LSST and the Solar System

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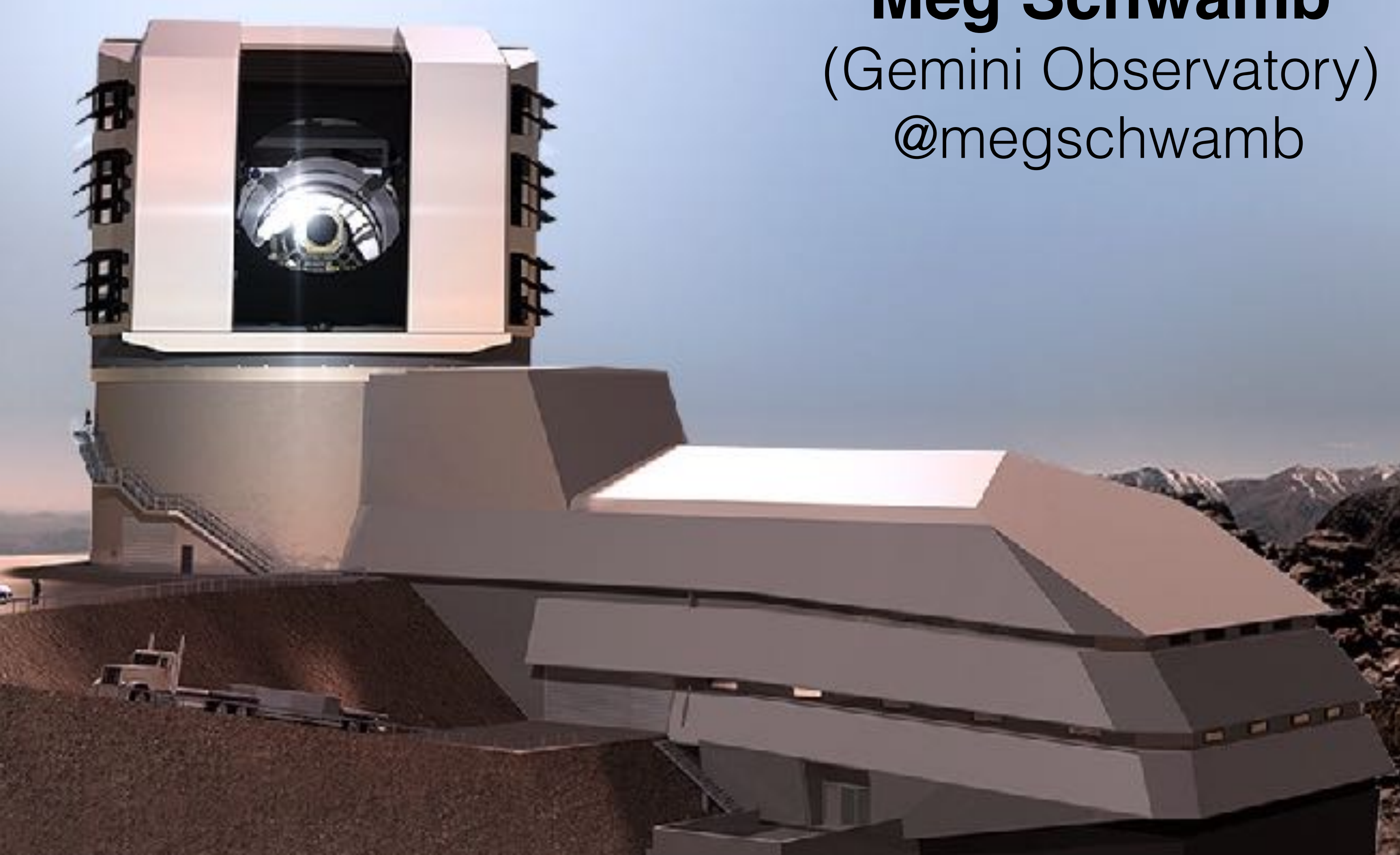
(Gemini Observatory)
@megschwamb

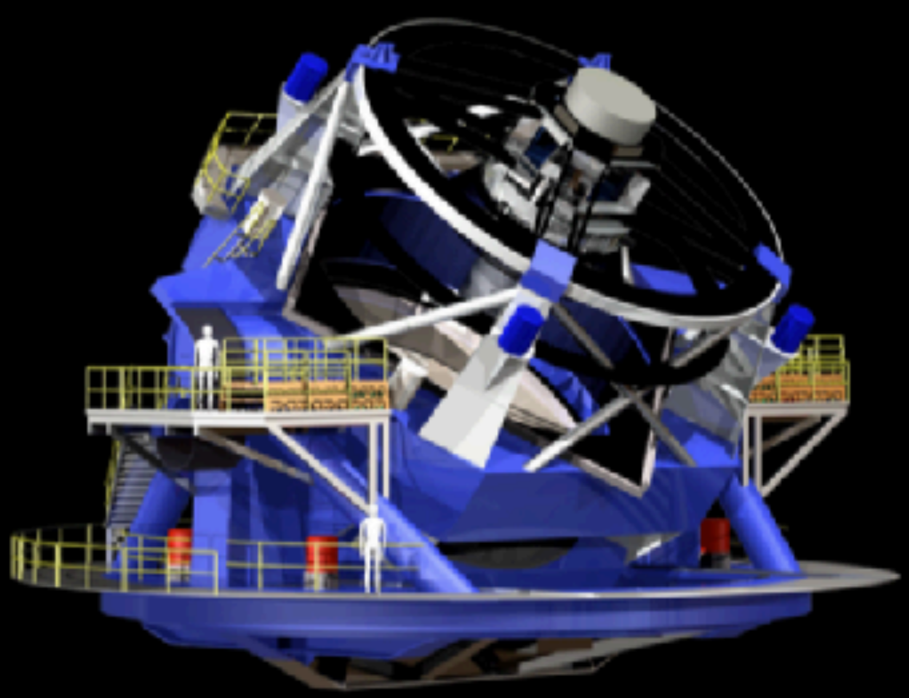


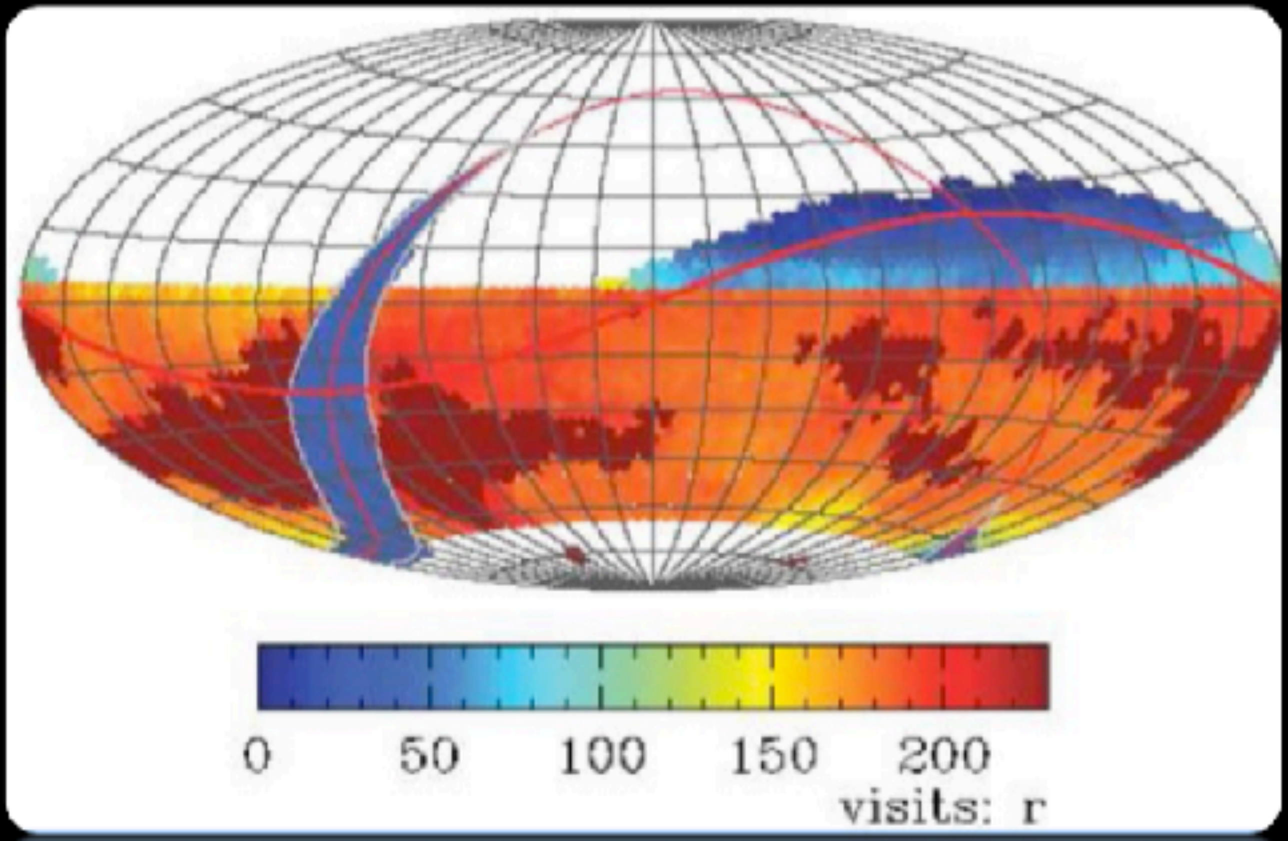
Large Synoptic Survey Telescope
Solar System Science Collaboration

LSST: A Deep, Wide, Fast, Optical Sky Survey

8.4m telescope   18000+ deg^2 10mas astrom.   r<24.5 (<27.5@10yr)

ugrizy   0.5-1% photometry





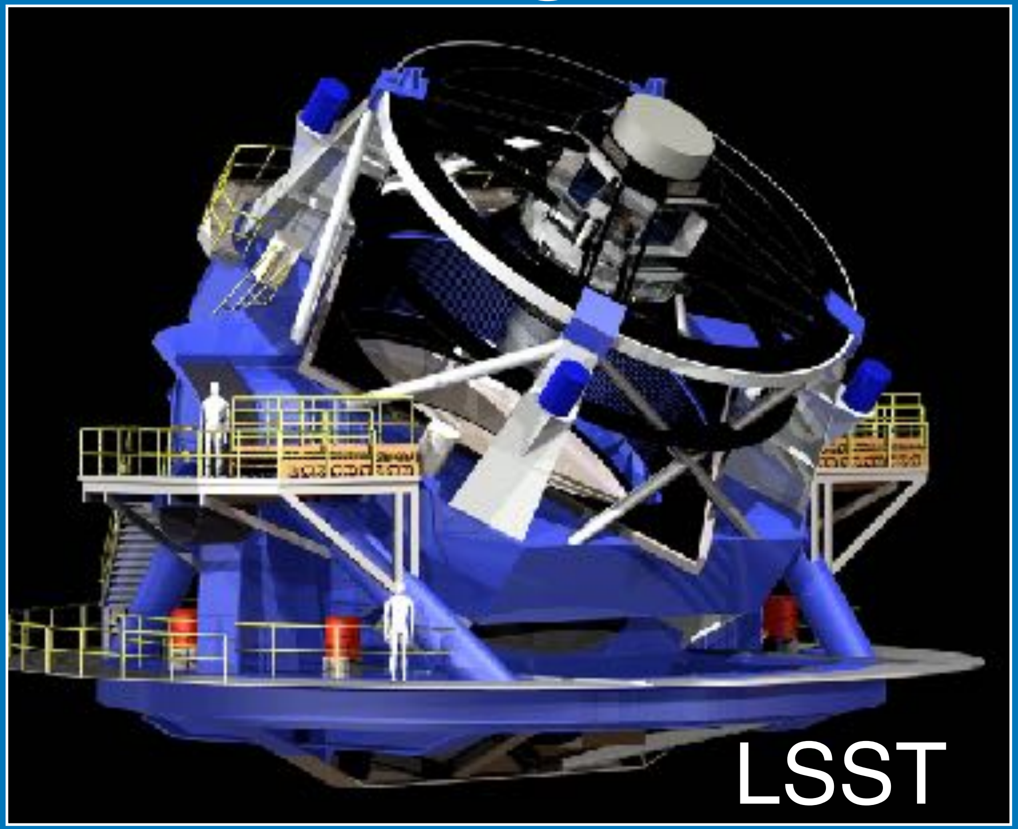
3.2Gpix camera   30sec exp/4sec rd   15TB/night   37 B objects

Imaging the visible sky, once every 3 days, for 10 years (825 revisits)

Slide Credit: Mario Juric

The data deluge is coming….

> 16th magnitude



- 20,000 deg^2 with 3-14 day cadence
- 800 visits per field over 10 years
- 6 million asteroids
- 8000 lensed AGN
- 10^{4-5} galaxy-scale lenses
- 4 billion galaxies

Four Key Science Themes:

- Constraining Dark Energy & Dark Matter
- Taking an Inventory of the Solar System
- Exploring the Transient Optical Sky
- Mapping the Milky Way

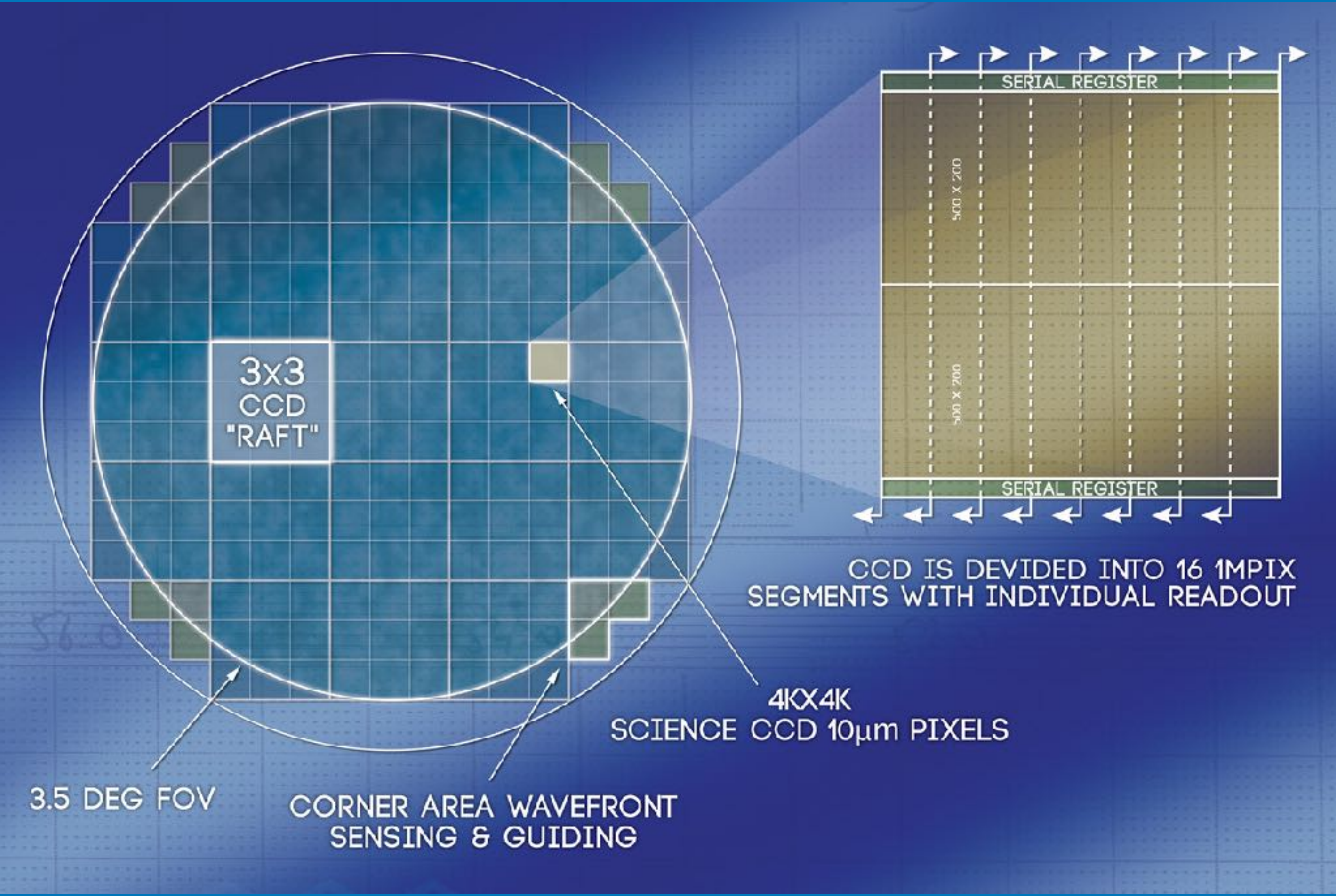


Image Credit: LSST/AURA/LSSTC

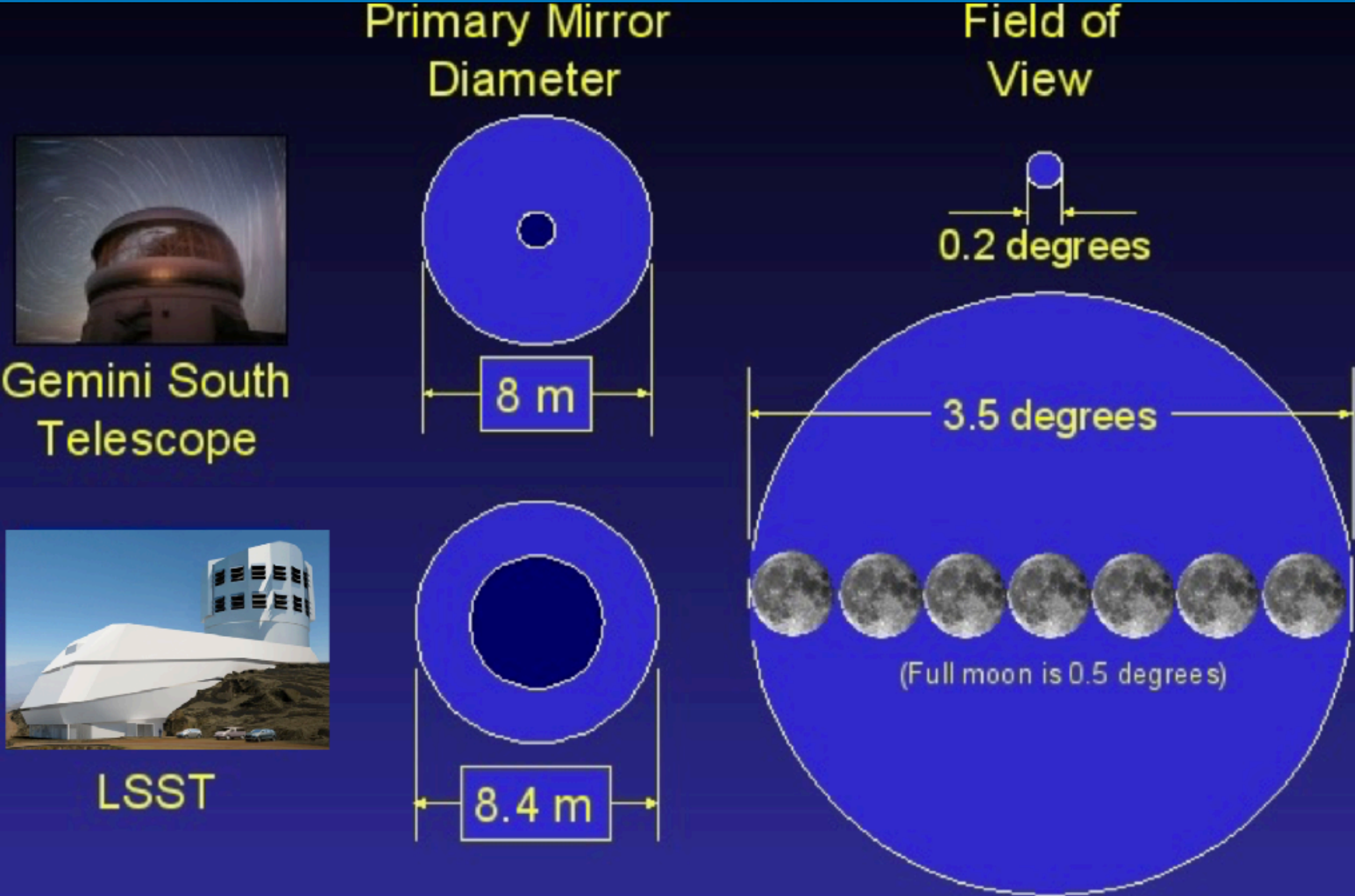


Image credit:Ivezić et al. (2016)

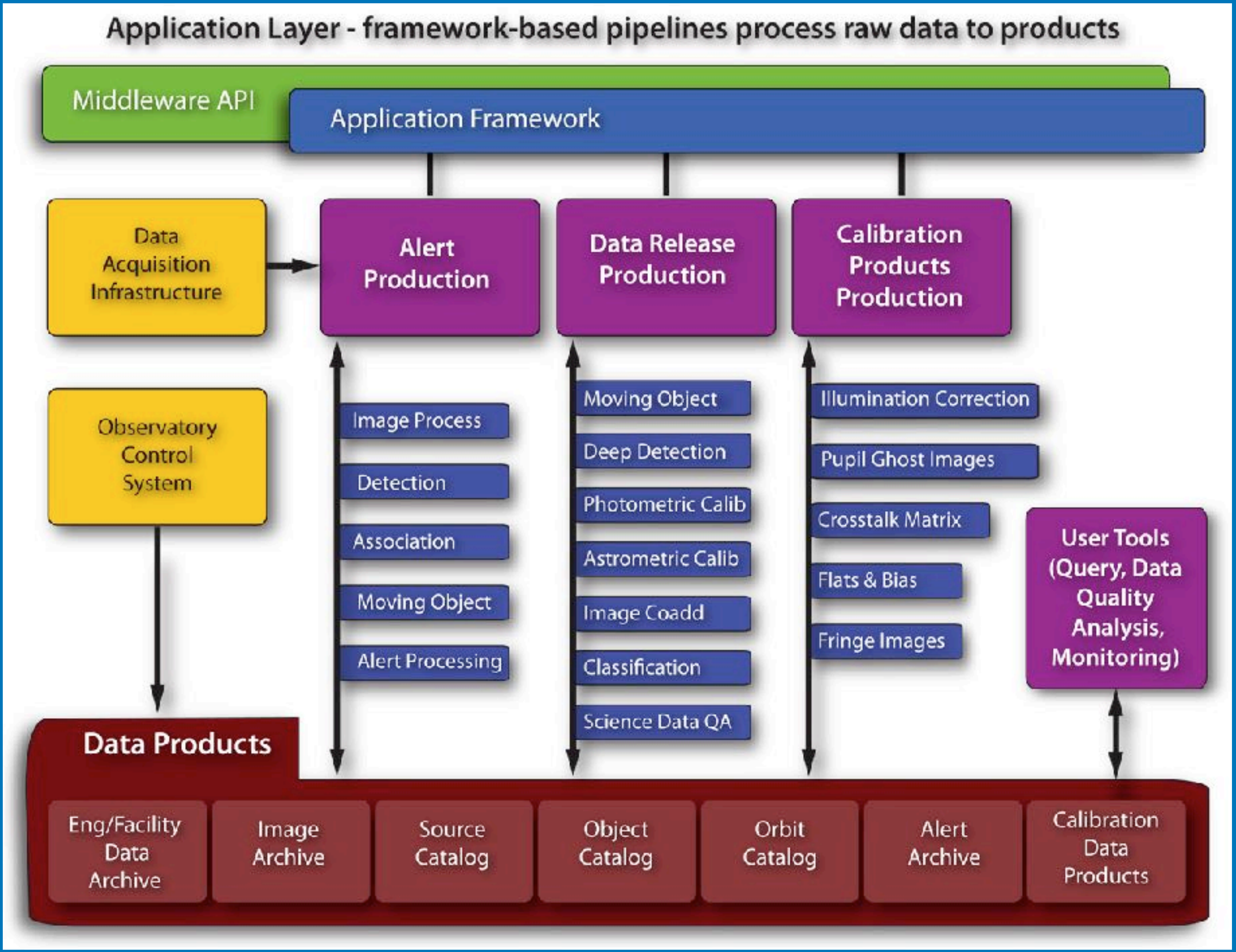


Image Credit: LSST/AURA/LSSTC

It's really coming! The summit is actually starting to look like the artist rendition!

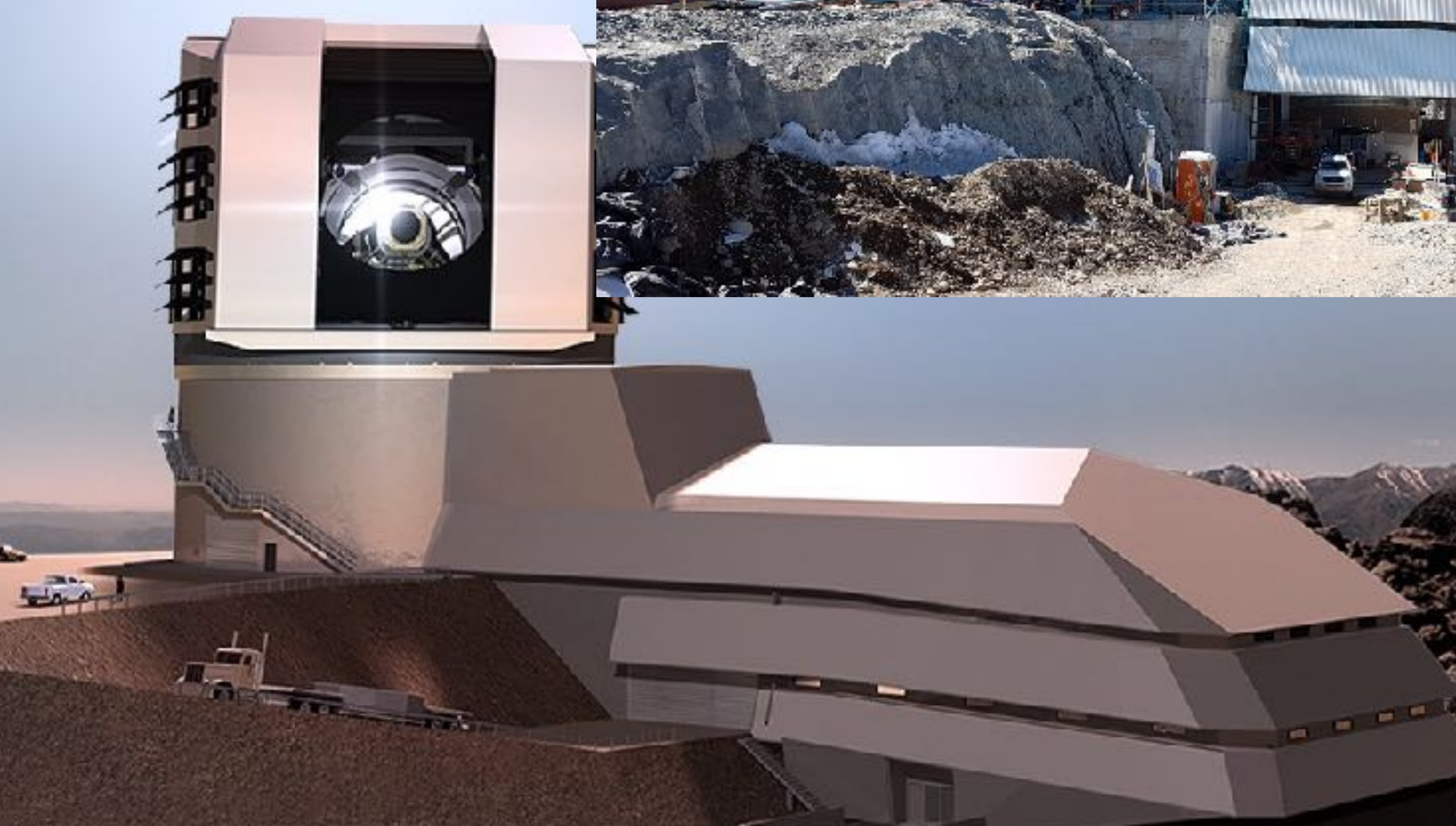


Image Credit: LSST

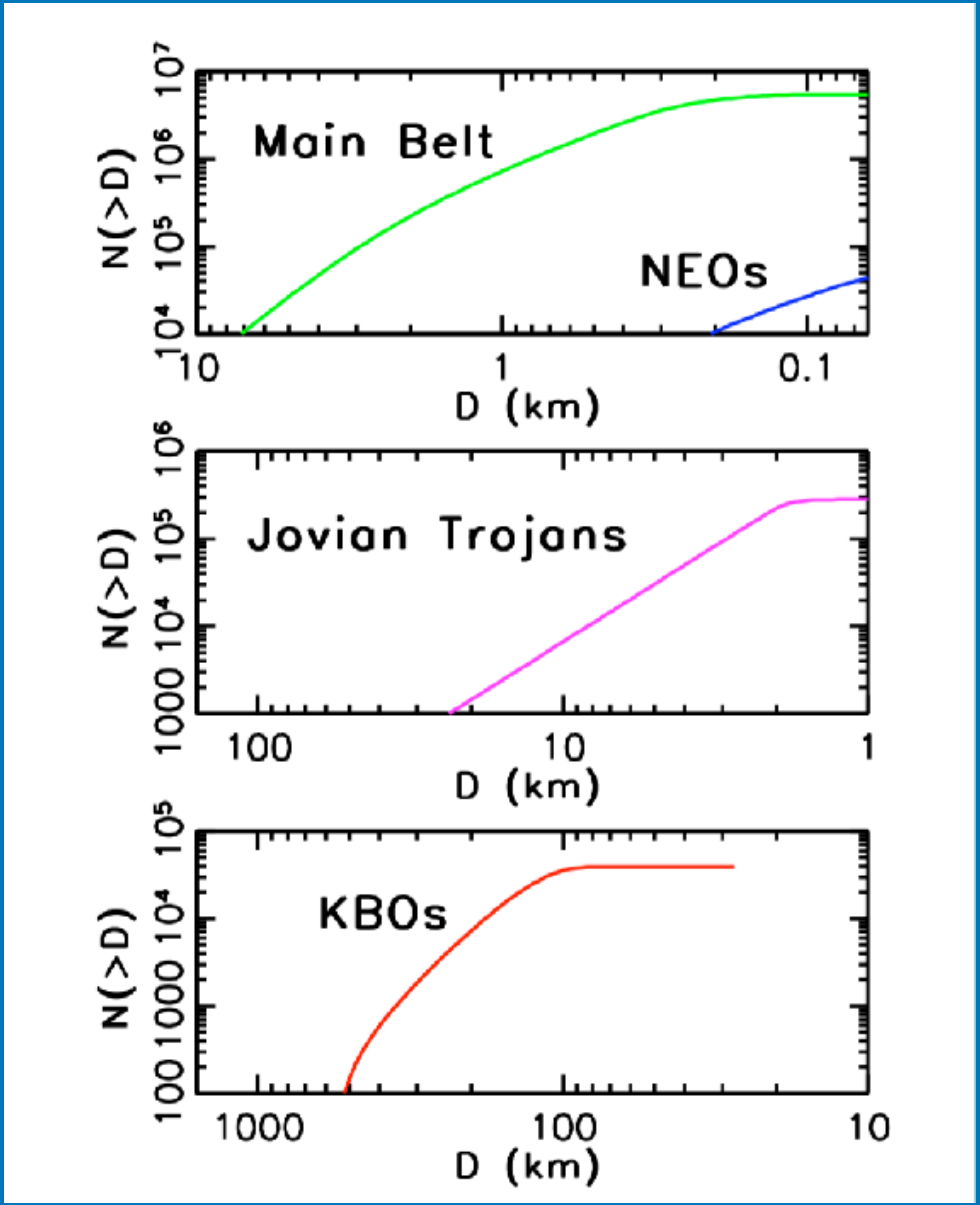
Construction of the Dome has started!

Slide Credit: LSST/AURA/LSSTC/Amanda Bauer

Information Resources For the Community

Resource	Description
www.lsst.org	Diverse materials available include: images, key numbers, key project documents, links to simulated data – including simulated observing strategies. New series of recorded talks by Project leadership.
News Digest	A weekly email update with LSST Project and LSST Corporation information sent from the Project out to staff and interested stakeholders in the scientific community. Anyone can sign up at www.lsst.org.
community.lsst.org	A Stack Overflow-like forum with public discussions about a wide-range of LSST-related issues. Both Project and community members participate in discussions and ask questions. This tool is available to everyone. Heavy usage from Data Mgmt and EPO.
lsstc.slack.com	Limited to Instant Messaging application for quick conversations. This tool is limited to project and science collaboration members, plus International PIs and a login is required. Both private and public discussion rooms. Numerous Project and Science users.

Slide Credit: Beth Willman



Slide Credit: LSST Science book

Table 5.1: Absolute magnitude at which a given detection completeness is reached[a]

Population	H(90%)	H(50%)	H(10%)	N^{b}_{LSST}
PHA	18.8	22.7	25.6	—
NEA	18.9	22.4	24.9	100,000
MBA	20.0	20.7	21.9	5.5 million
TR5	17.5	17.8	18.1	280,000
TNO	7.5	8.6	9.2	40,000
SDO	6.8	8.3	9.1	—

[a]Table lists absolute magnitude H values at which a differential completeness of 90%, 50% or 10% is reached. This is not a cumulative detection efficiency (i.e. completeness for $H > X$), but a differential efficiency (i.e. completeness at $H = X$). [b]Approximate total number of objects detected with LSST, in various populations. PHAs and SDOs are included in the counts of NEAs and TNOs.

Slide Credit: LSST Science book

Revised Data Delivery Schedule

Data Production Milestone	Start Date
First calibration data from Auxiliary Telescope	November 2018
First on-sky and calibration images with ComCam	May 2020
Images from Camera re-verification at Summit Facility	July 2020
Sustained observing with ComCam	August 2020
First on-sky and calibration data from Camera+Telescope	February 2021
Sustained scheduler driven observing with Camera+Telescope	April 2021
Start Science Verification mini-Surveys	June 2021

Slide Credit: Chuck F Claver

LSST Data Products

- A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
- A catalog of orbits for ~6 million bodies in the Solar System.

(Internally known as "Level 1")

Prompt

- A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion observations ("sources"), and ~30 trillion measurements ("forced sources"), produced annually, accessible through online databases.
- Reduced single-epoch, deep co-added images.

(Internally known as "Level 2")

Data Rel.

- User-produced added-value data products (deep KBO/NEO catalogs, variable star classifications, shear maps, …)

(Internally known as "Level 3")

User contributed

*For more details, see the **"Data Products Definition Document"**, http://ls.st/lse-163*

Slide Credit: Mario Juric

Key LSST Deliverables for Solar System Science

- Within 60 seconds of each observation: A real-time stream of observation reports (alerts) with information about astrometry, photometry, and shape including trailing, direction of motion.

- Every day: A stream of linked tracks reported to the Minor Planet Center.

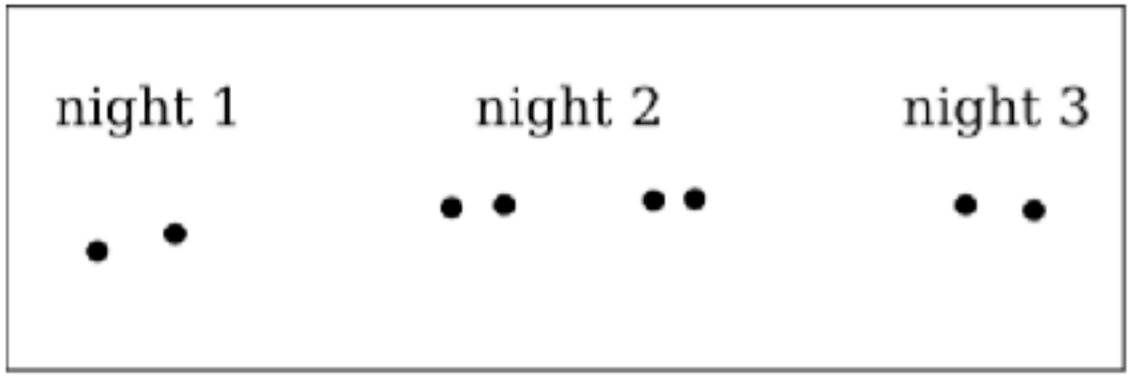
- Every day: A catalog of orbits for LSST-discovered objects.
- Annually: Precisely calibrated photometric catalog (ugrizy bands) accurate to 5mmag (systematics limited), with every data release.

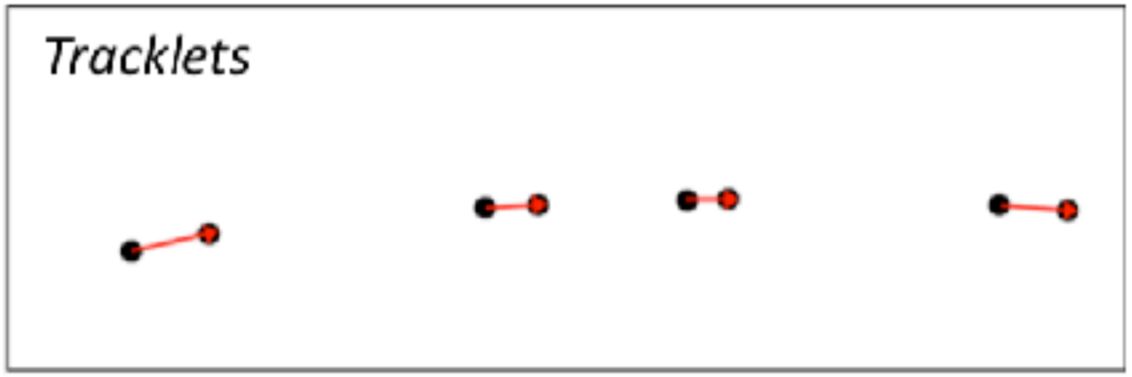
All LSST project Solar System products in some form will be public via alert stream and MPC

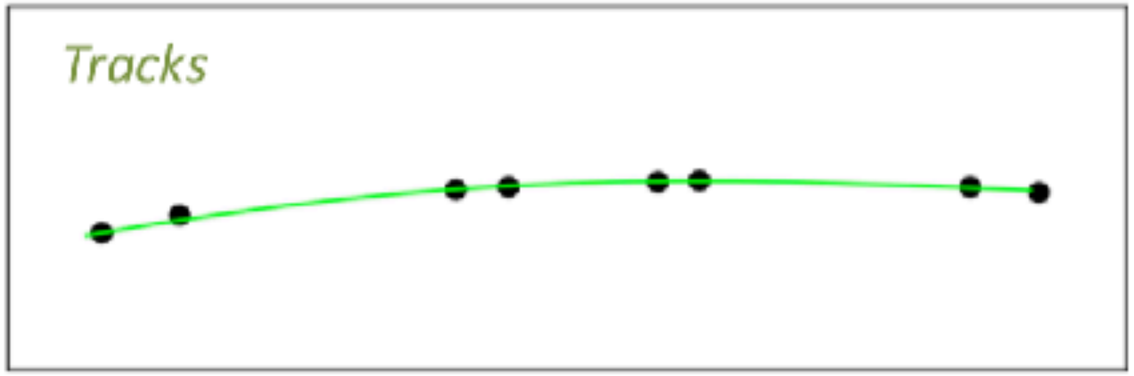
Slide Credit: Mario Juric

How LSST Discovers Objects

Requirement for reportable discovery: <u>at least</u> three pairs taken over three nights in a short (e.g., ~two week) period, fitting a Keplerian orbit (heliocentric).







Initial and Differential Orbit Determination.

Publication and Reporting to MPC.

This is the well known MOPS algorithm; e.g., Kubica (2007), Denneau (2006)

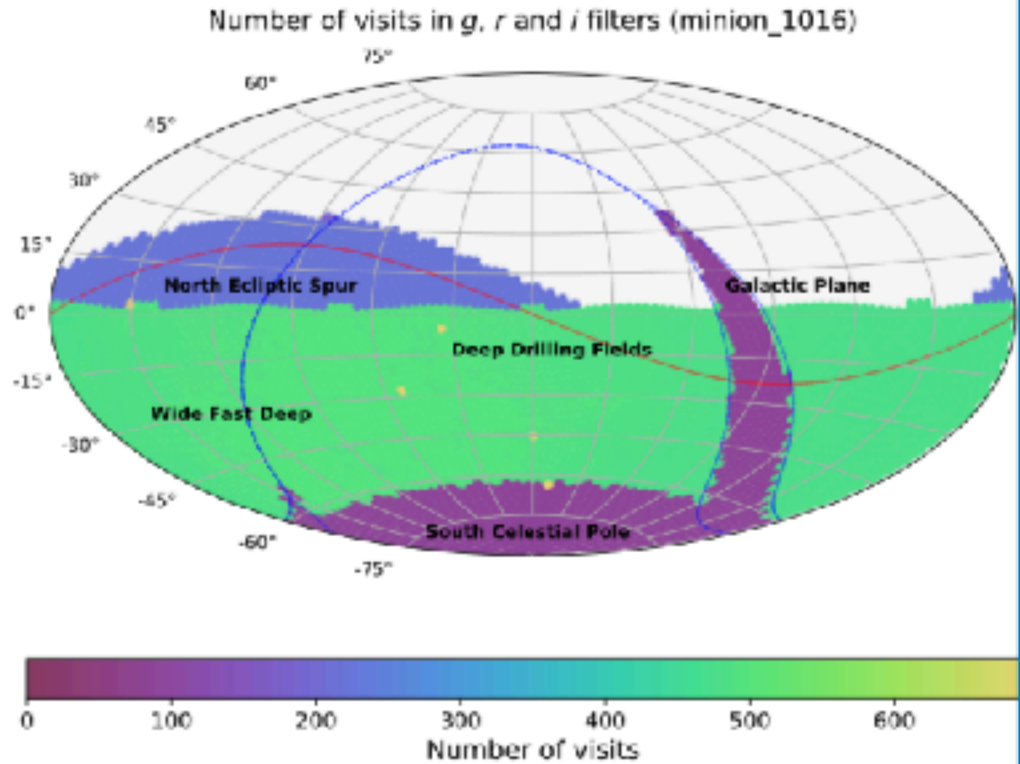
Terminology:

- ***tracklets***: potential linkages in the same night (linear extrapolation)
- ***tracks***: potential linkages over three nights (quadratic fit)
- ***reportable discovery***: a track that unambiguously fits a Keplerian orbit within the astrometric uncertainties
- ***MOPS***: the software system that links detections into reportable discoveries

Slide Credit: Mario Juric

Upcoming release of "OpSim" v4

- OpSim = "Operations Simulation"
  - Provides detailed pointing history of LSST
  - Contains scheduler + simulated observatory
- New 'v4' scheduler
  - Can 'balance' time between proposals better so that proposals with fewer requested visits (SCP/GP) do not finish early [see figure for 'proposal' footprints]
  - Can add airmass and/or Hour Angle bonus (so scheduler 'prefers' higher airmass or lower HA fields)
  - Easier to explore rolling cadence options
- https://lsst-sims.github.io/sims_ocs/



Slide Credit: Lynne Jones

Survey Strategy / Community Input Timeline

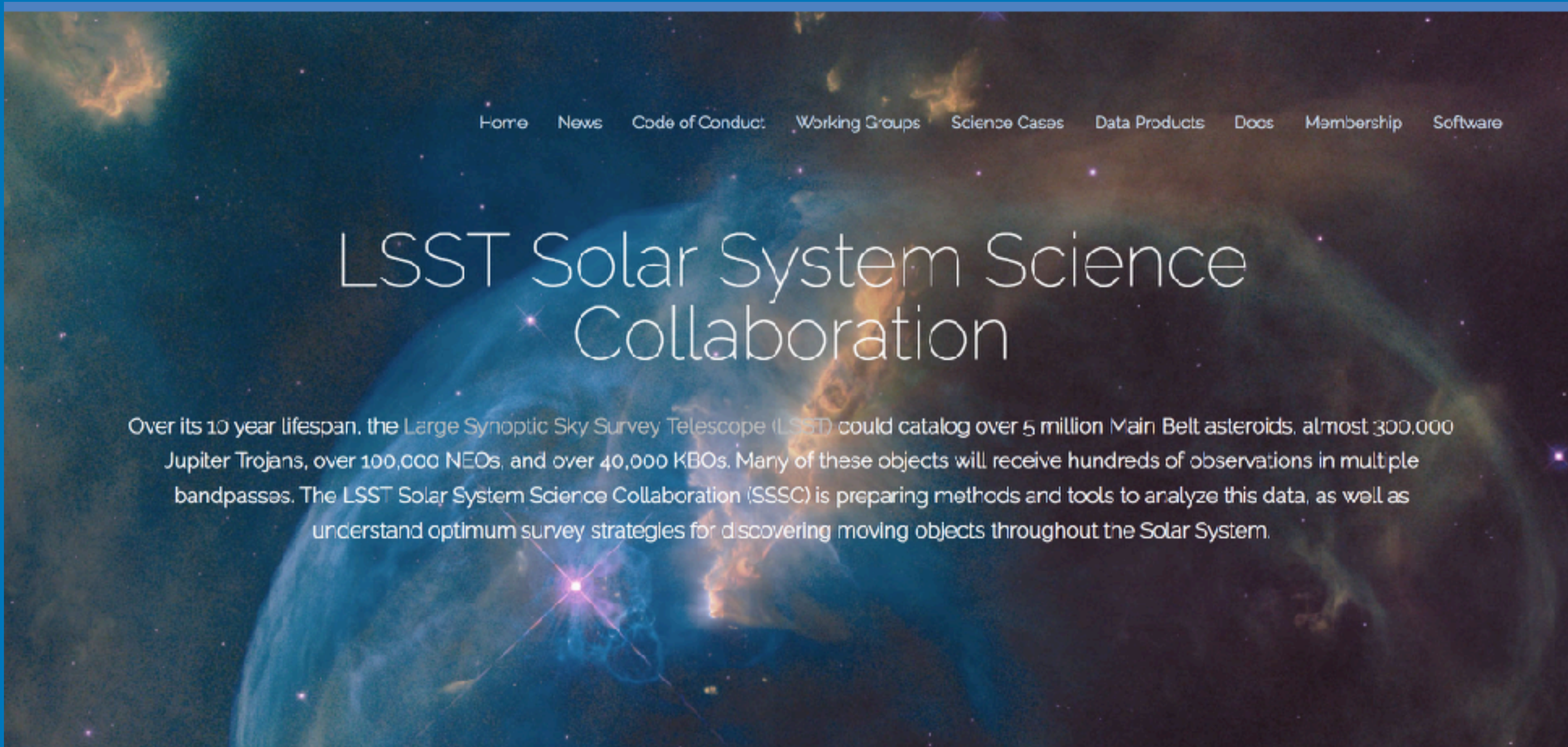
	Cadence Optimization	Calls to Community
2017	Start work on tools to run MAF & Opsim at scale	
	Rolling cadence experiments; DDF experiments/examples	Publish Observing Strategy white paper (OSWP) C
2018	Rolling cadence experiments evaluated with OSWP metrics; Mini-survey experiments/examples	D
	DDF WP -> simulated surveys; mini-survey experiments	C ... ers (
2019	Updated baseline with DDF + rolling cadence (June)	M Request for white paper and metrics update (Mar)
	Mini-survey WP -> simulated surveys;	White paper with metrics due (Aug)
2020	Finalize MAF and Opsim tools; deliver documentation and a series of simulated surveys to SAC; form SSC	
	Ask SAC and Survey Strategy Committee to recommend the initial observing strategy	
2021	Announce initial survey strategy and publish a baseline simulation that reproduces that strategy	

Combine DD & mini survey white papers:

call - early 2018

due - late 2018

Slide Credit: Lynne Jones



http://www.lsstsssc.org

News | Working Groups | Membership

SSSC Co-Chair emails: david.Trilling@nau.edu, mschwamb.astro@gmail.com

LSST Solar System Science Collaboration (SSSC)


David Trilling & Meg Schwamb
SSSC Co-Chairs

www.lsstsssc.org

Active objects Working Group (Lead: Alan Fitzsimmons): broadly consisting of all categories of activity in the minor planet populations: short period comets, long period comets, main belt comets, impact- or rotationally-generated active asteroids,etc

Community software/infrastructure development Working Group (Lead: Henry Hsieh): broadly consisting of people interested in helping build databases, software packages, etc to be used by the Solar System community on LSST data

Inner Solar System Working Group (Lead: Cristina Thomas): broadly consisting of the main belt, Mars/Jupiter Trojans, and Jupiter irregular satellites

NEOs (Near Earth Objects) and Interstellar Objects Working Group (Lead: Steve Chesley): broadly consisting of objects on orbits inward of or diffusing inward from the main belt as well as interstellar objects temporarily residing in the Solar System


Outer Solar System Working Group (Lead: Darin Ragozzine and Matt Holman): broadly consisting of KBOs, Centaurs, Oort cloud, Saturn/Neptune/Uranus Trojans, and Saturn/Neptune/Uranus irregular satellites

SSSC 2017 Events & Activities

- Lynne Jones (University of Washington) stepped down as SSSC co-chair. Meg Schwamb (Gemini Observatory) was elected, joining David Trilling (NAU) as co-chair.
- Launched new collaboration website (http://www.lsstsssc.org)
- Established topical working groups
- Adopted a Collaboration Code of Conduct (http://lsst-sssc.github.io/codeofconduct.html)
- Drafted a Collaboration Charter
- Restarted science roadmap effort. Roadmap to be published in early 2018
- Organized the LSST and the Solar System Workshop at the 49th Division for Planetary Sciences (DPS) meeting
- Provided input to Data Management on the format and content of the Solar System Database Schema

LARGE SYNOPTIC SURVEY TELESCOPE SOLAR SYSTEM SCIENCE ROADMAP

Megan E. Schwamb,[1] R. Lynne Jones,[2] Steven R. Chesley,[3] Alan Fitzsimmons,[4] Wesley C. Fraser,[4] Matthew J. Holman,[5] Henry Hsieh,[6] Darin Ragozzine,[7] Cristina A. Thomas,[6,8] David E. Trilling,[8] and Michael E. Brown[9]

on behalf of the LSST Solar System Science Collaboration

https://arxiv.org/abs/1802.01783

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ABSTRACT

The Large Synoptic Survey Telescope (LSST) is uniquely equipped to search for Solar System bodies due to its unprecedented combination of depth and wide field coverage. Over a ten-year period starting in 2022, LSST will generate the largest catalog of Solar System objects to date. The main goal of the LSST Solar System Science Collaboration (SSSC) is to facilitate the efforts of the planetary community to study the planets and small body populations residing within our Solar System using LSST data. To prepare for future survey cadence decisions and ensure that interesting and novel Solar System science is achievable with LSST, the SSSC has identified and prioritized key Solar System research areas for investigation with LSST in this roadmap. The ranked science priorities highlighted in this living document will inform LSST survey cadence decisions and aid in identifying software tools and pipelines needed to be developed by the planetary community as added value products and resources before the planned start of LSST science operations.

Science Roadmap (examples of science priorities) : NEOs Working Group

- Obtain an NEO catalog with high completeness and adequate orbit quality
- Obtain color measurements and broad phase coverage of cataloged NEOs
- Derive debiased orbit, abs. mag. and taxonomy distributions from the catalog
    - Including orbit-taxonomy correlations
- Obtain rotation states and shape modeling from sparse light curves
- Quantify the long term impact flux of smaller NEOs
- Timely notice of near-term close approaches or potential impacts
    - Facilitates external characterization efforts (radar, spectra, light curves)
    - May involve reporting of trailed detections outside of the normal MOPS protocol

Science Roadmap (examples of science priorities) : Inner Solar System Working Group

- Discovery-- includes all populations.

- Population studies--includes complete catalog for completeness and to quickly distinguish from newly discovered objects, orbit population models, astrometry to improve ephemerides for occultations.

- Lightcurves & shape models-- includes rotational periods and lightcurve inversion for shape.

- Colors & Composition-- includes colors of many things such as Trojans, irregular satellites, etc.

- Physical Properties & Ongoing Processes-- includes repeated detection of objects, not lightcurves-- such as improved phase curves, mass estimation from mutual gravitational interactions, non gravitational perturbations, binaries to derive mass.

Science Roadmap (examples of science priorities) : Outer Solar System Working Group

- Discovery and orbital classificiation of large numbers (10,000s) of outer solar system objects over a wide range of sizes (H>9) and orbits in support of many objectives, especially characterization of the size-frequency-orbit distribution of KBOs with implications for understanding the formation and evolution of the outer solar system (e.g., comet/Centaur pathways, collisional evolution, Neptune migration, etc.).

- Determination of rotational light curves for large numbers of objects from different dynamical classes -- with mimimal confusion from color and phase curves -- to study physical properties of KBOs including spin angular momentum distribution and binary frequency.

- Discovery and orbital classification of objects on unusual orbits inexplicable by the current planets, especially Inner Oort Cloud Objects (aka Sednoids) with high perihelia (q > 40) and objects with very high inclination (i > 40 deg), to place constraints on models for these objects (e.g., the putative Planet 9/X).

- Discovery, accurate/precise astrometry, and rapid delivery of calibrated image "postage stamps" to aid in stellar occultation predictions.

Science Roadmap (examples of science priorities) : Active Objects Working Group

- Main-belt comet discoveries and discovery of cometary activity in NEOS; addresses the presence of water ice in the asteroid belt and NEA popualtion, and the collisional evolution of asteroids.

- Determination of activity levels for a large number of short period comets (including Main Belt comets) over the period of their entire orbit, to model and understand the onset and termination of cometary activity on these objects. This includes colors for the objects while both active and inactive, with minimal confusion from phase angles and varying activity levels

- Detection and follow-up of anomalous outbursts and rapid brightening events above the expected brightness evolution of objects already known to be active

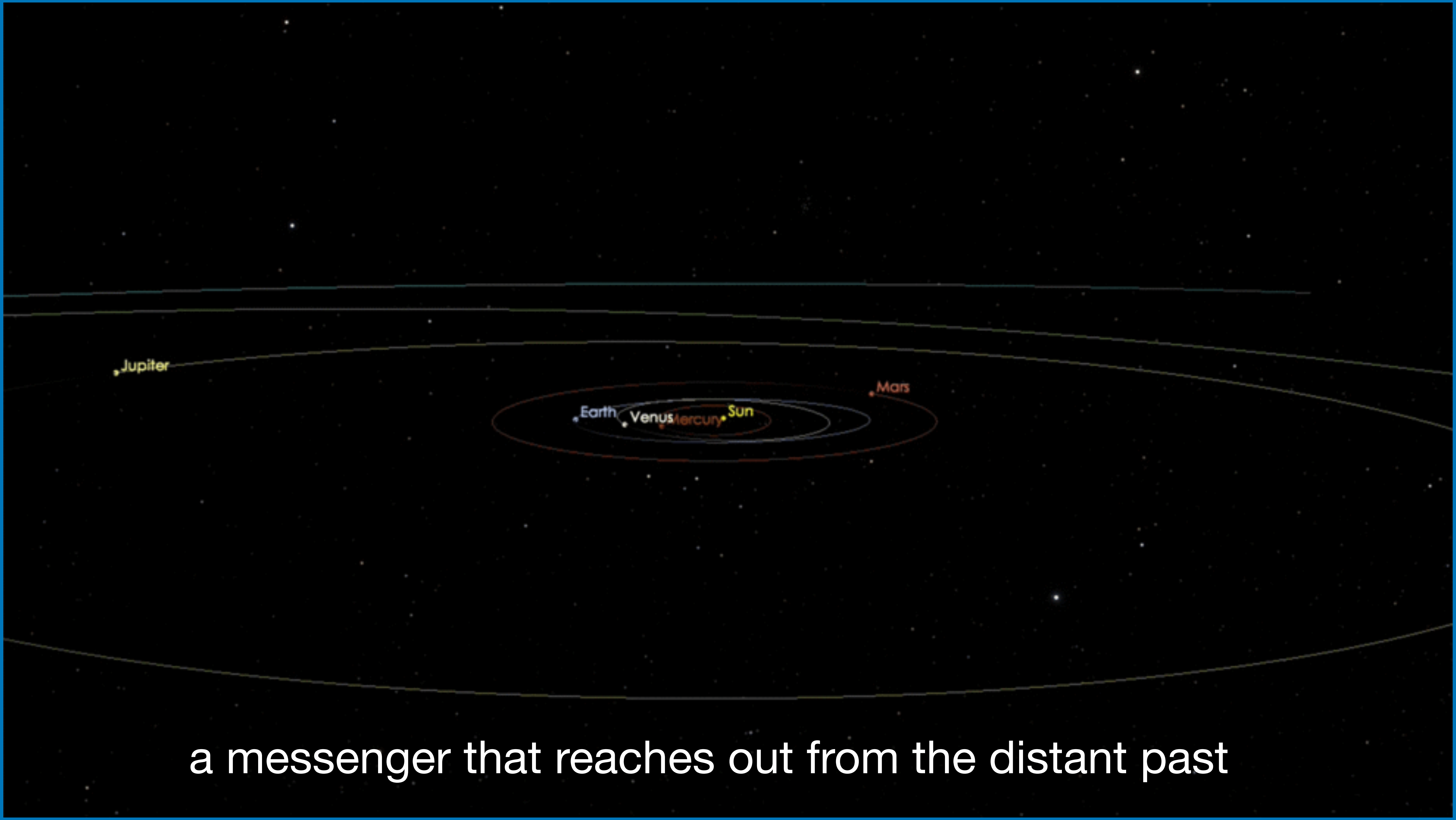
- Parameterization of non-gravitational evolution of orbits of comets and active asteroids.

- Discovery and orbital characterization of large numbers of long period comets to properly understand, define, and potentially redefine the dynamical classification of these objects,

SSSC Plans for 2018

- Finish Science Roadmap
  - ⭑ Finalize science priorities for Science Roadmap
  - ⭑ Develop metrics for our key science priorities to later code into the MAF (Metrics Analysis Framework) for testing success within the cadence simulations
- Give input and finalize with Data Management the Solar System Database Schema
- Plan and organize community response to Deep Drilling Field and Mini-Survey White Paper Calls
- Begin added-value product software development (possible tools for conversion to barycentric coordinates, simulated test datasets, etc)

‘Oumuamua - a case example



Credit: NASA/JPL-Caltech

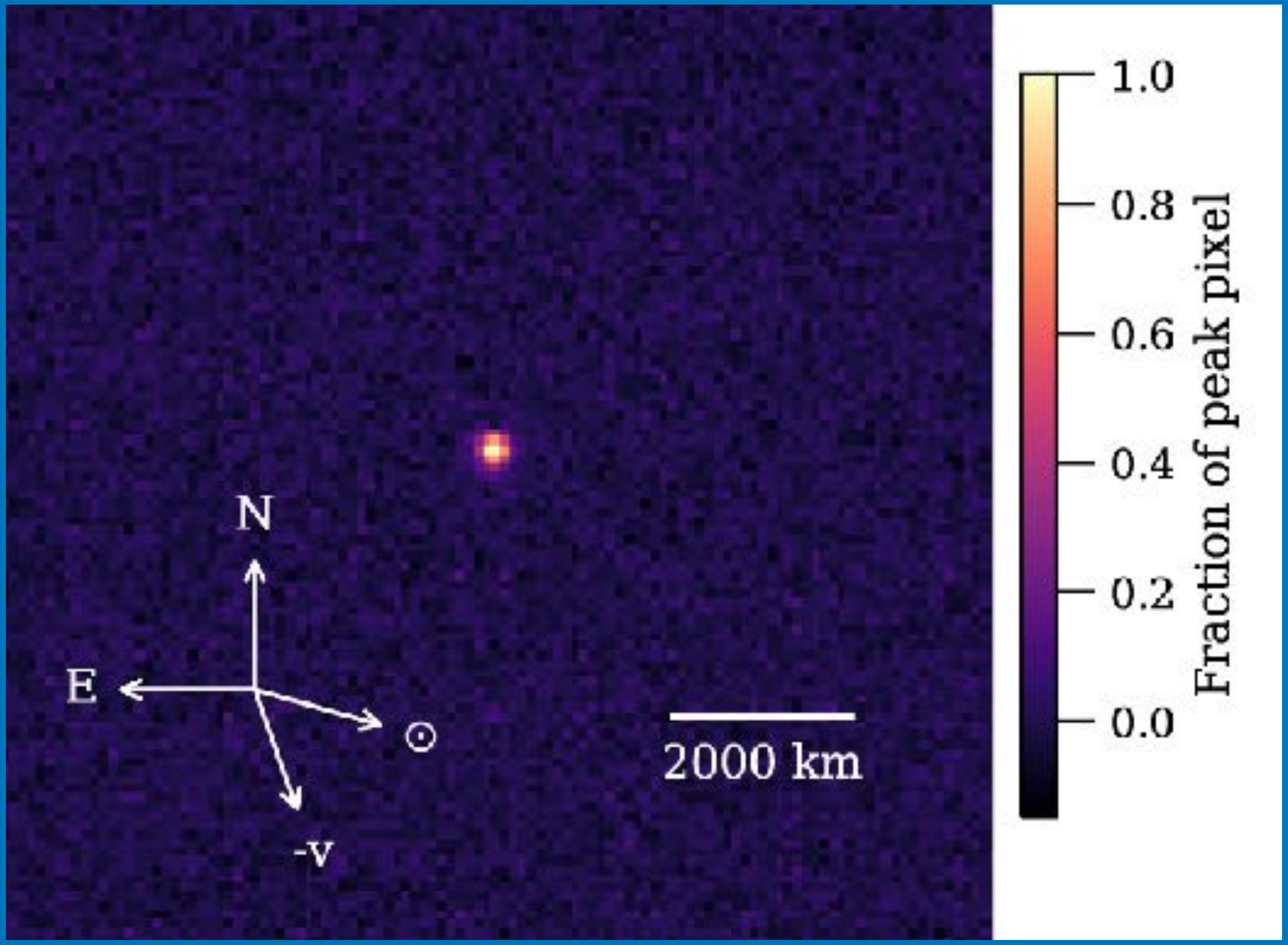
Pan-STARRS1 Observatory on Haleakalā, Maui

Credit: Rob Ratkowski

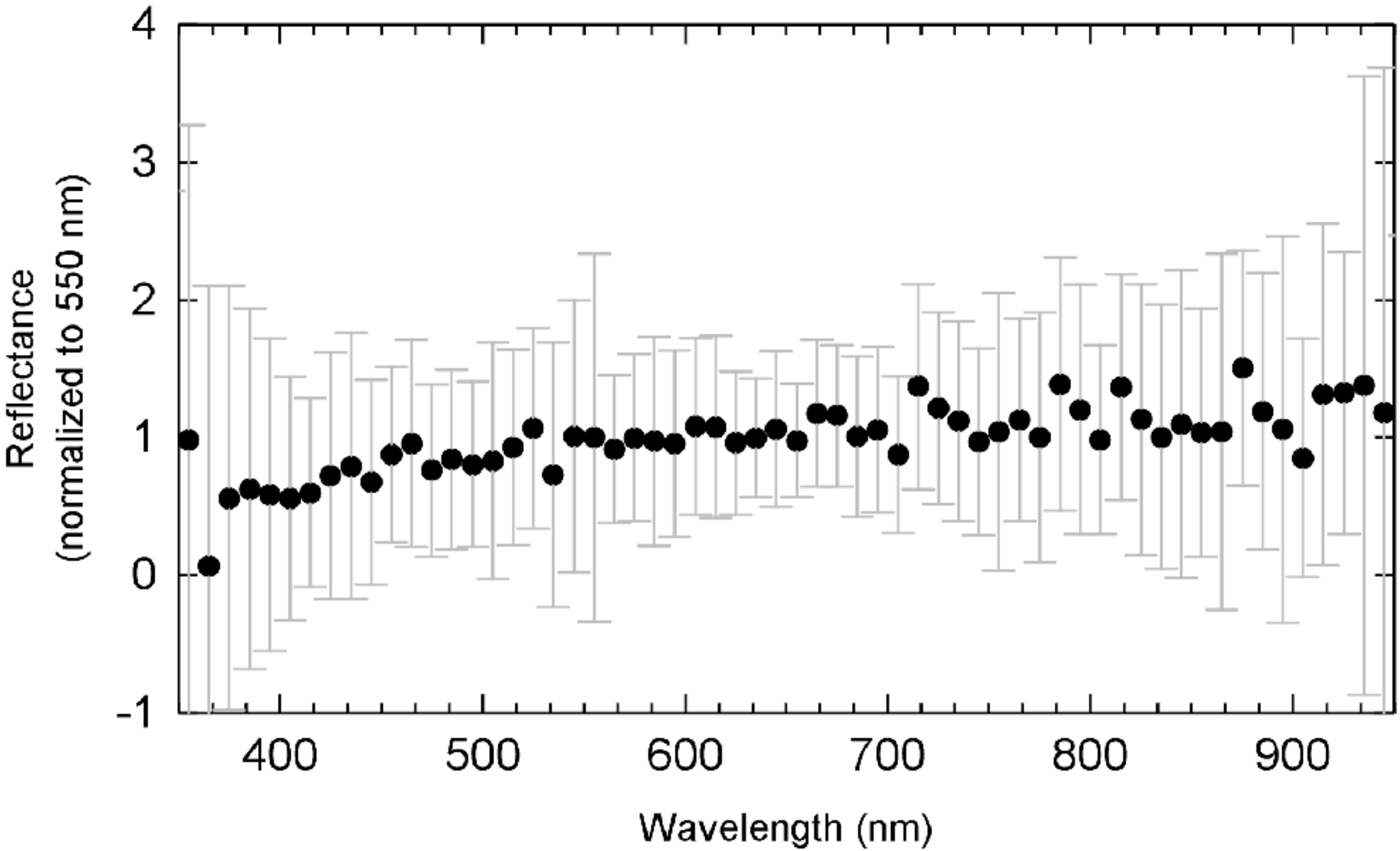

Pan-STARRS1
Gemini South
Gemini North
Apache Point 3.5m
Keck Telescopes
CFHT
Palomar Hale (200 inch)
VLT
William Herschel Telescope
UKIRT

It's not a comet…..

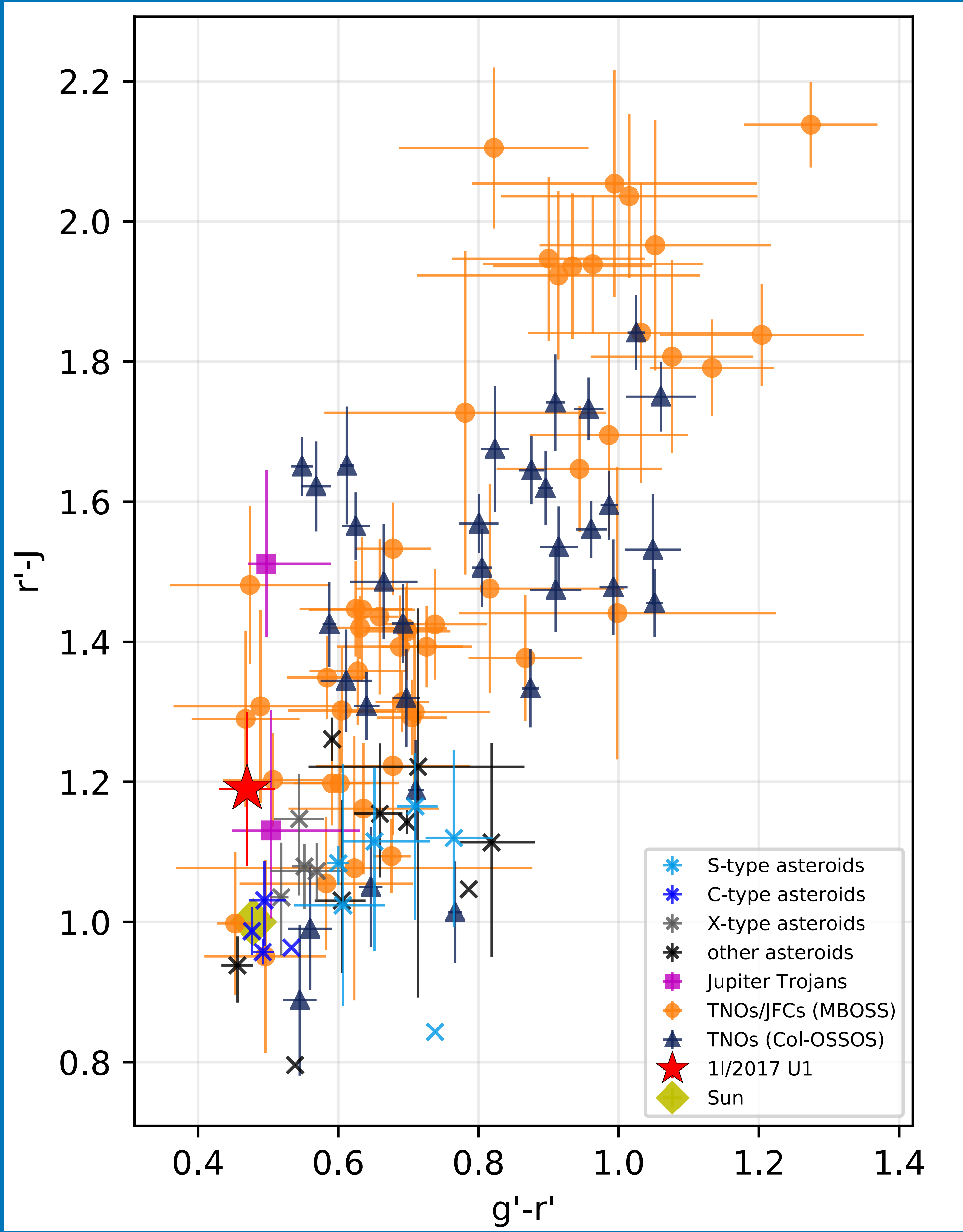
Credit: Meech et al. (2017) Photo Credit: Gemini Observatory/AURA/NSF



Credit: Knight et et al. (2017)

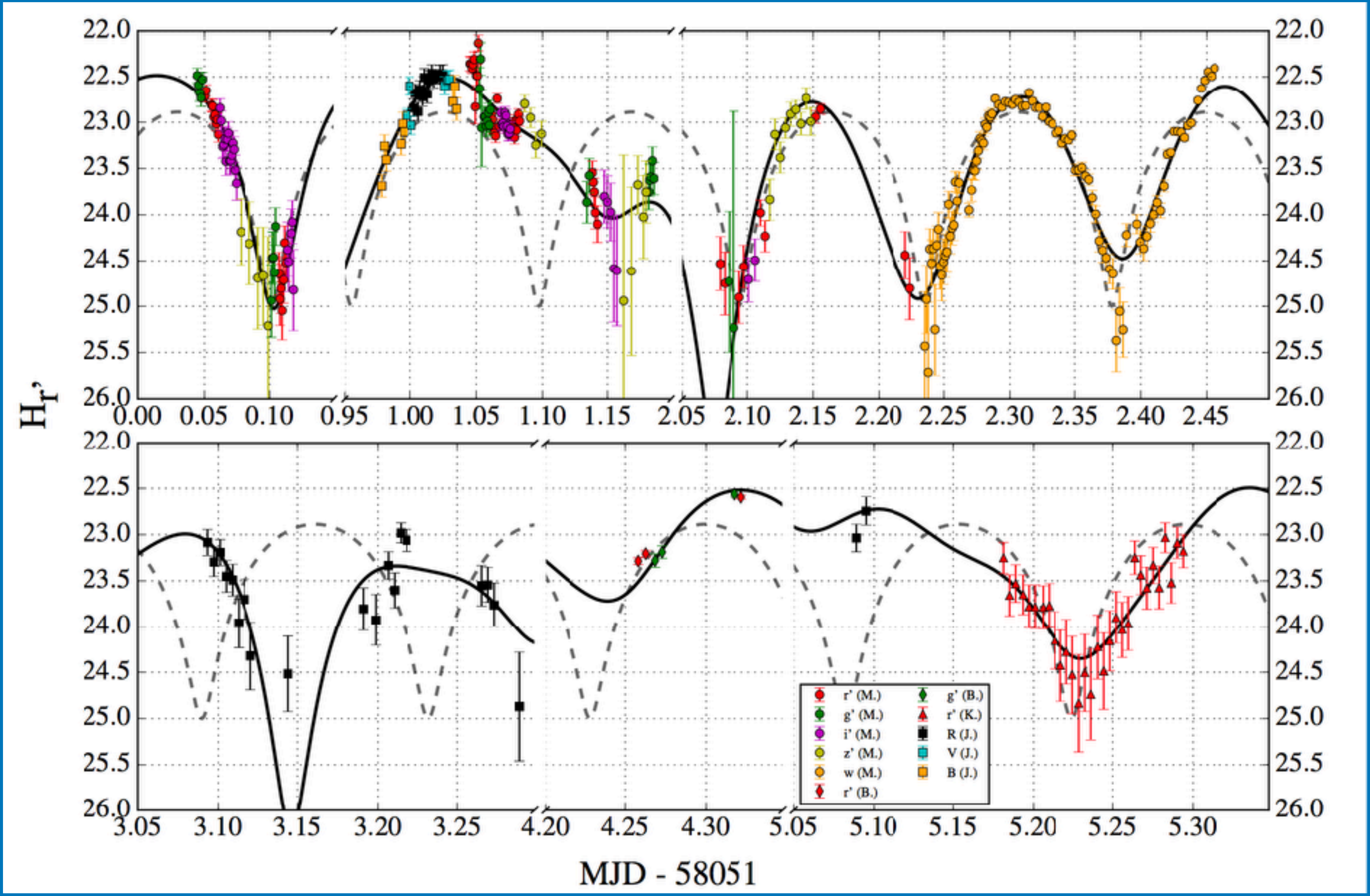


Credit: Ye et al. (2017)



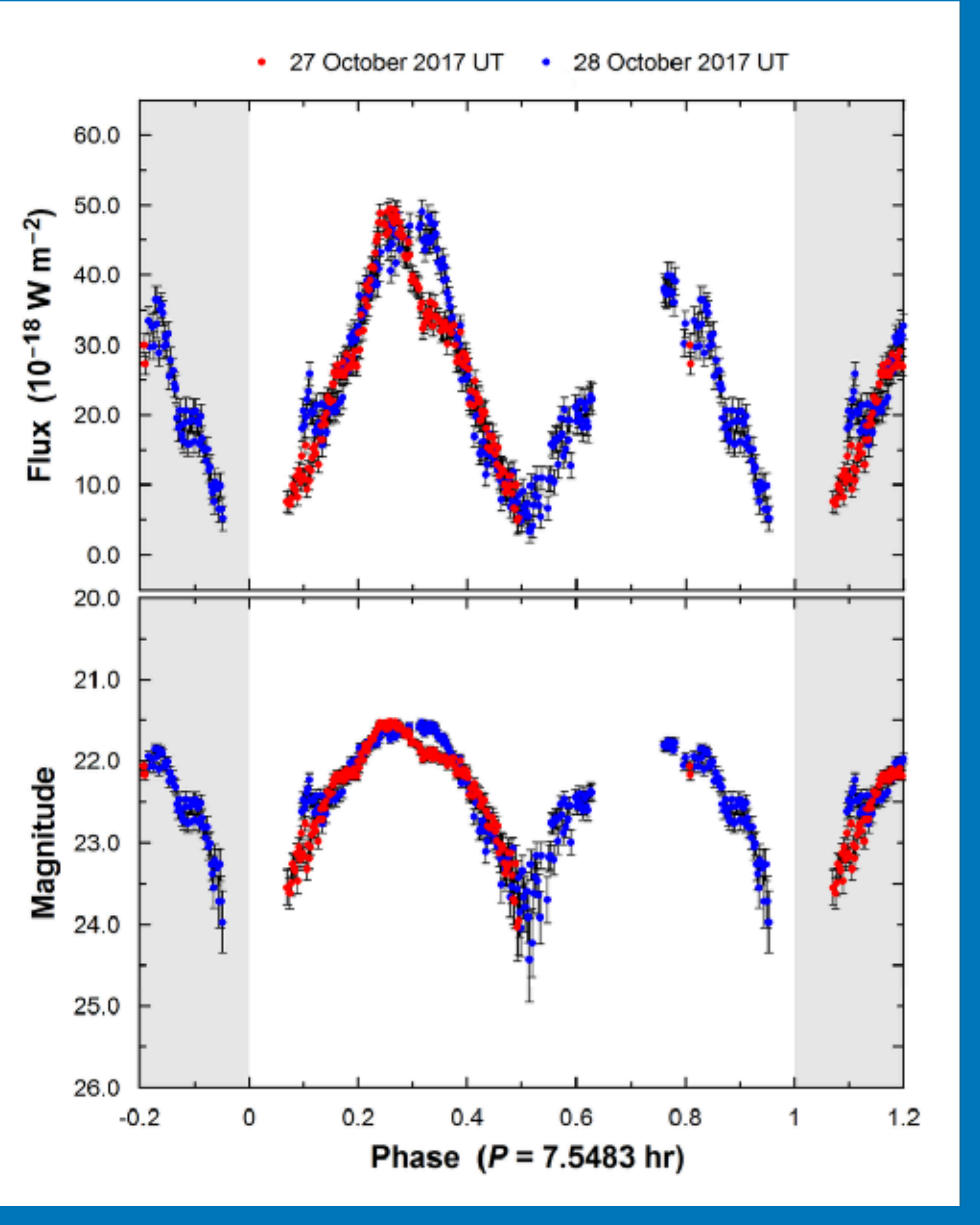
Credit: Bannister, Schwamb et al. (in 2017)

‘Oumuamua is tumbling



Credit: Fraser et al (submitted)

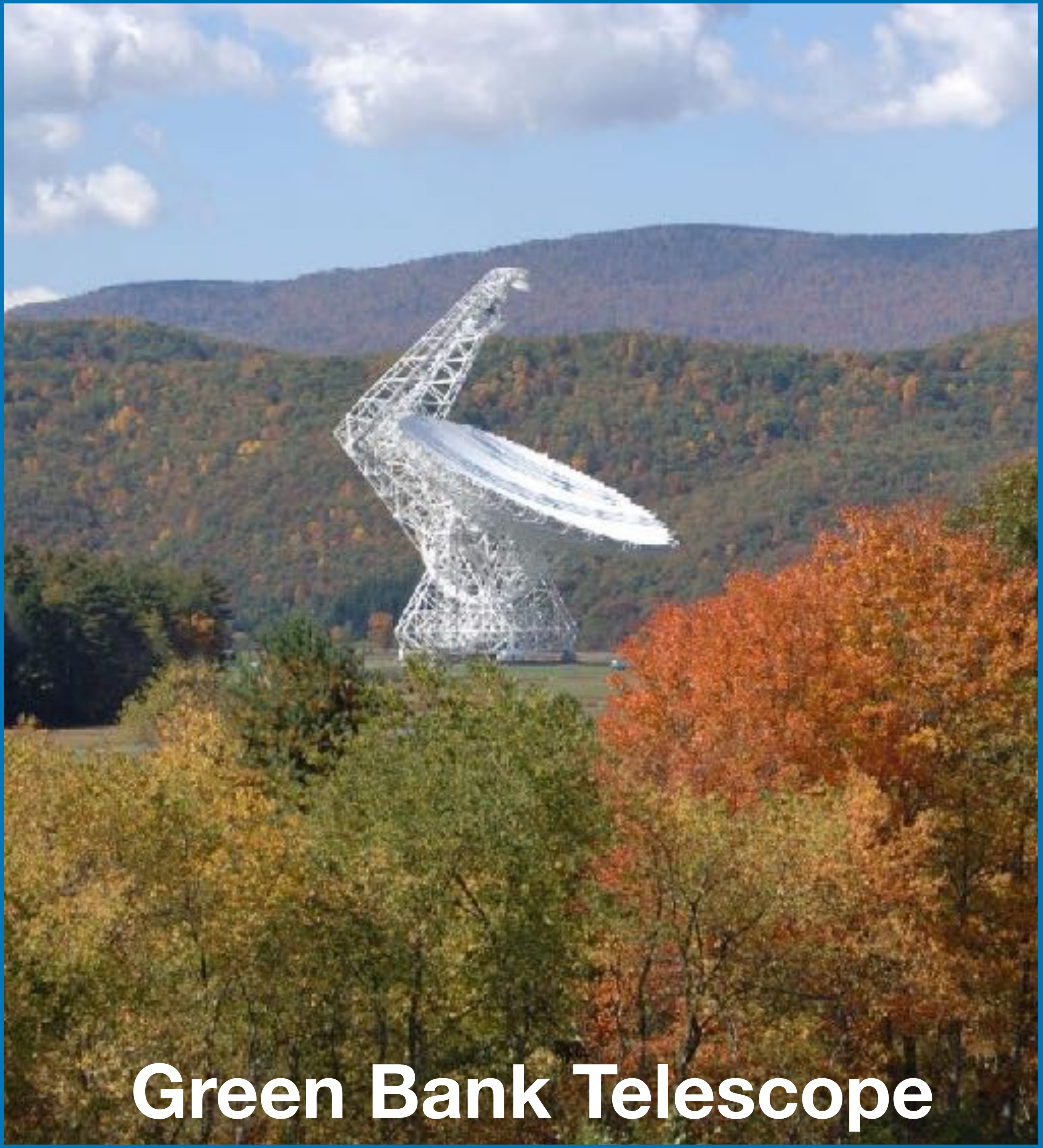
‘Oumuamua is tumbling



Credit: Drahus et al (submitted)

No radio signals detected

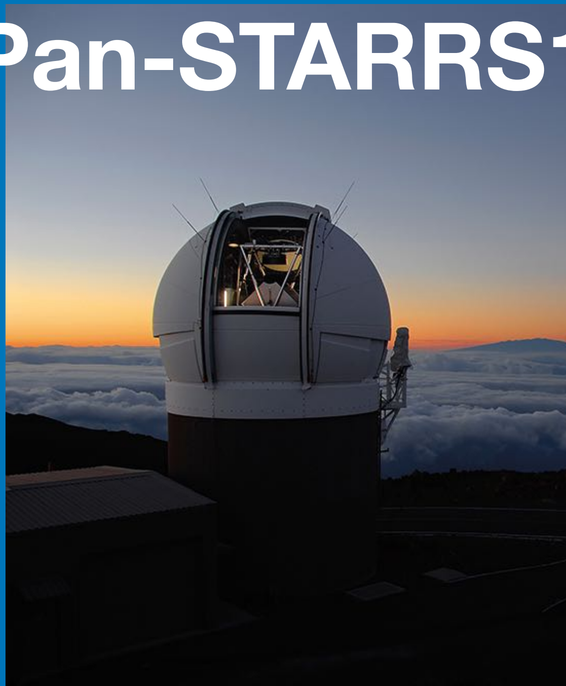
Credit: Colby Gutierrez-Kraybill
https://www.flickr.com/photos/cgk/1558787110/



Credit: NRAO

The first of more visitors to come…. LSST expected to find one a year

Credit: Gemini Observatory/AURA/NSF/Joy Pollard



Pan-STARRS1

Gemini South

Gemini North

Apache Point 3.5m

CFHT

Palomar Hale (200 inch)

Keck Telescopes

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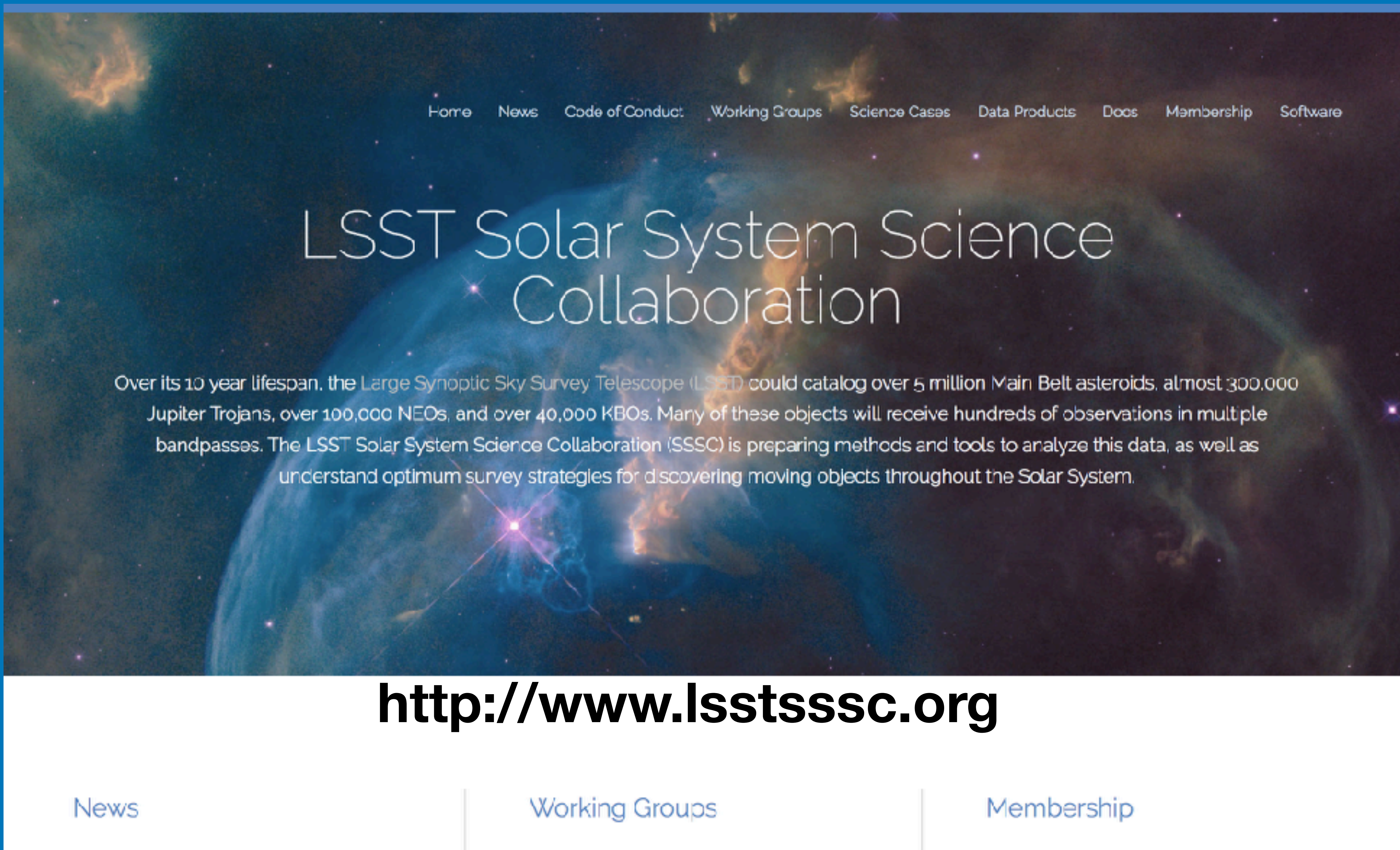
William Herschel Telescope

UKIRT

Large Synoptic Survey Telescope (LSST)

Image Credit: LSST

Science Operations Planned to Start in 2022



http://www.lsstsssc.org

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