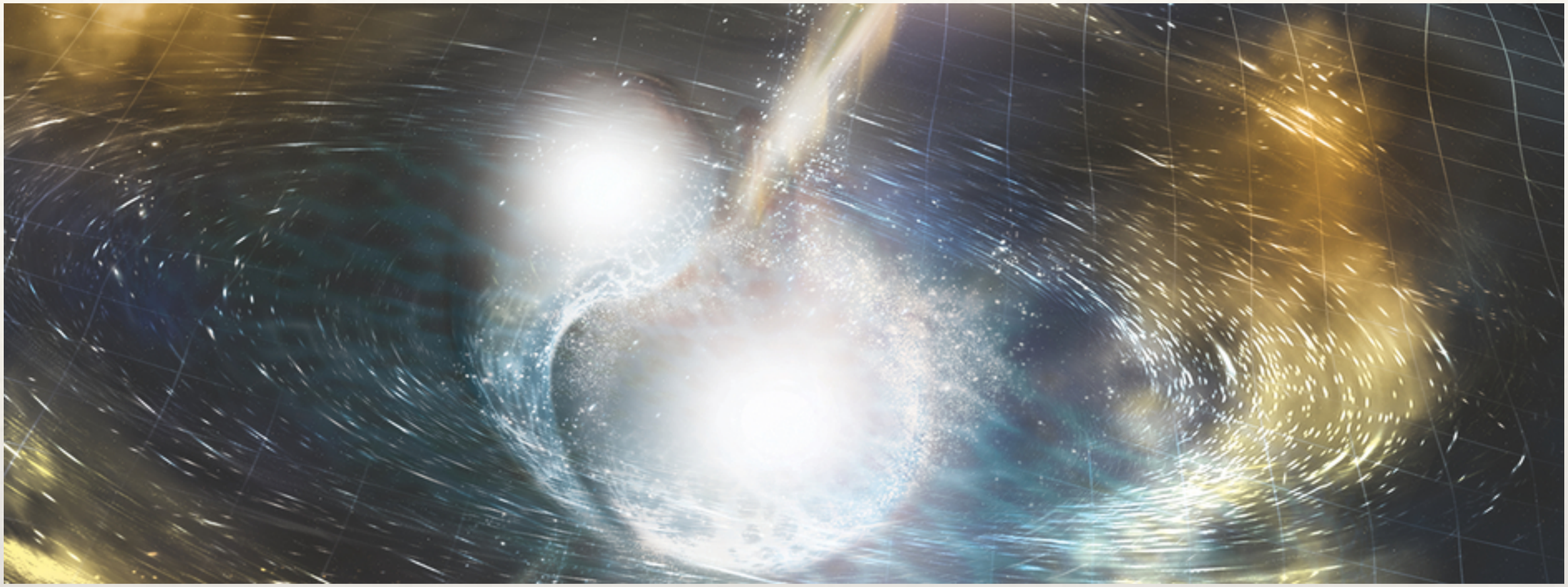

Follow-up of *Fermi* short GRBs with ZTF

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NASA GSFC / U. Maryland
March 19, 2019

Part I: Proposed Program

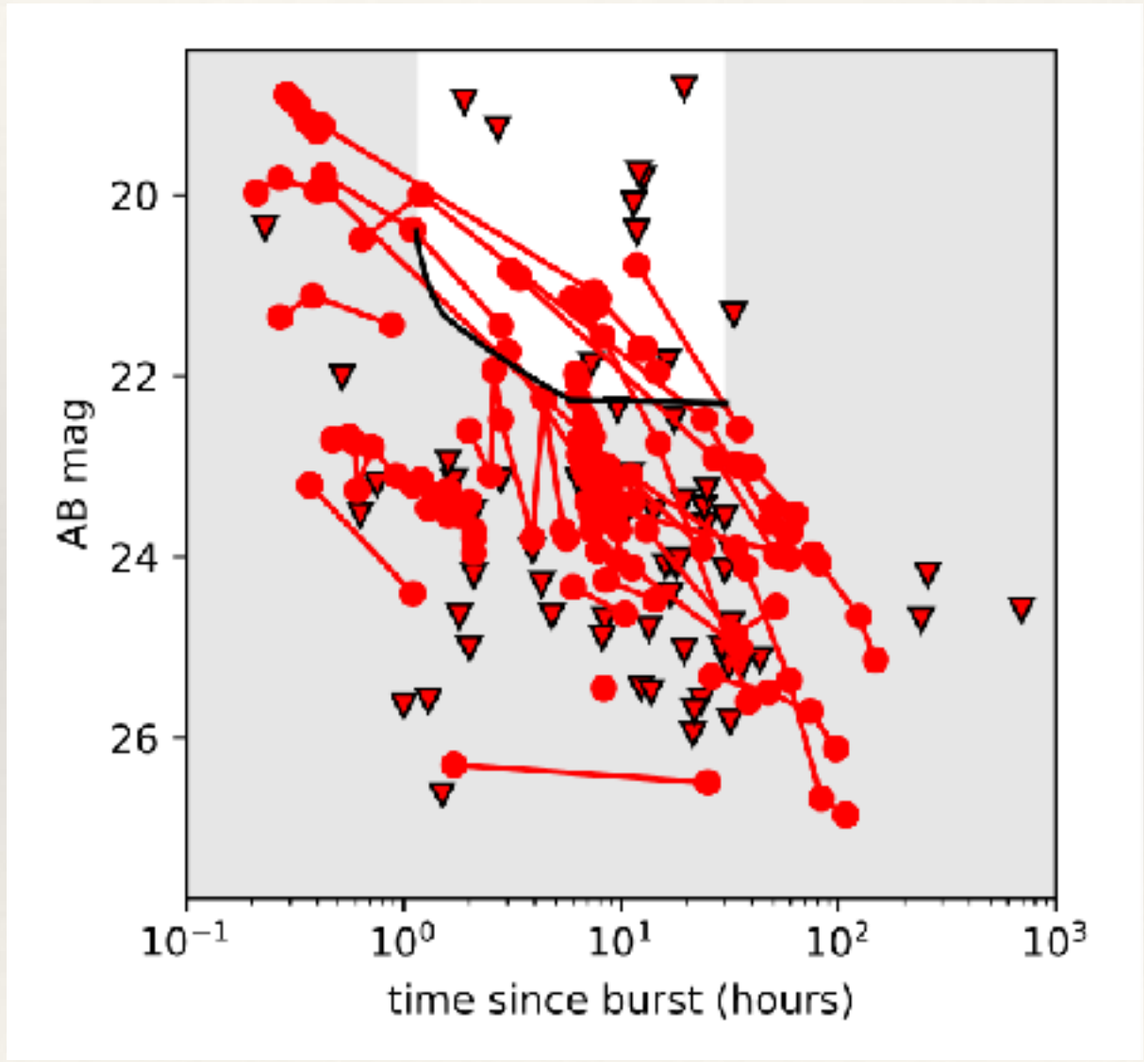
- Slides from March ZTF Meeting

Proposed Program

- Follow-up ~ 2 *Fermi* GRB short GRBs per month
  - Prioritize events that "look like" GW170817 (hard spike and soft thermal tail) and are promptly (~ 12 hours) accessible to Palomar
    - 2-3 epochs, logarithmically spaced, in g on Night 1 (Afterglow phase)
    - 1 g + 1 r/i on Night 2 (kilonova phase), if necessary
    - 1 g + 1 r/i on Night ~ 5 (kilonova phase), if necessary
- Only execute program until LIGO/Virgo O3 starts up (~ November/December 2018)

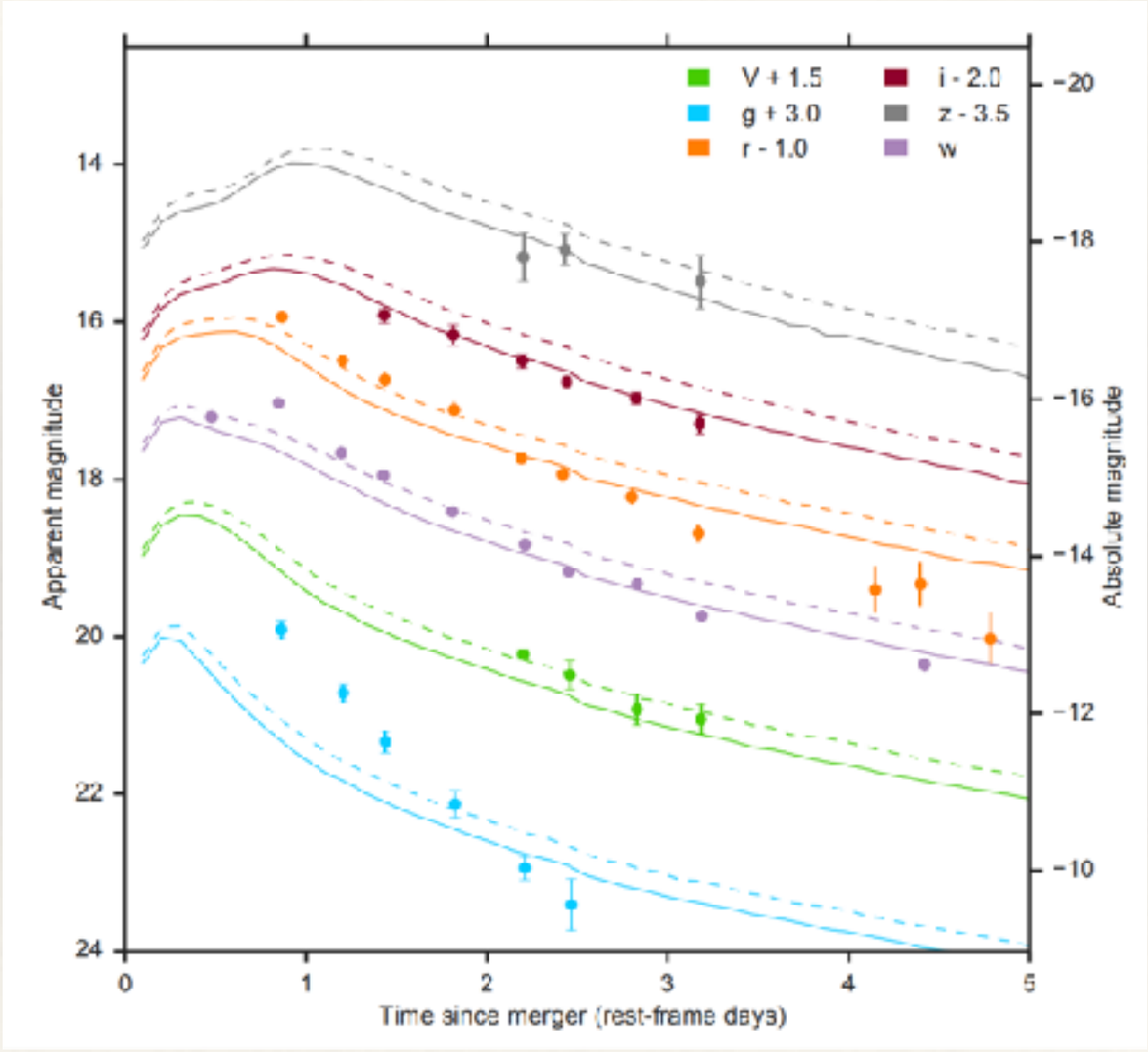
Night 1: Afterglow Phase

- Search for on-axis, distant events by their fast fading "afterglow" emission
- Exposure time ~ 2-3 min, to increase depth (but still shallower than references)
- False positive rate very low (50 events in 4 years of iPTF - Ho et al. 2018)
- ~ 20% of *Swift* short bursts would have detectable afterglows (terminate sequence if successful)



Nights 2+5: Kilonova Phase

- Search for counterpart that is
  - Extremely red (g - r > 1.0)
  - Redder than Night 1
  - Nearby galaxy association
- Longer exposures enables robust color measurement (even for fainter sources)
- Final epoch catches fast faders (in case color evolution of GW170817 unique)



Arcavi+ 2017

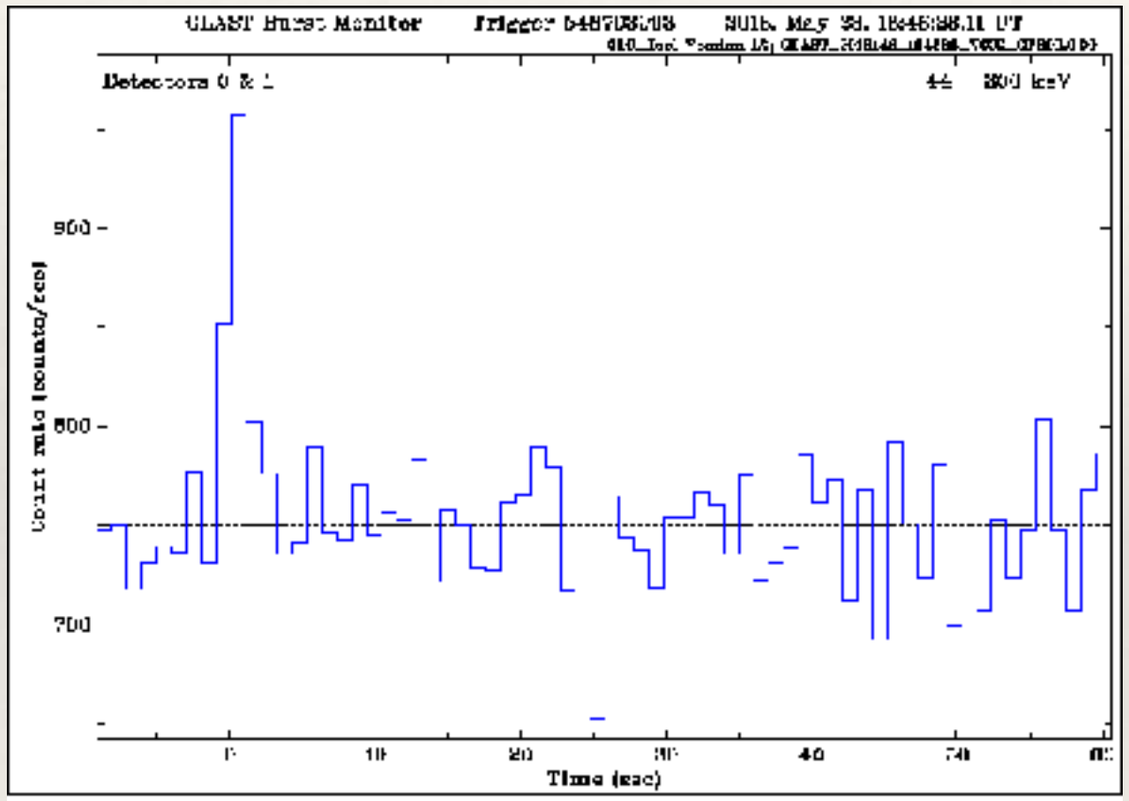
Fermi-ZTF Short GRB Summary

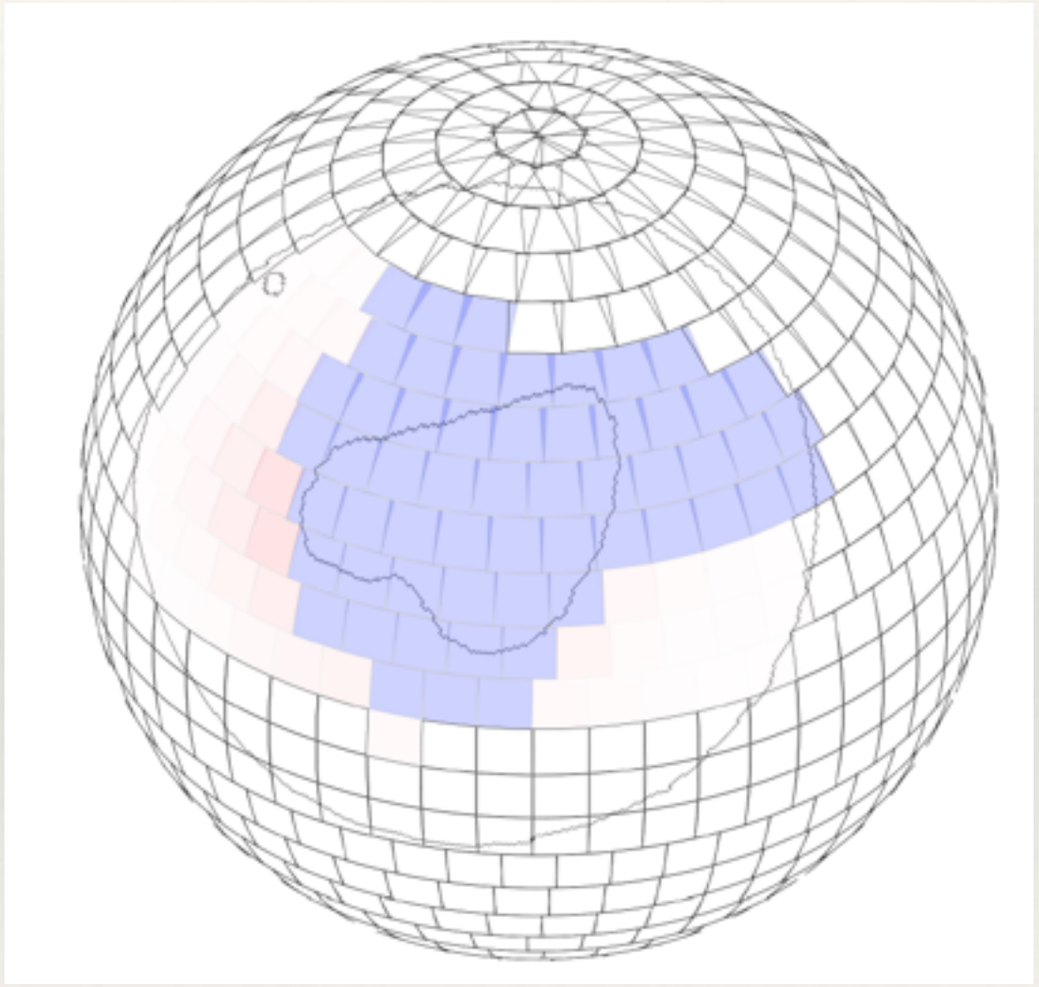
- Total request:
  - Per trigger: 1.5 hr N1 + 1 hr N2 + 1 hr N5 = 3.5 hr
  - Per month: 2 triggers = 7.0 hr
    - April-November: 8 months = 56 hr
- Possibility (though not guarantee) of kilonova detection **before** LV O3 starts up again
- Interesting (but not revolutionary) secondary science on the energetics and environments of short GRBs
- Important test case for GW follow-up in O3

Part II: Triggers Thus Far

- 4 Short GRBs from *Fermi*-GBM
  - GRB180523B (2900 square degrees; 60% coverage)
  - GRB180626C (300 square degrees; 87% coverage)
  - GRB180715B (250 square degrees; 36% coverage)
  - GRB180728B (350 square degrees; 90% coverage)
- Total time used: 10.0 hours
  - 1.3% of total ZTF time; 2.8% of partnership time
- Number of counterparts: 0

GRB180523B Example





A relatively “typical” short GRB (t ~ 2 s, hard spectrum). But somewhat more poorly localized than average

GRB180523B Example

Table 1. Success rates for the requested ZTF observation fields over each night.

Date	Fields Requested	Fields Observed	Fields in IPAC	Field Success Rate (>1 Quadrant)	IPAC Fields with all 64 Quadrants	Total Quadrant Success Rate
24-May	108	106	105	97%	38%	88%
25-May	95	94	94	99%	67%	98%

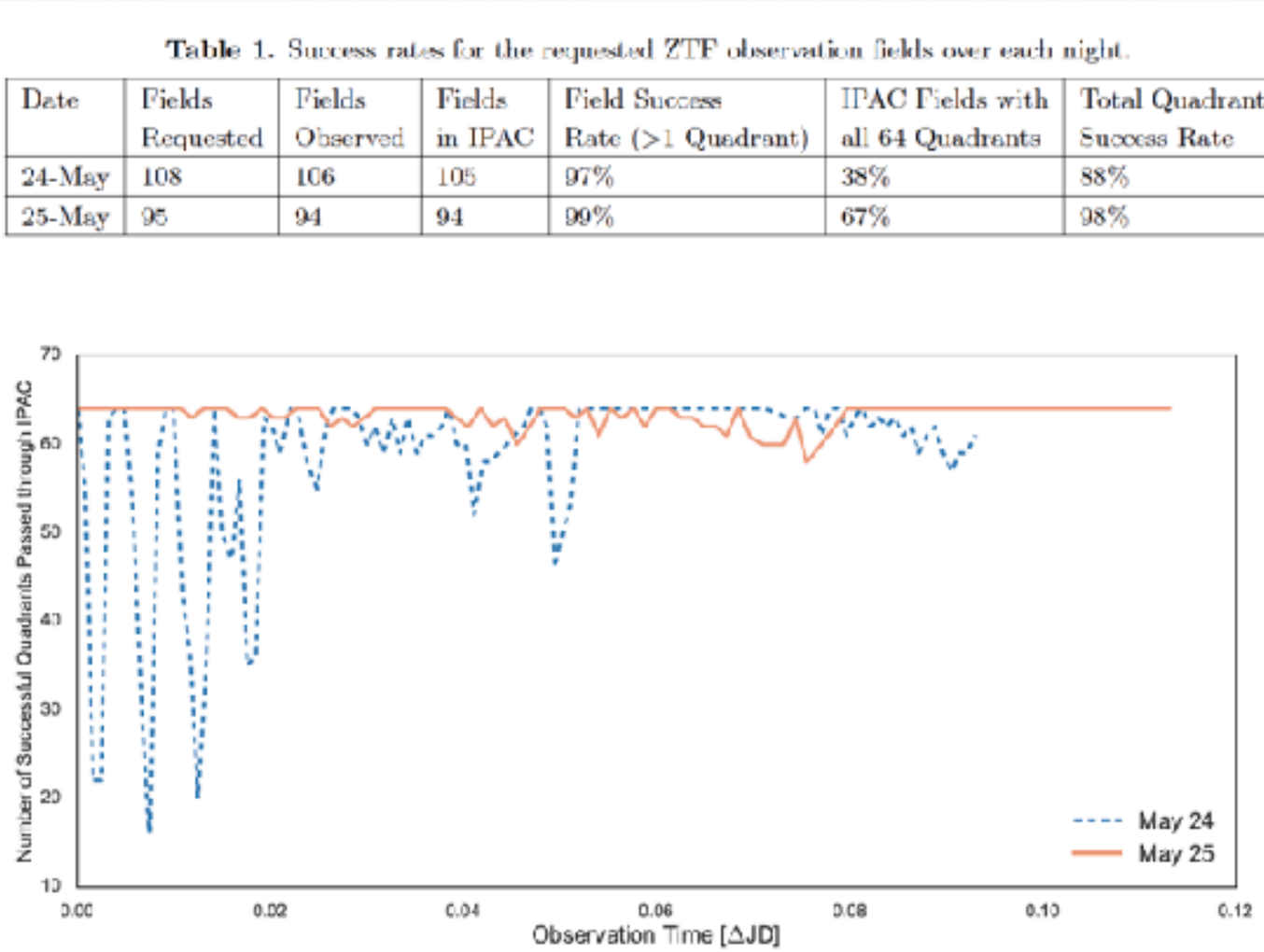


Figure 2. The number of successfully processed quadrants per ZTF observation field throughout each night.

Some issues with processing (bad seeing / focus testing at start of night 1), but after that went smoothly

GRB180523B Example

- A liberal filter applied in the GROWTH marshal:
  - Not a variable star or moving object
  - Rb > 0.3
  - Away from bright stars
  - In ToO fields
- Number of candidates: **113 (N1) + 350 (N2)**

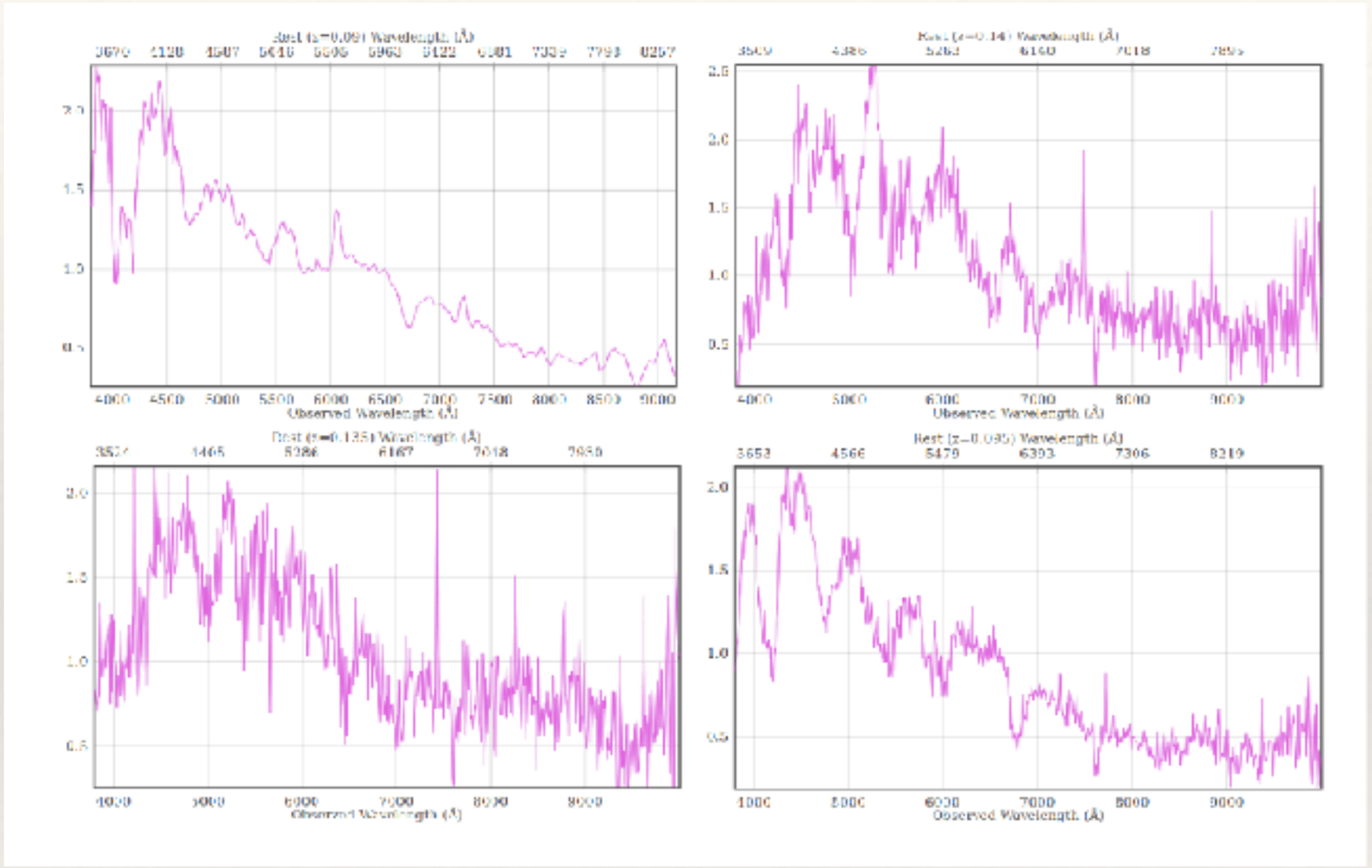
GRB180523B Example

Table 3. Follow-up for the candidates

Candidate	Coordinates	magnitude at discovery	Date of last observation	Data available	Classification	$\Delta m/\Delta t$
ZTF18aawozzj	12:31:09.02 +57:35:01.8	g—20.2	June 9	P200+DBSP Spectrum	SNIa at z—0.095	
ZTF18aawnbgg	10:40:54.05 | 23:44:43.3	r 19.88	June 9	P200 | DBSP Spectrum	SNIa at z 0.13	
ZTF18aawnvbj	10:12:41.17 +21:24:55.5	r—19.75	June 9	P200+DBSP Spectrum	SNIa at z—0.14	
ZTF18aawcwsx	10:40:33.46 | 47:02:24.4	r—19.84	June 5	P60 | SEDM Spectrum	SNIa at z—0.09	
ZTF18aawnbkw	10:38:47.66 | 26:18:51.8	r 19.91	June 12	KPED r 20.01		-0.1 mag /20 days
ZTF18aawmqwo	09:52:06.90 +47:18:34.8	r—19.98	June 21	KPED r—19.9		REVIEW
ZTF18aawmkik	08:51:11.45 | 13:13:16.7	r—19.04	June 12	KPED r—20.6		-1.56 mag /20
ZTF18aawnmlm	11:03:11.38 +42:07:29.9	r=20.12	June 19	KPED r=20.2		-0.08 mag /18
ZTF18aauhzav	10:59:29.32 +44:10:02.7	r—19.97	June 19	KPED r—16.5		REVIEW
ZTF18aavrhqs	11:58:09.57 | 63:45:34.6	r—19.99	June 21	KPED r—21.4		-1.41 mag /21
ZTF18aawmwwk	10:35:26.51 +65:22:34.3	r—19.9	June 21	KPED r—19.8		+0.1 mag /21
ZTF18aawwbwm	08:16:44.98 | 35:34:13.1	r—19.79	Not observable			
ZTF18aawmjru	08:39:11.39 +44:01:53.6	r=18.43	Not observable			
ZTF18aawmigr	08:48:01.76 +29:13:51.9	r—19.63	Not observable			

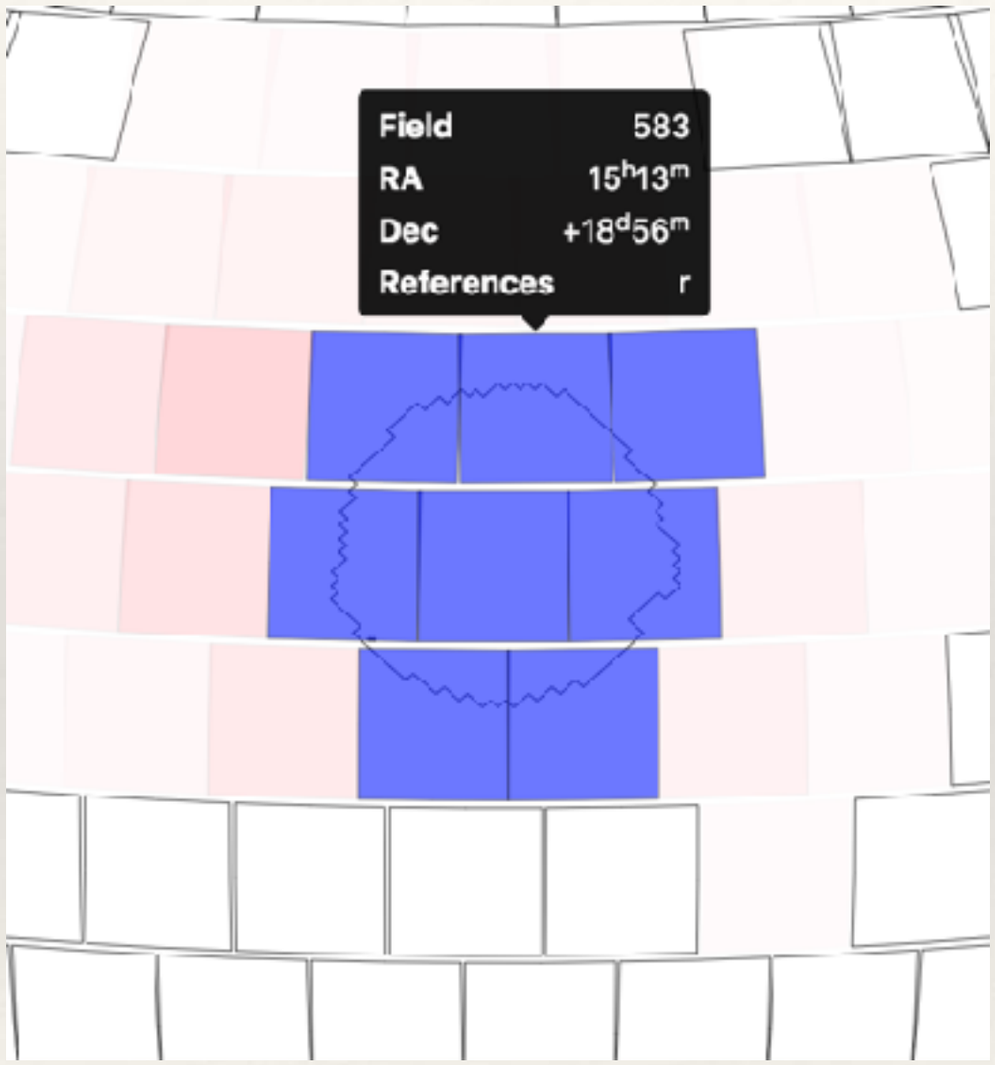
But nearly all had past detections from MSIP. To $r > 20.3$ ($g > 20.6$) mag, only **14** new transients in this 2900 deg^2 area

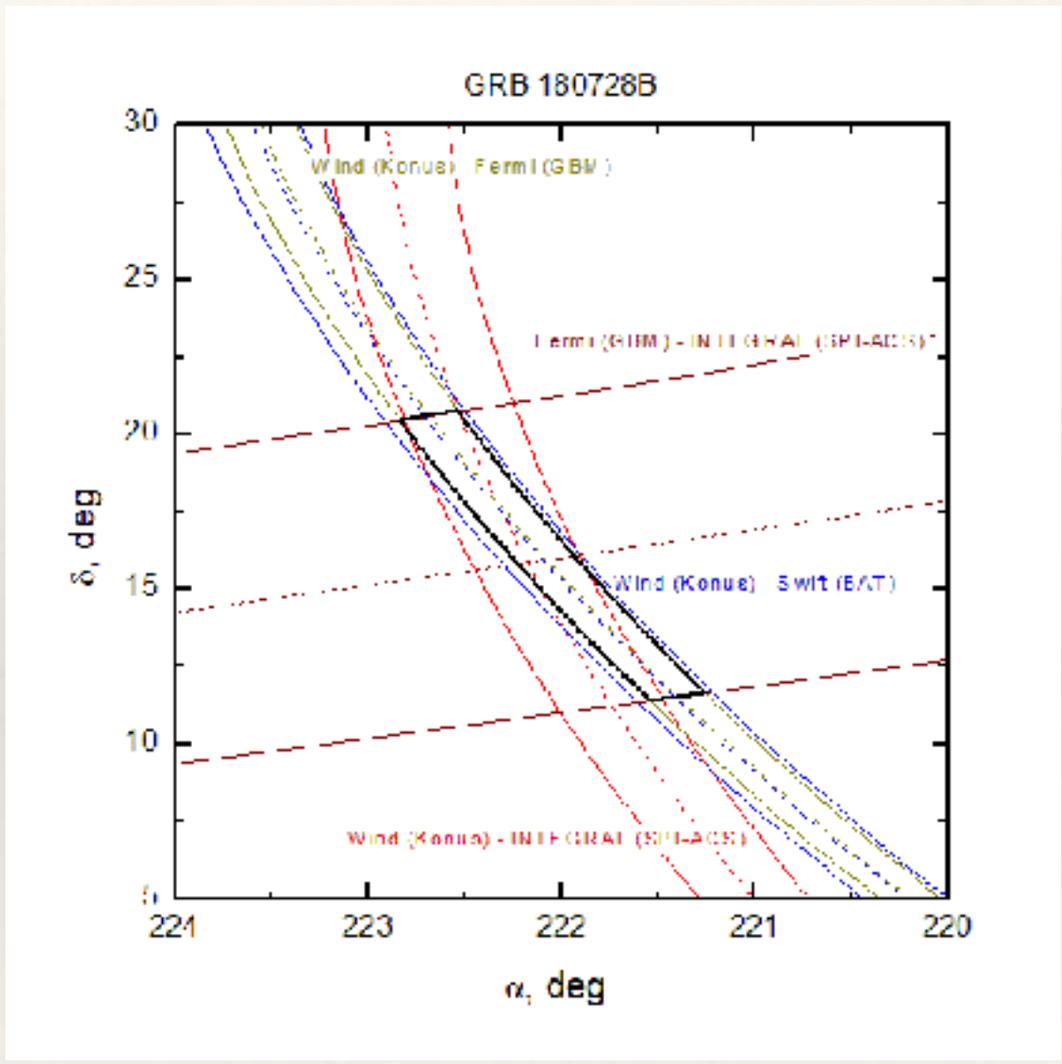
GRB180523B Example



All candidates consistent with (regular) SN or AGN

GRB180728B Example





For 2 of the GRBs we observed on N1, refined localization from IPN came on N2. In this case no overlap (because we didn't observe entire 90% localization)

Part III: Lessons Learned

- False Positive Rate: *Dramatically* reduced (relative to iPTF) from MSIP survey
- Image Depth: Issues with image subtractions in longer exposures (gain matching?) that remain to be worked out
- References: Lack of g-band references makes color information challenging (though getting better)
- Artifacts: Still number of artifacts to be tracked down

Lessons Learned I: False Positives

	Area	Depth	**New** Candidates
GRB180523B	2900	20.5	14
GRB180626C	250	21.0	0*
GRB180715B	350	21.5	14
GRB180728B	300	21.0	0*

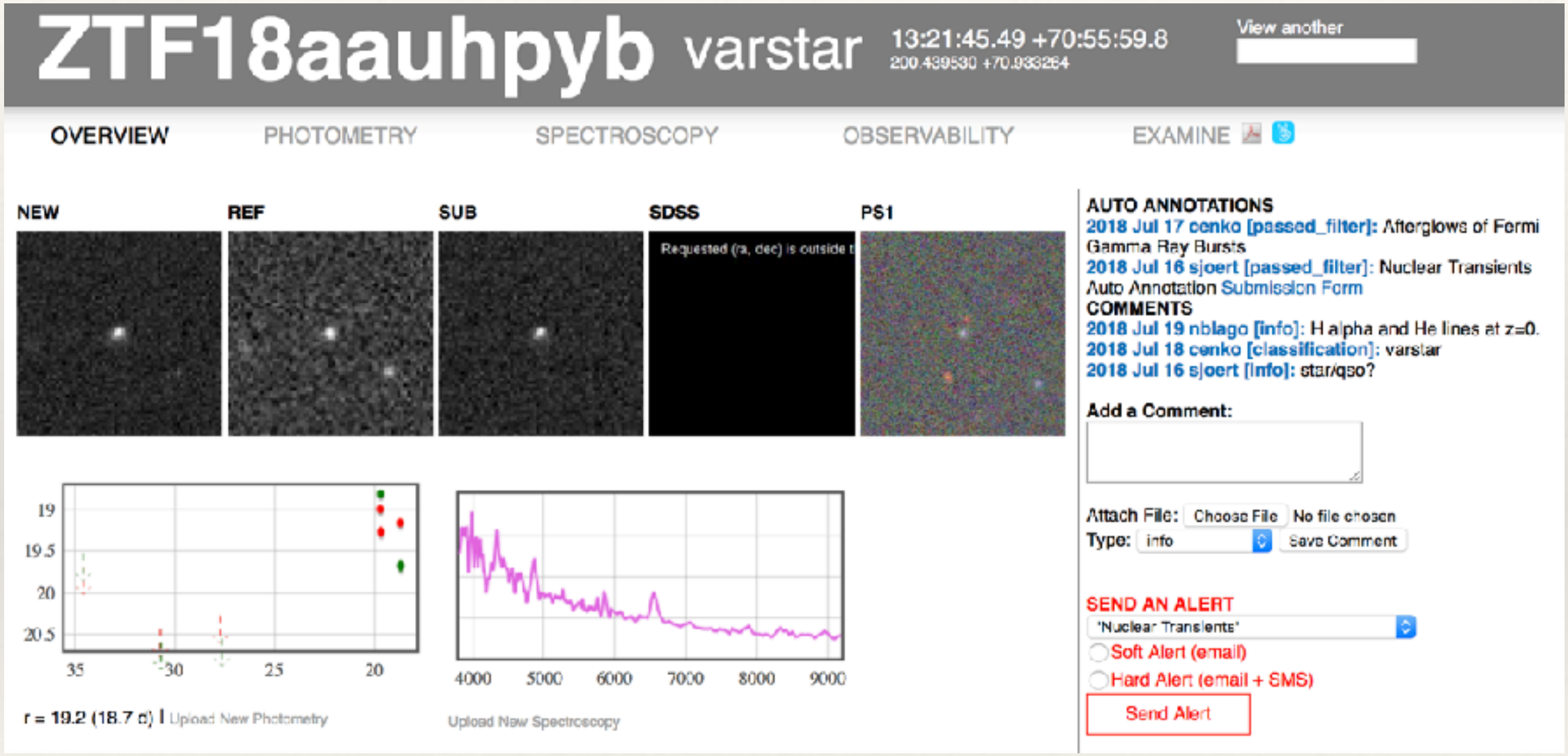
* = Revised localization from IPN at dt ~ 24 hours

Lessons Learned I: False Positives

ZTF ID	RA	DEC	discovery magnitude	last non-detection
ZTF18aamwzlv	13:06:44.59	+68:59:52.9	2018 Jul 16 g=21.26	2018 Jul 08 g>20.34
ZTF18abhbevp	14:21:00.83	+72:11:43.8	2018 Jul 16 g=20.64	2018 Jul 07 g>20.08
ZTF18abhbpkm	16:02:36.78	+70:47:05.1	2018 Jul 16 g=21.24	2018 Jul 13 g>20.52
ZTF18abhhjyd	13:02:32.07	+75:16:49.4	2018 Jul 16 g=21.24	2018 Jul 05 g>20.56
ZTF18abhbgan	15:43:18.86	+72:05:24.8	2018 Jul 16 g=21.22	2018 Jul 13 g>20.17
ZTF18abhbfoi	13:24:34.01	+70:56:47.5	2018 Jul 16 g=21.12	2018 Jul 08 g>20.55
ZTF18abhbcjy	14:20:50.39	+73:25:40.5	2018 Jul 16 g=20.65	2018 Jul 17 g>20.51
ZTF18abhaogg	13:42:45.47	+74:19:38.3	2018 Jul 16 r=20.40	2018 Jul 05 r>20.35
ZTF18abhbamj	15:26:58.78	+72:02:17.8	2018 Jul 16 g=21.22	2018 Jul 13 g>20.01
ZTF18abhawjn	13:31:27.33	+66:46:45.4	2018 Jul 16 r=21.19	2018 Jul 08 r>20.31
ZTF18abharzk	13:41:09.05	+70:43:06.8	2018 Jul 16 r=21.30	2018 Jul 08 r>20.28
ZTF18abhbckn	12:49:53.85	+73:02:00.5	2018 Jul 16 r=20.93	2018 Jul 08 r>19.96
ZTF18abhbfqf	13:16:00.24	+69:37:24.1	2018 Jul 16 g=19.59	2018 Jul 08 g>20.50
ZTF18aauhpyb	13:21:45.49	+70:55:59.8	2018 Jul 16 r=18.99	2018 Jul 08 r>20.28

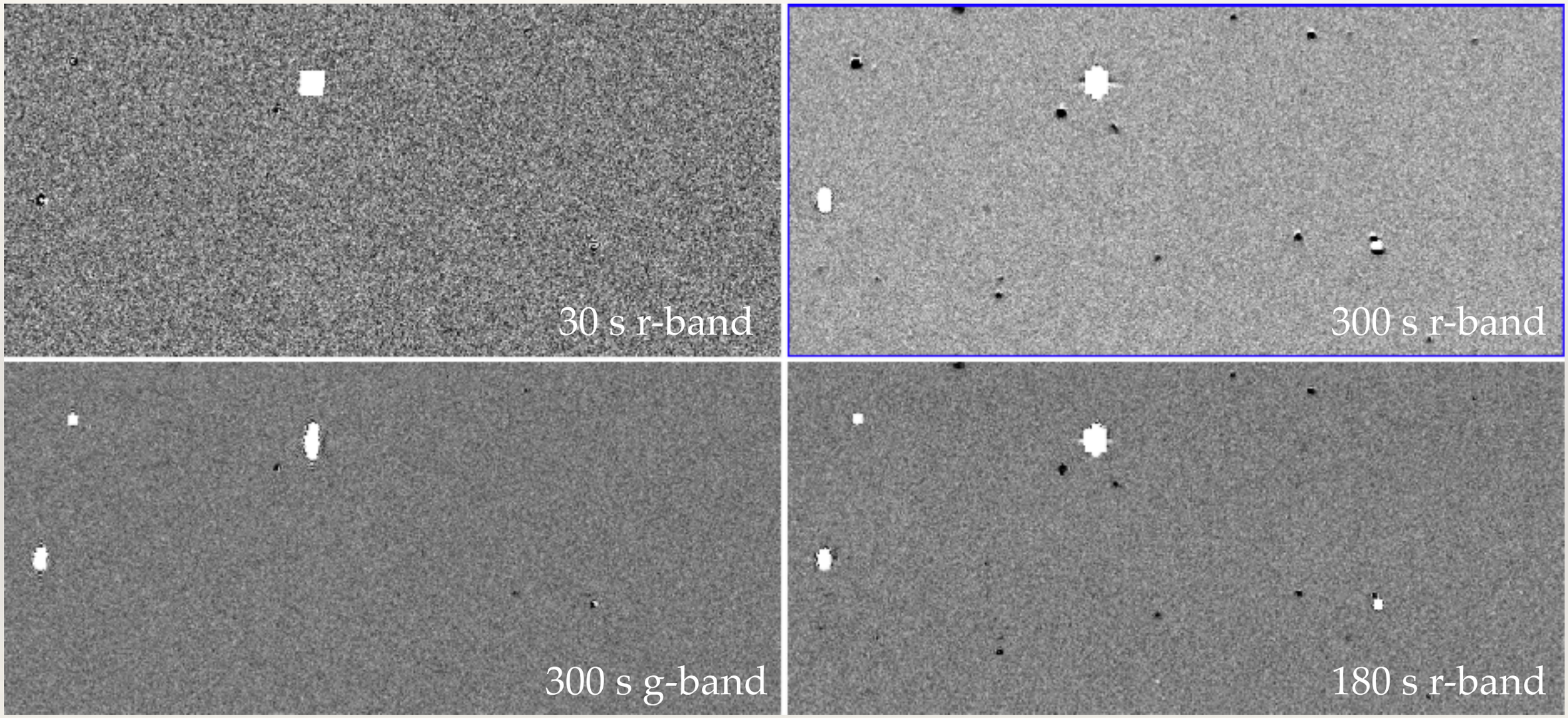
GRB180715B: 250 deg area search to r/g > 21.5 mag (300 s exposures).
14 new candidates without previous detections (even with deeper images).

Lessons Learned I: False Positives



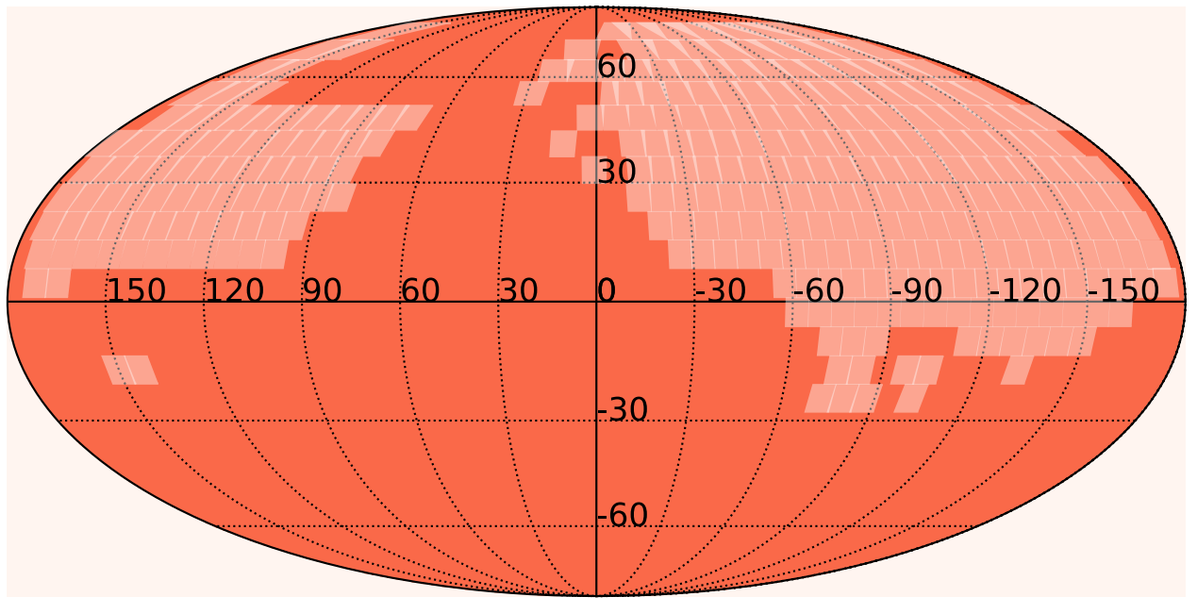
No previous detection ~ one week previous (deeper than detections).
Rapid blue to red evolution. But variable star (from SEDM spectrum).

Lessons Learned II: Image Depth

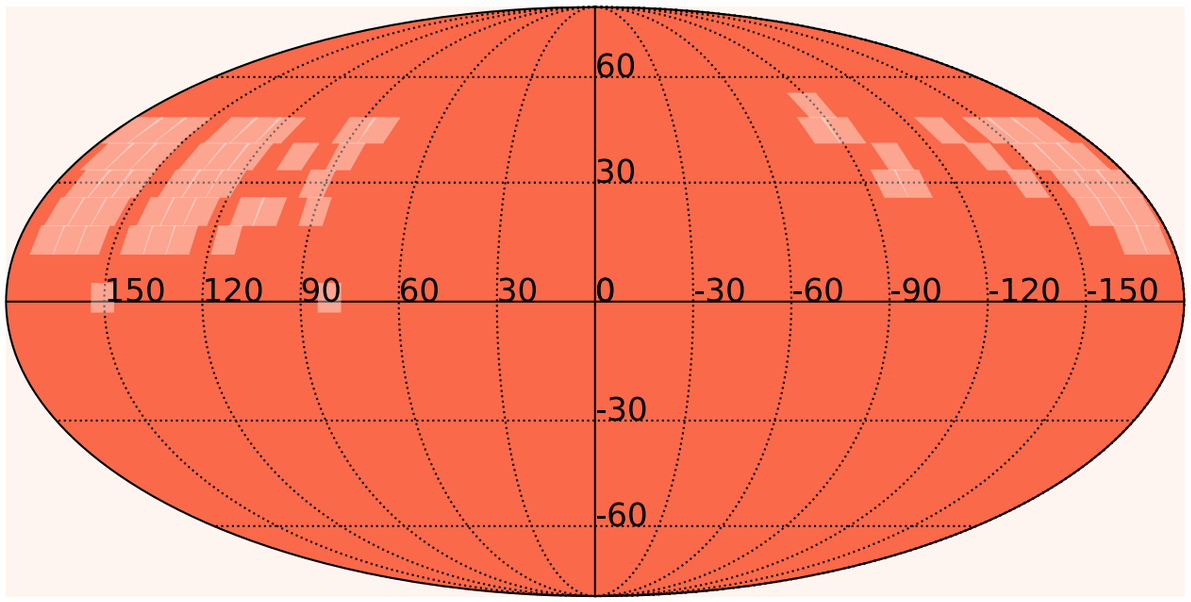


In *some* fields, gain matching issue in longer r-band exposures.
Limits number of candidates found (even brighter ones)

Lessons Learned III: References



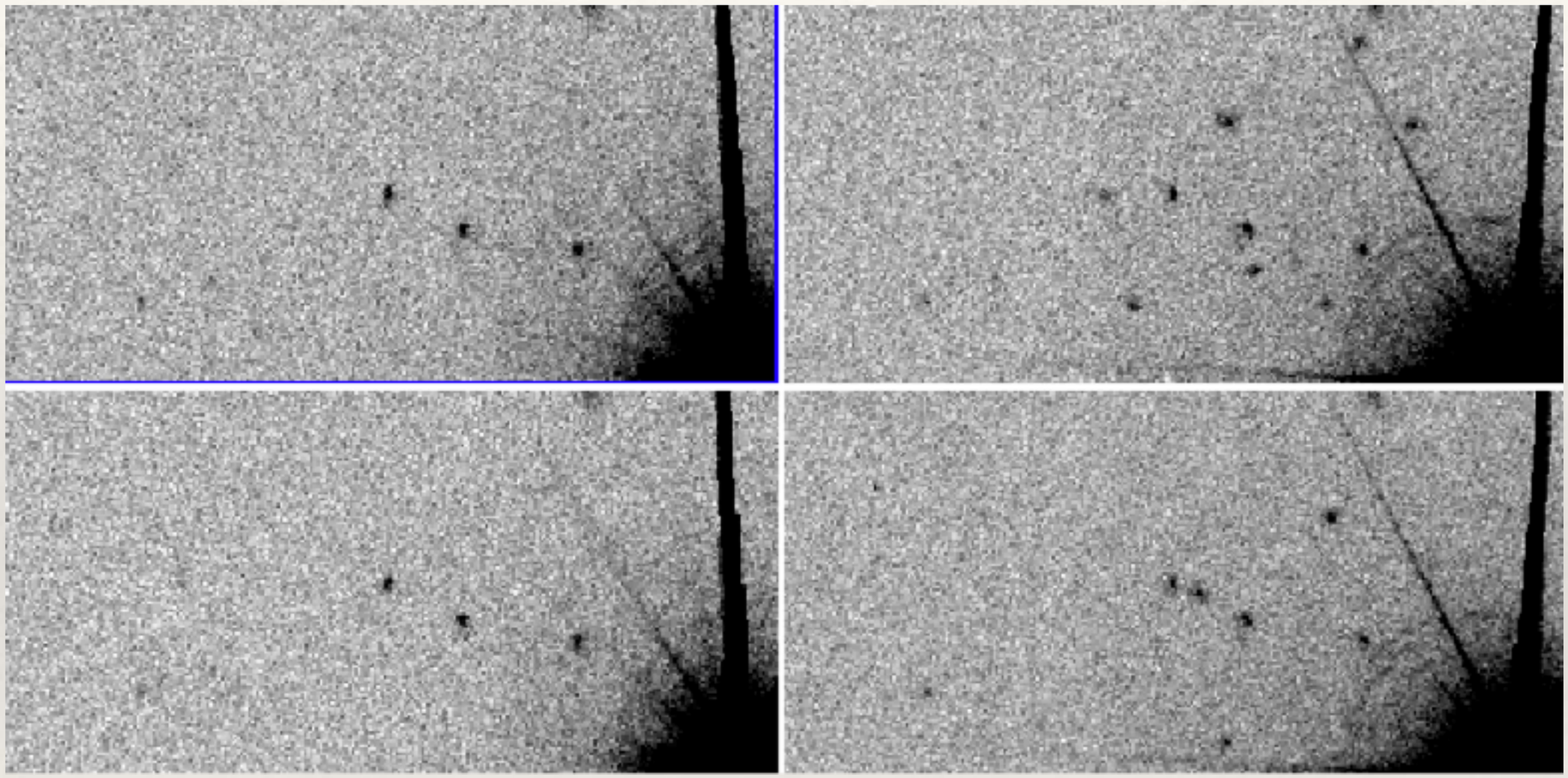
r-band: Primary Grid



r-band: Secondary Grid

Limited by reference availability - particularly in i-band, somewhat in g,
but also for *secondary* grid (12% loss of area with primary only)

Lessons Learned IV: Artifacts



These are actually images of the same location on the sky, but different CCD quadrants, over a time scale of ~ few hours (all r-band). Working on diagnosing and incorporating into pipeline.

Part IV: Plan Going Forward

- We were originally approved for 5 GRB (+5 neutrino) triggers, so we will be applying to continue this program until O3 (~ February 2019)
- We are revisiting optimal approach for areal coverage vs. depth vs. number of events followed
- Also working to incorporate “untriggered” short GRBs - weaker events (more nearby?) but longer latency