Rubin Observatory LSST: Status, Data Products, and Planetary Defense Contributions

Mario Juric

for the Rubin Solar System Team

Rubin Observatory Construction Project

DiRAC Institute, Department of Astronomy, University of Washington

Rubin Observatory Legacy Survey of Space and Time

The largest optical 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.

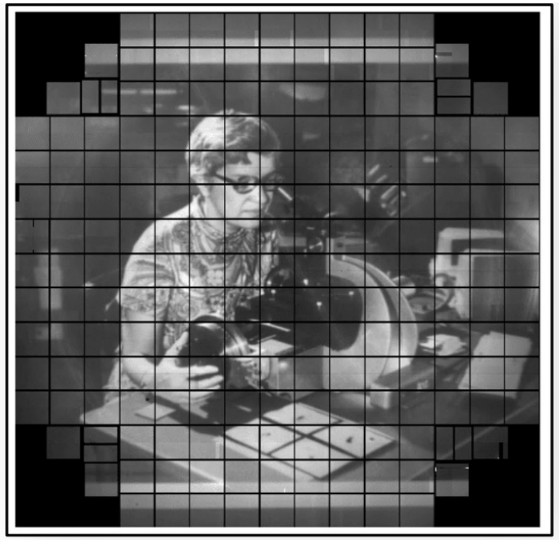
First Light: 2024.
Operations: early 2025.

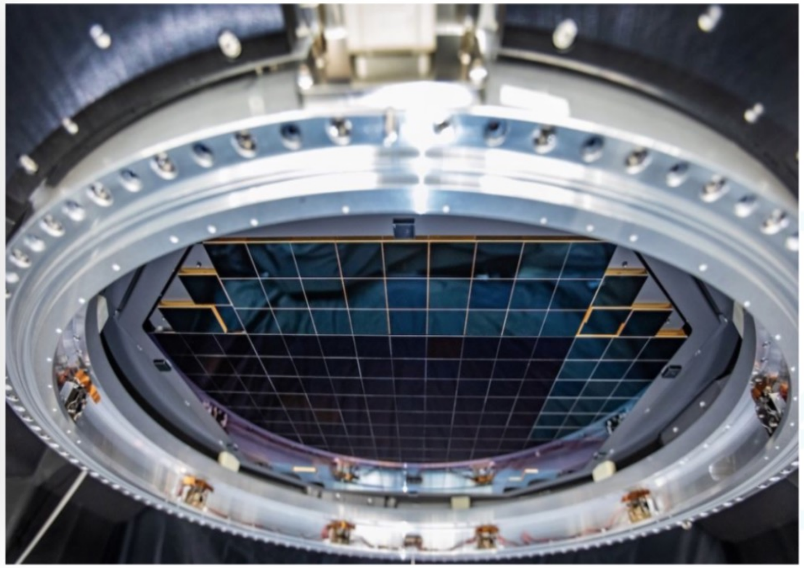
Rubin Observatory, July 15th 2021.

Nearly Done! Towards First Light in 2024.

Simonyi Survey Telescope,
March 15th 2023

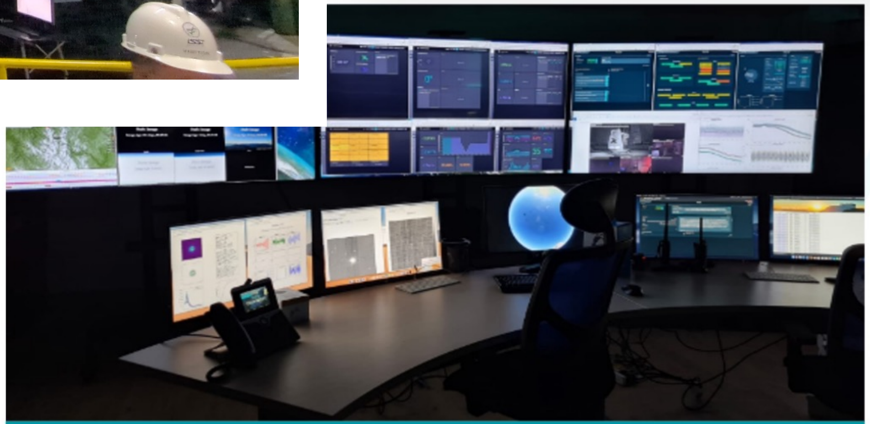
Telescope Mount Assembly



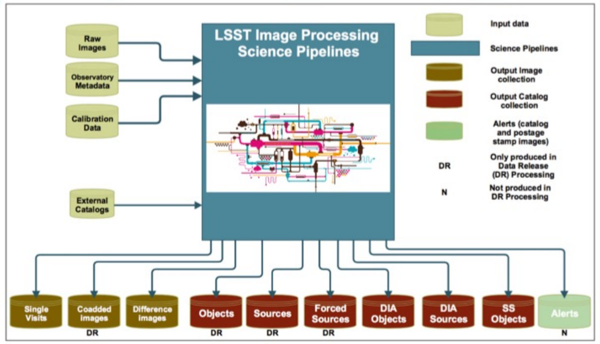


The complete focal plane of the future LSST Camera is more than 2 feet wide and contains 189 individual sensors that will produce 3,200-megapixel images.

LSST camera focal plane (3.2 Gpix)



Summit Control Room with



Schedule Forecast (as of April 2023)

VERA C. RUBIN OBSERVATORY

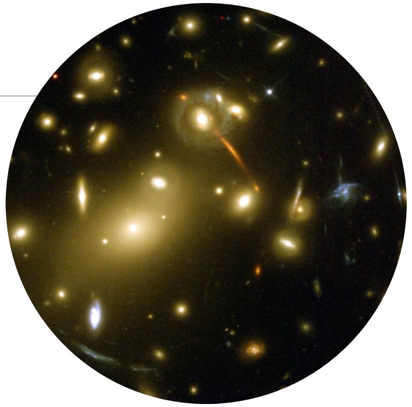
> EPO complete:	September 2022
> TMA complete:	March 2023
> Camera Pre-Ship Review:	July 2023
> Telescope ready for integrated optical testing:	February 2024
> Dome Complete	April 2024
> LSSTCam: System First Light:	Aug 2024
> Commissioning Science Verification Surveys done:	Dec 2024

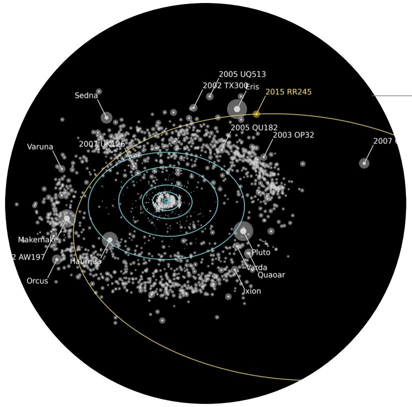
An evergreen forecast is available at https://ls.st/dates.

LSST Science Themes

Probing Dark Matter & Dark Energy

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



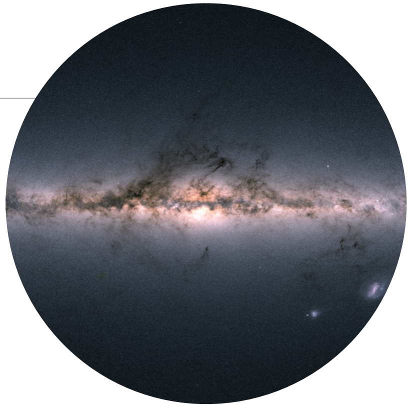


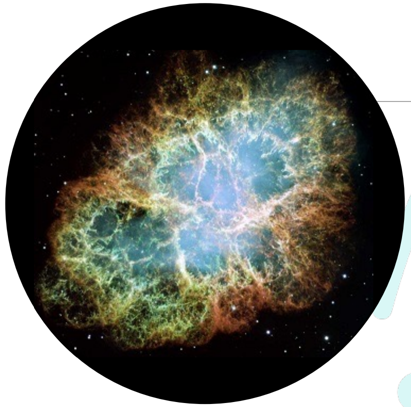
Inventory of the Solar System

- 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

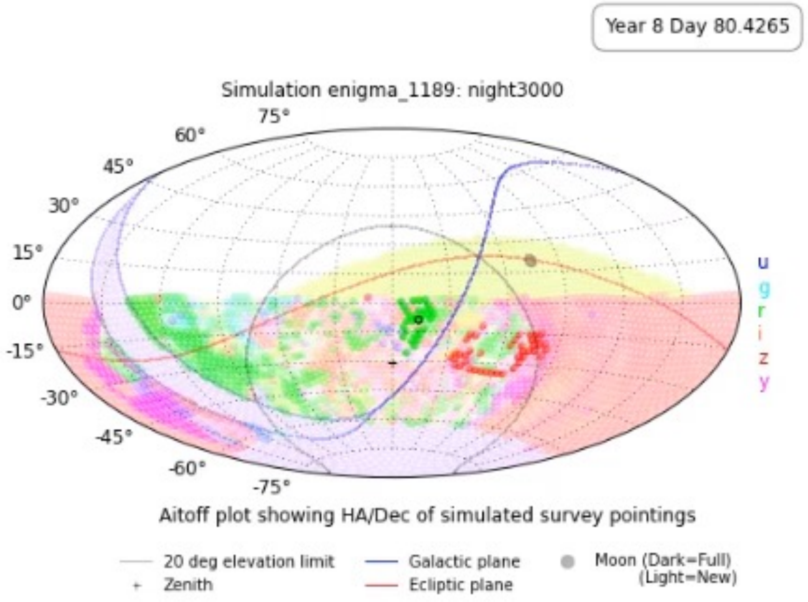


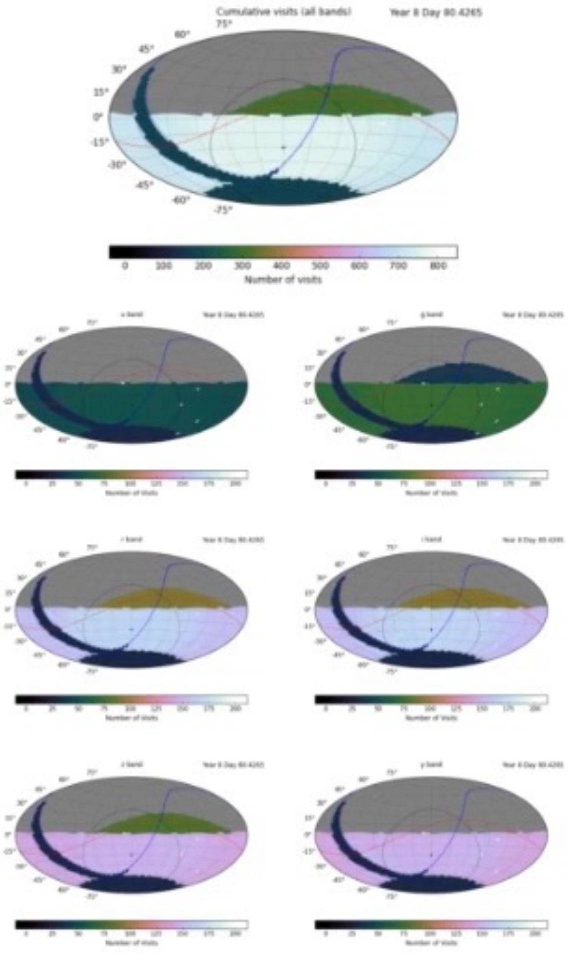


Exploring the Transient Optical Sky

- 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

- ~4000 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.

An comprehensive census of the Solar System

Animation: SDSS Asteroids (Alex Parker, SwRI)

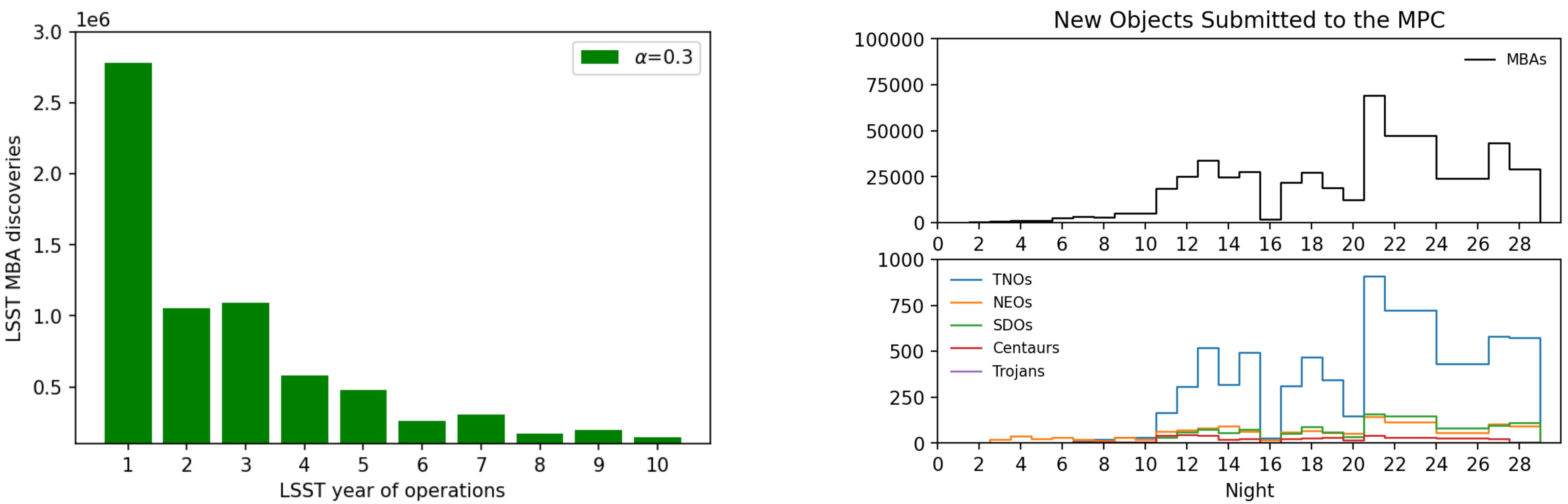
Estimates: Lynne Jones et al.

The LSST data can increase the number of known objects between 5x-30x, depending on the population.

	Currently Known*	LSST Discoveries**	Typical number of observations+
Near Earth Objects (NEOs)	~25,500	100,000	(D>250m) 60
Main Belt Asteroids (MBAs)	~1,000,000	5,000,000	(D>500m) 200
Jupiter Trojans	~10,000	280,000	(D>2km) 300
TransNeptunian Objects (TNOs) + Scattered Disk Objects (SDOs)	~4000	40,000	(D>200km) 450
Comets	~4000	10,000	?
Interstellar Objects (ISOs)	2	>10	?

These objects will be well-characterized (orbits, light curves, absmag estimates), and discovered with an exceptionally well understood selection function.

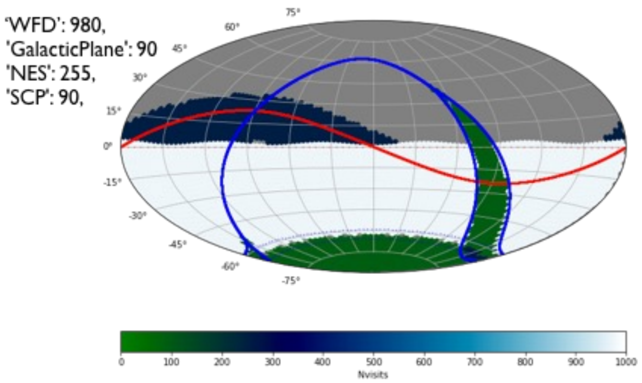
80% of discoveries occur in the first ~3 years



- Left: new object discovery rate as a function of time. → ***LSST will immediately enable significant small-body science.***

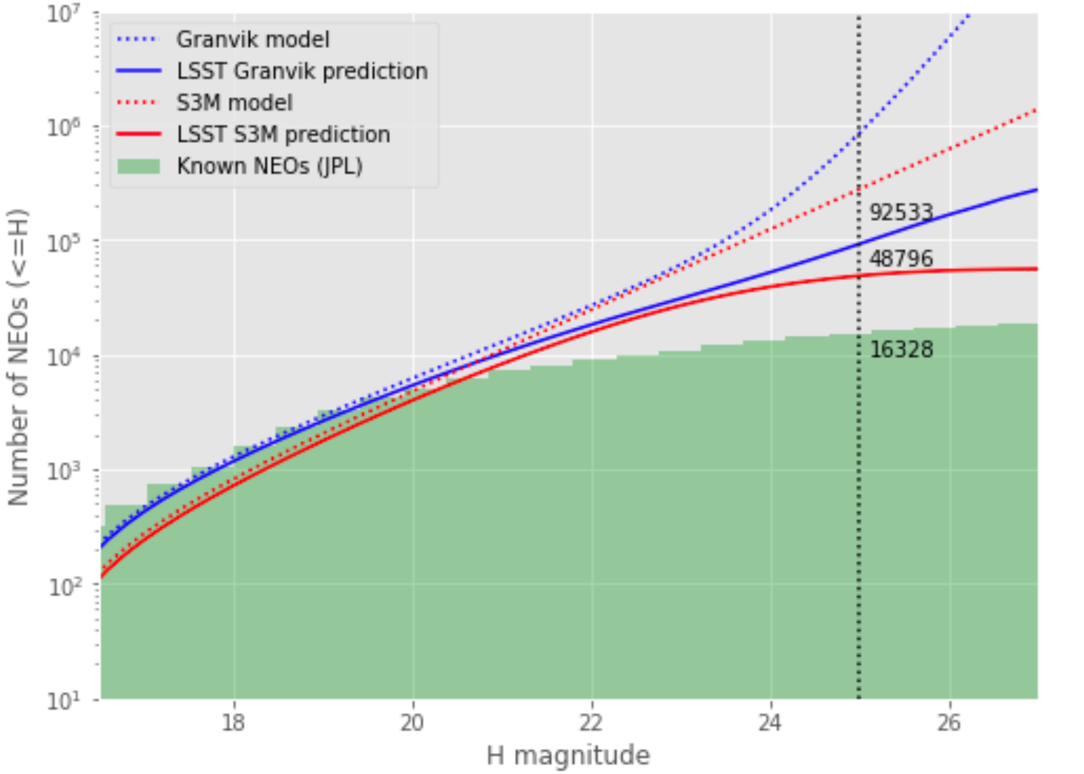
- Right: First four weeks of LSST (simulation; poor weather on nights 0-10). **Note 70k discoveries in night 21.**

Rubin will Drive the NEO Discovery Rates through the late 2020s



In v1.7 baseline strategy, after 10 years:

- 50-100K NEOs @ H<25
- 250K @ H<27



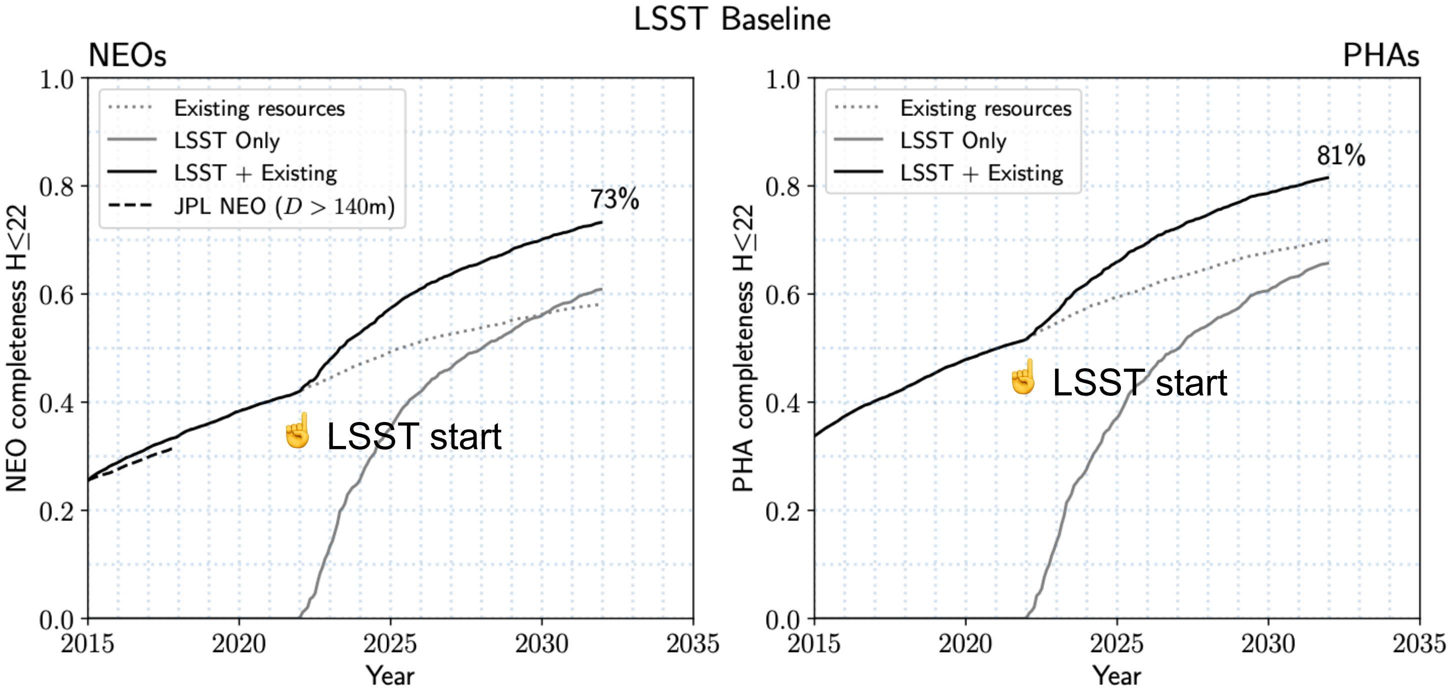
S3M - Grav et al 2011; Granvik - Granvik et al 2018

LSST will enable the construction of an NEO catalog with high completeness, orbit quality, and well-characterized observational selection function.

Measurement of the orbital, absolute magnitude, and taxonomy distributions within the NEO population, enabling the identification of correlations between taxonomy and orbital properties for all NEOs and the determination of the orbital distribution of fifty-meter+ scale objects

Assuming 15% albedo: H=25 -> D=50m | H=27 -> D=15m

Rubin's Planetary Defense Contribution



Rubin will contribute a significant increase in the rate of discovery of known NEOs and PHAs.

Considered alone, it would catalog ~65% of the PHA population.

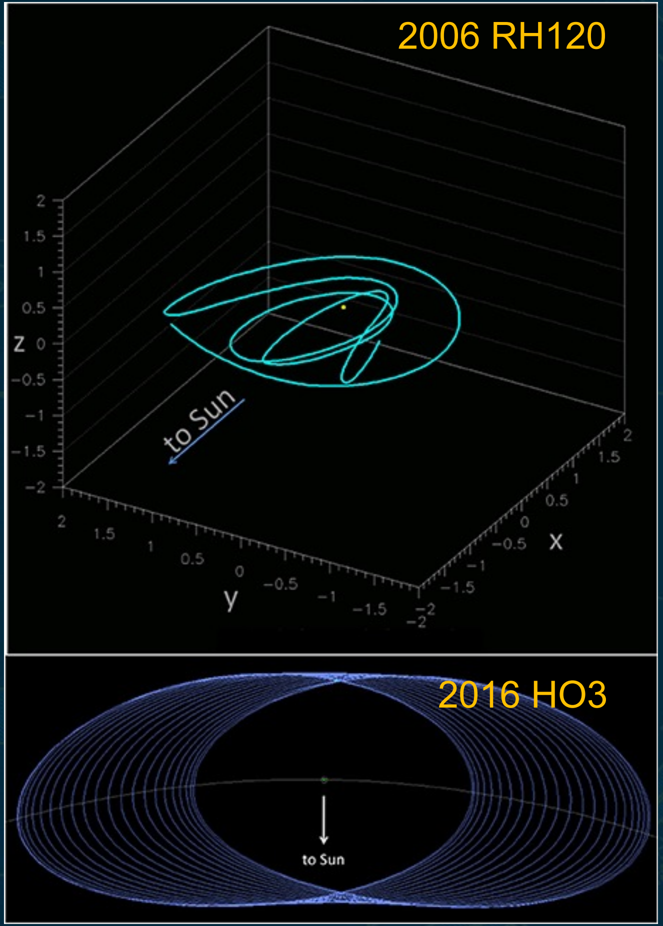
Combined with existing discoveries and survey system, the total will reach ~80%.

	10 year baseline, N_w=15		
Population	No LSST	Only LSST	LSST + others
NEO	59	61	73
PHA	72	66	81

Figures and tables from Jones et al (2018).

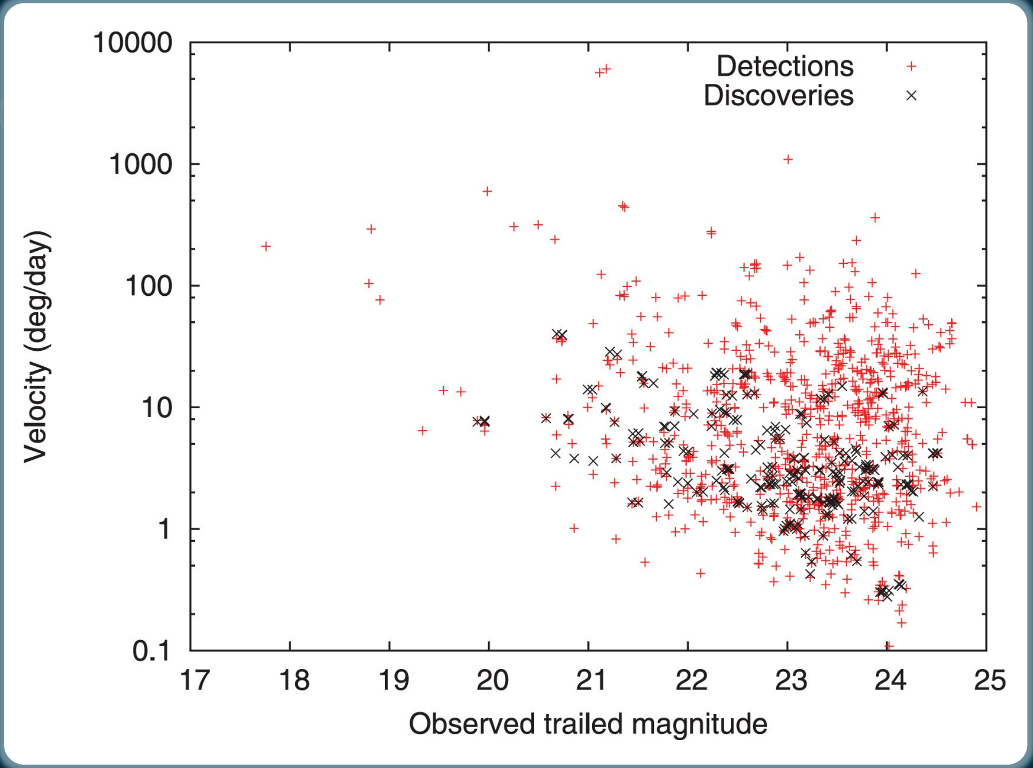
Note: NEO Surveyor contribution will add to these discoveries nudging the overall completeness over 90% by mid 2030s!

Temporarily Captured Objects ("Minimoons")



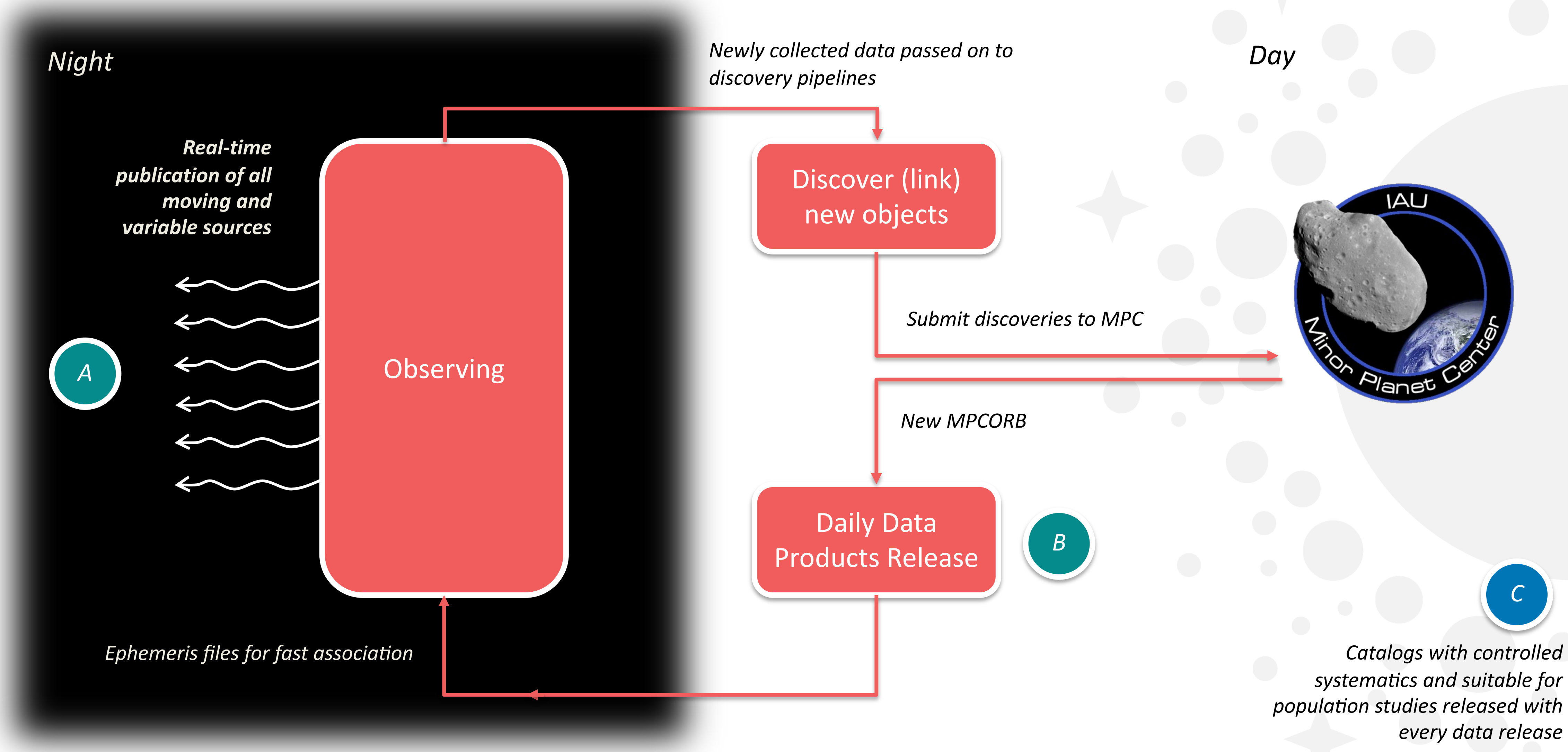
Jedicke et al. (2018)

- O(1-10) meter-sized bodies temporarily captured by the Earth/Moon system.
- **LSST can discover >one every two months.**
- Material properties.
- In-situ measurements and retrieval.



Fedorets et al. (2020), [*https://www.sciencedirect.com/science/article/pii/S0019103519304117*](https://www.sciencedirect.com/science/article/pii/S0019103519304117)

LSST Nightly/Daily Processing Loop



A one-page summary available at http://ls.st/Document-29545

Rubin will use an atypical search strategy

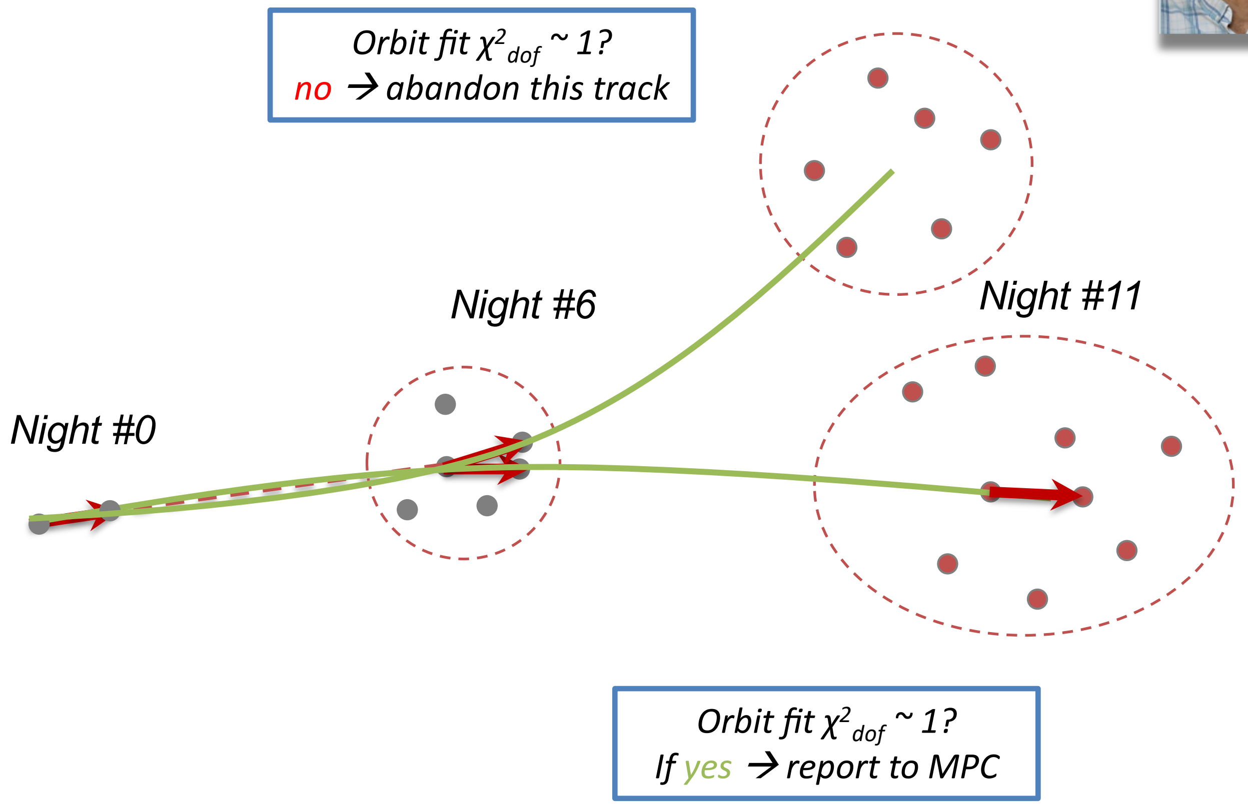
Ari Heinze' Rubin HelioLINC+ codes
Based on algorithms developed by
Holman+ (2018) and Eggl+ (2020)

- Most present day surveys take 3- or 4-observation tracklets and report them in a single night.

- Rubin will take pairs of pointings each night, separated by ~20-60 minutes.

- Tracklets *can* be constructed from pairs. But the purity of such tracklets would be low: there's a high chance of misassociation, association to artefacts, etc.

- Instead, a tracklet is only a candidate; it is confirmed by finding two more within a 15-day window. If the tree admit an orbit solution, the chance of mislinkage is negligible (~1e-5).



LSST SSO Detectability Criterion: **Well-fitting tracklets, with ≥2 observations, must be observed in at least three nights within a 15-day window.**

https://github.com/lsst-dm/heliolinc2

Algorithm and Implementation Details

THE ASTRONOMICAL JOURNAL

HelioLinC: A Novel Approach to the Minor Planet Linking Problem

Matthew J. Holman[1,2], Matthew J. Payne[1], Paul Blankley[2], Ryan Janssen[2], and Scott Kuindersma[2]
Published 2018 August 30 •
The Astronomical Journal, Volume 156, Number 3

+ Article information

Abstract

We present HelioLinC, a novel approach to the minor planet linking problem. Our heliocentric transformation-and-propagation algorithm clusters tracklets at common epochs, allowing for the efficient identification of tracklets that represent the same minor planet. This algorithm scales as $\mathcal{O}(N \log N)$ with the number of tracklets N, a significant advance over standard methods, which scale as $\mathcal{O}(N^3)$. This overcomes one of the primary computational bottlenecks faced by current and future asteroid surveys. We apply our algorithm to the Minor Planet Center's Isolated Tracklet File, establishing orbits for more than 200,000 new minor planets. A detailed analysis of the influence of false detections on the efficiency of our approach, along with an examination of detection biases, will be presented in future work.

(Holman et al. 2018)
(Heinze et al.; 2022)

Ari Heinze
Rubin HelioLINC+ codes

Performance

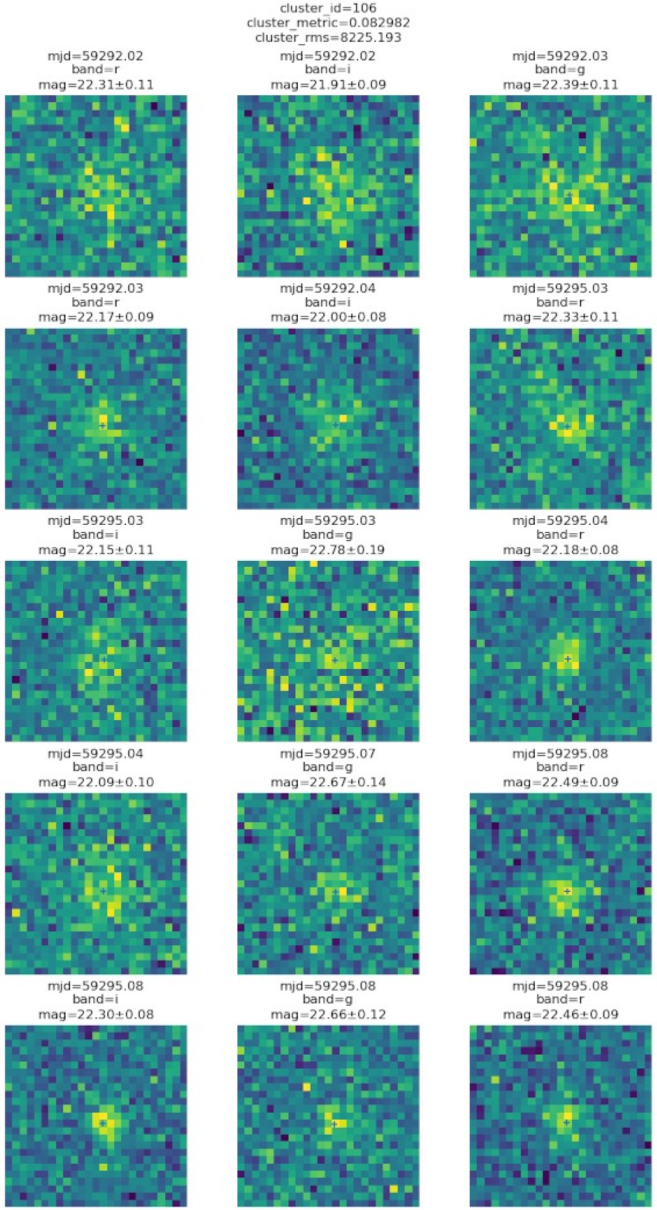
- Full-sky LSST tests : **97% completeness**.
- Full-sky LSST test for ISOs: **96% completeness**.
- NEOs: **>90% completeness** (in progress)
- In all cases, **purity >90%**, without using orbit determination chi^2 as a filter.
- **Scales as O(N *log* N)** with the number of tracklets

Code

- Completely in C++ (working on a small Python wrapper). **Fast.**
- https://github.com/lsst-dm/heliolinc2

Running on LSST-like data being acquired with DECam. Also testing on ATLAS data.

Code: Ari Heinze;
Cutouts: Steven Stetzler; Data: DECat, Melissa Graham

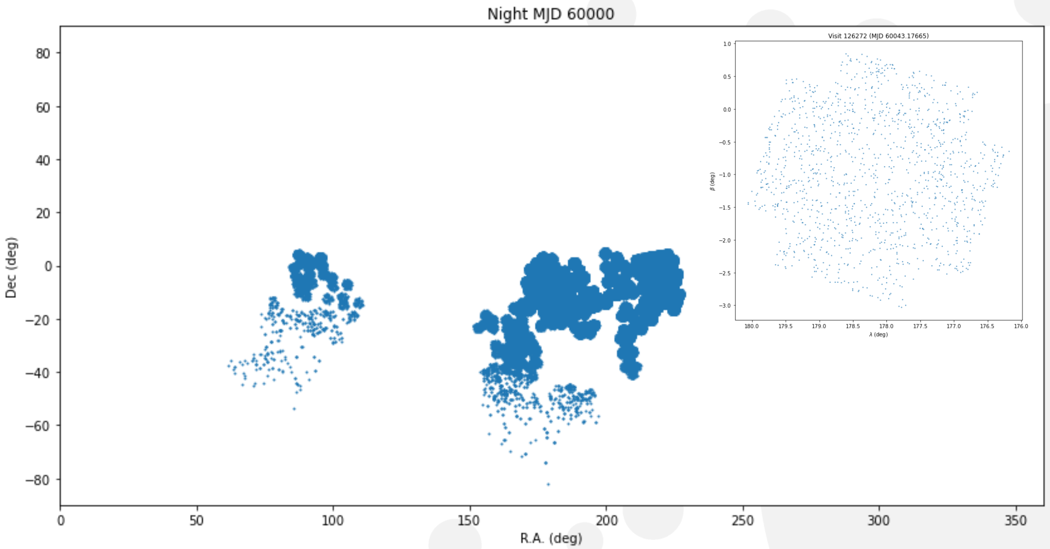


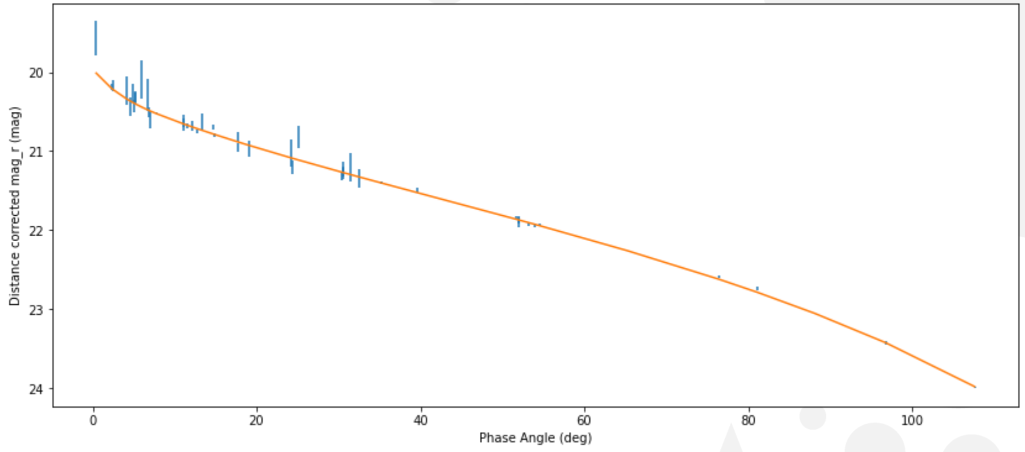
Getting Ready: Solar System Catalog Simulations

> Full 10yr dataset (~1Bn measurements)
> All SS* tables (SSObject, SSSource, MPCORB)
  - SSObject: prototype Daily Data Products Pipeline
> Using the baseline v1.7 cadence
> Realistic magnitude, astrometry errors
> Absolute magnitude fits (H, G system)

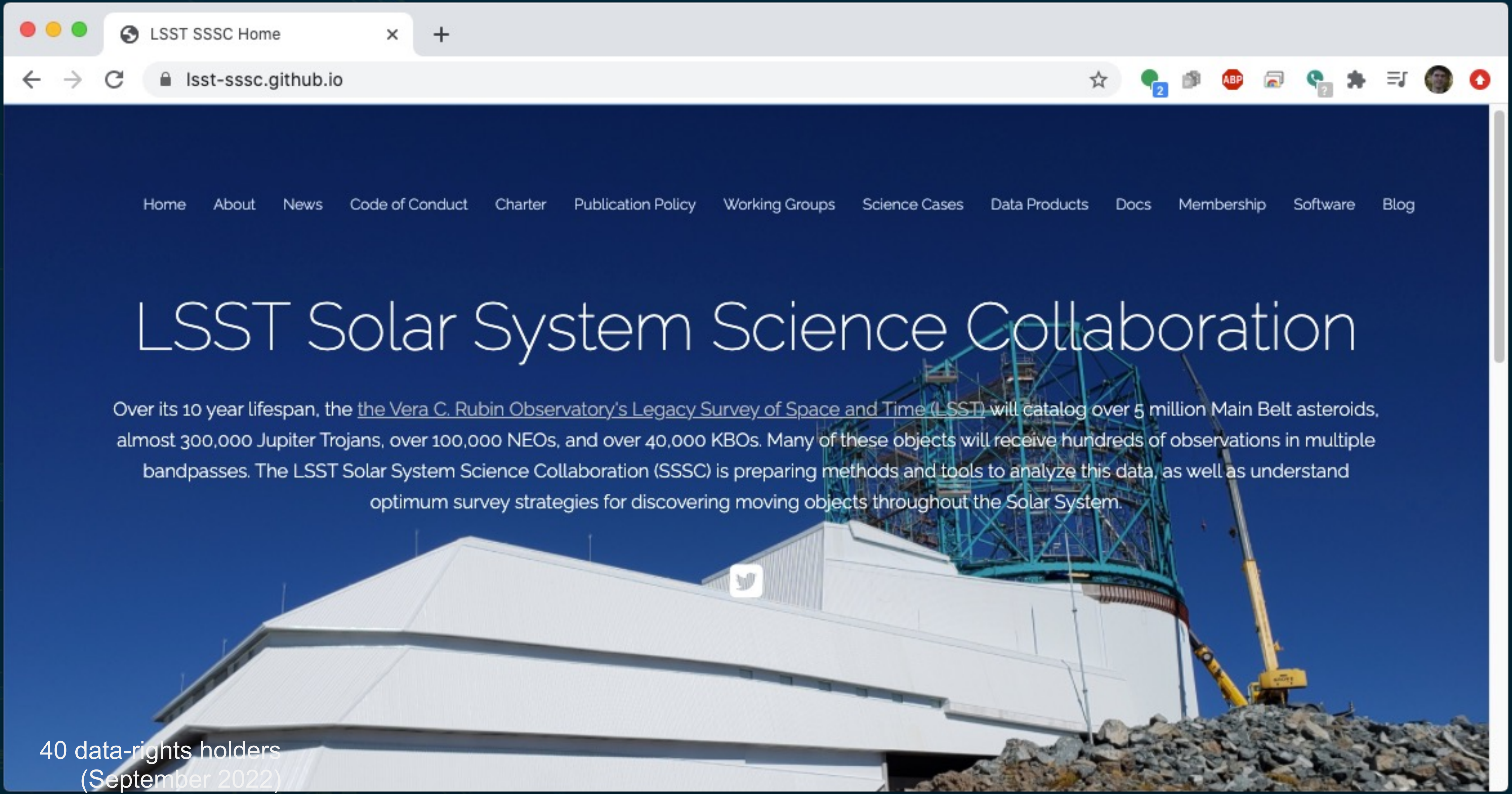
> Community-developed pipeline including software from Naidu, Fedorets, +Rubin's SSO team and UW Solar System Group team (including a number of undergraduate students: Cornwall, Berres, Chernyavskaya, Langford)

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





Join the LSST Solar System Science Collaboration: http://lsstsssc.org



40 data-rights holders
(September 2022)

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Summary

- Rubin Observatory, **entering commissioning in 2024**, will provide a comprehensive census of the Solar System.
- Astrometry and photometry will be available through the Minor Planet Center, and added-value products via the Rubin Science Platform
- Through it’s 10yr survey it will ~double the number of known PHAs, discover numerous imminent impactors and TCOs
- **A key planetary defense data source for the next decade.**

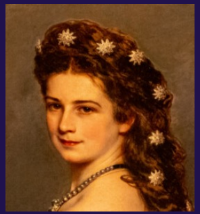
Contact, comments & questions: Mario Juric, mjuric@astro.washington.edu

Work of a Large Team!

+ the entire Rubin Data Management Team

Tom Wagg,
Hybrid catalogs & NEO estimates

Joachim Moeyens,
UW grad
THOR algorithm



Aditi Chauhan
UW undergrad (-> Axon)

Zach Langford,
UW undergrad (-> UPenn grad)

Bryce Kalmbach
LSST postdoc @ UW

Ari Heinze
HelioLINC+ codes

Stephen Portillo, 2018 DiRAC Fellow
Barycentric KBMOD stacking
-> Concordia U. Prof.

Pedro Bernardinelli,

2021 DiRAC Postdoctoral Fellow

Eli Lingat
UW undergrad

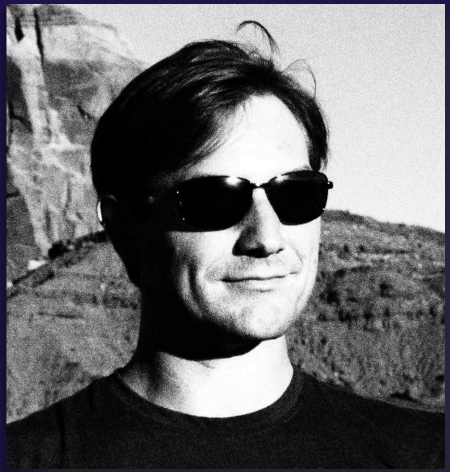
Lynne Jones et al.
Rubin Performance Scientist
UW -> AURA

Colin Chandler
LINCC Postdoc & PS
Active Asteroids

Sam Cornwall, Rubin Sims
UW undergrad (-> UIUC grad)

Aidan Berres
UW undergrad (-> UIUC grad)

Siegfried Eggl, HelioLinc 3D
UW -> UIUC Prof.



Petter Whidden, Hayden Smotherman
-> NY Times -> Northrop Grumman

Maria Chernyavskaya
UW undergrad (-> NAU grad)

Yasin Chowdury
UW undergrad

Steven Stetzler
UW grad
DECat Processing & sub-threshold detection algorithms

Sarah Greenstreet, DiRAC Scientist
Lead of the SSSC NEO+ISO WG
UW -> NOIRLab (2024)