Multi-messenger Astrophysics: *Gamma Rays and Neutrinos*

Paolo Lipari (INFN Roma Sapienza)
15th Agile Workshop
ASI headquarters 23-24 may 2017

"High Energy Universe"

The ensemble of astrophysical objects, environments and mechanisms that generate and store very high energy relativistic particles in the Milky Way and in the entire universe.

4 Messengers

Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

Understanding the

"High Energy Universe"

is one of the most significant and fascinating "Frontiers" in Science today.

1. Understanding the *COSMOS* where we live

2. The sources of the High Energy radiation can be the "laboratories" where we test
   (in conditions that are not achievable in "Earth based laboratories")
   our Fundamental Laws of Physics.

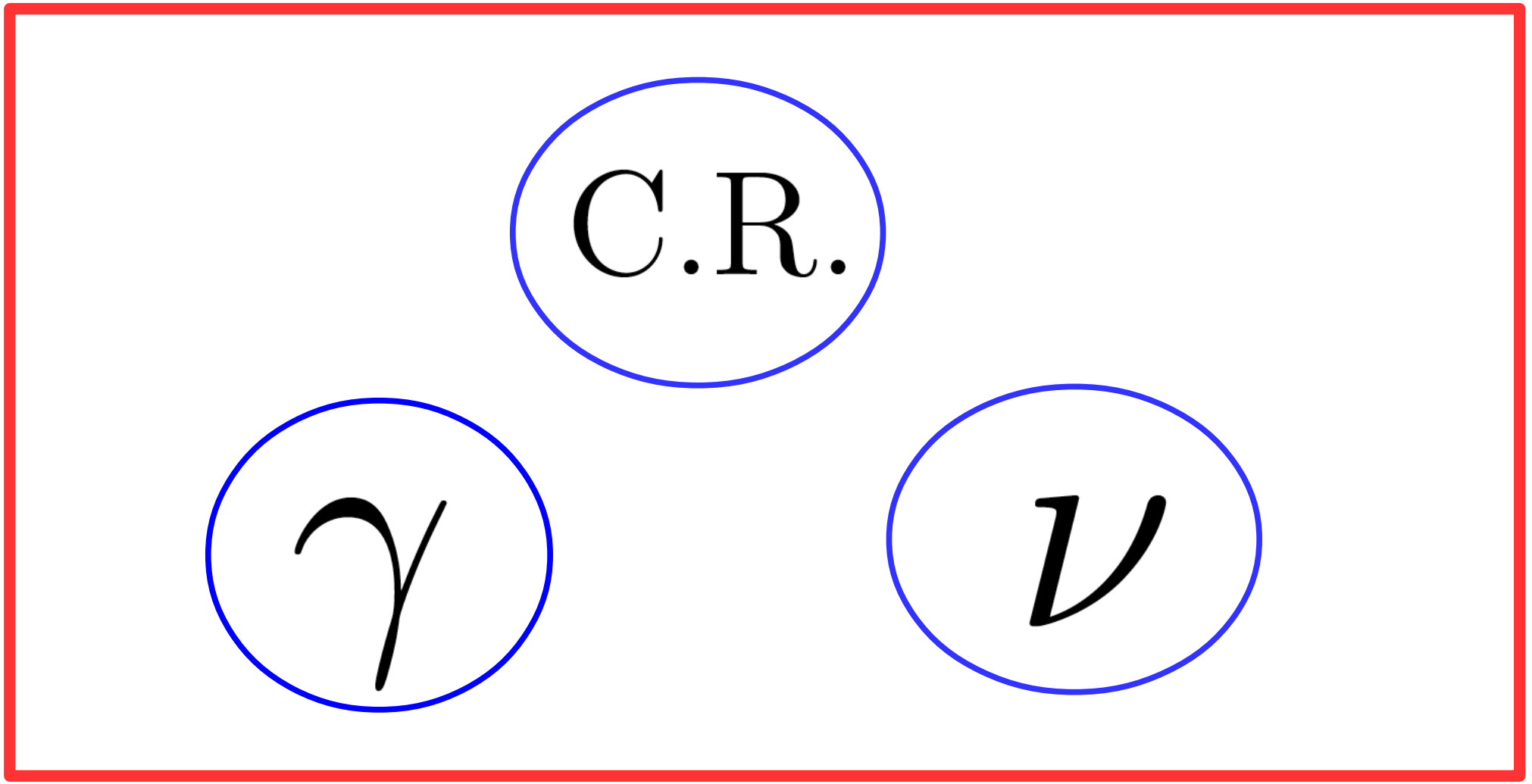
Neutrino Sources

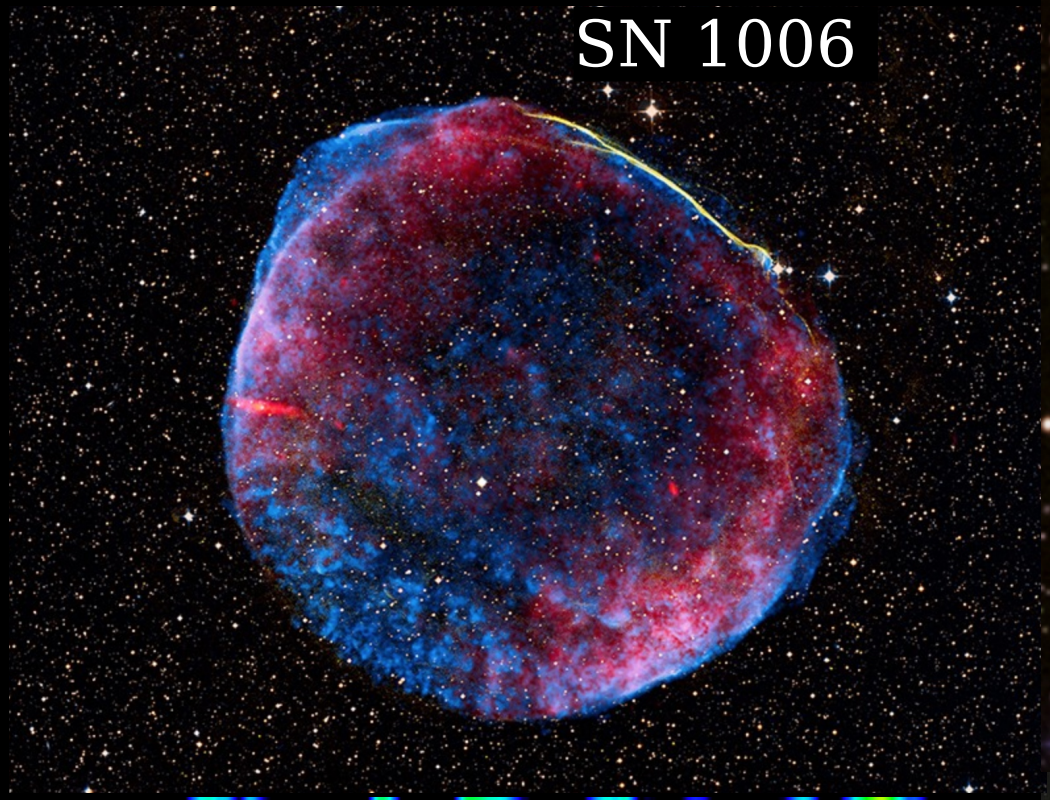
Cosmological Neutrinos $E_\nu \simeq 10^{-4}$ eV

Geo-neutrinos
Solar Neutrinos
SuperNova Neutrinos $E_\nu \simeq 10^{6} - 10^{8}$ eV

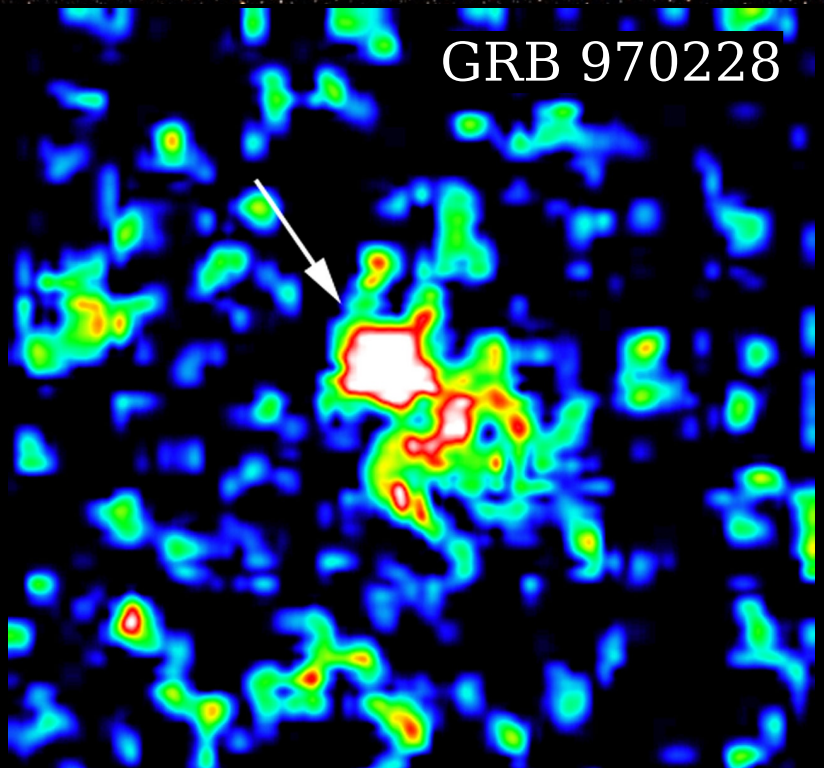
Neutrinos from the
"High Energy Universe" $E_\nu \simeq 10^{10} - 10^{23}$ eV

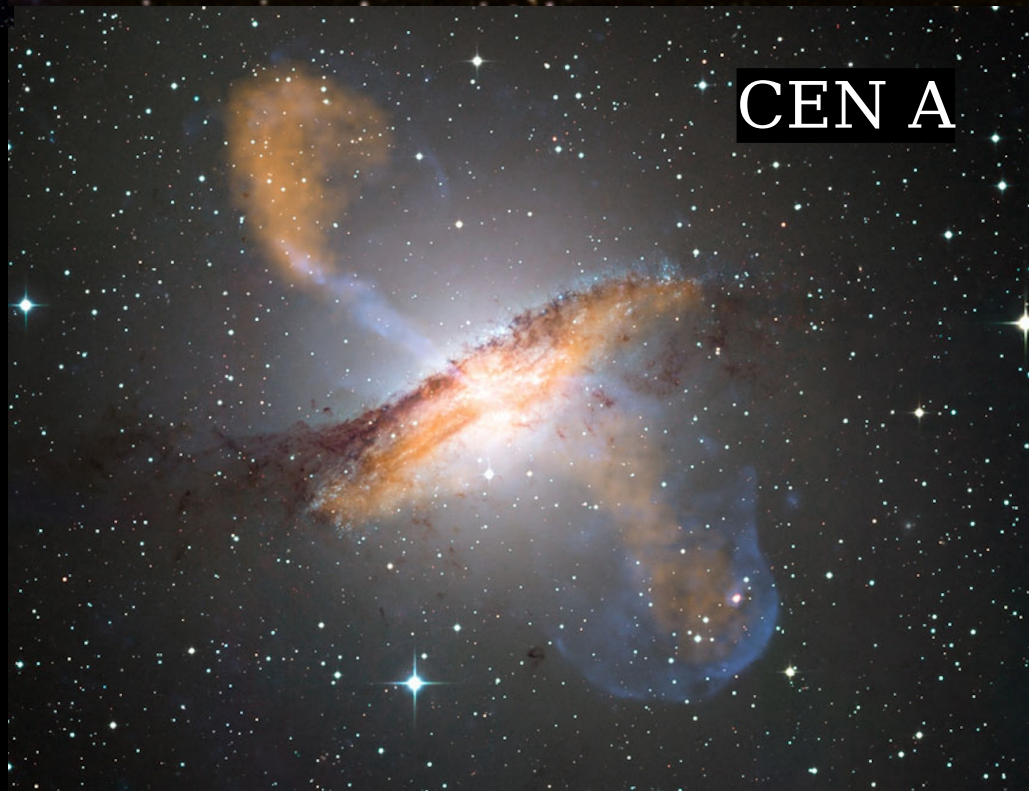
Intimate connection between the 3 *messengers*
in the Study of the High Energy Universe




SN 1006


Crab Nebula

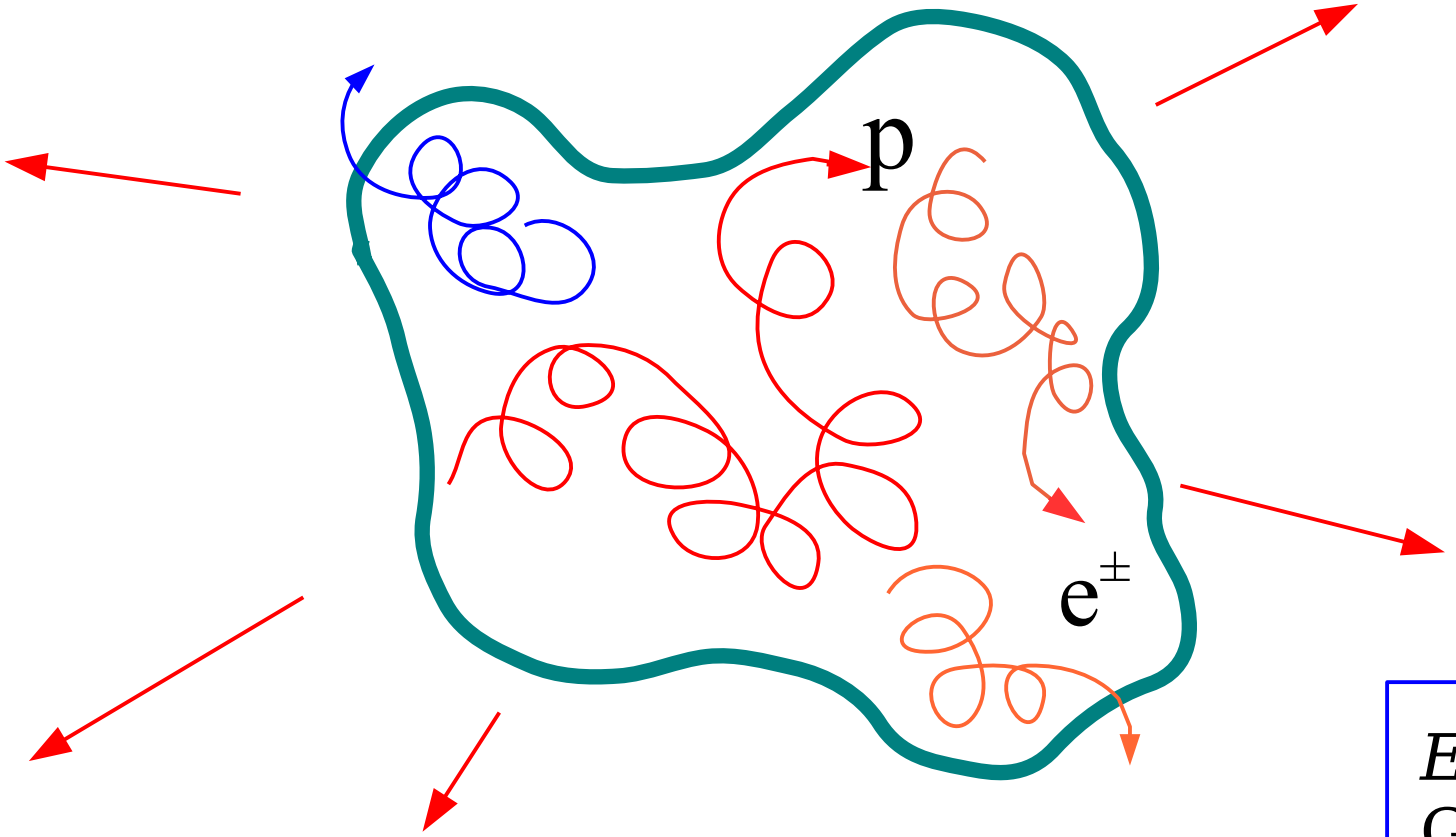

GRB 970228


CEN A

Extraordinary Beasts in the Sky

High Energy Astrophysical Sources:

Astrophysical object (or “event”)
that accelerates, and contains
(electrically charged) relativistic particles
(protons, electrons, nuclei....)



Interactions:
Emissions

gamma rays,
neutrinos

Escape:
Generation of CR

Fundamental Mechanism:

Acceleration of Charged Particles

to Very High Energy ("non thermal processes")
in astrophysical objects (or better "events").

Creation of Gamma Rays and Neutrinos
via the interactions of these relativistic charged particles.

"Hadronic"

$$p + \mathrm{X} \rightarrow \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^\circ \rightarrow \gamma \; \gamma$$

$$\pi^+ \rightarrow \mu^+ \; \nu_\mu$$

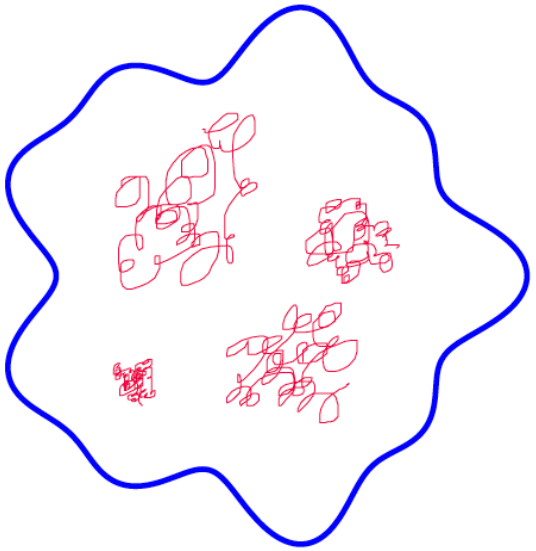
$$\hookrightarrow \; e^+ \; \nu_e \; \overline{\nu}_\mu$$

"Leptonic"

$$e^\pm \; \gamma_{\mathrm{soft}} \rightarrow \; e^\pm \; \gamma$$

$$e^\pm \; Z \rightarrow \; e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \rightarrow e^\pm \; \gamma_{\mathrm{syn}}$$



Population of relativistic protons: $N_p(E_p)$

Average density of the medium: n

Emission Rates of Photons and Neutrinos:

$$\dot{N}_{\nu,\gamma}(E) = \int_E^\infty dE_p \; N_p(E_p) \; [\sigma_{pp}(E_p)\, c\, n] \; \frac{dN_{\gamma,\nu}(E, E_p)}{dE}$$

$$p + \mathrm{X} \rightarrow \pi^+ \; \pi^- \; \pi^\circ \; \ldots$$

$$\pi^+ \rightarrow \mu^+ \quad \nu_\mu$$

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

$$\pi^\circ \rightarrow \quad \gamma \; \gamma$$

Simple relation between neutrino and gamma-ray emissions

IF the population of relativistic protons inside an astrophysical source is a *power law of exponent alpha*

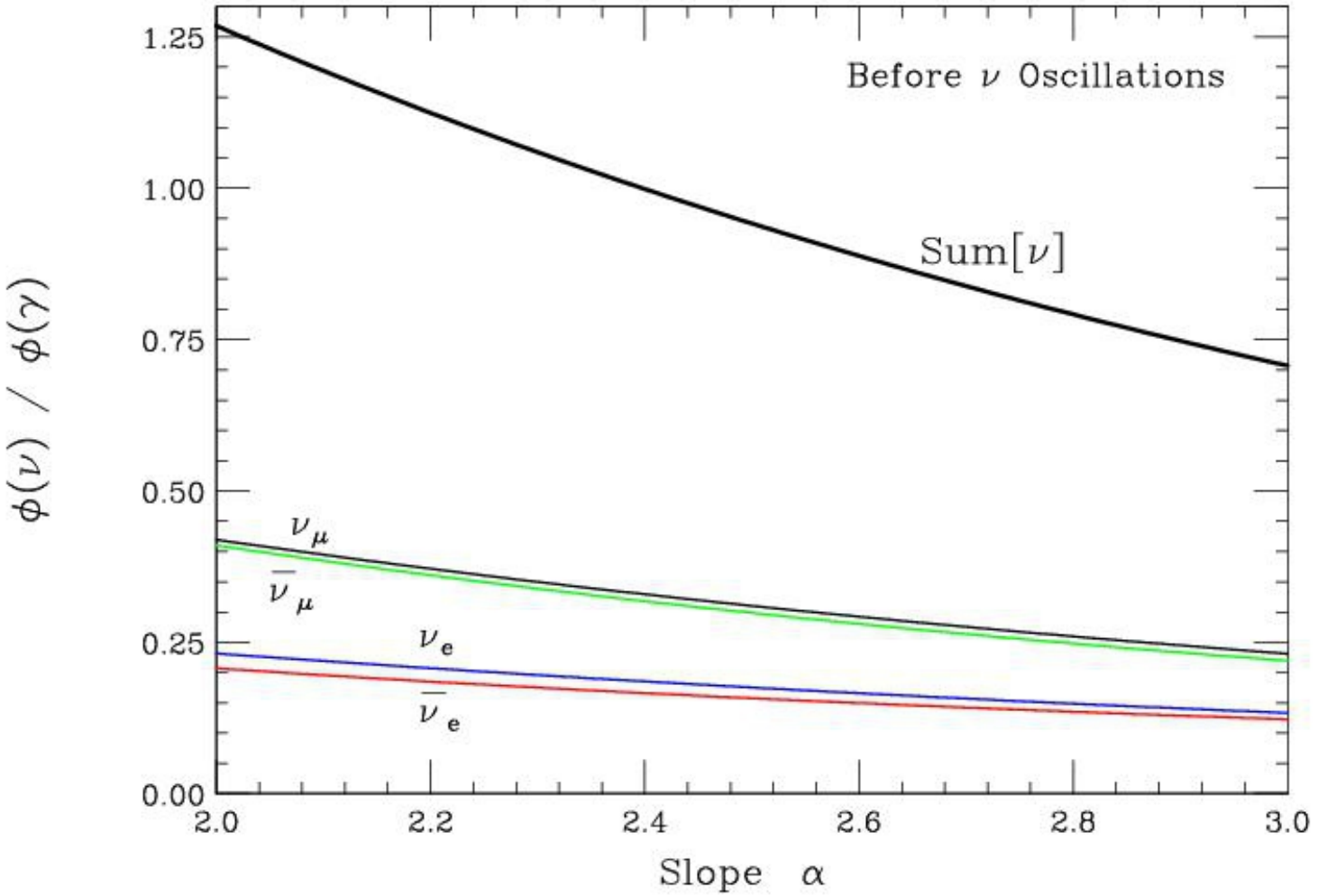
$$N_p(E) = K_p \; E_p^{-\alpha}$$

Then (in reasonably good approximation) the neutrino and photon emissions are also power laws with the *same exponent.*

$$\dot{N}_\nu(E) = Q_\nu \; E_\nu^{-\alpha}$$

$$\dot{N}_\gamma(E) = Q_\gamma \; E_\gamma^{-\alpha}$$

Ratio Neutrino-Photon (numerical calculation)



$$\pi^+ \approx \pi^- \approx \pi^\circ$$

$$\gamma/\nu \approx 1$$

$$\nu_\mu/\nu_e \approx 2$$

$$\nu/\overline{\nu} \approx 1$$

Spectral index of proton spectrum

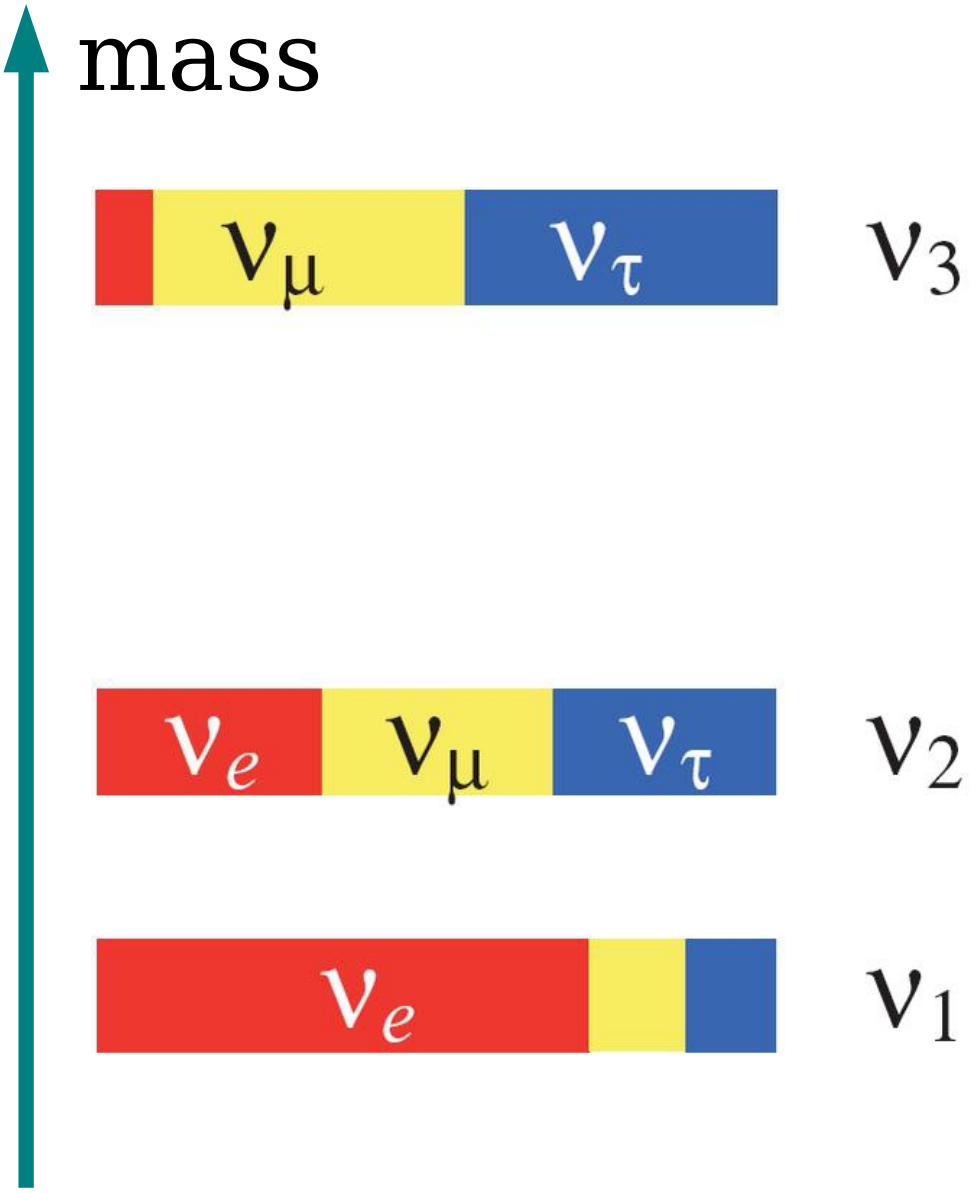
Neutrino Flavor, Neutrino masses

$$\{\ |\nu_e\rangle \quad , \quad |\nu_\mu\rangle \quad , \quad |\nu_\tau\rangle\ \}$$

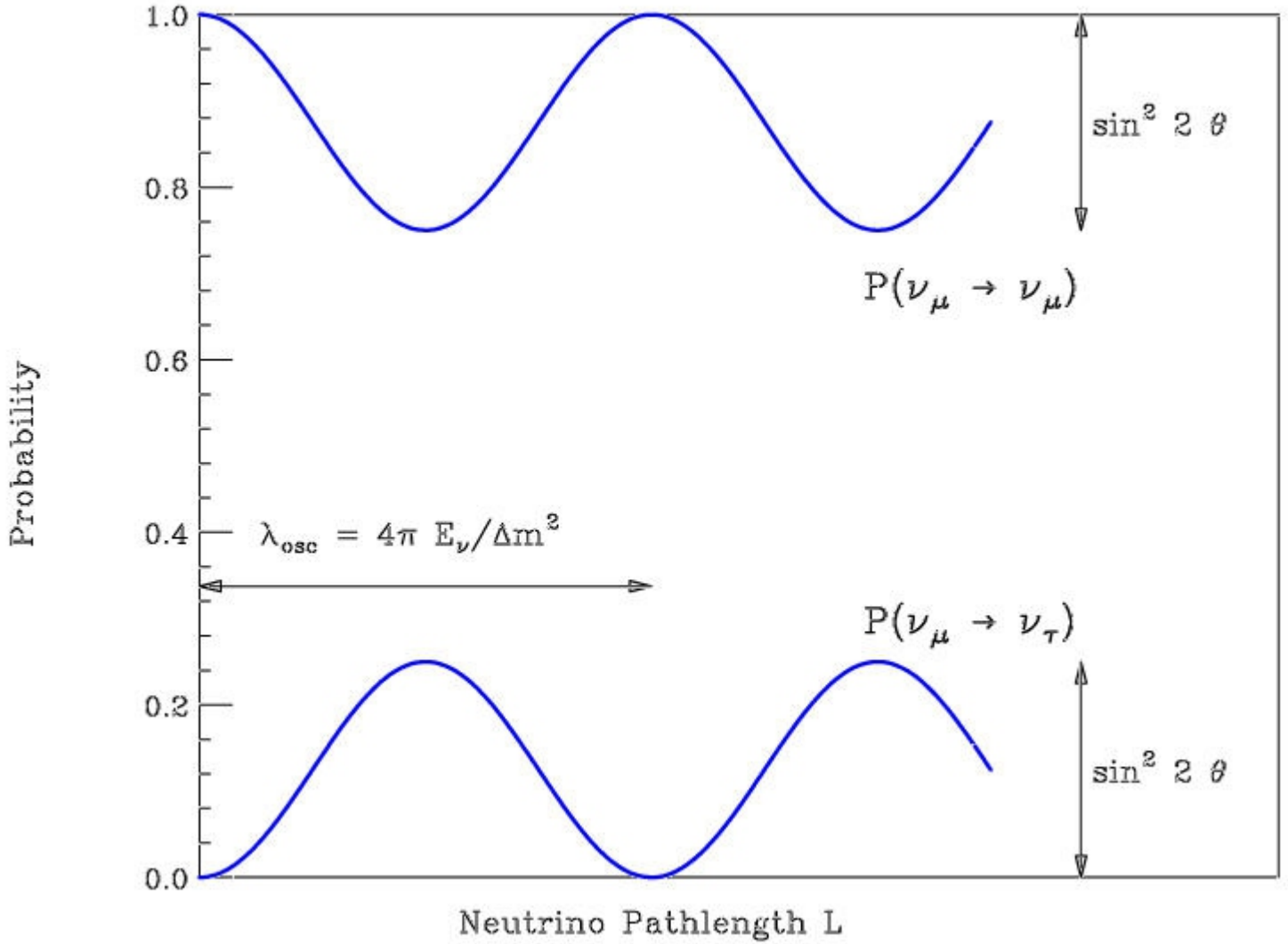
$$\{\ |\nu_1\rangle \quad , \quad |\nu_2\rangle \quad , \quad |\nu_3\rangle\ \}$$

$$P_{\alpha j} = |\langle \nu_\alpha | \nu_j \rangle|^2$$

$$= |U_{\alpha j}|^2$$



$$P(\nu_\mu \to \nu_\tau;\, L) = \sin^2 2\theta \, \sin^2 \left[1.27\, \Delta m^2(\mathrm{eV}^2) \frac{L(\mathrm{Km})}{E(\mathrm{GeV})} \right]$$



$$P_{\nu_\alpha \to \nu_\beta}(E_\nu, L) = \left| \sum_j U_{\beta j} U^*_{\alpha j} \; e^{-i\, m_j^2 \, \frac{L}{2E_\nu}} \right|^2$$

$$= \sum_{j=1,3} |U_{\beta j}|^2 \; |U_{\alpha j}|^2$$

$$+ \sum_{j<k} 2\,\mathrm{Re}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \cos\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)$$

$$+ \sum_{j<k} 2\,\mathrm{Im}[U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k}] \; \sin\left(\frac{\Delta m^2_{jk}\, L}{2E}\right)$$

Space averaged
flavor transition probability

Neutrinos created in volume
of sufficiently large linear size

$$X_{\mathrm{source}} \gg E/|\Delta m^2_{jk}|$$

Oscillating terms average to zero

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

$$\simeq \begin{pmatrix} 1-2v & v & v \\ v & (1-v)/2 & (1-v)/2 \\ v & (1-v)/2 & (1-v)/2 \end{pmatrix} \simeq \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}$$

$\theta_{13} \simeq 0$

$\theta_{23} \simeq 45^\circ$

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

$$\begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

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

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

"Standard mechanism"

$$\begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

much more "astrophysically plausible"

"Muon absorption"

Very high magnetic field

$$\begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} v \\ (1-v)/2 \\ (1-v)/2 \end{pmatrix} \approx \begin{pmatrix} 0.2 \\ 0.4 \\ 0.4 \end{pmatrix}$$

"Neutron decay"

Nuclear fragmentation

$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1-2\,v \\ v \\ v \end{pmatrix} \approx \begin{pmatrix} 0.6 \\ 0.2 \\ 0.2 \end{pmatrix}$$

Possibility of
"Modifications" of the neutrino flux
during propagation.

Investigate :
Flavor Oscillations
(with very long path-lengths)

[Pseudo-Dirac neutrinos
mass doublets with tiny
mass splitting]

$$z \simeq 1 \qquad \Delta m^2 \approx 10^{-18} \left(\frac{E}{100 \text{ TeV}} \right) \text{ eV}^2$$

Neutrino Decay [with very long lifetimes]

(9 orders of magnitude improvement)

.....

Important difficulty:
Properties of the neutrinos at the source
must be sufficiently well understood.

Prediction
of the neutrino flux
from a source observed
in gamma rays

Astrophysical
source

$$\phi_\gamma(E)$$

Earth

$$\phi_{\nu_\alpha}(E)$$

$$\phi_\gamma^{\text{leptonic}}(E) + \phi_\gamma^{\text{hadronic}}(E)$$

Possible absorption in the source
(and in propagation from the source)

Astrophysical source

$$\phi_\gamma(E)$$

Flavor oscillations
(good theoretical control)

Earth

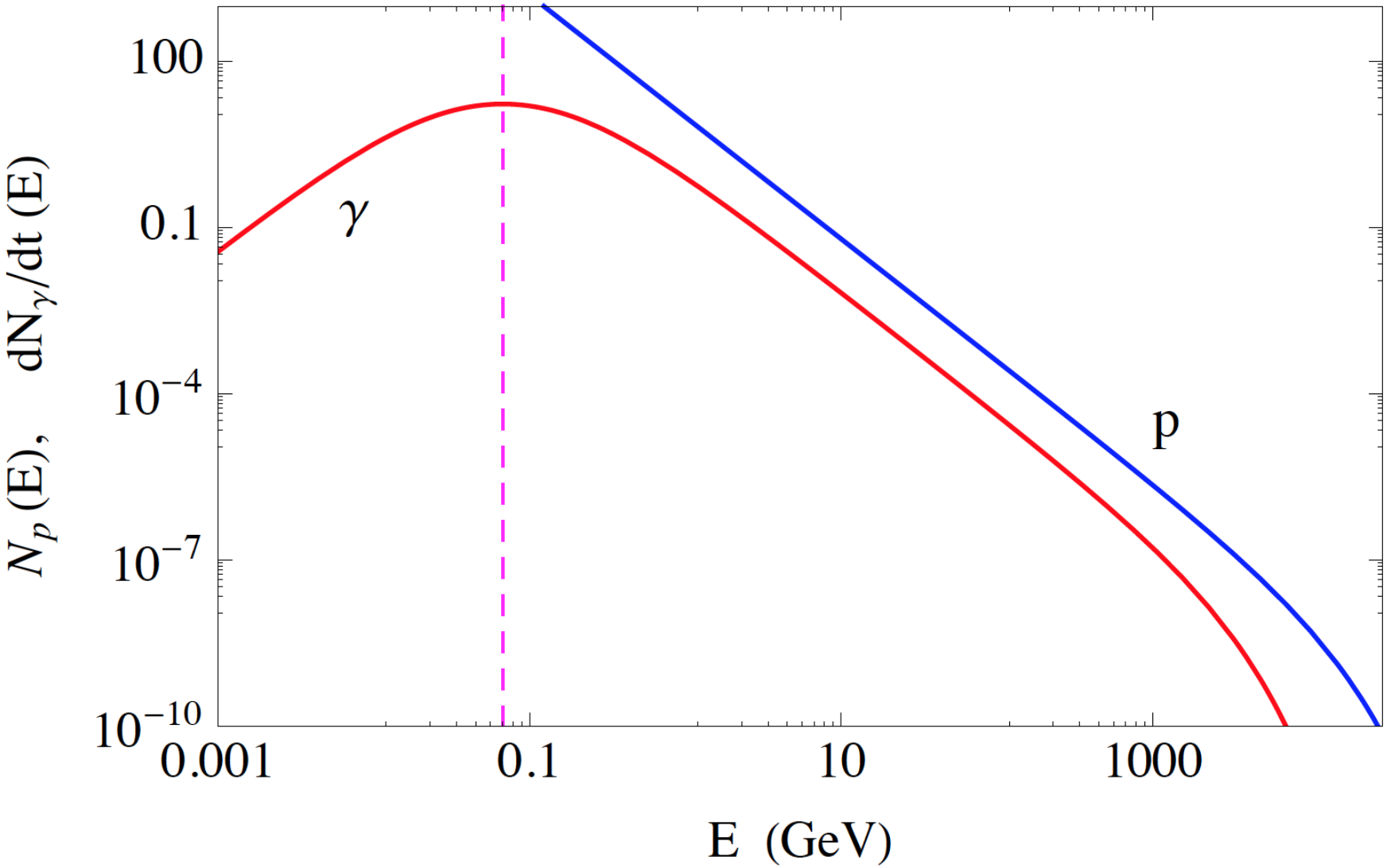
$$\phi_{\nu_\alpha}(E)$$

ENERGY EXTRAPOLATION

"Signature" of the hadronic mechanism:

The pi0 mass leaves its "imprint" on the shape of the photon spectrum

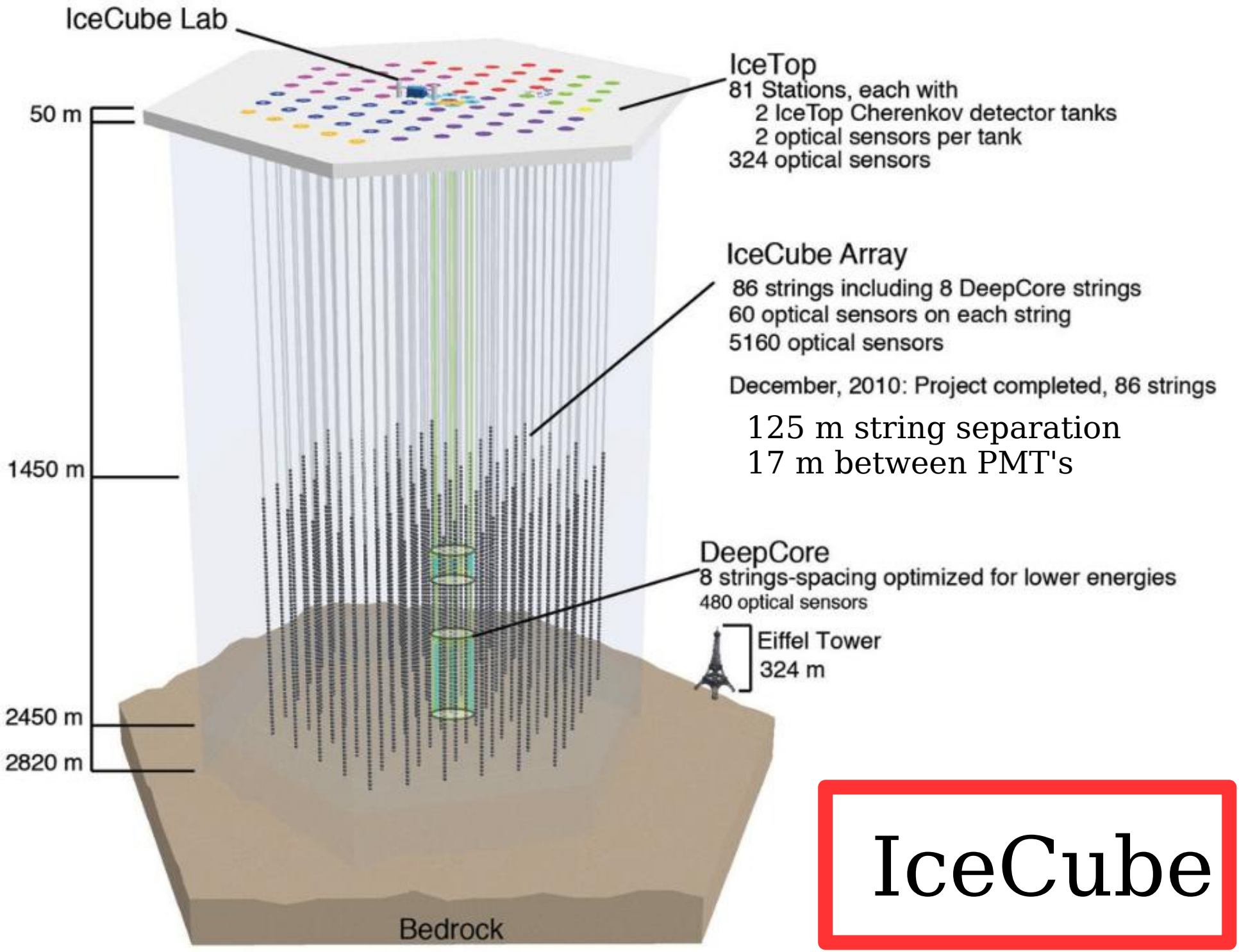
Spectrum symmetric around $E_\gamma = \frac{m_{\pi^\circ}}{2}$



Neutrino Telescopes

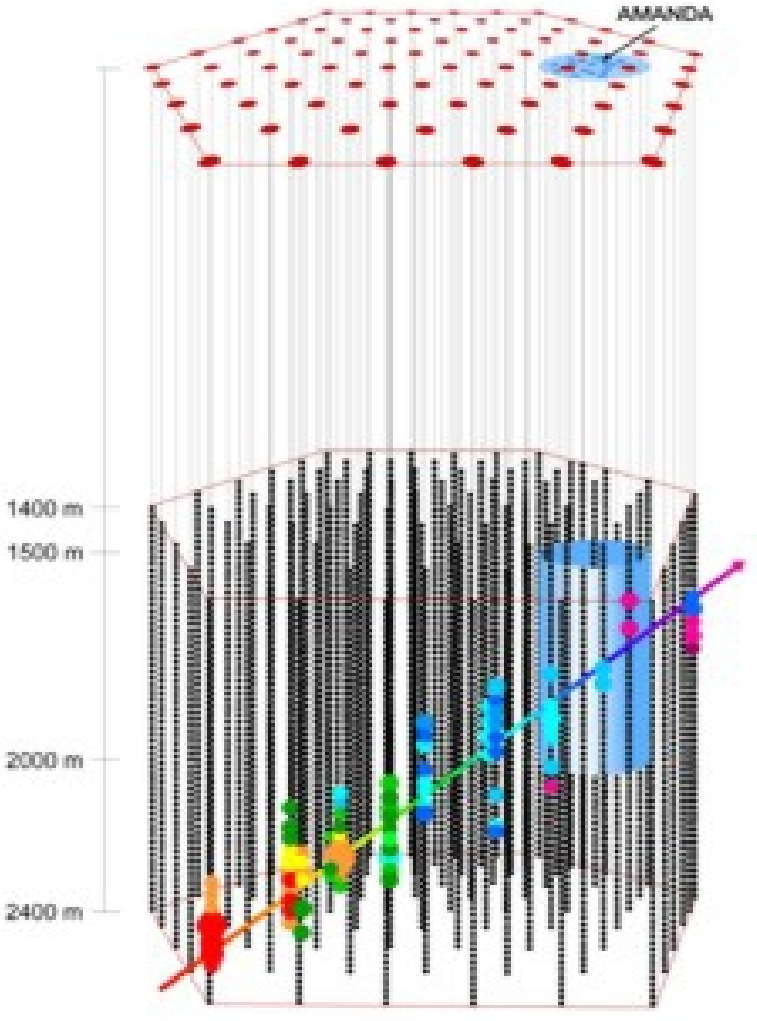
The “Km3” concept

Instrumentation of a large volume
of a transparent medium
(water or ice) with photon detectors (PMT's)


IceCube Lab
50 m
1450 m
2450 m
2820 m
Bedrock
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
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
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
IceCube

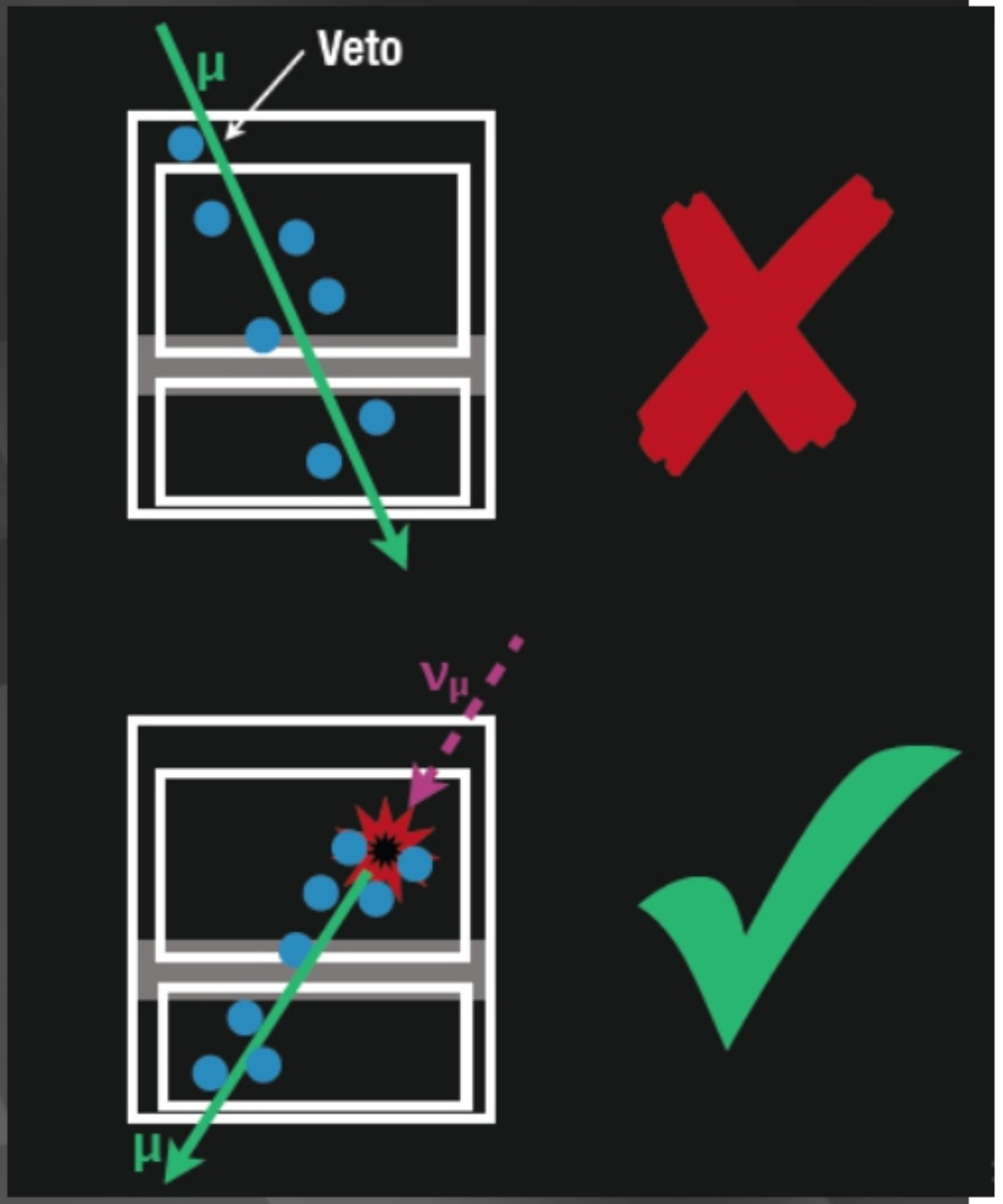
Amundsen-Scott South Pole station

Deployment of the strings



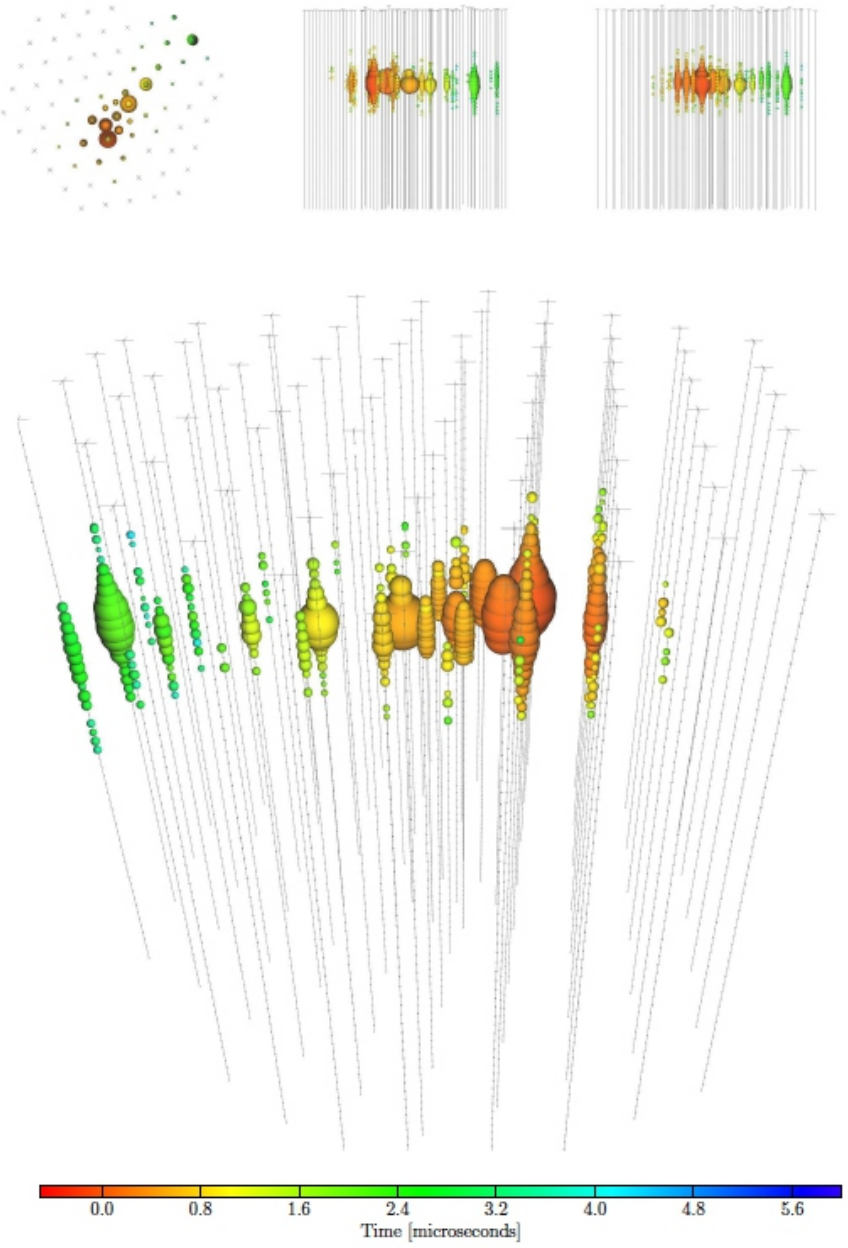
Contained events

- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution



loss in statistics is compensated by event definition

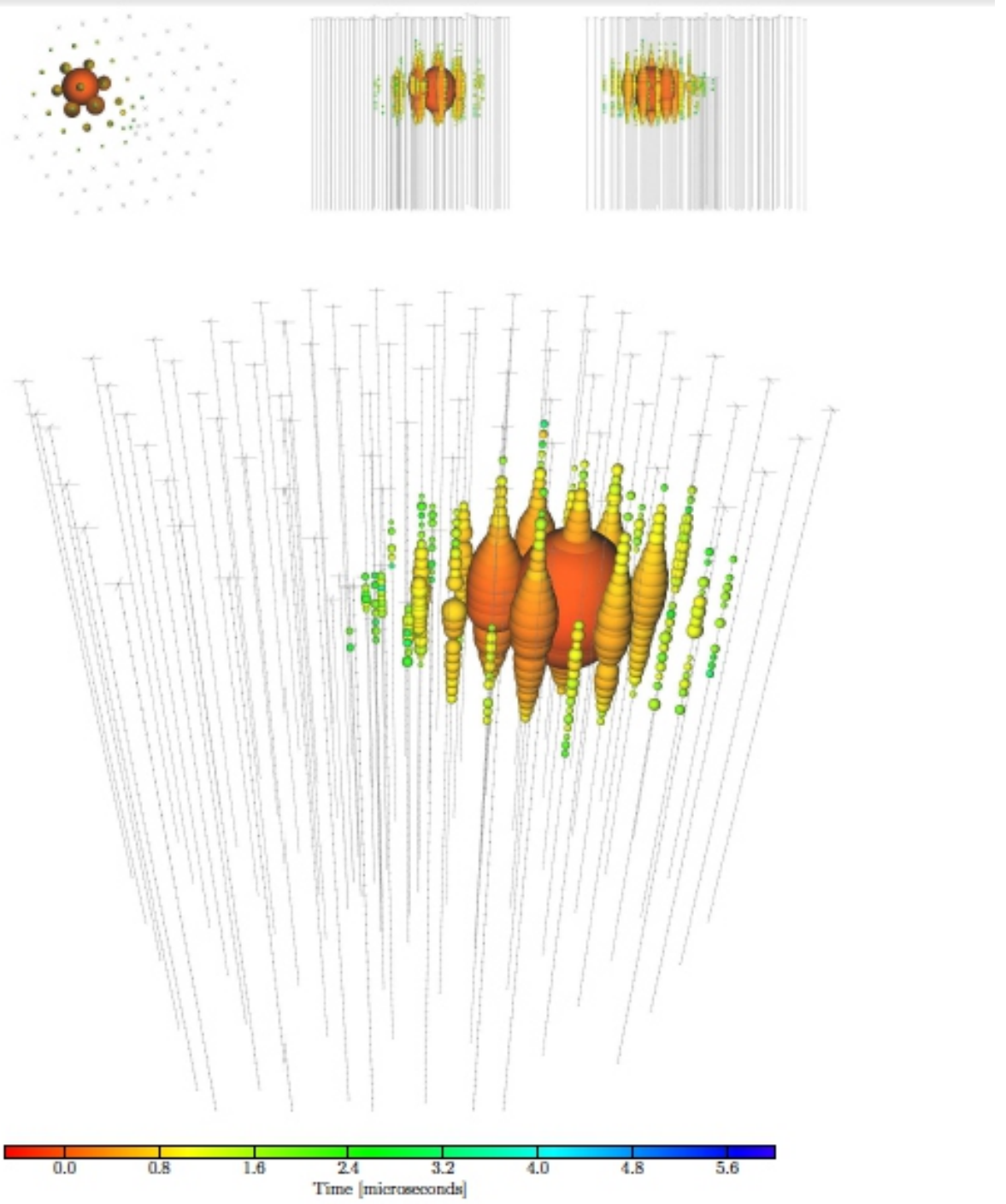
“TRACK”



Events with a Muon

Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$71.4^{+9.0}_{-9.0}$	55512.5516214	−0.4	110.6	$\lesssim 1.2$	Track

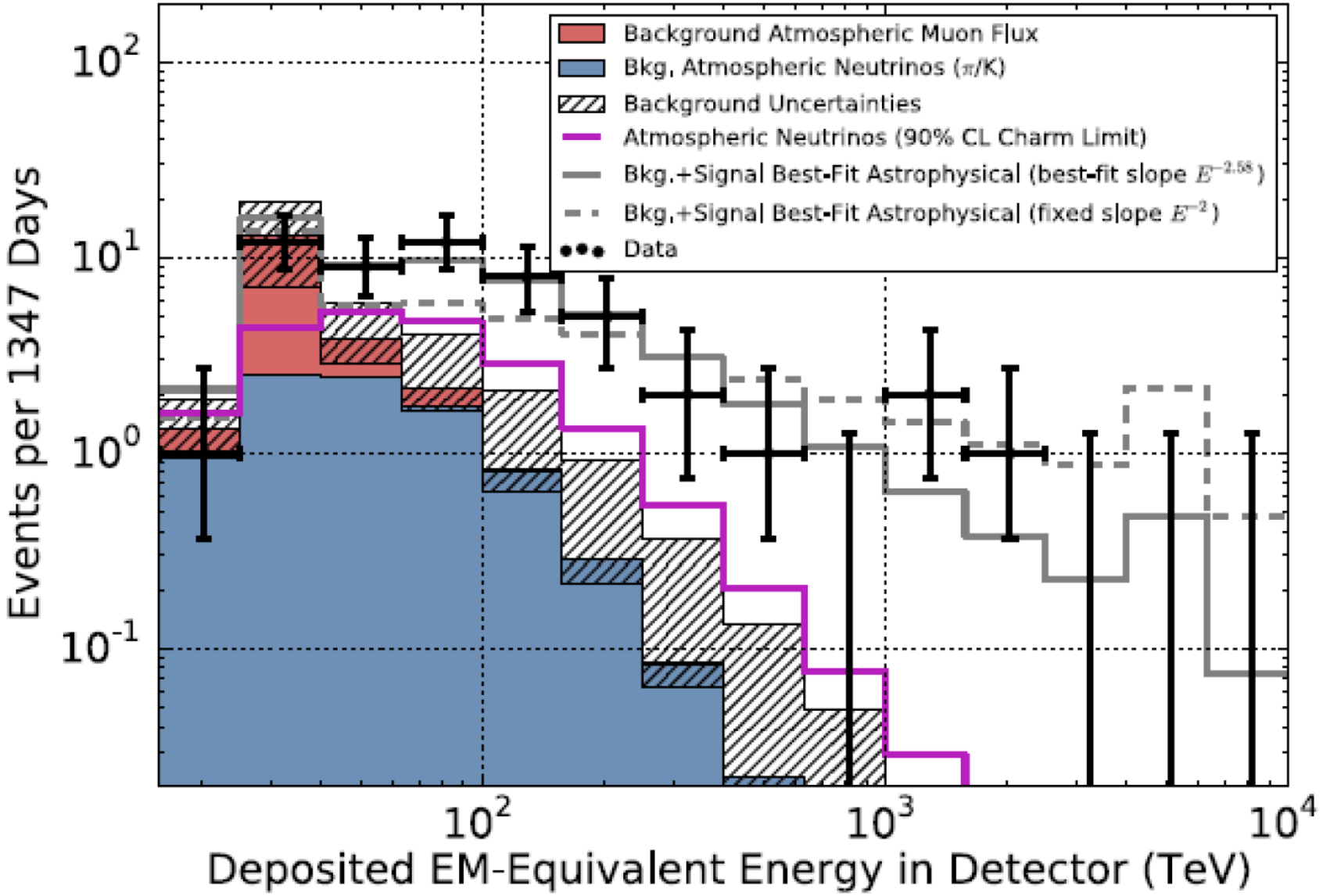
“Shower”



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$1040.7^{+131.6}_{-144.4}$	55782.5161816	−27.9	265.6	13.2	Shower

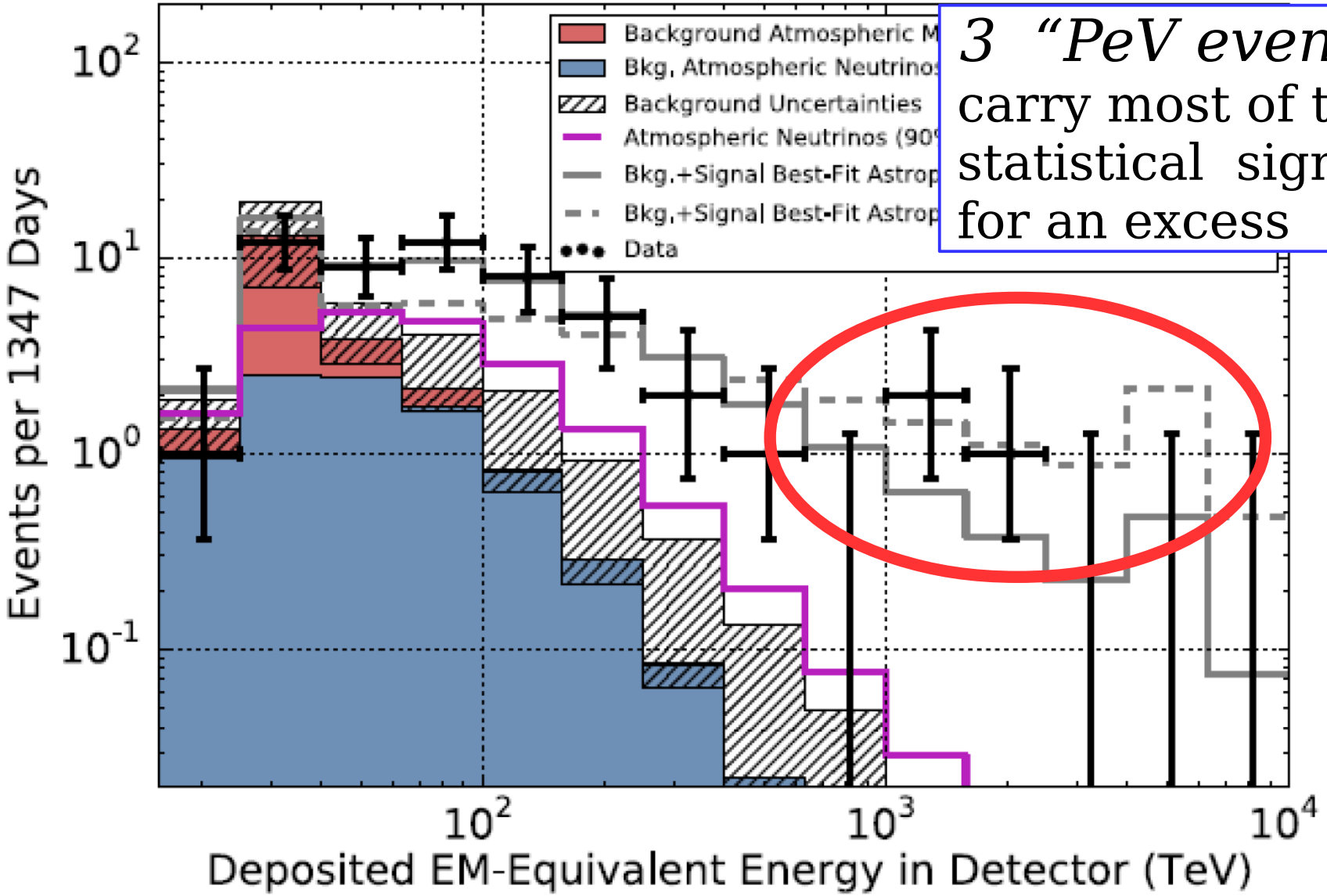
High Energy Starting Events [HESE]

First evidence for an extra-terrestrial h.e. neutrino flux

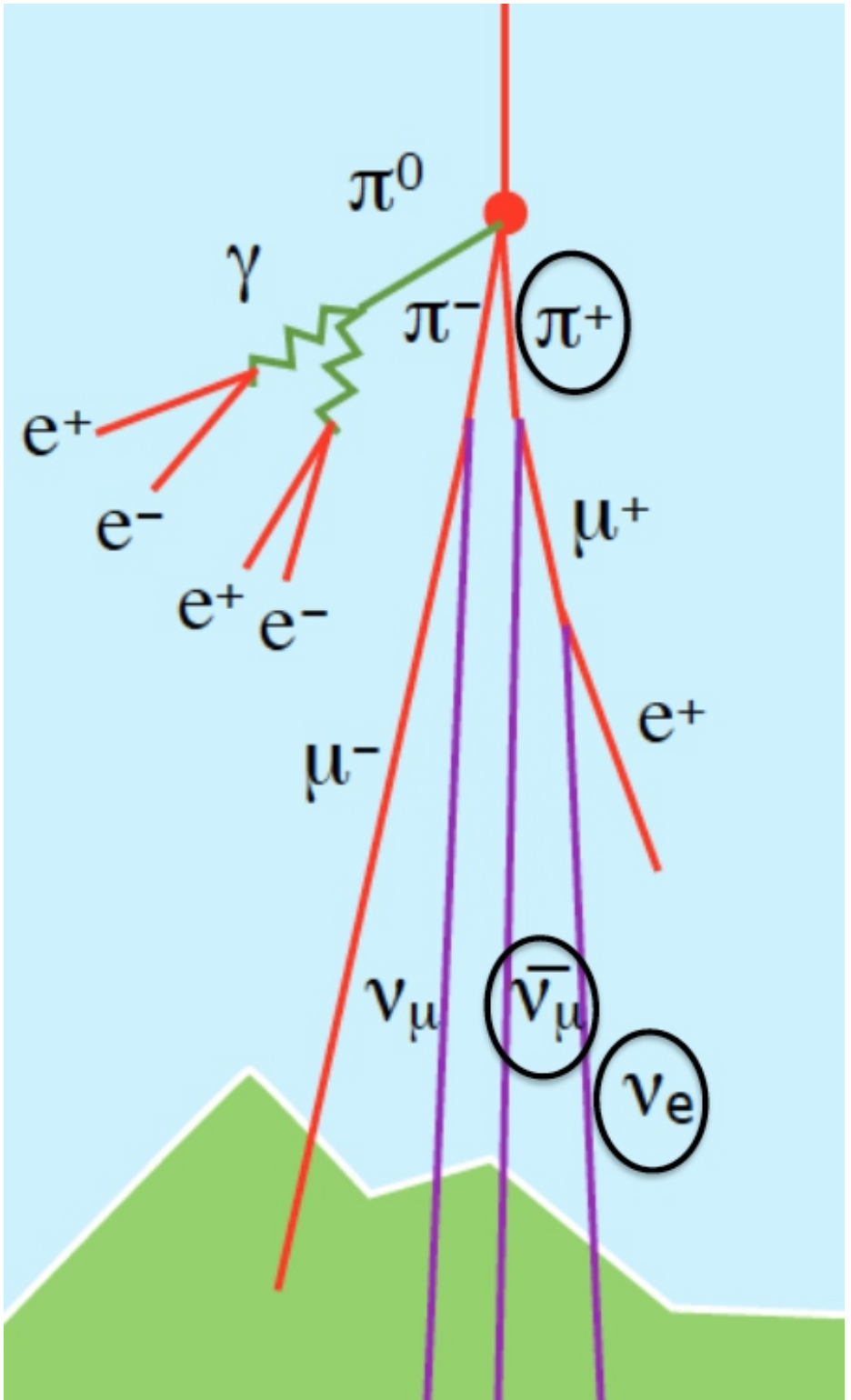


High Energy Starting Events [HESE]

First evidence for an extra-terrestrial h.e. neutrino flux



3 "PeV events" carry most of the statistical significance for an excess



Foreground

to the astrophysical neutrino signal

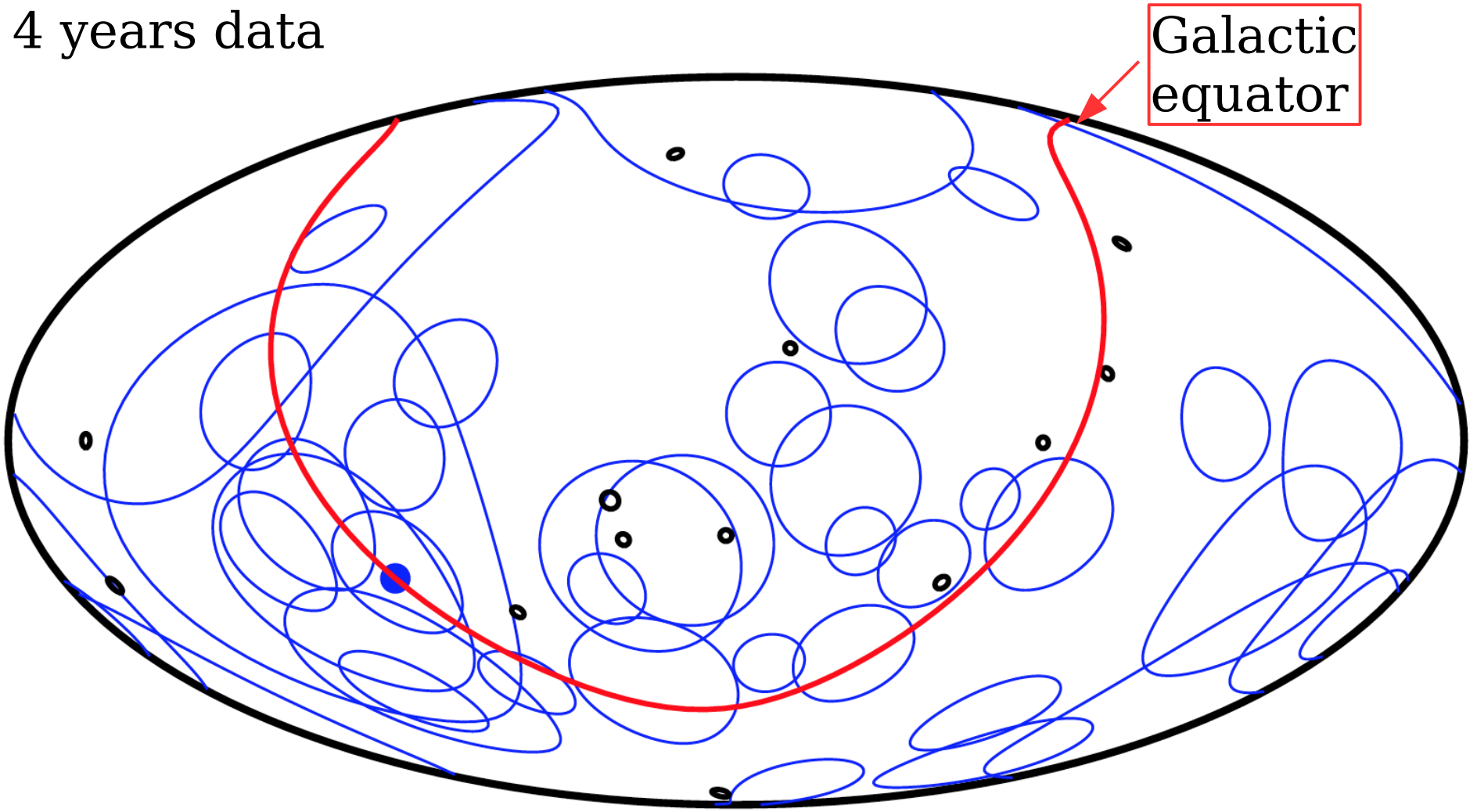
Atmospheric Neutrinos

$$\phi_{\nu_\alpha}(E,\Omega) = \phi^{\text{atm. standard}}_{\nu_\alpha}(E,\Omega) + \phi^{\text{atm. charm}}_{\nu_\alpha}(E,\Omega) + \phi^{\text{astro. extragalactic}}_{\nu_\alpha}(E,\Omega) + \phi^{\text{astro. Galactic}}_{\nu_\alpha}(E,\Omega)$$

	Conventional atmospheric neutrinos	"Prompt" atmospheric neutrinos	Astroph. neutrinos
Flavor	$\nu_e \approx \nu_\mu/40$ $\nu_\tau \approx 0$	$\nu_e \approx \nu_\mu$ $\nu_\tau \approx \nu_\mu/10$ $D_s^+ \to \tau^+ \nu_\tau$	$\nu_e \approx \nu_\mu$ $\nu_\tau \approx \nu_\mu$
Angular distr.	$\frac{\text{Horizontal}}{\text{Vertical}} \approx 10$	Isotropic	Isotropic [if extragal.]
Energy distr. $\phi_\nu(E)$	$\propto \frac{\phi_{\text{cr}}(E)}{E}$	$\phi_{\text{cr}}(E)\ \sigma_{c\bar{c}}(E)$	"Hard"

High Energy Starting Events

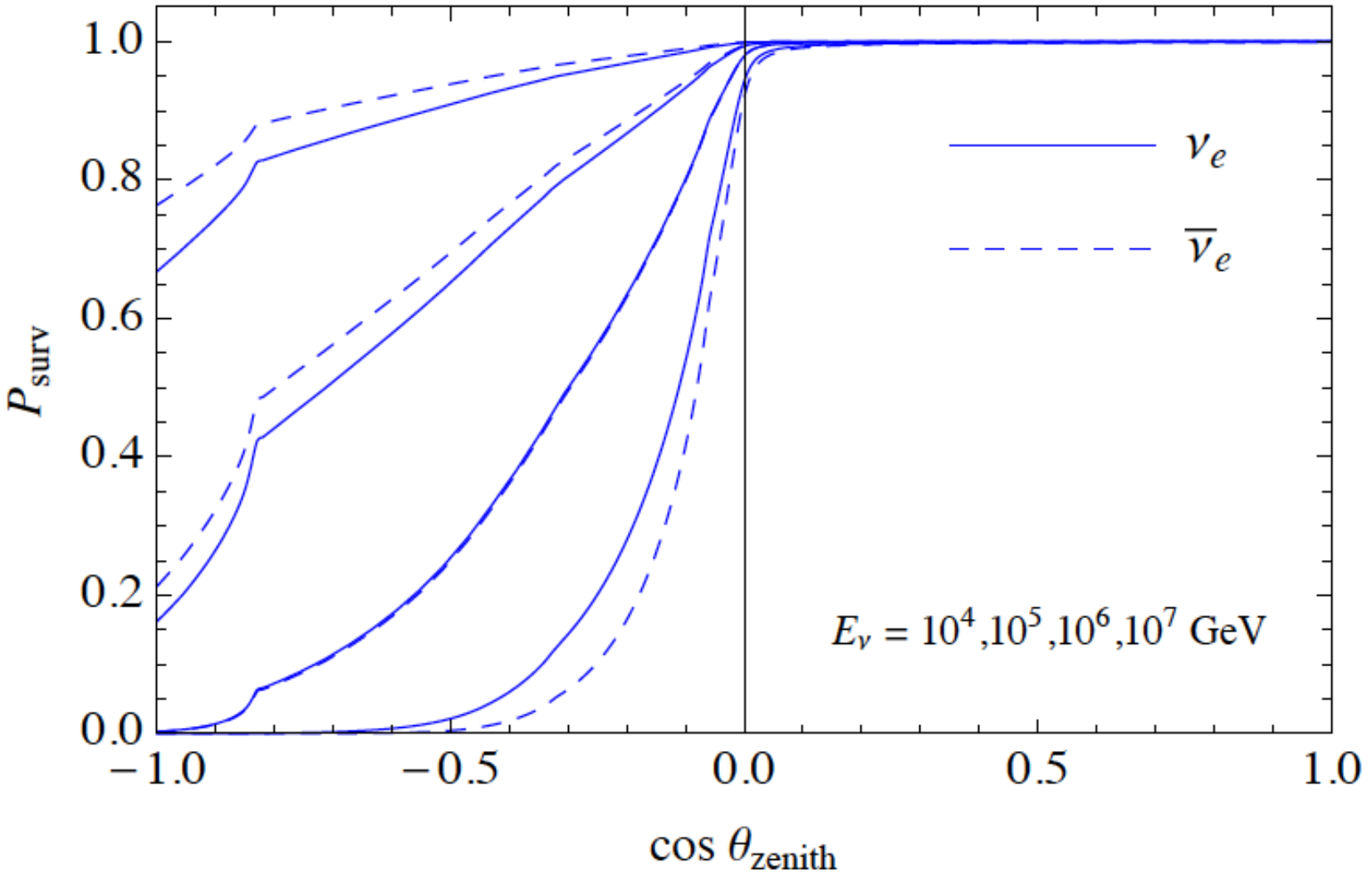
4 years data

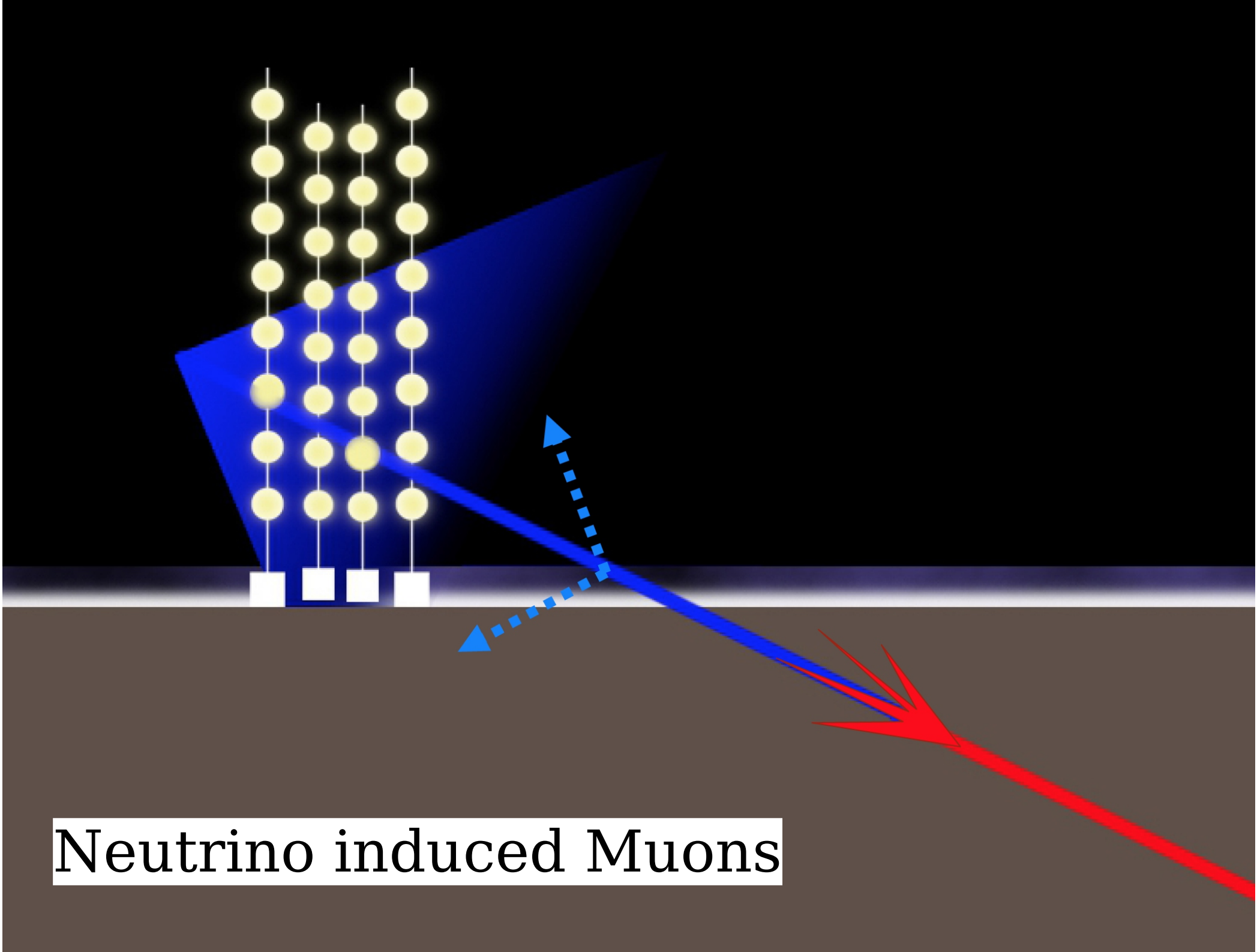


Track [(small) black circles]
Showers [(large) blue circles]

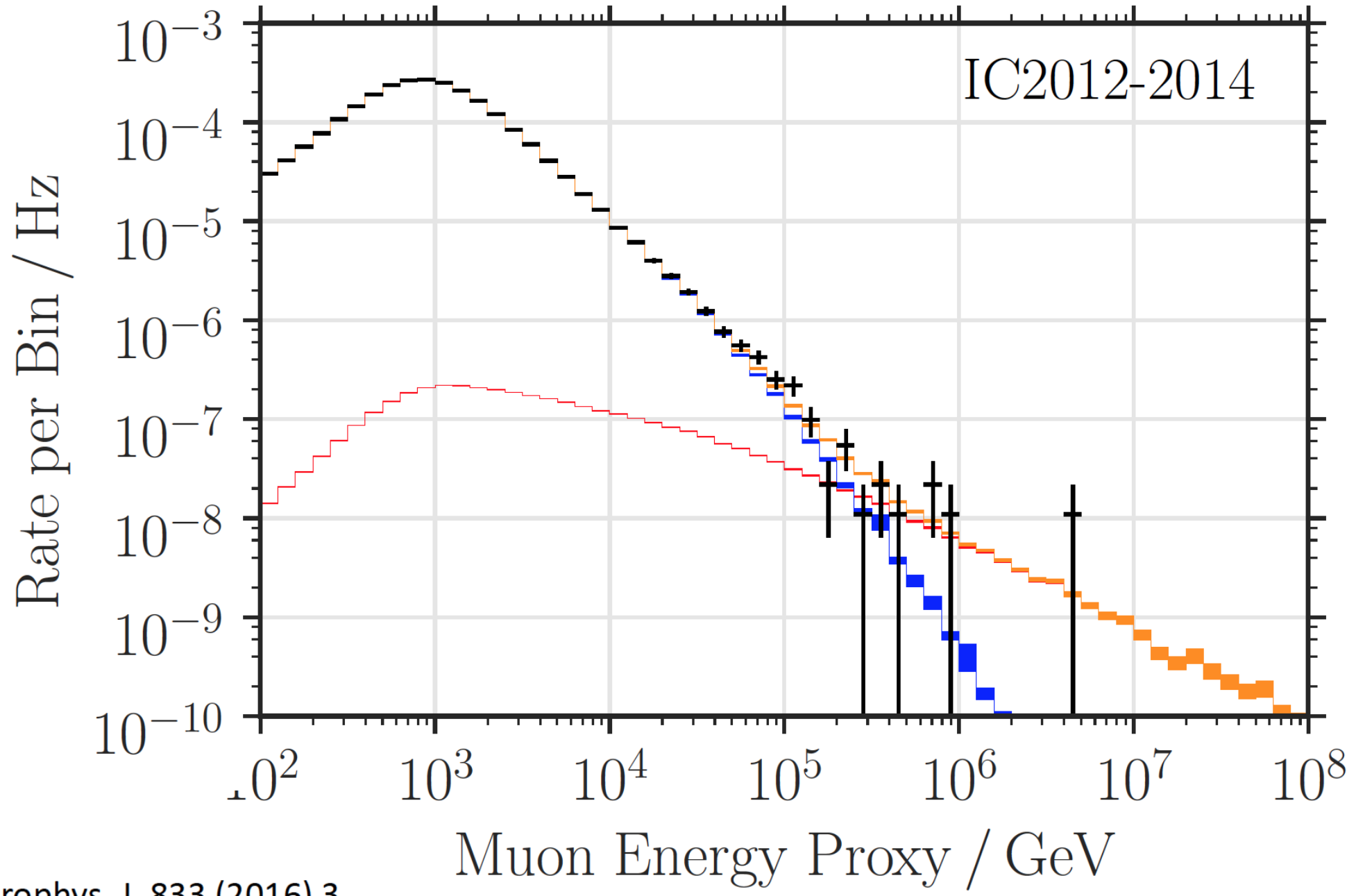
$E_{\rm vis} \gtrsim 30$ TeV

Absorption of neutrinos in the Earth

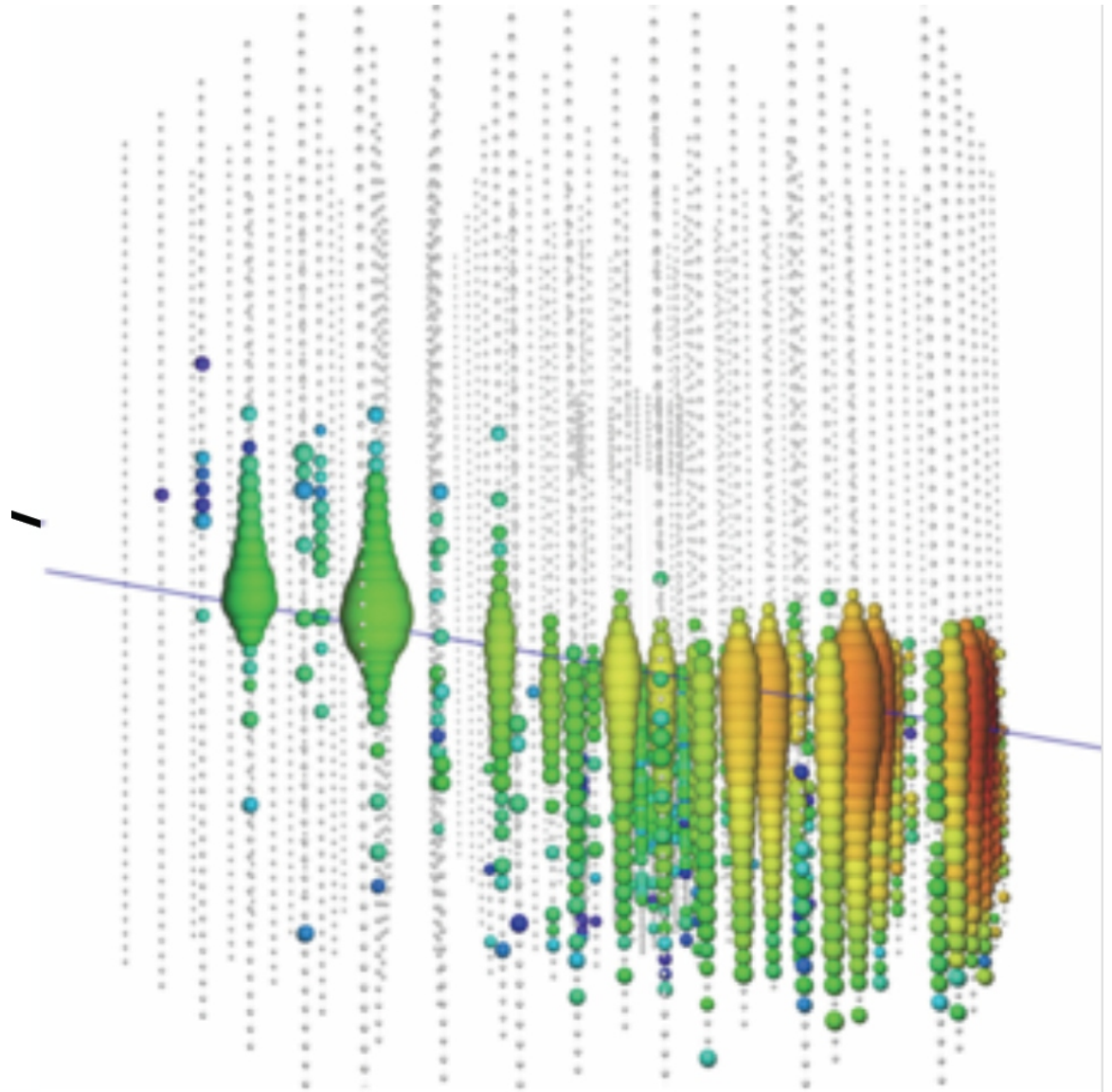



Neutrino induced Muons

Upgoing (neutrino induced) Muons



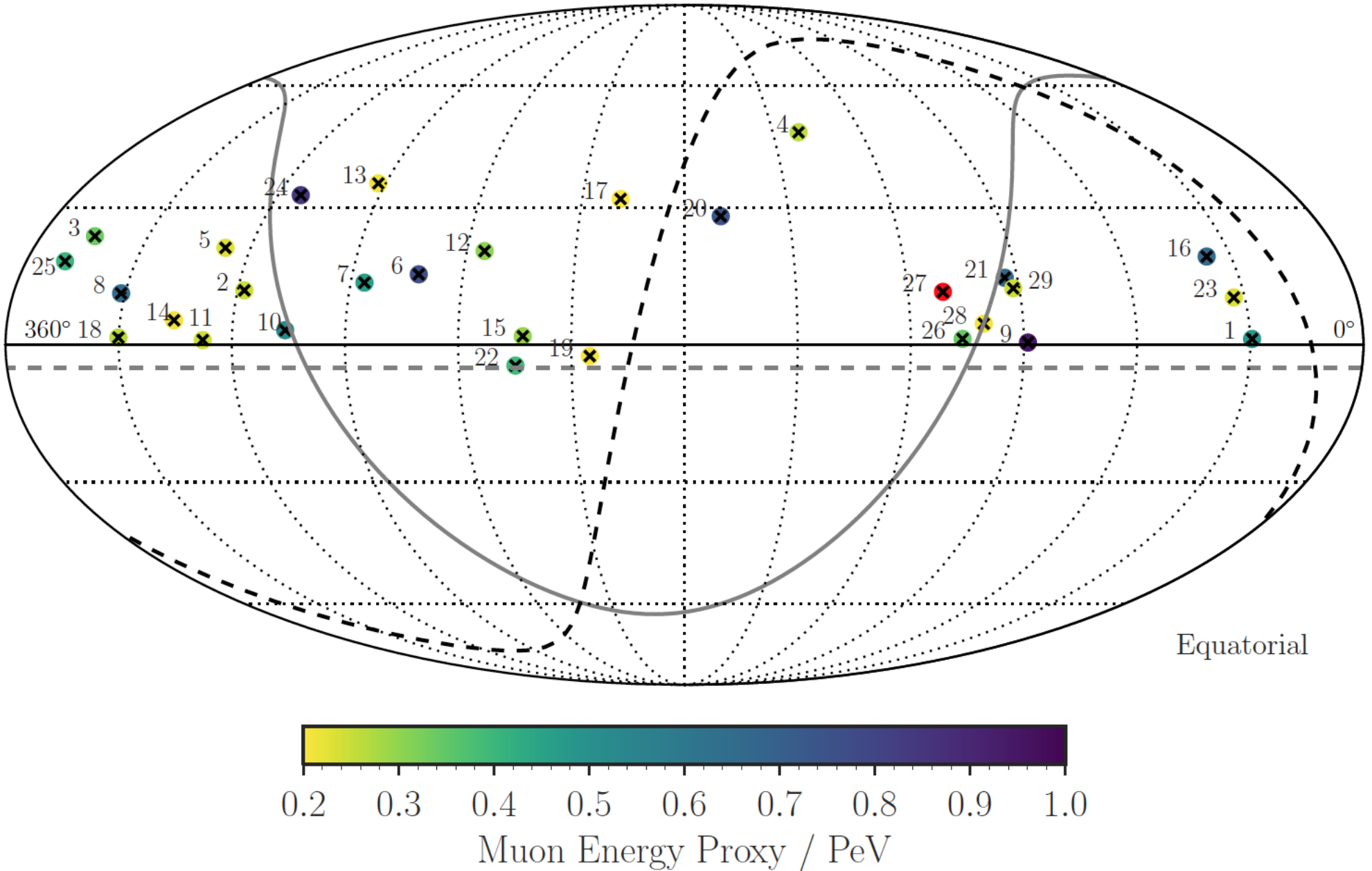
Astrophys. J. 833 (2016) 3



Deposited energy:
2.6±0.3 PeV

Upgoing muon events

$E_\mu \gtrsim 200$ TeV



Astrophys. J. 833 (2016) 3

Interpretation offered by IceCube collaboration:
(of the HESE events)

There in an excess of neutrino events
over the foreground of atmospheric neutrinos.

Consistent with an
isotropic (extragalactic) flux

with equal intensity for all 3 flavors (e, mu, tau)
[little sensitivity to the nu/antinu ratio.]

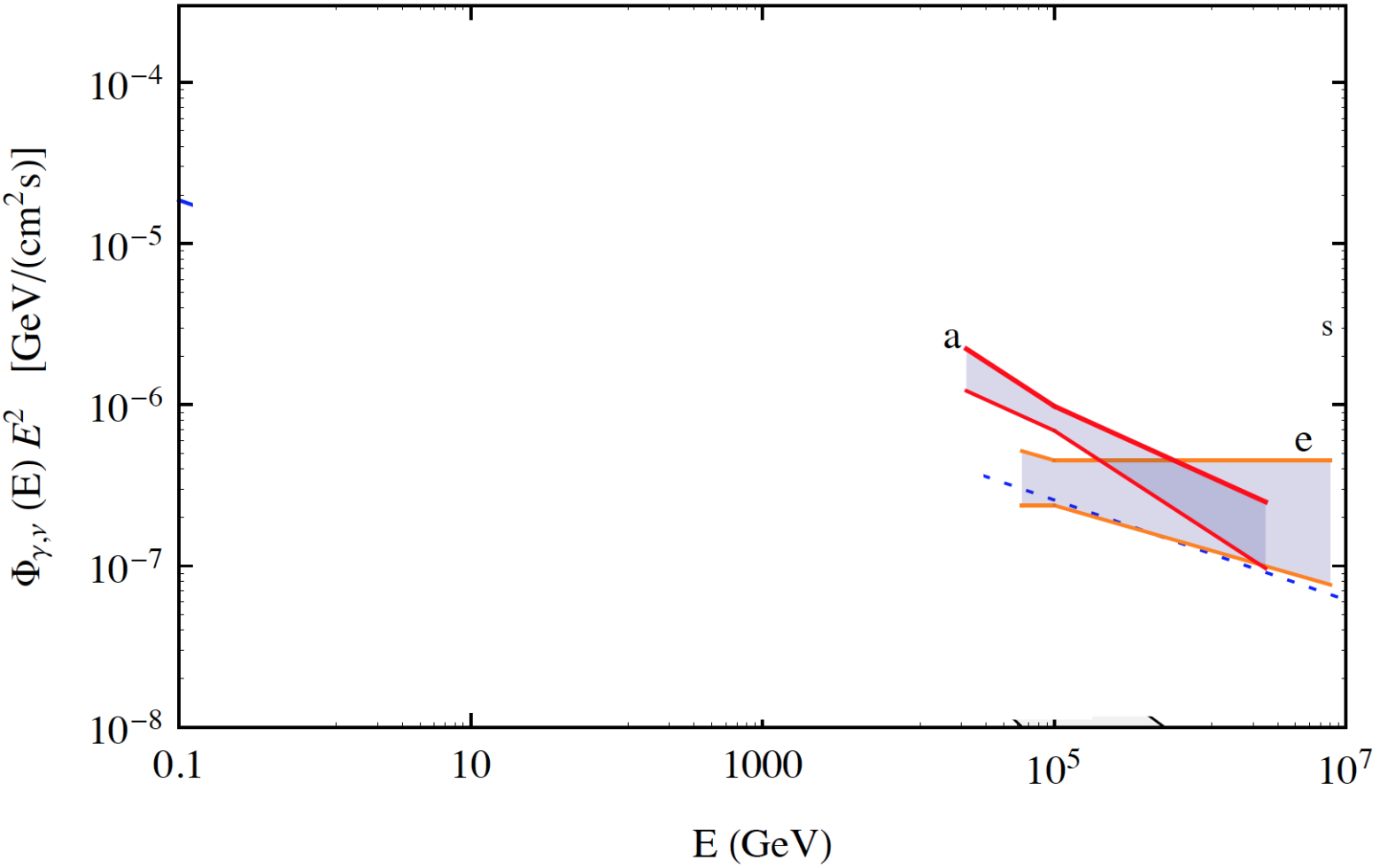
Simple Power Law:

$$\phi_\nu^{\text{astro}}(E) = \phi_0 \; E^{-2.50 \pm 0.09}$$

$$\phi_\nu^{\rm astro}(E) = \phi_0^{\rm HESE}\ E^{-2.50\pm0.09}$$

$$\phi_\nu^{\rm astro}(E) = \phi_0^{\mu\uparrow}\ E^{-2.13\pm0.13}$$

Estimates of the (equal-flavor) astrophysical flux



$$\phi_\nu^{\text{astro}}(E) = \phi_0^{\text{HESE}}\ E^{-2.50\pm0.09}$$

$$\phi_\nu^{\text{astro}}(E) = \phi_0^{\mu\uparrow}\ E^{-2.13\pm0.13}$$

Spectra are different ?
Possible “solutions” :

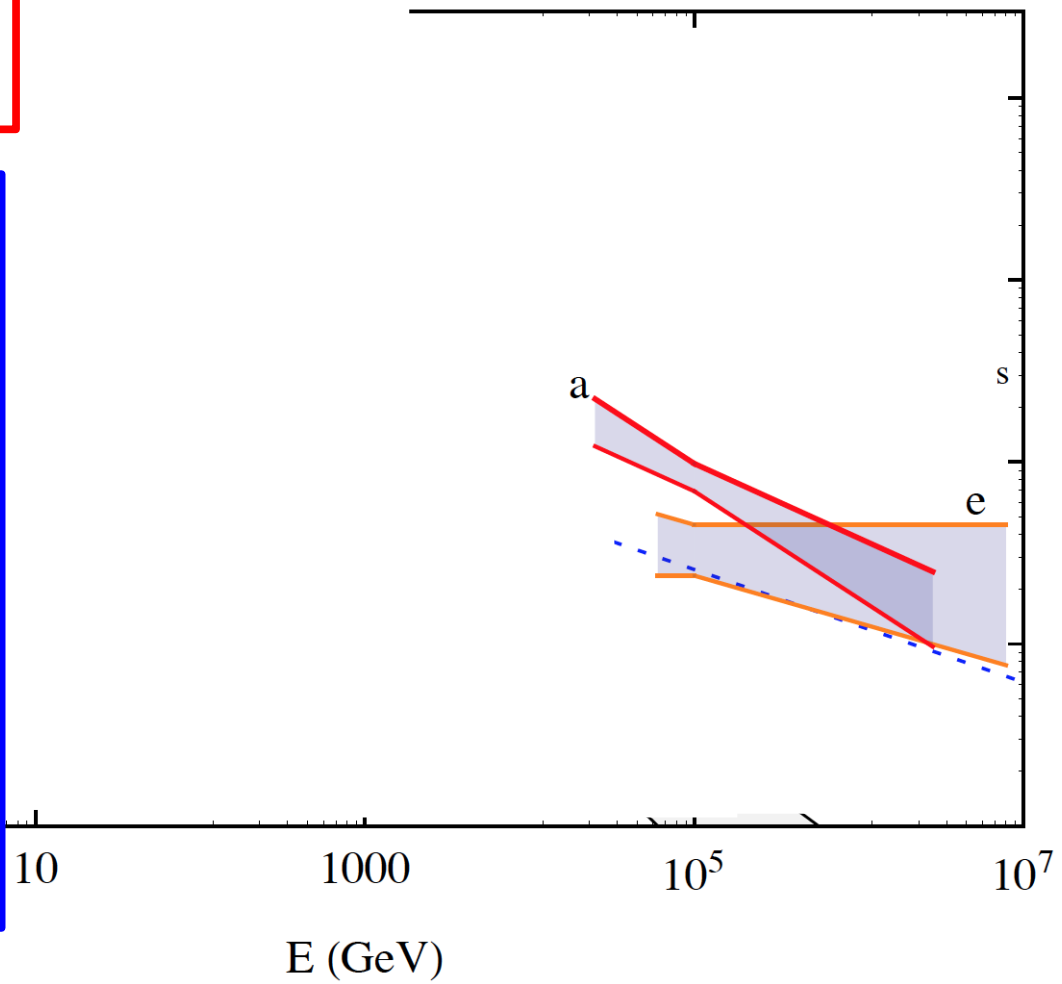
Systematic Effect ?

Break in the Spectrum

Two components
in the spectrum

Anisotropy ?

[Galactic + extragalactic components]



Questions on the IceCube signal:

1. Is the signal of astrophysical neutrinos real ?
   (or is the background/foreground poorly estimated) ?

1a. Could the signal be contaminated by a non negligible contribution of atmospheric neutrinos ?

2. Is the signal entirely extragalactic ?
   Or does it contains a non negligible Galactic component ?

3. If most of the signal is extragalactic,
   what can we say about the sources ?

3a. If there is a Galactic (perhaps subdominant) component what is its nature ?

Gamma Ray Sky

1. Ensemble of (quasi)-point sources

2. Diffuse Galactic Flux

80% of photons around 1 GeV

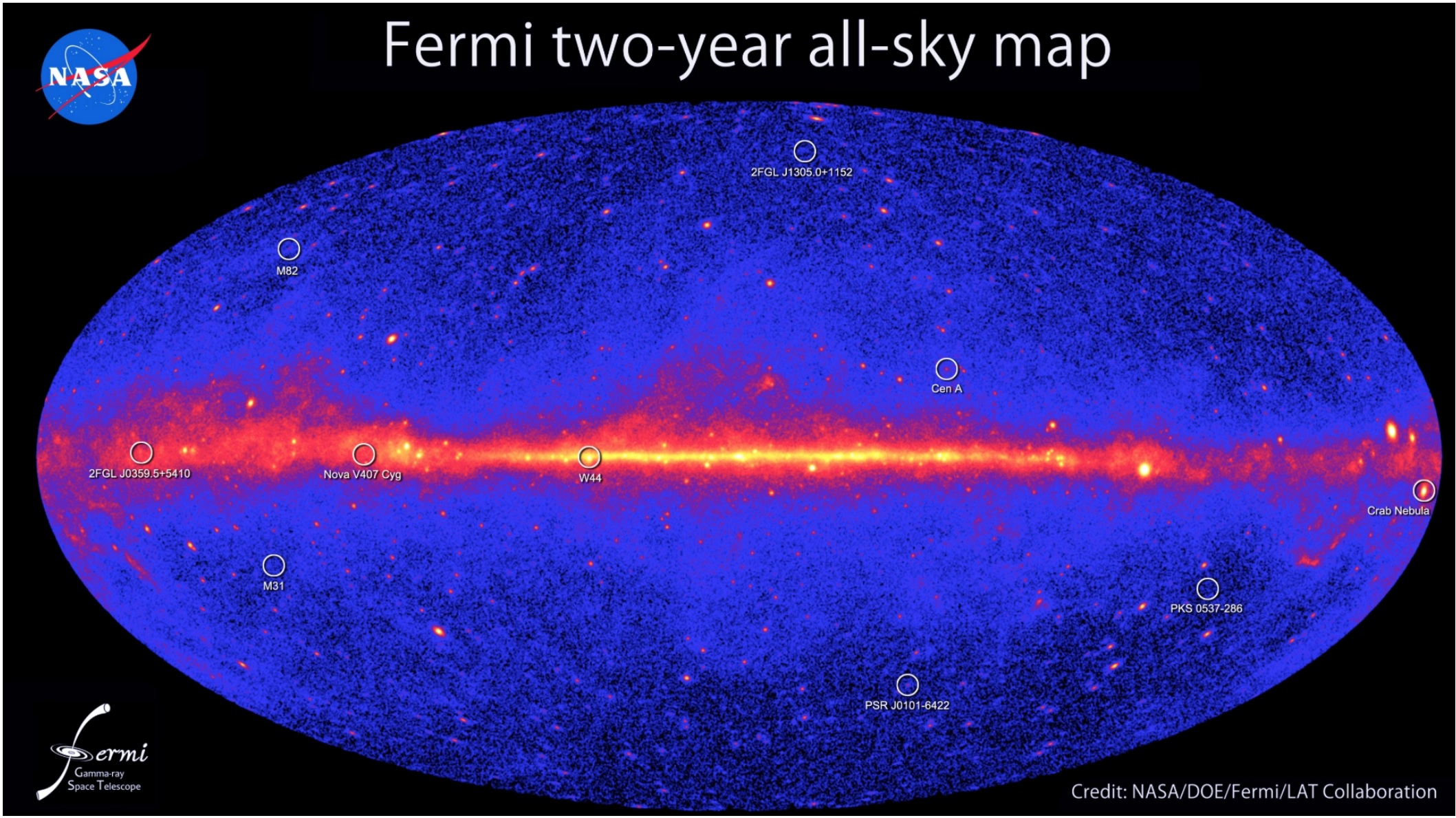
(generated by cosmic rays magnetically confined in the Milky Way)

3. Isotropic flux.

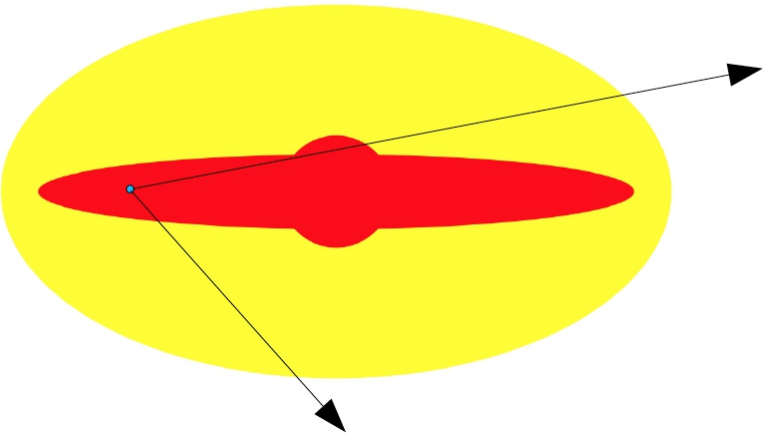
(attributed to an ensemble of unresolved extragalactic sources)

$E_\gamma \geq 100$ MeV

Gamma Ray Sky

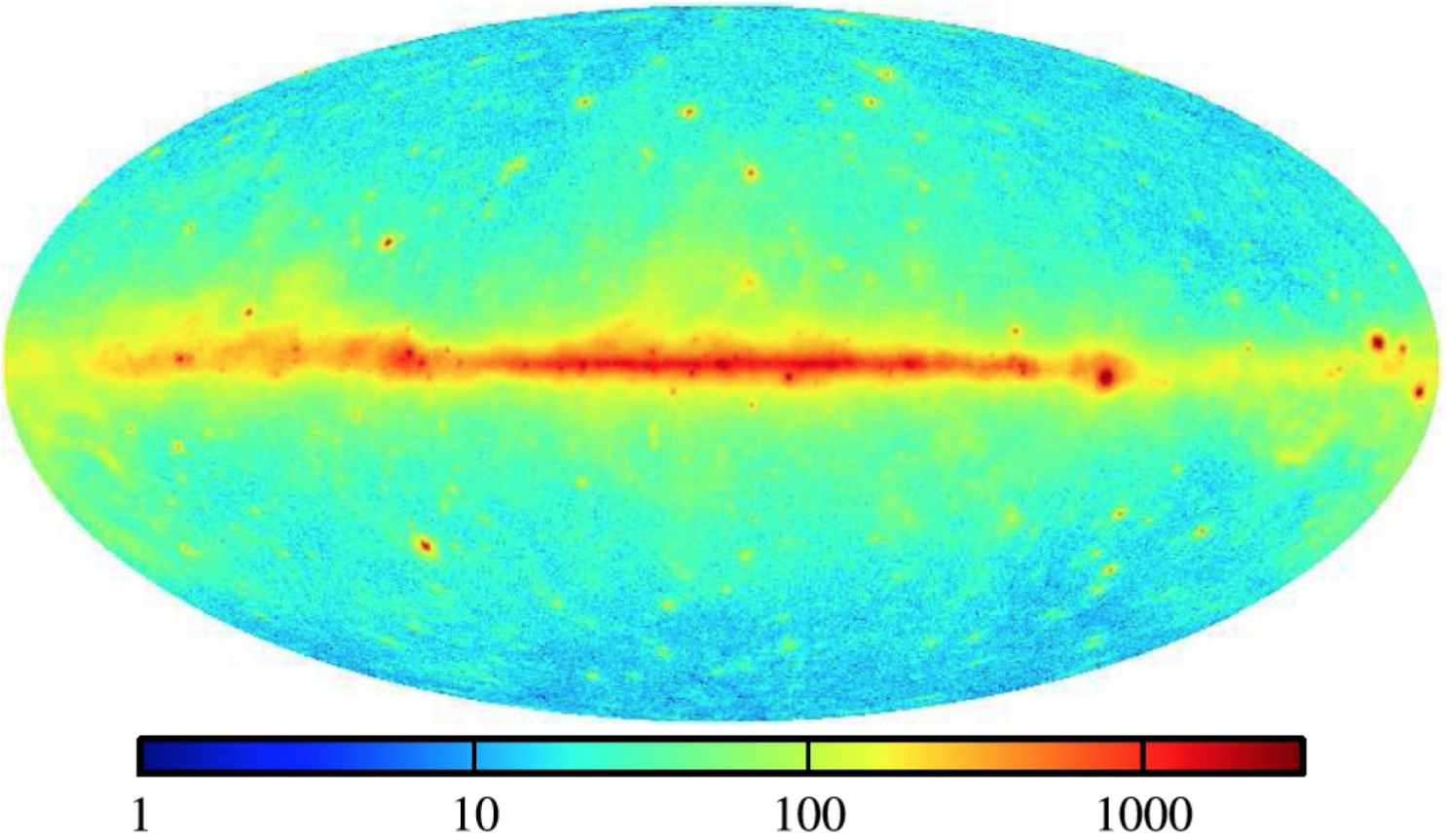


Diffuse Emission



Fermi–LAT counts

Galactic coordinates



50% of flux
+- 5 degrees
around equator

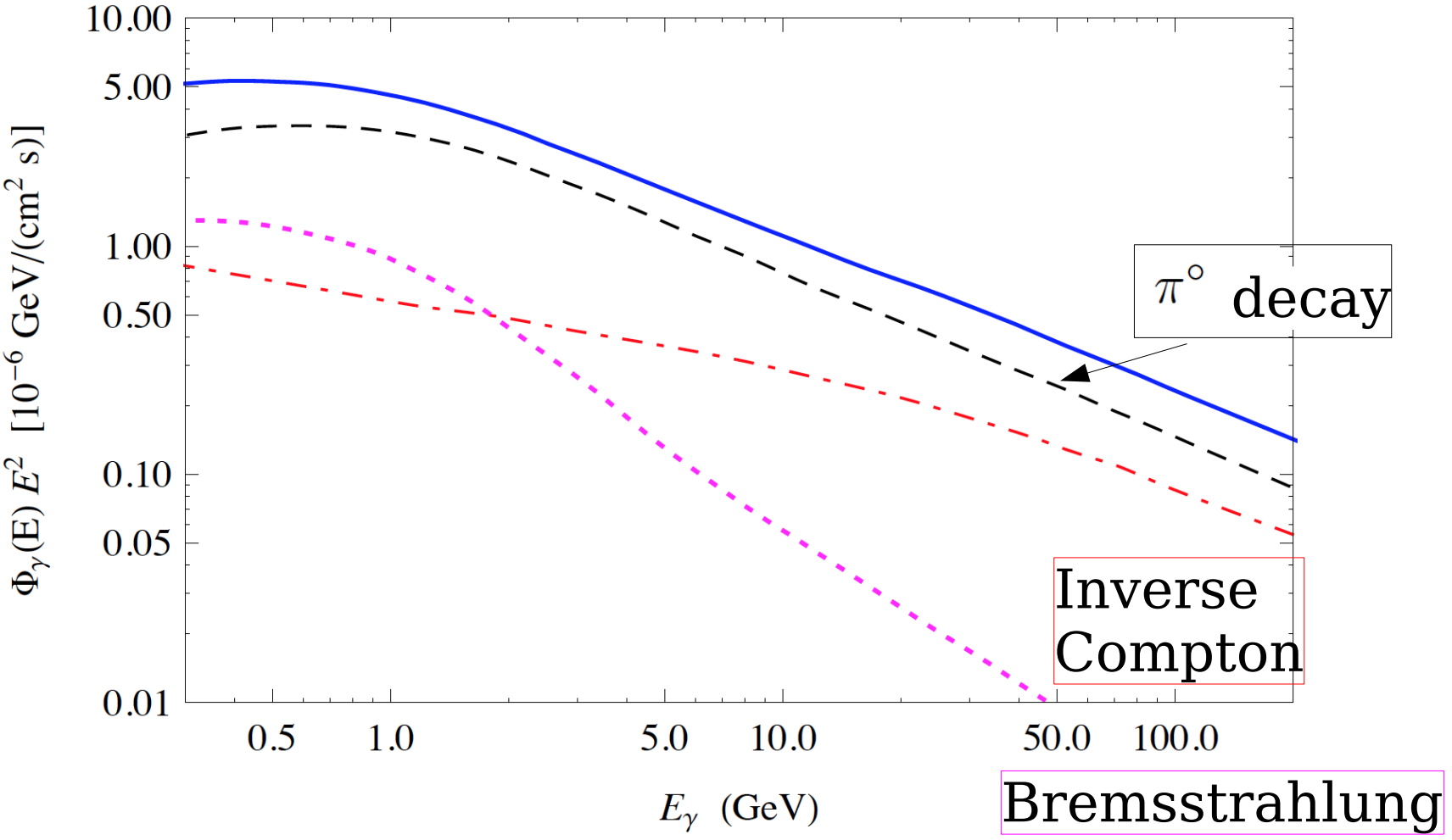
energy range 200 MeV to 100 GeV

Galactic Diffuse flux spectral shape

$$\phi_\gamma^{\text{diffuse}}(E_\gamma) \propto E_\gamma^{-2.70}$$

$$\alpha_\gamma^{\text{diffuse}} \approx 2.70 \pm 0.05$$

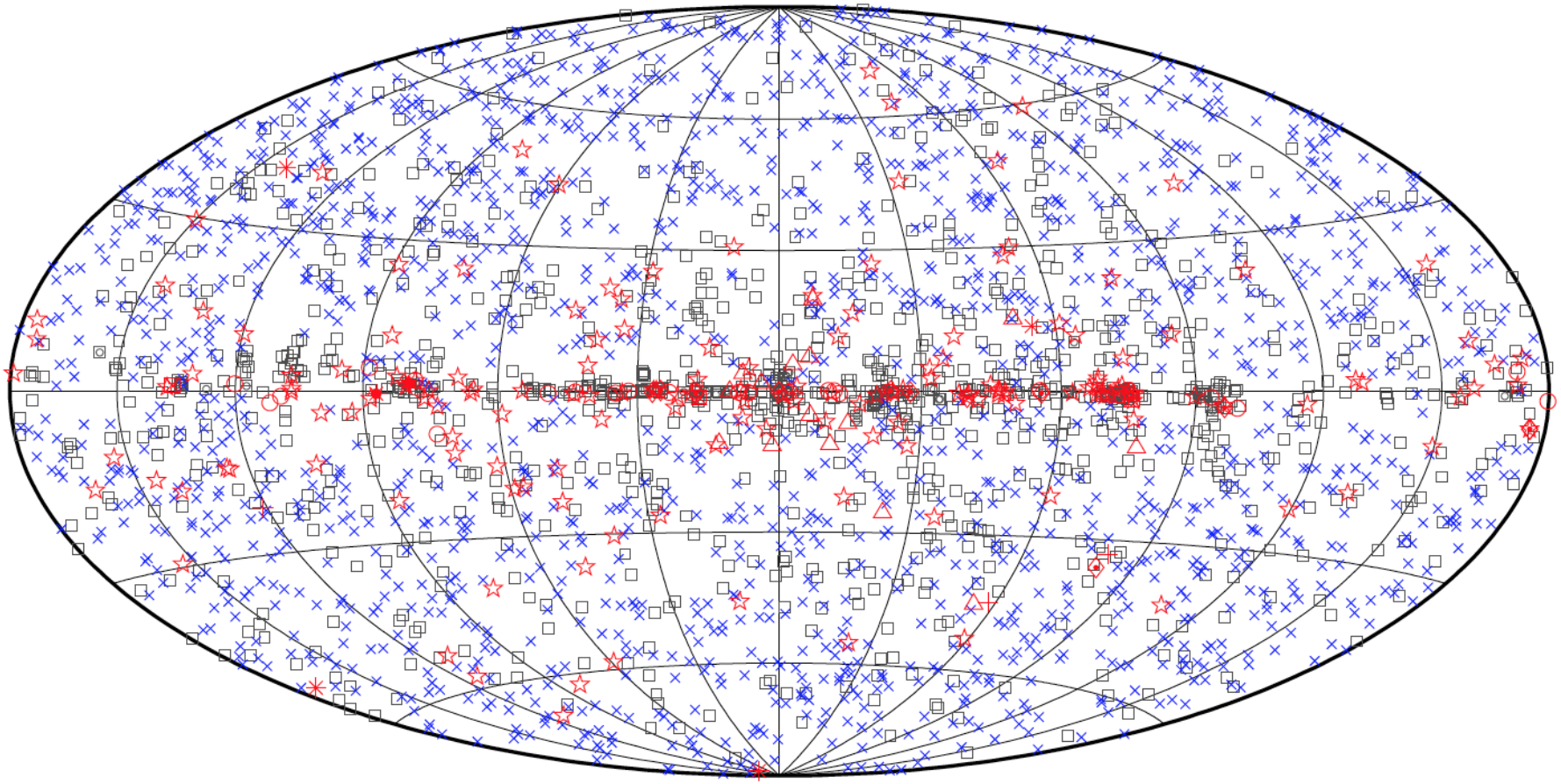
Decomposition (by FERMI) of the diffuse Galactic flux



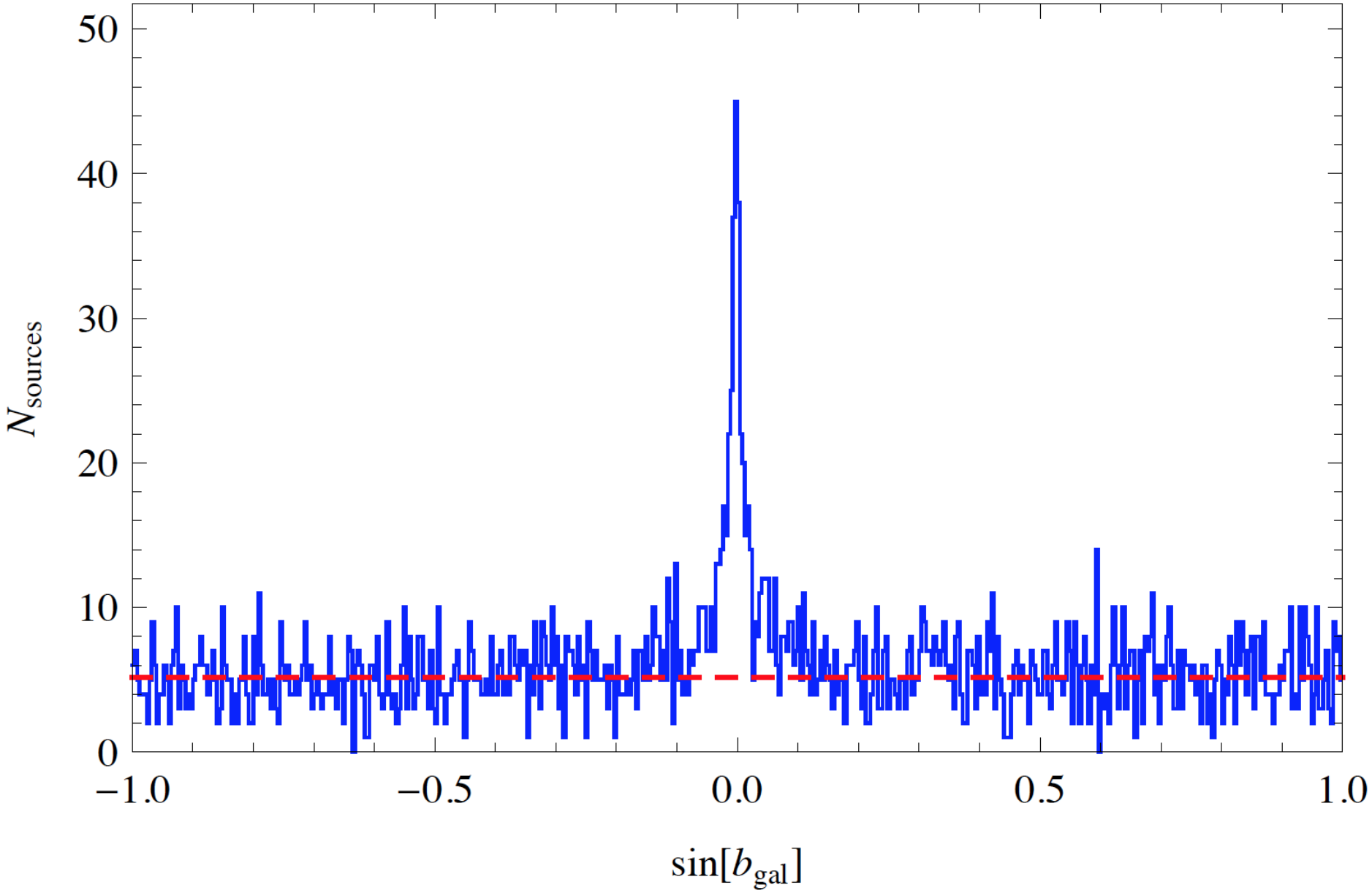
3rd FERMI Catalog

3034 sources

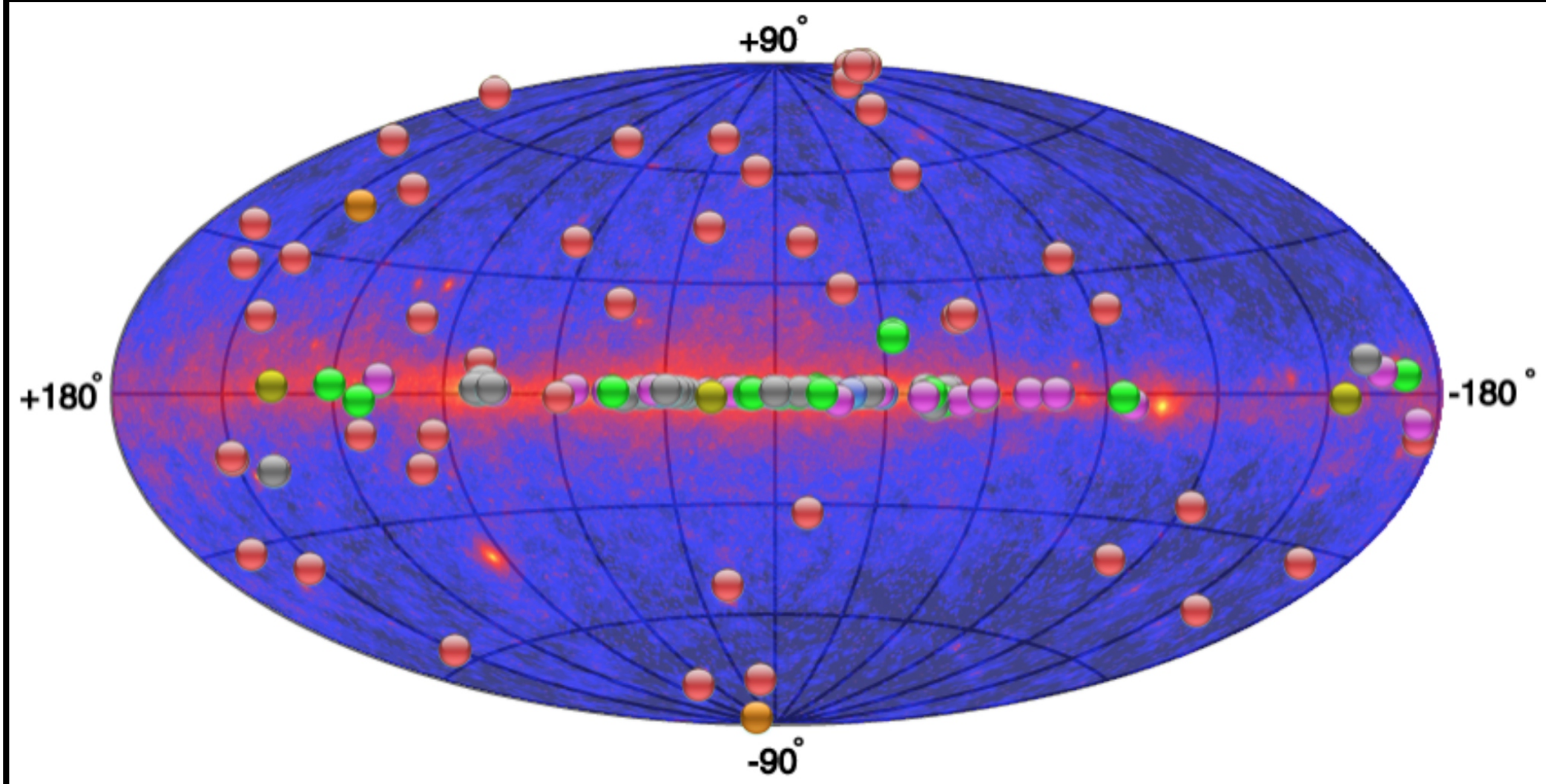
E > 100 MeV



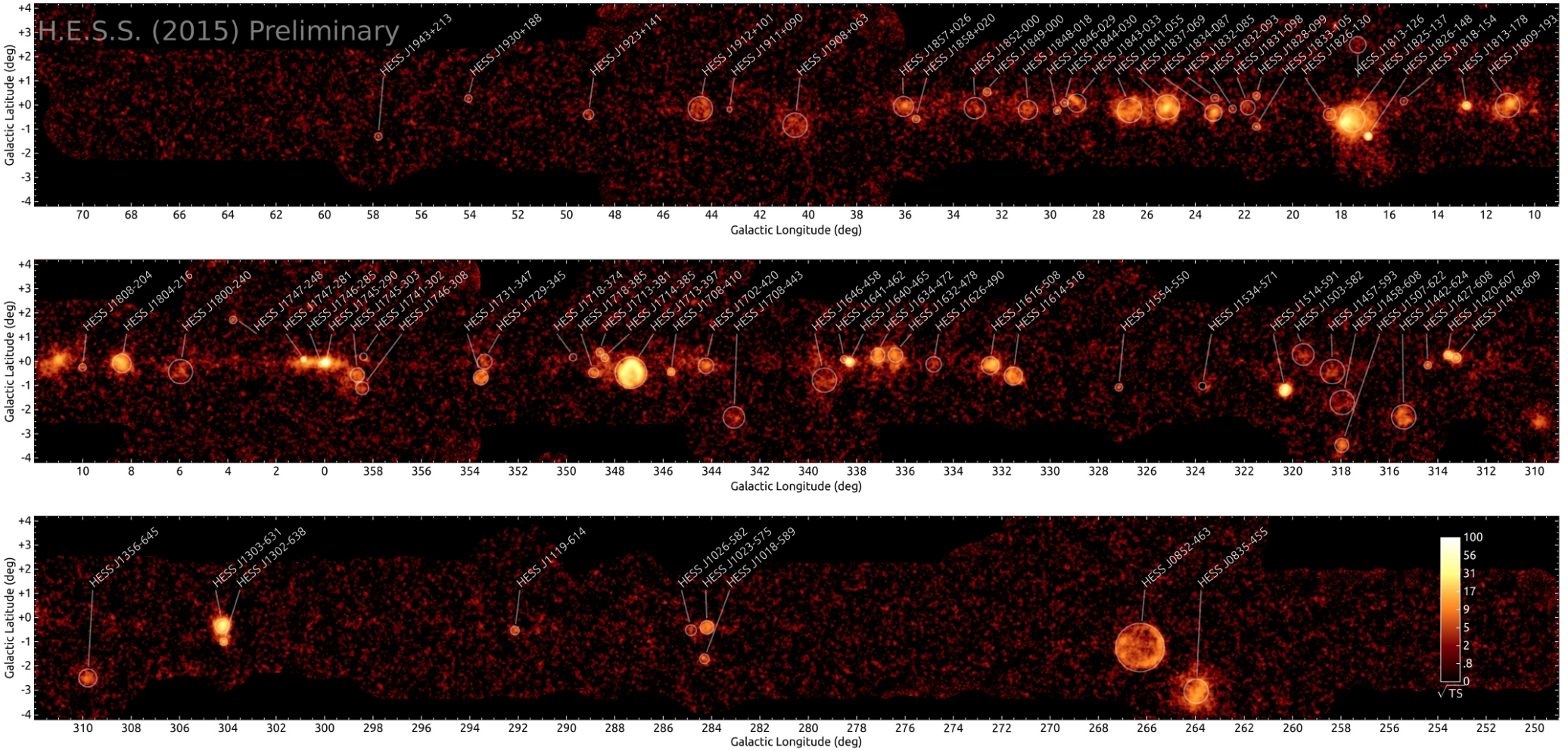
3034 3rd catalog sources [approximately 440 are galactic]



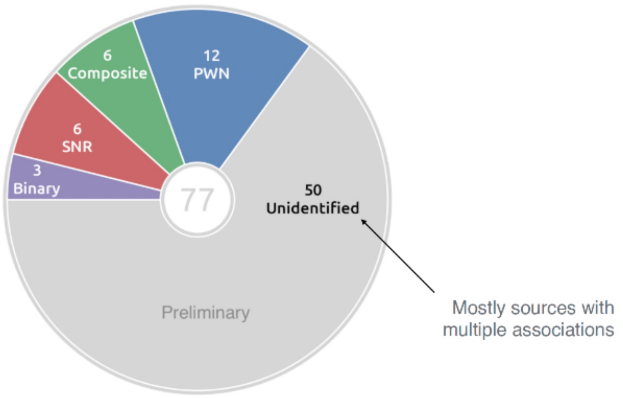
TeV Sky 170 → 200 Sources



blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky

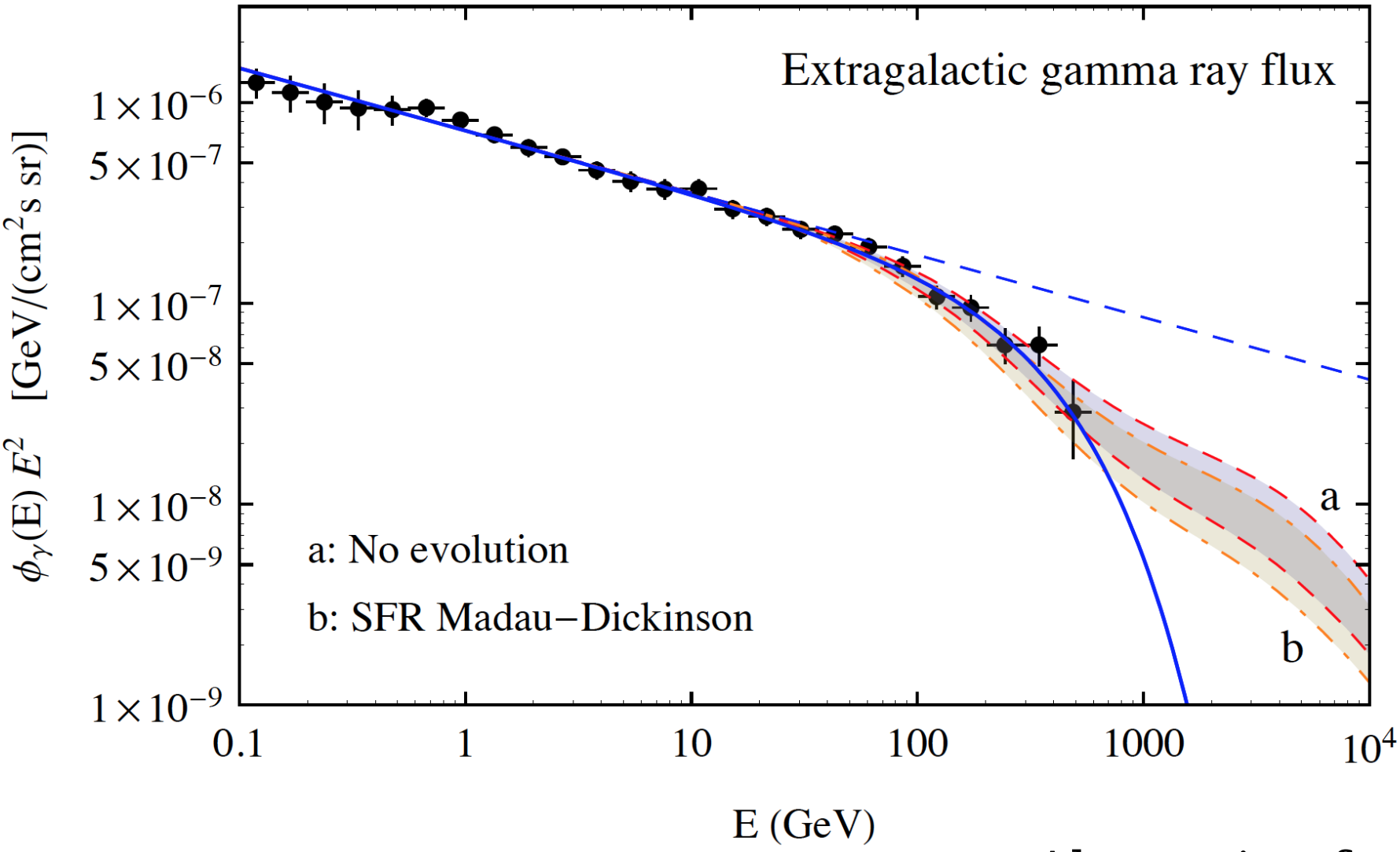


Firm identifications



HESS survey of Galactic Plane [ICRC 2015] 77 “firm identifications”

Extragalactic Gamma Ray flux

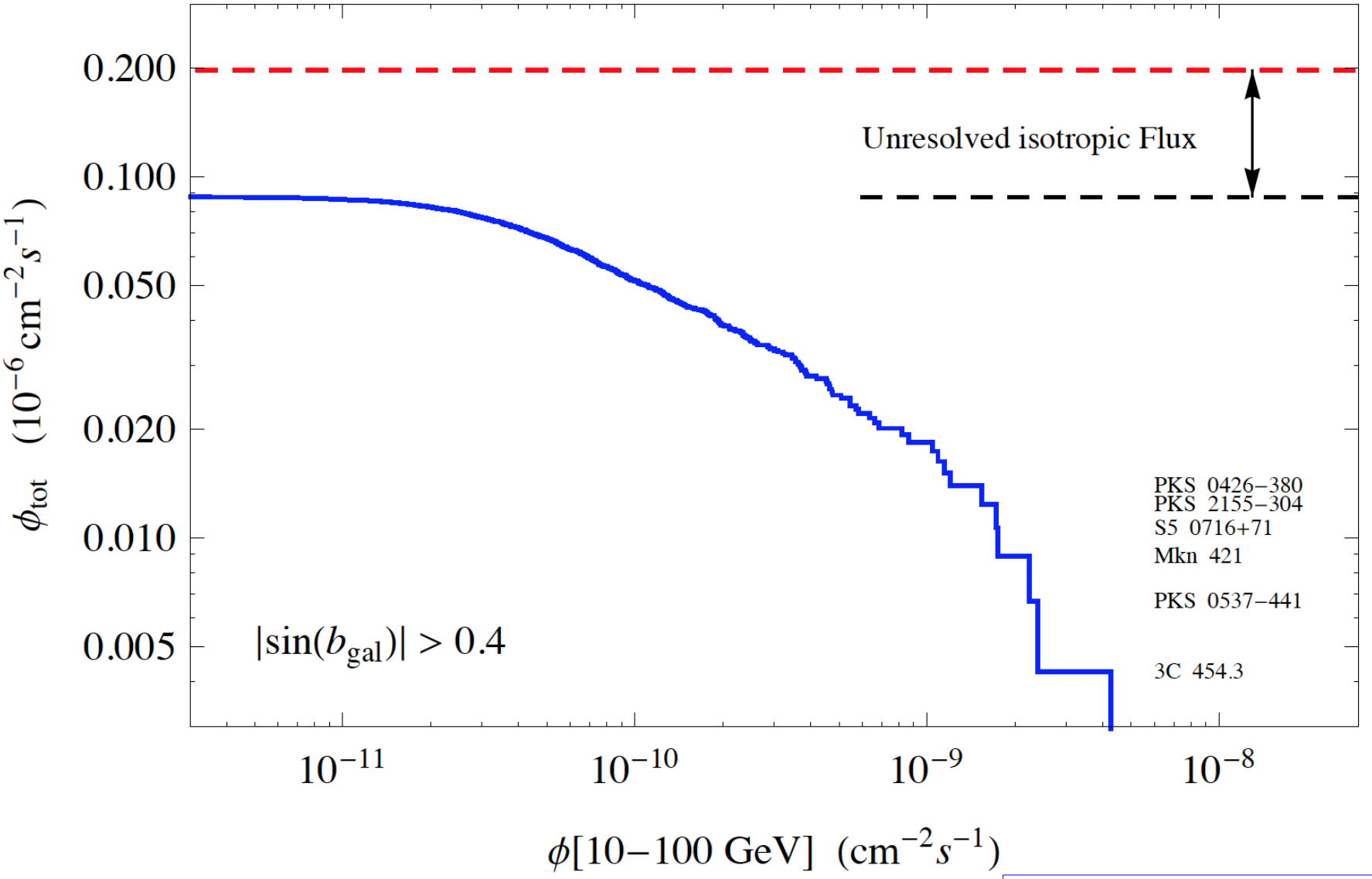


$$\phi_\gamma^{\rm iso}(E) \propto E^{-2.30\pm0.02}$$

Absorption for

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

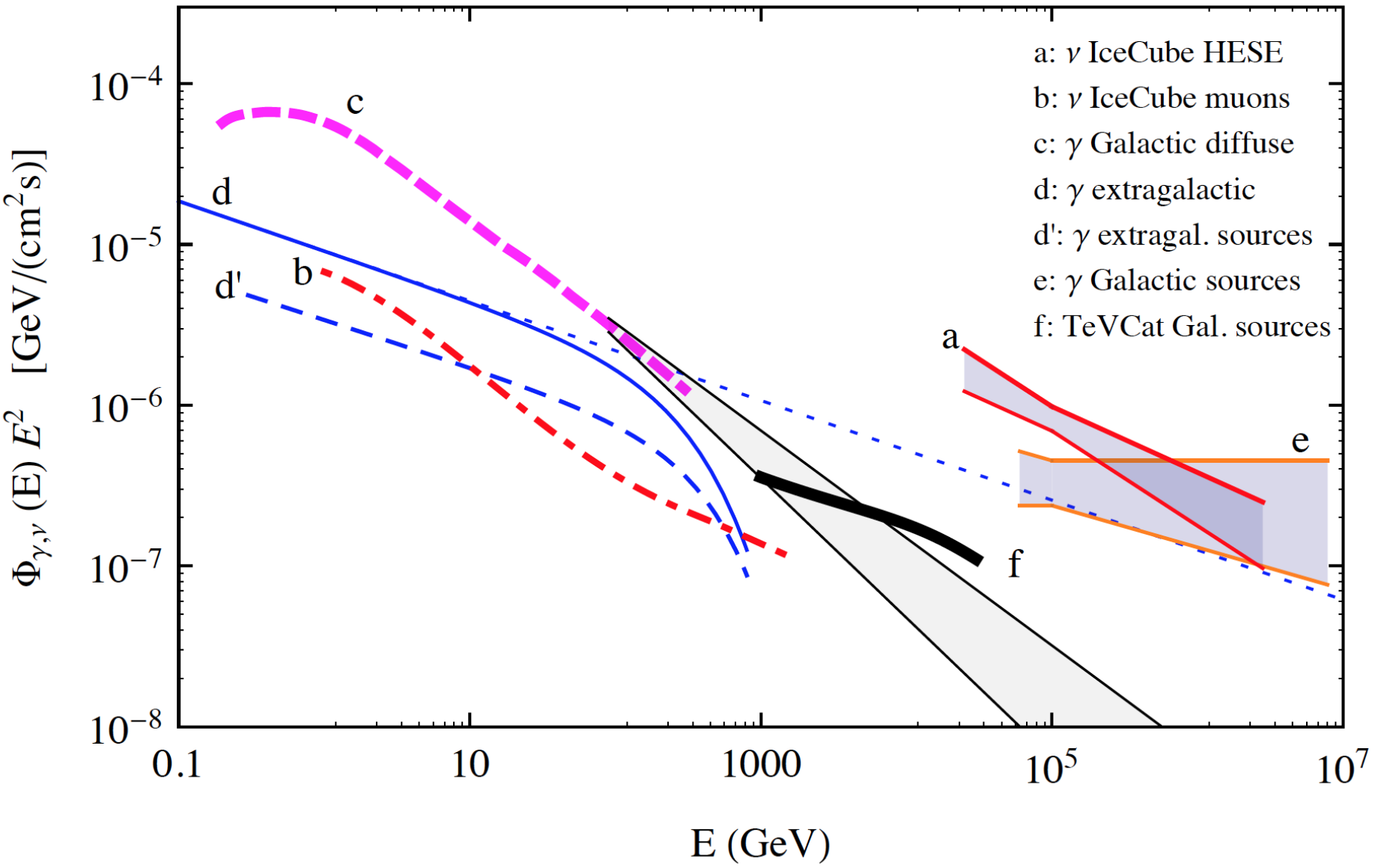
Extragalactic Flux : Resolved + unresolved sources



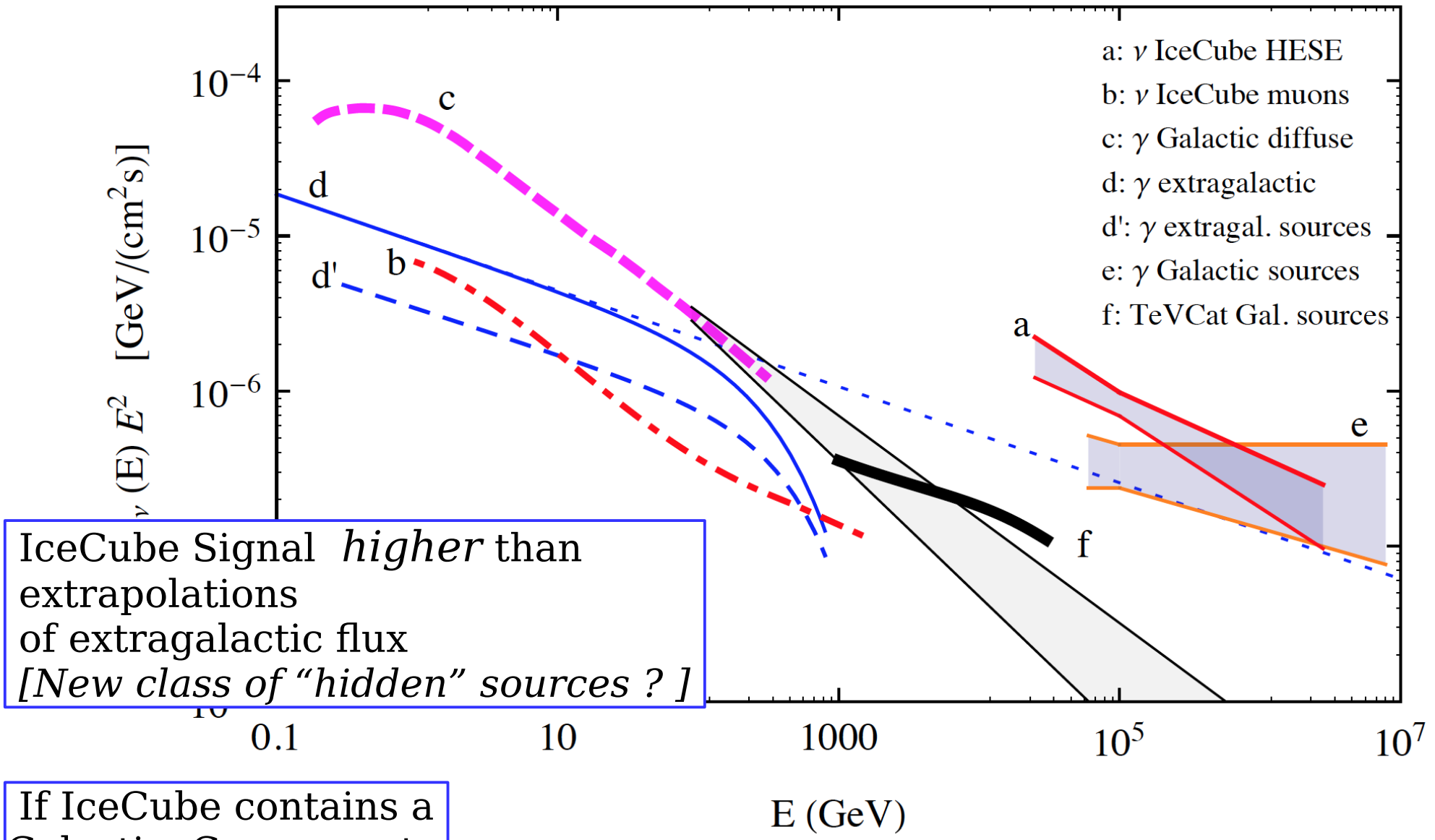
Extragalactic flux
dominated by “blazars” [AGN]

Brightest source
in the sky (3C454.3)
1.8 % of extragalactic light

Compare the *Neutrino Signal* to *Gamma Ray fluxes*

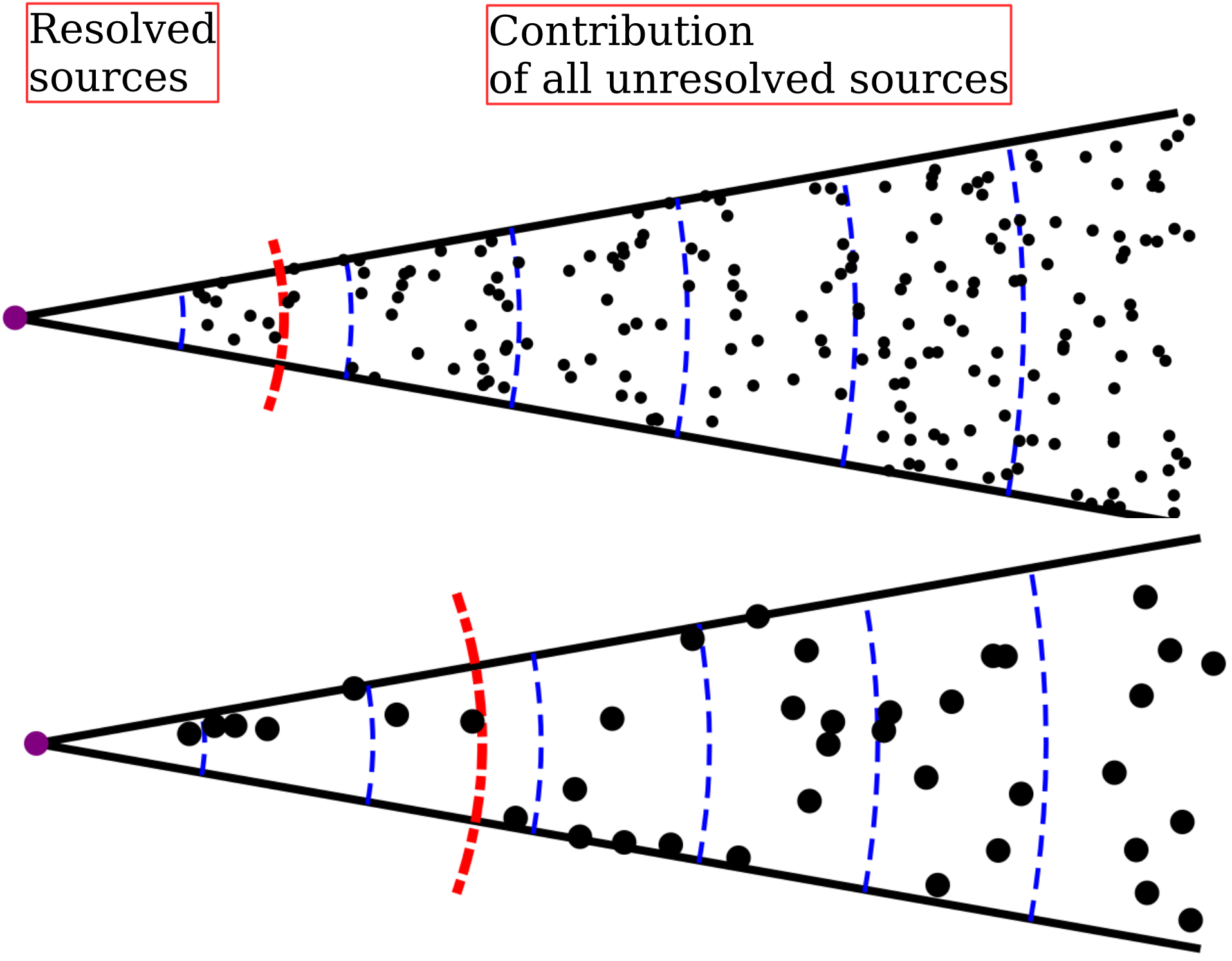


Compare the *Neutrino Signal* to *Gamma Ray fluxes*

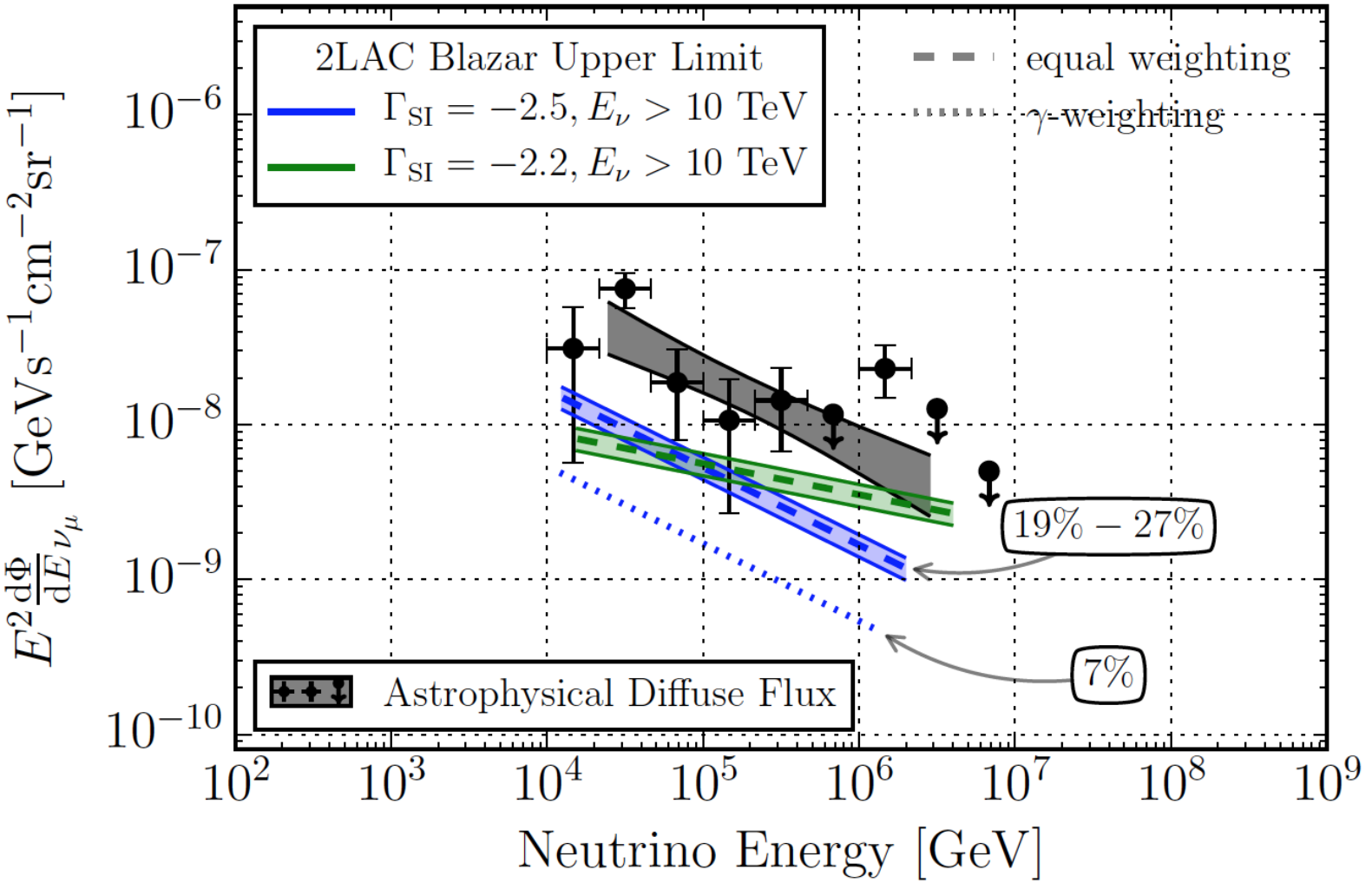


IceCube Signal *higher* than extrapolations of extragalactic flux
[New class of "hidden" sources ?]

If IceCube contains a Galactic Component. what is its origin ?


Resolved
sources
Contribution
of all unresolved sources

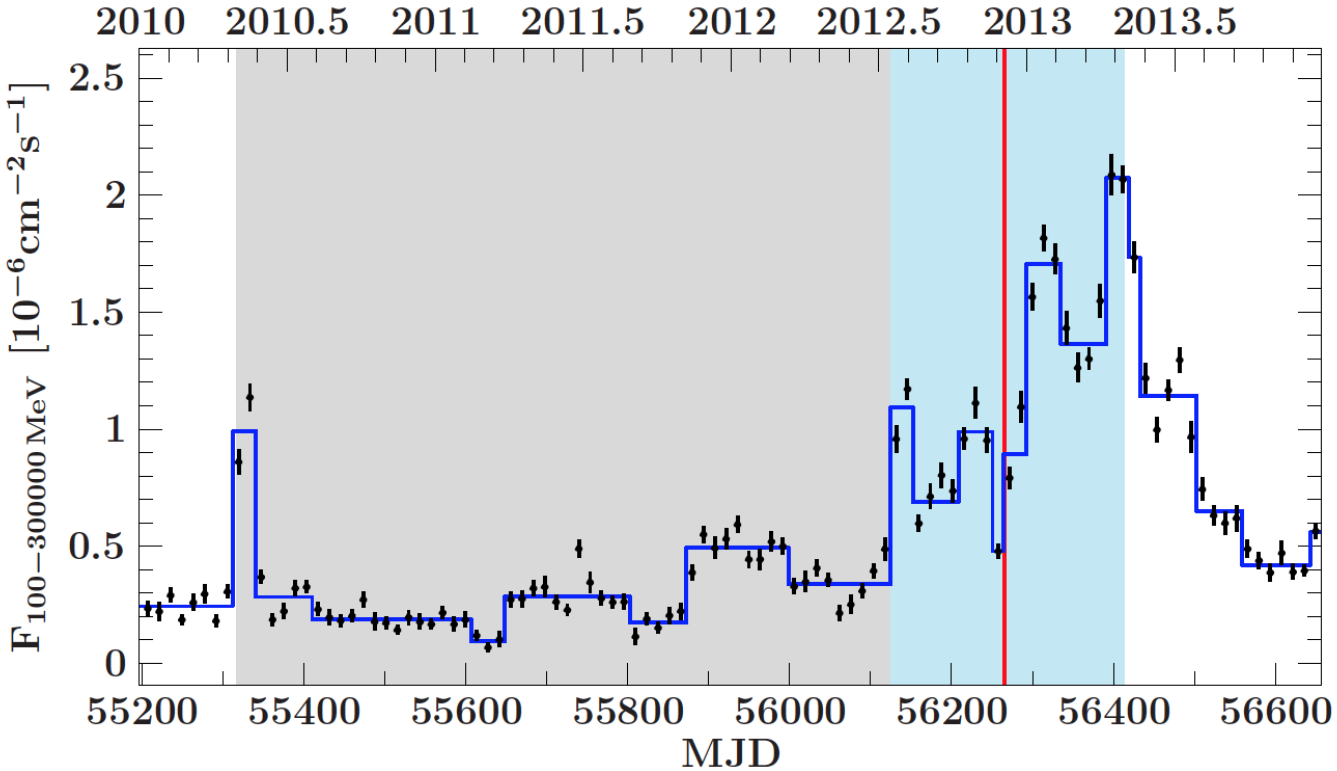
IceCube study of correlations with the FERMI 2LAC

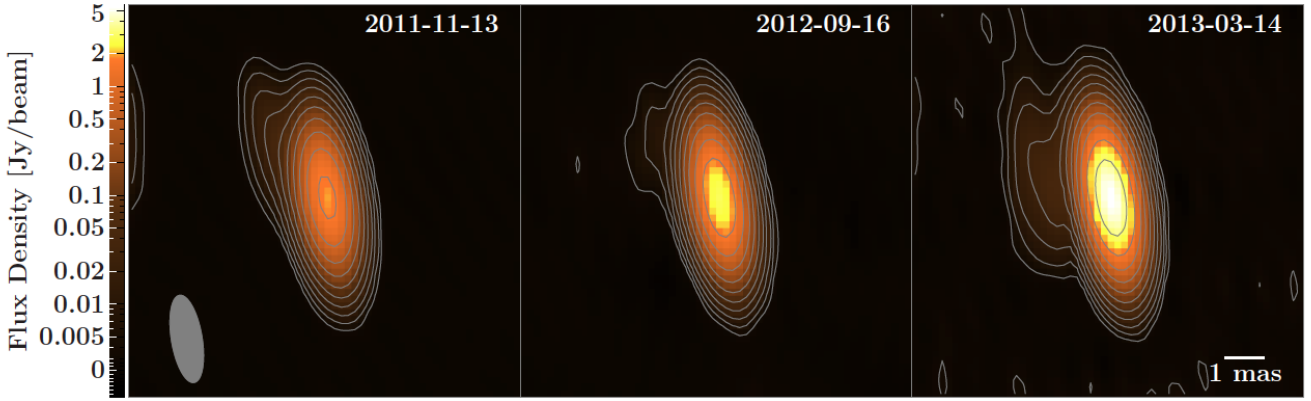


No correlation seen.
FERMI conclusion: upper limit on the Blazar contribution

M. Kadler *et al.*,
"Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event,"
Nature Phys. **12**, no. 8, 807 (2016)
[arXiv:1602.02012 [astro-ph.HE]].

γ-ray light curve of PKS B1424−418.



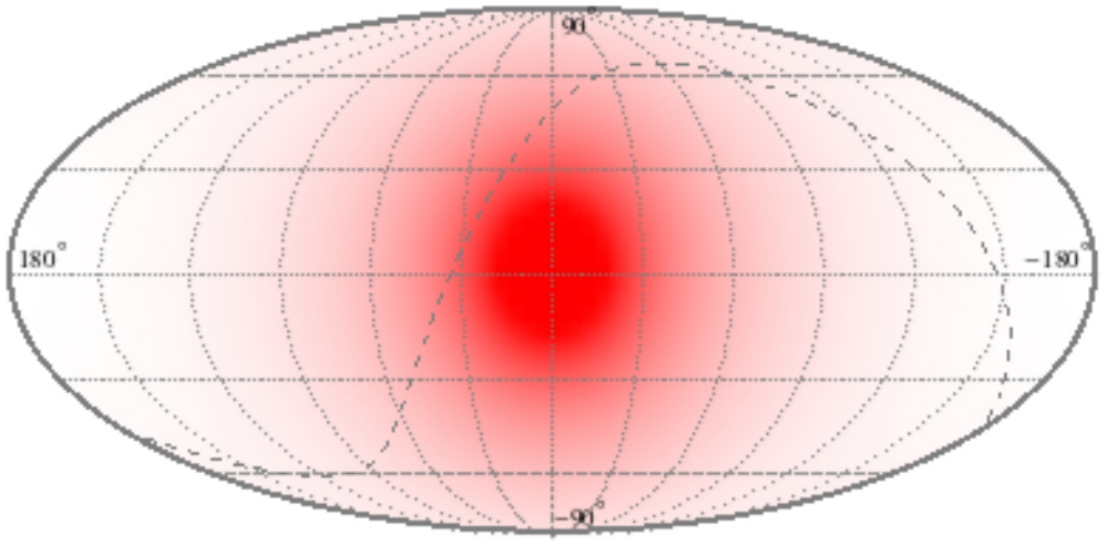


"Intriguing"
Coincidence

in time

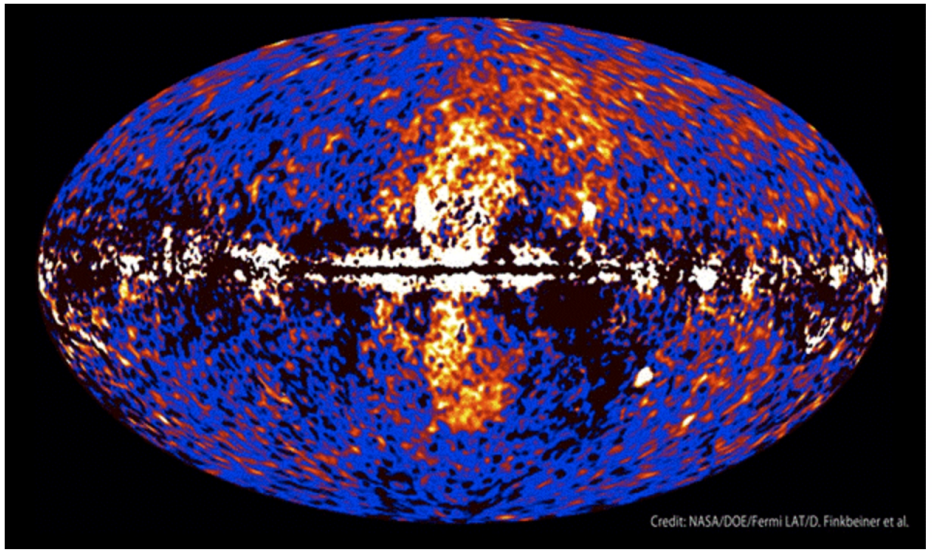
and direction
[error 15 degrees]

Does the IceCube signal have a Galactic component ?



Esmaili, Serpico

Dark matter decay model



Taylor, Gabici, Aharonian

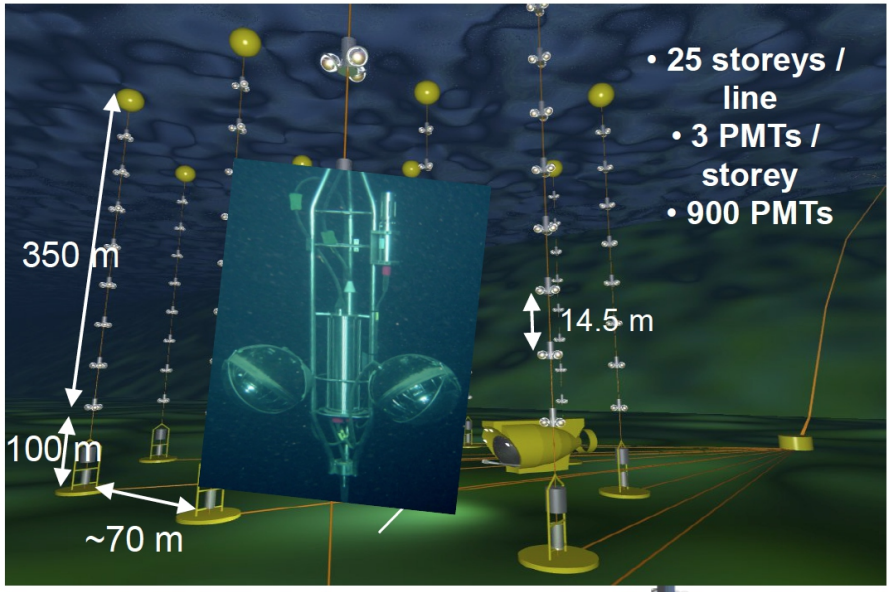
Large Galactic halo

$R \approx 100$ kpc

(inspired by “Fermi bubbles”)

Mediterranean Detectors

ANTARES Complete since 2008

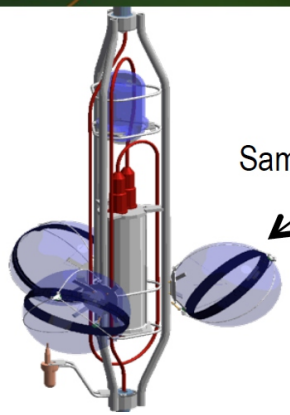


~10 Mton

12 lines

First Generation

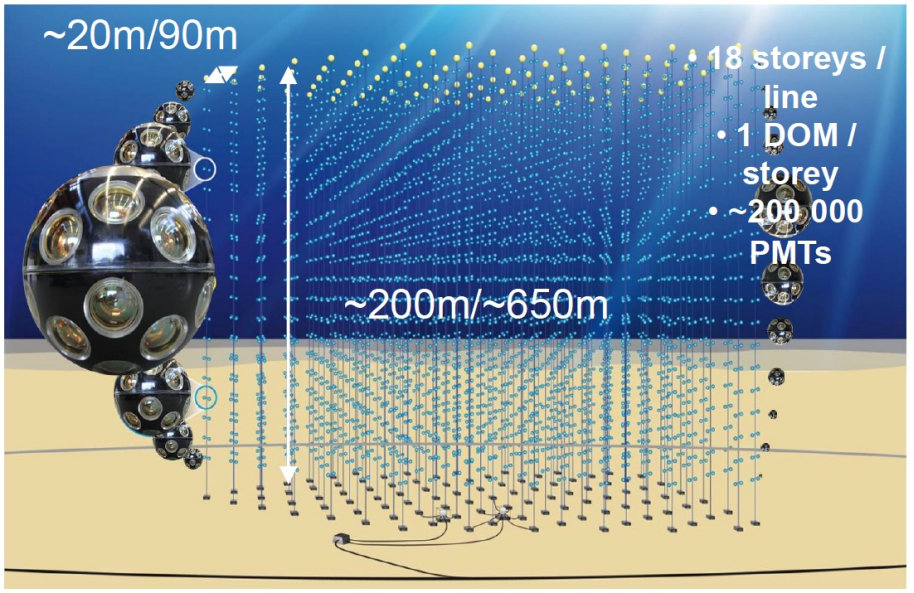
First line since 10 years



Same size

Com

KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation

~1 Gton ~6 Mton

Future neutrino telescopes

Final Comments:

The scientific potential
of *multi-messenger studies* of
the *"High Energy Universe"*
are extraordinarily interesting

Hopefully the "dream" of merging information from

Multi-wavelength photon studies
Neutrino emission
Cosmic Ray fluxes
Gravitational Waves

will turn into reality in a future that is not so distant

It is essential to pursue multi-messenger studies
in a coherent and coordinated form,
Because the different methods offer complementary
information, required to develop a complete understanding