Blazar neutrino emission models under scrutiny in wake of observational constraints

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Collaborators and references

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- Krauß, F., et al. (incl. Katz, U. & Mannheim, K.), **TANAMI blazars in the IceCube>; PeV-neutrino fields**, 2014 A&A 566 L7
- Adrian-Martinez, S., et al. (incl. Katz, U. & Mannheim, K.), **ANTARES constrains a blazar origin of two IceCube PeV neutrino events**, 2015, A&A 576 L 8
- Kadler, M., et al. (incl. Katz, U. & Mannheim, K.), **Coincidence of a high-fluence blazar outburst with a PeV energy neutrino event**, submitted (2015)

Which astrophysical objects emit PeV neutrinos ?

Blazar models under scrutiny

Blazars associated with PeV events

Antares constraints on TeV spectra

Which astrophysical objects emit PeV neutrinos?

- **IceCube excess consistent with isotropy**

  → Extragalactic source population

- **Calorimetrically dominant non-thermal population**

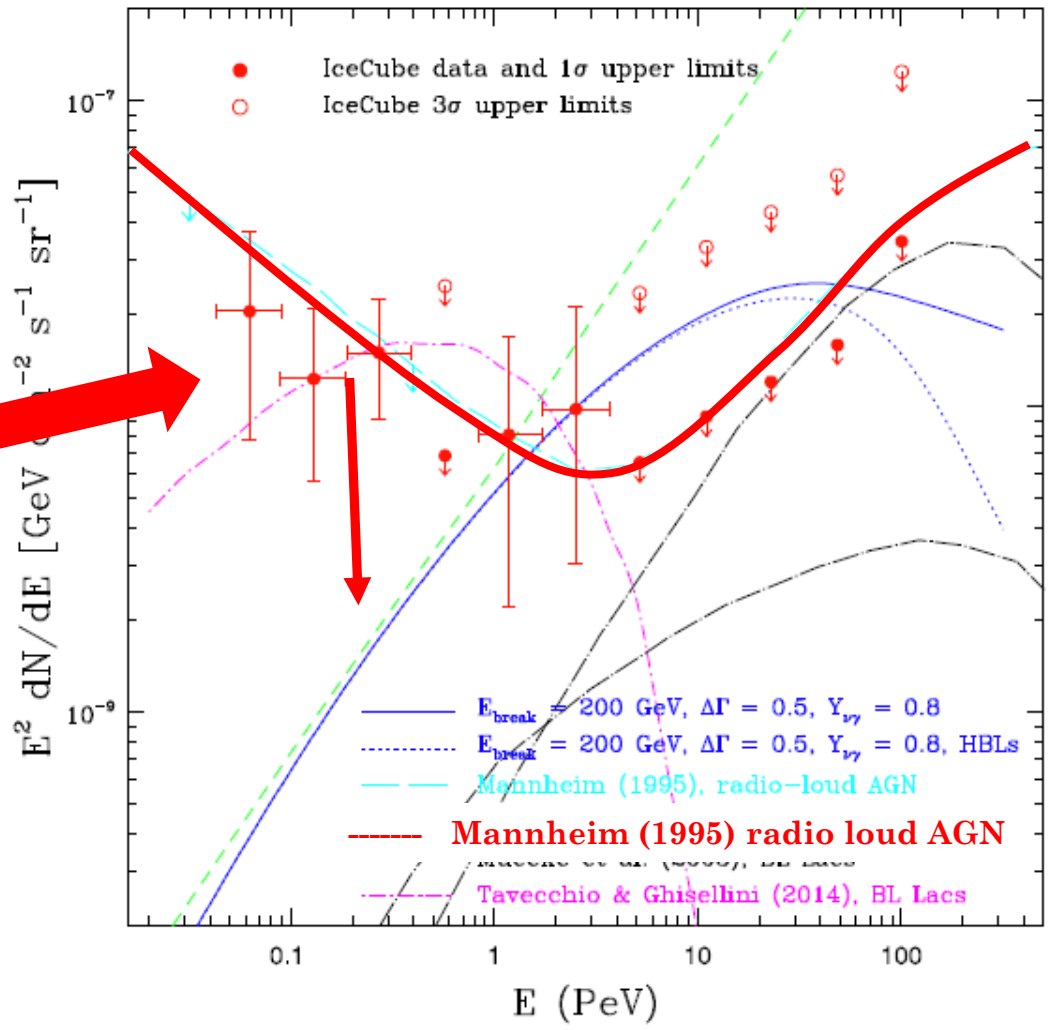
  → Radio-loud AGN (Blazars and Radio Galaxies)

- **Steep background → Signal events at highest energies**
- **Energy resolution (cascades) → Background suppression**
- **We choose the first three PeV events of IceCube for an astrophysical follow-up study → Ernie & Bert, Big Bird**

Which astrophysical objects emit PeV neutrinos?

Motivation: Prediction for radio-loud AGN (KM, 1995, APh 3, 295)

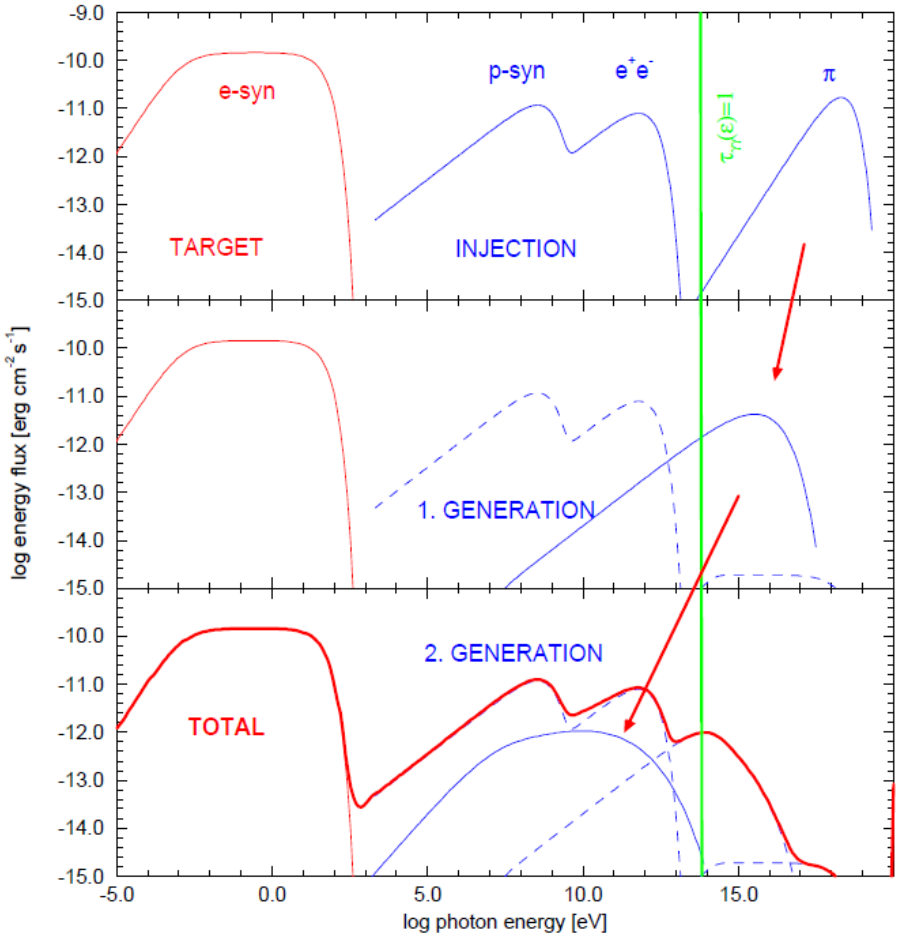
< 100 TeV: **upper limit** for neutrinos from pp-interactions (different beaming pattern)
> 100 TeV: **normalized** spectrum using extragalactic gamma ray flux



Padovani et al., MNRAS 452, 1877 (2015)

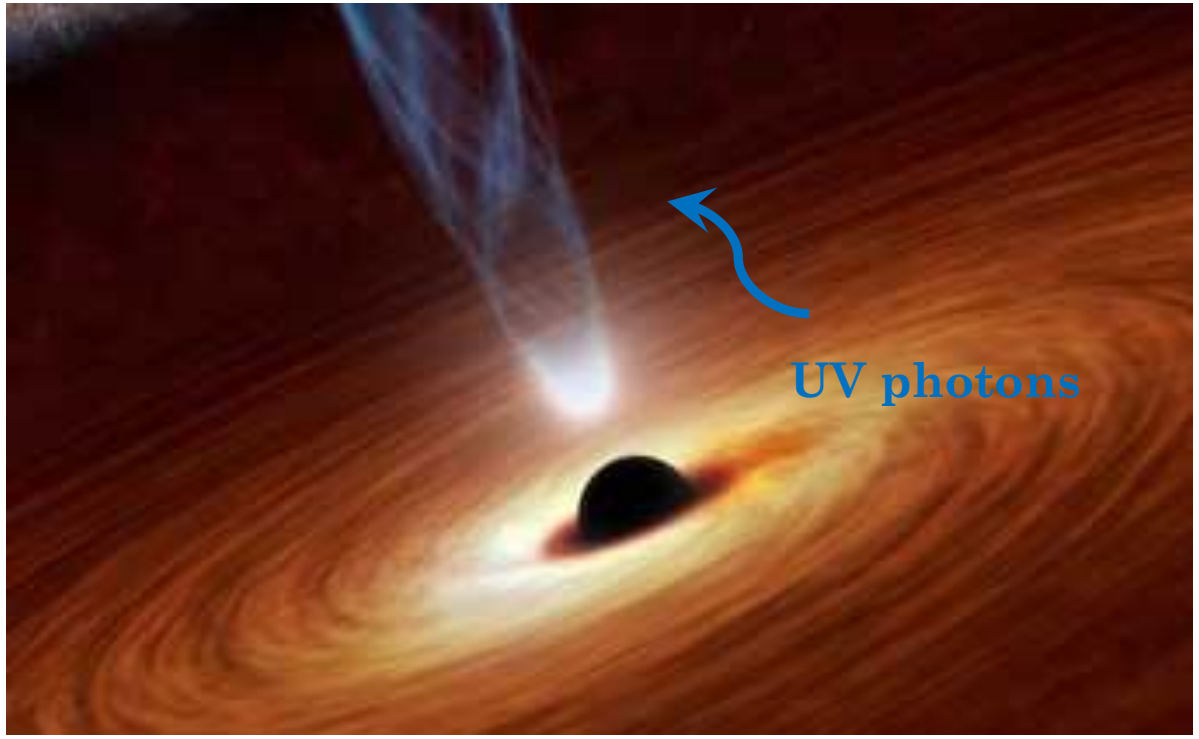
Blazar models under scrutiny

- **Extragalactic jets with shock acceleration (protons,electrons)**
- **Photo-meson production → neutrinos and gamma rays**
- **Gamma rays cascade < TeV with integral energy flux F_γ**
- **Neutrino energy flux $F_\nu = F_\gamma$**
- **Neutrino spectrum peaks at injection energies**



Proton-initiated electromagnetic cascade spectrum

Blazar models under scrutiny



Low accretion rate: Infrared synchrotron photons act as target photons for accelerated protons in **BL Lac objects**

High accretion rate: UV photons from disk and surrounding scattering medium act as target photons in **FSRQs**

Neutrino spectrum peaks at EeV (BL Lacs) or PeV (FSRQ)

→ Expect mainly FSRQs associations at PeV energies!

PeV events observed by IceCube

(as of 2014)

Southern events (Earth obscuration):

- **Bert IC 14 1.04 PeV**
- **Ernie IC 20 1.14 PeV**
- **Big Bird IC 35 2.00 PeV**

Blazars associated with Ernie & Bert

Source	RA[°]	Dec[°]	z	Class.	Θ [°]
0235−618	39.2218[b]	−61[b]	0.47[a]	FSRQ[a]	5.61
0302−623	45.9610[c]	1904[c]	1.35[a]	FSRQ[a]	5.98
0308−611	47.48	−60.9775[c]	1.48[a]	FSRQ[a]	7.39
1653−329	254.0699[b]	−32[b]	2.40[h]	FSRQ[h]	11.18
1714−336	259.400[d]	024[d]	?	BL Lac[f]	7.87
1759−396	270.67	−39.6689[e]	1.32[g]	FSRQ[g]	12.50

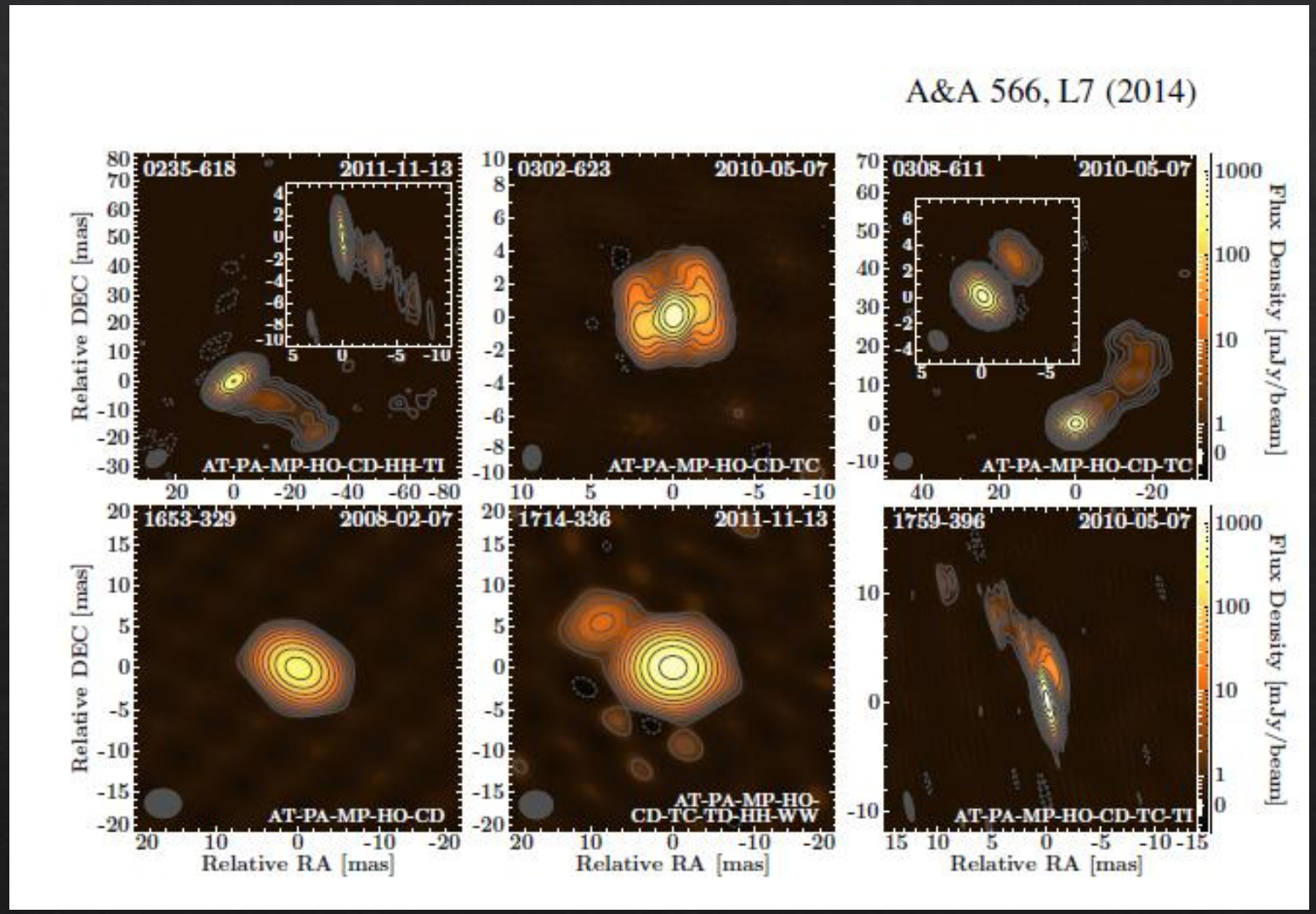
IC 20 Ernie

IC 14 Bert

1714-336 shows a strong thermal UV bump and is probably a FSRQ misclassified as BL LAC.

→ Coincident sources are radio and gamma-ray bright FSRQ!

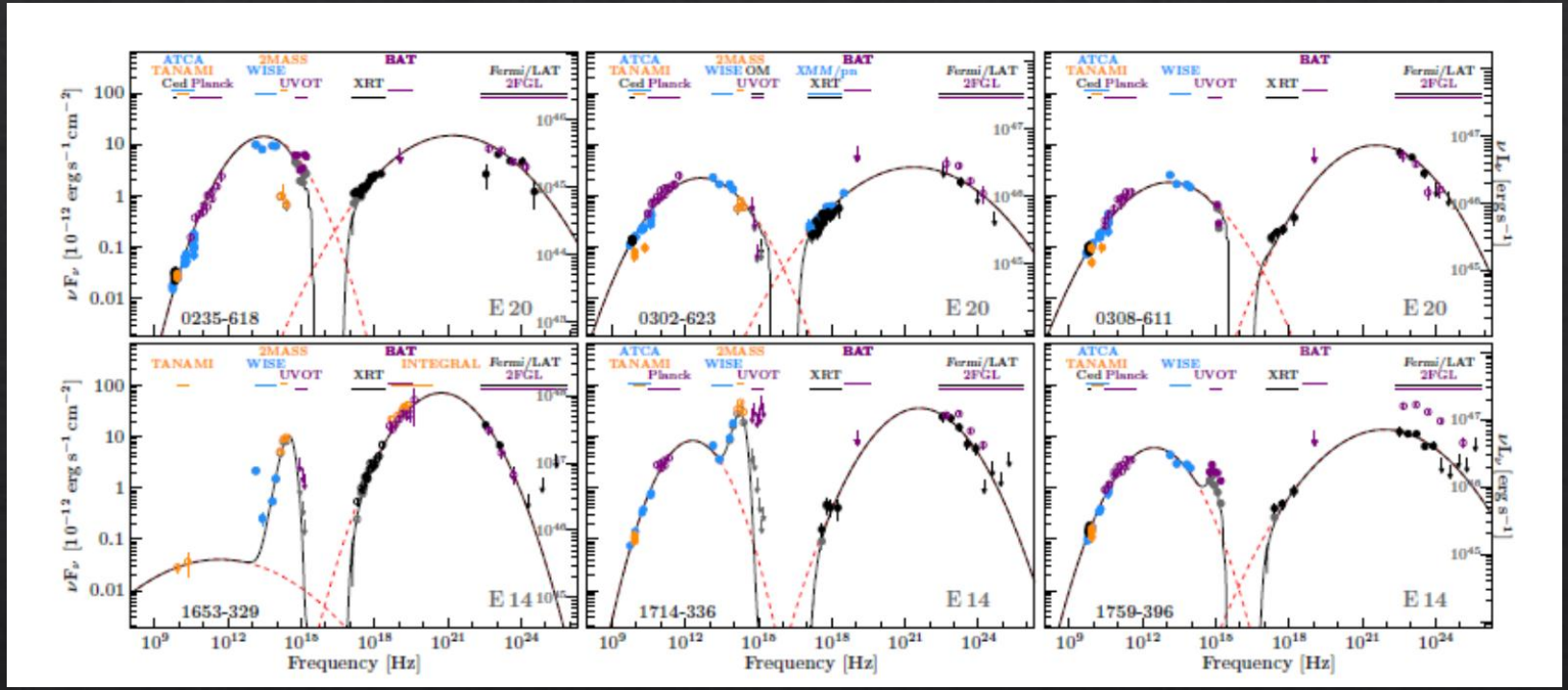
Blazars associated with Ernie & Bert



TANAMI Collaboration, Kadler et al.:

FSRQs show compact VLBI jets at radio frequencies

Blazars associated with Ernie & Bert



$$F_\nu = F_\gamma$$

Integrated spectral energy distributions gauge expected PeV neutrino fluxes

Blazars associated with Ernie & Bert

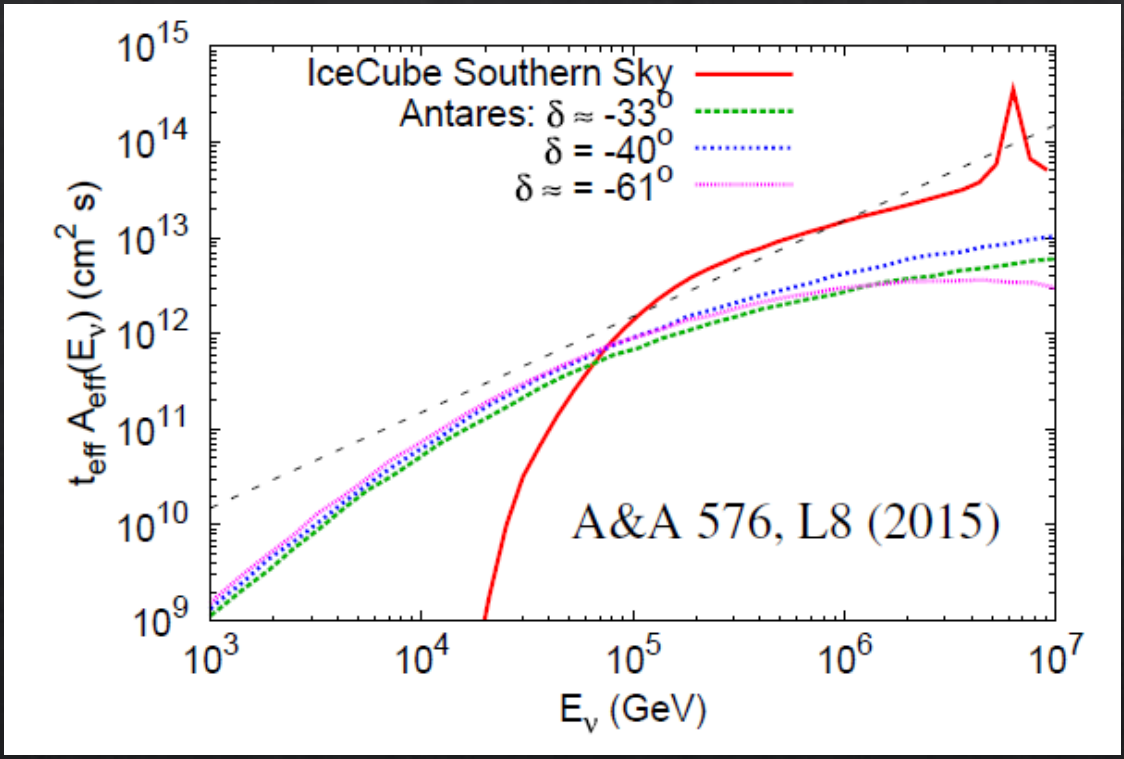
Source	F_γ(erg cm^{-2} s^{-1})	Events
0235–618	$\left(1.0^{+0.5}_{-0.5}\right) \times 10^{-10}$	$0.19^{+0.04}_{-0.04}$
0302–623	$\left(3.4^{+0.7}_{-0.7}\right) \times 10^{-11}$	$0.06^{+0.01}_{-0.01}$
0308–611	$\left(7.5^{+2.9}_{-2.9}\right) \times 10^{-11}$	$0.14^{+0.05}_{-0.05}$
1653–329	$\left(4.5^{+0.5}_{-0.5}\right) \times 10^{-10}$	$0.86^{+0.10}_{-0.10}$
1714–336	$\left(2.4^{+0.5}_{-0.6}\right) \times 10^{-10}$	$0.46^{+0.10}_{-0.12}$
1759–396	$\left(1.2^{+0.3}_{-0.2}\right) \times 10^{-10}$	$0.23^{+0.50}_{-0.40}$
Total		1.9 ± 0.4

Krauß et al. A&A (2014)

Maximum number of neutrino events at 1 PeV during 662 days of IceCube exposure from calorimetric relation

Additional neutrino events expected from faint, unresolved sources

ANTARES constraints on TeV spectra



ANTARES sensitivity for IceCube PeV event locations

Superior sensitivity at <50 TeV due to Earth muon background suppression

A&A 576, L8 (2015)

ANTARES constraints on TeV spectra

Source	N_{sig}	p	Limit	$N_{\nu,IC} = 1, 2, 3, 4$			
0235−618	0	1	1.3	−2.4	−2.1	−2.0	−1.9
0302−623	0	1	1.3	−2.4	−2.1	−2.0	−1.9
0308−611	0	1	1.3	−2.4	−2.1	−2.0	−1.9
1653−329	1.1	0.10	2.9	<−2.5	−2.5	−2.3	−2.2
1714−336	0.9	0.04	3.5	<−2.5	−2.5	−2.3	−2.2
1759−396	0	1	1.4	−2.4	−2.1	−2.0	−1.8

2FGL Name	Common Name	F_γ(erg cm^{-2}s^{-1})	$N^{\max}_{\nu,\mathrm{PeV}}$
2FGL J1230.2−5258	PMN J1229−5303	$(2.4^{+1.5}_{-1.5}) \times 10^{-11}$	0.14
2FGL J1234.0−5733	PMN J1234−5736	$(1.1^{+0.4}_{-0.4}) \times 10^{-11}$	0.06
2FGL J1303.5−4622	PMN J1303−4621	$(1.9^{+0.6}_{-0.6}) \times 10^{-11}$	0.11
2FGL J1303.8−5537	PMN J1303−5540	$(1.04^{+0.11}_{-0.11}) \times 10^{-10}$	0.38
2FGL J1304.3−4353	1RXS 130421.2−435308	$(2.11^{+0.25}_{-0.25}) \times 10^{-11}$	0.12
2FGL J1307.5−4300	1RXS 130737.8−425940	$(8.4^{+1.7}_{-1.7}) \times 10^{-12}$	0.05
2FGL J1307.6−6704	PKS B 1304−668	$(1.54^{+0.15}_{-0.15}) \times 10^{-10}$	0.89
2FGL J1314.5−5330	PMN J1315−5334	$(8.1^{+0.9}_{-0.9}) \times 10^{-11}$	0.47
2FGL J1326.7−5254	PMN J1326−5256	$(1.04^{+0.21}_{-0.18}) \times 10^{-10}$	0.59
2FGL J1329.2−5608	PMN J1329−5608	$(1.38^{+0.36}_{-0.29}) \times 10^{-10}$	0.93
2FGL J1330.1−7002	PKS B 1326−697	$(1.53^{+0.11}_{-0.11}) \times 10^{-10}$	0.89
2FGL J1352.6−4413	PKS B 1349−439	$(5.4^{+1.0}_{-1.0}) \times 10^{-11}$	0.32
2FGL J1400.6−5601	PMN J1400−5605	$(6.9^{+0.8}_{-0.8}) \times 10^{-11}$	0.40
2FGL J1407.5−4257	CGRaBS J1407−4302	$(1.6^{+0.5}_{-0.5}) \times 10^{-11}$	0.09
2FGL J1428.0−4206	PKS B1424−418	$(2.04^{+0.17}_{-0.16}) \times 10^{-10}$	1.57
2FGL J1508.5−4957	PMN J1508−4953	$(7.6^{+3.0}_{-2.3}) \times 10^{-11}$	0.55
2FGL J1514.6−4751	PMN J1514−4748	$(5.6^{+0.6}_{-0.6}) \times 10^{-11}$	0.32
Sum (2LAC)			7.9

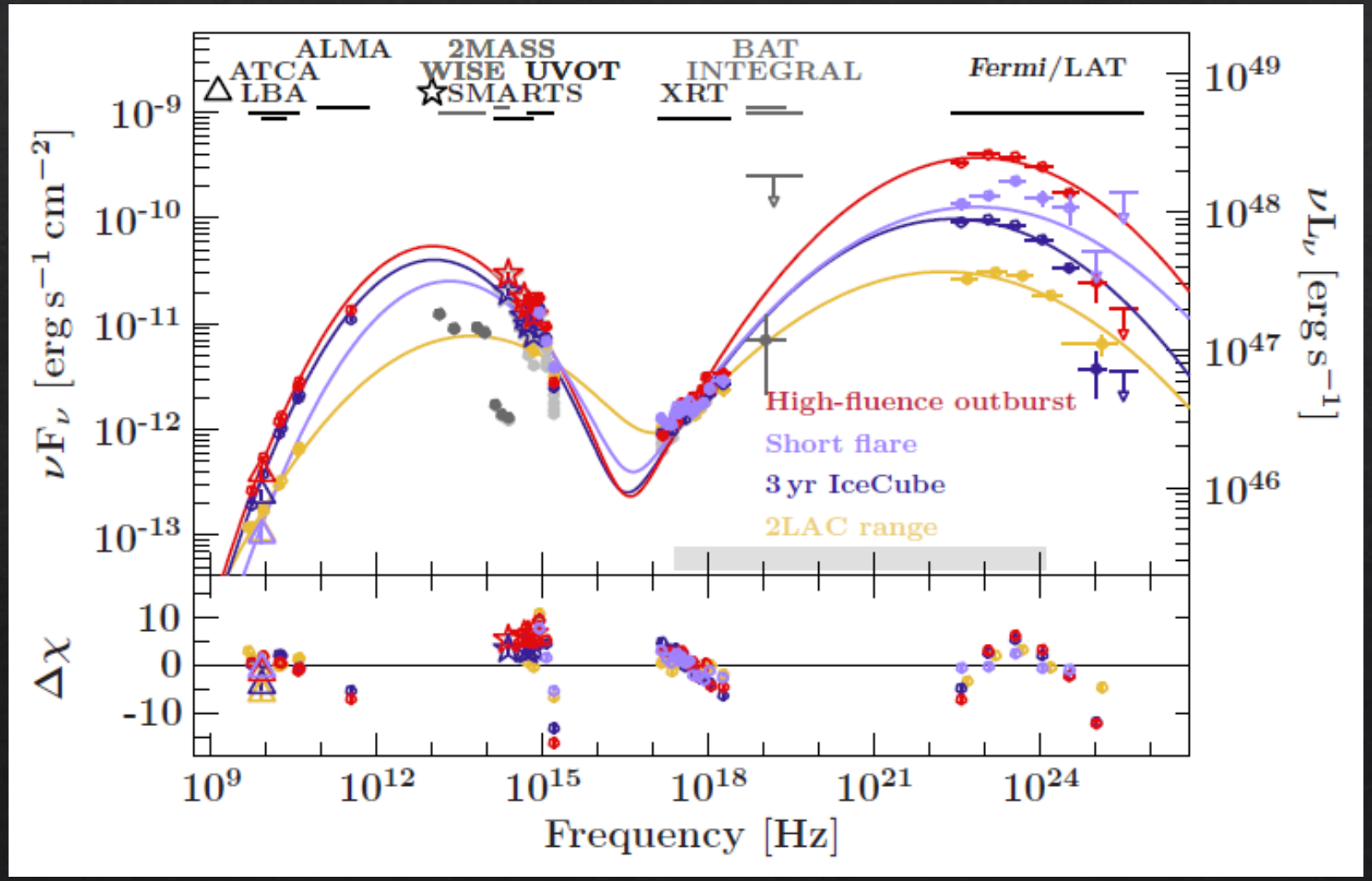
Blazars associated with Big Bird

17 blazars from the 2nd Fermi Catalogue

Strongest individual source:

B 1424-418 (FSRQ)

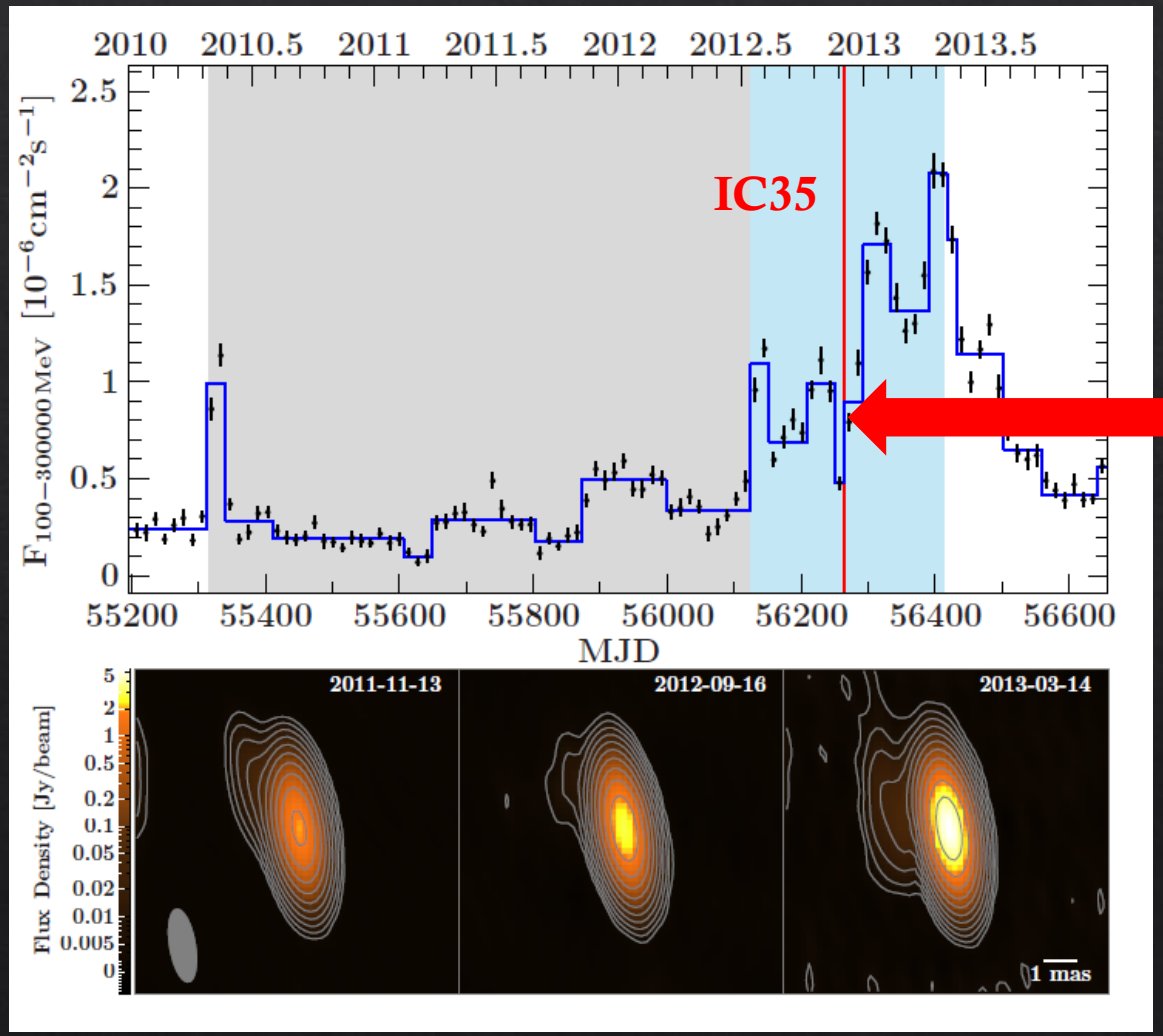
Blazars associated with Big Bird



B 1424-418:

Expected number of neutrino events increases above 2LAC estimate during 3-year IceCube exposure due to multi-frequency outburst

Blazars associated with Big Bird



High-fluence (pc-scale) radio and gamma-ray outburst of B1424-418: Temporally and spatially coincident with Big Bird neutrino event.

Probability for chance coincidence 5%.

Blazars associated with Big Bird

B1424-418 during 9 months of main outburst:

- Straw person's model with δ-distribution neutrino spectrum peaking at 2 PeV: Expect max. 4.5 events

- Realistic $E^{-2.3}$ neutrino spectrum from 30 TeV to 10 PeV: **Expect 0.11 events (Poisson probability for detecting 1 event is 10%, i.e. 3 times higher probability than for total 2LAC blazar emission in FOV of Big Bird)**

Why do we not detect PeV neutrinos from every bright blazar?

- 10 highest-fluence blazars from Fermi during 3 years of IceCube
- Northern hemisphere sensitivity to PeV events lower than southern hemisphere sensitivity
- Last column gives expected number of events associated with source based on positional coincidence
- Gravitationally-lensed blazar PKS1830-21 only marginally outside of R_{50} of IC14. Time of IC14 coincides with outburst.
- Only for 2 out of the 10 an association is expected

Name	R.A.	Dec.	F_γ	$N^{\max}_{\nu,\mathrm{PeV}}$	$N^{\mathrm{pred}}_{\nu,\mathrm{PeV}}$	$N^{\mathrm{pos}}_{\nu,\mathrm{PeV}}$
	[Deg]	[Deg]	$[10^{-10}\mathrm{erg\,cm^{-2}s^{-1}}]$	δ	$E^{-2.3}$	
PKS 1830-21	278.4	−21.1	(14.34 ± 0.27)	8.3	0.21	1
PKS B1510−089	228.2	−9.1	(13.31 ± 0.13)	7.7	0.19	0
3C 454.3	343.5	16.2	(37.50 ± 01.3)	7.6	0.19	0
PKS B1424−418	217.0	−42.1	(7.82 ± 0.16)	4.5	0.11	1
PKS B2326−502	352.3	−49.9	(4.69 ± 0.10)	2.7	0.07	0
PKS B0537−441	84.7	−44.1	(3.84 ± 0.08)	2.2	0.06	0
PKS B1222+216	186.2	21.4	(7.94 ± 0.12)	1.6	0.04	0
CTA 102	338.2	11.7	(6.42 ± 0.12)	1.3	0.03	0
(HB89) 1633+382	248.8	38.1	(6.28 ± 0.09)	1.3	0.03	0
B2 1520+31	230.5	31.7	(4.75 ± 0.25)	1.3	0.02	0

Why do we not detect PeV neutrinos from every bright blazar?

Most neutrinos originate from faint, unresolved sources:

- **Unresolved sources from faint end of blazar flux distribution**
- **Unresolved sources from much fainter unbeamed counterparts of blazars (radio galaxies)**

2nd Fermi catalogue (cf. Ackermann et al., ApJ, 2011)

- **50% blazar contribution to extragalactic gamma-ray background**
- **70% of total blazar emission from bright, resolved blazars**
- **30% of total blazar emission from faint, unresolved blazars**

If diffuse neutrino flux follows gamma-ray flux, < 1/3 of the PeV neutrinos originate from 2LAC gamma-ray blazars

Summary

- **The IceCube astrophysical neutrino flux is consistent with predictions for radio-loud AGN**

  Mannheim, Aph 3, 295 (1995), cf. Padovani et al., MNRAS 452, 1877 (2015)

- **FSRQ are expected to deliver the dominant PeV neutrino flux (photo-meson production with UV target photons from the accretion disk and the surrounding scattering medium)**

  Mannheim, NuPhS 256, 264 (2014), cf. Dermer, et al., JHEAp 3, 29 (2014)

- **For the first three PeV events detected by IceCube, positionally coincident blazars were shown to be energetically capable to produce these events**

  Krauß et al., (& Kadler, Katz, Mannheim) A&A 566, L7 (2014)

- **The spectral index must be flatter than -2.4 based on ANTARES follow-up analysis**

  Adrián-Martínez et al. (ANTARES), A&A 576, L8 (2015)

- **Although no single point source clustering has been observed yet due to the low statistics, the extreme outburst of B1424-418 had a probability of 95% to not coincide with Big Bird in position and time just by chance. During the 9-month outburst, the Poisson probability for detecting a PeV neutrino event from B1424-417 amounted to a sizeable ~10%.**
  Remark: Only less than 1/3 of the PeV neutrinos should stem from known 2LAC blazars.

  Kadler et al. (& Katz, Krauß, Mannheim), submitted (2015)