Neutrinos on Ice

3LAC counterparts to IceCube neutrinos above 100 TeV

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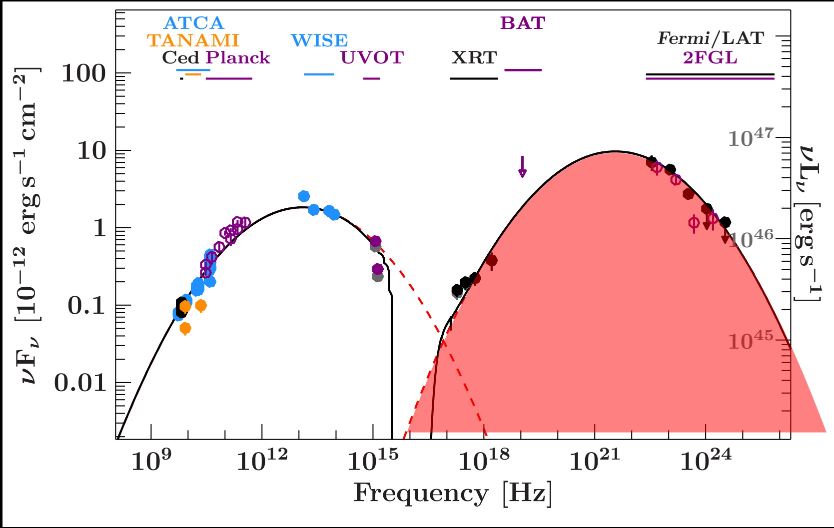
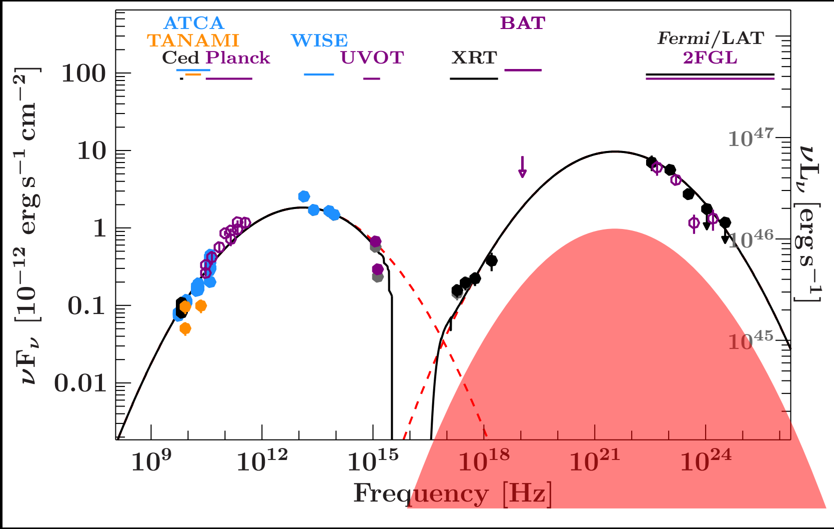
Papers in PDF link to journal article, slides available at https://fekrauss.com

- How hadronic are blazars?

- How hadronic can blazars be and still be consistent with IceCube?



Krauß F. et al. (2014)



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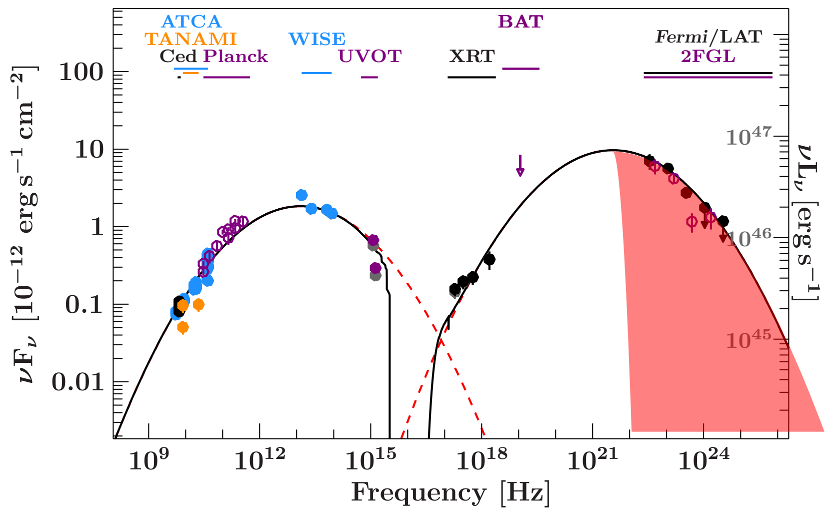


Krauß F. et al. (2014)

- What is the average percentage of hadronic emission?

  4%

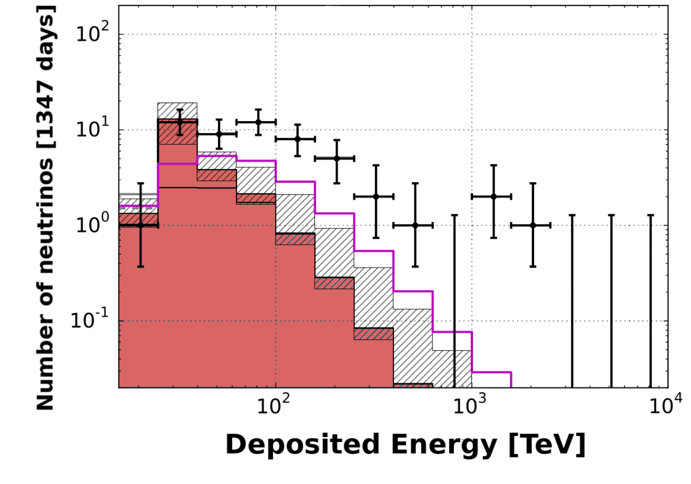
- Are all sources equally hadronic?

  ?

METHOD

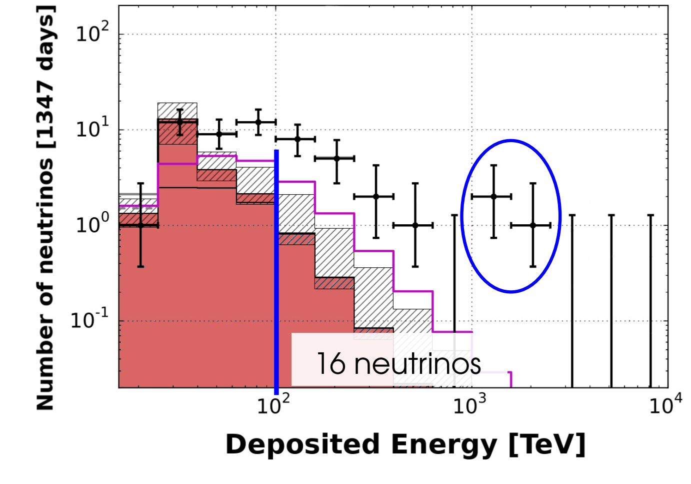
- SEDs of large sample of sources (179 3LAC blazars)
- Calculate neutrino estimates & compare to observed events

ICECUBE RESULTS



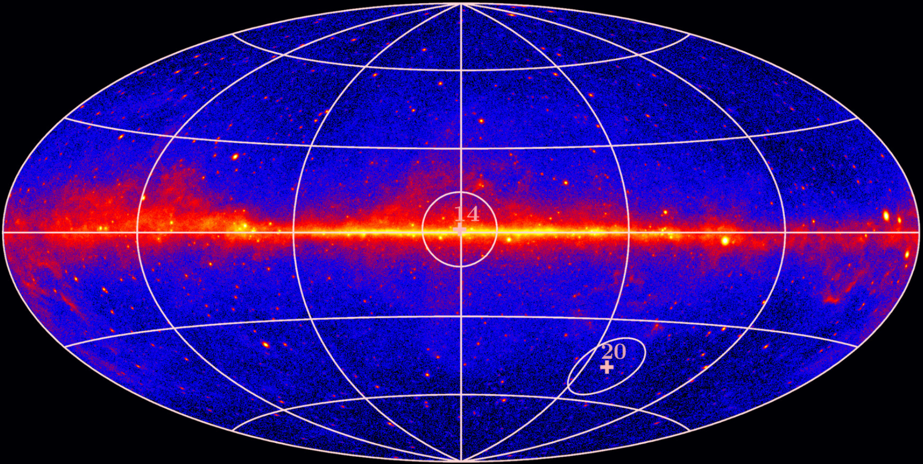
IceCube Collaboration (2013, 2013, 2014, 2015)

ICECUBE RESULTS



IceCube Collaboration (2013, 2013, 2014, 2015)

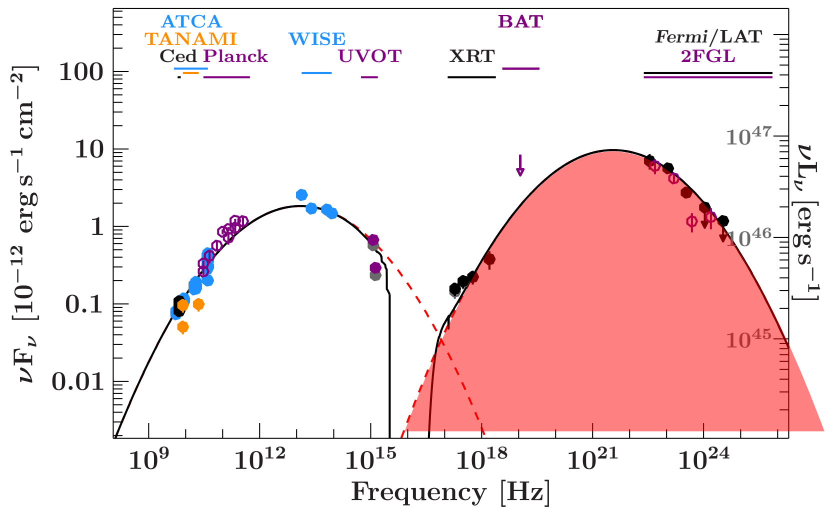
Identifying neutrino counterparts



Identifying source unfeasible for most neutrinos

Calculate neutrino emission for large number of sources

IDENTIFYING NEUTRINO COUNTERPARTS



Mannheim (1993), Mannheim (1995), Mücke (2000)

$$\int F_\nu(E_\nu)\, dE_\nu = \int F_\gamma(E)\, dE$$

Assumptions of Neutrino Calculation

- All of high-energy emission is of hadronic origin
- All of the neutrinos emitted at one energy (delta-peak)

$\rightarrow$ Calculated numbers are maximum possible number

Results

Previous Results

- Calorimetrically blazars can explain IceCube events

  Krauß et al. (2014)

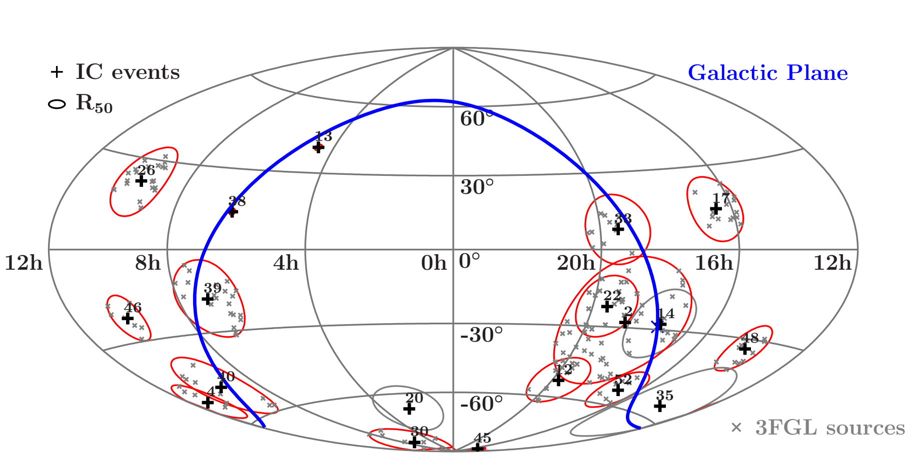
- First coincidence of blazar outburst and blazar: PKS 1424−418 and IC 35

  Kadler, Krauß et al. (2016), Nature Physics

- (TXS 0506+056 and IC 170922A)

NEUTRINOS $<$ 1 PEV

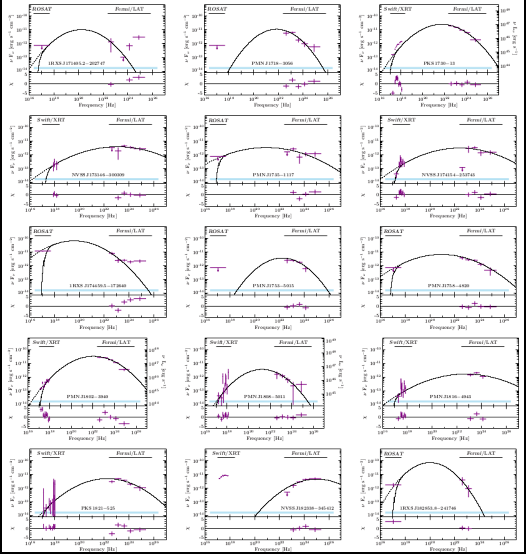
NEUTRINOS > 100 TEV



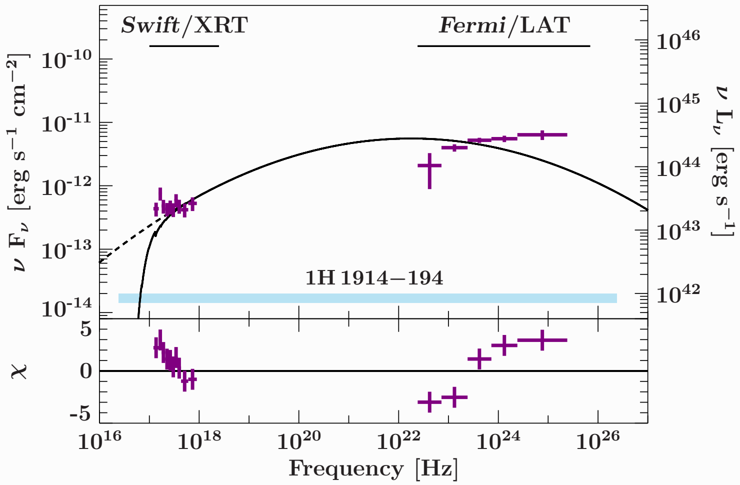
Krauß et al. (2018)

Calculate neutrino estimates N_ν

NEUTRINOS > 100 TEV



NEUTRINOS > 100 TEV: EXTREME HBL?



$\nu_{max} = 1.29$

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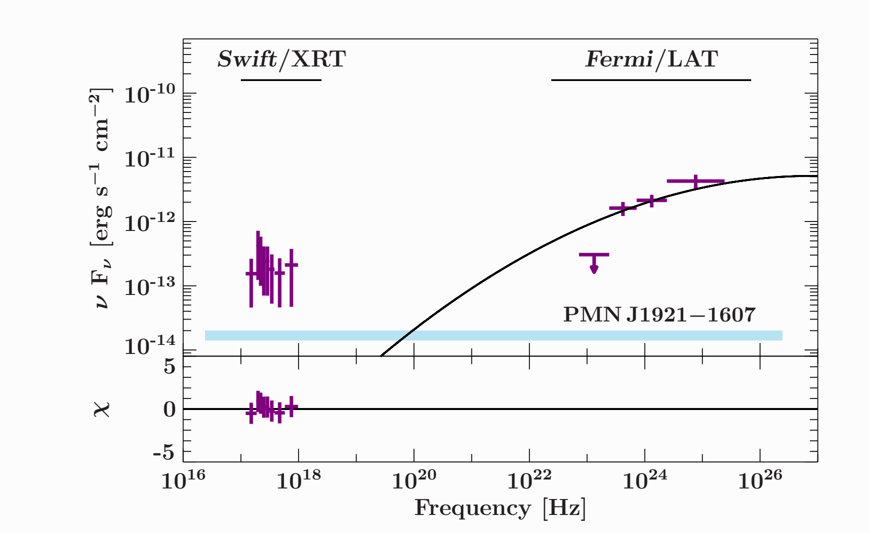

$\nu_{\text{max}} = 0.78$

NEUTRINOS > 100 TEV

$N_{\nu,\mathrm{max,fullsky}} = 3637$ maximum number

Neutrinos > 100 TeV

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$N_{\nu,\text{spec,fullsky}} = 712$ powerlaw neutrino spectrum

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$N_{\nu,\text{f,fullsky}} = 178$	ν flavors, blazar physics

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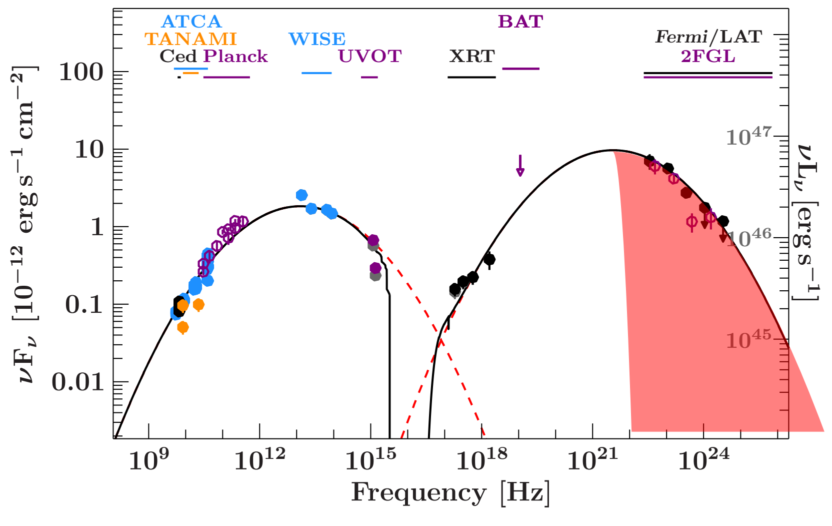
178 » 10 (16)

Neutrinos > 100 TeV



NEUTRINOS > 100 TEV

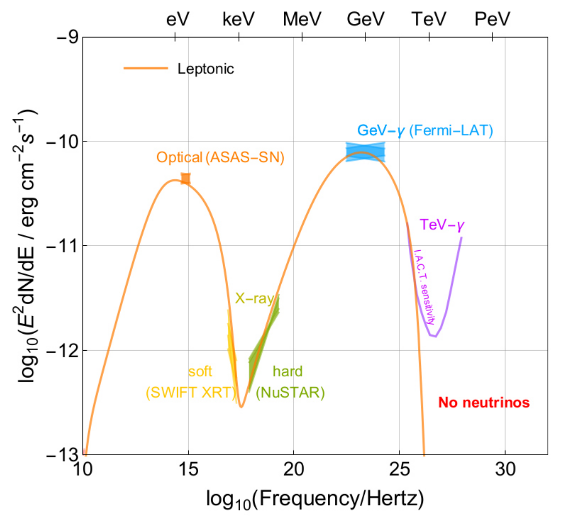
10 cosmic events (/16): 8% of emission hadronic

Considering unresolved blazars: ~4%

First constraint on hadronic contribution to SED

Is this consistent with previous results?

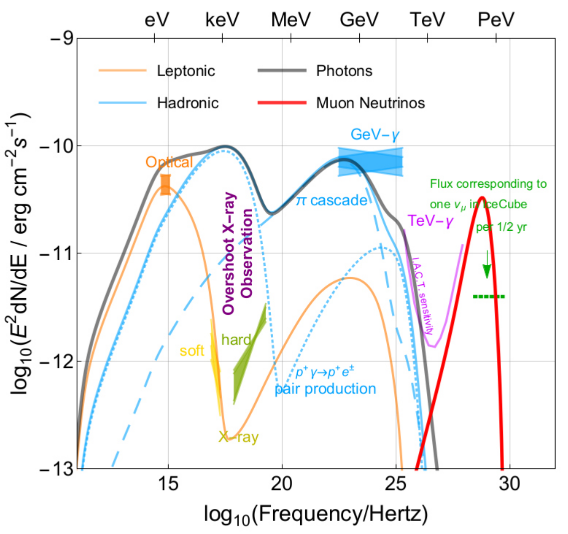
Multiwavelength modeling of TXS 0506+056



Leptonic model

(Gao et al., 2018; Keivani et al., 2018)

Multiwavelength modeling of TXS 0506+056



Hadronic model

(Gao et al., 2018; Keivani et al., 2018)

Conclusions

- Gamma-ray flux unreliable proxy of neutrino flux
- From IceCube constraints, we expect blazars to be $\sim 4\%$ hadronic on average
- Unclear whether different sources are less/more hadronic
- What is the contribution of blazars to IceCube neutrinos?

Backup

NEUTRINOS > 100 TEV

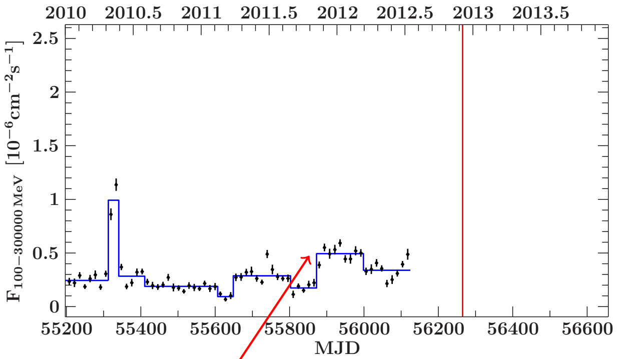
IC	$E_{\text{deposited}}$ (TeV)	MJD	$\alpha_{\text{J2000.0}}$ (°)	$\delta_{\text{J2000.0}}$ (°)	ang. res.	morphology
2	$117^{15.4}_{-14.6}$	55351.4659661	282.6	-28	25.4	Shower
4	$165.4^{19.8}_{-14.9}$	55477.3930984	169.5	-51.2	7.1	Shower
12	$104.1^{12.5}_{-13.2}$	55739.4411232	296.1	-52.8	9.8	Shower
13	$252.7^{25.9}_{-21.6}$	55756.1129844	67.9	40.3	<1.2	Track
14	$1040.7^{131.6}_{-144.4}$	55782.5161911	265.6	-27.9	13.2	Shower
17	$199.7^{27.2}_{-26.8}$	55800.3755483	247.4	14.5	11.6	Shower
20	$1140.8^{142.8}_{-132.8}$	55929.3986279	38.3	-67.2	10.7	Shower
22	$219.5^{21.2}_{-24.4}$	55941.9757813	293.7	-22.1	12.1	Shower
26	$210.0^{29.0}_{-25.8}$	55979.2551750	143.4	22.7	11.8	Shower
30	$128.7^{13.8}_{-12.5}$	56115.7283574	103.2	-82.7	8	Shower
33	$384.7^{46.4}_{-48.6}$	56221.3424023	292.5	7.8	13.5	Shower
35	$2003.7^{236.2}_{-261.5}$	56265.1338677	208.4	-55.8	15.9	Shower
38	$200.5^{16.4}_{-16.4}$	56470.1103795	93.3	14	<1.2	Track
39	$101.3^{13.3}_{-11.6}$	56480.6617877	106.2	-17.9	14.2	Shower
40	$157.3^{15.9}_{-16.7}$	56501.1641008	143.9	-48.5	11.7	Shower
45	$429.9^{57.4}_{-49.1}$	56679.2044683	219	-86.3	<1.2	Track
46	$158.0^{15.3}_{-16.6}$	56688.0702948	150.5	-22.3	7.6	Shower
48	$104.7^{13.5}_{-10.2}$	56705.9419933	213	-33.2	8.1	Shower
52	$158.1^{16.3}_{-18.4}$	56763.5448147	252.8	-54	7.8	Shower

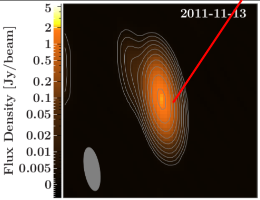
Obtain multiwavelength SEDs for all 3LAC counterparts

RESULTS FOR IC 35: VARIABILITY

Kadler, Krauss et al. (2016), Nature Physics

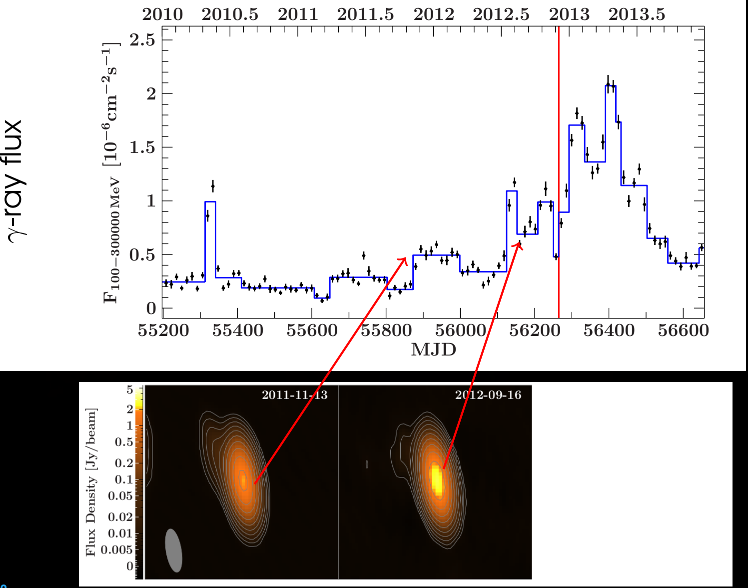
γ-ray flux





Results for IC 35: Variability

Kadler, Krauss et al. (2016), Nature Physics



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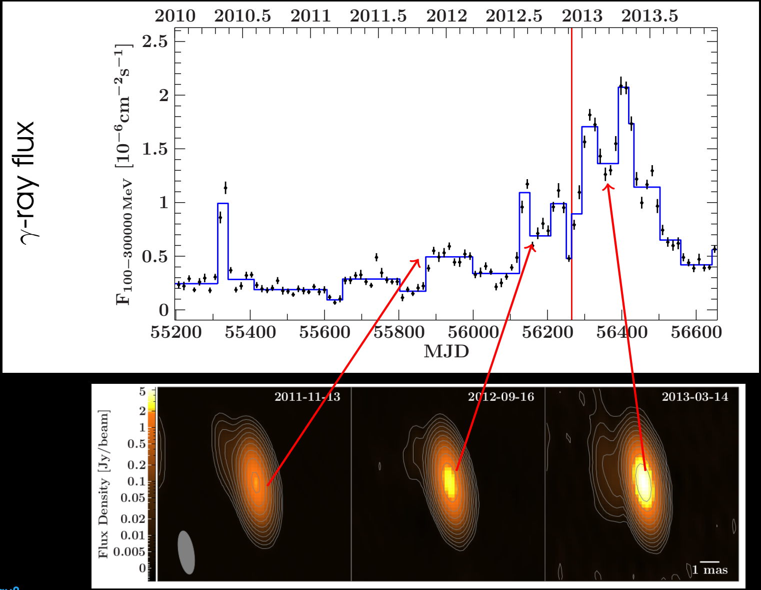
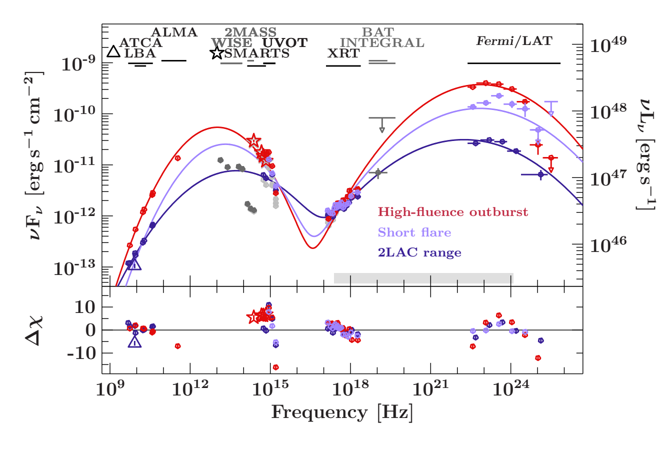


Results for IC 35: SED



$N_\nu = 5.7$ (IceCube time range)

Kadler, Krauß et al. (2016), Nature Physics

Chance coincidence of TXS 0506+056

Significance of association:

pre-trial: 4.1σ
post-trial: 3.0σ

But: signalness $\sim$0.5

Expected neutrinos during flare: 1.19 (Kreter, Kadler, Krauss et al., in prep.)

Chance coincidence of TXS 0506+056

Joint probability:

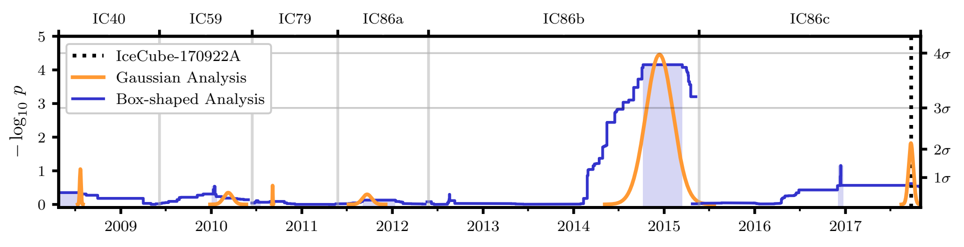
Null hypothesis: IC 35 & IC170922A are not from blazars

$p_{\mathrm{IC170922A/TXS0506+056}} = 1.8 \cdot 10^{-4} \sim 3.67\sigma$
$p_{\mathrm{IC35/PKS\ 1424-418}} = 0.05 \sim 2\sigma$

$p_{\mathrm{joint,Fisher}} \lesssim 10^{-4} \gtrsim 3.9\sigma$ (Kadler, Krauss, Kreter et al., in prep.)

Multiwavelength modeling & previous neutrino data

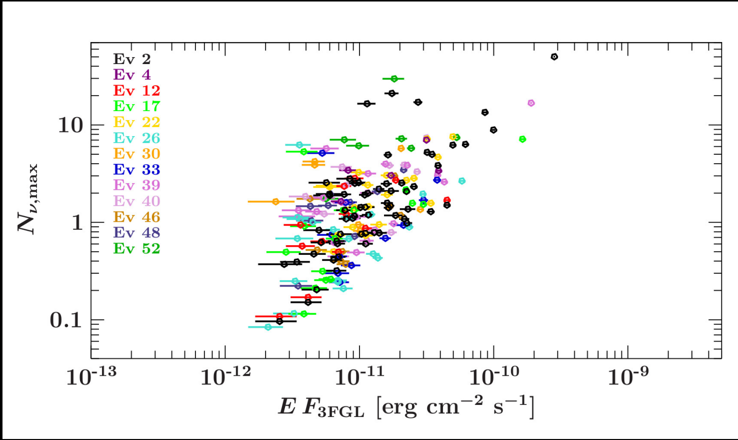
Neutrinos before IC170922A



flare post-trial: 3.5σ

IceCube (2018)

NEUTRINOS > 100 TEV



Fermi/LAT flux unreliable proxy of N_ν

Krauß et al. (2018)

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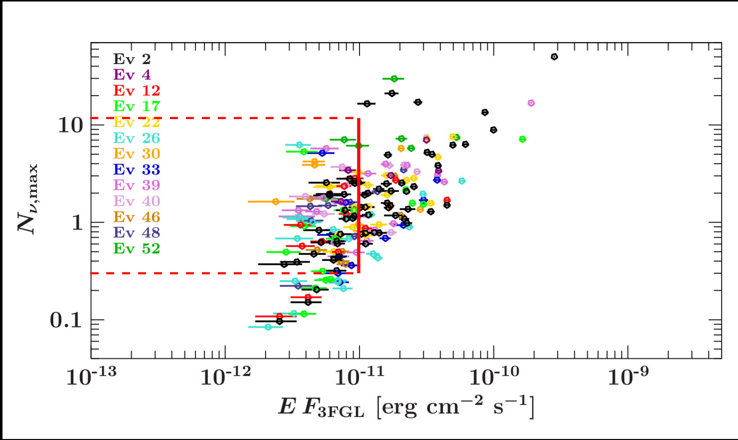

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