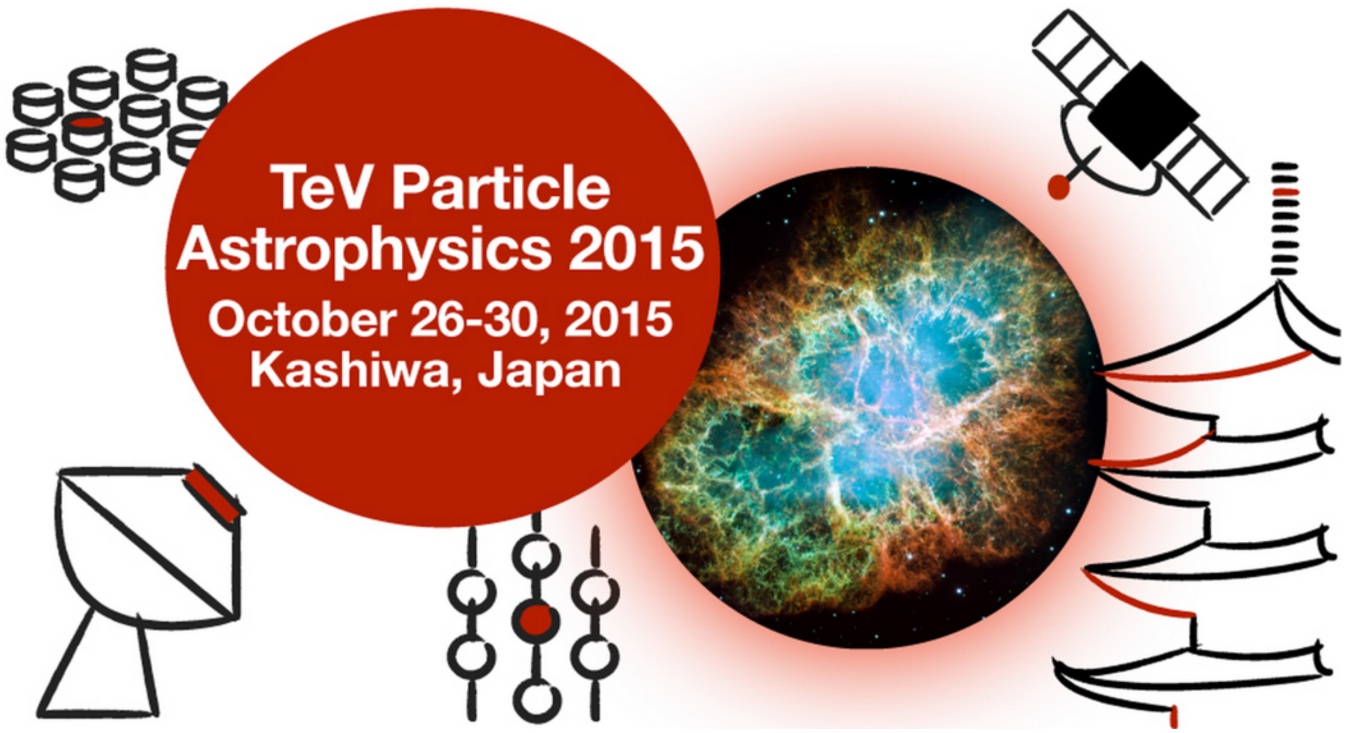


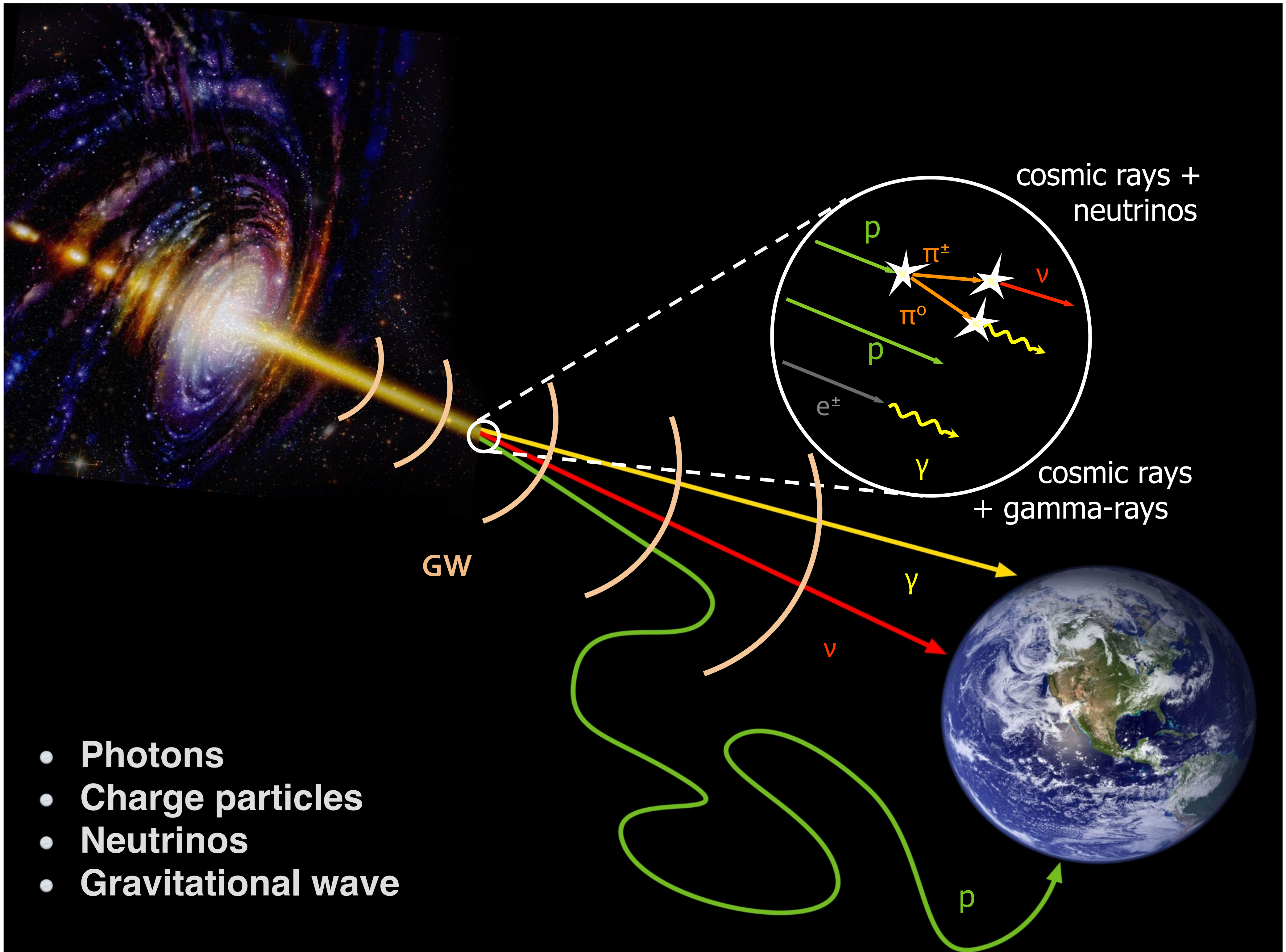
Multimessenger test of Hadronic model for Fermi Bubbles

Soebur Razzaque

University of Johannesburg

with Cecilia Lunardini and Lili Yang

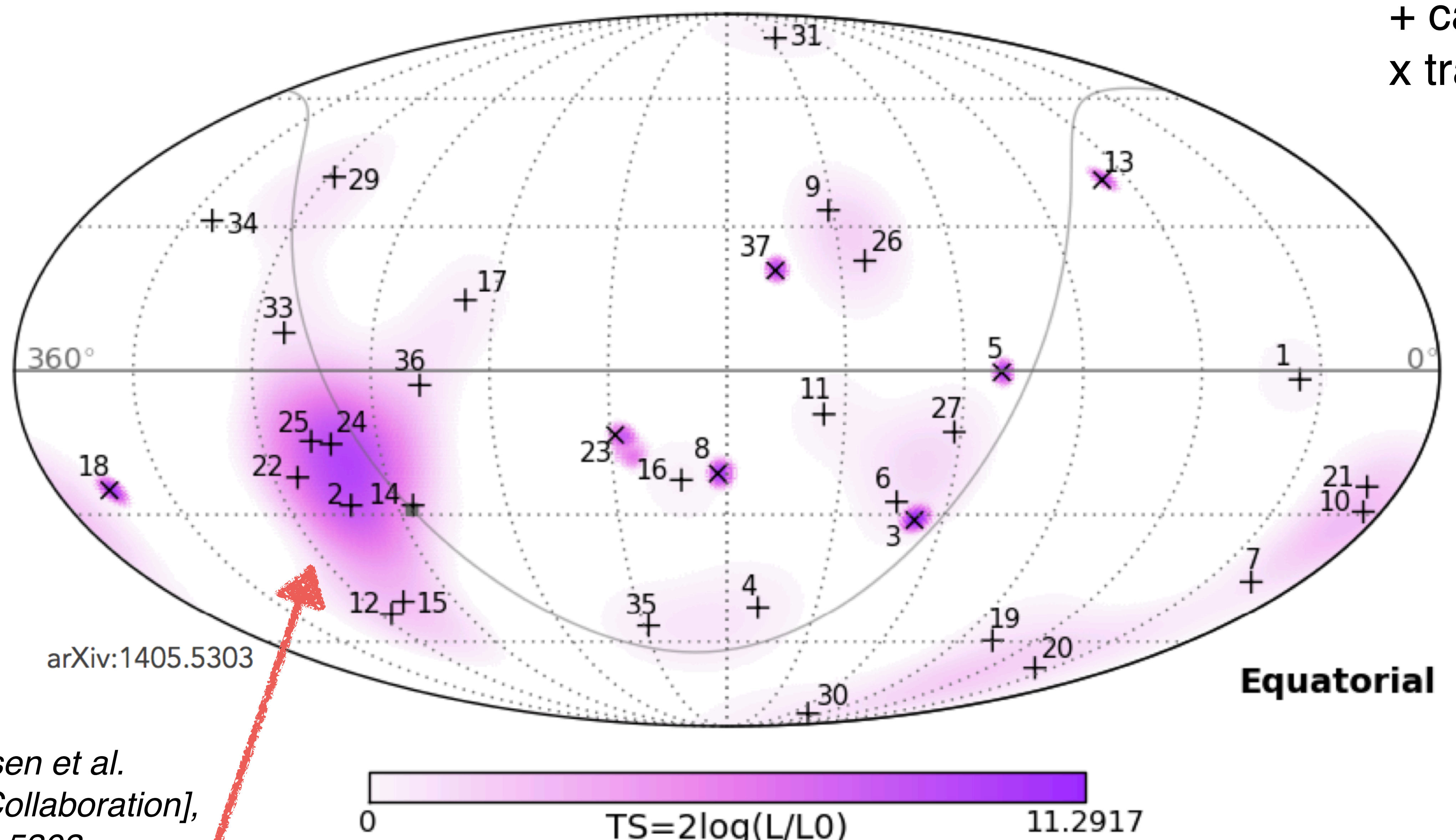
Multi-messenger Astronomy



IceCube Cosmic Neutrino Events (3 year)

37 events, ~9-25 from atmospheric muon and neutrino background

+ cascades
x tracks



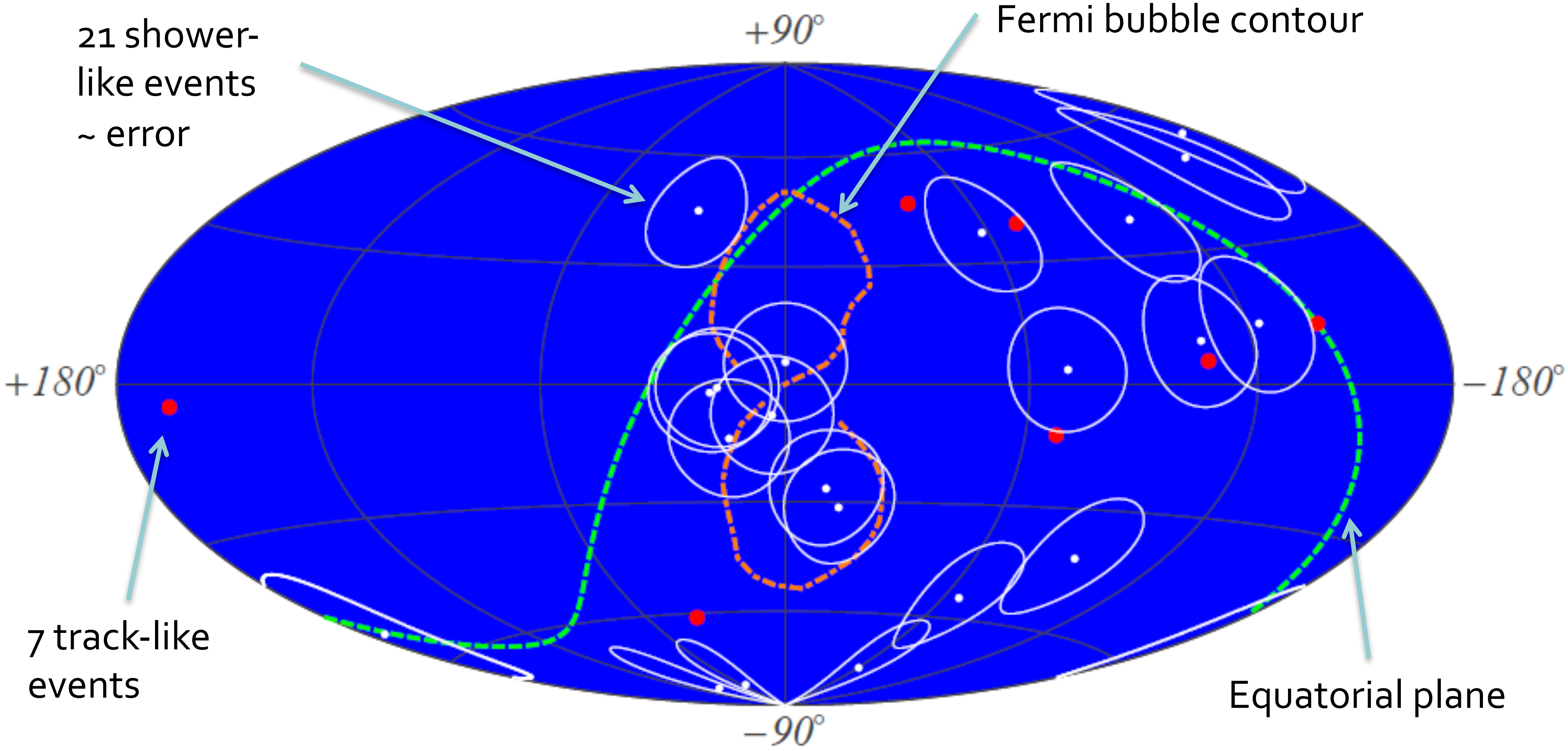
M. G. Aartsen et al. [IceCube Collaboration], arXiv:1405.5303

Hint (~8% chance) of clustering near the Galactic center

Angular resolution
~ 15° for cascades
~ 1° for tracks

A subset of events from Galactic Center region

2 year data (28 events)

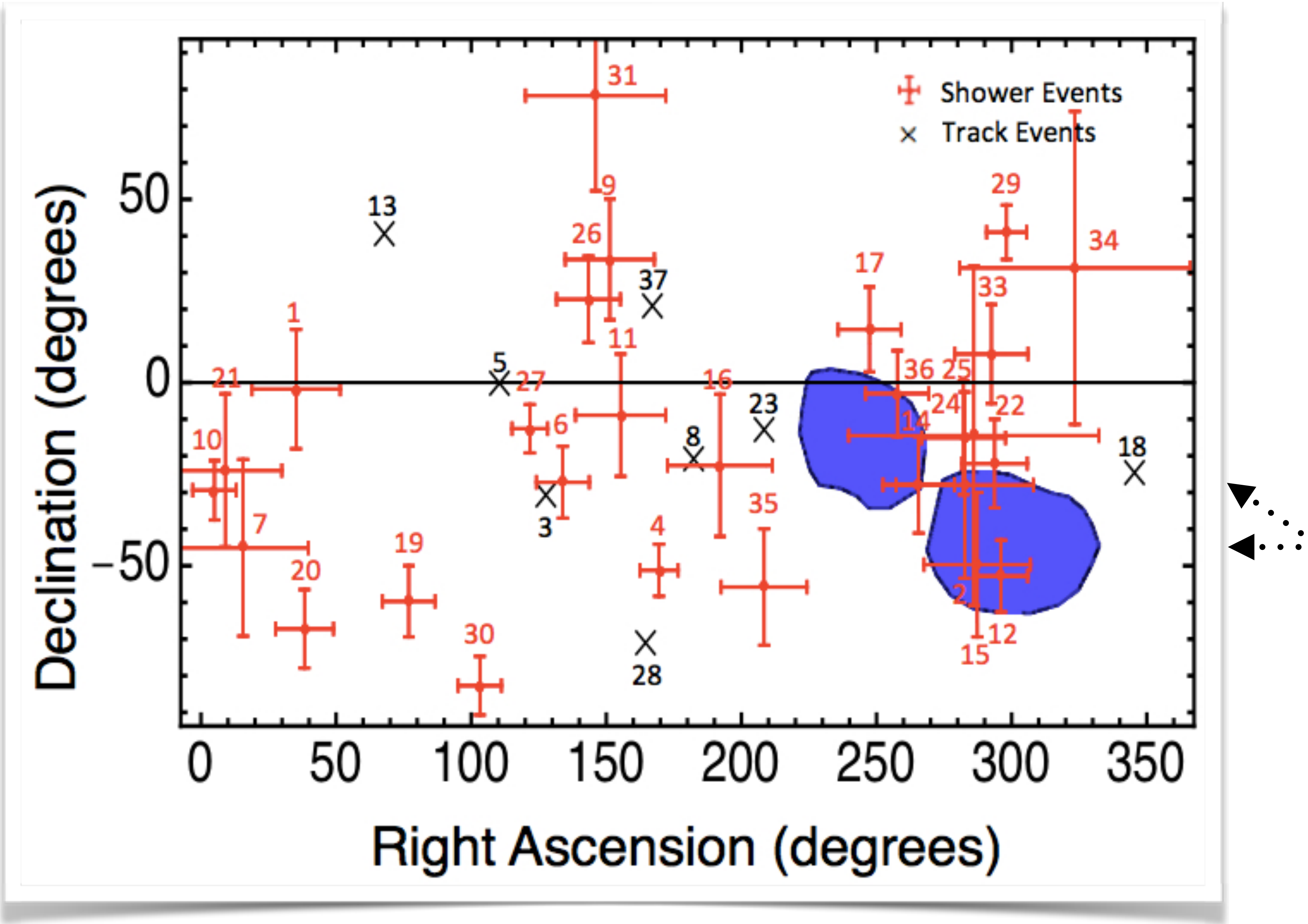


SR, PRD88, 081302 (2013)

Cosmic Neutrinos and Fermi Bubbles

IceCube 3 year data (37 events)

Cecilia Lunardini, SR, Lili Yang and Kristopher Theodoseau, PRD90, 023016 (2014)

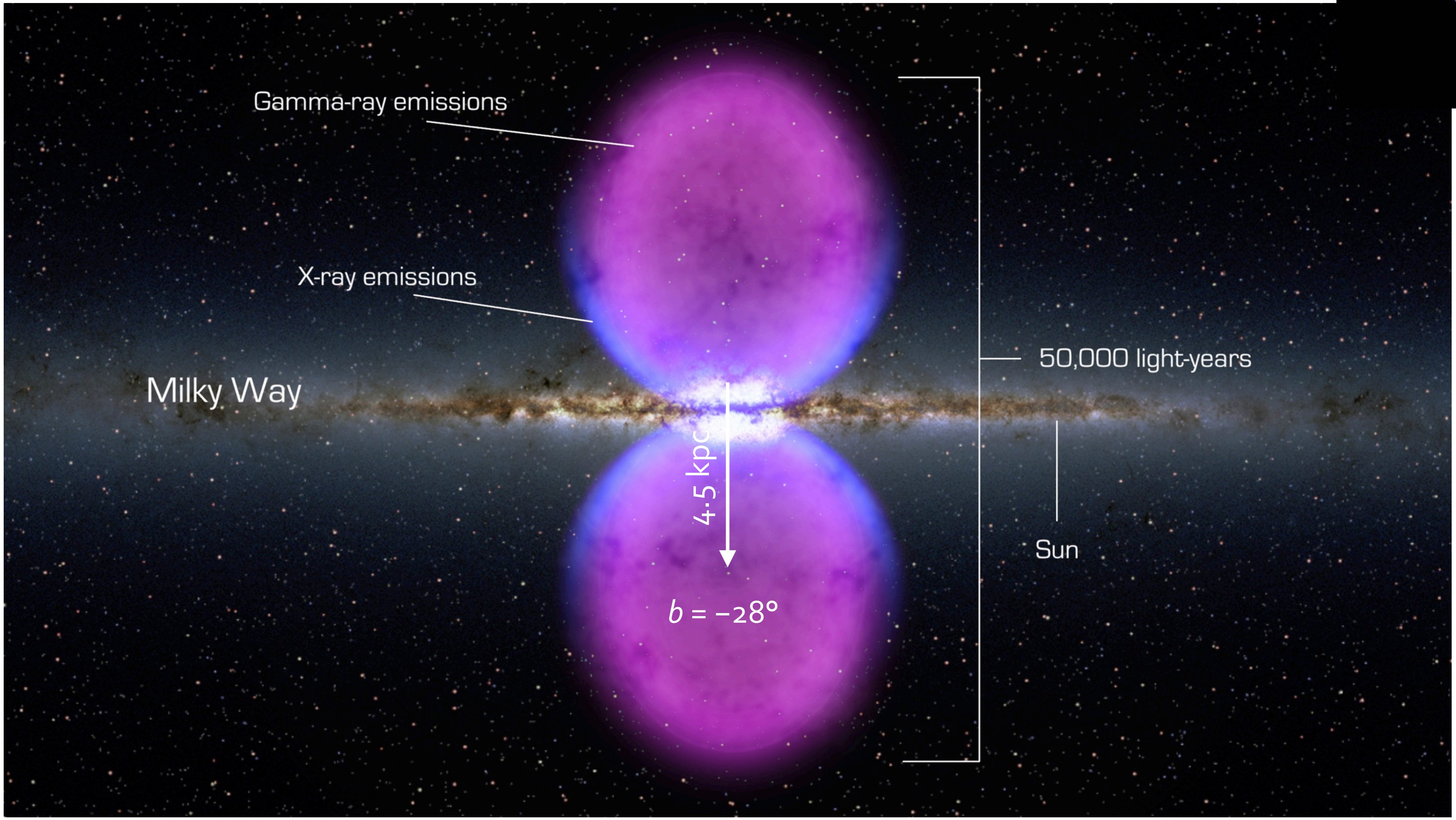


Fermi Bubble contours

- 5 strongly correlated cascade events (central coordinate values within FB)
- 4 weakly correlated cascade events (error ellipses touching FB contours)

Gamma Ray Fermi Bubbles

Huge gamma-ray emitting globular-shaped objects

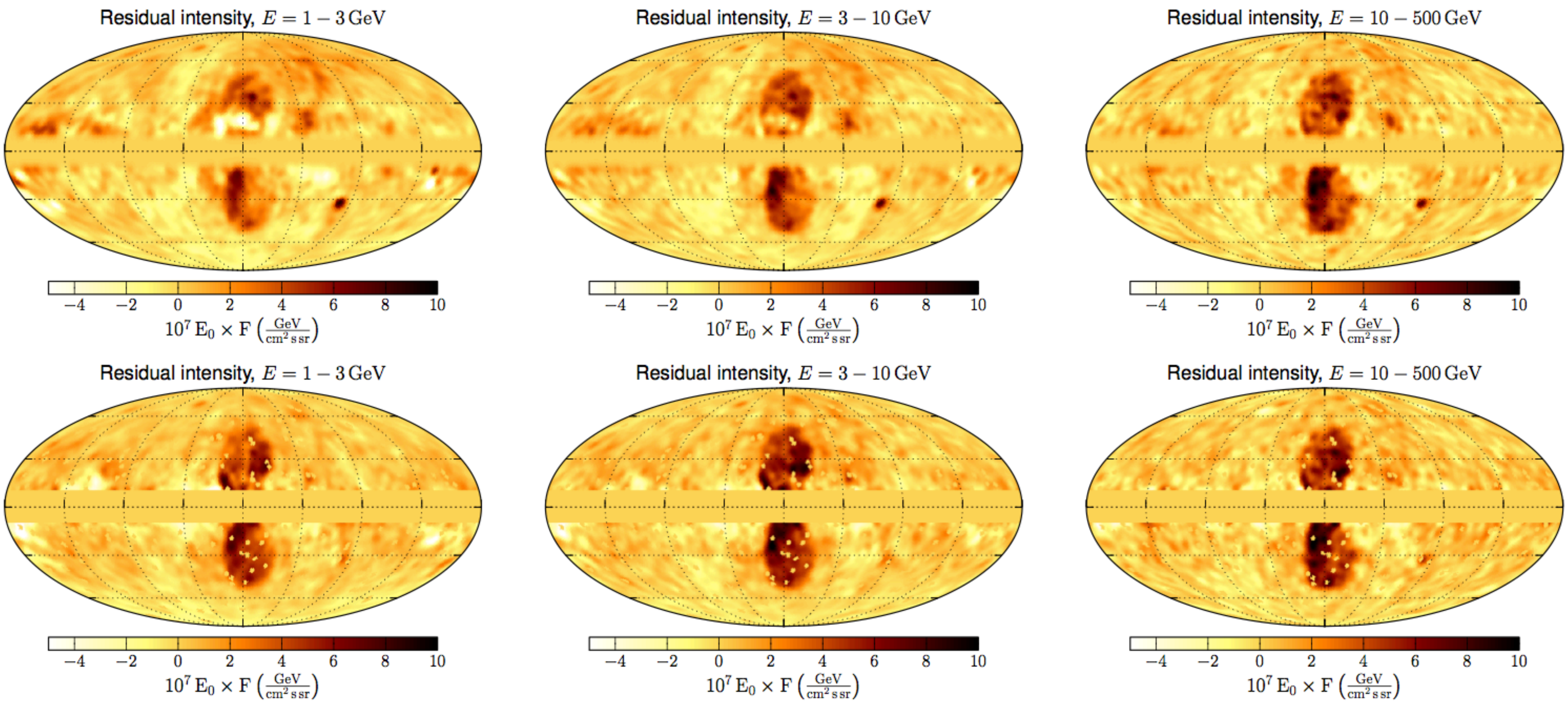


Credit: NASA Goddard Space Flight Center

Discovered by Finkbeiner et al. in Fermi-LAT data (2010)

Gamma Ray Fermi Bubbles

Uniform projected intensity, well-defined boundary, hard spectrum

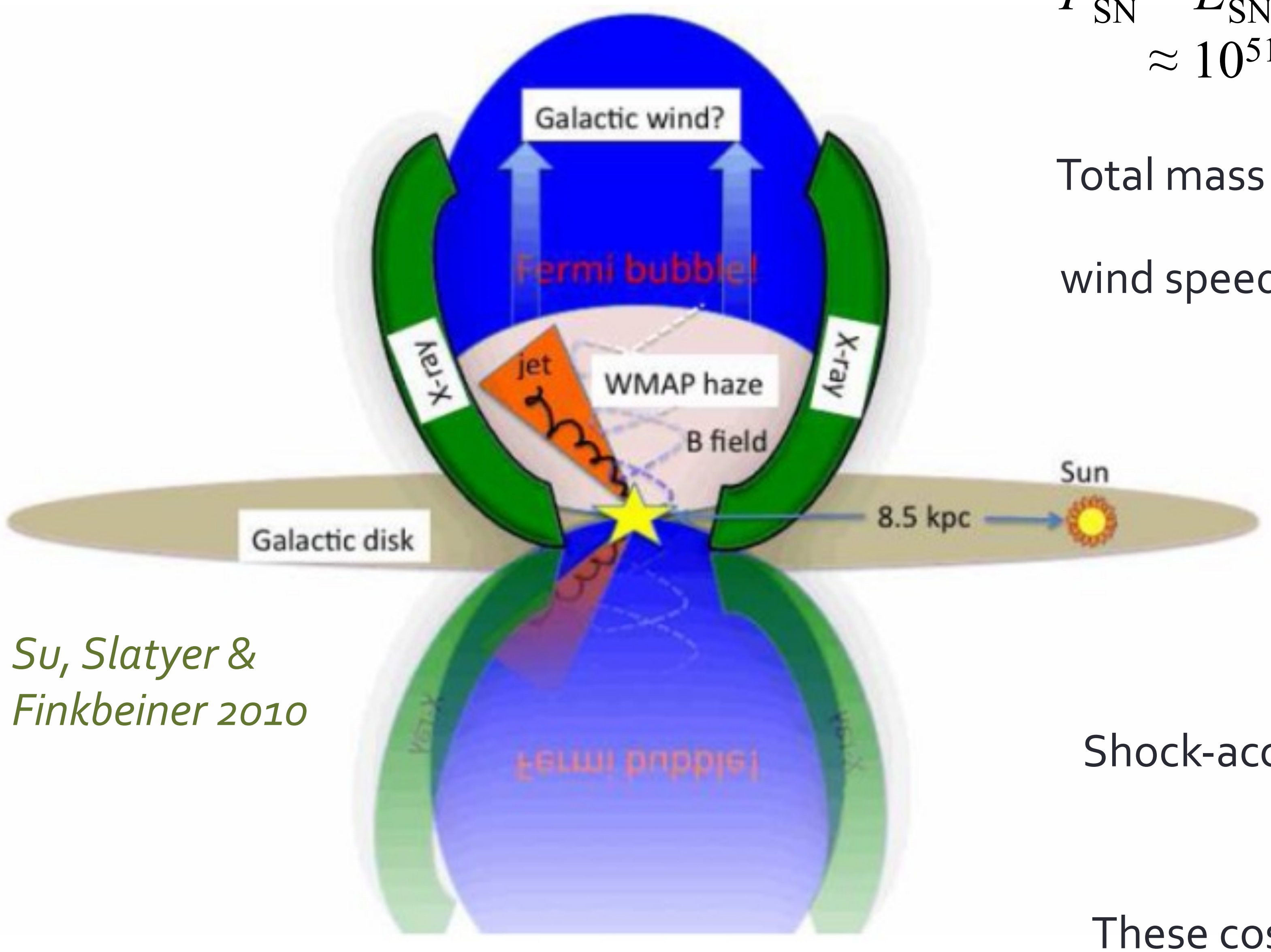


- *Top plots: residual maps using GALPROP templates*
- *Bottom plots: residual maps using local templates*

Fermi-LAT Collaboration (2014)

FB from Galactic Center Starburst Activity

Total energy output rate (power) from SNe around the Galactic Center



Su, Slatyer & Finkbeiner 2010

From infrared luminosity

$$P_{SN} = E_{SN} \times \text{rate}_{SN}$$
$$\approx 10^{51}\ \text{erg} \times 0.04/100\ \text{yr} \approx 1.3\times10^{40}\ \text{erg/s}$$

Total mass loss rate in wind: $M_w \sim 0.03\ M_{sun}/\text{yr}$

wind speed: $v_w \approx (2P_{SN}/M_w)^{1/2} \sim 1200\ \text{km/s}$

Bubble formation time scale

$$T_{bbl} > n_{gas}V_{bbl}/\varepsilon M_w \sim 3\times10^9\varepsilon^{-1}\ \text{yr}$$

$\sim 0.01/\text{cc}$, 2 blobs of $r = 3.5$ kpc

Shock-accelerated cosmic-ray power in wind

$$P_{CR} \sim 0.1 P_{SN} \sim 10^{39}\ \text{erg/s}$$

These cosmic-rays interact with bubble gas to produce π^0 decay γ's on a time scale

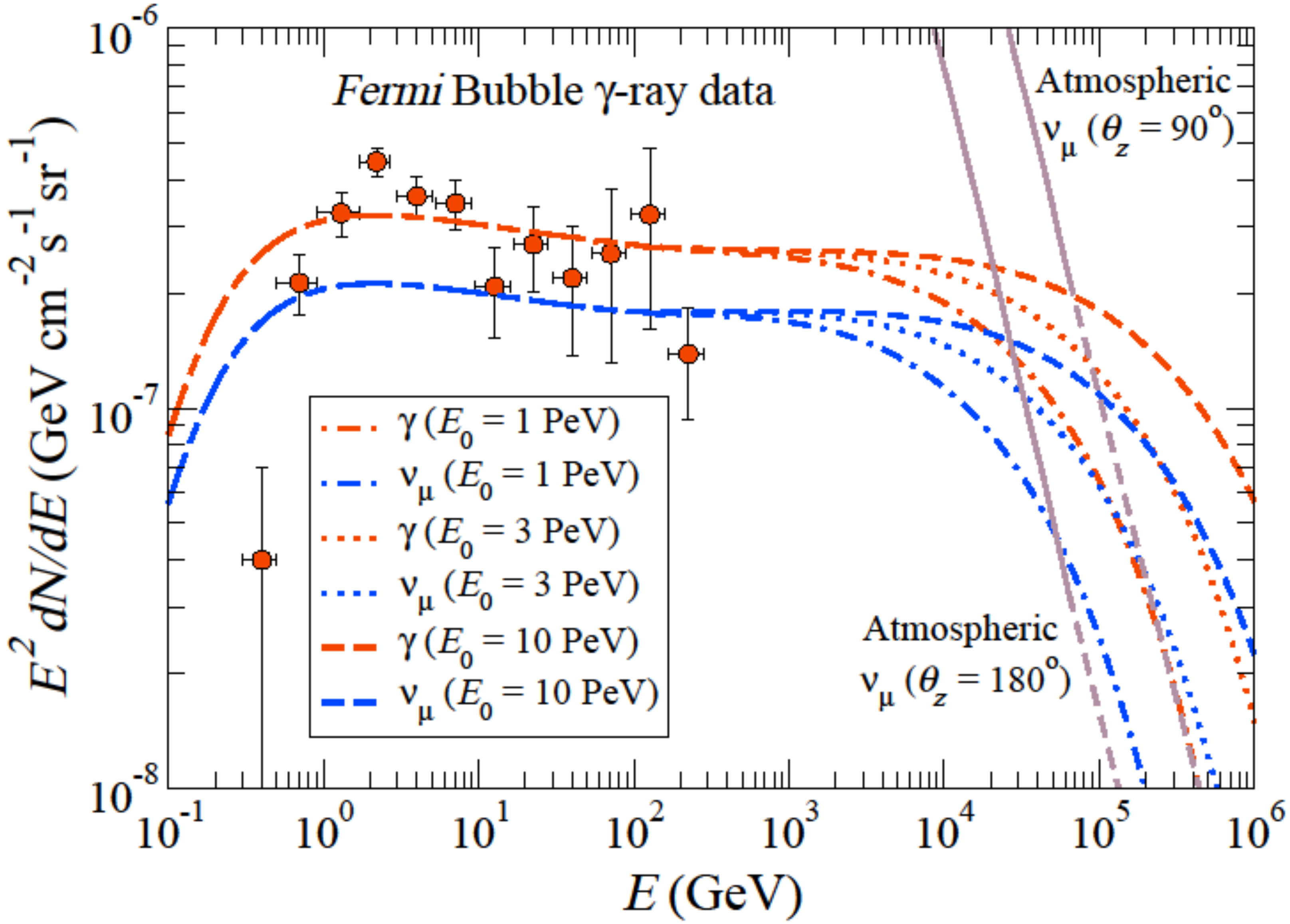
Hadronic model by *Crocker & Aharonian 2011* →

$$t_{pp} \approx (n_{gas}\sigma_{pp}\kappa_{pp}c)^{-1} \sim 5\times10^9\ \text{yr}$$

Gamma and Neutrino Fluxes from FB

pp - interactions of cosmic rays in Fermi Bubbles

Cecilia Lunardini and SR, PRL108, 221102 (2012)



Injected proton spectrum

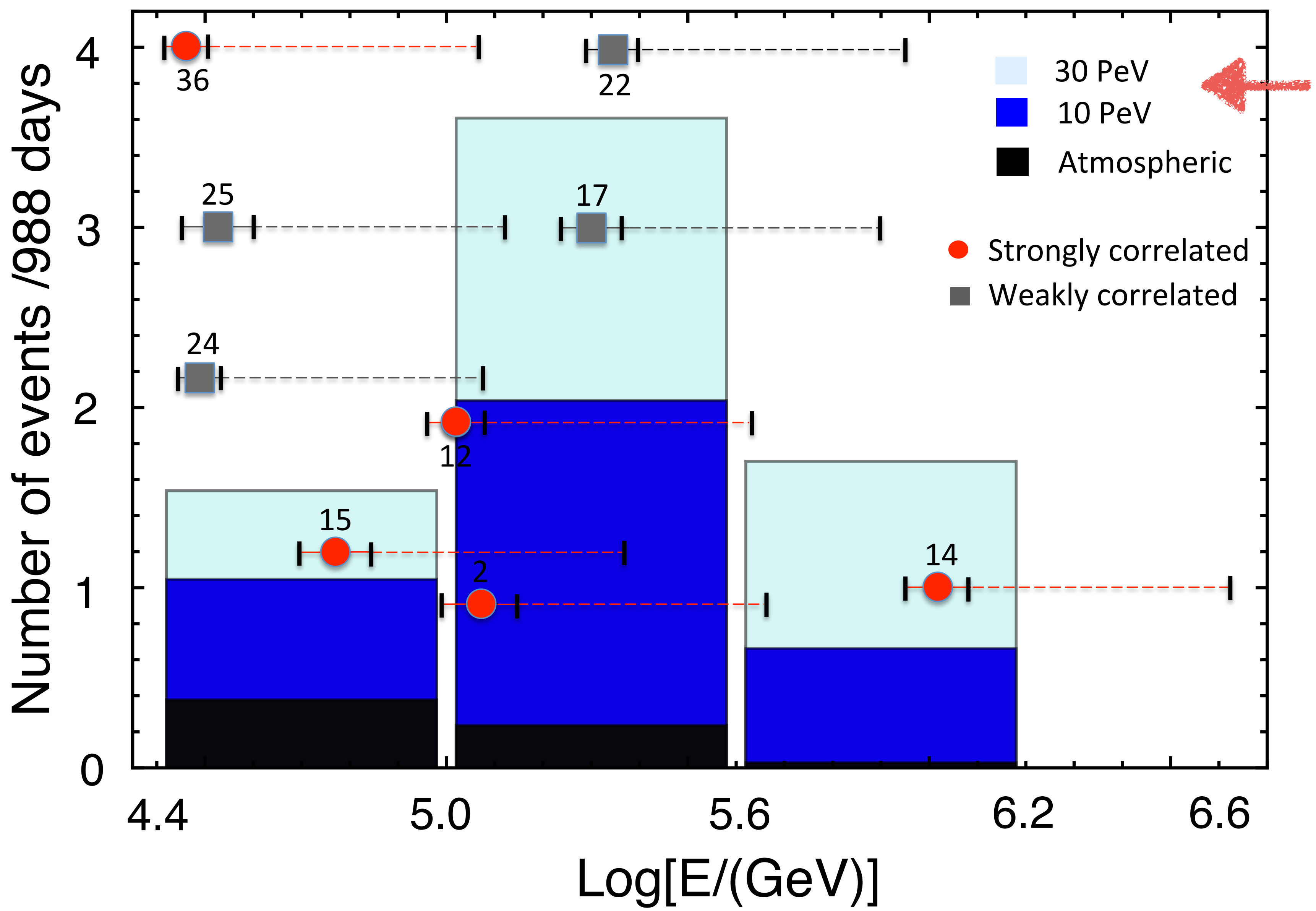
$$dN_p/dE \propto E^{-k} e^{-E/E_0}$$

Gas density in bubbles: 0.01/cc

- Gamma-ray power ~ 2 x 10^{37} erg/s
- Total energy in steady-state cosmic rays ~ 5 x 10^{55} erg
- Total energy in gamma rays over
- ~ 5 x 10^9 yr is ~ 3 x 10^{54} erg
- Typical ~ 10% hadronic model efficiency for gamma-ray production

IceCube Neutrino events from FB

Comparison of data and model in energy bins



cosmic-ray proton cutoff energy

Dominated by shower-like events

Cecilia Lunardini, SR, Lili Yang and Kristopher Theodoseau, PRD90, 023016 (2014)

Cecilia Lunardini, SR and Lili Yang, arXiv:1412.6240

VHE Gamma and Neutrino Fluxes from FB

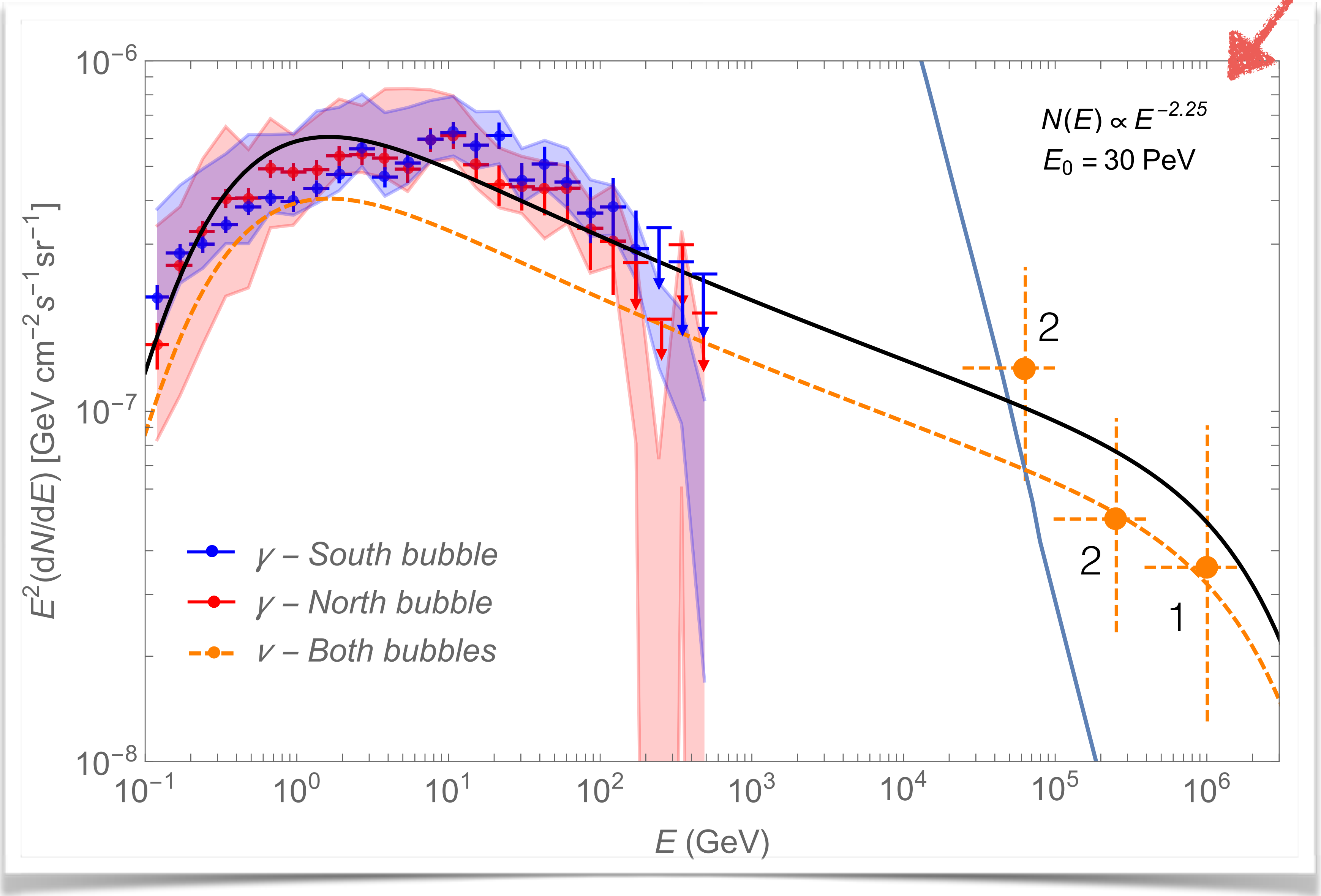
Test hadronic model using both neutrinos and VHE gamma rays

5-year Fermi-LAT data

M. Ackermann et al. [Fermi-LAT Collaboration], arXiv:1407.7905

Best-fit model

statistical + systematic errors



Require *pp* model to produce 5 neutrino events

Cecilia Lunardini, SR and Lili Yang, PRD92, 021301 (2015)

High Altitude Water Cherenkov (HAWC) Detector

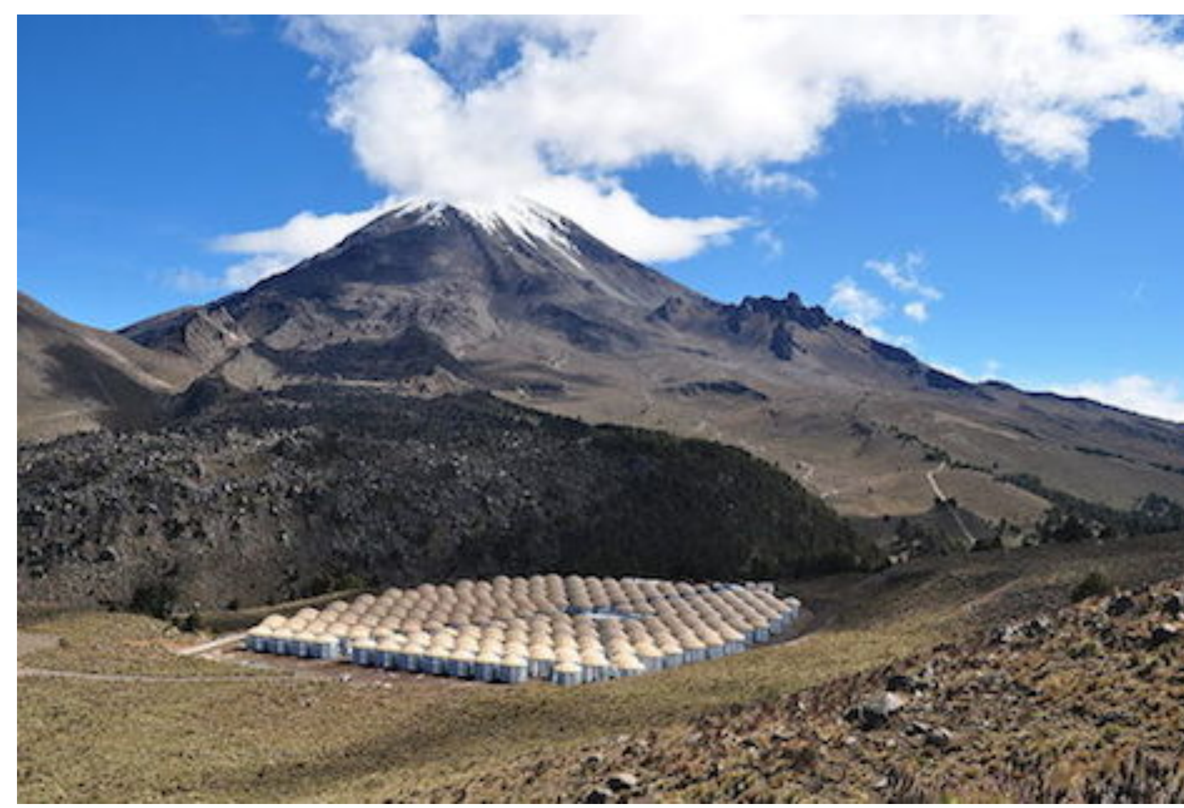
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

4100 m altitude near Sierra Negra Volcano, Puebla, Mexico

- 0.1 - 100 TeV
- 2pi sr Field of View
- 0.1 degree @ > 5 TeV

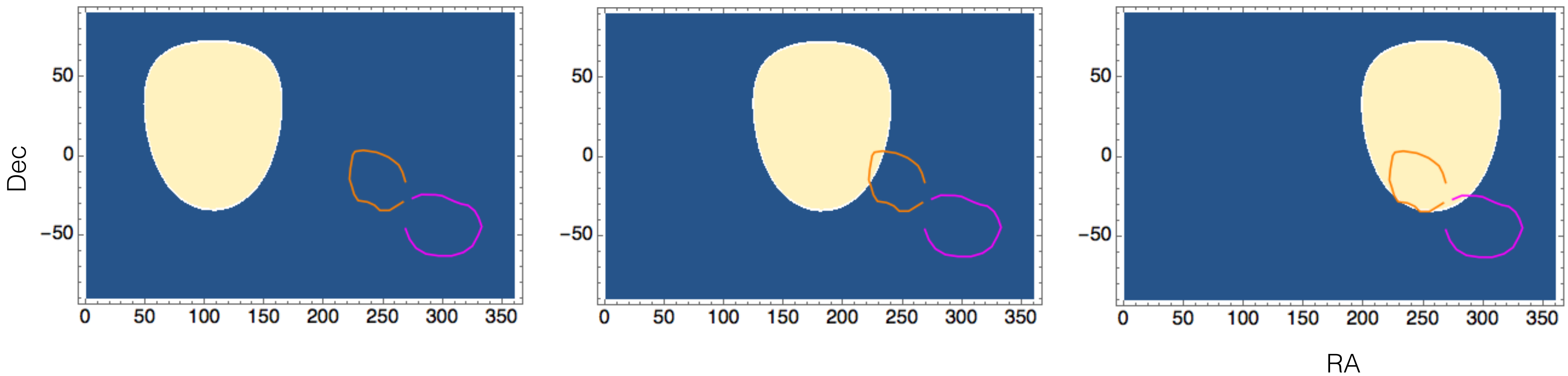
4 meters high
7.3 meters in diameter

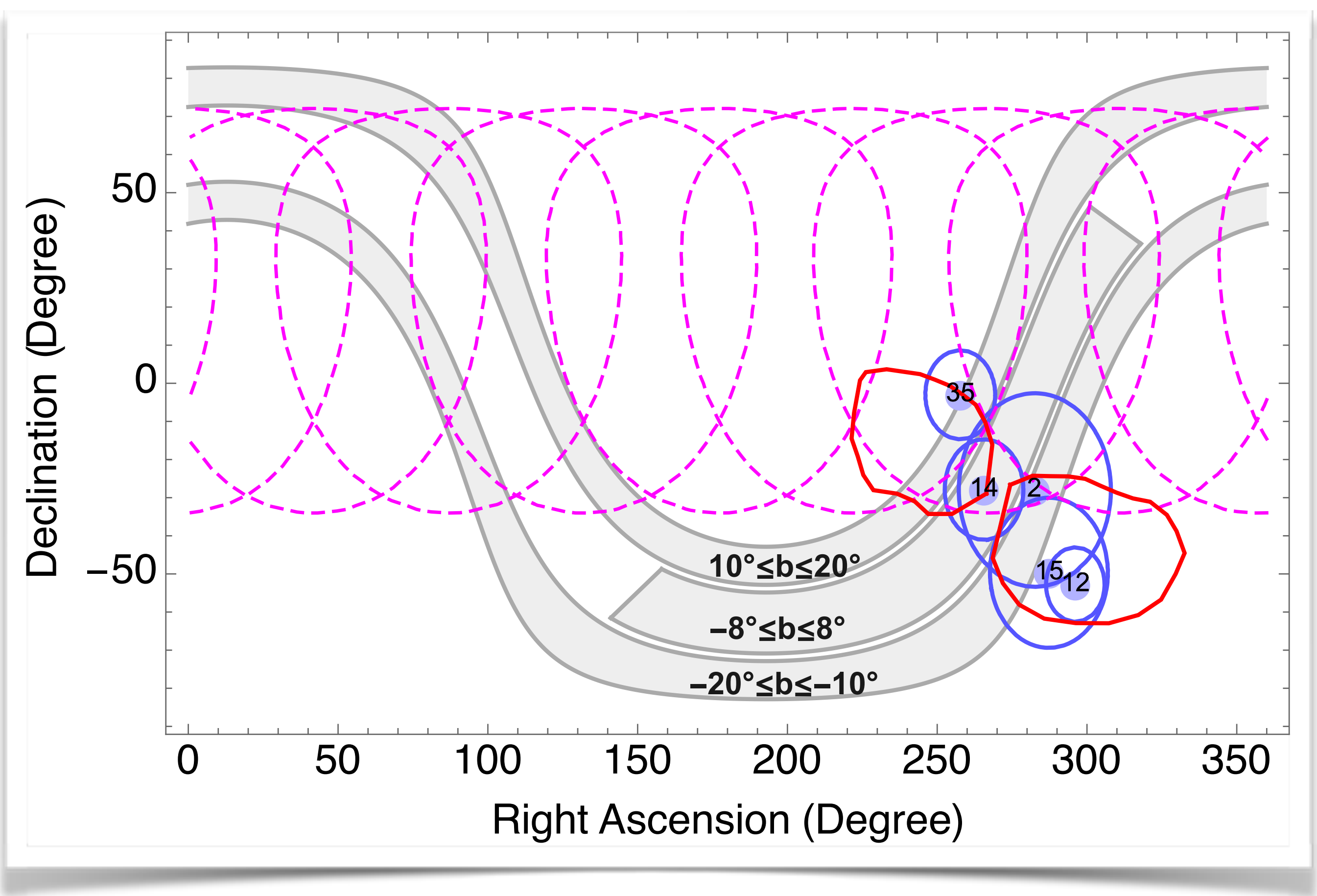
300 tanks in total,
with 4 PMTs per tank



Detecting Fermi Bubbles with HAWC

HAWC field-of-view overlapping Fermi Bubbles at different times of day



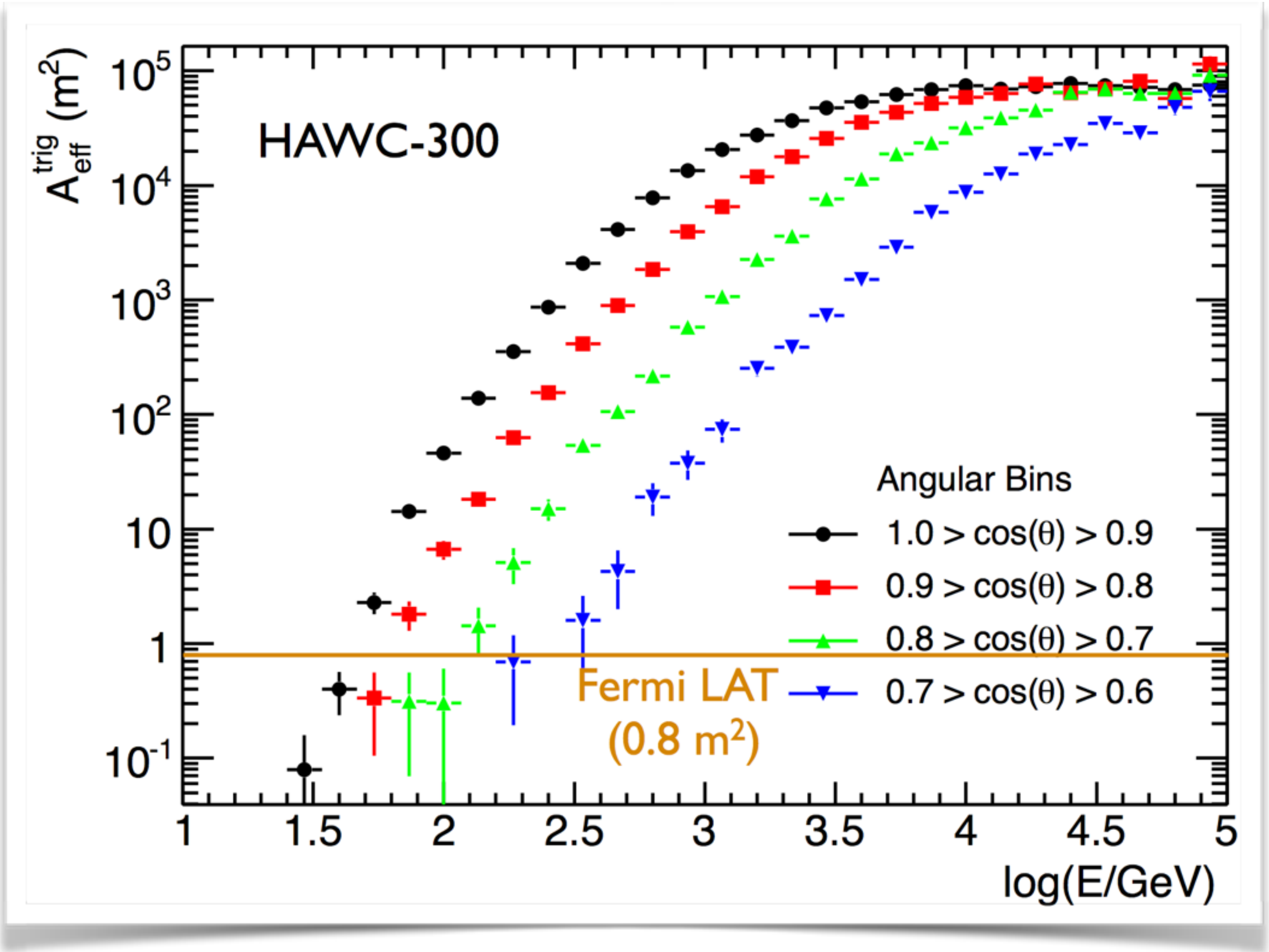


- **Overlap of HAWC field of view (magenta)**
- **Fermi Bubble contours (red)**
- **5 IceCube events (blue)**
- **Measured diffuse gamma-ray flux regions by Fermi-LAT (grey)**

Cecilia Lunardini, SR and Lili Yang, PRD92, 021301 (2015)

Detecting Fermi Bubbles with HAWC

HAWC effective area and averaged FB solid angle within FoV



D. Zaborov, HAWC Collaboration

Only a fraction of FB solid angle visible to HAWC in any given day (2-3 hours/day for North bubble)

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}

Event rate in HAWC

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

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

VHE Gamma and Neutrino Events

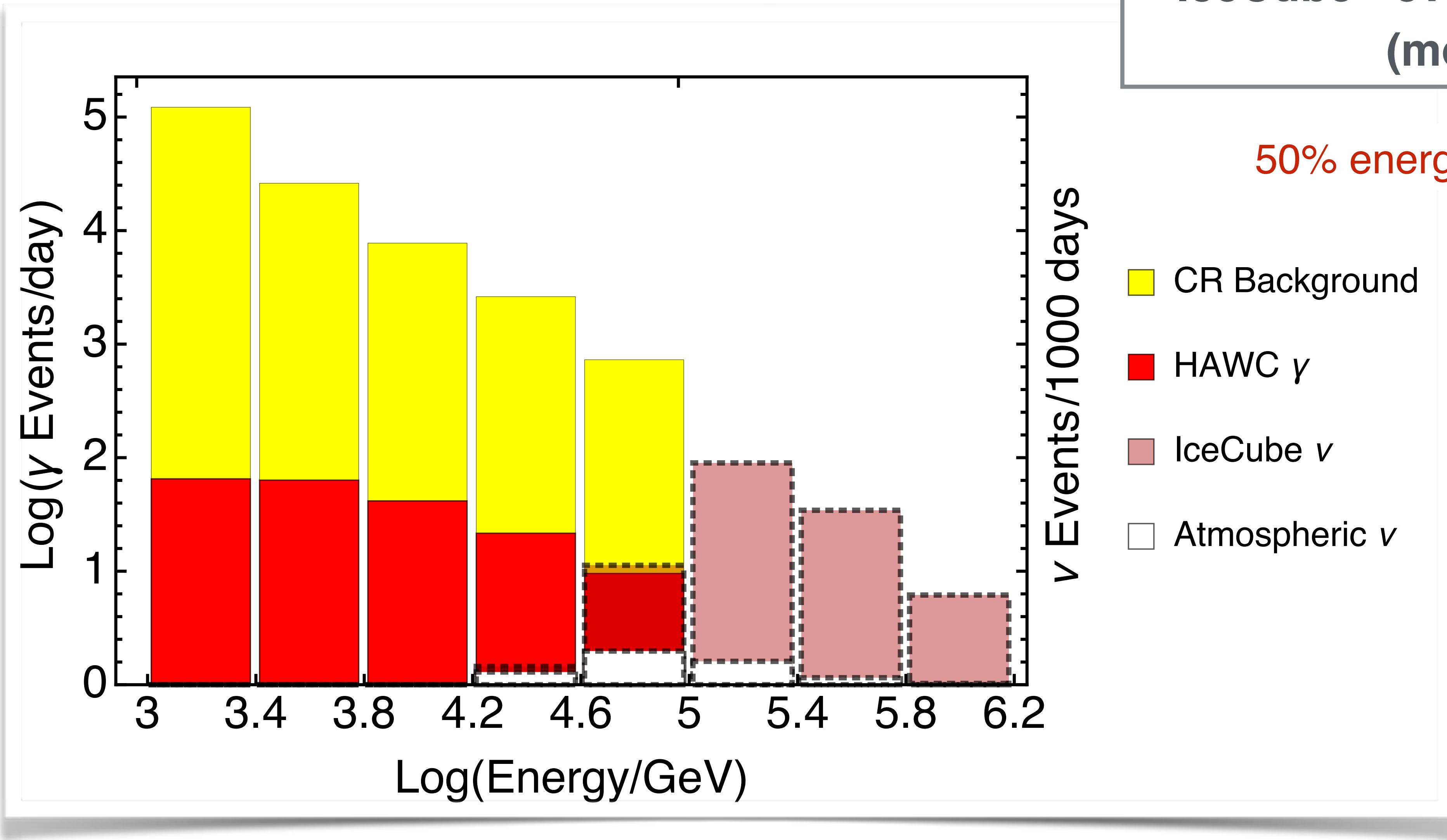
Multimessenger signal from Fermi Bubbles

Best-fit Cosmic-ray spectrum case

***k* = 2.25, E_0 = 30 PeV**

- **HAWC - events/day**
- **IceCube - events/1000 days (mostly cascades)**

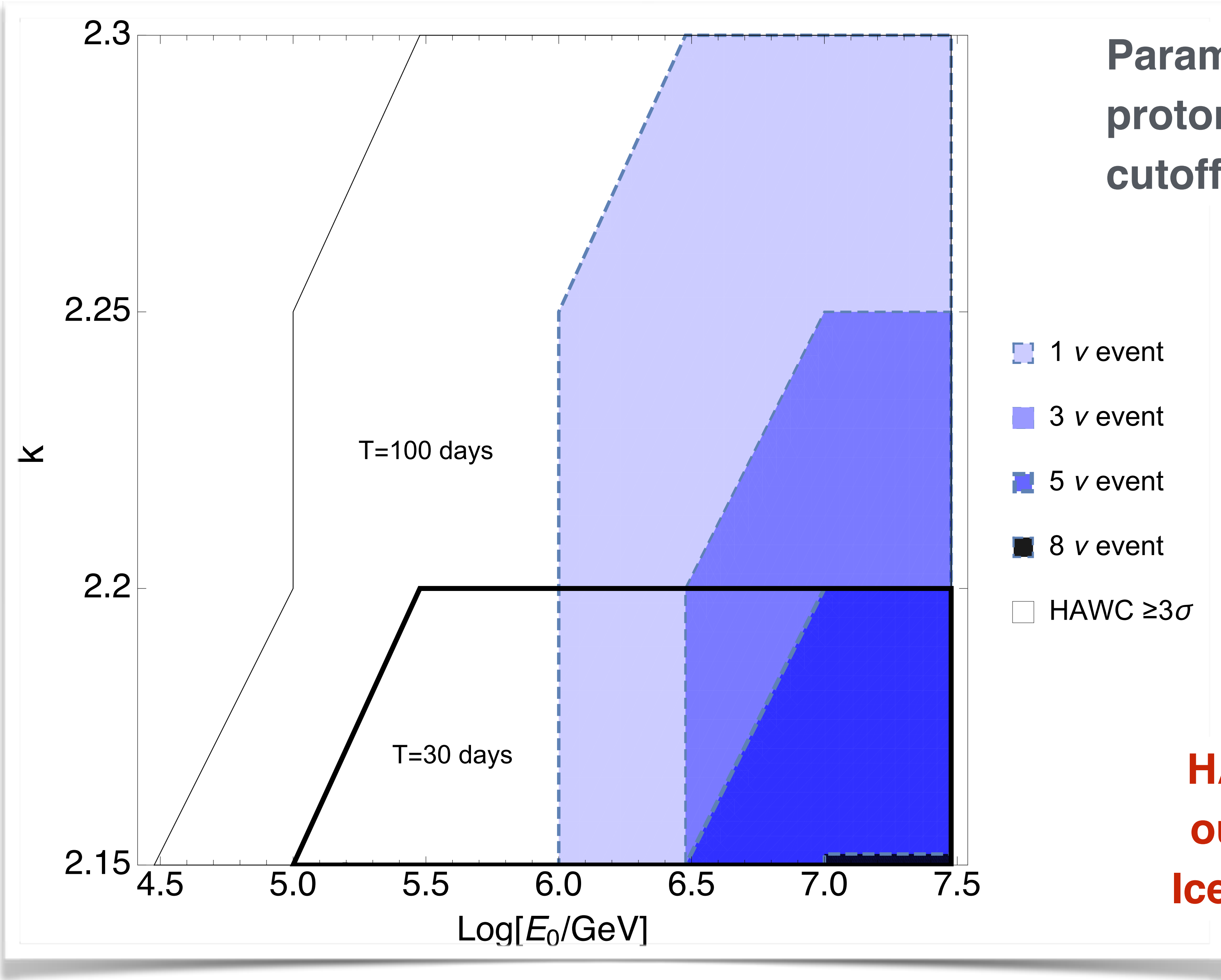
50% energy resolution for HAWC



Cecilia Lunardini, SR and Lili Yang, PRD92, 021301 (2015)

VHE Gamma and Neutrino Events

Constraints on hadronic model for Fermi Bubbles



Parameter space of injected proton spectral index (*k*) and cutoff energy (E_0)

$$dN_p/dE \propto E^{-k} e^{-E/E_0}$$

5 energy bins
4 angular bins

HAWC can confirm or rule out FB as source of some IceCube neutrinos in ~>1 yr

Cecilia Lunardini, SR and Lili Yang, PRD92, 021301 (2015)

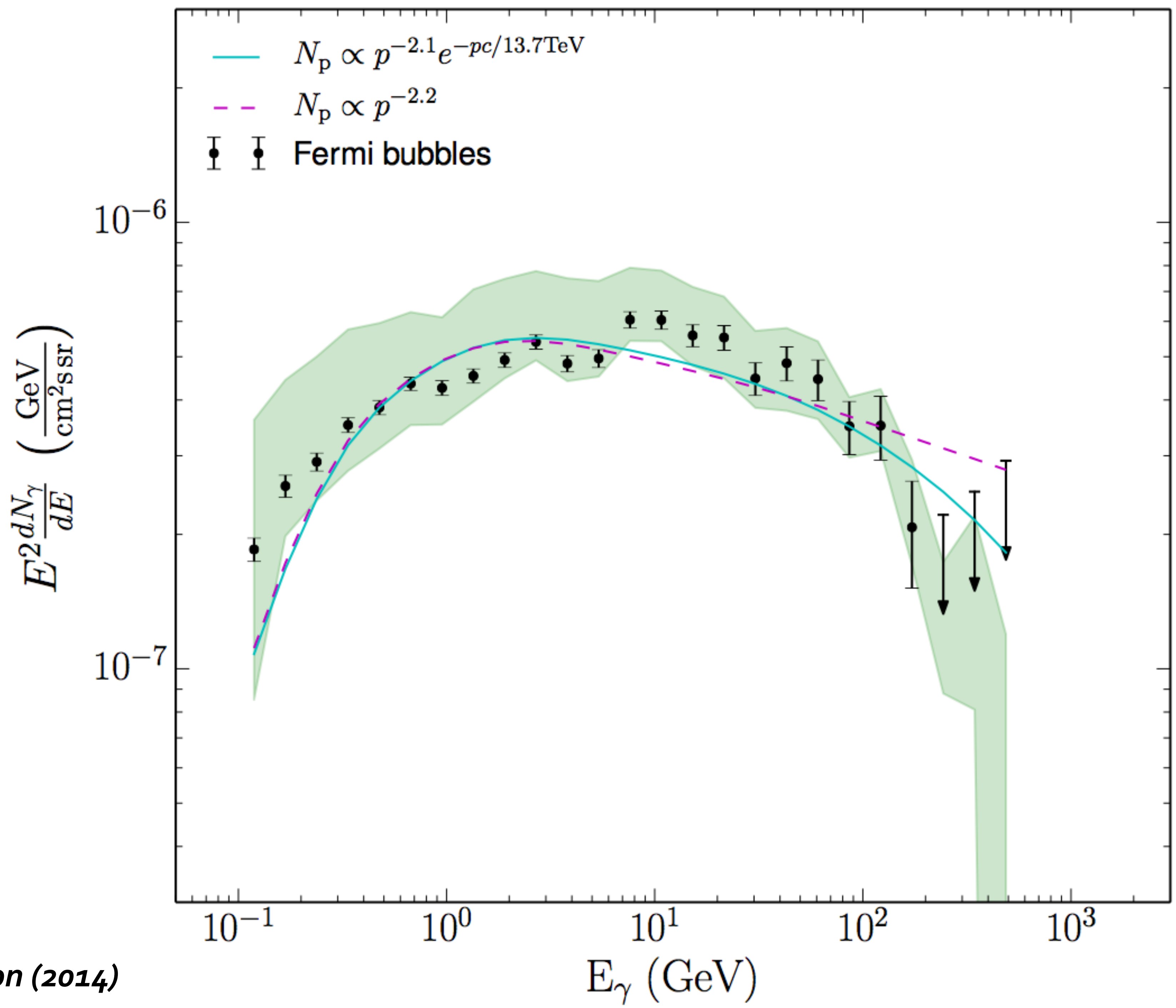
Summary

Fermi Bubbles at the Galactic Center could be the first multi messenger source - VHE gamma rays and Neutrinos

- 5-9 neutrino events are spatially correlated with FB
- Neutrinos follow gamma rays naturally in hadronic emission mechanism
- HAWC will be able to establish FB as VHE gamma and neutrino source or constrain the hadronic model of gamma-ray emission

Gamma Ray Fermi Bubble Spectra

Low-energy (< 200 GeV) Gamma-ray spectral models



Fermi-LAT Collaboration (2014)