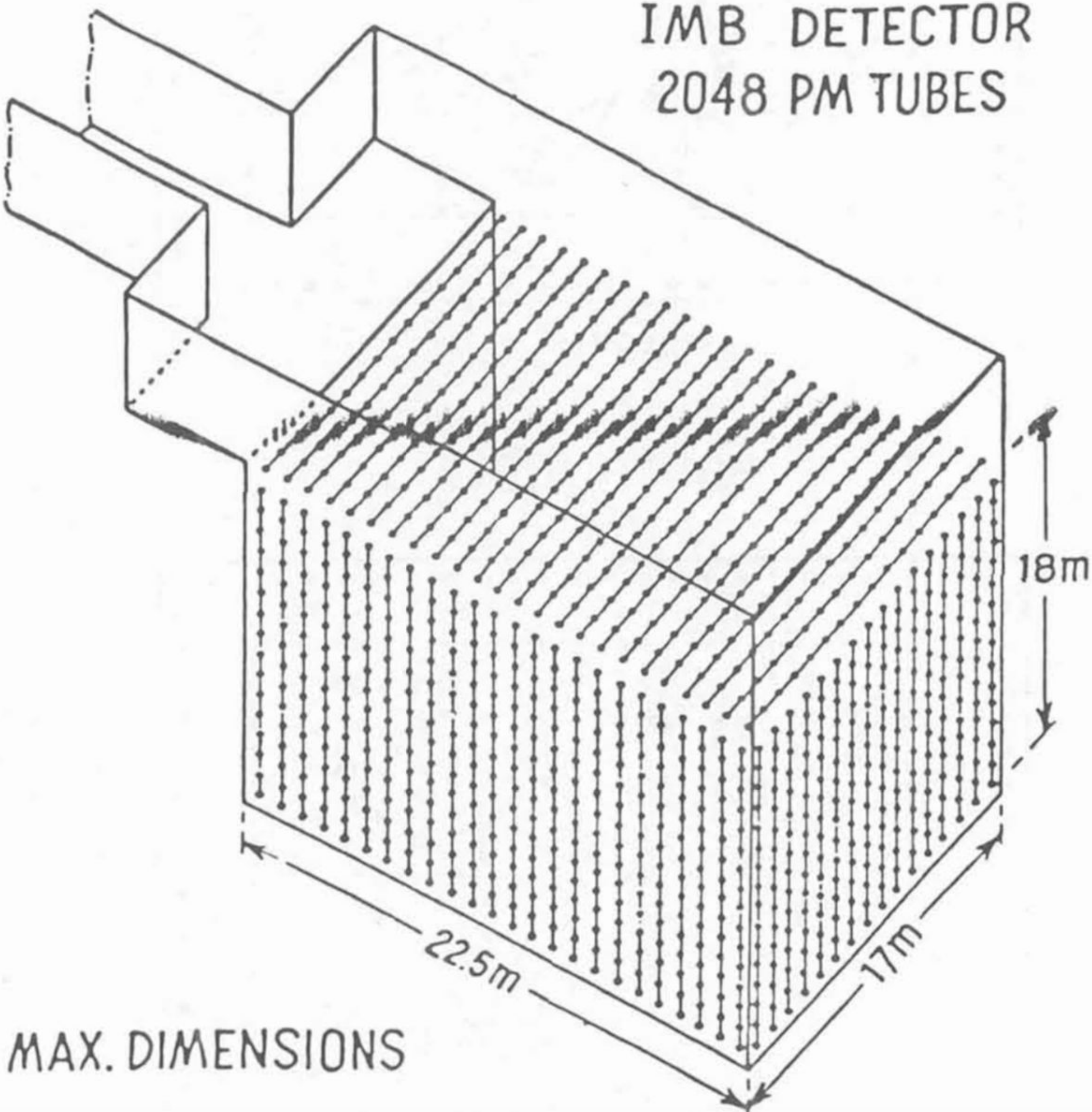
Event 14

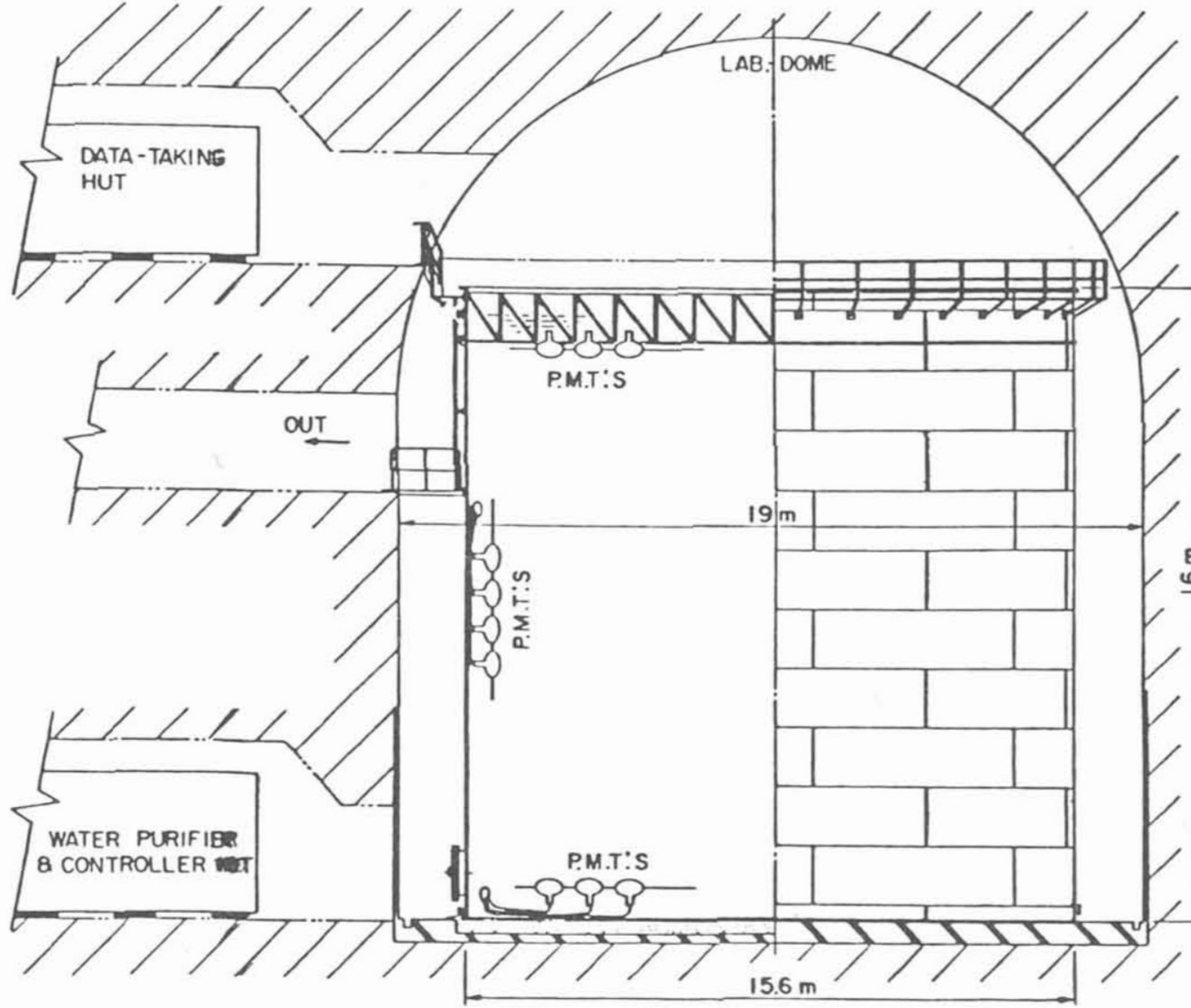


Kolar Gold Field (India) experiment



IMB detector (completed 1981)


IMB DETECTOR
2048 PM TUBES
18m
22.5m
17m
MAX. DIMENSIONS


LAB. DOME
DATA-TAKING
HUT
P.M.T.'S
OUT
19 m
P.M.T.'S
16 m
WATER PURIFIER
& CONTROLLER HUT
P.M.T.'S
15.6 m

V. S. Berezinsky and A. Y. Smirnov,
"Practically stable proton in the SU(5) Model"
Phys. Lett. B **97**, 371-375 (1980)

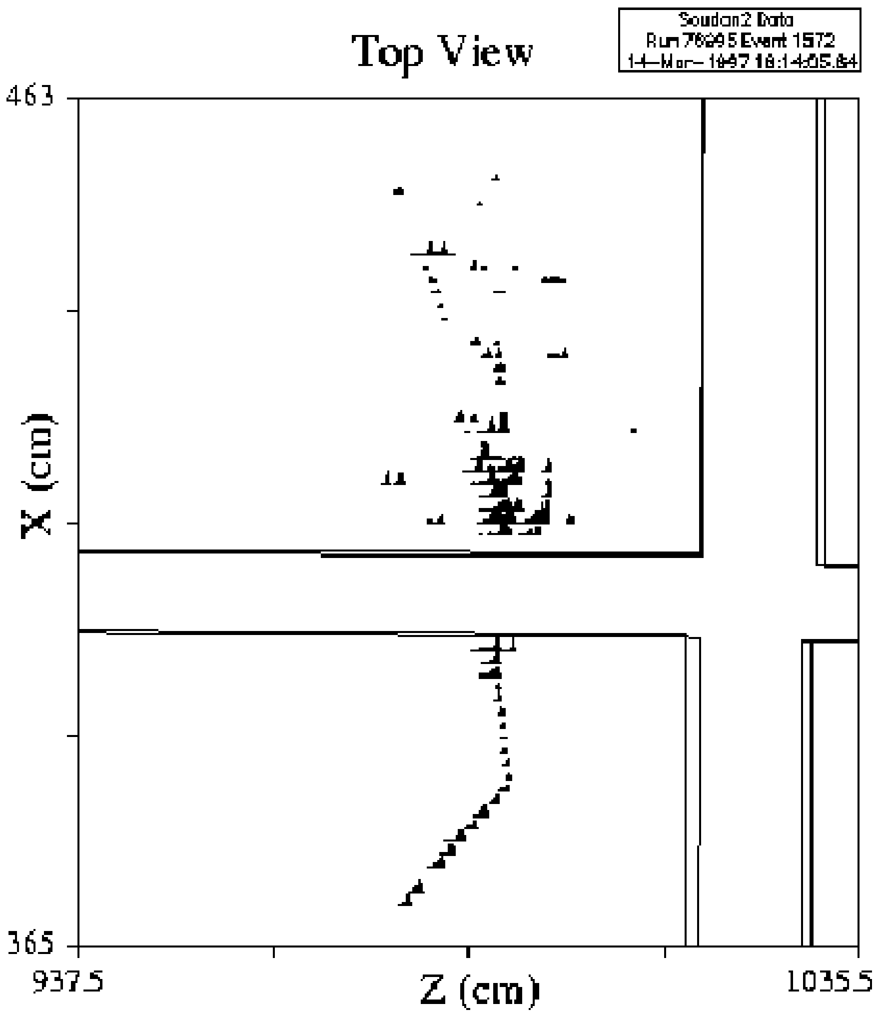
V. S. Berezinsky, B. L. Ioffe and Y. I. Kogan,
"The Calculation of Matrix Element for Proton Decay"
Phys. Lett. B **105**, 33 (1981)

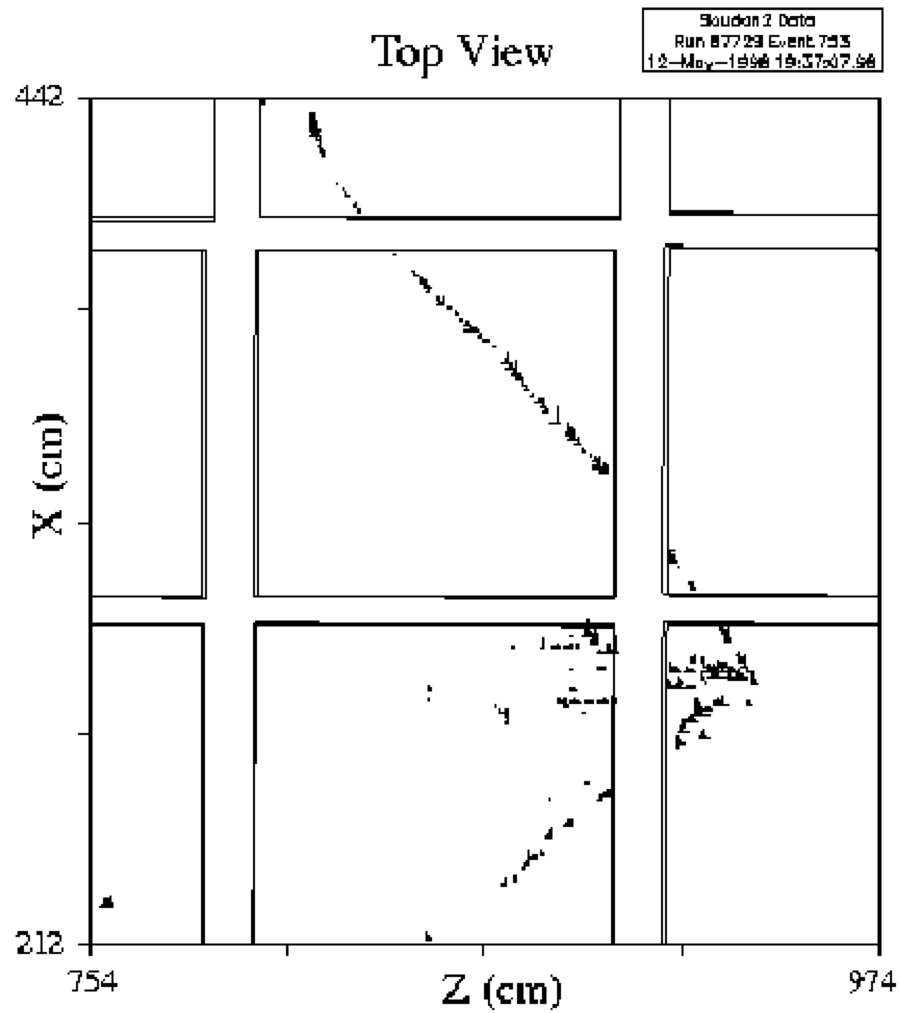
V. S. Berezinsky and A. Y. Smirnov,
"HOW TO SAVE MINIMAL SU(5)"
Phys. Lett. B **140**, 49-52 (1984)

V. S. Berezinsky, O. G. Ryazhskaya, C. Castagnoli and O. Saavedra,
"ON THE POSSIBILITY OF A SEARCH FOR A SUPERSYMMETRIC CHANNEL OF PROTON DECAY $p \to K^+ + \overline{\nu}$, WITH LIFETIME AROUND 10^{33} years"
Nucl. Phys. B **262**, 383-392 (1985)

Background ! Atmospheric Neutrino interactions

...(but your background can be my signal...)





[Soudan 2 detector]

Atmospheric Neutrinos

and

the discovery of *Neutrino Oscillations*

wonderful story
of how science works

From: Anomaly
To Hint
To Evidence
....
To Nobel prize

New detectors
better analysis

More refined models

The “Anomaly"

The Atmospheric neutrino Anomaly

Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

T. J. Haines, R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, R. Claus, B. G. Cortez, S. Errede, G. W. Foster, W. Gajewski, K. S. Ganezer, M. Goldhaber, T. W. Jones, D. Kielczewska, W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, J. Matthews, H. S. Park, L. R. Price, F. Reines, J. Schultz, S. Seidel, E. Shumard, D. Sinclair, H. W. Sobel, J. L. Stone, L. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

University of California, Irvine, Irvine, California 92717
University of Michigan, Ann Arbor, Michigan 48109
Brookhaven National Laboratory, Upton, New York 11973
Cleveland State University, Cleveland, Ohio 44115
University of Hawaii, Honolulu, Hawaii 96822
University of Notre Dame, Notre Dame, Indiana 46556
University College, London WC1E 8BT, United Kingdom
Warsaw University, Warsaw PL-00-681, Poland

(Received 6 June 1986)

We have developed an extensive model of atmospheric ν interactions which provide the backgrounds to nucleon-decay experiments. We report results from a 417-live-day exposure of the Irvine-Michigan-Brookhaven detector. During this time 401 contained events were observed at a rate and with characteristics consistent with atmospheric ν interactions. We have calculated the expected backgrounds to a variety of two- and three-body decay modes and have set lower limits on many nucleon partial lifetimes.

The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

T. J. Haines *et al.* [IMB Collaboration]
"Calculation of Atmospheric Neutrino Induced Backgrounds in a Nucleon Decay Search,"
Phys. Rev. Lett. **57**, 1986 (1986).

M. Nakahata *et al.* [Kamiokande Collaboration],
"Atmospheric Neutrino Background and Pion Nuclear Effect for Kamioka Nucleon Decay Experiment,"
J. Phys. Soc. Jap. **55**, 3786 (1986).

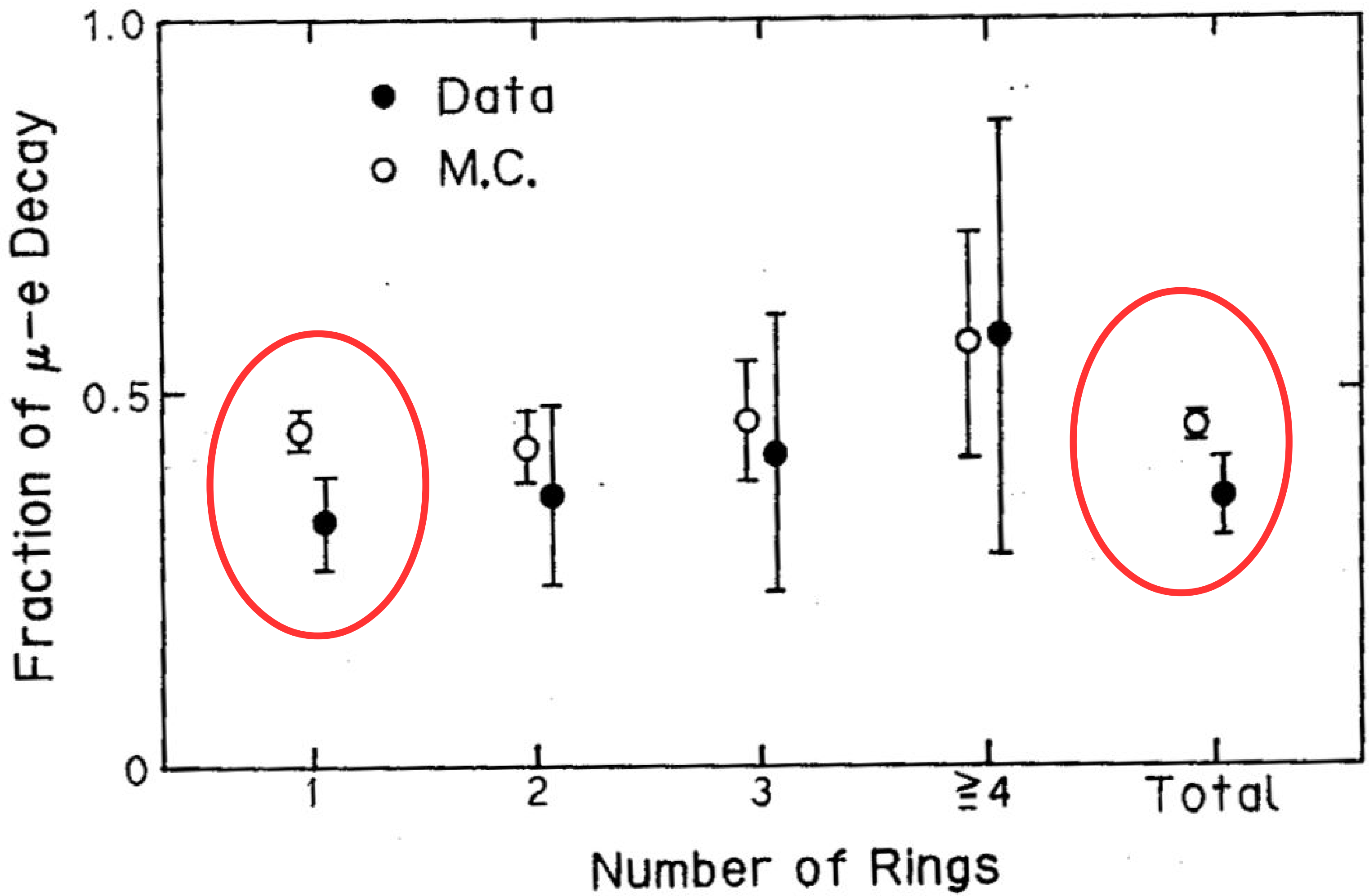


Fig. 19

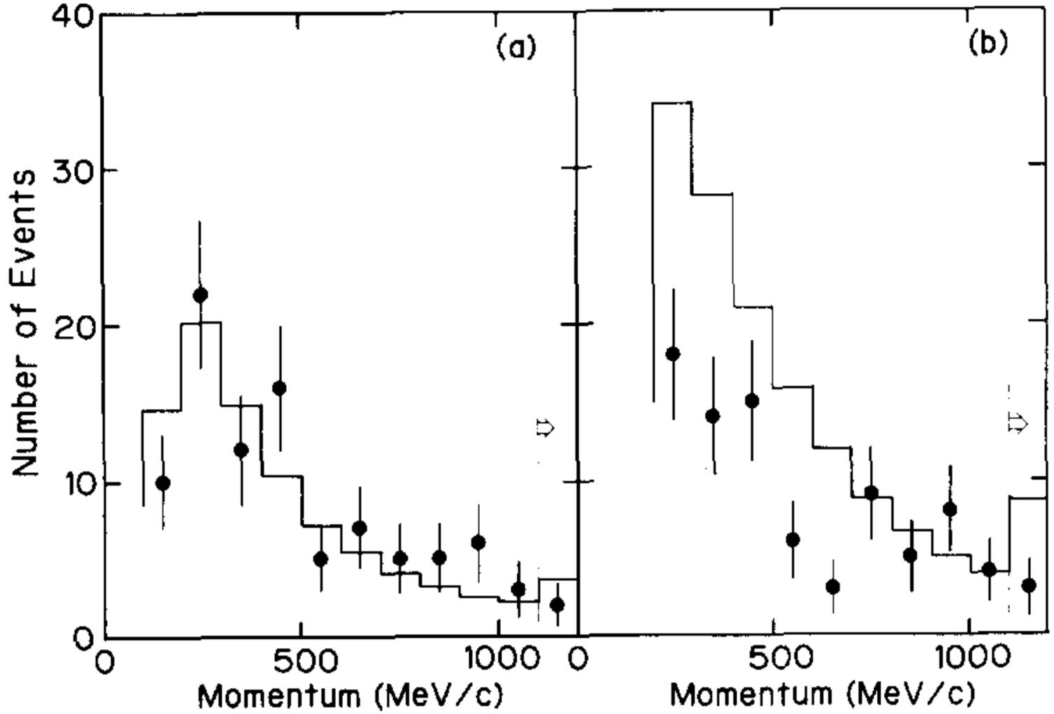


Fig. 1. Momentum distributions for: (a) electron-like events and (b) muon-like events. The last momentum bin sums all events with their momenta larger than 1100 MeV/c. The histograms show the distributions expected from atmospheric neutrino interactions.

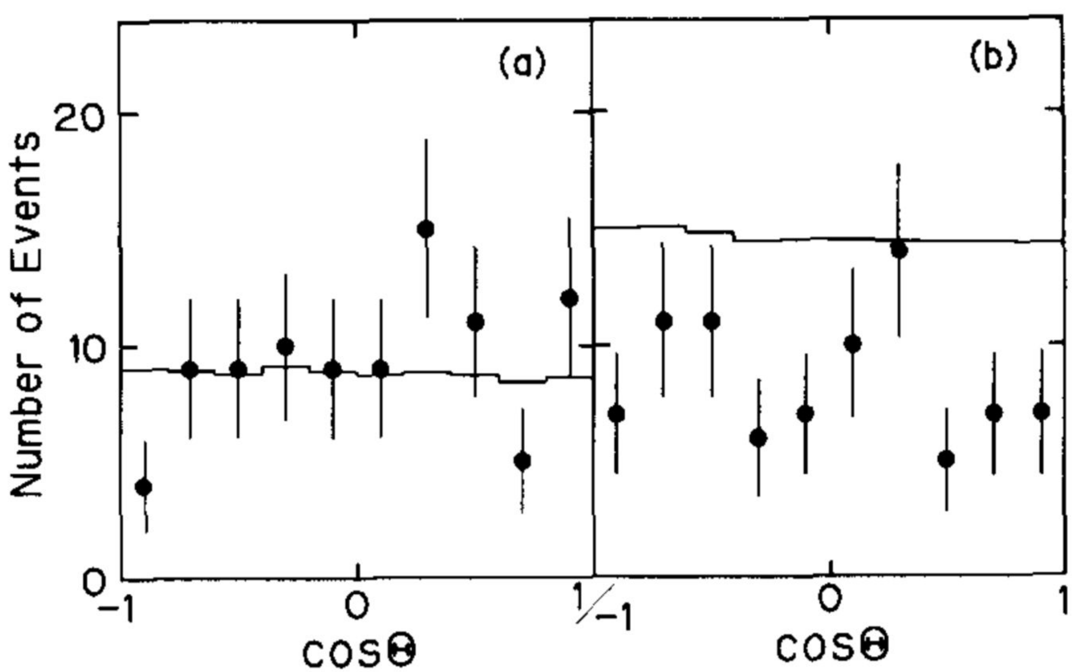


Fig. 2. Zenith angle distributions for: (a) electron-like events and (b) muon-like events. $\cos\Theta = 1$ corresponds to downward-going events. The histograms show the distributions expected from atmospheric neutrino interactions.

Kamiokande 1988

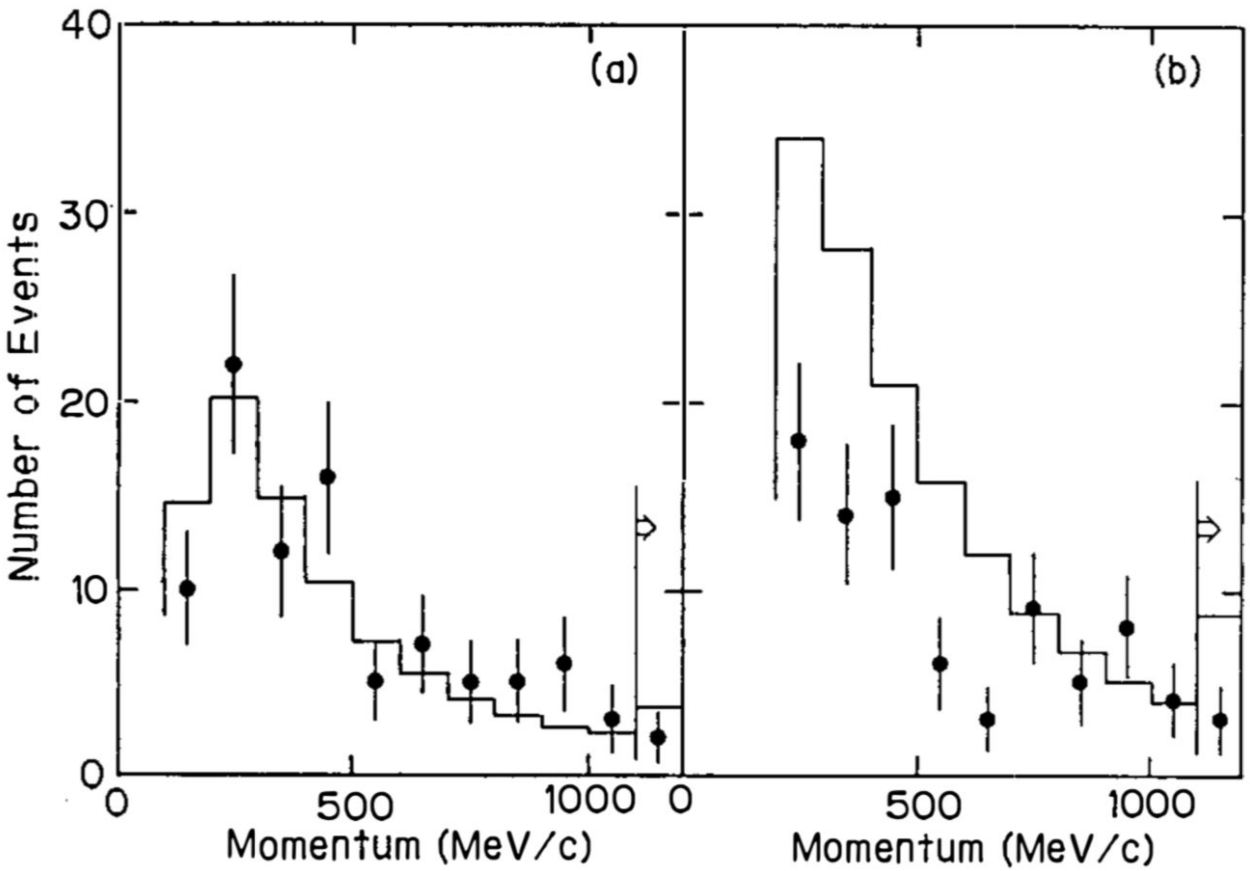
Can you separate muons from electrons ?!

the "anomaly"

Can you predict correctly nu_mu and nu_e ?

e-like

mu-like

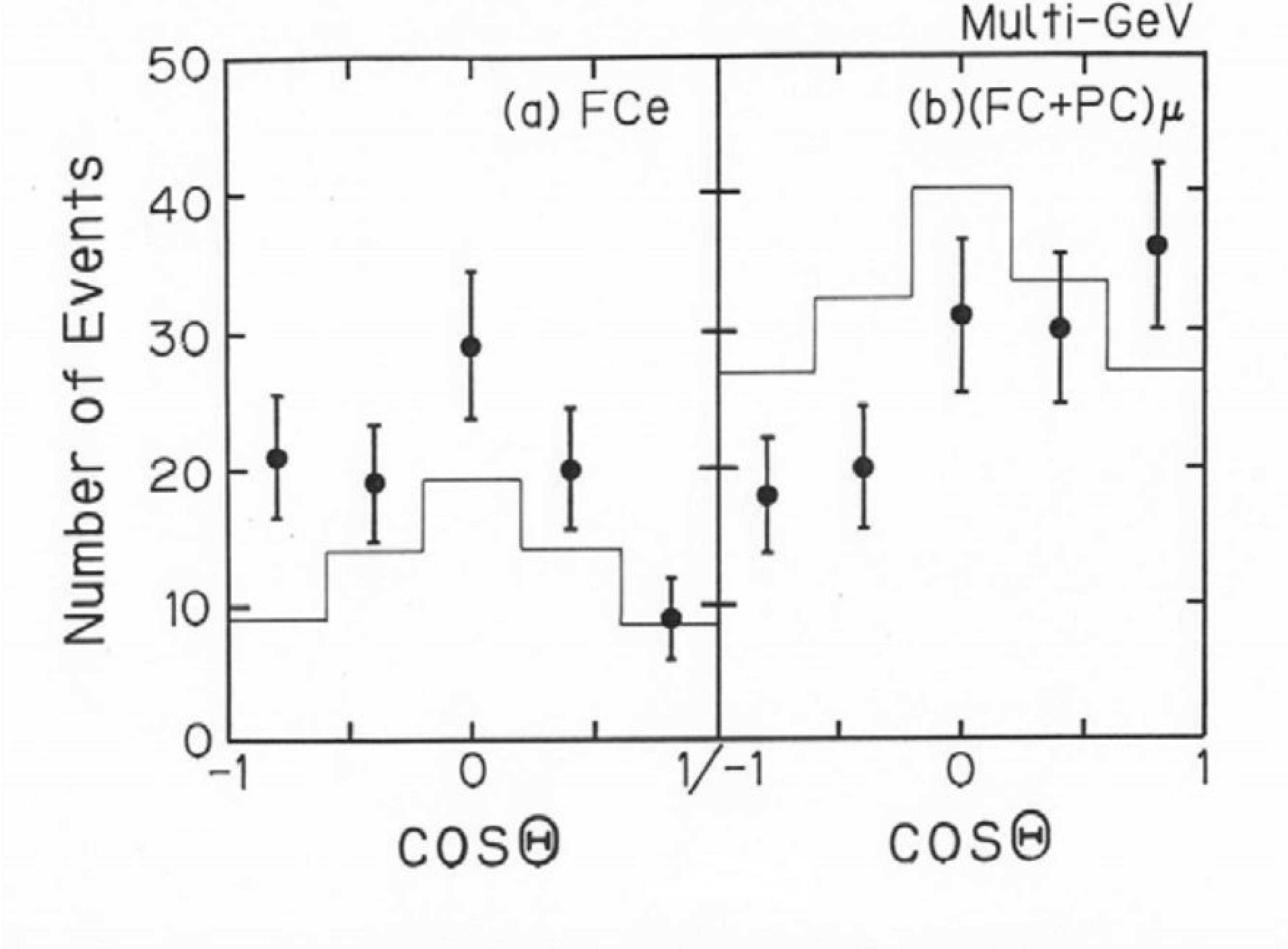


Kamiokande 1994

Zenith Angle (nu pathlength) dependence ?!!

The "hint"

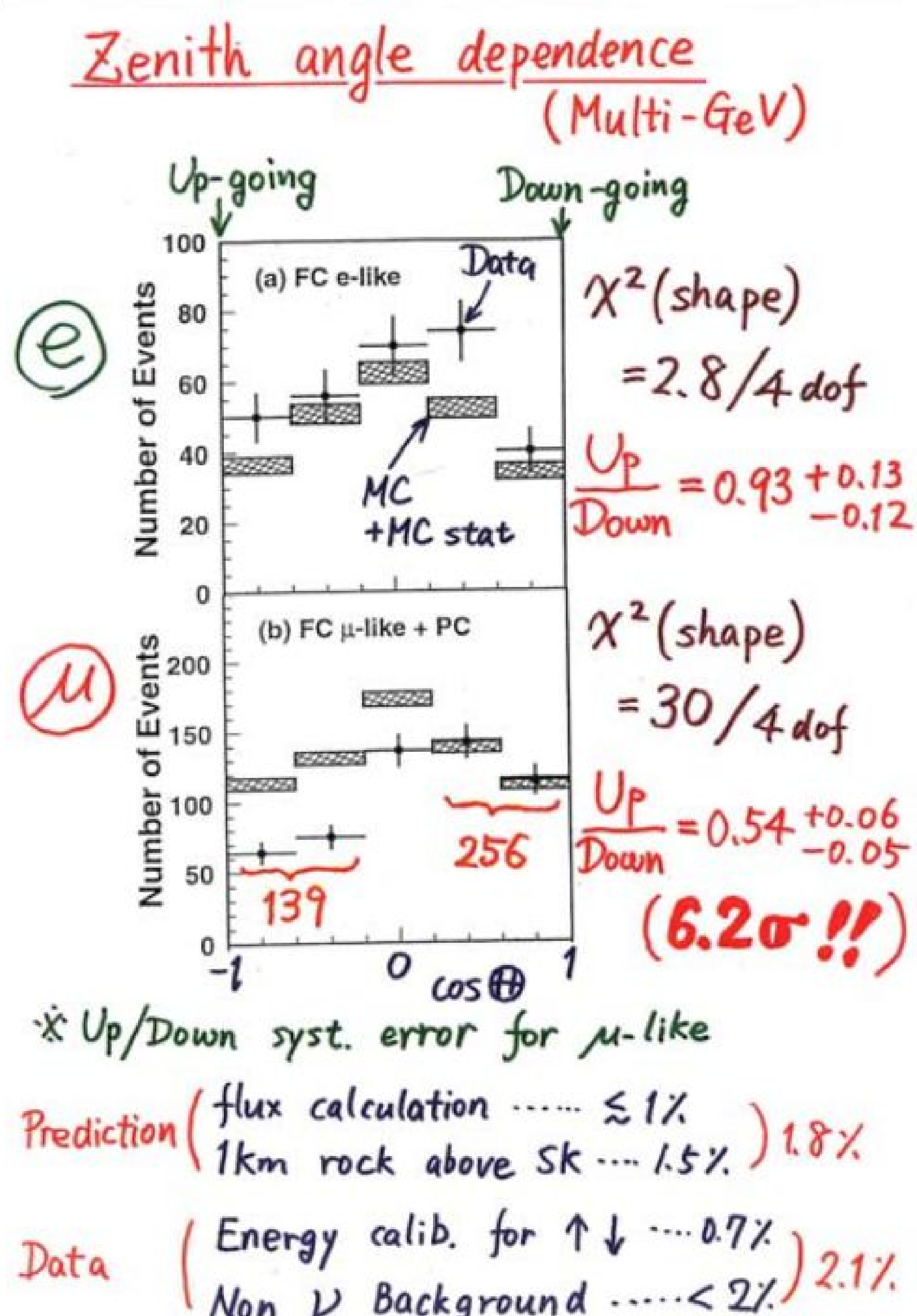
subGeV
mu-like



Takaaki
Kajita (1998)

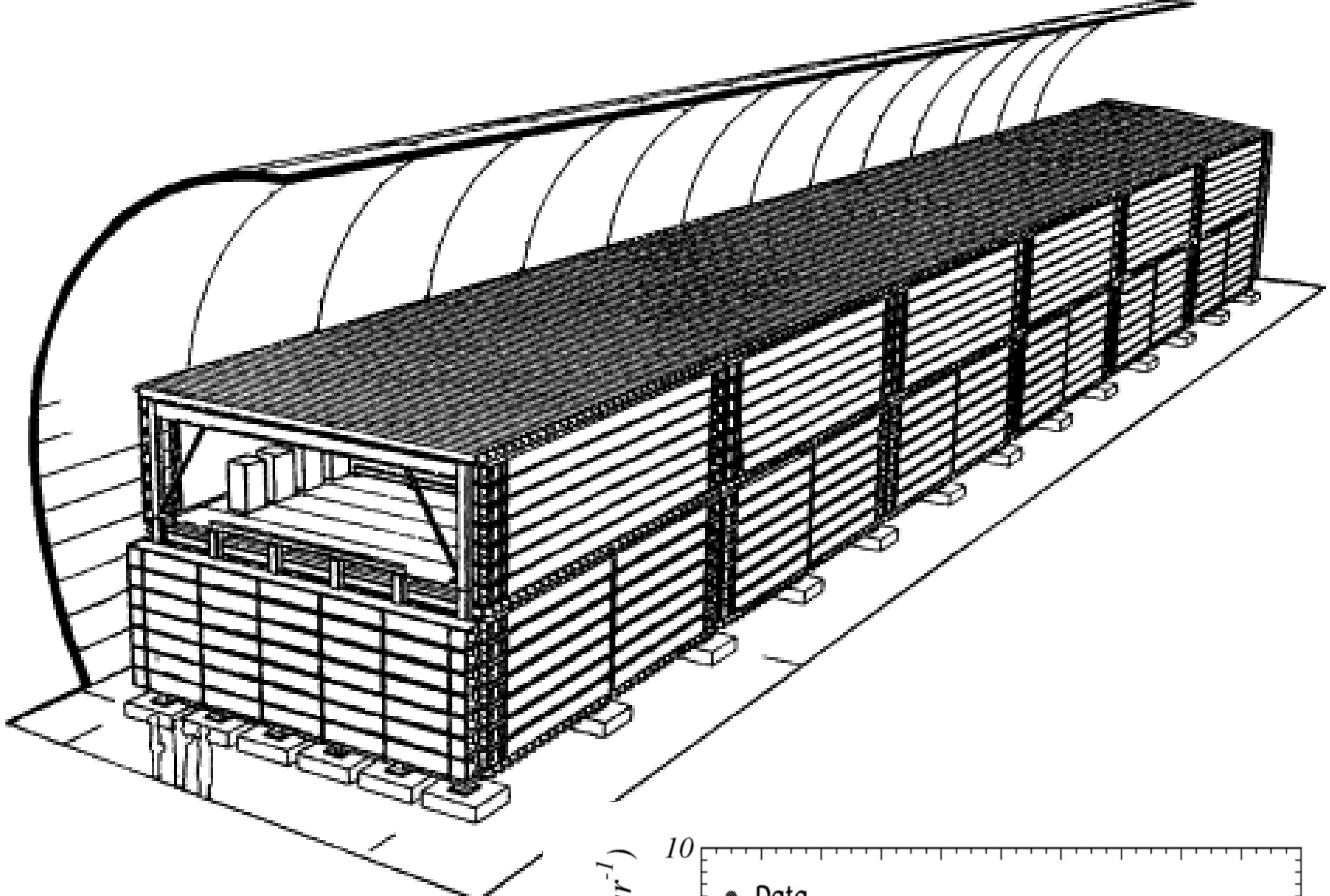
Super-Kamiokande

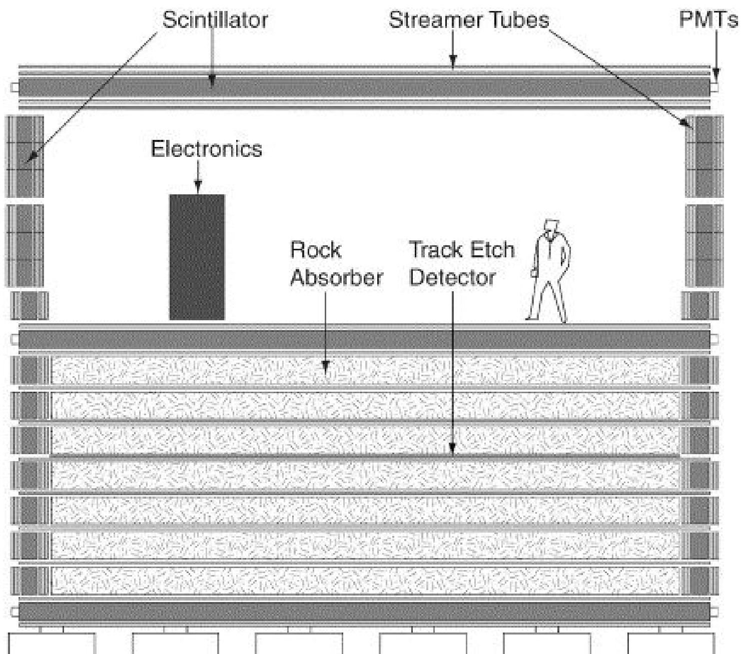
The “evidence” !!

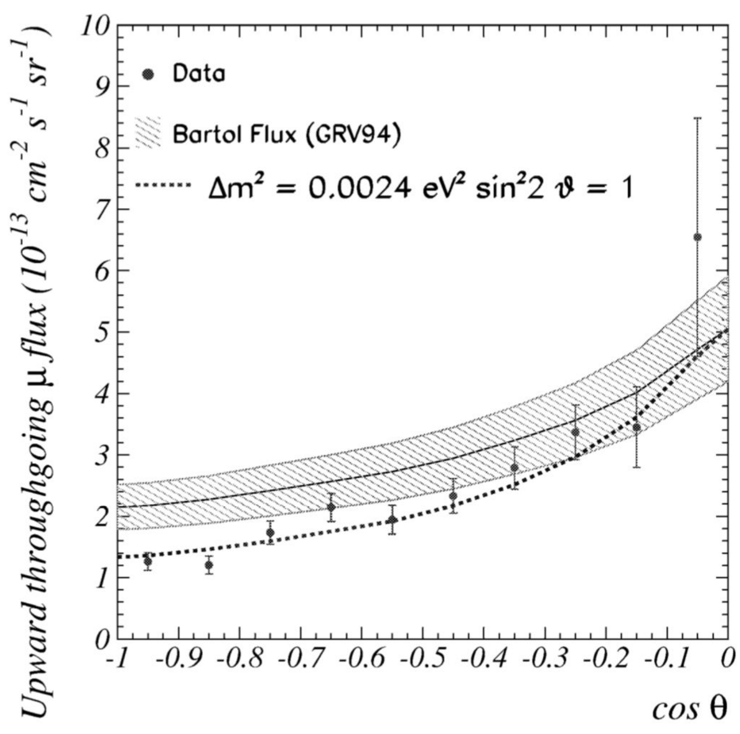


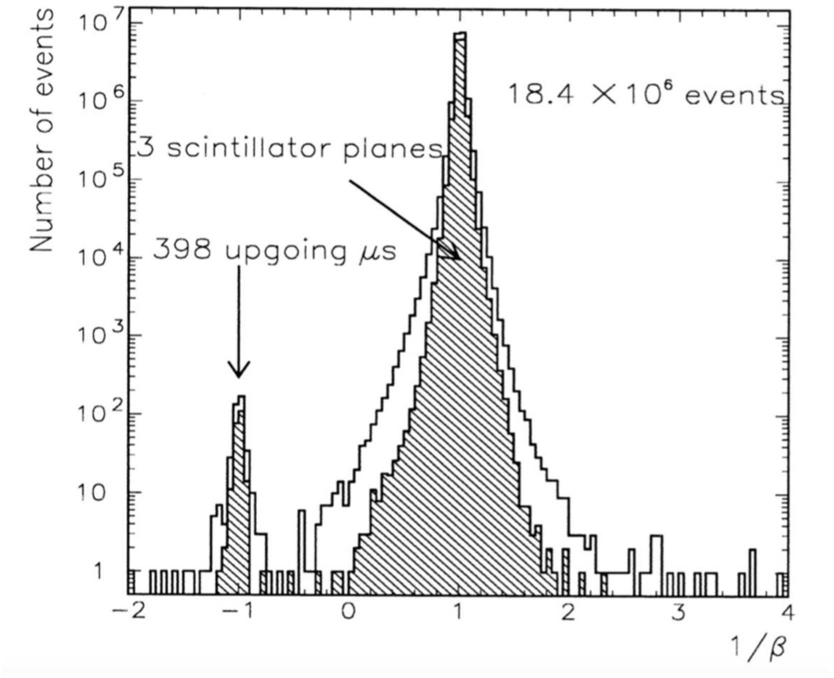
Takaaki Kajita receiving the 2015 Nobel prize in Physics

MACRO detector at Gran Sasso



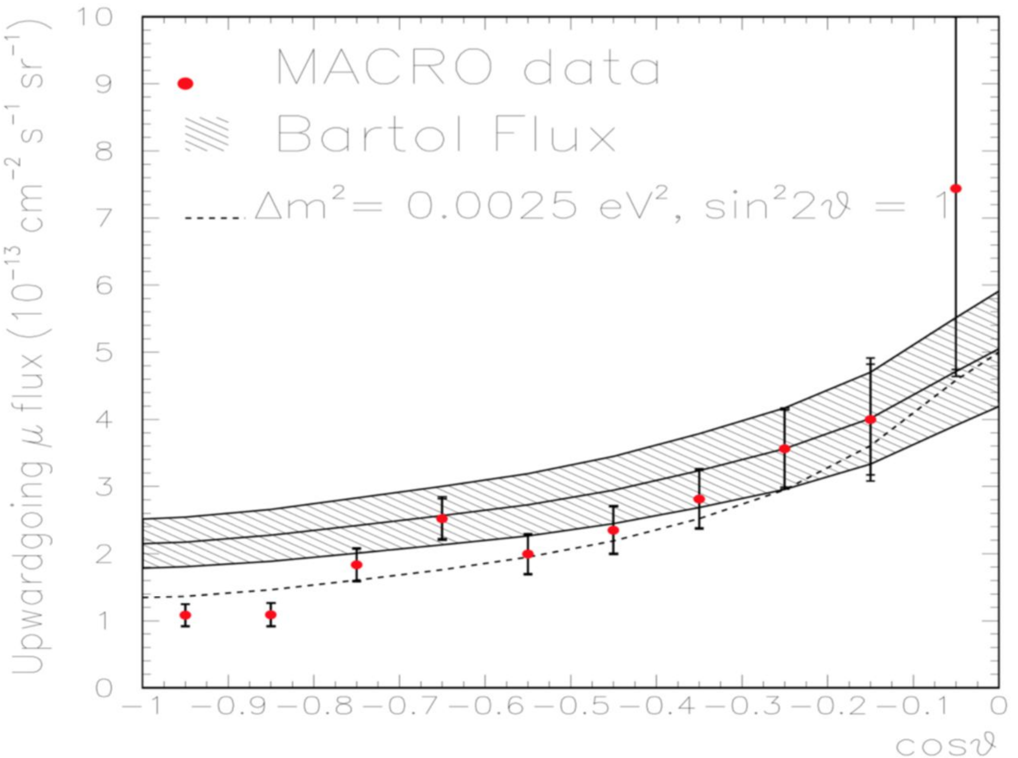






The MACRO data on "upgoing muons" (1998).

"Bartol neutrino flux"



Distortion of the angular distribution

$$\dot{N}_{\nu,\mathrm{events}} =$$

$$\phi_{\mathrm{CR}}(E_0) \otimes \begin{bmatrix} \text{Solar} \\ \text{Modulations} \end{bmatrix} \otimes \begin{bmatrix} \text{Geomagnetic} \\ \text{effects} \end{bmatrix}$$

$$\otimes \; \sigma_{p\mathrm{Air}\to\pi^\pm,K^{\pm,0}} \otimes \begin{bmatrix} \text{Weak} \\ \text{Decays} \end{bmatrix} \otimes \begin{bmatrix} \text{Shower} \\ \text{Calculation} \end{bmatrix}$$

$$\otimes \begin{bmatrix} \text{Neutrino} \\ \text{Propagation} \end{bmatrix}$$

$$\otimes \; \sigma_{\nu A}(E_\nu) \otimes \begin{bmatrix} \text{Detector} \\ \text{Properties} \end{bmatrix}$$

High Energy Sources

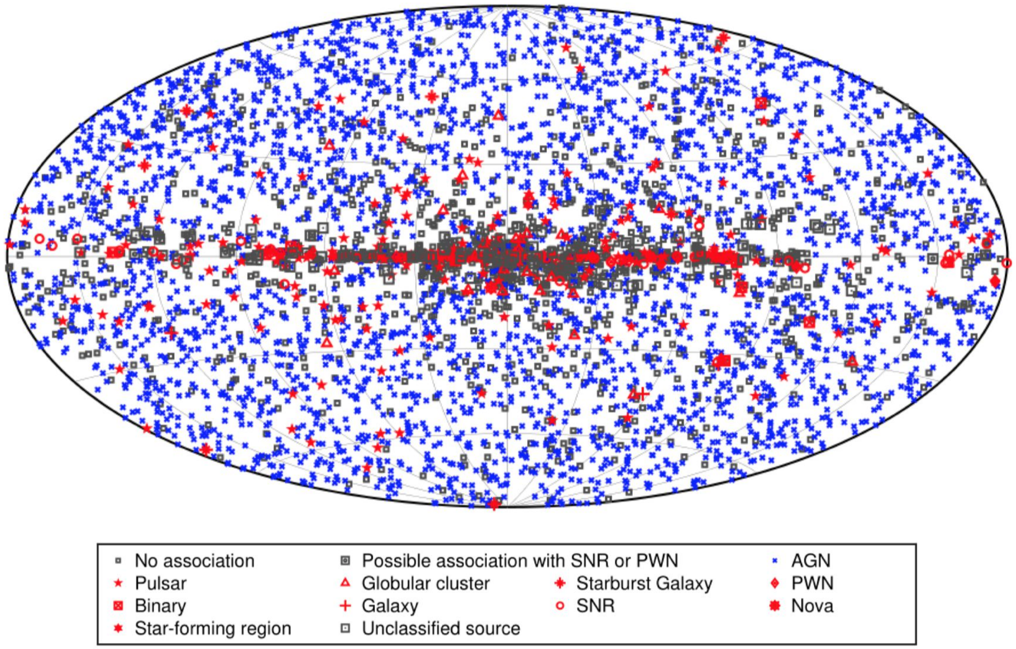
gamma rays

Neutrinos

Cygnus X-3

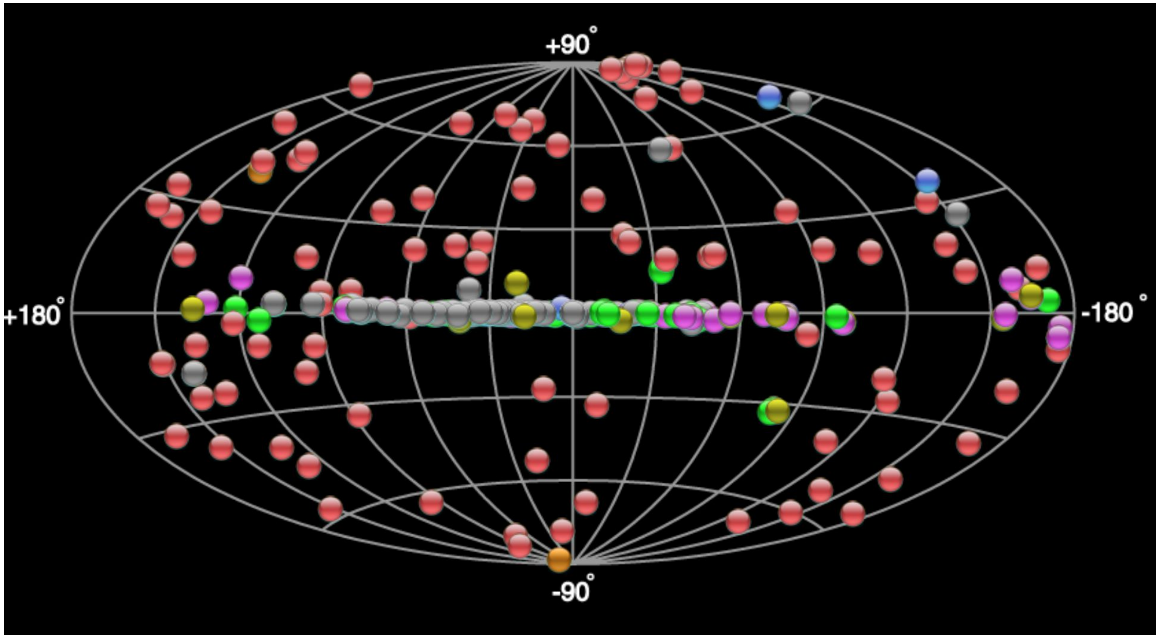
SN 1987A

FERMI 4th General Catalog 4FGL (7195 sources)

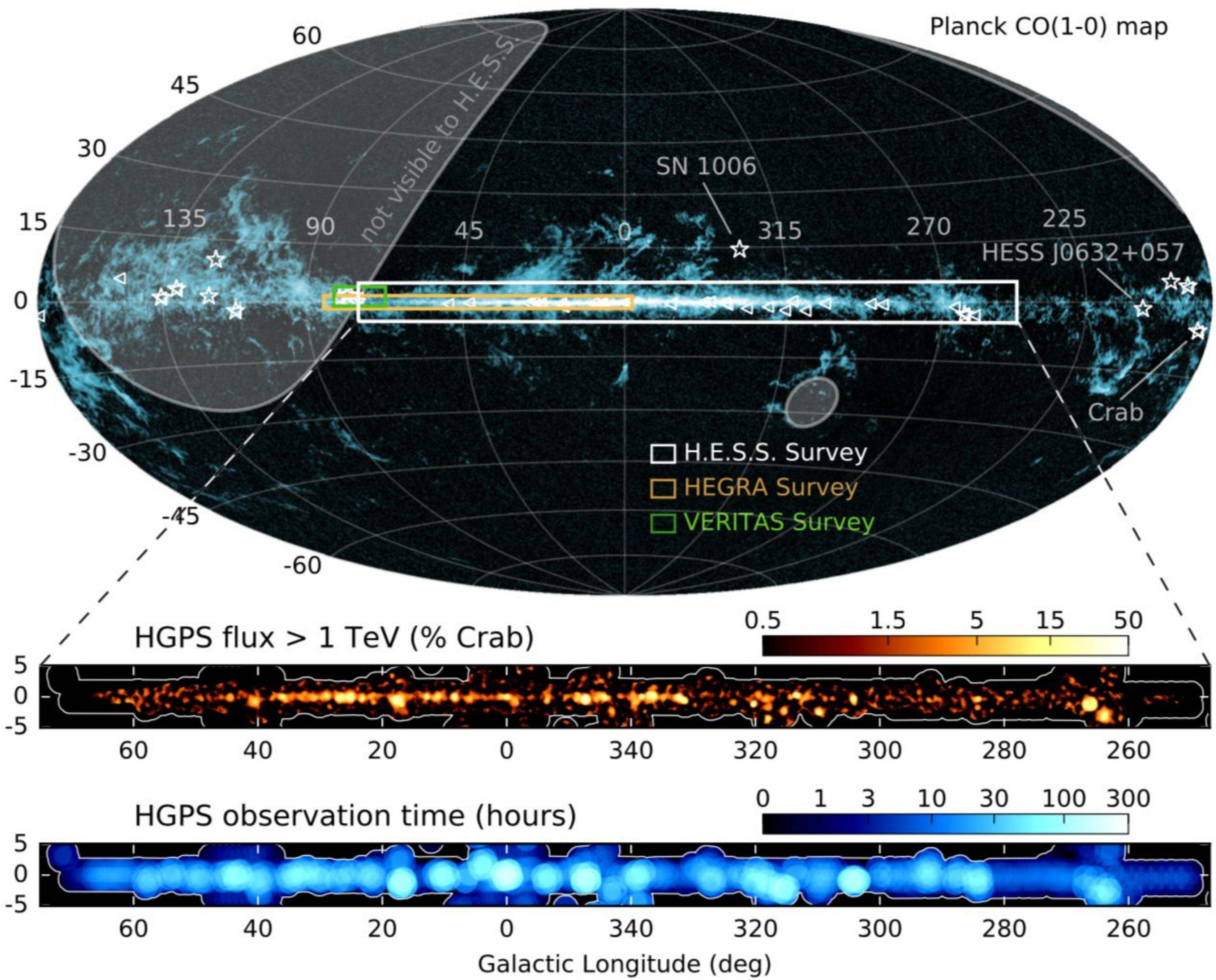


gamma-ray sky today

TevCat
[251 sources circa 2022]



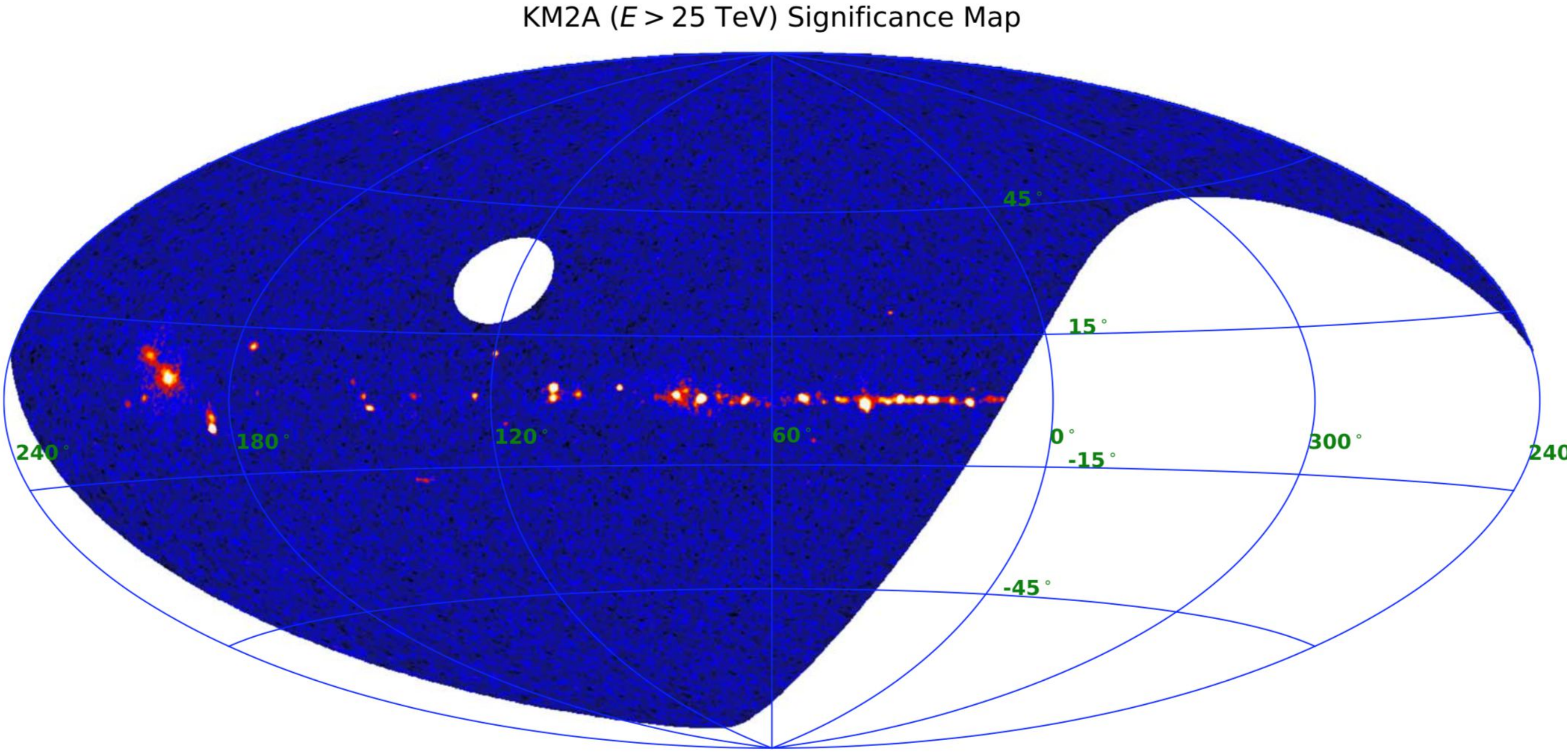
HESS Galactic Plane Survey (78 sources)



LHAASO KM2A catalog
E> 25 TeV

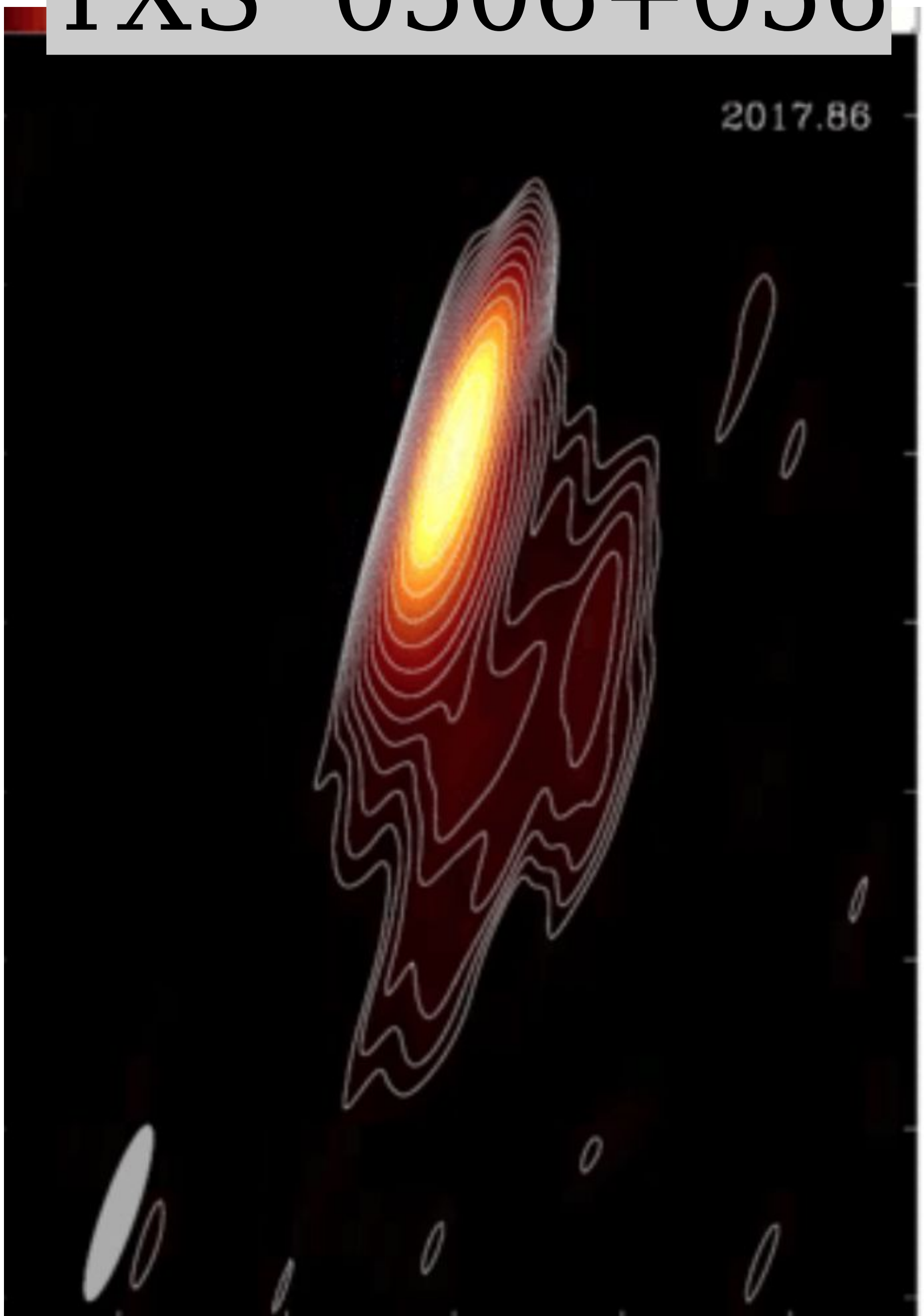
75 sources

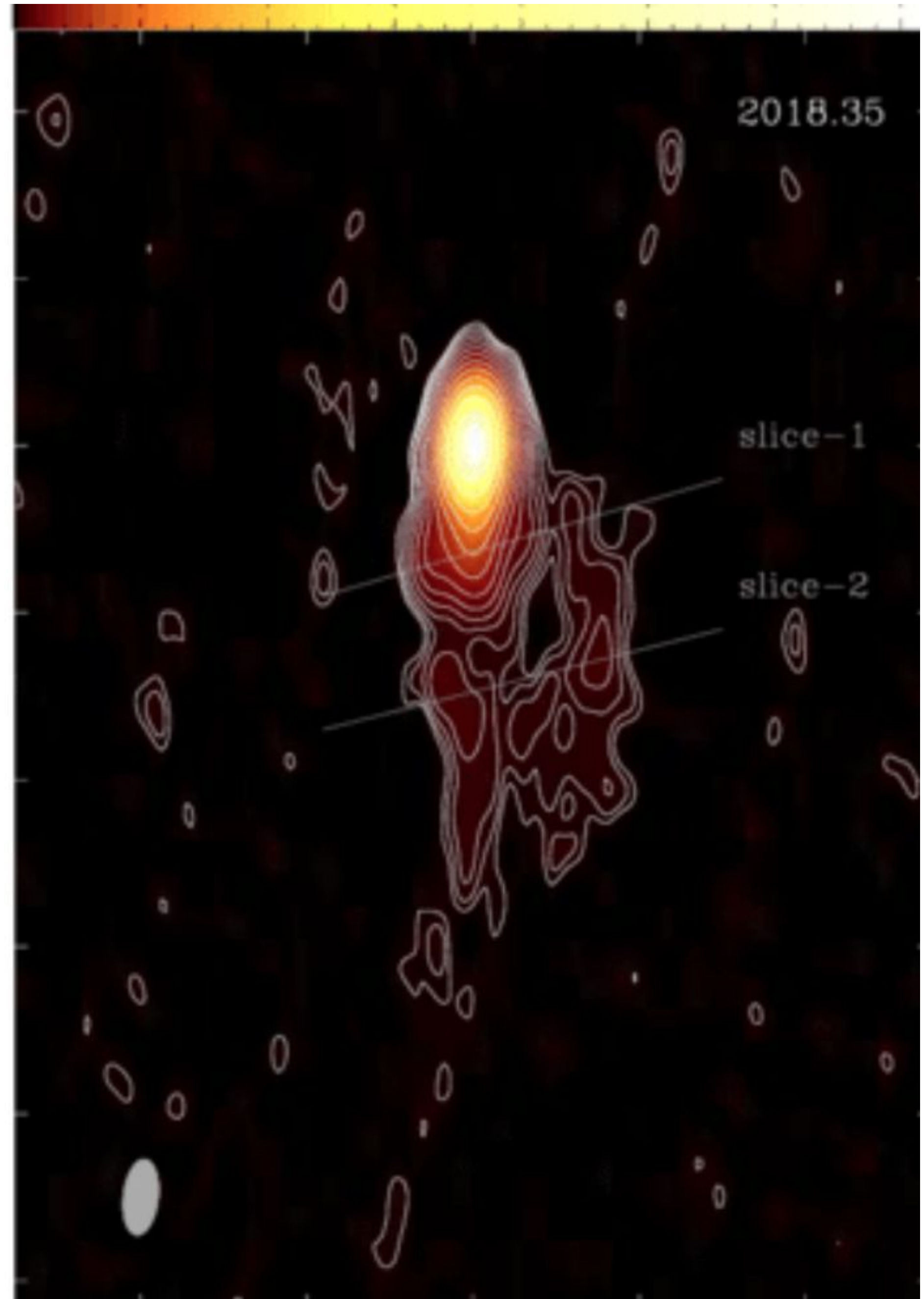
44 for E> 100 TeV



..... and high energy Neutrino sources !!

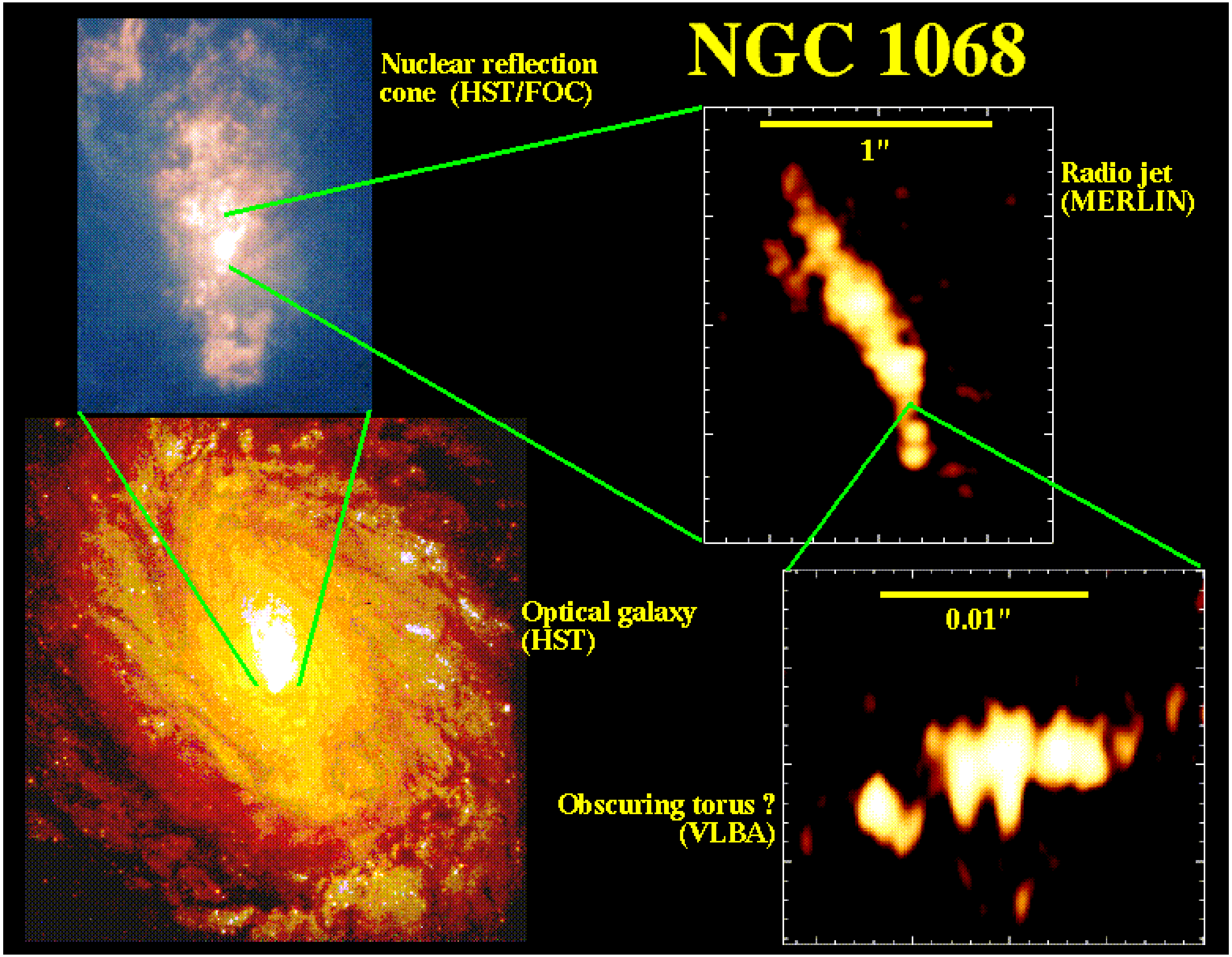
TXS 0506+056





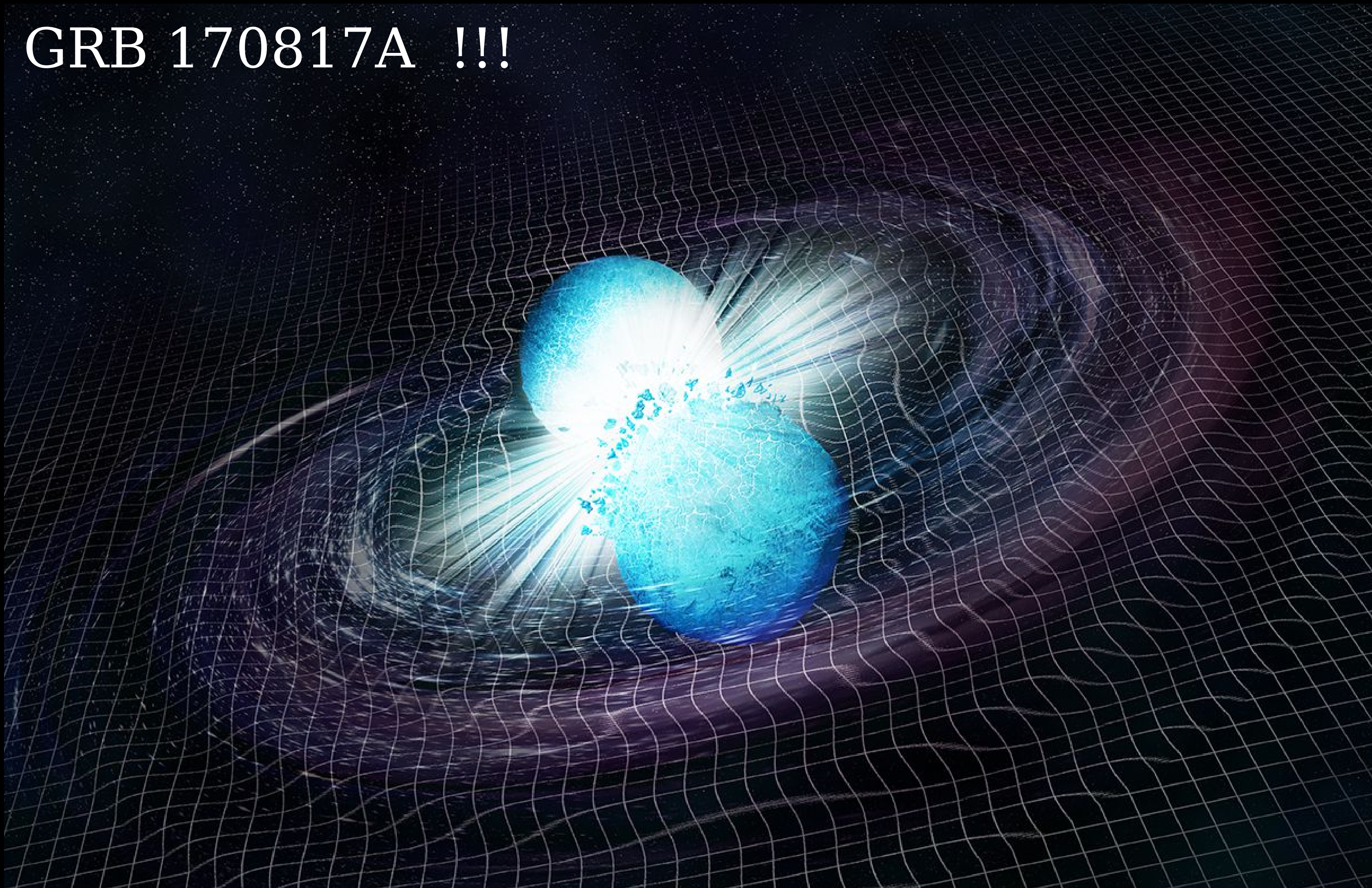
NGC 1068

Seyfert Galaxy
(also Starburst galaxy)



GW 171817

GRB 170817A !!!



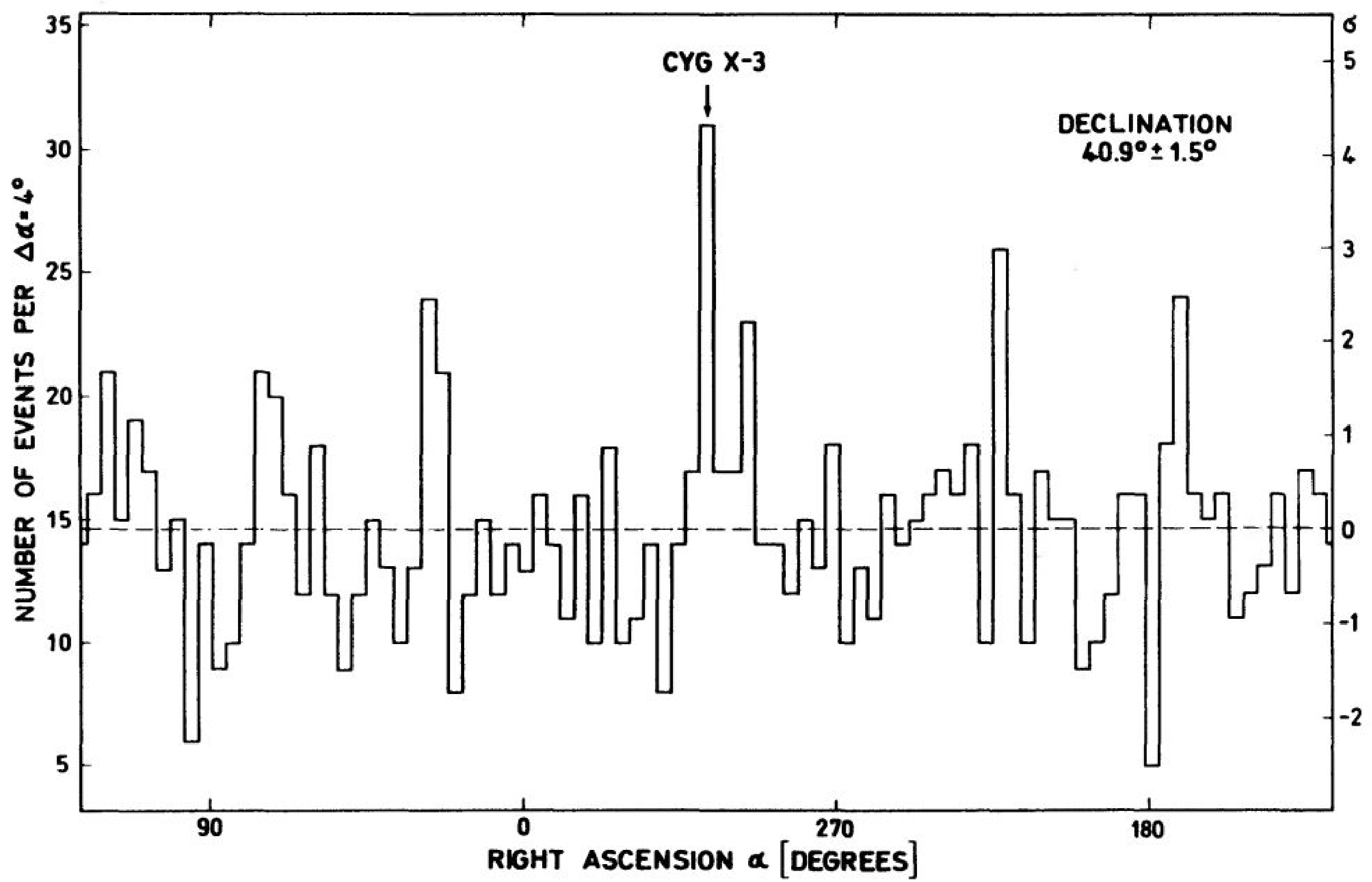
...... But until 1983

there were *zero sources* ......

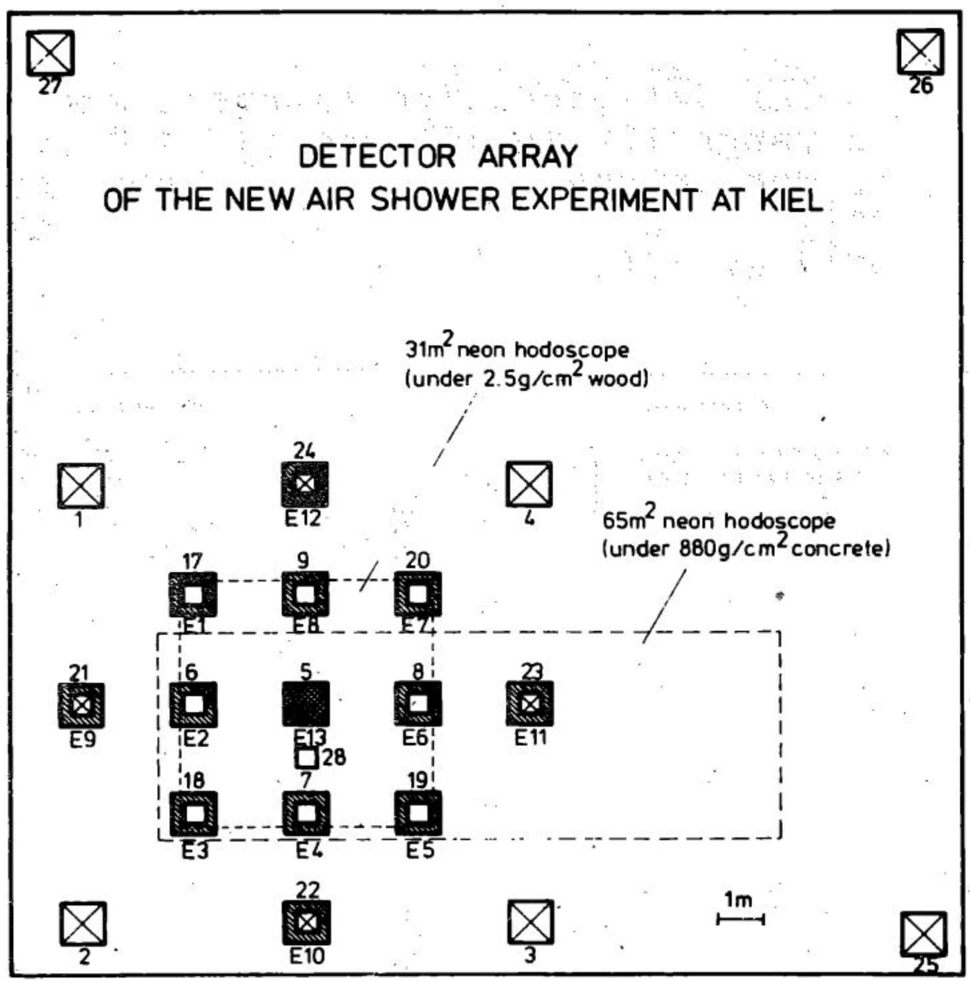
and then:

Detection of Cygnus X-3
(Kiel air shower detector)
Samorski and Stamm.   ApJ may 1983.

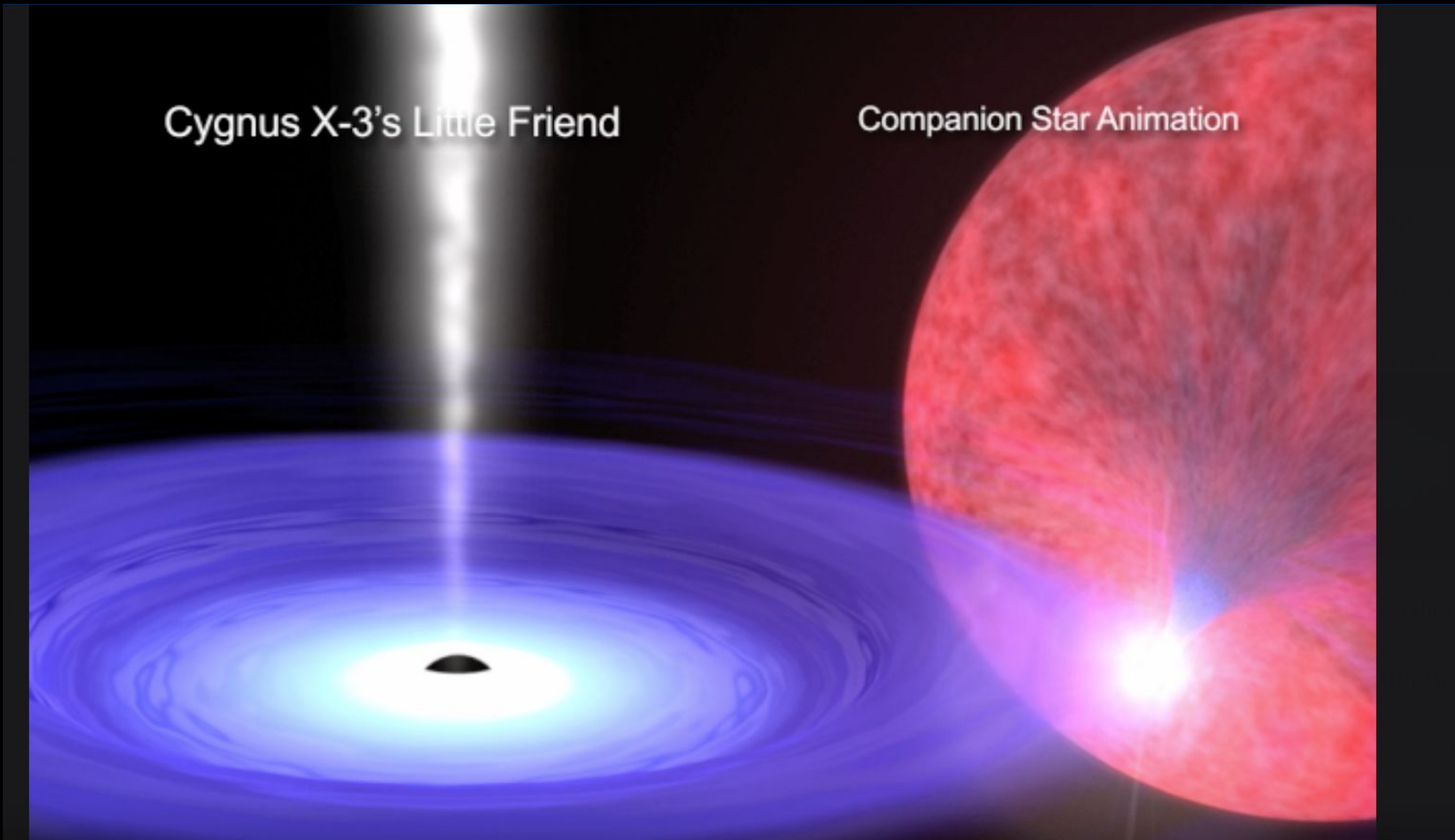
GAMMA-RAYS FROM CYG X-3



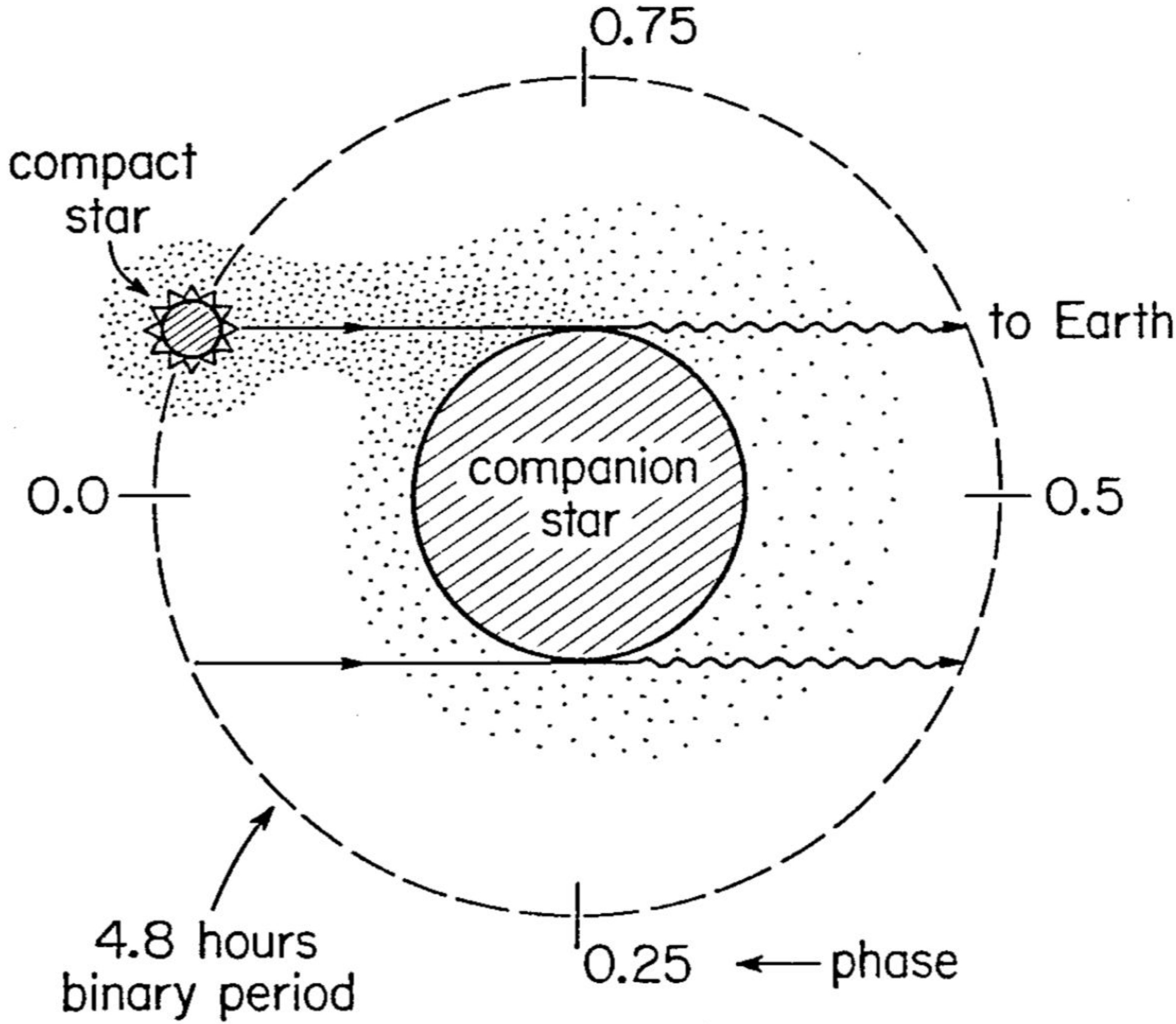
[Orbital period 4.8 hours.   Phase diagram]



M. Samorski and W. Stamm,
"Detection of 2×10^{15}-eV to 2×10^{16}–eV gamma Rays from Cygnus X-3"
Astrophys. J. Lett. **268**, L17-L21 (1983)

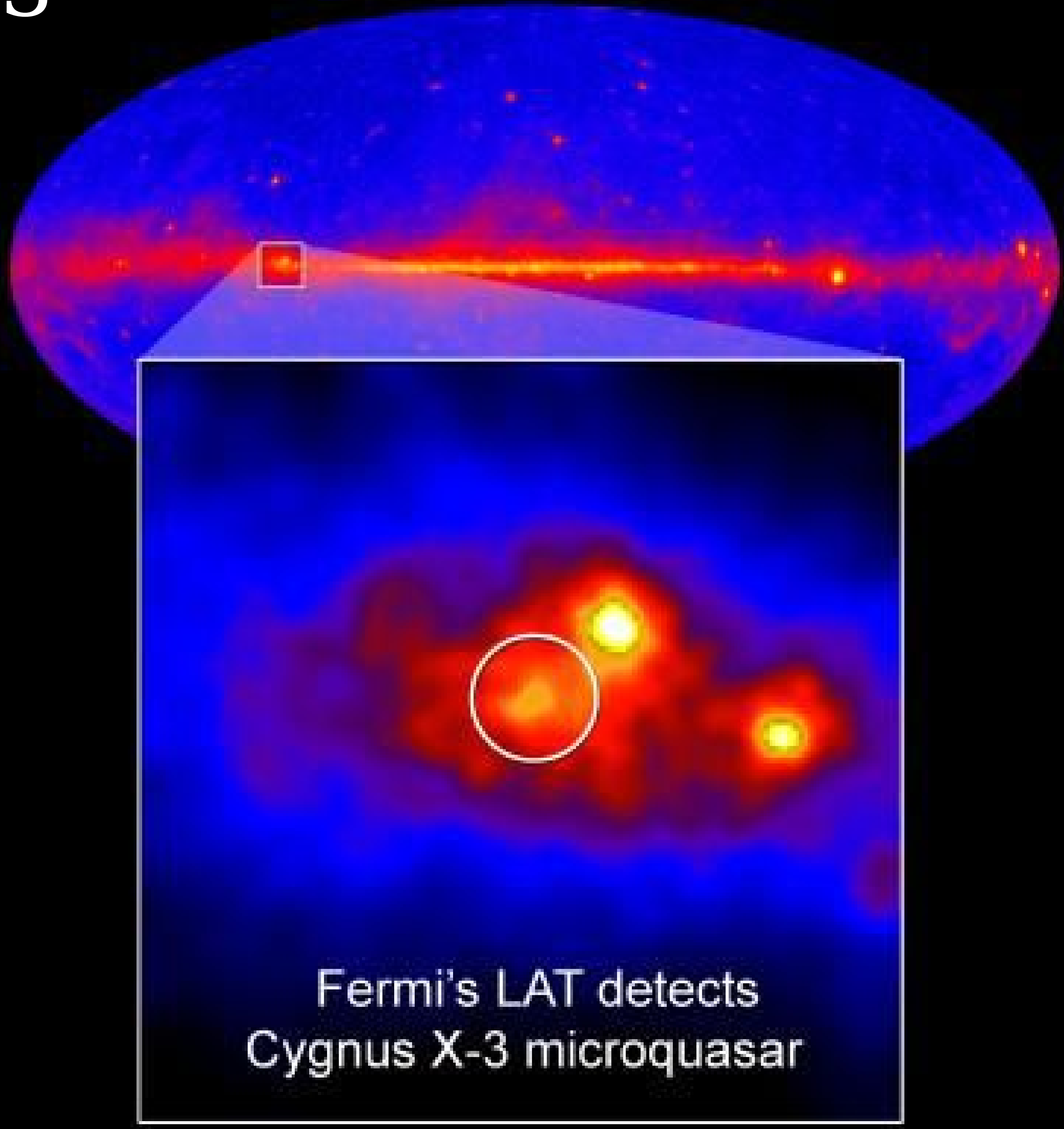

Cygnus X-3's Little Friend
Companion Star Animation

From Francis Halzen [1986]
“On the discovery of very high energy point sources”



Composite Image
X-ray   Chandra
Radio   Sub-Millimeter Array (SMA)

Cygnus X3

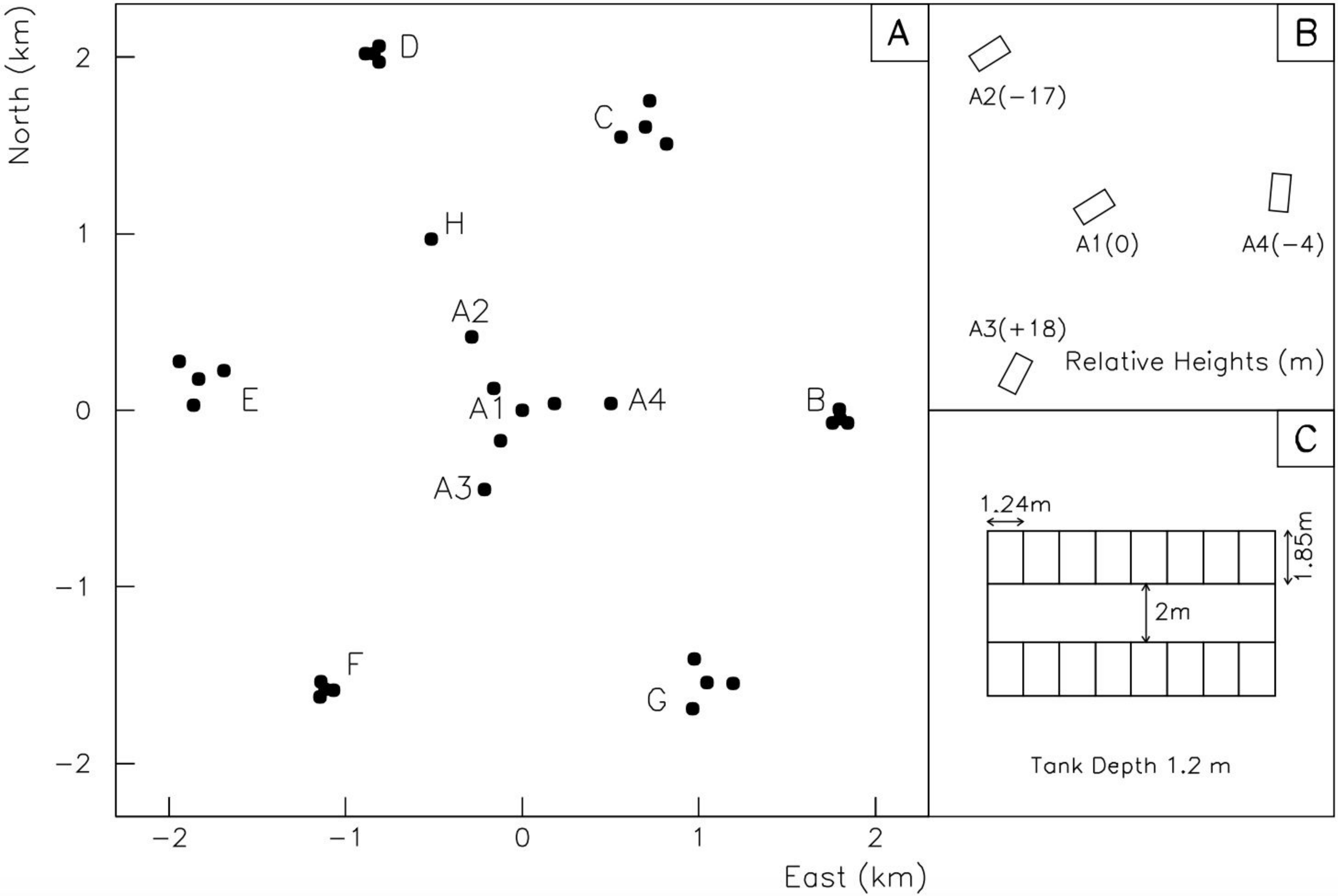


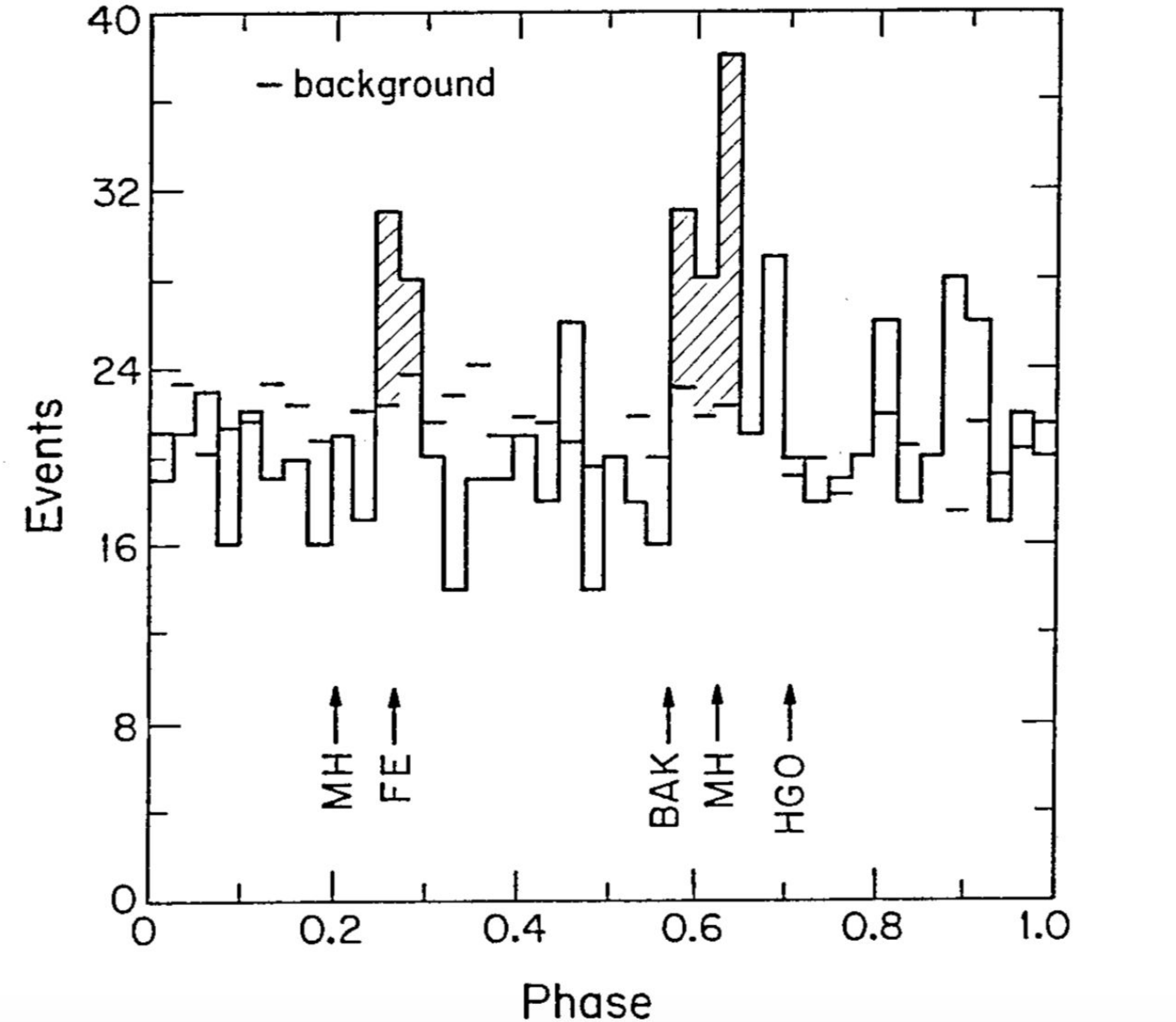
seen (today)
by FERMI-LAT

J. Lloyd-Evans, *et al.* [Haverah Park Array]
"Observation of gamma Rays $\geq 10^{15}$-eV from Cygnus X-3" '
Nature **305**, 784-787 (1983)

G. L. Cassiday, *et al.* [Fly's Eye Telescope]
"Evidence for 10^{18}-ev Neutral Particles
From the Direction of Cygnus X-3"
Phys. Rev. Lett. **62**, 383-386 (1989)

Haverah Park Array 12 km2 [1967 - 1987]





Phase distribution observed by Haverah Park

Underground Muon Observations !

G. Battistoni, *et al.* [NUSEX Detector]
"Observation of a Time Modulated Muon Flux
in the Direction of Cygnus X-3"
Phys. Lett. B **155**, 465-467 (1985)

M. L. Marshak, *et al.* [Soudan Detector]
"Evidence for Muon Production by Particles from Cygnus X-3"
Phys. Rev. Lett. **54**, 2079 (1985)

Detection with deep underground muons by the Mont Blanc and Soudan detectors

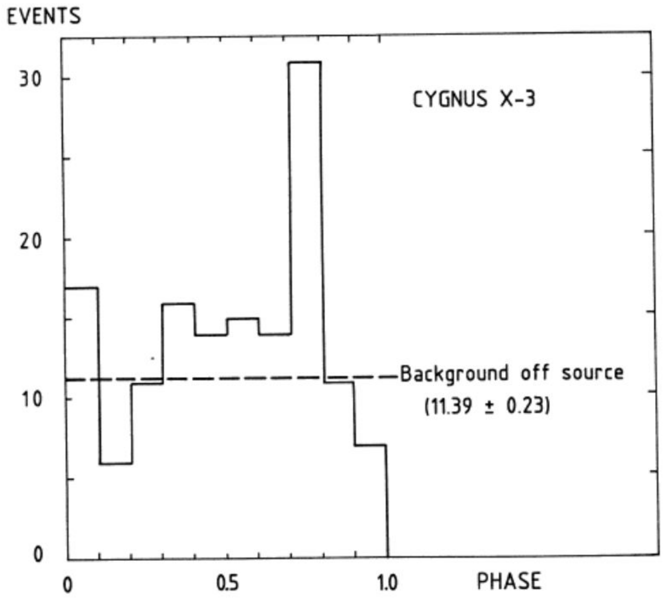
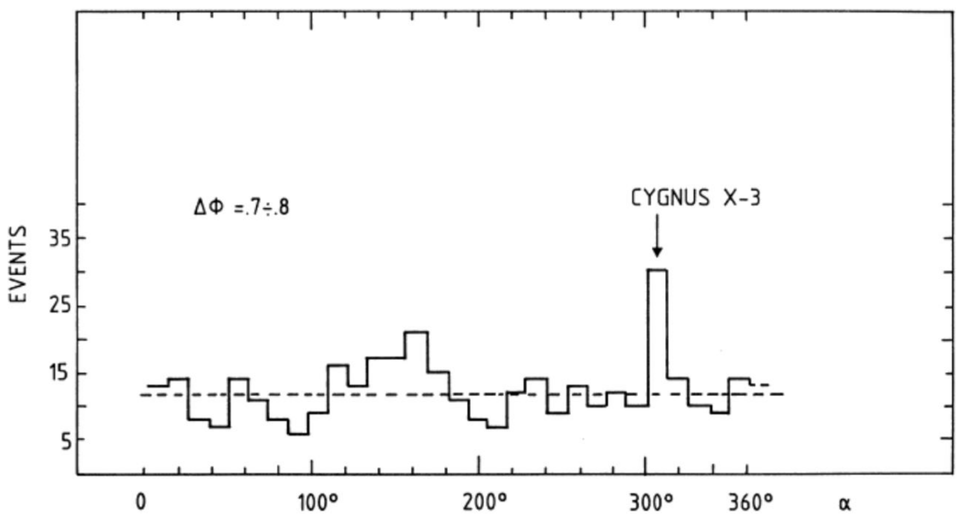
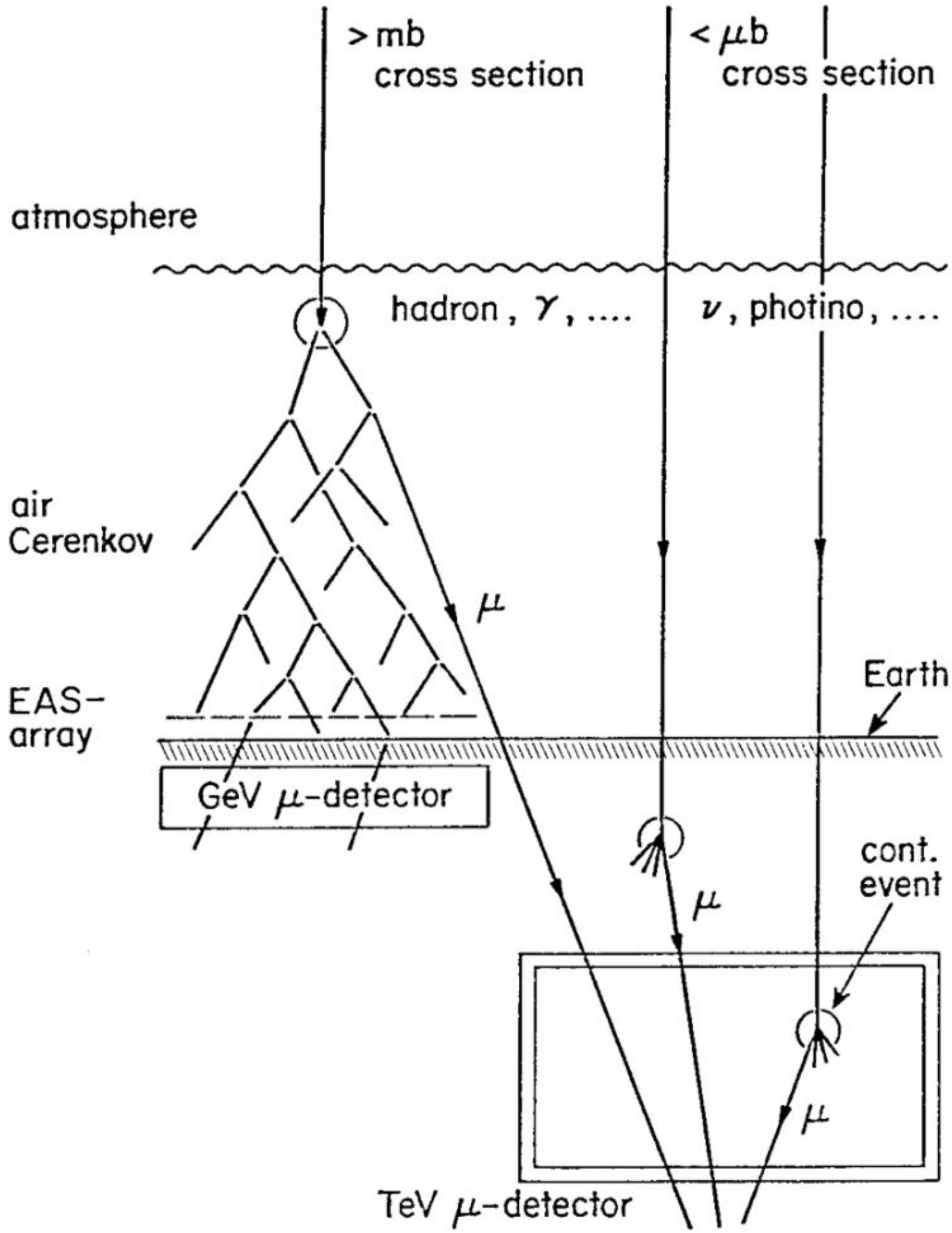


FIG. 1 - Phase distribution for muons arriving within 4.5° off the direction of Cygnus X-3 (June '82-January '85).



.... A cascade of papers with "wild" speculations
photinos, gluinos, glueballinos, ...

the "*cygnet*" models


> mb
cross section
< μb
cross section
atmosphere
hadron, γ, ...
ν, photino, ...
air
Cerenkov
μ
Earth
EAS-
array
GeV μ-detector
μ
cont.
event
μ
TeV μ-detector

V. S. Berezinsky, E. V. Bugaev and E. S. Zaslavskaya,
"CYGNUS X-3 AND PHOTINOS"
Sov. J. Nucl. Phys. **43**, 600 (1986) IYAI-P-0438.

V. S. Berezinsky, J. R. Ellis and B. L. Ioffe,
"Difficulties With Interpretation of Underground Muons From Cygnus X-3"
Phys. Lett. B **172**, 423-429 (1986)

V. S. Berezinsky, E. V. Bugaev and E. S. Zaslavskaya,
"MUONS FROM HIGH-ENERGY COSMIC PHOTINO"
Nuovo Cim. C **11**, 387-404 (1988)

Tom Gaisser wrote 15 papers discussing Cygnus X-3
(9 with Francis Halzen)
(8 with Todor Stanev)

T.K.Gaisser and T.Stanev,
“Calculation of Neutrino Flux From Cygnus X-3''
Phys. Rev. Lett. 54, 2265 (1985).

T.Stanev, T.K.Gaisser and F.Halzen,
“Muons in gamma showers from Cygnus X3 ?''
Phys. Rev. D 32, 1244-1247 (1985)

In these works the main lines of the emission from high energy sources (in neutrinos and gamma rays) are outlined

Letter | Published: 21 June 1984

Haleakala Cherenkov telescope

Hercules X-1—a 1,000 GeV γ-ray pulsar

J. C. Dowthwaite, A. B. Harrison, I. W. Kirkman, H. J. Macrae, K. J. Orford, K. E. Turver & M. Walmsley

Abstract

An X-ray pulsar has been detected for the first time as a very high-energy (VHE) γ-ray pulsar. X-ray emission from Hercules X-1 is multiply periodic with a pulsar period of 1.24 s, a binary orbital period of 1.7 day and a 35-day amplitude modulation of unknown origin characterized by a sharp turn-on followed by a slow decline over 11 days. During a drift-scan we have detected a significant 3-min outburst of VHE γ rays, which had a 1.24-s periodicity. This outburst occurred 35 days before an observed X-ray turn-on. The γ-ray luminosity during the outburst was of the same order as the X-ray luminosity. Together with the coincidence in time, this suggests a connection between the mechanisms giving rise to the γ-ray outburst and the X-ray turn-on. Subsequent monitoring of the source during a period when the X-ray flux was decreasing yielded some evidence of much weaker pulsed γ-ray activity at the pulsar period. We note a possible similarity between this system and Cygnus X-3.

Hercules X-1

T_{pulsar} = 1.24 seconds

T_{orbit} = 1.7 days

Observations by Haleakala Cherenkov telescope
of one more X-Ray pulsar
Chadwick et al. 1985.

4U 0115+63

T_{pulsar} = 3.61 seconds

T_{orbit} = 24.3 days

Detections of Hercules X-1

R. M. Baltrusaitis, *et al.*
"Evidence for 500 TeV gamma-ray emission from Hercules X-1"
Astrophys. J. Lett. **293**, L69-L72 (1985)

B. L. Dingus, *et al.*
"Ultrahigh-energy Pulsed Emission From Hercules X-1
With Anomalous Air Shower Muon Production"
Phys. Rev. Lett. **61**, 1906-1909 (1988)

L. K. Resvanis, *et al.*
"VHE gamma rays from Hercules X-1"
Astrophys. J. Lett. **328**, L9 (1988)

Chicago
Air
Shower
Array

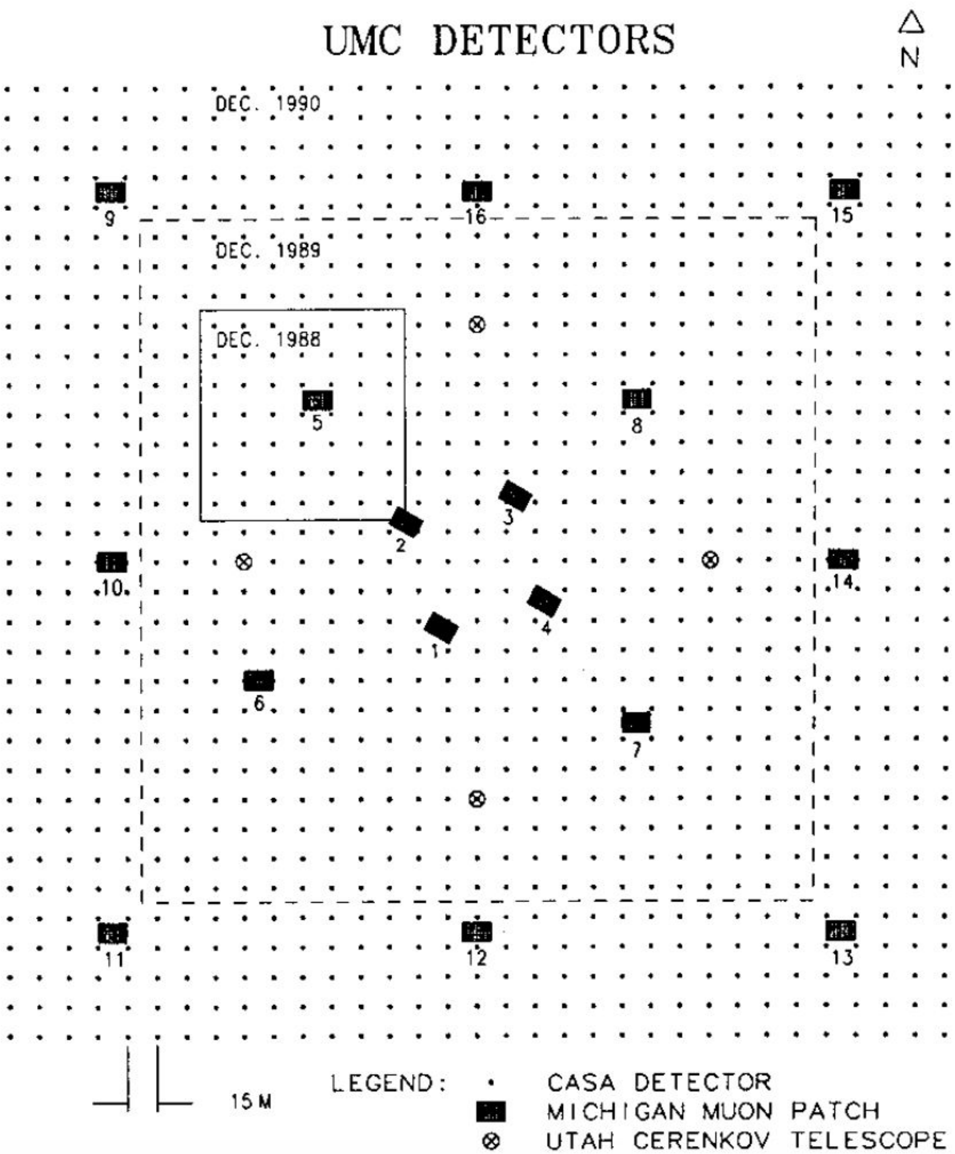
Michigan
Muon
Array

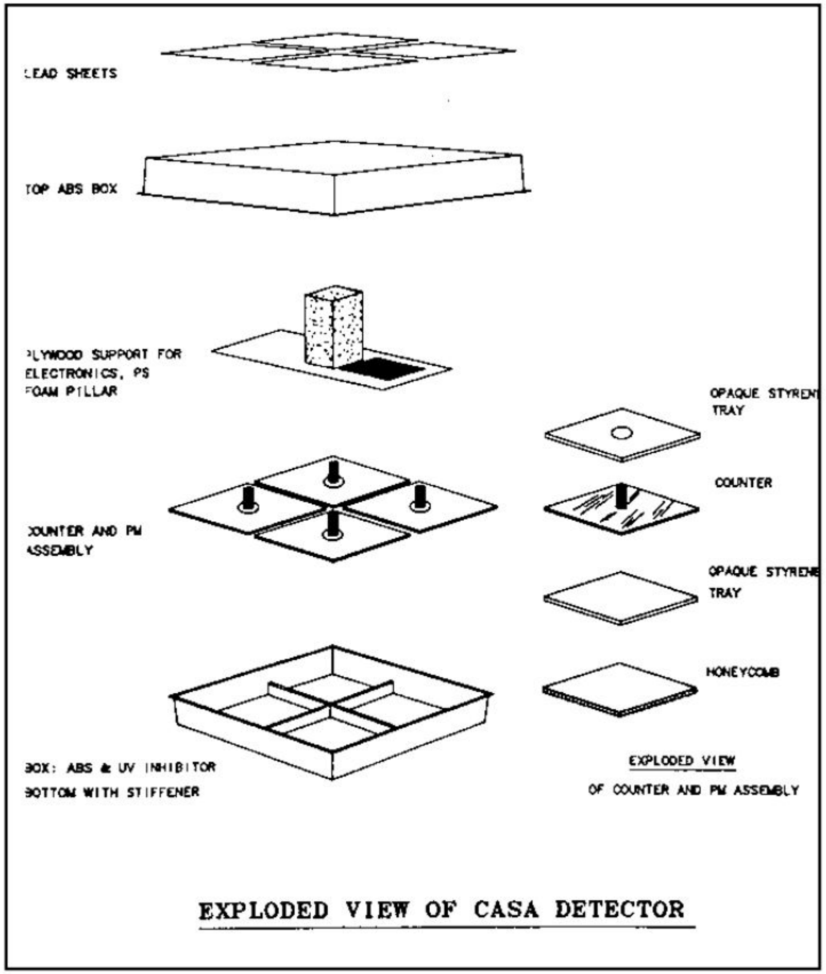
CASA-MIA telescope

CASA-MIA array UTAH

Construction 1988-1991
Data taking 1992 - 1998

1089 scintillator detectors
2500 meters of buried muon detector



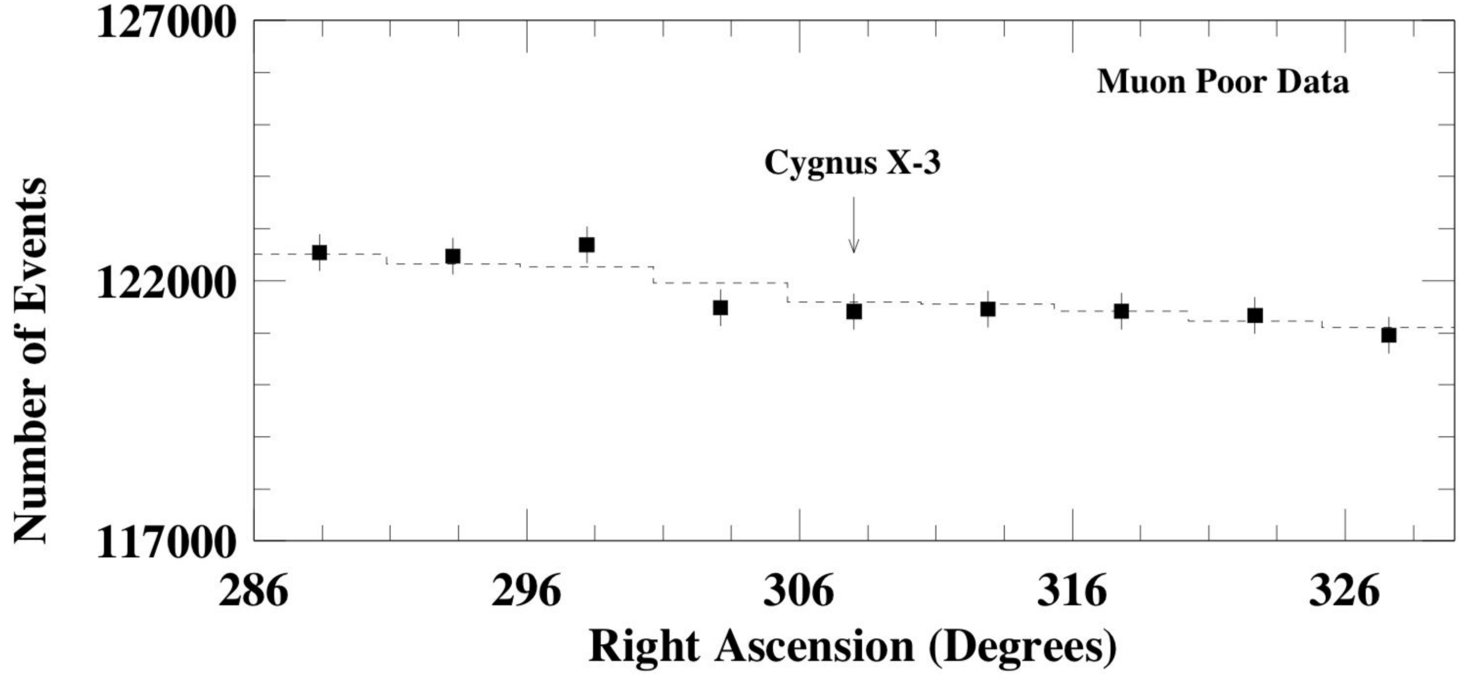



CHANCER -2.7

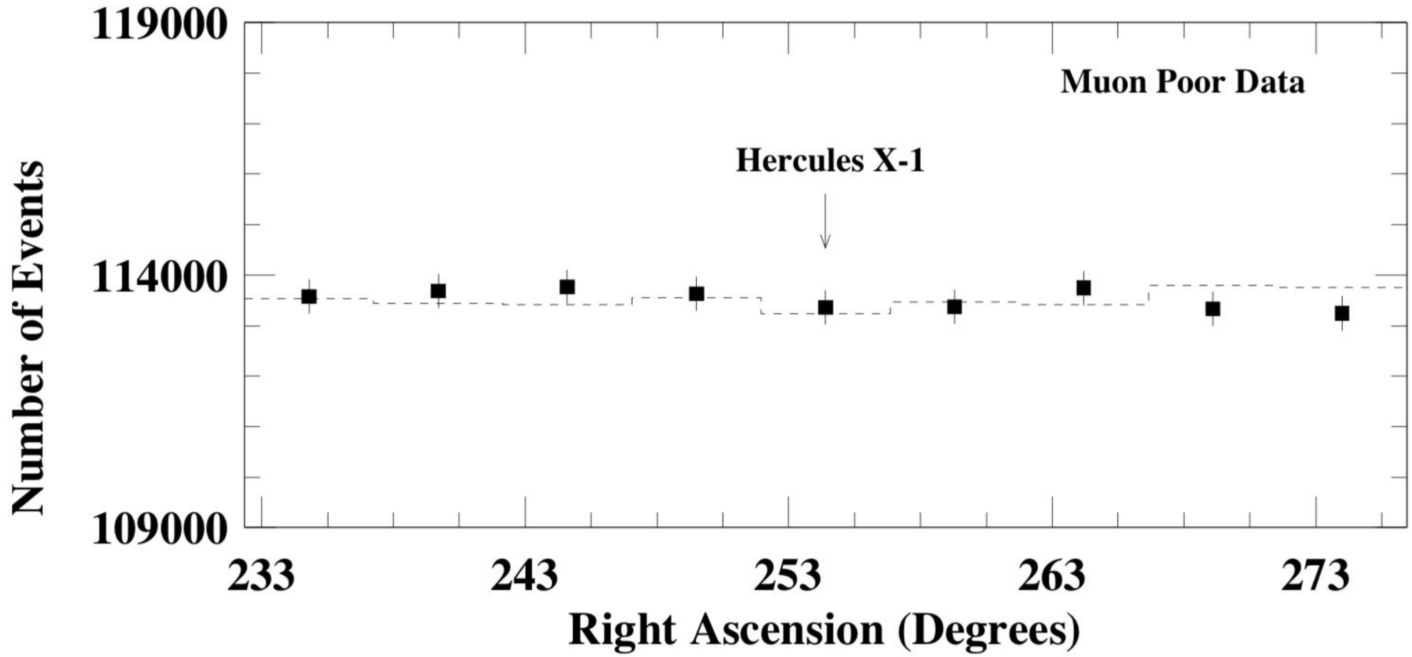
A. Borione *et al.* [CASA-MIA],
"A High statistics search for ultrahigh-energy gamma-ray emission from Cygnus X-3 and Hercules X-1"
Phys. Rev. D **55**, 1714-1731 (1997)
[arXiv:astro-ph/9611117 [astro-ph]].

CASA-MIA Collaboration

We have carried out a high statistics (2 Billion events) search for ultra-high energy gamma-ray emission from the X-ray binary sources Cygnus X-3 and Hercules X-1. Using data taken with the CASA-MIA detector over a five year period (1990-1995), we find no evidence for steady emission from either source at energies above 115 TeV. The derived upper limits on such emission are more than two orders of magnitude lower than earlier claimed detections. We also find no evidence for neutral particle or gamma-ray emission from either source on time scales of one day and 0.5 hr. For Cygnus X-3, there is no evidence for emission correlated with the 4.8 hr X-ray periodicity or with the occurrence of large radio flares. Unless one postulates that these sources were very active earlier and are now dormant, the limits presented here put into question the earlier results, and highlight the difficulties that possible future experiments will have in detecting gamma-ray signals at ultra-high energies.

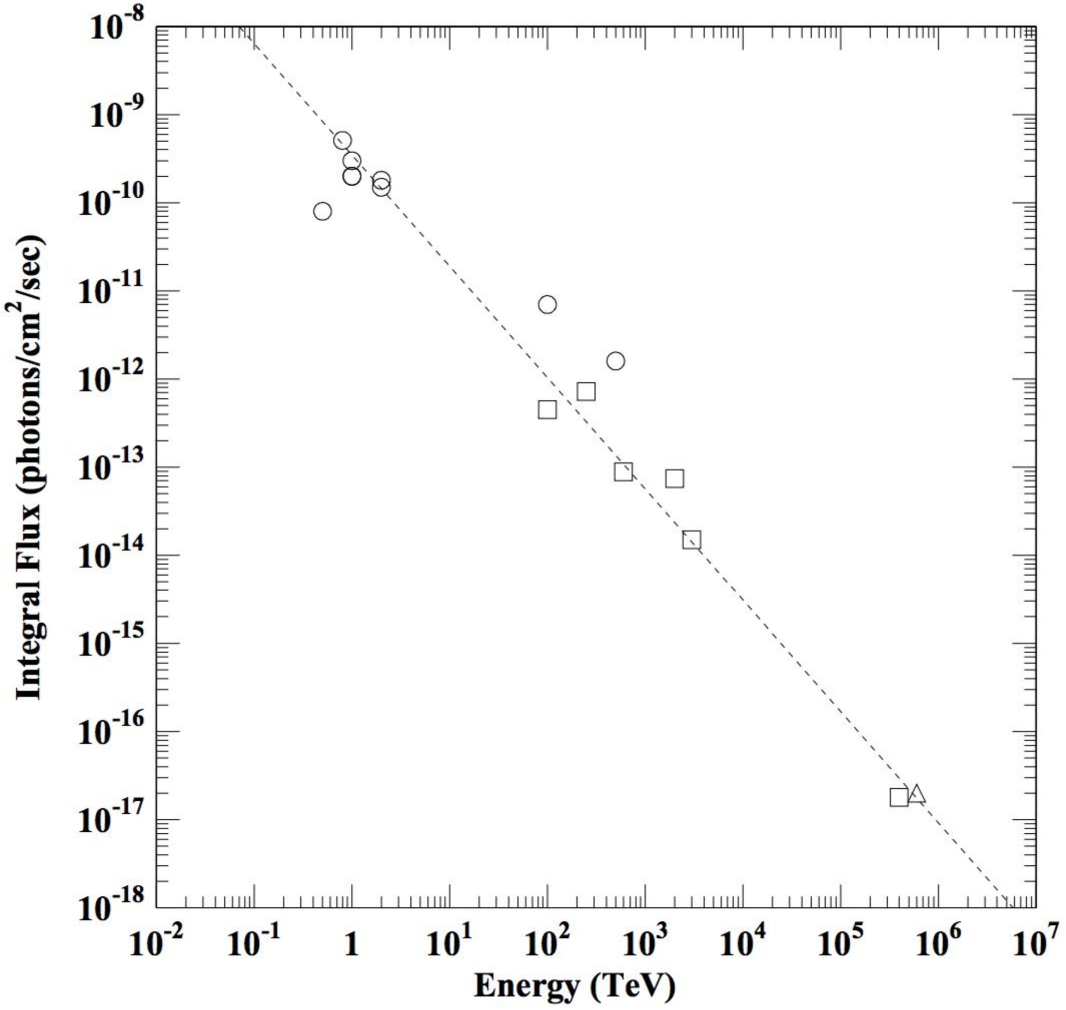


127000
122000
117000
Number of Events
Muon Poor Data
Cygnus X-3
286
296
306
316
326
Right Ascension (Degrees)



119000
114000
109000
Number of Events
Muon Poor Data
Hercules X-1
233
243
253
263
273
Right Ascension (Degrees)

Measurements of Cygnus X-3 [1975-1990]



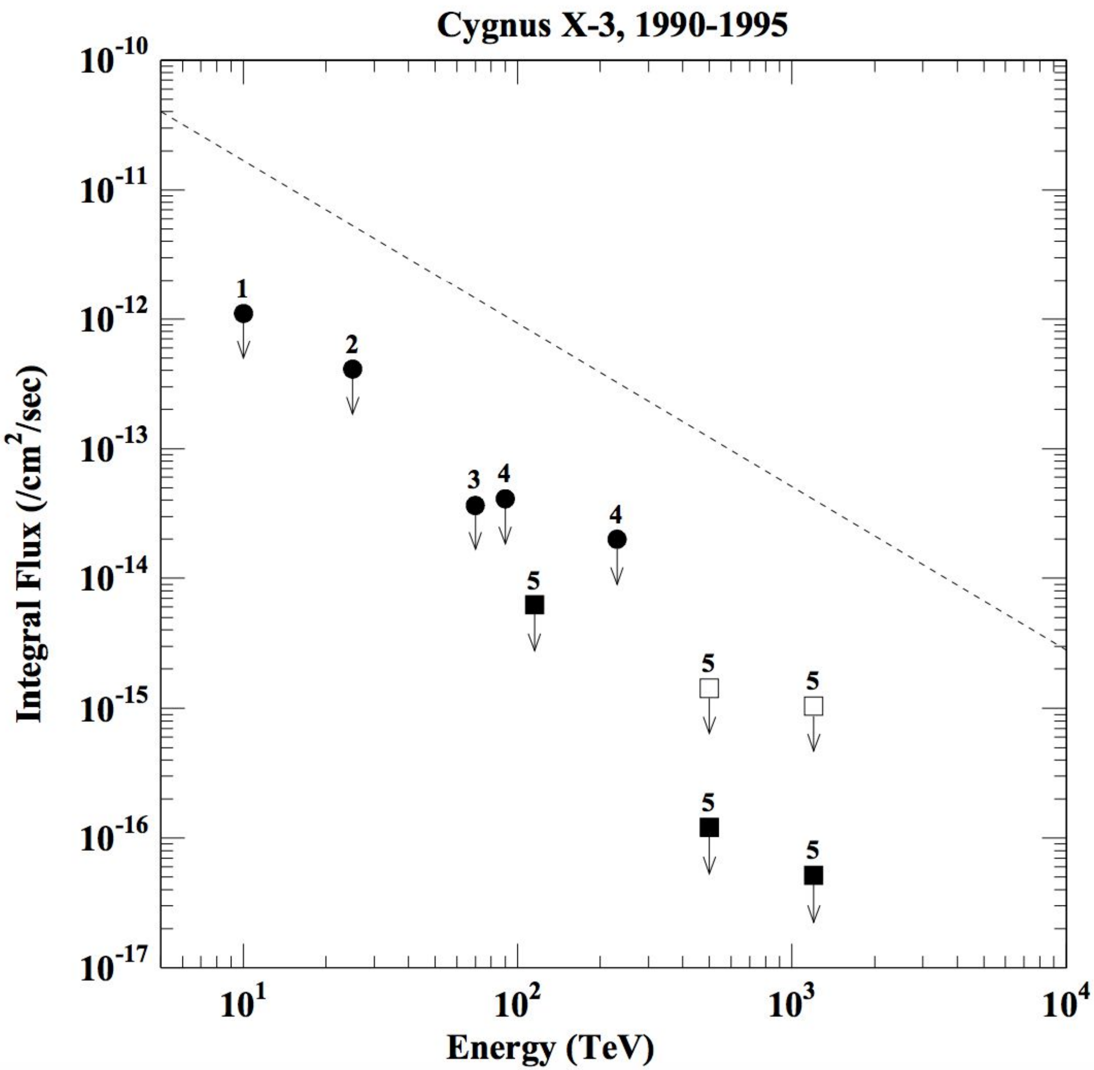


Figure 12: Flux limits reported between 1990 and 1995 on the steady emission of particles from Cygnus X-3. The squares (5) represent the results of this work. Open squares indicate limits on the emission of any neutral particle that creates air showers. Filled squares indicate limits on the emission of gamma-rays. The circles (1-4) represent results from other experiments: 1. Tibet [92], 2. HEGRA [95], 3. CYGNUS [93], and 4. EAS-TOP [94]. The dashed curve is the approximate power law fit to early results (reproduced from Figure 1).

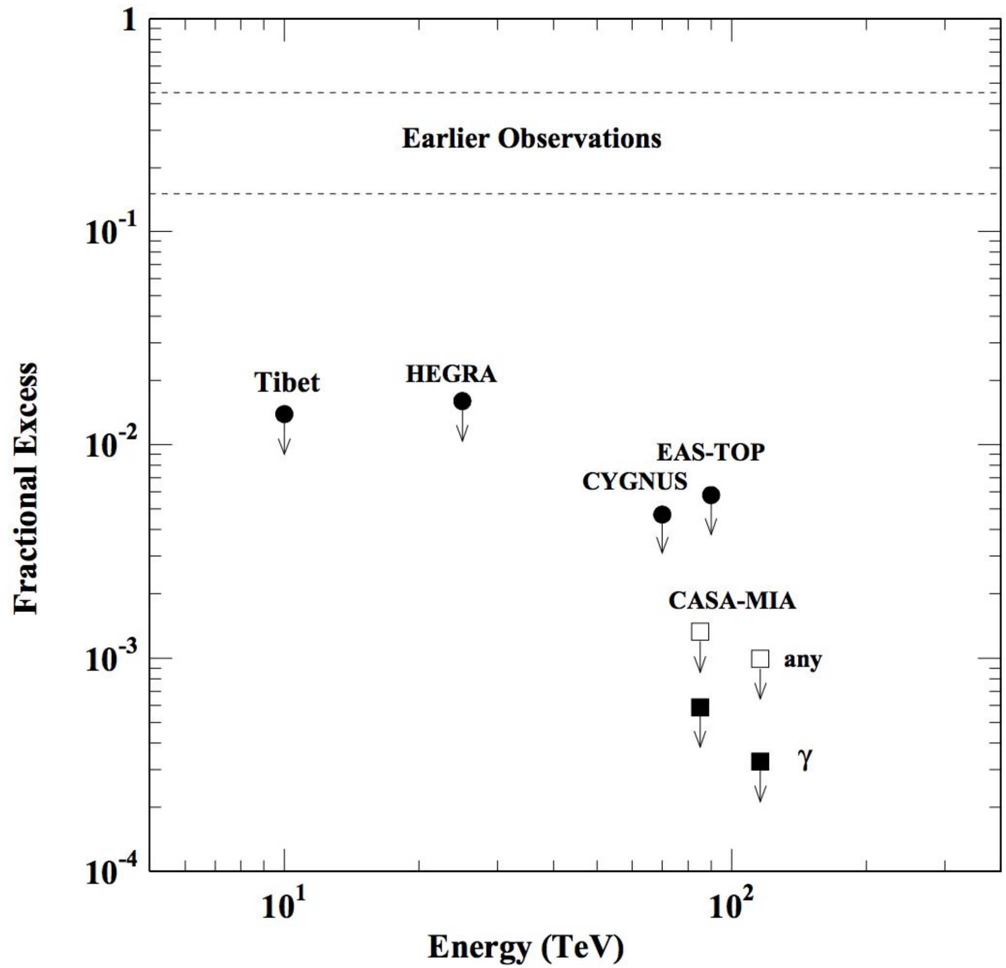


Figure 13: Limits reported between 1990 and 1995 on the fractional excess of gamma-rays from Cygnus X-3 relative to the cosmic ray background. The squares represent the results of this work. Open squares indicate limits on the emission of any neutral particle that creates air showers. Filled squares indicate limits on the emission of gamma-rays. The circles represent results from other experiments: Tibet [92], HEGRA [95], CYGNUS [93], and EAS-TOP [94]. The dashed lines indicate the range of fractional excess values corresponding to the fluxes reported by earlier experiments.

Profound impact in our field : Stimulated:

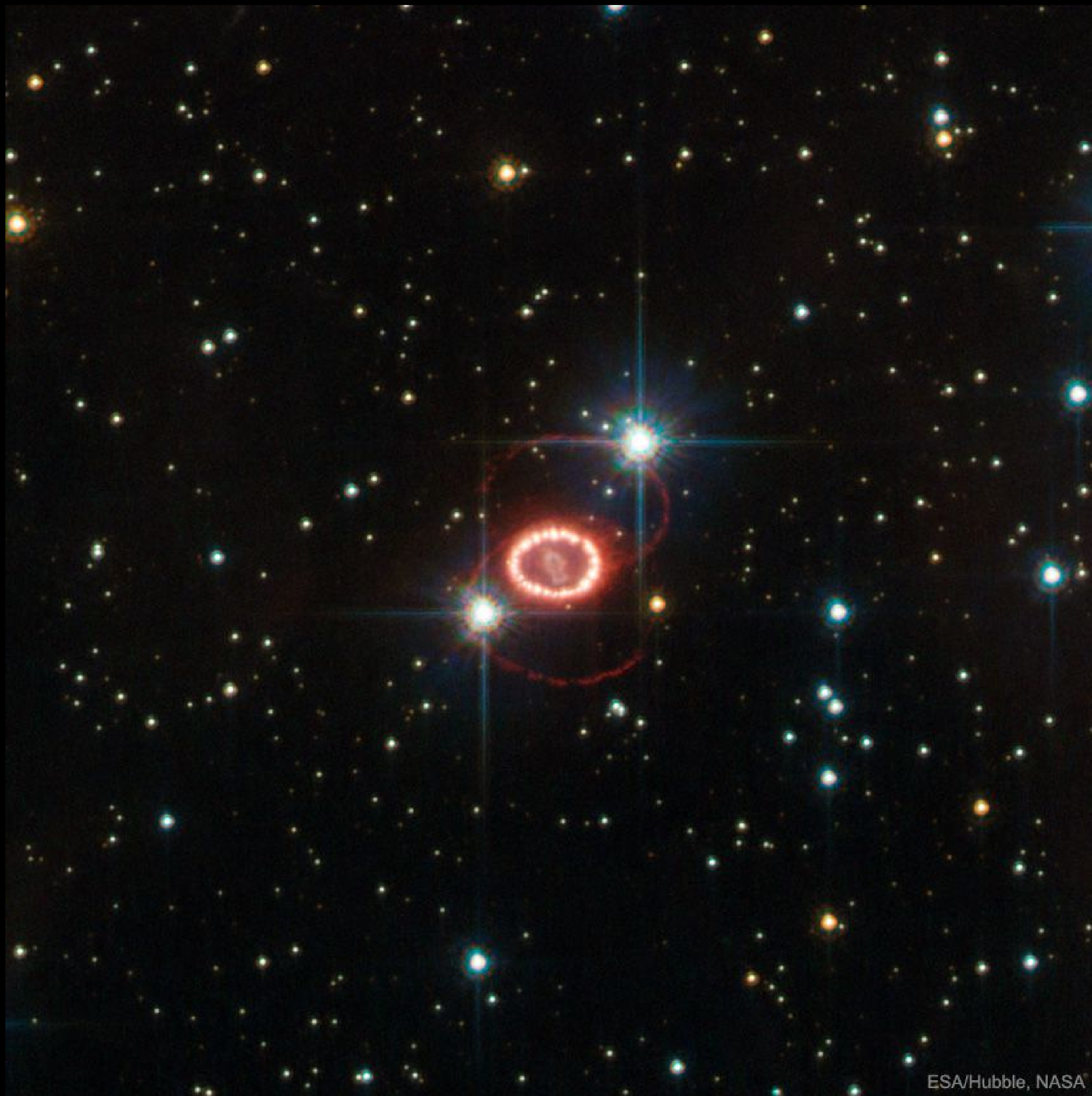
More Accurate calculations of the relation between primaries and gamma-rays and neutrinos

Modeling of Astrophysical sources

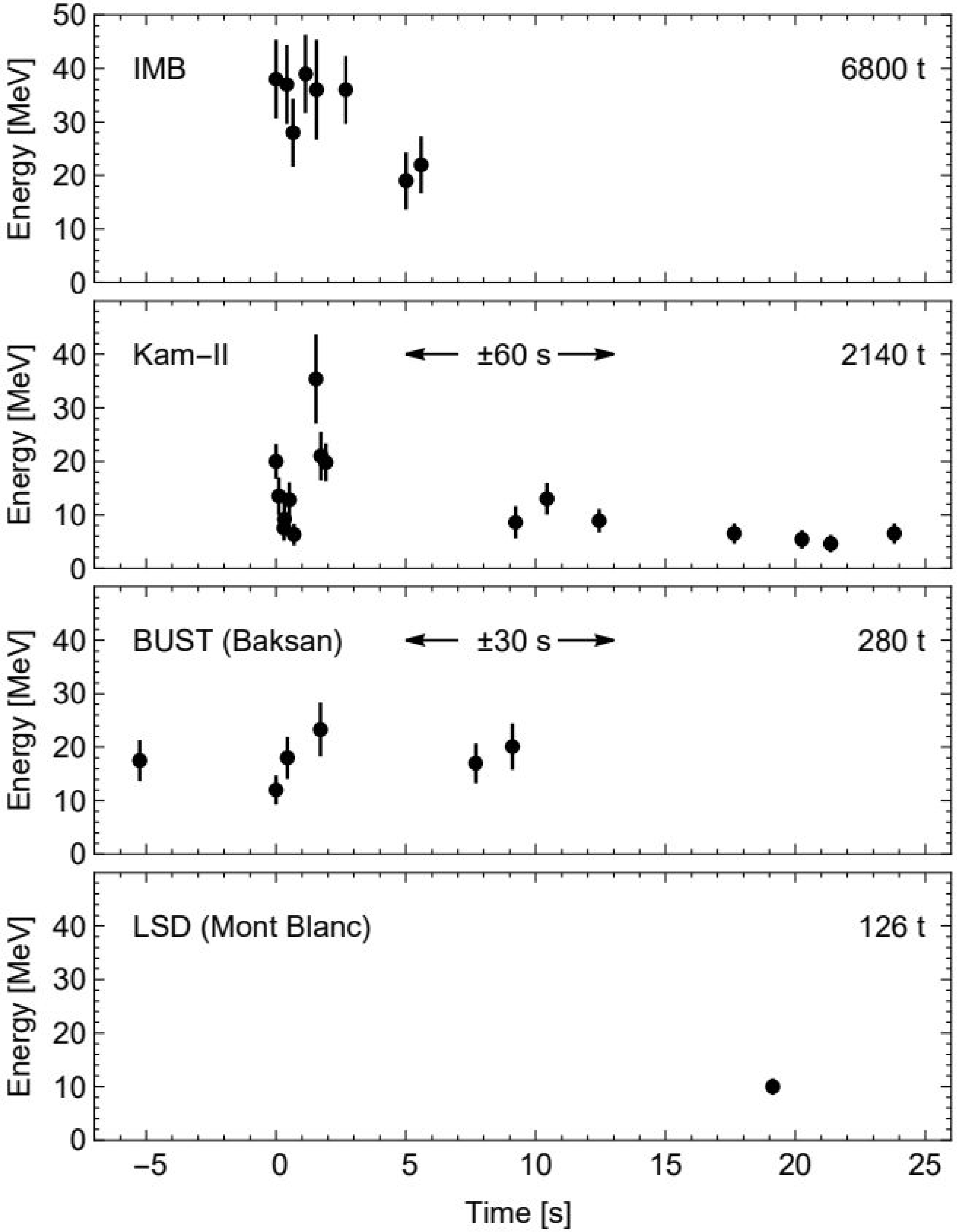
More sensitive Detectors !!

Better statistical methods

SN 1987A !!


ESA/Hubble, NASA

Observation of the neutrino burst from SN1987A by IMB, Kamiokande, Baksan (+ Mont Blanx)



6800 tons

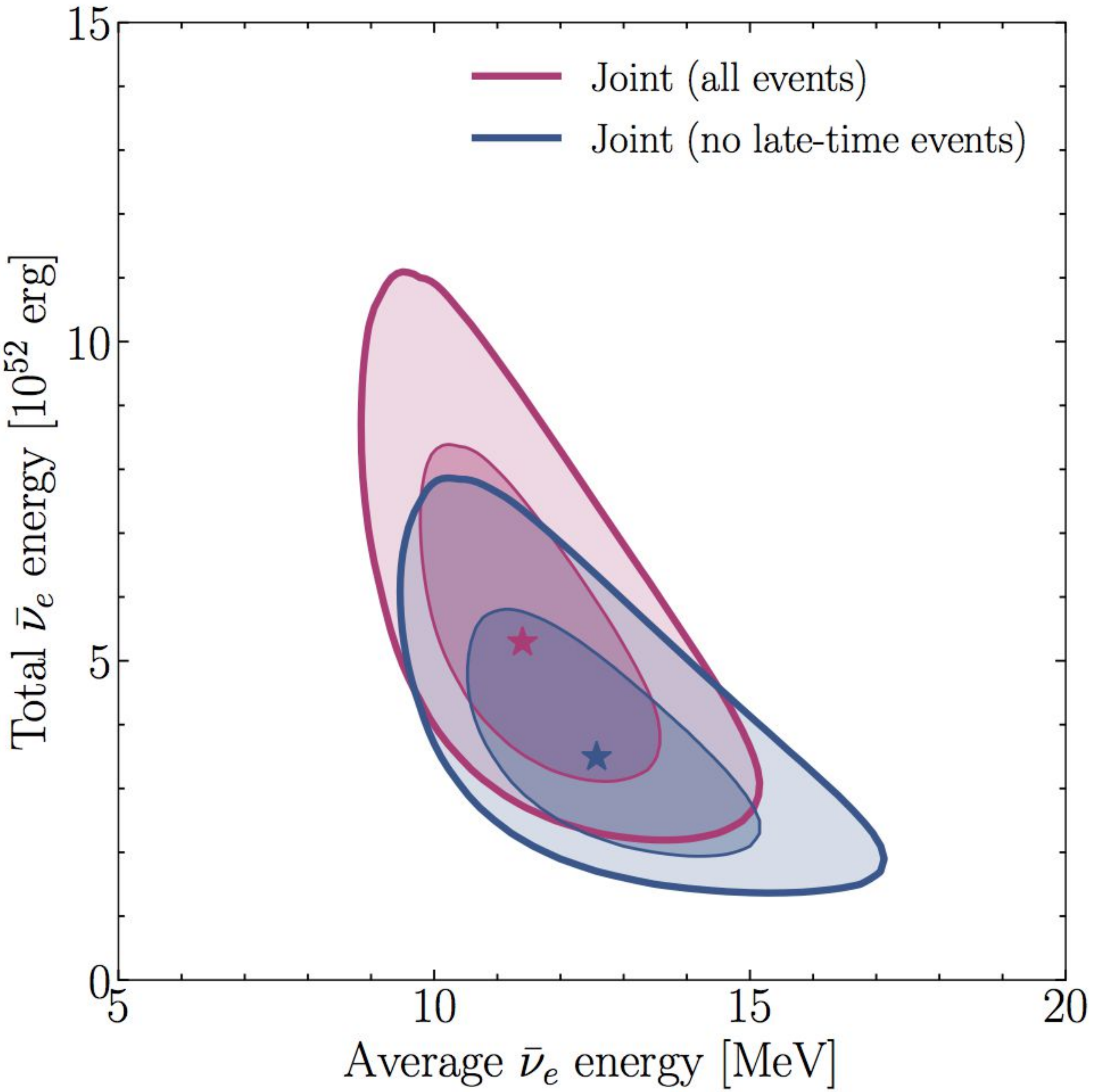
2140 tons

280 tons

125 tons

Fiducial mass

Confirmation of the fundamental elements of the Supernova explosion mechanism and neutrino emission



The study of the neutrino burst has allowed
to put important constraints on several phenomena

neutrino masses
Neutrino Magnetic moment
Axions
.....

We are all eagerly waiting for the next one !!!!

Very powerful stimulus for several studies including:

Acceleration in high energy sources

Cosmic rays and gamma radiation from the shell of SN1987A

V. S. Berezinsky & V. L. Ginzburg

Nature **329**, 807–809 (1987) | Cite this article

Abstract

Detection of high-energy gamma rays from young supernovae shells[1,2] can directly prove the hypothesis that the main sources of cosmic rays (CR) in our Galaxy are supernovae. This radiation is produced in nuclear collisions of accelerated protons and nuclei, through the decay of pions. On 13 April 1987 an attempt was made to measure the gamma radiation from SN1987A between 50 and 500 MeV in energy by an international team from Australia, UK, FRG and USA (R. Stauberg, personal communication).

Title: Pulsars and cosmic rays in the dense supernova shells
Authors: Berezinskii, V. S. & Prilutskii, O. F.
Journal: Astronomy and Astrophysics, vol. 66, no. 3, June 1978, p. 325-334.
Bibliographic Code: 1978A&A....66..325B

Summary. Cosmic rays injected by a young pulsar in the dense supernova shell are considered. The fluxes of gamma and neutrino radiation generated through decays of pions in the expanding shell are calculated. The maintenance of the Galactic cosmic ray pool by pulsar production is shown to have a difficulty: adiabatic energy losses of cosmic rays in the expanding shell require the high initial cosmic ray luminosity of pulsar, which results in too high flux of γ-radiation produced by young pulsars through π^0-decays (in excess over observed diffuse γ-ray background). The latter problem will be further discussed in paper II.

Other important contributions

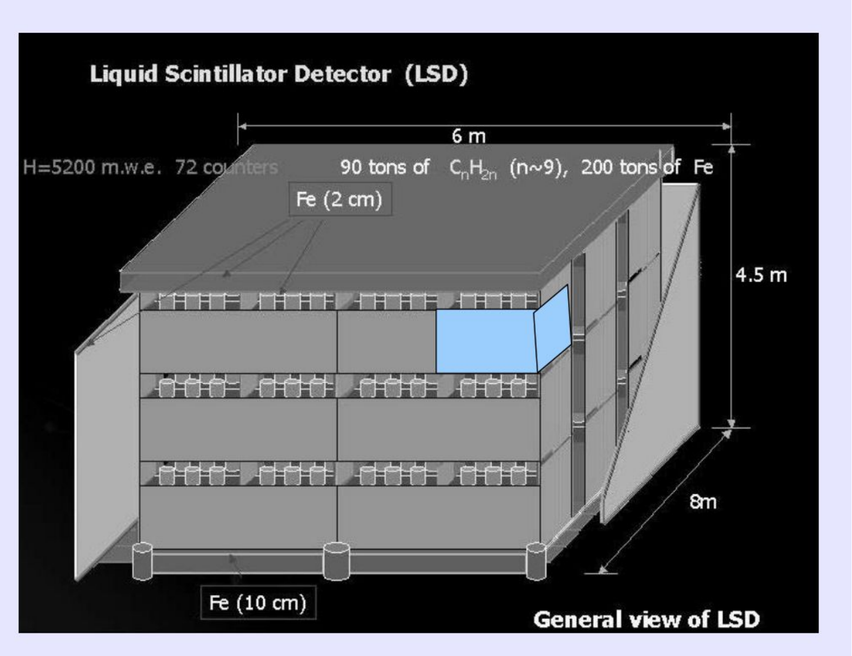
T. K. Gaisser, A. Harding and T. Stanev,
"Particle Acceleration and Production of Energetic Photons in Sn1987a"
Nature **329**, 314-316 (1987)
doi:10.1038/329314a0

T. K. Gaisser, T. Stanev and F. Halzen,
"ULTRAHIGH-ENERGY RADIATION FROM YOUNG SUPERNOVAE"
Nature **332**, 314 (1988)
doi:10.1038/332314a0

Many of the fundamental ideas about multi-messenger astrophysics are put on a firm basis during this years of "excitation"

The mistery of the

Mont Blanc signal



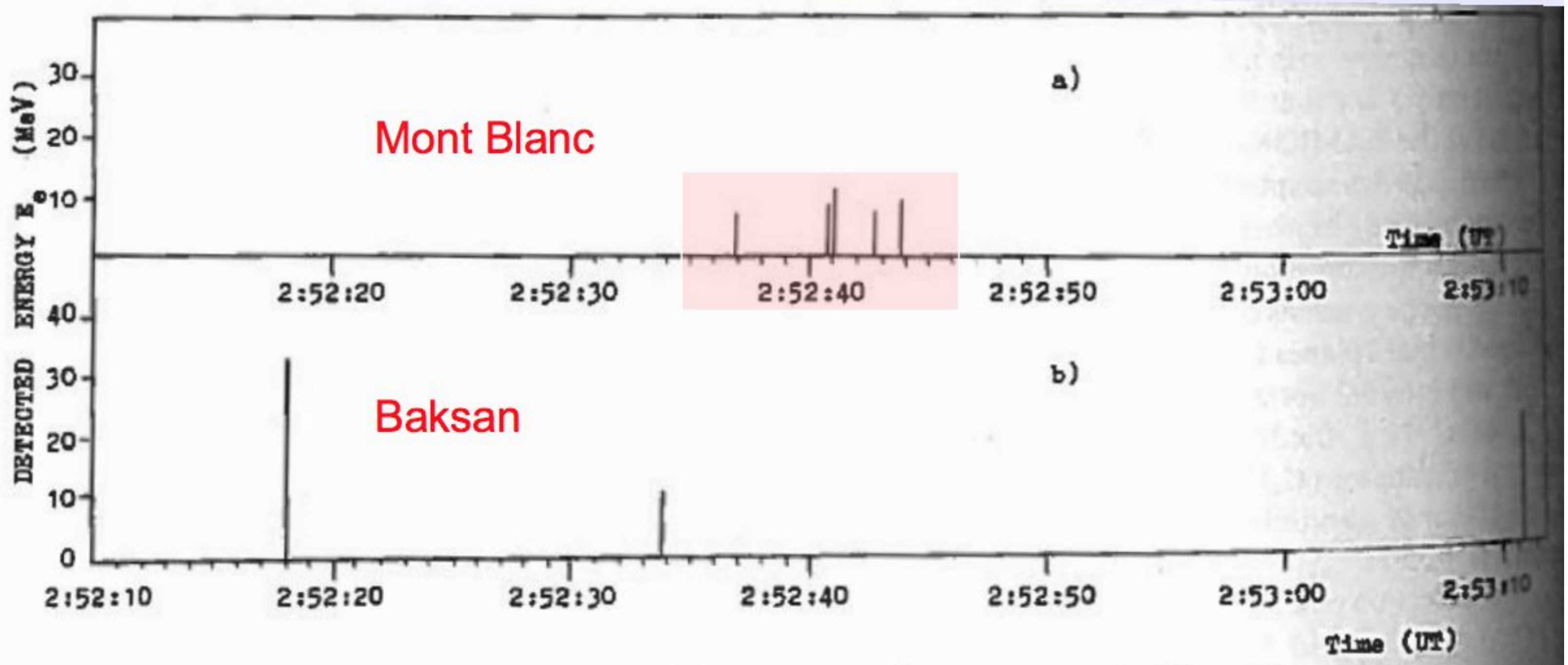


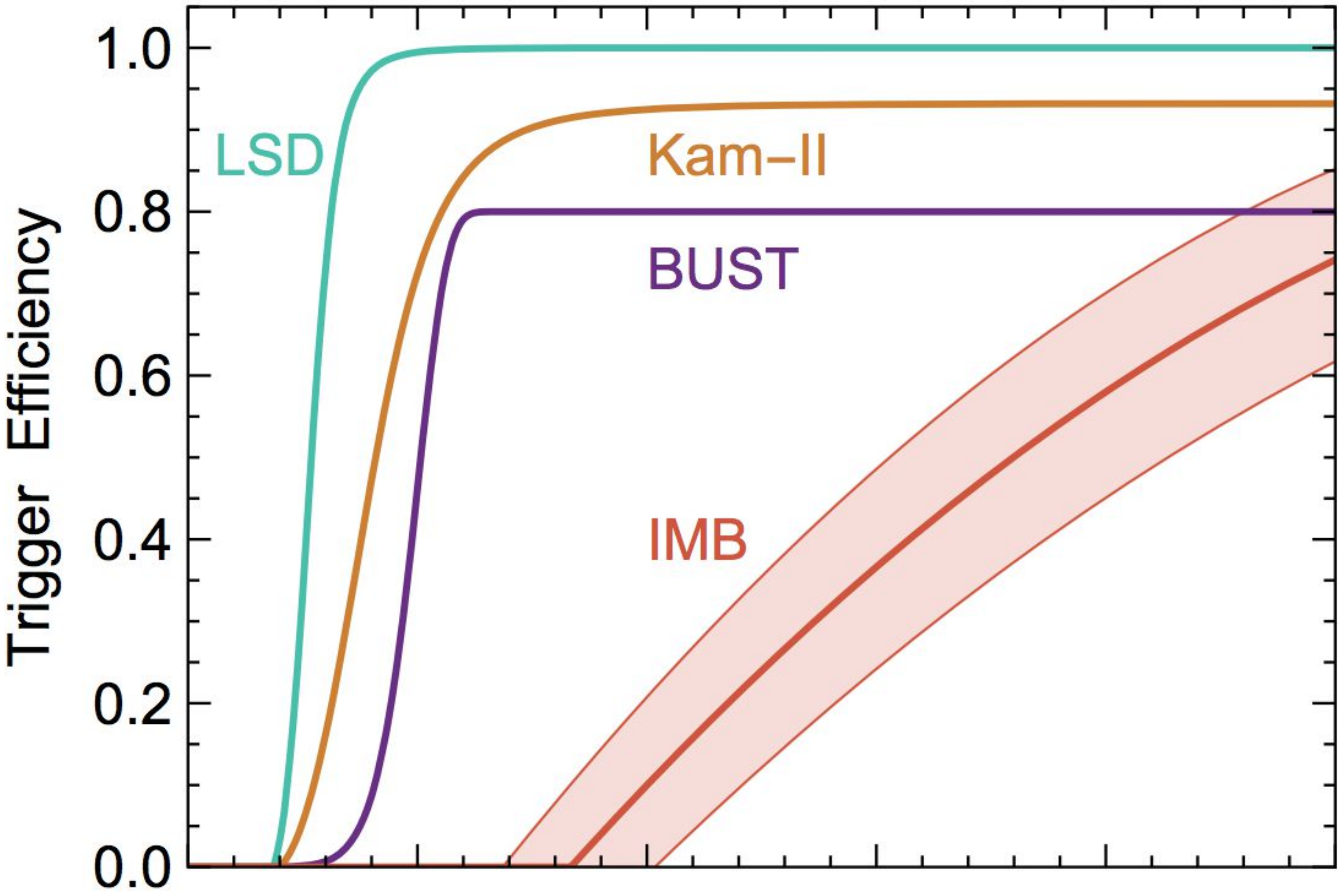
Fig. 1. The time sequences of events detected by the LSD (a) and the Baksan telescope (b) at 2:52 UT on February 23, 1987.

5 very low energy neutrinos in 7 seconds

Table I – Characteristics of the pulses in the burst detected on February 23rd, 1987

Event no.	Counter no.	Time (UT)	E_{vis} (MeV)
994	31	$2^h52^m36^s.79$	6.2
995	14	40.65	5.8
996	25	41.01	7.8
997	35	42.70	7.0
998	33	43.80	6.8

Thresholds of the different detectors



LSD had the lowest threshold

A. De Rujula, "May a Supernova Bang Twice?"
Phys. Lett. B **193**, 514-524 (1987)

V. S. Berezinsky, C. Castagnoli, V. I. Dokuchaev and P. Galeotti,
"On the possibility of a two-Bang supernova collapse"
Nuovo Cim. C **11**, 287-303 (1988)

The Mont Blanc group reports a burst of neutrinos in the LSD detector occuring the day before the optical discovery of SN1987A. The Kamiokande (K2) and IMB experiments see neutrino bursts ~4 h 43 min after LSD. The K2 observations at LSD time here said to contradict LSD. I argue that the K2 results strongly support the LSD pulse(!). I critically analyse the data, and prove that all experiments are compatible at all times. I discuss the plausibility and predictive power of a two-neutrino-burst scenario, wherein the progenitor's core first became a neutron star, and subsequently recollapsed into a black hole (or strange star) as matter left behind by a partially failed shock wave accreted on and around the neutron star, with a calculated fall-back time of a few hours

Topics in Astroparticle Physics in 1987

Today

Proton Decay → Will we ever see it ??

Solar neutrinos

Atmospheric Neutrinos
(Background for p decay
... but also for oscillations)

→ Profound understanding of *Flavor Oscillations*

High Energy Sources
Gamma Astronomy
Neutrino Astronomy

→ The "Golden Era" of Gamma Astronomy

The birth of Neutrino Astronomy

Cosmic Rays Origin

→ Great observations extending 12 orders of magnitude 10^8–10^{20} eV

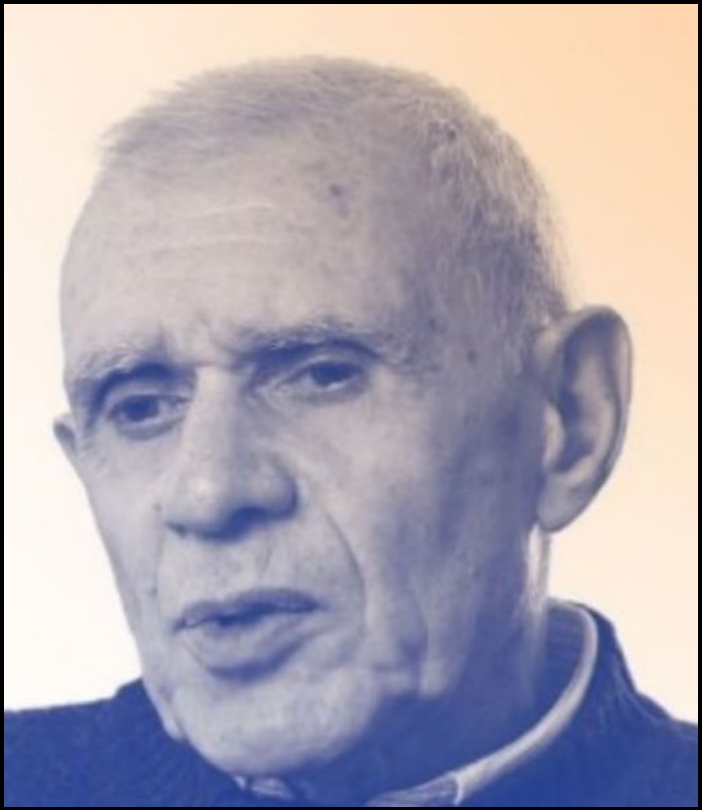
many problems remain open

Air Showers
Hadronic Interactions

→ The dark side of the Standard Model

The scientific legacy of

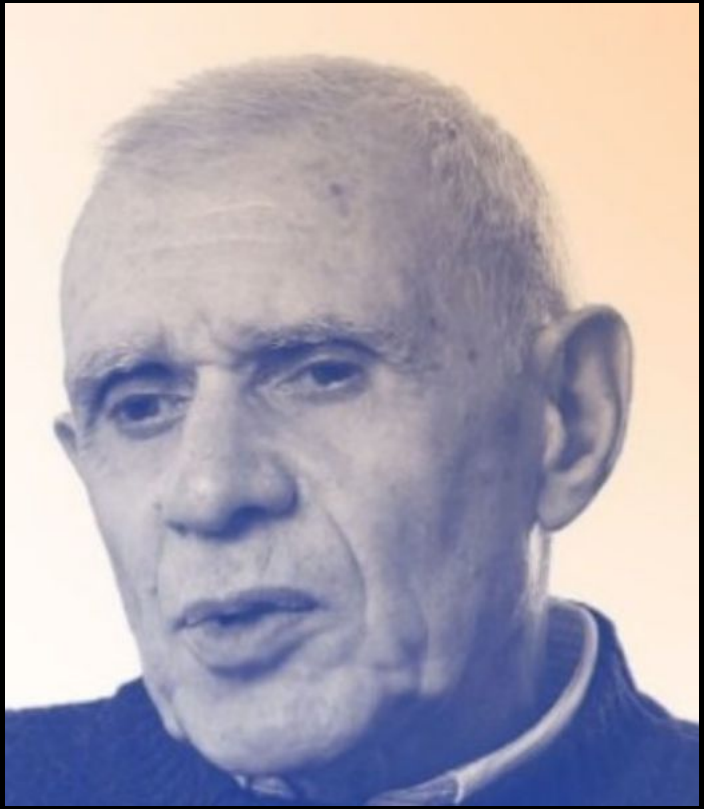
Veniamin Sergeyevich Berezinsky



The profound imprint of
his many ideas
(often right, sometimes wrong …
but always deep)
in a field the is now flourishing.

The scientific legacy of

Veniamin Sergeyevich Berezinsky



The profound imprint of
his many ideas
(often right, sometimes wrong ...
but always deep)
in a field the is now flourishing.

I can see an important part of his
legacy in front of me in this auditorium !

The generation(s) of younger
scientists formed discussing
with Venya, and that are now
pushing forward the frontiers
of what now we now call Astroparticle Physics

[*and have organized this meeting .* *Thanks* !].