Gamma Ray Astronomy

at Very High Energy

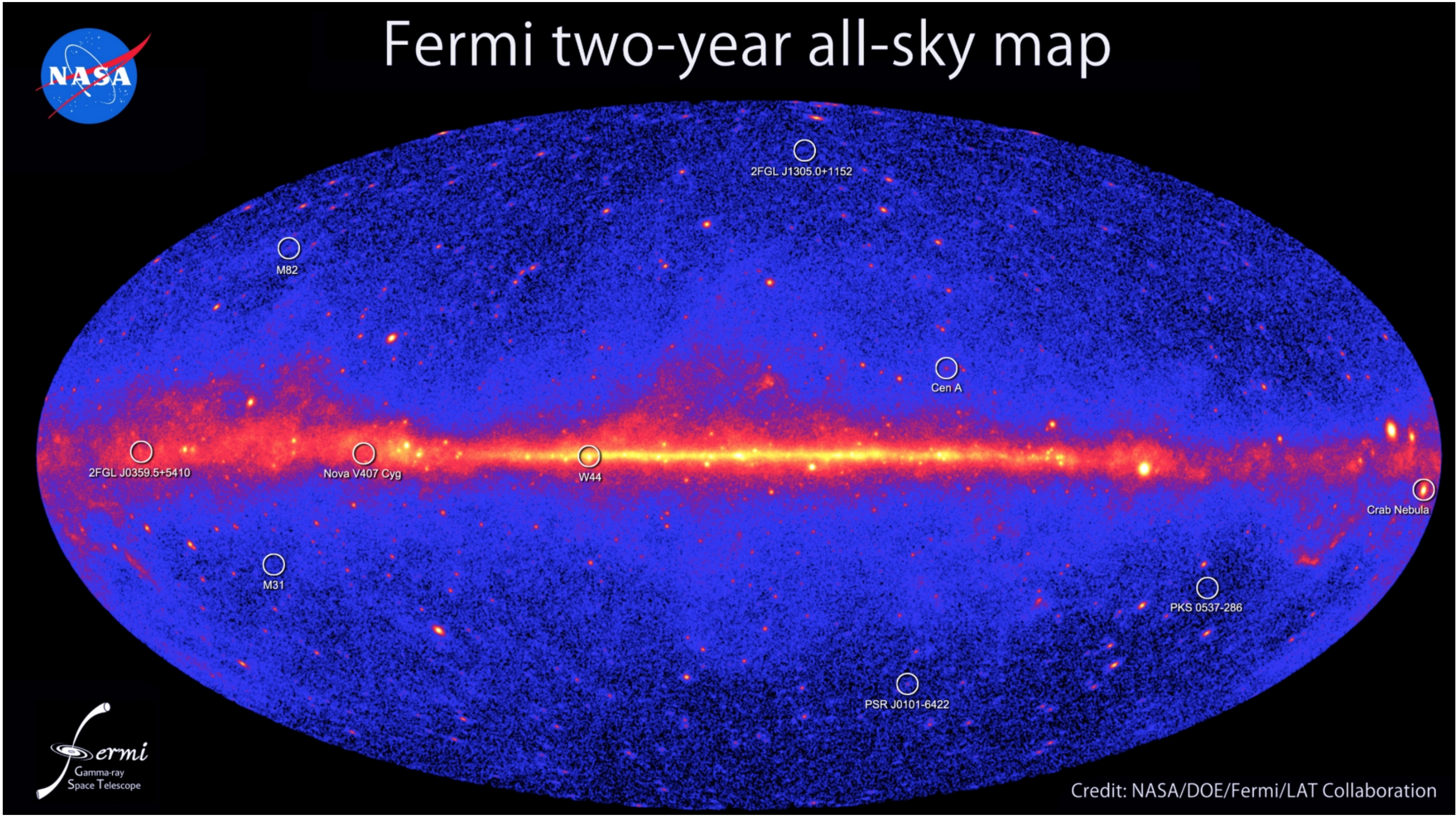
(E > 100 TeV)

Paolo Lipari, INFN Roma "Sapienza"

7th workshop on
Air Shower Detection at High Altitude

Torino 1st december 2016

Extraordinary success of Gamma Astronomy

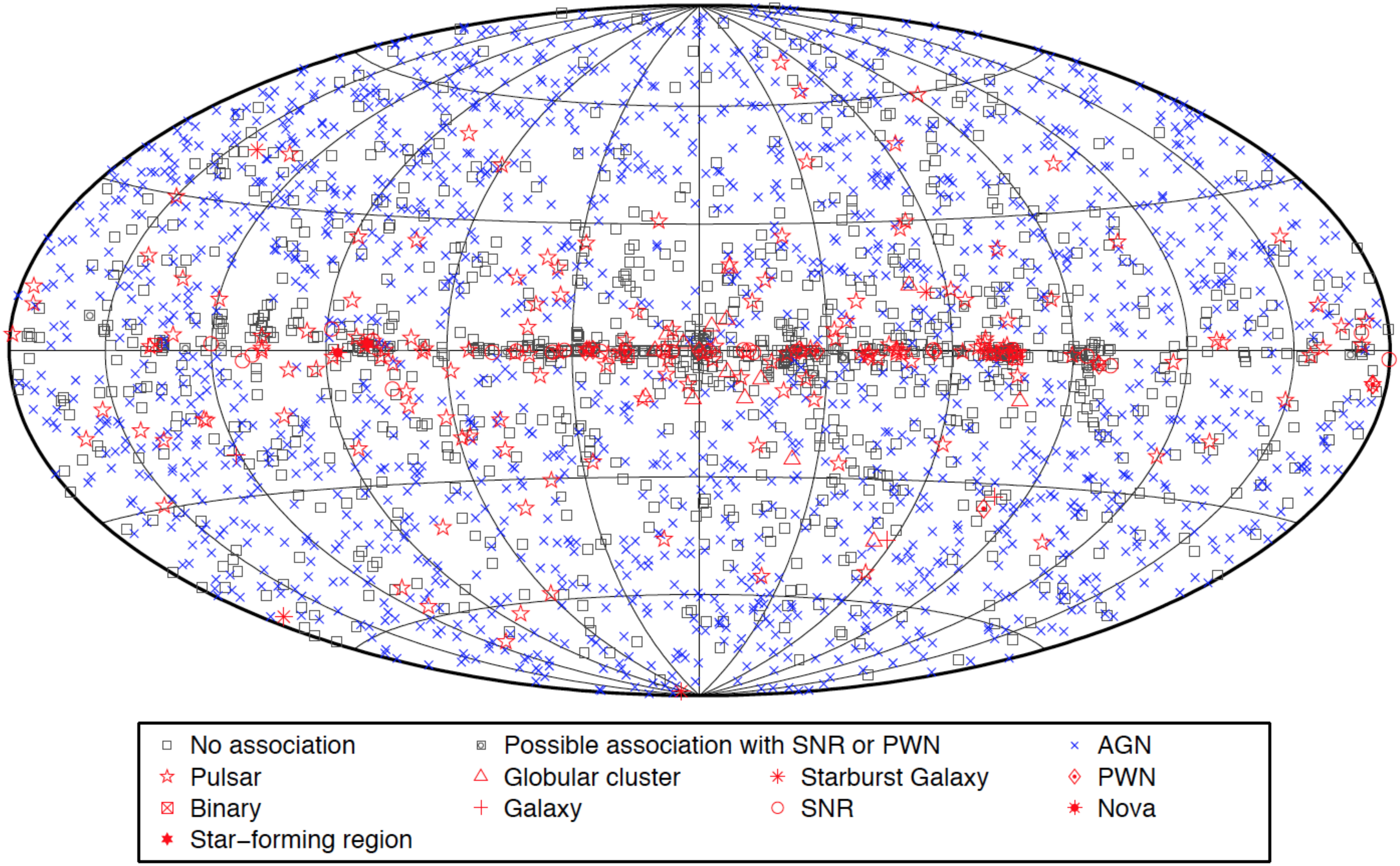


Credit: NASA/DOE/Fermi/LAT Collaboration

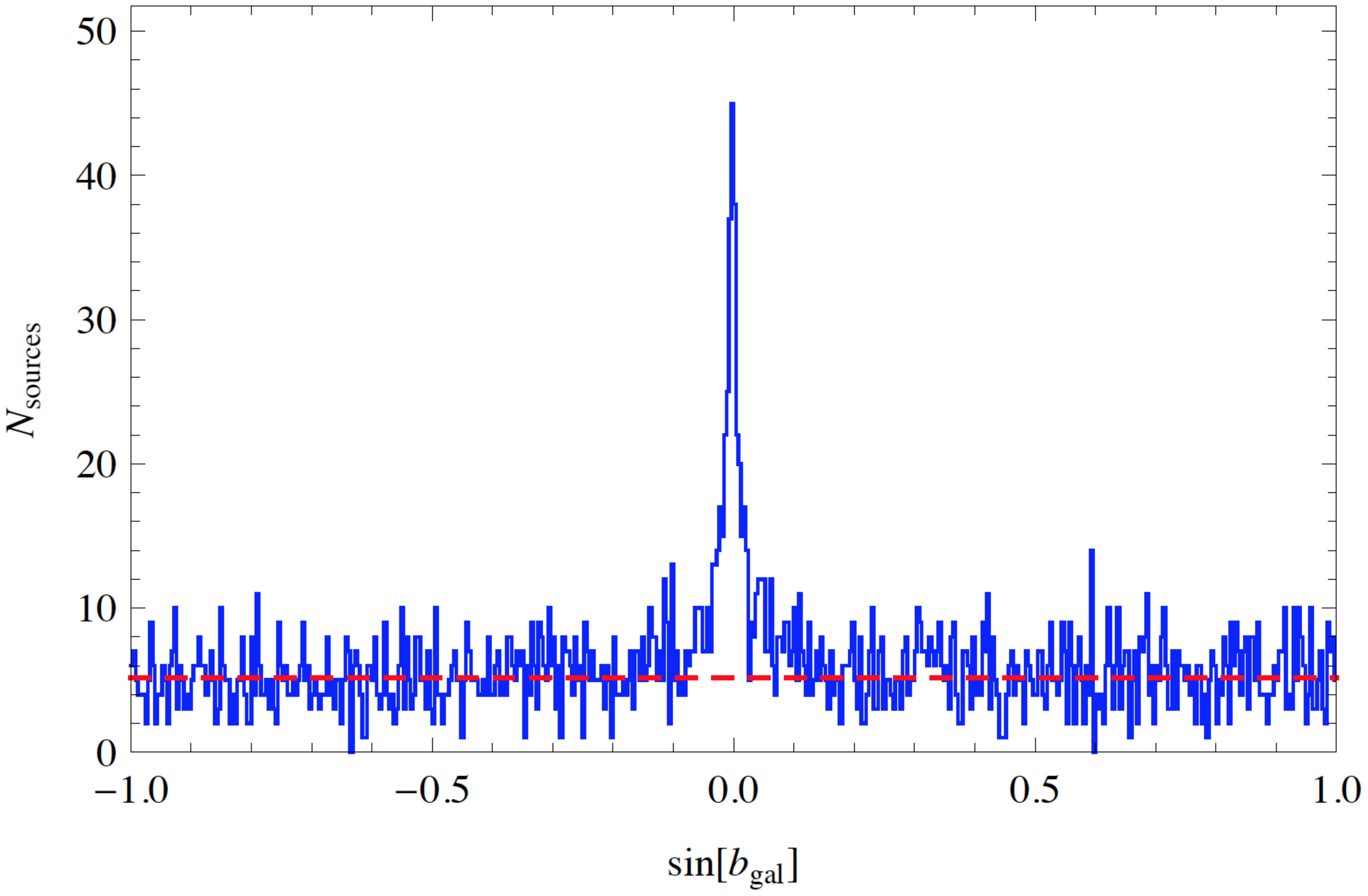
3rd FERMI Catalog

3034 sources

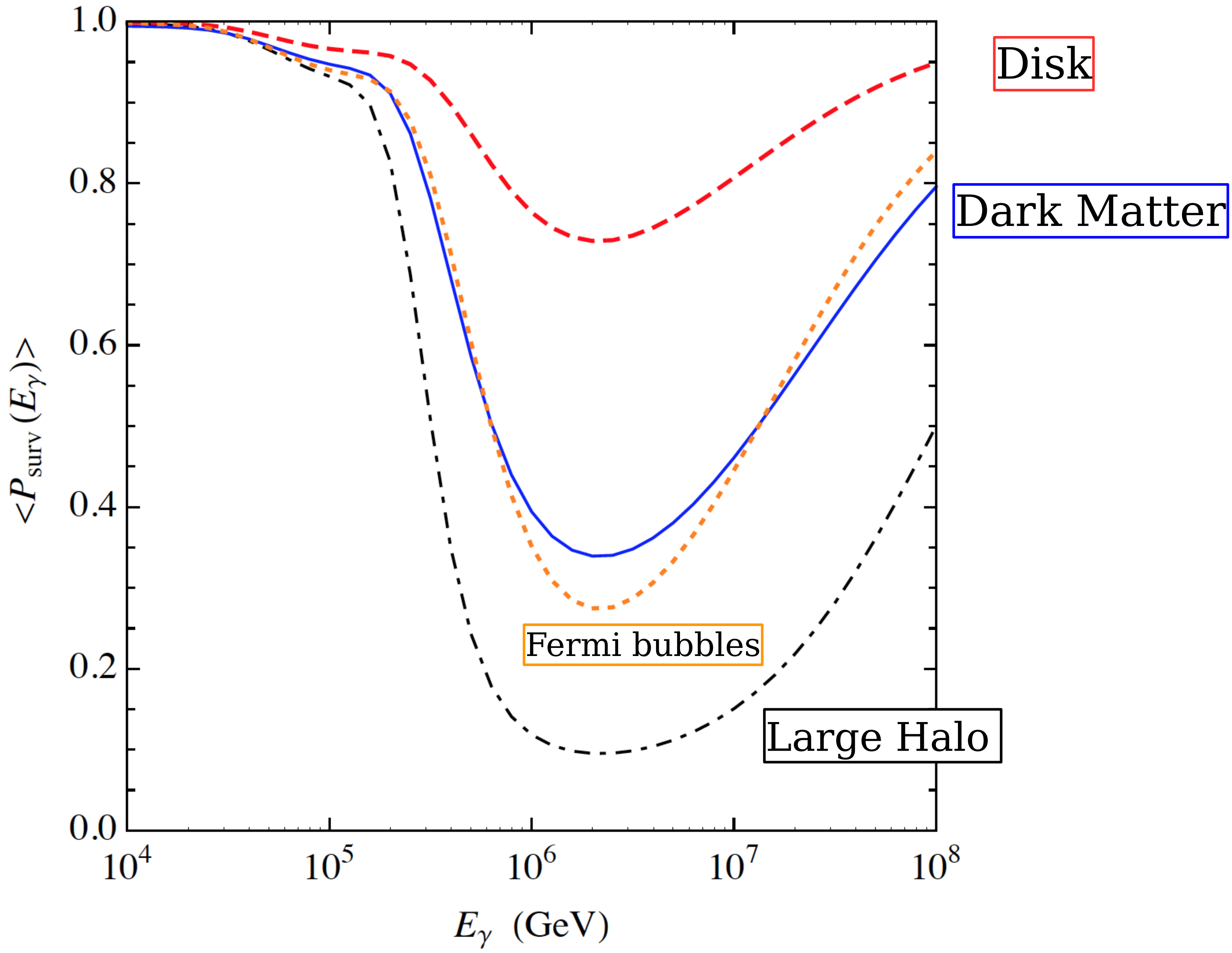
E > 100 MeV



3034 3rd catalog sources [approximately 440 are galactic]

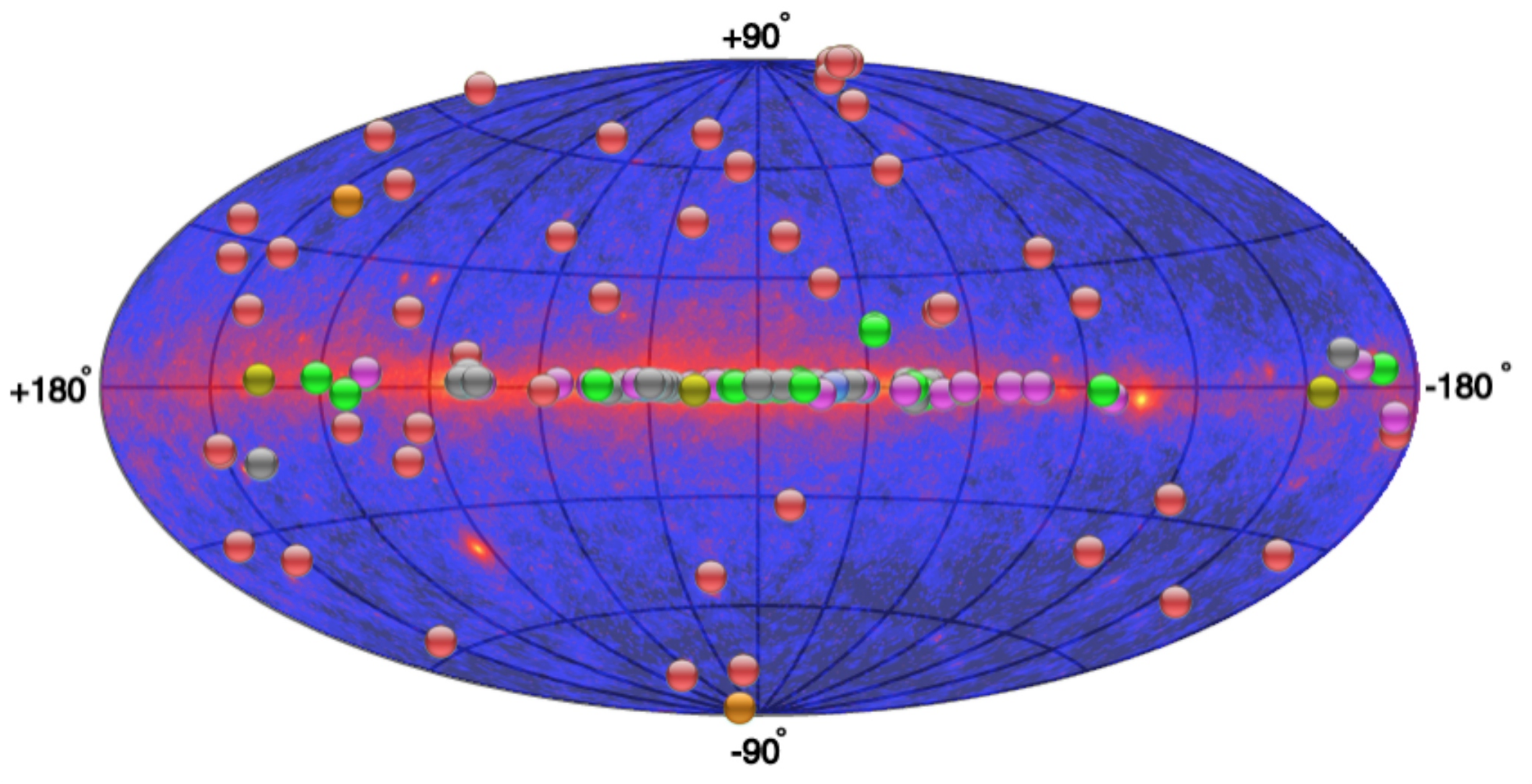


Average (all sky) Survival probability

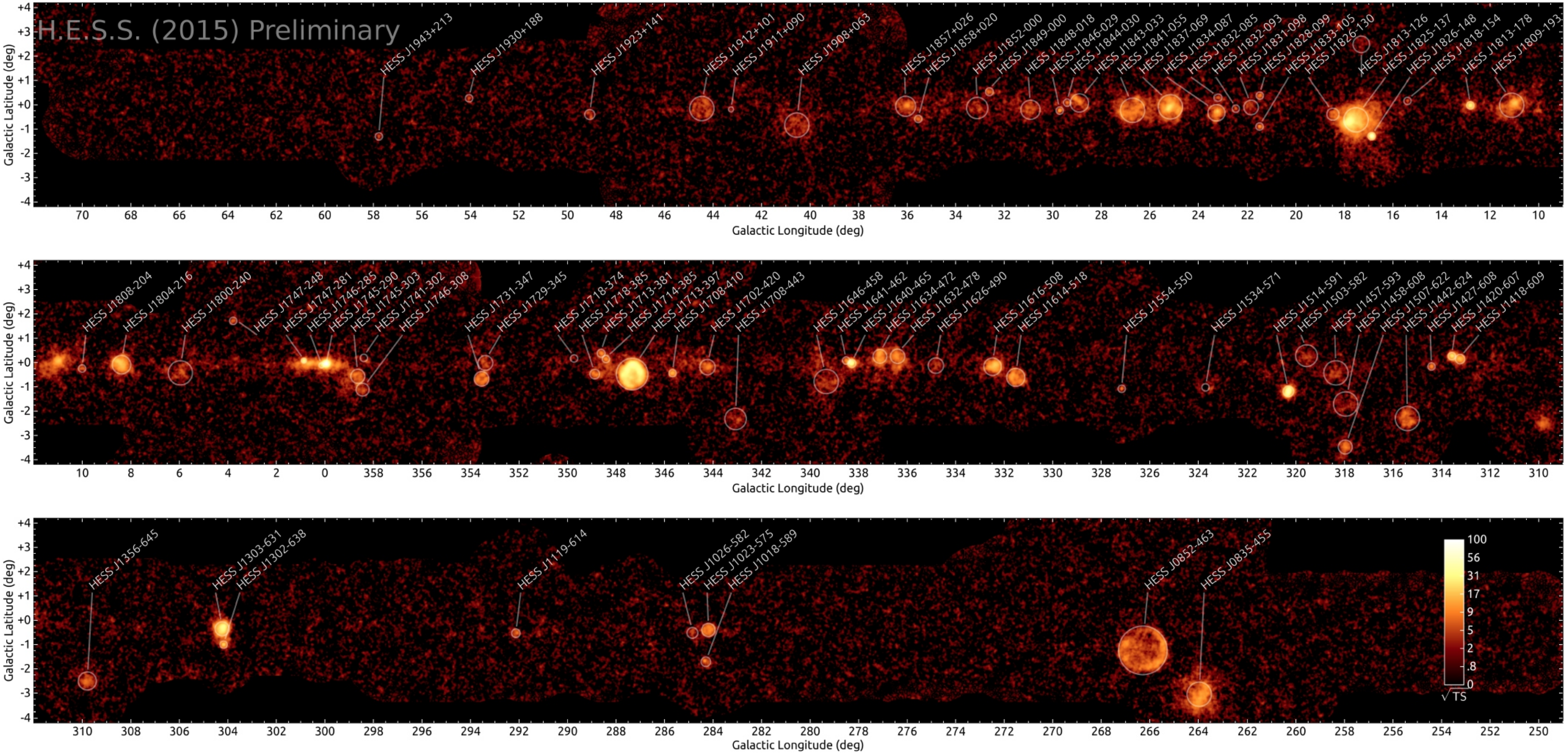


TeV Sky

170 → 200 Sources

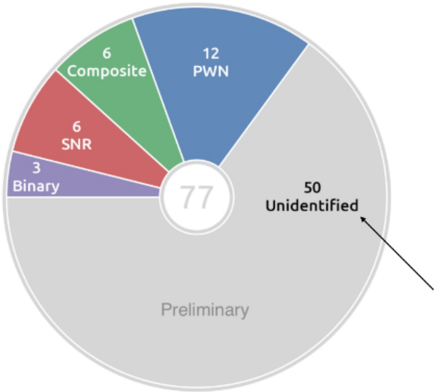


blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky



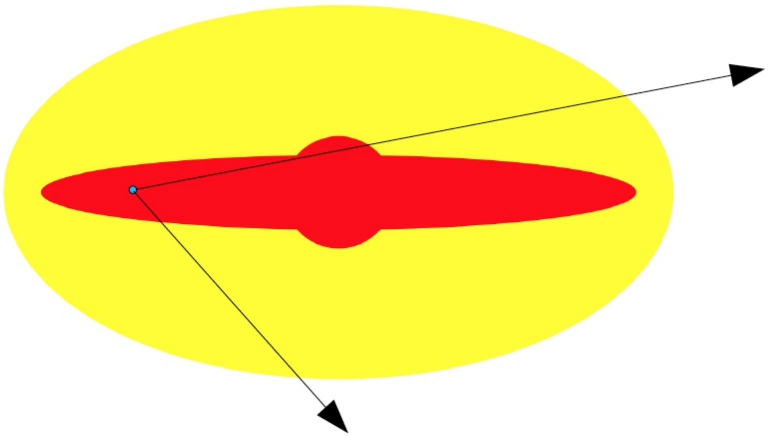
Firm identifications

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



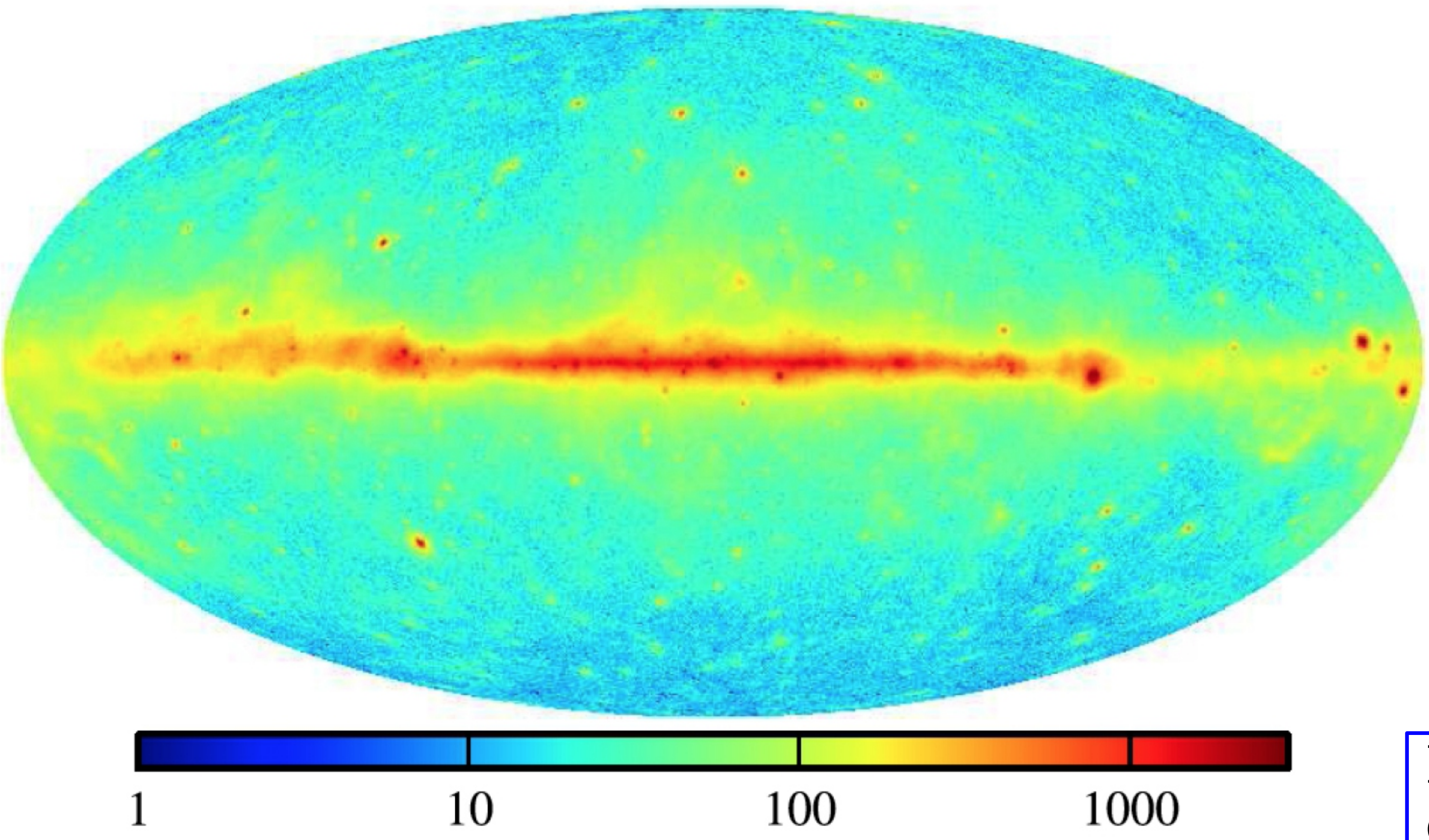
Mostly sources with multiple associations

Diffuse Emission



Fermi–LAT counts

Galactic coordinates



energy range 200 MeV to 100 GeV

Diffuse gamma rays
dominate the
all-sky emission

Several natural direction for the future:

Space detection

Cherenkov Telescopes

Air Shower Photon Detectors

[high altitude essential]

Higher sensitivity at “low energy”

Toward very high energy
100 TeV → PeV and possibly beyond

Sensitivity of an Air Shower Detector to a *point source* of Gamma Rays of celestial coordinates $\{\alpha, \delta\}$ in a detector of geographical latitude λ

Signal of Gamma Rays (above a minimum energy)

$$S \simeq \Phi_\gamma(E_{\rm min}) \; A \; T \; a(\delta, \lambda) \; \varepsilon_\gamma$$

Background (from Cosmic Rays)

$$B \simeq \Phi_{\rm cr}(E_{\rm min}) \; A \; T \; a(\delta, \lambda) \; \Delta\Omega \; \varepsilon_{\rm cr}$$

$$S \geq n_\sigma \; \sqrt{B}$$

$a(\delta, \lambda)$	(adimensional) exposure factor [visibility of source]
$\varepsilon_{\mathbf{cr}}$	Hadron Rejection factor
ε_{γ}	Gamma Ray identification efficiency
$\Delta\Omega \simeq \pi \, (\delta\theta)^2$	Detector Angular resolution
$\simeq \pi \, (1.585 \, \sigma_\theta)^2$	Gaussian point spread function

Visibility factor: $a(\delta, \lambda)$

adimensional quantity that takes into account:

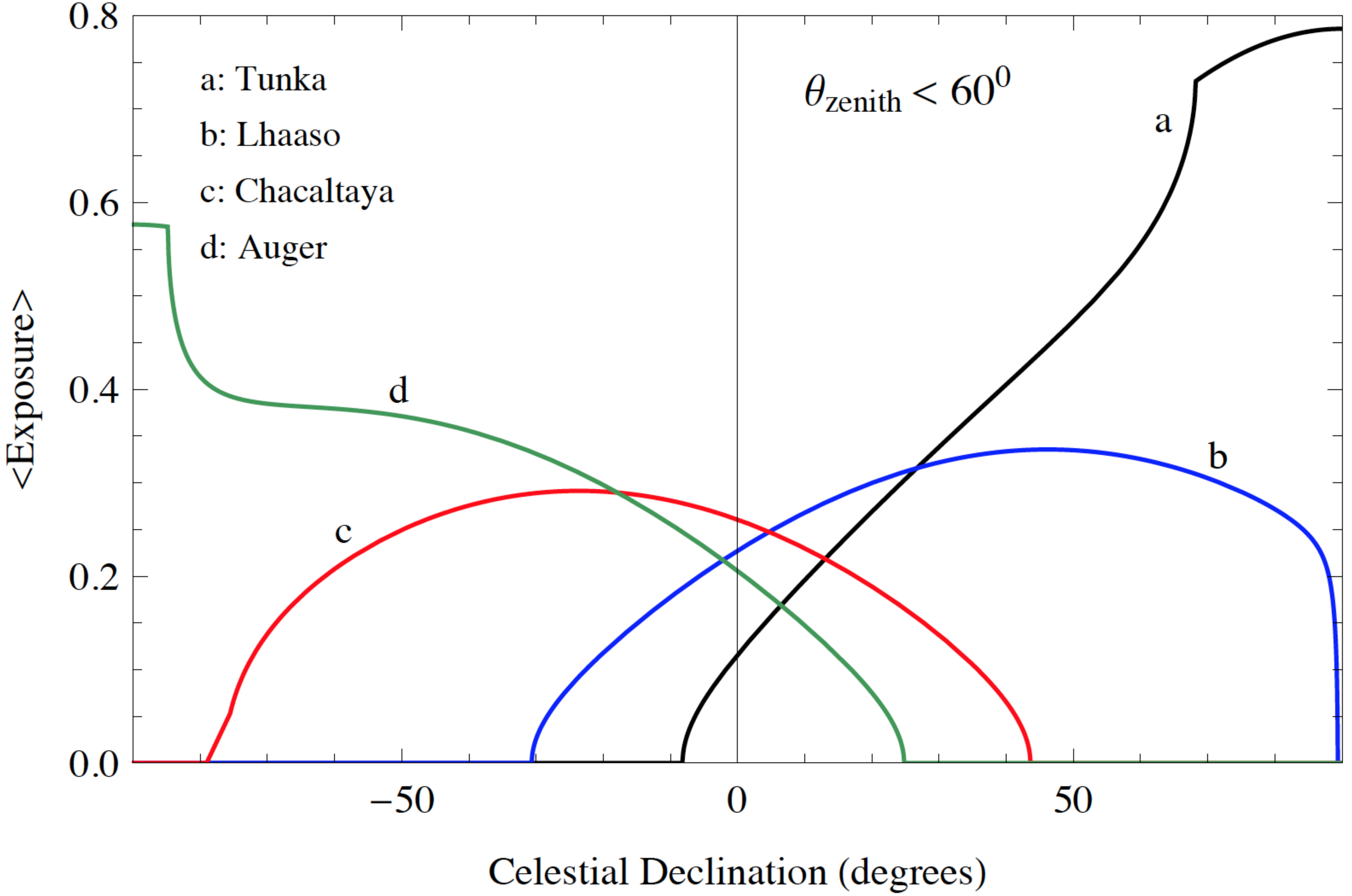
[1.] the fraction of time that a source is
in the detector field of view,

[2.] the (variable) inclination of the source.

$$a(\delta, \lambda, \theta_{\max}) = \frac{1}{2\pi} \int_0^{2\pi} dh \;\cos\theta(\delta, \lambda, h)\; \Theta[\theta_{\max} - \theta(\delta, \lambda, h)]$$

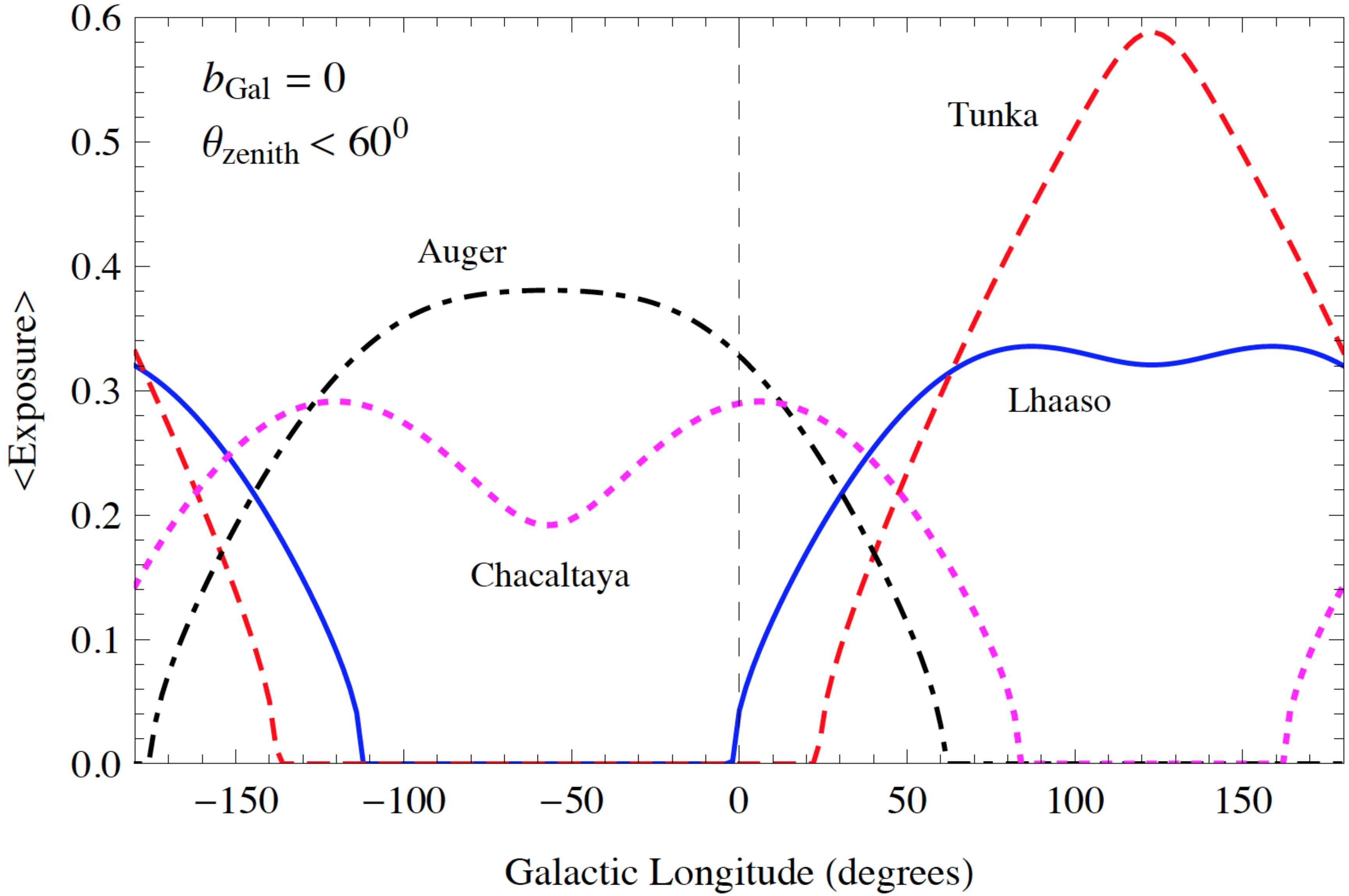
Integrating over all declination gives a result that is
independent from the detector latitude

$$\int_{-1}^{1} d\sin\delta \; a(\delta, \lambda) = \frac{\sin^2\theta_{\max}}{2}$$

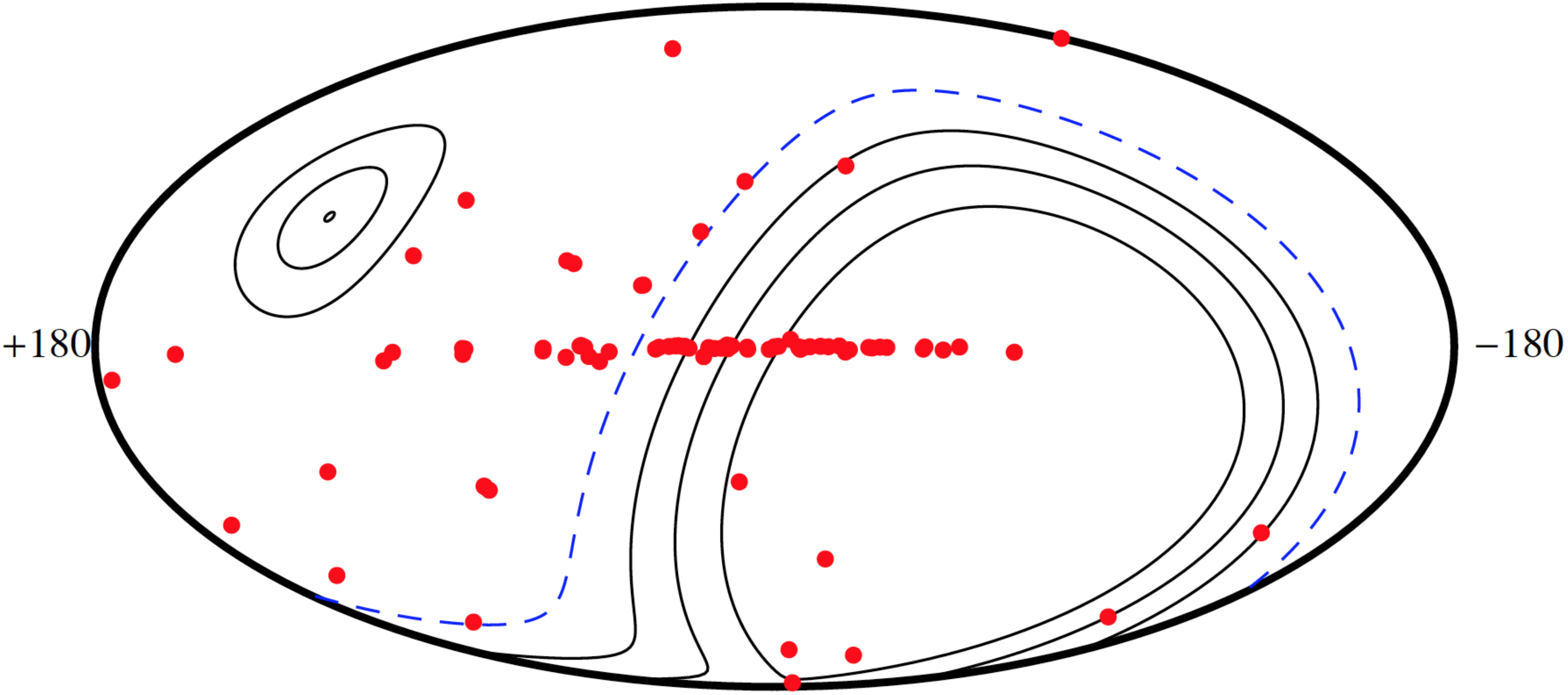

0.8
0.6
0.4
0.2
0.0
−50
0
50
<Exposure>
Celestial Declination (degrees)
a: Tunka
b: Lhaaso
c: Chacaltaya
d: Auger
$\theta_{zenith} < 60^0$
a
b
c
d

Visibility of the Galactic Disk

$$a[\delta(\ell, b=0);\ \lambda]$$

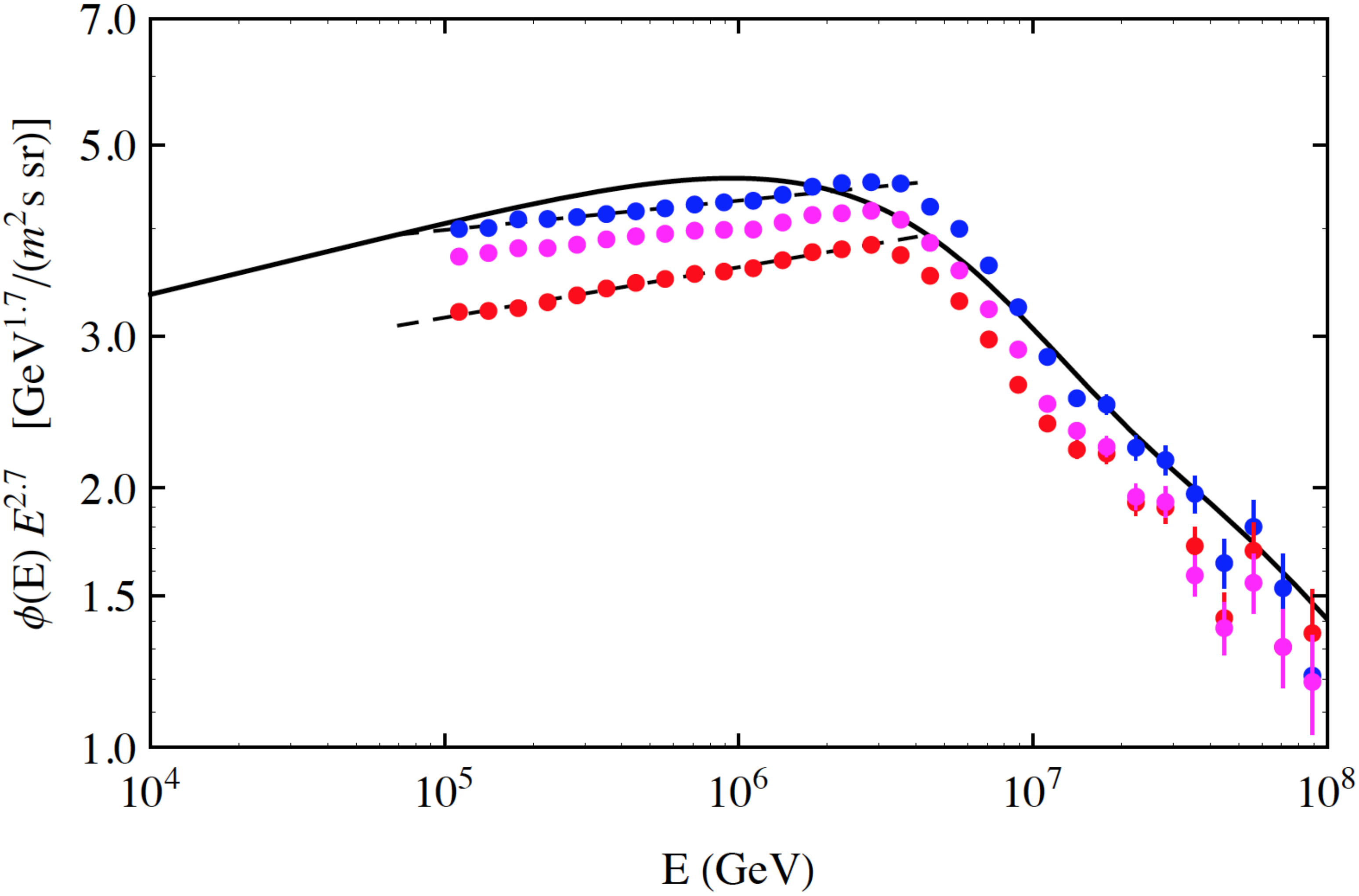


Sky visibility for the LHAASO detector position



Points =
TeVCat Sources

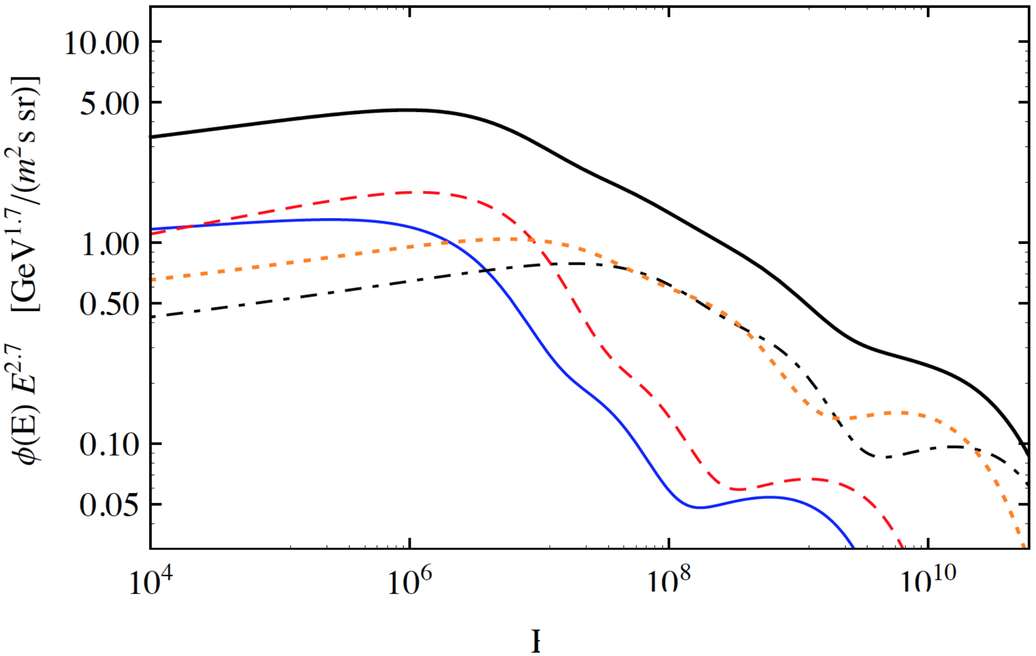
Evaluation of the Background:
Spectra of Cosmic Rays below and above the “Knee”



Points: Measurements
of Tibet experiment

Line:
Fit of Gaisser,Stanev ,Tilav

Composition of the CR

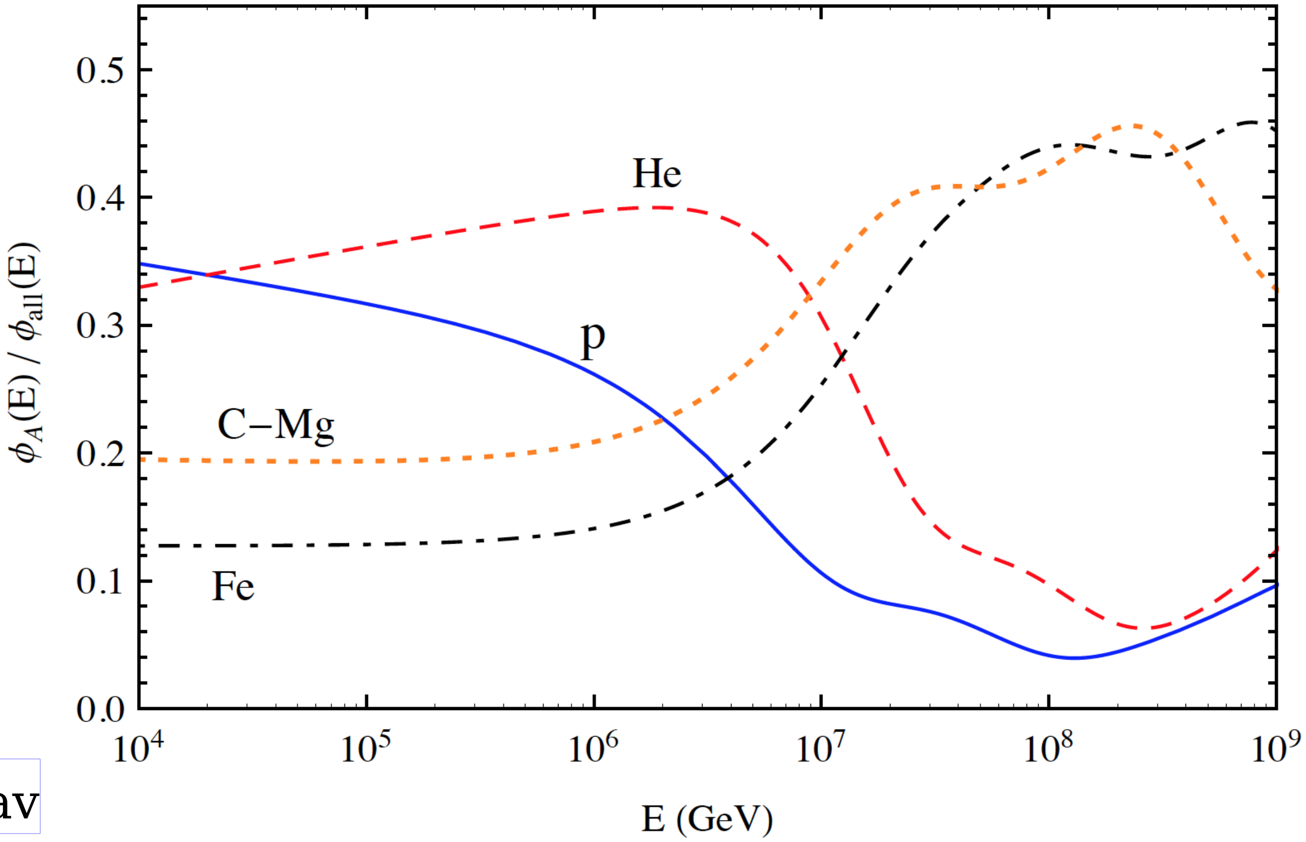


$$E_p \Longleftrightarrow E_\gamma^{\rm rec}$$

$$\varepsilon_{p\to\gamma}$$

$$E_{\rm He} \Longleftrightarrow E_\gamma^{\rm rec}$$

$$\varepsilon_{\rm He\to\gamma}$$



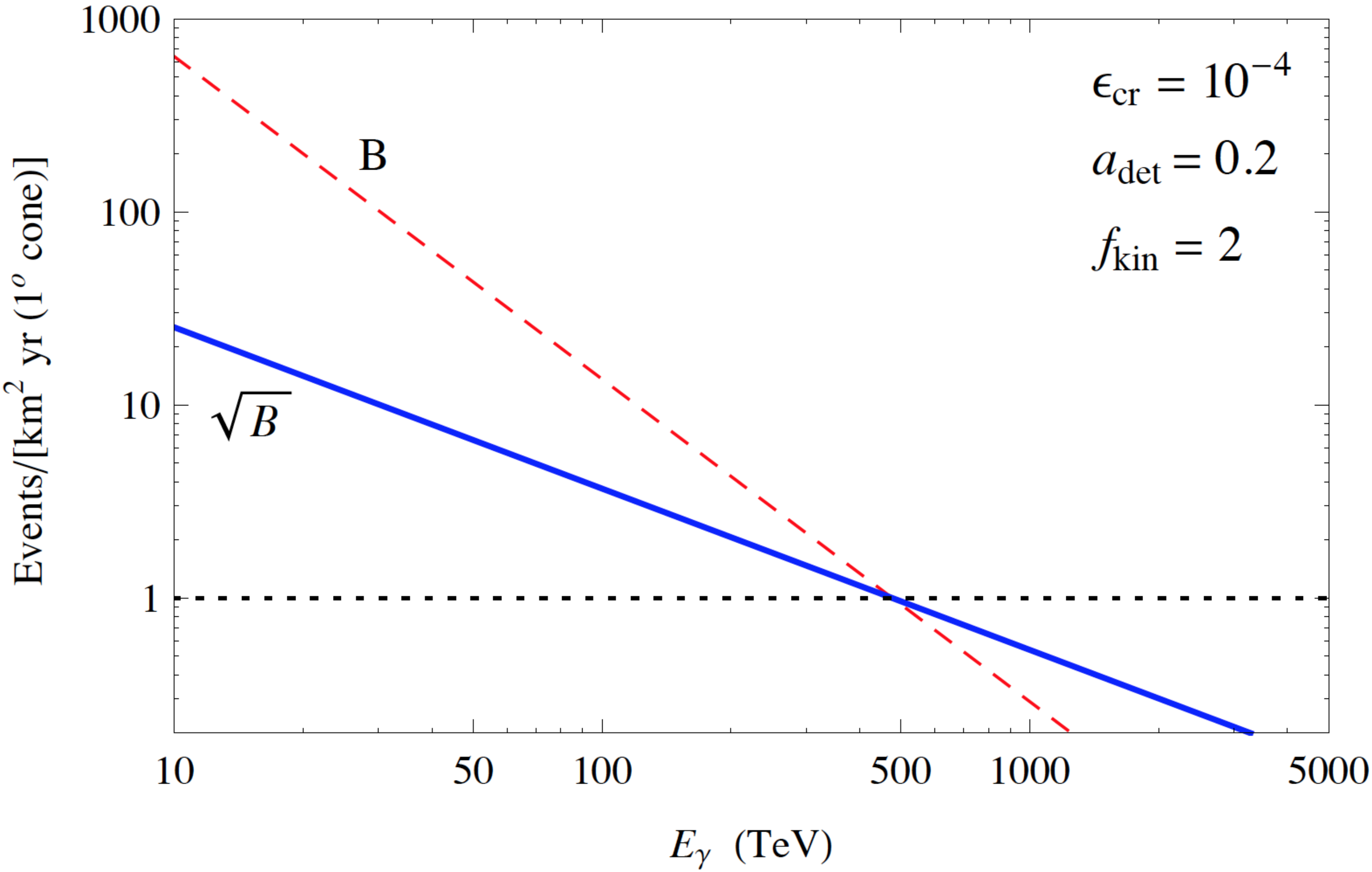
Fit of Gaisser,Stanev ,Tilav

Minimum detectable Gamma Ray Flux from a point source

$$\Phi_\gamma(E_{\rm min}) \gtrsim n_\sigma\, 1.5\times10^{-16} \left(\frac{E_{\rm min}}{100~{\rm TeV}}\right)^{-0.835} \quad ({\rm cm}^2~{\rm s})^{-1}$$

$$\left[\frac{{\rm km}^2}{A}\frac{\rm year}{T}\right]^{1/2} \left[\frac{0.2}{a(\delta,\lambda)}\right]^{1/2} \left[\frac{1^\circ}{\delta\theta}\right] \left[\frac{10^{-4}}{\varepsilon_{\rm cr}}\right]^{1/2} \left[\frac{\varepsilon_\gamma}{0.7}\right]$$

Estimate of the Background rate



Limit of No Background

$$\Phi_\gamma^{\min} \; A \; T \; a(\delta, \lambda) = N_{\min}$$

Request of $N_{\min}$ events

$$\Phi_\gamma^{\min} \approx 6.3 \times 10^{-17} \; [\mathrm{cm}^2 \; \mathrm{s}]^{-1}$$

$$\left[\frac{N_{\min}}{10}\right] \; \left[\frac{\mathrm{km}^2}{A} \frac{\mathrm{year}}{T}\right] \; \left[\frac{0.5}{a(\delta, \lambda)}\right]$$

The Large High Altitude Air Shower Array (LHAASO)

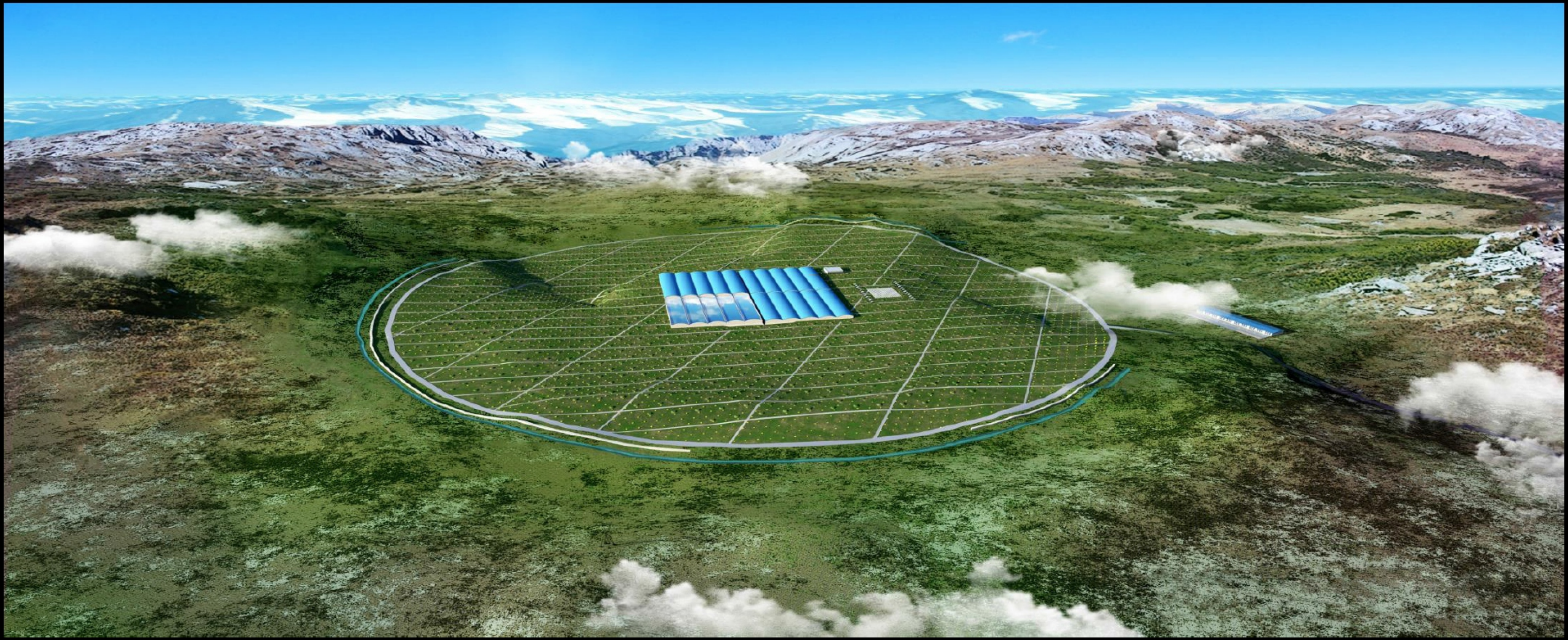
LHAASO detectors: 285, 315, 324, 335, 464, 470, 564, 833, 885, 894, 896, 901, 904, 908, 941, 985, 1042, 1079

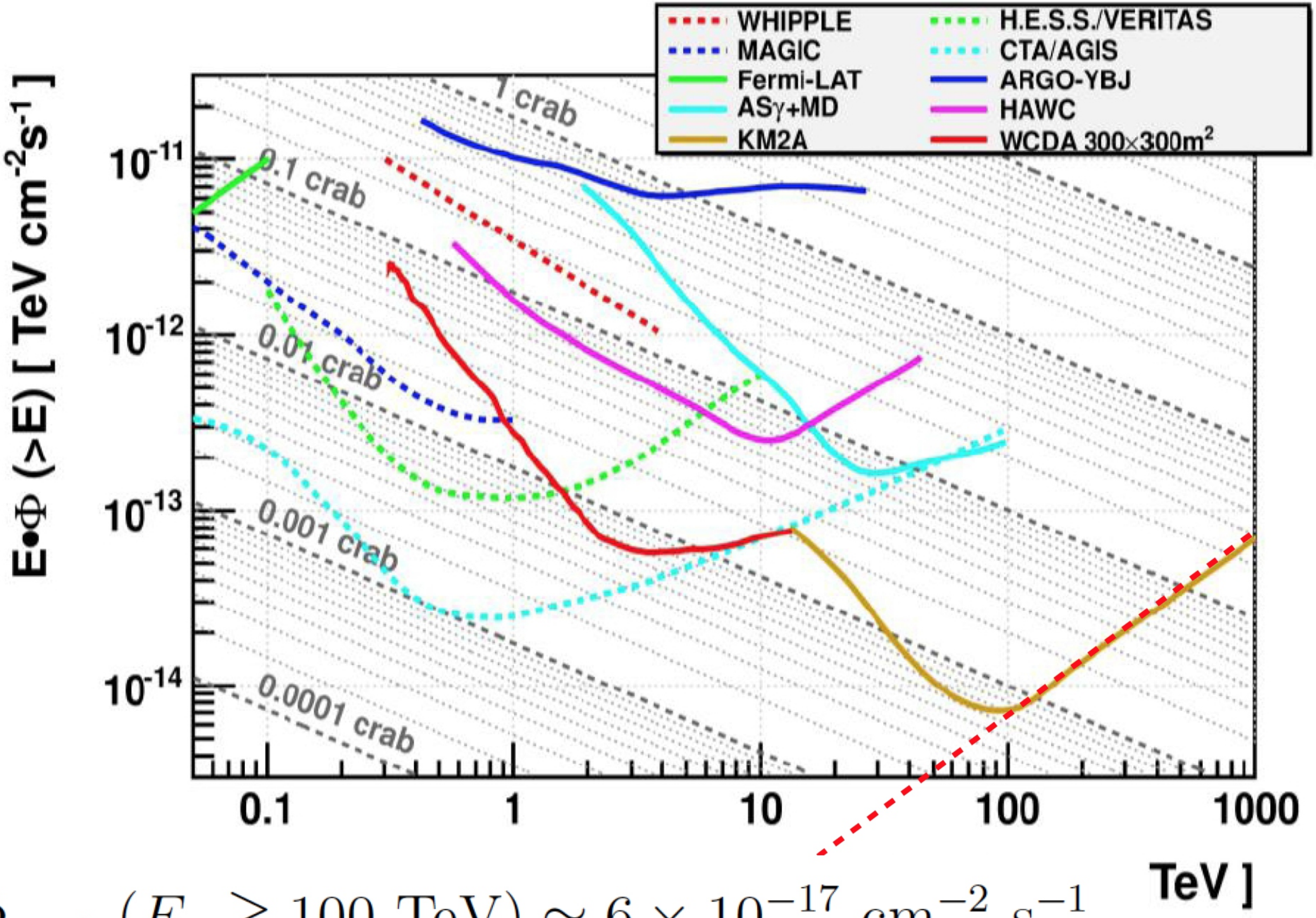
- air shower array of 1 km^2

. 75 000 m2 Water Cherenkov Detector Array (WCDA)

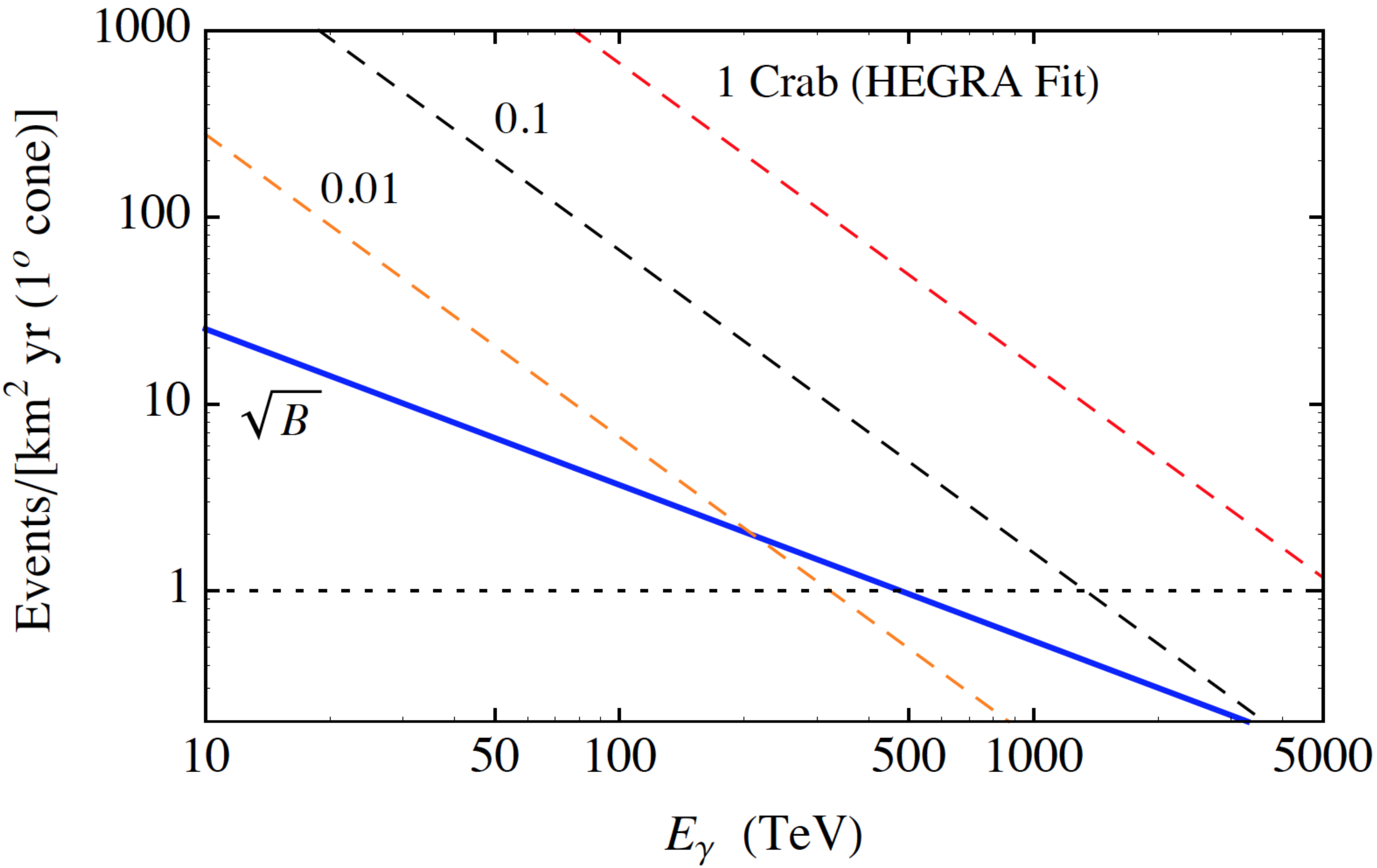
- 12 Wide-field Cherenkov telescopes (WFCTA)
- Infilled shower core detectors

Engineering at ARGO site (~1% LHAASO in operation for > 2 years)

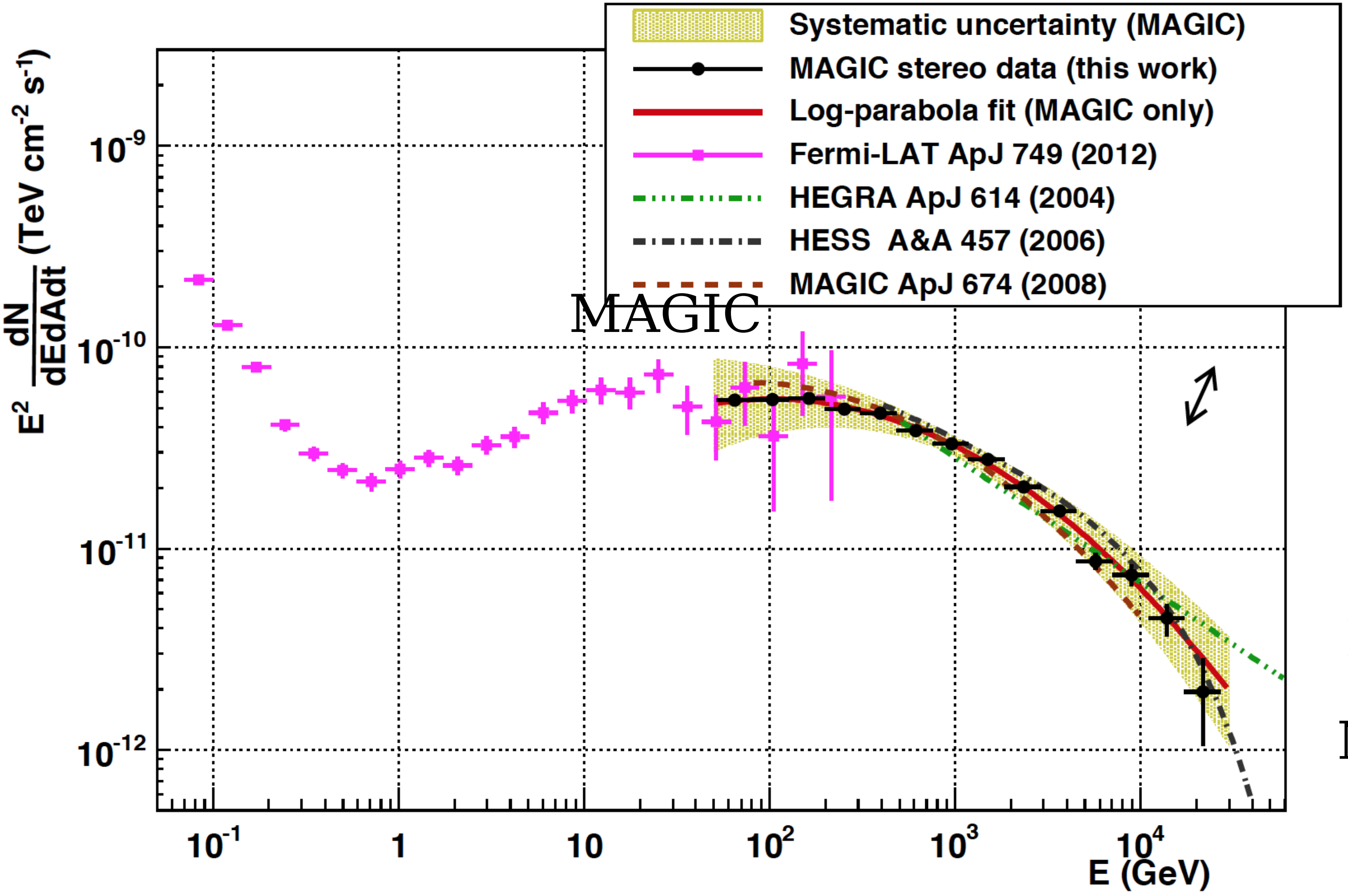




$$\Phi_{\gamma,\min}(E_\gamma \gtrsim 100\ \mathrm{TeV}) \simeq 6 \times 10^{-17}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$


1000
100
10
1
Events/[km^2 yr (1^o cone)]
1 Crab (HEGRA Fit)
0.1
0.01
$\sqrt{B}$
10
50
100
500
1000
5000
E_γ (TeV)

Crab Nebula differential spectrum:



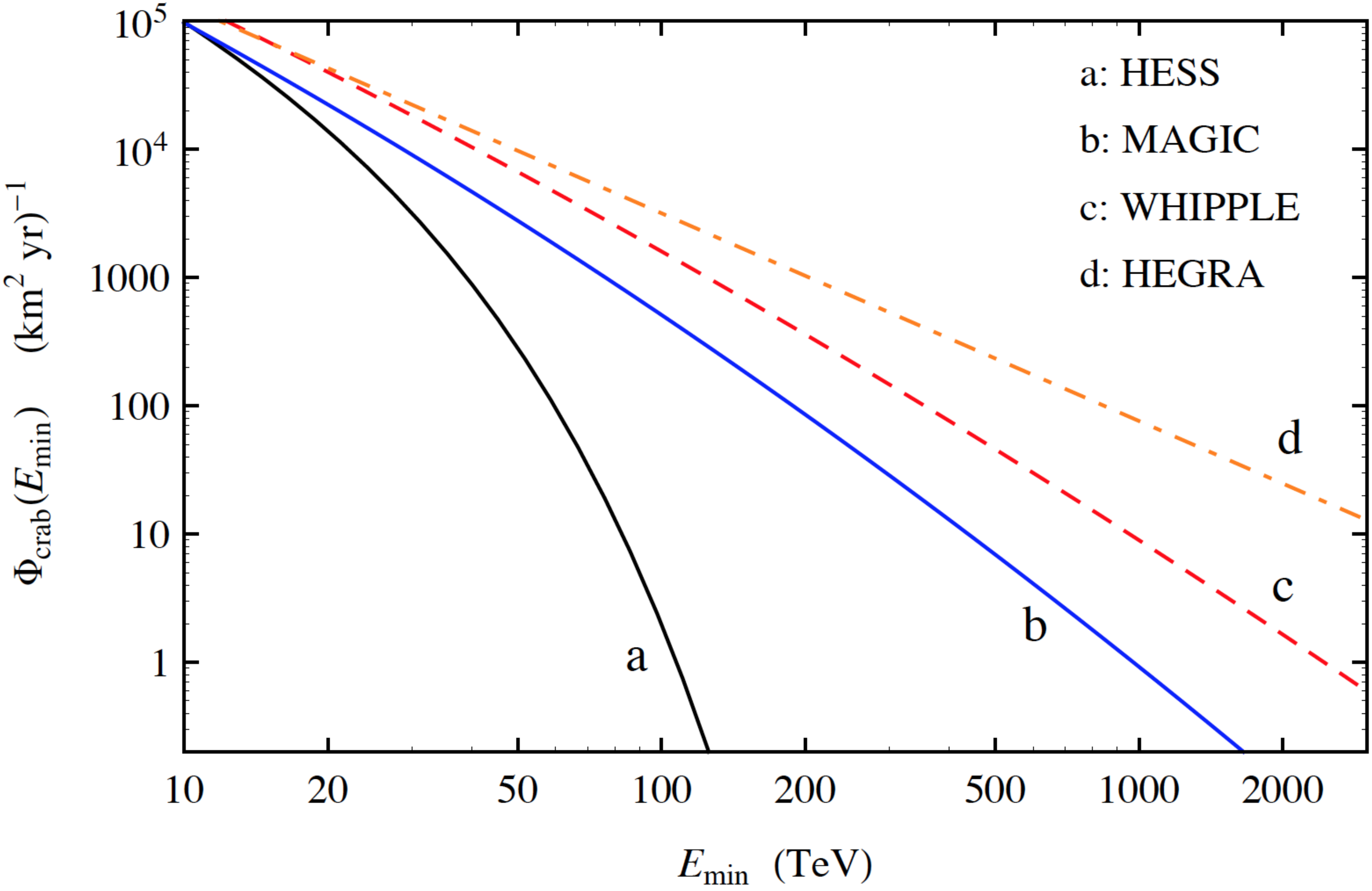
MAGIC

HEGRA

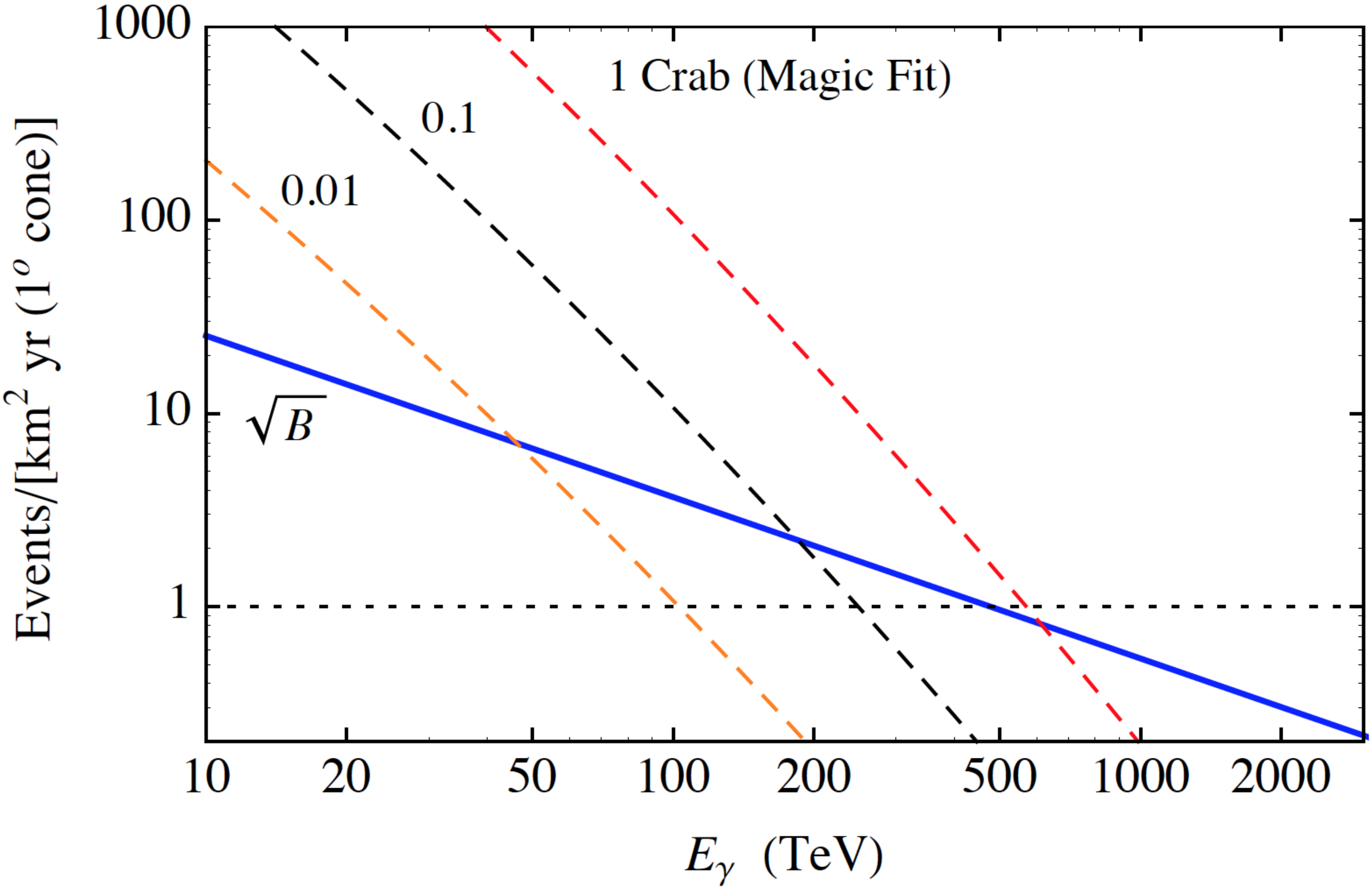
MAGIC

HESS

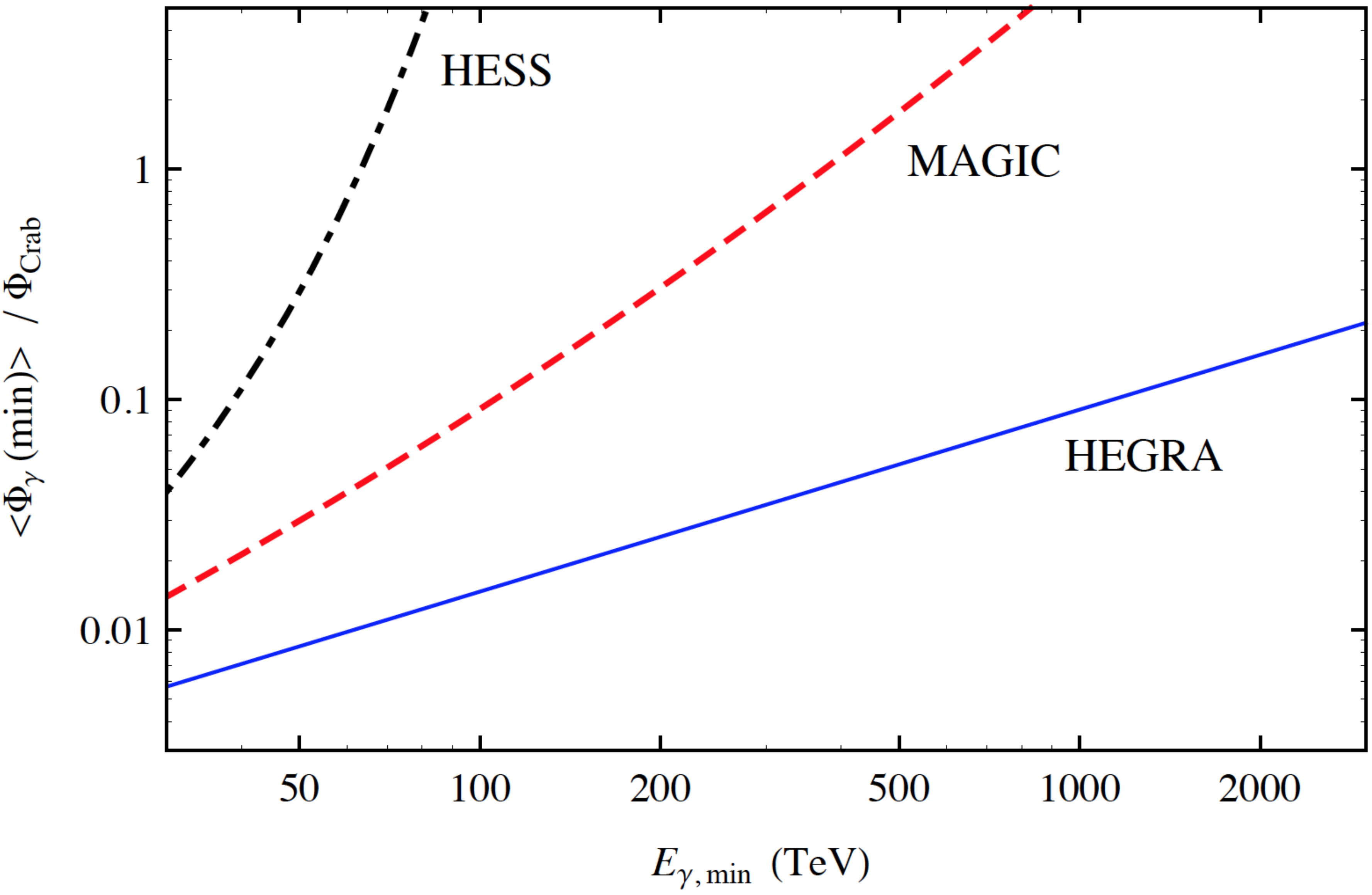
Crab Nebula *integral* spectrum:



Approximate Sensitivity of LHAASO



Sensitivity expressed in terms of “CRAB Units”



Sensitivity to a Diffuse Gamma Ray flux

Average flux in a region

$\pm 5^\circ$ Galactic latitude

45° Galactic longitude

$$\langle \Phi_\gamma^{\rm min}(E_{\rm min})\rangle \approx n_\sigma \; (1.14 \times 10^{-14}) \left(\frac{E_{\rm min}}{100 \; {\rm TeV}}\right)^{-0.835} ({\rm cm}^2 \, {\rm s} \, {\rm sr})^{-1} \times$$

$$\left[\frac{{\rm km}^2 \, {\rm yr}}{A \, t}\right]^{1/2} \left[\frac{0.20}{\langle a(\delta,\omega)\rangle}\right]^{1/2} \left[\frac{0.14}{\Delta\Omega}\right]^{1/2} \left[\frac{\varepsilon_{\rm cr}}{10^{-4}}\right]^{1/2} \left[\frac{0.7}{\varepsilon_\gamma}\right]$$

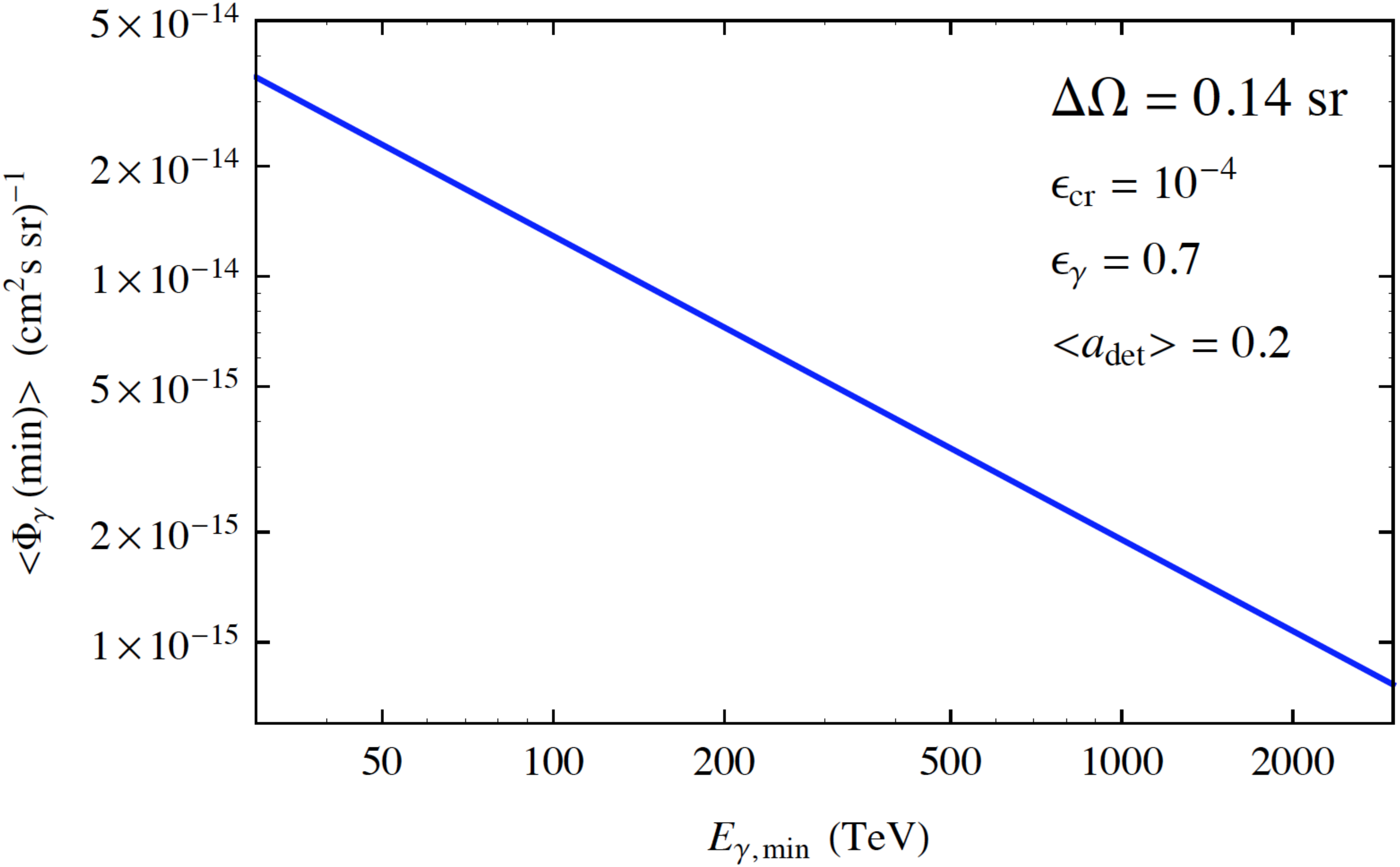
Sensitivity for a diffuse flux

[Average flux in a finite angular region]

$$\phi_{\min} \propto (\Delta\Omega)^{-1/2}$$

$$|b| \leq 5^\circ$$

$$\Delta\ell = 45^\circ$$

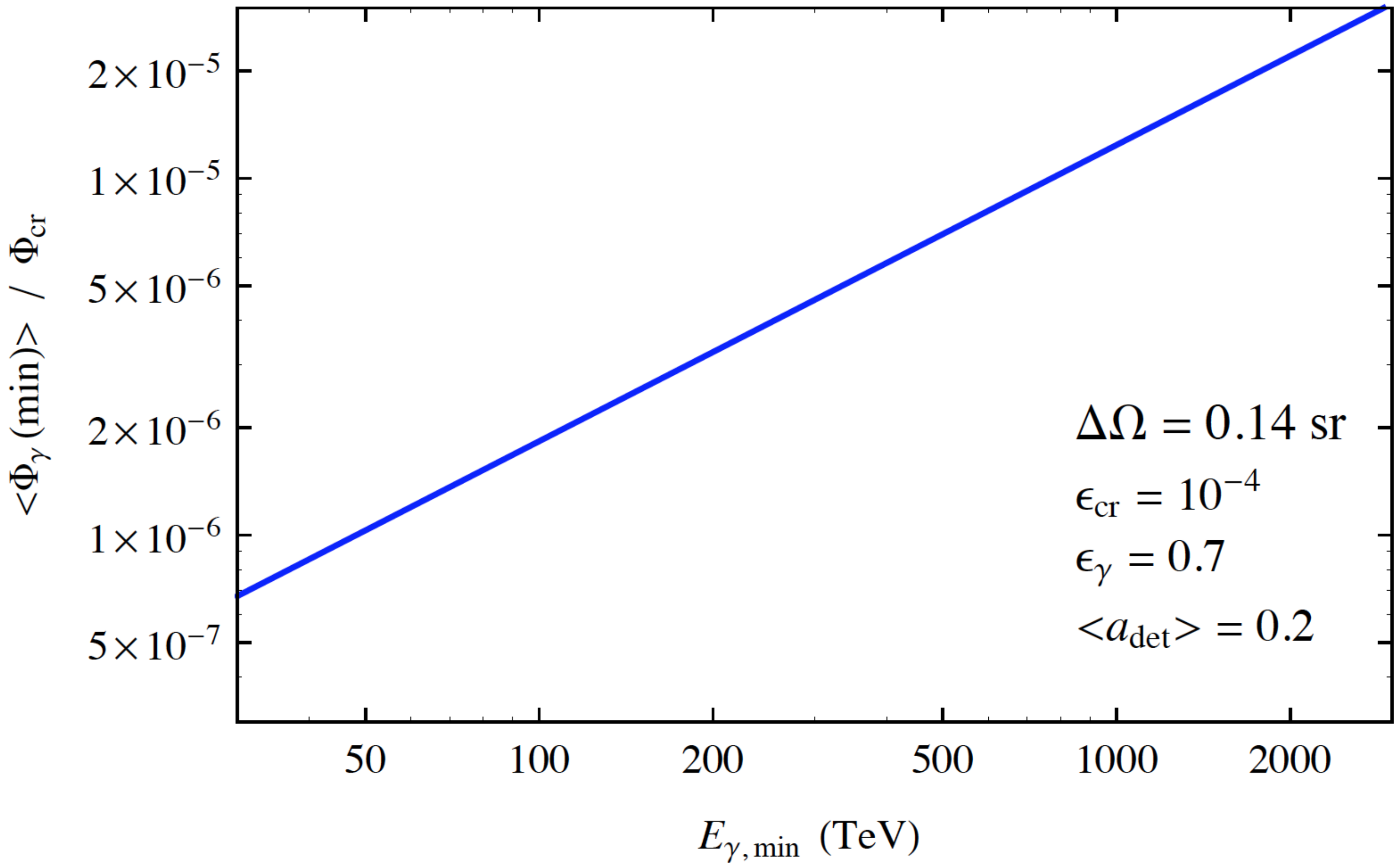


Sensitivity for a diffuse flux
[Average flux in a finite angular region]

(expressed as a fraction of the CR flux)

$$|b| \leq 5^\circ$$

$$\Delta\ell = 45^\circ$$



Note:

The sensitivity shown above
assumes the *comparison* of two sky regions

[an “off region” where the gamma-ray flux is negligible]

The sensitivity to a gamma ray flux
that is (quasi)-isotropic
(in a situation where there is no “off region”)

Depends on theoretical/systematic uncertainty
How accurately we can model
hadronic shower (and photon) showers
[probability that a CR shower “mimics” a photon shower]

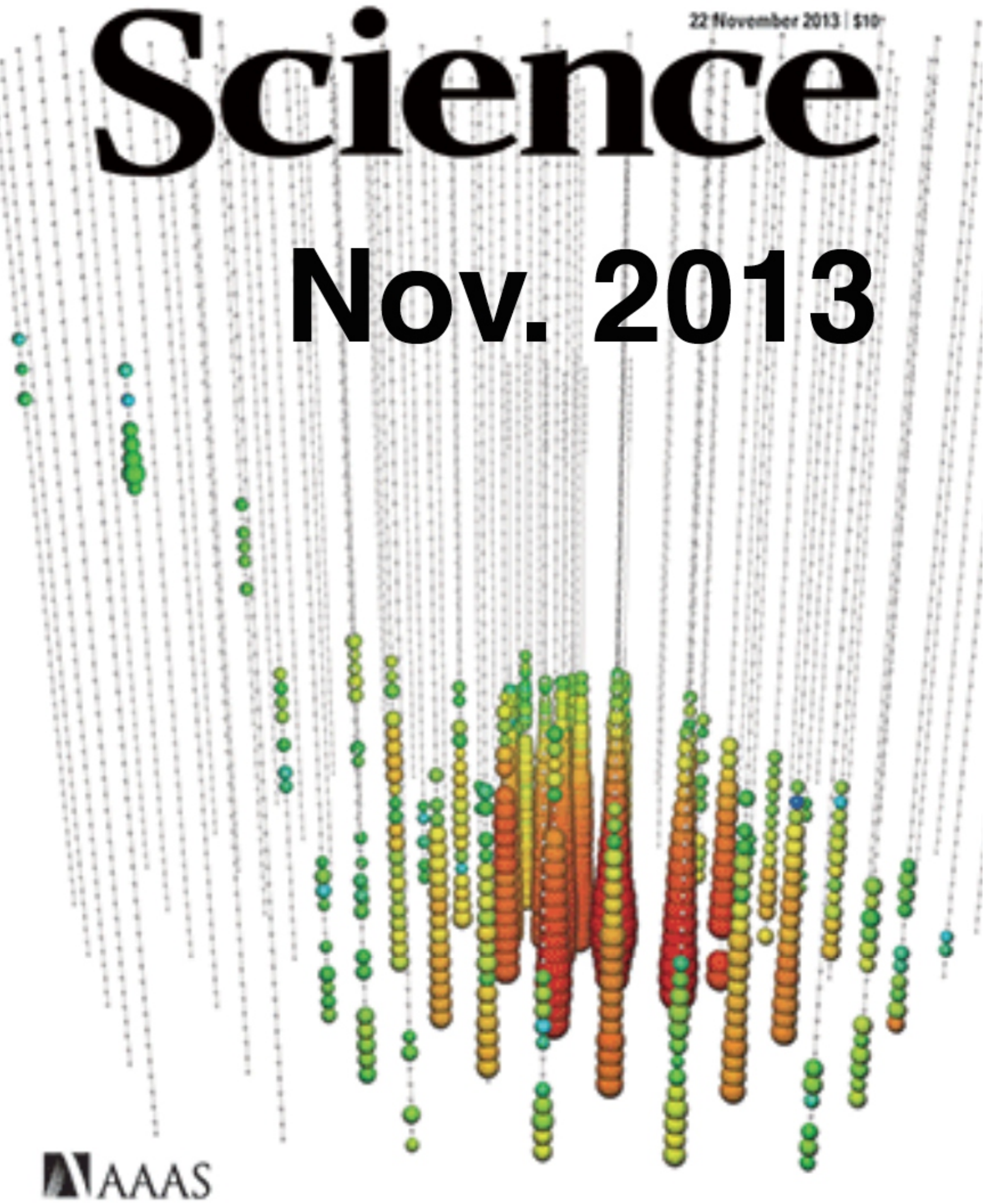
Neutrino Astronomy

From “Dream” to Reality

The first glimpse of the
“Neutrino Promised Land”
[Observations of High Energy
Astrophysical Neutrinos]

has been obtained by IceCube

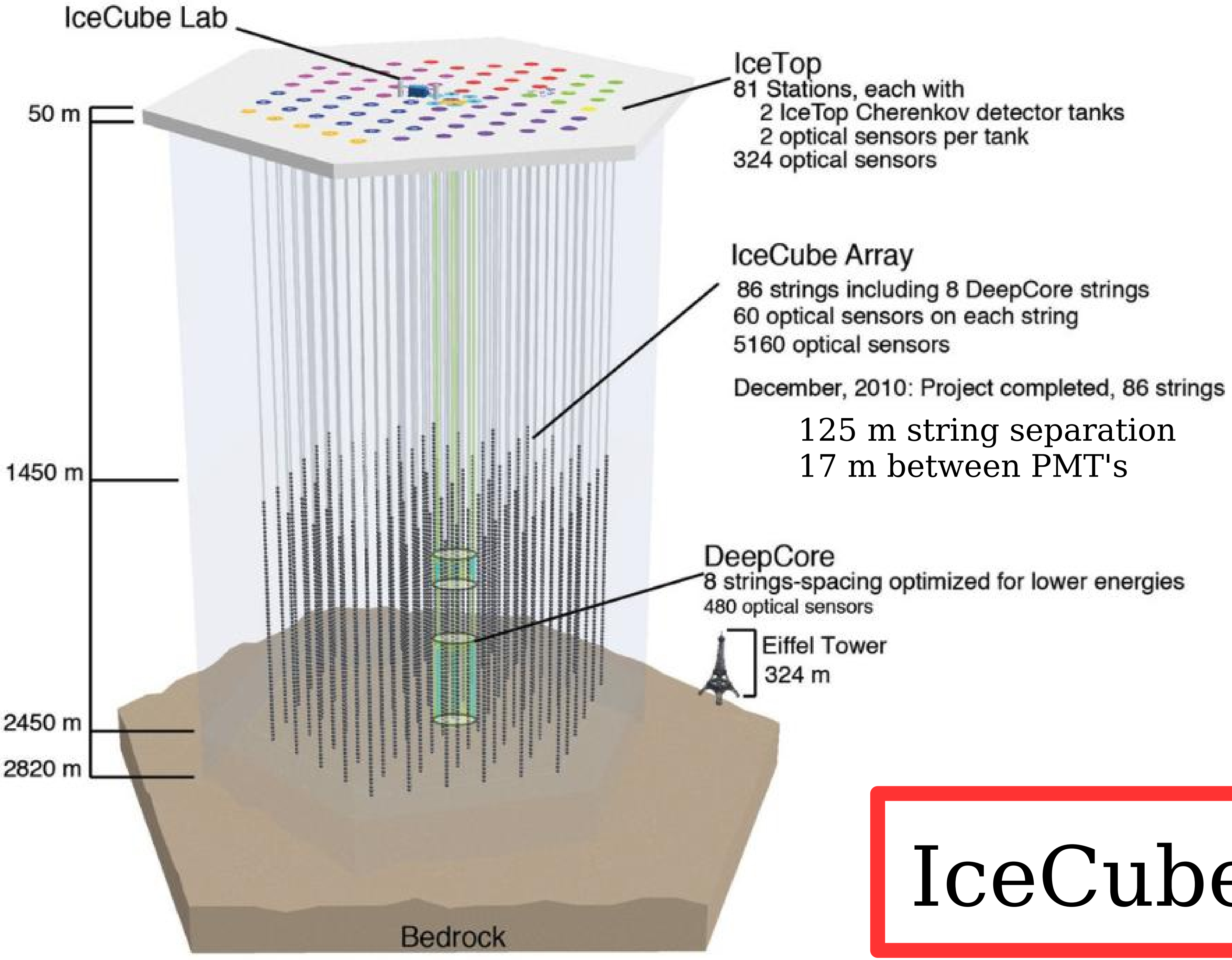
IceCube



Nov. 2013

“Evidence for
High Energy
Extraterrestrial Neutrinos
in the IceCube Detector”

2 years of data
→ 3 years of data
→ 4 years of data



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

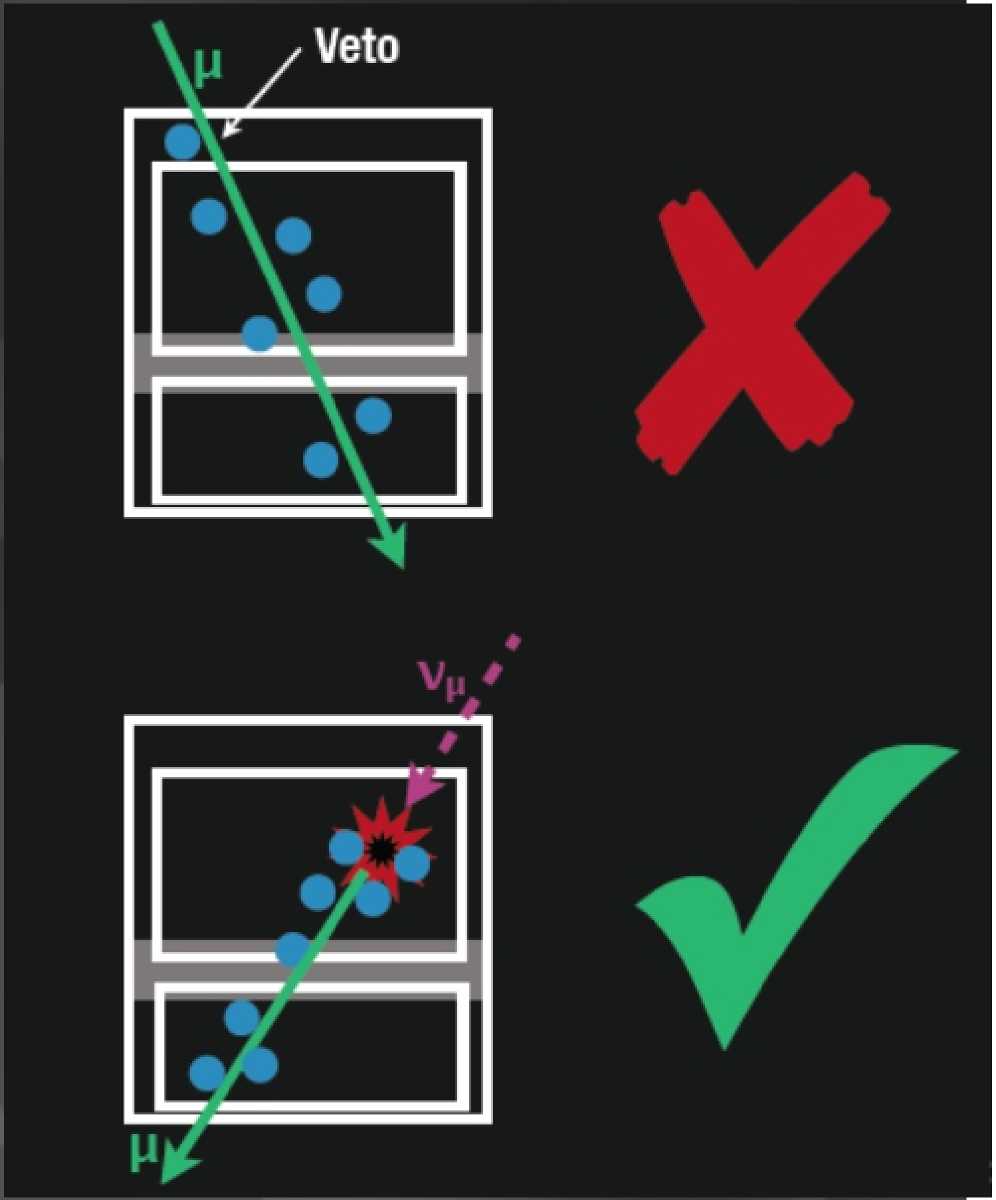
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

IceCube

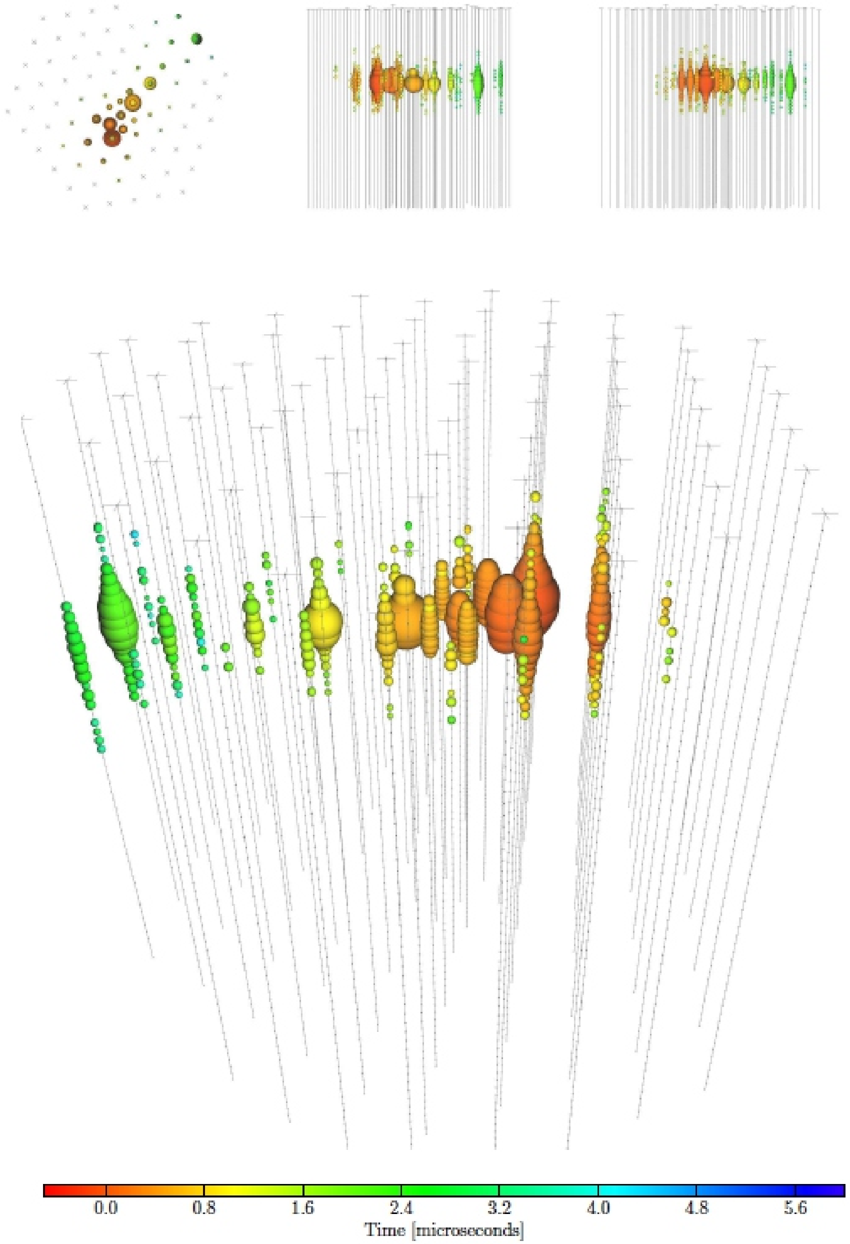
“Contained” events

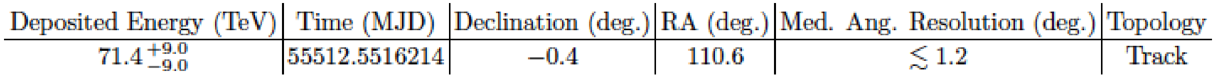
- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution



loss in statistics is compensated by event definition

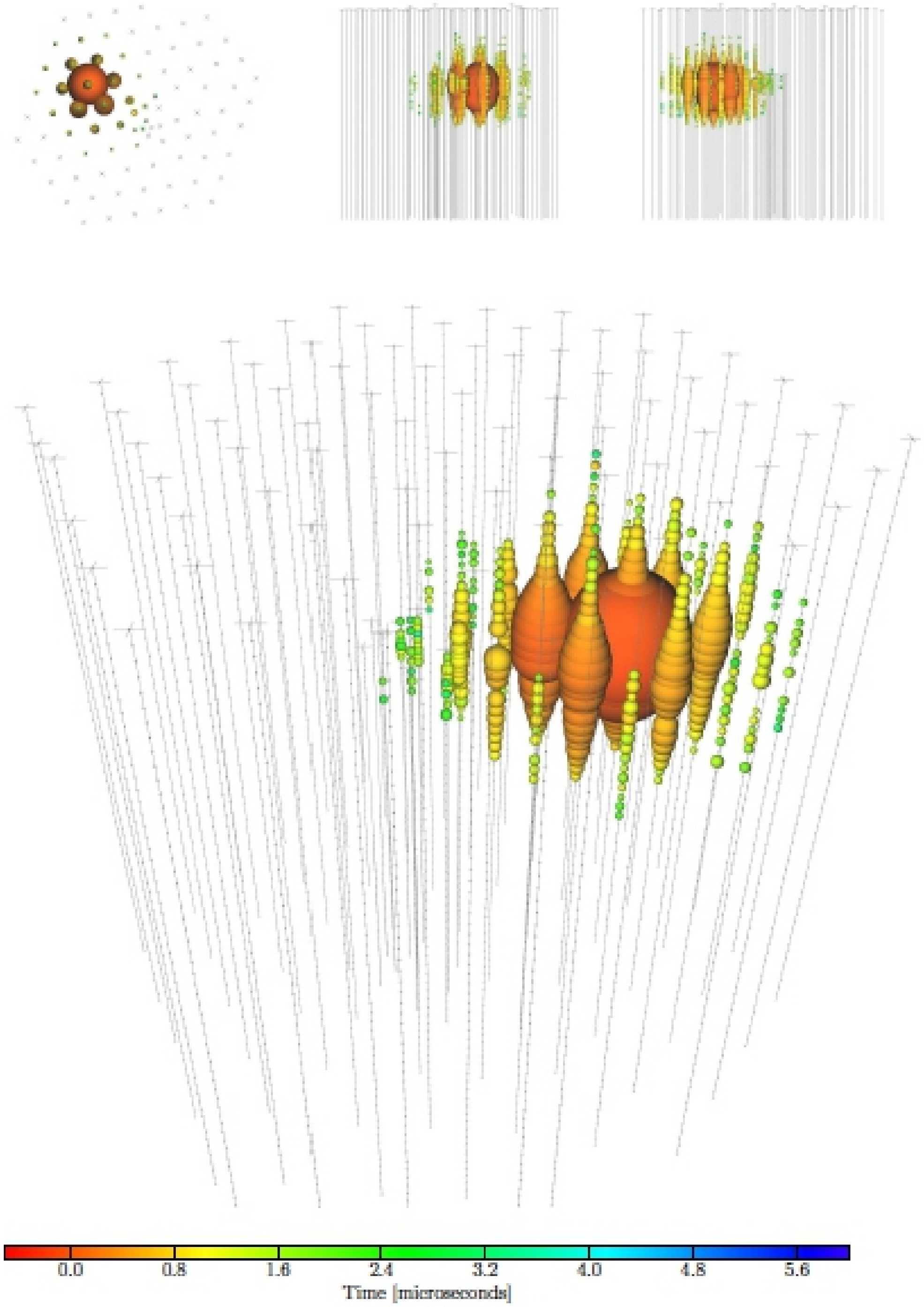
“TRACK”





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

IceCube contained events 4-years

Total Number of Events : 54

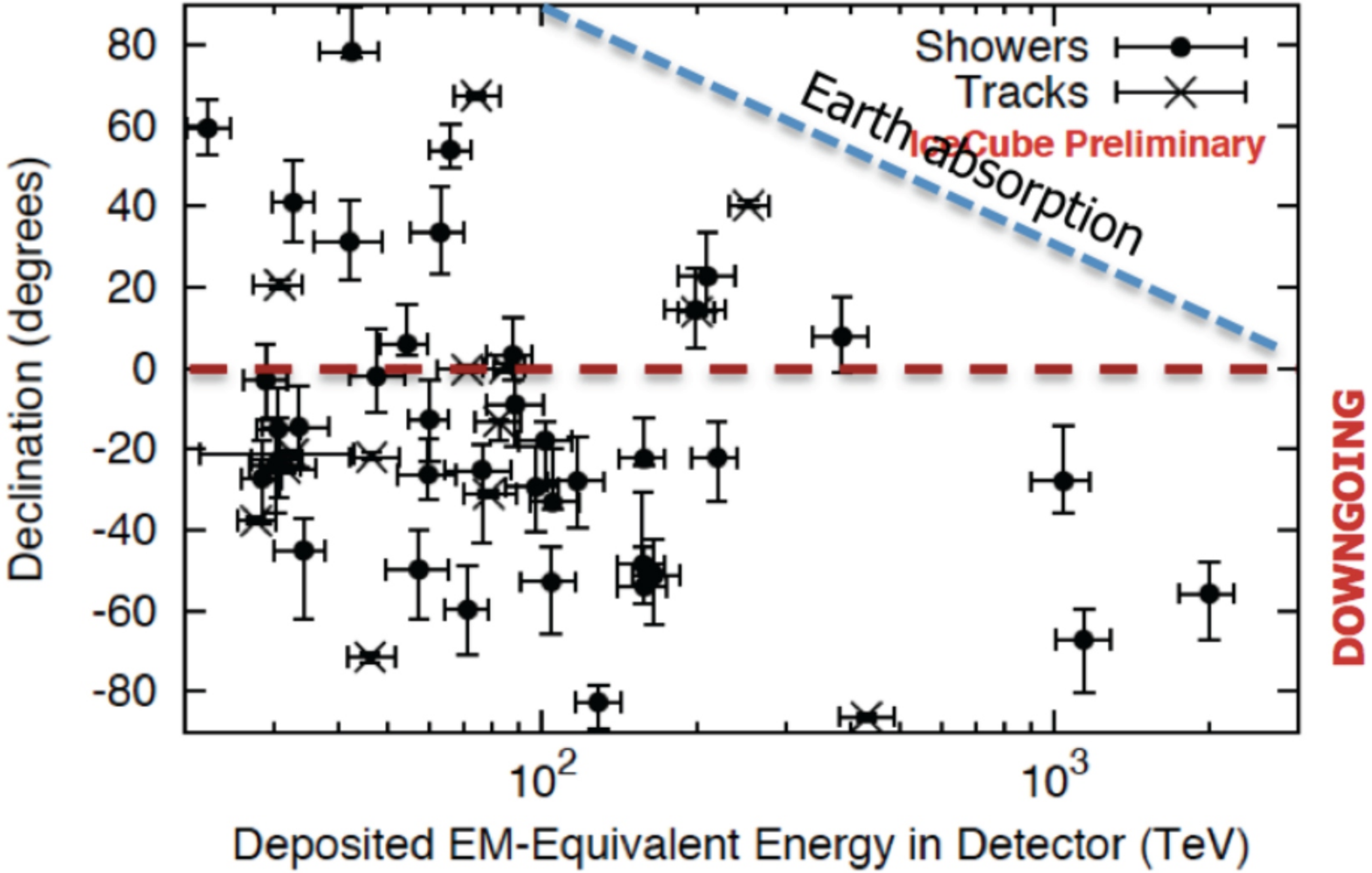
Background from
Down-going Muons 12.6 ± 5.1

Atmospheric
Neutrinos $9.0^{+8.0}_{-2.2}$

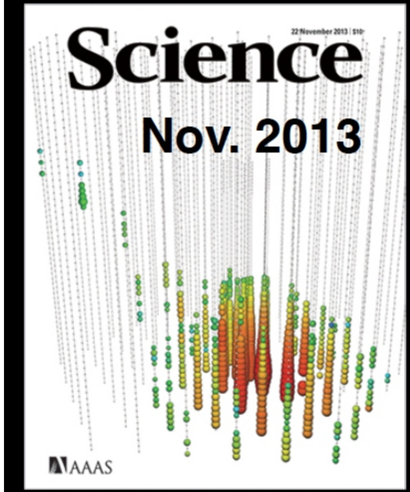
Excess = 6.5 sigmas

High Energy Starting Events (4 yr)

54 events observed

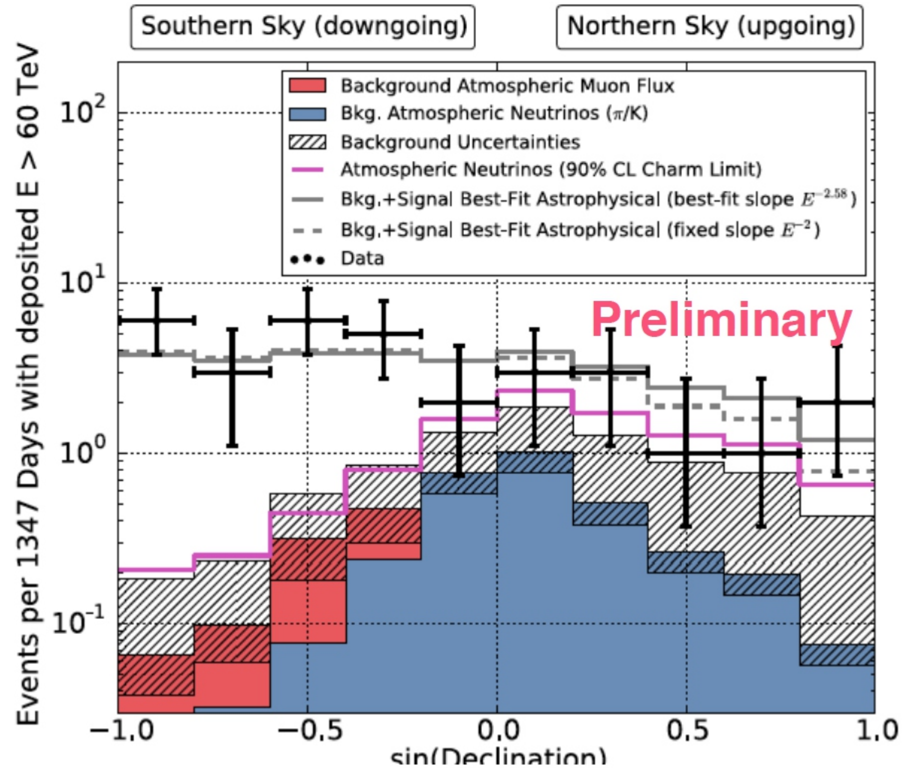


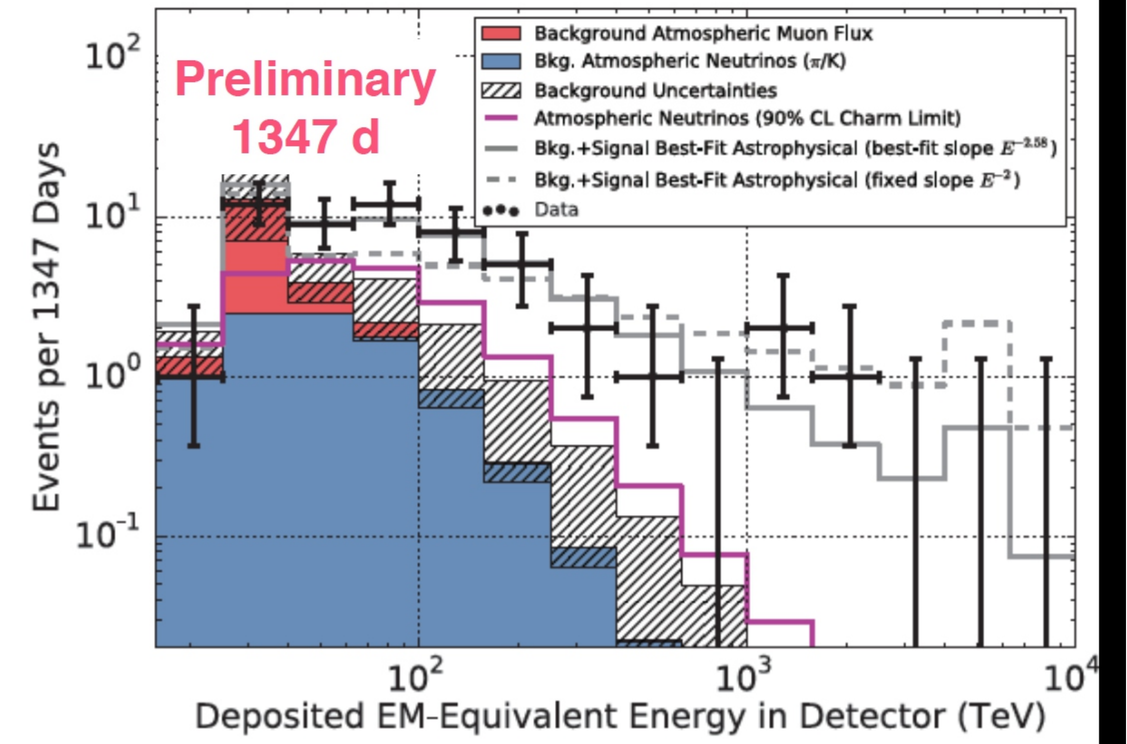
4 yr (2010-14) of HESE



Anti-coincidence veto + >6000 p.e. (>30 TeV)
54 events (17+events in PRL 113 (2014) 101101).
2 are evident background events.
Background:
Measured: 12.6 ± 5.1 atmospheric muon events
Atmospheric prompt component estimated using a previously set limit on atmospheric neutrinos with 59 strings: $9.0_{-2.2}^{+8.0}$

Kopper, Giang, Kurahashi, ICRC 2015, POS 1081,
PRL 113 (2014) 101101





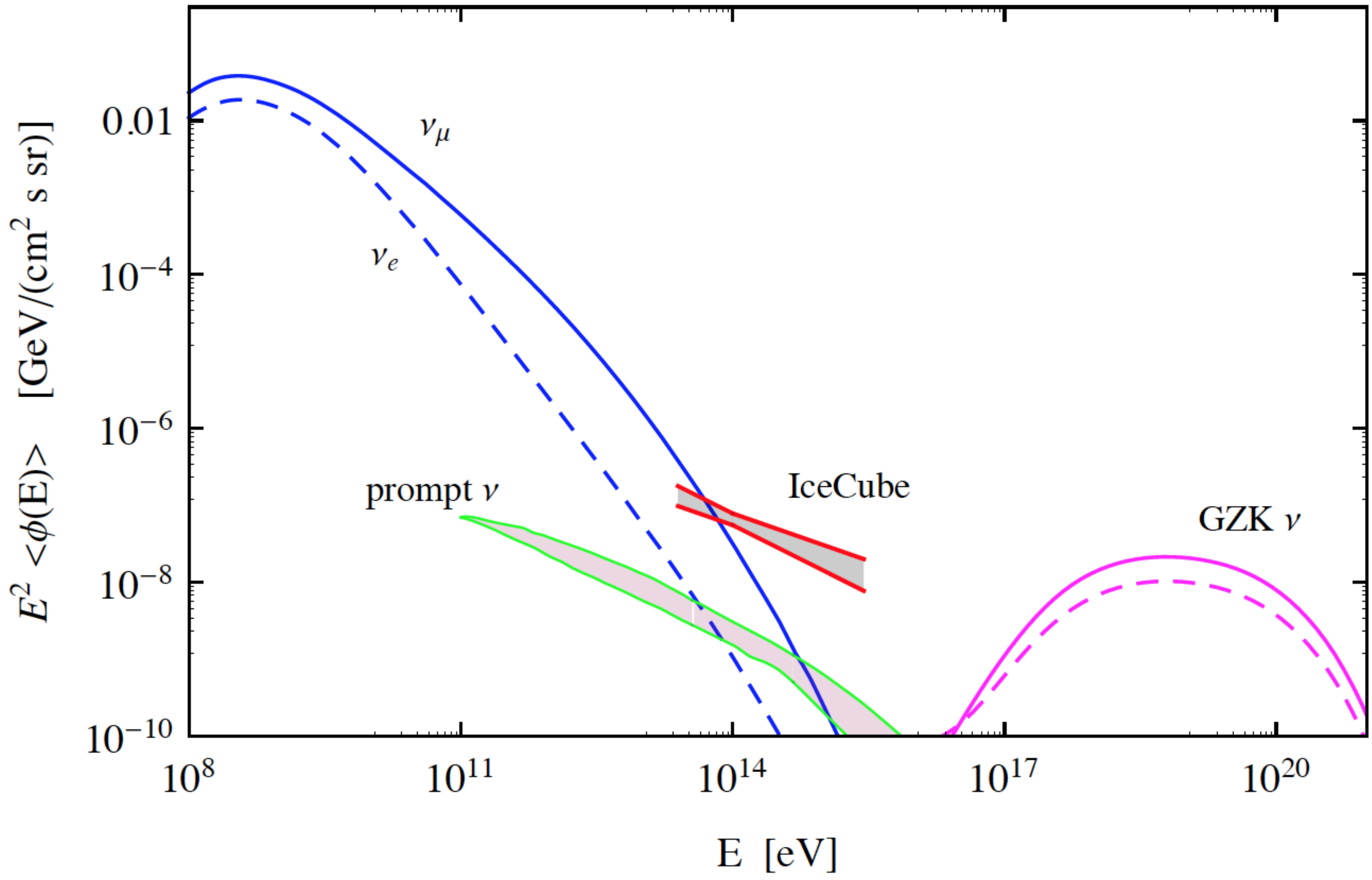
Neutrino Flux:

decomposition in a
“foreground” of atmospheric neutrinos
plus an astrophysical signal of extraterrestrial neutrinos

$$\phi_{\nu_\alpha}(E,\Omega) = \phi_{\nu_\alpha}^{\text{atmospheric}}(E,\Omega) + \phi_{\nu_\alpha}^{\text{astrophysical}}(E,\Omega)$$

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

Extragalactic Interpretation of the IceCube signal



$$\phi_\nu^{\mathrm{astro}}(E) \approx 6.7^{+1.1}_{-1.2} \times 10^{-18} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.50\pm 0.09} [\mathrm{cm}^2\ \mathrm{s\ sr\ GeV}]^{-1}$$

Best Fit of data [all neutrino flux]
as an isotropic extraterrestrial contribution

$$\phi_\nu^{\rm astro}(E) \approx 6.7^{+1.1}_{-1.2} \times 10^{-18} \left(\frac{E}{100 \text{ TeV}}\right)^{-2.50\pm0.09} [\text{cm}^2 \text{ s sr GeV}]^{-1}$$

$$\dot{N}_{\nu,\rm int} \simeq \phi_\nu(E)\; E \times (2\,\pi) \times \sigma_\nu(E)\, \frac{M_{\rm det}}{m_p}$$

$$\simeq 10 \text{ year}^{-1}$$

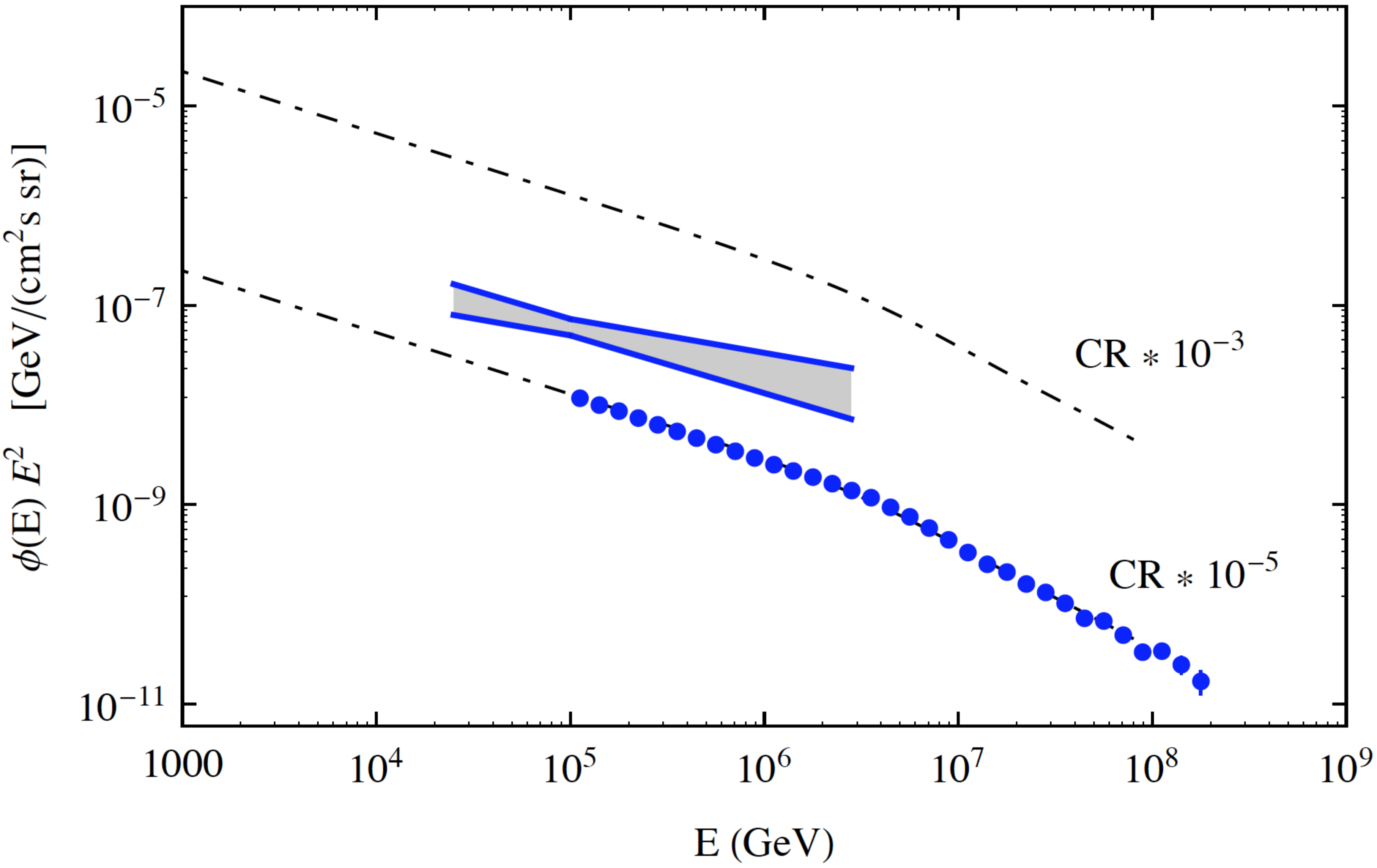
$$\sigma_\nu(100 \text{ TeV}) \simeq 2.02 \times 10^{-34} \text{ cm}^2$$

$$M_{\rm det} \simeq 420 \text{ Mton} \qquad \frac{M_{\rm det}}{m_p} \simeq 2.2 \times 10^{38}$$

IceCube signal

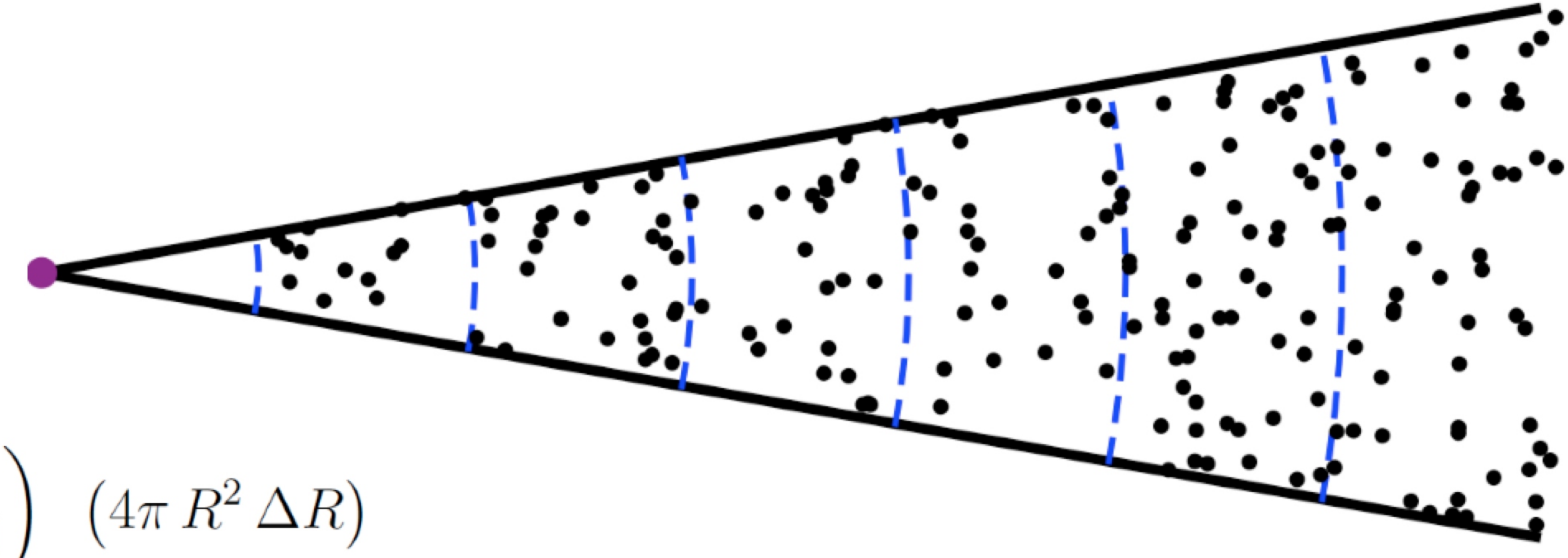
of astrophysical neutrinos

Interpreted as an isotropic (extragalactic flux)



Simplest interpretation:

Isotropic flux generated by the ensemble
of all (extragalactic) sources in the universe.



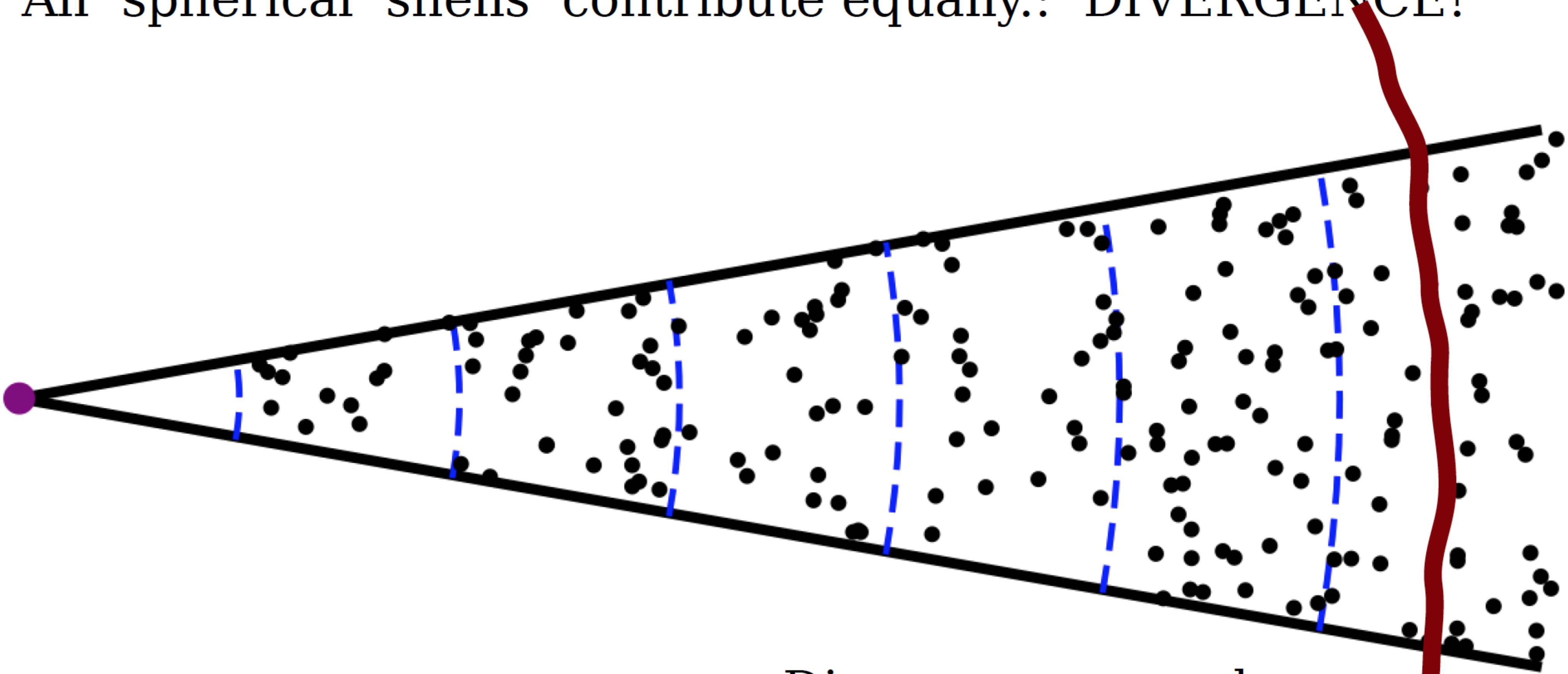
$$\left(\frac{1}{4\pi\, R^2}\right) \quad (4\pi\, R^2\, \Delta R)$$

Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ...

All spherical shells contribute equally.: DIVERGENCE!

Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ...

All spherical shells contribute equally.: DIVERGENCE!

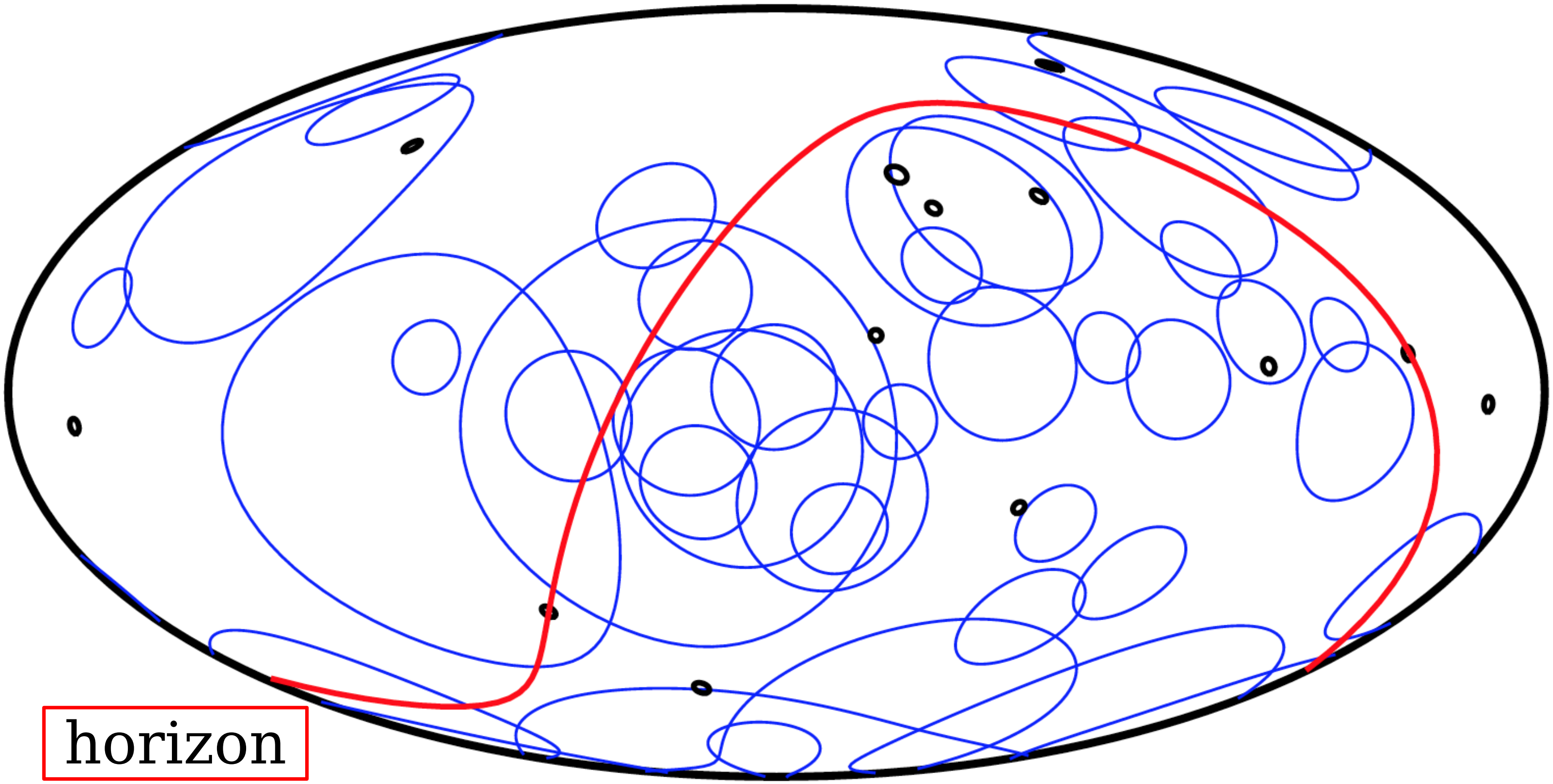


Divergence cured
By cosmological effects

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

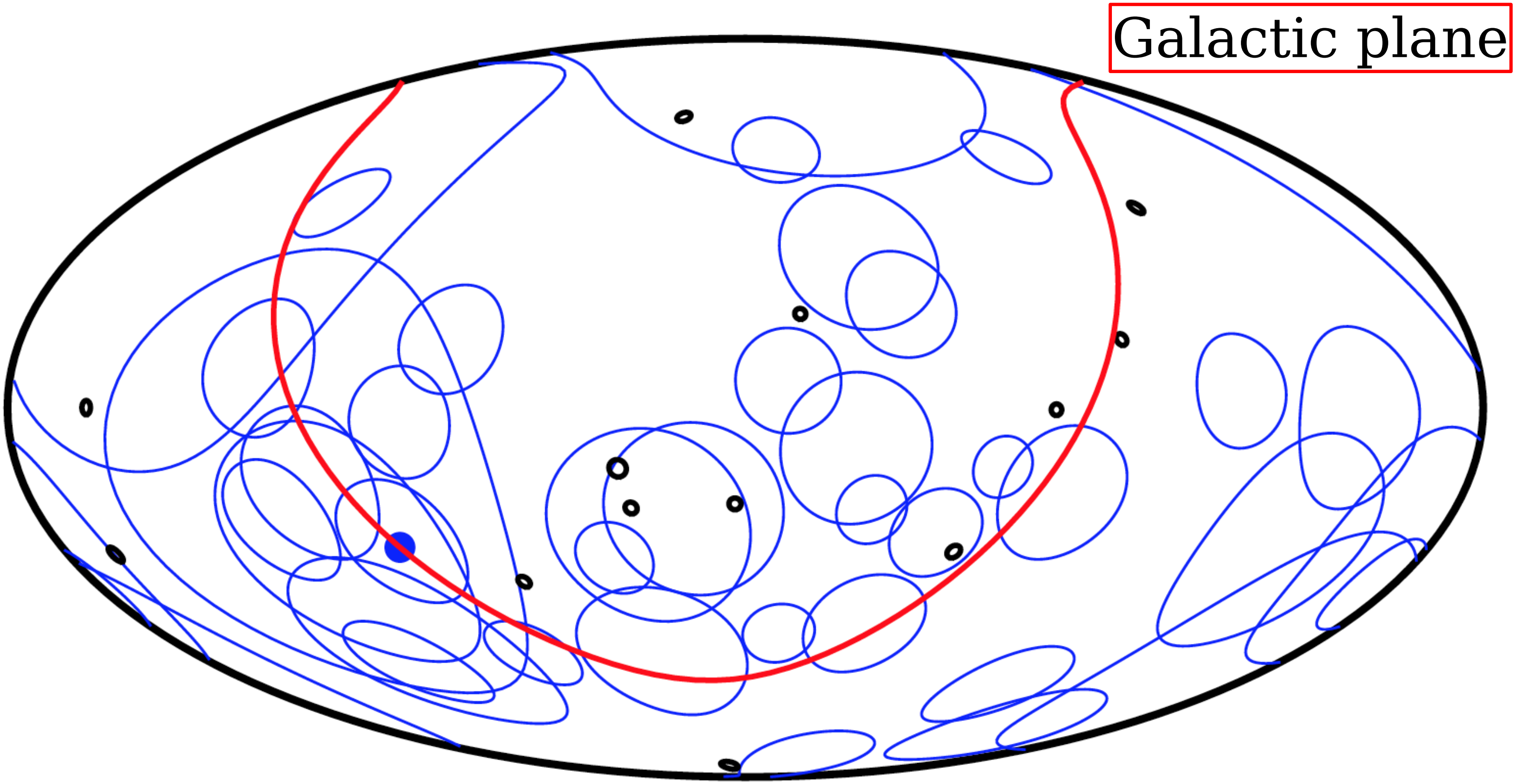
$$\boxed{R_{\rm Hubble} = \frac{c}{H_0} \quad \simeq 3 \text{ Gpc}}$$

IceCube 4-years HESE events

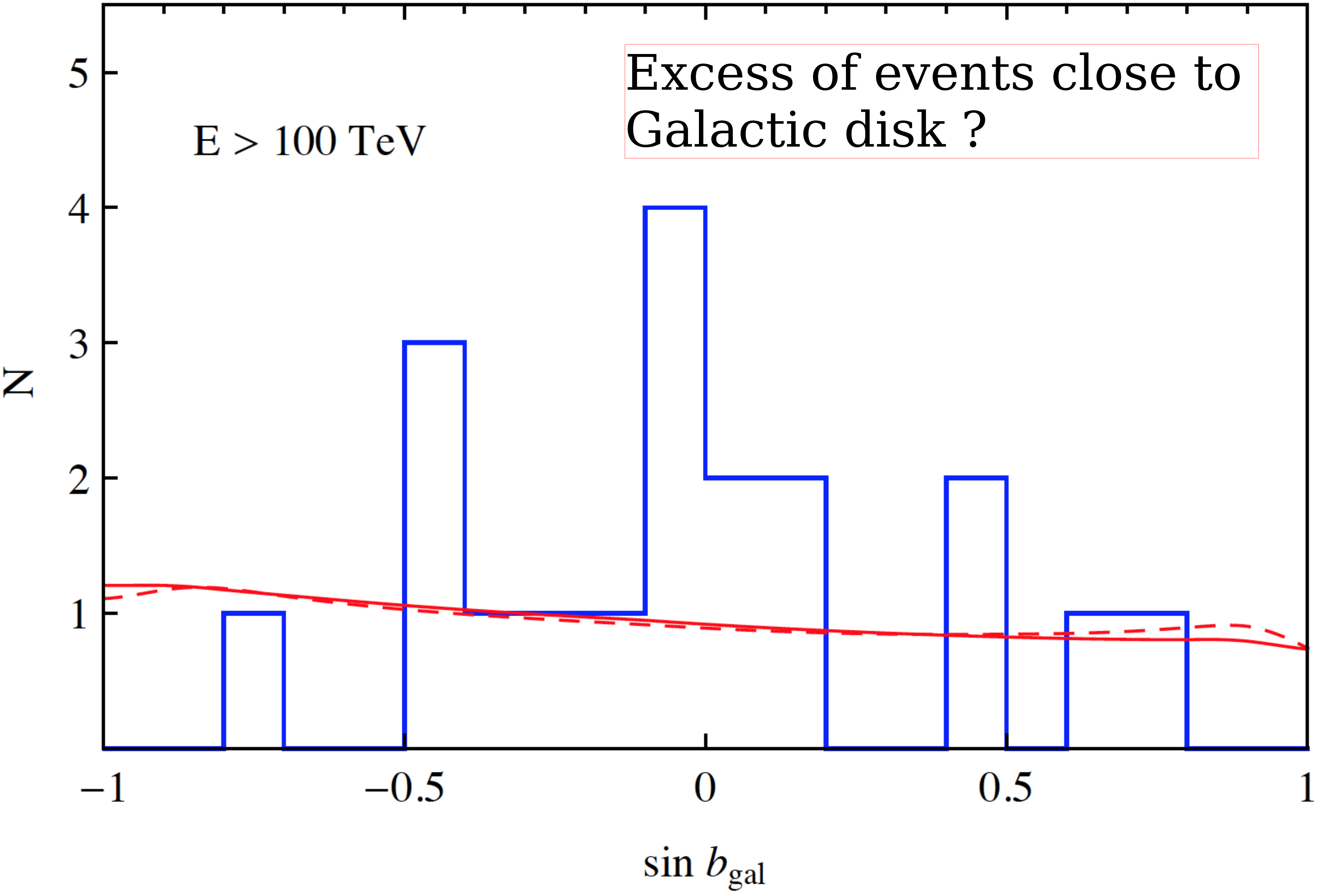


Galactic coordinates

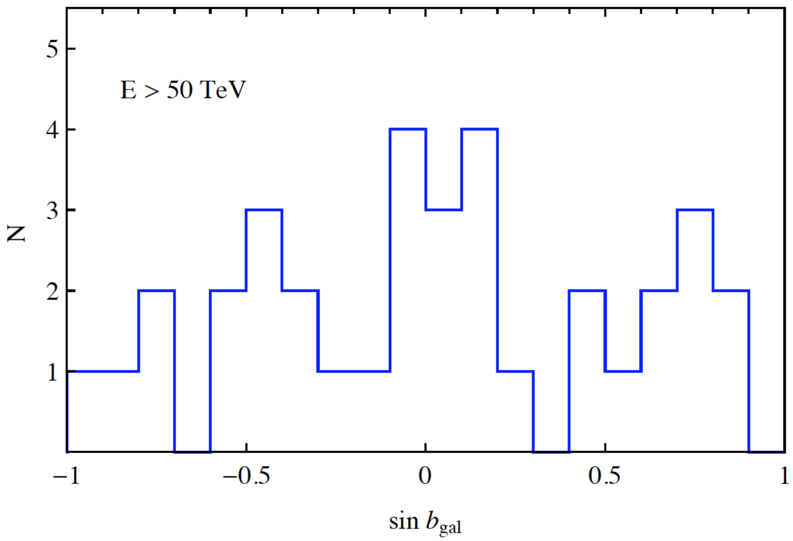
IceCube 4-years HESE events

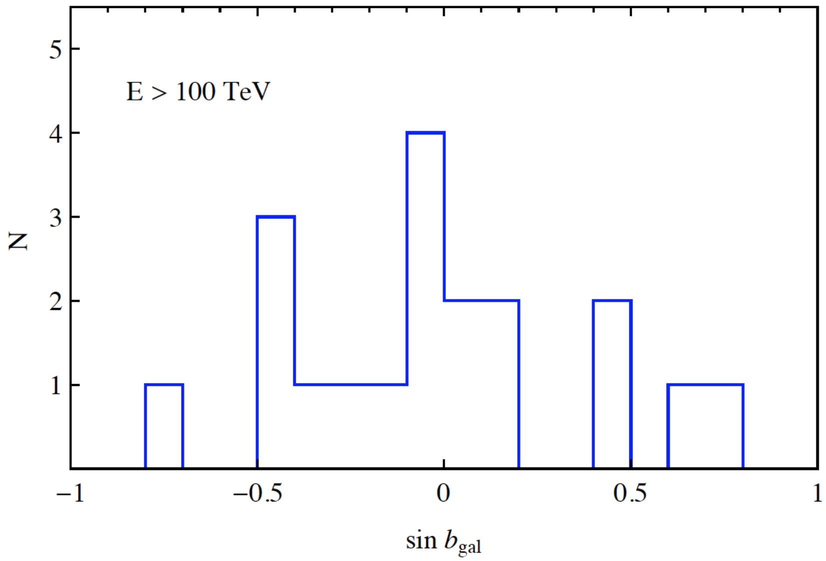


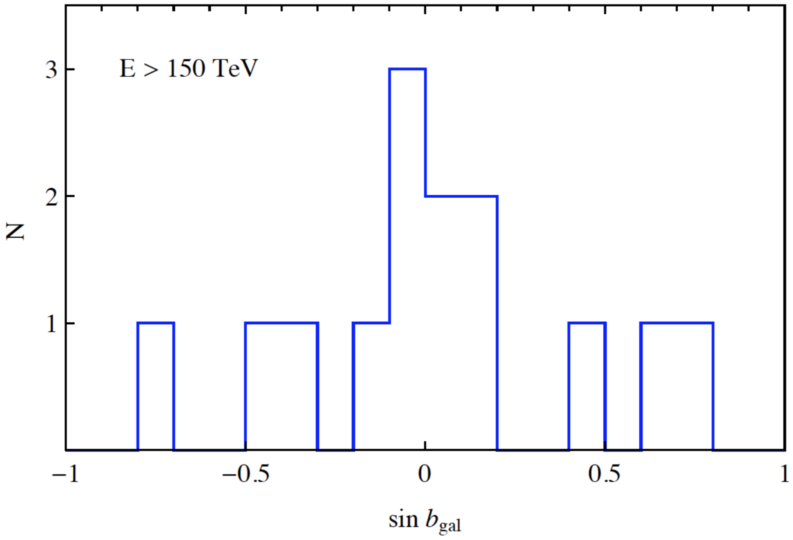
Celestial coordinates

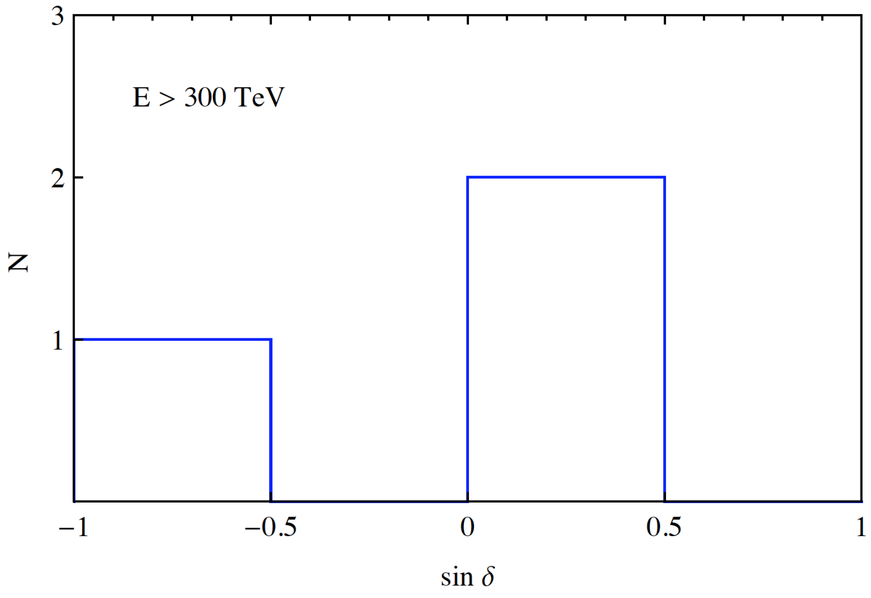


Excess of events close to Galactic disk ?

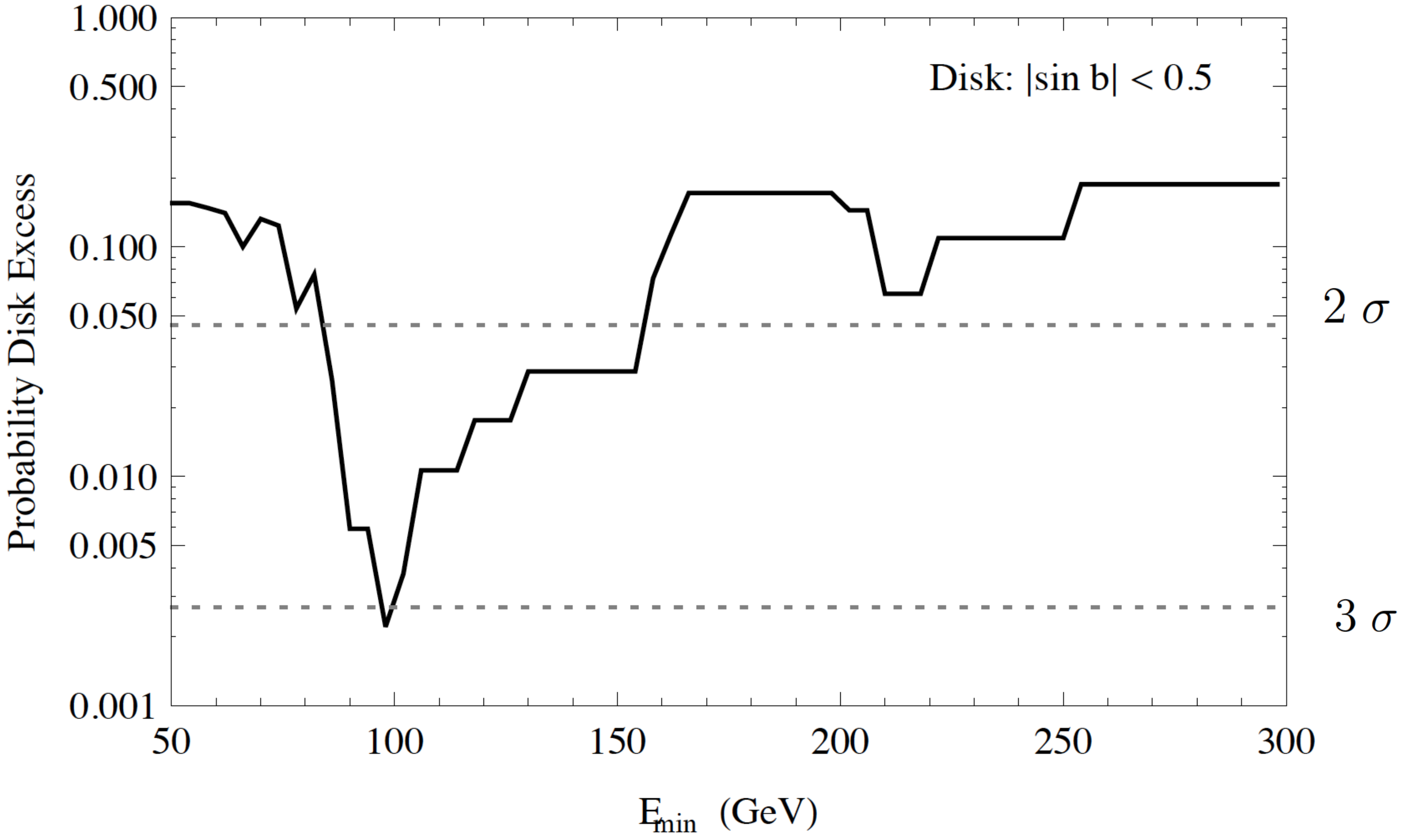

E > 50 TeV
N
5
4
3
2
1
−1
−0.5
0
0.5
1
sin $b_{\rm gal}$


E > 100 TeV
N
5
4
3
2
1
−1
−0.5
0
0.5
1
sin $b_{\rm gal}$


E > 150 TeV
N
3
2
1
−1
−0.5
0
0.5
1
sin $b_{\rm gal}$


E > 300 TeV
N
3
2
1
−1
−0.5
0
0.5
1
sin δ

In the IceCube signal:
is there an excess of events
from the Galactic Plane ?



Strict relation between

Neutrino Emission

$$\begin{tikzcd}
\pi^+ \arrow[r] & \nu_\mu \quad \mu^+ \arrow[dr, rounded corners, to path={|- (\tikztotarget)}] & \\
& & e^+ \quad \nu_e \quad \overline{\nu}_\mu
\end{tikzcd}$$

Gamma Ray emission

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

Emission mechanisms for gamma rays and neutrinos:

Interactions of 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 ”

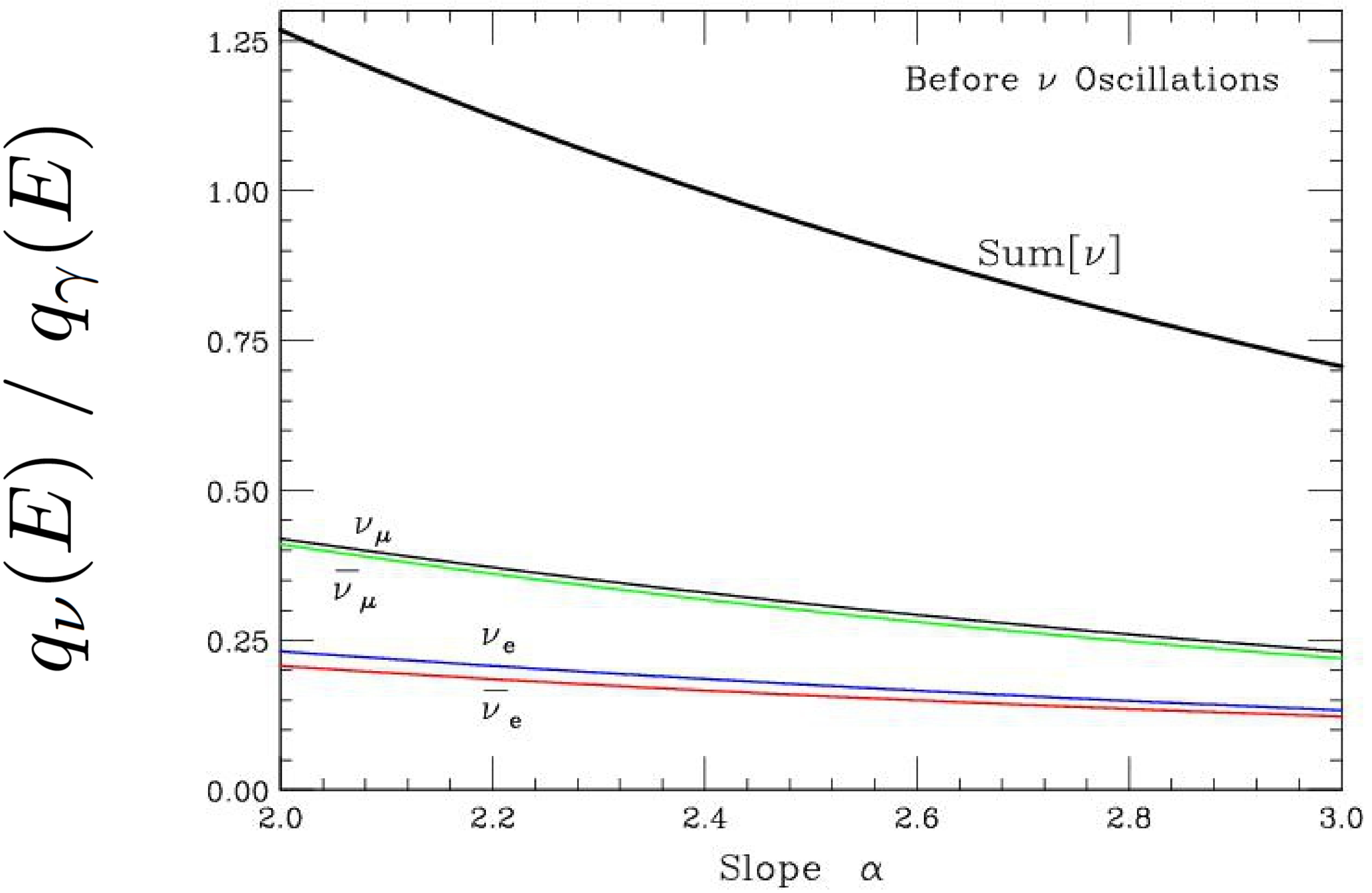
$$e^{\pm}\ \gamma_{\mathrm{soft}} \rightarrow e^{\pm}\ \gamma$$

$$e^{\pm}\ Z \rightarrow e^{\pm}\ \gamma\ Z$$

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

Ratio Neutrino-Photon (numerical calculation)

$p + \text{gas} \to \gamma \ , \ \nu$ $\qquad$ $N_p(E) \propto E^{-\alpha}$



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

$$q_\nu(E) \simeq q_\gamma^{\rm had}(E)$$

Approximately
equal emission
for photons and neutrinos

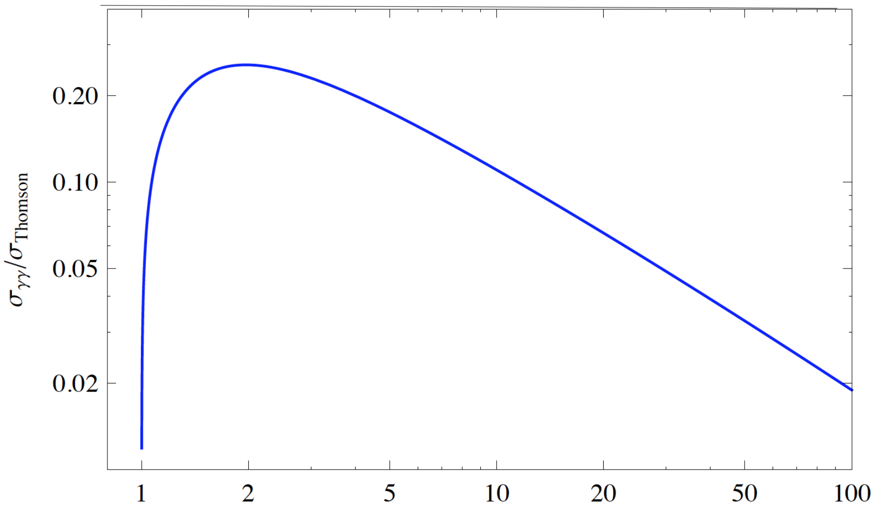
$$\phi_\nu(E) \simeq \phi_\gamma^\circ(E)$$ = No-absorption photon flux

$$\phi_\gamma(E) \simeq \phi_\gamma^\circ(E)\ \langle P_{\rm surv}(E)\rangle$$

Relation between the photon/neutrino fluxes
depends on photon absorption
(in the source and during propagation)

Gamma Ray Absorption:

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



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

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

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

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

$$\phi_\nu^{\mathrm{astro}} = \phi_\nu^{\mathrm{extra}} + \phi_\nu^{\mathrm{Gal}}$$

Corresponding photon fluxes

$$\phi_\gamma^{\mathrm{extra}} + \phi_\gamma^{\mathrm{Gal}}$$

Negligibly small
(photons absorbed)

Important target
of observation

Extragalactic Neutrinos

$$\phi_\nu^{\rm extra}(E) = \frac{c}{4\pi}\,\frac{1}{H_0}\int_0^\infty \frac{dz}{\mathcal{H}(z)}\; q_\nu[E(1+z), z]$$

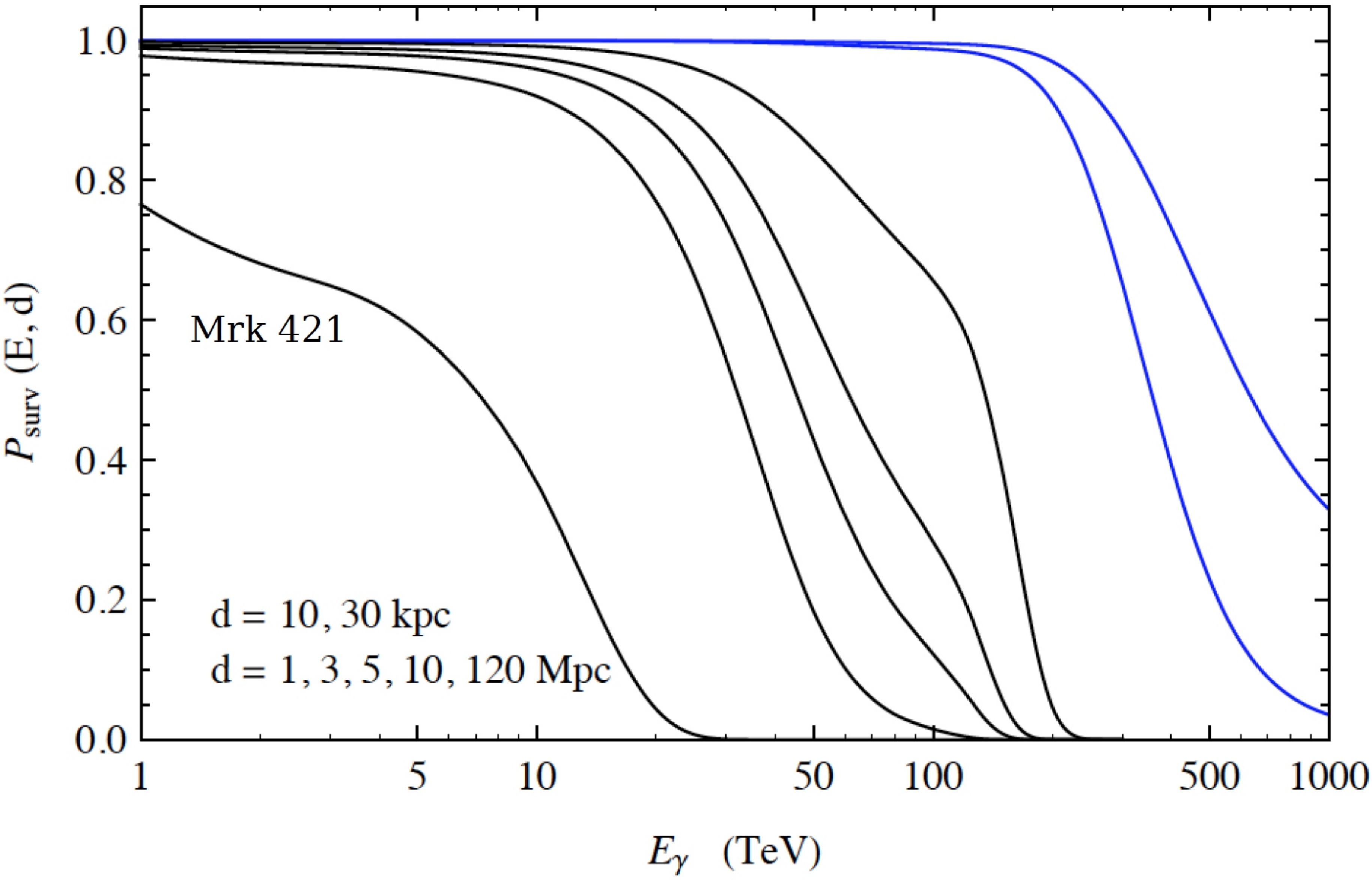
Integration over redshift (volume)
[most contribution from *distant, faint sources*]

$$\phi_\gamma^{\rm extra}(E) = \frac{c}{4\pi}\,\frac{1}{H_0}\int_0^\infty \frac{dz}{\mathcal{H}(z)}\; q_\gamma[E(1+z), z] \quad \exp[-\tau(E,z)]$$

$$\simeq 0$$

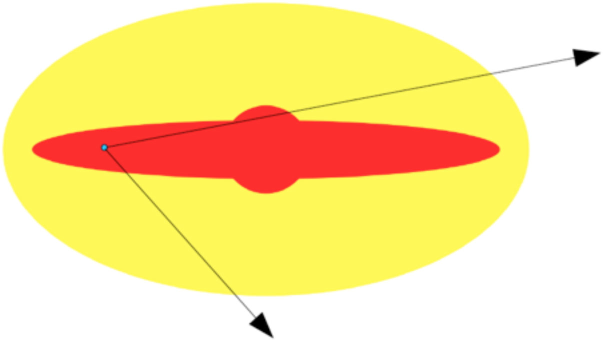
Gamma Ray absorption (intergalactic space)

Astronomy E>100 TeV : Galactic Astronomy



Galactic Source of Neutrinos

$$\phi_\nu^{\rm Gal}(E,\Omega) = \int_0^\infty d\ell \; q_\nu[E, \vec{x}_\odot + \ell\,\hat{\Omega}]$$

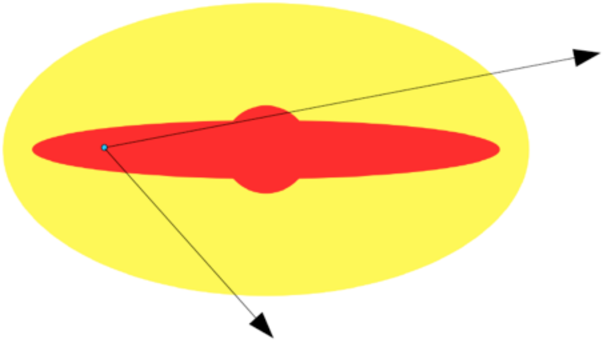


$$\phi_\nu^{\rm Gal}(E,\Omega) \Longleftrightarrow q_\nu(E,\vec{x})$$

Angular distribution of the flux

Spatial distribution of emission

Galactic Source of Neutrinos



$$\phi_\nu^{\rm Gal}(E,\Omega) = \int_0^\infty d\ell \; q_\nu[E, \vec{x}_\odot + \ell\,\hat{\Omega}]$$

$$\phi_\nu^{\rm Gal}(E,\Omega) \Longleftrightarrow q_\nu(E,\vec{x})$$

Angular distribution of the flux

Spatial distribution of emission

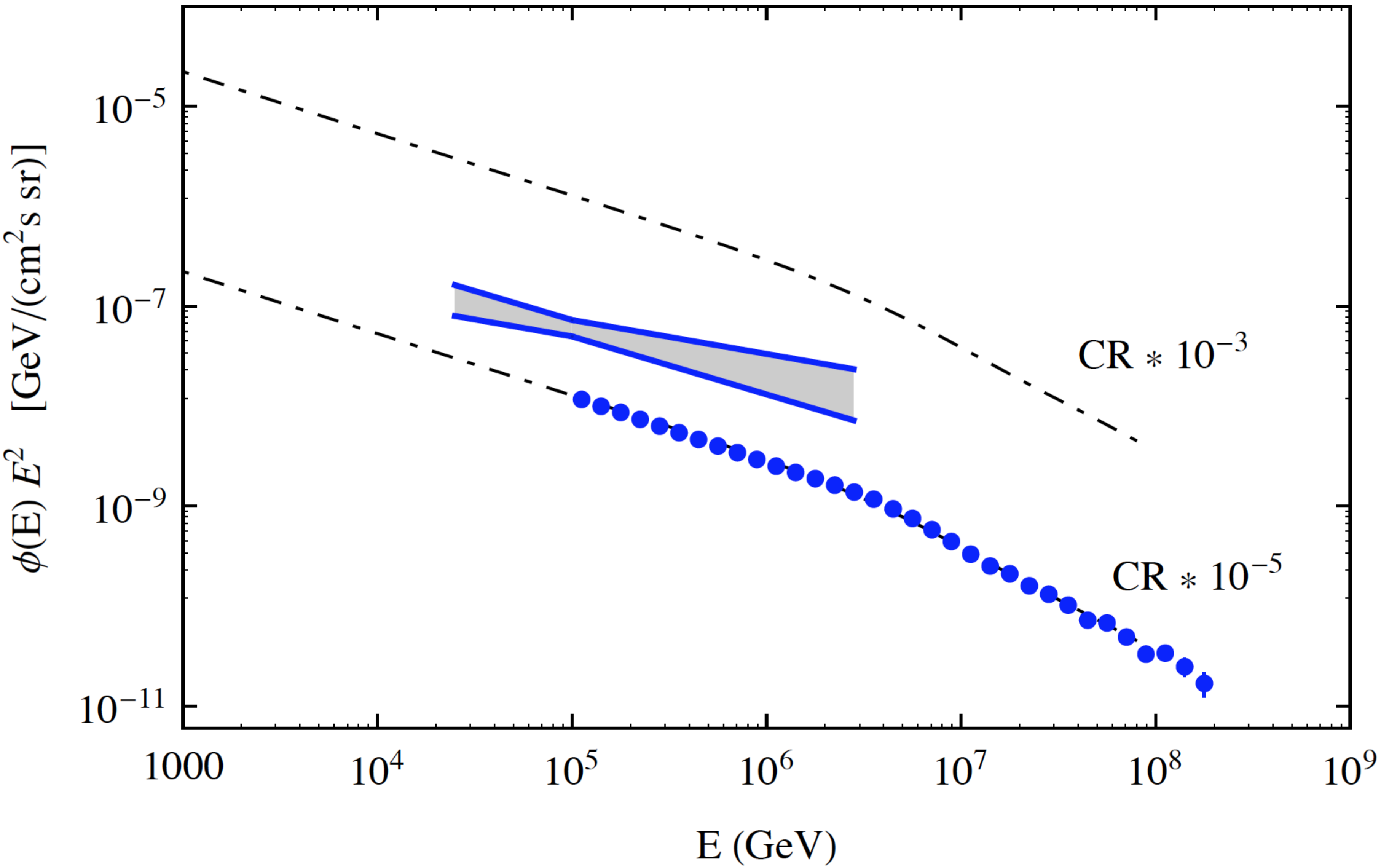
Corresponding Flux of Gamma Rays

$$\phi_\gamma^{\rm Gal}(E,\Omega) = \int_0^\infty d\ell \; q_\gamma[E, \vec{x}_\odot + \ell\,\hat{\Omega}] \; \exp\left[-\tau(E,\ell\,\hat{\Omega})\right]$$

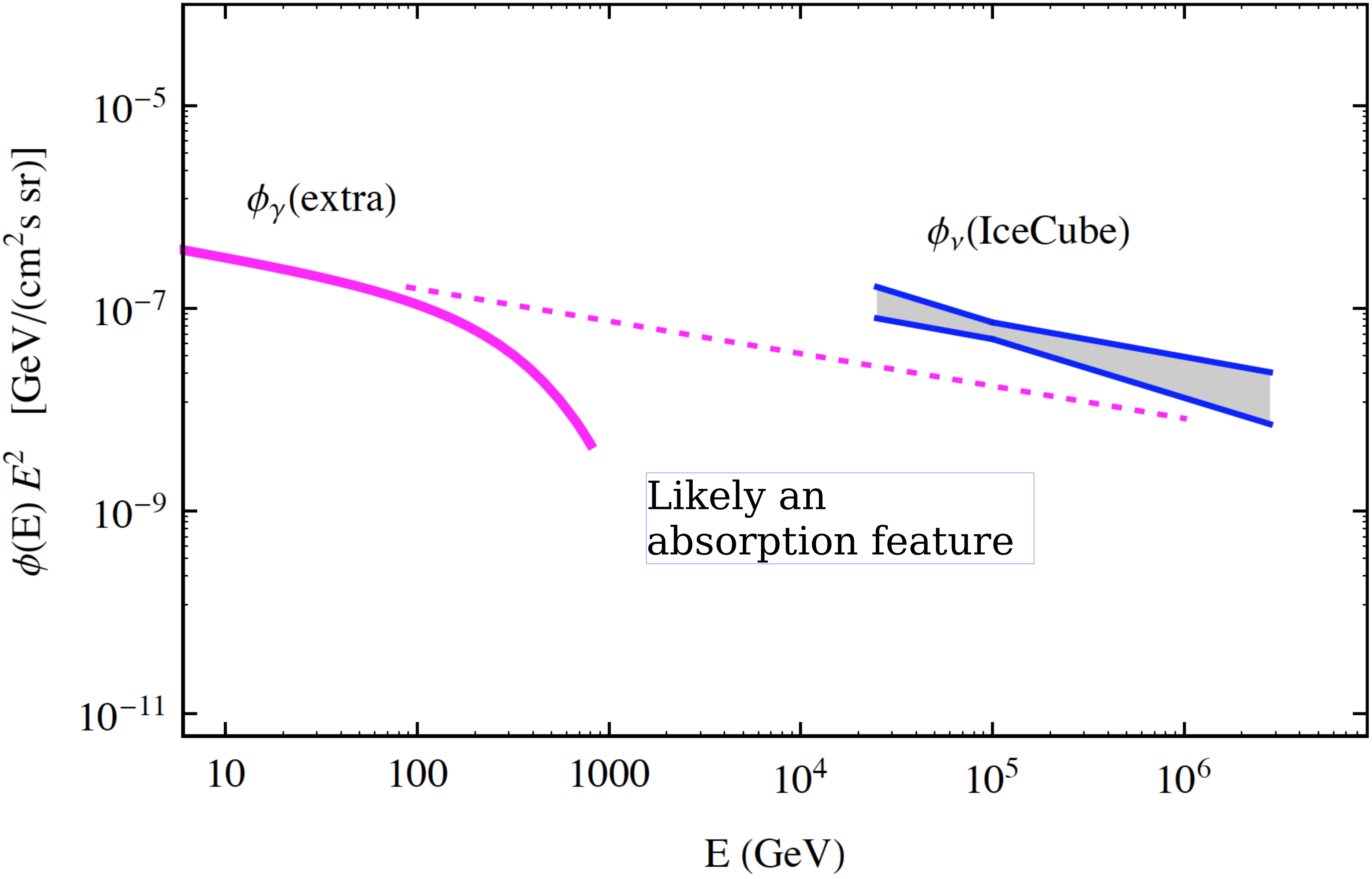
Absorption

IceCube signal
of astrophysical neutrinos

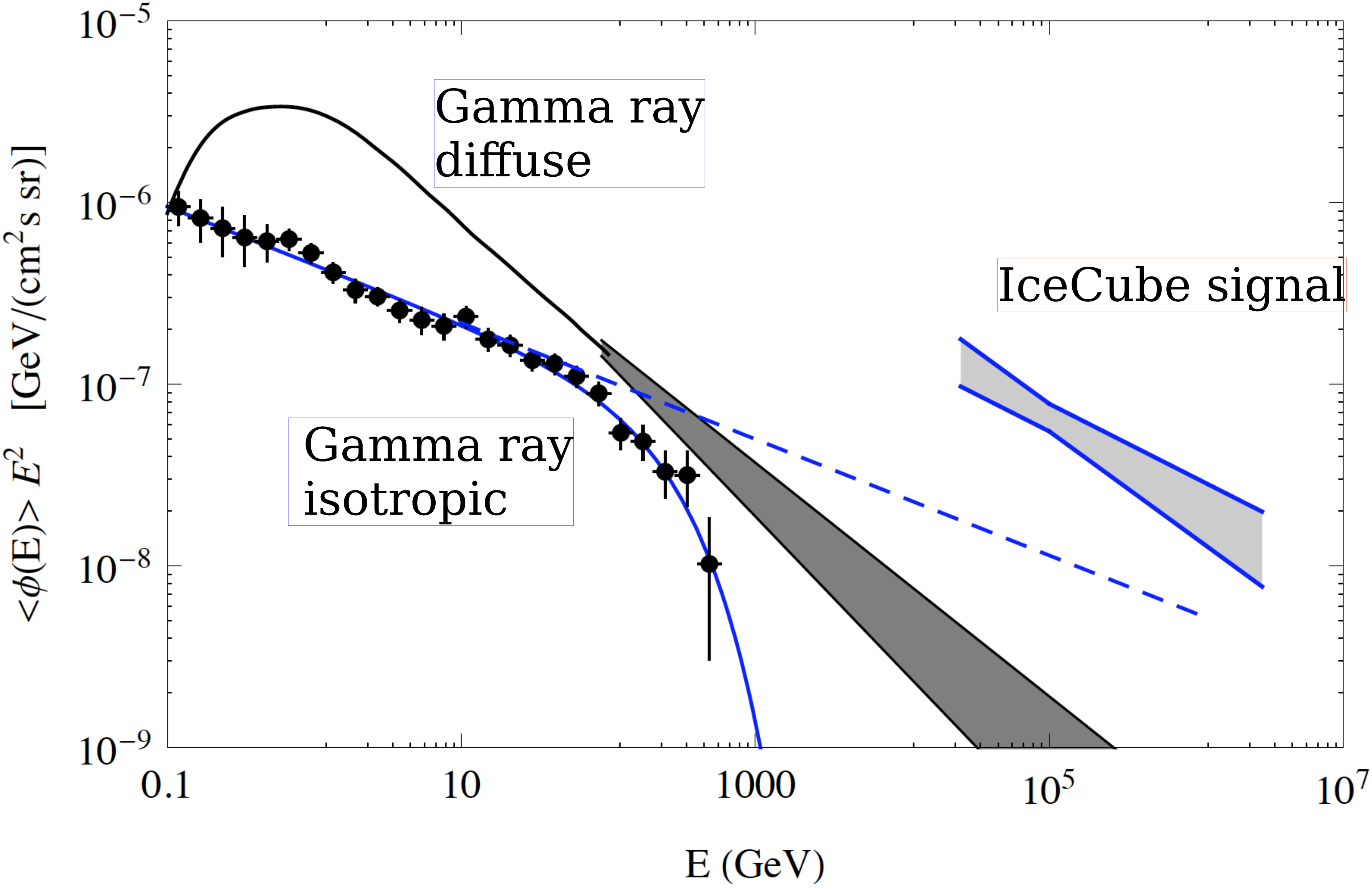
Interpreted as an isotropic (extragalactic flux)



Comparison with extragalactic gamma rays



Likely an absorption feature



Gamma ray diffuse
IceCube signal
Gamma ray isotropic
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.1
10
1000
10^5
10^7
E (GeV)
$<\phi(E)> E^2$ [GeV/(cm^2 s sr)]

Models for Galactic Neutrinos

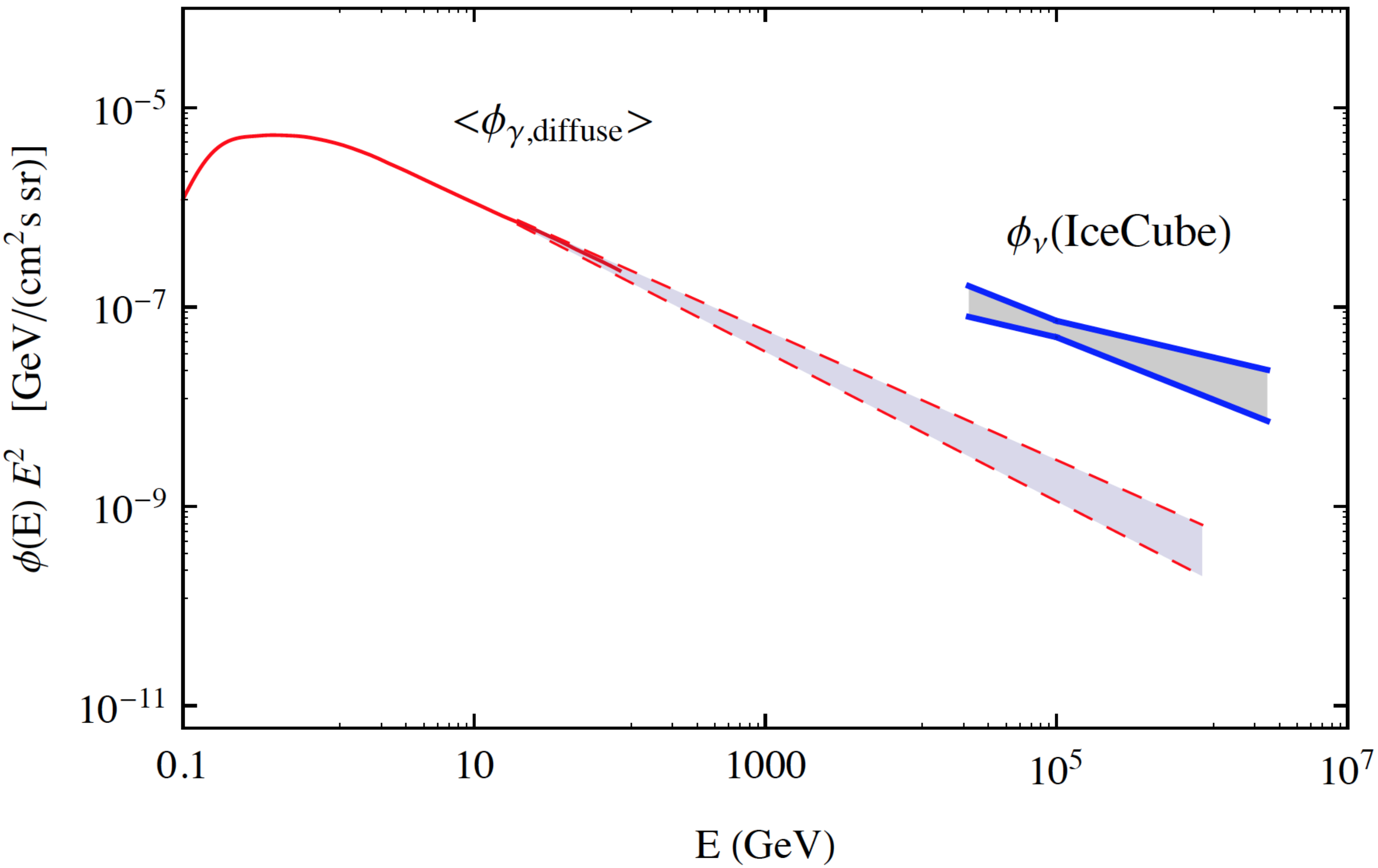
- “Standard” mechanism of production
  (Cosmic Ray interactions in the interstellar medium).

- Dark Matter Decay
  (in the form of a Super Massive particle)

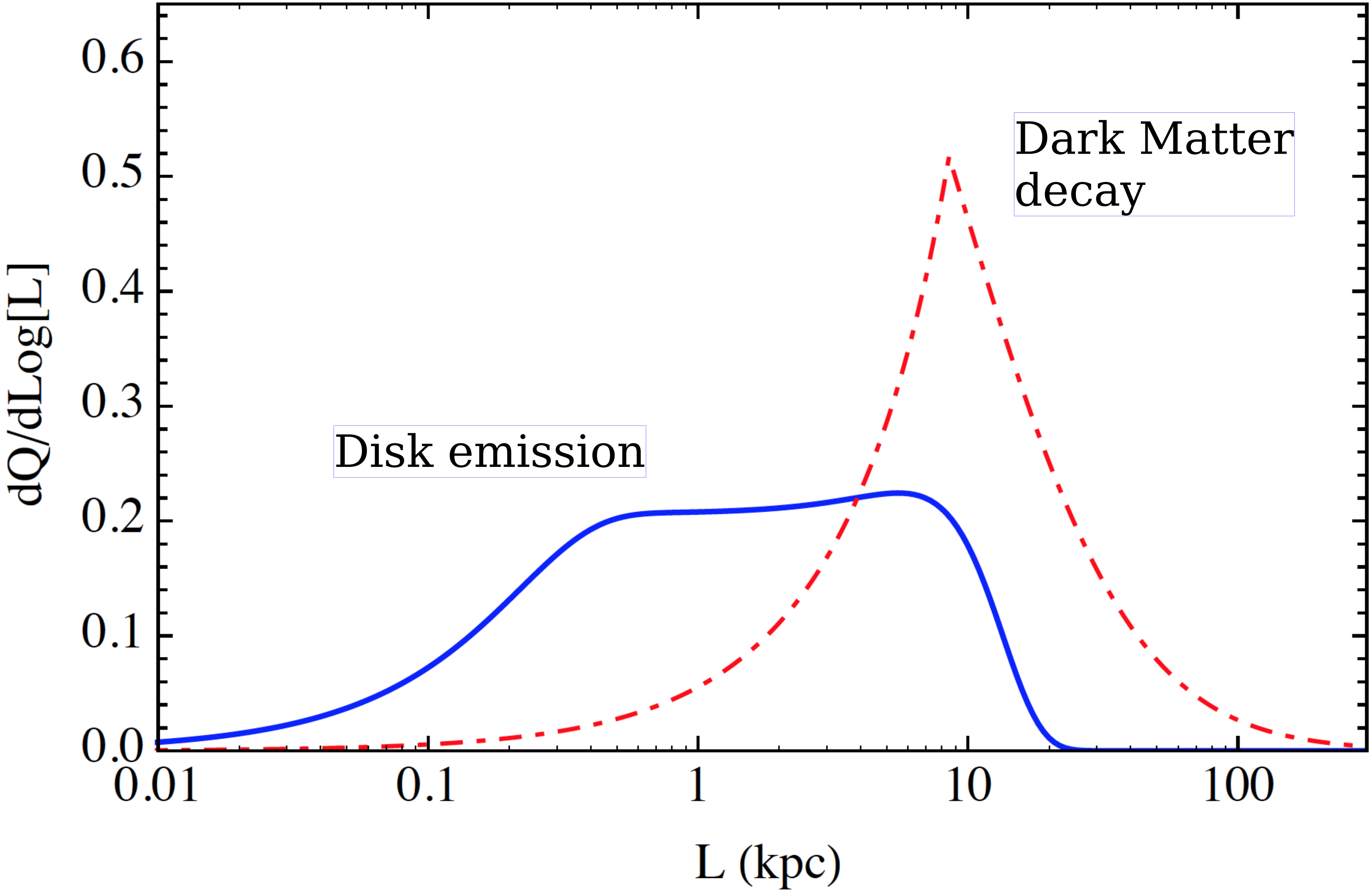
- Large Halo model

- Fermi bubbles

Comparison of IceCube result with diffuse Galactic gamma rays

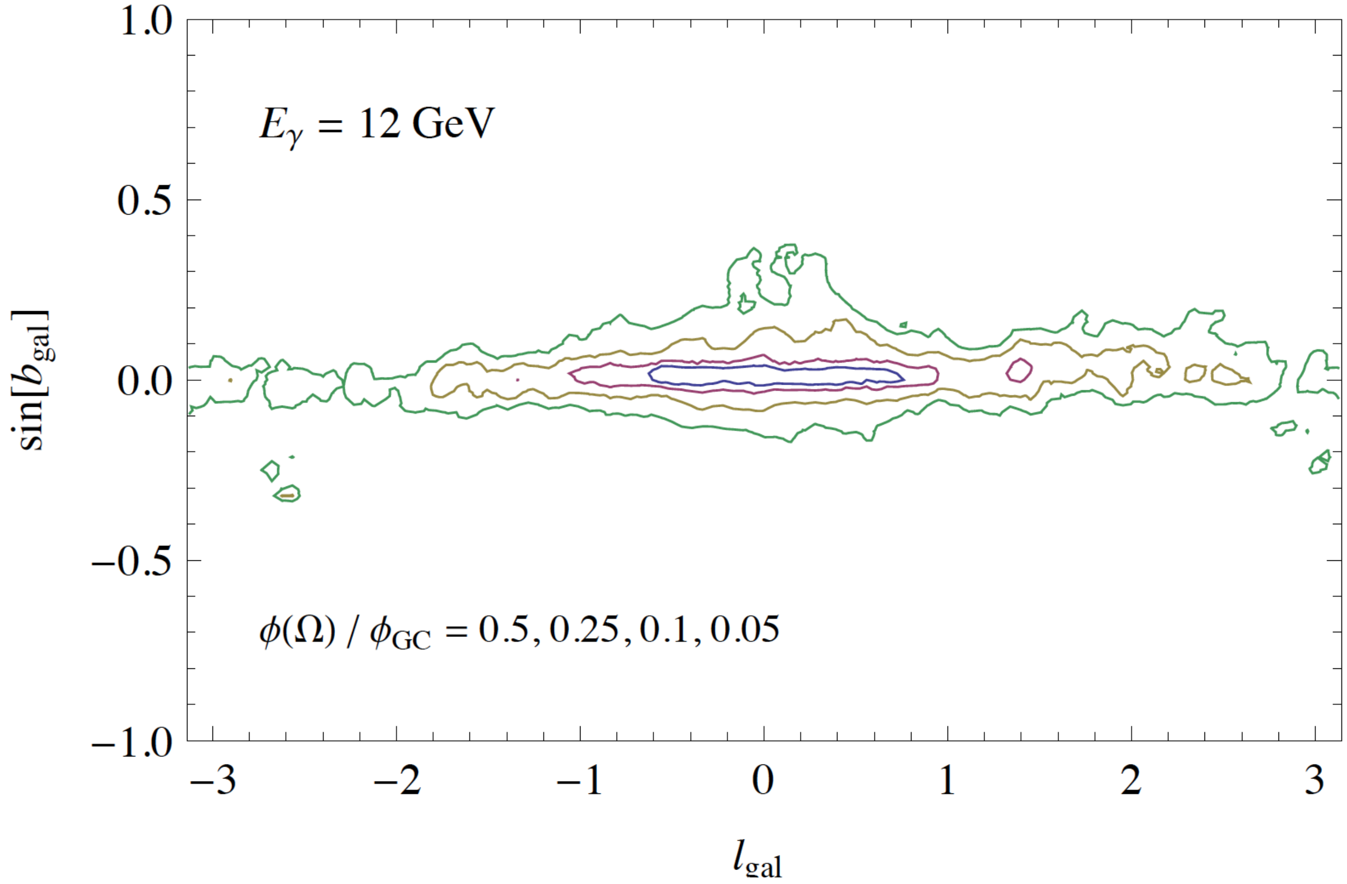


Extrapolation of the measurement of the diffuse Gamma Ray flux of FERMI


Dark Matter decay
Disk emission
dQ/dLog[L]
L (kpc)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.01
0.1
1
10
100

Fermi measurement of the diffuse flux

$$\langle \Phi_\gamma(E_{\min}) \rangle \simeq 4.6 \times 10^{-8} \left(\frac{E_{\min}}{10\ \text{GeV}} \right)^{-1.74} [\text{cm}^2\,\text{s}\,\text{sr}]^{-1}$$

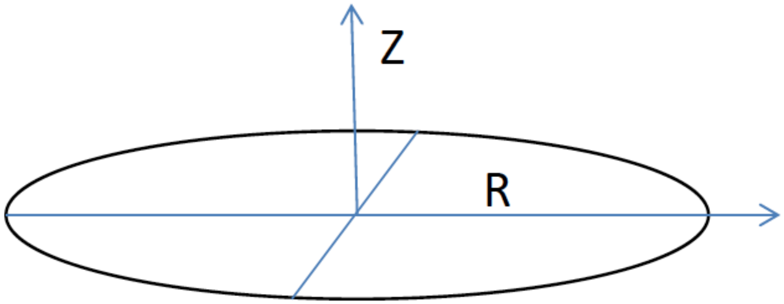


50% of flux
in latitude band
±5°

extrapolation

$$\langle \Phi_\gamma(E_{\min}) \rangle \simeq 6.0 \times 10^{-15} \left(\frac{E_{\min}}{100\ \text{TeV}} \right)^{-1.74} [\text{cm}^2\,\text{s}\,\text{sr}]^{-1}$$

Phenomenological model to describe the diffuse emission



Spatial distributions:

Exponential model:

$$q_\gamma\,(R,Z) = C\ \exp\ (\frac{-R}{R_0} - \frac{|Z|}{Z_0})$$

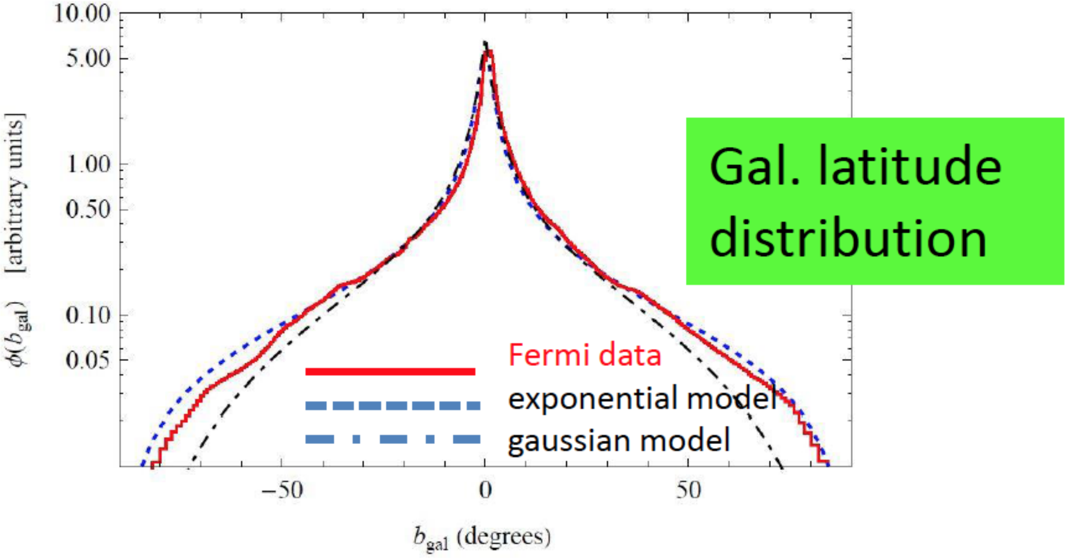
R_0 = 3.9 kpc Z_0 = 0.27 kpc

Gaussian model:

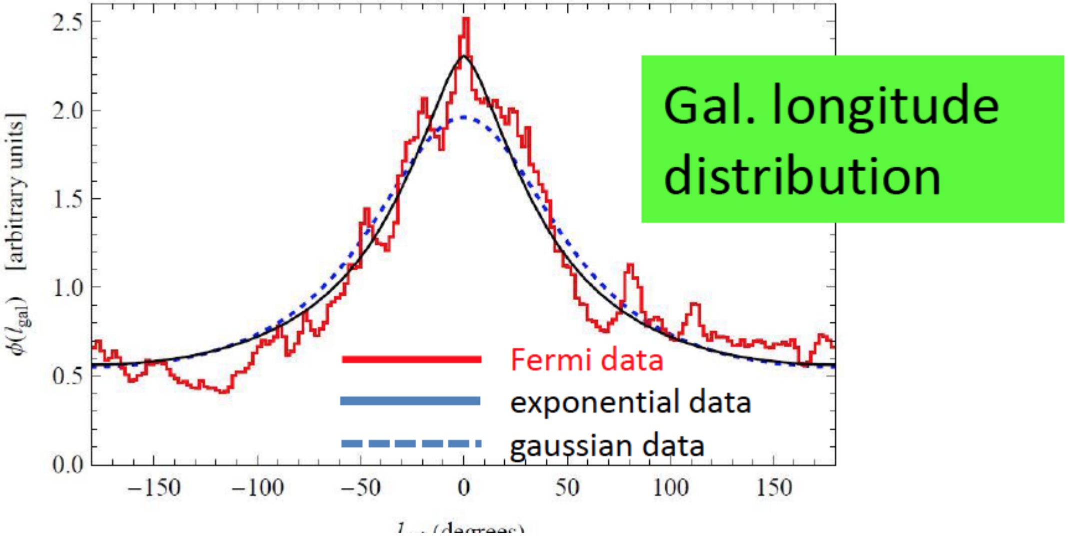
$$q_\gamma\,(R,Z) = C'\ \exp\ (\frac{-R^2}{2R_0^2} - \frac{|Z|2}{2Z_0^2})$$

R_0 = 5.2 kpc Z_0 = 0.22 kpc

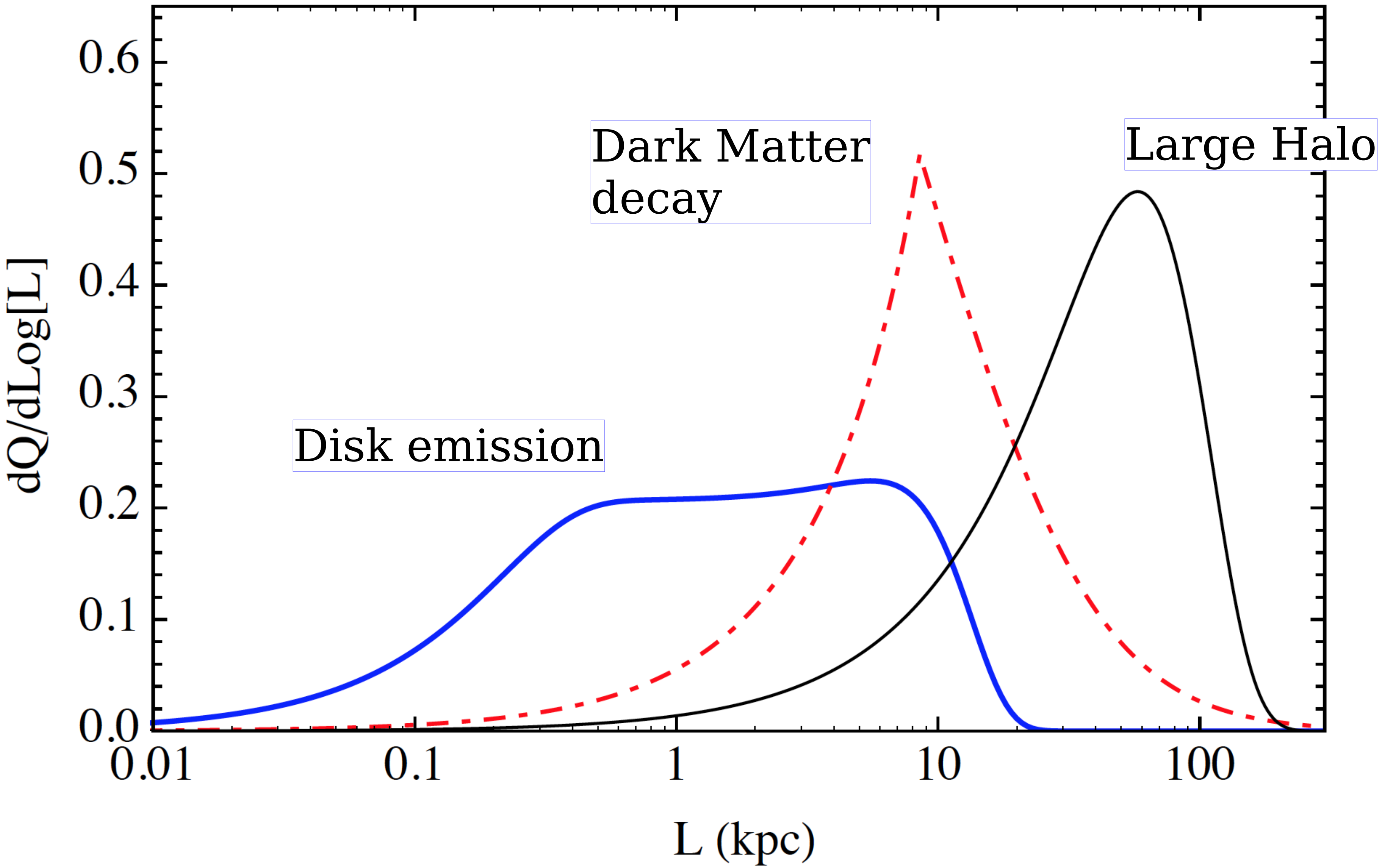
γ-ray flux (10-100 GeV)

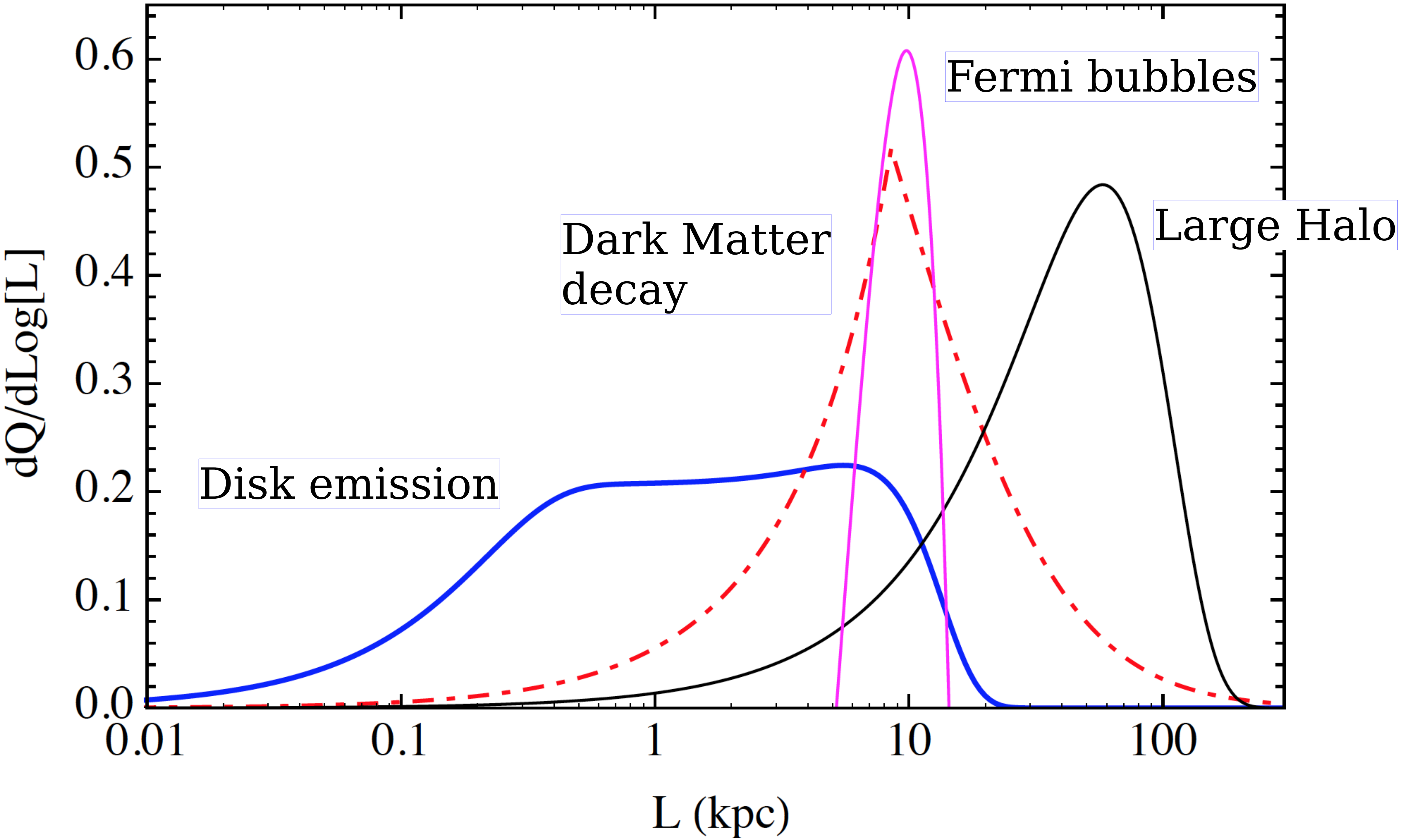


Gal. latitude distribution

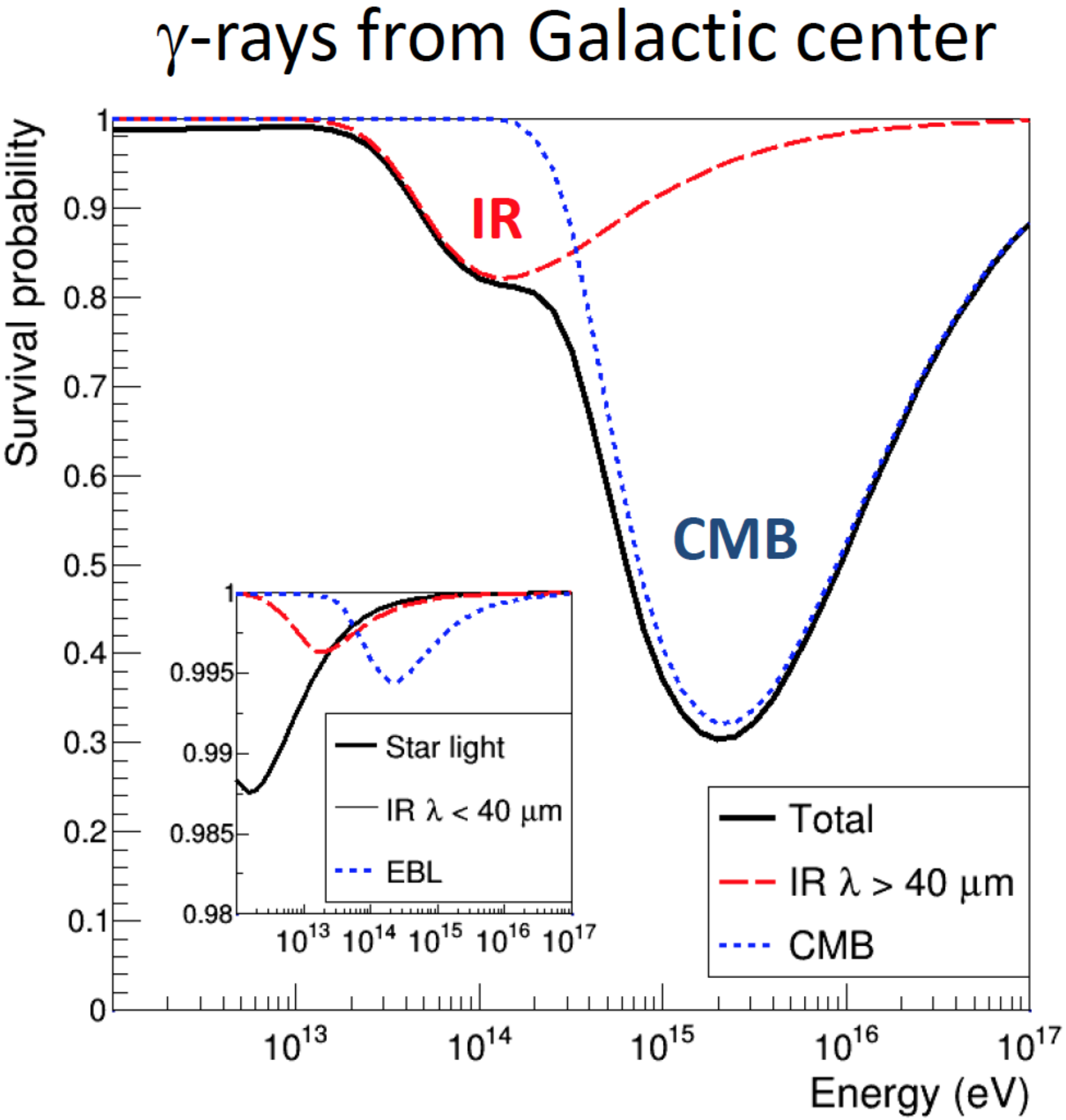


Gal. longitude distribution


Dark Matter decay
Large Halo
Disk emission
dQ/dLog[L]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.01
0.1
1
10
100
L (kpc)


Fermi bubbles
Large Halo
Dark Matter decay
Disk emission
dQ/dLog[L]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.01
0.1
1
10
100
L (kpc)

Survival Probabilities for Gamma Rays



Absorption pattern
has two maxima

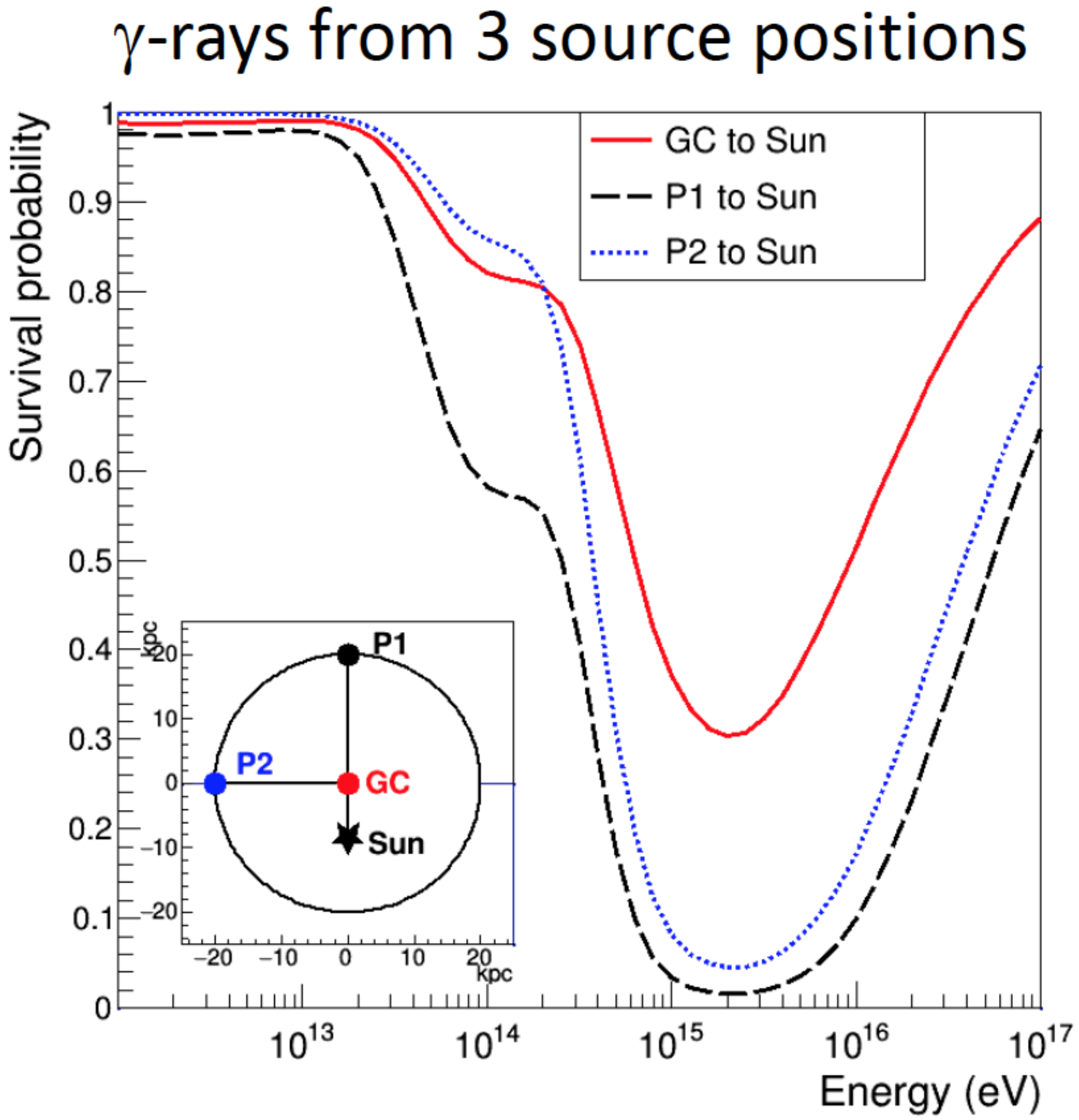
$$E_\gamma \simeq 150 \text{ PeV}$$

[from dust emitted radiation]

$$E_\gamma \simeq 2.2 \text{ PeV}$$

[from CMBR]

Survival Probabilities for Gamma Rays



Gamma Astronomy

$$E_\gamma \lesssim 300 \text{ TeV}$$

Possible in all Galaxy

$$P_{\text{abs}} \lesssim 0.45$$

Gamma Astronomy

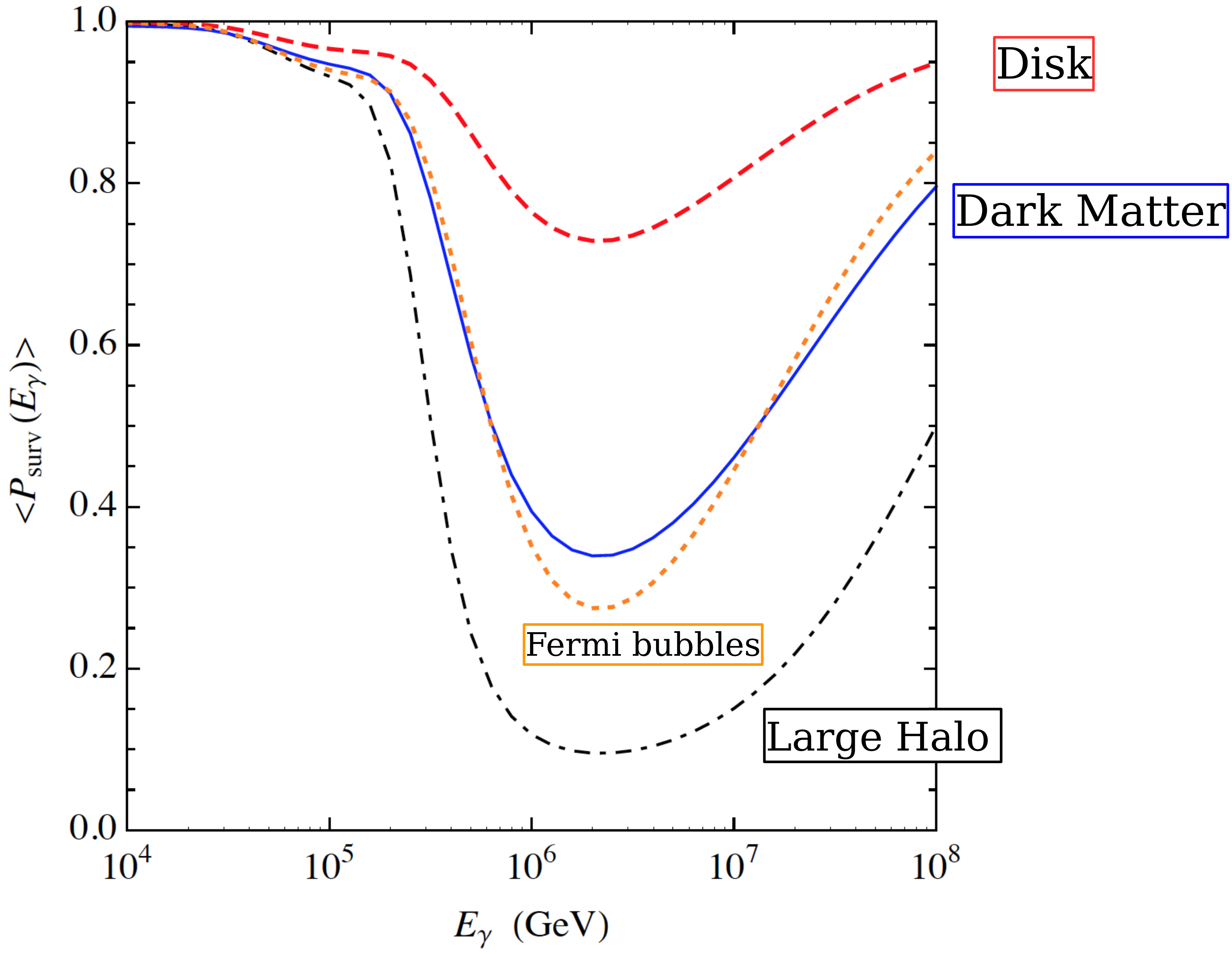
$$E_\gamma \gtrsim 1 \text{ PeV}$$

Possible only in a fraction of the Galaxy

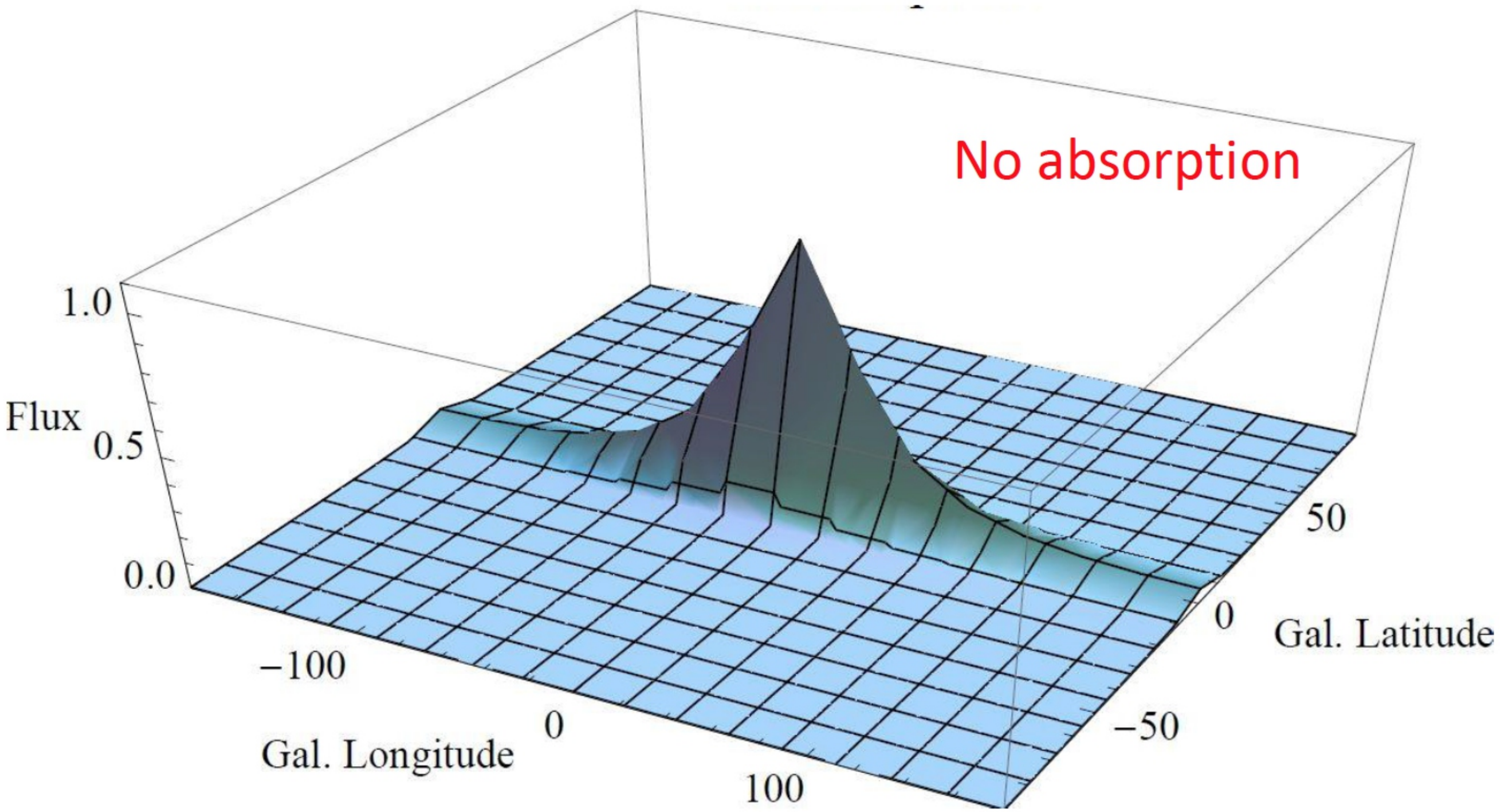
$$P_{\text{abs}} \lesssim 0.7$$

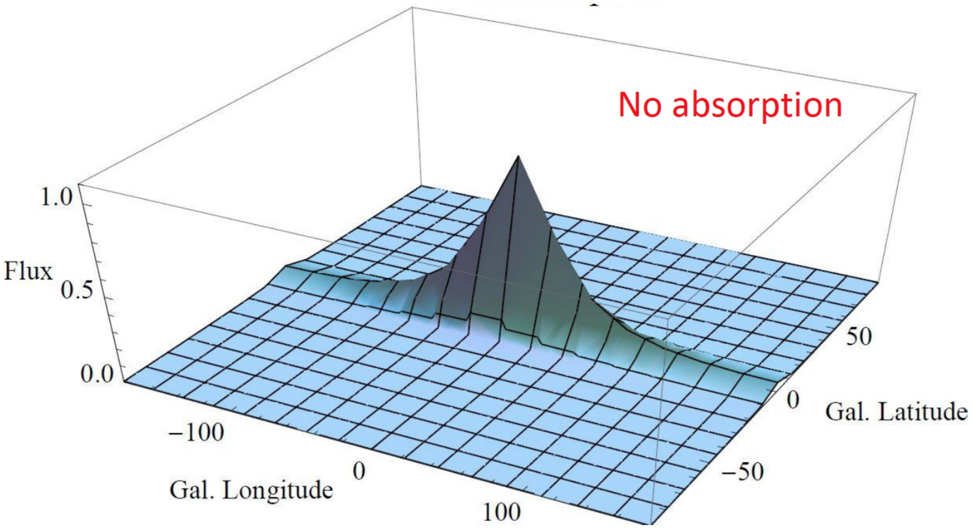
$$d \lesssim 8 \text{ kpc}$$

Average (all sky) Survival probability

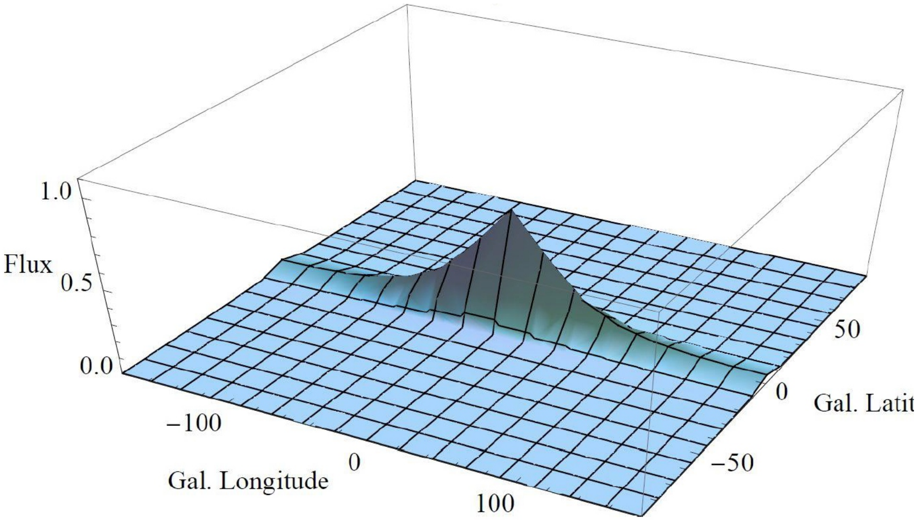


Angular distribution of the diffuse Galactic Emission

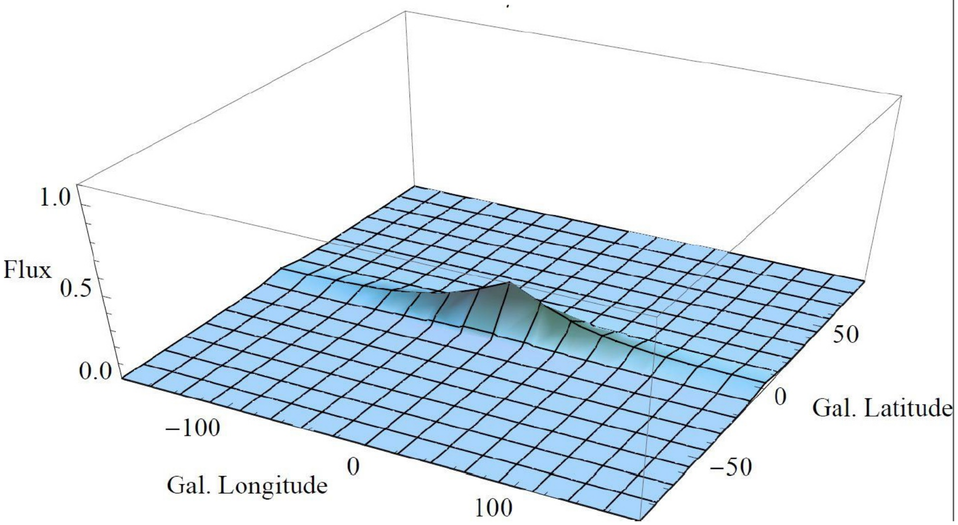



No absorption

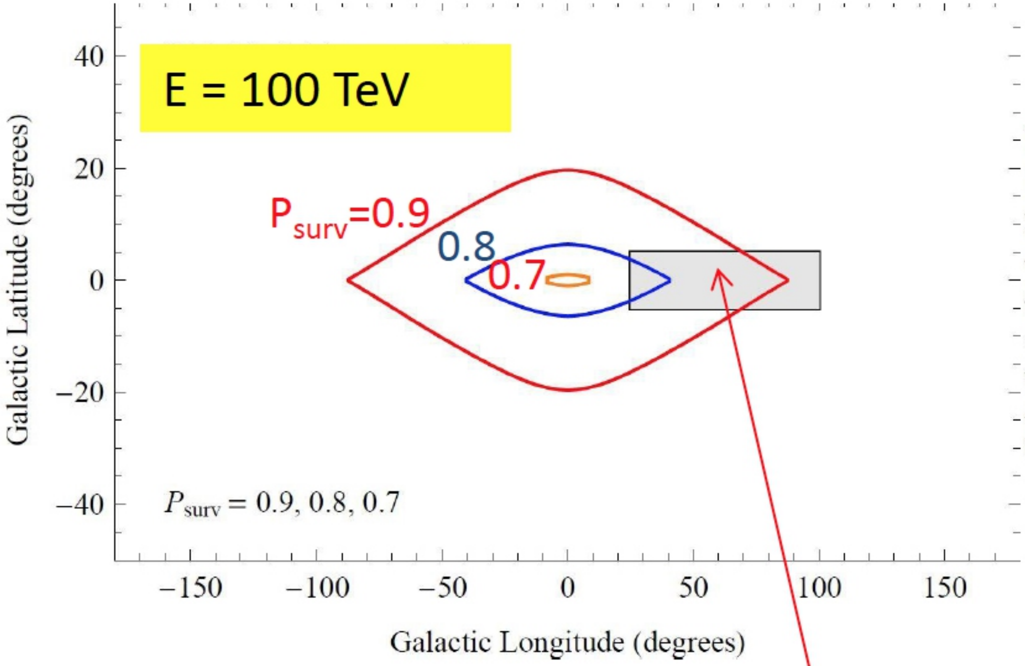
$E_\gamma = 100\ \mathrm{TeV}$



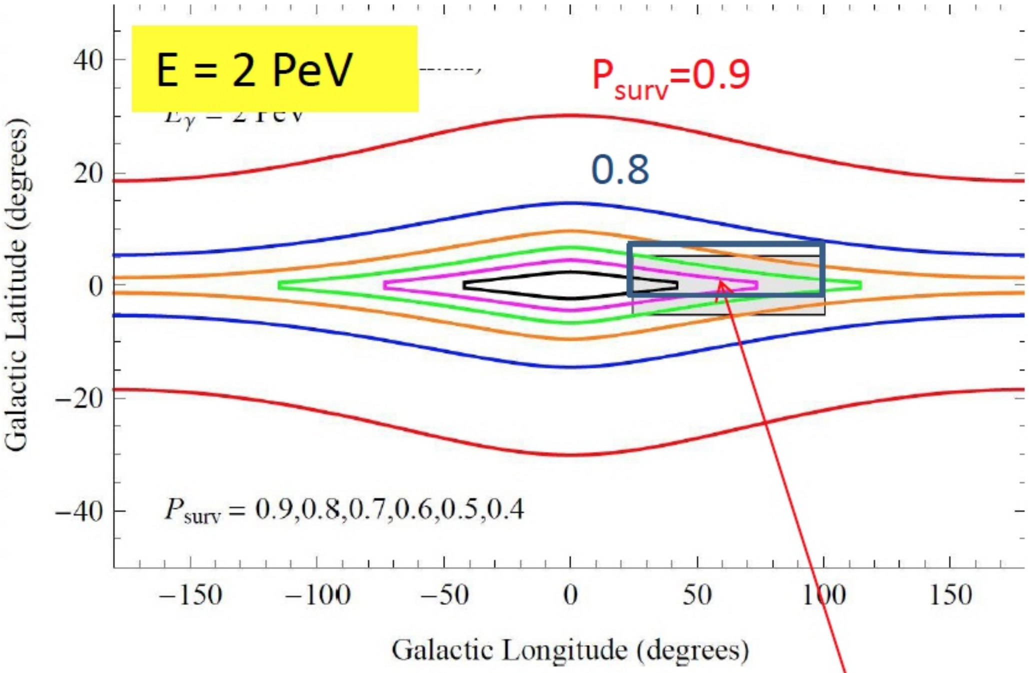
$E_\gamma = 2\ \mathrm{PeV}$



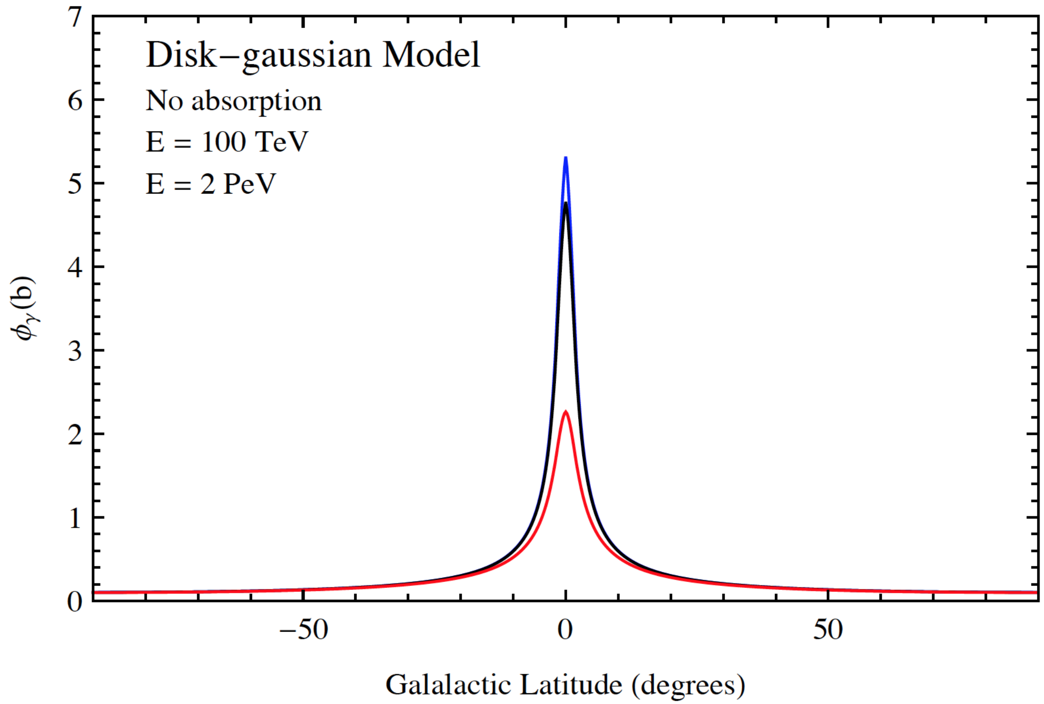
Survival Probability of Gamma Rays from the Galactic diffuse flix

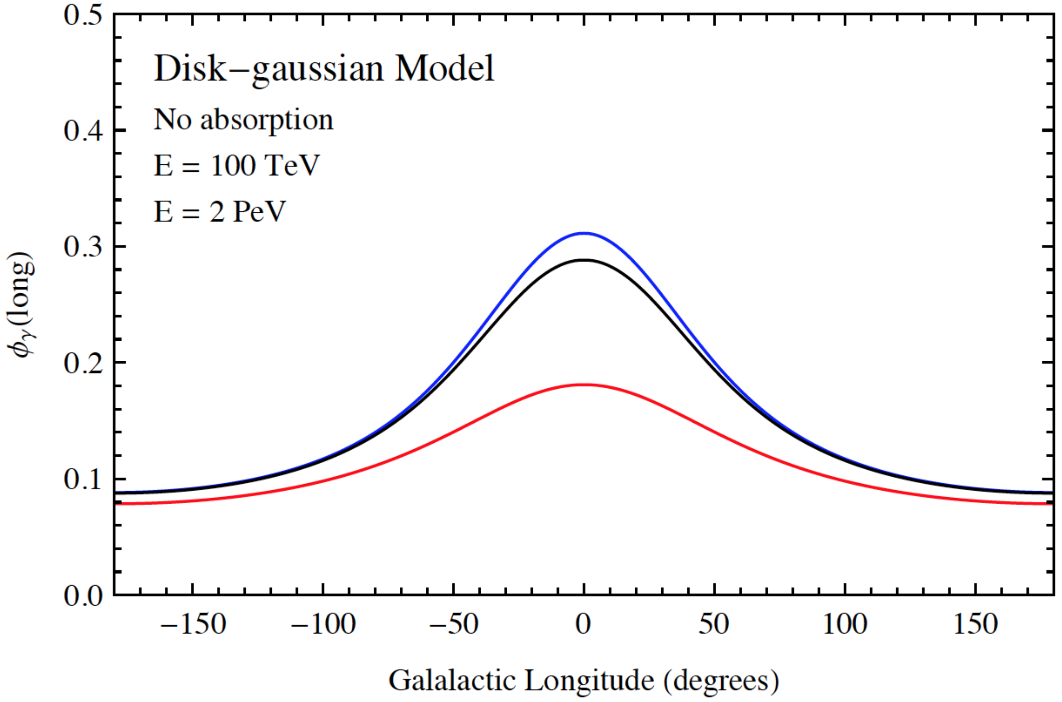


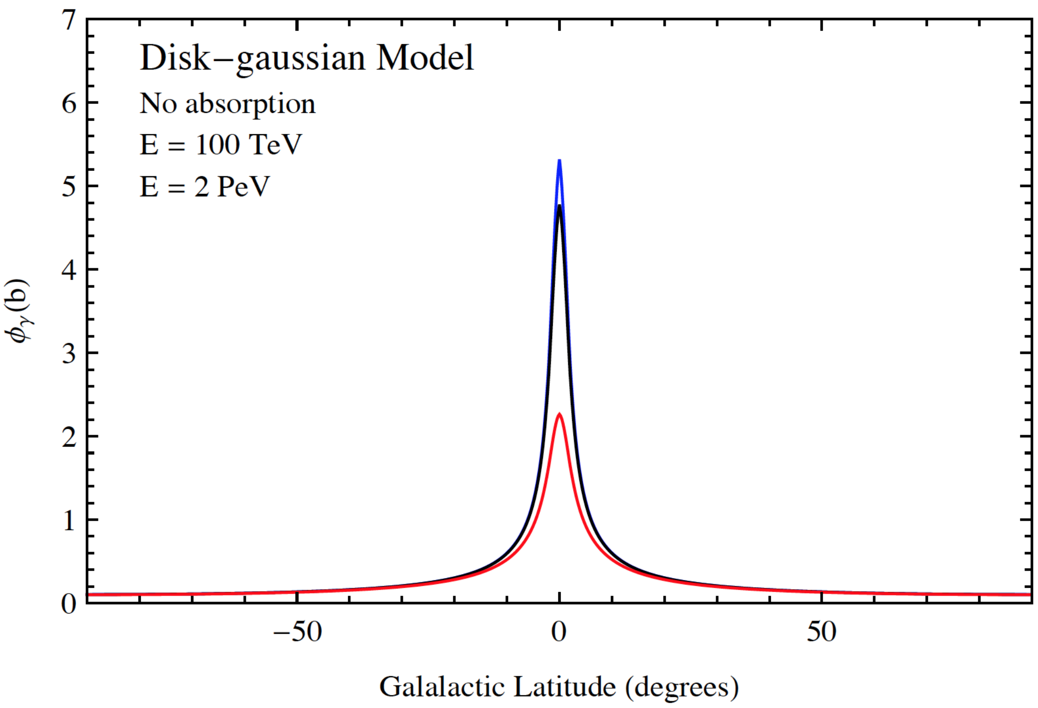
Region l=25°-100° |b|= 5°
P_{surv} = 0.75

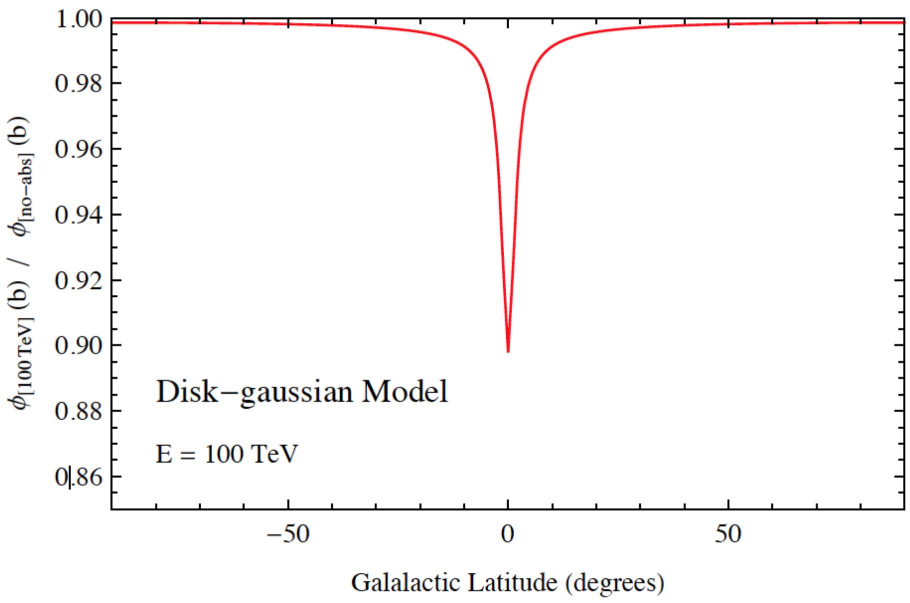


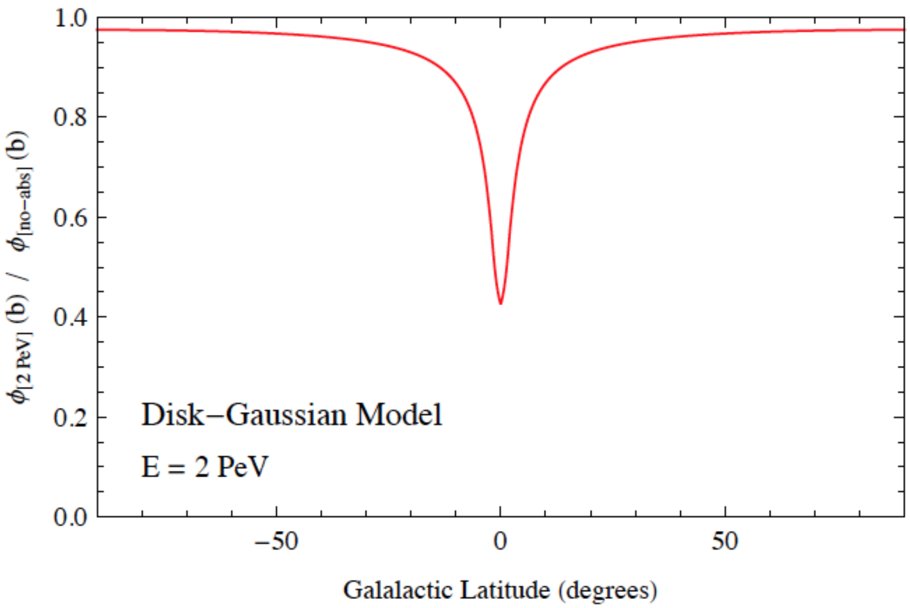
Region l=25°-100° |b|= 5°
P_{surv} = 0.51


Disk−gaussian Model
No absorption
E = 100 TeV
E = 2 PeV
ϕ_γ(b)
0
1
2
3
4
5
6
7
−50
0
50
Galalactic Latitude (degrees)

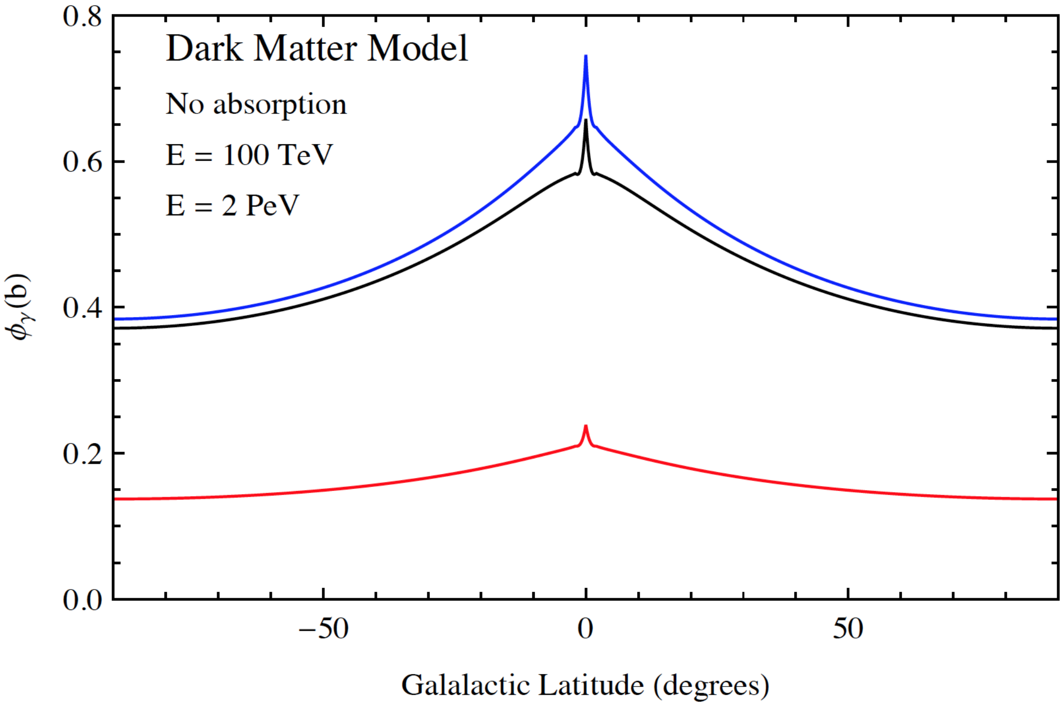

Disk−gaussian Model
No absorption
E = 100 TeV
E = 2 PeV
ϕ_γ(long)
0.0
0.1
0.2
0.3
0.4
0.5
−150
−100
−50
0
50
100
150
Galalactic Longitude (degrees)

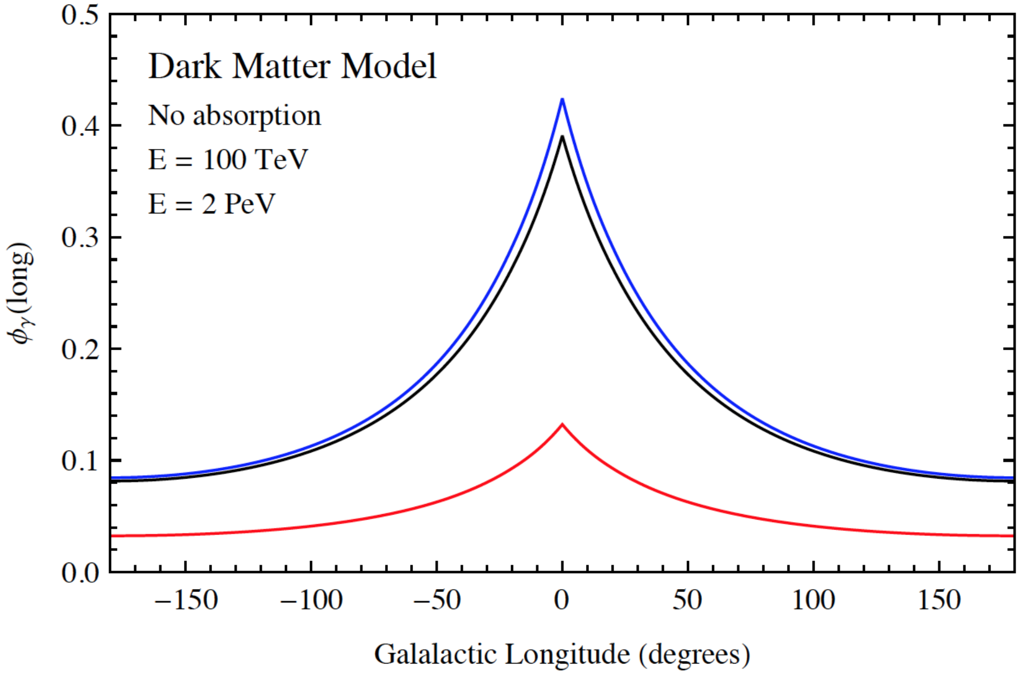

Disk−gaussian Model
No absorption
E = 100 TeV
E = 2 PeV
$\phi_\gamma(b)$
Galalactic Latitude (degrees)
0
1
2
3
4
5
6
7
−50
0
50


$\phi_{[100\,\mathrm{TeV}]}(b)$ / $\phi_{[\mathrm{no-abs}]}(b)$
Disk−gaussian Model
E = 100 TeV
Galalactic Latitude (degrees)
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
−50
0
50


$\phi_{[2\,\mathrm{PeV}]}(b)$ / $\phi_{[\mathrm{no-abs}]}(b)$
Disk−Gaussian Model
E = 2 PeV
Galalactic Latitude (degrees)
1.0
0.8
0.6
0.4
0.2
0.0
−50
0
50

Dark Matter Decay Model





Measurements of the Gamma Ray Galactic diffuse flux

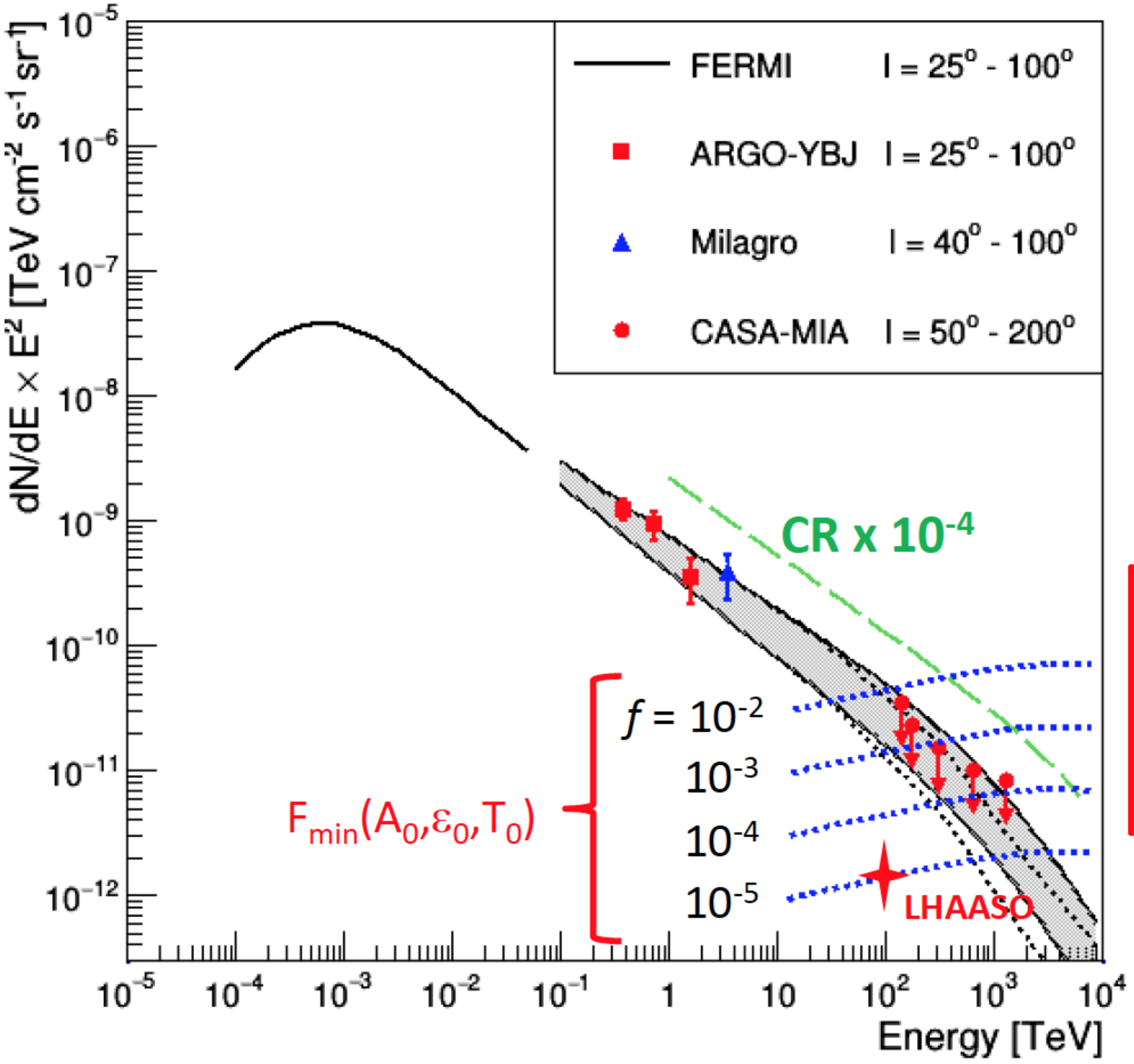
FERMI	100 MeV – 100 GeV	All sky		
HESS	E > 250 GeV	$l = -75^\circ$ to 60°	$\|b\| < 2^\circ$	(2014)
ARGO-YBJ	0.3 - 1 TeV	$l = 25^\circ$ to 100°	$\|b\| < 5^\circ$	(2015)
MILAGRO	> 3.5 TeV	$l = 40^\circ$ to 100°	$\|b\| < 5^\circ$	(2005)
	15 TeV	$l = 30^\circ$ to 85°	$\|b\| < 10^\circ$	(2008)

Above 100 TeV only upper limits: BASJE, EASTOP, UMC...

The lowest are:

CASA-MIA	140-1300 TeV	$l = 50^\circ$ to 200°	$\|b\| < 2^\circ, 5^\circ, 10^\circ$	(1996)

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:

$$F_{min}(A,\varepsilon,T) = F_{min}(A_0,\varepsilon_0,T_0)\sqrt{\frac{A_0T_0}{AT}\,\frac{\varepsilon_0}{\varepsilon}}$$

Assumptions:

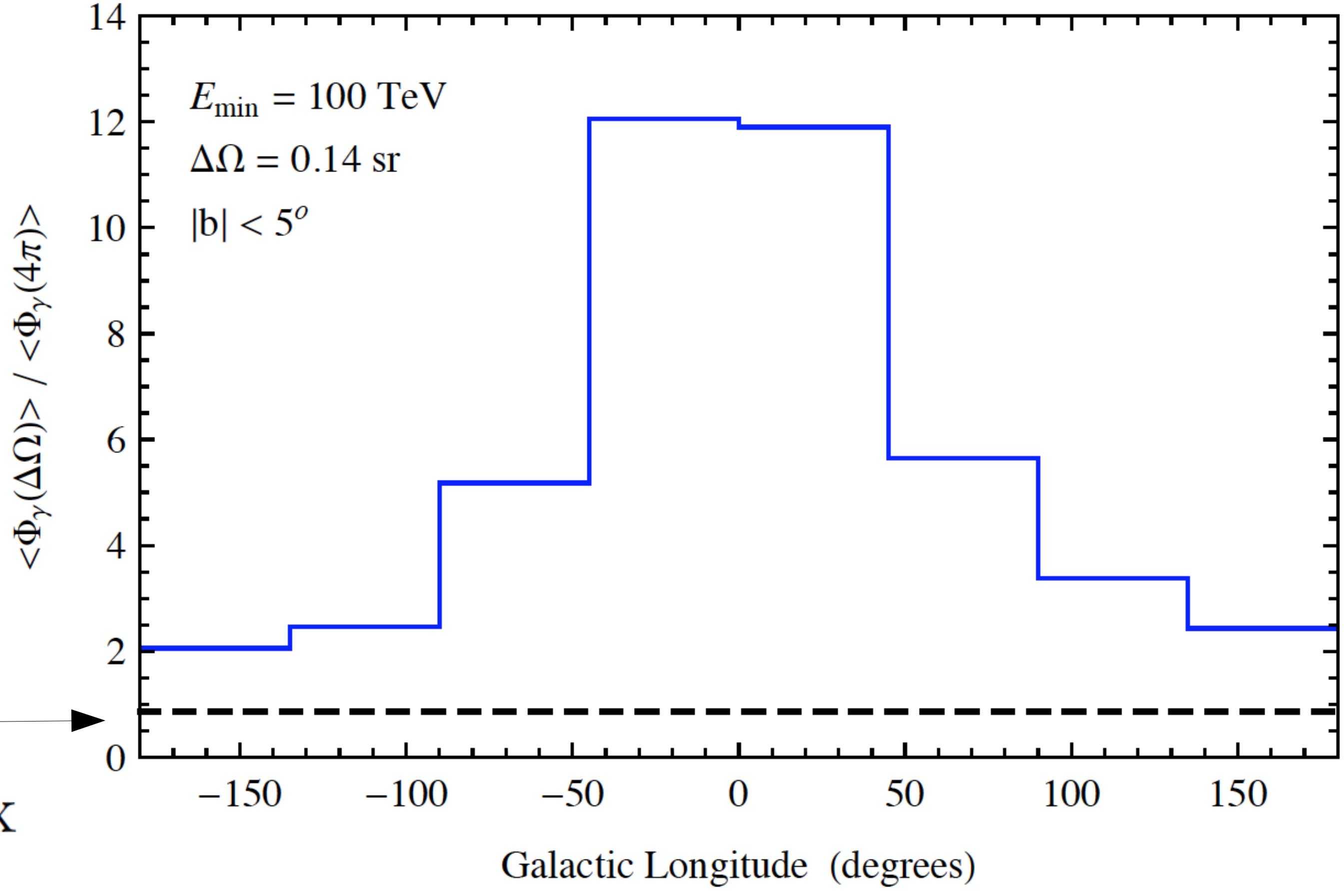
[1.] Angular distribution at E > 100 TeV
Approximately equal to what is observed at 10-100 GeV

[2.] Spectra extrapolated from FERMI results $\propto E_{\gamma}^{-2.7}$

[3.] Assume same exposure as LHAASO
for the region $25^\circ \leq \ell \leq 100^\circ$

$$|b| \leq 5^\circ$$

$$\Delta\ell = 45^\circ$$



$1\ \sigma$ flux

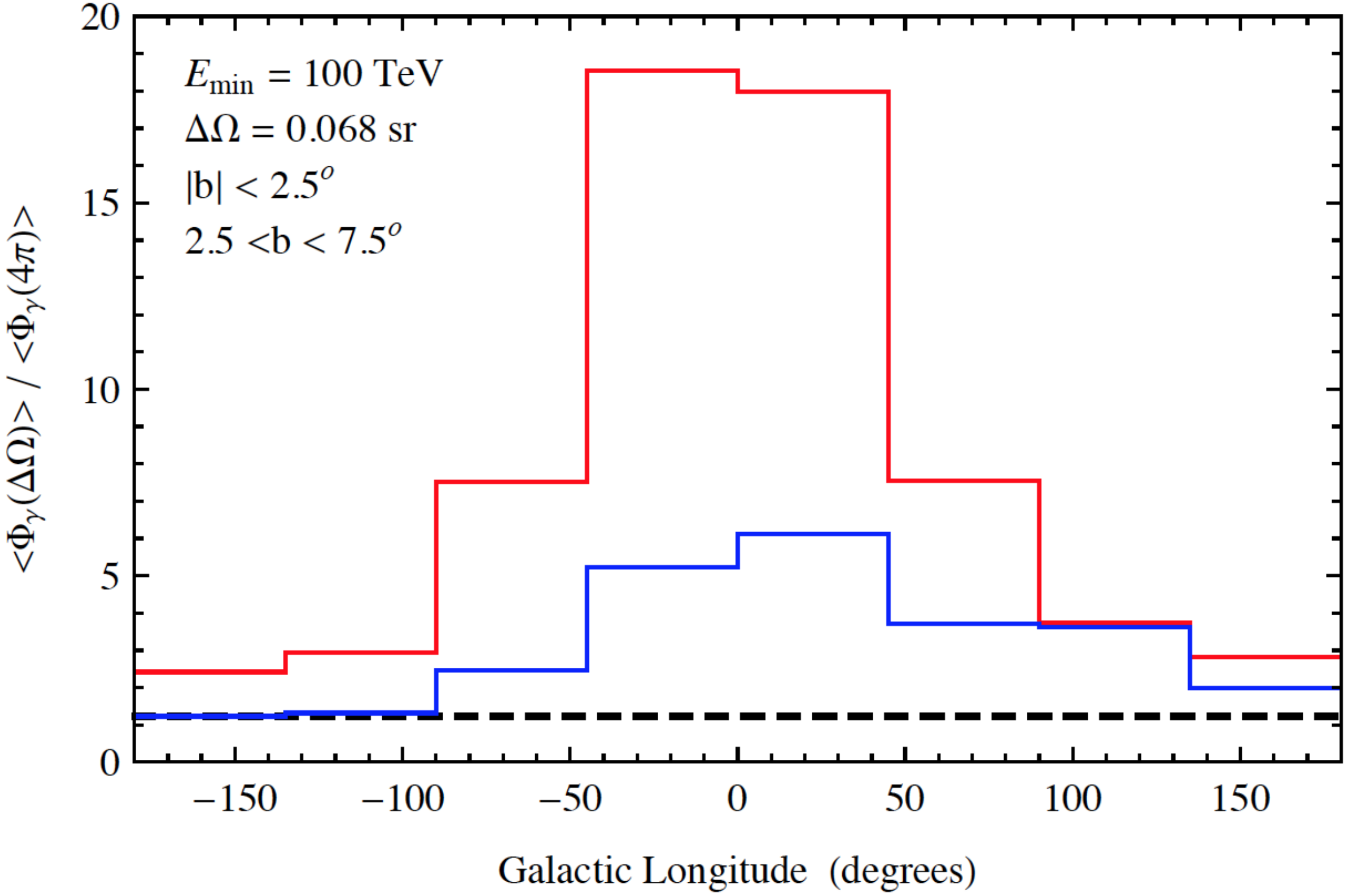
Possibility to study the “width” of the disk diffuse emission

$$|b| \leq 2.5^\circ$$

$$\Delta\ell = 45^\circ$$

$$2.5^\circ < b \leq 7.5^\circ$$

$$\Delta\ell = 45^\circ$$

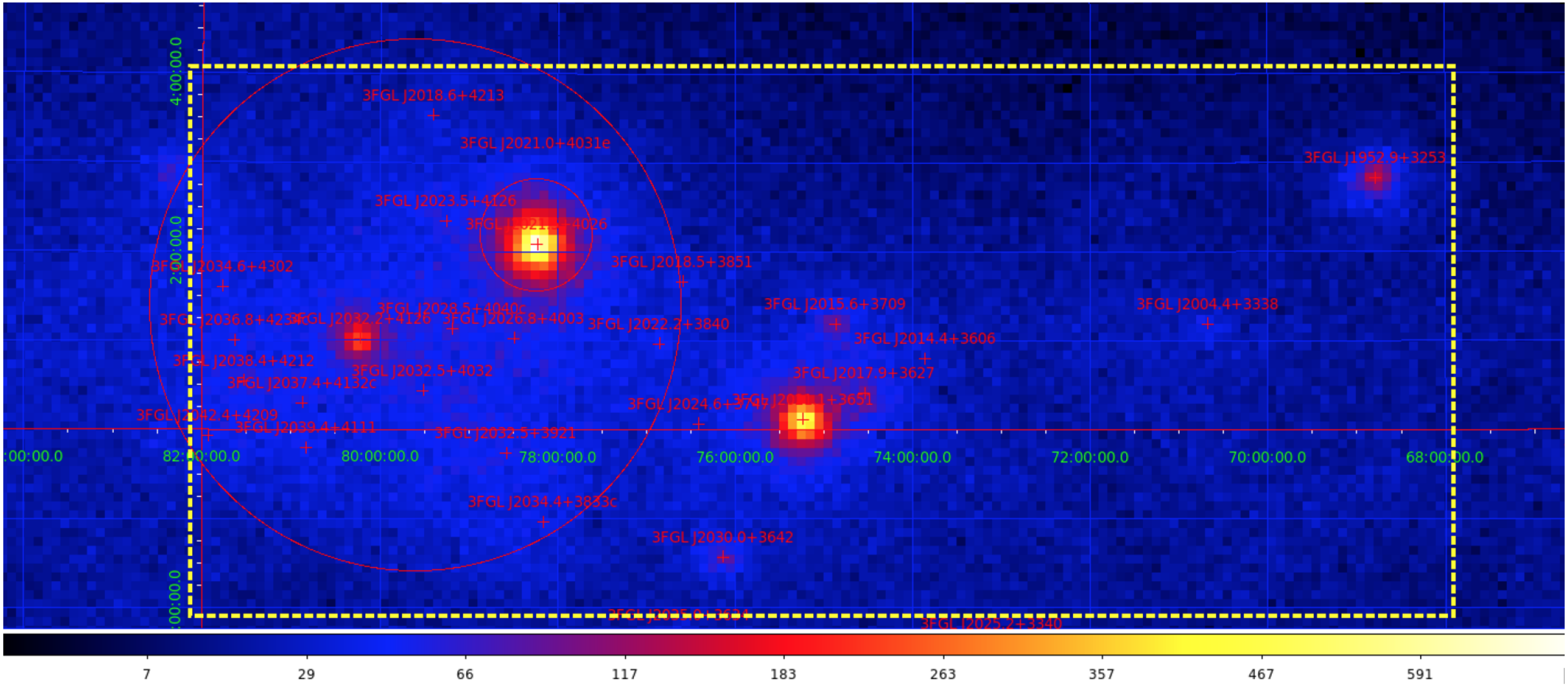


Cygnus Region

$$67^\circ \leq \ell \leq 82^\circ$$

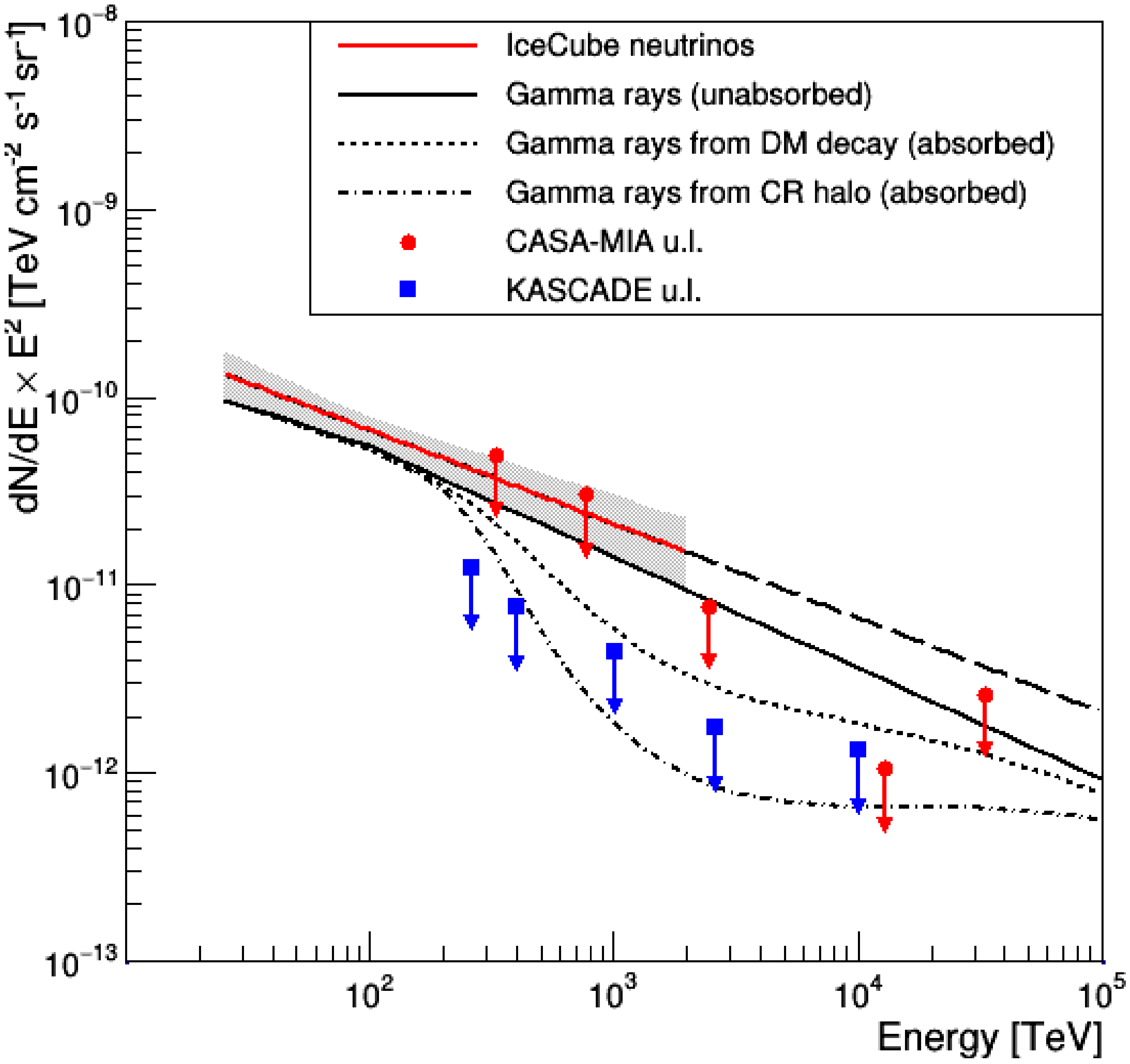
$$-1^\circ \leq b \leq 4^\circ$$

VERITAS skan



Count Map of Fermi

Interpretation of IceCube as a Galactic signal:



A comment on “PeVatrons”

A comment on "PeVatrons"

The Nature of the "KNEE" in the Cosmic Ray Spectrum

Accelerator feature

[Maximum energy of acceleration.
implies that all accelerators are similar]

Structure generated by propagation

[implies that the (main) Galactic CR accelerators must be capable to accelerate to much higher energy]

If the “knee” is a propagation effect,

then the Milky Way contains
“super-PeVatrons”
and the study of these objects requires
Gamma Astronomy at Higher energy

Strong interest in the
PeV gamma ray (and neutrino) astronomy

Conclusions:

The exploration of the gamma ray sky at very high energy (E > 100 TeV) is challenging, but has great scientific interest, and is in fact crucial for a full understanding of the Galactic CR.

The measurement of the *spectral shape of individual sources* is of fundamental importance to determine the properties of the emission mechanisms.

The study of the *Diffuse Galactic emission* with Wide Field of View instruments is also of great interest for the understanding of high energy processes in the Galaxy.

Gamma Ray Absorption must be considered carefully, but does not preclude Galactic studies (even at PeV energies).

Telescopes with an area of order 1 Km^2 and good rejection capabilities can observe the Galactic Diffuse emission in most (or essentially all) models.

If the IceCube signal has a subdominant, but significant Galactic component, the associated gamma ray emission is detectable by these telescopes, (and these observations are essential to complement the HE neutrino studies).