Flux upper limits from a targeted search for extragalactic transients with the Atacama Cosmology Telescope

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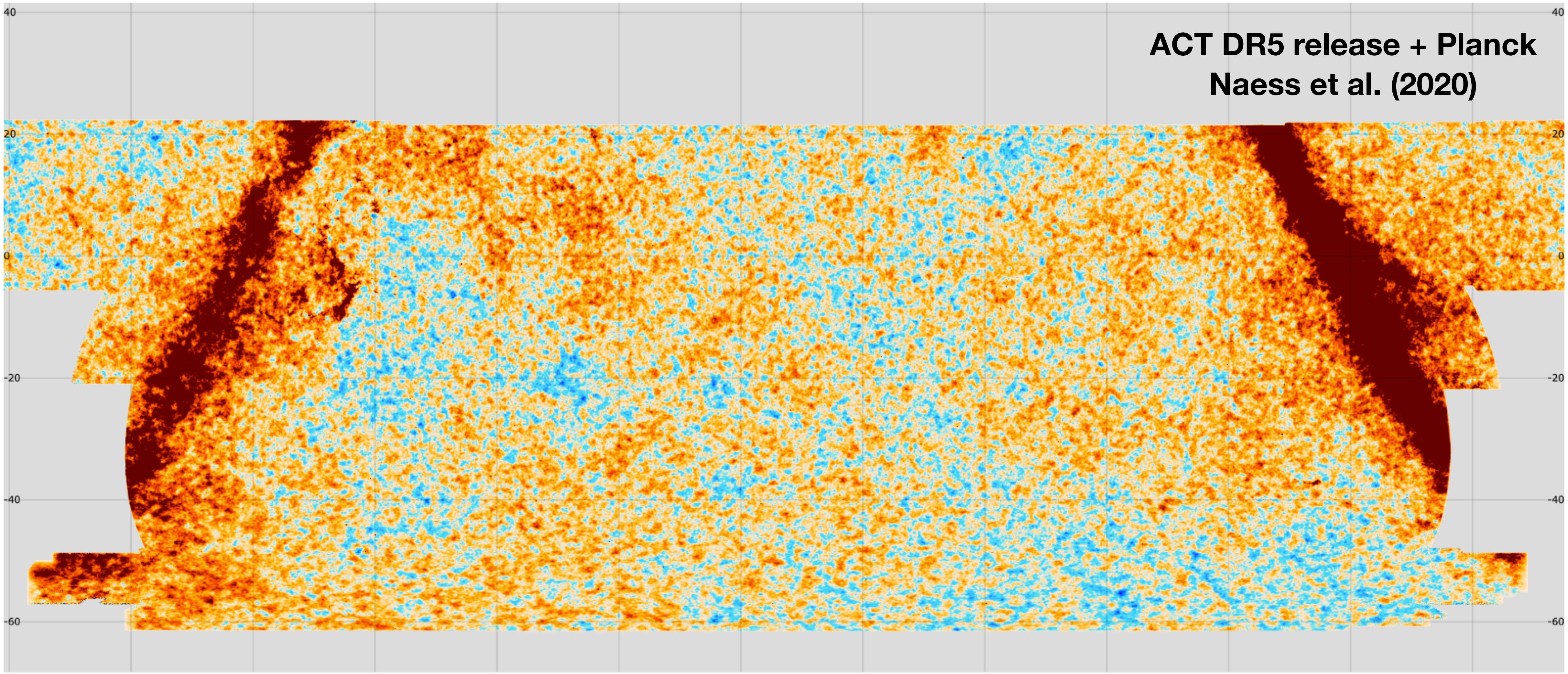
Credit: A. Hincks

The Transient and Variable Universe 2023, U of Illinois, Urbana-Champaign, June 22, 2023

Motivation

- CMB experiments scan a large fraction of the sky all day and night.
- For example, ACT observed 18k sq. deg. (40% of the sky)
- We might catch transient events in the mm. by chance.



Extragalactic transients

- Sources dominated by **synchrotron emission**: rapid ejecta from relativistic jets interaction with the circumstellar medium, accelerating free electrons.

- **Gamma Ray Bursts** (GRBs):
  - Highly energetic explosions from very massive stars in high redshift galaxies.
  - Ejection of material at relativistic speeds.

- **Tidal Disruption Events** (TDEs):
  - Destruction of stars close to supermassive black holes.
  - Unbound stellar debris is ejected at high speeds.

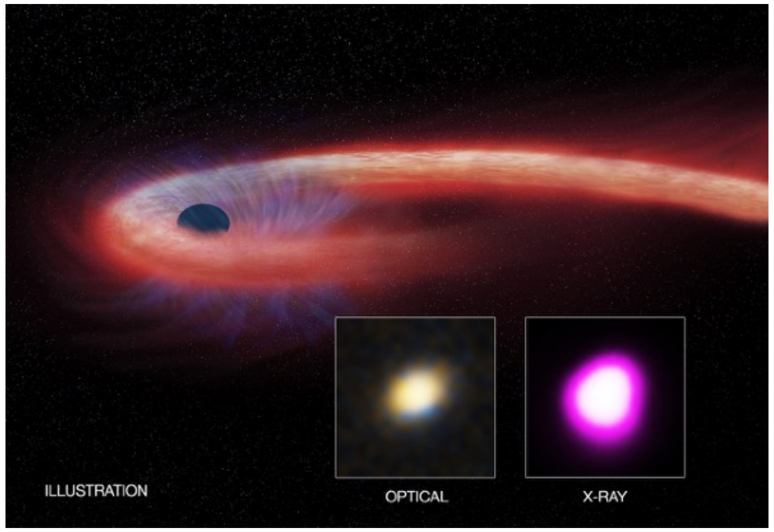
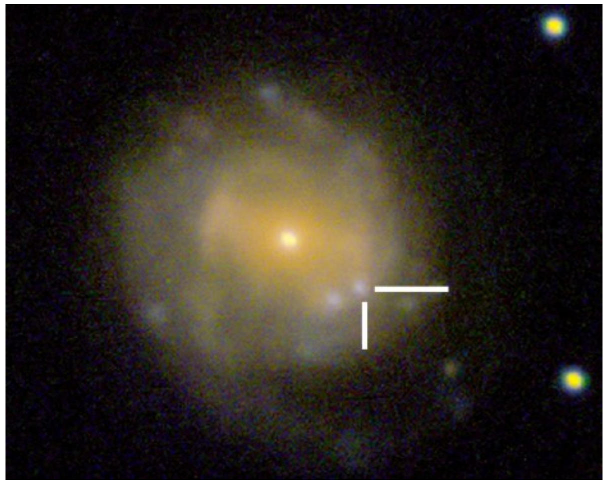


Illustration: CXC/M. Weiss; X-ray: NASA/CXC/UNH/D. Lin et al, Optical: CFHT

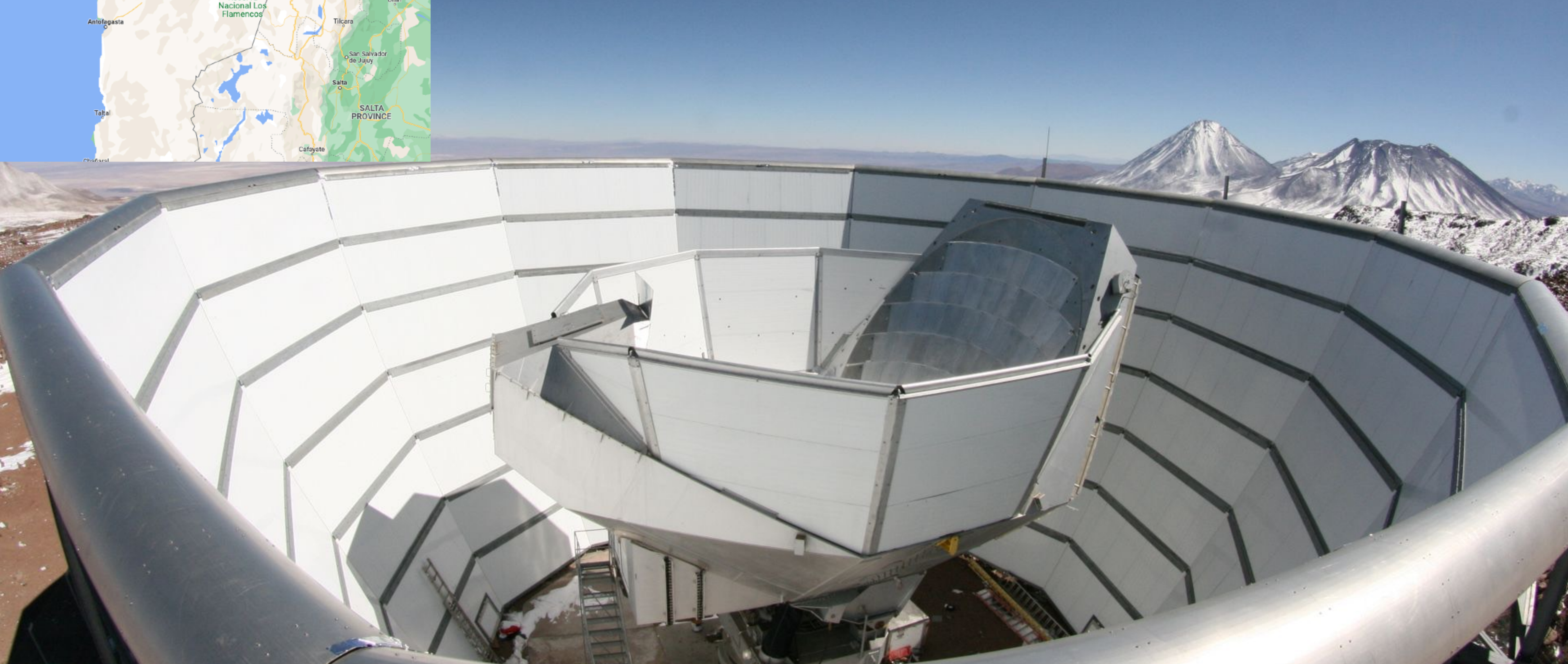
- **Supernovae** (SNe):
  - Not expected to produce significant mm emission.
  - A few examples exist.
  - **FBOT AT 2018cow** (Ho+ 2019) inspired this work with significant mm emission and could have been observed by ACT.



AT 2018cow, Sloan Sky Digital Survey

The Atacama Cosmology Telescope

- Observed between 2008 and 2022 at multiple frequencies in the Atacama Desert, Chile.
- At an altitude of 5200 meters, with excellent conditions for millimeter astronomy.
- 6-meter primary mirror, with a resolution of 1.4 arcmin at 150 GHz (2mm).



Credit: M. Devlin

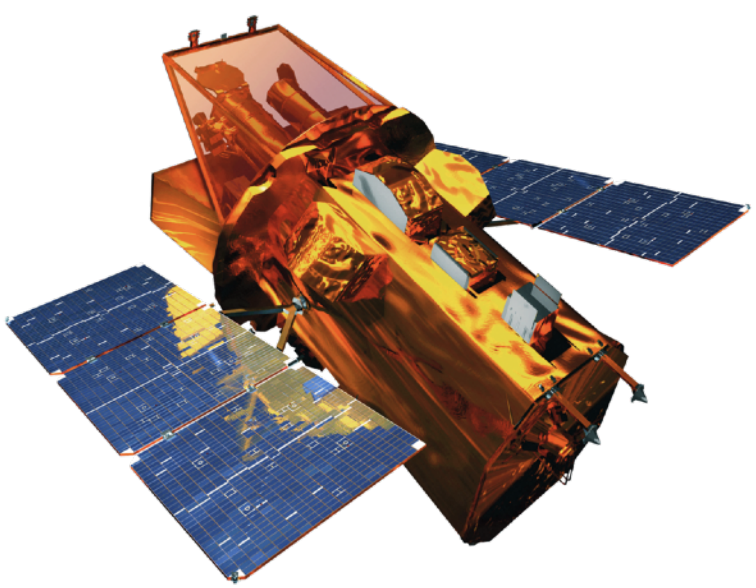
The Atacama Cosmology Telescope

- We have many examples of extragalactic sources in catalogs.
- We can go back and look at ACT data to see if we detected something by chance, hence a **Targeted Search**.
- We use data in the period **2013-2021**, in 3 frequencies channels: **f090**, **f150** and **f220**

Channel	Array	Band Centre (GHz)[a]	Bandwidth (GHz)[b]	Synchrotron Band Centre (GHz)[c]	Data Start Date	Data End Date
f090	PA3	93.3	31.1	93.2	2015 April 21	2016 December 22
	PA5	96.5	19.0	96.5	2017 May 11	2021 June 18
	PA6	95.3	23.1	95.3	2017 May 11	2019 December 19
f150	PA1	145.4	39.6	145.3	2013 September 10	2016 June 12
	PA2	145.9	36.7	145.7	2014 August 23	2016 December 22
	PA3	144.9	27.8	144.7	2015 April 21	2016 December 22
	PA4	148.5	36.7	148.3	2017 May 11	2021 June 18
	PA5	149.3	28.1	149.2	2017 May 11	2021 June 18
	PA6	147.9	31.1	147.8	2017 May 11	2019 December 16
f220	PA4	226.7	66.6	225.0	2017 May 11	2021 June 18

Extragalactic transients

GRBs (88 sources)



Neil Geherls
Swift Observatory

TDEs (12 sources)

Table 1 Table of tidal disruption events reported in the literature

Name	Survey[a]	Waveband	Redshift	log L_{BB}[b] (erg s^{-1})	log T_{BB} (K)	Reference[c]
NGC 5905	ROSAT	X	0.01124	40.94	5.84	Bade et al. 1996
RX J1624+75	ROSAT	X	0.0636	43.38	6.05	Grupe et al. 1999
RX J1242-11A	ROSAT	X	0.050	42.60	5.84	Komossa & Greiner 1999
RX J1420+53	ROSAT	X	0.147	43.38	5.67	Greiner et al. 2000
GALEX D3-13	GALEX	U	0.3698	43.98	4.66	Gezari et al. 2006
SDSS J1323+48	XMM	X	0.0875	44.30	5.91	Esquej et al. 2007
GALEX D1-9	GALEX	U	0.326	43.48	4.59	Gezari et al. 2008
TDXF J1347-32	ROSAT	X	0.0366	42.73	6.14	Cappelluti et al. 2009
GALEX D23H-1	GALEX	U	0.1855	43.95	4.70	Gezari et al. 2009
SDSS J1311-01	Chandra	X	0.195	41.74	6.14	Maksym, Ulmer & Eracleous 2010
SwiftJ1644	Swift	G	0.353	ND	ND	Bloom et al. 2011
2XMMi J1847-63	XMM	X	0.0353	42.82	5.96	Lin et al. 2011
SDSS-TDE1	SDSS	O	0.136	43.64	4.42	van Velzen et al. 2011
SDSS-TDE2	SDSS	O	0.2515	44.54	4.37	van Velzen et al. 2011
PS1-10jh	PS	O	0.1696	44.47	4.59	Gezari et al. 2012
SDSS J1201+30	XMM	X	0.146	45.00	6.06	Saxton et al. 2012
SwiftJ2058	Swift	G	1.186	ND	ND	Cenko et al. 2012b
WINGS J1348+26	Chandra	X	0.0651	41.79	6.06	Maksym et al. 2013
PS1-11af	PS	O	0.4046	44.16	4.28	Chornock et al. 2014
RBS 1032	ROSAT	X	0.026	41.70	6.11	Maksym et al. 2014b
PTF-09ge	PTF	O	0.064	44.04	4.08	Arcavi et al. 2014
PTF-09axc	PTF	O	0.1146	43.46	4.08	Arcavi et al. 2014
PTF-09djl	PTF	O	0.184	44.42	4.41	Arcavi et al. 2014
ASASSN-14ae	ASAS-SN	O	0.0436	43.87	4.29	Holoien et al. 2014
3XMM J1521+07	XMM	X	0.179	43.51	6.30	Lin et al. 2015
SwiftJ1112	Swift	G	0.89	ND	ND	Brown et al. 2015
ASASSN-14li	ASAS-SN	O	0.02058	43.66	4.52	Holoien et al. 2016b
ASASSN-15lh	ASAS-SN	O	0.2326	45.34	4.30	Dong et al. 2016
ASASSN-15oi	ASAS-SN	O	0.0484	44.45	4.60	Holoien et al. 2016b
iPTF-16axa	PTF	O	0.108	43.82	4.46	Hung et al. 2017
iPTF-16fnl	PTF	O	0.0163	43.18	4.47	Blagorodnova et al. 2017
3XMM J1500+01	XMM	X	0.1454	43.08	6.06	Lin et al. 2017
OGLE16aaa	OGLE	O	0.1655	44.22	4.36	Wyrzykowski et al. 2017
XMMSL1 J0740-85	XMM	X	0.0173	42.61	6.00	Saxton et al. 2017
iPTF-15af	PTF	O	0.07897	44.10	4.85	Blagorodnova et al. 2019
AT2017eqx/PS17dhz	PS	O	0.1089	43.82	4.32	Nicholl et al. 2019
AT2018zr/PS18kh	PS	O	0.071	43.78	4.14	van Velzen et al. 2021
AT2018bsi/ZTF18aahqkbt	ZTF	O	0.051	43.87	4.53	van Velzen et al. 2021
AT2018dyb/ASASSN-18pg	ASAS-SN	O	0.018	44.08	4.40	Leloudas et al. 2019
AT2018fyk/ASASSN-18ul	ASAS-SN	O	0.059	44.48	4.54	Wevers et al. 2019
AT2018hco/ATLAS18way	ATLAS	O	0.088	44.25	4.39	van Velzen et al. 2021
AT2018hyz/ASASSN-18zj	ASAS-SN	O	0.04573	44.10	4.25	Gomez et al. 2020
AT2018iih/ATLAS18yzs	ATLAS	O	0.212	44.62	4.23	van Velzen et al. 2021

Only ~100 discovered.

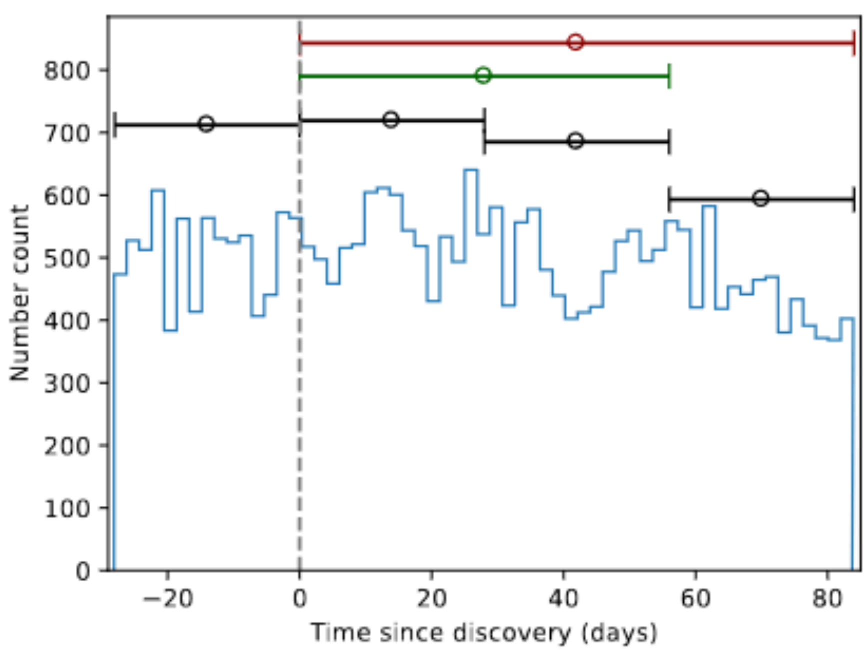
We check the catalog of the review Gezari (2021) + ZTF (Van Velzen+ 2021) and eROSITA (Sazonov+ 2021) recent discoveries

SNe and ATs (203 sources)

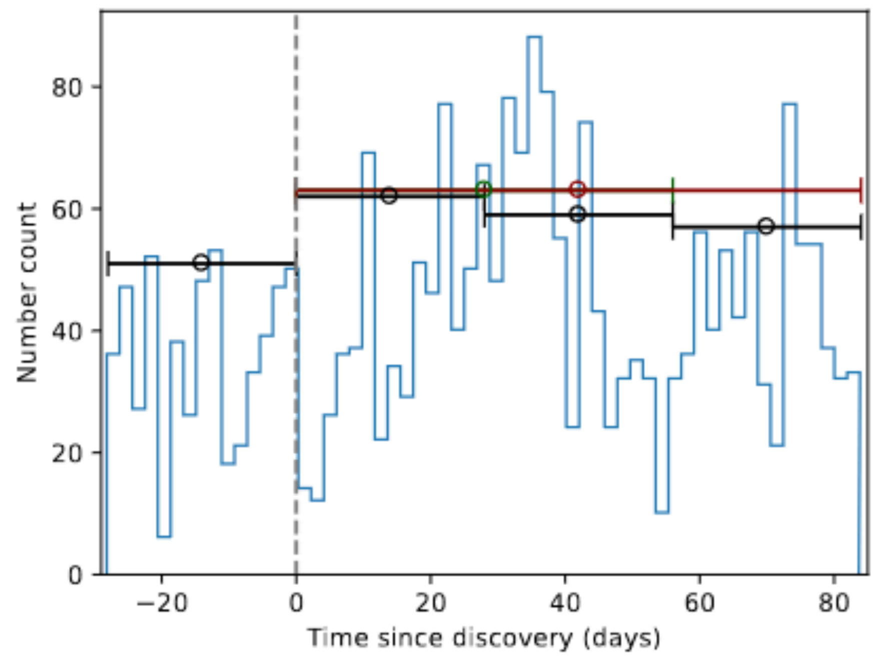
The Open Supernova Catalog (Guillochon+ 2014)
We limit to z<0.014
Astronomical Transients (Ats) are also included

Observations and Results

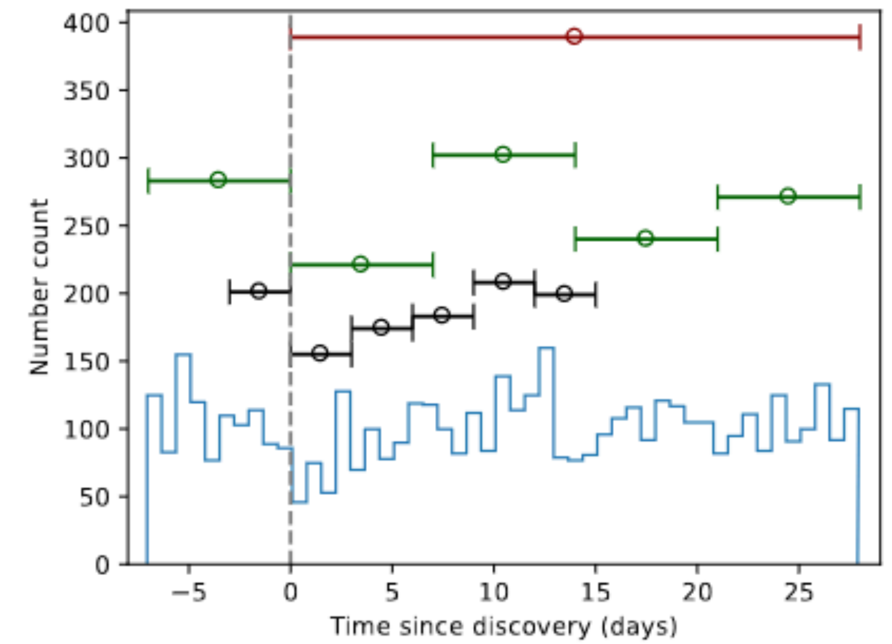
Total number of observations, for all frequencies and arrays



SNe and ATs

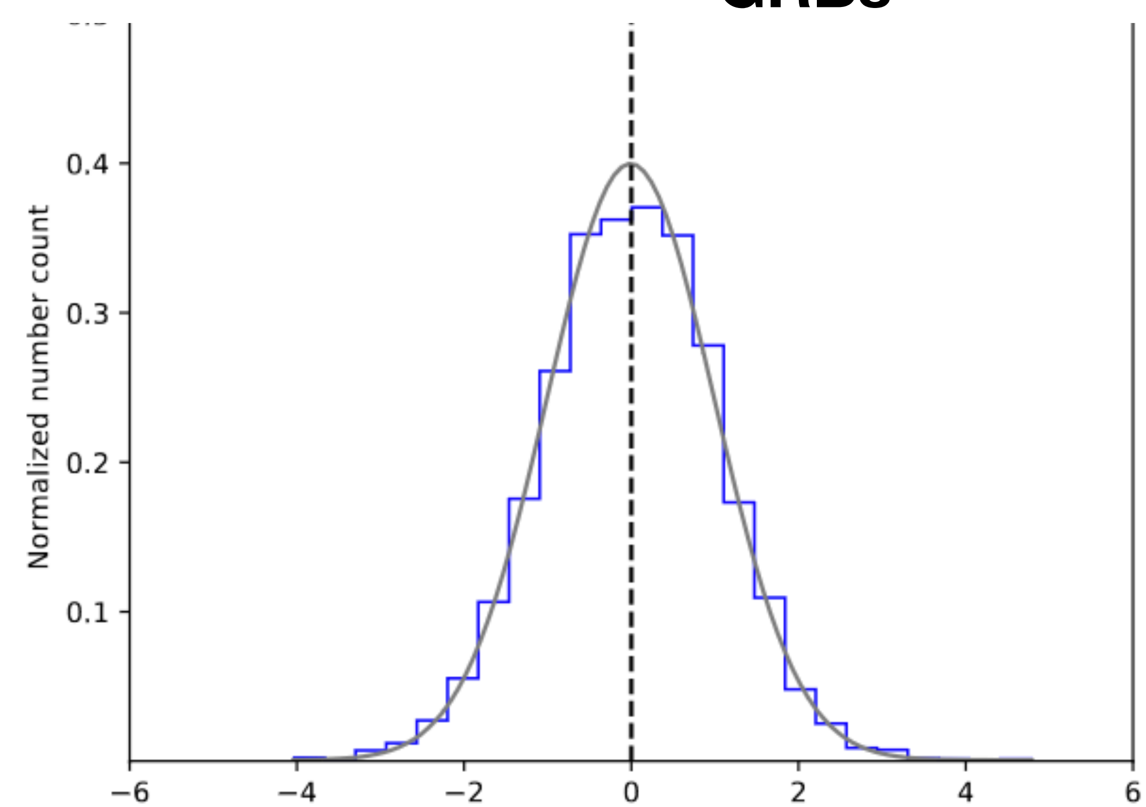


TDEs



GRBs

- We map in limited time ranges and apply a **matched filter** to measure the flux.
- No significant detections, except one.
- ACT sensitivity for a single obs is a few tens of mJy.
- S/N of measured flux (right) from all maps consistent with random fluctuations. A few high S/N maps are consistent with noise from incomplete coverage or stripy noise.



Observations and Results

Table 4. Examples of the upper limits on flux density for GRBs. The columns correspond to the time range of the map in days, with 0 being the discovery time. The numbers are 95 per cent upper limits and in mJy. The position is in degrees.

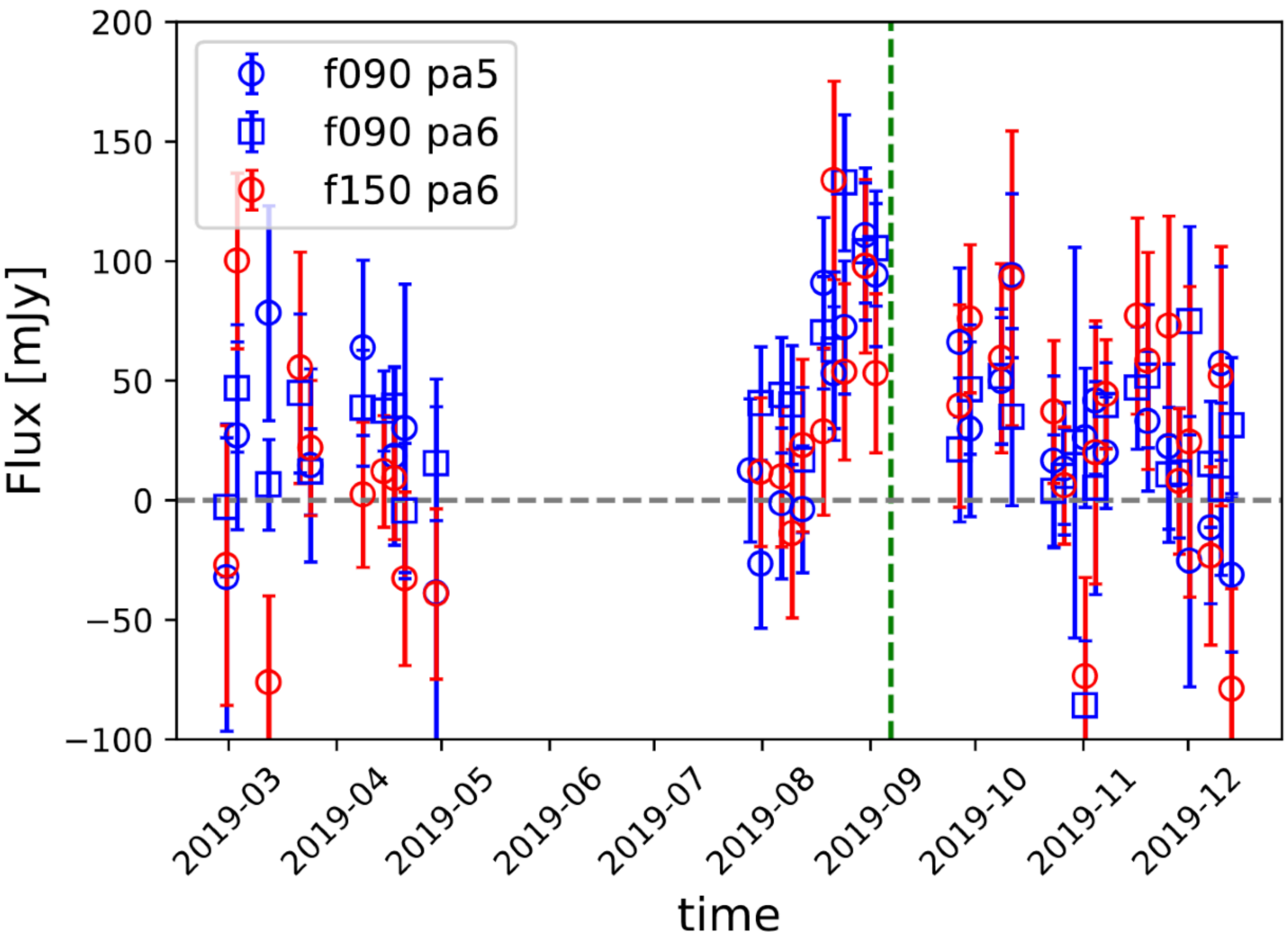
				Time interval for the map relative to alert (in days)											
GRB Name	**RA/Dec** deg.	**Discovery**	**Freq.**	**[−3,0]** mJy	**[−7,0]** mJy	**[0,3]** mJy	**[3,6]** mJy	**[6,9]** mJy	**[9,12]** mJy	**[12,15]** mJy	**[0,7]** mJy	**[7,14]** mJy	**[14,21]** mJy	**[21,28]** mJy	**[0,28]** mJy
131031A	29.6102/-1.5788	2013-10-31	f150	9.9	13.0	23.2	14.3	19.2	10.8	6.7	14.7	8.3	5.3	5.1	4.1
150710A	194.4705/14.3181	2015-07-10	f090	65.3	37.9	115.7	—	33.2	24.8	65.3	46.2	19.5	36.3	19.0	17.7
			f150	29.9	21.9	47.8	—	26.3	46.0	29.9	22.9	26.6	38.1	30.1	17.6
171027A	61.6907/-2.6221	2017-10-27	f090	—	21.8	33.2	18.5	—	23.8	—	14.4	25.8	14.5	13.9	6.5
			f150	—	54.2	28.5	30.6	—	17.0	—	20.5	37.0	16.7	22.7	11.2
			f220	—	295.7	139.5	118.7	—	134.2	—	123.8	148.6	62.8	85.7	61.4
191004B	49.2042/-39.6348	2019-10-04	f090	19.0	28.9	45.0	19.0	41.3	18.5	11.8	16.1	15.9	15.2	46.6	9.8
			f150	31.0	60.8	22.5	28.7	48.6	23.6	22.4	22.6	20.9	41.5	24.2	16.7
			f220	129.6	113.6	140.2	—	181.9	—	93.8	68.0	181.9	94.7	100.3	46.4

This table is published in its entirety in the machine-readable format online. A portion is shown here for guidance regarding its form and content.

- We can place 95% CI flux upper limits.
- Example table for GRBs, full results can be found on the ACT page in NASA LAMBDA.

AT 2019ppm

- AT 2019ppm was reported by ZTF on September 7th, 2019.
- "Known SDSS and/or MILLIQUAS QSO/AGN"
- Coincident with **NGC 2110**, a known Seyfert II galaxy.
- Detected excess over background at ~5 σ in our f090 and f150 channels in the previous 28 days to discovery.
- Consistent with AGN activity of the host galaxy.



Light curve during the 2019 season, each data point is 3 days

Stacking maps

We can stack multiple events using a Maximum Likelihood approach. The flux $\mathbf{f}_i$ of map i with covariance κ_i is modeled as

$$\mathbf{f}_i = \mathbf{a}R_i(\nu_j, t_k) + \mathbf{n}_i$$

where ni is the noise of the map, R_i is the weight of the event i normalized to a reference event, and a is the detection statistic we aim to measure.
The ML solution for this is

$$\hat{a} = \frac{\sum_i R_i(\nu_j, t_k)\kappa_i \mathbf{f}_i}{\sum_i R_i(\nu_j, t_k)^2 \kappa_i}$$ with noise inverse covariance $\mathbf{A} = \sum_i R_i(\nu_j, t_k)^2 \kappa_i$

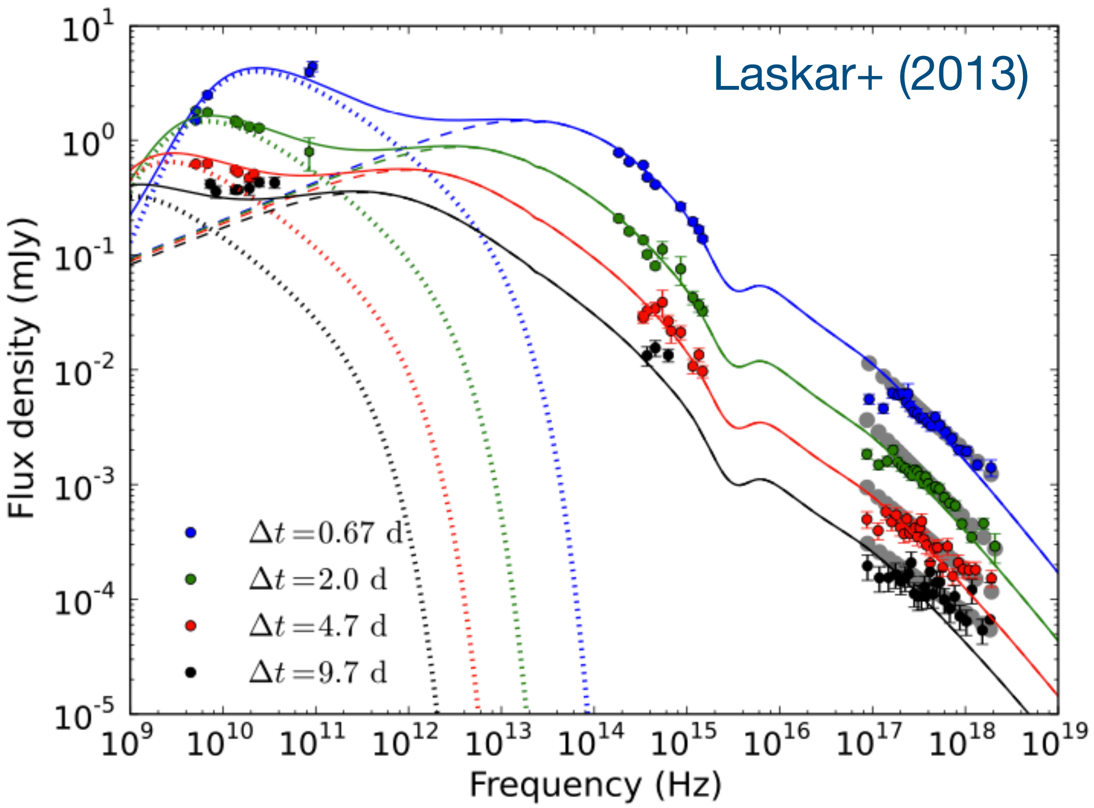
Stack the same class of transient, for a common time range and frequency, but also across time and/or frequency.

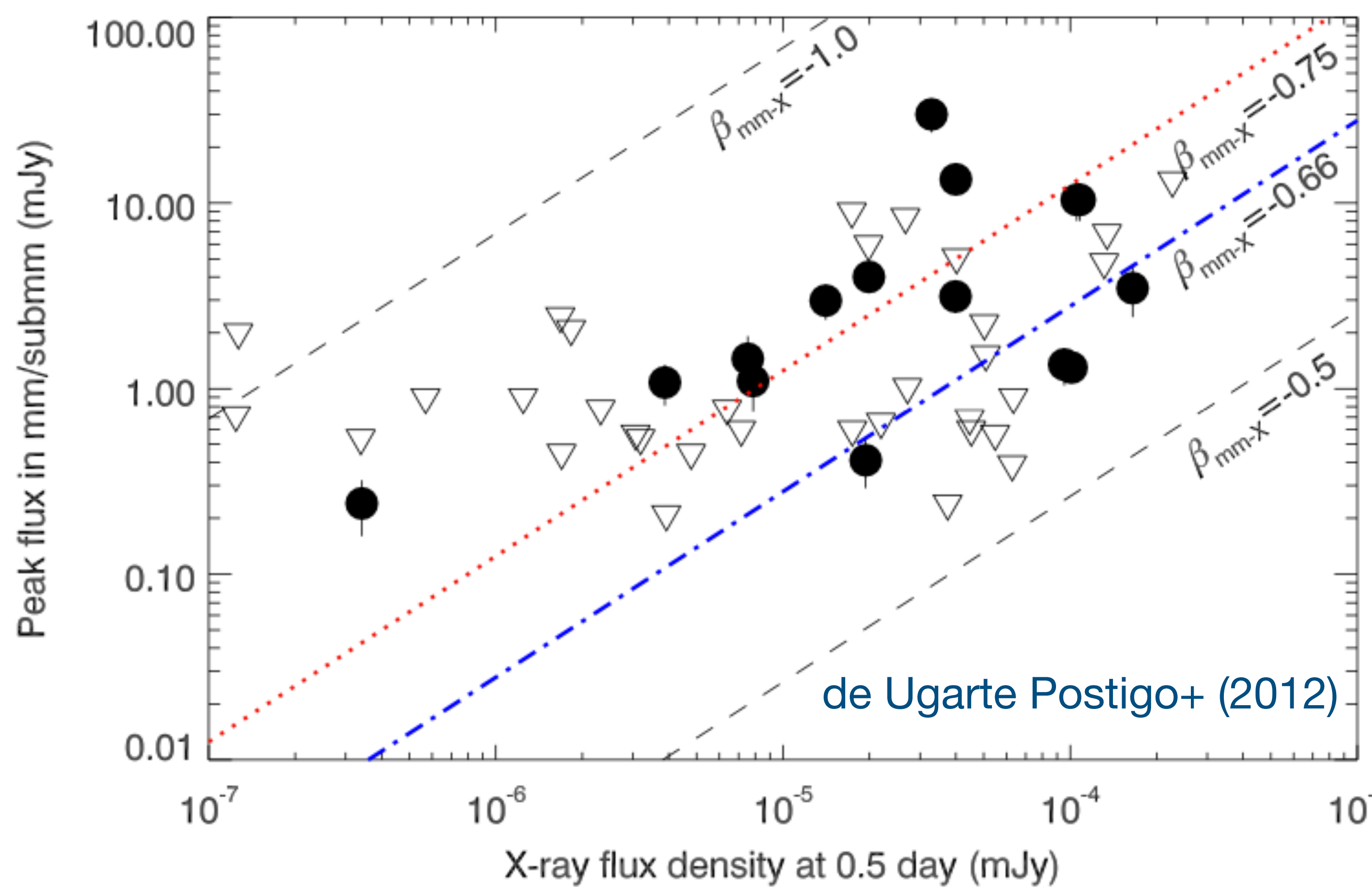
Stacking maps

The weight R_i can be chosen to be a proxy of mm flux normalized by a reference:

- **SNe**: we use inverse distance2 with distance = 7.5 Mpc (distance to **SN 2011dh**)
- **TDEs**: Same as Sne, with distance = 92.6 Mpc (distance to **TDE ASASSN-14li**)
- **GRBs**: we use the 24-hour X-ray flux, normalized to the flux of **GRB 130427A**, our reference. We transform across frequency and time using the model from Laskar+ (2013) and van der Horst (2014).

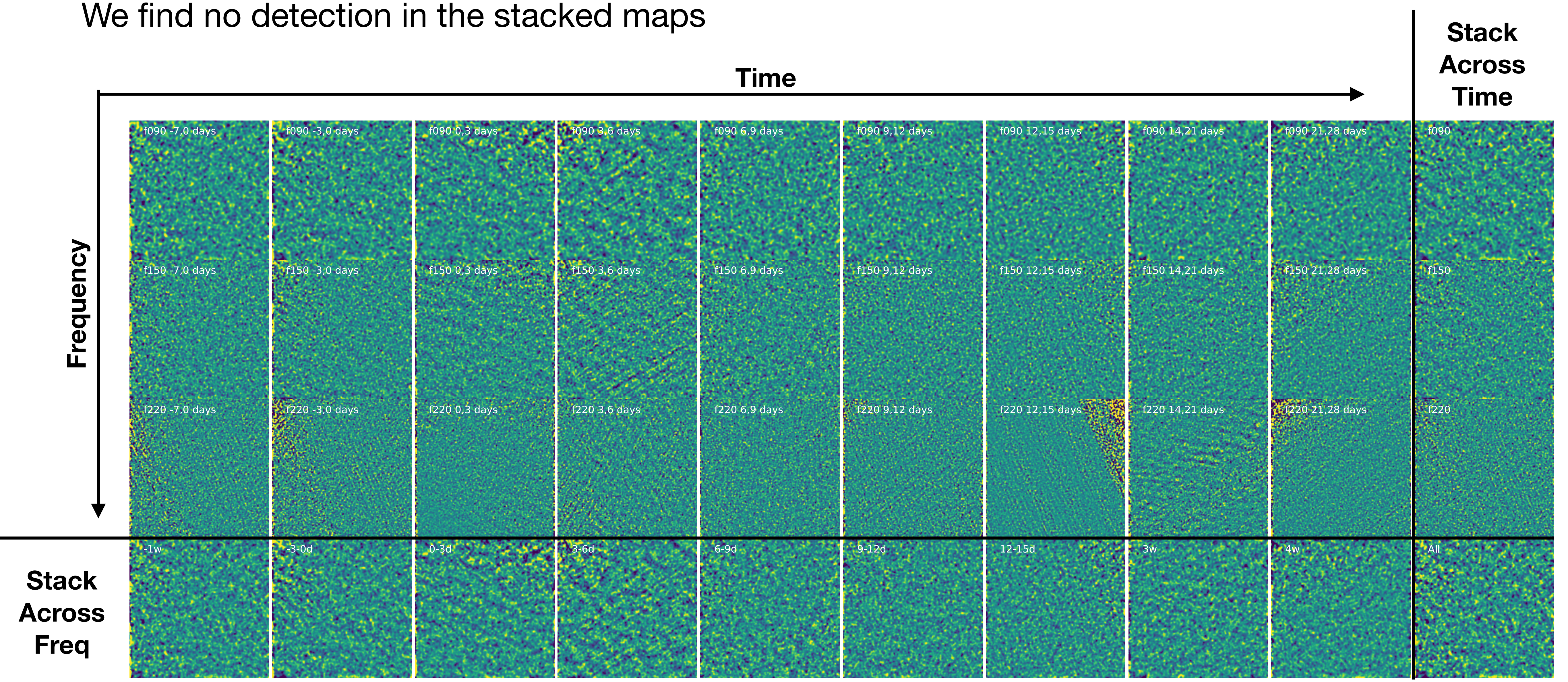
We stack **GRBs**, **TDEs**, only **core-collapse SNe** and only **type Ia SNe**.





Stacking maps

We find no detection in the stacked maps



Stacked results for GRBs

Stacking maps

We find no detection in the stacked maps

Table 8. Characteristic luminosity for stacked GRBs. The units are $10^9\,L_\odot$. This is calculated from the mean mm flux for the reference GRB 130427A as explained in Section 4.2.4. We stress that when weighting the stacks and averaging across time and frequency, we make the explicit assumption that every GRB in the stack is a copy of GRB 130427A, scaled by a factor. Under this assumption, the stacked map would have the mean mm flux of GRB 130427A, which is located at a distance of 1852 Mpc. We also show the characteristic luminosity for the reference in each stacked map, where the flux is scaled from the model SED.

Band	**days [−7,0]**		**days [−3,0]**		**days [0,3]**			**days [3,6]**			**days [6,9]**		
	νL_ν	err	νL_ν	err	νL_ν	err	ref	νL_ν	err	ref	νL_ν	err	ref
f090	3.20	1.92	5.89	2.54	3.56	3.34	0.14	1.75	4.51	0.05	5.35	9.40	0.04
f150	−5.37	3.45	−3.86	4.83	−3.53	6.97	0.19	0.39	8.44	0.07	−0.24	14.98	0.06
f220	21.52	20.53	−1.11	22.34	18.57	51.57	0.26	57.79	85.87	0.12	170.91	87.41	0.11
Across freqs.	2.24	3.71	6.94	4.87	1.86	2.81	0.14	1.35	3.44	0.05	4.91	6.36	0.04

days [9,12]			**days [12,15]**			**days [14,21]**			**days [21,28]**			**across time**		
νL_ν	err	ref	νL_ν	err	ref	νL_ν	err	ref	νL_ν	err	ref	νL_ν	err	ref
1.21	2.47	0.04	-3.87	3.10	0.04	4.15	2.68	0.03	-3.03	2.80	0.02	4.69	1.90	0.14
−1.25	4.33	0.06	−4.57	4.97	0.06	−6.27	4.68	0.04	1.85	4.86	0.03	−4.65	3.57	0.19
12.88	26.47	0.10	28.89	31.37	0.07	17.14	29.03	0.05	−3.34	28.10	0.04	13.22	18.87	0.26
0.41	1.74	0.04	−3.03	2.18	0.04	1.01	2.11	0.03	−1.41	2.21	0.02	0.47	0.47	0.14

Measured flux from stacks transformed to characteristic luminosity, assuming the distance to the reference GRB 130427A.

Stacking maps

We find no detection in the stacked maps

Table 8. Characteristic luminosity for stacked GRBs. The units are $10^9\ L_\odot$. This is calculated from the mean mm flux for the reference GRB 130427A as explained in Section 4.2.4. We stress that when weighting the stacks and averaging across time and frequency, we make the explicit assumption that every GRB in the stack is a copy of GRB 130427A, scaled by a factor. Under this assumption, the stacked map would have the mean mm flux of GRB 130427A, which is located at a distance of 1852 Mpc. We also show the characteristic luminosity for the reference in each stacked map, where the flux is scaled from the model SED.

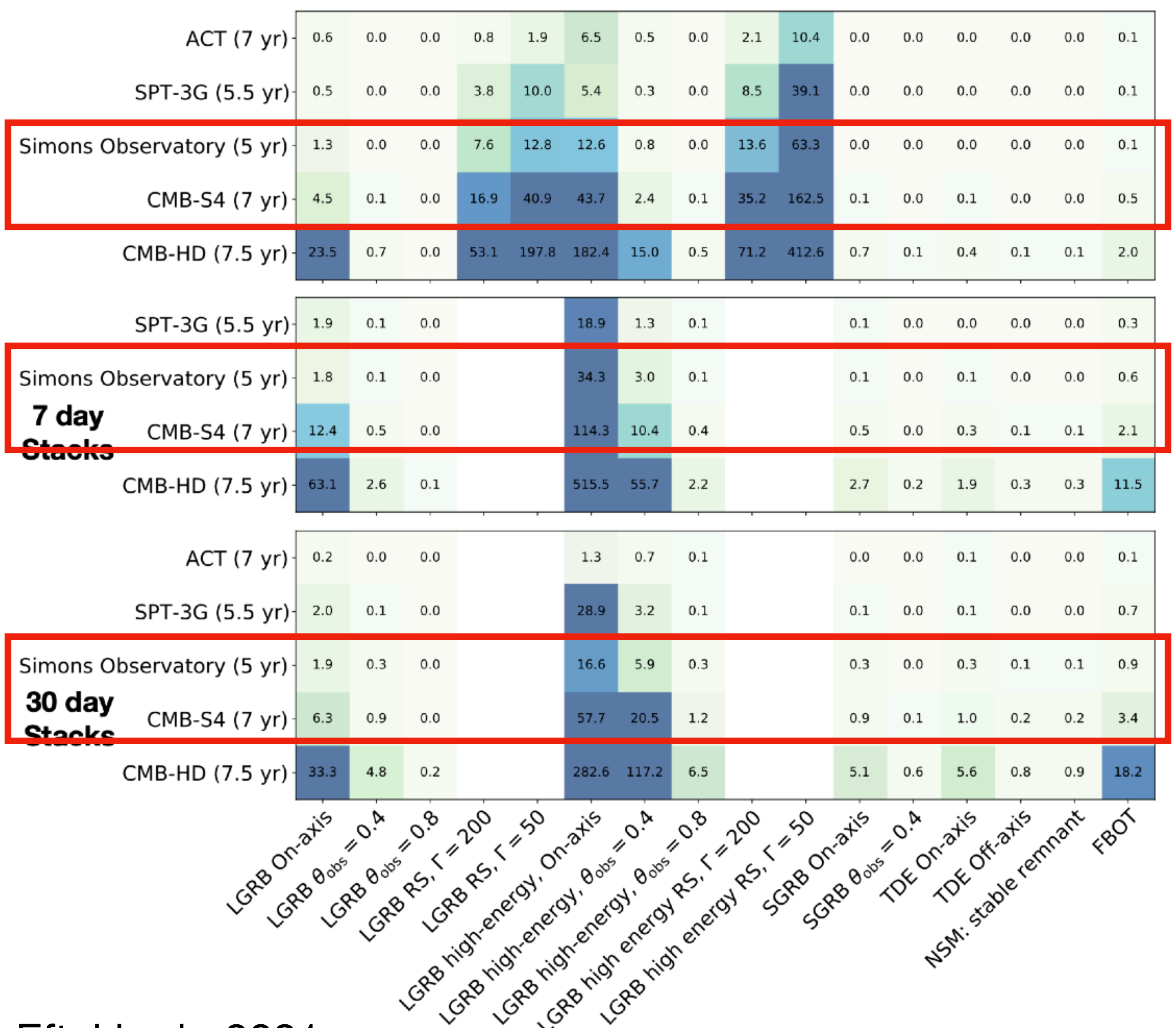
Band	days [−7,0]		days [−3,0]		days [0,3]			days [3,6]			days [6,9]		
	νL_ν	err	νL_ν	err	νL_ν	err	ref	νL_ν	err	ref	νL_ν	err	ref
f090	3.20	1.92	5.89	2.54	3.56	3.34	0.14	1.75	4.51	0.05	5.35	9.40	0.04
f150	−5.37	3.45	−3.86	4.83	−3.53	6.97	0.19	0.39	8.44	0.07	−0.24	14.98	0.06
f220	21.52	20.53	−1.11	22.34	18.57	51.57	0.26	57.79	85.87	0.12	170.91	87.41	0.11
Across freqs.	2.24	3.71	6.94	4.87	1.86	2.81	0.14	1.35	3.44	0.05	4.91	6.36	0.04

days [9,12]			days [12,15]			days [14,21]			days [21,28]			across time		
νL_ν	err	ref	νL_ν	err	ref	νL_ν	err	ref	νL_ν	err	ref	νL_ν	err	ref
1.21	2.47	0.04	-3.87	3.10	0.04	4.15	2.68	0.03	-3.03	2.80	0.02	4.69	1.90	0.14
−1.25	4.33	0.06	−4.57	4.97	0.06	−6.27	4.68	0.04	1.85	4.86	0.03	−4.65	3.57	0.19
12.88	26.47	0.10	28.89	31.37	0.07	17.14	29.03	0.05	−3.34	28.10	0.04	13.22	18.87	0.26
0.41	1.74	0.04	−3.03	2.18	0.04	1.01	2.11	0.03	−1.41	2.21	0.02	0.47	0.47	0.14

Measured flux from stacks transformed to characteristic luminosity, assuming the distance to the reference GRB 130427A.

Even stacking all GRBs across all frequencies and time intervals, we reach S/N~1/3

What about future surveys?

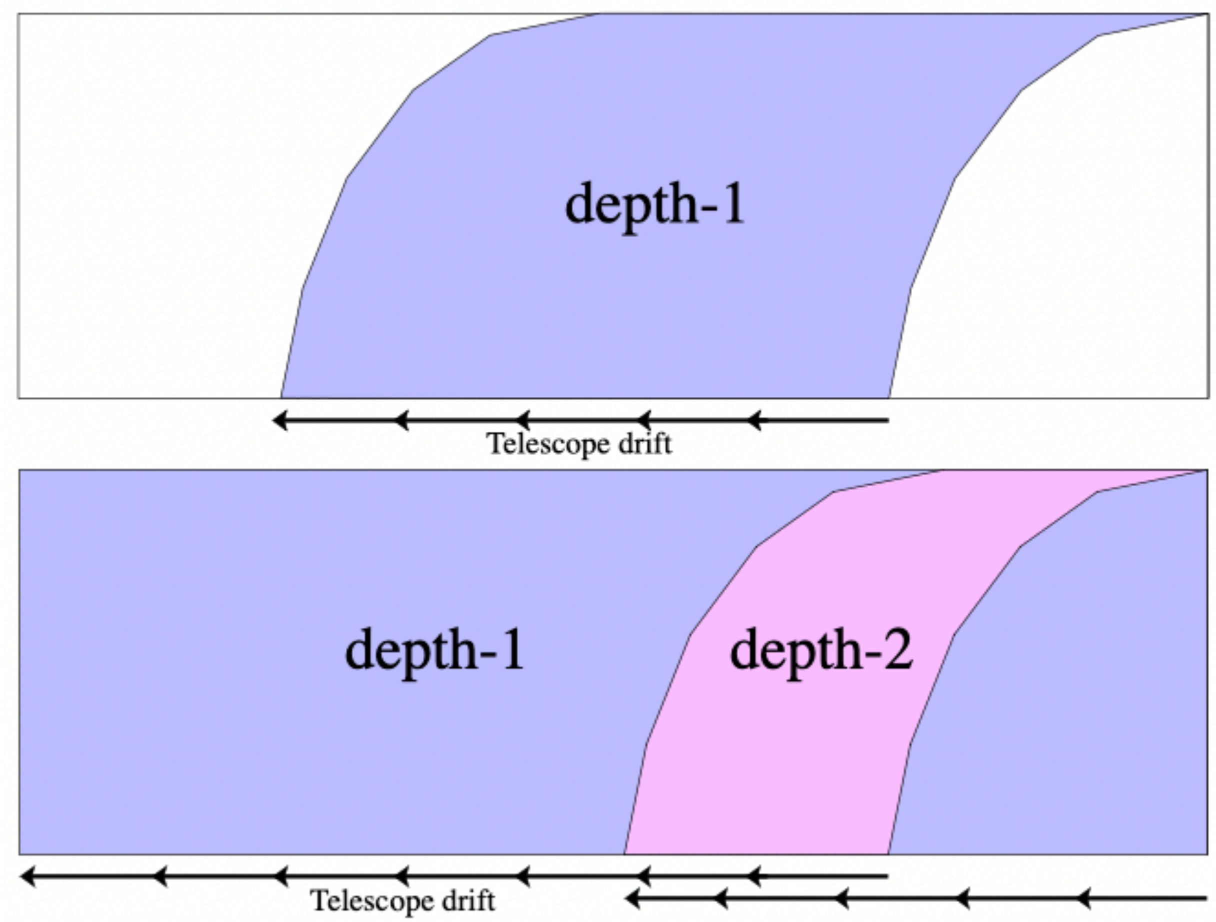


Eftekhari+ 2021

- **Simons Observatory** (SO) is about to start operations.
- Much better sensitivity:
  - 4.7x the amount of detectors in f090, f150, f220.
  - ~3x more coverage due to regular cadence and improvements in observing efficiency.
  - All this would **improve the GRB stack from S/N 1/3 -> 1.3**
  - On top of that, 3 other freq. channels + **Advanced SO** (recently approved) would double the amount of detectors and time.
- Searching transients in ACT data will inform our operation to find transients in SO.
- At the end of decade **CMB-S4** will improve even more + transient alerts on almost real time
- Both SO and CMB-S4 are predicted to detect dozens of GRBs + other sources. See Eftekhari+ 2021 and talk by E. Biermann.

SO: Analysis Working Group ST, Sources and Transients

- ACT work and experience on transients can be applied to SO: Large Aperture Telescope (LAT) instrument is very similar to ACT, and also the same people.
- SO will have a scanning strategy with regular cadence.
- **Map-based** search:
  - Based on **Depth-1 maps**, which map a single pass of the telescope.
  - Simulations of observations, injection of fake transients.
  - Forecast how well we can find them and measure their flux.
- **Time stream-based** search:
  - Fast signals could be detected directly in the time stream, such as Pulsars and FRBs.
  - Forecast a potential detections.



Credit: S. Naess

Summary

- CMB experiments scan the sky constantly -> serendipitous detection of mm transients.
- ACT is looking in the time domain: Blind search for transients (see talk by Y. Li).
- This talk was about a targeted search for GRBs, TDEs, SNEs and assorted ATs from catalogs.
- We find no transients, except one event consistent with AGN activity from the host galaxy.
- Stacking multiple events together can improve S/N.
- Much better sensitivity from future surveys, techniques in this work can be used.
- We should detect mm transient regurlarly with SO and CMB-S4. Stay tuned.

Thank you!

Credit: A. Hincks