Neutrinos from Shredded Stars

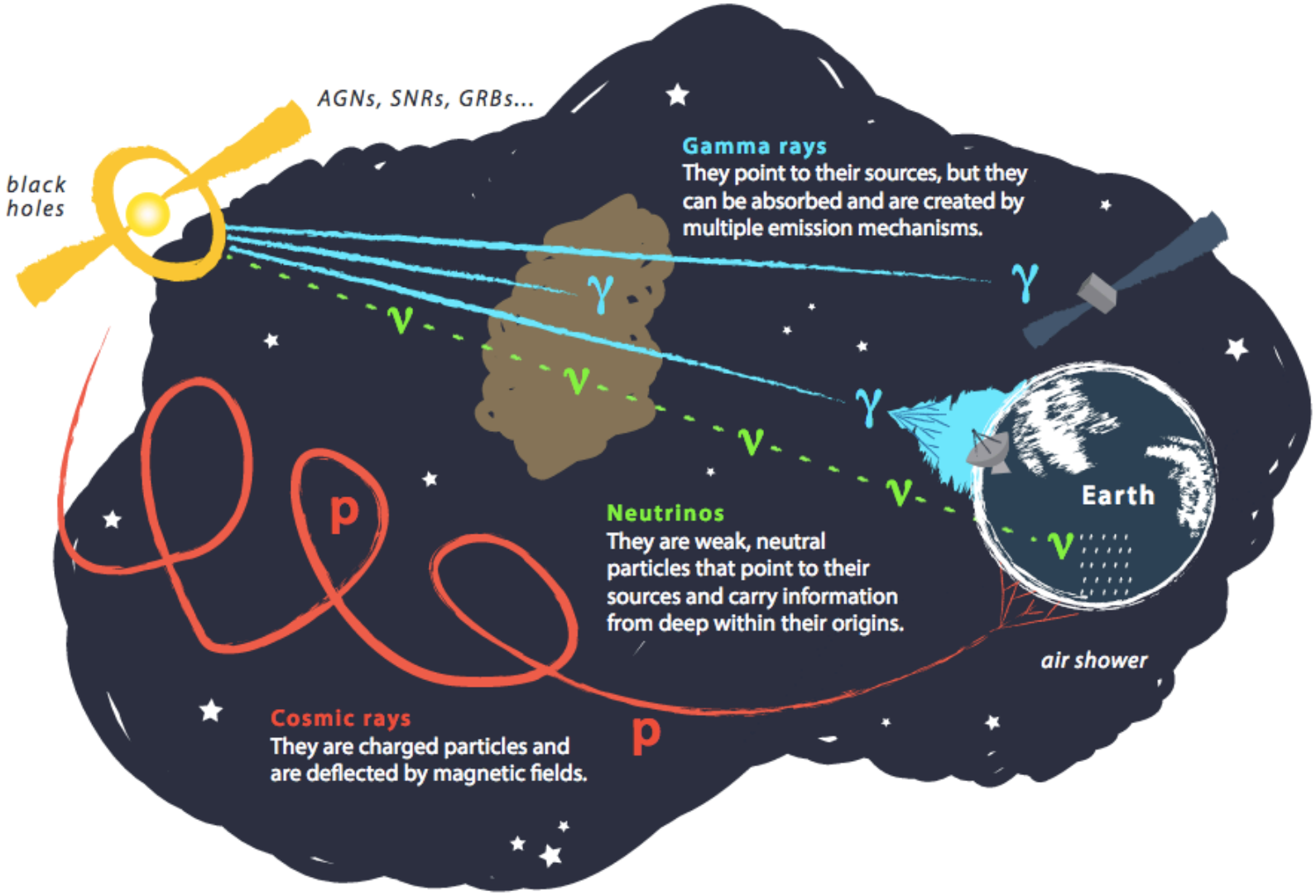
Robert Stein

APC, 11/11/20

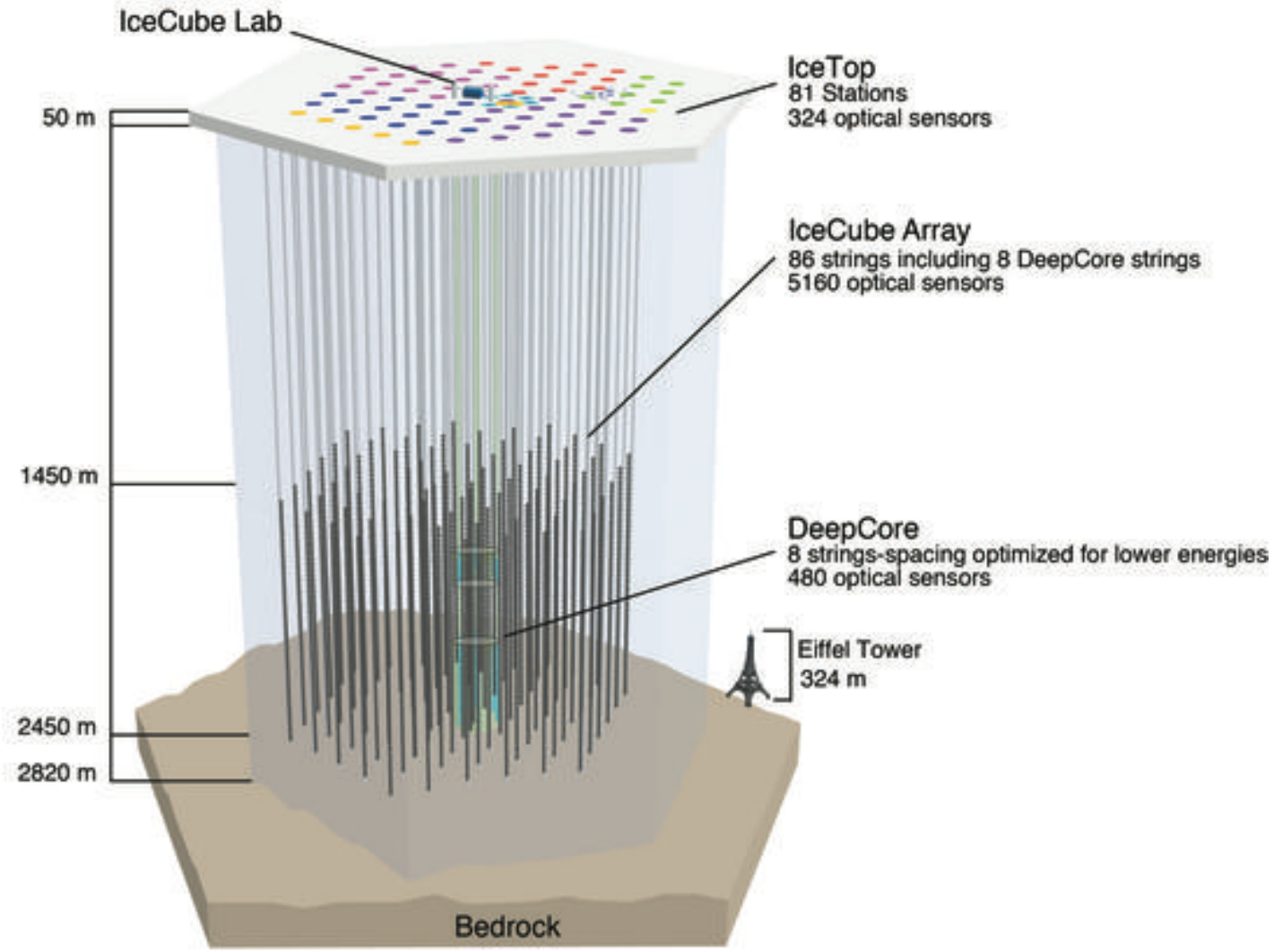
HELMHOLTZ
Young Investigators

DESY.

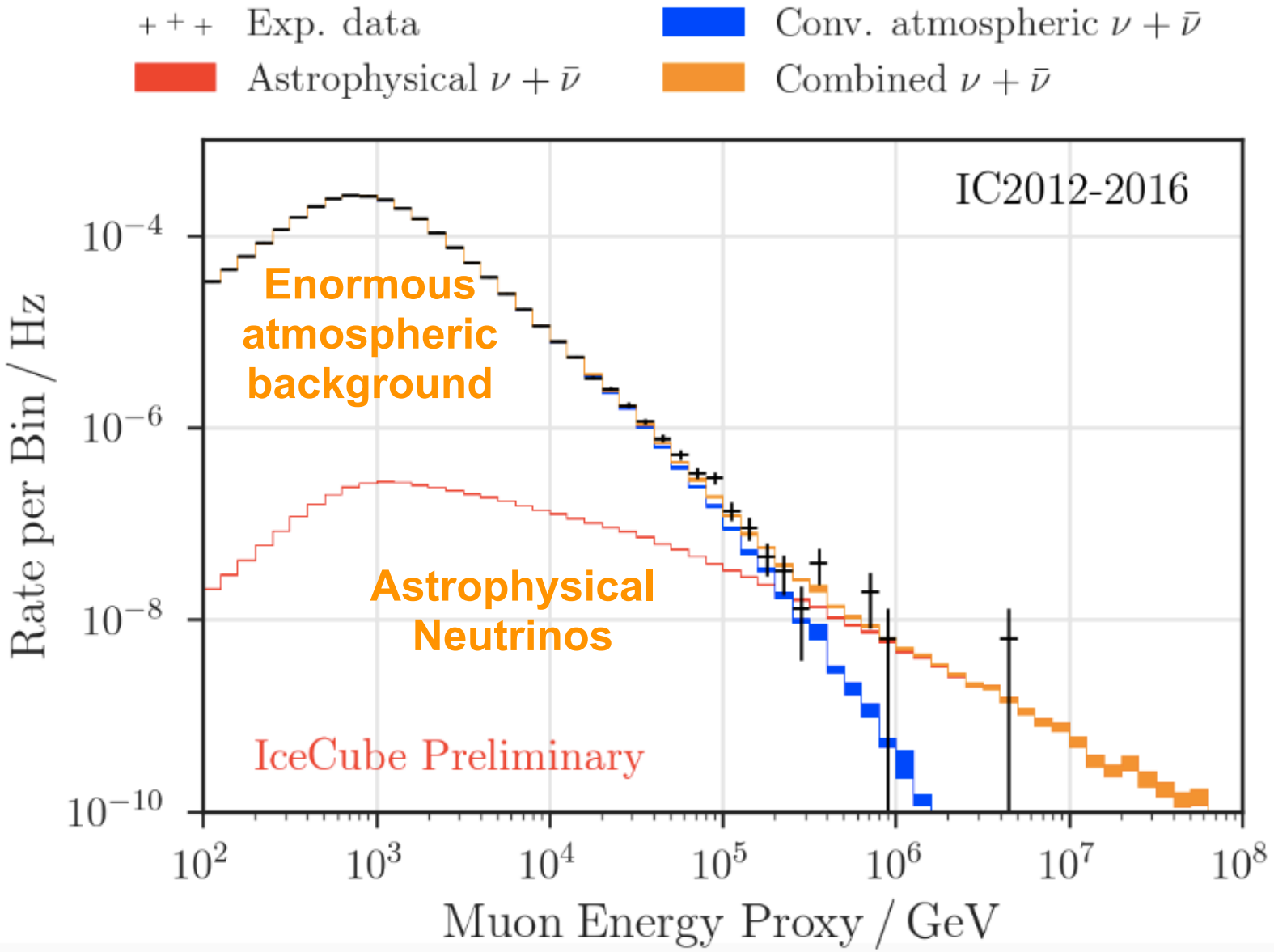
An introduction multi-messenger astronomy



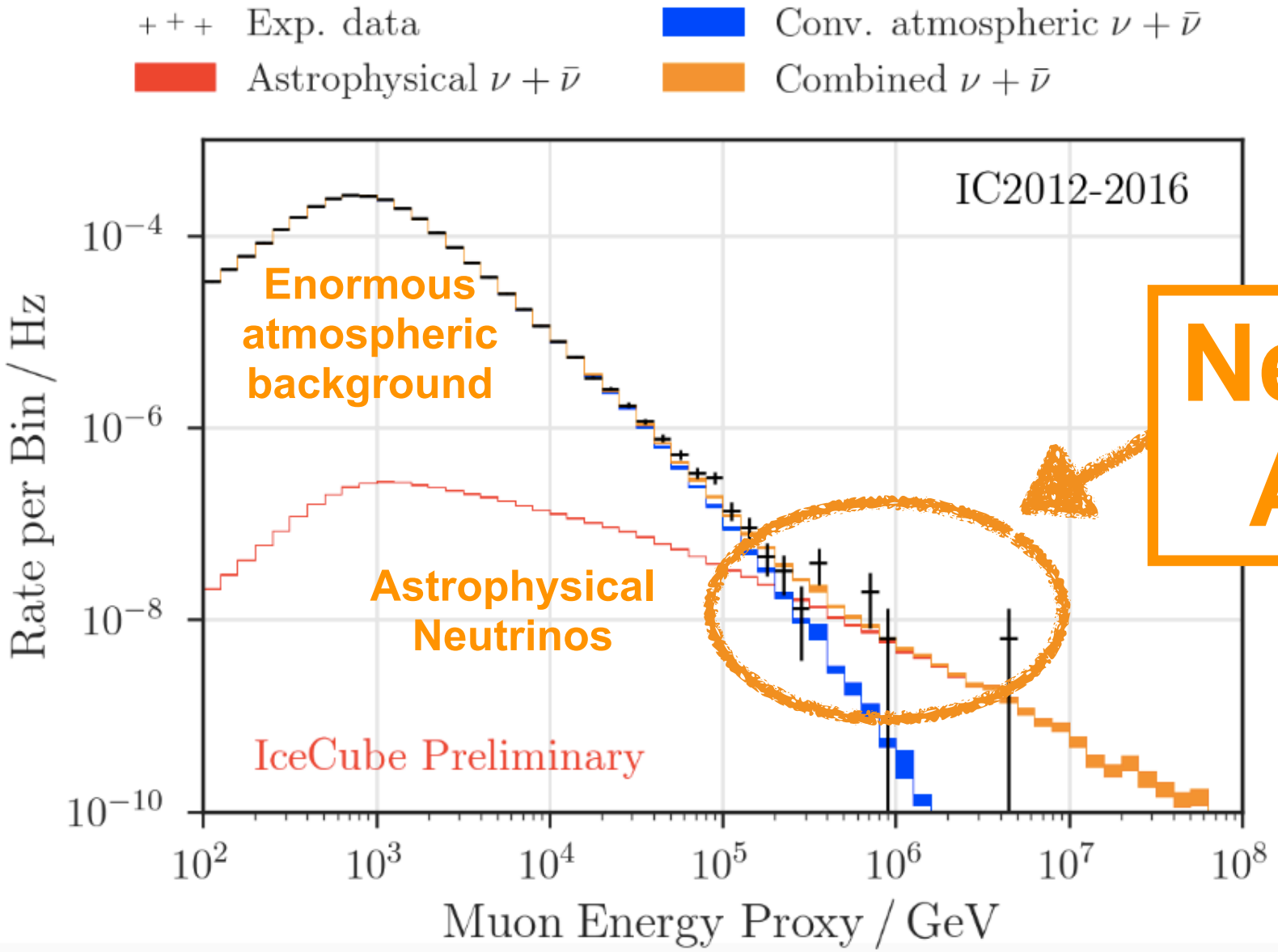
The IceCube Neutrino Observatory



Neutrino Astronomy in a nutshell

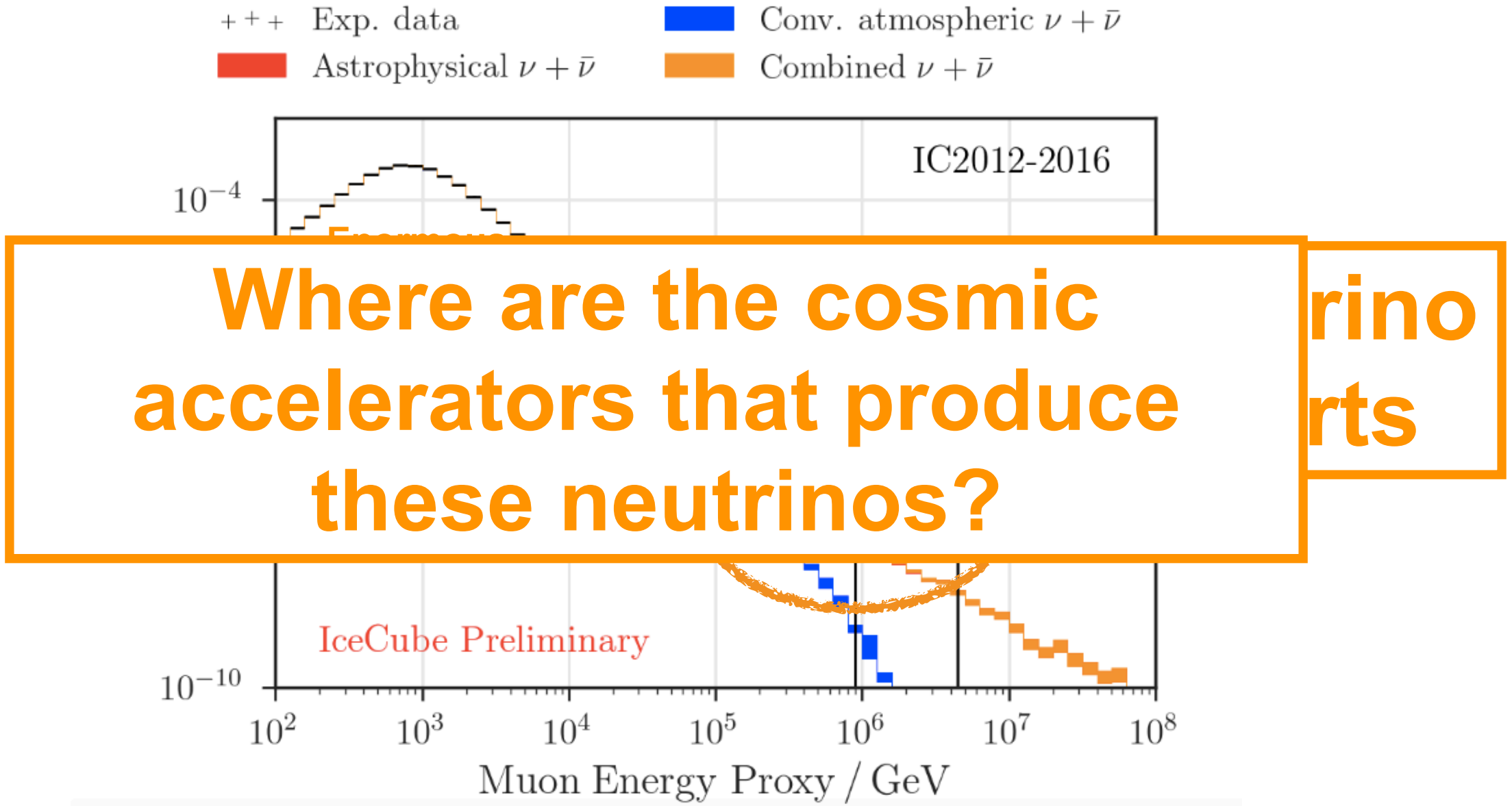


Neutrino Astronomy in a nutshell



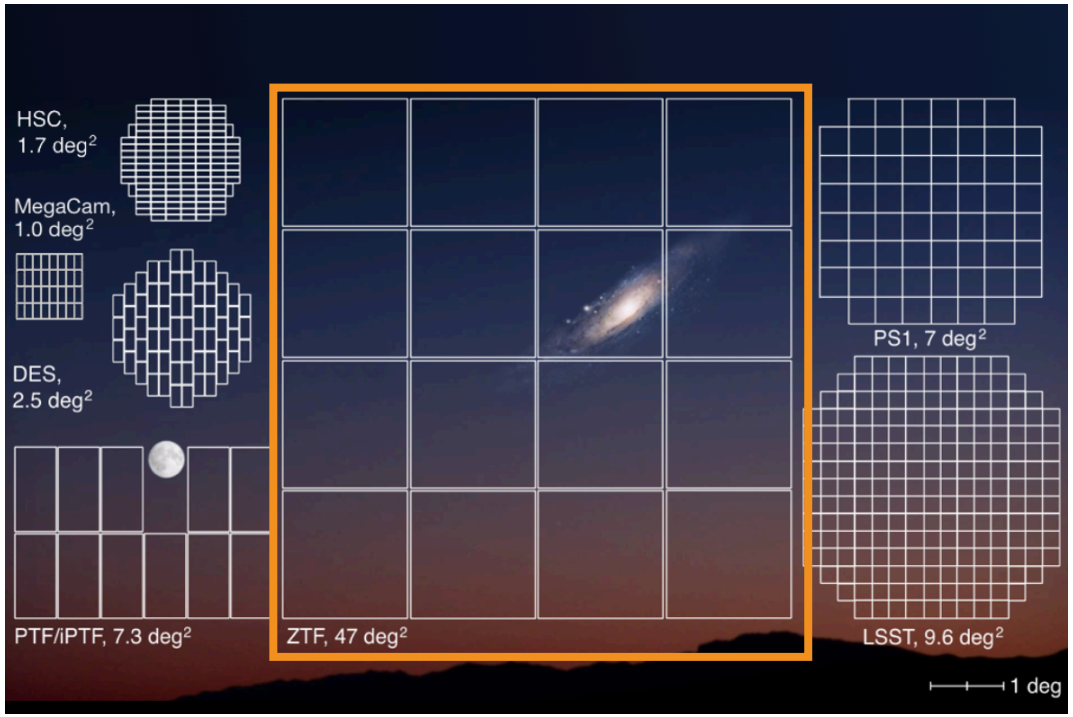
Neutrino Alerts

Neutrino Astronomy in a nutshell



Where are the cosmic accelerators that produce these neutrinos?

The Zwicky Transient Facility (ZTF)



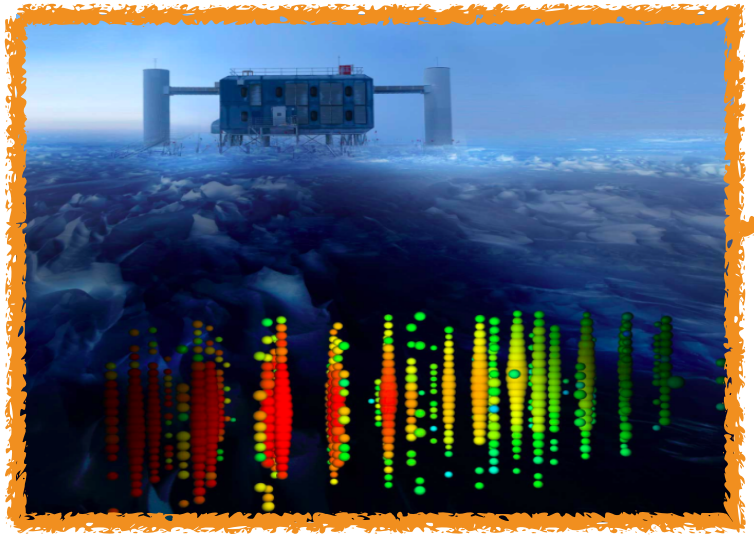
ZTF is an optical telescope with huge 47 sq. deg f.o.v. Optimised for volumetric survey speed.

Scans northern sky every 2 nights, to ~20.5 mag in g and r, as part of a public survey.

Designed as a stepping stone from “scrapbook astronomy” to “big data astronomy”

The neutrino follow-up program

~500k objects per night

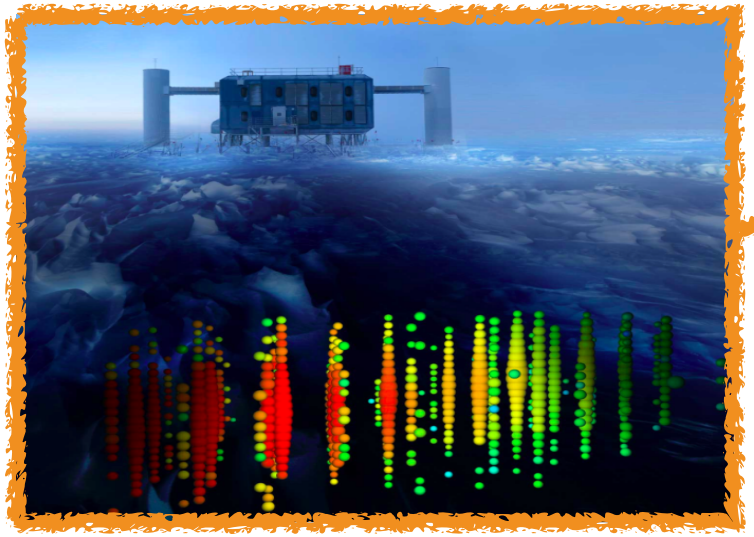


Neutrino direction and time

Find counterpart?

The neutrino follow-up program

~500k objects per night



Neutrino direction and time

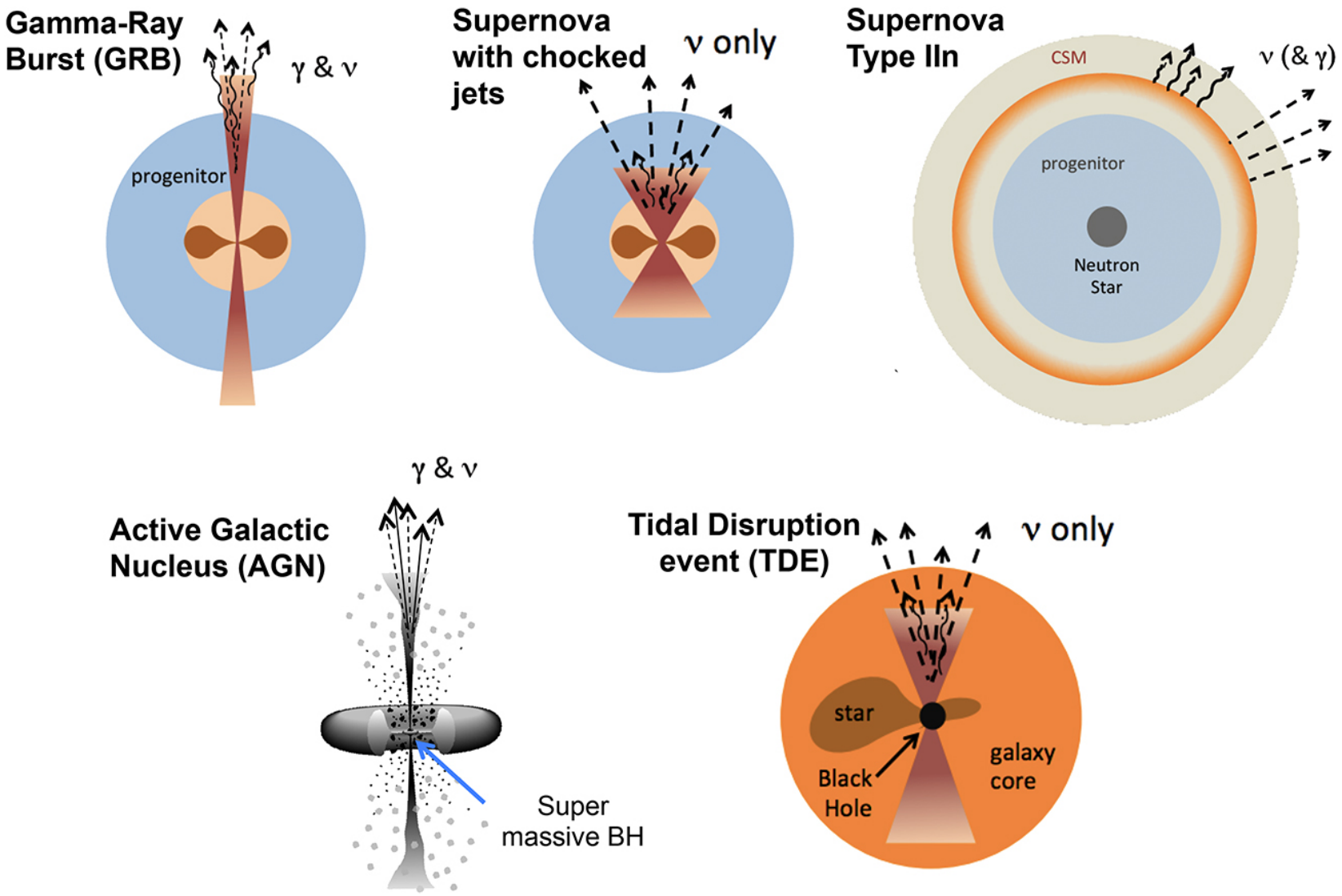
Reject stars, asteroids, planets

Correlate

Spectroscopically classify few remaining objects

Find counterpart?

What are we looking for?



ZTF neutrino follow-up program

8/31 alerts followed-up

Event	R.A (deg)	Dec (deg)	90% area (sq. deg.)	ZTF obs (sq. deg.)	Signalness	Ref
IC190503A	120.28	+6.35	1.94	1.37	36%	40,41
IC190619A	343.26	+10.73	27.16	21.57	55%	42,43
IC190730A	225.79	+10.47	5.41	4.52	67%	44,45
IC190922B	5.76	-1.57	4.48	4.09	51%	46–48
IC191001A	**314.08**	**+12.94**	**25.53**	**20.56**	**59%**	**11,15,49**
IC200107A	148.18	+35.46	7.62	6.22	-	39,50
IC200109A	164.49	+11.87	22.52	20.06	77%	51,52
IC200117A	116.24	+29.14	2.86	2.66	38%	53–55

Table 1: Summary of the eight neutrino alerts followed up by ZTF, with IC191001A highlighted in bold. The area column indicates the region of sky observed at least twice by ZTF, within the reported 90% localisation, and accounting for chip gaps. The *signalness* describes the probability that each neutrino is of astrophysical origin, rather than arising from atmospheric backgrounds. One alert, IC200107A, was reported without a signalness estimate.

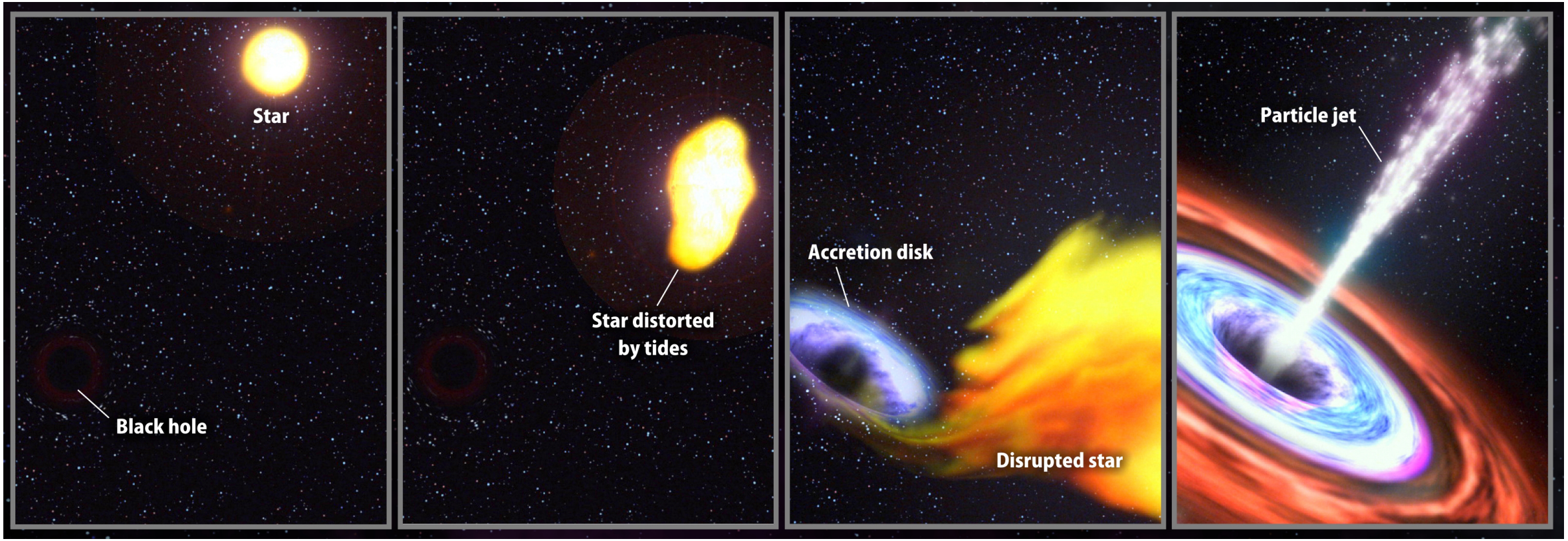
23/31 alerts not followed-up

Cause	Events
Alert Retraction	*IC180423A*[56], *IC181031A*[57], *IC190205A*[58], *IC190529A*[59]
Proximity to Sun	*IC180908A*[60], *IC181014A*[61], *IC190124A*[62], *IC190704A*[63]
	IC190712A[64], *IC190819A*[65], *IC191119A*[66], *IC200227A*[67]
Low Altitude	*IC191215A*[68]
Southern Sky	*IC190331A*[69], *IC190504A*[70]
Poor Signalness & Localisation	*IC190221A*[71], *IC190629A*[72], *IC190922A*[73]
	IC191122A[74], *IC191204A*[75], *IC191231A*[76]
Bad Weather	*IC200120A*[77,78]
Telescope Maintenance	*IC181023A*[79]

Table 2: Summary of the 23 neutrino alerts that were not followed up by ZTF since survey start on 2018 March 20. Of these, 4/23 were retracted, 11/23 were inaccessible to ZTF for various reasons, 6/23 were deemed alerts of poor quality, while just 2/23 were due to telescope downtime.

ZTF has (conditions-permitting) followed up every accessible alert since March 2018, except those low-quality alerts with both signalness < 50% and 90% area > 10 sq. deg.

What are Tidal Disruption Events (TDEs)?



Credit: NASA

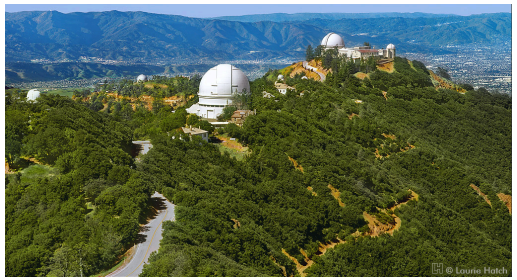
1 2 3 4

A comprehensive multi-messenger observation campaign

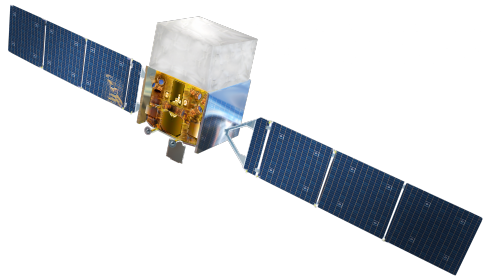
Radio

Optical

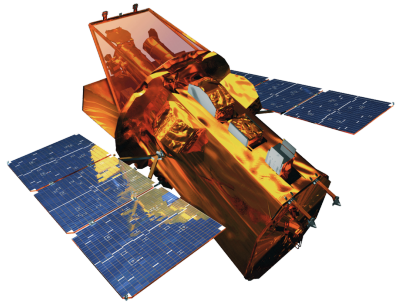
Spectroscopy

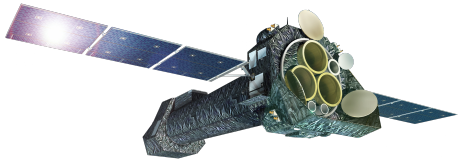


Gamma-ray



UV + X-ray





A comprehensive multi-messenger observation campaign

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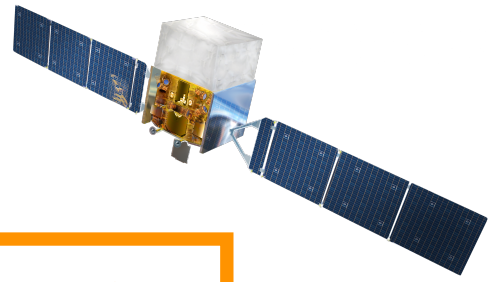
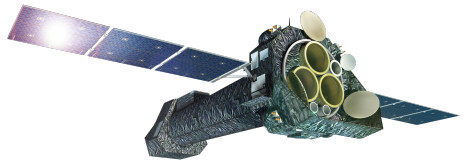
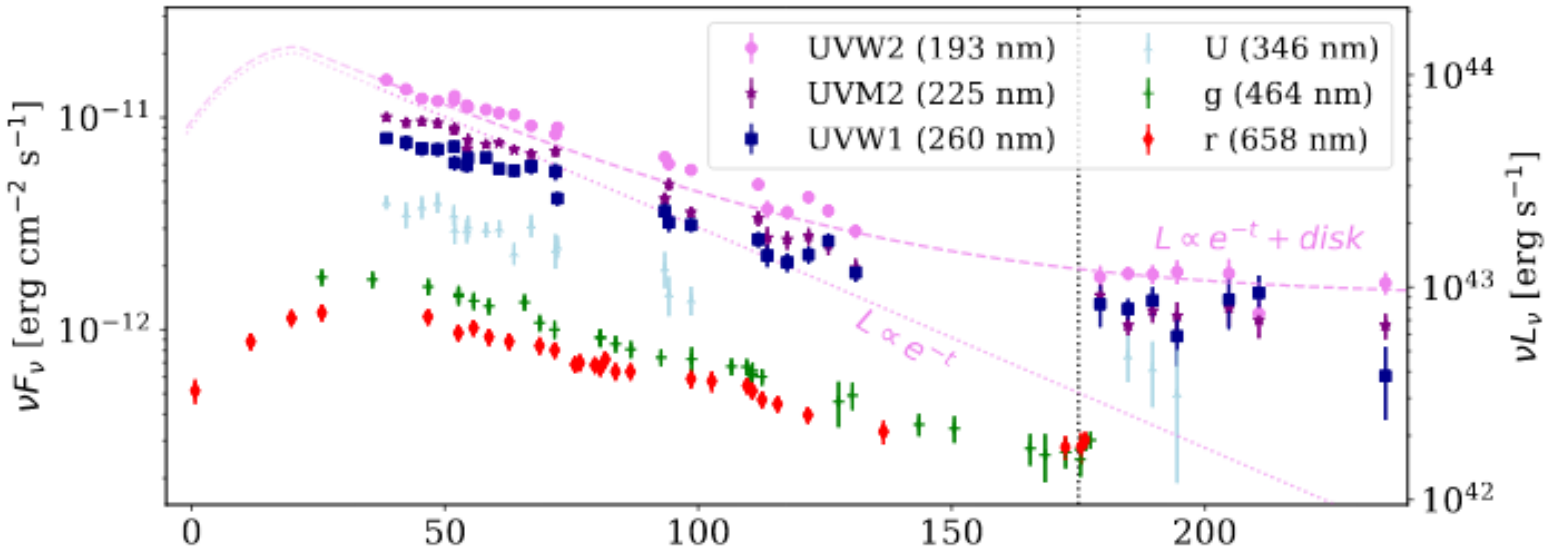


Data from a dozen instruments across the electromagnetic spectrum



IC191001A + AT2019dsg

https://arxiv.org/abs/2005.05340



Bright, radio-emitting TDE found coincident with IC191001A.

Radio reveals first direct evidence of a central engine in a thermal TDE. Data suggest that conditions are compatible with neutrino production.

TDEs are rare. Accounting for all 8 neutrino campaigns and ZTF RE TDE density (1 per 10000 sq. deg.), the probability to find any coincident radio-emitting TDE is 0.5%.

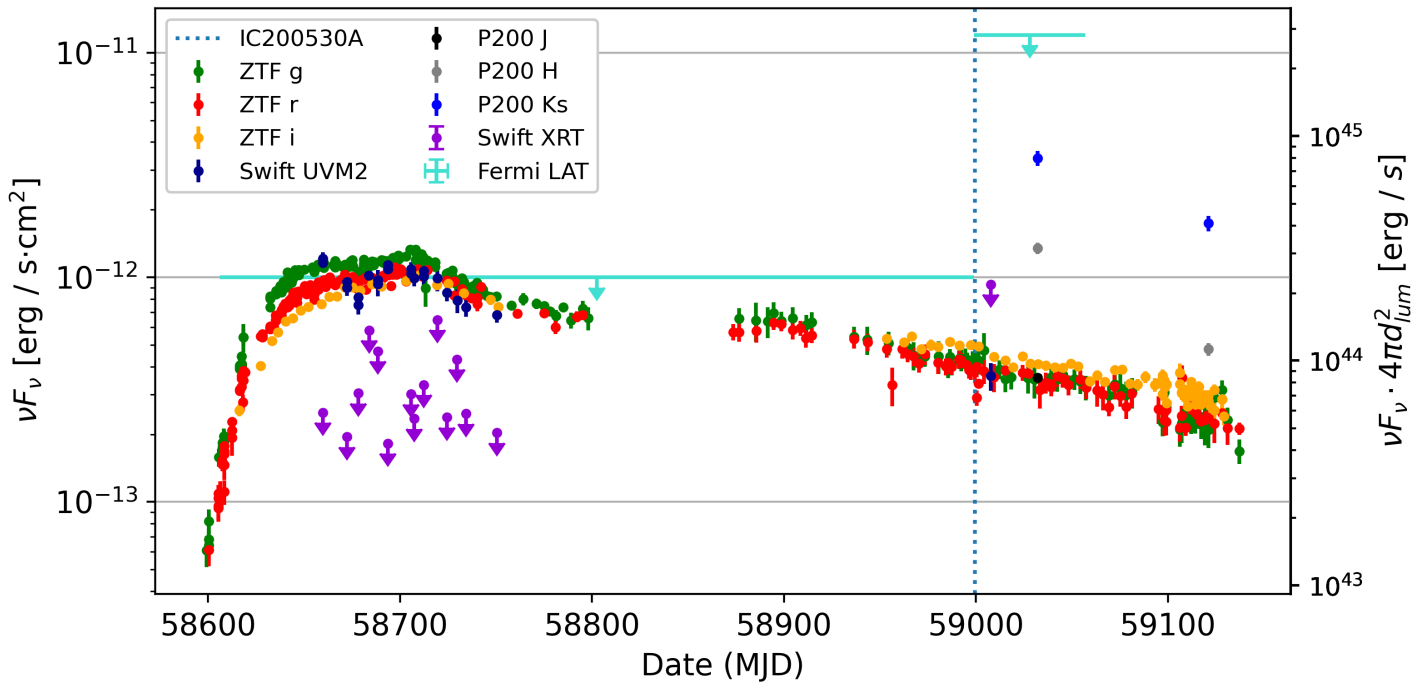
Suggests TDEs contribute to the astrophysical neutrino flux.

But we kept looking…

Event	R.A. (J2000) [deg]	Dec (J2000) [deg]	90% area [sq. deg.]	ZTF obs [sq. deg.]	Signalness	Reference
IC190503A	120.28	+6.35	1.94	1.37	36%	Blaufuss (2019a); Stein et al. (2019f)
IC190619A	343.26	343.26	27.16	21.57	55%	Blaufuss (2019b); Stein et al. (2019g)
IC190730A	225.79	+10.47	5.41	4.52	67%	Stein (2019a); Stein et al. (2019a)
IC190922B	5.76	-1.57	4.48	4.09	51%	Blaufuss (2019c); Stein et al. (2019b,c)
IC191001A	**314.08**	**+12.94**	**25.53**	**20.56**	**59%**	**Stein (2019b); Stein et al. (2019d,e)**
IC200107A	148.18	+35.46	7.62	6.22	-	Stein (2020a); Stein & Reusch (2020)
IC200109A	164.49	+11.87	22.52	20.06	77%	Stein (2020b); Reusch & Stein (2020a)
IC200117A	116.24	+29.14	2.86	2.66	38%	Lagunas Gualda (2020a); Reusch & Stein (2020b,c)
IC200512A	295.18	+15.79	9.4	9.3	32%	Lagunas Gualda (2020b); Reusch et al. (2020a)
IC200530A	**255.37**	**+26.61**	**22.2**	**22.0**	**59%**	**Stein (2020c); Reusch et al. (2020e,d,a)**
IC200620A	162.11	+11.96	1.2	1.2	32%	Santander (2020a); Reusch et al. (2020b)
IC200916A	109.78	+14.36	3.6	3.6	32%	Blaufuss (2020); Reusch et al. (2020c,b)
IC200926A	96.40	-4.33	1.45	1.3	44%	Lagunas Gualda (2020c); Reusch et al. (2020e)
IC200929A	29.53	+3.47	1.01	0.9	47%	Lagunas Gualda (2020d); Weimann et al. (2020)
IC201007A	265.17	+5.34	0.57	0.5	88%	Santander (2020b); Reusch et al. (2020f)
IC201021A	260.82	+14.55	6.9	6.3	30%	Lagunas Gualda (2020e); Stein et al. (2020a)

We have now completed 16 follow-up campaigns to date, out of 51 neutrinos.

And have now found AT2019fdr!



Very luminous nuclear transient found coincident with IC200530A (z=0.267).

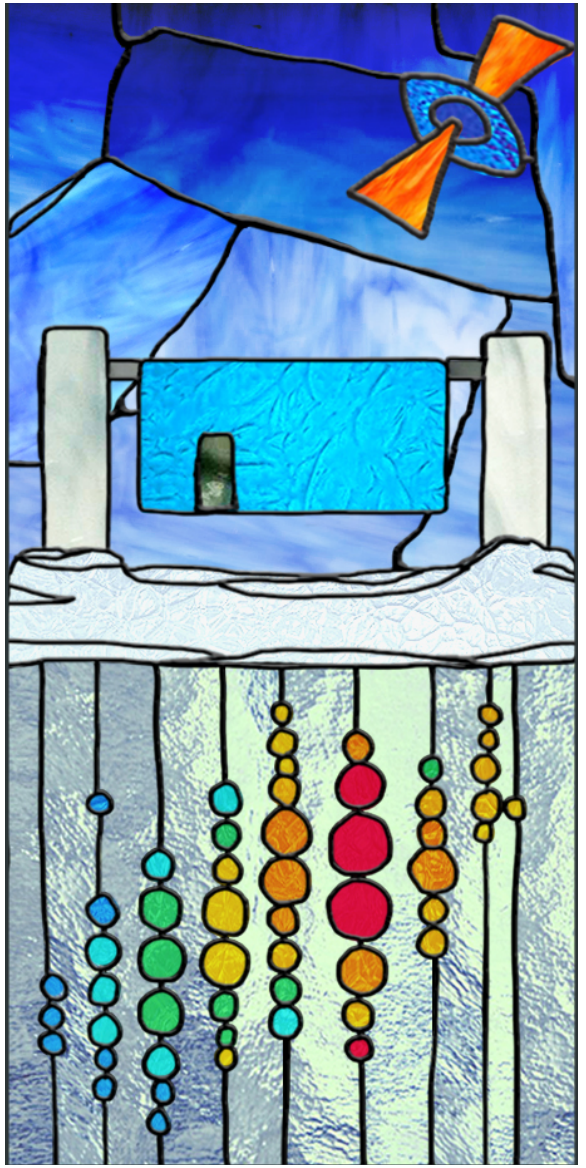
Data analysis still ongoing, but most likely a second TDE. Paper in prep (S. Reusch et al.)

Lightning rarely strikes twice. Strong evidence of an emerging trend.

[p=~0.005% to get two radio-emitting TDEs by chance]

Summary

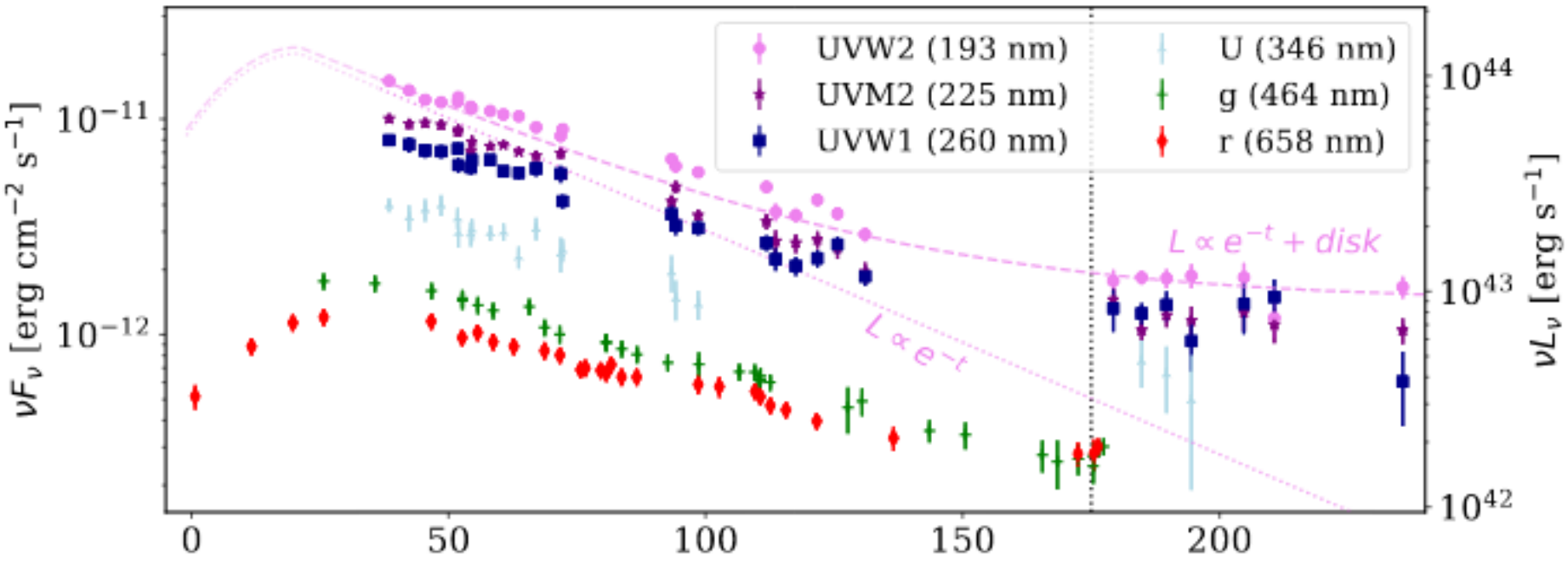
- Still searching for sources of cosmic rays + neutrinos
- ZTF has a dedicated neutrino follow-up program, with analysis using AMPEL
- AT2019dsg paper submitted to journal, hopefully published soon.
- Have since found a second likely neutrino TDE, AT2019fdr, with paper in prep.
- **Strong evidence of an emerging trend. With ZTF, we are performing the first systematic search that can identify TDEs.**
- **Our program is continuing with ZTF-II, and we hope to find even more associations!**



Credit: IceCube

Backup

Introducing AT2019dsg ("ZTF-BranStark")



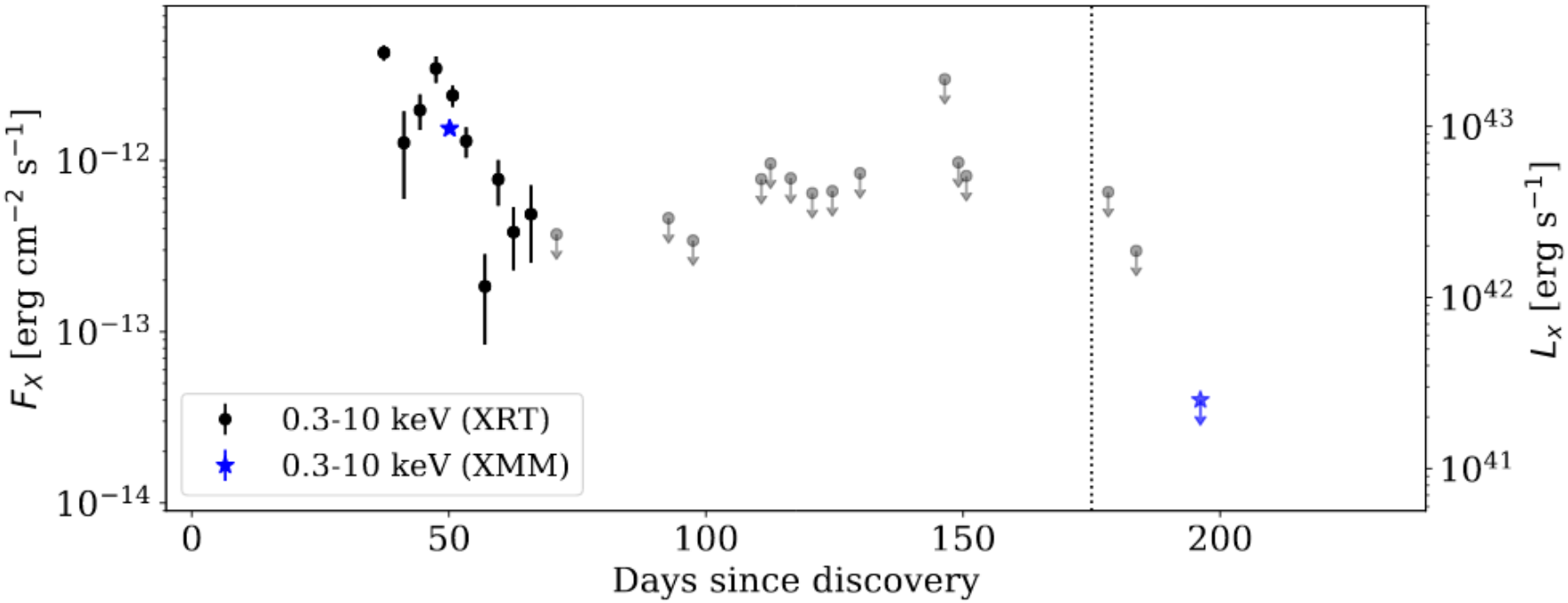
Discovered in April 2019 by ZTF, lots of data! Neutrino arrived ~175 days post-discovery.

As for most TDEs, well-described by thermal emission ($T \sim 10^{4.6}$ K, $R \sim 10^{14.5}$ cm, $L_{peak} \sim 10^{44.5}$ erg s^{-1})

Relatively early/bright plateau, consistent with accretion disk formation. (z = 0.051)

Emission from pretty hot + bright UV photosphere

X-rays are more puzzling…



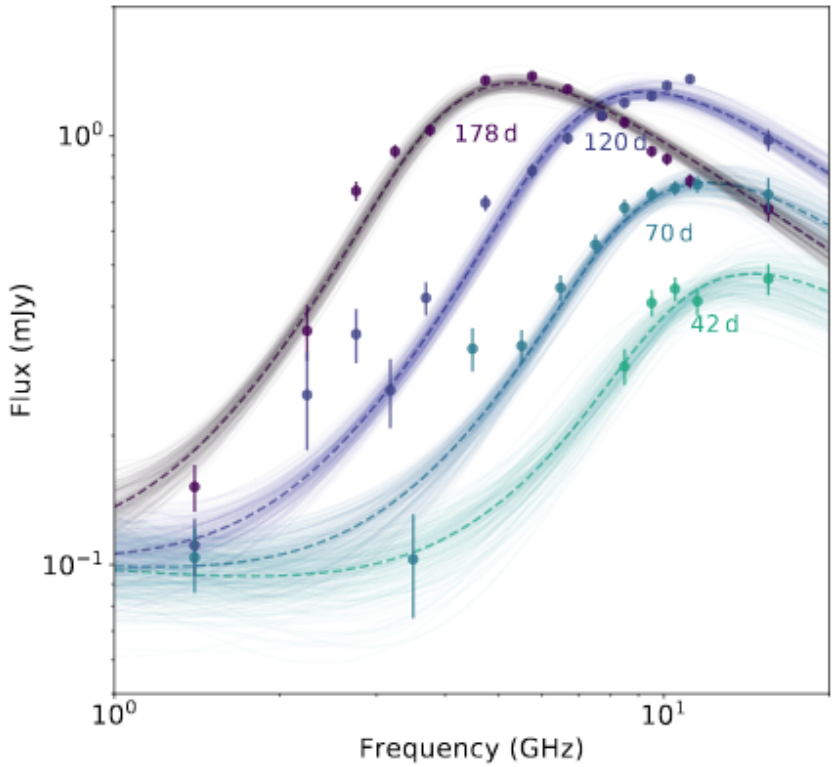
First observed around optical peak. Initially bright (L_x/L_{opt} ~ 0.1)

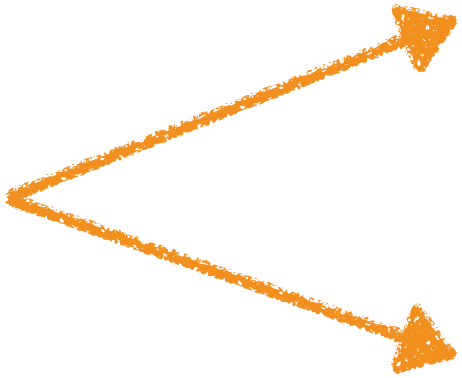
Fades extremely quickly. At least factor 100 decrease over ~170 days

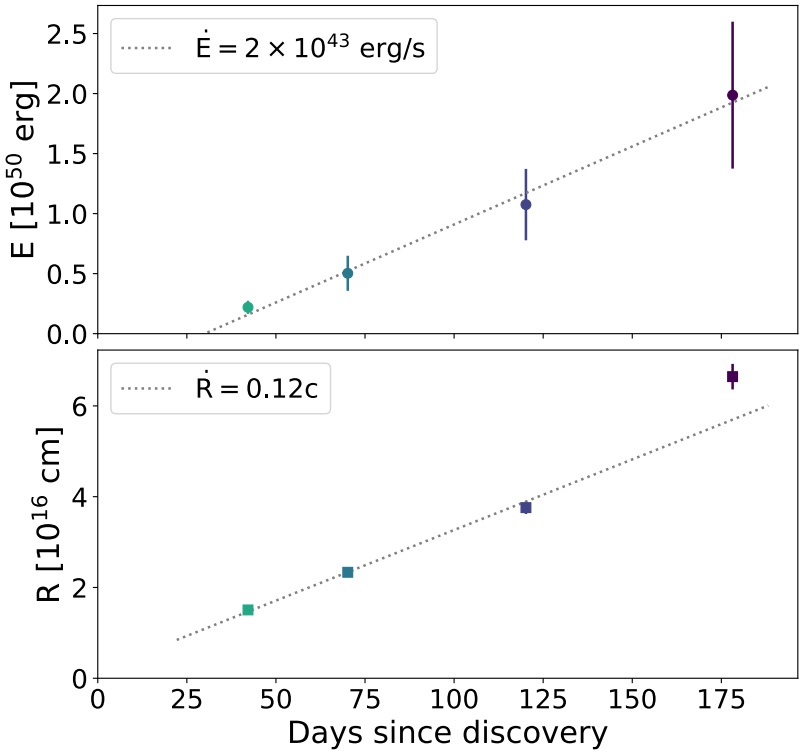
As for other TDEs, described by thermal X-rays with T ~ $10^{5.8}$ K, small inferred R ~ 2x10^{11} cm

X-rays from inner region. Fading due to cooling or obscuration? X-rays in TDEs are poorly-understood.

Radio data is unprecedented for a TDE







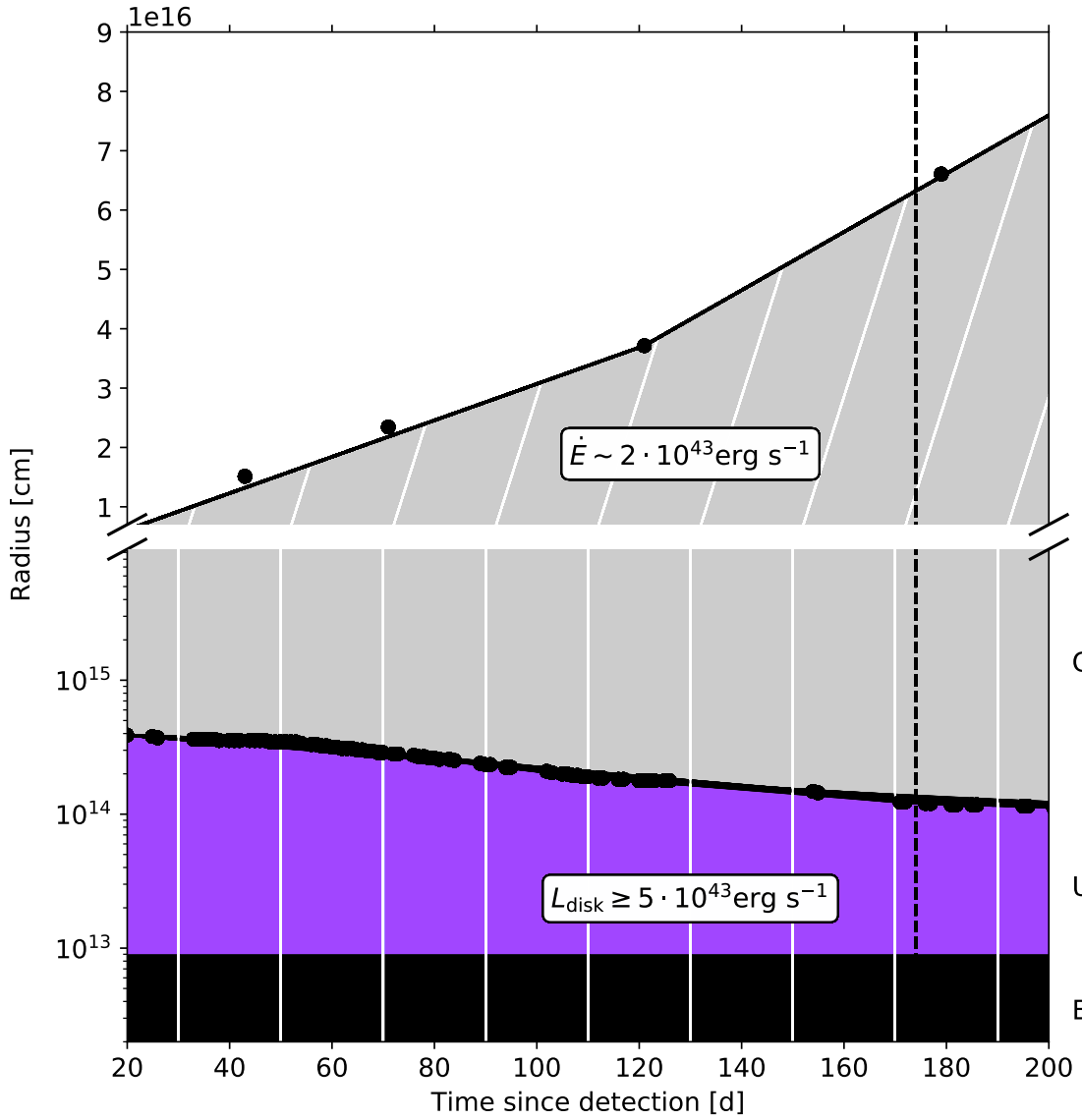
Radio analysis reveals extended synchrotron-emitting outflow

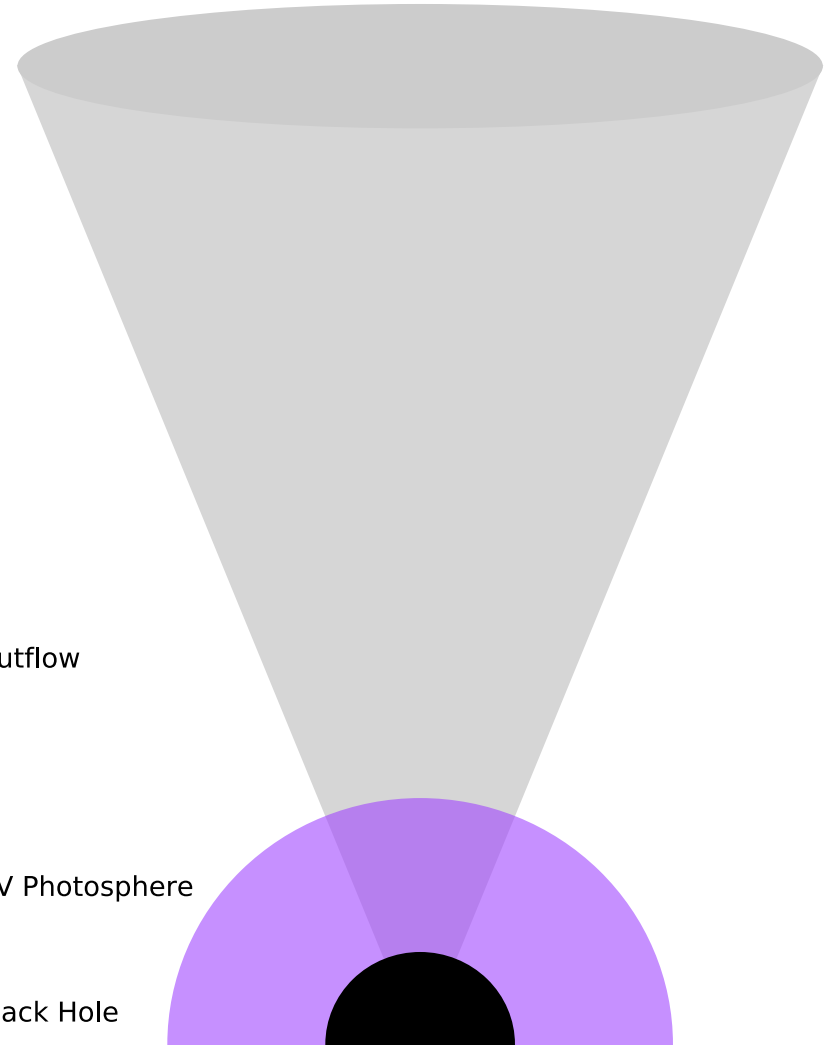
Expands ~10^{16} cm to ~10^{17}cm, with strong (3σ) evidence for late-time acceleration.

Inferred energy in outflow increases (~linearly) in each epoch to ~2 x10^{50} ergs

Reveals a central engine powering non-thermal emission! (First direct evidence)

A combined multi-wavelength picture





AT2019dsg as a neutrino source

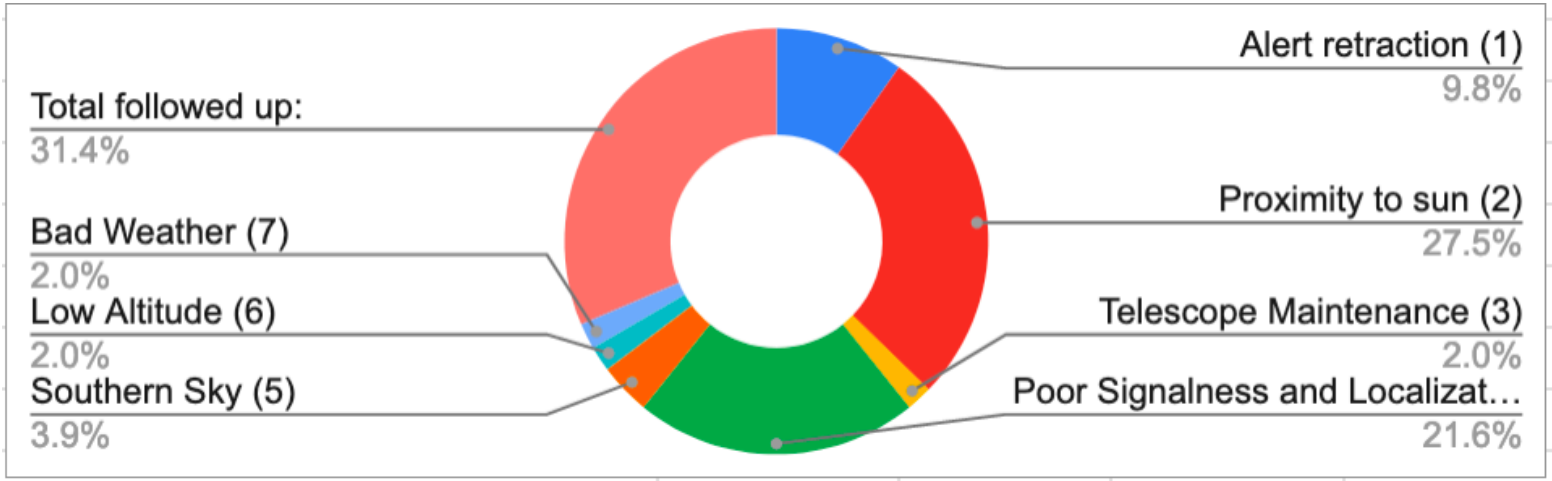
Less guessing, more data!

- Particle accelerator for protons? ✓ → Central engine revealed, with high inferred B fields to contain particles during acceleration, satisfies Hillas criteria
- Target for protons to collide with ✓ → Dense UV photosphere; Perhaps X-ray photosphere?; Ambient matter? (We do infer a high density)
- Sufficient system energy ✓ → Estimate $>10^{50}$ erg just from outflow. Consistent with expectations, given strong Eddington bias. (https://arxiv.org/abs/1809.06865)

Conditions consistent with requirements for ~PeV neutrino production

The neutrino follow-up program with ZTF-I

Summary	Counts	Percent
Alert retraction (1)	5.00	14.29
Proximity to sun (2)	14.00	40.00
Telescope Maintenance (3)	1.00	2.86
Poor Signalness and Localization (4)	11.00	31.43
Southern Sky (5)	2.00	5.71
Low Altitude (6)	1.00	2.86
Bad Weather (7)	1.00	2.78
Total followed up:	16.00	
Total not followed up:	35.00	



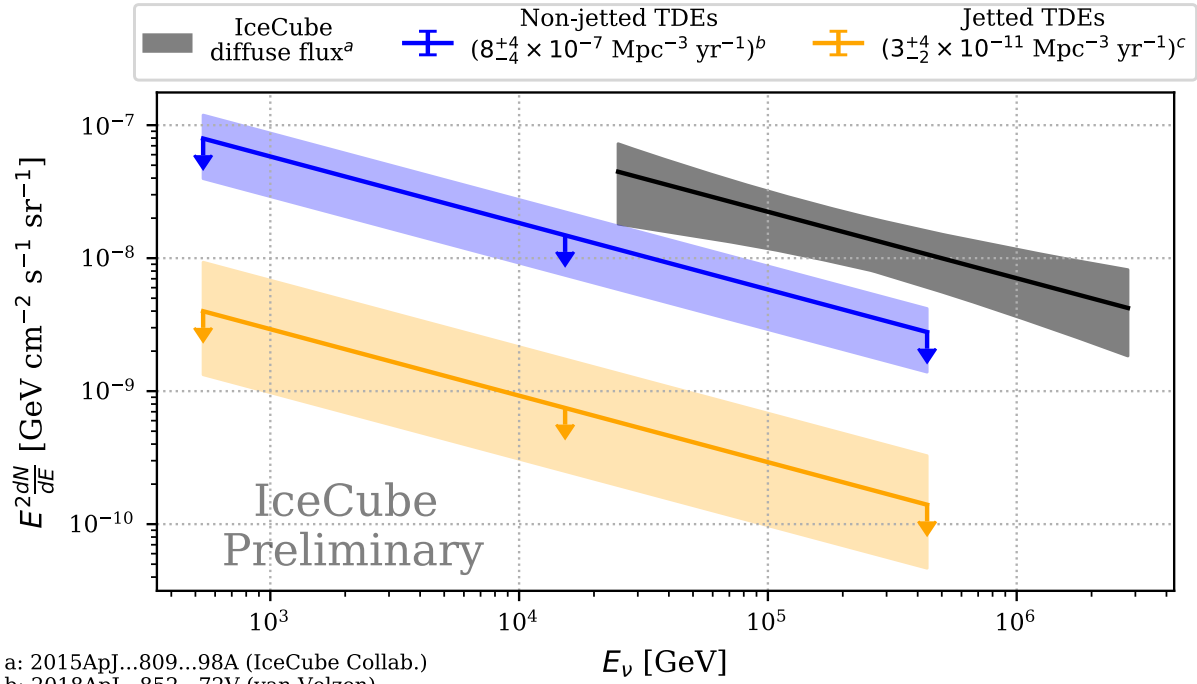
What are the implications of AT2019dsg/IC191001A?

Association suggests that TDEs contribute to the astrophysical neutrino flux

Icecube reported no “offline” evidence for correlation between neutrinos and TDEs, TDEs must contribute <~39% of total flux

Two TDE-neutrino association out of 16 follow-up campaigns is compatible with the IceCube limit

More TDE-neutrino associations will be key to understanding the role of TDEs as cosmic accelerators



a: 2015ApJ...809...98A (IceCube Collab.)
b: 2018ApJ...852...72V (van Velzen)
c: 2015ApJ...812...33S (Sun et al.)

With evolution from Sun et al.[c]

https://arxiv.org/abs/1908.08547