Outer Solar System science in the era of large surveys

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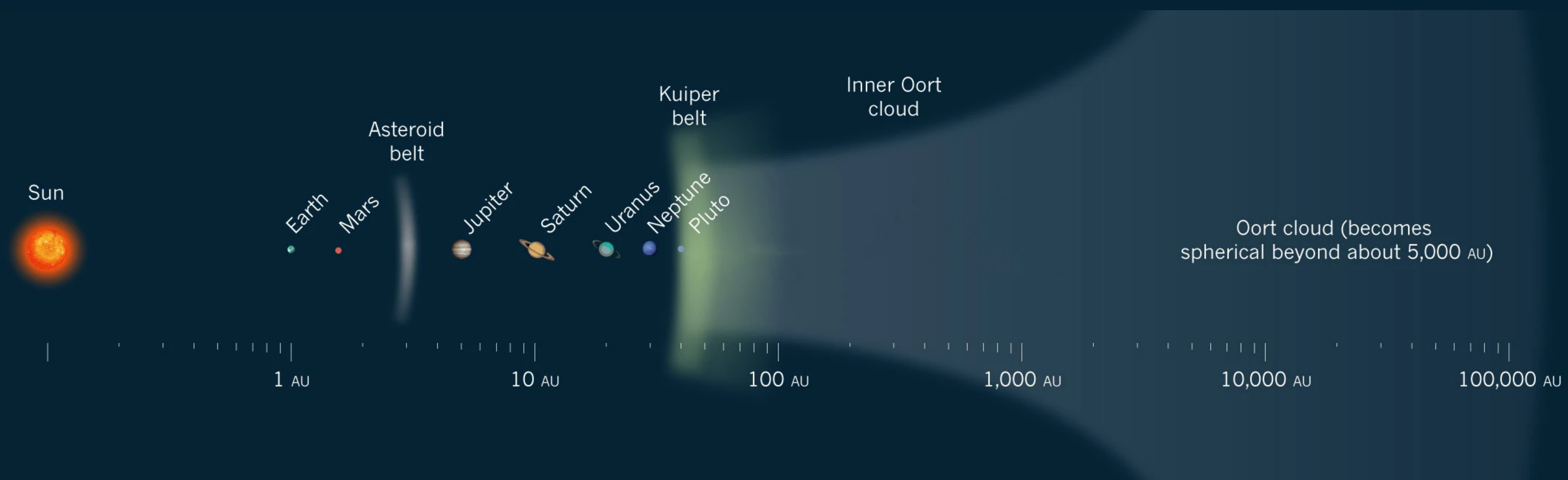


Earth: 1 au

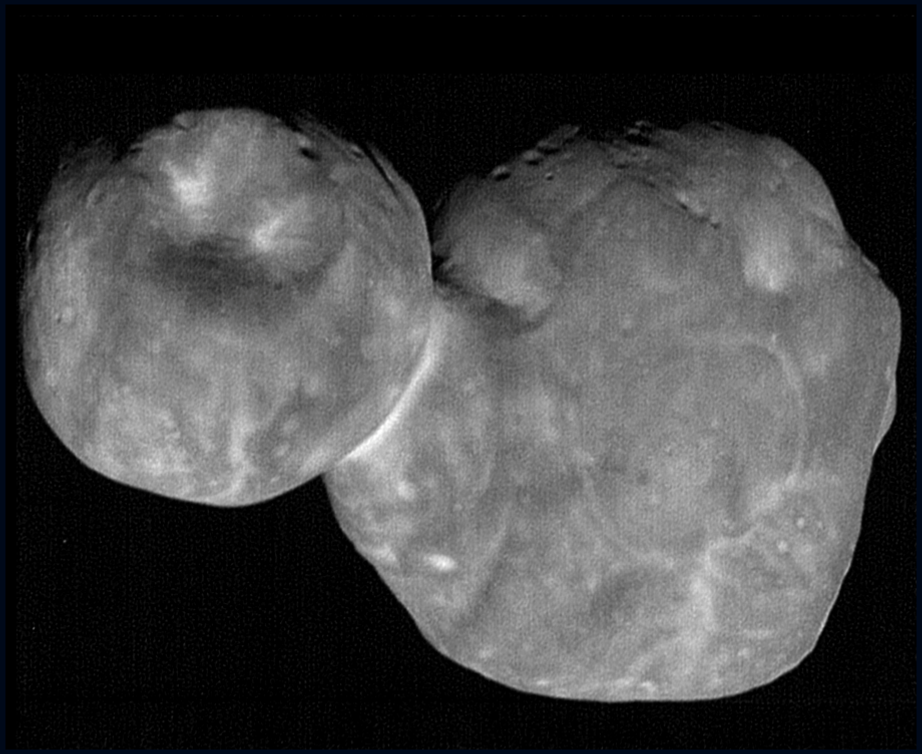
Neptune: 30.1 au

Pluto: 39.2 au

Schwamb (2014) - Nature 507, 435–436 (adapted)

The Trans-Neptunian region

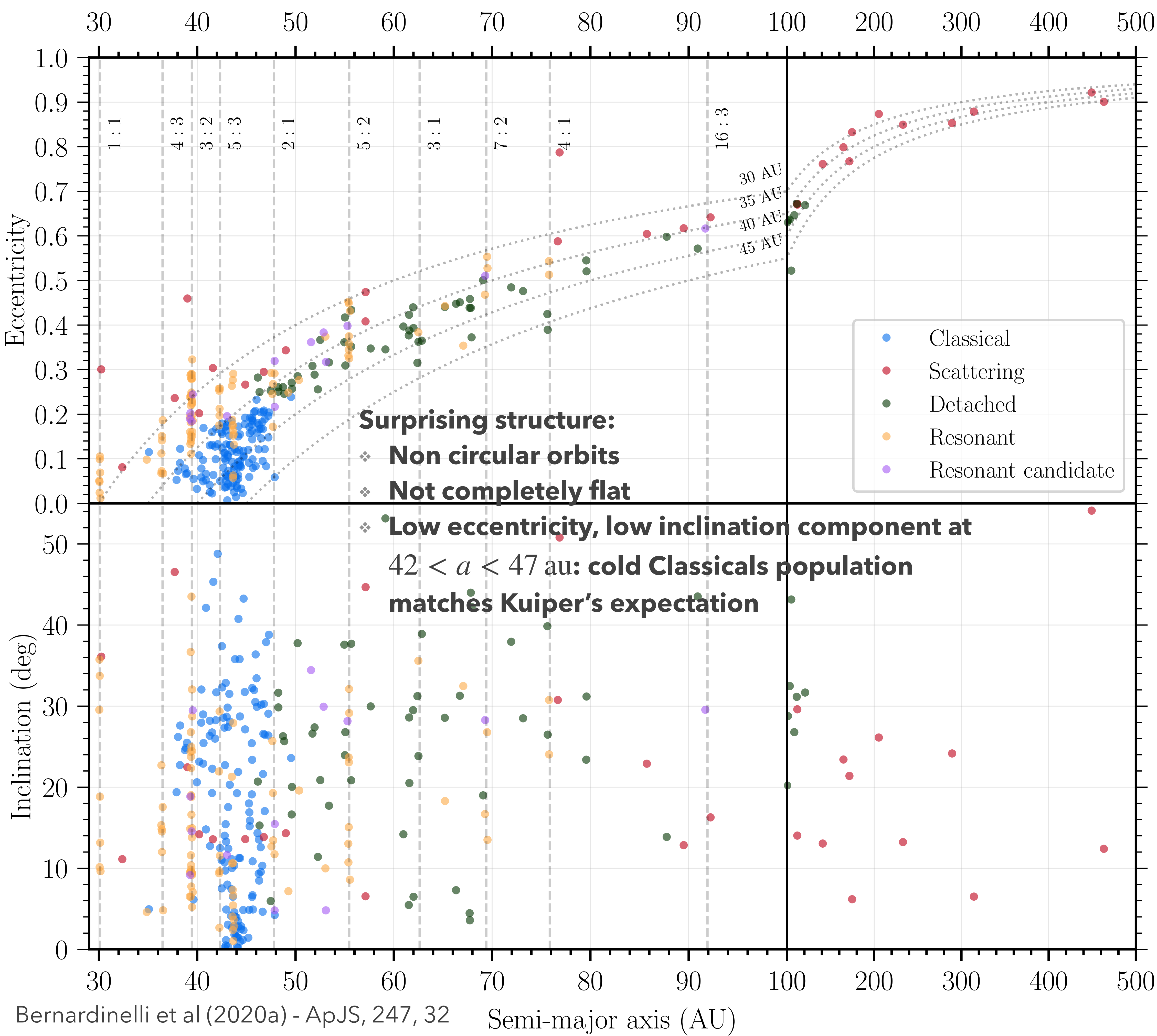
- Kuiper belt postulated in the 1950s (Edgeworth 1943, Kuiper 1951) as a circular, flattened reservoir of bodies, remnant from planetary formation
- Pluto discovered in 1930, the second object in 1992 (Albion)
- About 4000 objects known today



Pluto: 2372km (~0.18 Earth diameters)

Arrokoth (2014 MU69): 30km

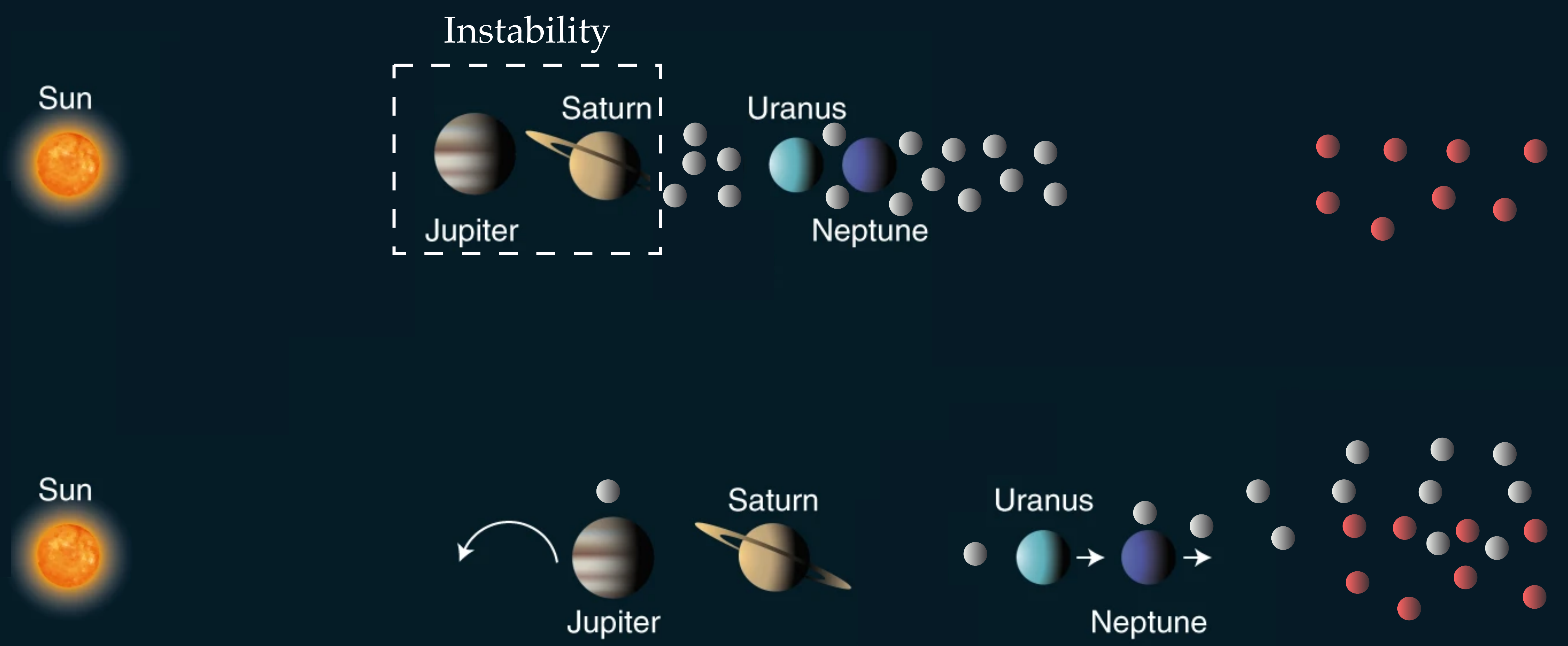
Images taken in fly-bys with the NASA New Horizons probe



Surprising structure:

- **Non circular orbits**
- **Not completely flat**
- **Low eccentricity, low inclination component at $42 < a < 47$ au: cold Classicals population matches Kuiper's expectation**

Bernardinelli et al (2020a) - ApJS, 247, 32



Pike (2018) - Nature 2, 858–859 (adapted)

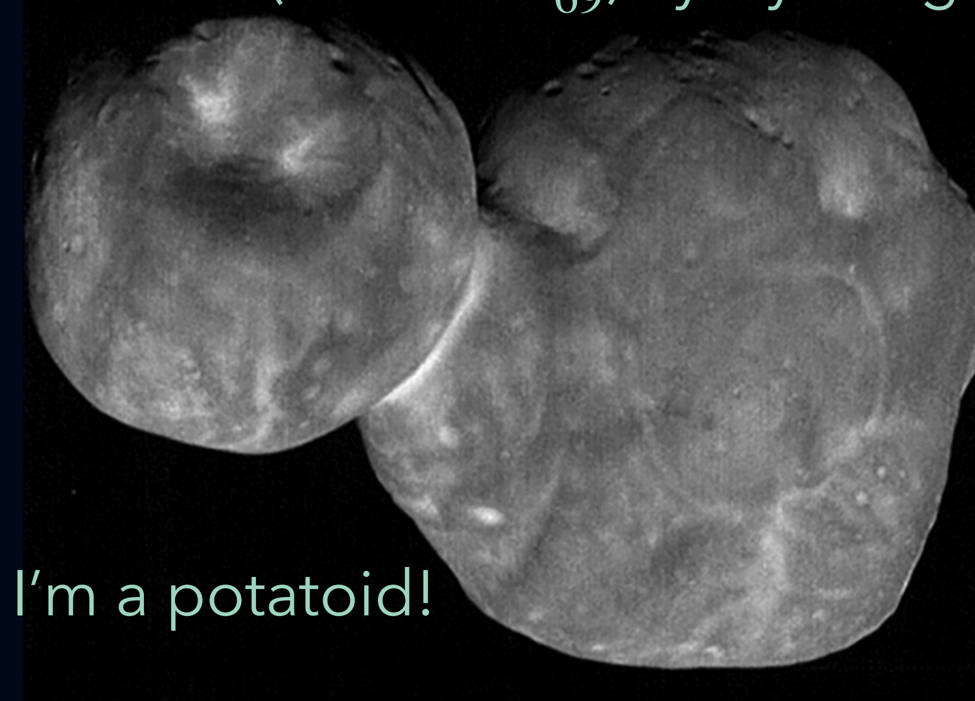
The Trans-Neptunian region

- Region shaped by major dynamical events in the history of the Solar System:
  - Large scale changes in the orbits of the giant planets
  - Fine details such as speed and smoothness of Neptune's migration imprint different present-day structure
  - Objects have recent or current gravitational interactions with Neptune (mean motion resonances, scattering)
  - Possible presence of a ninth planet in the solar system???

Minimalist view of TNO compositions and shapes

- Variability is usually associated with differences in surface shapes (TNOs are ~potatoes) at different spin angles, or albedo variations in the surface, rounder objects are less variables than ellipsoids or contact binaries
- Surface colors for TNOs are typically indicative of composition, color classes indicate distinct formation region in protoplanetary disk
- TNOs can also be binaries: ~50 systems have well determined mutual orbits, usually requiring years of HST time. Only 9 have “wide” orbits

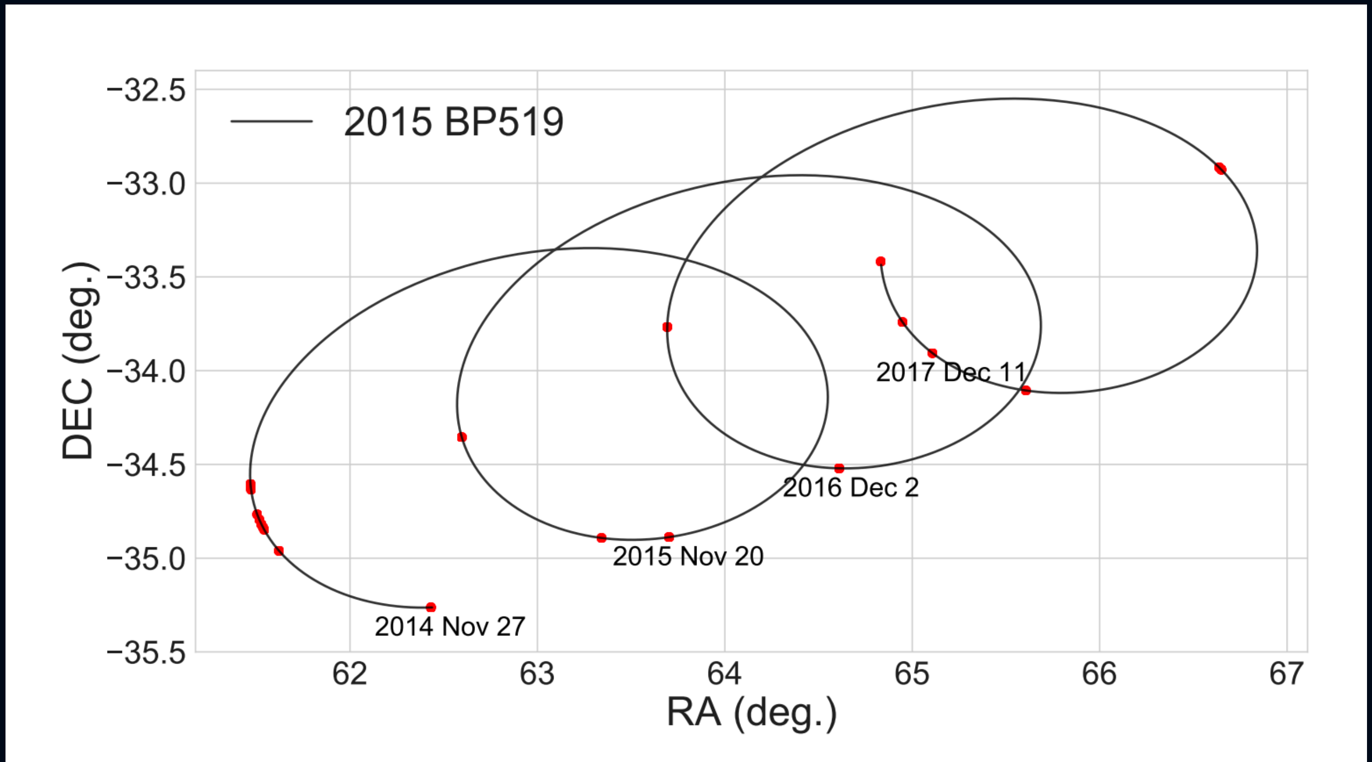
Arrokoth (2014 MU_{69}) fly-by images



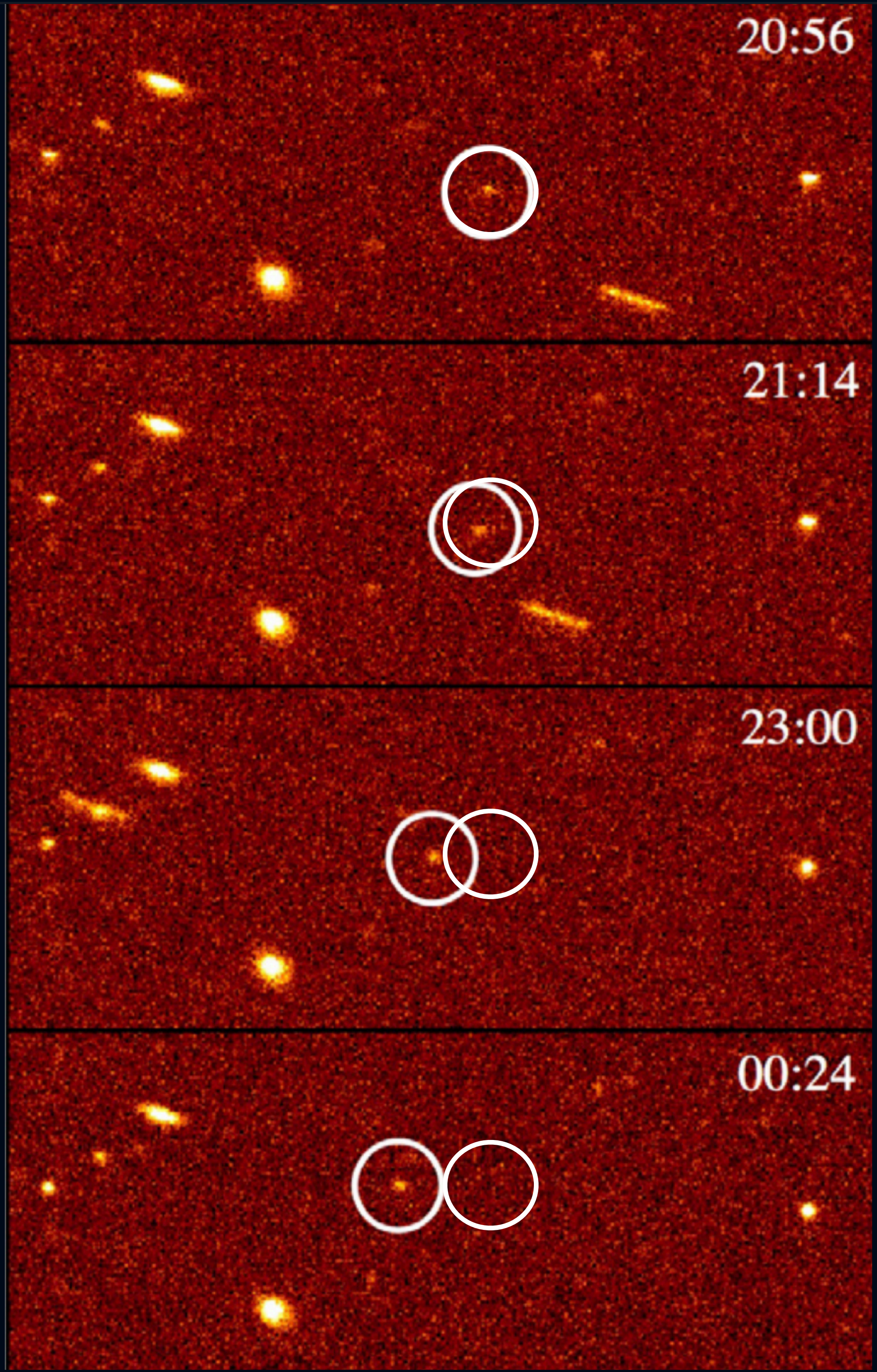
A potato

Observing Trans-Neptunian Objects

- Objects on the solar system move significantly on the sky: 5″/hr typical for a TNO
- Motion is easy to distinguish with a dedicated survey strategy: "tracklets" of multiple detections indicative of rate and direction of motion
- Reflected sunlight: $f \propto \frac{A}{d^4}$, absolute magnitude H is the intrinsic brightness of the object (proxy for size)



Becker et al (2018) - AJ, 156, 81



Jewitt & Luu (1993) - Nature, 362, 730 (modified)

Credits: Fermilab

- 6 year coverage of 5000 deg² in 5 optical/NIR bands + small high cadence area
- Focused on mapping galaxies for cosmology, NOT finding Solar System objects
- Guess what? Needle in a haystack problem (for those who are counting, I think this is at least the 6th talk in this conference to use this analogy)
- Main object catalog: Bernardinelli et al (2022) - ApJS, 258, 41

Discovery process

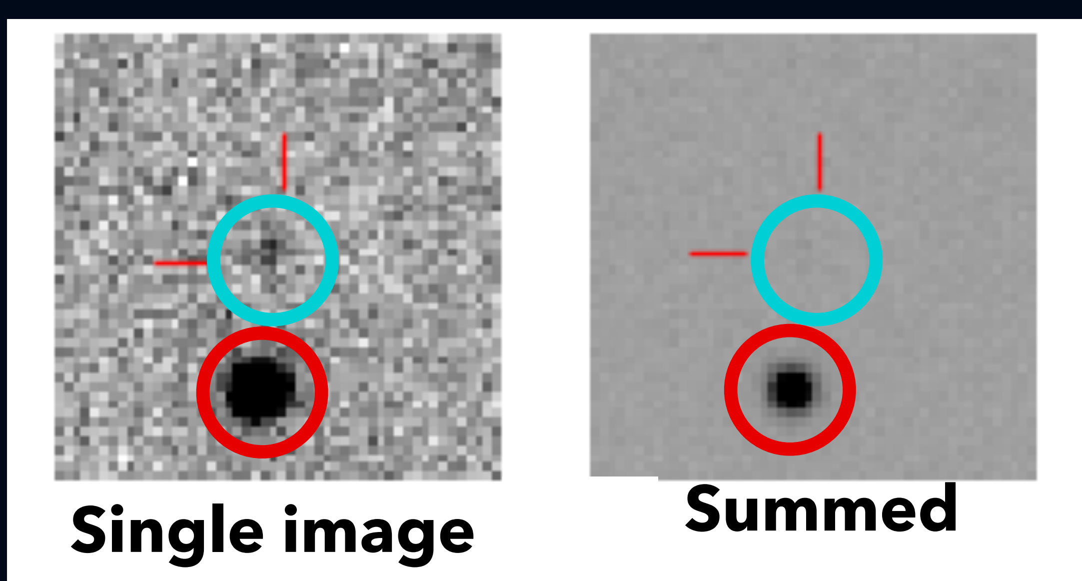
- **Single-epoch data:** all detections from a given exposure
- **Transients:** potential moving sources on the sky
- **Pairs:** group of 2 transients that might belong to the same object
- **Triplet:** group of 3 transients that might belong to the same object
- **20 million CPU-hours**
- **Candidate:** group of $n \geq 7$ transients that looks like an orbit
- **Confirmed object:** group of n transients that comes from a real Solar System source

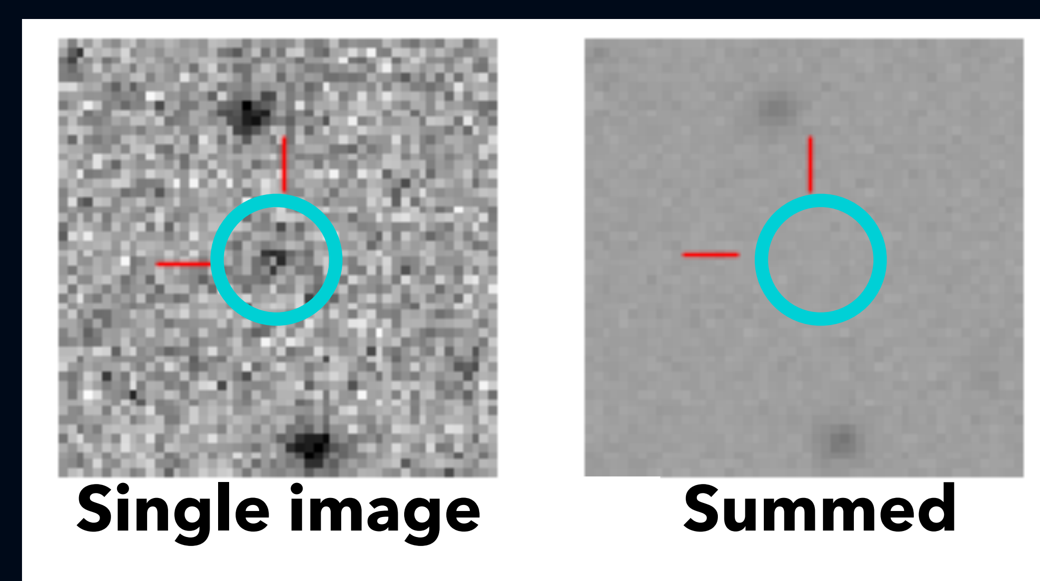
Step	Numbers
Exposures	80.000
Transients	108M
Pairs	$> 10^{13}$
Triplets	10^{12}
Candidates	≈ 10000
Real objects	814

Transient identification

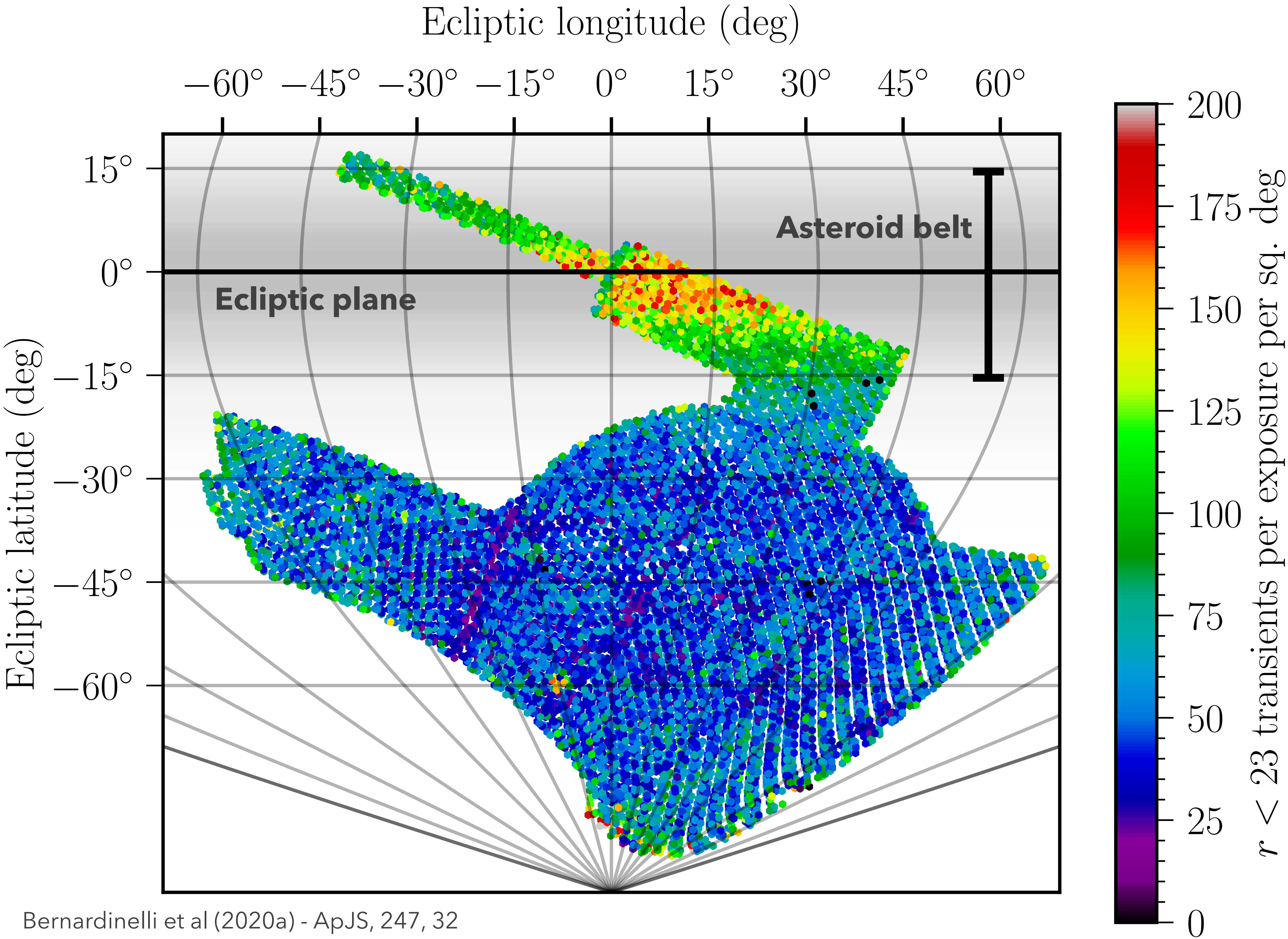
- Positional matching of all sources in individual images as well as summed images
- Moving sources appear only once in a given spot on the sky over all years of data, and are either fainter or undetectable in the summed images
- Primary source of contamination: asteroids, undistinguishable from TNOs in this step

$$1.6 \cdot 10^{10}\,\mathrm{SE} \rightarrow 1.1 \cdot 10^{8}\ \mathrm{transients}$$



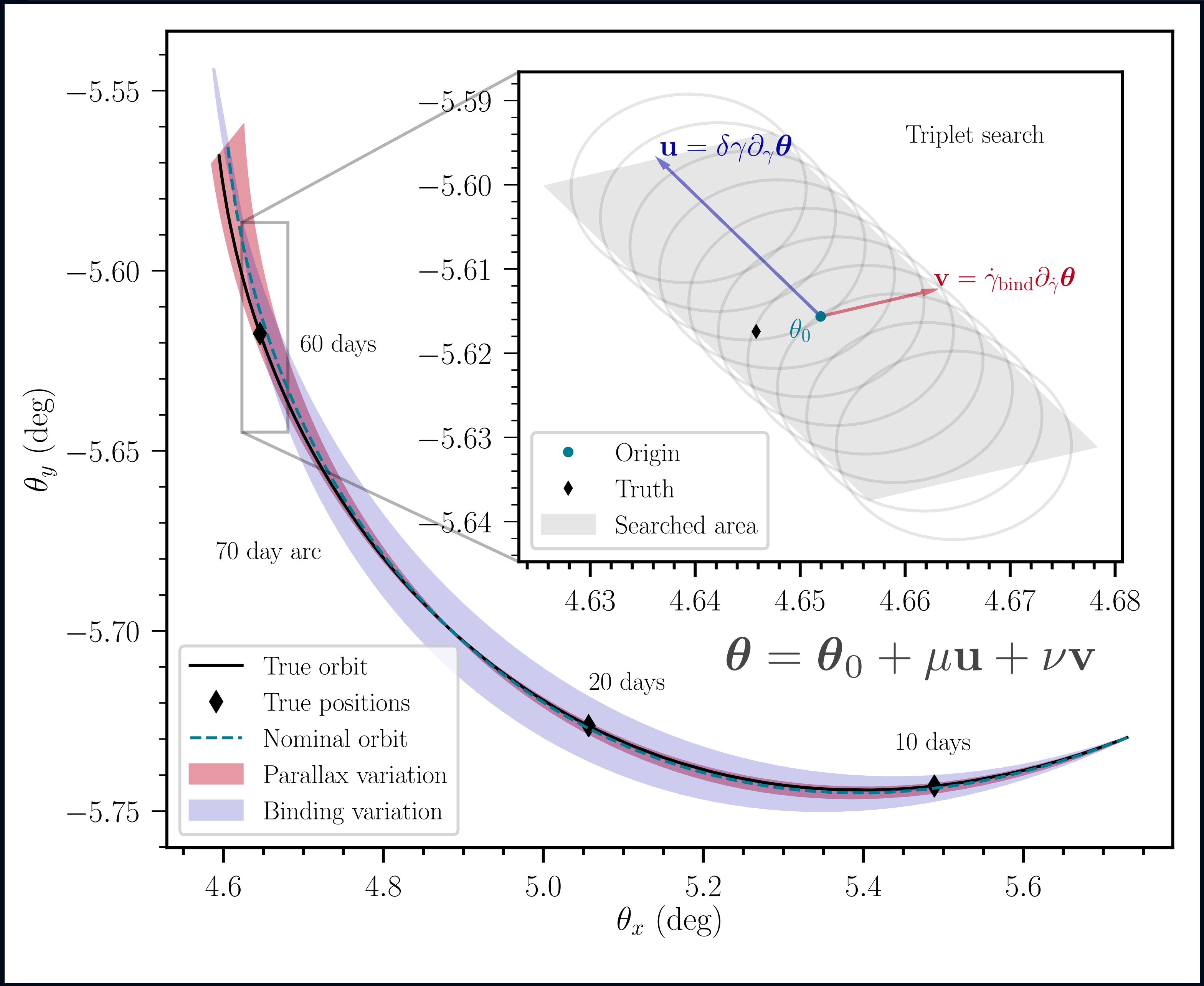


Moving object **Static source**



Bernardinelli et al (2020a) - ApJS, 247, 32

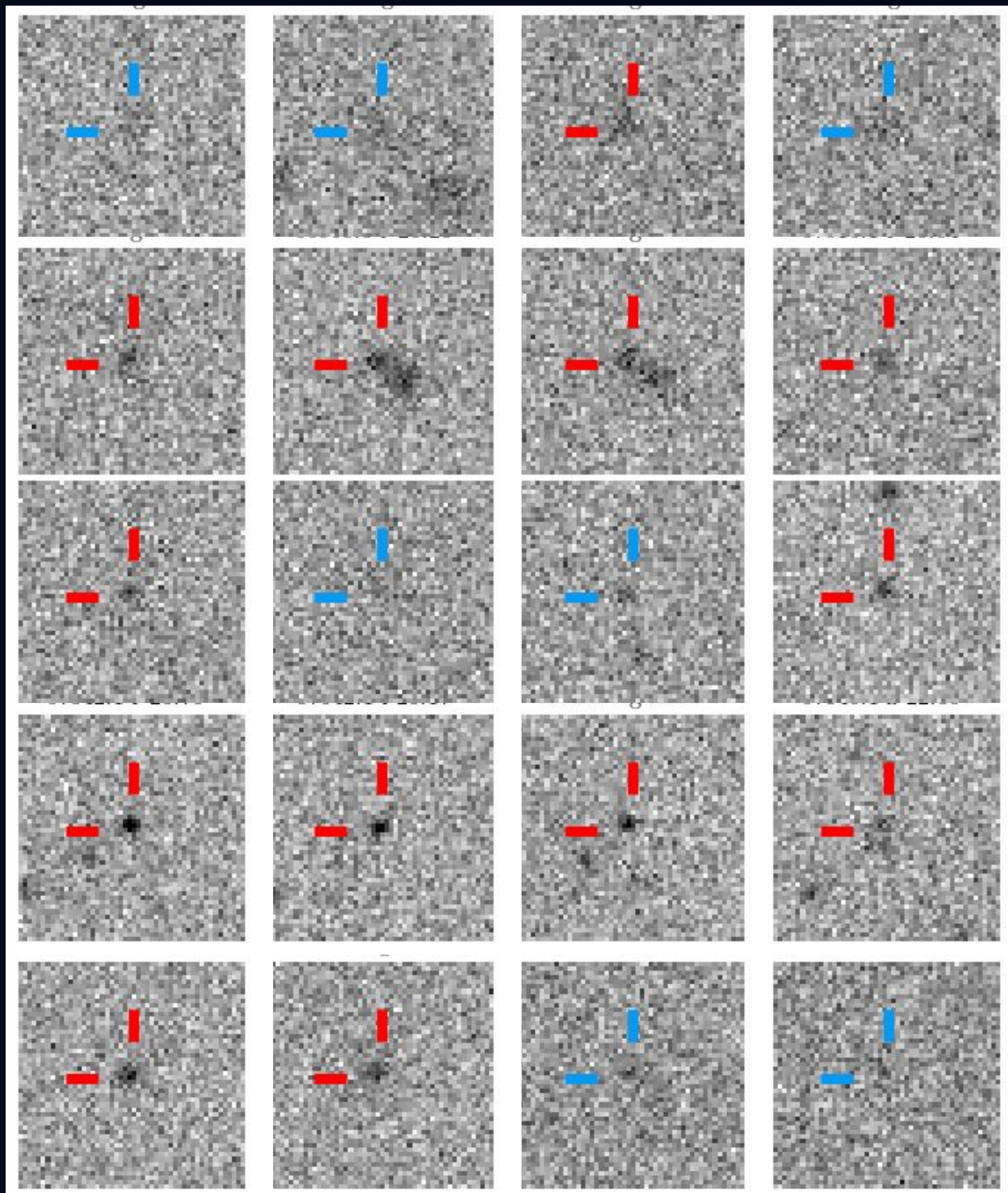
Orbit linking



- Which $\mathcal{O}(10)$ detections belong to the same object?
- Triplets of detections define an orbit (6 phase space coordinates): $\mathcal{O}(n^3)$ problem
- Instead of testing all triplets, search for detections consistent with motion defined by the first two and a nominal distance to object
- From triplet to orbit: **extremely computationally expensive** (15-20 million CPU hours)
- Search targeted $d > 29$ au

10^8 transients → 10^{13} pairs → 10^{12} triplets → 10^5 candidates

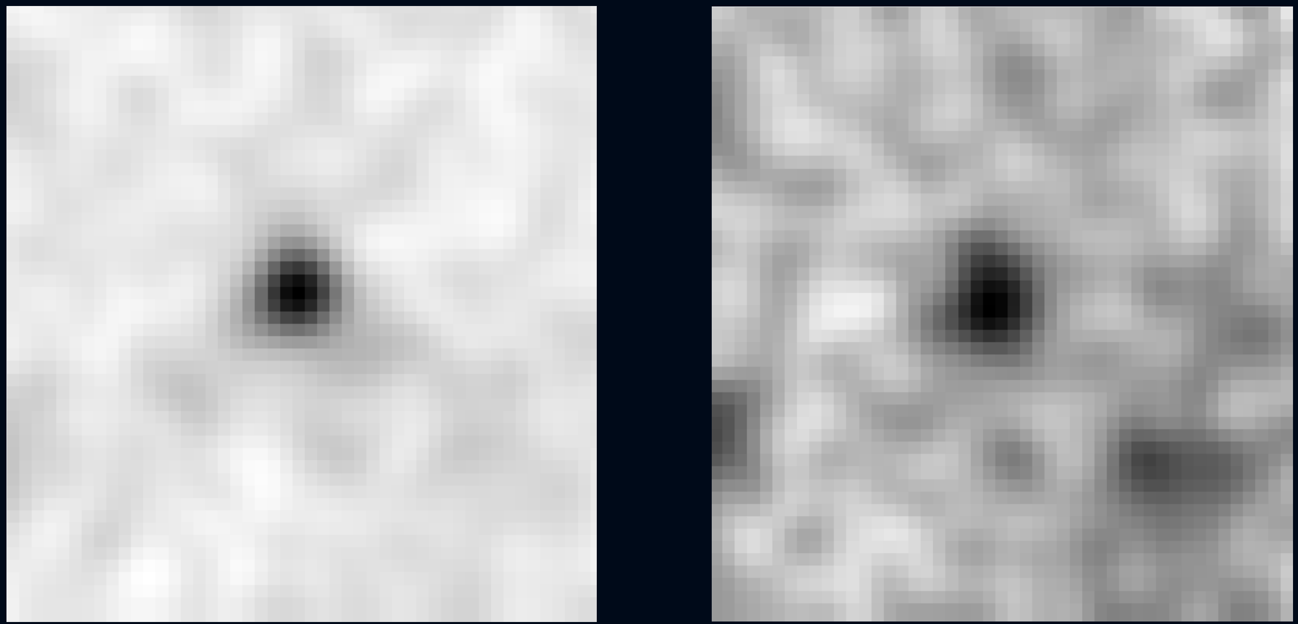
Red: detected   Blue: not detected



- Sub-threshold significance (STS) test: Inspect images where object is expected to be, but is too faint to be detected
- Real objects have signal in image sum:

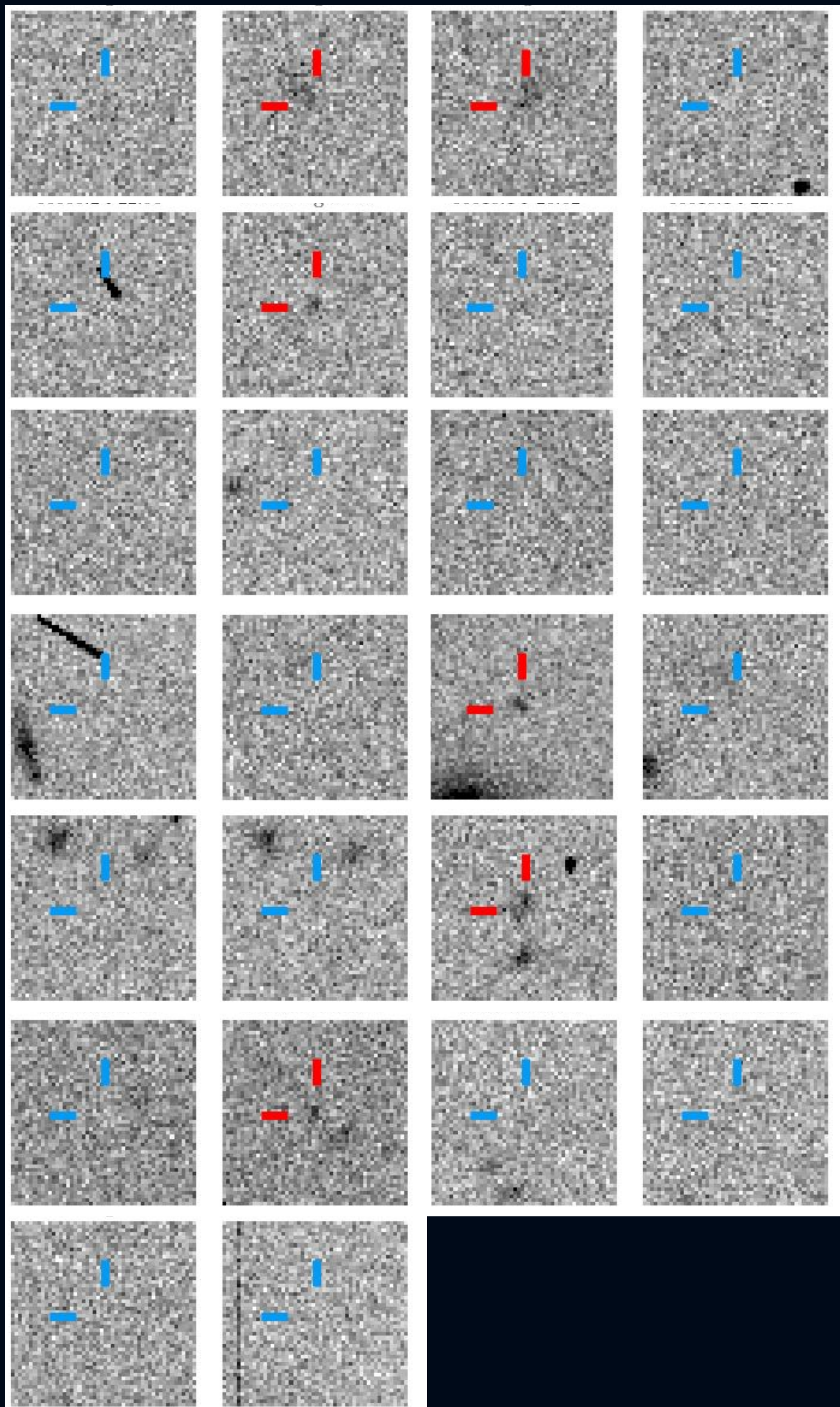
$$\mathrm{STS} = \mathrm{S/N\ over}\ N\ \mathrm{undetected\ images}$$

Red + Blue   Blue



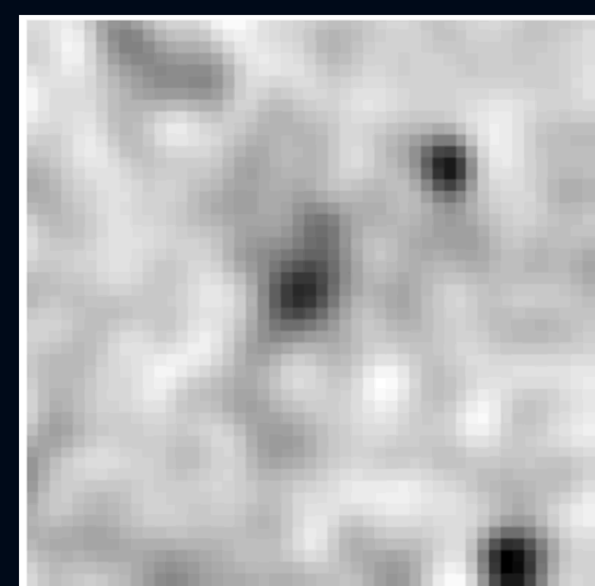
$$\mathrm{STS} \sim 12$$

Red: detected Blue: not detected

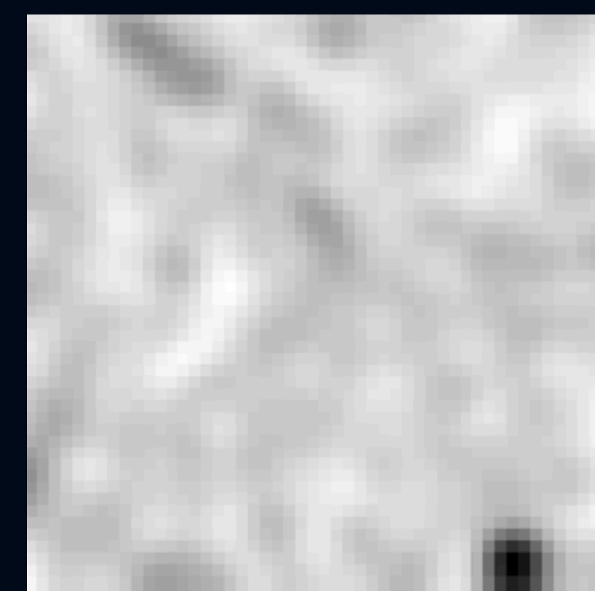


- Inspect images where object is expected to be, but is too faint to be detected
- False linkages have no signal
- 814 objects pass indicate both high STS and pass visual inspection

Red + Blue



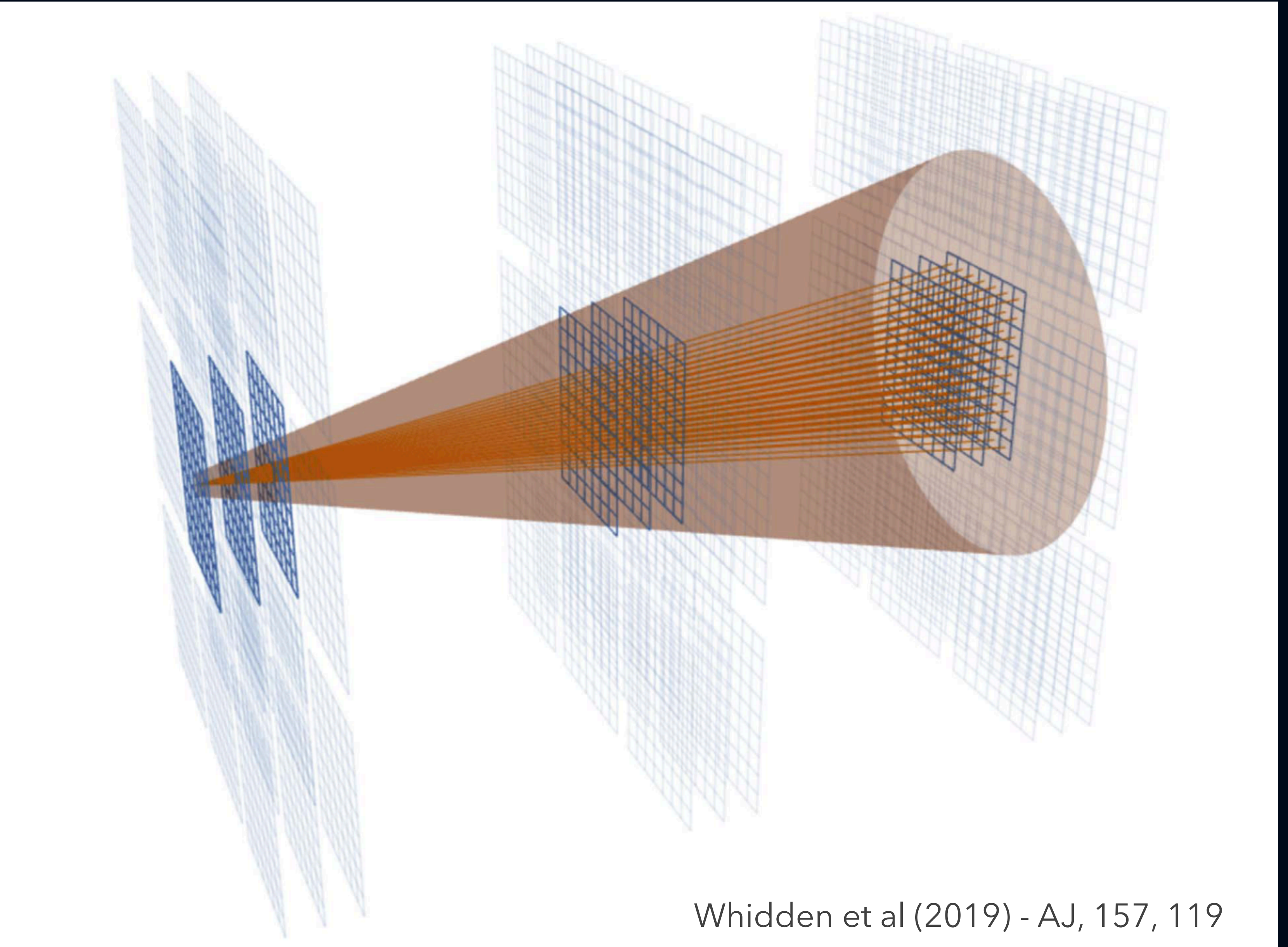
Blue



$\mathrm{STS} \sim 0$

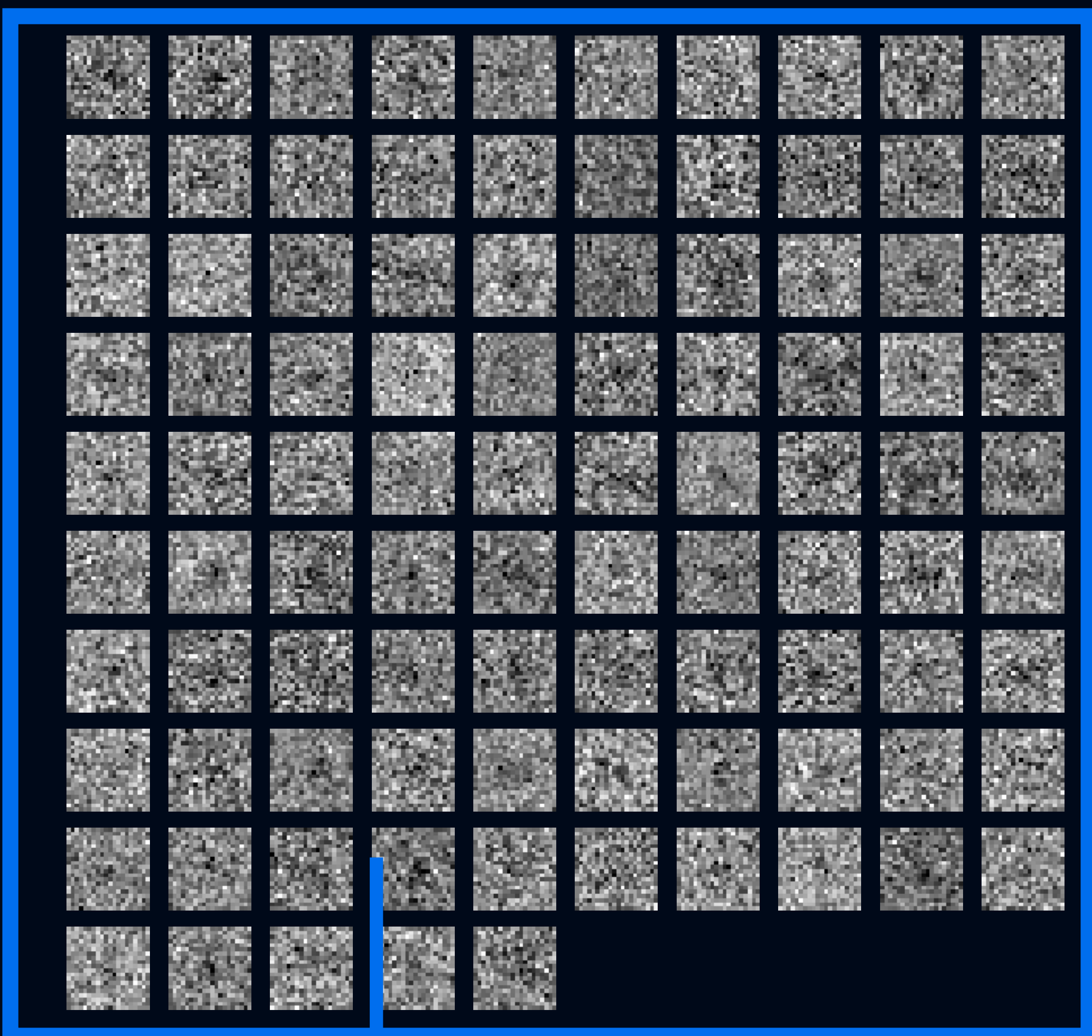
How can we go DEEPer?

- Finding fainter "static" sources:
    - Stack multiple images at the same spot
    - Take longer exposures
- Why doesn't this work for Solar System objects? Objects move (stacks don't immediately help) and trail (longer exposures aren't that useful)
- Solution: **shift and stack**
    - Dozens of high cadence images are stacked along all physically reasonable trajectories

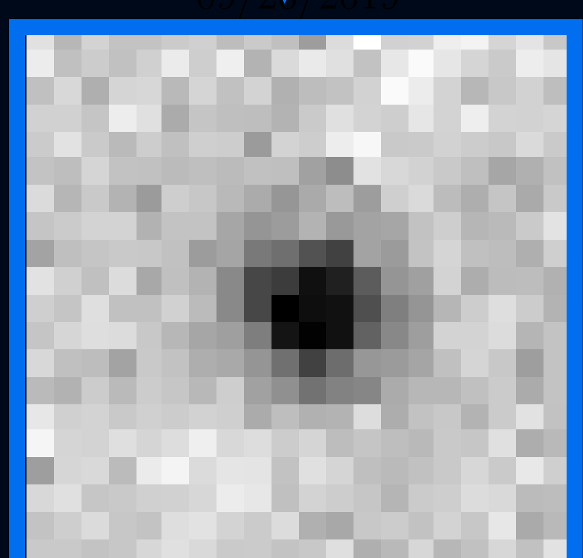


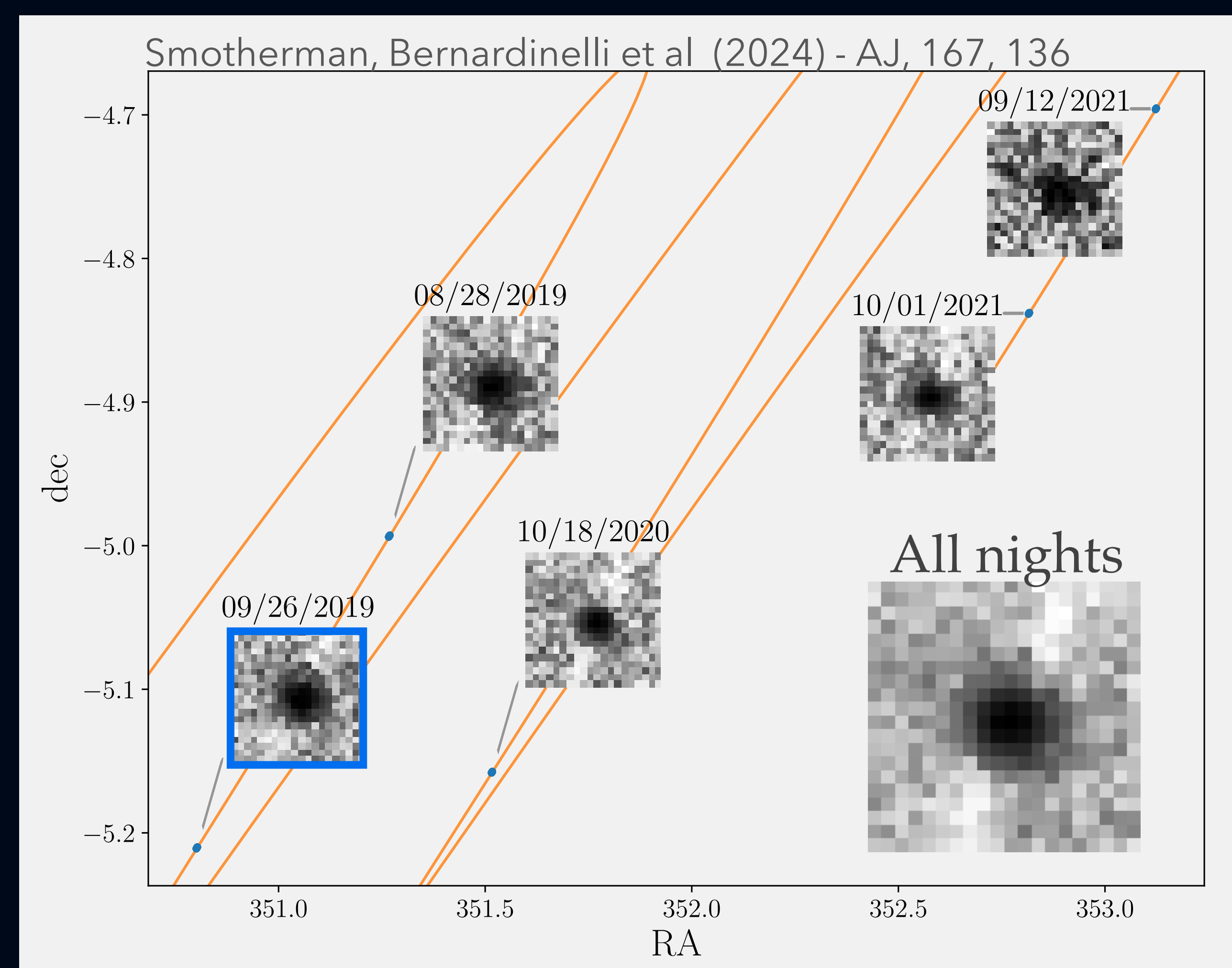
Whidden et al (2019) - AJ, 157, 119

The DEEP survey



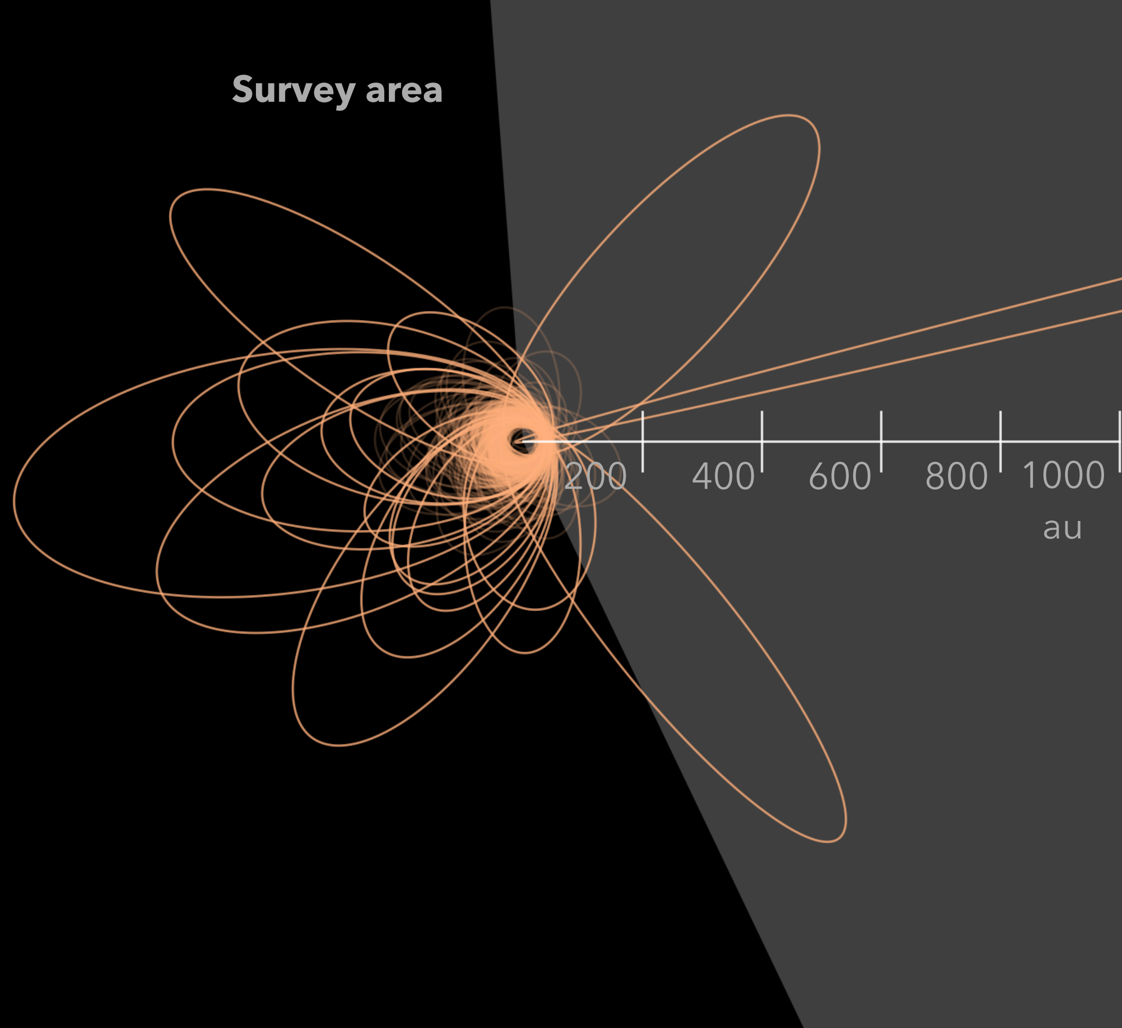
- 90-100 images of the same field in a span of 4 hours
- CNN acts as a “real”/“false” identifier, ~20k candidates vetoed by
- Objects repeatedly found across multiple years enable detailed dynamical characterization
- First multi-year results: sample of 110 TNOs





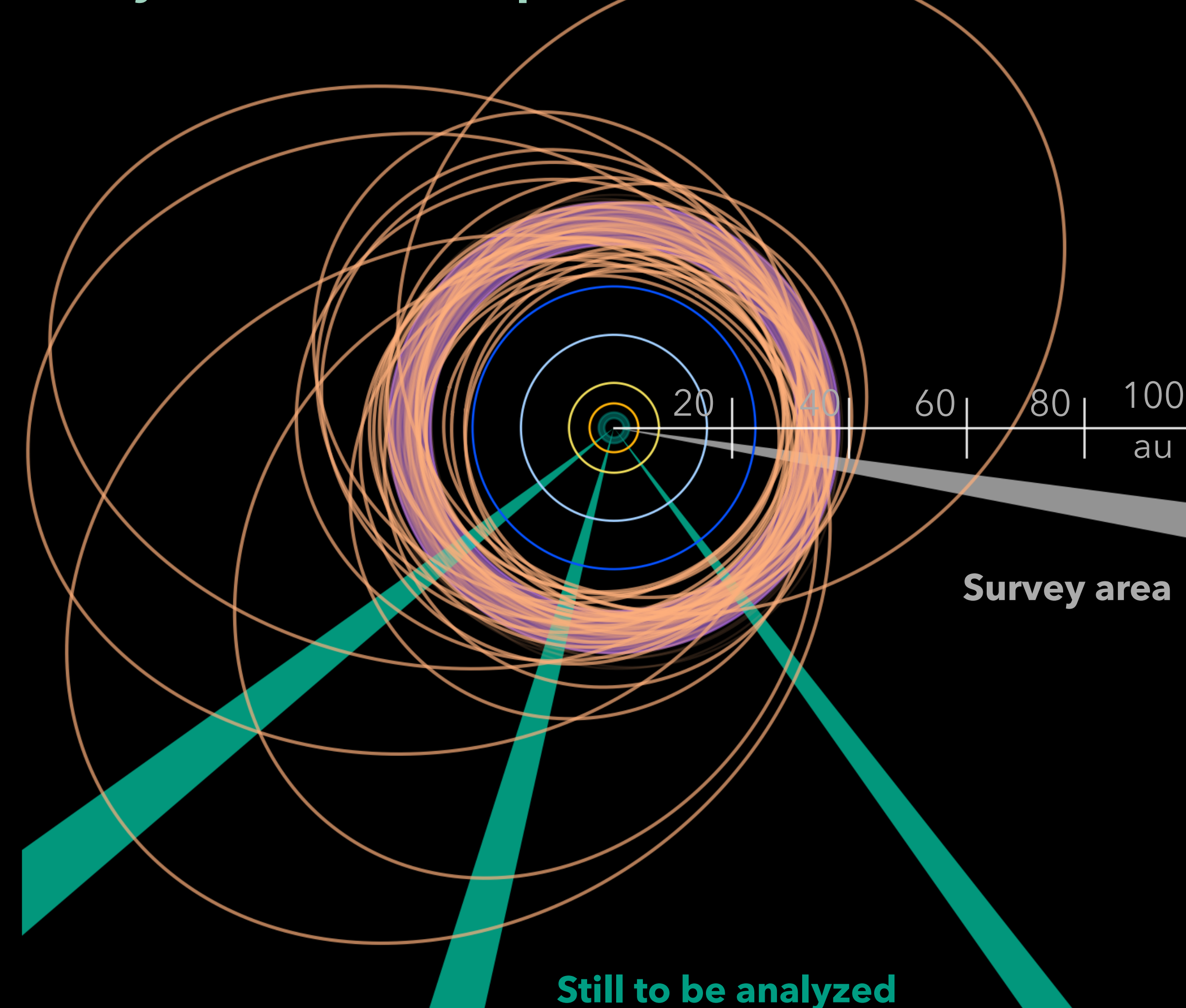
THE DARK ENERGY SURVEY

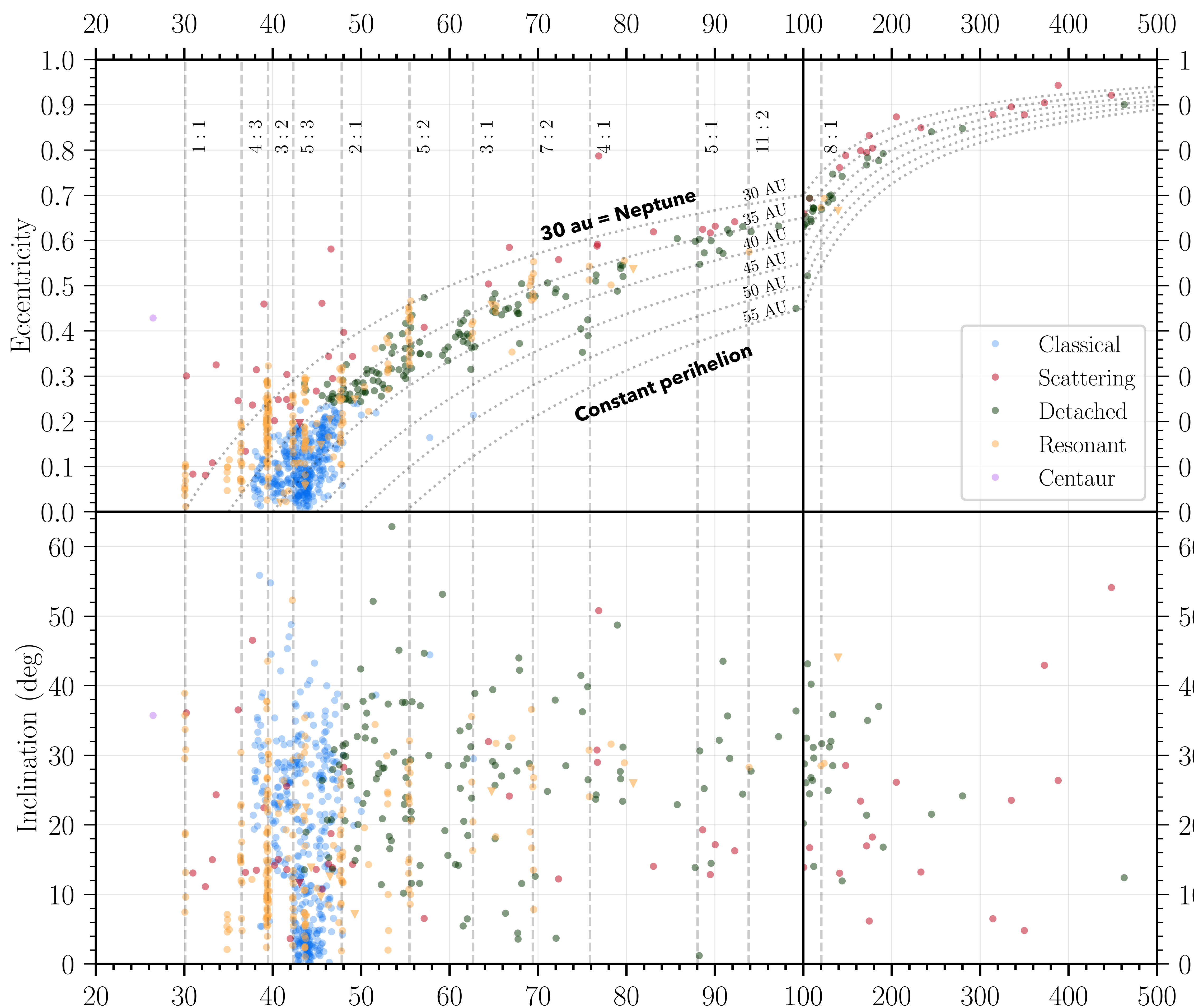
- **814 objects, dynamical diversity due to off-ecliptic coverage**
  - **Second largest TNO survey (largest has 818 objects!)**
- **50% completeness at $m_r \sim 23.8$, so typical object has $H_r \approx 7$ (roughly 150 km)**



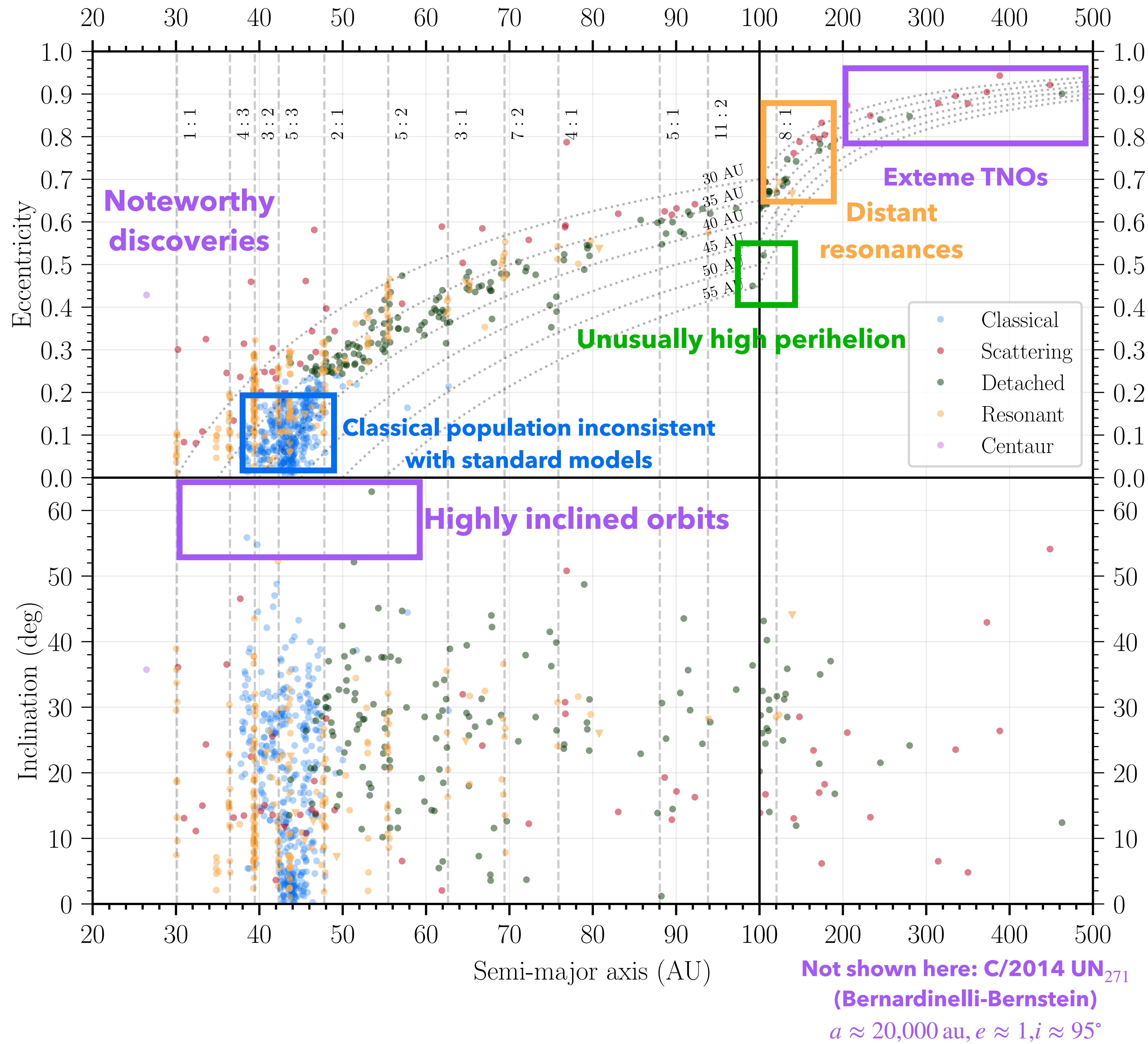
DECAM ECLIPTIC EXPLORATION PROJECT

- **110 objects, mostly cold Classicals as fields are centered in the ecliptic plane and close to Neptune's longitude**
- **50% completeness at $m_{VR} \sim 26.0$, typical object has $H_{VR} \approx 9$ (roughly 50 km)**
- **Only 1/6 of the data processed!**

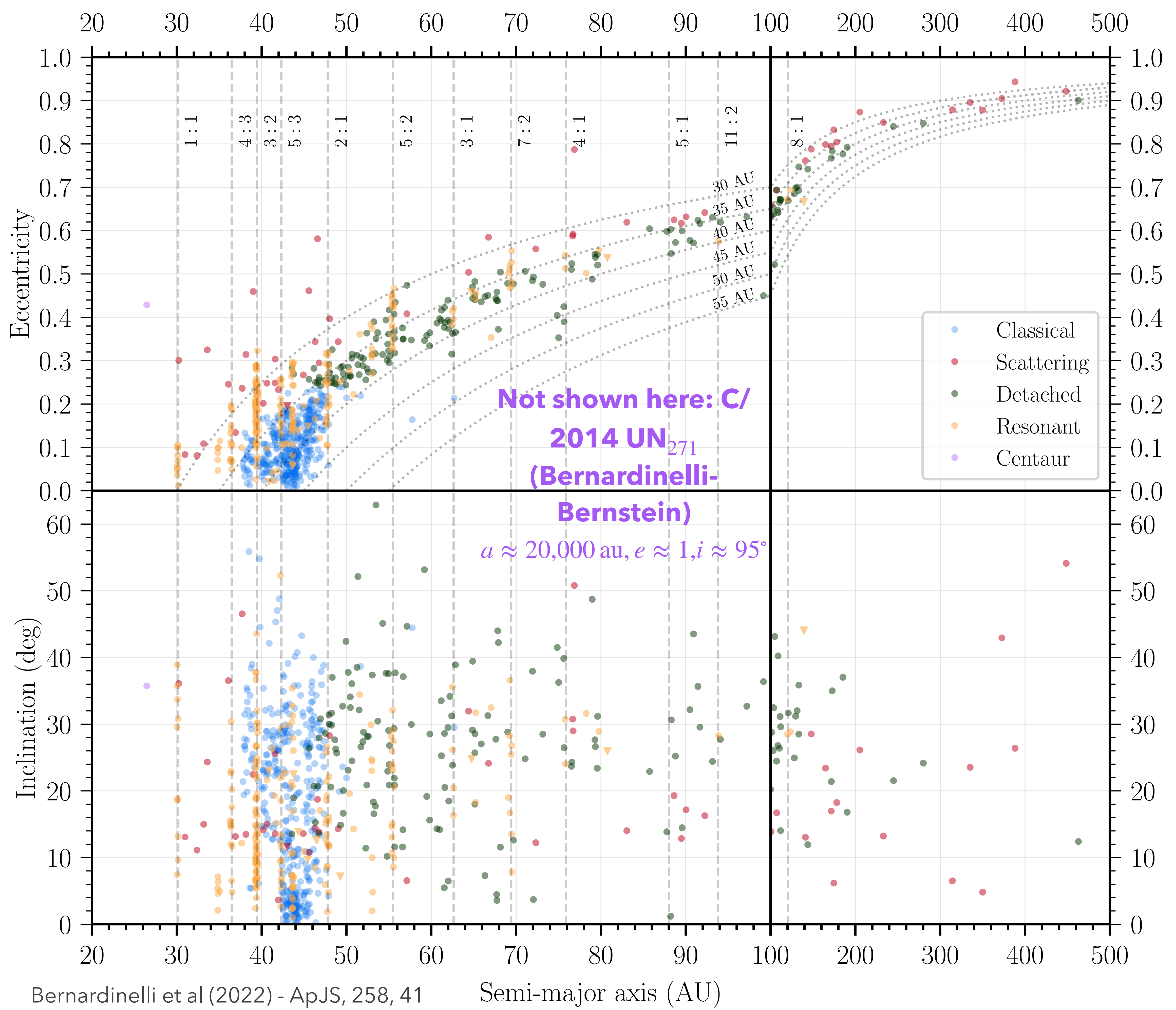




Bernardinelli et al (2022) - ApJS, 258, 41



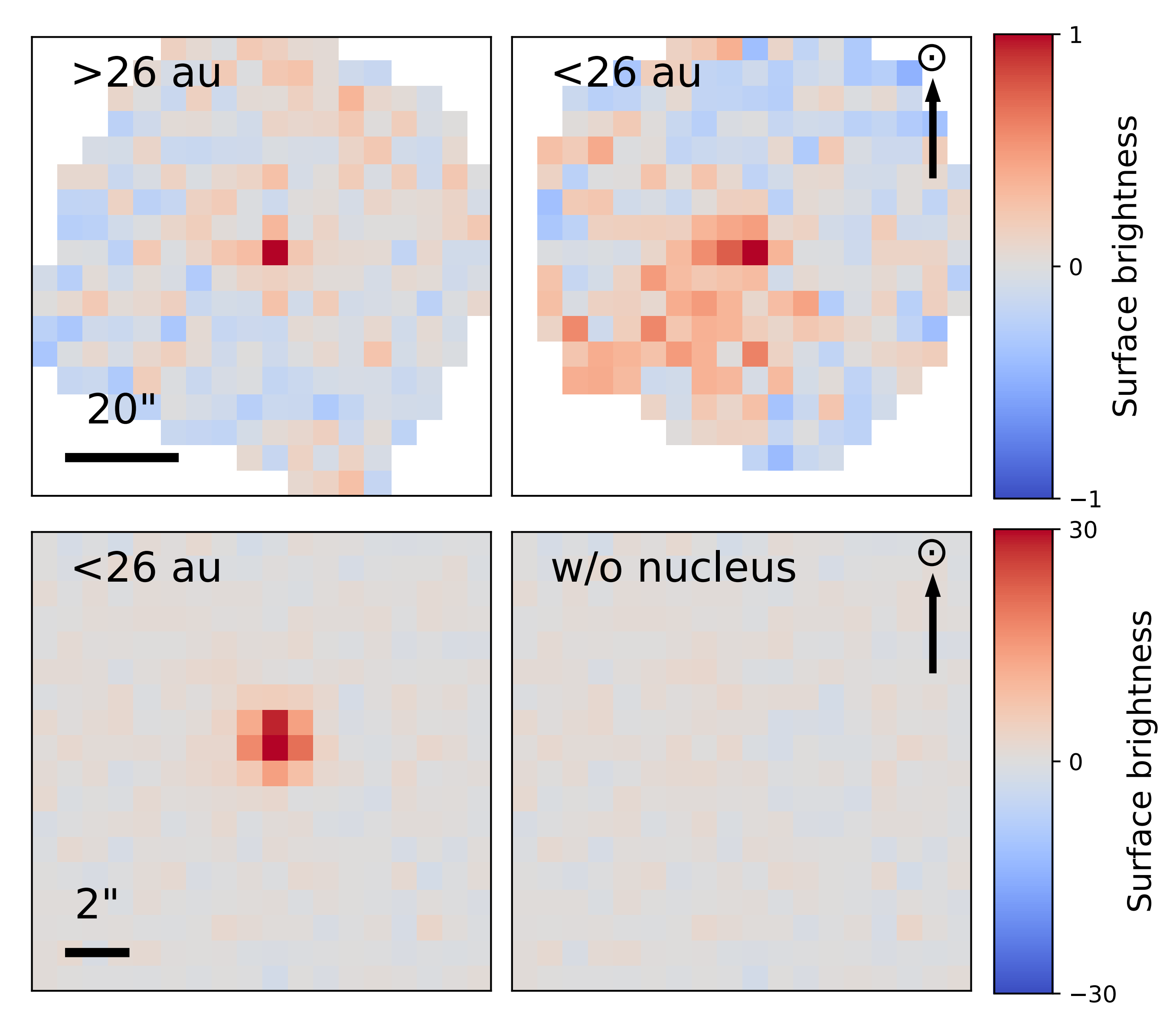
Noteworthy discoveries
Exteme TNOs
Distant resonances
Unusually high perihelion
Classical population inconsistent with standard models
Highly inclined orbits
Classical
Scattering
Detached
Resonant
Centaur
1 : 1
4 : 3
3 : 2
5 : 3
2 : 1
5 : 2
3 : 1
7 : 2
4 : 1
5 : 1
11 : 2
8 : 1
30 AU
35 AU
40 AU
45 AU
50 AU
55 AU
Eccentricity
Inclination (deg)
Semi-major axis (AU)
Not shown here: C/2014 UN271
(Bernardinelli-Bernstein)
$a \approx 20{,}000$ au, $e \approx 1$, $i \approx 95°$



Bernardinelli et al (2022) - ApJS, 258, 41

C/2014 UN271: 💎

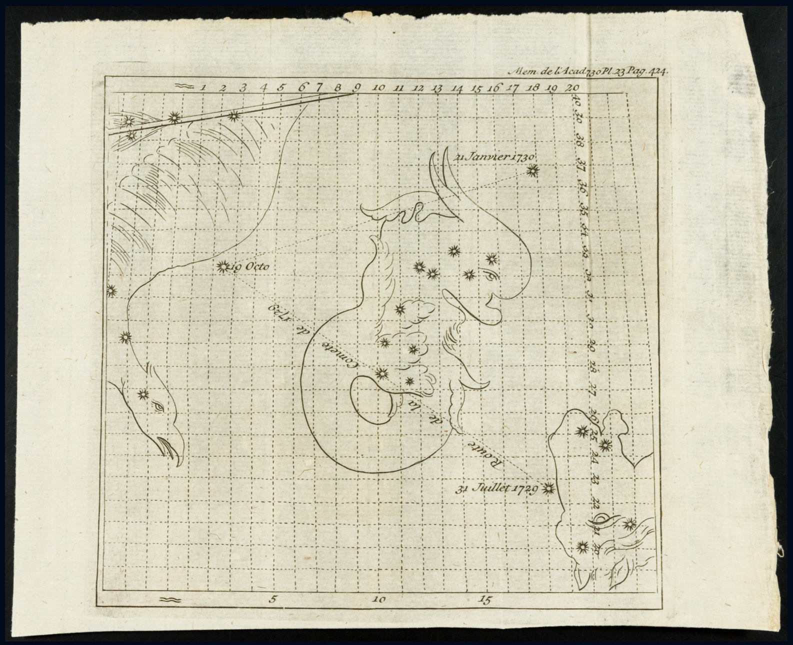
- Orbit clearly representative of an Oort Cloud comet
- Absolute magnitude $H_r \approx 8.0 \implies D \approx 155\,\mathrm{km}$, later confirmed with ALMA thermal measurement ($D = 137 \pm 17\,\mathrm{km}$, Lellouch et al 2022)
- Coma starts to develop at $26\,\mathrm{au}$ with surface brightness: $30\,\mathrm{mag/arcsec}^2$ (in even more esoteric units: $0.004\,e^{-}/\mathrm{sec/pixel!}$)



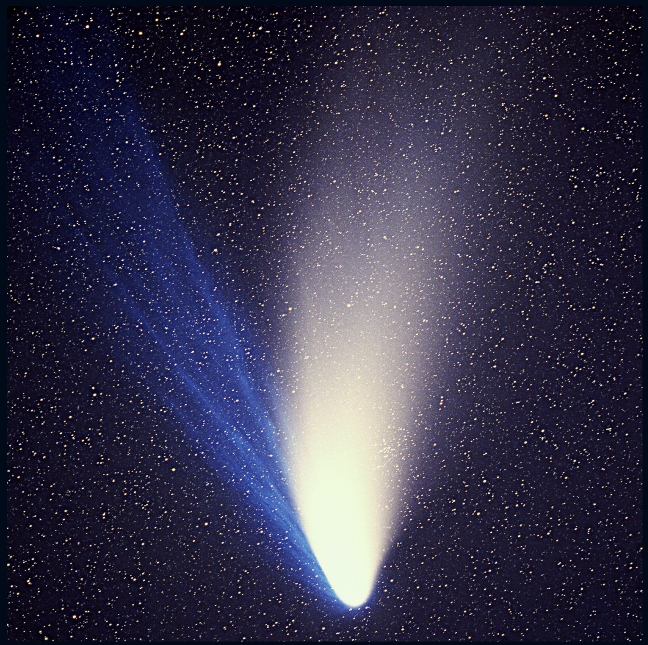
Bernardinelli et al (2021) - ApJL, 921, L37

Why is this a big deal?

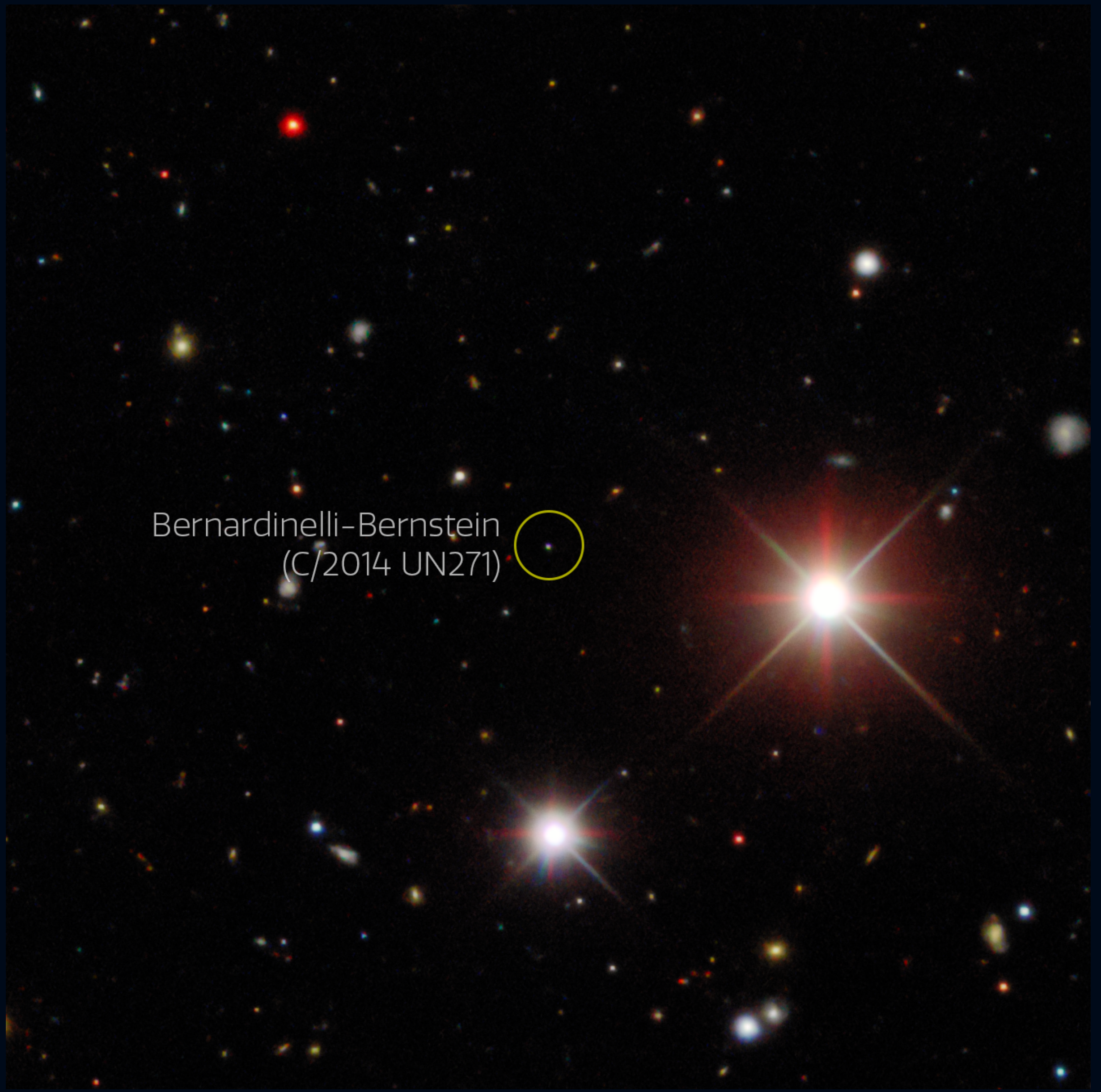
- Comets are usually found at distances $d < 15$ au
- Only 2 comets before BB have shown activity farther than 20 au from the Sun (C/2017 K2: 24 au; C/2010 U3: 26 au)
- Comets usually have diameters < 10 km, last ~100km long period comet was discovered ~300 years ago



C/1729 P1 (Sarabat): 100km???



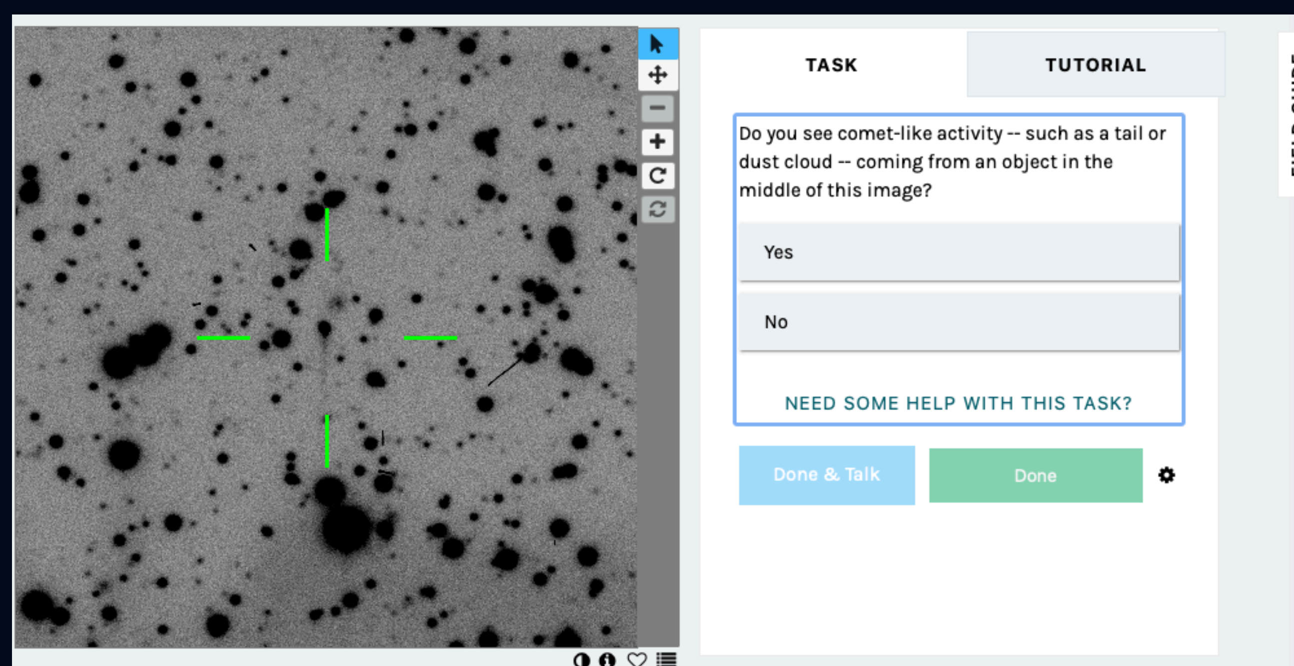
C/1995 O1 (Hale-Bopp): 60km

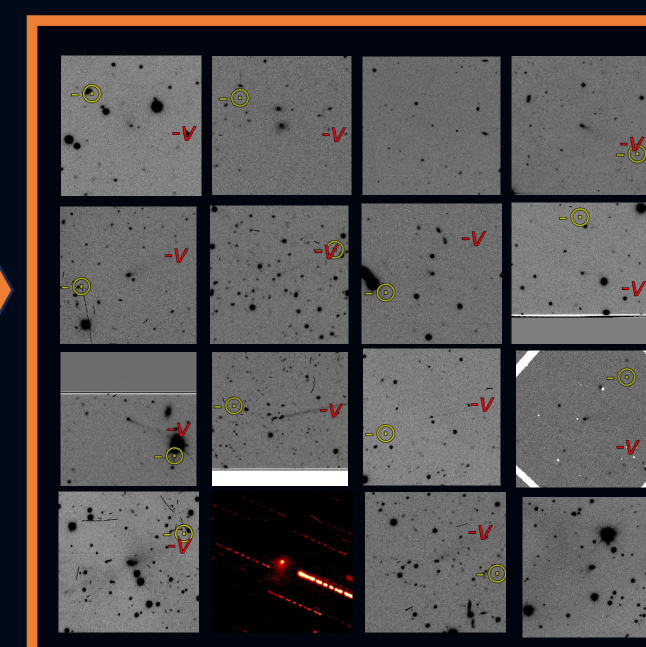


C/2014 UN_{271}(B-B): 137km

What other active objects are hidden in survey data?

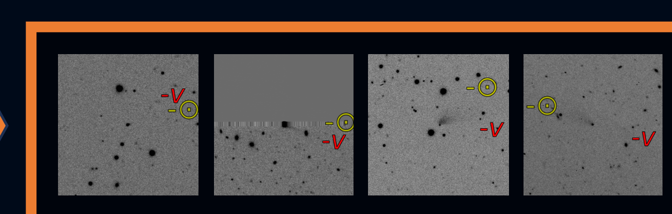
- Active Asteroids citizen science project (Chandler et al 2024) to identify active asteroids in public DECam data
- TailNet0: CNN-based classifier (Sedaghat et al 2024 for first discoveries)
- 25+ new active asteroids identified





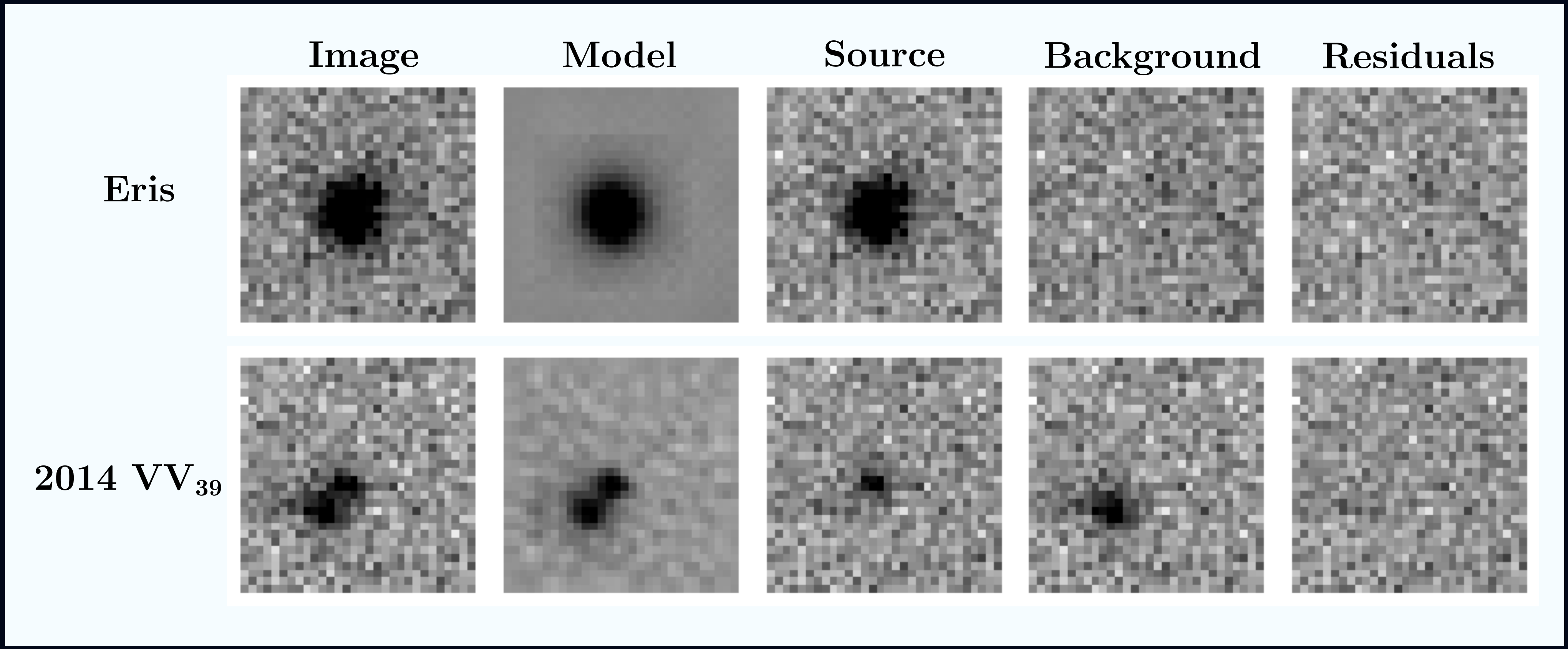
www.activeasteroids.net

TailNet0 Prototype AI Assistant

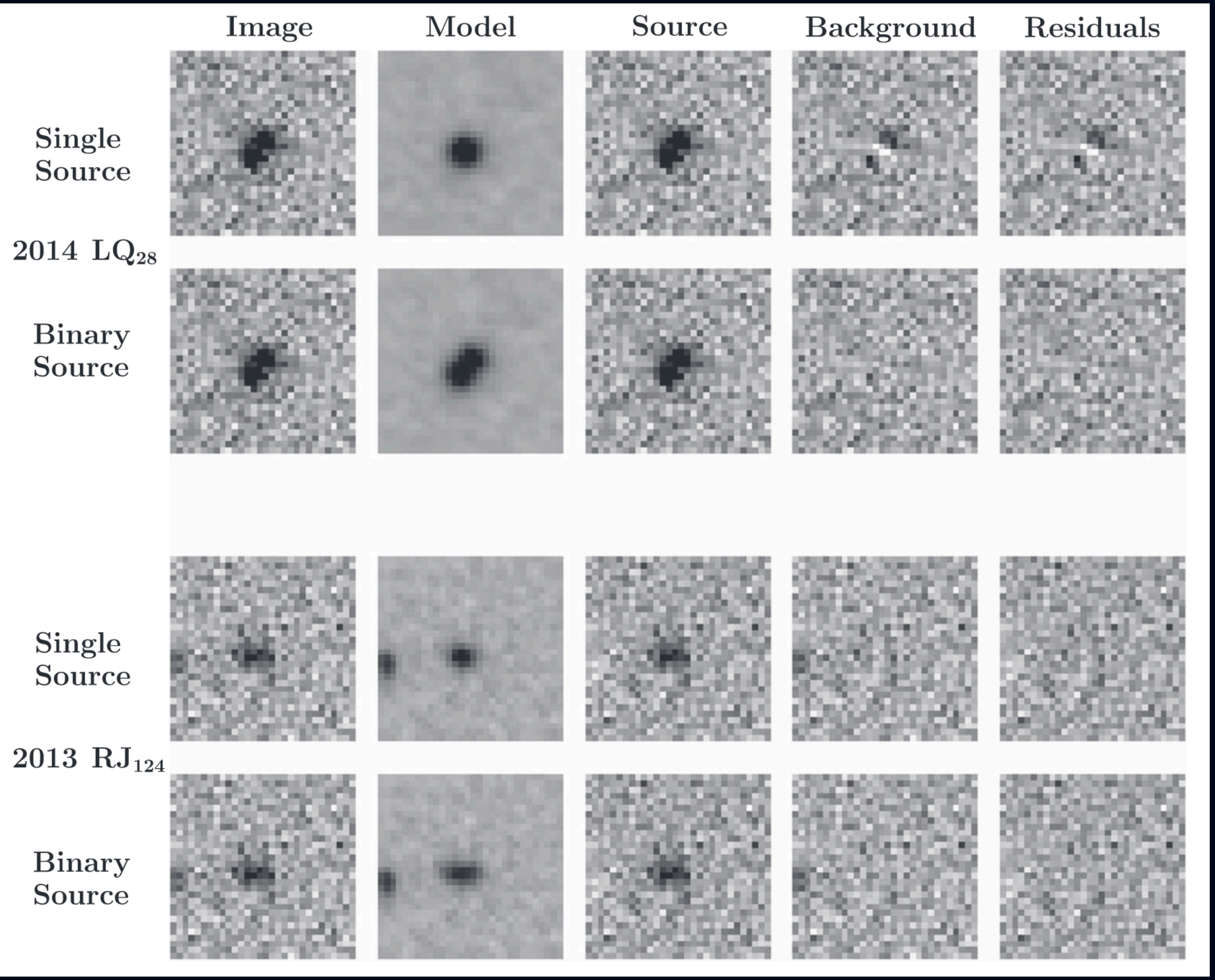


Going back to TNOs… let's talk about photometry!

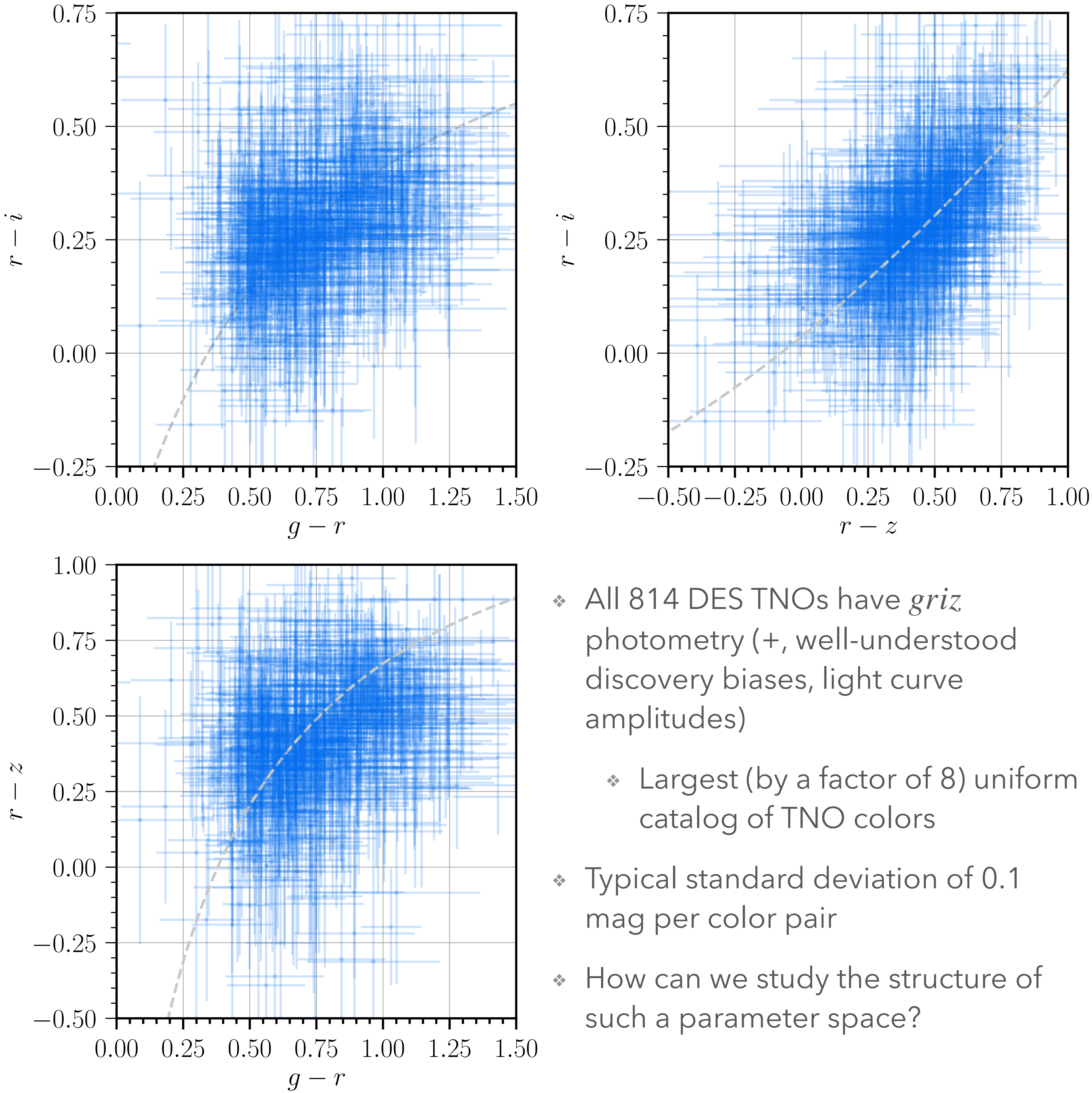
- Scene modeling photometry (SMP):
  - Optimal flux measurements in presence of background sources
  - Bonus: forced photometry of subthreshold TNOs, required for lightcurve amplitude estimation
- Mosaic of background sources and target source: with known positions, the solution is linear and can use all exposures in region around target



Bernardinelli et al (2023) - ApJS, 269,18

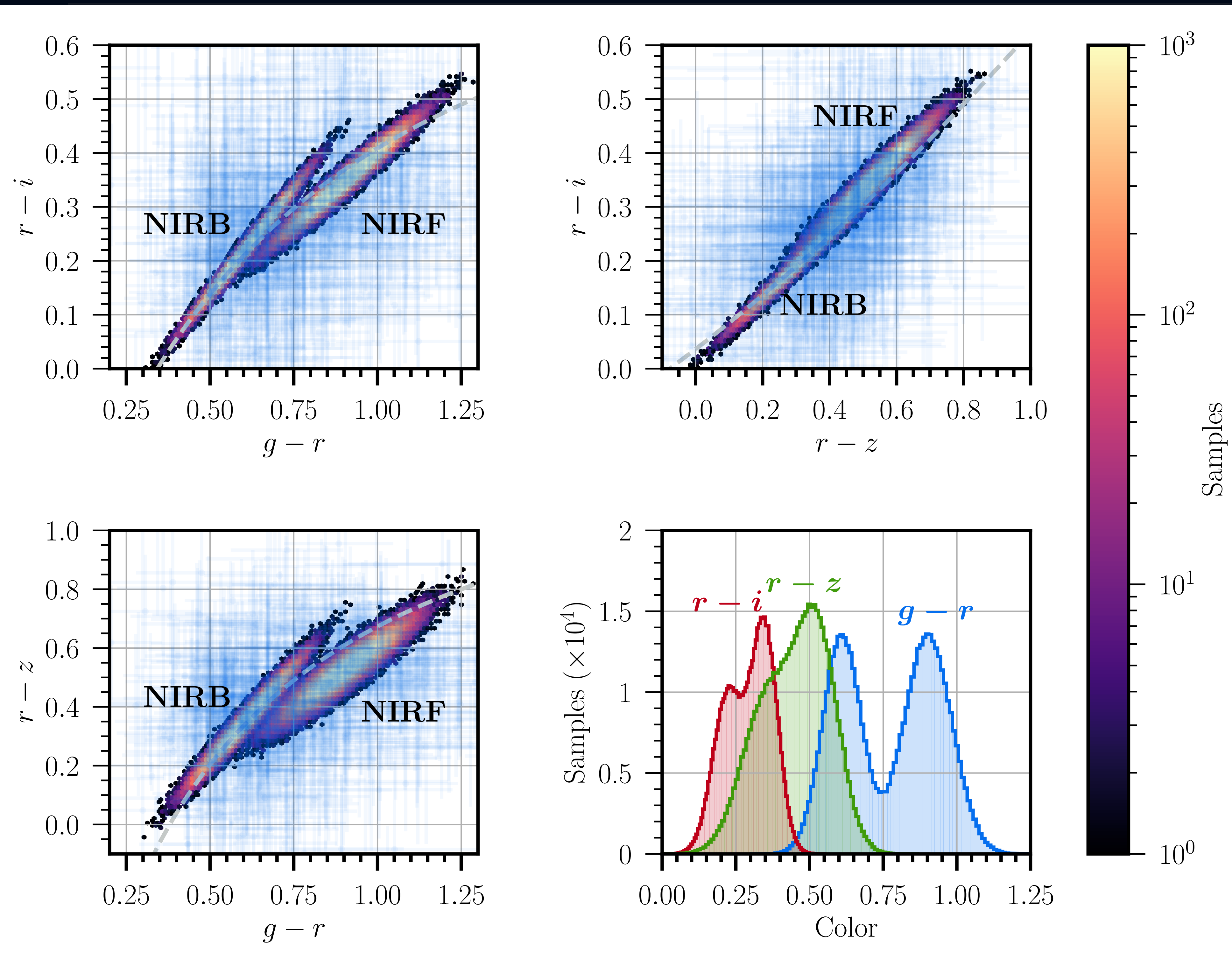


- SMP can be extended to fit multiple sources (and their relative positions) instead of one, solution decouples relative positions from fluxes
- Improvement in model χ^2 can determine if object is binary, SMP accounts for potential confusion due to static source
- Application to DES data leads to two new wide binary discoveries



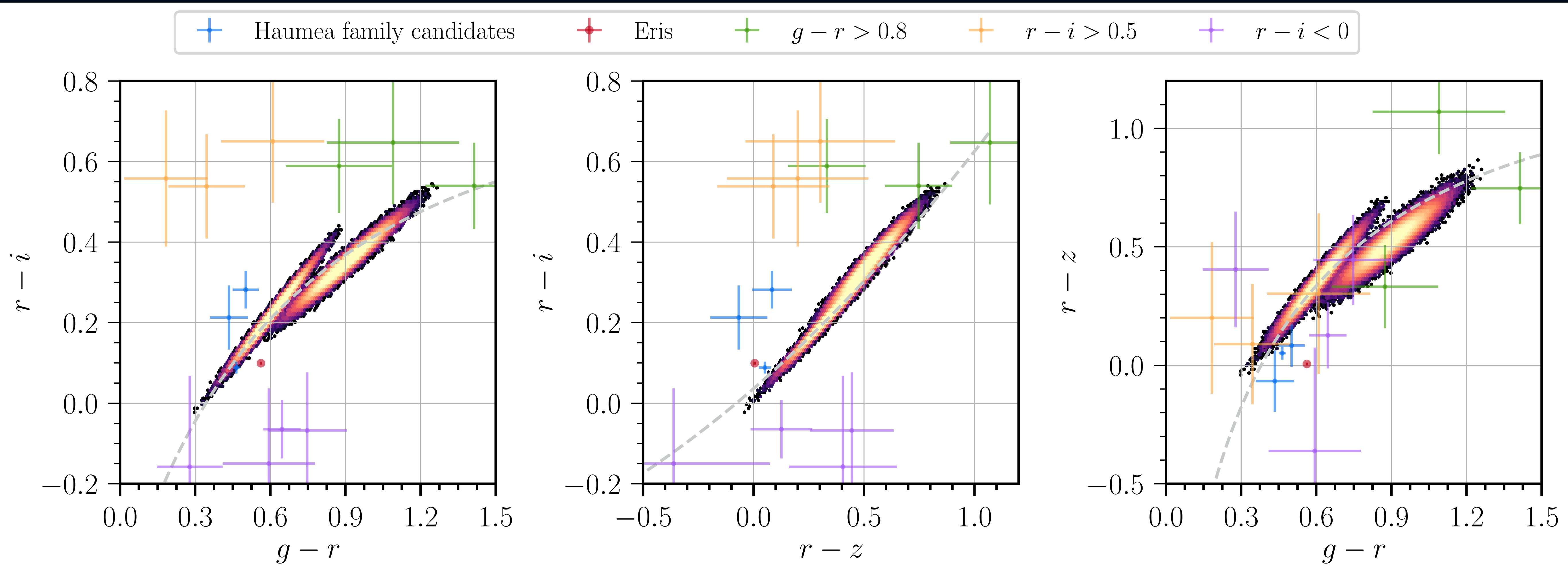
- All 814 DES TNOs have *griz* photometry (+, well-understood discovery biases, light curve amplitudes)
    - Largest (by a factor of 8) uniform catalog of TNO colors
- Typical standard deviation of 0.1 mag per color pair
- How can we study the structure of such a parameter space?

Solution: Gaussian mixture models



- Training procedure is aware of data uncertainties, selection functions and **does not require the number of components to be defined a priori**
  - Model starts with a very high number of components that get annihilated if they do not contribute to model
  - Resulting model automatically determines the optimal number of color classes needed to describe the data
- Two component model: “blue” (NIRB) and "red" (NIRF) TNOs occupying distinct color loci

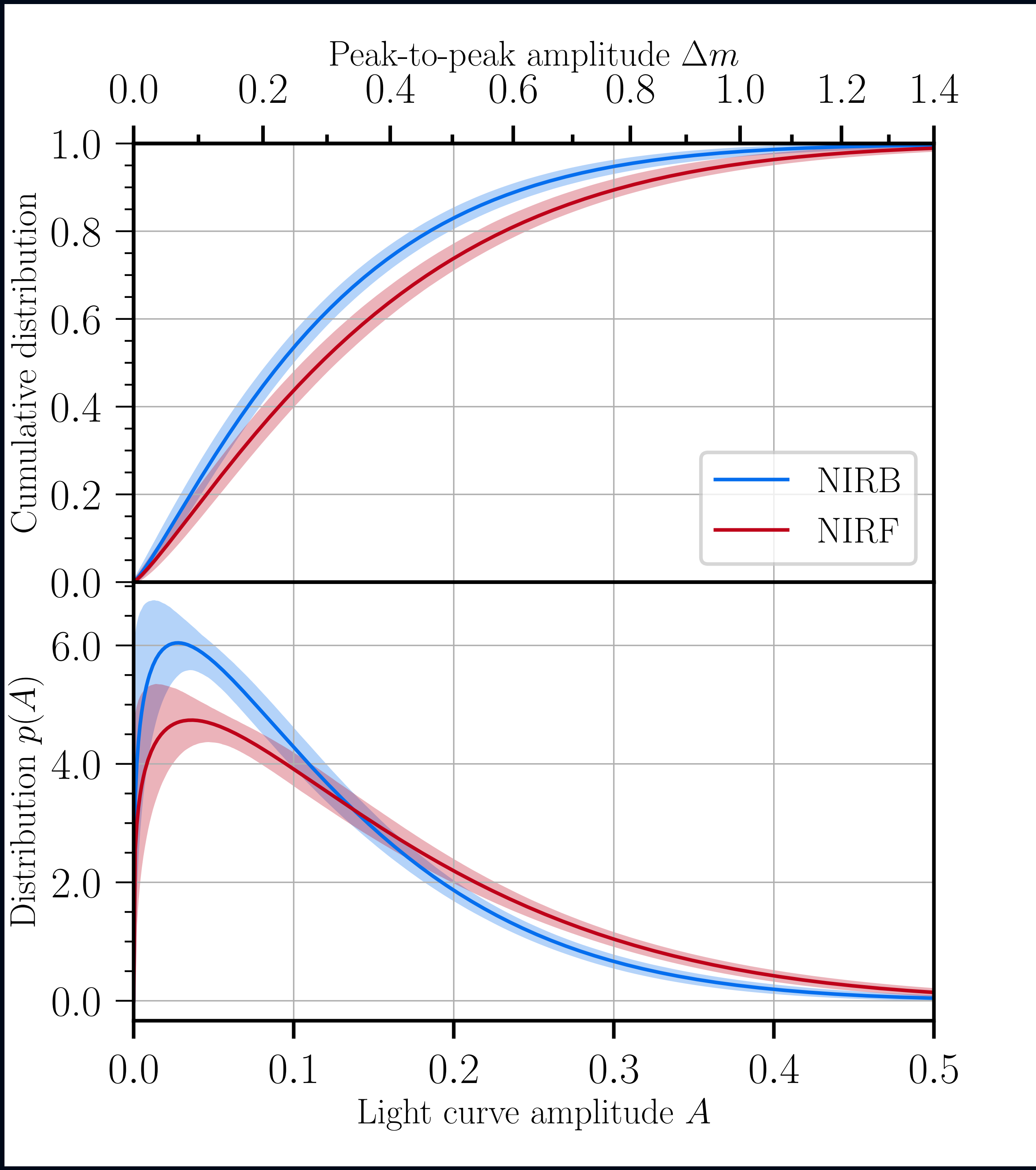
But not everything fits the model..



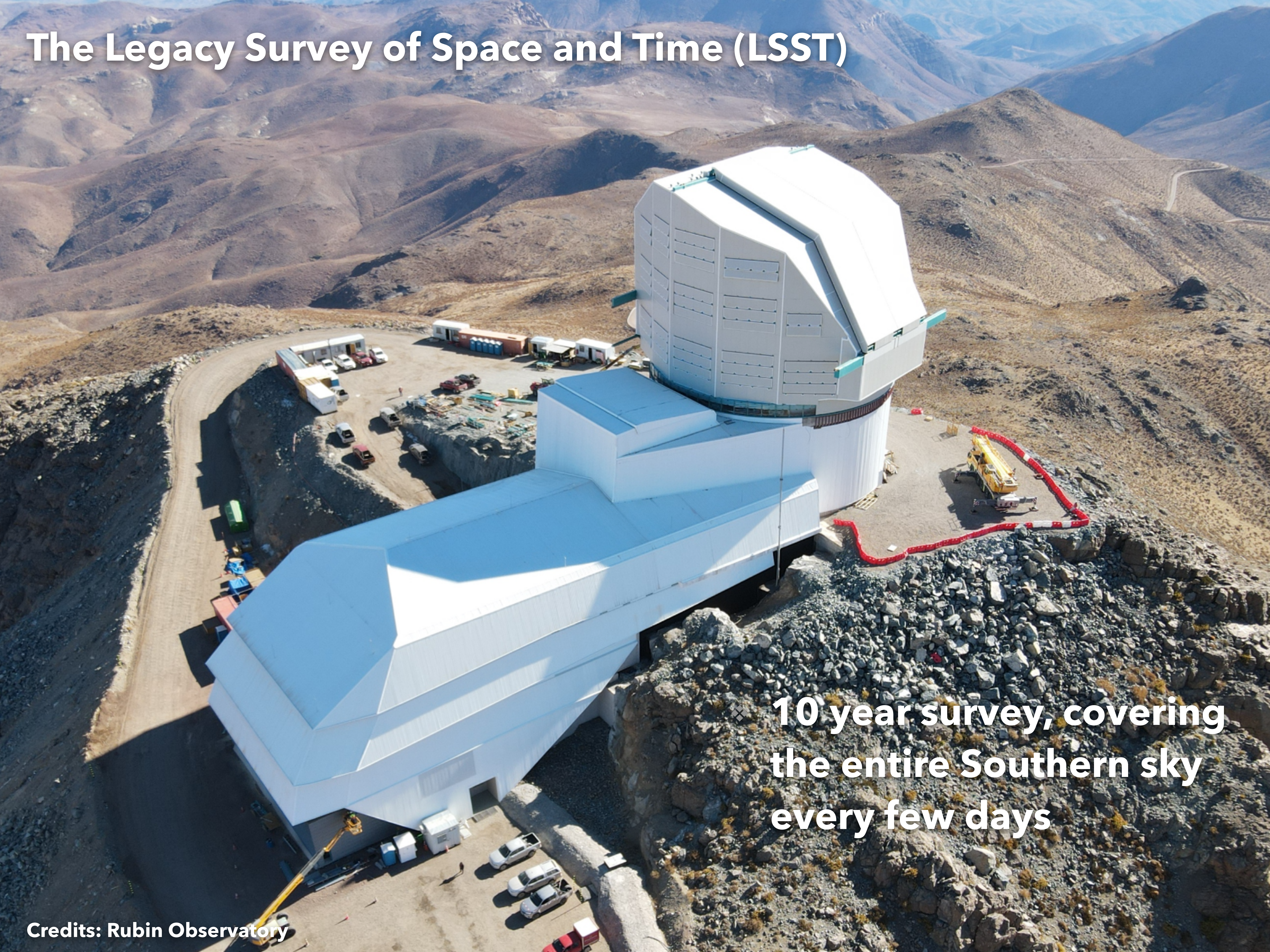
- Color outliers ($\geq 3\sigma$ from both components, expect ~1in 800+ objects) require another explanation
- Collisional families (blue points), dwarf planets (red), poor measurements, or transplants from another Solar System region?

Mixture of physical families

- With fixed GMM components, adding other parameters to mixture model allows probabilistic analysis of color dependent effects
- Example: red TNOs are more variable than blue TNOs
  - Red TNOs are more elliptical or have a higher rate of contact binaries
- And lots of other fascinating effects: color dependent size or inclination distributions, color occupation per class, ….



The Legacy Survey of Space and Time (LSST)



10 year survey, covering the entire Southern sky every few days

Credits: Rubin Observatory

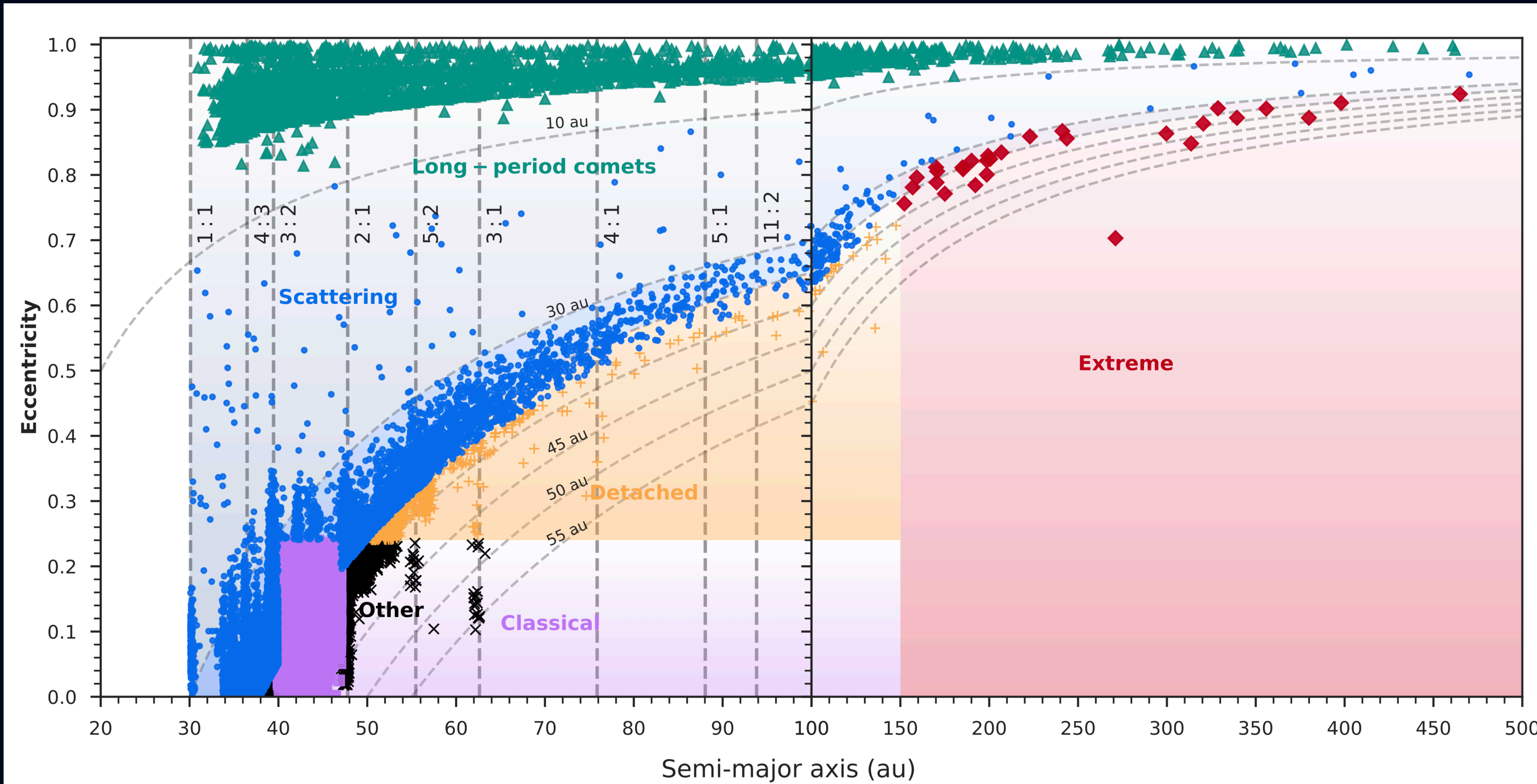


Figure credits: A. Plazas Malagón, Rubin CST

- Simulated catalog of TNO discoveries after 10 years of Rubin operations, part of the Rubin Data Preview 0.3: dp0-3.lsst.io (Bernardinelli, Kurlander et al)
- **Density of objects is realistic given Rubin expectations!**

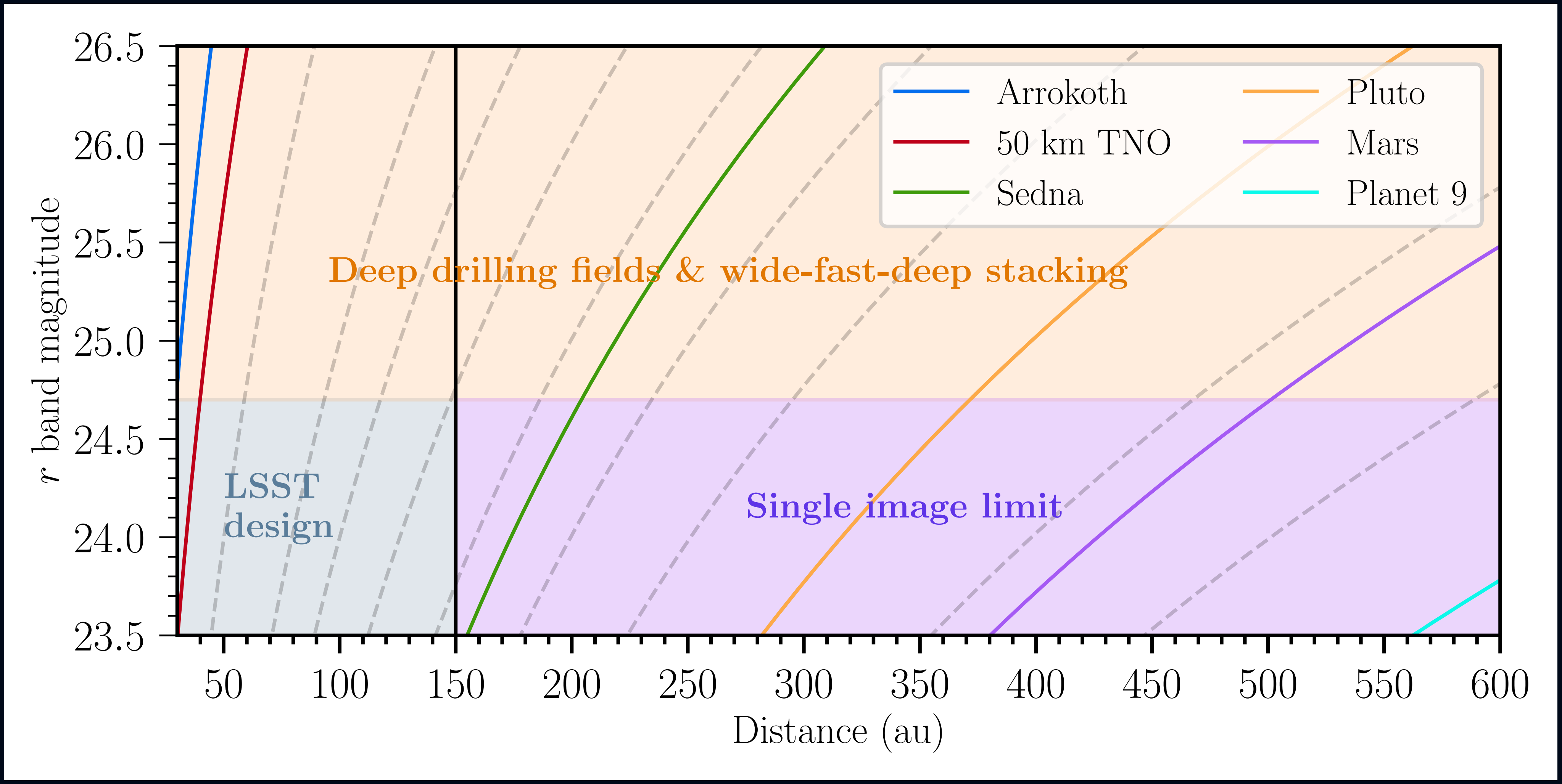
What happens when the Rubin Observatory "turns on"?

Population	Currently known (approximately)	Rubin estimates
Near-Earth objects	20.000	200.000
Main belt asteroids	800.000	6.000.000
Jupiter Trojans	8.000	280.000
Trans-Neptunian objects	**4.000**	**40.000**
Comets	4.000	10.000
Distant comets	**4**	**20?**
Interstellar objects	2	10?
Planets beyond Neptune	**0**	**????????????**

- Virtually all objects will eventually have multi-year orbits, multi-band photometry and several images to be searched for binarity or activity
- The majority of the discoveries will happen in the first year of LSST
- LSST + shift and stack: 100,000 TNOs!

But LSST will not find *everything*

- LSST cadence makes the automated discovery of objects beyond ~150 au challenging: other approaches are needed
- Shift-and-stack over long time baselines (e.g. ~1yr) could substantially increase the object yield
  - **We (as a field) need to think about false positives in both cases**



Summary

- The outer Solar System is full of exotic objects (“rare gems”) that exhibit interesting dynamics, activity, sizes, colors, or formation histories (or all of these!)
- Intense data mining is needed to discover objects even in dedicated surveys (eg DEEP), let alone other datasets (eg DES)
- LSST will be a transformational project for TNO science, but even automated pipelines will not find all objects that will be hiding in the data

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