Solar System Synergies in the Era of LSST

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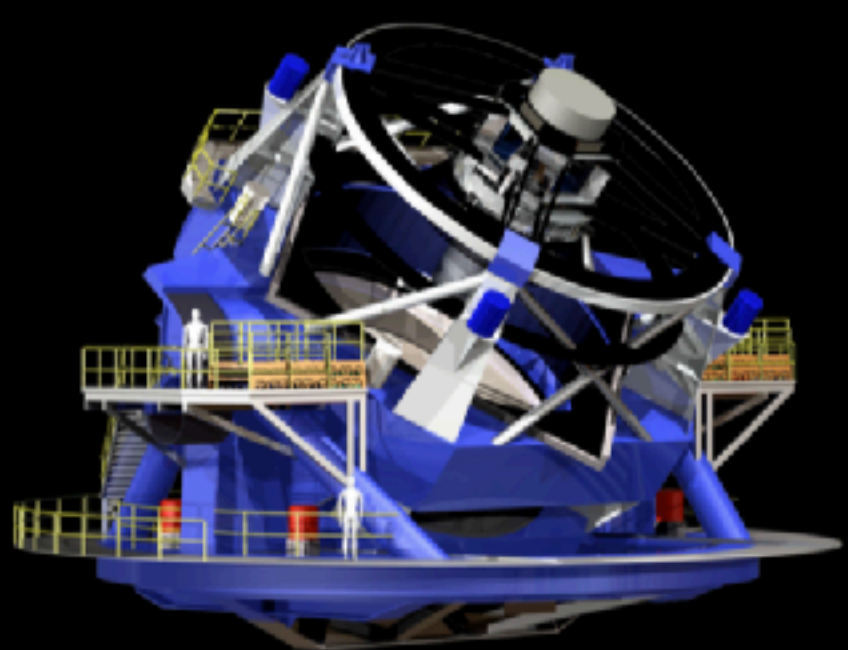
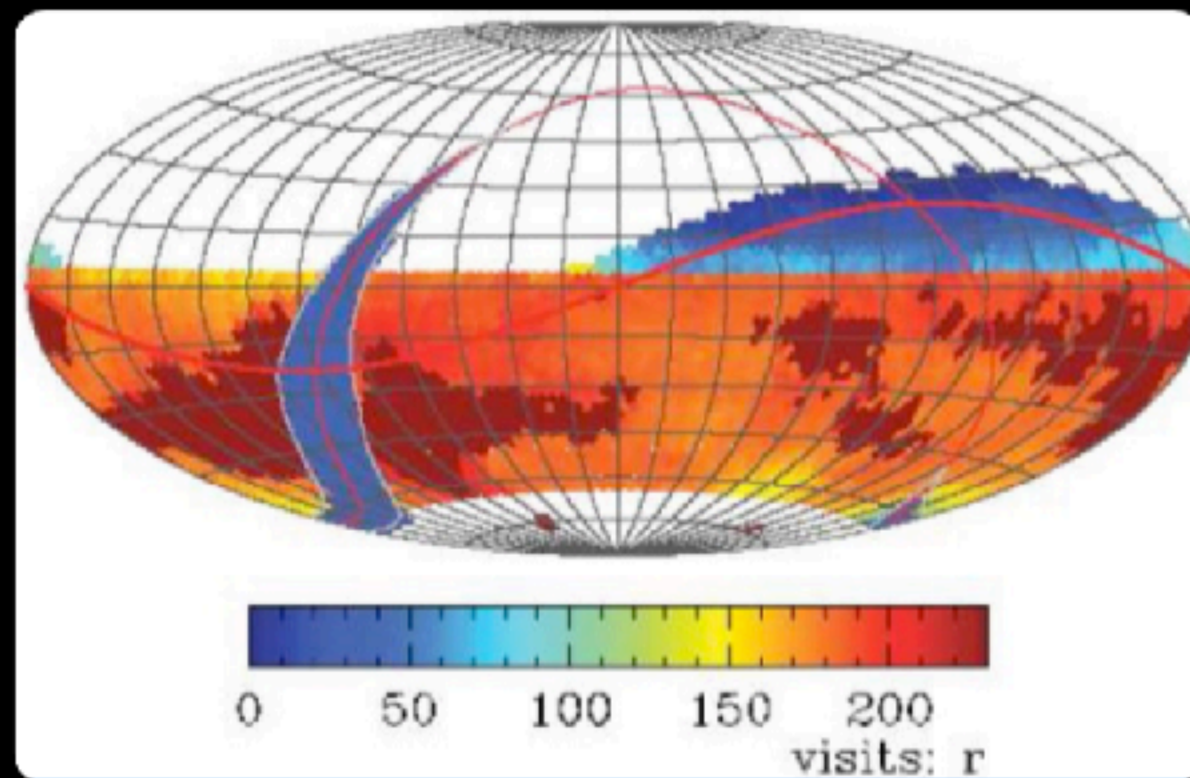
Image Credits: AURA/Gemini/NSF

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





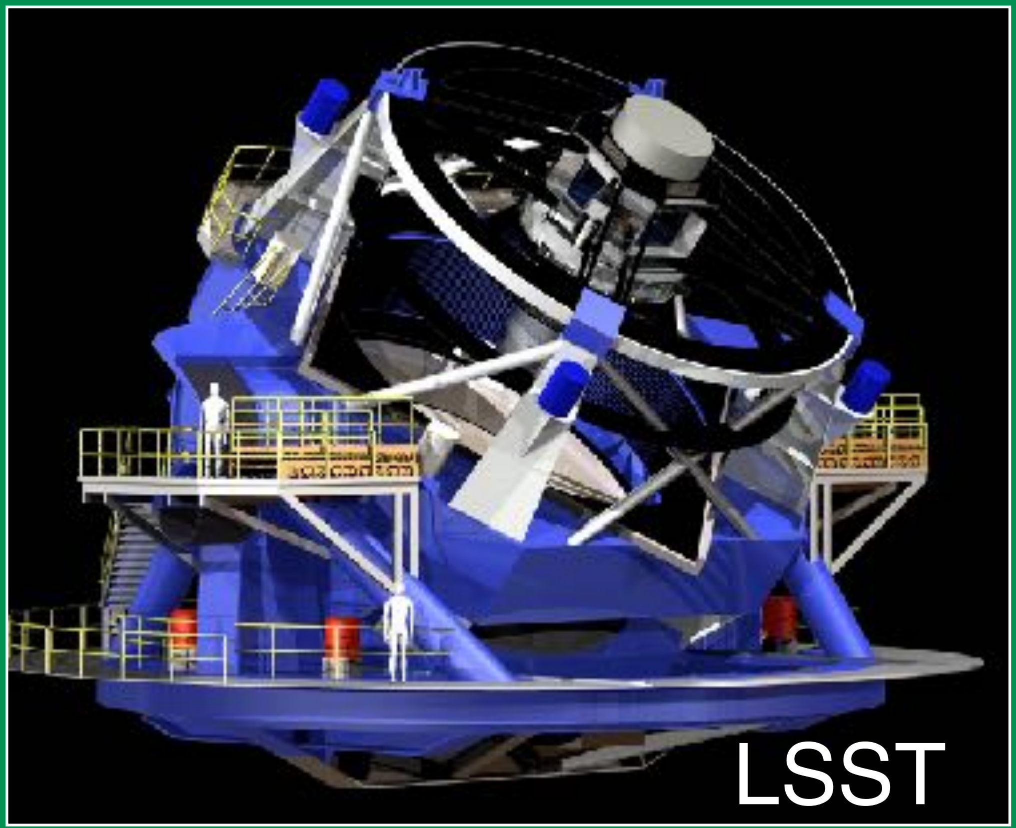
3.2Gpix camera   30sec exp/4sec rd   15TB/night   37 B objects

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

Slide Credit: Mario Juric

The data deluge is coming….

16 < r< ~24.5



- 20,000 deg^2 with 3-14 day cadence
- 800 visits per field over 10 years
- 6 million asteroids
- 8000 lensed AGN
- $10^{4\text{-}5}$ 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


BIG
DATA

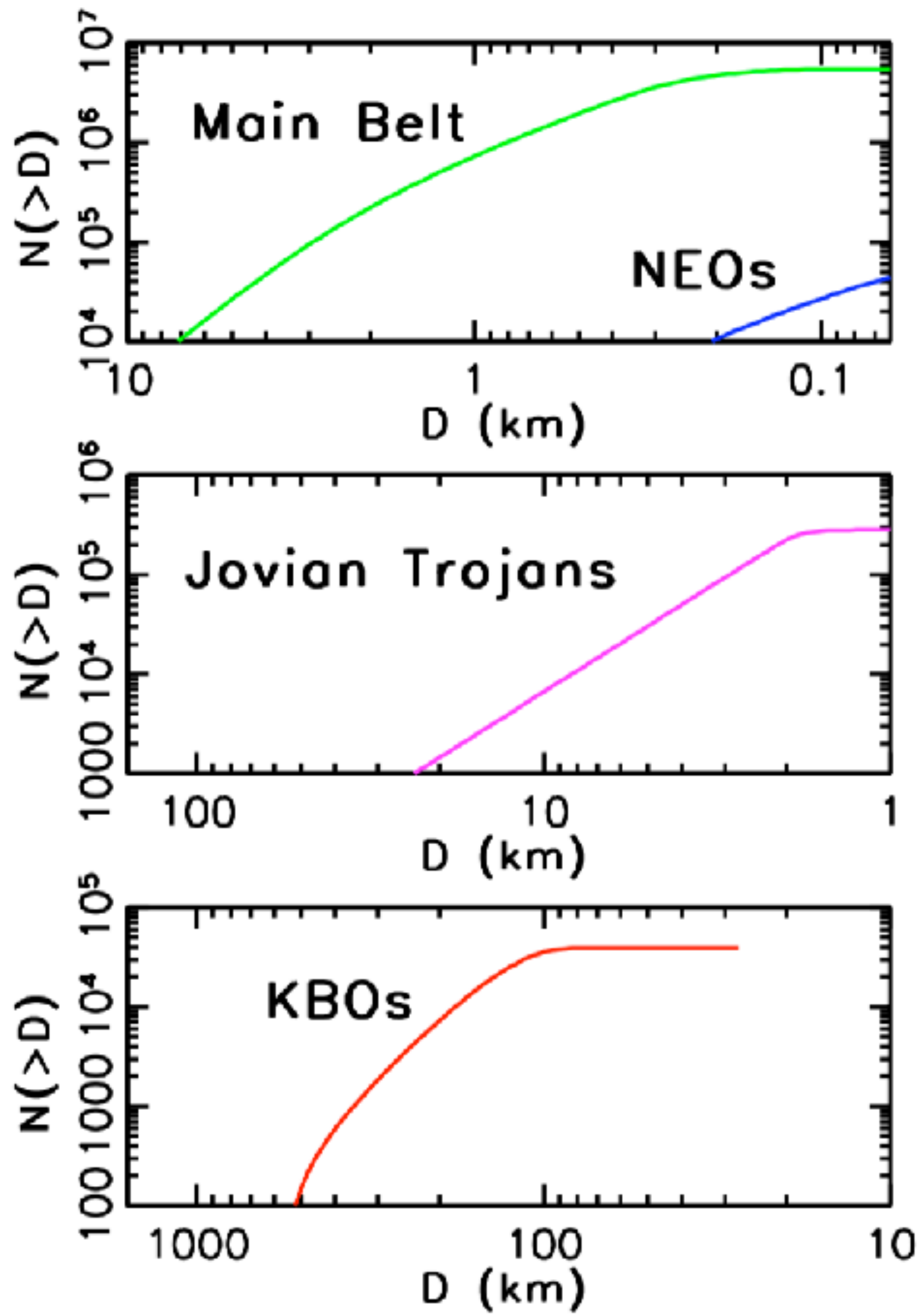
Large Synoptic Survey Telescope (LSST)

Image Credit: LSST

Science Operations Planned to Start in 2022

It’s Really Coming!

Slide Credit: LSST/AURA/LSSTC



Slide Credit: LSST Science book

	Currently Known*	LSST Discoveries**	Median number of observations+	Observational arc length+
Near Earth Objects (NEOs)	14,500	100,000	(D>250m) 60	6.0 years
Main Belt Asteroids (MBAs)	650,000	5,500,000	(D>500m) 200	8.5 years
Jupiter Trojans	6000	280,000	(D>2km) 300	8.7 years
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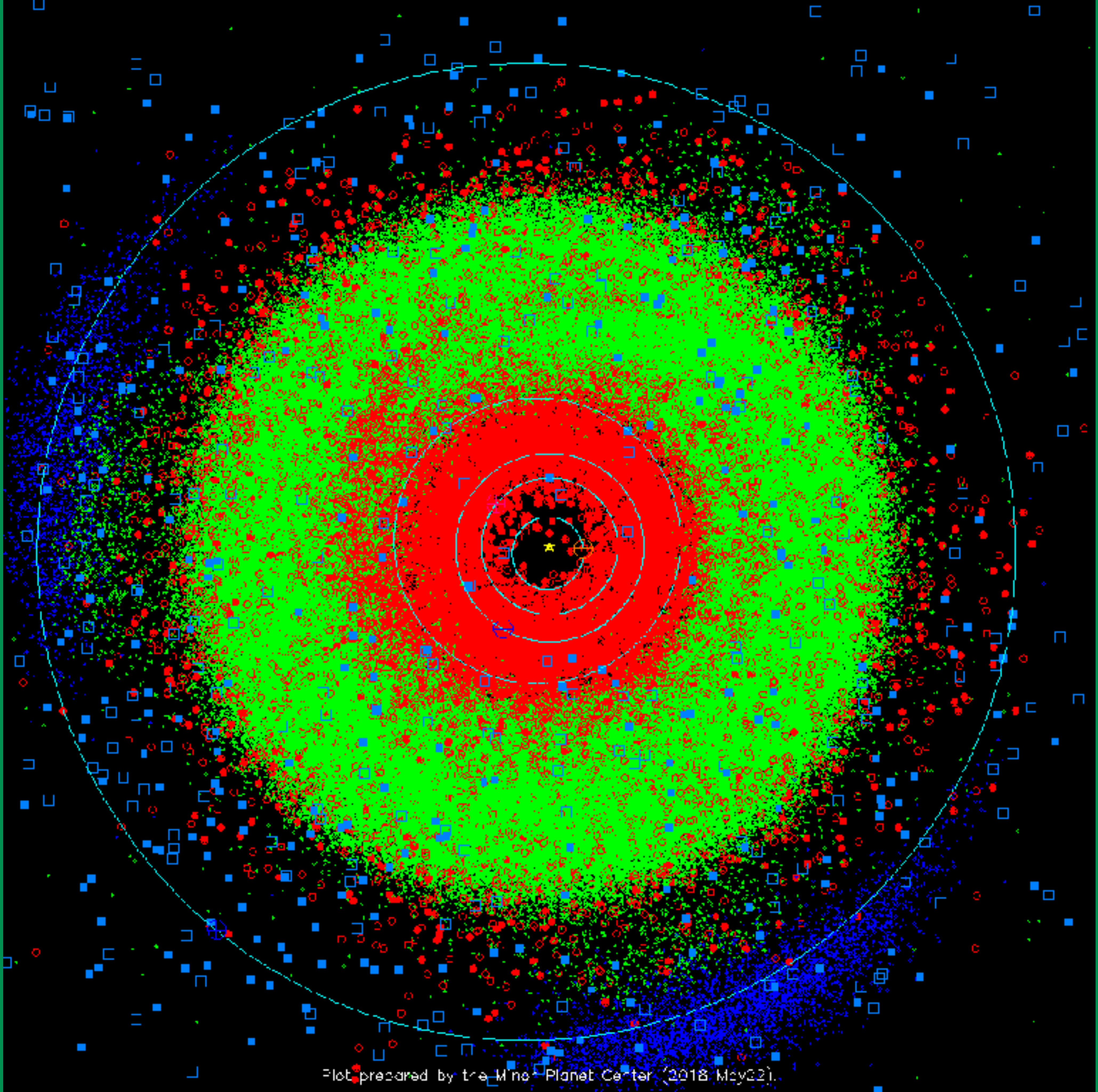
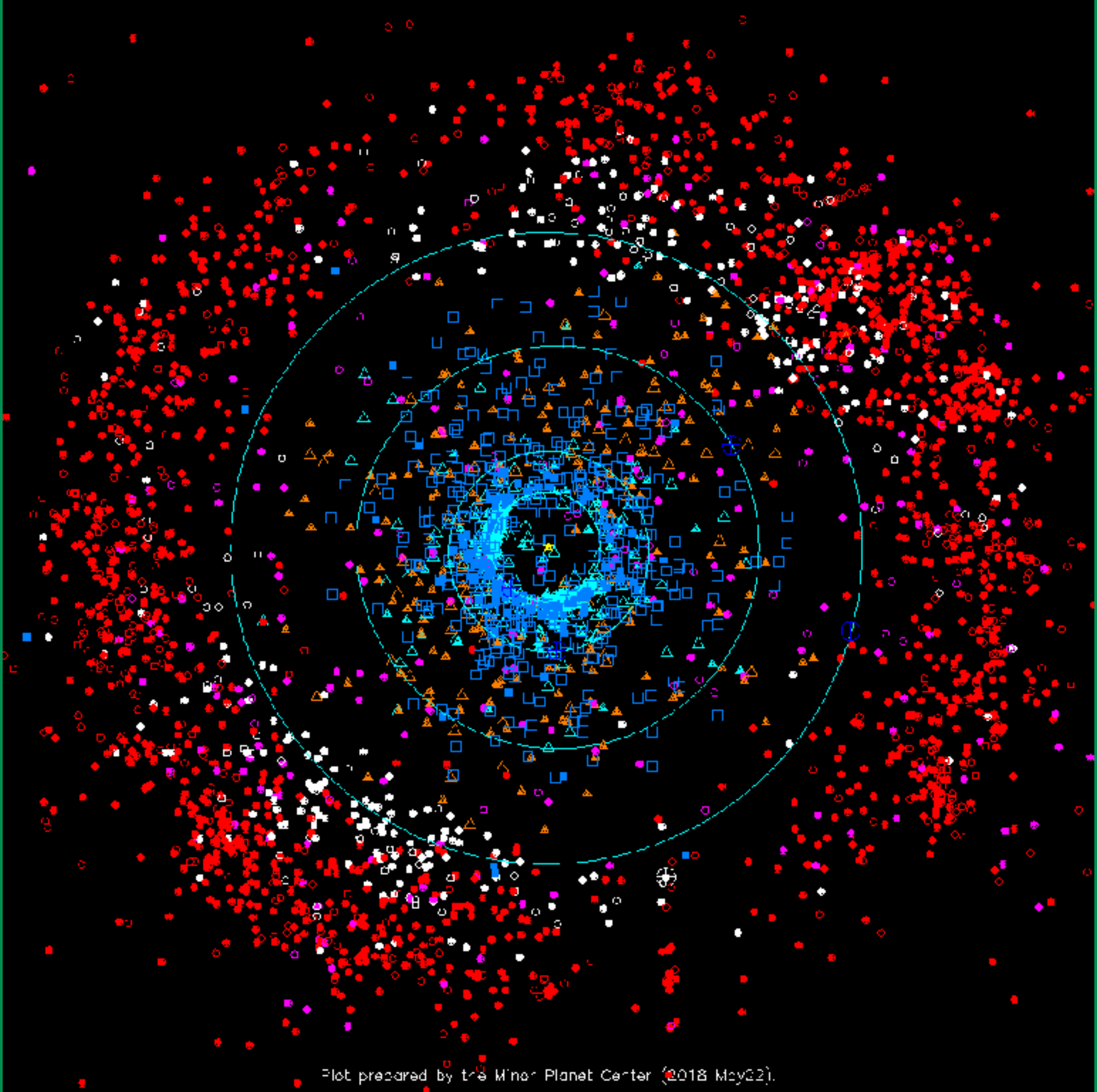
Slide Credit: LSST Science book/Lynne Jones


Plot prepared by the Minor Planet Center (2018 May22).


Plot prepared by the Minor Planet Center (2018 May22).

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.

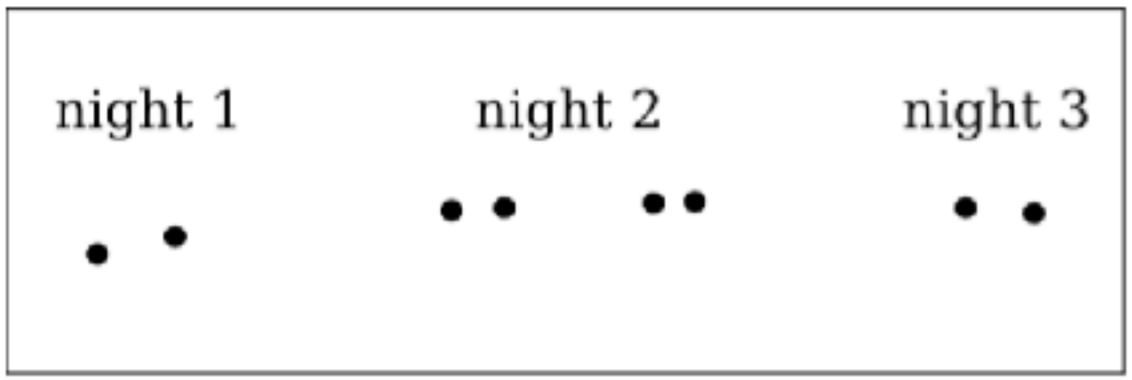
- Every day: A catalog of orbits for LSST-discovered objects.
- Annually: Precisely calibrated photometric catalog (ugrizy bands) accurate to 5mmag (systematics limited), with every data release.

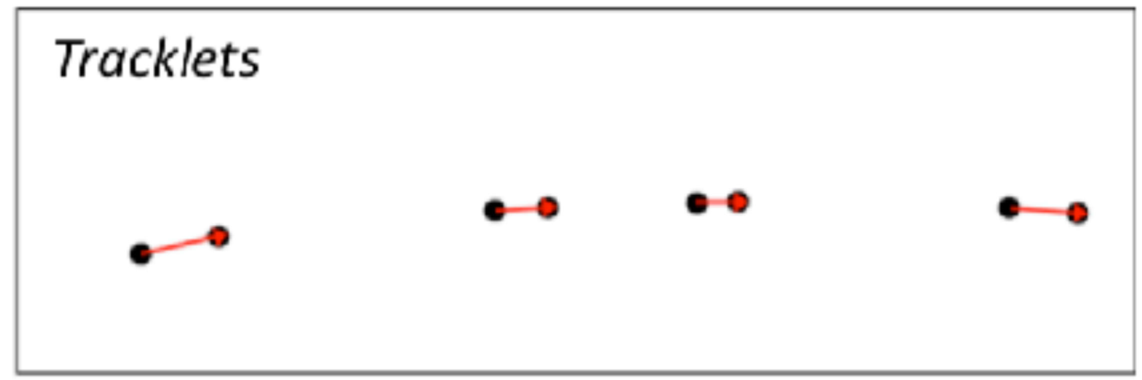
All LSST project Solar System products in some form will be public via alert stream and MPC

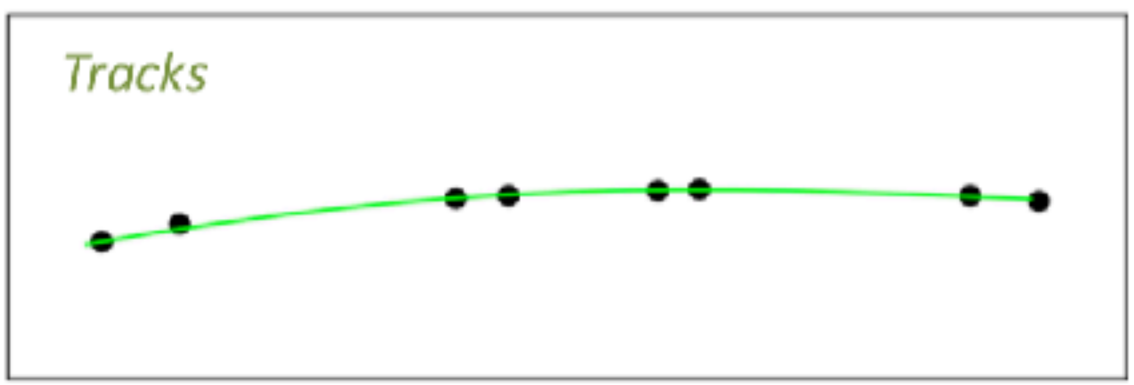
Slide Credit: Mario Juric

How LSST Discovers Objects (for distances less than ~200 AU)

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.

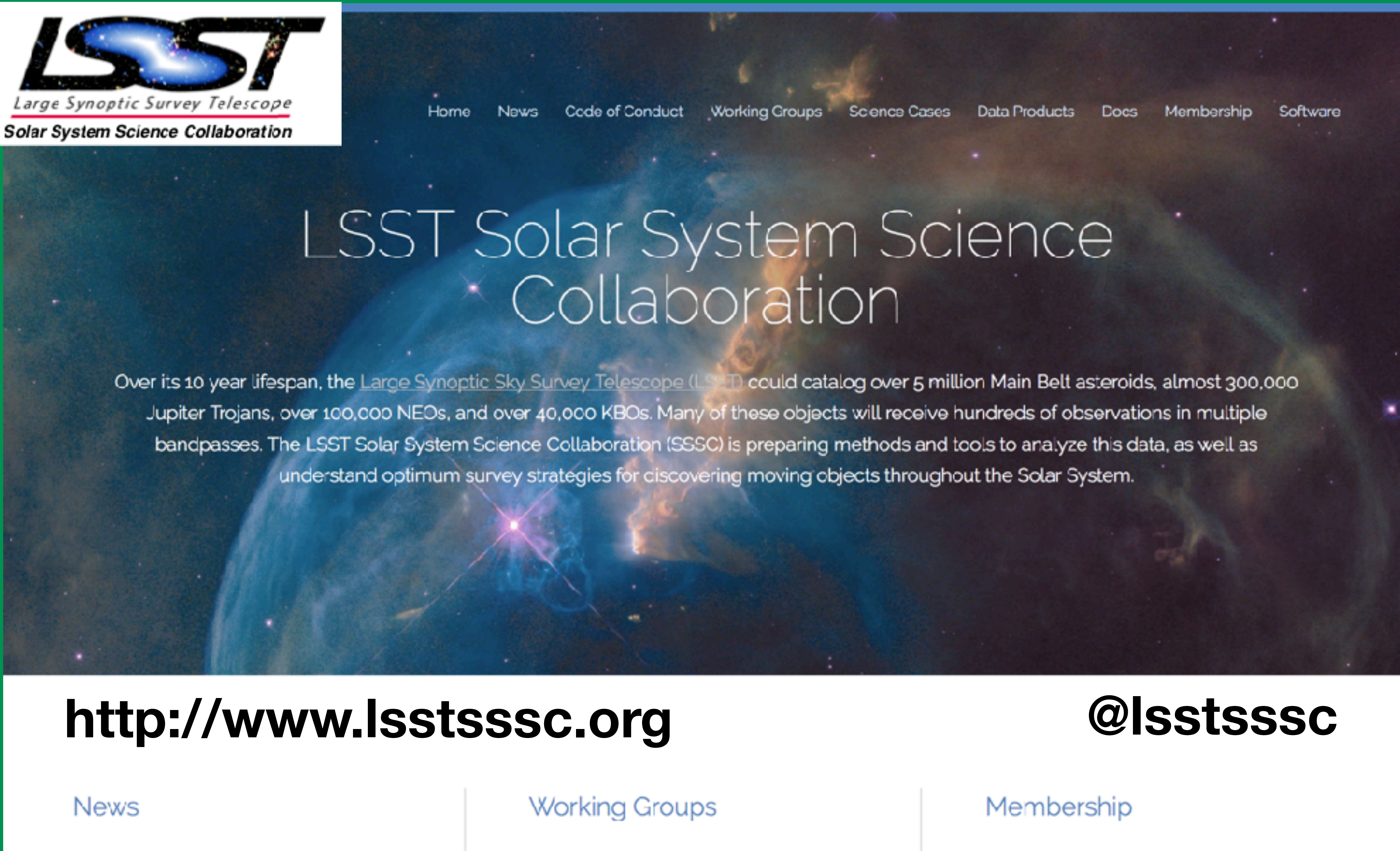
This is the well known MOPS algorithm; e.g., Kubica (2007), Denneau (2006)

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

Large Synoptic Survey Telescope
Solar System Science Collaboration



http://www.lsstsssc.org **@lsstsssc**

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

LARGE SYNOPTIC SURVEY TELESCOPE SOLAR SYSTEM SCIENCE ROADMAP

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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.

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

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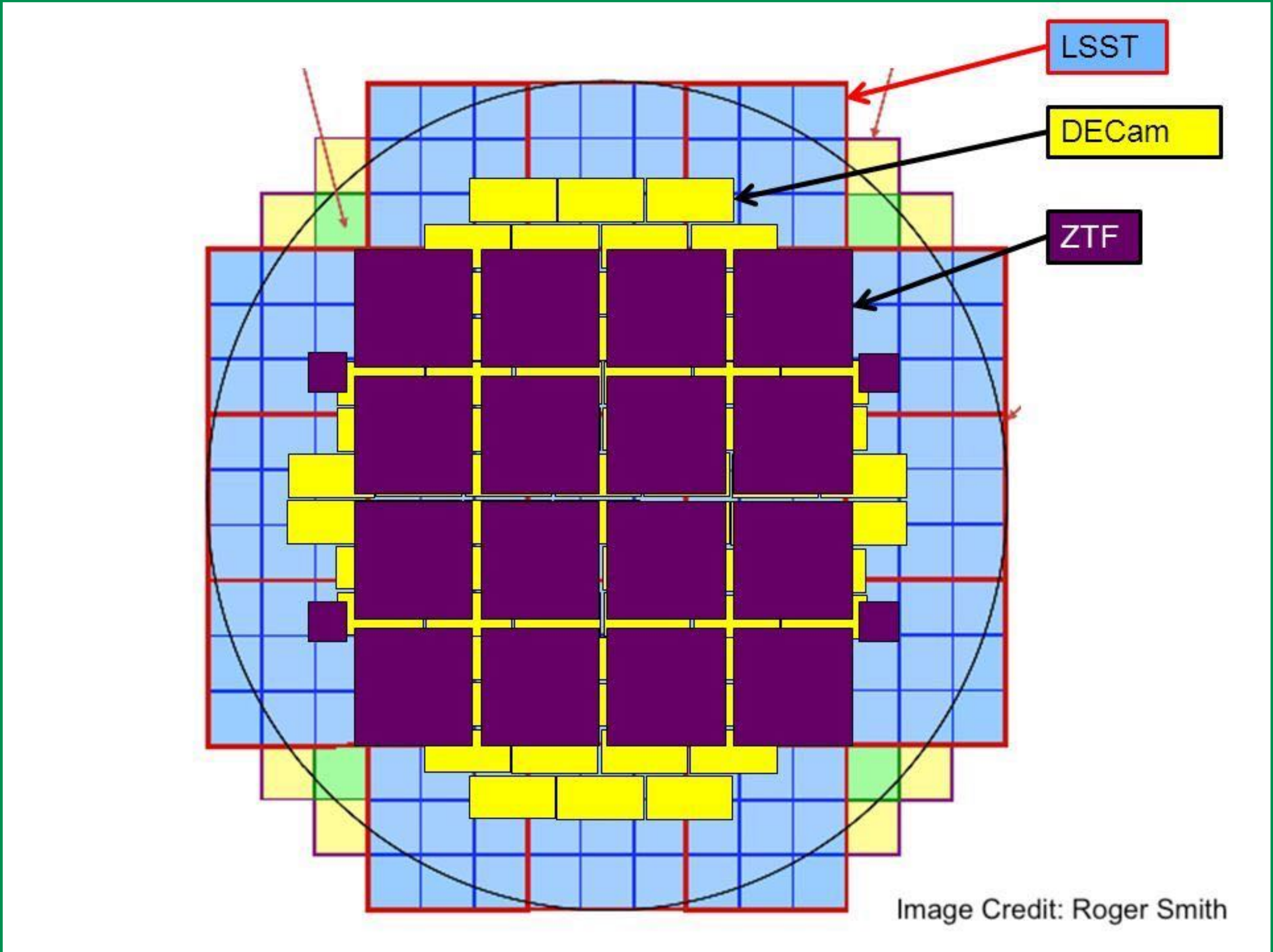
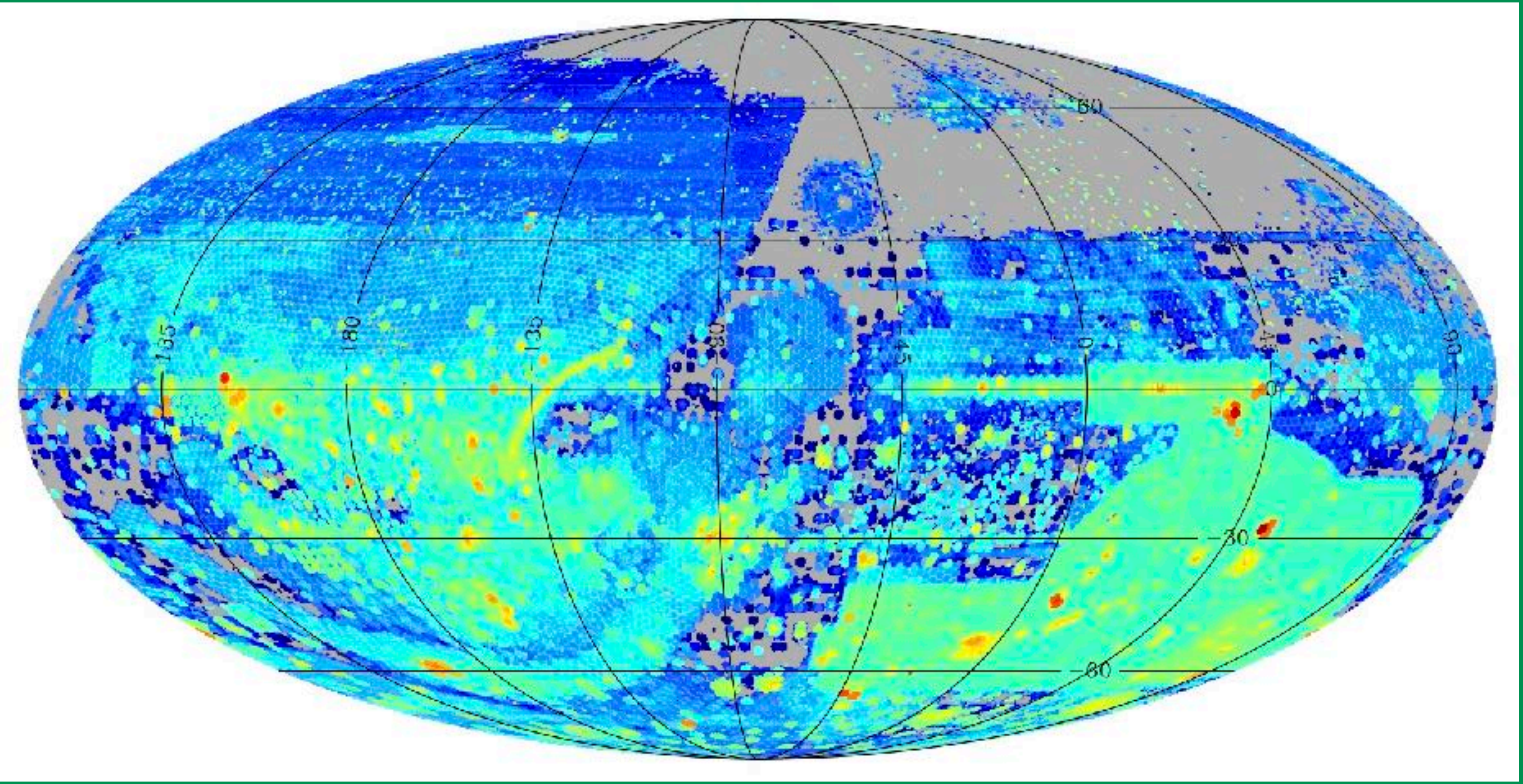
Slide Credit: LSST Science book/Lynne Jones


LSST
DECam
ZTF
Image Credit: Roger Smith

Pre-covery of Brighter Objects from Past DECam Fields

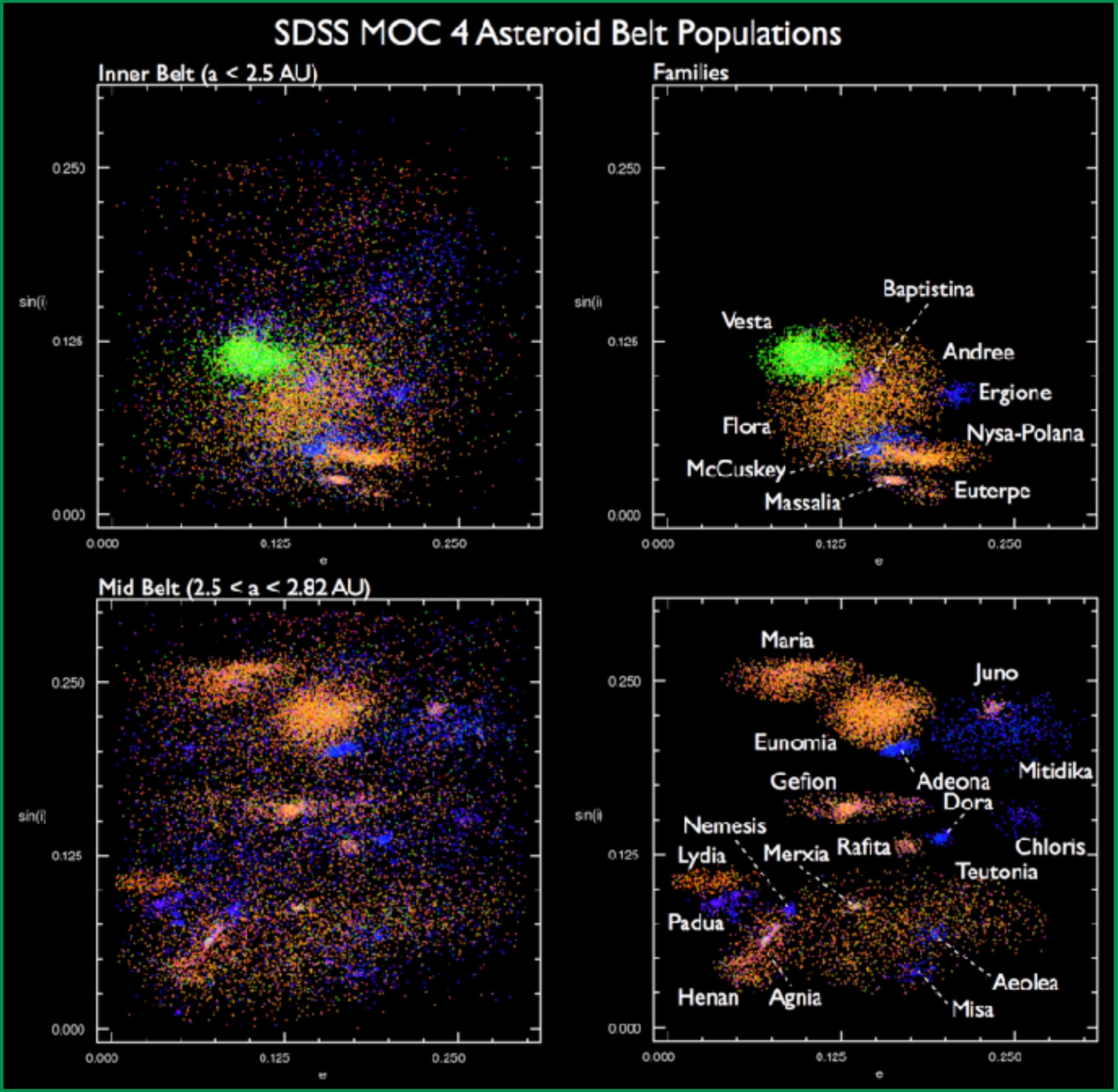


NOAO Data Lab

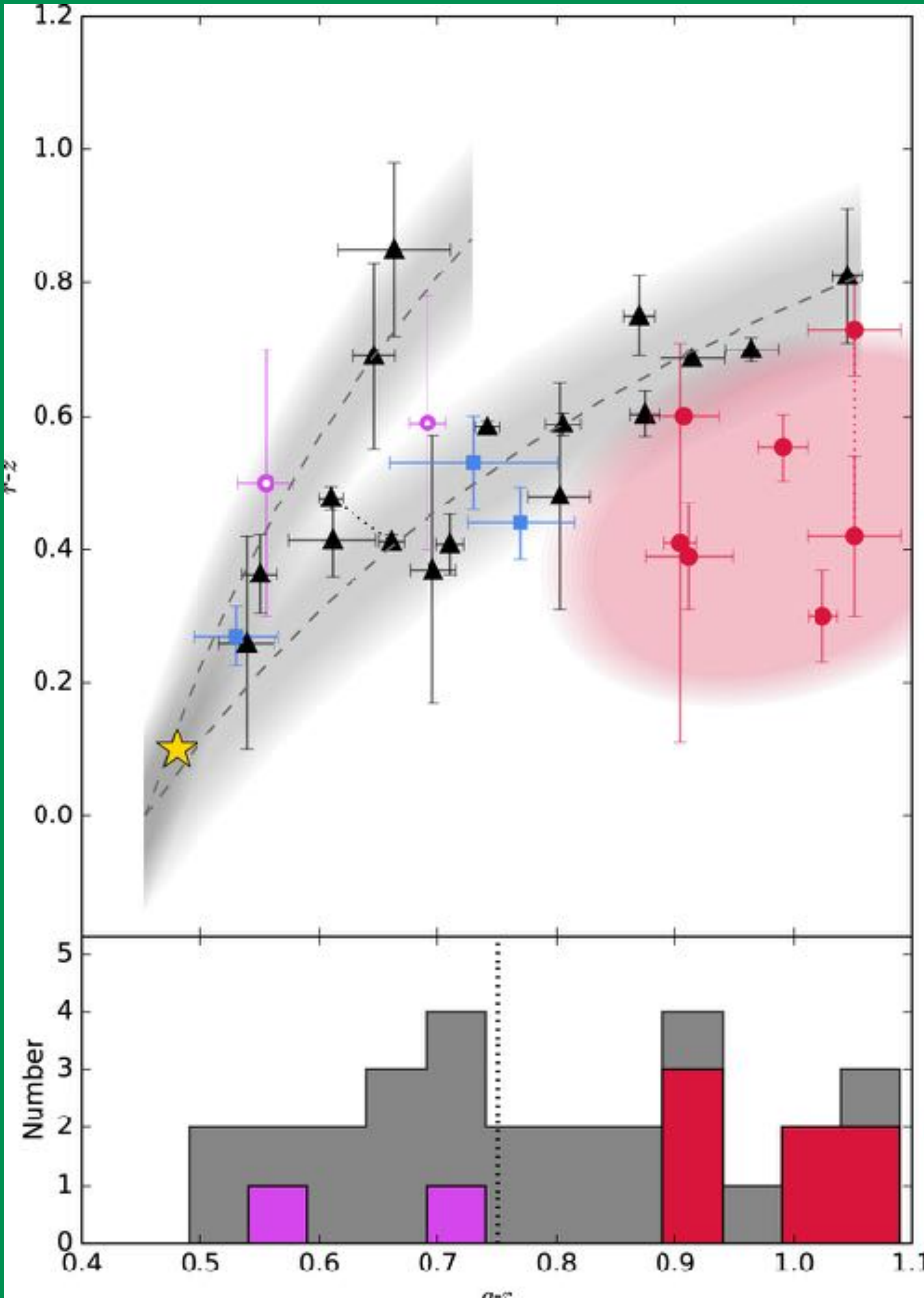
DECam Asteroid Database

https://datalab.noao.edu/dad.php

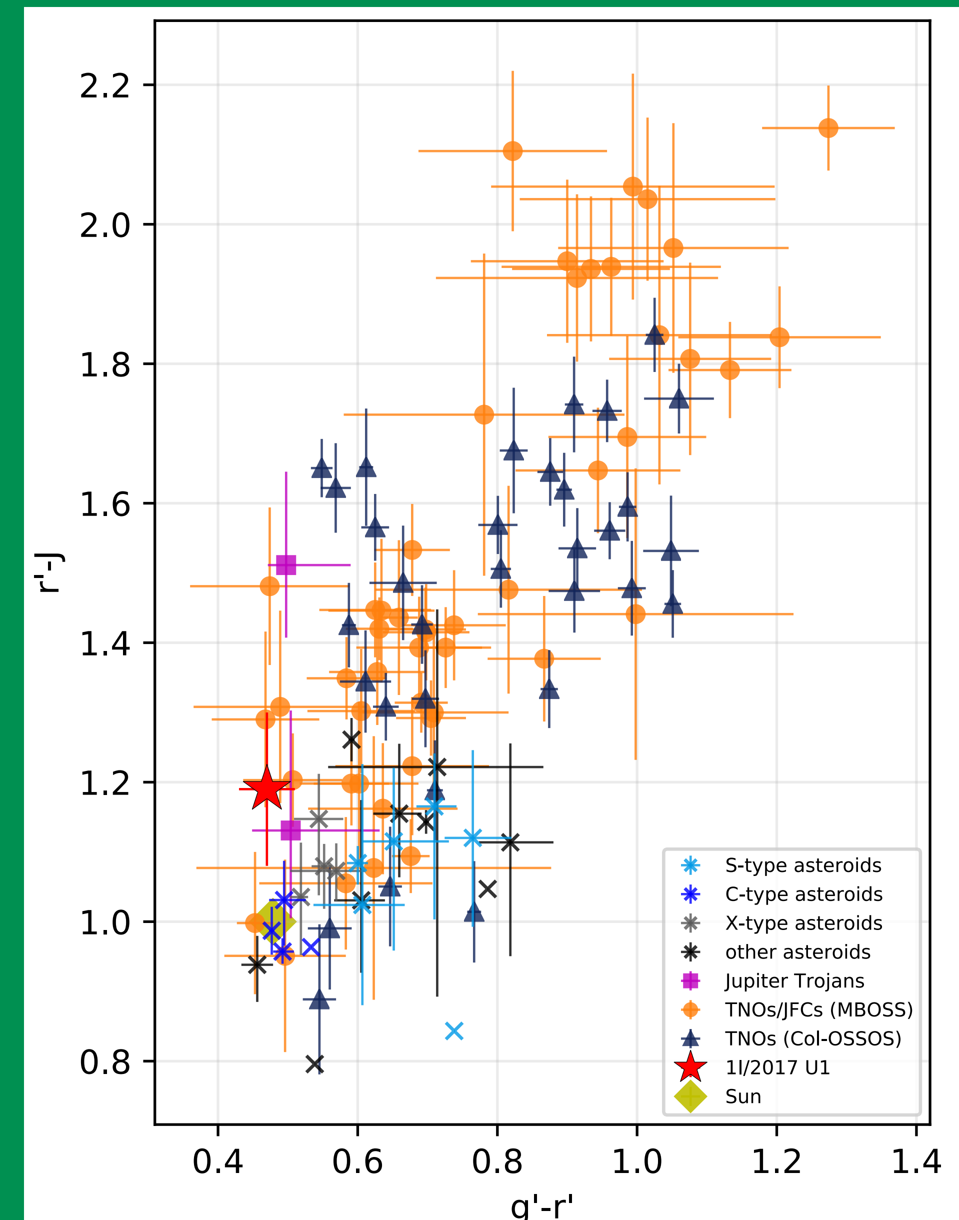
Asteroid Colors



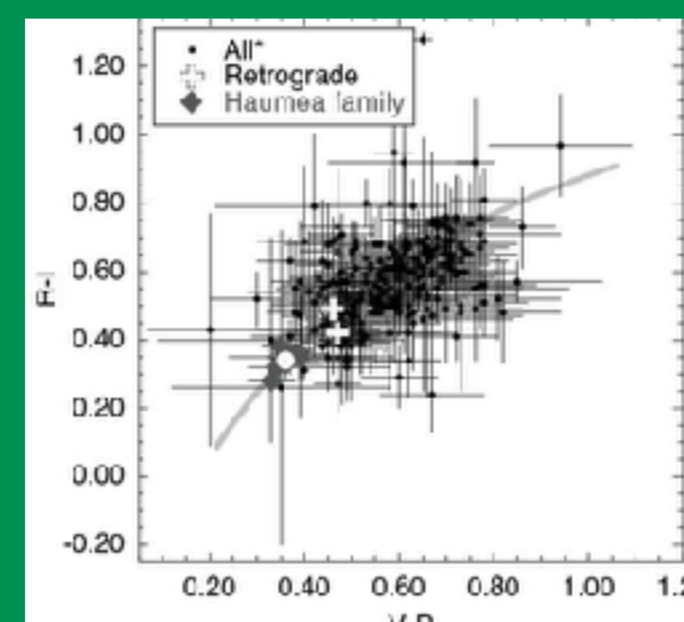
Credit Parker et al (2008)



Credit: Pike, Fraser, Schwamb et al. (2017)

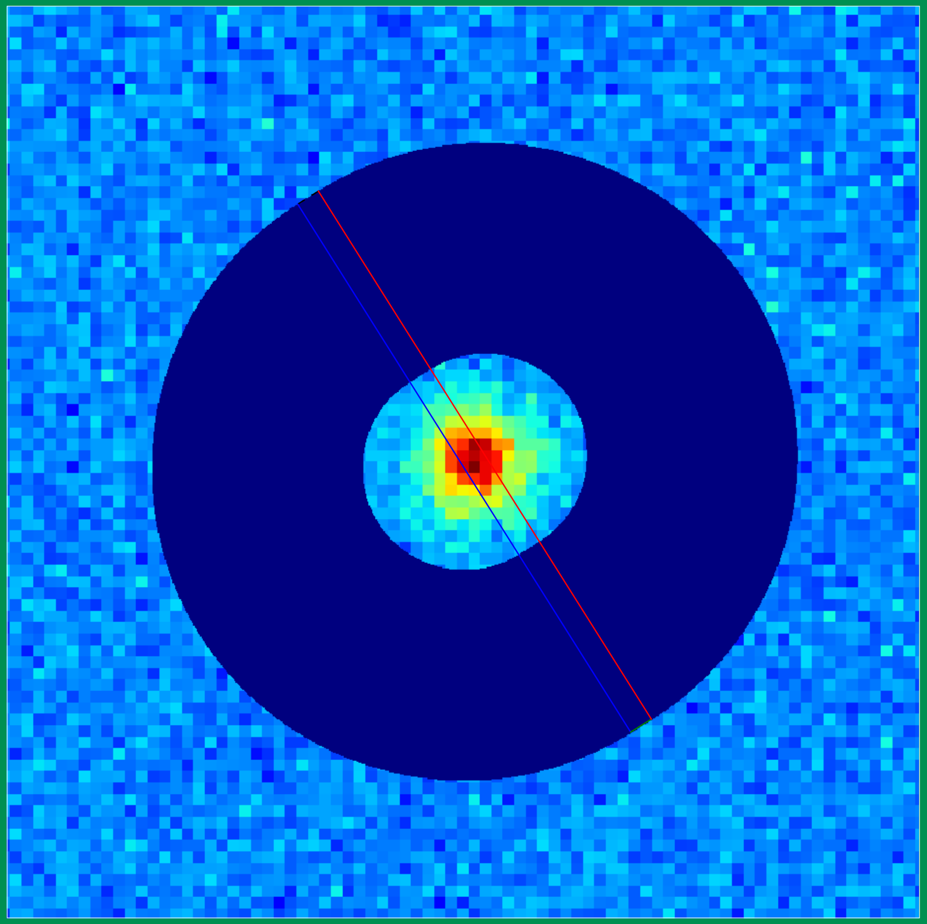


Credit: Bannister, Schwamb et al. (2017)



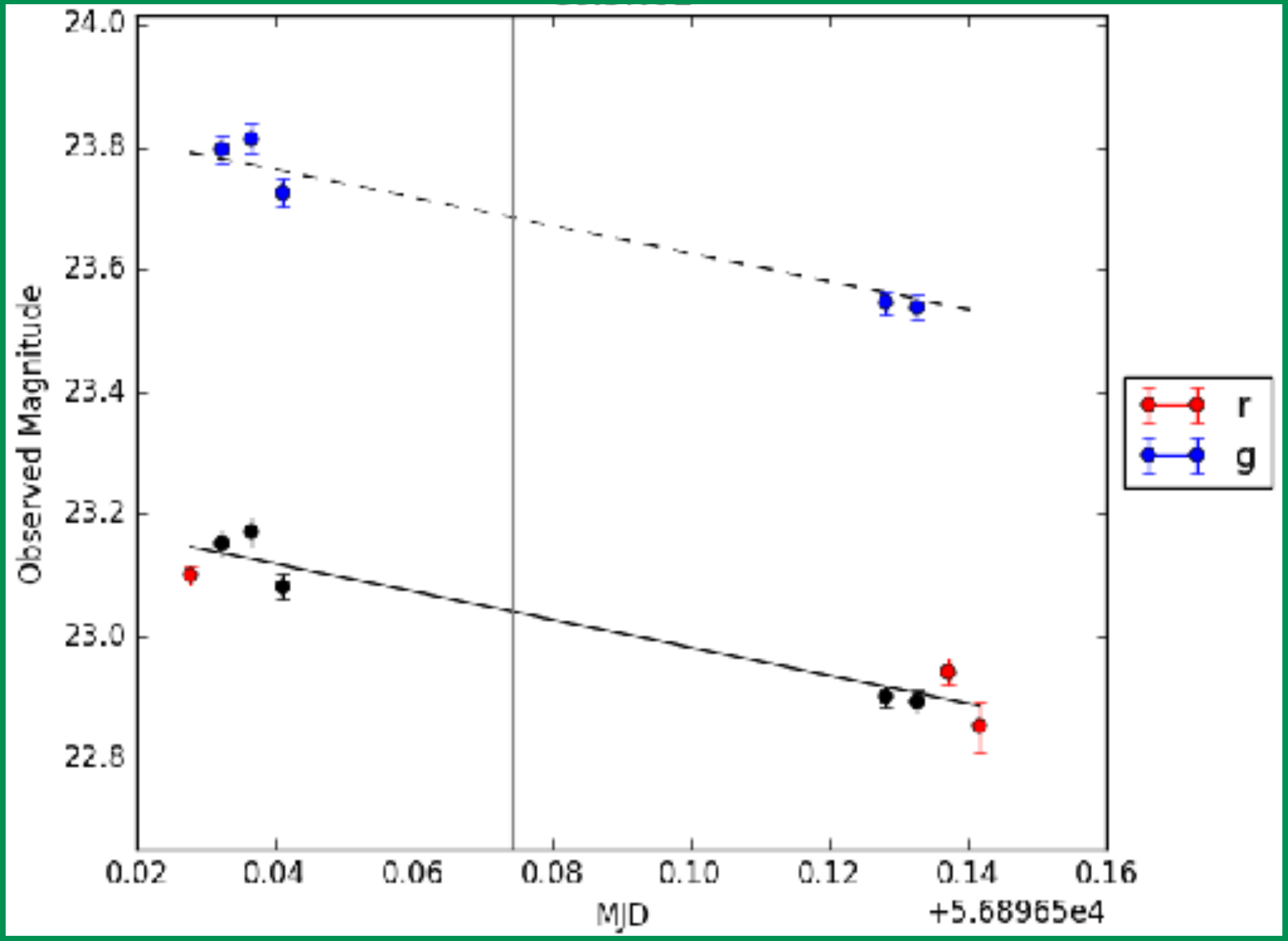
Credit: Peixinho et al (2018)

Challenges: High Precision Photometry & Light curve/Rotational Variability



TRIPPy: **TR**ailed **I**mage **P**hotometry in **Py**thon

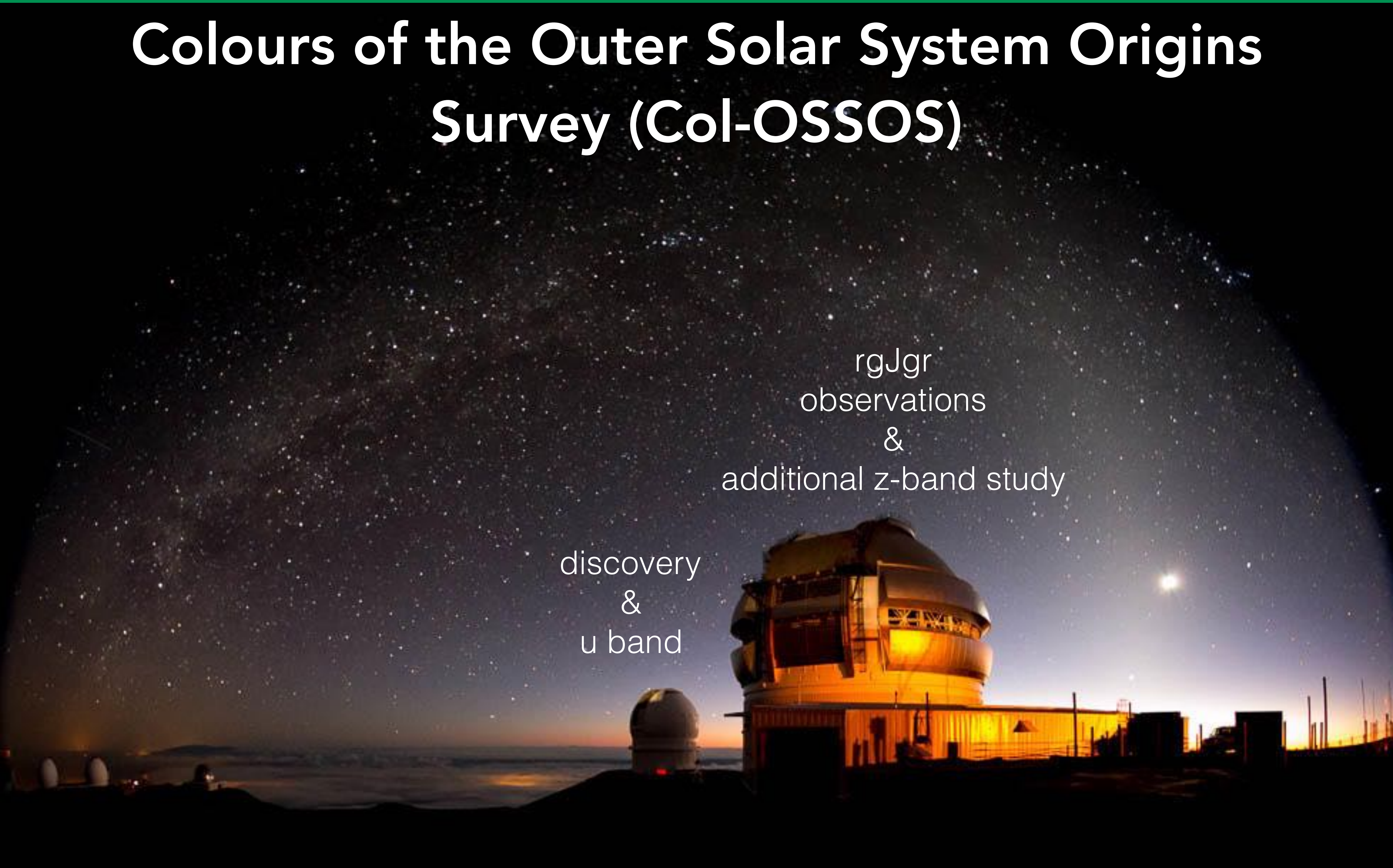
Fraser, Alexandersen, Schwamb, et al (2016)



Schwamb et al. (in prep)

https://github.com/fraserw/trippy

Colours of the Outer Solar System Origins Survey (Col-OSSOS)



Gemini Queue or Priority Visitor Observer Calls Up CFHT Queue Observer to Coordinate

Image credit: Gemini/AURA/NSF

Rotating Bodies - Light curves

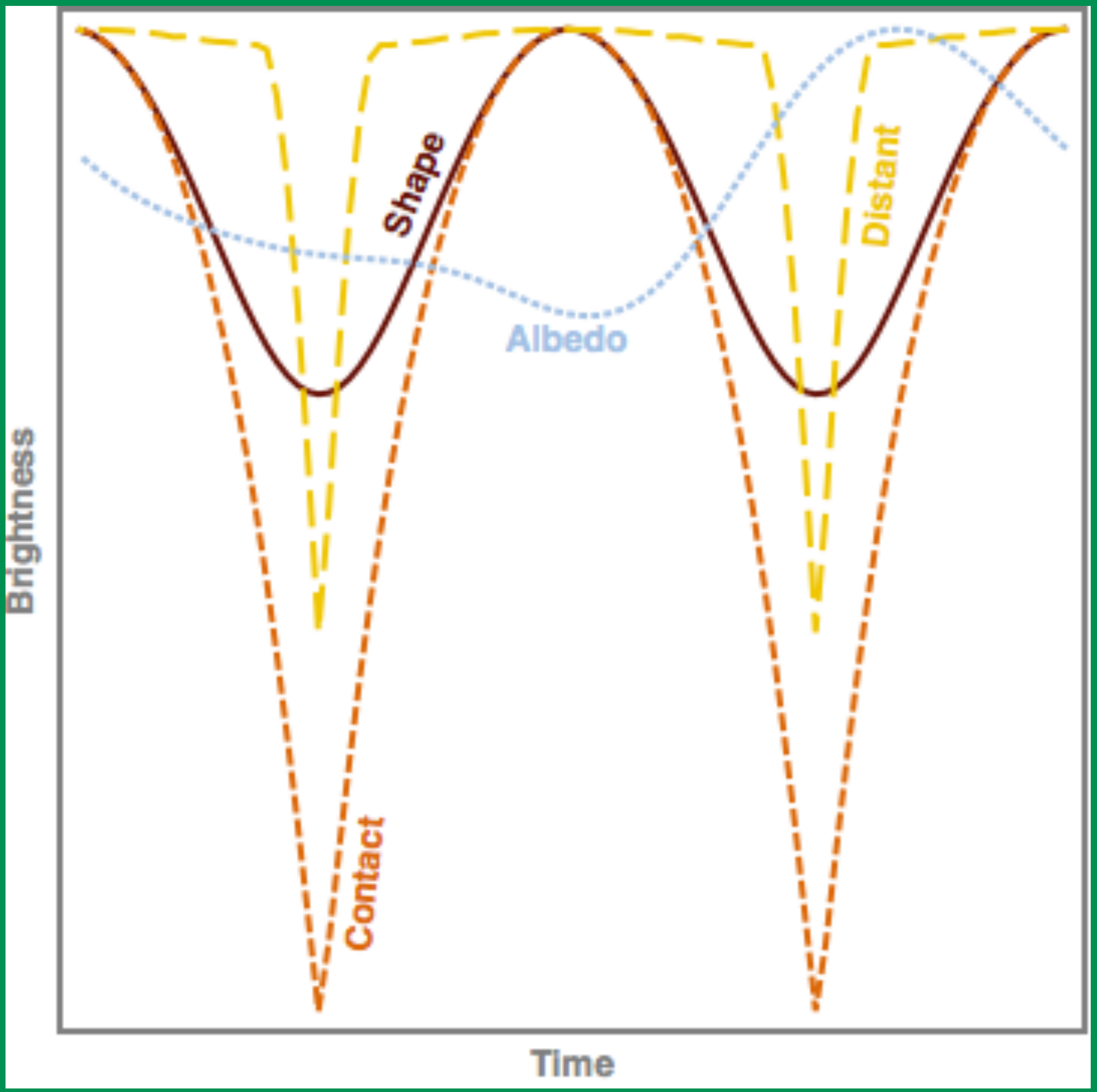


Image credit: Pedro Lacerda

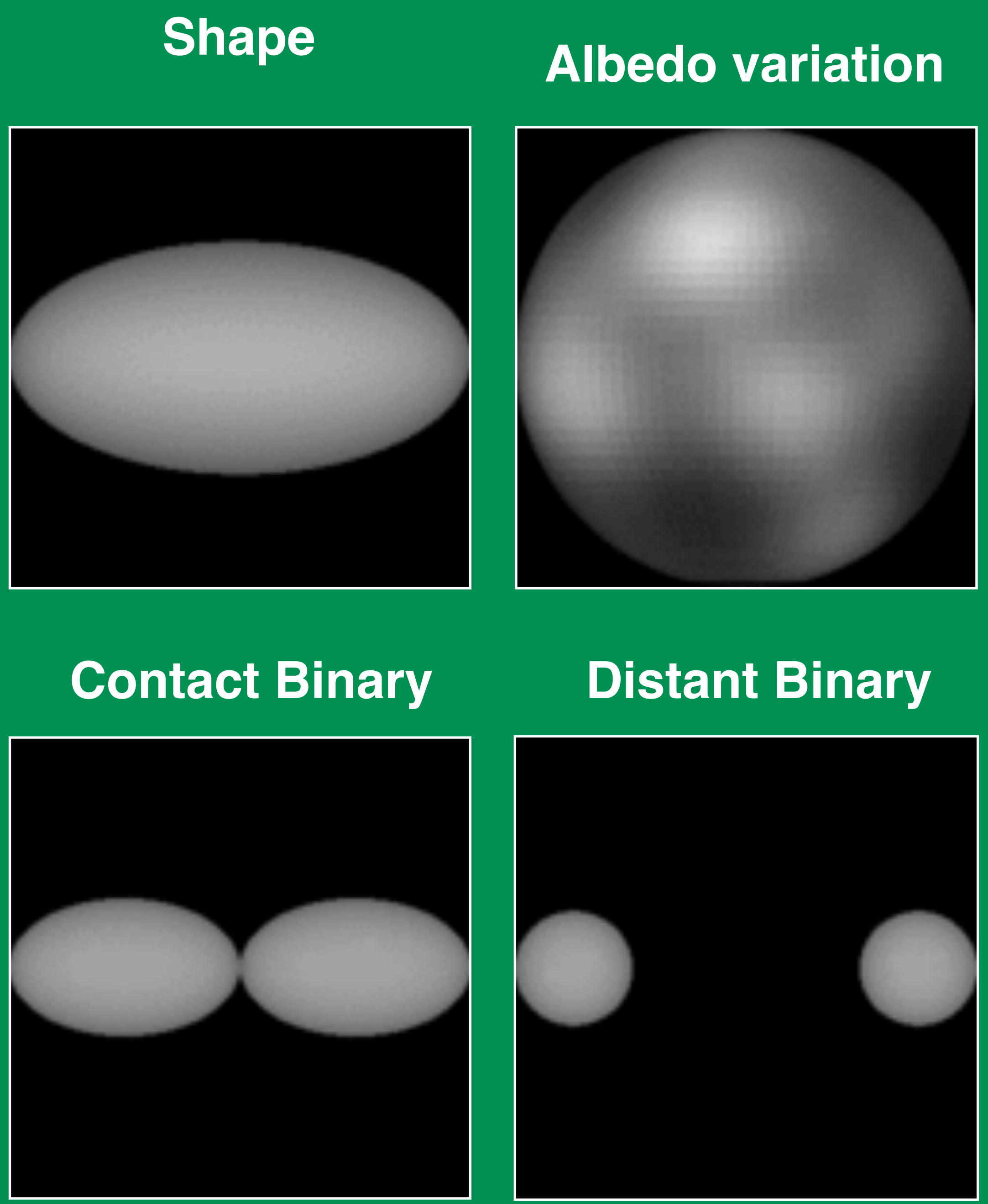
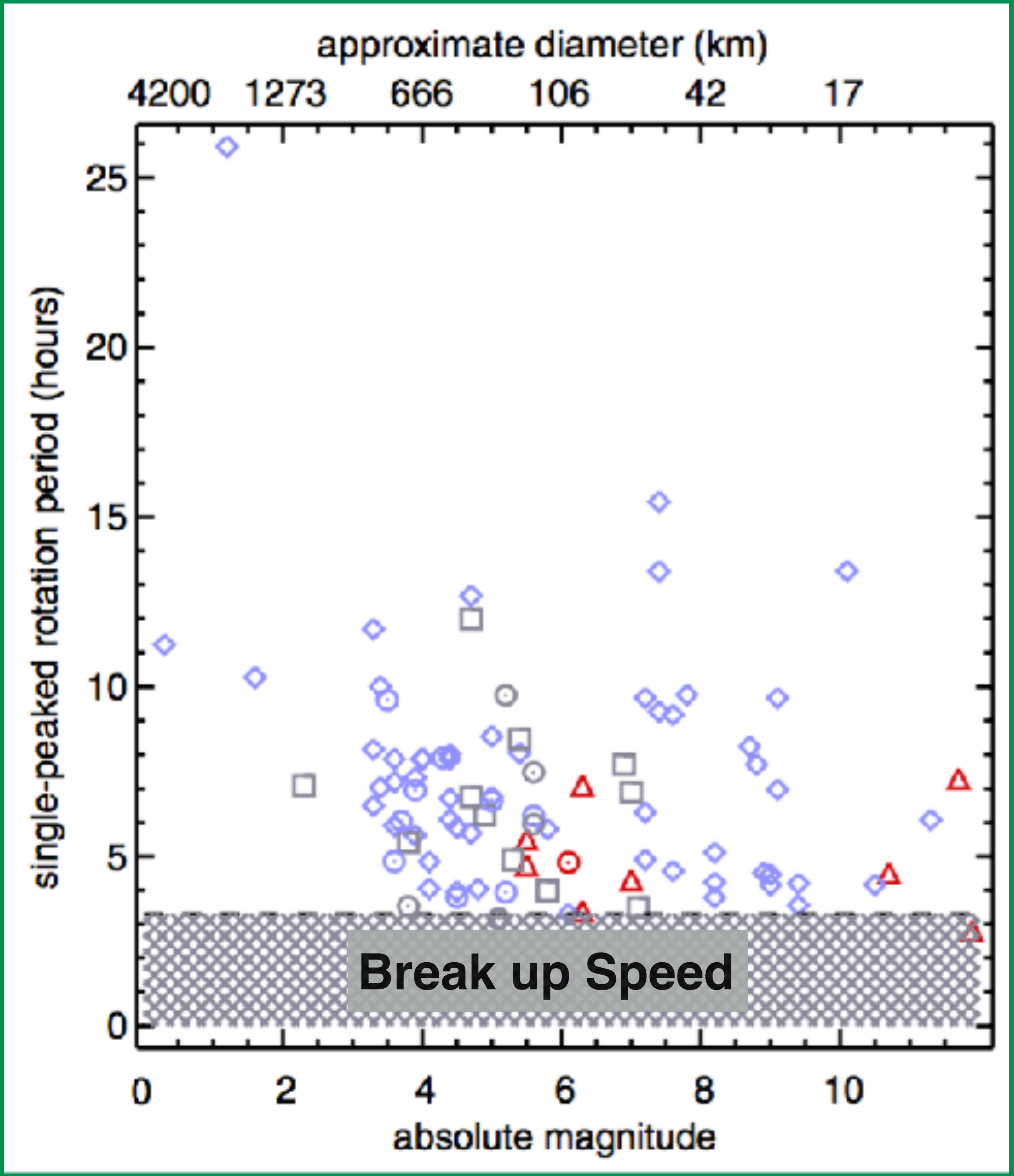


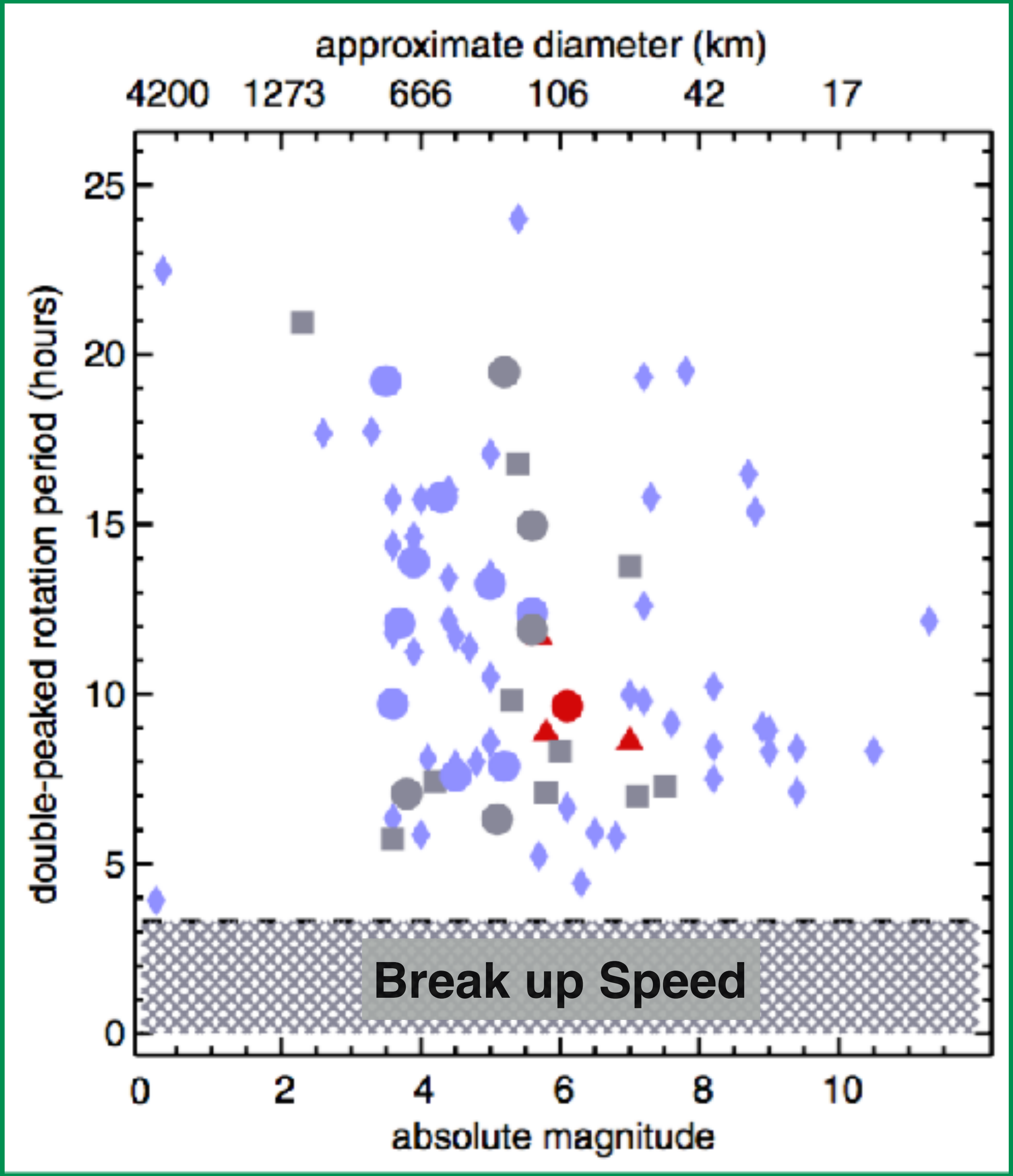
Image credit: Pedro Lacerda

Light curves/Rotational Variability

Single-Peaked Light curves



Double-Peaked Light curves

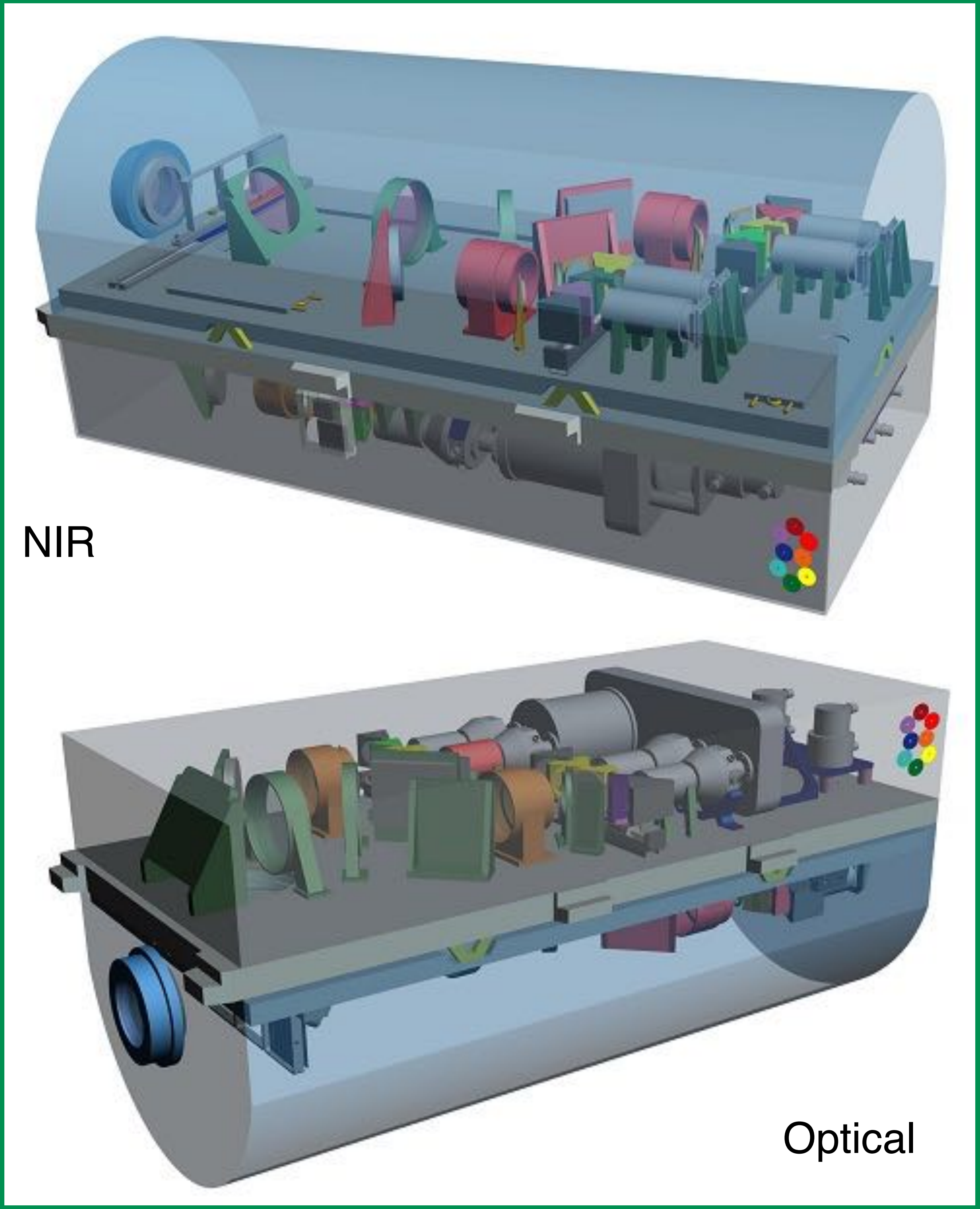


Bennechi & Sheppard (2013)

Don’t forget Gemini South and SOAR

Image Credit: LSST/AURA/LSSTC

Gemini South and OCTOCAM



simultaneous 0.33 to 2.3 μm
(u, g, r, i, z, J, H and Ks) in imaging

0.4 to 2.3 μm in spectroscopy

One Target at a Time

Image credit: Gemini/AURA/NSF

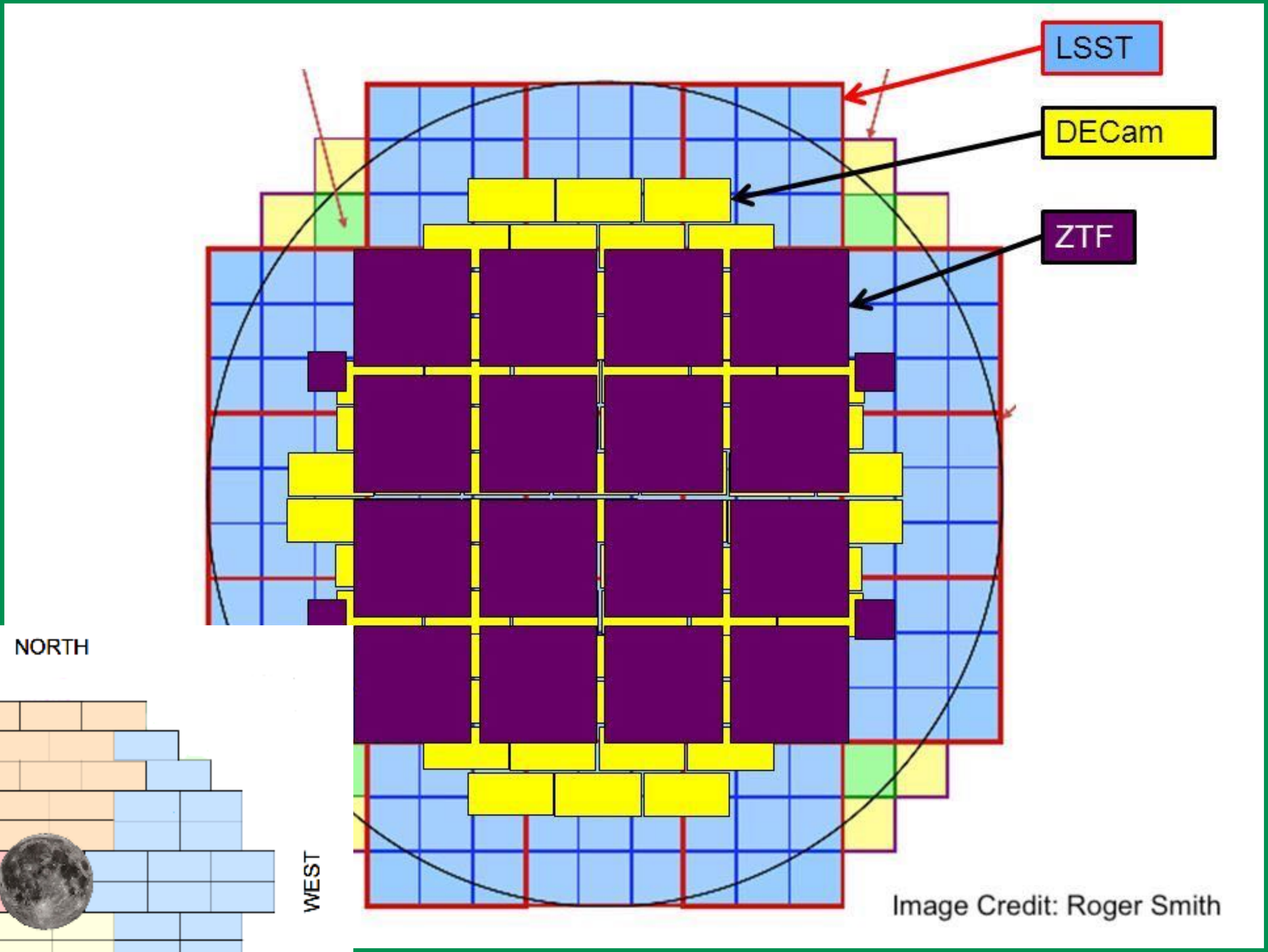

LSST
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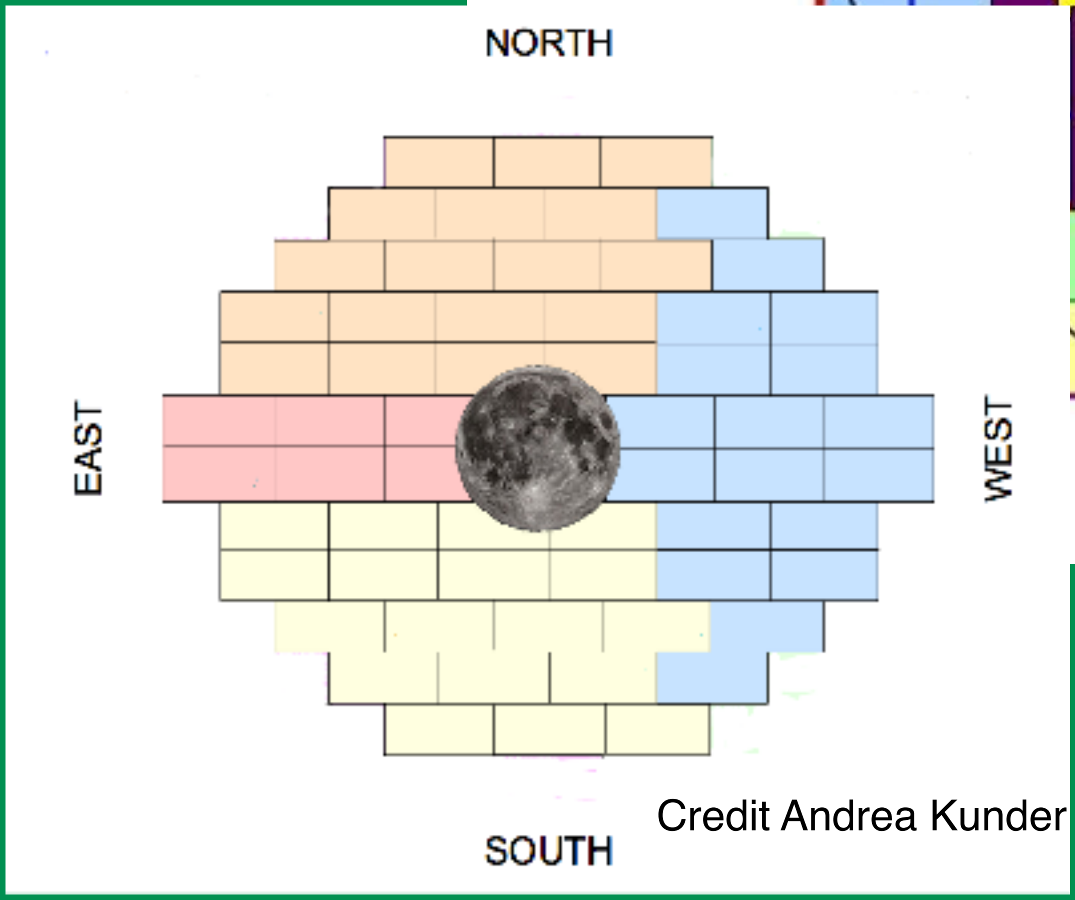
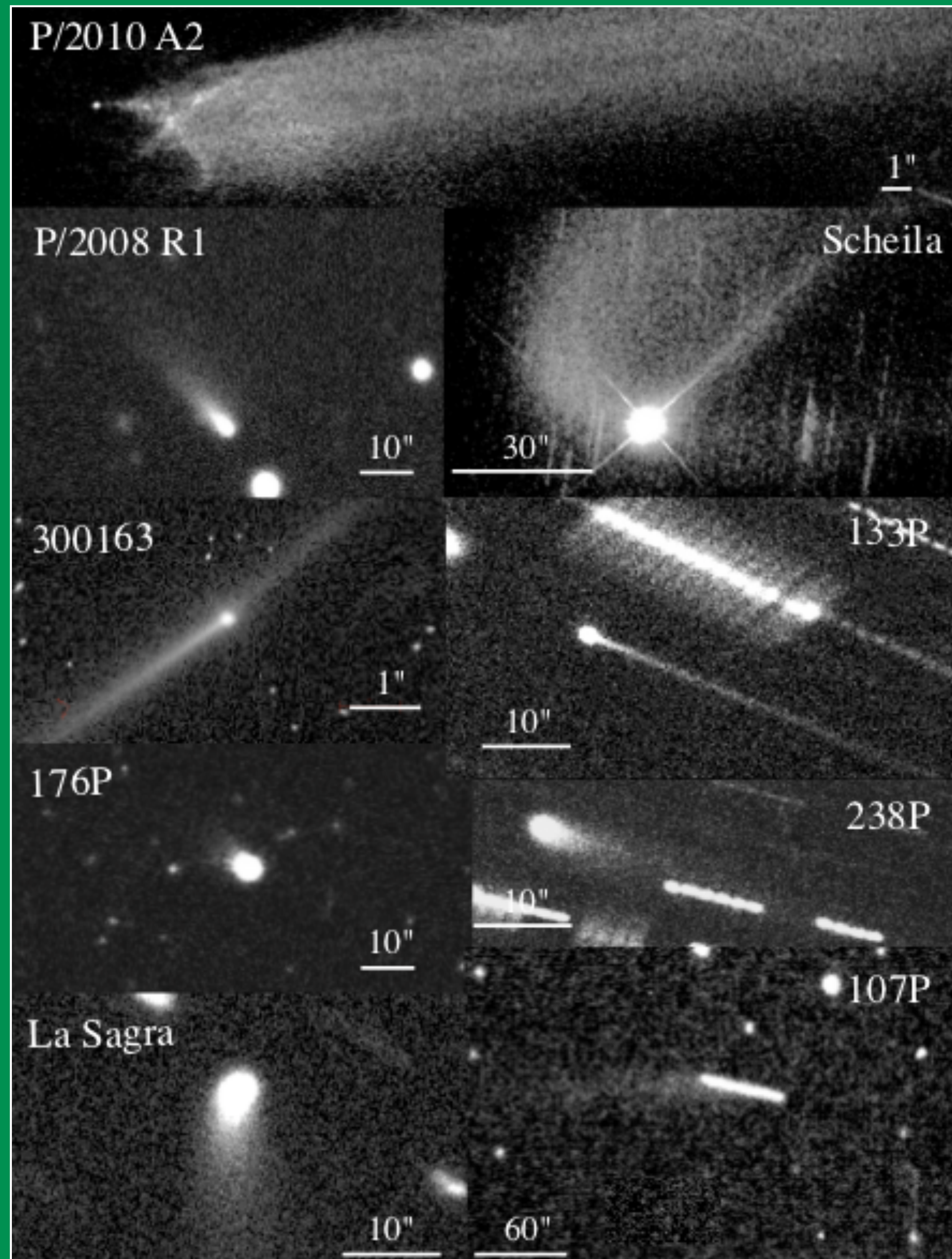
Image Credit: Roger Smith


NORTH
EAST
WEST
SOUTH
Credit Andrea Kunder

Active Asteroids/Main Belt Comets



Solar System Triggers won't be coming from ANTARES

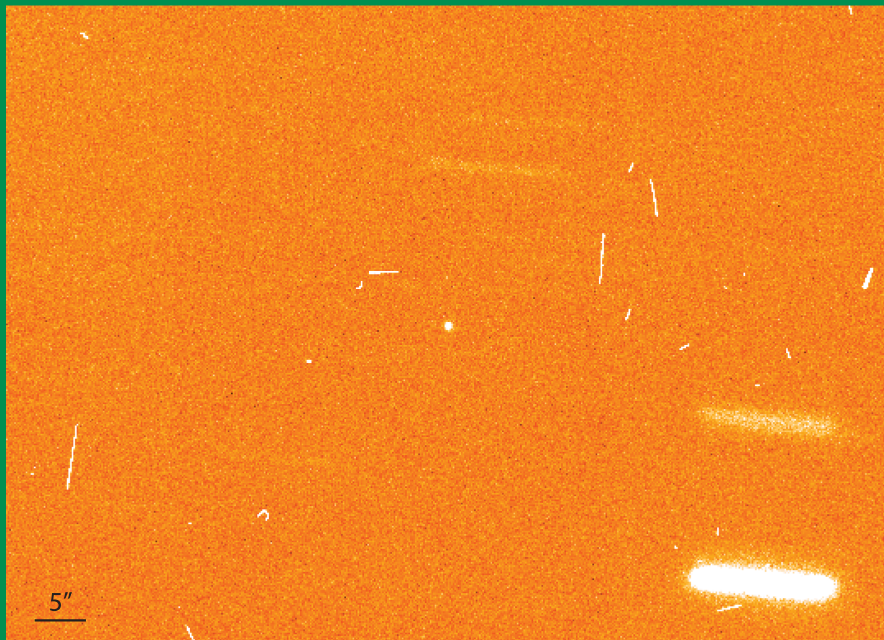
Jewitt (2012)

Interstellar Objects

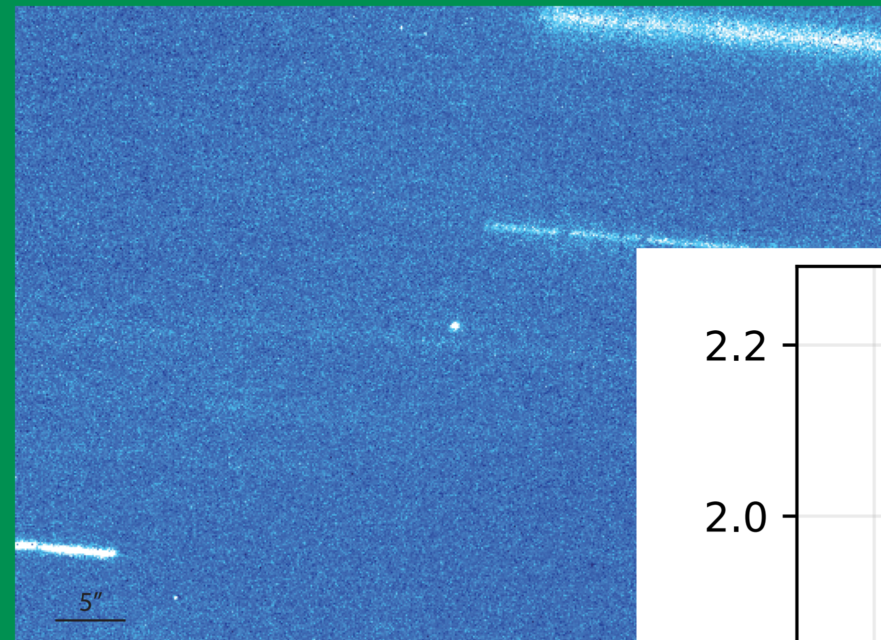
Credit: NASA/JPL-Caltech


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

Optical r-band

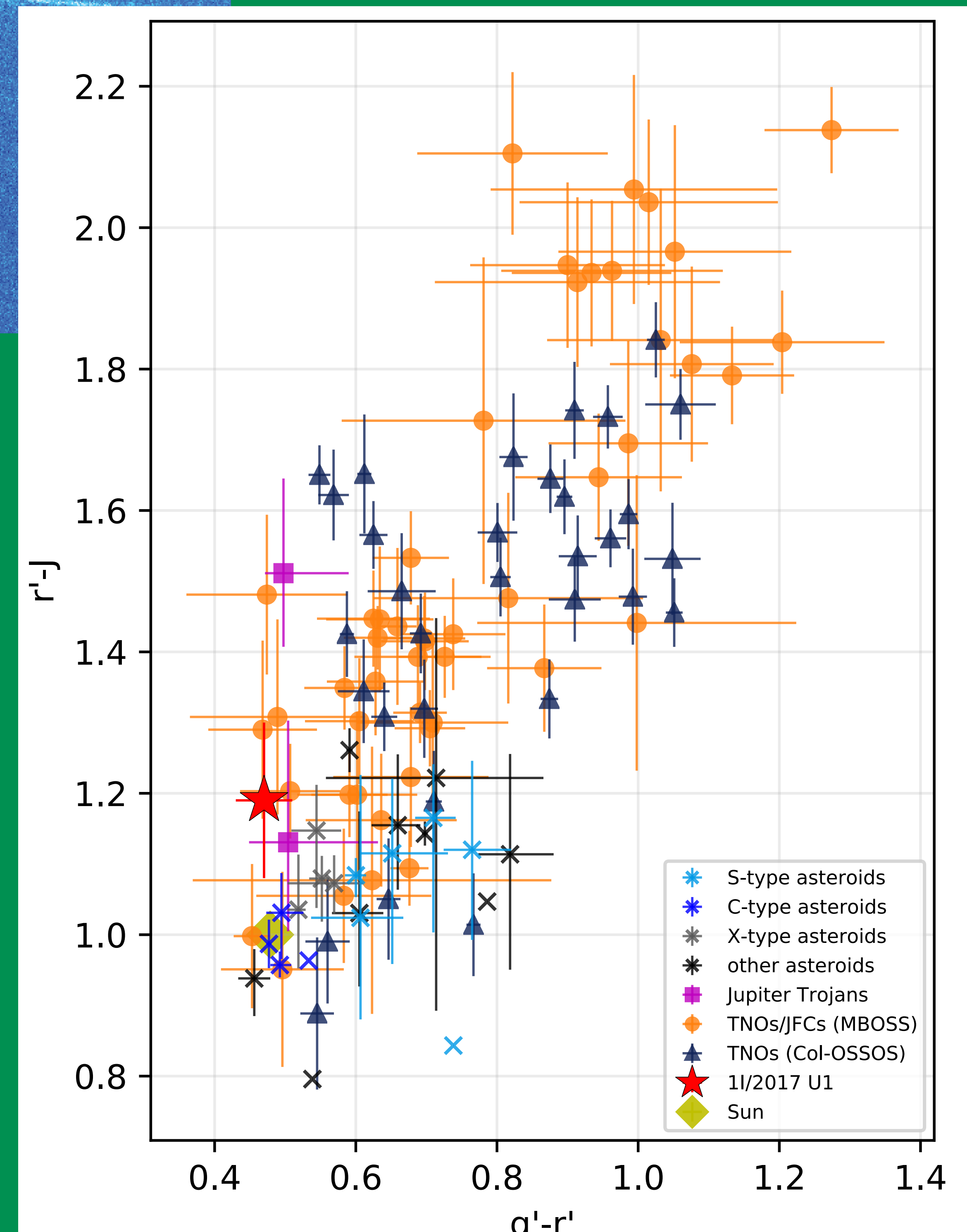


Near-infrared J-band

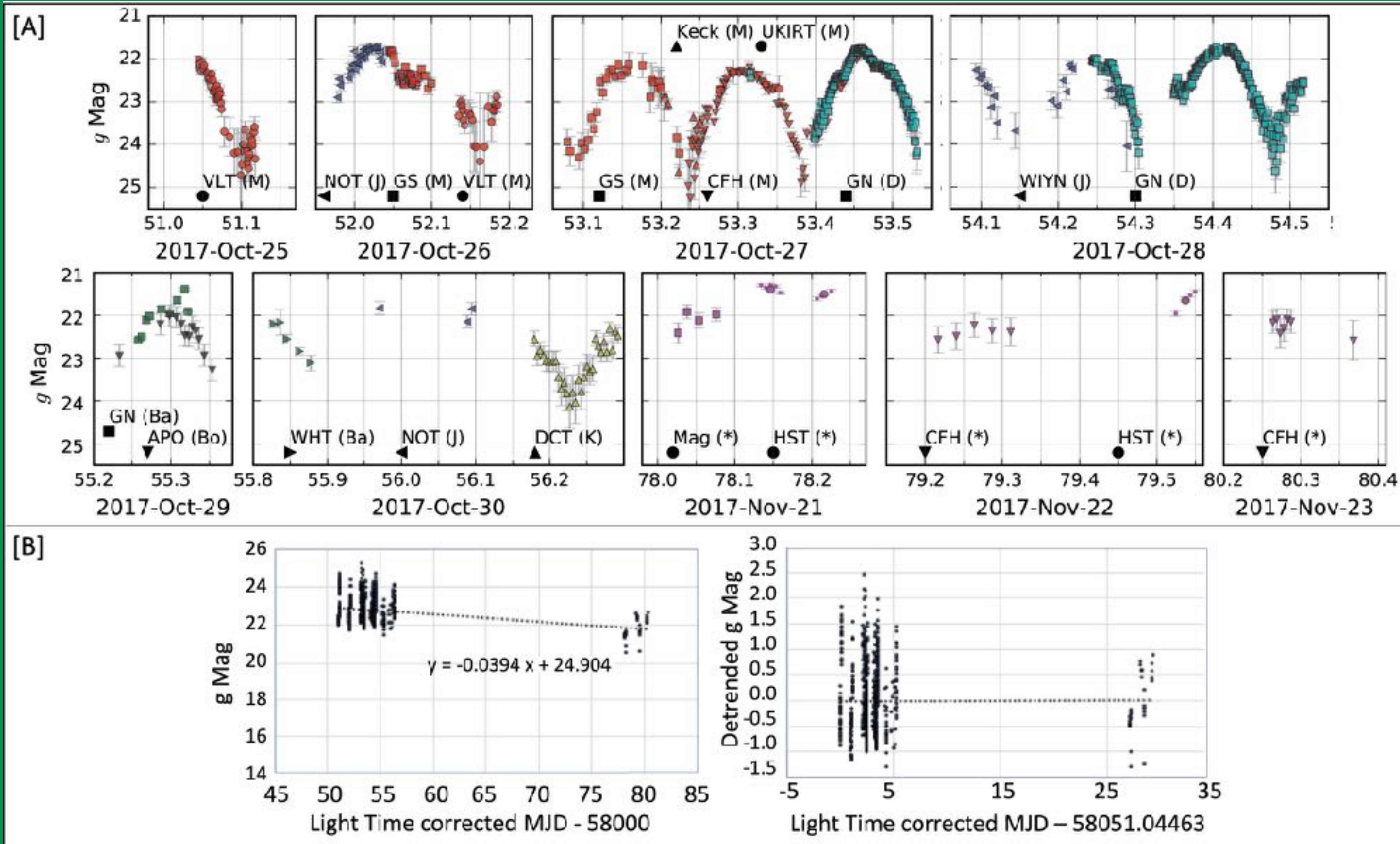


Credit: Bannister, Schwamb et al. (2017)

Col-OSSOS Photometry of ‘Oumuamua

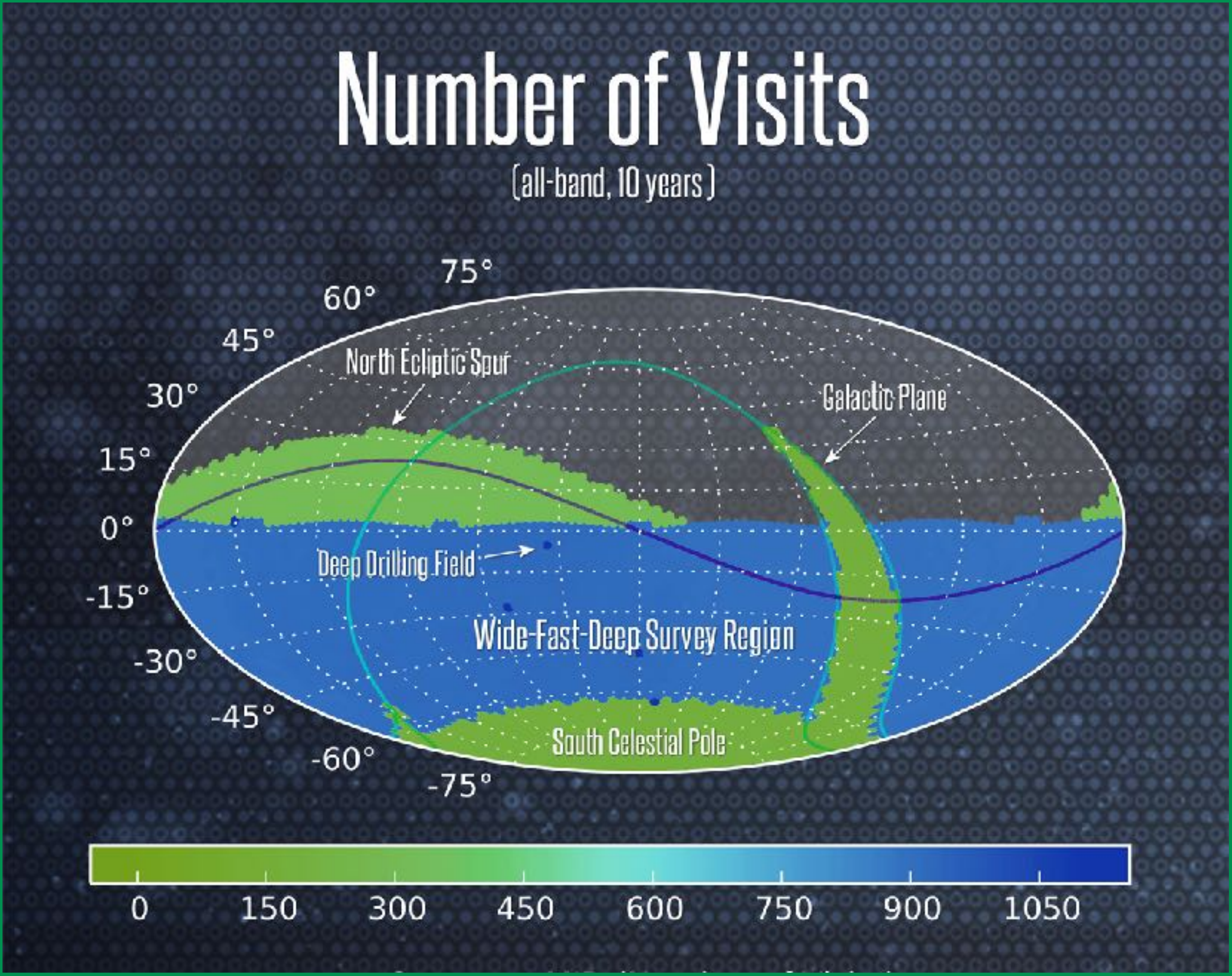


Credit: Bannister, Schwamb et al. (2017)



Credit: Belton et al. (2018)

LSST Observing Strategy Is Not Set



Slide Credit: LSST/AURA/LSSTC

LSST Observing Strategy Is Not Set

Science-Driven Optimization of the LSST Observing Strategy

LSST Science Collaborations: Phil Marshall, Timo Anguita, Federica B. Bianco, Eric C. Bellm, Niel Brandt, Will Clarkson, Andy Connolly, Eric Gawiser, Zeljko Ivezic, Lynne Jones, Michelle Lochner, Michael B. Lund, Ashish Mahabal, David Nidever, Knut Olsen, Stephen Ridgway, Jason Rhodes, Ohad Shemmer, David Trilling, Kathy Vivas, Lucianne Walkowicz, Beth Willman, Peter Yoachim, Scott Anderson, Pierre Antilogus, Ruth Angus, Iair Arcavi, Humna Awan, Rahul Biswas, Keaton J. Bell, David Bennett, Chris Britt, Derek Buzasi, Dana I. Casetti-Dinescu, Laura Chomiuk, Chuck Claver, Kem Cook, James Davenport, Victor Debattista, Seth Digel, Zoheyr Doctor, R. E. Firth, Ryan Foley, Wen-fai Fong, Lluis Galbany, Mark Giampapa, John E. Gizis, Melissa L. Graham, Carl Grillmair, Phillipe Gris, Zoltan Haiman, Patrick Hartigan, et al. (52 additional authors not shown)

(Submitted on 14 Aug 2017)

The Large Synoptic Survey Telescope is designed to provide an unprecedented optical imaging dataset that will support investigations of our Solar System, Galaxy and Universe, across half the sky and over ten years of repeated observation. However, exactly how the LSST observations will be taken (the observing strategy or "cadence") is not yet finalized. In this dynamically-evolving community white paper, we explore how the detailed performance of the anticipated science investigations is expected to depend on small changes to the LSST observing strategy. Using realistic simulations of the LSST schedule and observation properties, we design and compute diagnostic metrics and Figures of Merit that provide quantitative evaluations of different observing strategies, analyzing their impact on a wide range of proposed science projects. This is work in progress: we are using this white paper to communicate to each other the relative merits of the observing strategy choices that could be made, in an effort to maximize the scientific value of the survey. The investigation of some science cases leads to suggestions for new strategies that could be simulated and potentially adopted. Notably, we find motivation for exploring departures from a spatially uniform annual tiling of the sky: focusing instead on different parts of the survey area in different years in a "rolling cadence" is likely to have significant benefits for a number of time domain and moving object astronomy projects. The communal assembly of a suite of quantified and homogeneously coded metrics is the vital first step towards an automated, systematic, science-based assessment of any given cadence simulation, that will enable the scheduling of the LSST to be as well-informed as possible.

https://arxiv.org/abs/1708.04058

Observing Strategy Optimization – Next Steps

1) *Develop tools* (running operations simulations at scale & improvements in the Metrics Analysis Framework) that will enable production and analysis of hundreds of simulated cadences

2) *Interact with the community* and stakeholders:
Call for mini-survey and Deep Drilling Field white papers - Summer 2018 (due late 2018)

3) *Produce, analyze and document a set of Observing Strategies* and present to the SAC for a final strategy recommendation (in 2020) to begin the survey.

Slide Credit Beth Wilman

Outstanding Questions:

How will DECam be involved in the alert stream and other trigger/TOO LSST follow-up?

LSST follow-up requires large amount of observing time - how will NOAO DECam time be carved up in LSST era?

Solar System follow-up may be useful for other LSST follow-up (and vice versa), how do we link the community and share?

LSST deep drilling field/mini-survey white paper call comes out very soon, are there possibilities to partner with DECam observations?

Image Credit: NOAO/AURA