Discovering undiscoverable asteroids

The power of DECam, its archive, and novel algorithms

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Kathleen Kiker, Nate Tellis, Allan Posner, Ed Lu
and the ADAM::THOR team

DiRAC
DATA INTENSIVE RESEARCH IN
ASTROPHYSICS AND COSMOLOGY

ASTEROID
INSTITUTE
A PROGRAM OF B612

* B612 Asteroid Institute Graduate Student Fellow

Solar System @ UW

Joachim Moeyens,
UW grad
THOR algorithm

Tom Wagg,
Hybrid catalogs & NEO estimates

Zach Langford,
UW undergrad (-> U. Penn)

Bryce Kalmbach
LSST postdoc @ UW

Ari Heinze
HelioLINC+ codes

Pedro Bernardinelli,

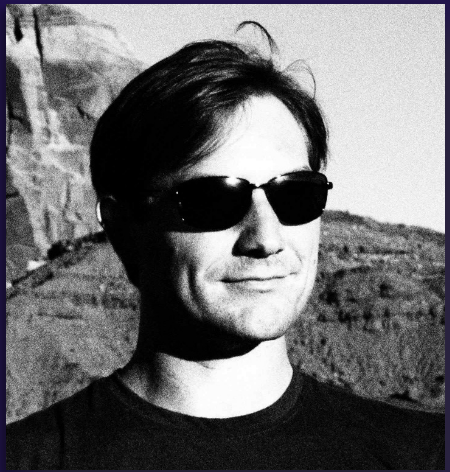
2021 DiRAC Postdoctoral Fellow

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

Lynne Jones et al.
Rubin Performance Scientist

Aidan Berres
UW undergrad (-> UIUC grad)

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



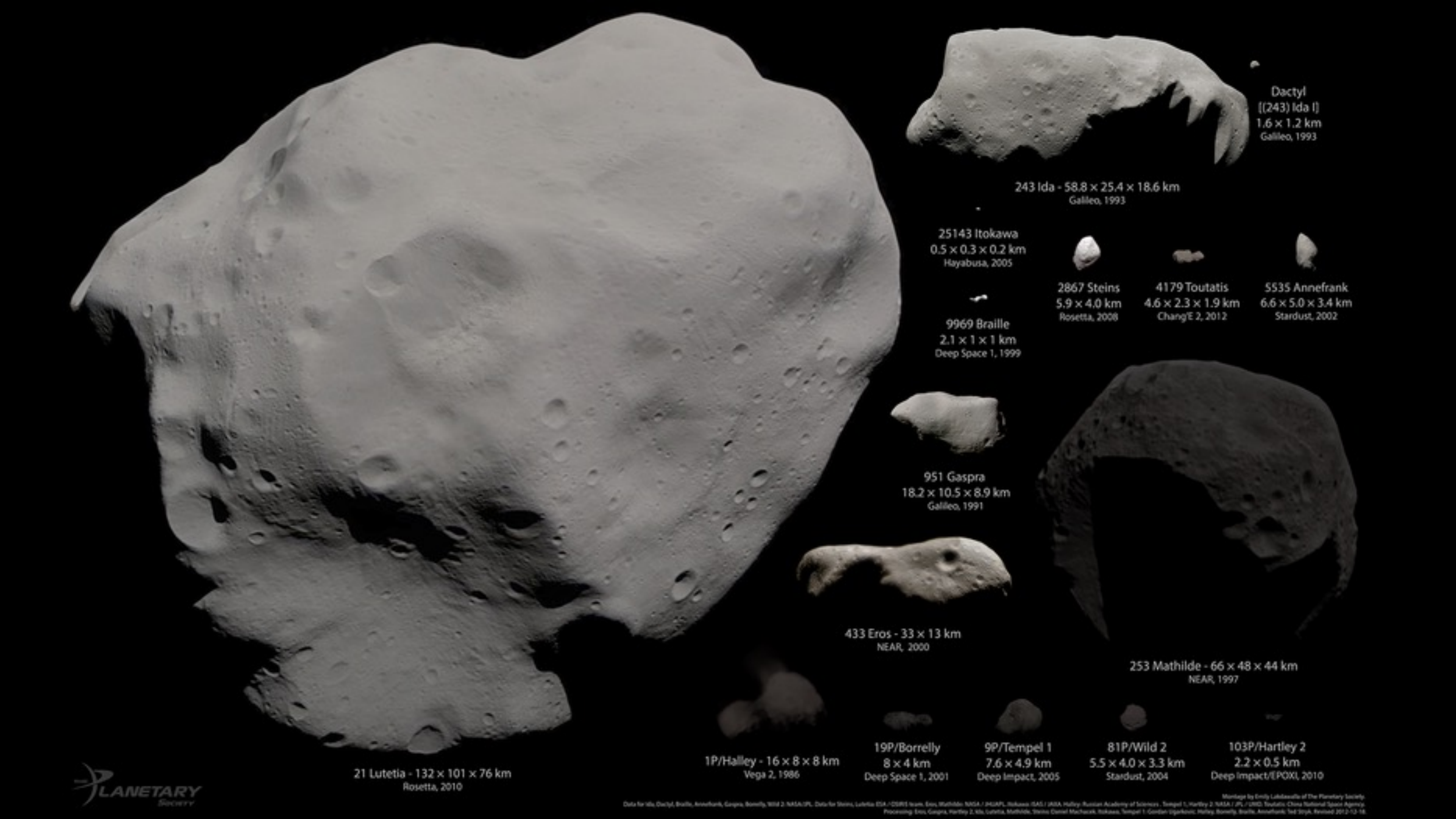
Steven Stetzler
UW grad
DECat Processing & sub-threshold detection algorithms

Maria Chernyavskaya
UW undergrad (-> NAU grad)

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

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

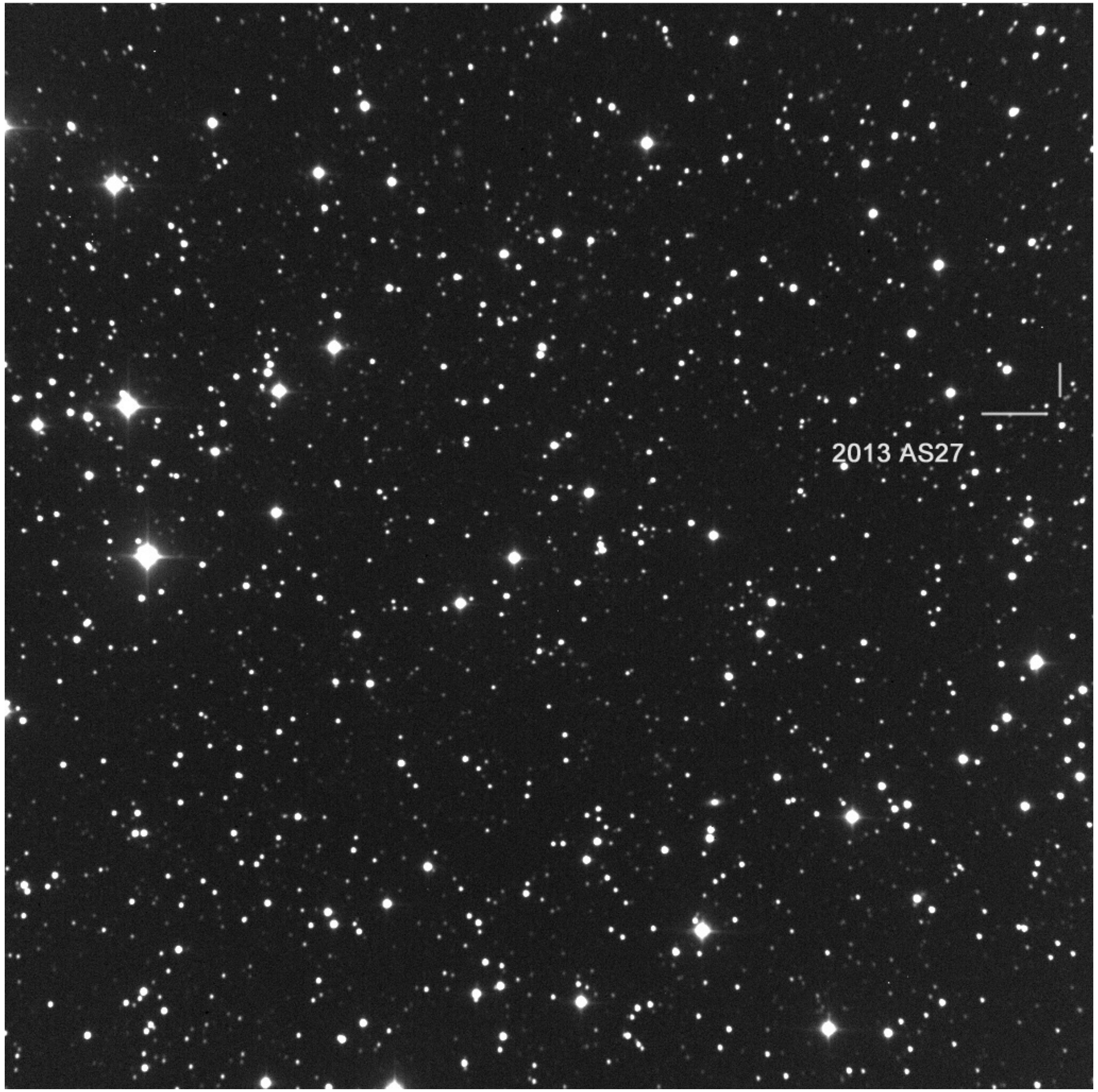
+ B612 Asteroid Institute collaborators …



Dactyl
[(243) Ida I]
1.6 × 1.2 km
Galileo, 1993
243 Ida - 58.8 × 25.4 × 18.6 km
Galileo, 1993
25143 Itokawa
0.5 × 0.3 × 0.2 km
Hayabusa, 2005
2867 Steins
5.9 × 4.0 km
Rosetta, 2008
4179 Toutatis
4.6 × 2.3 × 1.9 km
Chang'E 2, 2012
5535 Annefrank
6.6 × 5.0 × 3.4 km
Stardust, 2002
9969 Braille
2.1 × 1 × 1 km
Deep Space 1, 1999
951 Gaspra
18.2 × 10.5 × 8.9 km
Galileo, 1991
433 Eros - 33 × 13 km
NEAR, 2000
253 Mathilde - 66 × 48 × 44 km
NEAR, 1997
21 Lutetia - 132 × 101 × 76 km
Rosetta, 2010
1P/Halley - 16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
PLANETARY SOCIETY

Finding Asteroids

Credit: a sequence of images of asteroid (1078) Mentha by the UK Spaceguard Centre (https://spaceguardcentre.com)



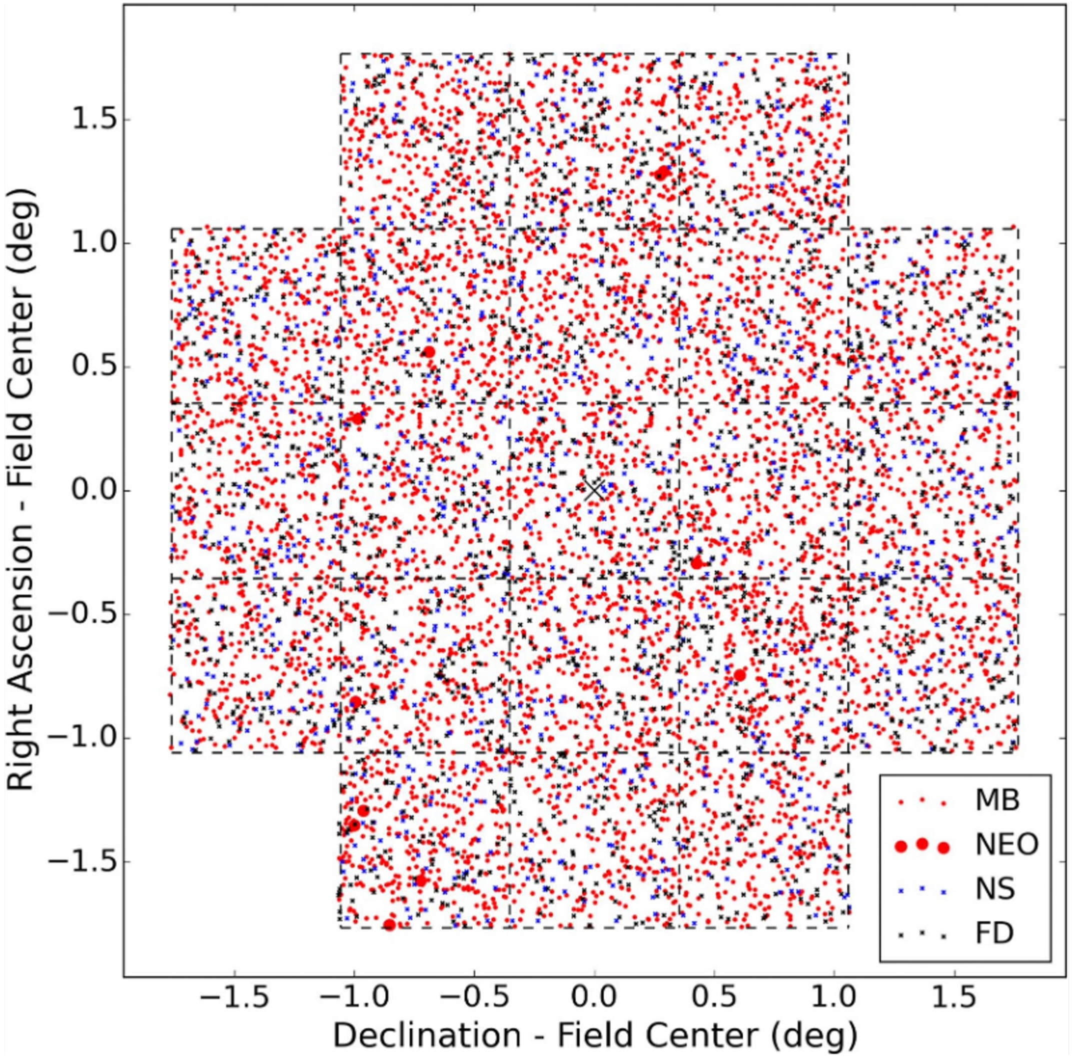
Identifying *"tracklets"*

In shallow imaging, two closely-spaced images can be sufficient to unambiguously identify the asteroid.

More observations are needed to determine the orbit; the asteroid should typically be re-observed one or two nights later.

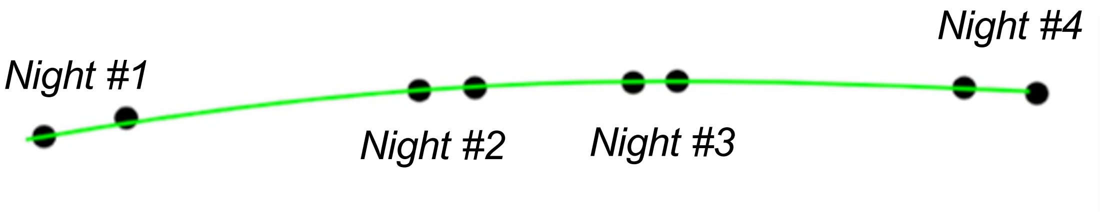
Photo credit: Gary Hug via the Planetary Society (http://www.planetary.org/explore/projects/neo-grants/images/Hug-2013AS27-Discovery-Images.html)

DEEP SURVEYS: FULL OF ASTEROIDS!



Above: Simulation by Veres & Chesley (2017)

Deep sky images have high object densities. Tracklets become probabilistic.



We construct algorithms to "link" *possible* combinations from different nights.

Ari Heinze and Siegfried Eggl's HelioLiNC Advanced

Matt Holman et al. (2019)

Optimized LSST Implementation: HelioLinC+

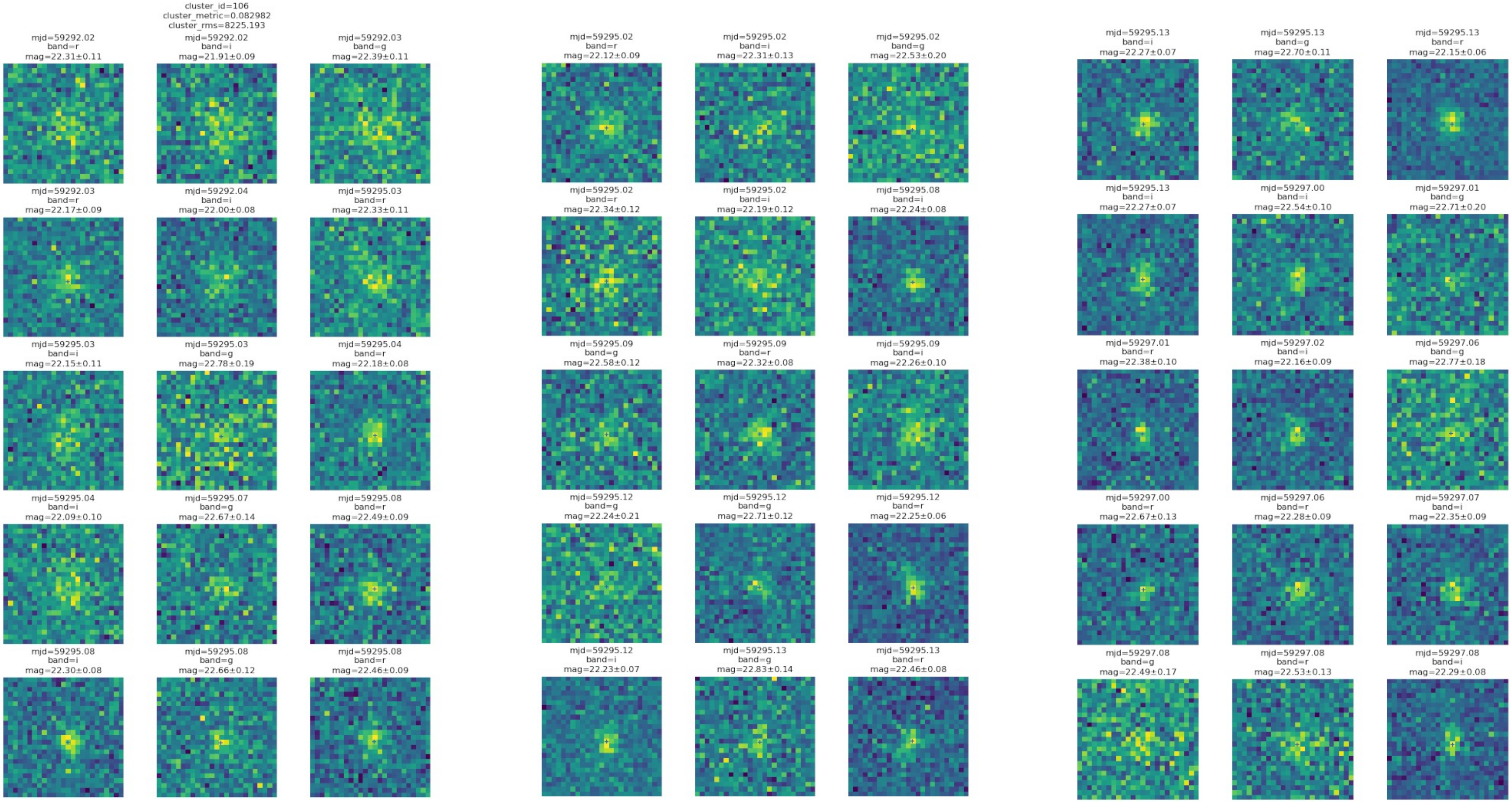
Ari Heinze
HelioLINC+ codes

– Science performance
  - Full-sky LSST tests over a two-week linking window: **97% completeness**.
  - Full-sky LSST test for interstellar objects: **96% completeness**.
  - LSST NEO discovery performance: **~70% completeness (not tuned yet)**.
  - In all cases, **purity >90%**, without using orbit determination chi^2 as a filter.

– Scaling and performance
  - **Scales as O(N *log* N)** with the number of tracklets; MOPS scaled as $O(N^3)$
  - The constant factor is ~small: a few heliocentric distances explore most of the parameter space
  - The code is completely in C++ (working on a small Python wrapper). **Fast.**

– Results: We may be able to replace a small cluster with a ~single machine for LSST-scale workloads *and* we are robust to unanticipated differencing issues (!).

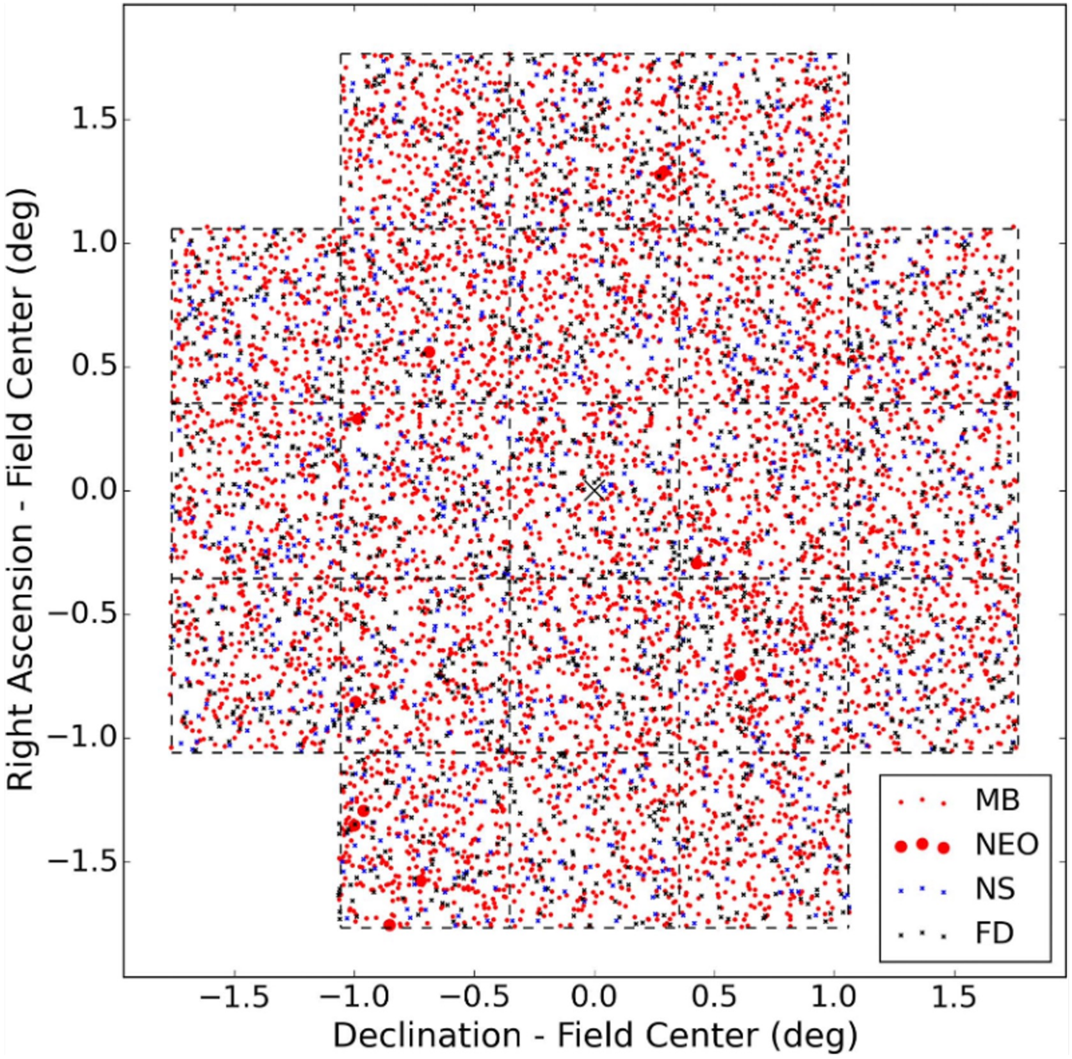
Running on real LSST-like data being acquired on DECam. Also tested w. ATLAS.



*Cutouts by **Steven Stetzler (UW)**; Data: DECat, PI: **Melissa Graham (UW)***

Can we do better?

CAN WE DO BETTER?



Above: Simulation by Veres & Chesley (2017)

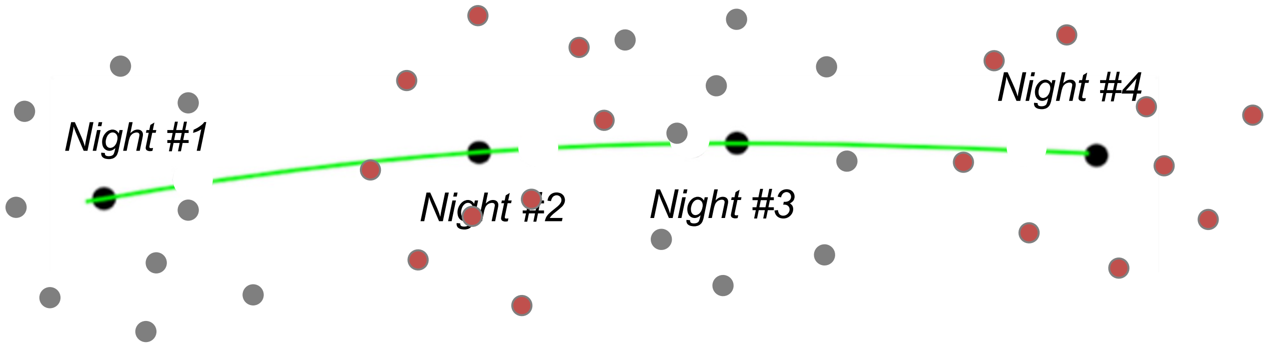
Every time we have to take a pair of images, we half the amount of sky we could observe each night…

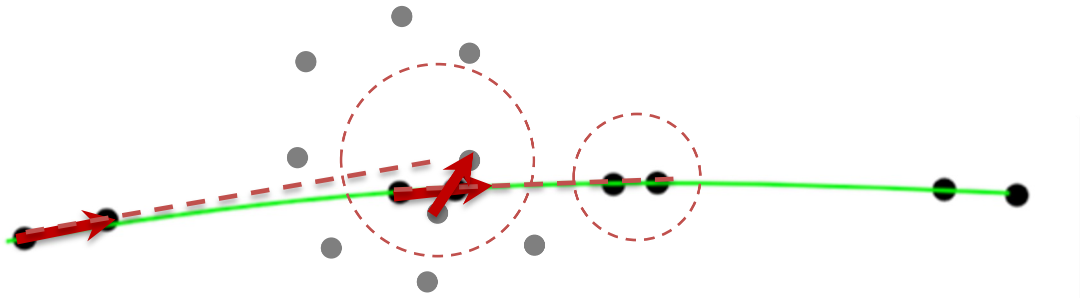
Could we link asteroids with just a *single* observation each night?

Why is “the linking problem” hard? (and how to solve it)

- If the linkage is known (the observations that go together), it’s trivial to verify it (fit an orbit).
- If the linkage is unknown, naïve algorithms would scale as ***$O(N^k)$***, where *N* is the number of detections within a distance an asteroid can plausibly move to next observation (**1-6 deg for ~6 days**), and k is the number of detections needed to confirm the discovery (*k*~5). Computationally tough, $O(10^{20})$ for LSST.

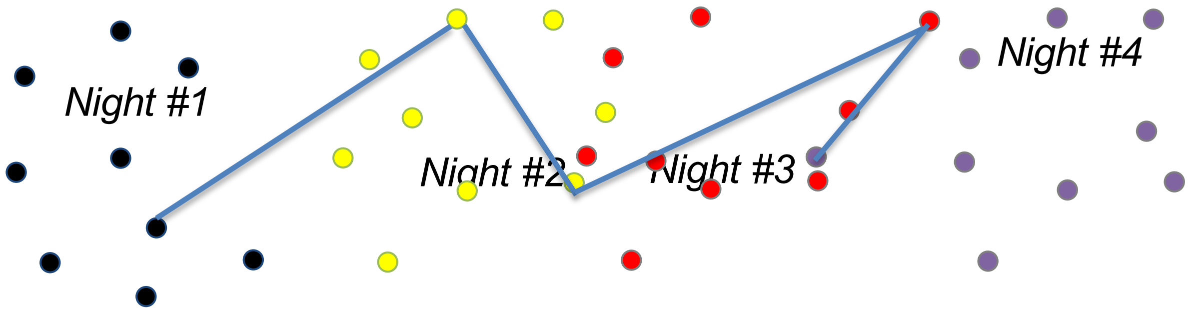
- ”Tracklets” simplify this problem by dramatically reducing the number of choices.
- But the cost is a cadence constraint – need two observations to create tracklets.



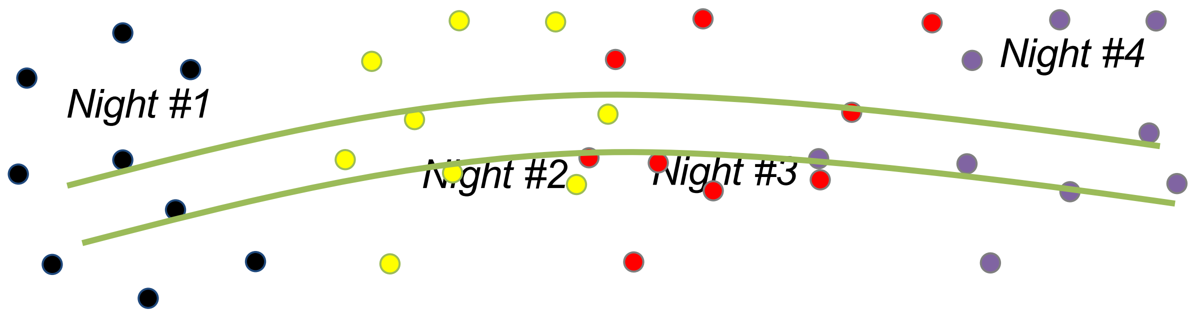


Why is "the linking problem" hard? (and how to solve it)

- The naïve algorithm is obviously too naïve. Most combinations seem clearly implausible.
- Why? They're dynamically impossible, even at a coarse scale (admitting large observational errors). In fact, there are *__many,__* *__many,__* more implausible than plausible trajectories in the dataset of all combinations.



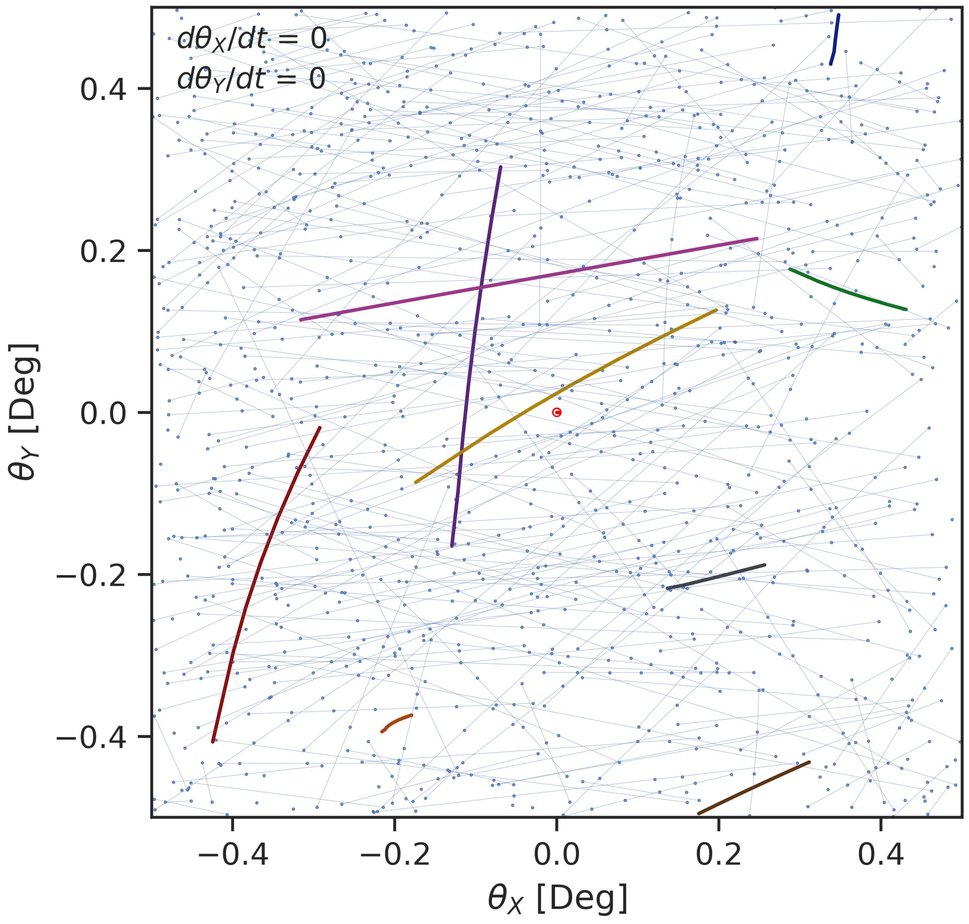
- So let's turn things around: rather than testing each combination for whether it admits an orbit solution, let's ***__test each plausible orbit__*** **and check if it passes "near" actual observations**.
- This looks formidable at first (covering a 6D phase space!) but turns out it can be done quite sparsely: a few "test orbits" will surface most plausible candidates for a link.



THOR: Tracklet-less Heliocentric Orbit Recovery

Joachim Moeyens, MJ, et al. (2021)
http://github.com/moeyensj/thor

- Define a "test orbit", a trial orbit that may (or may not) contain a body.
  - We typically use state vectors (r, v), rather than Keplerian elements
- Define a small "bundle" of orbits around the test orbit, (Δr, Δv). Objects on these orbits will stay close to a particle on the test orbit over short timespans (month).
- Map the particles from the bundle onto the sky. A rough approximation is sufficient.
- Transform all observations in that region into the frame that follows the test orbit particle (assuming distance *r*).

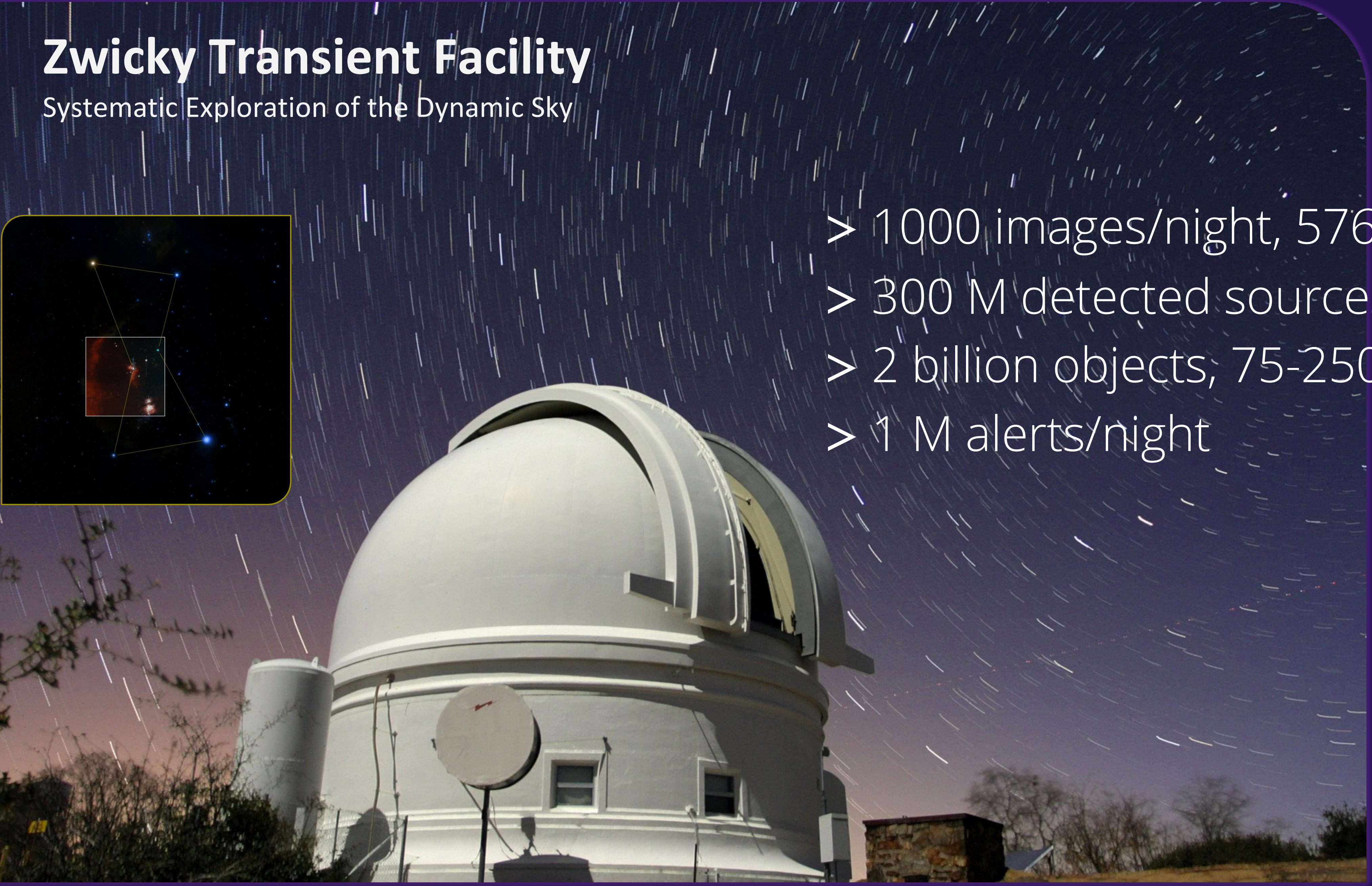


- Result:
  - In the transformed frame, the test orbit particle will cluster at (0, 0)
  - Particles on orbits from the bundle will (approximately) trace lines
    - This is, effectively, an expansion of the trajectory relative to a nearby orbit
    - They can now be picked up by Hough transform or similar.
- Cover the observable areas of the phase space, find all asteroids.

Note: You can think of this as "shift-and-stack" in catalog space, nonlinear, over long timespans.

Zwicky Transient Facility

Systematic Exploration of the Dynamic Sky



- > 1000 images/night, 576 mpix
- > 300 M detected sources/night
- > 2 billion objects, 75-250 mea/obj/year
- > 1 M alerts/night

Public-Private Partnership.
40% obsv. on LSST-like cadence, immediately public.

http://ztf.caltech.edu

Running THOR on ZTF Data

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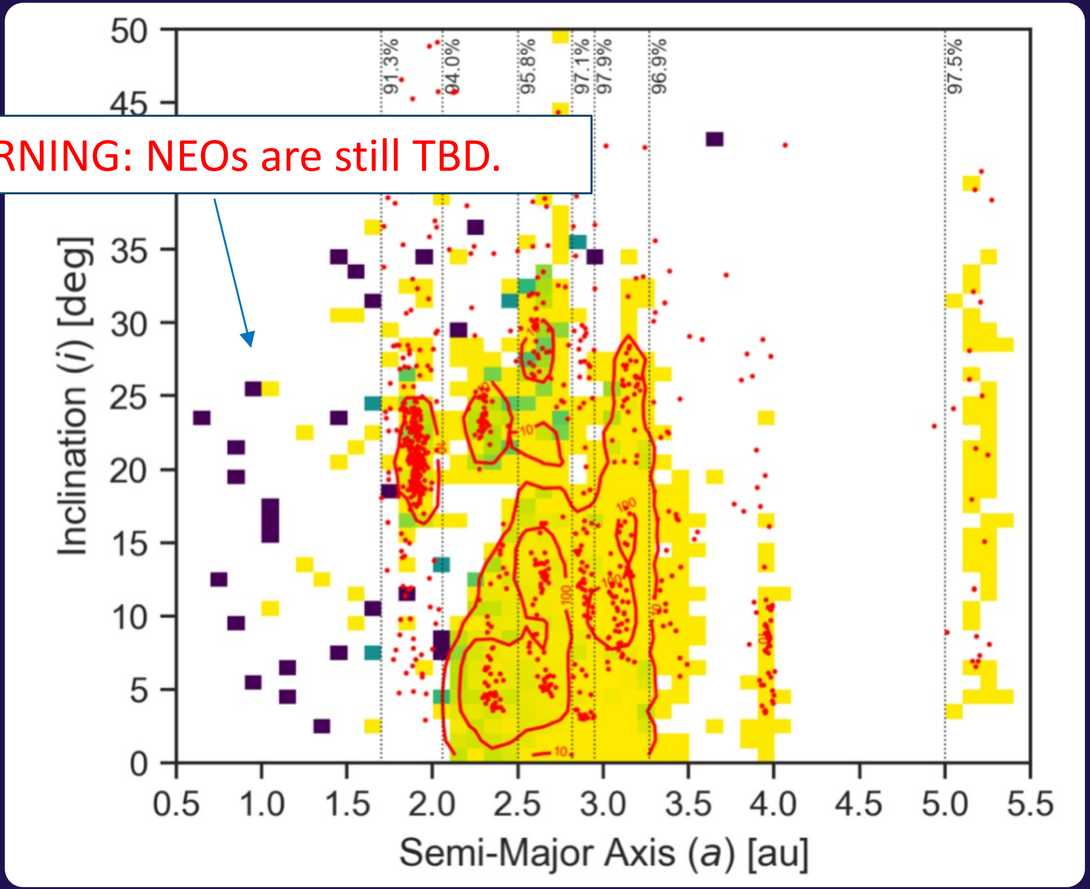
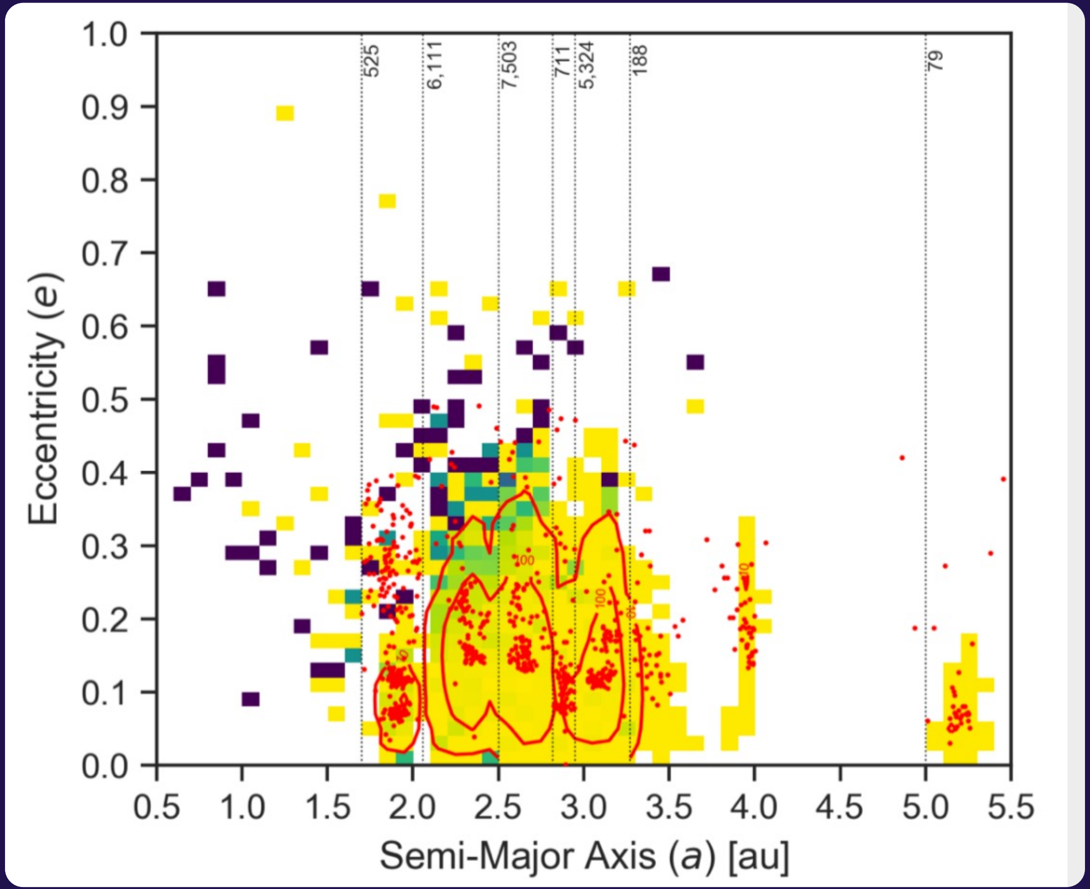
Results: recovered 95.6% of known objects. Found a dozen new ones. Also pre-covered a comet.

WARNING: NEOs are still TBD.





Just 44% findable by classical MOPS, 66.4% by ZMODE.

Moeyens et al. (2021)

More interesting: NOIRLab Source Catalog (NSC)

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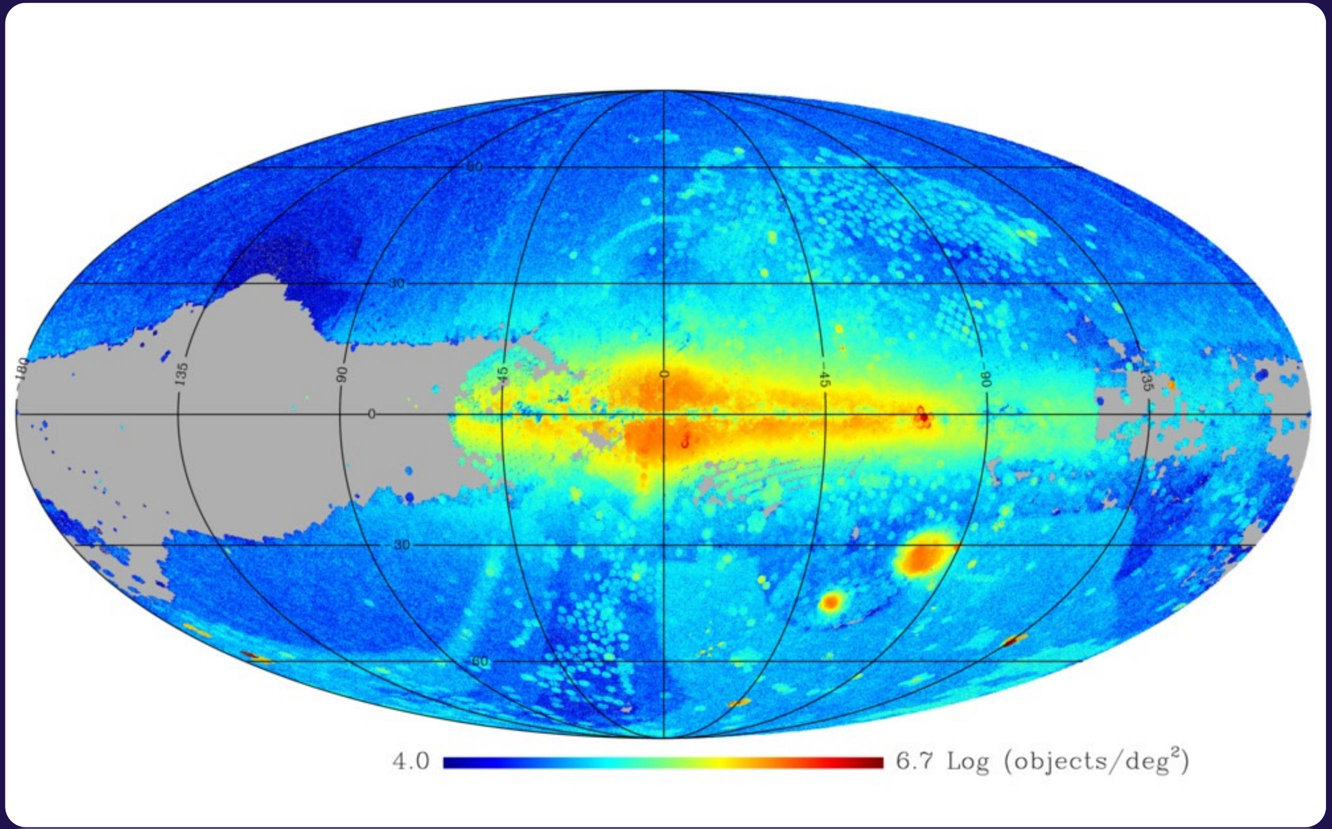
- The NOIRLab Source Catalog (NSC) is a catalog of nearly all of the public imaging data in NOIRLab's Astro Data Archive

- 68 billion individual source measurements
- Dominated by DECam + Blanco 4m measurements (3/4 of all exposures)
- Deep (~23rd magnitude in most filters)

- ~1.7 billion don't appear to be static (i.e., could be asteroids).



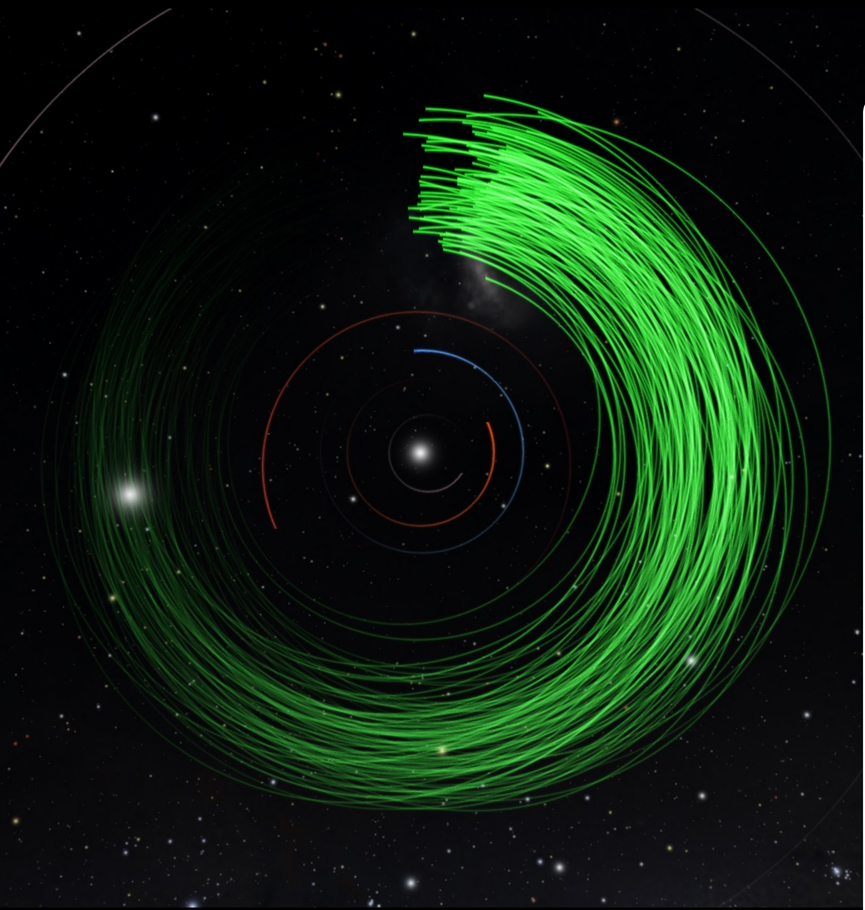
NSC DR2 Object Density Map

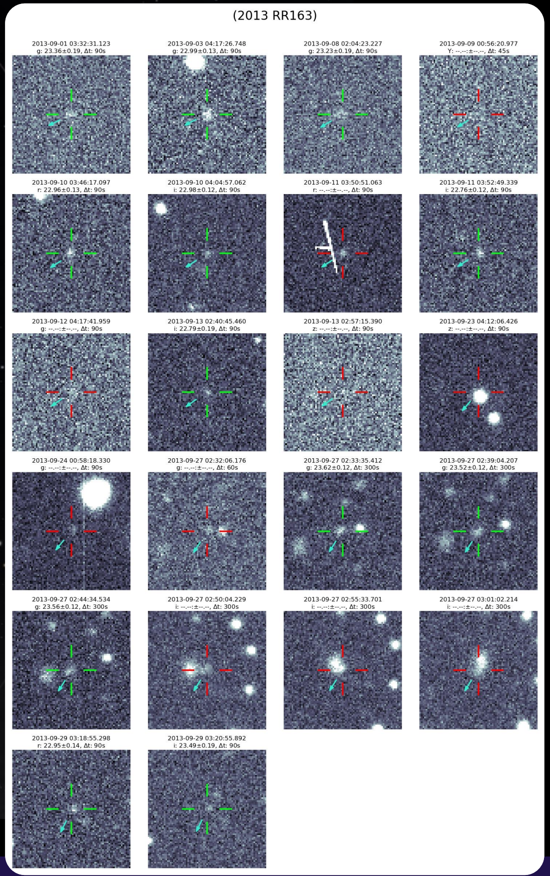
Initial run on 0.2% of data (15% of September 2013)

- Identified ~1200 known asteroids
- Linked 104 new objects (MPC-designated)
- Also pulled in a number of tracklets from the ITF.

- The vast majority have no 3-obsv tracklets (unidentifiable with “usual” software)
- A number of them have no tracklets (pairs of observations in a single night) at all.

- Extrapolating to the whole dataset, we’re looking at ~10-40k of new discoveries.
- The full dataset is being run right now.

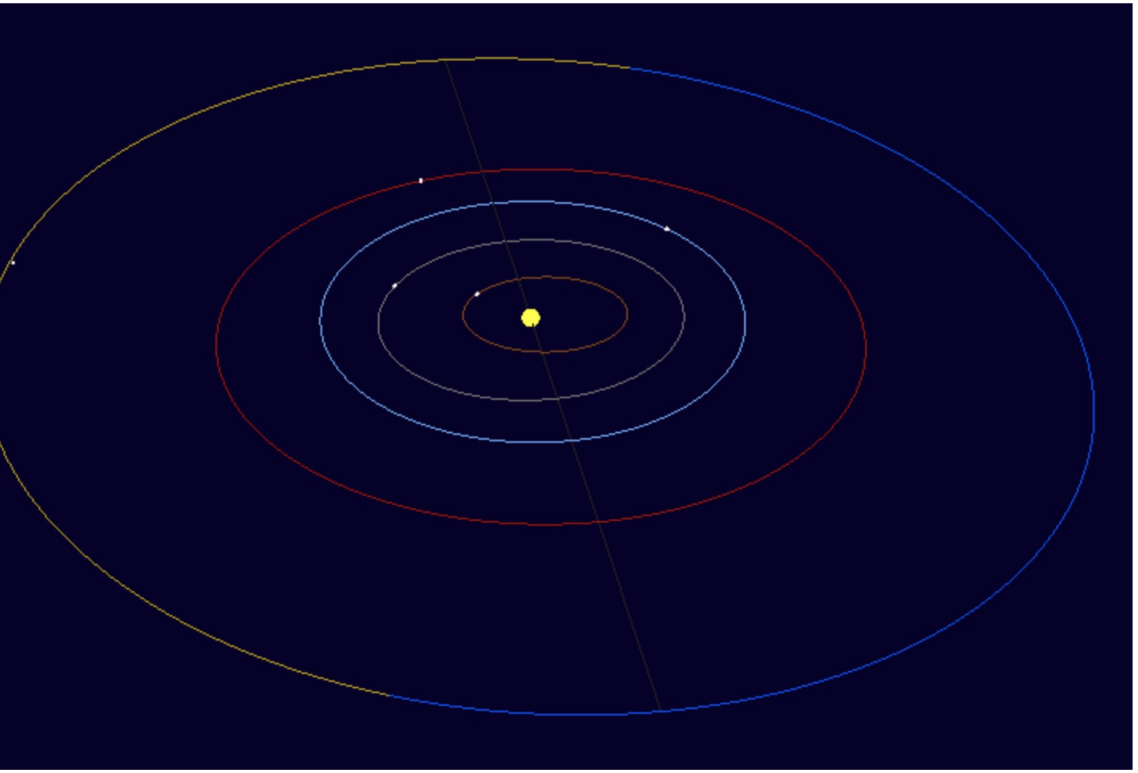




- Est. cost: ~5M core-hours for the entire NSC dataset.

Moeyens, MJ, et al. (in prep)

https://minorplanetcenter.net/db_search/show_object?object_id=2013+RR165



semimajor axis (AU)	2.5811065
mean anomaly (°)	25.55764
mean daily motion (°/day)	0.23768140
aphelion distance (AU)	2.805
period (years)	4.15
P-vector [x]	0.84731874
P-vector [y]	-0.49443833
P-vector [z]	-0.19385996
Q-vector [x]	0.52963184
Q-vector [y]	0.75971149
Q-vector [z]	0.37726459
absolute magnitude	18.61
phase slope	0.15

uncertainty	1
reference	E2022-L13
observations used	40
oppositions	5
arc length (days)	2418
first opposition used	2011
last opposition used	2017
residual rms (arc-secs)	0.26
perturbers coarse indicator	M-v
perturbers precise indicator	003E
first observation date used	2011-01-30.0
last observation date used	2017-09-13.0
computer name	Veres

2013 RR165: An object discovered with ADAM::THOR, with previously unrecognized observations spanning over 6 years (!)

THOR: Implementation

- https://github.com/moeyensj/thor
- The core code is in Python + Numba JIT
- Optimizing performance, investigating GPU port.

- Parallelization on B612's ADAM ("Asteroid Discovery, Analysis and Mapping") astrodynamics platform on Google Cloud (https://adam.b612.ai).
- Why cloud? Available CPU power, scalability, the ease of building services.

- Hope to offer "asteroid discovery as a service": upload your detections, we'll find any asteroids that are in there.

Making any dataset an “asteroid search” dataset

- Many more datasets w/o nightly revisits now become usable for asteroid searches. And DECam archival data is a prime example of that!

- NOIRLab Source Catalog is <u>fantastic</u> for this purpose: good astrometry, well documented, single-epoch data available.

- Thank you for building this product (and please make a DR3 ☺)!

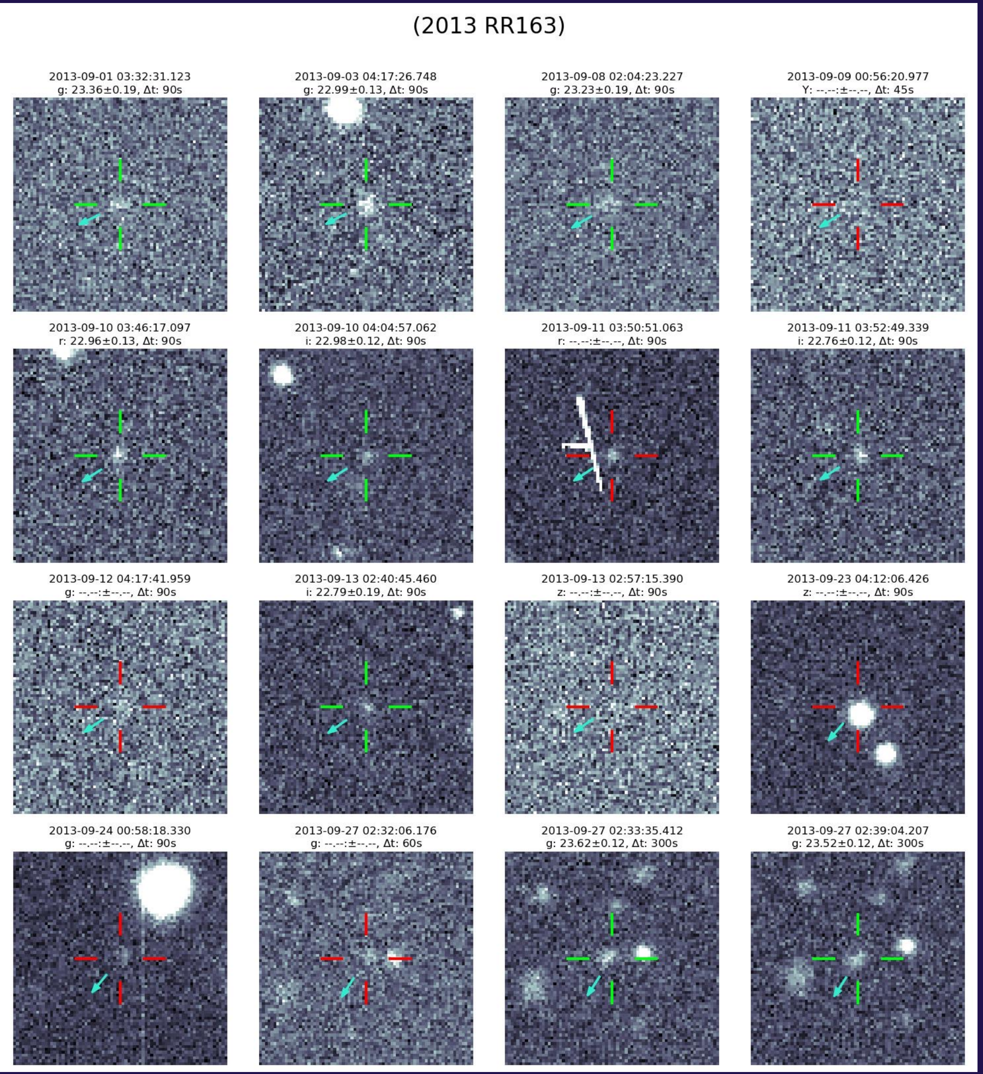
- Other DECam reduction efforts: please keep/pass along single-epoch data!

Things that are useful for efforts like these

1. Bulk catalog access: we'd like to easily grab everything.
   - Right now we're scraping the SQL database. Not pleasant.
   - We love files™!

2. Fast image cutout service.
   - ***Incredibly*** useful for visual confirmation, precise fits (note to Rubin: this will remain true even for LSST!).
   - We'd like latencies of O(1s) when building mosaics such as 👉

NSC asteroid cutout mosaic generator
https://github.com/B612-Asteroid-Institute/cutouts



What can we do with THOR(-like) algorithms?

- It allows searching of archival data but also, …
- … it allows for better yields and cadence re-optimization of future surveys.

- Example #1: with a tracklet-less algorithm, the LSST would be free to (in theory) double the area of the sky observed each night. Helps with non-Solar System science.
- Example #2: w. THOR + cadence changes, the LSST could half the number of remaining unknown PHAs (Jones et al. 2018).
- Example #3: a tracklet-less algorithm *may* enable a mission such as NASA NEO Surveyor to reach the 90% PHA discovery mandate.

- **A O($5M) investment in algorithms and computing could yield O($100M+) improvements on O($1Bn) missions.**

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A Universe Understood Through
Data-Intensive Discovery

Thank You! Questions?

https://dirac.astro.washington.edu

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