# NEUTRINOS FROM THE FERMI BUBBLES

Cecilia Lunardini
Arizona State University
RIKEN BNL Research Center

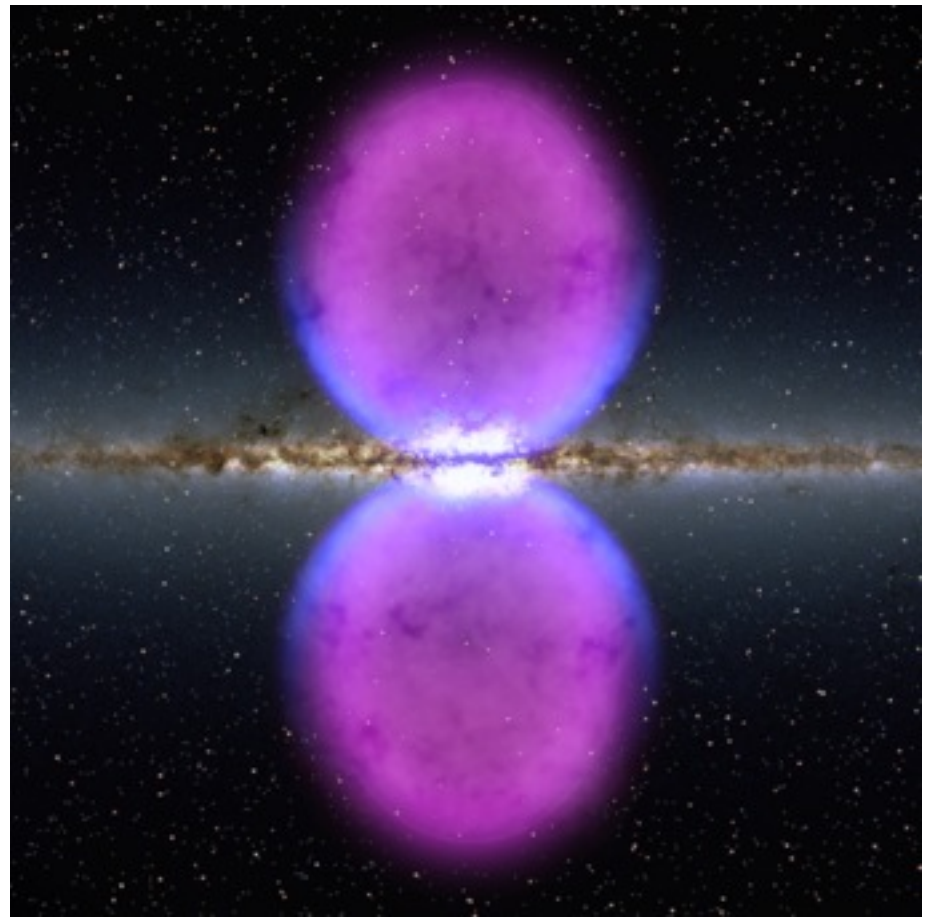
C.L. & Soebur Razzaque, arXiv:1112.4799,
accepted in Physical Review Letters

- Gamma rays from the Fermi Bubbles: hadronic origin?
- High energy neutrino counterpart
- Detectability at $Km^3$ detectors
- Implications

# The Fermi Bubbles

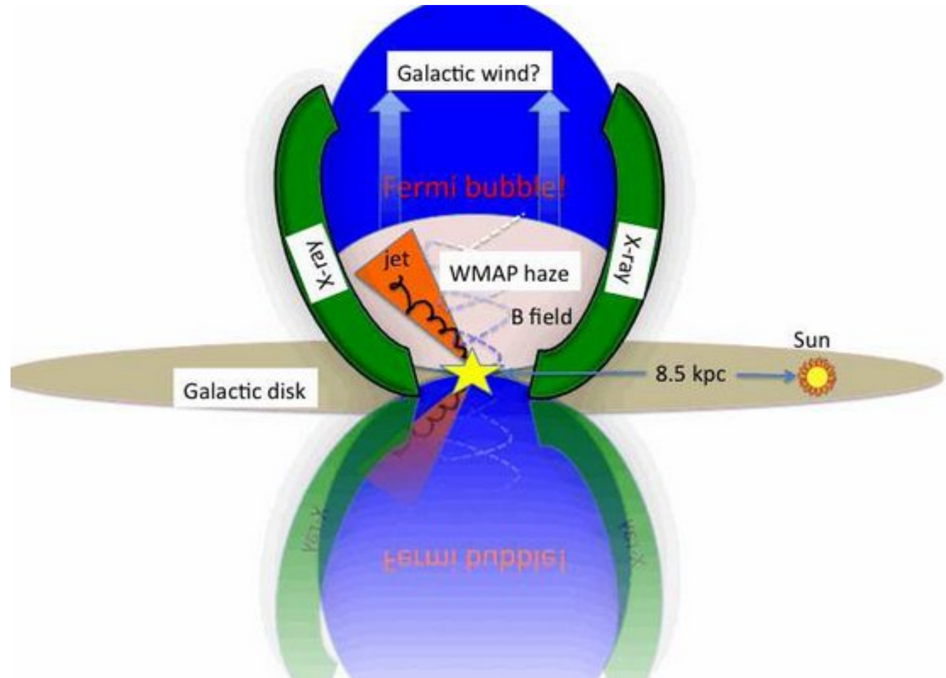
# Basic facts: a new *galactic* structure

- 2 spheroids, R ≈ 4 kpc
- Fermi-LAT discovery
  Su, Slatyer & Finkbeiner, ApJ. 724, 1044 (2010)
- Emit gamma rays
  - Detected up to ~ 100 GeV

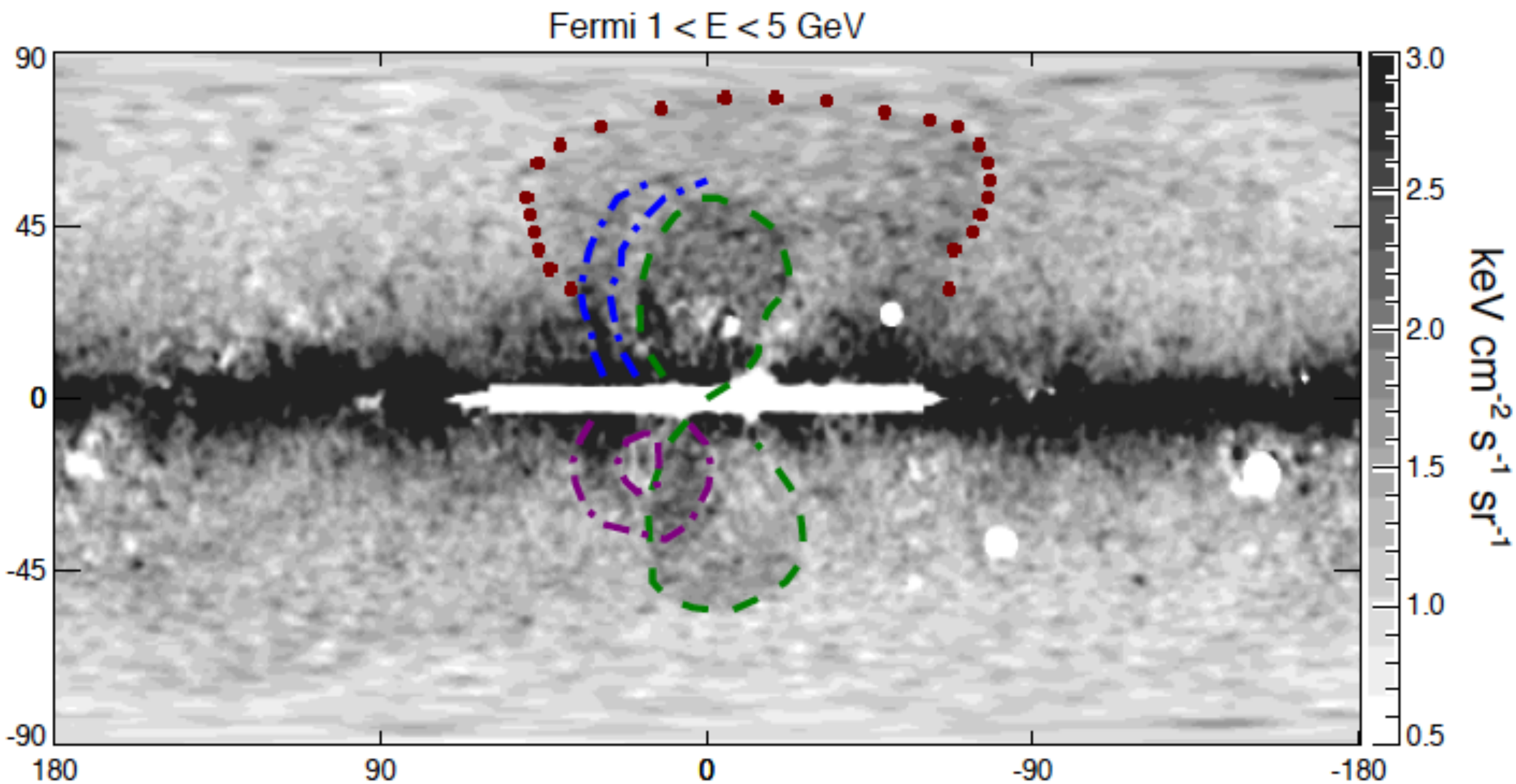


Artist's concept, NASA/GSFC

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



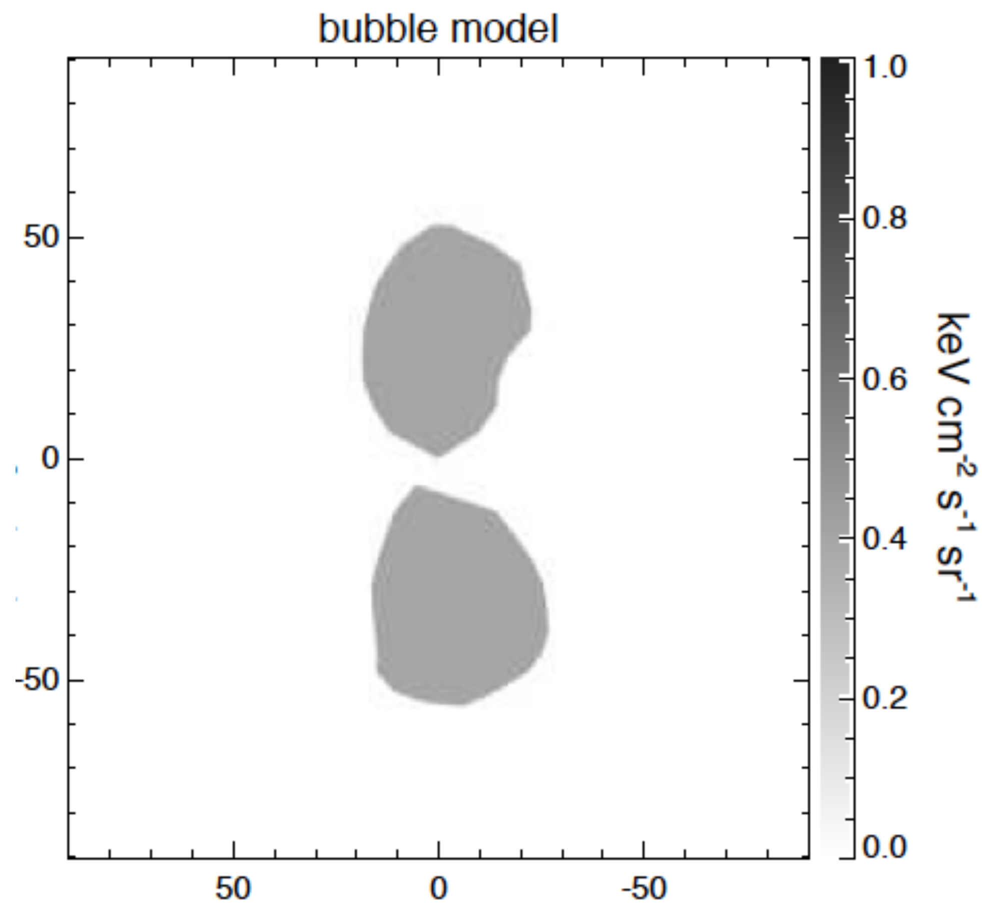

Finkbeiner, ApJ. 614, 186 (2004)
Snowden et al., ApJ. 485, 125 (1997).



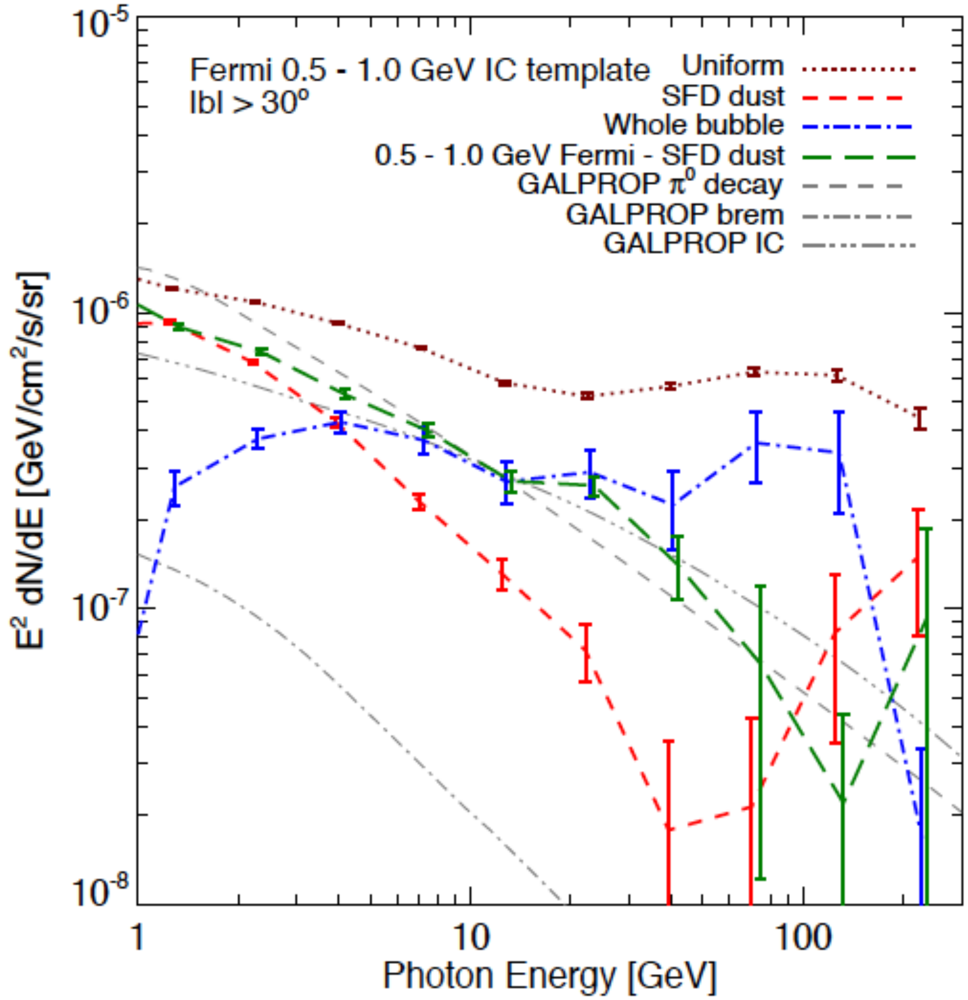
Fermi 1 < E < 5 GeV
90
45
0
-45
-90
180
90
0
-90
-180
3.0
2.5
2.0
1.5
1.0
0.5
keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$

- Uniform projected intensity
  - Puzzling!

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



- Spectrum: $E^{-k}$,
  - k~ 2 – 2.3



# 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

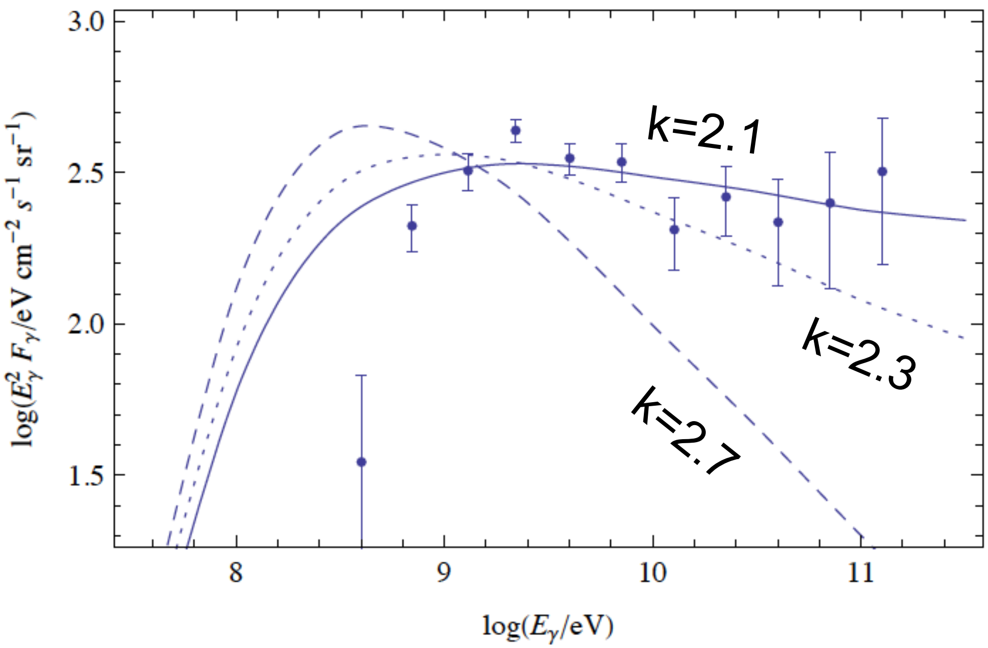
- *High energy protons*

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

# The hadronic scenario

- Steady state regime ("saturation")
  - Explains k~ 2.1 spectrum
- GeV downturn due to $\pi^0$ production threshold




Crocker and Aharonian, PRL 106, 2011

# Unique signature: neutrino counterpart!

- Hadronic shower:
  - same as atmospheric neutrinos, neutrino beams

$$
\begin{aligned}
p + p &\rightarrow \pi^{\pm} + X \\
\pi^{+} &\rightarrow \mu^{+} \nu_{\mu} \\
\mu^{+} &\rightarrow e^{+} \nu_{e} \bar{\nu}_{\mu} \\
\pi^{-} &\rightarrow \mu^{-} \bar{\nu}_{\mu} \\
\mu^{-} &\rightarrow e^{-} \bar{\nu}_{e} \nu_{\mu}
\end{aligned}
$$

  - *Trace gamma rays* in spectrum and spatial distribution
  - New signal for Km-scale detectors → *potential to probe physics and origin of the Fermi Bubbles!*

Crocker and Aharonian, PRL 106, 2011

# High energy neutrinos from the Fermi Bubbles

C.L. & S. Razzaque, arXiv:1112.4799, Phys. Rev. Lett., in press

# Flux calculation: ingredients

- Parent proton spectrum: , k~ 2.1- 2.3,  $E_0$ ~ 1-10 PeV

$$N_p(E) = N_0 E^{-k} \exp(E/E_0)$$

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

- Analytics + SIBYLL code:

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

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

$$K_\pi \approx 0.17$$

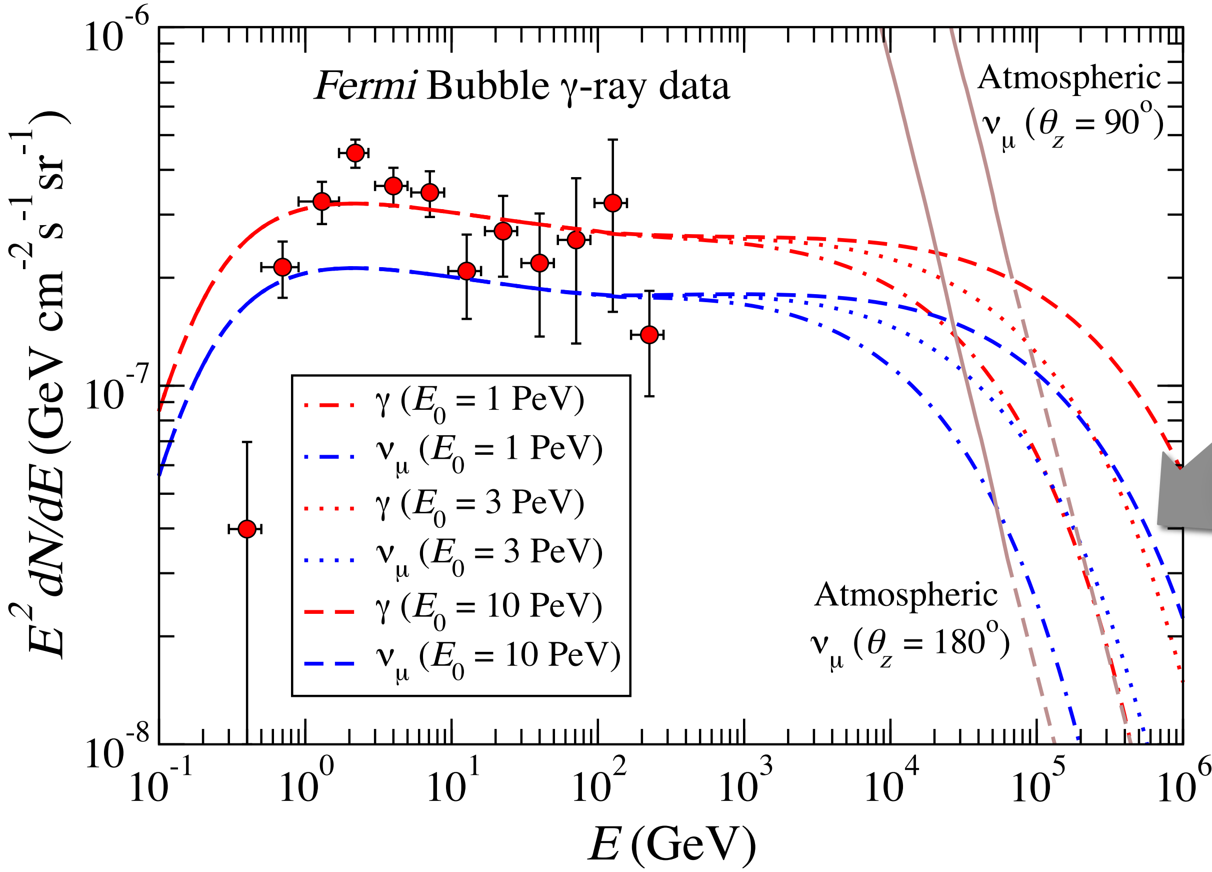
$$E_c = E_\pi / K_\pi + m_p$$

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

- Exceeds atmospheric background
  - Detectable above ~ 20 TeV, for $E_0$>3 PeV

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

k=2.1




× ½ after flavor *oscillations*

E.g., Costantini & Vissani, Astropart.Phys. 23 (2005) 477

# 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

# Detectability at Km$^3$ detectors

# Number of events

$$N_\nu = \int_0^{t_{exp}} dt \int_{\substack{\Sigma(t) \\ \theta_1 \leq \theta_z \leq \theta_2}} d\Omega \int_{E_{th}}^{\infty} dE \Phi(E) A_\nu(E, \theta_z)$$

$$\simeq t_{exp} \langle \Omega(\theta_1, \theta_2) \rangle_t \int_{E_{th}}^{\infty} dE \Phi(E) \langle A_\nu(E) \rangle_\theta \ ,$$

Running time

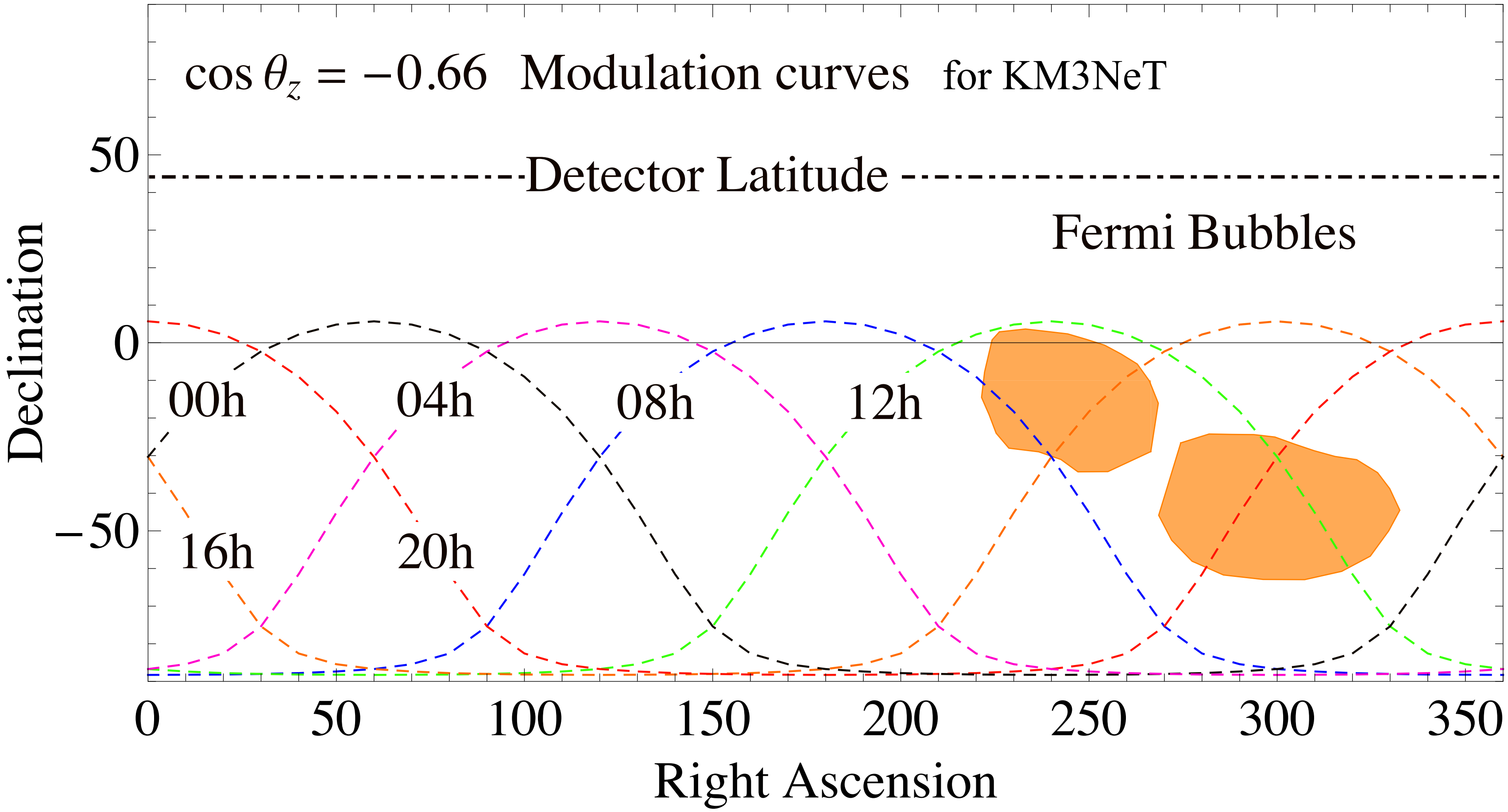
Day-averaged solid angle in zenith bin

Zenith-averaged effective area of detector

- Zenith bins: *sub-horizon* only (w/r to detector)
  - $\cos\theta_z$ = -1,-0.66 ; -0.66,-0.33 ; -0.33, 0

# Solid angle: geometry

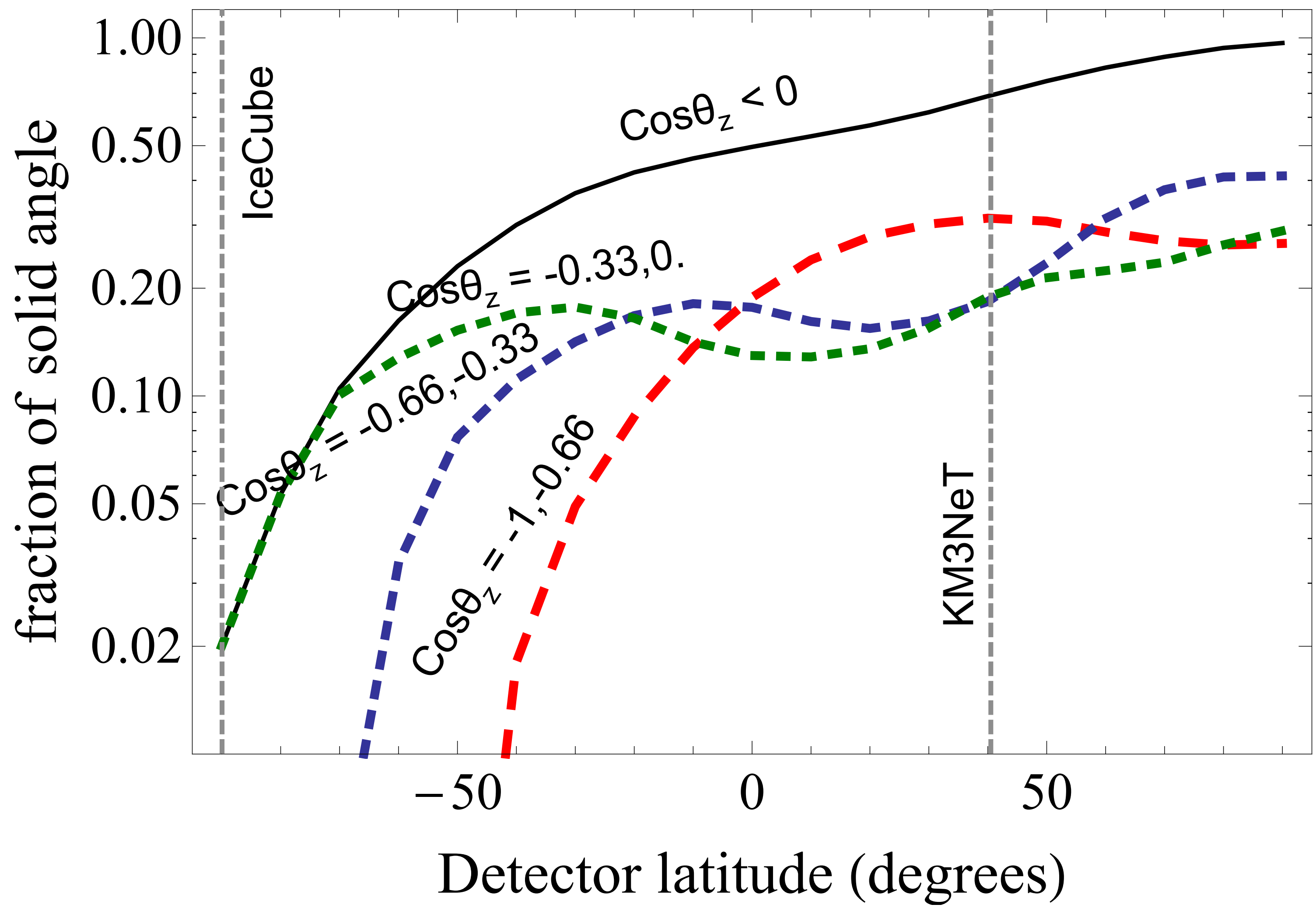
In equatorial coordinates:



- Total solid angle, subtended by both bubbles: $\Omega_b$ = 0.808 sr

- IceCube (running):
  - Antarctica, $\theta_{lat}$ = -90 deg. *, only 2.5% sub-horizon!*

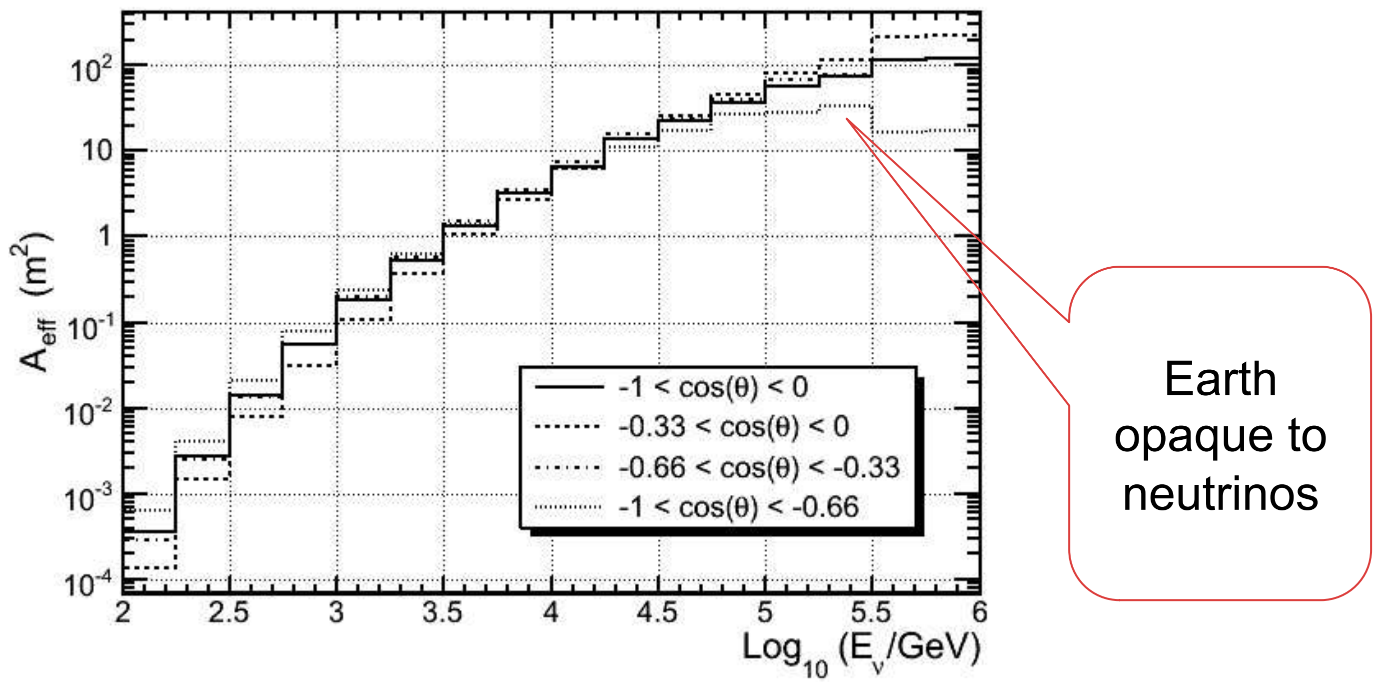
- Km3NET (proposed):
  - Mediterranean, $\theta_{lat}$ = +43 deg. *, 70% sub-horizon!*
  - Best for deepest zenith bin (lower background)



fraction of solid angle
1.00
0.50
0.20
0.10
0.05
0.02
−50
0
50
Detector latitude (degrees)
IceCube
KM3NeT
Cosθ_z < 0
Cosθ_z = -0.33,0.
Cosθ_z = -0.66,-0.33
Cosθ_z = -1,-0.66

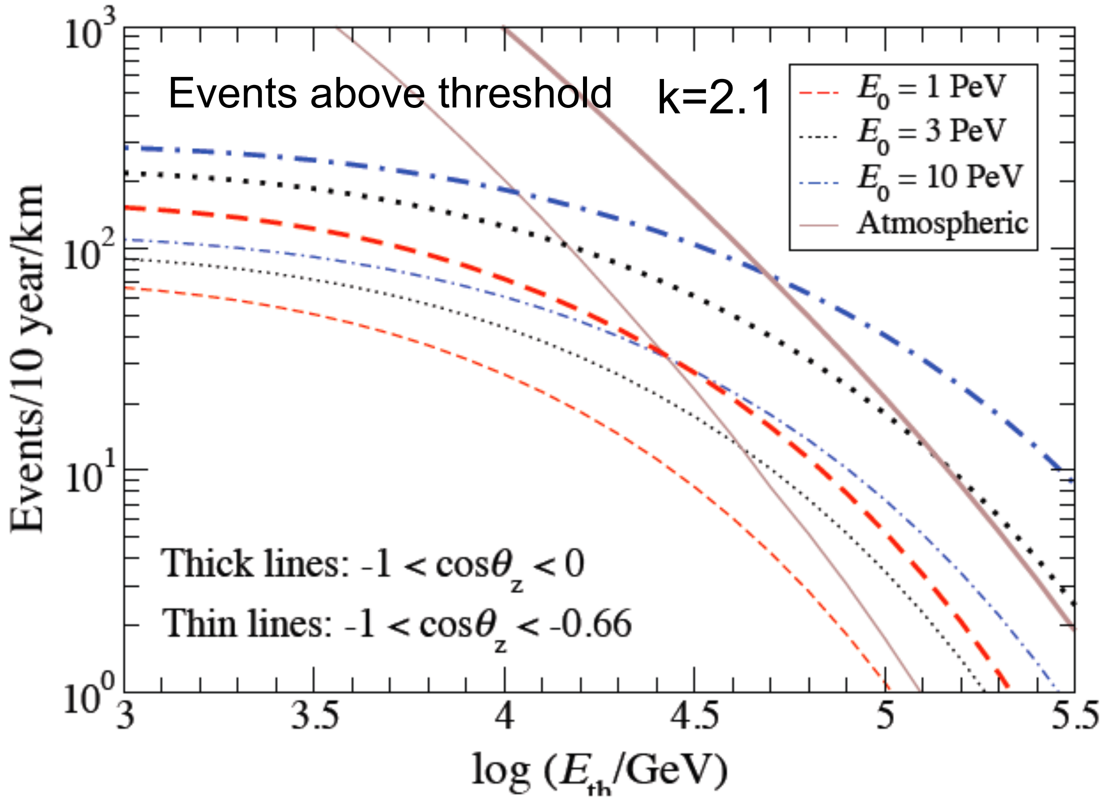
# Effective area/exposure

- Cross section and detector response, $\nu_\mu$ dominates
- Use 20 IceCube years: $t_{exp}\langle A_\nu(E)\rangle_\theta = 20\ \mathrm{yr} \times A_{\mathrm{IC40}}$
  - Realistic for expanded IceCube (IC80) and KM3NeT



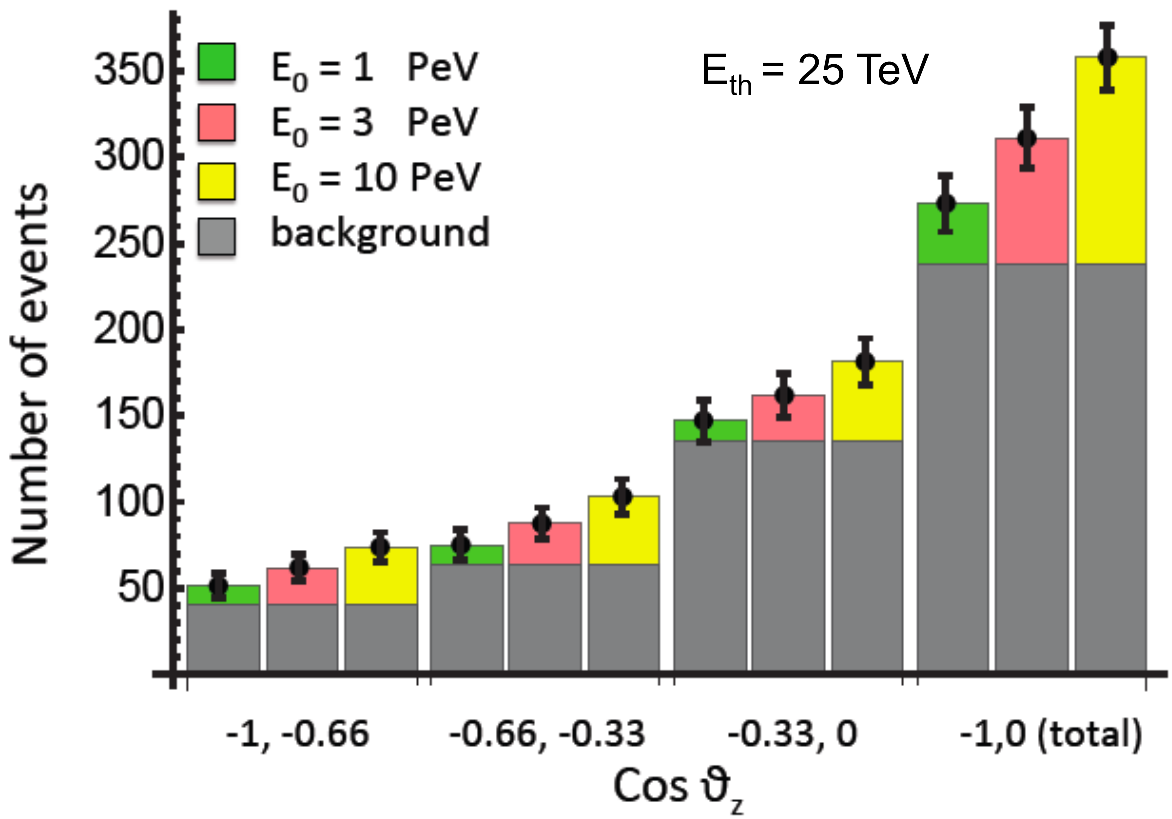

Abbasi et al., PRD 83, 012001 (2011)

# Signal and background at KM3NeT




- Statistical significance : $\Delta = N_{sig}/\sqrt{N_{sig} + N_{bkg}}$
  - Maximum for $E_{th}$ = 20-30 TeV ; for *deepest bin* (lower background) and *total sub-horizon* (higher statistics)

- signal exceeds 3 σ for $E_0$>3 PeV
- Detailed data fit will increase significance
  - correlation with bubble shape and position



# IceCube potential

- Excess not significant, *but* :
  - Could constrain proton spectrum (large $E_0$, allowed by Fermi-LAT)
  - Potential/motivation to increase sensitivity above horizon, reduce background, …

| | $E > 10^4$ GeV | $E > 10^5$ GeV |
|---|---|---|
| events, 1 PeV cutoff | 2.8 | 0.3 |
| events, 3 PeV cutoff | 5.1 | 1.1 |
| events, 10 PeV cutoff | 8.0 | 2.4 |
| background | 59 | 1.7 |

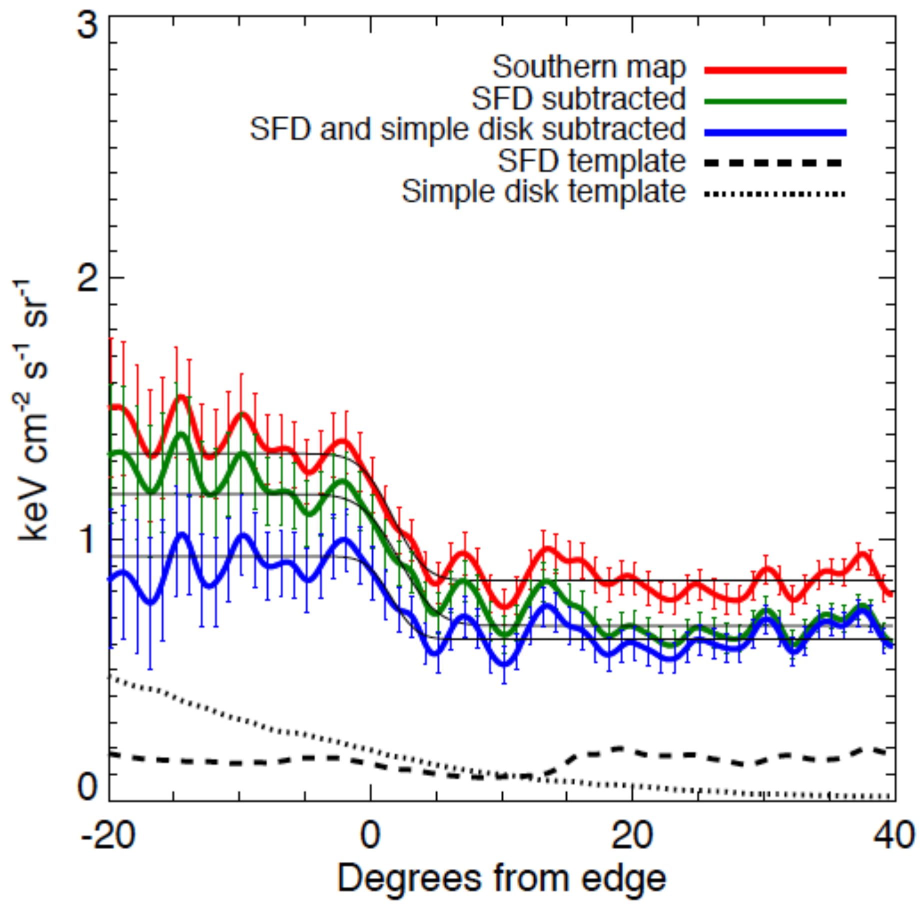
# Final remarks

- Fermi bubbles: a potential new source of high energy neutrinos
  - galactic, extended

- Observable at a Km-scale detector
  - Northern hemisphere optimal (motivation!)
  - south pole worst, requires upgrade, interesting constraints possible

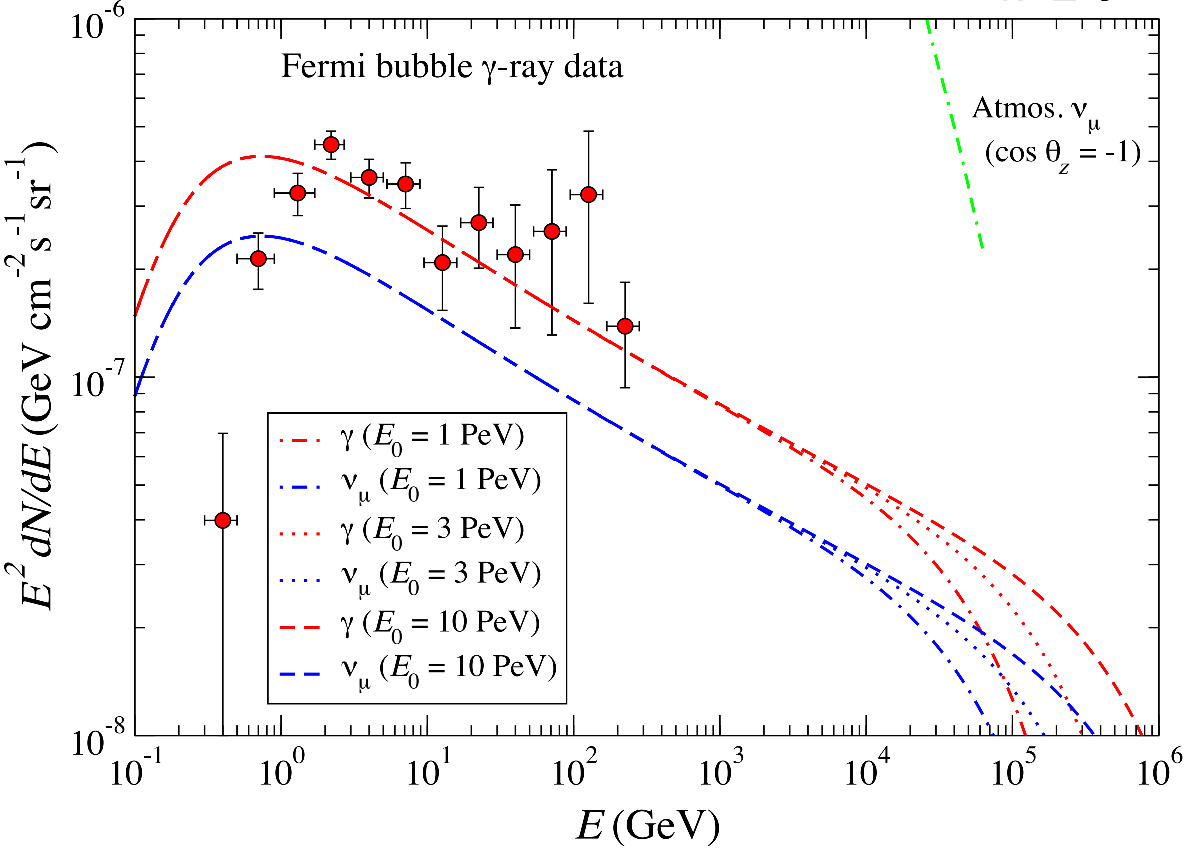
- *A test of the hadronic model of gamma ray emission*
  - *Origin of the bubbles*
  - *Physics of high energy galactic phenomena: time scales, energetics*

backup



Southern map
SFD subtracted
SFD and simple disk subtracted
SFD template
Simple disk template
keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$
Degrees from edge
3
2
1
0
-20
0
20
40

k=2.3



Fermi bubble γ-ray data
Atmos. $\nu_\mu$
($\cos\theta_z$ = -1)
γ ($E_0$ = 1 PeV)
$\nu_\mu$ ($E_0$ = 1 PeV)
γ ($E_0$ = 3 PeV)
$\nu_\mu$ ($E_0$ = 3 PeV)
γ ($E_0$ = 10 PeV)
$\nu_\mu$ ($E_0$ = 10 PeV)
$E^2\, dN/dE$ (GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$)
$E$ (GeV)