HelioLinc3D: Advances and Challenges in Multi-night Asteroid Linking

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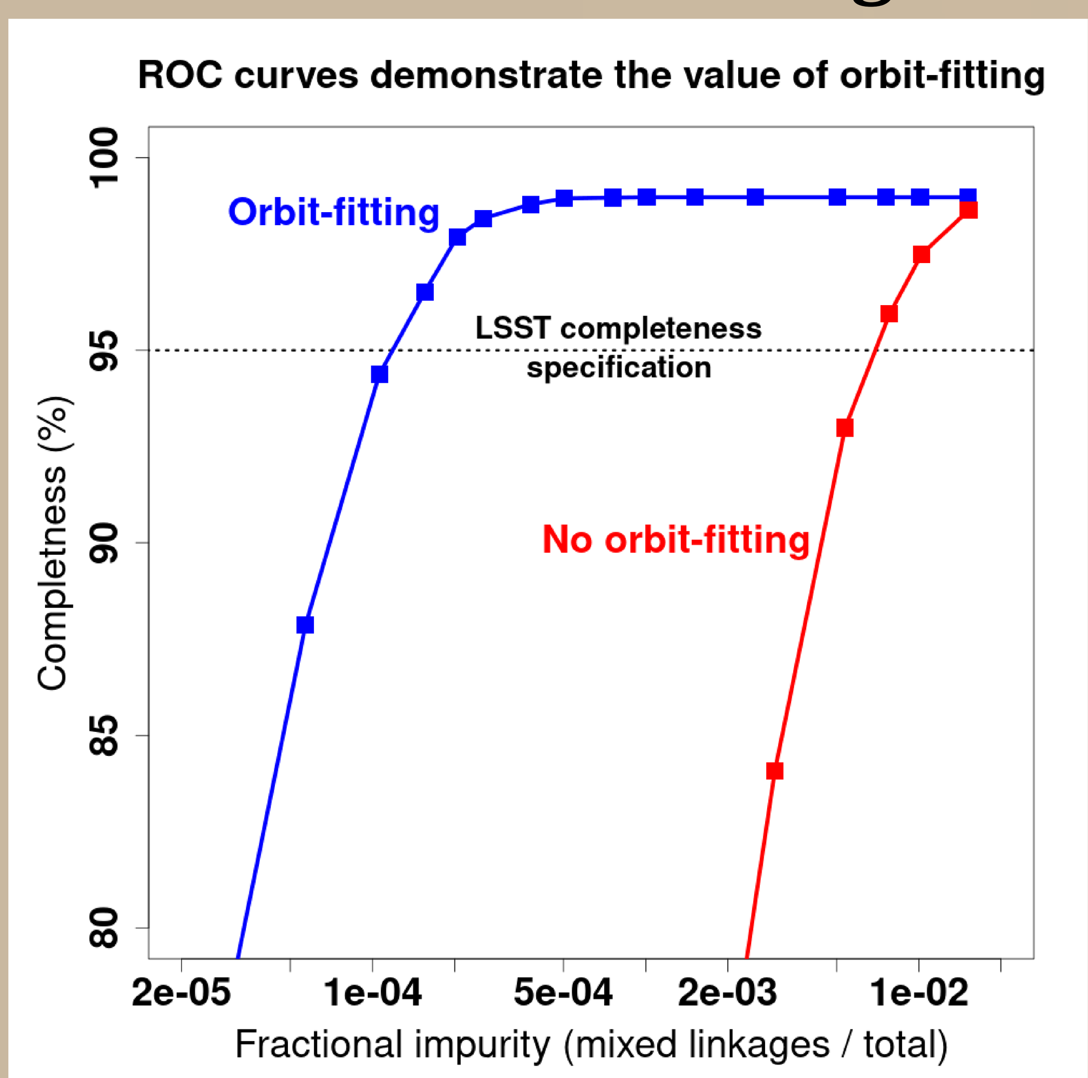
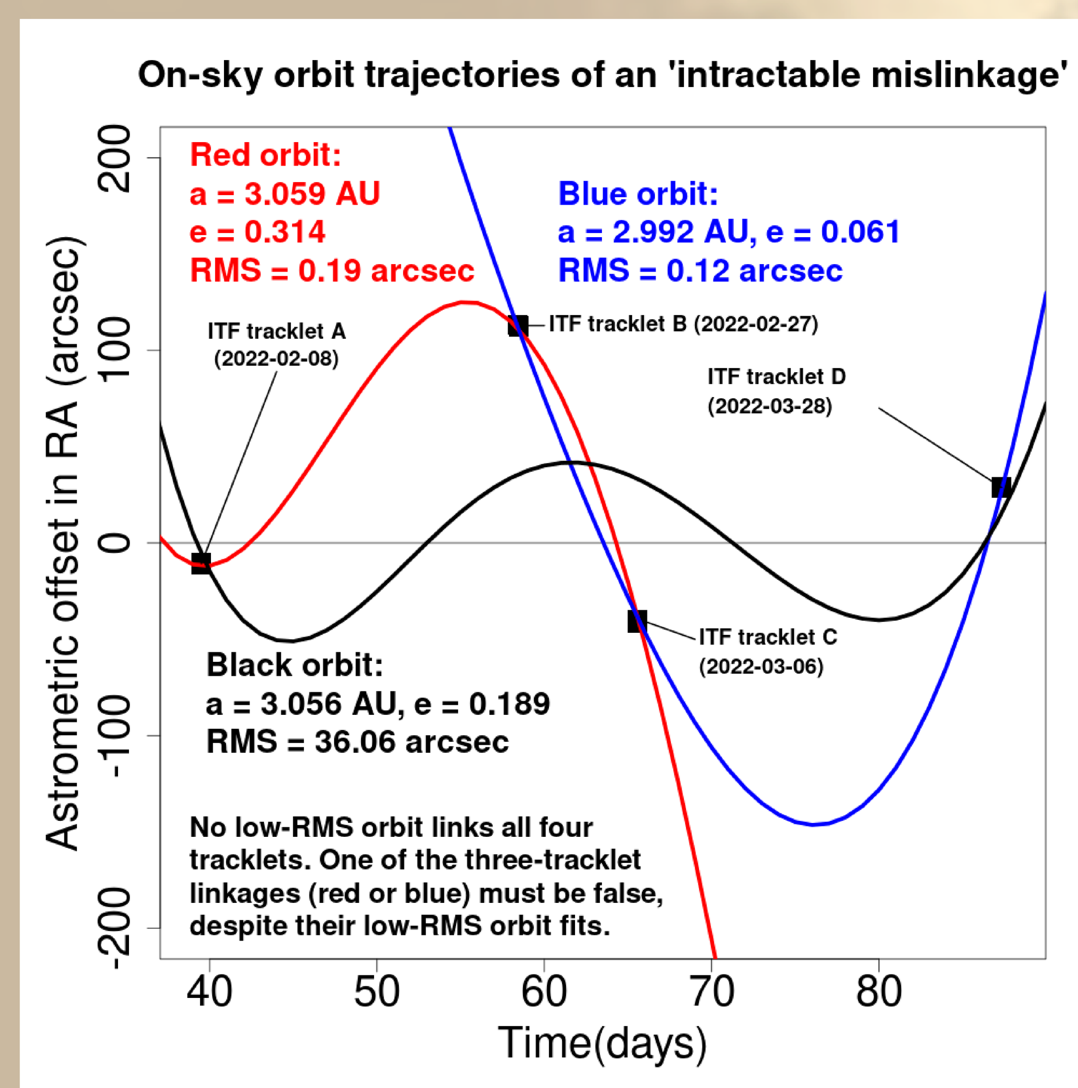
The HelioLinc3D algorithm we have implemented in C++ solves the multi-night asteroid linking problem for LSST, surpassing the 95% completeness specification for both NEOs and main belt asteroids in simulated data. Since last year's release of a beta version on GitHub (https://github.com/lsst-dm/heliolinc2), we have added fast orbit-fitting for all candidate linkages at the de-duplication stage. This improves the ROC (completeness vs. impurity) curve, enabling much higher purity at the same completeness. Tests on real data confirm the algorithm's ability to discover asteroids: in ATLAS data we found a new PHA, 2022 SF289, the first NEO discovered with any form of HelioLinC. In the Isolated Tracklet File (ITF) we have identified hundreds of four-tracklet linkages, while two that we submitted as a test were confirmed by the MPC as new main belt asteroids 2022 AM51 and 2022 BK62. Rare false linkages identified in the ITF are not failures of HelioLinc3D but algorithm-independent 'intractable' mislinkages: they contain measurements of two different asteroids but can nevertheless be fit with an orbit that is statistically indistinguishable from fits to correct single-object linkages. Although no criteria can distinguish them definitively from good linkages, intractable mislinkages are more likely to have uneven sampling in time, large brightness variation, and high-eccentricity orbit fits.

Orbit-fitting



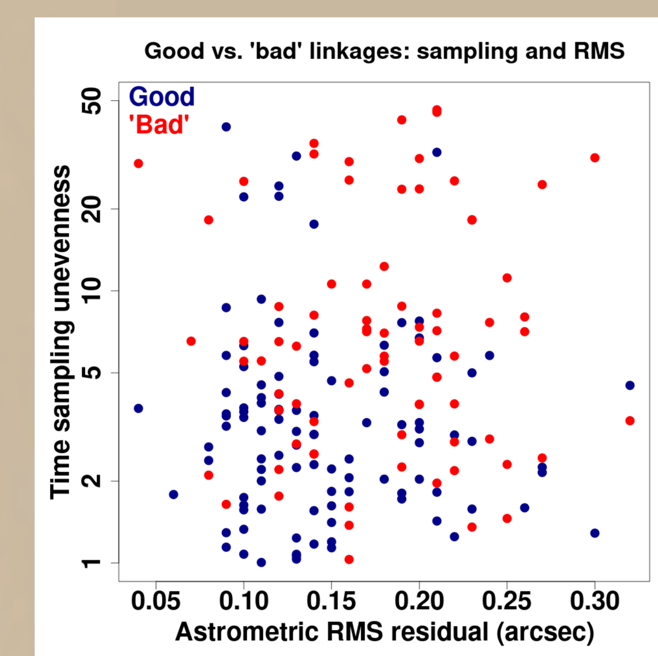
LEFT: Post-processing of HelioLinc3D output is required to remove duplicate (overlapping) and spurious linkages. Our new post-processing code employs fast orbit fitting via the Method of Herget, and uses the astrometric RMS residual of the fit as the main component of its quality metric. This plot, based on simulated LSST observations of mostly main-belt asteroids, shows how the new code with orbit-fitting enables high completeness with far fewer false (mixed) linkages.

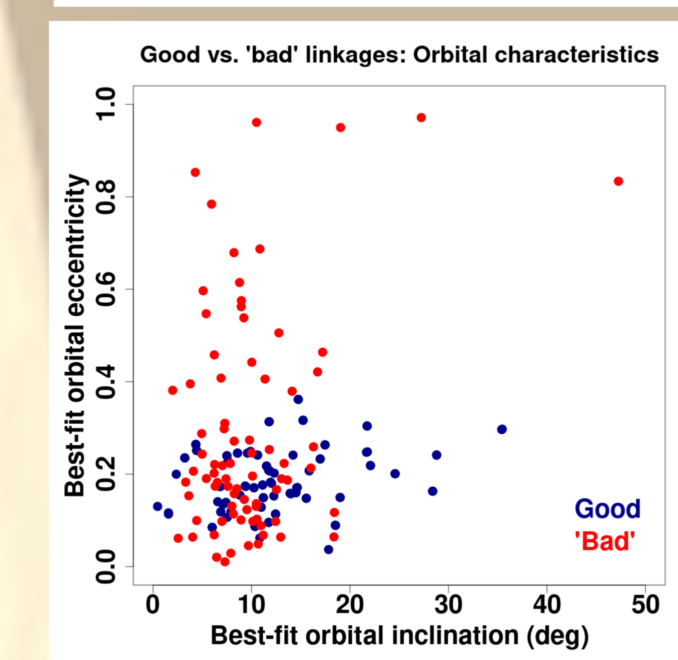
Intractable mislinkages

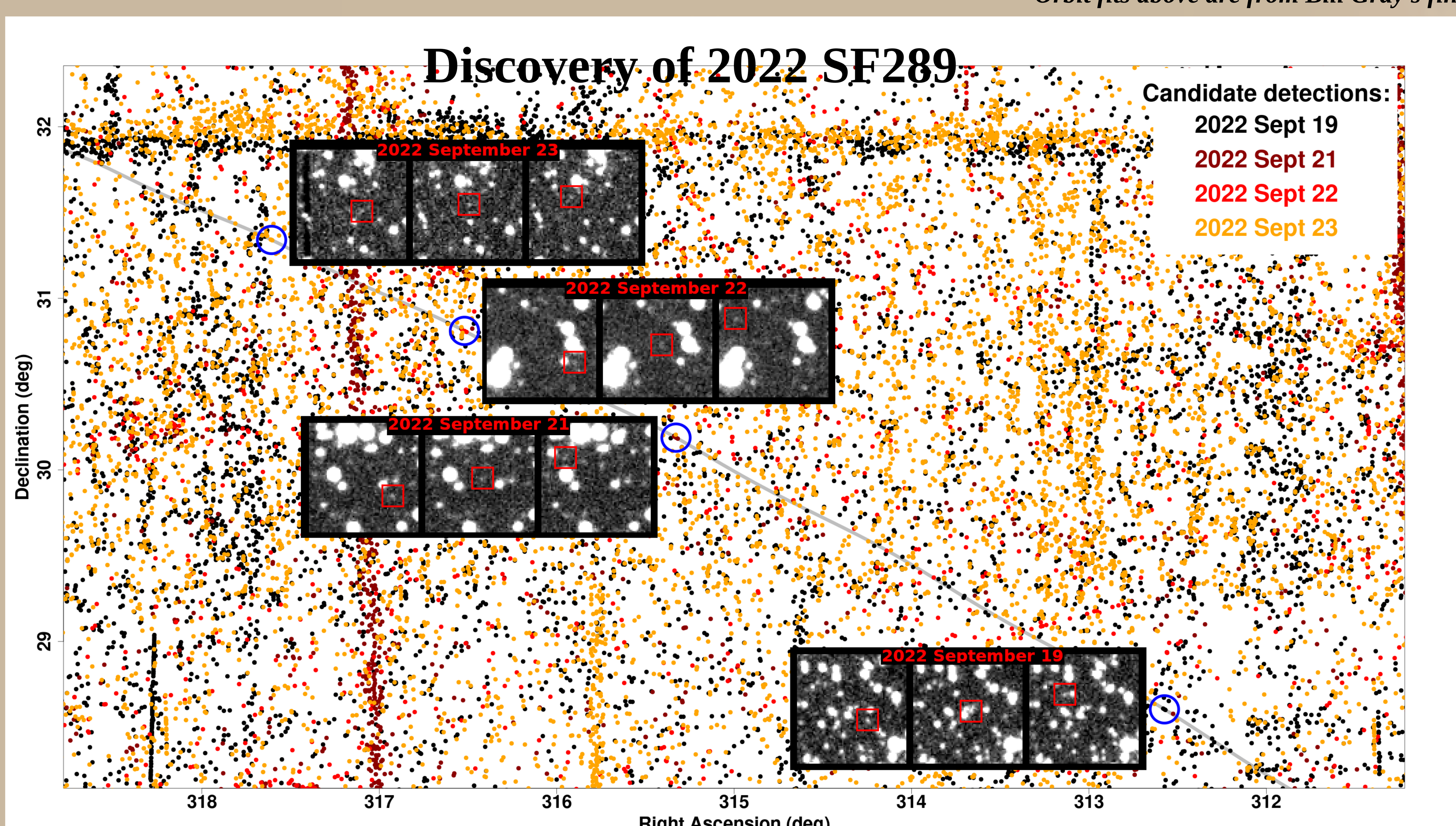


LEFT: Among the few false linkages that remain, a significant fraction are 'intractable', meaning that (even though false) they can be fit with a physically reasonable orbit with low RMS residuals. The plot at left illustrates a case of this type from the MPC's isolated tracklet file (ITF). Tracklets A, B, and C can be linked with a low-RMS orbit fit, as can tracklets B, C, and D – but the best-fit orbit to the merged linkage ABCD has impossibly bad astrometric residuals. This proves that one at least of the linkages ABC and BCD must be false – but this is not a flaw in HelioLinc3D because the linkage is actually consistent with a physical orbit, even though it is false.

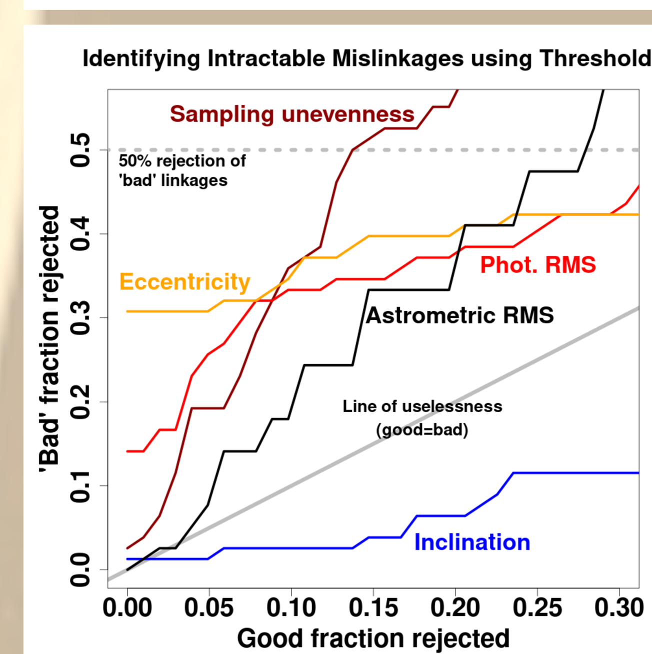
Orbit fits above are from Bill Gray's find_orb.





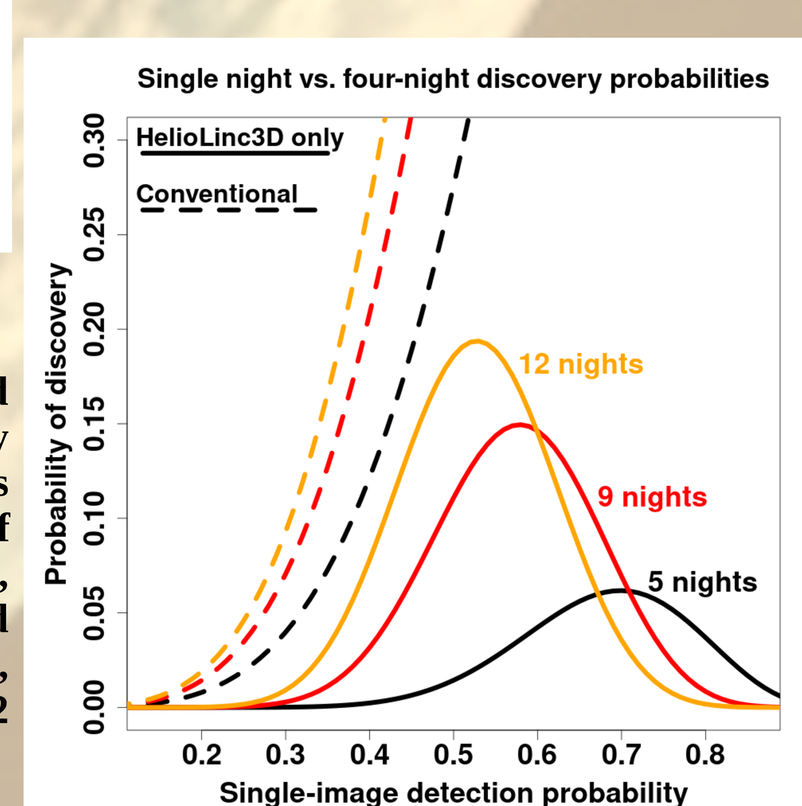


ABOVE: We used HelioLinc3D to discover a new PHA, 2022 SF289, in archival data from the ATLAS survey. Our discovery linkage included four tracklets, each containing three observations. This is the first NEO discovery with any form of HelioLinC algorithm.



THREE PLOTS AT RIGHT: Intractable mislinkages call into question the feasibility of making asteroid discoveries based on only three tracklets, as LSST seeks to do. Our ITF results enable us to explore what regions of parameter space are most likely to contain mislinkages. If two overlapping linkages are incompatible, one at least must be bad – while if they are compatible, both are good. Hence we construct a good sample and a 'bad' sample (of which up to half might actually be good), and use them to create the plots. TOP: Astrometric RMS is only a weak indicator of bad linkages. By contrast, 'unevenness' – which we define as the ratio of the largest to the smallest inter-tracklet time interval – correlates strongly with bad linkages. MIDDLE: bad linkages are also more likely to be fit with high-eccentricity (but not high-inclination) orbits. BOTTOM: Using a sliding threshold to eliminate linkages with the highest values of various parameters, we explore what parameters can be used to exclude a large fraction of bad linkages but not many good ones. Sampling unevenness is the best, but eccentricity and astrometric and photometric RMS residuals could also be useful. By contrast, high inclination is more likely to indicate a good linkage than a bad one.

RIGHT: Like most NEO surveys, ATLAS takes four images of each survey field each night. Had ATLAS detected 2022 SF289 in all four images from any night, it would have been promptly discovered and not left for us to find with HelioLinc3D. Instead, 2022 SF289 was detected three times on each of four different nights – *but never four times*. The solid curves at right give the probability of this scenario – an object imaged four times per night is detected three times on at least four nights, but never four times – under various values for the number of nights 2022 SF289 was imaged, and using the approximation of a constant per-image detection probability. Our illustrative values of 5, 9, and 12 nights correspond roughly to 30%, 50%, and 70% usable weather over the ~17 days that 2022 SF289 was observable. HelioLinc3D might boost the discovery rates of current surveys by ~10%.



CONCLUSION: HelioLinc3D exceeds LSST specifications and has discovered a PHA in real data from the ATLAS survey. Algorithm-independent 'intractable' mislinkages in both real and simulated data present a challenge to the LSST goal of discovering asteroids based on just three tracklets. However, three-tracklet linkages may be safe in some regions of parameter space. In other regions, aggressive automated searches to find additional detections (if any) may be required to confirm three-tracklet discoveries.

Background image: Earth from Apollo 11, credit NASA

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