Two detections per night:

Implementing LSST's audacious asteroid-finding paradigm

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While most asteroid surveys aim to image each survey field four times per night, the Vera Rubin Observatory's Legacy Survey of Space and Time (LSST) cadence of two repeat visits per night cannot confidently identify new asteroids in a single night's data. Instead, an asteroid must be linked across several nights before it can be discovered. This multi-night discovery paradigm requires new algorithms, methods, and substantially greater computing resources. Four images per night is an established standard for good reason, and surveys that use it will continue to make important contributions in the LSST era. But in spite of serious challenges, the LSST's aggressive new strategy has been successfully implemented. We describe these challenges and innovations, the intrinsic limitations of multi-night linking, and the first NEO discoveries with two-detection-per-night linking.

Processing in three phases

1 **Tracklet creation** using `make_tracklets`

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'tracklets' (single-night linkages)
Mostly 'pairs' (2-point tracklets)
Time span typically ~ 1 hour
Overlap allowed
No expectation of purity
Nearly all not real

↓

2 **Multi-night linking** using `heliolinc`

↓

multi-night linkages
At least 6-8 points
Time span up to 14 days
Overlap allowed
No expectation of purity
No orbit fits, many not real

↓

3 **Post-processing** using `link_planarity`

↓

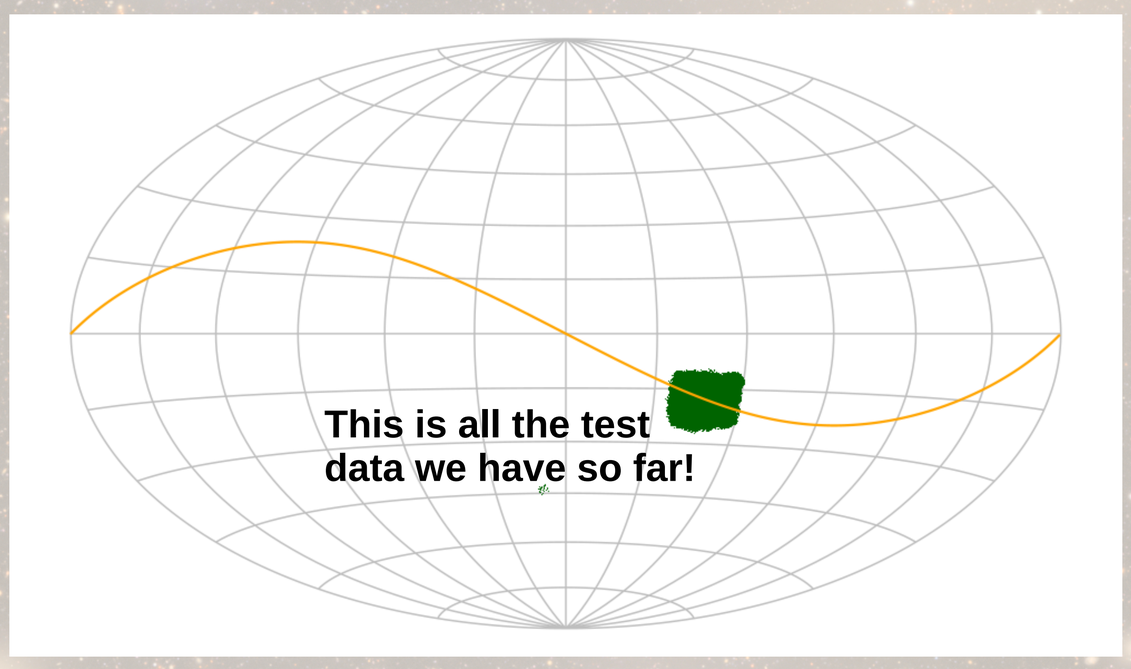
Purified linkages from heliolinc
No overlap allowed
Expected to be pure
Keplerian orbit with small residuals
Genuine asteroid discoveries!

Challenges

- **Multi-night linking of asteroids detected only twice per night is the main pathway for LSST asteroid discovery.**
- **This discovery pathway has never before been demonstrated at scale on real data.**
- **There has been real uncertainty about whether it is possible.**
- **LSST's 'minimal discovery criterion' of two detections per night over three nights within a 14-day period ('2×3 in 14') may produce too many false discoveries. Quantifying the false-positive rates with LSST-grade data is our top priority.**
- **Candidate linkages must be vetted (and iteratively purified of spurious detections that appear as astrometric outliers) using computationally expensive orbit-fitting.**

Innovations

- **Use of a 6-D rather than a 4-D parameter space reduces false discoveries.**
- **Fully Keplerian as opposed to approximate quadratic hypotheses for `heliolinc`.**
- **Initial round of purification using inferred coplanarity of linked detections rather than expensive orbit-fitting [our `link_planarity` algorithm].**
- **We can rescue the two-detections-per-night paradigm from its false discovery rate by requiring four nights of observations rather than just three – a ('2×4 in 14') discovery criterion.**



Limitations of available test data

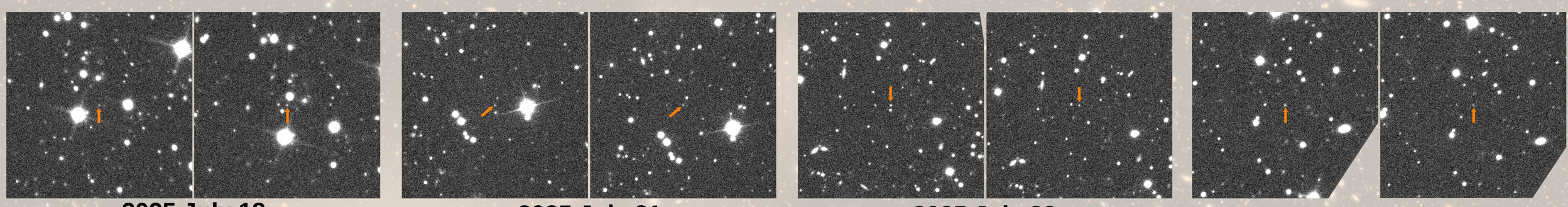
- **Winter weather, tests of other systems, and upstream processing delays impose limitations.**
- **Viable test data covers only the green area in the sky map at left.**
- **Even within this area, gaps in cadence and coverage make some nights unusable.**
- **Most images below design sensitivity (but this is improving as the the Active Optics System is tuned).**

Intrinsic limitations of multi-night linking

- **Computationally intensive!**
- **More vulnerable to confusion.**
- **Sensitivity landscape more complex, hard to predict.**
- **Not sensitive to NEOs with brief encounters / very high velocities.**
- **More vulnerable to weather.**
- **LSST will be great, but ongoing successful surveys should <u>not</u> switch to an LSST-like cadence.**

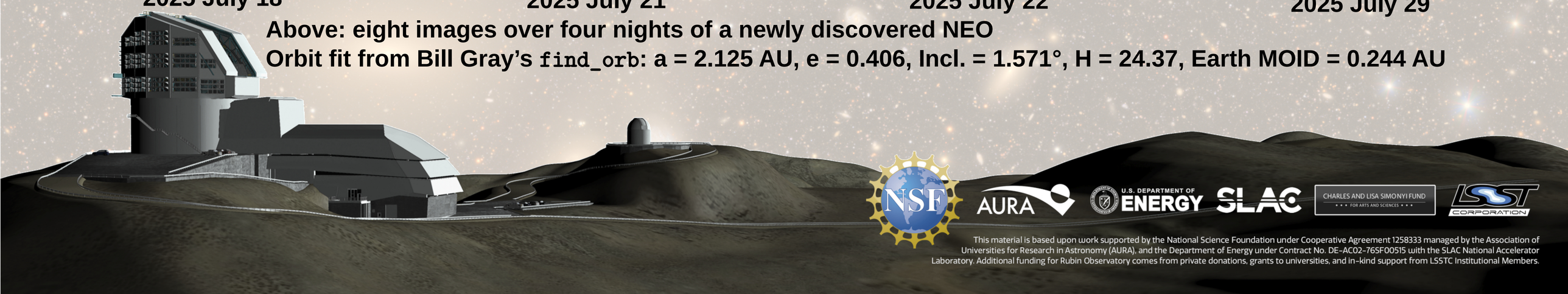
Results

- **Using two-detection-per-night linking on real Rubin data, we have made 4-night linkages of 23000 candidate asteroids and 3-night linkages of 8800 more.** (Note: many of these linkages include some nights with more than two detections. However, 6444 linkages comprise <u>exclusively</u> two-detection nights, and for 10608 linkages a majority of nights have just two detections.)
- **Purity appears to be 100% for four-night ('2×4 in 14') linkages.**
- **4687 four-night objects including four NEOs (images of one of them below) appear to be new discoveries.**
- **These are the <u>first ever NEO discoveries</u> to be found by multi-night linking of data with only t<u>wo detections per night.</u>**



2025 July 18 | 2025 July 21 | 2025 July 22 | 2025 July 29

Above: eight images over four nights of a newly discovered NEO
Orbit fit from Bill Gray's `find_orb`: a = 2.125 AU, e = 0.406, Incl. = 1.571°, H = 24.37, Earth MOID = 0.244 AU



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