Radar as a tool to study the Solar System

GBT/AO Single Dish Workshop
September 16, 2021

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Planetary Radar Science Group

ARECIBO OBSERVATORY
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Outline

- What is a radar system and why do we use it for Solar System studies
- Introduction to Radar Systems and observing methods
- Results from planetary radar observations

- Introduction to Solar System radar data processing

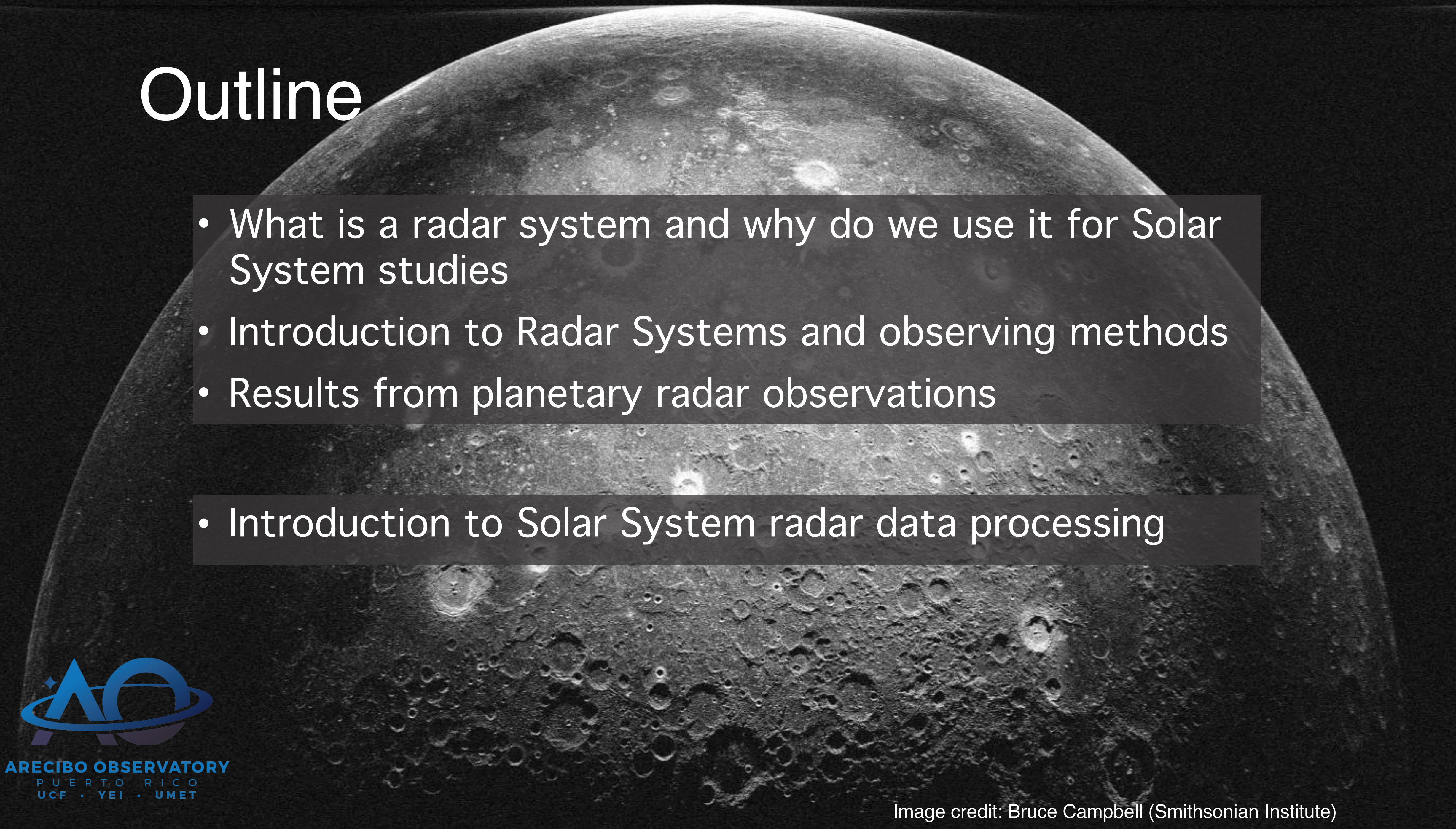

Image credit: Bruce Campbell (Smithsonian Institute)

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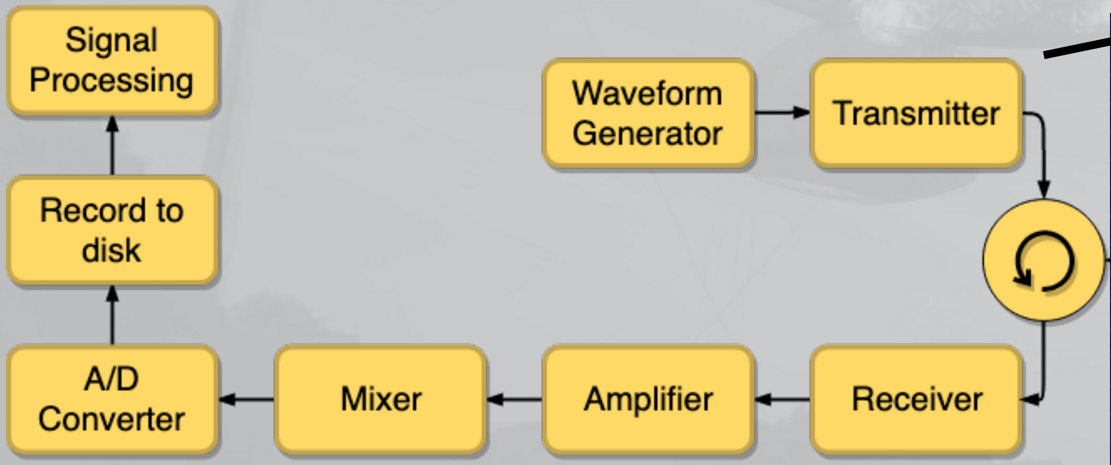
- RAdio Detection And Ranging
- Active remote sensing – we control the signal!
- Maximize signal properties to enhance SNR
- Measure reflected radio waves (so targets must be reflective)



Signal Processing

Record to disk

A/D Converter

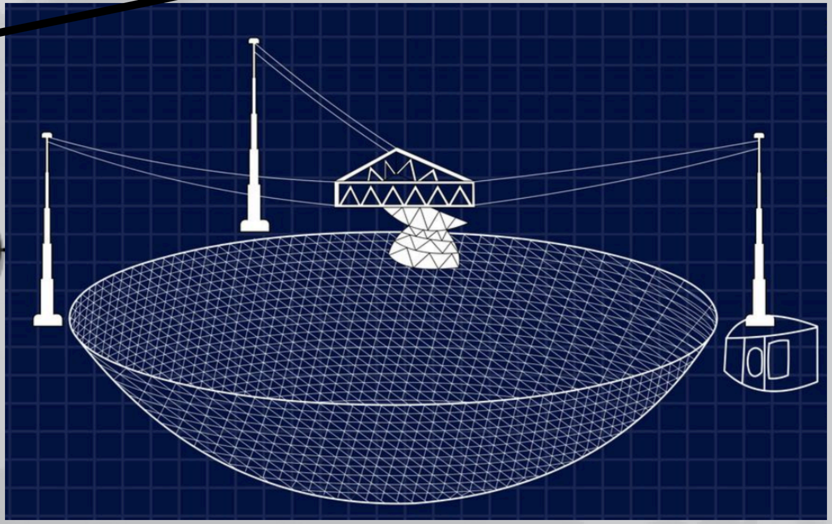
Mixer

Amplifier

Receiver

Waveform Generator

Transmitter



Klystron Amplifier

Image source: https://en.wikipedia.org/wiki/Klystron

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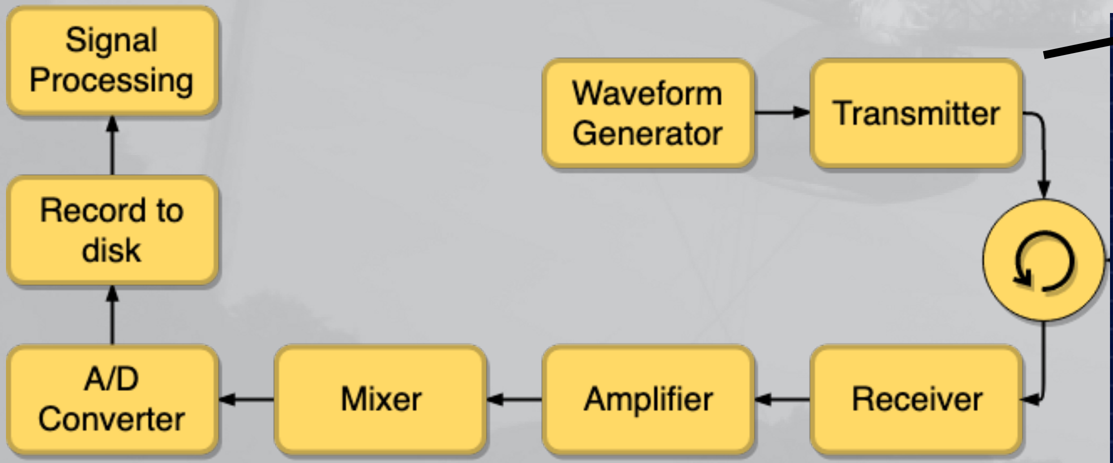
Solid State Amplifier



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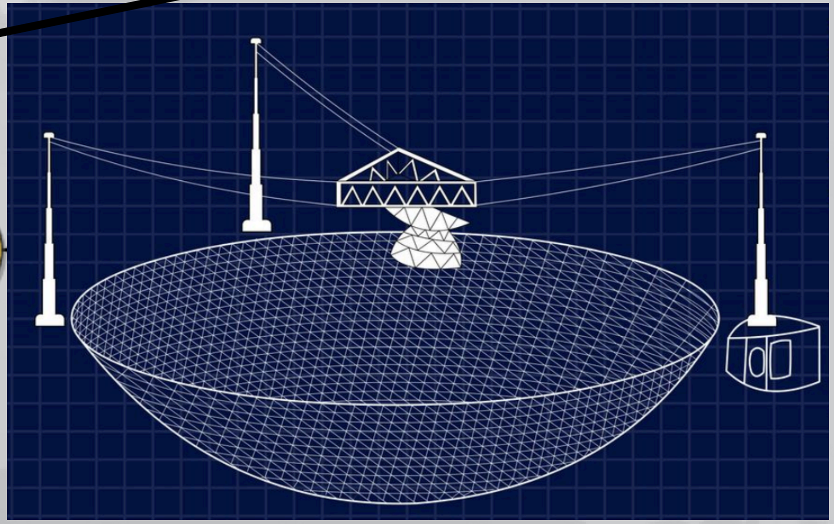

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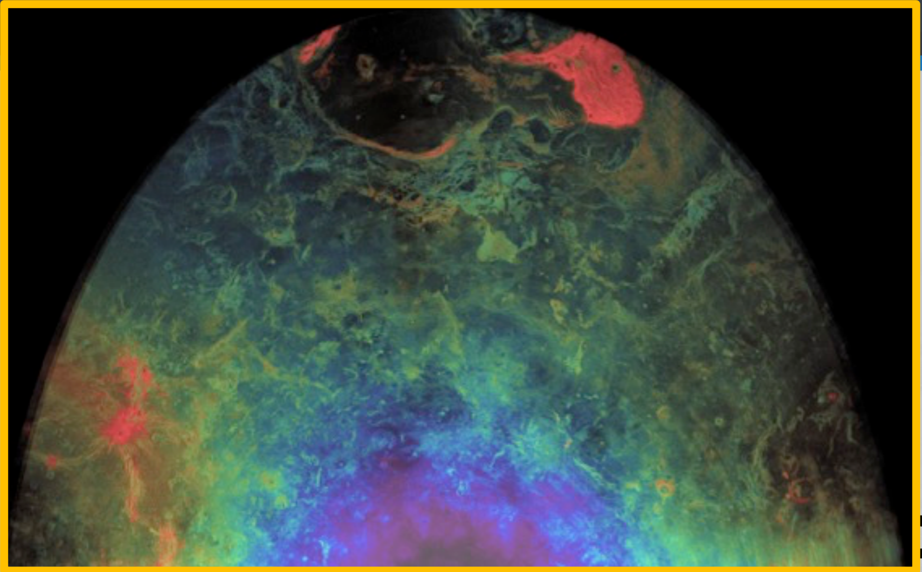
Image credit: Lynn Carter (LPL)



Why use ra … e … s in space?

Penetrate through atmospheres

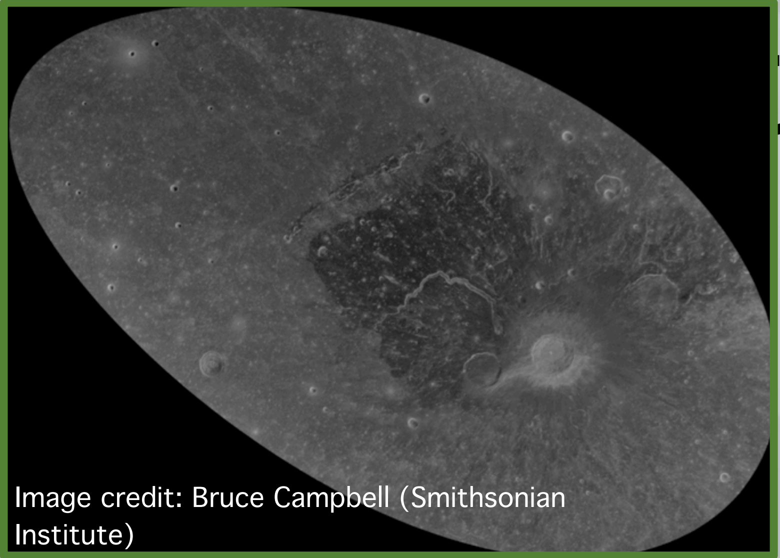


Image credit: Bruce Campbell (Smithsonian Institute)

Reveal buried features

Image at resolutions comparable to space missions

Use polarimetry to detect surface properties

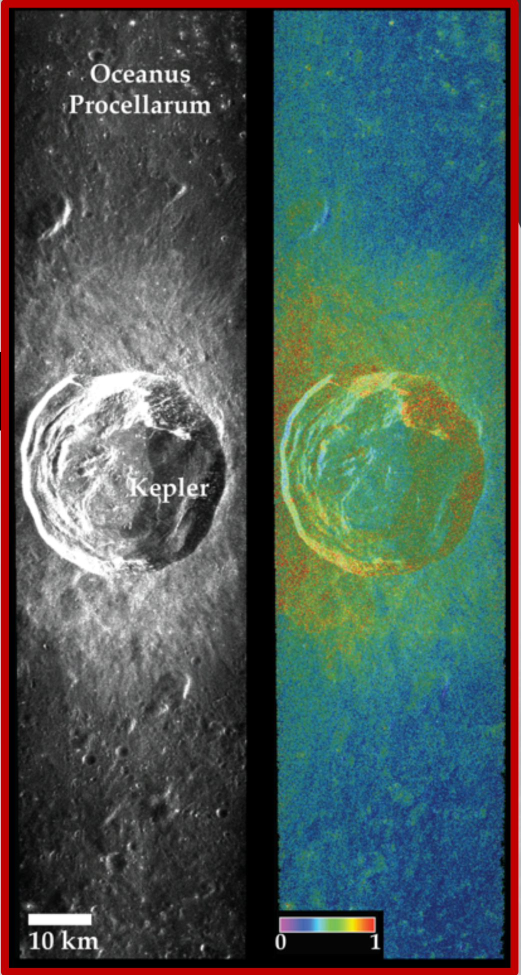
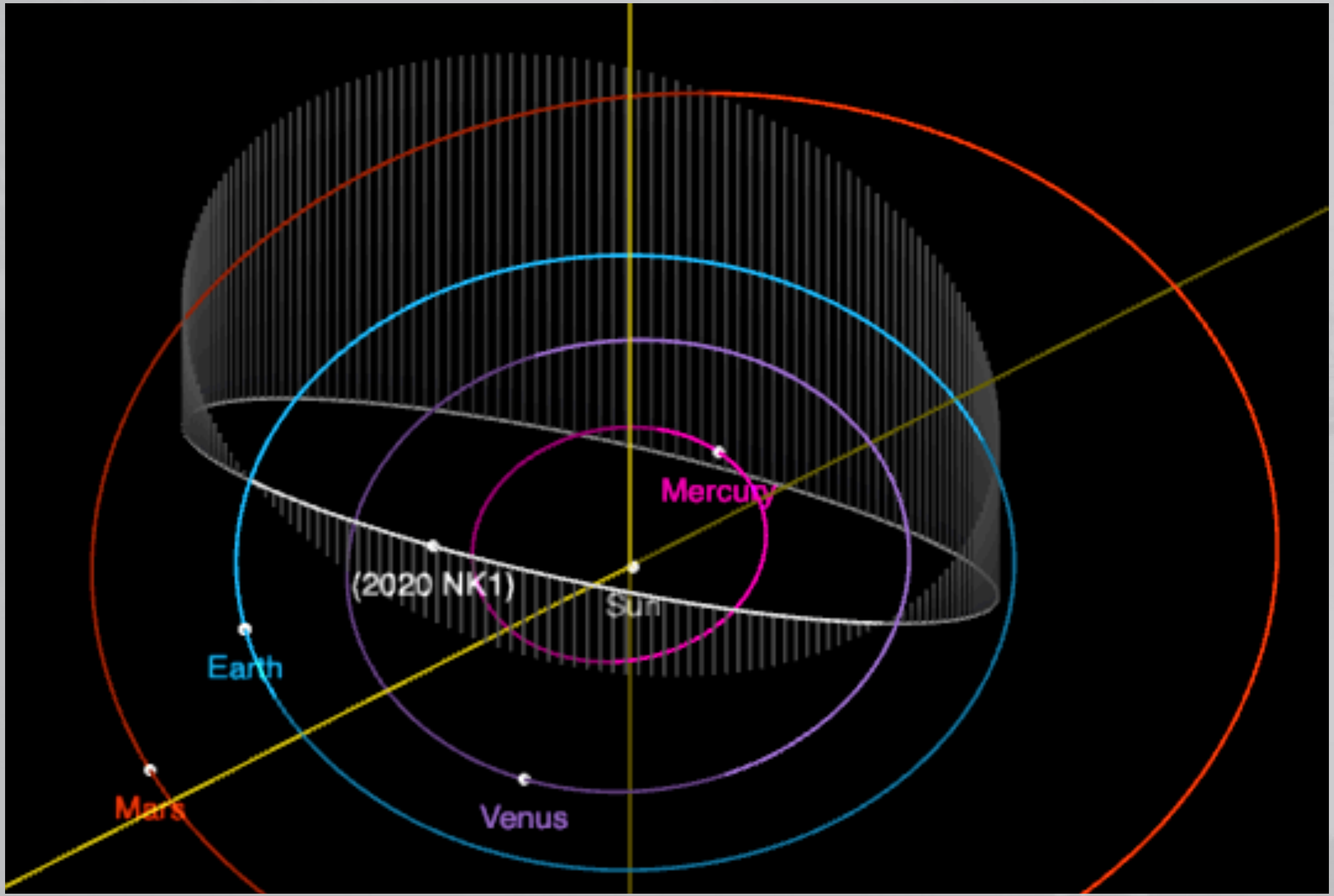


Image credit:
G. Wes Patterson (JHU/APL)

Astrometry: refining orbits of celestial bodies



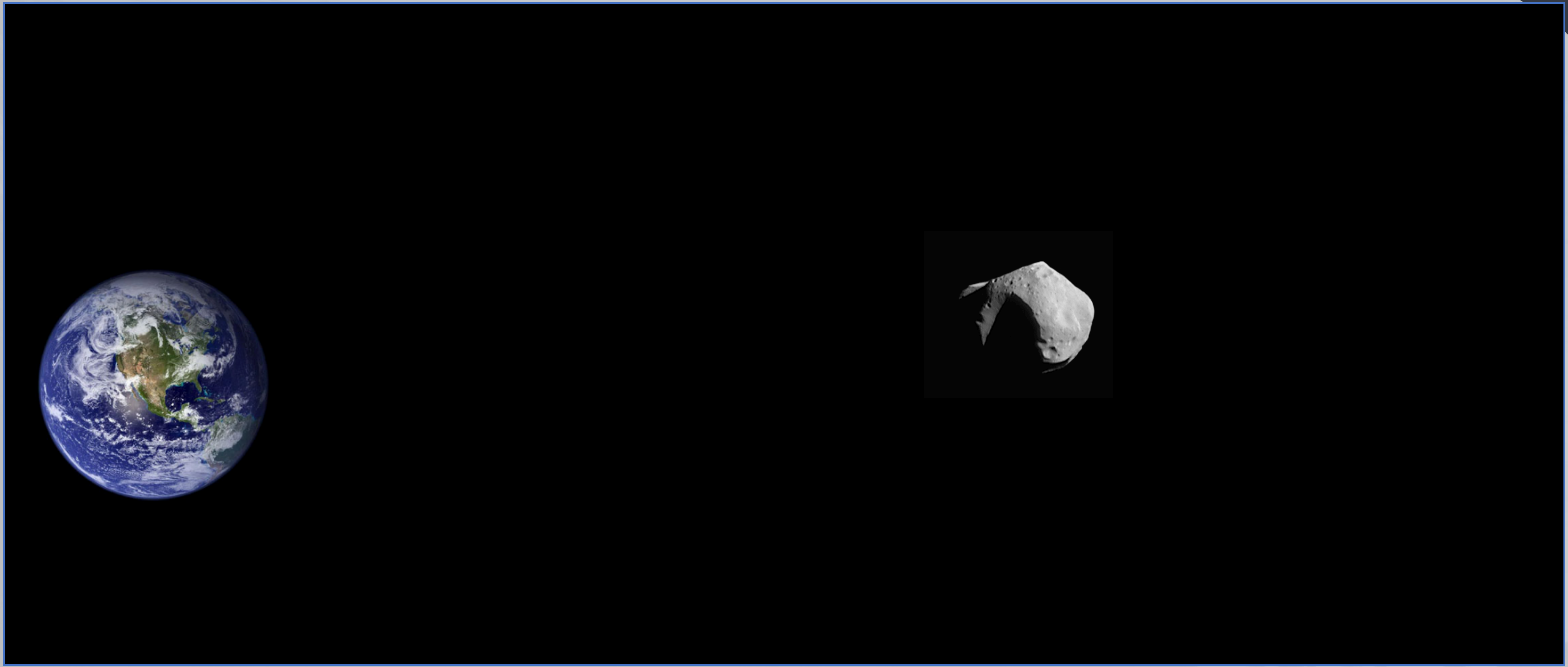
- Range (distance) resolution as fine as ~5 m
- Relative velocity resolution as fine as ~ 10 mm/s

Image credit: https://ssd.jpl.nasa.gov/sbdb.cgi#top

Astrometry: refining orbits of celestial bodies

Image credit: Jon Giorgini (JPL)

Astrometry: refining orbits of celestial bodies



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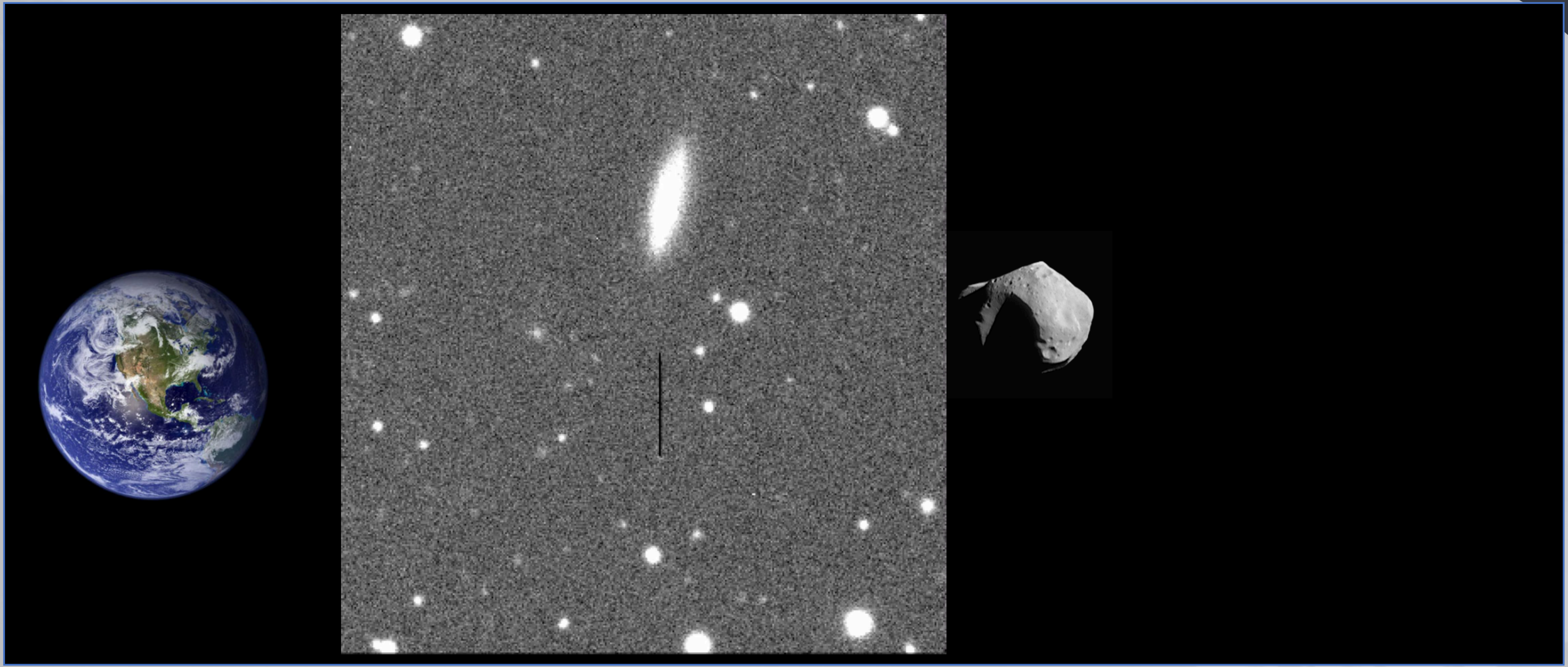

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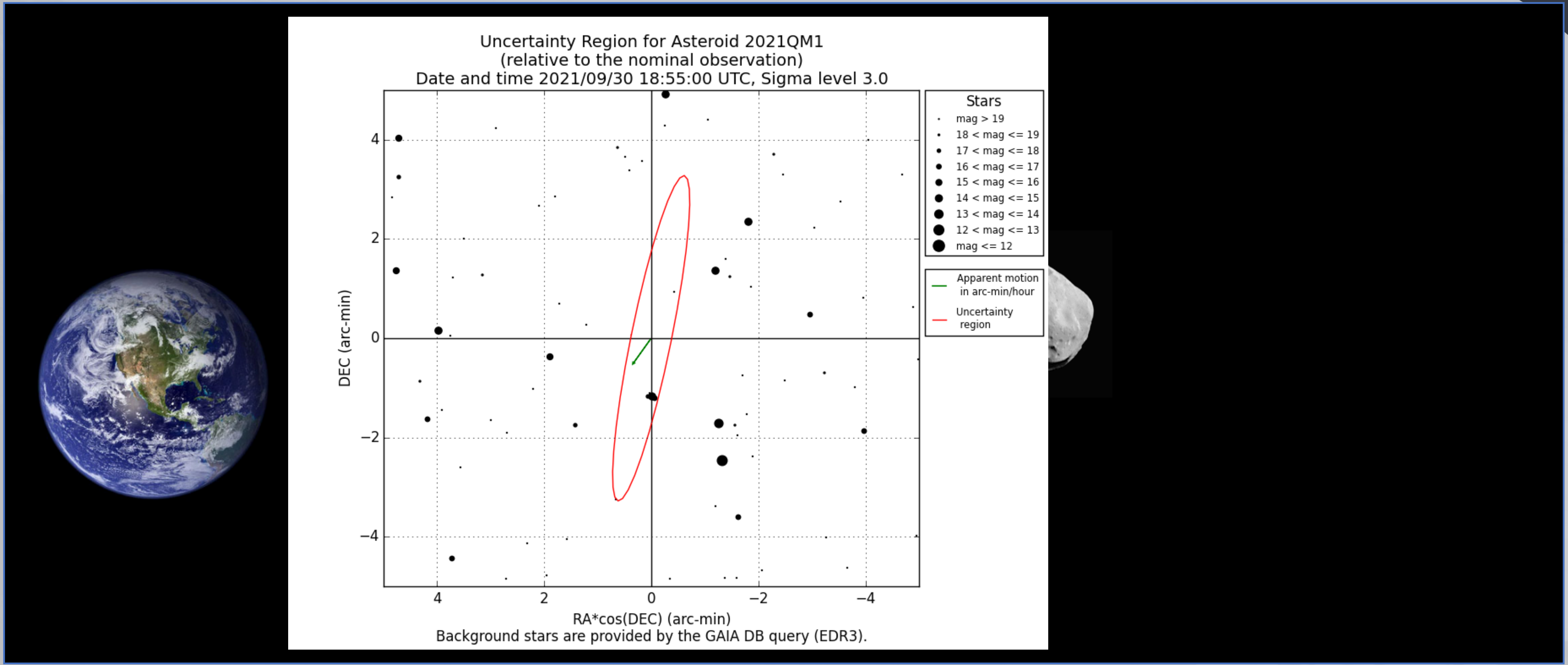

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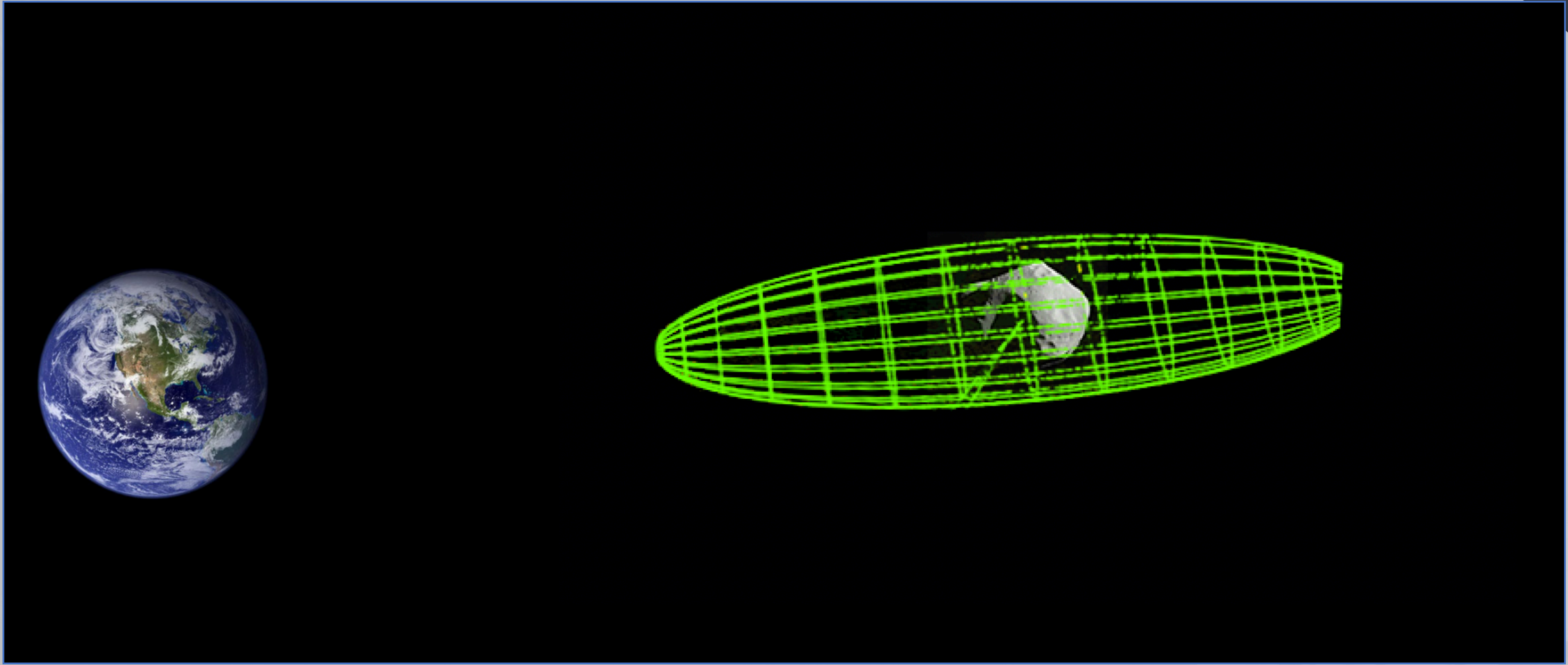

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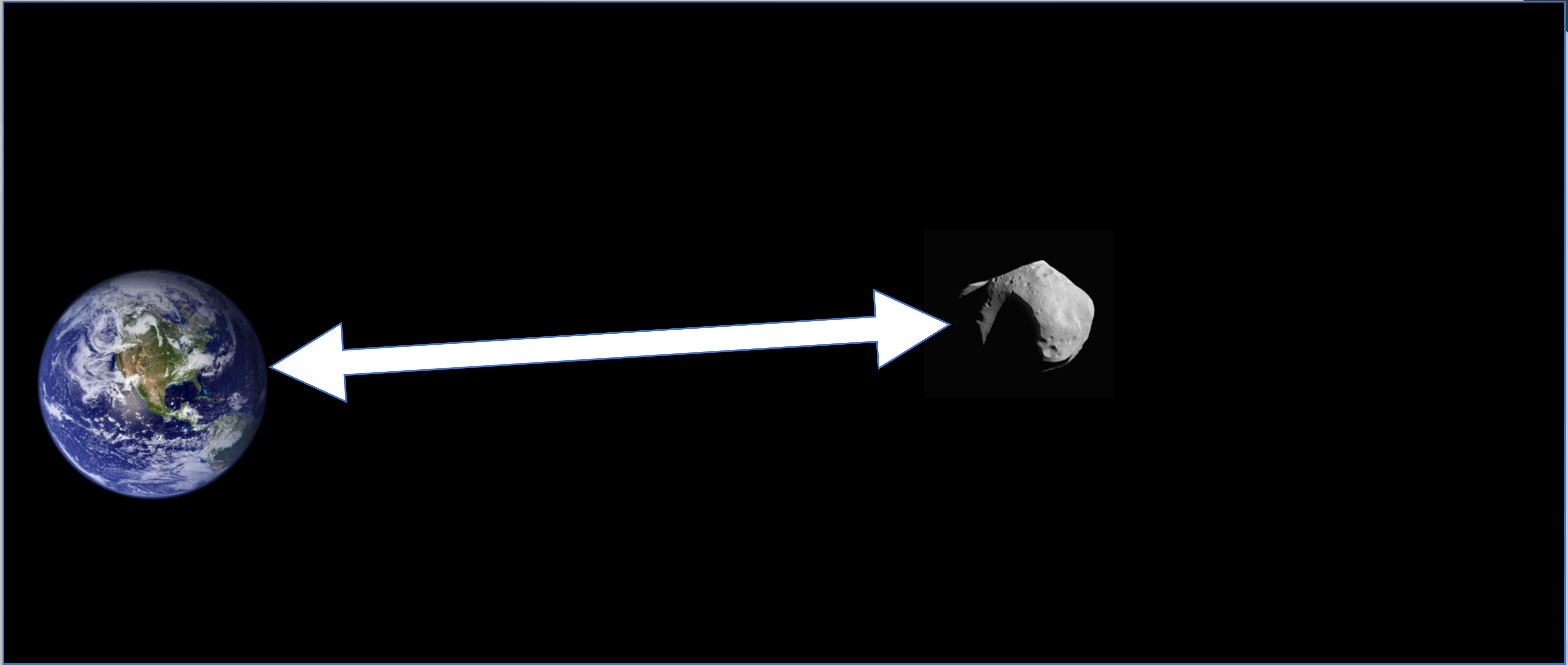

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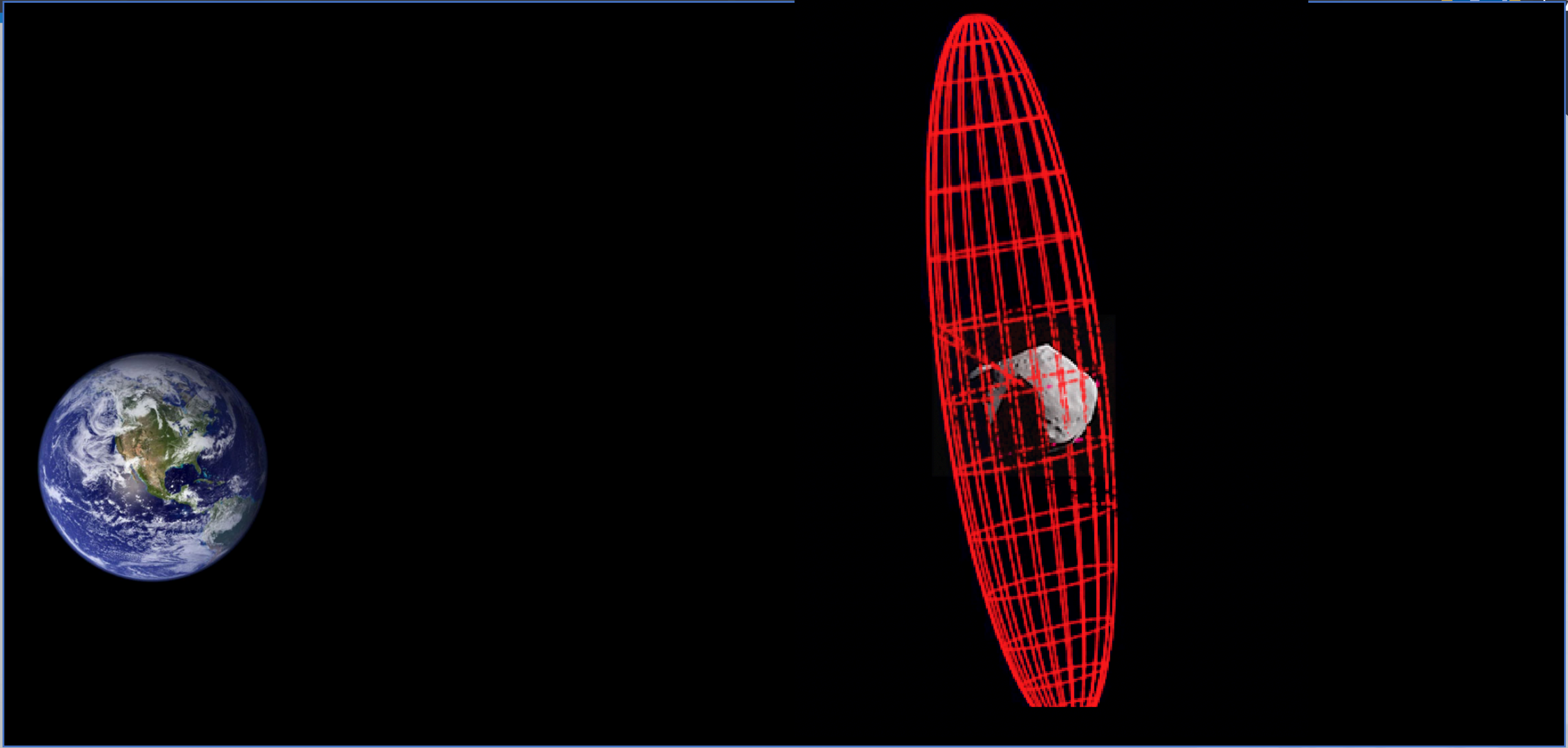

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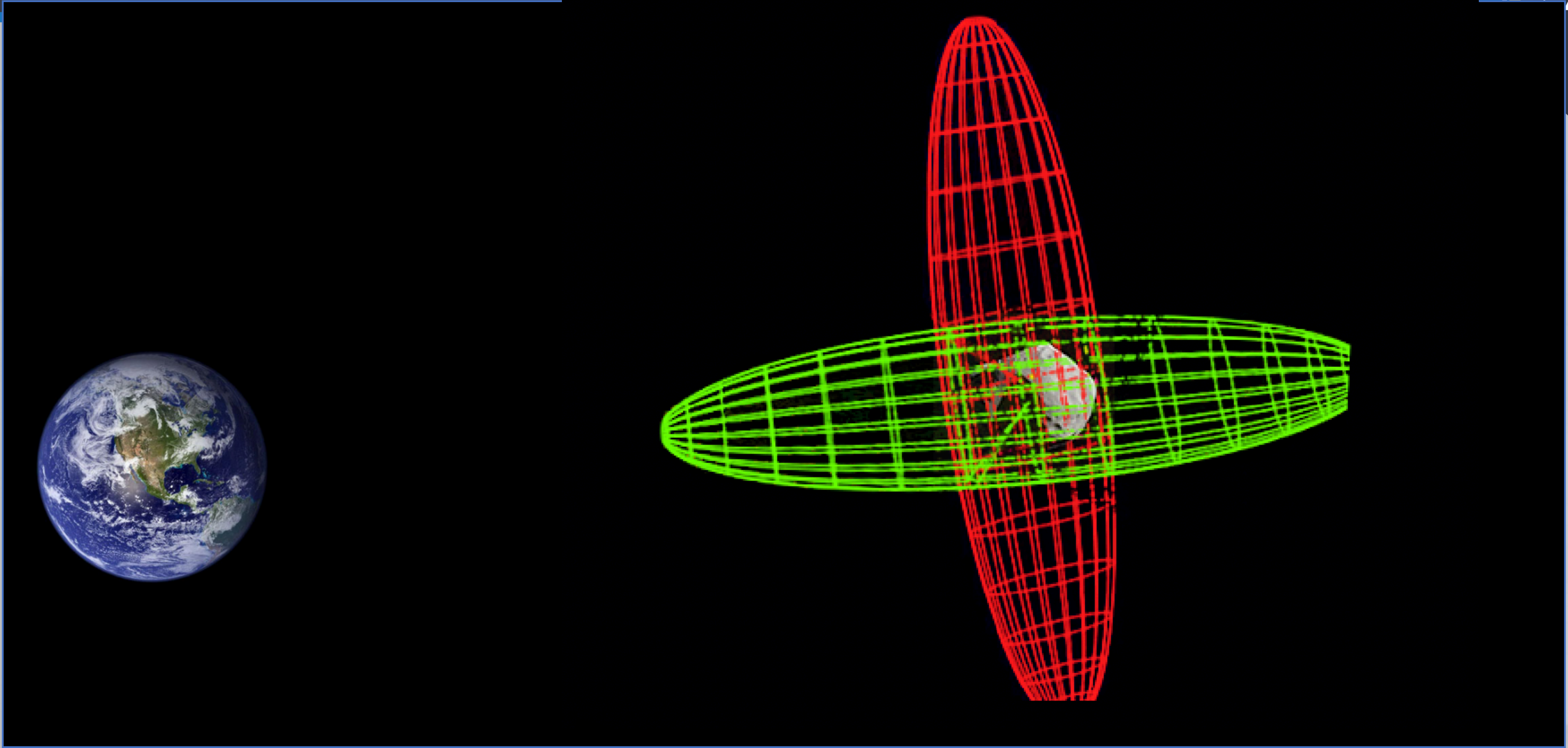


Image credit: Jon Giorgini (JPL)

Arecibo, Goldstone, GBT


Image credit: NASA/JPL-Caltech

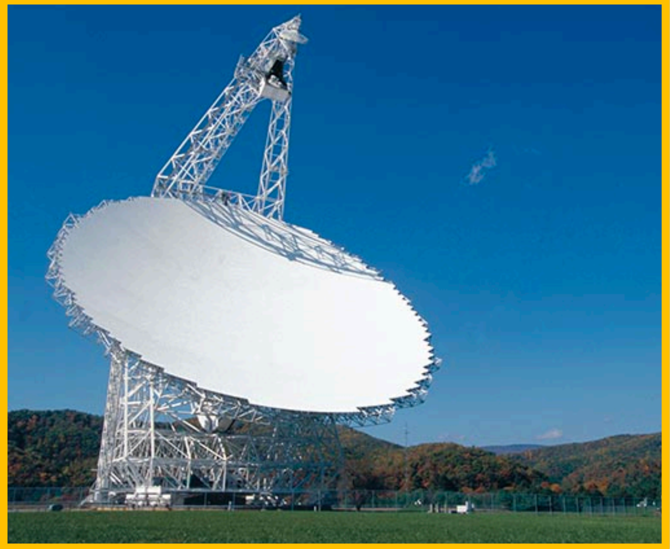
- Declination range: -35°–90° (79% of the whole sky)
- Several antennas (the largest, DSS-14: 70 m)
- Transmitter frequency: 8560 MHz (3.5 cm)
- Power up to 500 kW
- ~70 objects/year attempted, ~60 detected

Goldstone Solar System Radar

Arecibo Observatory

- Declination range: -1–38 (32% of the whole sky)
- 305 m antenna
- Transmitter frequency: 2380 MHz (12.6 cm)
- Power up to 1 MW
- ~100 objects/year attempted, ~80 detected

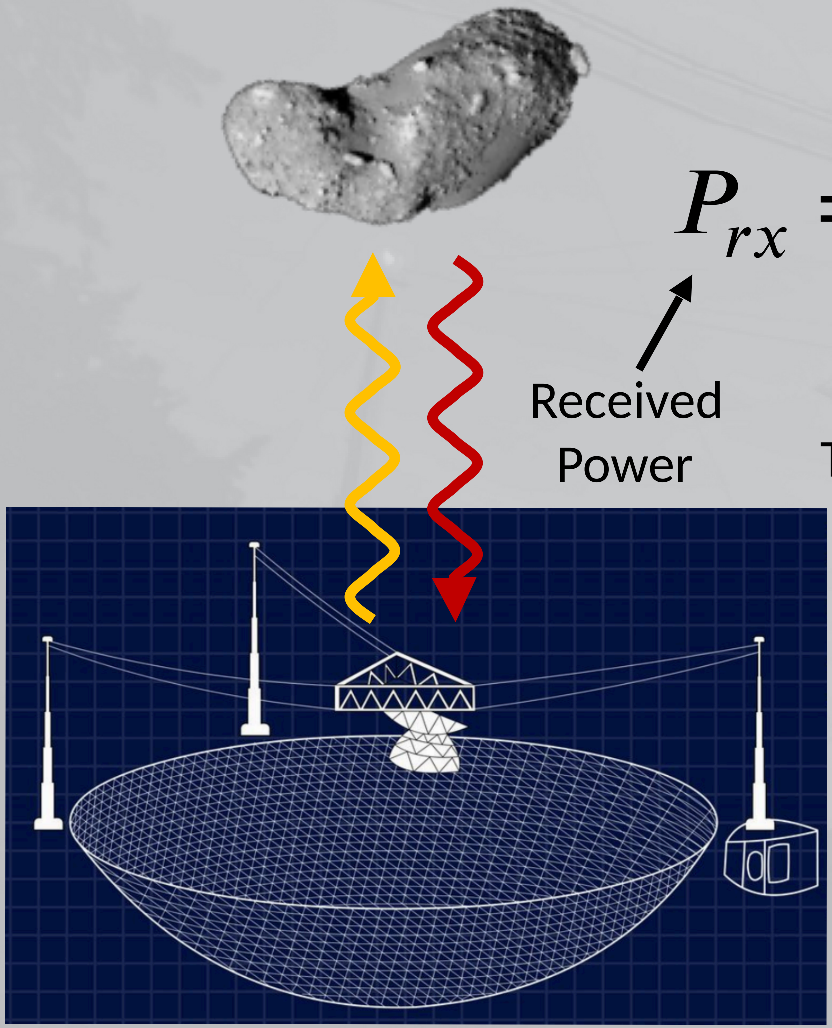
Arecibo, Goldstone, GBT



- Declination range: -46°–90° (86% of the whole sky)
- 100m antenna

Green Bank

The Radar Equation



$$P_{rx} = \left[P_{tx}\right]\left[G_{tx}\right]\left[\frac{1}{4\pi r^2}\right]\left[\sigma\right]\left[\frac{1}{4\pi r^2}\right]\left[A_{eff}\right]$$

Radar Cross Section

Received Power

Transmitted Power

Transmitter Gain

Geometric Spreading

Effective Aperture

Image credit: JAXA

Continuous Wave (CW)

- **Continuous Wave (CW) signals:**
  - This is when we transmit a continuous signal with a **constant amplitude, phase, and frequency.**
  - We cannot differentiate signals based on when they arrive **(no range information).** This **only gives us information on the shift in frequency, or Doppler shift of the reflected signal**, based on the motion of the target.

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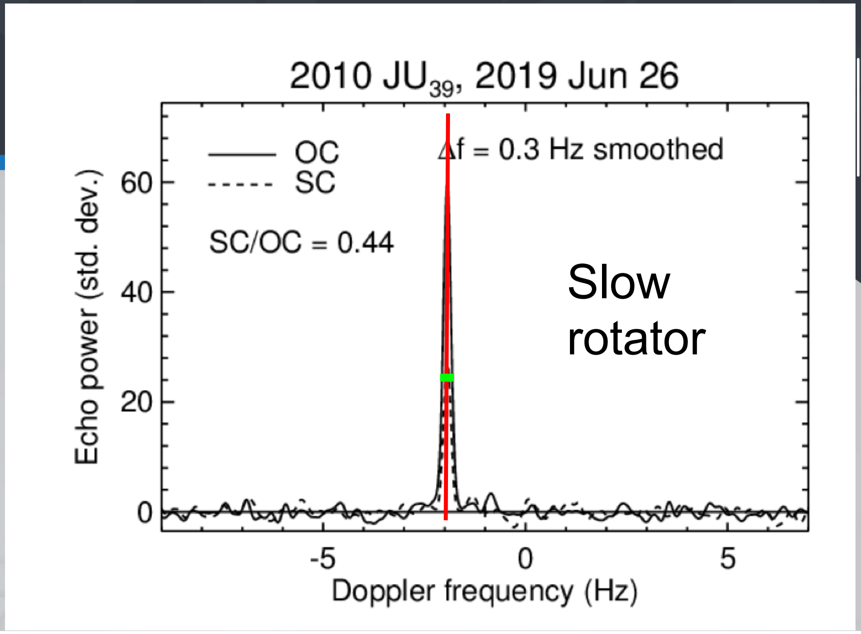
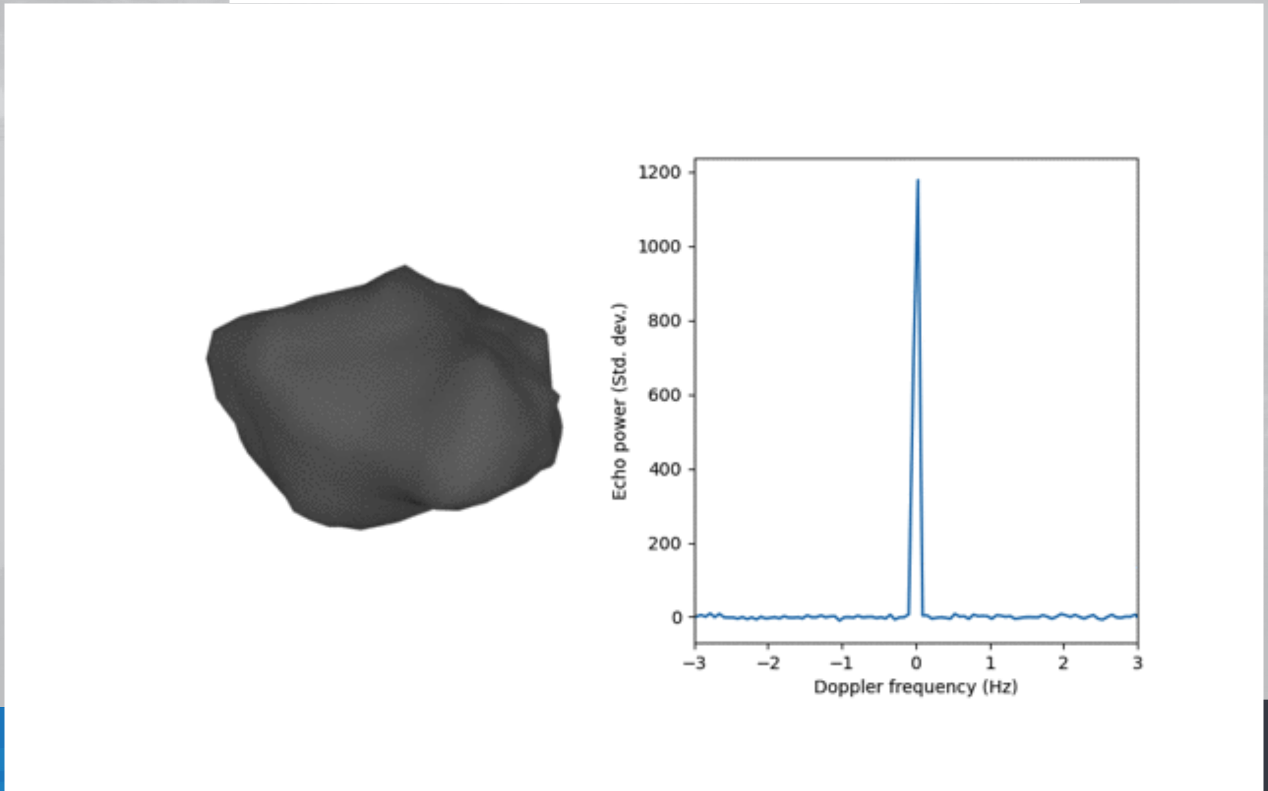


Slow rotator



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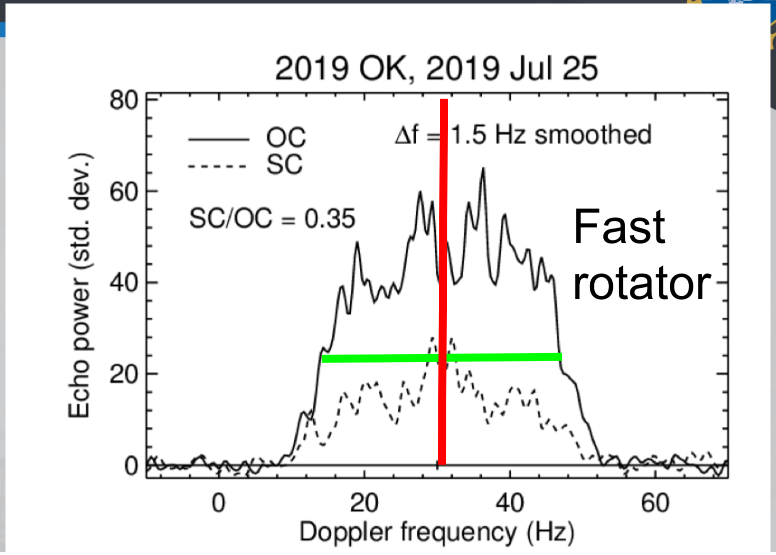
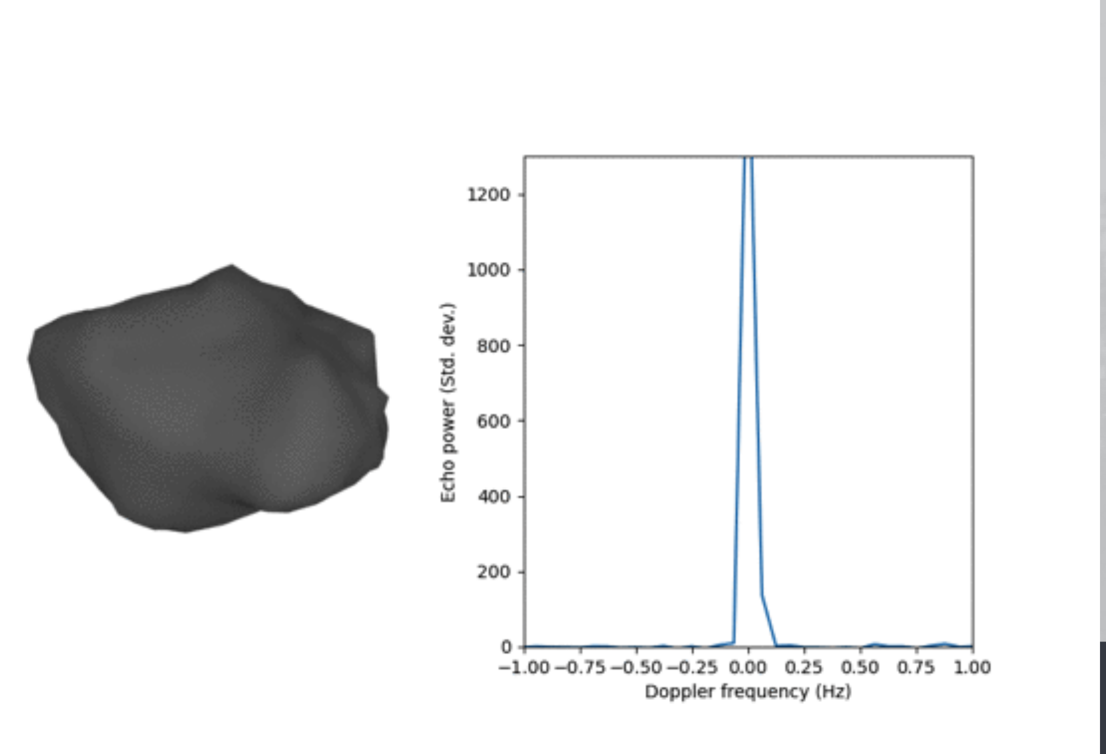
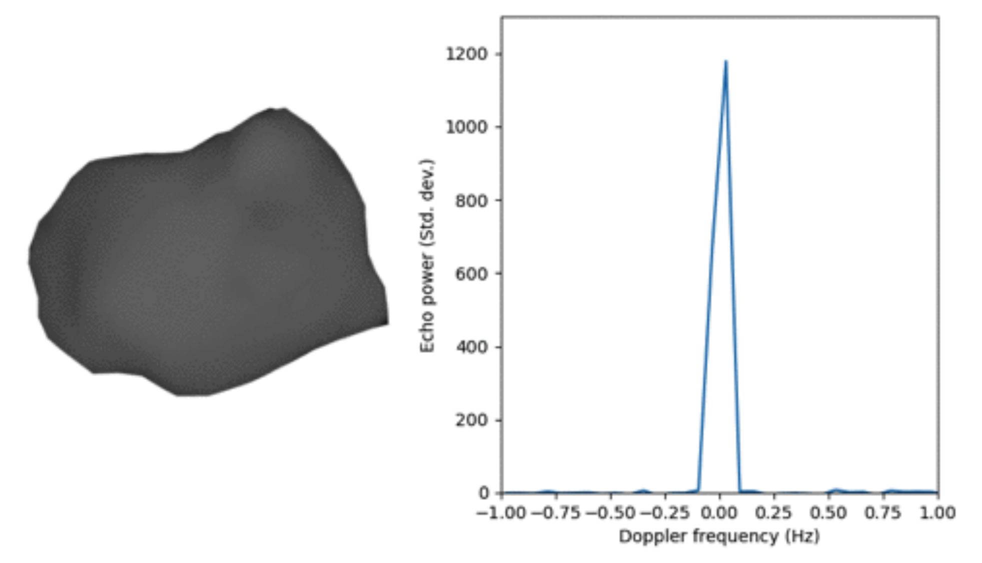




SNR: Detectability

- Target's doppler bandwidth depends on size and spin state:

$$B = \frac{4\pi D cos\phi}{\lambda_0 P_{spin}}$$



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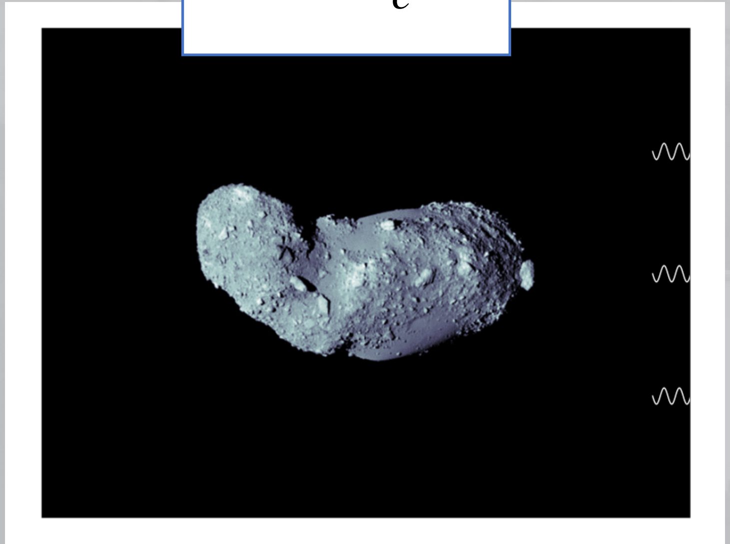

$$\Delta f = \frac{2v}{c} f_e$$

Doppler equation: $f_o = \left(1 \pm \frac{2v}{c}\right) f_e$

$$v = \frac{\pi D}{P} \qquad f_e = \frac{c}{\lambda}$$

$$B = \frac{2v}{c} f_e - \left(-\frac{2v}{c} f_e\right)$$

$$B = \frac{4\pi D}{\lambda P}$$

SNR: Detectability

- Target's doppler bandwidth depends on size and spin state:

$$B = \frac{4\pi D cos\phi}{\lambda_0 P_{spin}}$$

- RMS noise power depends on bandwidth, integration time, and system temperature:

$$N_{rms} = kT_{sys}\sqrt{\frac{B}{\tau}}$$

k = Boltsmann's constant

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- Need SNR of ~6 for detection, but much higher SNR for imaging

$$SNR = \frac{P_{rx}}{N_{rms}}$$

$$P_{rx} = \frac{P_{tx}G_{tx}\sigma A_{eff}}{(4\pi)^2 r^4}$$

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SNR ~ (System factor)(Target factor) $\sqrt{\Delta t}$

System factor~ $\frac{P_{\text{tx}}G_{ant}A_{\text{eff}}}{T_{\text{sys}}\lambda^{1/2}}$

Target factor ~ $\frac{\hat{\sigma}D^{3/2}P^{1/2}}{r^4}$

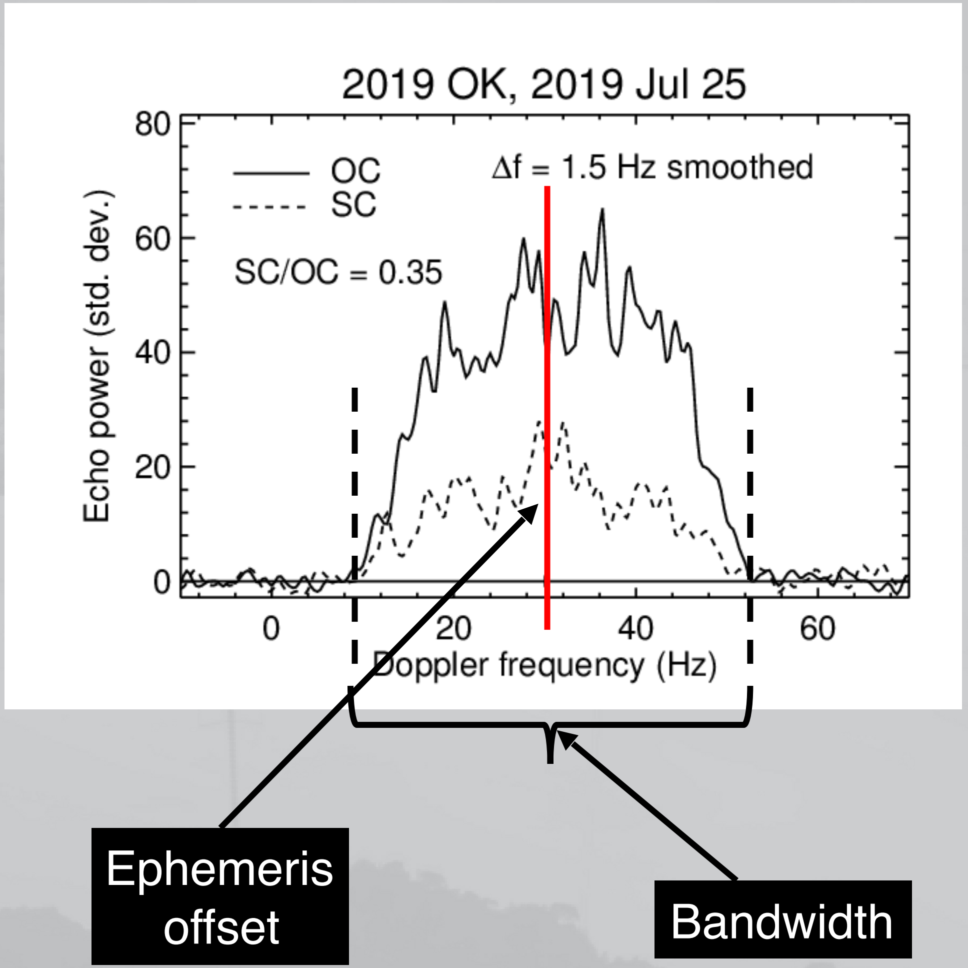
$\hat{\sigma}$ = radar albedo

For every CW detection we learn:

- **Astrometry:** ~ 30 Hz offset in line-of-sight velocity of target
- **Rotation rate:** estimate from bandwidth and size

$$B = \frac{4\pi D cos\phi}{\lambda_0 P_{spin}}$$

- **CPR:** related to surface roughness and composition



Ephemeris offset

Bandwidth

Coded Waveforms

- **Coded (modulated) signals:**
  - By adding some code, or time structure, to the transmitted signal, either **by varying the frequency, phase, or amplitude, we can determine ranges of targets**, or what distances from the telescope different portions of the signal were reflected from.

  - Convolve received signal with transmitted signal in **matched filter**.

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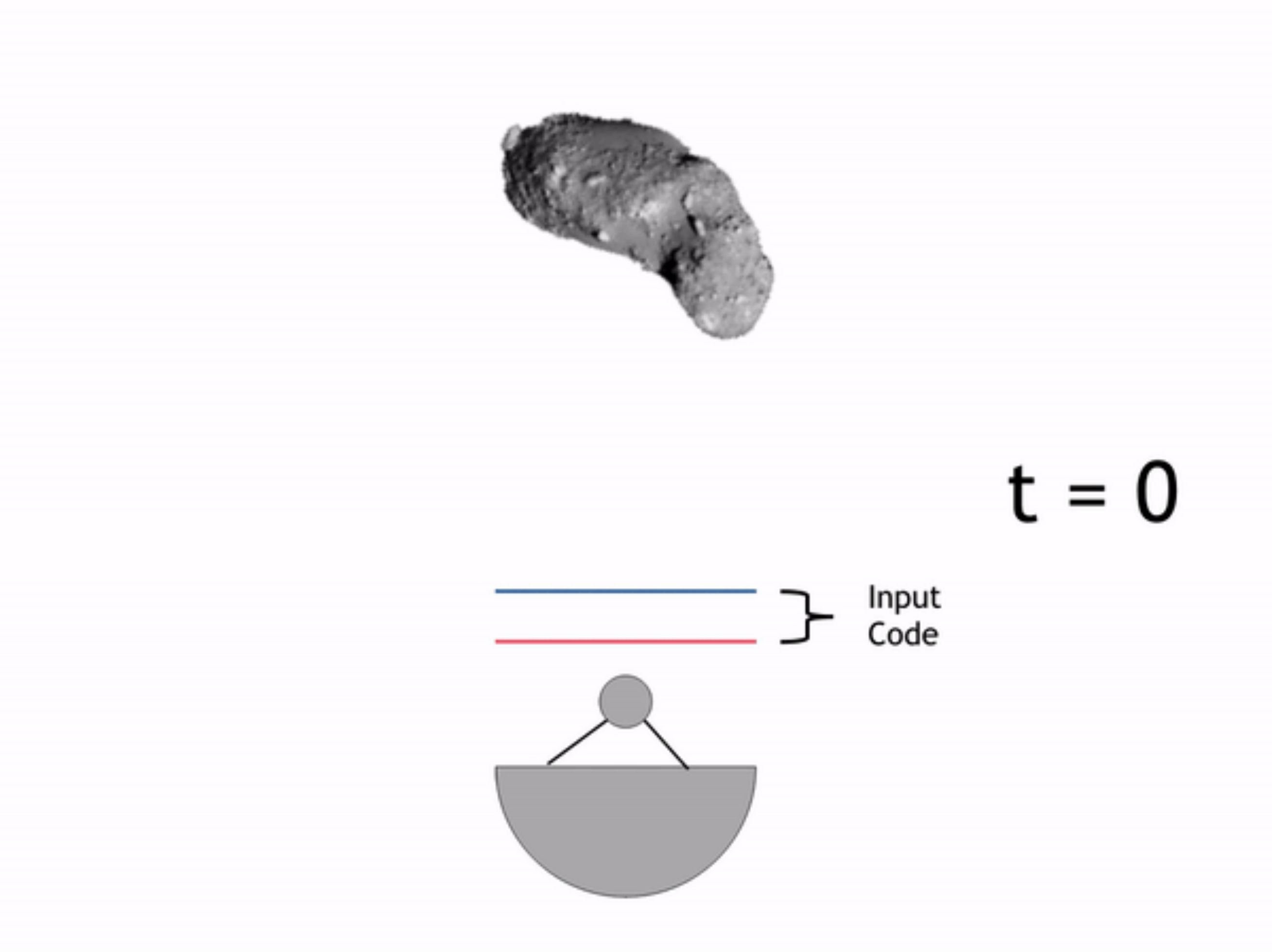
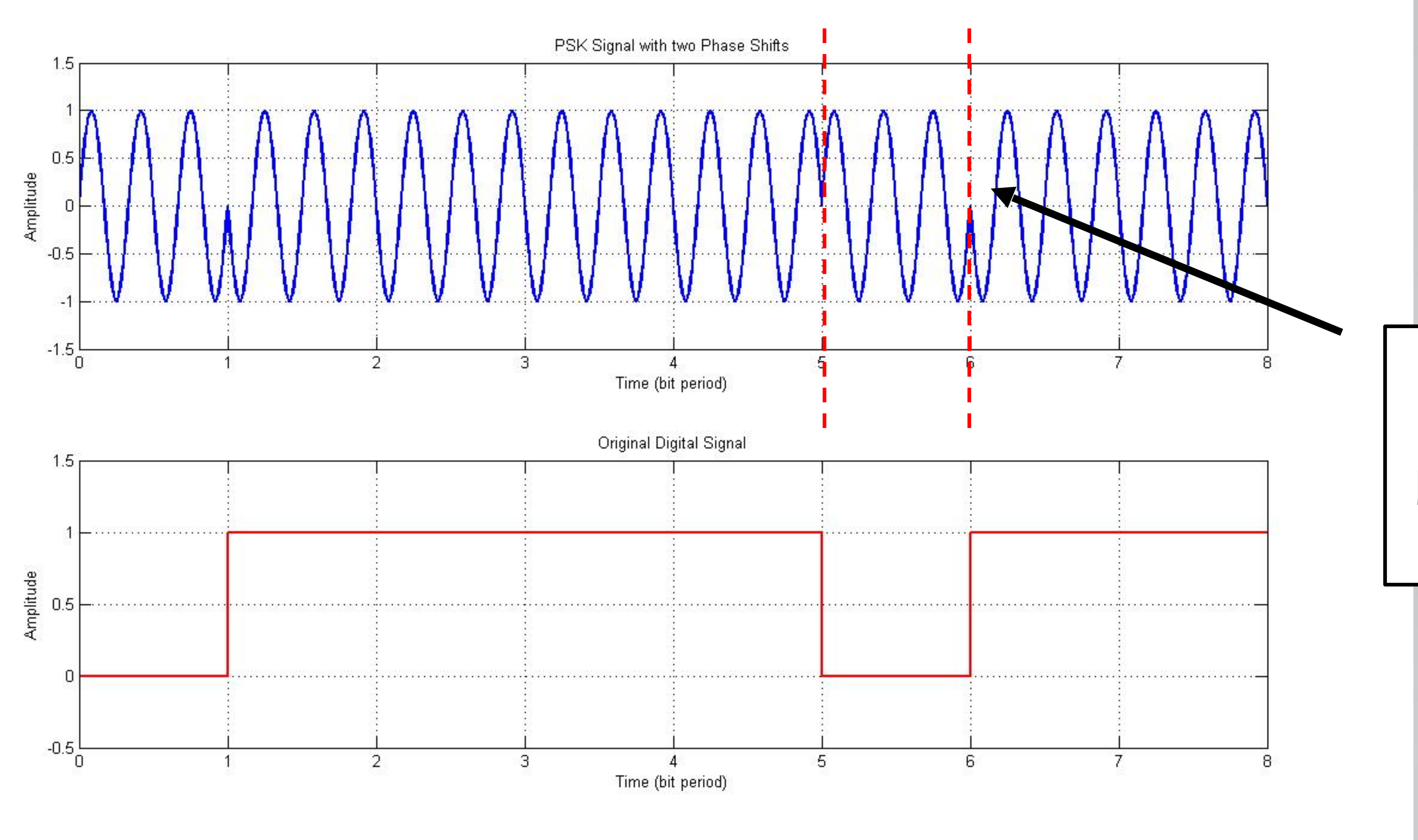


Binary Phase Coded Waveform

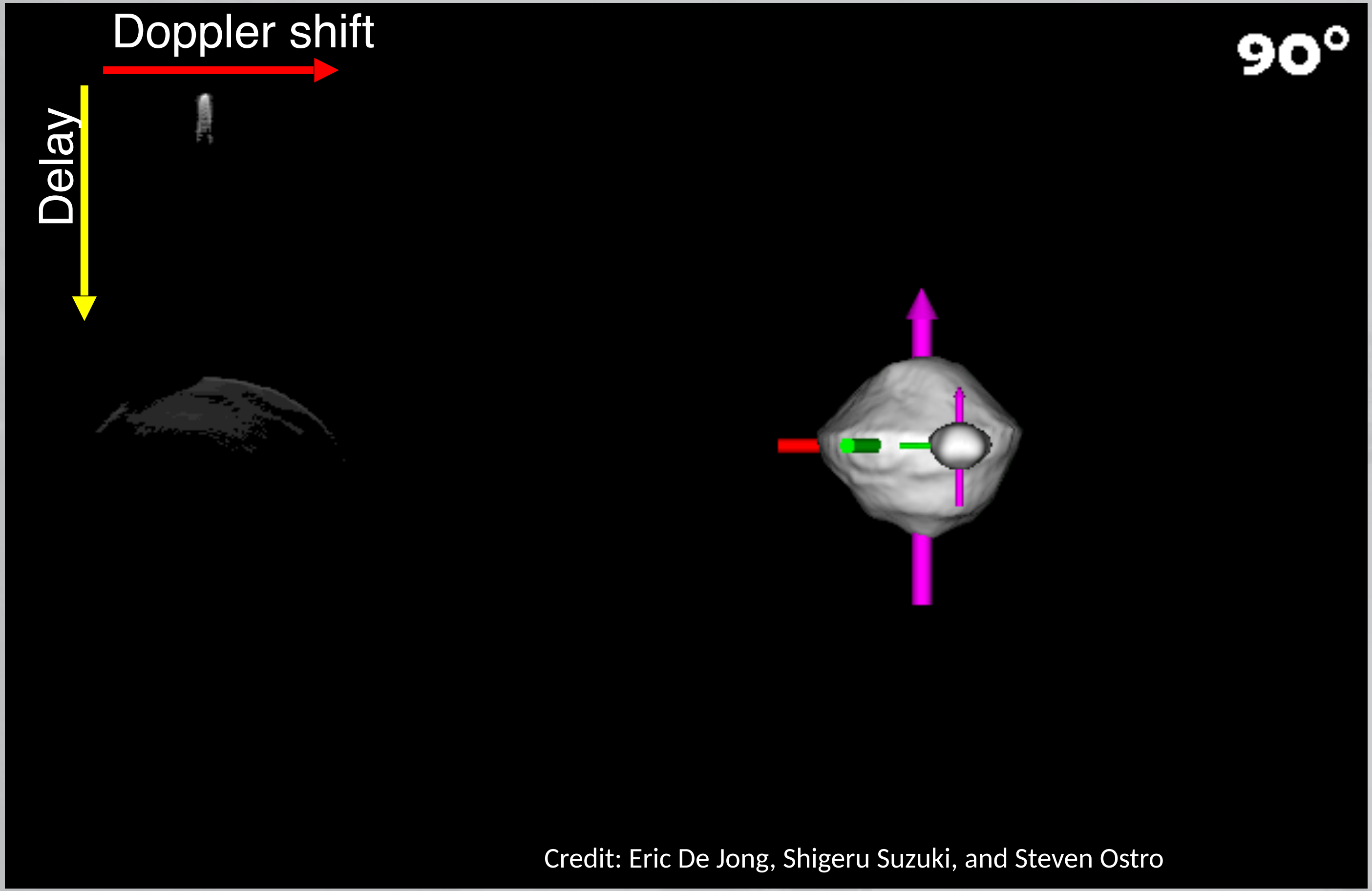


One baud, defined as the length of time between phase shifts

$$\Delta r = \frac{c \bullet baud}{2}$$

- Code Bandwidth = 1/[baud][codelength]

delay-Doppler Imaging



Credit: Eric De Jong, Shigeru Suzuki, and Steven Ostro

Time Delay: Distance
- Vertical axis
- Increasing downward
- Points at the top are closest to the observer

Doppler Frequency: Velocity
- Horizontal axis
- Increasing to the right
- Points on the right are approaching the observer

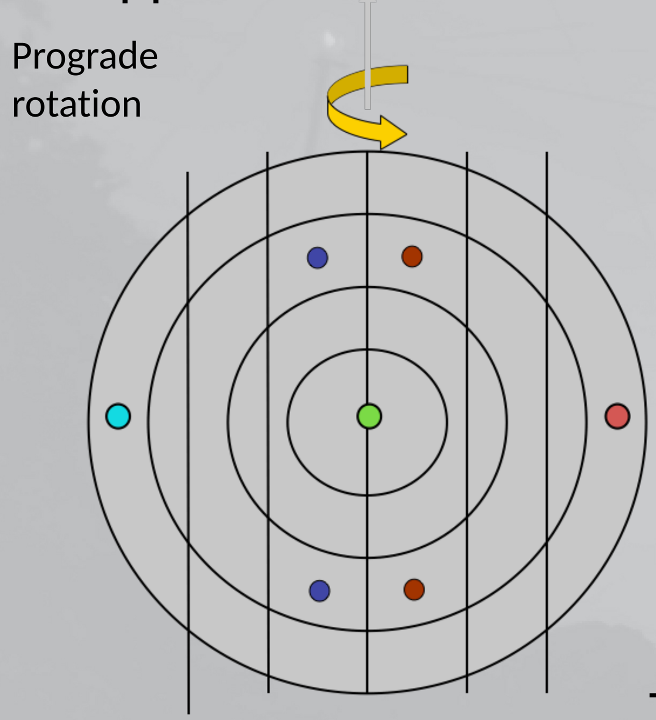
- Splitting signal into discrete range & frequency bins
- Requires high SNR

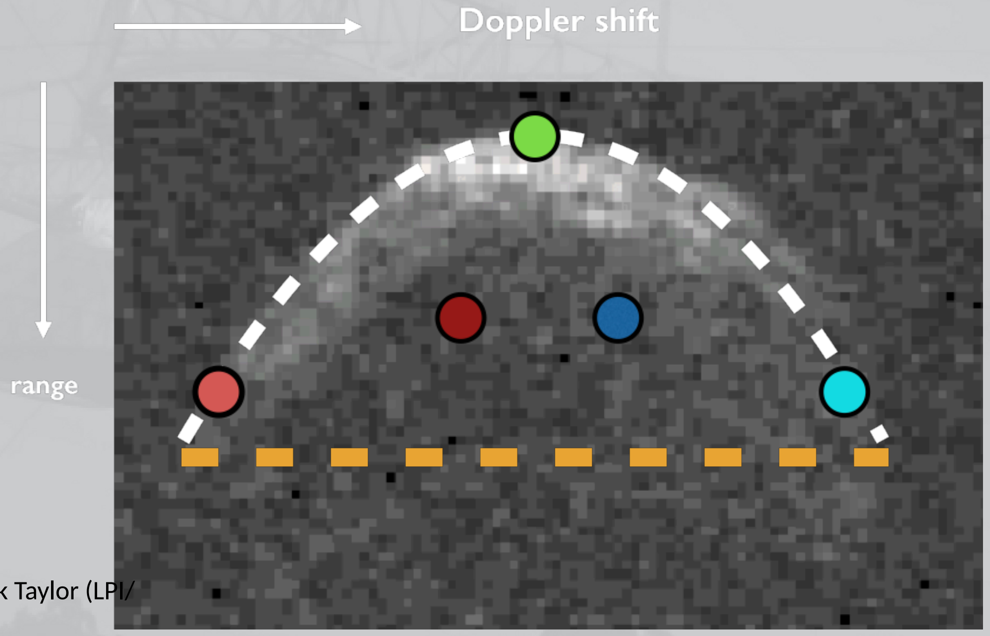
3D – 2D ambiguity

Circles: points at the same distance (range) from observer

Vertical Lines: points of constant Doppler shift

Blue dots are blue shifted, red dots are red-shifted, green dots are not Doppler shifted

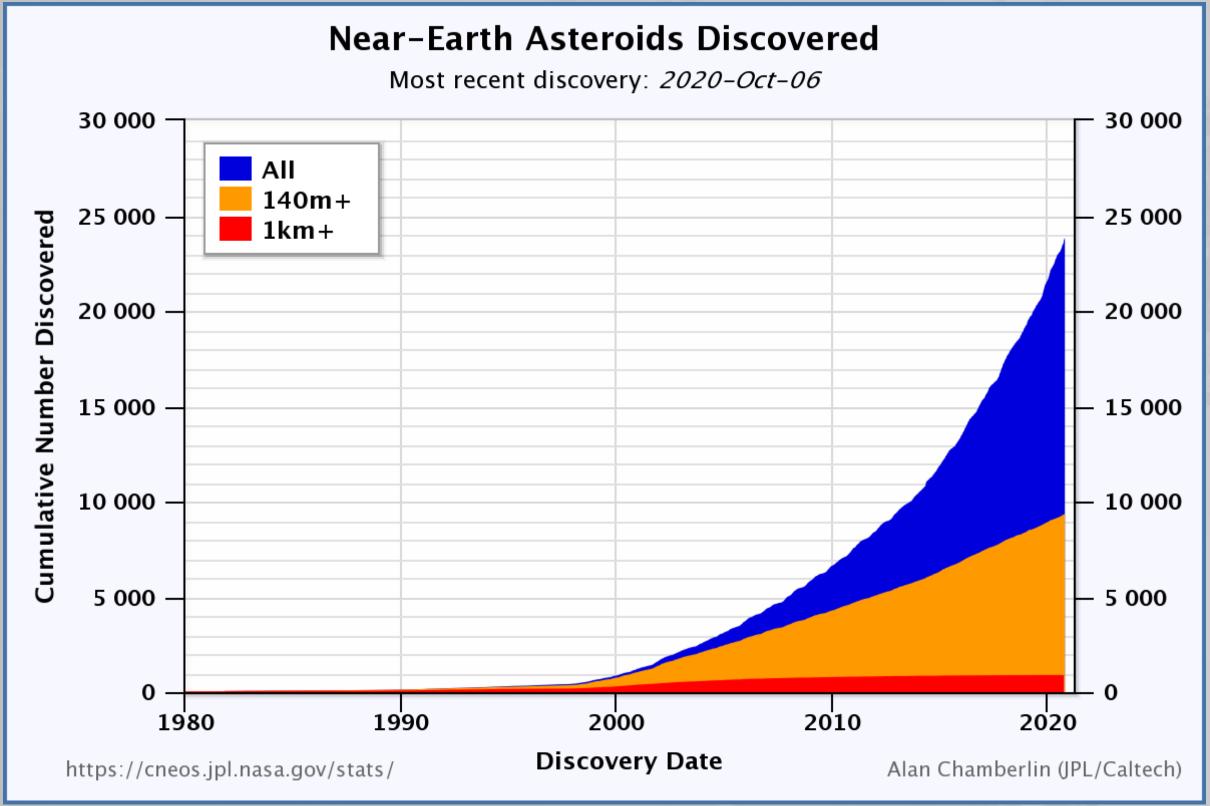




Courtesy Patrick Taylor (LPI/USRA)

The two blue and red dots map to the same point in a radar image (north/south ambiguity)

Arecibo Observatory detects and characterizes ~100 near-Earth objects (NEOs) per year



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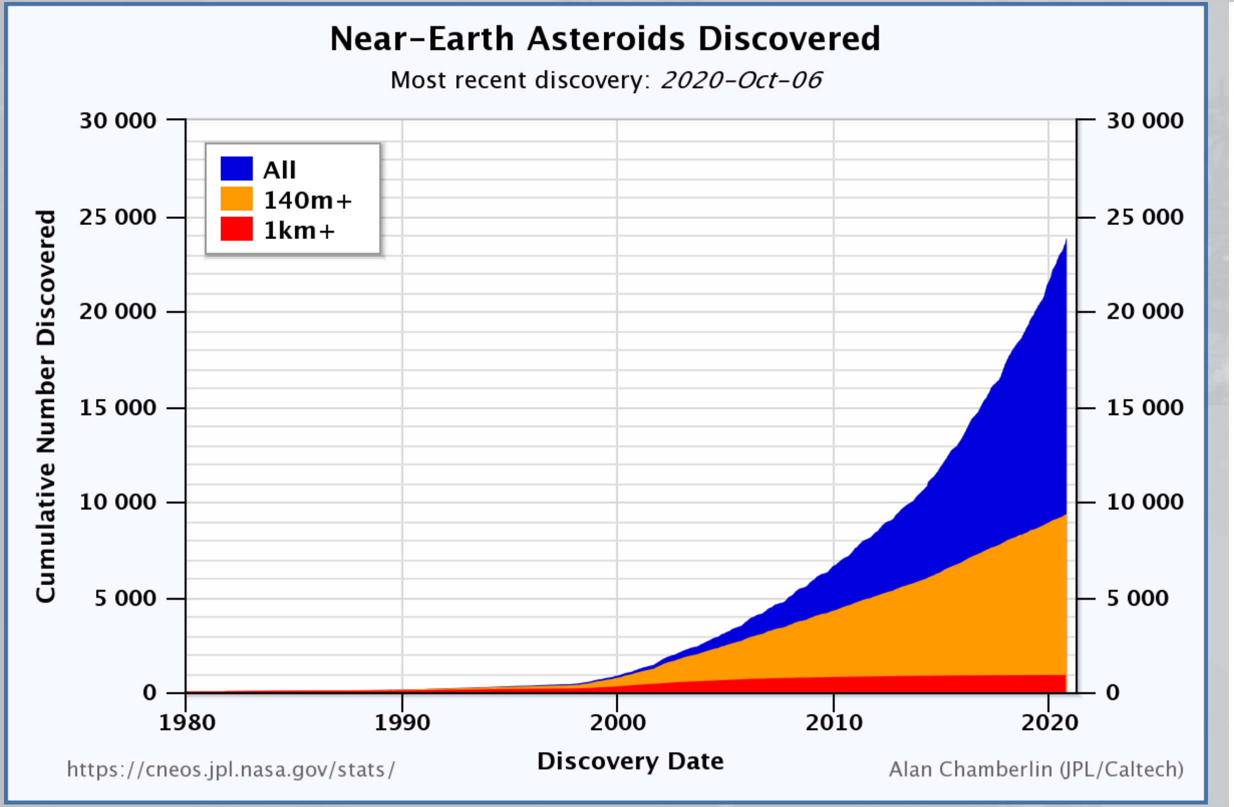

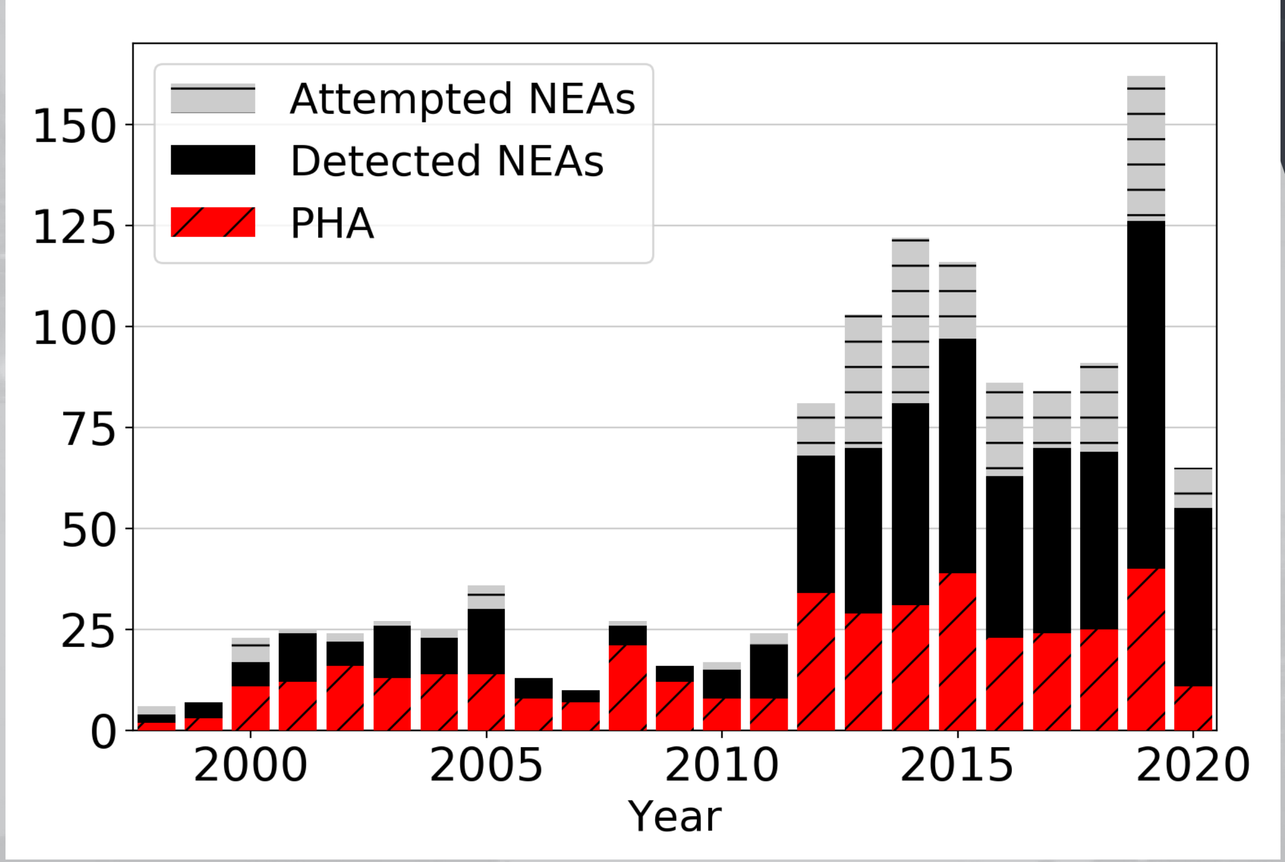

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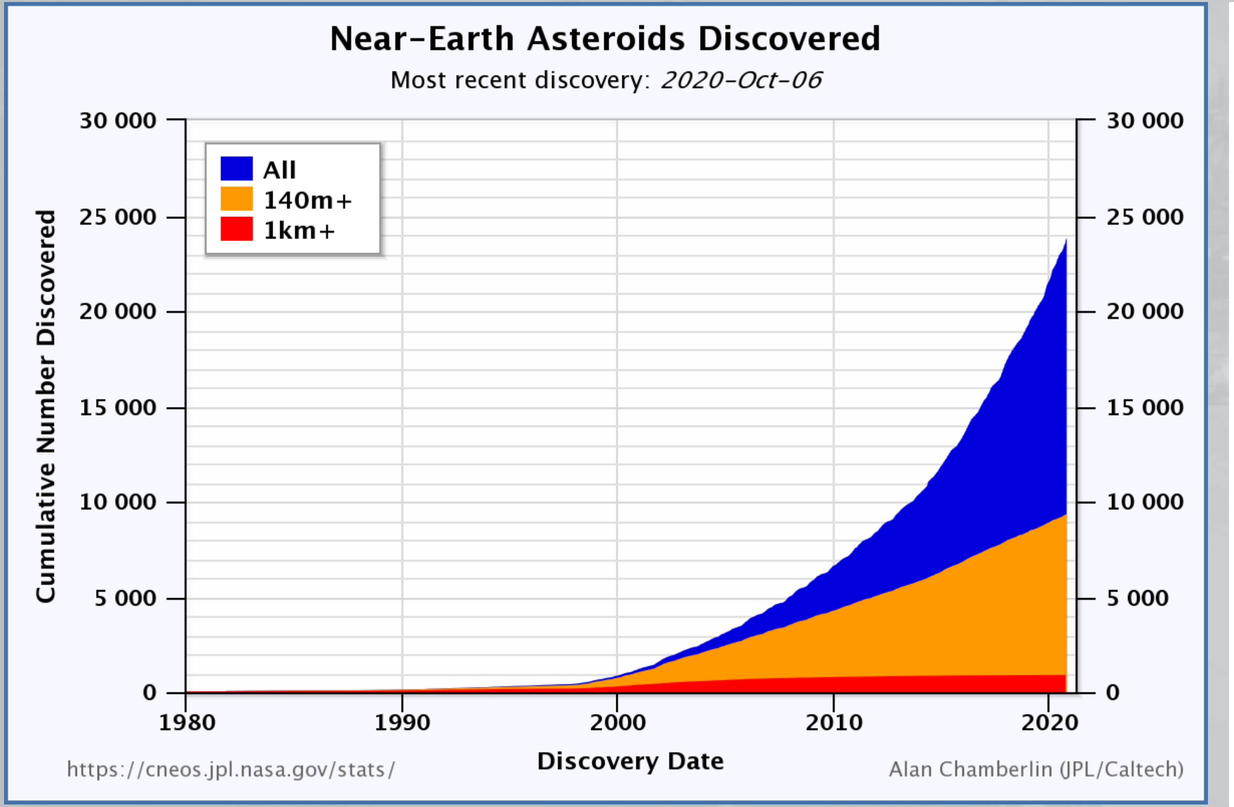
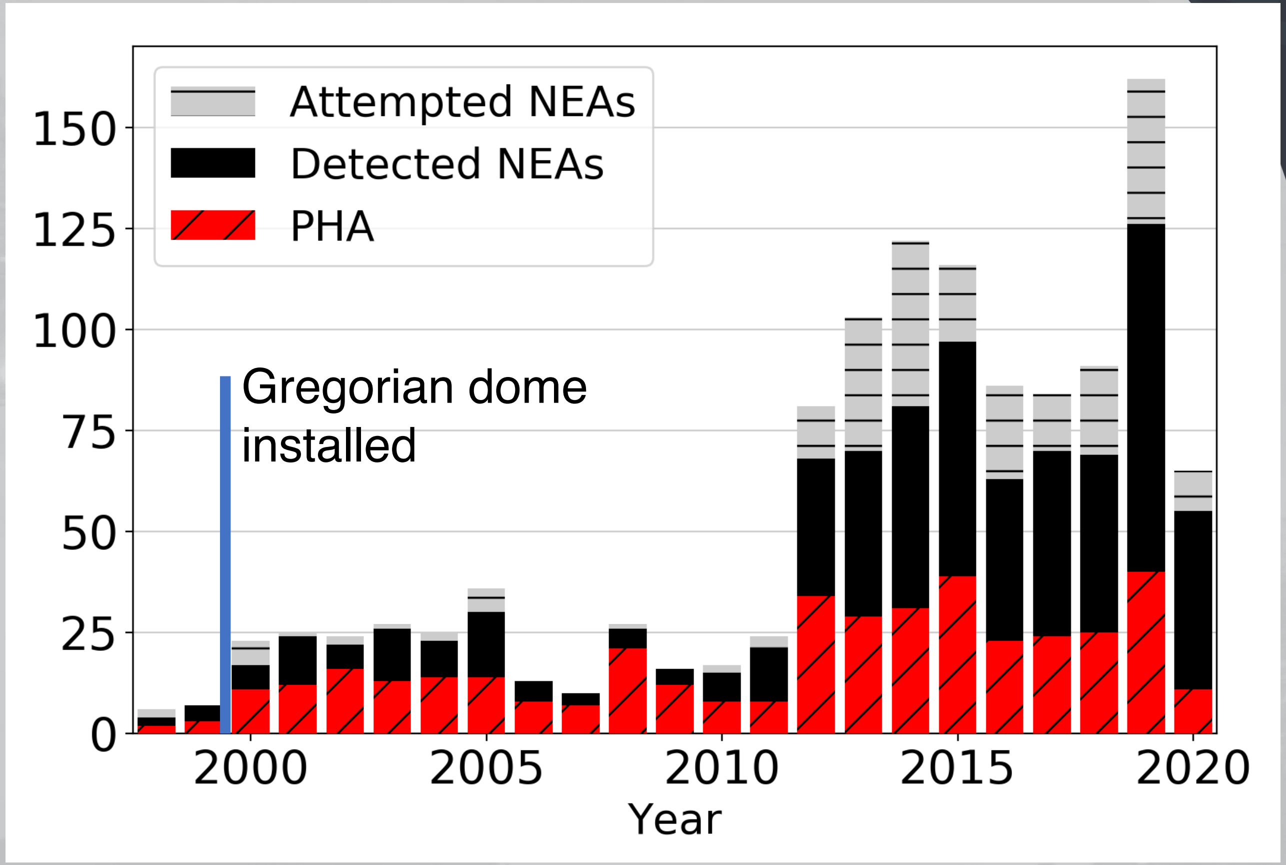

Near-Earth Asteroids Discovered

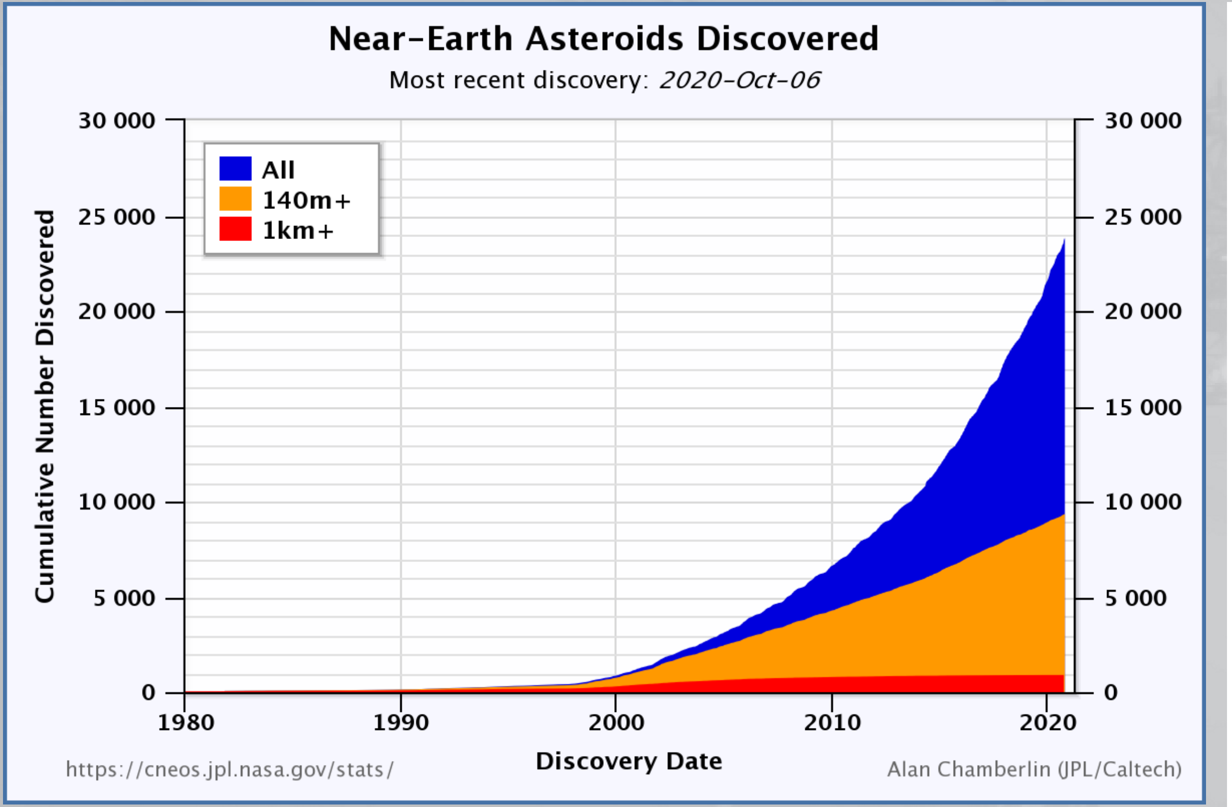
Most recent discovery: *2020-Oct-06*

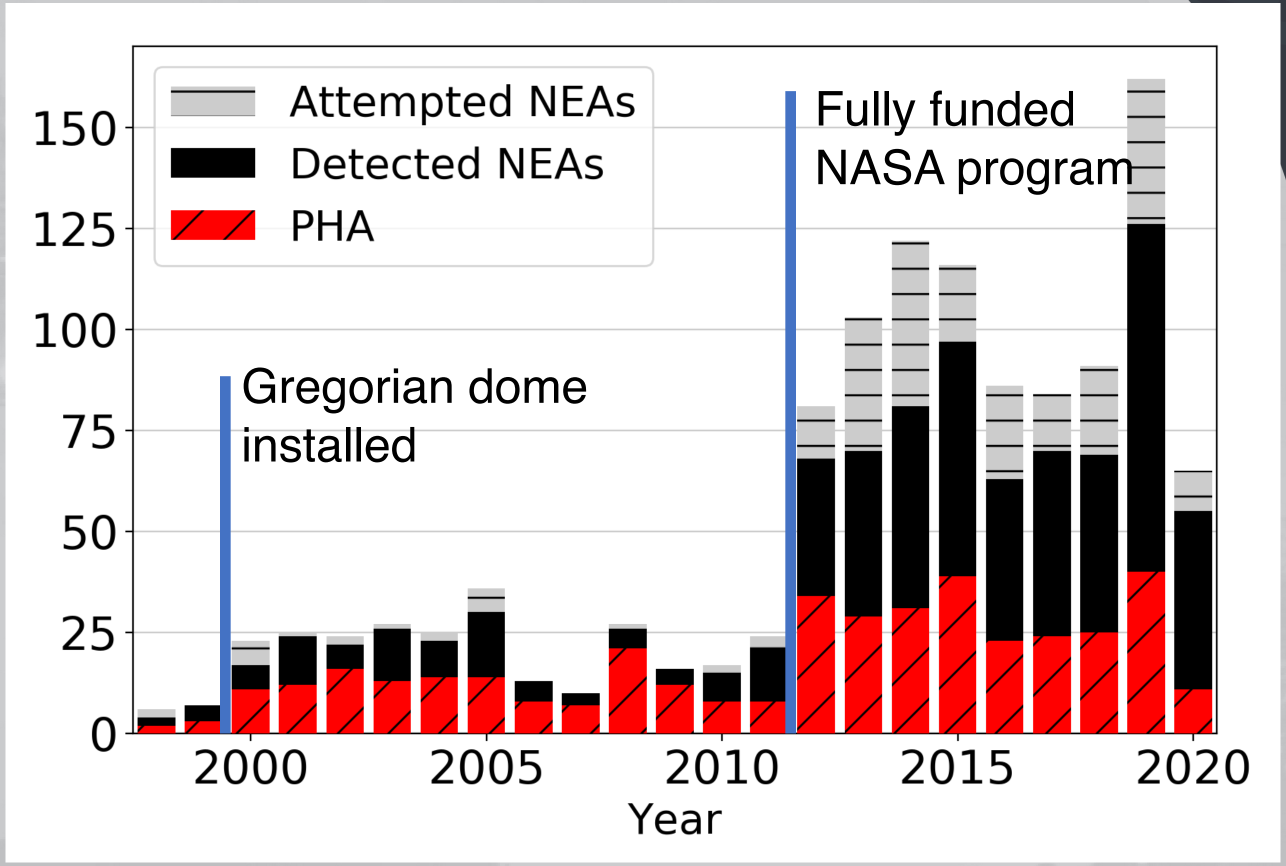
https://cneos.jpl.nasa.gov/stats/

Alan Chamberlin (JPL/Caltech)


Gregorian dome installed

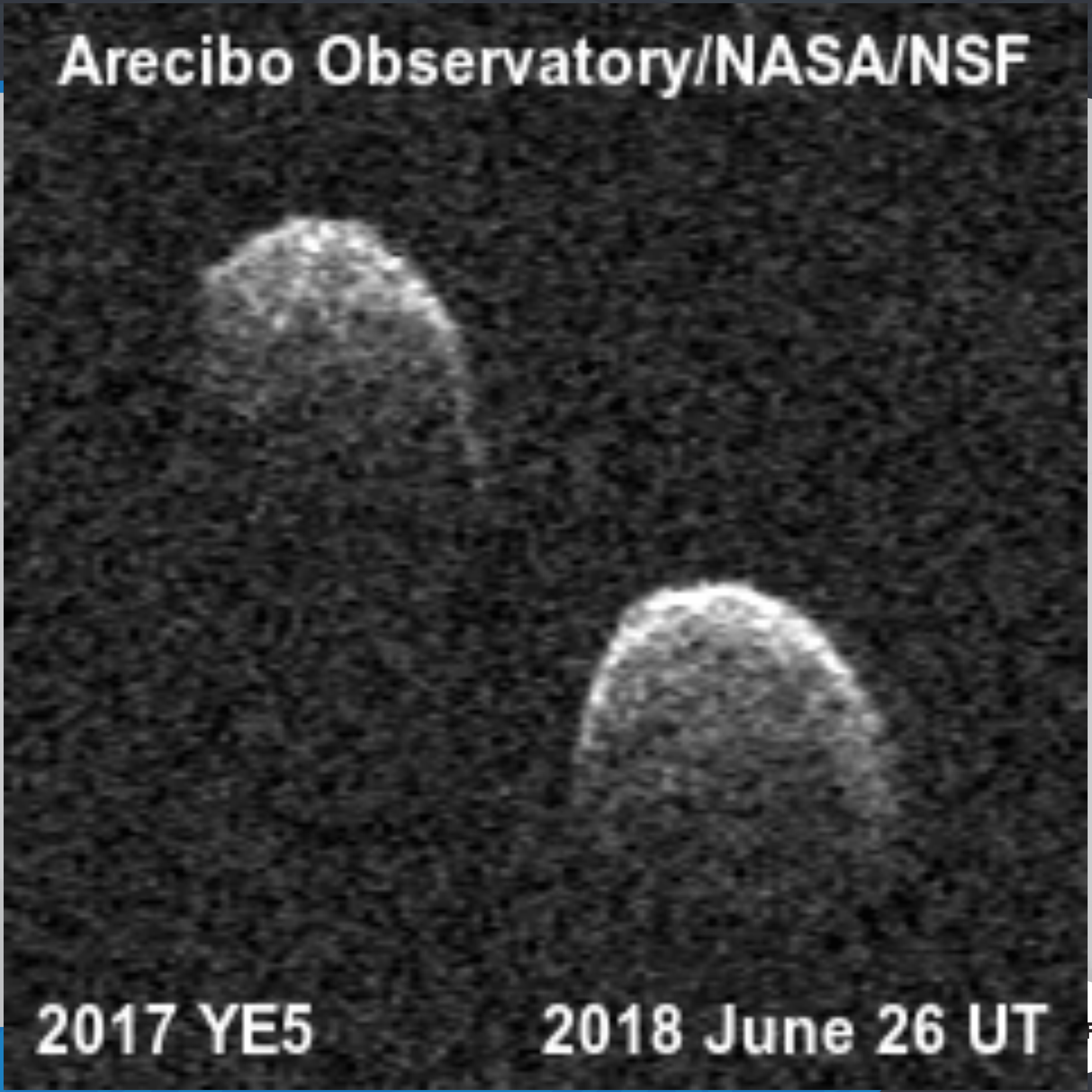
Arecibo Observatory was detecting and characterizing ~100 near-Earth objects (NEOs) per year





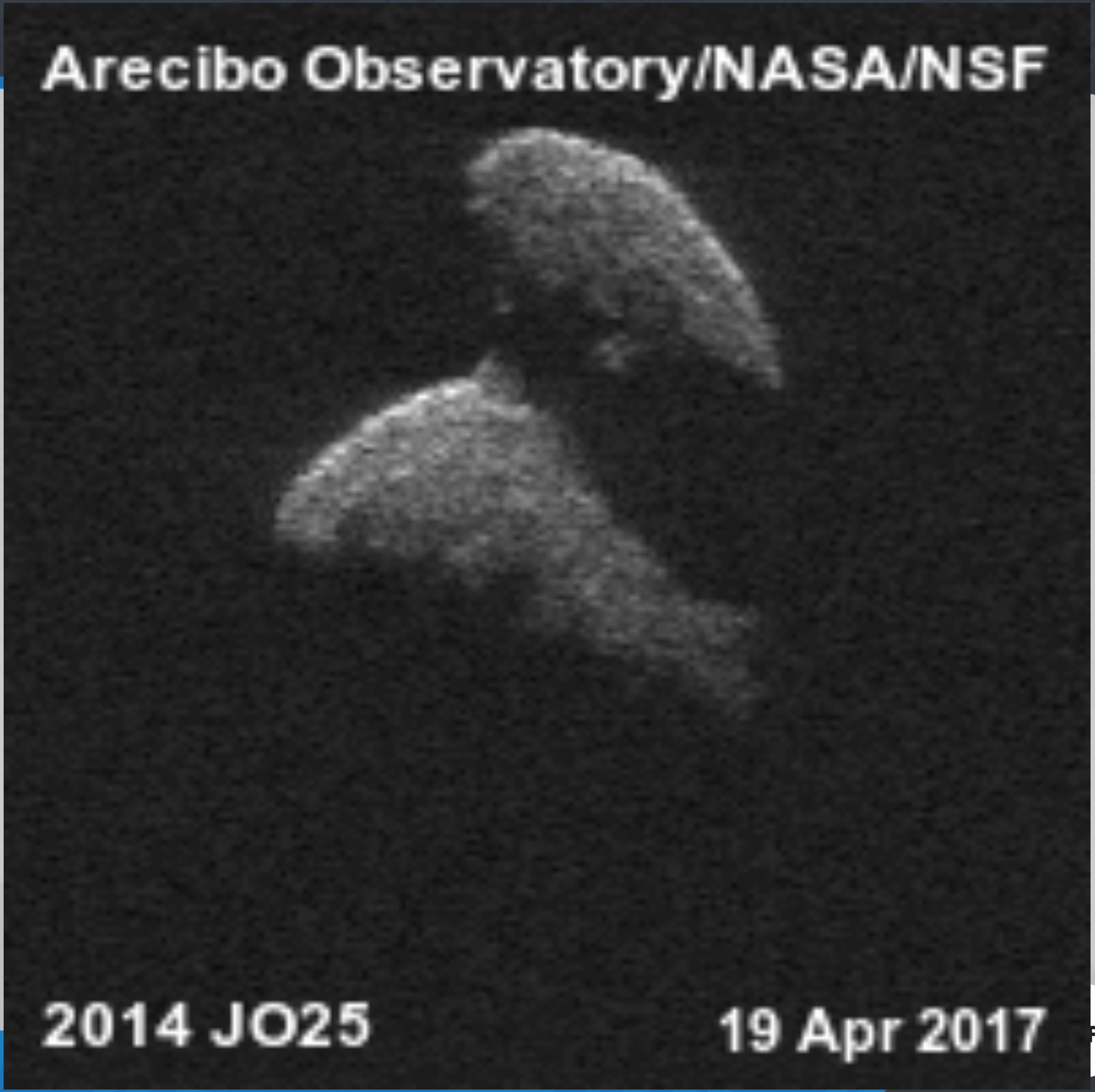
2017 YE5

- Equal mass binary (only four known NEAs!)
- 7.5 m/pixel
- 20-24 hr period
- Albedo difference between bodies



2014 JO25

- PHA
- Contact binary ~15 % of NEAs
- 7.5 m/pixel
- ~ 870 m
- 4.5 hr rotation period

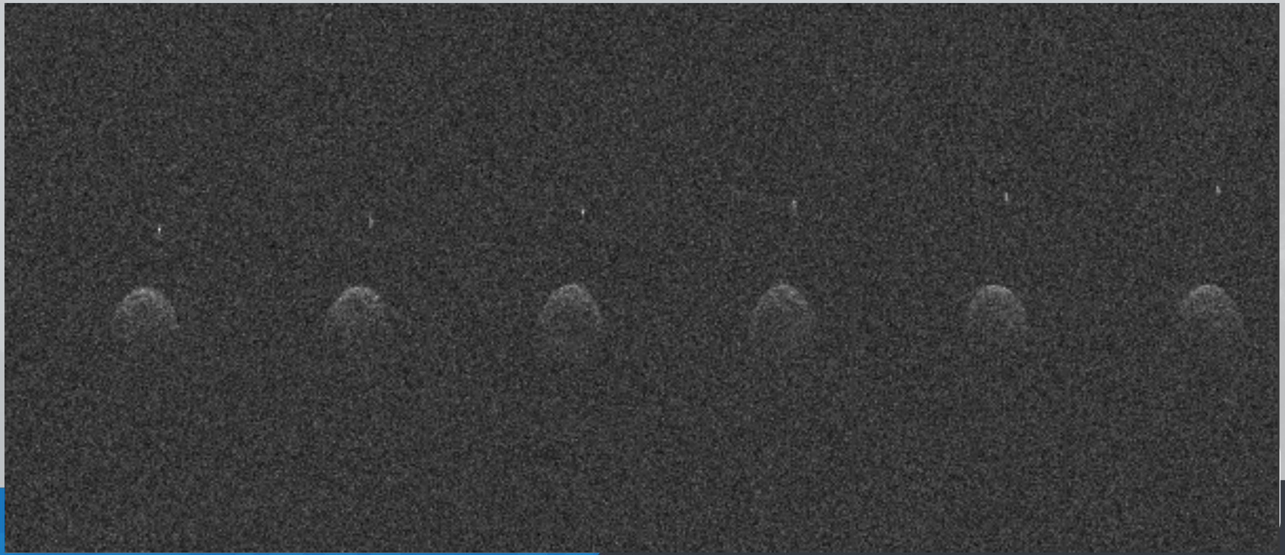


3200 Phaethon

- 2nd largest PHA known
- 75 m/pixel
- ~ 6 km
- 3.6 hr rotation period
- Surface features visible (crater or boulder?)
- Target of JAXA's DESTINY+ mission set to launch 2022

Didymos

- PHA
- Binary system
- 7.5 m/pixel
- ~ 760 m
- 2.3 hr rotation period
- Target of NASA's DART mission

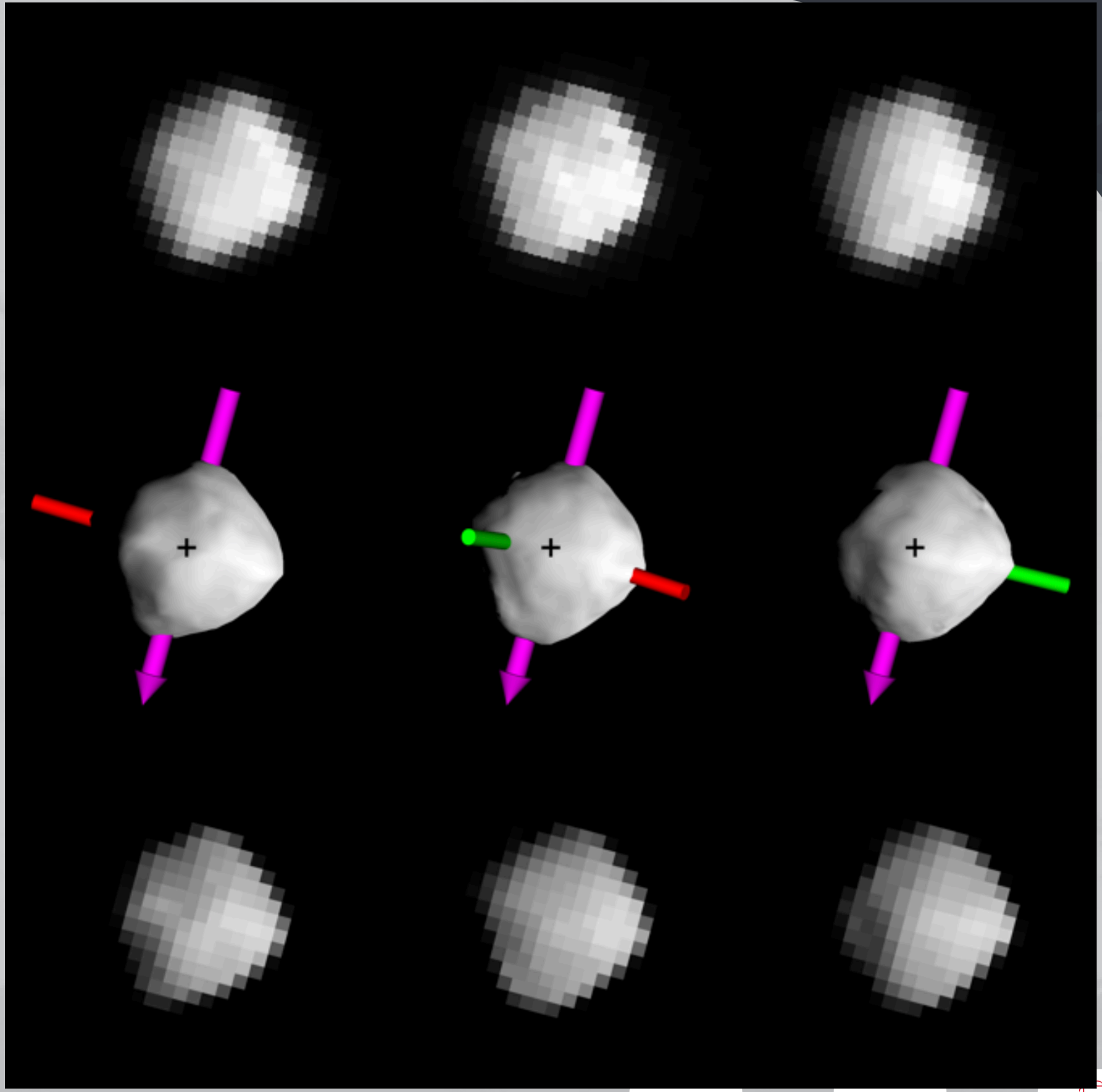


1998 OR2

- Observed April 2020
- PHA
- 7.5 m/pixel
- ~2.3 km
- 4 hr rotation period
- Prominent crater visible in the " leading edge"

Science Return

- Precise astrometry
- Surface Properties
- Discover binary asteroids
- Shape and spin state
  - Recently confirmed by NASA's OSIRIS-REx mission to 101955 Bennu



Nolan et al. (2019) *50th LPSC*

Mercury


Image Credit: Arecibo Observatory/NASA/Edgard G. Rivera-Valentin (USRA, LPI)/UCF

Mercury
Arecibo S-Band
22 July 2019

- In the late 1960’s Arecibo data determined the rotation rate to be 59 days, as opposed to 88 days previously accepted!
- Strong reflections from craters at the poles indicate water ice.

Venus

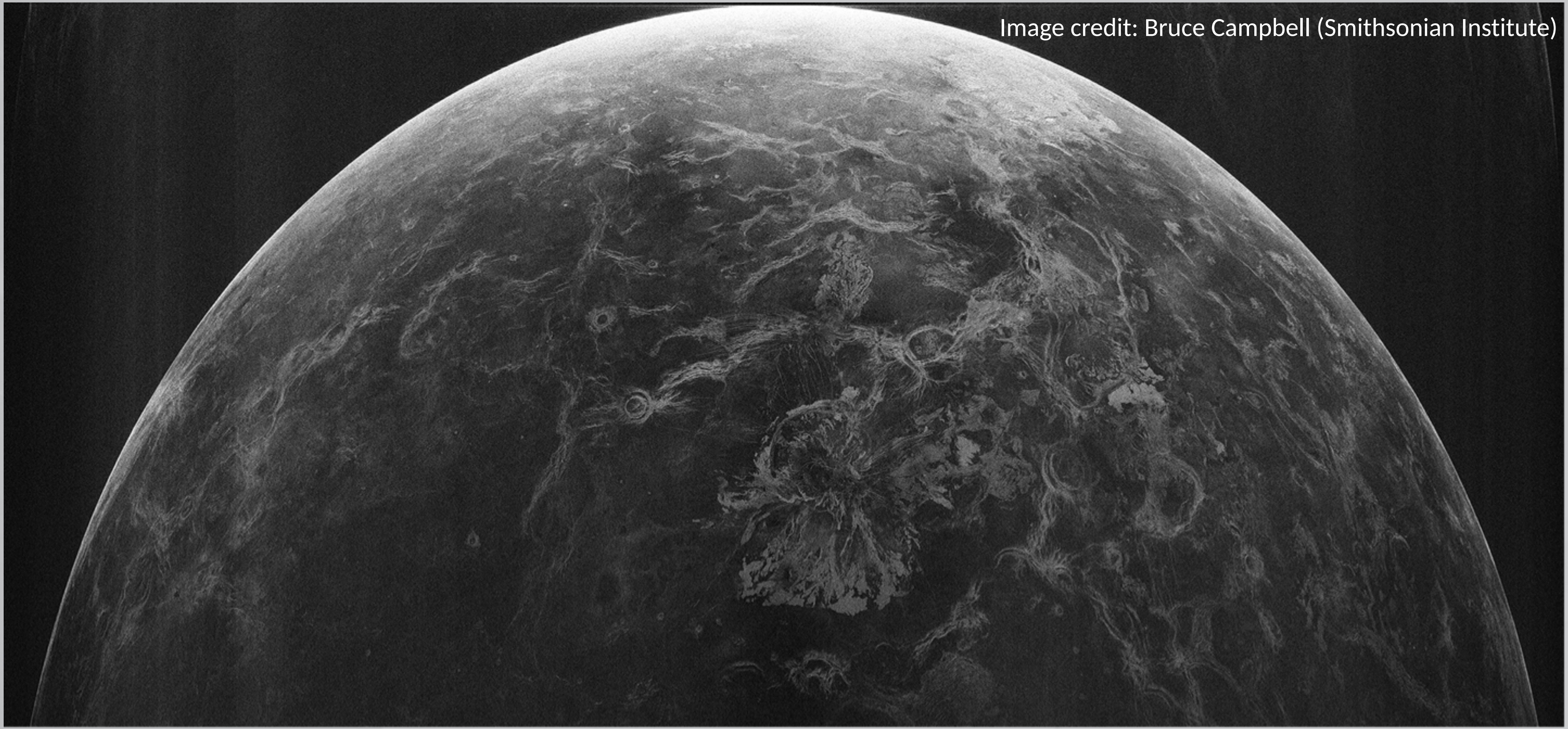


Image credit: Bruce Campbell (Smithsonian Institute)

- Thick cloudy atmosphere and intense pressure and temperature at surface makes optical/infrared remote sensing and landing missions difficult.
- Radar penetrates clouds, revealing surface and sub-surface features.

Venus

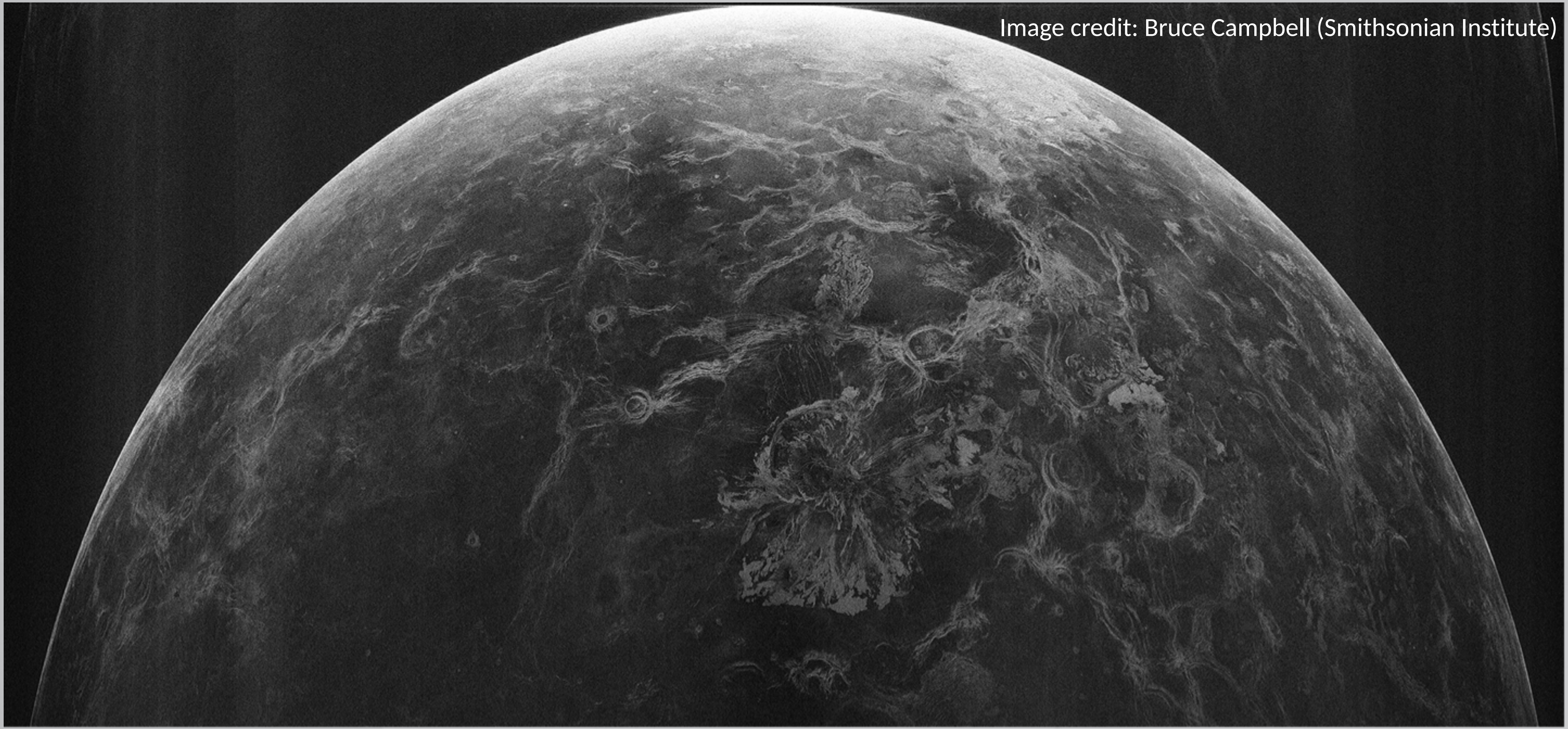
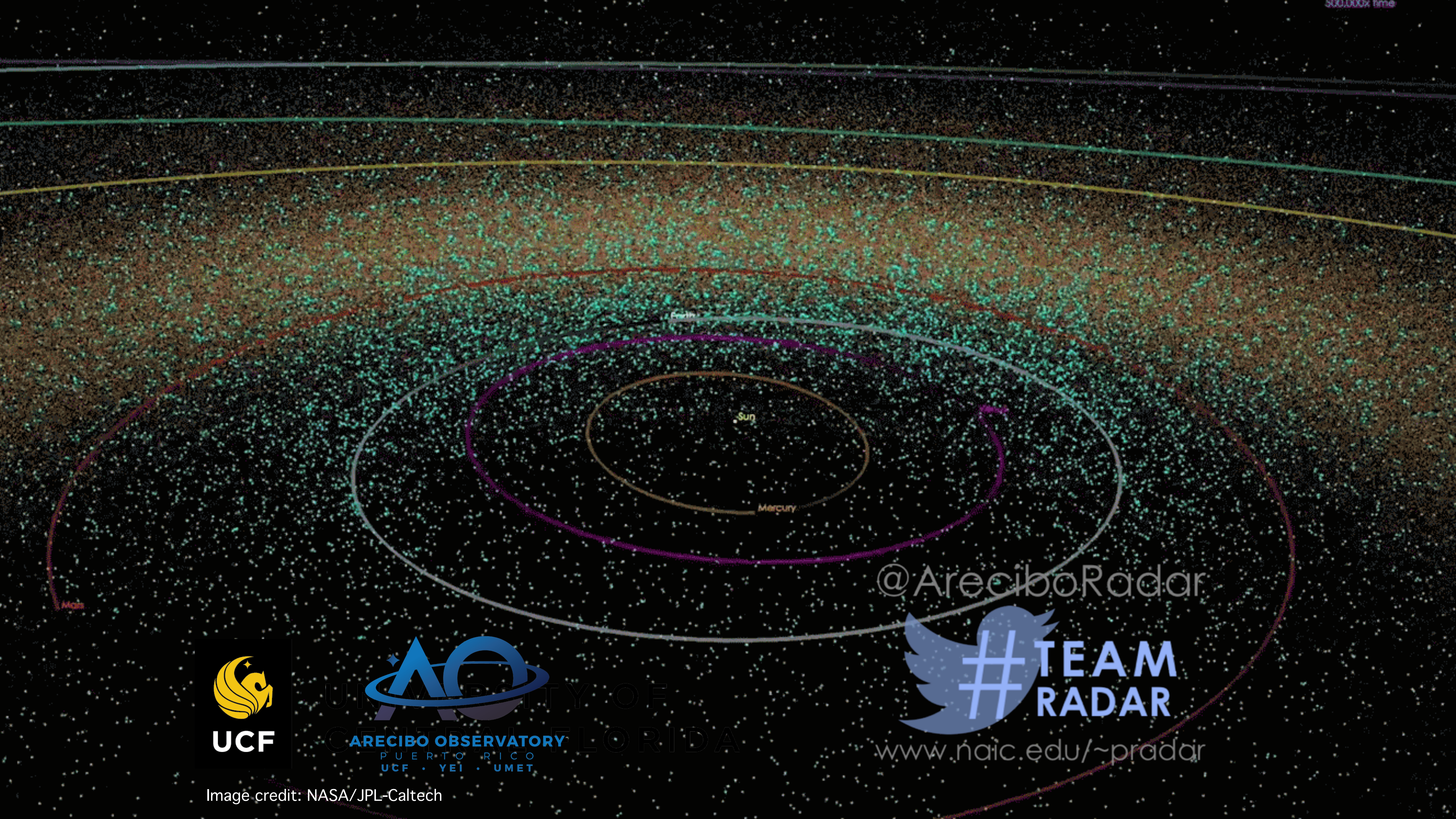


Image credit: Bruce Campbell (Smithsonian Institute)

- Determination of the core size, spin period, spin period variation, precession rate

  Spin state and moment of inertia of Venus (Margot et al. 2021)



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