LSST Solar System Processing: Status and Plans

Mario Juric,
University of Washington
LSST Solar System Processing Product Owner

for the LSST DM Prompt Processing Team

LSST @ EUROPE3
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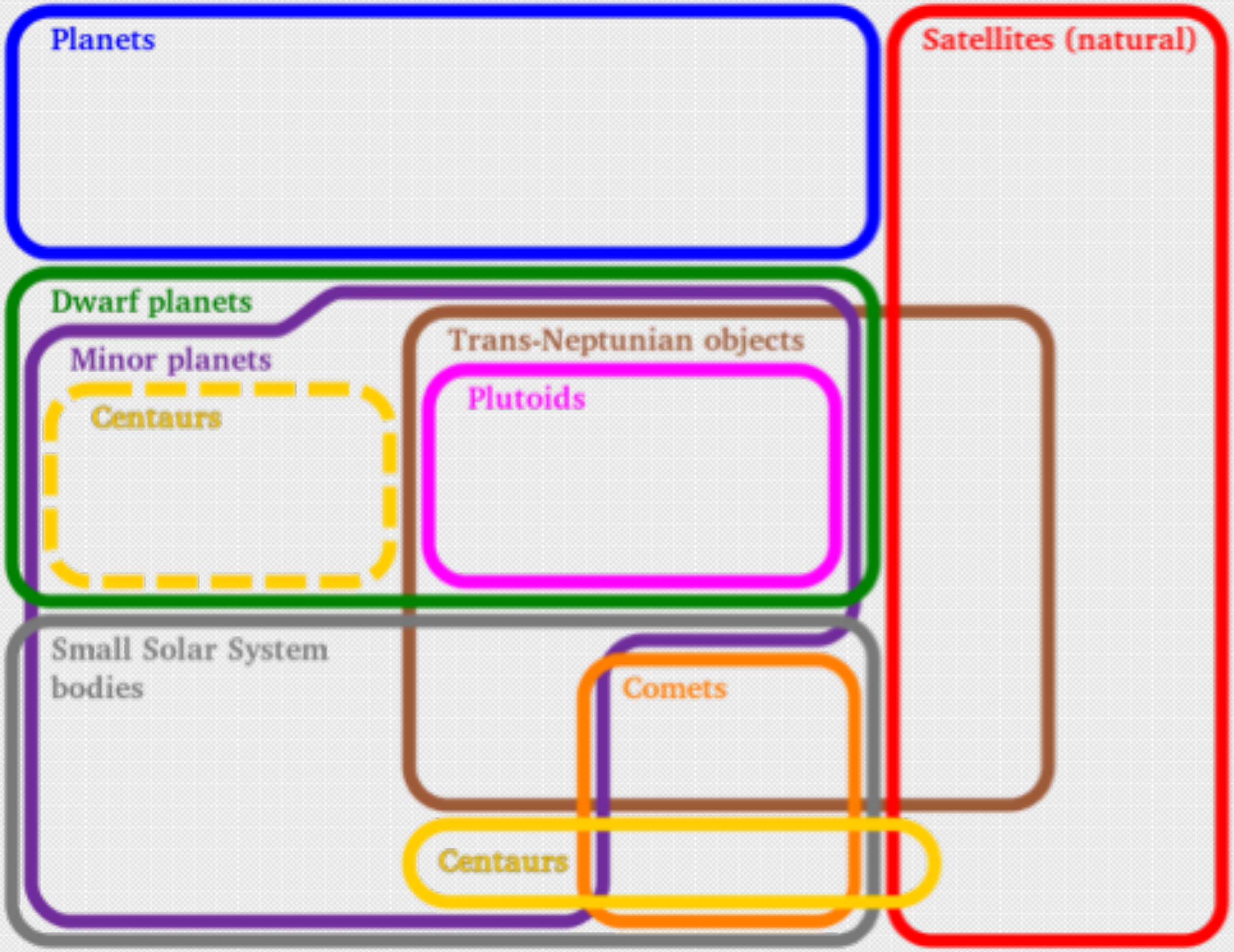
The Diversity of Solar System Science

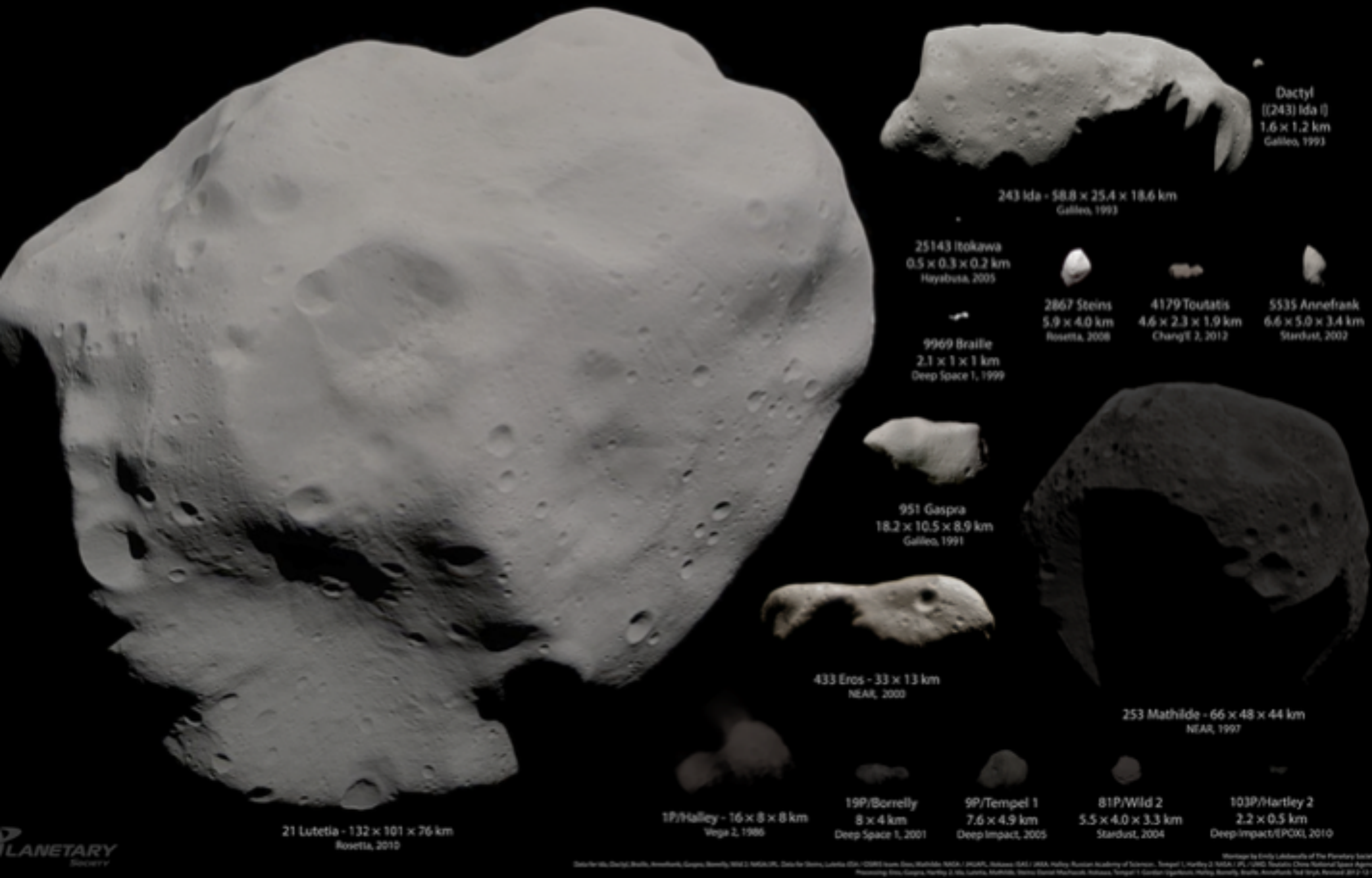


Most LSST Solar System Science will come from studies of Small Solar System Bodies (SSB) and Dwarf Planets (alternatively, Minor Planets + Comets)

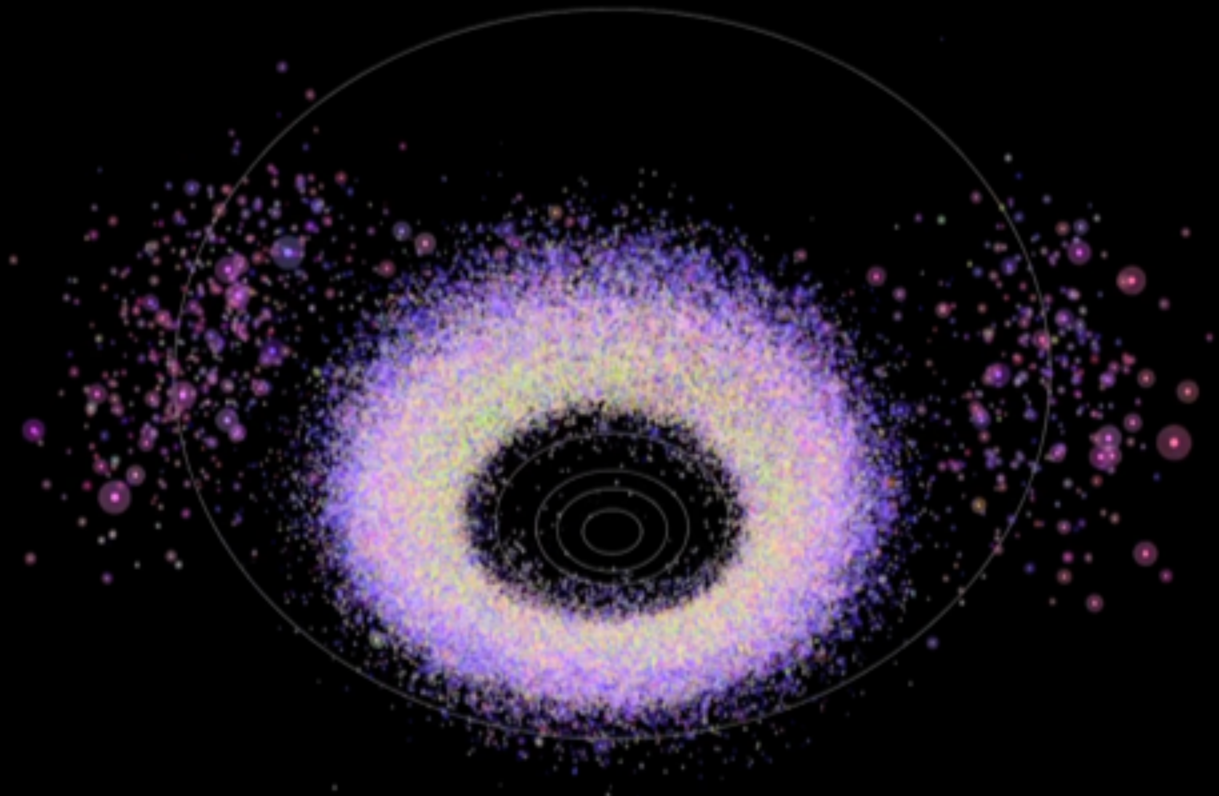
For us, anything moving* in the Solar System qualifies as a "Solar System Object"

A helpful(?) diagram courtesy of Wikipedia: https://en.wikipedia.org/wiki/Small_Solar_System_body

Asteroids in the Solar System

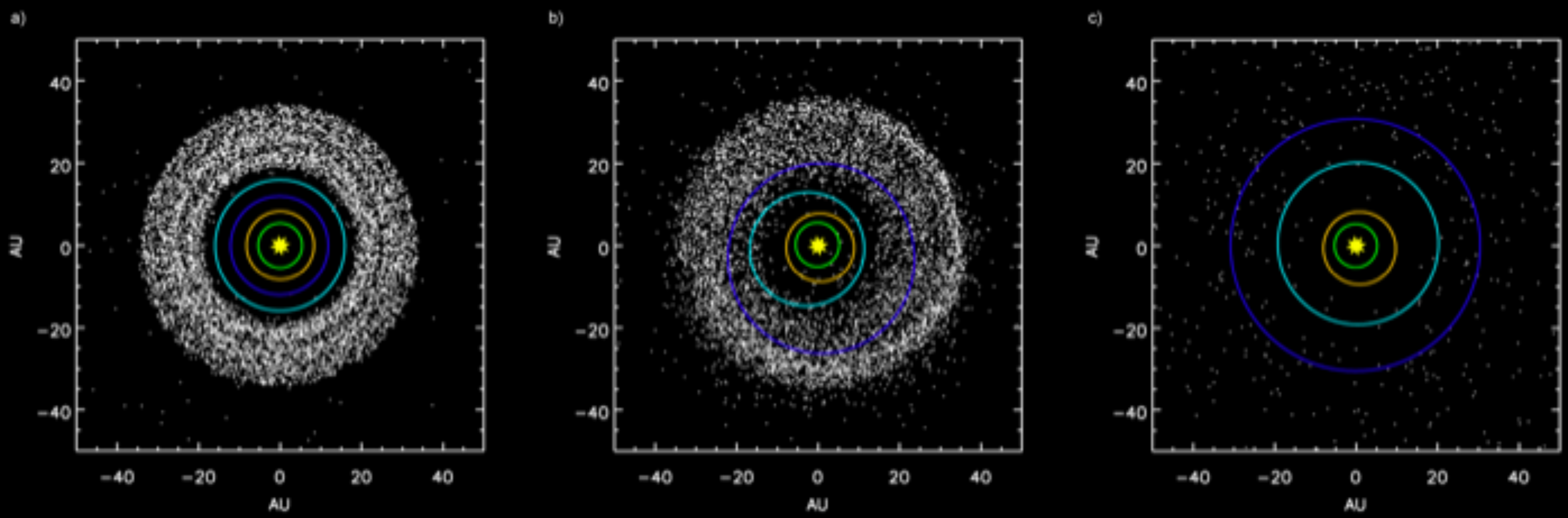


Asteroids in the Solar System



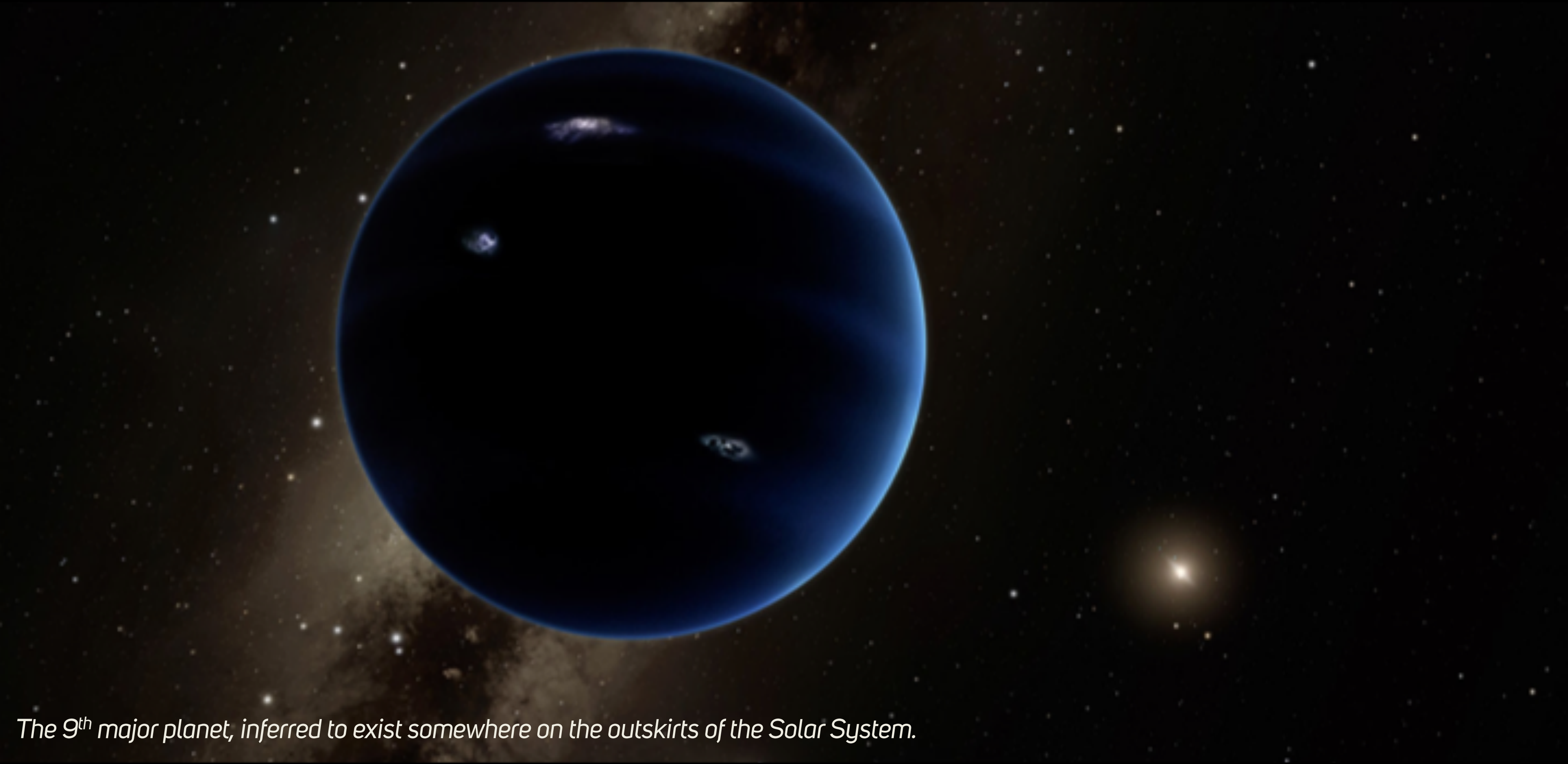
SDSS Asteroids
(Alex Parker, SwRI)

Minor Planets and Decoding the History of the Solar System



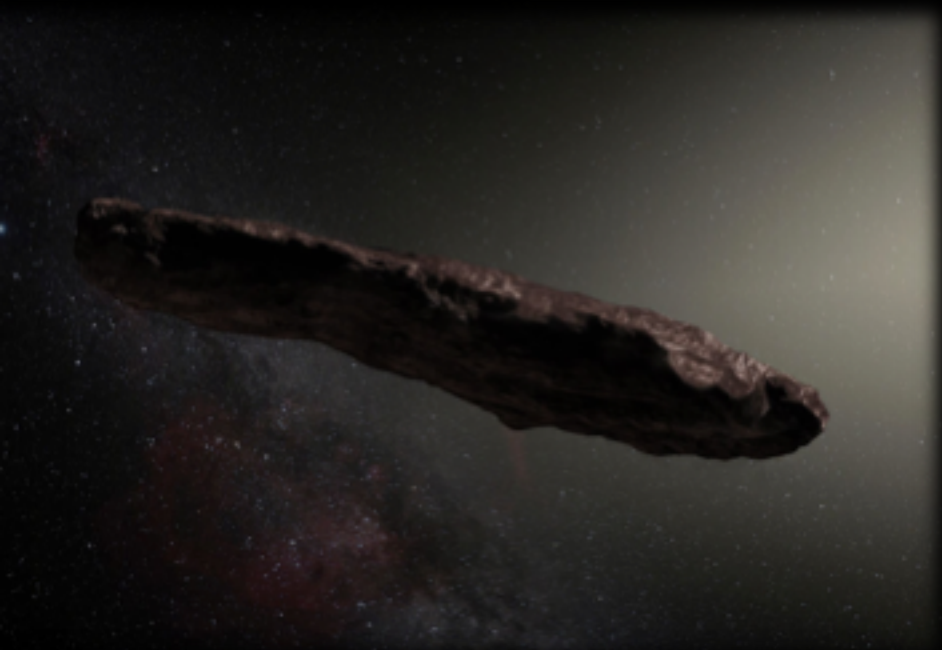
The "Nice model" of Solar System evolution

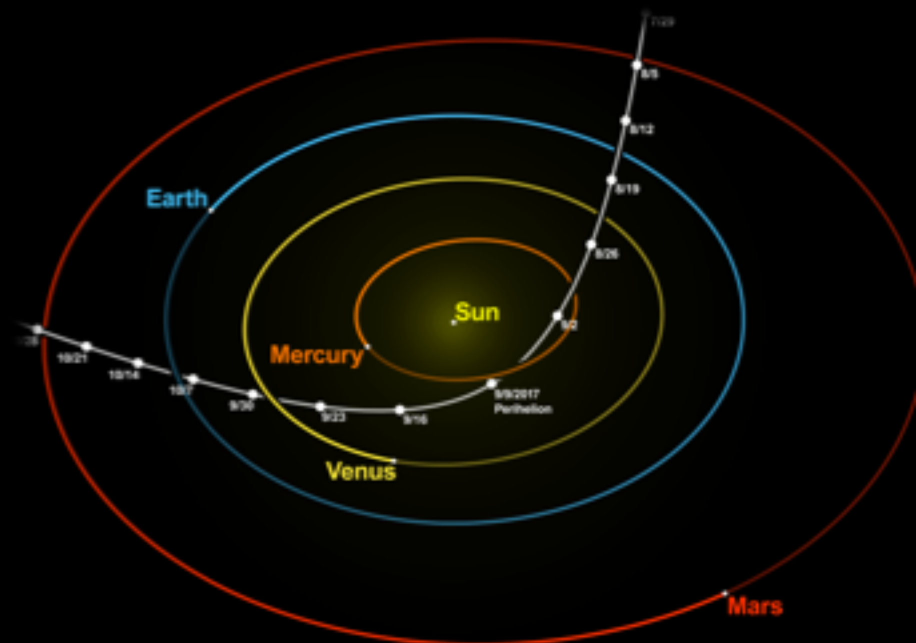
TNOs: Hints of Planet X (?)



The 9th major planet, inferred to exist somewhere on the outskirts of the Solar System.

Beyond the Solar System: The 1st Discovery of an Interstellar Object Passing through the Solar System





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NEOs: Planetary Defense

Expected Solar System Object Yields

	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
TransNeptunian Objects (TNOs) + Scattered Disk Objects (SDOS)	2000	40,000	(D>200km) 450	8.5 years

Lynne Jones, priv comm (results of analysis of minion_1016 OpSim run)

Solar System Data Products

LSST will provide three types of products to enable Solar System science:

Prompt Products

Real-time
(60 seconds)

Daily Orbit Catalog

Data Release Products

Data Release Orbit Catalogs
(~yearly)

Prompt Products: Real-Time

- DIASources are associated with known moving objects in real-time (in time to send the alerts)…

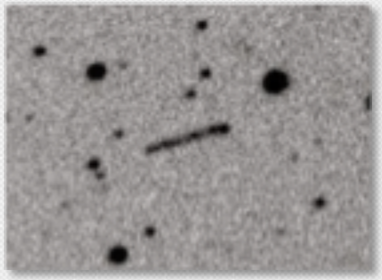
ssObjectId	uint64	ID of the SSObject this source has been linked to, if any.

- … and trailed sources are identified as such.

DIASource Table
http://ls.st/lse-163

trailFlux	float	nmgy	Calibrated flux for a trailed source model[41,42]. Note this actually measures the flux *difference* between the template and the visit image.
trailRadec	double[2]	degrees	Centroid for trailed source model.
trailLength	float	arcsec	Maximum likelihood fit of trail length[43,44].
trailAngle	float	degrees	Maximum likelihood fit of the angle between the meridian through the centroid and the trail direction (bearing, direction of motion).
trailCov	float[15]	various	Covariance matrix of trailed source model parameters.
trailLnL	float		Natural *log* likelihood of the observed data given the trailed source model.
trailChi2	float		χ^2 statistic of the model fit.

Enable rapid identification and follow-up of fast moving asteroids (NEOs)



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

Prompt Products: Daily Updated Orbit Catalog

- These are aimed to provide a catalog of objects to enable their identification in subsequent LSST imaging (and further follow up).
- **Product:** Catalog of orbits and physical properties of objects discovered by LSST (DPDD, Table 3)
  - Orbits
  - Physical properties (H, G)
- Some desiderata:
  - This catalog should be as complete as possible
    - The software should evolve as rapidly as needed to keep it complete
  - This should be cross-matched to external catalogs

Table 3: SSObject Table

Name	Type	Unit	Description
ssObjectId	uint64		Unique identifier.
oe	double[7]	various	Osculating orbital elements at epoch (q, e, i, Ω, ω, M_0, epoch).
oeCov	double[28]	various	Covariance matrix for oe.
arc	float	days	Arc of observation.
orbFitLnL	float		Natural log of the likelihood of the orbital elements fit.
orbFitChi2	float		χ^2 statistic of the orbital elements fit.
orbFitNdata	int		The number of data points (observations) used to fit the orbital elements.
MOID	float[2]	AU	Minimum orbit intersection distances[53]
moidLon	double[2]	degrees	MOID longitudes.
H	float[6]	mag	Mean absolute magnitude, per band [14, magnitude-phase system].
G_1	float[6]	mag	G_1 slope parameter, per band [14, magnitude-phase system].
G_2	float[6]	mag	G_2 slope parameter, per band [14, magnitude-phase system].
hErr	float[6]	mag	Uncertainty of H estimate.
g1Err	float[6]	mag	Uncertainty of G_1 estimate.
g2Err	float[6]	mag	Uncertainty of G_2 estimate.
flags	bit[64]	bit	Various useful flags.

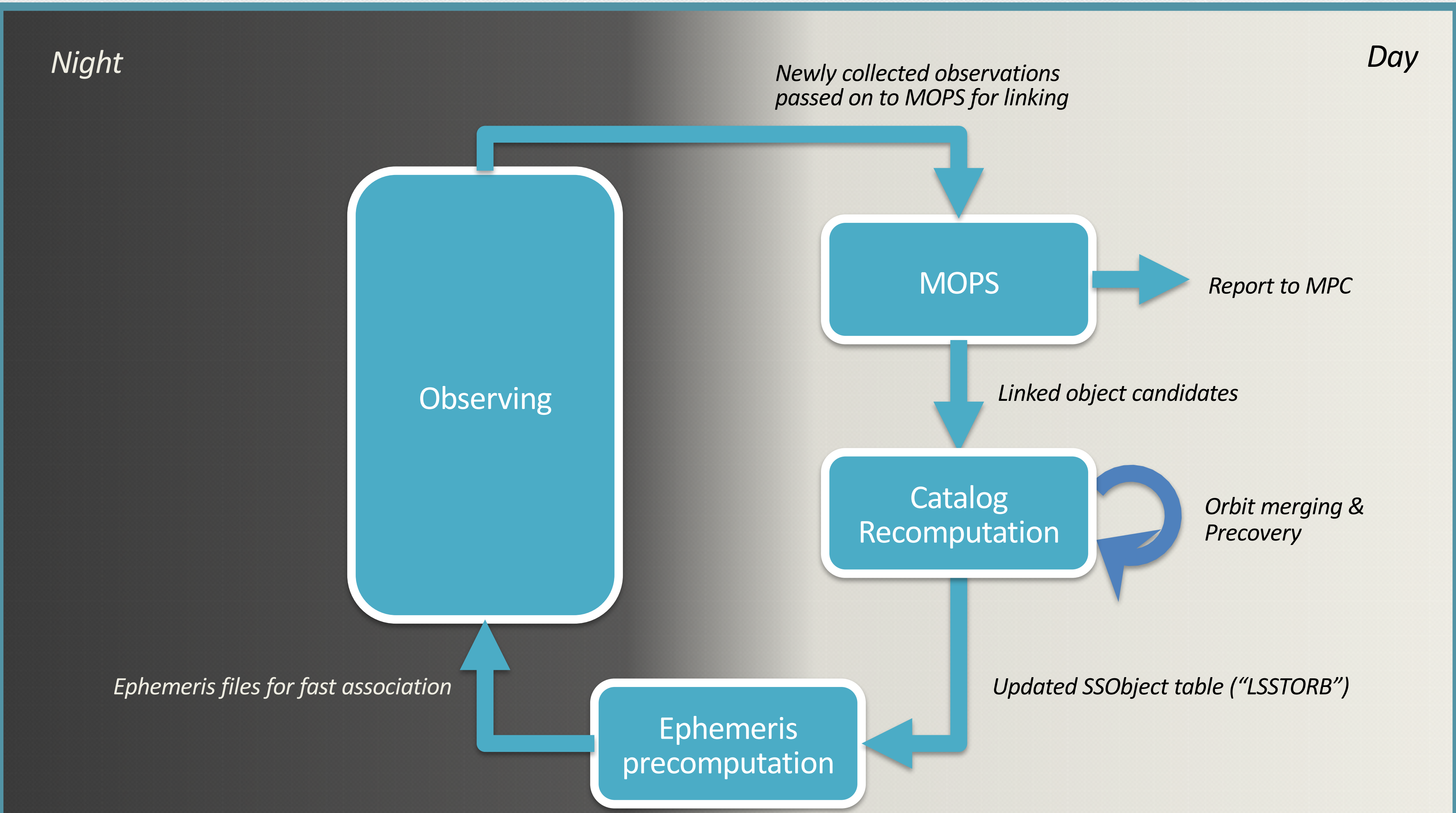
Continued on next page

Data Release Products

- The goal is to provide a catalog of moving objects that enables estimates of completeness and population studies.

- The contents is the same as for catalogs generated in daily processing, but:
  1. This catalog is generated with a single version of MOPS
  2. This catalog takes advantage of improved astrometry and photometry available in data release processing.
  3. (This catalog includes LSST-only information)

Prompt Solar System Processing Flow (Current)



For DR: Reprocess

Some (Key) Issues

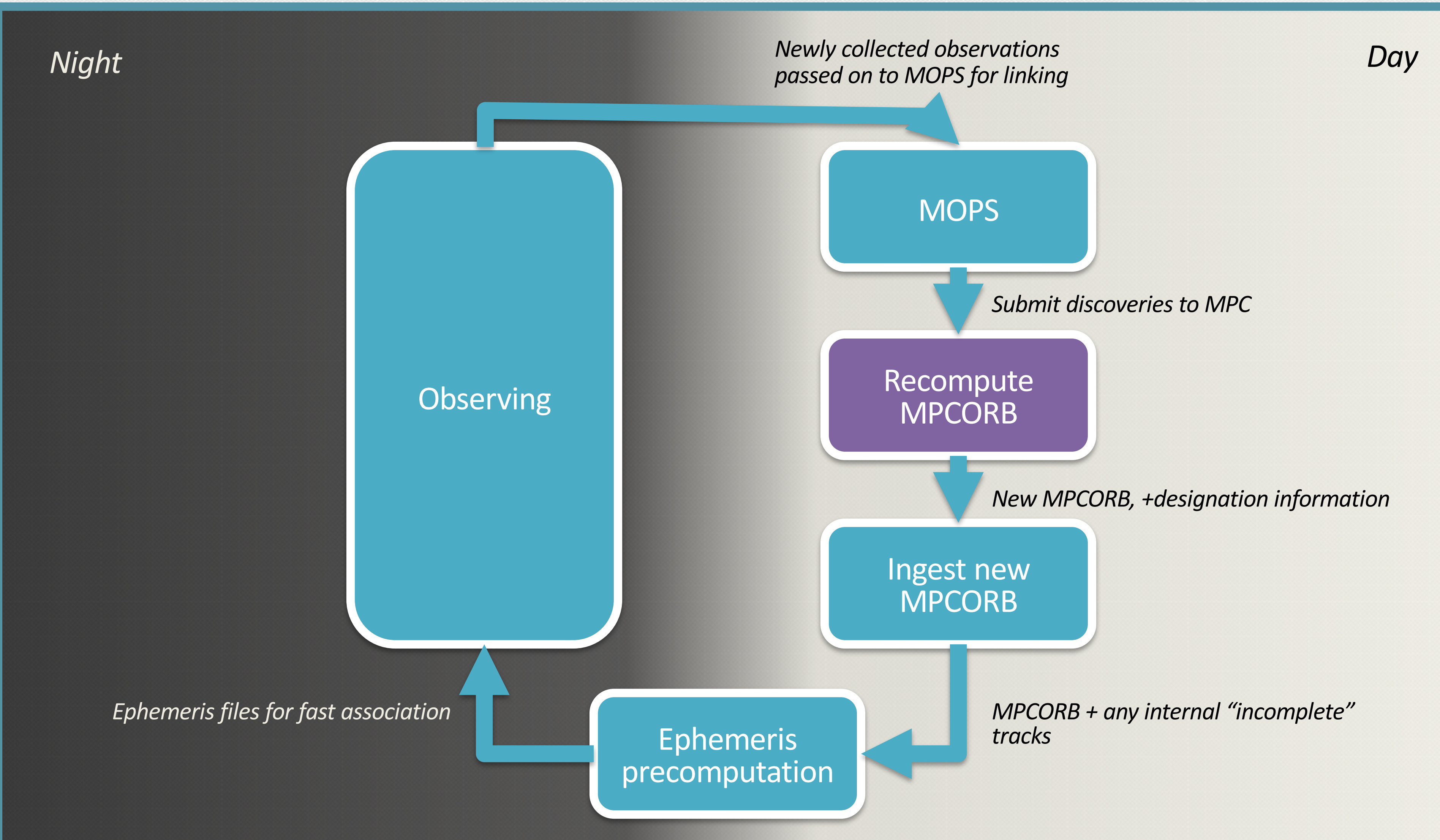
- Associating the observed sources with objects from the MPC catalog followed a relatively complex scheme.
  - Consequence: each object would have an LSST ID and/or a MPC designation, causing bookkeeping headaches.

- We didn't plan to cross-reference the LSST catalog to the MPC catalog.
  - Consequence: Everyone in the community would have to write code to establish that "LSST123456" is really (2309) Spock (and such codes are somewhat non-trivial)

- Tracklets that are never linked are not reported to the MPC.
  - Objects where LSST's tracklet could be linked to a tracklet from another survey are lost.

Caused us to look over the past ~year whether we can do better

Prompt Solar System Processing: Changes



Daily Solar System Products Changes

Old

SSObject Table
("LSSTORB")

DIASource Table
("LSSTOBS")

New

MPCORB Catalog

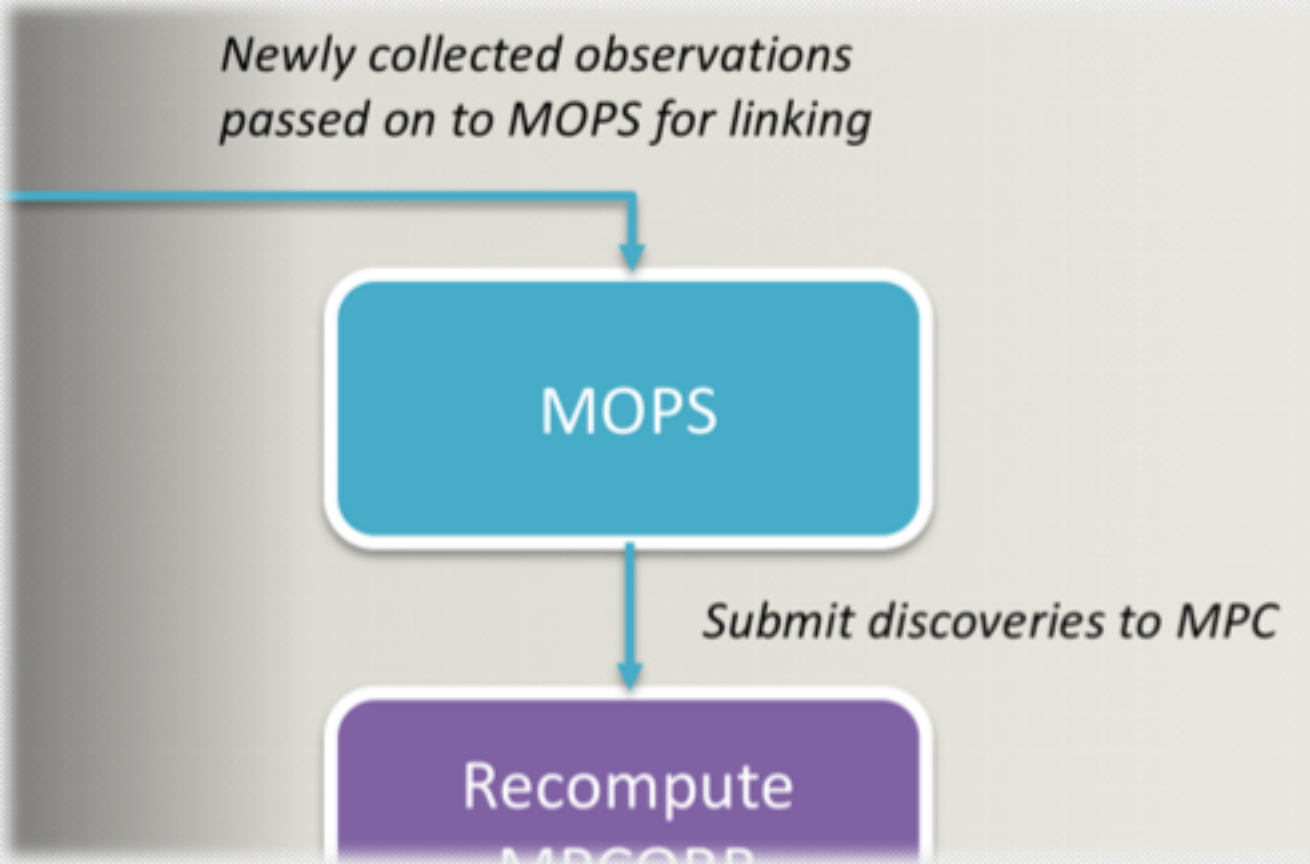
LSSTPHYS
(absolute magnitudes, addt'l useful quantities)

DIASource Table
("LSSTOBS")

This Brings Significant Improvements

- The orbit catalog used for association is now maximally complete at all times.
- Solves the cross-match problem: cross-matching two orbit catalogs is not entirely trivial (there will always be corner cases). Now there is only one catalog.
  - Reduces community confusion: no “LSST catalog” vs “MPC catalog”
- No need to do anything special to take advantage of LSST data if all one cares about are orbits – it’s all in MPCORB. Makes the LSST data more accessible/useful.
- Places the LSST into a more general (and partially existing) framework of how surveys work with the MPC
- Opens the possibility to submit *all* tracklets to the MPC, including trails
- Enables cross-survey linking at MPC: LSST’s first tracklet may complete a track that some other survey has started nights before; detectable with MPC’s existing tools. Shortens time to discovery of new objects.

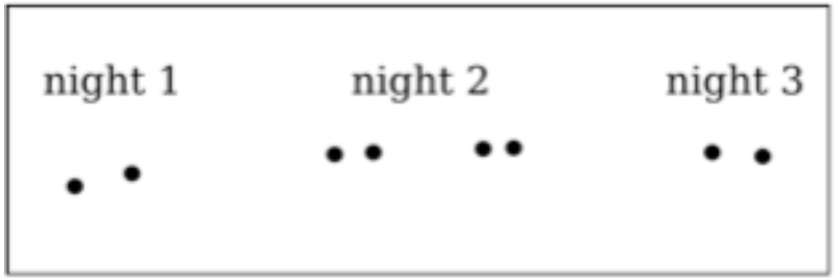
MOPS Updates

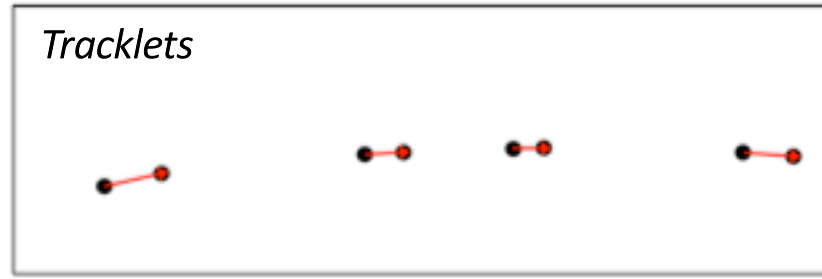


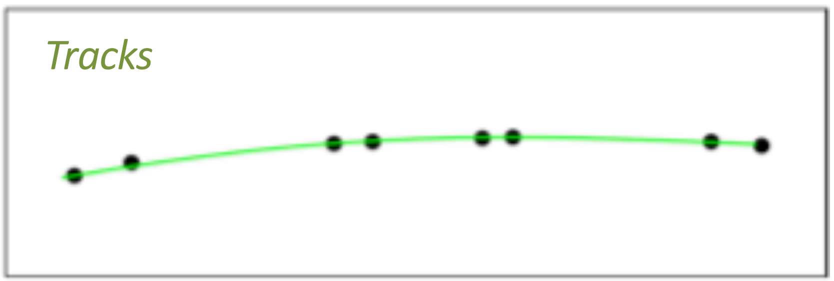
MOPS (Moving Objects Processing System) *is the pipeline that associates individual source detections as being due to a single object moving through the Solar System.*

Asteroid Linking for LSST: "2+2+2"

Requirement for reportable discovery: at least 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

Note: some asteroids will also be immediately recognizable due to measurable trailing.

Key Challenge: Night-to-night Linking

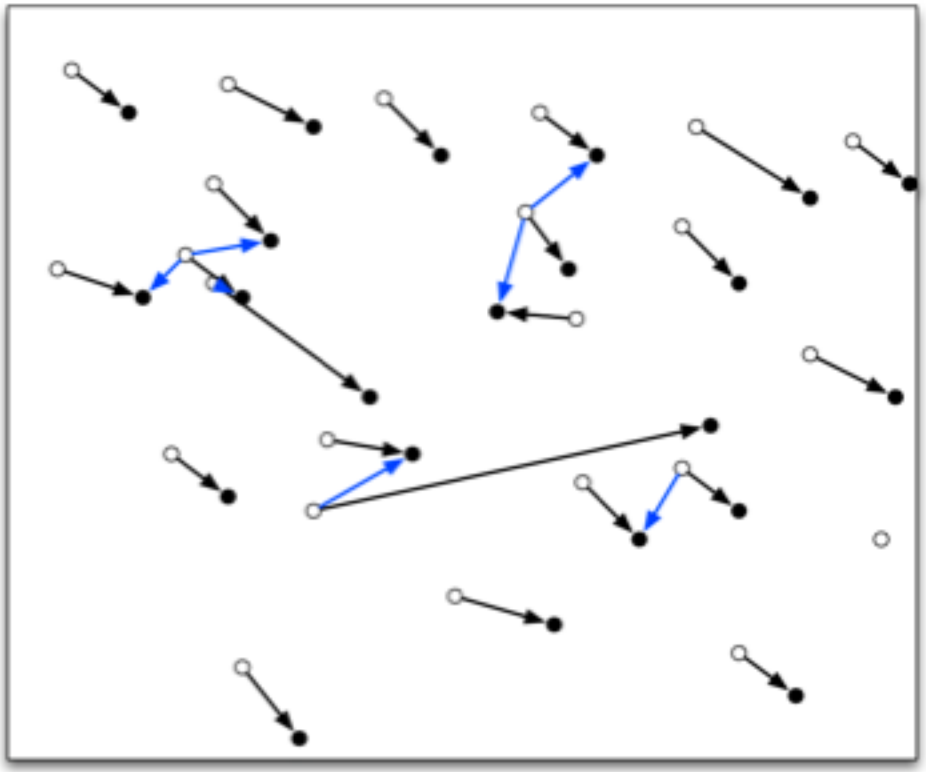


Figure 1. from Denneau et al. (2006), ADASS XVI

Conceptual diagram of intra-night linking. Open and solid circles are detections in night #1 and #2, respectively. The arrows indicate plausible true and false tracklet links (black and blue, respectively).

- If the density of detections is high (irrespective of whether they're real or not), there are multiple plausible linkages for each pair (left).
- Those linkages cascade into generating multiple plausible tracks when linked from night to night.
- Those tracks must be tested using orbit fits ("orbit determination"; OD) to reject false linkages, which is computationally expensive (but tractable; more later).
- If the density of detections is *exceptionally* high, OD may not be able to reject them all. More observations would be needed to confirm the identification.
- A major issue on PanSTARRS PS1 (up to 50:1 FP rates). Can one do better?

LSST Study of Asteroid Discovery Efficiency

The Large Synoptic Survey Telescope as a Near-Earth Object Discovery Machine

R. Lynne Jones[1], Colin T. Slater[1], Joachim Moeyens[1], Lori Allen[2], Tim Axelrod[3], Kem Cook[4], Željko Ivezić[1], Mario Jurić[1], Jonathan Myers[5], Catherine E. Petry[6]

Abstract

Using the most recent prototypes, design, and as-built system information, we test and quantify the capability of the Large Synoptic Survey Telescope (LSST) to discover Potentially Hazardous Asteroids (PHAs) and Near-Earth Objects (NEOs). We empirically estimate an expected upper limit to the false detection rate in LSST image differencing, using measurements on DECam data and prototype LSST software and find it to be about 450 $\deg^{-2}$. We show that this rate is already tractable with current prototype of the LSST Moving Object Processing System (MOPS) by processing a 30-day simulation consistent with measured false detection rates. We proceed to evaluate the performance of the LSST baseline survey strategy for PHAs and NEOs using a high-fidelity simulated survey pointing history. We find that LSST alone, using its baseline survey strategy, will detect 66% of the PHA and 61% of the NEO population objects brighter than $H = 22$, with the uncertainty in the estimate of ± 5 percentage points. By generating and examining variations on the baseline survey strategy, we show it is possible to further improve the discovery yields. In particular, we find that extending the LSST survey by two additional years and doubling the MOPS search window increases the completeness for PHAs to 86% (including those discovered by contemporaneous surveys) without jeopardizing other LSST science goals (77% for NEOs). This equates to reducing the undiscovered population of PHAs by additional 26% (15% for NEOs), relative to the baseline survey.

A paper produced in response to NASA inquiries about LSST's capabilities as an NEO discovery machine.

Though focused on NEOs, its conclusions about MOPS efficiency are valid across most SSO populations.

Bottom line: MOPS will satisfy LSST moving object linking requirements.

Jones et al. 2018, Icarus, 303, 181
https://arxiv.org/abs/1711.10621

New Developments: Improved Algorithms

FINDING ASTEROIDS DOWN THE BACK OF THE COUCH:
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]

[1] *Harvard-Smithsonian Center for Astrophysics, 60 Garden St., MS 51, Cambridge, MA 02138, USA*
[2] *School of Engineering and Applied Sciences, Harvard University, 29 Oxford St., Cambridge, MA 02138, USA*

Submitted to ApJ/AJ May 2018

ABSTRACT

We present 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 $O(N \log N)$, with the number of tracklets N, a significant advance over standard methods, which scale as $O(N^3)$. 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 $\sim 41{,}000$ new minor planets.

Exploring whether to switch the LSST MOPS baseline to the Holman et al. algorithm

Going Forward: The LSST DM Solar System Team

Postdoc
(to be hired)

The LSST Solar System Products & Software Team

Joachim Moeyens (UW; Research Associate)
Mario Juric (UW; Solar System Product Owner)

Lynne Jones (UW; LSST Performance Scientist)
Eric Bellm (UW; Prompt Processing Lead)

+ many, many, others from the overall LSST DM effort!

Summary

- Making the Solar System Data Products better based on feedback form the Solar System Science Collaboration.
  - Expect the formal baseline change request later this year

- Continuing to develop and test LSST MOPS software

- Re-energizing the Solar System Processing effort with an expanded team.

Building strong ties to the Solar System Science Collaboration: making sure we deliver the best products LSST can provide.

Getting your feet wet: the Zwicky Transient Facility

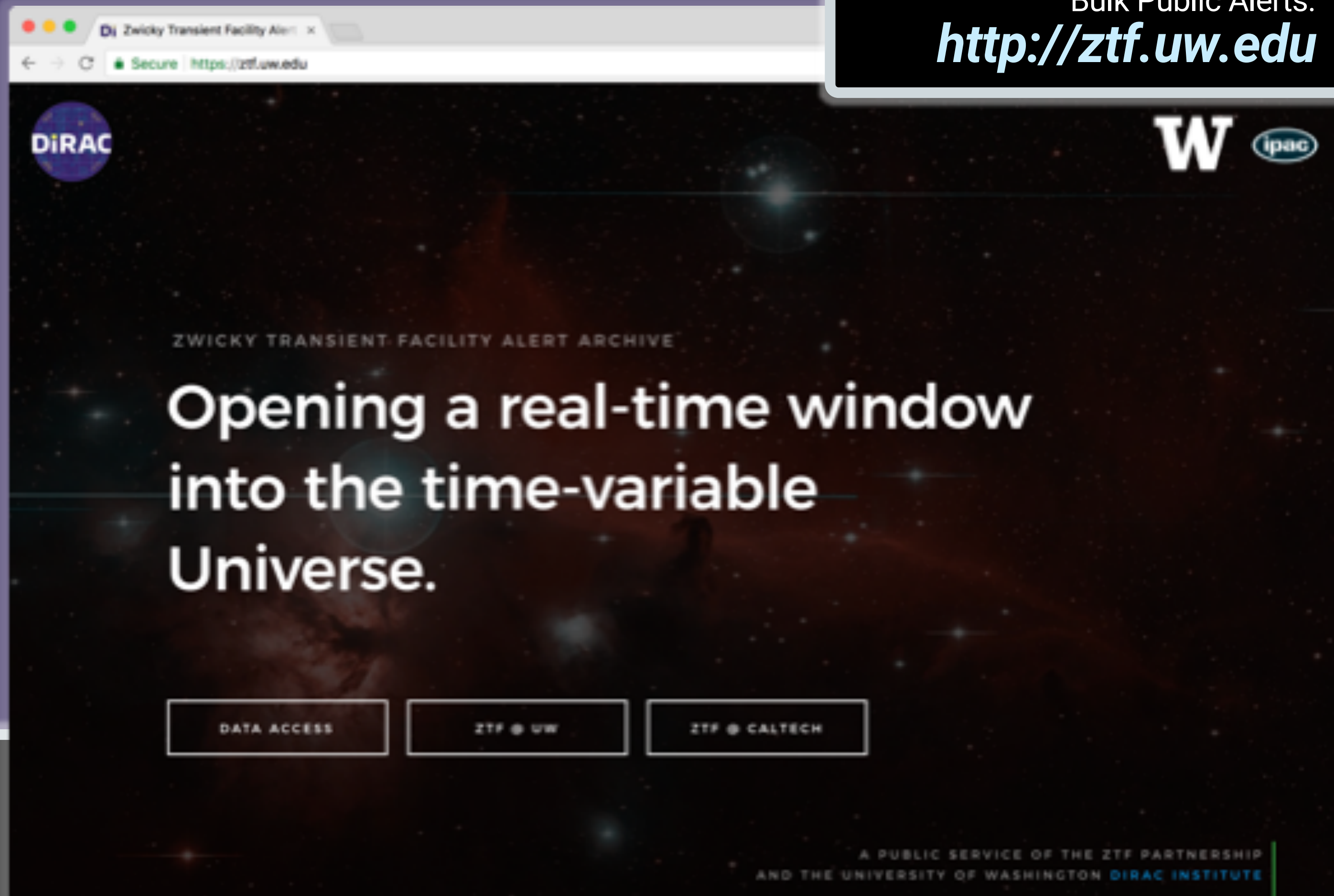
Bulk Public Alerts:
http://ztf.uw.edu

http://ztf.caltech.edu

Three months into ops, ZTF had **submitted ~600,000 measurements** to the MPC (~**320 new objects**).

The new discoveries include **seven NEOs,** one of which **(2018 CL) is a PHA**.

Five of these seven new NEOs were detected by the **ZTF streak-detection pipeline** (Waszczak et al. 2017).



ZTF alerts from the public survey (~40%) are now available in bulk!

Streaming coming later this summer (via ANTARES and others).

Caltech