Workshop on Perspectives on the Extragalactic Frontier: from Astrophysics to Fundamental Physics
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Angular Correlation Studies with neutrinos, UHECRs and Sources

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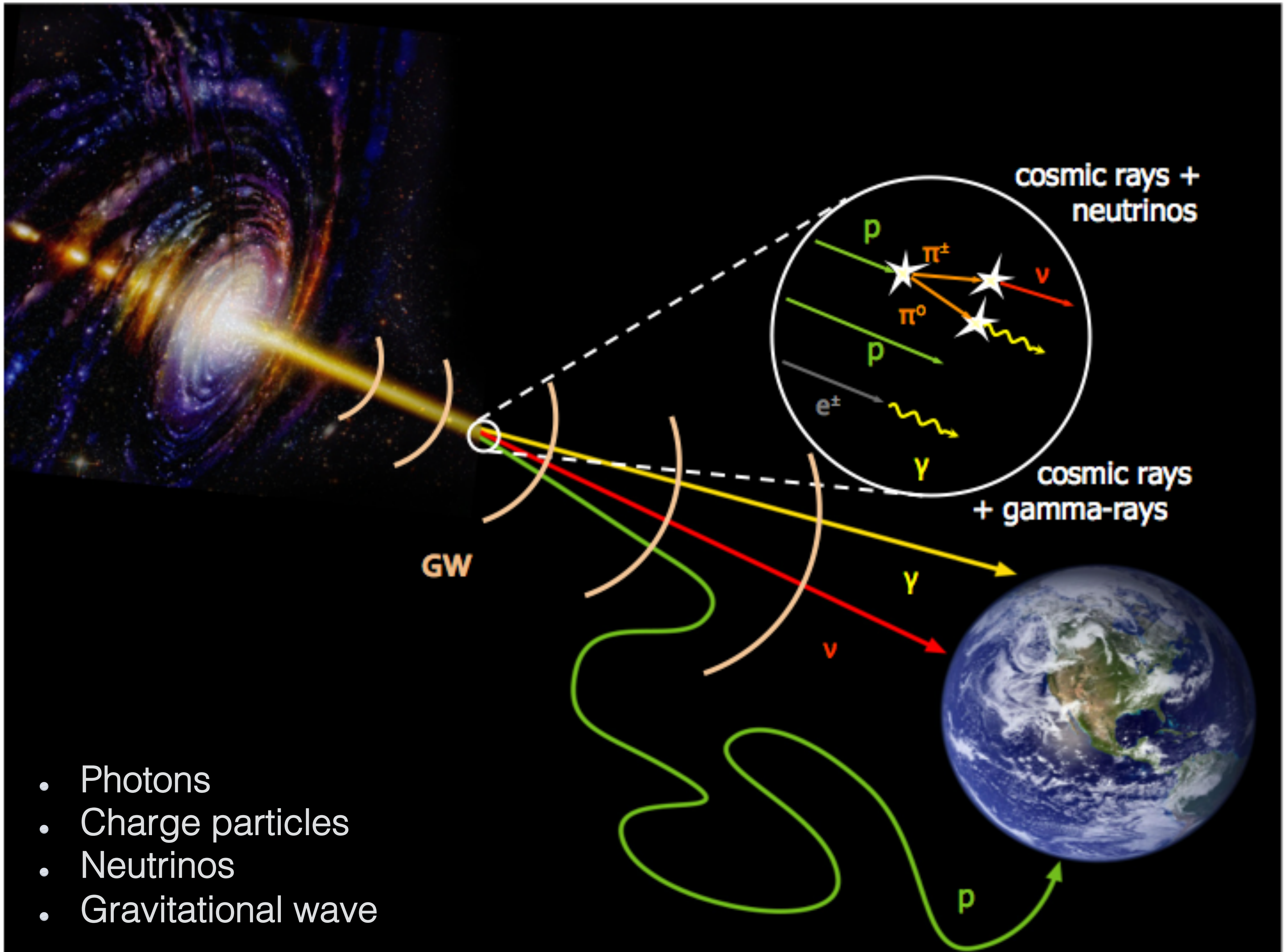
Multi-messenger Astronomy



- Photons
- Charge particles
- Neutrinos
- Gravitational wave

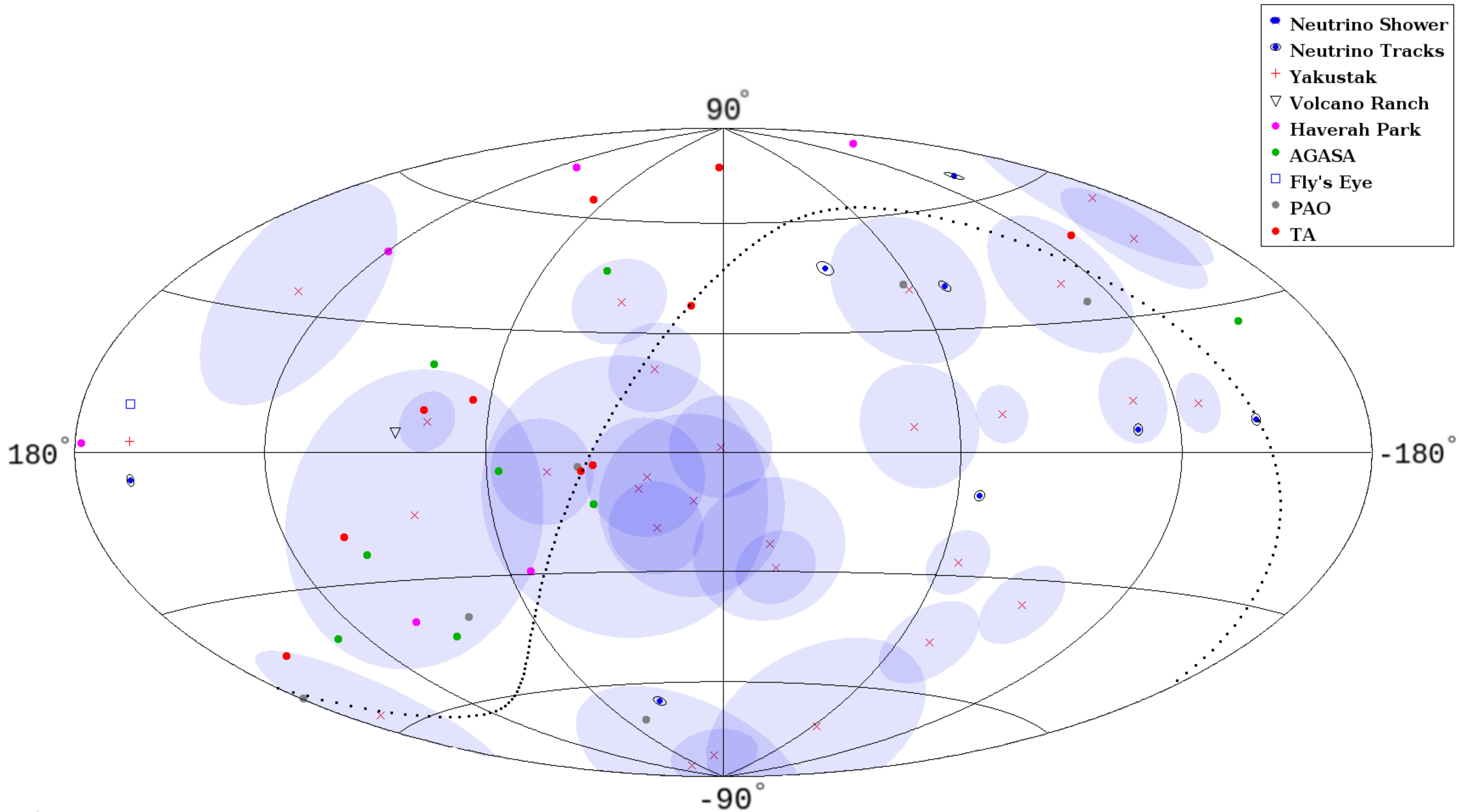
Angular Correlation of HESE with Ultrahigh-Energy Cosmic Rays

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 (3-yr HESE sample)

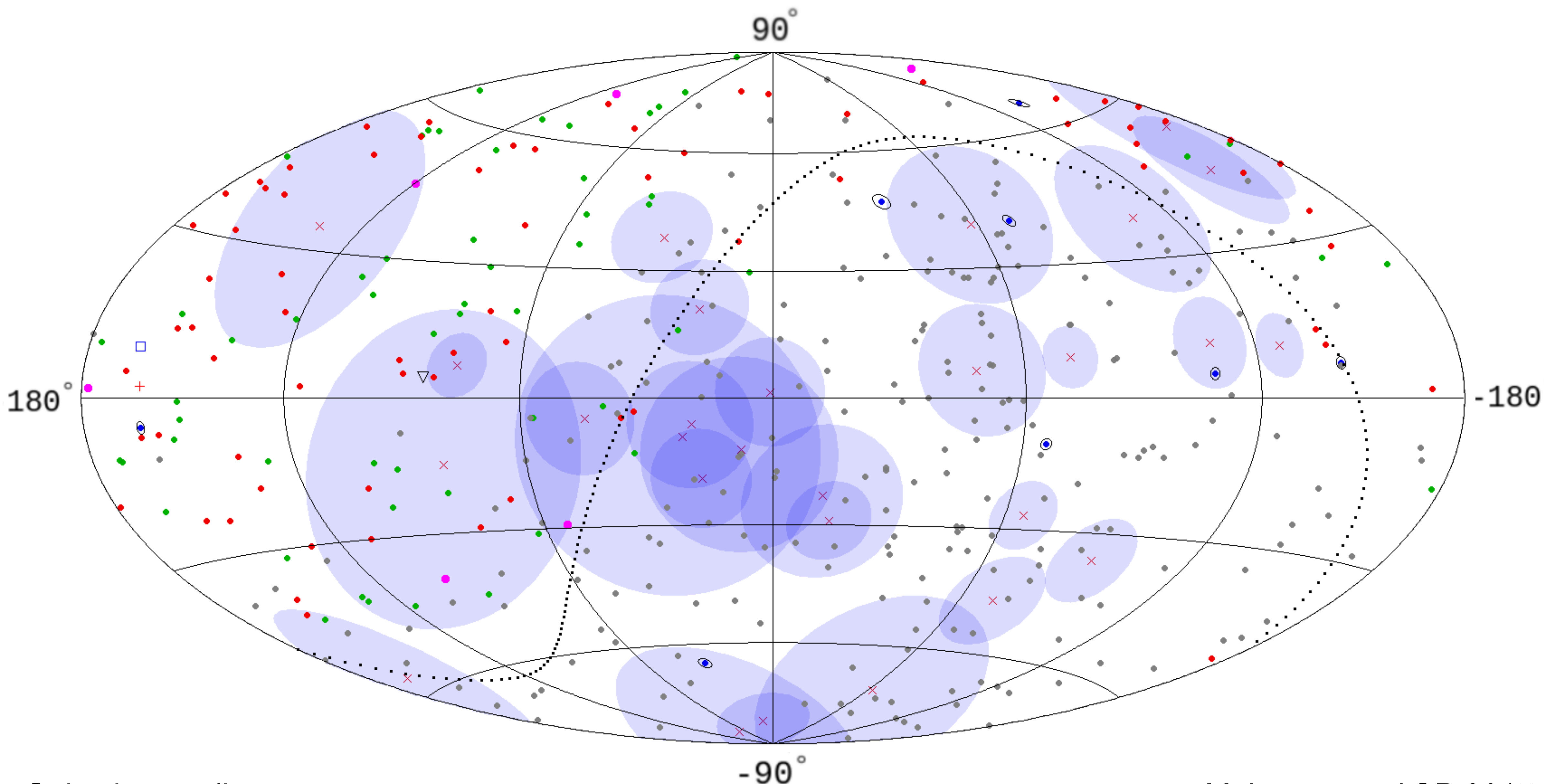


Galactic coordinates

Moharana and SR 2015

>80 EeV Cosmic Rays and Neutrinos

60 UHECR and 35 Neutrino events (3-yr HESE sample)



Galactic coordinates

Moharana and SR 2015

Statistics of Correlation - I

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: $\gamma = \cos^{-1}(\hat{x}_{\text{neutrino}} \cdot \hat{x}_{\text{UHECR}})$

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 the i-th neutrino event

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

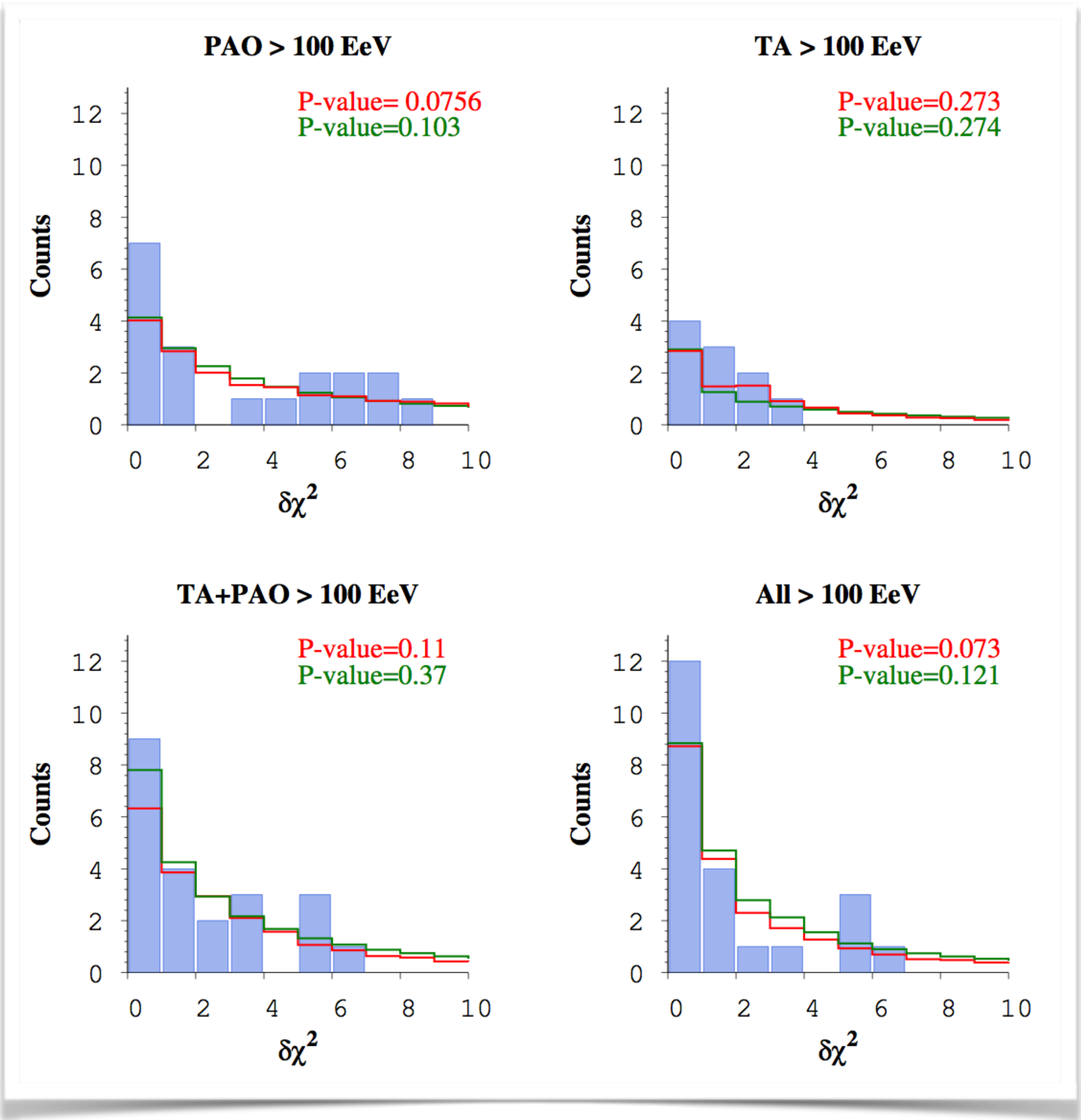
Null distribution:

- 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



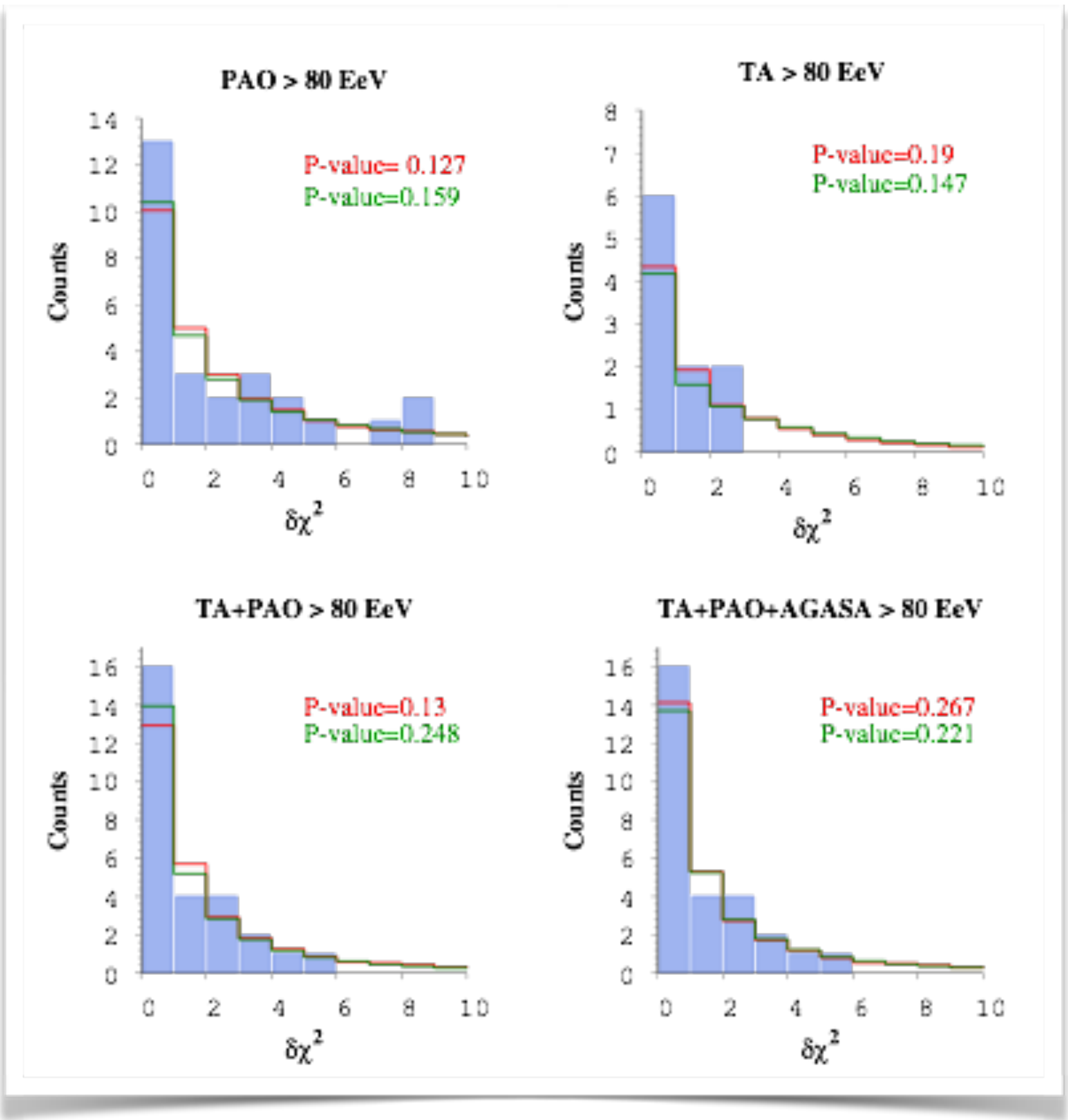
- **Small hint of correlation between UHECRs and cosmic neutrino data**
- **~90% chance probability**
- **Dominated by PAO data**

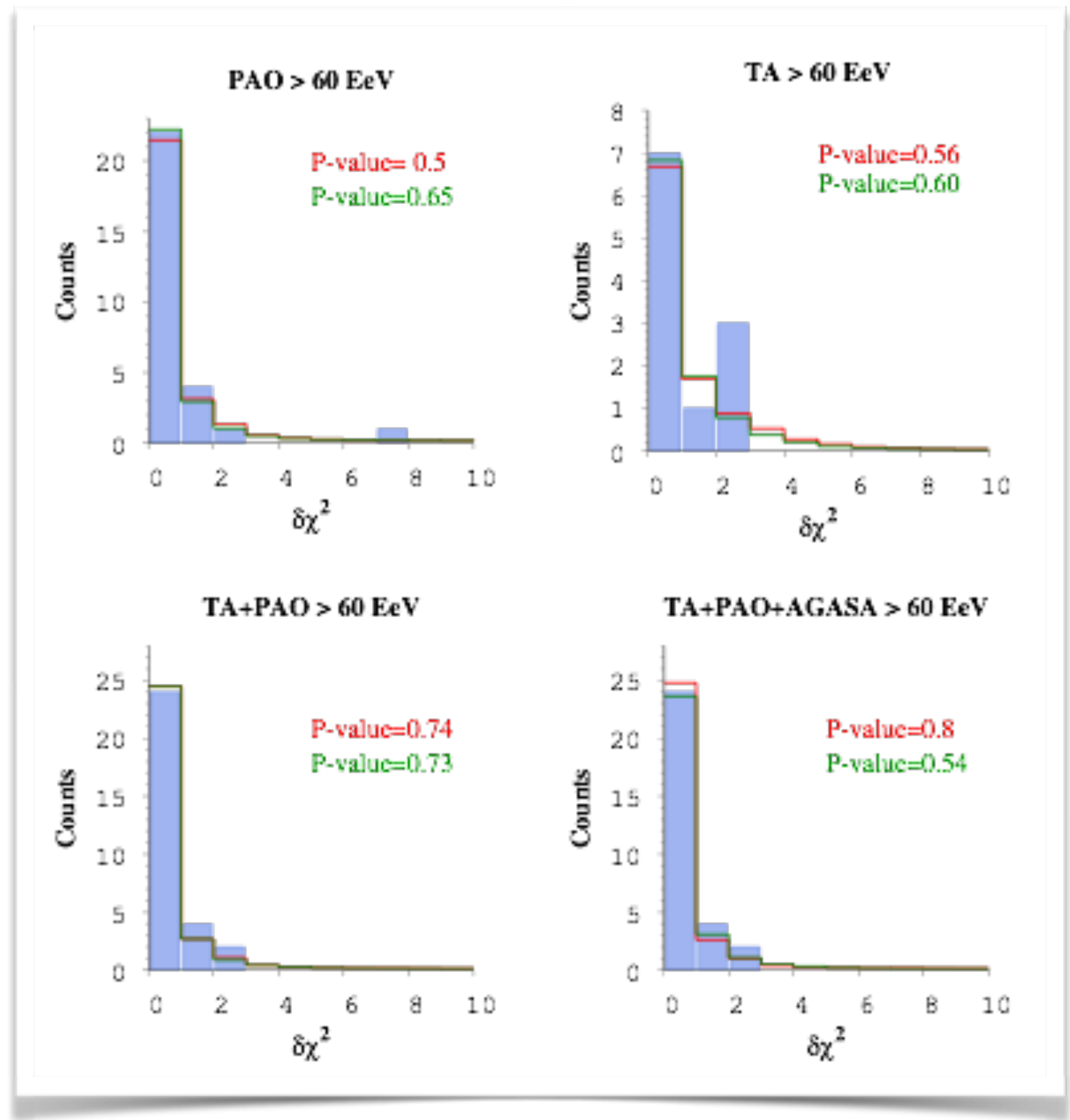
- Two null distributions:
- *Semi-isotropic null (red)*
- *Exposure-corrected null (green)*

Moharana and SR 2015

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)

Angular Correlation of HESE with Star-forming/ Supernova-related Sources

Motivation

- **Well motivated sources of cosmic rays up to at least the “knee” of the cosmic-ray spectrum**
  - Some evidence from gamma-ray observations (pp interactions)
- **High-energy neutrino production motivated and modeled (various scenarios)**
  - *….*
  - *Loeb & Waxman 2006*
  - *….*
- **Search and model supernova/starburst activity for IceCube HESE neutrinos**
  - *Anchordoqui, Paul, da Silva et al. 2014*
  - *Tamborra, Ando, Murase 2014*
  - *Emig, Lunardini & Windhorst 2015*
  - *Bechtol, Ahlers, Di Mauro, Ajello & Vandenbroucke 2015*
  - *….*

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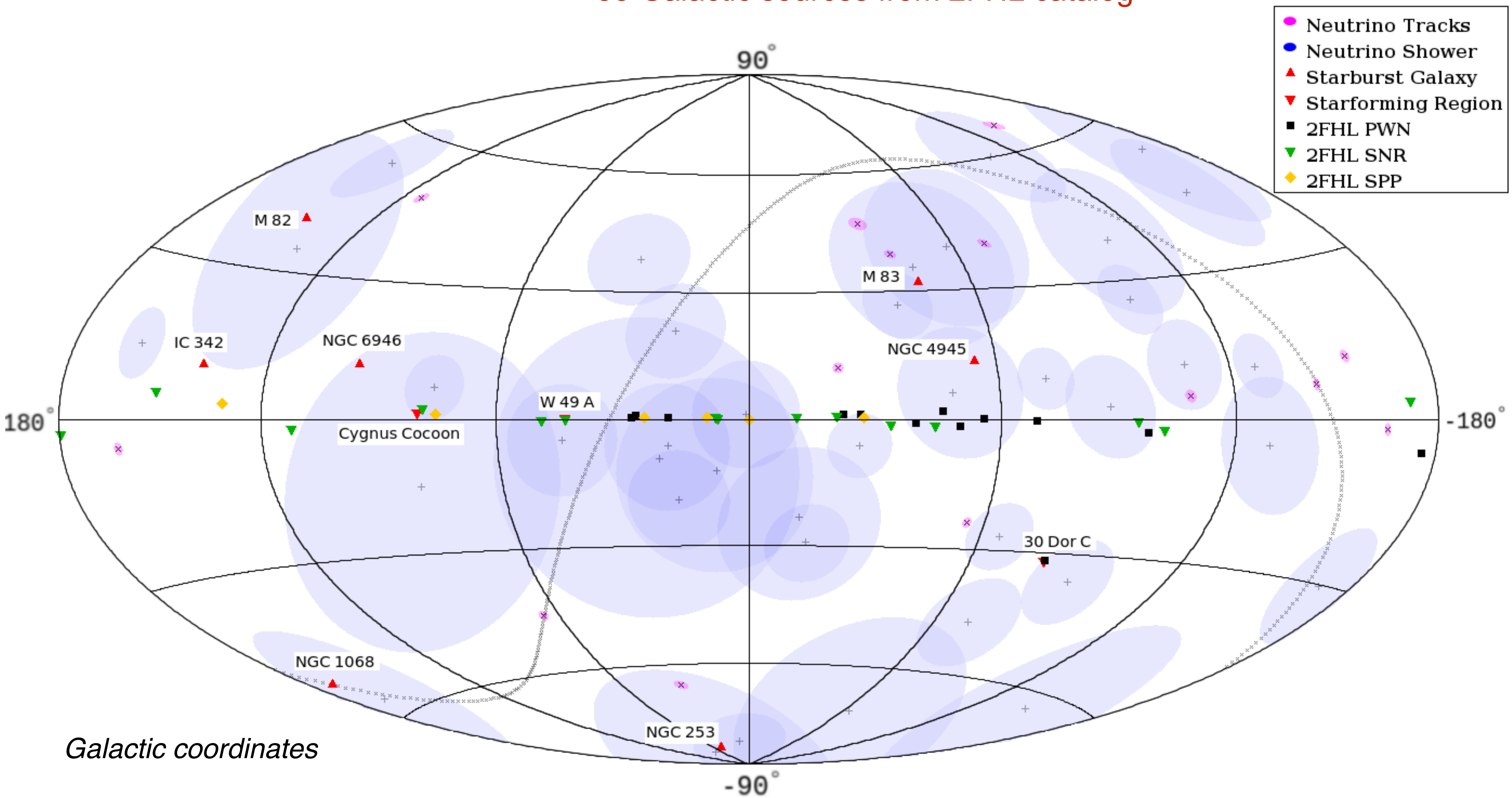
  - *Bechtol, Ahlers, Di Mauro, Ajello & Vandenbroucke 2015*
  - *….*

- **Study correlation between sources and HESE neutrinos**
- **Model gamma-ray emission with pp interactions**
- **Compare neutrino emission from pp model with data**

4-yr HESE and SN-related source samples

- HESE: 39 showers and 14 track events
- Sources: 7 Starburst galaxies
  3 star-forming regions
  33 Galactic sources from 2FHL catalog



Galactic coordinates

Source Samples

Source set name	# of sources	Source type
Sample-I	7	4 IRAS + 3FGL and 3 IRAS
Sample-II	7	4 IRAS + 3FGL and 3 TeVCAT local Starforming Reg.
Sample-III	33	2FHL SNRs+PWNs+SPPs
Sample-IV	12	2FHL PWNs
Sample-V	15	2FHL SNRs
Sample-VI	6	2FHL SPPs

- **Samples I and II from *Emig, Lunardini and Windhorst 2015***
  Infra-Red Astronomical Satellite (IRAS) sources, flux *S*(100 um) > 250 Jy
- **3FGL: 4-year Fermi-LAT Point Source Catalog, *arXiv:1501.02003***
  100 MeV – 300 GeV, 3033 sources
- **2FHL: The second catalog of hard Fermi-LAT sources, *arXiv:150804449T***
  50 GeV – 2 TeV; 80 month data; 360 sources; 33 Galactic
  PWN – Pulsar Wind Nebula
  SNR – Super-Nova Remnant
  SPP – Super-Nova Remnant or Pulsar Wind Nebula
- **TeVCat: 176 sources, http://tevcat.uchicago.edu/**

Statistics of Correlation – II

Angular separation between the neutrino and source $\gamma = \cos^{-1}(\hat{x}_{\text{neutrino}} \cdot \hat{x}_{\text{source}})$

Divide the angular error $\delta\theta$ of the HESE events in $M = 10$ concentric rings

Count the number of sources in each of the rings → forming a neutrino-source pair n_j^{data}

$$(j-1)\delta\theta/M \leq \gamma < j\delta\theta/M, \qquad j = 1, 2, \ldots M$$

Mean Monte Carlo simulated pairs $\bar{n}_j^{\text{mc}} = \sum_{i=1}^{N} n_{ij}^{\text{mc}}/N \qquad N = 100{,}000$

Variance in Monte Carlo simulated pairs $\sigma_j^2 = \frac{1}{N}\sum_{i=1}^{N}\left(n_{ij}^{\text{mc}} - \bar{n}_j^{\text{mc}}\right)^2$

Relative excess of pairs in data and simulation $(n_j^{\text{data}} - \bar{n}_j^{\text{mc}})/\sigma_j \qquad j = 1, 2, \ldots M$

Tinyakov & Tkachev 2001

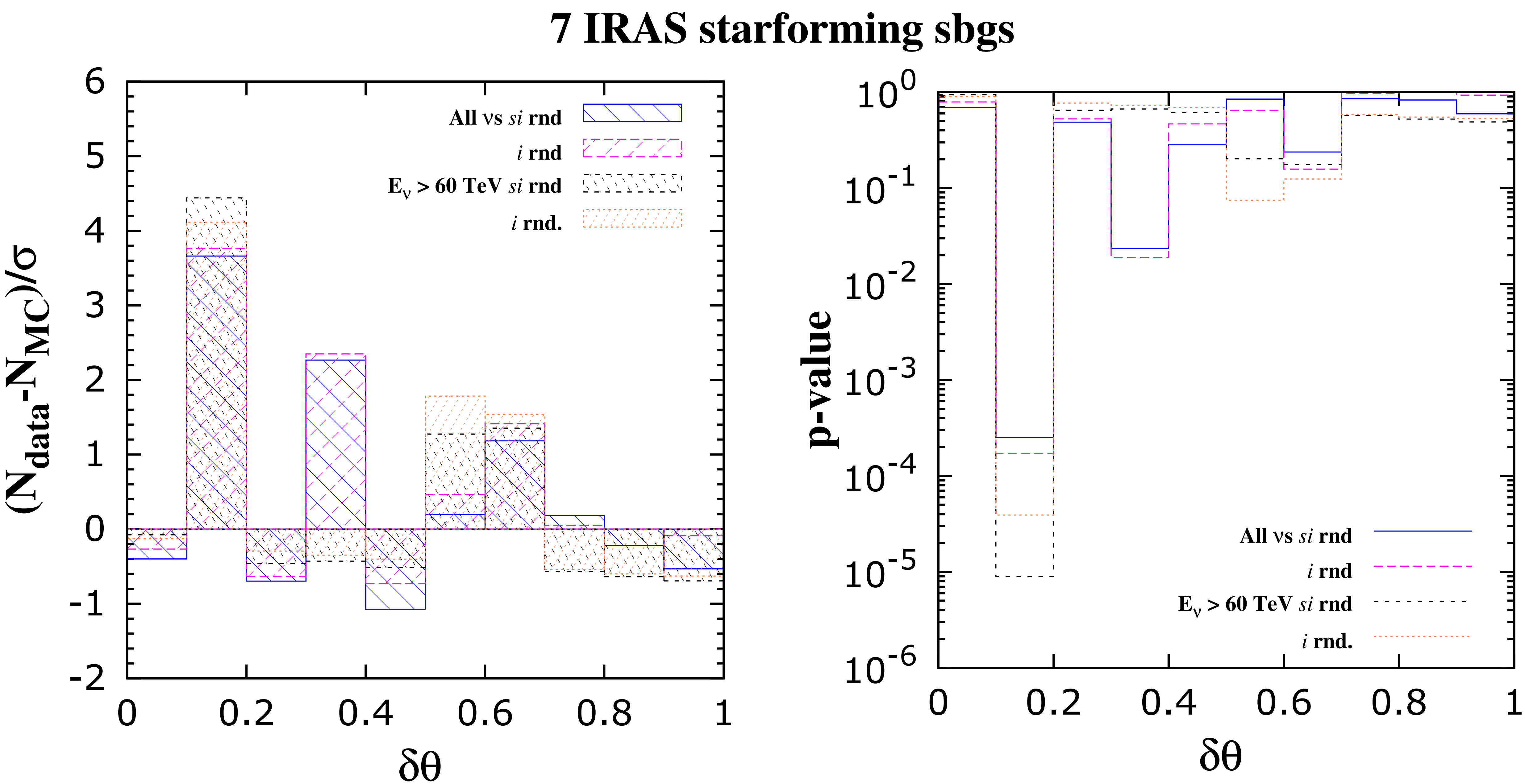
Monte Carlo simulated data: Isotropic distribution of sources (isotropic null)

(Galactic sources concentrated within +/-10 deg Galactic plane)

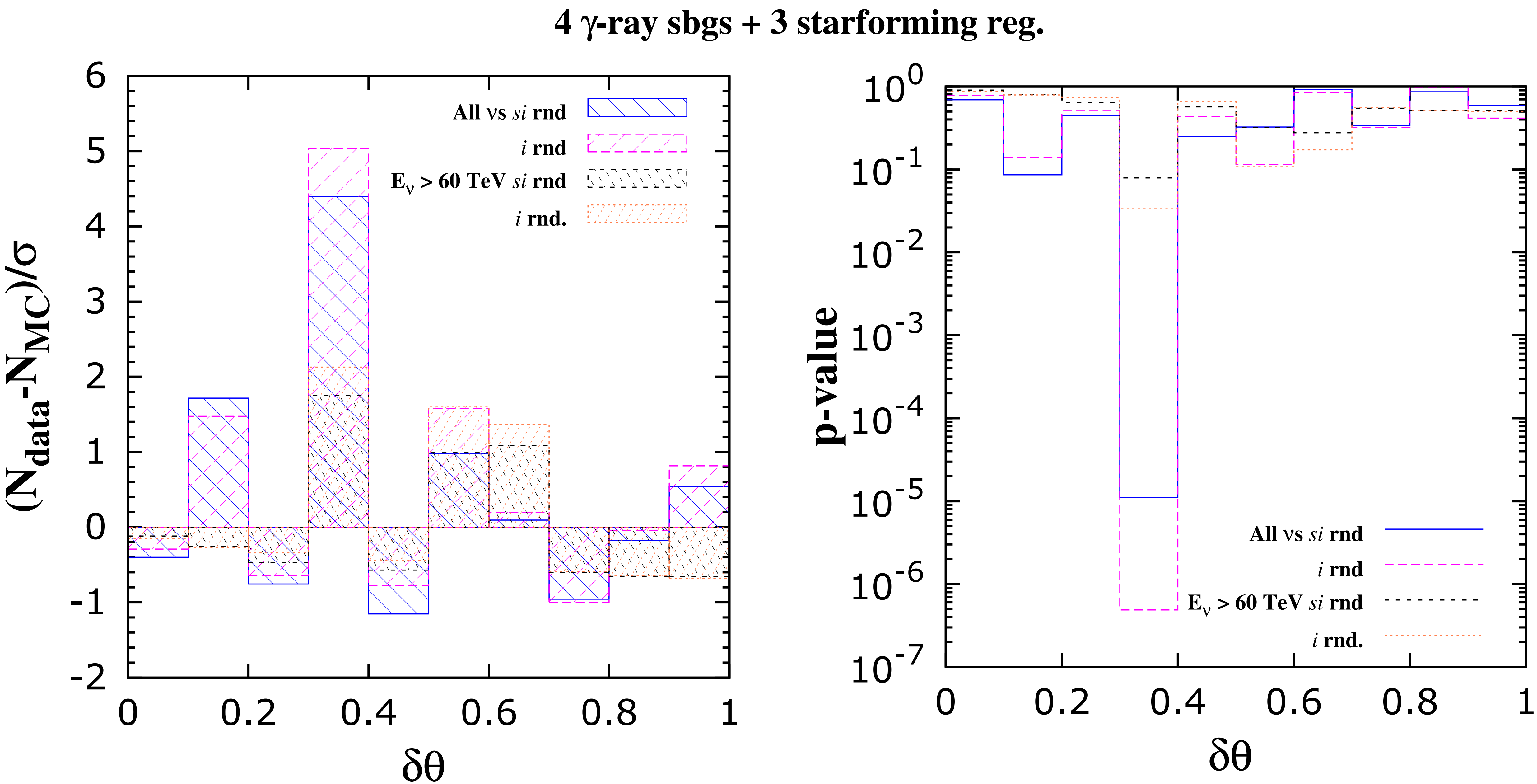
Isotropic distribution in Gal. longitude only (semi-isotropic)

Correlation Results: Sample - I
Infrared bright starburst galaxies (7)

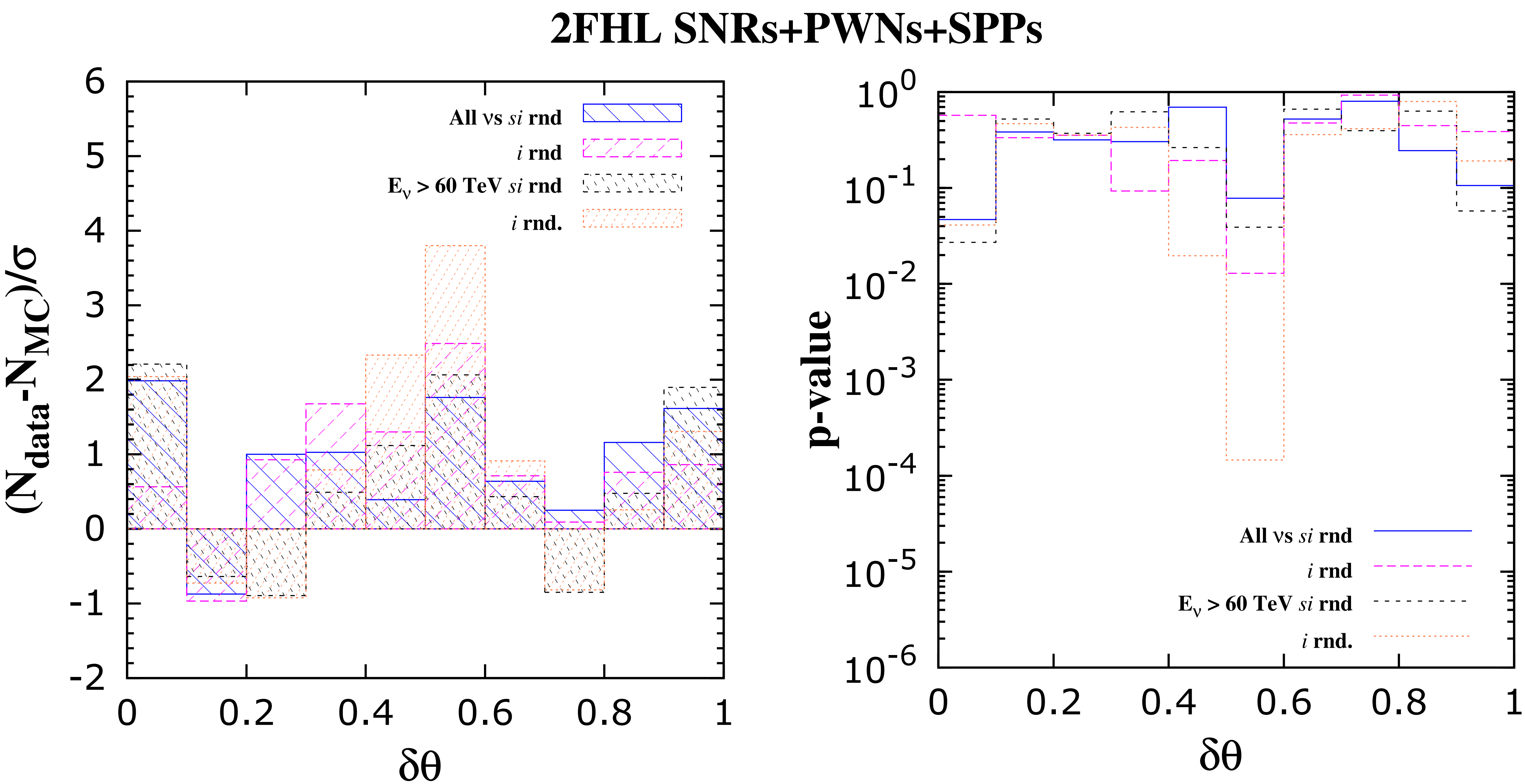
Gaussian significance



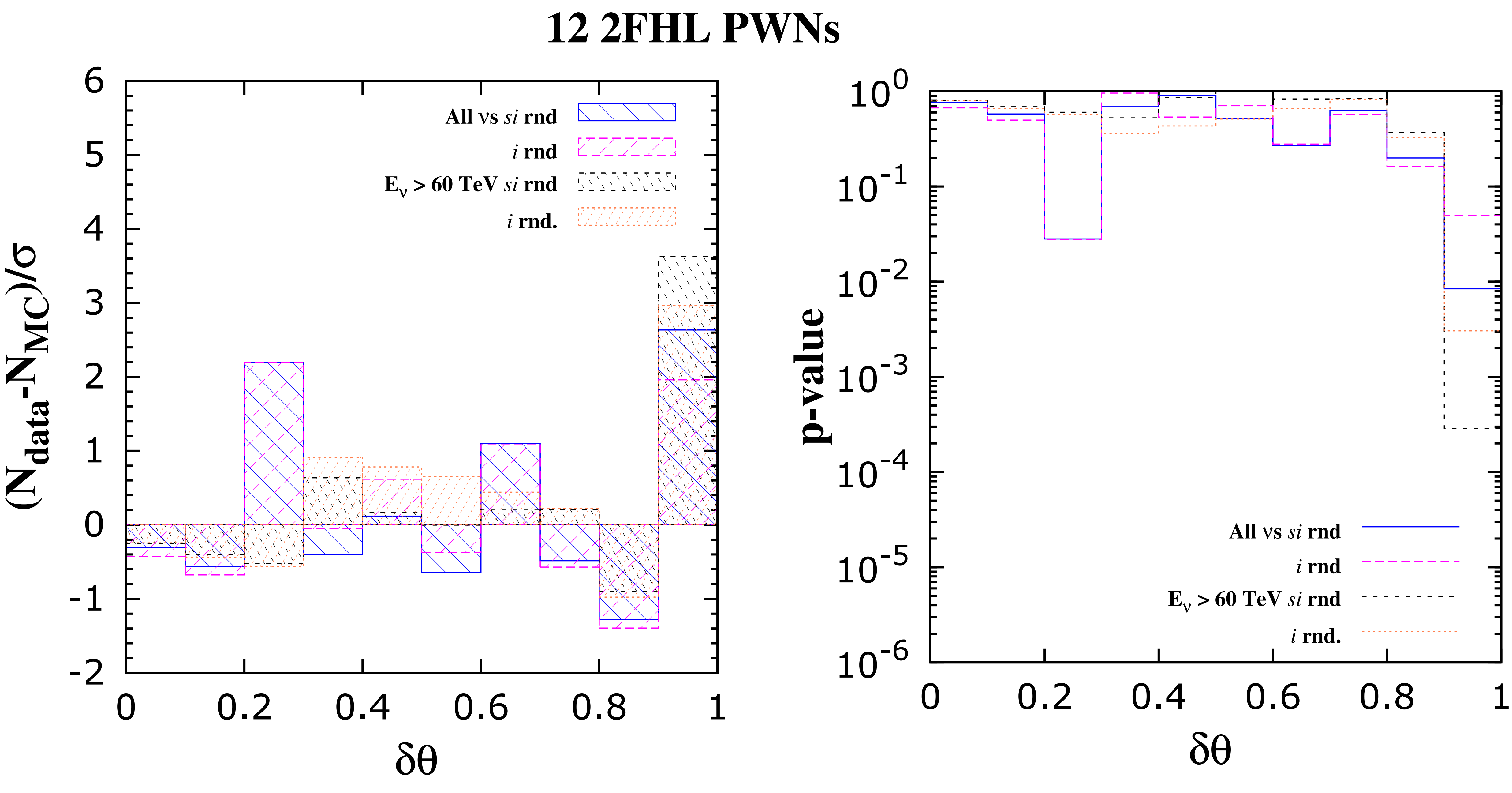
Correlation Results: Sample – II TeV-detected starburst galaxies (4) and starforming regions (3)



Correlation Results: Sample - III
2FHL Galactic sources (33)

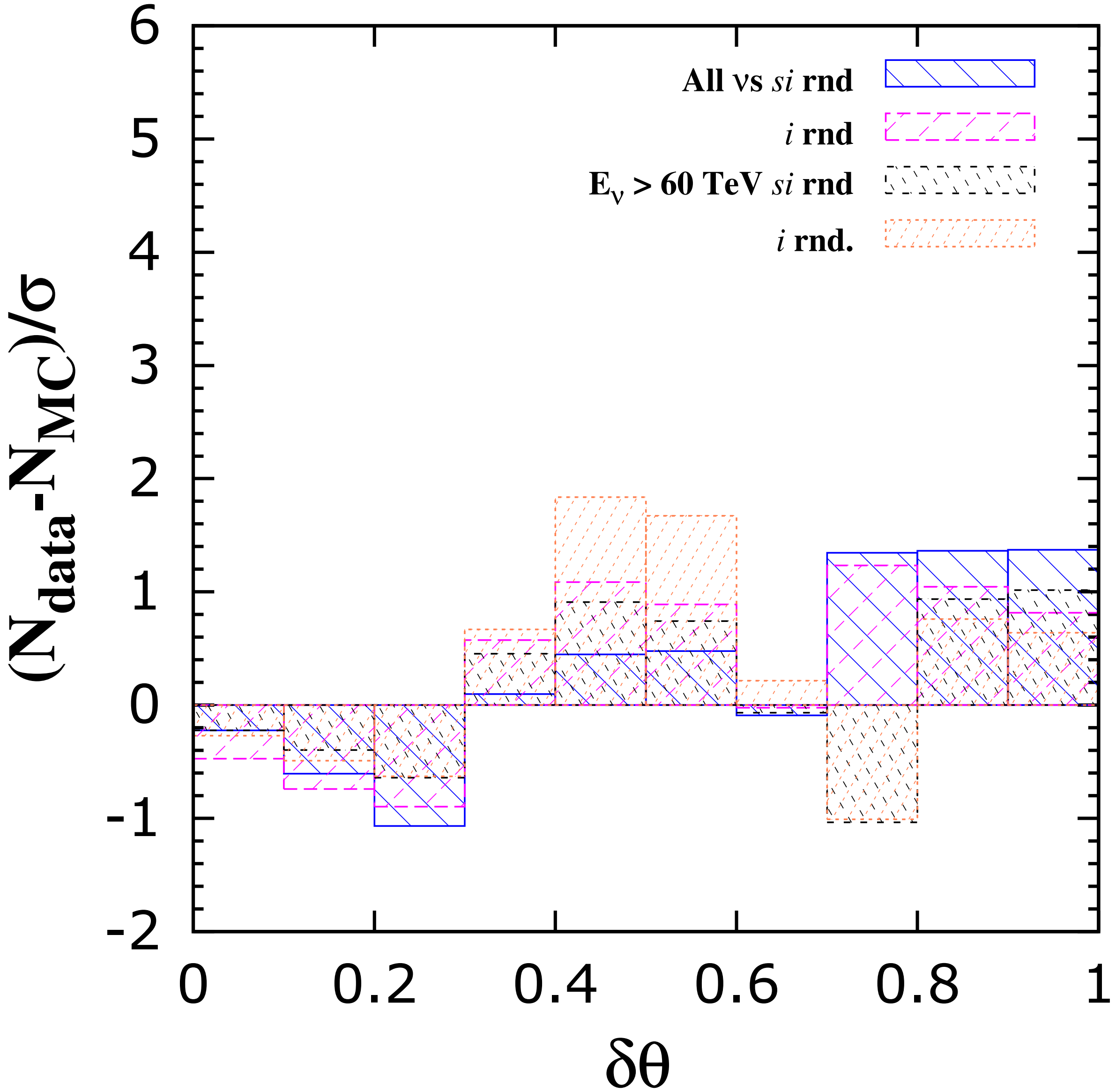


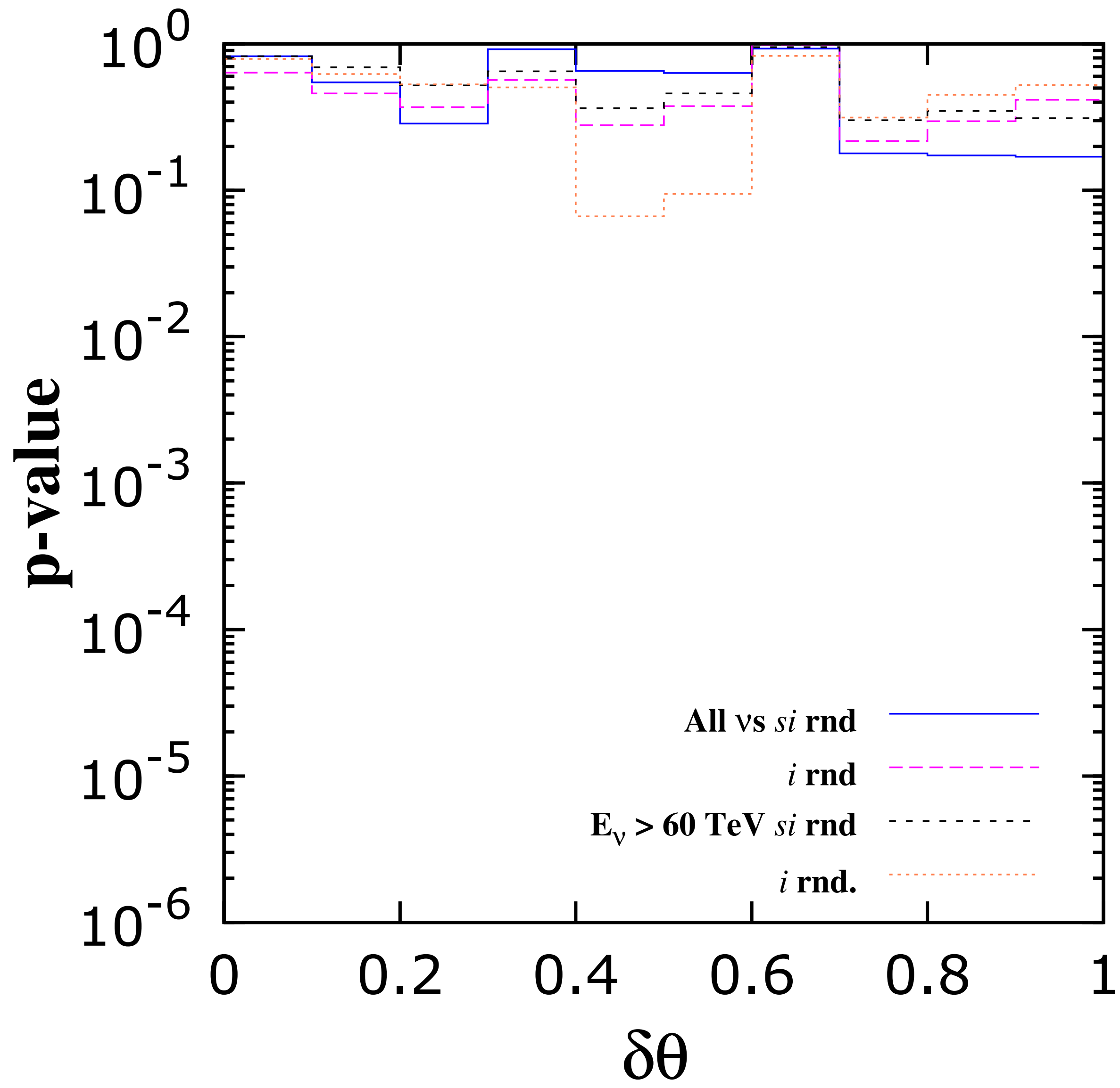
Correlation results: Sample – IV
2FHL pulsar wind nebulae (12)



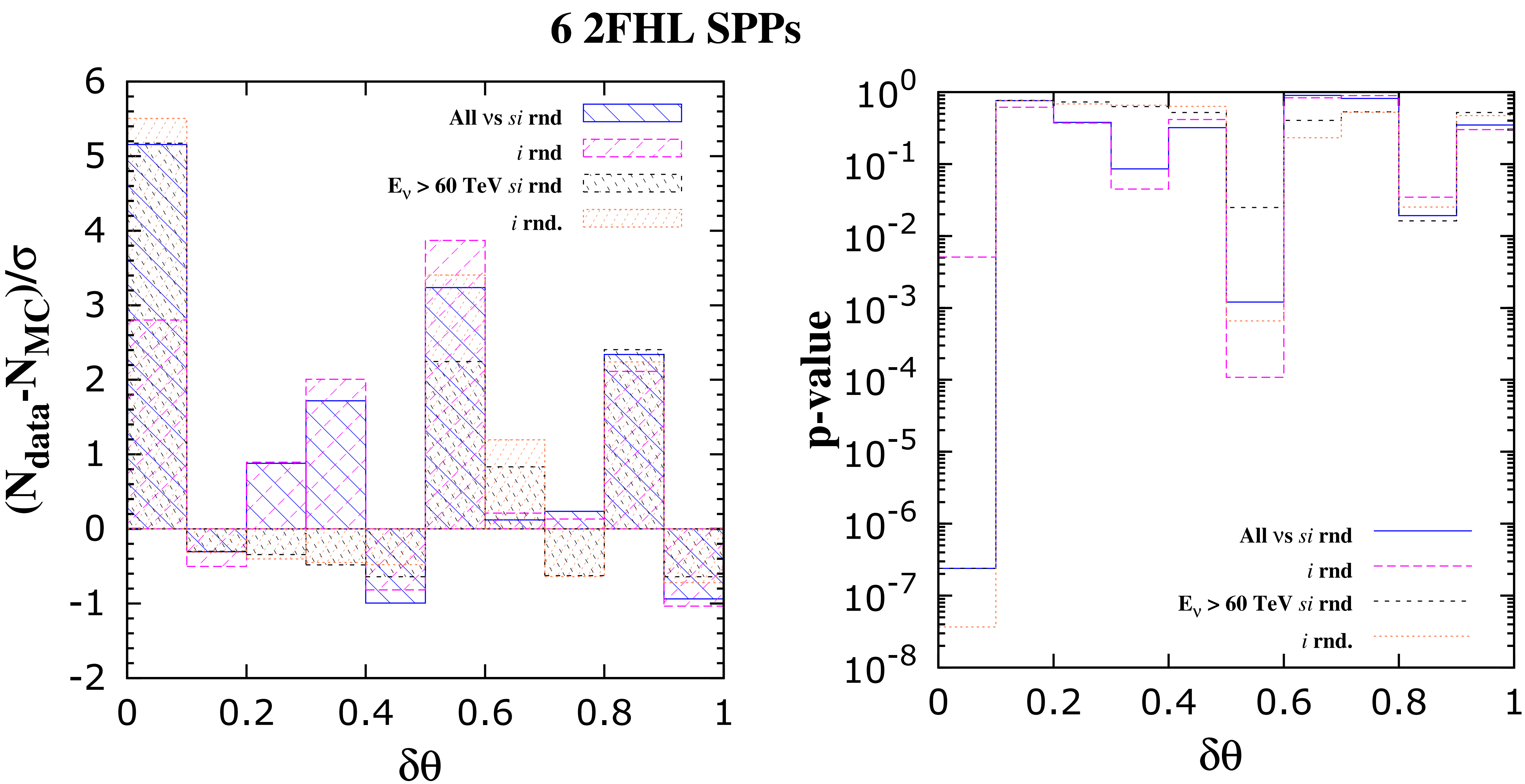
Correlation results: Sample – V
2FHL supernova remnants (15)

15 2FHL SNRs





Correlation results: Sample – VI
2FHL supernovae/pulsar wind nebulae (6)



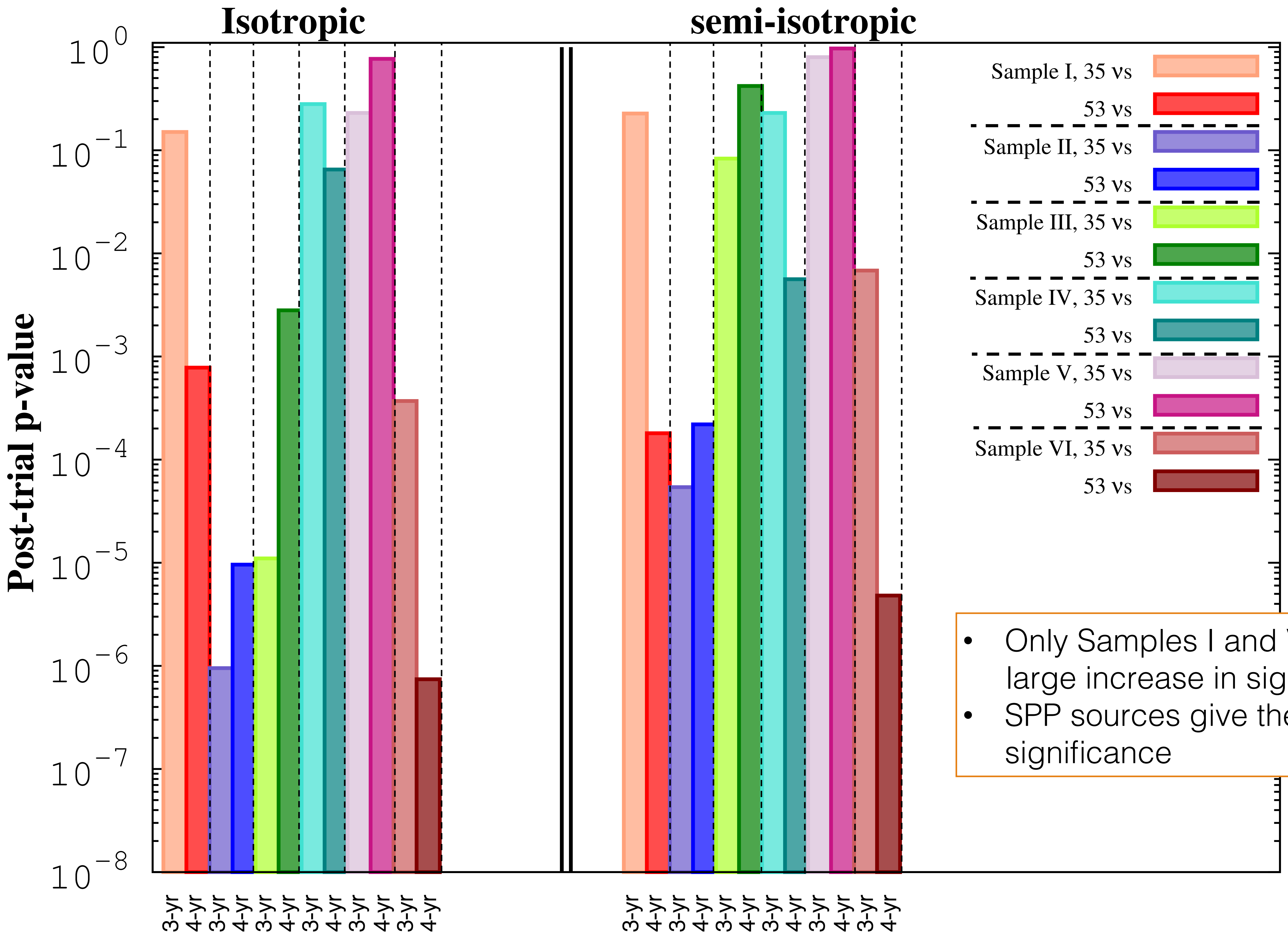
Correlation results: p-values pre-trial and post-trial

post-trial (Post trial p-value si rnd) | post-trial (Post trial p-value i rnd)

	Source sets	All νs si rnd p-value	$E_\nu >$ 60 TeV si rnd p-value	Post trial p-value si rnd	All νs i rnd p-value	$E_\nu >$ 60 TeV i rnd p-value	Post trial p-value i rnd
4-yr HESE	Sample-I	2.5×10^{-4}	9×10^{-6}	1.8×10^{-4}	1.7×10^{-4}	3.9×10^{-5}	7.8×10^{-4}
	Sample-II	1.1×10^{-5}	8×10^{-2}	2.2×10^{-4}	4.8×10^{-7}	3.3×10^{-2}	9.6×10^{-6}
	Sample-III	4.7×10^{-2}	2.7×10^{-2}	0.42	1.2×10^{-2}	1.4×10^{-4}	2.8×10^{-3}
	Sample-IV	8.4×10^{-3}	2.8×10^{-4}	5.6×10^{-3}	2.78×10^{-2}	3.4×10^{-3}	6.5×10^{-2}
	Sample-V	0.17	0.30	0.97	0.21	6.6×10^{-2}	0.77
	Sample-VI	2.4×10^{-7}	2.4×10^{-7}	4.8×10^{-6}	1.1×10^{-4}	3.7×10^{-8}	7.4×10^{-7}
3-yr HESE	Sample-I	1.3×10^{-2}	5.8×10^{-2}	0.23	8.3×10^{-3}	9.1×10^{-3}	0.15
	Sample-II	2.7×10^{-6}	2.5×10^{-2}	5.4×10^{-5}	4.8×10^{-8}	4.8×10^{-3}	9.5×10^{-7}
	Sample-III	2.13×10^{-2}	4.34×10^{-3}	8.3×10^{-2}	4.7×10^{-3}	5.3×10^{-7}	1.1×10^{-5}
	Sample-IV	1.27×10^{-2}	3.34×10^{-2}	0.23	1.6×10^{-2}	0.15	0.28
	Sample-V	7.6×10^{-2}	0.12	0.8	0.13	1.32×10^{-2}	0.23
	Sample-VI	3.43×10^{-4}	5.7×10^{-3}	6.8×10^{-3}	2.4×10^{-5}	1.9×10^{-5}	3.7×10^{-4}

Semi-isotropic null (columns 2–4) | Isotropic null (columns 5–7)

Change in correlation p-values from 3-yr to 4-yr HESE samples



- Only Samples I and VI show large increase in significance
- SPP sources give the highest significance

pp-model for Gamma-ray and Neutrino production in starburst galaxies, star-forming regions and supernova remnants

Cosmic-ray proton spectrum $N_p = N_0 \, E_p^{-\alpha} \, exp(-E_p/E_0)$ 3 parameters

pp interactions with surrounding gas *neutral and charged pions decay to gamma and neutrino*

gamma-ray spectrum

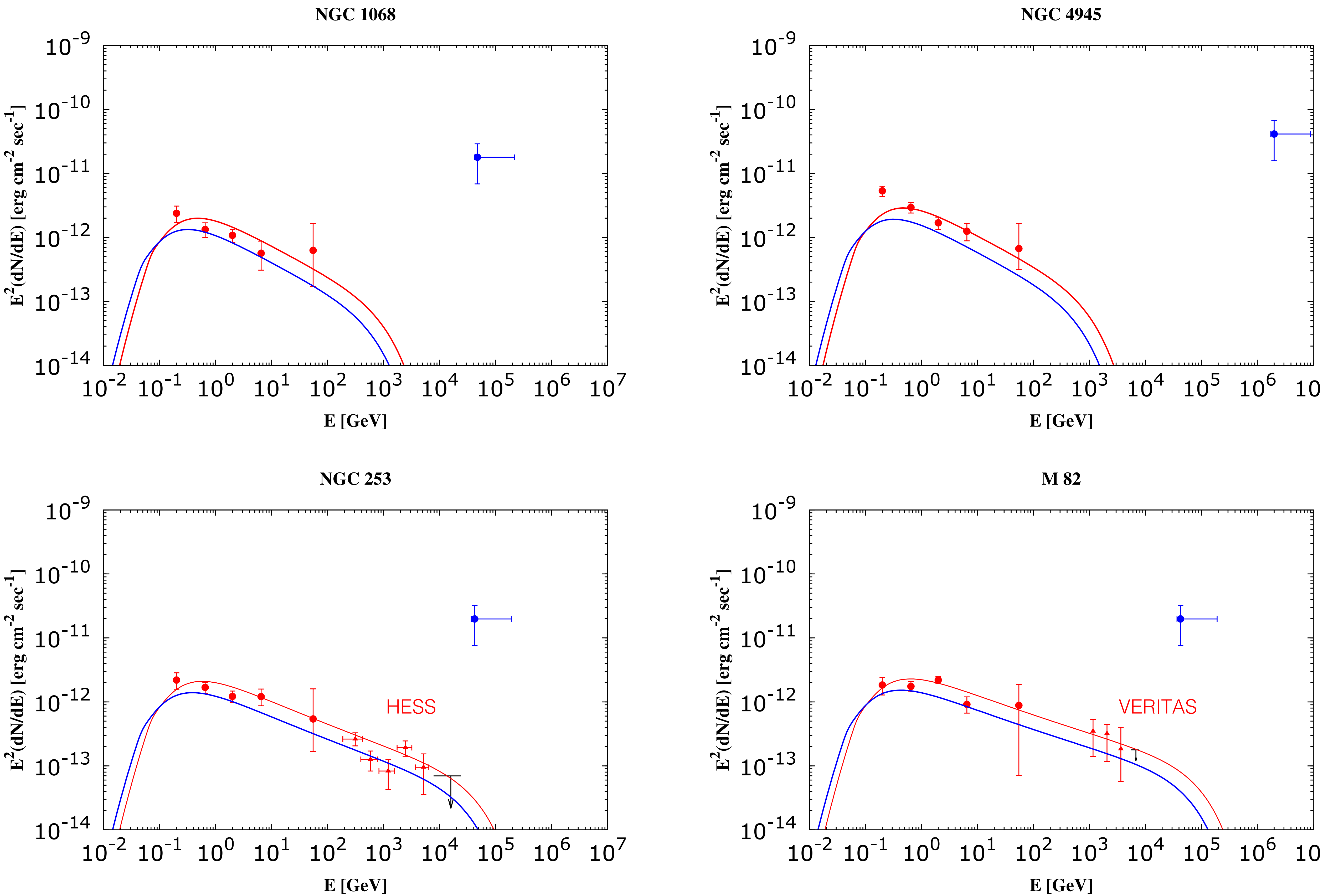
$$\frac{dN_\gamma}{dE_\gamma} = \frac{2c\tilde{n} \left< n_H \right>}{4\pi D_L^2 K_\pi} \int_{E_{\pi,th}}^{\infty} dE_\pi \frac{\sigma_{pp}(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} N_p(E_\pi)$$

Aharonian & Atoyan 1995

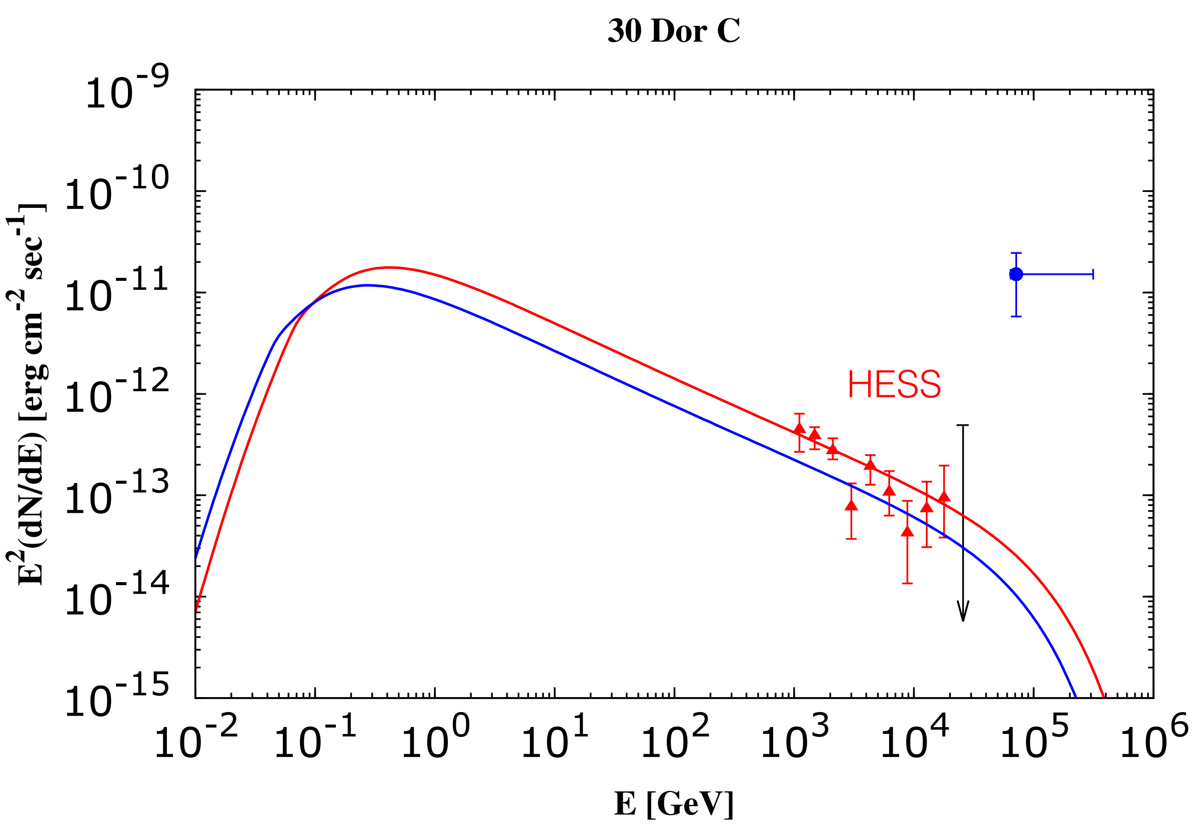
Neutrino spectrum ~2/3 of gamma-ray spectrum

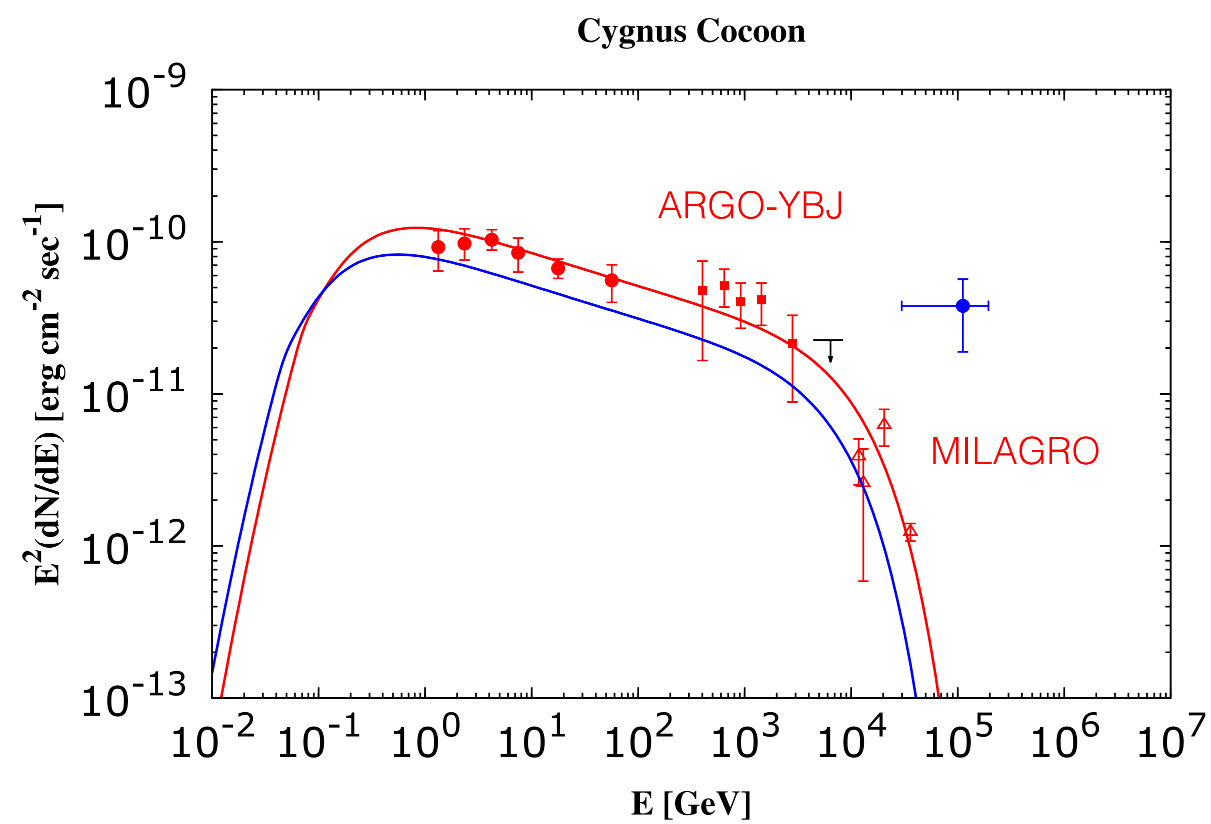
Use typical interstellar gas density of 1 particle/cc

pp-model: starburst galaxies



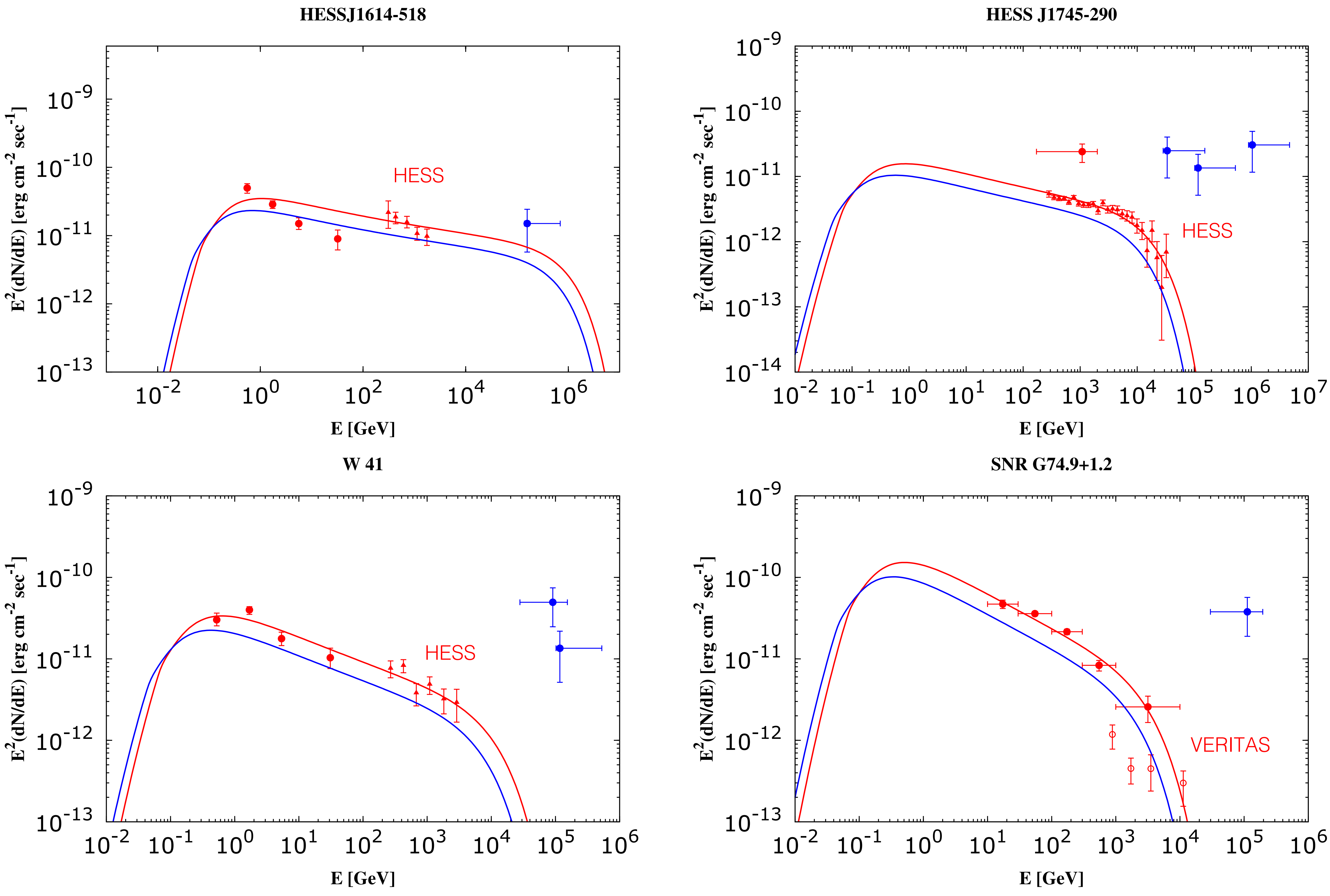
pp model: star-forming regions





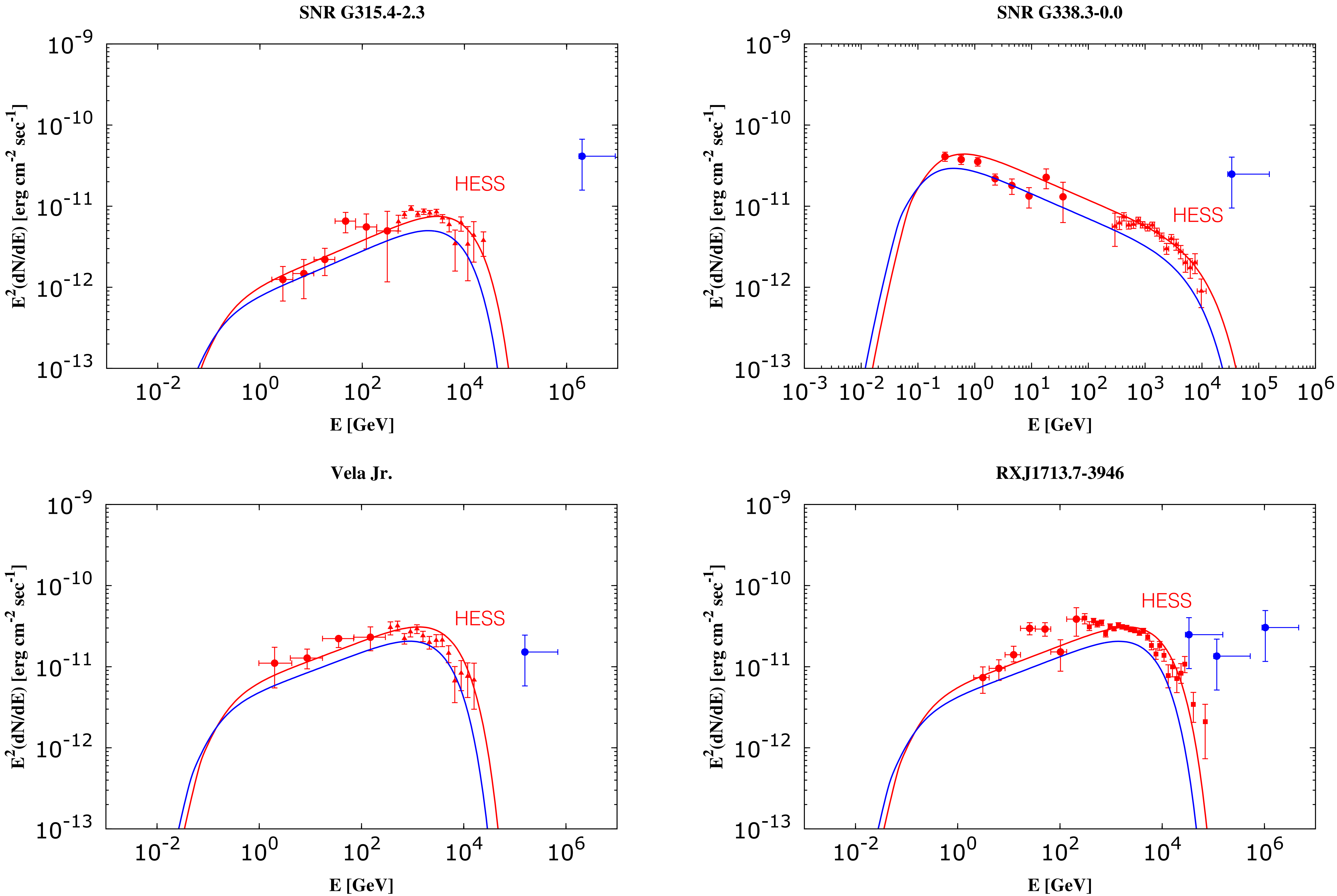
- 4 starburst galaxies and 2 star-forming regions are correlated with HESE
- The other star-forming region is listed in the 2FHL catalog as SNR
- Typical γ-ray luminosity for starburst galaxies: ~ 10^{40} erg/s, pp efficiency ~ 5%
- Star-forming region γ-ray luminosity ~ 10^{30} – 10^{32} erg/s

pp model: SPP sources



one is not correlated with neutrinos and the other is not a TeV source

pp model: supernova remnants



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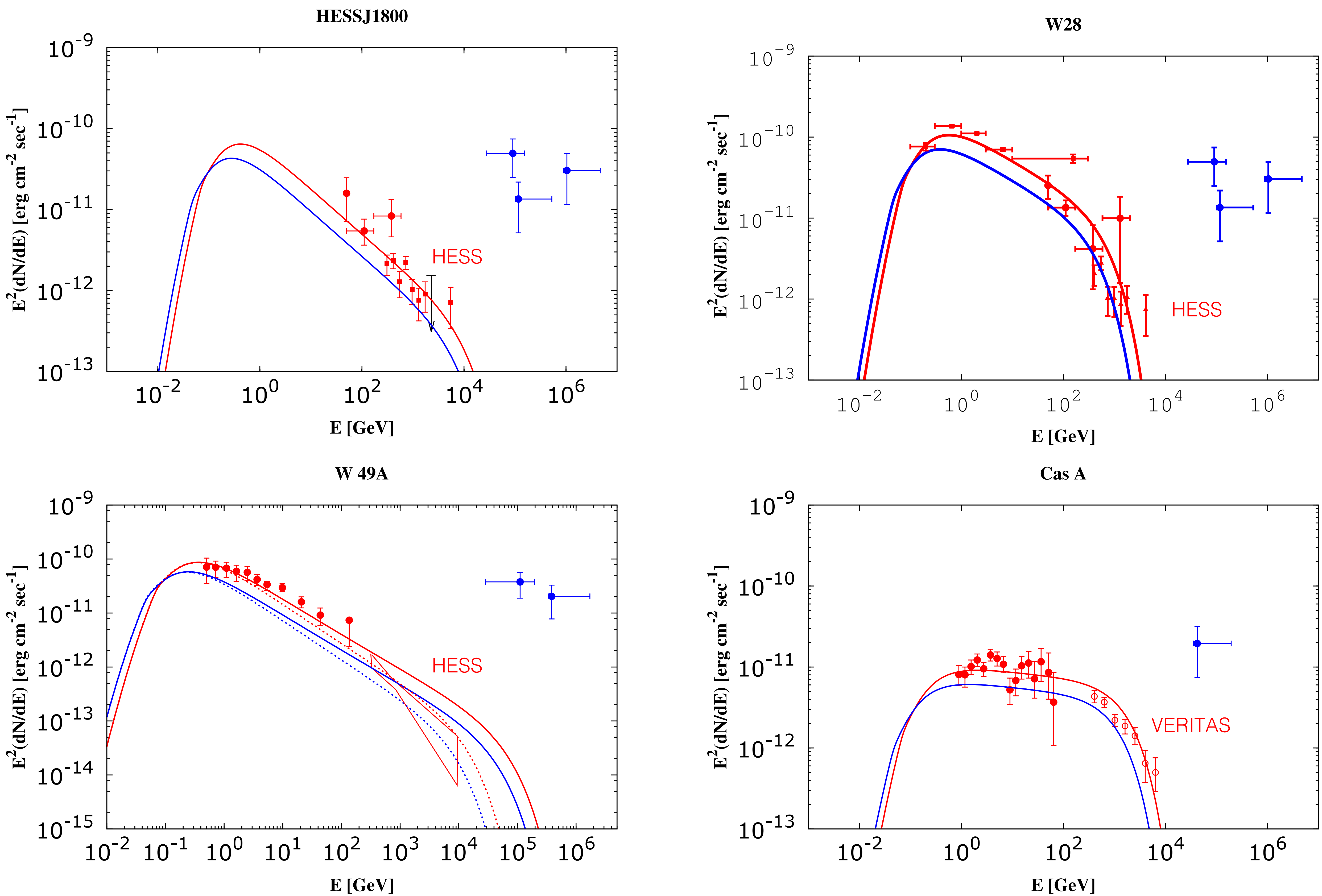

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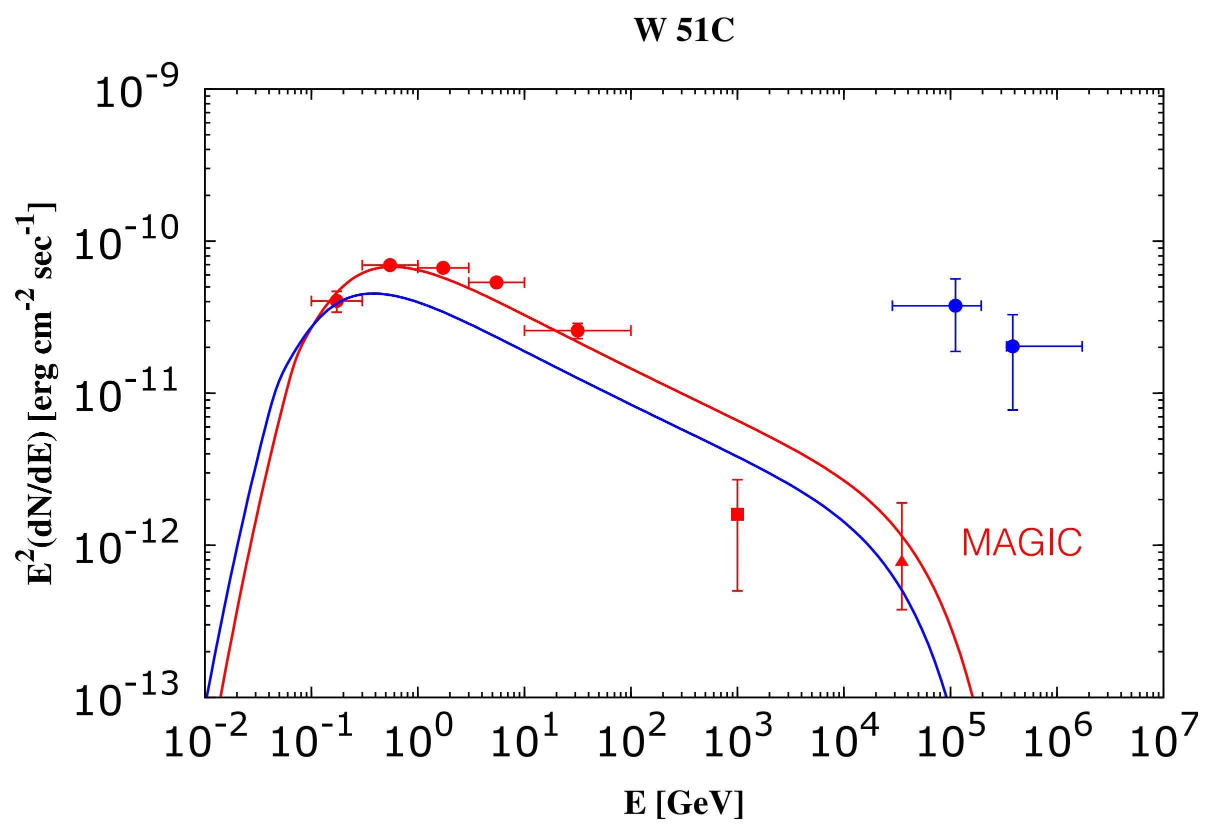

- **4 starburst galaxies and 2 star-forming regions are correlated with HESE**
- **The other star-forming region is listed in the 2FHL catalog as SNR**
- **Typical γ-ray luminosity for supernova remnants: ~ 10^{32} – 10^{36} erg/s, pp efficiency ~ 5 – 10%**
- **Star-forming region γ-ray luminosity ~ 10^{30} – 10^{32} erg/s**

Summary

- **Extragalactic neutrino sources**
  - **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)**
      - **Weak statistical significance (*Emig, Lunardini, Windhorst 2015*)**
- **Supernova-related sources**
  - **Significant correlation with some source samples (IRAS, 2FHL)**
  - **pp interaction model fitting gamma-ray data cannot account for neutrino flux**
  - **Additional/new mechanism needed for neutrino production, if these are the sources**

Summary

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Are these correlations accidental?

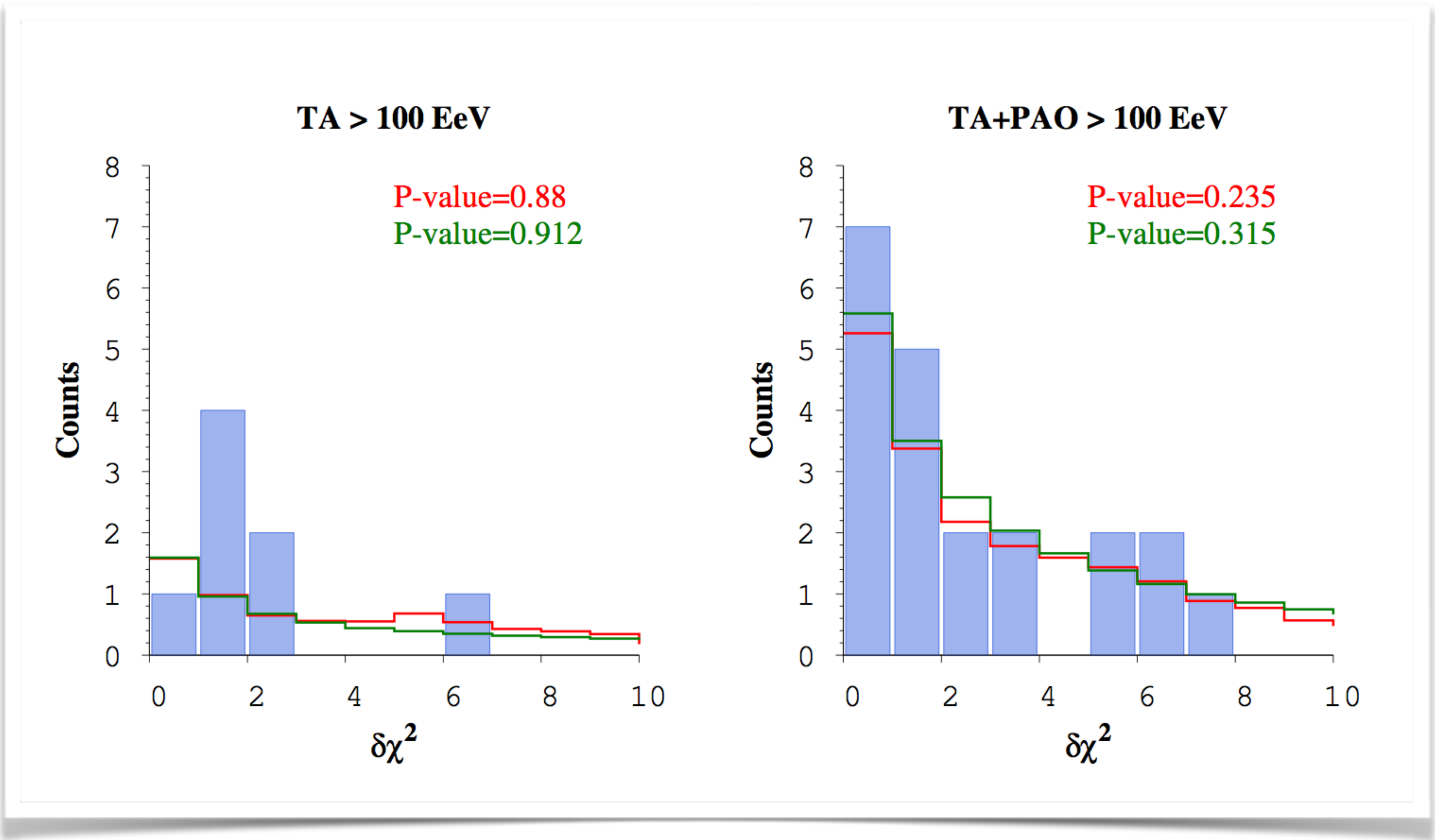
What are the sources of neutrinos?

Backup Slides

Results with energy rescaling, >100 EeV

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

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



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.

Sources and HESE ID, pp-model parameters

Sources	Neutrino ID	Distance	Fitting Parameters			
Names	Number	D_L	E_0 [TeV]	α	$L_{CR}/10^{40}$ [erg/sec]	$L_\gamma/10^{40}$ [erg/sec]
NGC 253	7, 10, 21	3.1 Mpc	500	2.4	6.8	0.38
NGC 1068	1	13.7 Mpc	10	2.5	120	6.13
IC 342	-	-	-	-		
M 82	31	3.6 Mpc	1000	2.35	165	9.84
NGC 4945	35	3.9 Mpc	10	2.5	14.2	0.72
M 83	-	-	-	-		
NGC 6946	-	-	-	-		
W 49A	25, 33, 34	11.4 kpc	100	2.77	3.7×10^{-3}	1.5×10^{-4}
Cygnus Cocoon	29, 34	50 pc	100	2.26	1.1×10^{-7}	7.1×10^{-9}
30 DorC	34	100 pc	1000	2.6	5.7×10^{-8}	1.1×10^{-10}
2FHL SPPs						
HESSJ1614-518	52	10 kpc	10^4	2.2	1.9×10^{-4}	1.1×10^{-4}
HESS J1745-290	25, 2, 14	8.5 kpc	150	2.25	4.2×10^{-4}	2.71×10^{-5}
W 30	24, 25, 2, 14	-	-	-		
W 41	24, 25, 2	4 kpc	100	2.35	1.9×10^{-4}	1.1×10^{-4}
SNR G74.9+1.2	29, 34	12 kpc	31.6	2.47	7.2×10^{-3}	3.8×10^{-4}
PSR J0205+6449	-	-	-	-		

Sources and HESE ID, pp-model parameters

Sources	Neutrino ID	Distance	Fitting Parameters			
Names	Number	D_L	E_0 [TeV]	α	$L_{CR}/10^{40}$ [erg/sec]	$L_\gamma/10^{40}$ [erg/sec]
SNR G315.4-2.3	35	2.5 kpc	100	1.77	1.4×10^{-3}	1.04×10^{-4}
SNR G326.3-1.8	-	-	-	-	-	-
SNR G338.3-0.0	25	8.6 kpc	100	2.35	1.1×10^{-3}	6.5×10^{-5}
VelaJr	40	0.2 kpc	50	2.25	2.9×10^{-7}	1.8×10^{-8}
PuppisA	-	-	-	-		
RXJ1713.7-3946	25	1 kpc	80	1.8	7.2×10^{-6}	7.7×10^{-7}
HESSJ1800-240A	24, 25, 2, 14	2 kpc	100	2.6	8.3×10^{-5}	$4. \times 10^{-6}$
W 28	24, 25, 2, 14	2 kpc	6	2.4	1.4×10^{-4}	7.4×10^{-6}
W 49B	25, 34, 35	9.90×10^5	100	2.77		
W 51C	25, 34, 35	4.3 kpc	500	2.4	4.2×10^{-4}	2.4×10^{-5}
IC 443	-	-	-	-		
S 147	-	-	-	-		
Gamma Cygni	29, 34	-	-	-		
SNR G150.3+4.5	-	-	-	-		
Cas A	34	3.4 kpc	15	2.1	4.2×10^{-5}	2.8×10^{-6}