LSST Solar System Overview & Update

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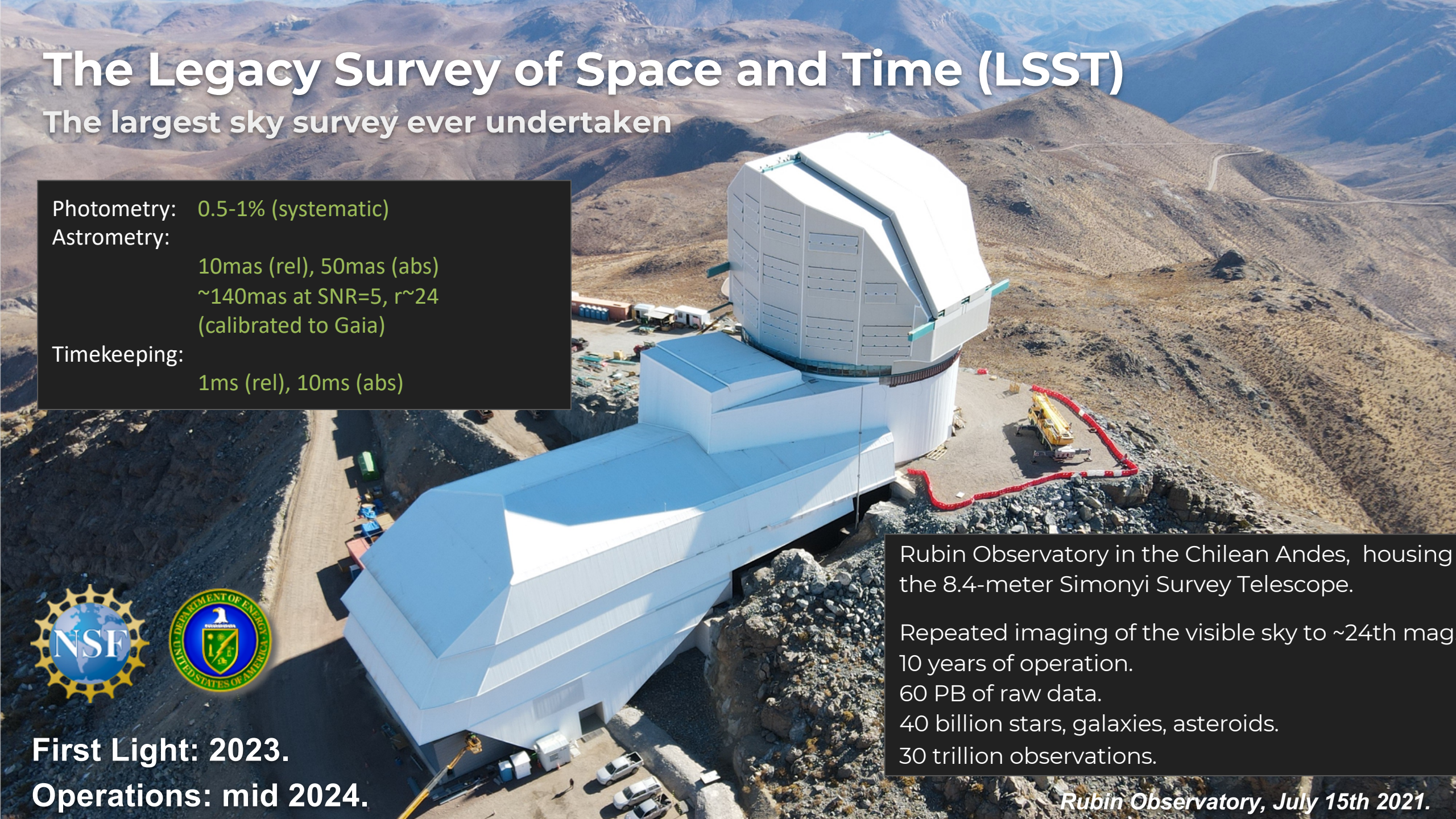
Rubin Solar System Pipelines Construction Team
University of Washington & Princeton Uni.

(+) graduate students
(*) undergraduate students

The Legacy Survey of Space and Time (LSST)

The largest sky survey ever undertaken

Photometry: 0.5-1% (systematic)
Astrometry:
10mas (rel), 50mas (abs)
~140mas at SNR=5, r~24
(calibrated to Gaia)
Timekeeping:
1ms (rel), 10ms (abs)



Rubin Observatory in the Chilean Andes, housing the 8.4-meter Simonyi Survey Telescope.

Repeated imaging of the visible sky to ~24th mag
10 years of operation.
60 PB of raw data.
40 billion stars, galaxies, asteroids.
30 trillion observations.

First Light: 2023.
Operations: mid 2024.

Rubin Observatory, July 15th 2021.

Schedule Forecast (as of April 2022)

> TMA and Dome contracts substantially complete:	July 2022
> EPO complete:	September 2022
> LSSTCam shipped from SLAC to Chile:	April 2023
> Telescope ready for integrated optical testing:	May 2023
> ComCam: Engineering First Light:	June 2023
> LSSTCam ready for I&T at the telescope:	July 2023
> LSSTCam: System First Light:	October 2023
> Science Pipelines ready for Science Verification Surveys:	November 2023
> Commissioning Science Verification Surveys completed:	March 2024
> Operations Readiness Review completed: (4 months of schedule contingency)	March 2024

Data Products for Small Body Science

(no changes from last year)

I. Real-Time Alerts within 60 sec

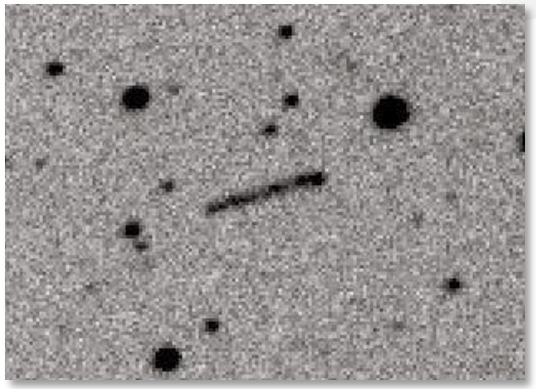
A. Real-time Alerts (>=2M SSO observations/night)	
Astrometry	±10 mas (bright; ±140 faint)
PSF flux	±10 mmag (bright end)
Aperture flux	±10 mmag (bright end)
Trailed source fit	Flux and on-sky motion for fast-moving (trailed) objects
Appearance characterization	Moments and extendedness of the object's image
Spuriousness score	Probability that the detection is an artifact
Nearby static objects	Information on adjacent objects (up to three)
MPC designation	Given for known objects
Predicted position and magnitude	Given for known objects

Details: DIASource tables in http://ls.st/oug

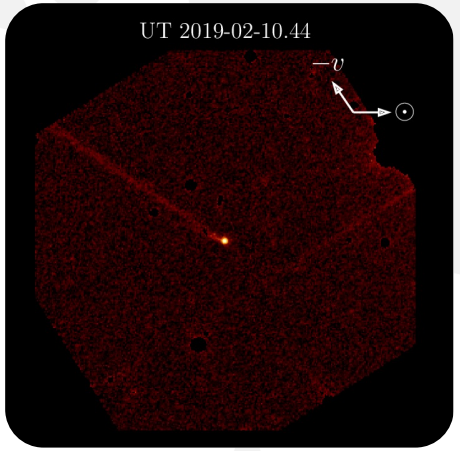
Measurements of all detections on difference images, including known and unknown SSOs.

Suitable for real-time discovery of trailed objects, and activity of known objects.

Allows us to monitoring ~0.5-1M small bodies for activity, each night.



2014 MF6 (PHA), 60sec exposure, MPC Q62 (Guido, Howes & Nicolini)



(6478) Gault outburst
(Ye et al, for the ZTF Collaboration)

II. Daily Catalog

B. Daily Solar System Products (>= 5.5M objects)	
Orbits	Computed by the MPC
Light-curve characterization	Period, light curve shape, other features
Absolute magnitude estimates	Estimates of (H, G12) in u,g,r,i,z,y bands
MOID	Minimum Orbit Intersection Distance (Earth)
Extendedness indicators	Is/was the object comet-like in its appearance?

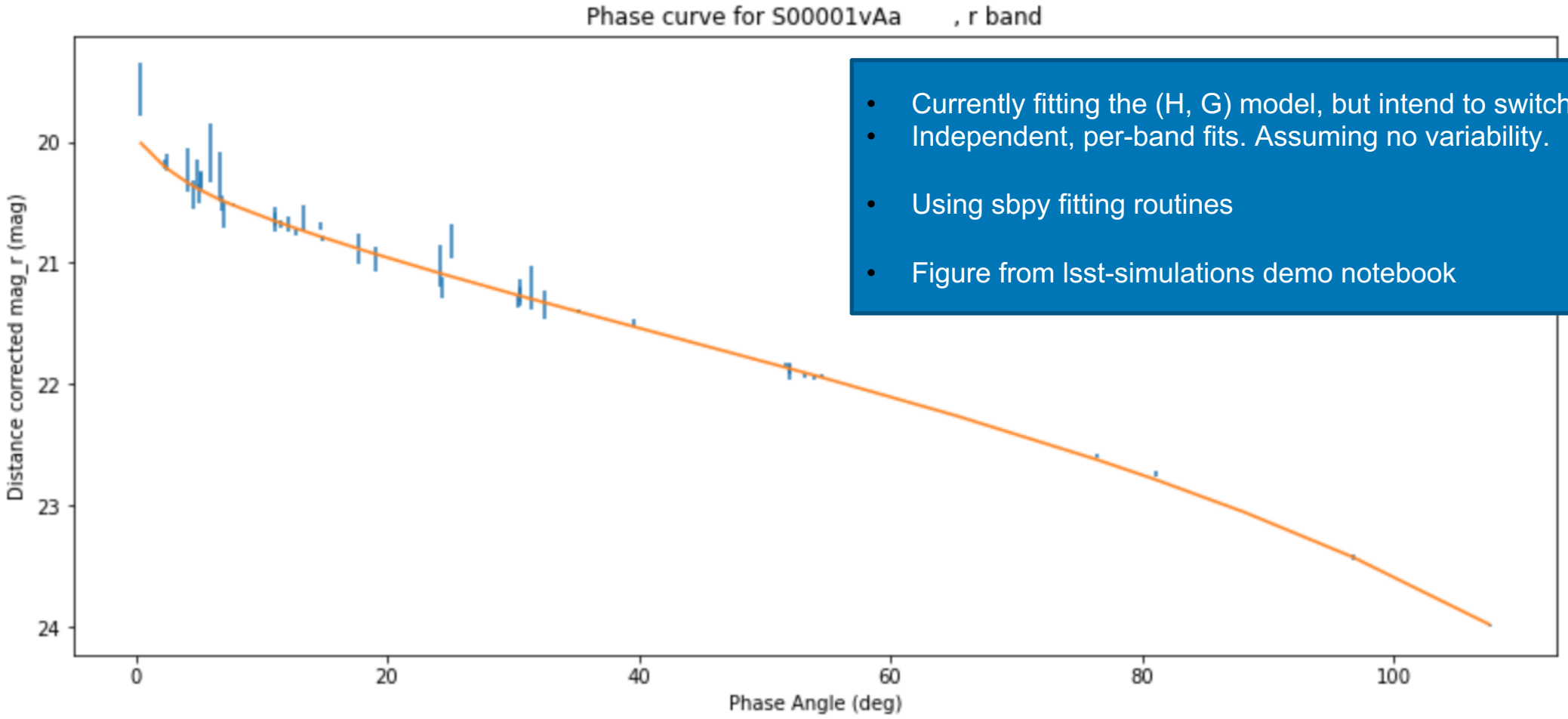
A catalog of orbits and physical properties, recomputed daily. The orbit solutions and designations will be obtained from the MPC.

The physical properties (absolute magnitudes, light curves, extendedness characterization) will be computed from LSST data.

The most up-to-date catalog of physically well-characterized small bodies in the Solar System.

Details: SSObject and SSSource tables in http://ls.st/oug

Computing Physical Properties



- Currently fitting the (H, G) model, but intend to switch to (H, G12)
- Independent, per-band fits. Assuming no variability.
- Using sbpy fitting routines
- Figure from lsst-simulations demo notebook

III. High-Quality Data Release Catalogs

C. Solar System Data Release Products (every year)	
High-fidelity reprocessing	Catalogs derived from re-reductions of all survey data using improved calibrations and a single, well-characterized, software release. **A "gold" version of the daily catalog.**
The LSST Catalog of Solar System Objects	**A catalog, suitable for population studies**, of objects detected by LSST with orbits estimated using only LSST data.

Details: SSObject and SSSource tables in http://ls.st/oug

LSST will reprocess all data once a year, publishing well-characterized and manually QA-ed data releases (DR).

The Solar System aspects of a data release include a "gold" version of the daily catalog (improved astrometry and photometry), and a special "LSST-only" catalog of Solar System objects, suitable for population studies.

We will also deliver the linking software, information about the selection functions, and metadata necessary to enable debiasing of the population.

Software Development Updates

(many changes from last year!)

HelioLinC+ (*)

An LSST-capable Implementation of HelioLinC

Ari Heinze, Siegfried Eggl, ++

(*) Note: working title…

Milestones in HL+ development (1/2)

- Change from linking in 2-D to full 3-D solar system Cartesian coordinates
- Implementation of 3-D algorithm in python, successful tests over few-degree fields
- Recognition that a C++ implementation was needed for full-sky performance (speed and memory-efficiency)
- Addition of ‘acceleration’ (really 2nd time derivative of heliocentric distance) to the search dimensions of distance and radial velocity
- Implementation of powerful post-processing ‘cluster consolidation’
- Full-sky tests of C++ implementation with >95% completeness on asteroids with simulated perfect astrometry

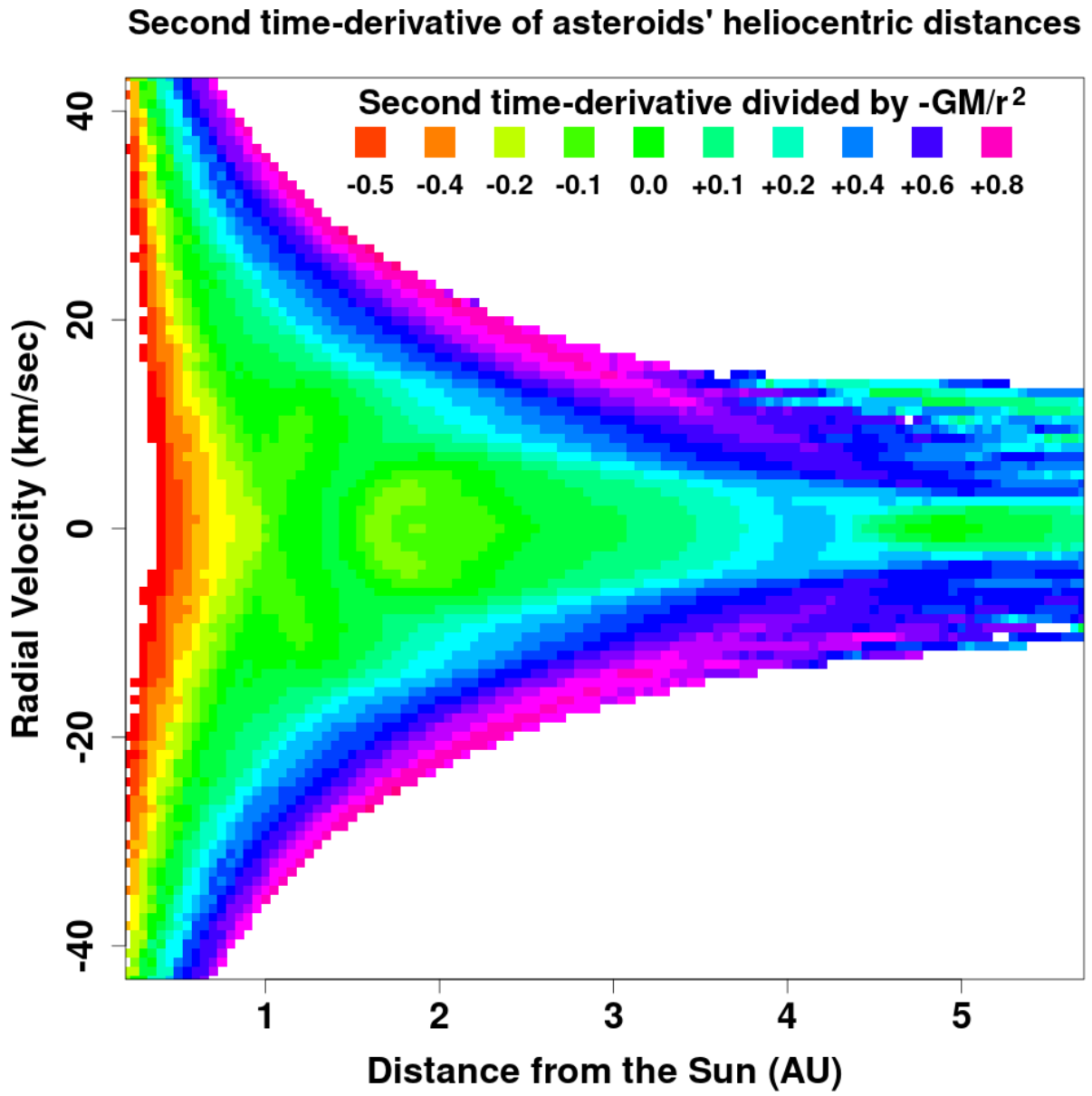
Milestones in HL+ development (2/2)

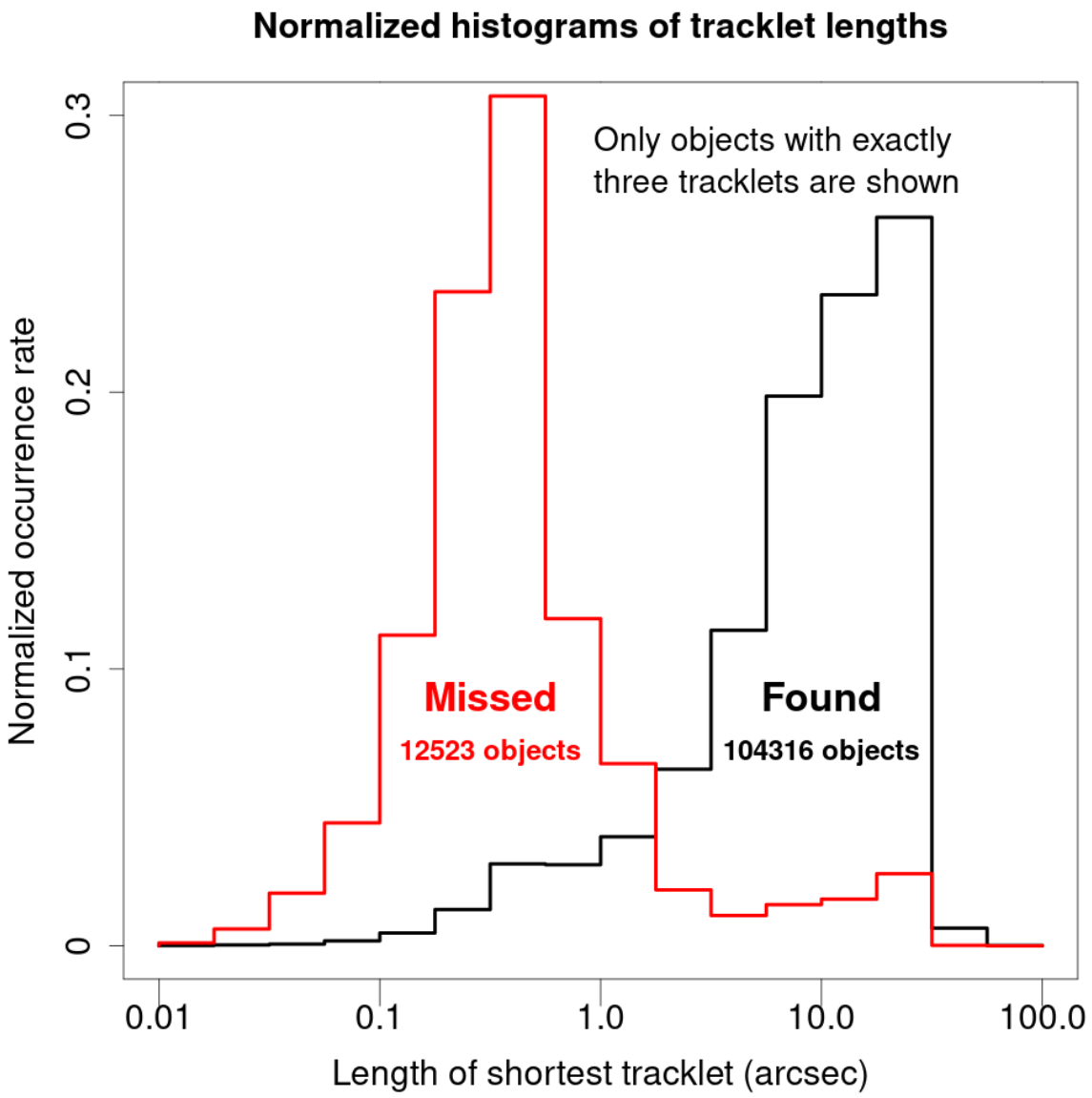
- Recognition of impossibility of linking very short tracklets in the presence of astrometric error
- Establishment of a minimum time span of 5 minutes for valid tracklets; nominally ‘findable’ objects decreased by only 5.9%
- Full-sky tests over a two-week period delivered 97.4% completeness including simulated astrometric error.
- Tracklet consolidation: treat many-point tracklets as ‘effective pairs’ with improved astrometric precision from fitting all the points
- Successful tests on real data from DECam and ATLAS
- Generation of >10,000 simulated detectable interstellar objects
- Full-sky test of interstellar mode for heliolinc, delivering 95.6% completeness on interstellar objects with astrometric errors

Our C++ implementation of heliolinc effectively searches a grid in the first three terms of a Taylor Series expansion of heliocentric distance as a function of time.

The color scale gives the average value of the 2nd derivative for real asteroids in each bin of heliocentric distance and radial velocity.

Previous versions of heliolinc used a constant value of +1.0, which is not a good guess anywhere.



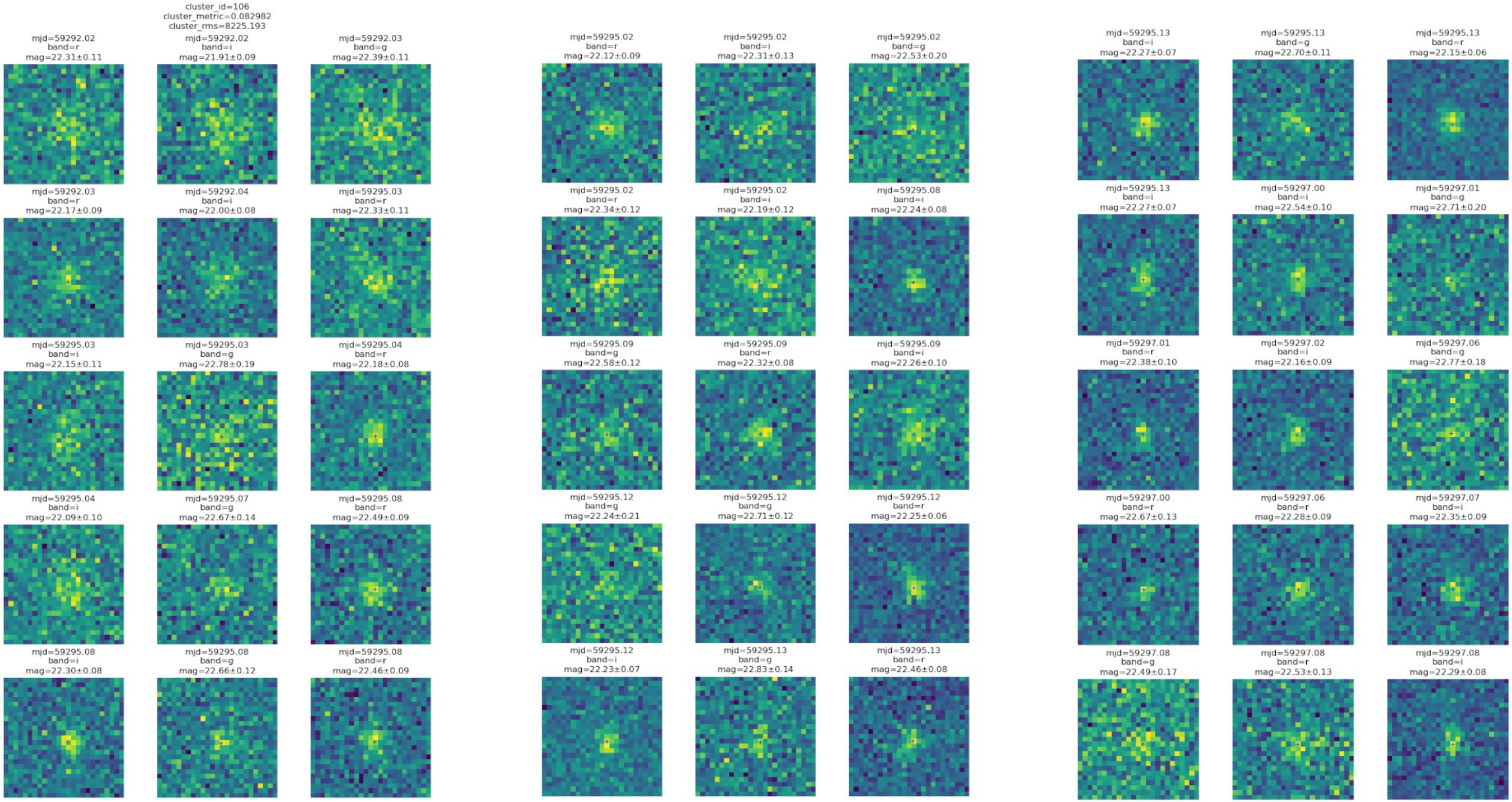


Even with 0.05 arcsec astrometry, angular velocities of short tracklets are typically wrong by >10%.

Integrated over time, velocity errors put the object in the wrong place and make a successful linkage impossible.

We choose a threshold in time span (5 min) rather than in angular arc, because the time span can be controlled by scheduling.

Cutouts of a previously unknown asteroid in the DECam Deep Drilling Fields, linked across five night by HL+.



Steven Stetzler *produced these cutouts from data acquired through* ***Melissa Graham's*** *observing proposal.*

Linking Pipeline Summary

> Computational and linking performance meets requirements for all but NEO populations. NEO linking at ~70% (conservatively).

> Testing on simulations, cautiously starting to run it on real data.

> We have a high degree of confidence that this will work!

> Next steps

- Performant orbit determination.
- Bring NEO linking performance to 95%+ regime.
- Hope to fully retire linking risks in the next 12 months. (i.e., have ops-ready code).

Association and Precovery Pipelines

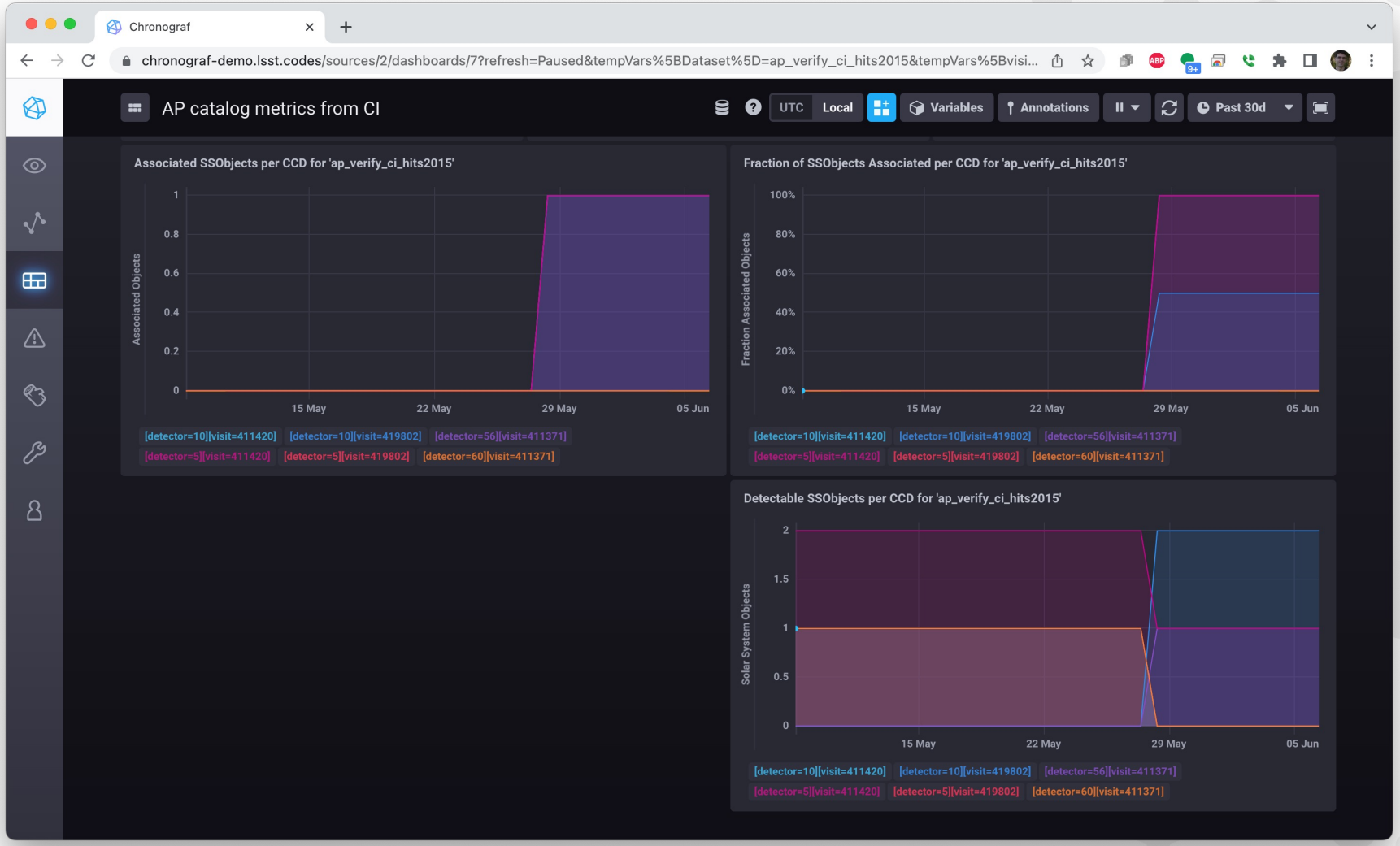
Known Asteroid Association (v0.0.1)

Have the first version of the code that associates known objects in the field.

Presently a simple positional match, uses SkyBot for ephemerides computation.

Running daily+ within the prompt processing pipeline QA runs.

Running on real data: HITS (DECam), COSMOS (HSC)



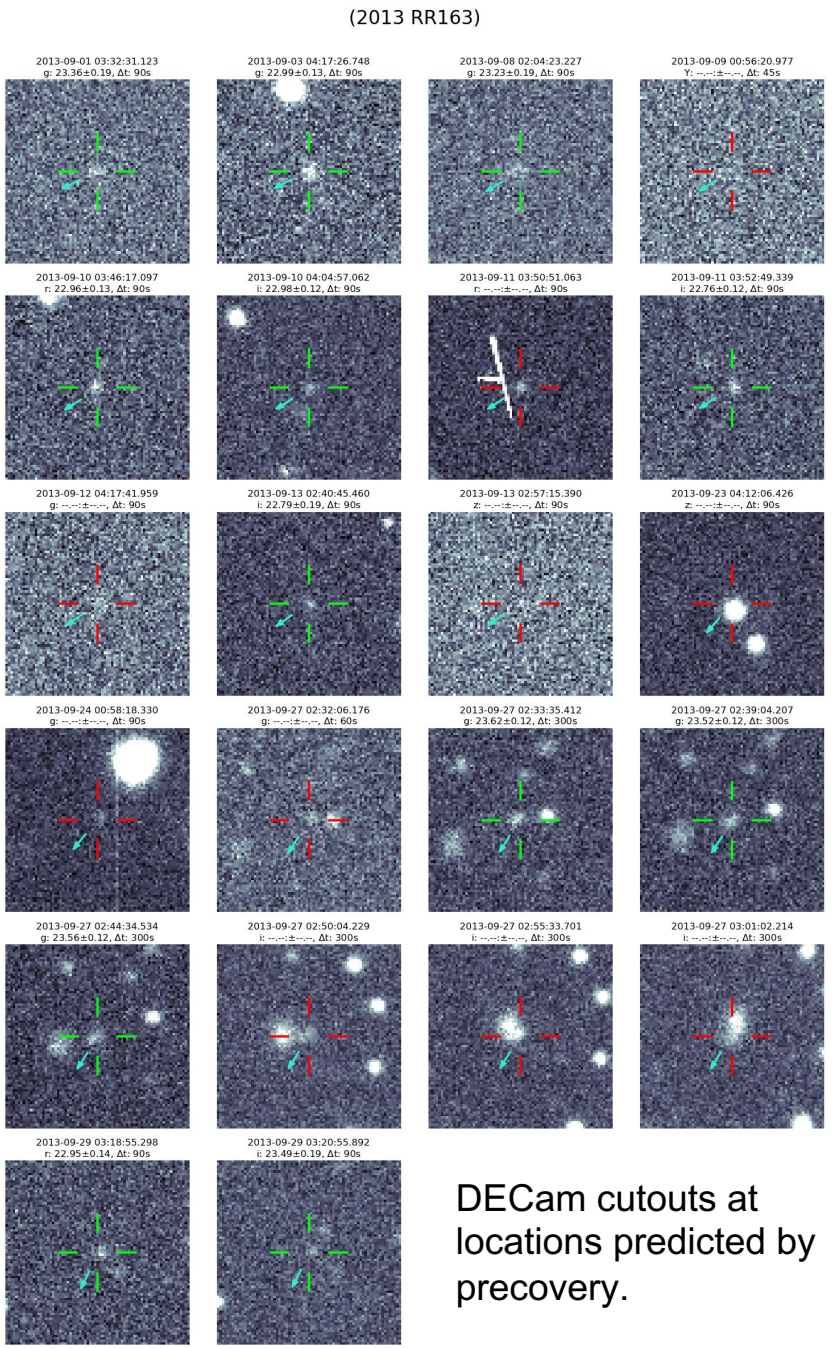
S. Eggl, C. Morrison, K. Findeisen

Precovery

- Looking to adopt a general package UW developed with the B612 Asteroid Institute
  - Spencer Nelson (UW), Joachim Moeyens (UW), Steven Stetzler (UW), Kat Kiker (AI), Nate Tellis (AI)
  - Code: https://github.com/B612-Asteroid-Institute/precovery
  - Service (closed beta): https://adam.b612.ai/#precovery

- **Fast:** O(40s) to find counterparts of a single object in a catalog of ~1.7Bn detections. See a path to ~O(10s).
- **Scalable:** CPU, not I/O, intensive – trivially parallelizable. Already meets the LSST performance requirements.

- TODO: smarter association (covariances, local density).



DECam cutouts at locations predicted by precovery.

Prompt Processing Pipeline Components

Elements running in 60 seconds and/or touching the pixels

Trailed Source Fitting Merged

> Trailed-source measurements in the Science Pipelines
  - Estimates the centroid, flux, length, angle, and uncertainties.
  - Now run by default in ImageDifferenceTask
  - https://github.com/lsst/meas_extensions_trailedSources

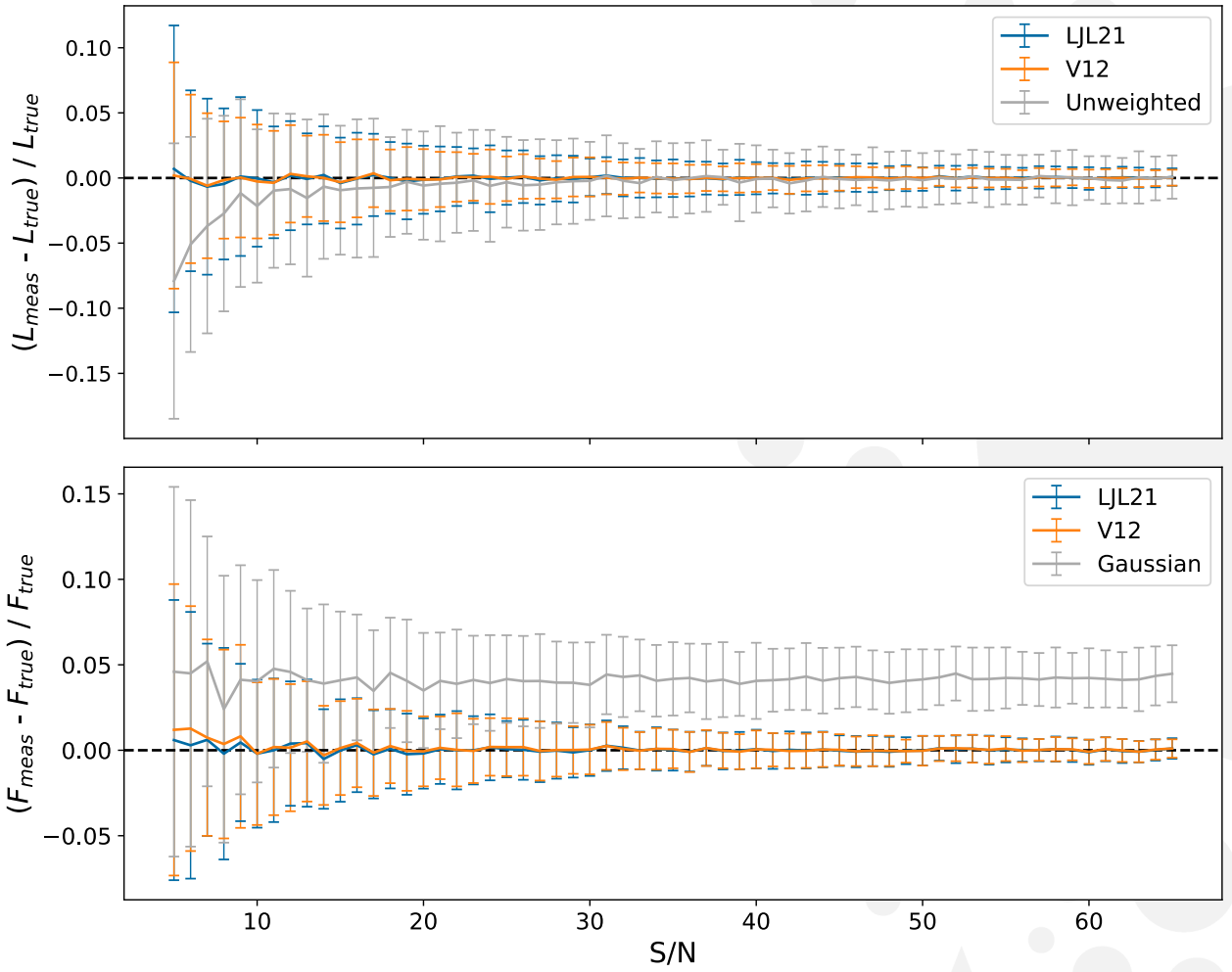
> Added trailed-sources to stack injection code

> Implements a fast, semi-analytic, fitting technique using adaptive 2nd order moments
  - Paper nearing completion (Langford et al.)

Trailed Source Algorithm Performance

- Marginal precision difference between moments and Veres et al 2012 algorithms
- ~10x speed up, and less variance in compute time for moments approach

Plots show median fractional errors in length (top) and flux (bottom) versus signal-to-noise for trails with ***Gaussian*** PSF. Error bars are inner-quartile range.



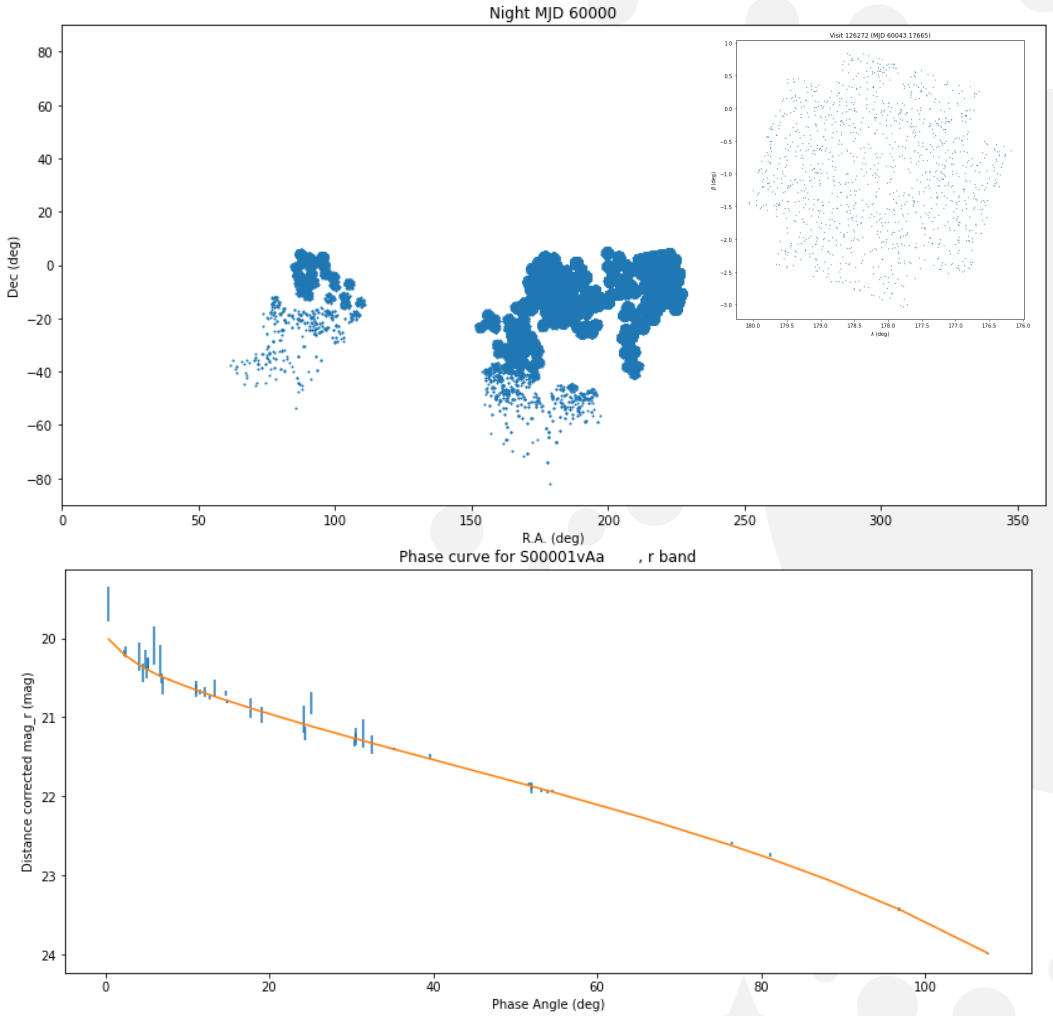
Simulations, Testing, and MPC Interfaces

Simulations: 2021 version, more in prep

Notebooks at https://github.com/lsst-sssc/lsst-simulation/

- Full 10yr dataset (~1Bn measurements)
- All SS* tables (SSObject, SSSource, MPCORB)
  - SSObject: prototype Daily Data Products Pipeline
- Using the (now old) baseline 1.7 cadence
- Realistic magnitude, astrometry errors
- Absolute magnitude fits (H, G system)
- Using the same chosen technology (PostgreSQL)

- Community-developed pipeline including software from Naidu, Fedorets, +Rubin's SSO team and UW Solar System Group's most excellent band of undergrads (Cornwall, Berres, Chernyavskaya, Langford)



Hybrid Solar System Catalogue

Tom Wagg @ UW

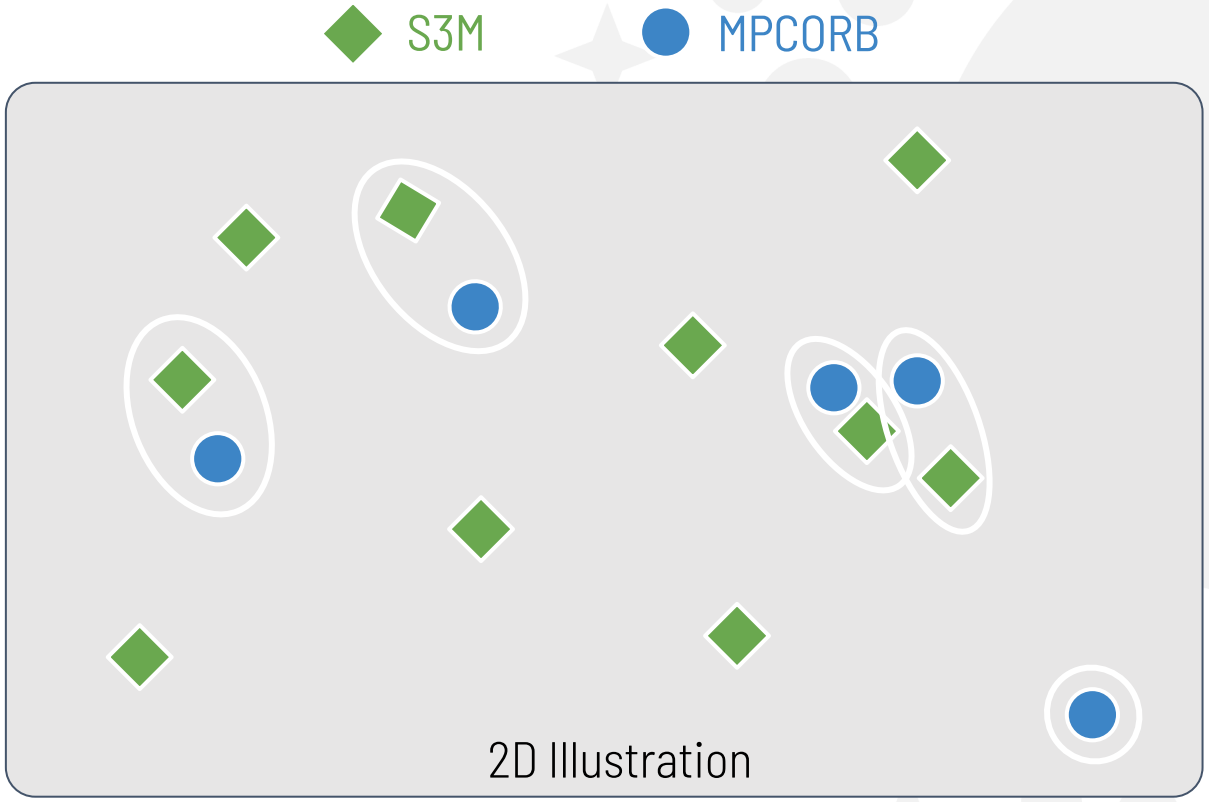
Motivation: Make predictions for LSST that account for prior observations - let's not predict the (re)discovery of Ceres!

We create the hybrid catalogue by replacing S3M objects with real detections from MPCORB

Bin data in absolute magnitude, for each MPCORB object

- Find nearest 100 neighbours in S3M that haven't yet been replaced
- Replace S3M object that has the closest velocity
- (If no objects are close then just add MPCORB object directly)

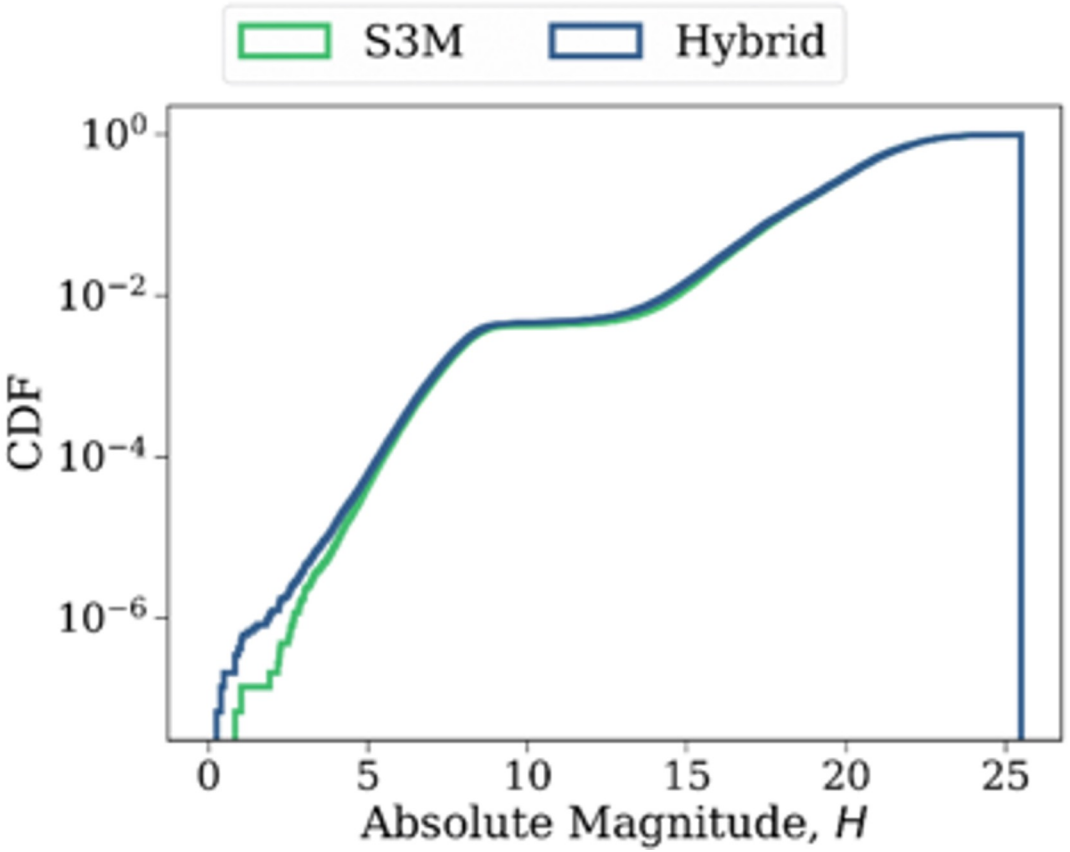
Code: https://github.com/dirac-institute/hybrid_sso_catalogue



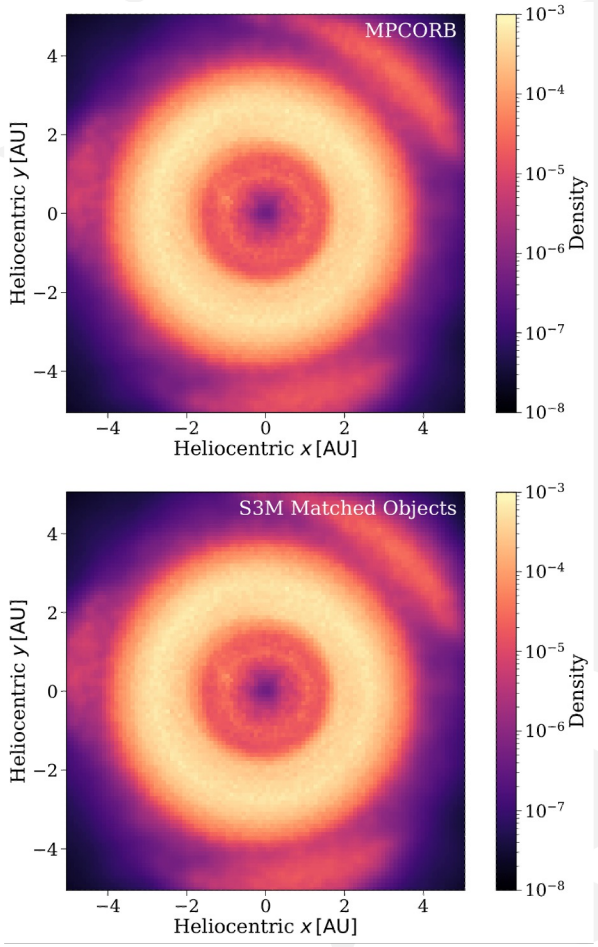
(Wagg et al., in prep)

Hybrid Solar System Catalogue

Tom Wagg @ UW



Left: CDF of the Hybrid and S3M catalog H-mag distributions. The two are essentially identical (by design), with real objects being given a priority when reconciliation is impossible



Right: Spatial distribution of hybrid vs. MPCORB. They're essentially identical in the inner Solar System.

(Wagg et al., in prep)

Joachim Moeyens, Sam Cornwall, Ari, Siegfried, +++

MPC Data Exchange Challenge #2

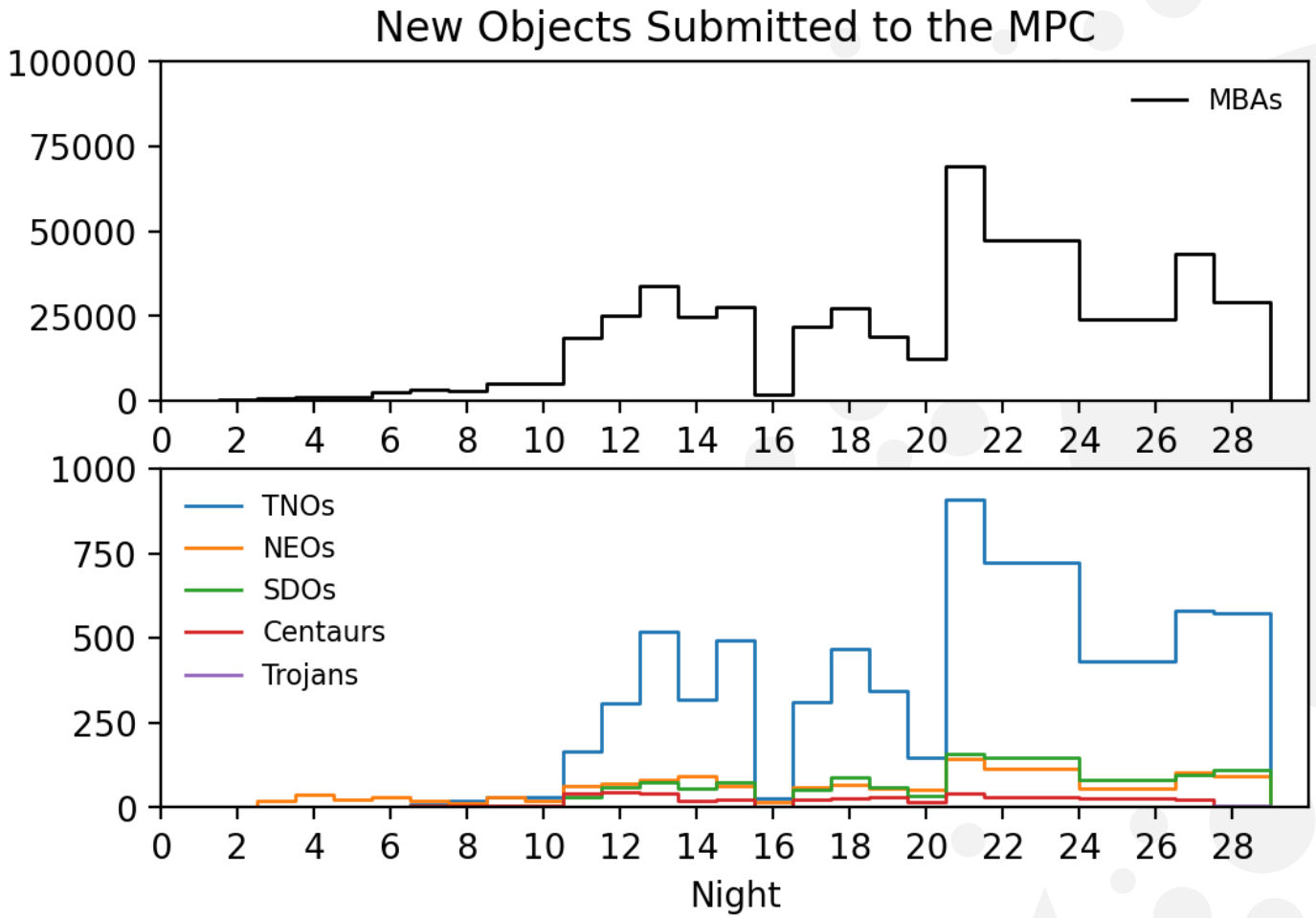
Note: Full report being worked on

Ran a successful second integration test with the Minor Planet Center (March 2022)

Used the Hybrid catalog to simulate the first month of LSST survey (starting on March 1st, 2022). Created ADES PSV formatted files. **A typical night brings in ~25,000 new discoveries.** (Note the bad weather in the first few nights!).

The MPC accepted and **automatically** processed submissions for nights 3, 4, and 5. We pulled the updated catalogs/designations. **The processing was done using the new, scalable, AWS system.** Night 21 (70k discoveries) caused timeouts (fixable).

Take-home points: the system worked. Next step – submit data linked with HelioLINC (simulated and real).



A HUGE thanks to everyone at the MPC for helping us put this together: Matt (P & H), Federica, Margaret, Michael, +++

Looking Ahead…

> Make available the simulated survey using the hybrid catalog [summer]

> Working with Leanne Guy to add the SolSys database to the RSP [?]

> Full HelioLinC implementation (including OD) [next 6 mo.]

> Running HelioLinC on DECAT survey, submitting to the MPC [next 6 mo.]

> Conda-installable HelioLinC beta available for broad use [next 6 mo.]

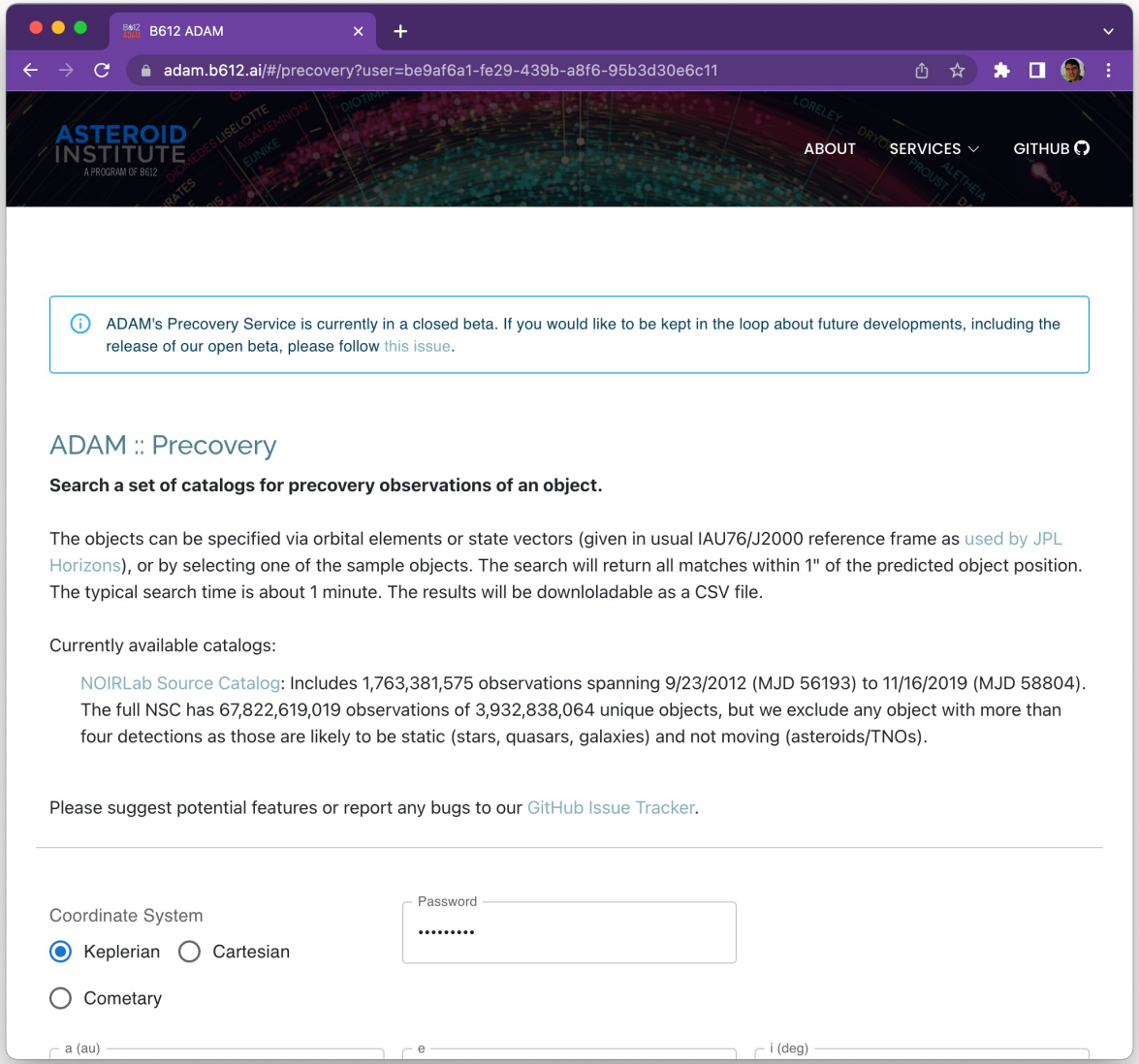
> MPC integration: simulated HelioLinC-ed data and submit real data. [next 12 mo.]

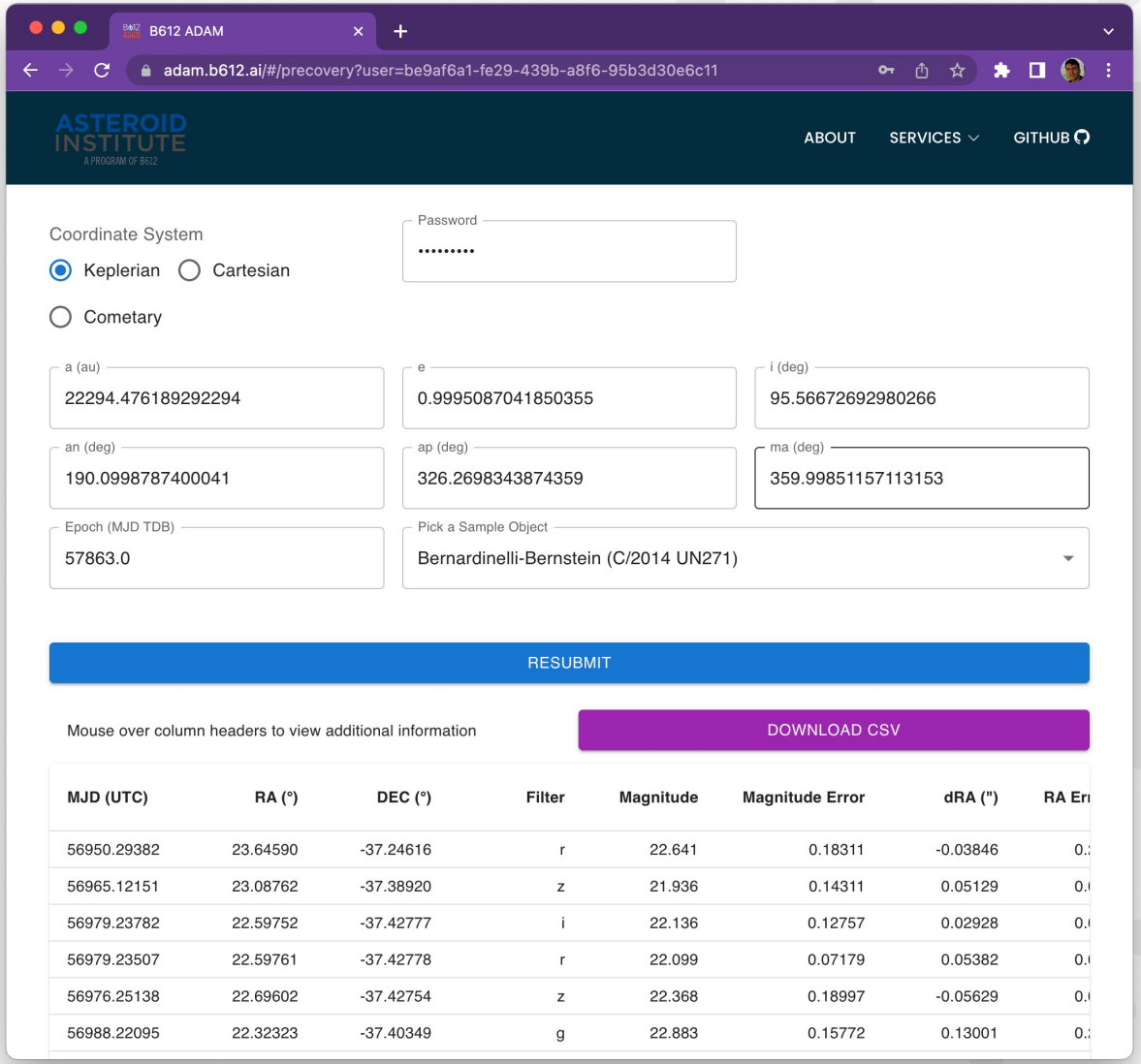
> Integrate SolarSystem pipeline with LSST Prompt Processing. [next 12 mo.]

> **Put all the pieces together & run on real data… we're almost there!**

Backups

https://adam.b612.ai/#precovery

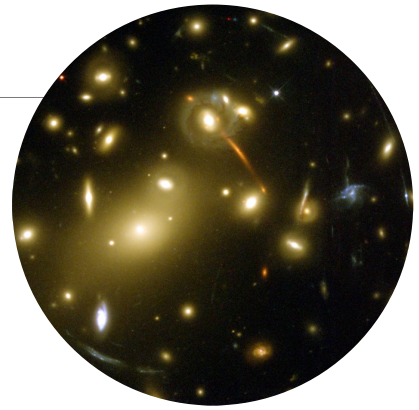


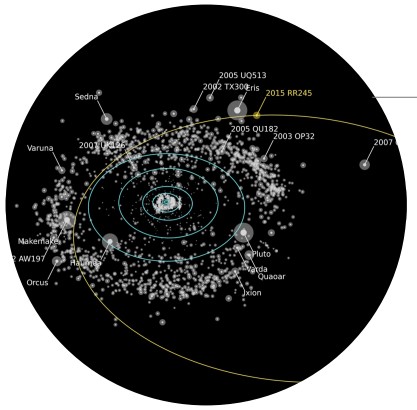


LSST Science Themes

Probing Dark Matter & Dark Energy

- Strong & Weak Lensing
- Large Scale Structure
- Galaxy Clusters, Supernovae



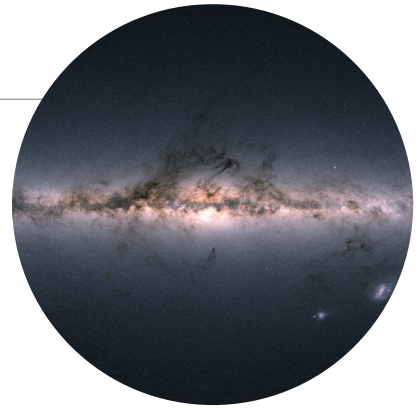


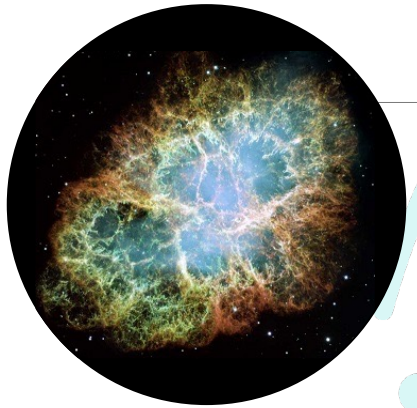
Inventory of the Solar System

- Comprehensive small body census
- Comets and ISOs
- Planetary defence

Mapping the Milky Way

- Structure and evolutionary history
- Spatial maps of stellar characteristics
- Reach well into the halo

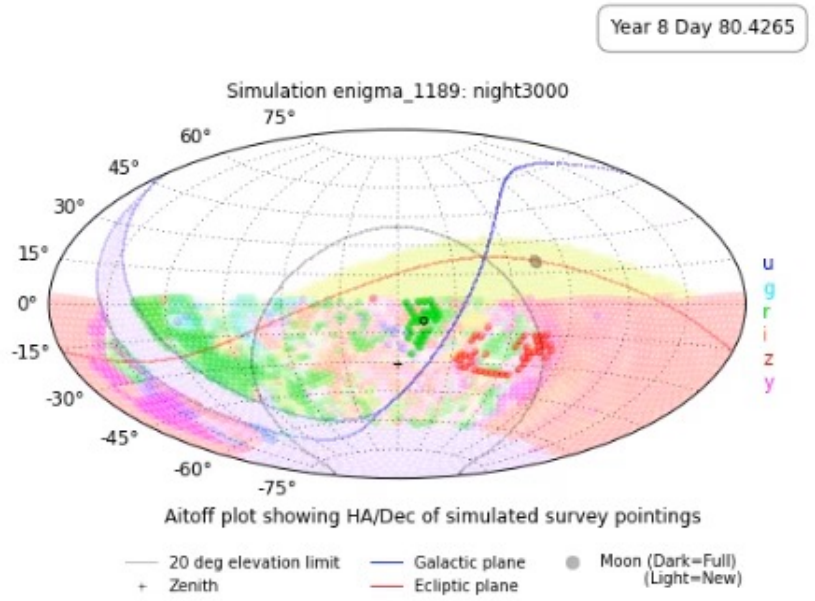


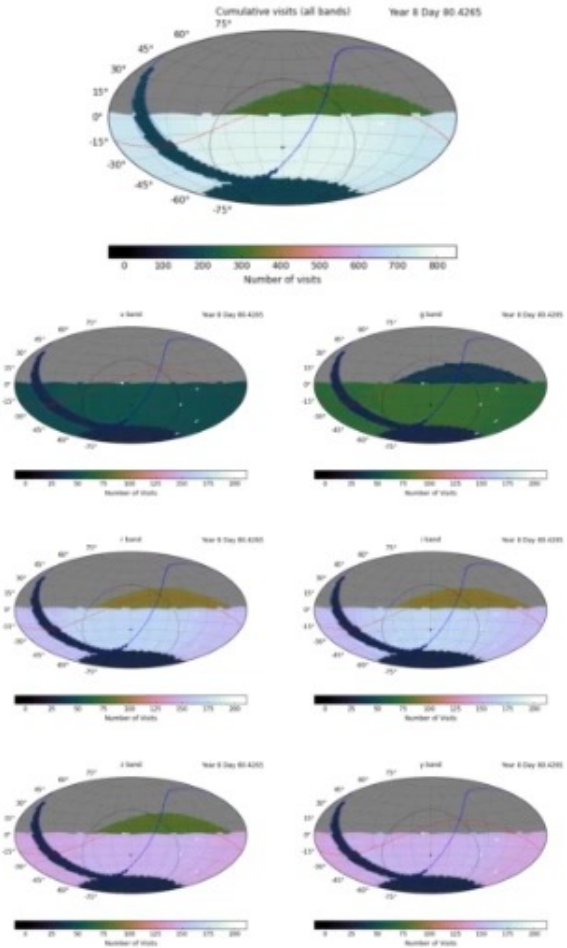


Exploring the Transient Optical Sky

- Variable stars, Supernovae
- Fill in the variability phase-space
- Discovery of new classes of transients

A single uniform survey of the visible sky





LSST will execute a single* survey designed to support all four science themes.

How to think about LSST:

- 500 pointings per night
- 2 visits to each pointing
- 10 deg^2 per visit, to r~24th mag

- ~5000 unique deg^2 surveyed per night
- Repeat for ~3300 nights.

(*) There's also smaller (<10% of time) set of "special survey programs" designed to explore extreme corners of discovery space.