Solar System Science from the Dark Energy Camera Deep Drilling Field Survey

Steven Stetzler

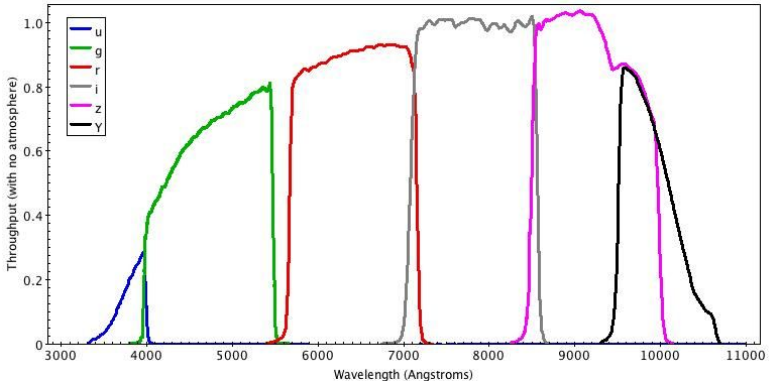
with: Mario Juric, Yasin Chowdhury, Aren Heinze, Melissa Graham

Outline

- The Dark Energy Camera (DECam) and the Deep Drilling Field (DDF) Survey
- The upcoming Legacy Survey of Space and Time (LSST)
- Processing image data with the LSST Science Pipelines
- Solar system science: discovery and characterization of main belt asteroids
- Shift-and-stack for faint object detection: towards discovery of Planet IX in the first year of LSST data

Dark Energy Camera (DECam)

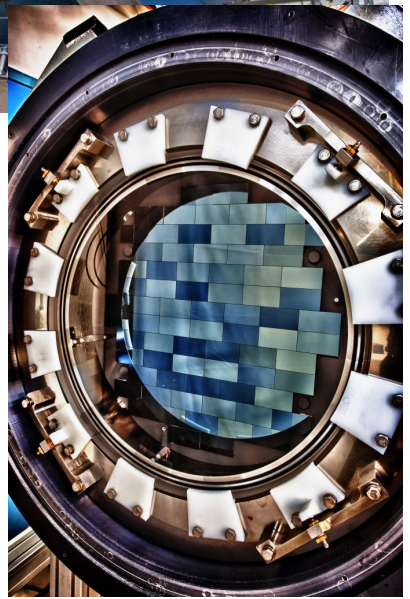
- Mounted on the 4m Blanco telescope in Chile
- Camera composed of 62 2K x 4K CCDs
- In front of the camera, one of several “photometric filters” are placed: g, r, i



violet green

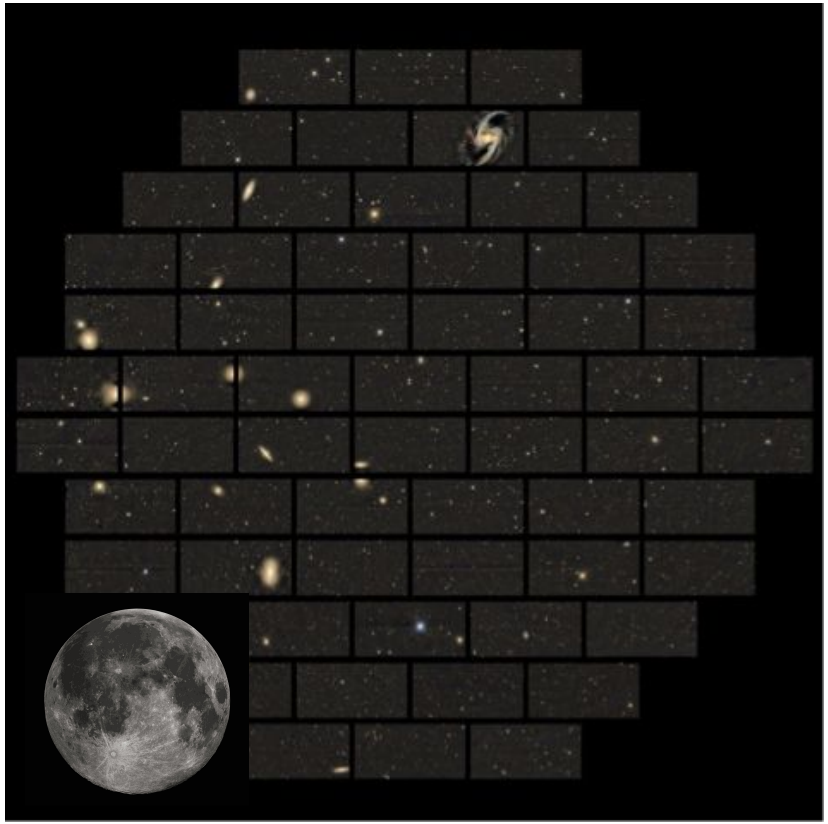
blue red

infrared →



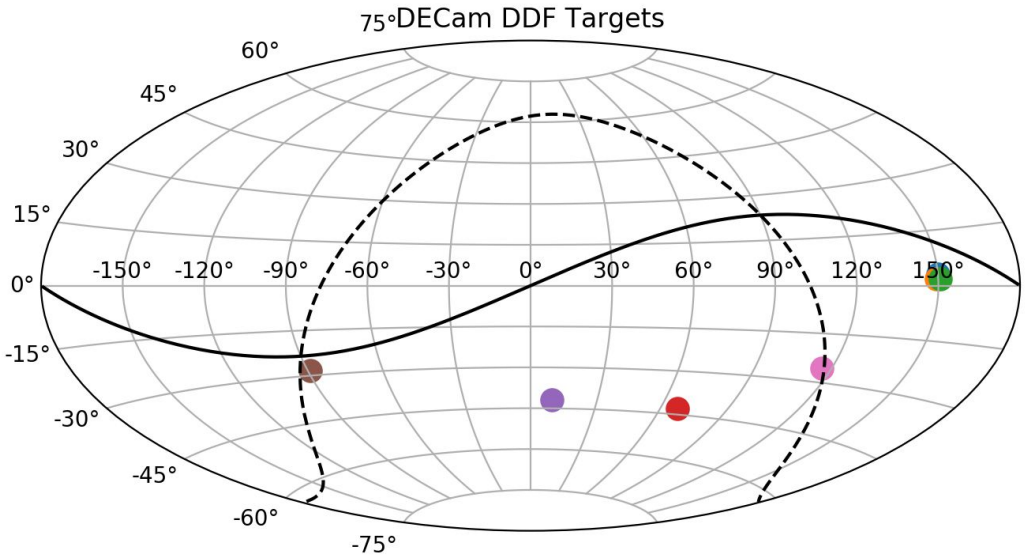
Dark Energy Camera (DECam)

- Mounted on the 4m Blanco telescope in Chile
- Camera composed of 62 2K x 4K CCDs
- In front of the camera, one of several “photometric filters” are placed: g, r, i, z
- A wide field field of view: ~3 deg^2



DECam Deep Drilling Field (DDF) Survey

- 7 regions of the sky observed every 3 nights with 5 exposures in gri+z to r~23.5 from March-June 2021 and still in-progress



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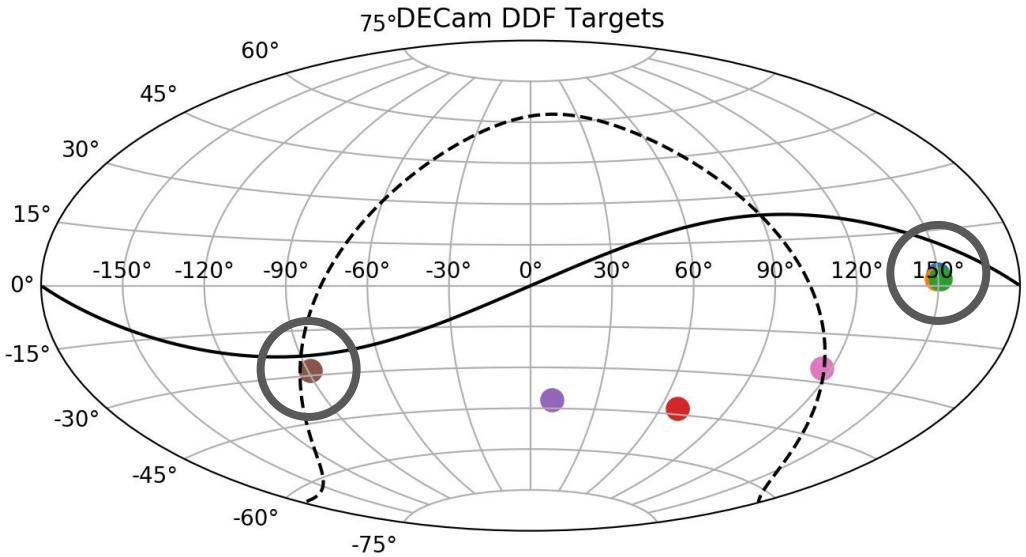
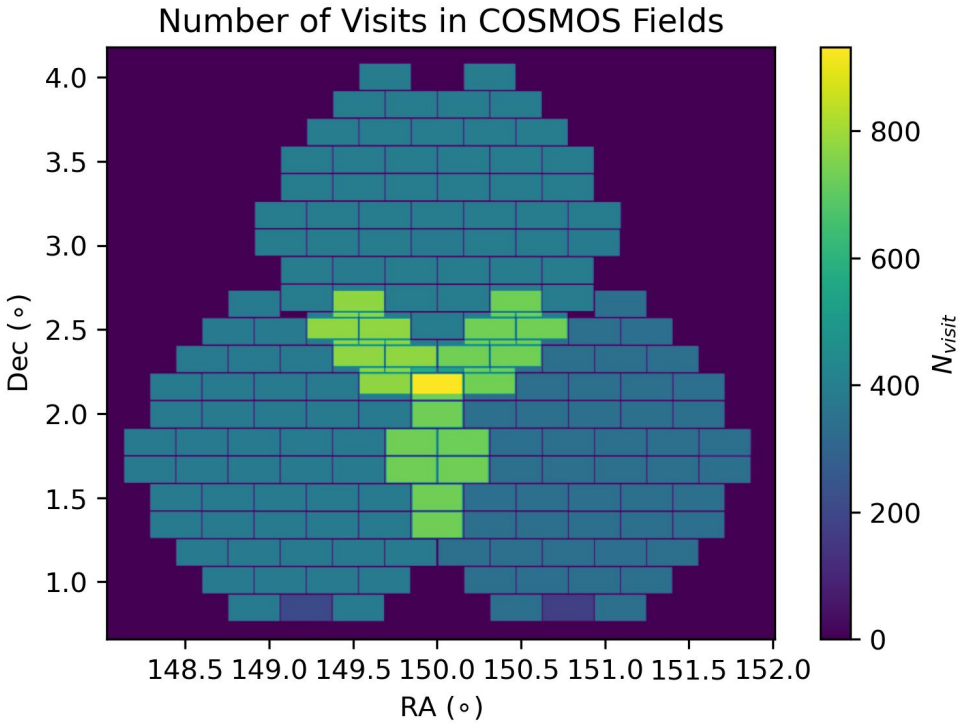


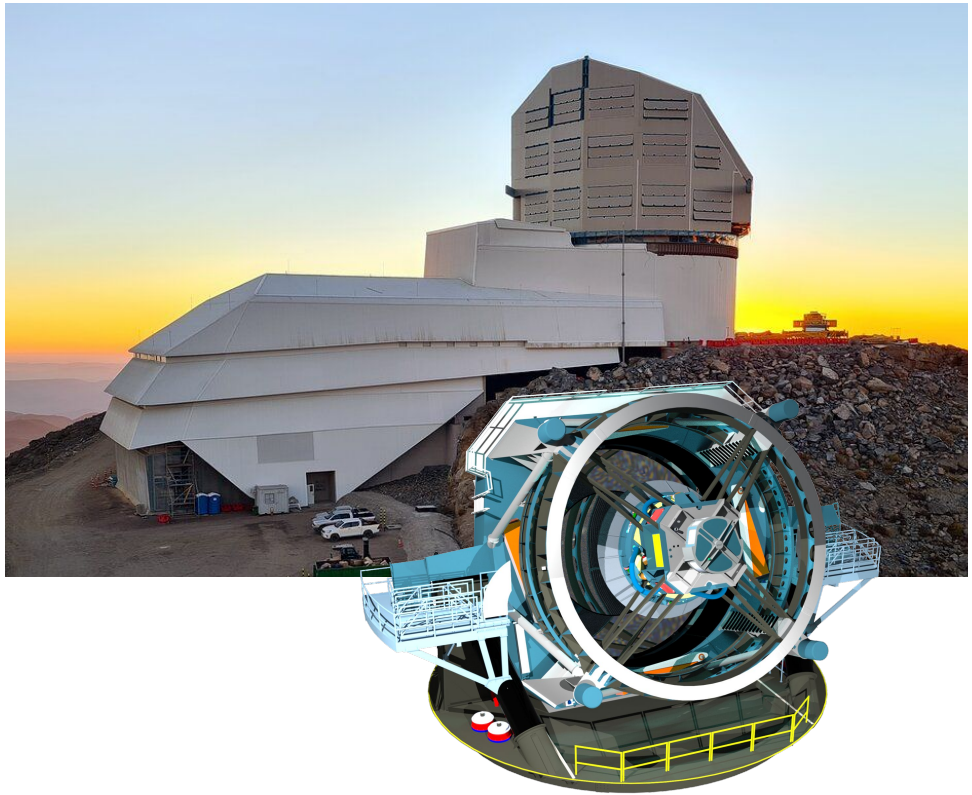
DECam Deep Drilling Field (DDF) Survey

- 7 regions of the sky observed every 3 nights with 5 exposures in gri+z to r~23.5 from March-June 2021 and still in-progress
- 4 pointings on the sky within 10 deg of the ecliptic
- The 300-900 multi-filter images provide a rich dataset for studying variable stars, supernovae and solar system objects



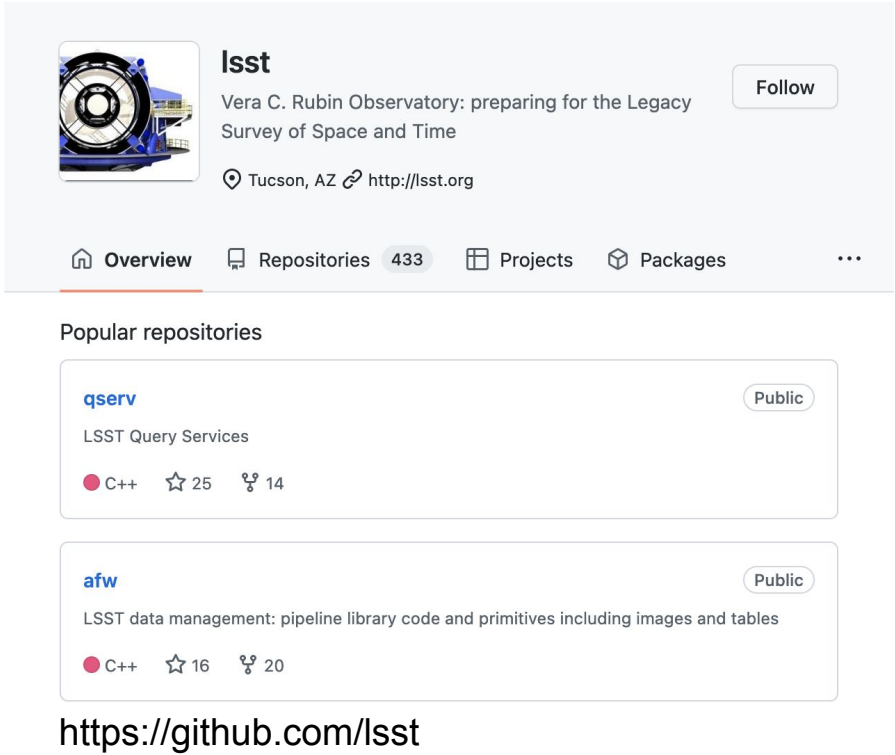
A Precursor to the Legacy Survey of Space and Time

- This survey is a **direct precursor** to the Deep Drilling Fields of the Legacy Survey of Space and Time (LSST), the **next generation survey**. A multi-filter 10-year survey of the entire southern sky
- We are using the DECam DDF dataset to **understand the technical challenges** of processing LSST images and extract **novel solar system science** from them



Data Processing: The LSST Science Pipelines

- Open source image reduction code
- We used the LSST science pipelines to convert ~5TB of raw DECam images to “science ready” images, readying the pipelines for production use on LSST data in ~1-2 years
- Processing scales to 100s of nodes by using distributed computing plugins: HTCondor, Parsl, PanDA

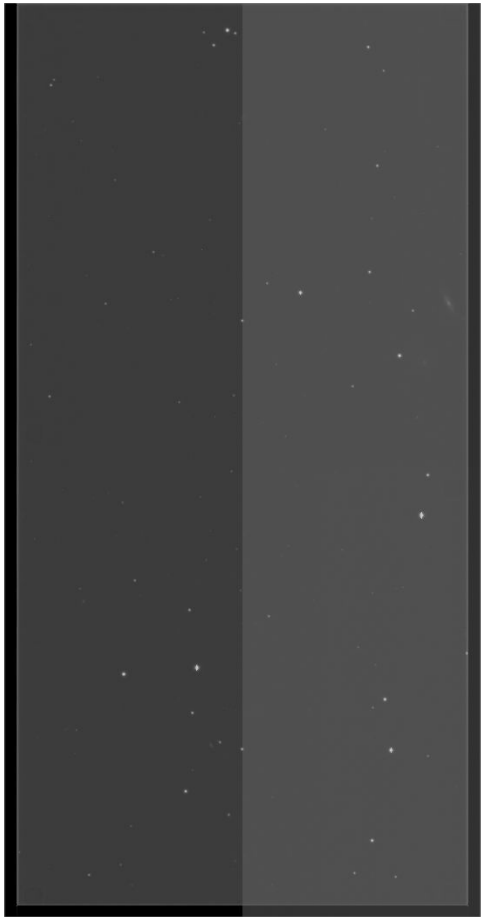


https://github.com/lsst

Data Processing

- Raw images contain signatures of the camera and the observing environment

Raw Image



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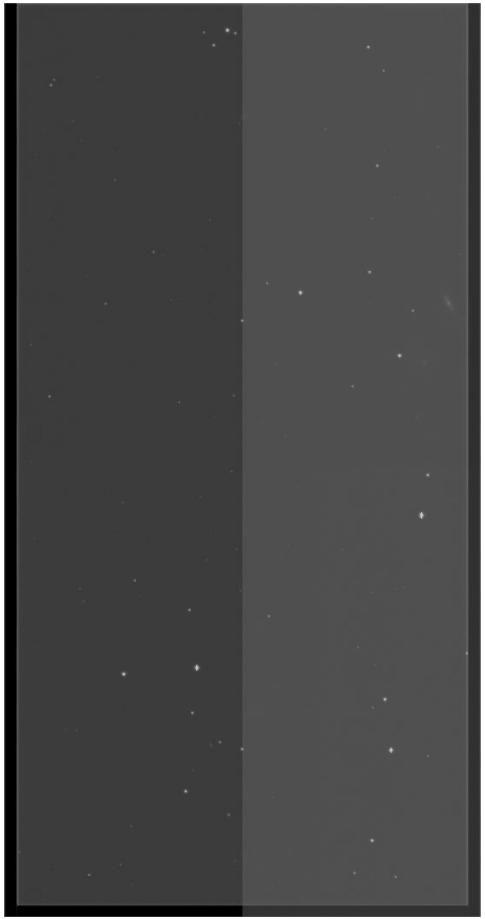

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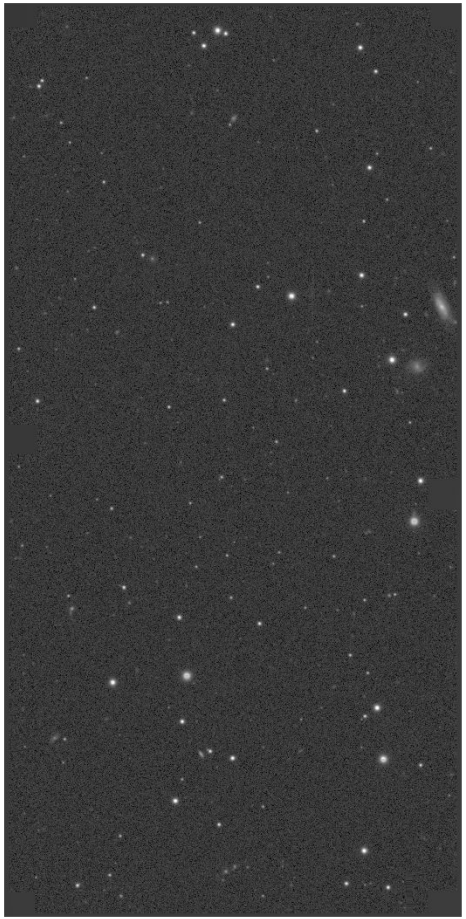

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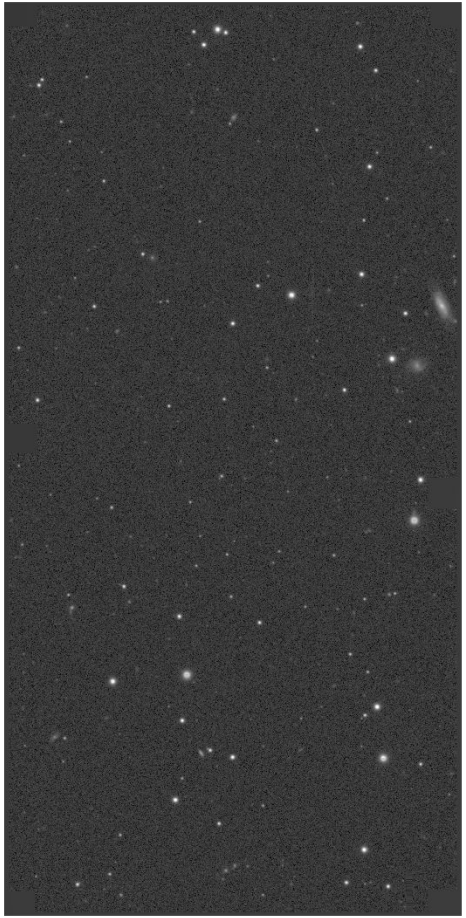
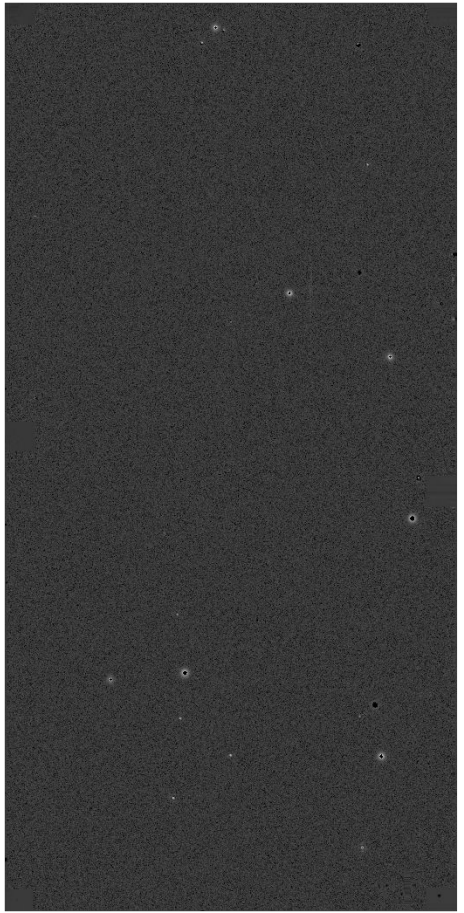
- A model of the sky -- a “template image” -- is subtracted from the calibrated exposure producing a difference image: **variable sources appear in these images**

Calibrated Image



Difference Image



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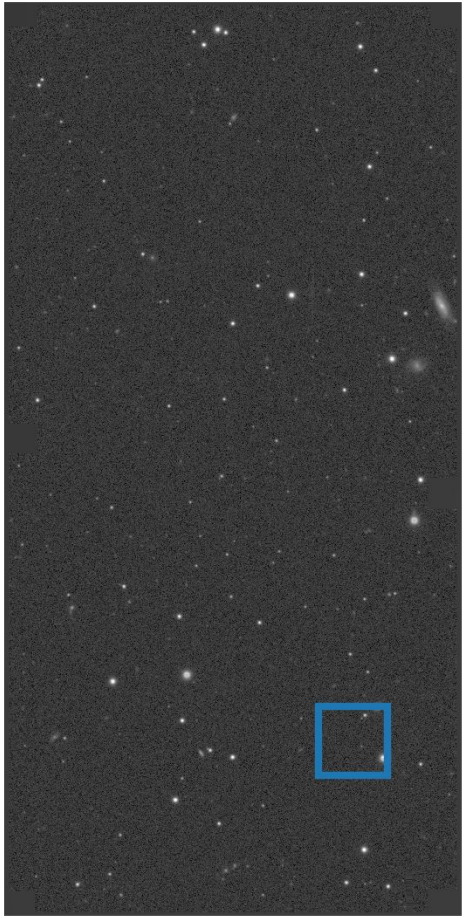

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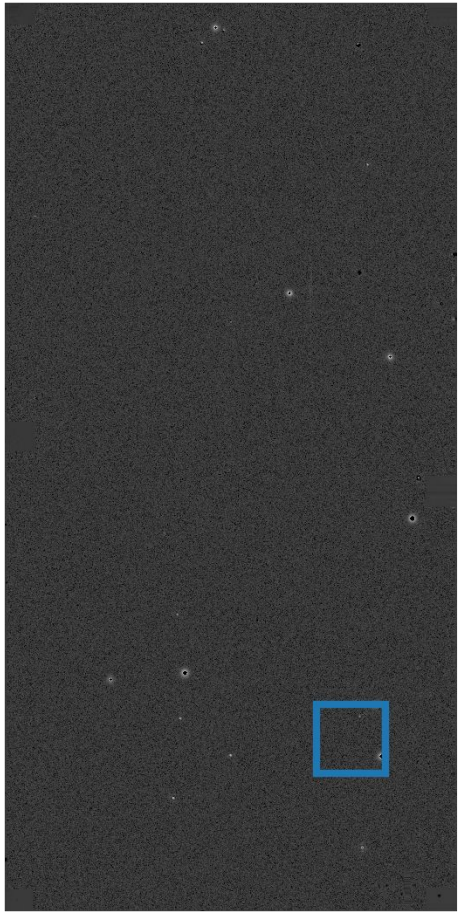
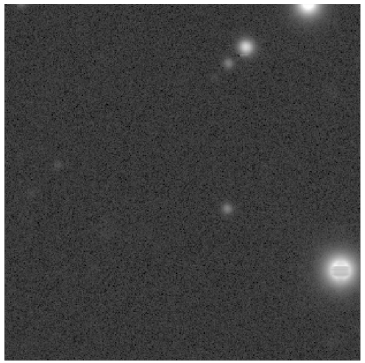


Data Processing

Exposure 1 Band r

Calibrated Image



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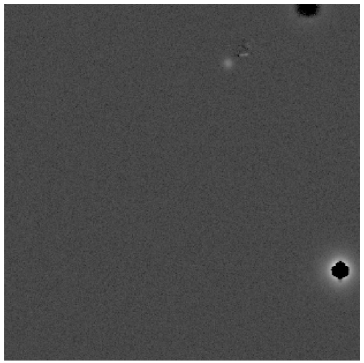

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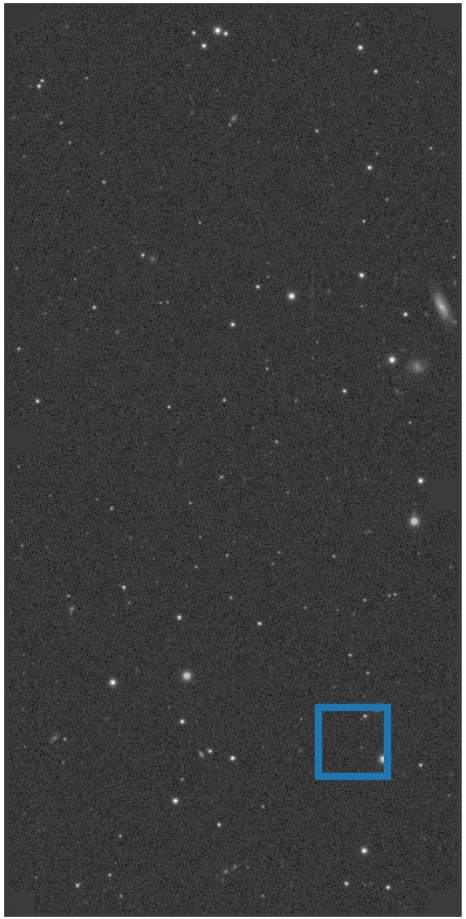

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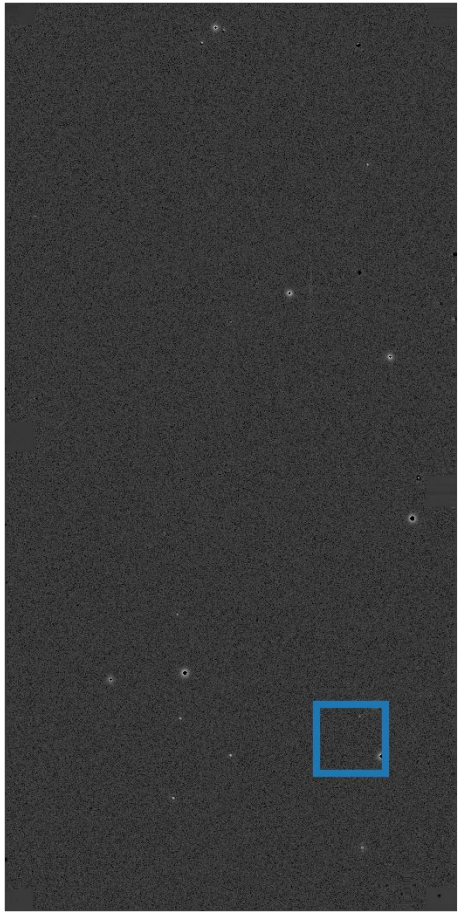

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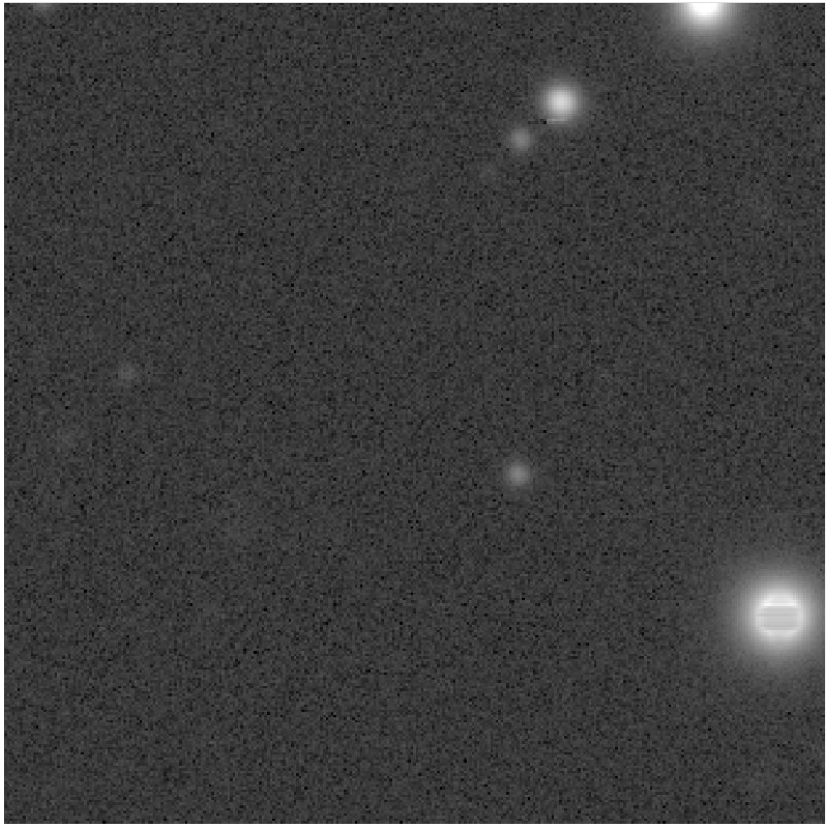

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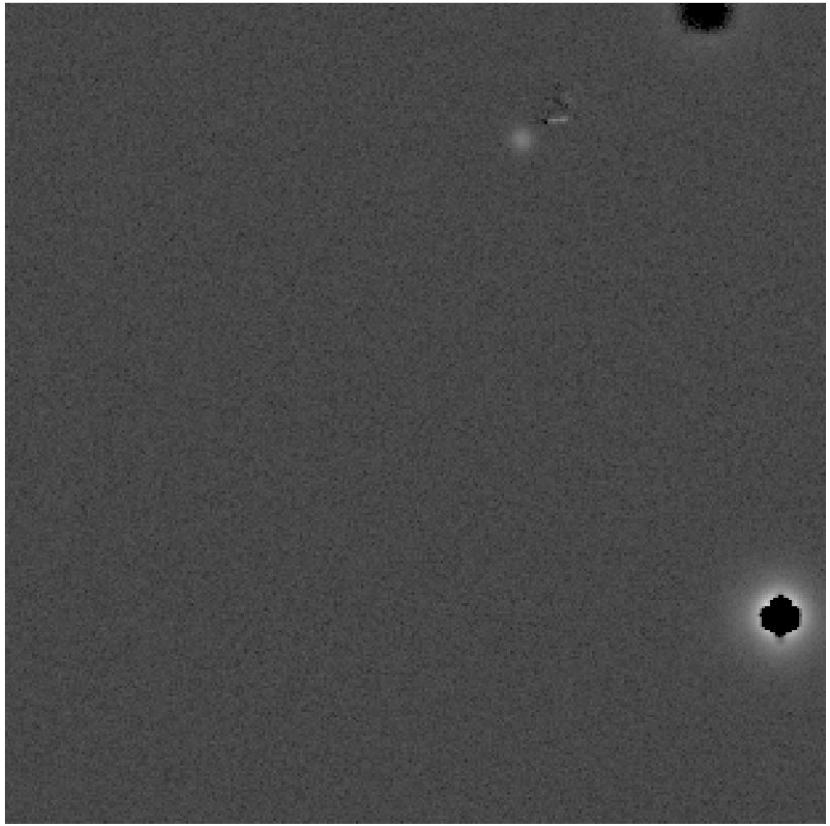
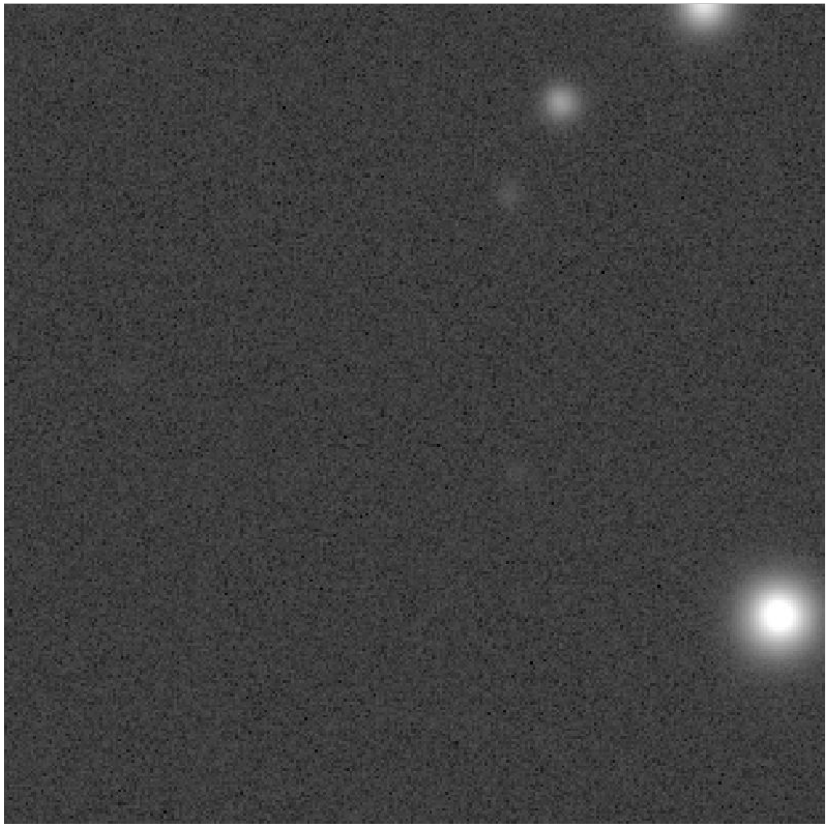
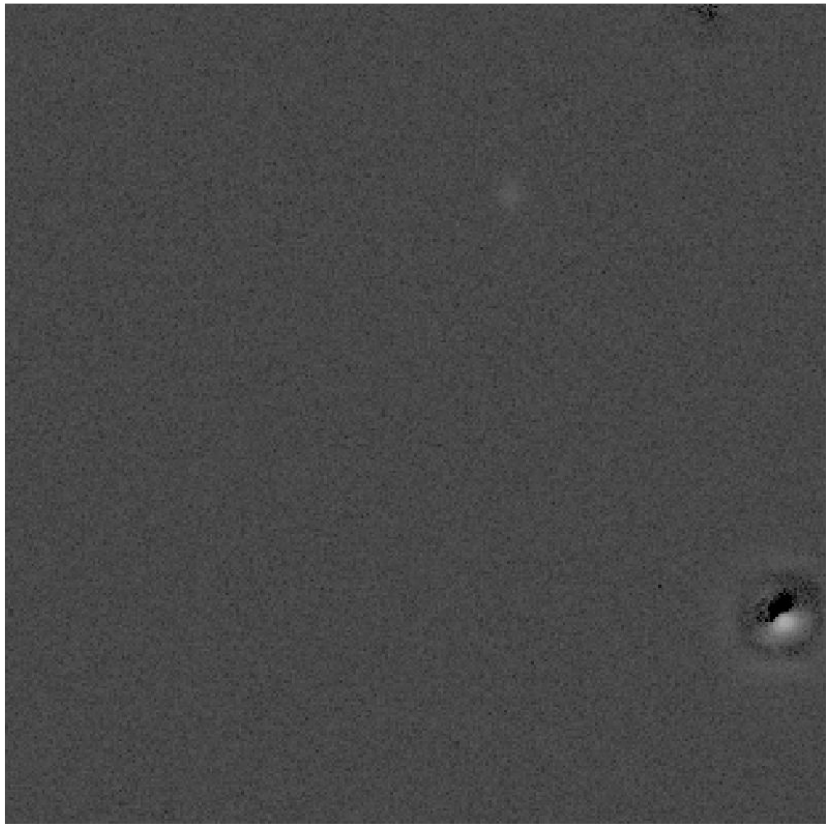


Exposure 2 Band g

Calibrated Image



Difference Image



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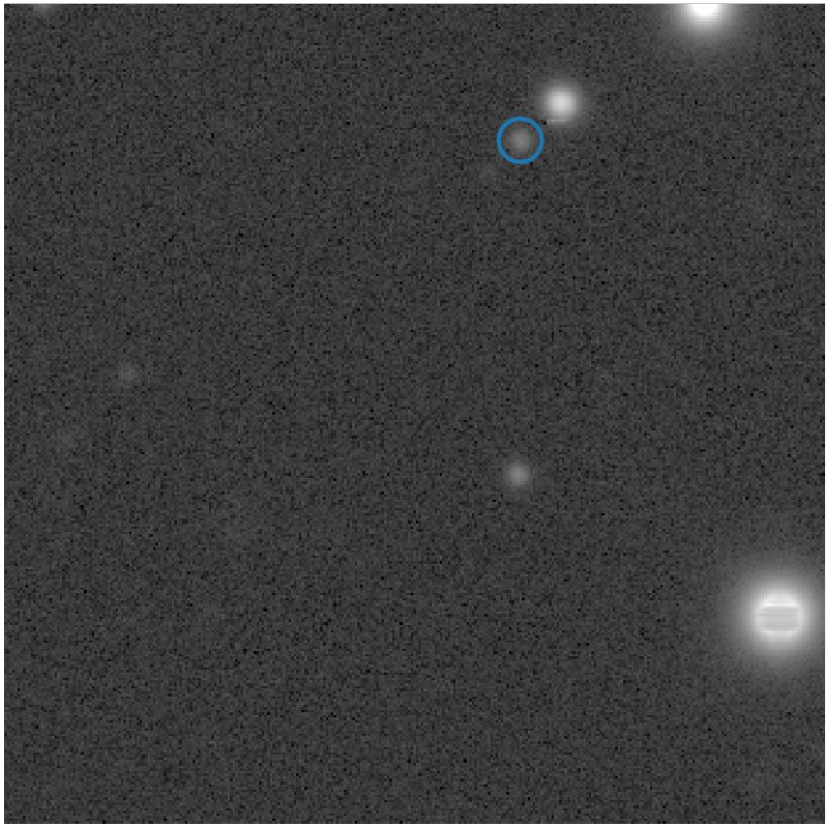

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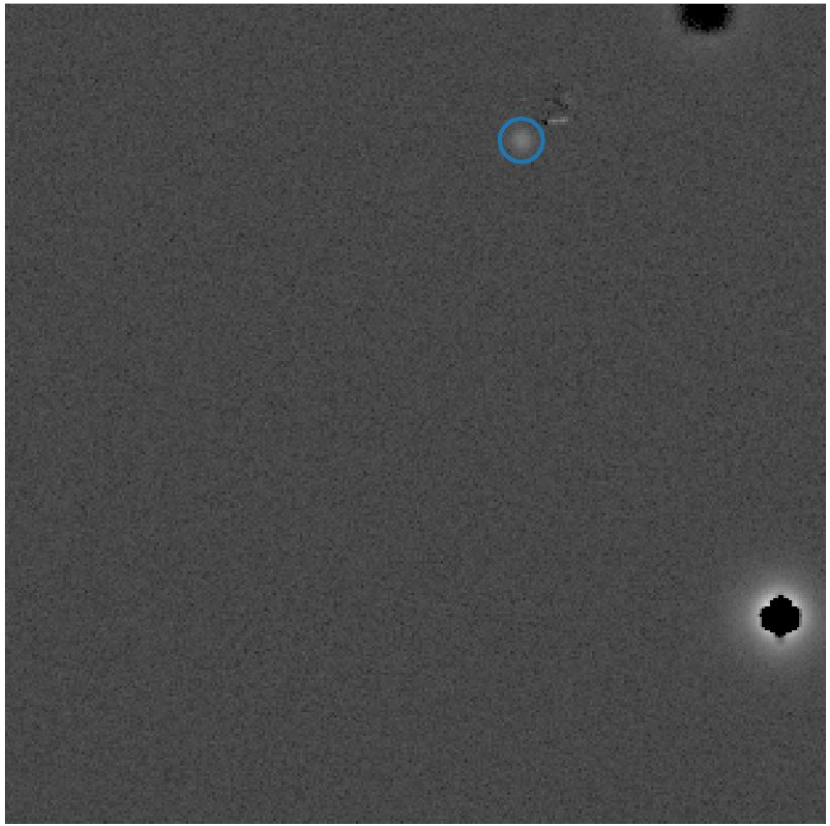

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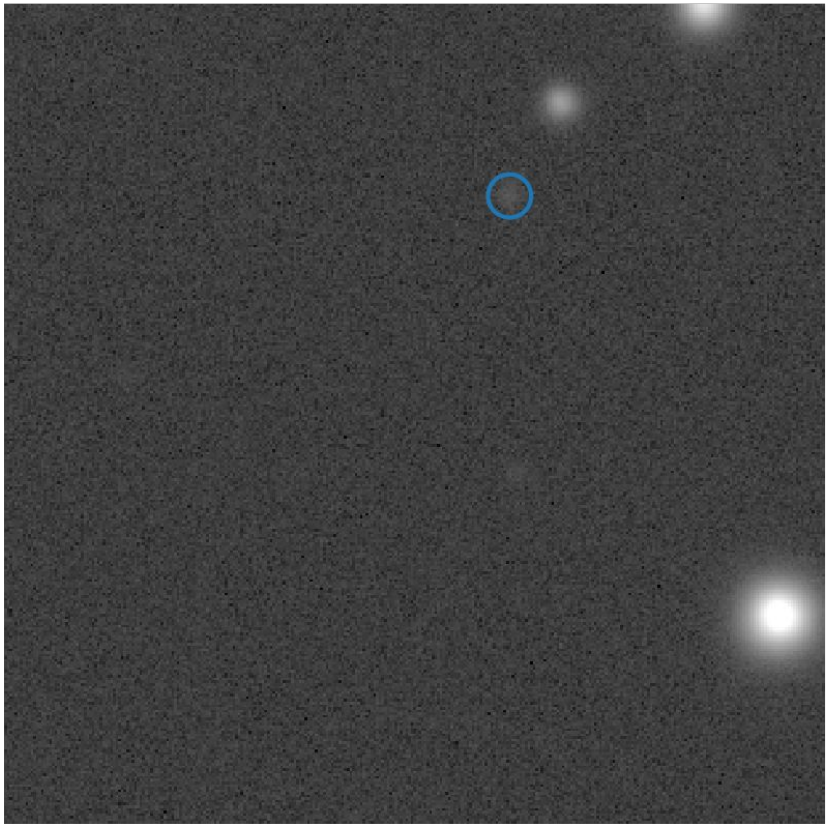

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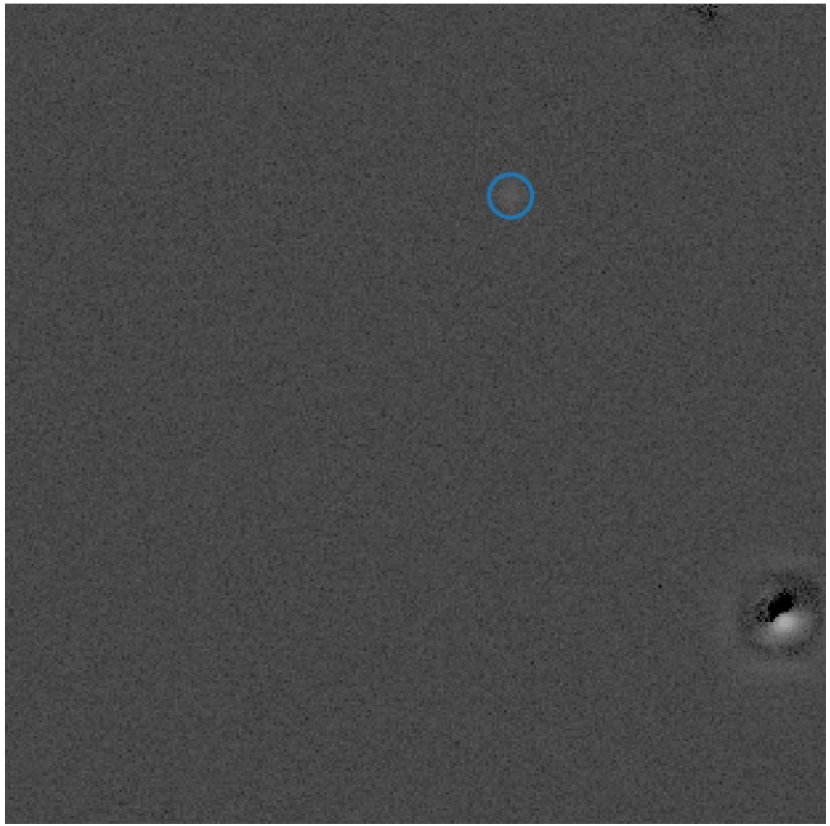
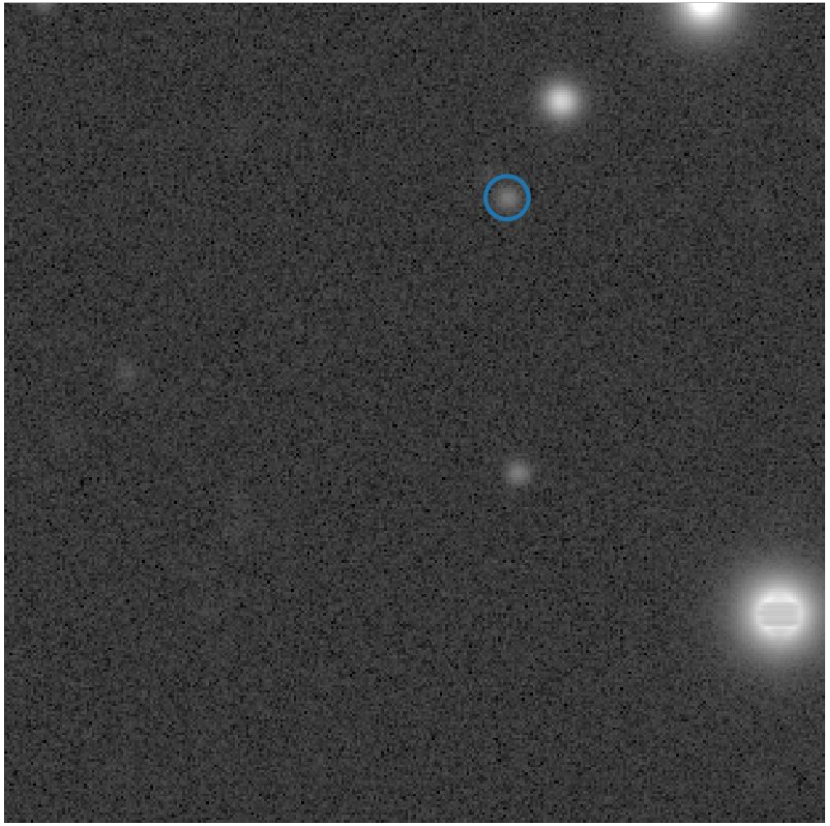
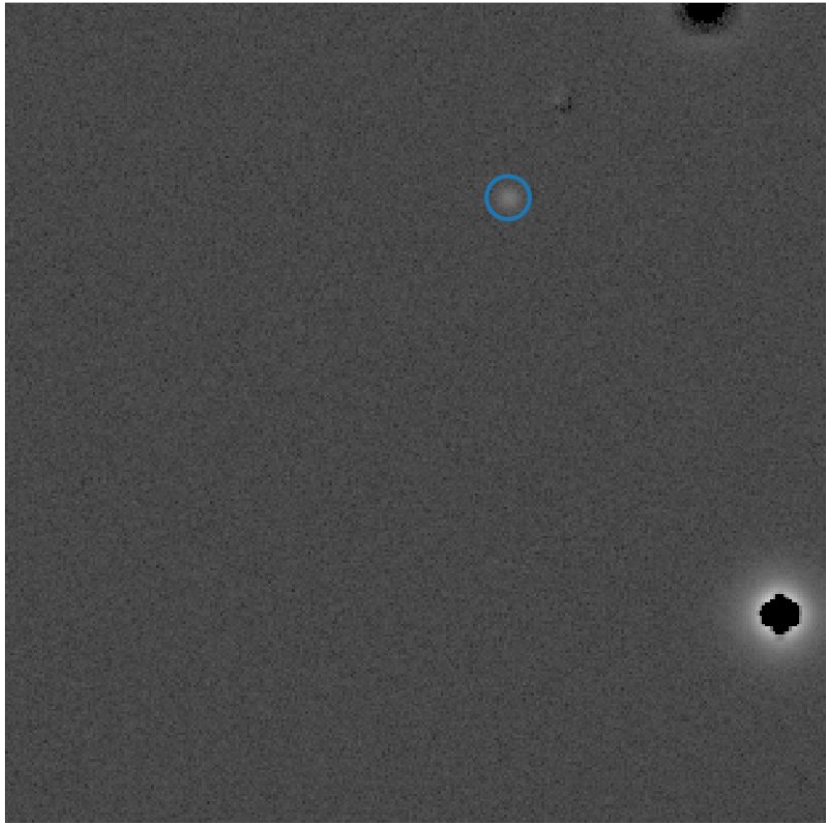


Exposure 3 Band r

Calibrated Image

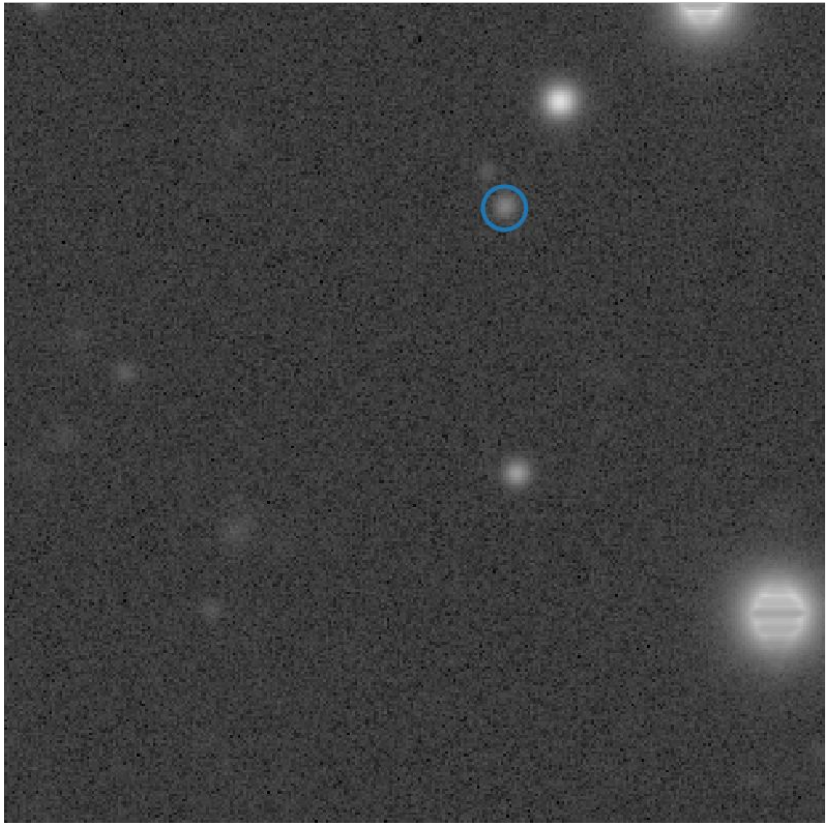


Difference Image

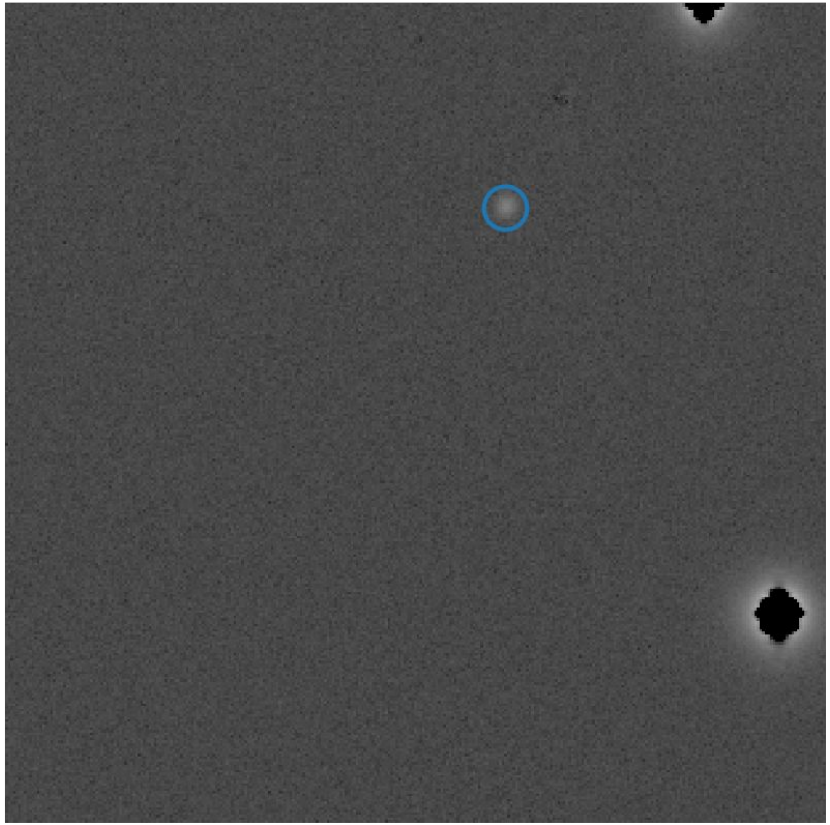


Exposure 4 Band i

Calibrated Image

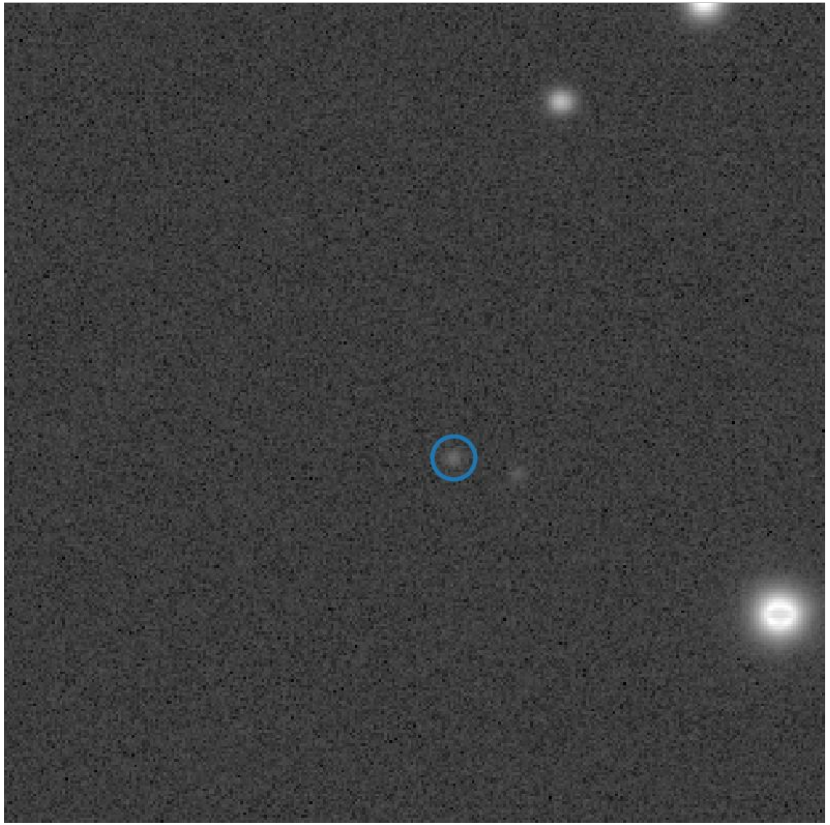


Difference Image



Exposure 5 Band g

Calibrated Image



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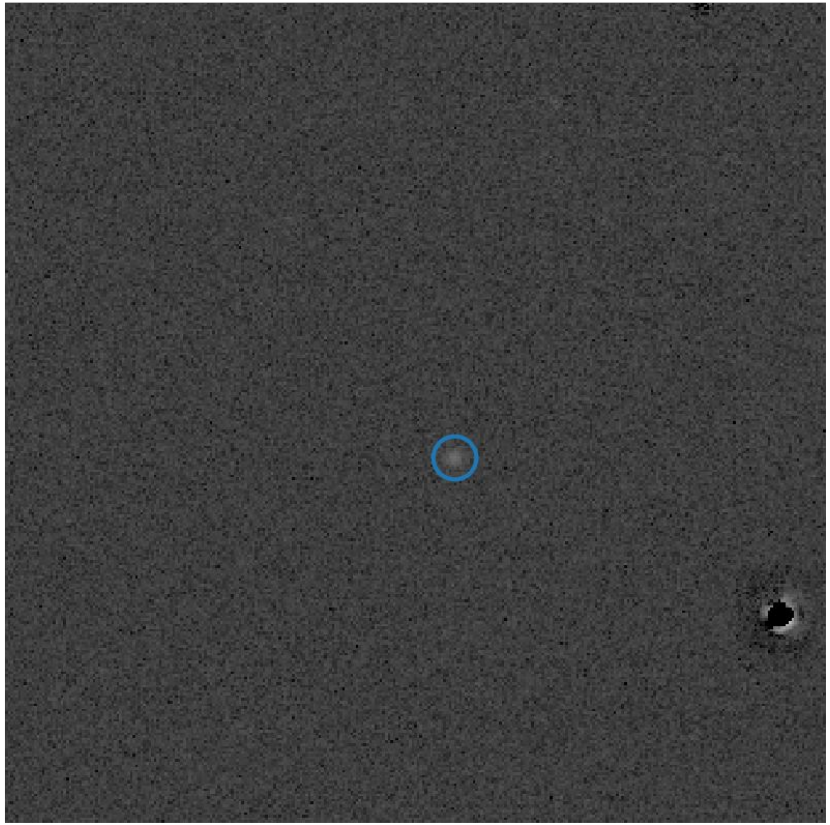

Exposure 6 Band r

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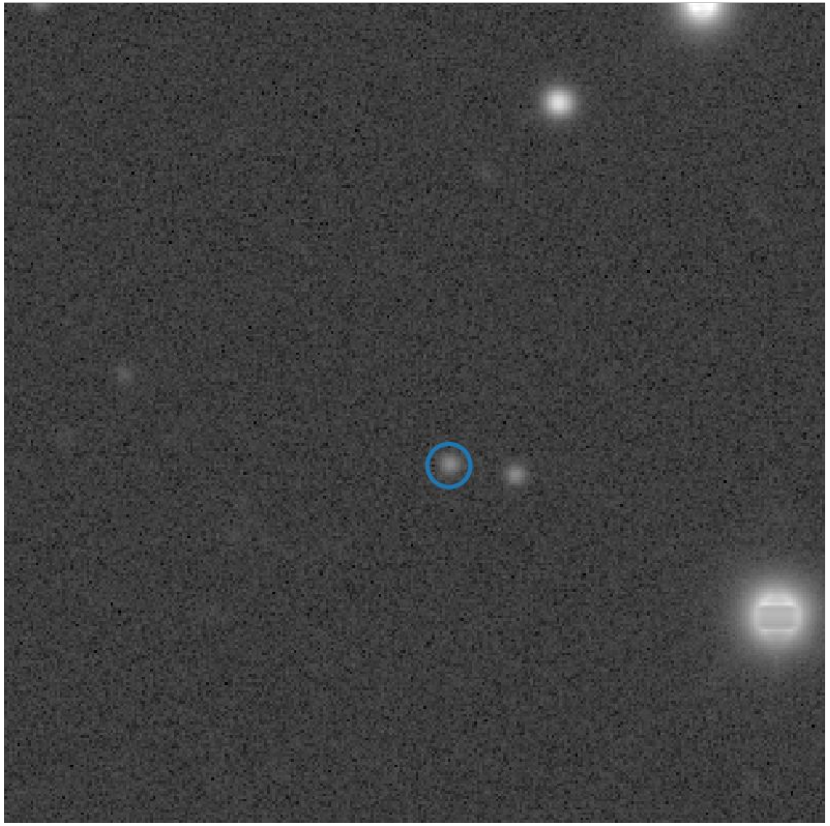

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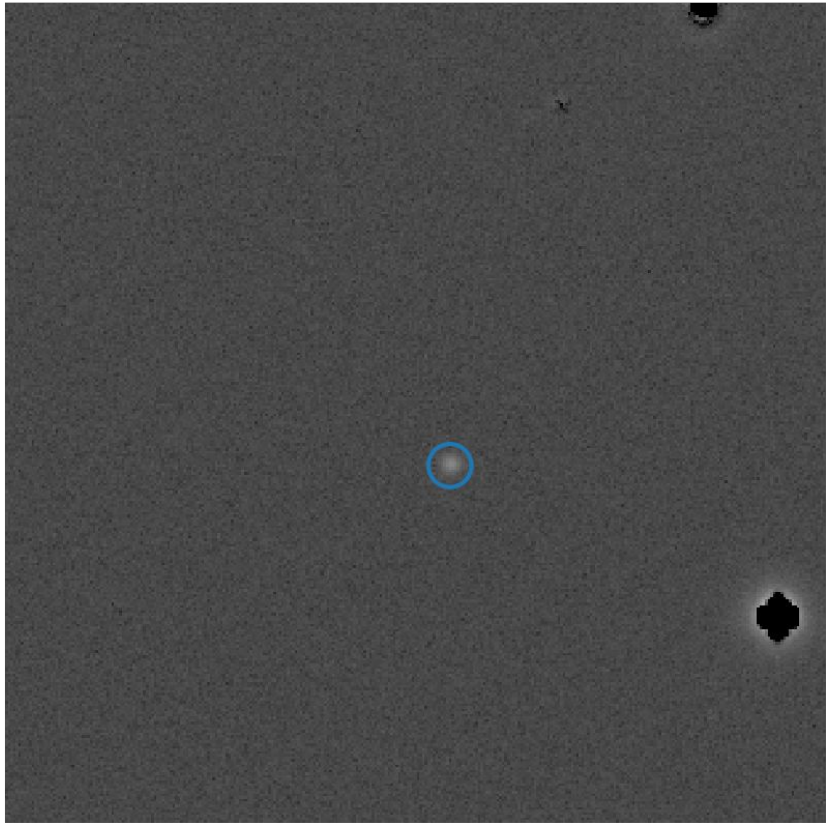

Exposure 7 Band i

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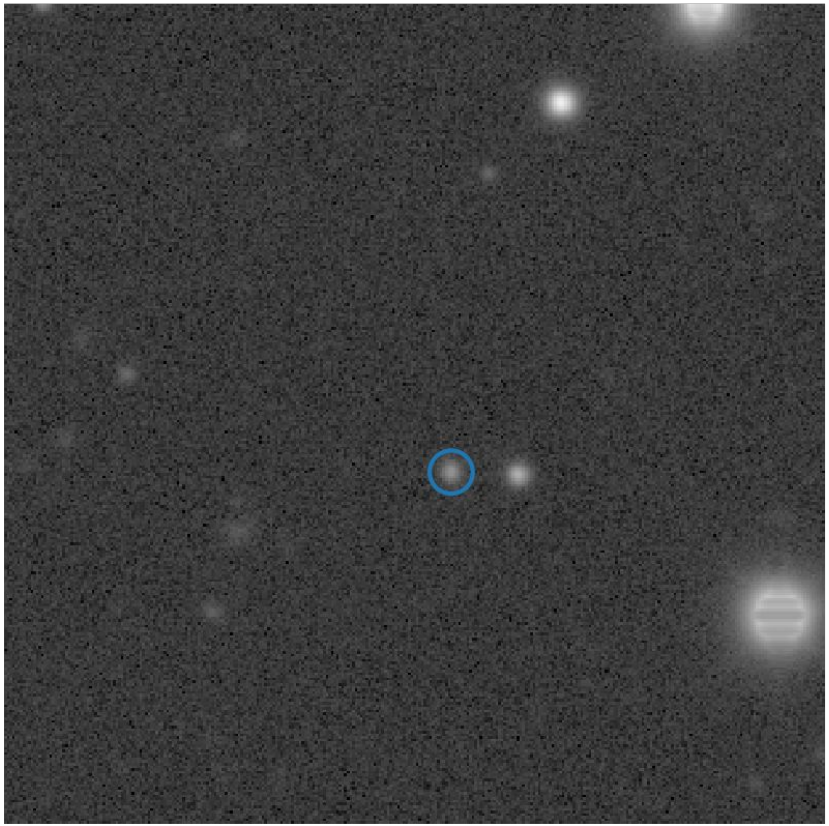

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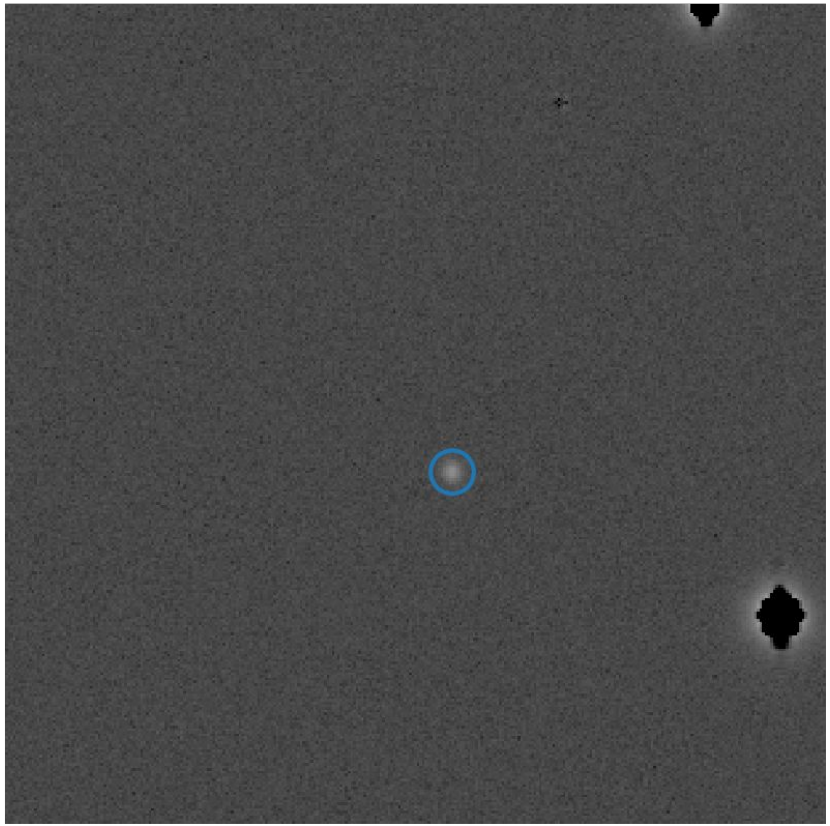

Exposure 7 Band i

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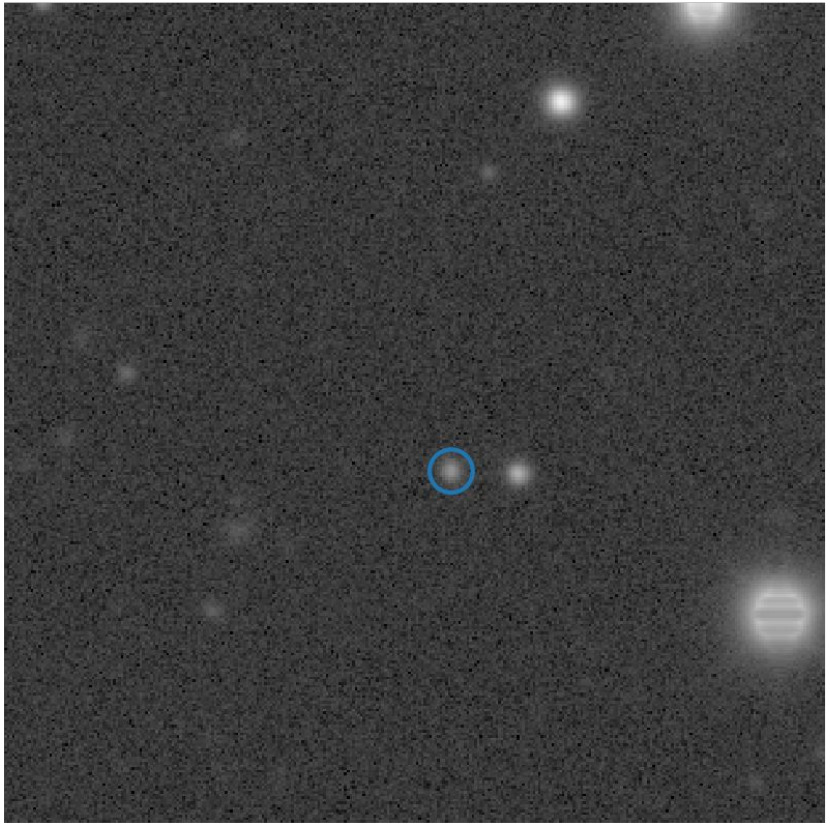

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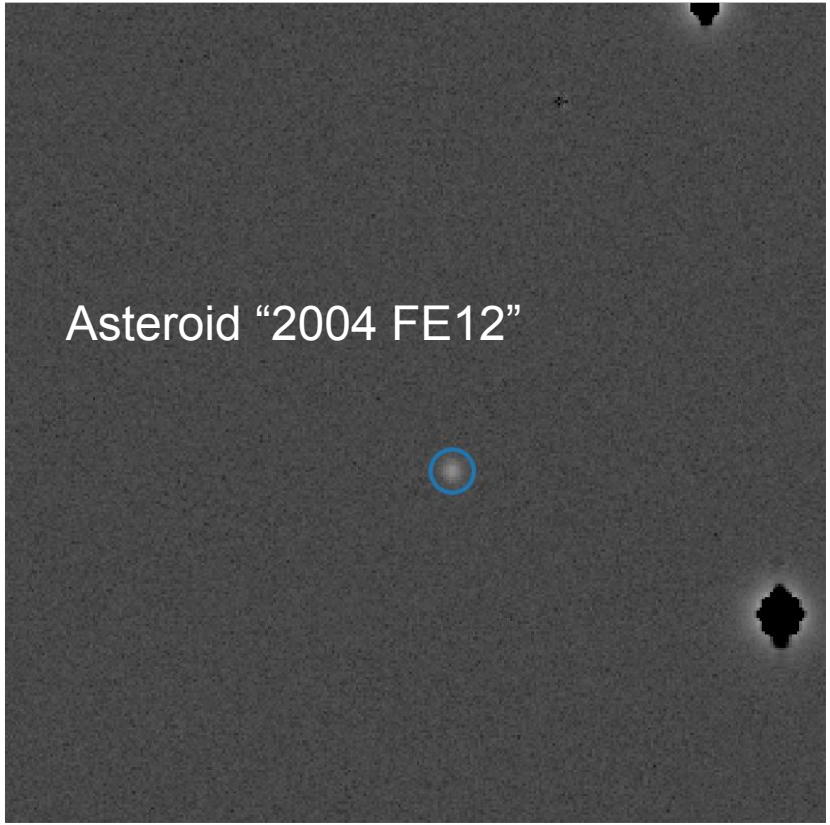

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- In this survey, we have observed **~8,000 known asteroids** like 2004 FE12
- What can we do with these observations?

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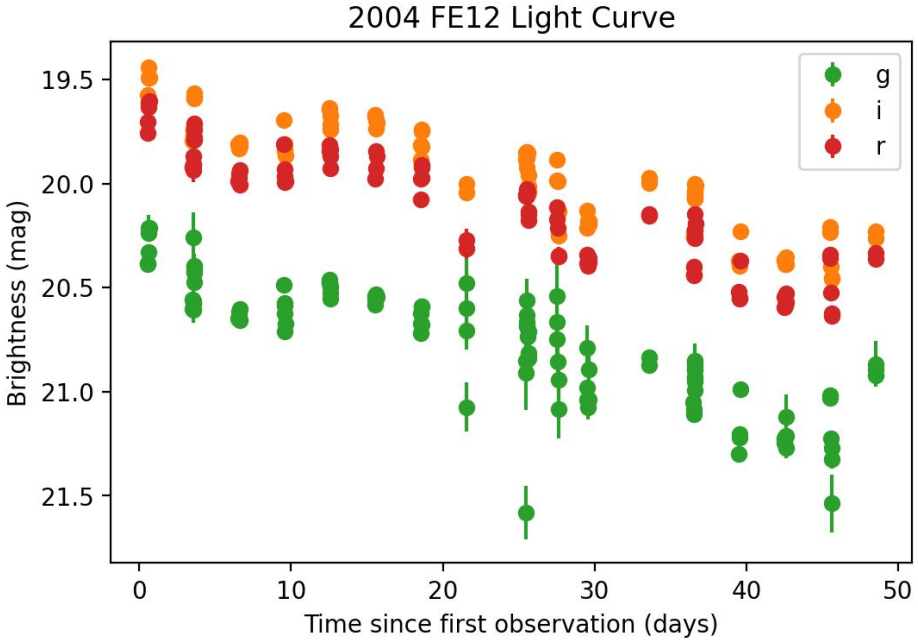
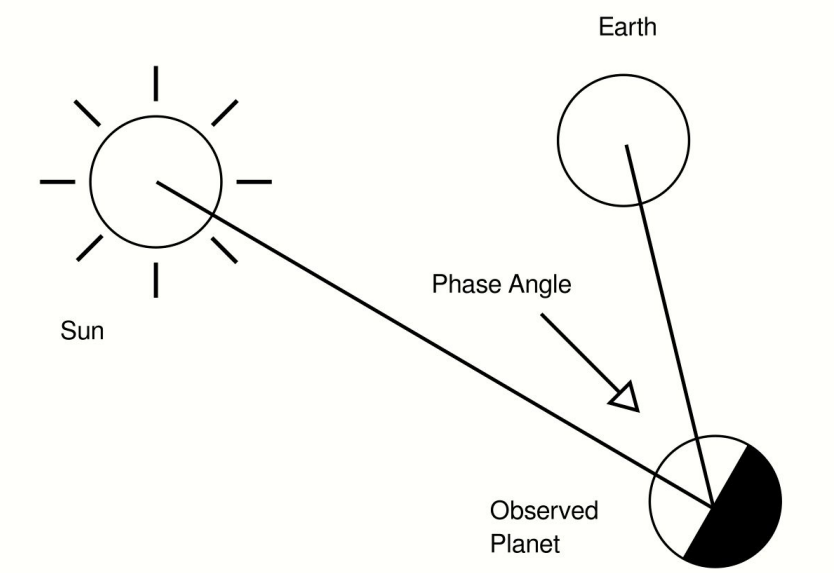
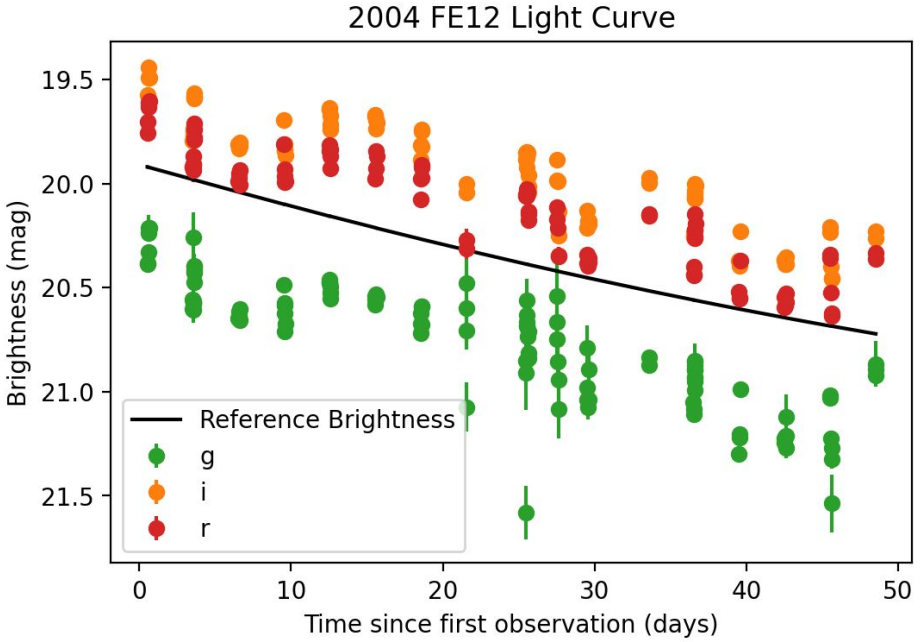
- We can characterize them through their light curves: how their brightness changes over time



Asteroid Discovery and Characterization

- We can measure the **brightness** of 2004 FE12 over time in **different filters**





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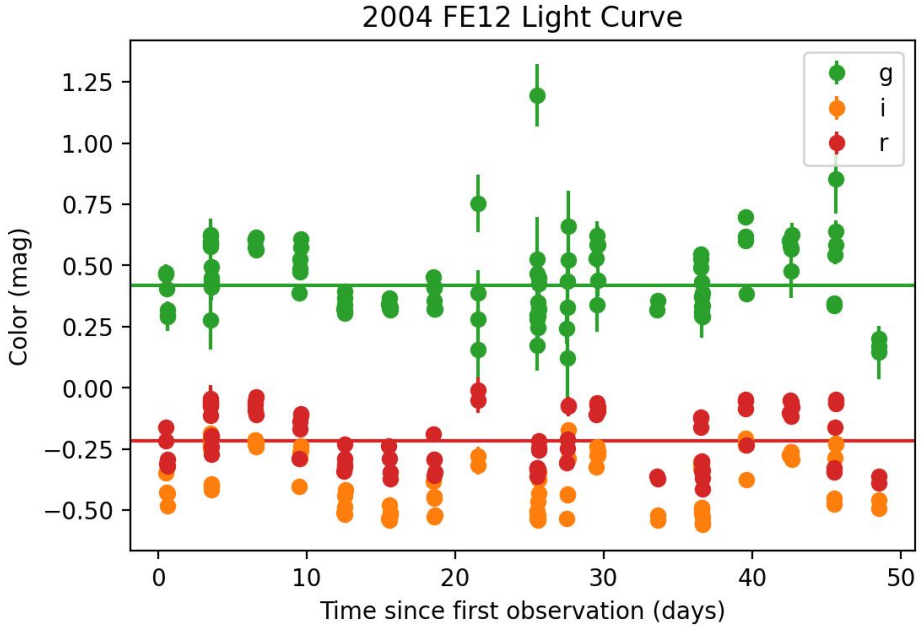
- We can measure the brightness of 2004 FE12 over time in different filters
- The “**color**” of the asteroid can be measured



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- We can measure the brightness of 2004 FE12 over time in different filters
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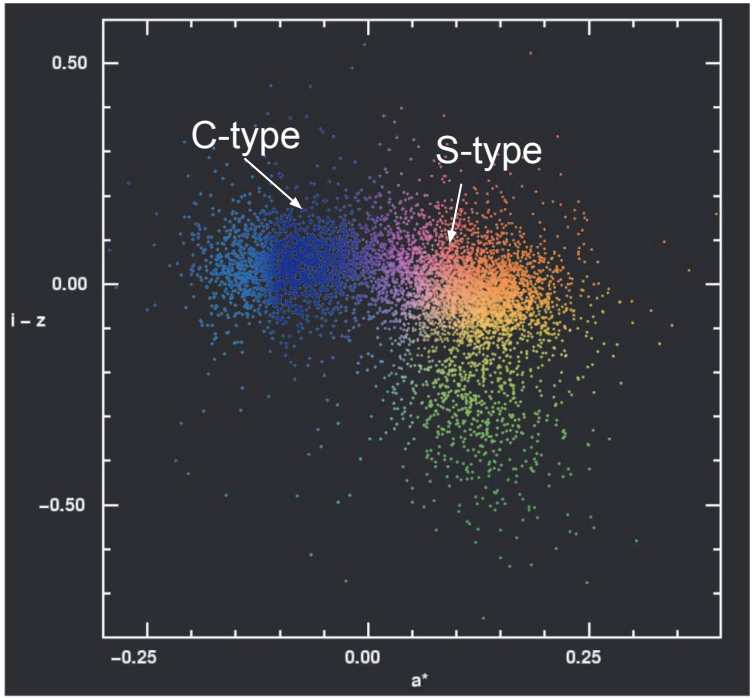

Credits: Ivezic et al. 2002

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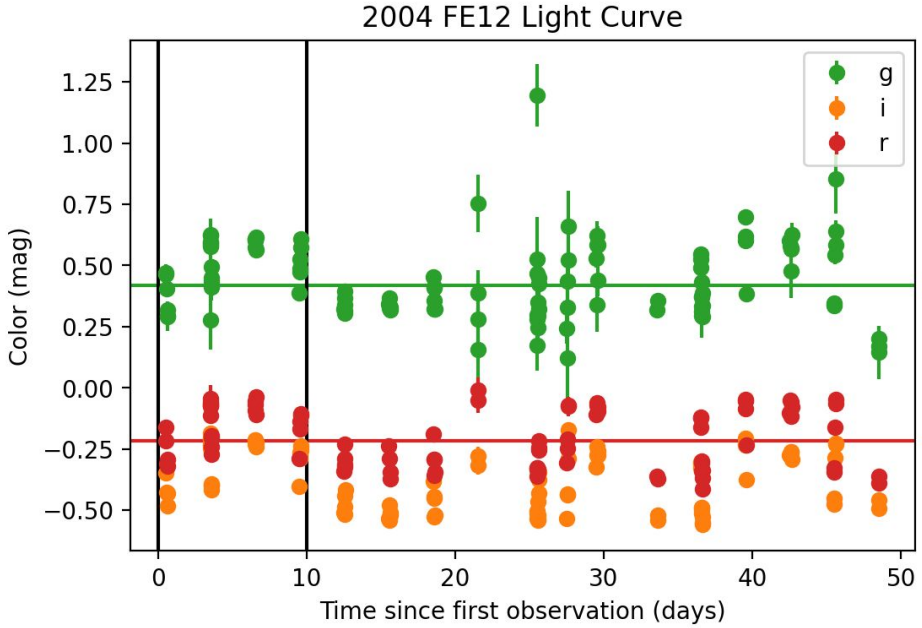

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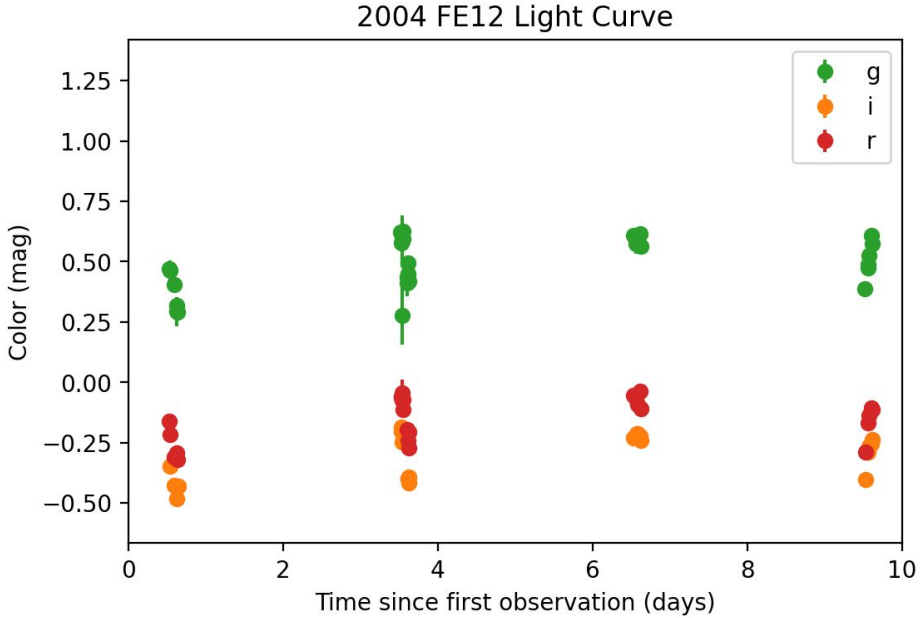

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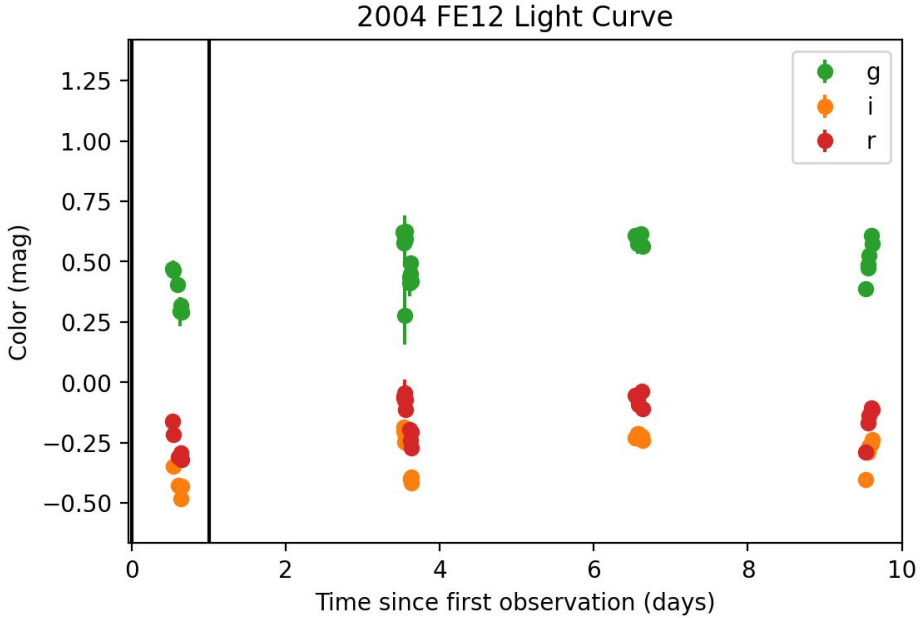

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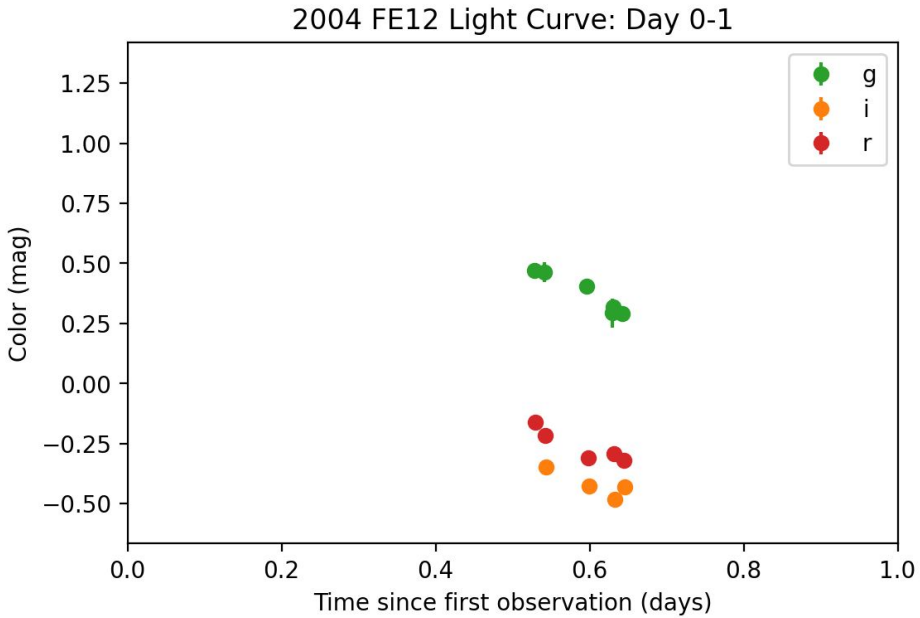

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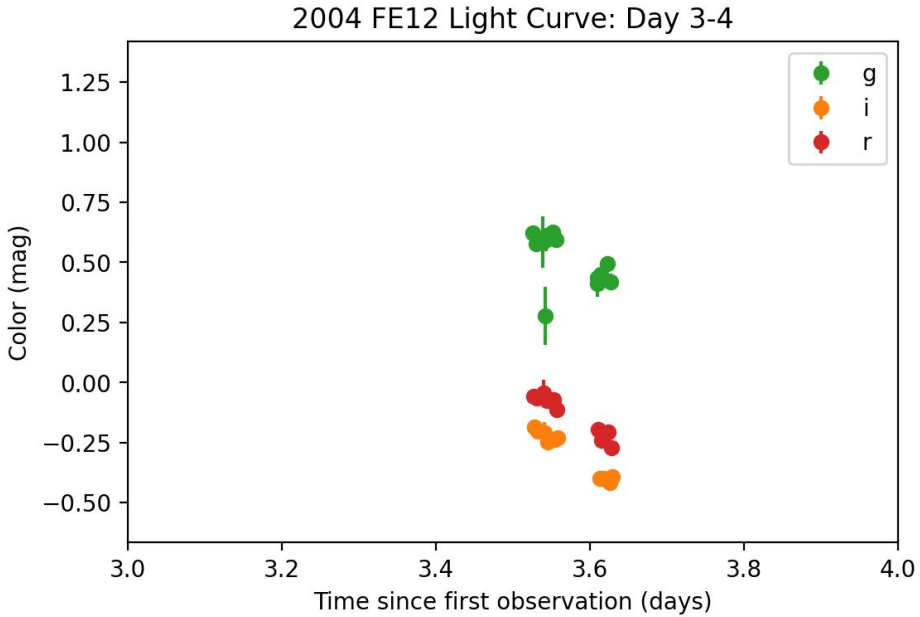

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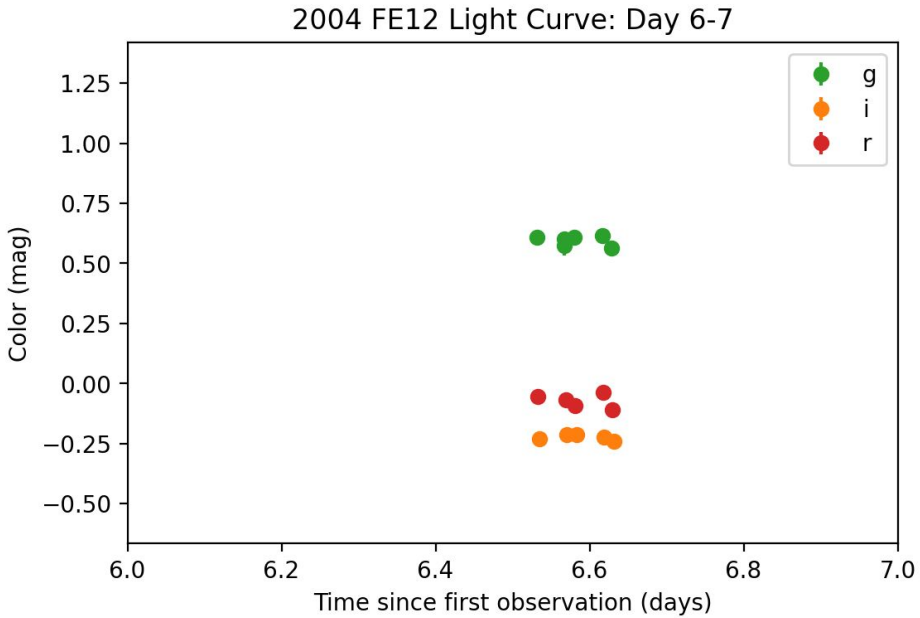

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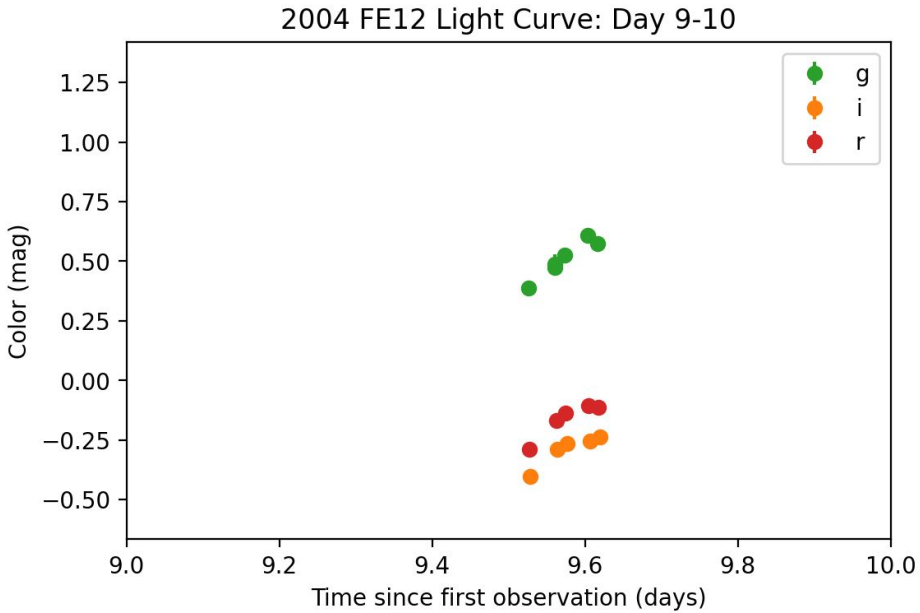

Asteroid Discovery and Characterization

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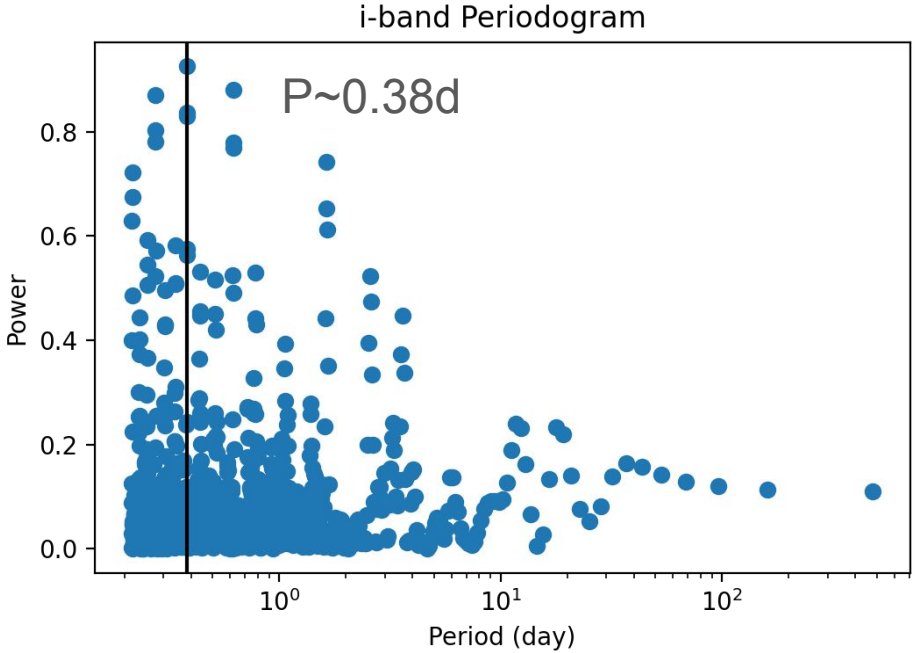

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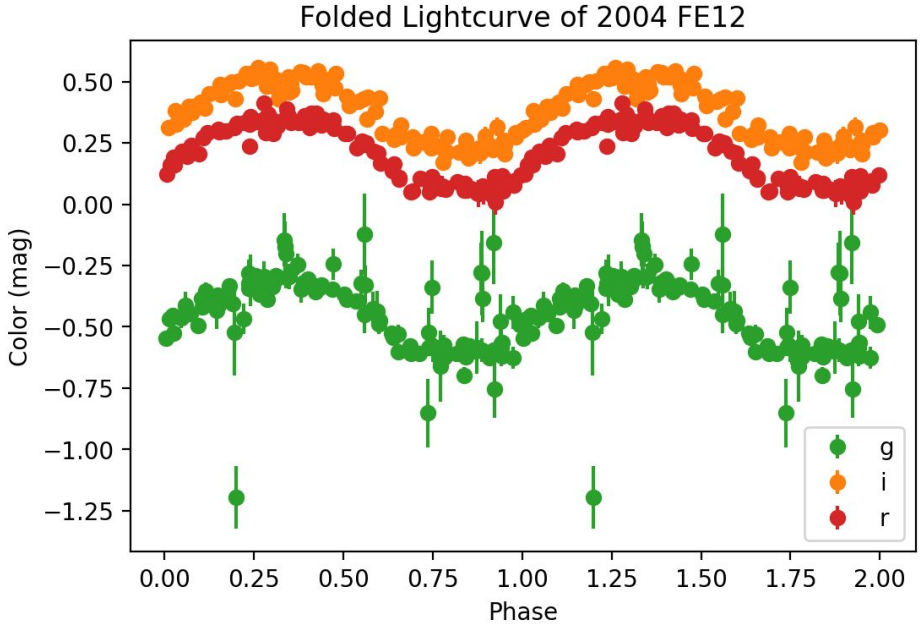

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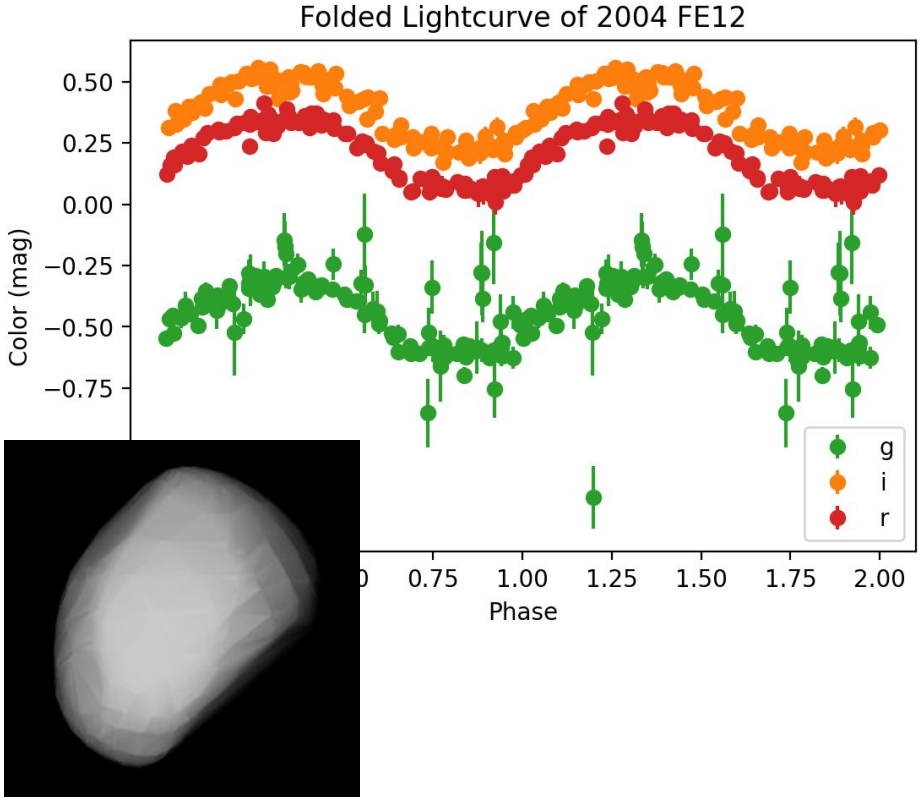
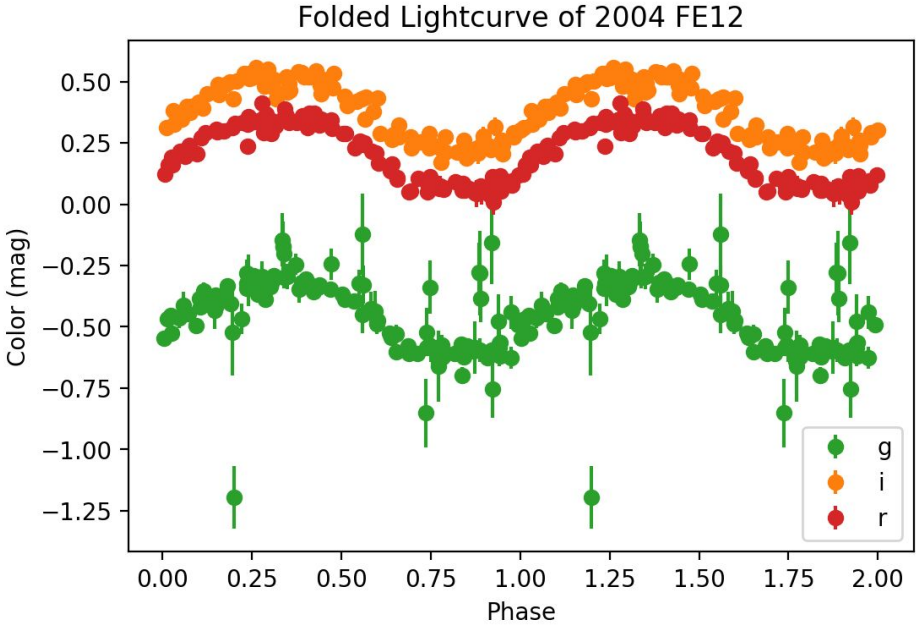
- Light curves → **shape models**



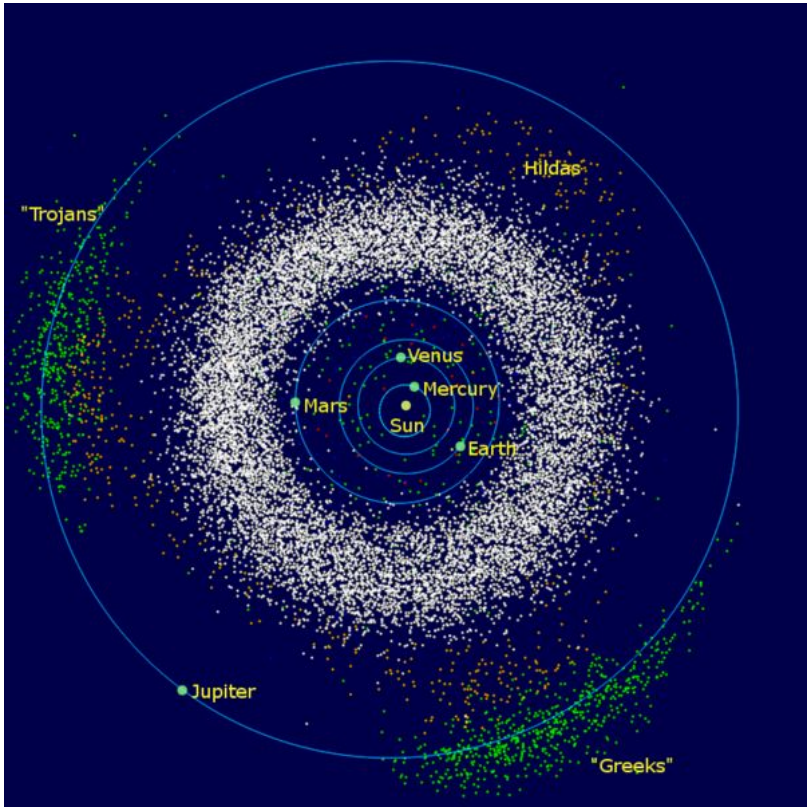
Asteroid Discovery and Characterization

- In this survey, we have observed **~8,000 known asteroids**
- For all: colors surface properties
- For well measured: rotation periods and shape models.
- We have used a portion of this dataset to discover 10s of new asteroids with an undergrad at UW, with the potential to discover many more



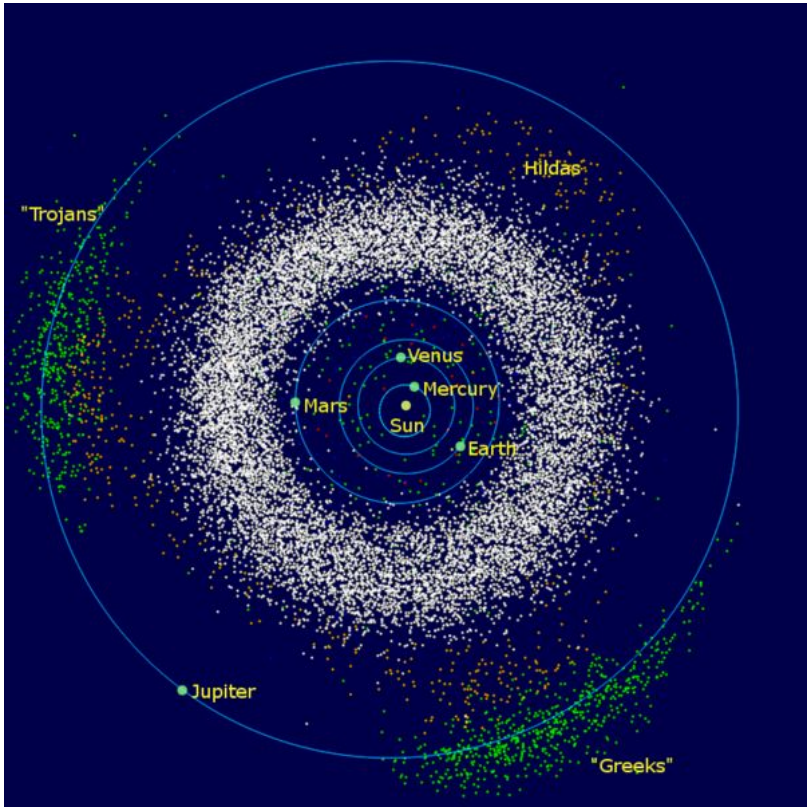
Asteroid Discovery and Characterization

- These kinds of analyses let us characterize “Main Belt” asteroids, the small bodies in the inner solar system



Asteroid Discovery and Characterization

- These kinds of analyses let us characterize “Main Belt” asteroids, the small bodies in the inner solar system
- But we can use different detection techniques to discovery **Trans Neptunian Objects** (TNOs)**,** very **faint objects** at the outer reaches of the solar system



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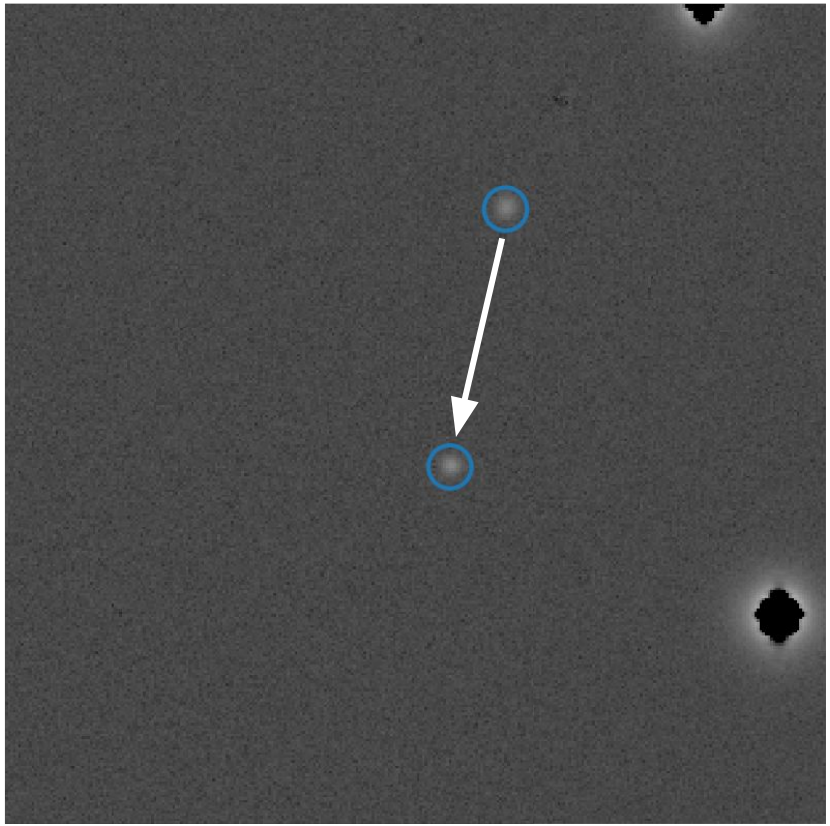

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- Guess a starting pixel (x, y) and a velocity (v_x, v_y)
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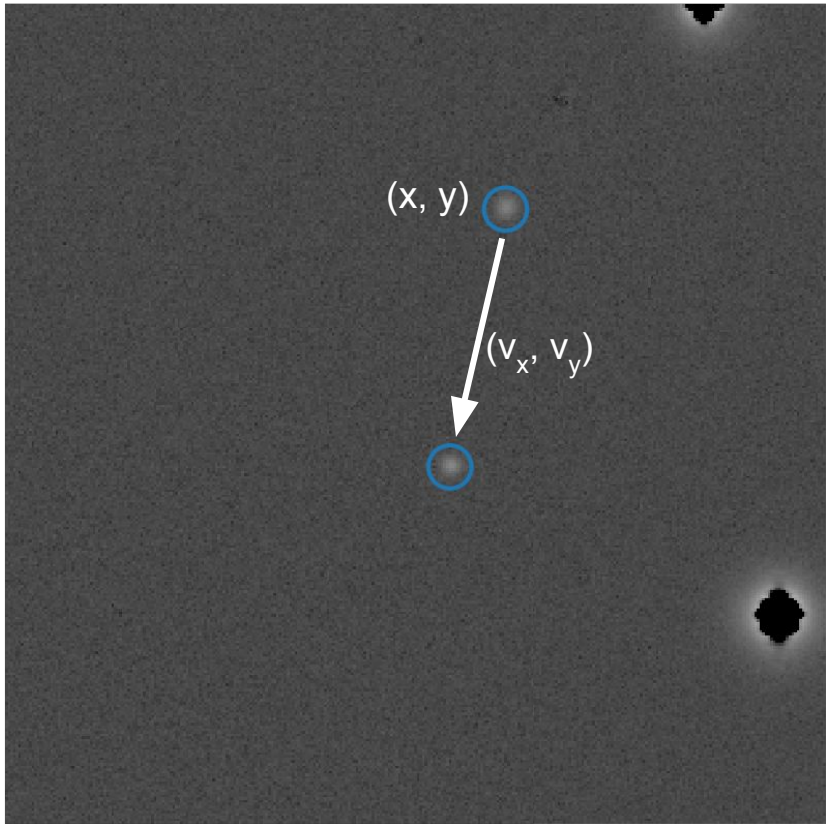

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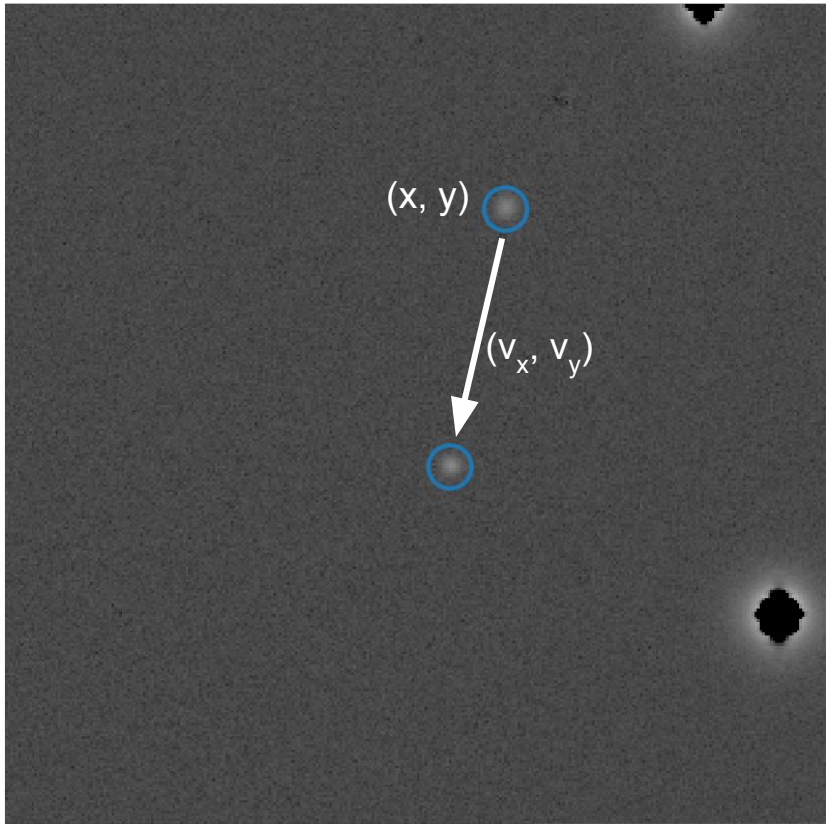
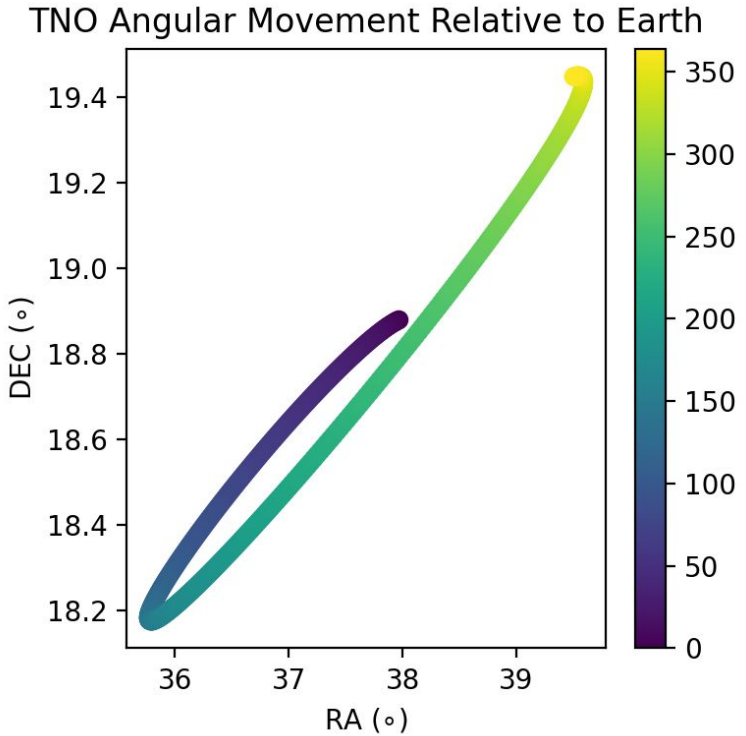
- KBMOD: **Accelerate this using GPUs**: 10^{10} trajectories through 10 images in 1 minute

Difference Image



Shift-and-Stack over Long Time Baselines

- **Issue**: on-sky trajectories of solar system objects are non-linear over week-month long time baselines



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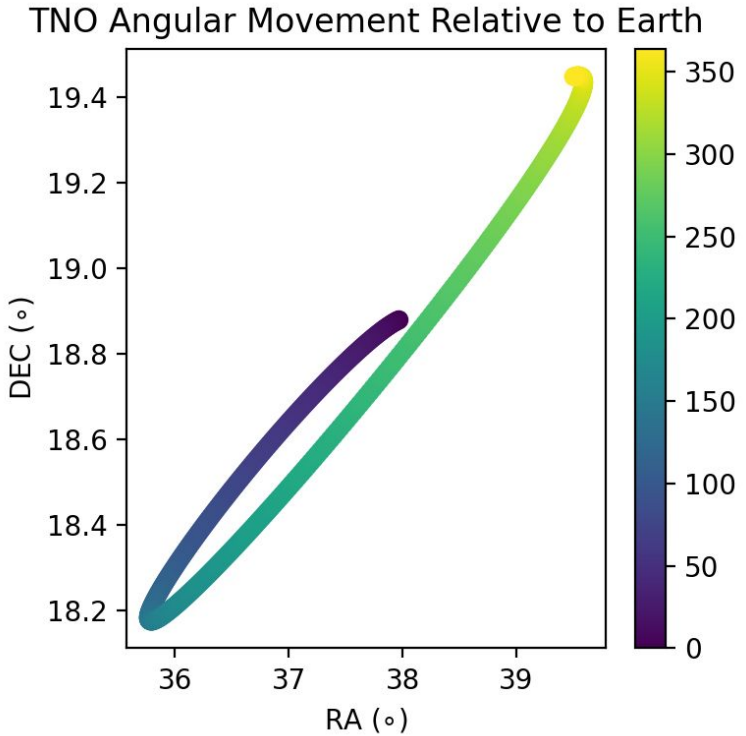
- Issue: on-sky trajectories of solar system objects are non-linear over week-month long time baselines
- **Solution**: Guess the distance of the object, to allow us to model the wiggle
- Adds an **extra dimension** to the problem



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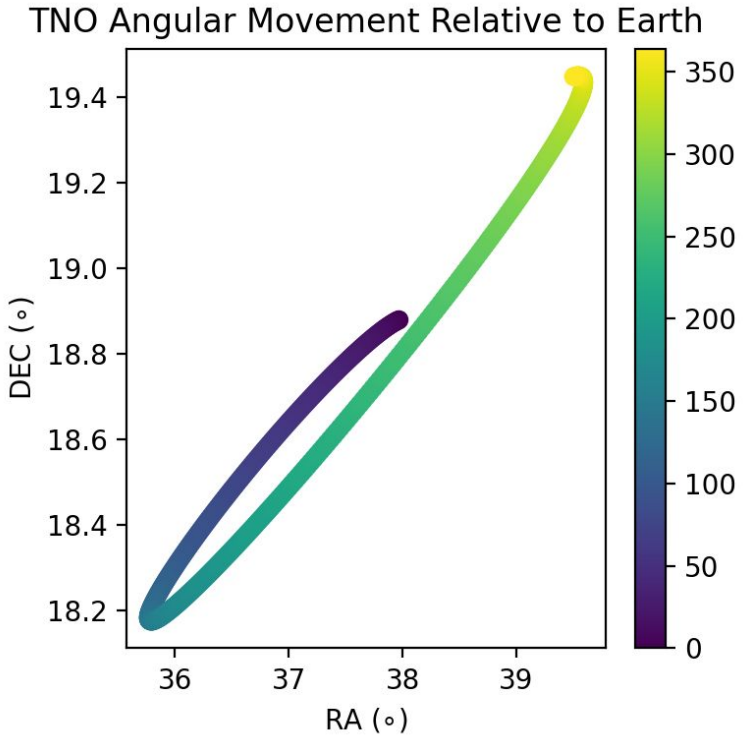
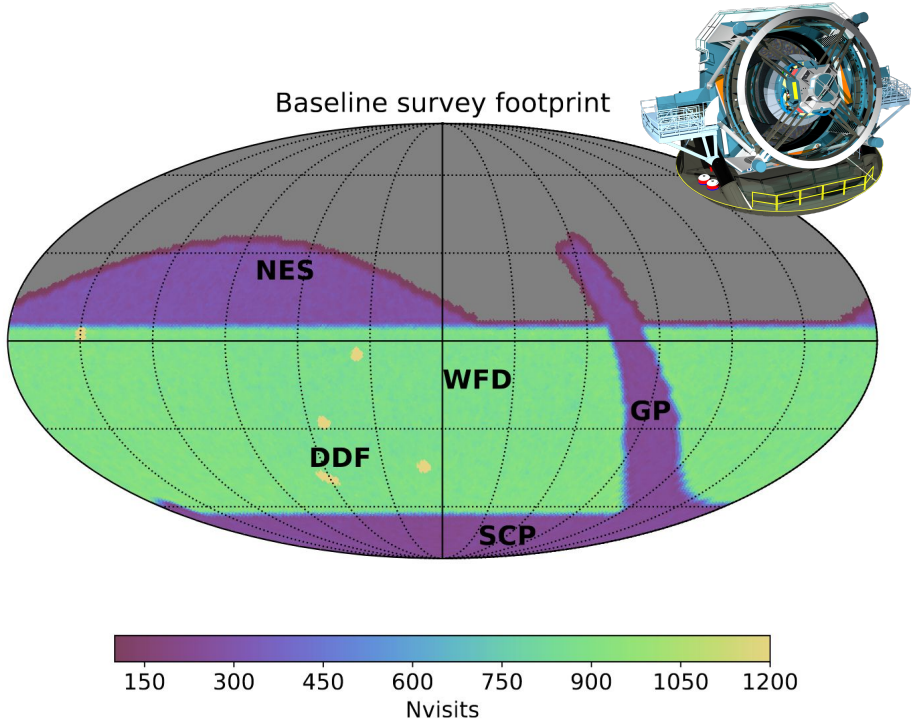
- Solution: Guess the distance of the object, to allow us to model the wiggle
- Adds an extra dimension to the problem
- Applying shift-and-stack to this dataset will be a **first application** of these extended searches using KBMOD



Towards LSST: Shift-and-stack for Faint Object Detection

- ~80 images over ~3 months across the entire ecliptic in the first year
- Shift-and-stack will require ~3.5M GPU-hours (~5000 GPU-months)
- The payoff is large: ~10x more TNOs discovered and potentially the putative Planet IX
- Applying shift-and-stack to the DECam DDF data is the first step towards this ambitious goal



Thanks

Thanks to:

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- CSGF: Lindsey, Michelle, Kris, the steering committee, fellows, and alumni