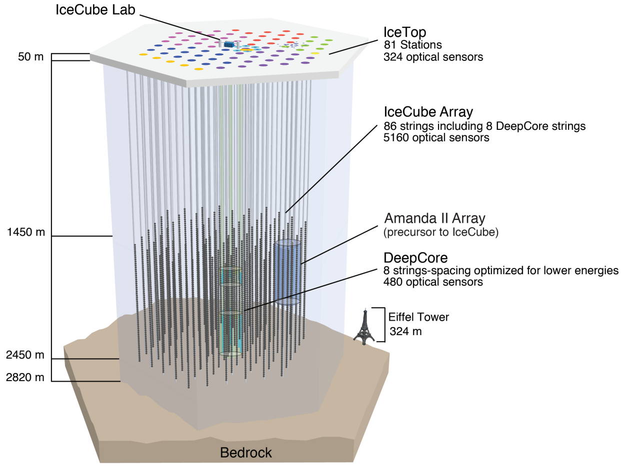
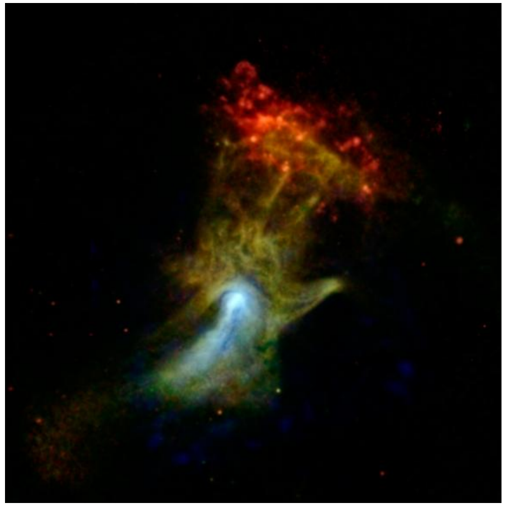




Extreme blazars as counterparts of IceCube neutrinos

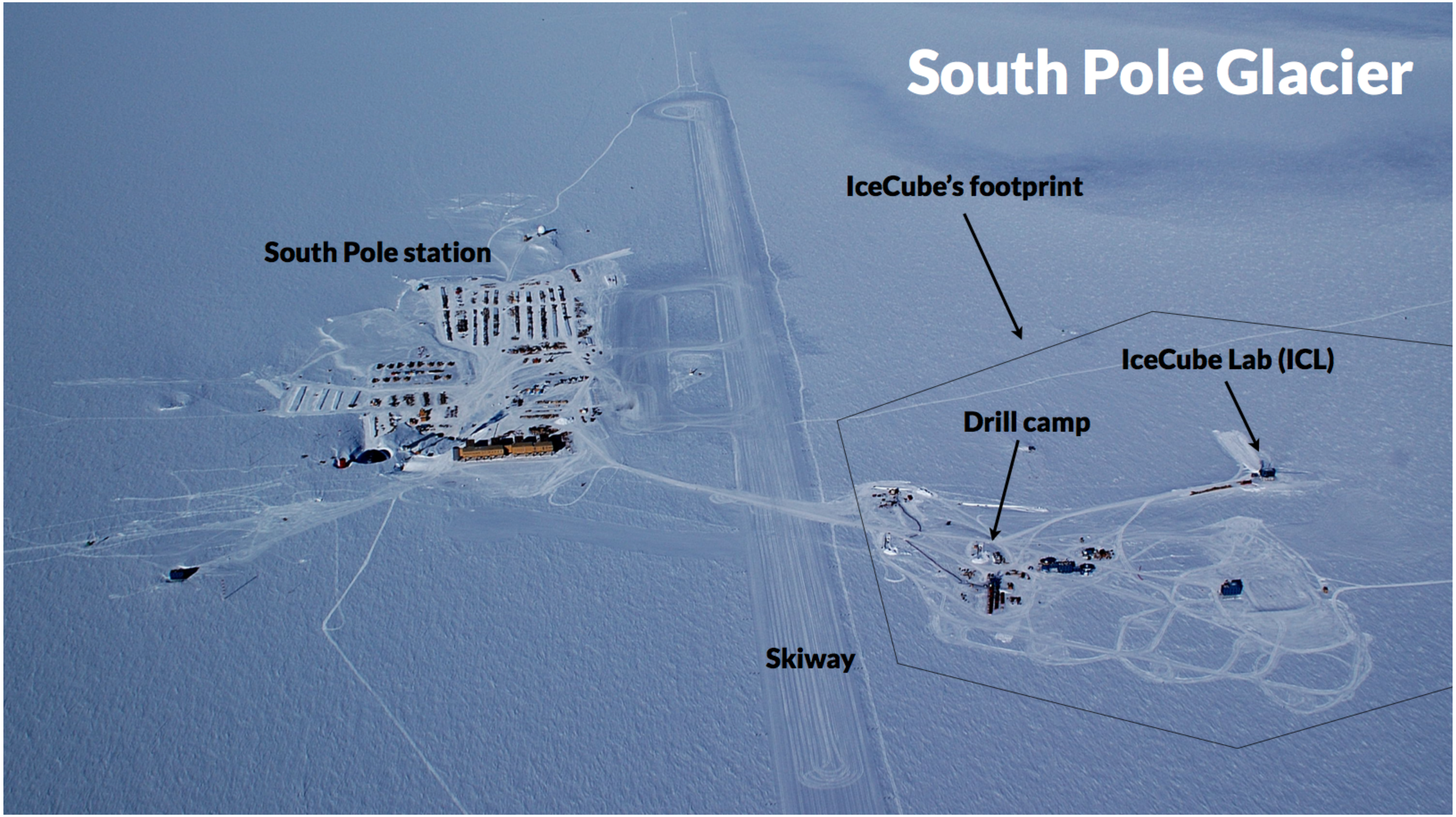
Paolo Padovani, ESO, Germany

with Elisa Resconi (TUM, Germany), Paolo Giommi (ASDC, Italy), Maria Petropoulou (Purdue University, Indiana), and others

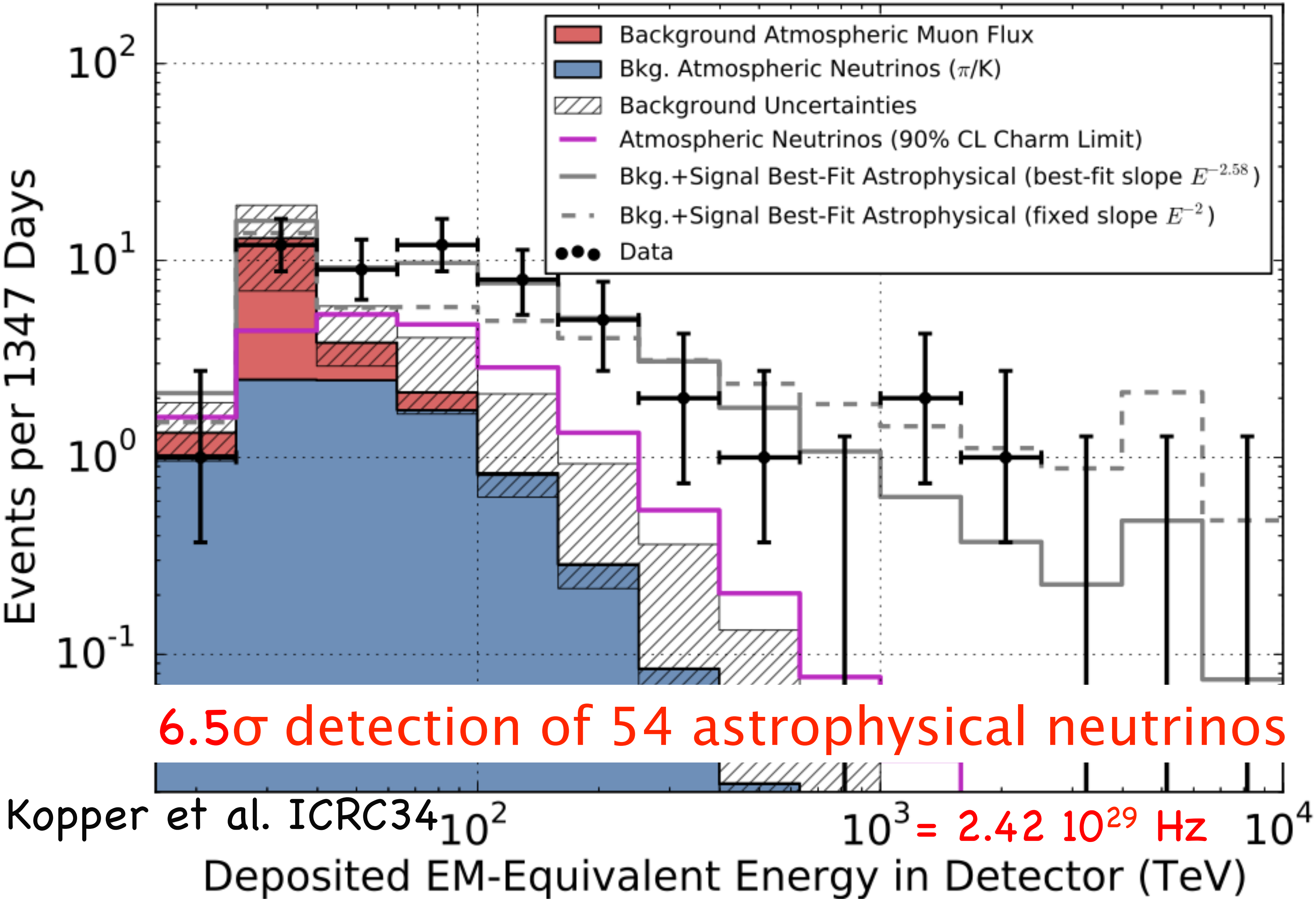
Correlation between strong, VHE γ-ray HBL and IceCube neutrinos at 0.4%

* Mostly based on Padovani et al. (2016), MNRAS, 457, 3582

IceCube


South Pole Glacier
IceCube's footprint
South Pole station
IceCube Lab (ICL)
Drill camp
Skiway

IceCube (2015) [4 years]



Kopper et al. ICRC34

Our list

- deposited E ≥ 60 TeV (to reduce background)
- angular error ≤ 20° (to reduce counterparts)

→ 30 events + 21 tracks (angular errors ~ 0.4°) = 51 IceCube events

Table 1. Selected list of high-energy neutrinos detected by IceCube.

IceCube ID	Dep. energy (TeV)	νf_ν [a] (10^{-11} erg cm^{-2} s^{-1})	RA (2000)	Dec (2000)	Median angular error (deg)	b_{II} (deg)
3	$78.7^{+10.8}_{-8.7}$	$1.4^{+3.3}_{-1.2}$	08 31 36	−31 12 00	≤1.4	+5
4	165^{+20}_{-15}	$0.8^{+1.9}_{-0.7}$	11 18 00	−51 12 00	7.1	+9
5	71.4±9.0	$1.3^{+3.0}_{-1.1}$	07 22 24	−00 24 00	≤1.2	+7
9	$63.2^{+7.1}_{-8.0}$	$2.1^{+4.7}_{-1.7}$	10 05 12	+33 36 00	16.5	+54
10	$97.2^{+10.4}_{-12.4}$	$1.2^{+2.8}_{-1.0}$	00 20 00	−29 24 00	8.1	−83
11	$88.4^{+12.5}_{-10.7}$	$1.1^{+2.5}_{-0.9}$	10 21 12	−08 54 00	16.7	+39
12	104±13.0	$0.9^{+2.1}_{-0.8}$	19 44 24	−52 48 00	9.8	−29
13	253^{+26}_{-22}	$1.2^{+2.7}_{-1.0}$	04 31 36	+40 18 00	≤1.2	−5
14	1041^{+132}_{-144}	$1.1^{+2.6}_{-0.9}$	17 42 24	−27 54 00	13.2	+1
17	200±27	$1.2^{+2.9}_{-1.0}$	16 29 36	+14 30 00	11.6	+38
19	$71.5^{+7.0}_{-7.2}$	$1.3^{+3.0}_{-1.1}$	05 07 36	−59 42 00	9.7	−36
20	1141^{+143}_{-133}	$1.1^{+2.6}_{-0.9}$	02 33 12	−67 12 00	10.7	−47
22	220^{+21}_{-24}	$0.7^{+1.7}_{-0.6}$	19 34 48	−22 06 00	12.1	−19
23	$82.2^{+8.6}_{-8.4}$	$1.5^{+3.5}_{-1.3}$	13 54 48	−13 12 00	≤1.9	+47
26	210^{+29}_{-26}	$1.1^{+2.6}_{-0.9}$	09 33 36	+22 42 00	11.8	+45
27	60.2±5.6	$1.8^{+4.0}_{-1.5}$	08 06 48	−12 36 00	6.6	+10
30	129^{+14}_{-12}	$0.8^{+1.9}_{-0.7}$	06 52 48	−82 42 00	8.0	−27
33	385^{+46}_{-49}	$1.4^{+3.2}_{-1.2}$	19 30 00	+07 48 00	13.5	−5
35	2004^{+236}_{-262}	$1.4^{+3.3}_{-1.2}$	13 53 36	−55 48 00	15.9	+6
38	201±16	$1.2^{+2.9}_{-1.0}$	06 13 12	+14 00 00	≤1.2	−2
39	101^{+13}_{-12}	$0.9^{+2.0}_{-0.7}$	07 04 48	−17 54 00	14.2	−5
40	157^{+16}_{-17}	$0.8^{+1.8}_{-0.6}$	09 35 36	−48 30 00	11.7	+3
41	$87.6^{+8.4}_{-10.0}$	$1.4^{+3.2}_{-1.2}$	04 24 24	+03 18 00	11.1	−30
44	$84.6^{+7.4}_{-7.9}$	$1.4^{+3.1}_{-1.1}$	22 26 48	+00 00 00	≤1.2	−46
45	430^{+57}_{-49}	$0.9^{+2.0}_{-0.7}$	14 36 00	−86 18 00	≤1.2	−24
46	158^{+15}_{-17}	$0.8^{+1.8}_{-0.7}$	10 02 00	−22 24 00	7.6	+26
47	$74.3^{+8.3}_{-7.2}$	$1.6^{+3.8}_{-1.4}$	13 57 36	+67 24 00	≤1.2	+48
48	105^{+14}_{-10}	$0.9^{+2.1}_{-0.8}$	14 12 24	−33 12 00	8.1	+27
51	$66.2^{+6.7}_{-6.1}$	$2.2^{+5.0}_{-1.8}$	05 54 24	+54 00 00	6.5	+14
52	158^{+16}_{-18}	$0.8^{+1.8}_{-0.7}$	16 51 12	−54 00 00	7.8	−6
	2600±300		07 21 22	+11 28 48	0.27	+12

Looking for the "right" sources

- PeV neutrinos → protons with $E \approx 10 - 100$ PeV
- *pp* and *pγ* collisions → $E_\gamma \approx 2 \times E_\nu$ and $F_\gamma \approx 2 \times F_\nu$
- Look for γ-ray sources!
  - ✓ E.g. only < 1% of all known AGN are in the *Fermi* 3FGL catalogue ($E > 100$ MeV)
- 60 TeV $< E_\nu <$ 2 PeV → 120 TeV $< E_\gamma <$ 4 PeV!

Using the best catalogues

- *Fermi* 2FHL catalogue (E > 50 GeV; Ackermann et al. 2016): 257 sources ($|b_{II}| > 10°$), > 90% blazars
- 2WHSP catalogue (2nd Wise High Synchrotron Peaked; Chang, Arsioli, Giommi, PP, in prep.): ~ 1,700 *blazars + candidates*; $\nu_{peak,synch} > 10^{15}$ Hz; 35 sources TeV-detected (148 potential: FoM), ~ 350 in *Fermi* 3FGL
- *Fermi* 3LAC catalogue (E > 100 MeV; Ackermann et al. 2015): 1,444 sources ($|b_{II}| > 10°$), ~99% blazars

Statistical analysis

- N_ν: neutrino events with at least one γ–ray counterpart
- $N_\nu(f_\gamma)$ or $N_\nu(\mathrm{FoM})$
- chance probability determined on 10^5 – 10^6 randomised samples
- results: p–value vs. f_γ or FoM

Statistical analysis

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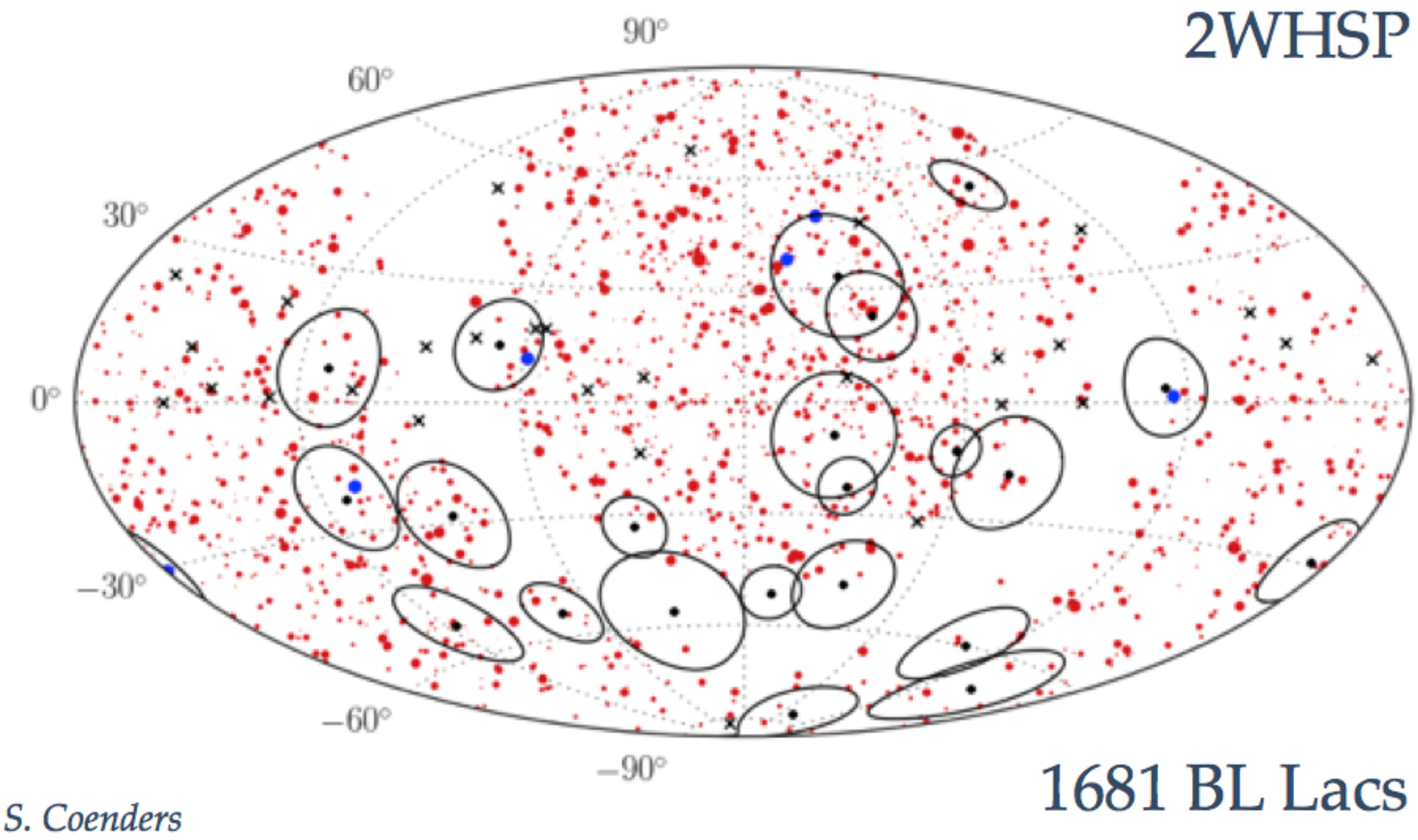
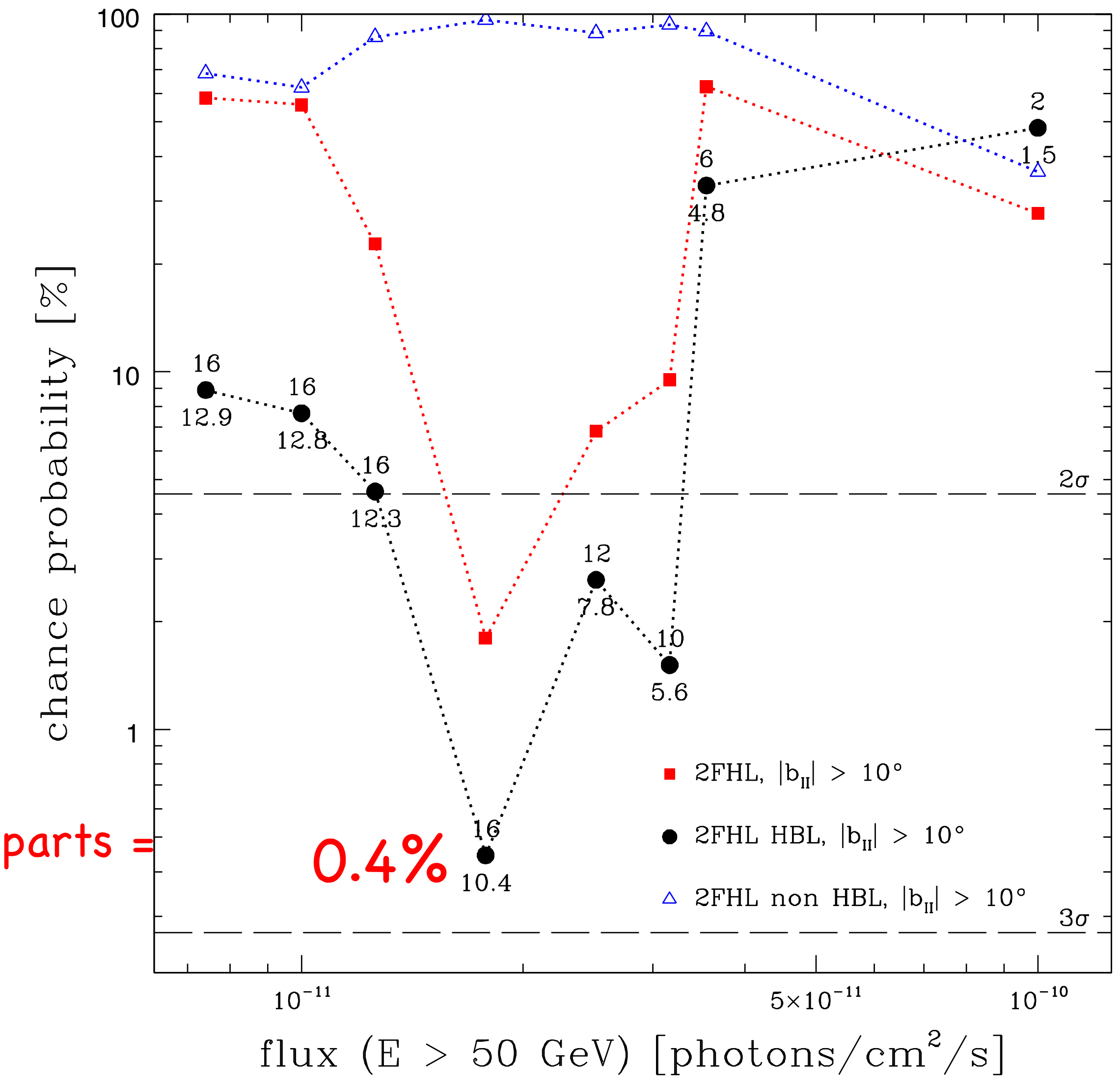


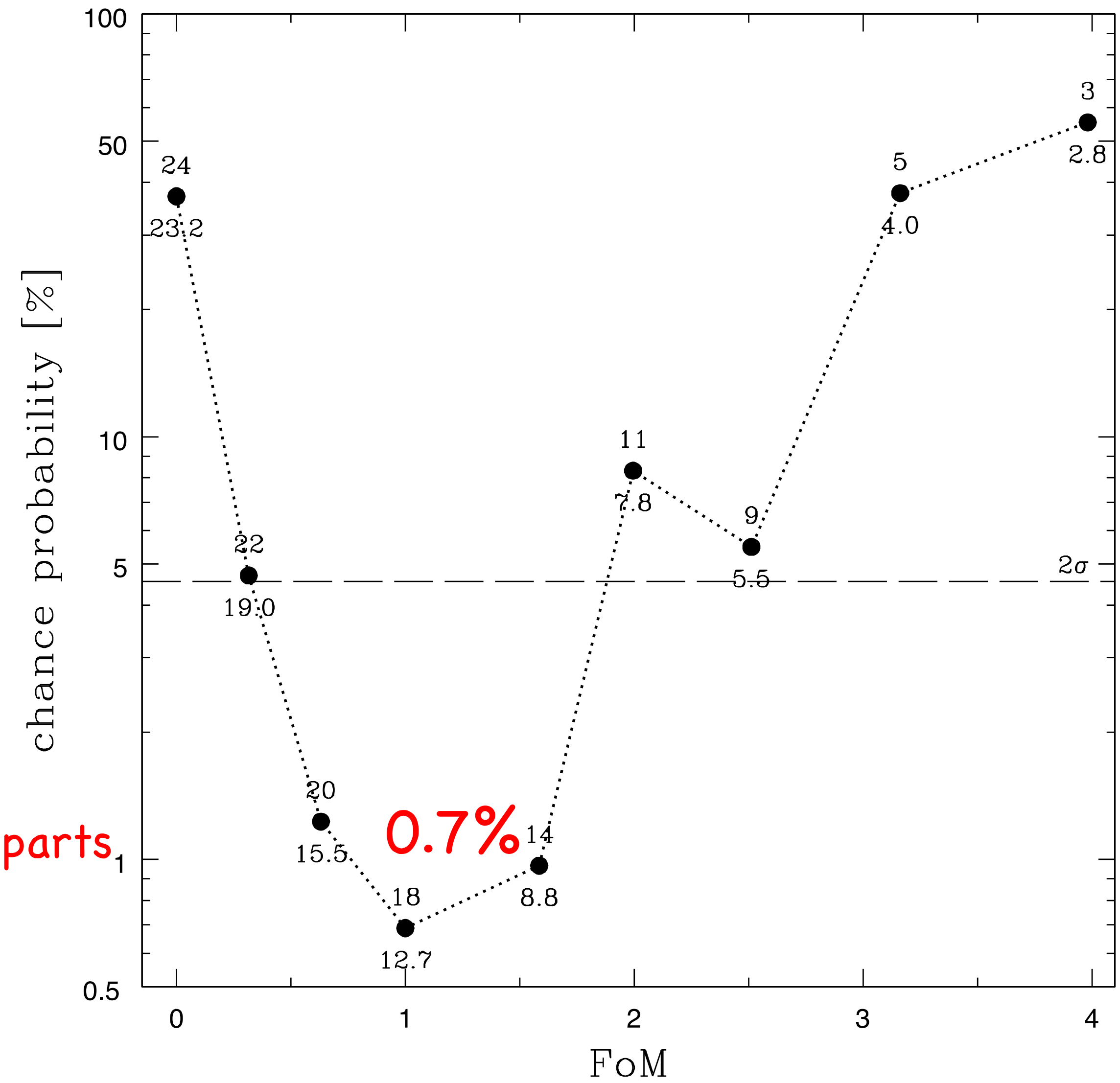
Results: 2FHL



"real" counterparts = 16 − 10.4 ~ 5

0.4%

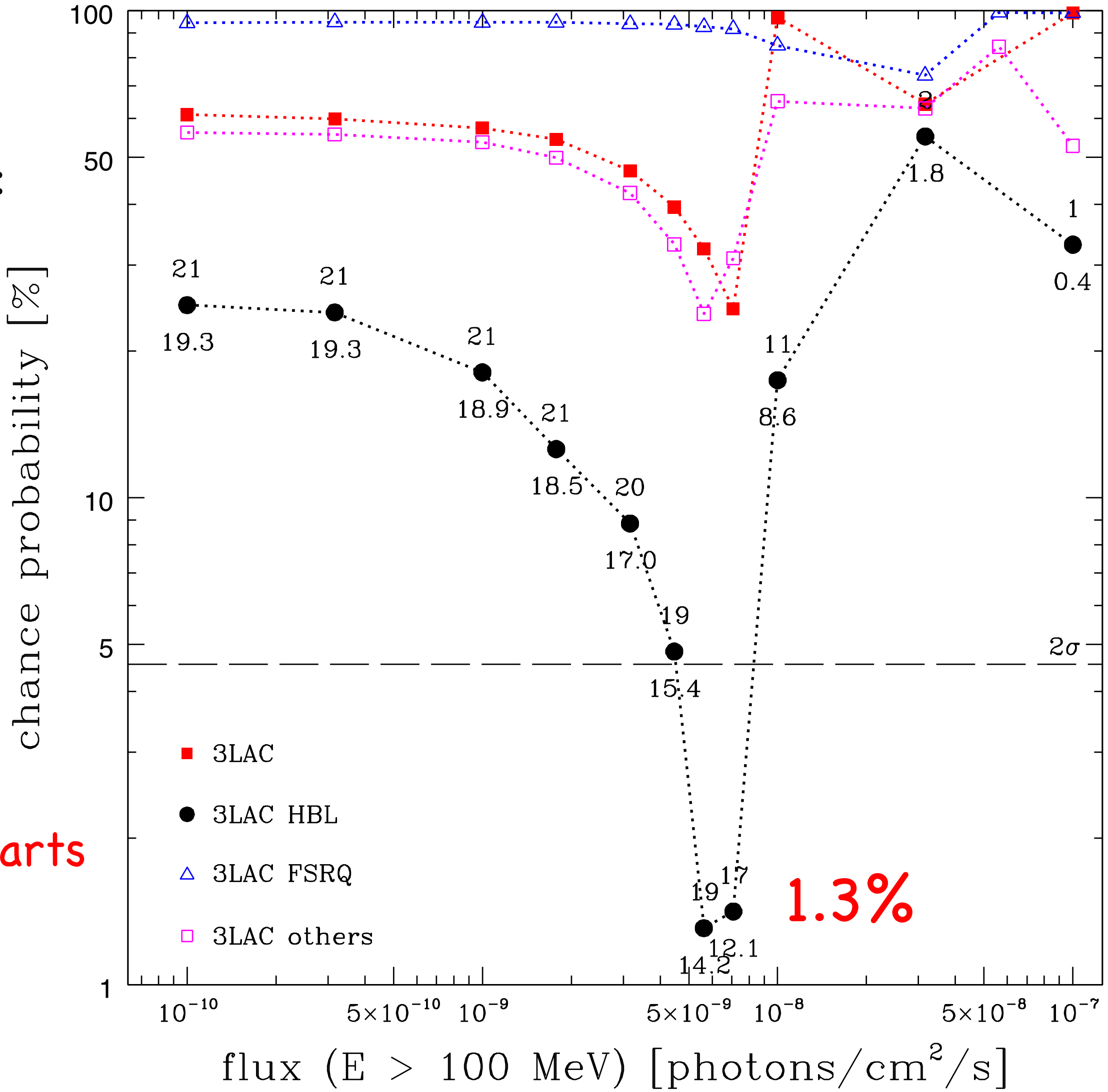
Results: 2WHSP



"real" counterparts ~ 5

Results: 3LAC

agrees with Glüsenkamp et al. 2015 (2LAC: no signal, max. blazar contrib. < 20%)



"real" counterparts ~ 5

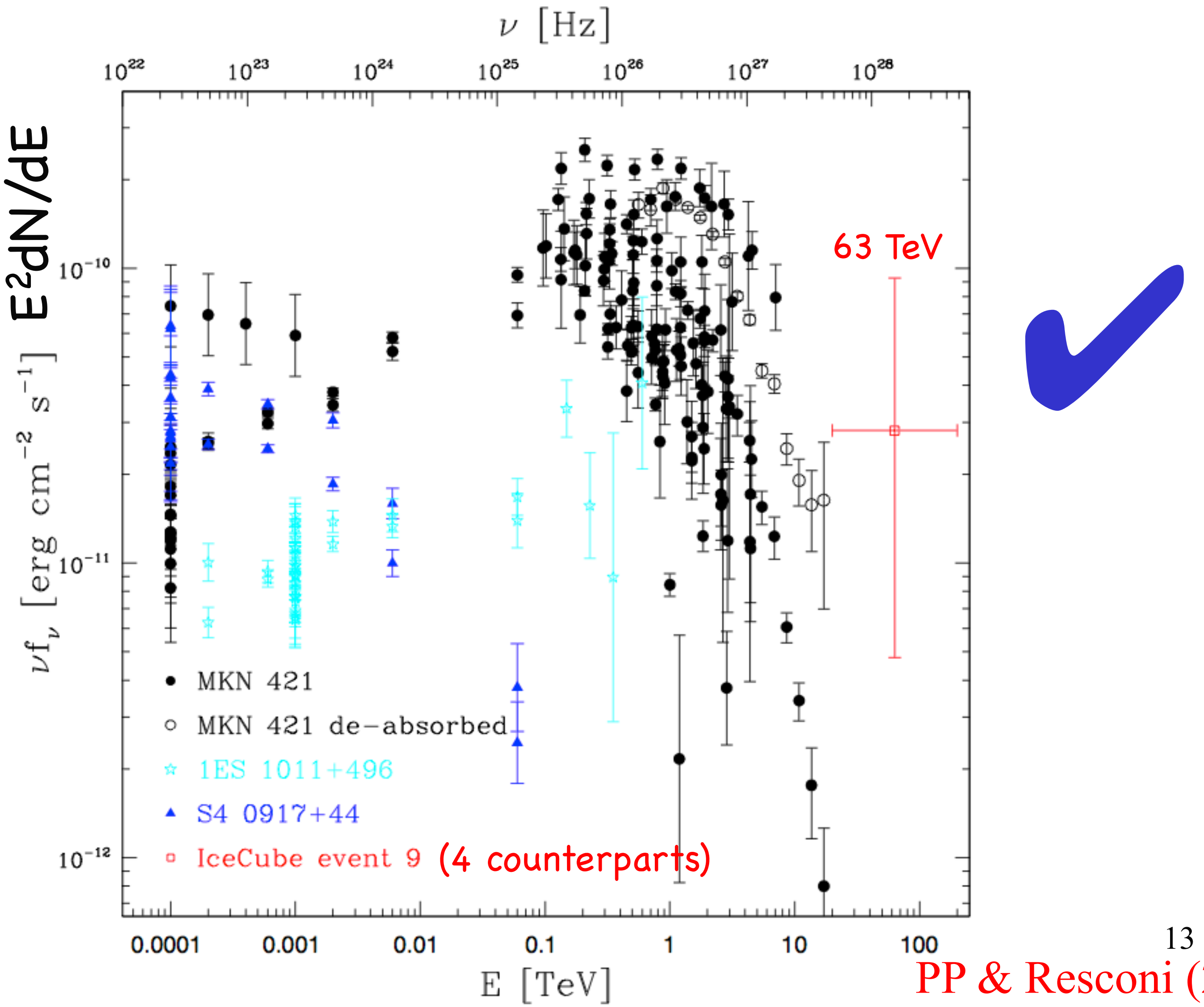
37 HBL matched to 18 IceCube neutrinos (two doubles)

ID	2WHSP name	2FHL name	Common name	offset (deg)	z	FoM	flux[a]	Comments
9	J091037.0+332924	J0910.4+3327	Ton 1015	11.4	0.350	2.0	0.283	positional match (PR14)
	J091552.4+293324	J0915.9+2931	B2 0912+29	11.2	>0.19	2.5	0.324	positional match (PR14)
	J101504.1+492600	J1015.0+4926	**1ES 1011+496**	15.9	0.212	4.0	1.62	most probable match (PR14)
	J110427.3+381231	J1104.4+3812	**MKN 421**	12.8	0.031	57.5	12.4	most probable match (PR14)
10	J235907.8−303740		**H 2356−309**	4.7	0.165	2.0	0.69[b]	most probable match (PR14)
11	J095302.7−084018	J0952.9−0841	1RXS J095303.4−084003	7.0	–	0.8	0.385	positional match (PR14)
	J102243.7−011302	J1022.7−0112	1RXS J102244.2−011257	7.7	>0.36	1.3	0.171	positional match (PR14)
	J102658.5−174858	J1027.0−1749	1RXS J102658.5−174905	9.0	0.267	1.0	0.196	most probable match?
12	J193656.1−471950	J1936.9−4721	PMN J1936−4719	5.6	0.265	1.3	0.240	most probable match?[c]
	J195502.8−564028	J1954.9−5641	1RXS J195503.1−56403	4.2	–	1.0	0.127	positional match
	J195945.6−472519	J1959.6−4725	SUMSS J195945−472519	5.9	–	1.0	0.183	positional match
	J200925.3−484953	J2009.4−4849	PKS 2005−489	5.6	0.071	10.0	0.970	positional match (PR14)
14	J171405.4−202752	J1713.9−2027	1RXS J171405.2−202747	9.9	–	1.3	0.275	most probable match?
17	J155543.0+111124	J1555.7+1111	**PG 1553+113**	8.9	–	7.9	4.20	most probable match (PR14)
19	J050657.8−543503	J0506.9−5434	1RXS J050656.8−543456	5.1	>0.26	1.0	0.131	positional match (PR14)
	J054357.2−553207	J0543.9−5533	1RXS J054357.3−553206	6.4	–	2.5	0.527	positional match[d]
20	J014347.3−584551	J0143.8−5847	SUMSS J014347−584550	10.1	–	2.0	0.161	positional match[e]
	J035257.4−683117	J0352.7−6831	PKS 0352−686	7.6	0.087	2.0	0.228	positional match (PR14)
22	J191744.8−192131	J1917.7−1921	**1H1914−194**	4.8	0.137	1.6	0.814	most probable match (PR14)
		J1921.9−1607	PMN J1921−1607	6.7	–	–	0.397	most probable match?(PR14)[f]
	J195814.9−301111	J1958.3−3011	1RXS J195815.6−30111	9.7	0.119	1.3	0.282	most probable match?(PR14)[f]
26	J090534.9+135806	J0905.7+1359	MG1 J090534+1358	10.9	–	1.0	0.192	positional match (PR14)
	J091552.4+293324[g]	J0915.9+2931	B2 0912+29	7.9	>0.19	2.5	0.324	positional match (PR14)
27	J081627.2−131152	J0816.3−1311	PMN J0816−1311	2.4	–	2.5	0.344	positional match[e]
35	J130421.0−435310	J1304.5−4353	1RXS 130421.2−435308	14.3	–	2.0	0.235	positional match (PR14)
	J130737.9−425938	J1307.6−4259	1RXS 130737.8−425940	14.8	–	3.2	0.351	positional match (PR14)
	J131503.3−423649	J1315.0−4238	1ES 1312−423	14.6	0.105	2.5	0.157	positional match (PR14)
	J132840.6−472749	J1328.6−4728	1WGA J1328.6−4727	9.2	–	0.4	0.209	positional match
	J134441.7−451007		SUMSS J134441−451002	10.7	–	1.0		positional match
39		J0622.4−2604	PMN J0622−2605	12.8	0.414	–	0.258	positional match
	J063059.5−240646	J0631.0−2406	1RXS J063059.7−240636	10.0	–	1.6	0.322	positional match
	J064933.6−313920	J0649.6−3139	1RXS J064933.8−31391	14.2	–	0.8	0.225	most probable match?
40	J102356.1−433601		SUMSS J102356−433600	9.7	–	2.5	2.08[b]	most probable match?
41	J041652.4+010523	J0416.9+0105	**1ES 0414+009**	2.9	0.287	3.2	0.269	most probable match
46	J094709.5−254100		1RXS J094709.2−254056	4.7	–	1.0		positional match
	J102658.5−174858[h]	J1027.0−1749	1RXS J102658.5−174905	7.4	0.267	1.0	0.196	most probable match?
48	J144037.8−384655	J1440.7−3847	1RXS J144037.4−38465	8.0	–	1.3	0.184	positional match
51	J054030.0+582338	J0540.5+5822	GB6 J0540+5823	4.8	–	1.6	0.187	positional match
	J060200.4+531600	J0601.9+5317	GB6 J0601+5315	1.3	–	1.0	0.101	positional match

M:

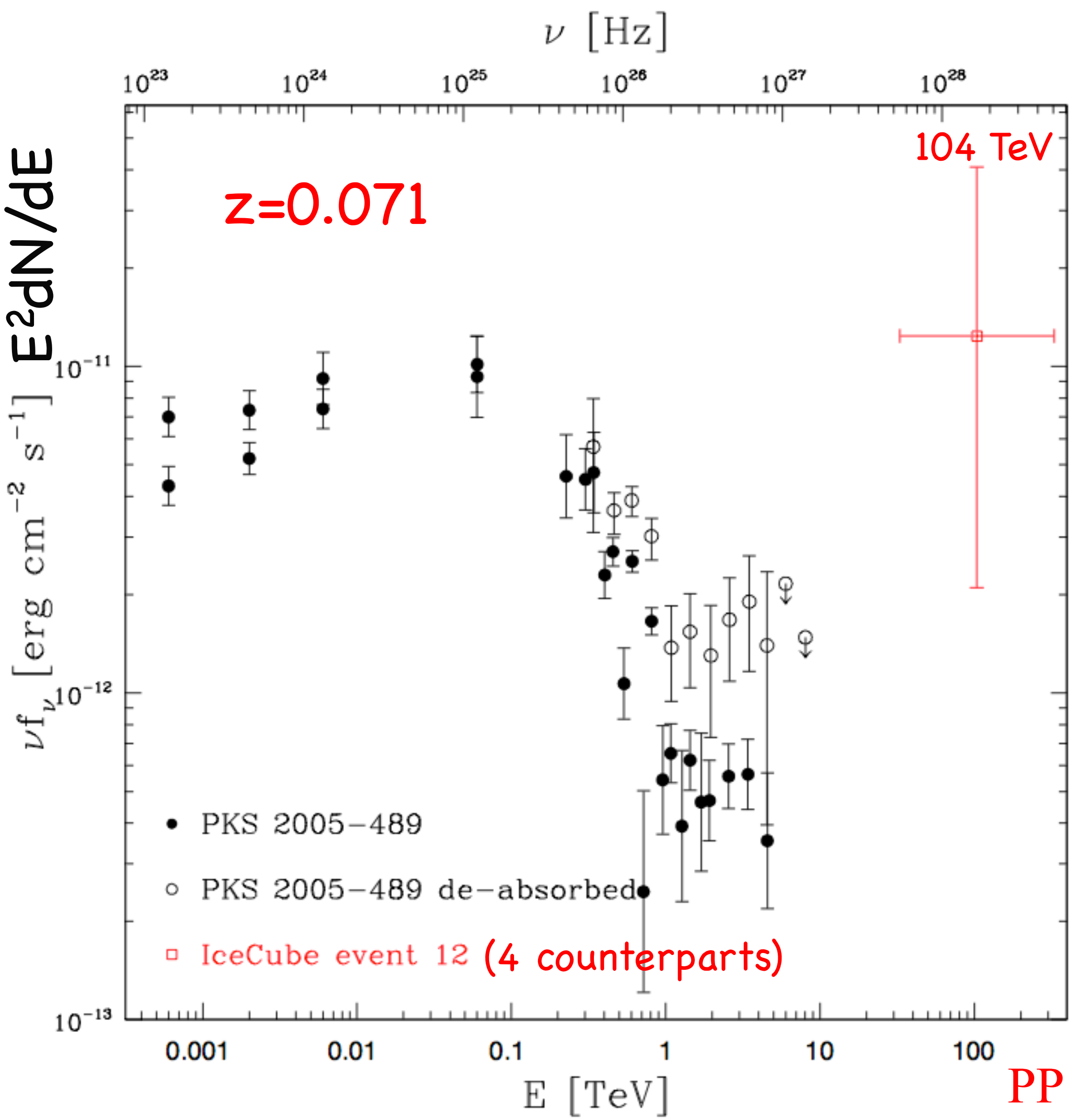
Notes. [a]f (E >50 GeV) in units of 10^{-10} ph cm^{-2} s^{-1}.

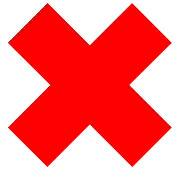
“Hybrid” SED: MKN 421



PP & Resconi (2014)

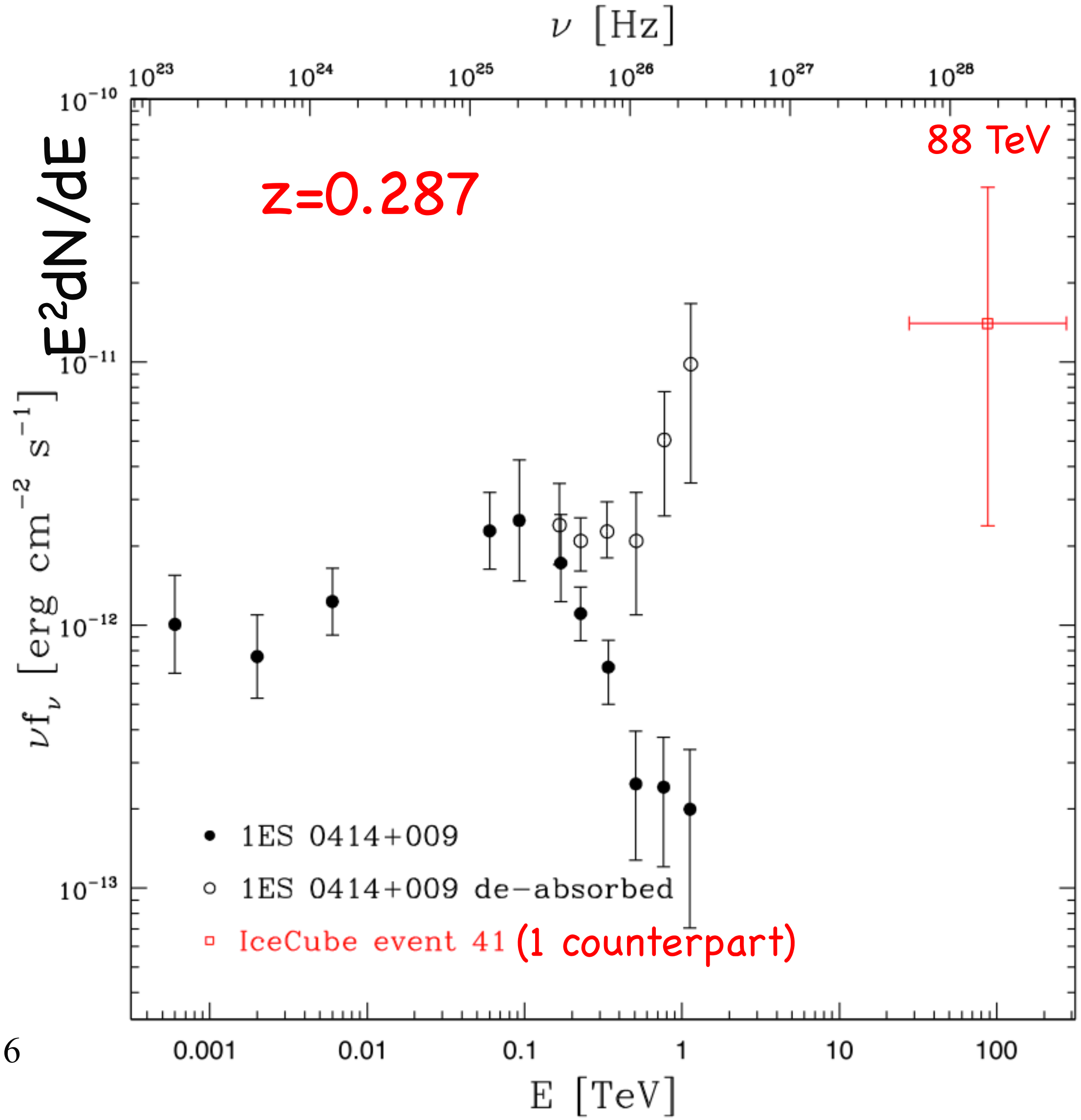
“Hybrid” SED: PKS 2005-489





PP & Resconi (2014)

“Hybrid” SED: 1ES 0414+009



yes

Table 2. 2FHL HBL sources with $F(>50\,\mathrm{GeV}) \geq 1.8 \times 10^{-11}$ photon cm^{-2} s^{-1} and 2WHSP sources with FoM $\geq$1.0 in one median angular error radius around the positions of the IceCube events. The counterparts of the most probable matches are indicated in boldface.

ID	2WHSP name	2FHL name	Common name	offset (deg)	z	FoM	flux[a]	Comments
9	J091037.0+332924	J0910.4+3327	Ton 1015	11.4	0.350	2.0	0.283	positional match (PR14)
	J091552.4+293324	J0915.9+2931	B2 0912+29	11.2	>0.19	2.5	0.324	positional match (PR14)
	J101504.1+492600	J1015.0+4926	**1ES 1011+496**	15.9	0.212	4.0	1.62	most probable match (PR14)
	J110427.3+381231	J1104.4+3812	**MKN 421**	12.8	0.031	57.5	12.4	most probable match (PR14)
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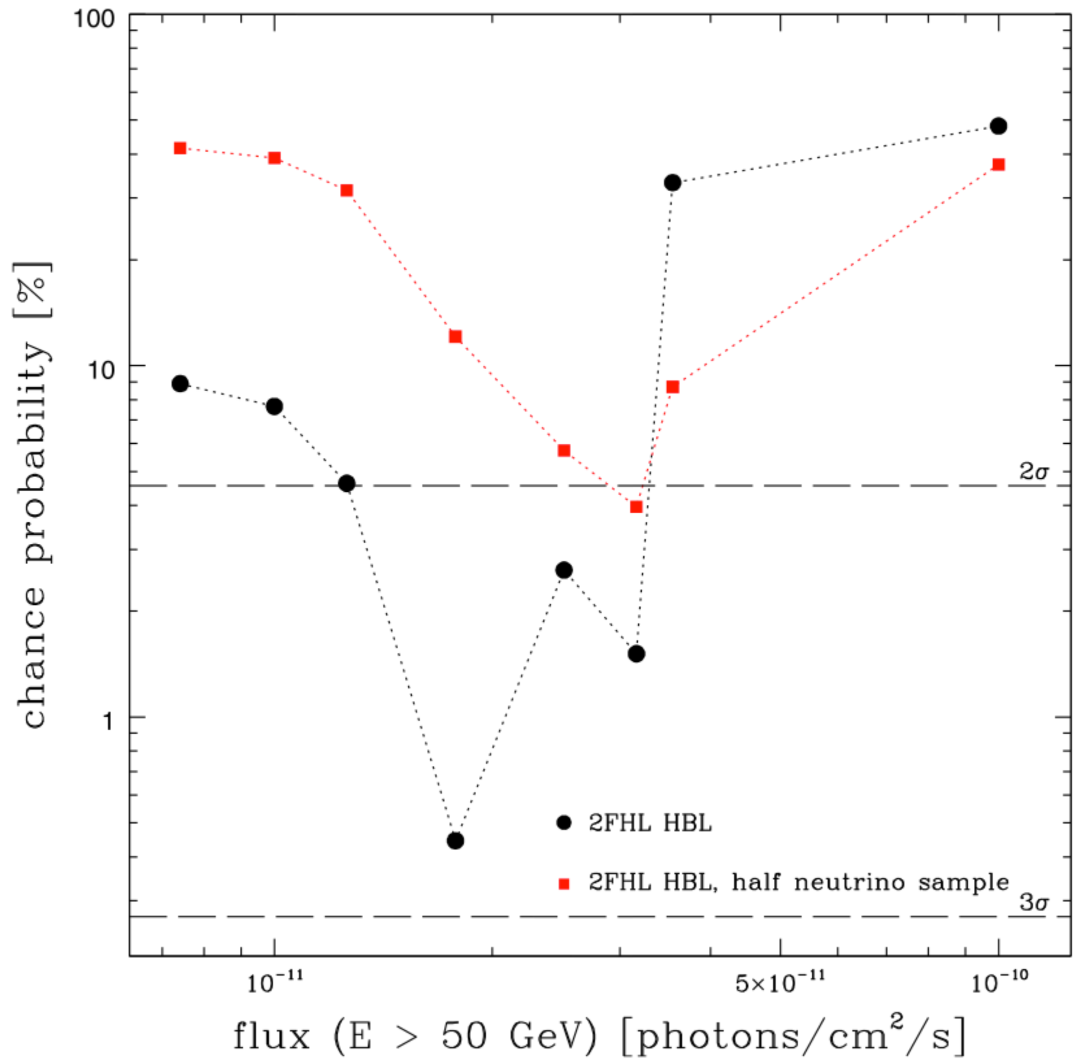
11	J095302.7−084018	J0952.9−0841	1RXS J095303.4−084003	7.0	–	0.8	0.385	positional match (PR14)
	J102243.7−011302	J1022.7−0112	1RXS J102244.2−011257	7.7	>0.36	1.3	0.171	positional match (PR14)
	J102658.5−174858	J1027.0−1749	1RXS J102658.5−174905	9.0	0.267	1.0	0.196	most probable match?
12	J193656.1−471950	J1936.9−4721	PMN J1936−4719	5.6	0.265	1.3	0.240	most probable match?[c]
	J195502.8−564028	J1954.9−5641	1RXS J195503.1−56403	4.2	–	1.0	0.127	positional match
	J195945.6−472519	J1959.6−4725	SUMSS J195945−472519	5.9	–	1.0	0.183	positional match
	J200925.3−484953	J2009.4−4849	PKS 2005−489	5.6	0.071	10.0	0.970	positional match (PR14)
14	J171405.4−202752	J1713.9−2027	1RXS J171405.2−202747	9.9	–	1.3	0.275	most probable match?
17	J155543.0+111124	J1555.7+1111	**PG 1553+113**	8.9	–	7.9	4.20	most probable match (PR14)
19	J050657.8−543503	J0506.9−5434	1RXS J050656.8−543456	5.1	>0.26	1.0	0.131	positional match (PR14)
	J054357.2−553207	J0543.9−5533	1RXS J054357.3−553206	6.4	–	2.5	0.527	positional match[d]
20	J014347.3−584551	J0143.8−5847	SUMSS J014347−584550	10.1	–	2.0	0.161	positional match[e]

≈ 5 "most probable" matches (plus ≈ 5 possible ones) out of 51 IceCube neutrinos → HBL component at 10-20%

	J130737.9−425938	J1307.6−4259	1RXS 130737.8−425940	14.8	–	3.2	0.351	positional match (PR14)
	J131503.3−423649	J1315.0−4238	1ES 1312−423	14.6	0.105	2.5	0.157	positional match (PR14)
	J132840.6−472749	J1328.6−4728	1WGA J1328.6−4727	9.2	–	0.4	0.209	positional match
	J134441.7−451007		SUMSS J134441−451002	10.7	–	1.0		positional match
39		J0622.4−2604	PMN J0622−2605	12.8	0.414	–	0.258	positional match
	J063059.5−240646	J0631.0−2406	1RXS J063059.7−240636	10.0	–	1.6	0.322	positional match
	J064933.6−313920	J0649.6−3139	1RXS J064933.8−31391	14.2	–	0.8	0.225	most probable match?
40	J102356.1−433601		SUMSS J102356−433600	9.7	–	2.5	2.08[b]	most probable match?
41	J041652.4+010523	J0416.9+0105	**1ES 0414+009**	2.9	0.287	3.2	0.269	most probable match
46	J094709.5−254100		1RXS J094709.2−254056	4.7	–	1.0		positional match
	J102658.5−174858[h]	J1027.0−1749	1RXS J102658.5−174905	7.4	0.267	1.0	0.196	most probable match?
48	J144037.8−384655	J1440.7−3847	1RXS J144037.4−38465	8.0	–	1.3	0.184	positional match
51	J054030.0+582338	J0540.5+5822	GB6 J0540+5823	4.8	–	1.6	0.187	positional match
	J060200.4+531600	J0601.9+5317	GB6 J0601+5315	1.3	–	1.0	0.101	positional match

Notes. [a]f (E >50 GeV) in units of 10^{-10} ph cm^{-2} s^{-1}.

The future



100
10
1
chance probability [%]
2σ
3σ
2FHL HBL
2FHL HBL, half neutrino sample
10⁻¹¹
5×10⁻¹¹
10⁻¹⁰
flux (E > 50 GeV) [photons/cm²/s]

Main messages

- Strong, VHE γ-ray HBL (extreme blazars) can explain ≈ 10 – 20 % of the IceCube signal: p-value $\gtrsim$ 0.4%
- Other blazars give null results
- Room for other populations: some Galactic sources (SNRs) have interesting hybrid SEDs
- Limited by neutrino statistics: more data from IceCube (and KM3NeT, IceCube-Gen2, etc.) will hopefully turn our hint (~ 3σ) into a discovery (~ 5σ) → *hadronic processes in blazars*

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 443, 474–484 (2014) doi:10.1093/mnras/stu1166

Are both BL Lacs and pulsar wind nebulae the astrophysical counterparts of IceCube neutrino events?

P. Padovani[1★] and E. Resconi[2]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 448, 2412–2429 (2015) doi:10.1093/mnras/stv179

Photohadronic origin of γ-ray BL Lac emission: implications for IceCube neutrinos

M. Petropoulou,[1†] S. Dimitrakoudis,[2] P. Padovani,[3] A. Mastichiadis[4] and E. Resconi[5]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 452, 1877–1887 (2015) doi:10.1093/mnras/stv1467

A simplified view of blazars: the neutrino background

P. Padovani,[1,2★] M. Petropoulou,[3†] P. Giommi[4,5] and E. Resconi[6]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 457, 3582–3592 (2016) doi:10.1093/mnras/stw228
Advance Access publication 2016 January 27

Extreme blazars as counterparts of IceCube astrophysical neutrinos

P. Padovani,[1,2★] E. Resconi,[3] P. Giommi,[4,5] B. Arsioli[4,5,6] and Y. L. Chang[4,6]