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Astrophysical Sources of the IceCube Cosmic Neutrino Events

Soebur Razzaque

University of Johannesburg

with *Cecilia Lunardini and Lili Yang - arXiv:1504.07033*

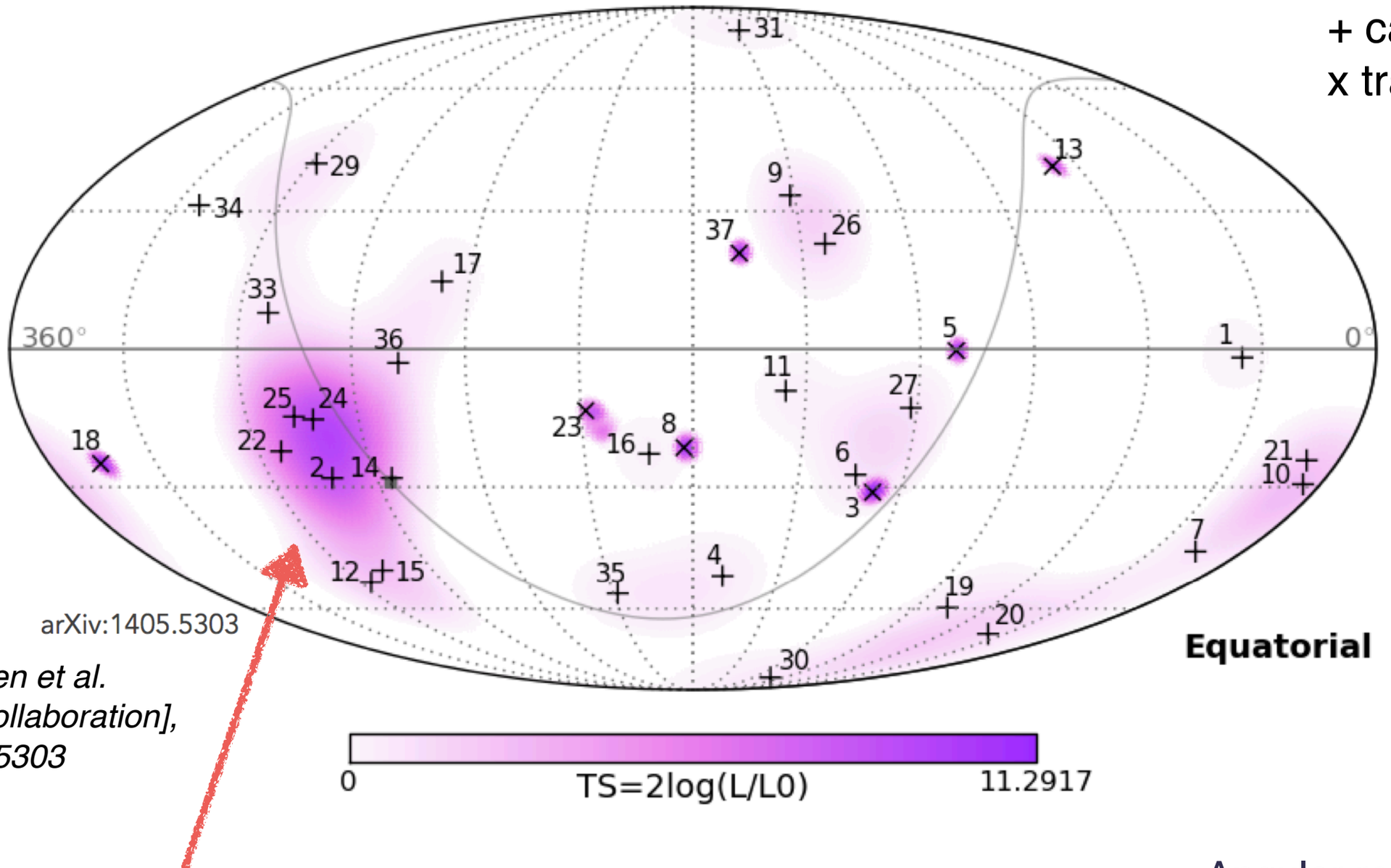
Reetanjali Moharana - arXiv:1501.05158

Outline of talk

- Plausible sources of IceCube cosmic neutrinos
  - Gamma-rays and UHECRs can provide clues
- Galactic source - Fermi Bubbles
- Extragalctic sources - UHECR sources?

IceCube Cosmic Neutrino Events (3 year)

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



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

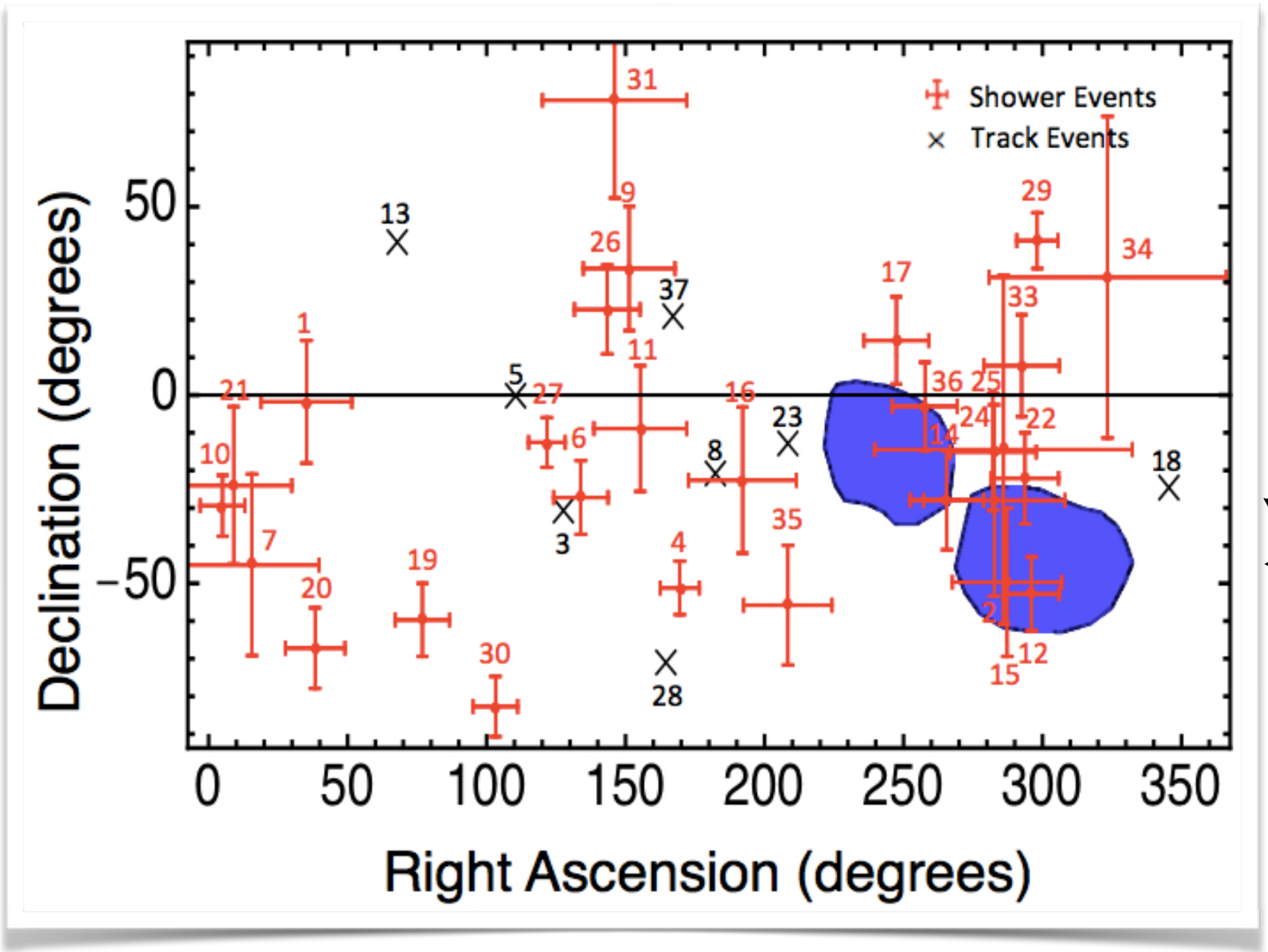
Hints (~8% chance) of clustering near the Galactic center

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

Cosmic Neutrinos and Fermi Bubbles

Lunardini, SR & Yang
- arXiv:1412.6240

IceCube 3 year data (37 events)

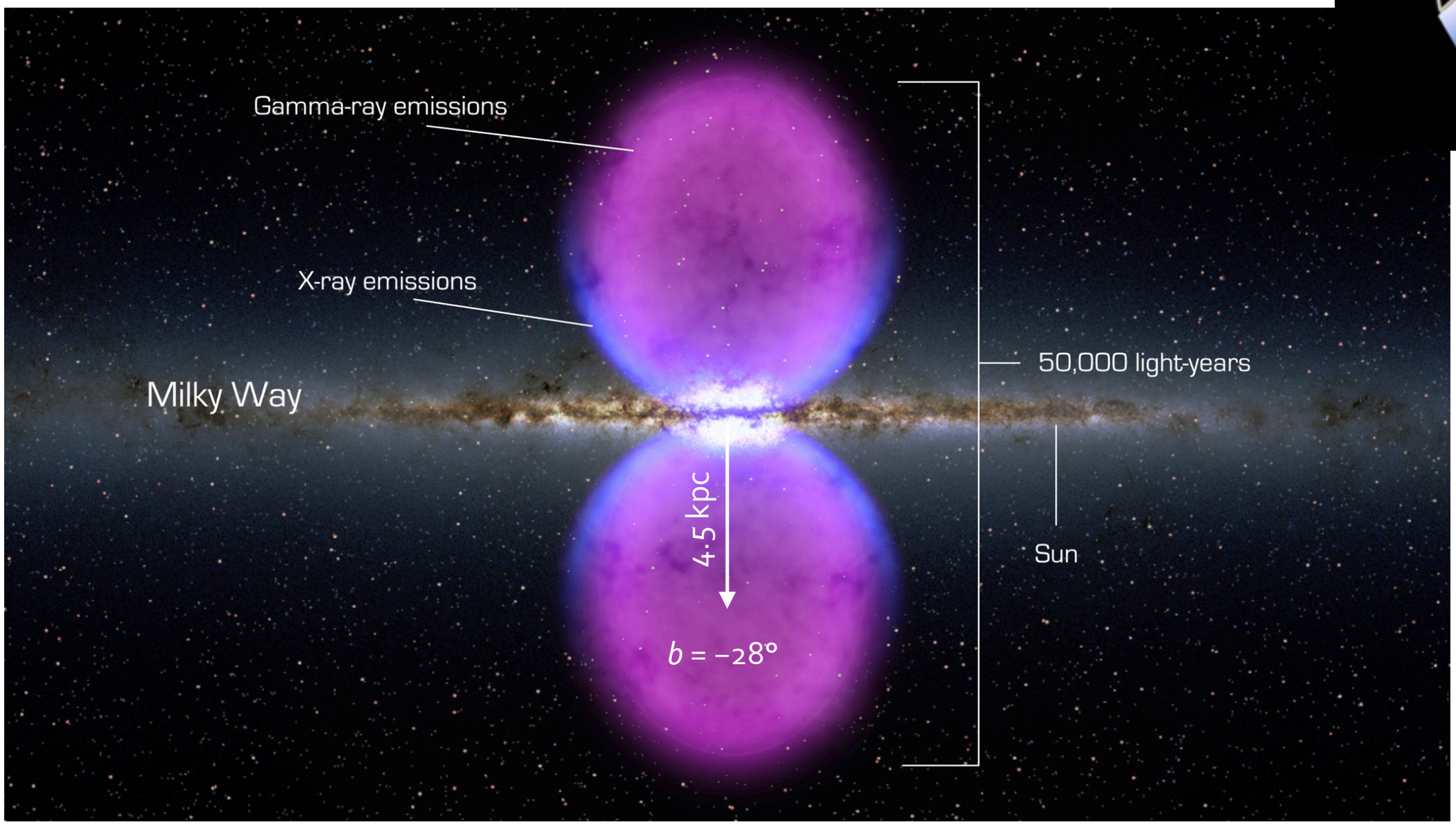


Fermi Bubble contours

- **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

Hard spectrum, uniform projected intensity, well-defined boundary

VHE Gamma and Neutrino Fluxes from FB

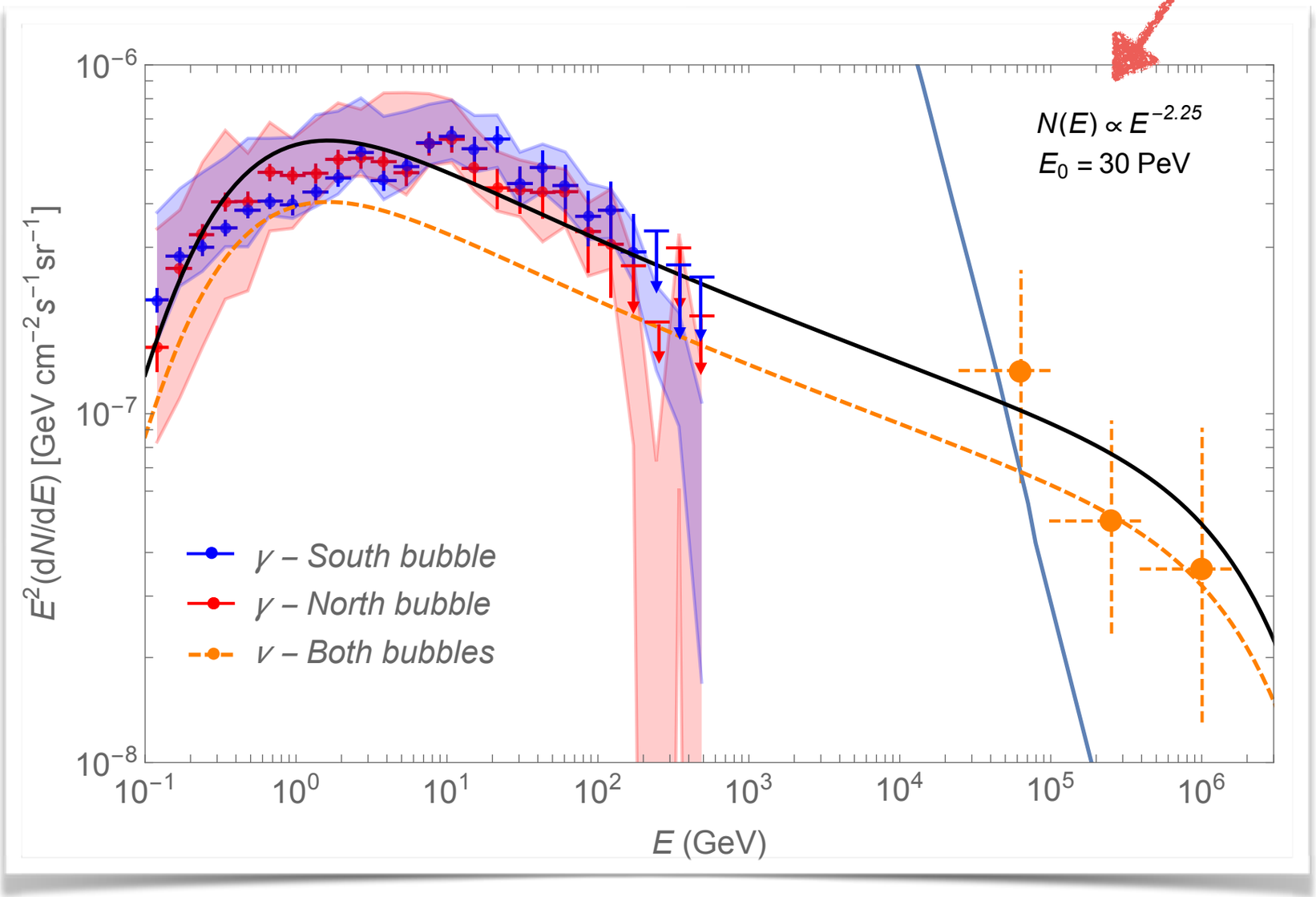
5-year Fermi-LAT data | ***pp*-interaction - Injected proton spectrum** | **Best-fit model**

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

$$dN_p/dE \propto E^{-k} e^{-E/E_0} \qquad \chi^2/dof \approx 13/40$$

gamma-ray data with upper limits

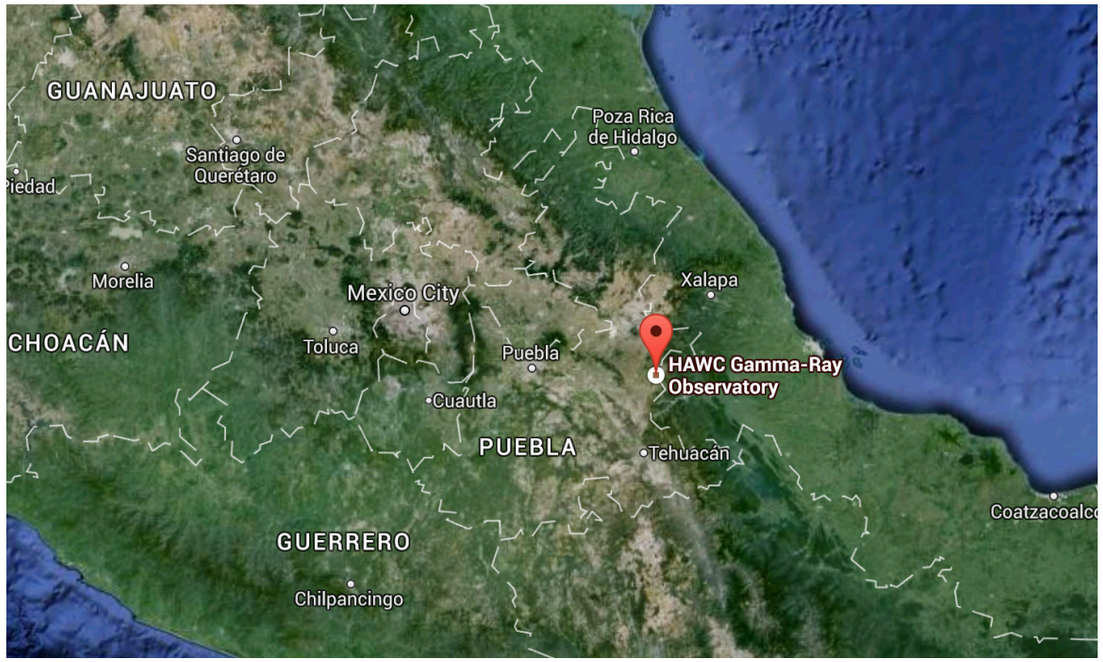
statistical + systematic errors



Require *pp* model to produce 5 neutrino events

VHE Gamma Rays from Fermi Bubbles

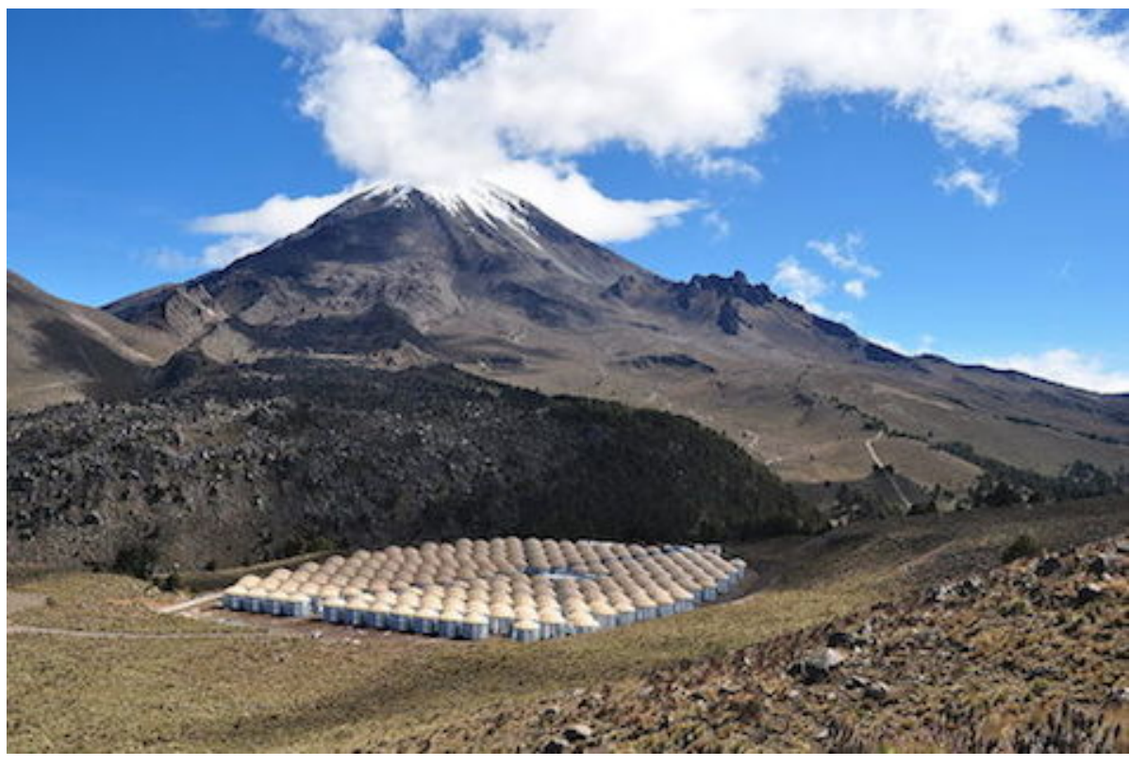
4100 m altitude near Sierra Negra Volcano, Puebla, Mexico



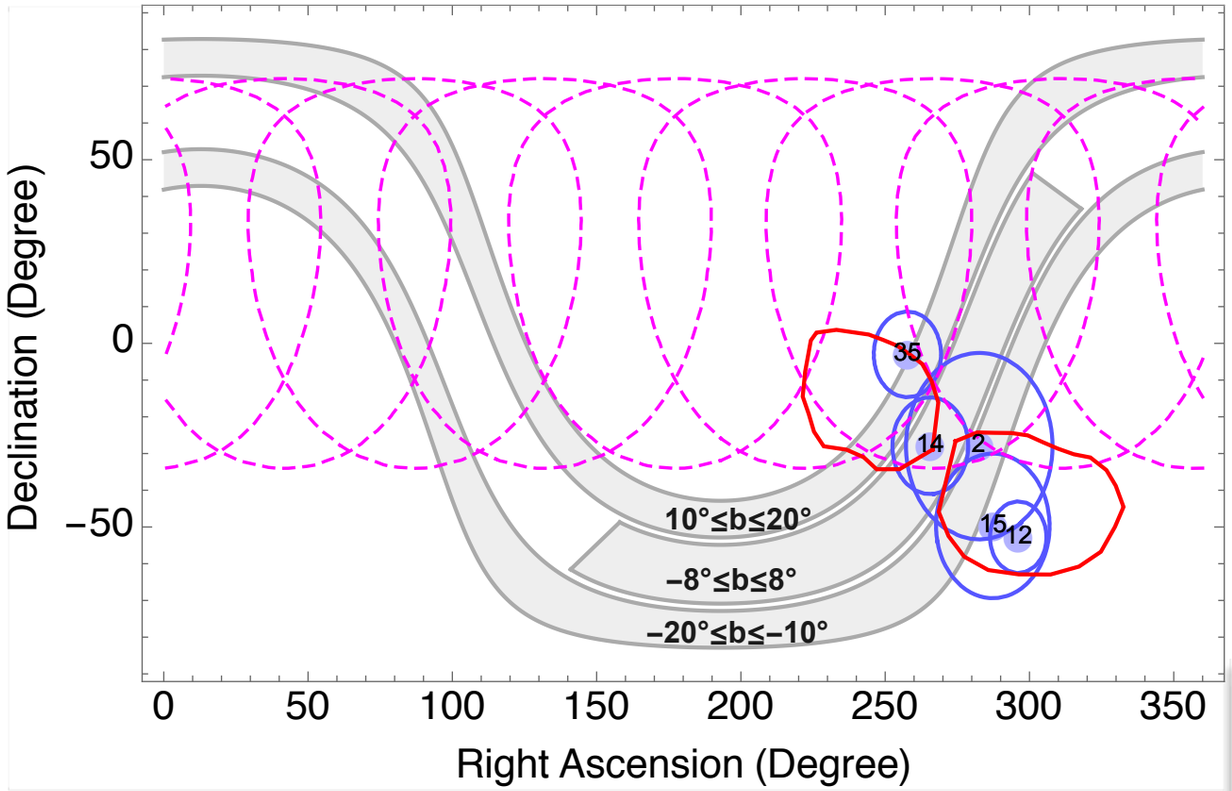
- 0.1 - 100 TeV
- 2pi sr Field of View
- 0.1 degree @ > 5 TeV

4 meters high
7.3 meters in diameter

300 tanks in total,
with 4 PMTs per tank



Detecting Fermi Bubbles with HAWC

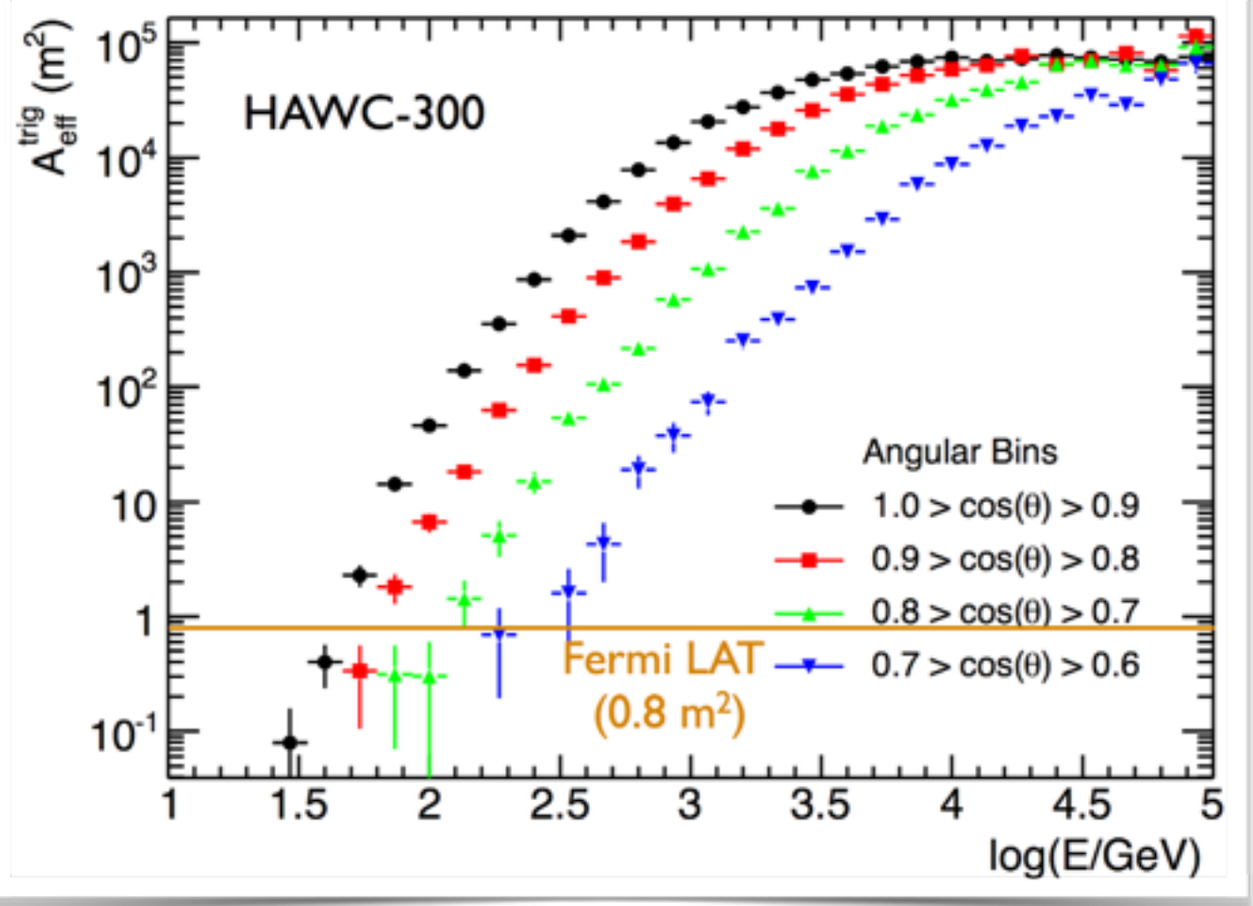


- Overlap of HAWC field of view (magenta)
- Fermi Bubble contours (red)
- 5 IceCube events (blue)
- Measured diffuse gamma-ray flux regions by Fermi-LAT (grey)

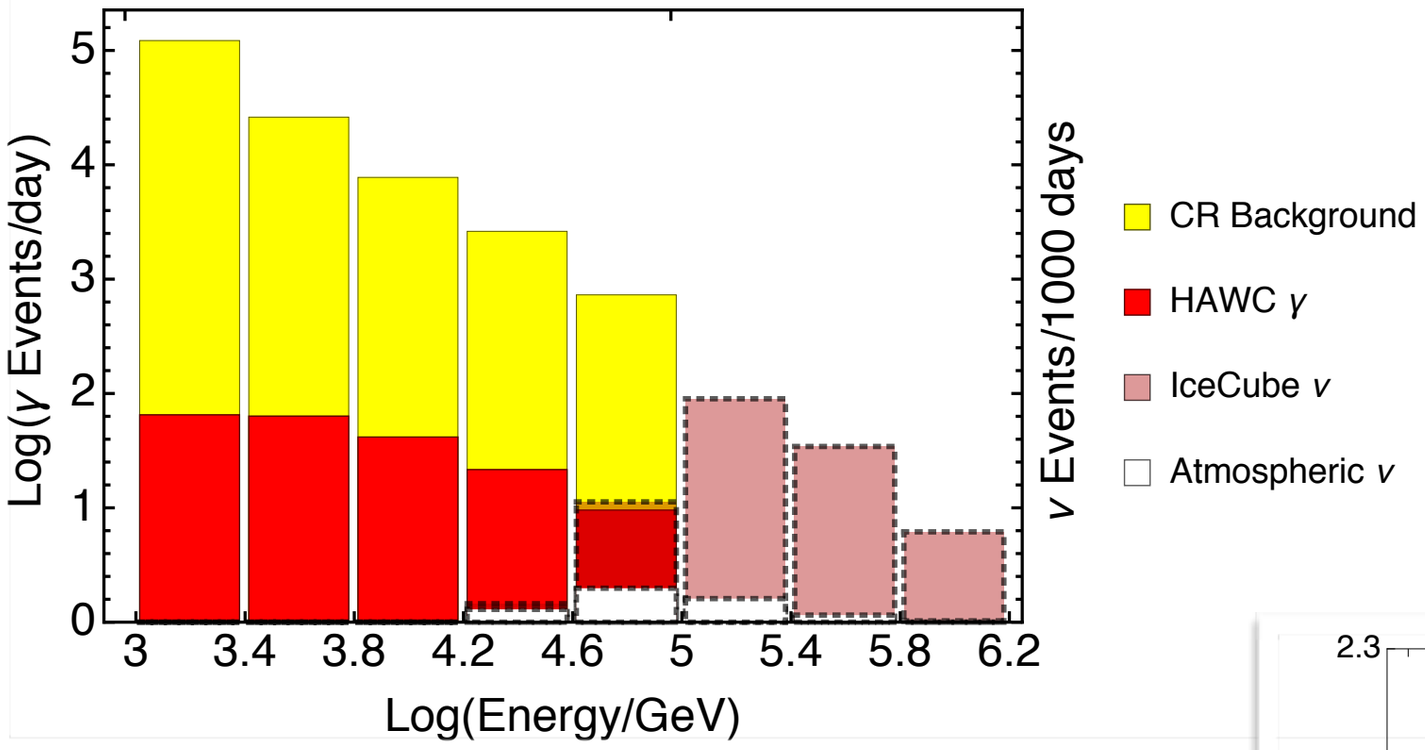
D. Zaborov for HAWC Collaboration

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}



VHE Gamma and Neutrino Events



Best-fit case

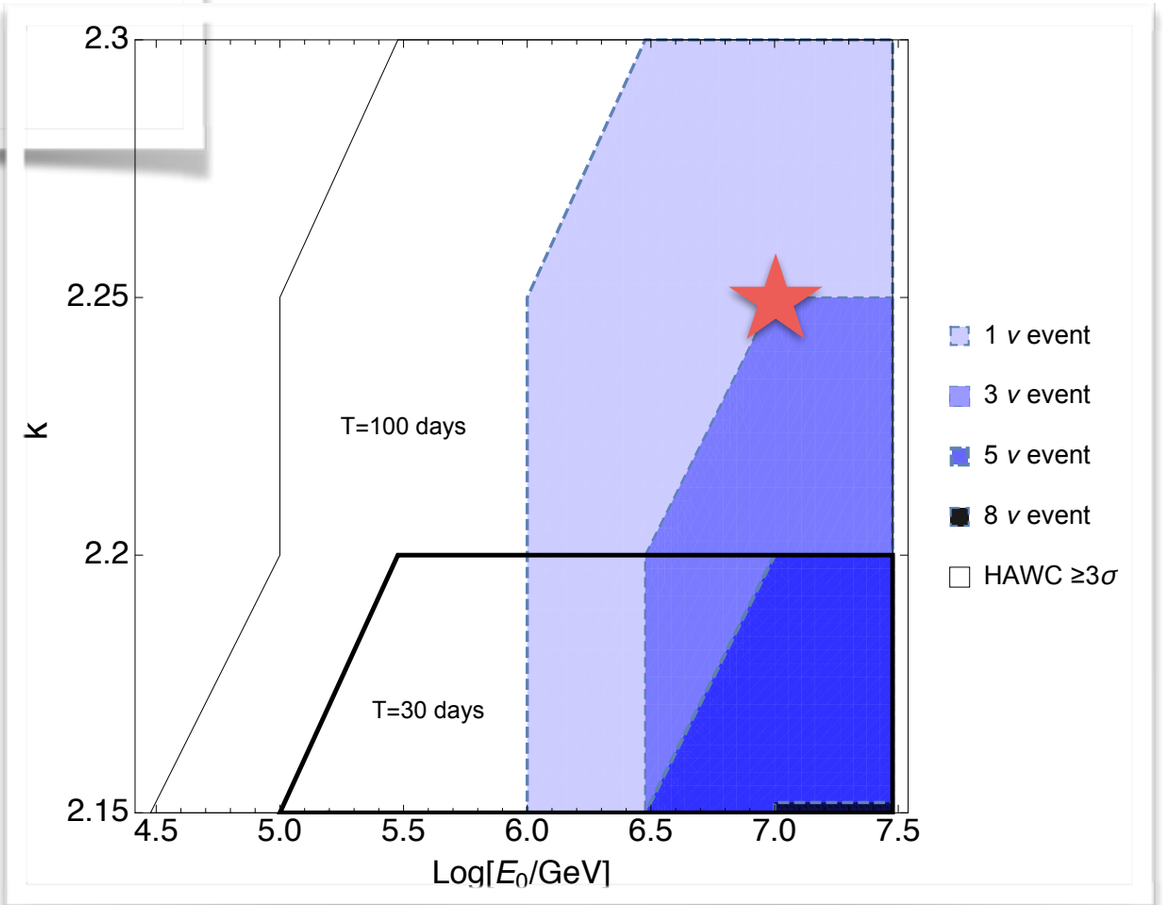
k = 2.25, E_0 = 30 PeV

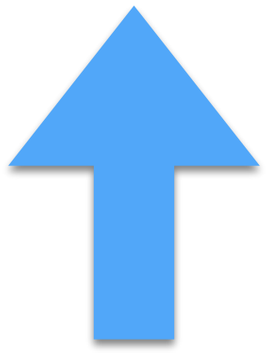
- **HAWC - events/day**
- **IceCube - events/1000 days (mostly cascades)**

50% energy resolution for HAWC

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

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





Galactic Sources

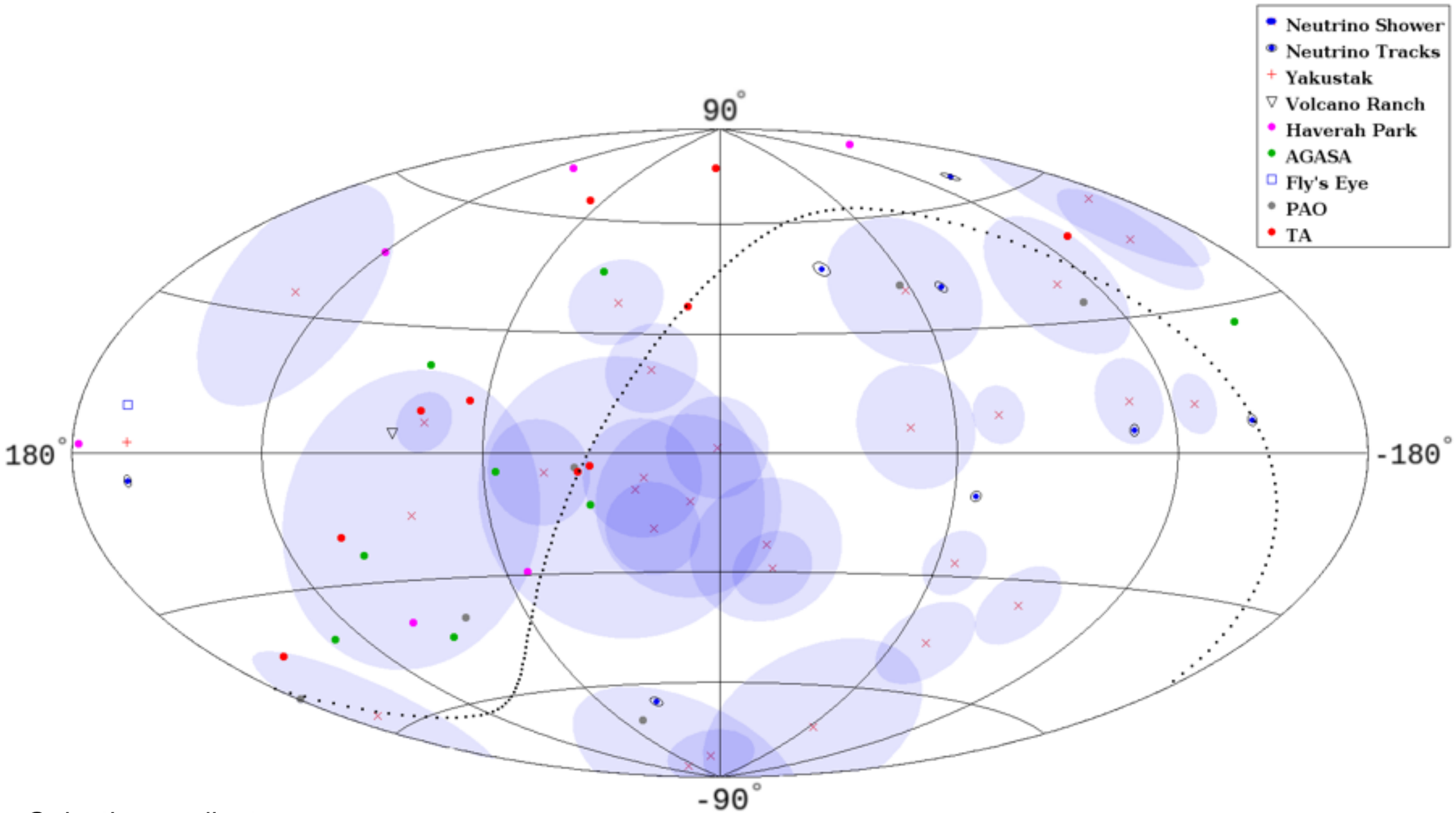
Extragalactic Sources

Adopt a strategy …

- **Sources of ultrahigh-energy (≥ 80 EeV) cosmic rays are nearby**
  - Within a ‘GZK radius’ of ~240 Mpc (z~0.06)
- **UHECRs deflect by an angle of the order of 1° in the Galactic and intergalactic magnetic field (assuming protons)**
  - Can potentially point to their sources
  - Much better pointing resolution than the cascade ν events (~15°)
- **Sources of UHECRs most likely accelerate particles over a wide energy range (Fermi acceleration mechanism)**
  - Can potentially produce < 2 PeV neutrinos detected by IceCube

>100 EeV Cosmic Rays and Neutrinos

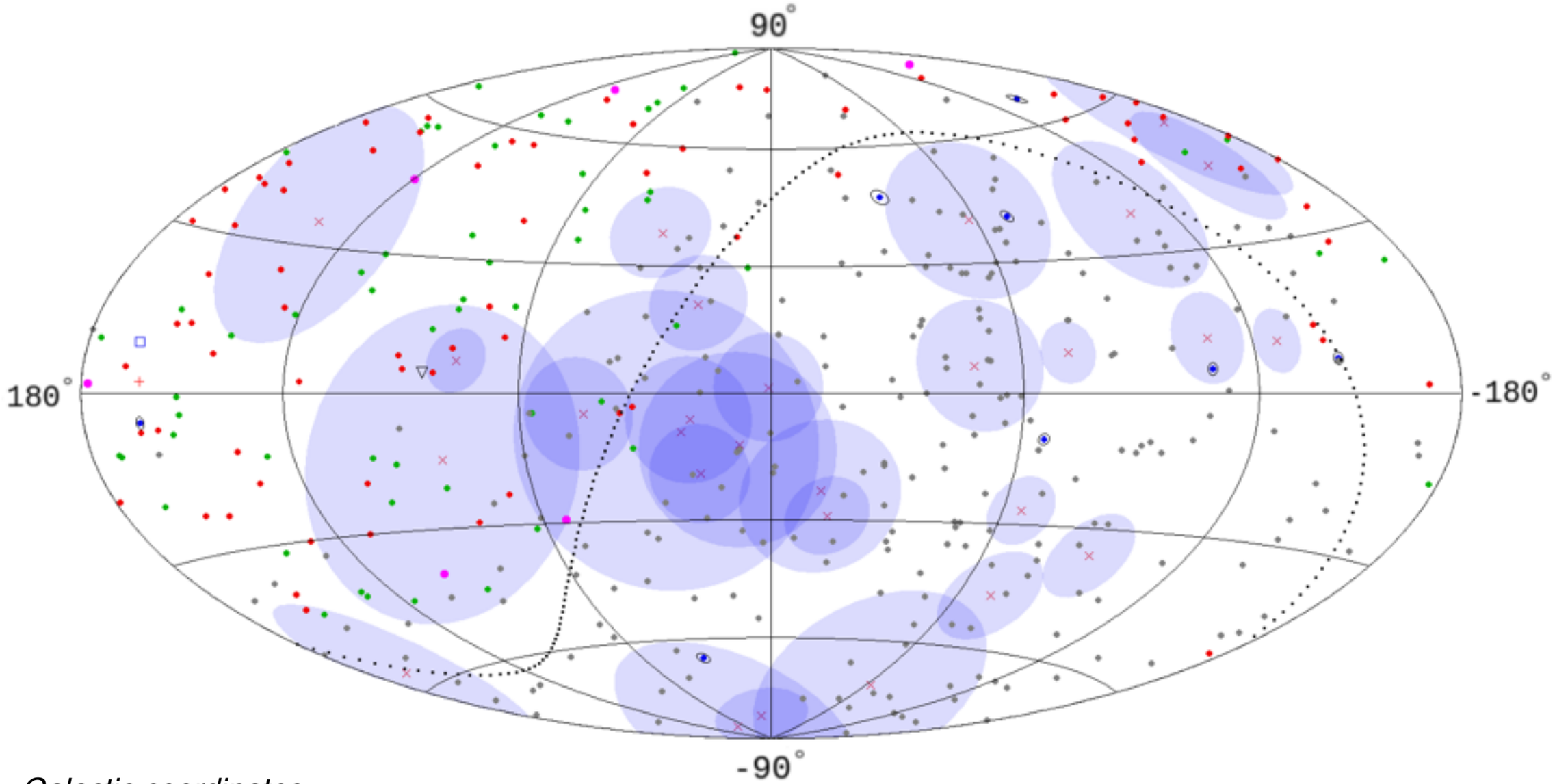
33 UHECR and 35 Neutrino events



Galactic coordinates

>80 EeV Cosmic Rays and Neutrinos

60 UHECR and 35 Neutrino events



Galactic coordinates

Invariant Statistics

Virmani, SR, et al. 2002

Unit vectors in the sky: $\hat{x} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)^T$

Angular separation between vectors: $\gamma = \cos^{-1}(\hat{x}_{\rm neutrino} \cdot \hat{x}_{\rm UHECR})$

Statistic: $\delta\chi_i^2 = \min_j(\gamma_{ij}^2/\delta\gamma_i^2)$ $\quad i \equiv \text{neutrino} \;\; ; \;\; j \equiv \text{UHECR}$

Angular error of i-th neutrino event

$\delta\chi_i^2 \leq 1$ Good-fit (forms a basis of correlation)

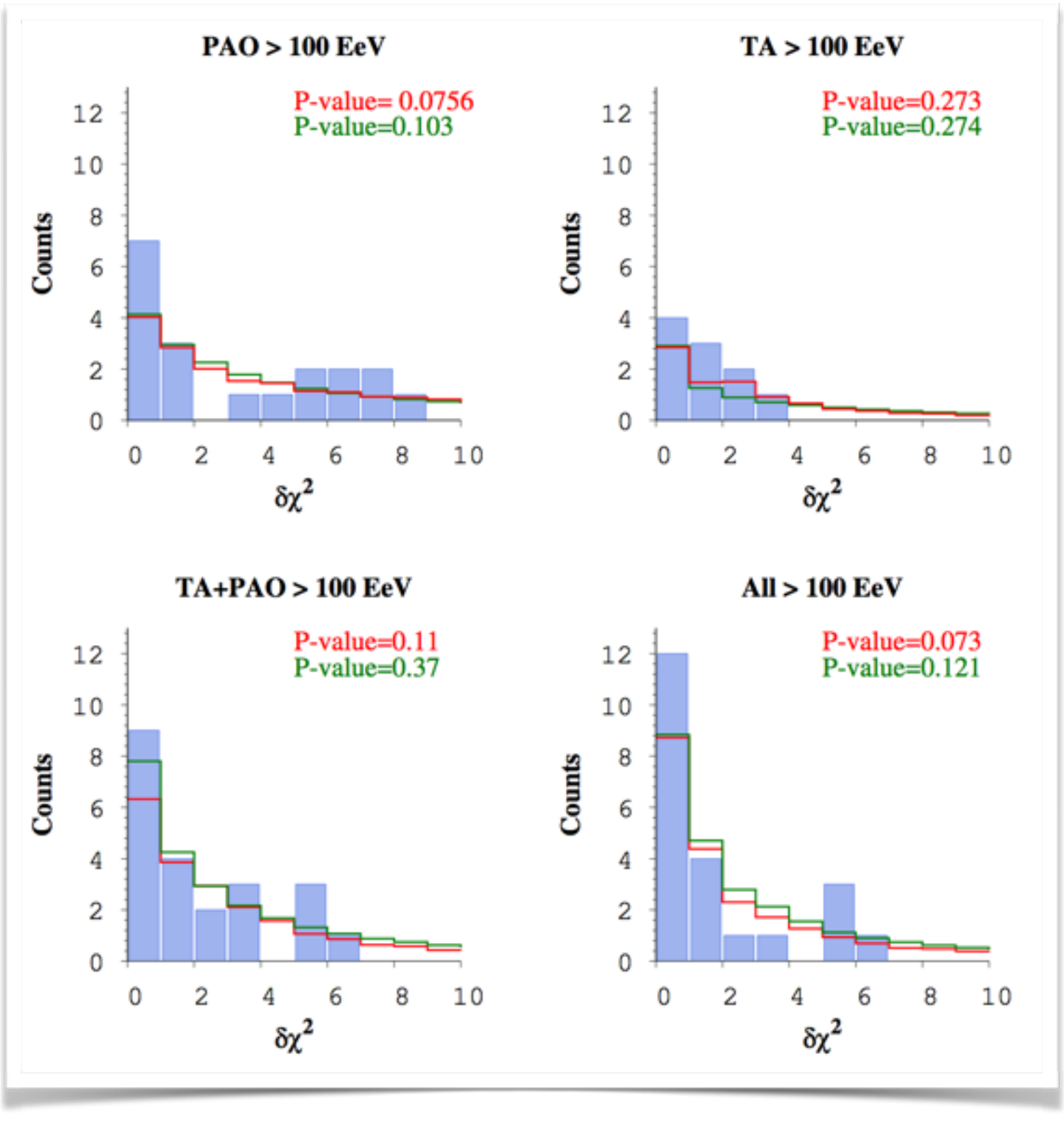
Null distribution:

- Randomly vary UHECR directions and evaluate $\delta\chi_i^2$ distribution
- Keeping detector-specific declination-dependence
- 100,000 randomly generated data sets

***p* - value:**

- Number of times Nhits within $\delta\chi_i^2 \leq 1$ in simulated data sets/100,000

Cross-correlation Results, >100 EeV

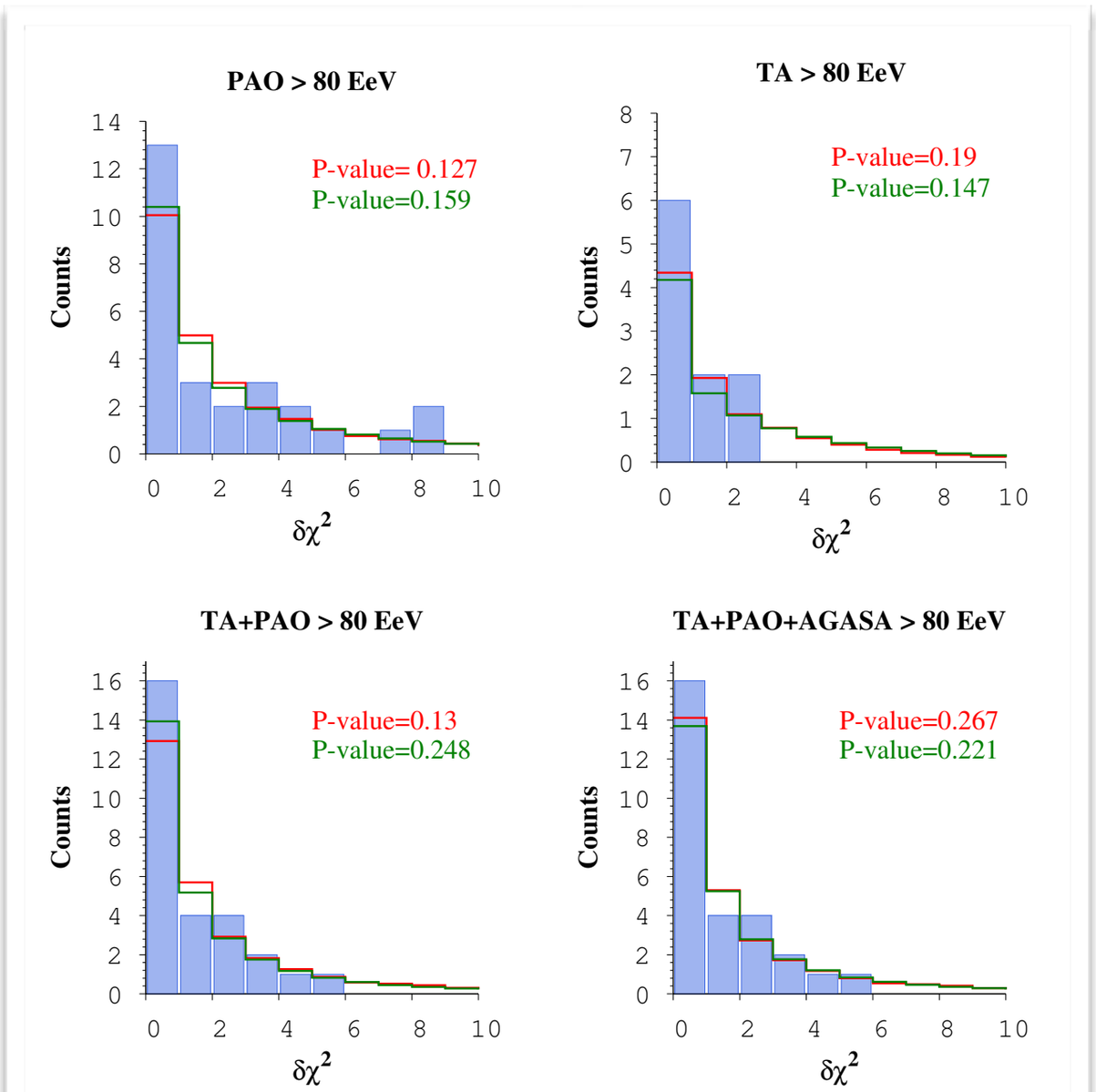


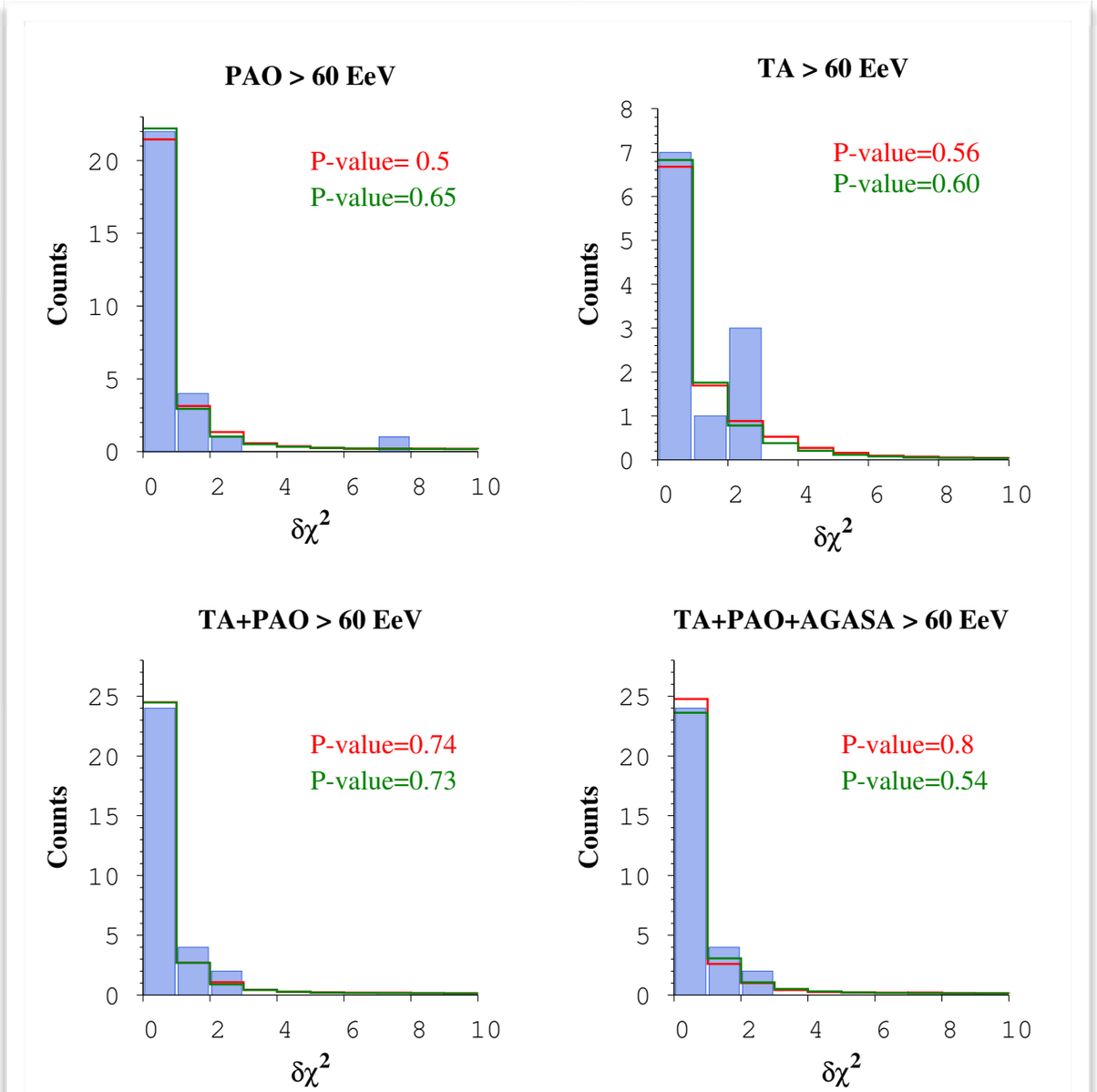
- **Small hint of correlation between UHECRs and cosmic neutrino data**
- **~90% chance probability**
- **Dominated by PAO data**

- Two null distributions:
- *Semi-isotropic null (red)*
- *Exposure-corrected null (green)*

Cross-correlation Results, >80 EeV, >60 EeV

Significance (p-value) decreases with decrease of energy threshold





Source search around UHECR directions

Neutrino Event #	UHECR			*Swift* X-ray Source Catalog [24]		
	RA	Dec	Experiment	Name	z	Type
1	45.6	−1.7	PAO	NGC 1142	0.0289	Sy2
				NGC 1194	0.0136	Sy1
				MCG +00-09-042	0.0238	Sy2
				NGC 1068	0.0038	Sy2
11	150.1	−10.3	PAO	2MASX J10084862-0954510	0.0573	Sy1.8
17	241.5	23	AGASA	2MASX J16311554+2352577	0.0590	Sy2
29, 34	295.6	43.52	TA	2MASX J19471938+4449425	0.0539	Sy2
				ABELL 2319	0.0557	GC
				Cygnus A	0.0561	Sy2
21	352.6	−20.2	PAO	PKS 2331-240	0.0477	Sy2
2, 24, 25	294.5	−5.8	AGASA	2MASX J19373299-0613046	0.0103	Sy1.5
34	340.6	12	PAO	MCG +01-57-016	0.0250	Sy1.8
				MCG +02-57-002	0.0290	Sy1.5
				UGC 12237	0.0283	Sy2
	349.0	12.3	AGASA	NGC 7479	0.0079	Sy2/Liner
				2MASX J23272195+1524375	0.0457	Sy1
				NGC 7469	0.0163	Sy1.2
	352.6	−20.2	Haverah Park	NGC 7679	0.0171	Sy2

Neutrino Event #	UHECR			Kühr Radio Source Catalog [25]		
	RA	Dec	Experiment	Name	z	Type
1	45.6	−1.7	PAO	NGC 1068	0.0038	Sy2
21	352.6	−20.8	PAO	PKS 2331-240	0.0477	Sy2
34	340.6	12	PAO	NGC 7385	0.0255	GC

Table 4. Sources correlated with UHECRs and neutrino events simultaneously.

- UHECRs (>100 EeV) must be correlated with one or more ν events
- Search within a 3° error circle around UHECR directions
- Search within z=0.06
- Use X-ray, gamma-ray, radio source catalogues

- UHECRs, >100 EeV, in correlation with neutrinos point to sources in *Swift* BAT X-ray catalog
- Sources are dominantly weak AGNs (Syfert galaxies)

Summary

- **Huge gamma-ray Fermi bubbles at the Galactic center**
  - **5-9 neutrino events are spatially correlated with FB**
  - **Neutrinos follow gamma rays naturally in hadronic mechanism**
  - **HAWC will be able to establish FB as neutrino source or constrain the hadronic model of gamma-ray emission**

- **Extragalactic neutrino sources**
  - **Some hints (90% CL) of correlation with UHECRs, >100 EeV**
    - **UHECRs in turn point to X-ray bright sources in Swift-BAT catalog**
    - **Dominantly Seyfert galaxies (AGN)**
    - **More data will be needed …**

Backup Slides

FB from Galactic Center Starburst Activity

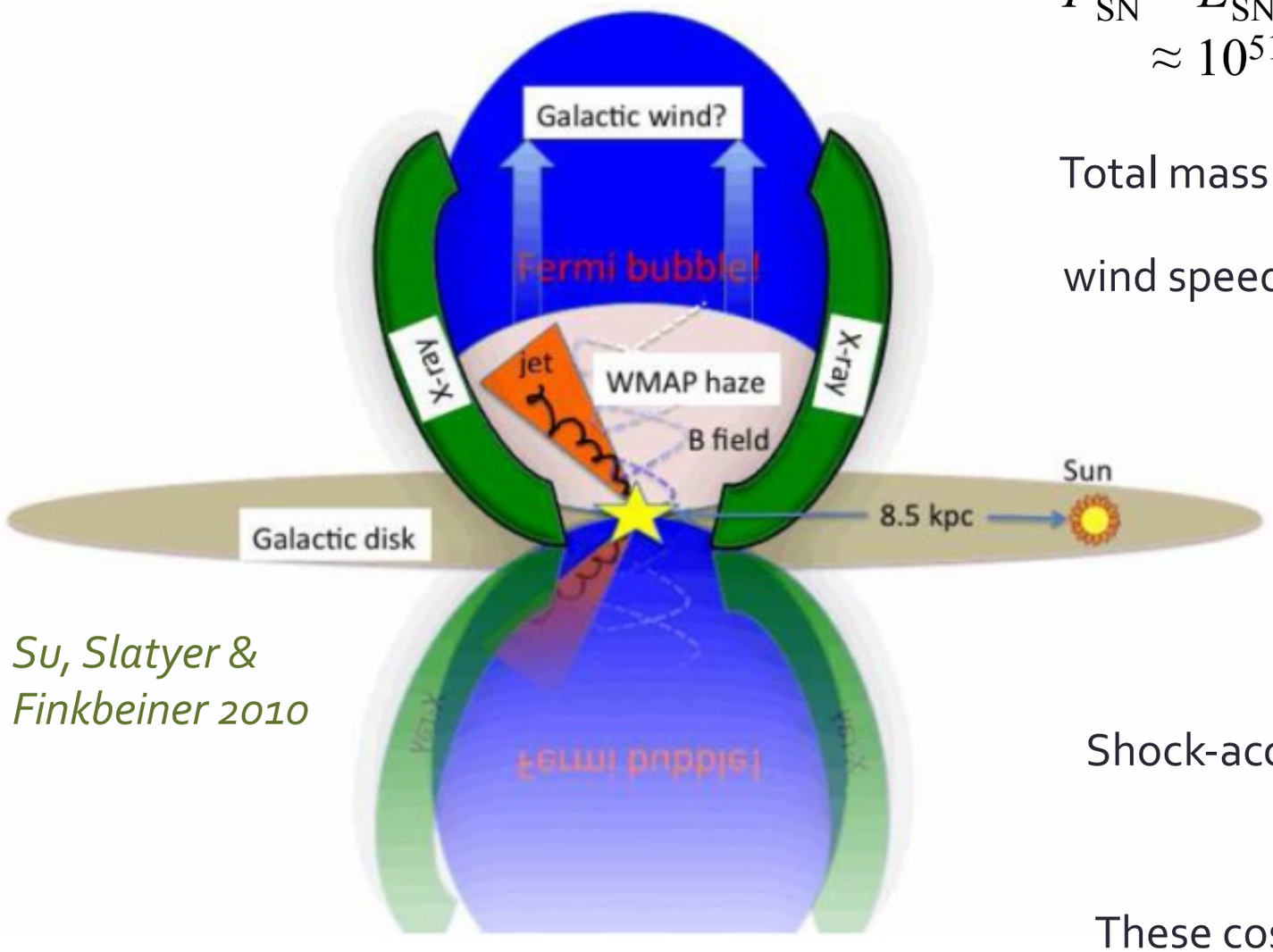
Total energy output rate (power) from SNe around the Galactic Center

From infrared luminosity

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

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

wind speed: $v_{\rm w} \approx (2P_{\rm SN}/M_{\rm w})^{1/2} \sim 1200\ {\rm km/s}$



Su, Slatyer & Finkbeiner 2010

Bubble formation time scale

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

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

Shock-accelerated cosmic-ray power in wind

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

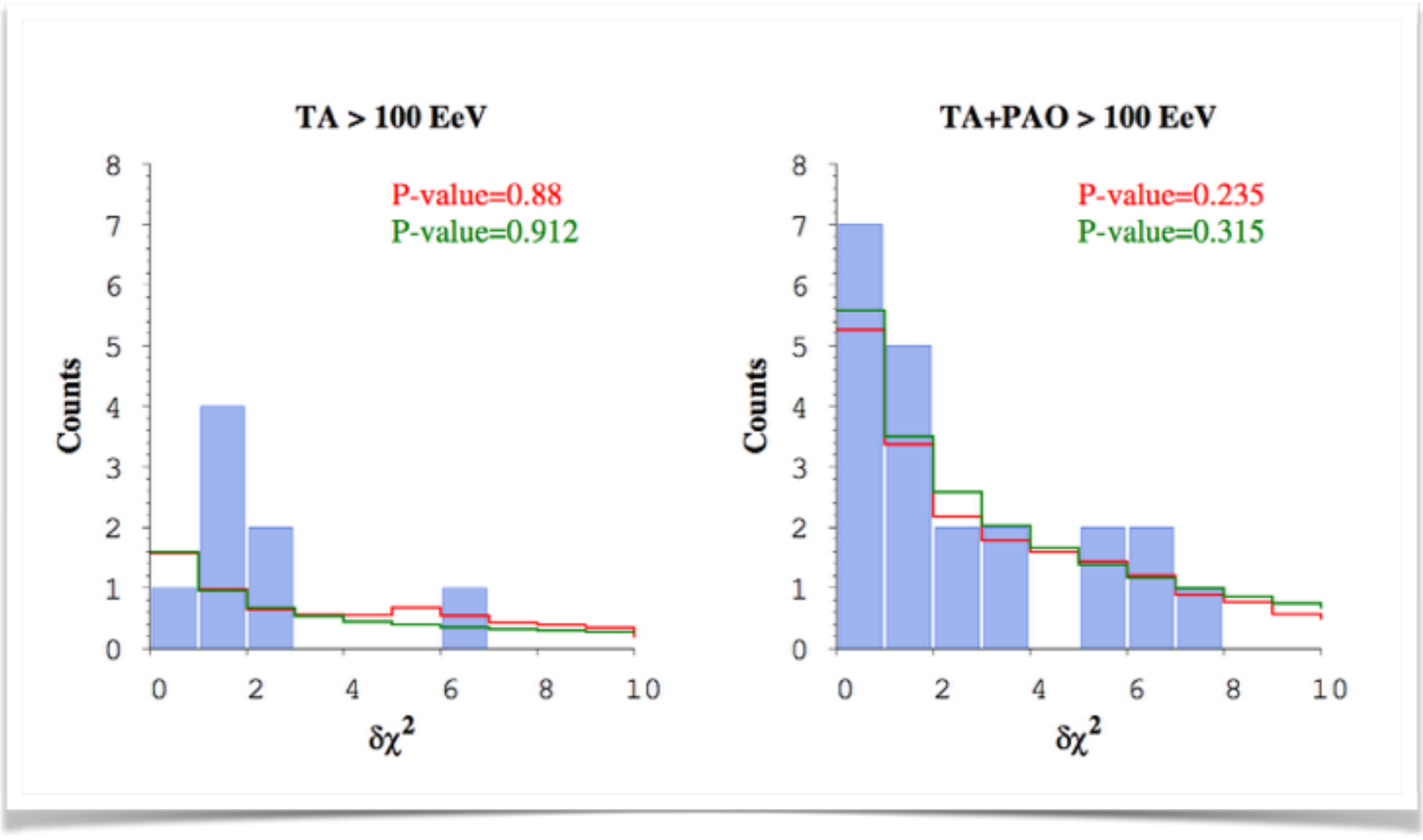
These cosmic-rays interact with bubble gas to produce π^0 decay γ's on a time scale

Hadronic model by *Crocker & Aharonian 2011* ➔ $t_{\rm pp} \approx (n_{\rm gas}\sigma_{\rm pp}\kappa_{\rm pp}{\rm c})^{-1} \sim 5\times10^{9}\ {\rm yr}$

Results with energy rescaling, >100 EeV

- Energy of TA events are rescaled down by 25%
- 10 TA events ==> 4 TA events
- No significant correlation for TA or TA+PAO data

A. Aab et al. [TA and PAO Collaborations] 2014



X-ray, Neutrino and UHECR Luminosities

Source name	L_X (10^{44} erg/s) /L_R (10^{41} erg/s)	L_ν (10^{44} erg/s) $\kappa = 2.1$	$= 2.3$	$L_{\rm cr}$ (10^{44} erg/s) $\kappa = 2.1$	$= 2.3$
NGC 1142	1.58/0.012(74 GHz)	0.95	1.0	0.7	5.4
NGC 1194	0.12/0.00012(1.4 GHz)	0.2	0.2	0.04	0.2
MCG +00-09-042	0.17/0.0043(1.4 GHz)	0.64	0.71	0.3	2.1
NGC 1068	0.031/0.0034(31.4 GHz)	0.016	0.017	0.001	0.007
2MASX J10084862-0954510	1.04/0.0028(1.4 GHz)	3.9	4.32	44	578
2MASX J16311554+2352577	0.79/0.0048(1.4 GHz)	4.1	4.6	1600	22000
2MASX J19471938+4449425	1.66/0.0045(1.4 GHz)	6.8	7.6	211	26000
ABELL 2319	1.78/0.0046(1.4 GHz)	3.7	4.1	270	3500
Cygnus A	11.2/314(14.7 GHz)	3.7	4.1	290	3700
PKS 2331-240	0.81/1.32(31.4 GHz)	2.6	2.9	9.5	102
2MASX J19373299-0613046	0.055/0.0012(1.4 GHz)	0.24	0.26	1.3	7.3
MCG +01-57-016	0.23/0.0026(1.4 GHz)	0.71	0.78	0.5	3.6
MCG +02-57-002	0.25/0.00084(1.4 GHz)	0.95	1.1	1.0	7.5
UGC 12237	0.23/0.0011(1.4 GHz)	0.91	1.	0.9	6.6
NGC 7479	0.029/0.04(22 GHz)	0.07	0.08	0.3	1.4
2MASX J23272195+1524375	0.51/0.24(1.4 GHz)	2.4	2.7	280	2900
NGC 7469	0.4/0.0056(365 MHz)	0.3	0.3	2.2	14
NGC 7679	0.1/0.00033(1.4 GHz)	-	-	-	-
NGC 1068	0.031/0.0034(31.4 GHz)	0.016	0.017	0.001	0.007
PKS 2331-240	0.81/1.32(31.4 GHz)	2.6	2.9	9.5	102
NGC 7385	- /0.17(31.4 GHz)	0.7	0.8	0.5	4.0

Table 5. Neutrino (25 TeV–2.2 PeV) and cosmic-ray (500 TeV–180 EeV) luminosities required for the correlated sources in Table 4 to produce observed data. Also listed are *Swift*-BAT X-ray luminosity [24] radio luminosity for these sources, with corresponding radio frequencies in parentheses.