Catalina Sky Survey:

Imminent Impactor Detection and Follow-up Coordination

Eric J. Christensen

On behalf of CSS + NEOfixer

D. C. Fuls, A. R. Gibbs, S. M. Larson, R. L. Seaman, D. Fay, J. B. Fazekas, A. D. Grauer, B. Gray, H. Groeller, J. K. Hogan, R. A. Kowalski, G. J. Leonard, D. Rankin, A. Serrano, F. C. Shelly, J. Sosa, K. W. Wierzchos

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CSS: Imminent Impactors

- CSS attributes for impactor detection
  - Instrumentation
  - Operations model
  - Survey strategy
- 2022 WJ1: the CSS perspective
- NEOfixer follow-up broker

CSS attributes: instrumentation

- Simple cameras. G96 and 703 use single-detector, monolithic cameras (STA-1600 10560 x 10560 CCDs).
- 2x2 binning. Advantages are many:
  - Faster readout time for high open-shutter efficiency
  - Smaller file sizes, easier to process, transport and store
  - Larger pixel scales minimize trailing of nearby objects
  - CSS survey camera pixel scale ranges from 1.0” – 3.0” / pix
  - PSFs generally undersampled, but image quality is uniform across a range of typical seeing

CSS attributes: operations model

- Near real-time processing of survey data:
  - Multiple processing workstations located at the telescope
  - Fully processed ~5 minutes after last image readout
- Expert observers visually validating + reporting
  - Typical reporting latency for NEO candidates or follow-up tracklets is ~10 minutes after last image
- Built-in follow-up capability.
  - Dedicated follow-up telescopes available; survey telescopes can be re-tasked
  - Try to get a 2+ hour arc on all same-night discoveries, and additional obs on very fast (>10 deg/day) NEO candidates
  - Impact probability (IP) can be very low for an impactor’s discovery tracklet. Follow-up quickly exposes higher IP

CSS attributes: cadence + detection

- Survey fields get 4 visits, revisit interval (TTI) of ~8 minutes. Discovery tracklets are short, <30 min.
- Lunation plan for G96:
  - +60 to -25 Declination, solar elongation >80 deg. (12 nights)
  - Additional survey sets at evening and morning near-Sun sweet spots (~2 nights)
  - ”Opposition blitz” campaigns: (4 nights/lunation)
- Detection software tuned to maximize efficiency at ~1 deg/day (for H<22 NEOs), but sensitive from ~0.1 – ~15 deg/day.
- Detection software tolerates significant acceleration or centroiding errors
- No trail-fitting (yet)

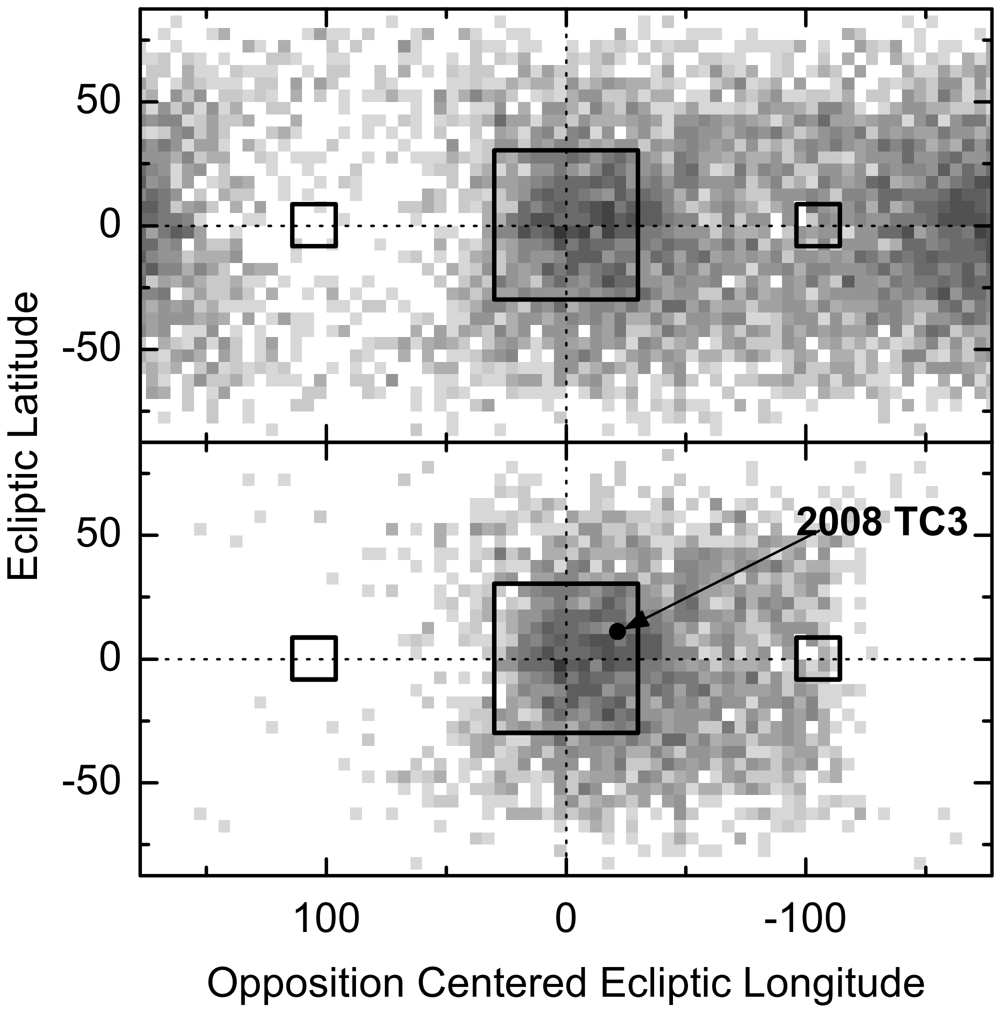
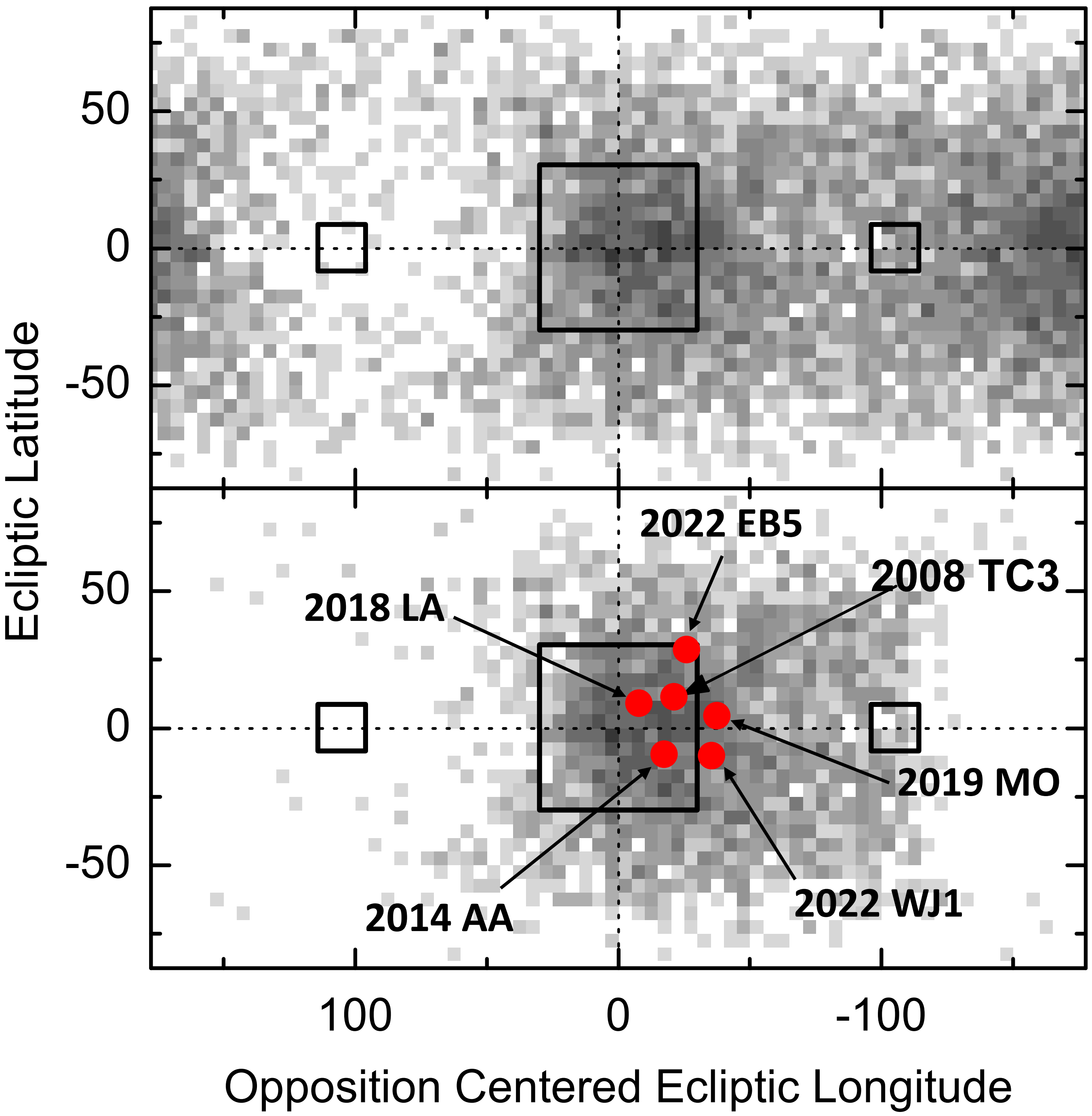


Fig. 14.— (*top*) Sky-plane probability distribution for 3 m diameter impactors (bolides) 1 day before impact with no restrictions on brightness and apparent motion. (*bottom*) Same as above but with $V < 22.7$ and apparent motion < 12 deg/day. Approximate PS1 search regions are shown as solid rectangles (the opposition region is in the center and the sweet spots are on the left and right). The position of 2008 TC_3 at discovery by the Catalina Sky Survey is highlighted.

Veres et. al (2009) told us where to look for imminent impactors (Fig. 14 from *Detection of Earth-impacting asteroids with the next generation all-sky surveys)*

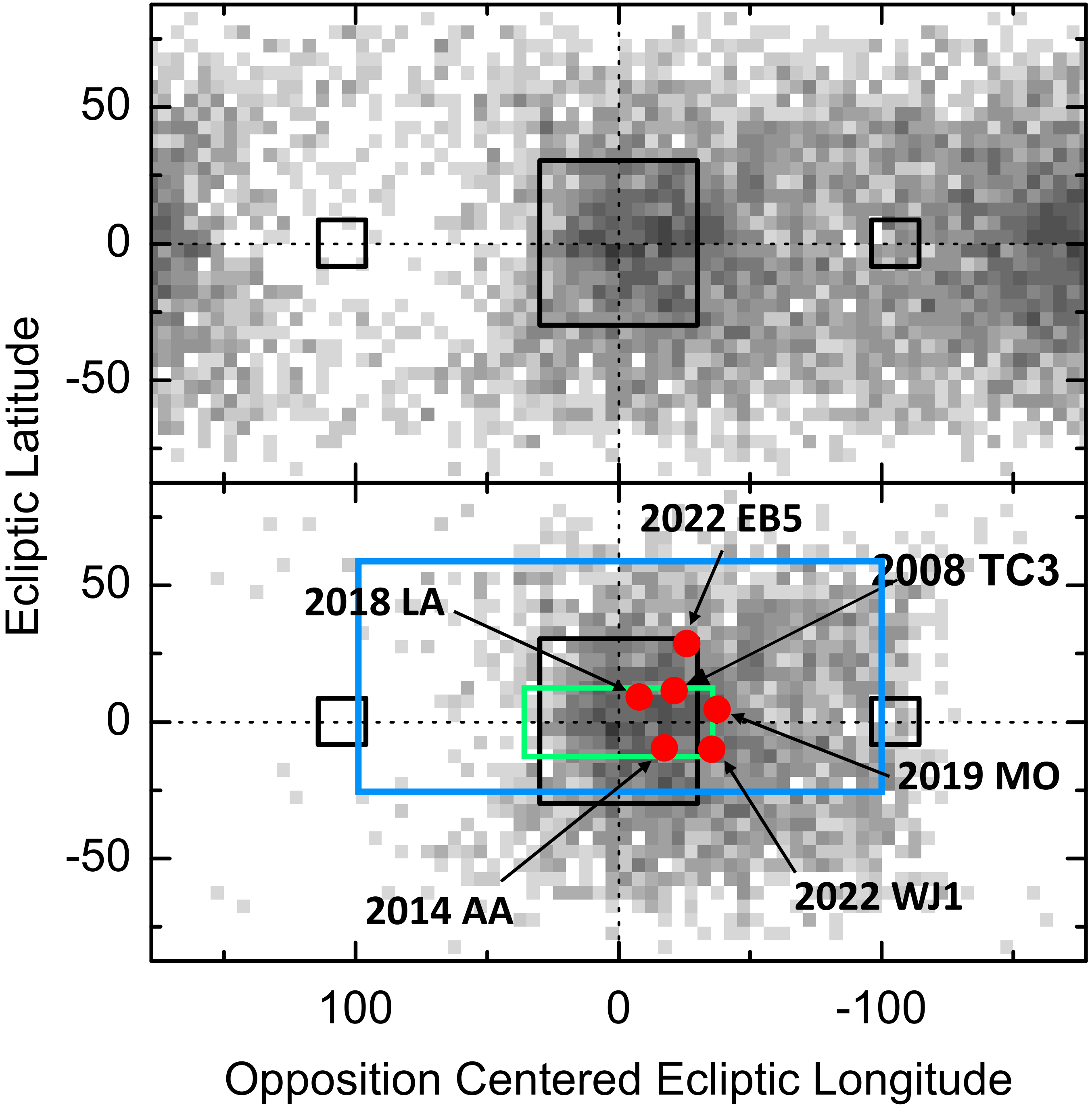
Bright imminent impactors cluster near opposition westward of opposition



In 2022, we now have a sample size of 6!

All six impactors discovered within a ~1200 deg^2 area just west of opposition

All six impactors were V~19 or brighter at discovery



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Blue box shows G96 approximate monthly field of regard (~1x per lunation)

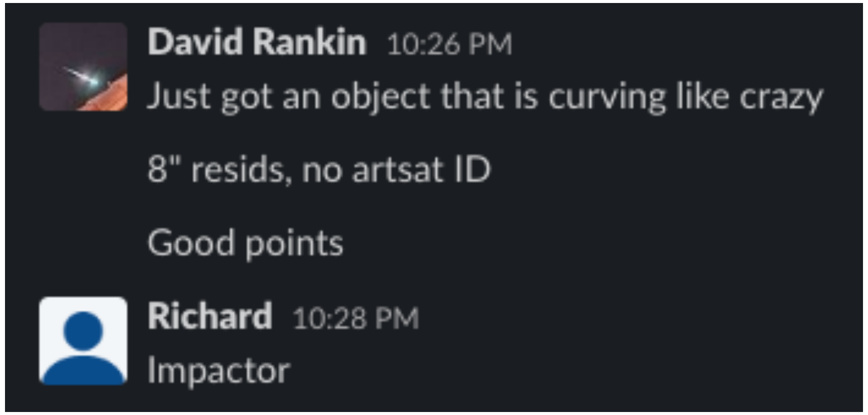
Green box shows G96 "opposition blitz" field of regard (additional ~2x per lunation)

2022 WJ1

- Successful imminent impactor scenario! Detection, follow-up, impact warning, some characterization observations(?), even warning people near the impact zone
- Additional serendipitous entry observations – all-sky and security cameras; falling meteorites detected by doppler weather radar
- First “real-time” impactor for CSS – Scout alert was published during the Arizona nighttime
  - CSS reported 6 additional tracklets (vs. 1-2 for previous impactors)
  - Collected 10-min time-series photometry sequence from I52, analysis ongoing
- CSS internal Slack channel was busy that night

2022 WJ1 timeline

- 04:53 - 05:18 - G96 survey images obtained
- 05:26 - G96 reports C8FF042



- 05:31 - C8FF042 posted to NEOCP
- 05:35 - first G96 follow-up begins
- 05:38 - first Scout alert received
- 05:40 - first G96 follow-up reported
- 05:44 - station 734 begins follow-up observations
- 05:47 - first NEOScan alert received
- 06:10 - Scout 1.00 impact probability alert received
- 06:24 - Public postings to neo-observe and mpml
- 06:25 - reported from Schmidt - untargeted detection
- 06:38 - initiated handoff to ATLAS
- …….. - additional obs from H36, U52, G96, T12, I41
- 08:28 - impact near Brantford, Ontario, Canada

Where are the meteorites? Infrasound detection? Any other unpublished data?

NEOfixer https://neofixer.arizona.edu

- NEOfixer is a NEO follow-up brokering service for observers
- NEOfixer goals:
  - Improve the NEO orbit catalog, from a planetary defense perspective
  - Provide NEO follow-up observers with current customized recommendations
  - Foster coordination among follow-up observers
- NEOfixer considers and scores all cataloged NEOs and all NEOCP/PCCP objects
- Object priorities are dynamic, changing throughout the night
- Orbits, ephemerides + uncertainties are independently calculated by Find_Orb

NEOfixer

Targets Status FAQ API Contact eric Log out Register Search site

Targets (I52)

Filters: Showing 1 to 100 of 1,651 entries

Telescope: I52

Column visibility CSV Print PDF

Previous 1 2 3 4 5 … 17 Next

Show 100 entries

Search:

Packed	Object	Priority	Score	Cost (min)	Import	Urgency	RA (hr)	Dec. (°)	Mag. (V)	Uncert. (°)	Rate ("/min)	Elong. (°)	GC	Last Obs.	Arc Length	RMS (")	U	H	MOID (AU)	NEO	Impact	Status	Interest
C8L5CQ2	C8L5CQ2	critical	10.85	6	33	75.2	12:19:48	+51:12:42	19.6	1.0592	8.4	99	0	1.2d	2.2h	0.4	11.9	23.0	0.018	100	-	-	-
C8L5EE2	C8L5EE2	very high	8.42	6	71	1.9	23:17:39	+38:26:24	20.9	0.0498	4.5	104	2	11.5h	2.4h	0.2	12.4	21.7	0.005	96	-	-	-
P21CjeL	P21CjeL	very high	8.21	14	31	1.3	01:47:21	+44:09:39	20.9	0.2723	2.8	132	2	11d	3.1h	0.1	10.8	23.0	0.027	100	-	-	-
K21J04L	2021 JL4	high	7.88	10	35	0.8	07:57:49	-04:10:32	20.2	0.3347	6.1	133	2	1.5y	20d	0.3	7.1	23.2	0.010	100	-	-	-
K22W11U	2022 WU11	high	7.75	3	16	0.7	06:42:17	+38:33:39	19.5	0.0760	15.0	157	1	13d	2.0d	0.4	9.3	25.3	0.008	100	-	-	-
N00kxn7	N00kxn7	high	7.69	45	64	4.0	08:07:46	-37:01:54	17.8	2.0048	1.7	108	11	18d	12.5h	0.4	12.4	18.7	0.112	87	-	-	-
P11Coaw	P11Coaw	high	7.53	36	21	1.5	01:00:32	+35:04:11	21.8	0.4303	1.1	123	1	10d	4.1h	0.1	11.8	19.7	0.410	42	-	-	-
P21CnH6	P21CnH6	high	7.53	37	34	1.1	23:31:44	+34:51:17	21.9	0.2743	0.3	105	1	11d	3.1h	0.2	11.8	19.5	0.255	52	-	-	-
C8L5E52	C8L5E52	high	7.07	208	9	86.3	22:58:04	+39:30:43	21.2	5.3255	3.9	101	2	13.9h	0.5h	0.0	12.5	26.6	0.009	100	-	-	-
K20X01F	2020 XF1	high	7.00	122	23	1.0	23:51:59	+21:20:21	22.3	0.7432	5.0	105	0	1.9y	29d	0.4	7.3	21.7	0.183	100	-	-	-
K04G00A	2004 GA	med-high	6.93	34	64	0.2	06:44:58	+49:23:02	21.1	0.7325	0.9	149	1	18y	71d	0.5	5.3	20.2	0.048	100	-	-	-
K08V14G	2008 VG14	med-high	6.60	148	23	0.9	23:06:12	+04:59:08	22.5	0.6302	2.6	89	0	14y	53d	0.5	5.7	20.5	0.302	100	-	-	-
K18J00E	2018 JE	med-high	6.58	43	49	1.0	21:56:36	-10:29:00	22.1	0.0655	2.7	67	0	4.5y	47d	0.4	5.7	20.9	0.058	100	-	-	-
mor1426	mor1426	med-high	6.58	26	11	0.3	05:06:31	+11:02:10	21.3	0.2892	0.5	168	2	11d	1.2d	0.5	11.3	22.5	0.328	46	-	-	-
K22W08T	2022 WT8	med-high	6.55	2	25	0.5	08:33:28	+40:20:31	19.9	0.0031	3.2	136	0	13d	2.0d	0.2	9.1	21.5	0.170	100	-	-	-
K21L04J	2021 LJ4	med-high	6.49	394	45	0.2	13:37:59	-17:22:54	22.1	0.7712	2.3	52	1	1.5y	4.3d	0.1	9.3	20.0	0.129	100	-	-	-
K21X04S	2021 XS4	med-high	6.45	146	9	1.9	07:53:27	-11:17:21	20.7	2.2429	21.0	129	4	1.0y	3.9d	0.3	7.2	26.0	0.032	100	-	-	-
K01R17X	2001 RX17	med-high	6.43	81	26	1.0	23:40:03	-17:07:45	22.3	0.2351	2.4	88	0	21y	119d	0.5	4.8	20.5	0.258	100	-	-	-
K18R08R	2018 RR8	med-high	6.37	142	36	1.0	22:22:34	-21:23:03	22.5	0.1716	2.2	69	0	4.1y	54d	0.3	6.0	19.2	0.251	100	-	-	-
C8L4RT2	C8L4RT2	med-high	6.36	5	11	0.7	01:25:41	+47:29:19	20.4	0.0095	14.0	128	2	14.2h	21.1h	0.3	8.6	26.1	0.012	100	-	-	-
K15HH1P	2015 HP171	med-high	6.32	22	36	1.0	23:01:50	-25:51:22	21.7	0.0410	4.2	76	0	7.0y	220d	0.4	4.5	20.1	0.188	100	-	-	-
K22X00Q	2022 XQ	med-high	6.28	3	38	1.4	14:01:02	+49:24:56	20.4	0.0005	16.8	85	0	2.7d	8.6d	0.3	9.9	21.9	0.046	100	-	-	-

NEOfixer Object pages

- Each object has a page with:
  - Plot showing NEOfixer priority score and sub-scores for the next week
  - Orbital elements from Find_Orb
  - Scoring breakdown
  - Ephemeris
  - Benefit plot
  - Observations
  - Residuals
  - Orbit viewer
- Site (500) has all objects; topocentric sites only link to objects visible from that site

NEOfixer communication

- Primarily geared toward NEO follow-up observers, but site is open to the public
- Create and account and input site, telescope and instrumentation information for customized results
- Website is configurable – filters, columns, ordering
- API also available to programmatically fetch recommended target names, ephemerides, uncertainty information, exposure times
- Primary data source is MPC-provided astrometry. Auxiliary data sources include Scout, Sentry, NHATS, JPL radar astrometry.
- Other sources can be added (e.g. other impact monitoring services)
- Sites can communicate observing status (may observe, will observe, observing, observed, reported, canceled). Status messages change objects' priority for other sites

NEOfixer scoring

Calculate and combine *five independent quantities*:

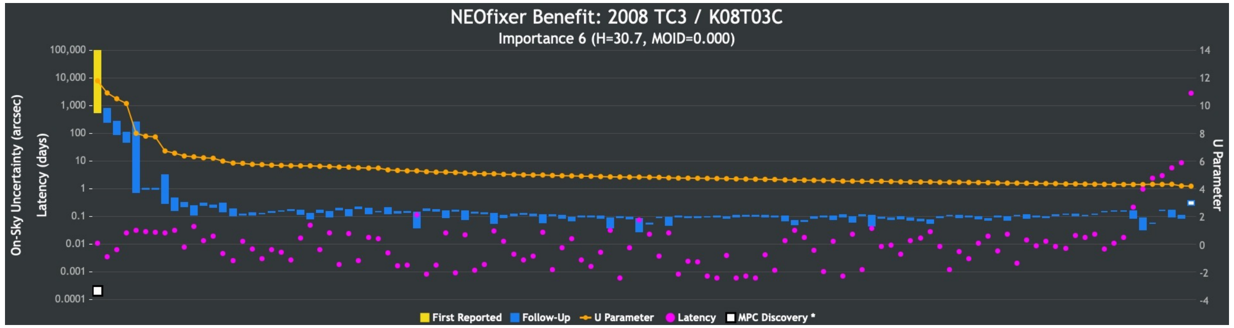
Per object:

- Importance of each NEO / NEOCP object
  - How large (H); how close (MOID), potential impacts or other interest?
- Confidence that the object exists + linkage is correct
  - How reputable is the submitter; confirming observations?

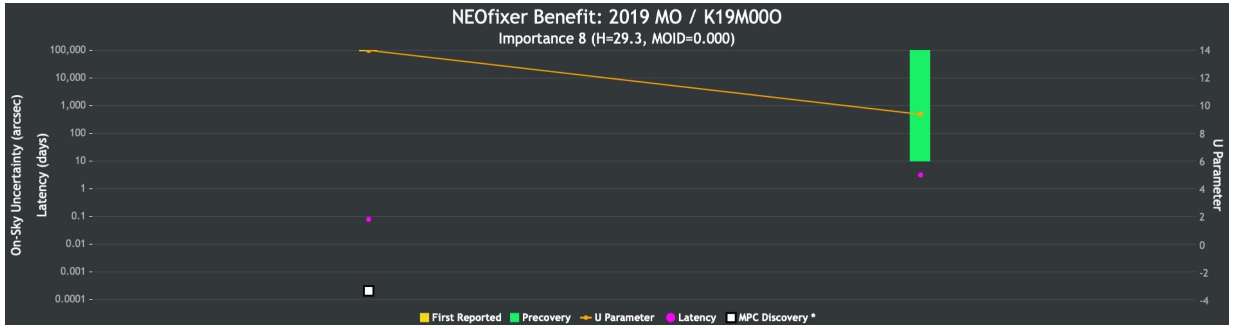
Per observation:

- Cost to observe
  - Calculated per telescope+instrument+site combination
- Benefit to object's orbit
  - Sky-plane uncertainty as a proxy for orbital uncertainty
- Urgency to observe
  - Becoming easier or more difficult to observe? What are other sites' intentions?

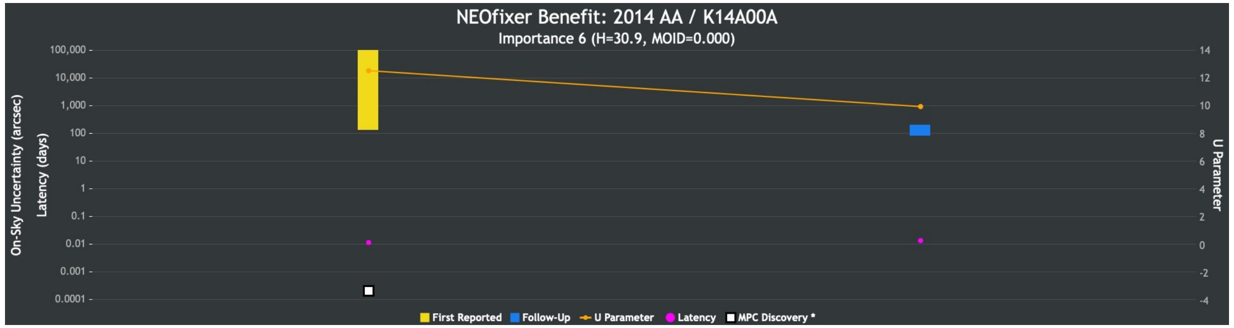
2008 TC3 – impact alert somewhat delayed



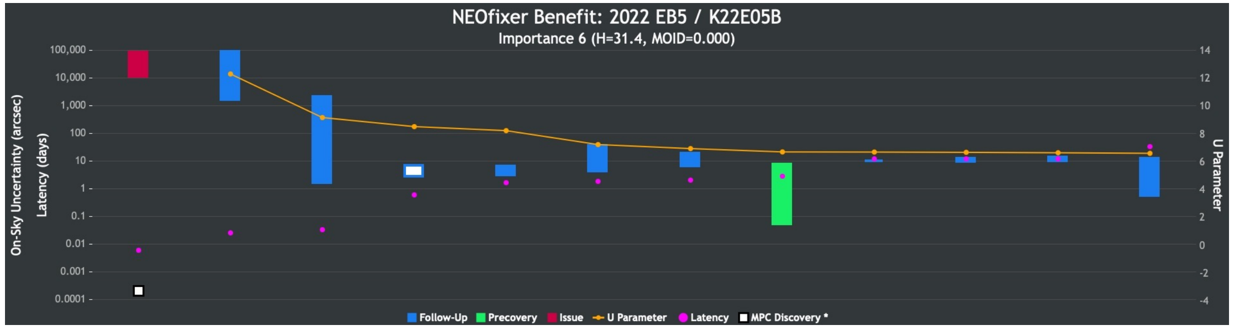
2019 MO – no impact alert



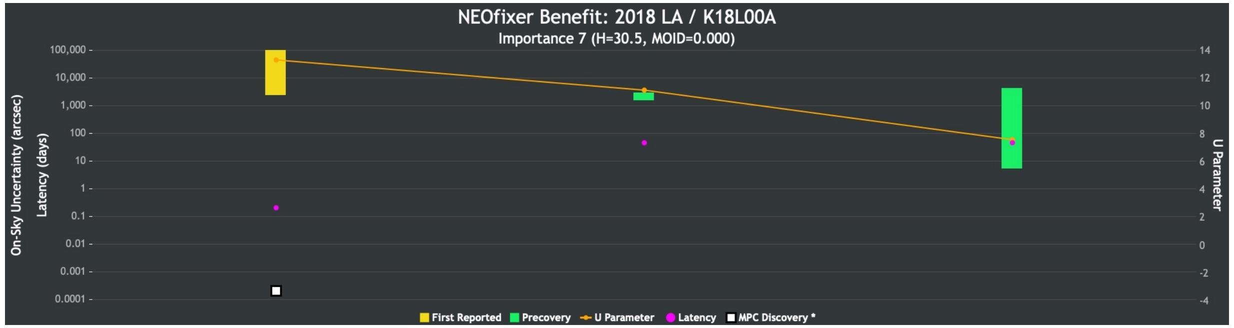
2014 AA – impact alert delayed



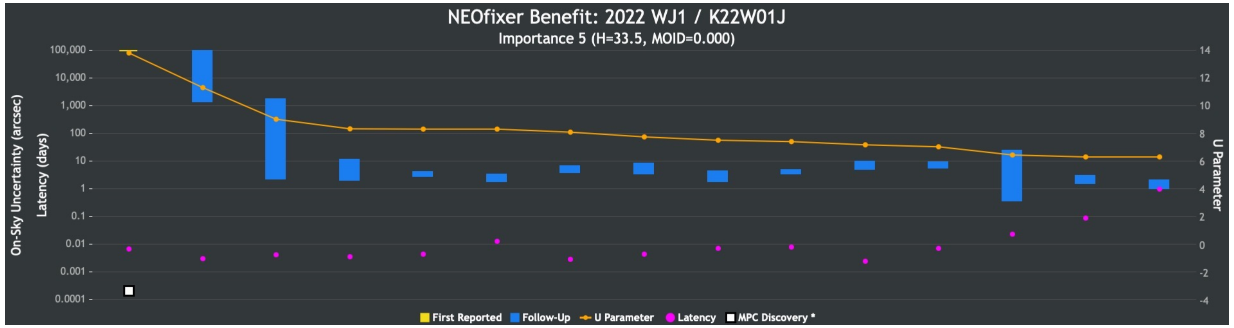
2022 EB5 – prompt impact alert



2018 LA – impact alert delayed



2022 WJ1 – prompt impact alert



Conclusion

- CSS survey design enables imminent impactor detection
  - Prompt processing, validation and reporting
  - Sensitive to accelerating objects
  - Frequent visits to area west of opposition
- NEOfixer (https://neofixer.arizona.edu):
  - Customized NEO follow-up recommendations for any observer
  - Follow-up coordination framework
  - Imminent impactors are elevated in priority
- Contact me at eric@arizona.edu for questions about CSS, NEOfixer, or to be added to the neo-observe@list.arizona.edu email list