NSF's NOIRLab

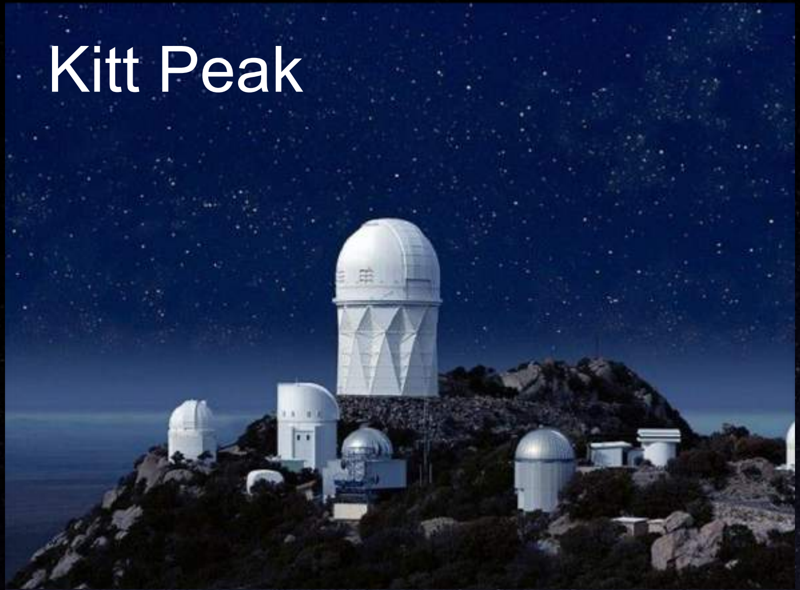
Present and Future Impact on Studies of Small Bodies in the Solar System

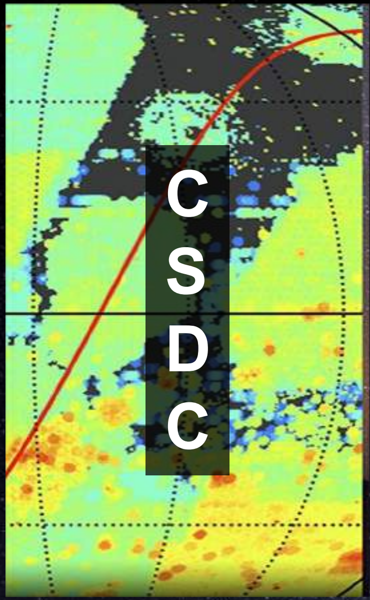
Patrick McCarthy, Mario Juric
Bob Blum, Zeljko Ivezic
and
Heidi Hammel

March 31, 2021

Planetary Science Decadal Panel on Small Bodies

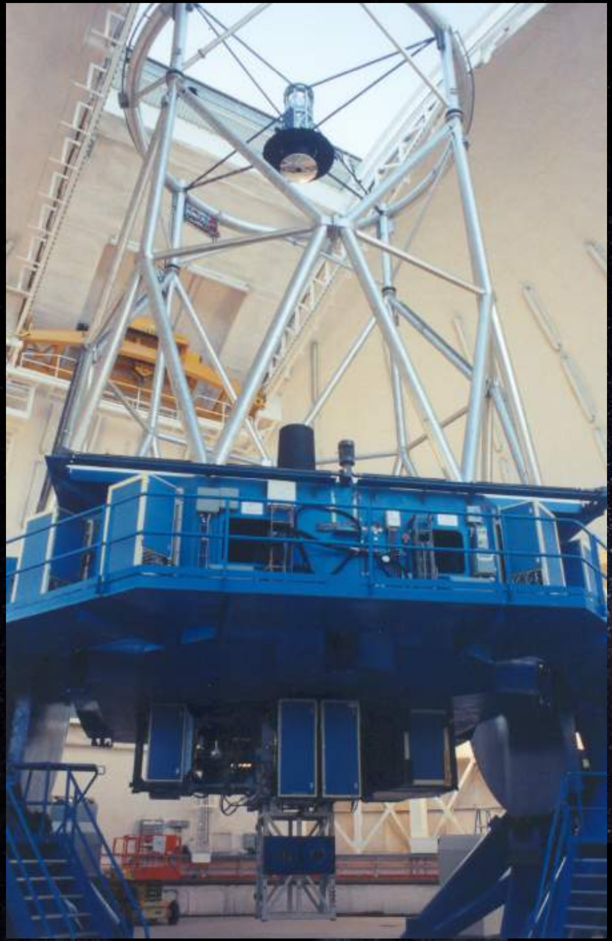
NSF's NOIRLab

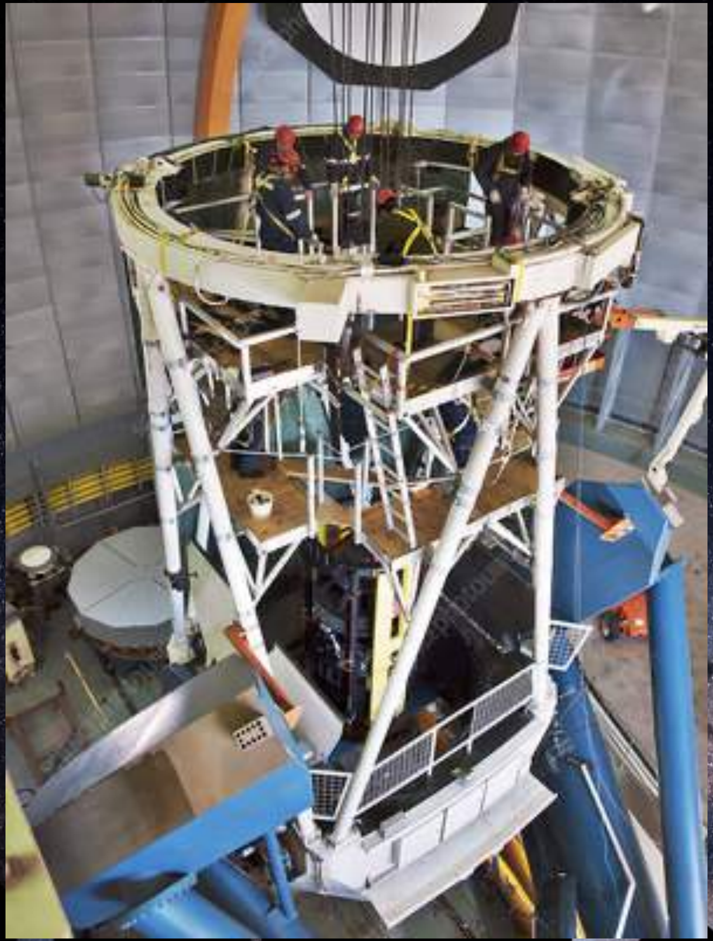




Discovering Our Universe Together

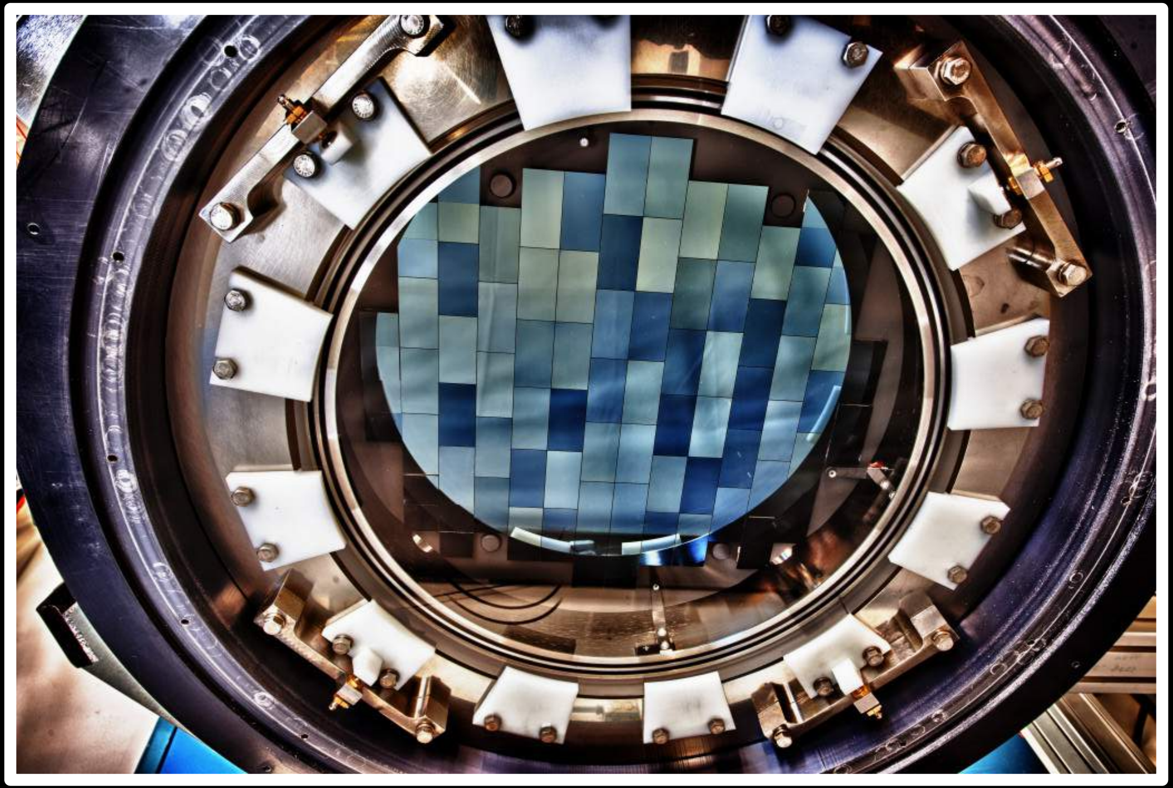
Observing Assets





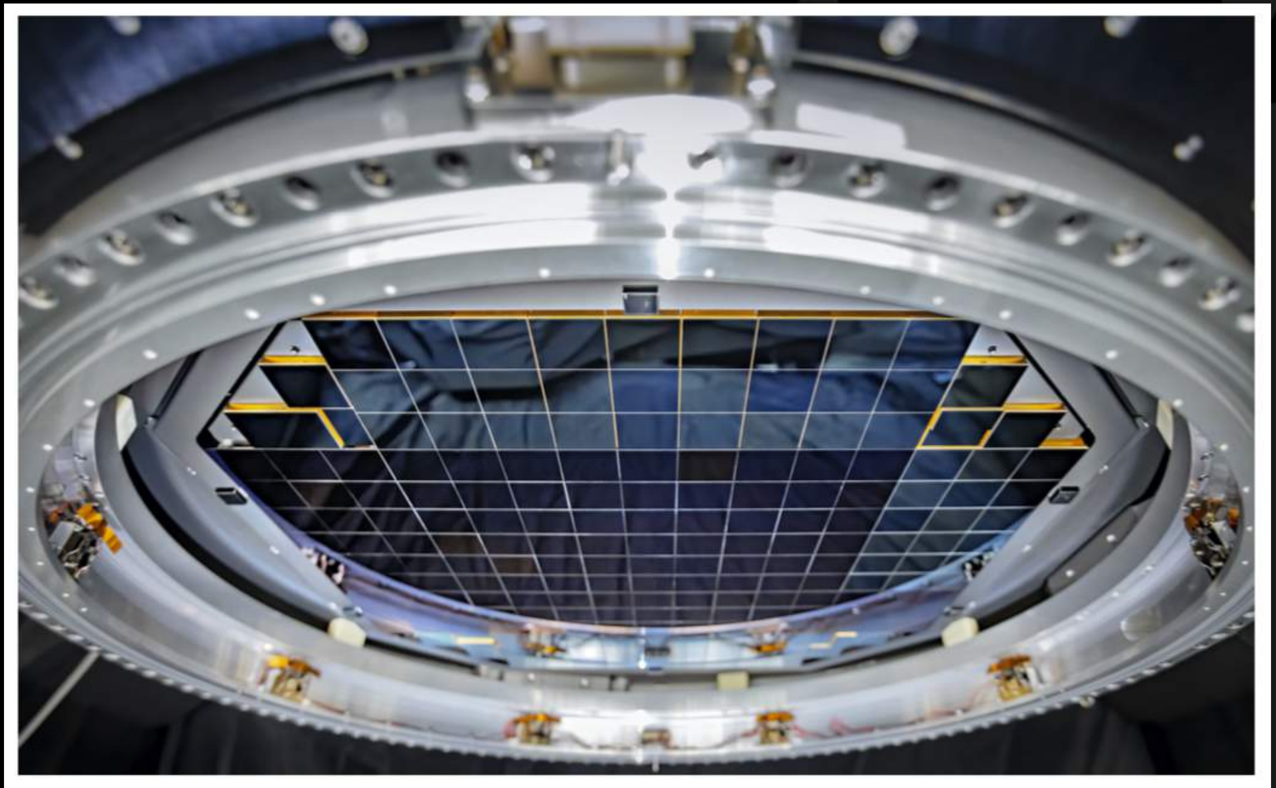
Coming Soon!

Wide Field Imagers on 4m and 8m



Dark Energy Camera on the Blanco 4m telescope

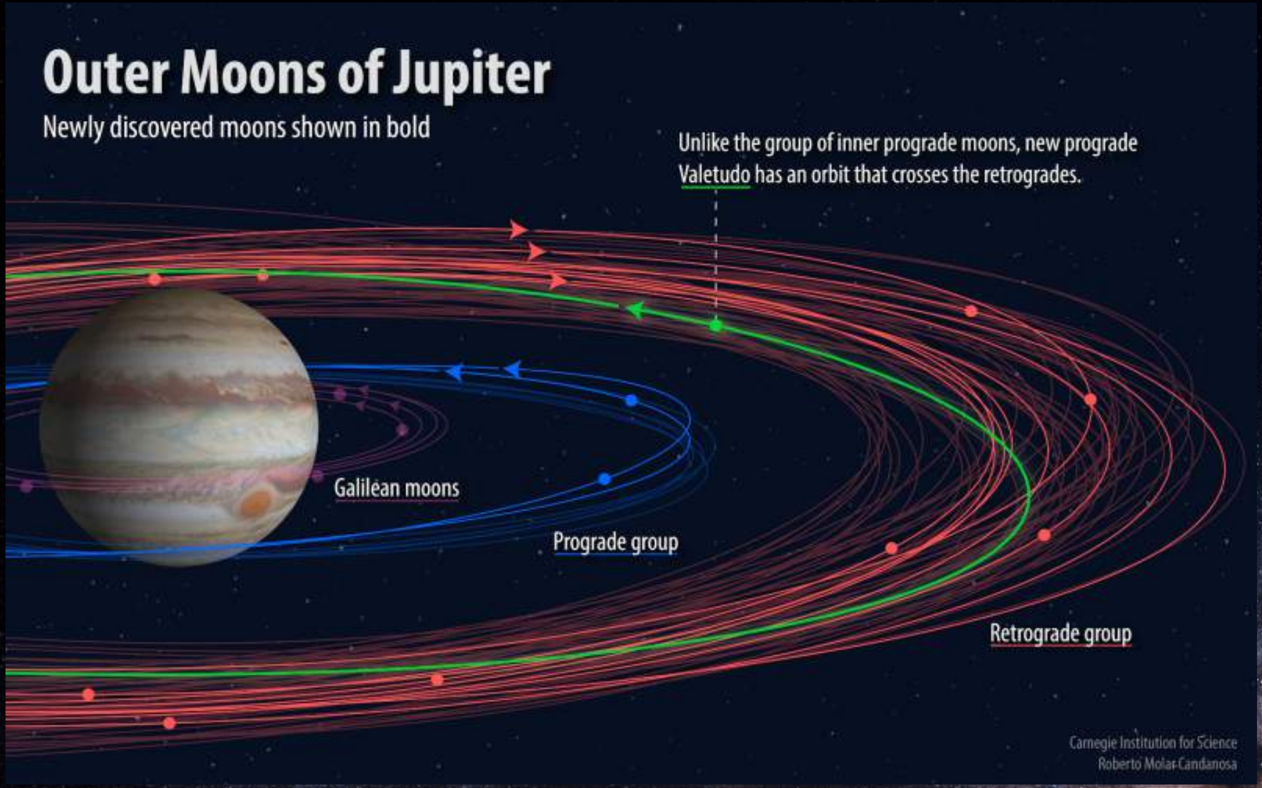
500 M pixels
2.2 degree field of view



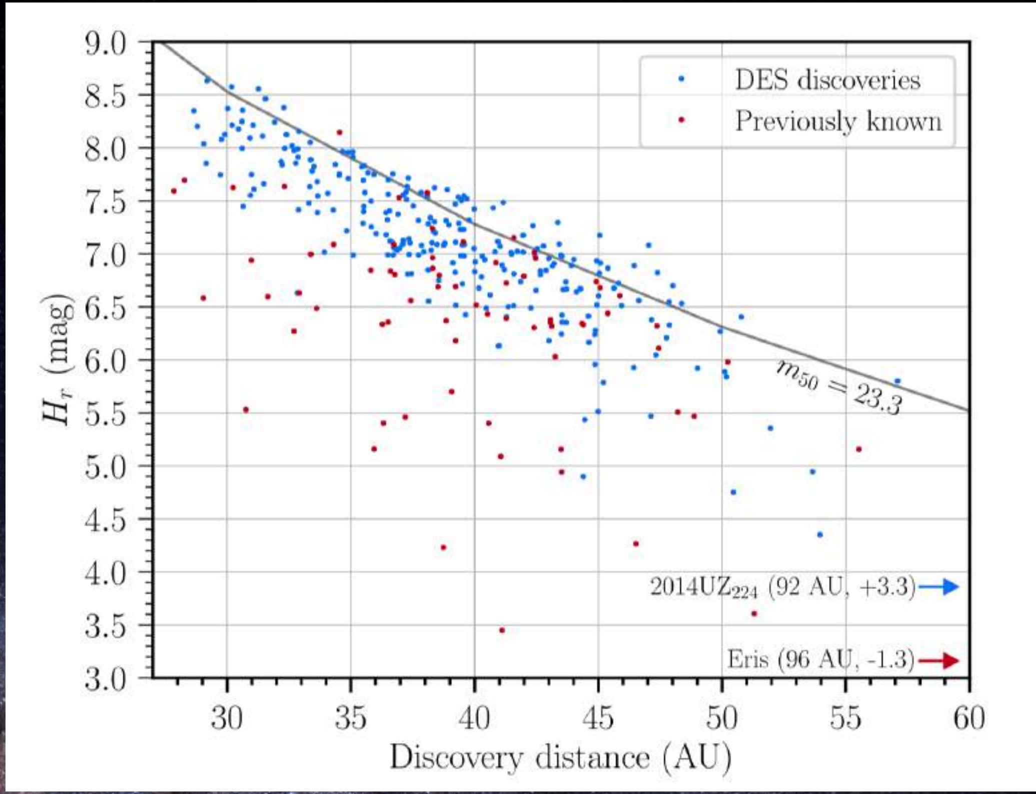
LSST Camera on the Rubin 8m telescope

3,200 M pixels
3.5 degree field of view

DECam – Satellites, TNOs, KBOs



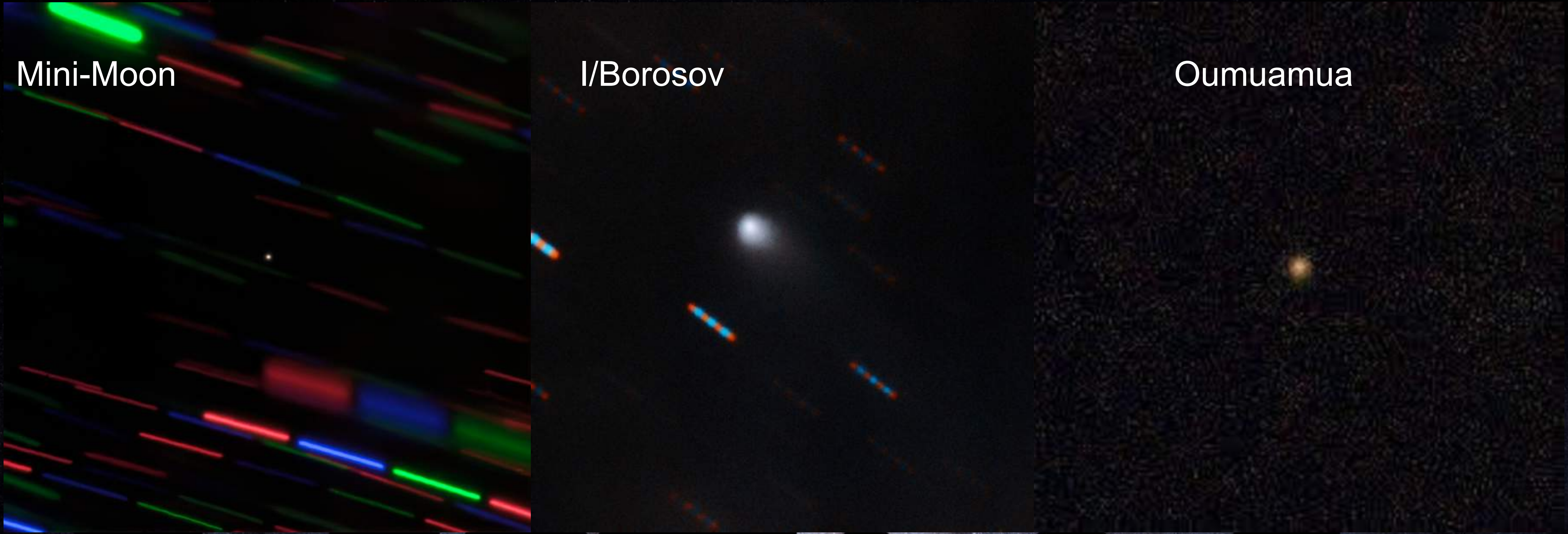
New Jovian Satellites
Shepard et al. 2018



TNOs from Dark Energy Survey
Bernardinelli et al. 2020

Small Bodies – Near and Far

Multi-Color Imaging with Gemini



Trouble on the Horizon

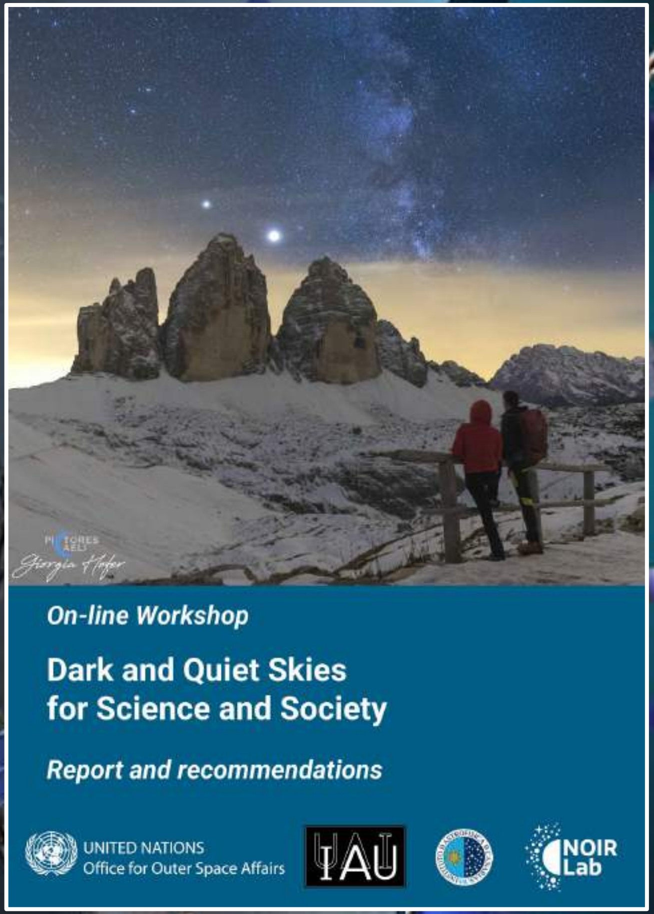


Image credit: Pete Marenfeld (NSF's NOIRLab)

Small Body Science with Rubin's Legacy Survey of Space and Time (LSST)

Mario Juric

Rubin Solar System Pipelines Construction Lead
University of Washington

for the Rubin Construction Project

Vera C. Rubin Observatory

An 8.4m optical survey telescope, on Cerro Pachón, Chile

3.2Gpix, 2-second readout camera (ugrizy filters, 0.2”/pix)

Site construction began April 2015

A 10 year LSST survey
starting in Oct. 2023

Photometry: 0.5-1% (systematic)

Astrometry:

10mas (rel), 50mas (abs)
~140mas at SNR=5, r~24
(calibrated to Gaia)

Timekeeping:

1ms (rel), 10ms (abs)

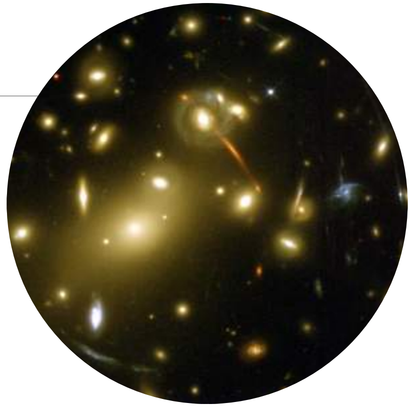
Total Eclipse over Cerro Pachon, July 2, 2019
Photo: K. Reil LSST/DOE/SLAC

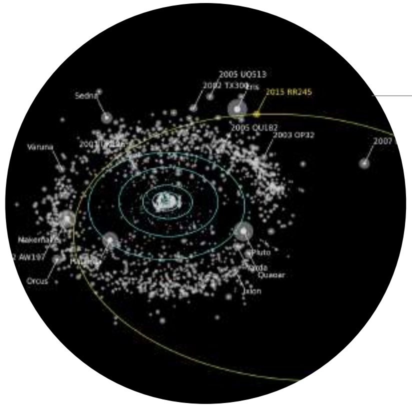

Rubin Observatory, March 2021.
BURGER

LSST Science Themes

Probing Dark Matter & Dark Energy

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



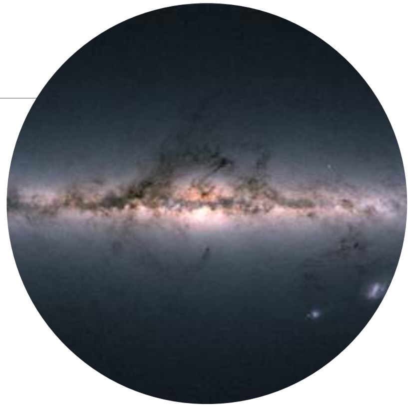


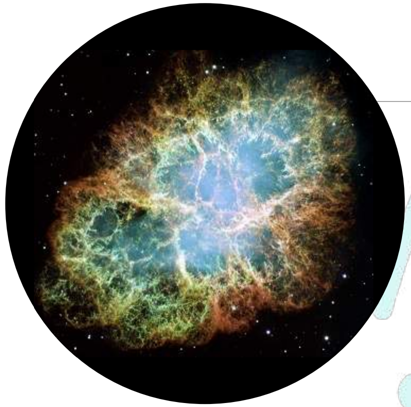
Inventory of the Solar System

- 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

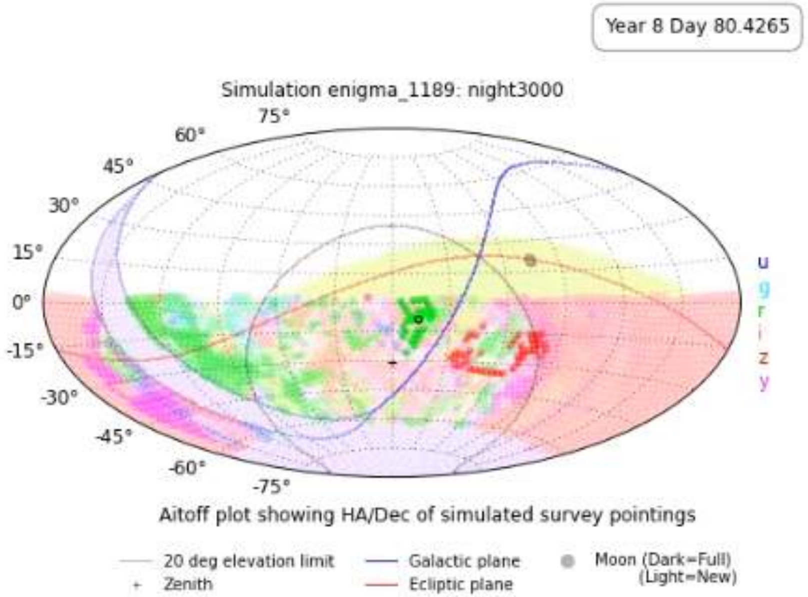




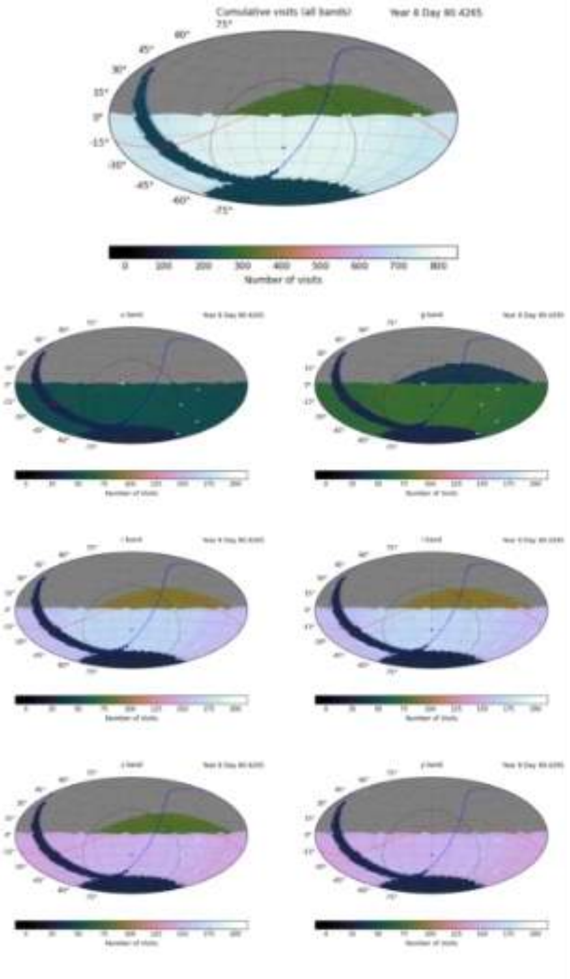
Exploring the Transient Optical Sky

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

A single uniform survey of the visible sky



Aitoff plot showing HA/Dec of simulated survey pointings



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~24^{th} 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.

Data Products for Small Body Science

I. Real-Time Alerts within 60 sec

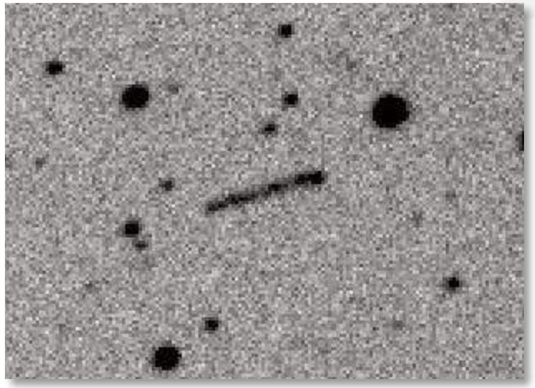
A. Real-time Alerts (>=2M SSO observations/night)	
Astrometry	±10 mas (bright; ±140 faint)
PSF flux	±10 mmag (bright end)
Aperture flux	±10 mmag (bright end)
Trailed source fit	Flux and on-sky motion for fast-moving (trailed) objects
Appearance characterization	Moments and extendedness of the object's 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

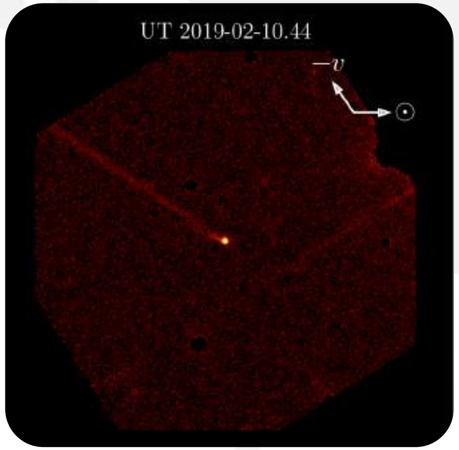
Measurements of all detections on difference images, including known and unknown SSOs.

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

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.

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.

Enabling Solar System Science

(a selection of opportunities)

Discovery *and characterization* mission

Animation: SDSS Asteroids (Alex Parker, SwRI)

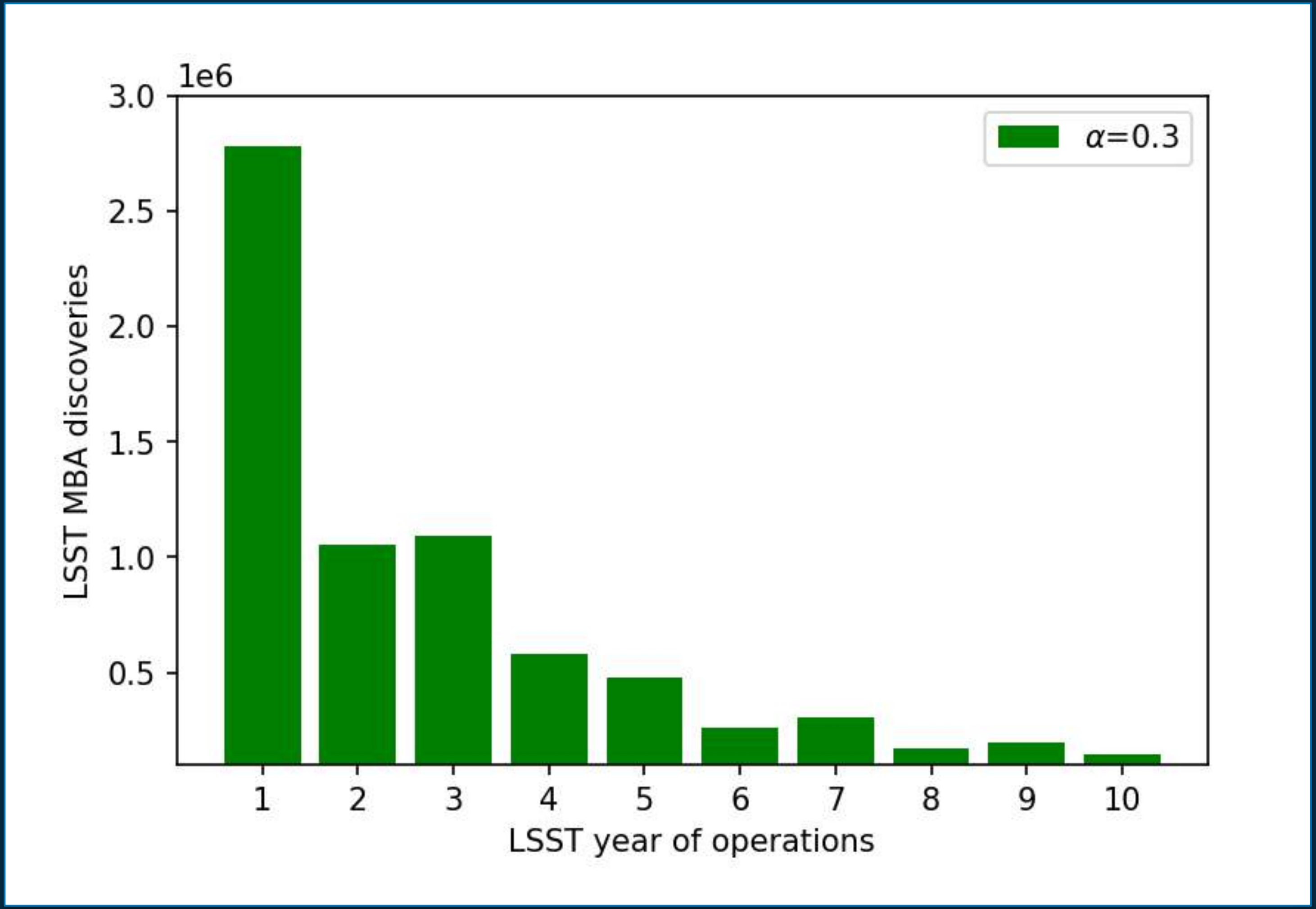
Estimates: Lynne Jones et al.

The LSST will 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 <u>well-characterized</u> (orbits, light curves, absmag estimates), and discovered with an exceptionally well understood selection function.

80% of discoveries occur early (~ 2023-2026)

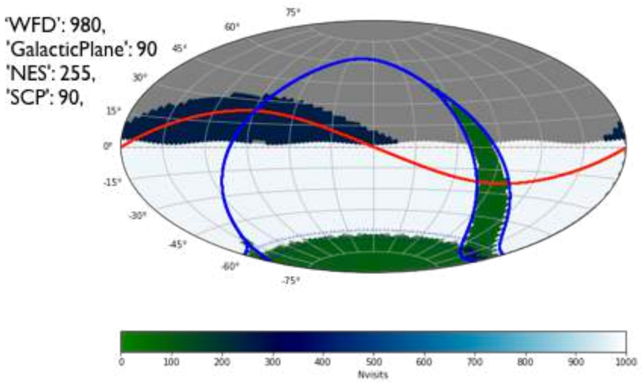


Most Solar System discoveries occur early in the survey (first ~3 years).

Exceptions are some sub-populations of NEOs, ISOs, and science that requires many re-observations.

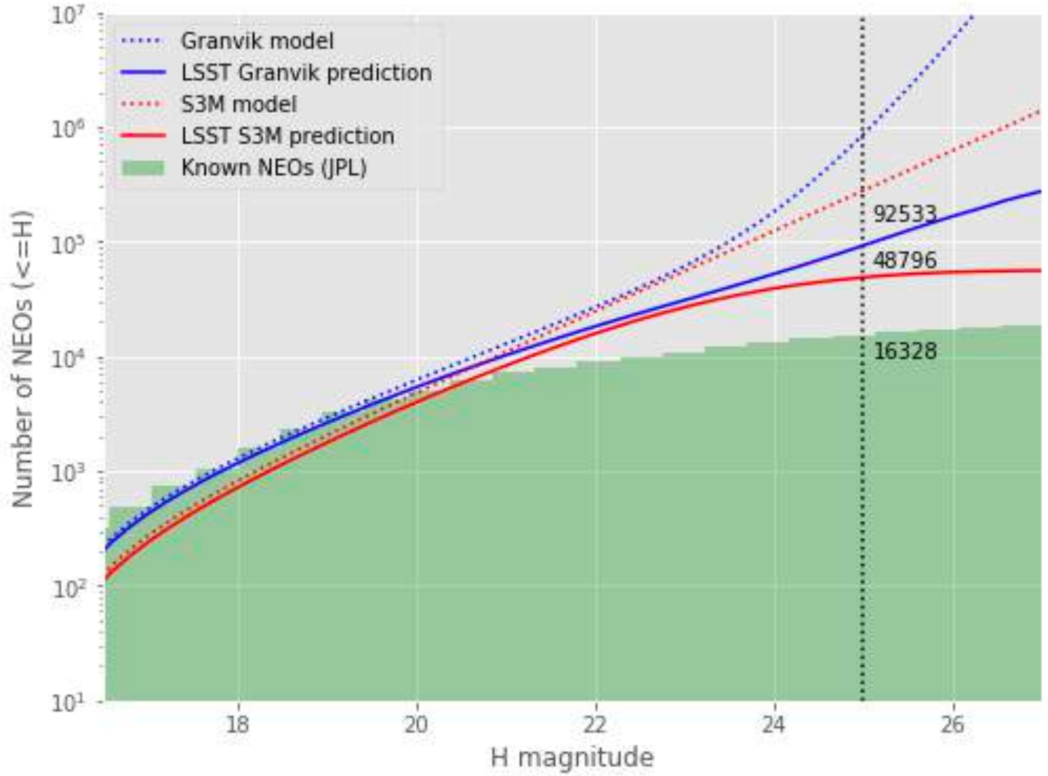
→ ***LSST will immediately enable significant small-body science.***

Rubin will Drive the NEO Discovery Rates through the 2020s



In current baseline strategy, after 10 years:

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



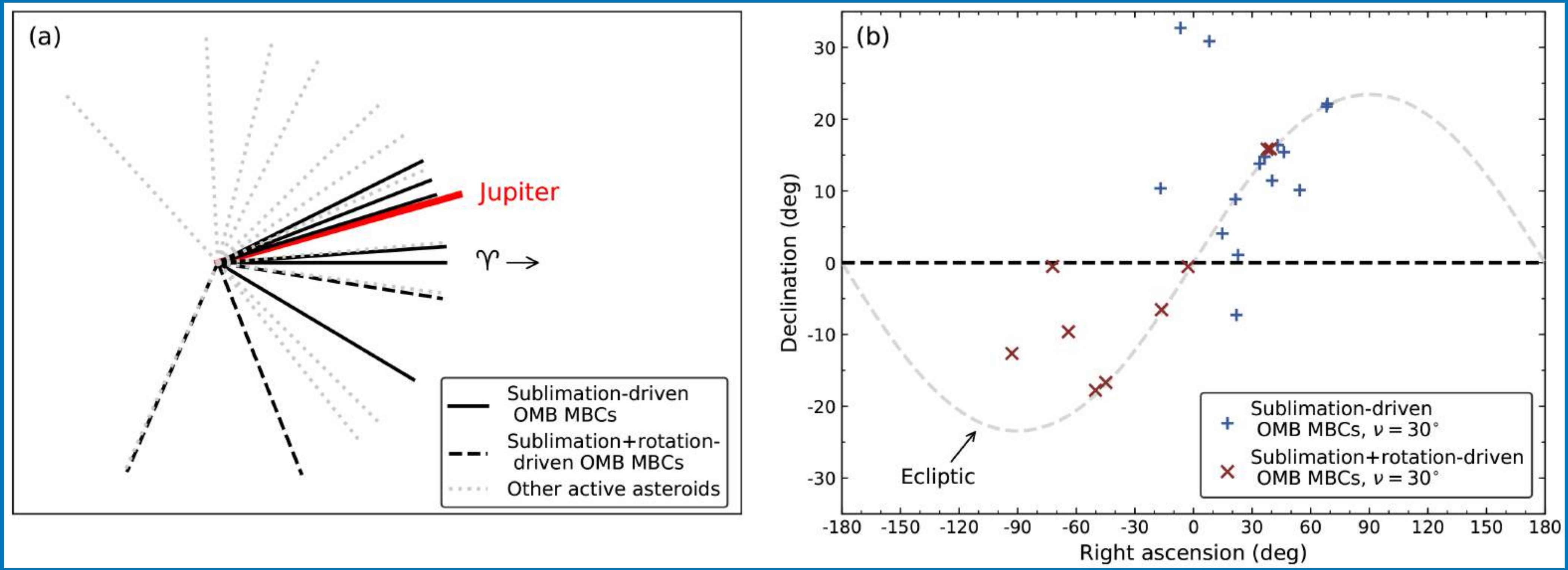
S3M - Grav et al 2011; Granvik - Granvik et al 2018

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

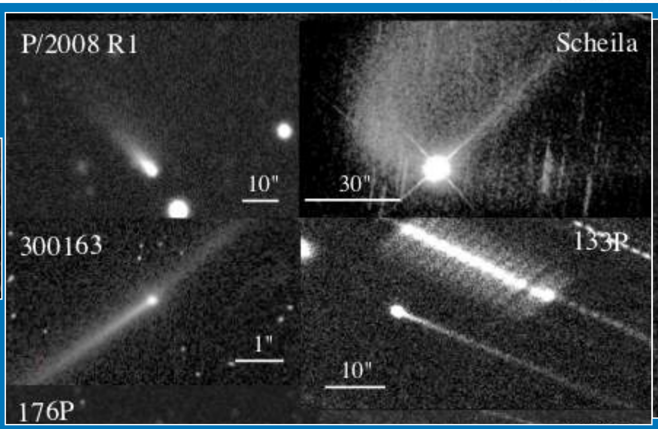
Measurement of the orbital, absolute magnitude, and taxonomy distributions within the NEO population, enabling the identification of correlations between taxonomy and orbital properties for all NEOs and the determination of the orbital distribution of fifty-meter+ scale objects

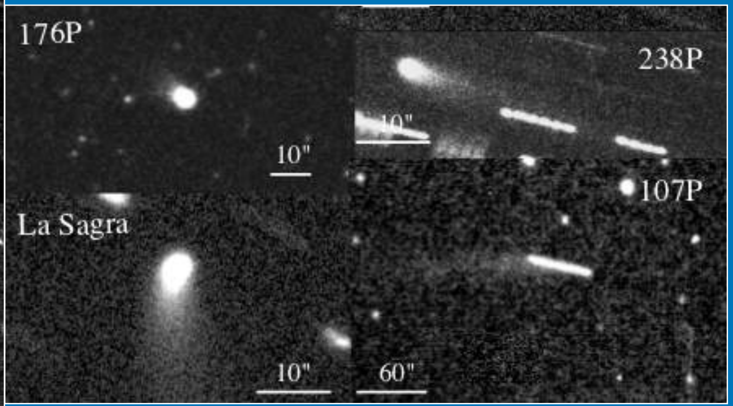
Assuming 15% albedo: H=25 -> D=50m | H=27 -> D=15m

Explore the Origin of Main Belt Comets and Active Asteroids



Ki et al (2018).Adapted by Henry Hsieh





Jewitt (2012)

Nightly monitoring of ~0.5-1M asteroids for activity.

Figures contributed by Meg Schwamb (SSSC)

Science Opportunities: Outer Solar System

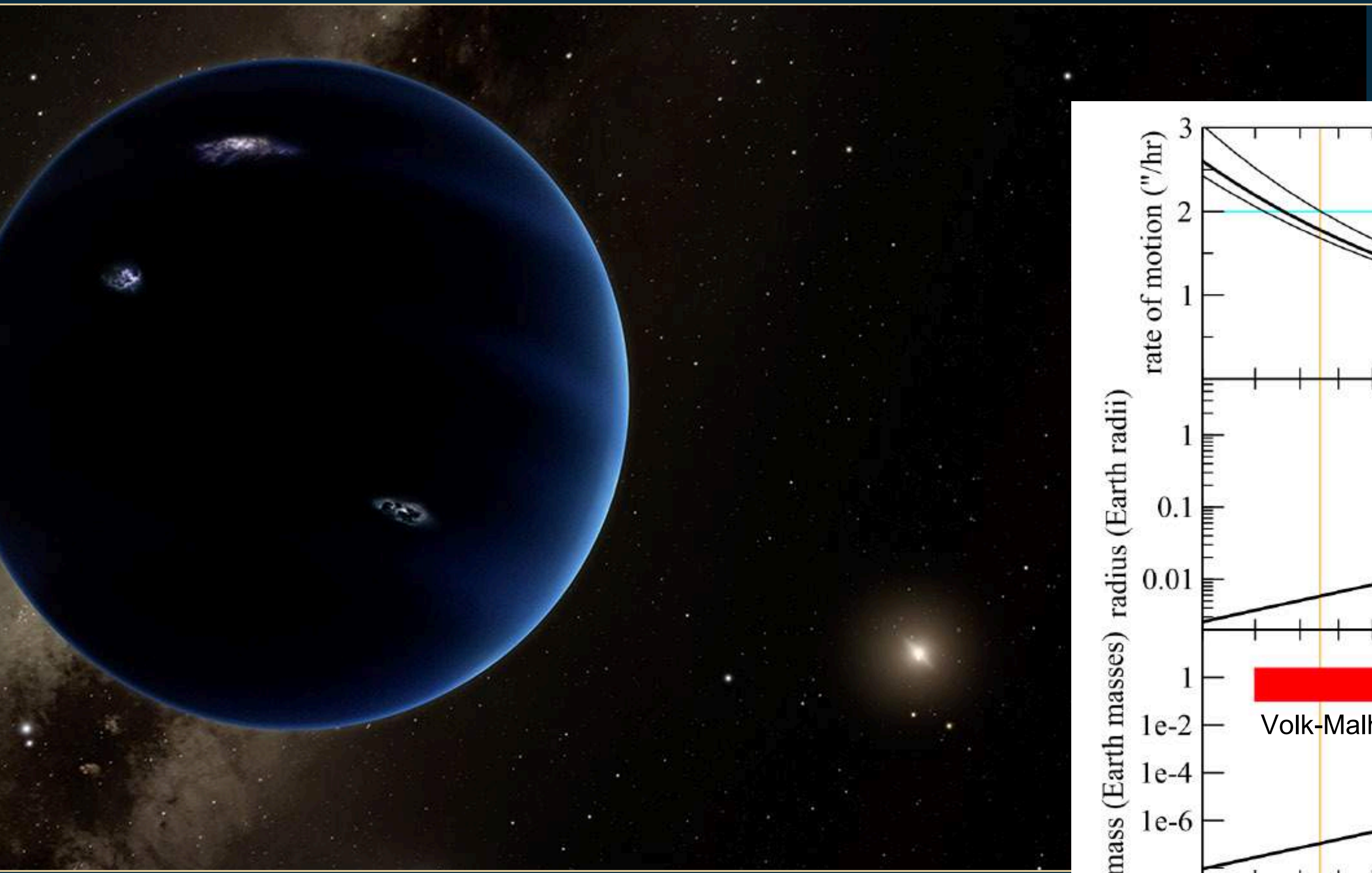
VERA C. RUBIN OBSERVATORY

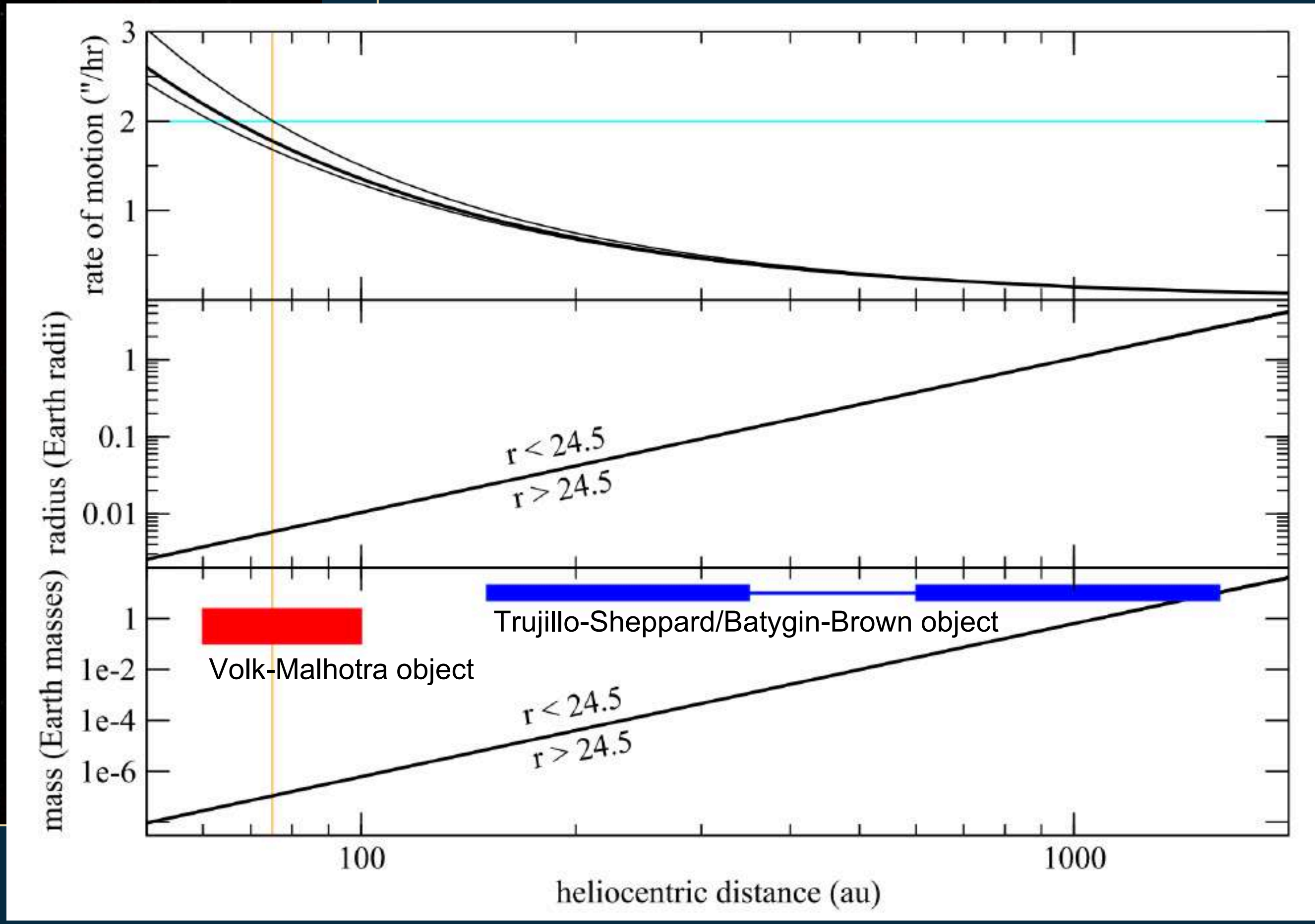
1. Characterizing the size-frequency-orbit distribution of KBOs (H>9), probing the formation and evolution of the outer solar system
2. Discovery and orbital classification of objects on unusual or extreme orbits, especially inner Oort cloud objects (i.e. Sedna-like objects) with high perihelia (q > 40 au) and objects with very high inclination (i > 40 deg).
3. Colors for large numbers of KBOs and correlations with dynamical information; understanding the formation of the outer solar system (e.g., chemical distribution in the primordial disk; collisional families).
4. Determination of rotational light curves for large numbers of objects from different dynamical classes; physical properties of KBOs, including spin angular momentum distribution and binary frequency.
5. Discovery and orbital classification of large numbers of objects in resonance with the giant planets, especially the libration islands of high-order resonances of Neptune; constraints on models of Neptune migration.
6. Discovery and clear characterization (e.g., PSF shape) of binaries and multiple systems wide enough to be resolved or partially resolved.

Schwamb et al., "Large Synoptic Survey Telescope Solar System Science Roadmap"
https://arxiv.org/abs/1802.01783

Planet(s) 9+

Rubin will directly and exhaustively survey ~60% of the sky for the proposed unknow planets, and indirectly set strong constraints on their (non)existence by characterizing the KBO population.



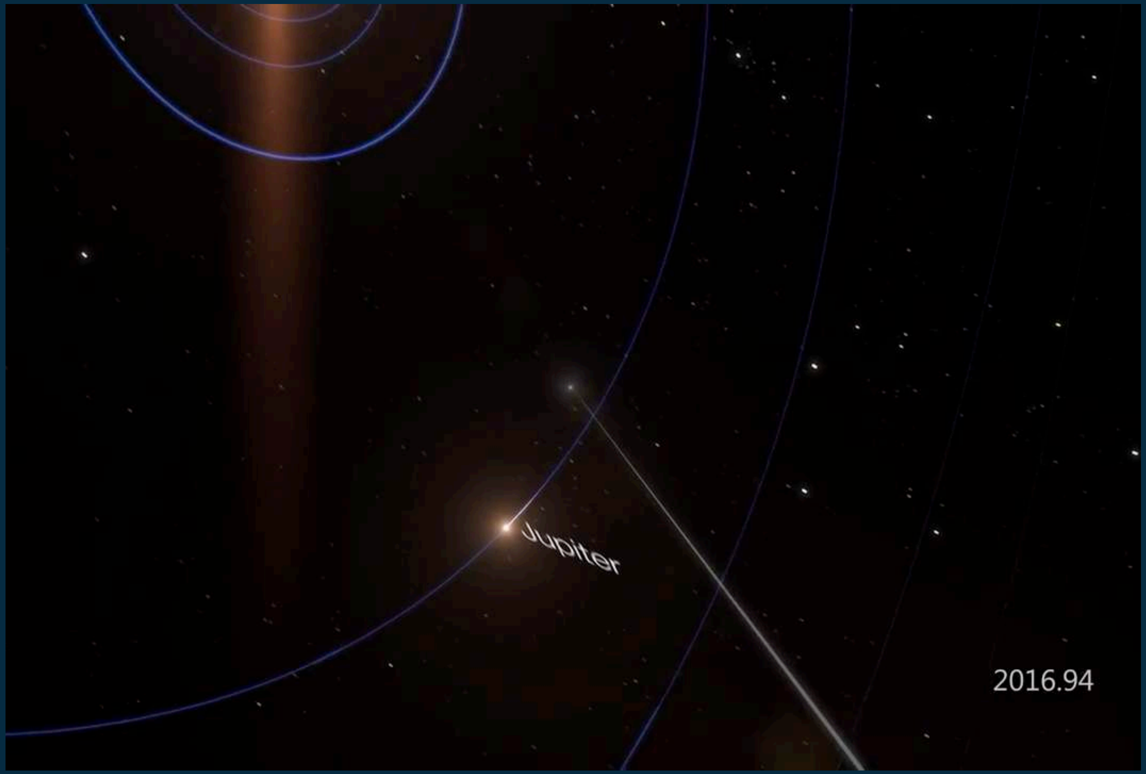


Trilling, Bellm, & Malhotra (2018)

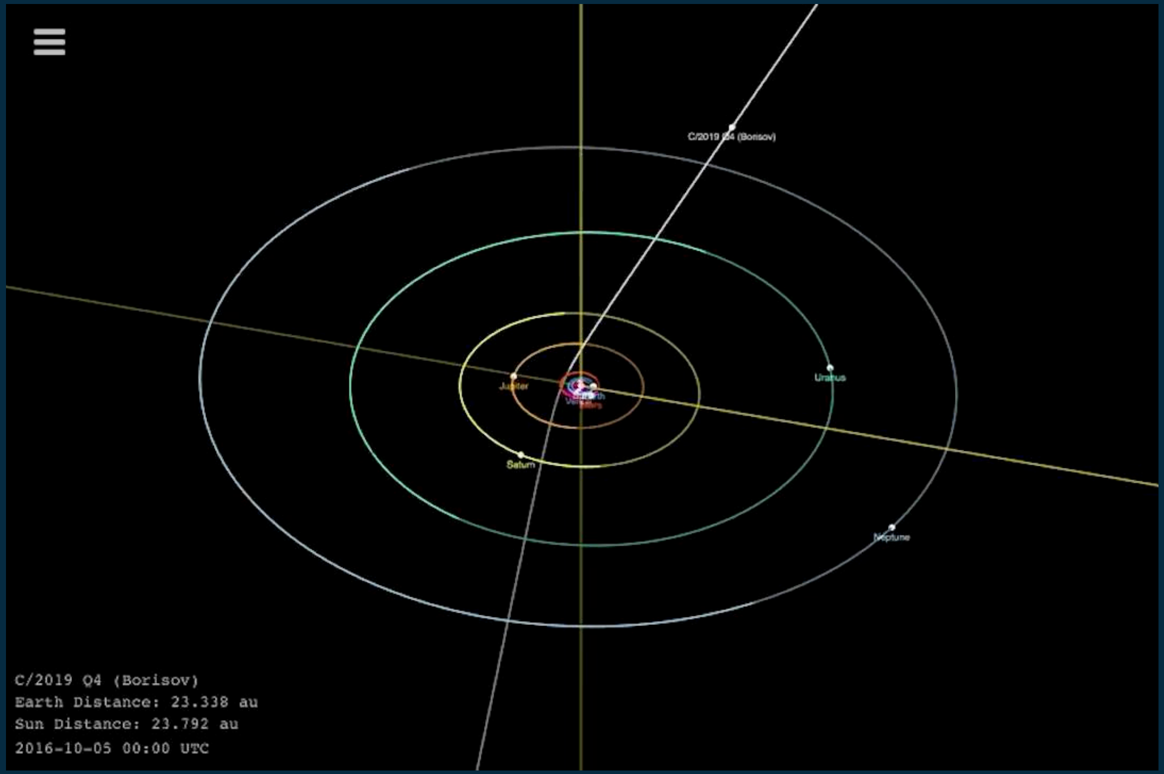
Interstellar Objects: O(10+)

We expect Rubin to discover >= 1 interstellar object per year.

1I/2017 U1 (‘Oumuamua)



C/2019 Q4 (Borisov)



https://www.youtube.com/watch?v=iwv1RxtsmA0

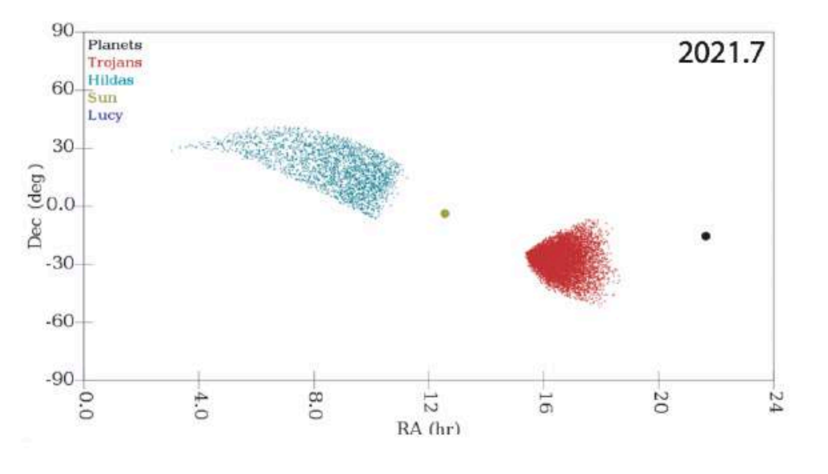
Credit: ESO, M. Kornmesser, L.Calcada.

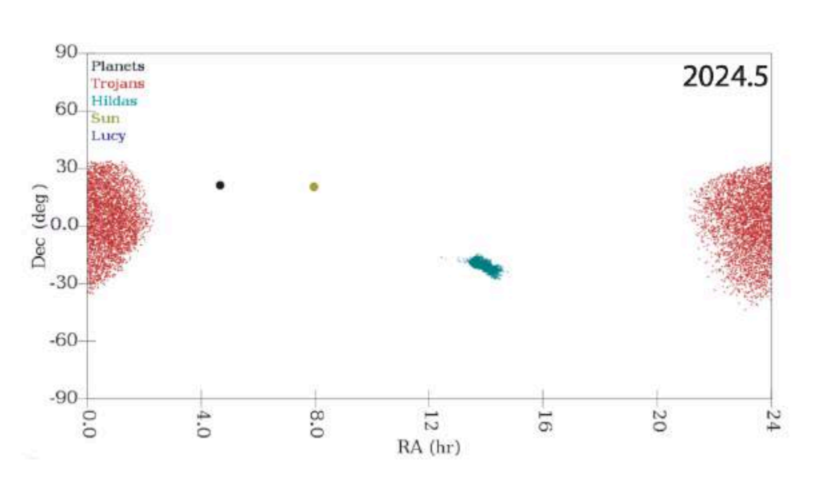
https://www.youtube.com/watch?v=vqMJo3DHOfg

Credit: NASA/JPL-Caltech and Steve Spaleta (Space.com)

Synergies with other missions

- **NEO Surveyor**
  - Expected to launch in or after 2025, NEO Surveyor will provide NIR observations and add to discoveries of NEOs.
- **Lucy mission**
  - Opportunities for identifying additional Lucy targets in Trojan and Hilda populations.
  - See Schwamb, Levison and Buie for details (https://arxiv.org/pdf/1808.10099.pdf)
- **Roman Space Telescope**
  - TOO opportunities for Roman
  - Follow-up of planet-sized KBOs in the Galactic Plane
  - Complementary sky coverage
  - (https://arxiv.org/pdf/1709.02763.pdf)
- **Comet Interceptor**
  - A mission to intercept a comet; LSST likely to discover its target
  - (details on slide in Supplementary Information)





Discovery opportunities for Lucy targets (Schwamb, Levison, and Buie 2018)

Looking Ahead

Supporting Solar System Science with Rubin / LSST

- Rubin facility and operations are already funded, but science investigations are to be competed through usual grant calls (e.g. NASA/SSO or NSF/AAG). It's proven challenging to fund preparatory work needed to maximize community readiness for first LSST science (e.g. software pipelines, simulations, collaborations).

- If the U.S. community is not adequately prepared for Rubin data on Day 1, there's a chance of rare discoveries (ISOs, NEOs, …) being missed or relinquished to international research teams (given the Solar System data are immediately public).

- A targeted funding framework, or explicit review criteria to encourage support of preparatory work for LSST and early LSST Solar System, would be a significant step in mitigation of this issue.

Summary – Rubin and Small Bodies

- Rubin Observatory construction is nearing completion. First light is expected in 2022, with the start of LSST survey operations expected in October 2023.

- Once operational, the LSST will become a prime source of discoveries and data for small bodies of the Solar System, enlarging the known samples of various populations by 5x-30x. It will deliver targets for follow-up observations and intercept missions, as well as catalogs to future missions can add to (e.g., Roman or NEOSM’s IR observations).

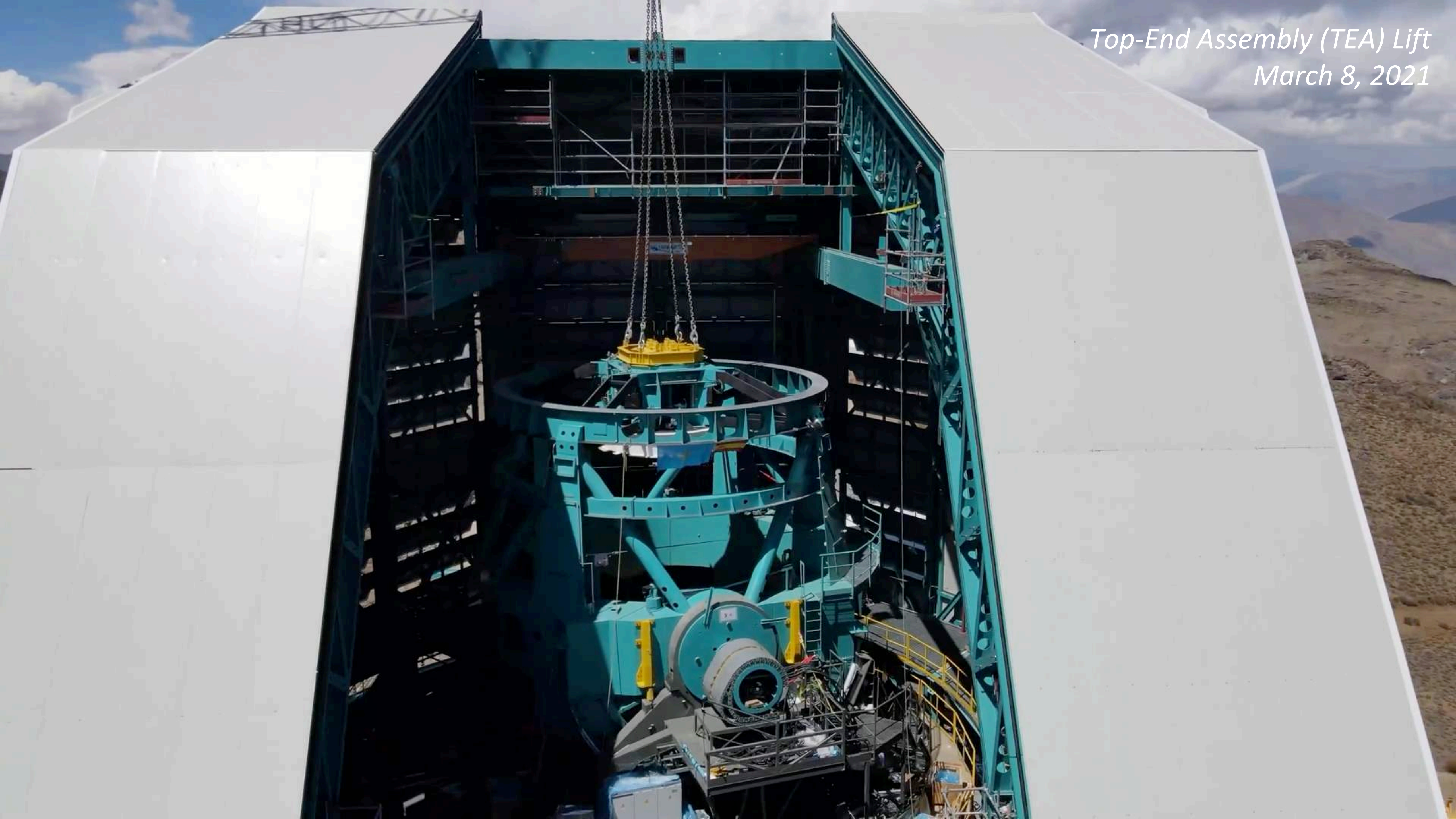
- A remaining challenge is to prepare the U.S. Solar System community for the arrival of Rubin data so they are utilized to their full potential. A targeted funding framework, or explicit review criteria encouraging funding of preparatory work for LSST and early LSST Solar System science may help alleviate this issue.

NOIRLab and Planetary Science

Assets funded by the DOE to support Dark Energy science are now key capabilities for studies of small bodies in the solar system

Where do we go next?

- Sustained support for operations and data analysis essential
- Many avenues and opportunities remain untapped
- Stronger connections between NSF's NOIRLab and the planetary community would be beneficial for all
- Inter-agency collaborations can ensure the long-term support needed for this science

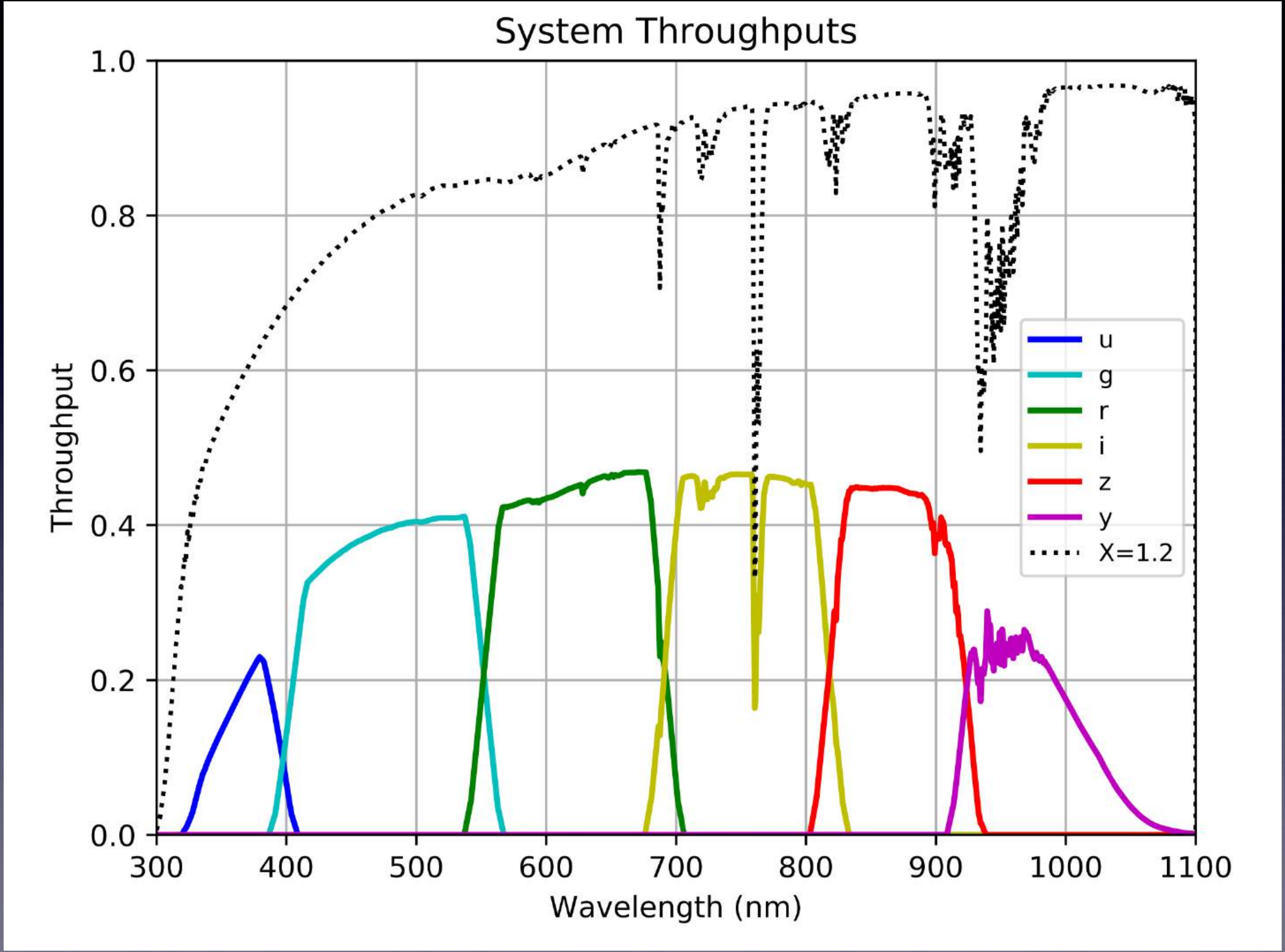

Top-End Assembly (TEA) Lift
March 8, 2021


THANK YOU
Discovering Our Universe Together

Supplementary Information

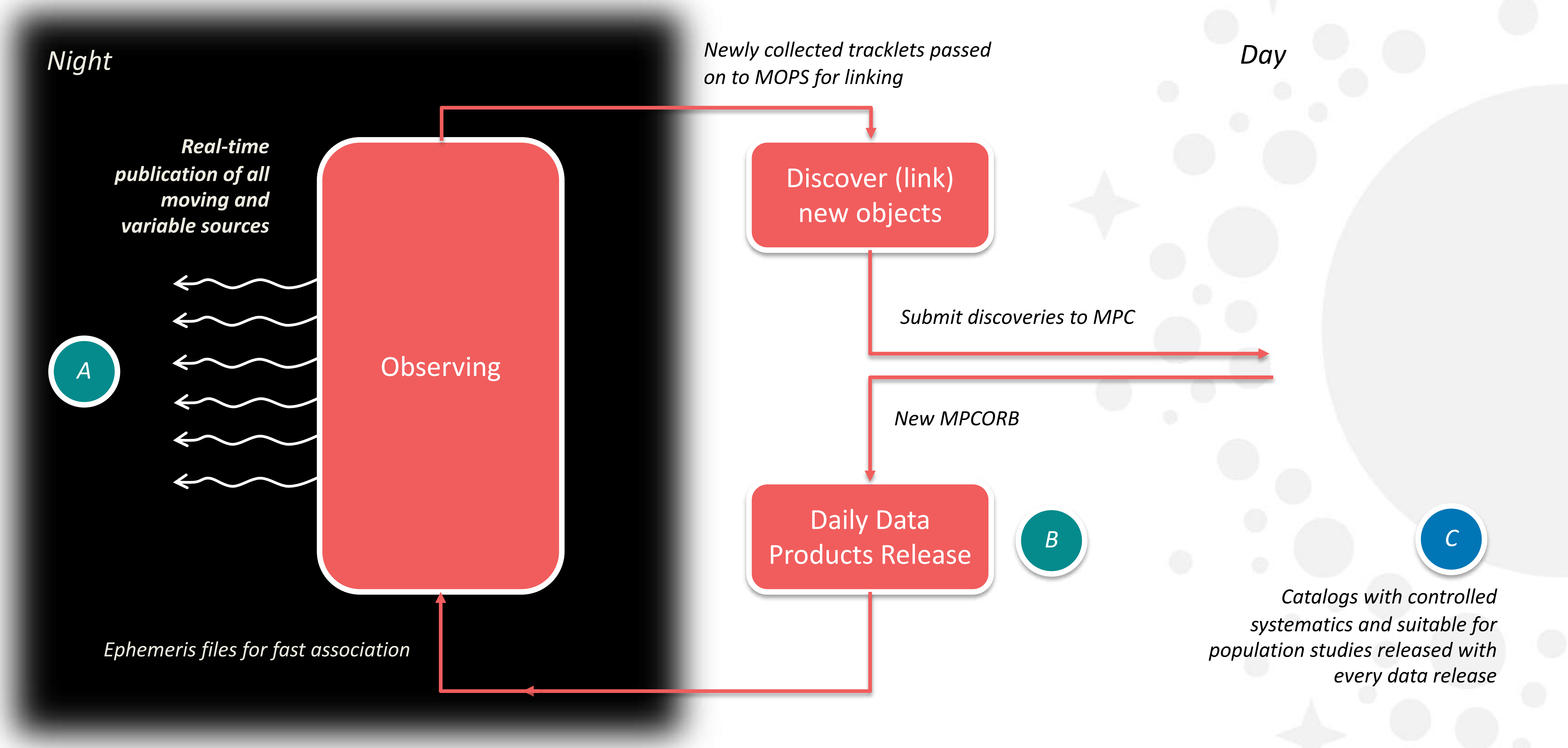
Table 1. The LSST Baseline Design and Survey Parameters

Quantity	Baseline Design Specification
Optical config.	Three-mirror modified Paul-Baker
Mount config.	Alt-azimuth
Final f-ratio, aperture	$f/1.234$, 8.4 m
Field of view, étendue	9.6 deg^2, 319 m^{2}deg^2
Plate scale	50.9 μm arcsec^{-1} ($0\farcs2$ pixels)
Pixel count	3.2 gigapixels
Wavelength coverage	320 – 1050 nm, $ugrizy$
Single-visit depths, design[a]	23.9, 25.0, 24.7, 24.0, 23.3, 22.1
Single-visit depths, min.[b]	23.4, 24.6, 24.3, 23.6, 22.9, 21.7
Mean number of visits[c]	56, 80, 184, 184, 160, 160
Final (co-added) depths[d]	26.1, 27.4, 27.5, 26.8, 26.1, 24.9
Median delivered image quality	0.8 arcsec



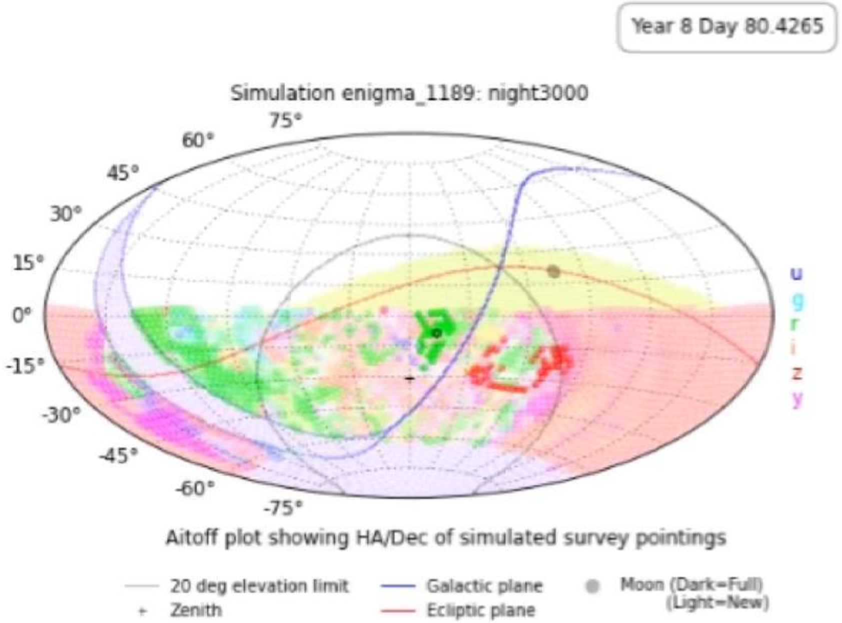
System Throughputs
1.0
0.8
0.6
0.4
0.2
0.0
Throughput
300
400
500
600
700
800
900
1000
1100
Wavelength (nm)
u
g
r
i
z
y
X=1.2

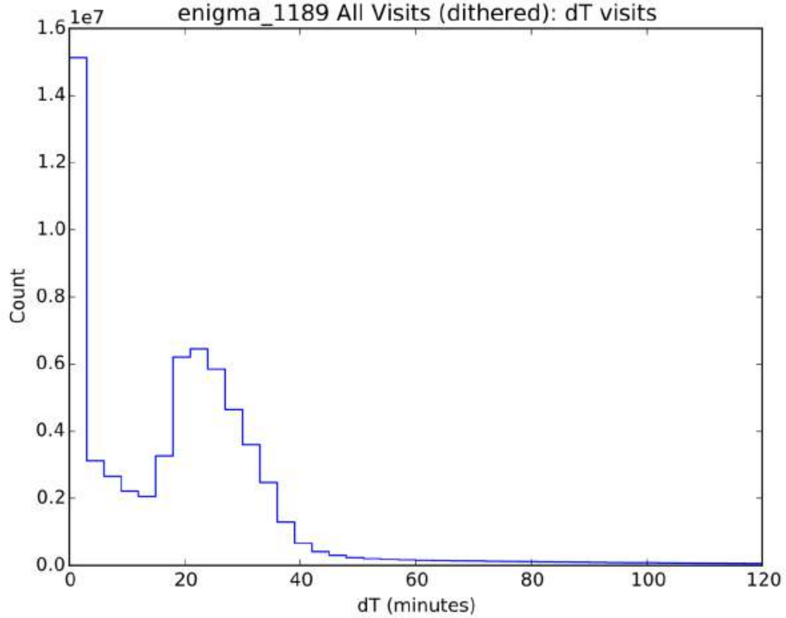
LSST Nightly/Daily Processing Loop

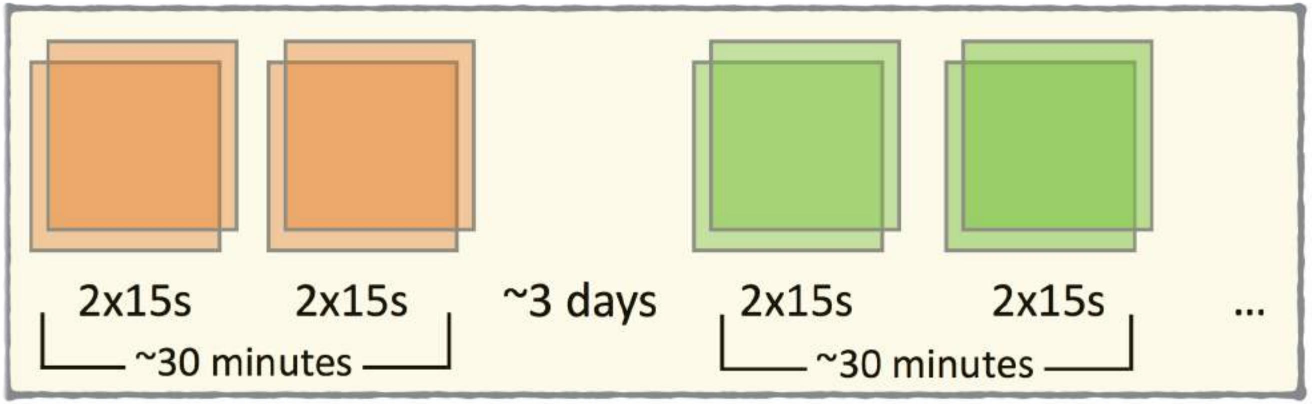


A one-page summary available at http://ls.st/Document-29545

Cadence Enabling Small Body Linking







1 visit = 2x15s back-to-back exposures

2 visits per night (30-60 minutes)

Revisit ~3-4 days

Asteroid Sizes with LSST: 20–25% accuracy (almost as good as IR)

Icarus 341 (2020) 113575

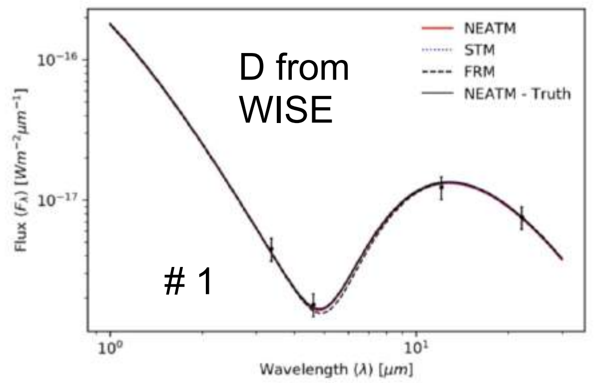
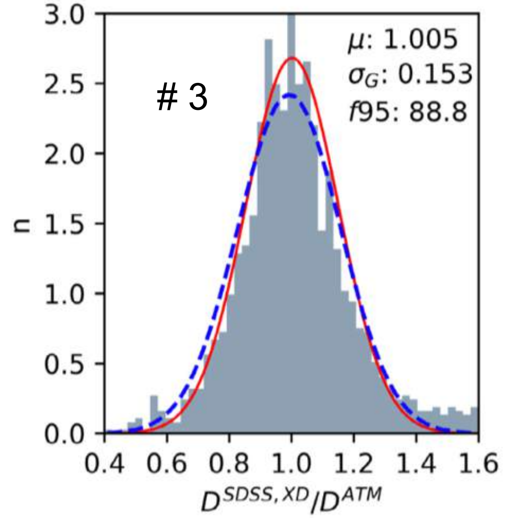
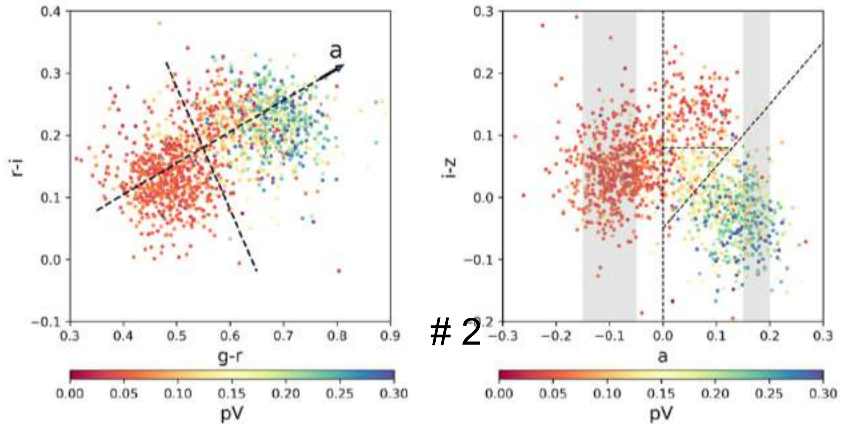


Fig. 1. The solid line shows the synthetic spectral energy distribution (SED) generated using the NEATM model for an asteroid with $D = 1$ km, $T_1 = 422$ K, $\epsilon(\lambda) = 0.7$, asteroid-Sun distance of 3 au, and an observer at 2 au from the asteroid. The four symbols with error bars correspond to the four in-band fluxes for the WISE observatory at the same distance from the asteroid. The error bars





1) D from WISE, H from SDSS: pV (visual geom. albedo)

2) pV strongly correlated with colors: ML mapping

3) SDSS-only estimates agree with WISE sizes with rms ~ 15%

WISE delivered sizes for 100k+ asteroids, accurate to about 15-20%

SDSS colors available for 40k+

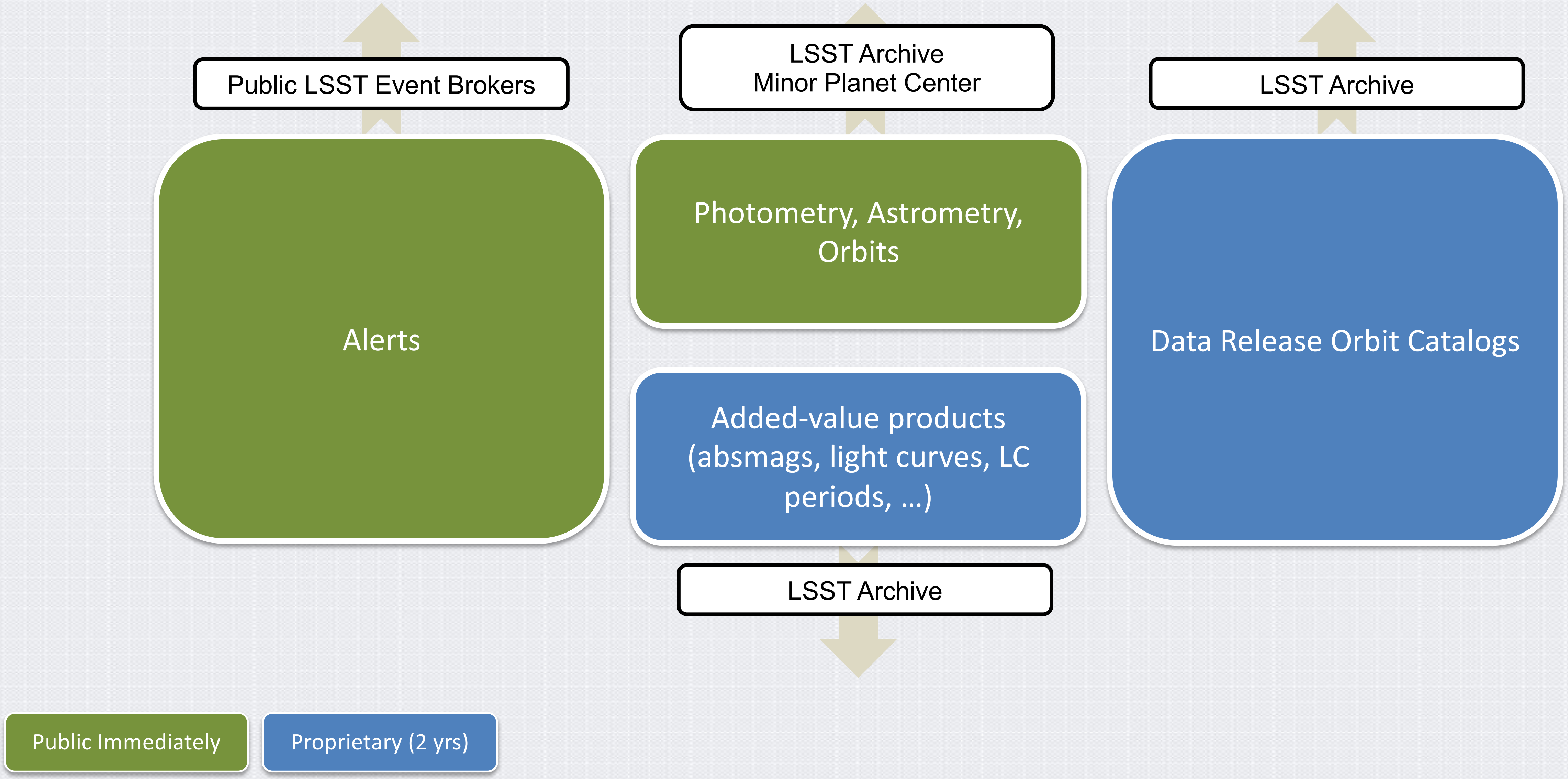
WISE + SDSS: visual albedo is strongly correlated with optical colors

Predictions for LSST: it will deliver sizes, calibrated with WISE dataset and accurate to 20-25% , for about 6 million asteroids.

Asteroid size estimates with LSST data will be only a factor of 1.3 to 1.4 less accurate than WISE-based size estimates

Details: Mainzer et al. (2012, 2015)
Moeyens, Myhrvold & Ivezic (2020)
Ivezic & Ivezic (2021)

Obtaining the LSST Solar System Data Products



Solar System Data Products

Prompt Products

A

Alerts

B

Daily Solar System Object Catalog

C

Data Release Orbit Catalogs
(~yearly)

Data Release Products

Production cadence

~1 minute

~24 hours

~1 year

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

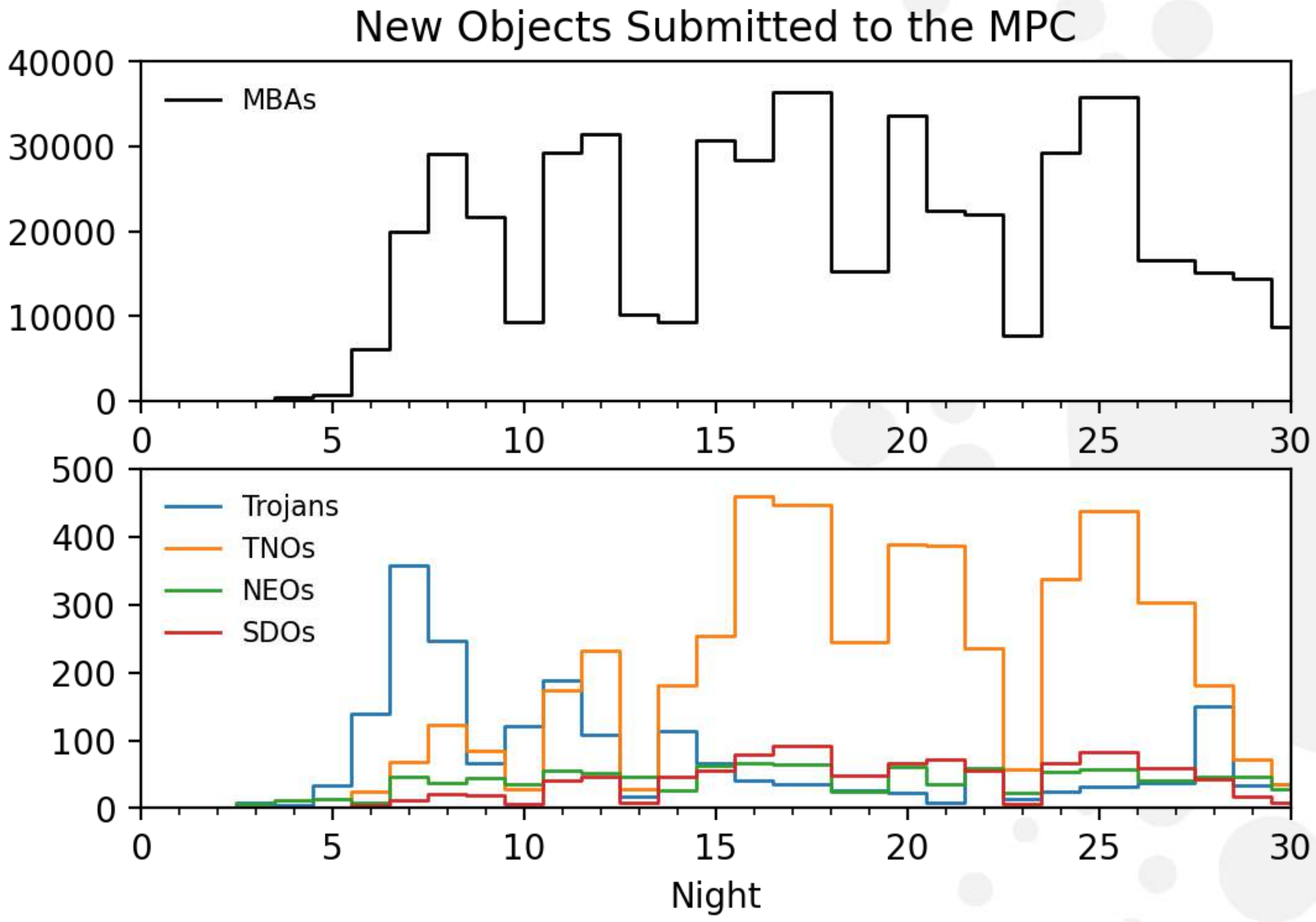
Integration with the Minor Planet Center

Ran a successful initial integration test with the Minor Planet Center (October 2020)

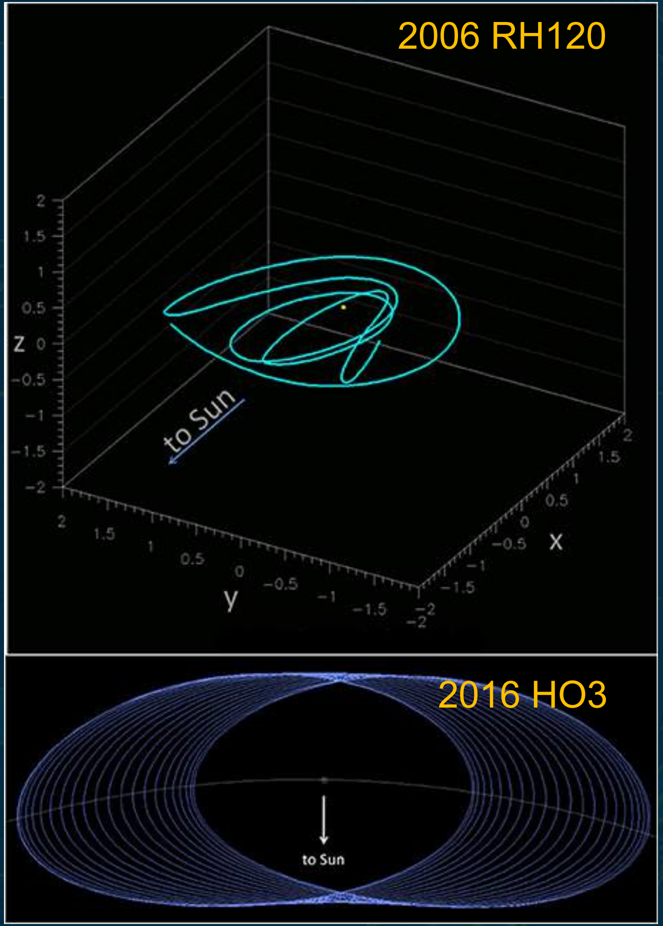
Made mock, full-size, submissions for the first three weeks of the LSST survey (ADES PSV format). **A typical night early in the LSST will bring 17,000 new discoveries.**

The MPC accepted and manually processed the submissions, through to the generation of a new MPCORB catalog. **The process took approximately 4 hours.**

No architectural bottlenecks identified; assuming MPC capacity is enlarged as expected no significant problems.

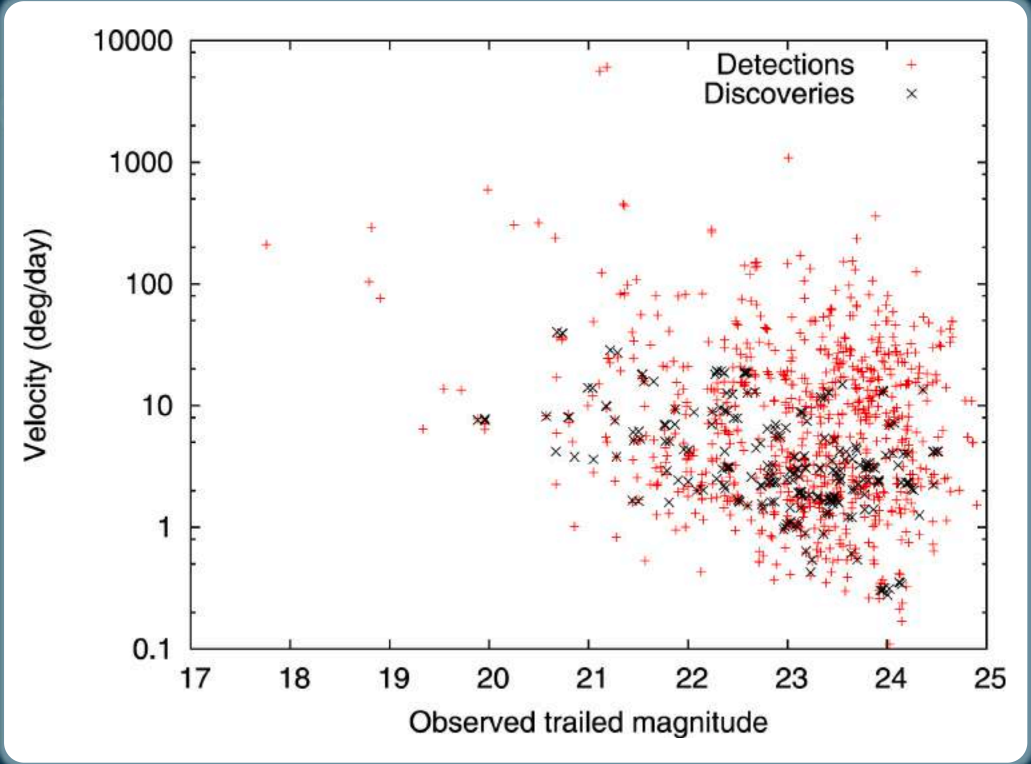


Temporarily Captured Objects (“Minimoons”)



Jedicke et al. (2018)

- Meter-sized bodies temporarily captured by the Earth/Moon system. LSST will discover >= 1/yr.
- Material properties.
- In-situ measurements and retrieval.



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

Science Opportunities: Inner Solar System

1. Trojans (Mars and Jupiter): orbital and absolute magnitude distributions, size frequency distributions of different taxonomic classes.
2. High quality astrometry, ephemerides improvements for stellar occultation predictions.
3. Active asteroids and the collisional environment within the asteroid belt
4. Colors and compositions of families and populations (Jupiter's irregular satellites, Mars/Jupiter Trojans, Hildas, Cybeles, and Phobos and Deimos) and their correlations with dynamical properties. Understanding the chemical distribution in the primordial disk; collisional family parent bodies and formation events; giant planet migration models
5. Rotational light curves to study physical properties of asteroids, including the spin angular momentum distribution, shape distribution, and binary frequency.
6. Measurement of asteroid masses and bulk densities
7. Detection and frequency of rotational fission within the non-NEO asteroid populations to probe internal structure and test dynamical models.

Schwamb et al., "Large Synoptic Survey Telescope Solar System Science Roadmap"
https://arxiv.org/abs/1802.01783

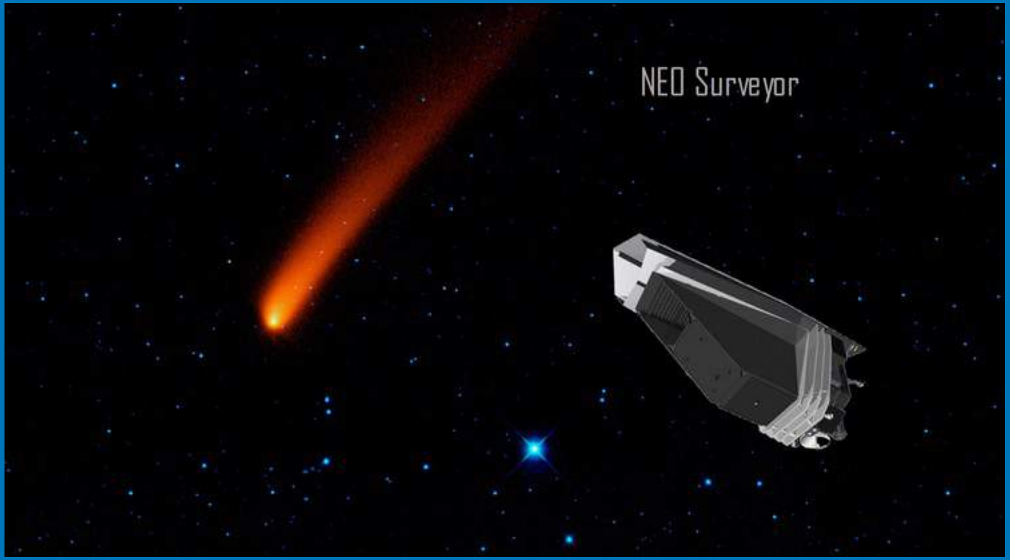


Image credit: University of Arizona

Synergies with NASA's Near-Earth Object Surveillance Mission

Expected to launch in 2025 and beyond, NEO Surveyor will provide near-infrared observations and discoveries of NEOs. LSST will be surveying in the optical (urgizy) providing a complementary dataset in the optical for objects imaged and found by NEO Surveyor in the infrared.

Slide contributed by Meg Schwamb (SSSC)

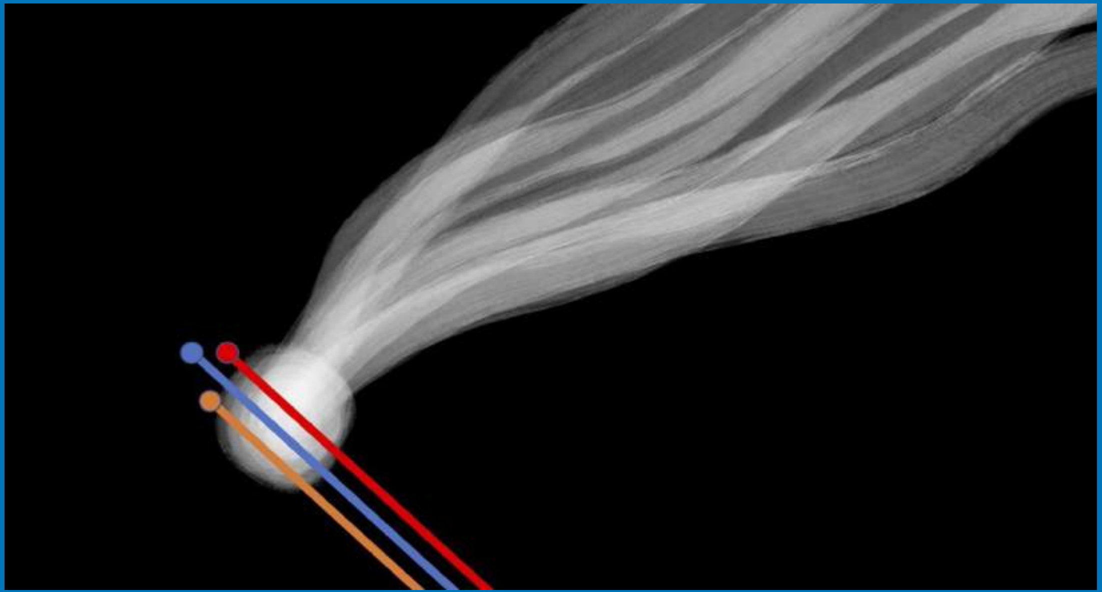


Image credit: Geraint Jones

Synergies with ESA's Comet Interceptor mission

www.cometinterceptor.space

PI: Geraint Jones (UCL)
Deputy PI : Colin Snodgrass (University of Edinburgh)

ESA F-class mission to fly by a comet with 3 spacecraft (one provided by JAXA): Launch expected in 2028. Comet Interceptor will sit at L2 and when a suitable target is found & reachable, the main spacecraft will leave L2 to intercept

Discovering 10,000 comets, LSST will likely find Comet Interceptor's target.

There will be coordinated community ground-based follow-up to characterize potential Comet Interceptor targets.

Slide contributed by Meg Schwamb (SSSC)