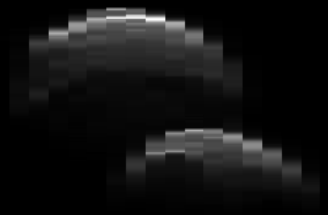
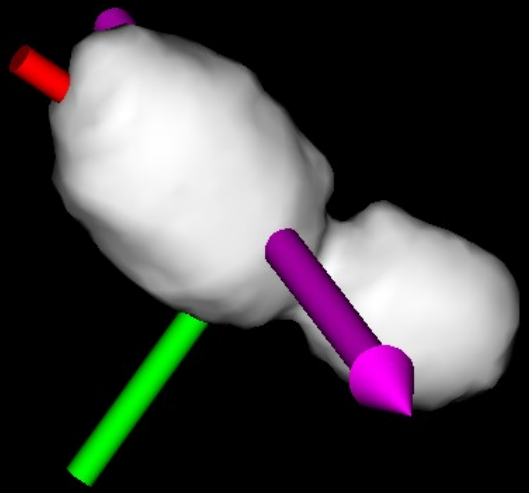
Shape Modeling

Sean Marshall

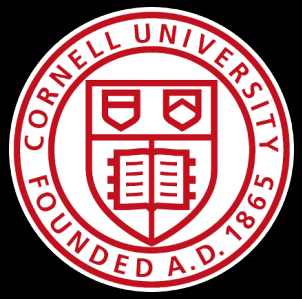
Arecibo Observatory

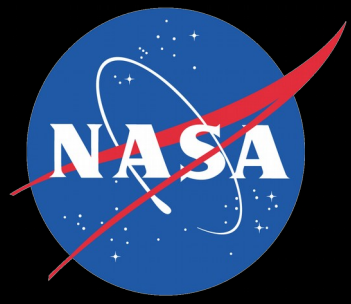




Shape Modeling Collaborators

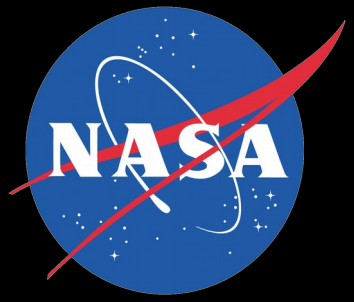
- Ellen Howell, Mike Nolan, Jenna Crowell (U. of Arizona); Patrick Taylor (LPI)
- Chris Magri (University of Maine), Yan Fernandez (U. Central FL), Ron Vervack (Johns Hopkins U. / APL)
- Marina Brozović, Lance Benner, Shantanu Naidu, Jon Giorgini, Joseph Jao, Clement Lee, Michael Hicks (JPL); Don Campbell (Cornell)
- And others...





Outline

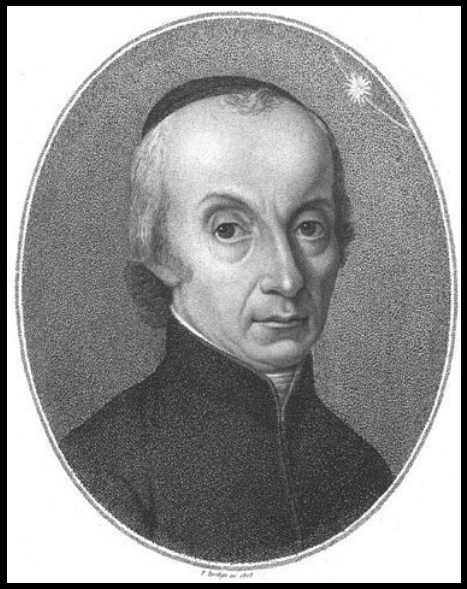
- Brief background on asteroids
- Shape modeling
  - With 85989 (1999 JD6) as an example
  - Using machine learning



Brief History

- 1801: Giuseppe Piazzi discovered Ceres
  - Appeared as a point (not a comet)
  - Orbit between Mars and Jupiter
  - Initially called a planet (but, faint and small)

Earth, Moon, and Ceres (to scale)
https://commons.wikimedia.org/wiki/File:Ceres_Earth_Moon_Comparison.png



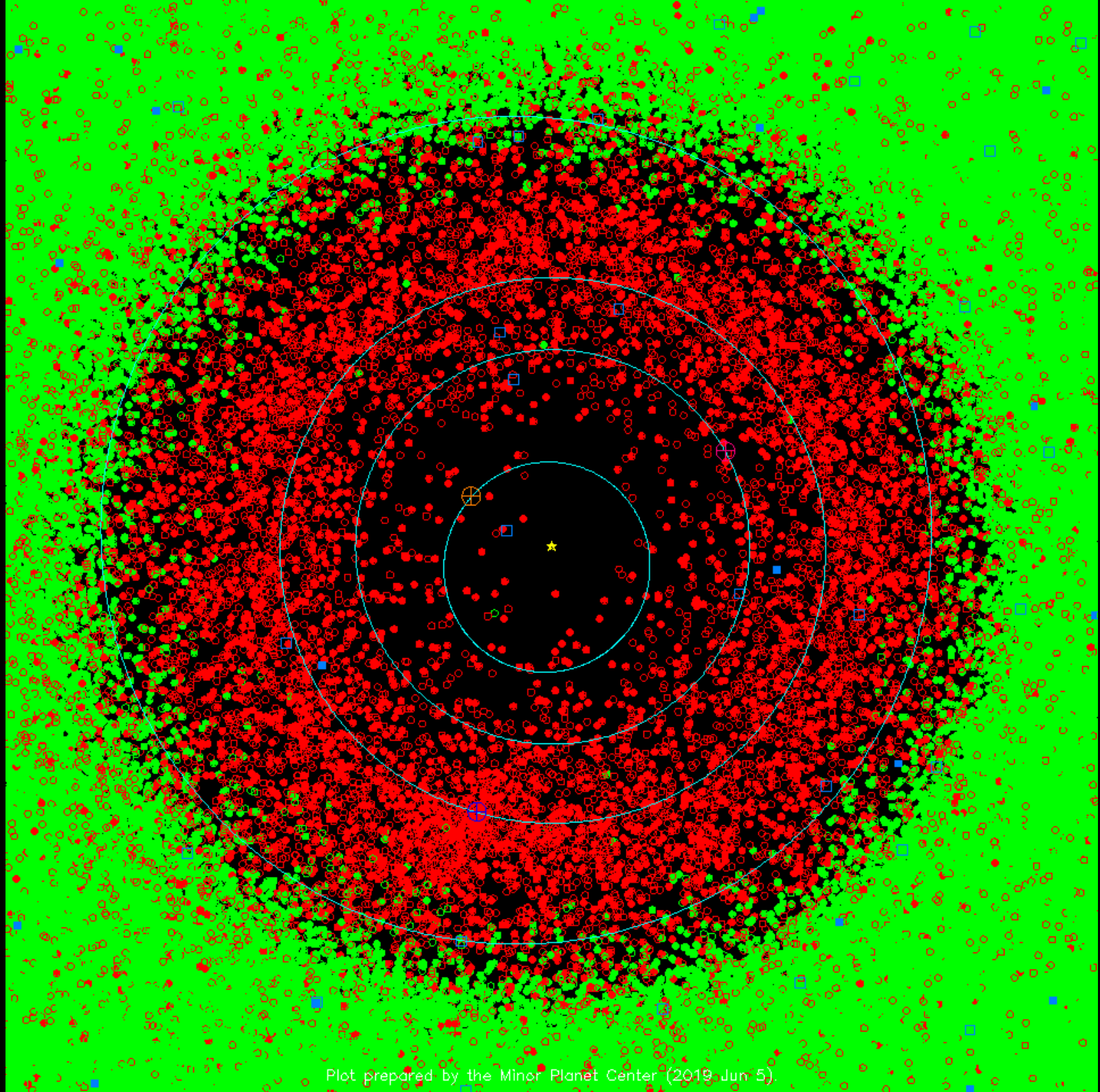
Piazzi (not to scale)
https://en.wikipedia.org/wiki/File:Giuseppe_Piazzi.jpg

Brief History

- By 1807, three more objects discovered in asteroid belt (Pallas, Juno, Vesta)
- Then, no others discovered until 1845
- Soon after that, several every year
- 1898: Discovery of Eros (near-Earth!)

Eros from NASA's NEAR-Shoemaker (2000-2001), https://commons.wikimedia.org/wiki/File:Eros-433.jpg

Known Minor Planets

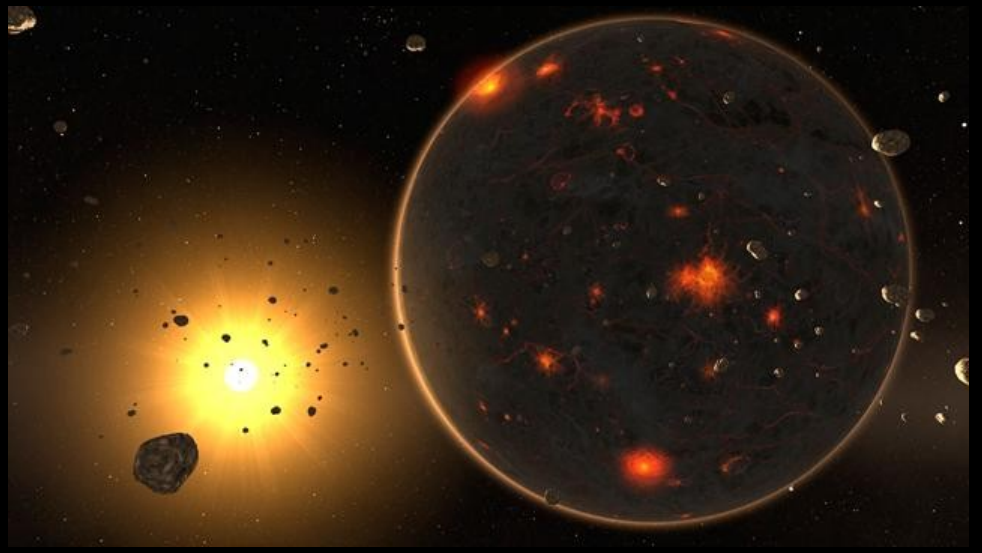


https://minorplanetcenter.net/iau/lists/InnerPlot2.html

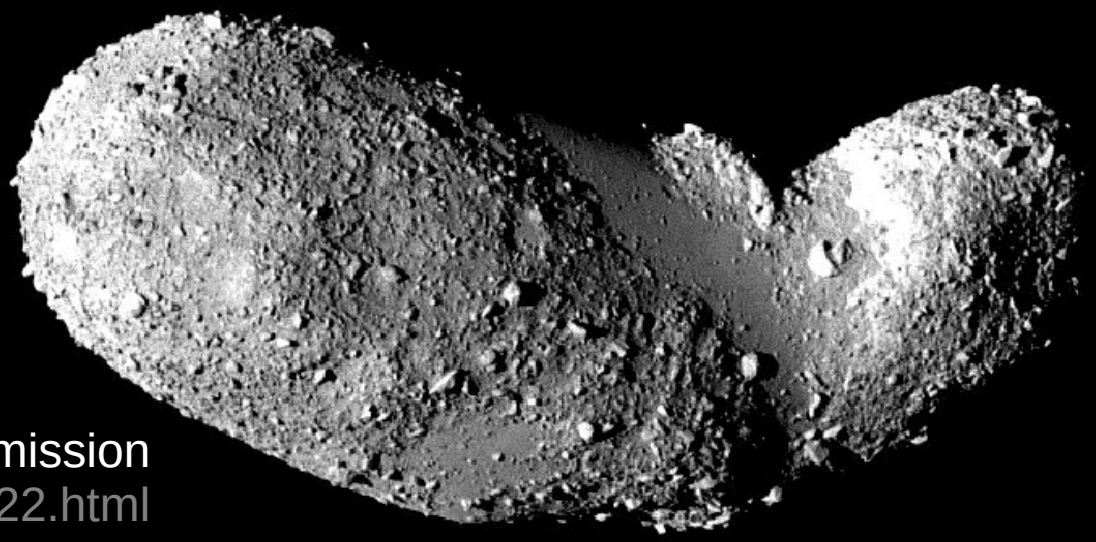
Why Study Asteroids?

- Insights into the early Solar System

www.bbc.co.uk/science/earth/earth_timeline/late_heavy_bombardment



- Lots of variety
  - And we've barely begun exploring them!



Itokawa, from the Japanese Hayabusa mission
apod.nasa.gov/apod/ap070422.html

Why Study Asteroids?

- Targets for future exploration
  - “Stepping stones to Mars” - Morrison
- Resources (?)
- Of interest to Congress and the public

www.jpl.nasa.gov/news/news.php?release=2013-131

www.nasa.gov/jpl/asteroid/asteroid-redirect-mission-20140214/

Why Study Asteroids?

- And that other reason...

impact.arc.nasa.gov/
gallery_main.cfm

commons.wikimedia.org/wiki/
File:Chicxulub_impact_-
_artist_impression.jpg

Why Study Asteroids?

- Chelyabinsk, Russia, on February 15, 2013

commons.wikimedia.org/wiki/File:Chelyabinsk_meteor_trace_15-02-2013.jpg

newswatch.nationalgeographic.com/2013/07/01/russian-meteor-shockwave-circled-globe-twice/

commons.wikimedia.org/wiki/File:Broken_window_%28%D1%80%D0%B0%D0%B7%D0%B

Impact Hazard

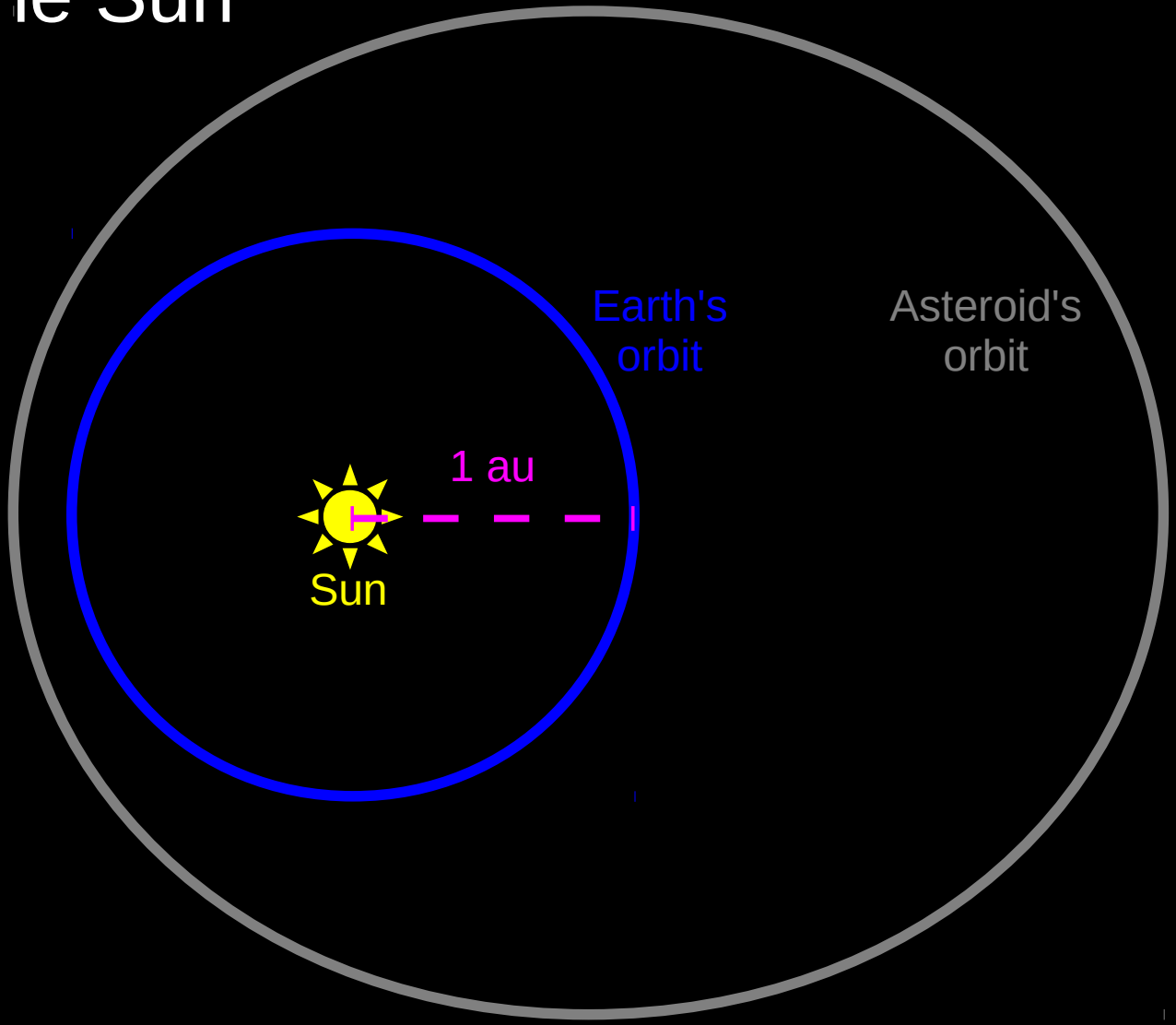
- More risk from not-yet-discovered asteroids
- Top *known* risks:
  - 1950 DA: 0.012% chance of impact in 2880
  - Bennu: 0.037% chance in 2175-2199

commons.wikimedia.org/wiki/File:Chelyabinsk_meteor_trace_15-02-2013.jpg

www.asteroidmission.org/wp-content/uploads/2014/04/img-osr.jpg

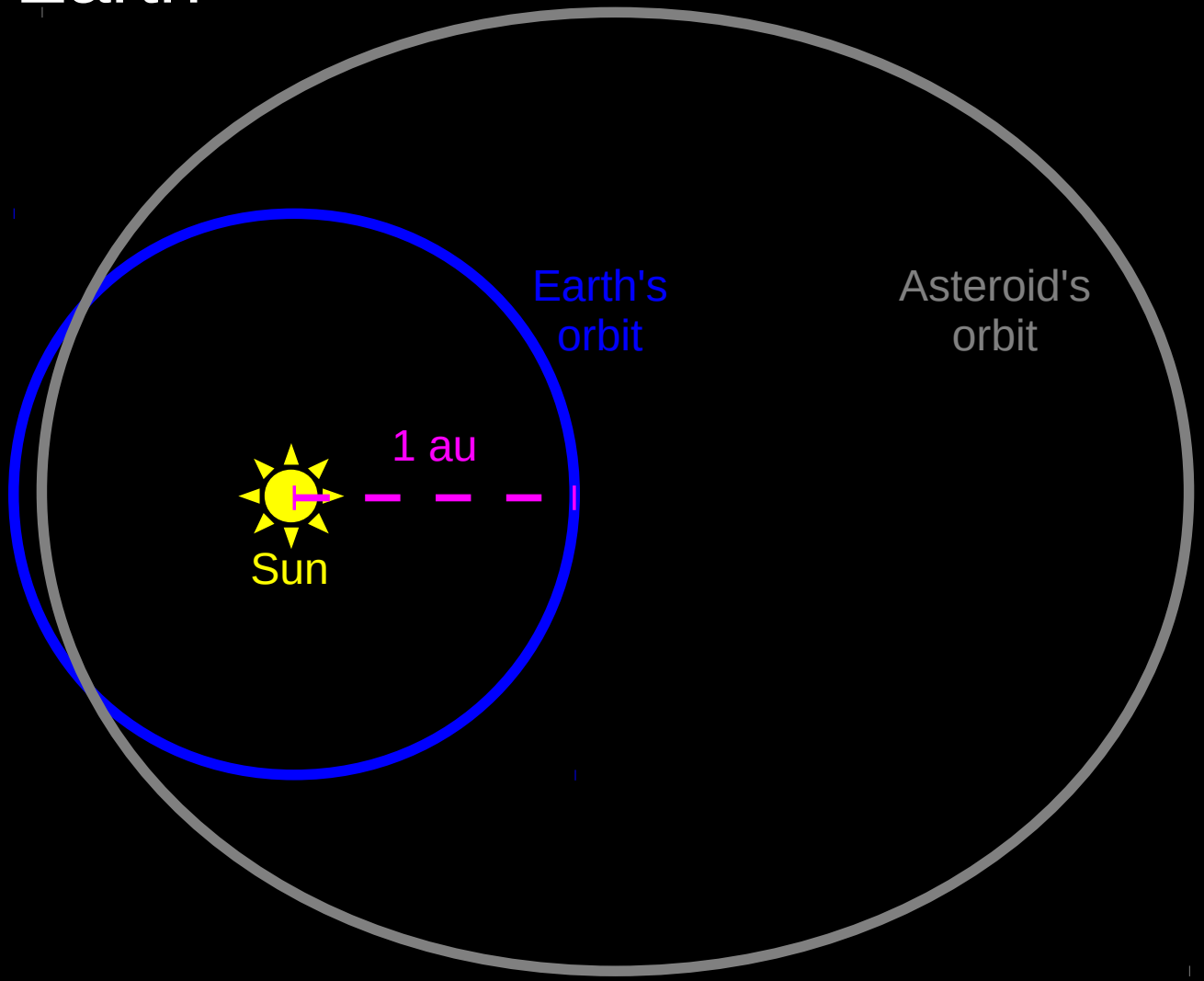
Definitions

- **Near-Earth Object**: Orbit brings it within 1.3 au of the Sun



Definitions

- **Potentially Hazardous**: Can come within 0.05 au of Earth



How to Study Asteroids?

- Zap them with radar! Measure the echo

Arecibo (305 m diameter)
www.naic.edu/public/about/photos/hires/aoviews.html

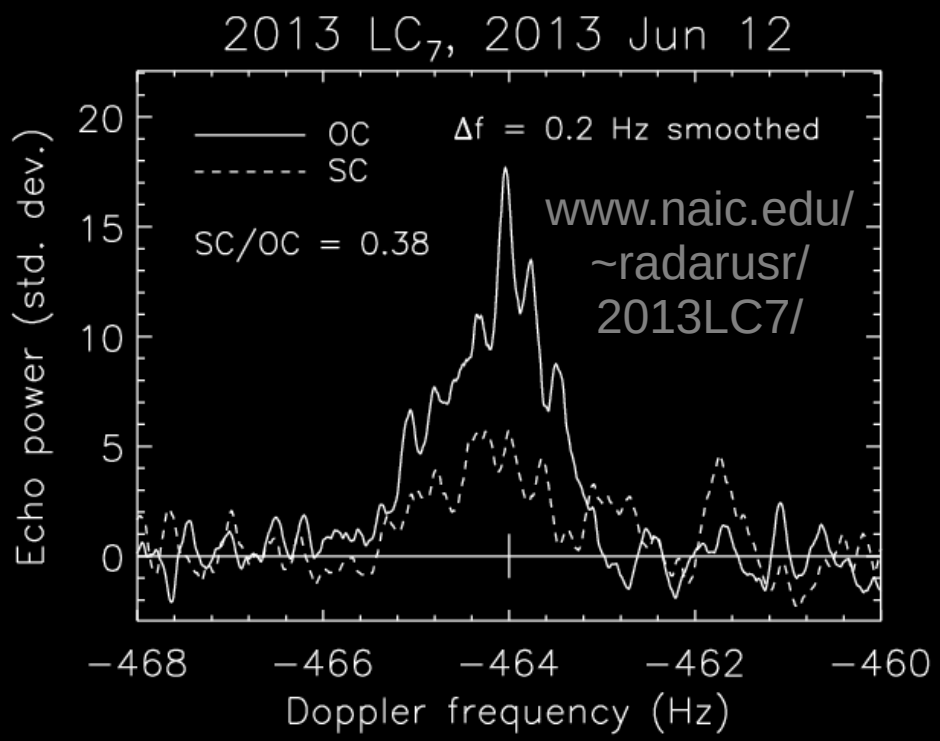
Green Bank Telescope (100 m diameter)
science.nrao.edu/facilities/gbt

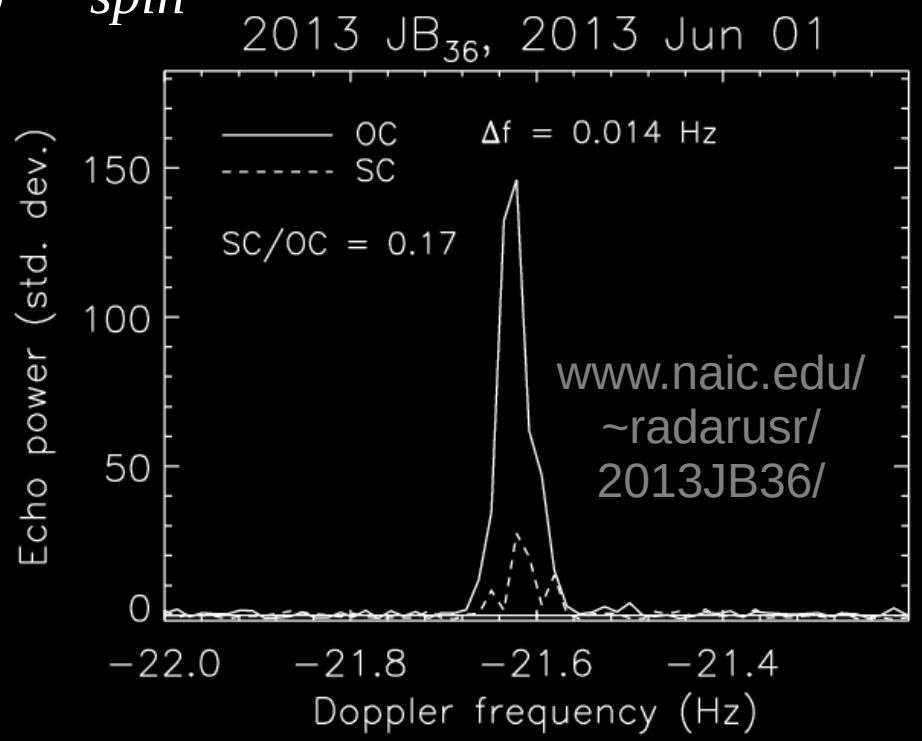
Goldstone (70 m diameter)
en.wikipedia.org/wiki/File:Goldstone_DSN_antenna.jpg

Measuring Frequency

- Transmit at a single frequency (CW)
- Receive radar echo at a range of frequencies

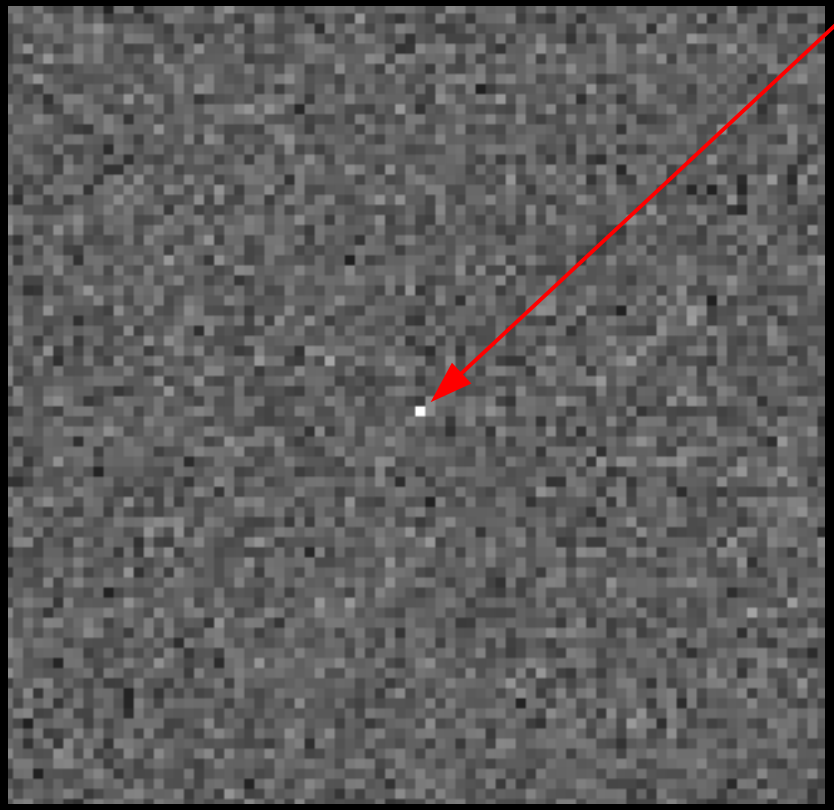
$$B = \frac{4\pi D \cos\phi}{\lambda_0 P_{spin}}$$





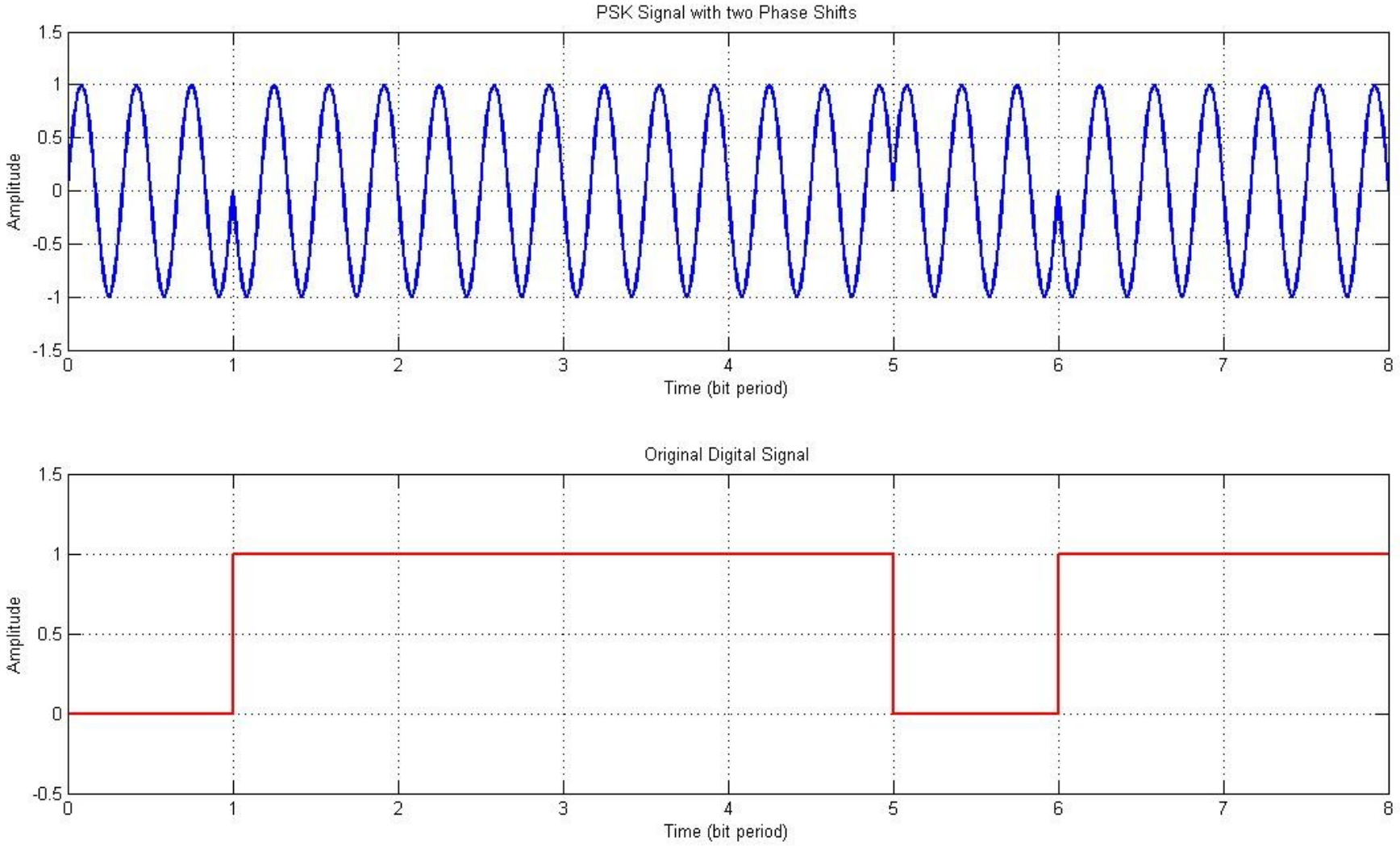
Measuring Delay (Time)

- Measure the length of time between radar transmission and echo reception
  - Measured to microsecond accuracy (or better)
  - Gives range (distance) to asteroid



www.naic.edu/~radarusr/2002GT/

Measuring Delay (Time)



https://au.mathworks.com/matlabcentral/fileexchange/30582-binary-phase-shift-keying?focused=5187825&tab=function

Measure Both (Time and Frequency)

- Resolve radar echo into time (delay) and (Doppler-shifted) frequency

Doppler →

Delay ↓

www.naic.edu/~radarusr/
2005NZ6/apr28.gif

Doppler →

Delay ↓

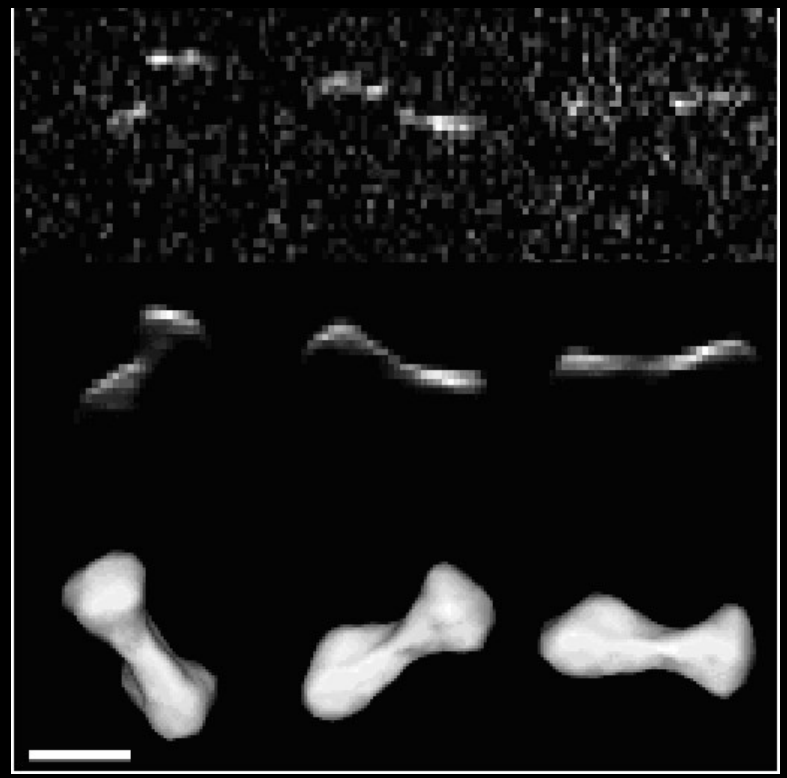
www.jpl.nasa.gov/video/
details.php?id=1359

Radar “Images”

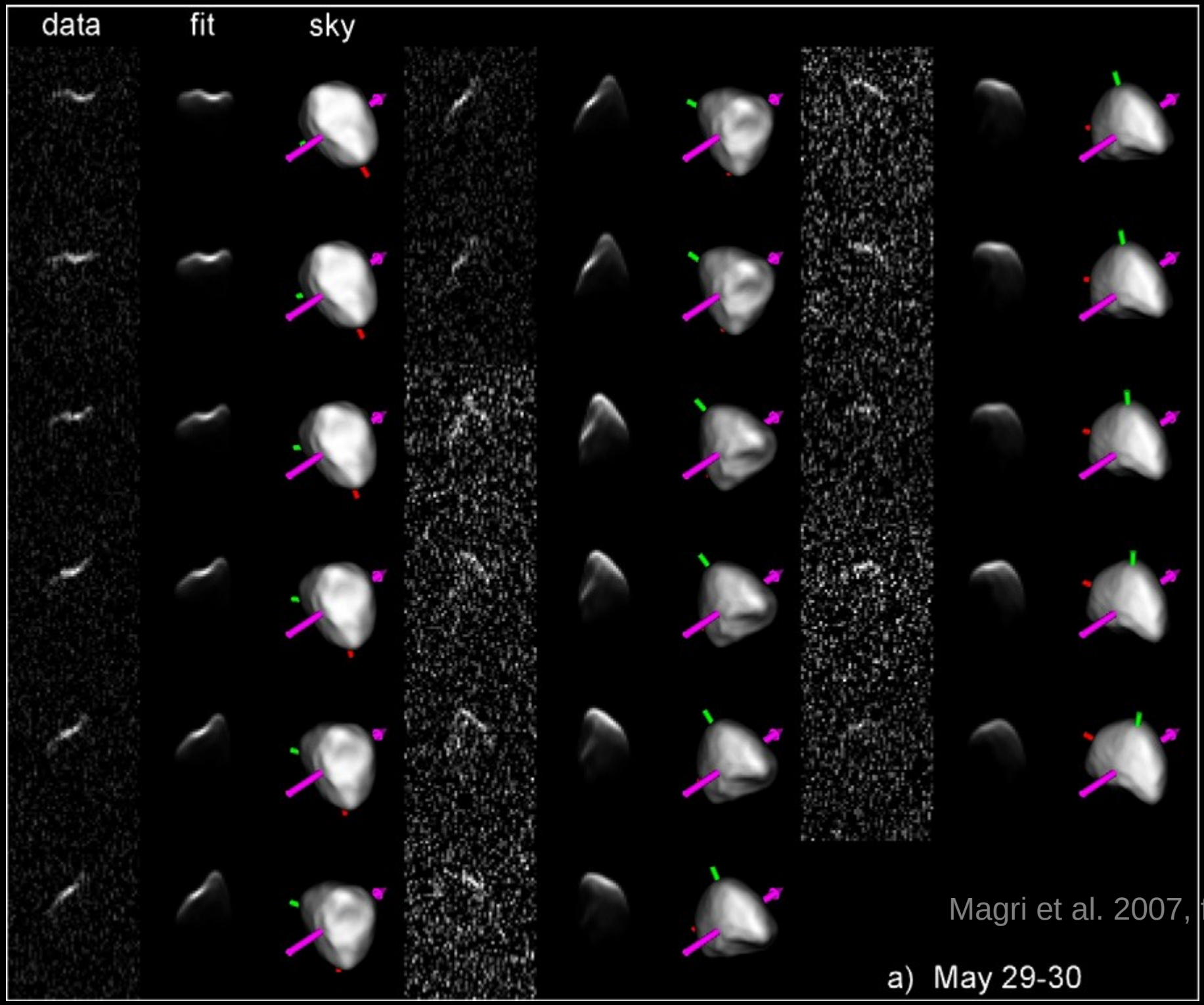
www.naic.edu/
~radarusr/
1998QE2/

Radar-Derived Shape Models

- Inverse problem: Find the shape that best fits the (noisy) observed Delay-Doppler “images”
- Put all observational data into the shape modeling software



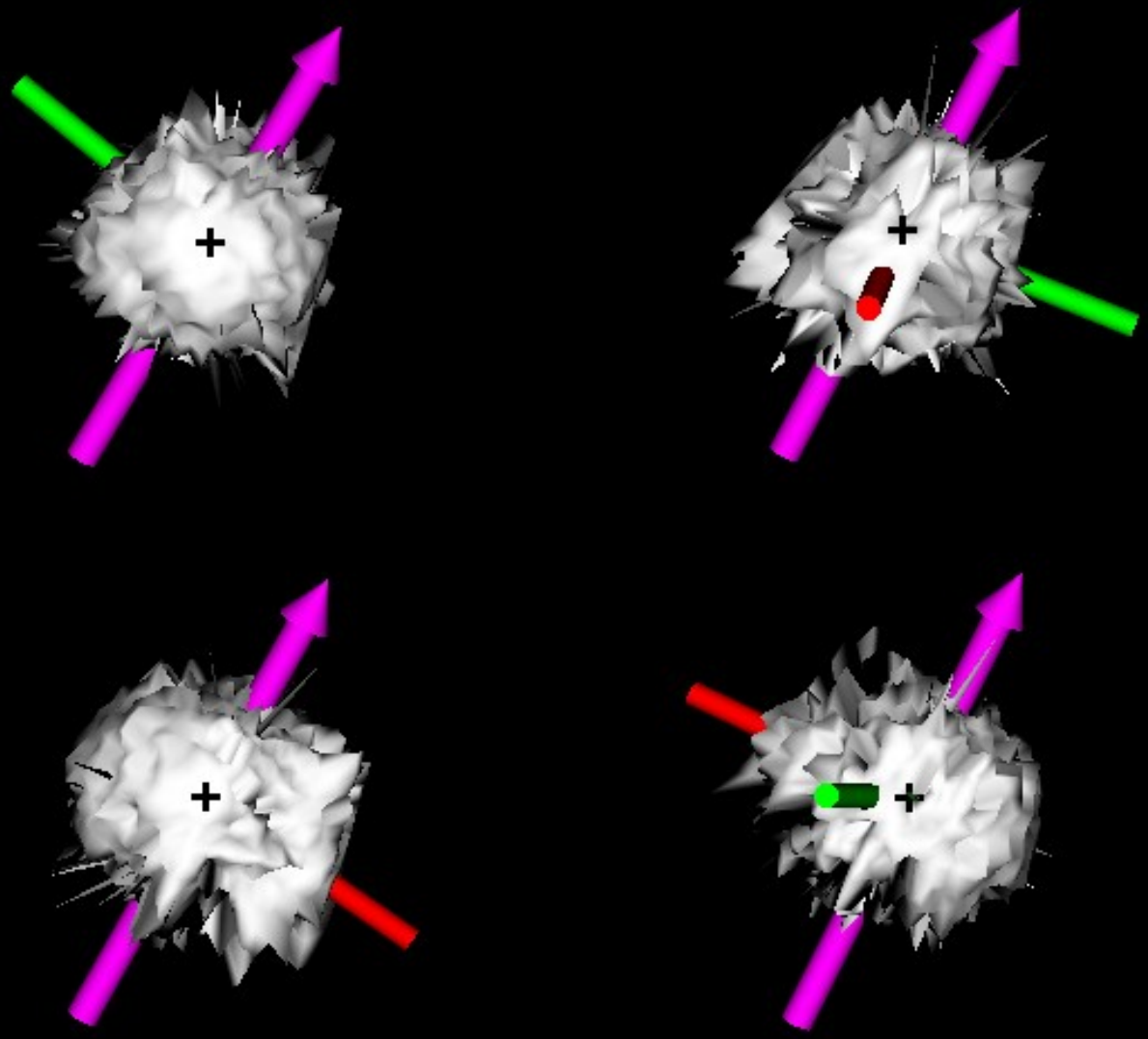
www.naic.edu/general/images/SCIENCE/Planetary/artts/kleo.jpg



Magri et al. 2007, figure 1a

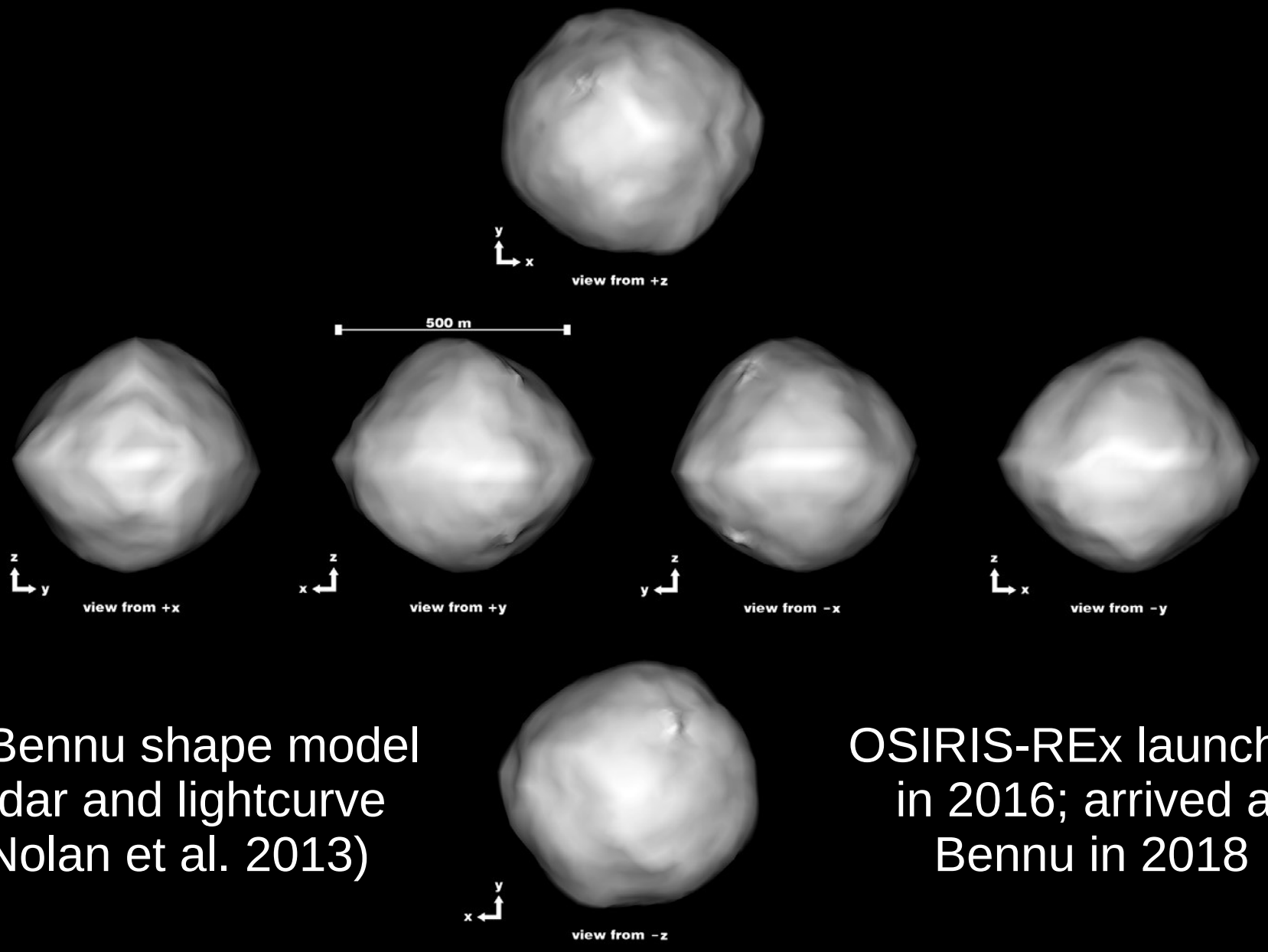
Penalty Functions

- SHAPE fit for 1998 QE2 secondary



Images from Alessondra Springmann (QE2 paper in prep)

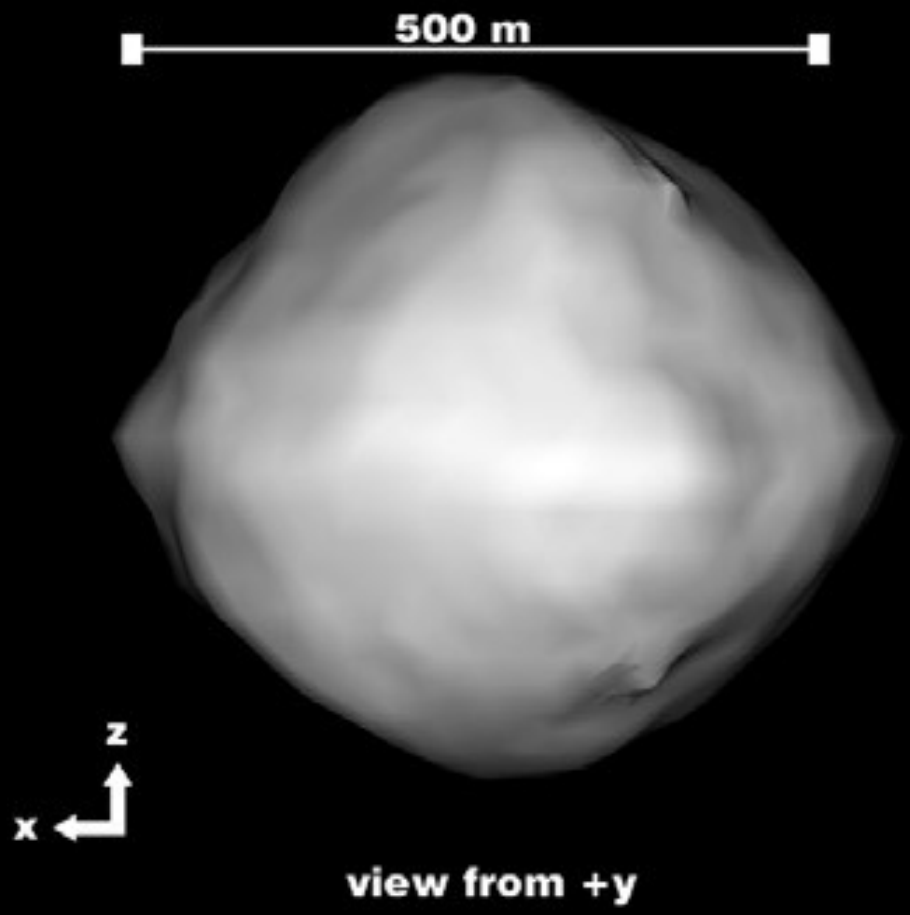
Validating Shape Models



101955 Bennu shape model from radar and lightcurve data (Nolan et al. 2013)

OSIRIS-REx launched in 2016; arrived at Bennu in 2018

Validating Shape Models



101955 Bennu shape model from radar and lightcurve data (Nolan et al. 2013)

Bennu seen by OSIRIS-REx (not quite the same rotation phase)

(switch to other file)

Backup Slides

Radar Equations: Signal

- Power received from radar echo (monostatic):

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

- P_{tx} is transmitted power
- G is system gain (directionality) $G = \frac{4\pi A_{eff}}{\lambda^2}$
- r is the distance to the target
- σ is the target's radar cross section $\sigma = \hat{\sigma} A_{proj}$
- A_{eff} is the receiver's effective collecting area

Radar Equations: Noise

- Noise power:

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

- T_{sys} is the system temperature (convenient representation of the system's noise)
- τ is the integration time
- B is the target's (frequency) bandwidth

$$B = \nu_0 \frac{4 v_{spin} \cos\phi}{c} = \frac{4 \nu_0}{c} \frac{\pi D \cos\phi}{P_{spin}} = \frac{4 \pi D \cos\phi}{\lambda_0 P_{spin}}$$

Radar Equations: Signal and Noise

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

en.wikipedia.org/wiki/File:Goldstone_DSN_antenna.jpg

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

- Signal-to-noise ratio:

$$SNR = \frac{P_{rx}}{N_{rms}} = \frac{G P_{tx} A_{eff} \sigma \sqrt{\tau}}{(4\pi r^2)^2 k T_{sys} \sqrt{B}}$$

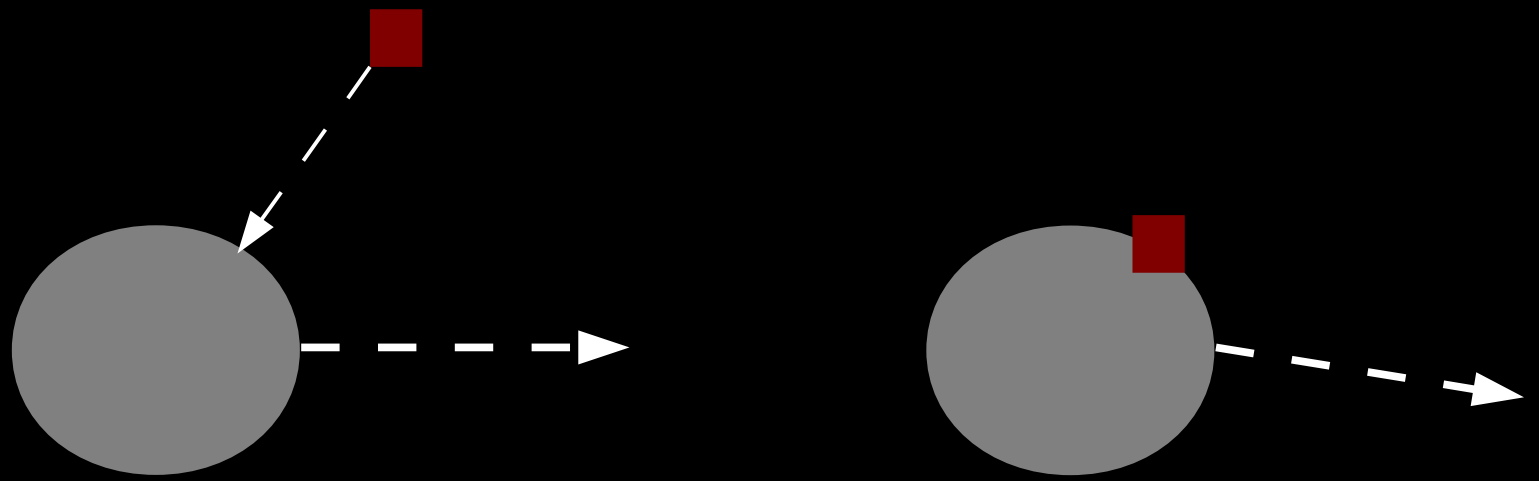
www.naic.edu/public/about/photos/hires/aoviews.html

What's In a Name?

- For asteroids with a well-known orbit:
  - Number based on order of discovery
  - Also a name (could be anything)
  - e.g. (99942) Apophis
- For recently discovered asteroids:
  - A systematic name based on the date of discovery
  - e.g. 2004 MN4, 2012 DA14

Deflection Methods

- Kinetic impactor



- Nuclear detonation