Going further with high-energy multi-messenger astronomy

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cosmic rays + others —> temporal coincidence impossible (deflections) but studies of diffuse fluxes



Neutrino flares and TXS 0506+56

IC170922A 90% - area: 0.97 square degrees

6.2

5.0

Declination



6.2

5.8

5.4

5.0°

Fermi-LAT Counts/Pixel

3

nal

0

Declination

RESEARCH



	correlated and are expressed as a pair, (Φ_{100} ,	, γ), The resultant <i>P</i> value is defined as the fraction of $ $ box-shaped time window, the uncertainties are				
	where Φ_{100} is the flux normalization at 100.7	he un-				
	INE Une time dependent analysis uses the same	to Voregrapho the ob Post-trials n-value for association: 3 0 m that it				
	mulation of the likelihood but searches	for Because the detecto indow				
	clustering in time as well as space by introduc	ing selections changed as s, which				
	an additional time profile. It is performed s	ep-, dependent analysis is performed by operating on , lead to different weightings of the events as a				
	arately for two different generic profile shape	S: a each data-taking period separately. (A flare that function of time, both windows identify the same				
	2009 Groussian-schaped time window and stbox-shaped	ped 2015 pansa boundary between berozoeriods couldoeber, tonre interval assignificant. For the box-shaped				
$^{-1}$	• MAGITIME 9 Windowy Each analysis varies the rend	tral partially detected in either period, but with re- time window, the best-fitting parameters are sim-				
× ⁻ -	time of the window, T_0 , and the duration	$T_{\rm W}$ duced significance.) An additional look-elsewhere illar to those of the Gaussian window, with fluence				
Elu	V H (from seconds to Vears) of the potential signal	1 to correction then needs to be applied for a result in t^{-1} at 100 TeV and spectral index given by $E^2 J_{100} =$				
0 ⁻¹¹	find the four parameters (Φ_{100} , γ , T_0 , T_W) t	that, an individual data segment, given by the ratio of $12.2^{+1.0} \times 10^{-4}$ TeV cm ⁻² and $\gamma = 2.2 + 0.2$. This				
- -	0 per maximize the likelihood ratio, which is defin	ned ' the total 9.5-year observation time to the obser- ' fluence corresponds to an average flux over				
م م	4 as the test statistic <i>TS</i> . (For the Gaussian ti	me vation time of that data segment (30). $158 \text{ days of } \Phi_{100} = 1.6^{+0.7} \times 10^{-15} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$.				
Elux cm⁻	Gewindown Tonepresents twice the standard	de-				
د	viation)) The test statistic includes a factor t	hat Neutrinos from the direction of dependent result by performing the analysis at				
10 1	O corrects for the look-elsewhere effect aris	the coordinates of TXS 0506+056 on randomized				
${f s}^{-1}$	• Swift (0.3 keV - 10 keV) from all of the possible time windows that co	uld The results of the time-dependent analysis per-				
RESEARCH	RESEARCHORDEREE 20)	formed at the coordinates of TXS 0506 \pm 056 are the naranteters: $\Phi_{rec} \propto T_c T_{rec}$ We find that the				
	Eor each analysis method (time-integrated a	and shown in Fig. 1 for each of the six data periods fraction of randomized trais that result in a more				
lower limit of	10 The addition of the second and the second of the second	$\frac{1}{10}$ shown in Fis. 1 for each of the six data periods. Indefinition of fundomized that the real data is 7×10^{-5} for				
the assumed a	istrophysical charge in the strange of the strange	b while the box-shaped time window B and 3×10^{-5} for the				
The state n	ajority of neutrinos detected by neutrino at the observed track ene	rev and zenith , a single neutrino to an astrophysical source.				
IceCube	from cosnic-ray interactions within 7 fangle in cecube is of astrophysic	arorigin. This of Following the alert, recube performed a structure of the ratio of the total observation time				
trinos are doi	nihant at energies below 100 TeV (14) was reported to be 56.5% (Although os a Adtober 2017 Although a did it on a lead a statemends to the IC86b observation time (0.5 years/3 years)				
their spectrun	n falls steeply with energy, allowing IceCube can robustly identify astr	ophysical neu- of neutrinos was found from the direction of TXS. On the energies of the events their proximity to results in P values of 2×10^{-4} and 10^{-4} respec-				
astrophysical	neutrinos to be m lablesily locfubet neutrino/datagisamples vid	1 ual neutrinos 1° 0506 (55) Near the time of the alert, the canon 5° to 1° results in 1° values of $2^{\circ} \times 10^{\circ}$ and $3^{\circ} \times 10^{\circ}$, respect				
	Op O	cluse in g in time This is illustrated in Fig 2.				
	3 9.5-year data nple. Sample numbers	ing inferince. This is indistructed in Fig. 2, indice is no a prior reason to prefer one of the				
Fig. 1. Event	display for side view	5.72				
170922A. The	e time at which a	$_{65}$				
DOM observe	d a signal is	the next				
reflected in th	le color of the hit,					
and yellow for	latest. Times	77.41 77.37 77.33				
shown are rel	ative to the first					
DOM hit acco	rding to the track					
later times ar	e shown with the	r_{c}^{-1} $r_{$				
same colors a	as the first and	$2 \wedge 10$				
last times, res	spectively. The	be lecube (50%)				
cross the dete	ector is ~3000 ns.	5.0 liceCube (90%)				
The size of a	colored sphere is	PKS 0502+049 CET LaTITLY				
proportional t	o the logarithm					
observed at the DOM, with						
larger spheres	s corresponding	0 500 1000 1500 2000 2500 3000 125m 78.5 78.0 77.5 77.0 76.5 A similar nanoseconds				
to larger signals. The total signals are total s						
charge recurrences and the problem in the problem						

Candidate Neutrino Source: TXS 0506+056

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Keivani et al. 2018





leptonic with radiatively subdominant hadronic component detection proba. with IC in real time during 6-month flare = 1-2%lucky? observed neutrino flux

but the 2014-2015 neutrino flares require higher rates (L~ 10⁴⁷ erg/s over 158 days ~ 4 x average gamma-ray luminosity) Gao et al. 2018 Cerruti et al. 2018 Zhang, Fang & Li 2018 Gokus et al. 2018 Sahakyan 2018

Multi-zone or more complicated models?

- Additional photomeson production by external radiation fields
- hadronuclear production (e.g., jet-cloud interaction) More parameters introduced, the setup is ad-hoc

Murase, Oikonomou, Petropoulou 2018

cosmic rays + others —> temporal coincidence impossible (deflections) but studies of diffuse fluxes



Population constraints from GW+neutrino non-detection

Albert et al. 2019 ApJ 870 134

Advanced LIGO

IceCube+ANTARES

Upper limits on rate density of GW+neutrino sources



Why focus on transient sources?

Meszaros et al. 2019

IceCube

Pierre Auger Observatory



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The new high-energy transient zoo





Young pulsars

Long Gamma Ray Bursts AGN/Blazars flares, time-variabilities

Black hole mergers

Tidal disruption events

Superluminous Supernovae

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double black hole merger

The new high-e

Murase & Bartos 2019

ACN/RIAZARE

Source	Rate density	EM Luminosity	Duration	Typical Counterpart
	$[{\rm Gpc}^{-3} {\rm yr}^{-1}]$	$[\mathrm{erg} \ \mathrm{s}^{-1}]$	$[\mathbf{s}]$	
Blazar flare ^a	10 - 100	$10^{46} - 10^{48}$	$10^6 - 10^7$	broadband
Tidal disruption event	0.01 - 0.1	$10^{47} - 10^{48}$	$10^6 - 10^7$	jetted (X)
	100 - 1000	$10^{43.5} - 10^{44.5}$	$> 10^6 - 10^7$	tidal disruption event (optical,UV)
Long GRB	0.1 - 1	$10^{51} - 10^{52}$	10 - 100	prompt (X, gamma)
Short GRB	10 - 100	$10^{51} - 10^{52}$	0.1 - 1	prompt (X, gamma)
Low-luminosity GRB	100 - 1000	$10^{46} - 10^{47}$	1000 - 10000	prompt (X, gamma)
GRB afterglow		$< 10^{46} - 10^{51},$	> 1 - 10000	afterglow (broadband)
Supernova (II)	10^{5}	$10^{41} - 10^{42}$	$> 10^5$	supernova (optical)
Supernova (Ibc)	3×10^4	$10^{41} - 10^{42}$	$> 10^5$	supernova (optical)
Hypernova	3000	$10^{42} - 10^{43}$	$> 10^{6}$	supernova (optical)
NS merger	300 - 3000	$10^{41} - 10^{42}$	$> 10^5$	kilonova (optical/IR)
		10^{43}	$> 10^7 - 10^8$	radio flare (broadband)
BH merger	10 - 100	?	?	?
WD merger	$10^4 - 10^5$	$10^{41} - 10^{42}$	$> 10^5$	merger nova (optical)

^aBlazar flares such as the 2017 flare of TXS 0506+056 are assumed for the demonstration.

Abbreviations: BH, black hole; EM, electromagnetic; GRB, gamma-ray burst; NS, neutron star; WD, white dwarf.

Black hole mergers

Tidal disruption events

Superluminous Supernovae

A "Hillas diagram" for high-energy neutrino transients

Guépin & KK 2017





Inteolo butting: subto be probed transients



Observed high-energy multi-messenger transients

Murase & Bartos 2019 Guépin & KK 2017

AGN/Blazars

flares, time-variabilities

e.g., Kimura et al. 2017, 2018 Biehl et al. 2018 Decoene, Guépin, Fang, KK, Metzger, 2020 Ahlers & Halser 2020

Fang & Metzger 2018

Magnetars

(AXP/SGR)

Neutron star mergers

KK & Silk 2016 De Wasseige et al. 2019

> Black hole mergers

Tidal disruption events

Young pulsars

Long Gamma Ray Bursts

Superluminous Supernovae

Computing high-energy neutrino fluxes



High-energy neutrinos from binary neutron-star mergers



Coincident detection with gravitational waves



cosmic rays + others —> temporal coincidence impossible (deflections) but studies of diffuse fluxes



UHE neutrinos: an unchartered territory!

Alves Batista, de Almeida, Lago, KK, 2018 GRAND Science & Design, 2018 KK, Allard, Olinto 2010

