IAUS 331: SN 1987A, 30 years later, La Reunion, February 20-24, 2017

Supernova Remnants and High Energy Neutrinos

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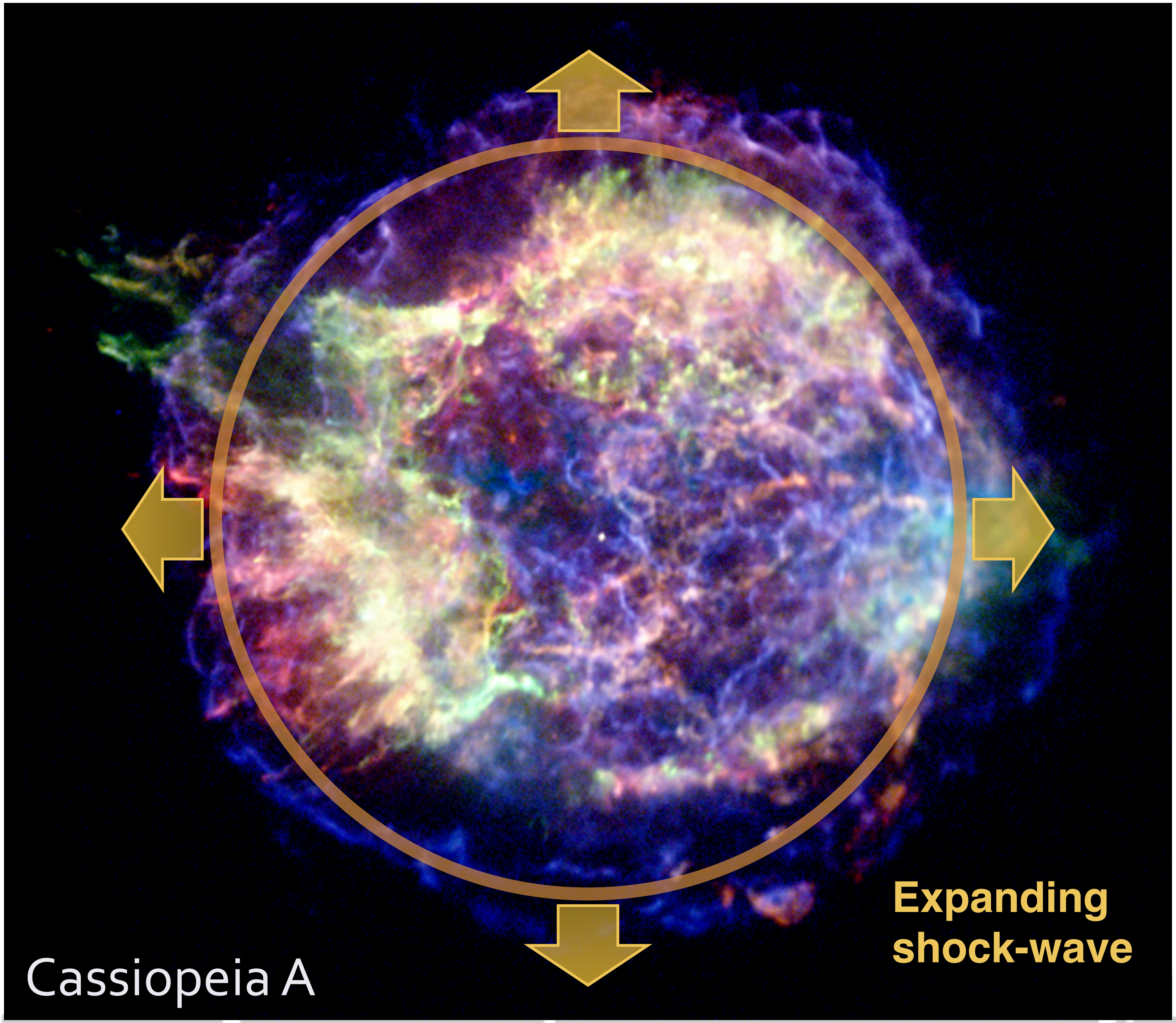
Reetanjali Moharana & S.R., JCAP 12, 021 (2016)

Motivation

Well motivated sources of cosmic rays up to the "knee" of the cosmic-ray spectrum

Some evidence from gamma-ray observations (*pp* interactions)



Motivation

High-energy neutrino production motivated and modeled (various scenarios)

Search and model supernova/starburst activity for IceCube HESE neutrinos

Loeb & Waxman 2006

Anchordoqui, Paul, da Silva et al. 2014

Tamborra, Ando & Murase 2014

Emig, Lunardini & Windhorst 2015

⇨ Interesting hint of correlation of neutrino arrival directions with starburst sources

Smoking-gun signature of cosmic-ray acceleration?

Bechtol, Ahlers, Di Mauro, Ajello & Vandenbroucke 2015

….

Motivation-Outline

High-energy neutrino production motivated and modeled (various scenarios)

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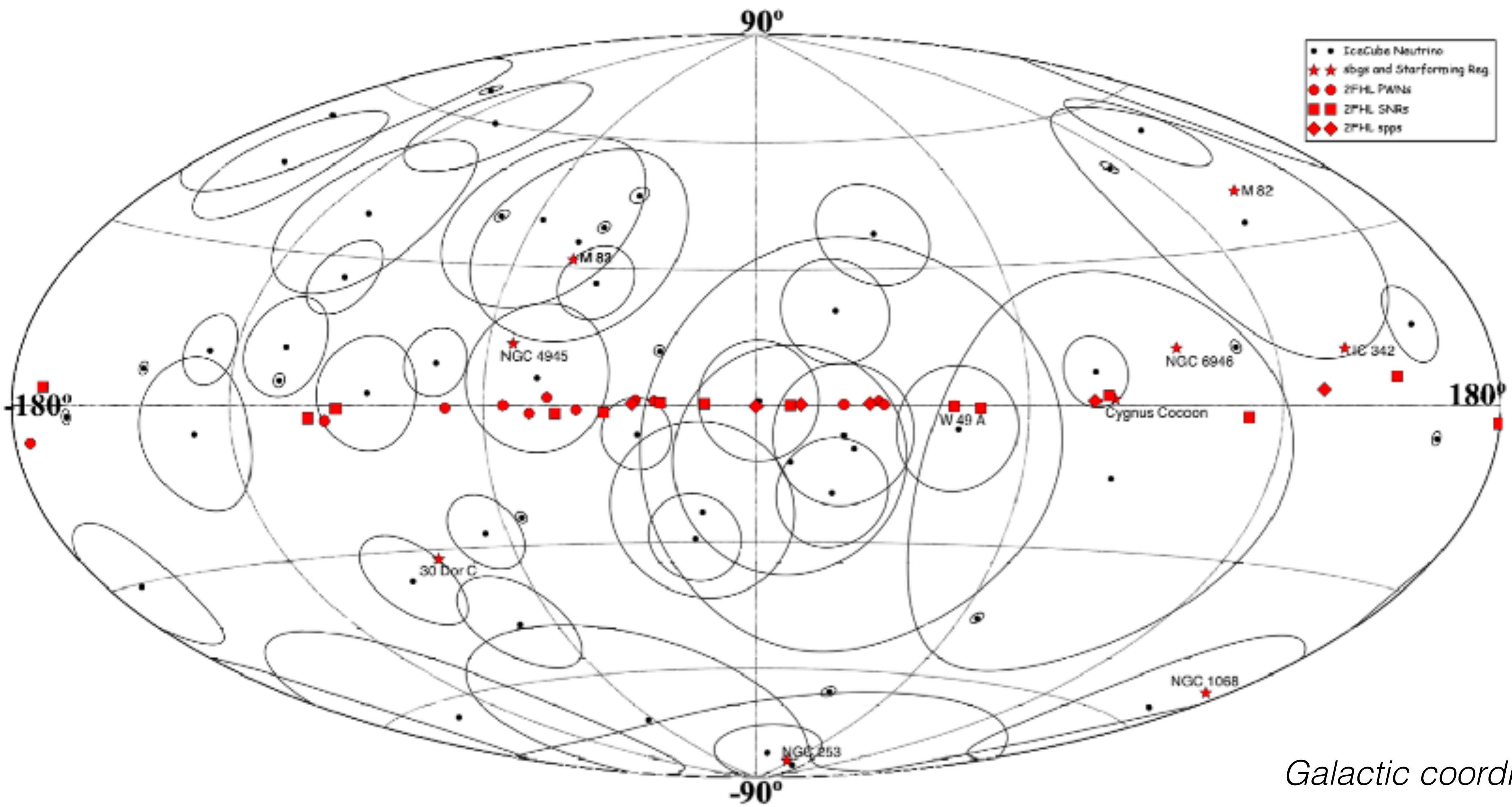
- Study correlation between sources and HESE neutrinos
- Model gamma-ray emission with *pp* interactions
- Compare neutrino emission from *pp* model with data
- Draw conclusions

IceCube 4-year HESE sample

High probability of being extra-terrestrial: *39 shower events, 14 track events*



Galactic coordinates

Fermi 2FHL Galactic sources, Starburst galaxies and star-forming regions

Angular correlation with starburst sources

SN-related source samples

SN-related source samples for statistical study

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:1508.04449*

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/

Cross-correlation statistics

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

Divide the angular error δθ of the HESE events in *M* = 20 concentric rings
Count the number of sources in each of the rings forming a neutrino-source pair: n_j^{data}

$$(j-1)2\delta\theta/M \leq \gamma < j2\delta\theta/M \qquad j = 1, 2, \dots M$$

Tinyakov & Tkachev 2001

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

Monte Carlo simulated data:

Isotropic distribution of sources (isotropic null)

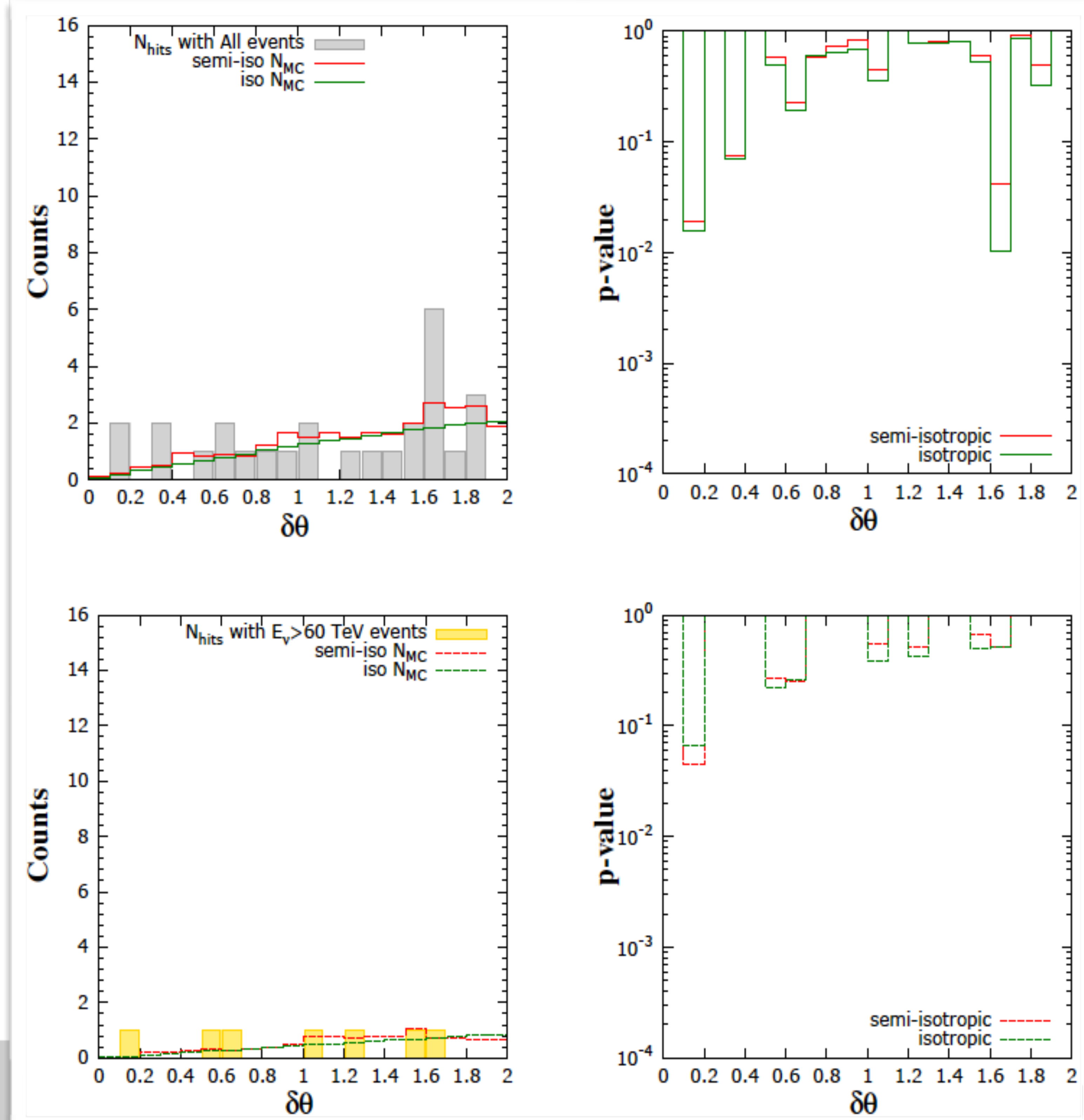
(Galactic sources concentrated within +/-10 deg Galactic plane)

Isotropic distribution in Galactic longitude only (semi-isotropic)

p - value: (frequentist's approach)

Number of times the simulated pairs are equal or greater than data in a given ring/N

Cross-correlation results - Sample I

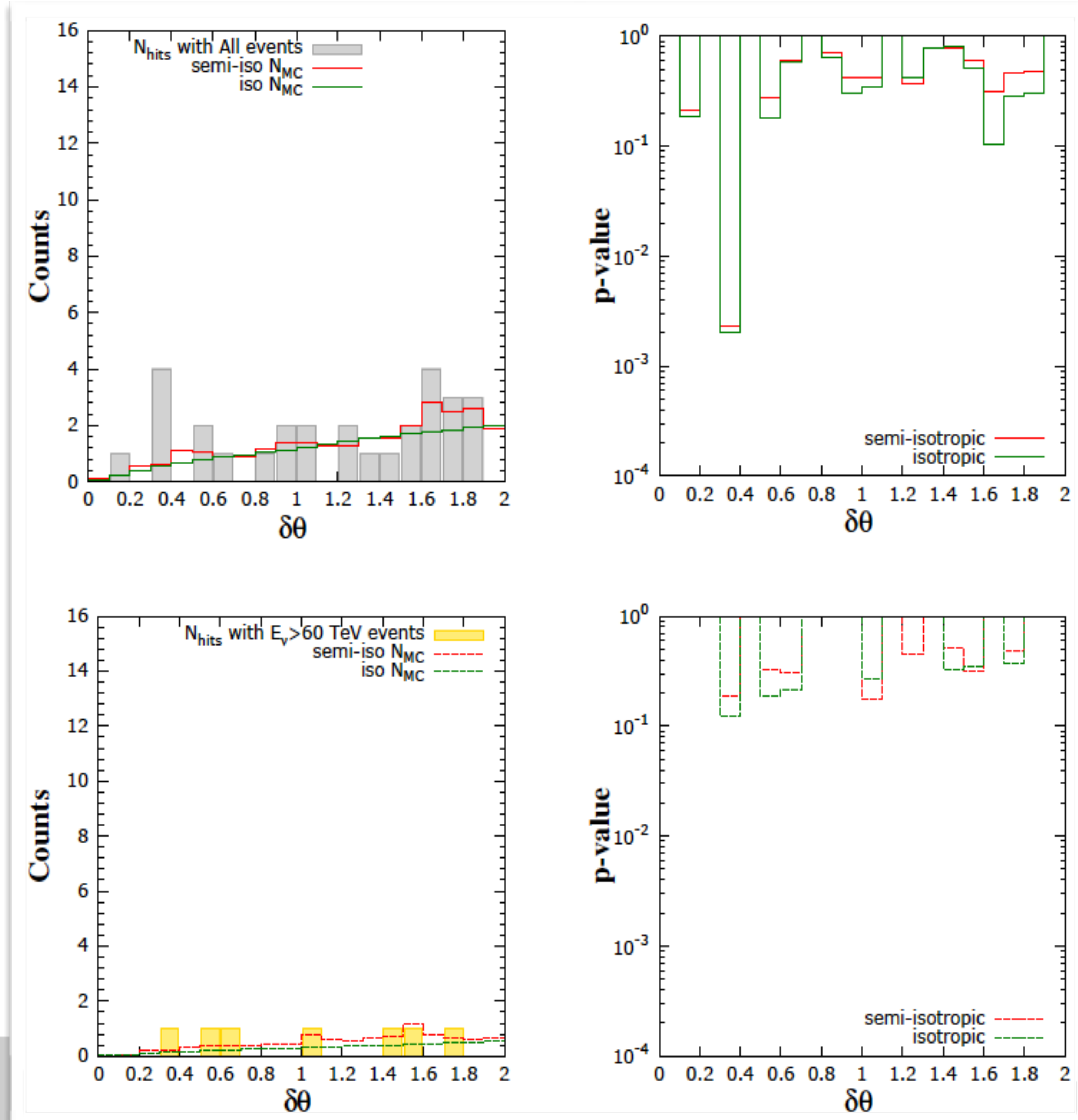


Results from cross-correlation study of the 7 infrared bright starburst galaxies and the IceCube cosmic neutrinos in 4-year sample.

Top panels – All neutrino events

Bottom panels – Events above 60 TeV

Cross-correlation results - Sample II

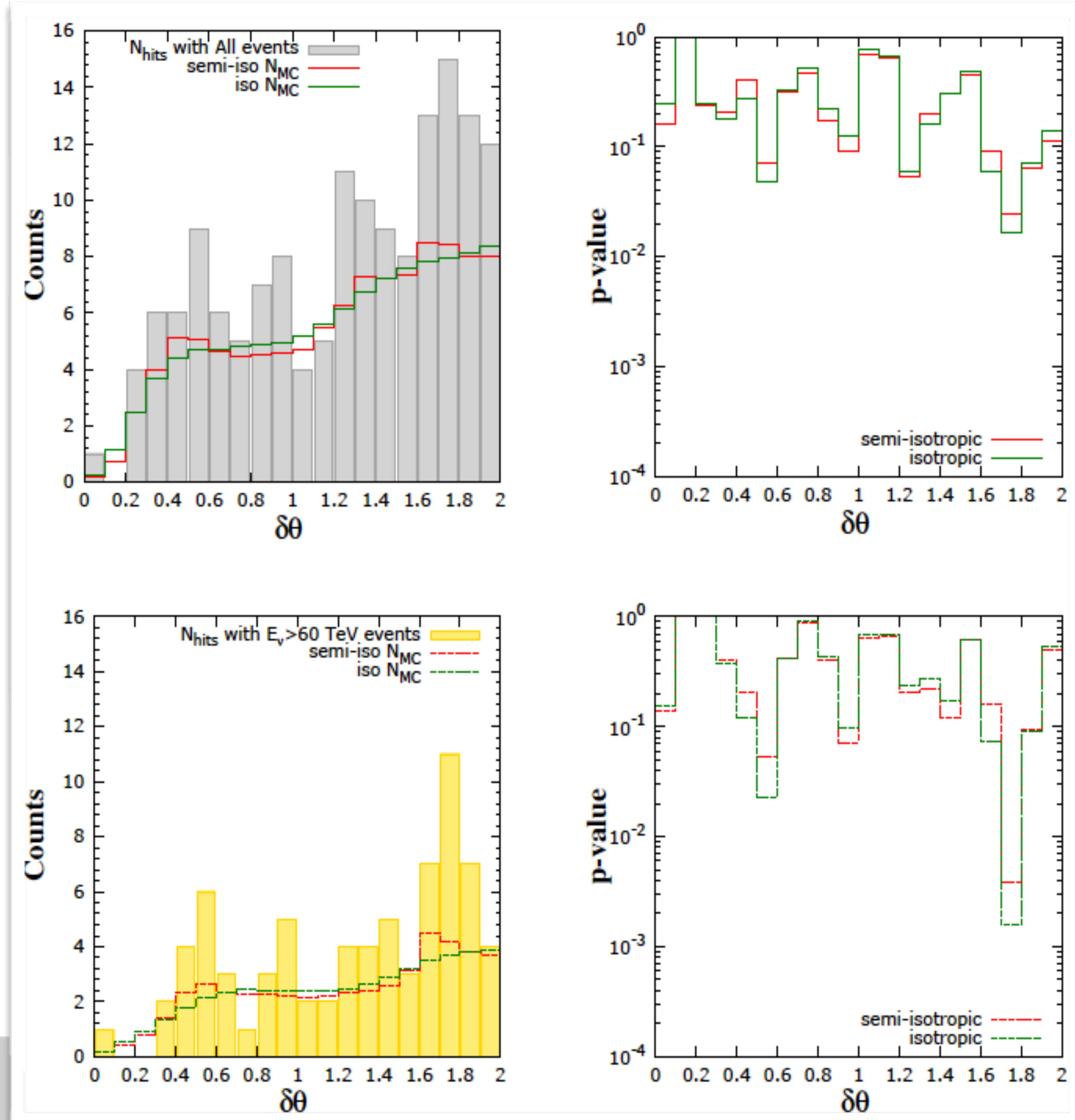


Results from cross-correlation study of the 7 TeV-detected starburst galaxies and regions and the IceCube cosmic neutrinos in 4-year sample.

Top panels – All neutrino events

Bottom panels – Events above 60 TeV

Cross-correlation results - Sample III

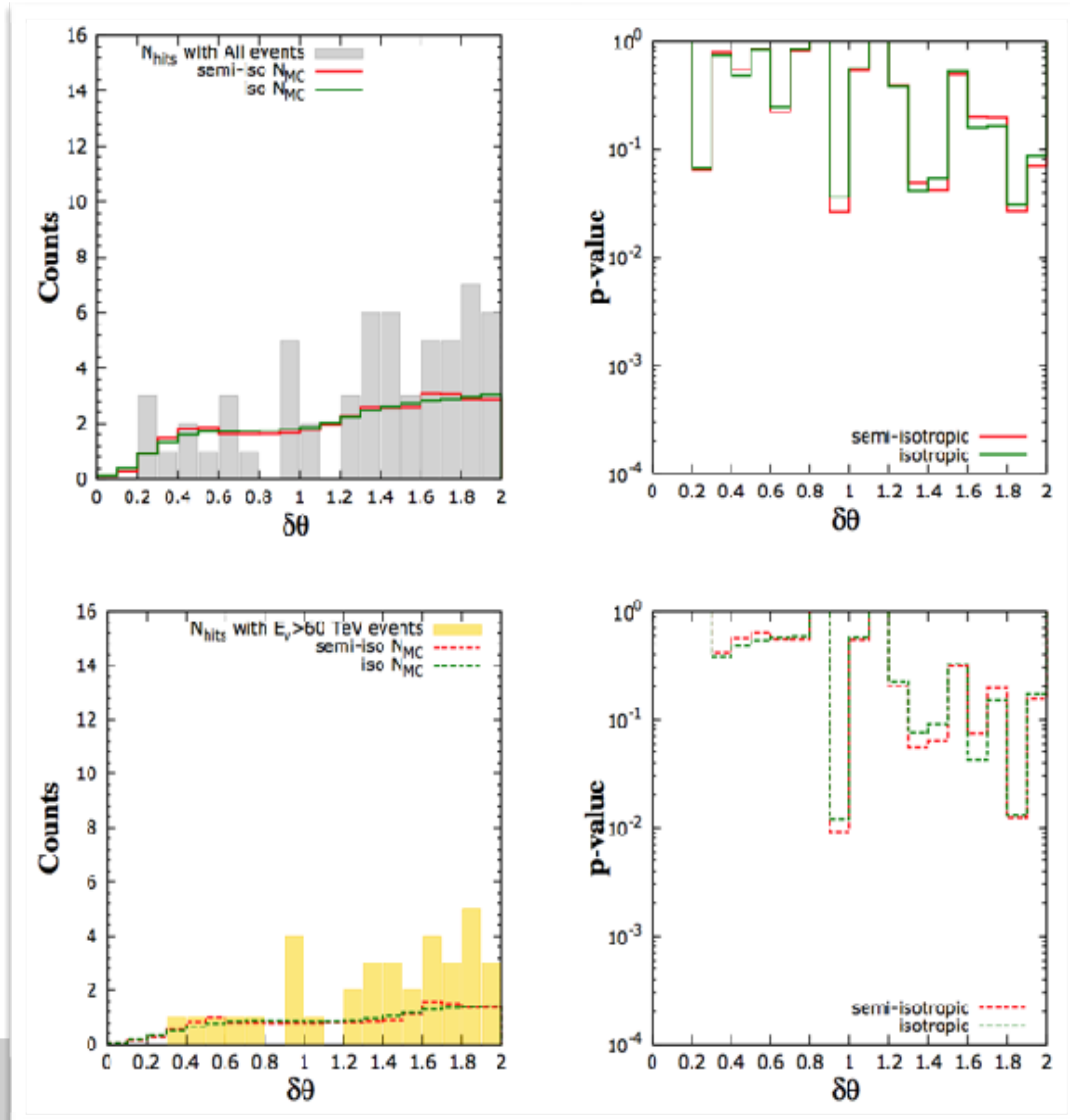


Results from cross-correlation study of the 33 Galactic sources from the Fermi-2FHL catalog (above 50 GeV) and the IceCube cosmic neutrinos in 4-year sample.

Top panels – All neutrino events

Bottom panels – Events above 60 TeV

Cross-correlation results - Sample IV

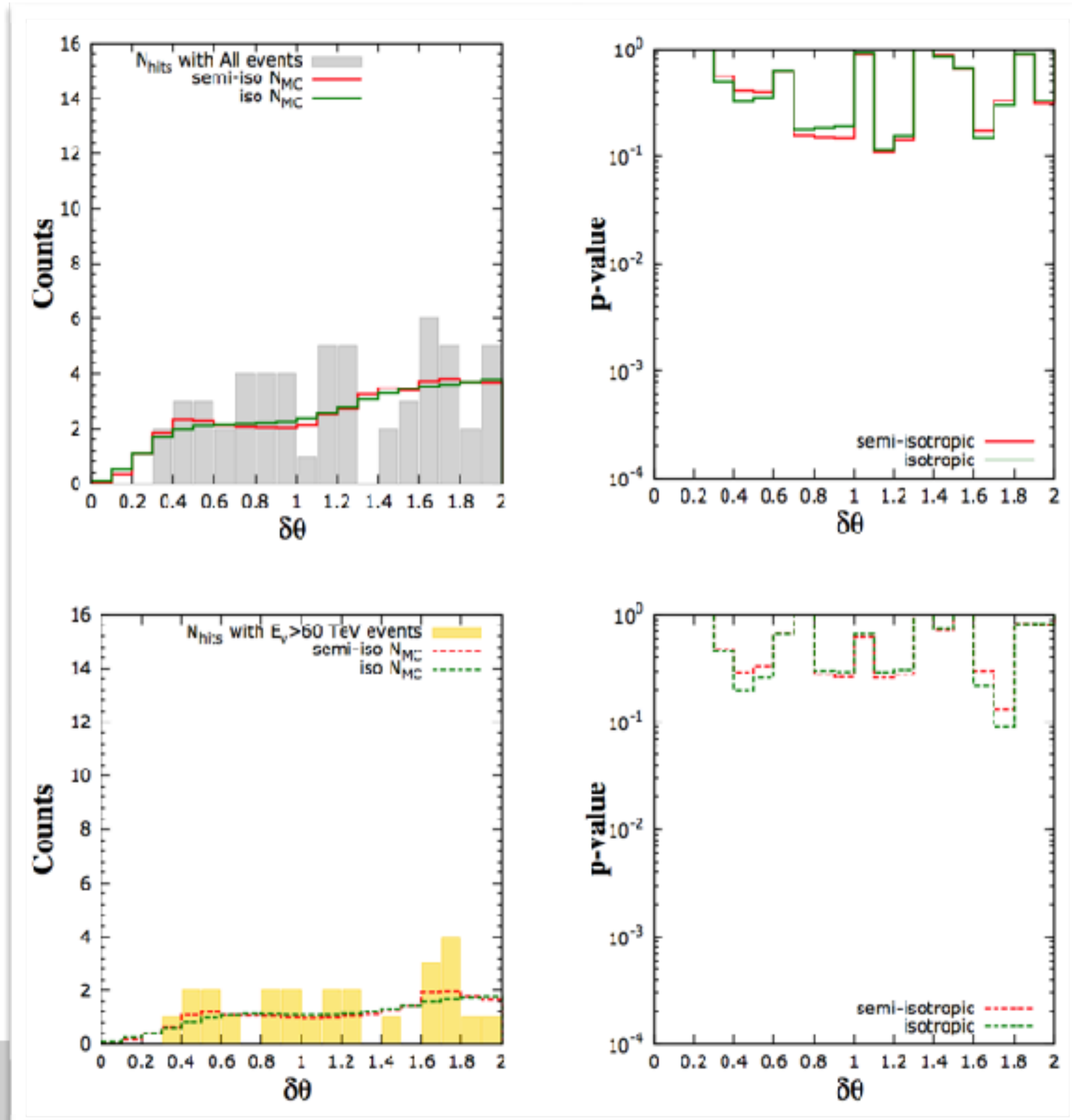


Results from cross-correlation study of the 12 Galactic PWNs from the Fermi-2FHL catalog (above 50 GeV) and the IceCube cosmic neutrinos in 4-year sample.

Top panels – All neutrino events

Bottom panels – Events above 60 TeV

Cross-correlation results - Sample V

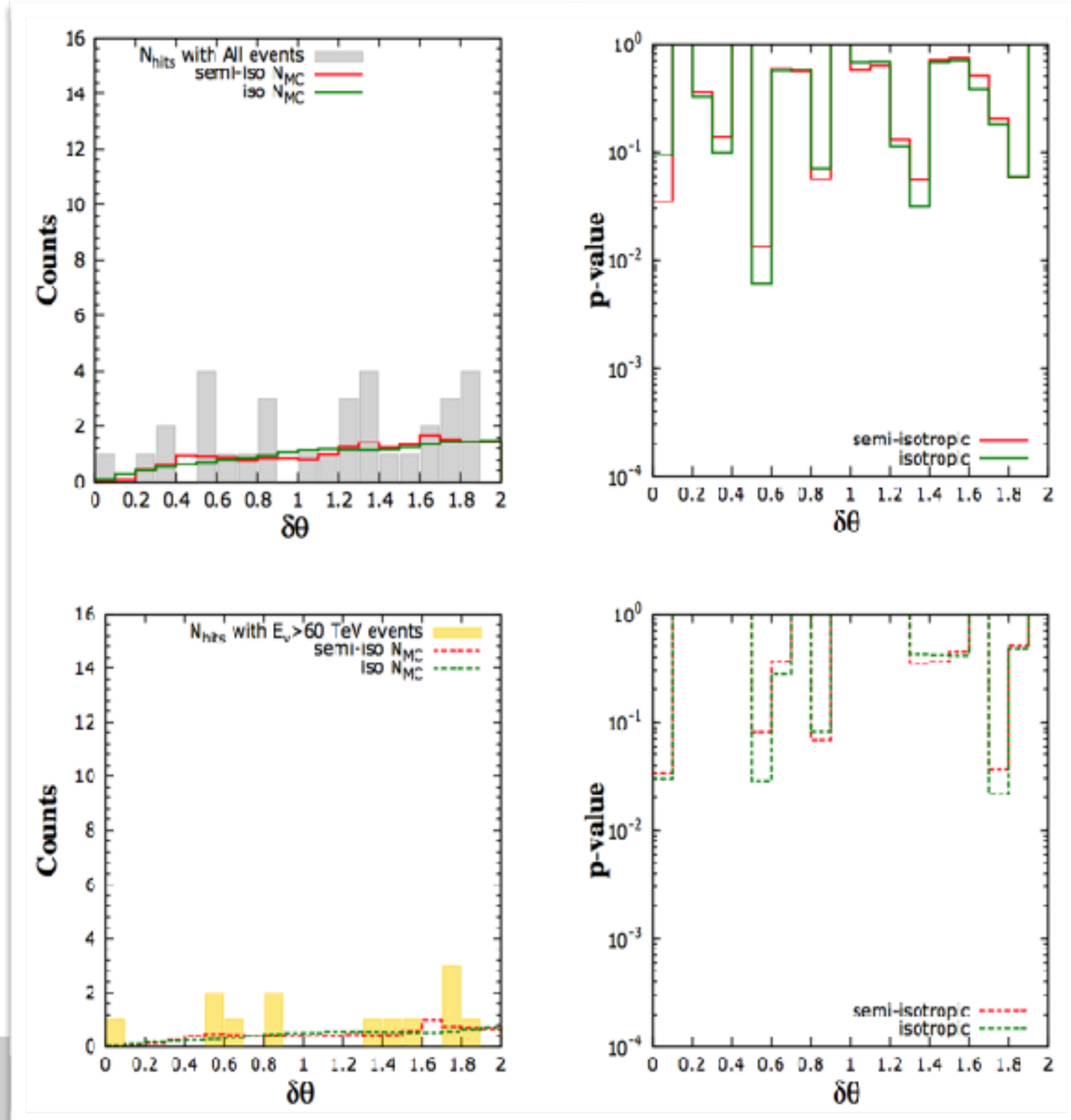


Results from cross-correlation study of the **15 Galactic SNRs from the Fermi-2FHL catalog (above 50 GeV)** and the IceCube cosmic neutrinos in 4-year sample.

Top panels – All neutrino events

Bottom panels – Events above 60 TeV

Cross-correlation results - Sample VI



Results from cross-correlation study of the **6 Galactic SPPs from the Fermi-2FHL catalog (above 50 GeV)** and the IceCube cosmic neutrinos in 4-year sample.

Top panels – All neutrino events

Bottom panels – Events above 60 TeV

Correlation results: Global p-values

post-trial post-trial

Source sets	All νs *semi*-isotropic random p-value	$E_\nu > 60$ TeV *semi*-isotropic random p-value	Post trial p-value *semi*-isotropic random	All νs isotropic random p-value	$E_\nu > 60$ TeV isotropic random p-value	Post trial p-value isotropic random
Sample-I	1.9×10^{-2}	0.518	0.54	$1. \times 10^{-2}$	6.6×10^{-2}	0.34
Sample-II	2.3×10^{-3}	0.177	$\boxed{8.8 \times 10^{-2}}$	2×10^{-3}	0.123	7×10^{-2}
Sample-III	2.4×10^{-2}	3.8×10^{-3}	0.141	1.7×10^{-2}	1.6×10^{-3}	$\boxed{6 \times 10^{-2}}$
Sample-IV	2.65×10^{-2}	9.23×10^{-3}	0.3112	3×10^{-2}	1.2×10^{-2}	0.38
Sample-V	0.11	0.13	0.99	0.15	8.95×10^{-2}	0.97
Sample-VI	1.33×10^{-2}	3.4×10^{-2}	0.4149	6.1×10^{-3}	2.12×10^{-2}	0.22

Semi-isotropic null

Isotropic null

Weak / statistically insignificant correlation

Hadronic modeling of gamma and neutrino

Spectra of gamma and neutrino

Estimate neutrino flux from events within 2x angular errors around correlated source directions

Fit gamma-ray data in the VHE range using pi0 decay photons and estimate corresponding neutrino flux

- 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*

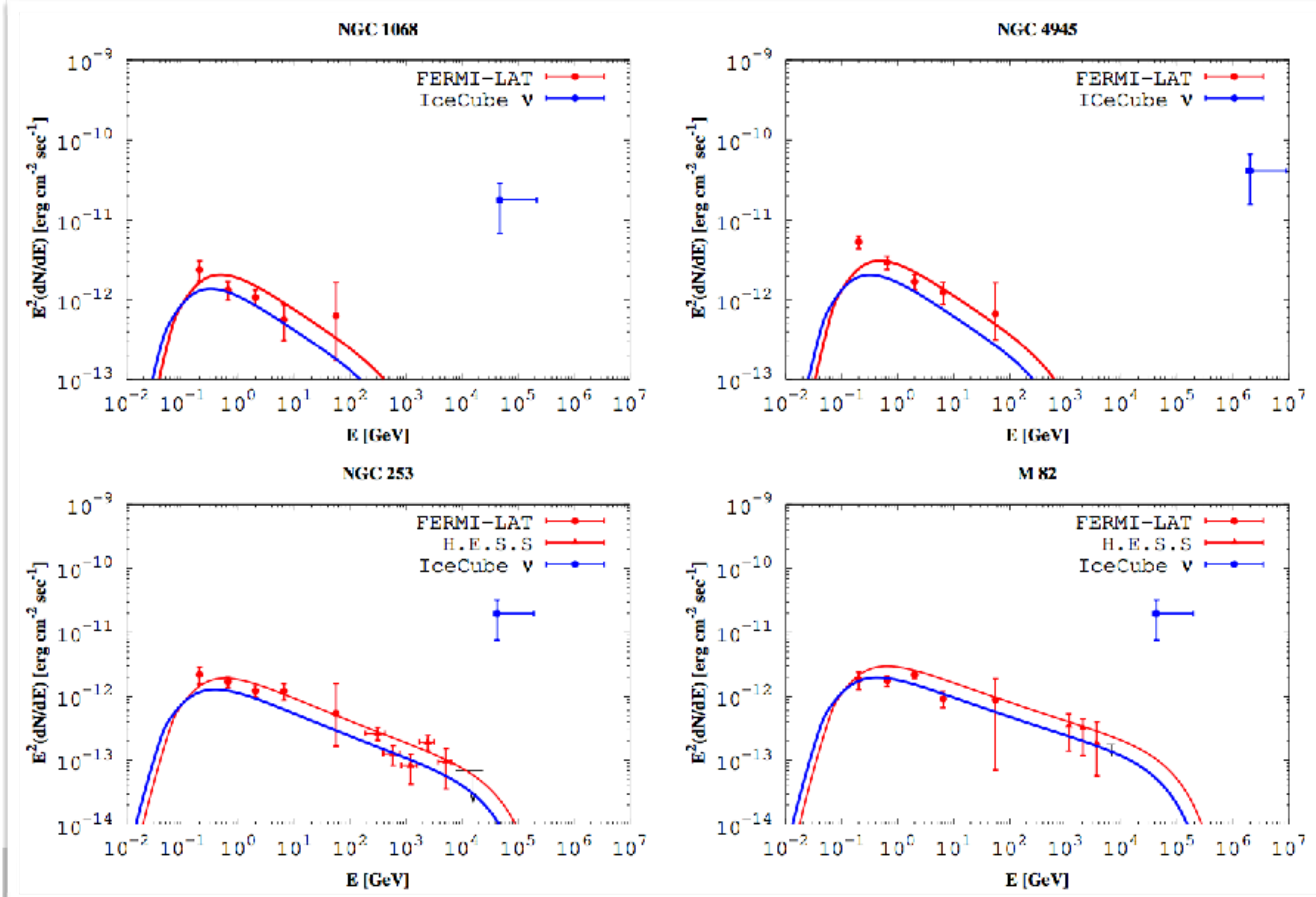
- gamma-ray spectrum from pi0 decay: $$\frac{dN_\gamma}{dE_\gamma} = \frac{2c\tilde{n}\,\langle n_H \rangle}{4\pi D_L^2 K_\pi} \int_{E_{\pi,th}}^{\infty} dE_\pi \frac{\sigma_{pp}(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} N_p(E_\pi)$$

Gas density ~1/cm^3

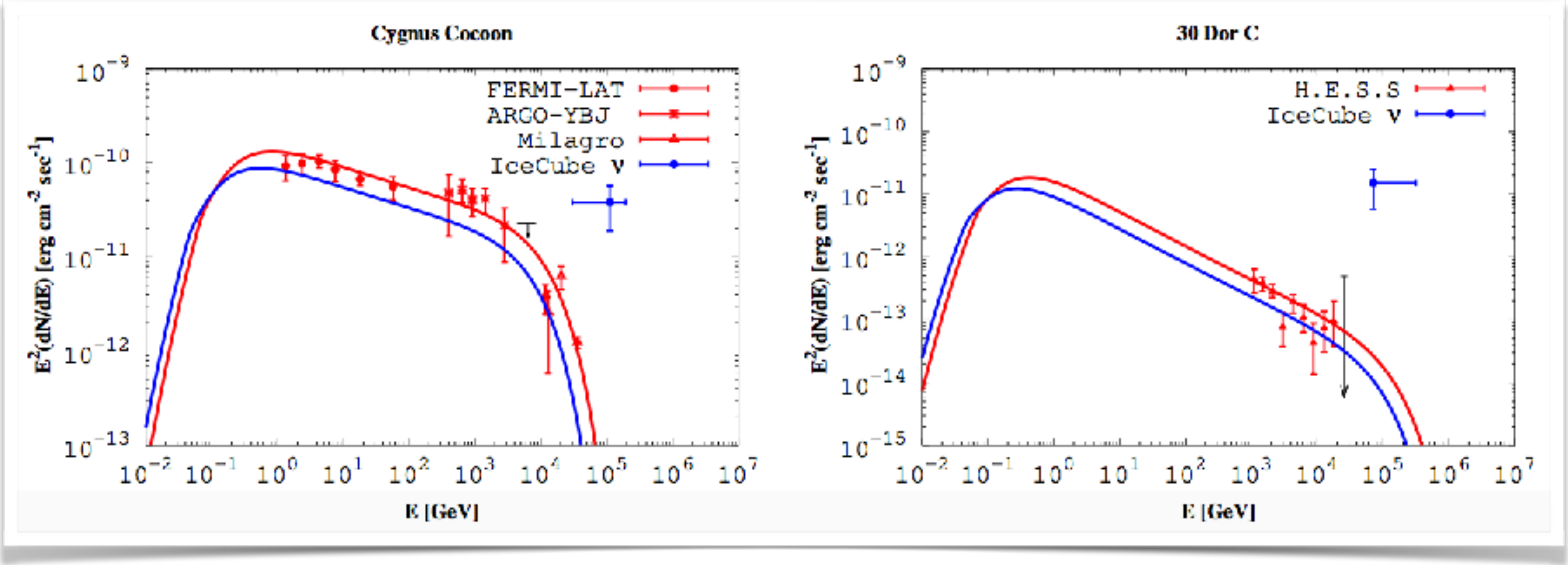
Aharonian & Atoyan 1995

- neutrino spectrum is ~2/3 of the gamma-ray spectrum

Starburst galaxies

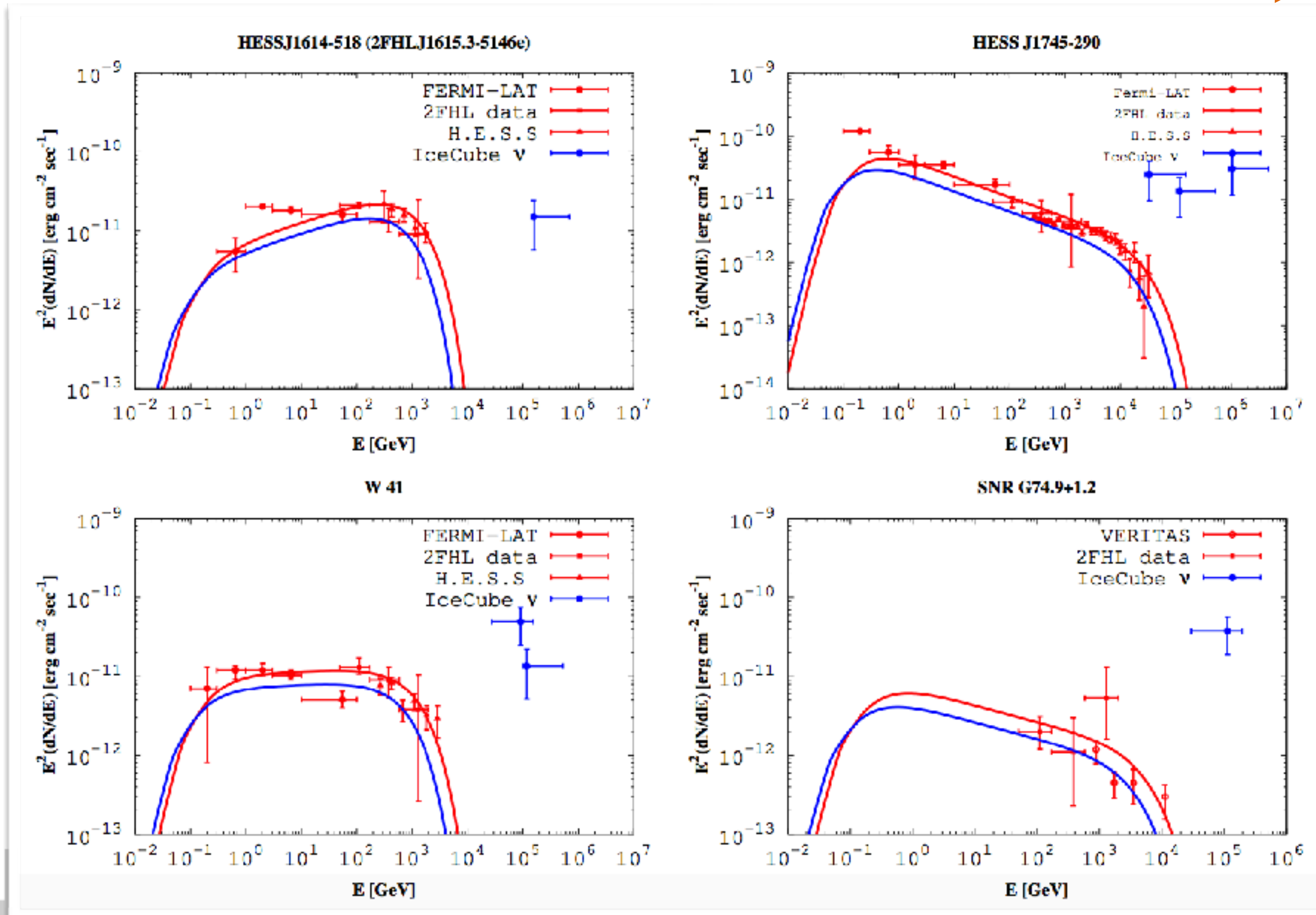


Star-forming regions

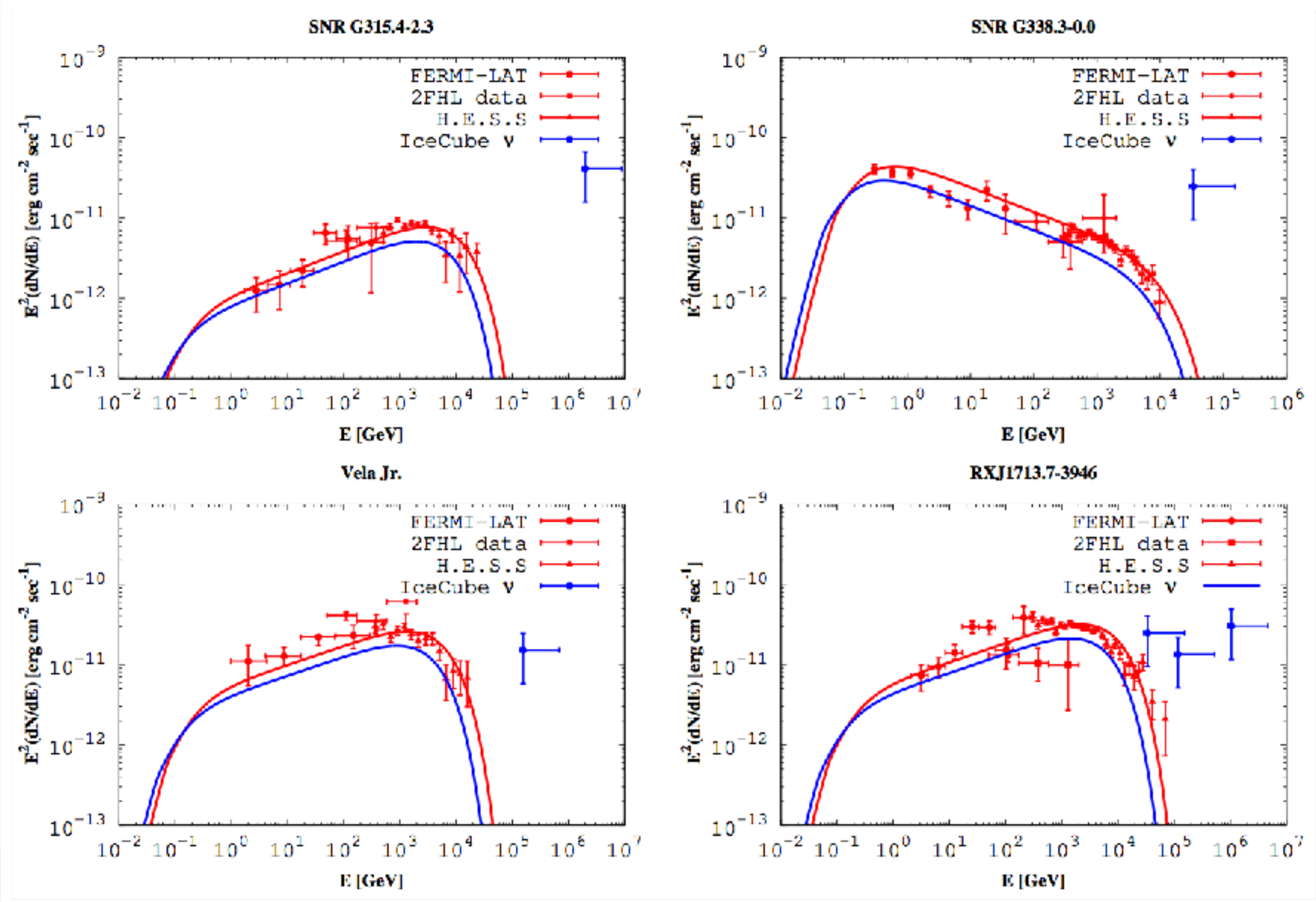


- 4 starburst galaxies and 2 star-forming regions are correlated with HESE
- The other star-forming region is listed in the 2FHL catalog as SNR
- Typical γ-ray luminosity for starburst galaxies: ~ 10^{40} erg/s, *pp* efficiency ~ 5%
- Star-forming region γ-ray luminosity ~ 10^{30} – 10^{32} erg/s, *pp* efficiency ~ 5%
- Cosmic-ray cutoff energy ~ 0.01 - 1 PeV

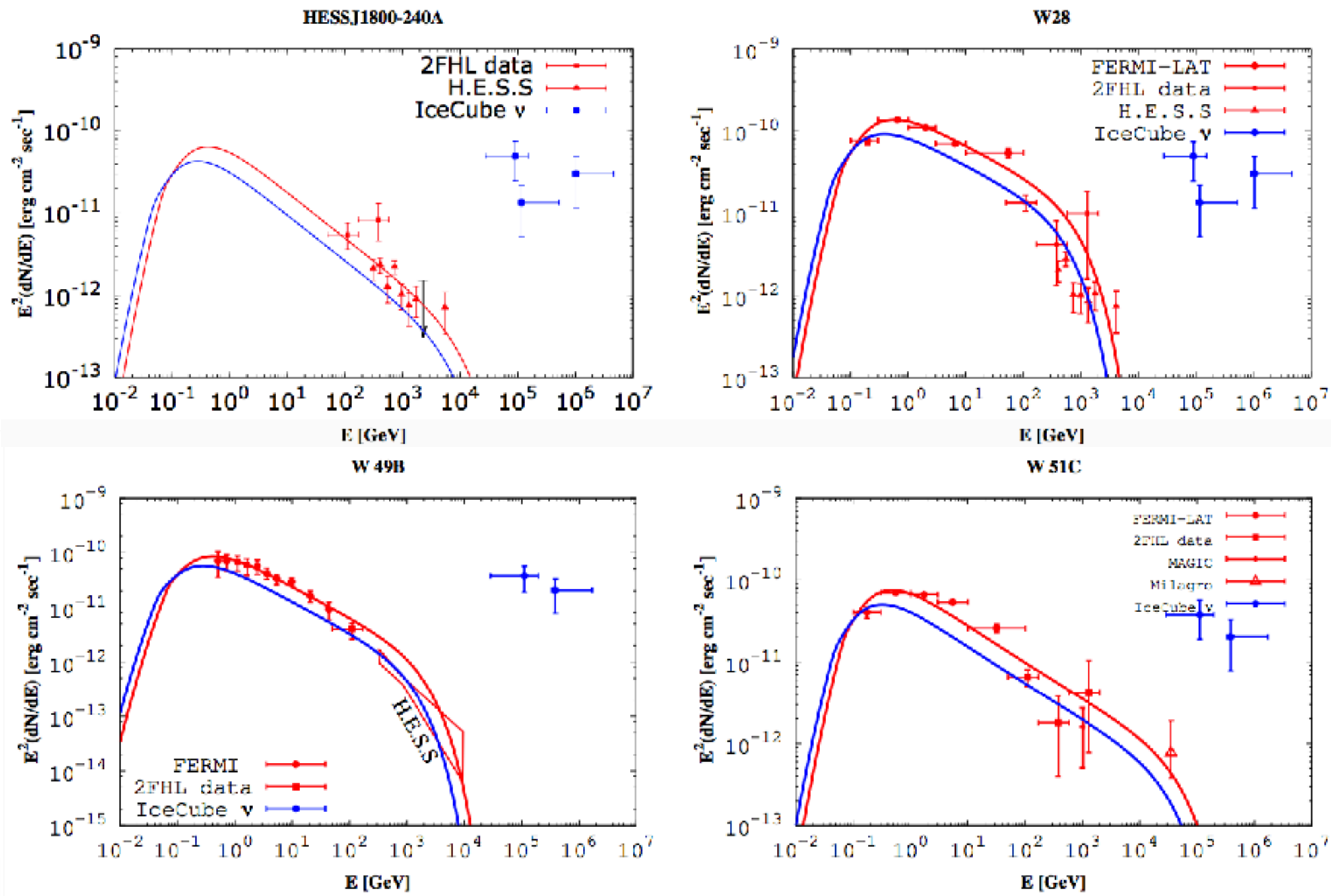
SPP (SNR or PWN) sources



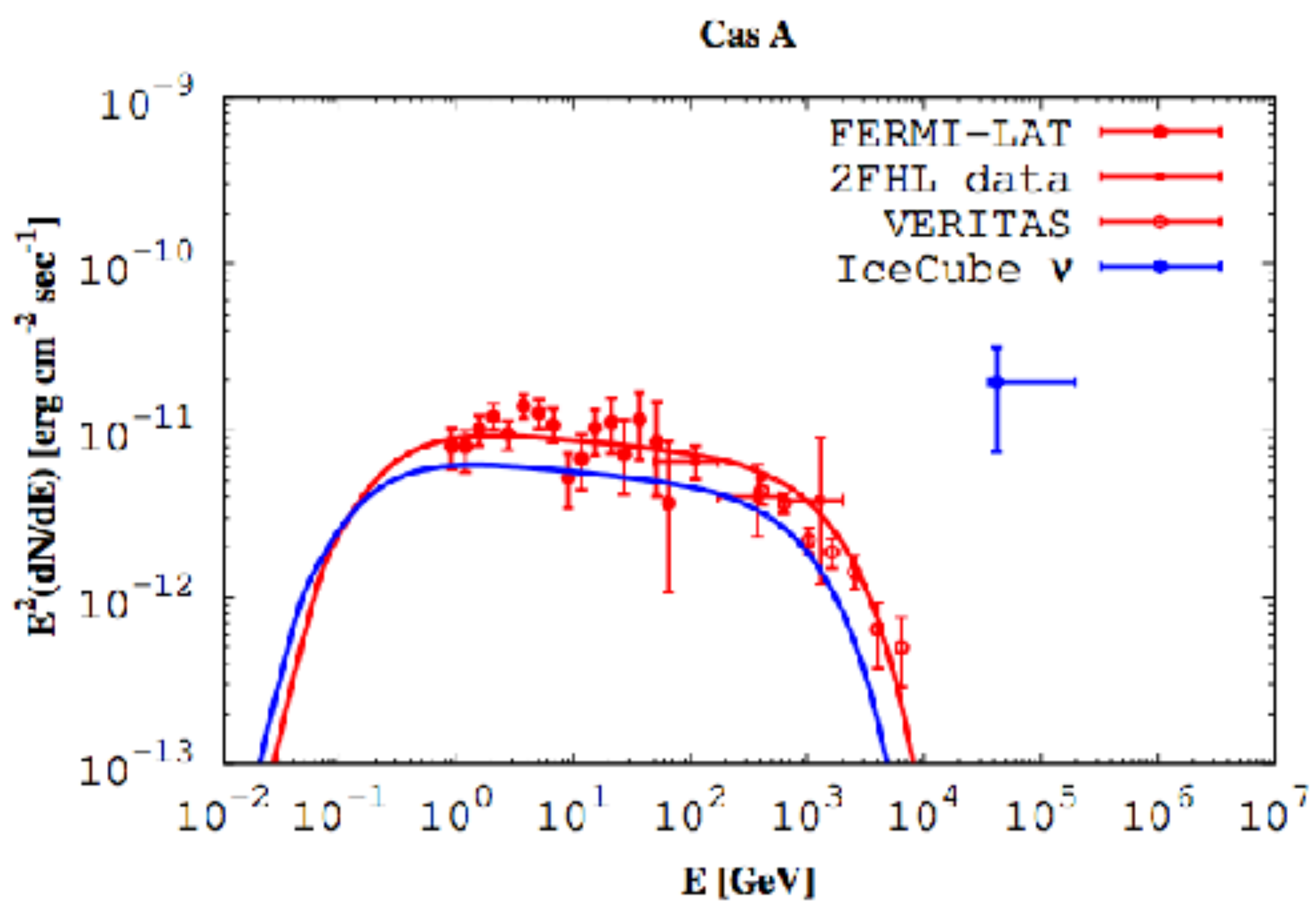
Supernova remnants



Supernova remnants



Supernova remnants



- 4 SPP and 9 SNRs are correlated with HESE neutrinos
- Typical γ-ray luminosity for: ~ 10^{32} – 10^{36} erg/s, *pp* efficiency ~ 5 – 10%
- Cosmic-ray cutoff energy ~ 0.01 - 0.5 PeV

Summary and outlook

HE neutrinos from supernova-related sources

- Weak (statistically insignificant) correlation with IRAS+3FGL+TeVCat and 2FHL
- *pp* interaction model, fitting gamma-ray data, cannot account for neutrino flux

May be …

Other scenarios - early phase: not discussed

Hypernovae with semi-relativistic jets/outflows

Razzaque, Meszaros & Waxman, PRL 93, 181101 (2004)

Ando & Beacom, PRL 95, 061103 (2005)

Shock breakout

Waxman & Loeb, PRL 87, 071101 (2001)

Hypernovae with high-velocity wind

Wang, Razzaque, Meszaros & Dai, PRD 76, 083009 (2007)

Future progress

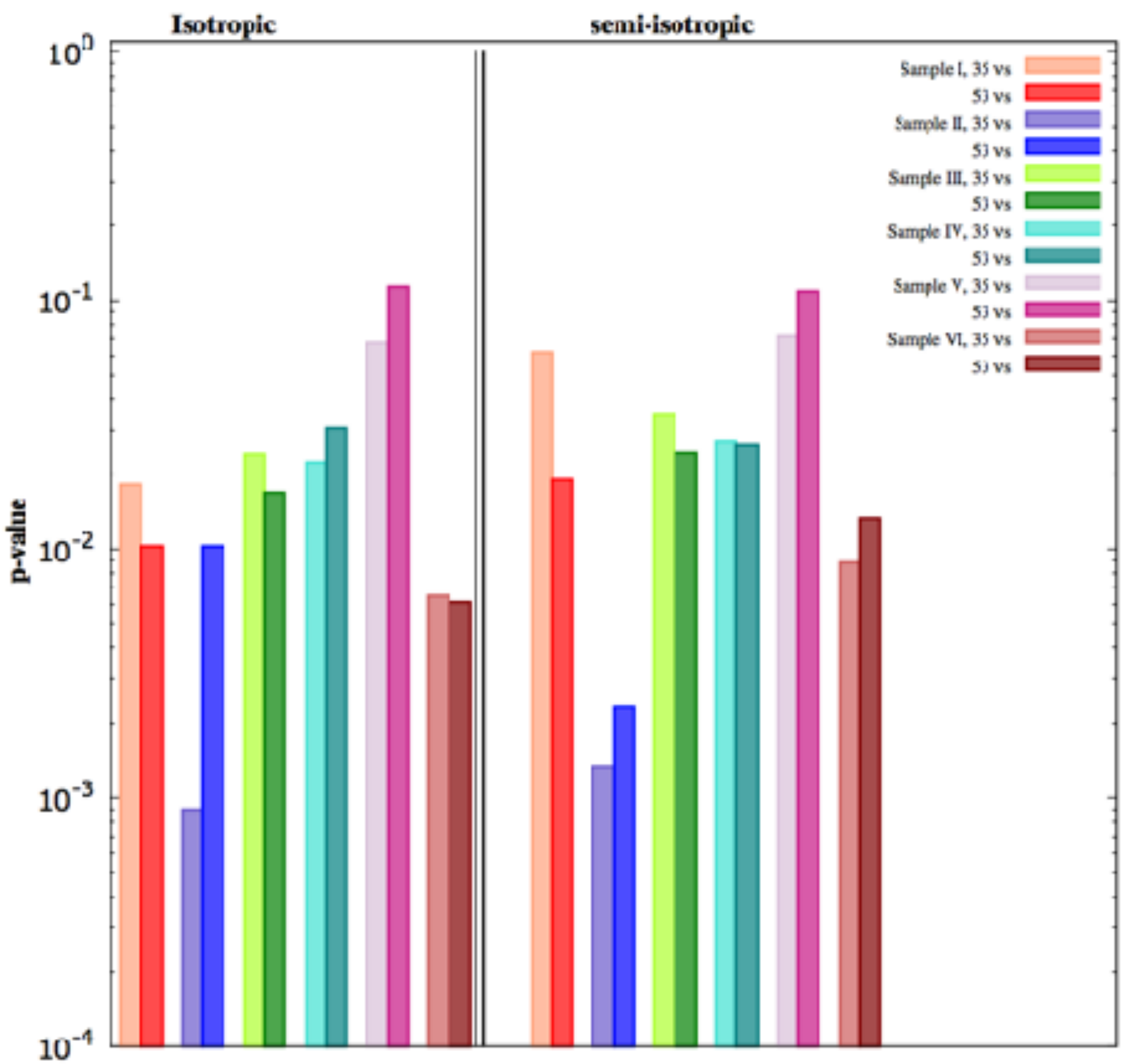
Better angular resolution of the neutrino events - tracks and cascades

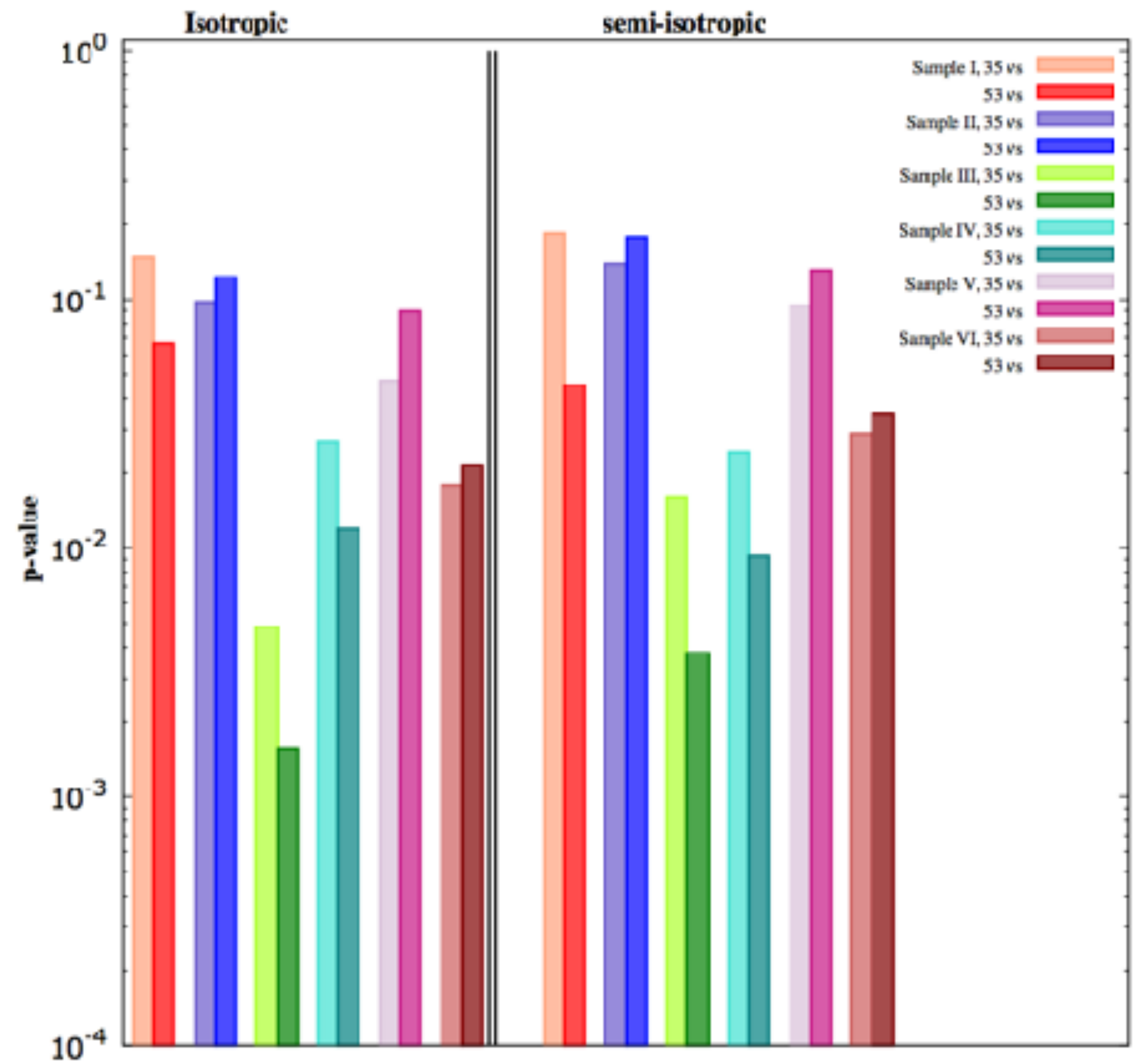
No correlation - ambiguous, diffuse emission from many SNRs (?)

Significant correlation - new research area, additional component (?)

Backup Slides

Change of p-value with time (3 yr and 4 yr)





> 60 TeV events

All events

Hadronic model parameters

Starburst galaxies and regions

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	6.5	0.44
NGC 1068	1	13.7 Mpc	10	2.5	115.7	7.61
IC 342	31	-	-	-		
M 82	31	3.6 Mpc	1000	2.35	14.6	1.
NGC 4945	35	3.9 Mpc	10	2.5	14	0.61
M 83	16	-	-	-		
NGC 6946	34	-	-	-		
W 49A	25, 34, 35	-	-	-	-	
Cygnus Cocoon	29, 34	50 pc	100	2.26	1.4×10^{-7}	9.5×10^{-9}
30 DorC	34	100 pc	1000	2.6	5×10^{-8}	3.4×10^{-9}

Hadronic model parameters

Supernova remnants

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	1.6×10^{-5}	1.3×10^{-6}
SNR G326.3-1.8	-	-	-	-	-	-
SNR G338.3-0.0	25	8.6 kpc	100	2.35	1.2×10^{-3}	8×10^{-5}
VelaJr	40	0.2 kpc	50	1.8	3.8×10^{-7}	2.8×10^{-8}
PuppisA	-	-	-	-		
RXJ1713.7-3946	25	1 kpc	80	1.8	1.15×10^{-5}	9×10^{-7}
HESSJ1800-240A	24, 25, 2, 14	2 kpc	100	2.6	9.3×10^{-5}	6.2×10^{-6}
W 28	24, 25, 2, 14	2 kpc	8	2.4	1.8×10^{-4}	1.2×10^{-5}
W 49B	25, 33, 34	11.4 kpc	15	2.6	3×10^{-3}	$3. \times 10^{-4}$
W 51C	25, 34, 35	4.3 kpc	500	2.5	4.3×10^{-4}	2.9×10^{-5}
IC 443	-	-	-	-		
S 147	-	-	-	-		
Gamma Cygni	29, 34	-	-	-		
SNR G150.3+4.5	-	-	-	-		
Cas A	34	3.4 kpc	15	2.1	5.7×10^{-4}	3.7×10^{-5}

Hadronic model parameters

Supernova remnants or pulsar wind nebulae (SPP)

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]
2FHL SPPs						
HESSJ1614-518	52	10 kpc	10	1.8	8.3×10^{-4}	5.6×10^{-5}
HESS J1745-290	25, 2, 14	8.5 kpc	250	2.37	1.16×10^{-3}	7.7×10^{-5}
W 30	24, 25, 2, 14	-	-	-		
W 41	24, 25, 2	4 kpc	10	2	1×10^{-4}	6.6×10^{-6}
SNR G74.9+1.2	29, 34	12 kpc	50	2.25	3.8×10^{-3}	2.5×10^{-4}
PSR J0205+6449	-	-	-	-		