Satellite flares in ZTF alert stream
and what we should expect in LSST

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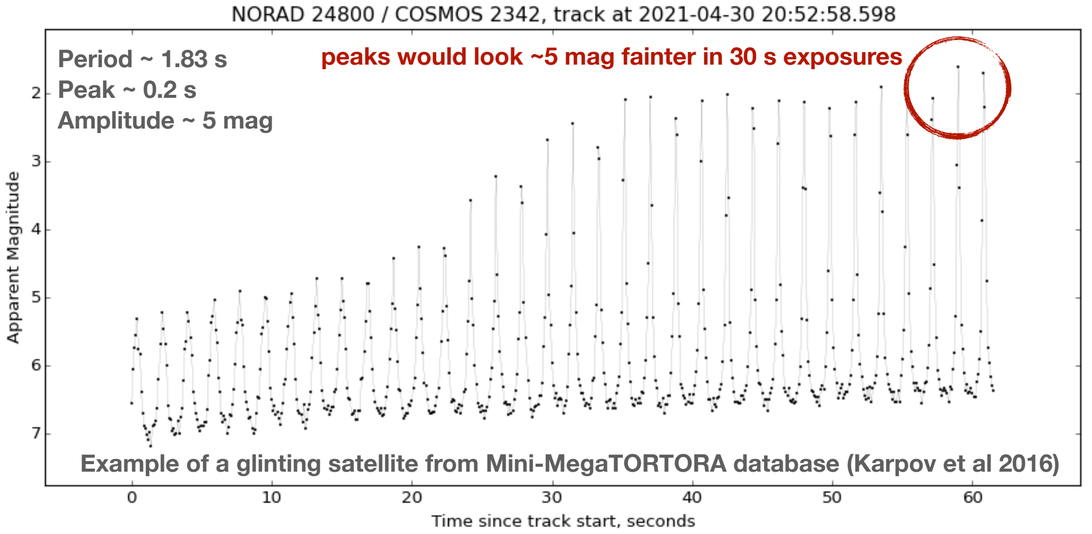
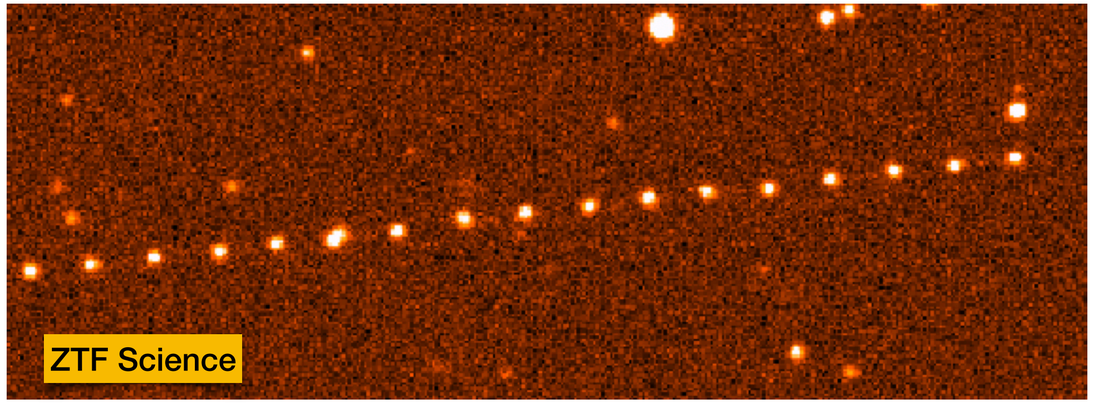
Rapid optical flashes

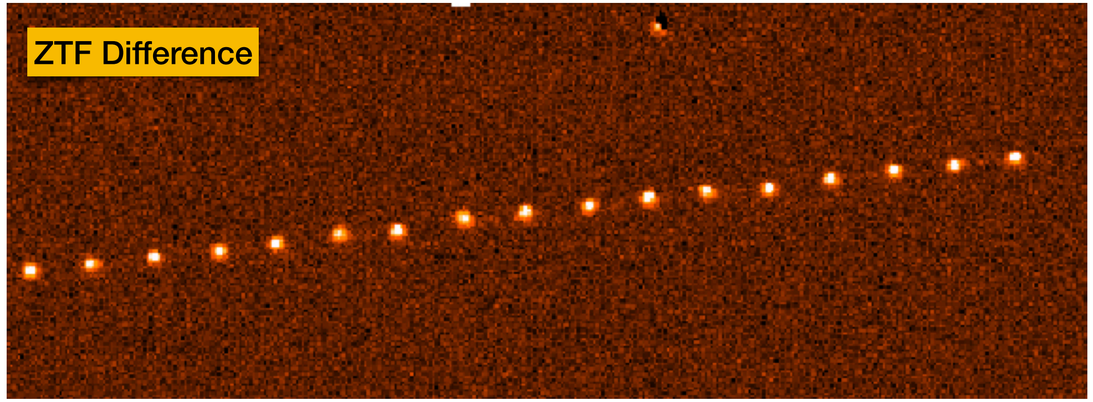
- Anything shorter than a day
  - GRBs, shock breakouts, stellar flares, ...
- Actual rapid (subsecond?) flashes
  - FRBs, ...
- Satellite flares are the most common :-(

  Perseus flasher, GN-z11-Flash



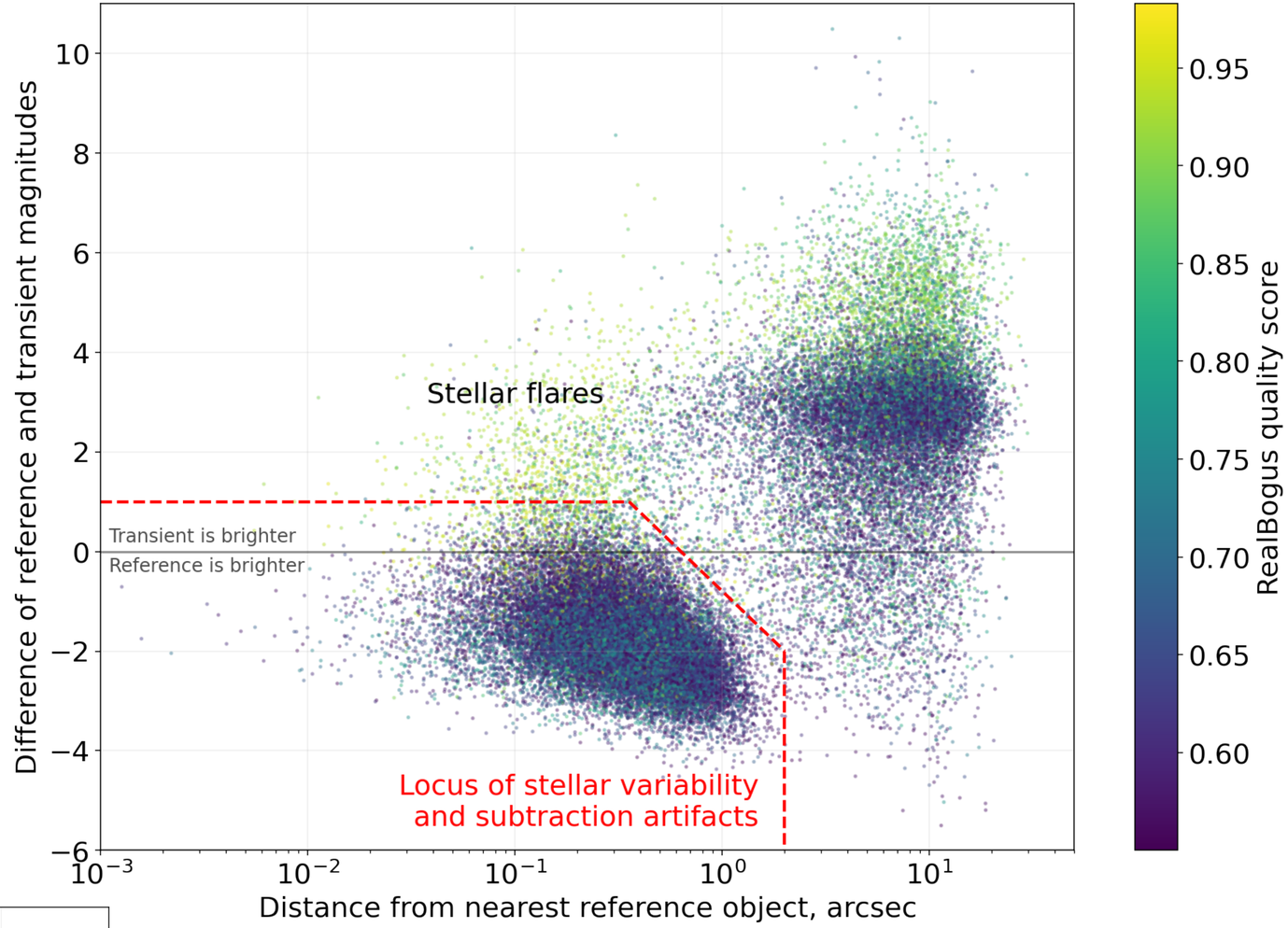


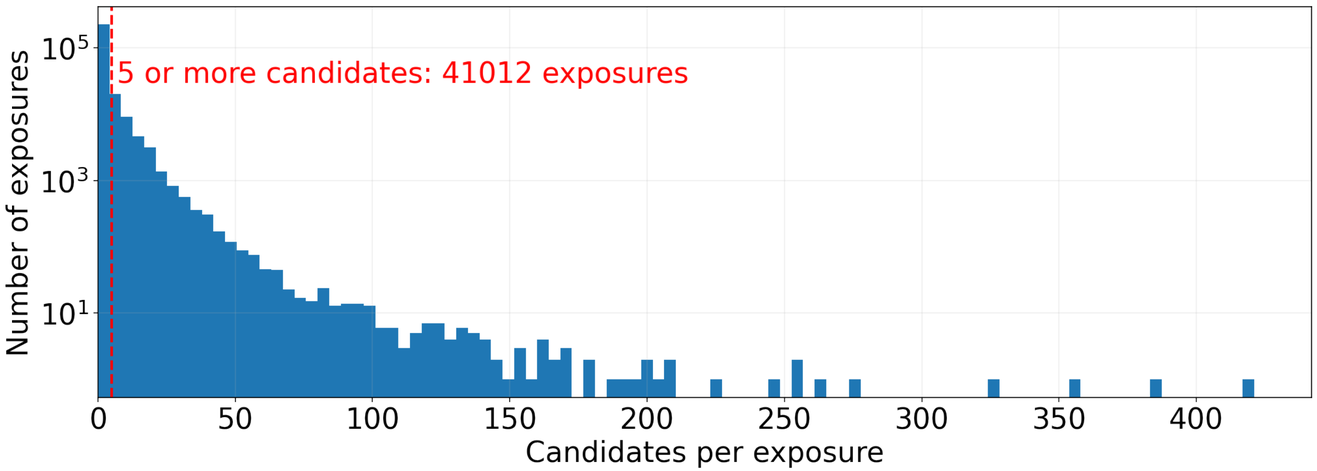
Some other random flaring satellite in ZTF data



Initial sample

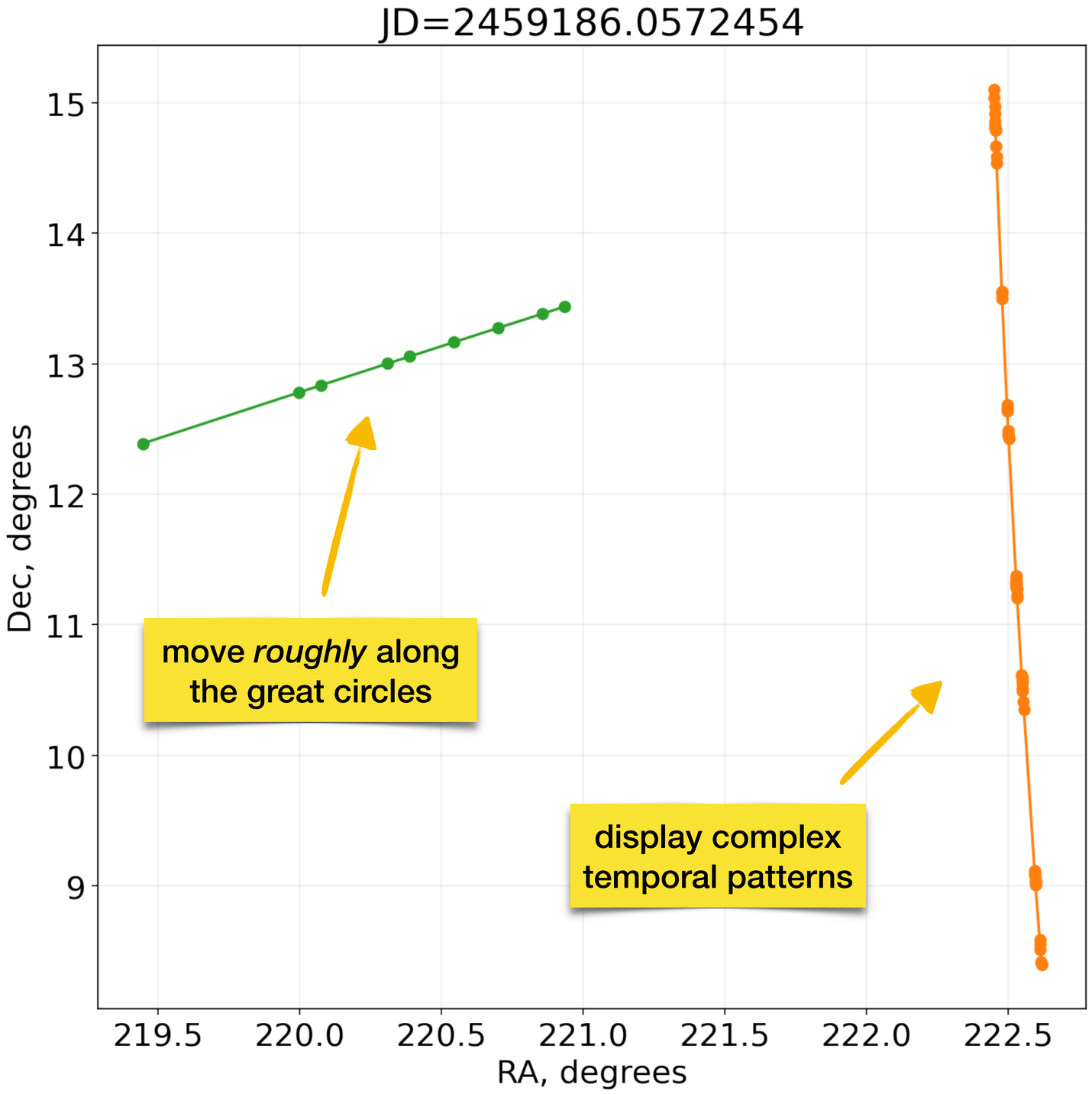
- Data between Nov 2019 and Dec 2021
- Quality cuts, SIMBAD, MPC
- ndethist=1, isdiffpos=t
- Locus of stellar variability and bad subtractions





164,163 exposures acquired from Nov 2019 till Dec 2021
113,422 (69%) exposures contain candidate events
41,012 (25%) exposures – 5 or more candidates

638,350 candidate events



Tracklets

- build great circles through every pair of dots
- select the ones with at least 5 dots closer than 1 arcsec
- merge the ones that are close enough

tracklet = several events detected on the same exposure and located along the same smooth curve on the sky

Limit of 5 points in order to minimize false associations, corresponding to 10^{-11} probability of a random coincidence for 5 candidate events per exposure, and 10^{-5} – for 50 candidates per exposure

6,450 unique tracklets with **73,368** (11.5%) events

Matching with satellites

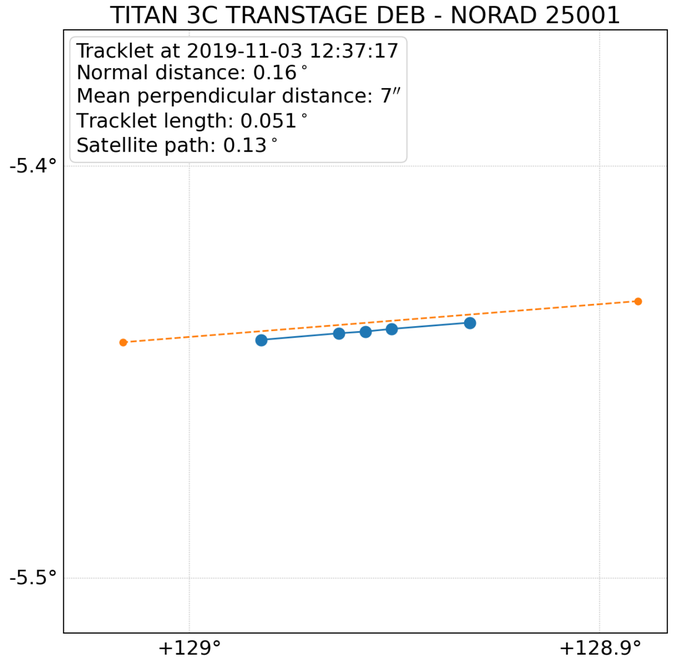
- TLE data from NORAD catalogue
- propagation using SkyField package
- closest co-linear tracks

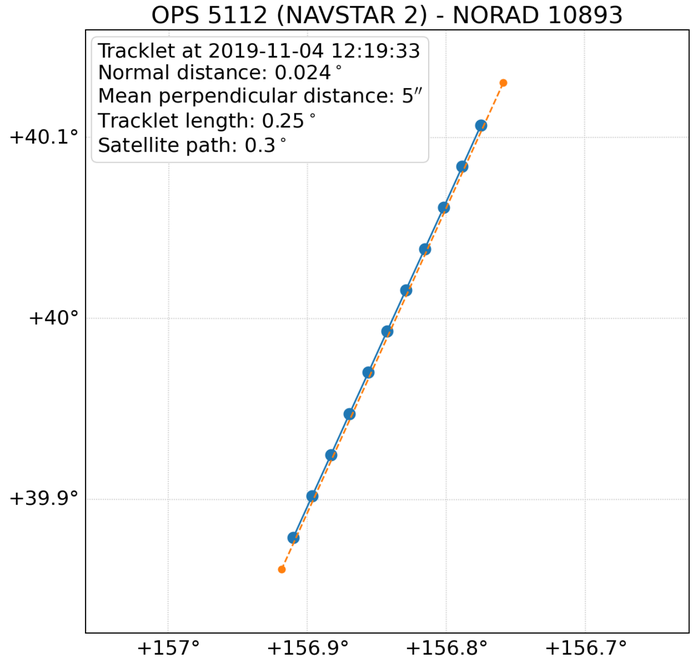
3,841 (60%) of tracklets matched with satellites
45,387 (62%) of tracklet events

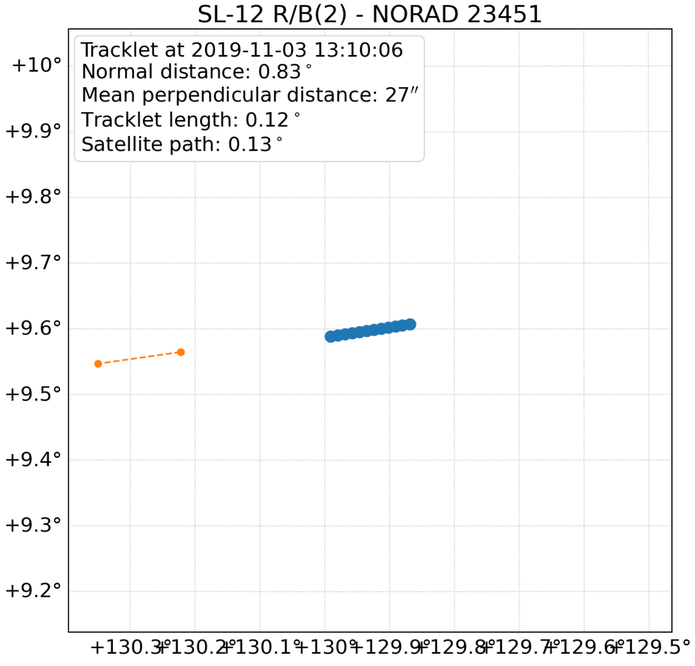
59,421 (9.3%) of all candidates also matched!

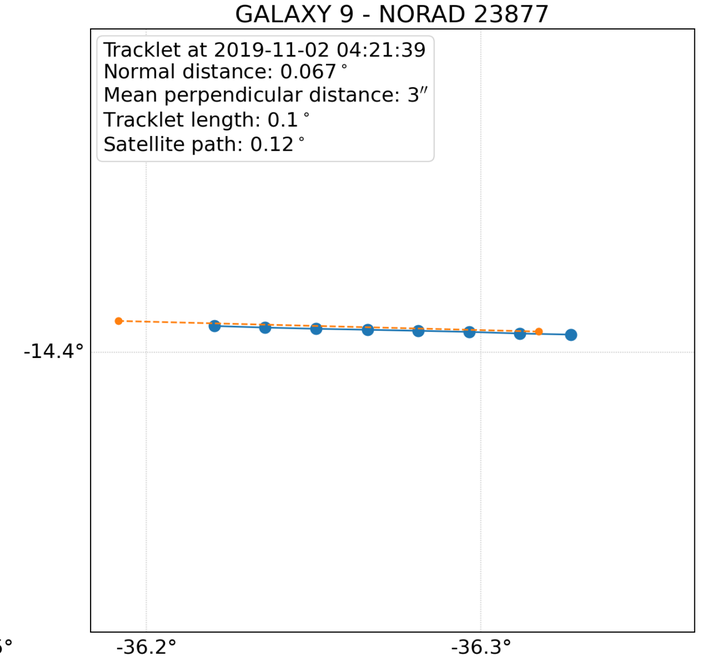
ID	Satellite name	Ntracklets	Nalerts	Status	a, km	RCS, m^2	Arc, deg.	P_m, s.	P_p, s.	τ, s.
21964	PALAPA B4	96	810	Unknown	42261	12.6	0.13	0.5	3	0.07
24769	BSAT-1A	95	1223	Inactive	42492	15.8	0.12	0.4	1	0.07
23314	THAICOM 2	84	937	Inactive	42359	1.3	0.12	0.5	3	0.07
14134	PALAPA B1	77	1151	Inactive	42199	1.3	0.12	0.4	2	0.07
23016	GALAXY 1R	74	727	Inactive	42463	8.3	0.12	0.7	3	0.07
25312	BSAT-1B	72	794	Inactive	42492	12.6	0.12	0.4	2	0.07
20402	JCSAT 2	71	677	Inactive	42659	8.2	0.12	0.3	2	0.07
14234	ARABSAT 1DR (TELSTAR 3A)	69	866	Inactive	42377	2.5	0.13	0.6	1	0.07
22931	THAICOM 1	68	671	Inactive	42474	1.0	0.12	0.5	3	0.07
20193	SIRIUS W (MARCOPOLO 1)	67	891	Unknown	42473	2.0	0.12	0.4	1	0.07
				— // —						
28556	ARIANE 1 DEB	1	5	Unknown	27013	0.1	0.051	0.7	1	0.2
22911	SOLIDARIDAD 1	1	5	Inactive	42164	12.5	0.12		4	0.07
15386	MARECS B2	1	5	Inactive	43429	3.2	0.11		3	0.07
26715	USA 157	1	5	Active	42166		0.12	1	1	0.07
44012	ATLAS 5 CENTAUR DEB	1	5	Unknown	29065		0.2	0.7	0.7	0.04
29516	SINOSAT 2	1	5	Inactive	44374	10.0	0.11	0.3	5	0.07
5589	TITAN 3C TRANSTAGE R/B	1	5	Unknown	43053	2.6	0.12	0.5	1	0.07
32387	RASCOM 1	1	5	Inactive	42508	9.0	0.12	0.4	2	0.07
30323	BEIDOU 1D	1	5	Inactive	42483	20.0	0.12	0.3	6	0.07
34705	IRIDIUM 33 DEB	1	5	Unknown	7023	0.0	13	0.003	0.2	0.0007

308 individual satellites, **97%** inactive

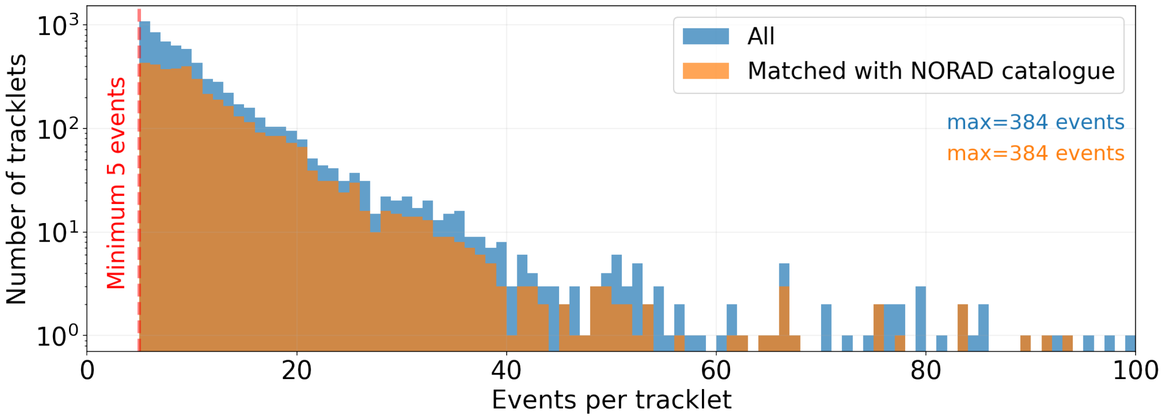


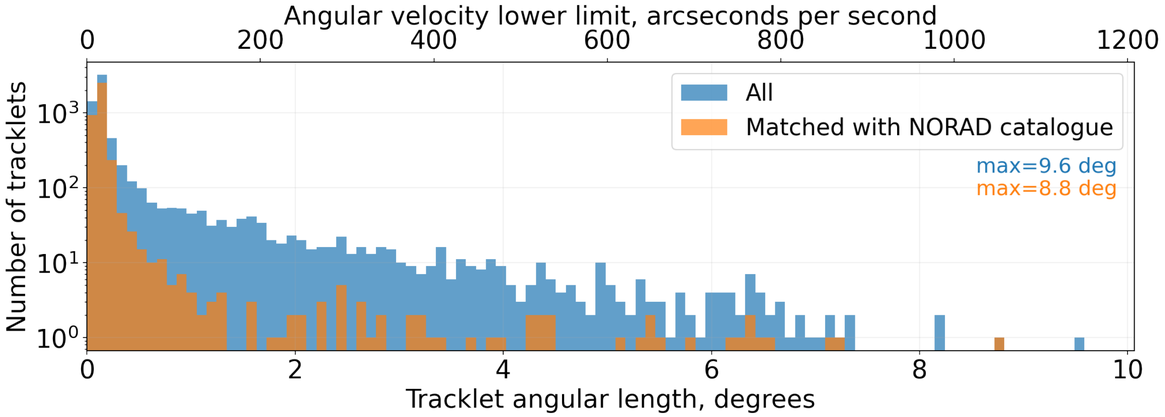


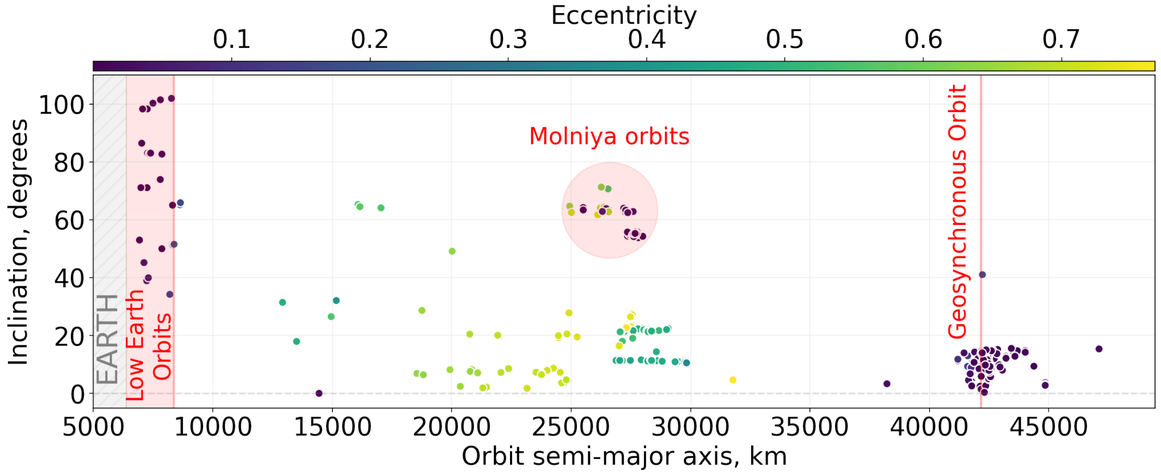


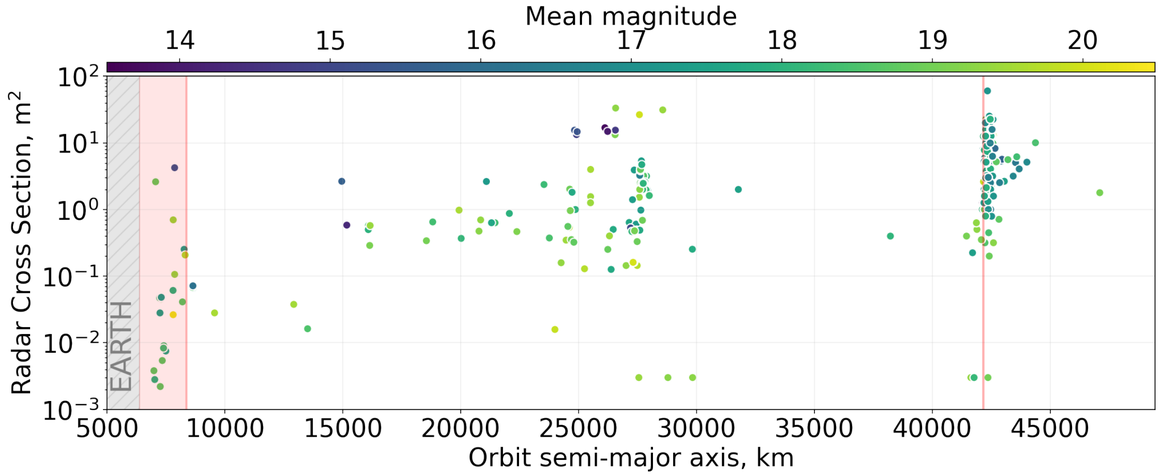


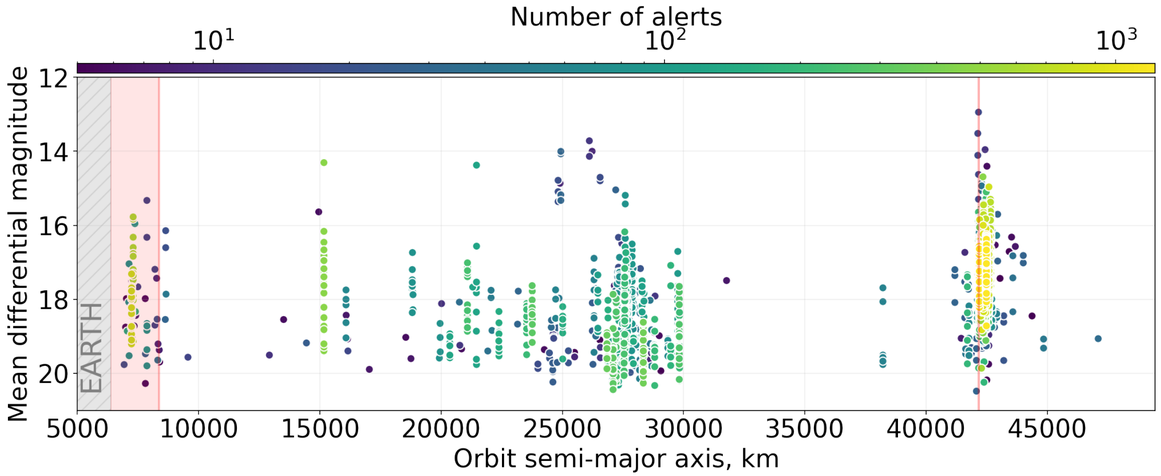
Matching with satellites









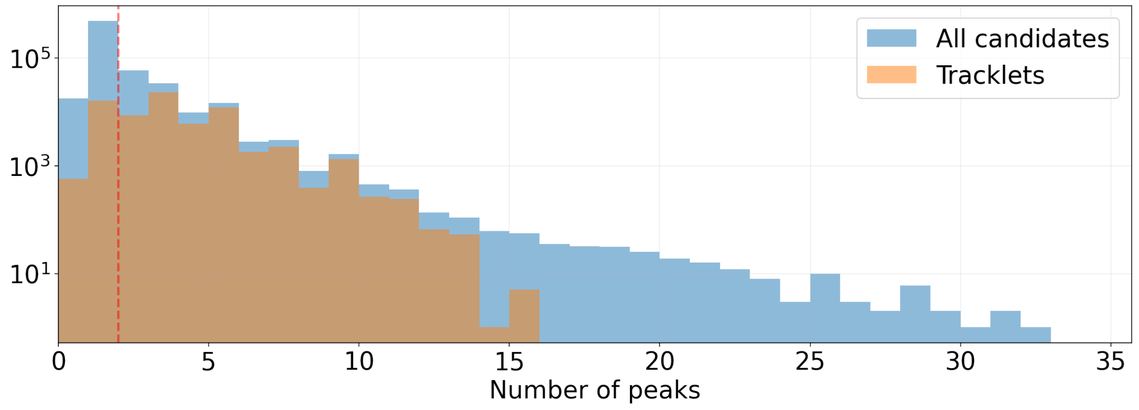


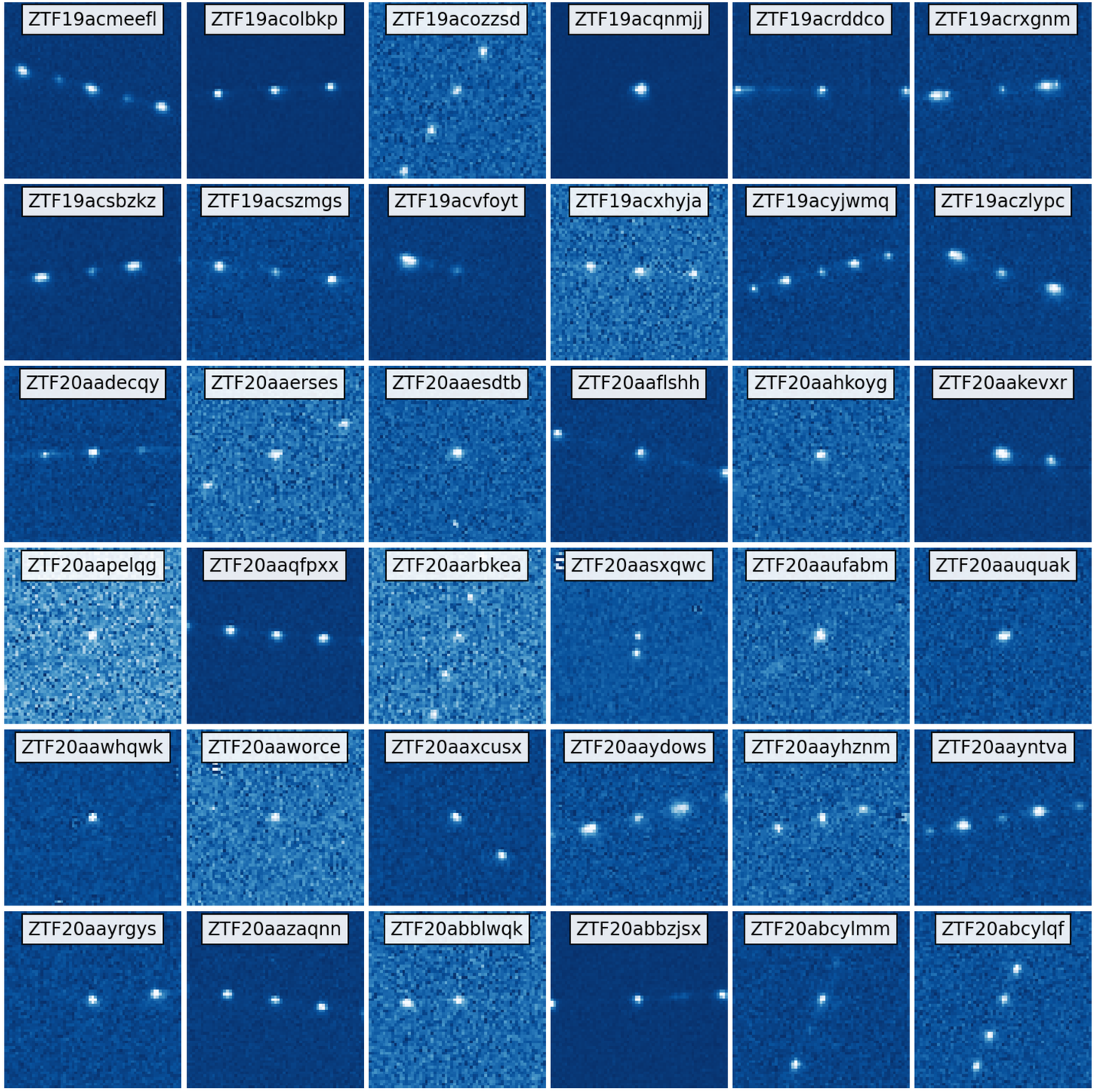
Morphological analysis

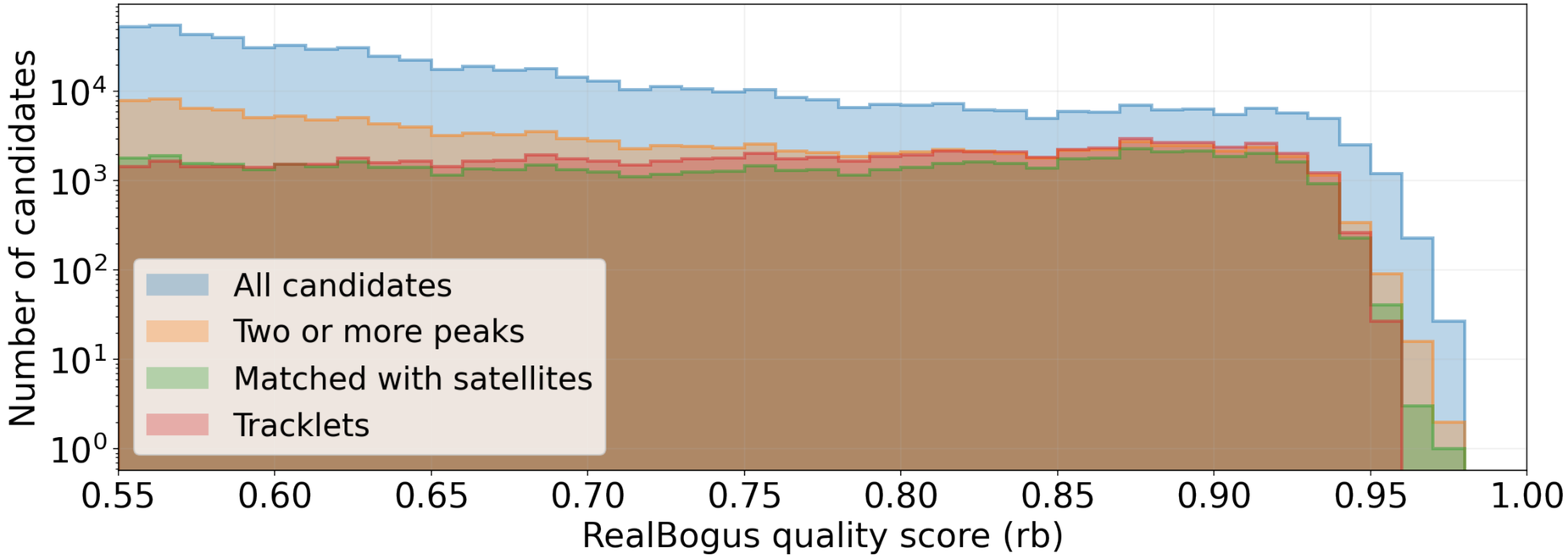
- simple peak detection after masking brighter objects on the templates
  not too reliable!

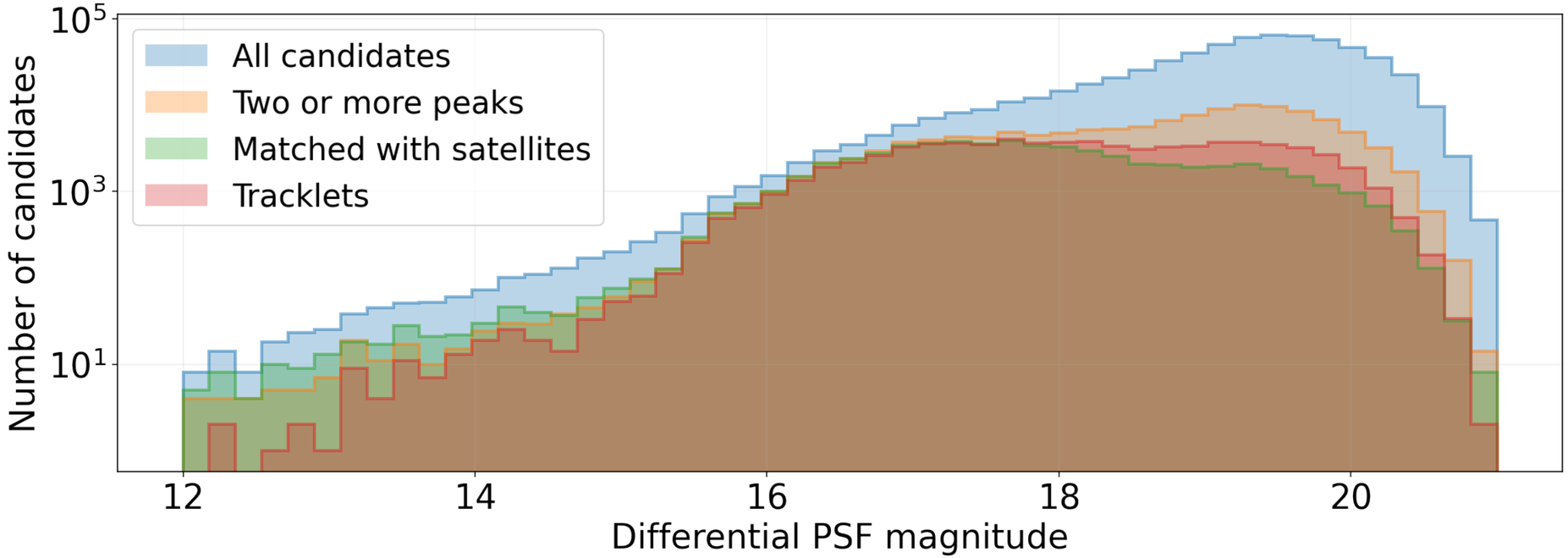
- **56,461** (77.0%) of tracklet events show two or more peaks

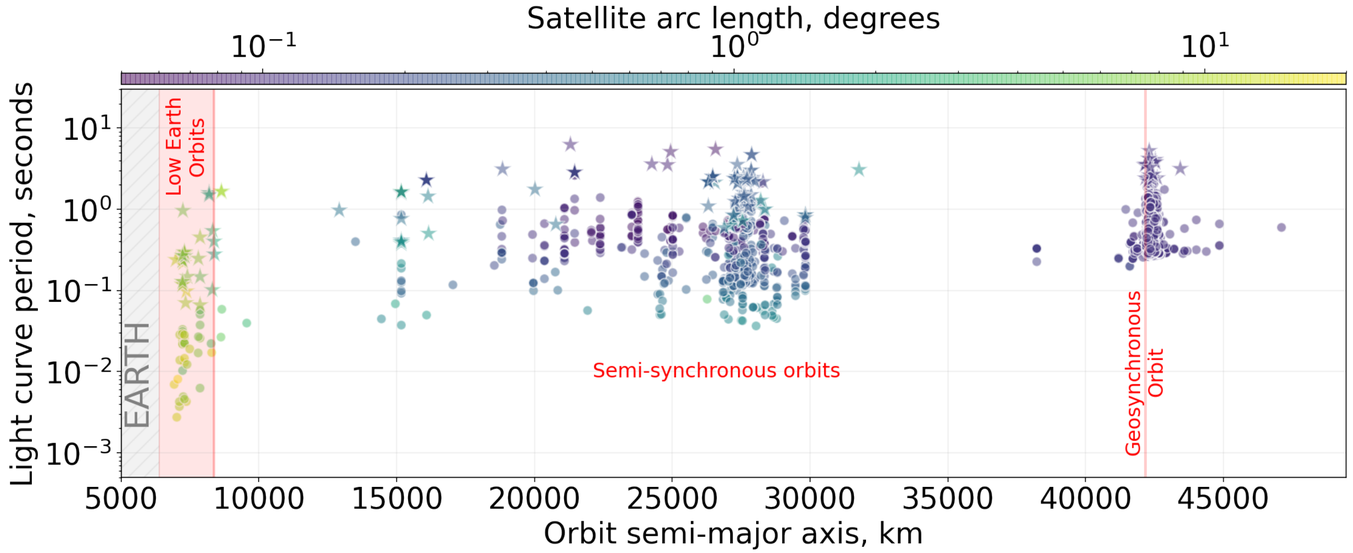
- **127,655** (20%) of all candidate events also show two or more peaks

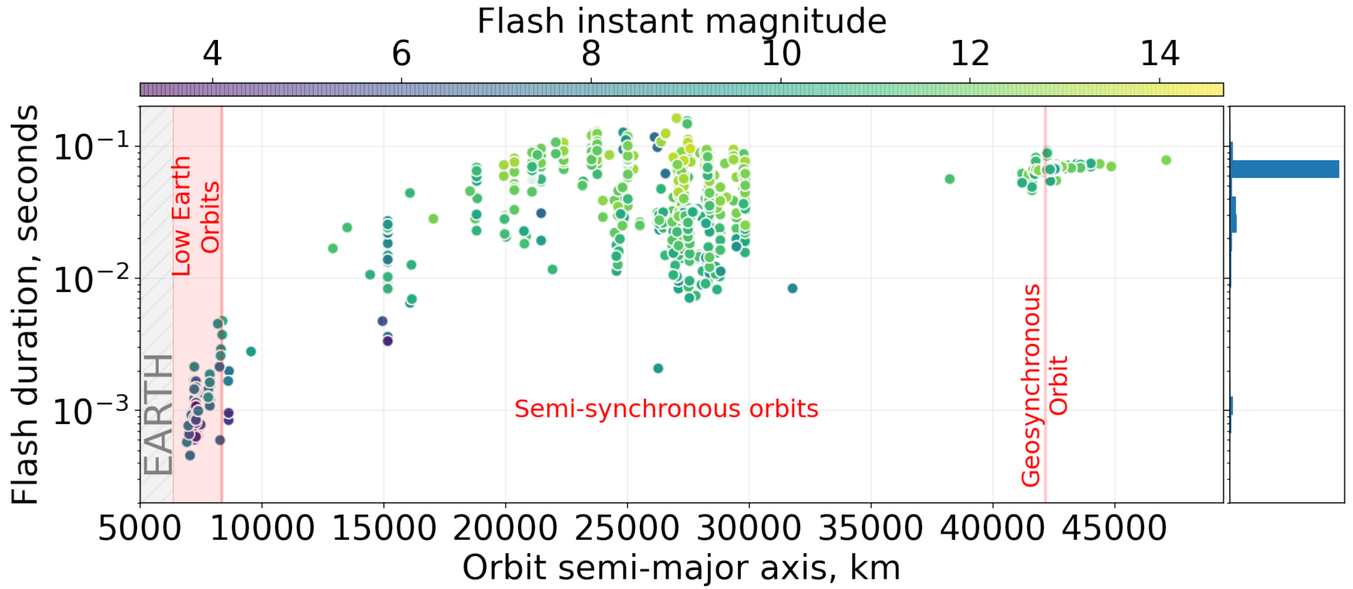





Number of candidates
10^4
10^3
10^2
10^1
10^0
All candidates
Two or more peaks
Matched with satellites
Tracklets
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
RealBogus quality score (rb)

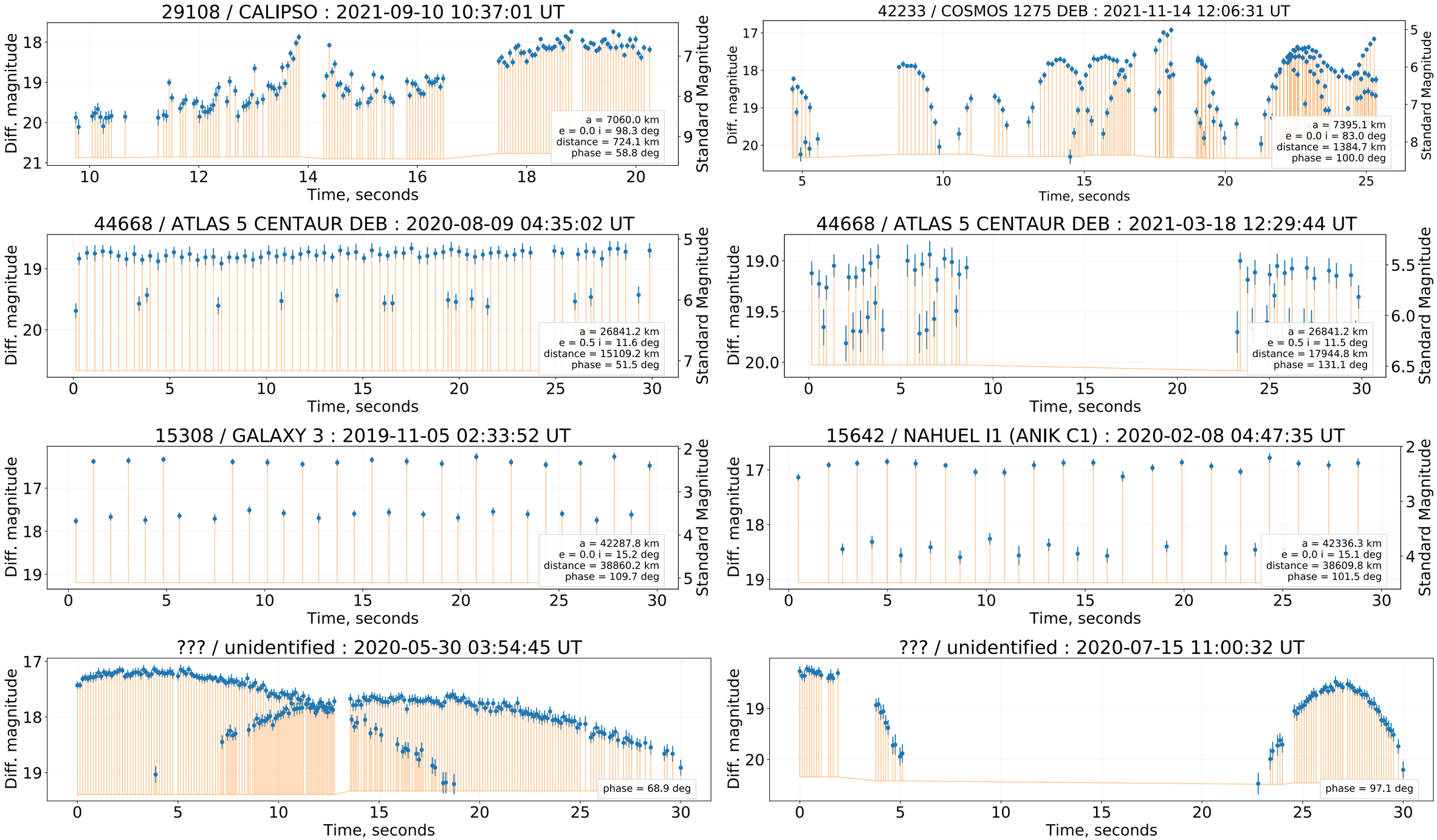

Number of candidates
10^5
10^3
10^1
All candidates
Two or more peaks
Matched with satellites
Tracklets
12
14
16
18
20
Differential PSF magnitude





Temporal properties

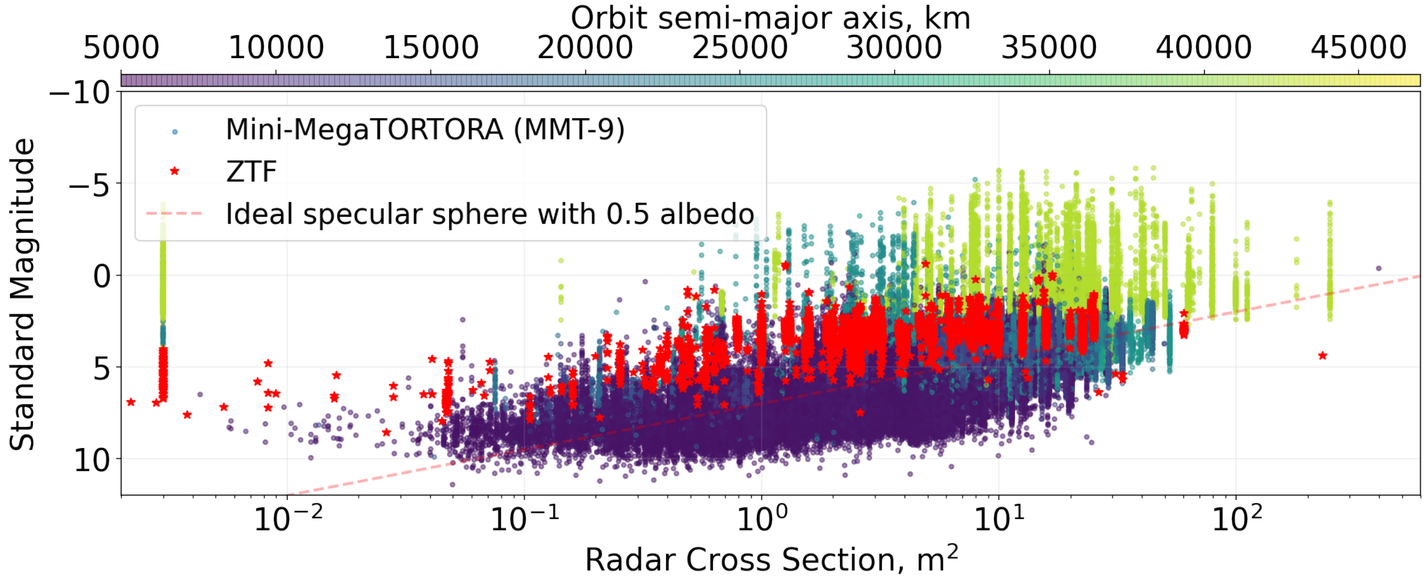
- association with known satellites gives true arc length
- distance between peaks / events gives period
- point-like shape gives flash durations / upper limits only!
- flash duration gives "instant" flash magnitude

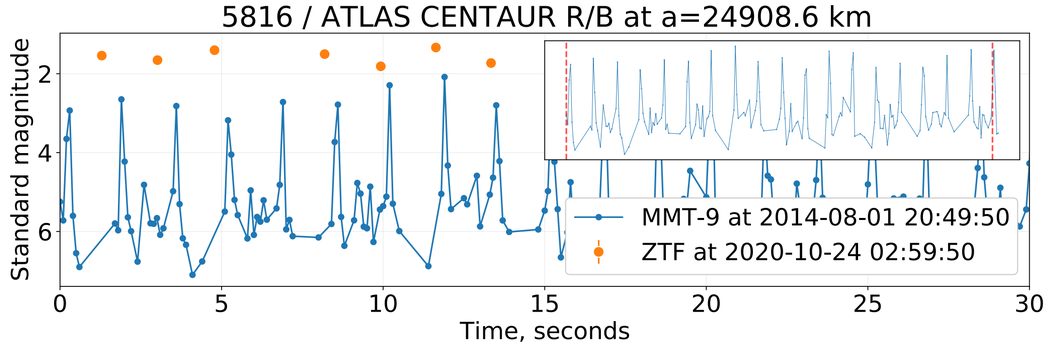

29108 / CALIPSO : 2021-09-10 10:37:01 UT
a = 7060.0 km
e = 0.0 i = 98.3 deg
distance = 724.1 km
phase = 58.8 deg
42233 / COSMOS 1275 DEB : 2021-11-14 12:06:31 UT
a = 7395.1 km
e = 0.0 i = 83.0 deg
distance = 1384.7 km
phase = 100.0 deg
44668 / ATLAS 5 CENTAUR DEB : 2020-08-09 04:35:02 UT
a = 26841.2 km
e = 0.5 i = 11.6 deg
distance = 15109.2 km
phase = 51.5 deg
44668 / ATLAS 5 CENTAUR DEB : 2021-03-18 12:29:44 UT
a = 26841.2 km
e = 0.5 i = 11.5 deg
distance = 17944.8 km
phase = 131.1 deg
15308 / GALAXY 3 : 2019-11-05 02:33:52 UT
a = 42287.8 km
e = 0.0 i = 15.2 deg
distance = 38860.2 km
phase = 109.7 deg
15642 / NAHUEL I1 (ANIK C1) : 2020-02-08 04:47:35 UT
a = 42336.3 km
e = 0.0 i = 15.1 deg
distance = 38609.8 km
phase = 101.5 deg
??? / unidentified : 2020-05-30 03:54:45 UT
phase = 68.9 deg
??? / unidentified : 2020-07-15 11:00:32 UT
phase = 97.1 deg
Diff. magnitude
Standard Magnitude
Time, seconds

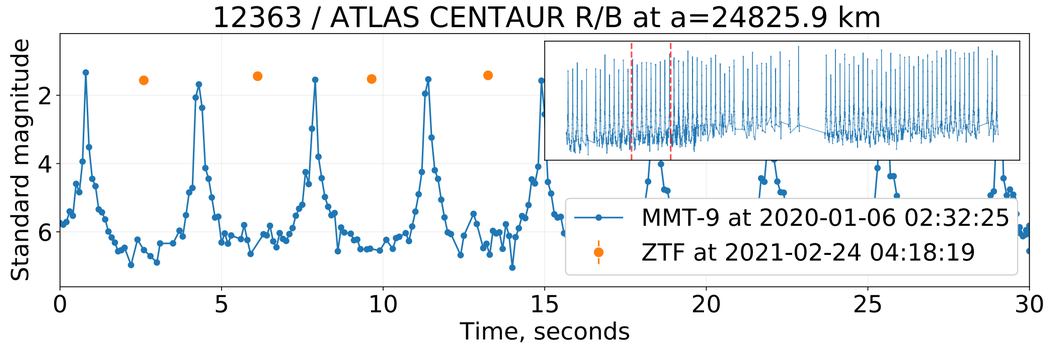
Brightness of the flares

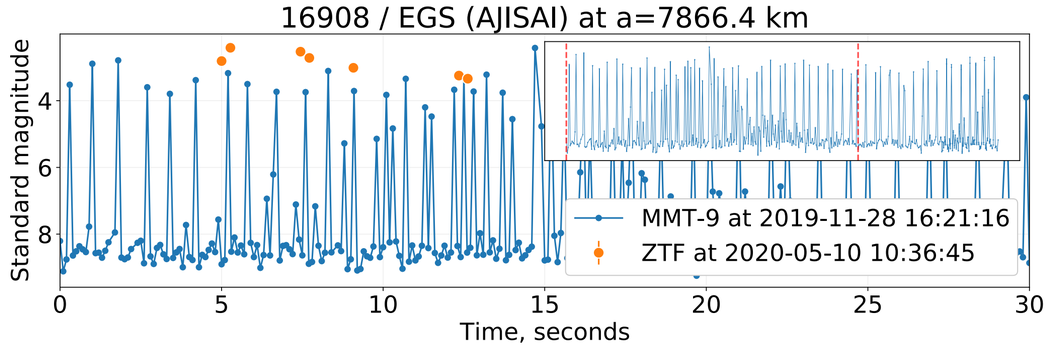
$$\mathrm{magpsf} = \mathrm{stdmag} + F(\phi) + 5\log\left(\frac{d}{1000\ \mathrm{km}}\right) - 2.5\log\left(\frac{\tau}{30\ \mathrm{s}}\right)$$

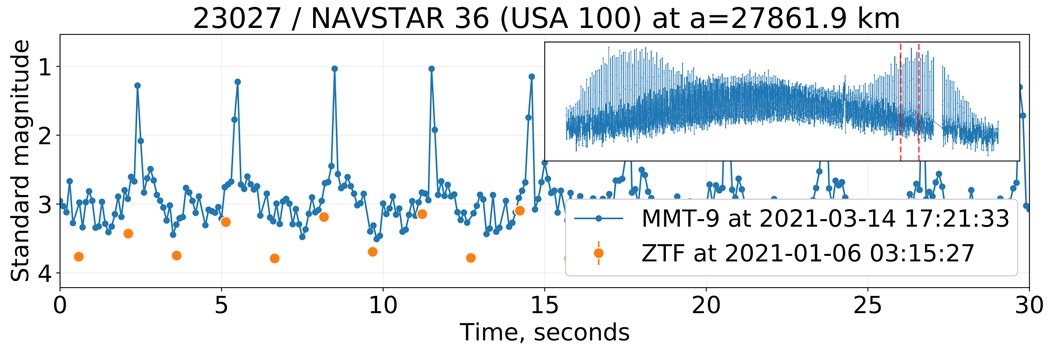
- distances from satellite associations
- durations from point-like shape
- high temporal resolution data from Mini-MegaTORTORA / MMT-9
  360,000 tracks of 9,500 satellites over 8 years, 10 fps, ~10 mag limit











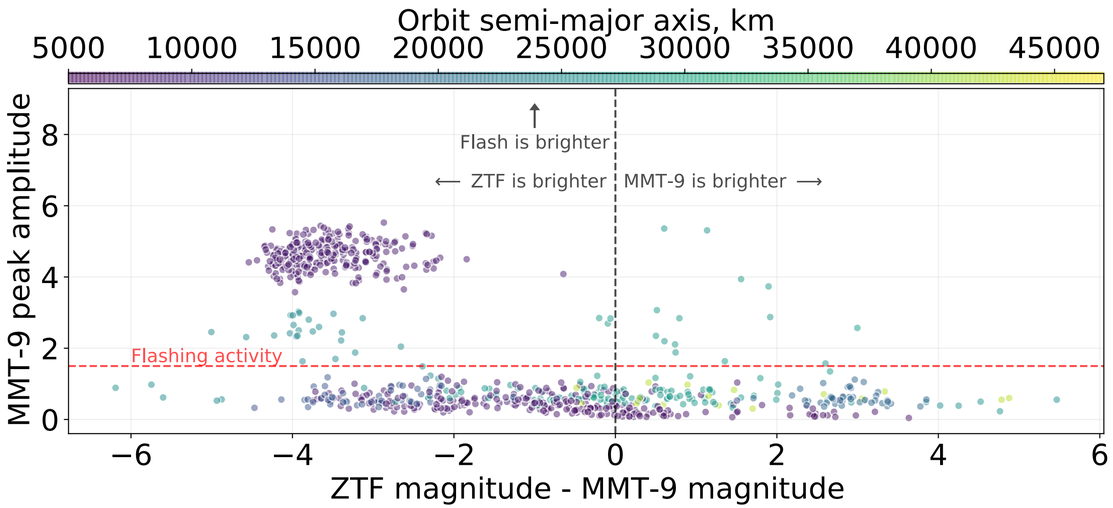


Figure 13. The amplitude of light curve peaks in Mini-MegaTORTORA (MMT-9) photometric database versus difference of their mean magnitudes as measured by ZTF and mean track magnitudes in Mini-MegaTORTORA data. For Mini-MegaTORTORA data, every individual track is considered individually to better accommodate for different observing conditions; also, the brightness corresponds mostly to the reflection from the main body of the satellite. For ZTF, on the other hand, just a single mean brightness value for every satellite is considered, and it corresponds to the peaks of the glints, i.e. the reflections from some specular reflective surfaces. We consider the satellite "flashing" in Mini-MegaTORTORA data if the peak amplitude is at least 1.5 magnitudes above the smoothed light curve trends. This division is shown with dashed red horizontal line.

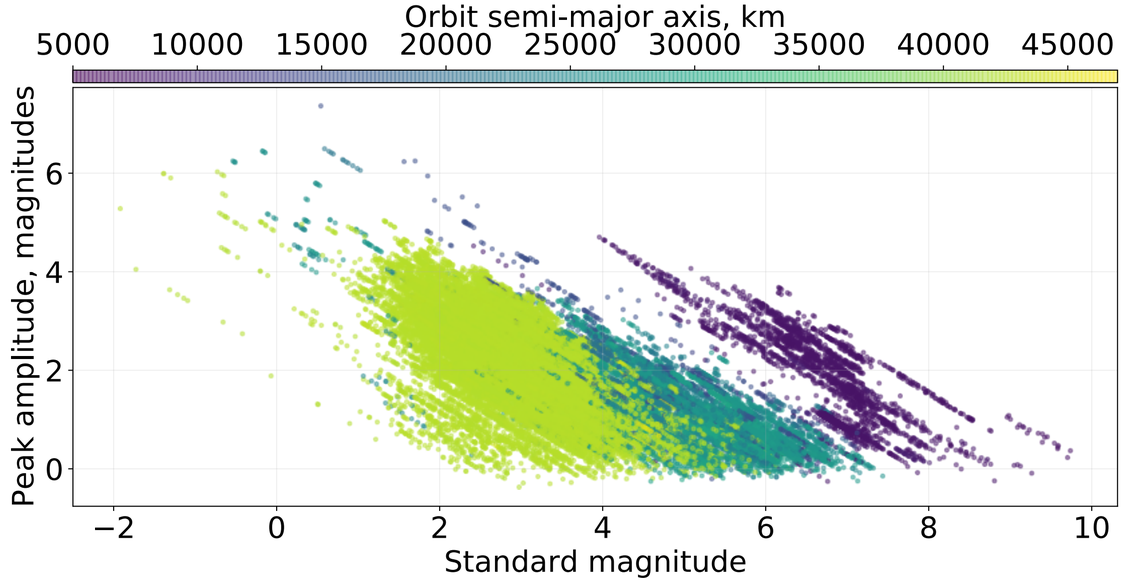


Figure 16. The amplitudes of light curve peaks in ZTF data for the events associated with known satellites as a function of their standard magnitudes and orbital parameters. The amplitudes are estimated from differential PSF magnitudes and differential detection limits of individual alerts, and are thus lower limits for actual flash amplitudes.

The flares have typical amplitudes of ~2-5 magnitudes above "quiescent" light curve

So what about LSST?..

- Visits are 2x15s, but only coadds will be analyzed
  so correction **apparent -> instant** magnitude will be the same

- Spatial resolution and seeing will be ~3-5 times better
  so **only shorter flashes** will still be point-like

- Pixel crossing time will be 2.5 times shorter
  so the "quiescent" trail will be **fainter by ~1 magnitude**

- Detection limit will be ~4 magnitudes better
  so the trail will be detectable at **~3 mag deeper**

- The trails are invisible in ZTF - so some will still be there?..