Astrofisica e Neutrini

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Astrophysics with Four MESSENGERS

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

Essentially all the information
We have on the Universe around us
has been obtained with photons.

The history of Astrophysics is the
EXTENSION of the range of
wavelength available for observations

Astrophysics with Four MESSENGERS

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

A New Messenger
with very different properties
that will allow to
"SEE" the universe
in a profoundly different way

Astrophysics with Four MESSENGERS

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

Study the structure and properties of the SOURCES

Study properties of the NEUTRINOS (oscillations, decay...)

Astrophysics with Four MESSENGERS

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

Relation between these fields

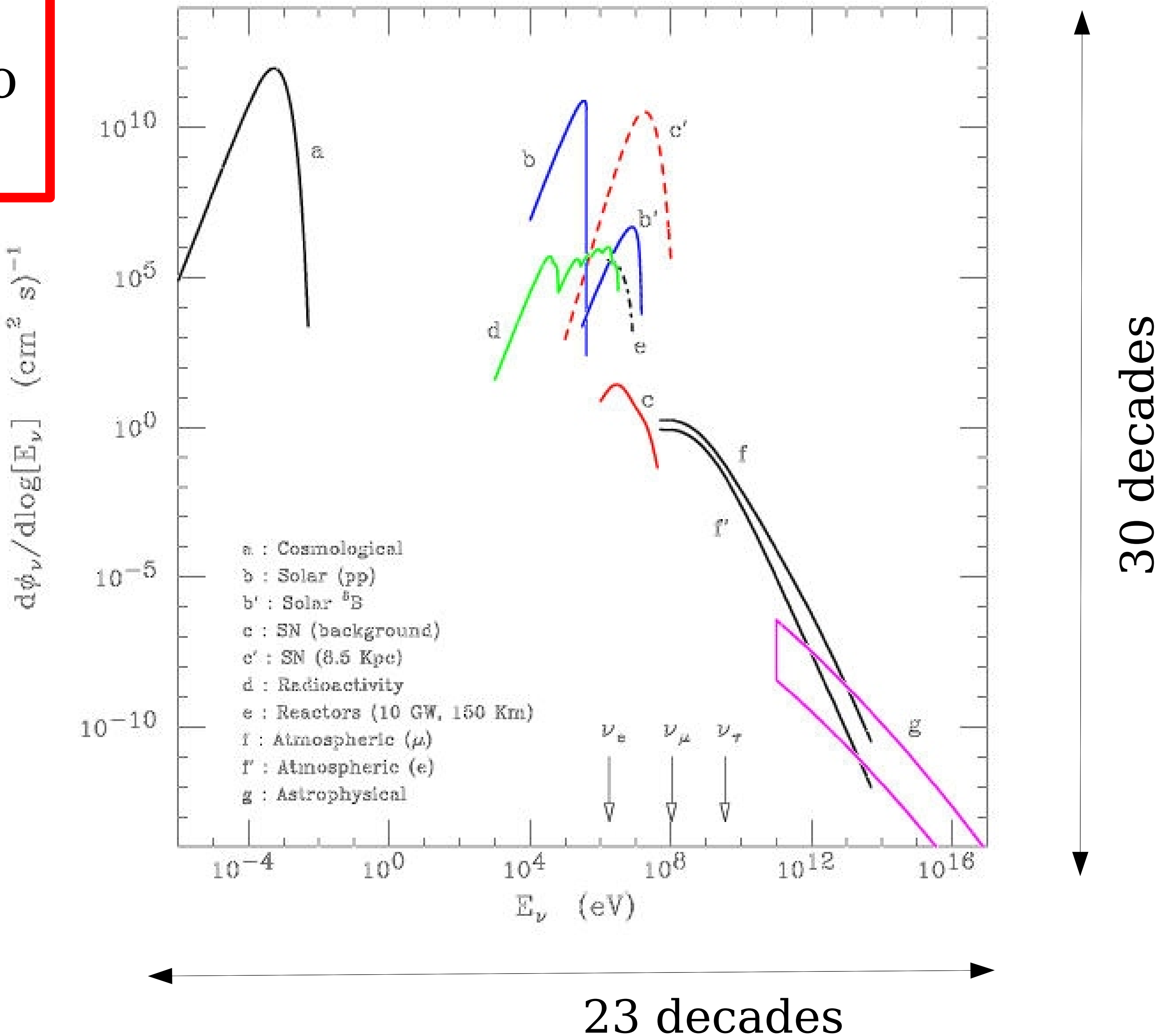
Observing same Objects / Events with ALL messengers at the same time ....

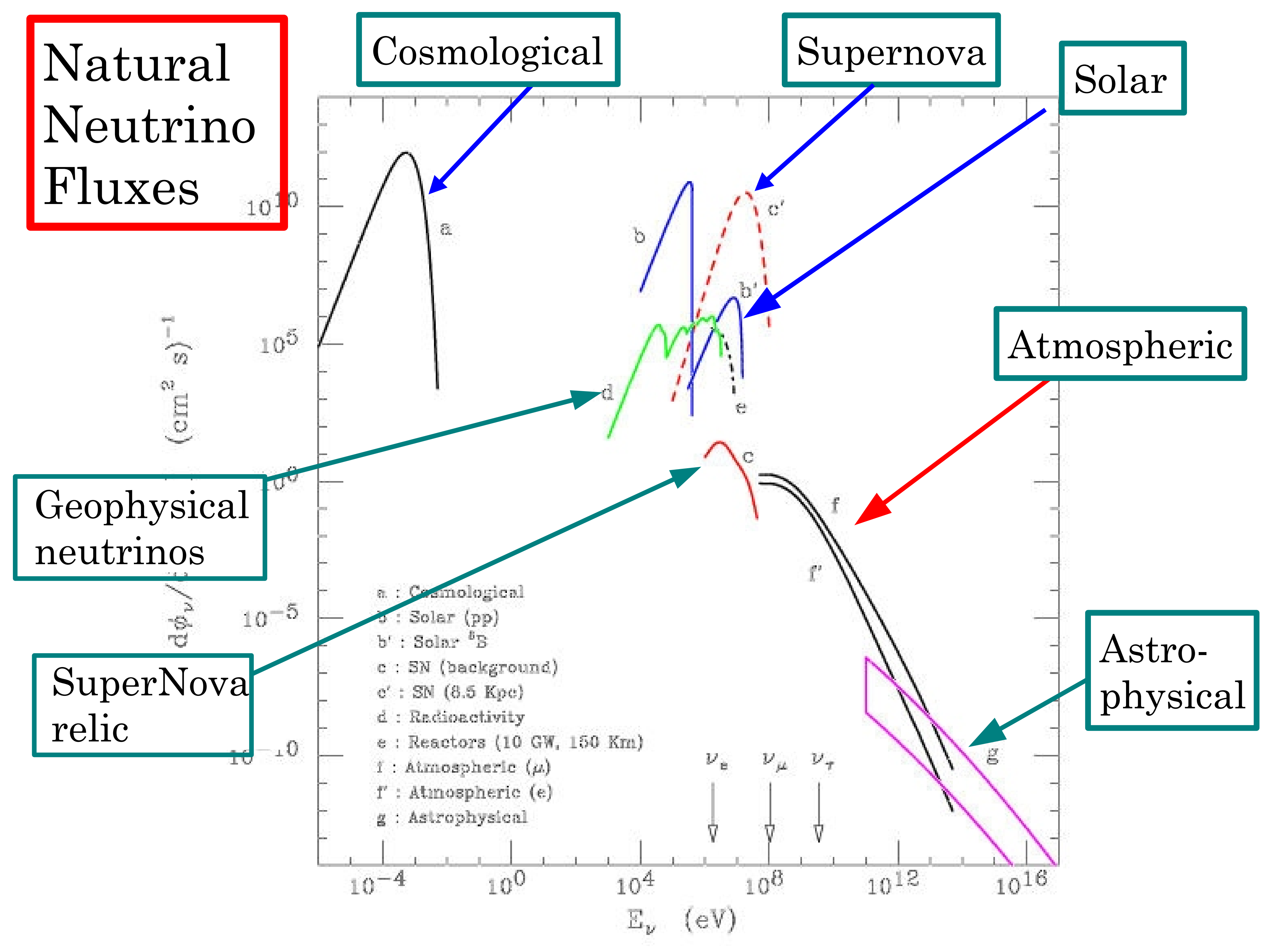
SPACE is
FULL of NEUTRINOS

that come from a
variety of Sources

in a very broad
interval of Energies

Natural Neutrino Fluxes





Natural Neutrino Fluxes
Cosmological
Supernova
Solar
Atmospheric
Geophysical neutrinos
SuperNova relic
Astro-physical
a : Cosmological
b : Solar (pp)
b' : Solar ⁸B
c : SN (background)
c' : SN (8.5 Kpc)
d : Radioactivity
e : Reactors (10 GW, 150 Km)
f : Atmospheric (μ)
f' : Atmospheric (e)
g : Astrophysical
ν_e ν_μ ν_τ
$d\phi_\nu/dE_\nu$ $(cm^2\ s)^{-1}$
E_ν (eV)

The Cross Section of the Neutrino is VERY SMALL

PROBLEM :

Detection is Very Difficult

Require Very Large Detectors

OPPORTUNITY:

Neutrinos come from

DEEP INSIDE Astrophysical Objects

Neutrino Astronomy (or Astrophysics) has just been born at the end of the last Century

TWO (+1) ASTROPHYSICAL OBJECTS have been "seen" in Neutrinos"

The SUN

SuperNova SN1987A

The Earth: Geophysical Neutrinos

SOLAR NEUTRINOS

Source of Energy of the SUN : Nuclear Fusion

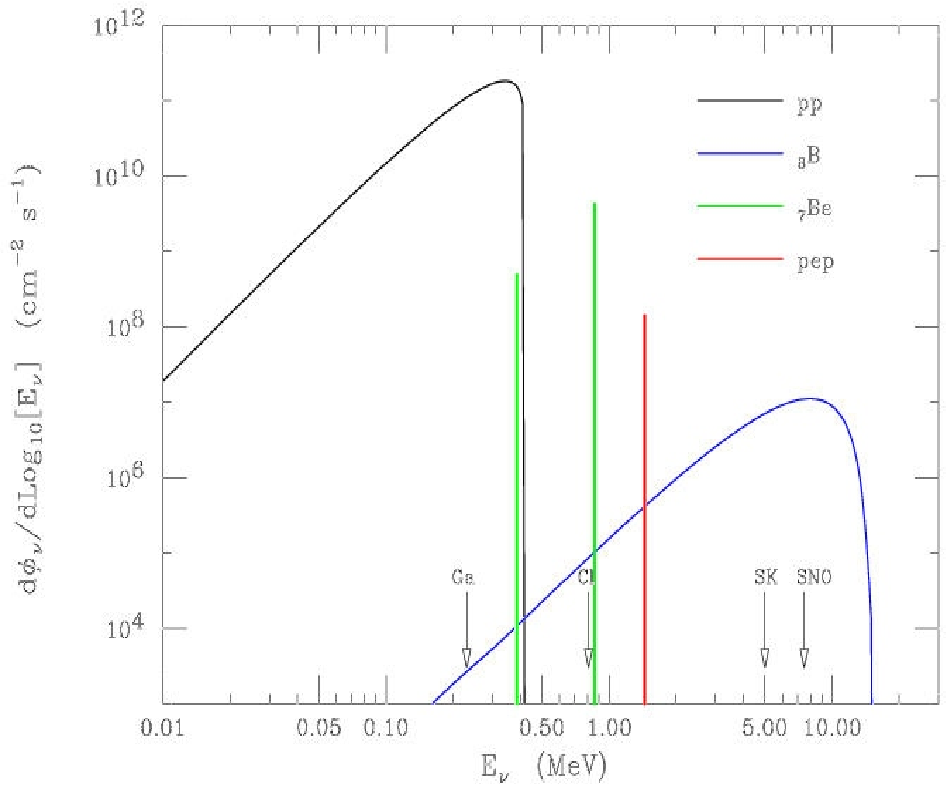
$$4p + 2e^- \to {}^4\text{He} + 2\nu_e$$

Energy Released per each Cycle

$$Q = 4m_p + 2m_e - m_{He} = 26.73 \text{ MeV}$$

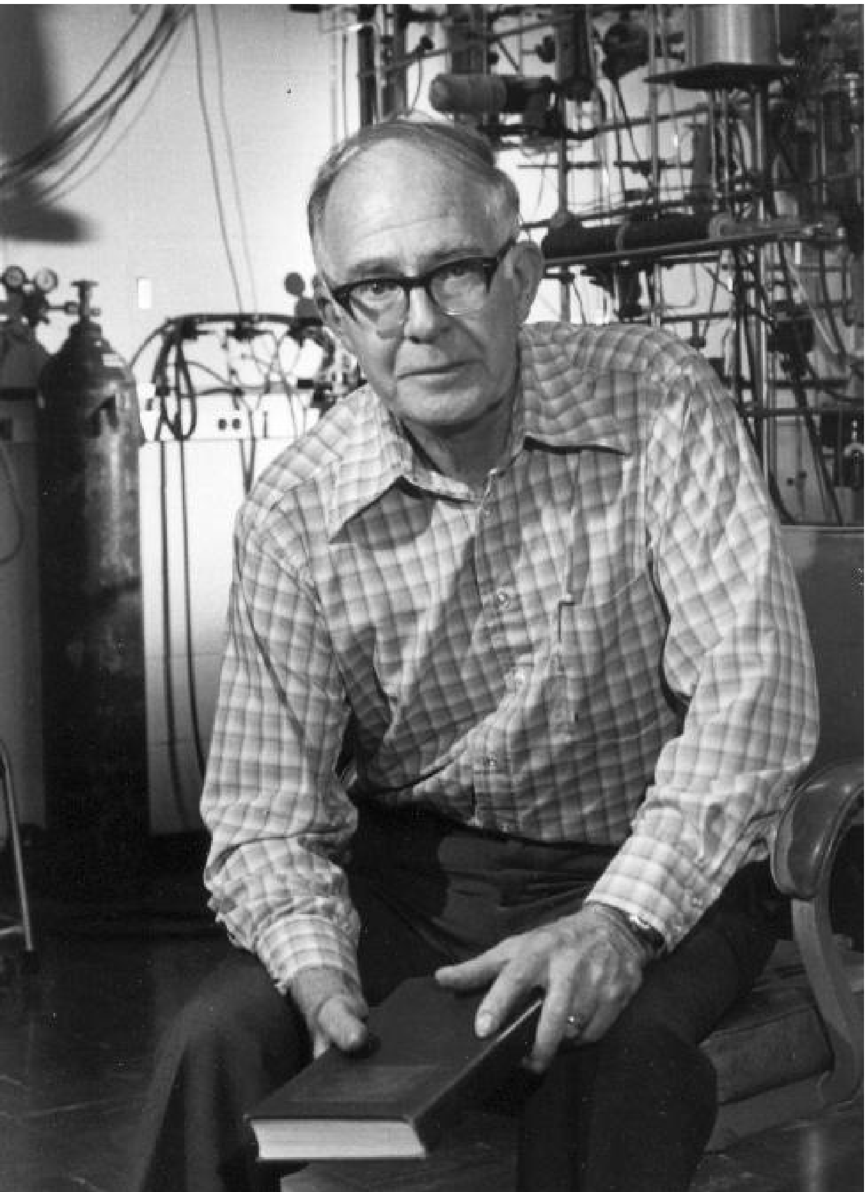
$$\Phi_{\nu_e} \simeq \frac{1}{4\pi\, d_\odot^2}\, \frac{2\, L_\odot}{(Q - \langle E_\nu \rangle)}$$

$$\phi_{\nu_\odot} \sim 6 \times 10^{10} \;(\text{cm}^2 \;\; \text{s})^{-1}$$



SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)



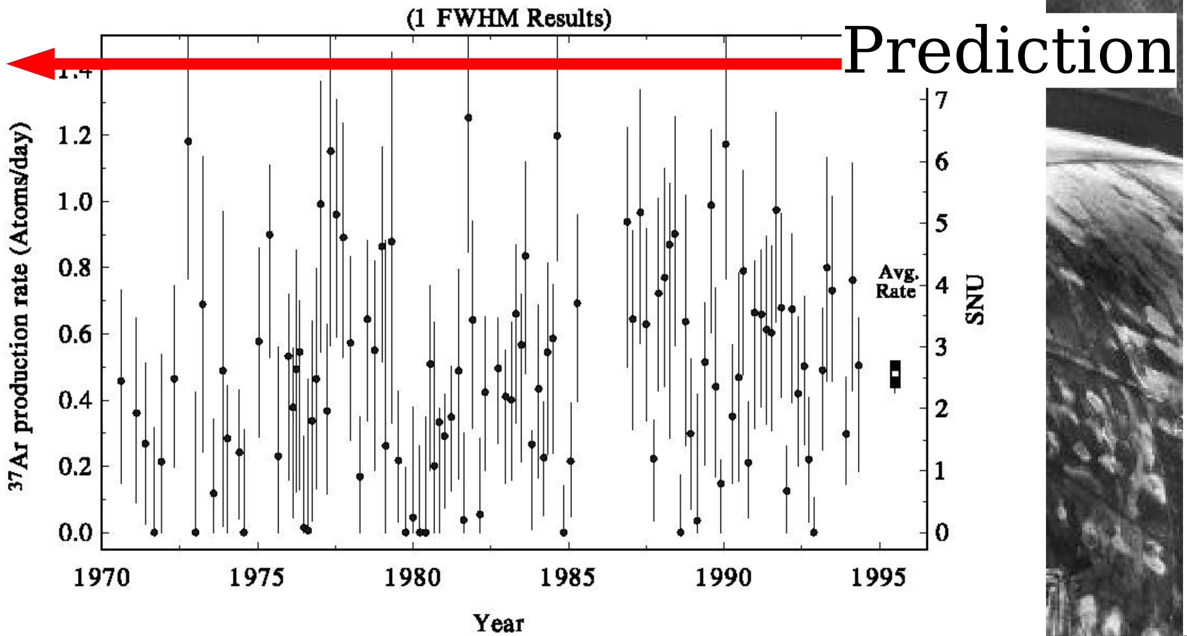
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of C_2Cl_4, so that the expected ^{37}Ar production rate is well above the background of the counter, 0.2 count per day. Using Bahcall's expression,

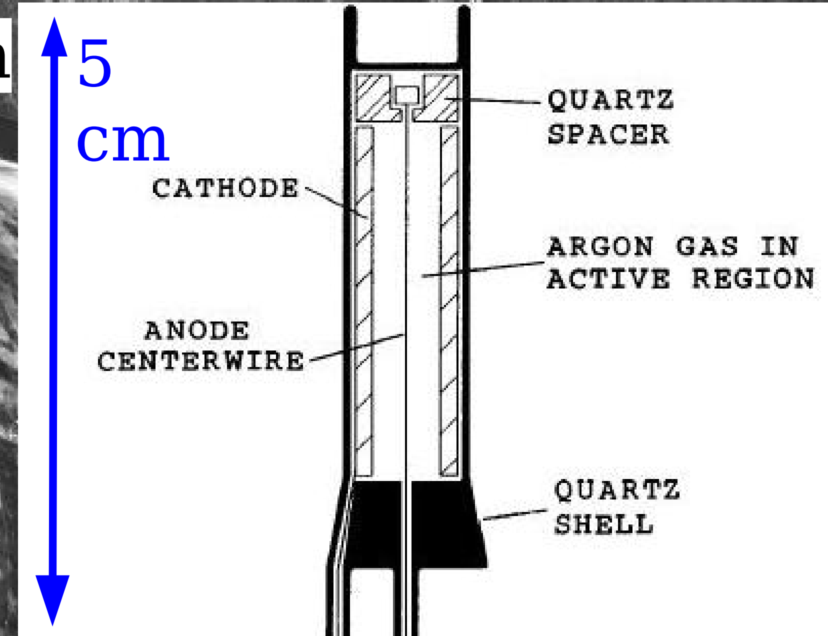
$$\sum \varphi_\nu(\text{solar})\,\sigma_{\text{abs}}$$

$$= (4 \pm 2) \times 10^{-35}\ \text{sec}^{-1}\ ({}^{37}\text{Cl atom})^{-1},$$

then the expected solar neutrino captures in 100 000 gallons of C_2Cl_4 will be 4 to 11 per day, which is an order of magnitude larger than the counter background.

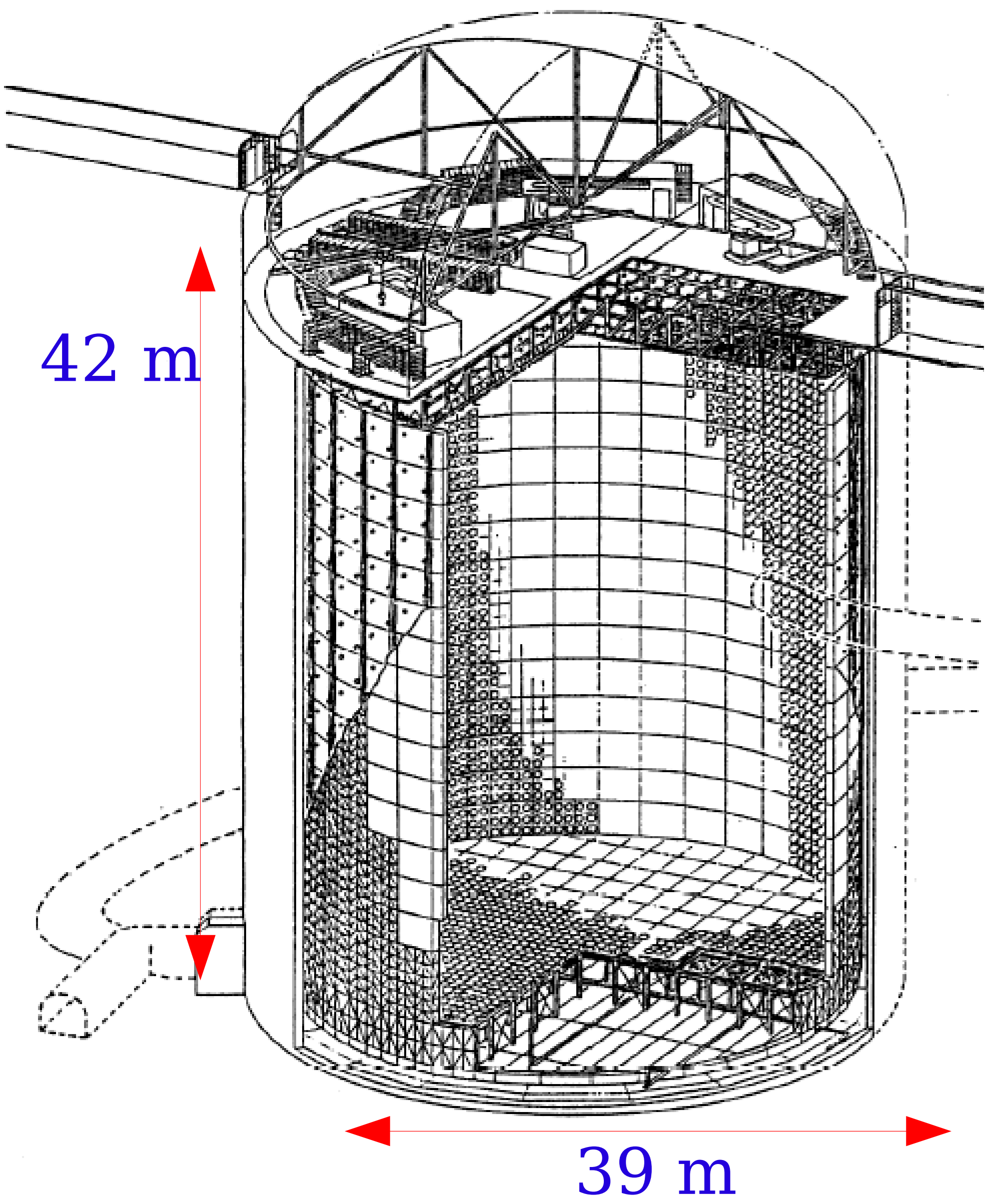


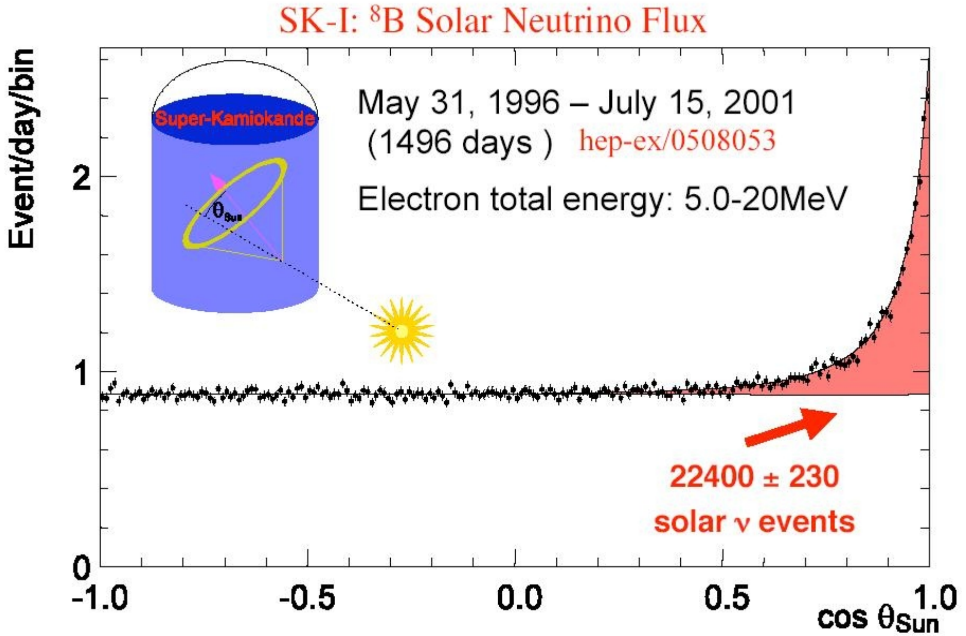
(1 FWHM Results)
Prediction
37Ar production rate (Atoms/day)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
SNU
0
1
2
3
4
5
6
7
Avg. Rate
1970
1975
1980
1985
1990
1995
Year



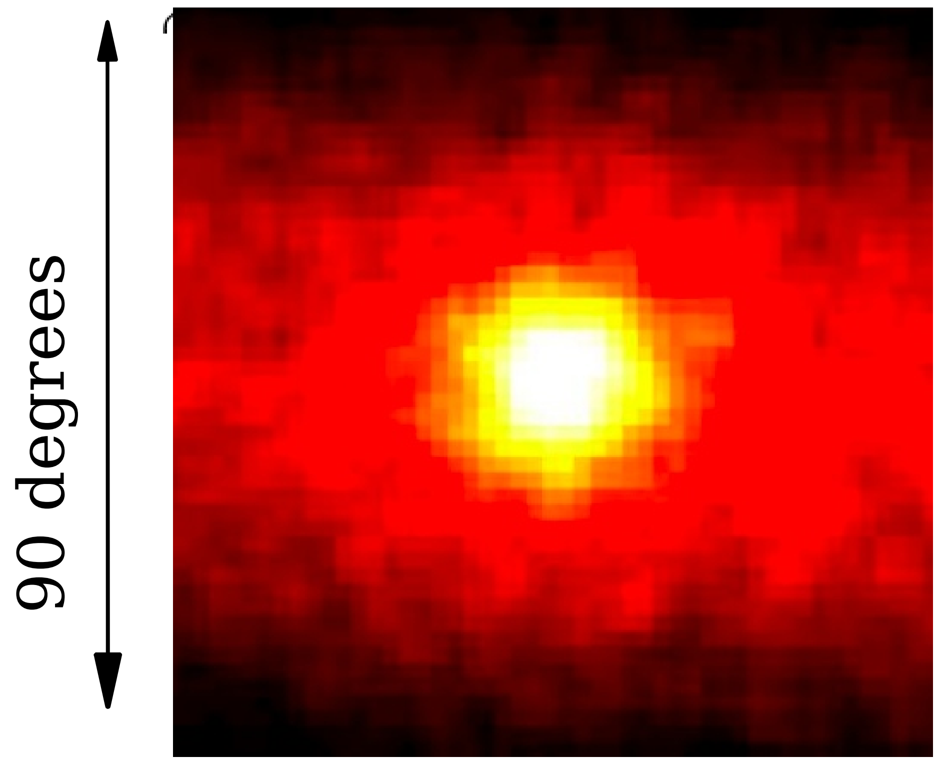
5 cm
QUARTZ SPACER
CATHODE
ARGON GAS IN ACTIVE REGION
ANODE CENTERWIRE
QUARTZ SHELL

Super Kamiokande





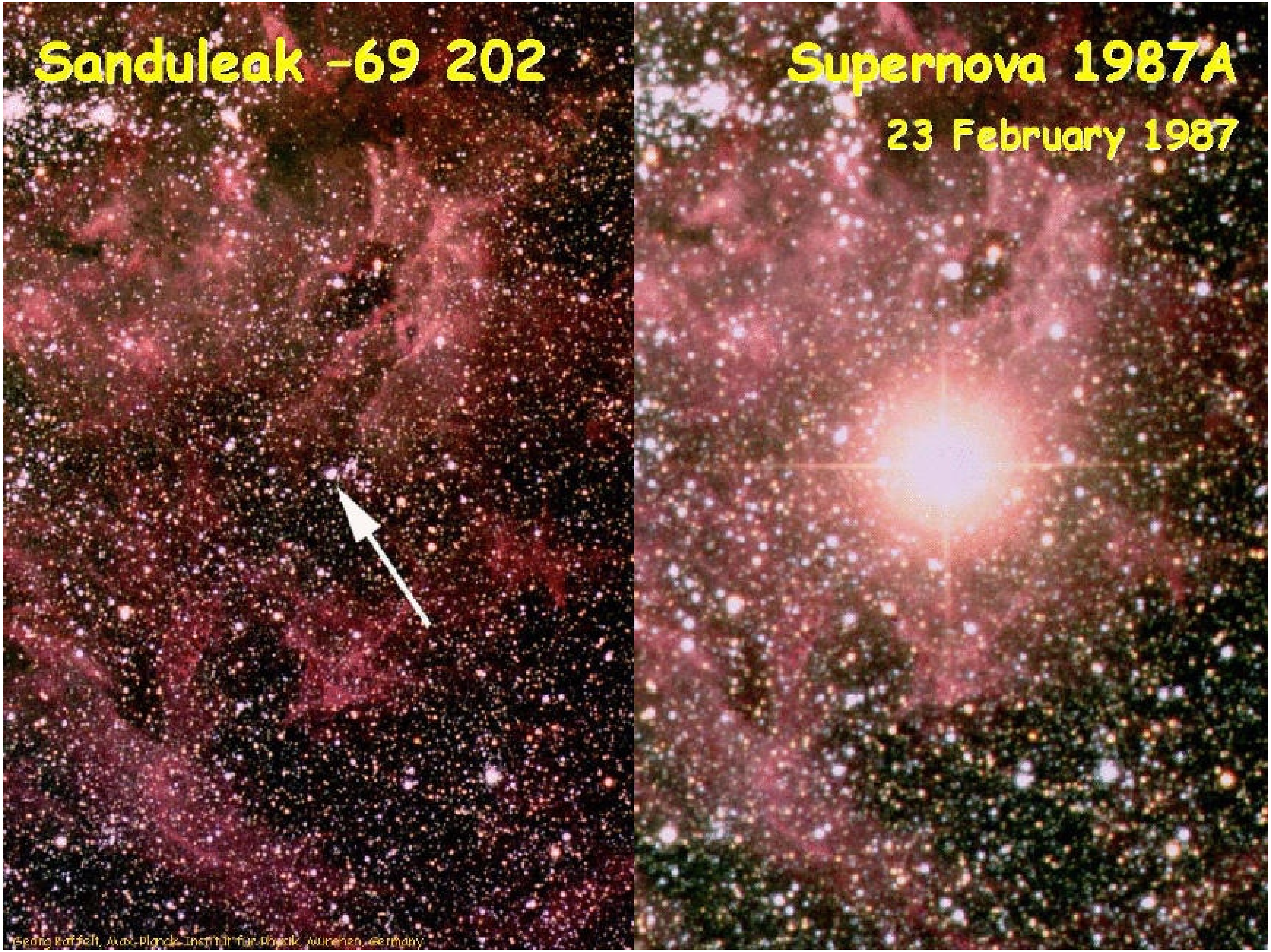
DATA/SM = 0.465± 0.015



NEUTRINOS
from
SUPERNOVAE
EXPLOSIONS
(Gravitational Collapse)

Energy 30 MeV

Neutrinos from Supernovae

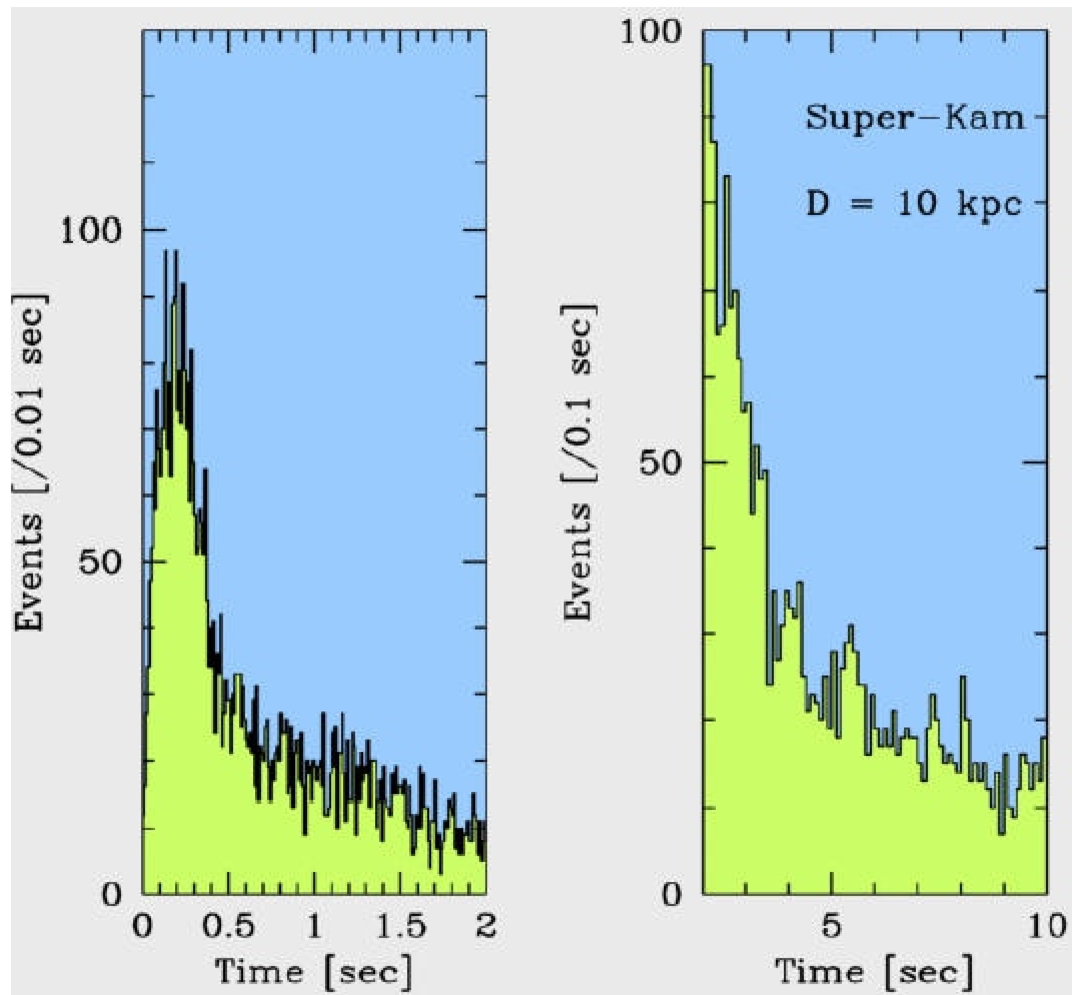


23 february 1987

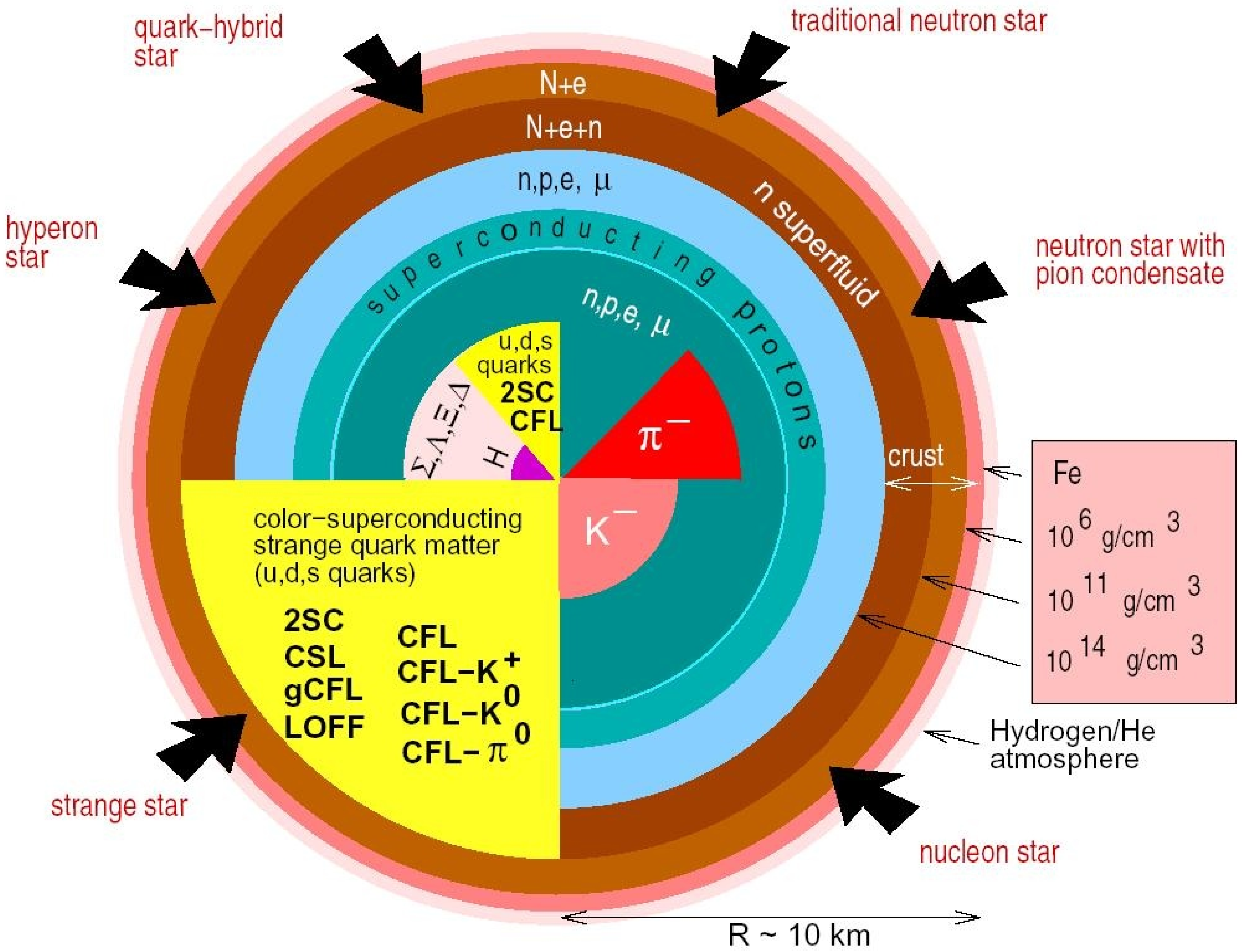
…. 24 years ago …….

We want a new close-by
(... but not too much…..)
Gravitational Collapse
Supernova

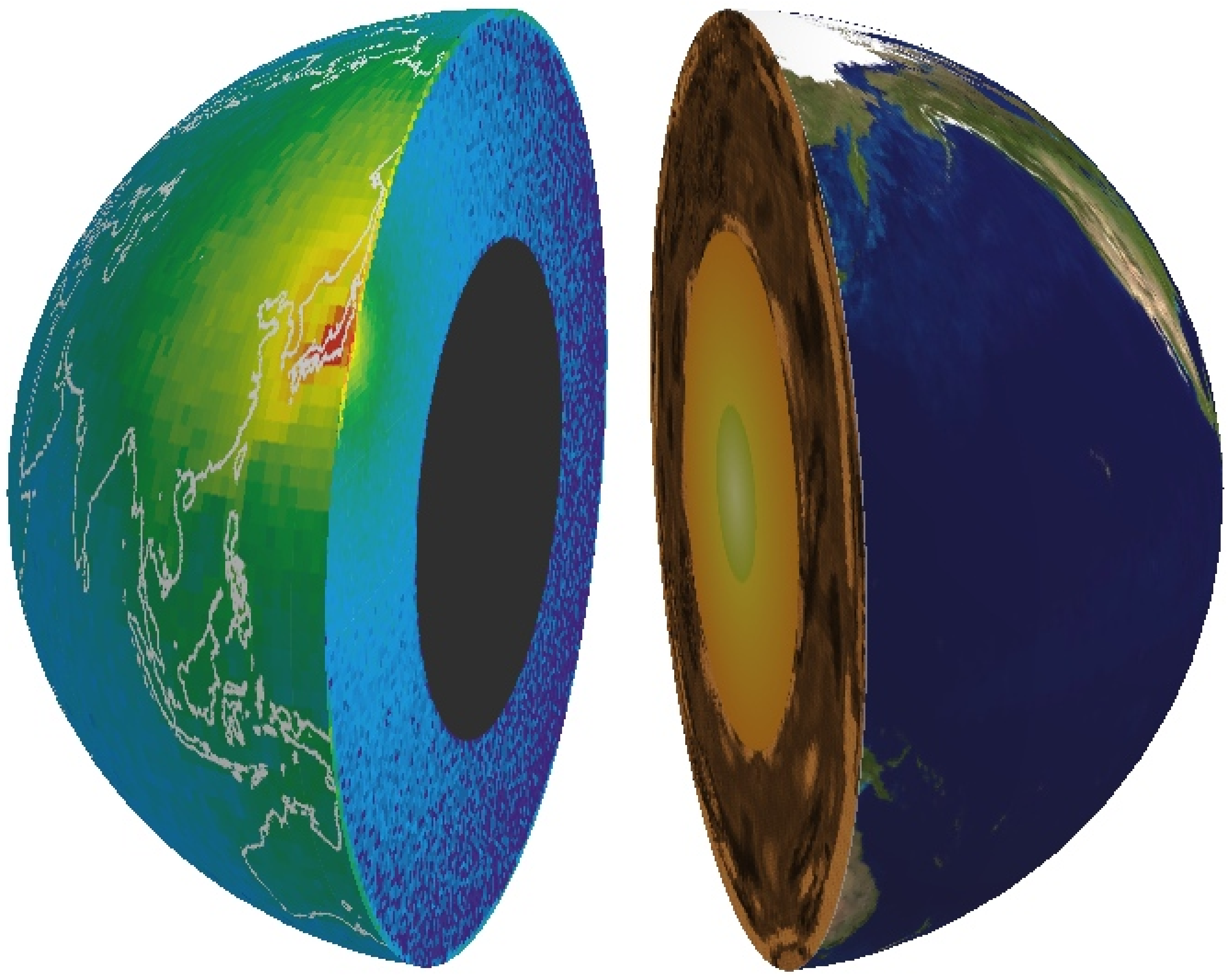
Scientific Potential
(with the new detectors)
is very important



NEUTRON STAR STRUCTURE



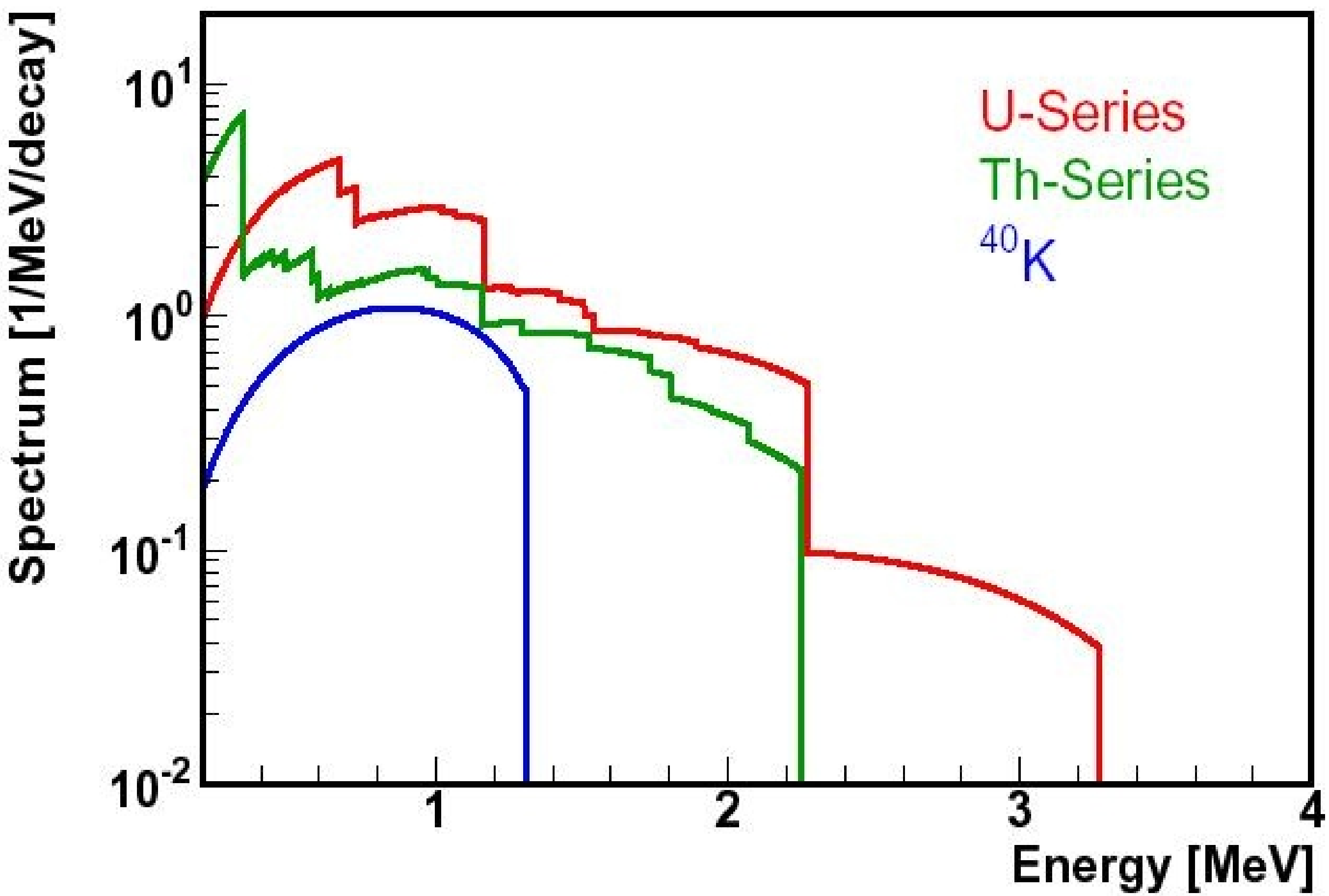
GEOPHYSICAL NEUTRINOS



$$^{238}\mathrm{U} \xrightarrow[100\%]{} {}^{206}\mathrm{Pb} + 8\,^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ [\mathrm{MeV}]$$

$$^{232}\mathrm{Th} \xrightarrow[100\%]{} {}^{208}\mathrm{Pb} + 6\,^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 42.7\ [\mathrm{MeV}]$$

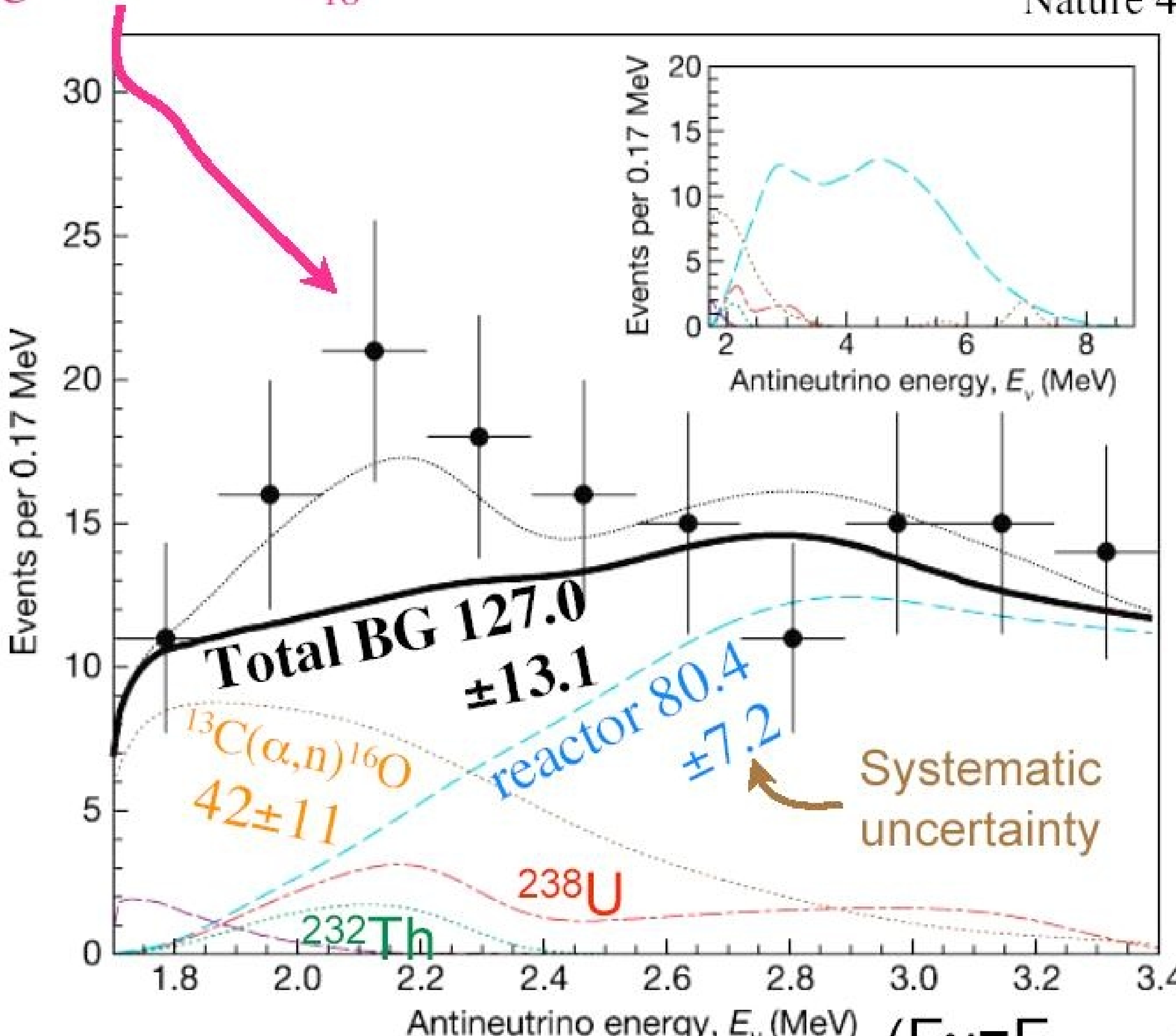
$$^{40}\mathrm{K} \xrightarrow[89.28\%]{} {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.311\ [\mathrm{MeV}]$$



Geoneutrino results

152 events observed
"signal" 25 $^{+19}_{-18}$

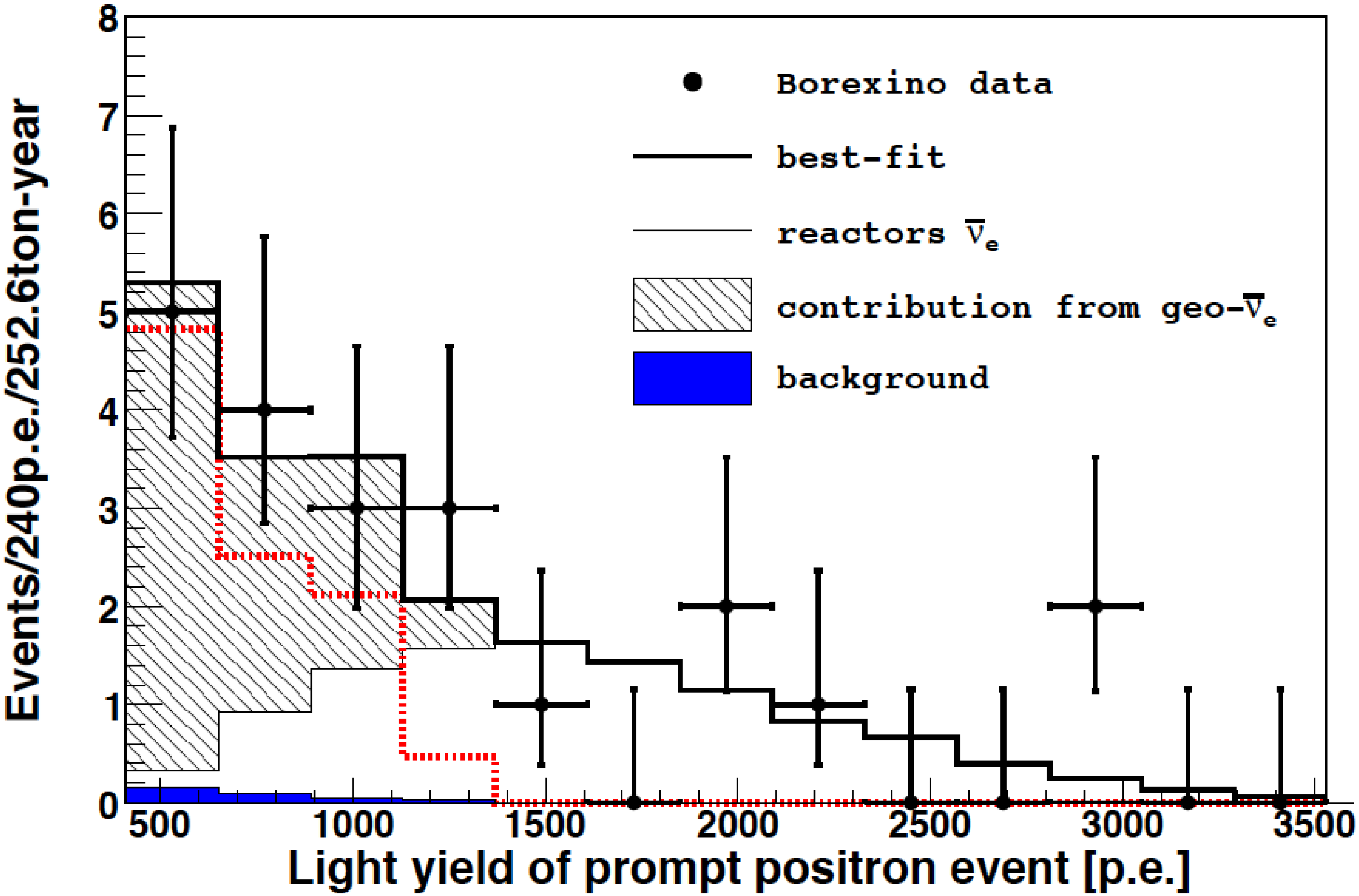
Nature 436, 28 July 2005



Data-set:
749.1 days
(Mar. 9, 2002
-Oct. 30, 2004)

Fiducial:
5 m radius

($E\nu = E_{prompt} + 0.8MeV$)



BOREXINO

(march 2010)

$$9.9^{+4.1}_{-3.4}$$ Events (1 sigma)

$$3.9^{+1.6}_{-1.3}(^{+5.8}_{-3.2})\ \text{events}/(100\ \text{ton}\cdot\text{yr})$$

The ORIGIN of COSMIC RAYS

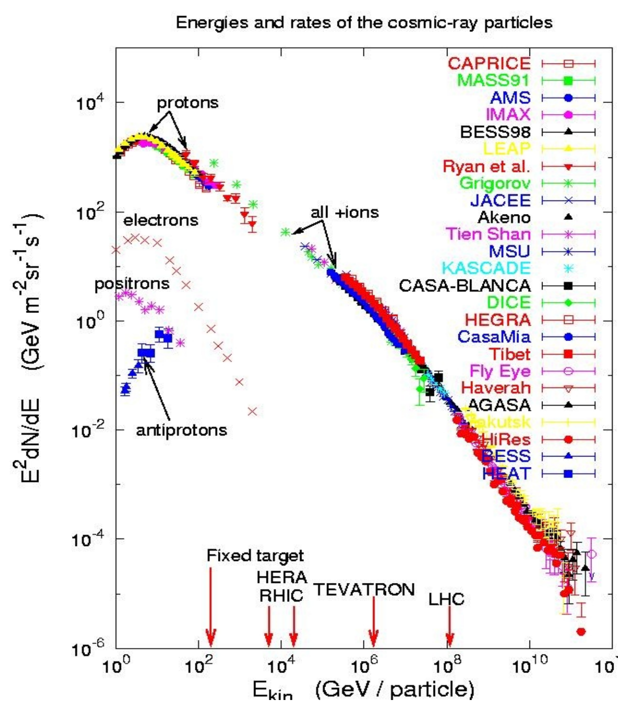
High Energy Astrophysics

COSMIC RAYS

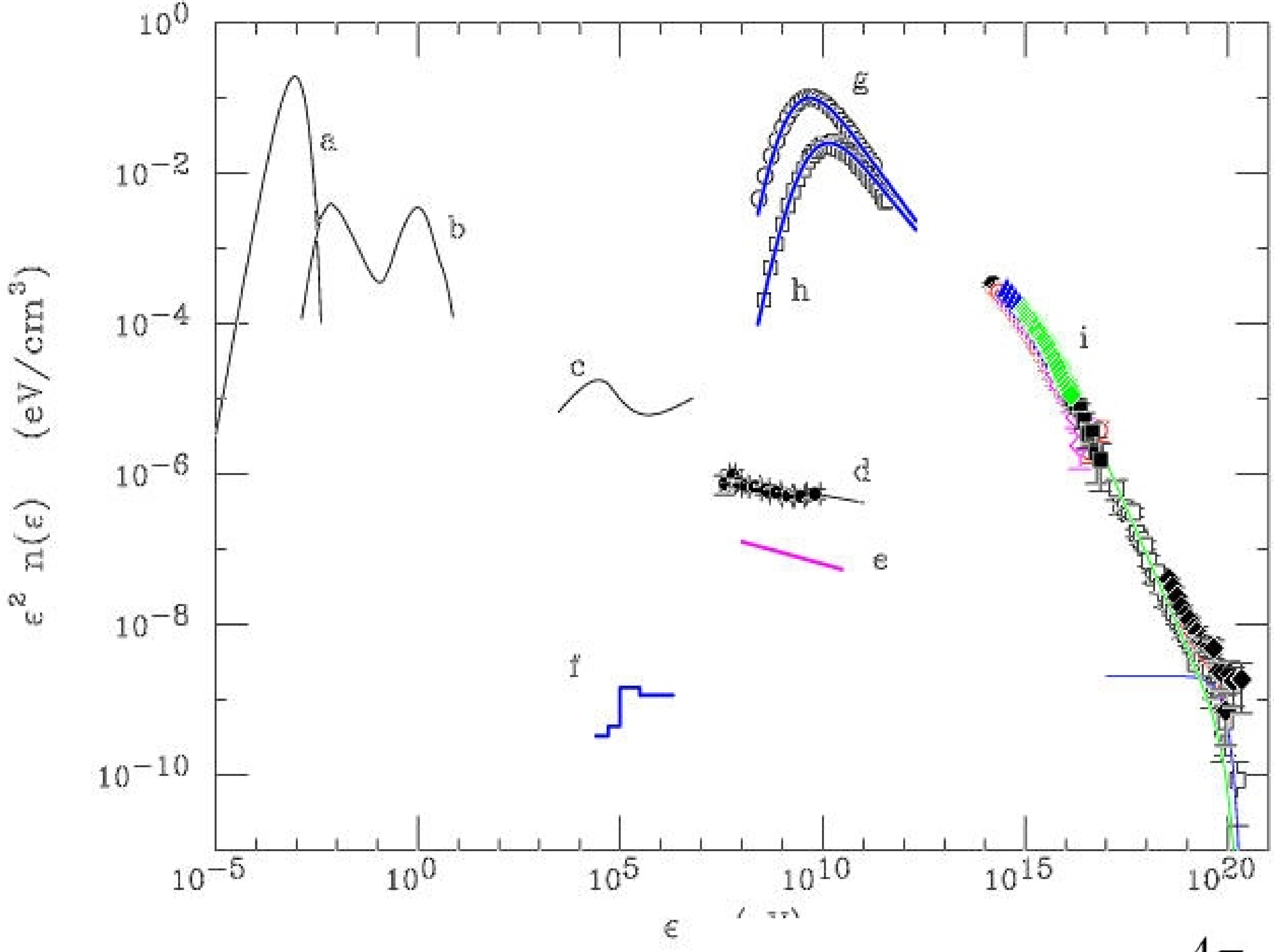
Victor Hess

before the balloon flight of 1912

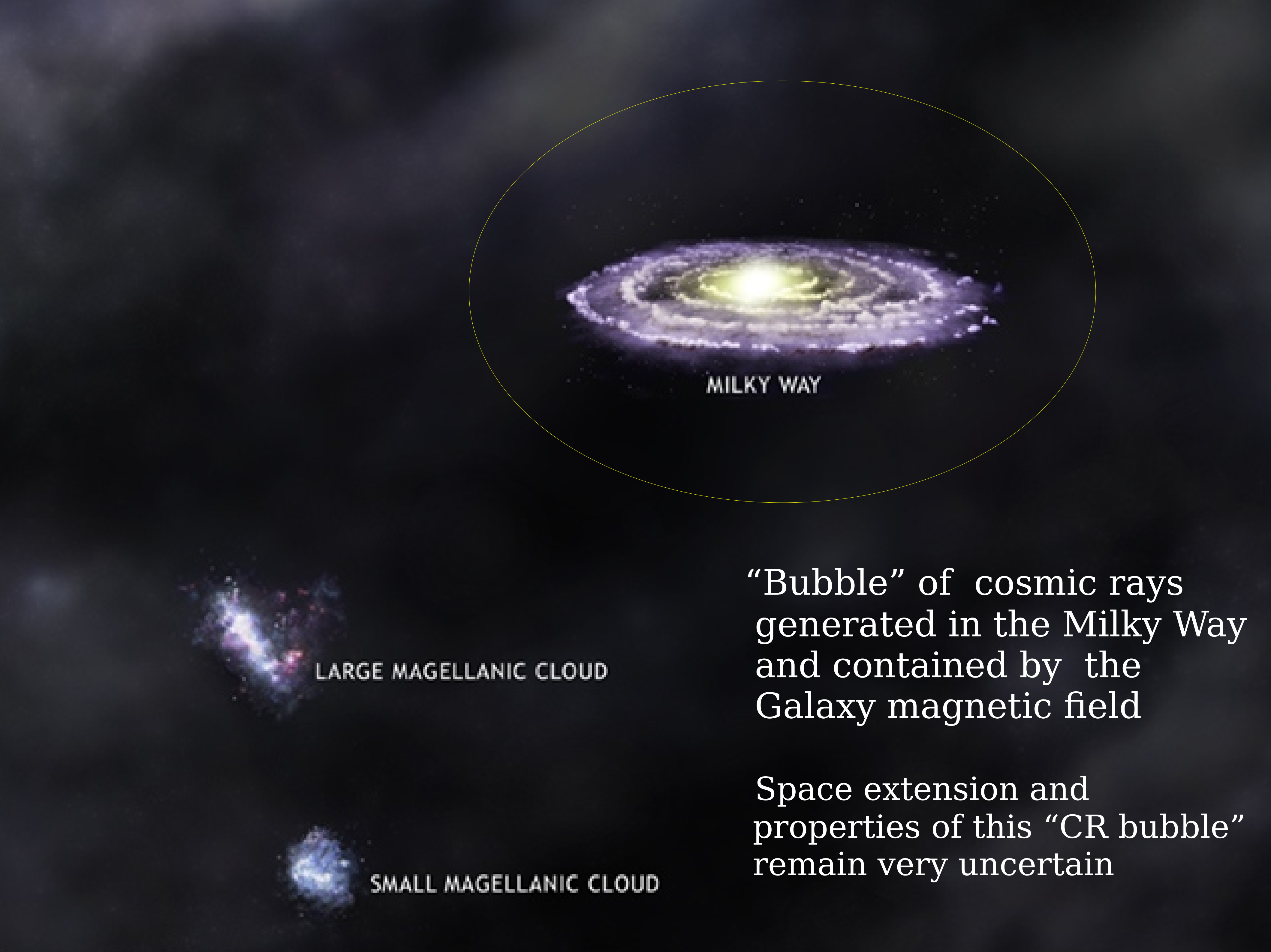
Discovery of Cosmic Rays
Beginning of
High Energy Astrophysics



Power Requirements for Cosmic Rays



$$\rho(E) = n(E)\ E = \frac{4\pi}{c}\ \phi(E)\ E$$



“Bubble” of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field

Space extension and properties of this “CR bubble” remain very uncertain

$$\phi_j(E) = \frac{c}{4\pi} n_j(E)$$

Flux of Cosmic Rays

$$N_j(E) = \int d^3x \; n_j(E, \vec{x})$$

Cosmic Rays contained
In the Milky Way

$$N_j(E) = Q_j(E) \times T_j(E)$$

$p, \quad \text{nuclei}(Z, A)$

$\overline{p}, \quad e^-, \quad e^+$

Different particles

Injection
of cosmic rays

Containment
time

Injection
of cosmic rays

Containment
time

$$N_j(E) = Q_j(E) \times T_j(E)$$

$$L_j = \int dE \; E \; Q_j(E)$$

LARGE Power
Requirement

$$\sim 5 \times 10^7 \; L_\odot$$

Spectral Shape
[Dynamics of acceleration process]

Source
Identification

Key problem!

Injection of cosmic rays

Containment time

$$N_j(E) = Q_j(E) \times T_j(E)$$

Competition of different times:

$$T_{\rm int}^{p,A}(E) \propto [\sigma_j(E)]^{-1} \sim \text{slowly varying}$$

Interaction (hadrons)

$$T_{\rm diffusion}\left(\frac{p\,c}{Z}\right) \propto \left(\frac{p\,c}{Z}\right)^{-\delta}$$

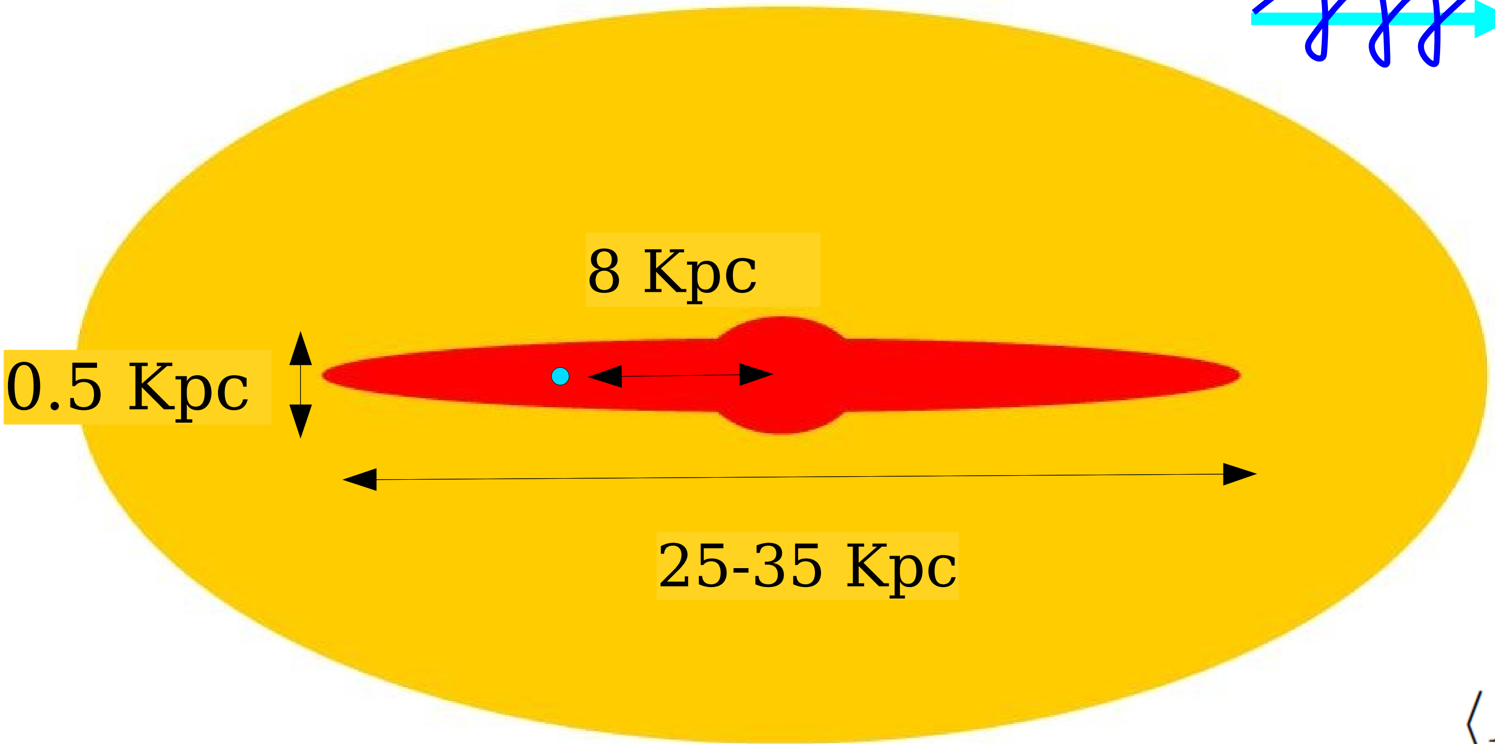
Escape from Galaxy

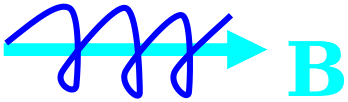
Rigidity

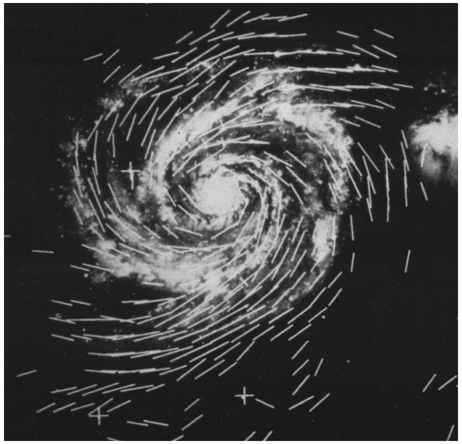
$$T_{\rm loss}^{(e^{\mp})}(E) \propto \frac{1}{E}$$

Energy losses (electrons/positrons)

m^{-4}







$$r_L = \frac{p_\perp c}{q\, B}$$

$$\langle B_{\rm MW} \rangle \simeq 3\ \mu\text{Gauss}$$

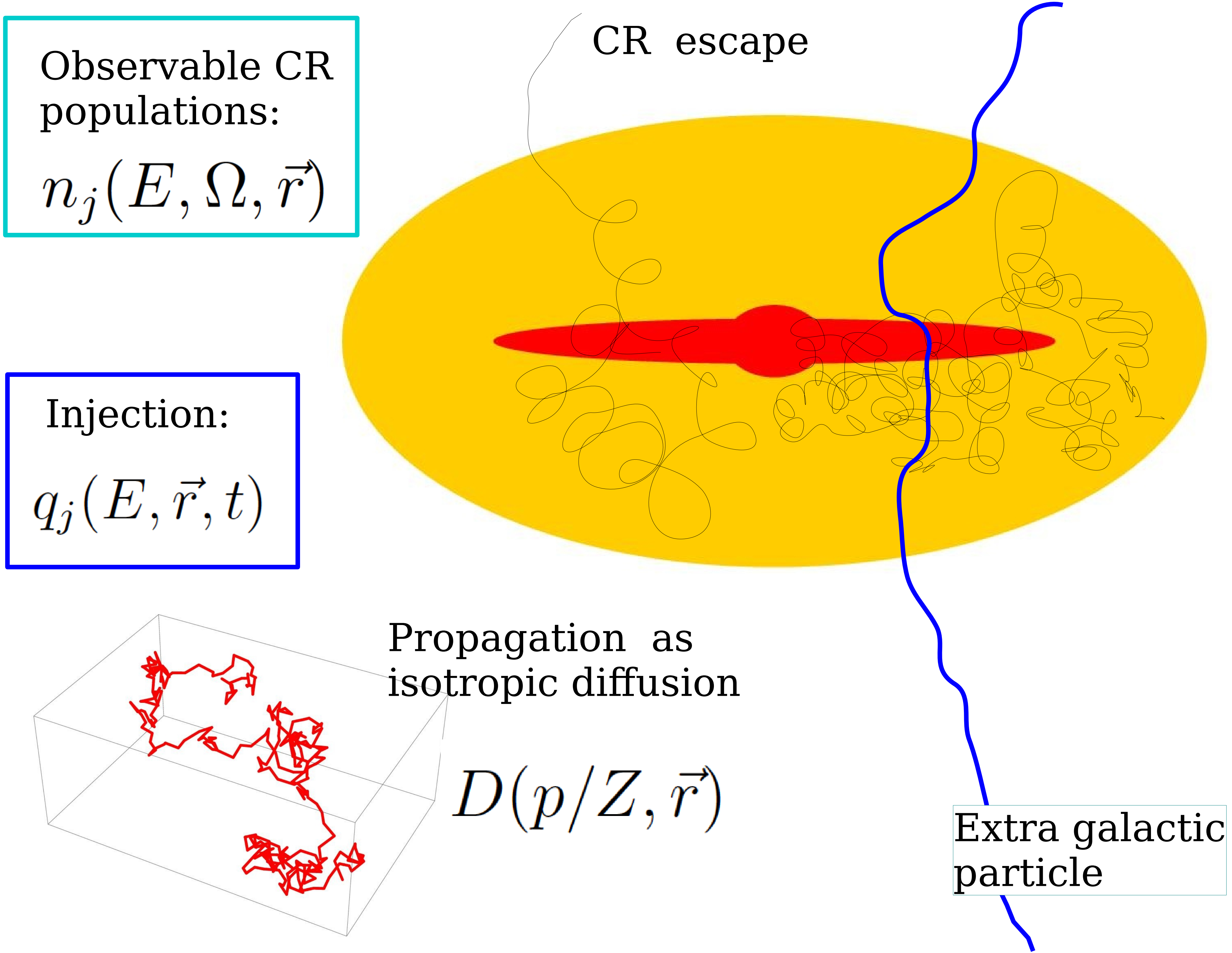
$$r_L = \frac{1.08\ \text{Kpc}}{Z} \left[\frac{E}{10^{18}\,\text{eV}}\right] \left[\frac{\mu\text{Gauss}}{B}\right]$$

$$r^p_{\rm Larmor}(100\ \text{GeV}) \simeq 3.6 \times 10^{-8}\ \text{Kpc}$$

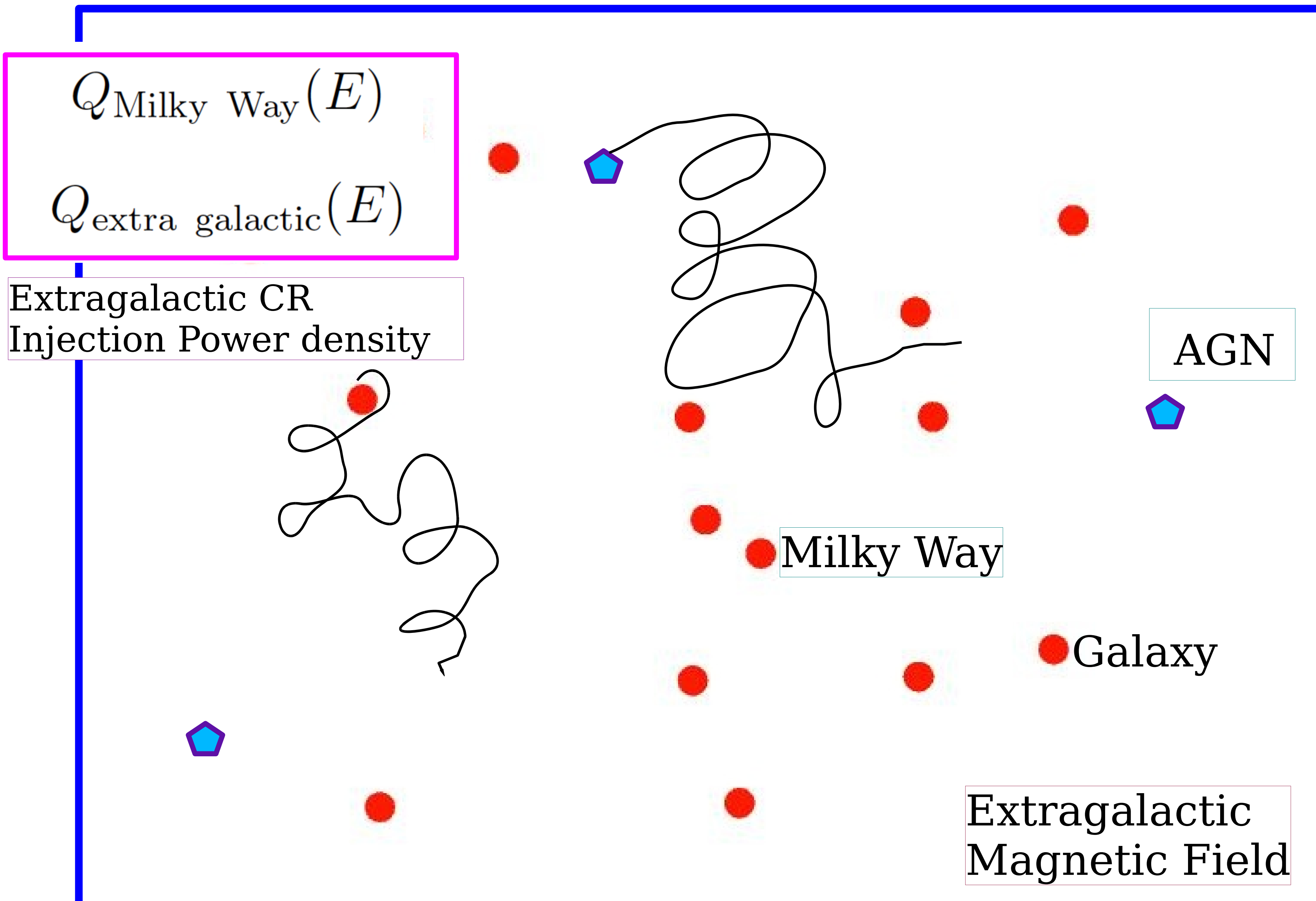
$$r^p_{\rm Larmor}(10^{20}\ \text{eV}) \simeq 36\ \text{Kpc}$$

$$r^{\rm Fe}_{\rm Larmor}(10^{20}\ \text{eV}) \simeq 1.4\ \text{Kpc}$$

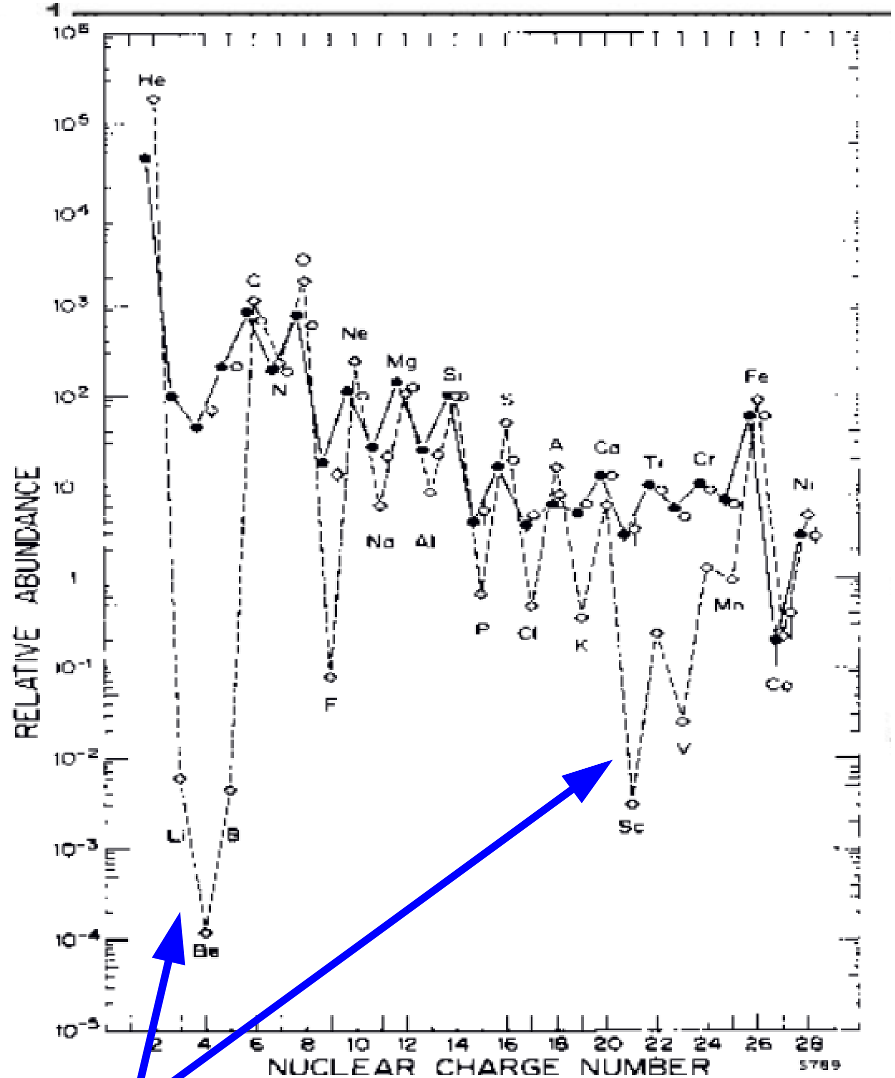
- Diffusion approximation
- Maximum energy for containment

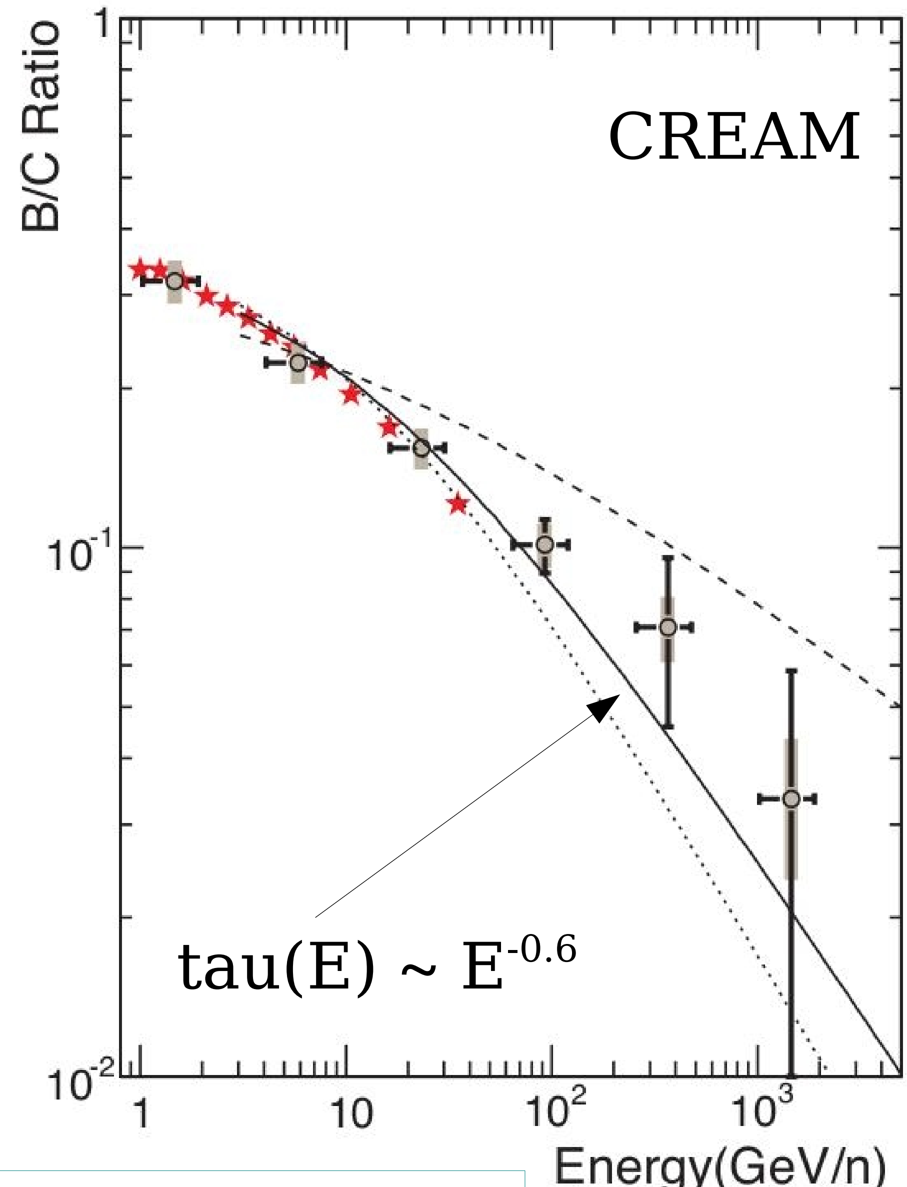

Observable CR populations:
$n_j(E, \Omega, \vec{r})$
CR escape
Injection:
$q_j(E, \vec{r}, t)$
Propagation as isotropic diffusion
$D(p/Z, \vec{r})$
Extra galactic particle

Piece of extragalactic space: Non MilkyWay-like sources



Cosmic Ray Composition





Overabundance of
- Li, Be, B
- Sub-iron elements

Atomic clocks [Be-10]

$$n_p(E) = Q_p(E) \times T_p^{\rm esc}(E)$$

$$n_p(E) = \frac{4\,\pi}{c}\,\phi_p(E)$$

$$n_p(E) \propto E^{-2.7}$$

$$T_p^{\rm esc}(E) \propto E^{-0.6}$$

$$Q_p(E) \propto E^{-2.1}$$

"Injection Spectrum"

Spectrum at accelerator

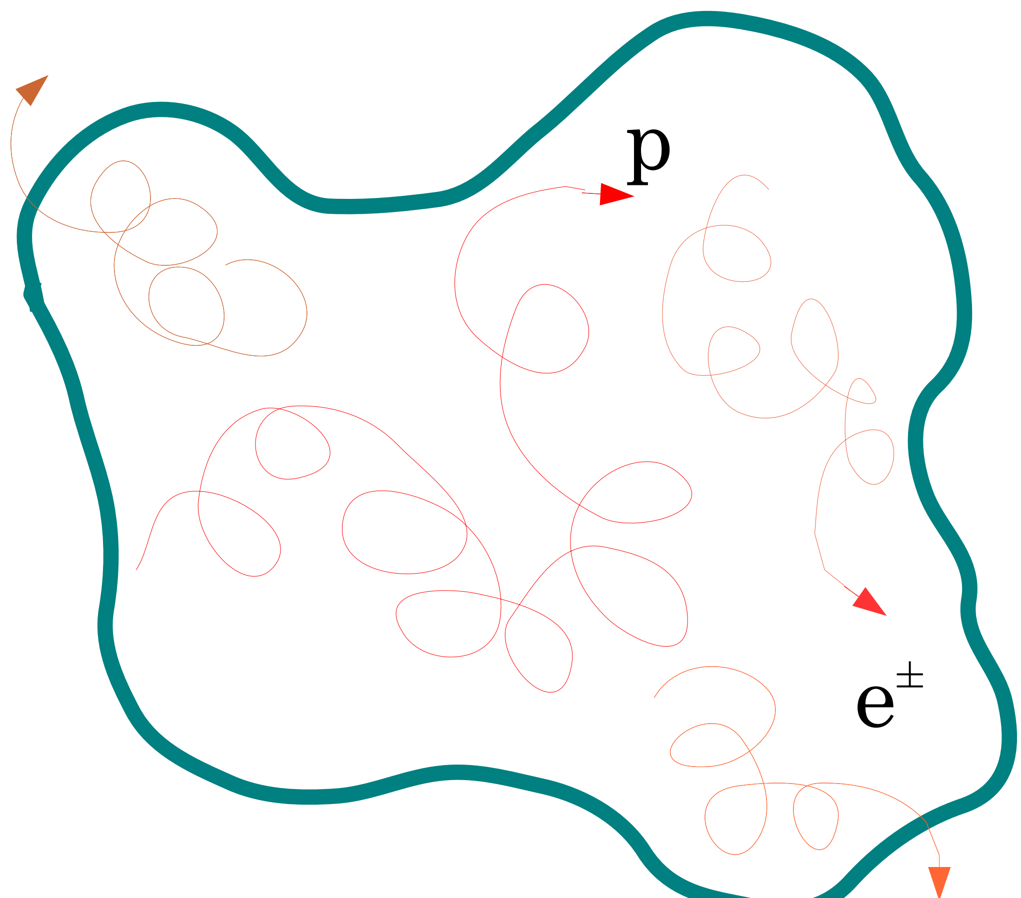
Intimate Relation between :

Cosmic Ray Physics

High Energy Gamma Astronomy

Neutrino Astronomy

“ASTROPHYSICAL” NEUTRINOS



Astrophysical Object containing:

Populations of relativistic protons, Nuclei electrons/positrons

Emission of:

Γαμμα rays

Neutrinos

Cosmic Rays

$$p + \text{target} \rightarrow \text{many particles}$$

$$\rightarrow p(n) + \pi^{+} + \pi^{-} + \pi^{\circ}$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

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

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

"Hadronic Emission"

$$e^{\mp} + B \rightarrow e^{\mp} + \gamma_{\text{synchrotron}}$$

$$e^{\mp} + \gamma_{\text{soft}} \rightarrow e^{\mp} + \gamma_{\text{Inverse Compton}}$$

"Leptonic Emission"

Estimate for astrophysical neutrino sources

2 "guides"

Multi-wavelength observations of astrophysical objects
Hypothesis [or guesses ...] of their structure
ENERGETICS, DYNAMICS

SNR
AGN
GRB

Leading candidates

Existence of Cosmic Rays !
Some sources at some level MUST exist

UHECR
Neutrino
"connection"

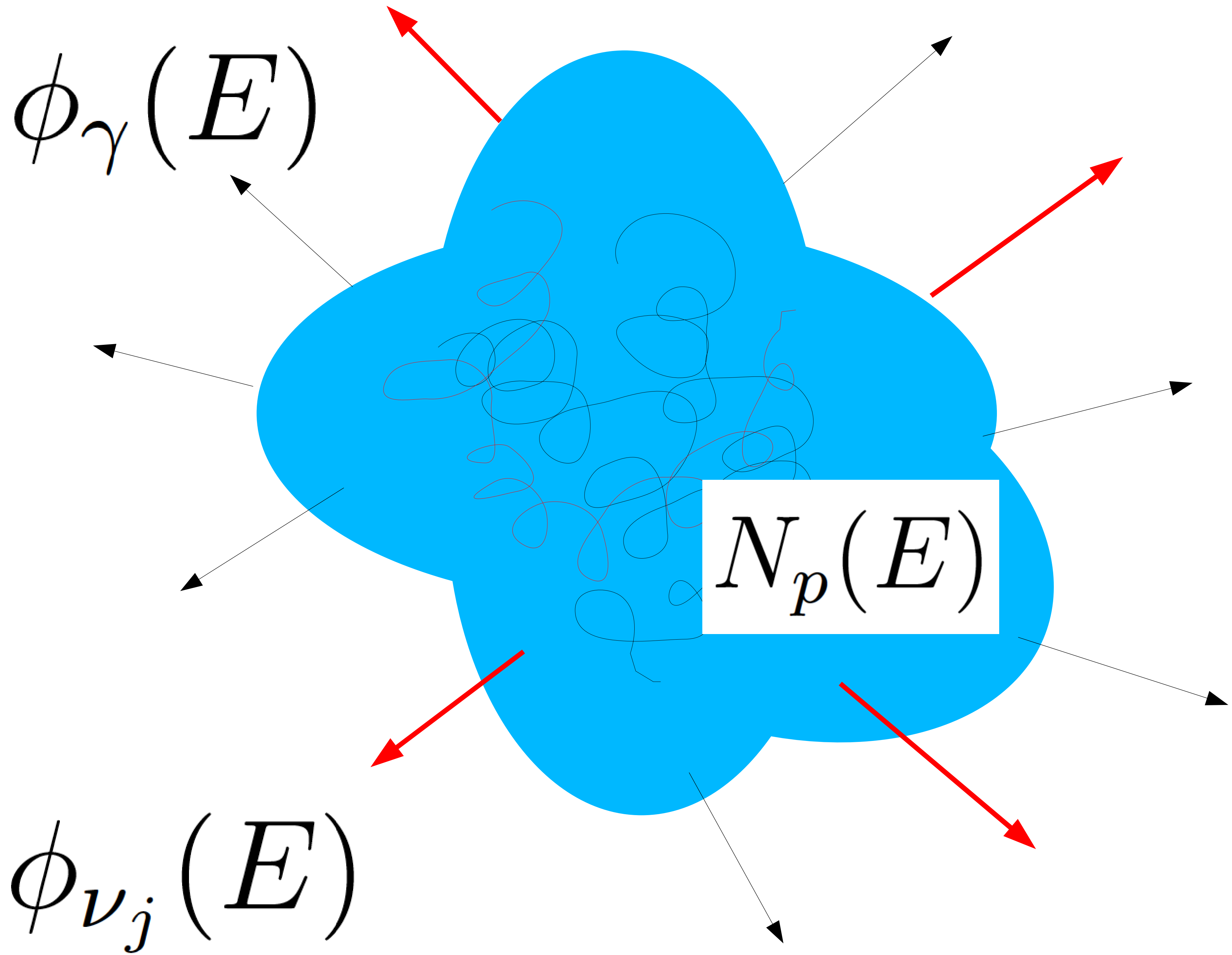
Relation between

PHOTONS and NEUTRINOS

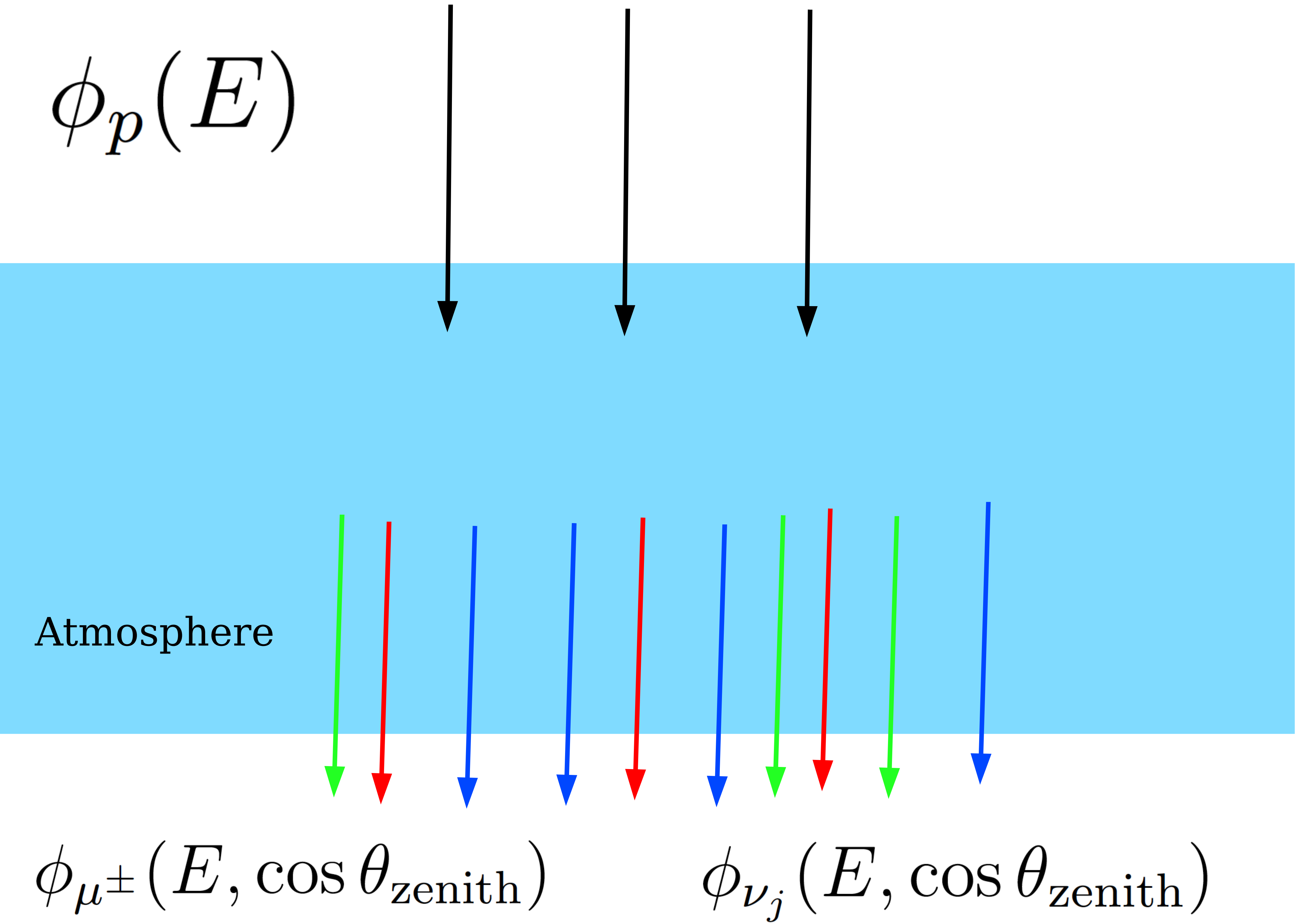
Assuming HADRONIC production for the photons:

In the absence of photon absorption

One Photon $\cong$ One Neutrino



$\phi_\gamma(E)$
$N_p(E)$
$\phi_{\nu_j}(E)$



$\phi_p(E)$
Atmosphere
$\phi_{\mu^\pm}(E, \cos\theta_{\mathrm{zenith}})$
$\phi_{\nu_j}(E, \cos\theta_{\mathrm{zenith}})$

Relation between:

- Cosmic Rays in the source
- Photon, Neutrino Flux

$$N_p(E) \simeq K\, E^{-\alpha}$$

Power law
c.r. population

Photon, neutrino fluxes also power law with same esponent

$$\phi_{\nu_j}(E) \simeq K\, E^{-\alpha} \times [\sigma_{pp}\, c\, n_{\rm target}] \times Z_{p\nu_j}(\alpha)$$

$$\phi_{\gamma}(E) \simeq K\, E^{-\alpha} \times [\sigma_{pp}\, c\, n_{\rm target}] \times Z_{p\gamma}(\alpha)$$

Number of particles of type b (with energy Eb)
Produced in the interaction of projectile particle
of type a (and energy Ea)

[Approximate scaling form]

$$\frac{dn_{a\to b}}{dE_b}(E_b; E_a) \simeq \frac{1}{E_a}\ F_{a\to b}\left(\frac{E_b}{E_a}\right)$$

Definition of the Z-factor

$$Z_{a\to b}(\alpha) = \int_0^1 dz\ z^{\alpha-1}\ F_{a\to b}(z)$$

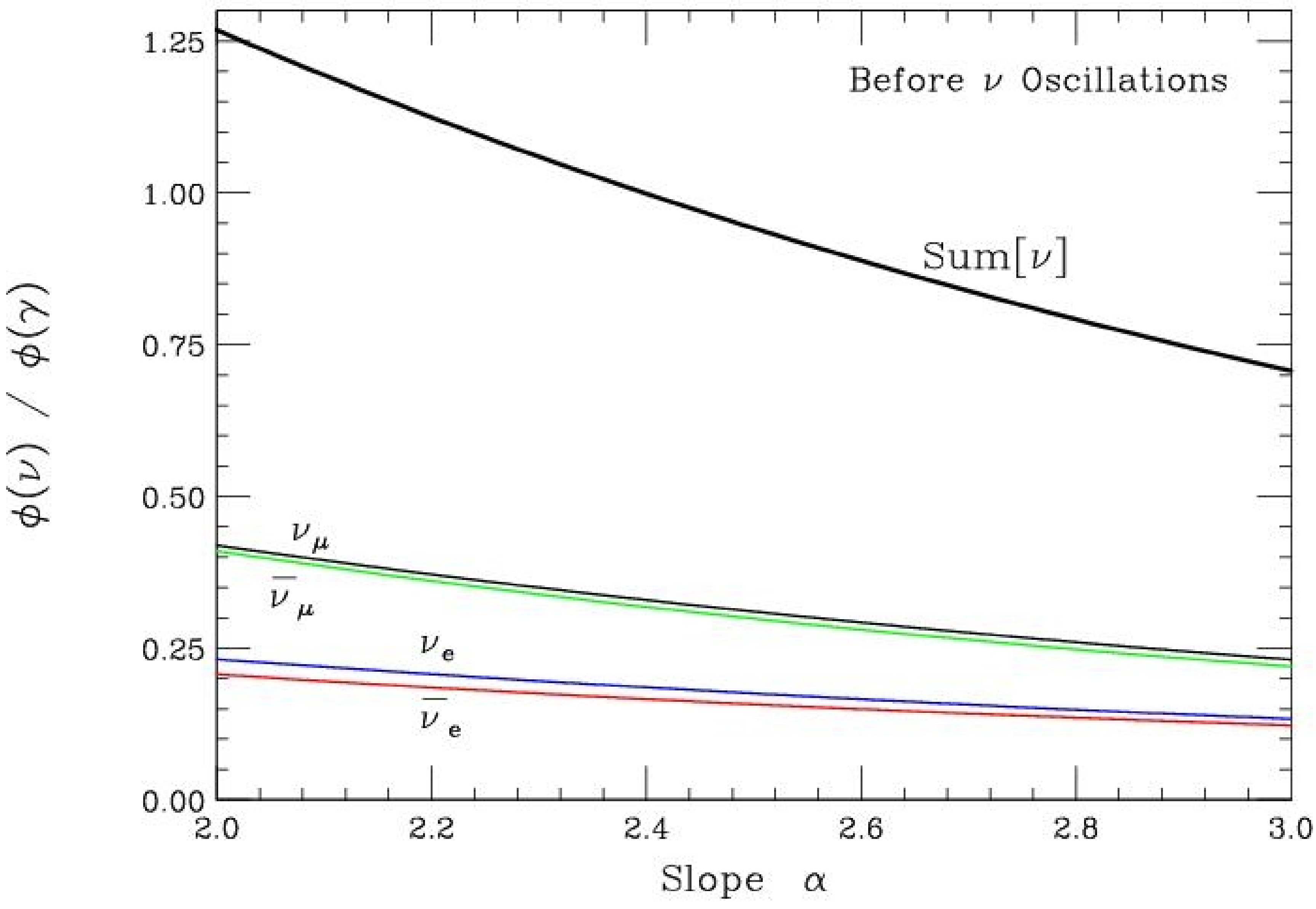
$$\phi_\pi(E_\pi) = \int_{E_\pi}^{\infty} dE_p \; \phi_p(E_p) \; \frac{dn_{p\to\pi}}{dE_\pi}(E_\pi, E_p)$$

$$= \int_{E_\pi}^{\infty} dE_p \; \left(K \; E_p^{-\alpha}\right) \; \frac{1}{E_p} \; F_{p\to\pi}\left(\frac{E_\pi}{E_0}\right)$$

$$= K \; E_\pi^{-\alpha} \; \boxed{\int_0^1 dz \; z^{\alpha-1} \; F_{p\to\pi}(z)}$$

$$= K \; \boxed{Z_{p\to\pi}(\alpha)} \; E_\pi^{-\alpha}$$

Ratio Neutrino-Photon $\phi(\nu)\ /\ \phi(\gamma)$



$$\{\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau\} \simeq \{1+\epsilon, 1-\epsilon, 2, 2, 0, 0\}$$

$$
\begin{aligned}
P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) &= \left| \sum_j U_{\beta j} U^*_{\alpha j} \; e^{-i\, m_j^2 \frac{L}{2E_\nu}} \right|^2 \\
&= \sum_{j=1,3} |U_{\beta j}|^2 \; |U_{\alpha j}|^2 \\
&+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \cos\left(\frac{\Delta m^2_{jk}\, L}{2E} \right) \\
&+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \sin\left(\frac{\Delta m^2_{jk}\, L}{2E} \right)
\end{aligned}
$$

$$
\langle P_{\nu_\alpha \to \nu_\beta} \rangle = \begin{pmatrix} 1-2v & v & v \\ v & (1-v)/2 & (1-v)/2 \\ v & (1-v)/2 & (1-v)/2 \end{pmatrix} \simeq \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}
$$

$$
v = \cos^2\theta_{12} \sin^2\theta_{12} \simeq 0.2
$$

Effect of Neutrino Oscillations

$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \langle P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)\rangle = \sum_j |U_{\alpha j}|^2 \, |U_{\beta j}|^2$$

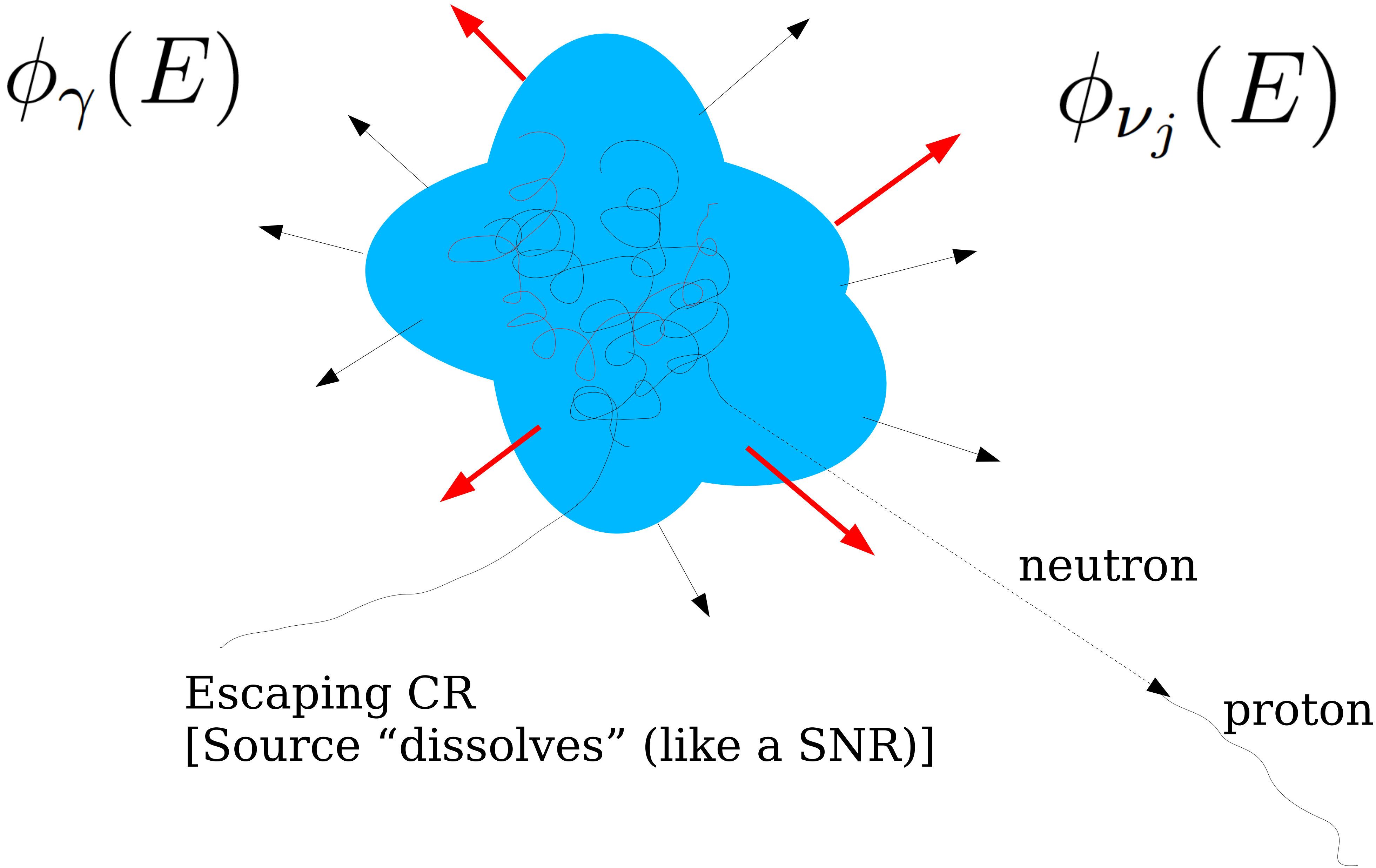
$$\simeq \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \qquad (1)$$

Before Oscillations

$$\{\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau\} \simeq \{1+\epsilon, 1-\epsilon, 2, 2, 0, 0\}$$

After Oscillations

$$\{\nu_e + \overline{\nu}_e, \nu_\mu + \overline{\nu}_\mu, \nu_\tau + \overline{\nu}_\tau\} = \{1, 1, 1\}$$



Production of Cosmic Rays Versus Neutrino/Photon spectra

$$q_\nu(E) \sim q_p(E)$$

Time averaged production rate of neutrinos
Time averaged production rate of Cosmic Rays
approximately equal

"Waxman – Bahcall Bound"

$q_p(E)$ Injection rate of extragalactic cosmic rays estimated by observation of the flux.

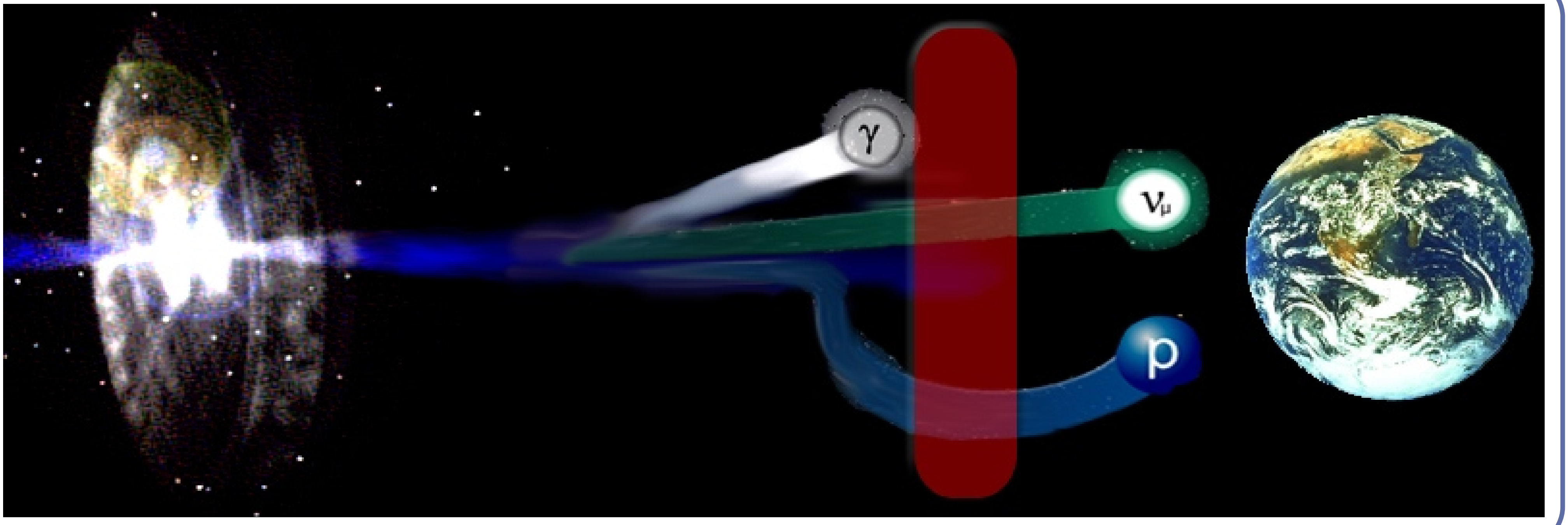
→ Estimate of the "diffuse" neutrino flux [summed over all sources]

Very direct connection with TeV Gamma Astronomy !!

A field that in the last few years has been Collecting remarkable results.

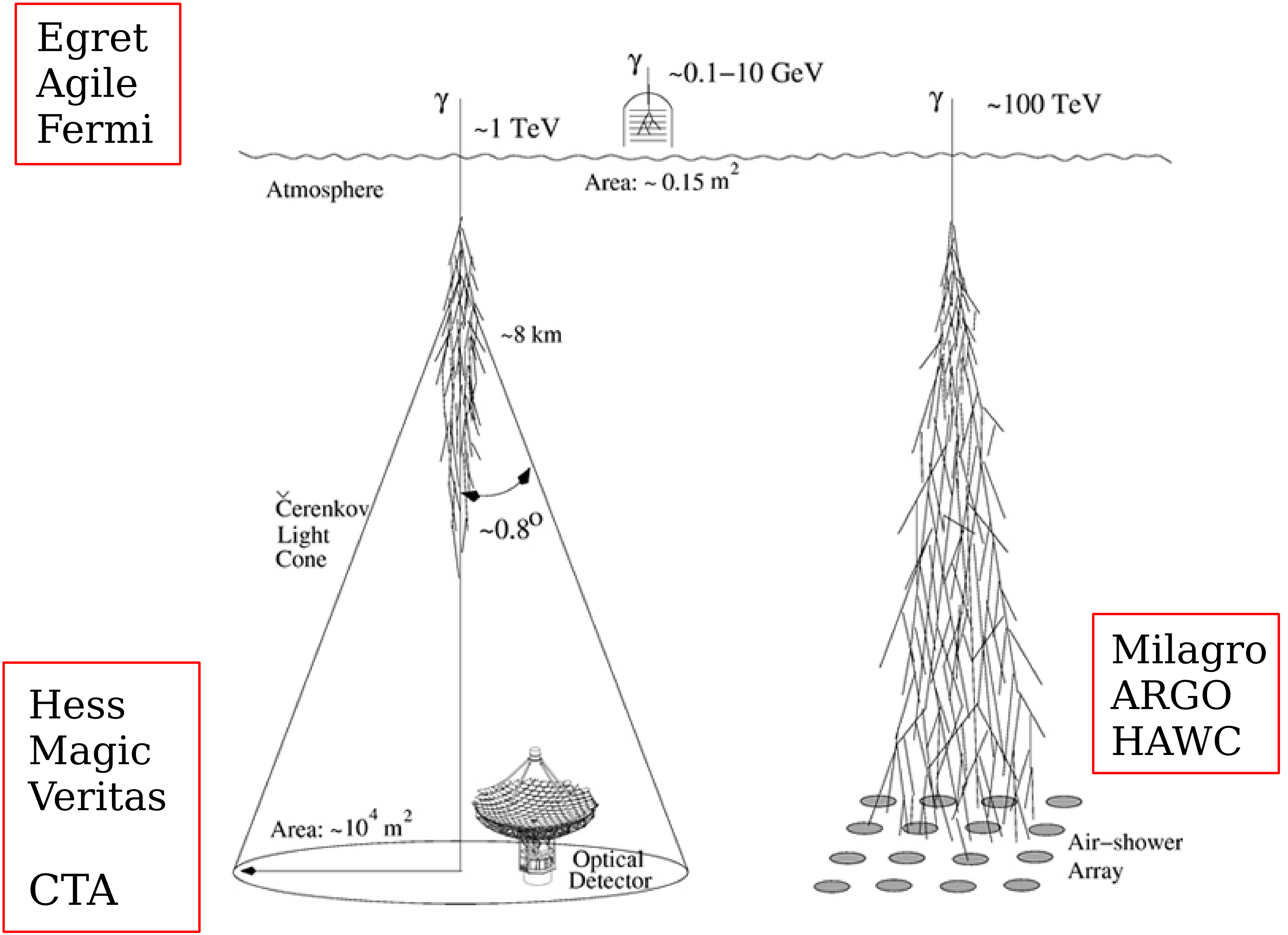
We have (HESS) a scan of the Milky Way disk !
We know which one are the brightest TeV sources
In our Galaxy, and the luminosity of these sources.

SNR
Pulsars
Pulsars Wind Nebulae
μ Quasars



Neutrino advantages :

1. Straight line propagation
2. No absorption


Egret
Agile
Fermi
γ
~1 TeV
γ
~0.1–10 GeV
γ
~100 TeV
Atmosphere
Area: ~ 0.15 m²
~8 km
Čerenkov
Light
Cone
~0.8°
Hess
Magic
Veritas
CTA
Milagro
ARGO
HAWC
Area: ~10⁴ m²
Optical
Detector
Air–shower
Array

AGILE

Piccolo Satellite italiane
ASI/INAF/INFN

Lanciato
23 aprile 2007
dalla base indiana
di Sriharikota.

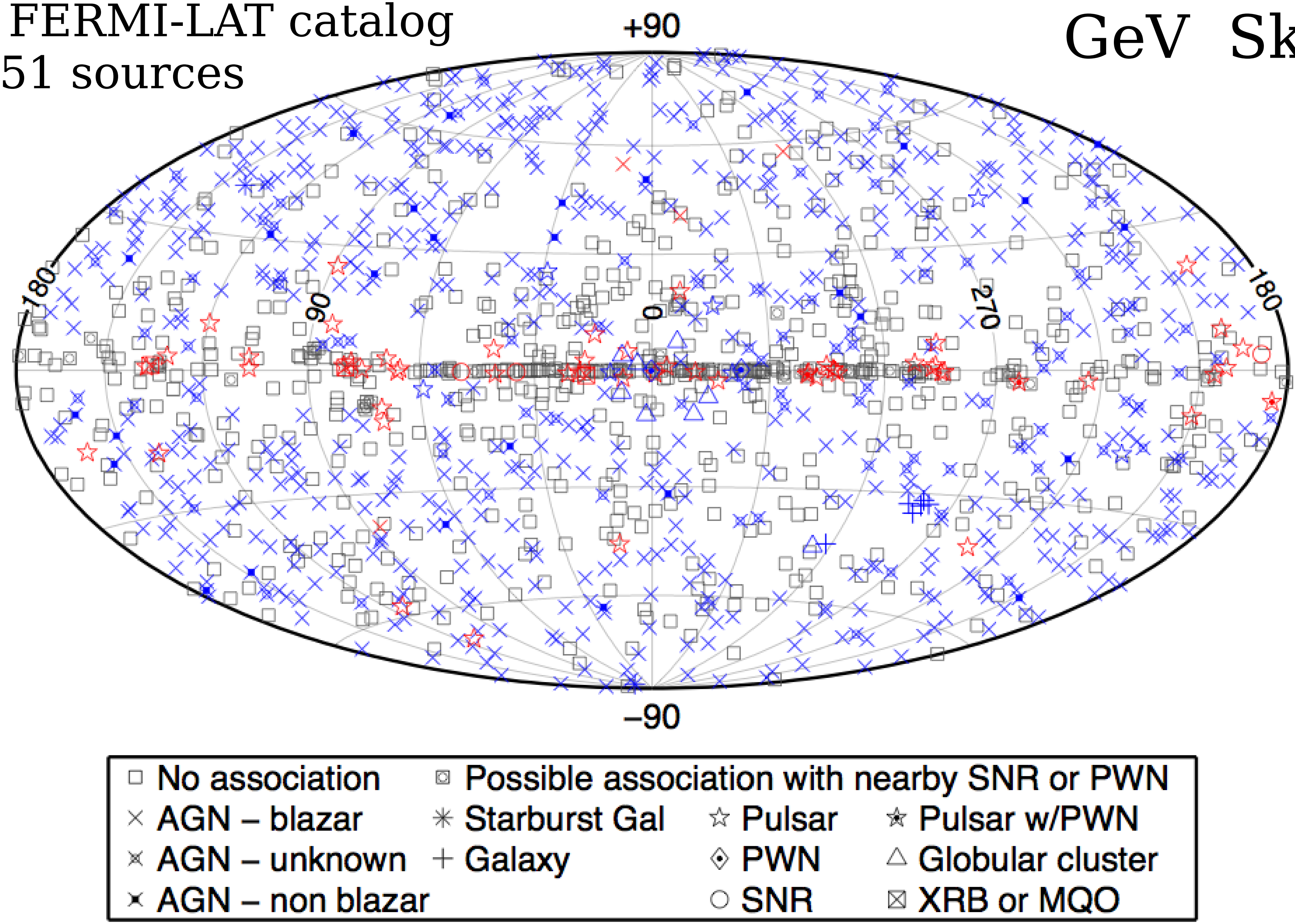
Orbita h=540 Km
inclinazione = 2.5°

Launch of (GLAST) FERMI telescope

11th june 2008

1st FERMI-LAT catalog
1451 sources

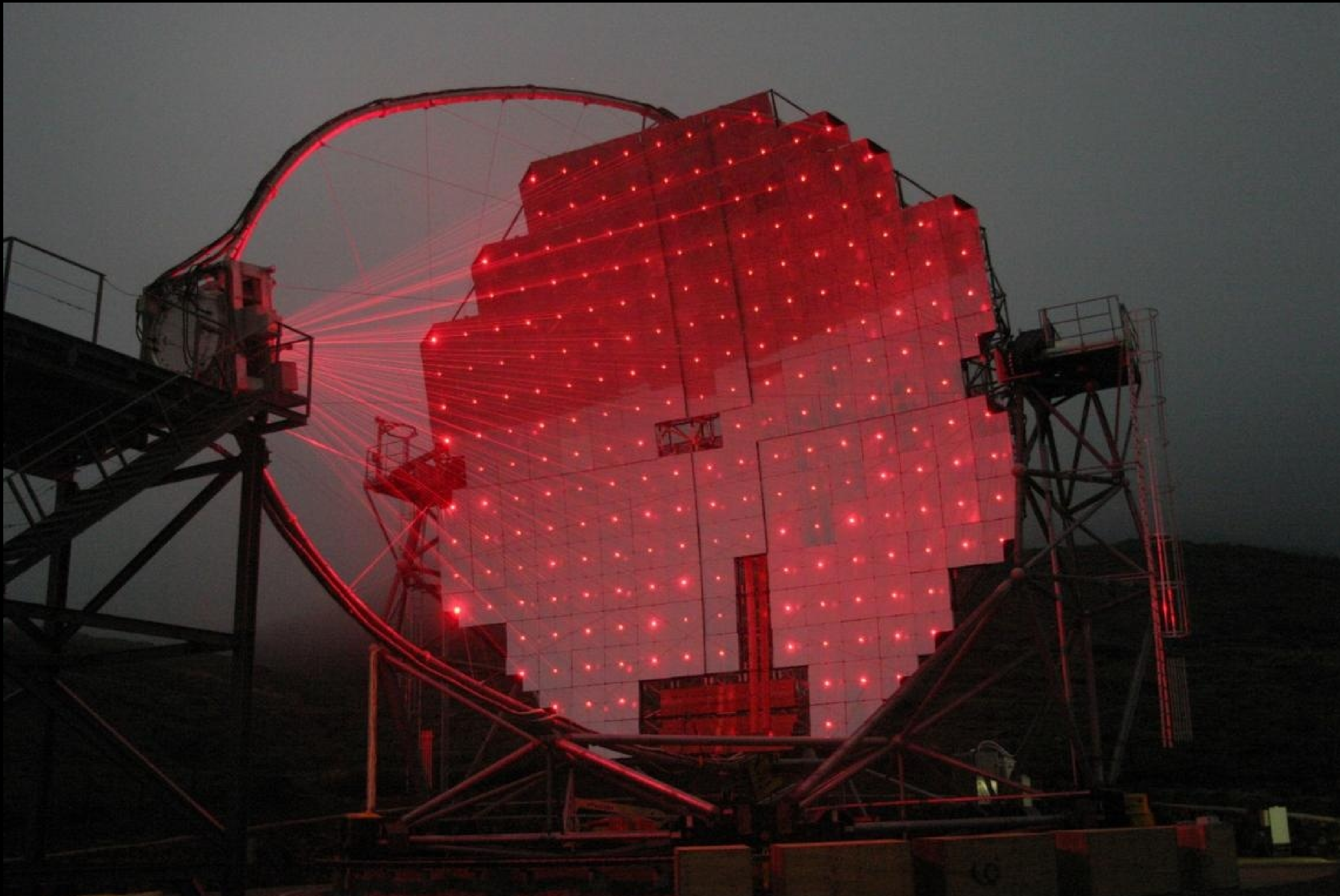
GeV Sky



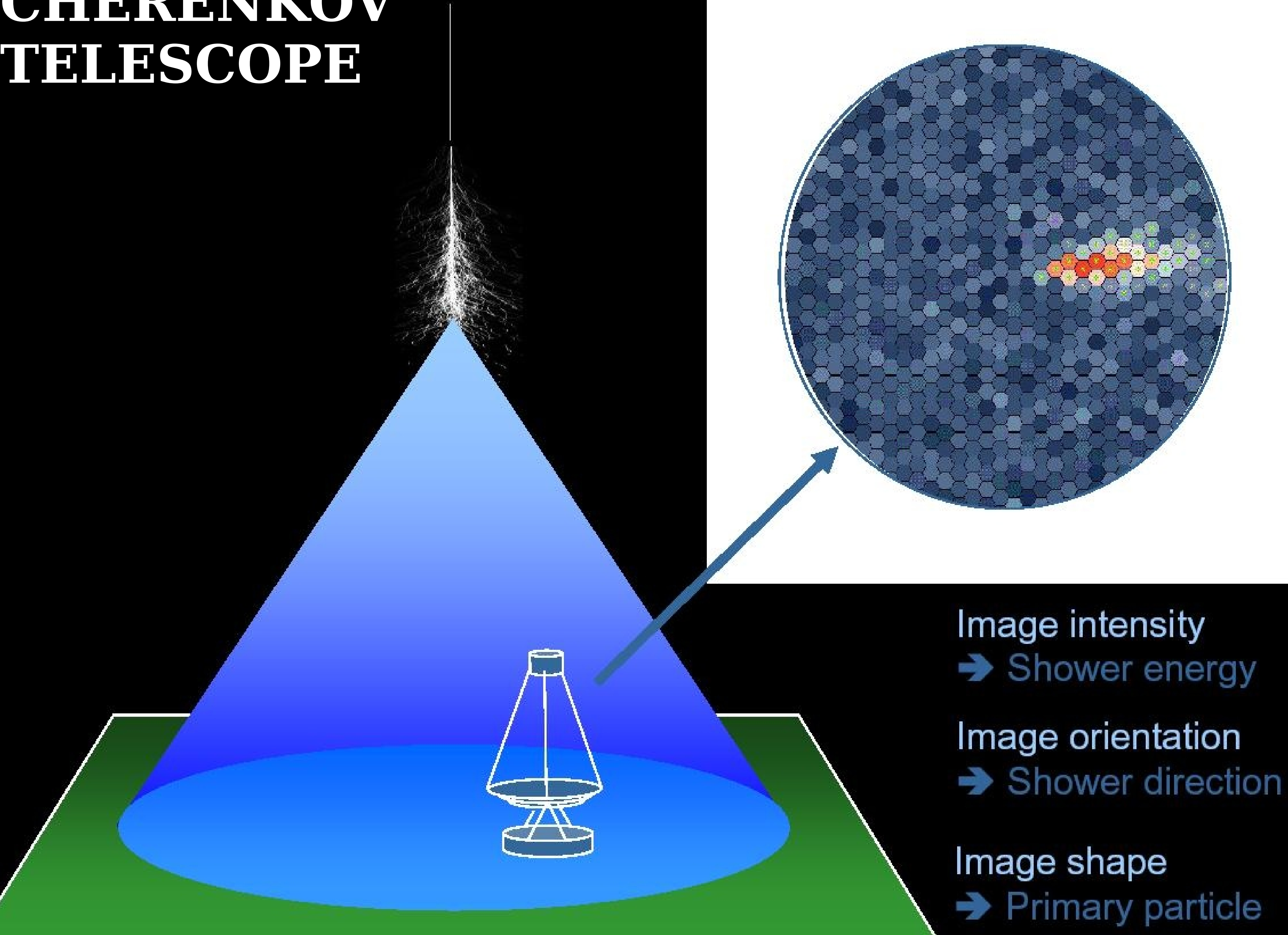
2nd catalog release imminent.

MAGIC 2 x 236 m^2

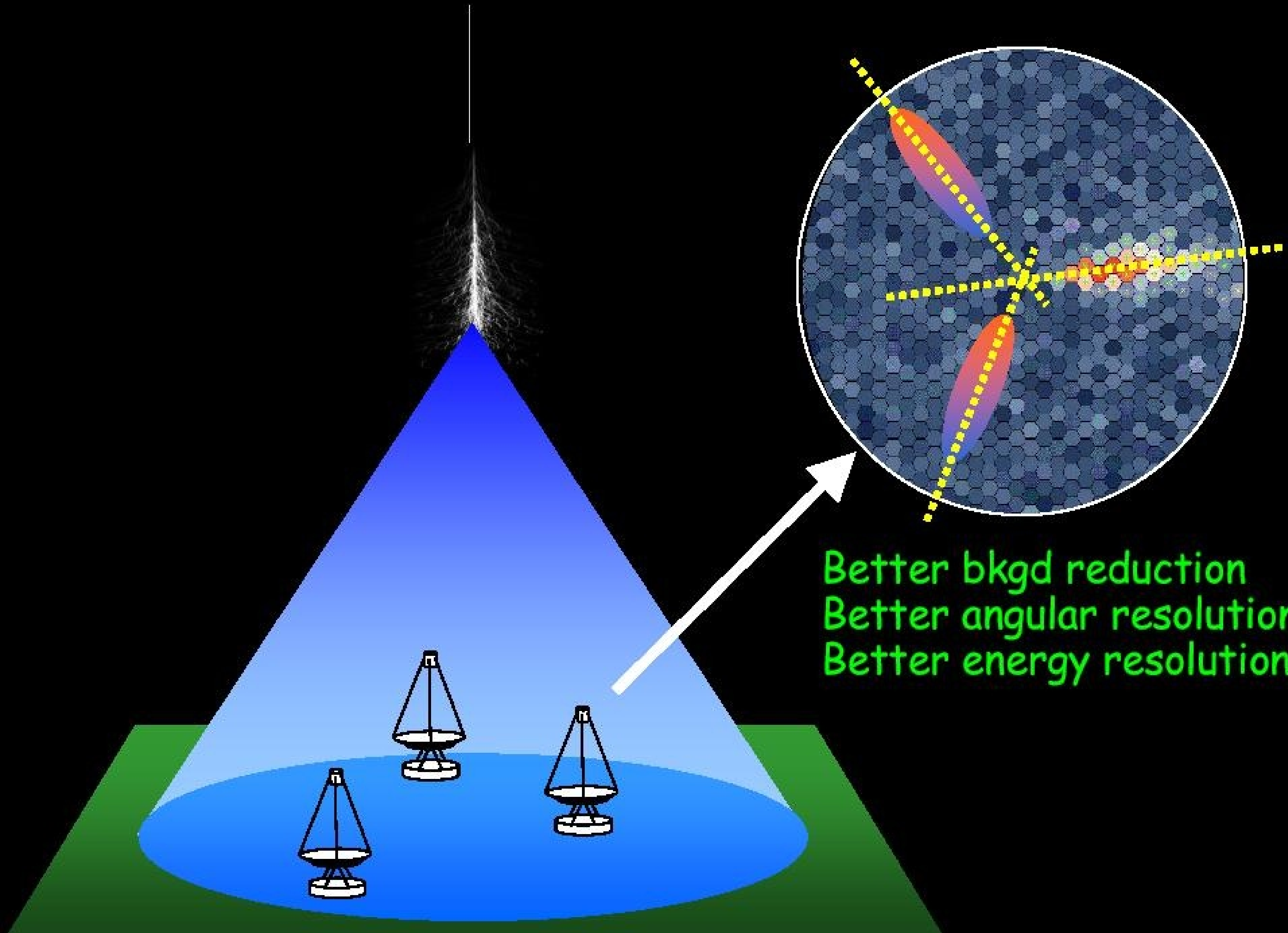
2^{nd} telescope : April 2009



CHERENKOV TELESCOPE

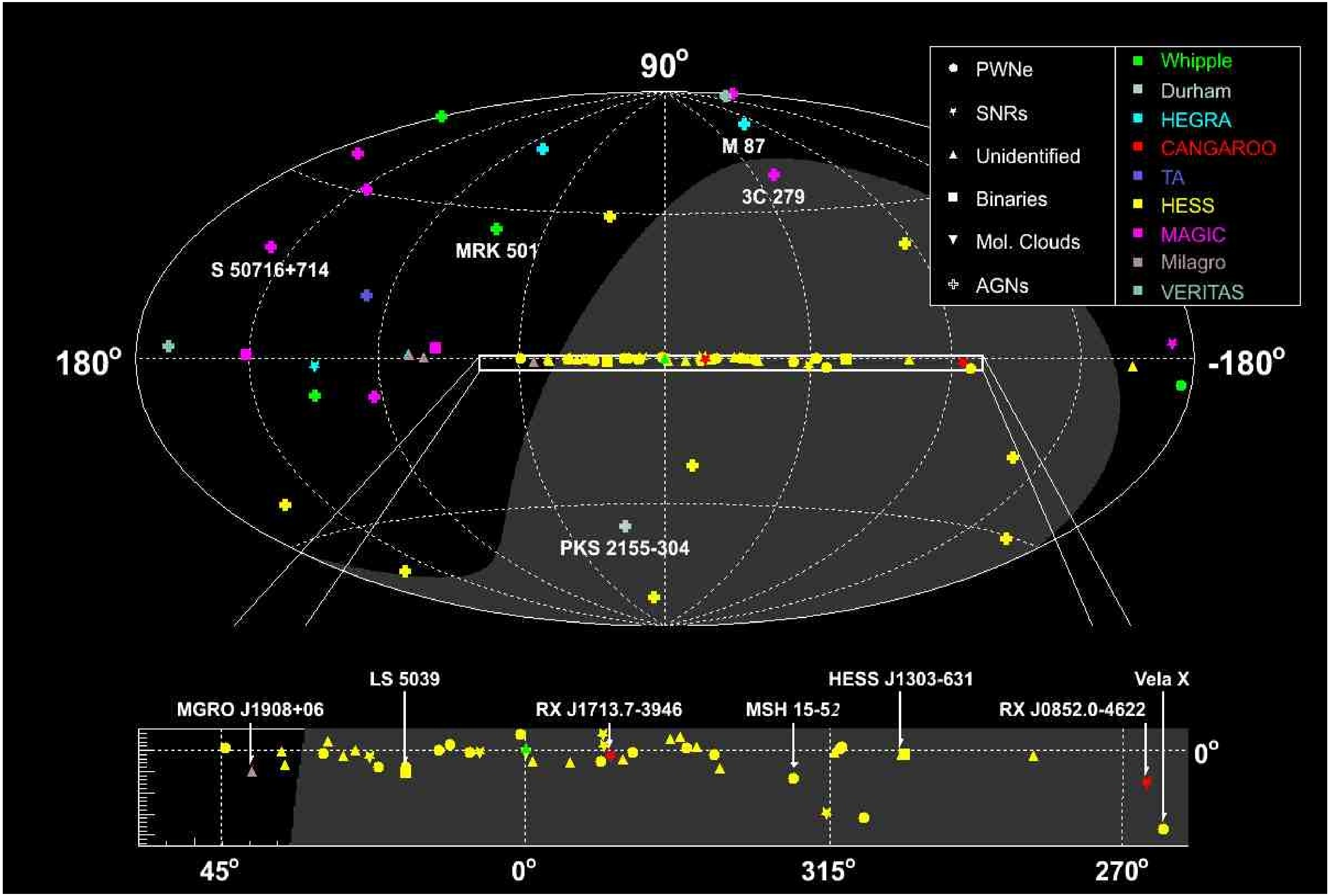


Systems of Cherenkov telescopes

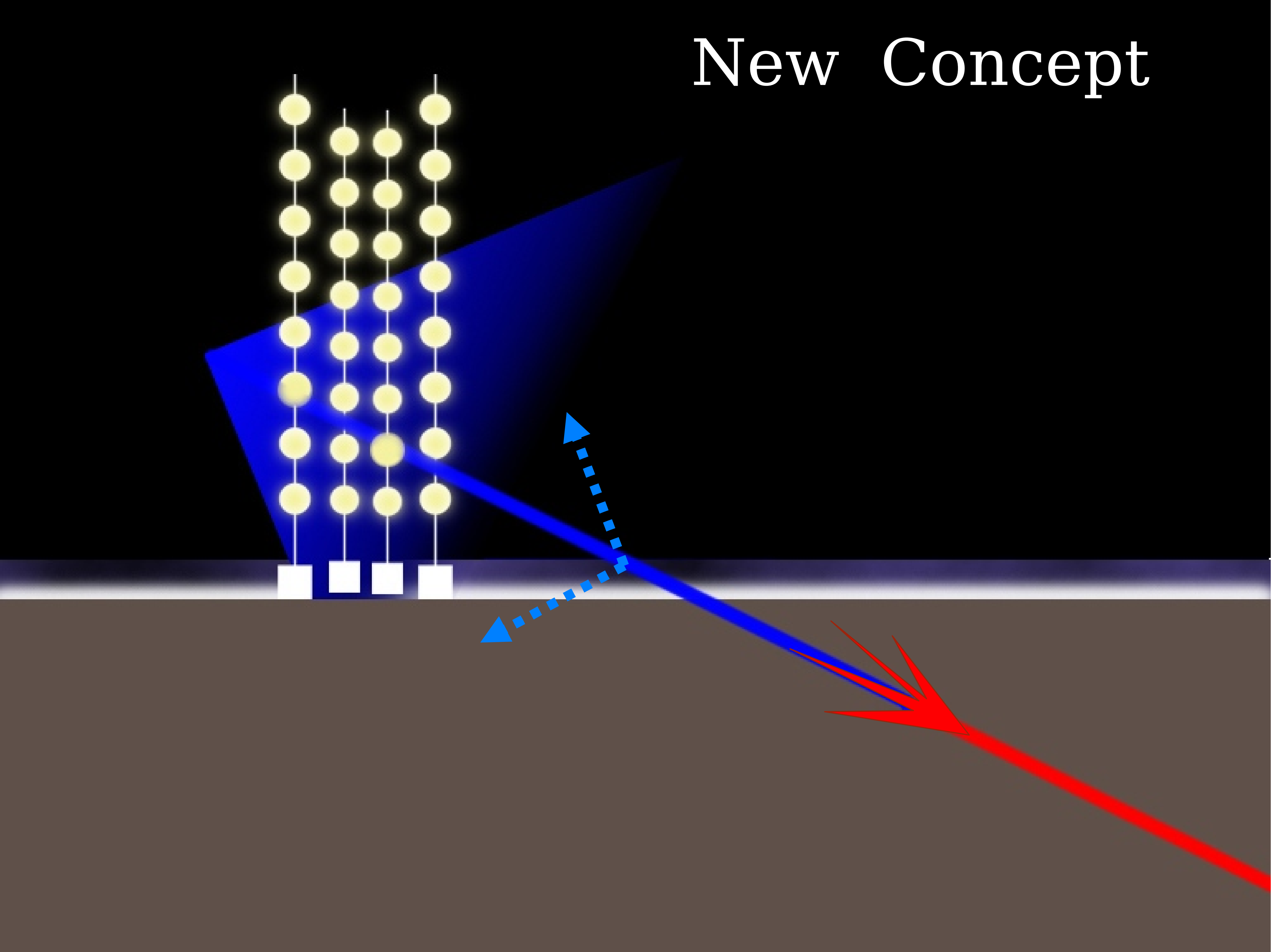


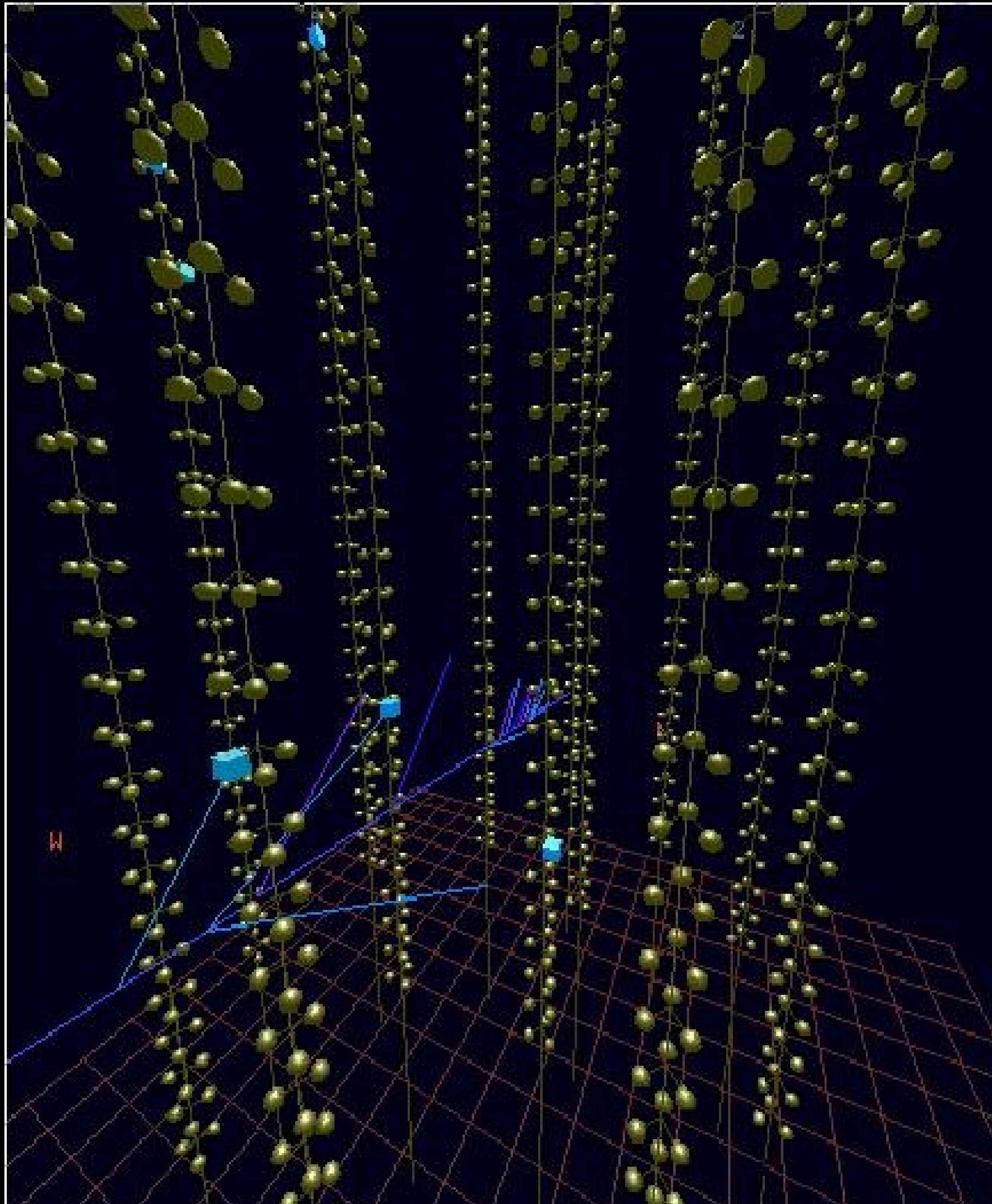
Better bkgd reduction
Better angular resolution
Better energy resolution

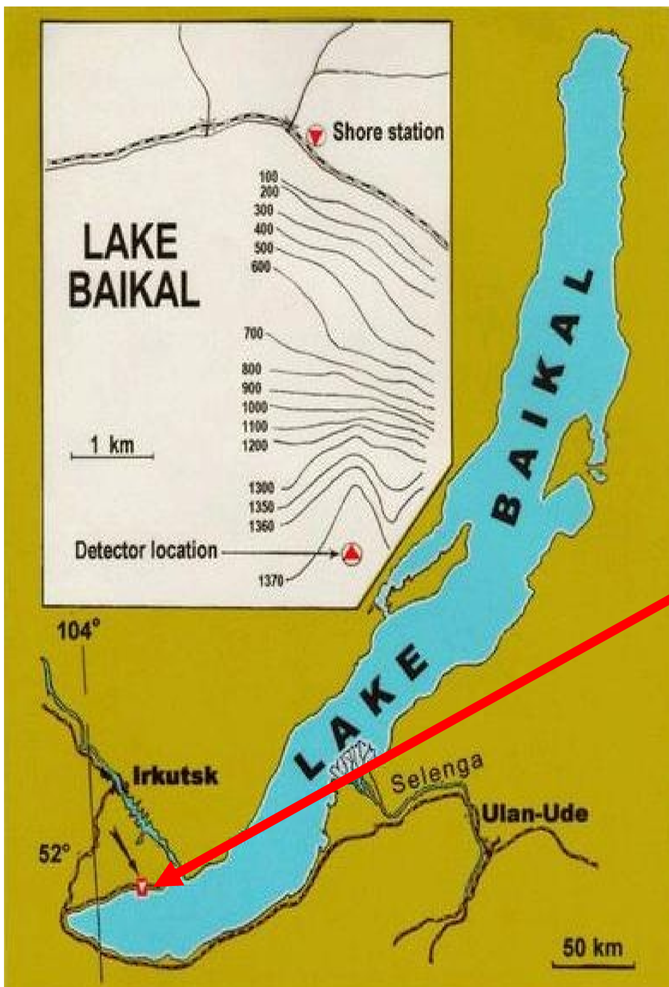
HE γ-ray sources

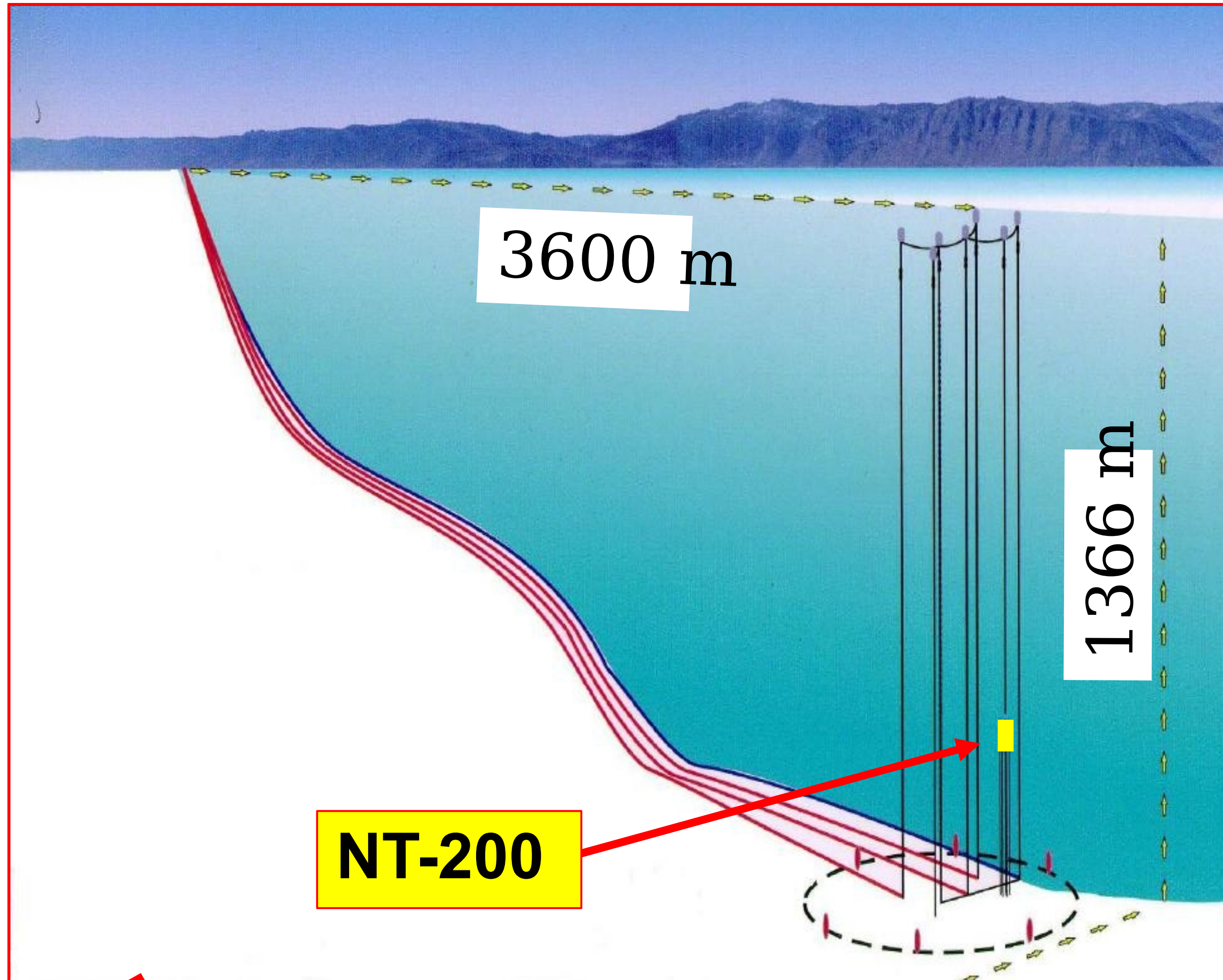


HIGH ENERGY NEUTRINO DETECTION


New Concept

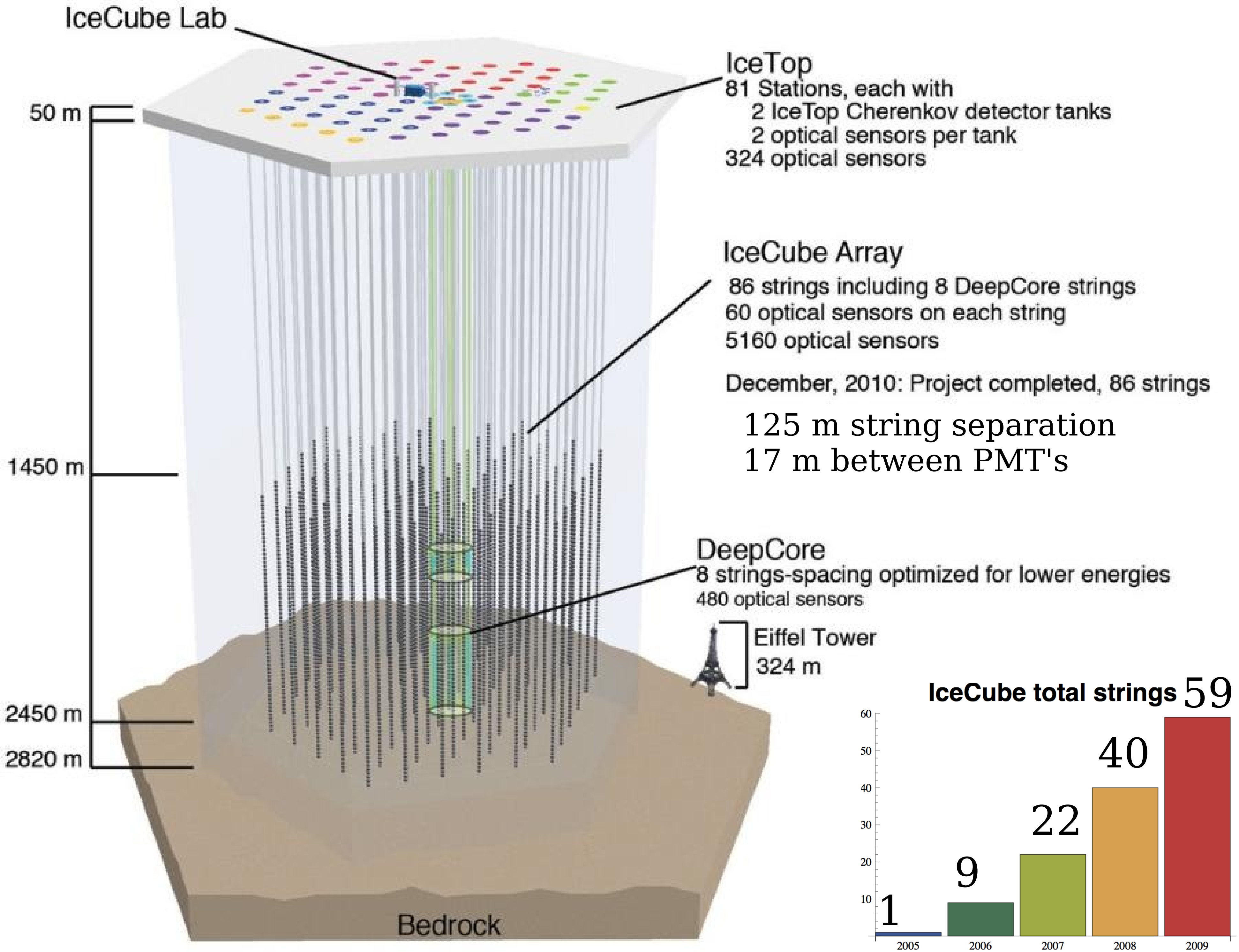

W



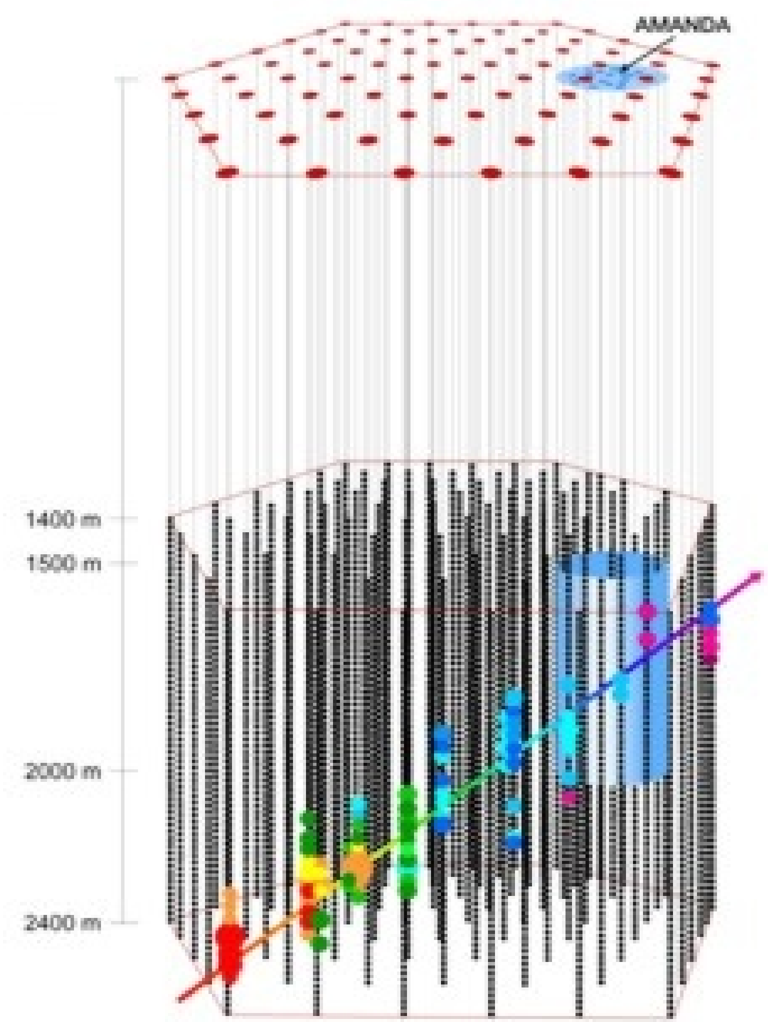


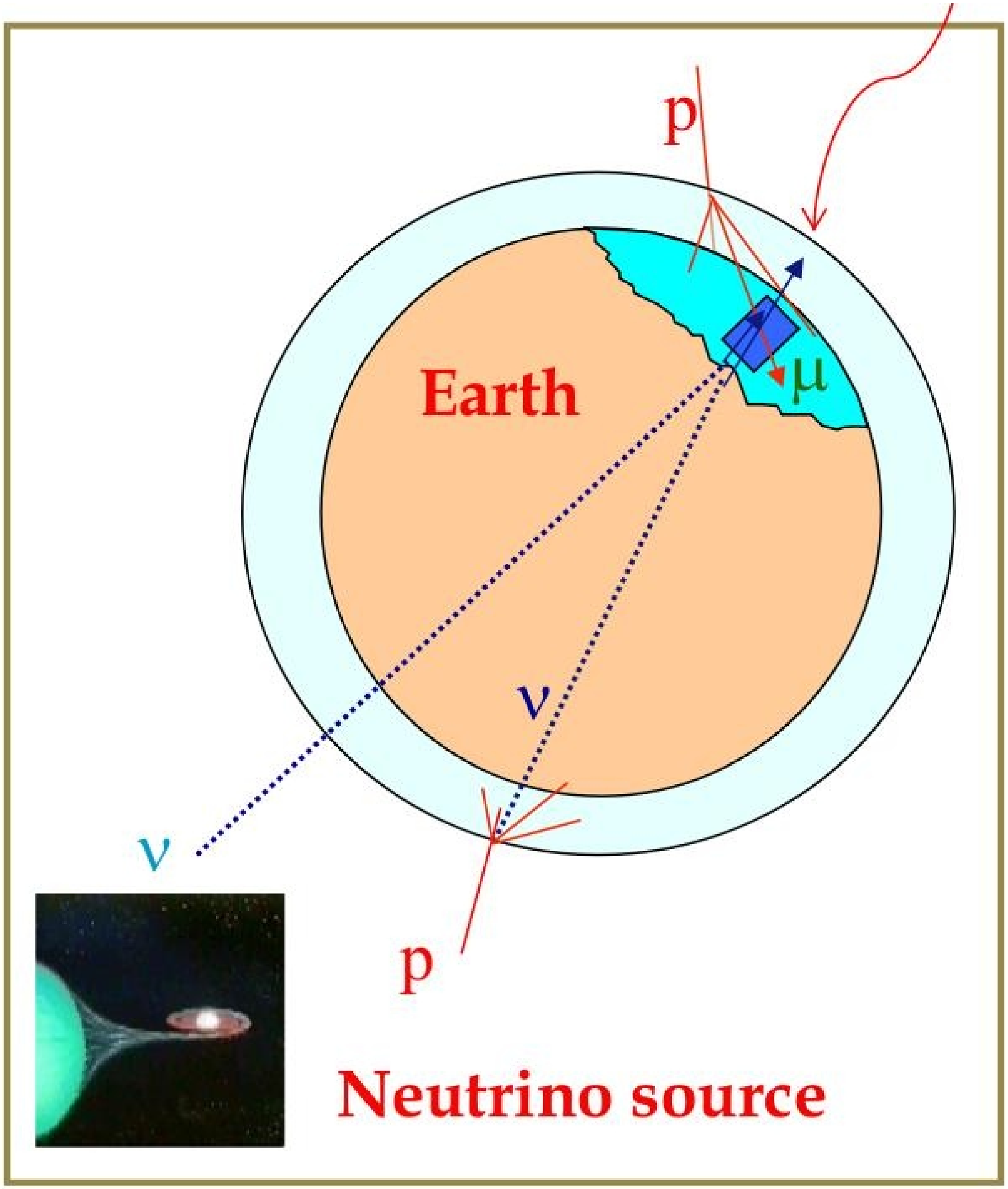
- 4 cables x 4km to shore.
- 1070m depth

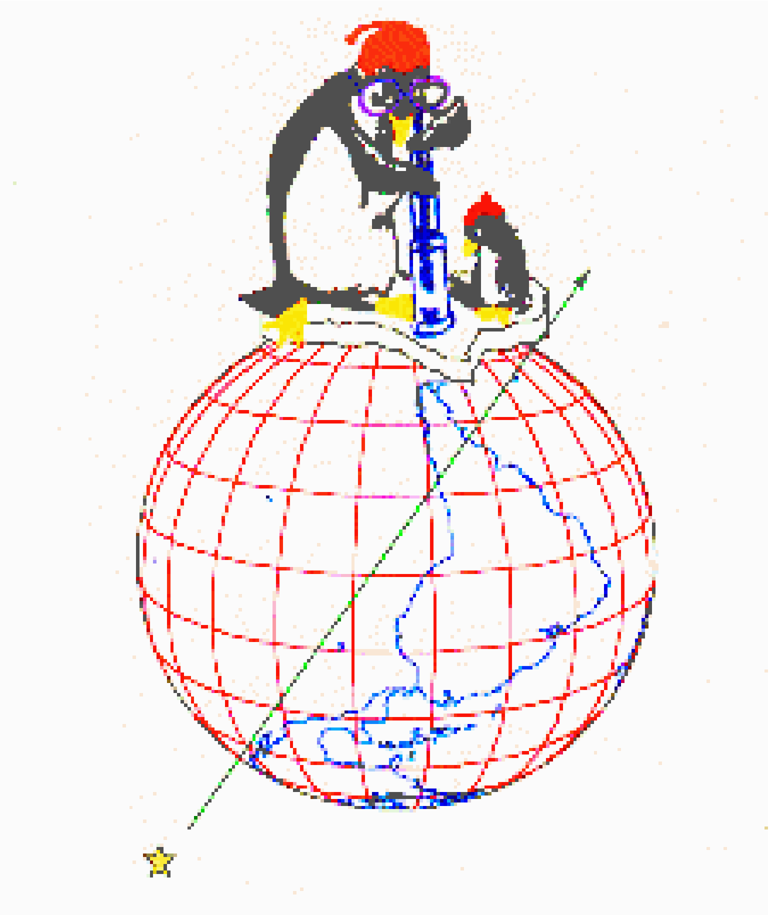
Amundsen-Scott South Pole station


IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
125 m string separation
17 m between PMT's
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock
IceCube total strings
1
9
22
40
59
10
20
30
40
50
60
2005
2006
2007
2008
2009

Deployment of the strings

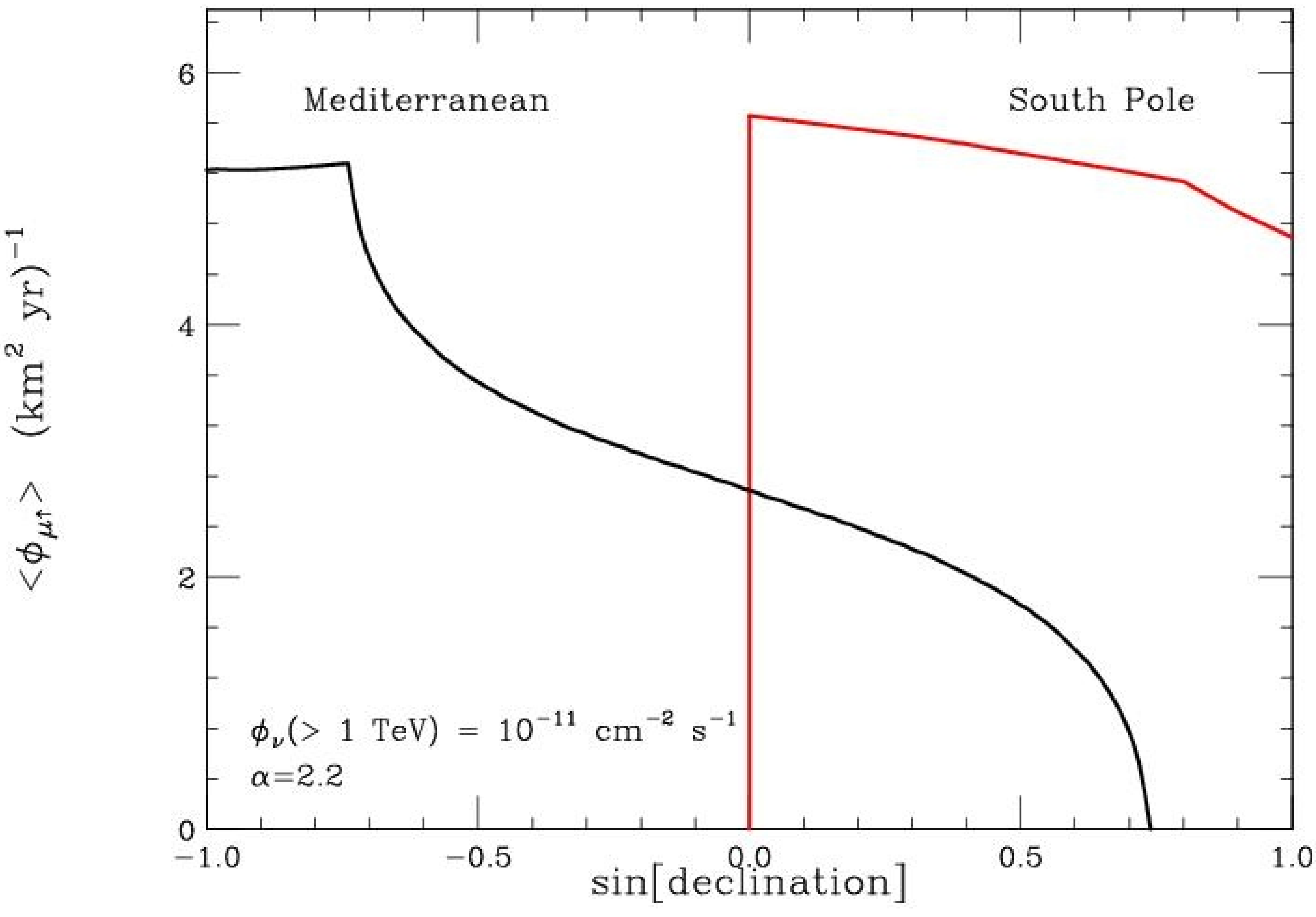






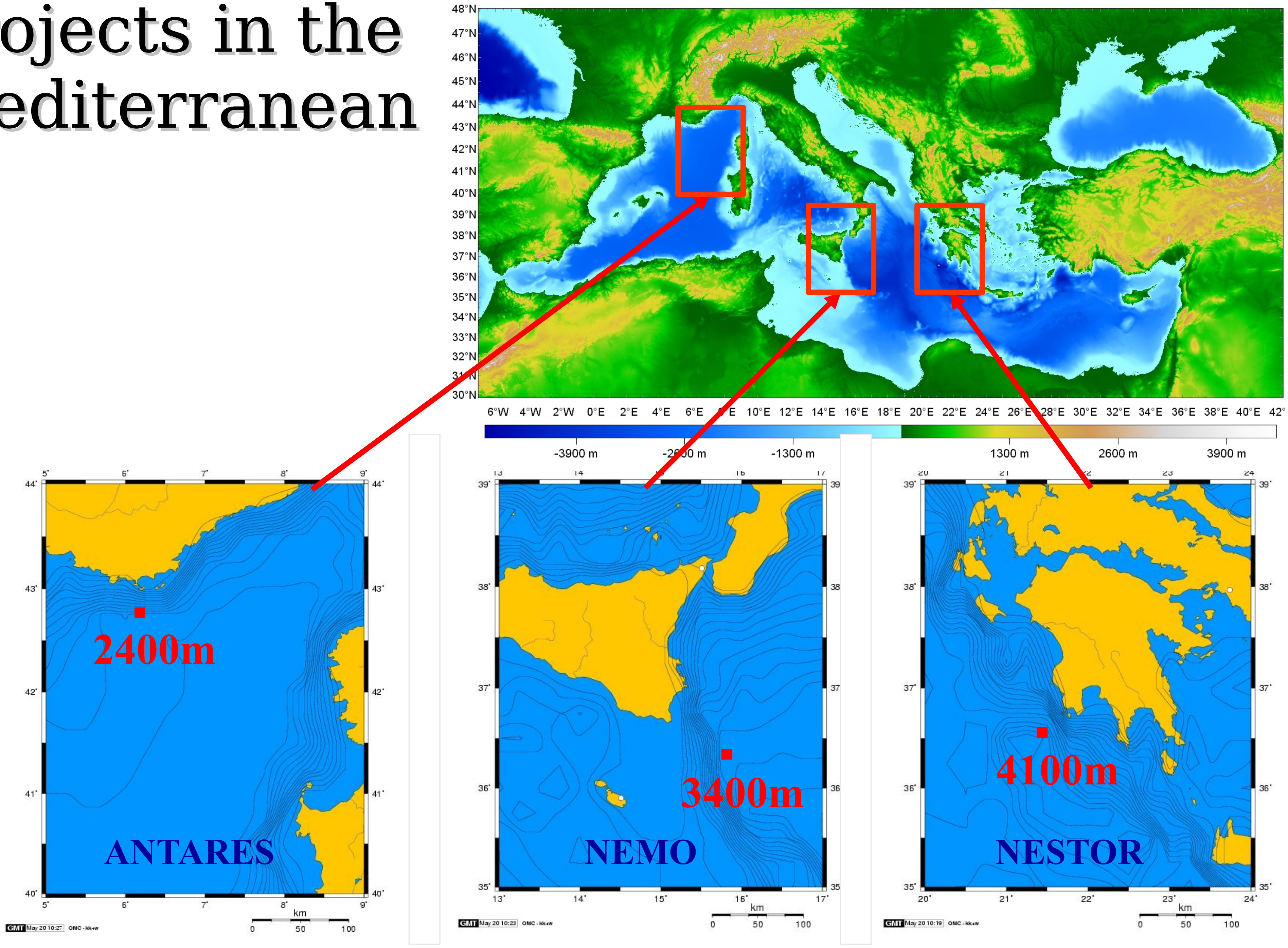
See only
½ of the SKY

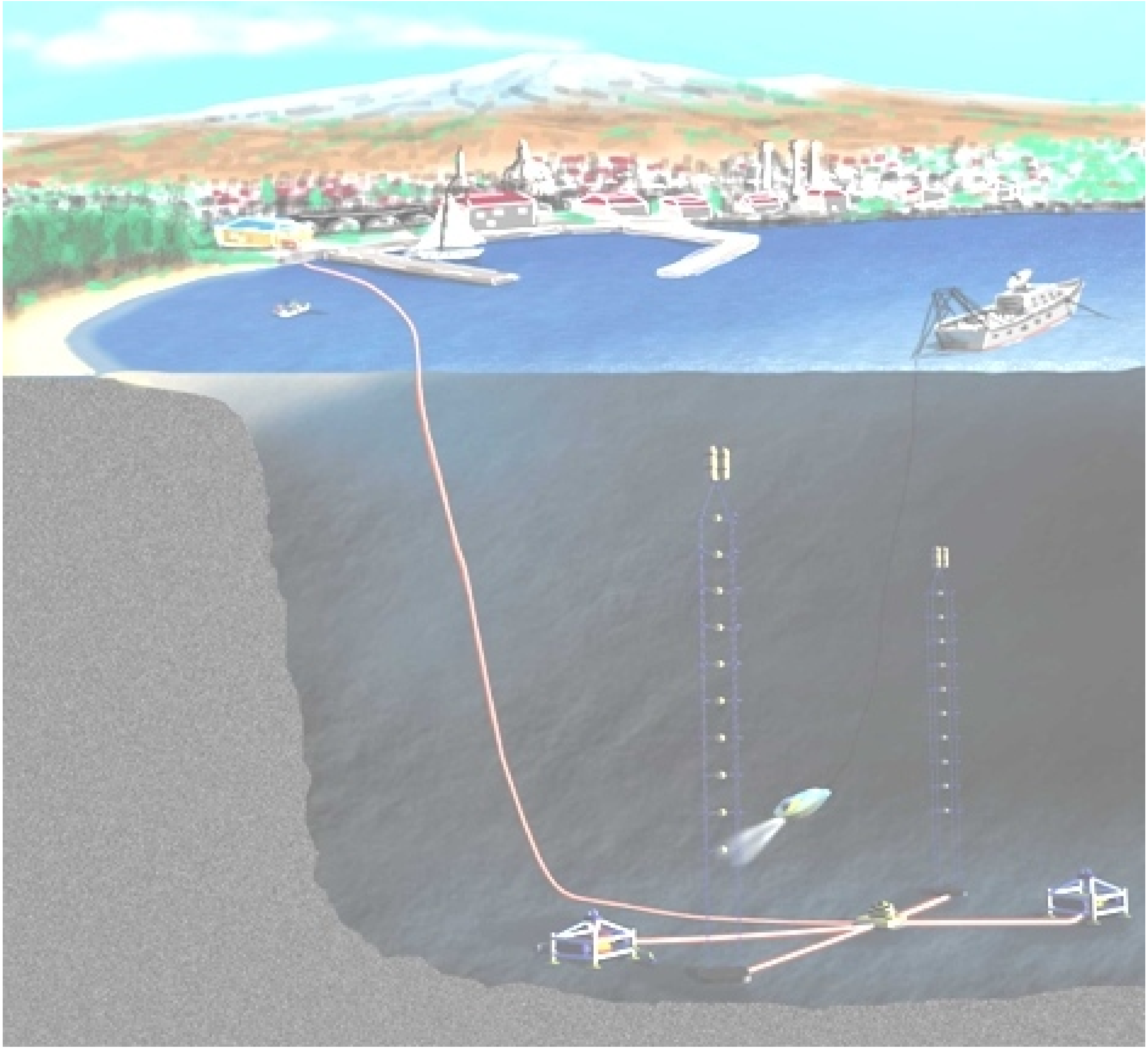
Complementarity of view. Mediterranean/South Pole



High energy neutrino telescopes world map

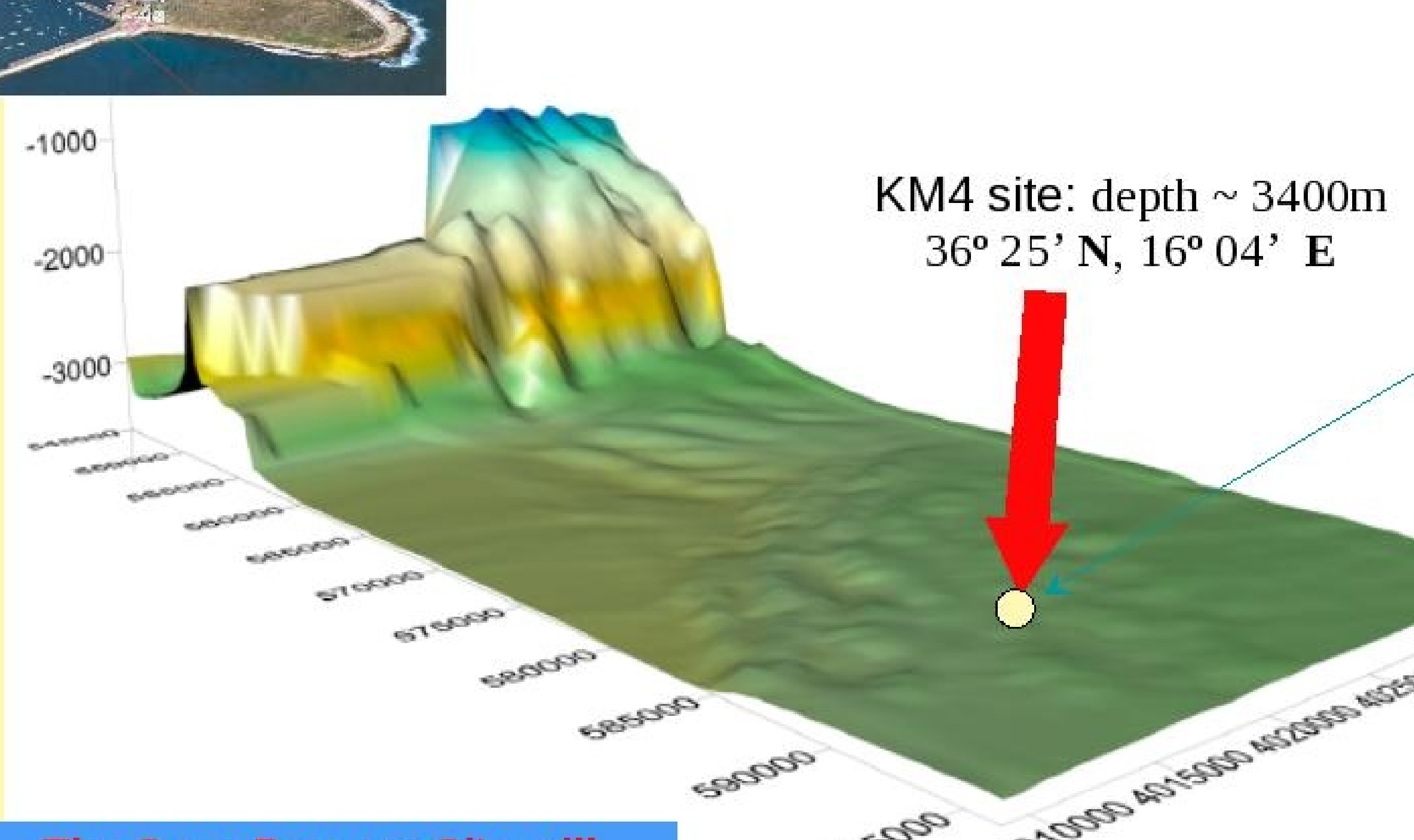
Projects in the Mediterranean

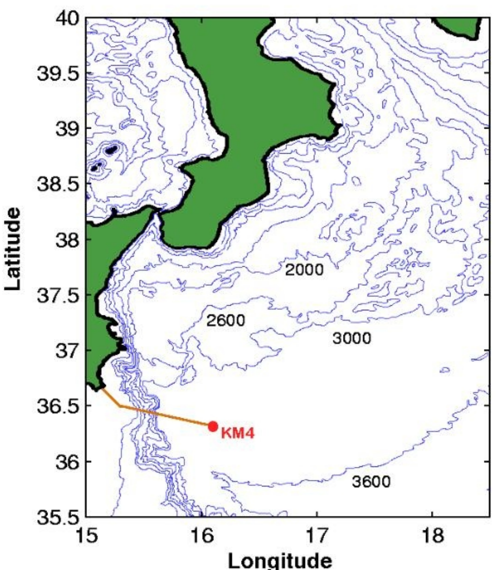




The Capo Passero site

Bathymetry, a 3D view



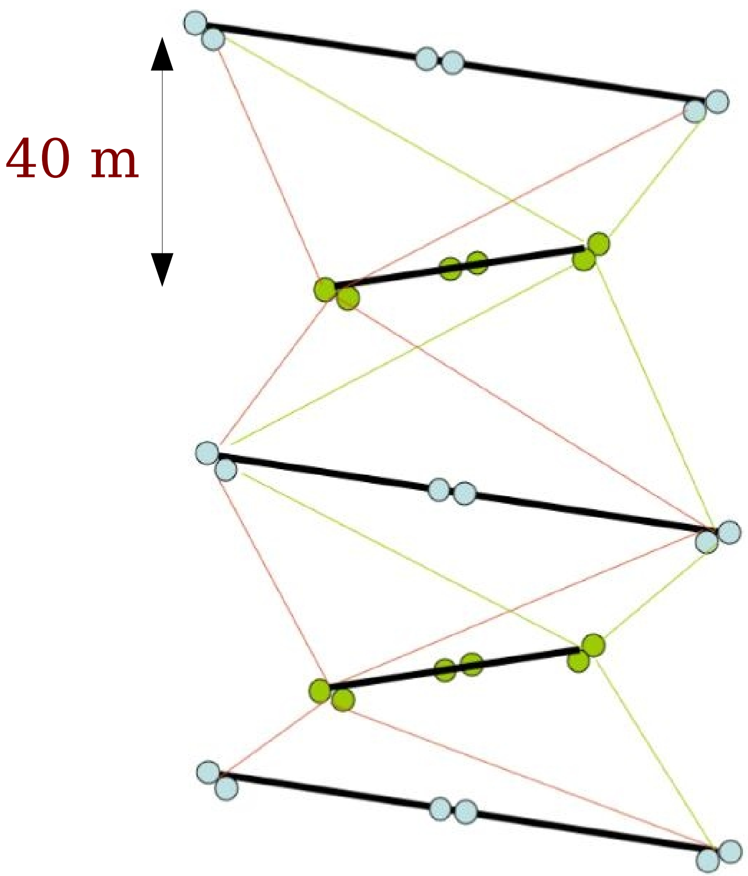


The Capo Passero Site will also provide a useful facility to test KM3NeT technologies


23 January 2005
ROV
25 Jan/05
INFN
OνDE connection

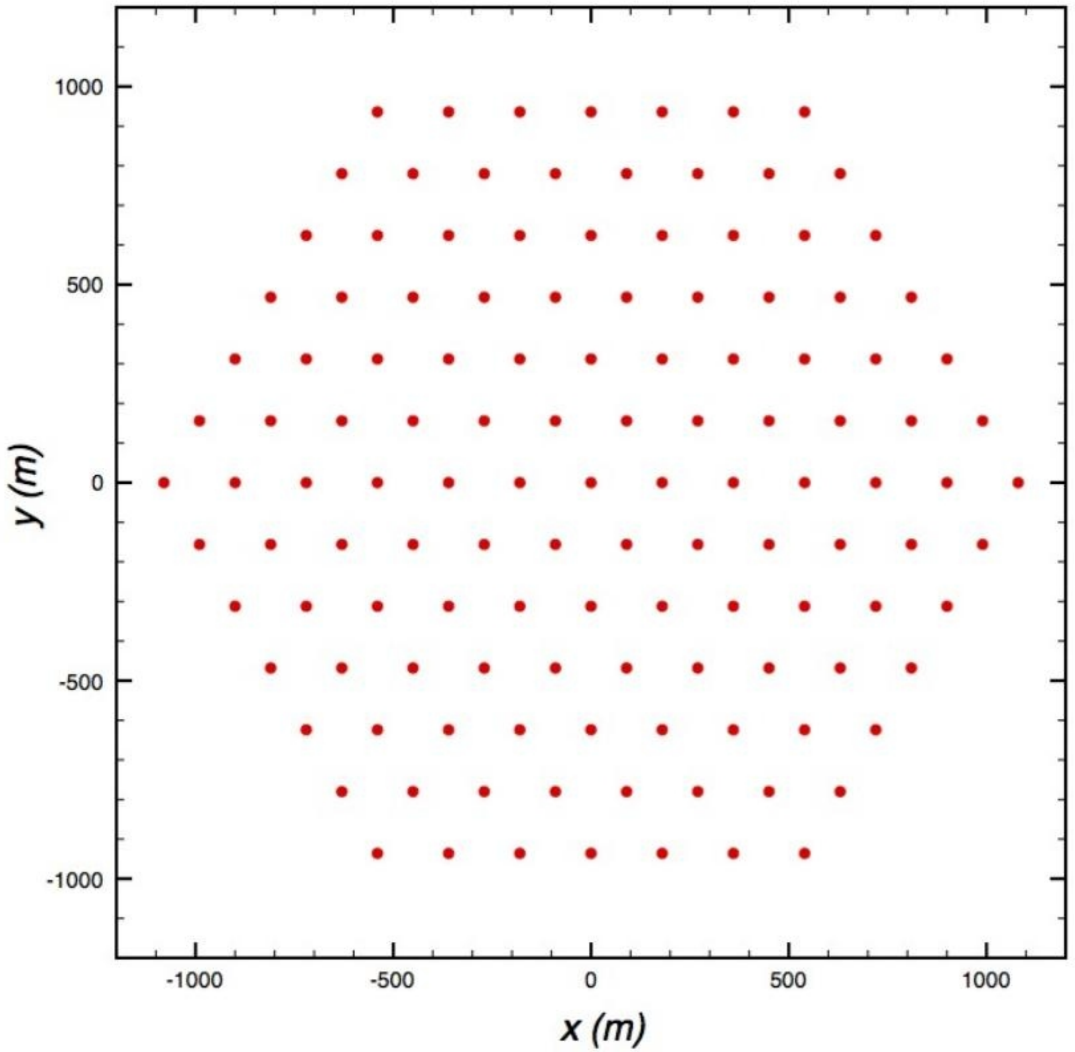
Possible structure of a "KM3" detector in the Mediterranean Sea:

"tower" [6 PMT's]



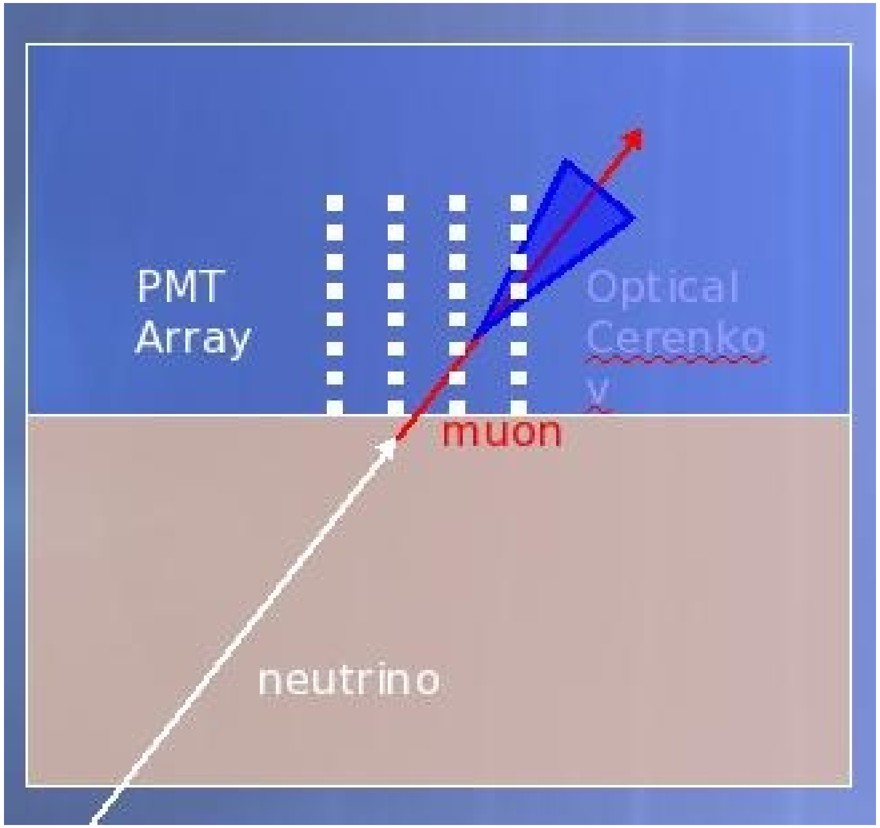
Detection Unit layout.

127 towers (180 m)

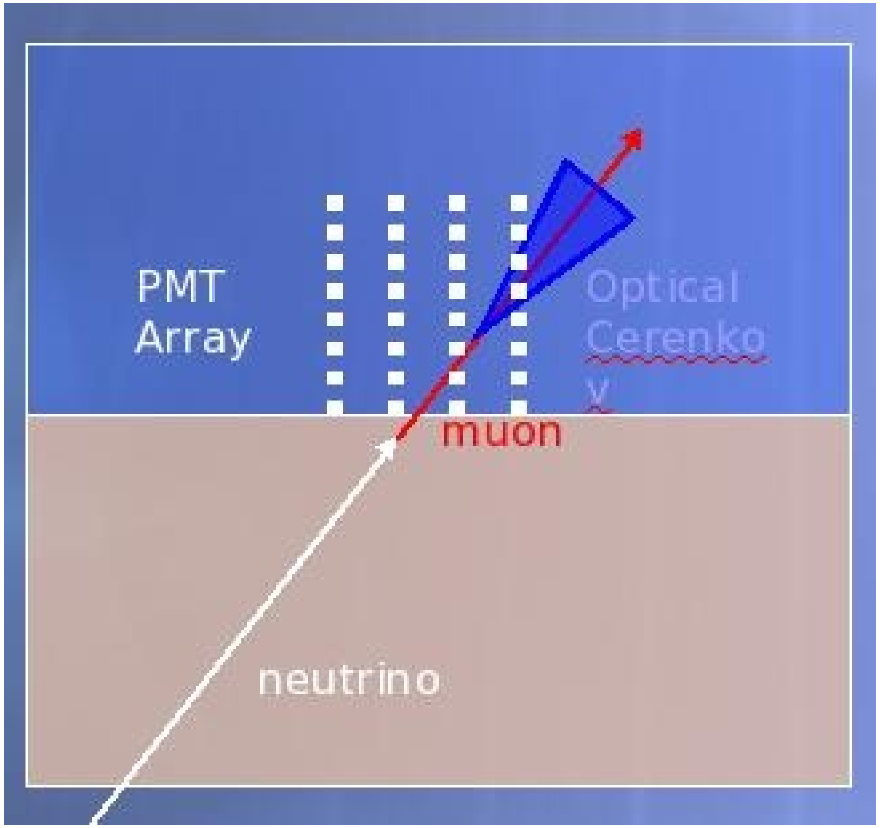


Multi-Site ?!

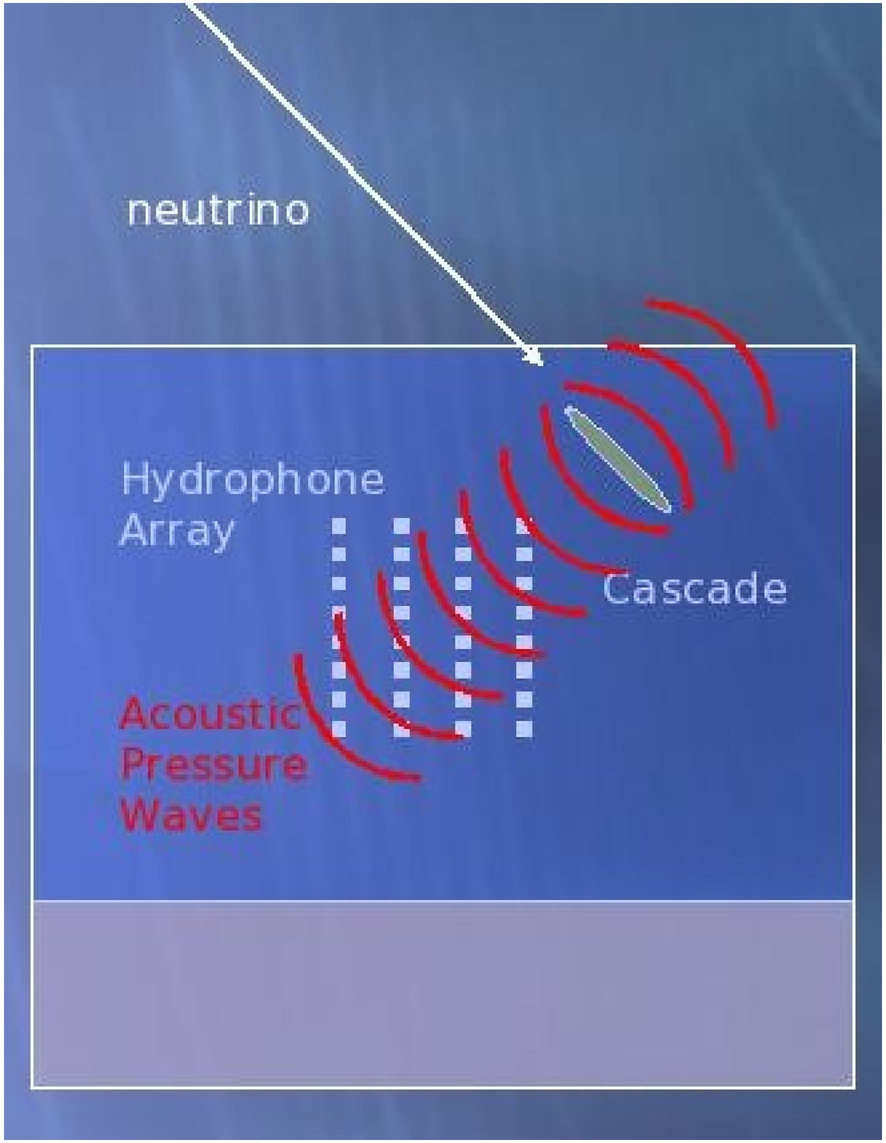
"OPTICAL Method"



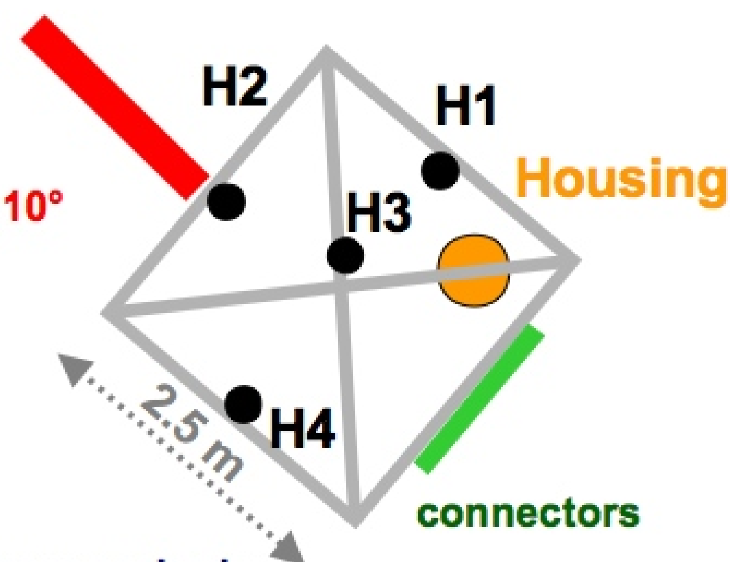
“OPTICAL Method”



“ACOUSTIC Method”

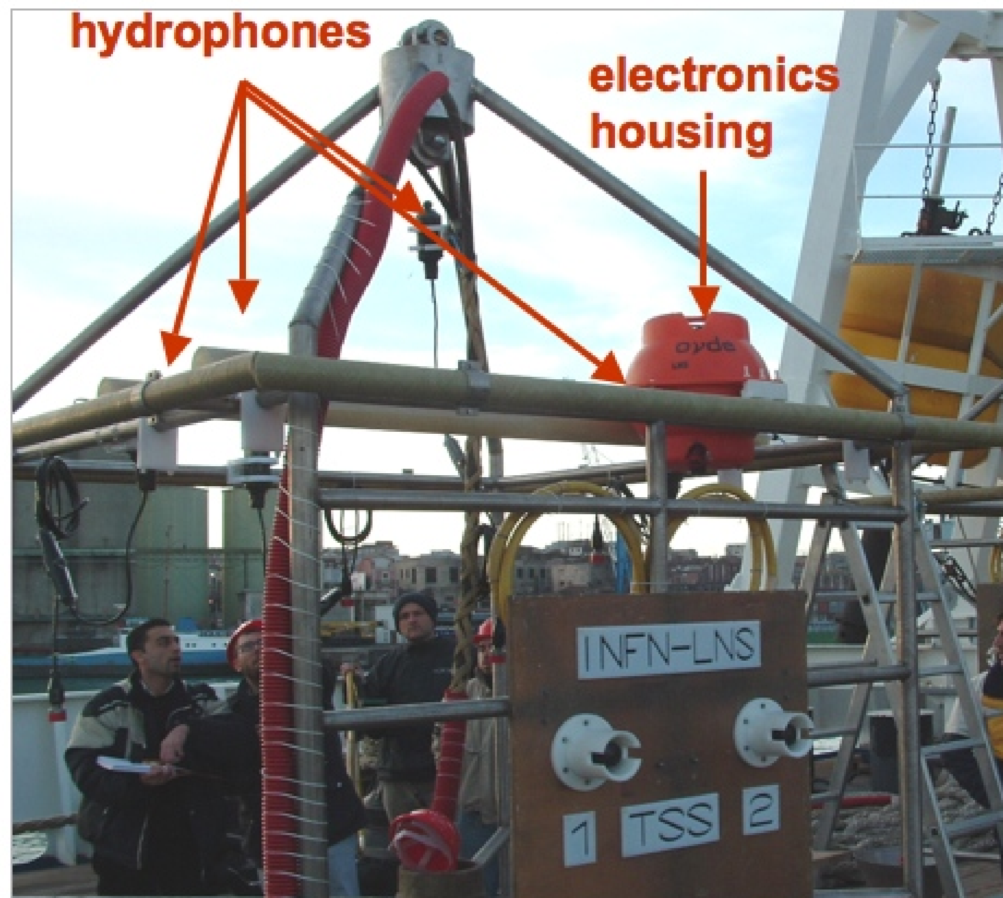


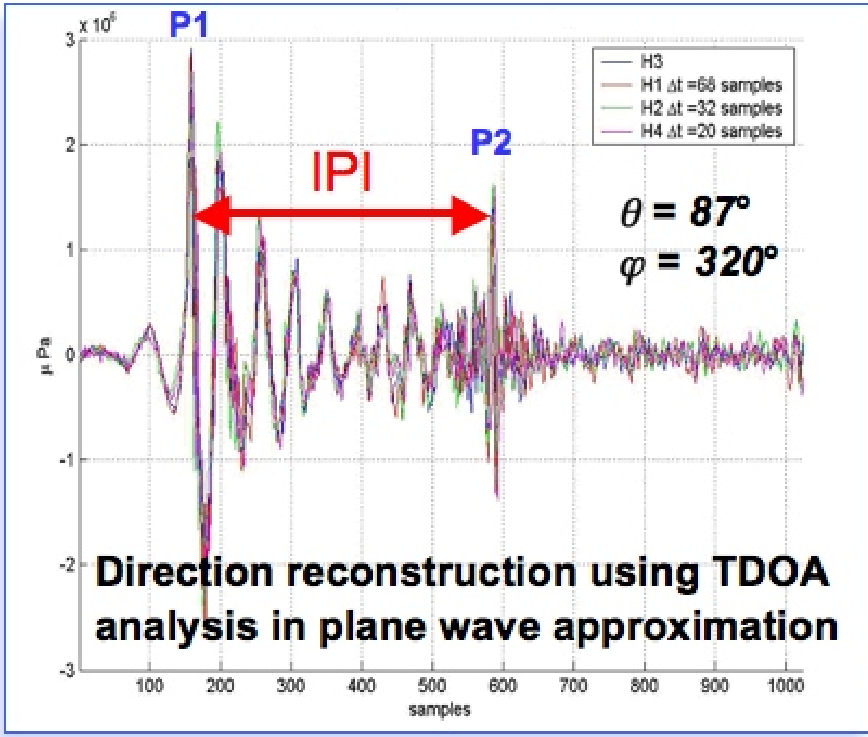
4 hydrophones (10 Hz-40 kHz bandwidth) synchronized.
Acoustic signal digitization (24bit@96 kHz) at 2000m depth.
Data transmission on optical fibers over 28 km.
On-line monitoring and data recording on shore. Recording 5’ every hour.
Data taking from Jan. 2005 to Nov. 2006 (NEMO Phase 1 deployed).

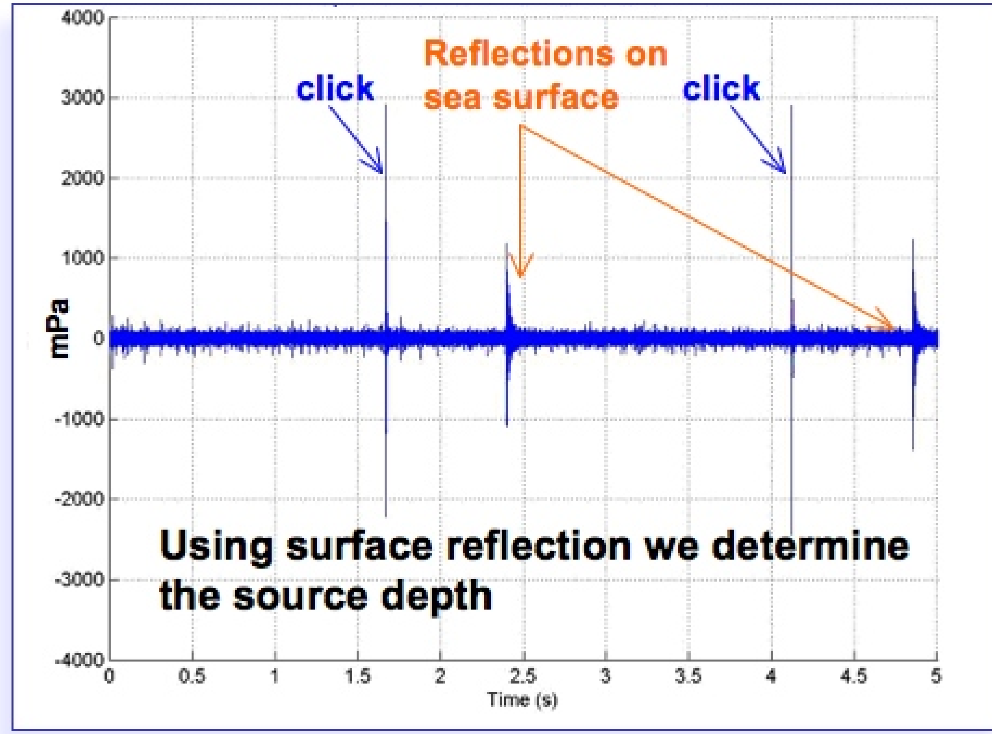


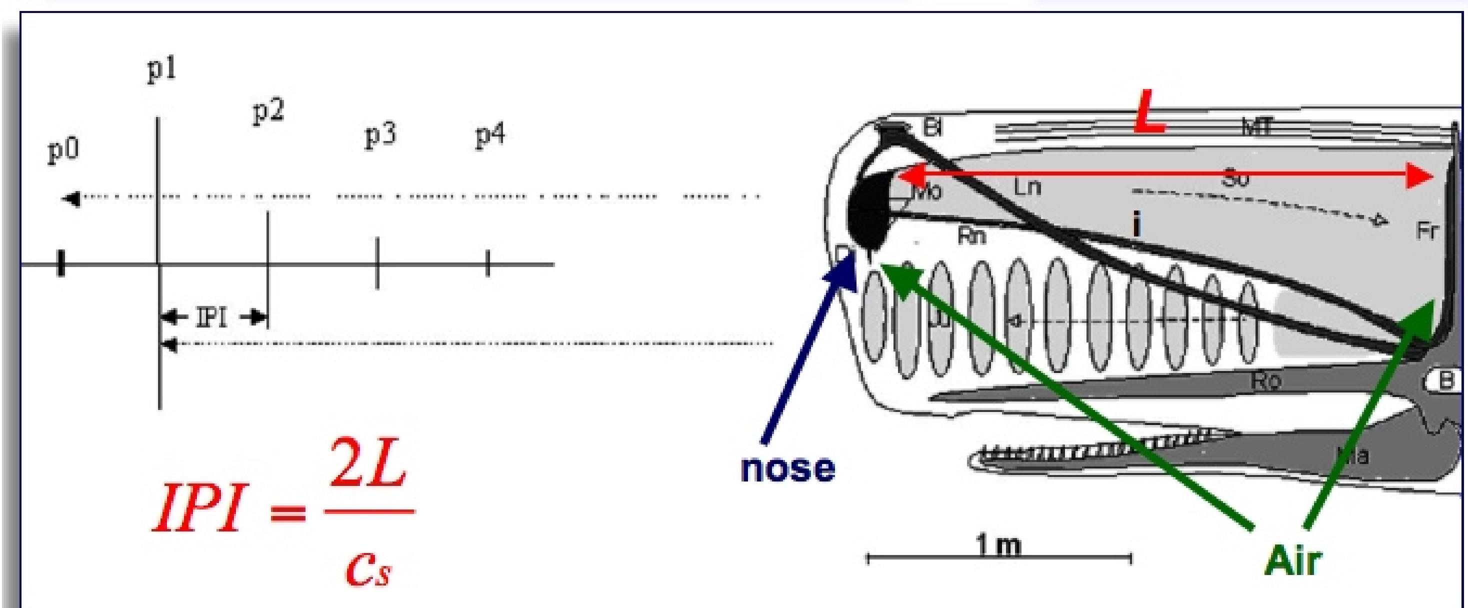
Height from seabed :
H1, H2, H4: ~ 2.6 m H3: ~ 3.2 m

In collaboration with Uni-Pavia CIBRA









Depth = 560 ± 5 m

L = 3.41 ± 0.05 m
Size = 9.72 - 10.50 m

Young male or female

NEMO

NEUTRINO MEDITERRANEAN OBSERVATORY

INTERDISCIPLINARIETA'

Components of the Neutrino Flux

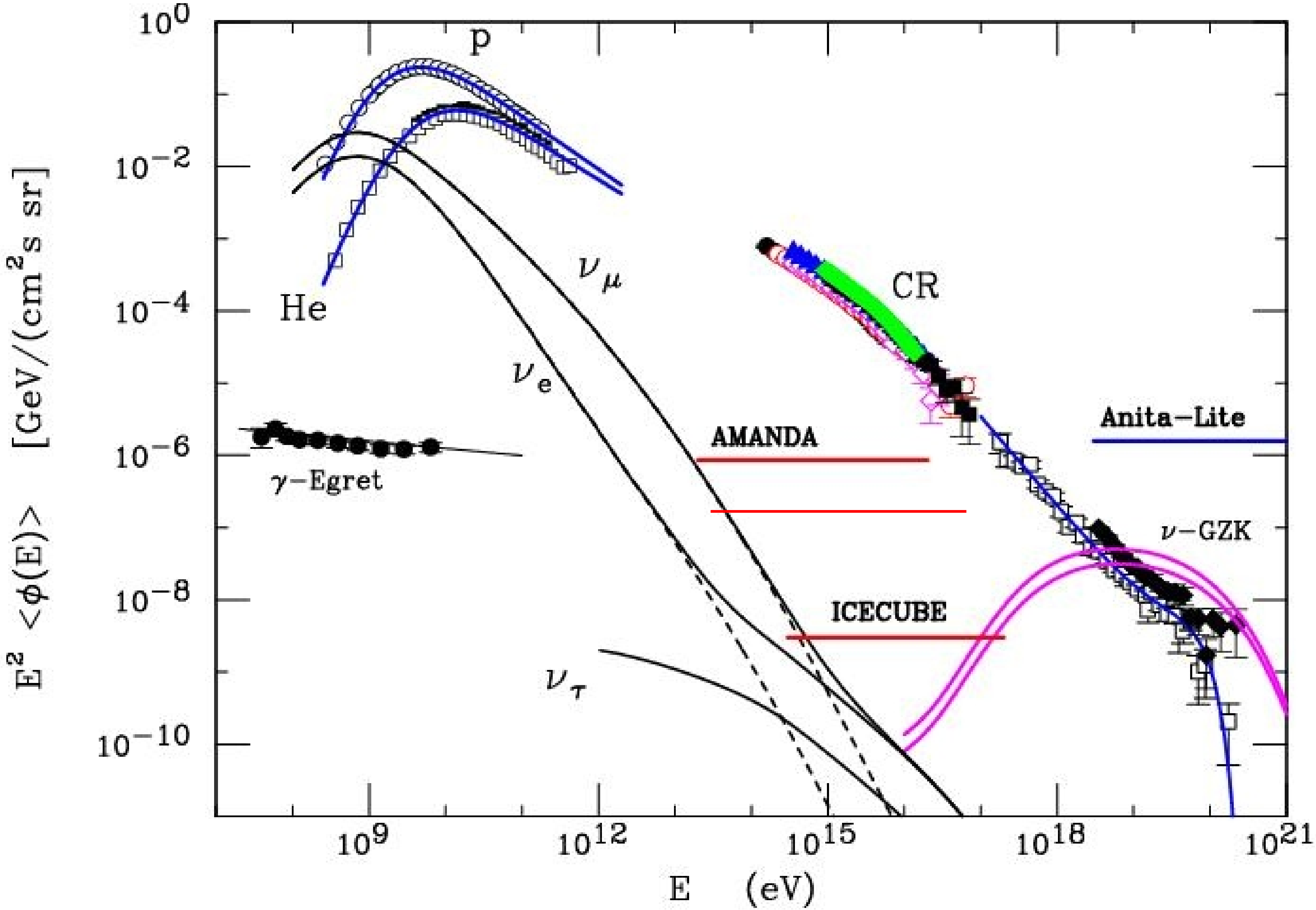
$$\phi_{\nu_\alpha}(E,\Omega) = \phi_{\rm atm}^{\rm standard}(E,\Omega) + \phi_{\rm atm}^{\rm prompt}(E,\Omega)$$

$$+ \phi_{\rm Galactic}(E,\Omega) + \phi_{\rm Extra\ Gal}(E,\Omega)$$

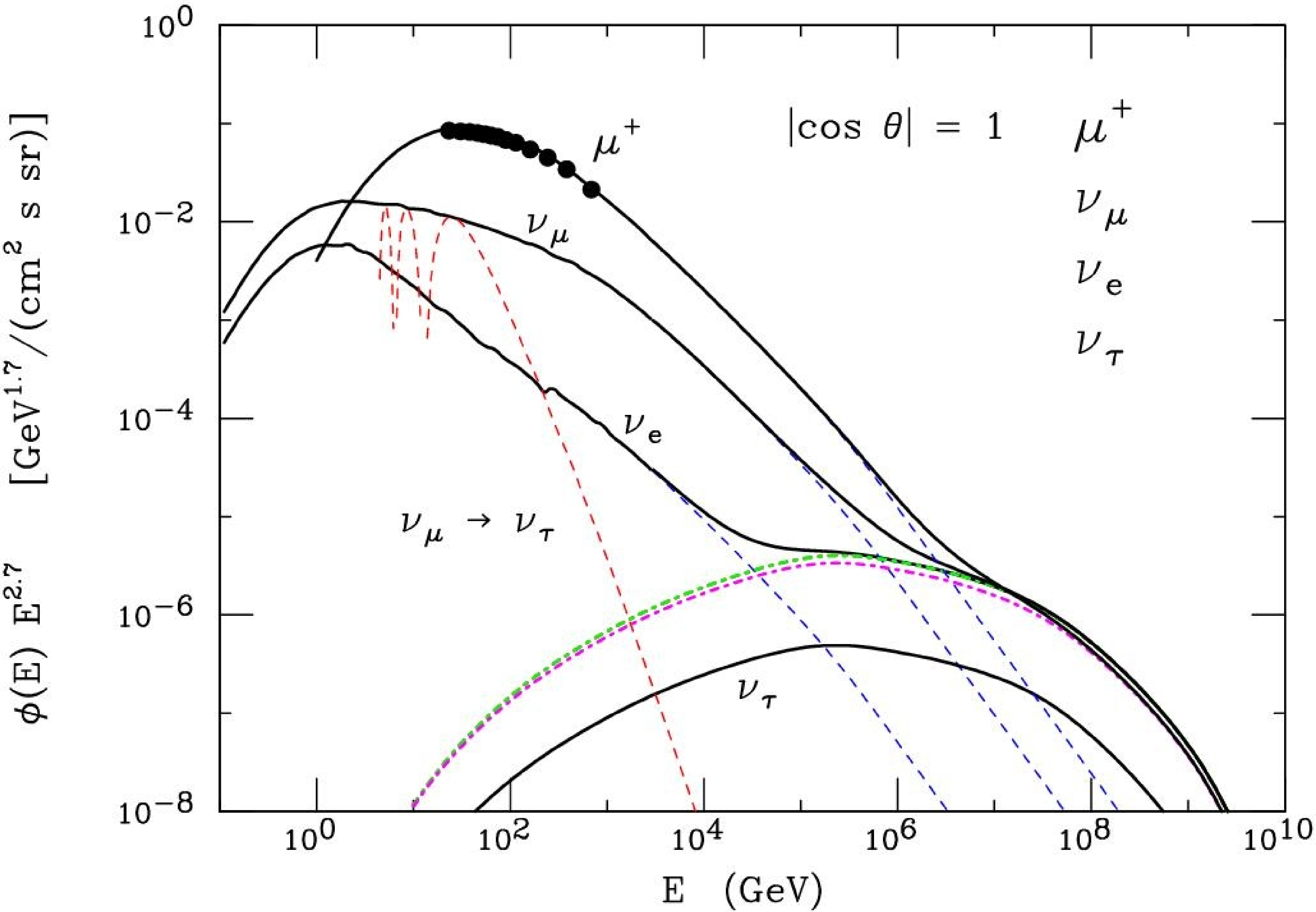
$$+ \sum_{\rm Galactic} \phi_j(E)\ \delta[\Omega - \Omega_j]$$

$$+ \sum_{\rm Extra\ Gal} \phi_k(E)\ \delta[\Omega - \Omega_k]$$

$$\sum_k \phi_k(E)\, \delta[\Omega - \Omega_k] \Longrightarrow \phi_{\rm Diffuse}(E)$$

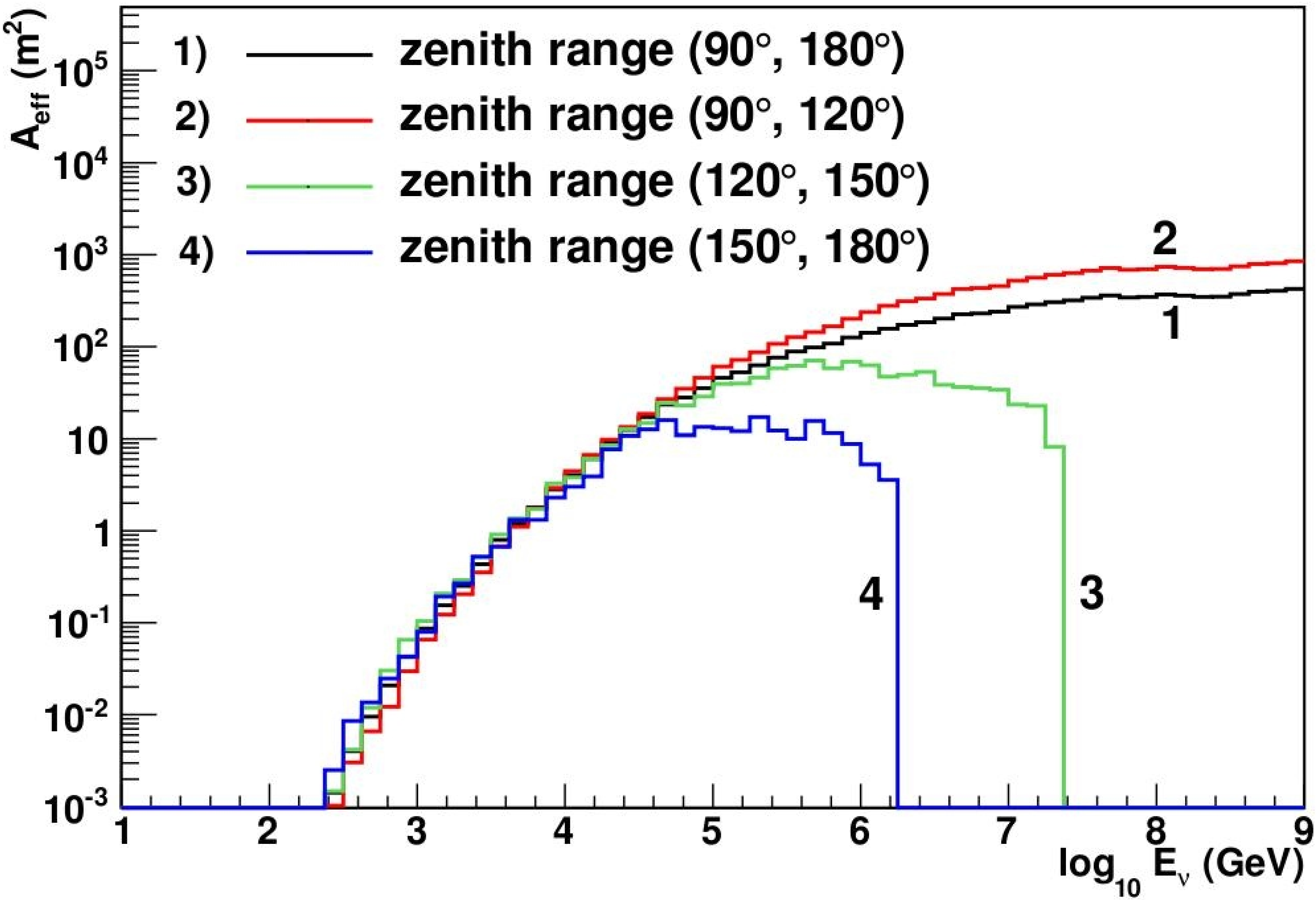


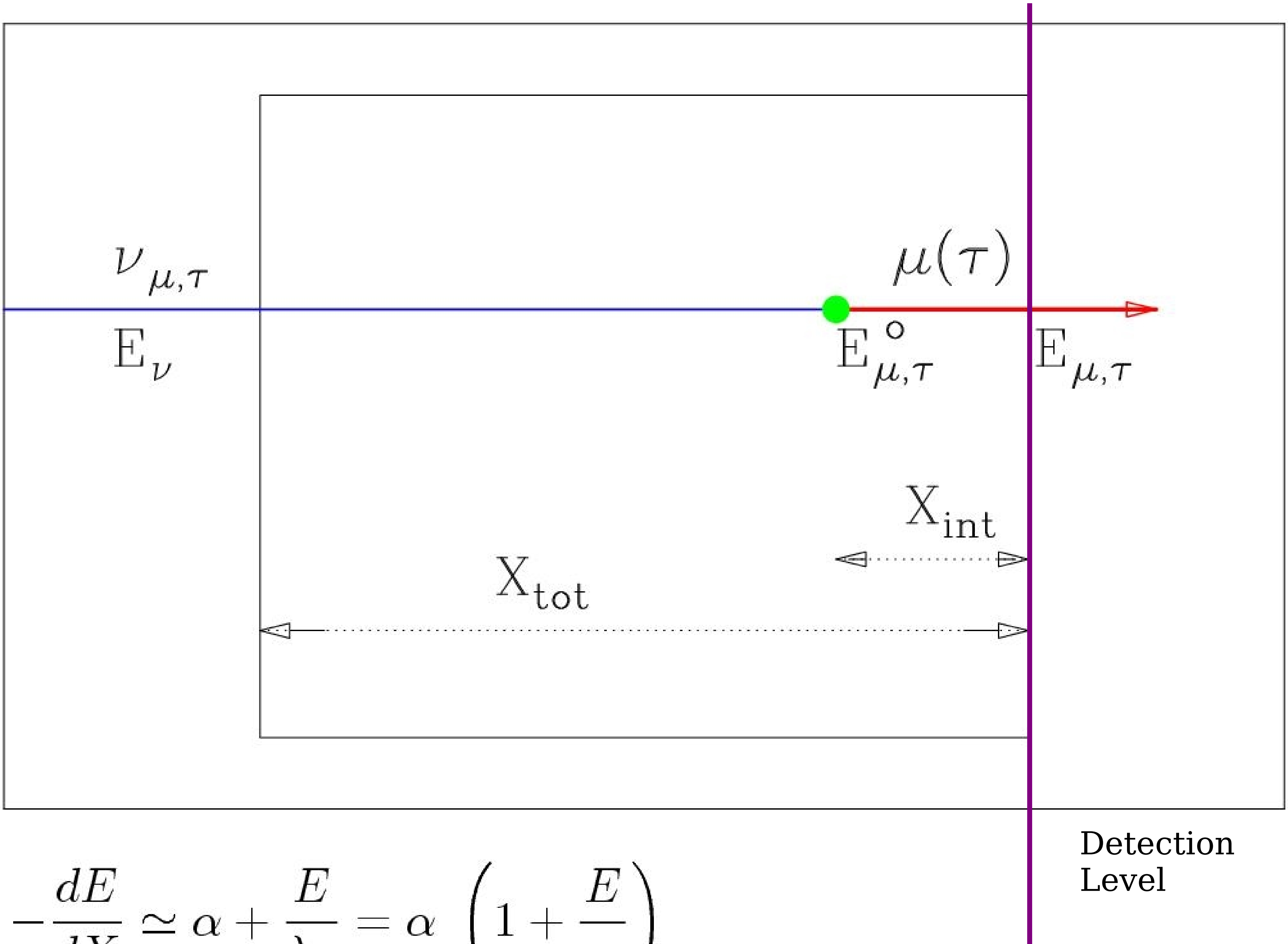
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^9
10^{12}
10^{15}
10^{18}
10^{21}
E (eV)
$E^2 \langle\phi(E)\rangle$ [GeV/(cm^{2}s sr)]
p
He
ν_μ
ν_e
ν_τ
γ−Egret
CR
AMANDA
ICECUBE
Anita−Lite
ν−GZK



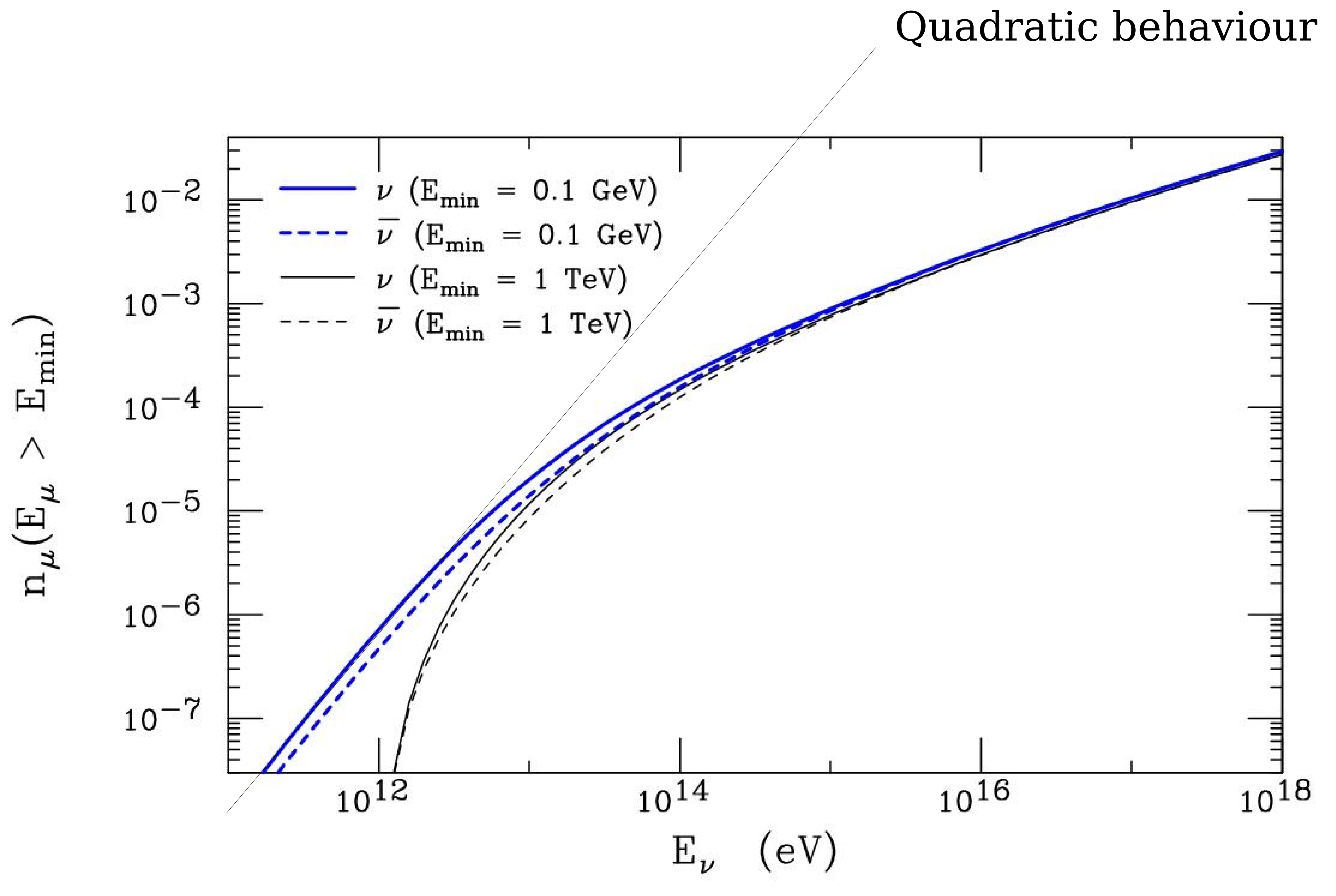
$|\cos\,\theta| = 1$
μ^+
μ^+
ν_μ
ν_e
ν_τ
$\nu_\mu \rightarrow \nu_\tau$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^2
10^4
10^6
10^8
10^{10}
E (GeV)
$\phi(E)\ E^{2.7}$ [GeV$^{1.7}$/(cm^2 s sr)]

IceCube Effective AREA (as a function of Neutrino Energy)

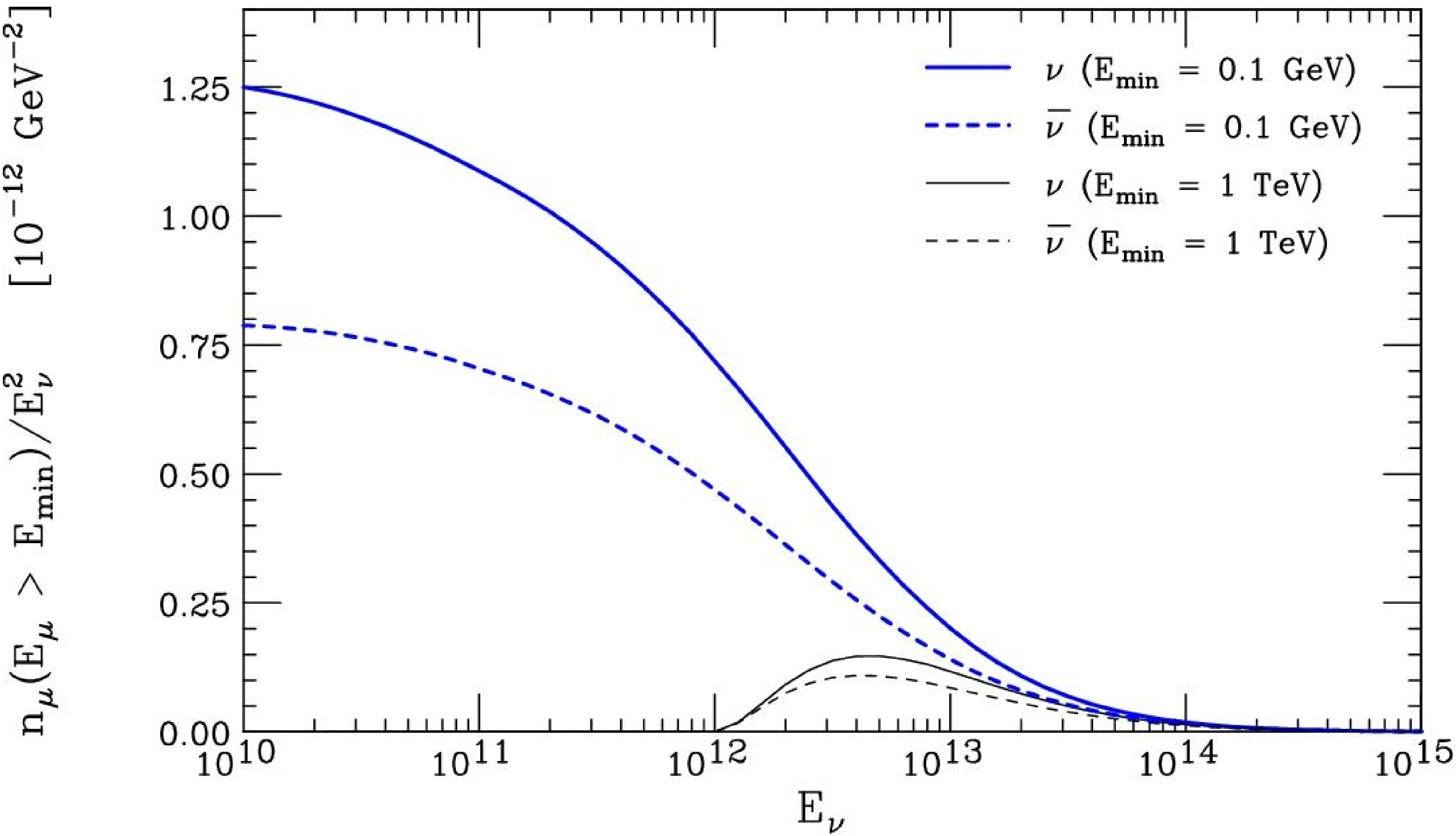




$$-\frac{dE}{dX} \simeq \alpha + \frac{E}{\lambda_\mu} = \alpha \left(1 + \frac{E}{\varepsilon_\mu}\right)$$



Quadratic behaviour
ν (E_{min} = 0.1 GeV)
$\bar{\nu}$ (E_{min} = 0.1 GeV)
ν (E_{min} = 1 TeV)
$\bar{\nu}$ (E_{min} = 1 TeV)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{12}
10^{14}
10^{16}
10^{18}
E_ν (eV)
$n_\mu(E_\mu > E_{min})$



ν (E_min = 0.1 GeV)
ν̄ (E_min = 0.1 GeV)
ν (E_min = 1 TeV)
ν̄ (E_min = 1 TeV)
1.25
1.00
0.75
0.50
0.25
0.00
10^10
10^11
10^12
10^13
10^14
10^15
E_ν
n_μ(E_μ > E_min)/E_ν^2 [10^−12 GeV^−2]

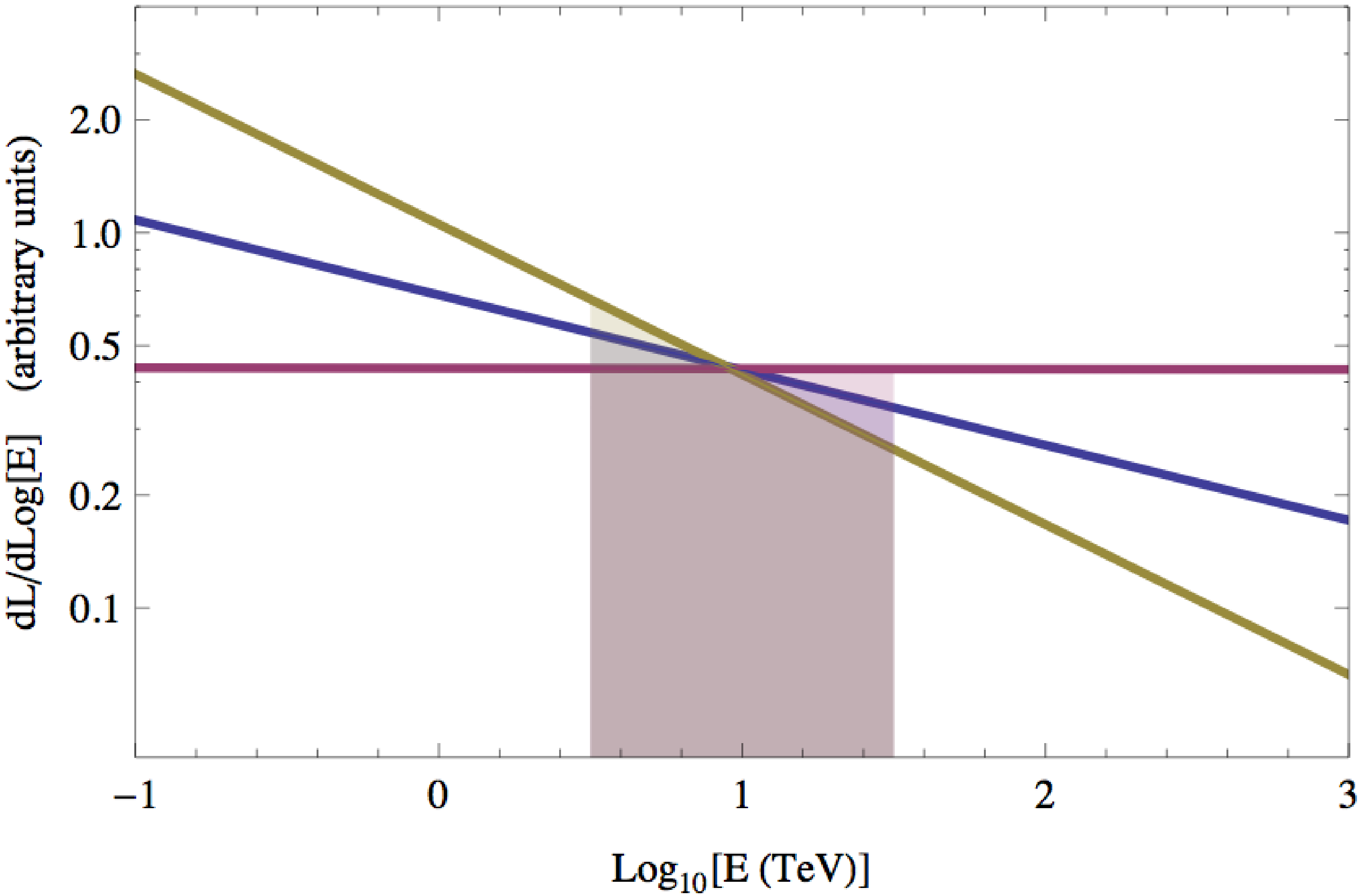
$$
\begin{aligned}
\left[\frac{d^2\sigma}{dx\,dy}\right]^{cc}_{\nu,\bar{\nu}}(x,y;E_\nu) &= \frac{{G_F}^2\,M\,E_\nu}{\pi}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2\Big\{y(xy+\eta)\;F_1^{\nu,\bar{\nu}} \\
&+ \left[1-y-\frac{M}{2E_\nu}(xy+\eta)\right]\;F_2^{\nu,\bar{\nu}} \mp \left[\frac{y}{2}(xy+\eta)-xy\right]\;F_3^{\nu,\bar{\nu}} \\
&+ \eta\,(xy+\eta)\;F_4^{\nu,\bar{\nu}} - 2\eta\;F_5^{\nu,\bar{\nu}}\Big\}
\end{aligned}
$$

$$
\left.\frac{d\sigma}{dE_\mu}\right|_\nu = \frac{2G_F^2\,m_p}{\pi}\left[Q+\overline{Q}\;\left(\frac{E_\mu}{E_\nu}\right)^2\right]\;E_\nu
$$

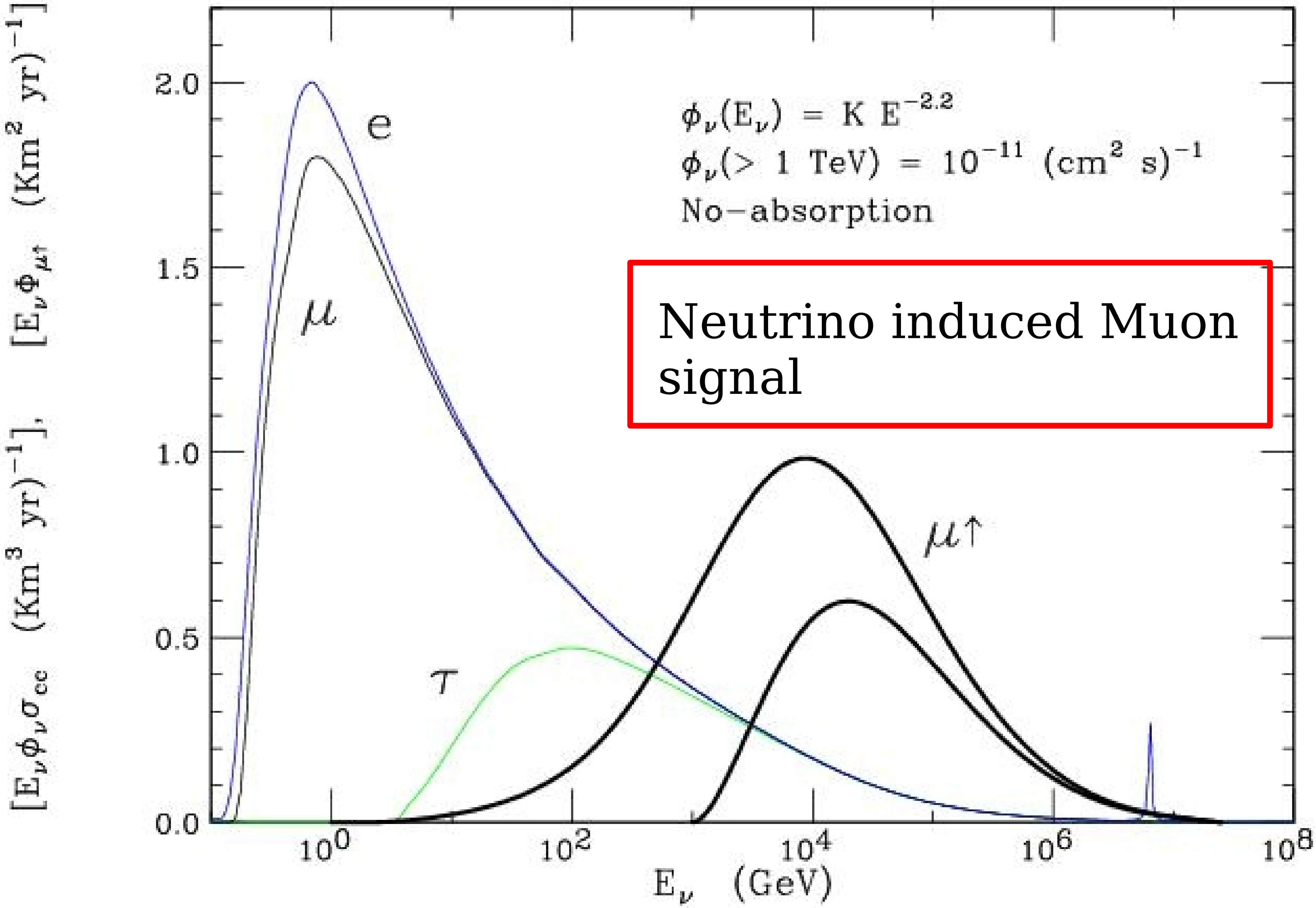
$$
\sigma_\nu(E_\nu) = \frac{2G_F^2\,m_p}{\pi}\left(Q+\frac{\overline{Q}}{3}\right)\;E_\nu
$$

NEUTRINO POINT SOURCES

“Standard Source”



$$\phi_\nu(E) = \frac{1}{4\,\pi\,r^2}\left[\frac{L^{\rm decade}(E_*)}{\ln 10}\;E_*^{\alpha-2}\right]\;E^{-\alpha}$$



$$\Phi_{\mu\uparrow} \simeq (1 \div 5) \left[\frac{\phi_\nu(\geq 1\ \text{TeV})}{10^{-11}\ (\text{cm}^2\,\text{s})^{-1}} \right] (\text{Km}^2\ \text{yr})^{-1}$$

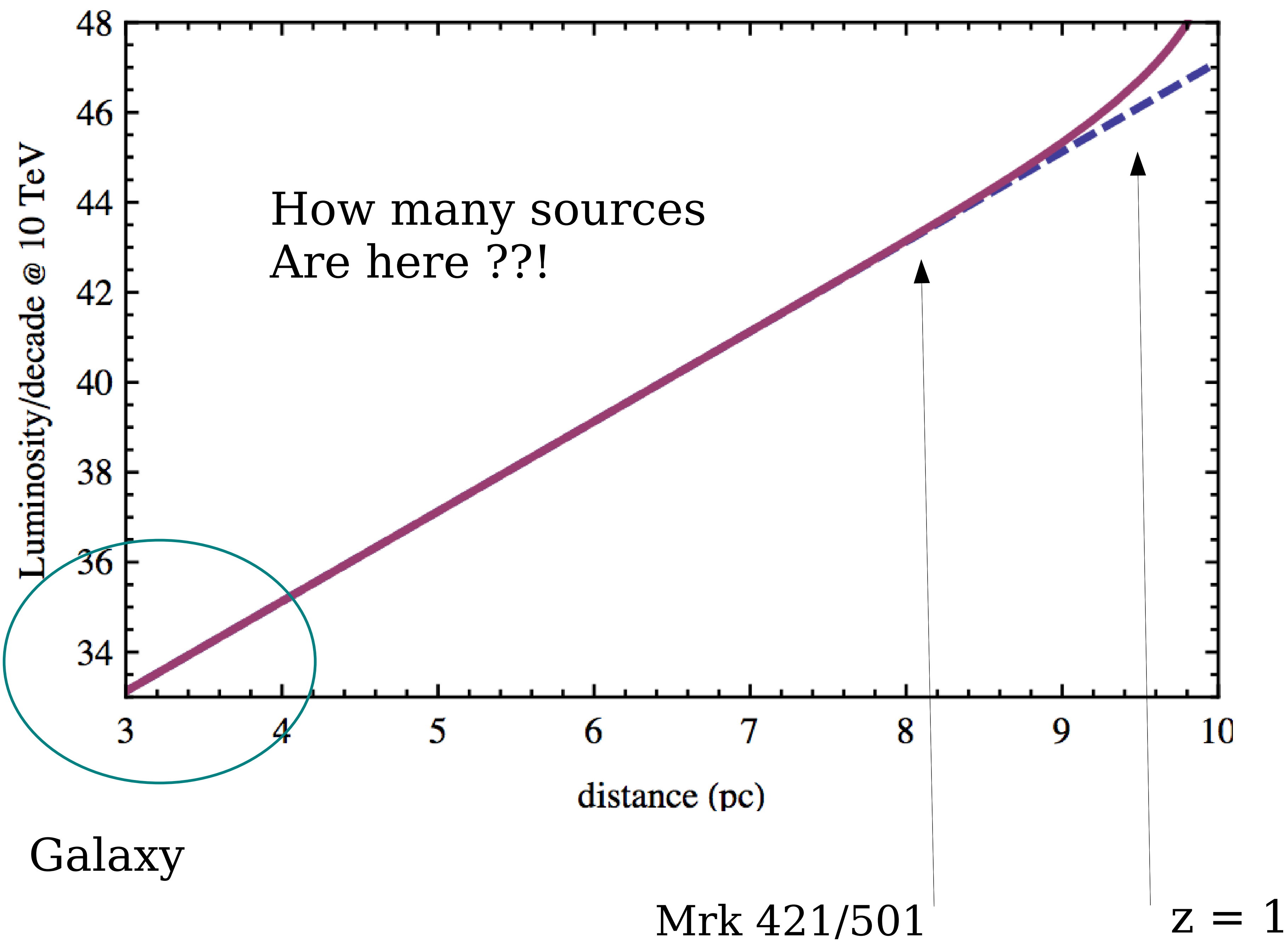
Energy Response: Peak @ 20 TeV

From the Neutrino Flux to the Muon induced signal.

$$N_{\mu\uparrow} \simeq 7.5 \times \left(\frac{L}{10^{34}\ \mathrm{erg/s}}\right) \left(\frac{\mathrm{Kpc}}{r}\right)^2 \left(\frac{A\,t}{\mathrm{Km}^2\,\mathrm{year}}\right)$$

$$N_{\mu\uparrow} \simeq 0.4 \times \left(\frac{L}{10^{46}\ \mathrm{erg/s}}\right) \left(\frac{A\,t}{\mathrm{Km}^2\,\mathrm{year}}\right) \frac{1}{z^2}$$

Line : 1 (muon event)/(km2 yr)



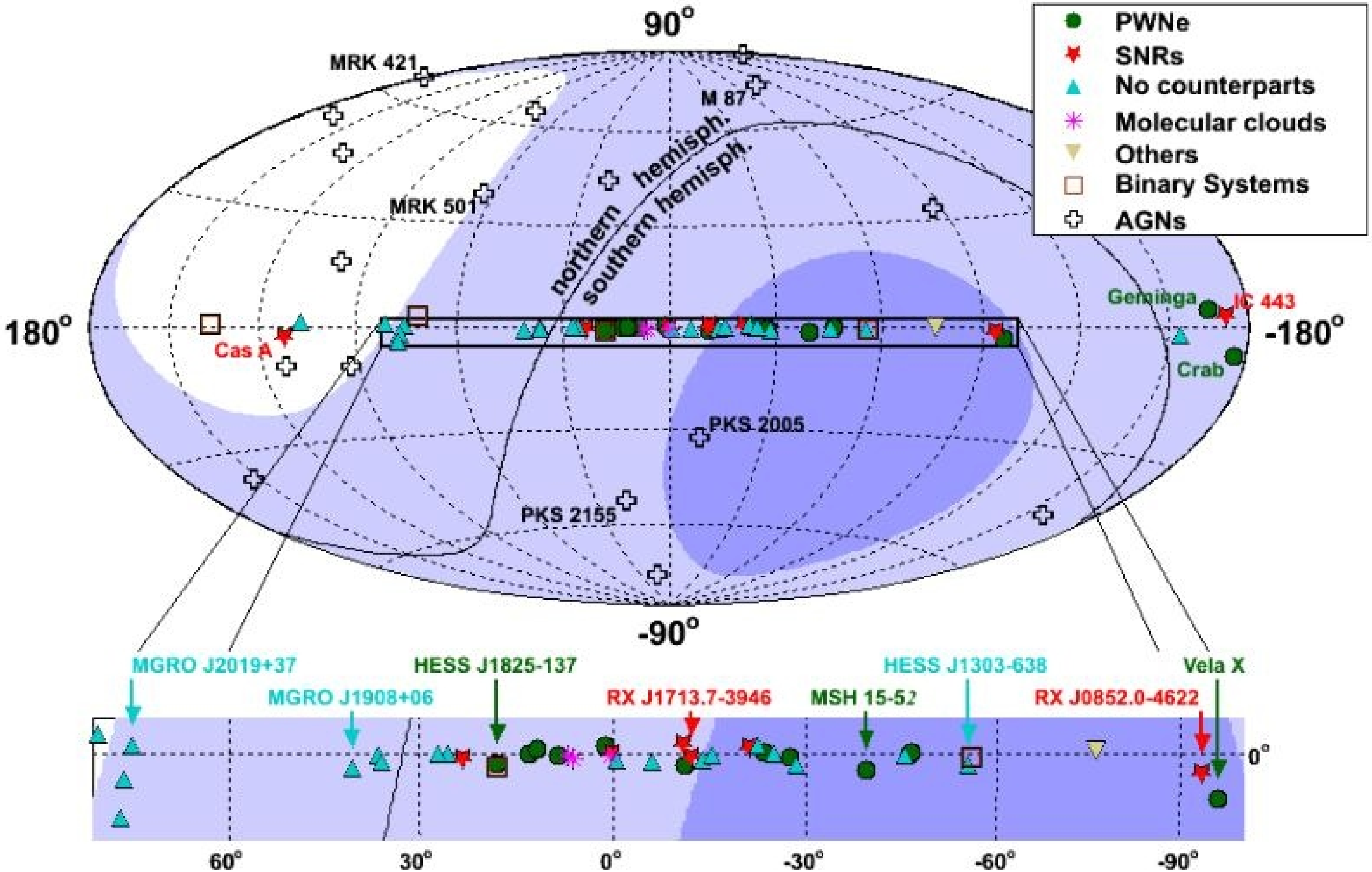
Cosmological effects

$$\frac{1}{r^2} \longrightarrow \frac{1}{r^2(z)\ (1+z)^{\alpha}}$$

Comoving distance

$$r(z) = \frac{c}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_\Lambda + \Omega_{\rm m}\,(1+z)^3}}$$

For neutrinos the universe is transparent !



90°
-90°
180°
-180°
PWNe
SNRs
No counterparts
Molecular clouds
Others
Binary Systems
AGNs
MRK 421
M 87
MRK 501
northern hemisph.
southern hemisph.
Geminga
IC 443
Cas A
Crab
PKS 2005
PKS 2155
MGRO J2019+37
HESS J1825-137
HESS J1303-638
Vela X
MGRO J1908+06
RX J1713.7-3946
MSH 15-52
RX J0852.0-4622
0°
60°
30°
0°
-30°
-60°
-90°

HESS

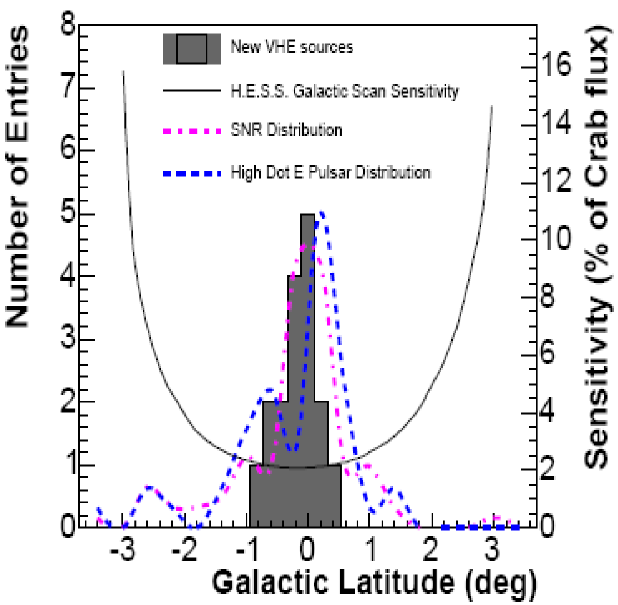
Science
March - 2005

“SCAN”

of the

Galactic Plane

15 New Sources
+ 3 Known



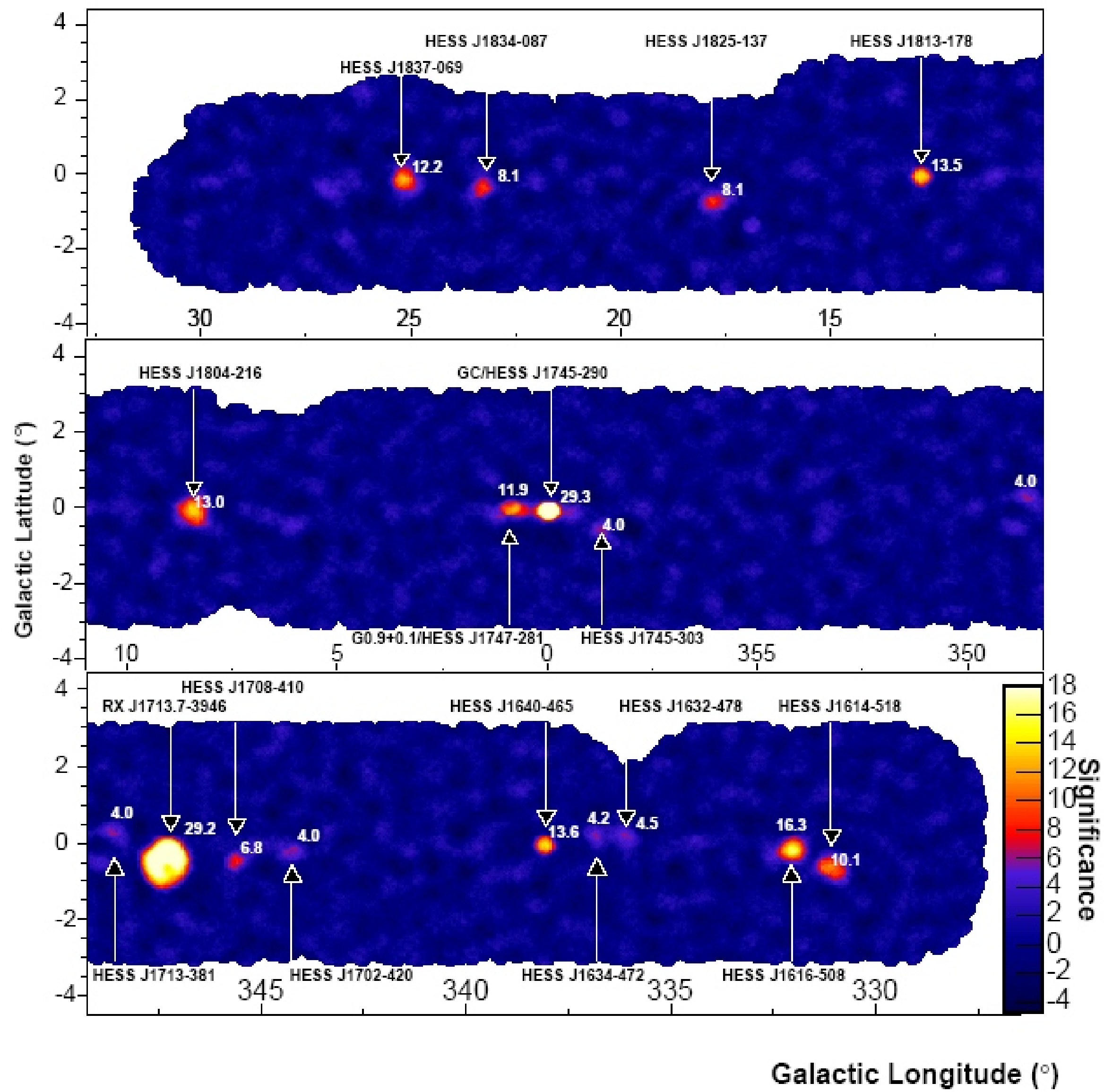


Table 3. Galactic sources.

	RA (h m)	Dec (° ′)	Flux[a]	Γ[b]	*s*[c]	Type	Association[d]
G1	02 40	+61 15	2.7	2.6	p	XRB	LSI+61 303 E0241+6103
G2	05 35	+22 01	22–37	2.4–2.8	p	PWN	Crab nebula
G3	06 16	+22 31	0.6	3.1	p	SNR	IS443
G4	06 33	+05 21	0.9	2.5	p	UID	Monoceros? E0634-0521?
G5	08 35	−45 34	9	1.7, 3.4 1.5(14)	e	PWN	Vela X
G6	08 52	−46 20	21	2.1	m	SNR?	R0852-4622
G7	10 23	−57 45	4.5	2.5	e	UID	Westerlund2
					stellar cluster in H II region		
G8	13 02	−63 49	1.3	2.7	p	BP	P1259-63
G9	13 03	−63 11	4.3	2.4	e	UID	
G10	14 18	−60 58	2.6	2.2	e	PWN?	G313.3+0.1?
G11	14 20	−60 45	3.5	2.2	e	PWN?	P1420-6048? E1420-6038?
G12	14 28	−60 51	1.3	2.2	e	UID	
G13	14 42	−62 29	2.7	2,5	e	SNR	RCW86
G14	15 14	−59 09	5.7	2.3	e	PWN	MSH15-52 P1509-58
G15	16 14	−51 49	8.1	2.5	e	UID	
G16	16 16	−50 53	6.7	2.4	e	PWN?	P1617-5055
G17	16 26	−49 05	4.9	2.2	e	UID	
G18	16 32	−47 49	5.3	2.1	e	UID	I16320-4751?
G19	16 34	−47 16	2.0	2.4	e	UID	I16358-4726? G337.2+0.1?
G20	16 40	−46 31	3.0	2.4	p	UID	G338.3-0.0? E1639-4702?
G21	17 02	−42 04	9.1	2.1	e	UID	P1702-4128?
G22	17 08	−41 04	2.7	2.5	p	UID	
G23	17 13	−38 11	0.7	2.3	e	UID	G348.7+0.3?
G24	17 13	−39 45	17 19	2.3 2.0(12)	m	SNR	R1713.7-3946 G347.3-0.5?
G25	17 18	−38 33	0.3	0.7(6)	e	PWN?	
G26	16 32	−34 43	6.1	2.3	e	UID	

CRAB Nebula
SNR: RX 1713.7 -3946 (SN 393A)
SNR: R0952-4622 (Vela Junior)

Table 4. Galactic sources—continued.

	RA (h m)	Dec (° ′)	Flux[a]	Γ[b]	*s*[c]	Type	Association[d]
G27	17 45	−29 00	2.5	2.2	p	UID (Galactic Center)	
G28	17 45	−30 22	2.5	1.8	e	UID	E1744-3011?
G29	17 47	−28 09	0.8	2.4	p	SNR?	G0.9+0.1
G30	18 00	−24 00	1.9	2.5	e	SNR?	W28
			0.8	2.7	e	molecular cloud	
G31	18 04	−21 42	5.7	2.7	e	UID	G8.7-0.1 P1803-2137?
G32	18 10	−19 18	4.6	2.2	e	PWN?	
G33	18 13	−17 50	2.7	2.1	p?	UID	G12.82-0.02?
G34	18 26	−13 44	20 21	2.4 2.2(25)	m	PWN	G18.0-0.7 P1826-1334
G35	18 26	−14 49	1.9	2.1	p	XRB	LS 5039
			2.3/0.1	1.9/2.5	gamma ray flux varies with 3.9d		
G36	18 33	−10 33	0.5	2.1	p	SNR PWN	G21.5-0.9 P1833-1034
G37	18 34	−08 45	2.6	2.5	e	UID	G23.3-0.3 W41?
G38	18 37	−06 56	5.0	2.3	e	UID	G25.5+0.0
G39	18 41	−05 33	12.8	2.4	e	UID	
G40	18 46	−02 59	0.6	2.3	p	SNR?	Kes75
					e	PWN?	P1846-0258
G41	18 57	+02 40	6.1	2.4	e	UID	
G42	18 58	+02 05	0.6	2.2	p?	UID	
G43	19 08	+06 30	8.8[h] 3.2	2.3 2.1	e	SNR?	G40.5-0.5
G44	19 12	+10 10			e	PWN?	P1913+1011?
G45	19 58	+35 12	2.3[g]	3.2	p	XRB	Cyg X-1
G46	20 19	+37 00	8.7[h]	2.3	e	PWN?	G75.2+0.1
G47	20 32	+41 30	0.6	1.9	e	UID	Cyg OB2?
			9.8[h]	2.3		?	
G48	23 23	+58 49	0.7	2.5	p?	SNR	Cas A

[a] Flux in the unit of 10^{-12} cm^{-2} s^{-1} TeV^{-1} at 1 TeV.
[b] Spectral index Γ when fitted by $E^{-\Gamma}$. See text for details.
[c] p: point-like, e: extended. m: morphological structure studied.

GALACTIC TeV catalog

Table 5. Extragalactic sources.

	RA	Dec	Flux[a]	Γ[b]	z[c]	Name
E1	02 32 53.2	+20 16 21	0.62	2.5	0.140	1ES 0229+200
E2	03 49 23.0	−11 58 38	0.45	3.1	0.188	1ES 0347−121
E3	05 50 40.8	−32 16 18	~0.3	2.8	0.069	PKS 0548-322
E4	10 15 04.1	+49 26 01	~0.3	4.0	0.212	1ES 1011+496
E5	s11 03 37.7	−23 29 31	0.4	2.9	0.186	1ES 1101−232
E6	11 04 27.6	+38 12 54	12–97	2.4–3.1(3)	0.031	Mkn 421
E7	11 36 26.4	+70 07 28	0.9	3.3	0.046	Mkn 180
E8	12 21 22.1	+30 10 37	1.3	3.0	0.182	1ES 1218+304
E9	12 30 54.4	+12 24 17	1	2.9	0.004	M87
E10	12 56 11.1	−05 47 22	[e]		0.536	3C279
E11	14 28 32.7	+42 40 20	1–2	2.6–3.7	0.129	H 1426+428
E12	15 55 43.2	+11 11 21	0.1–0.2	4.0	0.36?	PG1553+113
E13	16 53 52.1	+39 45 37	0.5–100	1.9–2.3(5)	0.034	Mkn 501
E14	19 59 59.9	+65 08 55	4–120	2.7–2.8 1.8(4–10)	0.047	1ES 1959+650
E15	20 09 29.3	−48 49 19	0.2	4	0.071	PKS 2005-489
E16	21 58 52.7	−30 13 18	2–3	3.3–3.4	0.116	PKS 2155-304
E17	22 02 43.3	+42 16 40	~0.3	3.6	0.069	BL Lacetae
E18	23 47 06.0	+51 42 30	1–5	2.3–2.5	0.044	1ES 2344+514
E19	23 59 07.9	−30 37 41	~0.3	~3.1	0.165	H 2356−309

[a] Flux in the unit of 10^{-12} cm^{-2} s^{-1} TeV^{-1} at 1 TeV.

[b] Spectral index Γ when fitted by $E^{-\Gamma}$.

[c] Red shift.

extra-GALACTIC TeV catalog

Absorption effects

TeV Galactic Sources
Measured by HESS, MAGIC

Have FLUX:

Flux (E_γ > 1 TeV) = 0.11 - 2.1

UNIT : $10^{-11}\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$

Three Brightest sources in the TeV sky:

CRAB NEBULA

2 young SNR
Vela Junior
RX 1713.7-3946

$$\Phi(E > 1\ \mathrm{TeV}) \simeq 10^{-11}\ (\mathrm{cm}^2\,\mathrm{s})^{-1}$$

TeV Photons in a Cherenkov Telescope

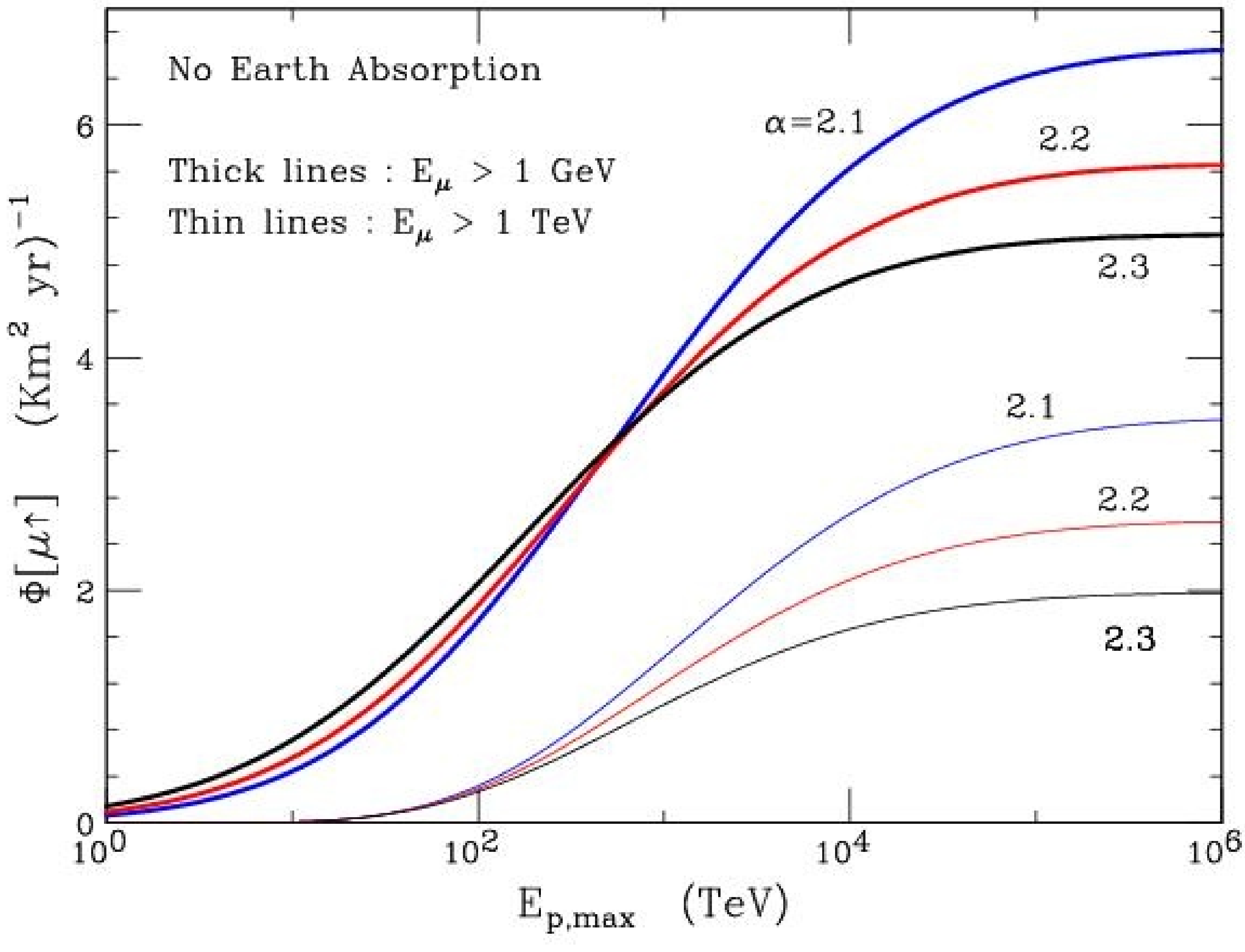
$$\sim 10\ \frac{\mathrm{events}}{\mathrm{hour}}$$

$$\phi(E) \propto E^{-2}$$

Up-going muons Neutrino telescope

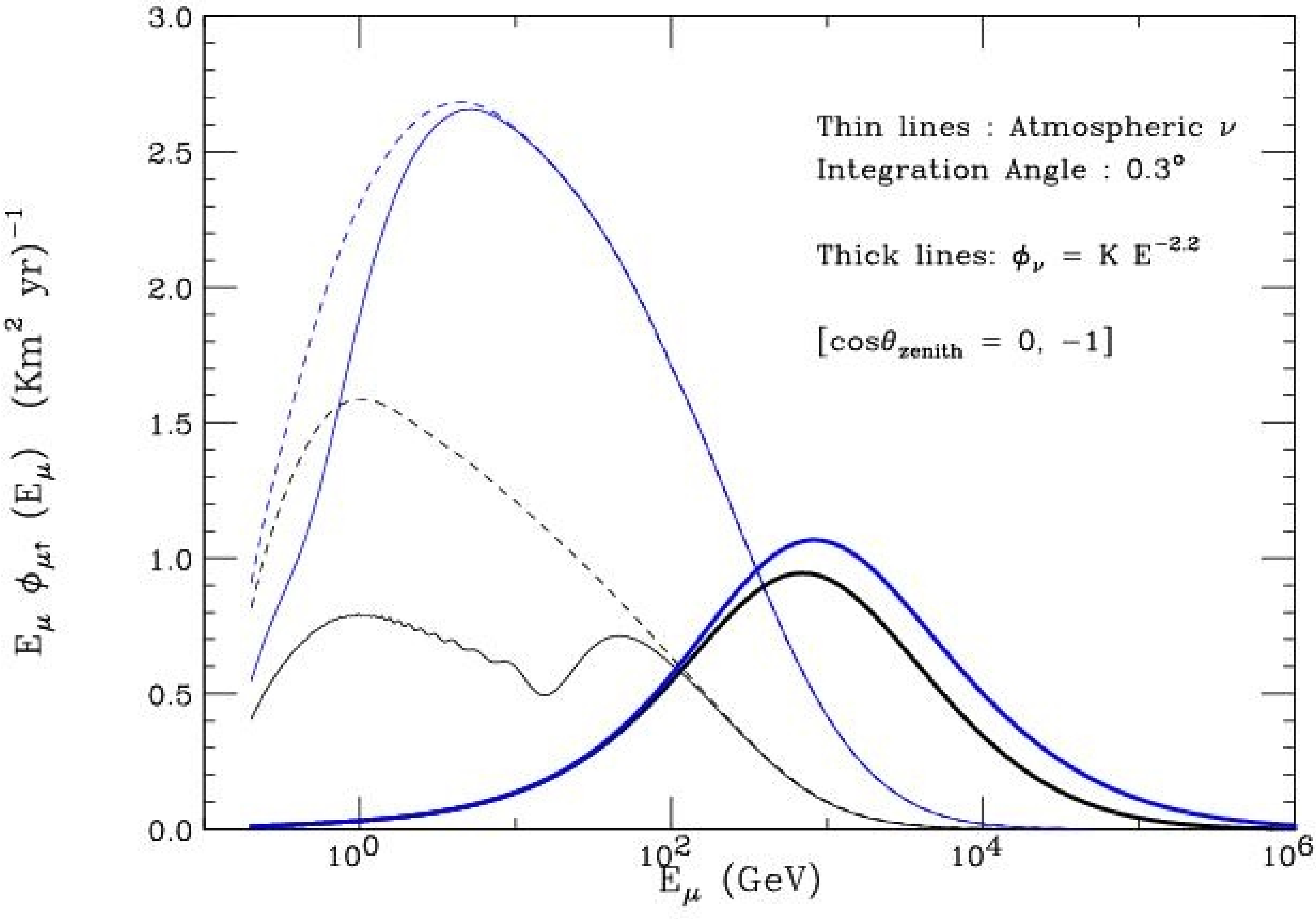
$$\sim 2\ \frac{\mathrm{events}}{\mathrm{Km}^2\,\mathrm{yr}}$$

Importance of cutoff !!

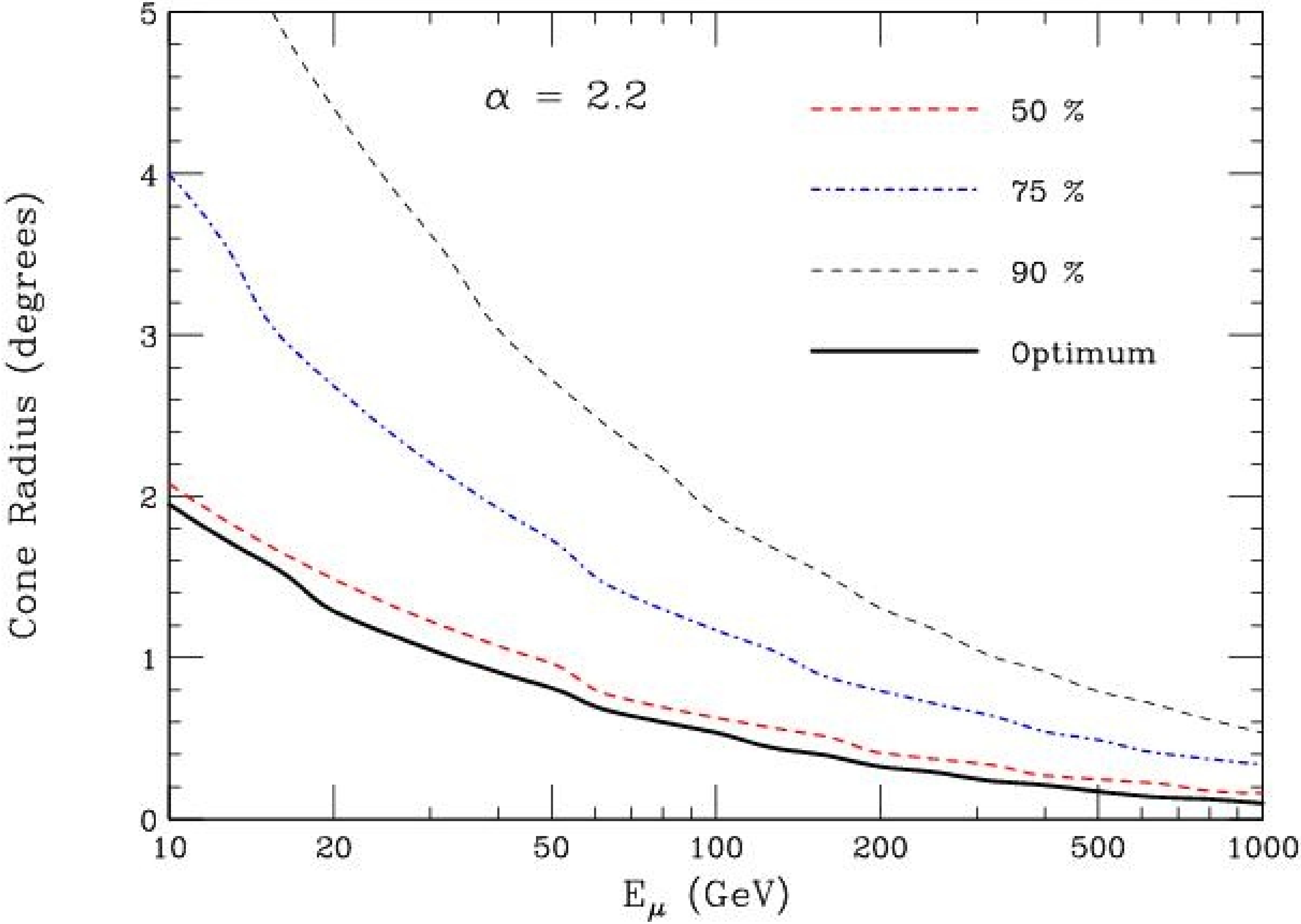


BACKGROUND

Atmospheric Neutrinos



Angular Distribution of the Neutrino – induced Muons



IF TEV emission of the
Brightest TeV sources
Is of hadronic nature

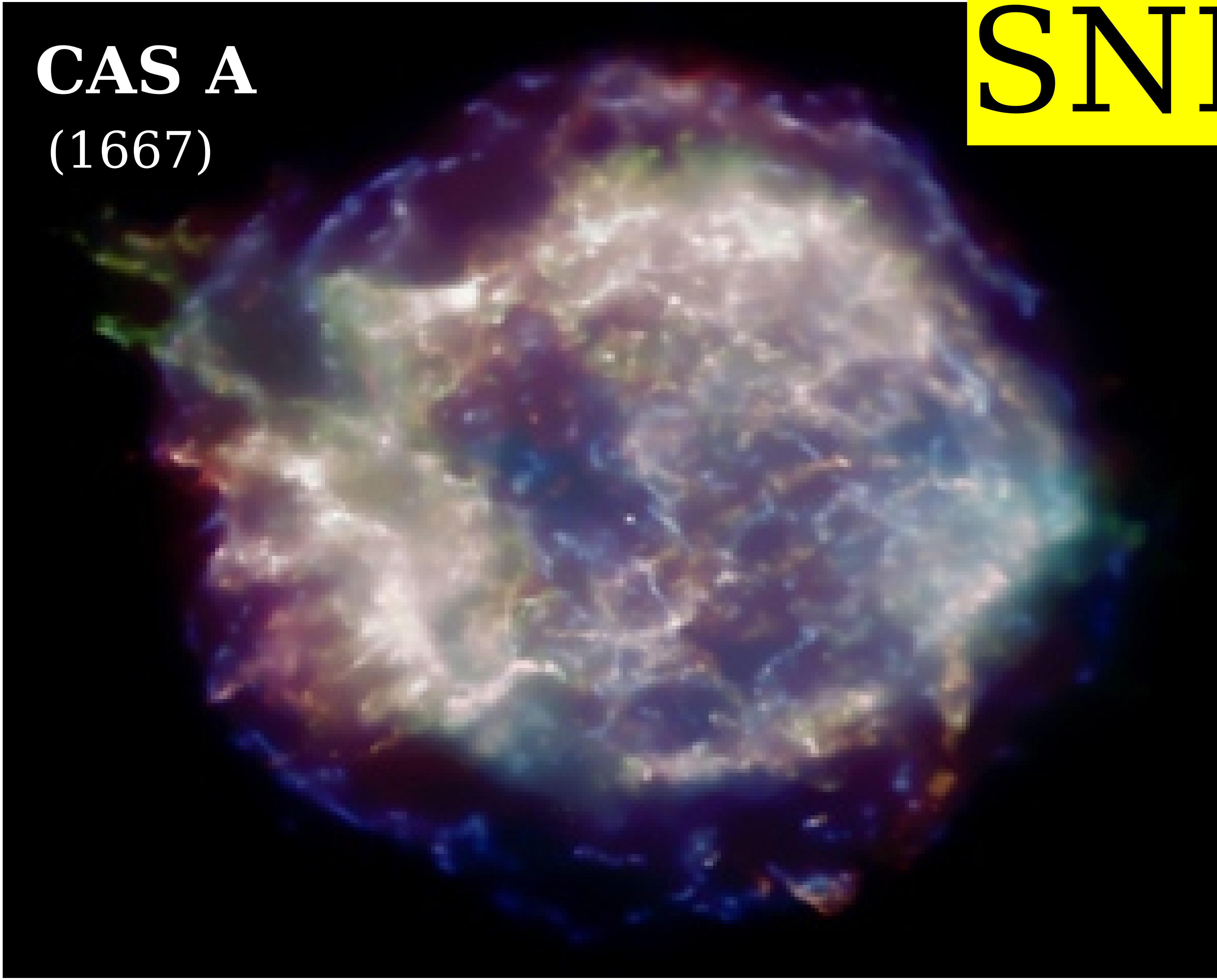
Detection with neutrinos
Is within reach .....

Few events / (km2 yr)

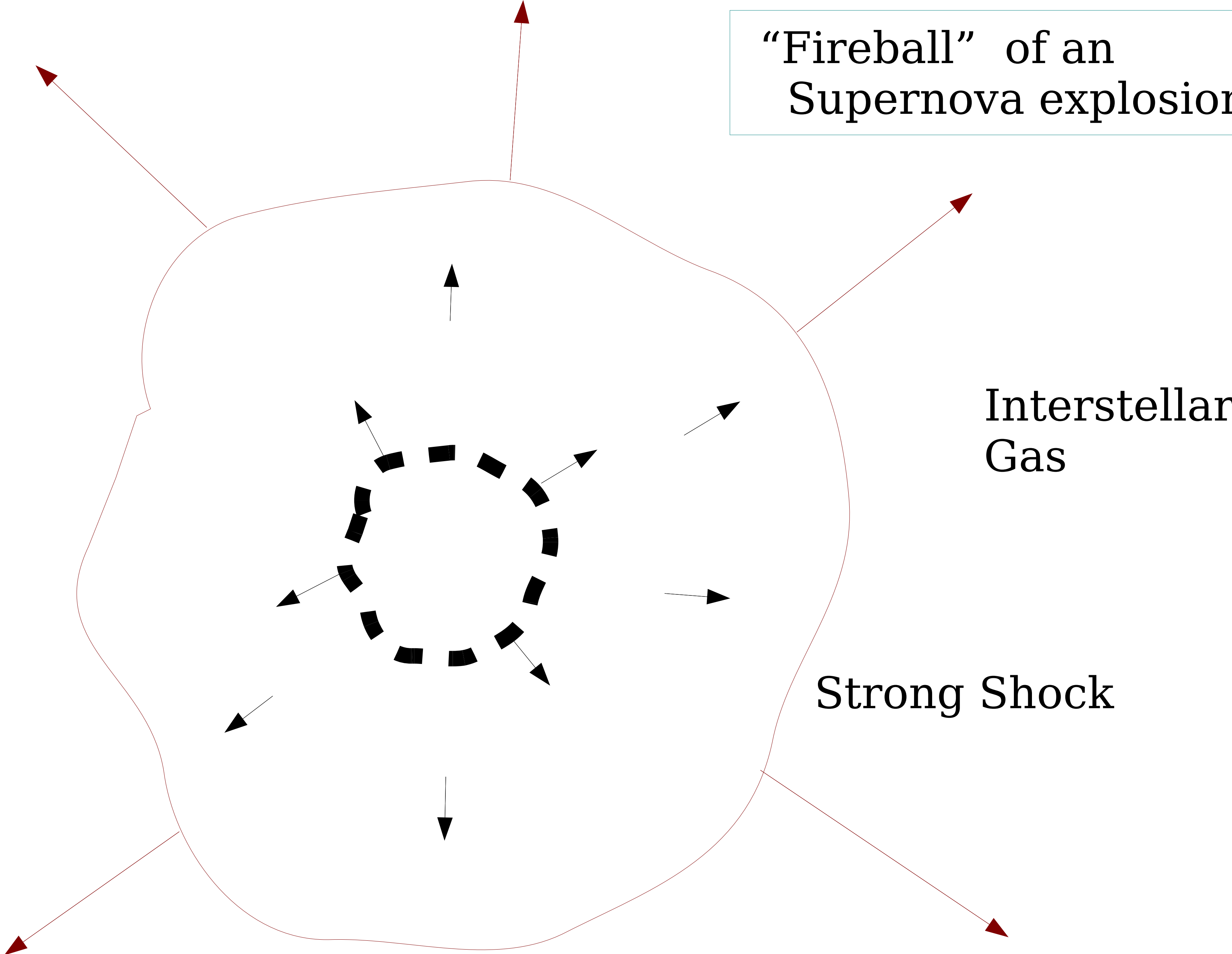
...but

NOT EASY !

SNR



“Fireball” of an Supernova explosion



Fermi 1st order acceleration

$$q(E) \propto E^{-(2+\varepsilon)}$$

POWERING THE GALACTIC COSMIC RAYS

$$L_{\rm cr}(\text{Milky Way}) \simeq \frac{\rho_{\rm cr}\, V_{\rm conf}}{T_{\rm conf}}$$

$$\simeq 2 \times 10^{41} \left(\frac{\rm erg}{\rm s}\right)$$

$$\simeq 5 \times 10^{7}\, L_{\odot}$$

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq E_{\rm SN}^{\rm Kinetic}\ f_{\rm SN}$$

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq \left[1.6 \times 10^{51}\ {\rm erg}\right]\ \left[\frac{3}{\rm century}\right]$$

$$M = 5\ M_{\odot}$$

$$v \simeq 5000\ {\rm Km/s}$$

$$L_{\rm SN\ kinetic}^{\rm Milky\ Way} \simeq 1.5 \times 10^{42}\ \frac{\rm erg}{\rm s}$$

Power Provided by SN is sufficient
with a conversion efficiency of 15-20 %
in relativistic particles

SuperNova RX J1713.7-3946

It is possible [or perhaps even likely]
That this will be the brightest neutrino source in the sky.

One of the brightest TeV objects.
Hadronic mechanism for the emission is likely
[some would say close to established]

A **crucial test**
for a telescope in the Northern hemisphere

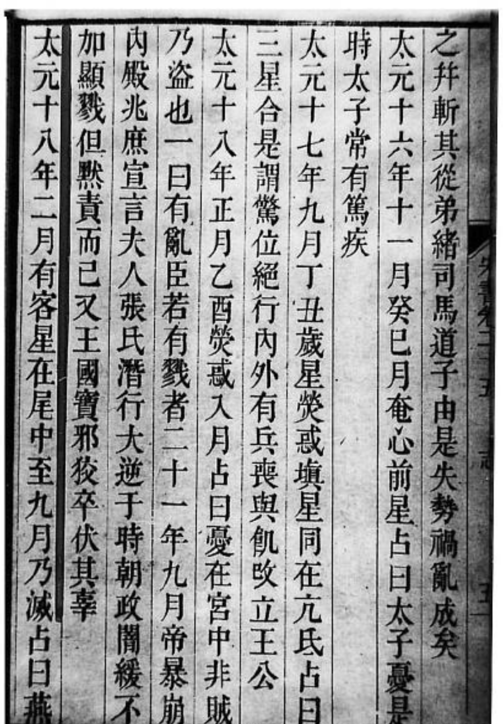
SuperNova 393A
RX J1713.7-3946

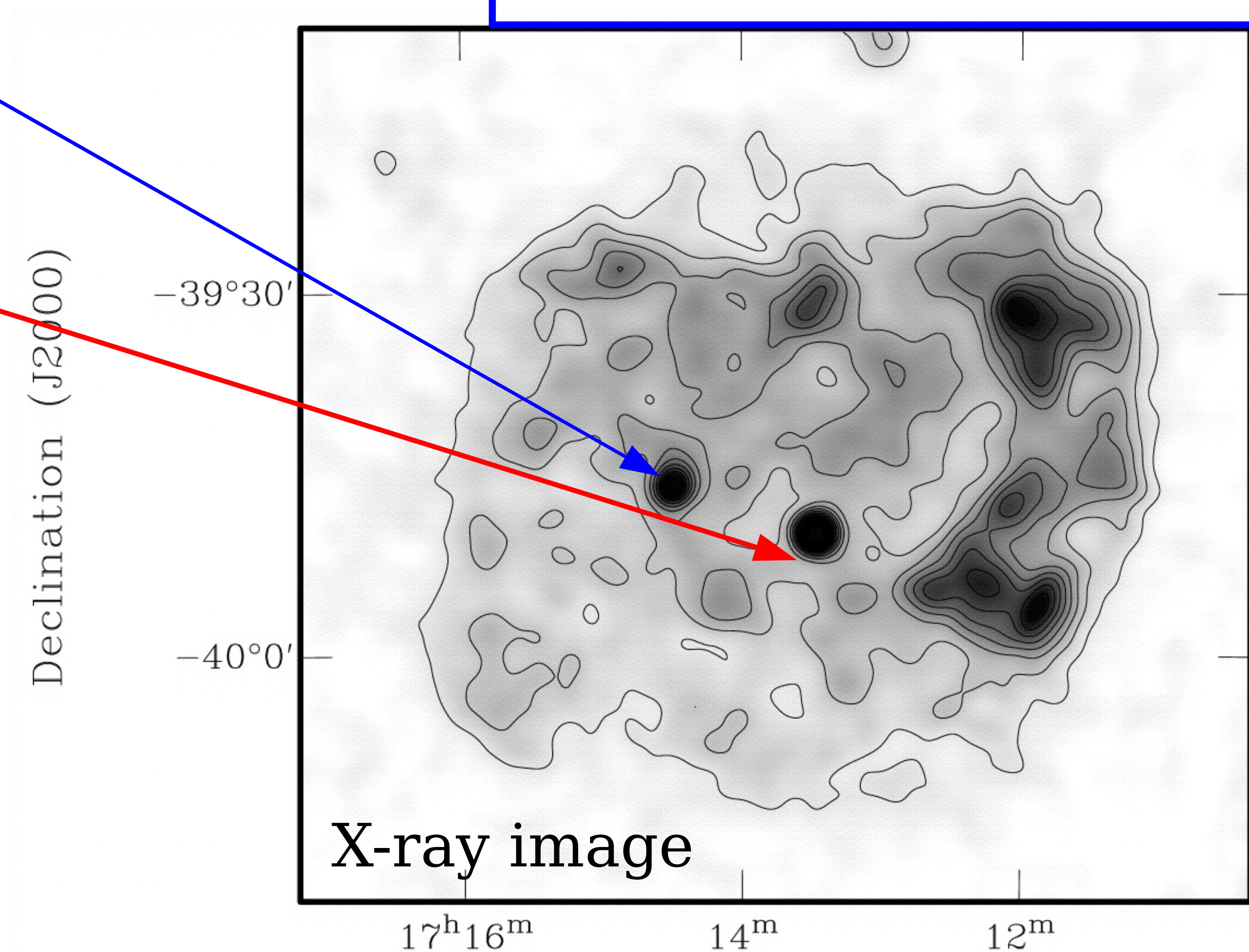
Observed in AD 393
By chinese court astromers
22-october, 19-november

(Re)-discovered in 1996
by the Roentgen Satellite

Foreground star

Neutron Star

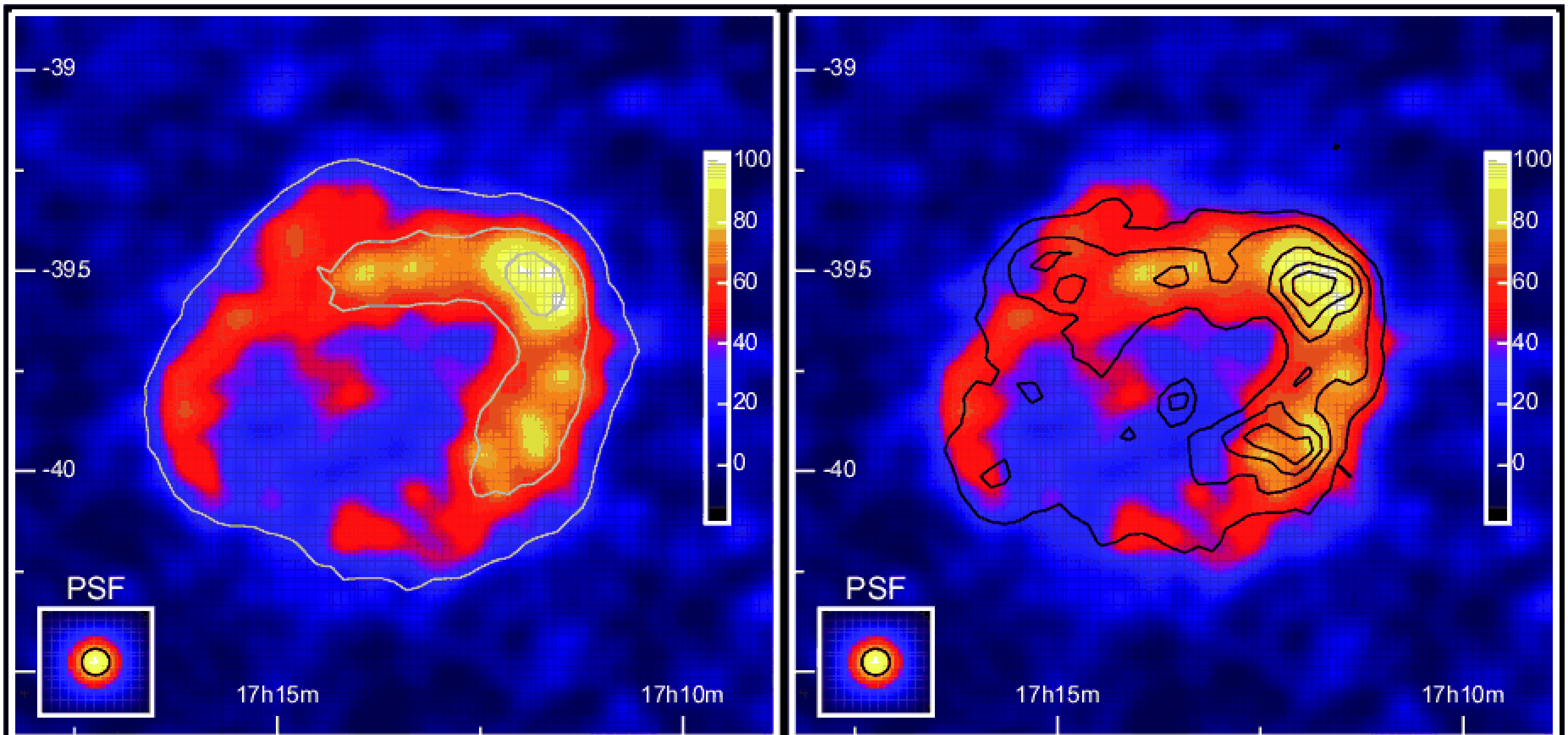

之幷斬其從弟緒司馬道子由是失勢禍亂成矣
太元十六年十一月癸巳月奄心前星占曰太子憂是
時太子常有篤疾
太元十七年九月丁丑歲星熒惑填星同在亢氐占曰
三星合是謂驚位絕行內外有兵喪與飢改立王公
太元十八年正月乙酉熒惑入月占曰憂在宮中非賊
乃盜也一曰有亂臣若有戮者二十一年九月帝暴崩
內殿兆庶宣言夫人張氏潛行大逆于時朝政闇緩不
加顯戮但黜責而已又王國寶邪狡卒伏其辜
太元十八年二月有客星在尾中至九月乃滅占曰燕



Detected in 2004 by HESS in TeV gamma rays

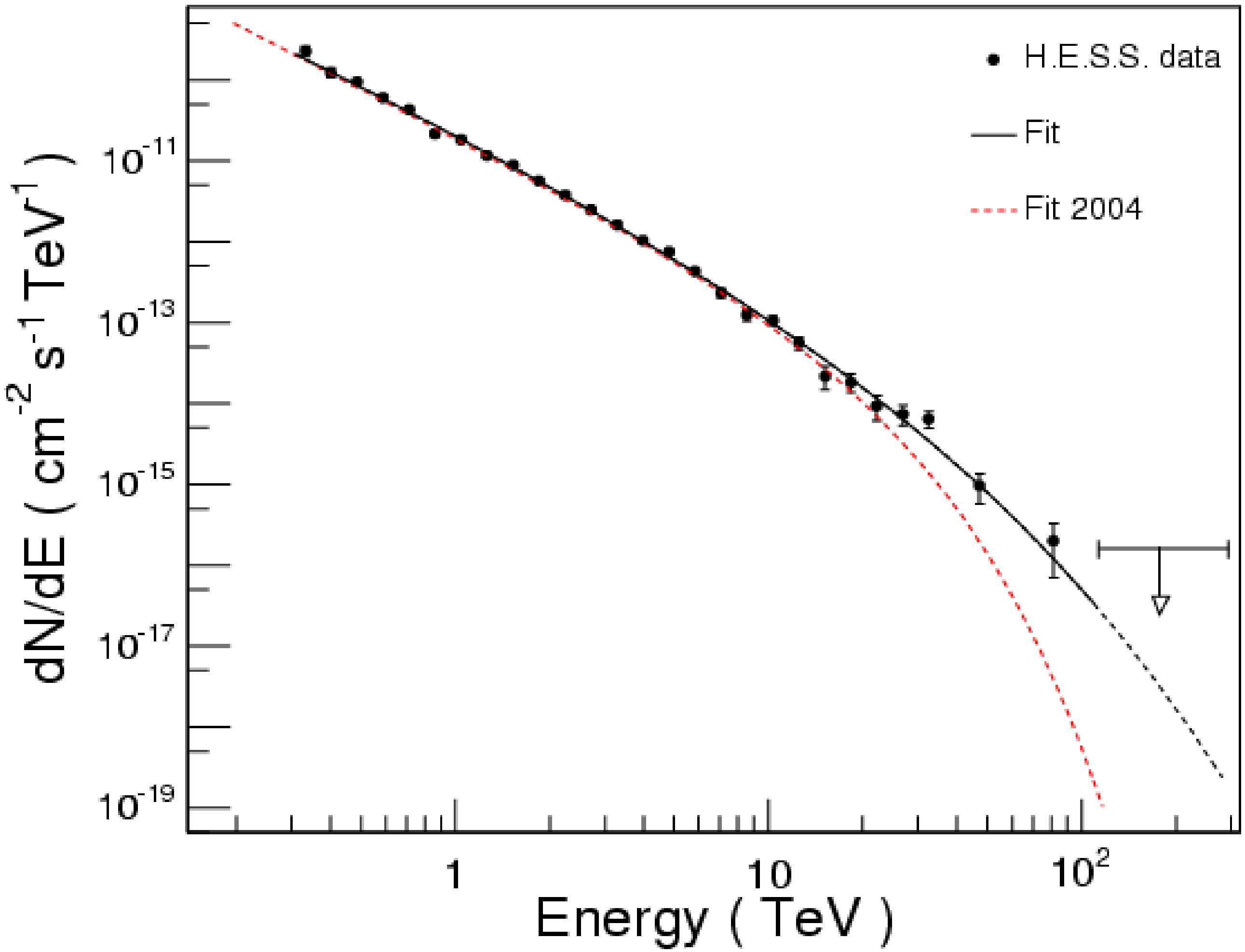
HESS Telescope

Remarkable observations with TeV photons



Comparison with ROSAT observation

ENERGY Spectrum



If gamma-rays are from π^0 decay, spectrum requires acceleration of protons to 200 TeV.

$$\phi_\gamma(E) = K\,E^{-\Gamma}$$

$$\Gamma = 2.19 \pm 0.09 \pm 0.15$$

$$\phi_\gamma(>1\ \mathrm{TeV}) = (1.47 \pm 0.17 \pm 0.37) \times 10^{-7}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}$$

$$\frac{dN_\gamma}{dt} \propto N_p \times n_{\rm target} \times \sigma_{pp}\, c$$

Hess estimate:

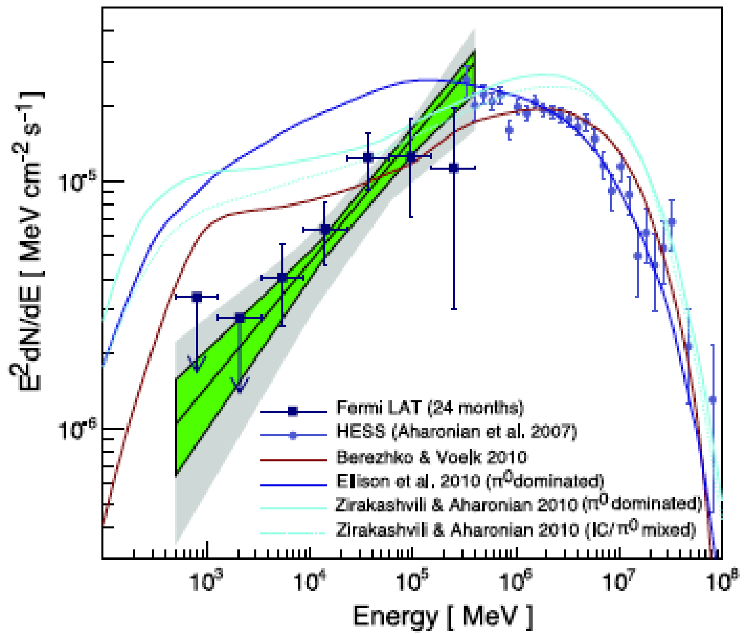
$$E^{\rm tot}_{{\rm relativistic}\ p} \simeq 0.2 \times 10^{51}\ {\rm erg}$$

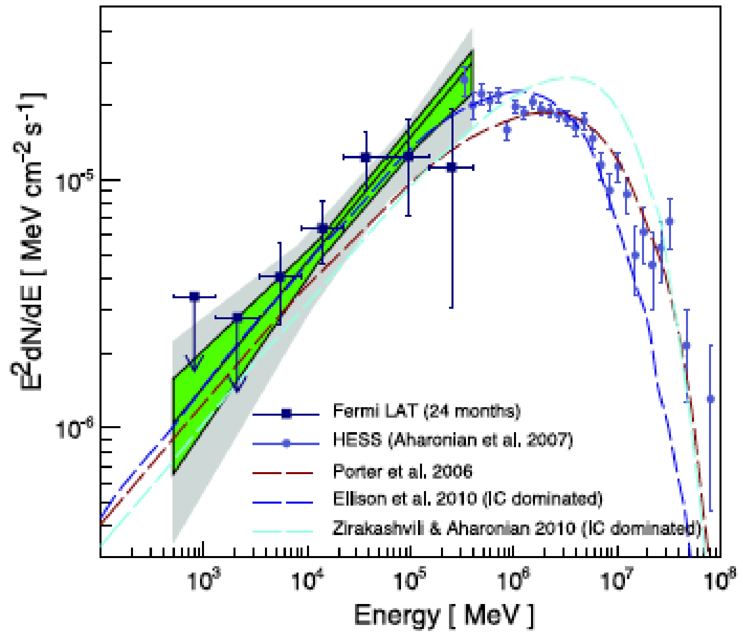
Essentially compatible with the
“Ortodoxy” (10% conversion of SN kinetic energy
into relativisic particles)

Observations of the young Supernova remnant RX J1713.7−3946 with the *Fermi* Large Area Telescope

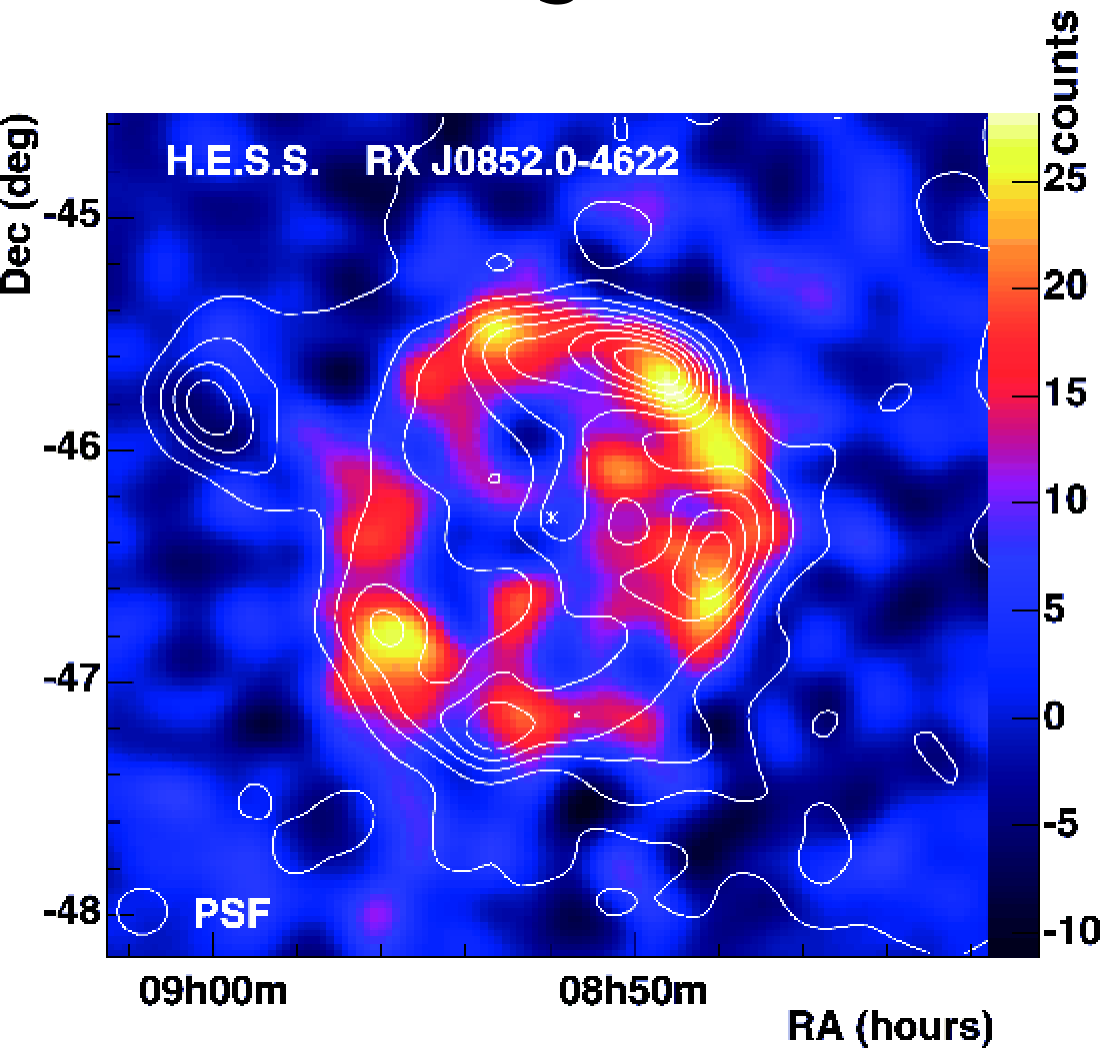
astro-ph/1103.5727.
29th march 2011

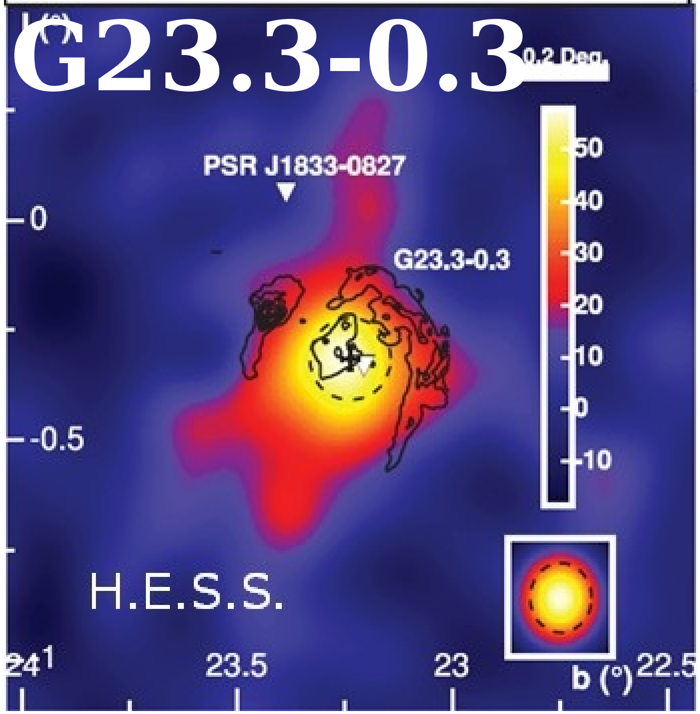
Favors
leptonic interpretation.

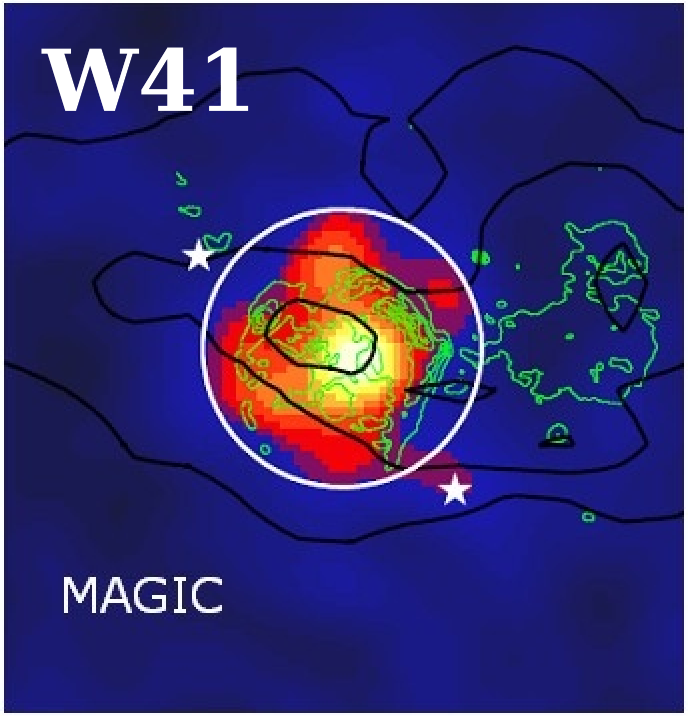




VELA JUNIOR


H.E.S.S. RX J0852.0-4622
counts
25
20
15
10
5
0
-5
-10
Dec (deg)
-45
-46
-47
-48
PSF
09h00m
08h50m
RA (hours)


G23.3-0.3
0.2 Deg.
PSR J1833-0827
G23.3-0.3
50
40
30
20
10
0
-10
0
-0.5
H.E.S.S.
24
23.5
23
22.5
b (°)


W41
MAGIC

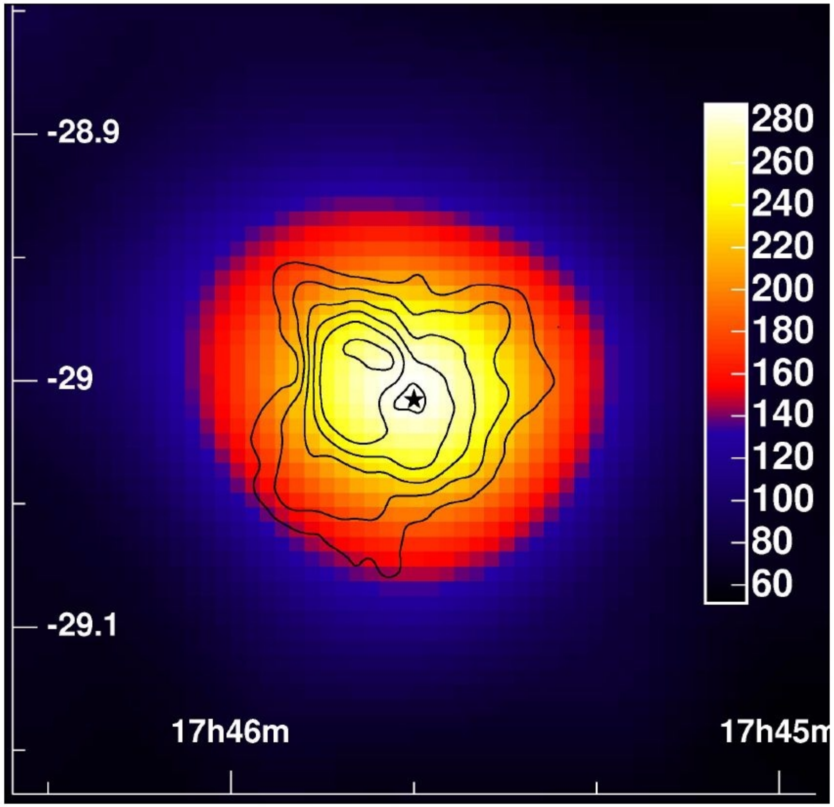
What about "ABSORBED SOURCES ?"

(Much) Higher flux in neutrinos than in photons ?

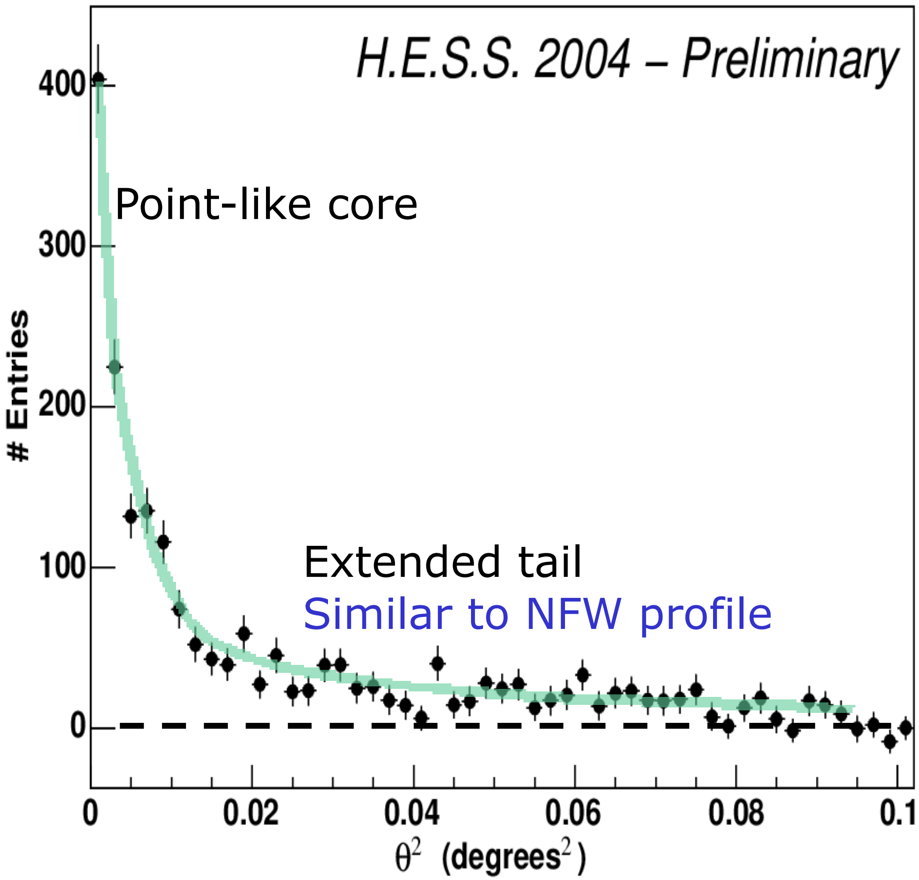
Best cases for making a bet:

- GALACTIC CENTER (of course !)
- MicroQuasars

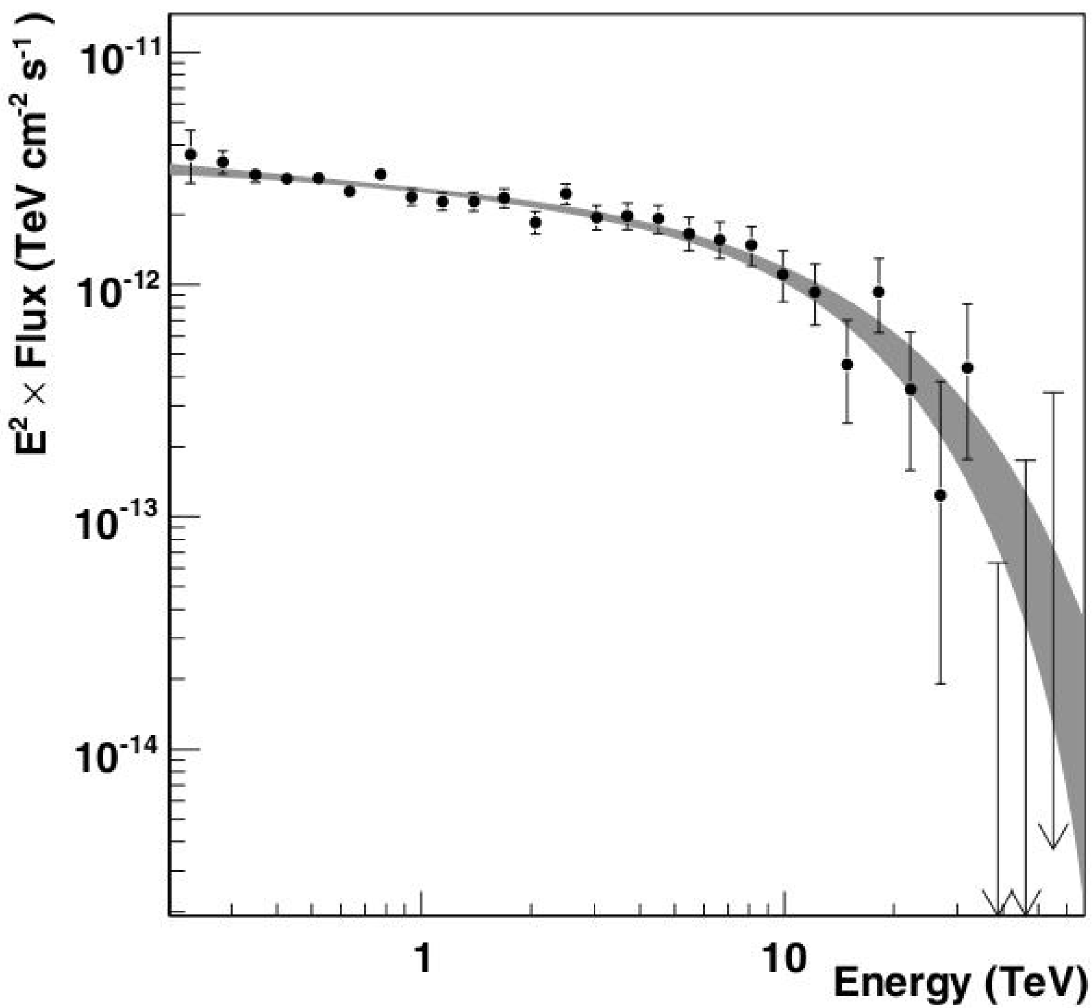
GALACTIC CENTER



Colors: H.E.S.S.
Contours: Radio

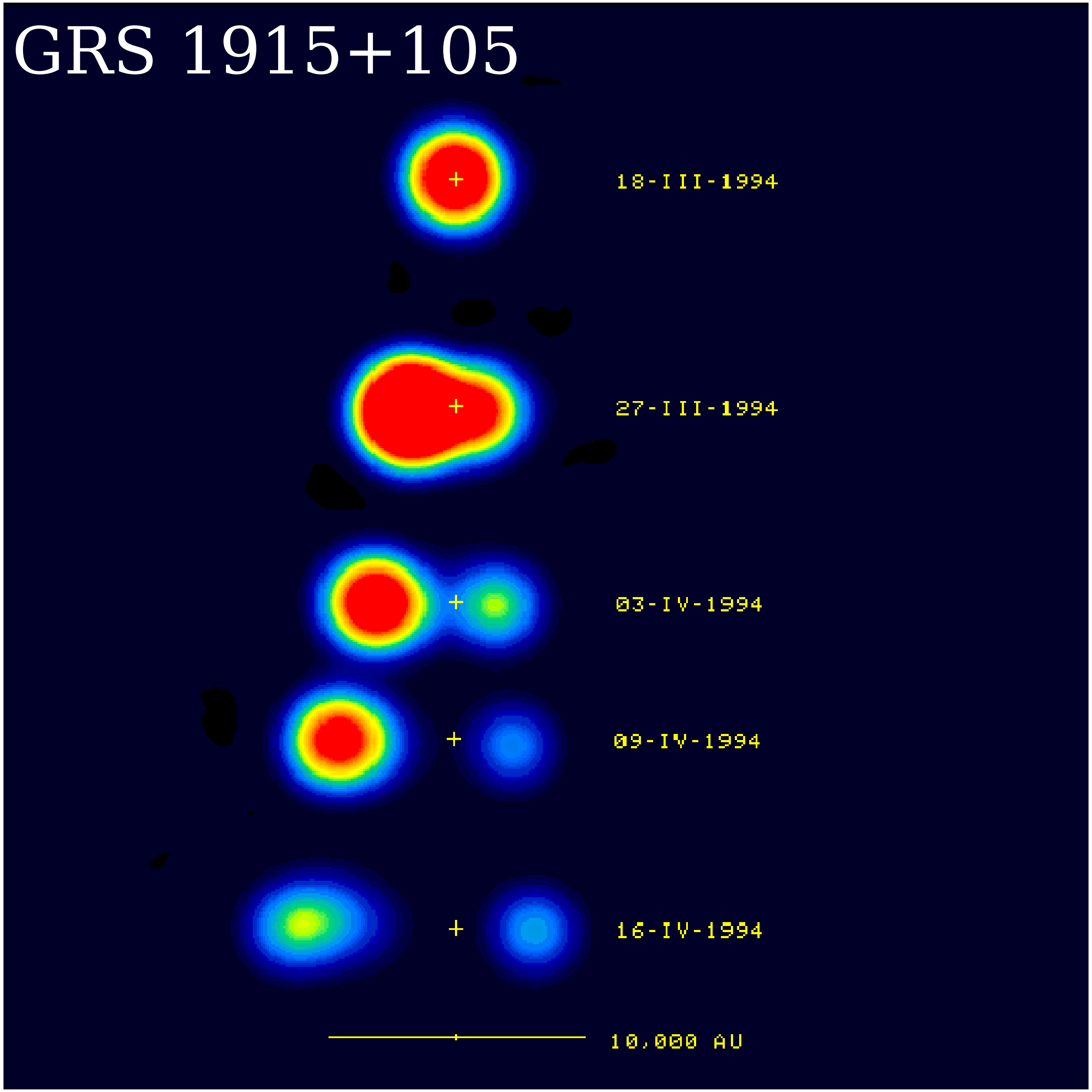


Angular distribution



Year	Φ_0 [a] (10^{-12}TeV^{-1}cm^{-2}s^{-1})	Γ [b]	$E_{\rm cut}$ [c] (TeV)	$E_{\rm cut,true}$ [d] (TeV)	$I(\geq 1$ TeV$)$ [e] (10^{-12}cm^{-2}s^{-1})	χ^2/d.o.f.
2004	2.40 ± 0.10	2.20 ± 0.07	20.70 ± 11.80	22.20 ± 11.80	1.81 ± 0.14	25/26
2005	2.56 ± 0.09	1.94 ± 0.07	9.09 ± 2.13	9.61 ± 2.13	2.09 ± 0.16	33/25
2006	2.35 ± 0.16	2.16 ± 0.11	32.90 ± 39.50	35.50 ± 39.50	1.88 ± 0.22	17/23
All	2.55 ± 0.06	2.10 ± 0.04	14.70 ± 3.41	15.70 ± 3.41	1.99 ± 0.09	23/26

MICROQUASARS

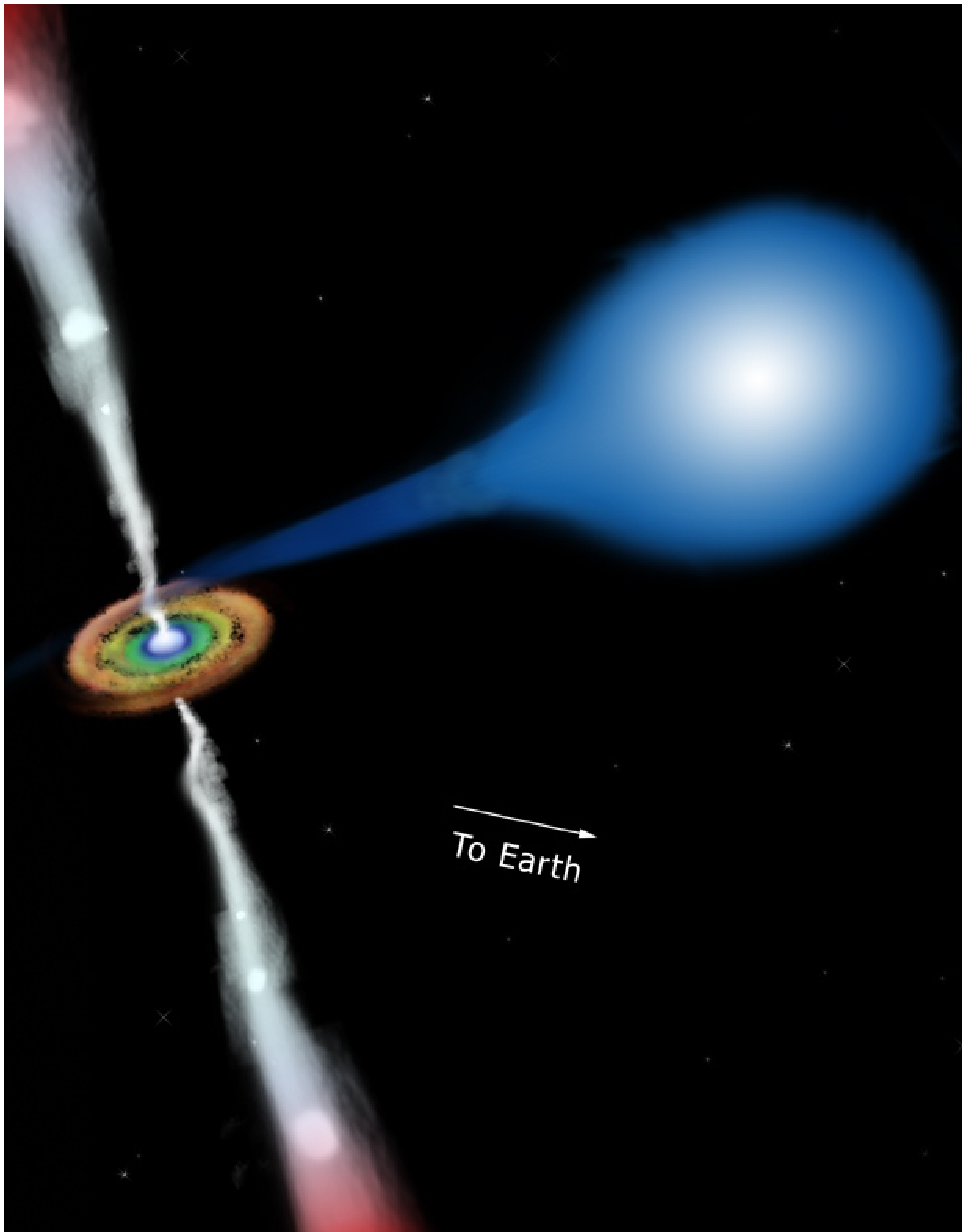


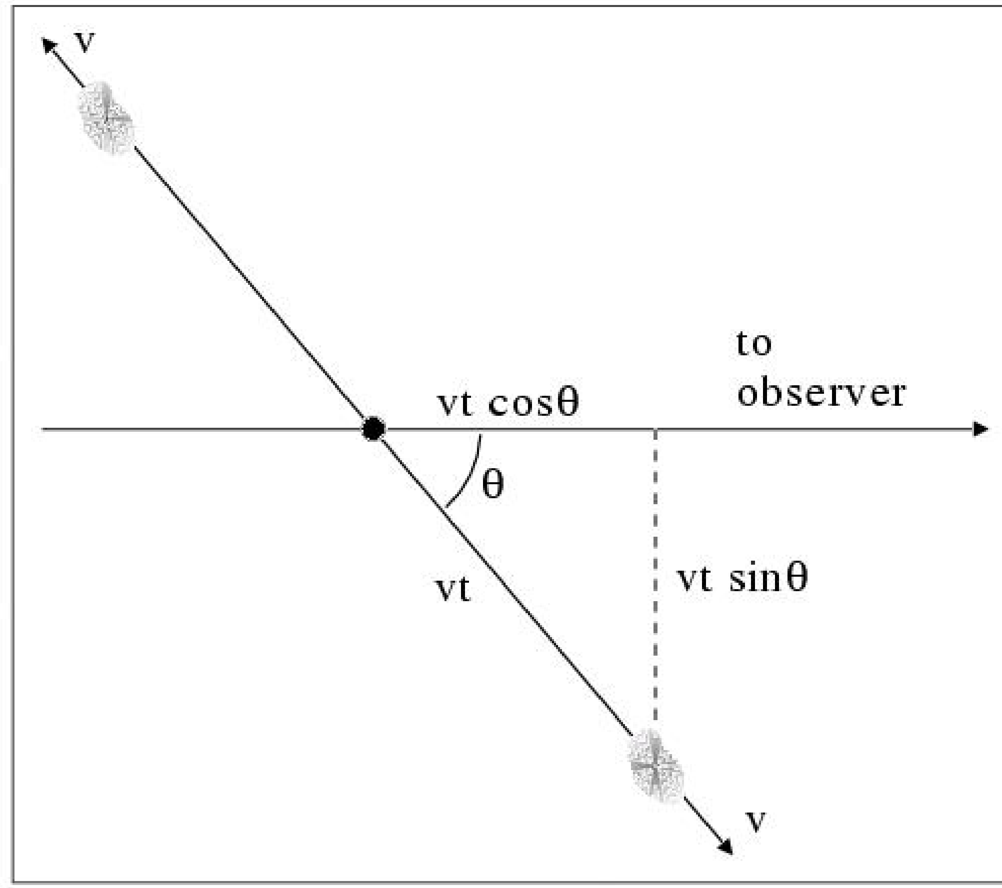
Galactic binary system with one stellar mass black hole

Symmetric emission of Plasma "blobs"

Detection in Radio (VLBI)

Geometry of the emission of the two jets

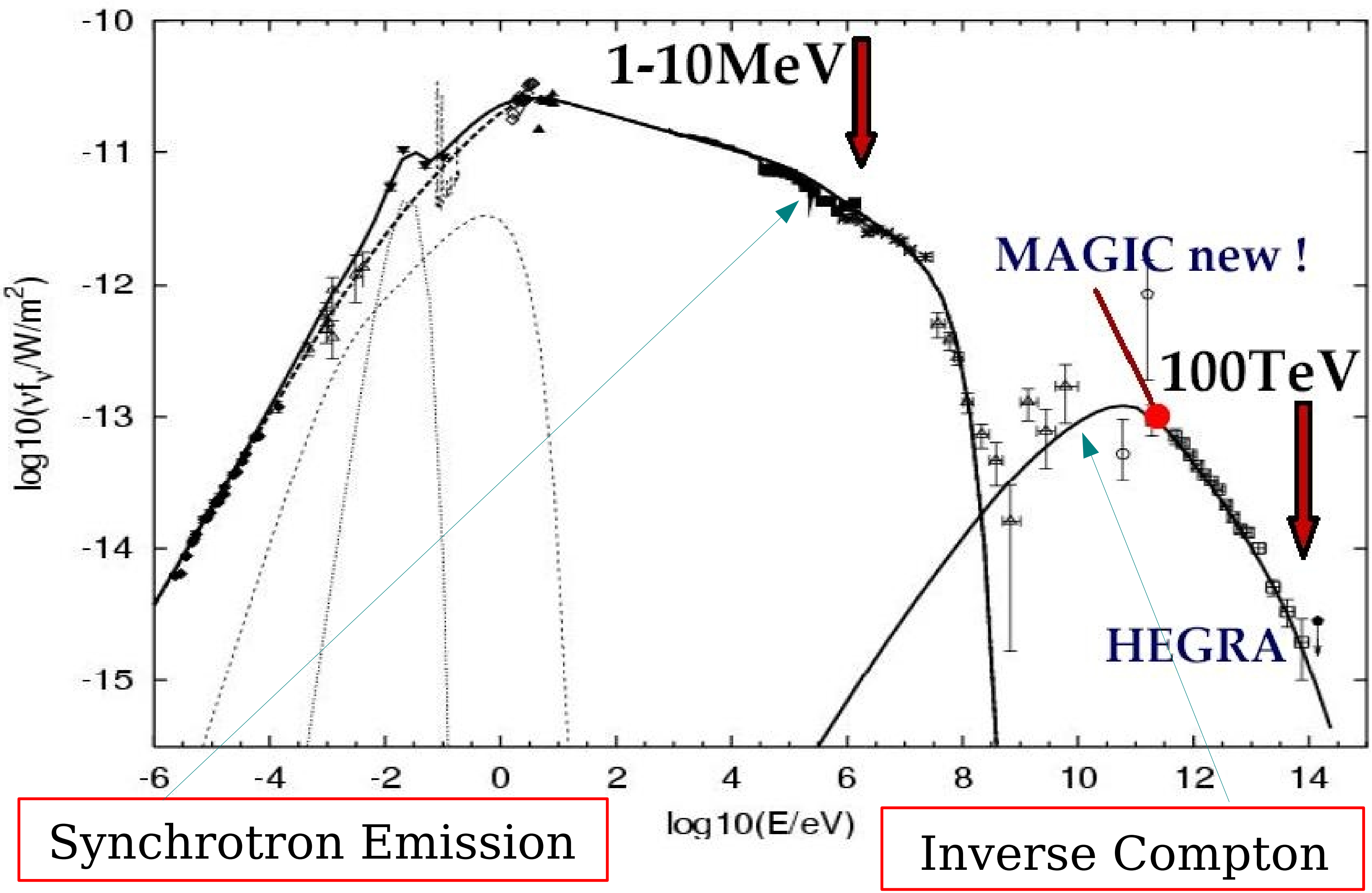




Intense radiation field
Of the companon star
Absorbs TeV photons [?]

CRAB NEBULA
(Self Synchrotron Compton)

Leptonic mechanism
(SSC satisfactory)



EXTRA-GALACTIC NEUTRINOS

UNRESOLVED FLUX

Sum of all High Energy
Neutrino Sources

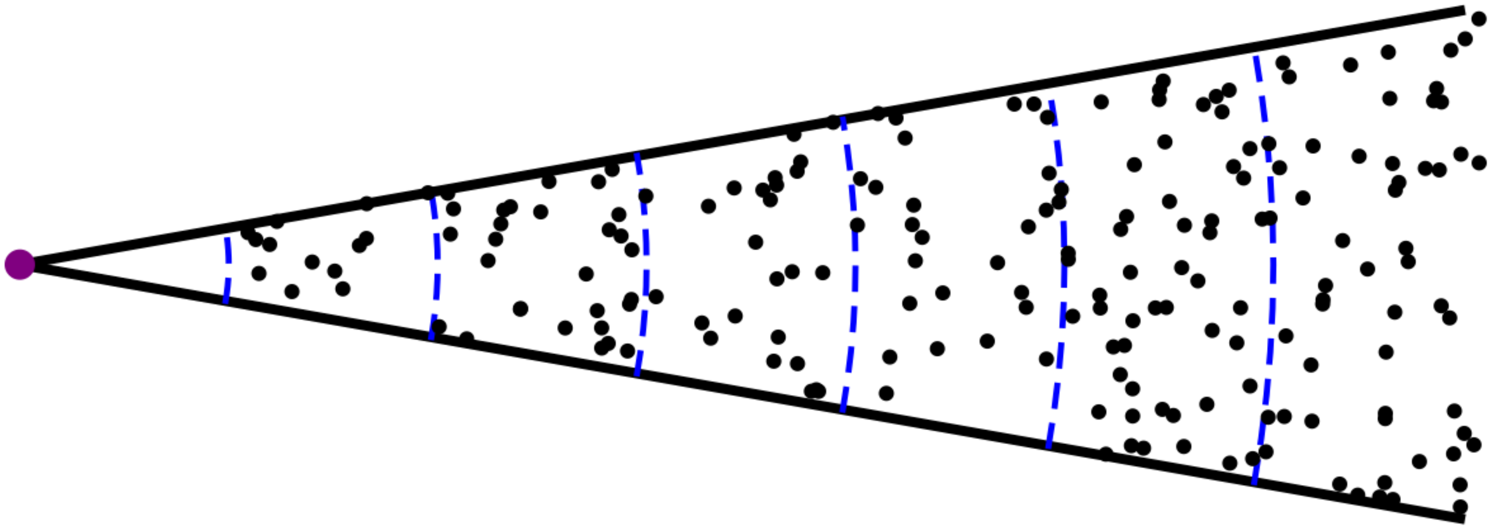
Individual Sources

AGN
GRB's

INCLUSIVE Extra-Galalactic Neutrino Flux

$$\phi_{\rm inclusive} = \sum_{\rm all\ sources} \phi_{\rm single\ source}$$

$$\phi_{\rm inclusive} = \int_{\rm all\ space} d^3r\ \phi_{\rm source}(\vec{r})$$



Integral dominated by large distances

Homogeneous Distribution of identical sources
In a static euclidean space:

$$\left.\frac{d\phi}{d\Omega}\right|_{\rm inclusive} = \frac{1}{d\Omega}\int_0^\infty dr\ (d\Omega\, n_s\, r^2)\ \frac{q}{4\,\pi\, r^2}$$

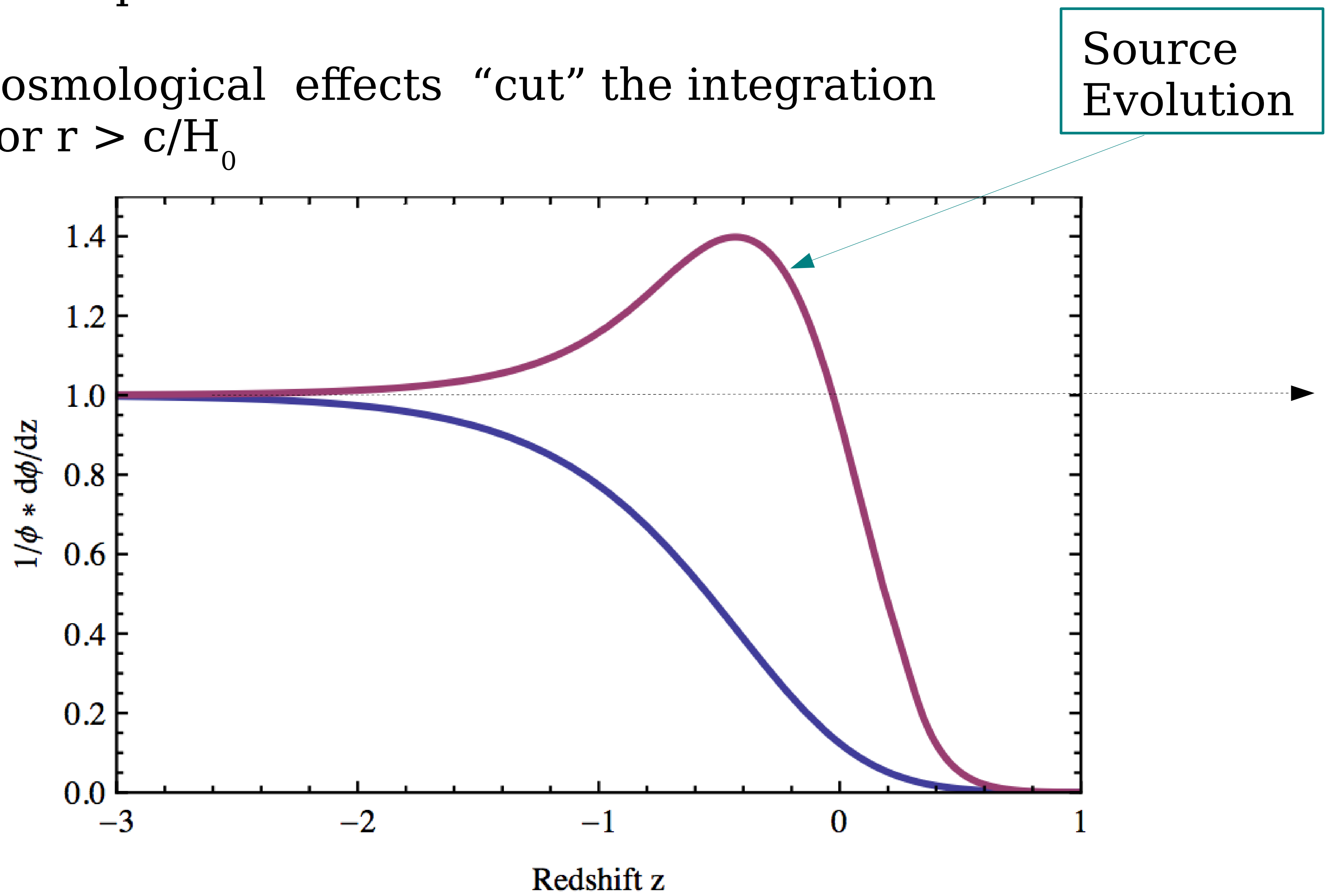
$$= \frac{n_s\ q}{4\,\pi}\ \int_0^\infty dr\ \mathbf{1} \to \infty$$

Flux is divergent ! Because of the contribution of
Many far, faint sources.

"The Olbers (Kepler) Paradox": Why is the night sky dark ?

Solution of the Paradox:
The expansion of the universe !

Cosmological effects "cut" the integration
For $r > c/H_0$



$$\phi_{\text{inclusive}}(E) = \left[\frac{1}{4\,\pi} \; \frac{c}{H_0} \; \frac{\mathcal{L}(E_*)}{\ln 10} \; E_*^{\alpha-2} \; \xi_\alpha \right] \quad E^{-\alpha}$$

$\mathcal{L}(E_*)$ = Power Density per energy decade at E = E*

$$\xi_\alpha = \int_0^\infty \frac{dz \; (1+z)^{-\alpha}}{\sqrt{\Omega_m \, (1+z)^3 + \Omega_\Lambda}} \; \frac{\mathcal{L}(z)}{\mathcal{L}(0)}$$

$$\phi_{\text{inclusive}}(E) = \left[\frac{1}{4\pi} \frac{c}{H_0} \frac{\mathcal{L}(E_*)}{\ln 10} E_*^{\alpha-2} \xi_\alpha \right] E^{-\alpha}$$

$\mathcal{L}(E_*)$ = Power Density per energy decade at E = E*

$$\xi_\alpha = \int_0^\infty \frac{dz\,(1+z)^{-\alpha}}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \frac{\mathcal{L}(z)}{\mathcal{L}(0)}$$

Spectral shape

Cosmology

Source evolution

$$\phi_{\mathrm{inclusive}}(E) = \left[\frac{1}{4\,\pi}\;\frac{c}{H_0}\;\frac{\mathcal{L}(E_*)}{\ln 10}\;E_*^{\alpha-2}\;\xi_\alpha\right]\quad E^{-\alpha}$$

$\mathcal{L}(E_*)$ = Power Density per energy decade at E = E*

$$\xi_\alpha = \int_0^\infty \frac{dz\;(1+z)^{-\alpha}}{\sqrt{\Omega_m\,(1+z)^3 + \Omega_\Lambda}}\;\frac{\mathcal{L}(z)}{\mathcal{L}(0)}$$

$\xi_\alpha \simeq 0.53 - 0.22\,(\alpha - 2)$ No source evolution

$\xi_\alpha \simeq 2.2 - 1.23\,(\alpha - 2)$ Source evolution

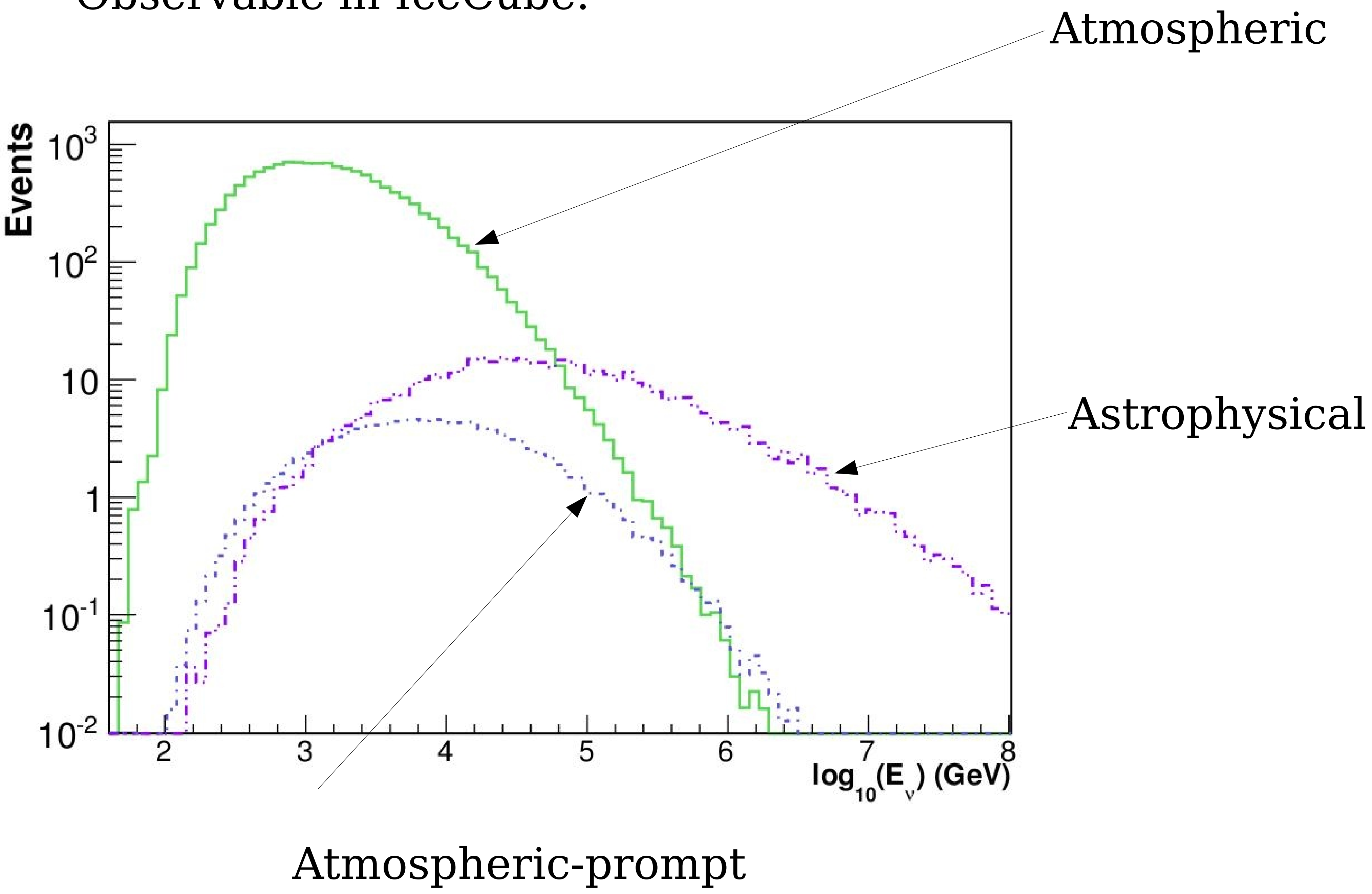
Existing (published) limit on the diffuse neutrino flux implies:

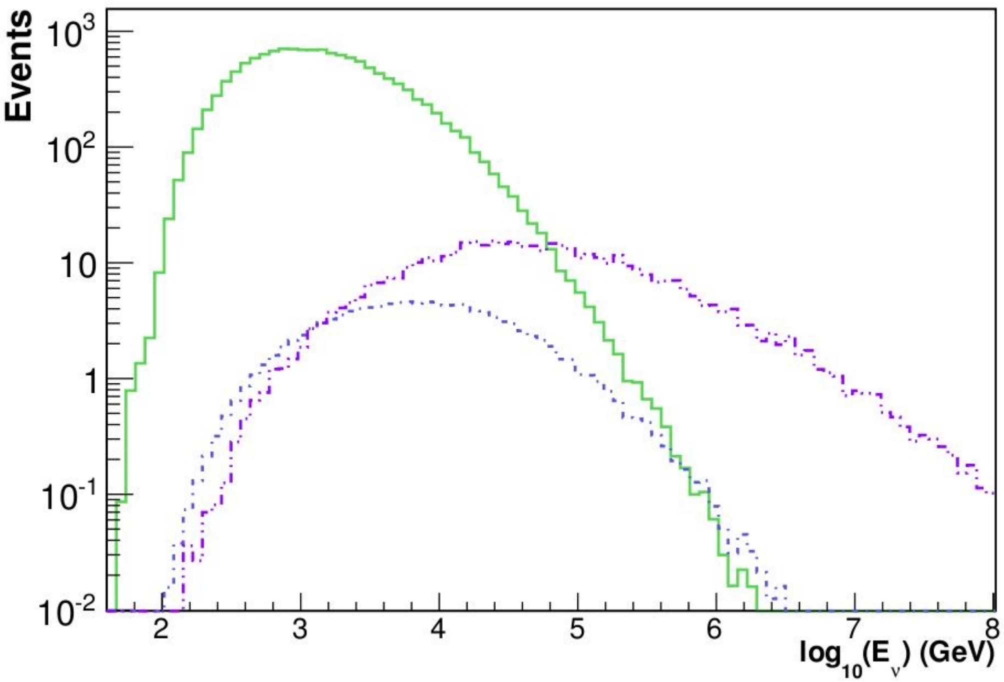
$$\mathcal{L}_\nu \leq 10^{37} \ \frac{\text{erg}}{\text{s Mpc}^3}$$

$$\mathcal{L}_{\text{SN}}^{\text{kin}} \simeq 3 \times 10^{40} \ \text{erg}/(\text{Mpc}^3\text{s})$$

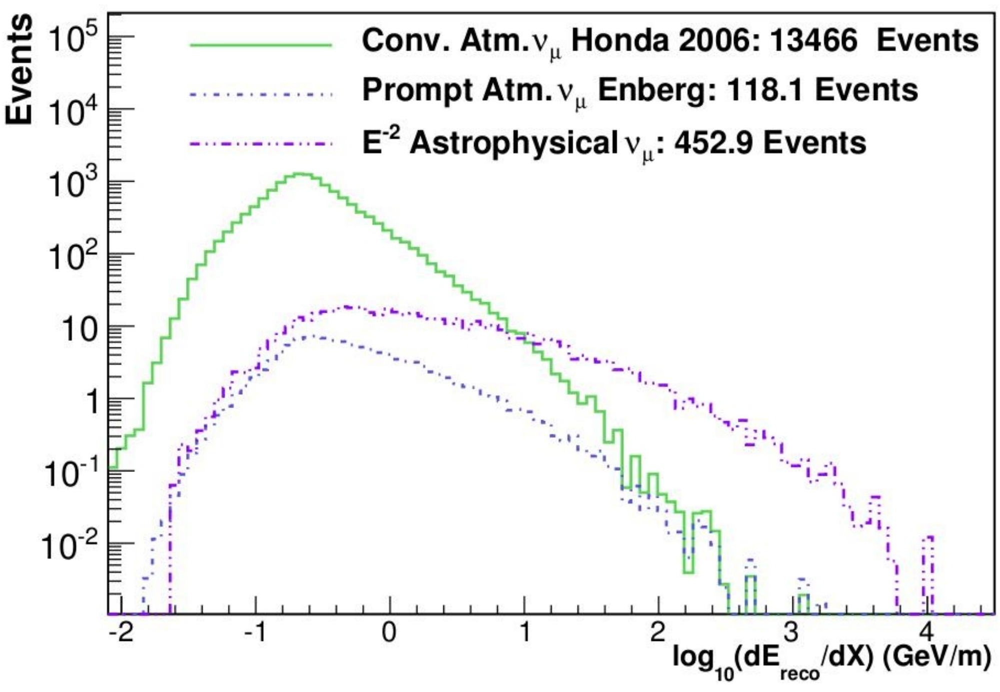
$$\mathcal{L}_{\text{AGN}}^{\text{bolometrix}} \simeq 2 \times 10^{40} \ \left(\frac{\text{erg}}{\text{s Mpc}^3}\right)$$

[MonteCarlo] Energy Spectrum of Neutrinos Observable in IceCube.





Neutrino Energy

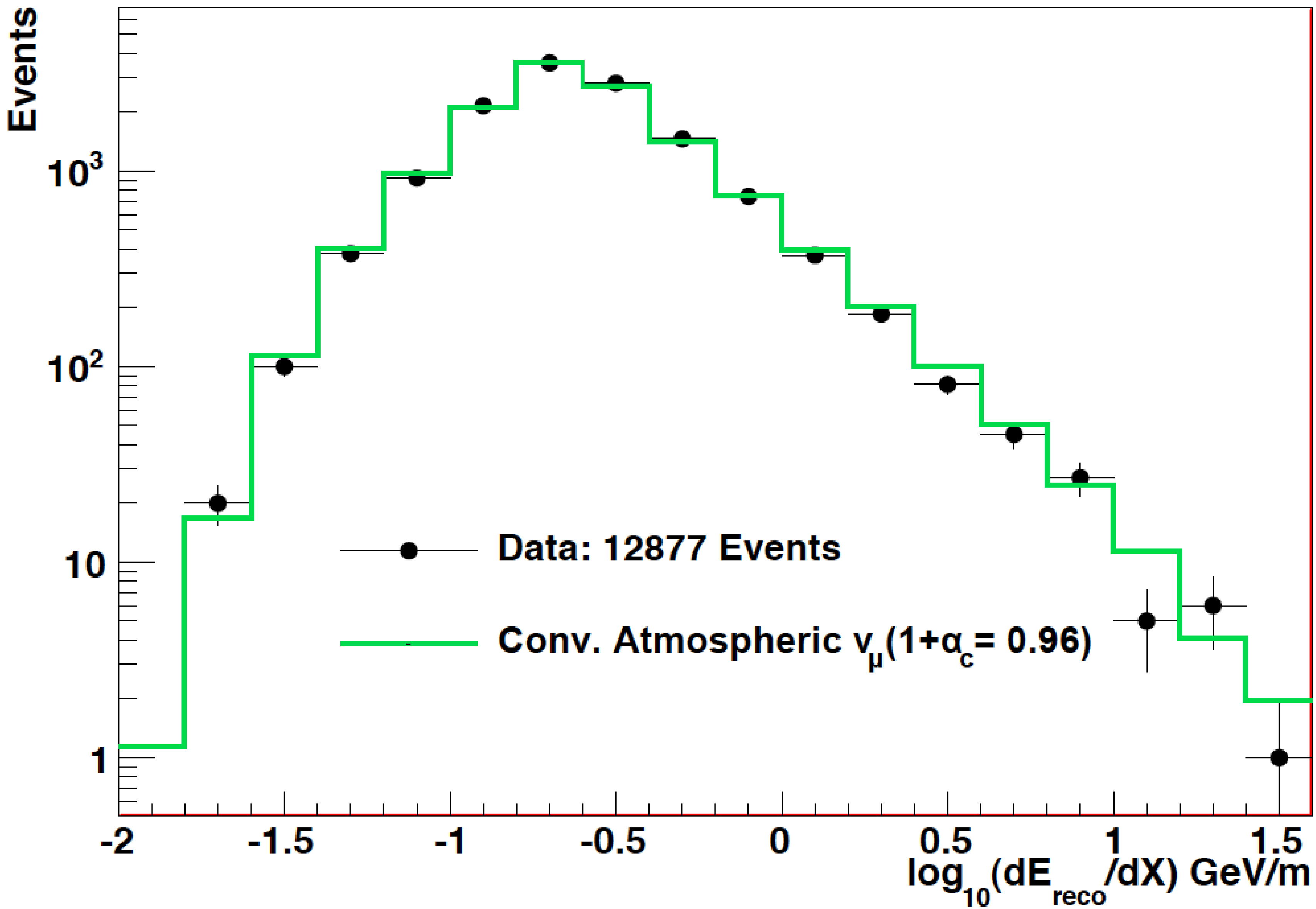


Reconstructed
Neutrino Energy

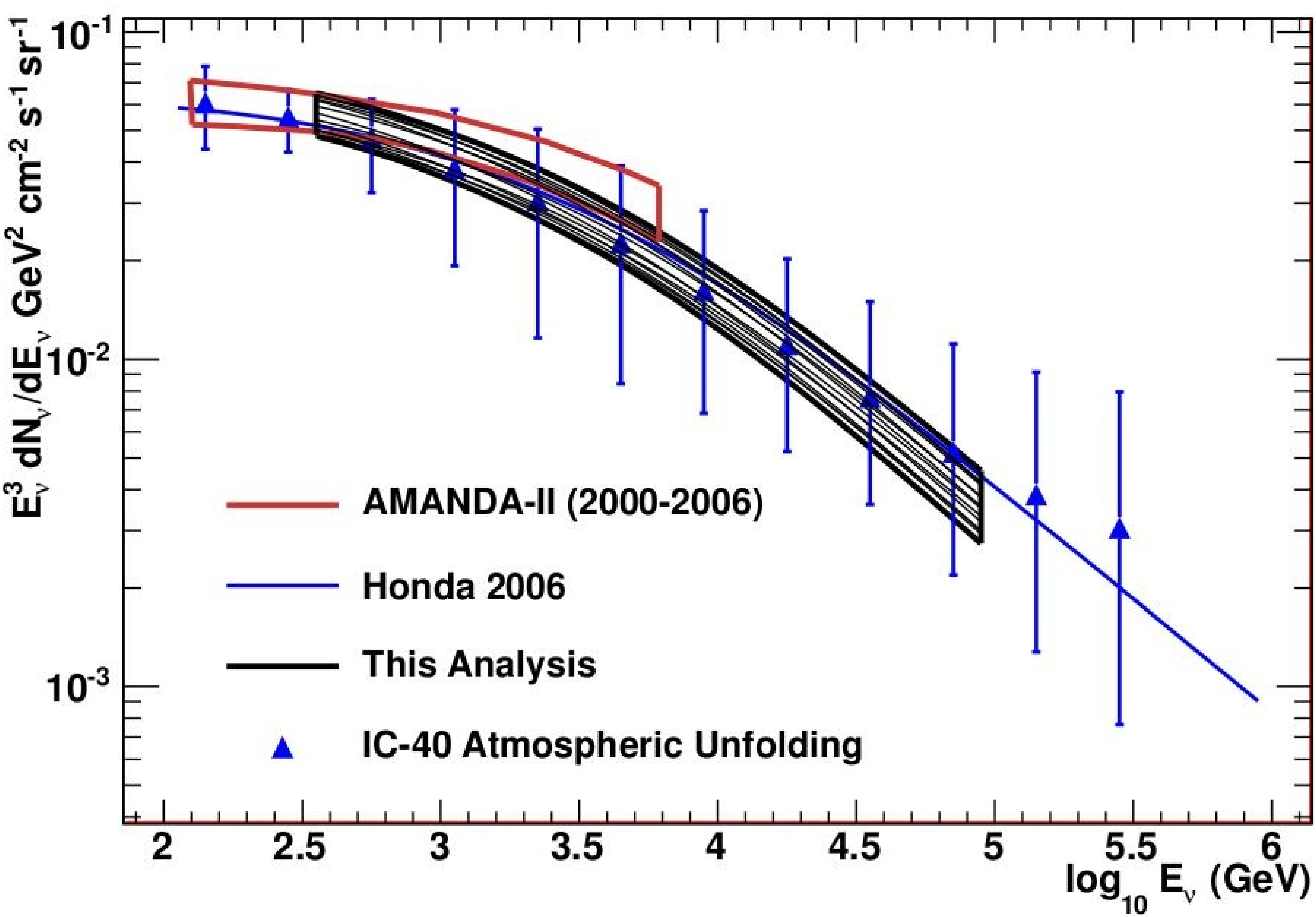
[From Muon Radiation]

$$-\frac{dE}{dX} \simeq \alpha + \frac{E}{\lambda_\mu} = \alpha \left(1 + \frac{E}{\varepsilon_\mu}\right)$$

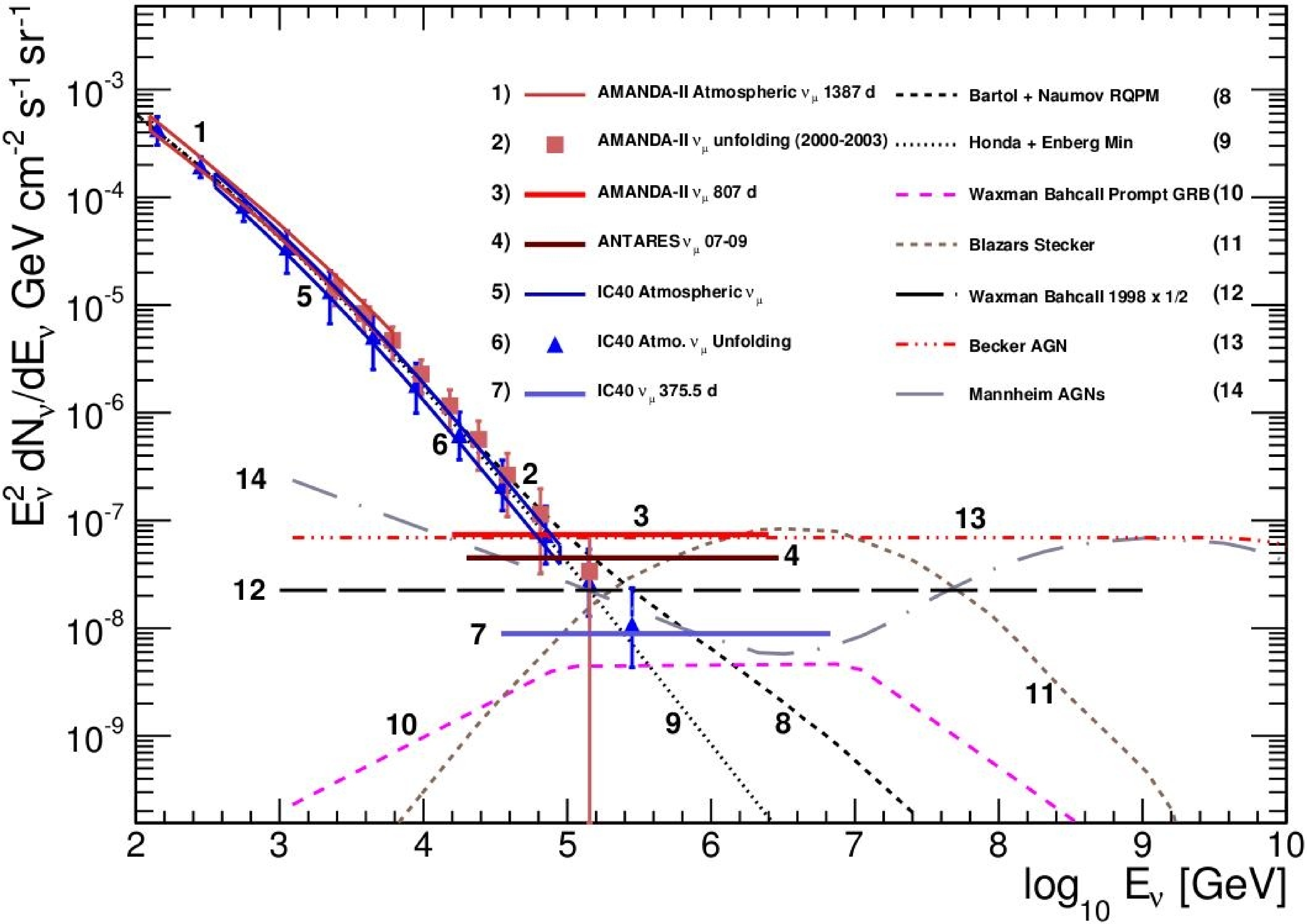
A Search for a Diffuse Flux of Astrophysical Muon Neutrinos with the IceCube 40-String Detector



No excess over atmospheric neutrinos

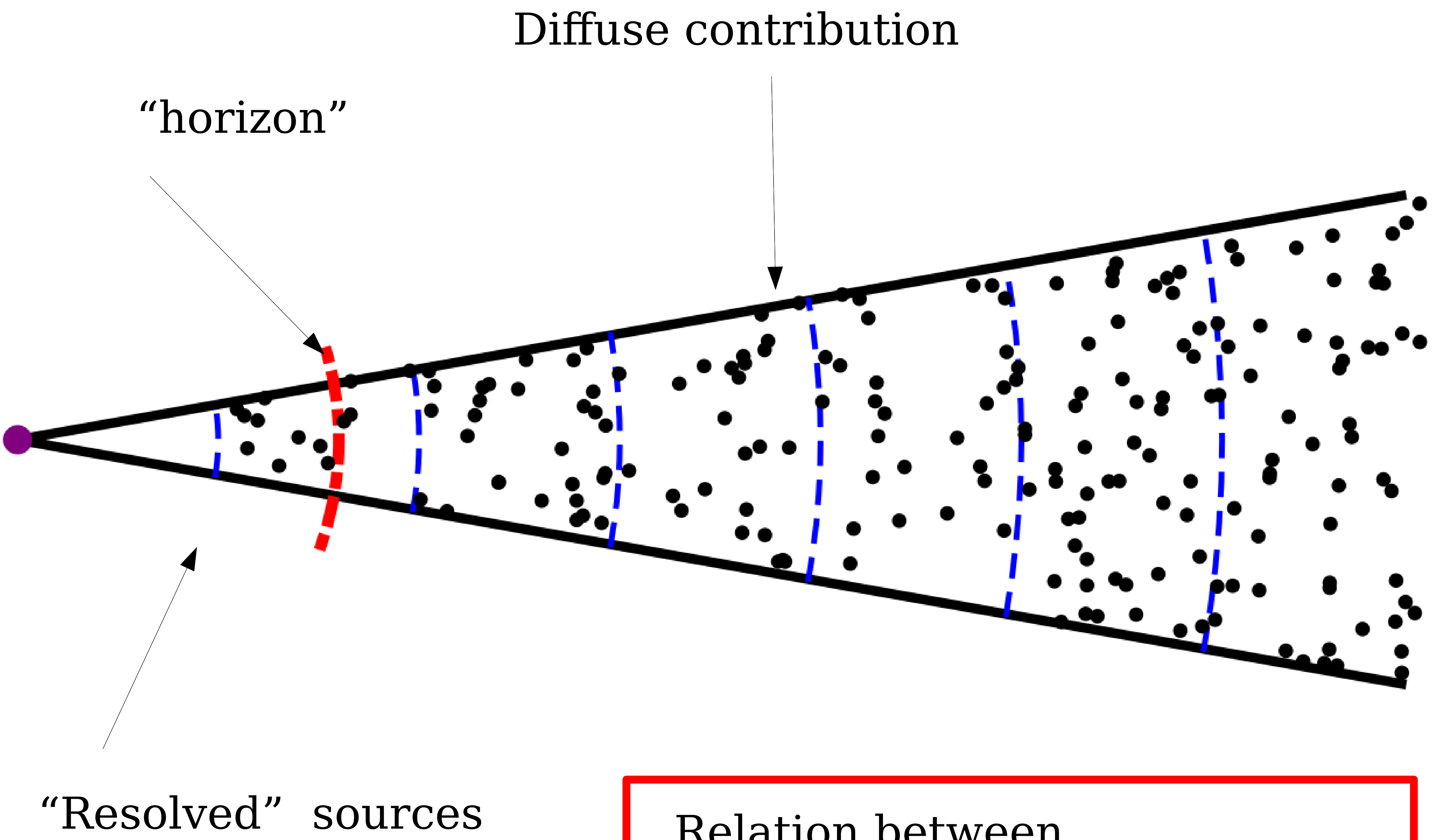


$E_\nu^3\, dN_\nu/dE_\nu$ GeV^2 cm^{-2} s^{-1} sr^{-1}
10^{-1}
10^{-2}
10^{-3}
2
2.5
3
3.5
4
4.5
5
5.5
6
$\log_{10} E_\nu$ (GeV)
AMANDA-II (2000-2006)
Honda 2006
This Analysis
IC-40 Atmospheric Unfolding

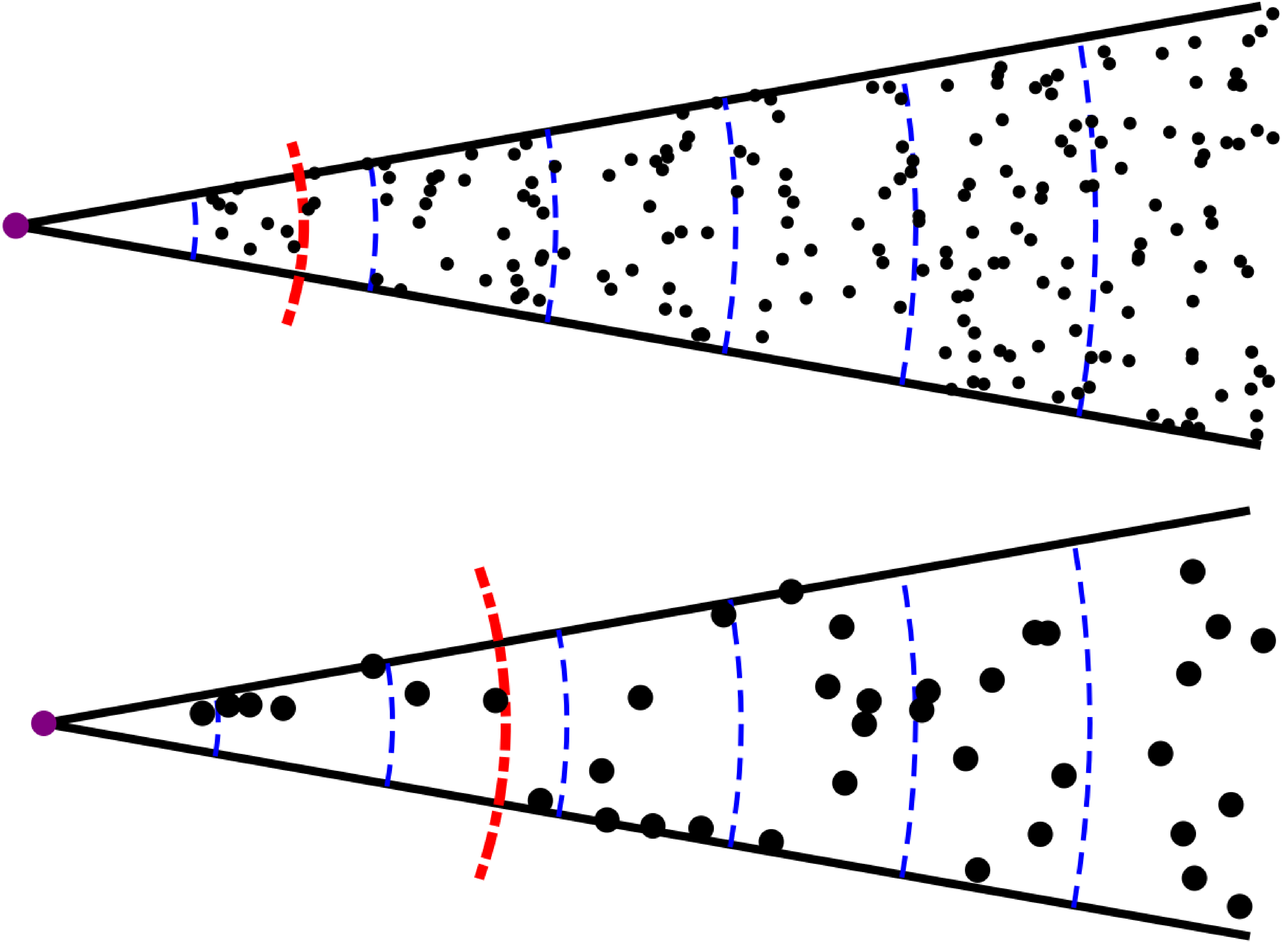


$E_\nu^2\, dN_\nu/dE_\nu$ GeV cm^{-2} s^{-1} sr^{-1}
$\log_{10} E_\nu$ [GeV]
1) AMANDA-II Atmospheric ν_μ 1387 d
2) AMANDA-II ν_μ unfolding (2000-2003)
3) AMANDA-II ν_μ 807 d
4) ANTARES ν_μ 07-09
5) IC40 Atmospheric ν_μ
6) IC40 Atmo. ν_μ Unfolding
7) IC40 ν_μ 375.5 d
Bartol + Naumov RQPM (8
Honda + Enberg Min (9
Waxman Bahcall Prompt GRB (10
Blazars Stecker (11
Waxman Bahcall 1998 x 1/2 (12
Becker AGN (13
Mannheim AGNs (14

Model	90% C.L.	3σ C.L.	5σ C.L	90% Energy Range (TeV-PeV)
E^{-2} $\left(\frac{\text{GeV}}{\text{cm}^2\ \text{s sr}}\right)$	0.89×10^{-8}	2.2×10^{-8}	4.0×10^{-8}	$35 - 7$
W-B Upper Bound	0.4	0.97	1.78	$35 - 7$
Stecker Blazar	0.1	0.32	0.42	$120 - 15$
BBR FSRQ	0.12	0.34	0.46	$35 - 7$
Mannheim AGN	0.05	0.21	0.4	$9 - 1$



Relation between
The diffuse flux
And the detected Point Sources



$$\phi_{\text{inclusive}} \propto \mathcal{L} = n_{\text{sources}}\ L$$

$$\phi_{\text{source}} \propto \frac{L}{r^2} \implies r_{\text{horizon}} \propto \sqrt{L}\,\sqrt{A\,t}$$

$$N_{[\text{det sources}]} = n_{\text{sources}} \left(\frac{4\,\pi}{3}\, r_{\text{h}}^3 \right)$$

$$N_{[\text{det sources}]} \equiv N_{\text{sources}}[\langle n_\mu \rangle \geq 1]$$

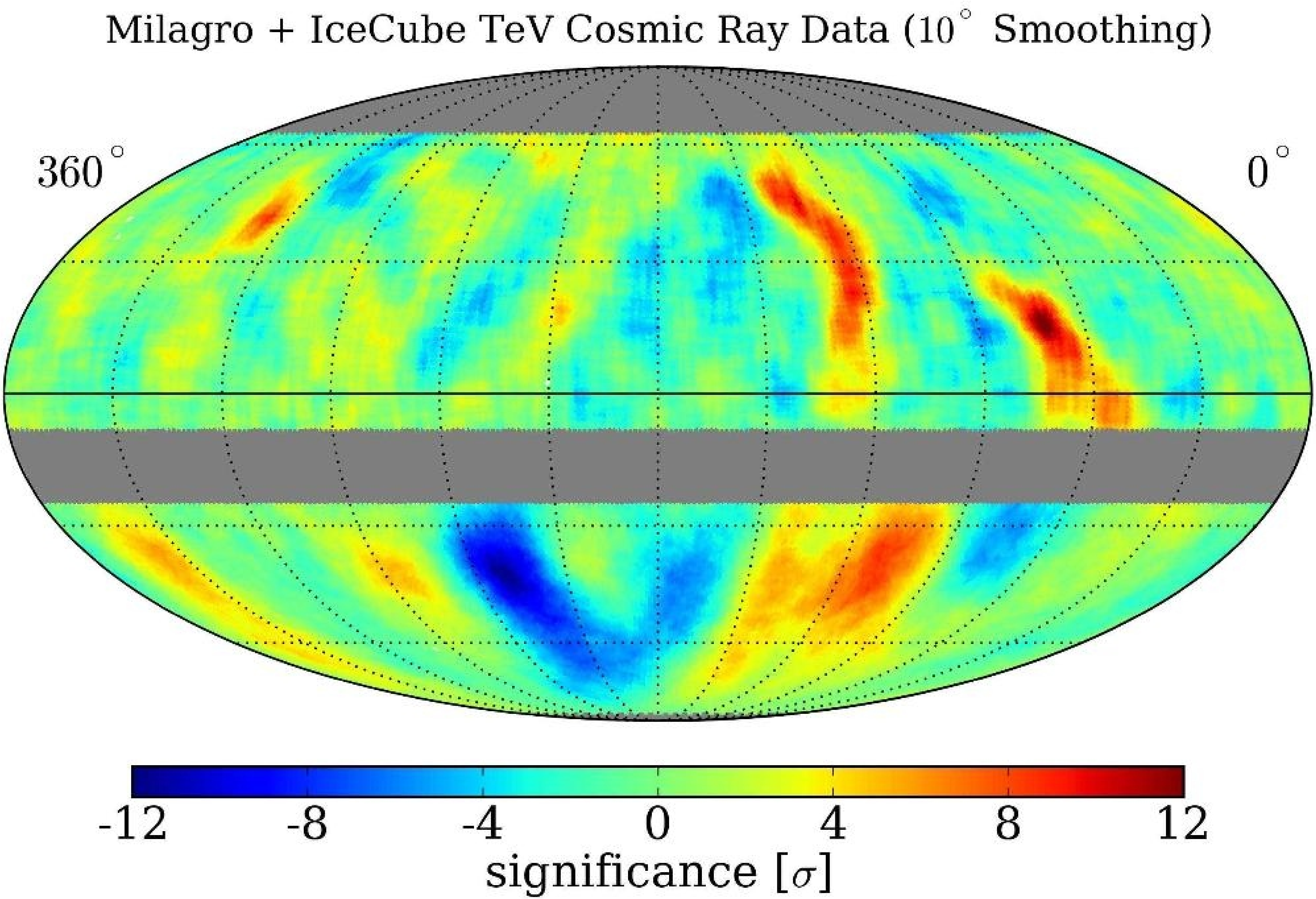
$$N_{[\text{det sources}]} \propto \frac{\mathcal{L}}{L} \left(\sqrt{L} \right)^3$$

$$N_{[\mathrm{det\ sources}]} \propto \frac{\mathcal{L}}{\bar{L}} \left(\sqrt{L}\right)^3$$

$\mathcal{L}$: Obtain from diffuse flux

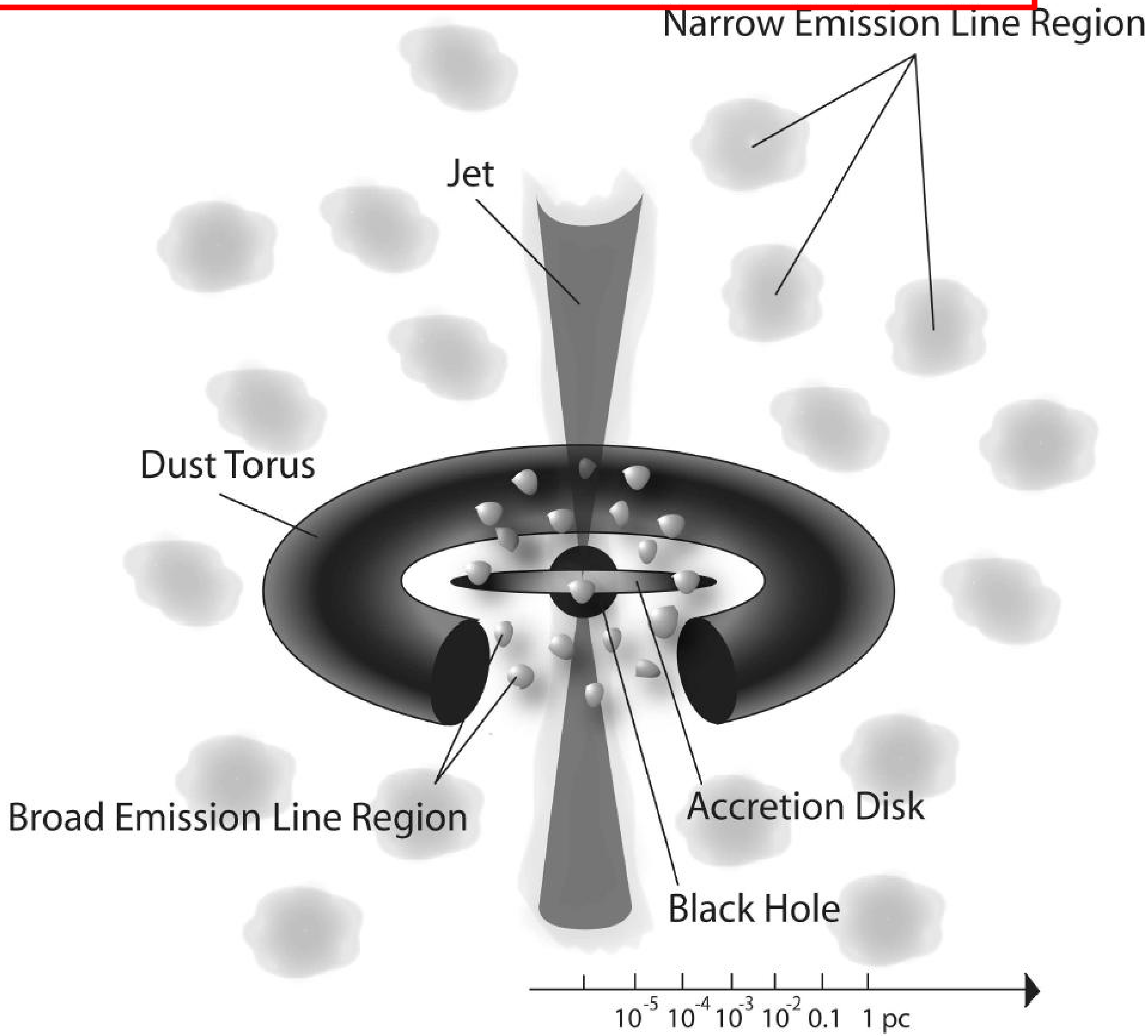
$\bar{L}$: Estimate from Astrophysical considerations.

$$N_{[\mathrm{det\ sources}]} \sim 1.2\ \mathcal{L}_{35}\ \sqrt{L_{45}}\ (A\ t)^{3/2}_{\mathrm{Km^2 yr}}$$

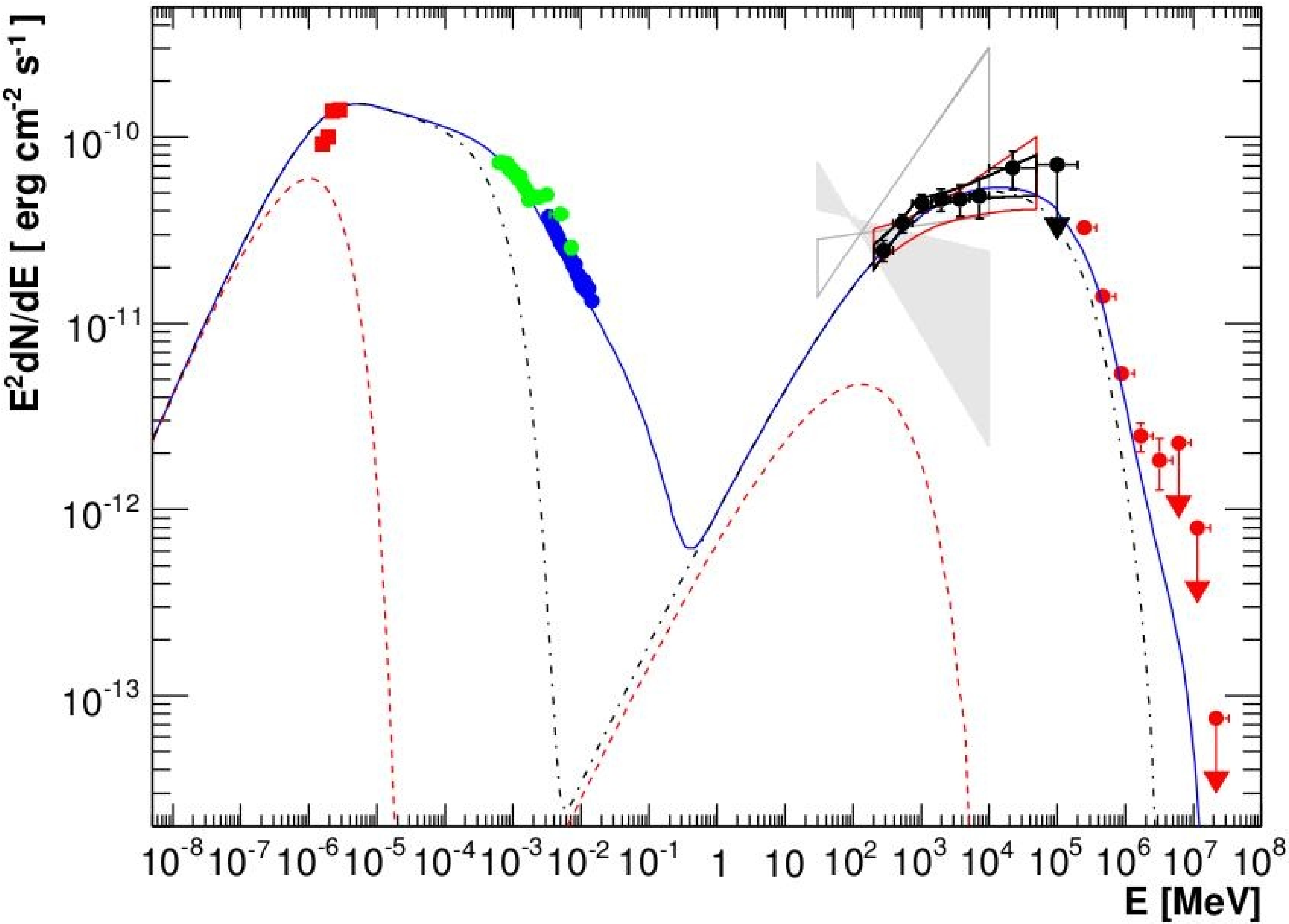


Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)
360°
0°
-12
-8
-4
0
4
8
12
significance [σ]

ACTIVE GALACTIC NUCLEI

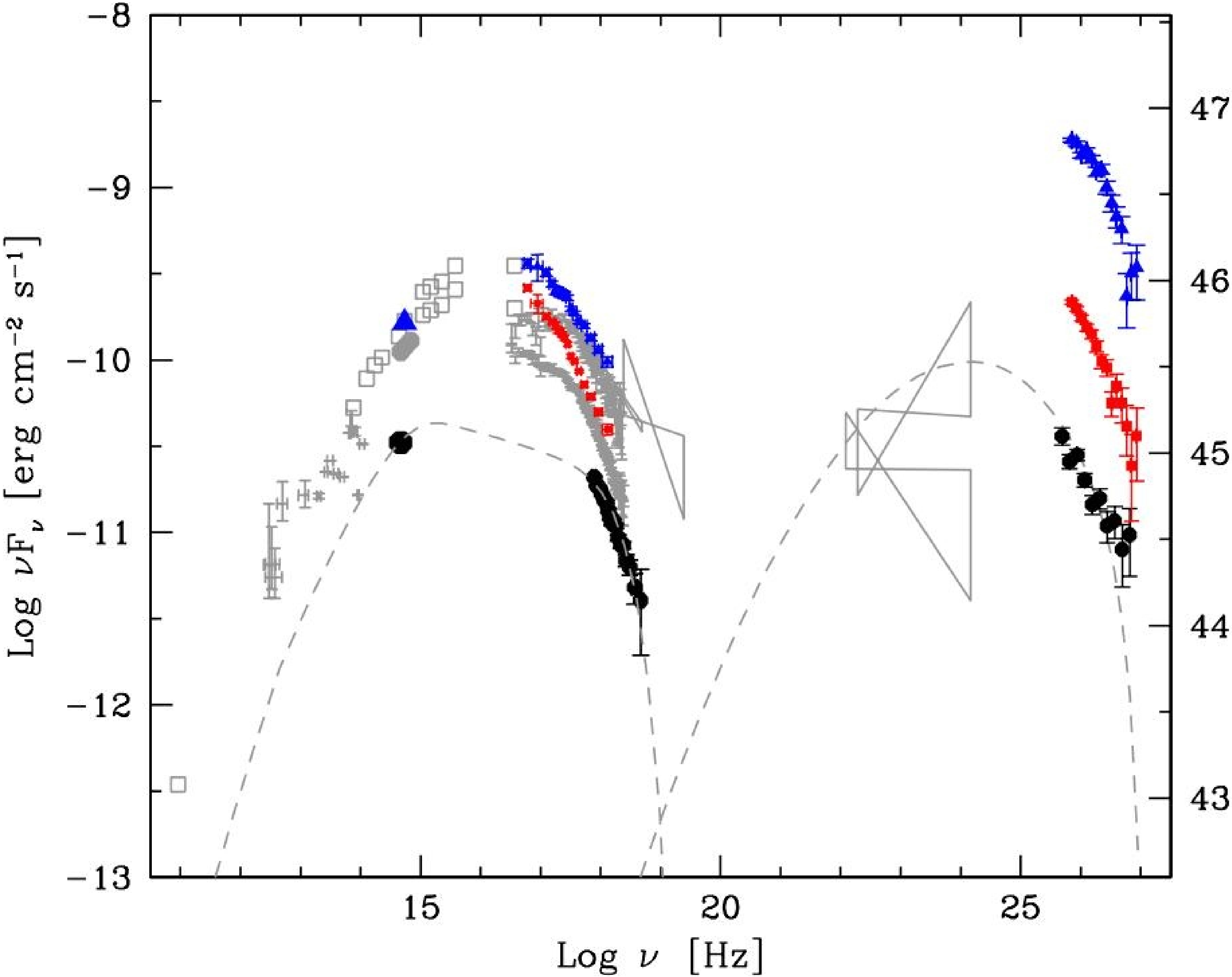


PKS 2155-304

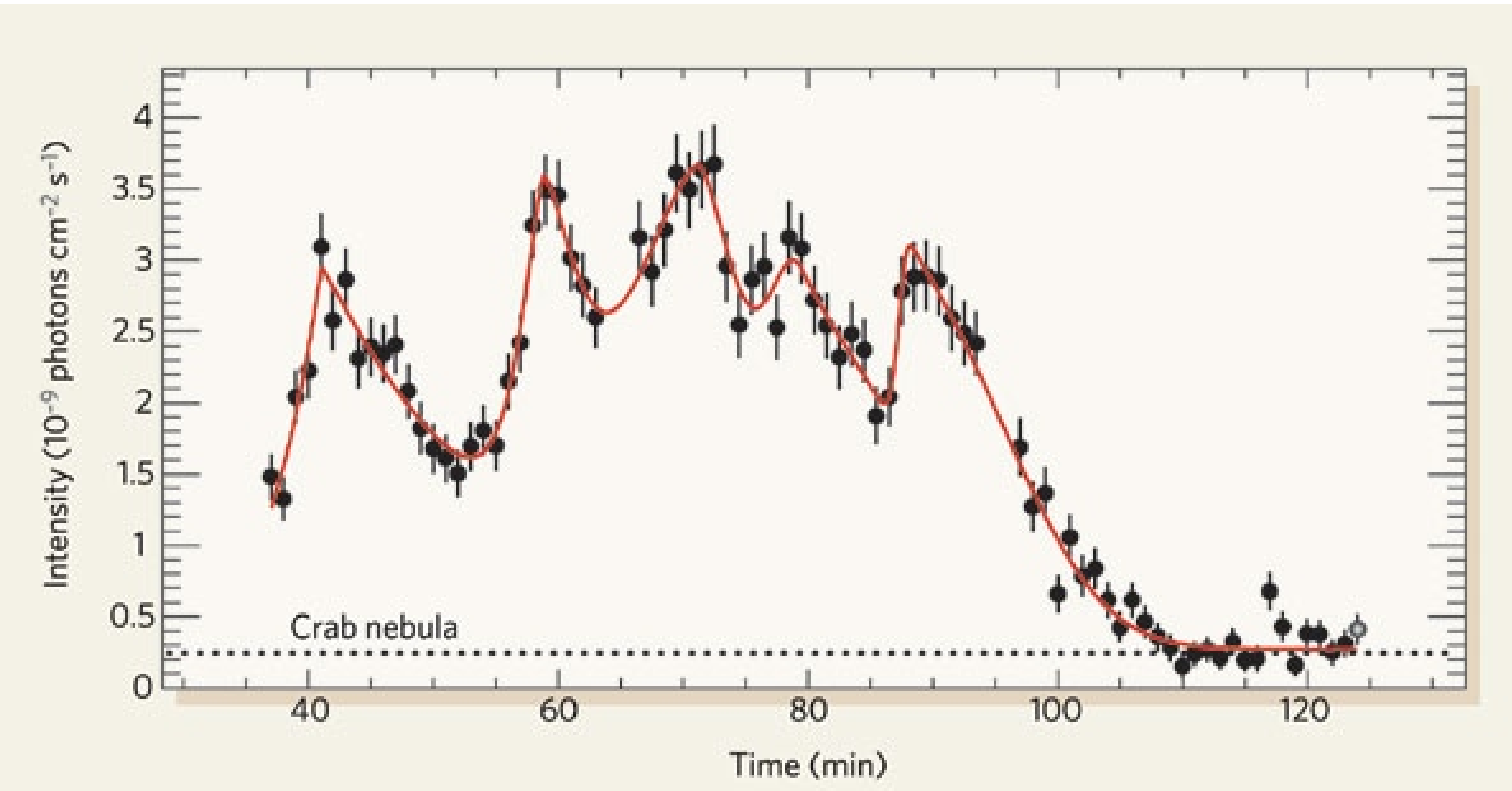


E^{2}dN/dE [erg cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8}
E [MeV]

PKS 2155-304

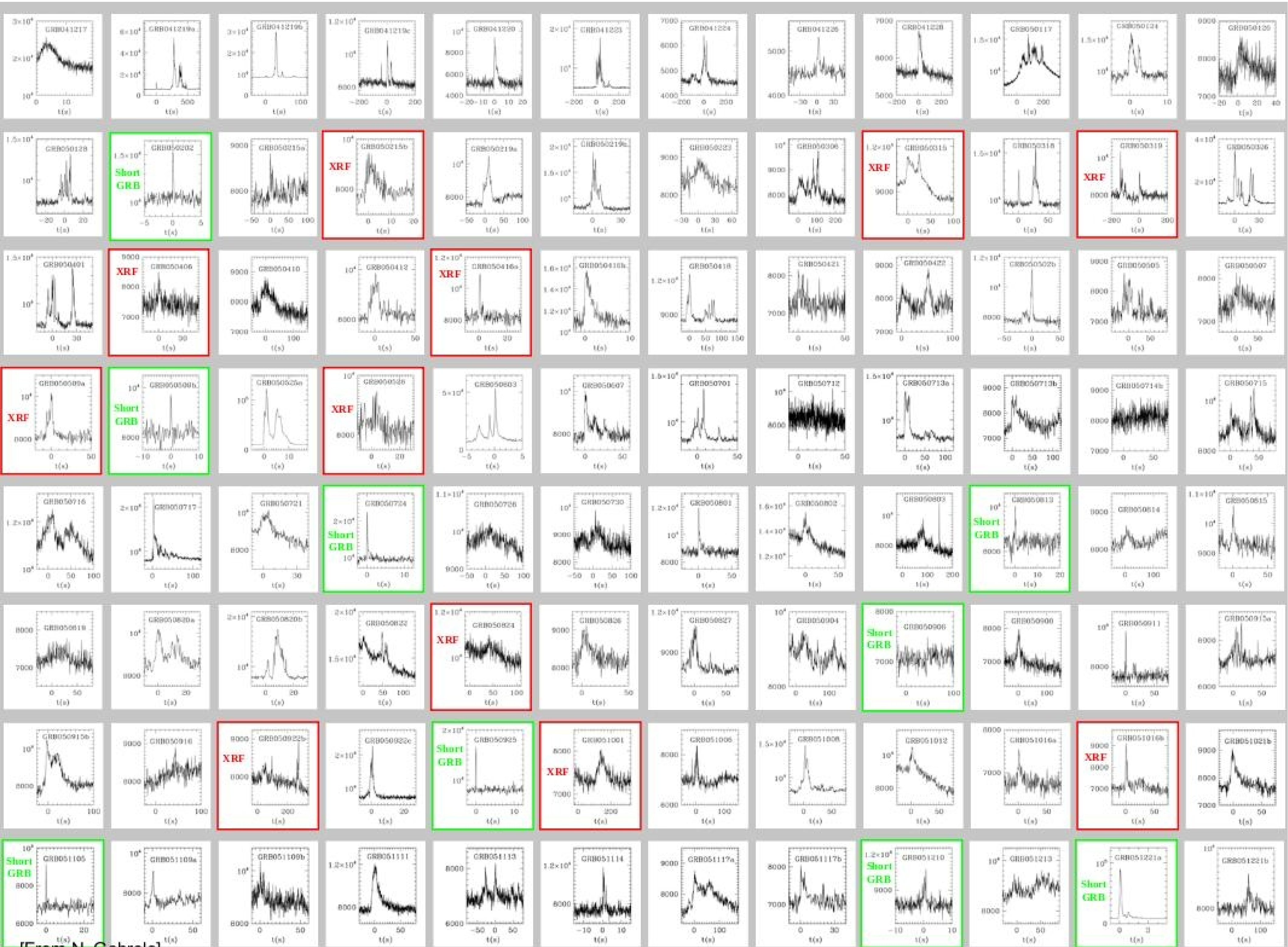


PKS 2155-304

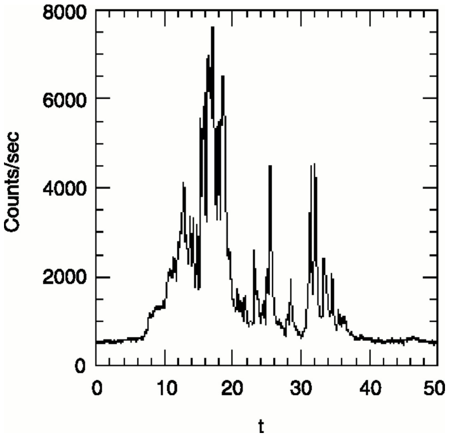


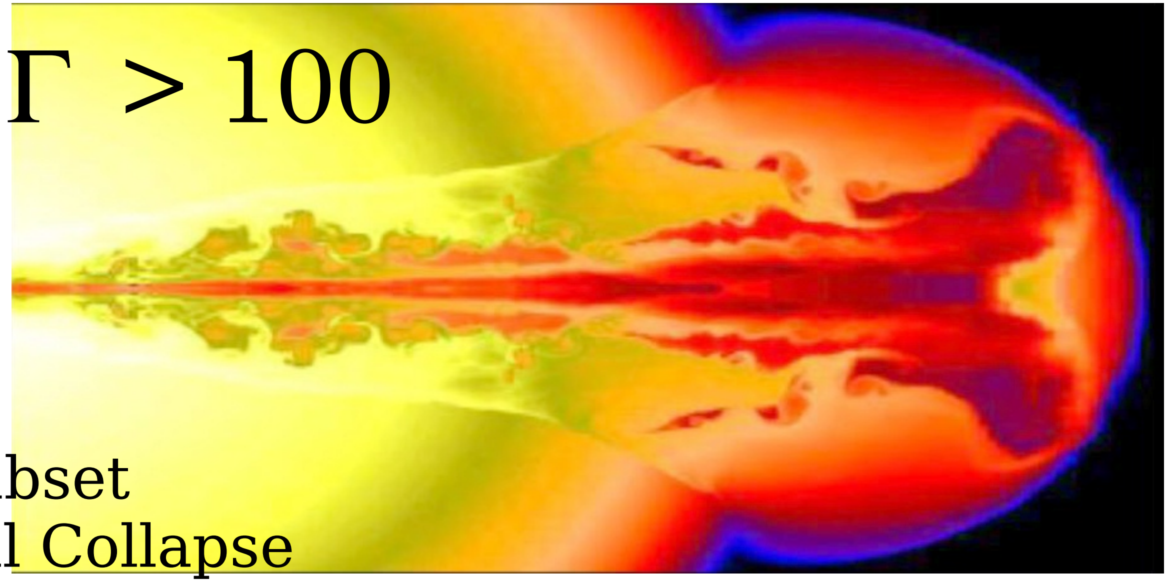
Intensity (10^{-9} photons cm^{-2} s^{-1})
0
0.5
1
1.5
2
2.5
3
3.5
4
Crab nebula
40
60
80
100
120
Time (min)

Gamma Ray Bursts



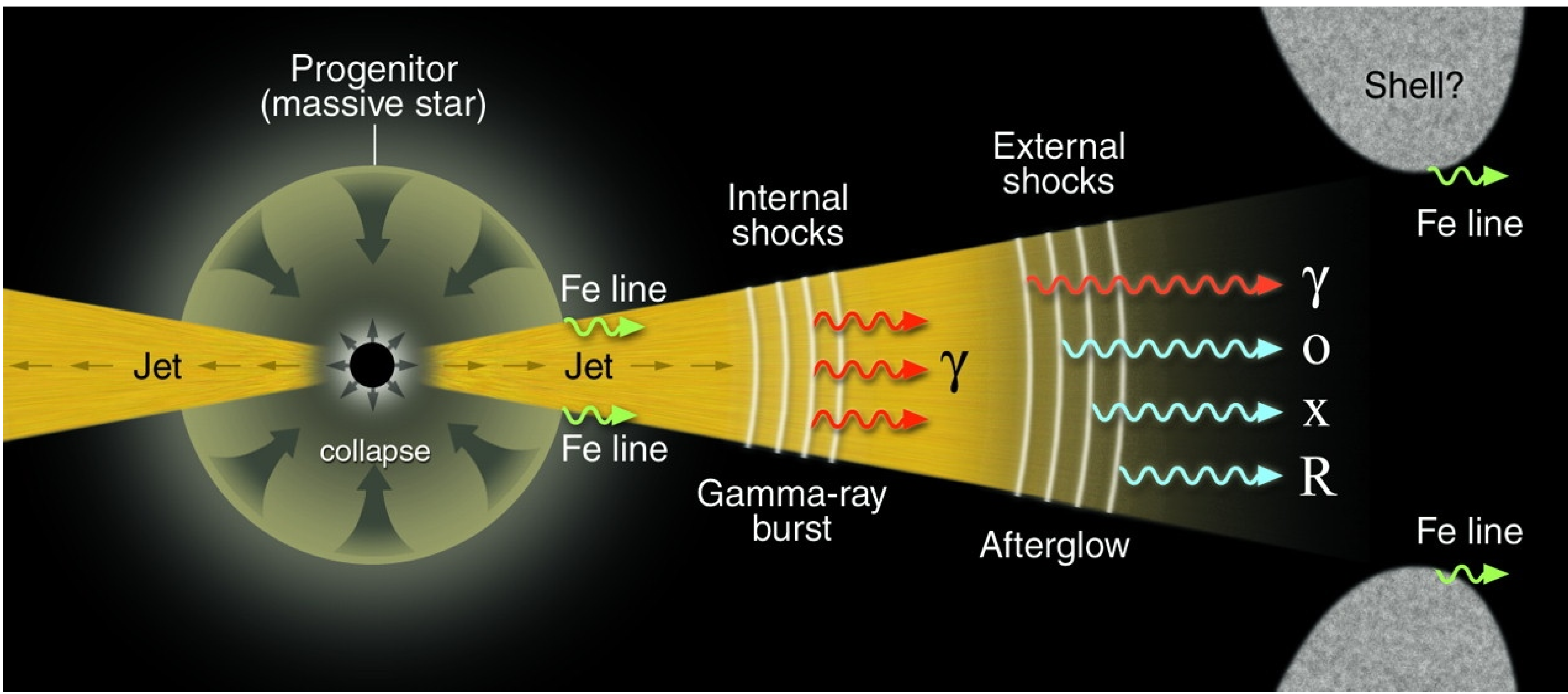
[From N. Gehrels]



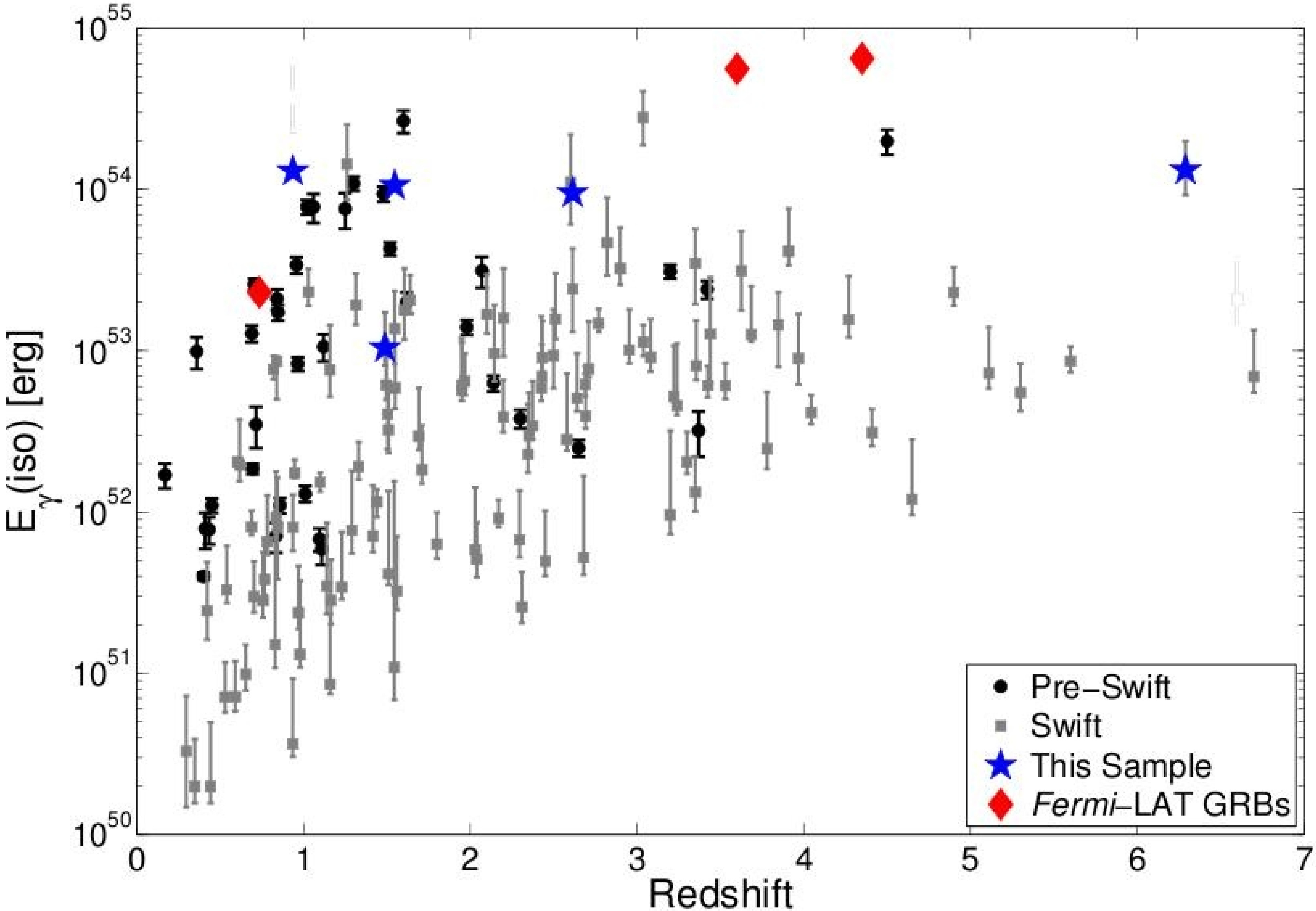


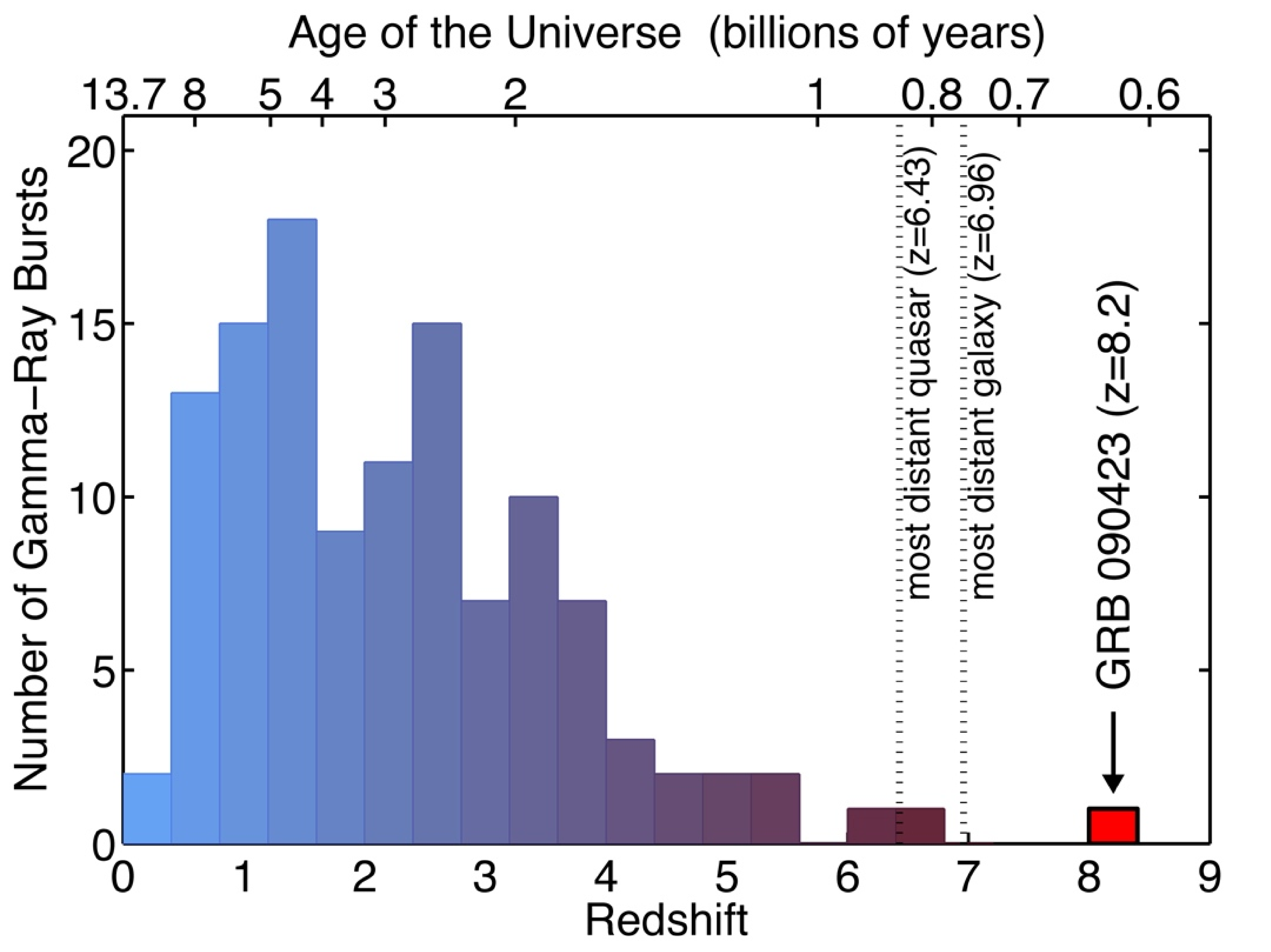
$\Gamma > 100$

GRB : associated with a subset
of SN Stellar Gravitational Collapse

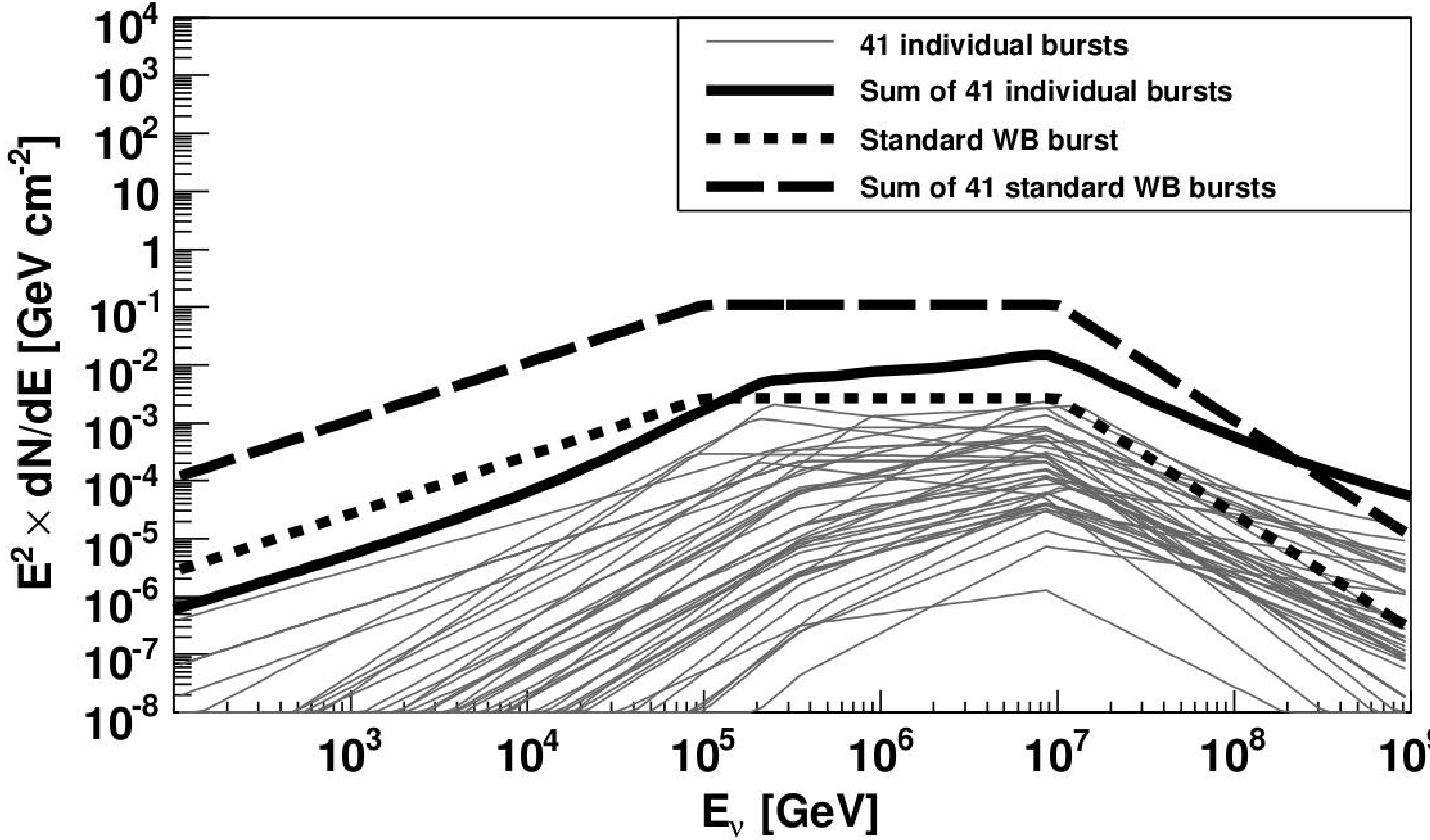


Extraordinary Large (beamed) Energy Output



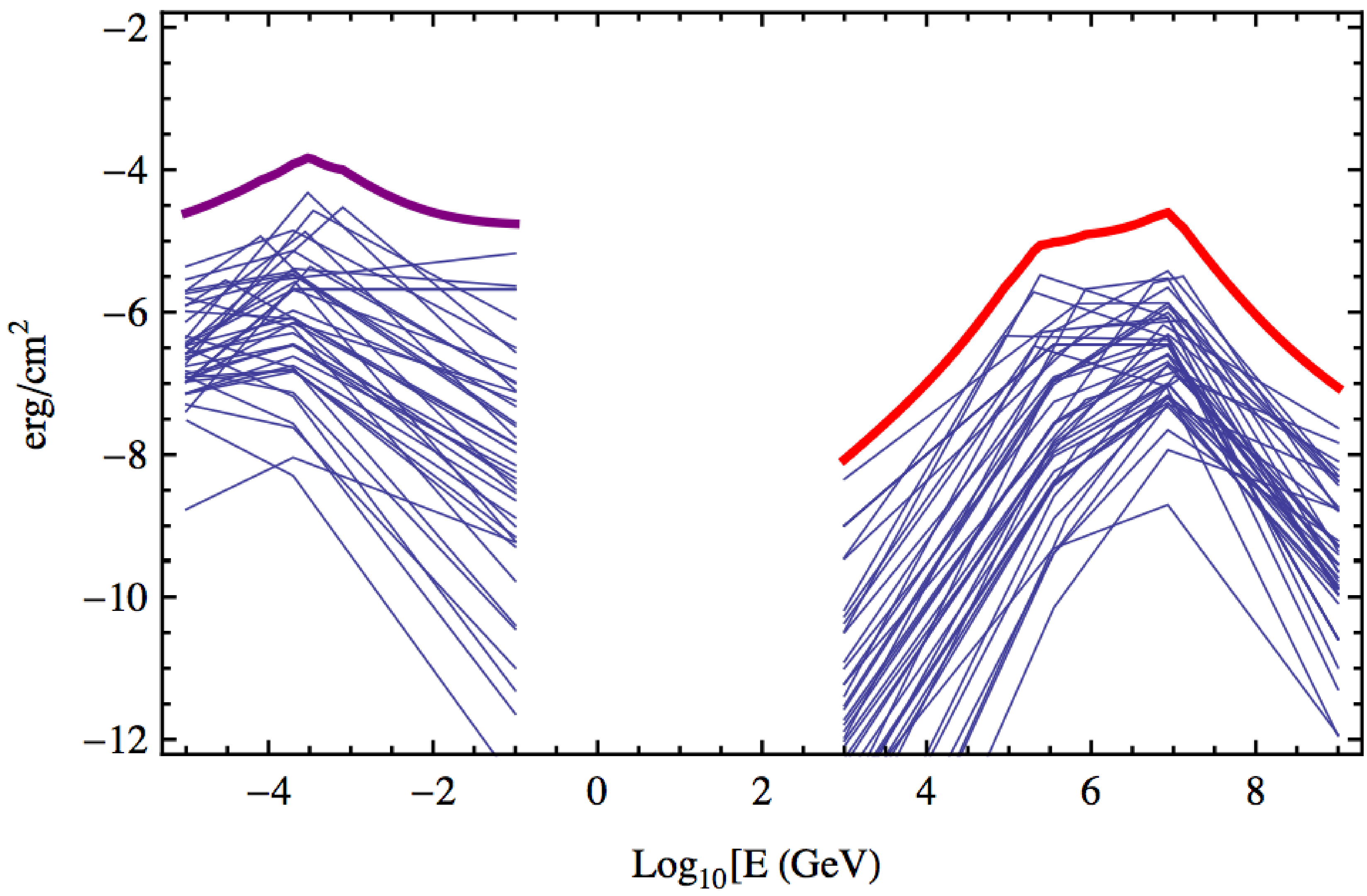


Age of the Universe (billions of years)
13.7 8 5 4 3 2 1 0.8 0.7 0.6
Number of Gamma-Ray Bursts
20
15
10
5
0
most distant quasar (z=6.43)
most distant galaxy (z=6.96)
GRB 090423 (z=8.2)
0 1 2 3 4 5 6 7 8 9
Redshift



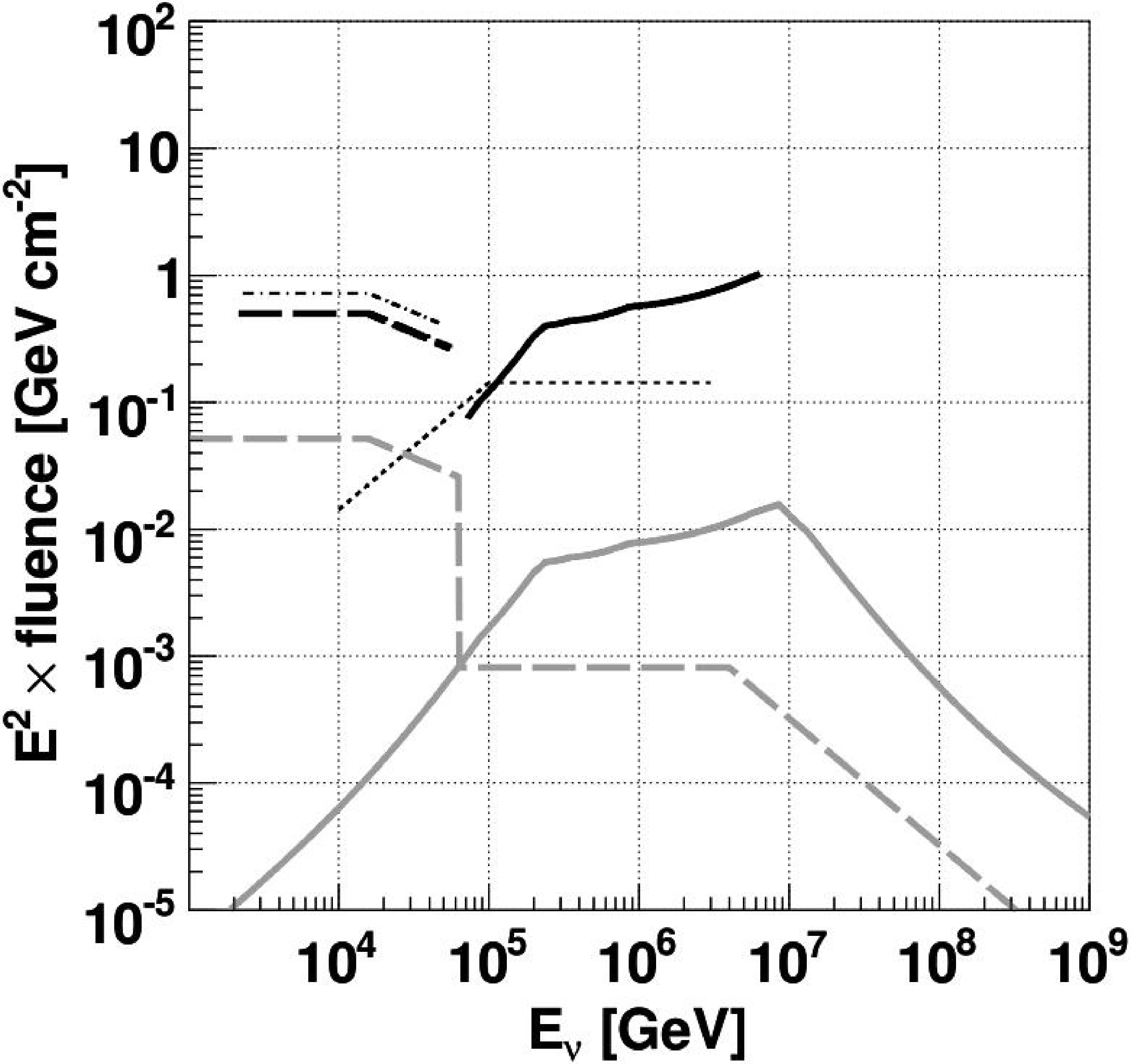
41 individual bursts
Sum of 41 individual bursts
Standard WB burst
Sum of 41 standard WB bursts
$E^2 \times dN/dE$ [GeV cm^{-2}]
E_ν [GeV]
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^3
10^4
10^5
10^6
10^7
10^8
10^9

41 GRB used by AMANDA



Photon
detection

Neutrino assumed
spectrum



10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$E^2 \times$ fluence [GeV cm^{-2}]
10^4
10^5
10^6
10^7
10^8
10^9
E_ν [GeV]

UHECR

1. Energy Spectrum

- Clear identification of a high energy suppression
  [the "END" (… well the "suppression")
  of exotic/fundamental physics modeling for UHECR].

- Excellent agreement between experiments
  ["small" but important question about the energy scale].

- Physical interpretation strongly coupled to (2., 3.)
  (anisotropy + composition). [proton GZK ?]

UHECR

Crucial Problem:

Galactic
Extragalactic
Transition

1. Energy Spectrum

2. Anisotropy

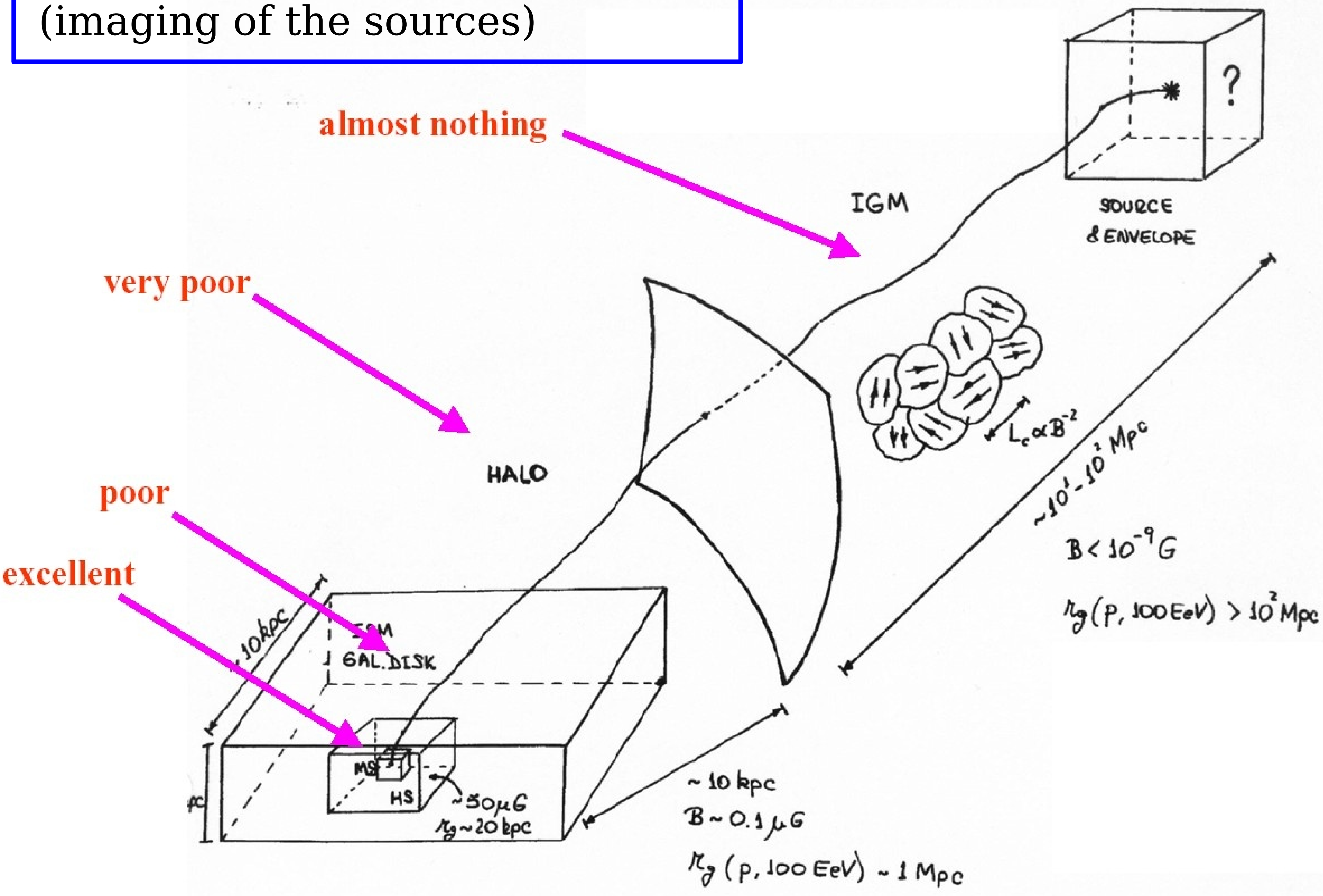
3. Composition

Significant
Experimental
Discrepancies

Auger/Hires

Confusing
situation.

COSMIC Ray ASTRONOMY [?!]
(imaging of the sources)

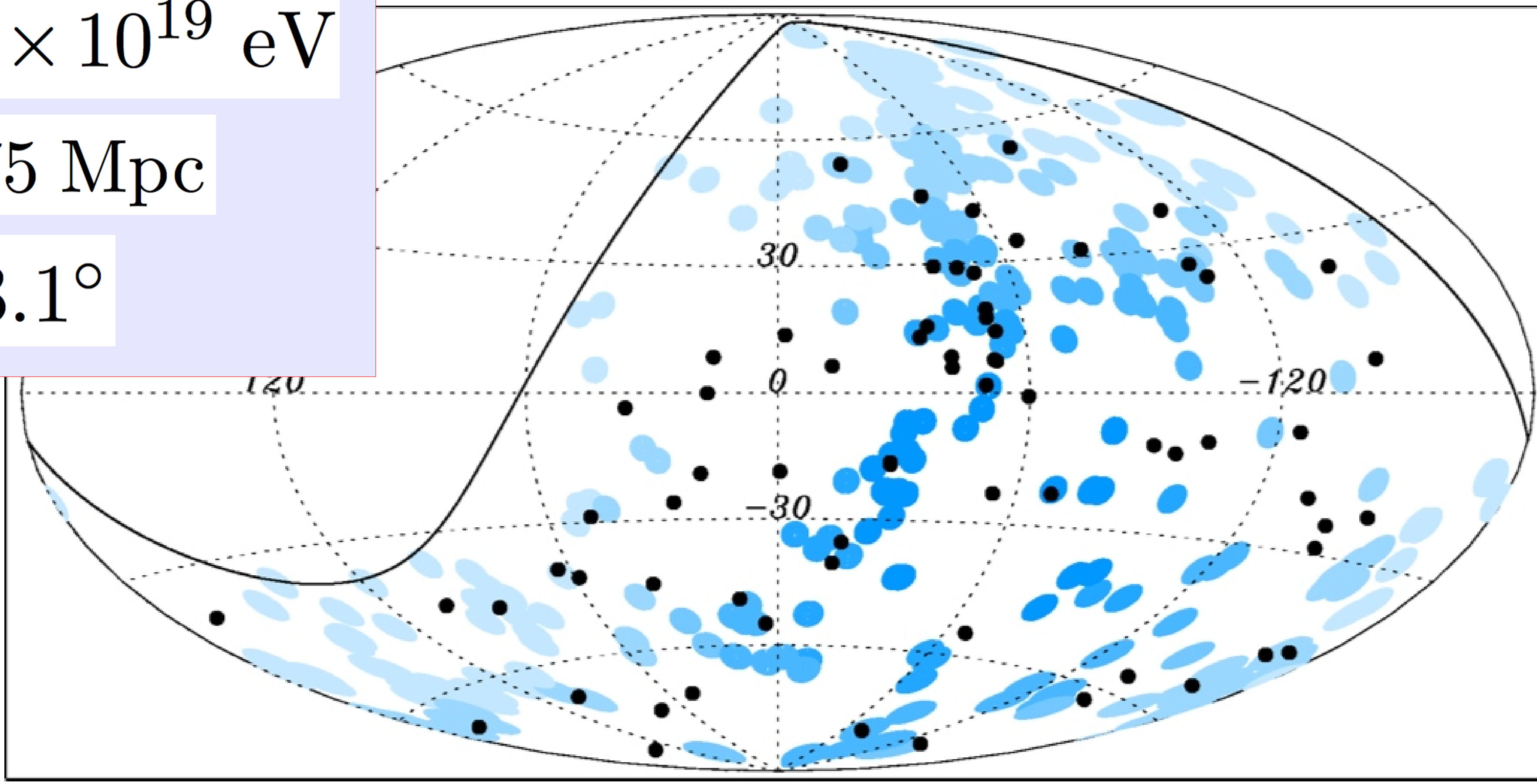


AUGER result on Correlations with the VCV AGN catalogue November 2008. Update september 2010.

6×10^{19} eV

75 Mpc

3.1°



Significant dilution
[but not disappearance]
of the statistical significance

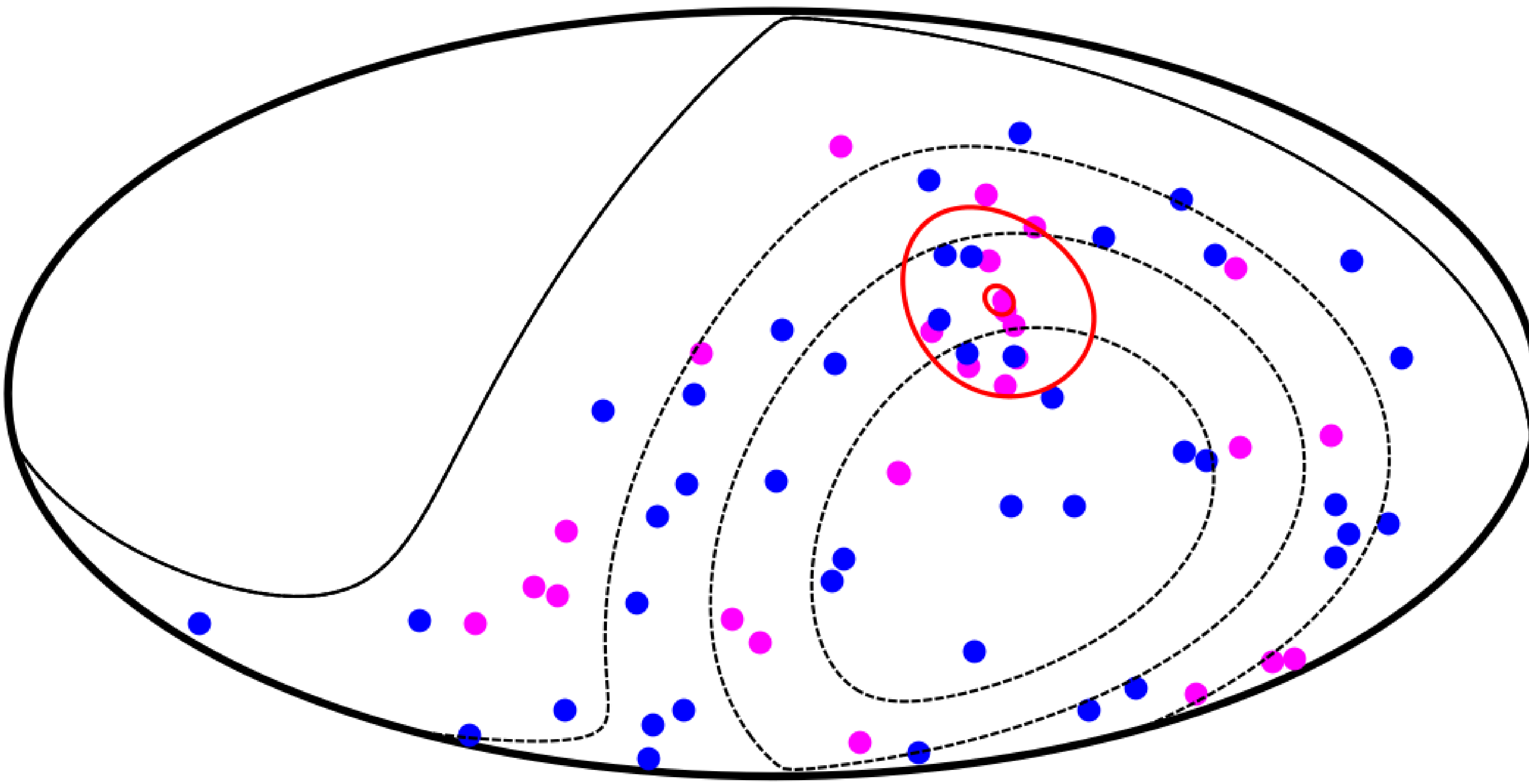
14 ev. 8 coincid. (2.9)
13 ev. 9 coincid. (2.7)
42 ev. 12 coincid.(8.8)

Discussion on CEN A

The AGN closest to us.

3 events within 3 degrees
8 events within 18 degrees

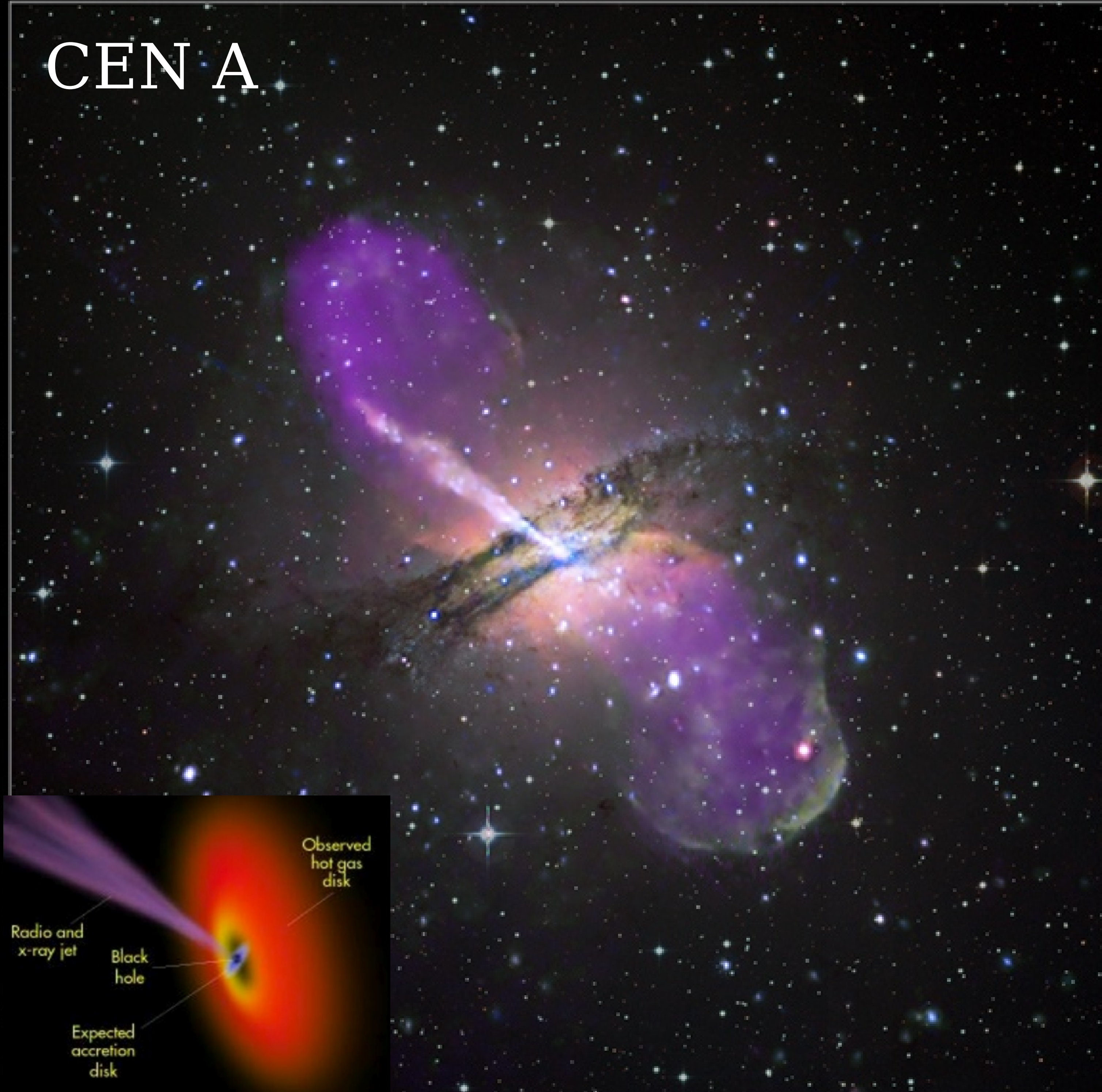
+0 events within 3 degrees
+5 events within 18 degrees



November 2008 (13 + 14 events)
Update september 2010 (+42 events)

3, 20 degrees circles

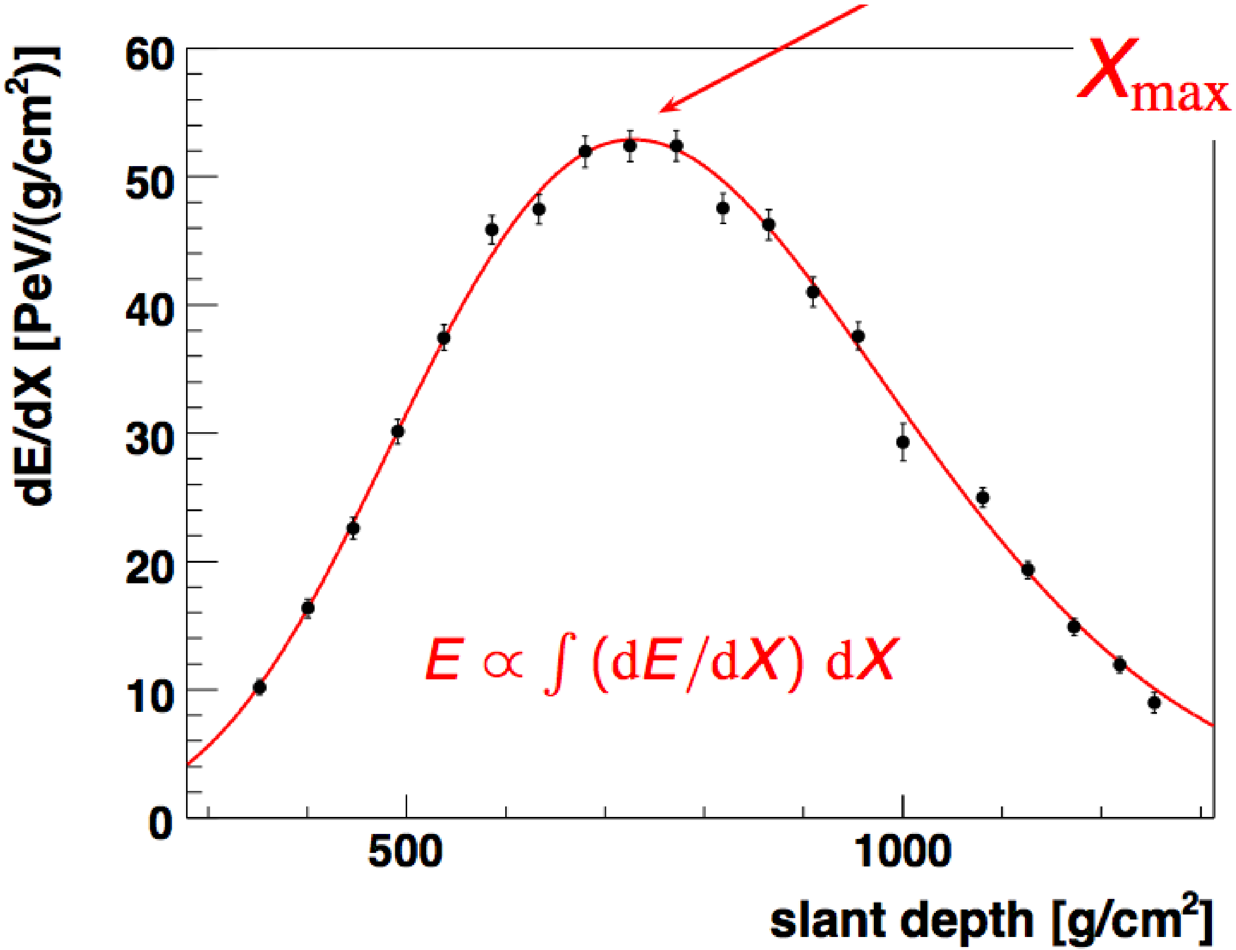
CEN A

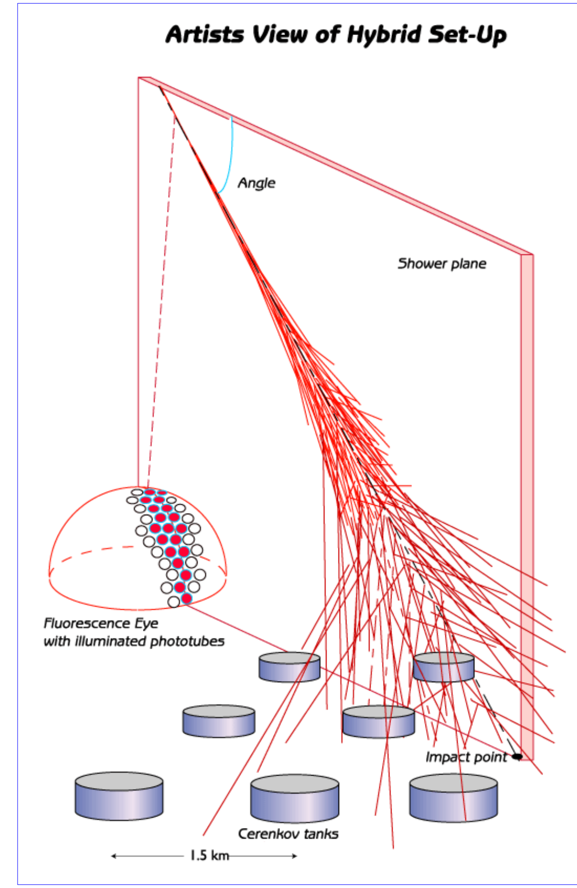

Radio and
x-ray jet
Black
hole
Expected
accretion
disk
Observed
hot gas
disk


X-RAY


RADIO


OPTICAL



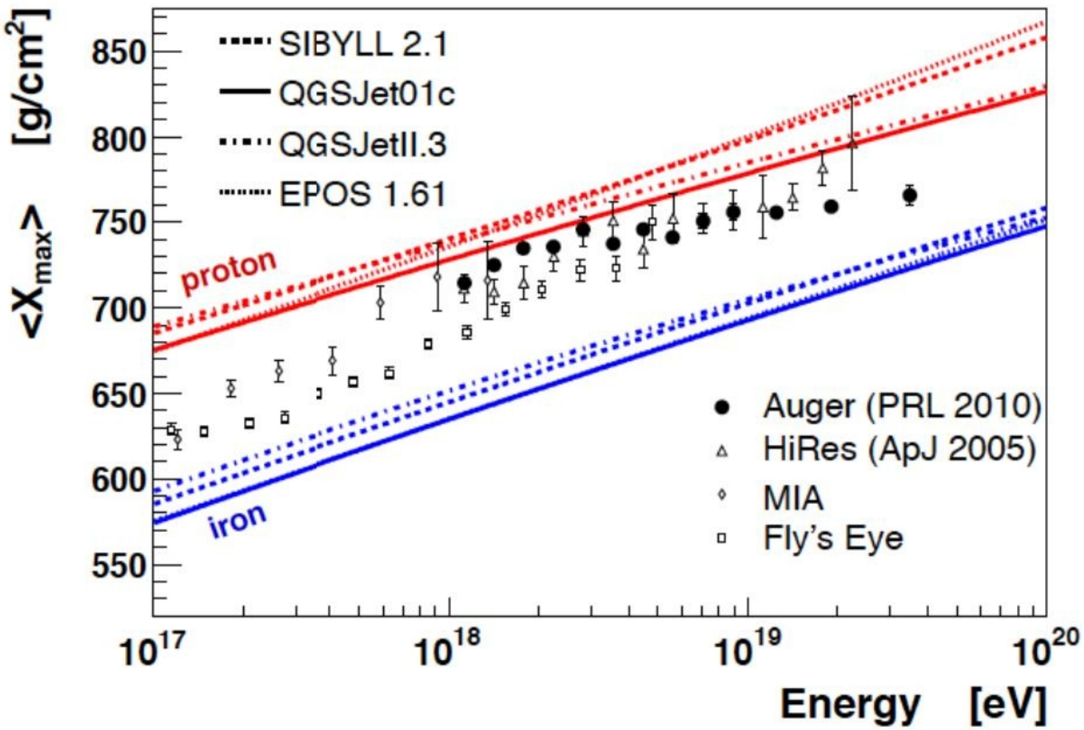


$$E_{\text{ionization}} = \int dX \; N_e(X) \left\langle -\frac{dE}{dX} \right\rangle$$

Area $\propto$ Energy

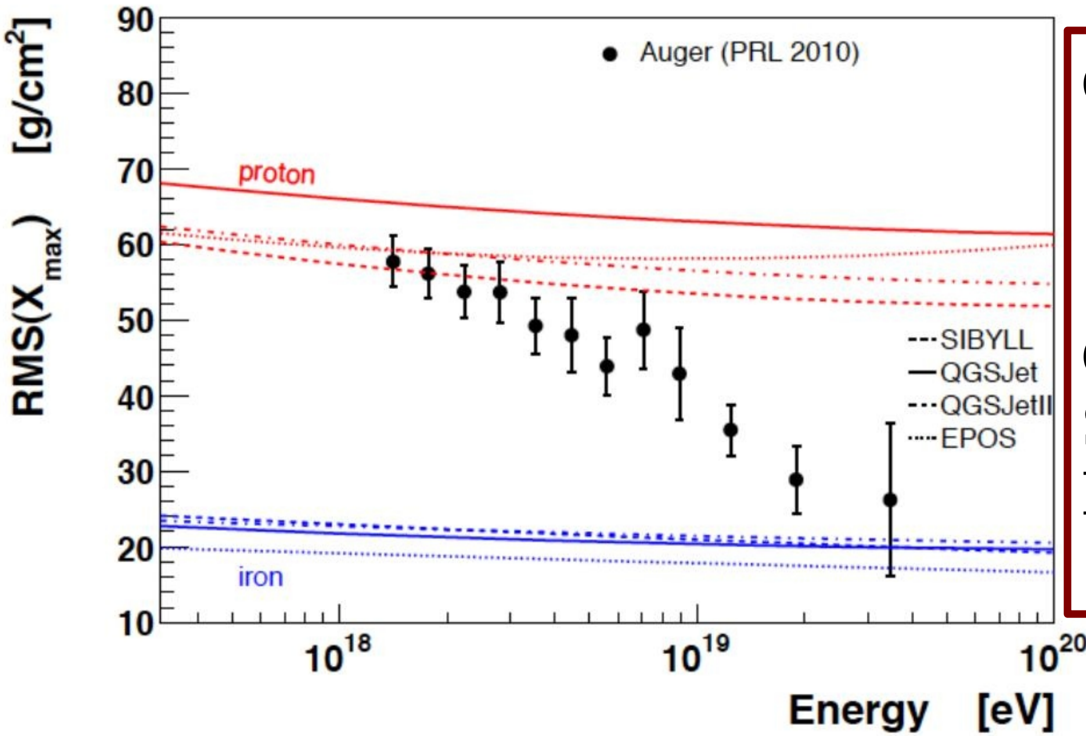
Shape depends on :

- Primary Identity
- Interaction Model



Mass Composition
becoming heavy ?
at very high energy ?

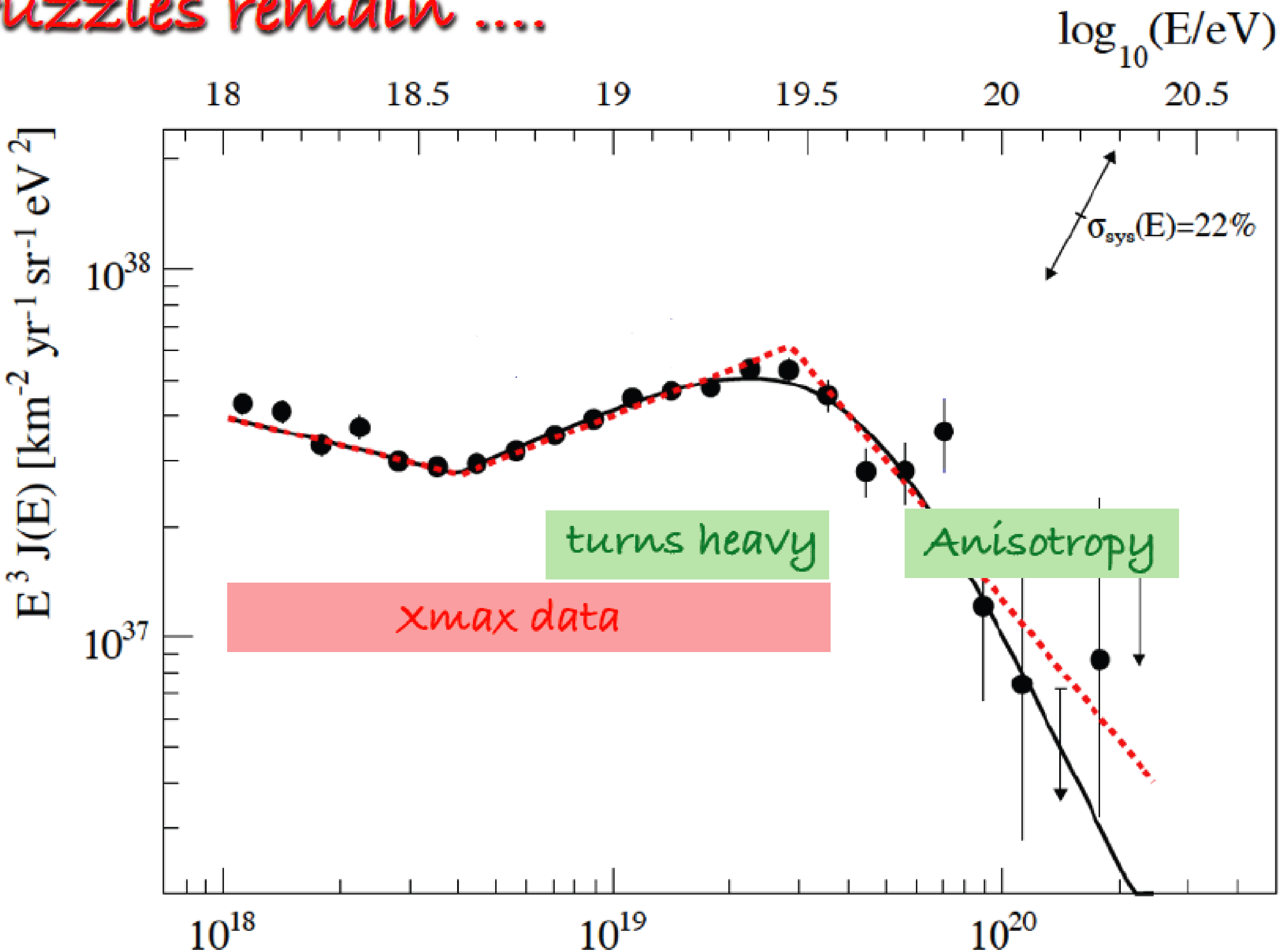
Significance would be
very important !
Constraints on the
structure and properties
of the astrophysical sources.



Observational controversy
NON confirmation
of HiRes

Correlation with sources
Small deviation in magnetic
Fields (Z < 3 ?)

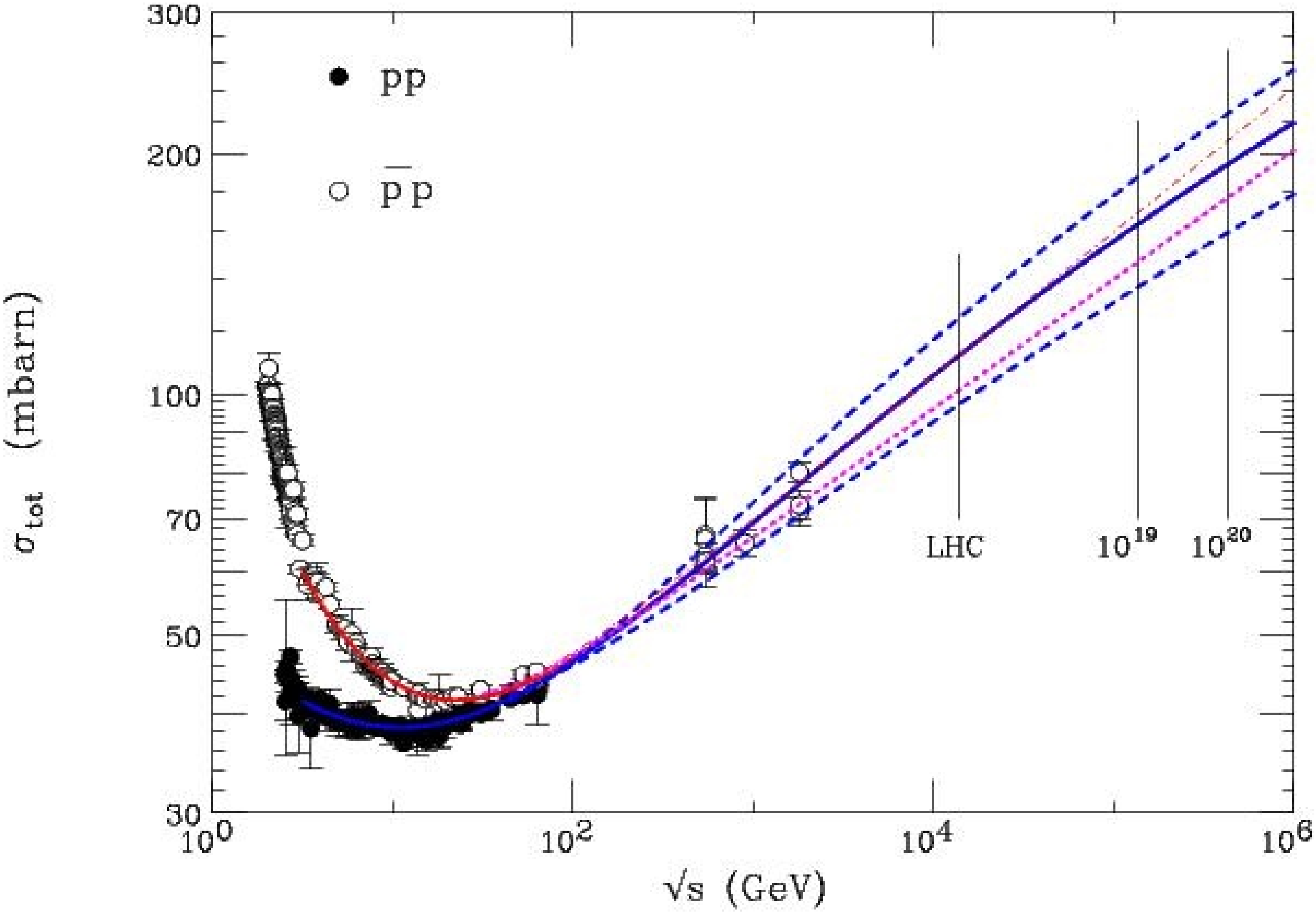
Puzzles remain ....

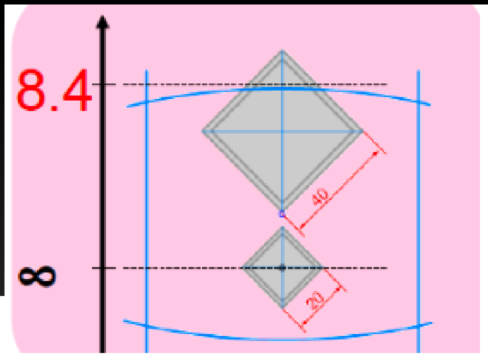


Johannes Knapp

LHC and Ultra-High Energy Cosmic Rays

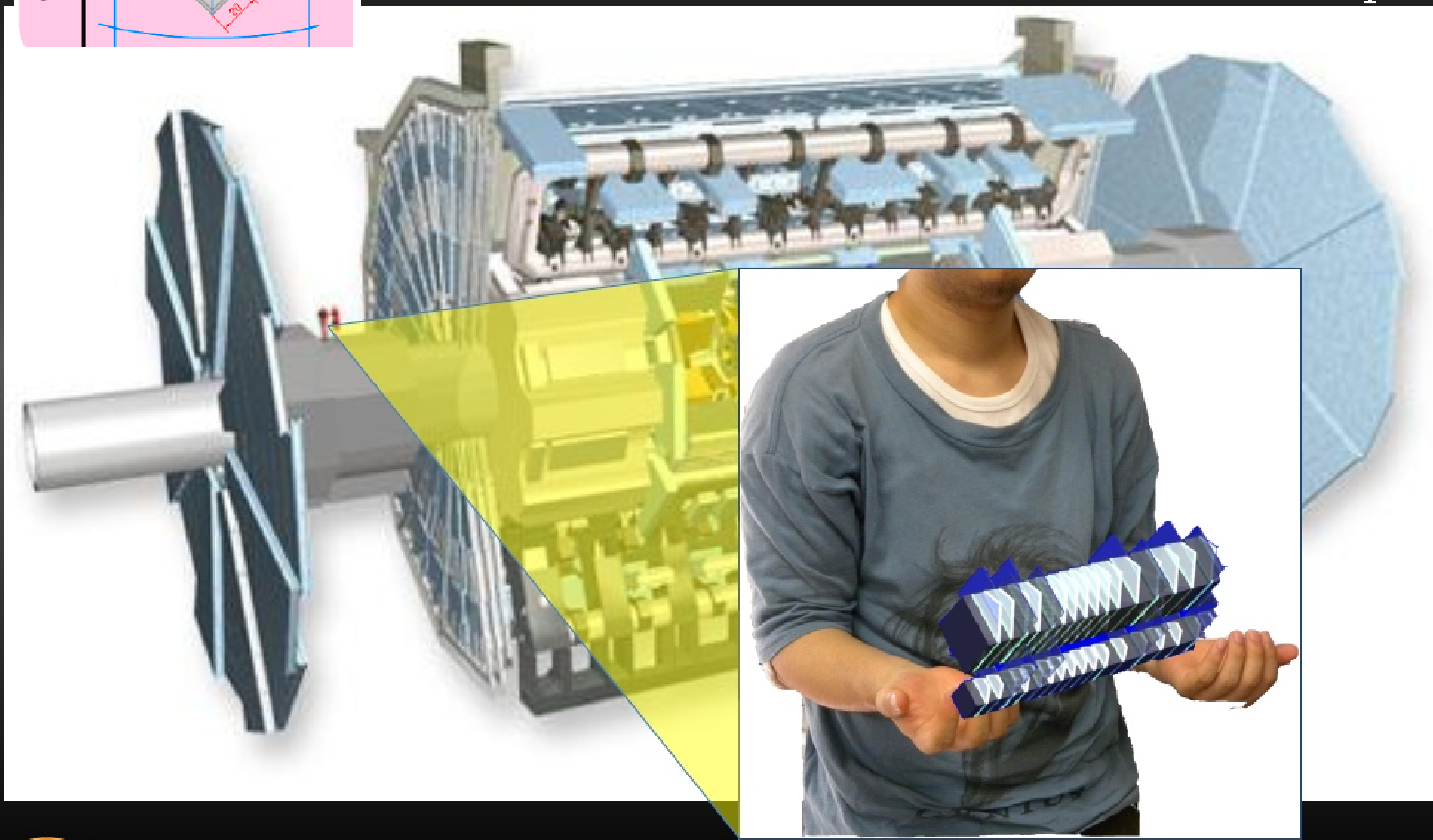
Total pp Cross Section



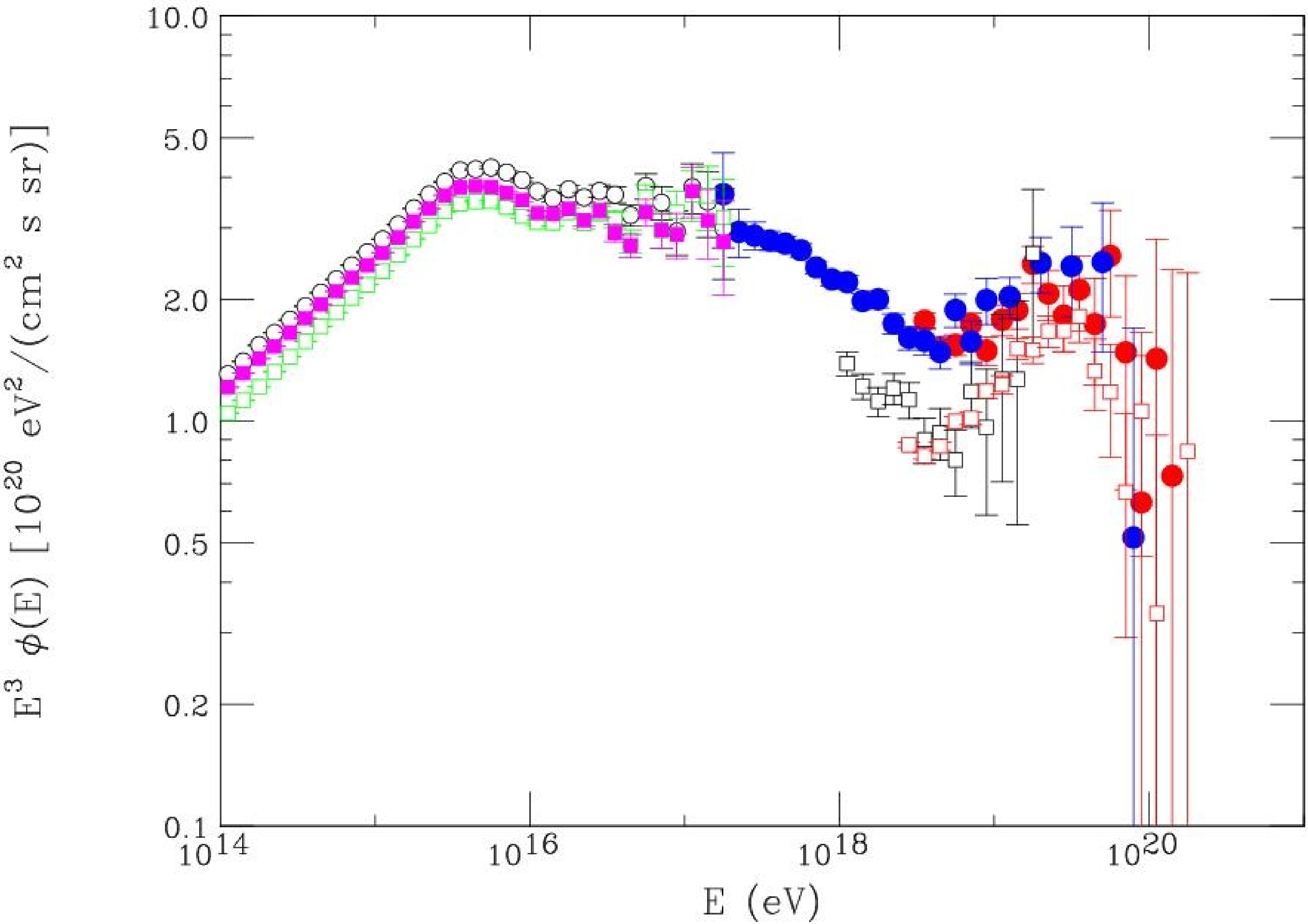


ATLAS & LHCf

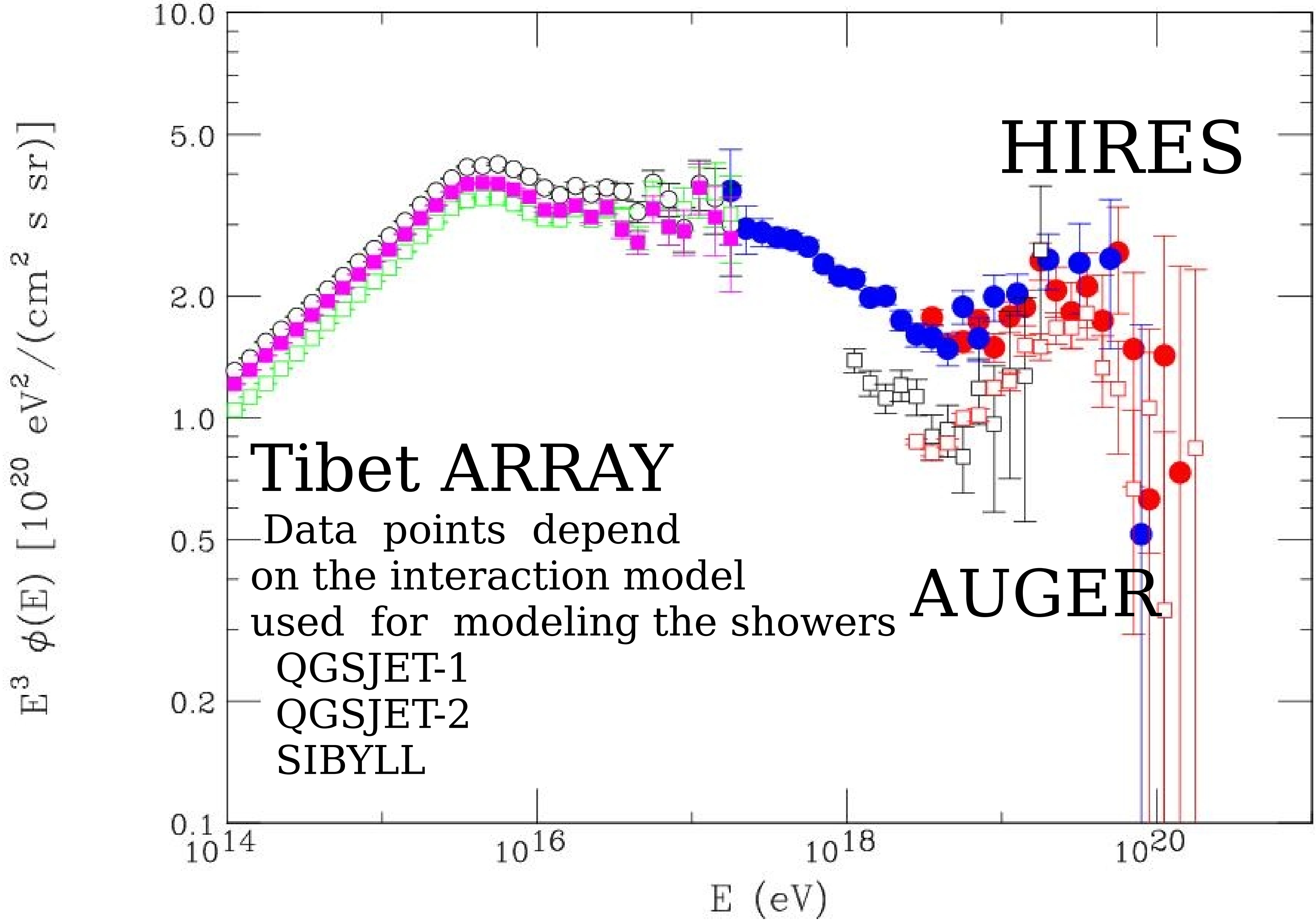
140 m from interaction point



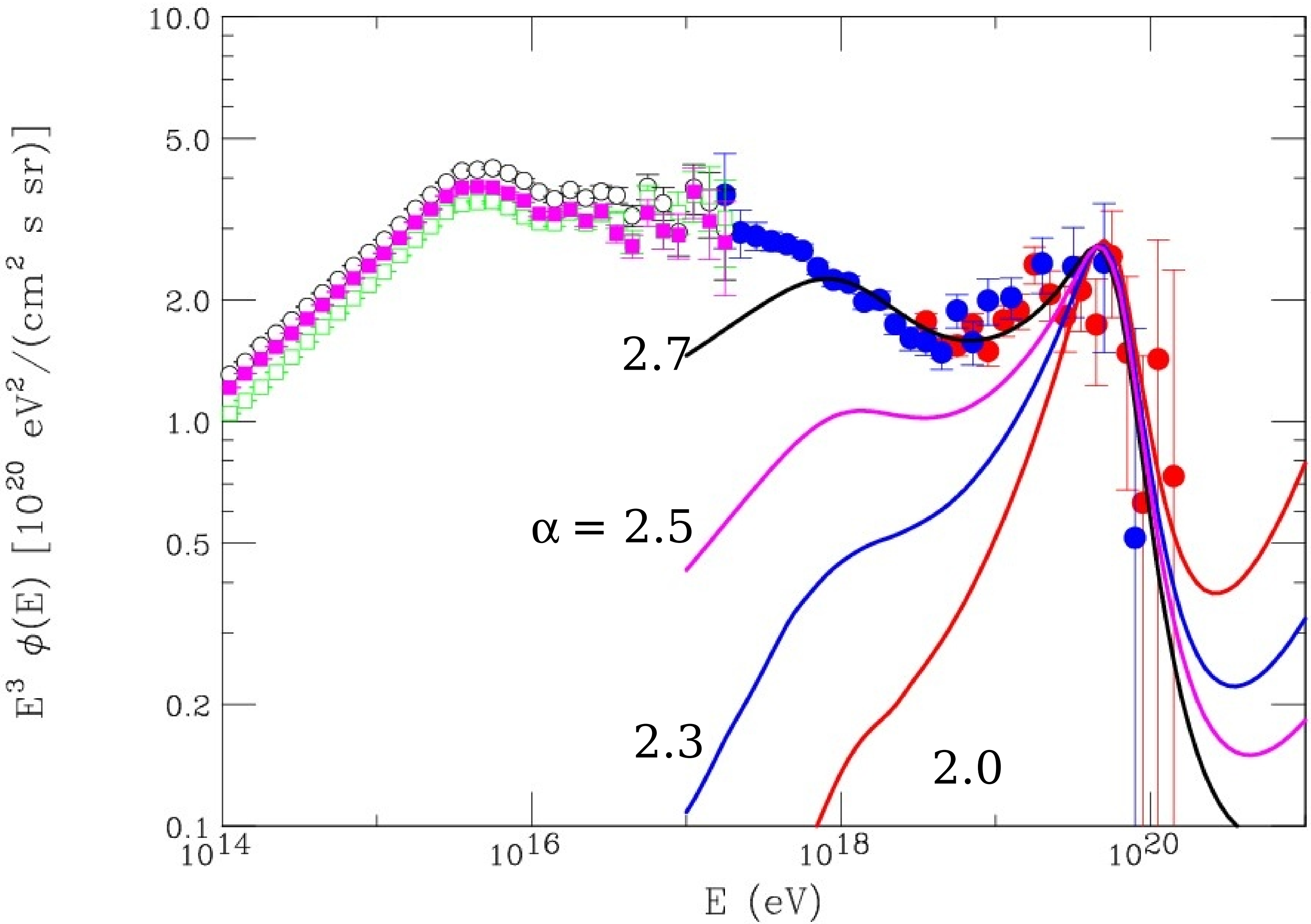
UHECR Flux * E^3 representation.



UHECR Flux * E^3 representation.



Power Law Injection (No Cosmic Evolution)



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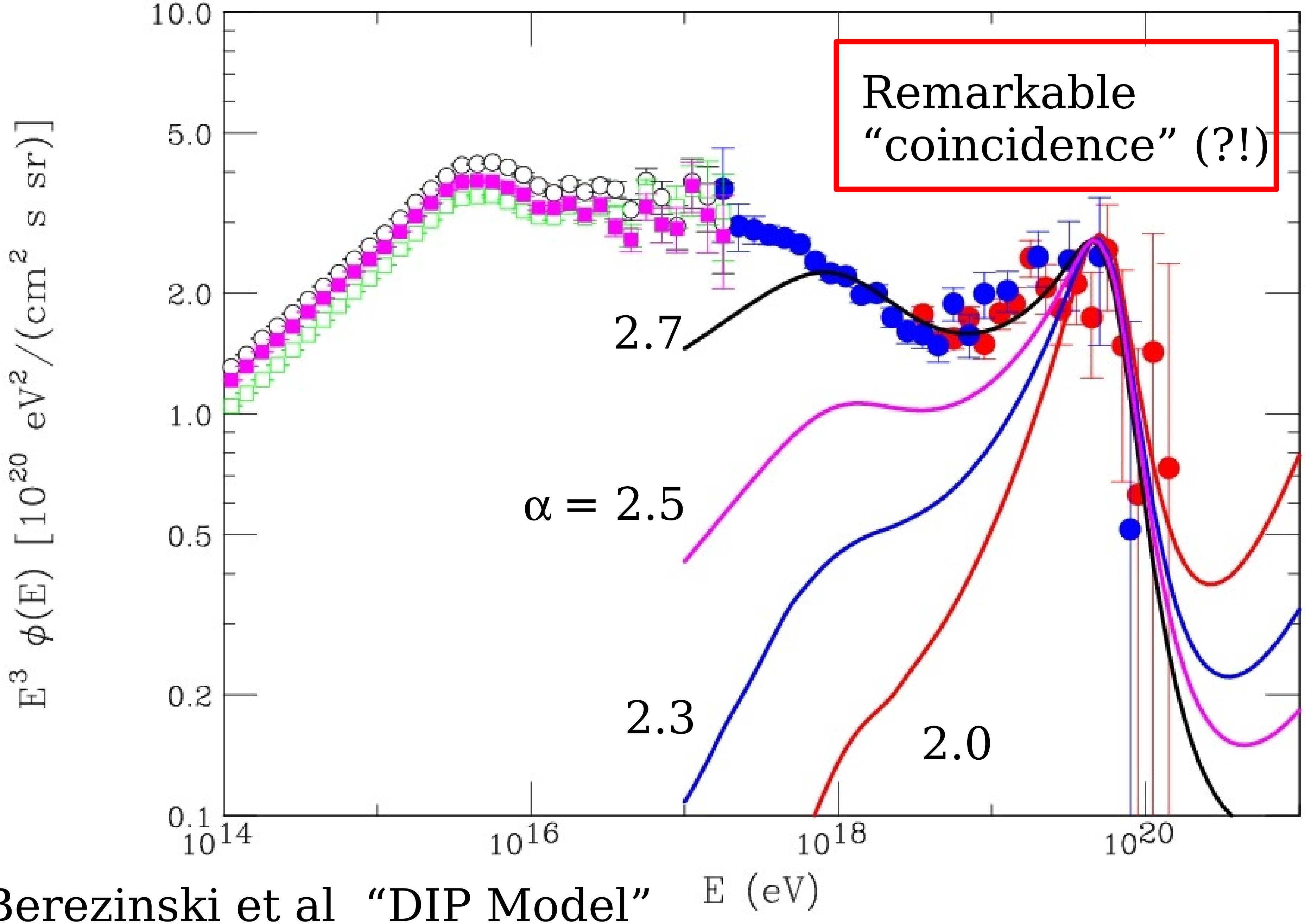
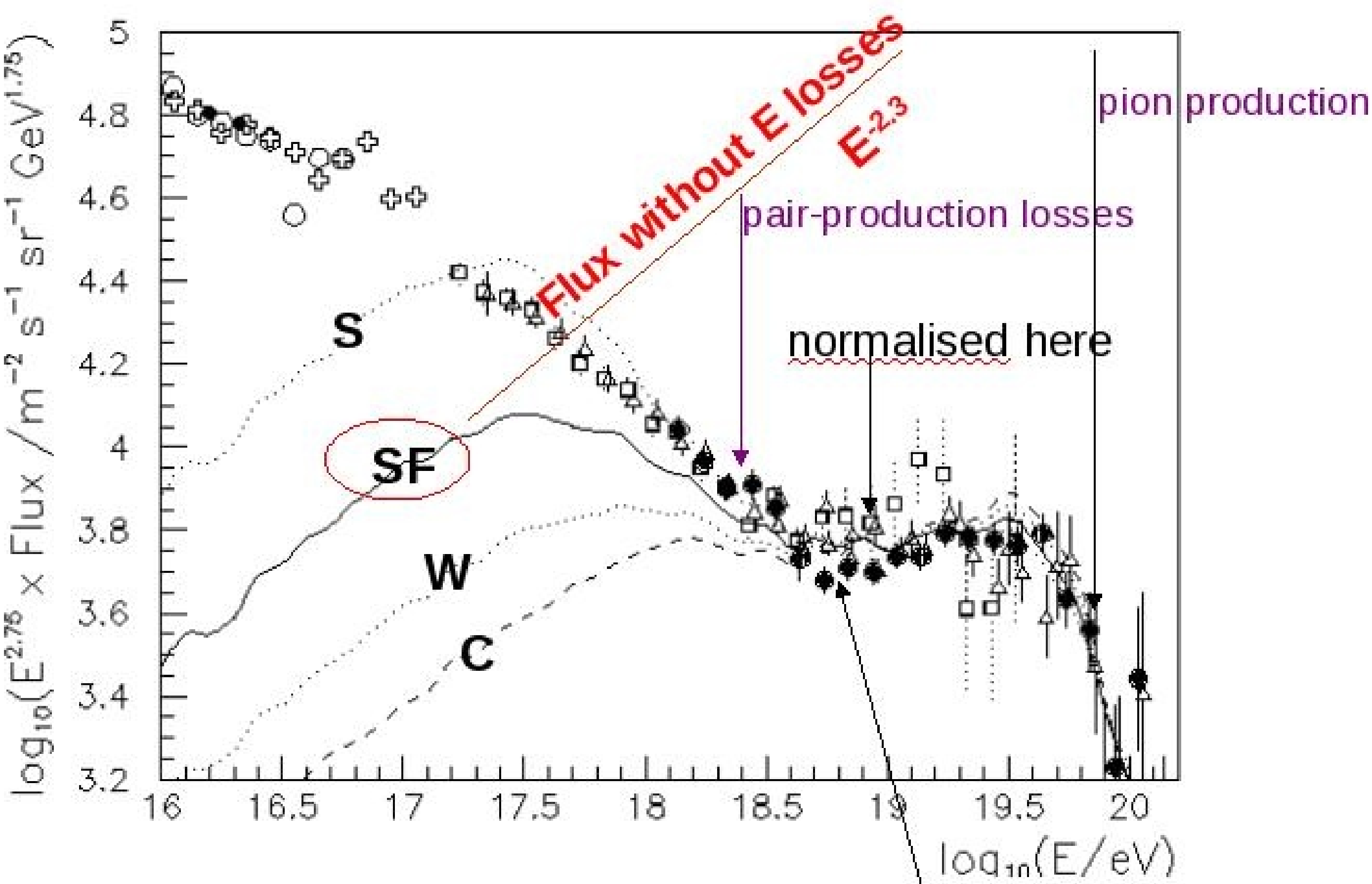


Berezinski et al "DIP Model"



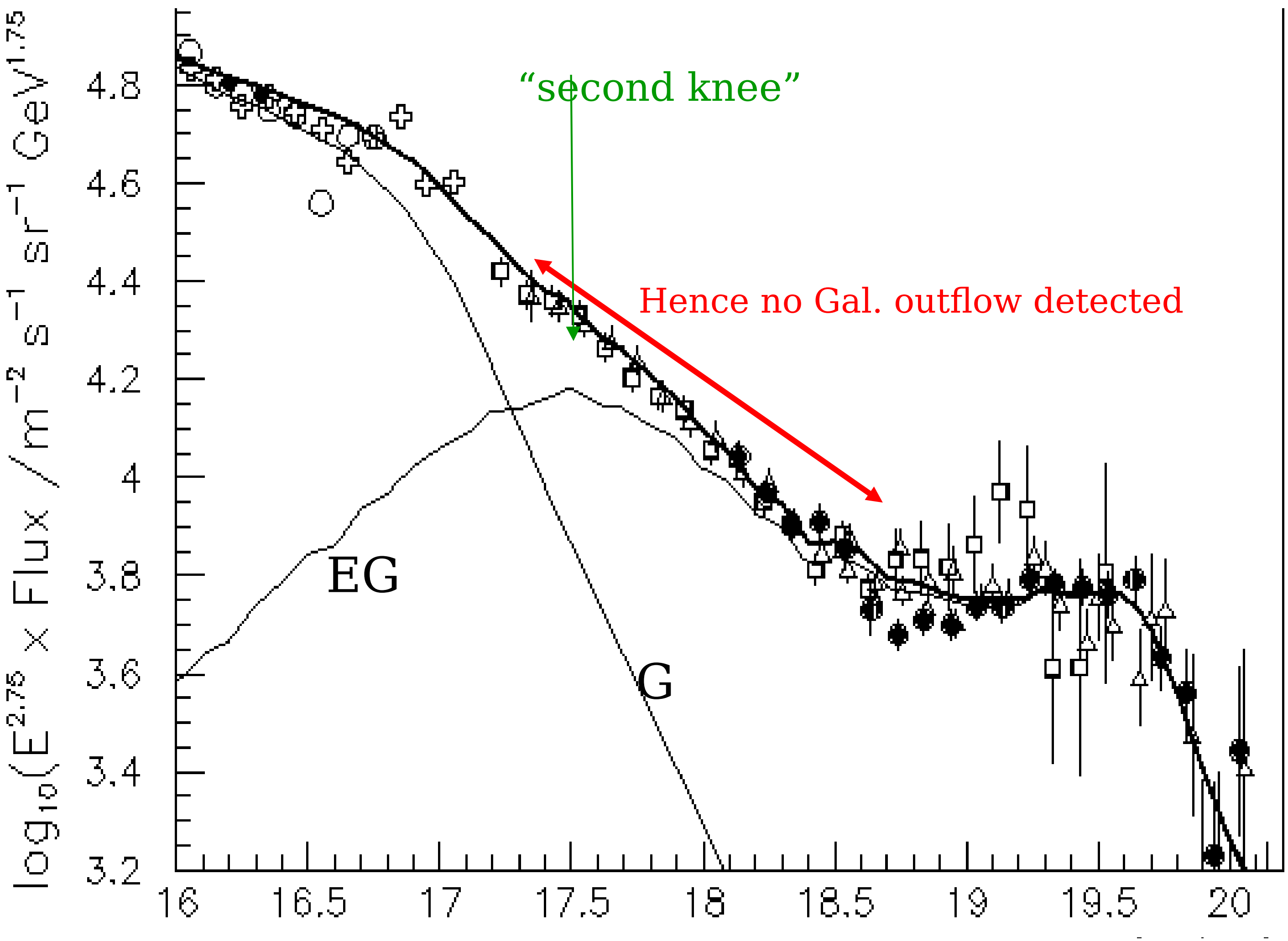
Spectrum of **protons** after struggling through the microwave treacle:

If initial spectrum dN/dE ~ $E^{-2.3}$,
Production rate in universe: **SF** = like Porciani-Madau star formation rate SF2; **C**=constant; **W**=PM $^{0.5}$; **S**= PM $^{1.5}$

The (e^+e^-)energy losses in CMBR produce an ANKLE in right place.

from Michael Hillas

Combine galactic and extragalactic part



from Michael Hillas

The idea to observe the Universe using Neutrinos
Is profoundly fascinating.

The insights about Nature that are possible
using this:
"New Way" to look at the Sky
can be profound.

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Is profoundly fascinating.

The insights about Nature that are possible using this:
"New Way" to look at the Sky
can be profound.

Neutrino Astronomy is an old "DREAM"

It is old because it is clearly important and its significance was very soon recognized.

The dream became reality with Solar and SuperNova neutrinos [E ~ 0.5 – 30 MeV]

At high energy (E > 10 GeV) neutrino astronomy remains (still) only a dream... [because it is difficult!]

Argument of Kenneth Greisen in his CR review of 1960
[to motivate construction of neutrino detectors:]

"The estimate of the neutrino flux may be too low,
since regions that produce neutrinos abundantly
may not reveal themselves in the types of radiation
yet detected"

This line of argument has been used
[with good reason (in my opinion) !]
for 50 years to motivate the construction of
Neutrino Telescopes of growing size.
[for example 1990's MACRO at Gran Sasso (~1000 m^2)]
[2000's AMANDA at the South Pole (~10^4 m^2)

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[for example 1990's MACRO at Gran Sasso (~ 1000 m^2)]
[2000's AMANDA at the South Pole ($\sim 10^4$ m^2)

The "KM^3 concept"

"The 'natural size' for a neutrino telescope is 1 Km^3 of water / ice"

For the "KM^3 concept"

the "moment of truth" has arrived.

IceCube has completed its construction
[but no astrophysical neutrino detection yet]

Difficult choices for the proponents of a neutrino detector of similar conception in the Mediterranean Sea

[looking at the Southern hemisphere of the celestial sphere]

A detector in the Mediterranean Sea
has one crucial advantage with respect
to IceCube at the South Pole:

A view of the center of our GALAXY (!)
Galactic Center
Galactic Sources

In principle also a better angular resolution
for the muon direction (less scattering in water).

Therefore smaller integration cone in the
study of point sources: smaller background.

Existing data

AMANDA

ANTARES

ICECUBE [22/80 strings 10 months (0.74 years live time)]
[40/80 strings 1 year]

No evidence for astrophysical Neutrinos

Disappointment ? YES....OF COURSE !!

Surprise ? Not really. In many ways an expected result

Problem ? In my opinion: YES

Disappointment….

The “Beaded String” Neutrino Telescopes
Have improved the sensitivity of these instruments
By two orders of magnitude !

They *could* have discovered sources!

In fact some of the limits
[for example on AGN models]
do have astrophysical significance.

….and then…
One could hope for surprises…

Francis Halzen: 1996

Table 1: New windows on the Universe

Telescope	Intended use	Actual results
optical (Galileo)	navigation	moons of Jupiter
radio (Jansky)	noise	radio galaxies
optical (Hubble)	nebulae	expanding Universe
microwave (Penzias-Wilson)	noise	3K cosmic background
X-ray (Giacconi...)	moon	neutron stars...
radio (Hewish, Bell)	scintillations	pulsars
γ-ray (???)	thermonuclear explosions	γ-ray bursts

Neutrino Telescopes {SNR, AGN,...} {???}

Francis Halzen: 1996

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γ-ray (???)	thermonuclear explosions	γ-ray bursts

Neutrino Telescopes	{SNR, AGN,...}	{???}

...The "Expected Unexpected Big Surprise"

.....remains still hidden.....

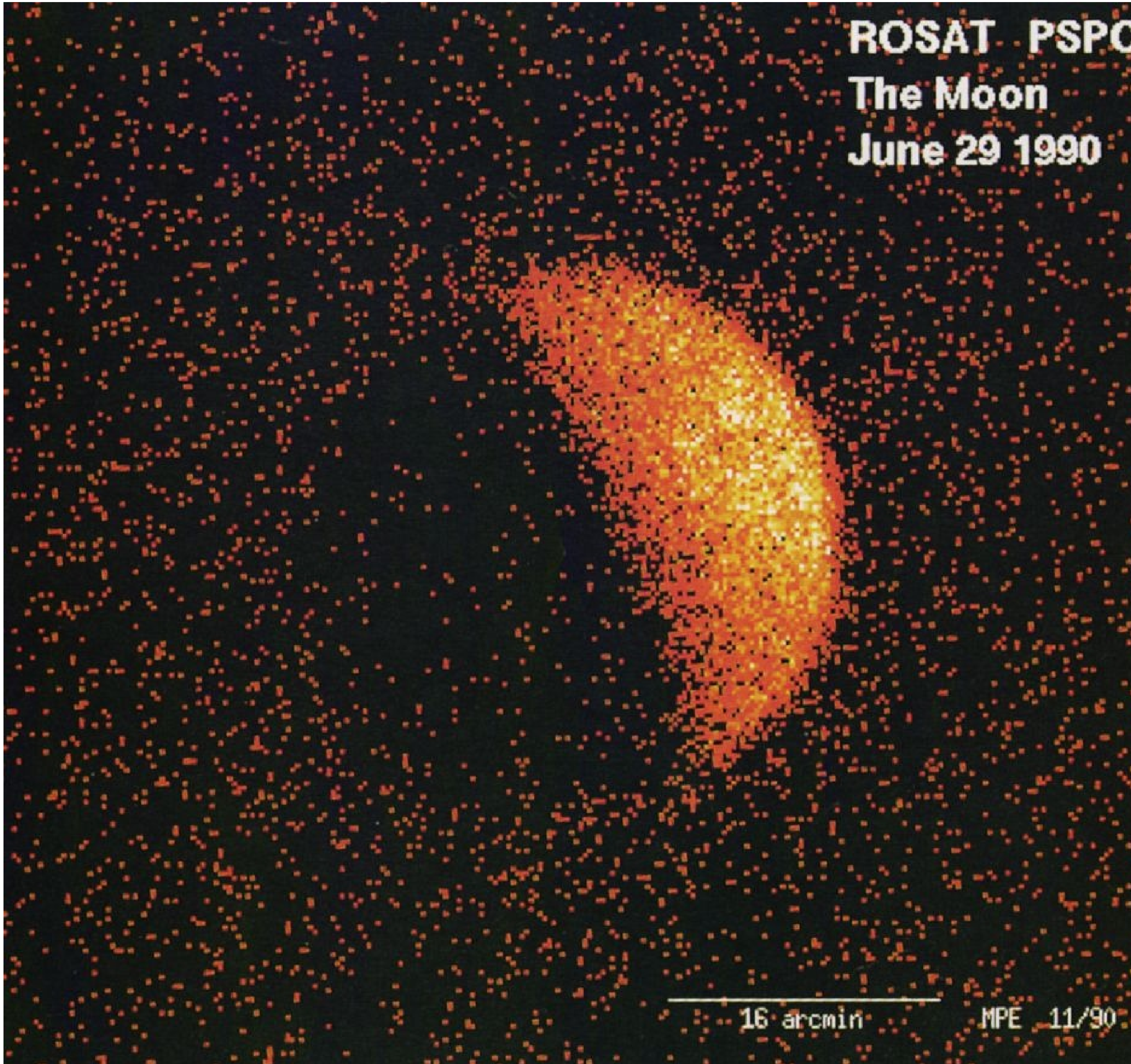
[and is after all not guaranteed]

X ray Sky

SKY

MUCH BRIGHTER than the MOON

7000 sources/$(^{o})^2$

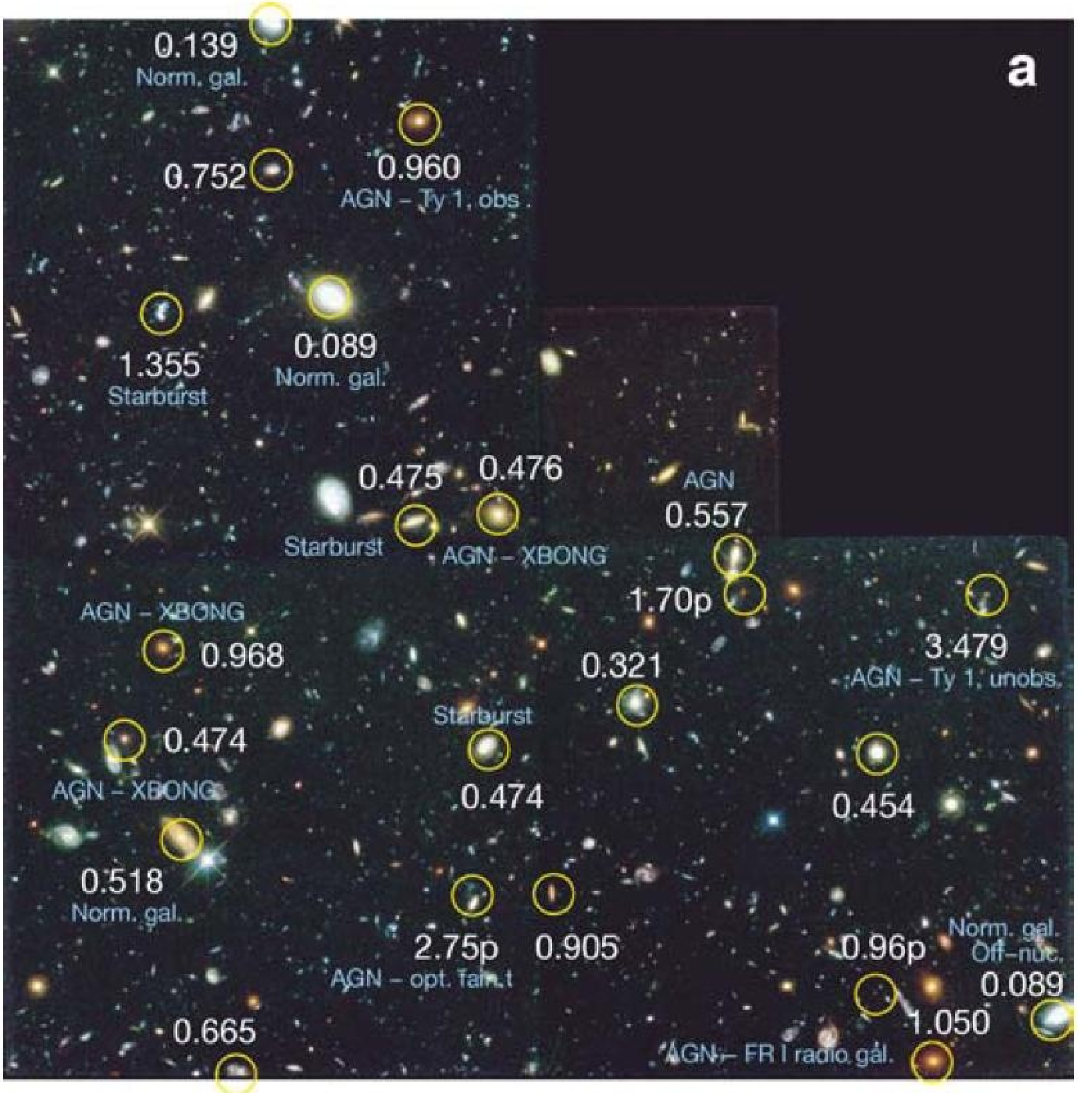


CHANDRA

Deep
Field
North

X-ray emission
from AGN

+
Pulsars,
binary systems
……



¼ , ½   of KM3 telescope and no neutrinos …

Surprise ?   Not Really.

Most cited review: Gaisser, Halzen, Stanev. Phys. Rep. 1995.

Table 5

	Muon energy	Events per year in 0.1 km^2	
		Ref. [72]	Ref. [75]
Atmospheric (angle averaged, per steradian)	> 1 GeV	7800	8300
	> 1 TeV	129	104
		$\cos\theta = 0.05$	$\cos\theta = 0.95$
Atmospheric in 1° circle, Ref. [75]	> 1 GeV	12.6	5.6
	> 1 TeV	0.21	0.05
		no abs.	with abs.
Extraterrestrial fluxes (angle averaged)	> 1 GeV	32.7	32.0
$\phi_\nu = 2.7 \times 10^{-5} (E_\nu/\mathrm{GeV})^{-1.7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	> 1 TeV	4.3	3.8
$\phi_\nu = 4.0 \times 10^{-8} (E_\nu/\mathrm{GeV})^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	> 1 GeV	8.8	6.6
	> 1 TeV	5.0	3.3
		plane of galaxy	AGN
Astrophysical diffuse fluxes (per steradian)	> 1 GeV	12–20	80–200
	> 1 TeV	1.5–3.0	40–200
	also $\nu_e(6.3\ \mathrm{PeV}) + e \to W^-$		0.3 per 1000 kton
Astrophysical point sources ($E_\mu > 1$ TeV)			
Galactic source (Eq. 37)/100			2.6
Extragalactic source			0.1–10
500 GeV WIMPS from ⊙			20

¼ , ½ of KM3 telescope and no neutrinos …

Surprise ? Not Really.

“Problem” ?

The Km3 neutrino concept
[In its current design]
risks to have a sensitivity below
the one needed to detect
the astrophysical fluxes

[or a “marginal” sensitivity]

…. Of course this “statement of doubt”
Could sound very ridicoulous soon …..

New unexpected sources could emerge!
[maybe tomorrow!]

Blazar emission could be accompanied
by detectable neutrino emission.

Very Interesting [speculative] ideas about
GRB could be “on the right track”

GRB neutrino emission detectable !!
[This would make neutrino telescopes real “stars”]

Neutrino Astronomy should be considered in the context of the scientific programs toward the understanding of the "High Energy Universe".

Neutrino Astronomy
Gamma Astronomy
Cosmic Ray Astrophysics

What is the significance of the observations of a small number of neutrinos from several sources ?

[Can the hadronic nature of the emission be established *without* neutrinos, from multiwavelength observations?]

Power of discrimination is widely considered as important

What could one learn about the neutrino properties
When astrophysical neutrinos are finally detected ?

Extraordinary Long Baselines

$$L_{\rm galactic} \simeq 3 \times 10^{22} \ {\rm cm}$$

$$L_{\rm extra} \simeq 1.3 \times 10^{28} \ z \ {\rm cm}$$

Oscillations with very small Dm2

[Pseudo-Dirac neutrinos
Mass doublet with tiny
Mass splitting]

$$\Delta m^2 \sim 10^{-18} \ {\rm eV}^2$$

Neutrino decay (9 orders of magnitude improvement)

Neutrino cross sections at very high energy

Final Comments (instead of conclusions)

The interest of Neutrino Astronomy is remarkable.

The difficulties are great.

Detector optimization requires identifying
"Physics priorities"

Focus on Galactic Sources
Deeper searches for Extra-galactic Sources
Search for GRB emission
"GZK" cosmogenic neutrinos.

Better angle, energy (for muon) resolution

Very large "sparse" detectors ?

Additional Topics for a complete discussion:

- Atmospheric Neutrinos
- Cosmogenic "GZK" Neutrinos
- Exotic Physics Neutrinos
  (Top-Down Models)
- Dark Matter Annihilation Neutrinos
  (from the Sun or the Center of the Earth)
- "Interdisciplinary studies"