High Energy Neutrino Astronomy

Paolo Lipari (INFN Roma Sapienza)
"Workshop Neutrino Telescopes"
Venezia, 13-17 march 2017

1. Introduction

2. Neutrinos and Gamma Rays

3. Neutrinos and Cosmic Rays

4. The IceCube Signal

5. Outlook

1. Introduction

- Why Neutrino Astronomy ?
- Neutrinos Sources
- Neutrinos and the "High Energy Universe"

[a] Use neutrinos as "messengers"
to study the universe.
"A new way to look at the sky"

[b] Study neutrino propagation,
infer fundamental properties of neutrinos
[masses, mixing, ...]

Neutrino Sources

Geo-neutrinos
Solar Neutrinos
SuperNova Neutrinos

$$E_\nu \simeq 1 - 100 \ \ \mathrm{MeV}$$

Neutrino Sources

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

Geo-neutrinos
Solar Neutrinos
SuperNova Neutrinos

$E_\nu \simeq 10^{6} - 10^{8}\ \ \mathrm{eV}$

Neutrinos from the
"High Energy Universe"

$E_\nu \simeq 10^{10} - 10^{23}\ \ \mathrm{eV}$

Neutrino Astrophysics is a very diverse field that extends in a very broad energy range

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

Geo-neutrinos
Solar Neutrinos
SuperNova Neutrinos

$E_\nu \simeq 10^{6} - 10^{8}$ eV

Dark Matter searches	$E_\nu \simeq 10^{10} - 10^{12}$ eV
Galactic Point Sources	$E_\nu \simeq 10^{12} - 10^{14}$ eV
IceCube Signal	$E_\nu \simeq 10^{14} - 10^{16}$ eV
GZK neutrinos	$E_\nu \simeq 10^{18} - 10^{20}$ eV
Decay Supermassive particles	$E_\nu \simeq 10^{23}$ eV

“High Energy Universe”

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

4 Messengers

Cosmic Rays,
Photons, Neutrinos

Gravitational Waves

2. Neutrinos and Gamma Rays

- Gamma Ray emission: "Leptonic" versus "Hadronic"
- Neutrinos versus Gamma Rays
- Flavor of Astrophysical Neutrinos
- The Gamma Ray Sky
- Gamma Ray absorption

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 "

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

$$\pi^\circ \to \gamma \; \gamma$$

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

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

"Leptonic "

$$e^\pm \; \gamma_{\rm soft} \to e^\pm \; \gamma$$

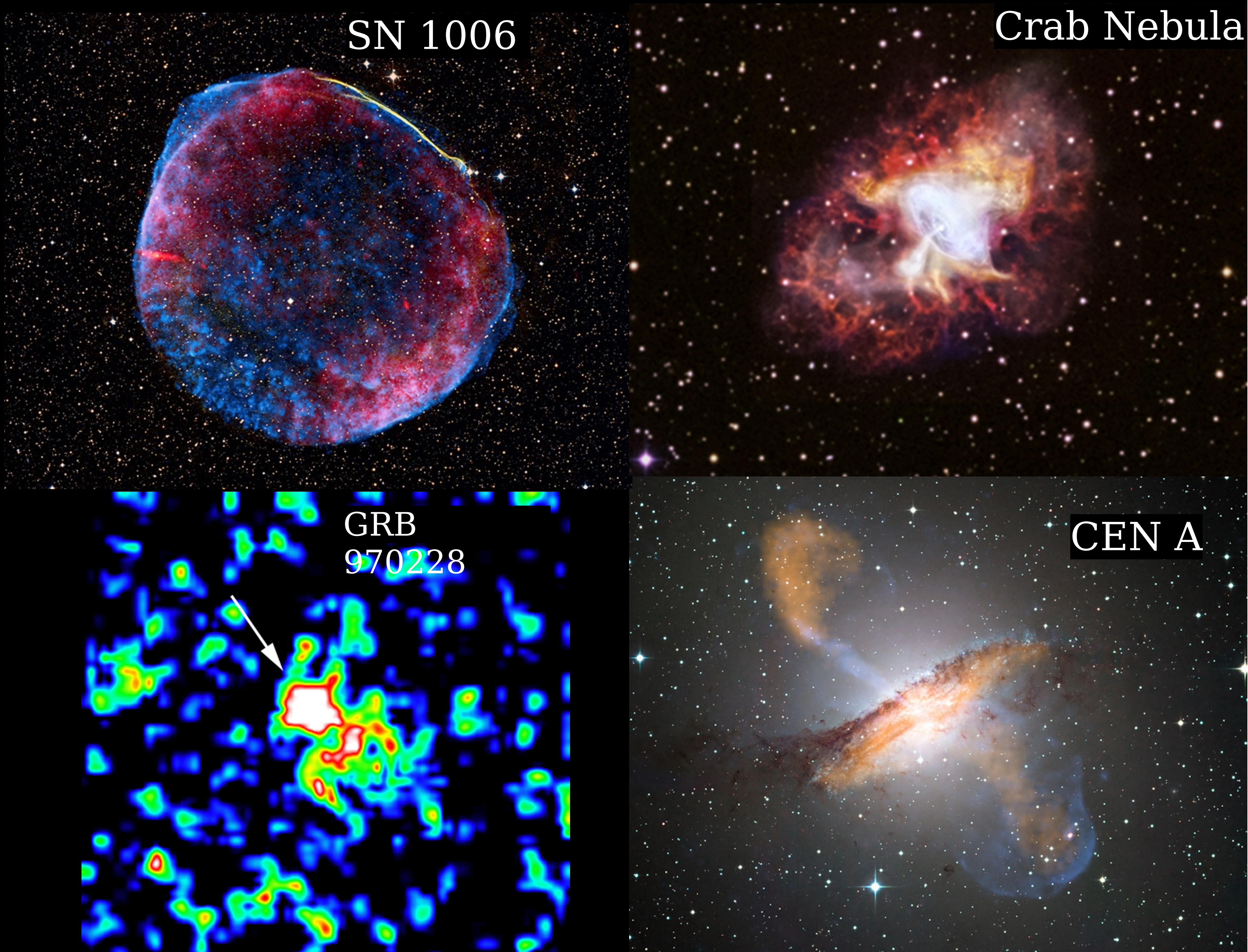
$$e^\pm \; Z \to e^\pm \; \gamma \; Z$$

$$e^\pm \; \vec{B} \to e^\pm \; \gamma_{\rm syn}$$

High Energy Astrophysical Sources:

Astrophysical object (or "event")
that accelerates, and contains
(electrically charged) relativistic particles

(protons, electrons, nuclei....)


SN 1006
Crab Nebula
GRB
970228
CEN A

High Energy Astrophysical Sources:

Astrophysical object (or "event")
that accelerates, and contains
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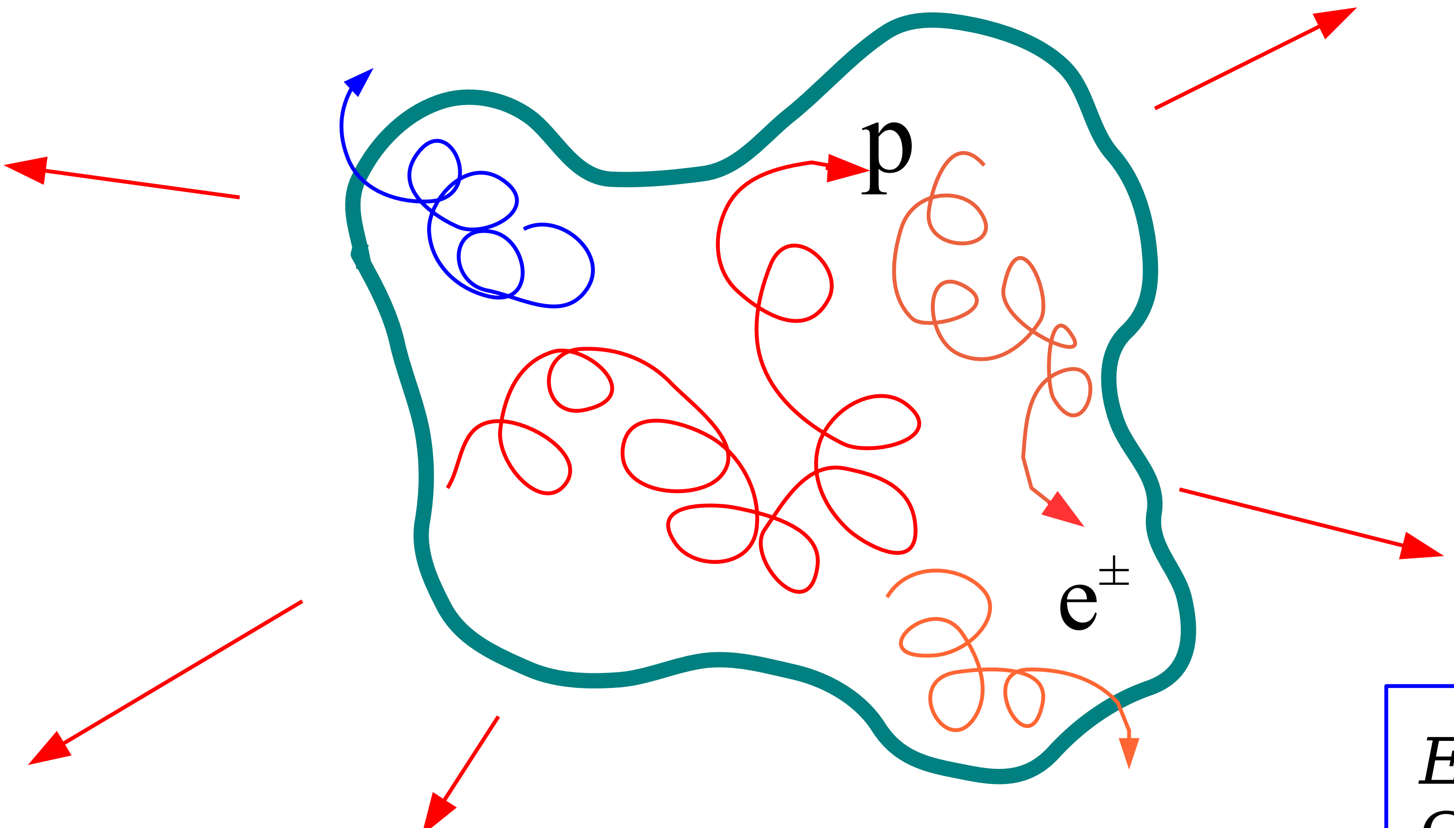
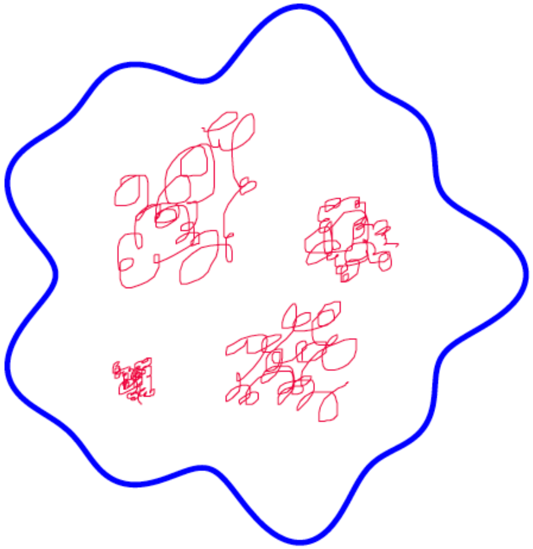
(protons, electrons, nuclei....)



Interactions:
Emissions

gamma rays,
neutrinos

Escape:
Generation of CR



Population of relativistic protons: $N_p(E_p)$

Average density of the medium: n

Emission Rates of Photons and Neutrinos:

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

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

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

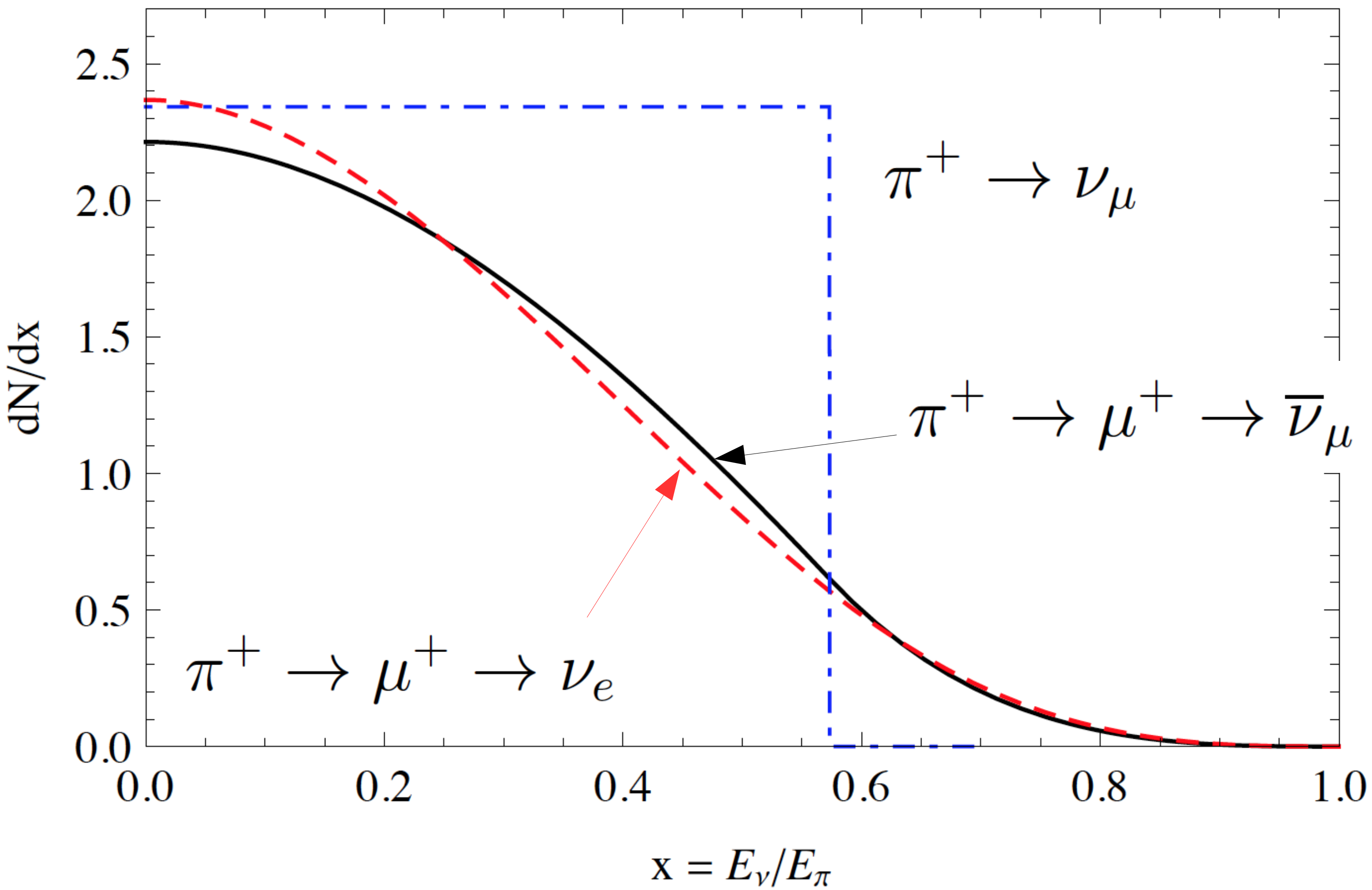
$$\mu^+ \to e^+ \; \nu_e \; \overline{\nu}_\mu$$

$$\pi^\circ \to \gamma \; \gamma$$

Simple relation between neutrino and gamma-ray emissions

Neutrino spectra in (chain) pion decay

$$\pi^+ \to \mu^+ \; \nu_\mu$$
$$\quad \hookrightarrow \; e^+ \; \nu_e \; \overline{\nu}_\mu$$



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

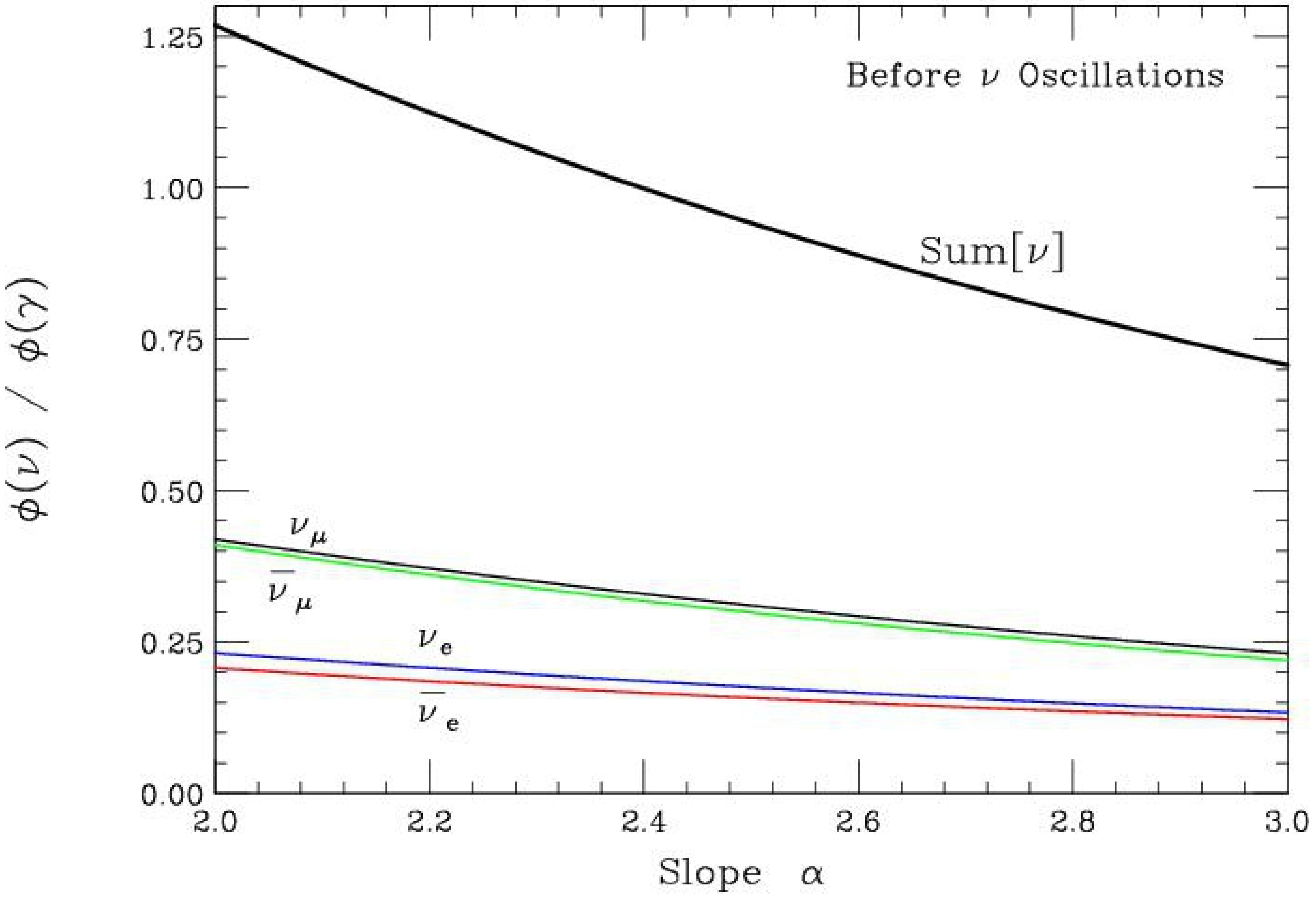
$$N_p(E) = K_p \; E_p^{-\alpha}$$

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)



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

$$\pi^0/\pi^\pm \approx 1/2$$

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

$$\pi^+/\pi^- \approx 1$$

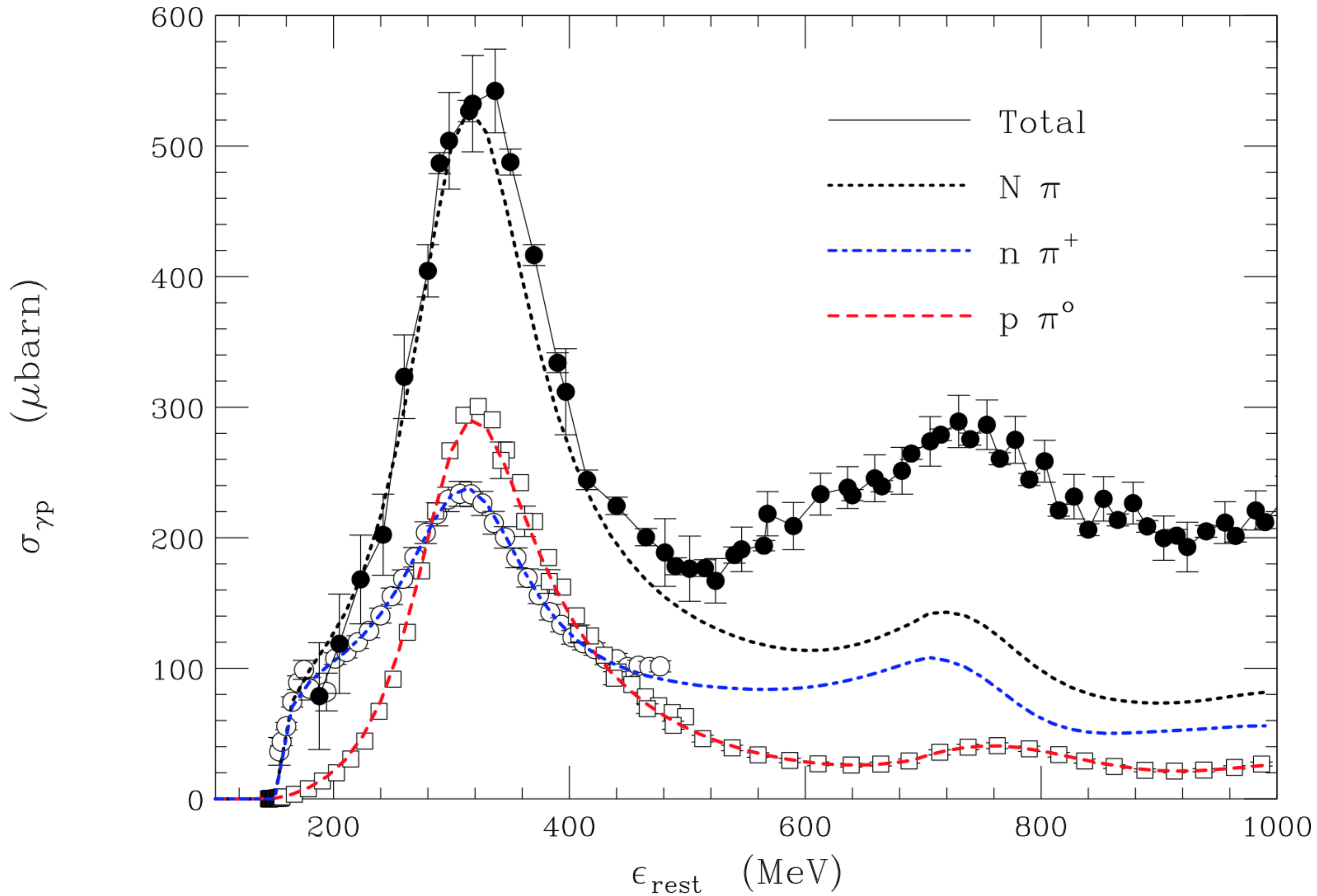
$$\nu/\overline{\nu} \approx 1$$

$p\gamma$ versus pp

Near Threshold:
single pion production

$$p + \gamma \to n + \pi^+$$
$$p + \gamma \to p + \pi^0$$

Cross section $p + \gamma \to \text{hadrons}$



$$\pi^+/\pi^- \gg 1$$
$$\pi^0/\pi^+ \approx 1$$
$$\gamma/\nu \approx 2$$
$$\nu/\overline{\nu} \approx 2$$

Energy threshold for photo-production:
(creation of a single pion):

$$s_{p\gamma} \geq (m_p + m_\pi)^2$$

Minimum photon energy for photo-production

of a proton of energy E_p

$$\varepsilon_{\text{min}} \propto E_p^{-1}$$

$$\varepsilon \geq \frac{1}{4\,E_p}\,(2\,m_p\,m_\pi + m_\pi^2)$$

The number of targets is a function of the proton energy

Proton *interaction probability* per unit time:
[Convolution of cross section with soft photons distributions]

$$K_{p\gamma}(E_p) = \sigma_{p\gamma} \otimes n_\gamma(\varepsilon)$$

$$K_{p\gamma}(E_p) = \int d\varepsilon \int_{-1}^{+1} \frac{d\cos\theta_{p\gamma}}{2} (1-\cos\theta_{p\gamma})\, n_\gamma(\varepsilon, \cos\theta_{p\gamma})\, \sigma_{p\gamma}(\varepsilon_r)$$

Target photon distribution
has approximately a power form:
[main example is Gamma Ray Bursts]

$$n_\gamma(\varepsilon) \propto \varepsilon^{-\beta}$$

$$K_{p\gamma}(E_p) \propto E^{\beta}$$

Interaction probability
that grows with energy
reflecting the target photon
spectral shape

Neutrino emission spectral shape in $p\ \gamma$ mechanism

$$N_p(E_p) \propto E_p^{-\alpha}$$

Relativistic protons

$$n_\gamma(\varepsilon) \propto \varepsilon^{-\beta}$$

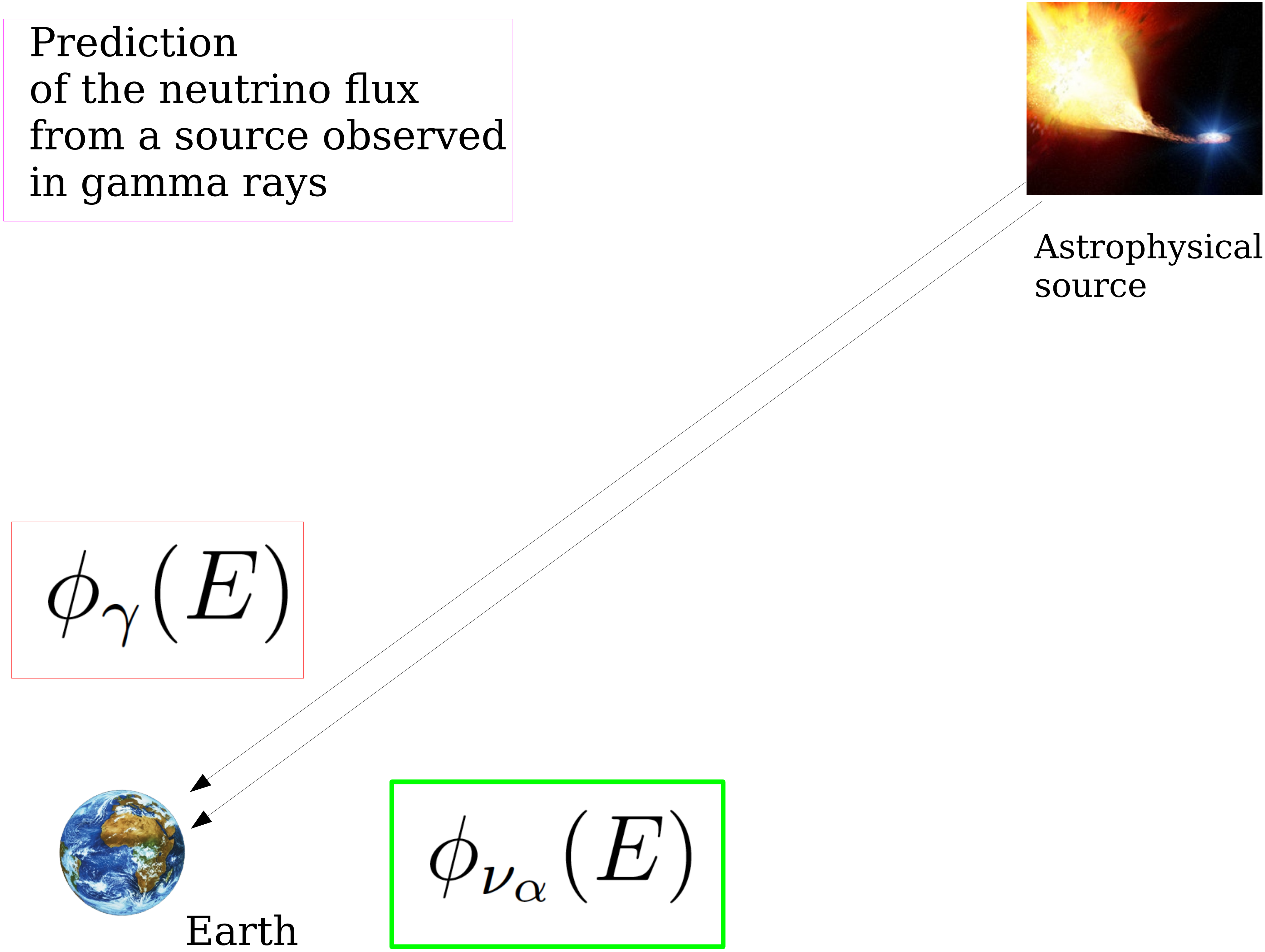
Target photon field

$$\dot{N}_\gamma(E_\gamma) \propto E_\gamma^{-\alpha+\beta-1}$$

Neutrino emission

$$\alpha_\nu \simeq \alpha - \beta + 1$$

Spectral index of the neutrinos
reflects the spectral indices of the interacting protons and of the target photons


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)

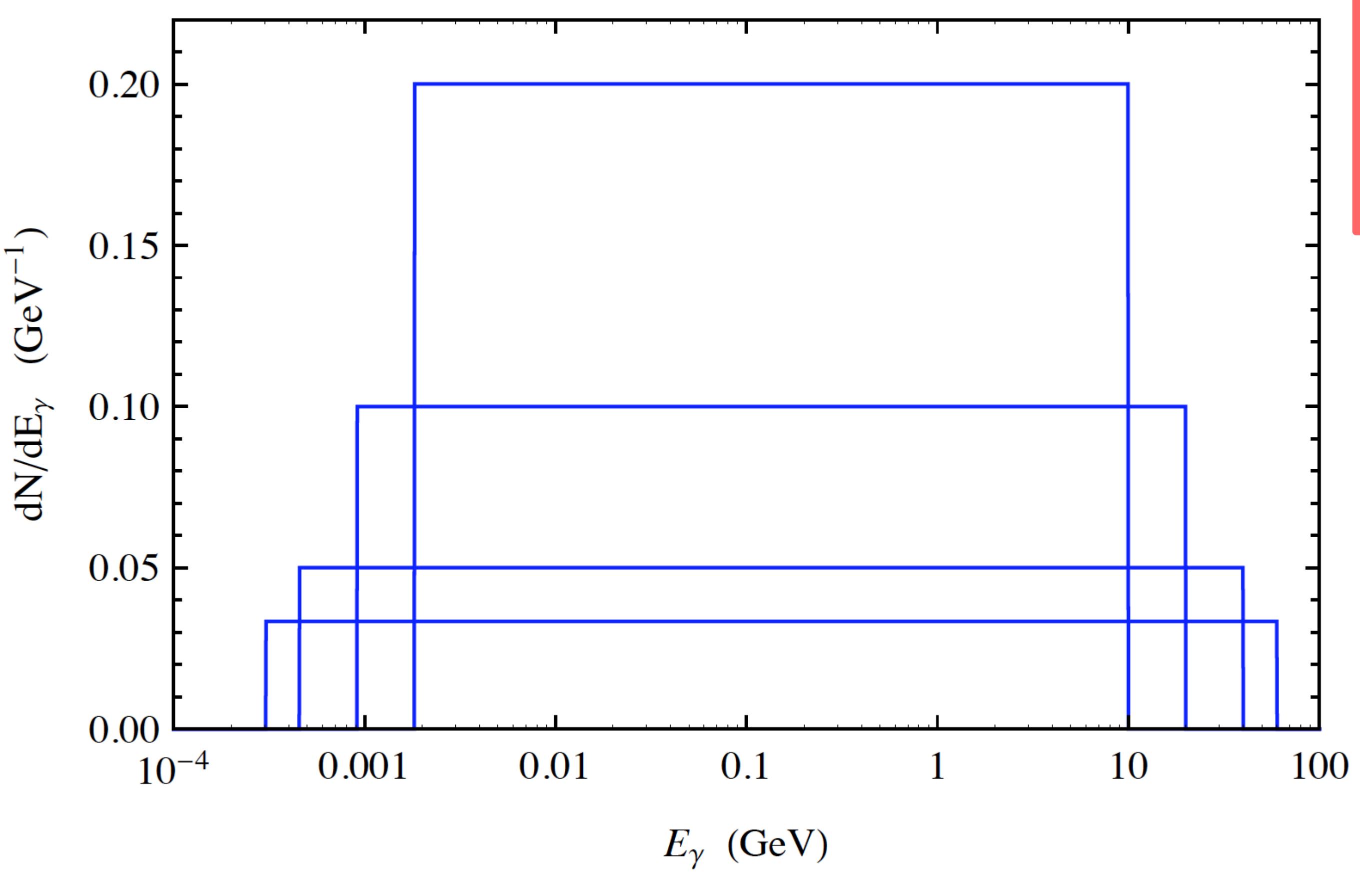
Earth

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

ENERGY EXTRAPOLATION

“Signature” of the hadronic mechanism:

The mass m_{π° leaves its “imprint” on the photon spectrum



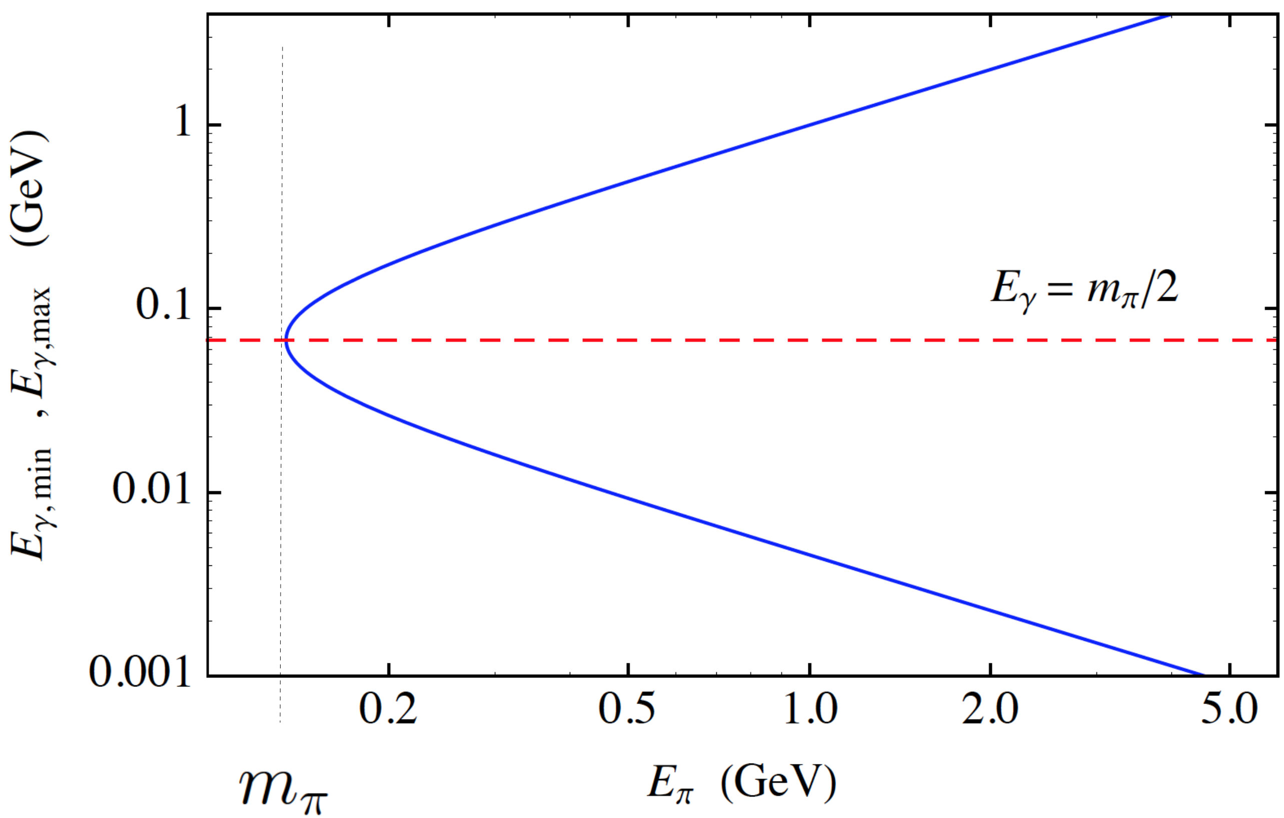
$$E_{\gamma,\min} = E_\pi \, (1 - \beta_\pi)$$

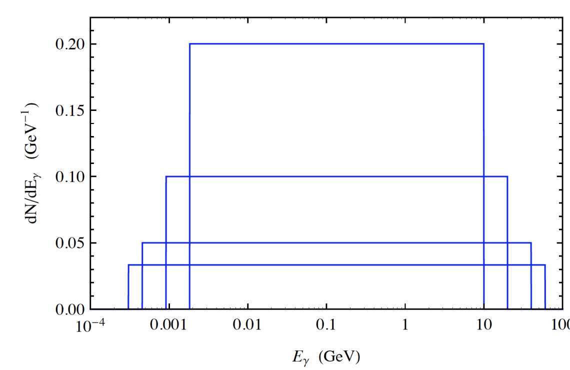
$$E_{\gamma,\max} = E_\pi \, (1 + \beta_\pi)$$

Pions of energy E_γ
can be created only by pions with energy $E_\pi \geq E_\pi^{\min}(E_\gamma)$

$$E_{\pi,\min}(E_\gamma) = E_\gamma + \frac{m_\pi^2}{4\,E_\gamma} = \frac{m_\pi}{2}\left[\frac{2E_\gamma}{m_\pi} + \frac{m_\pi}{2\,E_\gamma}\right]$$

[symmetry for “reflections” around $E_\gamma = m_{\pi^\circ}/2$]

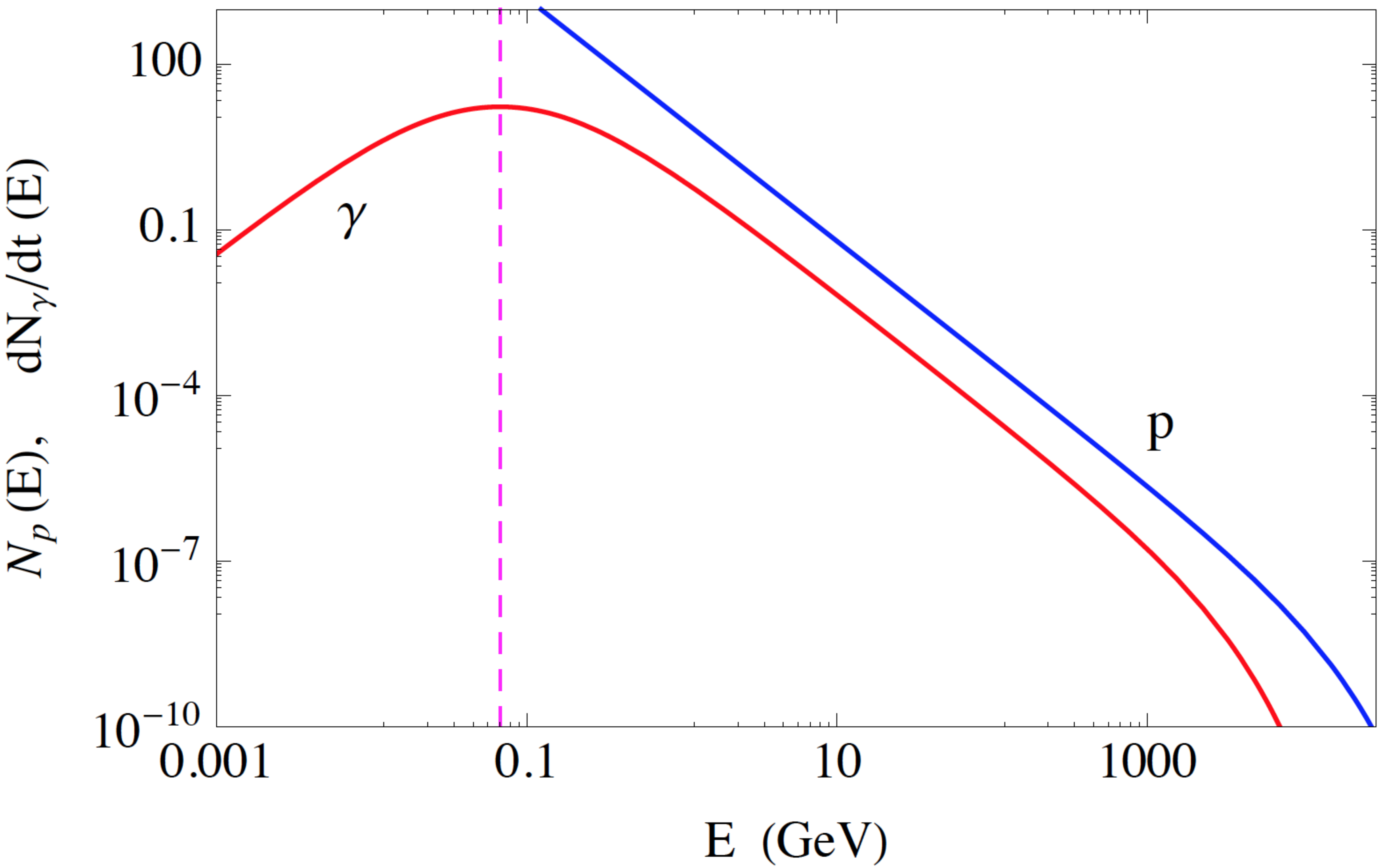




Spectrum symmetric around $E_\gamma = \frac{m_{\pi^\circ}}{2}$

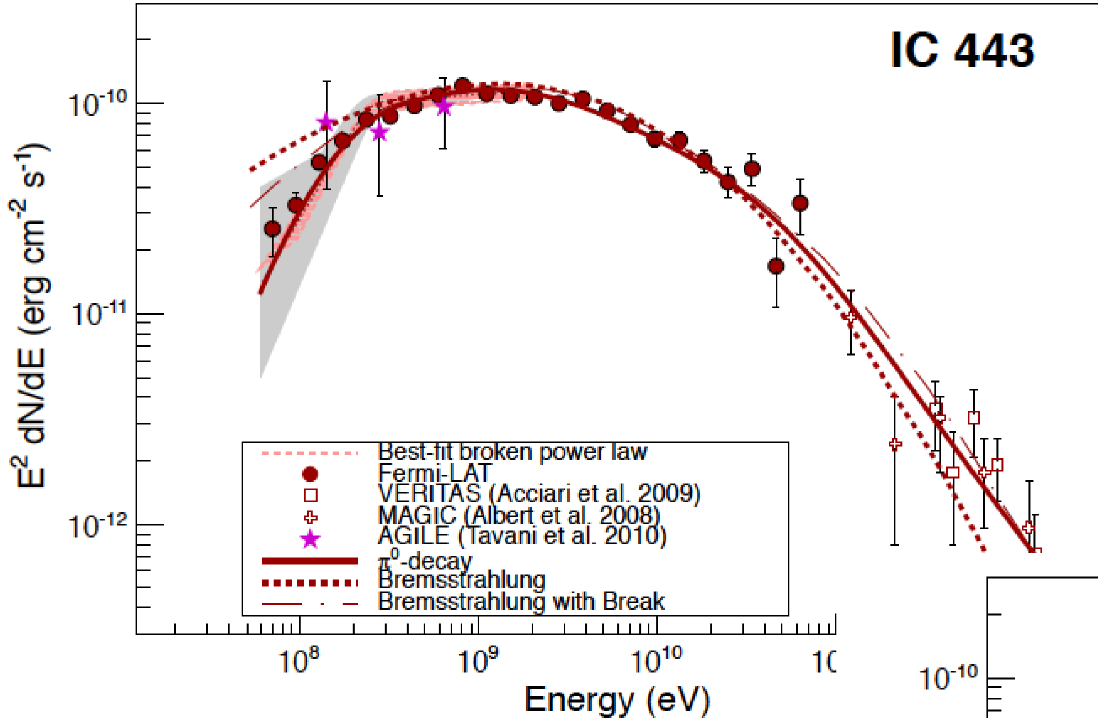
High energy cutoff:

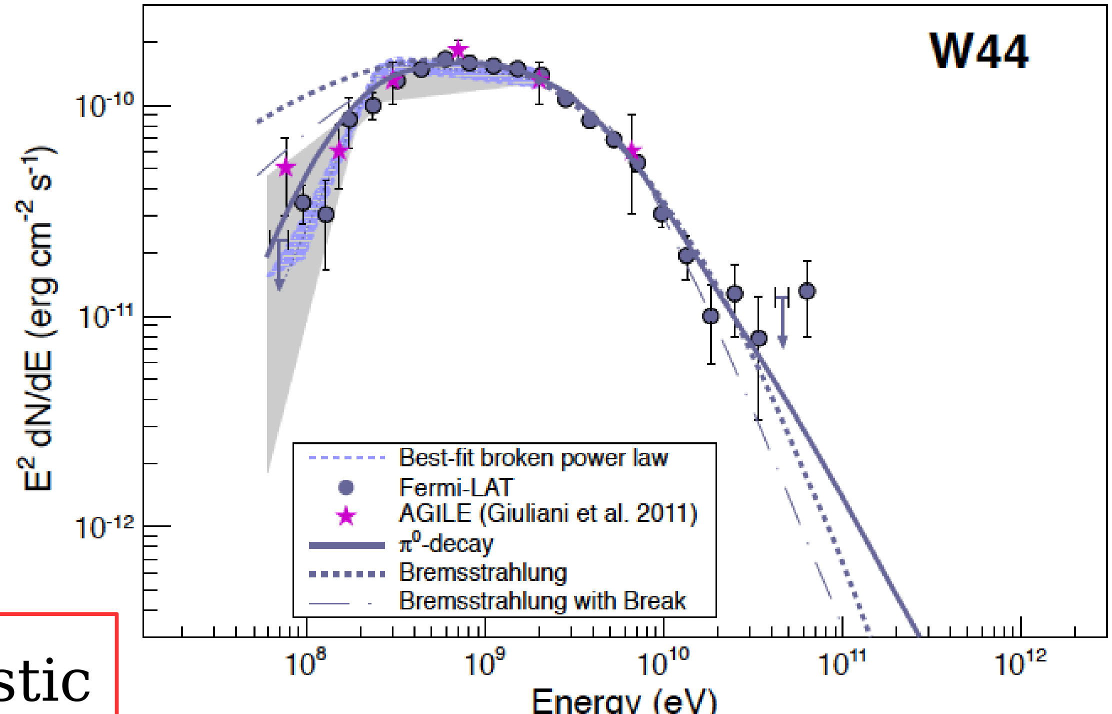
Reflects a possible cutoff in the Proton spectrum



Result of the FERMI collaboration

SCIENCE feb. 2013



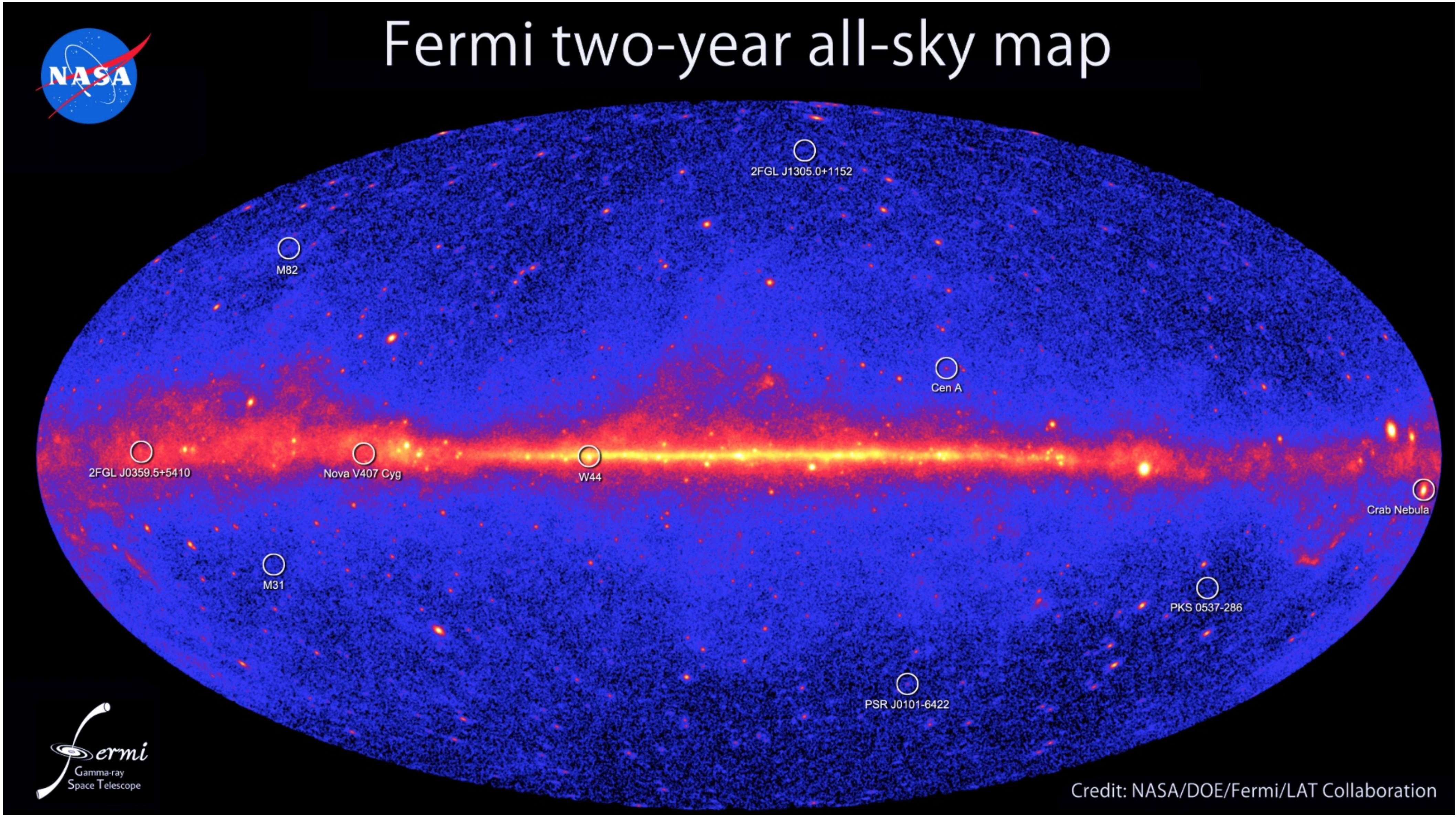


"Detection of the characteristic pion-decay signature in Supernova Remnants"

The Gamma Ray sky

- Diffuse Galactic Flux
- Galactic Sources
- Extragalactic Sources

$E_\gamma \geq 100\ \mathrm{MeV}$



1. Ensemble of (quasi)-point sources

2. Diffuse Galactic Flux

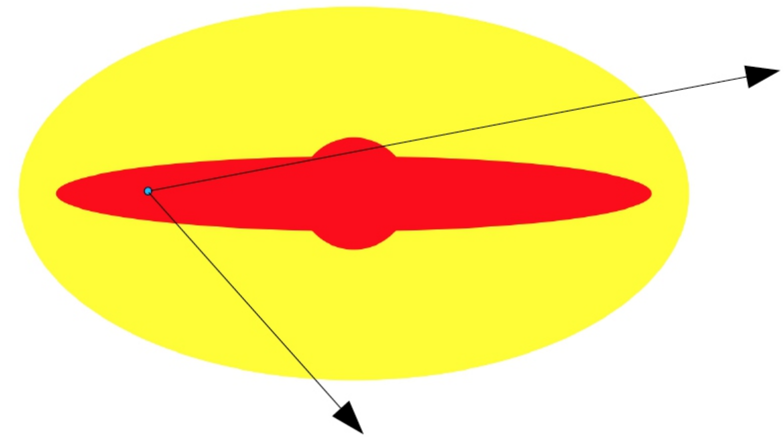
80% of photons around 1 GeV

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

3. Isotropic flux.

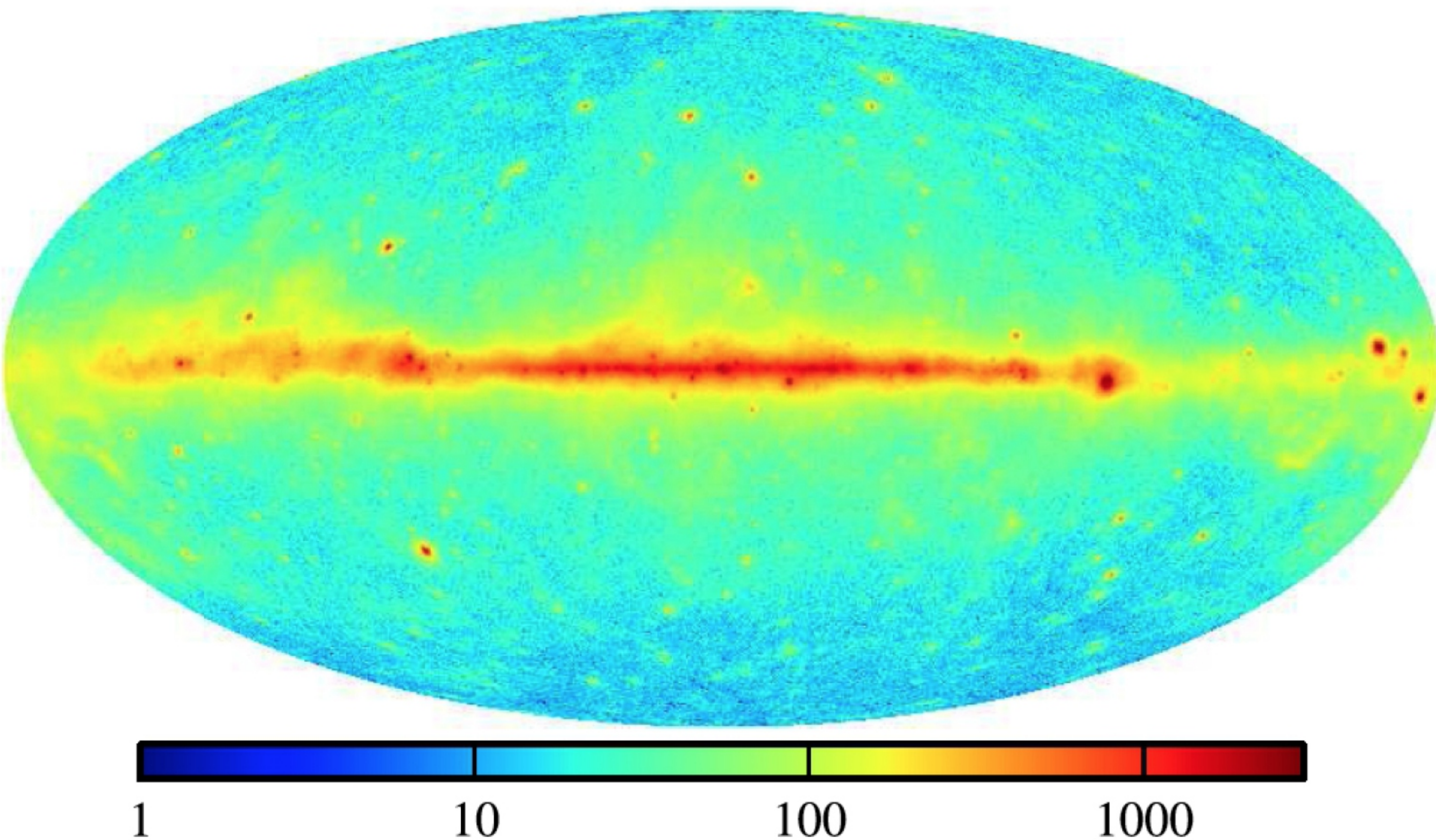
(attributed to an ensemble of unresolved extragalactic sources)

Diffuse Emission



Fermi–LAT counts

Galactic coordinates



energy range 200 MeV to 100 GeV

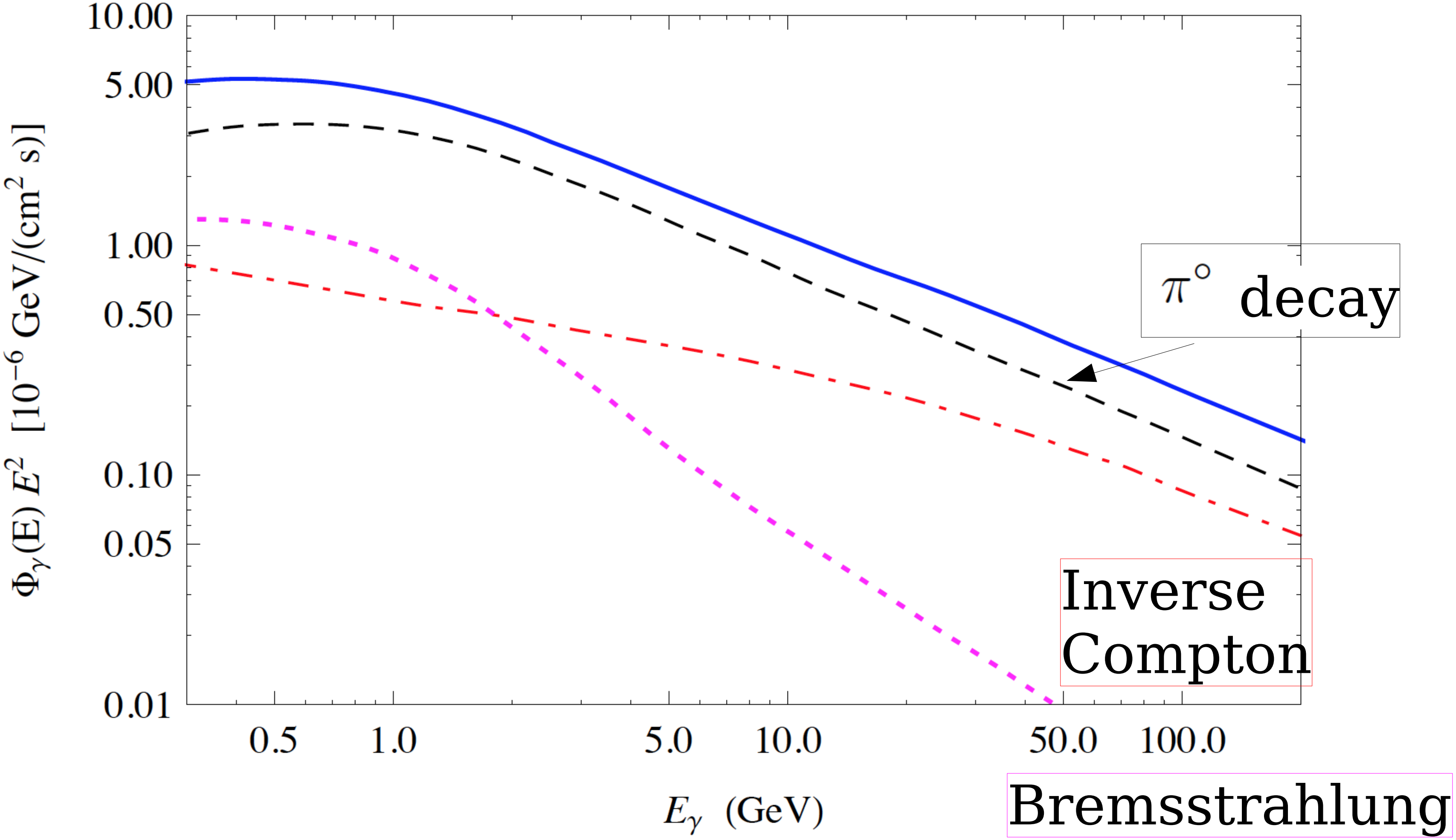
50% of flux
+- 5 degrees
around equator

Galactic Diffuse flux spectral shape

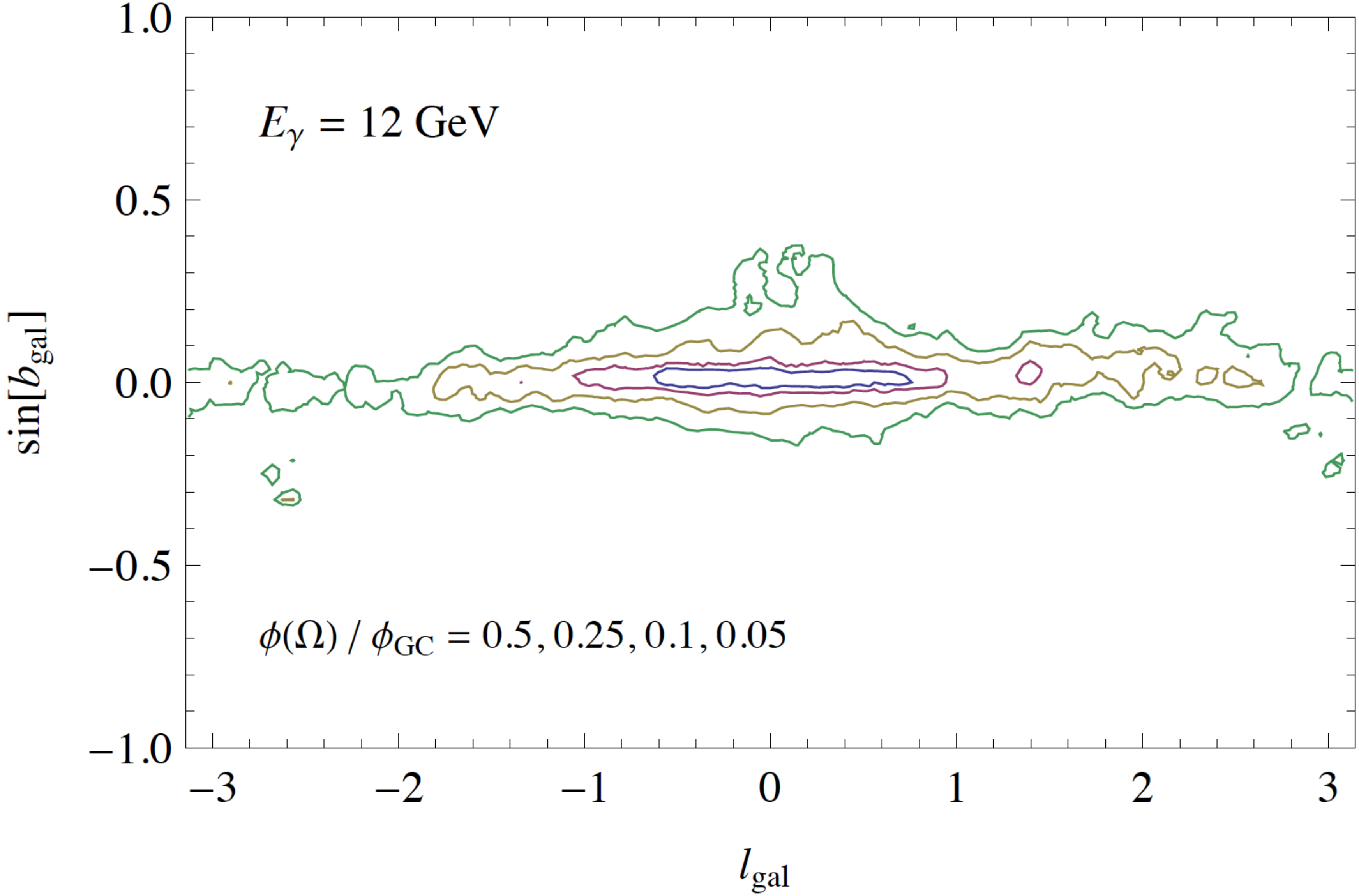
$$\phi_\gamma^{\rm diffuse}(E_\gamma) \propto E_\gamma^{-2.70}$$

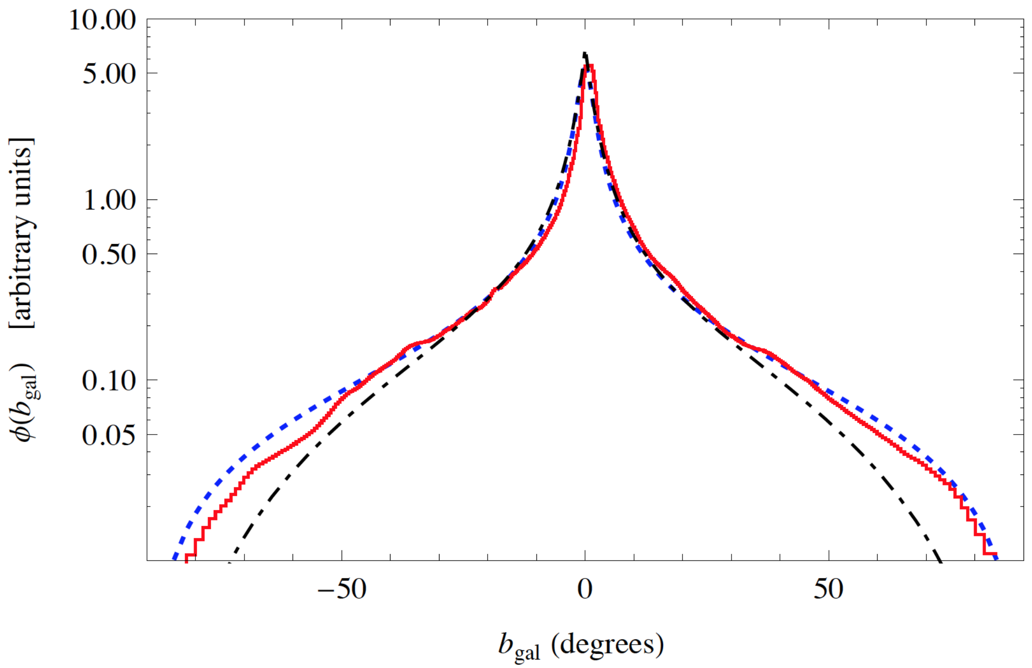
$$\alpha_\gamma^{\rm diffuse} \approx 2.70 \pm 0.05$$

Decomposition (by FERMI) of the diffuse Galactic flux



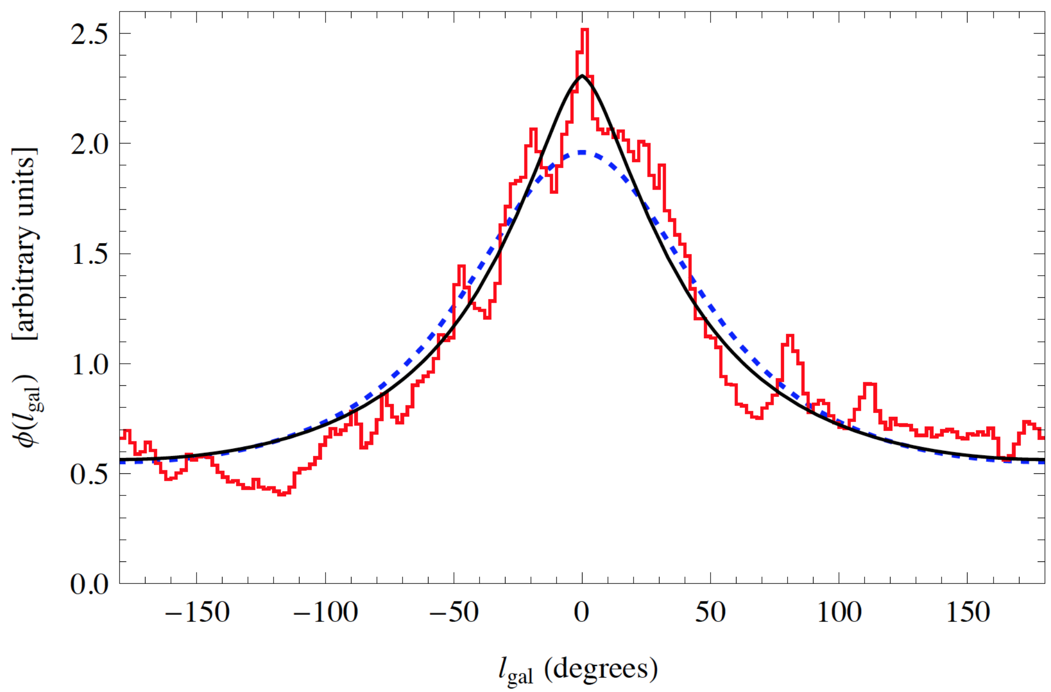
Angular distribution of the diffuse Galactic emission





Galactic Latitude distribution

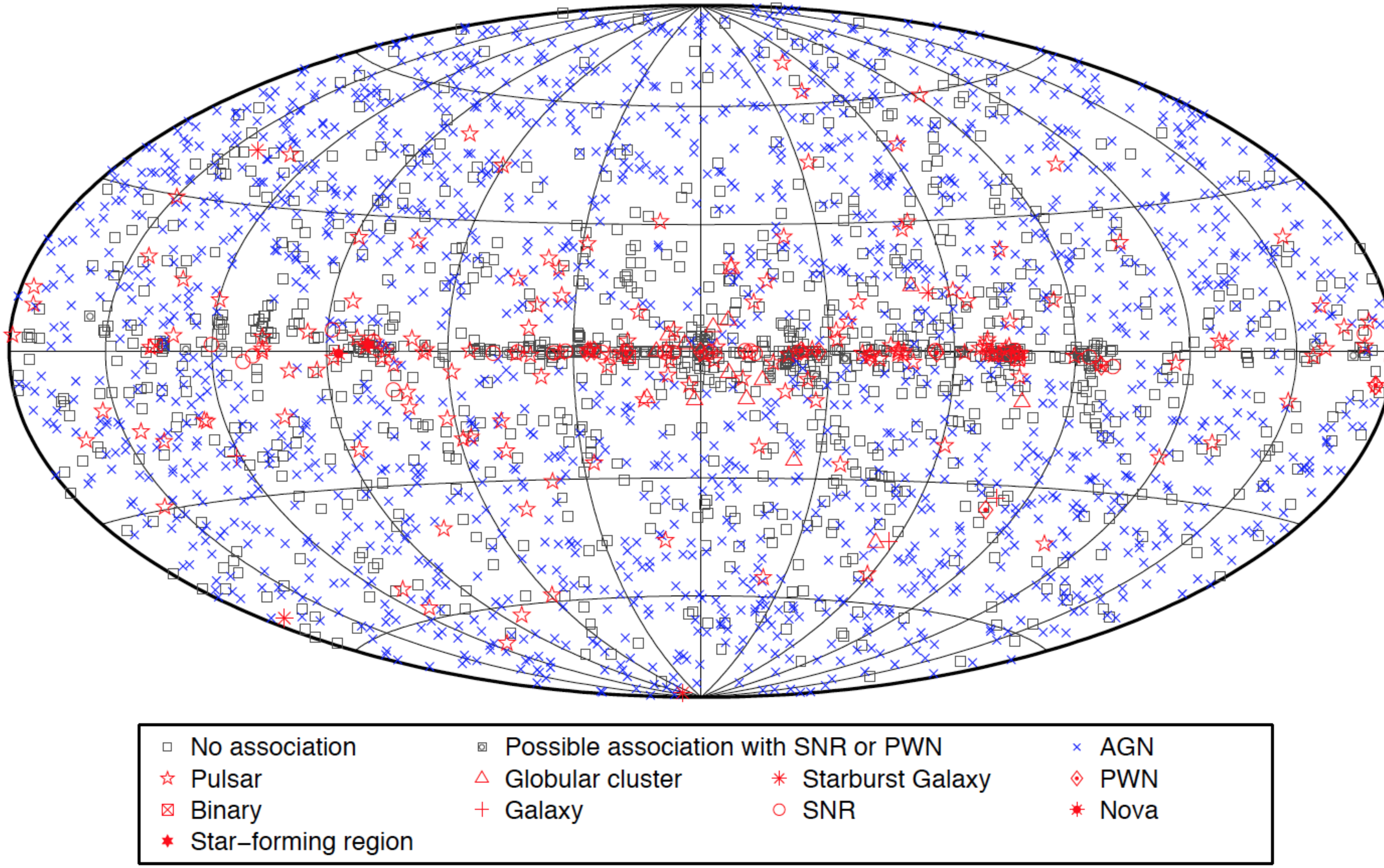
Galactic Longitude distribution



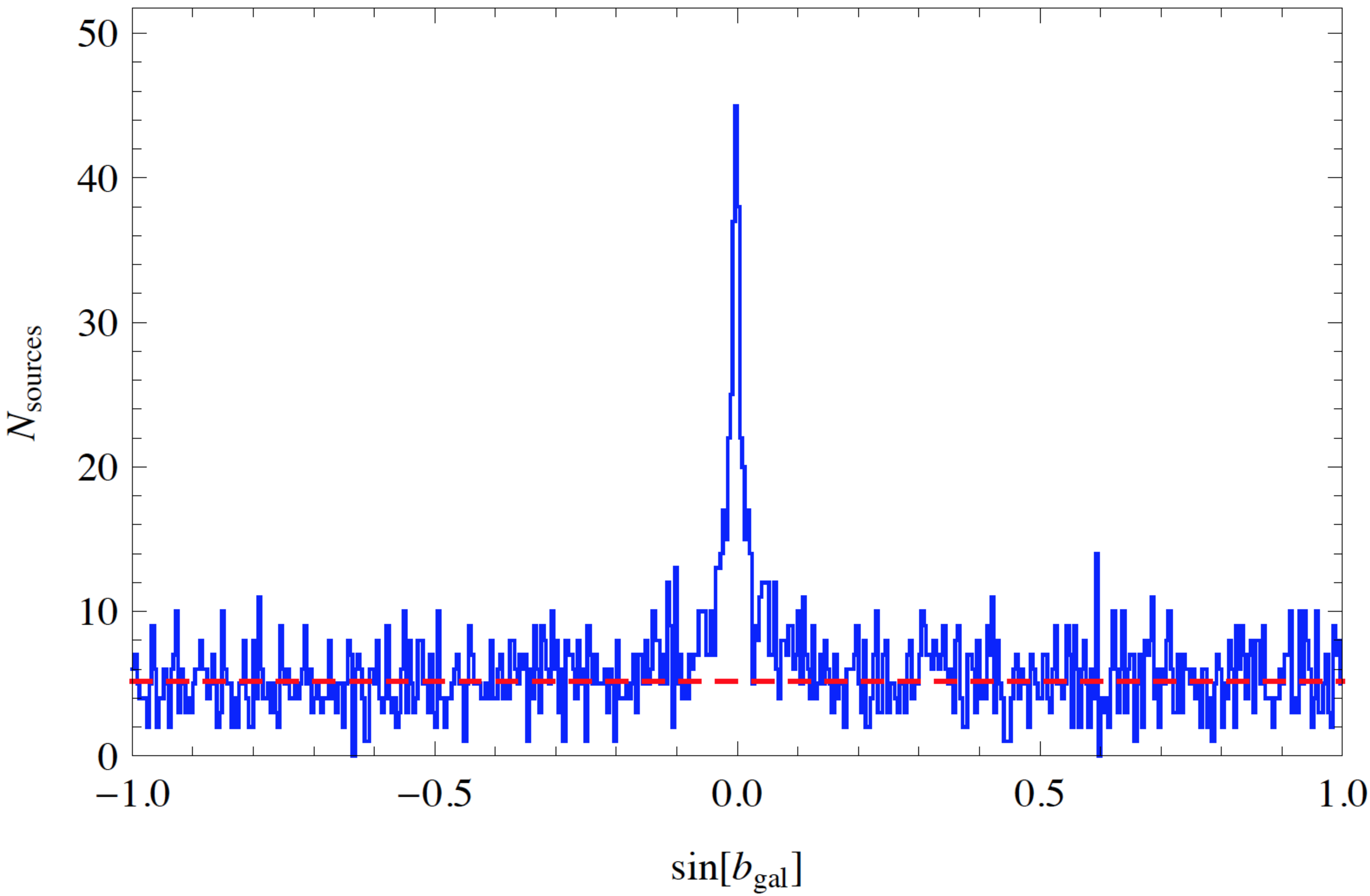
3rd FERMI Catalog

3034 sources

E > 100 MeV

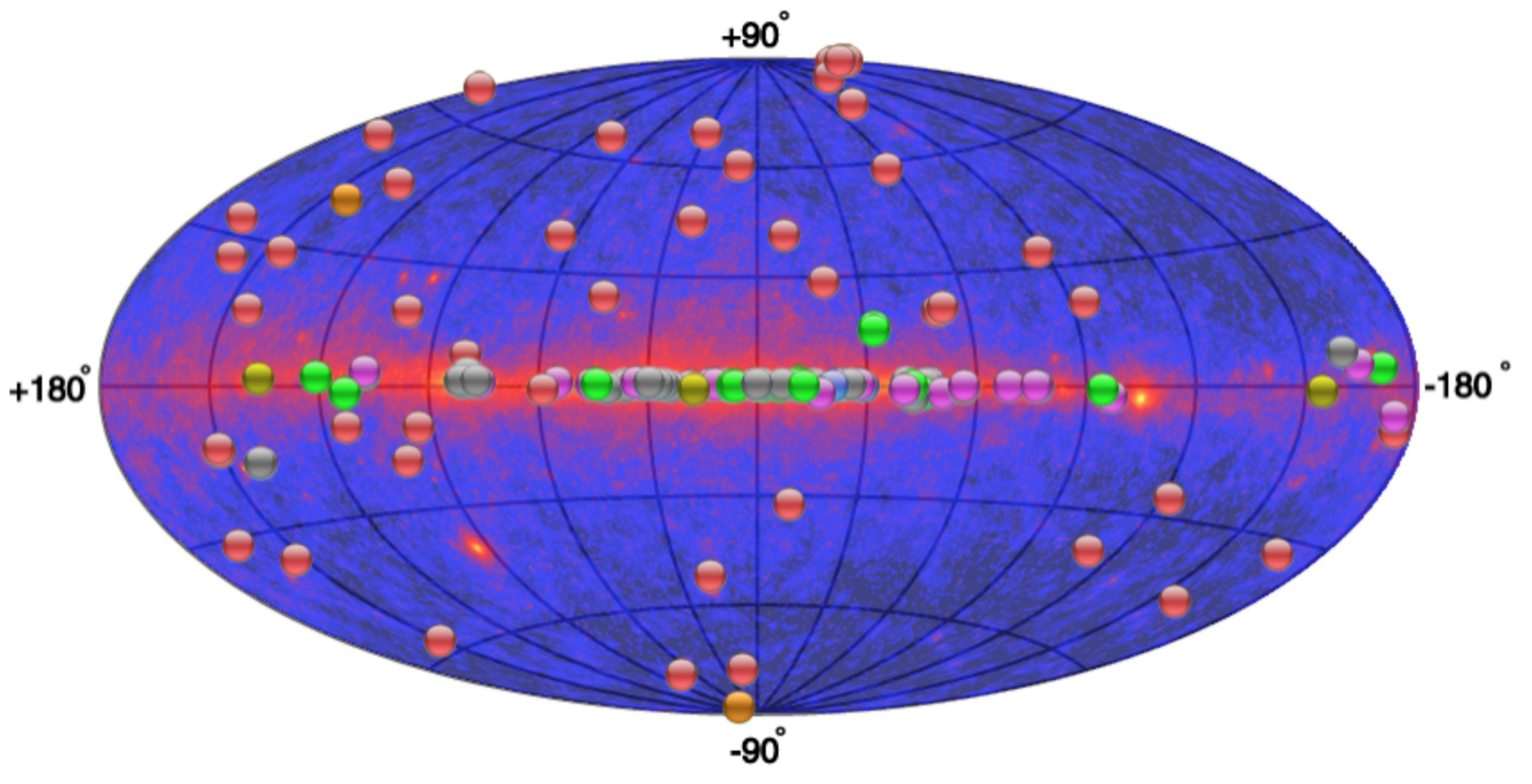


3034 3rd catalog sources [approximately 440 are galactic]

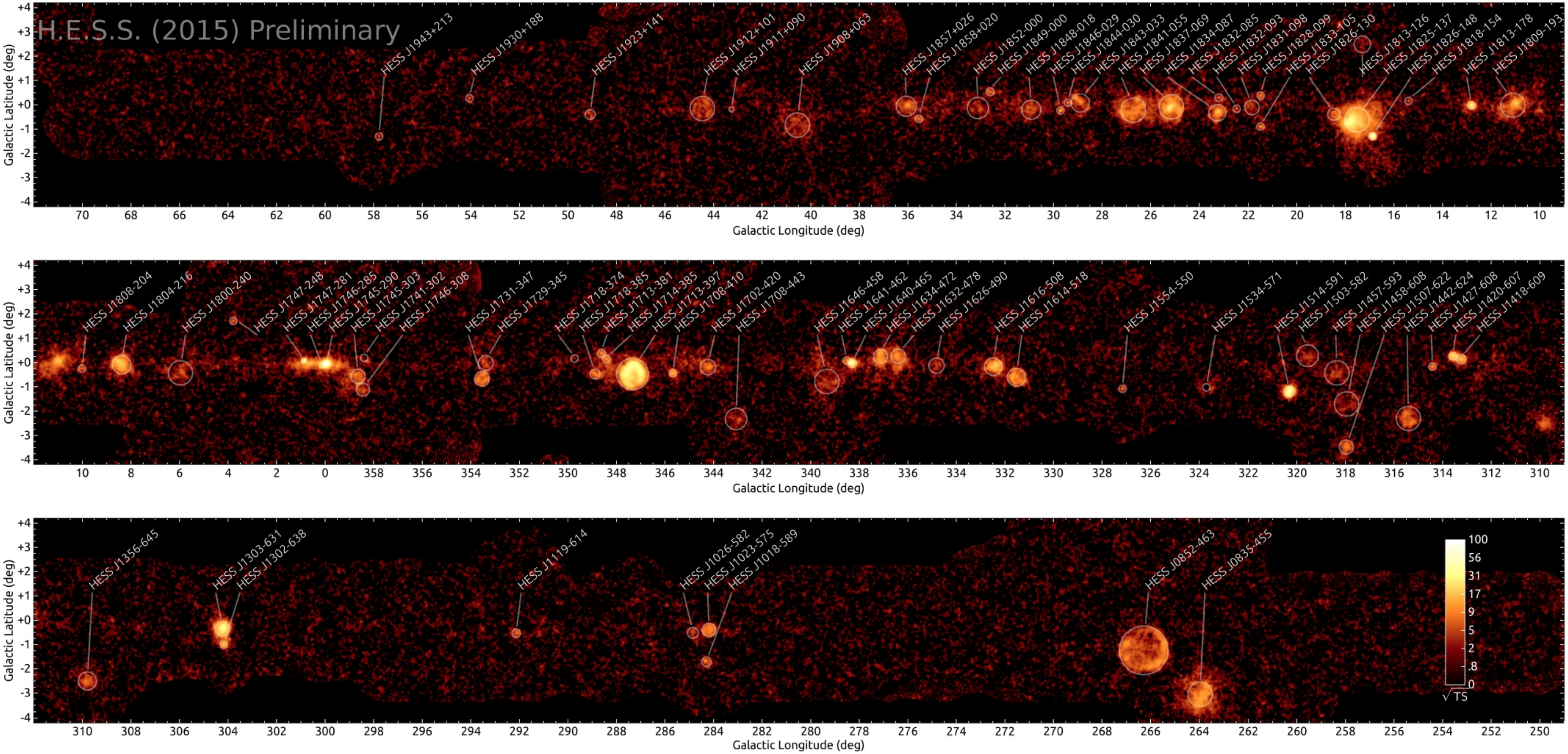


TeV Sky

170 → 200 Sources

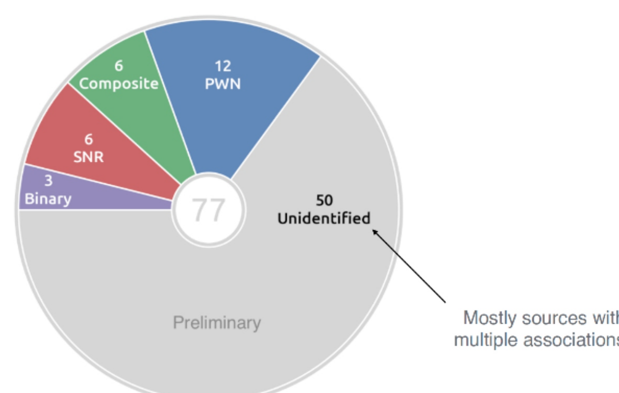


blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky



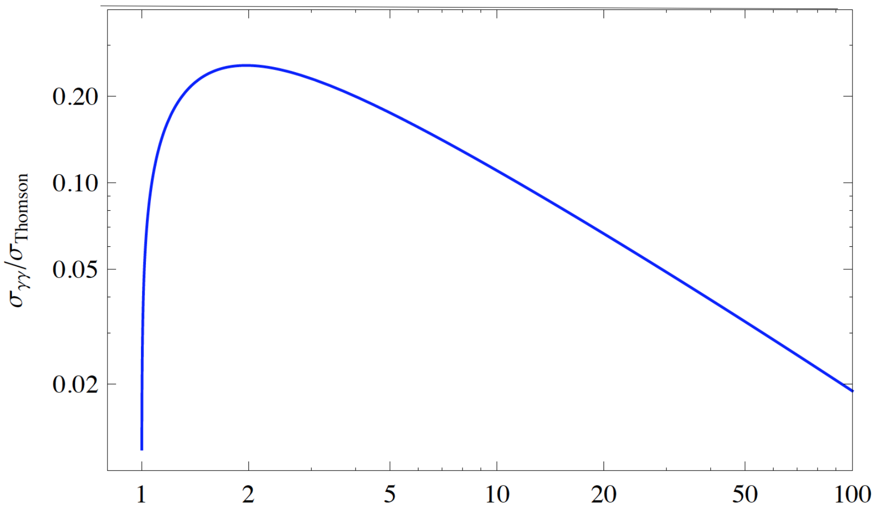
Firm identifications

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



Gamma Ray Absorption:

$$\gamma + \gamma \to e^+ + e^-$$



$$x = s/(4m_e^2)$$

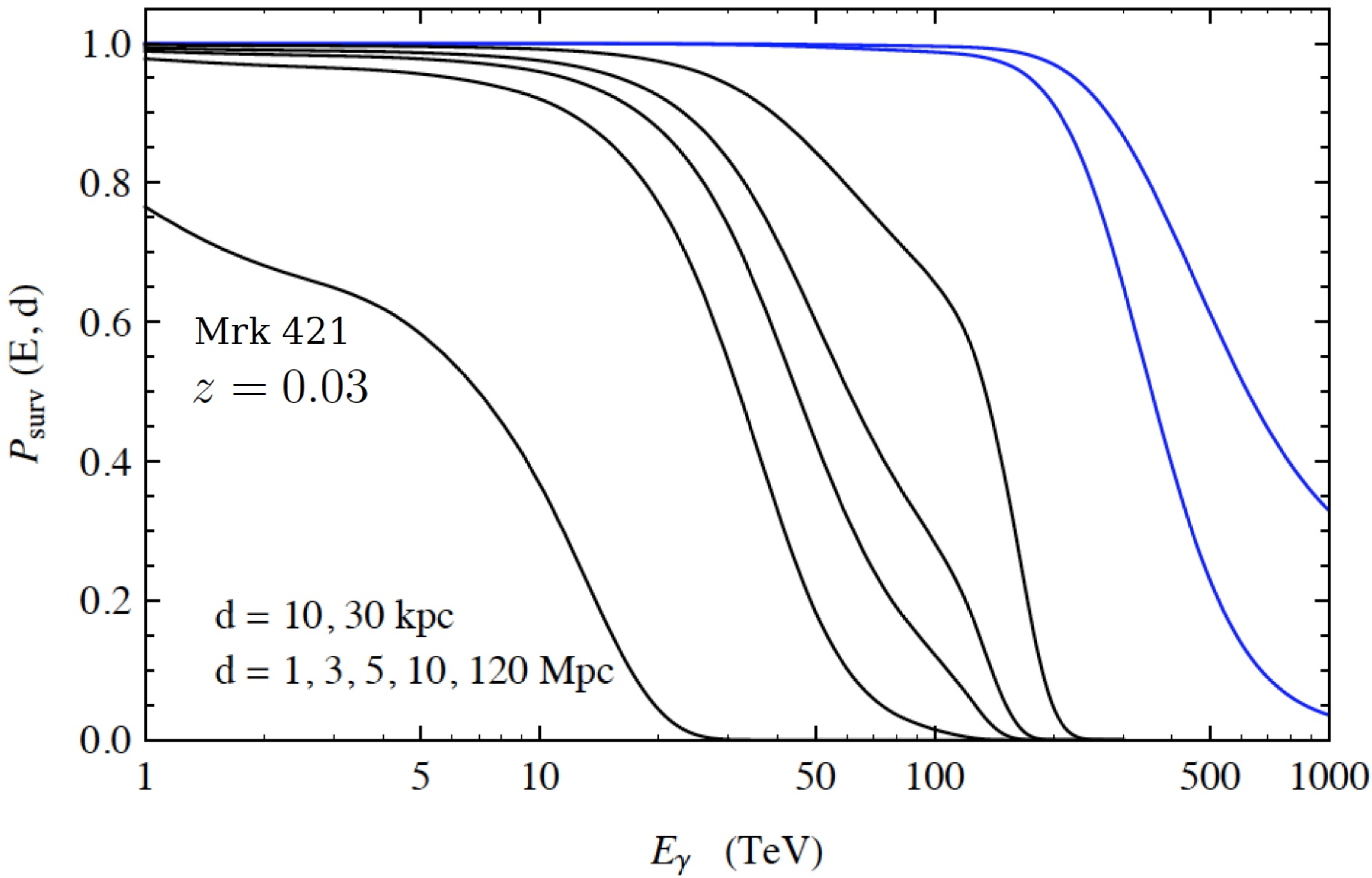
$$x = \frac{s}{4\,m_e^2} = \frac{E_\gamma\,\varepsilon\,(1-\cos\theta_{\gamma\gamma})}{2\,m_e^2}$$

$$\sigma_{\gamma\gamma}^{\rm max} \simeq 0.2554\ \sigma_{\rm Th}$$

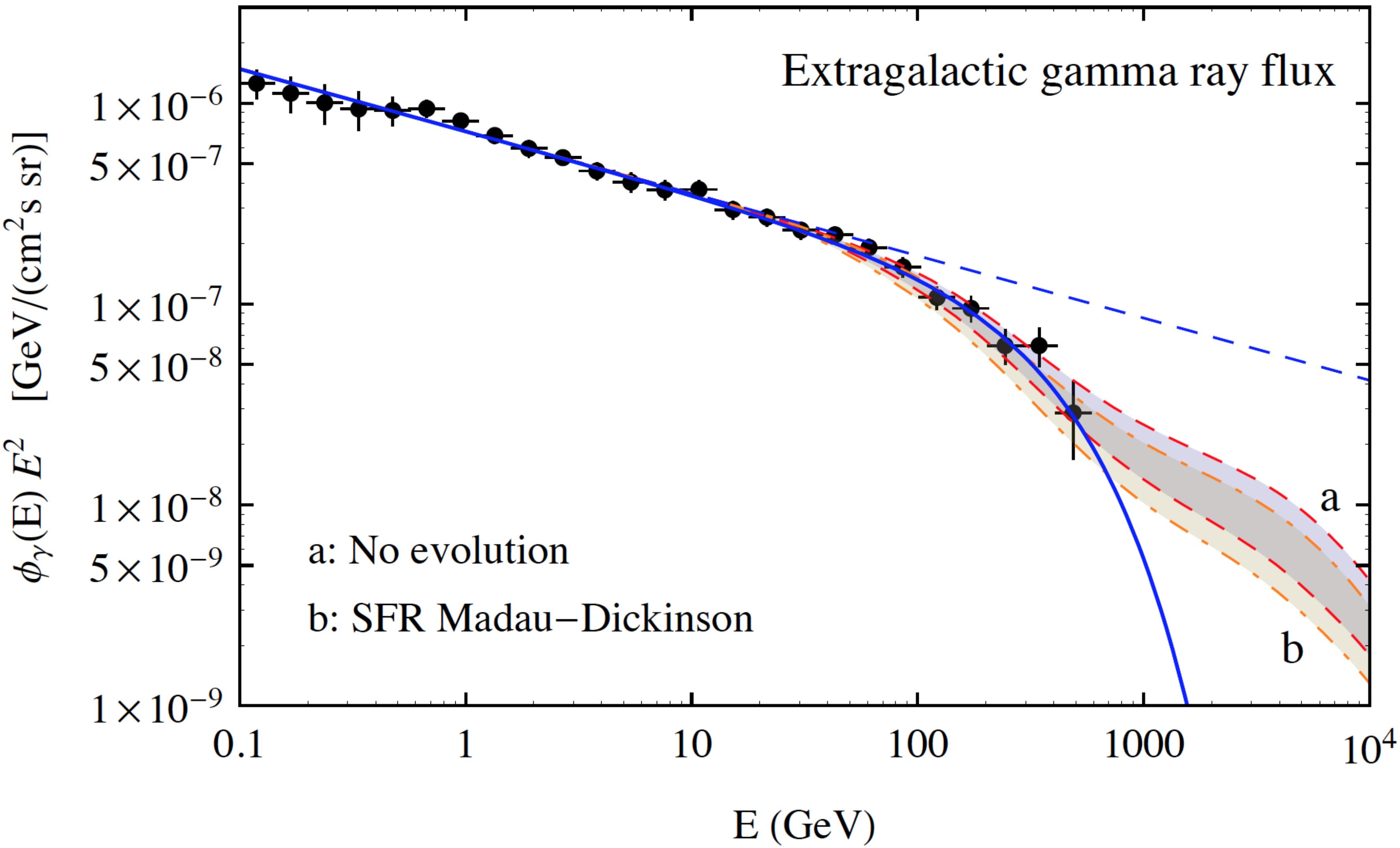
$$\simeq 1.70 \times 10^{-25}\ {\rm cm}^2$$

Gamma Ray absorption
(intergalactic space)

Astronomy E>100 TeV :
Galactic Astronomy



Extragalactic Gamma Ray flux



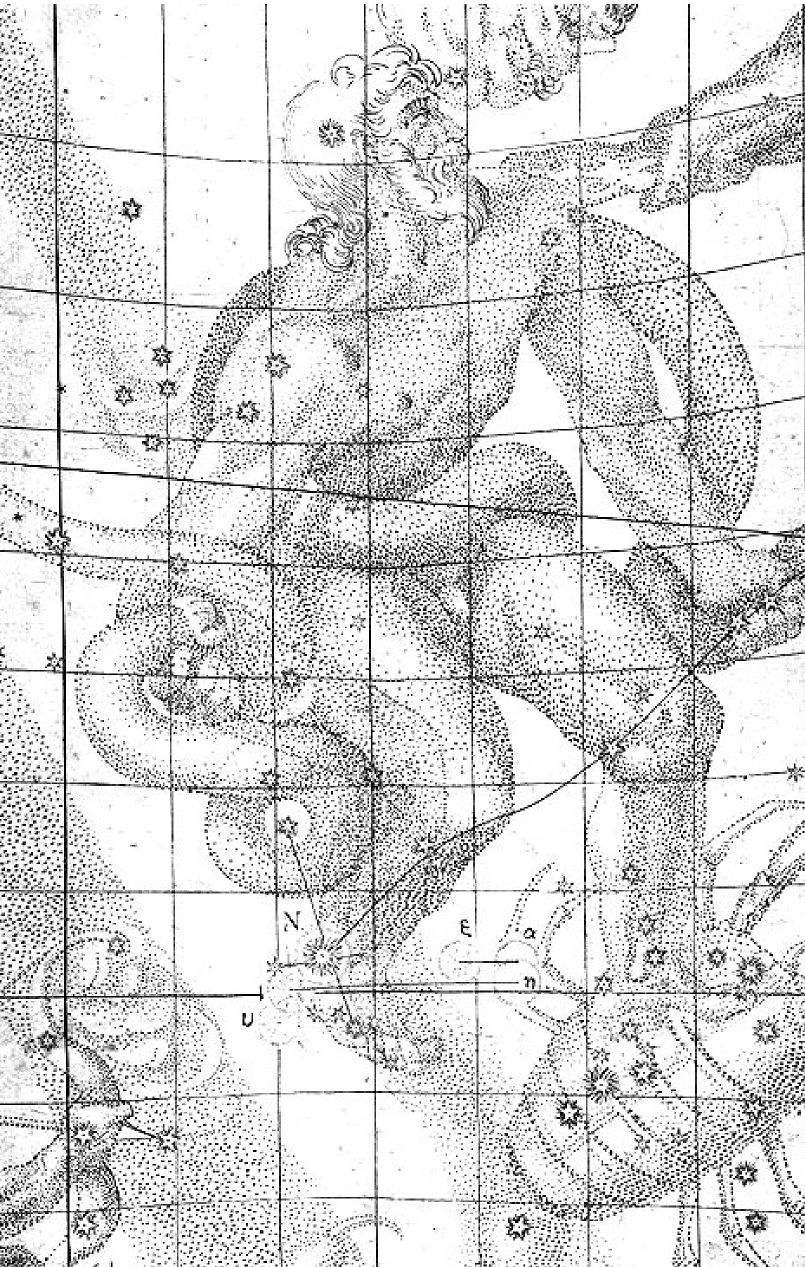
The Gamma Ray Sources:

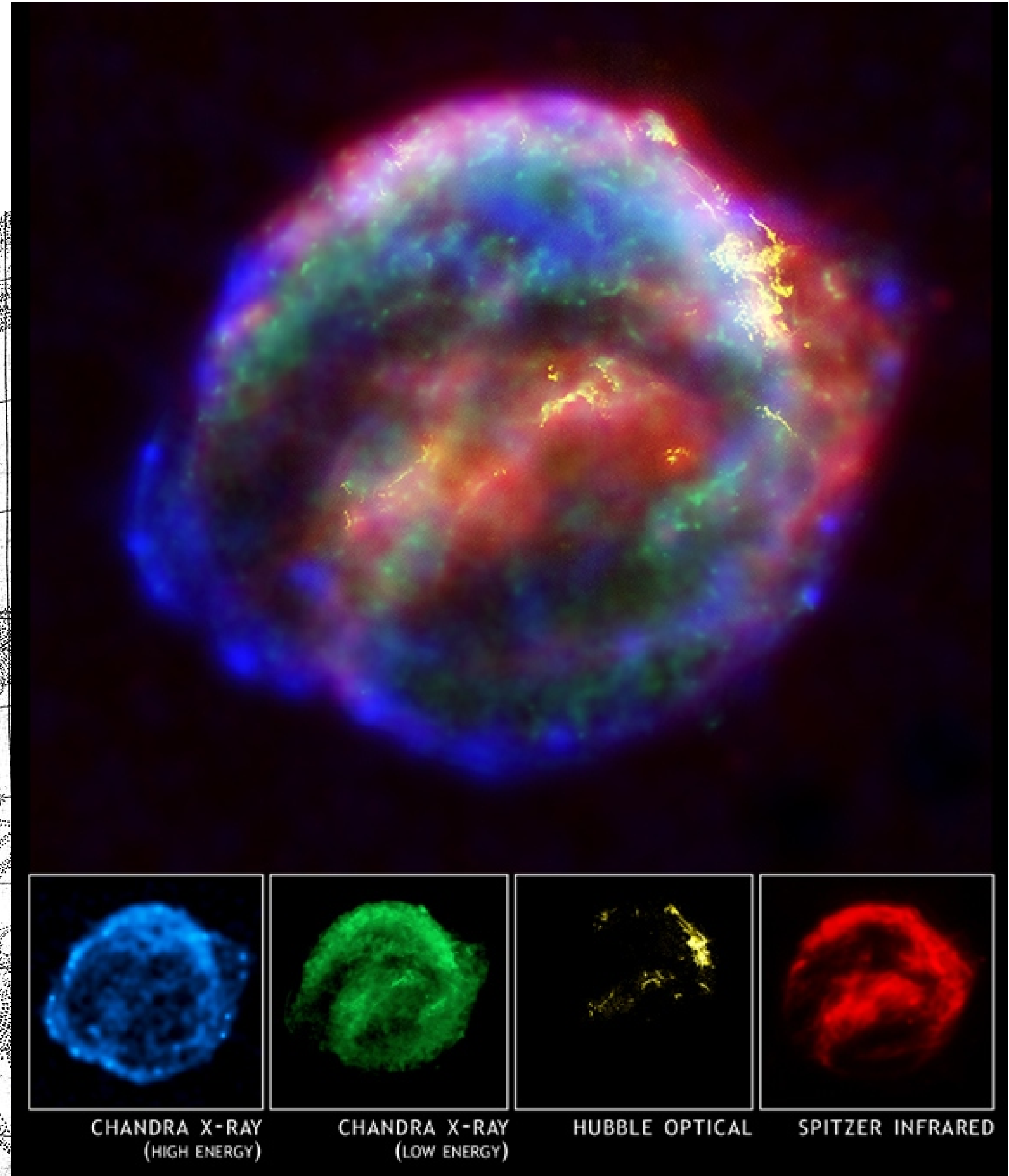
SNR
Pulsars
MicroQuasars
....

AGN
GRB's
.....

Wonderful Beasts in the Sky

Johannes Kepler,
De Stella Nova in Pede Serpentarii (1606)



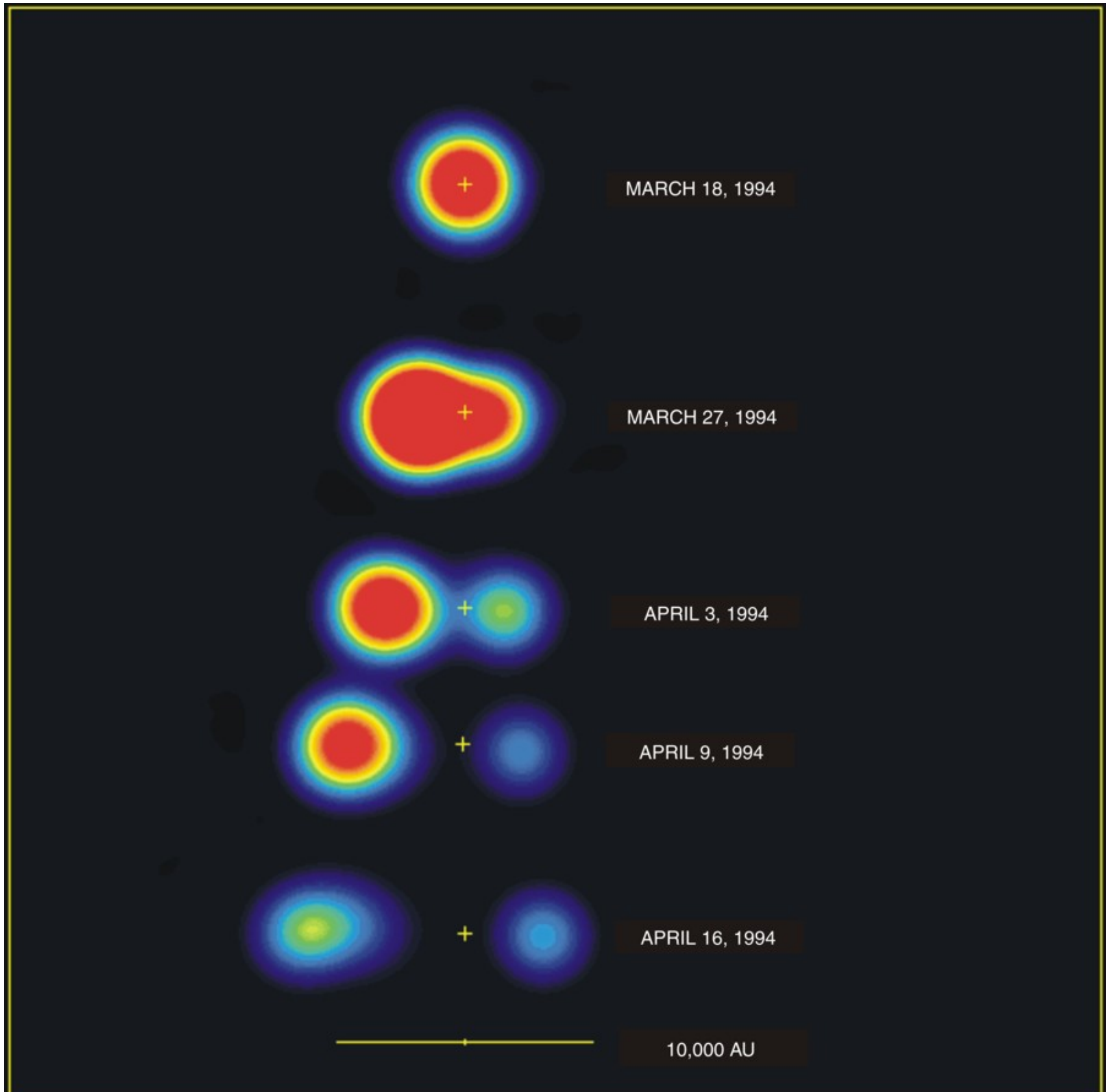


The CRAB Nebula

1 minute = 0.58 pc
= $1.8 * 10^{18}$ cm

Superluminal Motions in microQuasars in our Galaxy

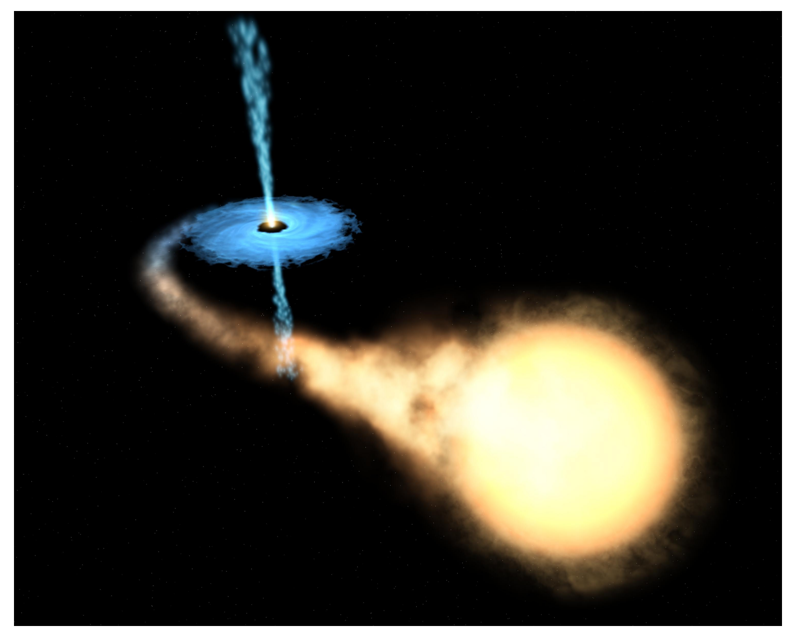
GRS1915+105



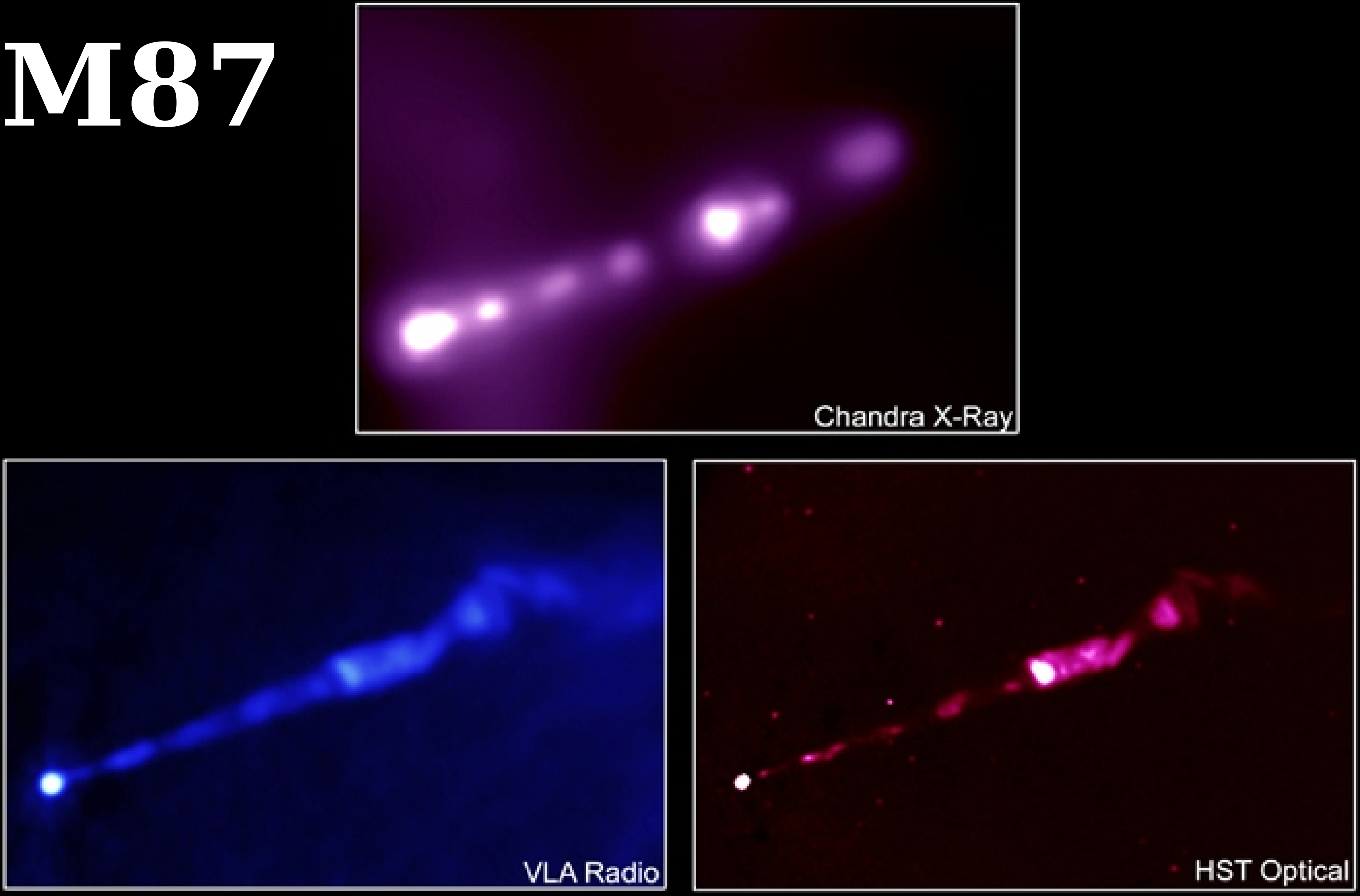
Observations in radio

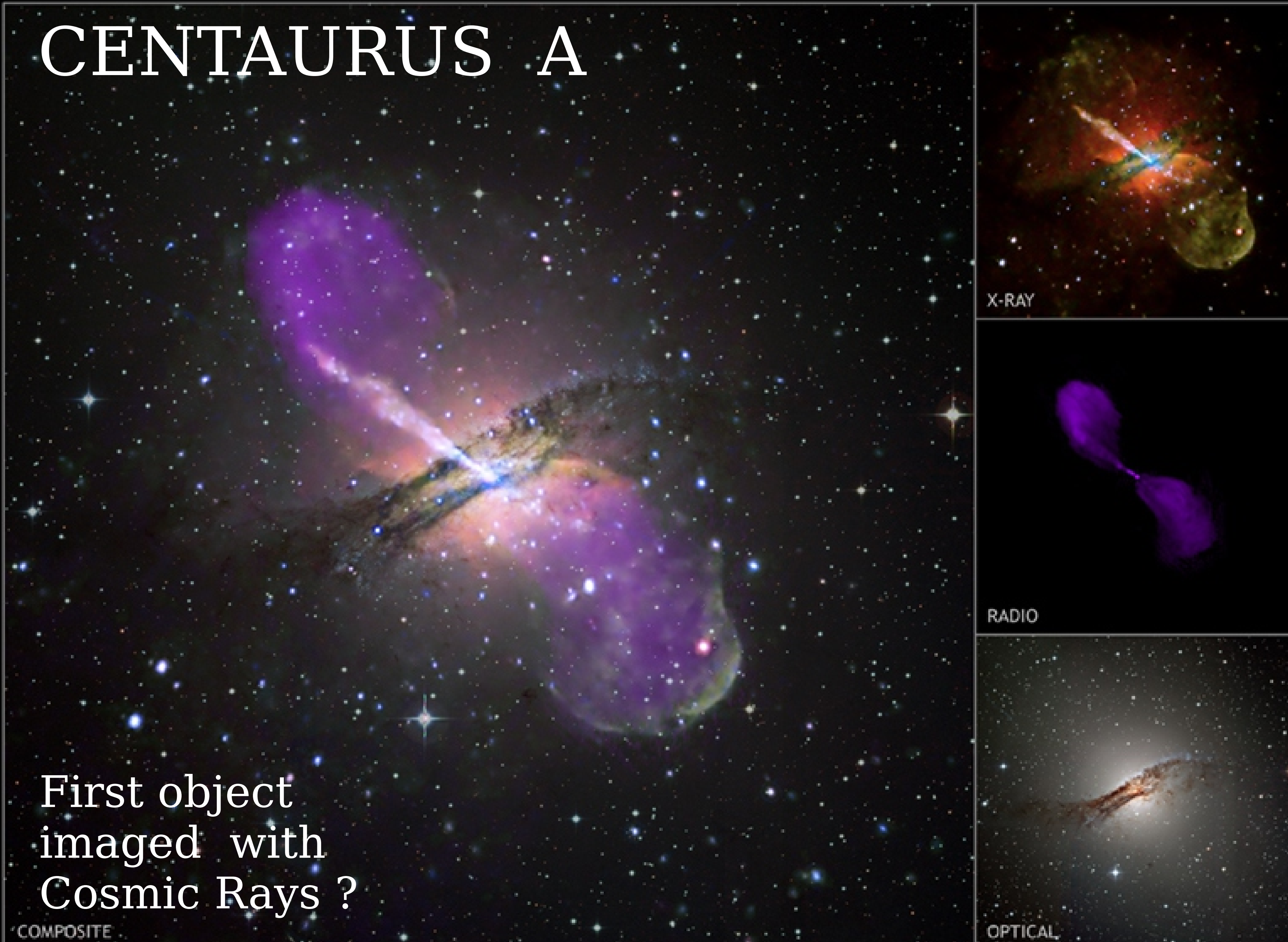
$$\lambda = 3.5 \text{ cm}$$

“Two pairs of bright radio condensations”

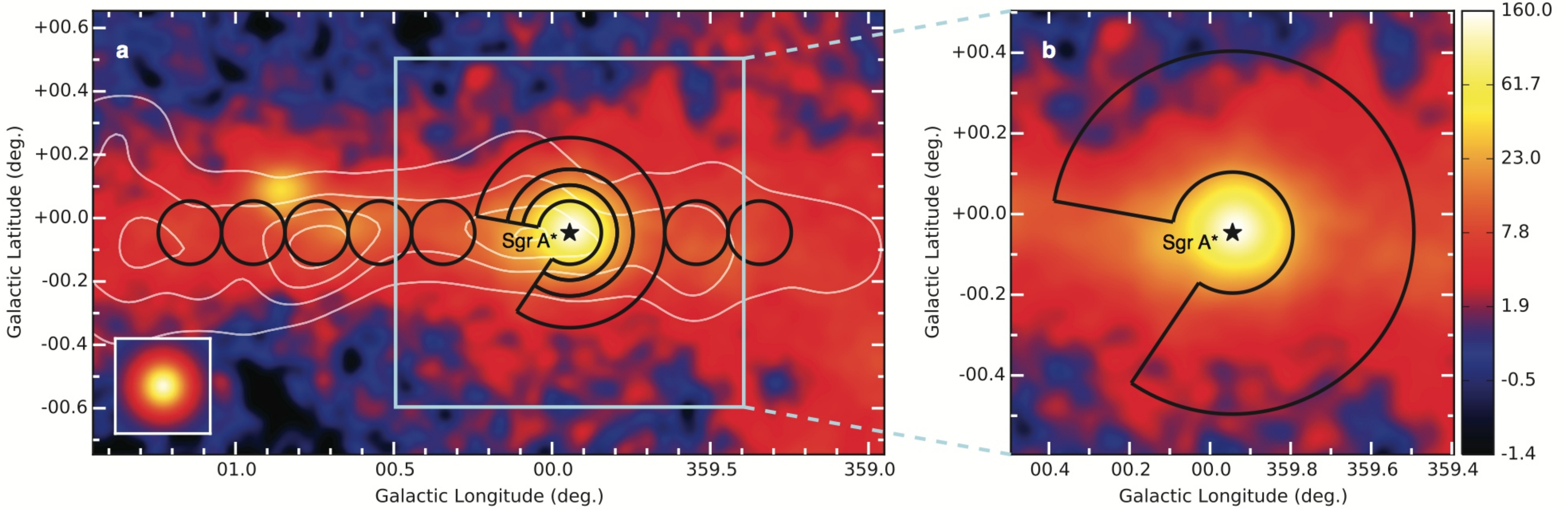


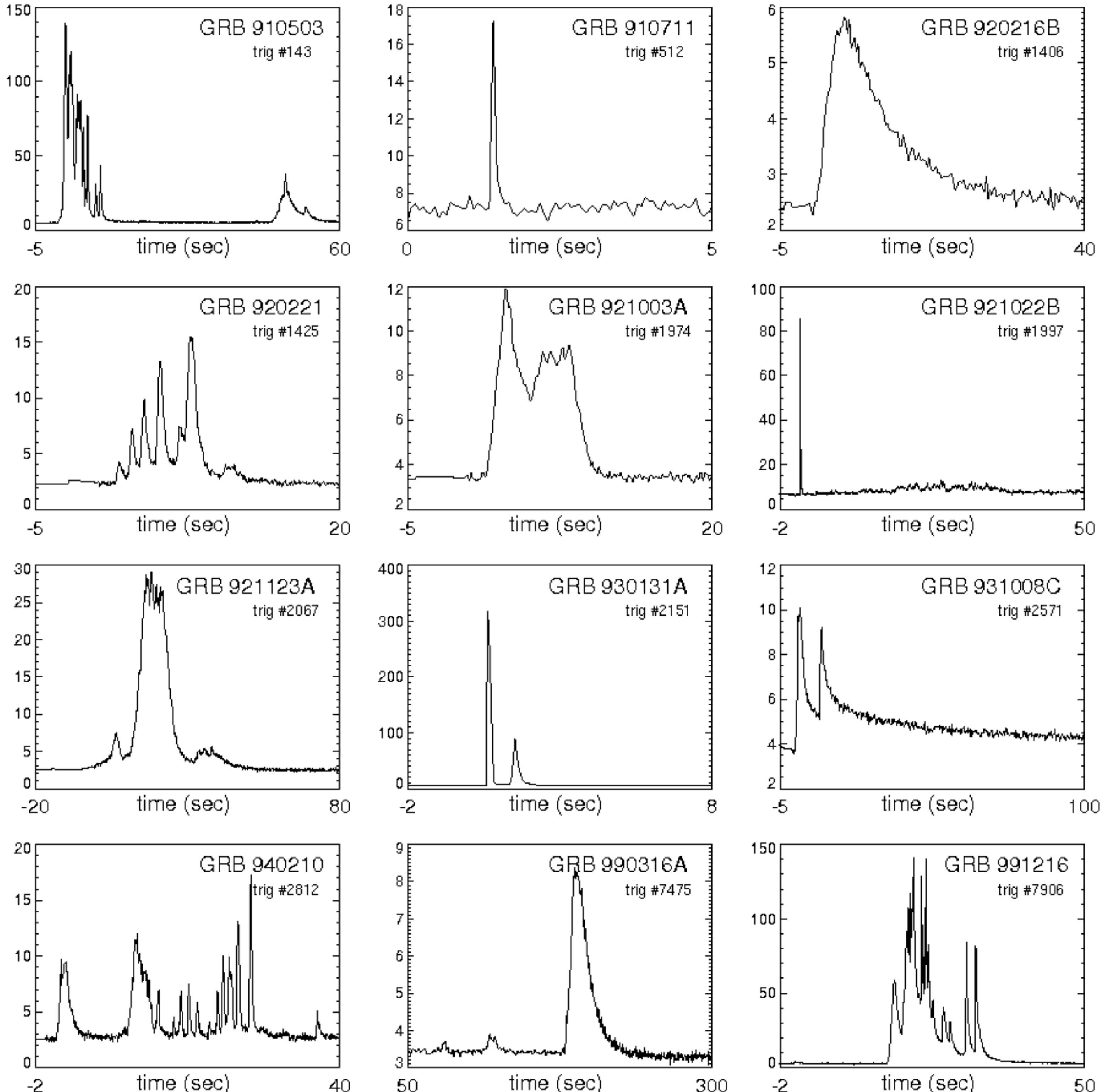
M87

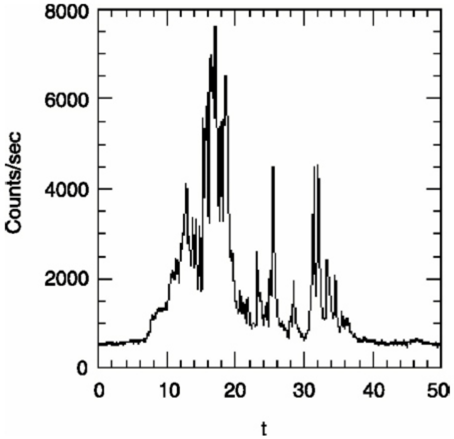



CENTAURUS A
First object imaged with Cosmic Rays ?
COMPOSITE
X-RAY
RADIO
OPTICAL

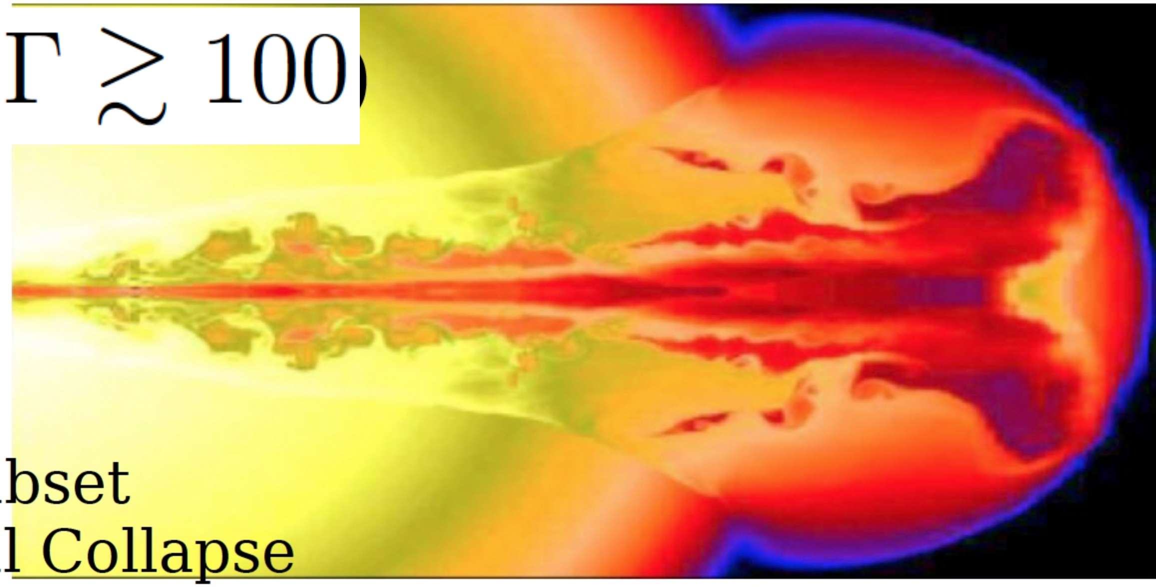
The Galactic Center
(extends to 1 PeV)



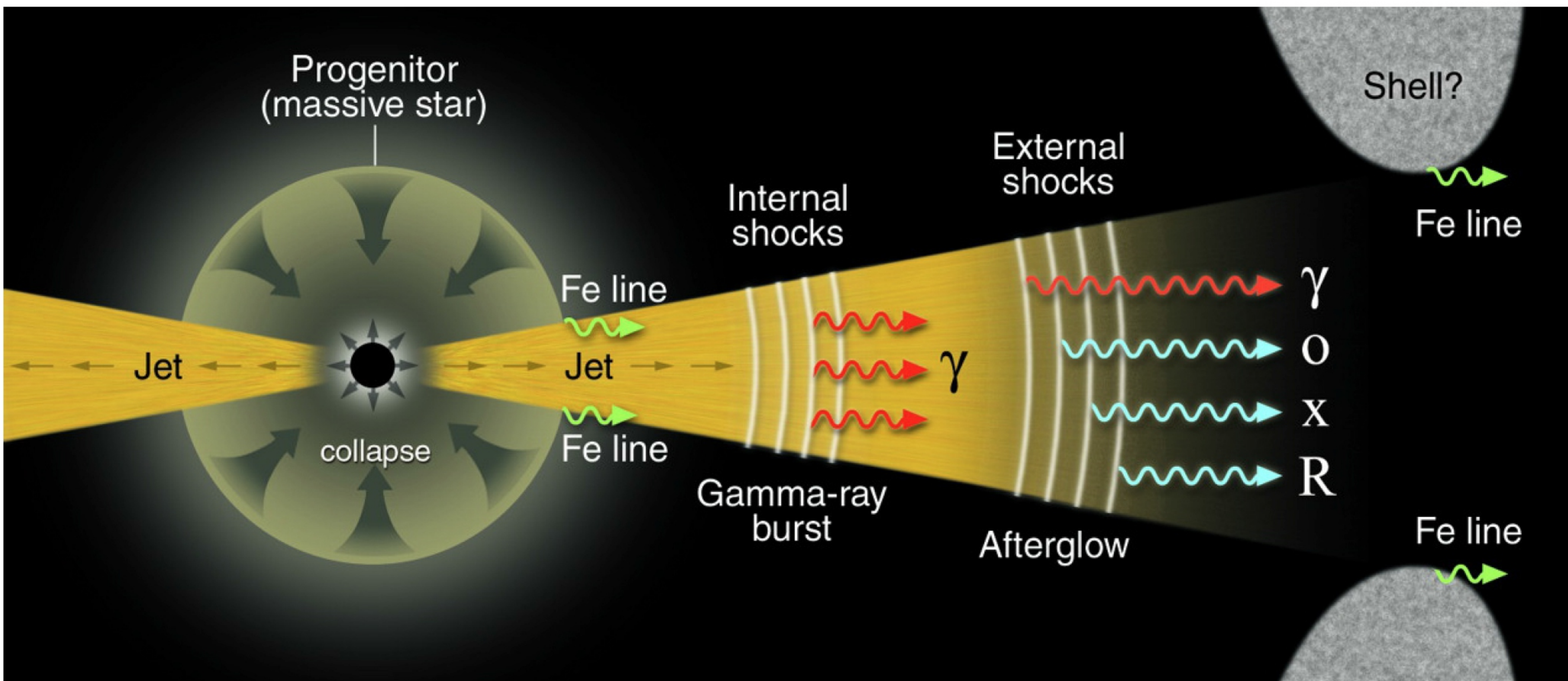

GRB 910503
trig #143
GRB 910711
trig #512
GRB 920216B
trig #1406
GRB 920221
trig #1425
GRB 921003A
trig #1974
GRB 921022B
trig #1997
GRB 921123A
trig #2067
GRB 930131A
trig #2151
GRB 931008C
trig #2571
GRB 940210
trig #2812
GRB 990316A
trig #7475
GRB 991216
trig #7906
time (sec)

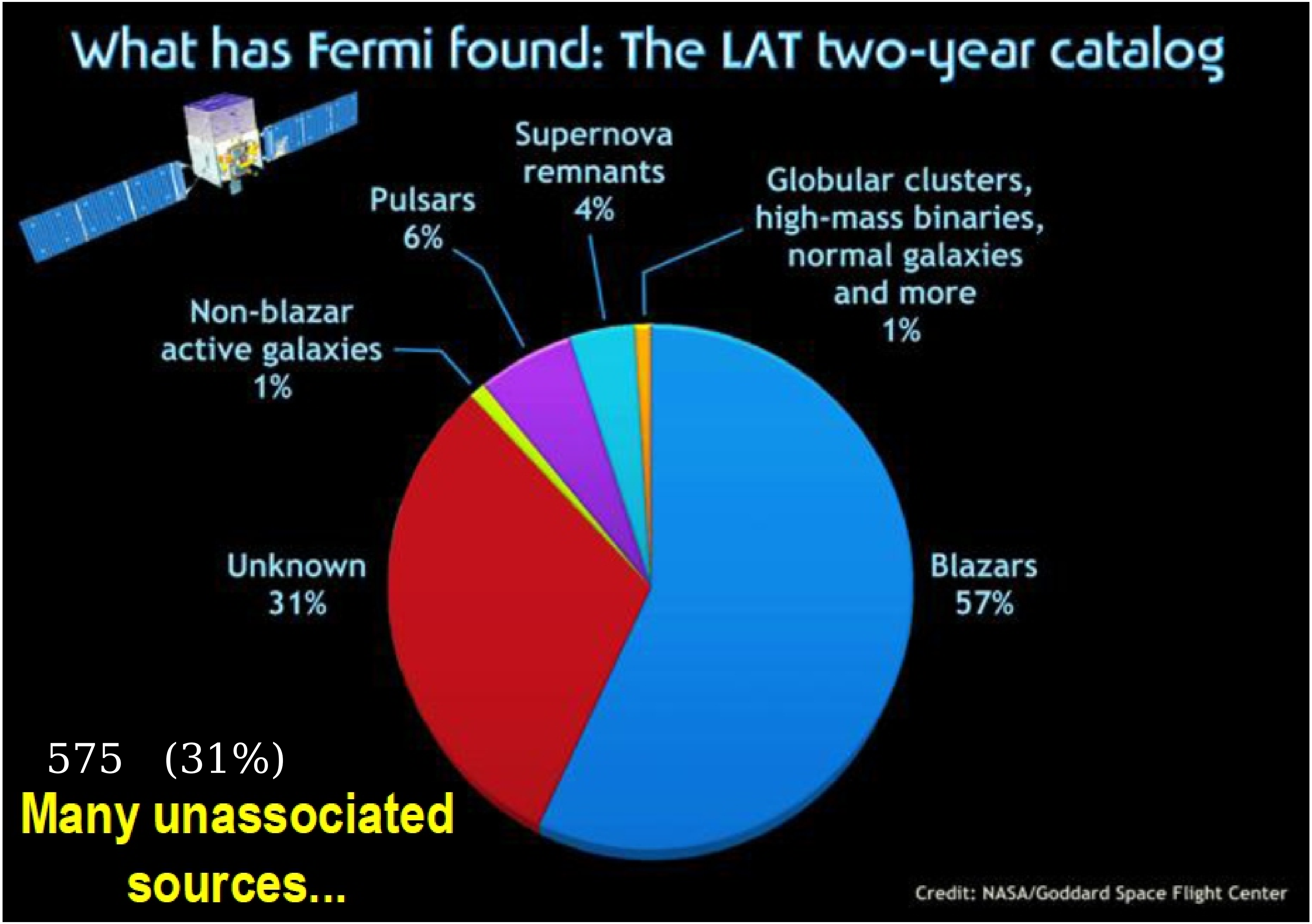


$\Gamma \gtrsim 100$

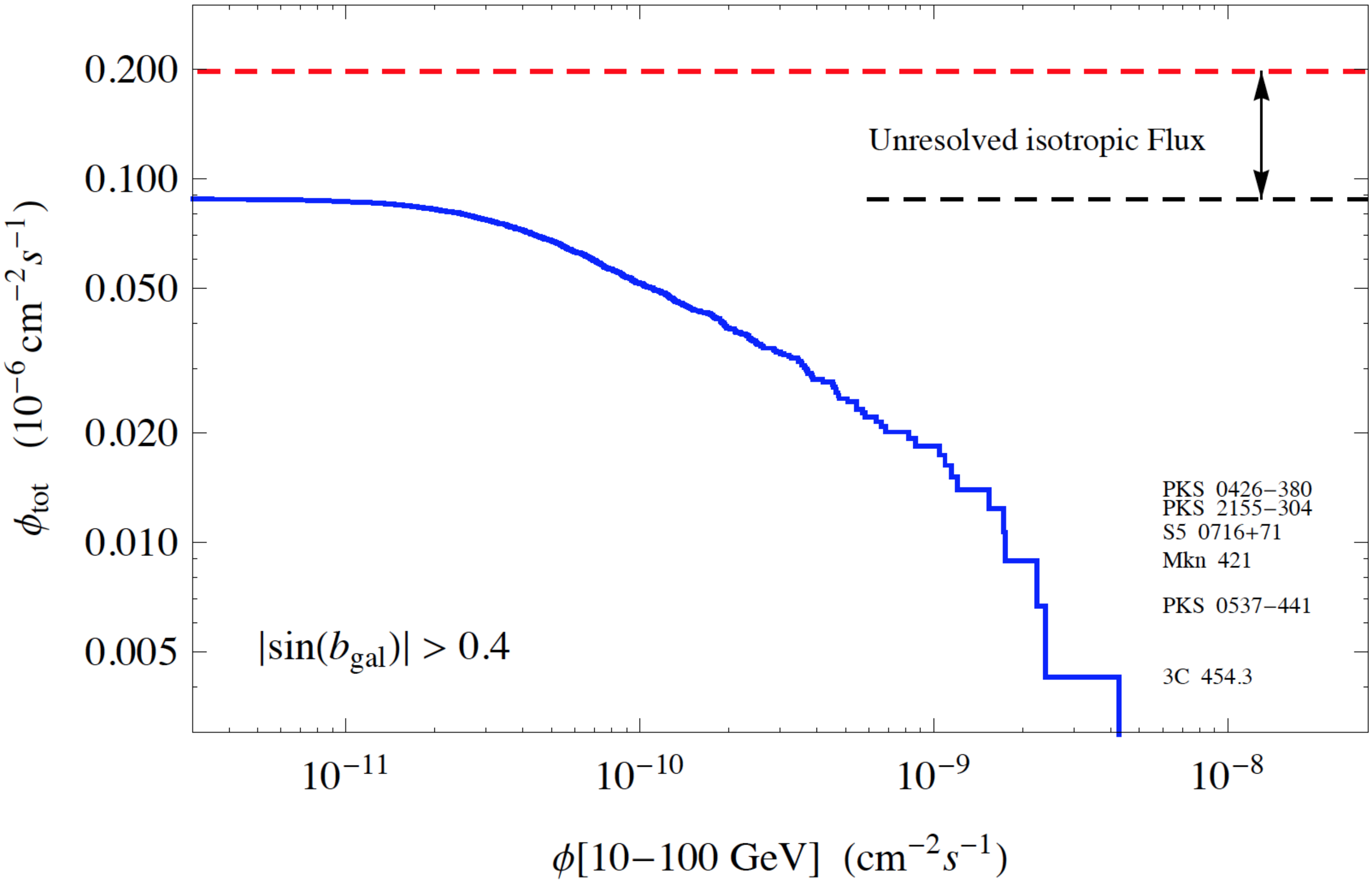


GRB : associated with a subset
of SN Stellar Gravitational Collapse

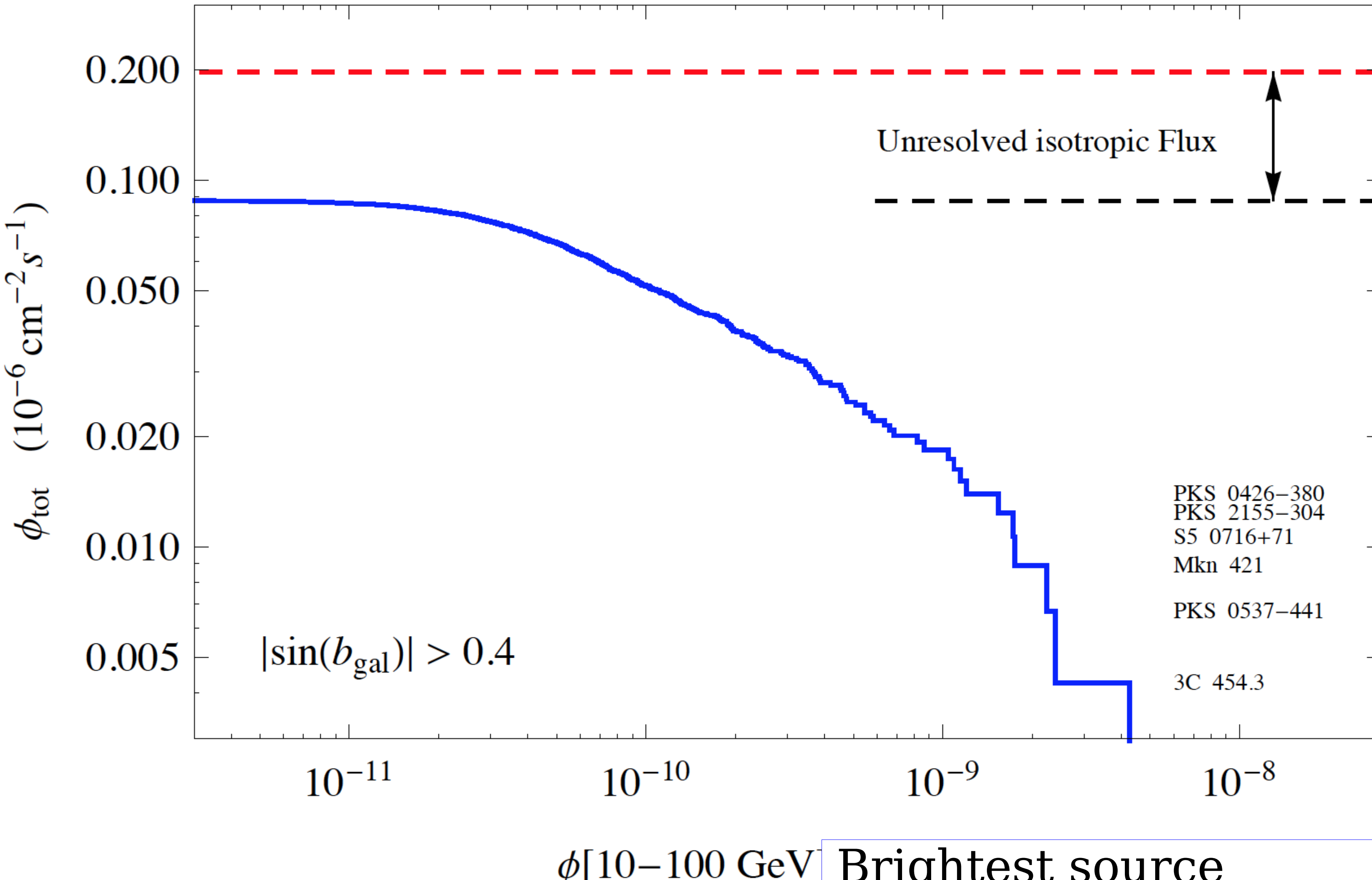



What has Fermi found: The LAT two-year catalog
Supernova remnants 4%
Pulsars 6%
Globular clusters, high-mass binaries, normal galaxies and more 1%
Non-blazar active galaxies 1%
Unknown 31%
Blazars 57%
575 (31%)
Many unassociated sources...
Credit: NASA/Goddard Space Flight Center

Extragalactic Flux : Resolved + unresolved sources



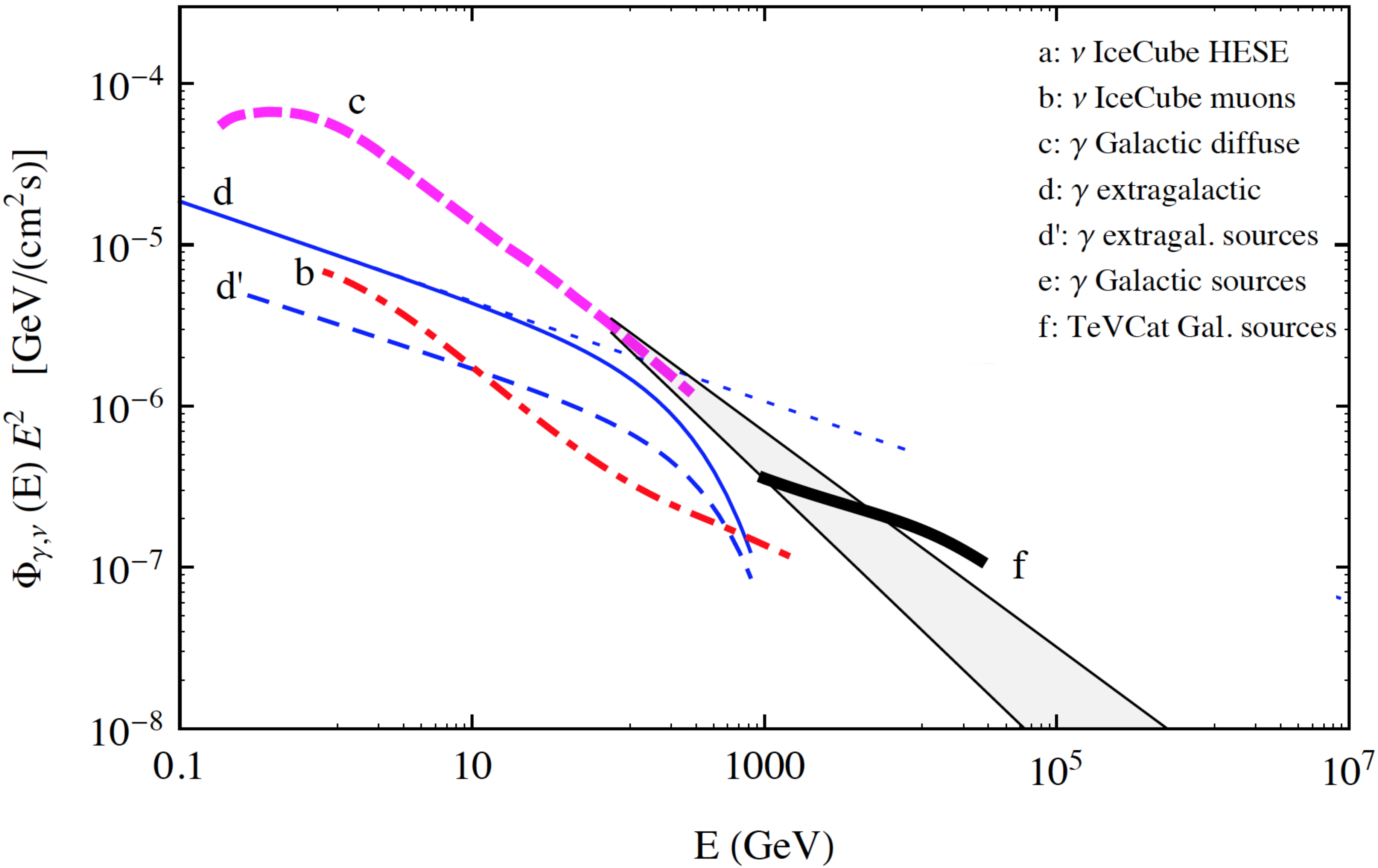
Extragalactic Flux : Resolved + unresolved sources



Extragalactic flux
dominated by “blazars” [AGN]

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

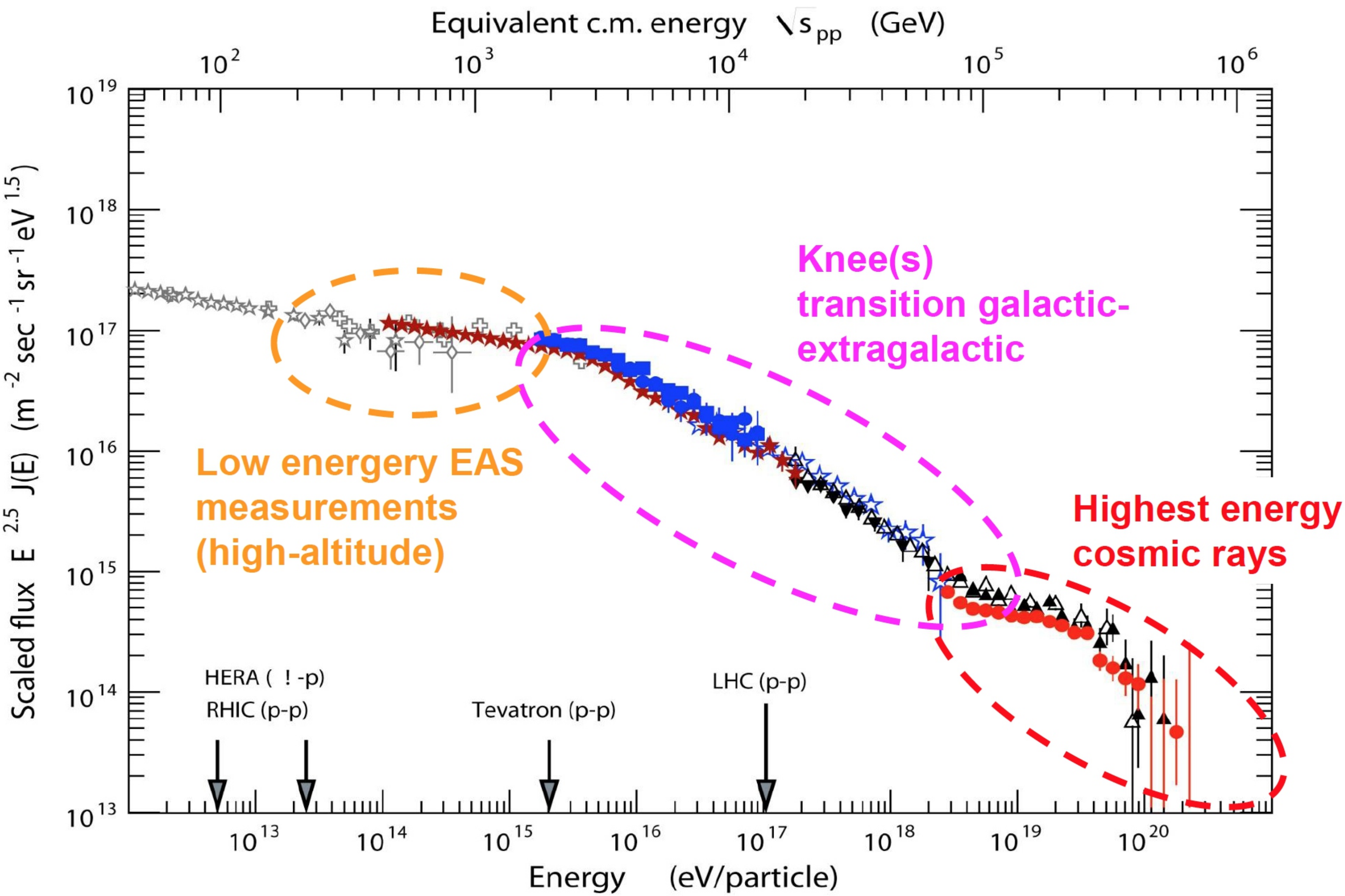
Angle integrated components of the Gamma Ray Sky



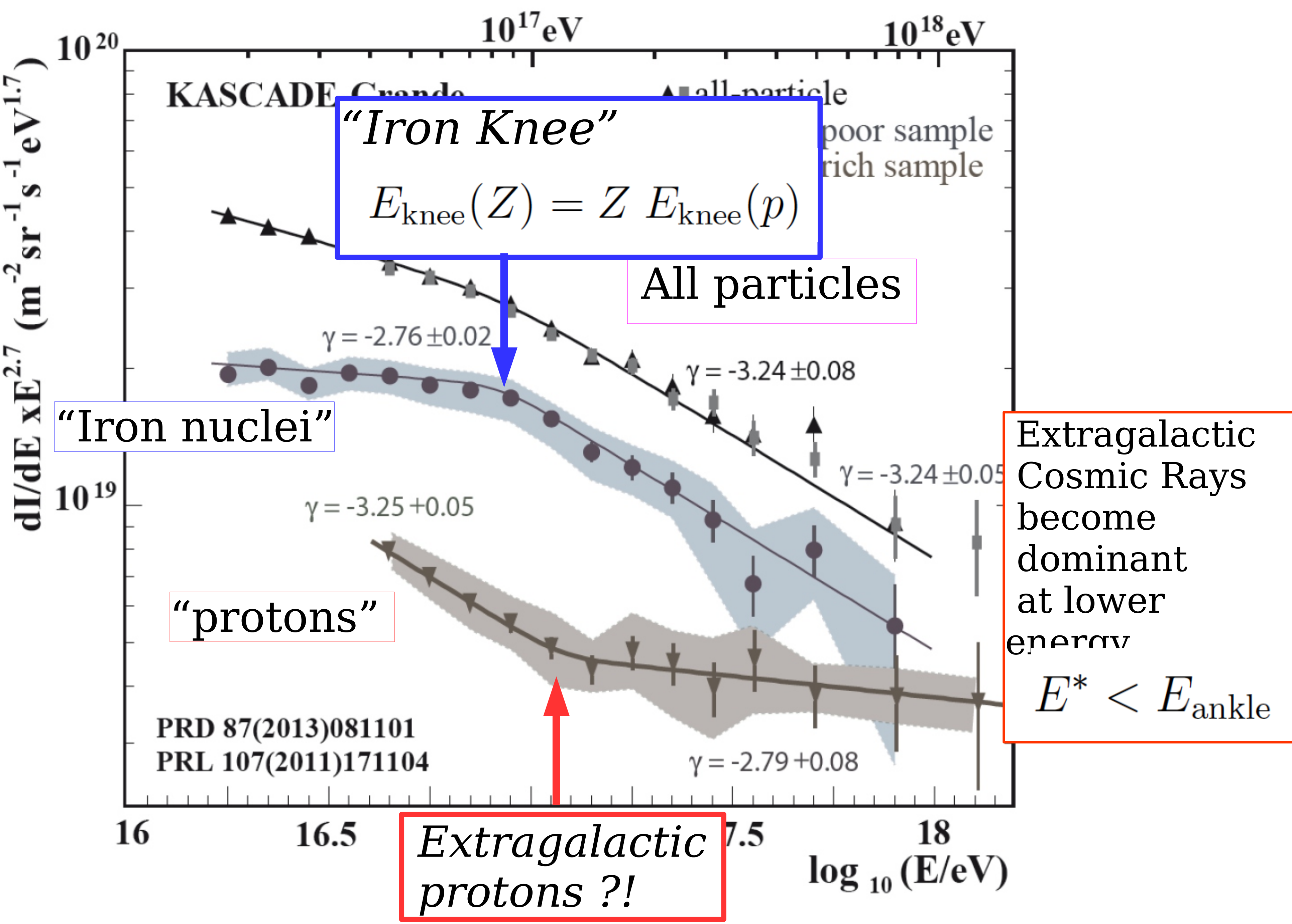
3. Neutrinos and Cosmic Rays

- Galactic and Extragalactic Cosmic Rays
- Cosmic Ray versus Neutrino emission

High-energy cosmic ray spectrum



Kascade-Grande results

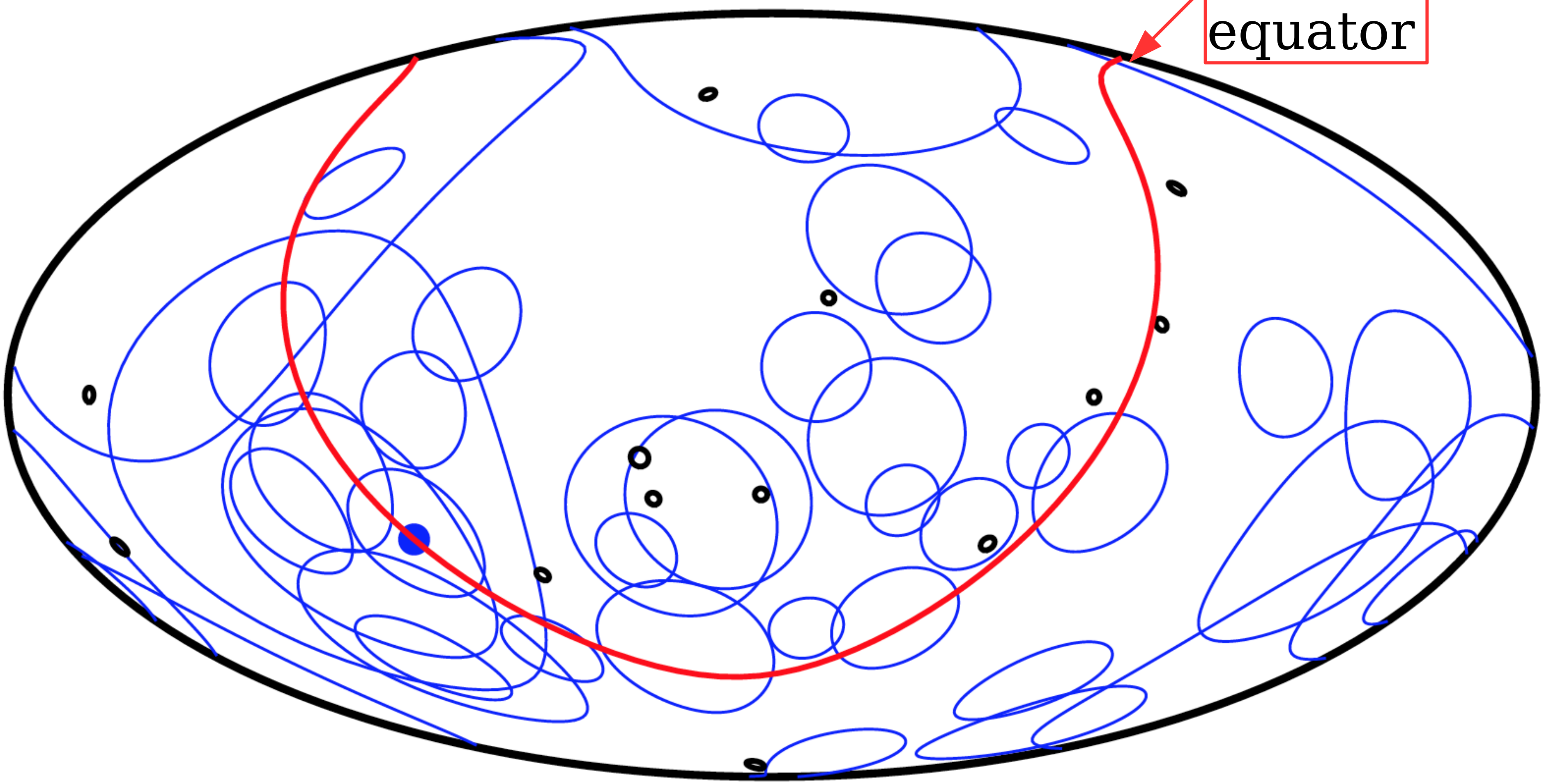


4. The IceCube Signal

- Atmospheric Foreground
  - "Conventional flux" ($\pi^{\pm}$, K decay)
  - "Prompt flux" (charm decay)
- Galactic versus Extragalactic
- Resolved versus Unresolved sources
- Neutrino Point Sources

High Energy Starting Events

4 years data

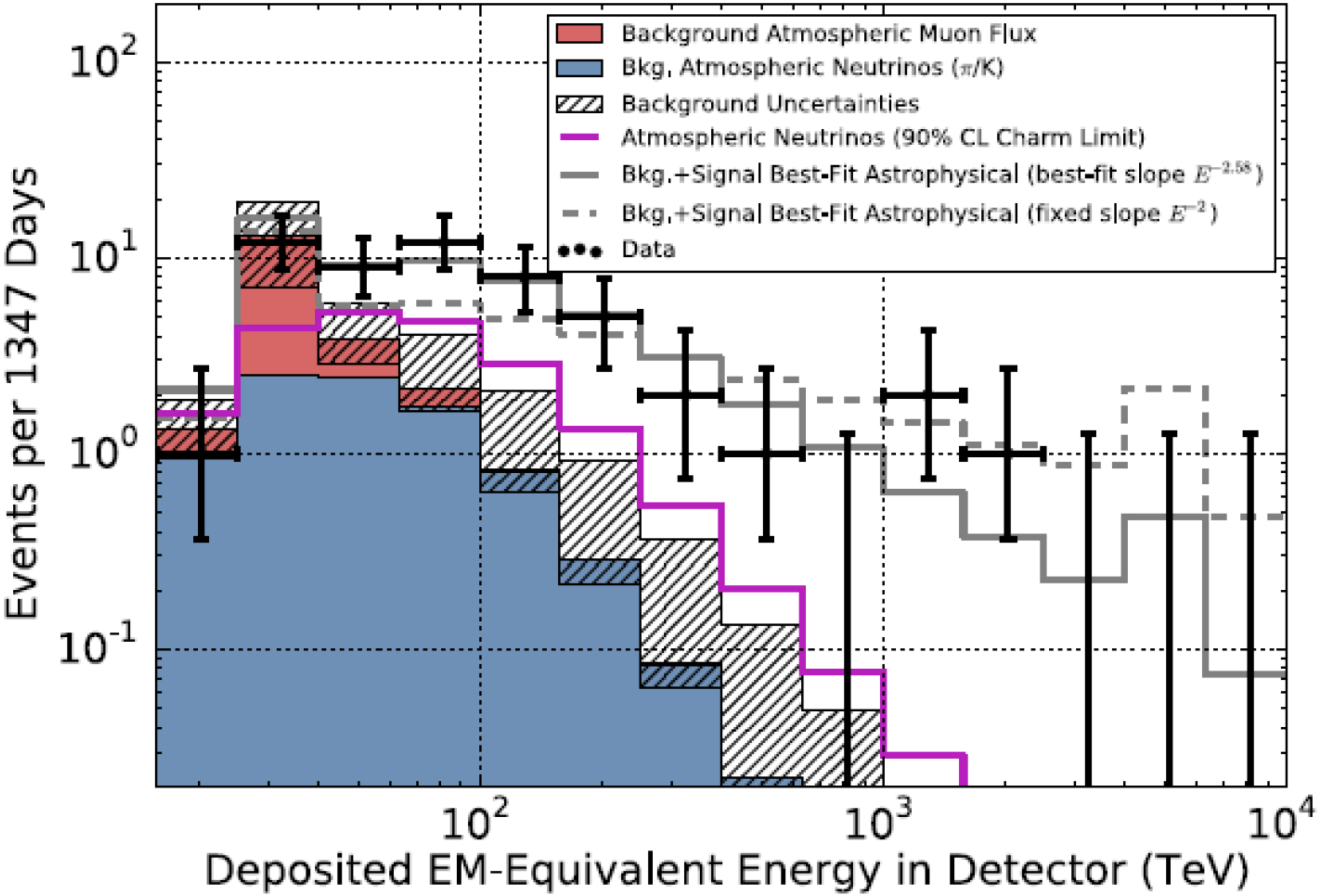


Track [(small) black circles]
Showers [(large) blue circles]

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

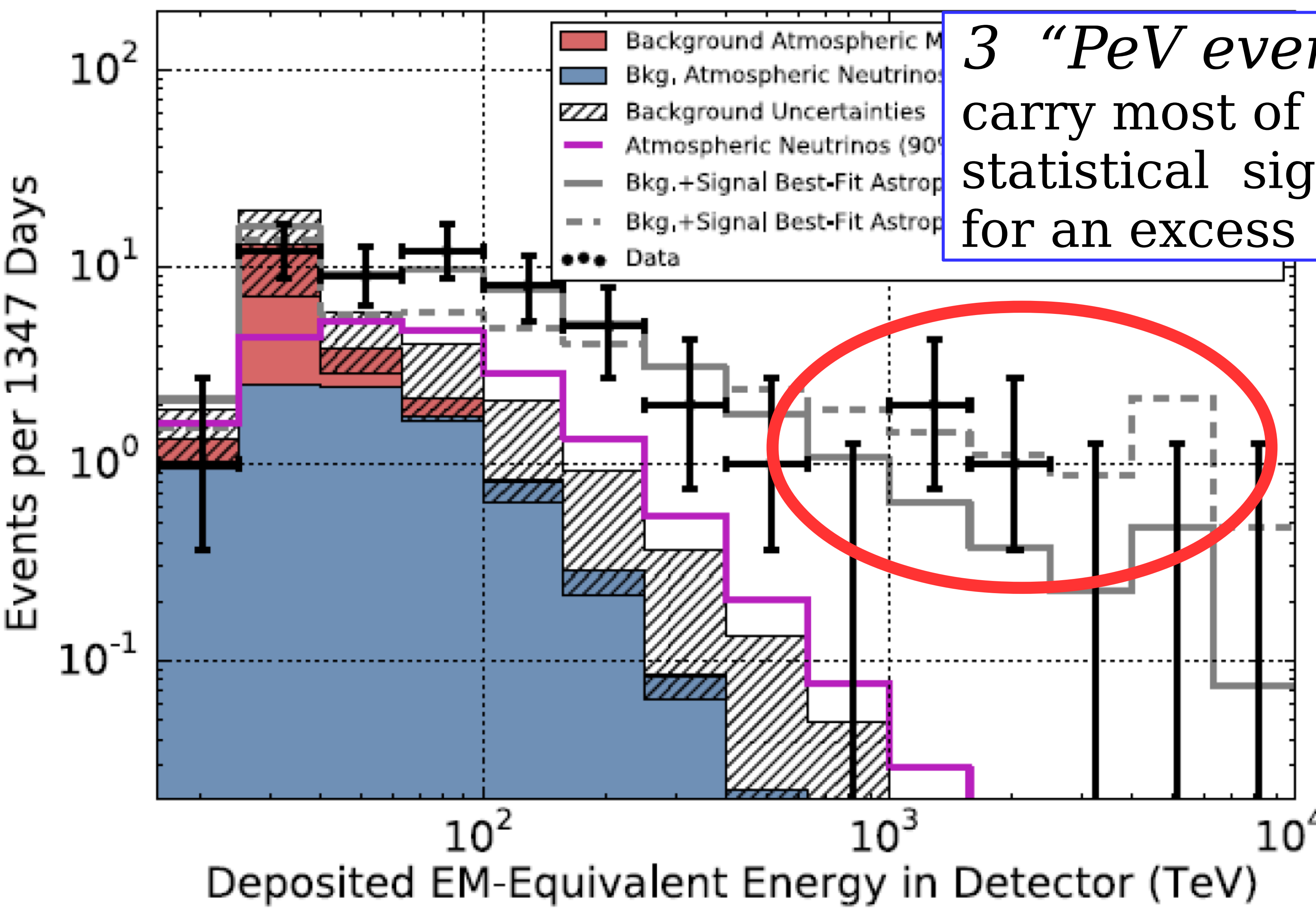
High Energy Starting Events [HESE]

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



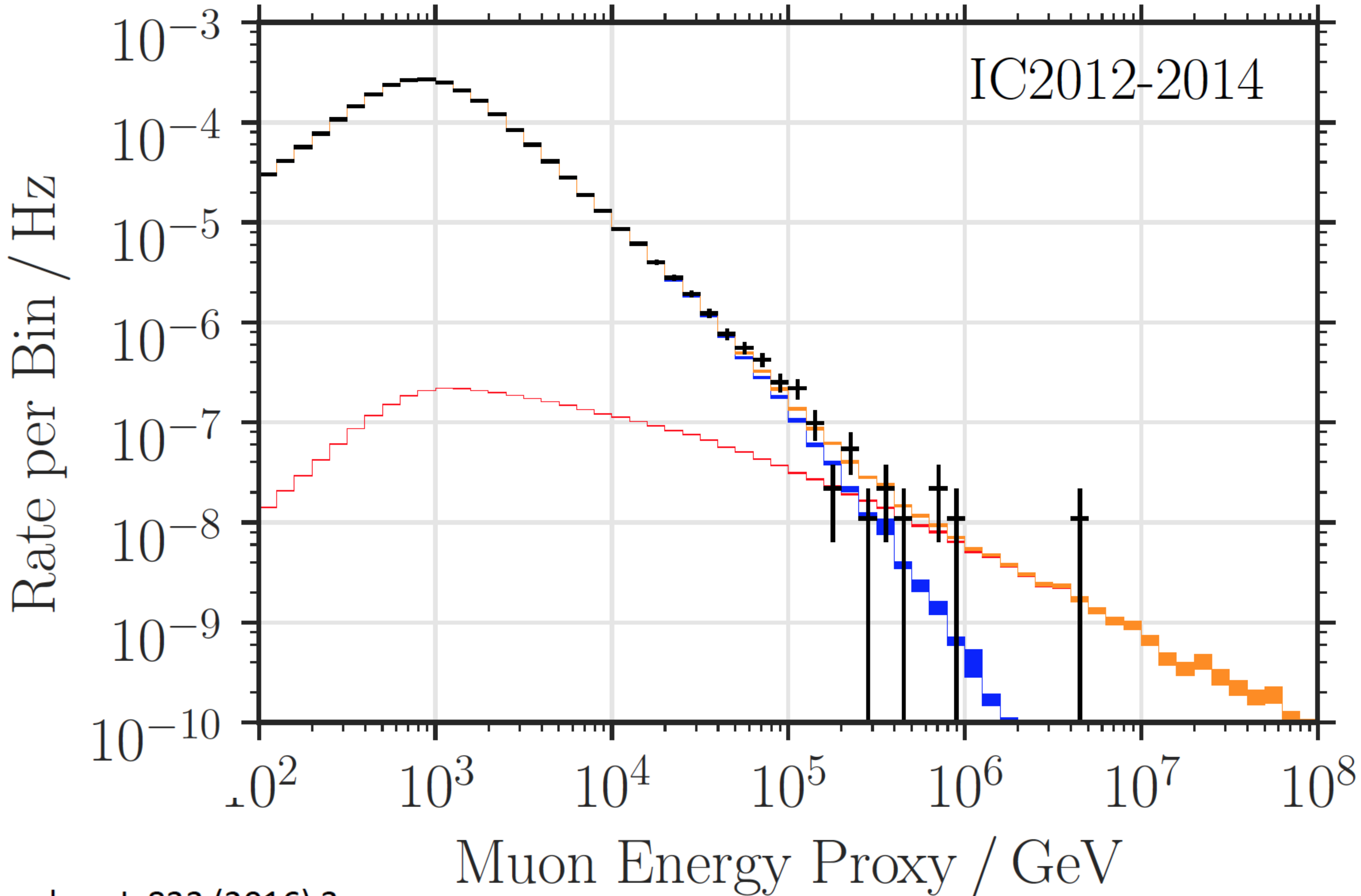
High Energy Starting Events [HESE]

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



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

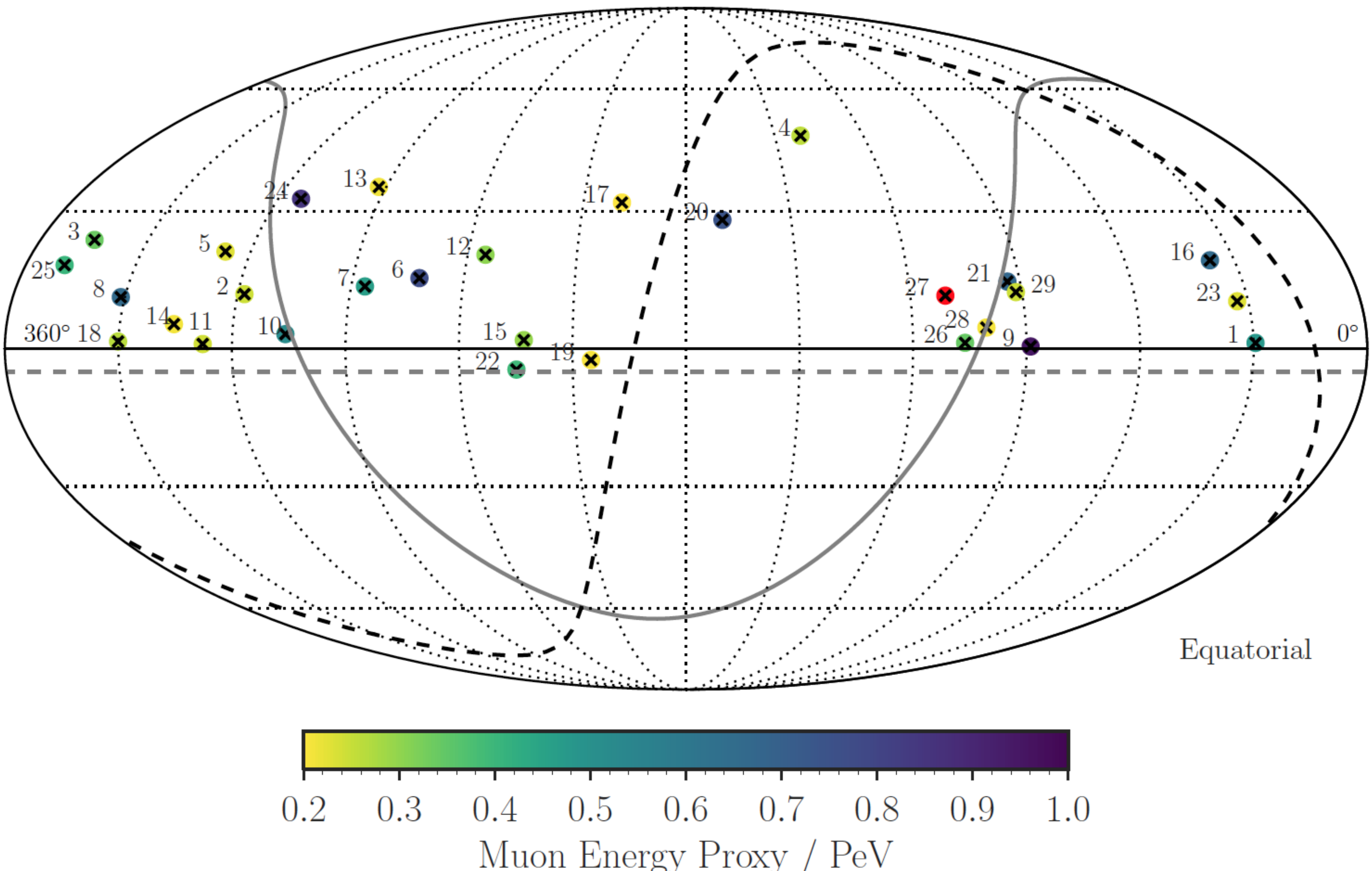
Upgoing (neutrino induced) Muons



Astrophys. J. 833 (2016) 3

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.]

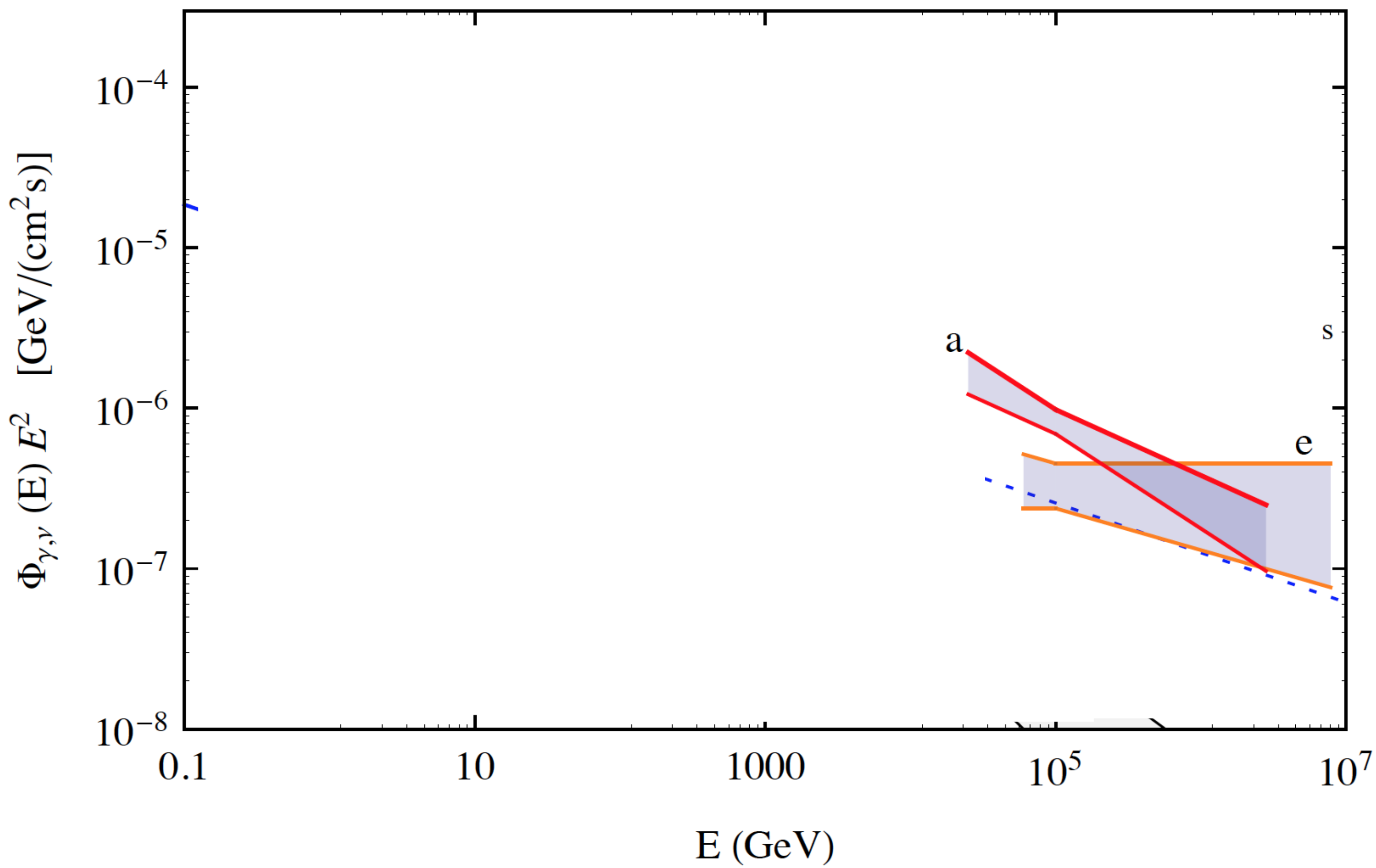
Simple Power Law:

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

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

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

Estimates of the (equal-flavor) astrophysical flux



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

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

Spectra are different ?
Possible "solutions" :

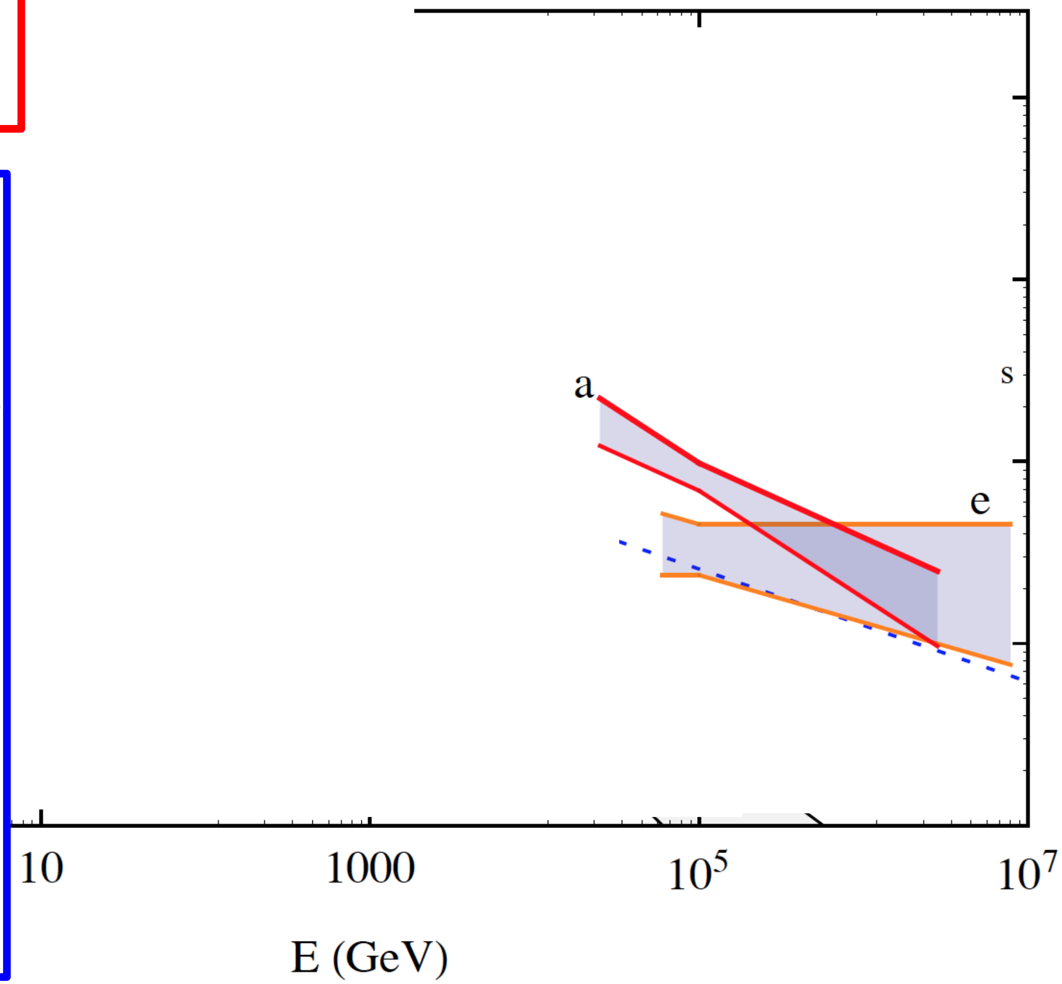
Systematic Effect ?

Break in the Spectrum

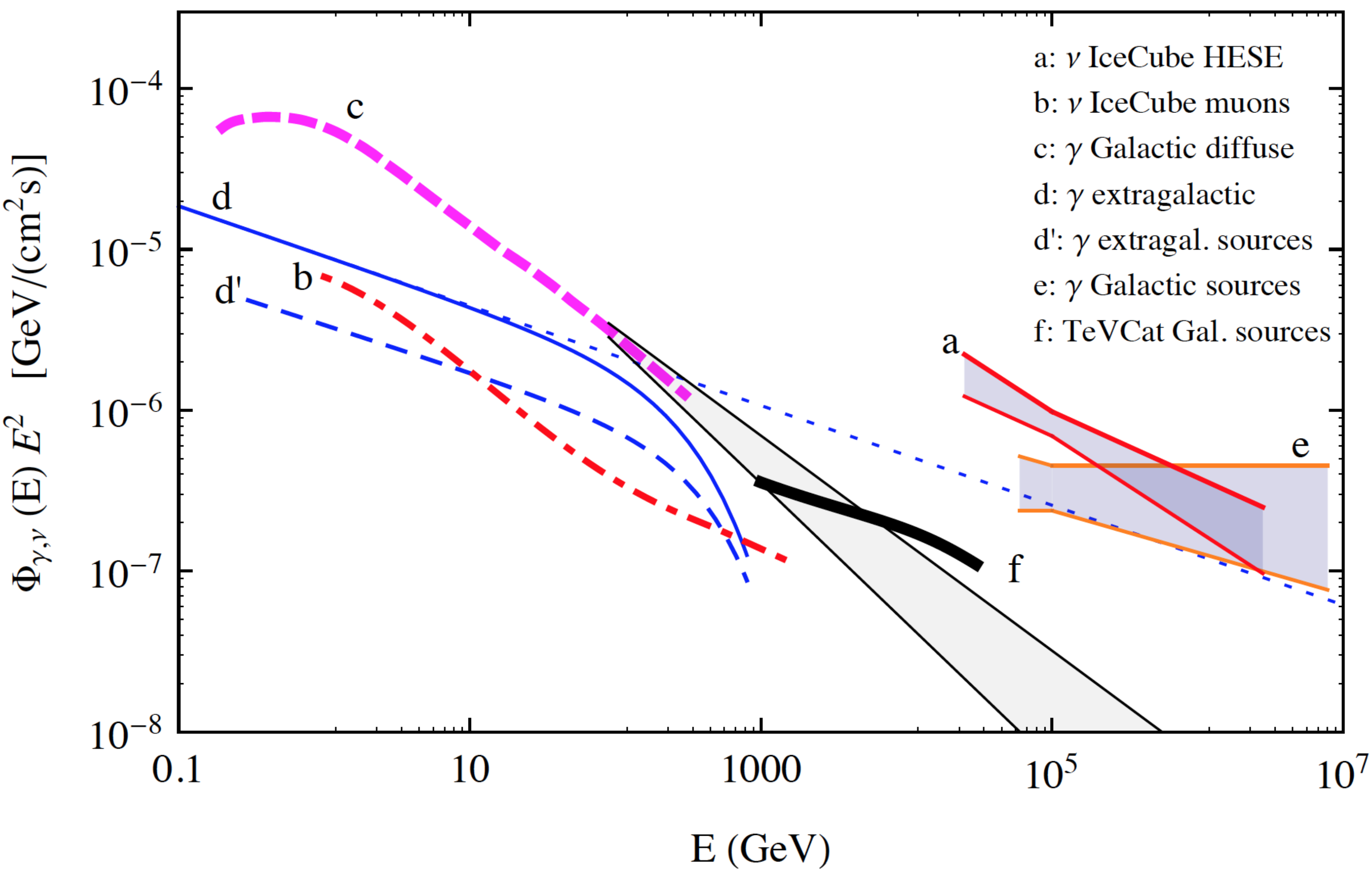
Two components
in the spectrum

Anisotropy ?

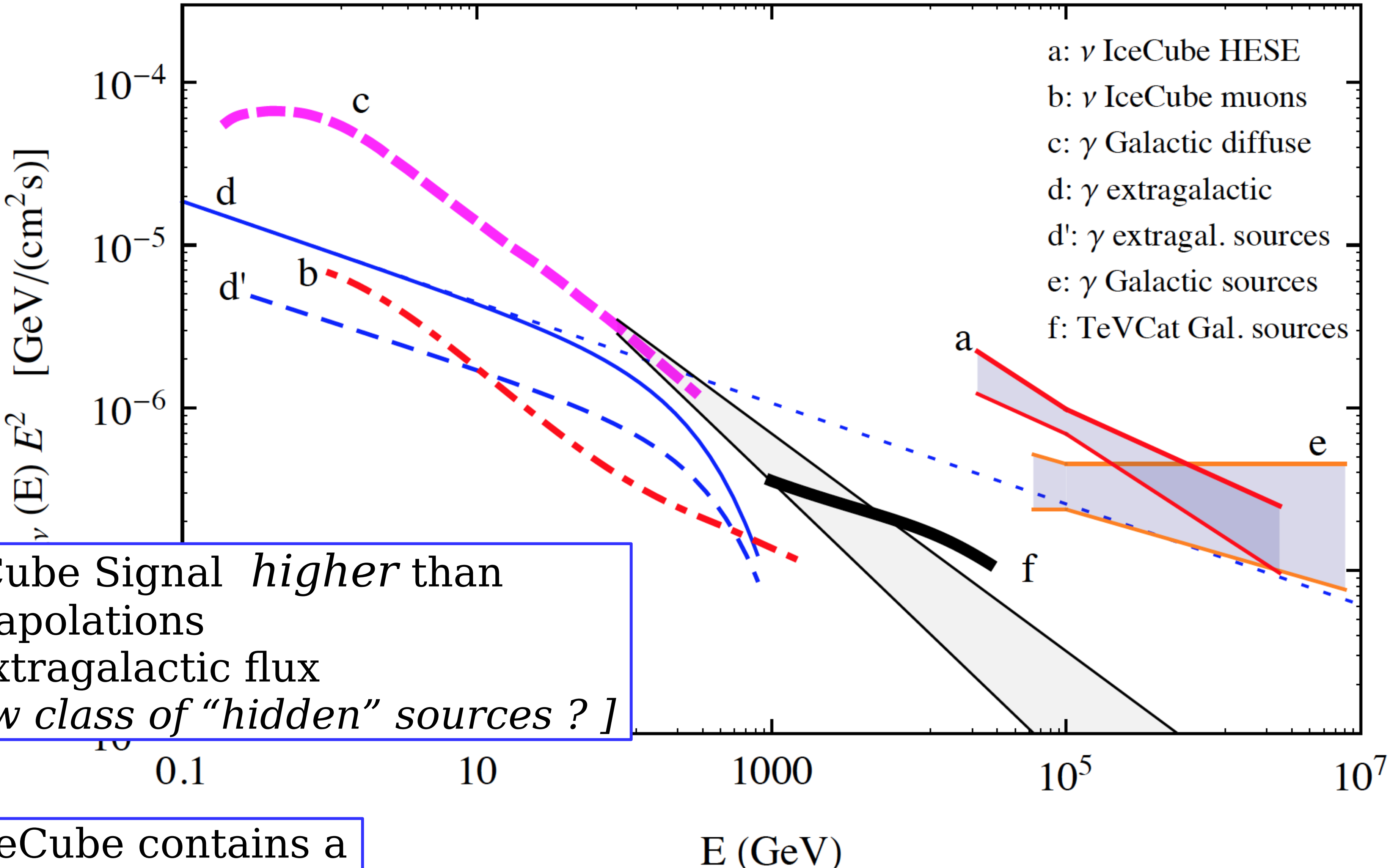
[Galactic + extragalactic components]



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 ?

(Testable) Assumptions:

1. Equal flavor

2. Isotropy (extragalactic flux)

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

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

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

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

Space averaged
flavor transition probability

Neutrinos created in volume
of sufficiently large linear size

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

Oscillating terms average to zero

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

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

$$\theta_{13} \simeq 0$$

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

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

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

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

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

"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

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

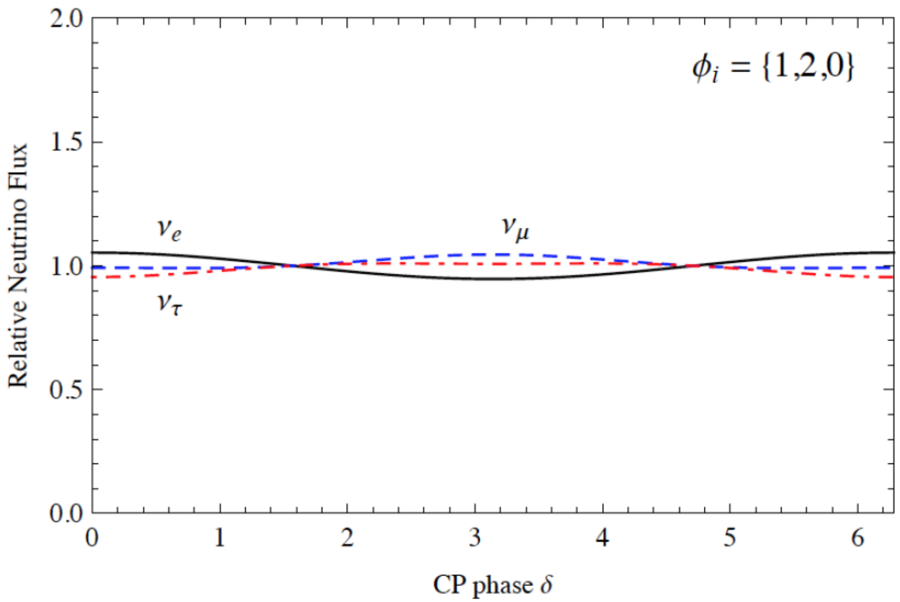
"Neutron decay"

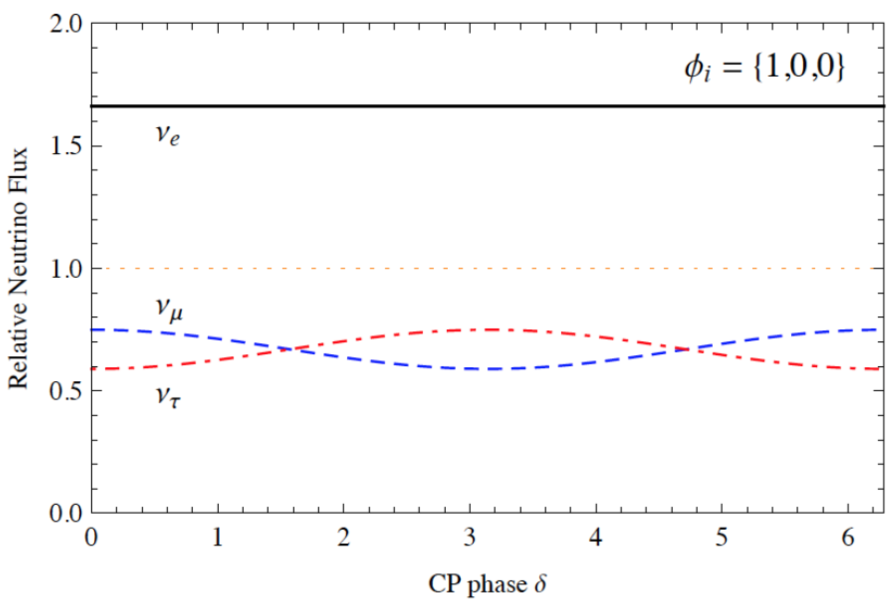
Nuclear fragmentation

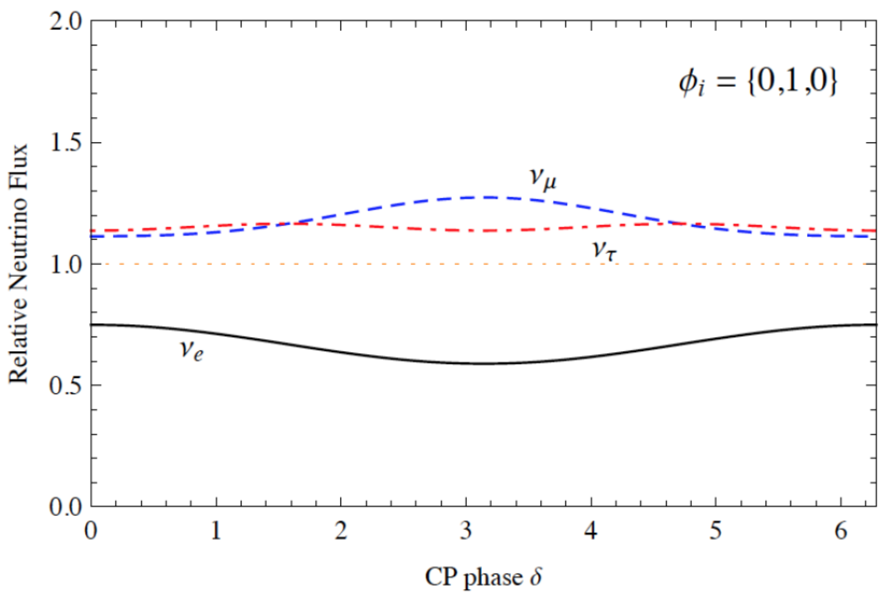
$$\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \Longrightarrow \begin{pmatrix} 1-2\,v \\ v \\ v \end{pmatrix} \approx \begin{pmatrix} 0.6 \\ 0.2 \\ 0.2 \end{pmatrix}$$

Include
best fit of oscillation
parameters
(delta dependence)

Significant presence of
tau-neutrinos







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.

Questions:

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 ?

$$
\begin{aligned}
\phi_{\nu_\alpha}(E,\Omega) = {} & \phi_{\nu_\alpha}^{\text{atm. standard}}(E,\Omega) \\
& + \phi_{\nu_\alpha}^{\text{atm. charm}}(E,\Omega) \\
& + \phi_{\nu_\alpha}^{\text{astro. extragalactic}}(E,\Omega) \\
& + \phi_{\nu_\alpha}^{\text{astro. Galactic}}(E,\Omega)
\end{aligned}
$$

Each component
of the neutrino flux
has characteristics:

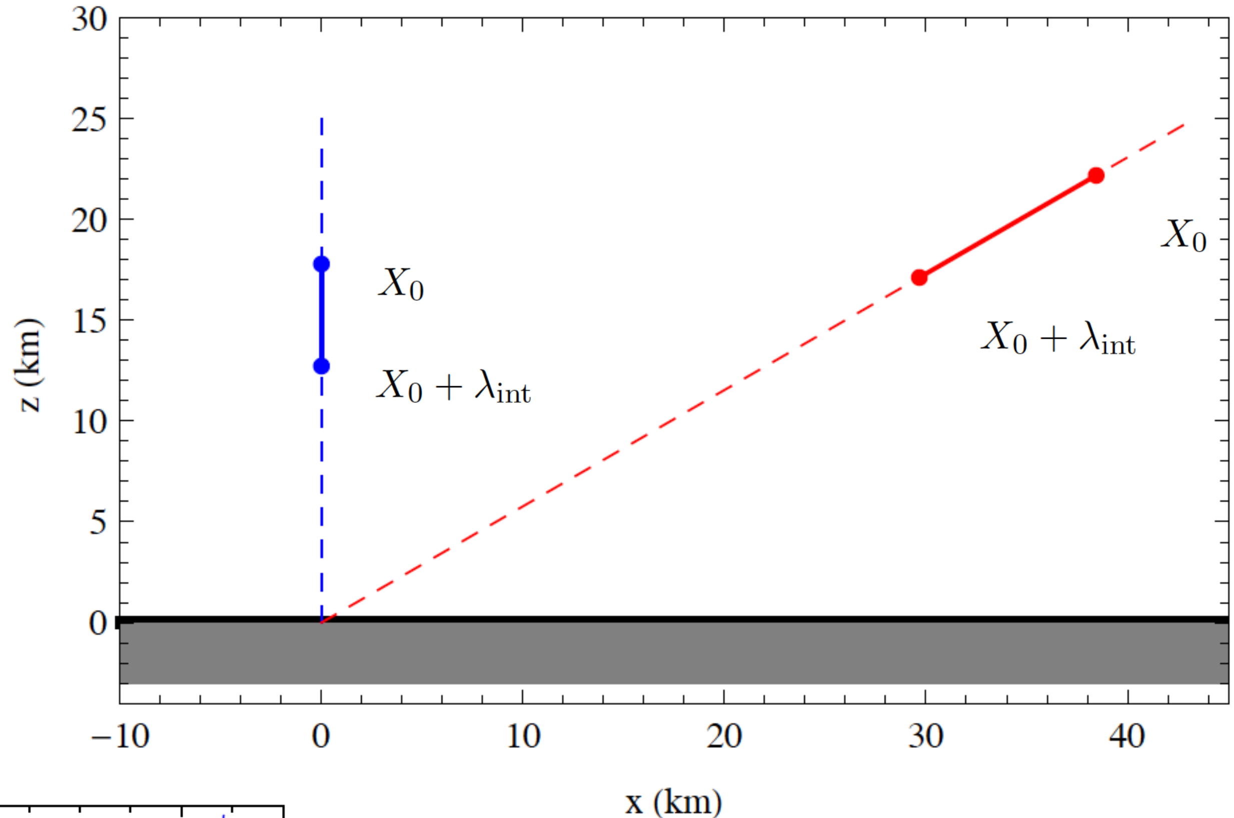
Flavor composition

Angular distribution

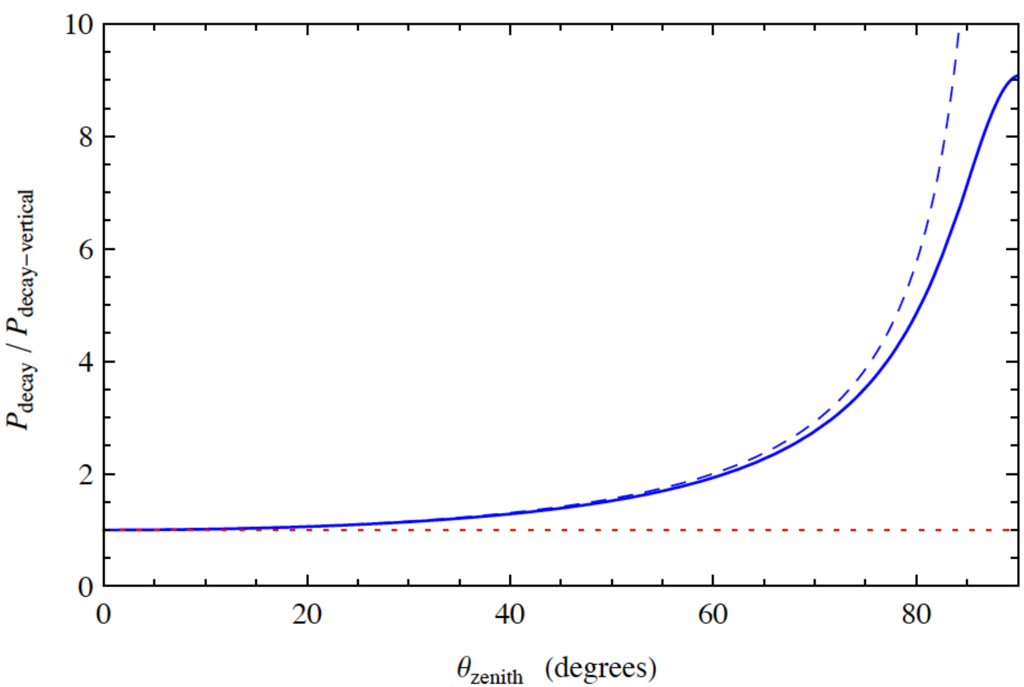
Energy distribution

Geometry
of Particle Decay

Long lifetime
$\pi^{\pm}$ K



Zenith angle
dependence



$$P_{\rm dec}(E) \propto \frac{1}{\ell_{\rm dec}} \propto \frac{m}{E}$$

$$\phi_\nu(\theta_{\rm z}) \propto \frac{1}{\cos\theta_{\rm z}}$$

	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. $\phi_\nu(E)$	$\propto \frac{\phi_{cr}(E)}{E}$	$\phi_{cr}(E)\ \sigma_{c\bar{c}}(E)$	"Hard"

Conventional atm. ne

"Prompt"

Astroph. neutrinos

Flavor

ν_e

ν

Angular distr.

Ho

V

Energy distr.

$\propto$

Separation of

"Atmospheric Charm"

Astrophysical

components

more challenging

$\nu_e \approx \nu_\mu$

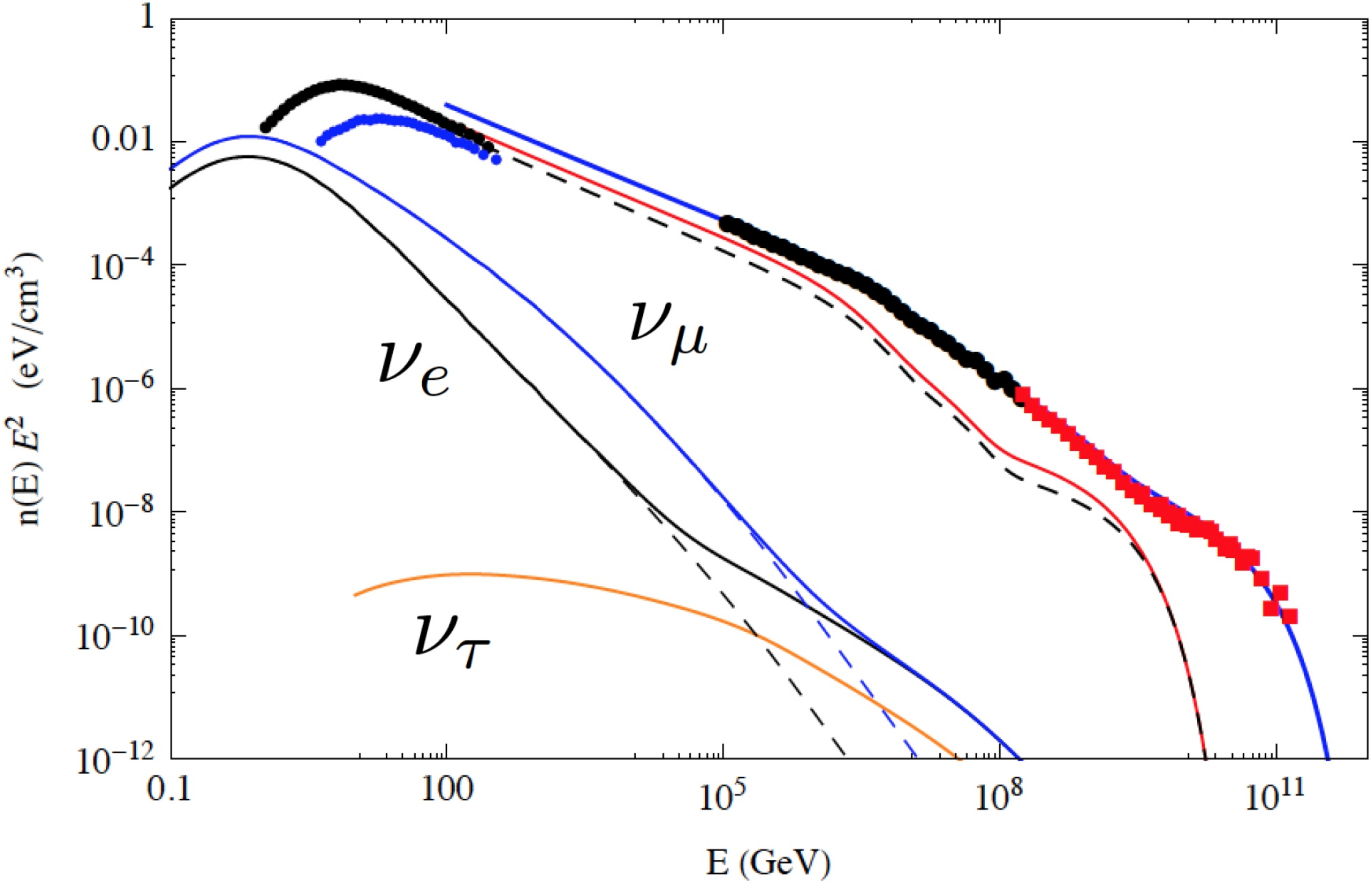
$\nu_\tau \approx \nu_\mu$

Isotropic

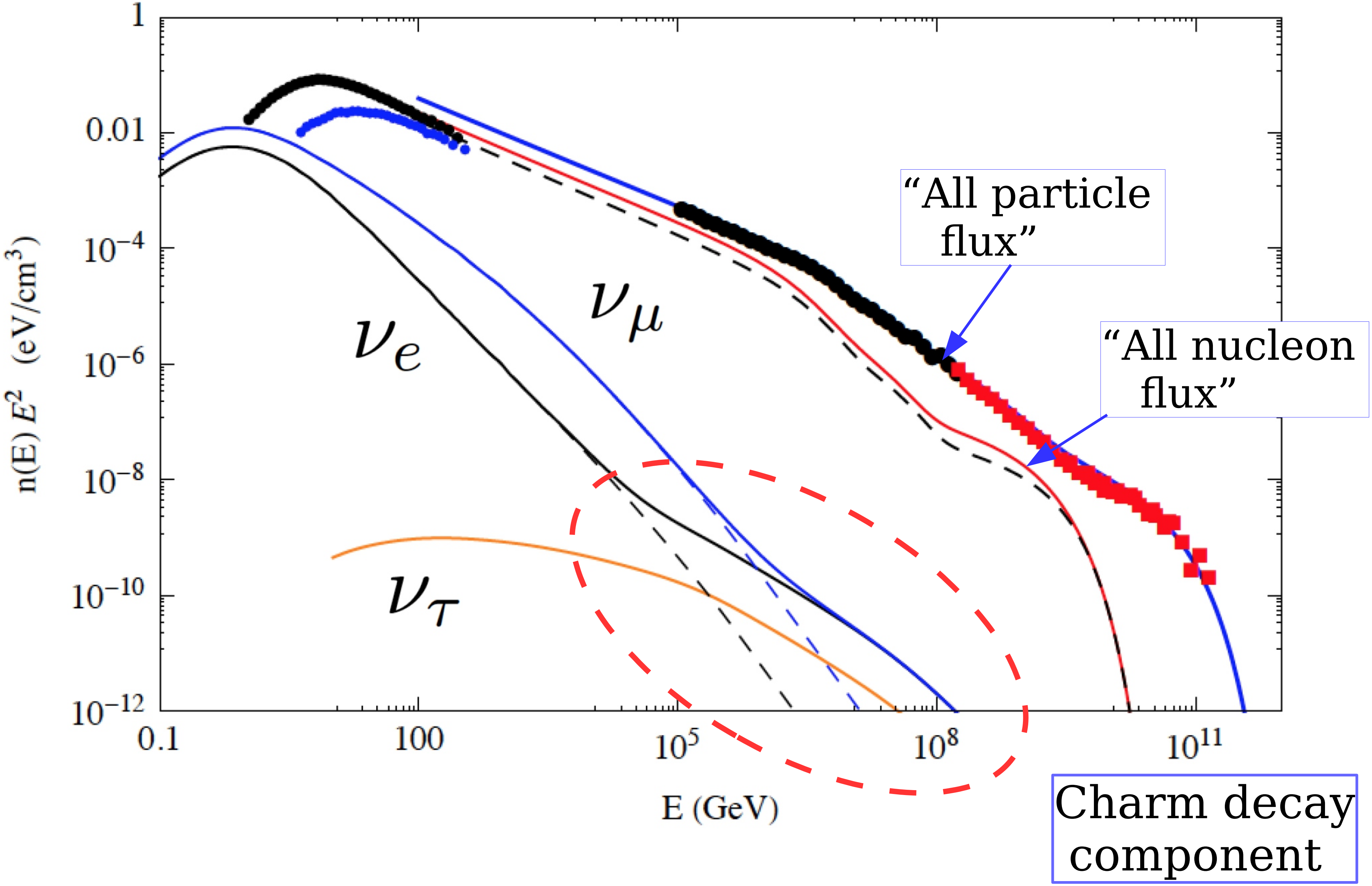
[if extragal.]

"Hard"

Angle integrated Neutrino fluxes $\nu + \overline{\nu}$



Angle integrated Neutrino fluxes $\nu + \overline{\nu}$



“All Nucleon flux” $E_{\rm tot} = A\, E_0$

$$\phi_N(E_0) = \sum_A A^2\, \phi_A(E_0\, A)$$

$$\phi_A(E) \simeq K_A\, E^{-\alpha}$$

$$K_A\, A^{-\alpha+2}$$

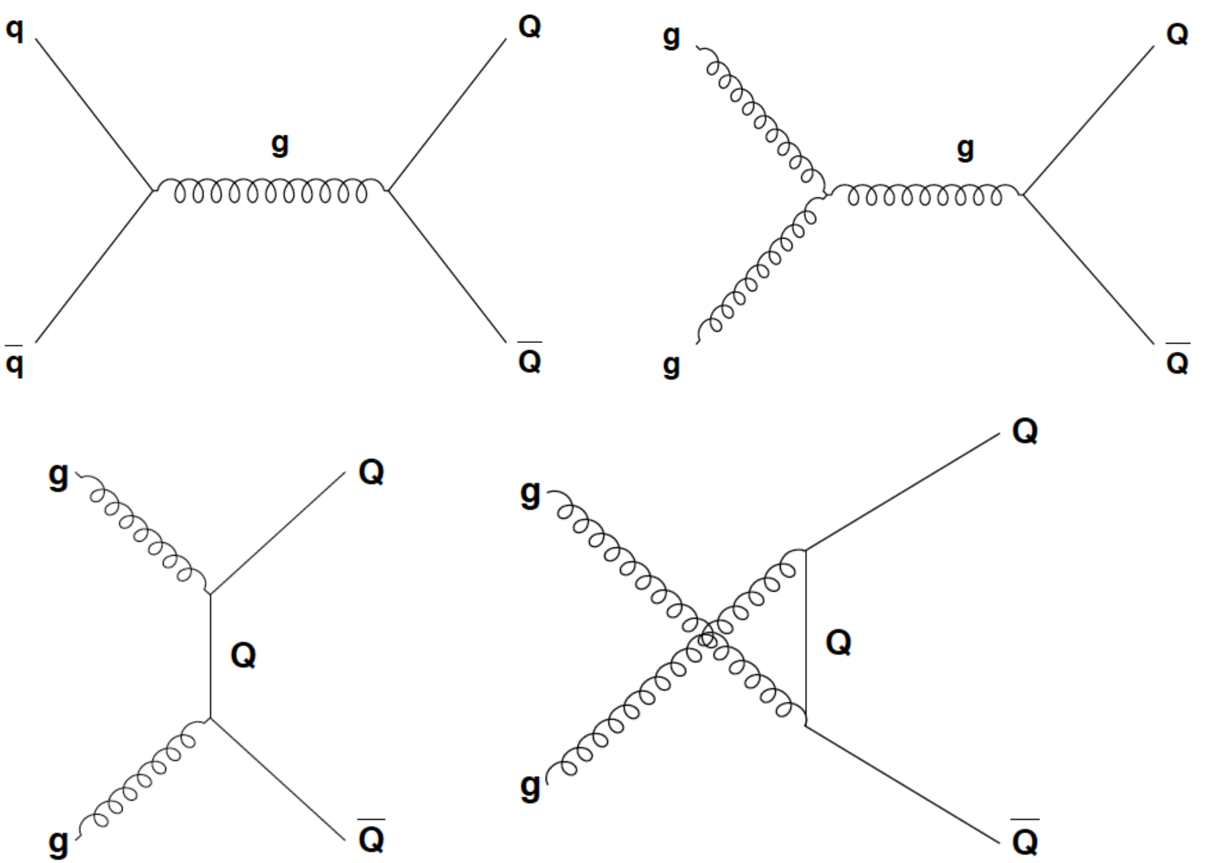
$$\alpha \approx 2.7\text{–}3 > 2$$

Nuclei contribution to neutrino production is suppressed

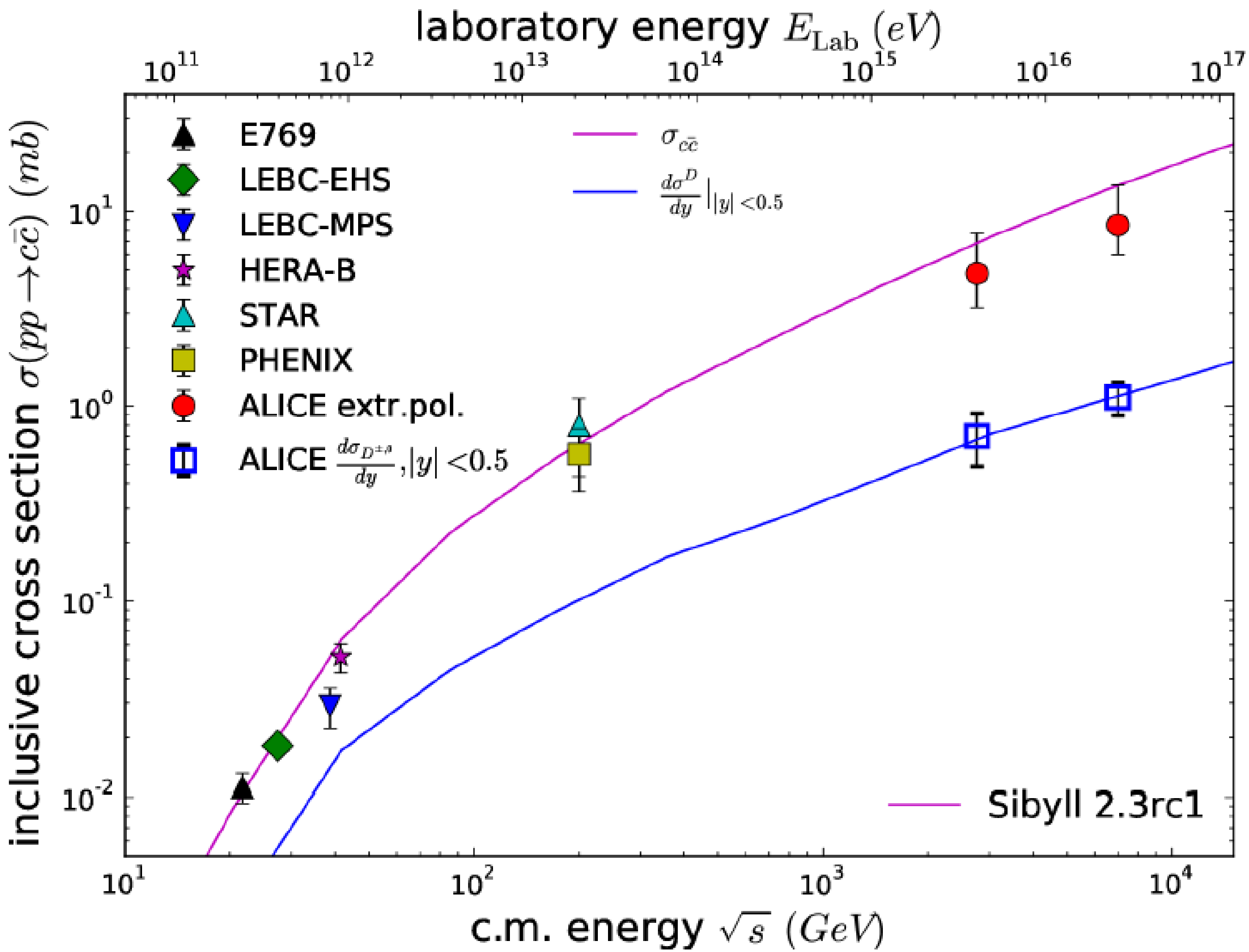
Uncertainty associated to the determination of the cosmic ray composition.

Dynamics of charm production
in hadronic interactions

Perturbative QCD calculation
(gluon fusion dominant)



Recent measurements of charm cross section at LHC (small phase space coverage).

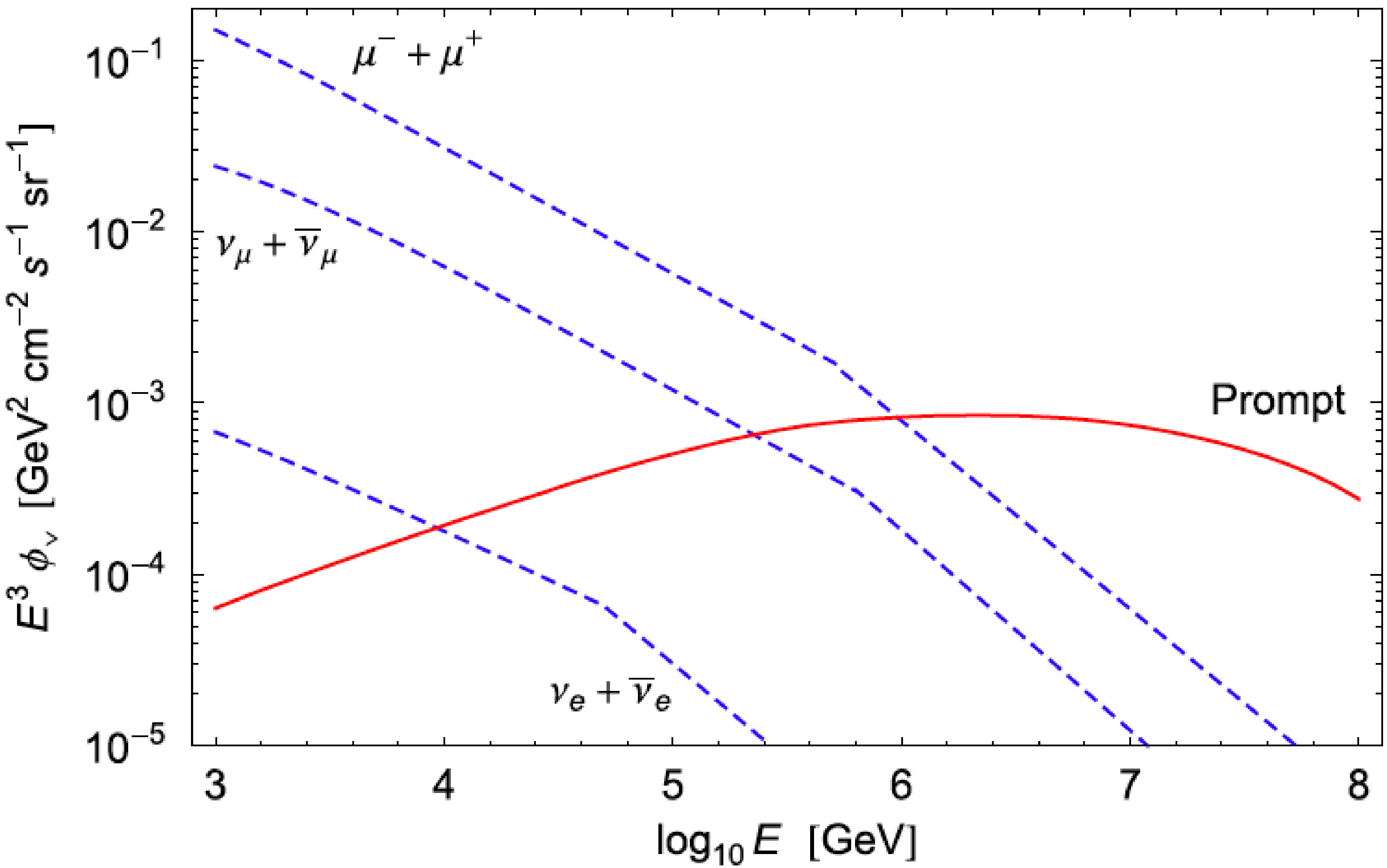


PHYSICAL REVIEW D 78, 043005 (2008)

Prompt neutrino fluxes from atmospheric charm

Rikard Enberg,[1] Mary Hall Reno,[2] and Ina Sarcevic[1,3]

Calculation used as reference by IceCube



Note: Uncertainties =
*Primary Flux * Charm production*

A. Bhattacharya, R. Enberg, M. H. Reno, I. Sarcevic and A. Stasto, "Perturbative charm production and the prompt atmospheric neutrino flux in light of RHIC and LHC," JHEP **1506**, 110 (2015) [arXiv:1502.01076 [hep-ph]].

R. Gauld, J. Rojo, L. Rottoli, S. Sarkar and J. Talbert, "The prompt atmospheric neutrino flux in the light of LHCb," JHEP **1602**, 130 (2016) [arXiv:1511.06346 [hep-ph]].

M. V. Garzelli *et al.* [PROSA Collaboration], "Prompt neutrino fluxes in the atmosphere with PROSA parton distribution functions," arXiv:1611.03815 [hep-ph].

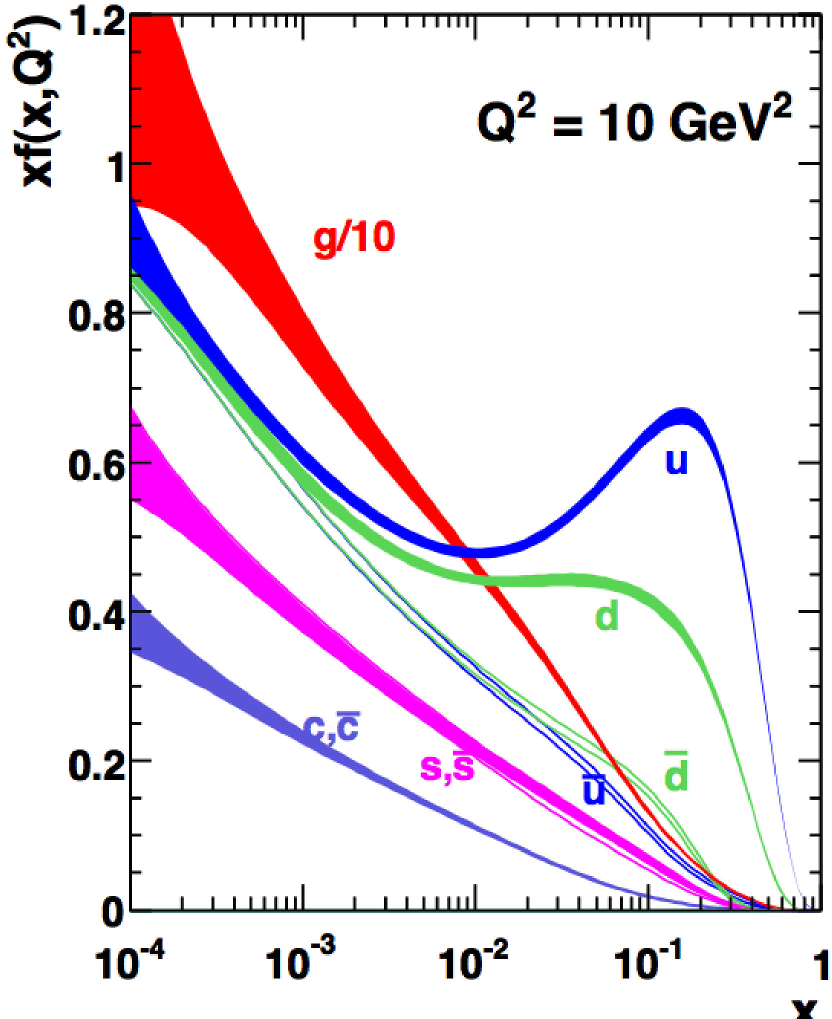
R. Laha and S. J. Brodsky, "IC at IC: IceCube can constrain the intrinsic charm of the proton," arXiv:1607.08240 [hep-ph].

F. Halzen and L. Wille, "Charm contribution to the atmospheric neutrino flux," Phys. Rev. D **94**, no. 1, 014014 (2016). [arXiv:1605.01409 [hep-ph]].

Non perturbative calculations

Possibility of "Intrinsic charm"

Qualitative idea:
Large component of charm in the Proton Parton Distribution Function.



$$pp \to \Lambda_c + D^- + \ldots$$

$$pp \to \Lambda_c + \overline{D}^\circ + \ldots$$

$$|\Lambda_c\rangle = [cud]$$

$$|D^-\rangle = [\overline{c}d]$$

$$|\overline{D}^\circ\rangle = [\overline{c}u]$$

On the Charm Contribution to the Atmospheric Neutrino Flux

Francis Halzen and Logan Wille[a]
Wisconsin IceCube Particle Astrophysics Center and Department of Physics,
University of Wisconsin, Madison, WI 53706, USA

We revisit the estimate of the charm particle contribution to the atmospheric neutrino flux that is expected to dominate at high energies because long-lived high-energy pions and kaons interact in the atmosphere before decaying into neutrinos. We focus on the production of forward charm particles which carry a large fraction of the momentum of the incident proton. In the case of strange particles, such a component is familiar from the abundant production of $K^+\Lambda$ pairs. These forward charm particles can dominate the high-energy atmospheric neutrino flux in underground experiments. Modern collider experiments have no coverage in the very large rapidity region where charm forward pair production dominates. Using archival accelerator data as well as IceCube measurements of atmospheric electron and muon neutrino fluxes, we obtain an upper limit on forward $\bar{D}^0\Lambda_c$ pair production and on the associated flux of high-energy atmospheric neutrinos. We conclude that the prompt flux may dominate the much-studied central component and represent a significant contribution to the TeV atmospheric neutrino flux. Importantly, it cannot accommodate the PeV flux of high-energy cosmic neutrinos, nor the excess of events observed by IceCube in the 30–200 TeV energy range indicating either structure in the flux of cosmic accelerators, or a presence of more than one component in the cosmic flux observed.

F. Halzen and L. Wille,
"Charm contribution to the atmospheric neutrino flux,"
Phys. Rev. D **94**, no. 1, 014014 (2016).
[arXiv:1605.01409 [hep-ph]].

Non perturbative mechanism could be the dominant for neutrino production (non-negligible effect)

On the Charm Contribution to the Atmospheric Neutrino Flux

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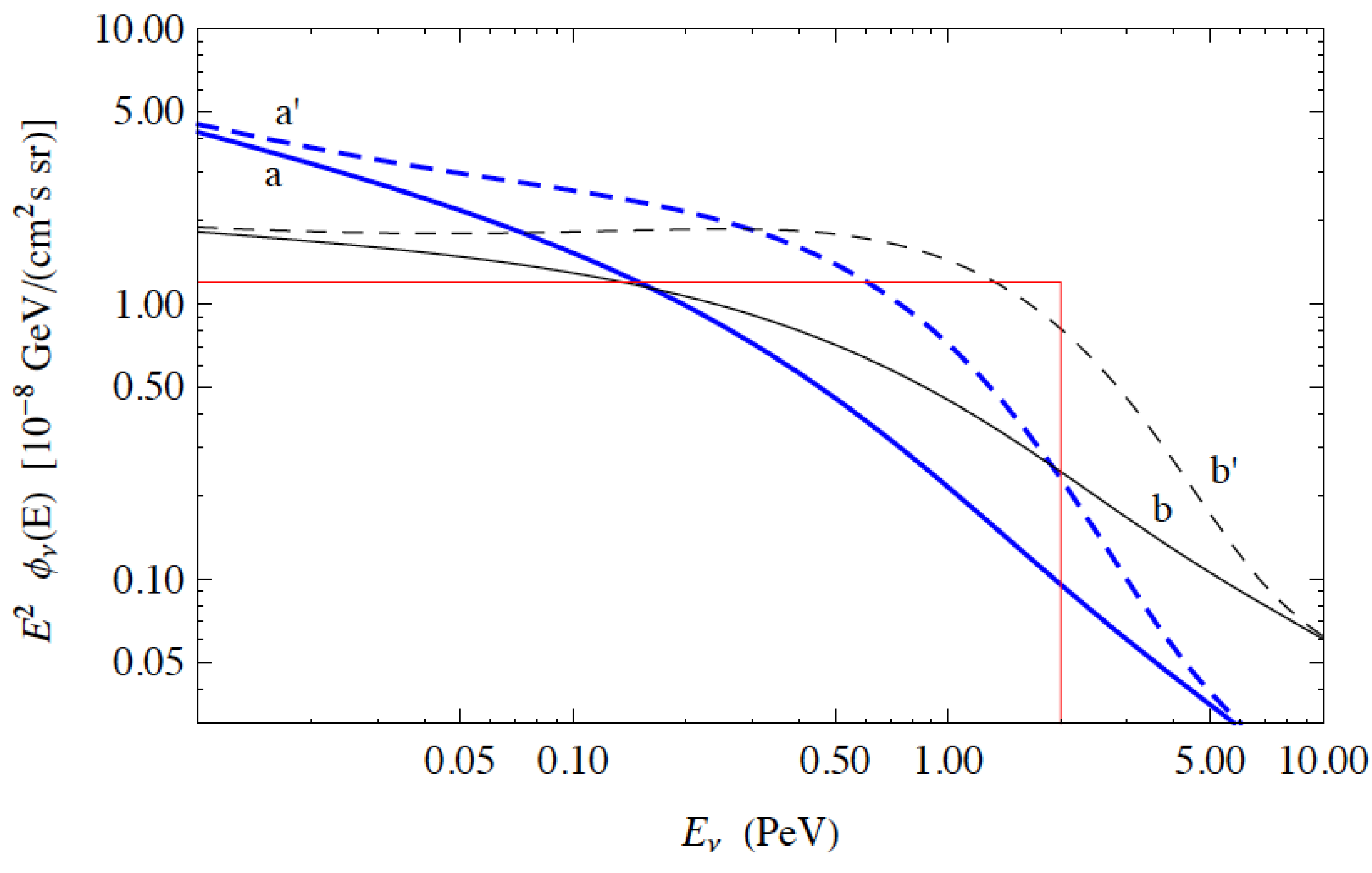
Wisconsin IceCube Particle Astrophysics Center and Department of Physics,
University of Wisconsin, Madison, WI 53706, USA

We revisit the estimate of the charm particle contribution to the atmospheric neutrino flux that is expected to dominate at high energies because long-lived high-energy pions and kaons interact in the atmosphere before decaying into neutrinos. We focus on the production of forward charm particles which carry a large fraction of the momentum of the incident proton. In the case of strange particles, such a component is familiar from the abundant production of $K^+\Lambda$ pairs. These forward charm particles can dominate the high-energy atmospheric neutrino flux in underground experiments. Modern collider experiments have no coverage in the very large rapidity region where charm forward pair production dominates. Using archival accelerator data as well as IceCube measurements of atmospheric electron and muon neutrino fluxes, we obtain an upper limit on forward $\bar{D}^0\Lambda_c$ pair production and on the associated flux of high-energy atmospheric neutrinos. We conclude that the prompt flux may dominate the much-studied central component and represent a significant contribution to the TeV atmospheric neutrino flux. Importantly, it cannot accommodate the PeV flux of high-energy cosmic neutrinos, nor the excess of events observed by IceCube in the 30–200 TeV energy range indicating either structure in the flux of cosmic accelerators, or a presence of more than one component in the cosmic flux observed.

F. Halzen and L. Wille,
"Charm contribution to the atmospheric neutrino flux,"
Phys. Rev. D **94**, no. 1, 014014 (2016).
[arXiv:1605.01409 [hep-ph]].

Note the conclusion

Very similar point on possible role
of non-perturbative contribution to charm production
[P.L. astro-ph/1308.2086].
(with (very speculative) possibility of larger flux)

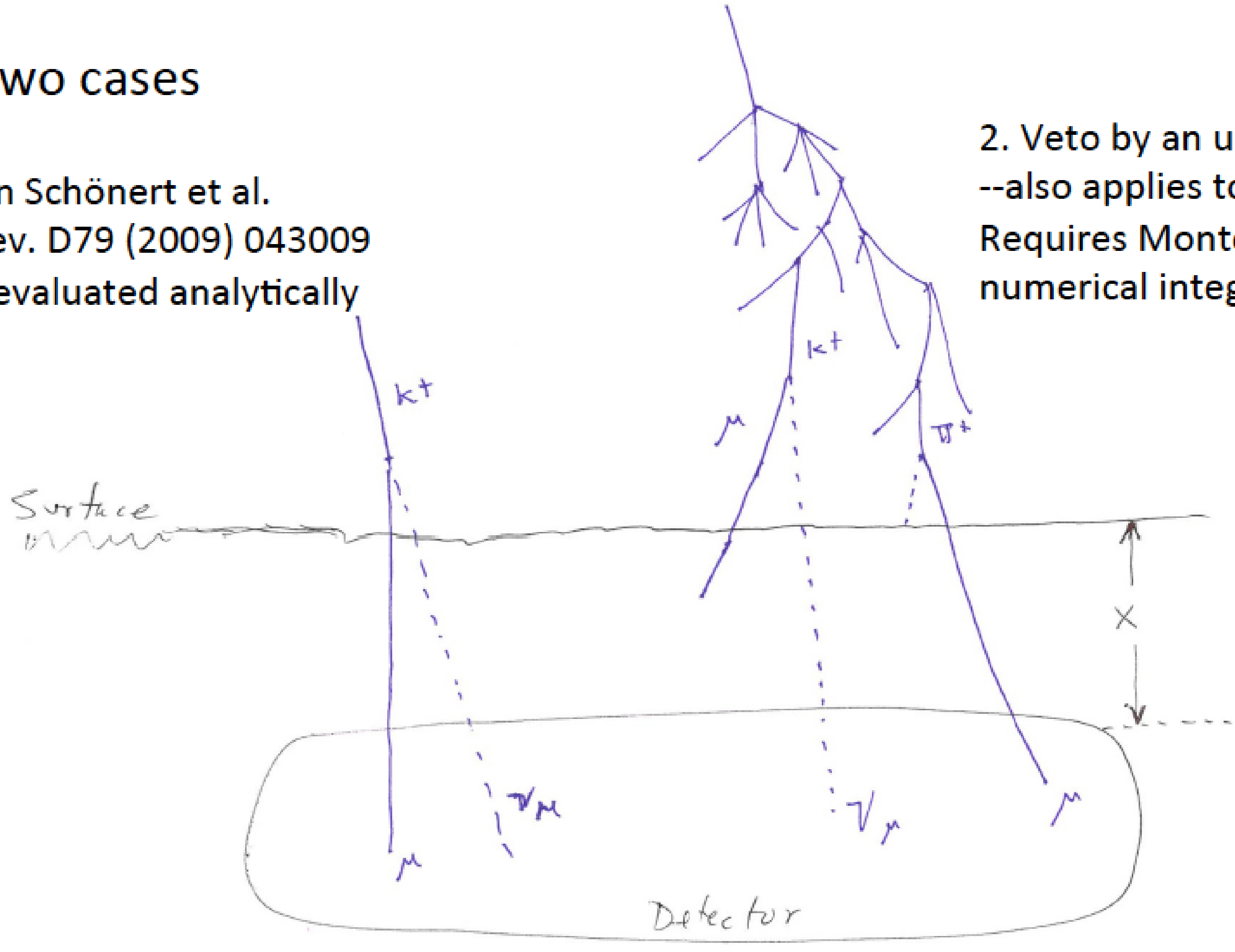


Atmospheric neutrino self veto

Two cases

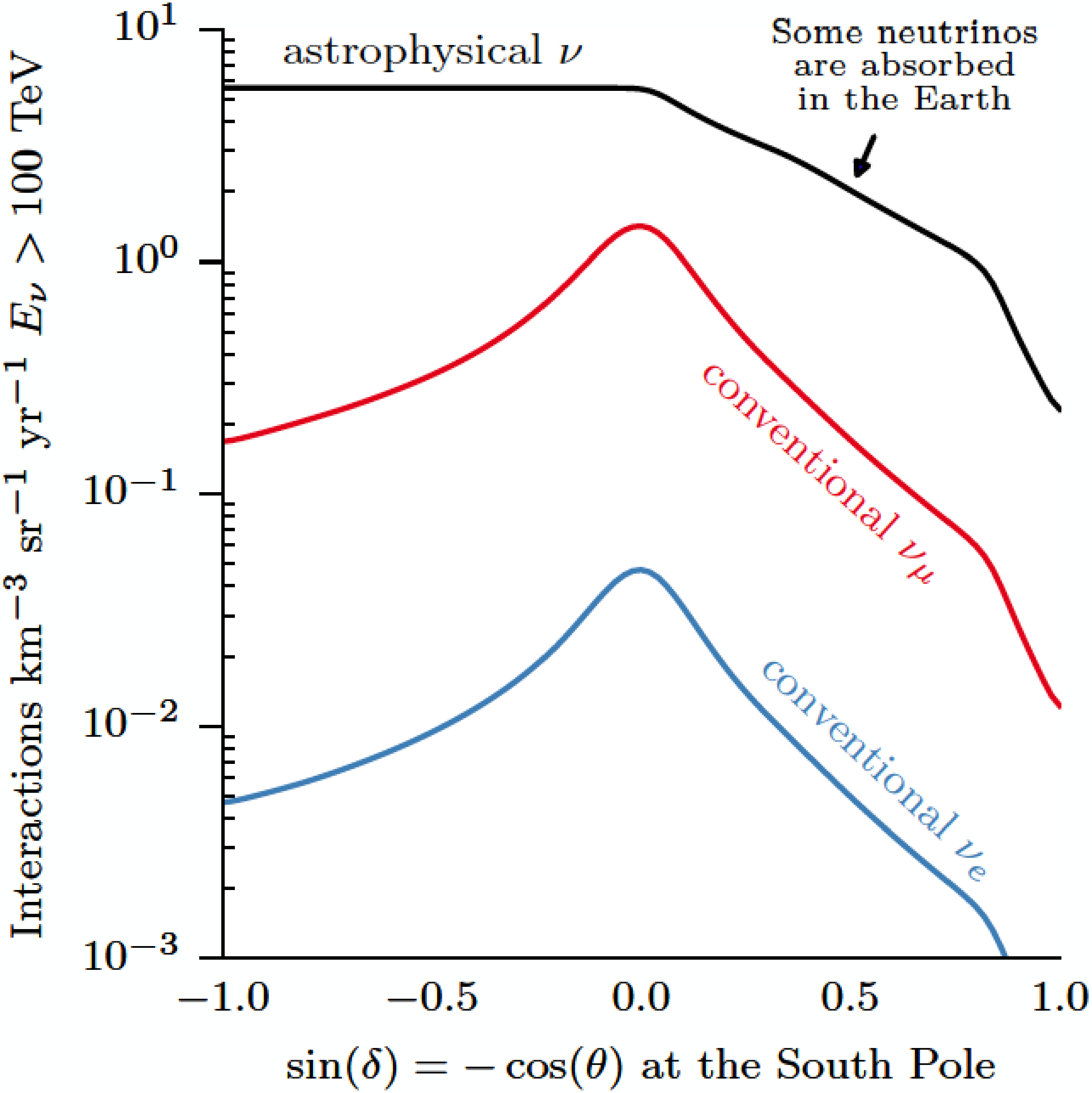
1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or
numerical integration



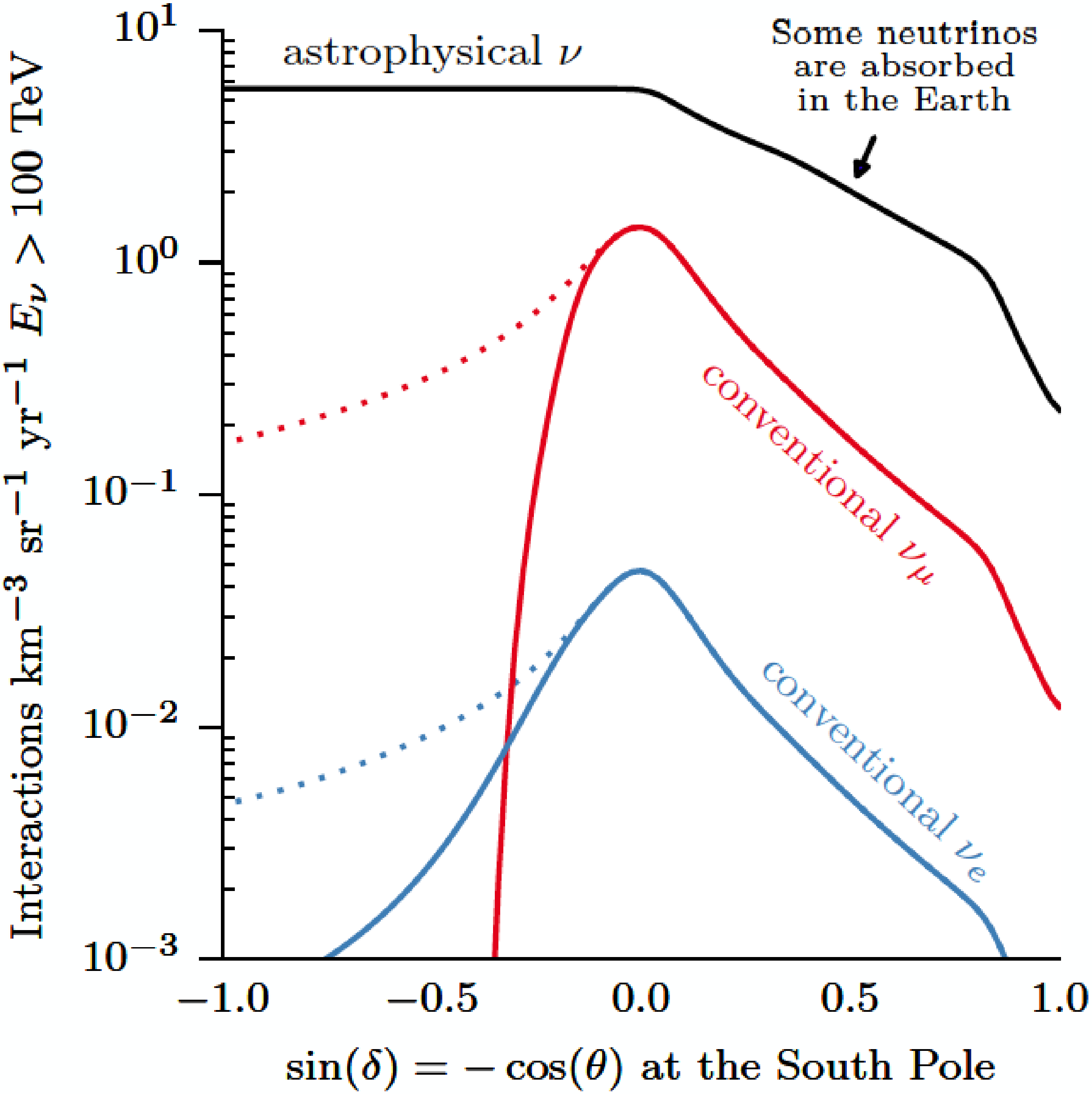
Experimental detection of charm component.

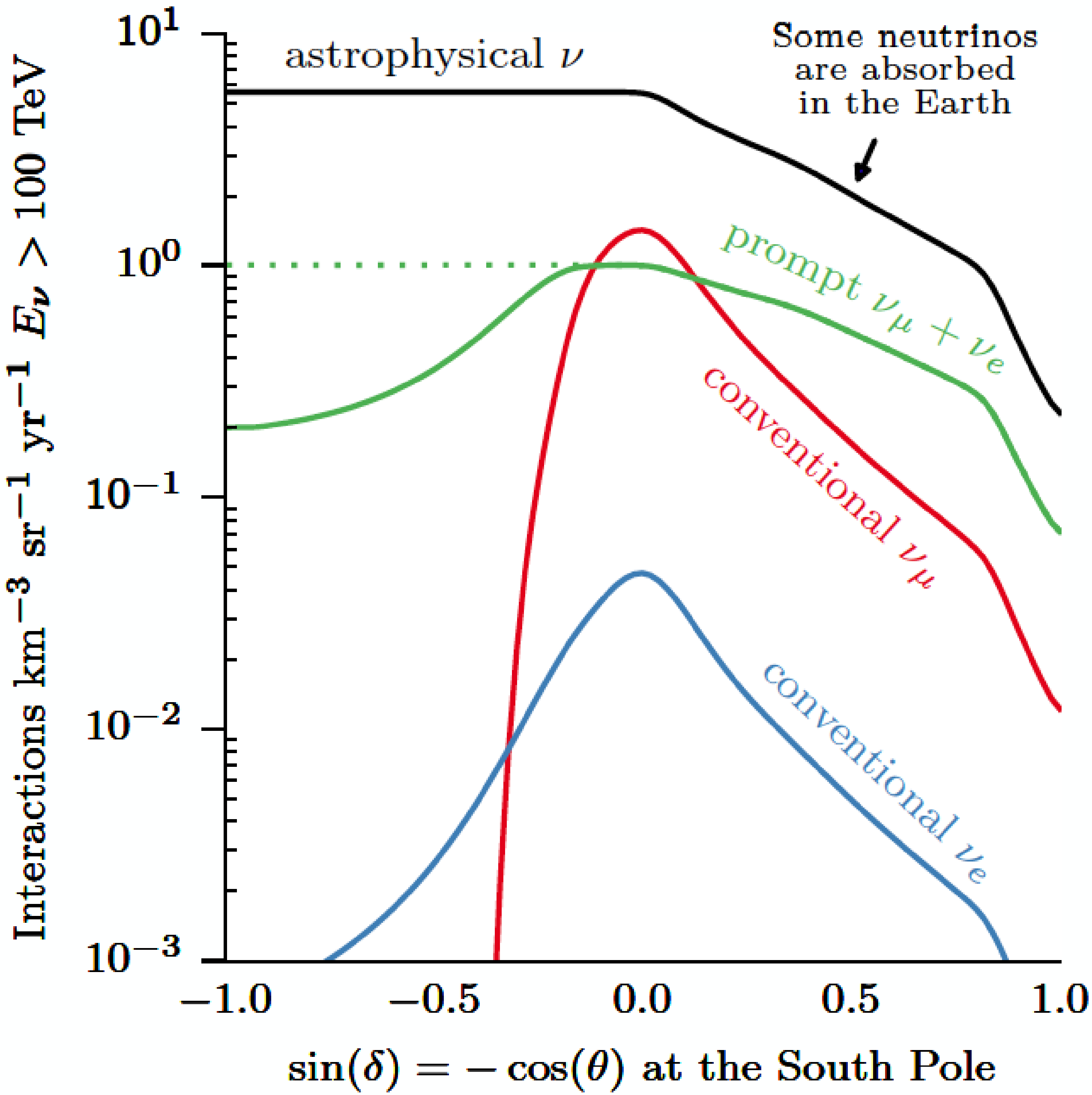
Tom Gaisser



astrophysical ν
Some neutrinos are absorbed in the Earth
conventional ν_μ
conventional ν_e
Interactions km^{-3} sr^{-1} yr^{-1} $E_\nu > 100$ TeV
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
−1.0
−0.5
0.0
0.5
1.0
$\sin(\delta) = -\cos(\theta)$ at the South Pole

Effect of VETO: *rejection of atmospheric neutrinos*





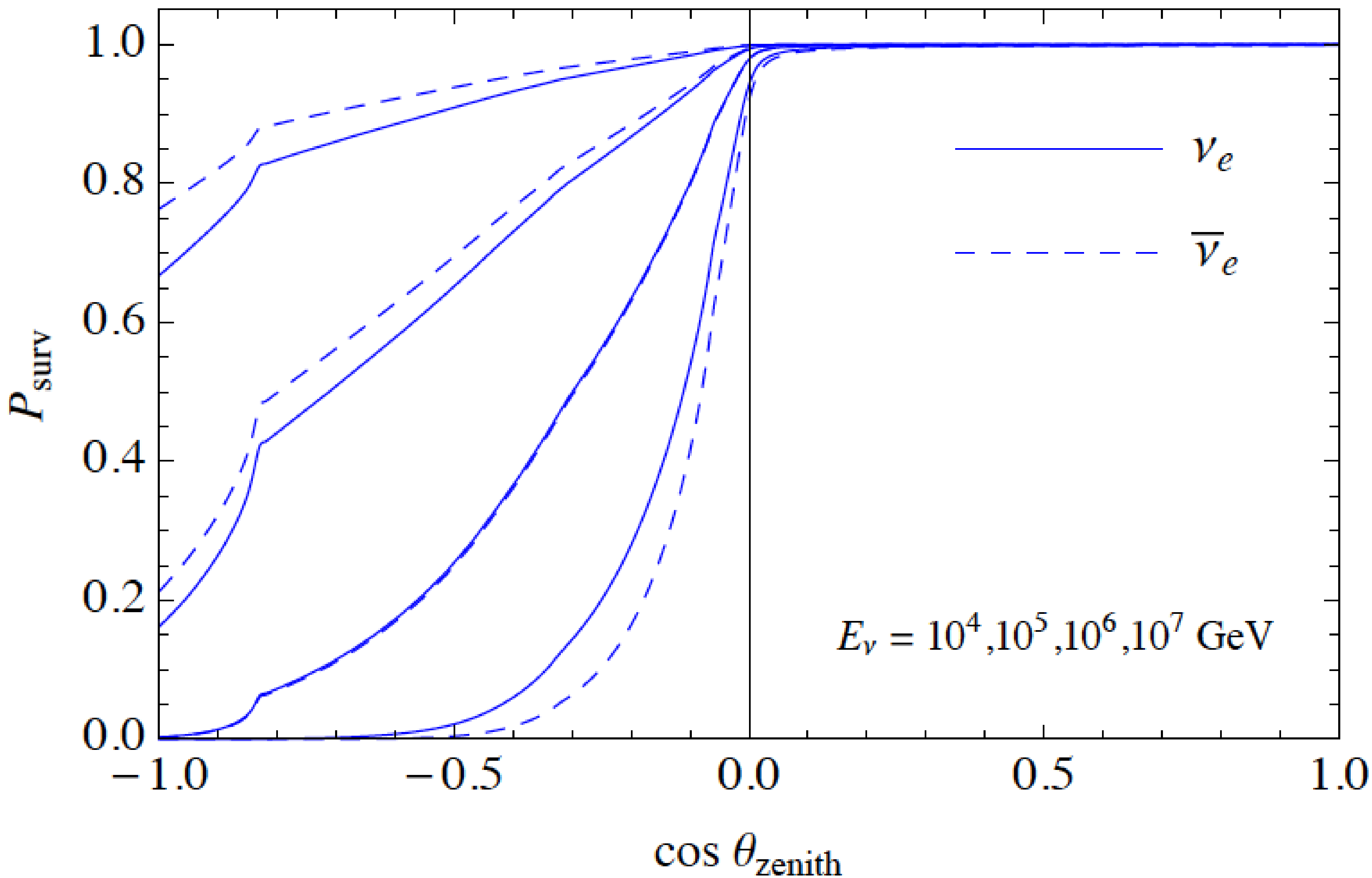
Effect allows to separate

Atmospheric-charm

from isotropic astrophysical

Absorption of neutrinos in the Earth

$$E_\nu = 10^4,\ 10^5,\ 10^6,\ 10^7\ \text{GeV}$$



My (very “conservative”) comment:

The possibility that a charm component is a
non negligible contamination
to the lower energy part of the IceCube signal
is unlikely but not impossible.

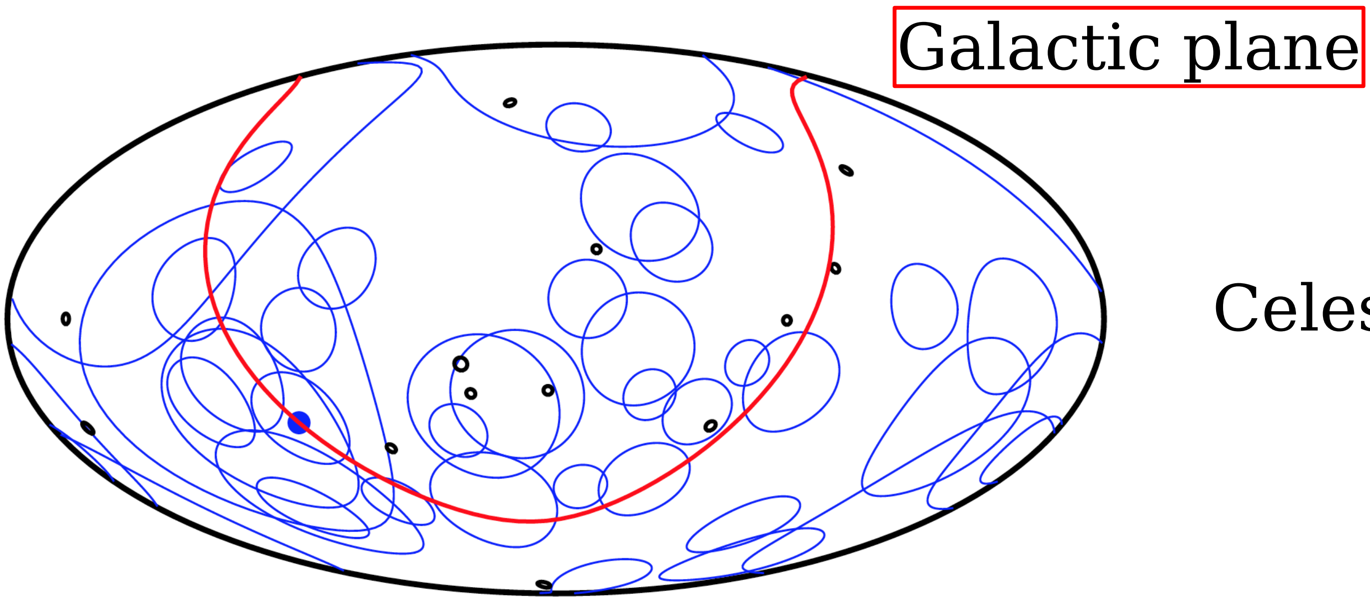
The possibility of performing
experimental studies in the very forward
region at LHC is certainly desirable.

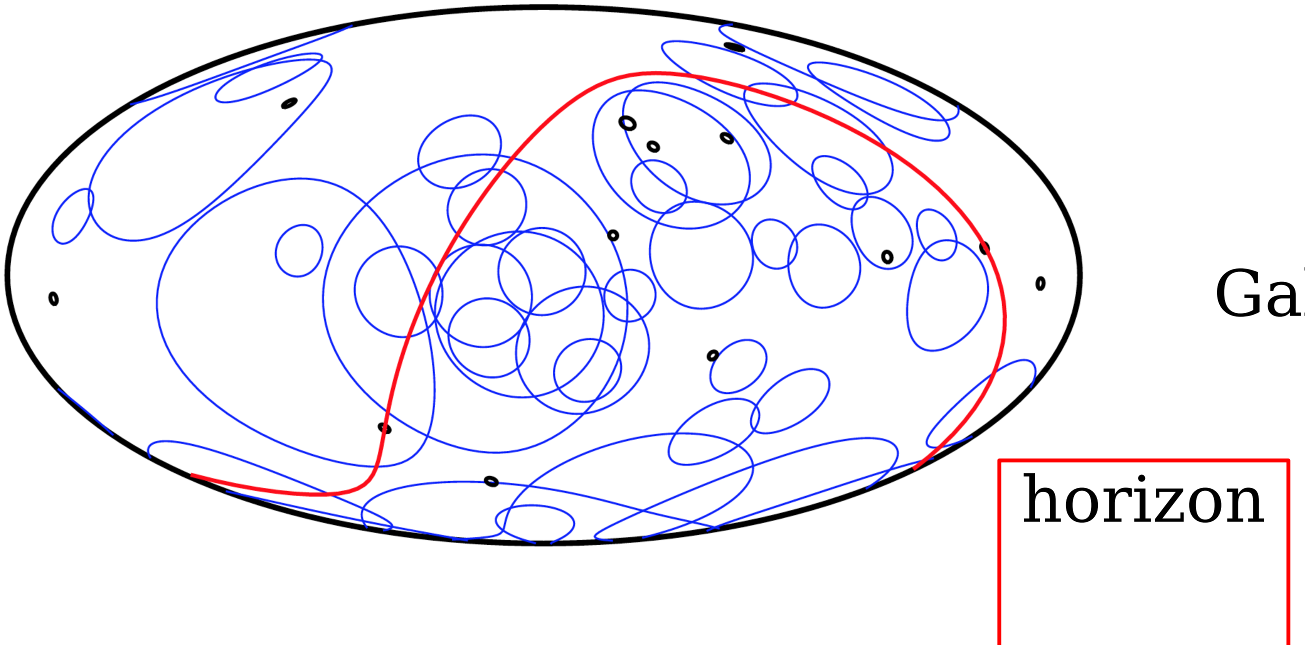
[in a program of experimental studies
that is also of interest
for the modeling of UHECR cosmic ray showers]

Preliminary studies are being made
[workshop SAS@LHC
(small angle spectrometer)@LHC]

Does the IceCube signal have a Galactic component ?

IceCube 4-years HESE events



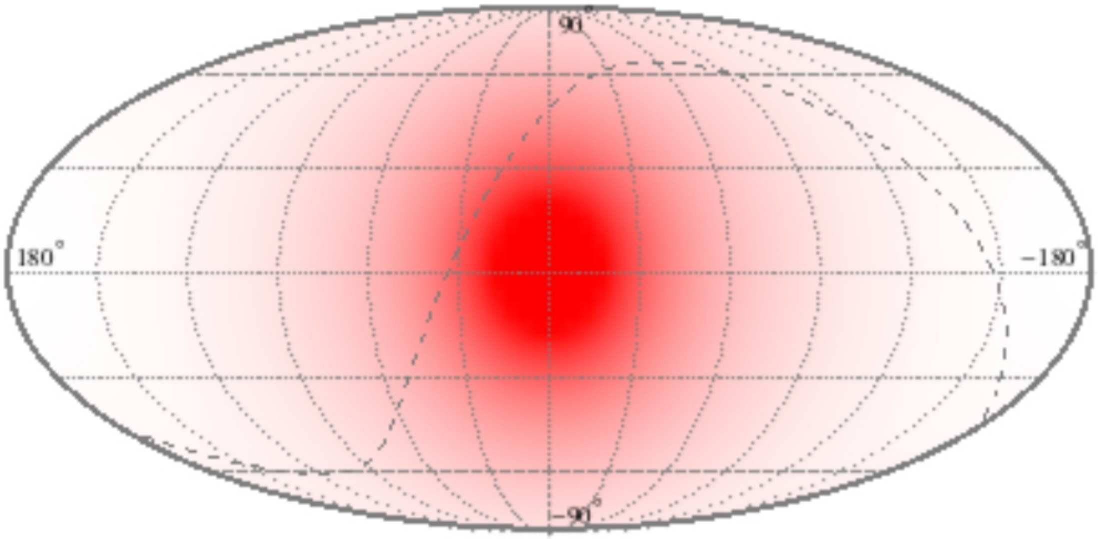


Does the IceCube signal have a Galactic component ?

There are models where the signal is *entirely* of Galactic origin.

A. Esmaili and P. D. Serpico,
"Are IceCube neutrinos unveiling PeV-scale decaying dark matter?,"
JCAP **1311**, 054 (2013)
[arXiv:1308.1105 [hep-ph]].

Expected angular distribution distribution

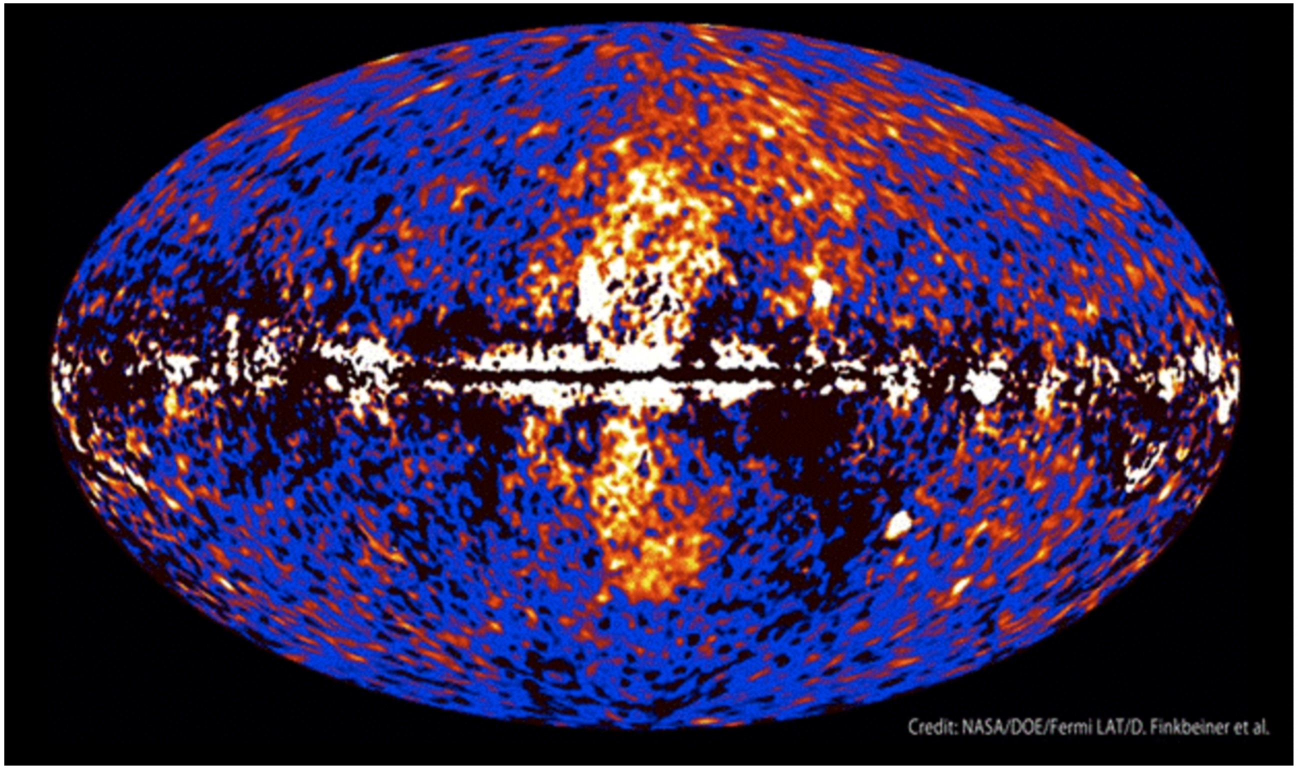


(a) PDF of DM decay

A. M. Taylor, S. Gabici and F. Aharonian,
"Galactic halo origin of the neutrinos detected by IceCube,"
Phys. Rev. D **89**, no. 10, 103003 (2014)
doi:10.1103/PhysRevD.89.103003 [arXiv:1403.3206 [astro-ph.HE]].

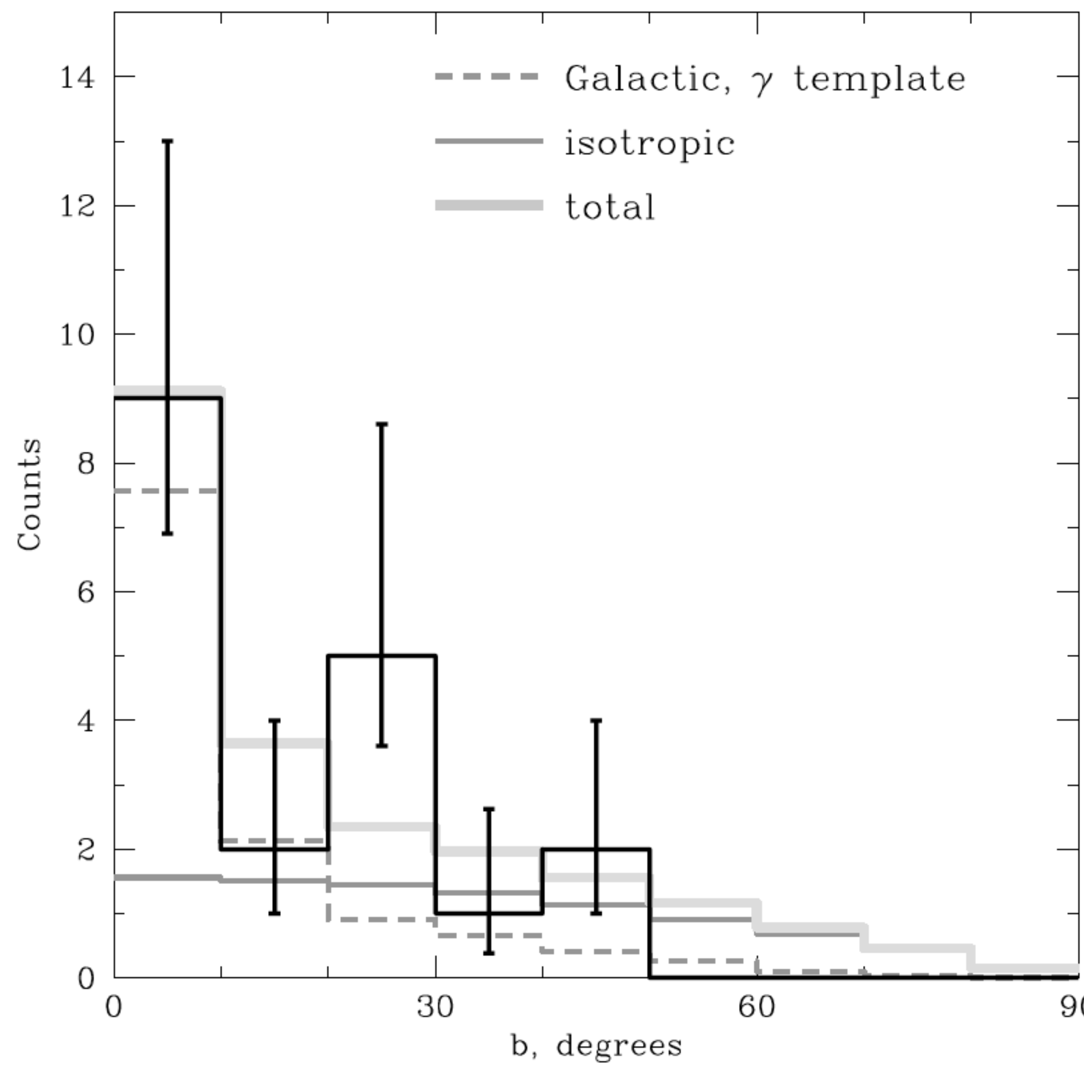
Very large (100 kpc) halo of cosmic rays

[Inspired (to a large extent) by the observations of the "Fermi Bubbles"]

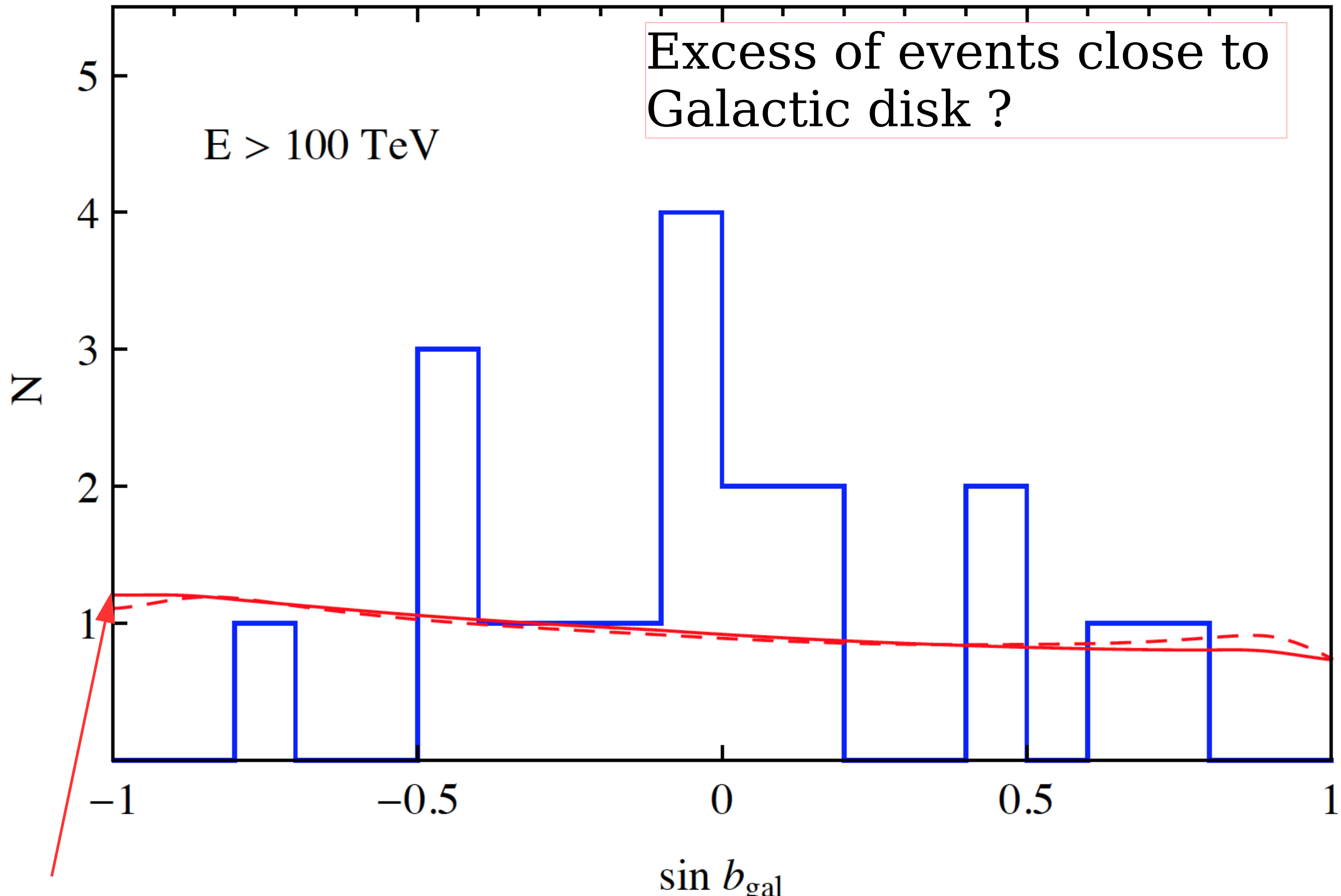


A. Neronov and D. V. Semikoz, "Evidence the Galactic contribution to the IceCube astrophysical neutrino flux," Astropart. Phys. **75**, 60 (2016) [arXiv:1509.03522 [astro-ph.HE]].

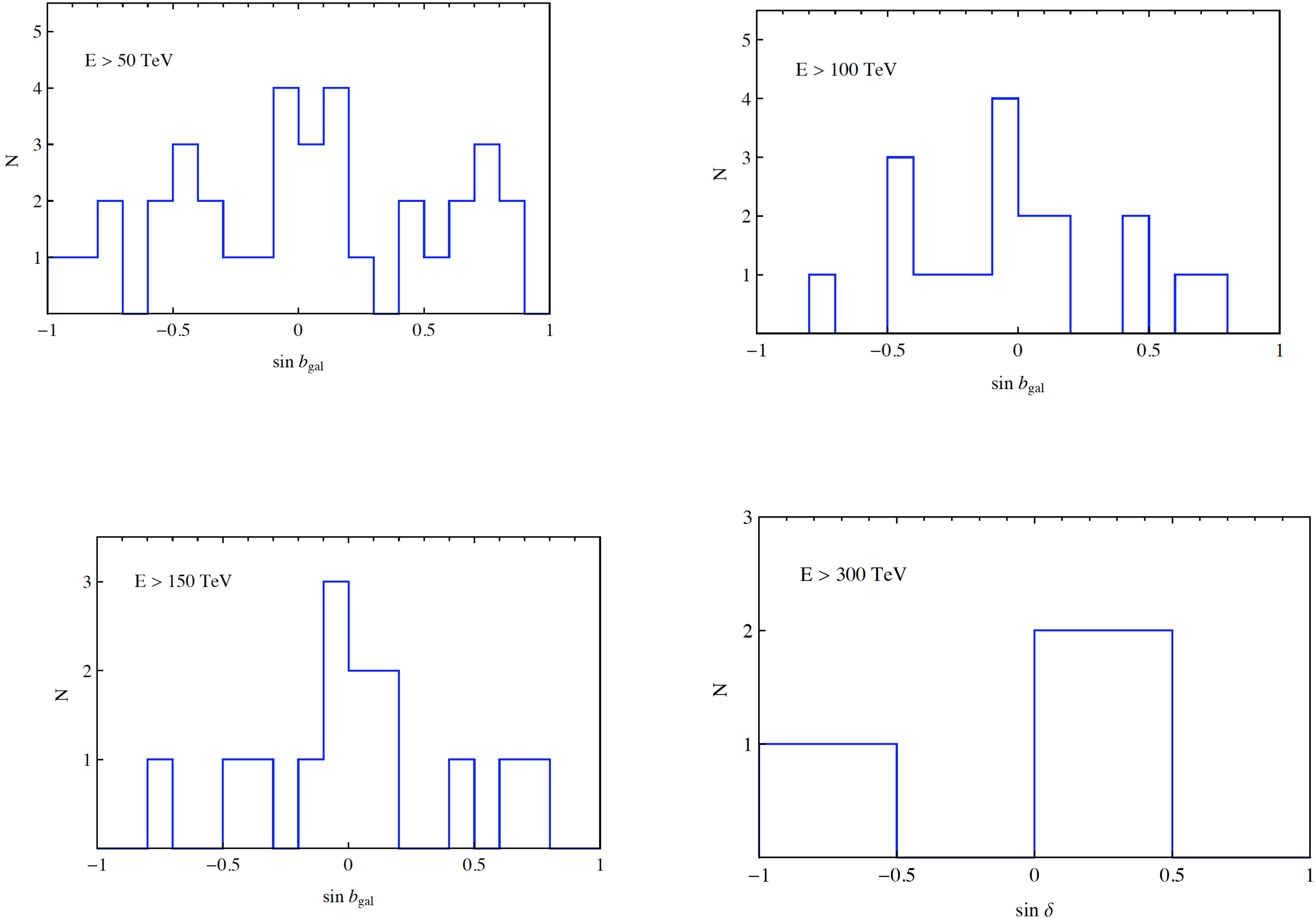
Emission from the disk



My own analysis



Prediction of isotropic flux



Excess from Galactic Equator ?

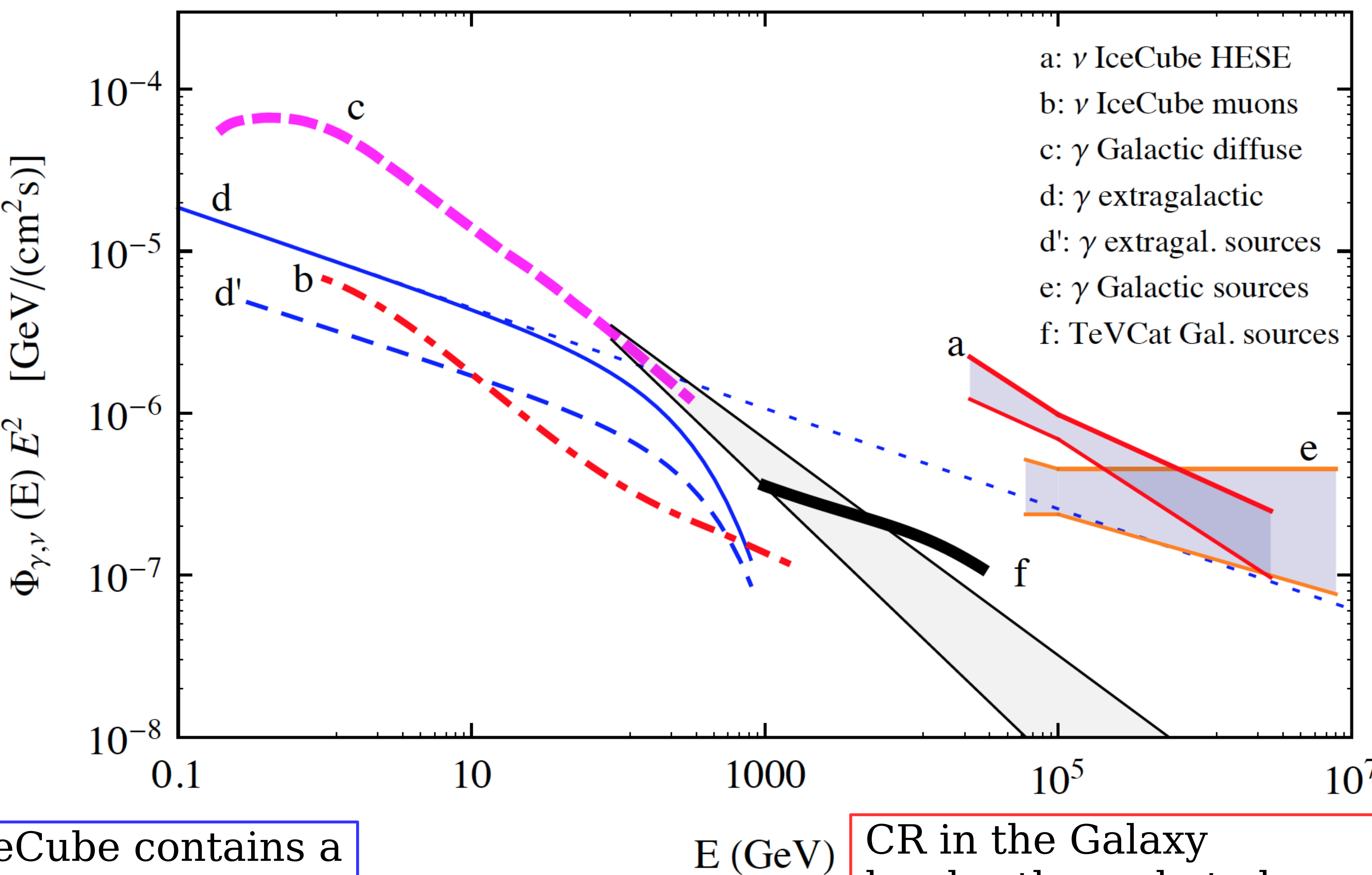
Several works discuss models where the IceCube signal has a Galactic and an ExtraGalactic component:

A. Palladino and F. Vissani,
"Extragalactic plus Galactic model for IceCube neutrino events,"
Astrophys. J. **826**, no. 2, 185 (2016)
[arXiv:1601.06678 [astro-ph.HE]].

A. Palladino, M. Spurio and F. Vissani,
"On the IceCube spectral anomaly,"
JCAP **1612**, no. 12, 045 (2016)
[arXiv:1610.07015 [astro-ph.HE]].

G. Pagliaroli, C. Evoli and F. L. Villante,
"Expectations for high energy diffuse galactic neutrinos for different cosmic ray distributions,"
JCAP **1611**, no. 11, 004 (2016)
[arXiv:1606.04489 [astro-ph.HE]].

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



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

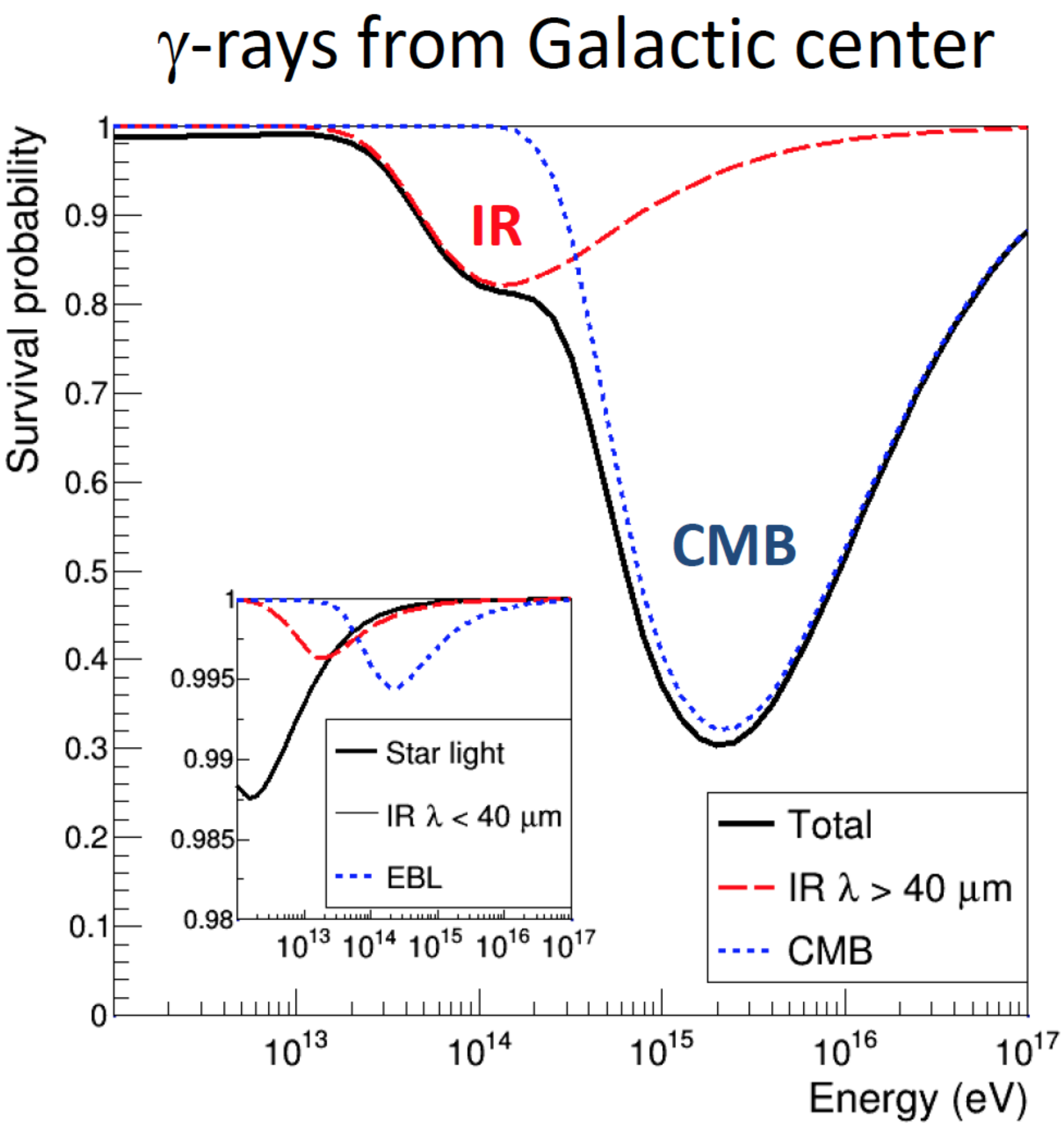
CR in the Galaxy harder than what observed at the Sun ?

Important implication of
Models with a Galactic component:

A gamma ray counterpart to the neutrino signal
is reduced (and distorted) by absorption effects
but is detectable by future gamma ray telescopes.
[and perhaps should already have been detected]

[Note that the IceCube signal emerges
at E=30 TeV – 1 PeV, a region where the
Gamma ray telescopes have not studied in depth]

Survival Probabilities for Gamma Rays



S.Vernetto and P.L. Phys.Rev. D (2016)

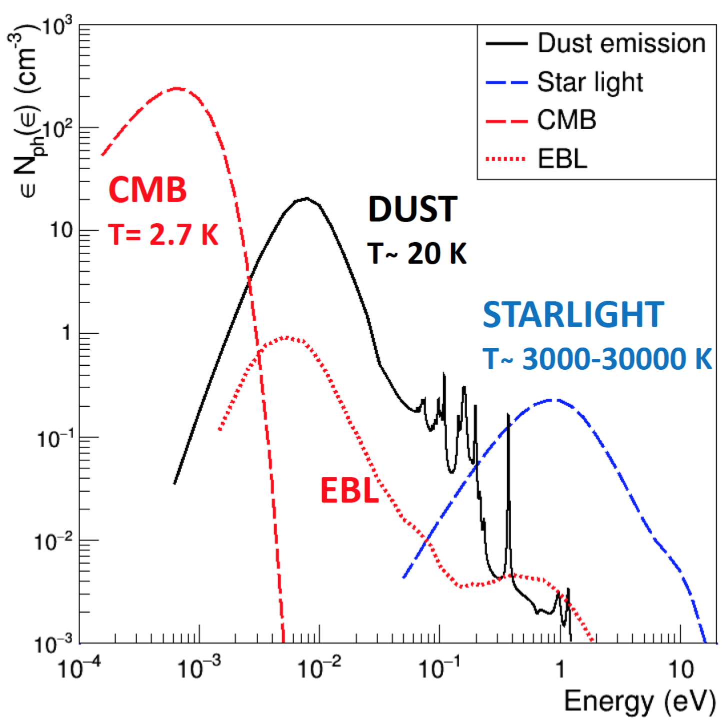
Absorption pattern has two maxima

$E_\gamma \simeq 150$ PeV

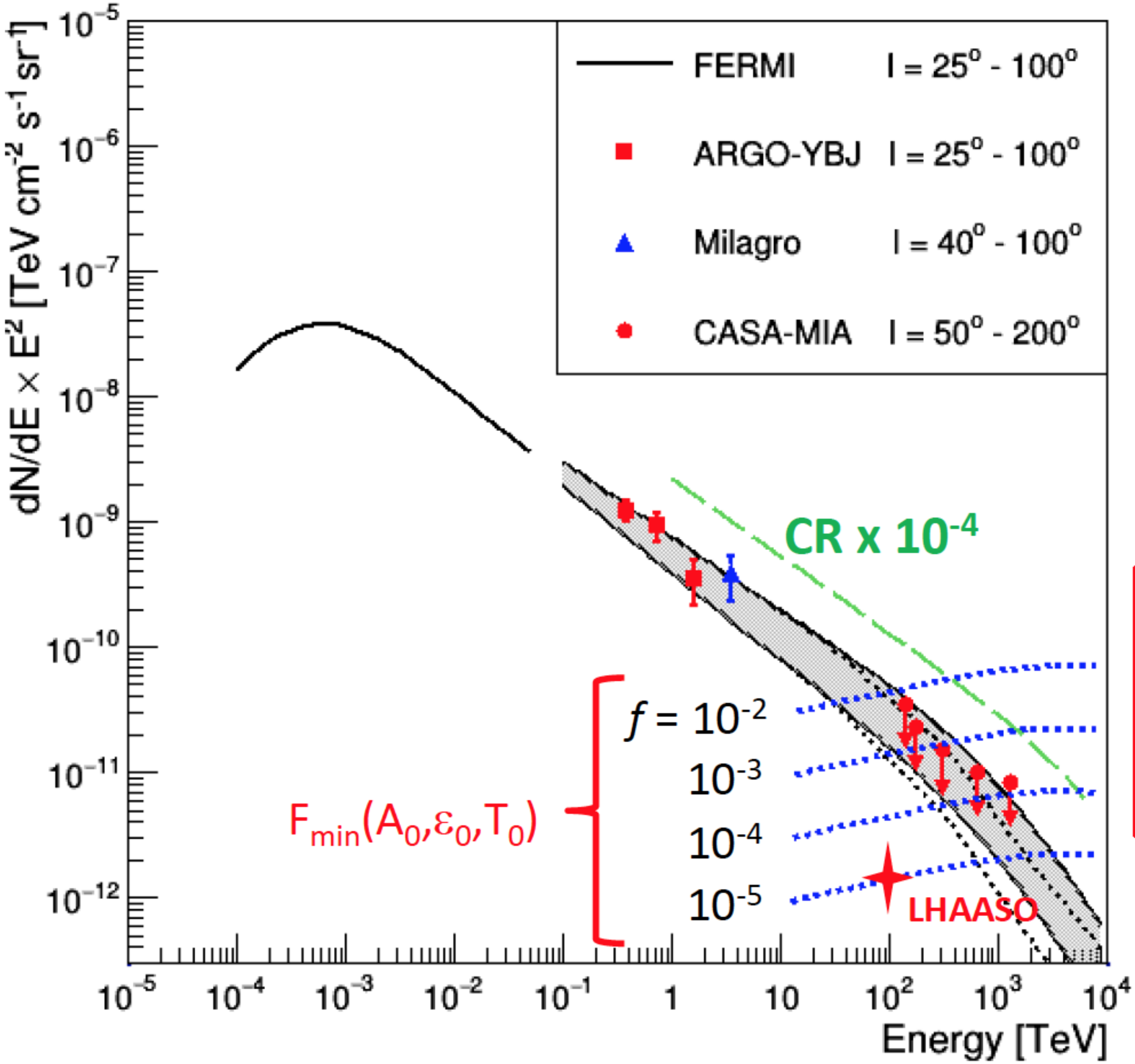
[from dust emitted radiation]

$E_\gamma \simeq 2.2$ PeV

[from CMBR]



Potential for the measurement of the diffuse Gamma Ray flux



Detector features:

- Effective area $A_0 = 1\ km^2$
- γ-ray detection efficiency $\varepsilon_0 = 1$
- Observation time $T_0 = 1$ year
- Latitude 30° N
- Maximum zenith angle 45°

Minimum observable flux (5 σ)

$F_{min}(A_0,\varepsilon_0,T_0)$ for different values of f

f = background rejection factor

Minimum flux for any A, ε and T:

$$F_{min}(A,\varepsilon,T) = F_{min}(A_0,\varepsilon_0,T_0)\sqrt{\frac{A_0 T_0}{AT}\ \frac{\varepsilon_0}{\varepsilon}}$$

S.Vernetto

Extragalactic Sources

$$\phi_\nu^{\rm extra}(E) = \sum_j \phi_j(E)$$

Extragalactic flux formed by an ensemble of discrete sources.

Identification of the class of sources

Extragalactic Sources

Flux observed at the Earth from source at redshift z

$$\phi(E,\ z) = \frac{1}{4\pi\, r^2(z)}\ q[E(1+z)]$$

"comoving distance"
of the source r(z)

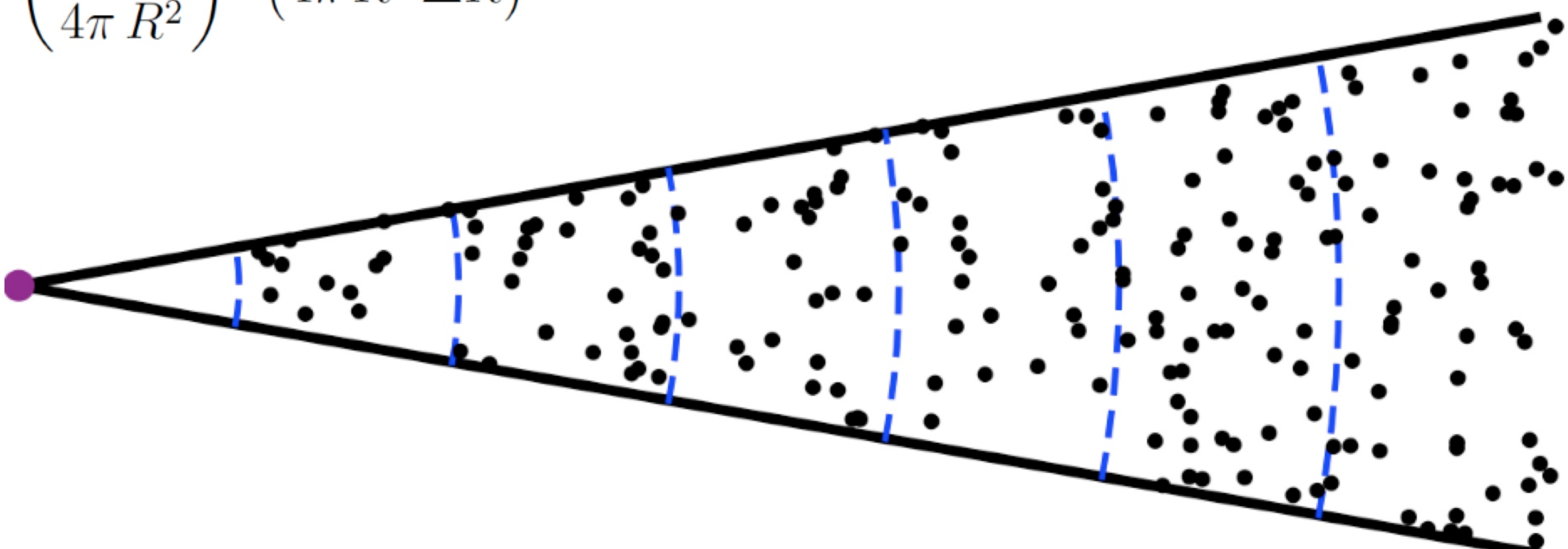
"energy redshift"

$$r(z) = \int_0^z \frac{dz'}{H(z')} = \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{1+\Omega_{\rm r}\,(1+z')^4 + \Omega_{\rm m}\,(1+z')^3 + \Omega_\Lambda}}$$

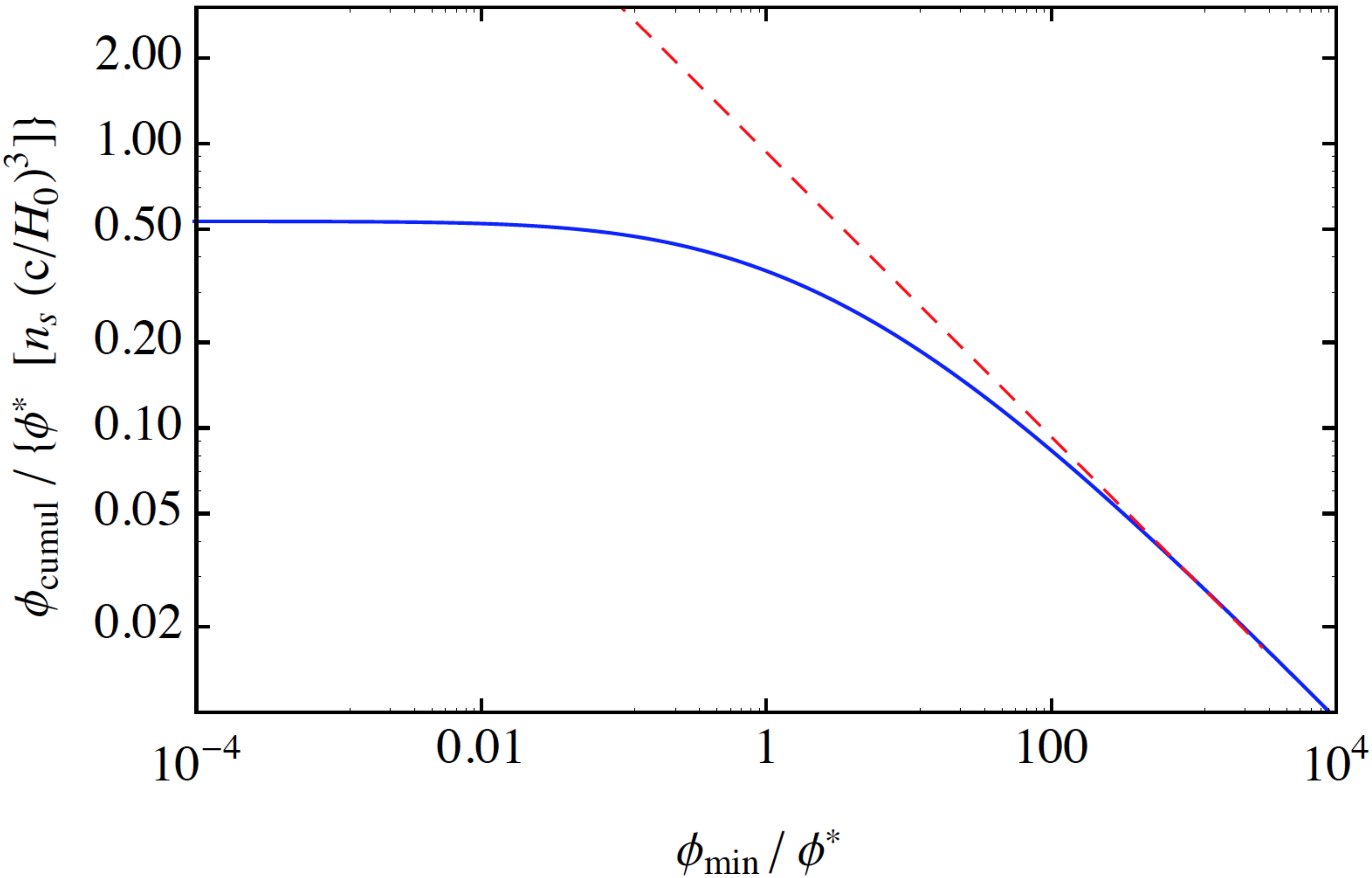
Ensemble of identical sources that
fill homogeneously the universe.

Static Euclidean universe:
Infinite flux ("Kepler Olbers Paradox")

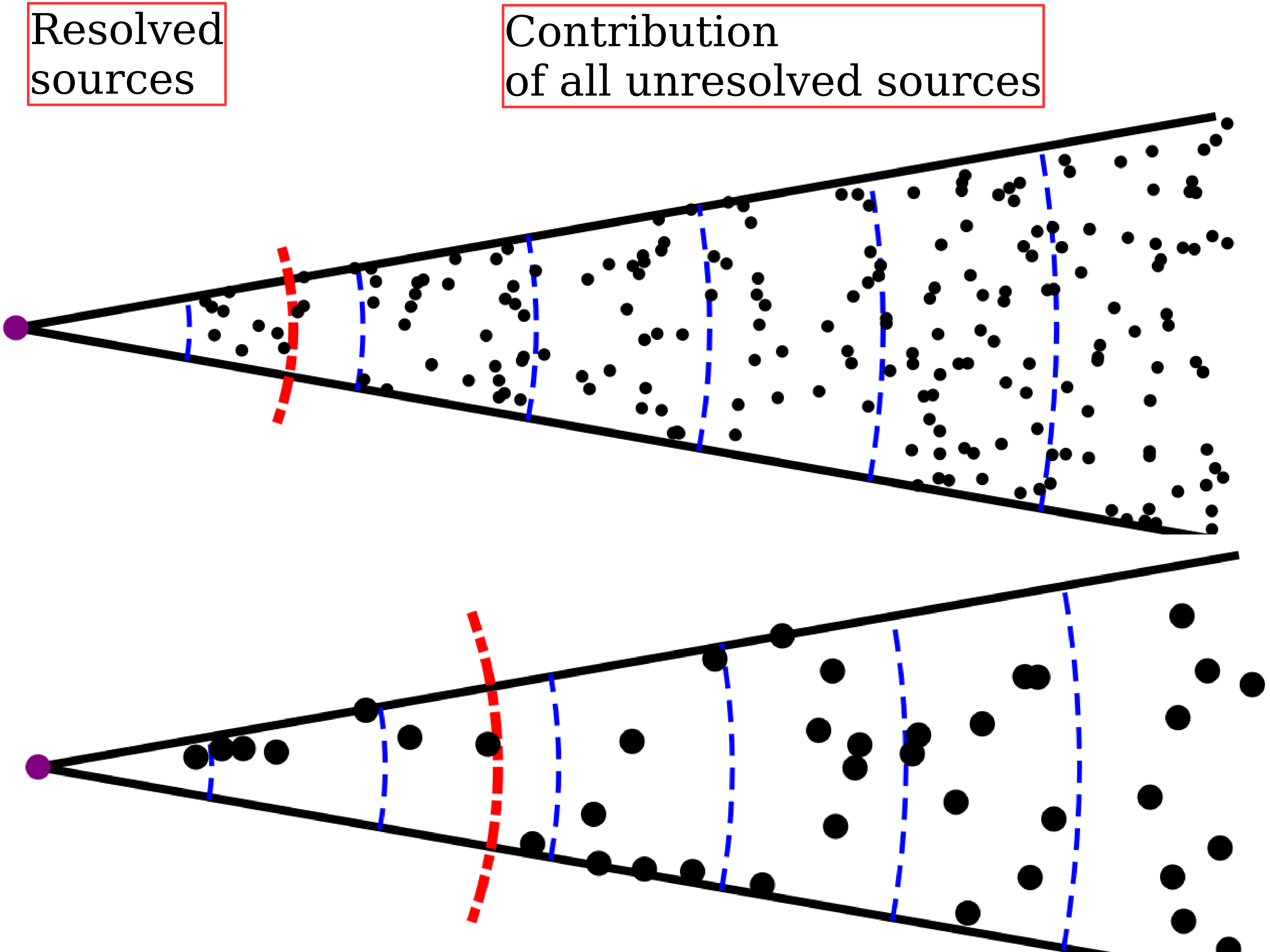
$$\left(\frac{1}{4\pi R^2}\right) \quad (4\pi R^2 \, \Delta R)$$



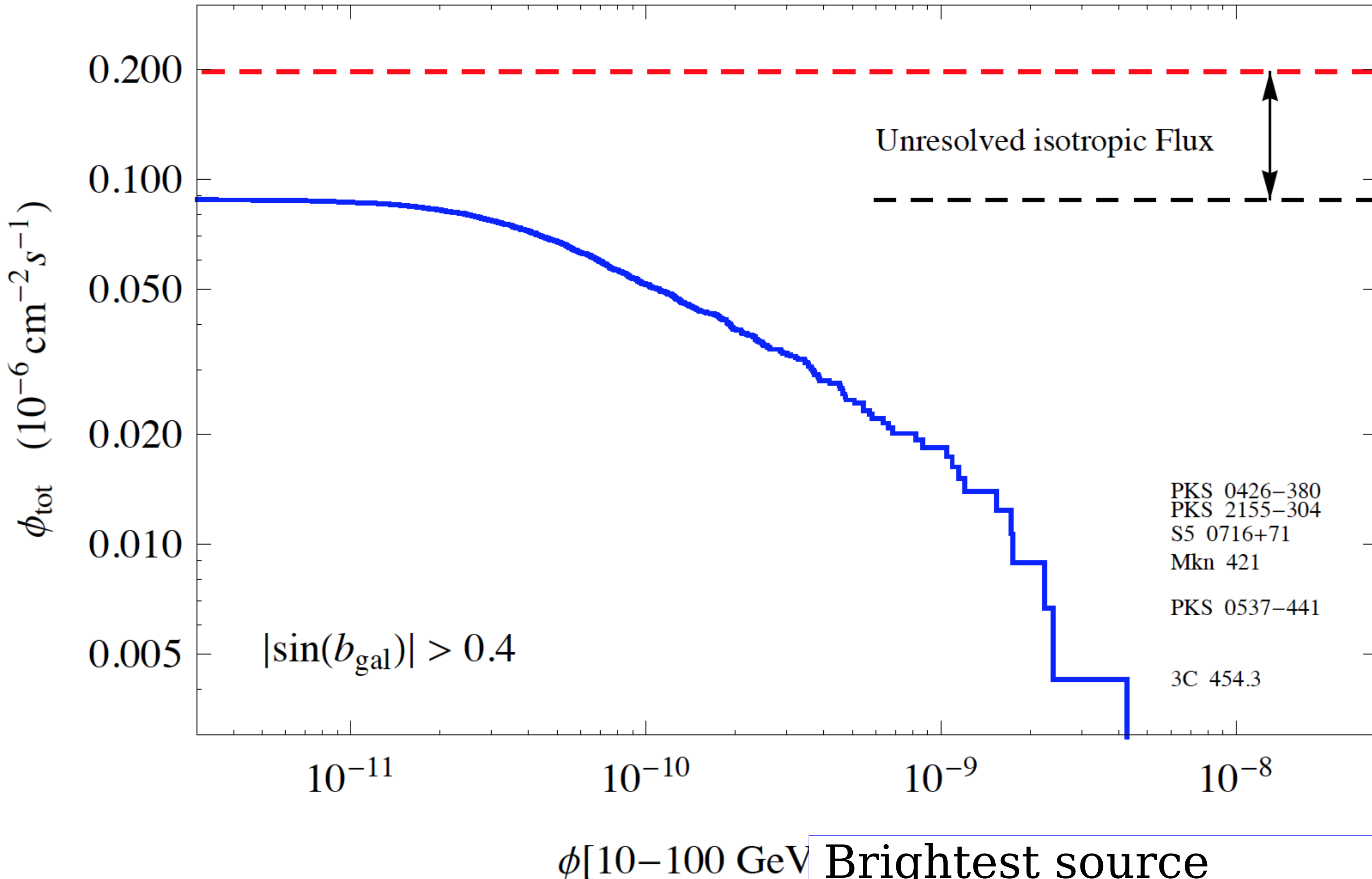
All spherical shells
contribute equally to the flux



$$\phi_* = \frac{q_s}{4\pi\,(c/H_0)^2}$$


Resolved sources
Contribution of all unresolved sources

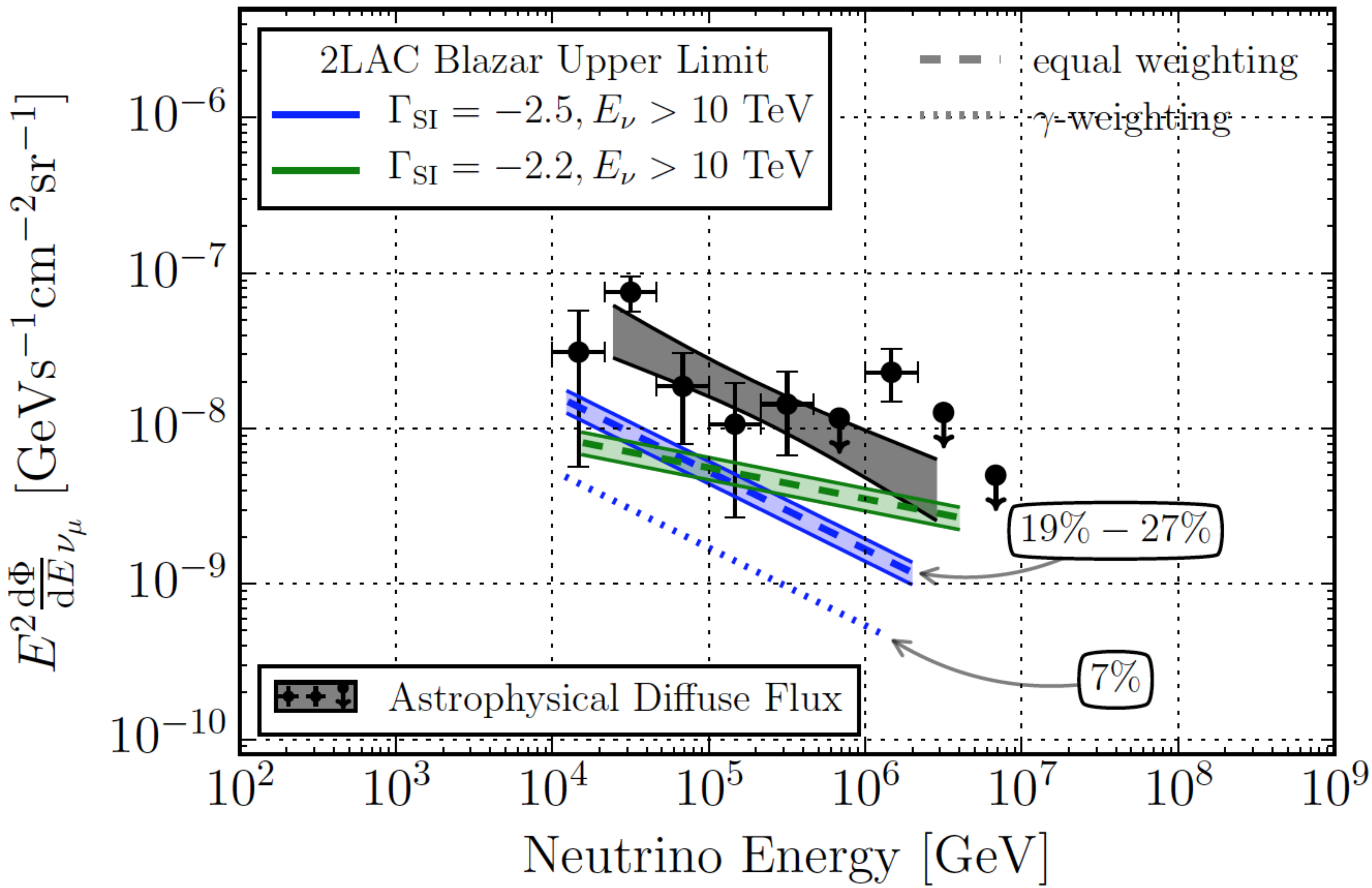
Extragalactic Flux : Resolved + unresolved sources



Extragalactic flux
dominated by “blazars” [AGN]

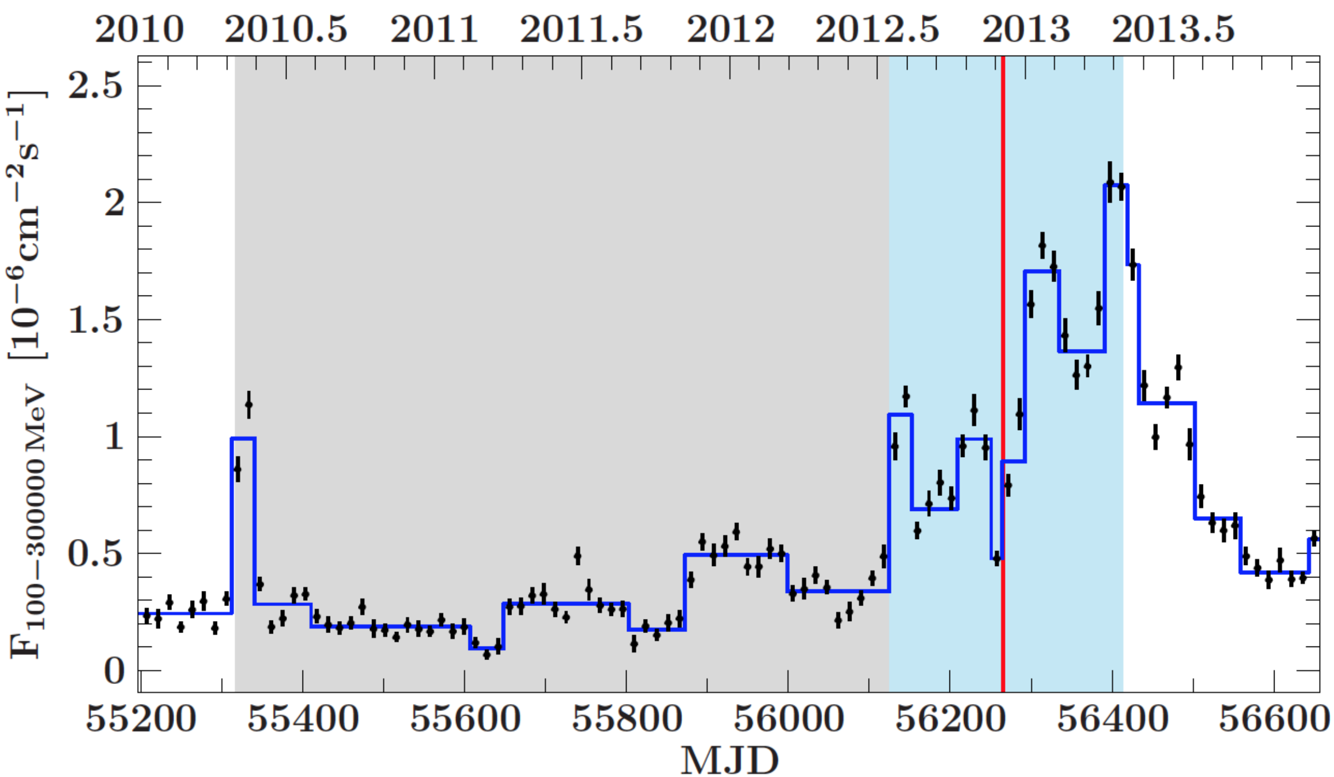
Brightest source
in the sky (3C454.3)
1.8 % of extragalactic light

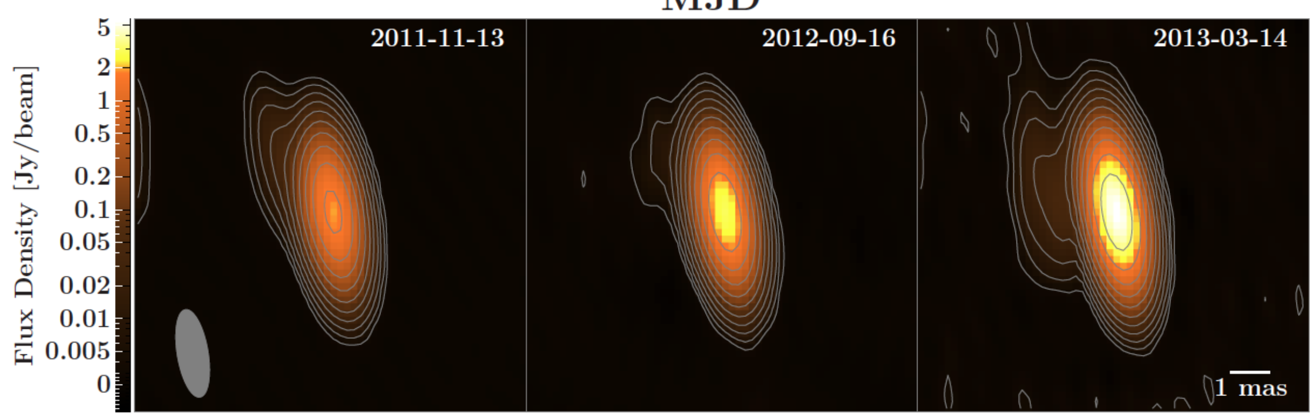
IceCube study of correlations with the FERMI 2LAC



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]].

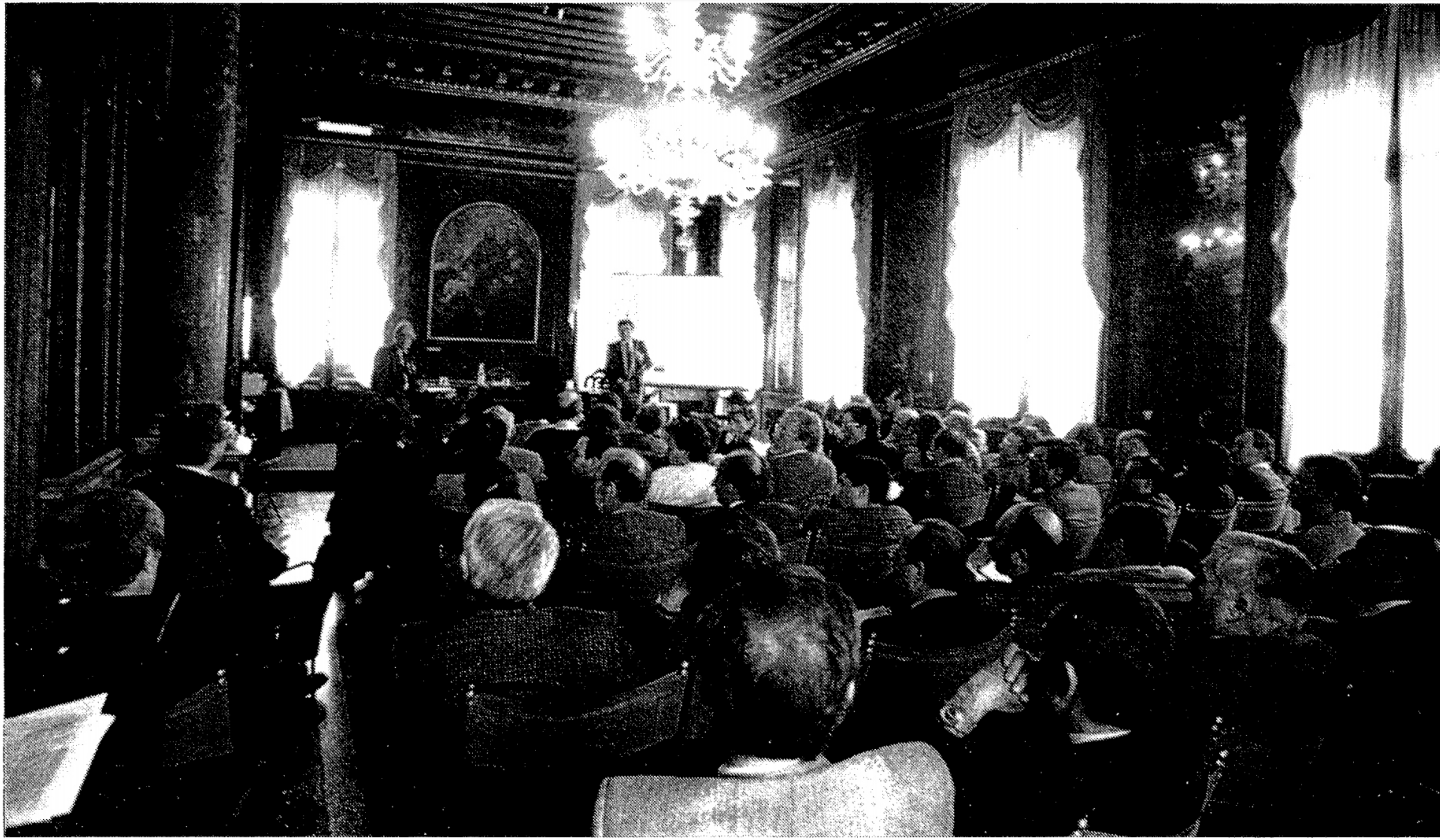
γ-ray light curve of PKS B1424−418.





5. Outlook

- What can we learn with astrophysical neutrinos ?



Modern physics in a classical setting – the Neutrino Telescopes Workshop in Venice's Palazzo Loredan.

Venezia 1989

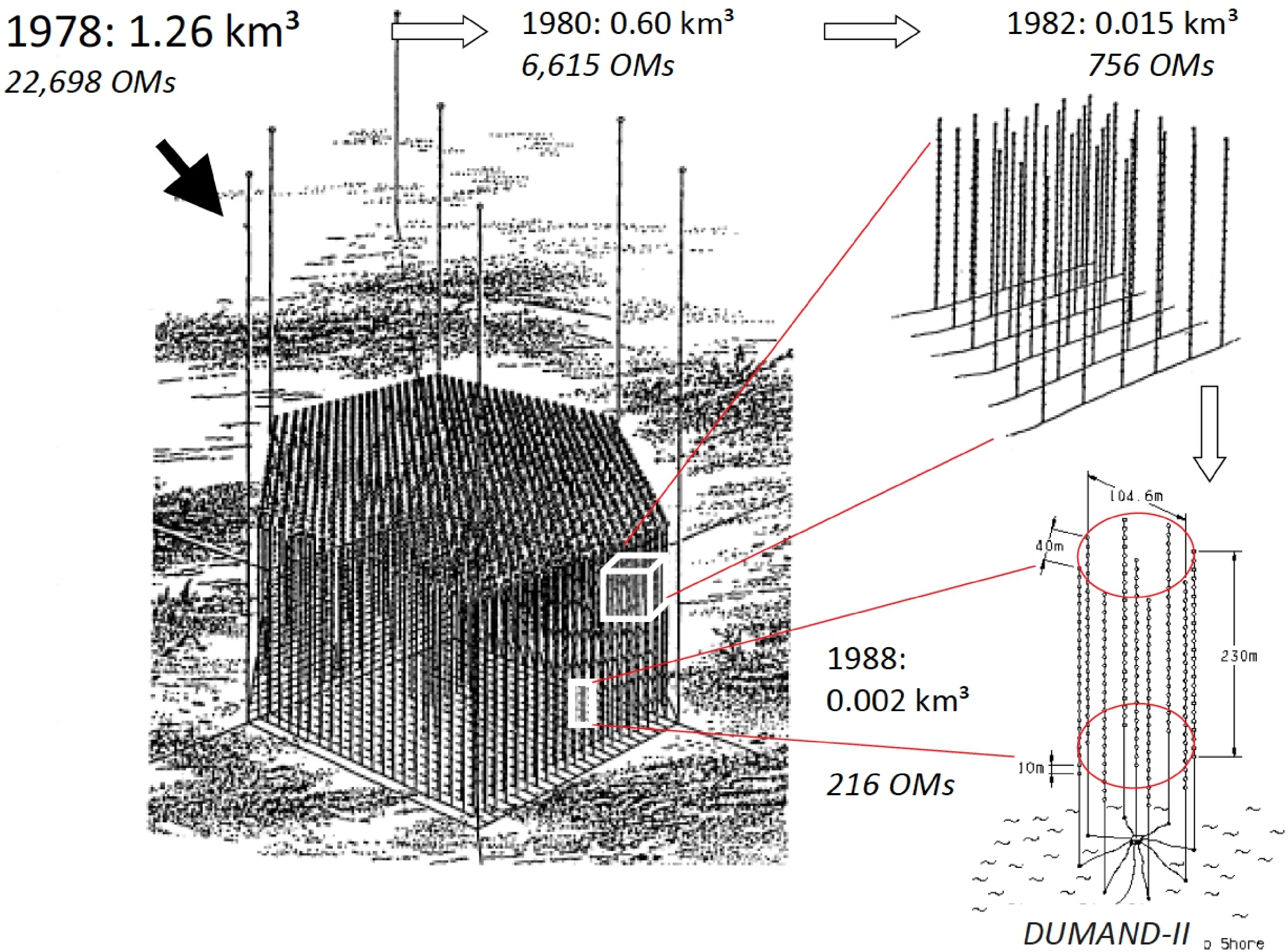
II Neutrino Telescope Workshop

CERN Courier 1989:

Picking up high energy neutrinos from distant sources is a major goal for the underground detectors (muons induced by atmospheric neutrinos are seen and their spectra are in reasonable agreement with calculations). The expected mechanisms for particle acceleration in binary stars and other systems, together with present data from high energy gamma ray telescopes, require that detectors intercepting neutrinos from distant point sources would have to be very large, bigger than 10^4 sq m, with good angular resolution, one degree or better, for the induced muons.

One natural solution to have cheap large area and volume is to go deep underwater and detect the muons by means of Cherenkov light. The DUMAND collaboration, after a successful test demonstrating the feasibility of an experiment 4000 m deep (June 1988, page 29), is about to set up its nine-string array off Hawaii. Meanwhile Soviet groups are at work in Lake Baikal and in the Mediterranean, and a US proposal aims at instrumenting an Arkansas lake for a combined neutrino- and gamma-ray telescope.

DUMAND idea


1978: 1.26 km³
22,698 OMs
1980: 0.60 km³
6,615 OMs
1982: 0.015 km³
756 OMs
1988:
0.002 km³
216 OMs
104.6m
40m
230m
10m
DUMAND-II

Letters to Nature 1991

1988

Nature **353**, 331-333 (26 September 1991) | doi:10.1038/353331a0; Accepted 26 July 1991

F. Halzen and J. G. Learned,
"High-energy Neutrino Detection In Deep Polar Ice,"
MAD/PH/428, UH-511-659-88.

Observation of muons using the polar ice cap as a Cerenkov detector

D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡

1. *, Department of Physics, University of California, Berkeley, California 94720, USA
†, Department of Physics, University of California, Irvine, California 92717, USA
‡Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA

DETECTION of the small flux of extraterrestrial neutrinos expected at energies above 1 TeV, and identification of their astrophysical point sources, will require neutrino telescopes with effective areas measured in square kilometres—much larger than detectors now existing[1–3]. Such a device can be built only by using some naturally occurring detecting medium of enormous extent: deep Antarctic ice is a strong candidate. A neutrino telescope could be constructed by drilling holes in the ice with hot water into which photomultiplier tubes could be placed to a depth of 1 km. Neutrinos would be recorded, as in underground neutrino detectors using water as the medium, by the observation of Cerenkov radiation from secondary muons. We have begun the AMANDA (Antarctic Muon and Neutrino Detector Array) project to test this idea, and here we describe a pilot experiment using photomultiplier tubes placed into Arctic ice in Greenland. Cerenkov radiation from muons was detected, and a comparison of count rate with the expected muon flux indicates that the ice is very transparent, with an absorption length greater than 18 m. Our results suggest that a full-scale Antarctic ice detector is technically quite feasible.

▲ Top

AMANDA 1992

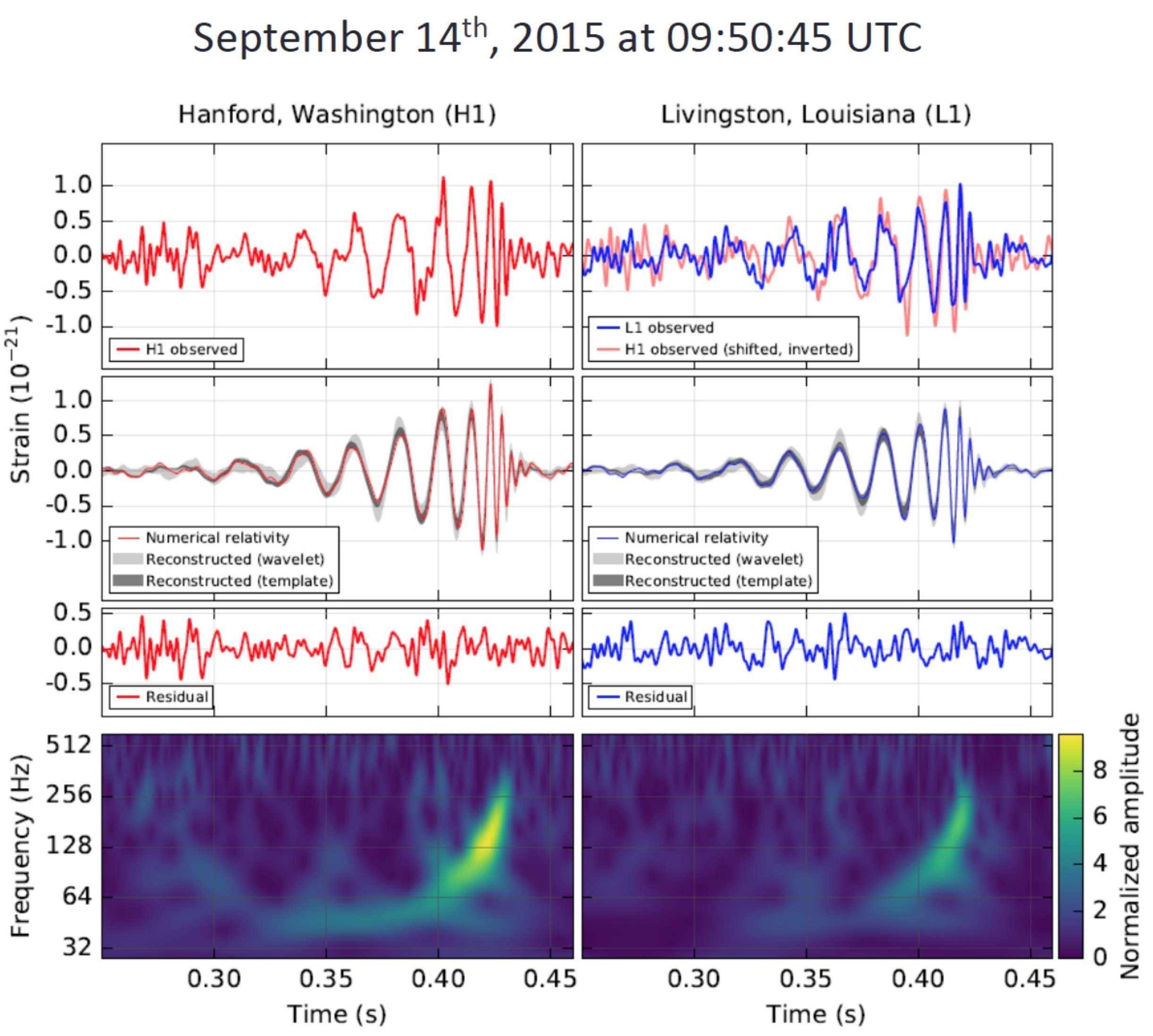
F. Halzen *et al.*,
"Antarctic muon and neutrino detector array,"
In *Venice 1992, Neutrino telescopes* 449-466

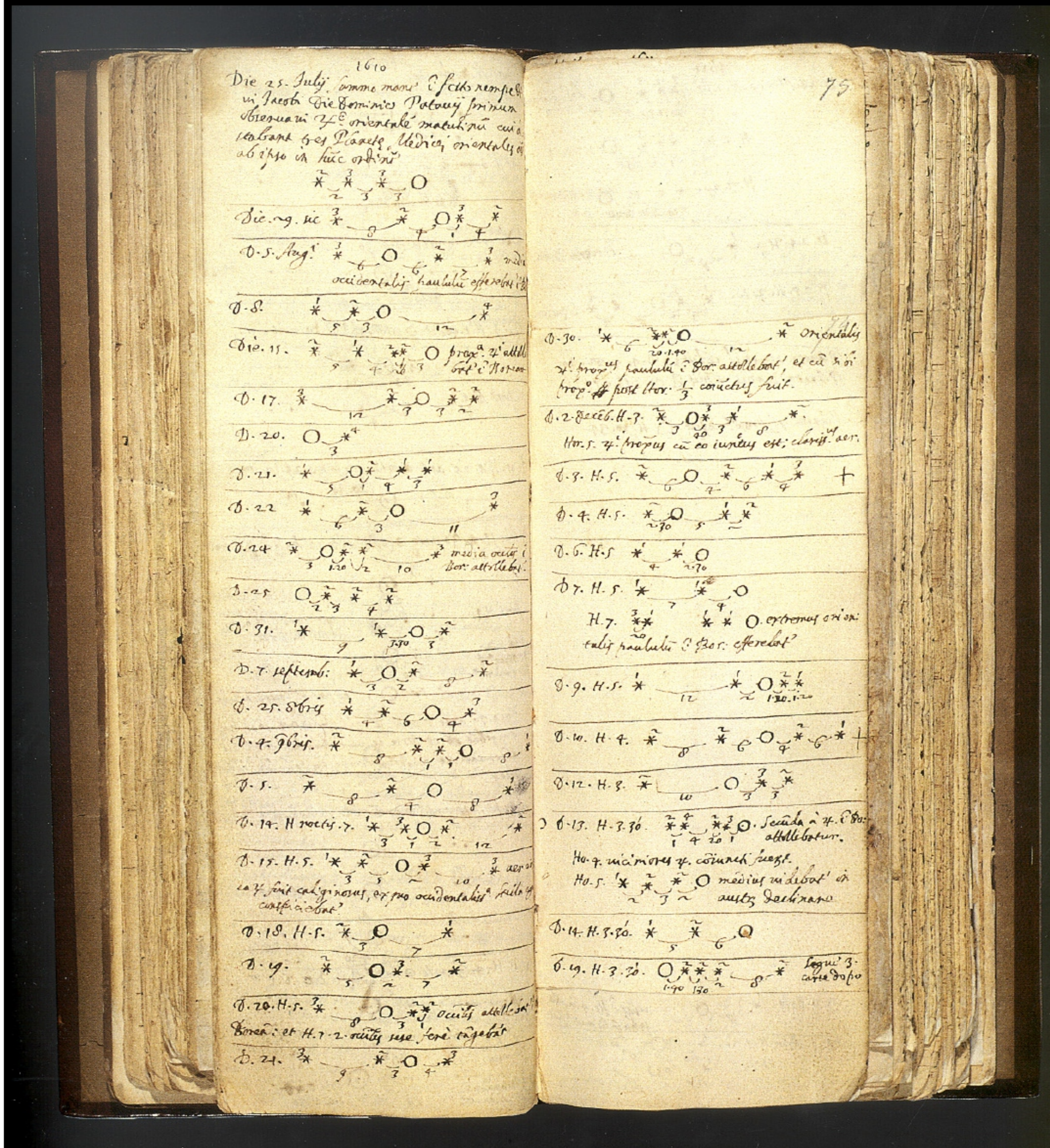
Neutrino Astrophysics
has made extraordinary progress

More in general:
Multi-messenger Astrophysics
is demonstrating to be a vibrant field,
and our understanding of the
"High Energy Universe"
is making rapid progress

GW150914: the signal

- Top row left – Hanford
- Top row right – Livingston
- Time difference ~ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)
- Third Row –residuals
- Bottom row – time frequency plot showing frequency increases with time (chirp)





from :Eugenio Coccia

7.5 msec

13.8 msec

15.26 msec

26.5 msec

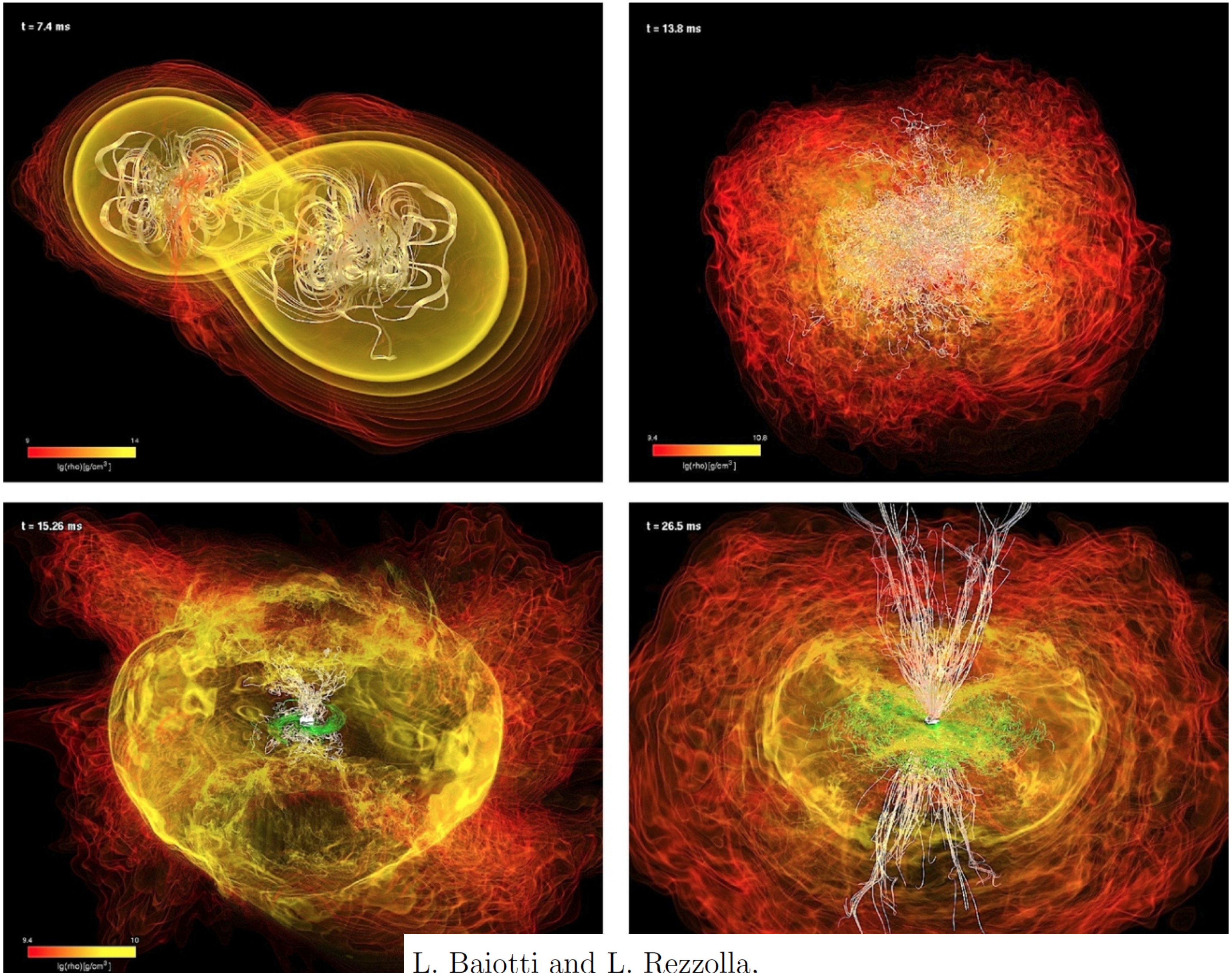


Figure 1. Snapshots at representative times of the evolu
the density, over which the magnetic-field lines are supe
to BH (t = 13.8 ms), while those in the lower row to th
in the torus and on the equatorial plane, while white lin
size of ~90/170 km, while the horizon has a diameter

L. Baiotti and L. Rezzolla,
"Binary neutron-star mergers: a review of Einstein's richest laboratory,"
Reports on Progress of Physics
arXiv:1607.03540 [gr-qc].

M. Kadler *et al.*,
"Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event,"
Nature Phys. **12**, no. 8, 807 (2016)
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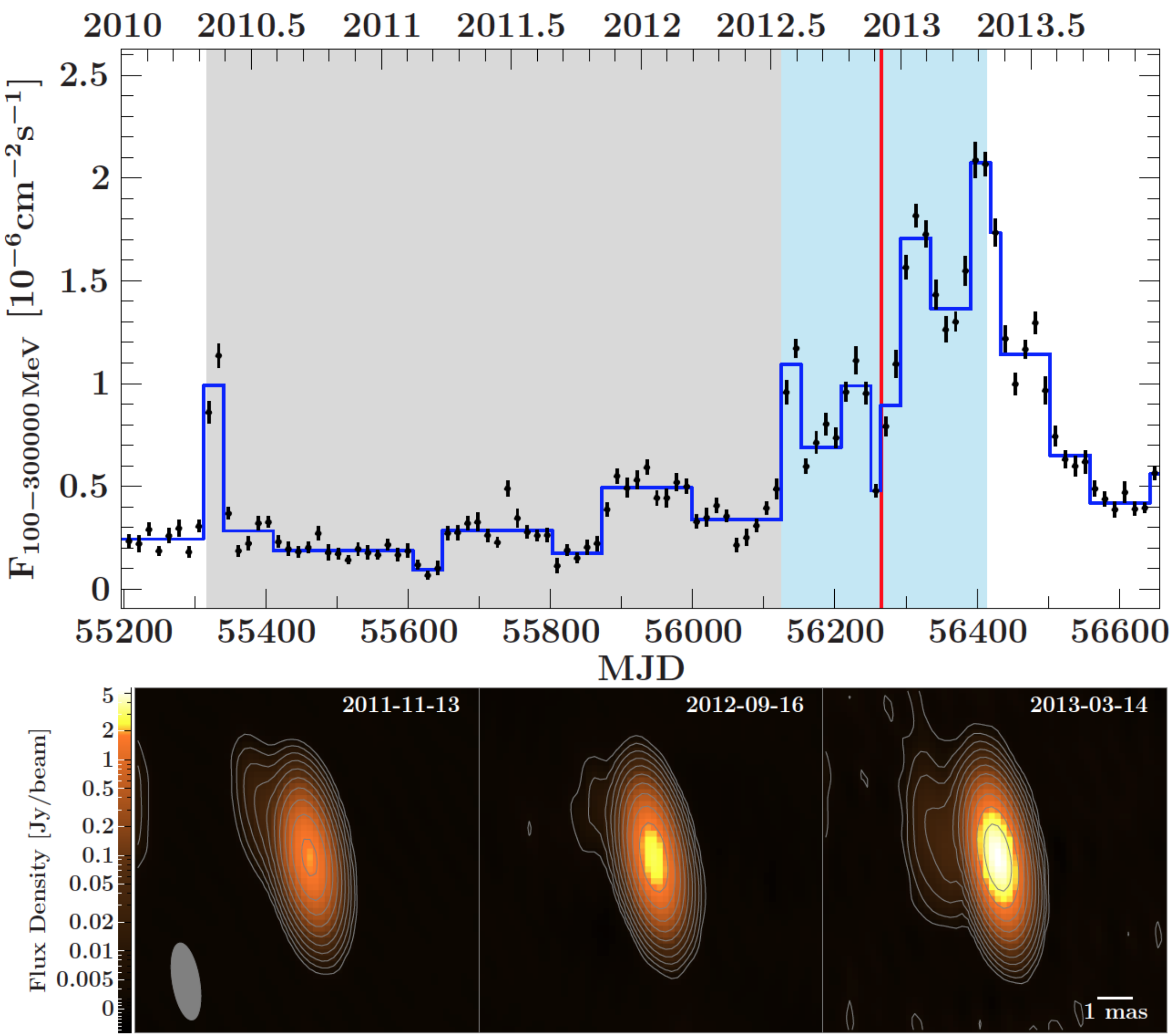
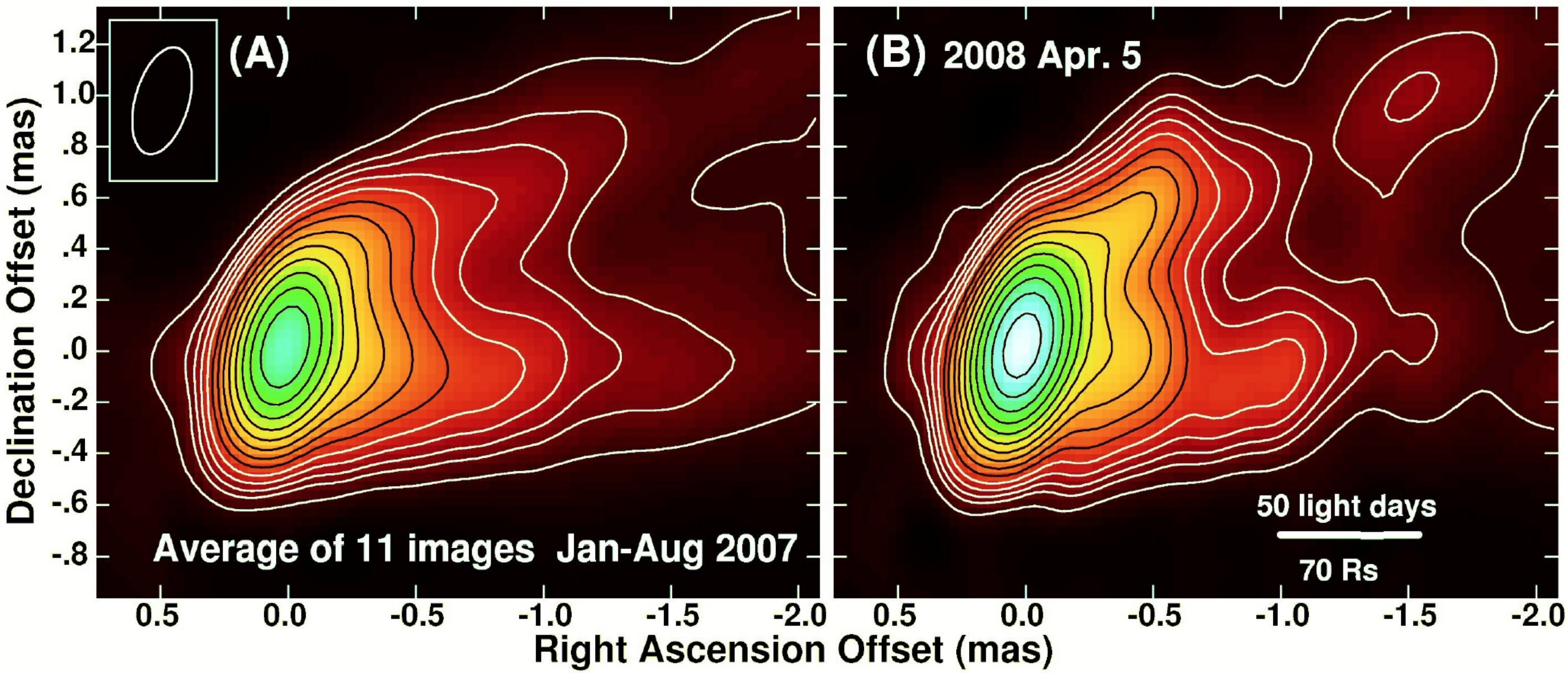


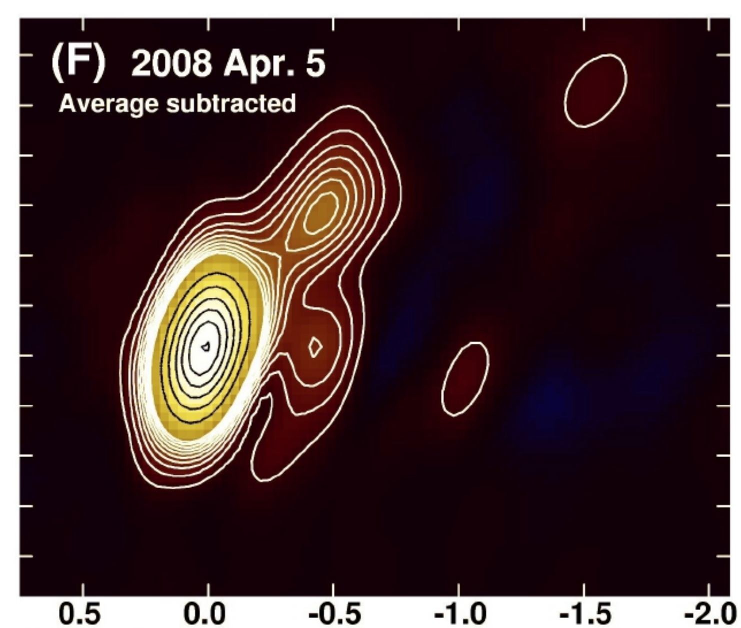


VLBA radio images of M87 at 43 GHz

Science 24 Jul 2009:
Vol. 325, Issue 5939, pp. 444-448
DOI: 10.1126/science.1175406

Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy

The VERITAS Collaboration, the VLBA 43 GHz M87 Monitoring Team, the H.E.S.S. Collaboration, the MAGIC Collaboration



The opening up of Gravitational Wave Astronomy
is a remarkable new development,

Hopefully the “dream” of merging information
from

Gravitational Waves
Multi-wavelength photon studies
Neutrino emission

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