NEUTRINOS AND GAMMA RAYS FROM THE FERMI BUBBLES

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C.L. , Soebur Razzaque, and Lili Yang, arXiv:1504.07033

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The Fermi Bubbles as multi-messenger candidates

The Very High Energy sky

- gamma ray astronomy: a mature field
  - 1989 : first detection of ~ TeV gamma rays

Weekes *et al. [Whipple Observatory]* ApJ 342, 1989, 379-395

  - revealed sites of hadron acceleration

$$p + N(\gamma) \rightarrow \pi^0 \quad + \quad \pi^{\pm} + \ldots$$

$$\searrow \gamma + \gamma \qquad \searrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$$

$$\searrow e^+ + \nu_e + \bar{\nu}_\mu \quad (e^- + \bar{\nu}_e + \nu_\mu)$$

  - *neutrino counterpart* expected

Berezinsky & Zatsepin, PLB28 (1969) 423-424

- neutrino astronomy: an infant field
  - 2013 : first detection of PeV astrophysical neutrinos

Aartsen et al. [IceCube coll.], PRL 111 (2013) 021103, Science 342 (2013) 1242856, PRL113 (2014) 101101

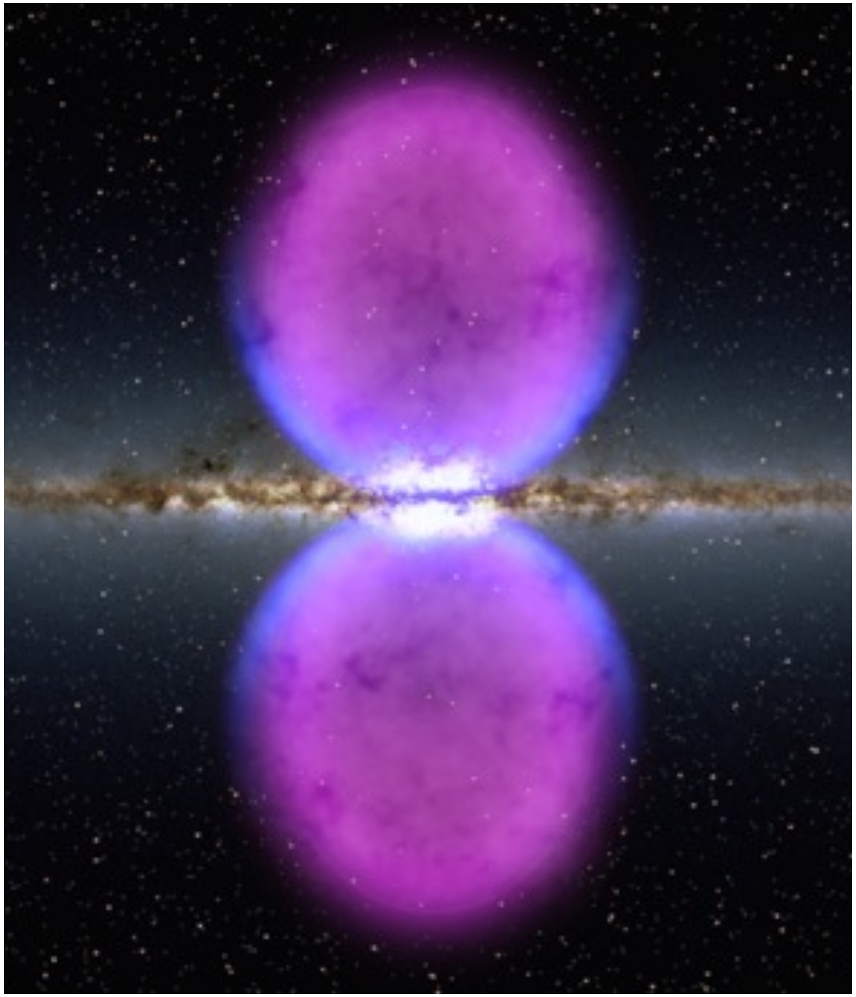
- looking for *single* source for *multi-messenger* study
  - case-study to develop in detail
  - close, bright candidates: Galactic Center, Fermi Bubbles

Fermi Bubbles: a new *galactic* structure

- Fermi-LAT discovery
  - spheroids, D≈8 kpc
  - 0.5 – 500 GeV γ rays

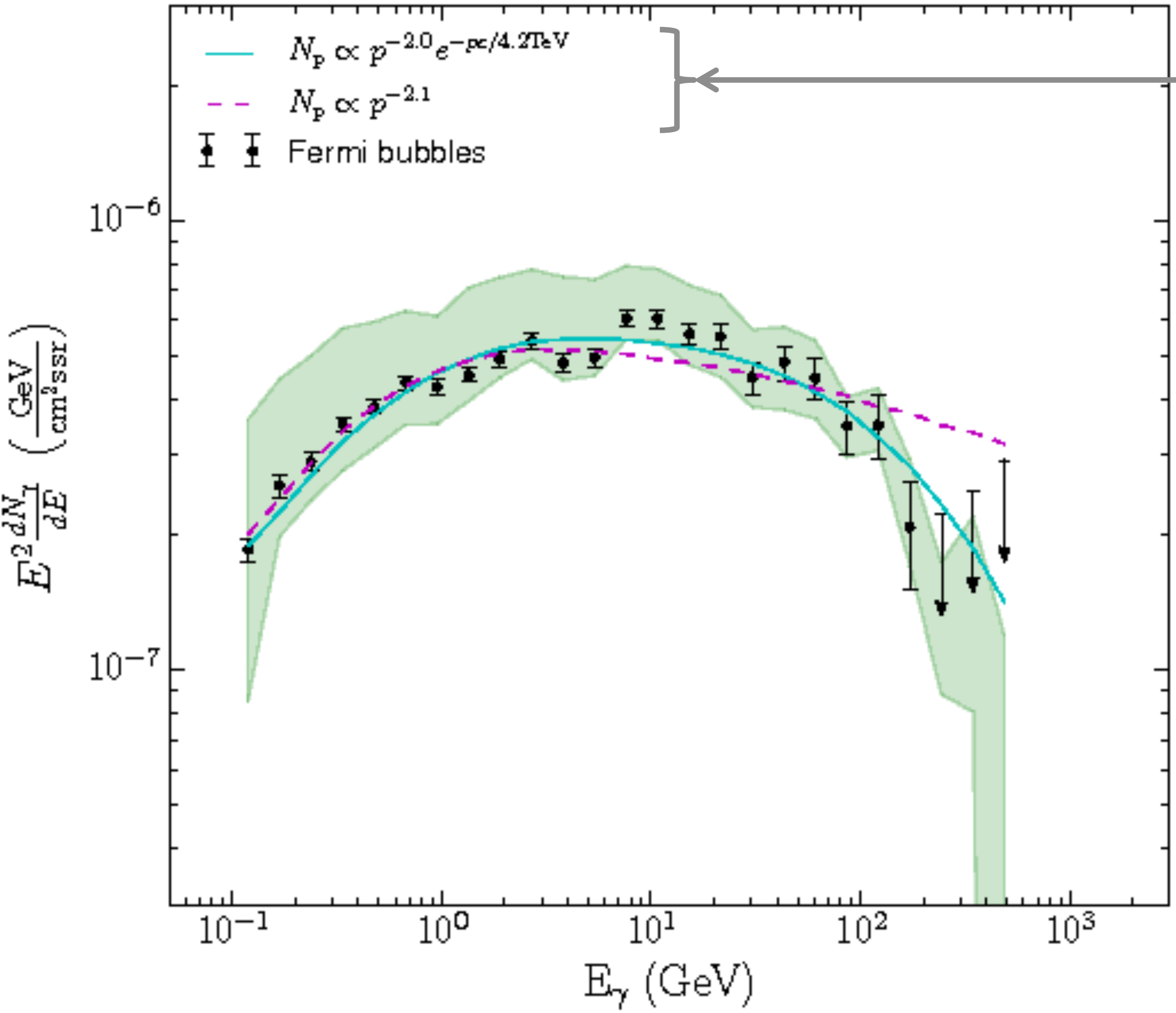
Su, Slatyer & Finkbeiner, ApJ. 724, 1044 (2010)

- possible origins
  - exotic
  - leptonic
  - *hadronic → neutrino counterpart!*



Artist's concept, NASA/GSFC

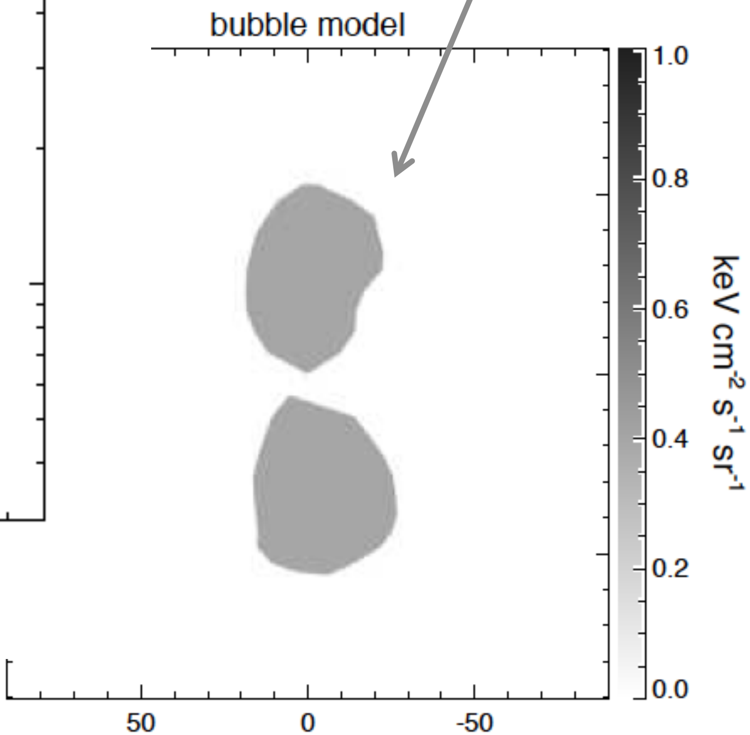
Hadronic model



M. Ackermann *et al.* 2014 *ApJ* 793 64

parent proton spectrum: power-law with cutoff

uniform projected intensity: puzzling!

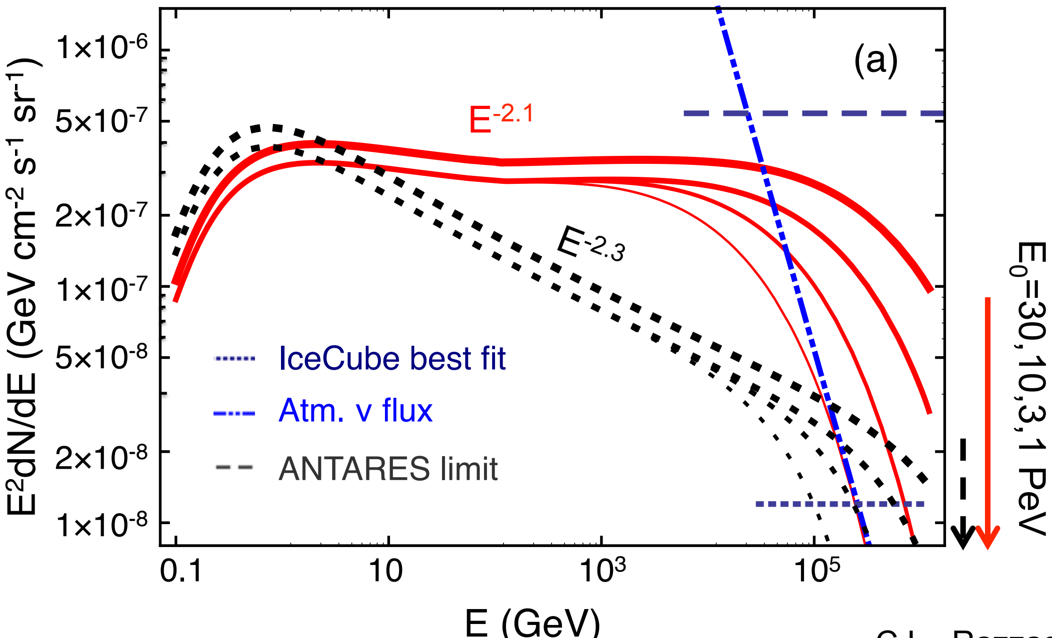


Su, Slatyer & Finkbeiner, ApJ. 724, 1044 (2010)

Neutrinos from (hadronic) Fermi Bubbles

- *New signal* for Km^3 detectors   Crocker and Aharonian, PRL 106, 2011
- detectable for multi-PeV proton cutoff

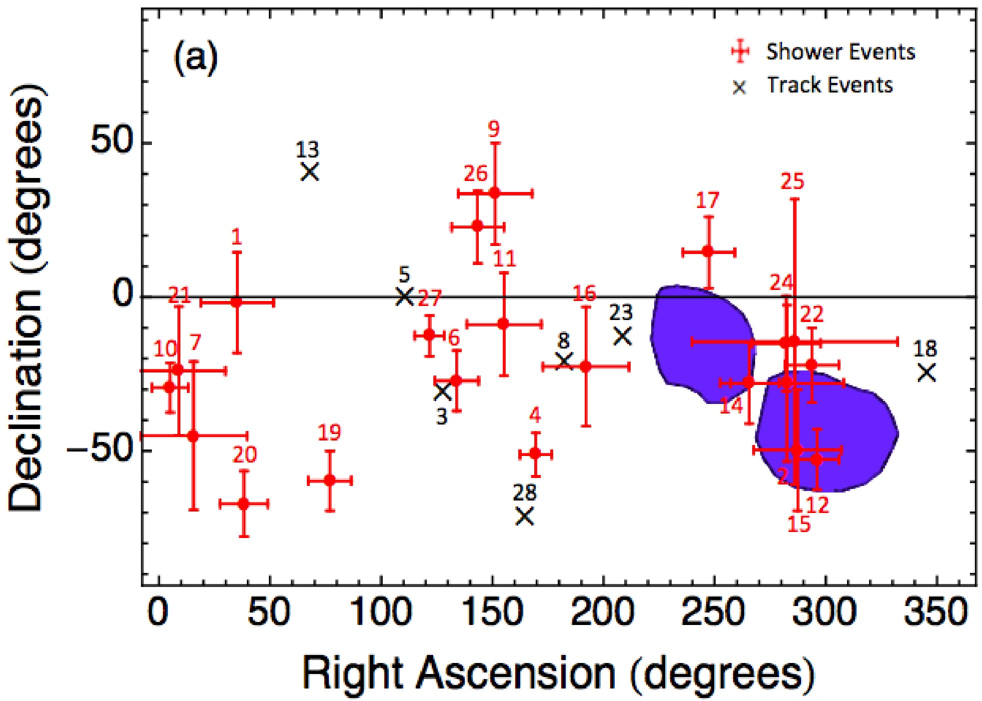
C.L. and S. Razzaque, PRL 108, 221102 (2012)
Adrian-Martinez et al. [ANTARES coll.] EPJ. C74 (2014)



C.L., Razzaque, Theodoseau and Yang, PRD90, 023016 (2014).

Already detected?

- 5 IceCube data strongly correlated
  - central value within the FB solid angle S. Razzaque, PRD 88, 081302 (2013)
  - consistent with Fermi-LAT data with hadronic model, multi-PeV cutoff C.L., Razzaque, Theodoseau and Yang, PRD90, 023016 (2014).



References

S. Razzaque, Phys. Rev. D 88, 081302 (2013)

J. C. Joshi, W. Winter and N. Gupta, MNRAS (April 21, 2014) 439 (4): 3414-3419, Erratum: MNRAS (January 2015) 446 (1): 892

M. Ahlers and K. Murase, Phys. Rev. D 90, no. 2, 023010 (2014)

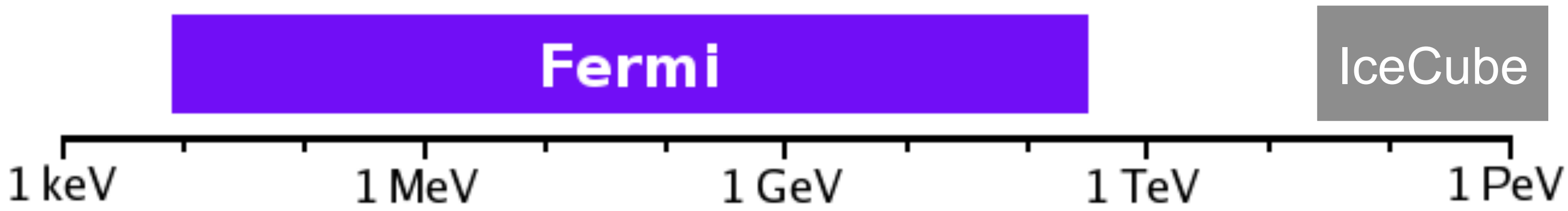
A. M. Taylor, S. Gabici and F. Aharonian, Phys. Rev. D 89, no. 10, 103003 (2014)

Adrian-Martinez et al. [Km3NeT], Astropart.Phys. 42 (2013) 7-14

The first neutrino-gamma connection?

- the Fermi Bubbles could be the *first* individual source seen in both VHE neutrinos and gamma rays

- energy gap: connection is *indirect*



- new data at 0.1- 100 TeV highly desirable
  - bridge gap, study γ and ν spectrum in *same* energy window

The near future: HAWC and IceCube

High Altitude Water Cherenkov (HAWC) Observatory

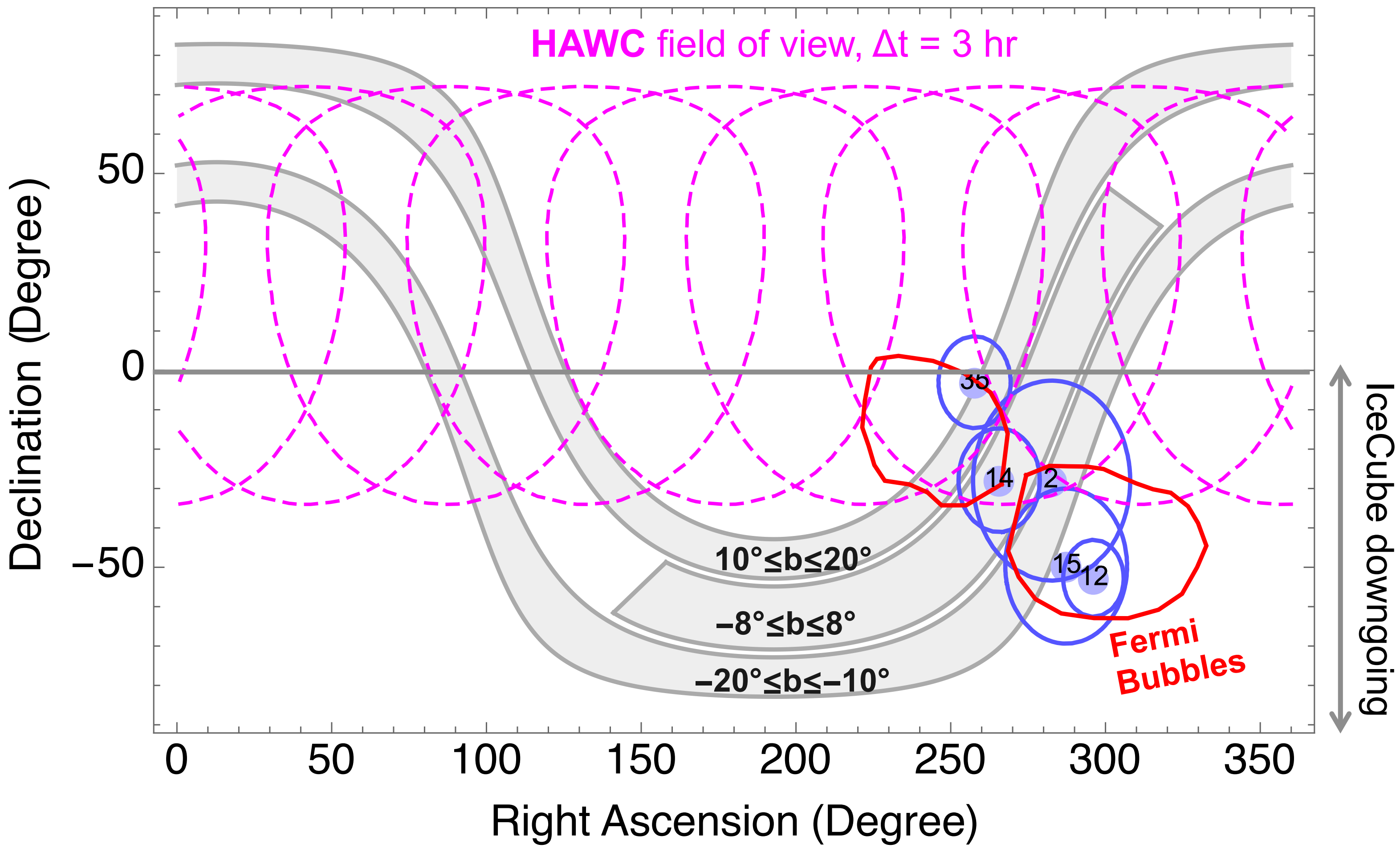
- air shower array
  - Mexico, 4100 m altitude, 300 water tanks, 22000 m^2
  - completed and *running* since March 2015.

- photon-induced airshowers
  - 0.1 – 100 TeV window
  - 0.1° resolution for E>5 TeV
  - effective area ~ 10^5 m^2 for E>3 TeV

- large field of view
  - 2 π sr ,~60° zenith aperture

from https://hawc.wipac.wisc.edu/

Observing the N bubble for ~2-3 hrs/day



Fluxes and event rates at HAWC and IceCube

Flux calculation: ingredients

- Parent proton spectrum: $dN_p/dE \propto E^{-k} \exp(-E/E_0)$
  - For Supernova Remnants (SNR) : k~ 2.1- 2.3, E_0 ~ 1-30 PeV
  - Remains hard due to saturation ($t_{acc} < t_{loss} < t_{esc}$)

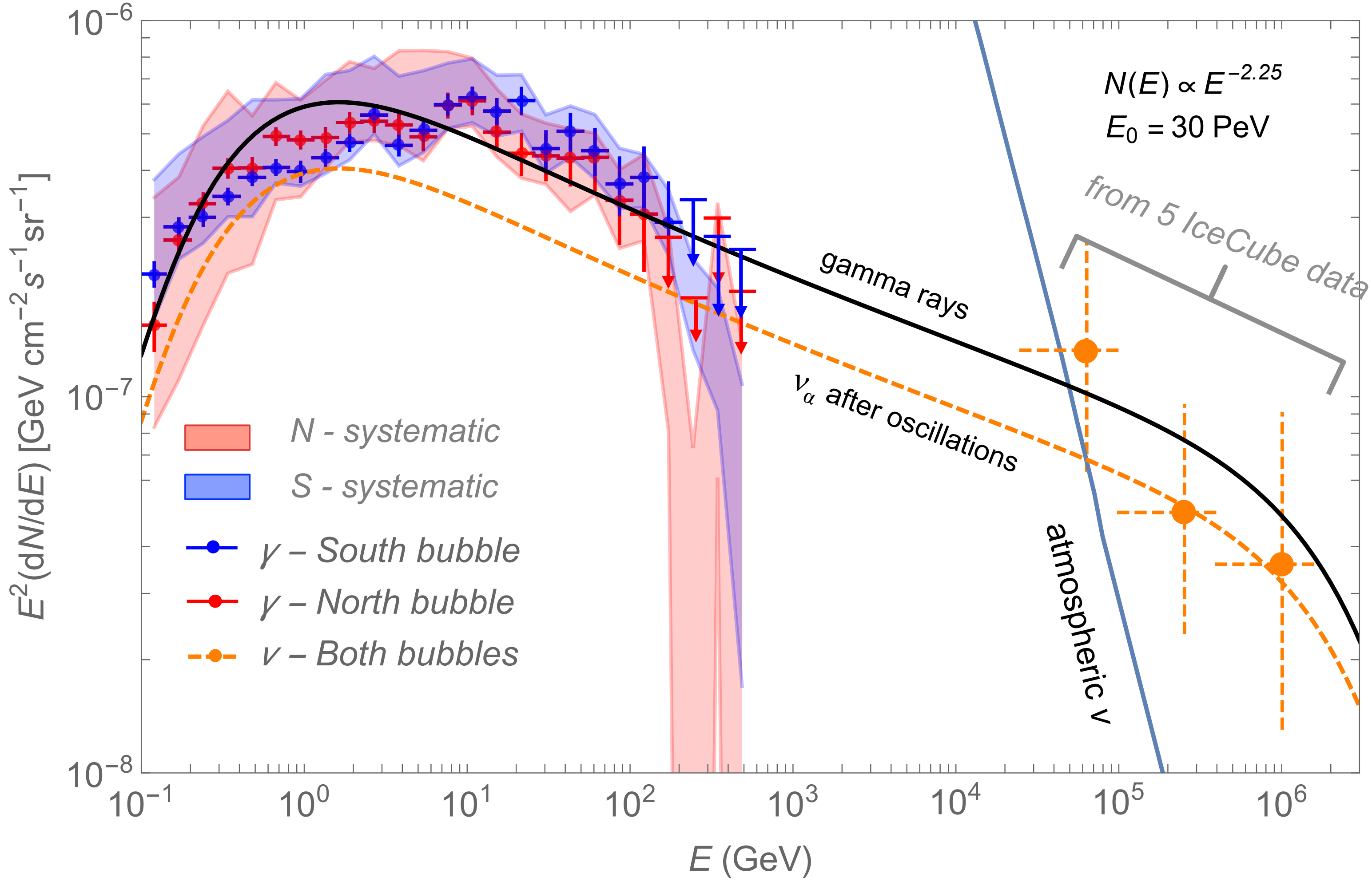
Crocker and Aharonian, PRL 106, 2011

- Avg. gas density: $\langle n_H \rangle \sim 10^{-2}\ \mathrm{cm}^{-3}$
  - favored by ROSAT data

M. Su, T. R. Slatyer and D. P. Finkbeiner, ApJ 724, 1044 (2010)

- Numerical calculation needed above 10 GeV
  - Parameterization of SYBILL code was used

Kelner, Aharonian and Bugayov, PRD 74, 034018 (2006)



- Fit to Fermi-LAT data: χ^2/dof = 13/40 after penalizing for violation of upper limits
- IceCube errors: Poisson statistics (C.L. > 55%)

CDF collaboration, statistics committee, note number 6438.

Number of events in zenith bin

$$N = \int_0^T dt \int_{\substack{\Sigma(t) \\ \theta_1 \leq \theta \leq \theta_2}} d\Omega \int_{E_{th}}^{\infty} dE \Phi(E) A(E,\theta)$$

$$\simeq T \langle f_\Omega(\theta_1,\theta_2) \rangle \Omega_{FB} \int_{E_{th}}^{\infty} dE \Phi(E) \langle A(E) \rangle_\theta$$

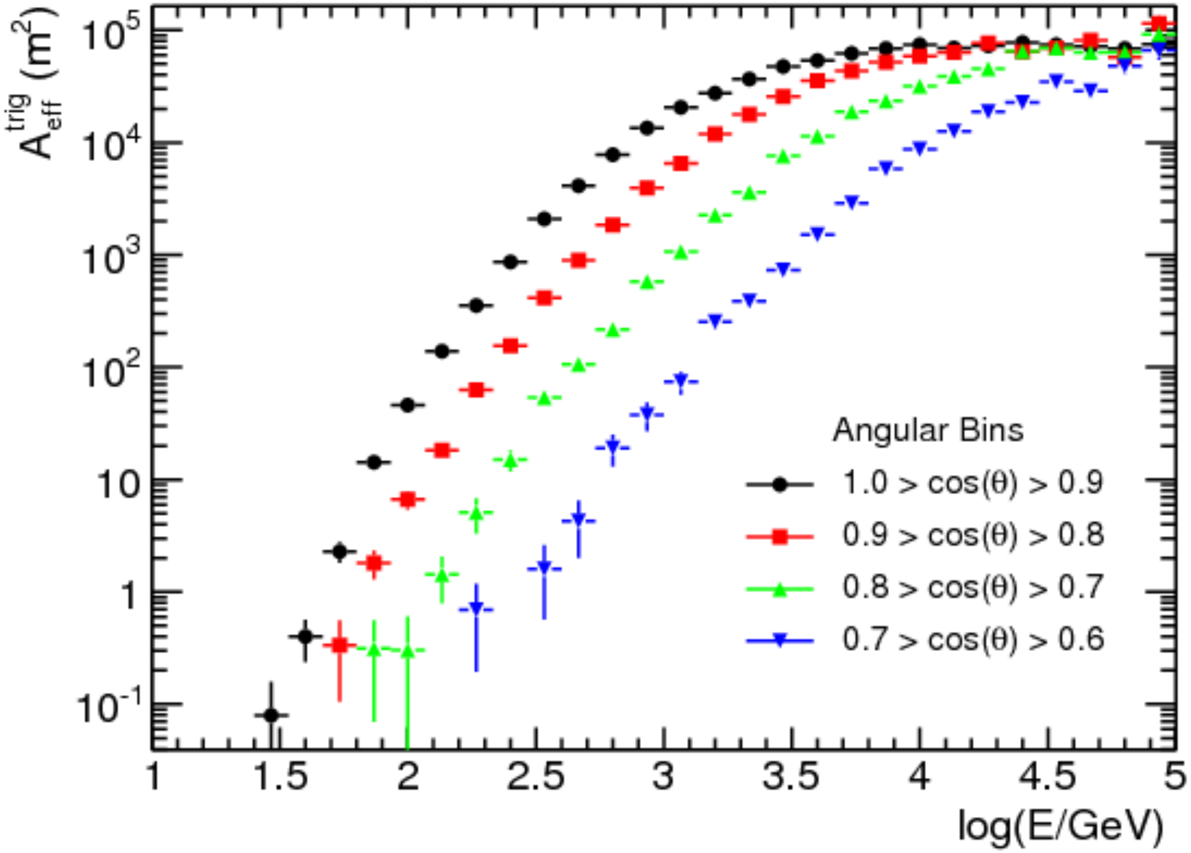
Running time

Day-averaged fraction of solid angle in zenith bin

Zenith-averaged effective area of detector

$\Omega_{\mathrm{FB}} \simeq 0.808\ \mathrm{sr}$ solid angle subtended by the bubbles (assume constant emission per solid angle)

HAWC: effective areas and zenith bins



interval of $\cos\theta$	$\langle f_\Omega \rangle$
[0.6, 0.7]	4.5×10^{-2}
[0.7, 0.8]	3.5×10^{-2}
[0.8, 0.9]	4.1×10^{-2}
[0.9, 1.0]	1.0×10^{-2}

D. Zaborov [HAWC Collaboration], PoS GRB 2012, 122 (2012).

background

- Dominant : cosmic ray hadrons
  - Signal/Background ~ 10^{-5} – 10^{-4}
  - hadron rejection efficiency : ~ 5 10^{-3} for E>10 TeV

Bernlohr et al. Astr. Part. Phys. 43, 2013, p. 171–188

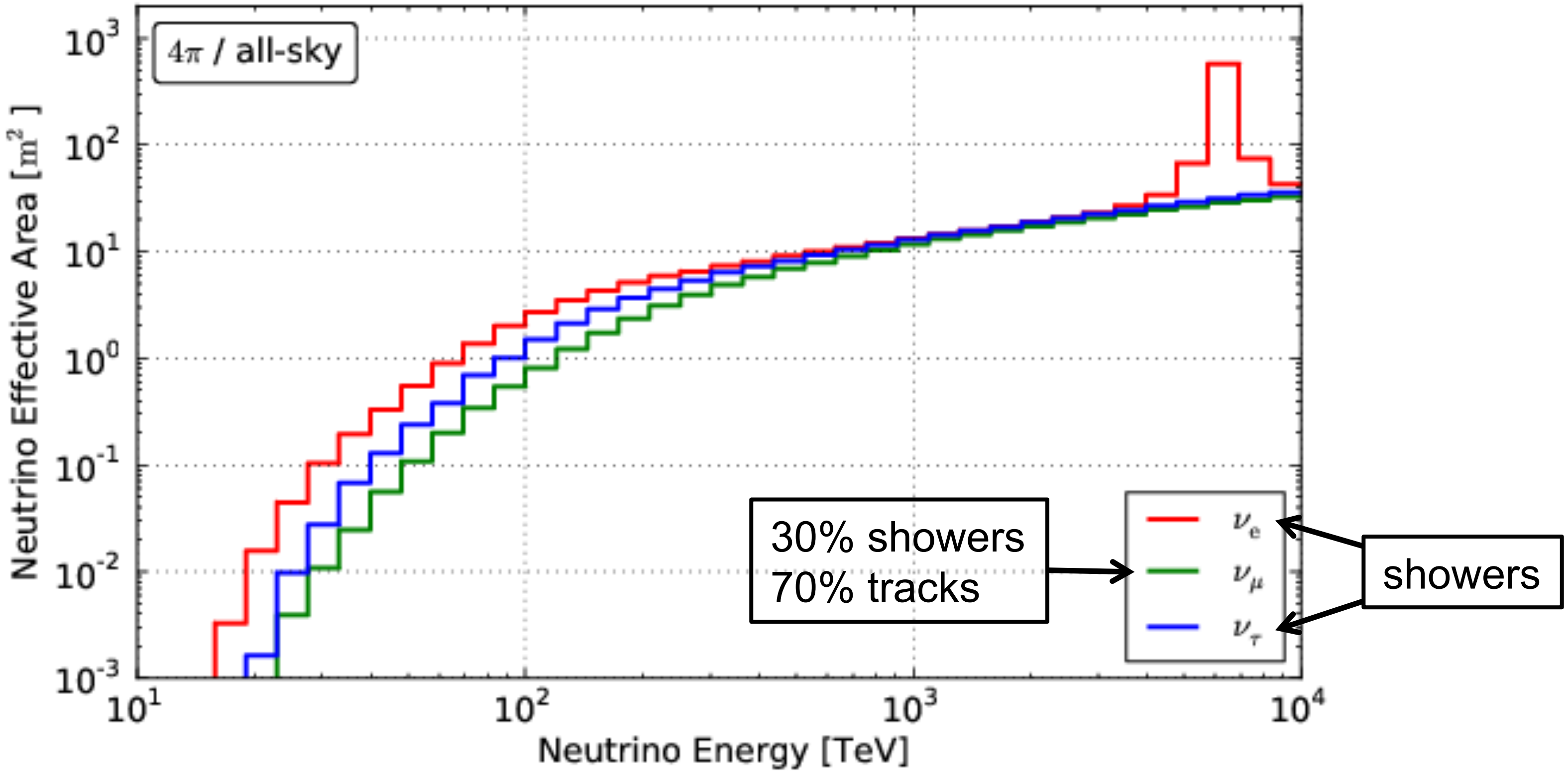
Abeysekara et al., Astropart. Phys. 50-52, 26 (2013) [arXiv:1306.5800]

- subdominant: diffuse gamma rays
  - measured by Fermi-LAT for the inner Galaxy region, high and low intermediate latitude region
  - $^{S}S^{Z}4^{R}20^{T}150^{C}5$ model, extrapolated

M. Ackermann et al. [Fermi-LAT Collaboration], Astro- phys. J. 750, 3 (2012)

IceCube: effective areas

M. G. Aartsen et al., Science 342, 1242856 (2013).



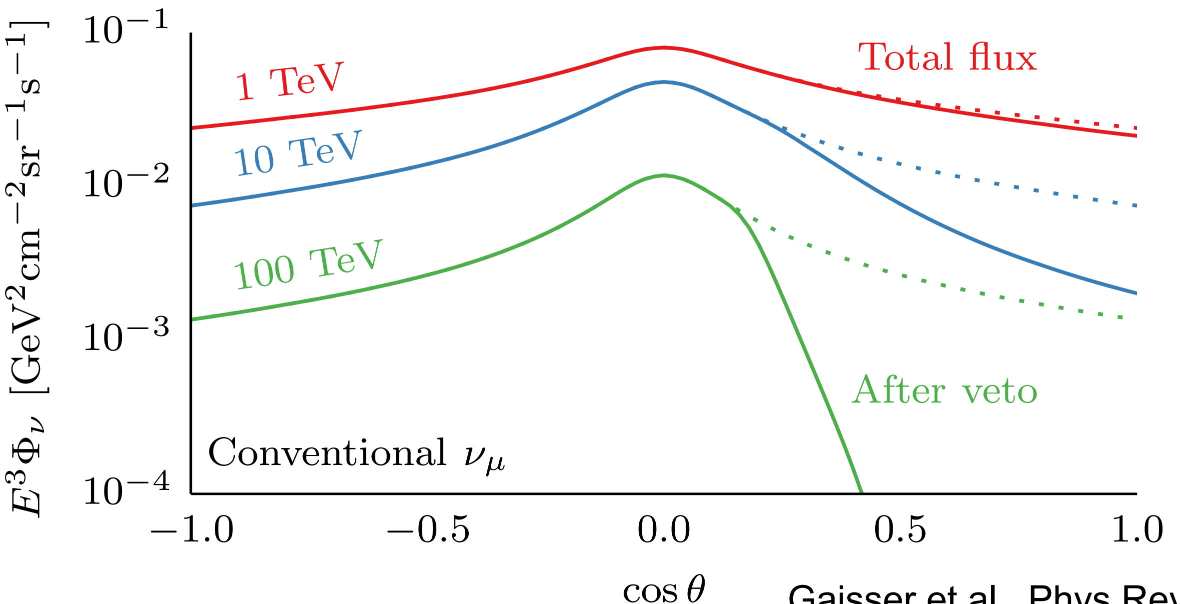
- down-going neutrinos
- From South Pole, full view all day: $f_{\Omega} \approx 1$

Background

- Atmospheric muons veto-able
- atmospheric neutrinos
  - muon/electron ~ 14 , zenith-symmetric

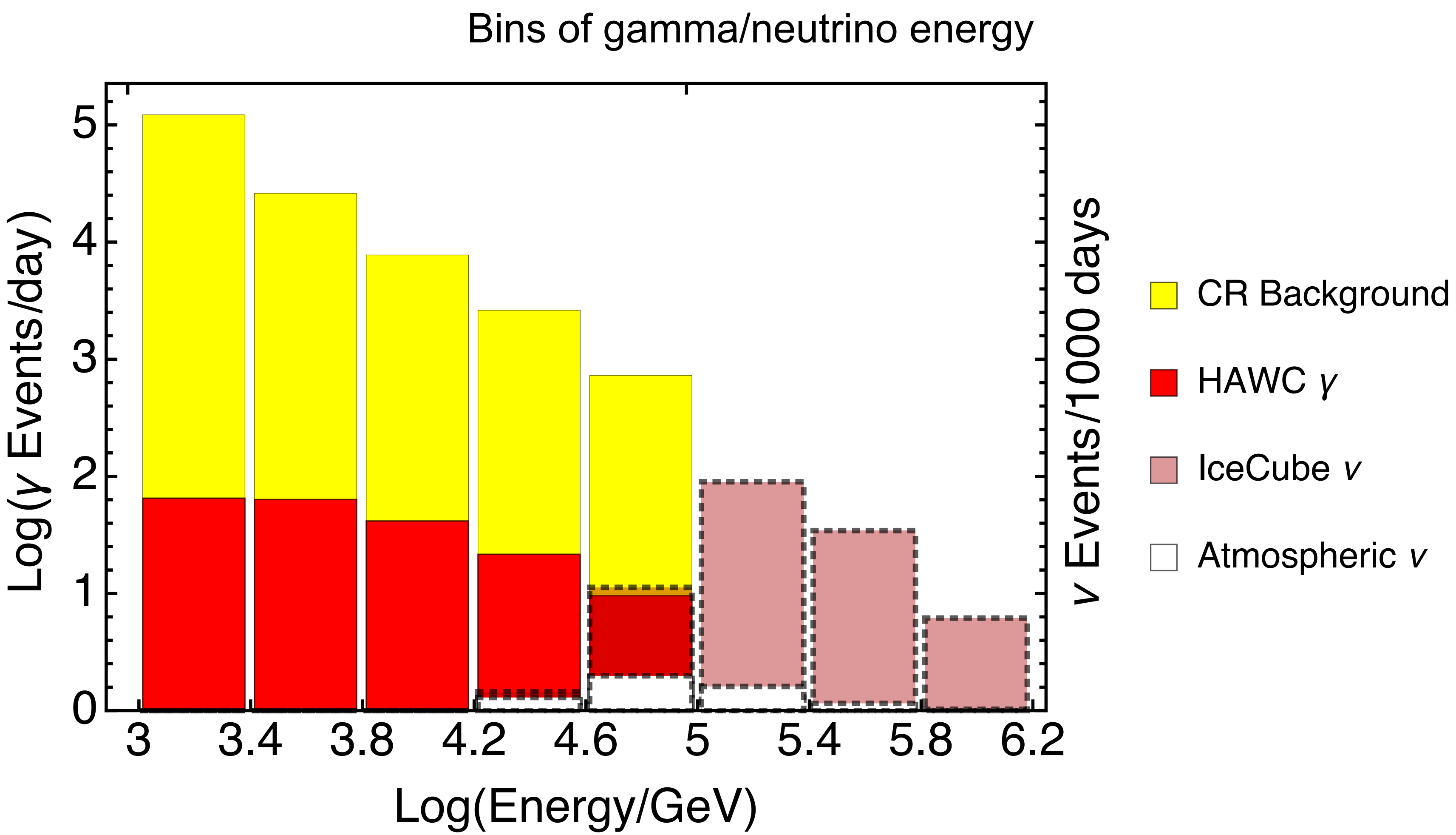
M. Honda et al., Phys.Rev. D75, 043006 (2007)

  - Included for FB shape + 15° around



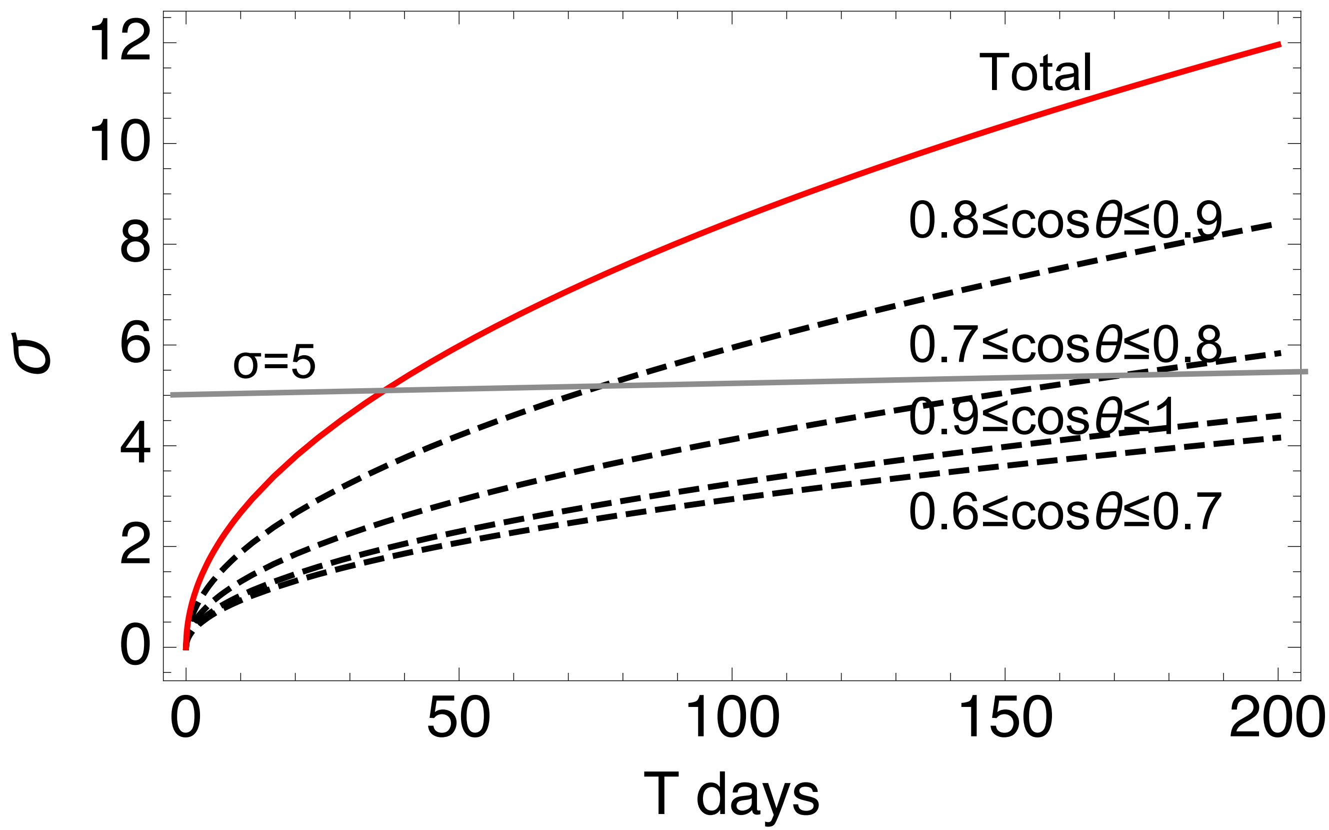
Gaisser et al., Phys.Rev. D90 (2014) 023009

Results: event rates



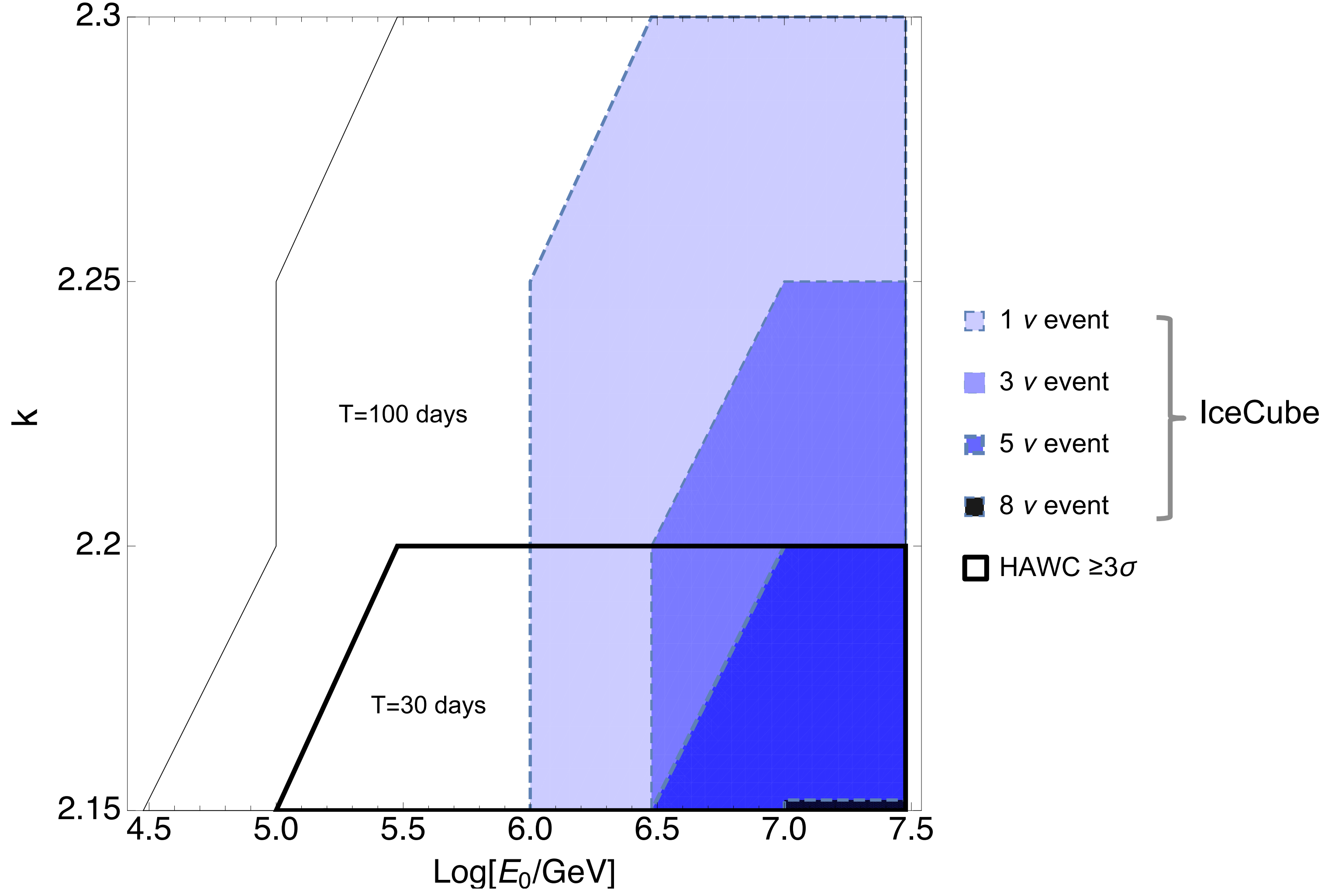
Significance at HAWC

$$\sigma = \sqrt{T}\sum_i w_i S_i / \sqrt{\sum_i w_i^2 (B_i + \bar{S}_i)} \qquad w_i = S_i/B_i$$



potential for discovery in few months!

HAWC + IceCube : constrain model



Observed at HAWC?	Observed at IceCube? Y	Observed at IceCube? N
Y	Hadronic origin Multi-PeV cutoff Hard spectrum	Sub-PeV cutoff or Soft spectrum or leptonic origin
N	??? Hadronic origin with opaque bubbles ? Exotic physics? (tension with Fermi-LAT?)	Sub-TeV cutoff (tension with Fermi-LAT?)

Discussion: the Fermi Bubbles as a multi-messenger case study

neutrino-gamma complementarity

IceCube

- Both bubbles
  - 15° resolution
  - Test symmetry
- E ~ 0.03 – 10 PeV
  - Beyond gamma ray sensitivity
- few yrs operation needed

HAWC

- North Bubble mostly
  - 0.1° resolution→ detailed map
  - Detailed spectrum
  - test uniform emission
- E ~ 0.1 – 100 TeV
  - Bridges Fermi-LAT and IceCube, with partial overlap
- < 1 yr operation needed

What can be learned?

- The Hadronic model of the Fermi Bubbles can be confirmed…
  - measure max energy of supernova remnant proton spectrum
  - favor ~ 10^9 years long star formation in the Galaxy

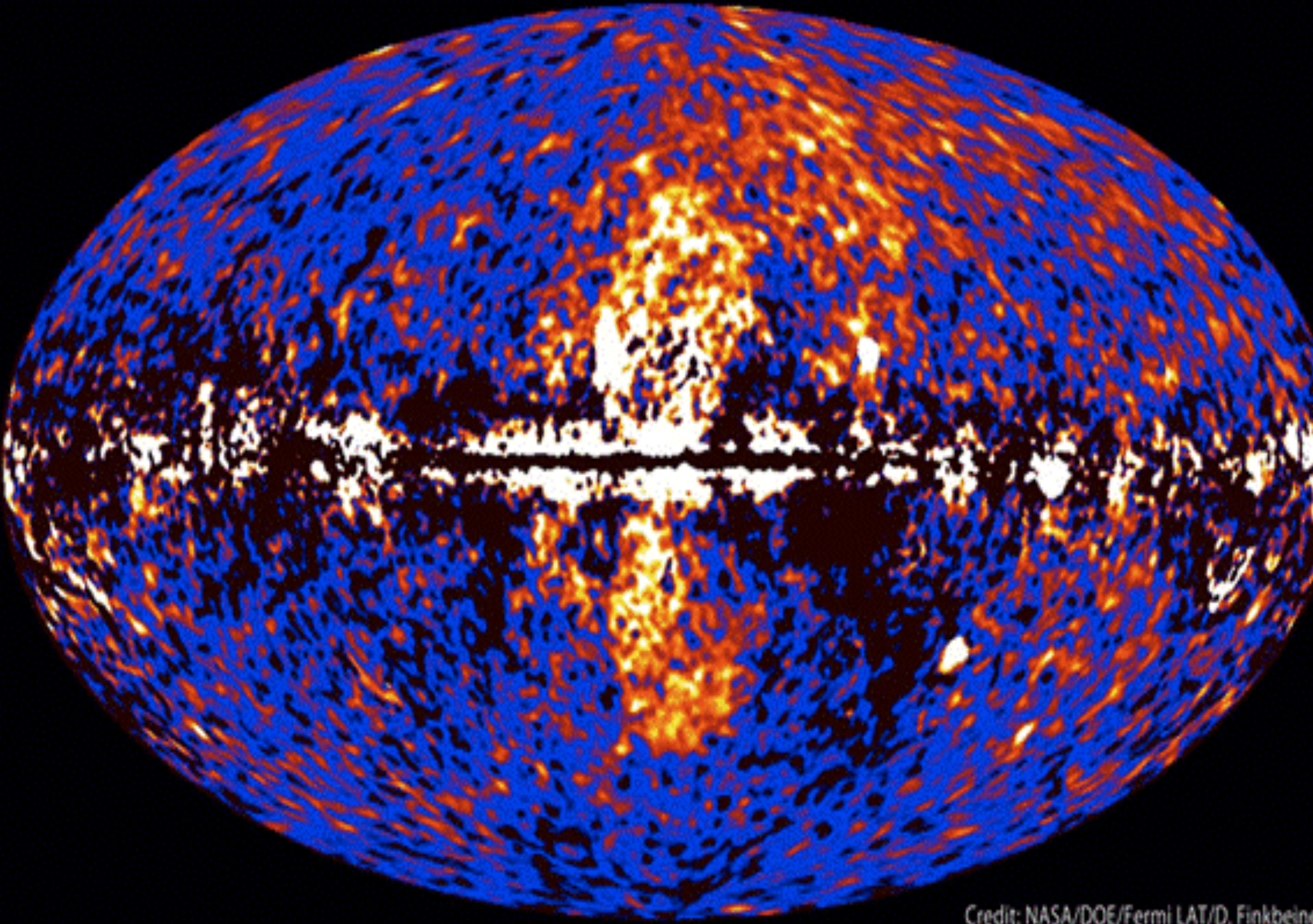
- but not excluded!
  - strong constraints on maximum acceleration energy

Future developments

- gamma rays: IceTop surface detector array (@IceCube)

- neutrinos : Km3NeT
  - larger effective area → significant excess in ~1 year (E_0 > 100 TeV)

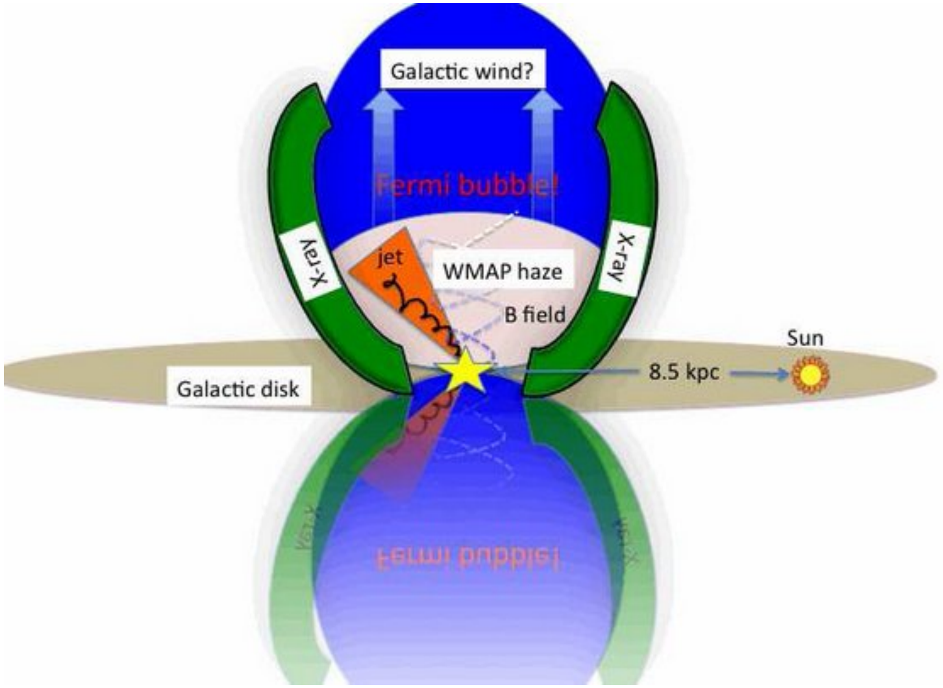
Adrian-Martinez et al. [Km3NeT], Astropart.Phys. 42 (2013) 7-14



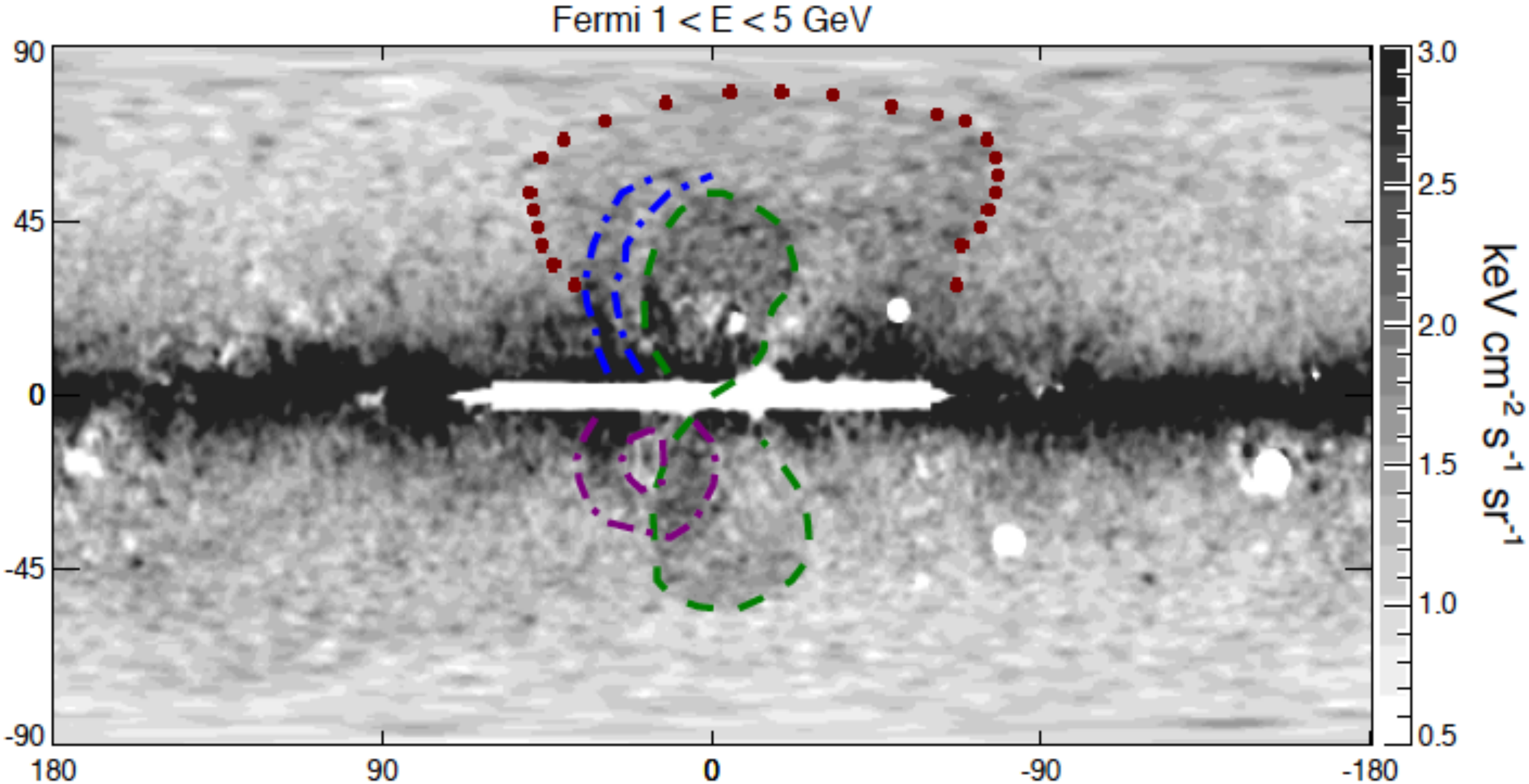
Credit: NASA/DOE/Fermi LAT/D. Finkbeine

Backup

- Spatially correlated with:
  - microwave haze (WMAP)
  - Thermal X-rays (ROSAT)



Finkbeiner, ApJ. 614, 186 (2004)
Snowden et al., ApJ. 485, 125 (1997).


Fermi 1 < E < 5 GeV
90
45
0
-45
-90
180
90
0
-90
-180
3.0
2.5
2.0
1.5
1.0
0.5
keV cm^{-2} s^{-1} sr^{-1}

Origin of the gamma rays in the FB?

- *Compton scattering of accelerated electrons*
- *Collisions of accelerated protons*

- Stars capture on central black hole
- Faint millisecond pulsars
- Dark matter annihilation

Dobler, et al., ApJ. 717, 825 (2010)
Su, Slatyer & Finkbeiner, ApJ. 724, 1044 (2010)
Malyshev, Cholis & Gelfand, ApJ. 722, 1939 (2010)
Crocker and F. Aharonian, PRL 106, 101102 (2011)
P. Mertsch and S. Sarkar, PRL 107, 091101 (2011)Guo & Mathews, arxiv:1103.0055
Cheng et al., arXiv:1103.1002

Electrons or protons?

- ***High energy electrons***

Su, Slatyer & Finkbeiner, ApJ. 724, 2010
Mertsch & Sarkar, PRL 107, 2011

  - From central black hole activity (shocks)
  - $e^- + \gamma \rightarrow e^- \gamma$
  - Requires ~ *10^6 years* activity

  - unnatural acceleration and diffusion

  - explains WMAP haze

- ***High energy protons***

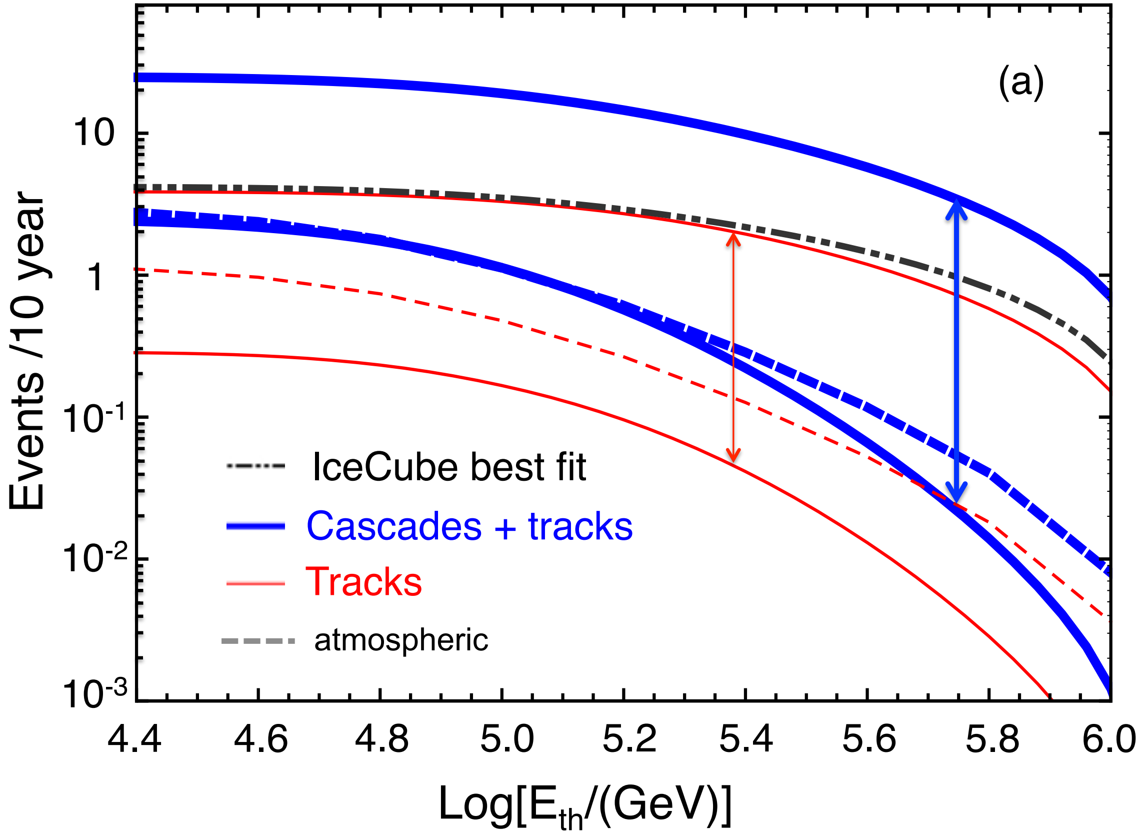
Crocker and Aharonian, PRL 106, 2011

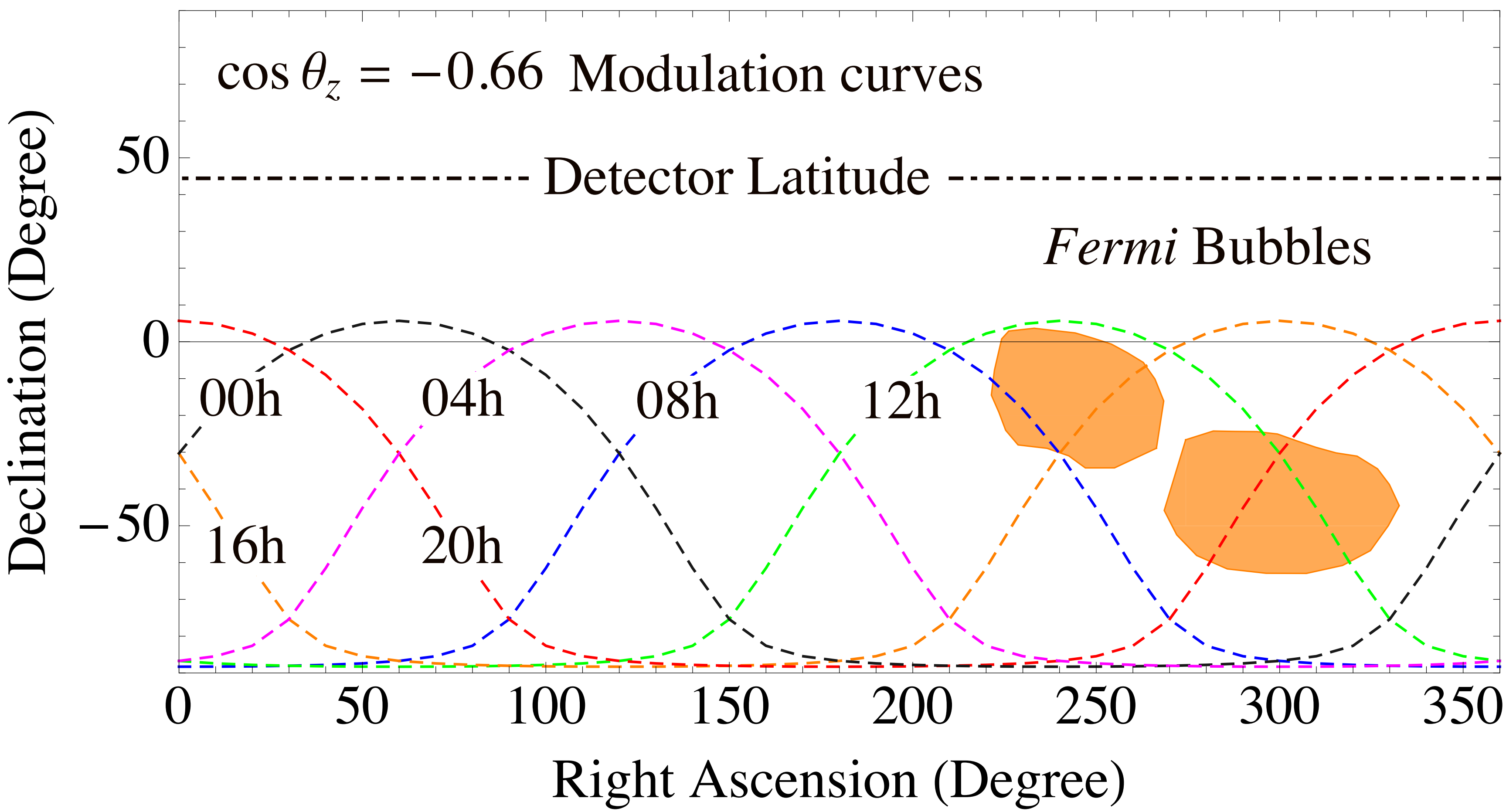
  - From supernova remnants
  - $p + p \rightarrow \pi^0 + \text{any}$, $\pi^0 \rightarrow \gamma\gamma$
  - Requires ~ *$10^9 - 10^{10}$ years* activity (star formation)
  - Large timescale, distinct from WMAP haze?
  - Explains GeV bump, natural energetics

Main numbers

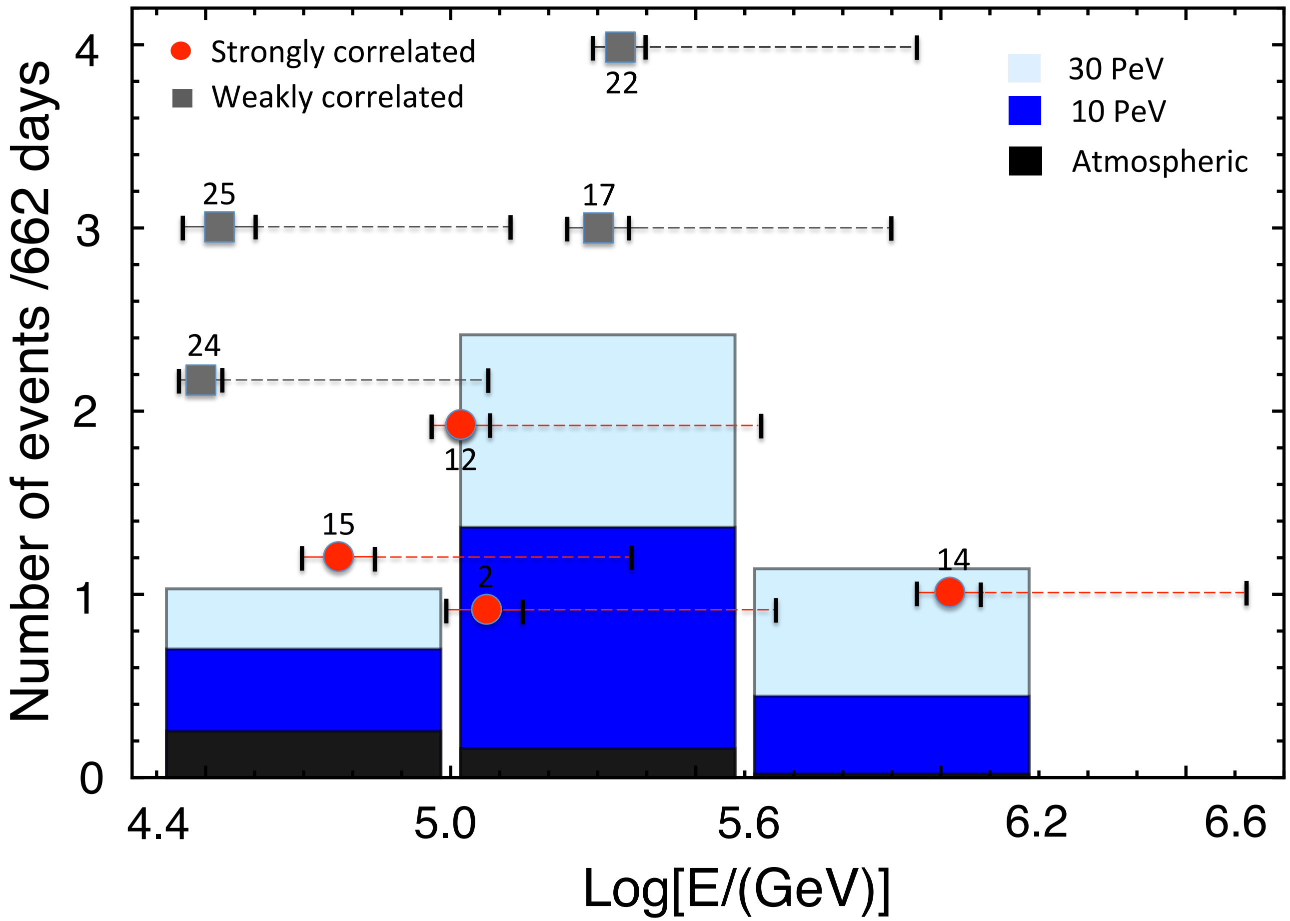
- Total number of protons in bubbles: ~ 10^{57}
- Total energy in protons: ~ 10^{55} - 10^{56} ergs
- Energy of gamma rays from bubbles: ~ 10^{54} ergs
  - Over few 10^{9} years lifetime
  - Few % efficiency, typical of hadronic models

- 3 σ significance at IceCube in ~ 7 years

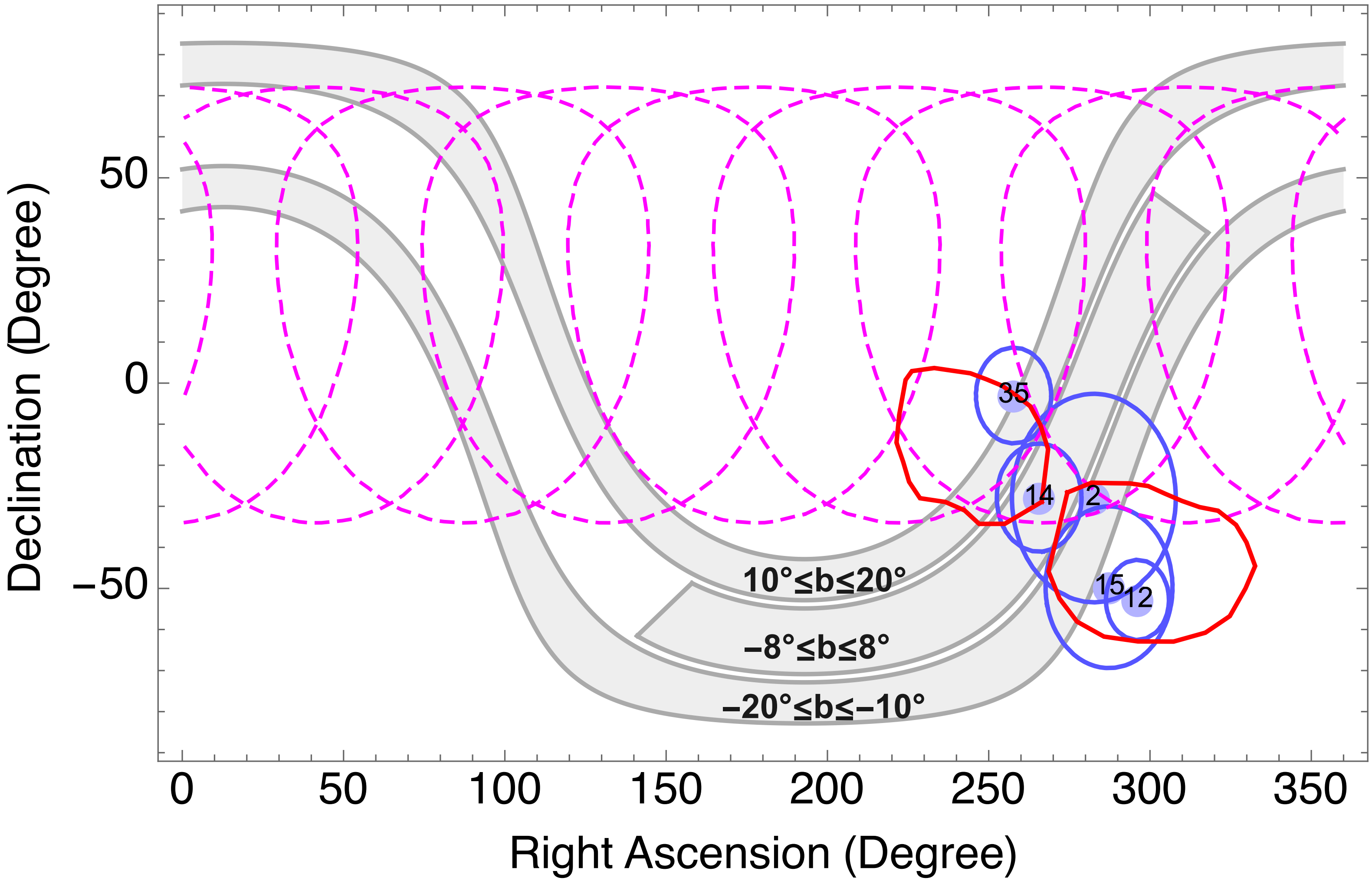




cos θ_z = −0.66 Modulation curves
Detector Latitude
Fermi Bubbles
00h
04h
08h
12h
16h
20h
50
0
−50
0
50
100
150
200
250
300
350
Declination (Degree)
Right Ascension (Degree)



C.L., Razzaque, Theodoseau and Yang, PRD90, 023016 (2014).



Declination (Degree)
Right Ascension (Degree)
50
0
−50
0
50
100
150
200
250
300
350
10°≤b≤20°
−8°≤b≤8°
−20°≤b≤−10°
35
14
2
15
12

Flavor composition

- Before oscillations

$$\nu_e : \nu_\mu : \nu_\tau = \epsilon : 1 : 0$$

  - ε~ 0.57 – 0.88 for E = TeV – PeV (pion decay kinematics)

- After oscillations : equilibration, within 30%

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

- Delta function approximation ($E_\pi/E_p = K_\pi$, const.)

$$\Phi_\gamma(E_\gamma) = \frac{\varphi\langle n_H\rangle}{4\pi D^2 K_\pi} \int_{E_{\pi,\mathrm{th}}}^{\infty} dE_\pi \, \frac{\sigma_{pp}(E_c)}{\sqrt{E_\pi^2 - m_\pi^2}} N_p(E_c)$$

$$K_\pi \approx 0.17 \qquad E_c = E_\pi/K_\pi + m_p$$

$$E_{\pi,\mathrm{th}} = E_\gamma + m_\pi^2/4E_\gamma$$

  - Full calculation is needed above 10 GeV
    - Parameterization of SYBILL code was used

Kelner, Aharonian and Bugayov, PRD 74, 034018 (2006)