Planetary Radar Astronomy and Green Bank's Impact

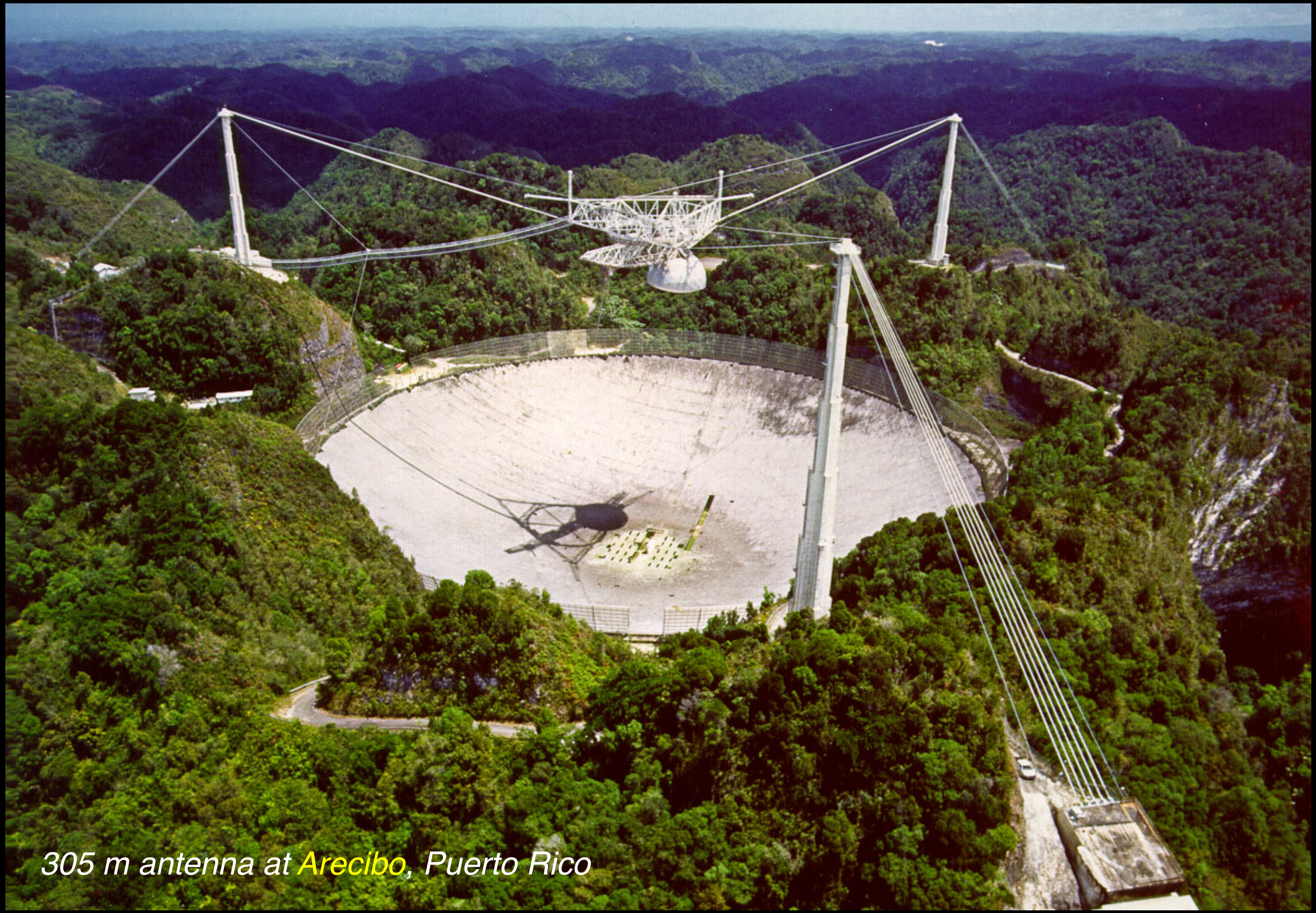
Jean-Luc Margot (UCLA)
Patrick Taylor (NRAO)

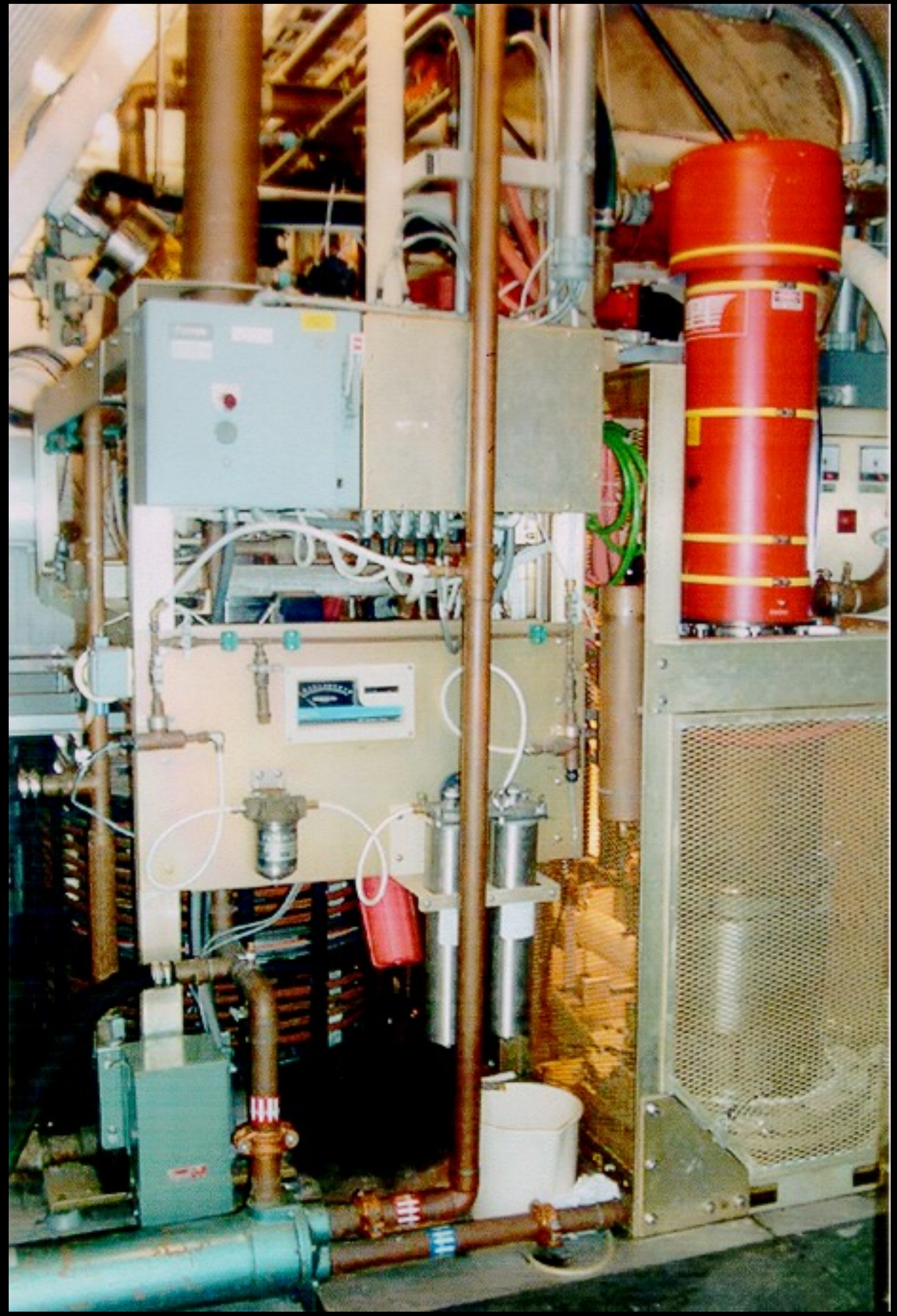
Outline

- Instruments
- Observables
- First science with GBT
- Accomplishments to date
- Future prospects

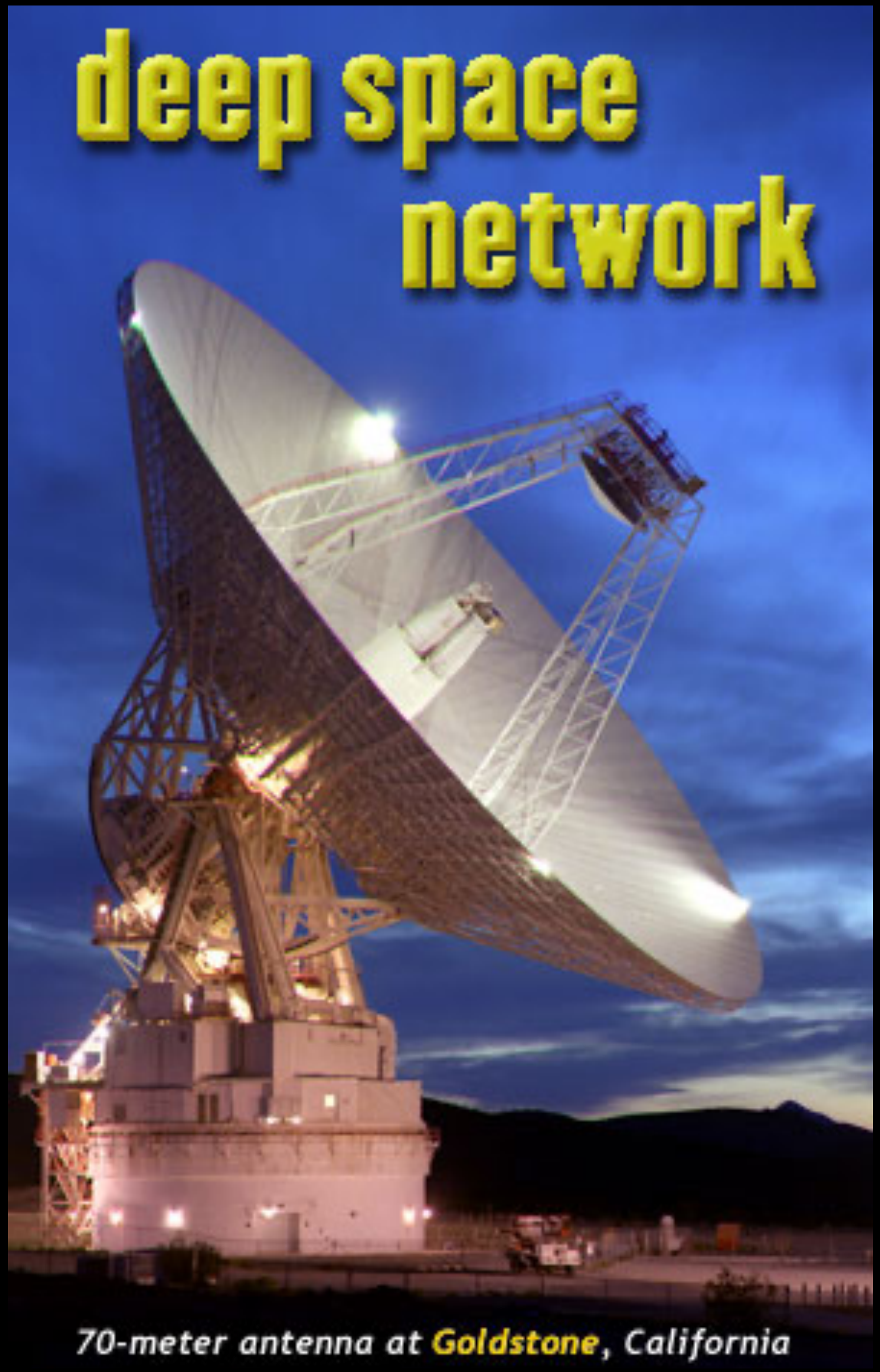
Instruments

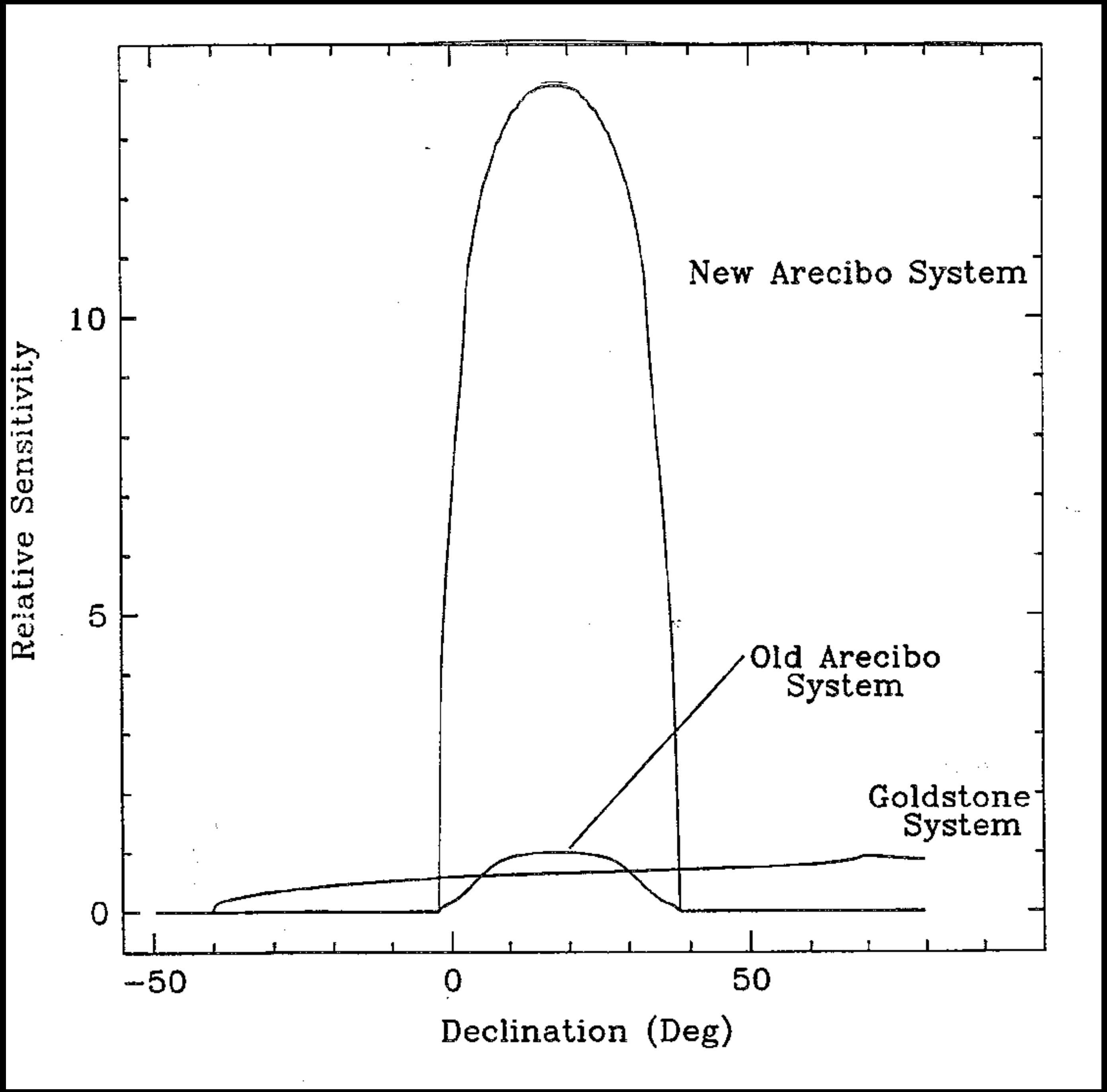
Arecibo





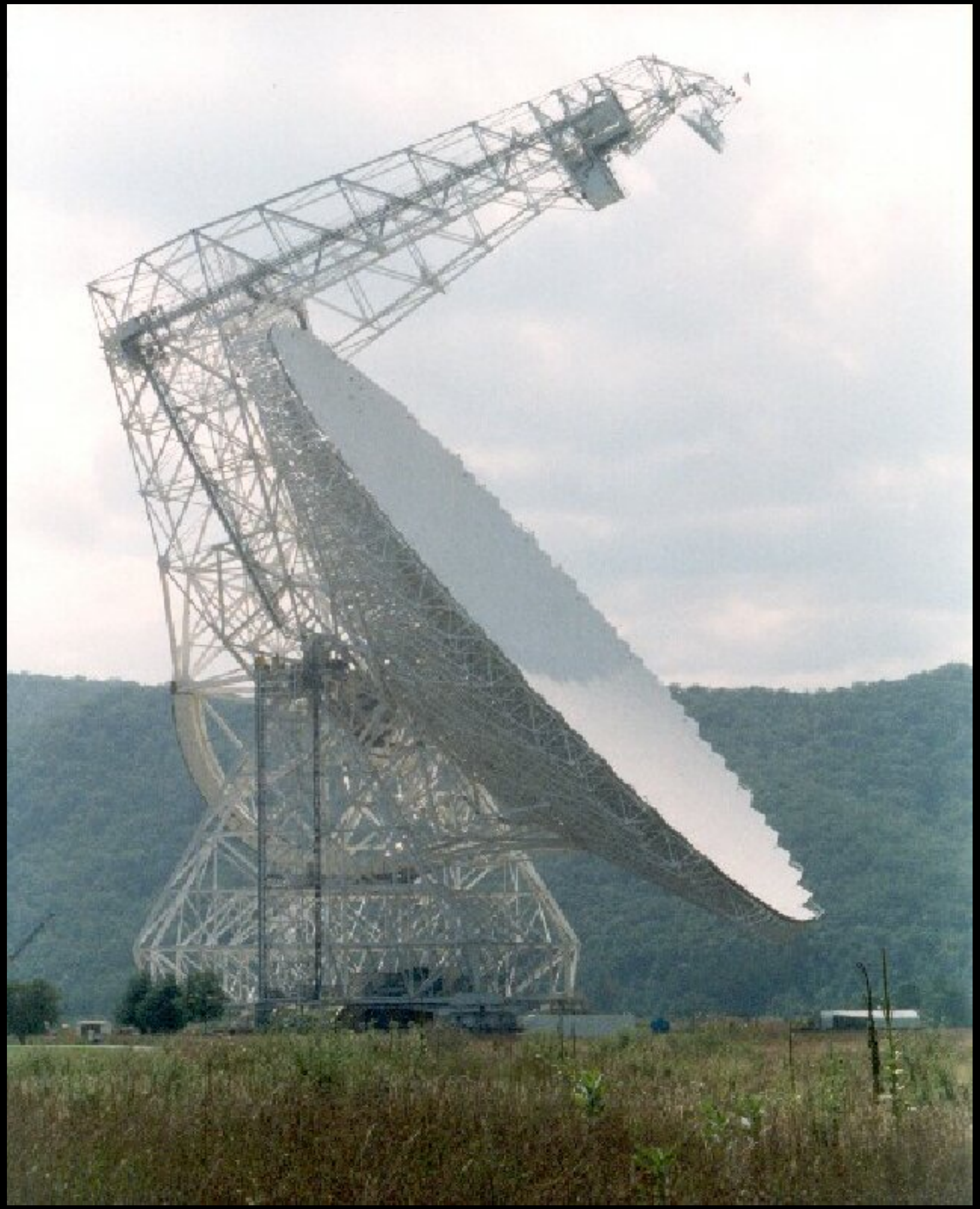
Goldstone





Ostro, Rev. Mod. Phys., 1993

Green Bank

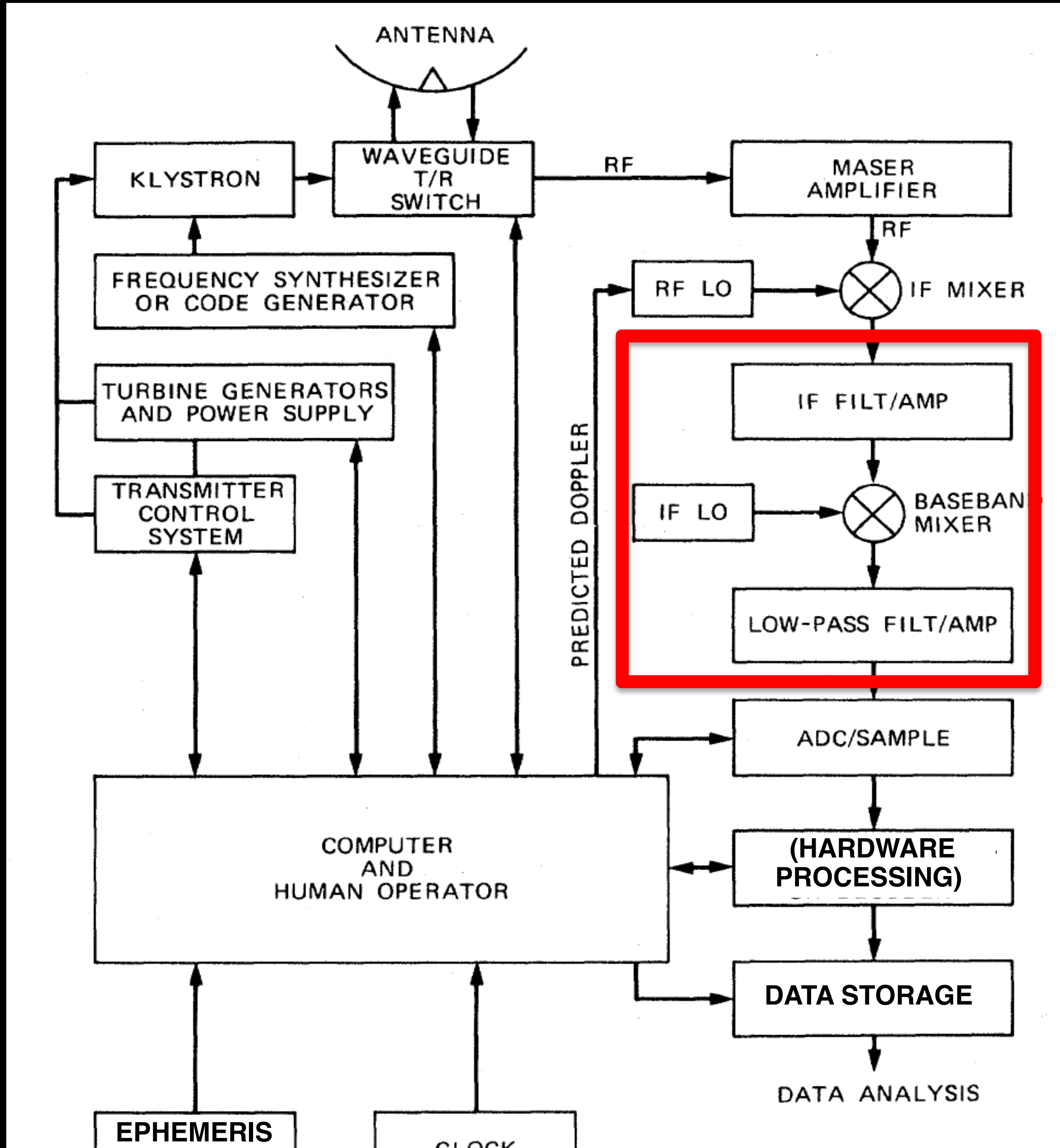


Relative Sensitivities of Various Transmitter–Receiver Combinations

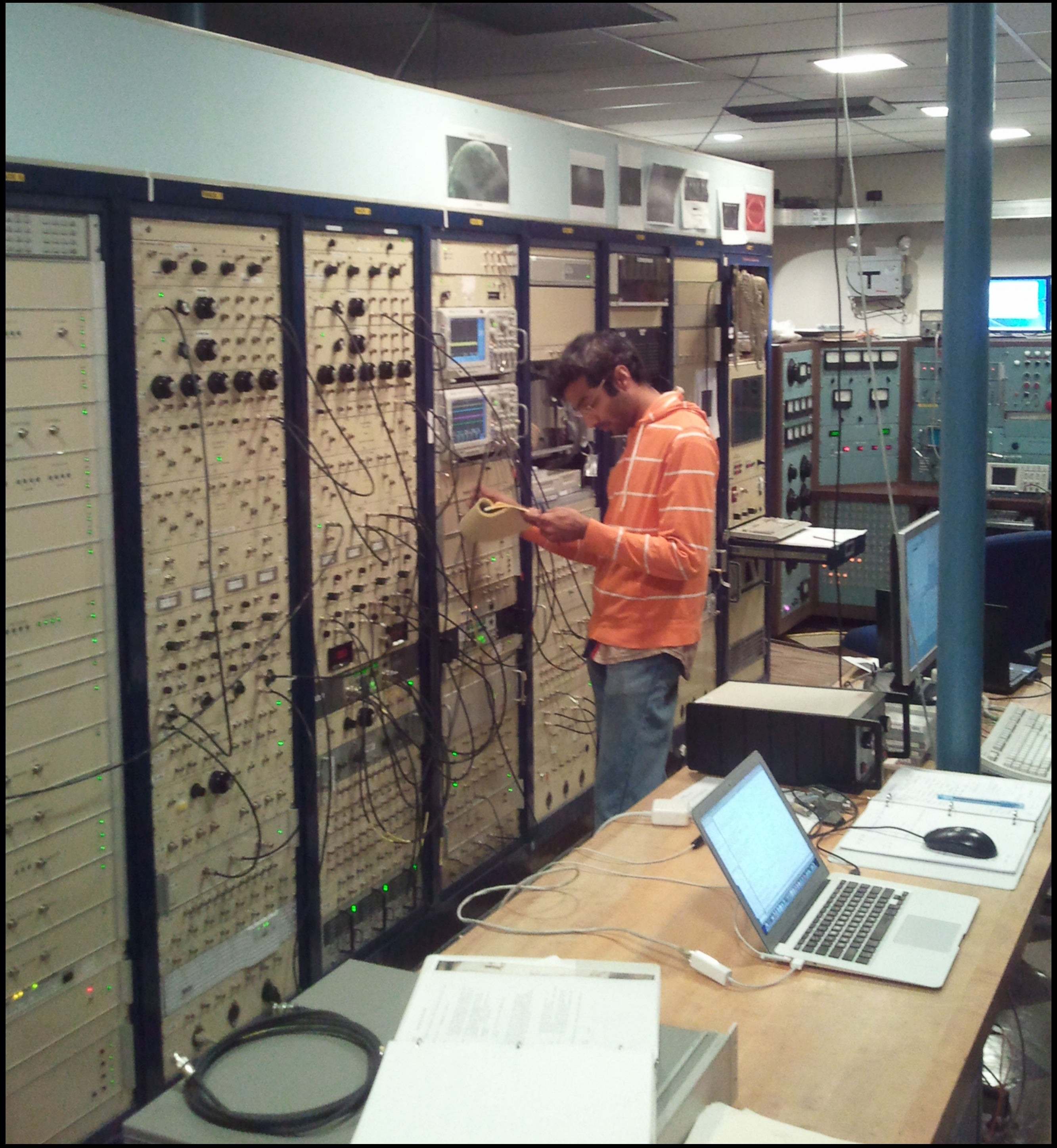
Transmitter	Receiver	Relative sensitivity
DSS-14	DSS-14	1
	Arecibo	5.1
	GBT	2.3
	DSS-13	0.3
Arecibo	Arecibo	15
	GBT	5
	DSS-13	0.6
	DSS-14	2.2
DSS-43	Parkes	0.007
DSS-43 (400 kW)	Parkes	0.03
DSS-13	Arecibo	0.2
	GBT	0.08

Naidu et al., AJ 152, 2016.

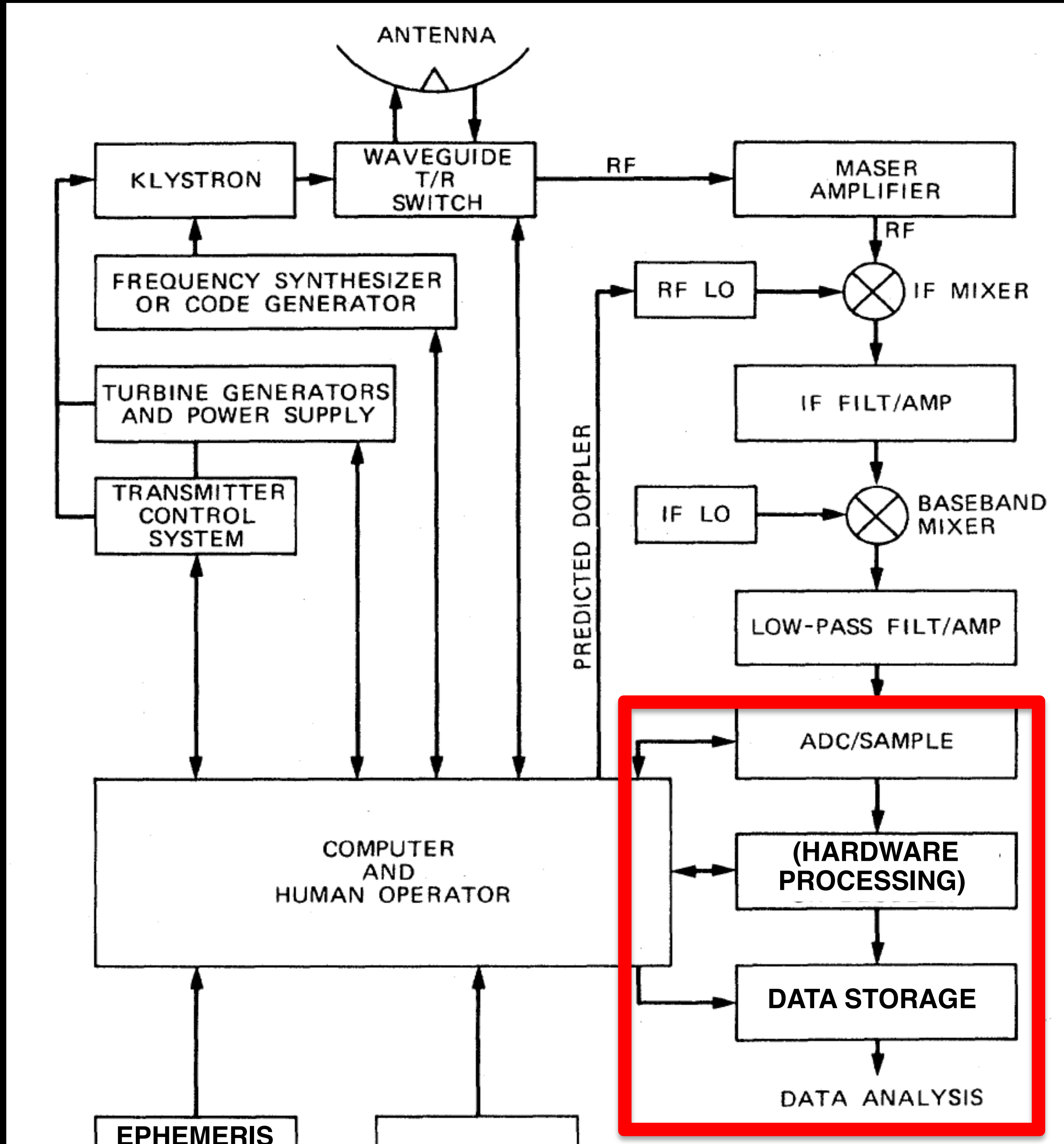
Radar System



Adapted from Ostro, 1993



Radar System



Adapted from Ostro, 1993

Data-Taking Hardware & Software

720 MHz to 30 MHz downconverter

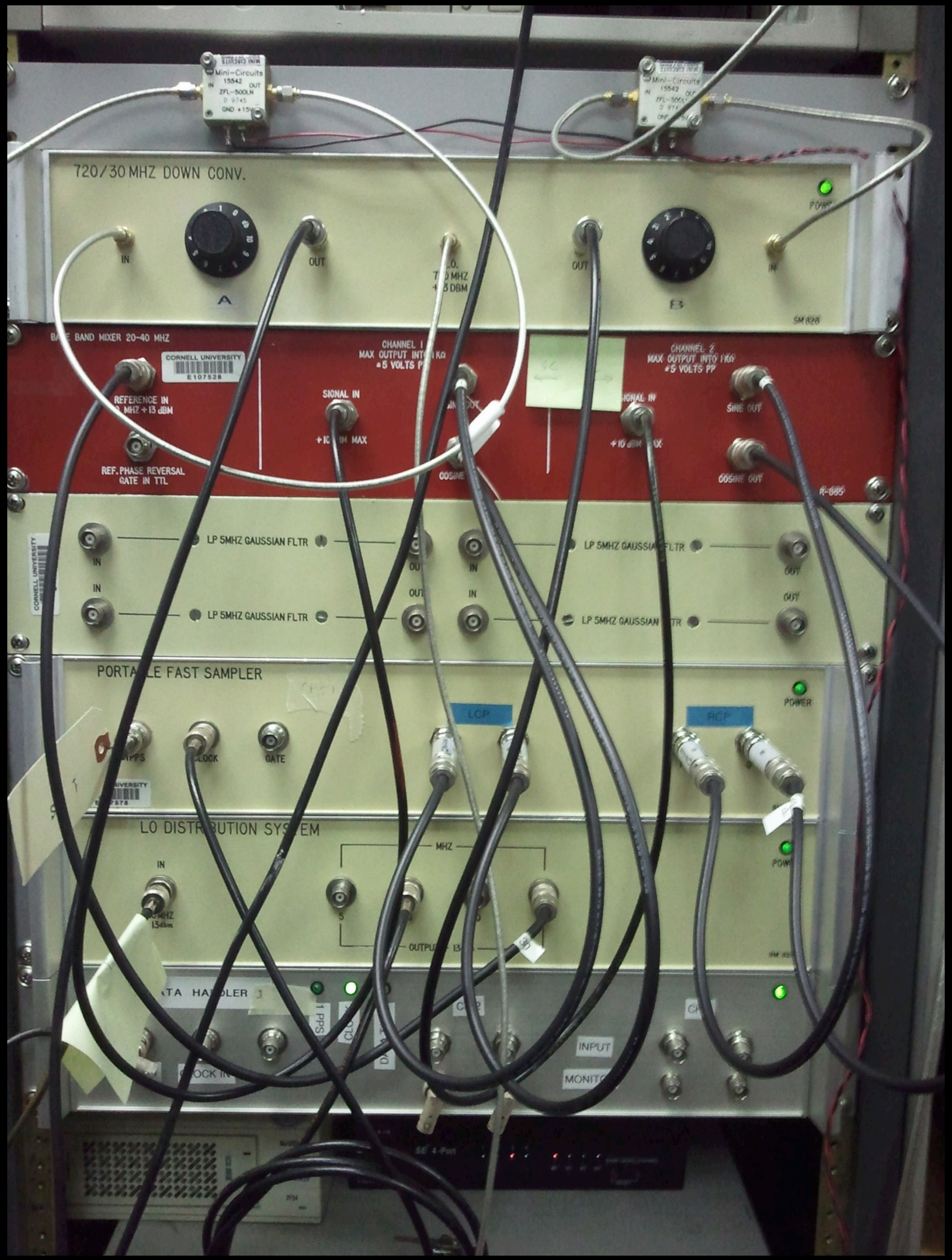
Baseband mixer

Low-pass filters

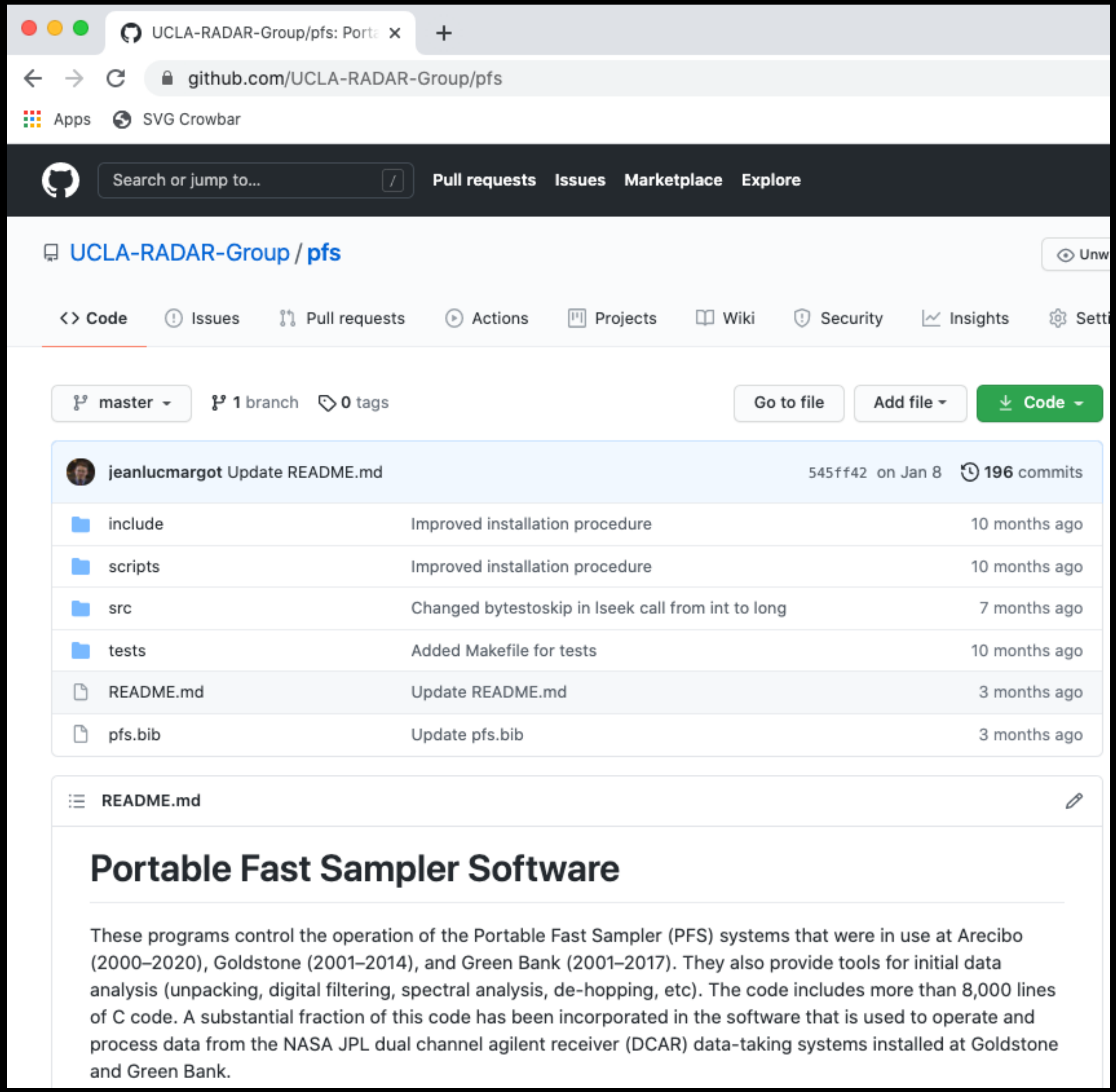
Data-taking unit

5, 10, 20 MHz clock distribution

JPL clone



The portable fast sampler
2 units at Arecibo, 4 units at Goldstone, 2 units at Green Bank



Margot, *JAI* 10, 2021

Radar Waveforms

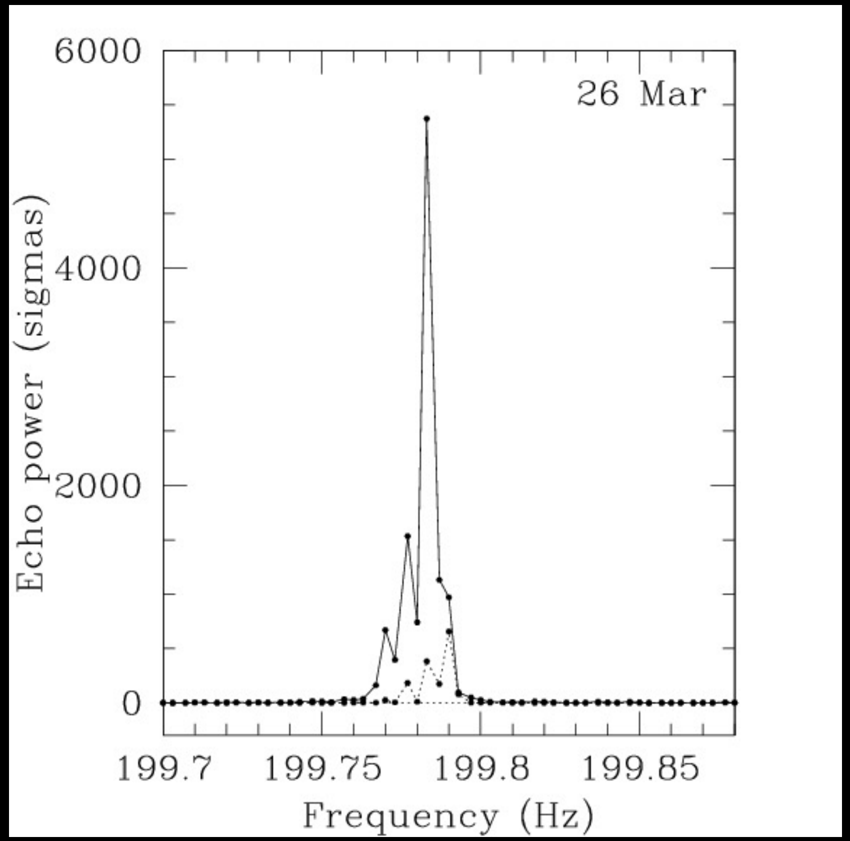
$$\mathbf{x}(t) = \mathbf{A}(t)\cos[2\pi f_c t + \phi(t)]$$

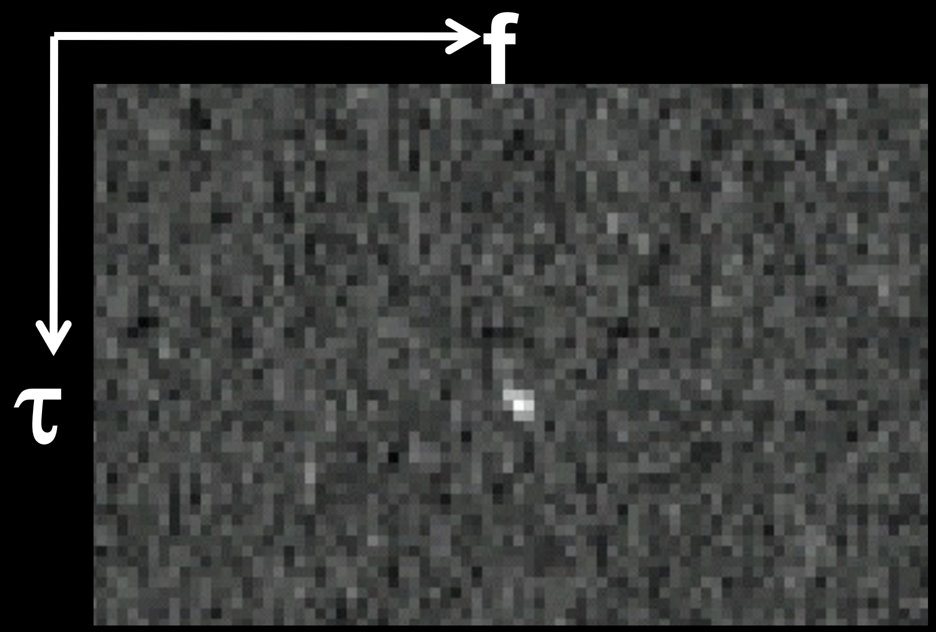
Radar Observables

- Time delay τ
- Doppler shift f
- Received power P_r
- Polarization properties S_i
- Interferometric phase ϕ
- Space-time correlation function χ

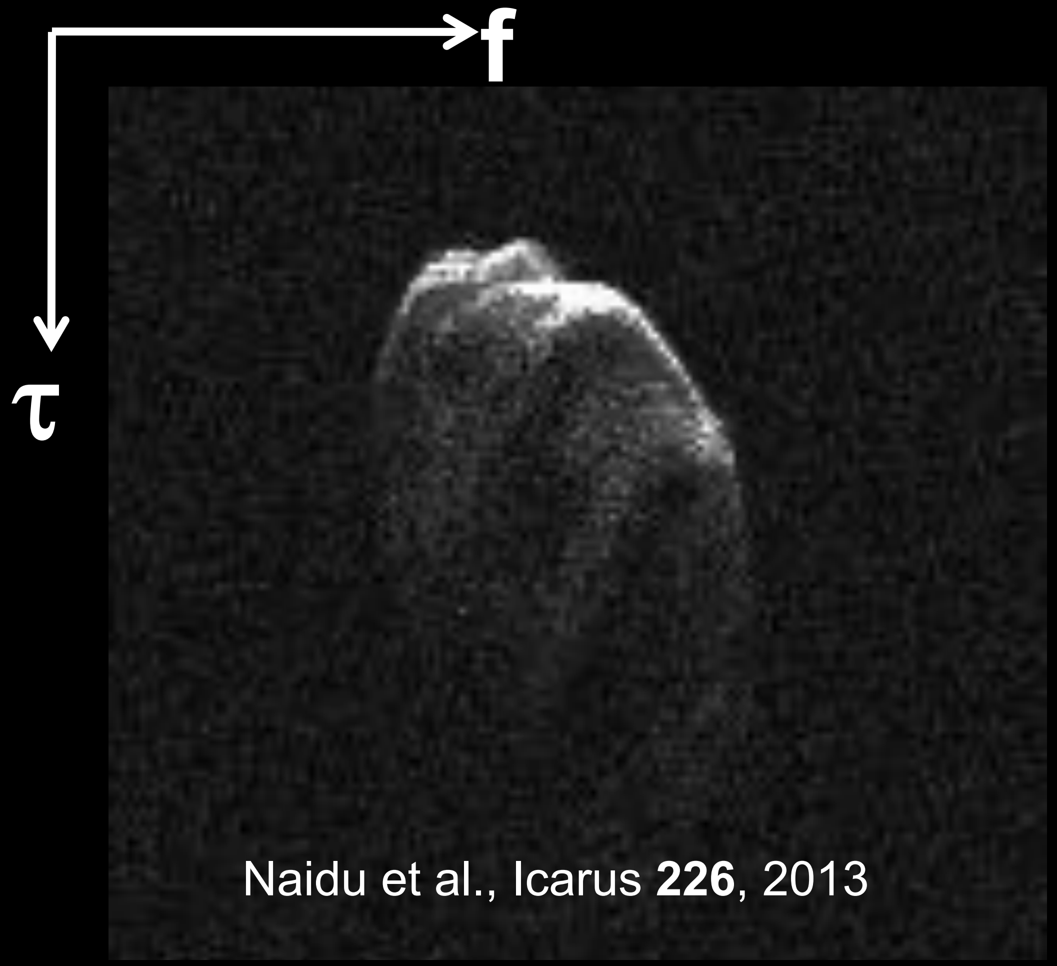
Dynamical Quantities

- Velocities
- Distances
- Orbits
- Spin orientation
- Spin rate



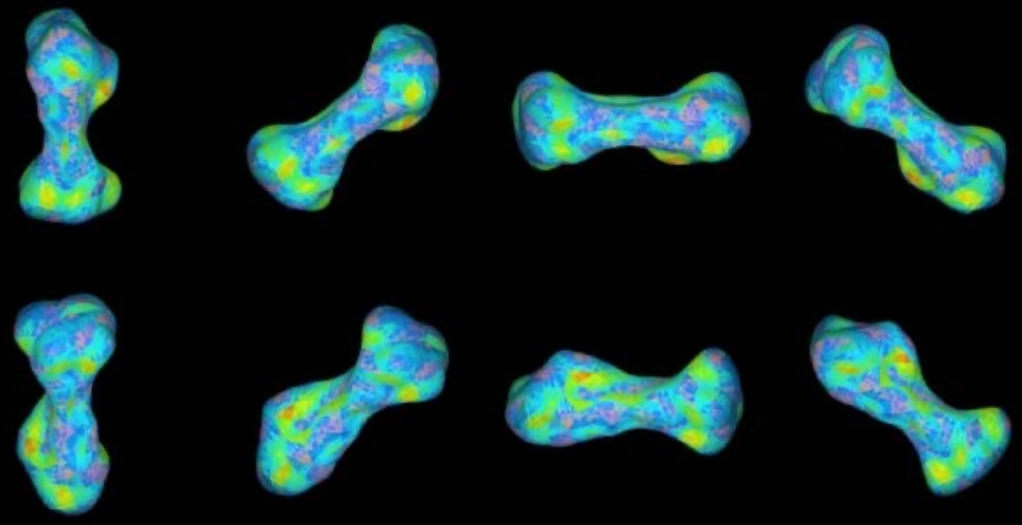


Morphology

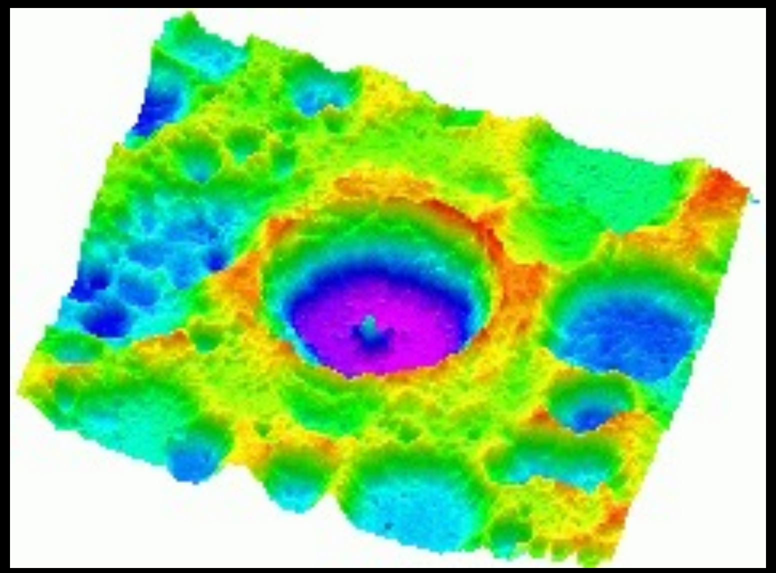


Naidu et al., Icarus **226**, 2013

- Images
- 3D shapes
- Topographic maps
- Surface change

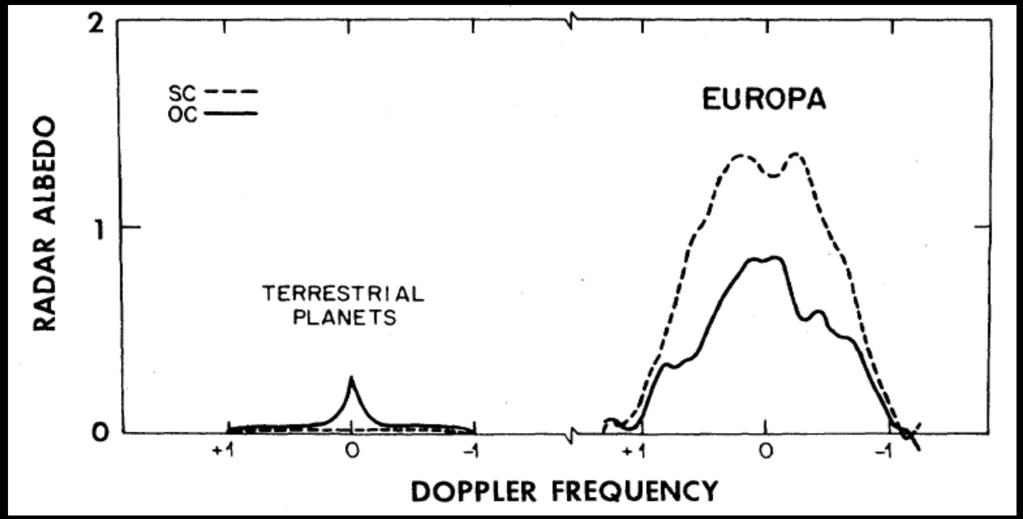


Ostro et al., Science **288**, 2000

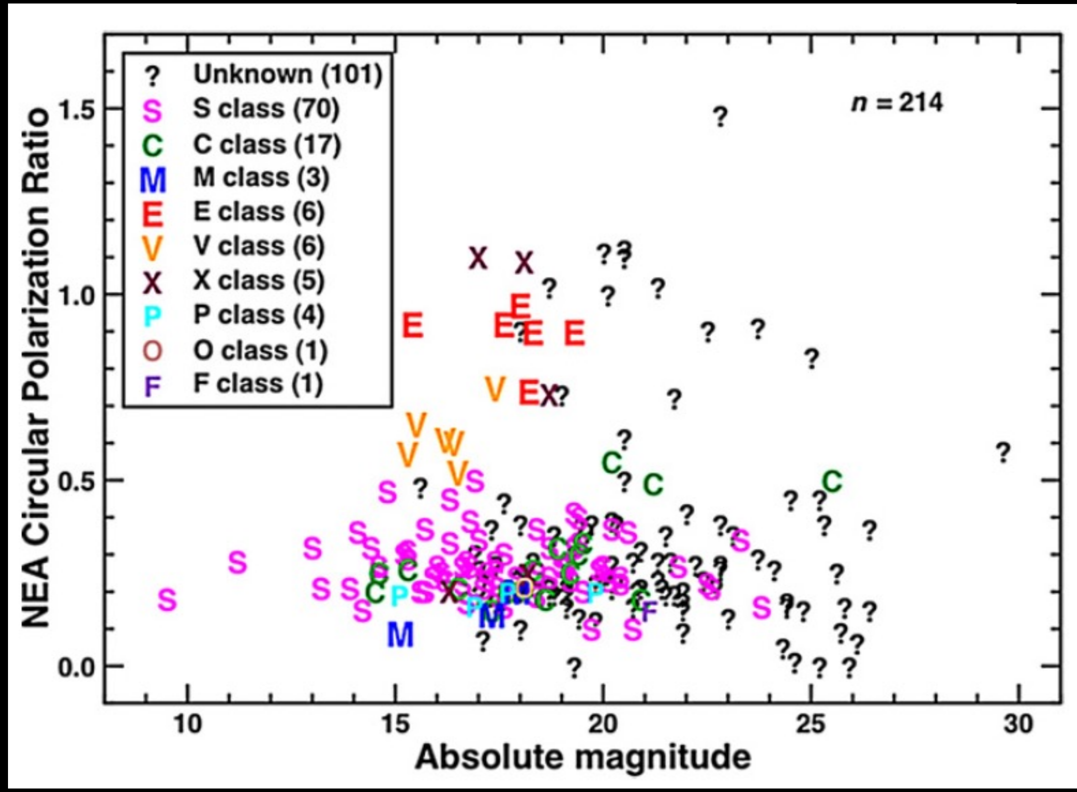


Margot et al., JGR **104**, 1999

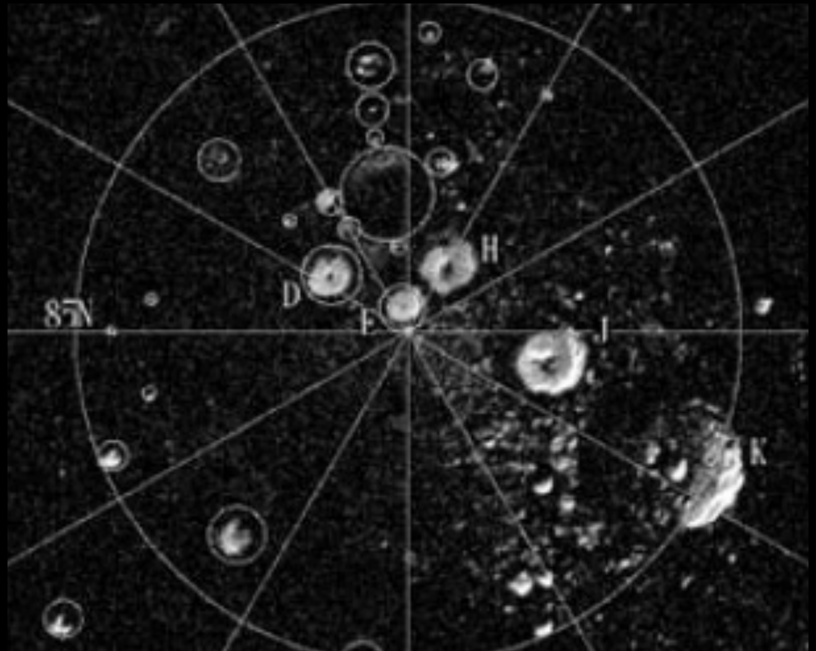
Surface Properties



Ostro, Rev. Mod. Phys. **65**, 1993



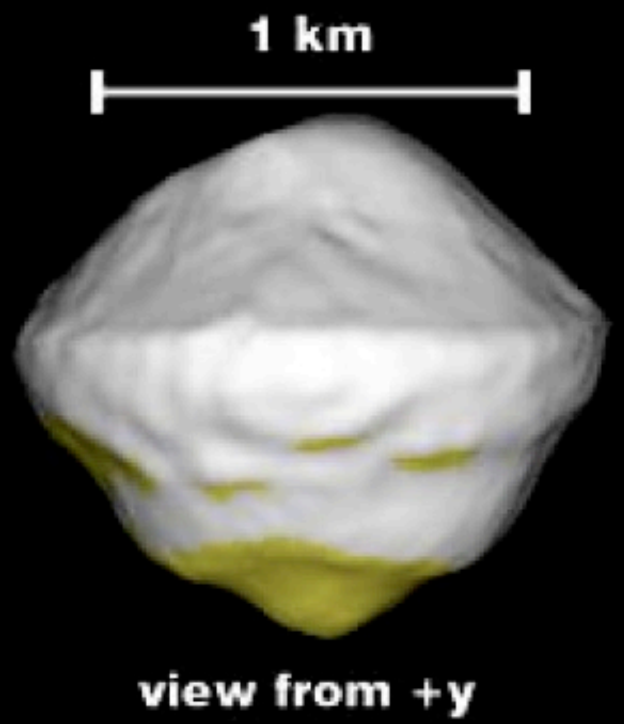
Benner et al., Icarus **198**, 2008



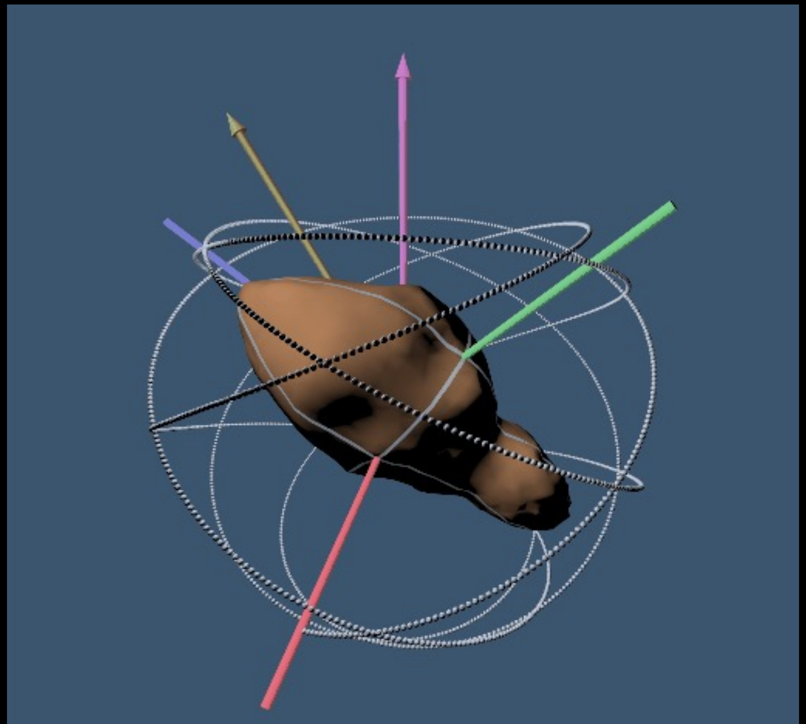
Harmon, SSR **132**, 2007

- Roughness
- Dielectric constant
- Near-surface density
- Composition

Interior Properties



Ostro et al., Science **314**, 2006

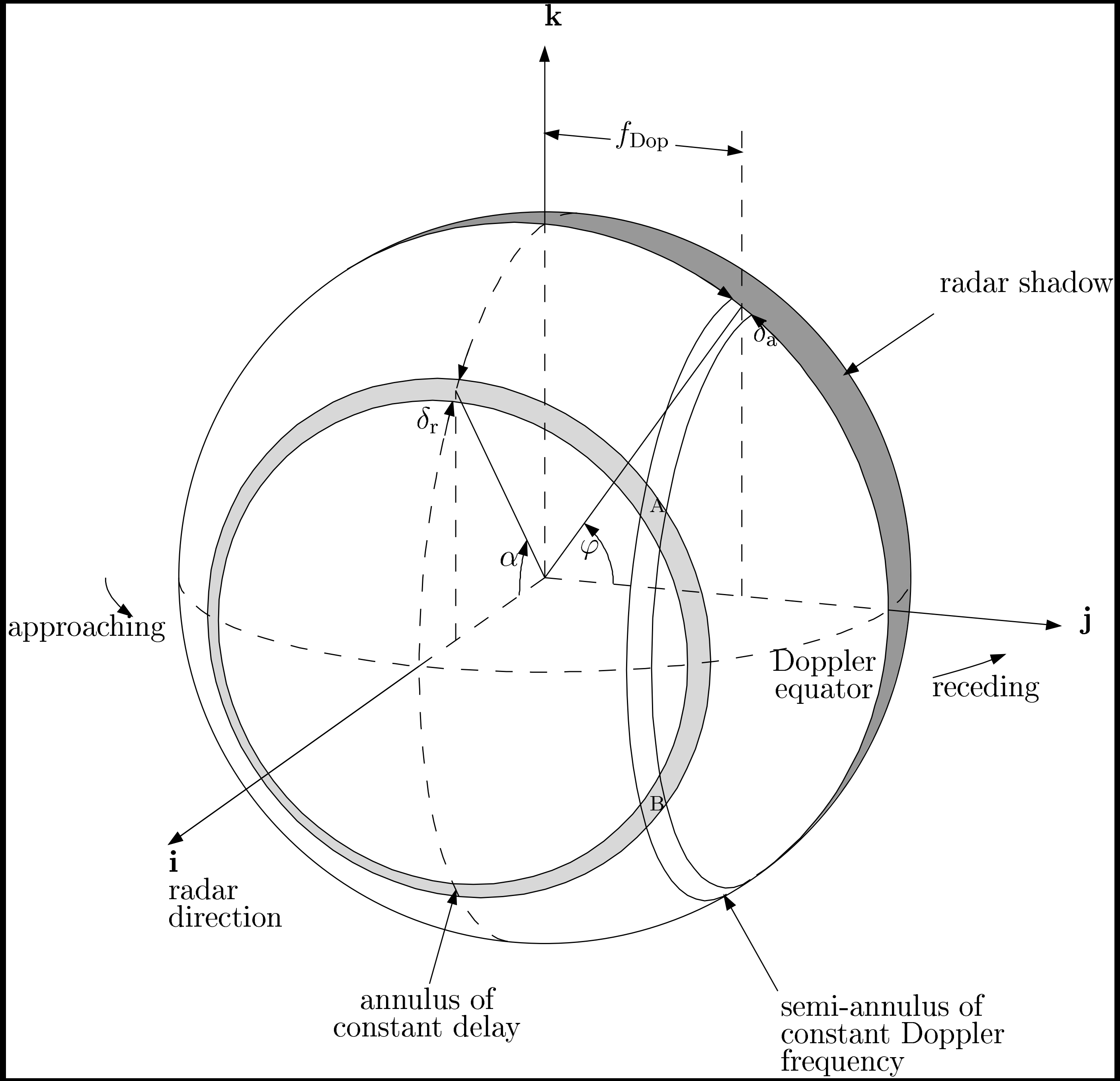

Hudson et al., Icarus **161**, 2003

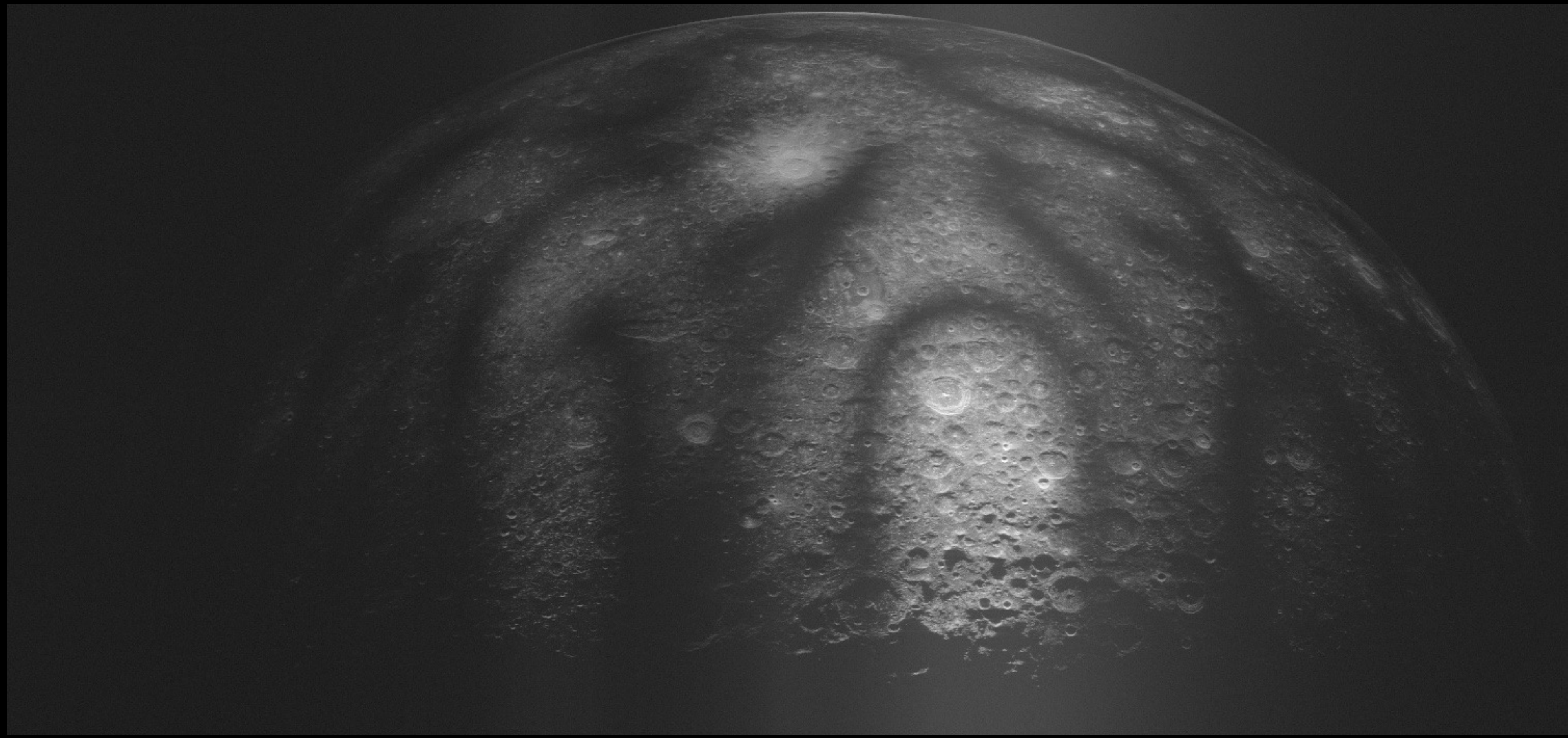
- Mass
- Bulk density
- Moments of inertia

Radar Measurements

- Velocities
- Distances
- Orbits
- Spin orientation
- Spin rate
- Mass
- Bulk density
- Moments of inertia
- Images
- Surface change
- Topographic maps
- 3D shape
- Roughness
- Dielectric constant
- Near-surface density
- Composition

Range-Doppler Imaging

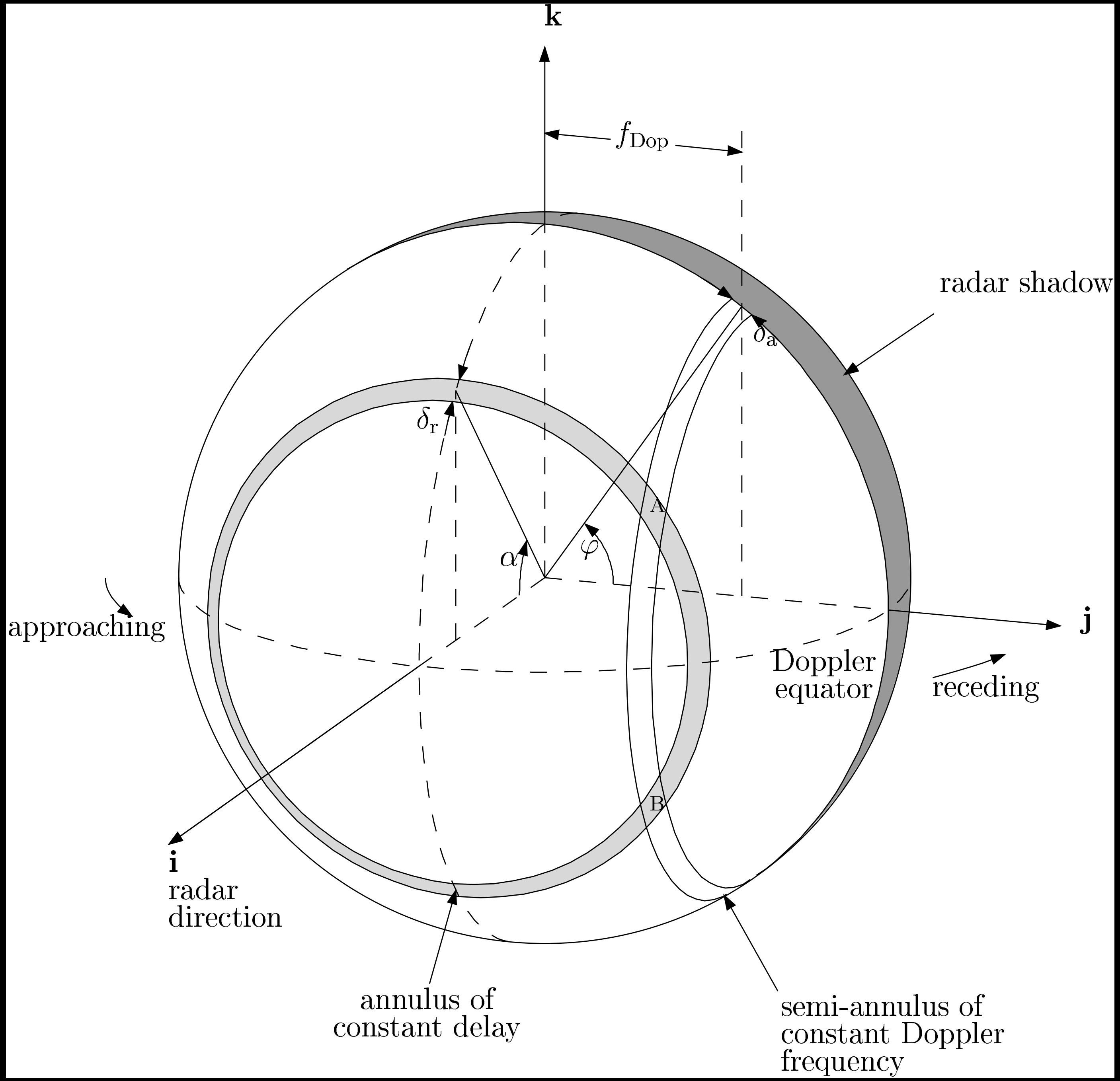




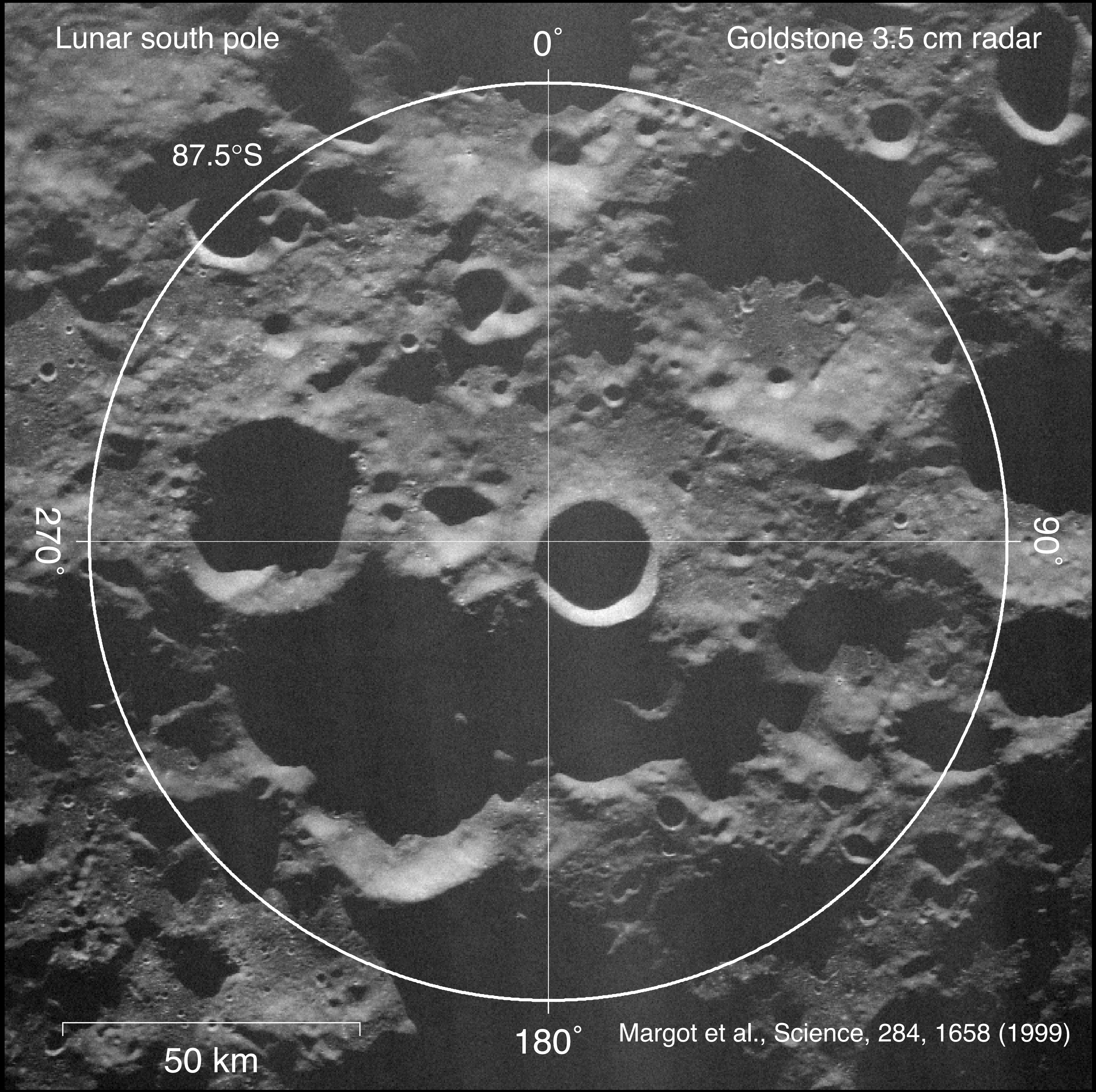
Margot et al., *IEEE TGRS* 38, 2000

Margot, *JAI* 10, 2021

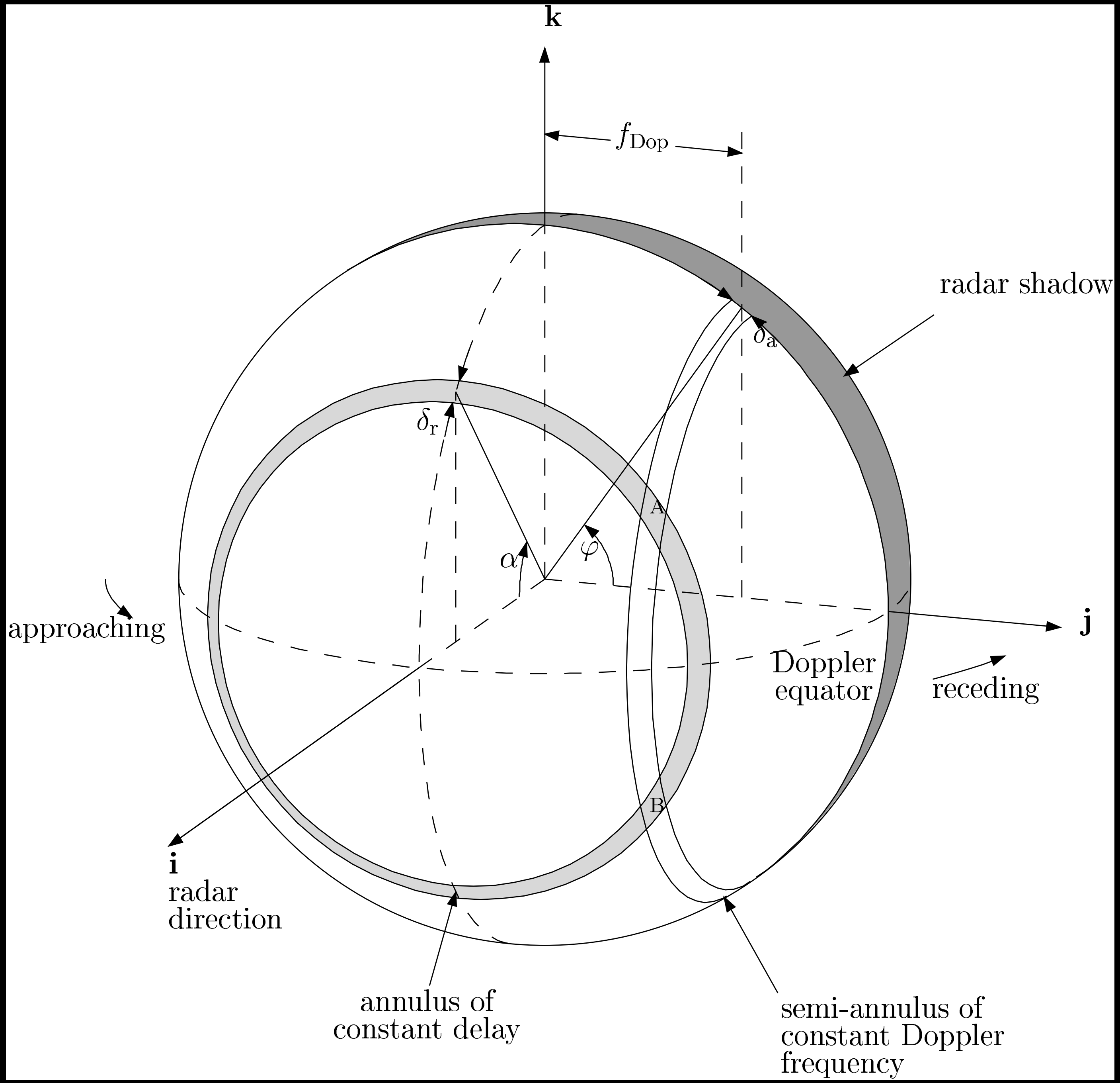
Range-Doppler Imaging

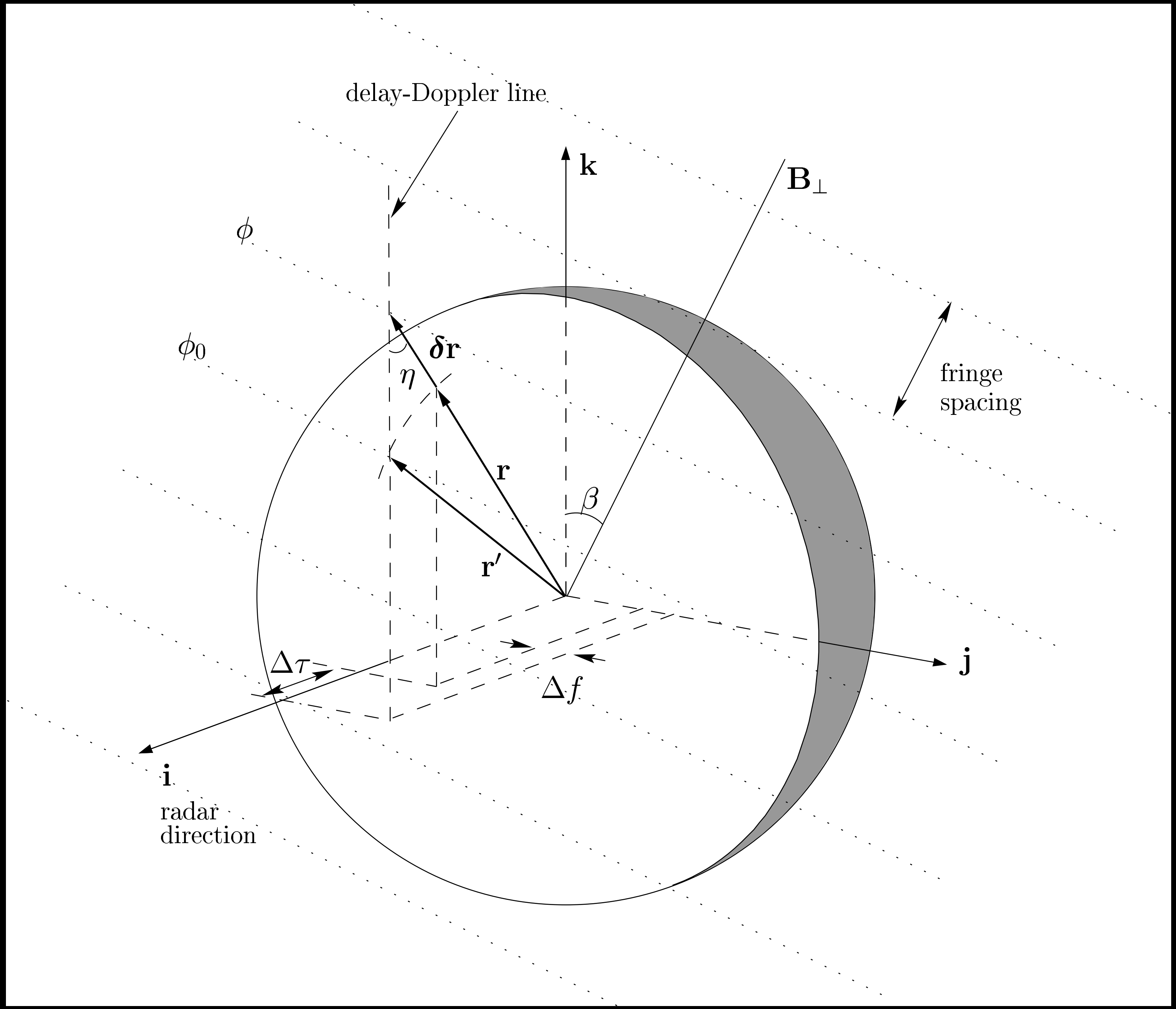


Margot et al., *IEEE TGRS* **38**, 2000



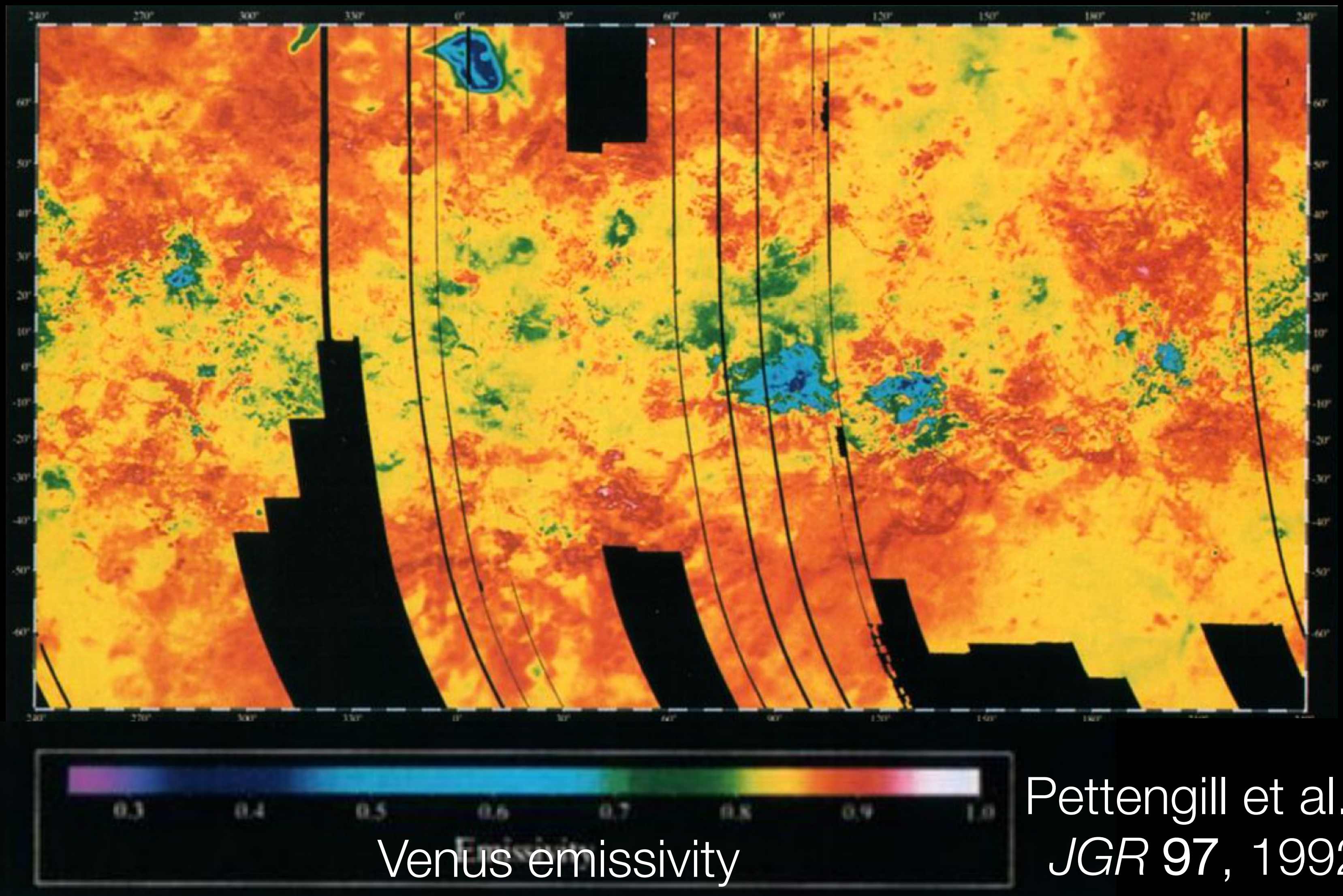
Range-Doppler Imaging and InSAR





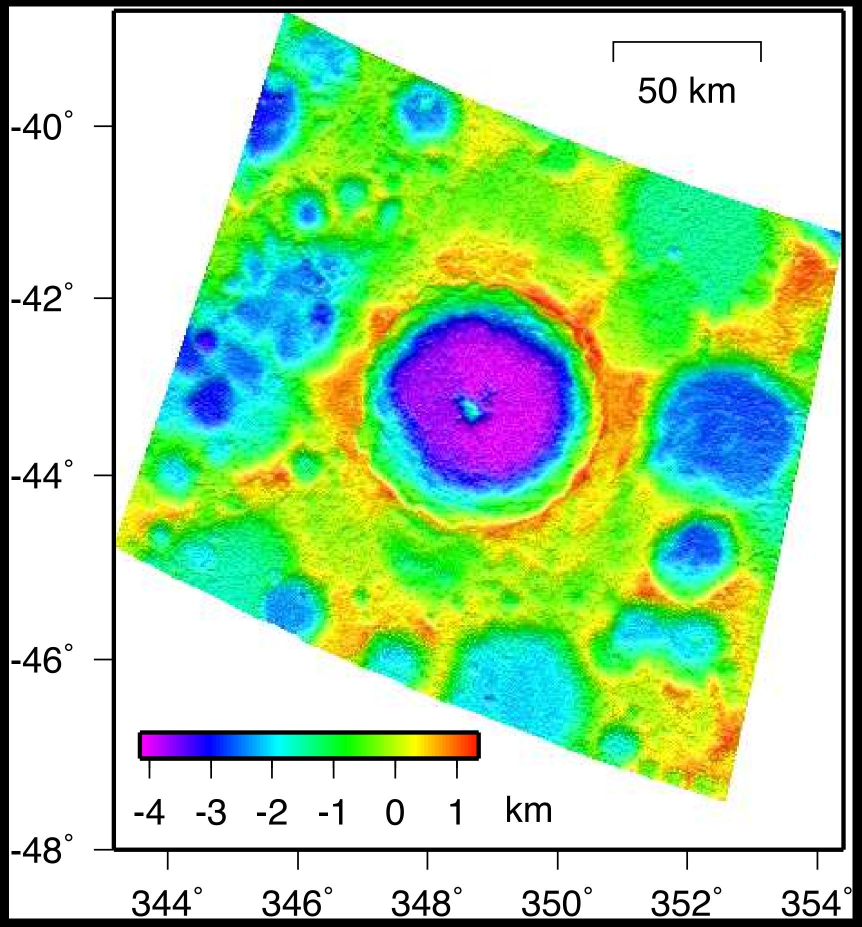
Margot et al., *IEEE TGRS* **38**, 2000

First Science Observations at GBT: Venus



Venus emissivity

Pettengill et al., *JGR* **97**, 1992



Lunar topography
Margot et al., *JGR* **104**, 1999

Goal: measure the topography of several high-reflectivity, low-emissivity mountains to explain the relationship between surface emissivity, reflectivity, and altitude on Venus (PI: Don Campbell)

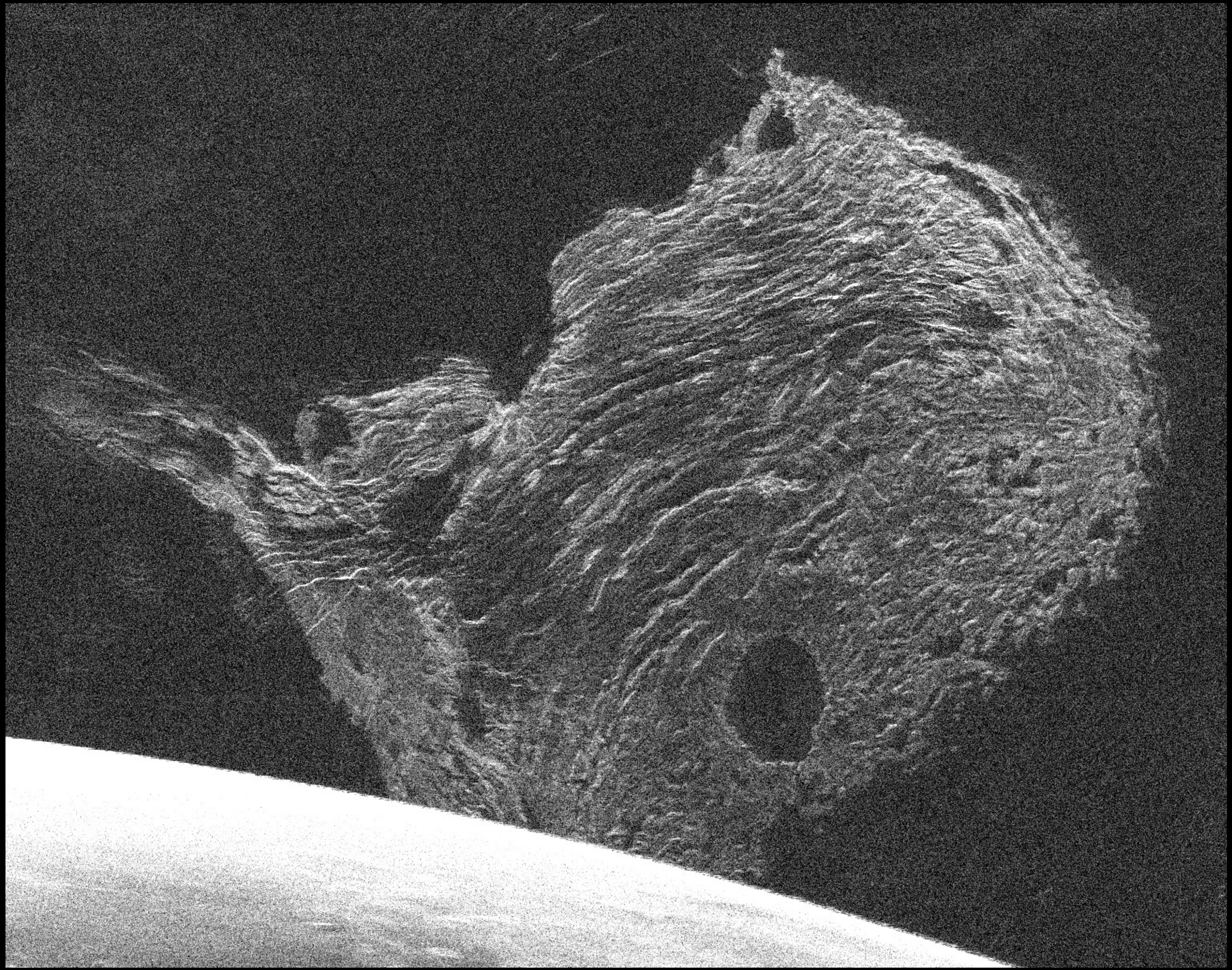
An Auspicious Start

Venus 24 Mar 2001

GB windy
& no internet

Arecibo-GBT Radar Image of Venus

Maxwell Montes



National Radio Astronomy Observatory
520 Edgemont Road
Charlottesville, VA 22903
http://www.nrao.edu

May 10, 2001

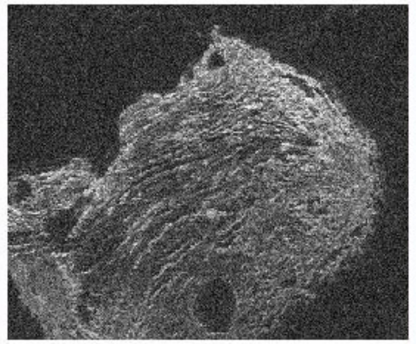
Contact:

Dave Finley, Public Information Officer
(505) 835-7302
dfinley@nrao.edu

New Radio Telescope Makes First Scientific Observations

The world's two largest radio telescopes have combined to make detailed radar images of the cloud-shrouded surface of Venus and of a tiny asteroid that passed near the Earth. The images mark the first scientific contributions from the National Science Foundation's (NSF) new Robert C. Byrd Green Bank Telescope in West Virginia, which worked with the NSF's recently-upgraded Arecibo telescope in Puerto Rico. The project used the radar transmitter on the Arecibo telescope and the huge collecting areas of both telescopes to receive the echoes.

"These images are the first of many scientific contributions to come from the Robert C. Byrd Green Bank Telescope, and a great way for it to begin its scientific career," said Paul Vanden Bout, director of the National Radio Astronomy Observatory (NRAO). "Our congratulations go to the scientists involved in this project as well as to the hard-working staffs at Green Bank and Arecibo who made this accomplishment possible," Vanden Bout added.



A portion of Maxwell Montes on Venus, imaged with the Arecibo-GBT radar system. This image shows detail as small as 1.2 kilometers. Courtesy Campbell et al., NRAO, NAIC, NSF.

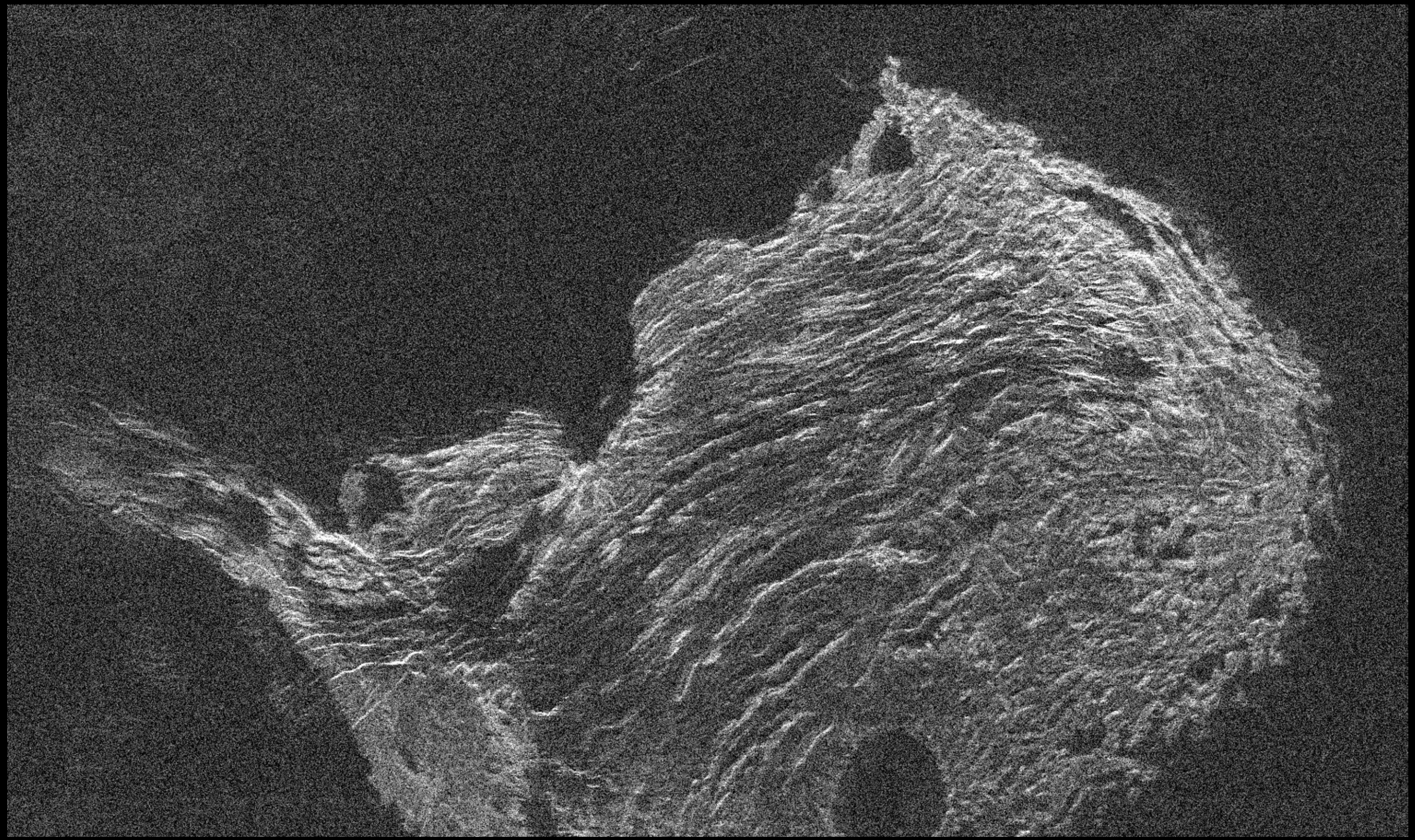
To the eye, Venus hides behind a veil of brilliant white clouds, but these clouds can be penetrated by radar waves, revealing the planet's surface. The combination of the Green Bank Telescope (GBT), the world's largest fully-steerable radio telescope, and the Arecibo telescope, the world's most powerful radar, makes an unmatched tool for studying Venus and other solar-system bodies.

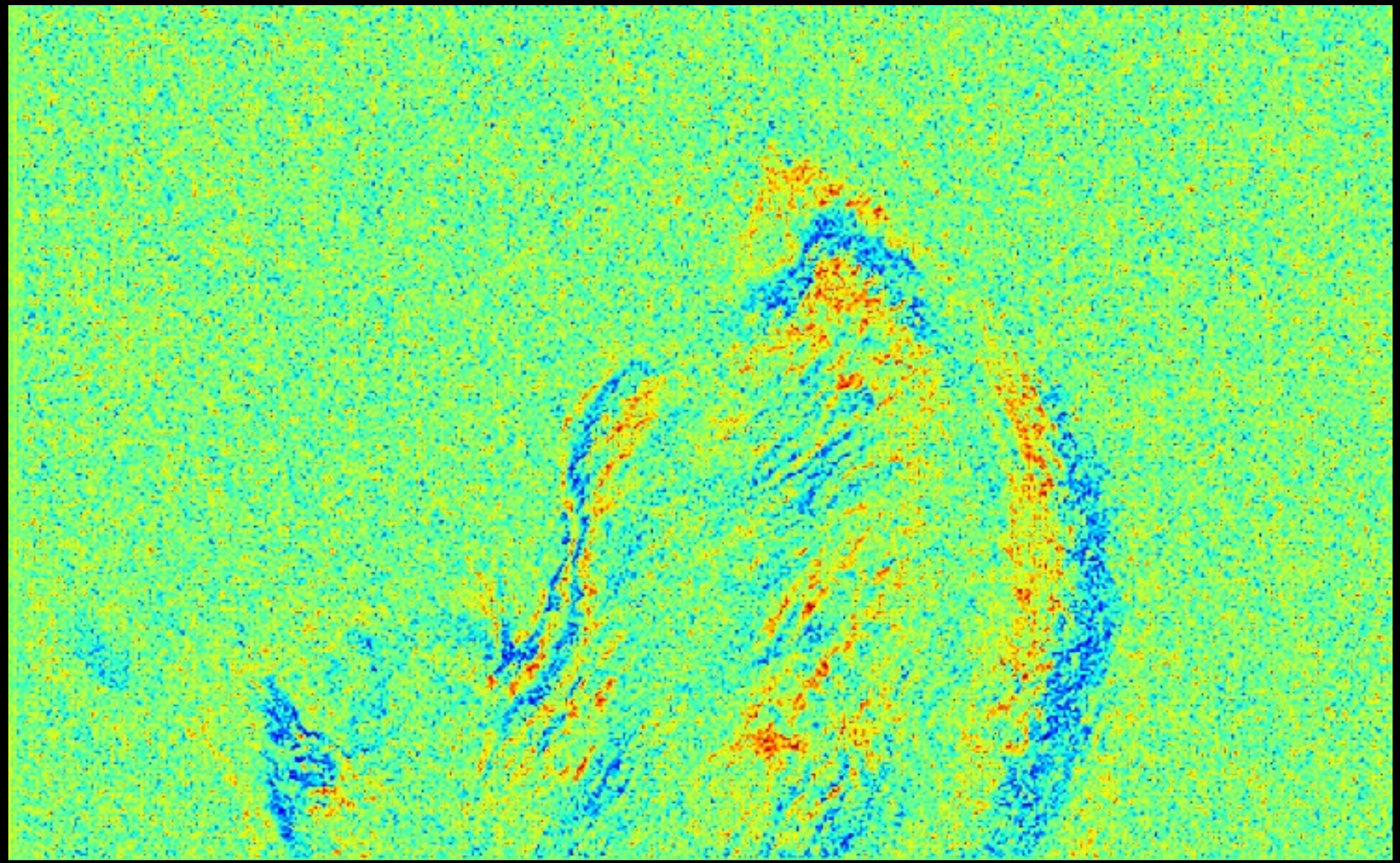
"Having a really big telescope like the new Green Bank Telescope to receive the radar echoes from small asteroids that are really close to the Earth and from very distant objects like Titan, the large moon of Saturn, will be a real boon to radar studies of the solar system." said Cornell University professor Donald Campbell, leader of the research team.

Ten years ago, the radar system on NASA's Magellan spacecraft probed though the clouds of Venus to reveal in amazing detail the surface of the Earth's twin planet. These new studies using the GBT and Arecibo, the first since Magellan to cover large areas of the planet's surface, will provide images showing surface features as small as about 1 km (3,000 ft), only three times the size of the Arecibo telescope itself.

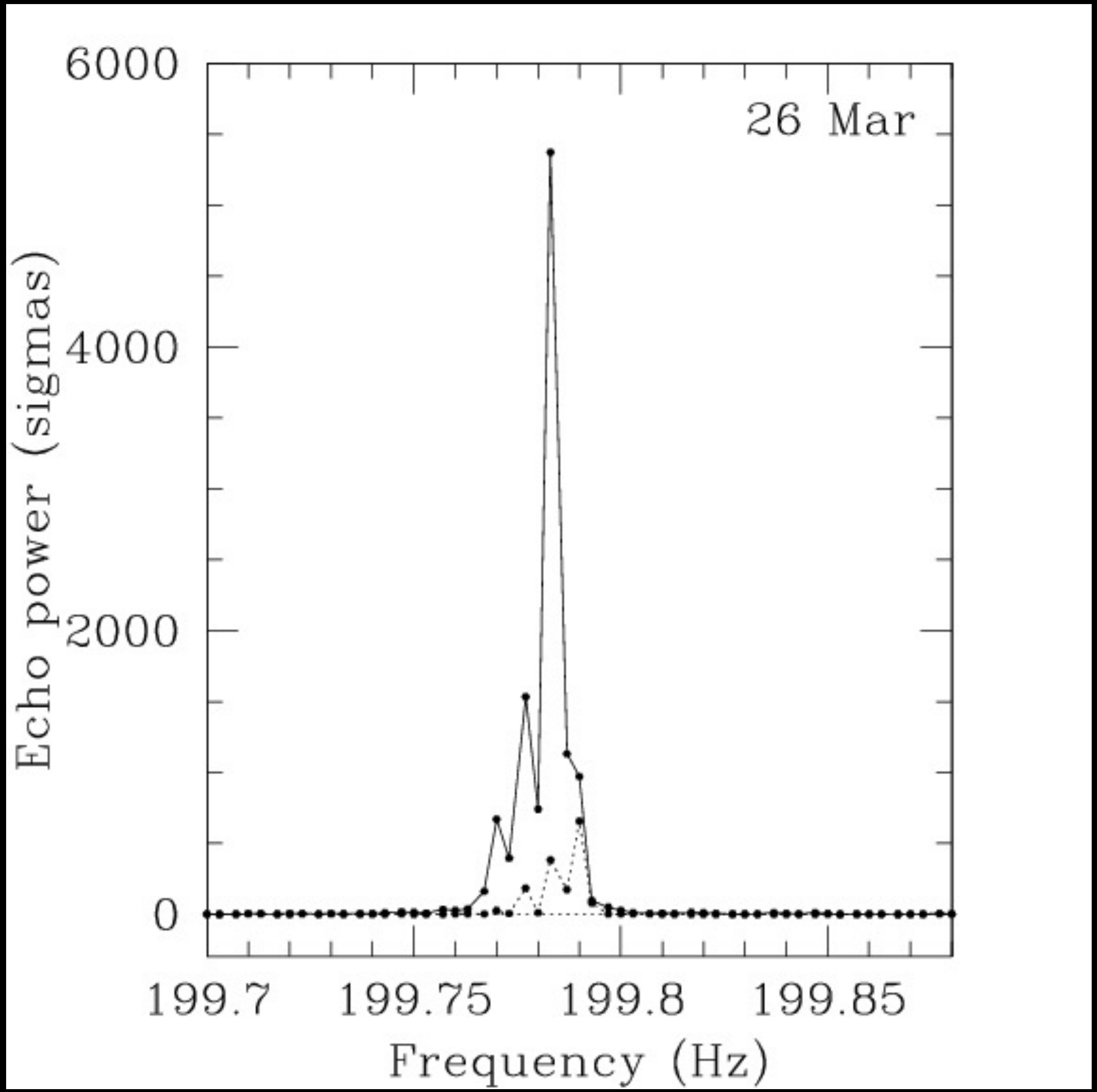
Venus may be a geologically active planet similar to the Earth, and the new images will be used to look for changes on Venus due to volcanic activity, landslides and other processes that may have modified the surface since the Magellan mission. The radar echoes received by both telescopes also can be combined to form a radar interferometer capable of measuring altitudes over some of the planet's mountainous regions with considerably better detail than was achieved by Magellan.

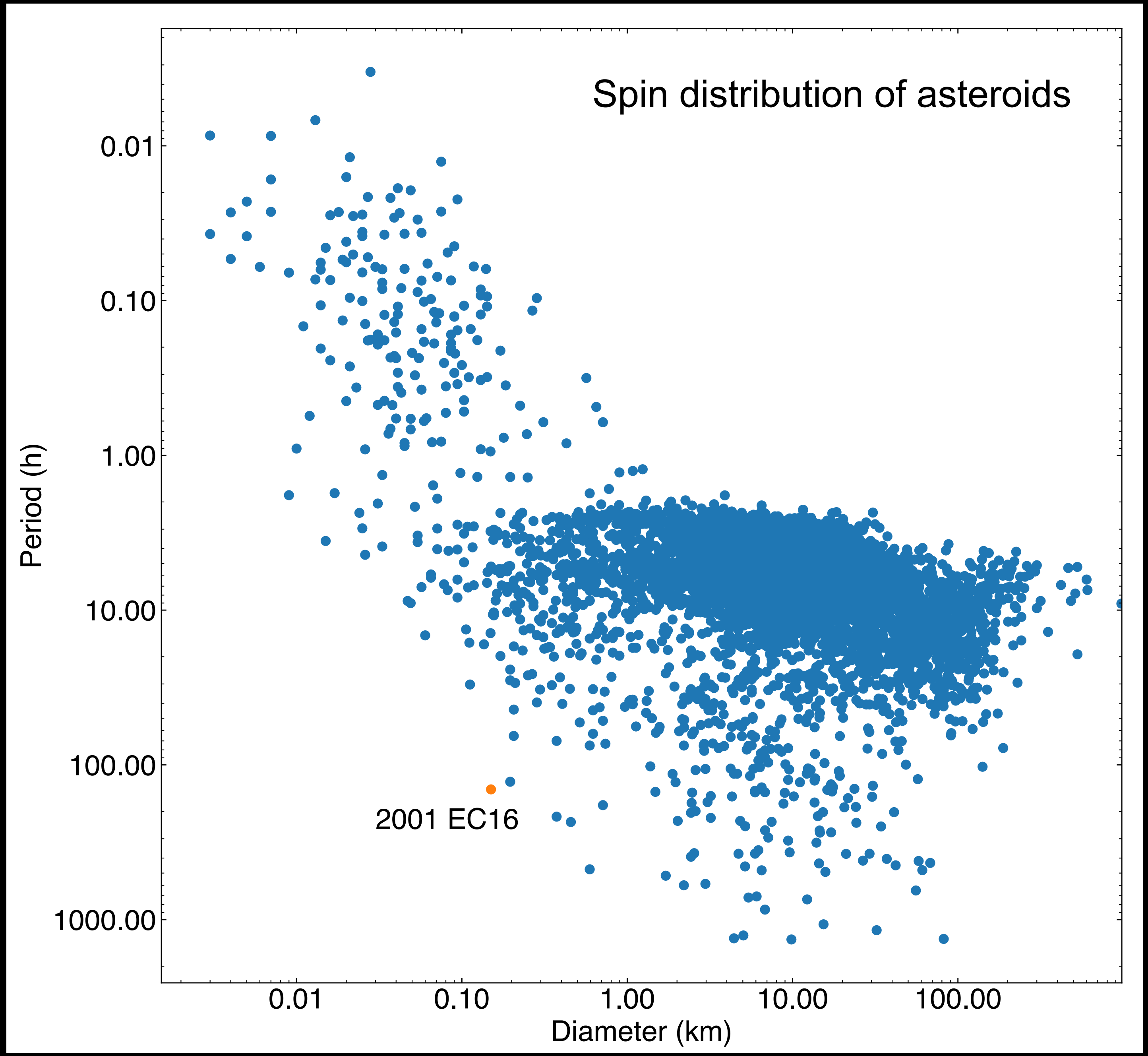
Interferometric Fringes



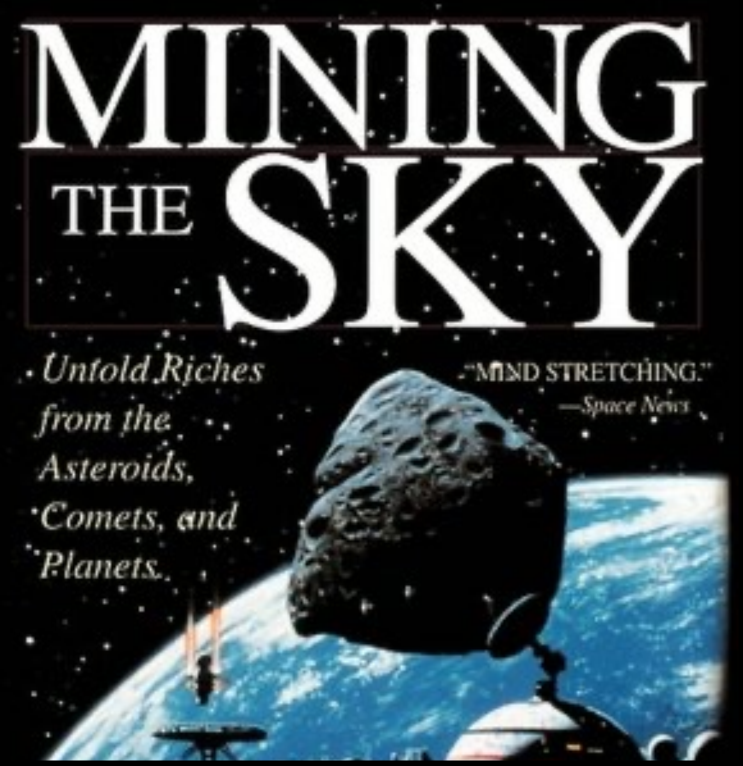


Second Science Observations: 2001 EC16



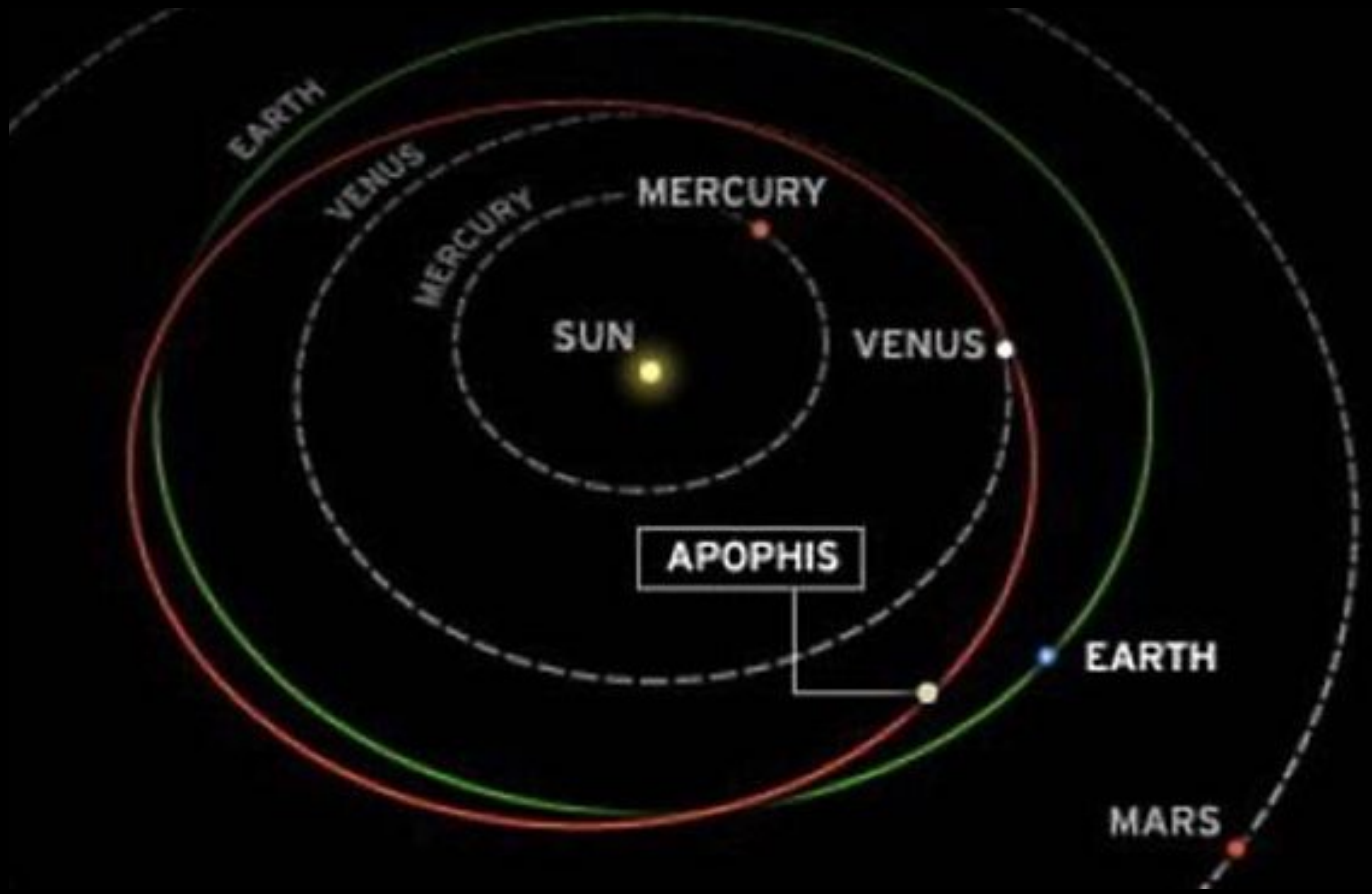


Importance of Near-Earth Asteroids

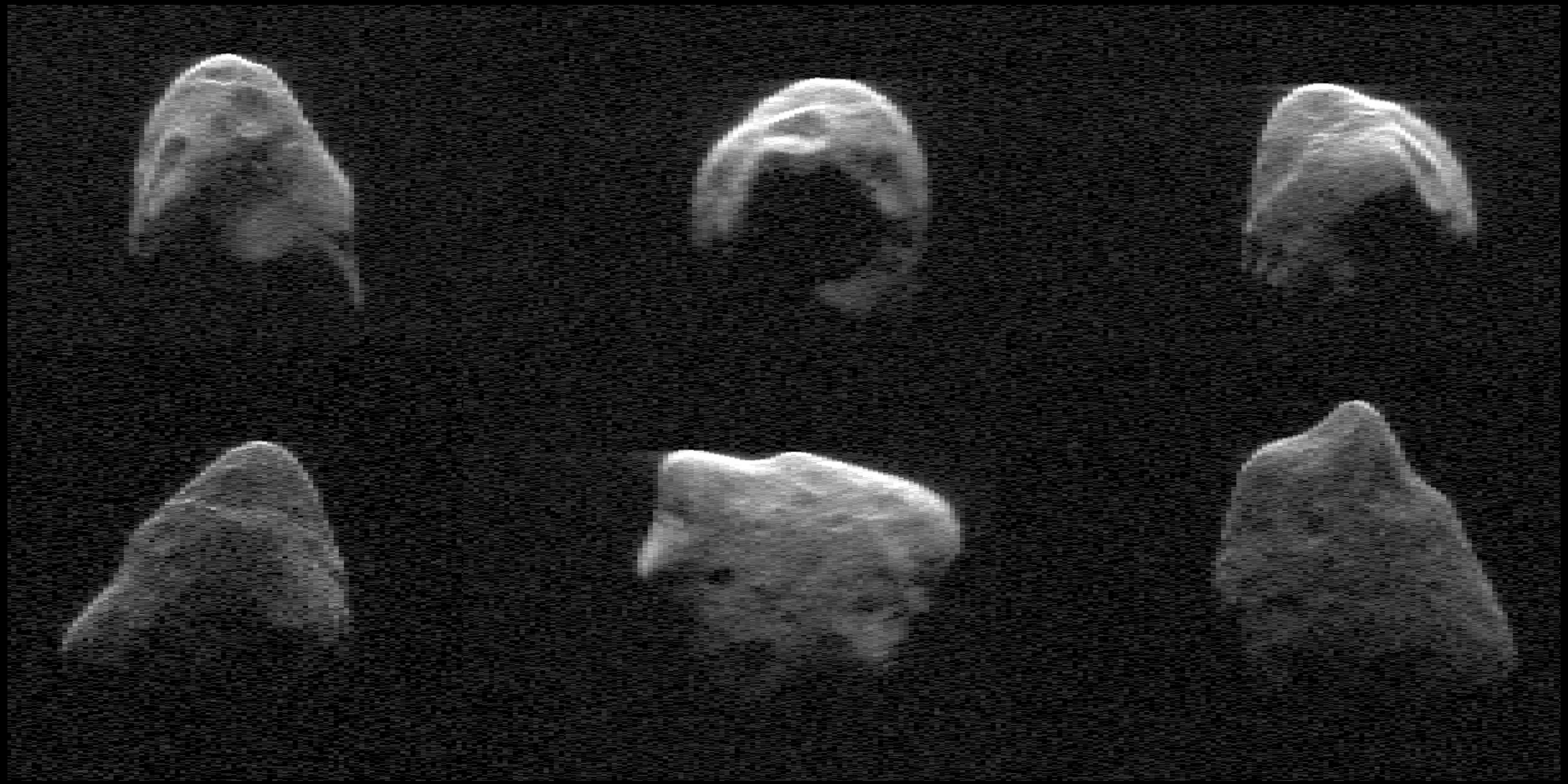


Importance of Radar Astronomy

Orbit determination

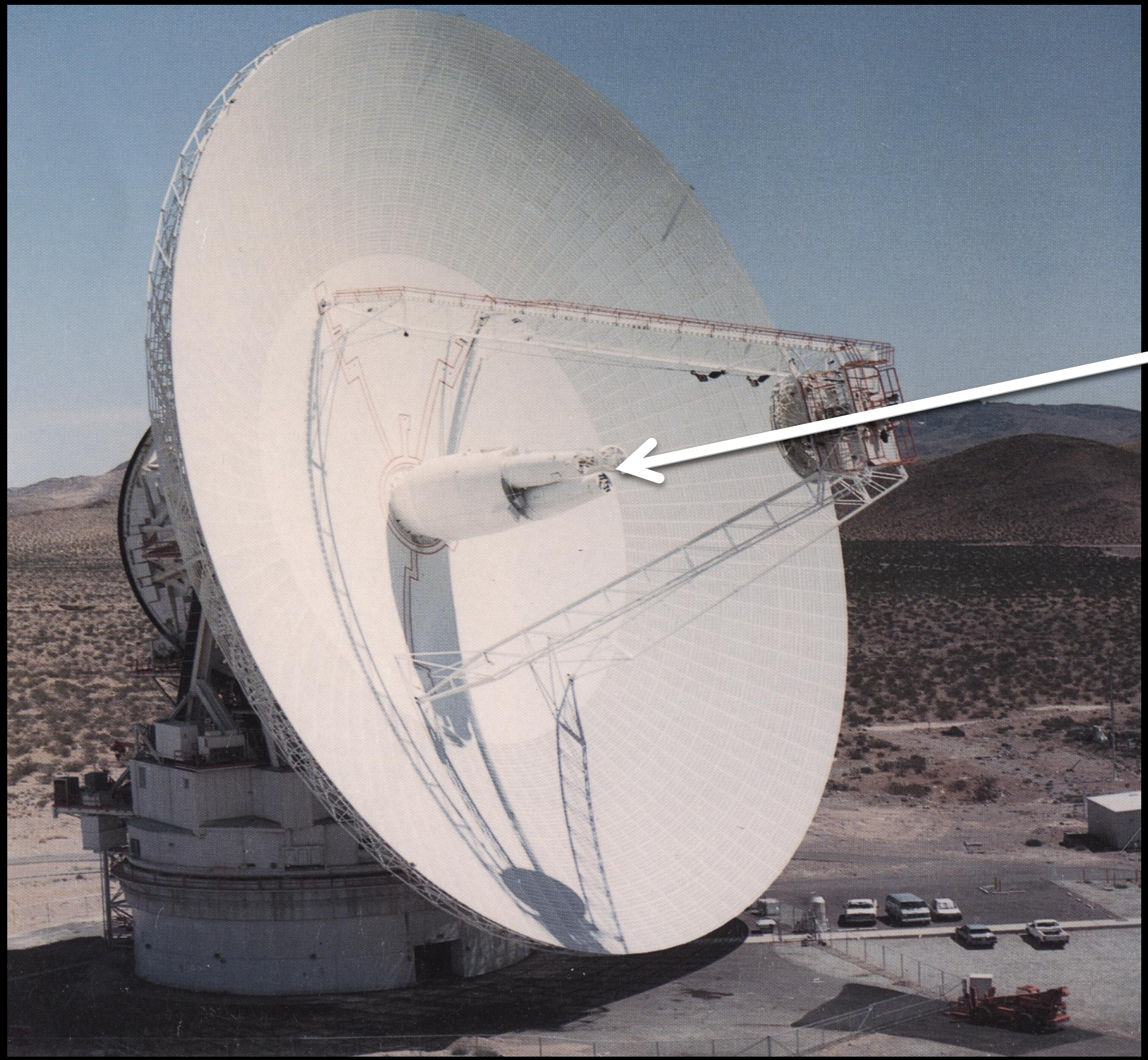


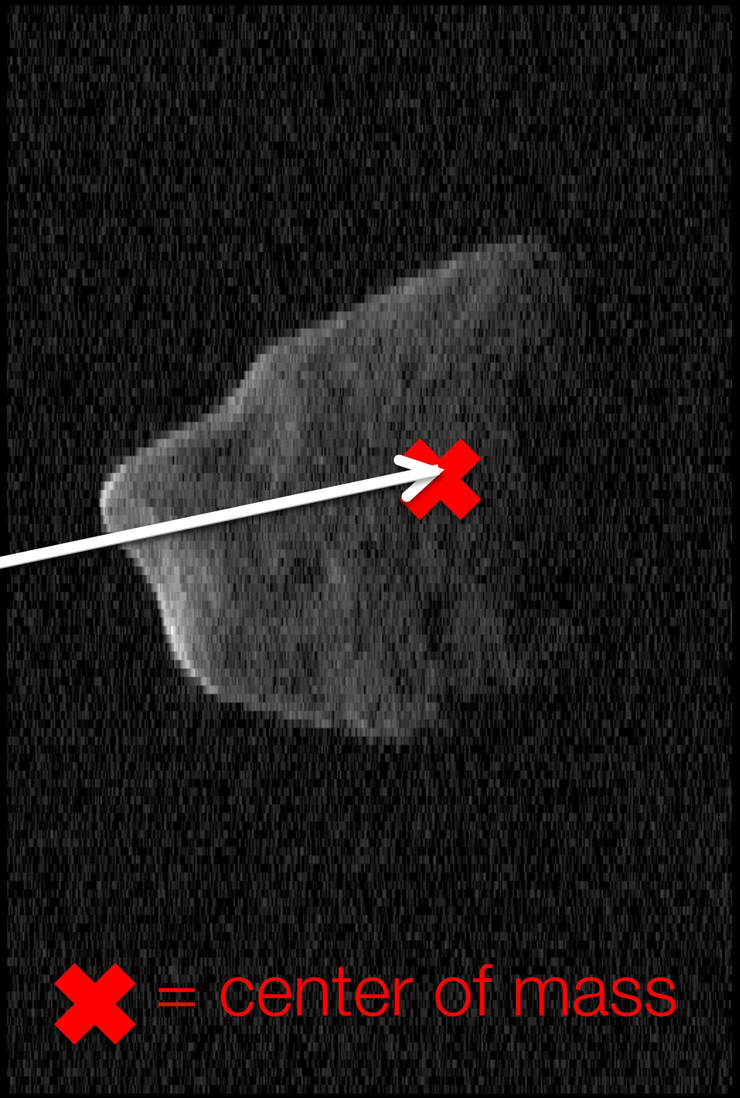
Physical characterization



Range Measurements

Fractional precision < 0.00000001



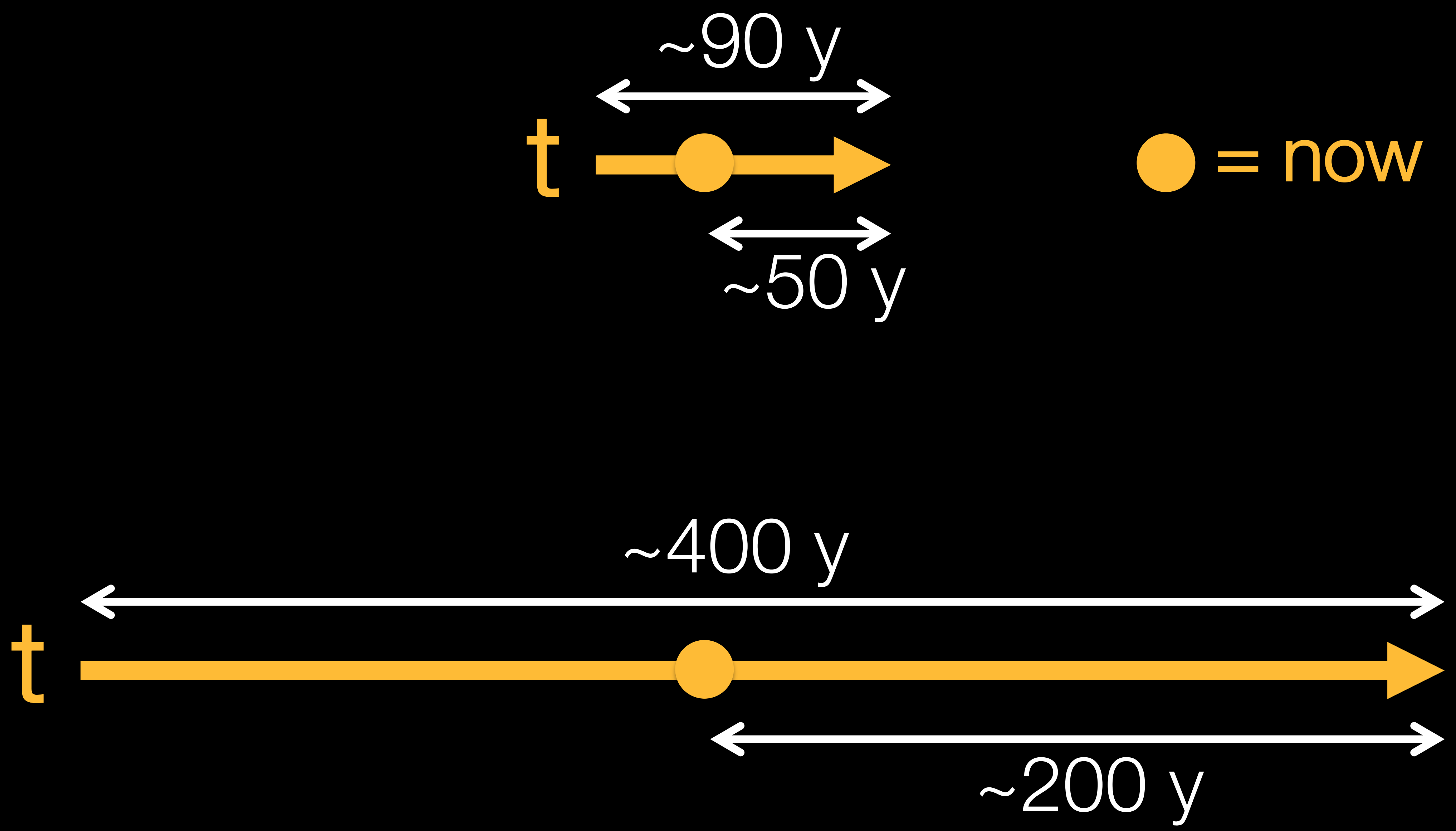


20 x better than optical

Time Interval of Reliable Trajectory Predictions (average case)

Without radar

With radar



Trajectory Prediction Uncertainties

Trajectory propagation factor	Along-track effect, km
(A) Galactic tide	−8400
(B) Numerical integration error	−9900
(C) Solar mass loss	+13300
(D) Solar oblateness (J2)	(+42100, +17600)
(E) 61 additional asteroids	-1.5×10^6
(F) Planetary mass uncertainty	$(+1.38, -1.54) \times 10^6$
(G) Solar radiation pressure	-11.2×10^6
Combined (A-G)	$(-11.0, -17.6) \times 10^6$
Yarkovsky effect only	$(+11.9, -71.0) \times 10^6$

Giorgini et al., Science 296, 2002.

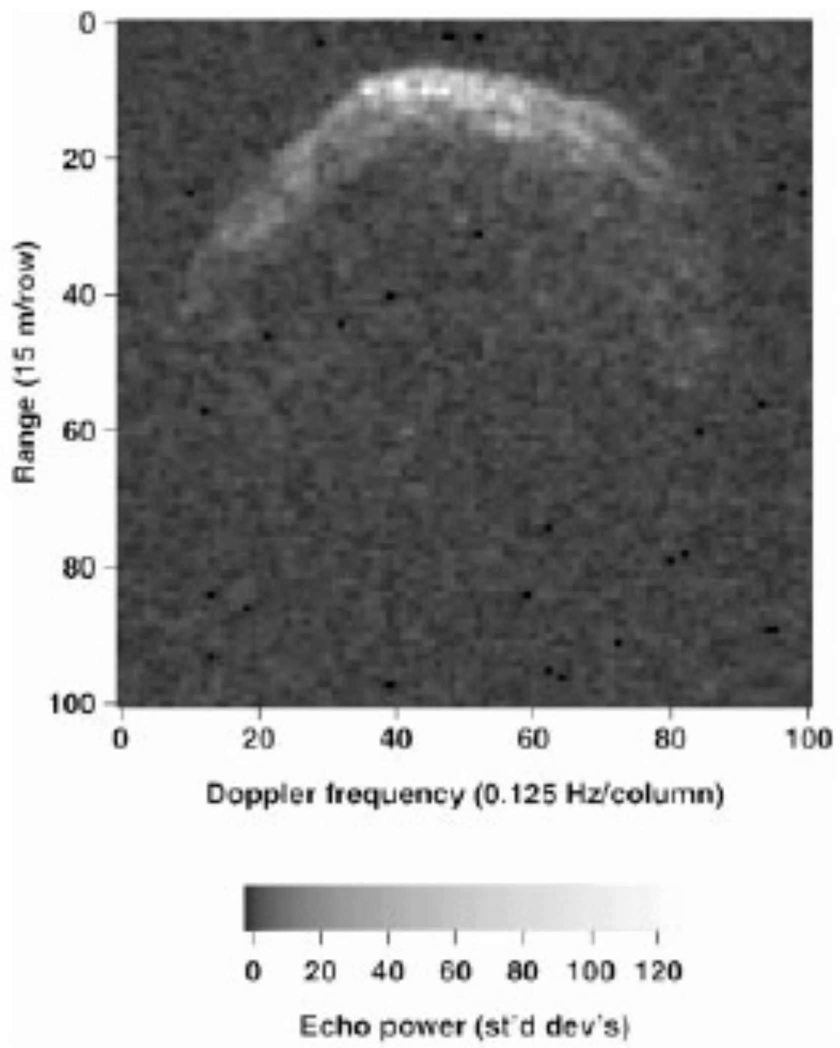
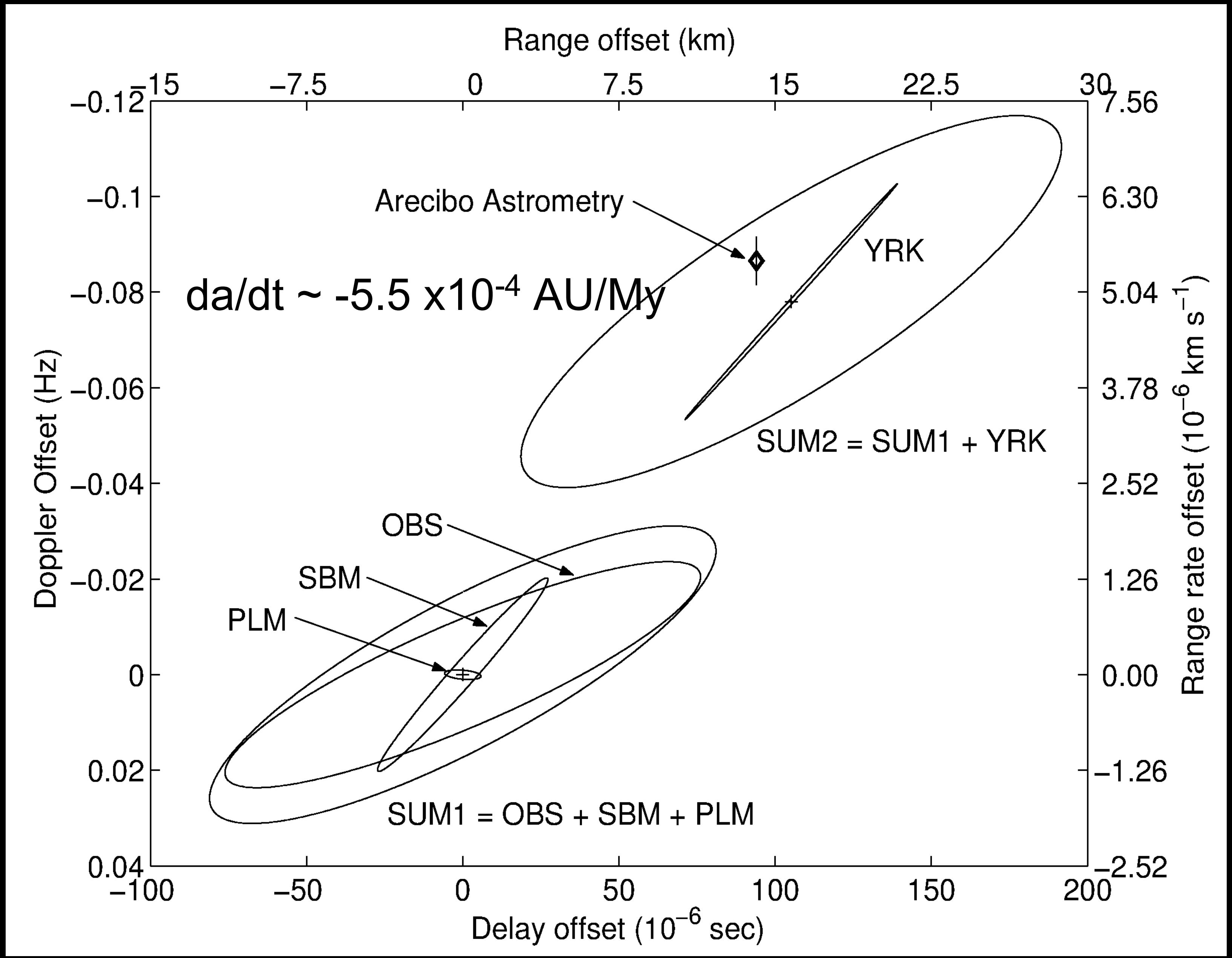
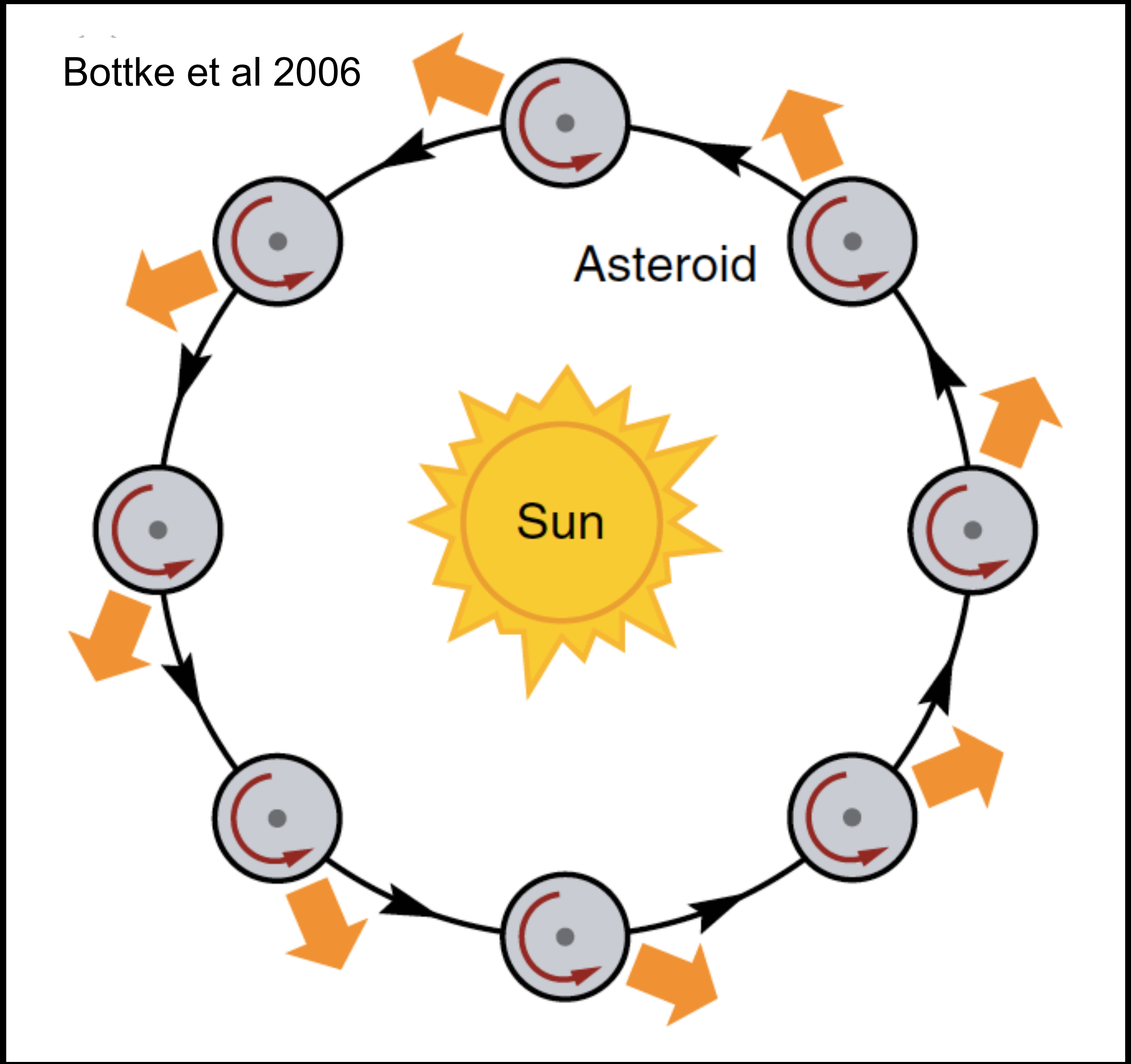


Fig. 1. Arecibo (2380 MHz, 13 cm) delay-Doppler echo-power image of 1950 DA on 4 March 2001, from a distance of 0.052 AU (22 lunar distances). Vertical resolution is 15 m, and horizontal resolution is 0.125 Hz (7.9 mm s^{-1} in radial velocity).

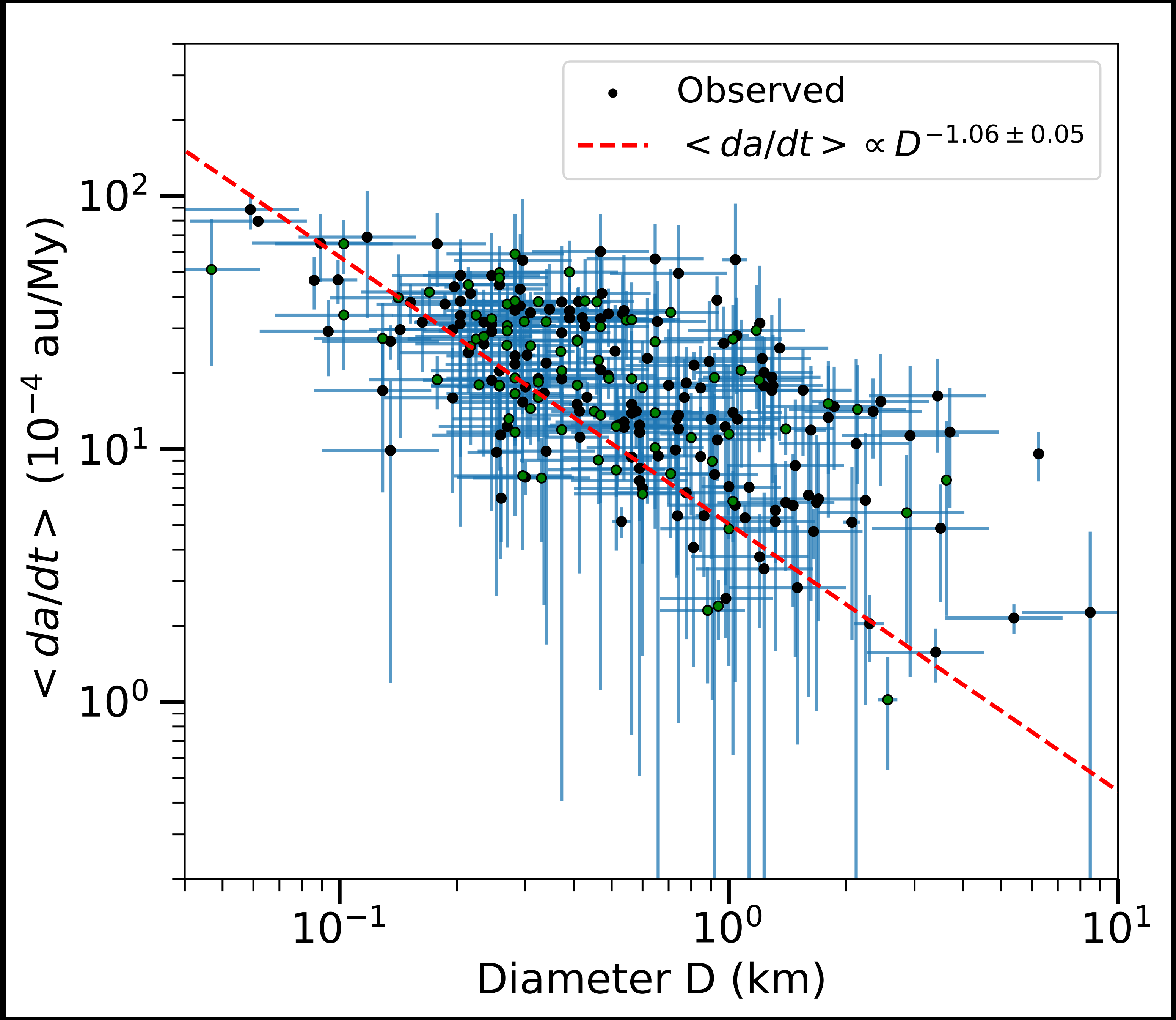


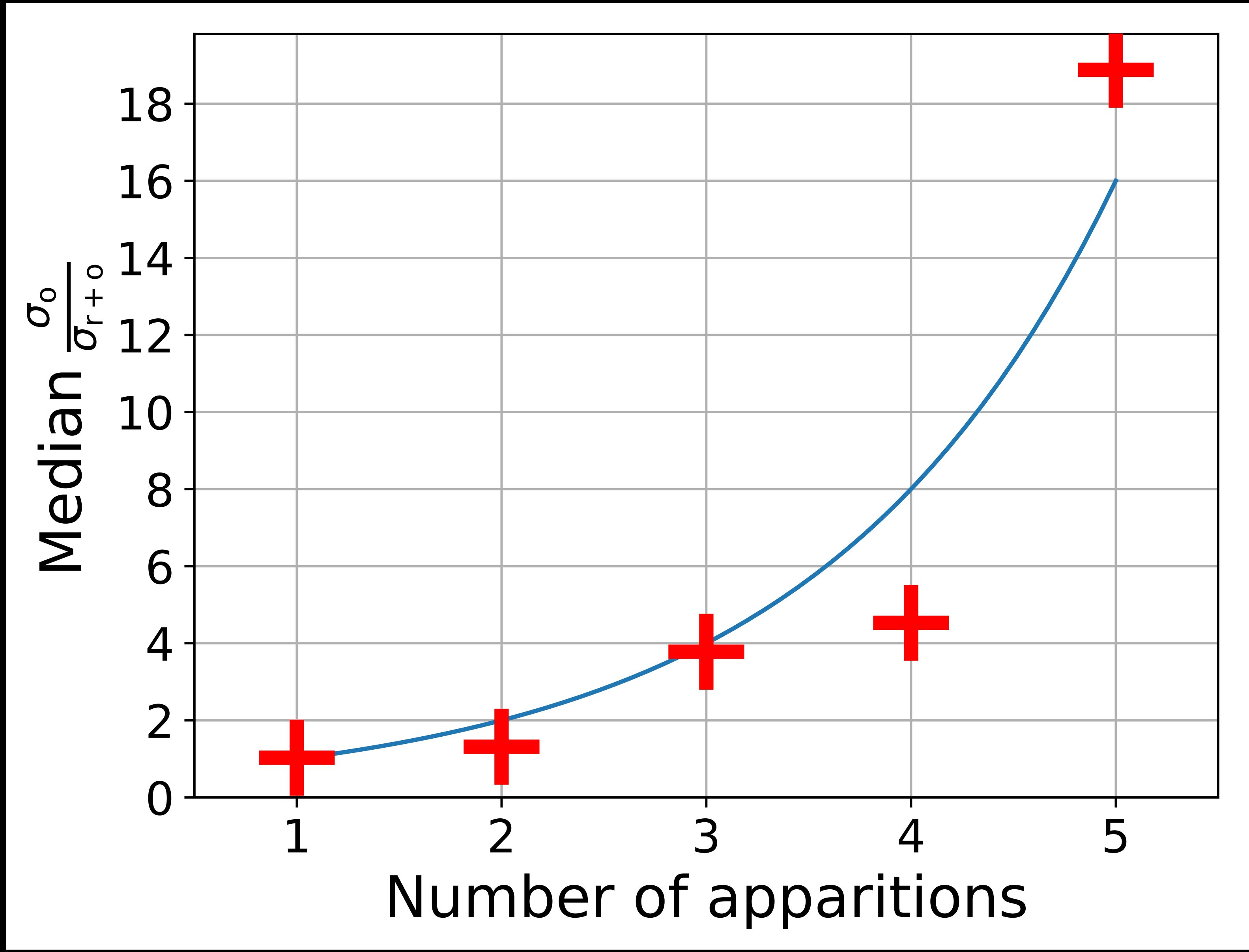
Chesley et al., Science 302, 1739, 2003.



Bottke et al., AREPS, 2006.

Yarkovsky Effect





Greenberg et al., AJ 159, 2020.

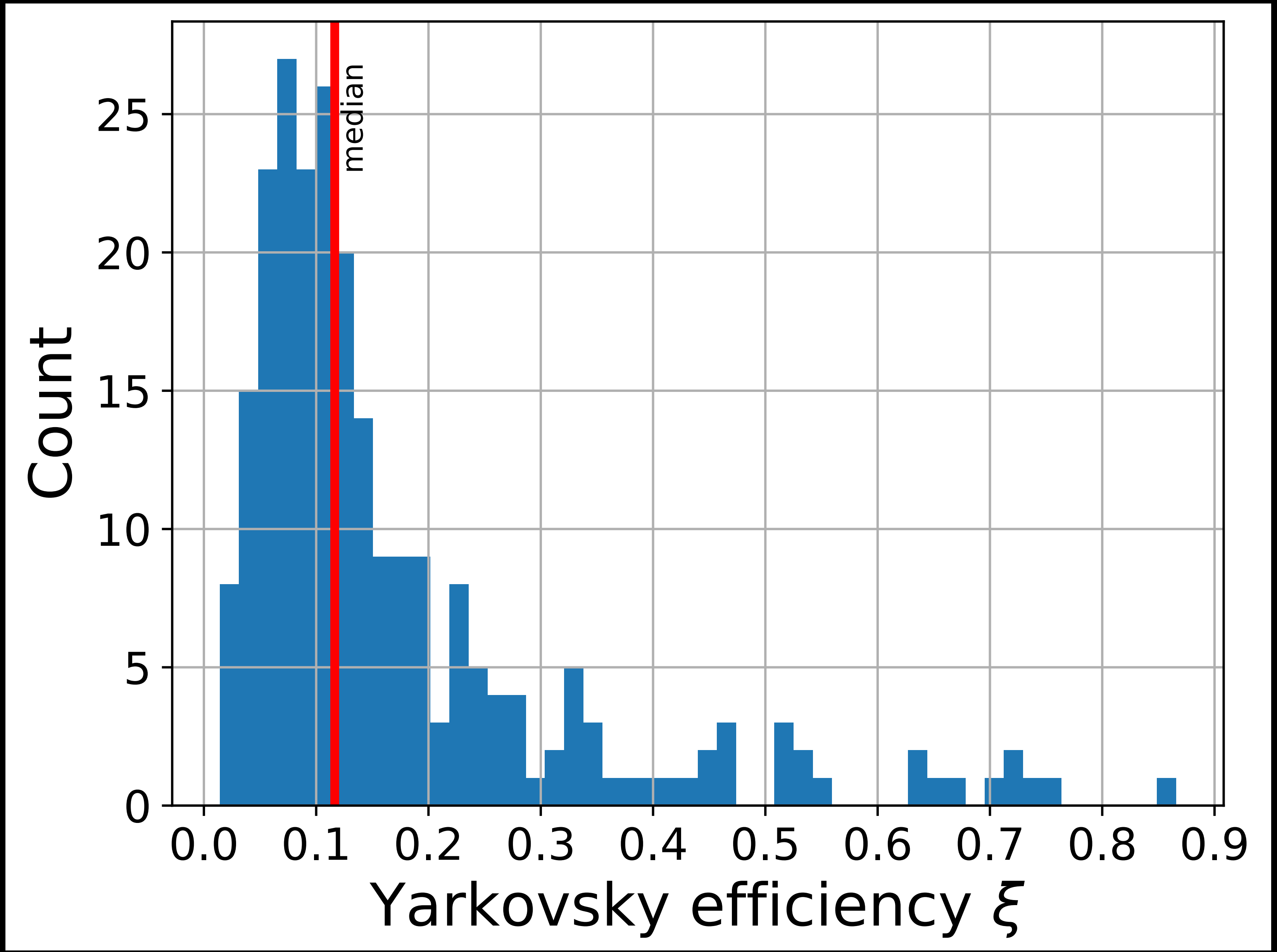
Yarkovsky Effect

$$\frac{da}{dt} = \pm \xi \frac{3}{4\pi} \frac{1}{\sqrt{a}} \frac{1}{1-e^2} \frac{L_\odot}{c\sqrt{GM_\odot}} \frac{1}{D\rho}$$

Yarkovsky efficiency

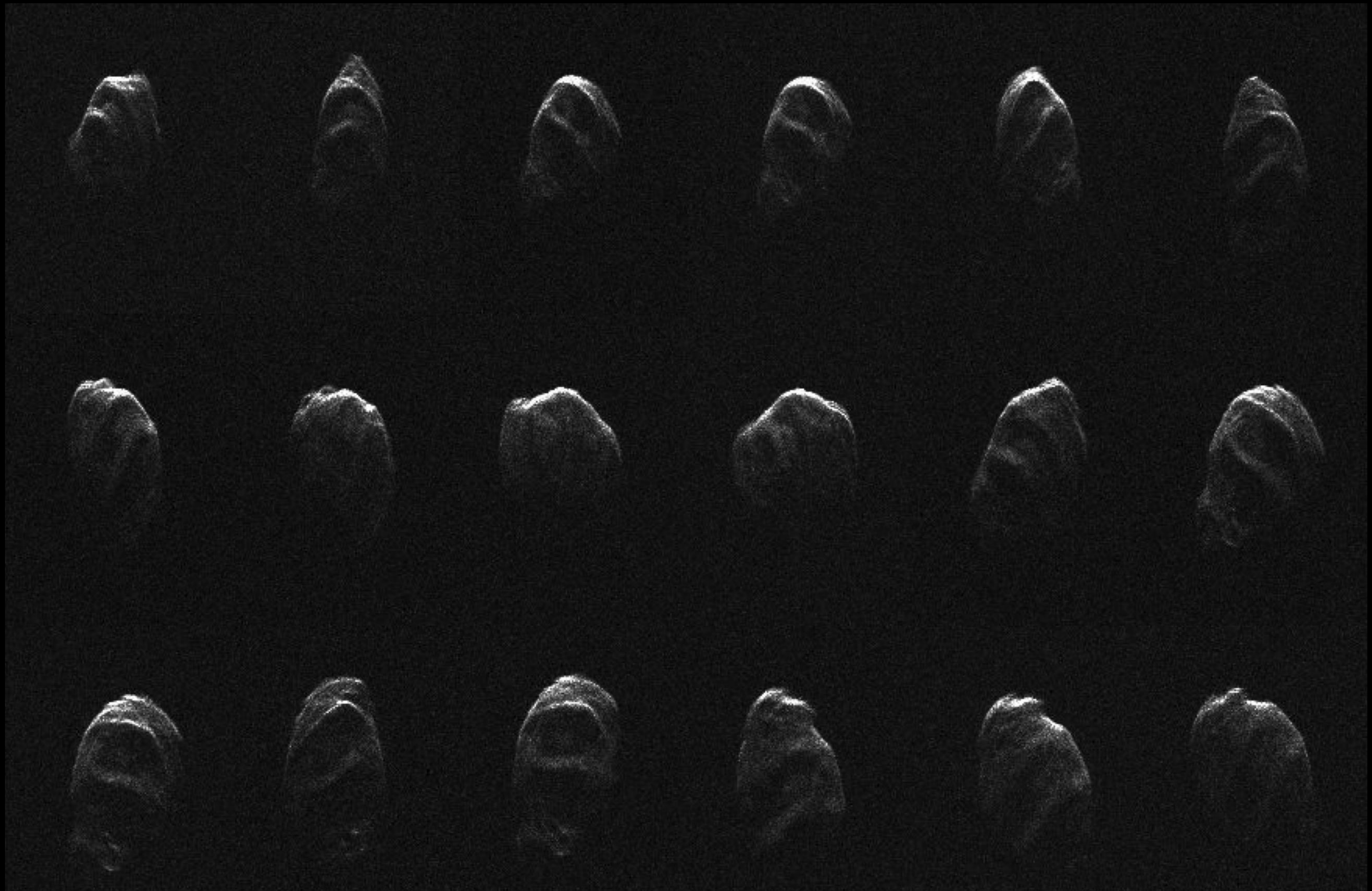
Diameter

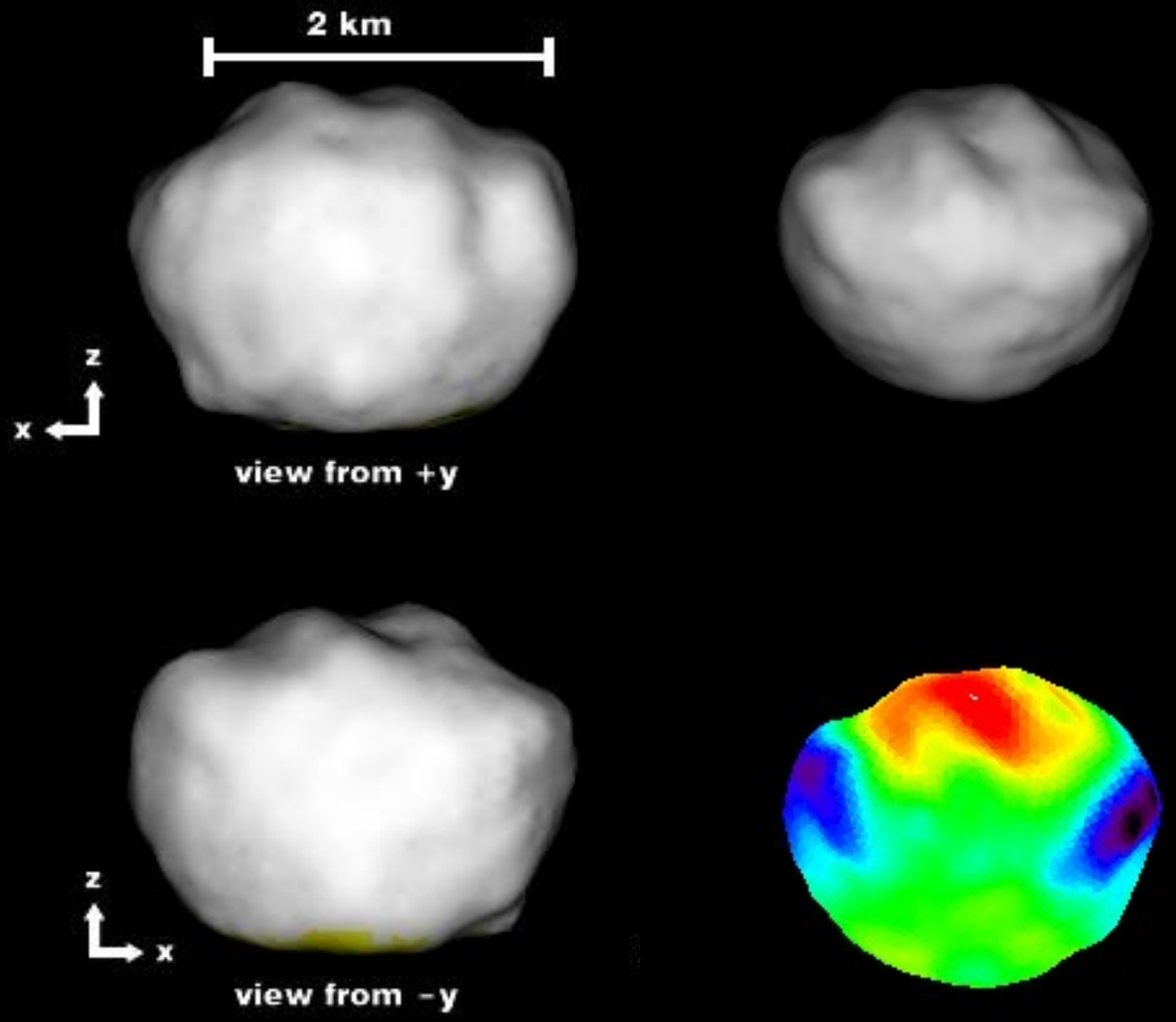
Density



Greenberg et al., AJ 159, 2020.

Near-Earth Asteroid 2000 ET70





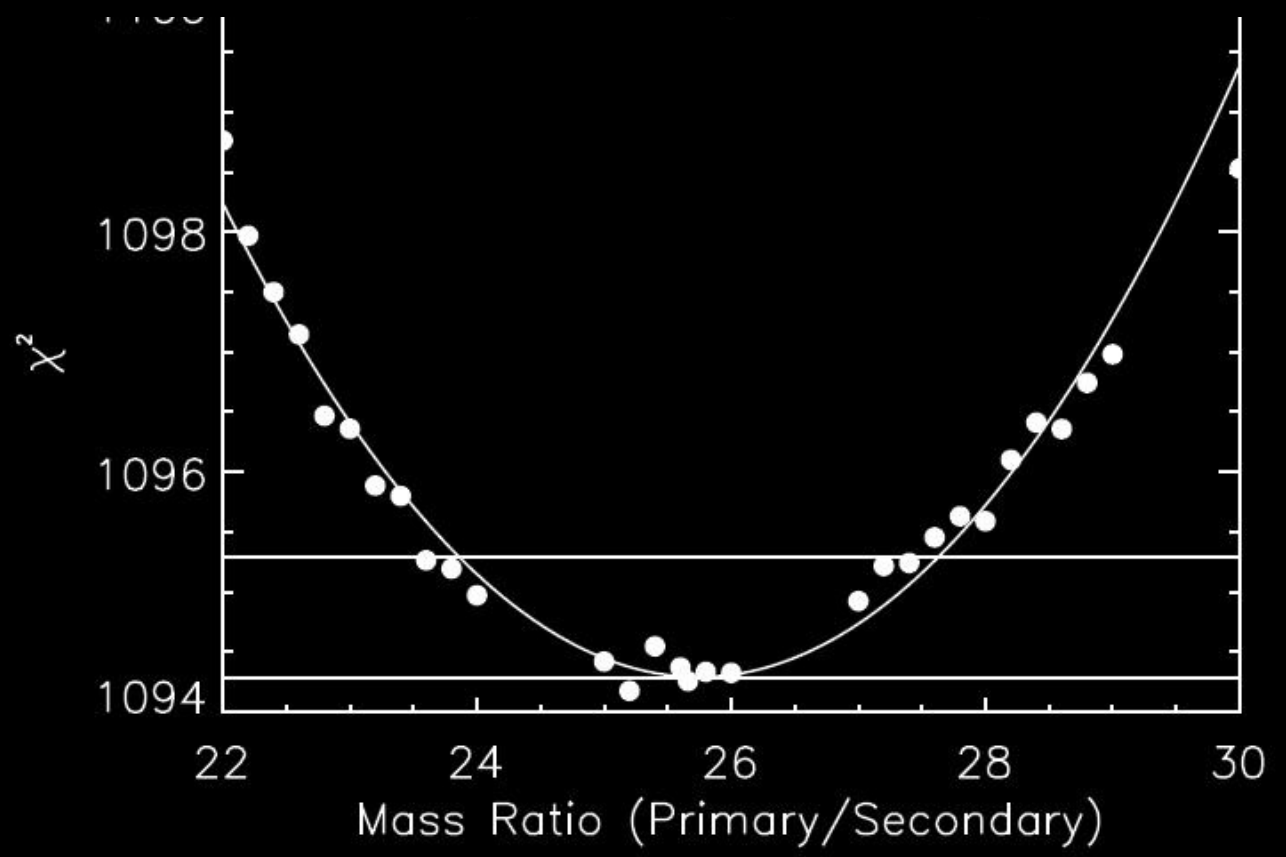
Naidu et al., Icarus 226, 2013.

Binary Asteroid 2000 DP107

Period	(1.755 +/- 0.007) days
Semi-Major axis	(2.620 +/- 0.16) km
Eccentricity	~0.010
System Mass	(4.6 +/- 0.5) x 10^{11} kg
Mass ratio	~1:20
Secondary spin	Synchronous

Margot et al., Science **296**, 2002.
Naidu et al., AJ **150**, 2015.

Component Masses and Volumes



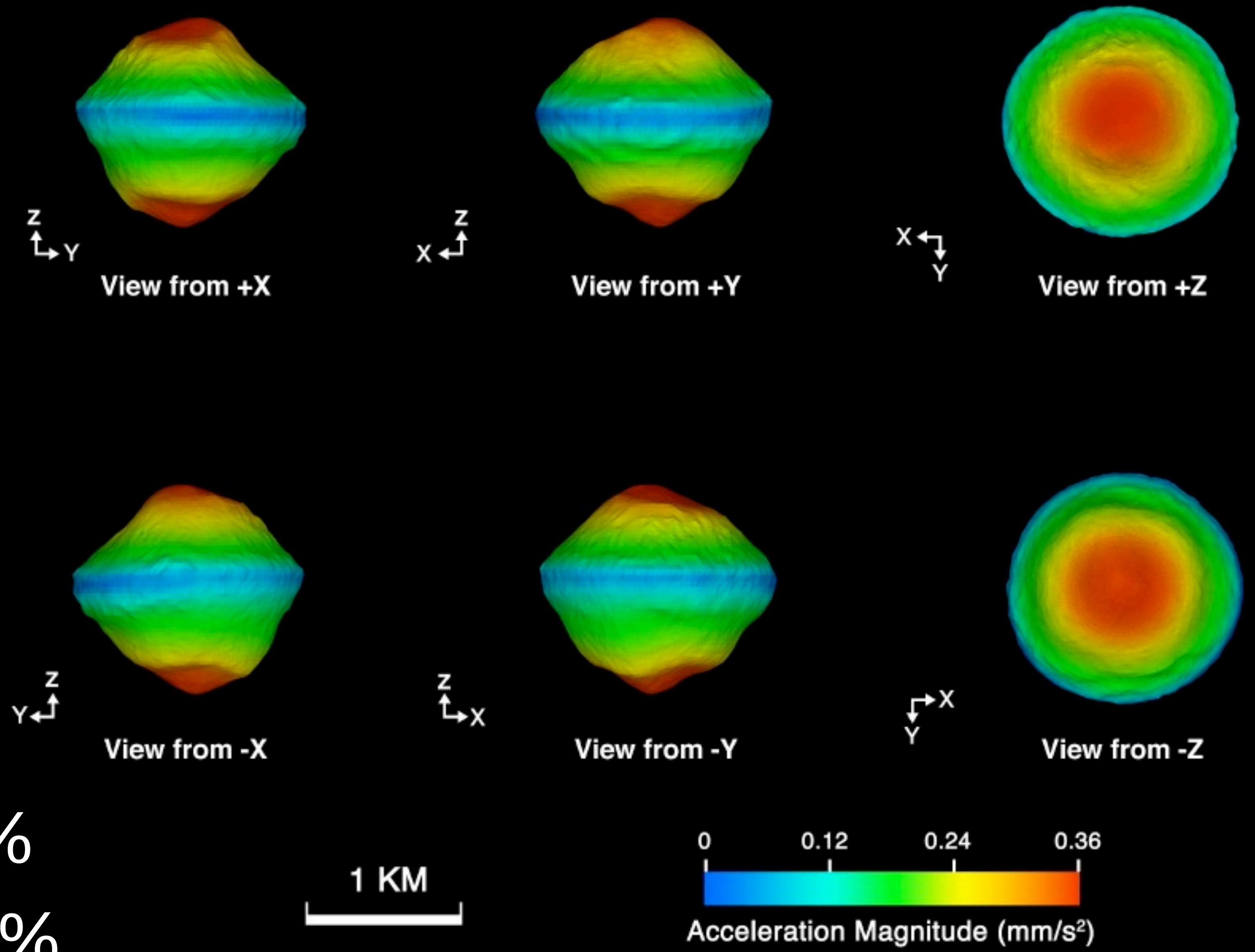
	mass (10^{11} kg)	% of system
Primary	4.8	96.3
Secondary	0.2	3.7

Margot et al., Science **296**, 2002.

	volume (10^8 m^3)	% of system
Primary	3.04	96.4
Secondary	0.11	3.6

Naidu et al., AJ **150**, 2015.

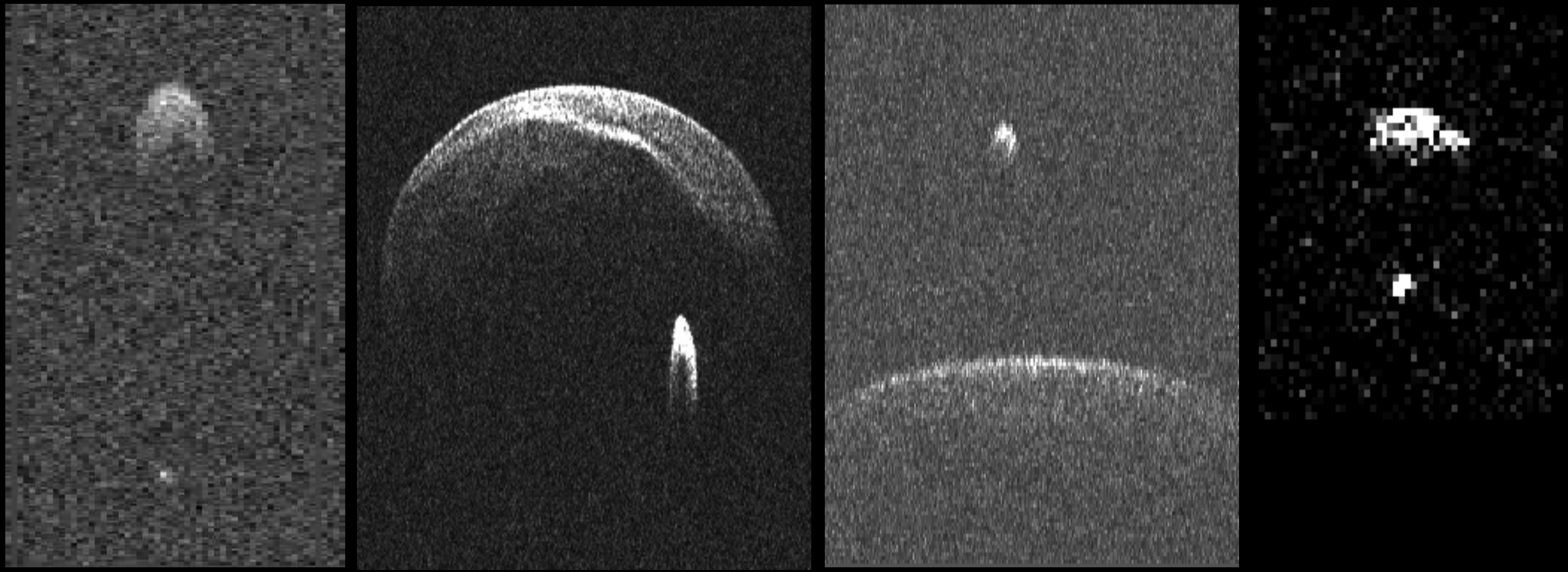
Binary Asteroid 1999 KW4



- ▶ Spin to 1%
- ▶ Mass to 2%
- ▶ Volume to 9%

Ostro et al., Science 314, 2006.

Binary NEAs Form by Spin-up



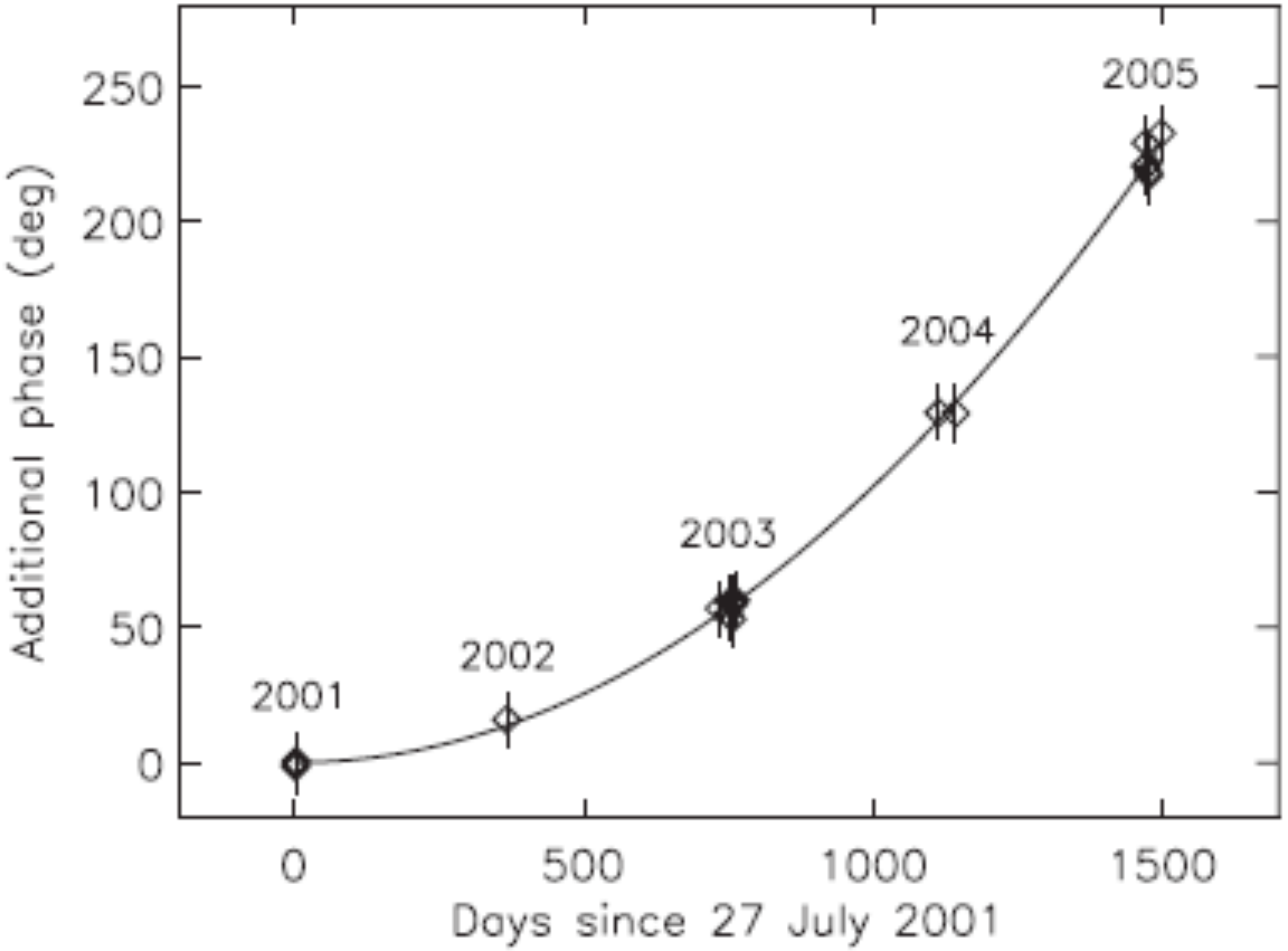
1998 ST27 | 1999 KW4 | 2002 BM26 | 2000 UG11
Benner et al. | Ostro et al. | Nolan et al. | Nolan et al.

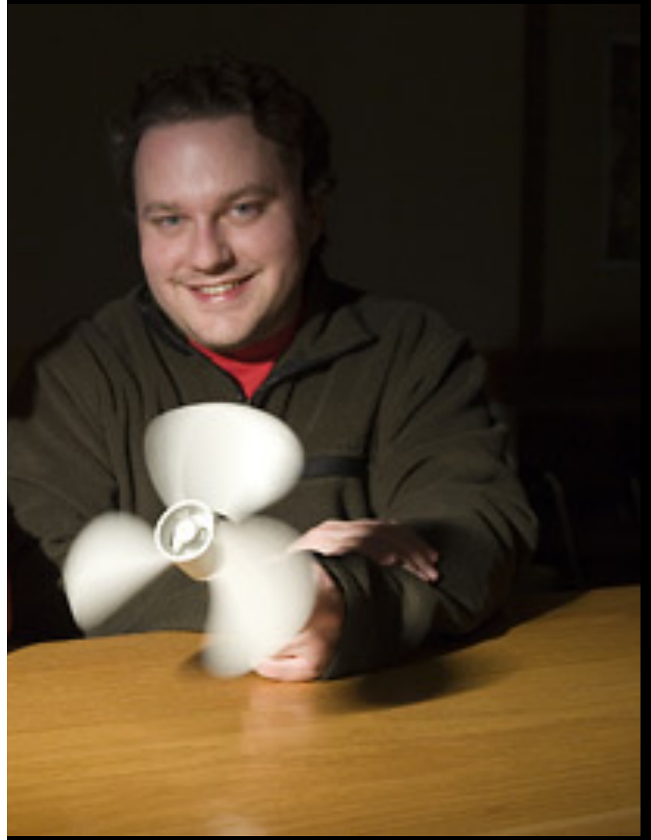
Primaries are spheroidal and fast rotators. Spin-up and mass shedding.

Margot et al., Science **296**, 2002.

Spin-up Mechanism is YORP

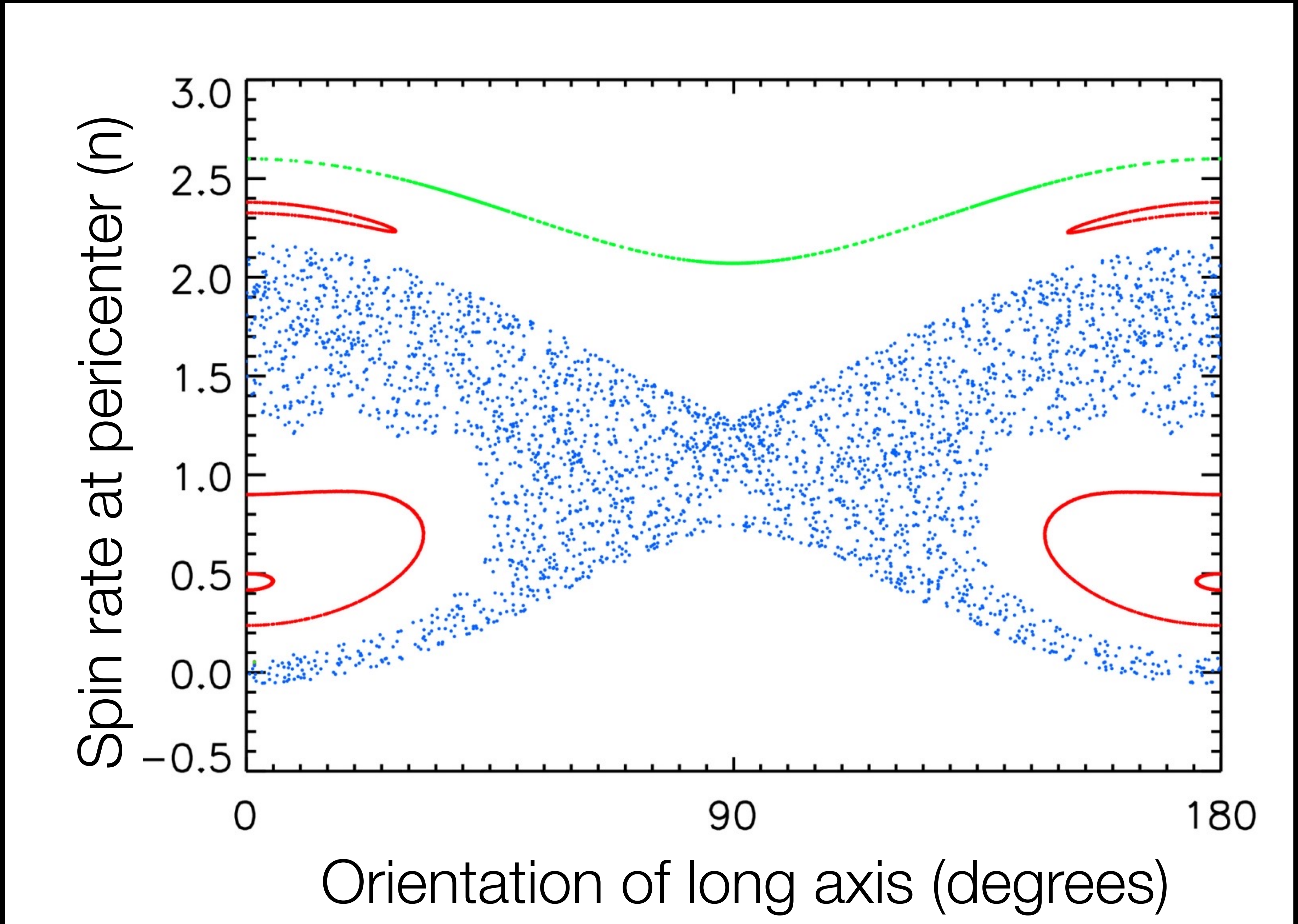
Fig. 2. Additional rotation phase required to link 20 optical light curves (*2*) from 2001 to 2005 using a shape model with pole (180°, –85°) fit to the 2001 light-curve data. The fitted curve is quadratic in time: $0.5\dot{\omega}t^2$, where $\dot{\omega}$ is the rate of change of the spin rate and t is time since the initial epoch of 0^h UT on 27 July 2001. Phases have conservative uncertainties of 10° because of their dependence on the exact shape and orientation of the asteroid.





Taylor et al., Science 316, 2007.

Spin Dynamics



Naidu and Margot, AJ **149**, 2015.

$$\frac{\Delta E_{chaos}}{E_0} \sim 0.4$$

$$\frac{\Delta E_{tides}}{E_0} \sim 10^{-8} / orbit$$

(Goldreich & Sari 2009)

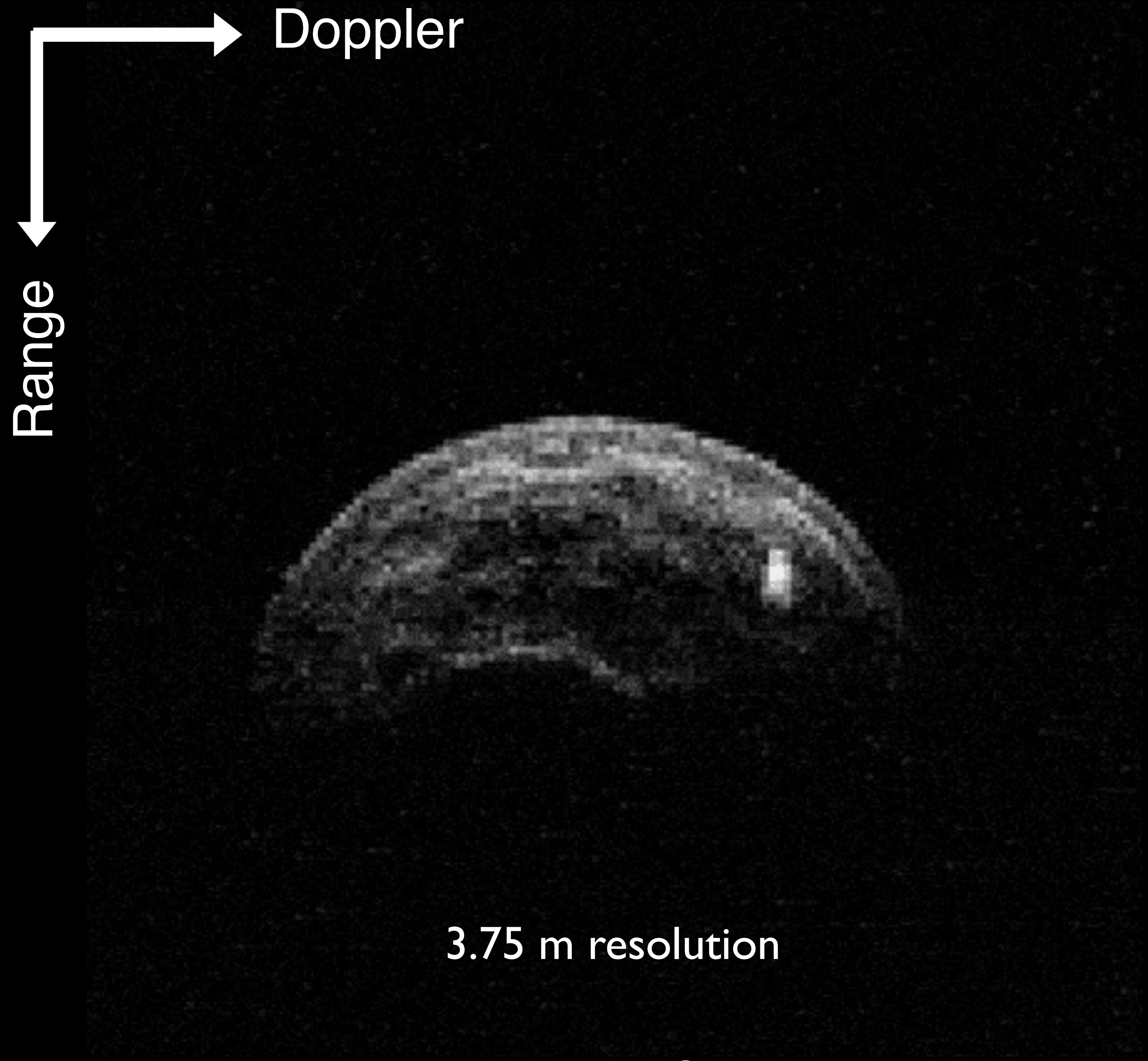
$$\frac{\Delta E_{YORP}}{E_0} \sim 10^{-7} / orbit$$

(Steinberg & Sari 2009)

Binary NEA 1991 VH
(Dp 650 m, Ds 280 m)

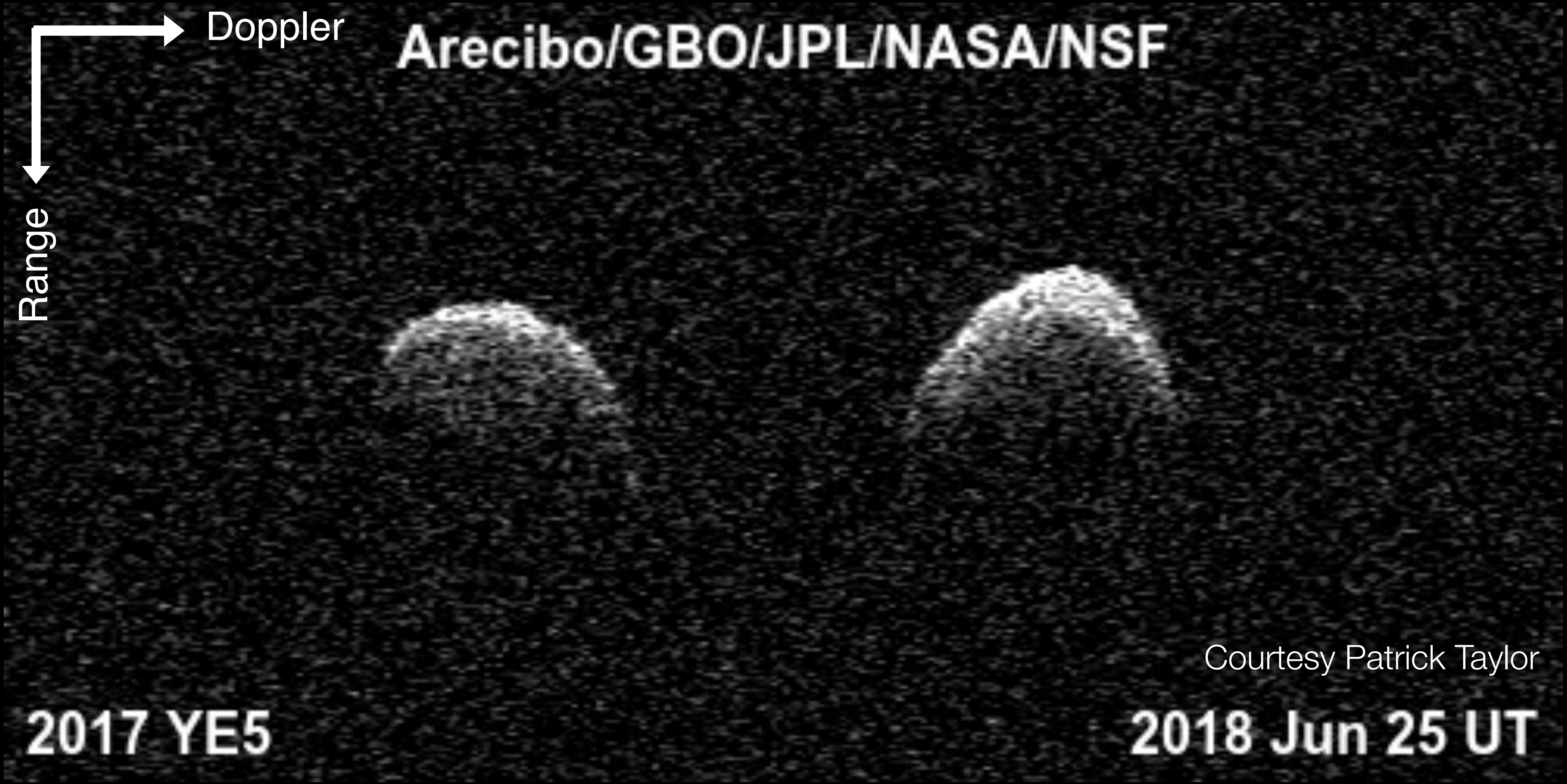
Binary Asteroid 2004 BL86

- 2015 (3.1 LD)
- Goldstone to GBT
- Primary ~ 350 m
- Secondary ~ 70 m
- ~14 h orbit period



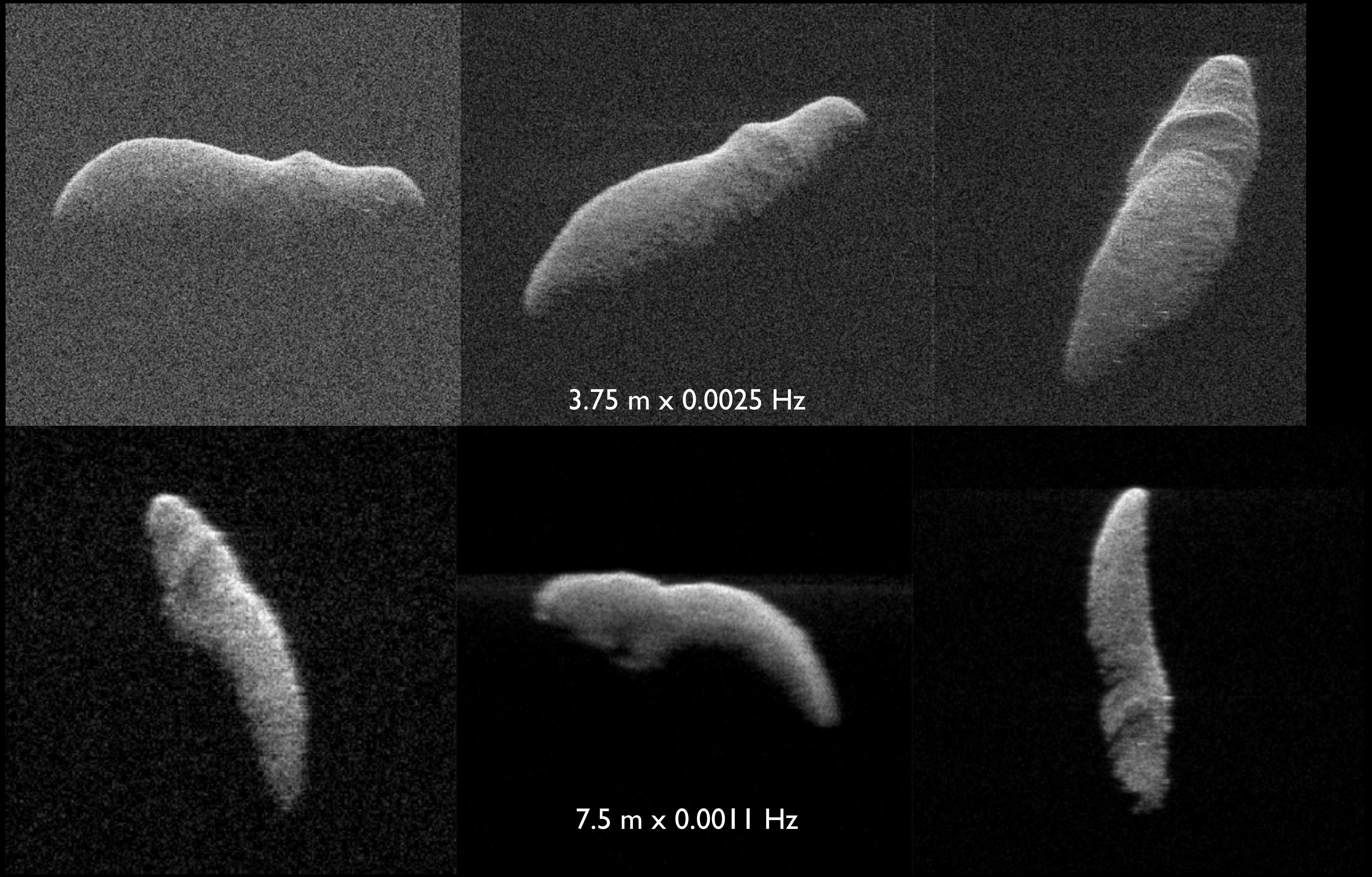
Courtesy Patrick Taylor

Equal-Mass Binary Asteroid



Tumbling Asteroid 2003 SD220

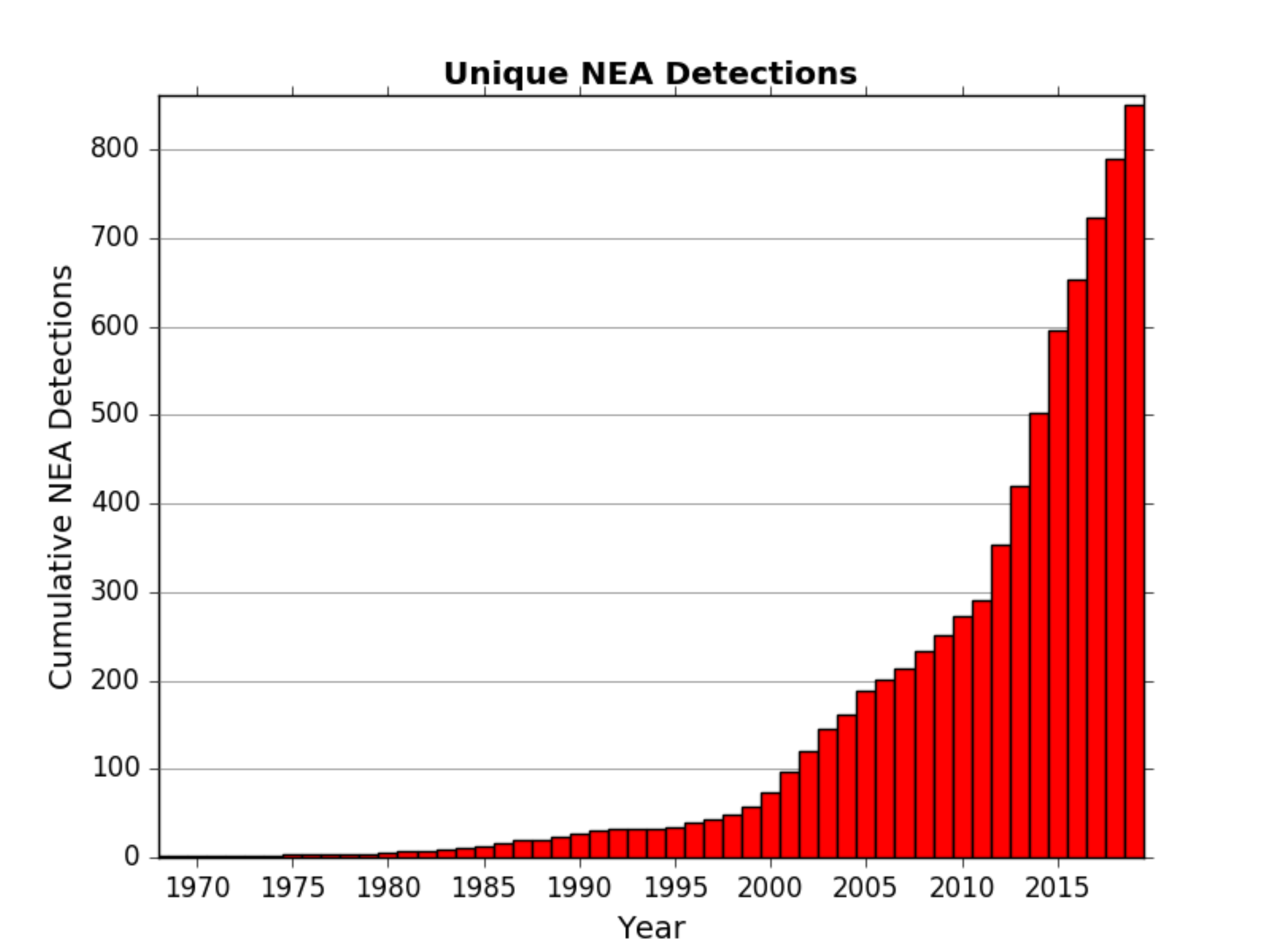
- ▶ 2018 (7 LD)
- ▶ > 2 km
- ▶ ~12 day period
- ▶ Top: DSN-GBT (X)
- ▶ Bottom: AO-GBT (S)



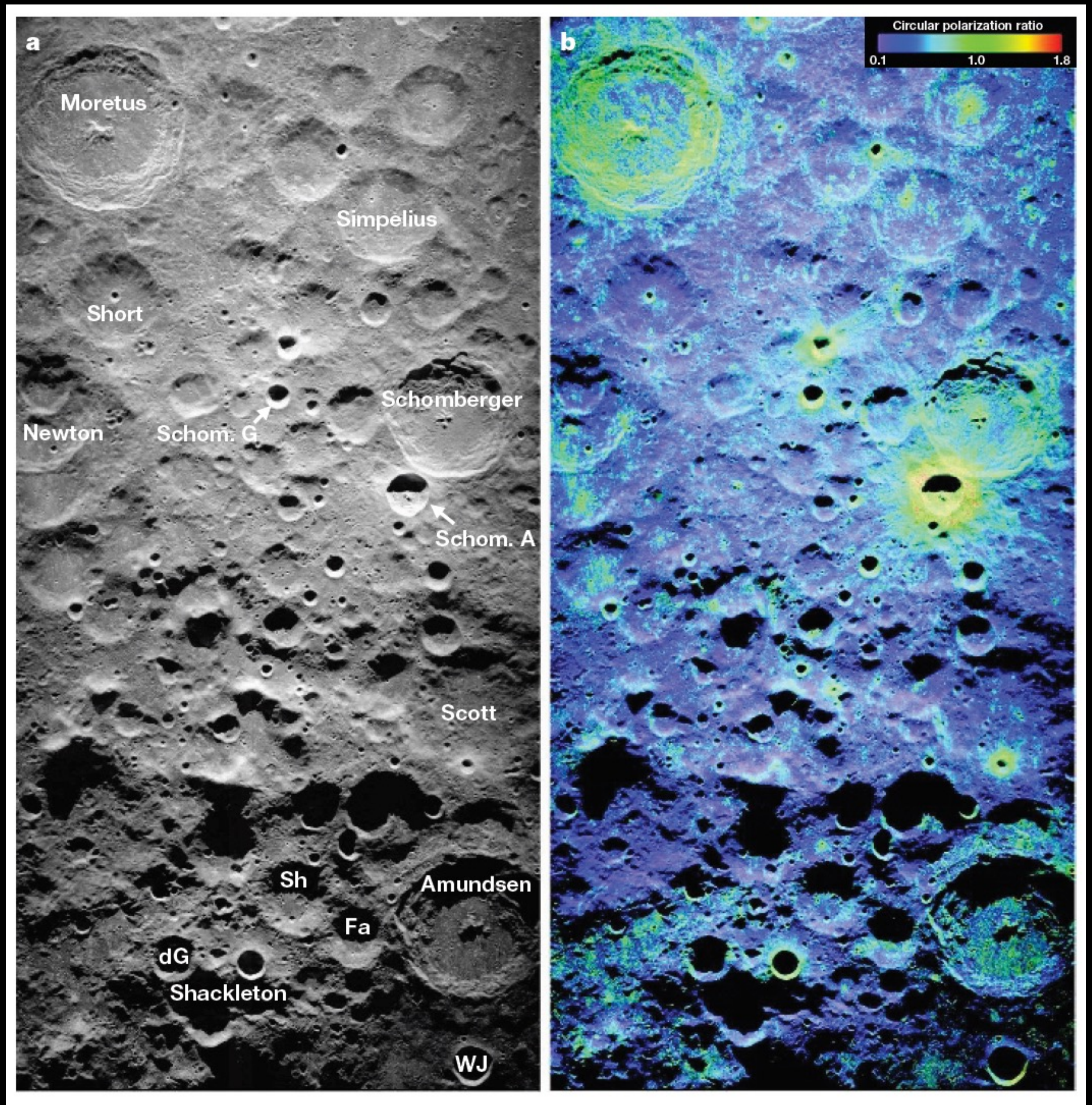
Courtesy Patrick Taylor

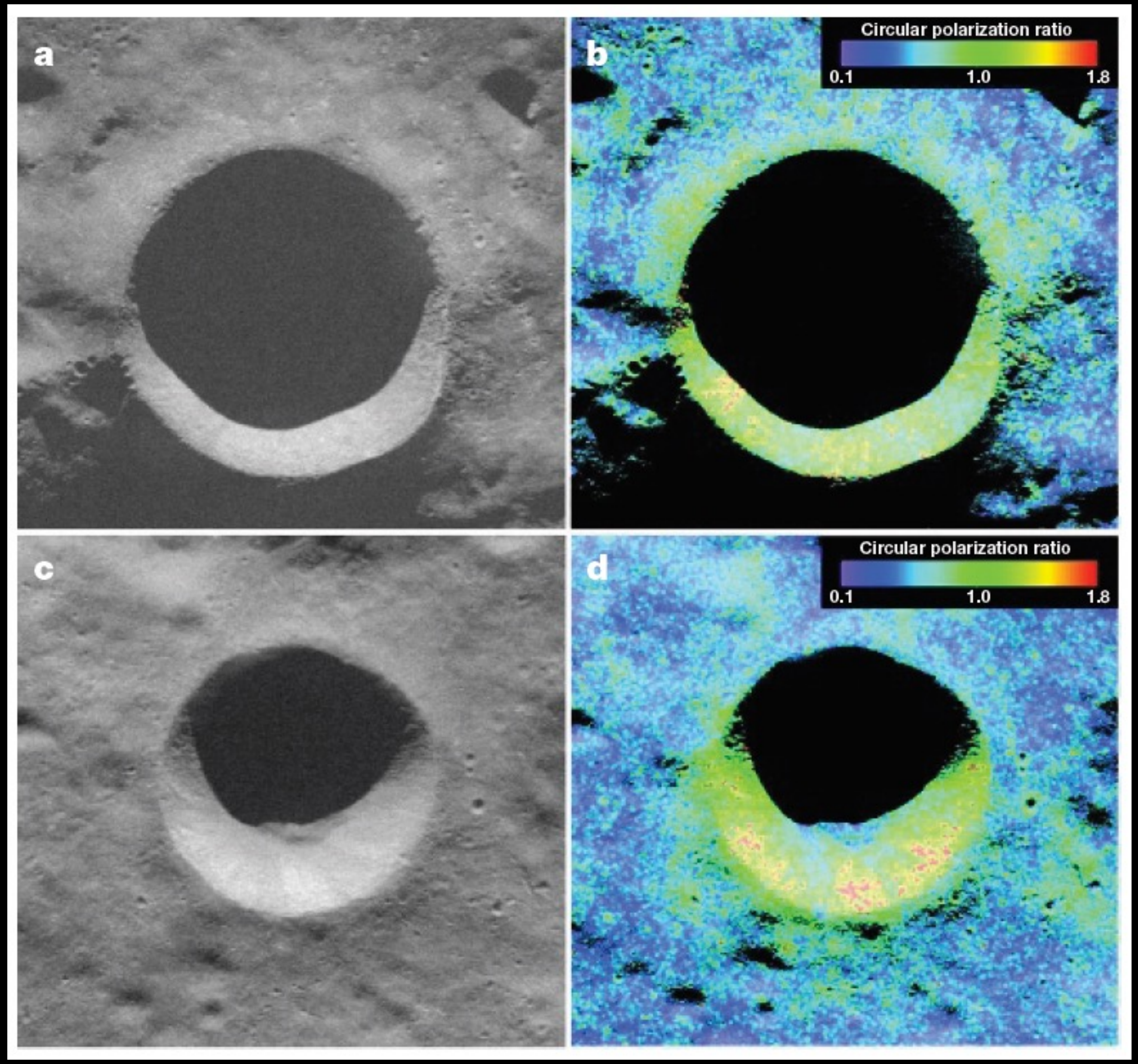
History of Asteroid Detections

http://radarastronomy.org



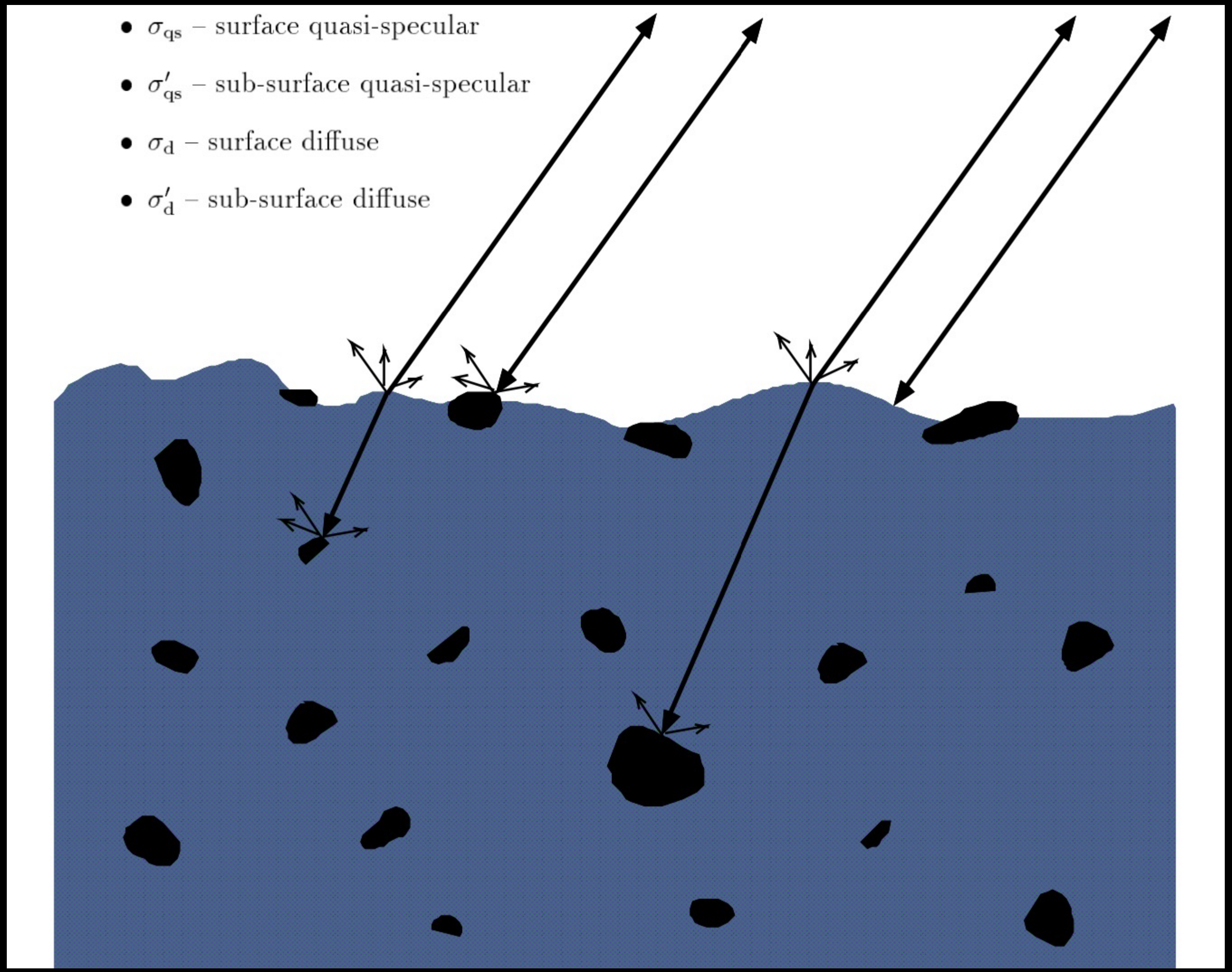
No Evidence for Thick Deposits of (Clean) Ice at the Lunar South Pole



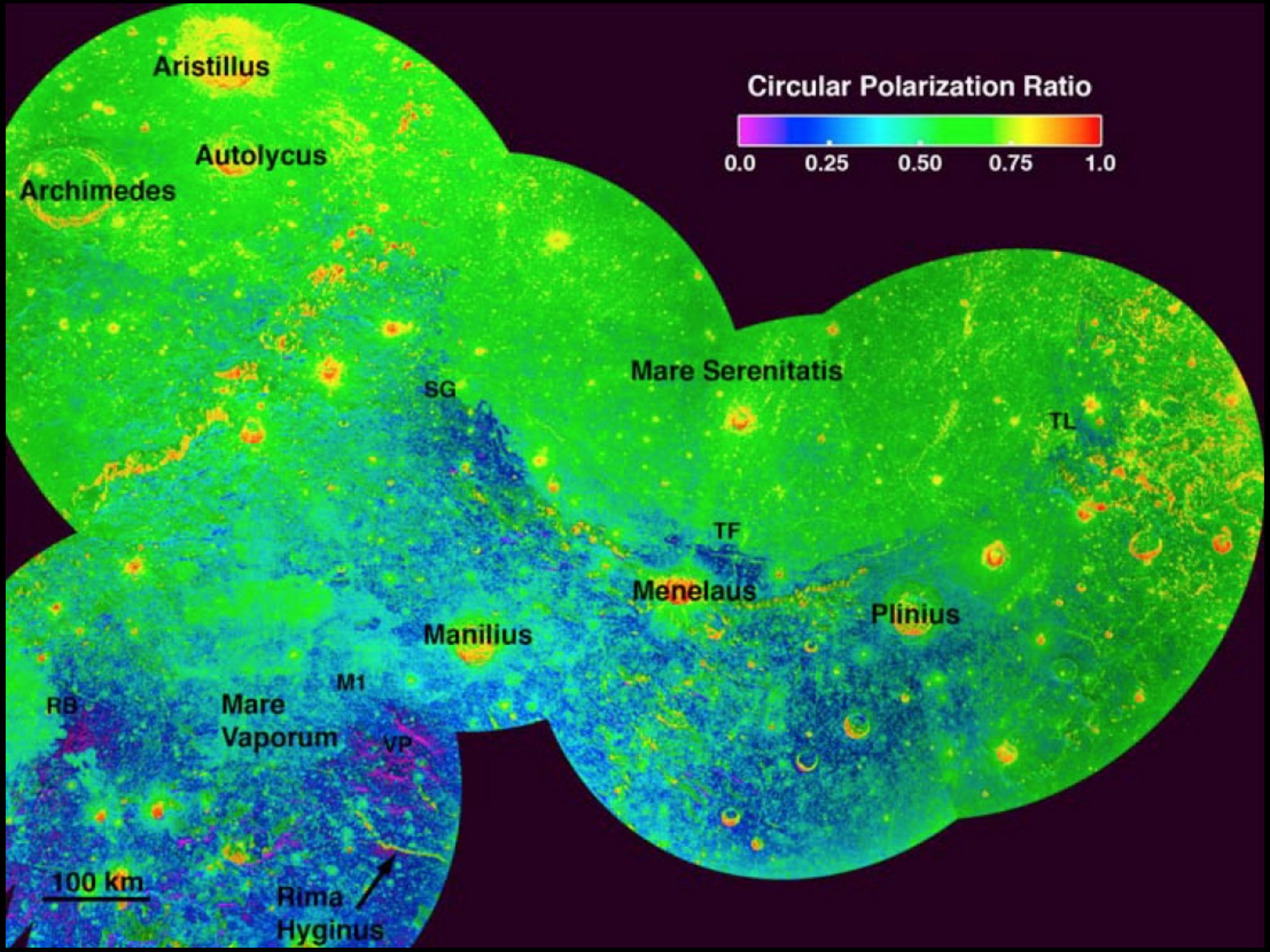


Campbell et al., *Nature* 443, 2006

Mapping of Pyroclastic Deposits

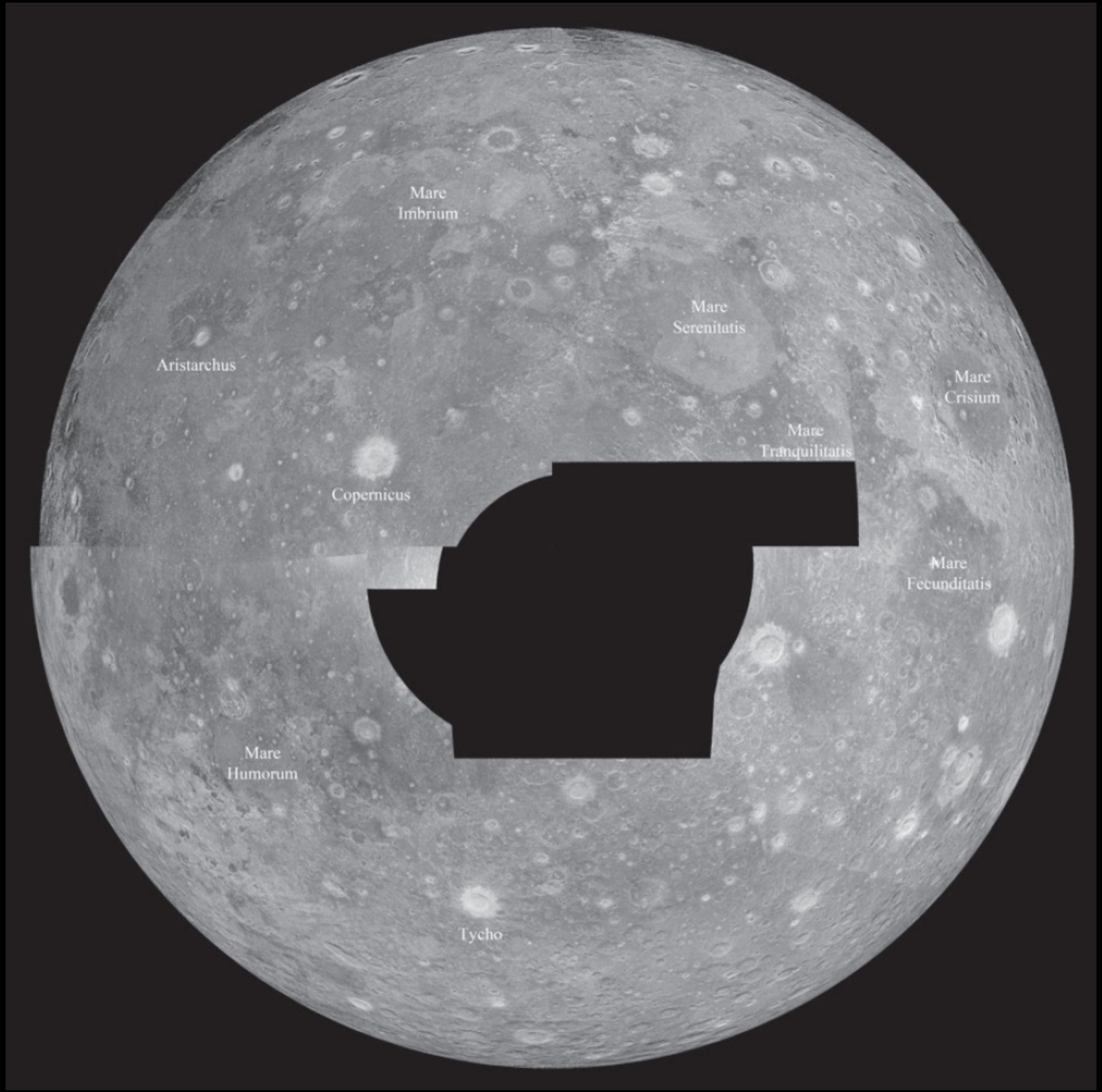


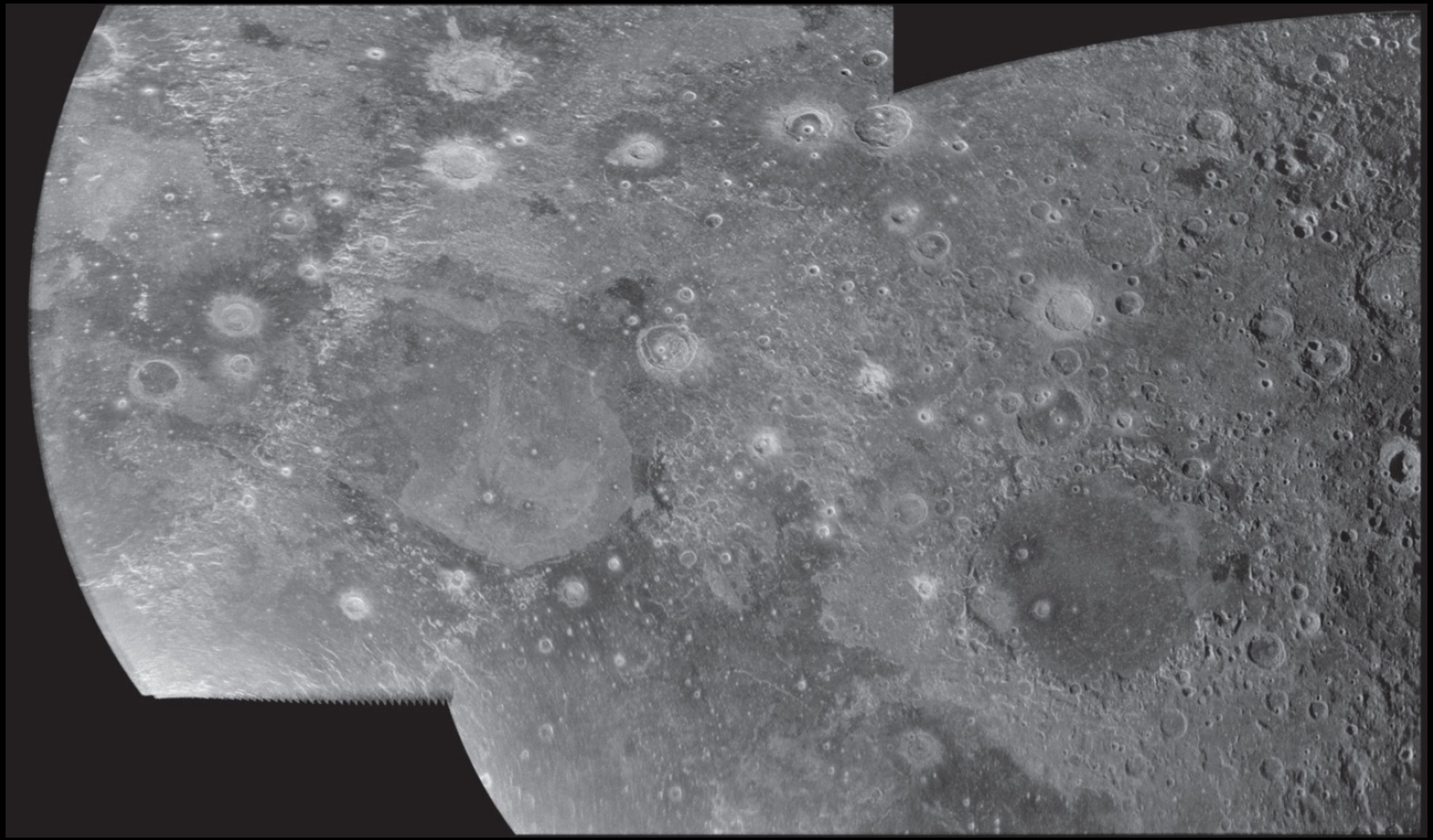
Stacy 1993



Carter et al., JGR, 2009

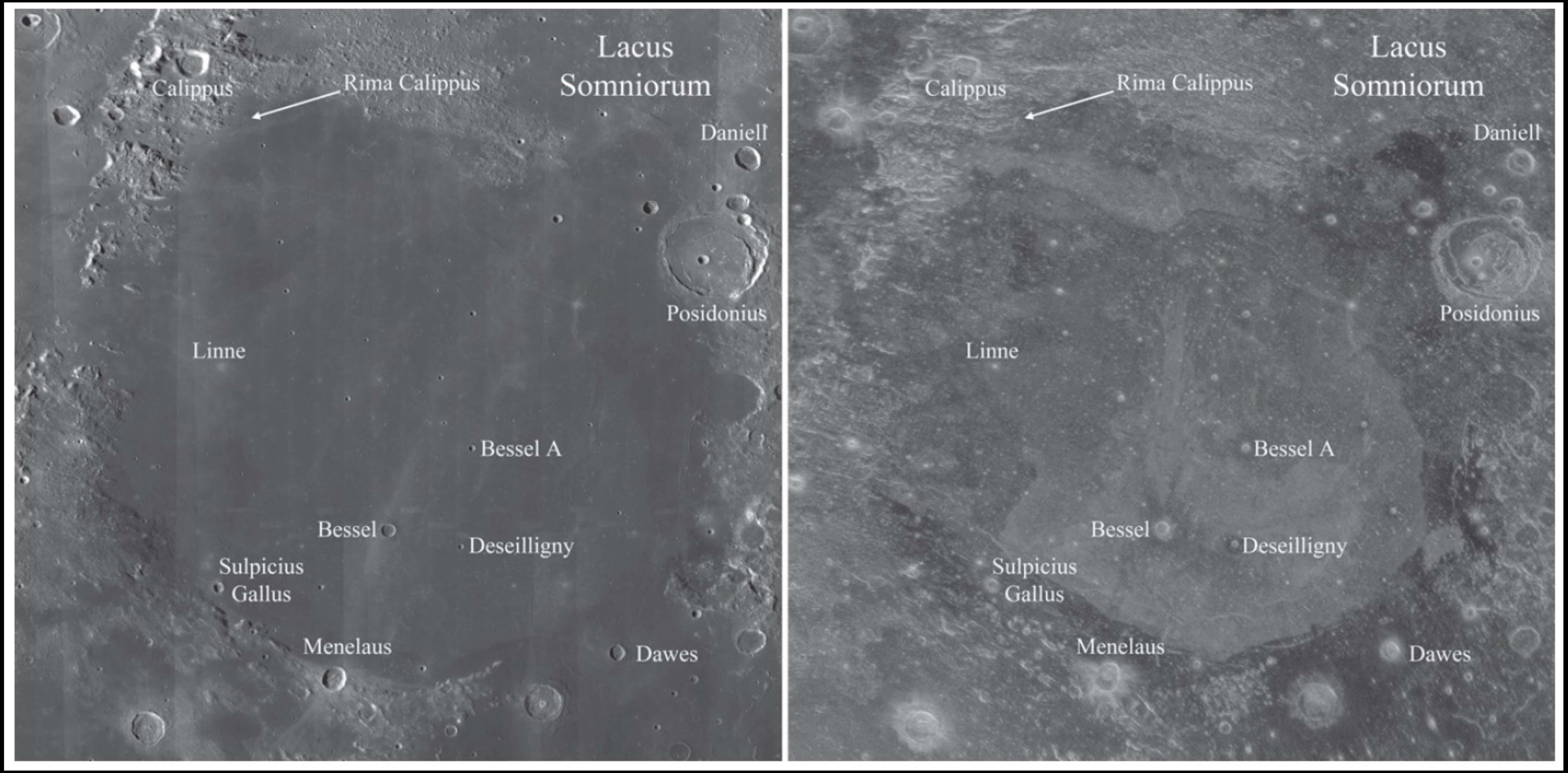
Mapping of the Moon at 70 cm Wavelength





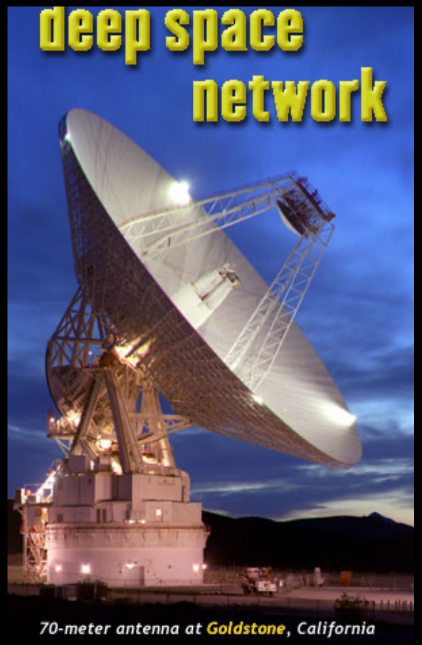
Campbell, PASP, 2016

Mapping of the Moon at 70 cm Wavelength

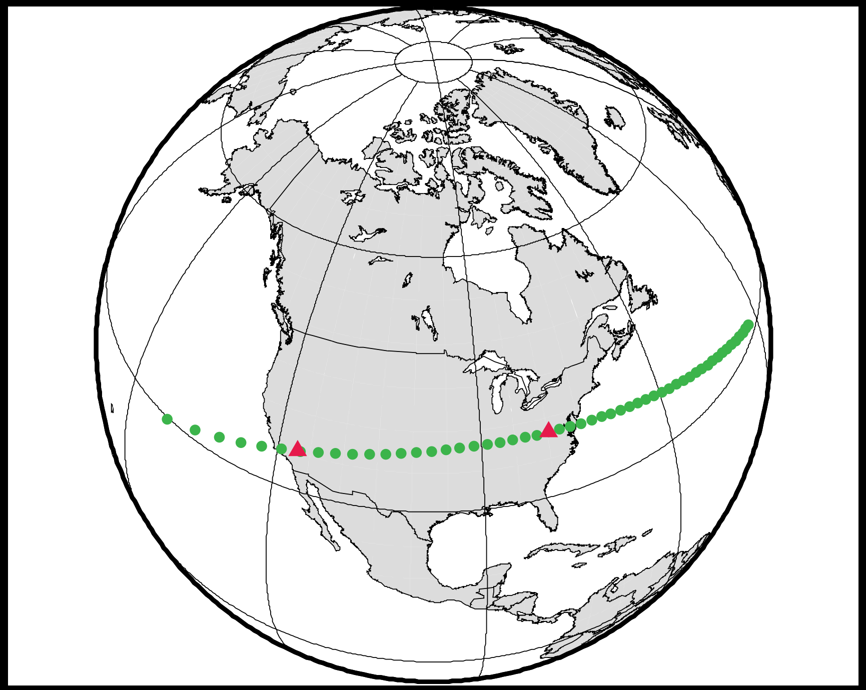


Campbell, PASP, 2016

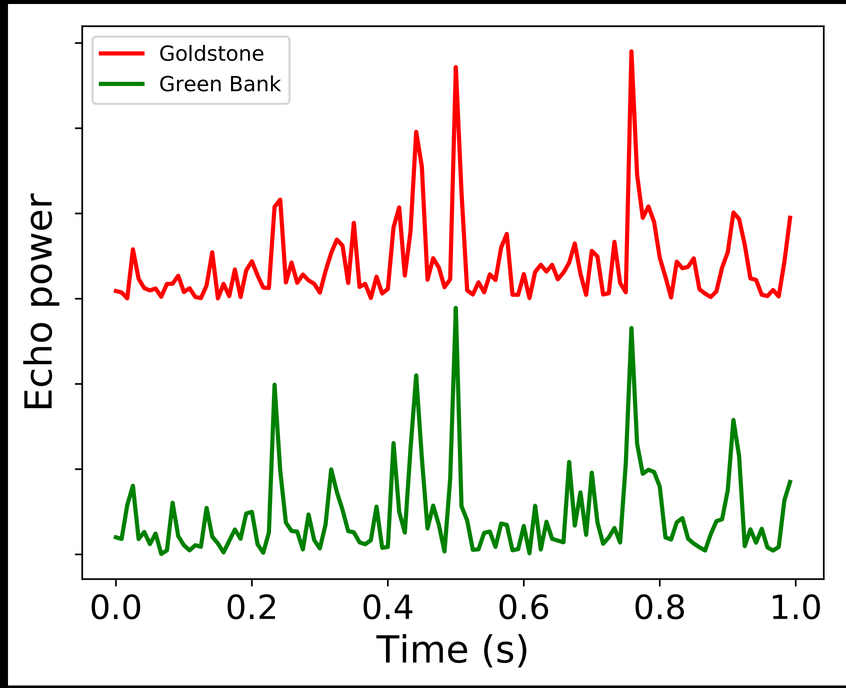
Radar Speckle Tracking



Goldstone, CA

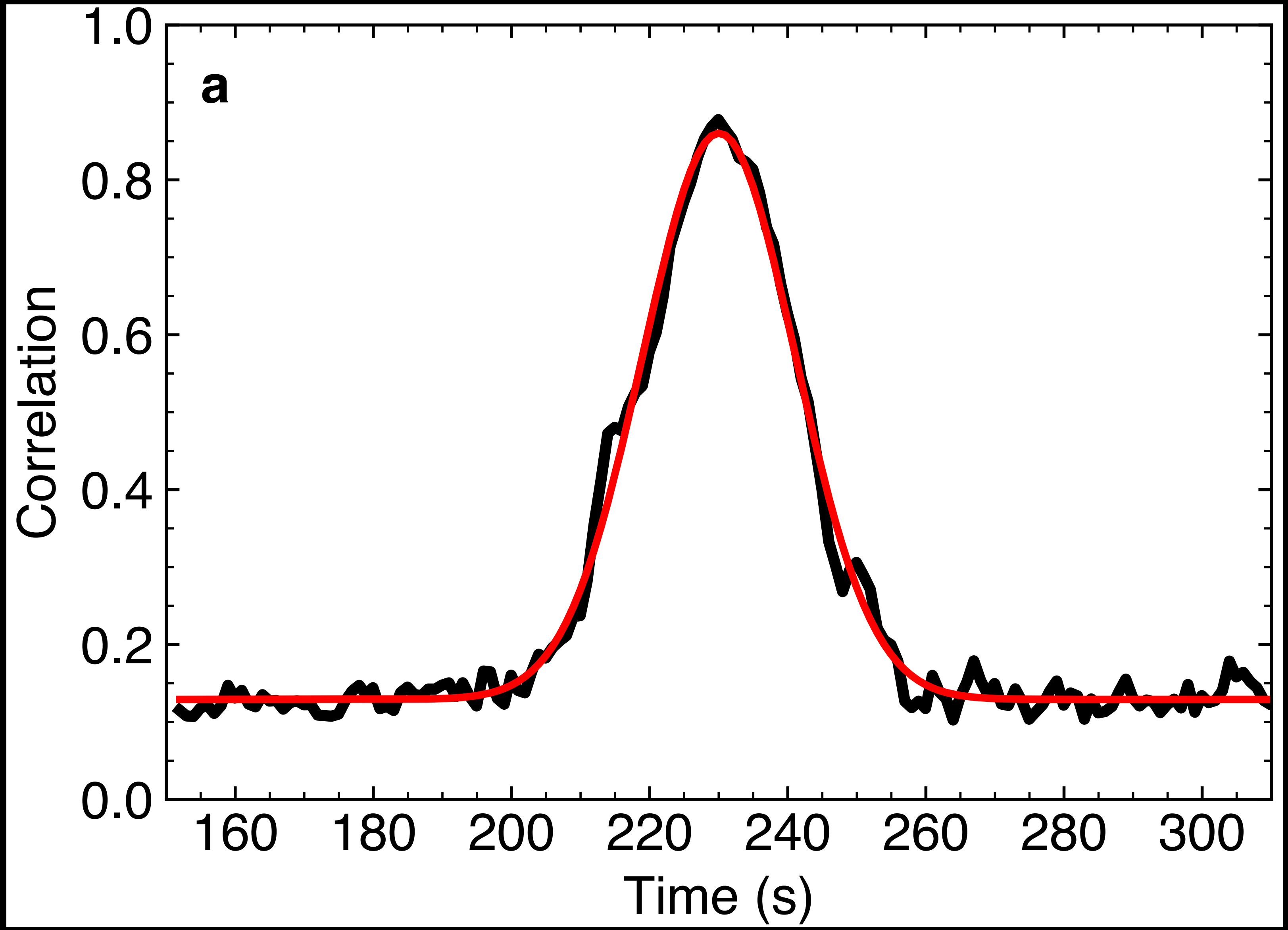


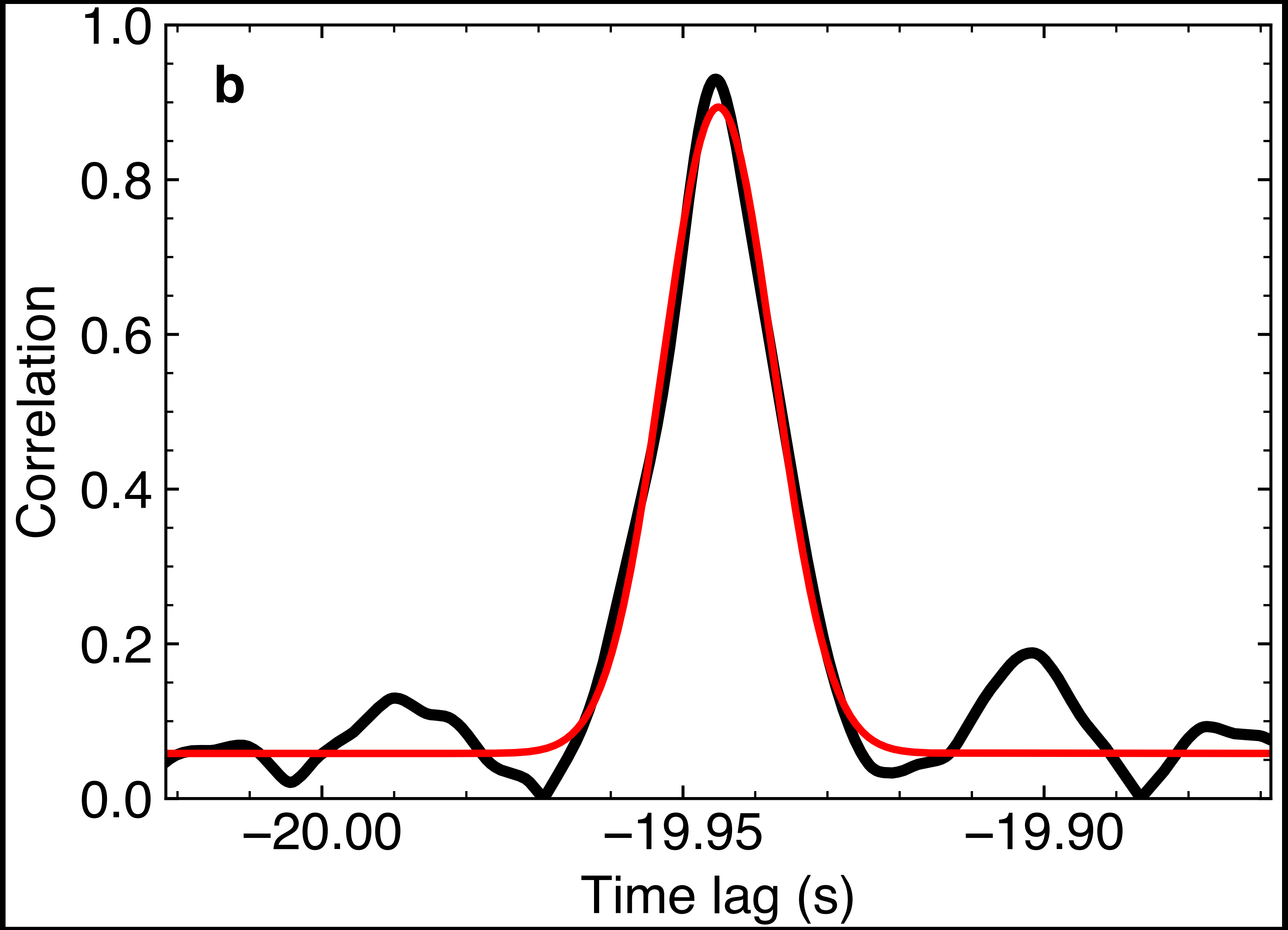
Green Bank, WV



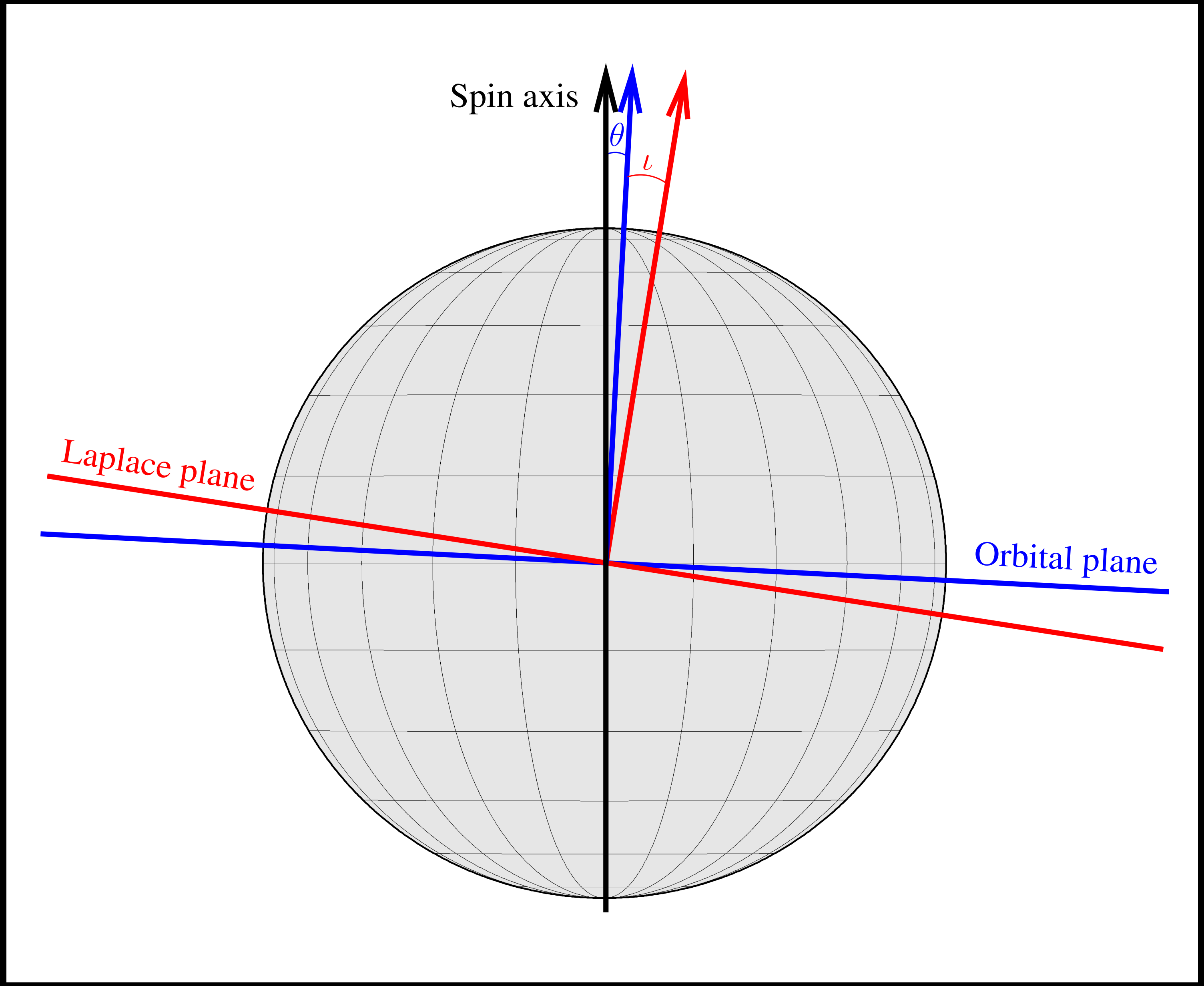
Green 1962, 1968
Holin 1988, 1992
Margot 2007, 2012

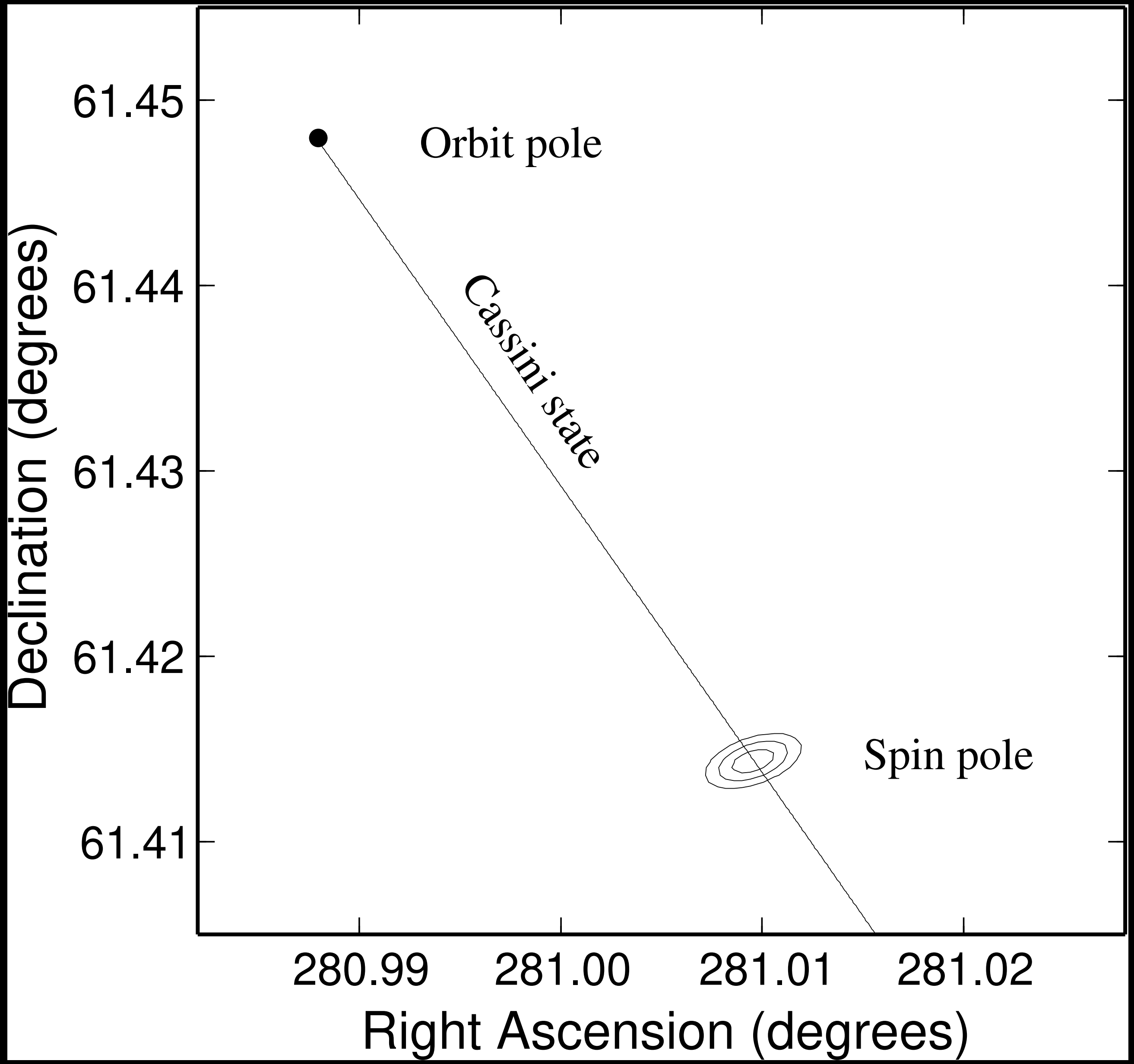
Space-Time Correlations





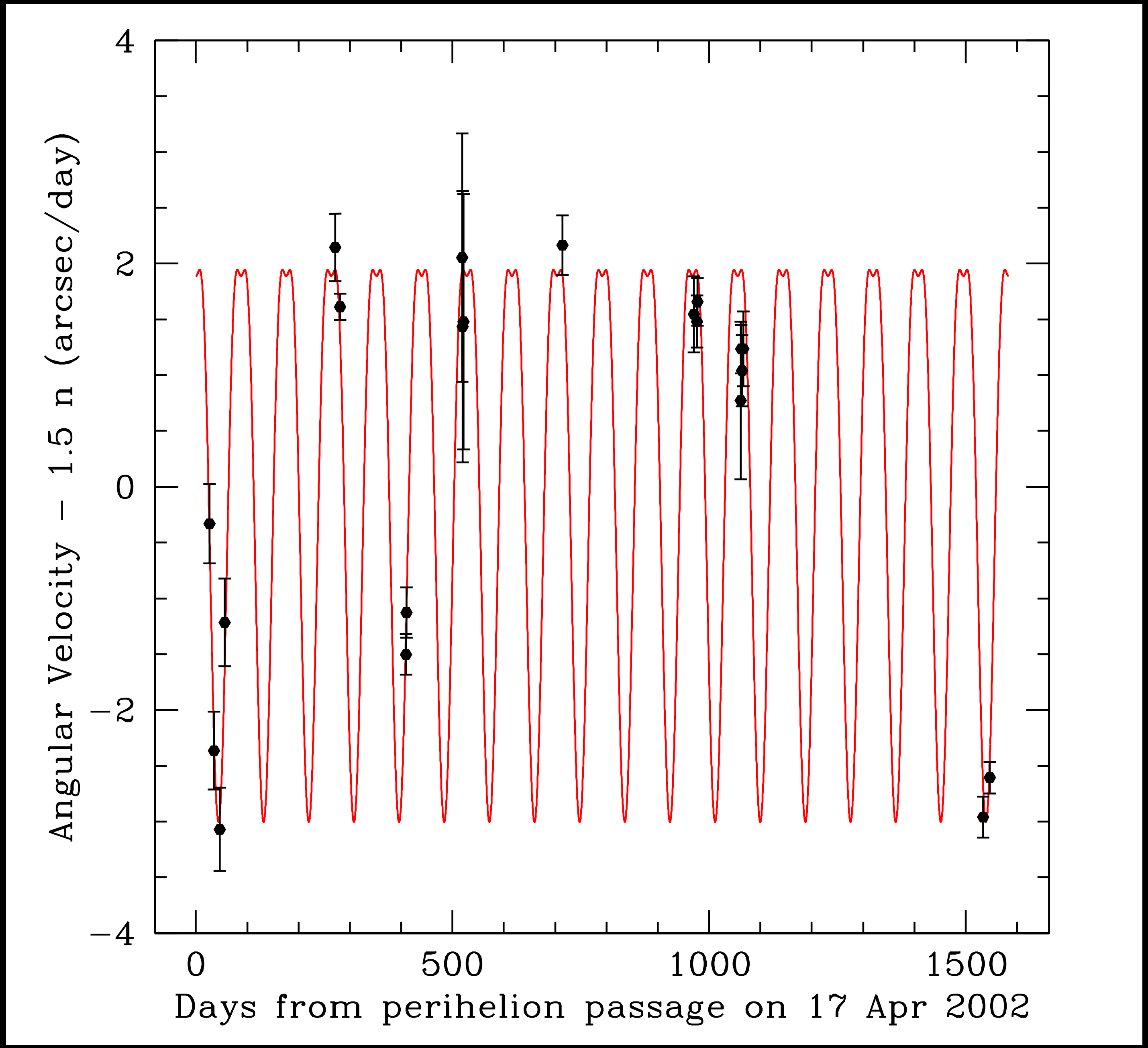
Mercury is in Cassini State 1

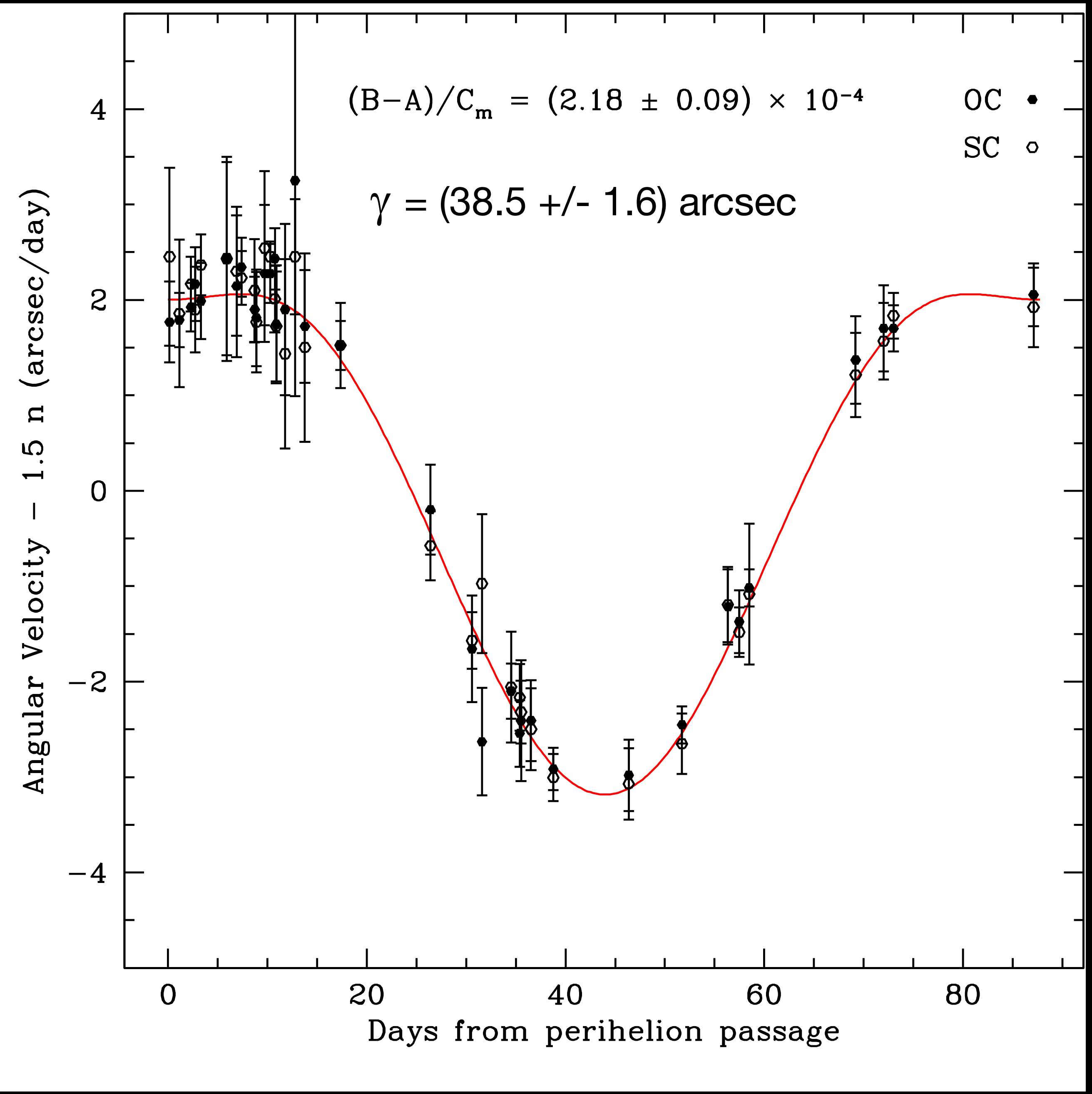




Margot et al., *Science* **316**, 2007

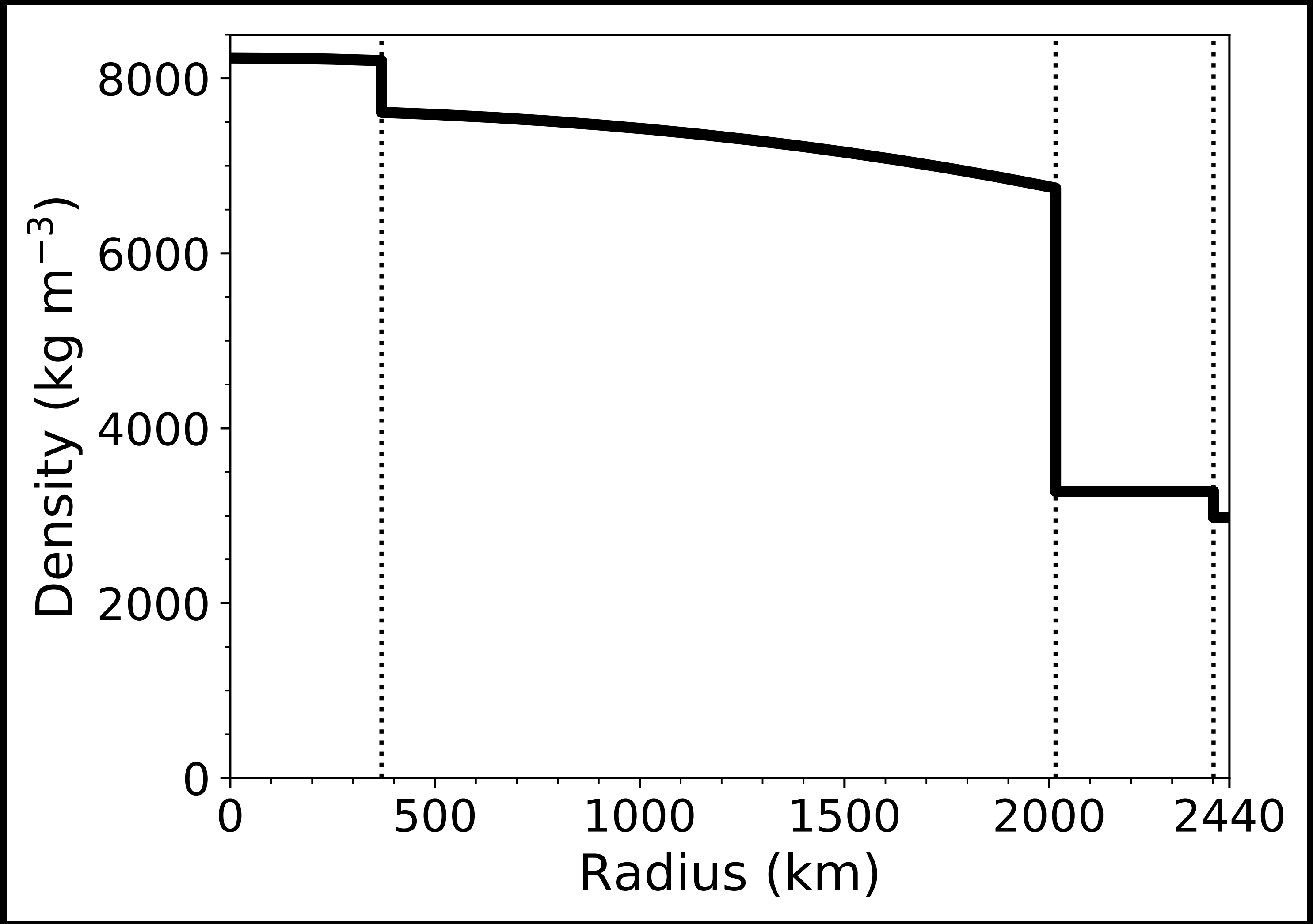
Mercury's Core is Molten

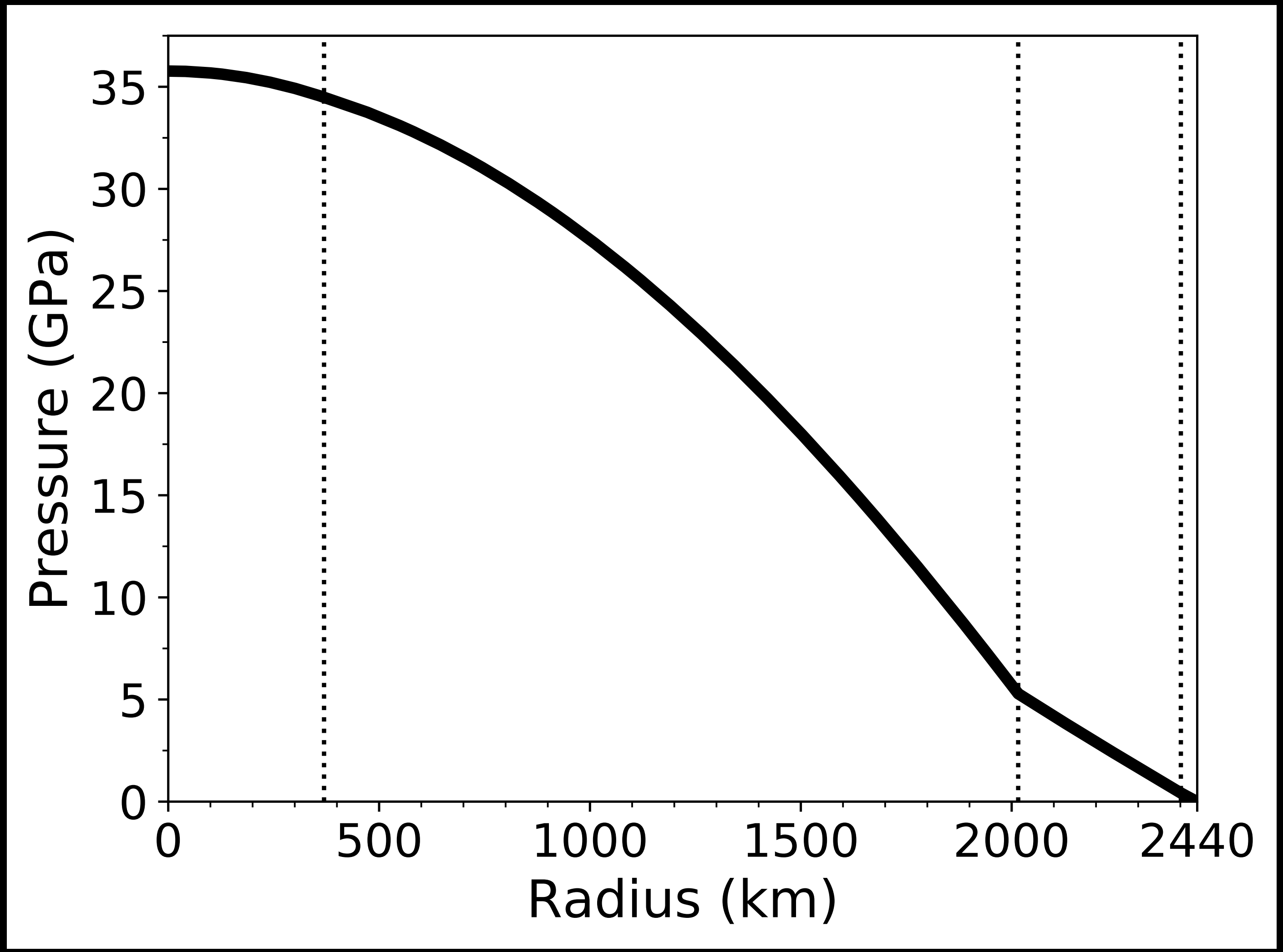




Margot et al., *Science* **316**, 2007

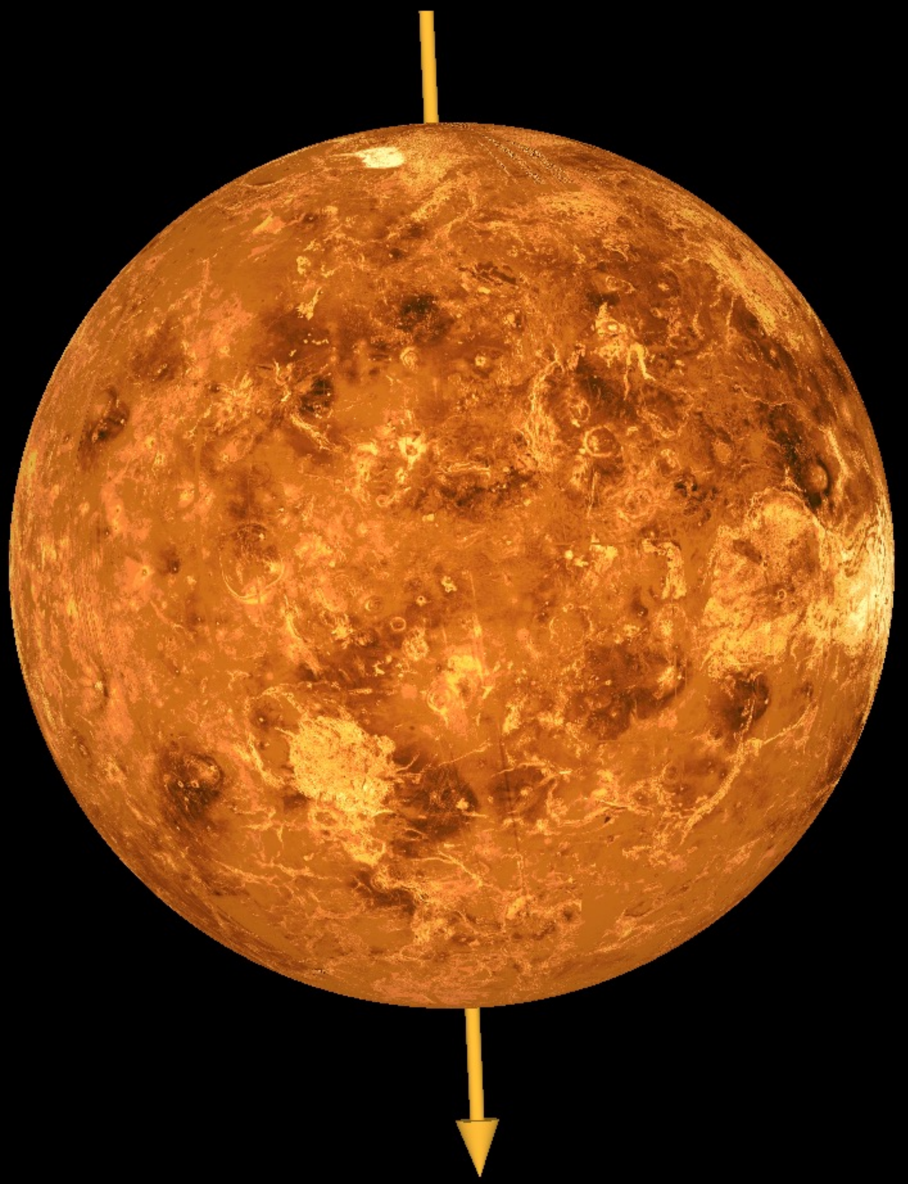
Measurement of Mercury's Core Size

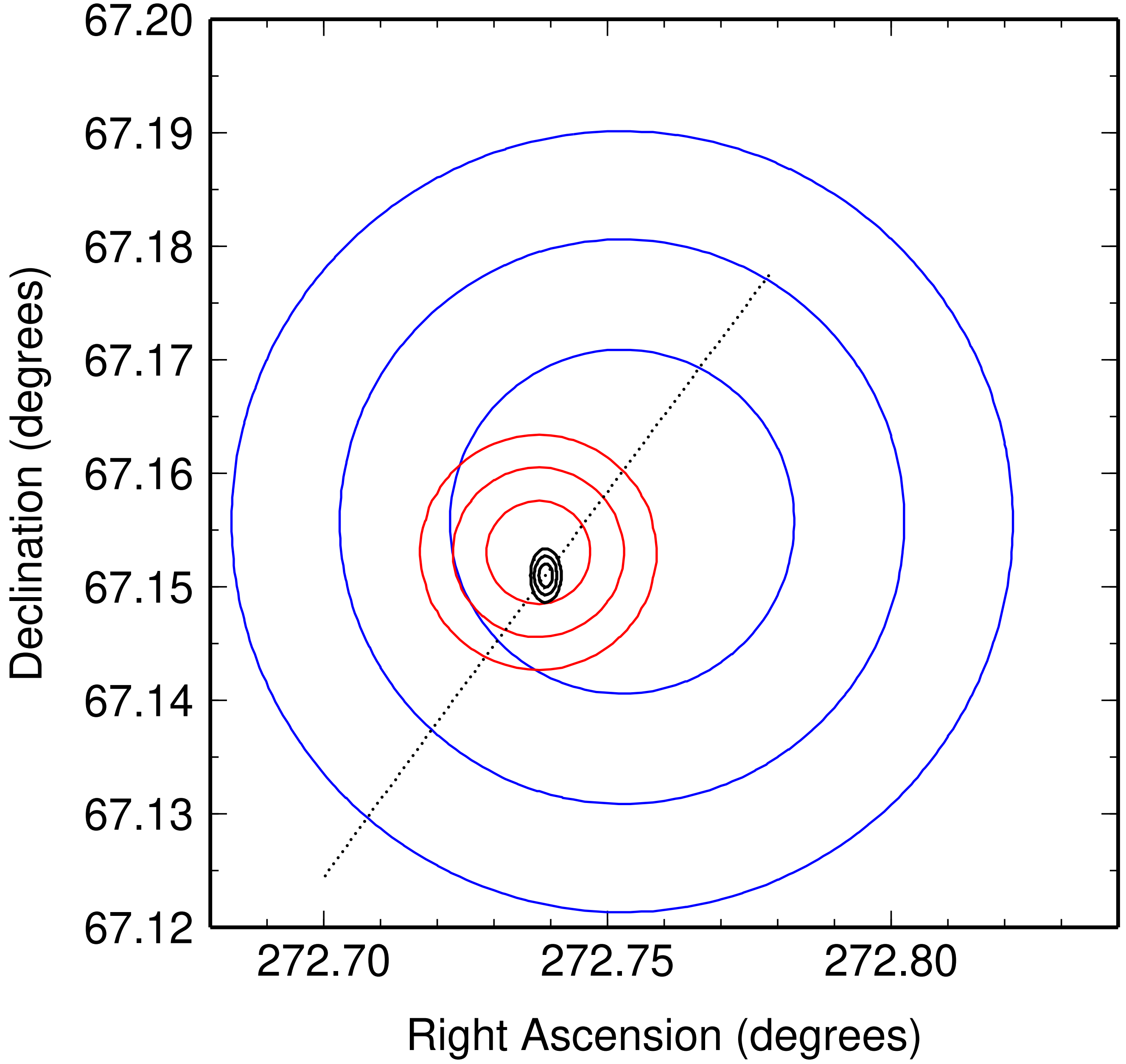




Margot et al., in Mercury – The view after MESSENGER (eds S. C. Solomon, B. J. Anderson, L. R. Nittler), 2018

Venus Spin Axis Orientation





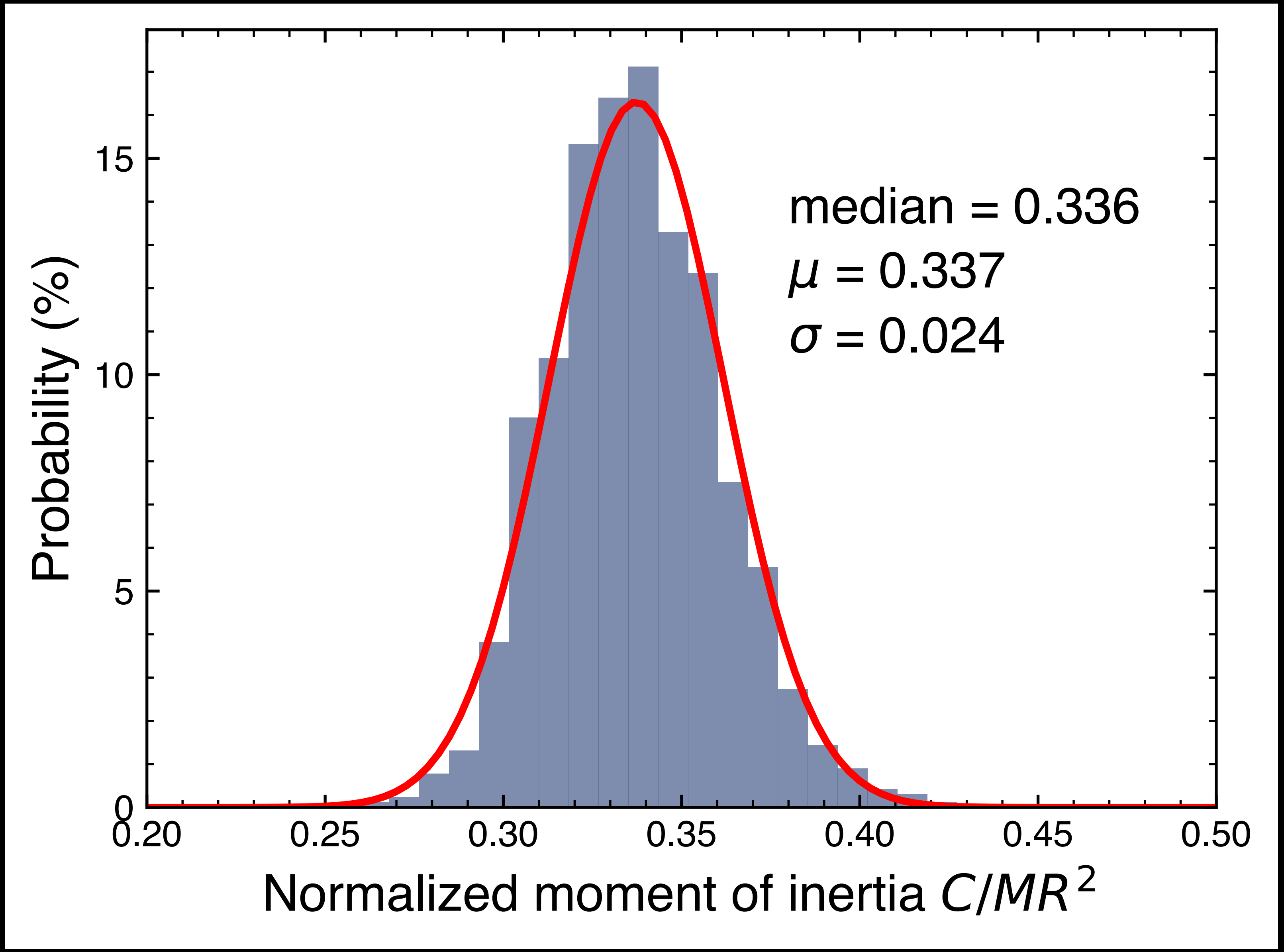
Davies et al. 1992
Magellan radar (46”)

Konopliv et al. 1999
Magellan gravity (14”)

Earth-based radar (3”)
(80 m on the surface)

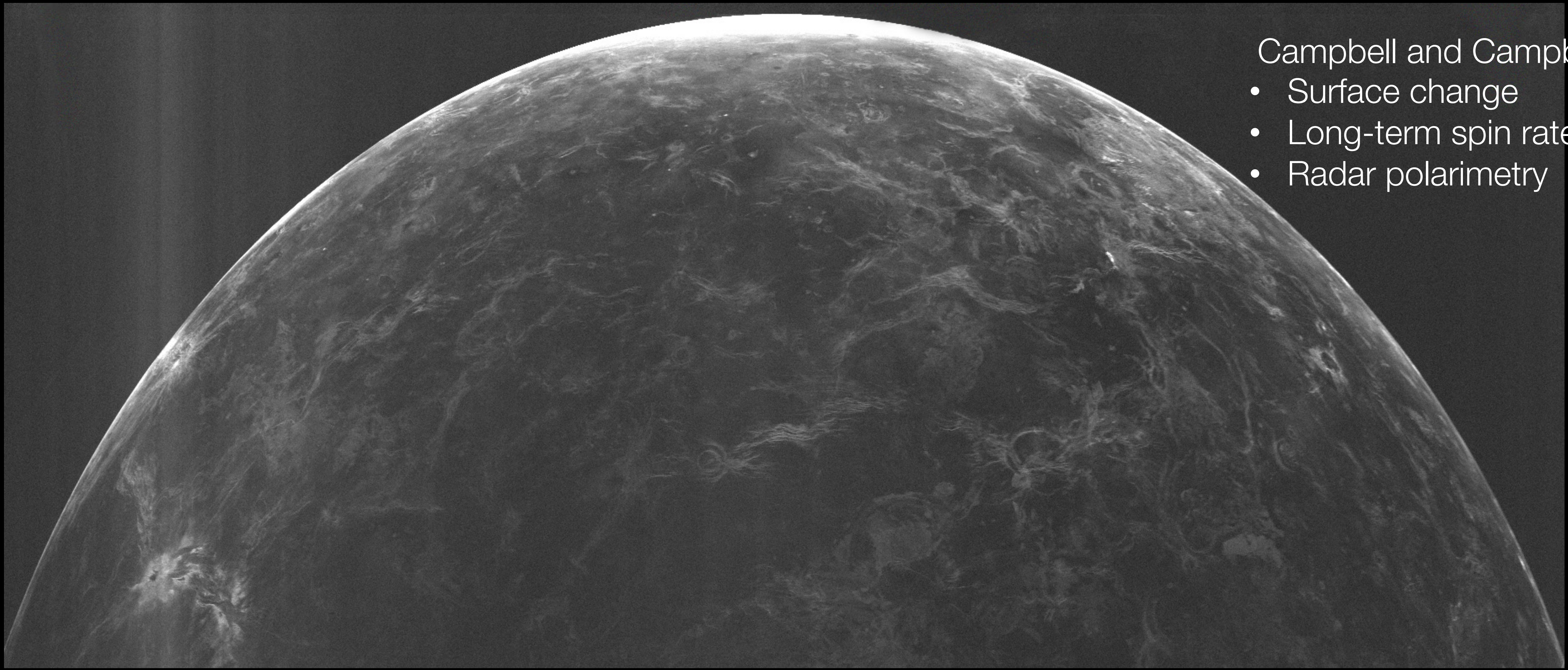
Margot et al., *Nature Astronomy* **5**, 2021.

Venus Moment of Inertia



Quantity	Least squares	Bootstrap mean	Std. dev.
RA (deg)	272.73911	272.73912	0.0008
DEC (deg)	67.15105	67.15100	0.0007
$d\psi/dt$ ($''$/y)	-44.89	-44.58	3.3
C/MR^2	0.3350	0.3373	0.024
C (10^{37} kg m^2)	5.972	6.013	0.43

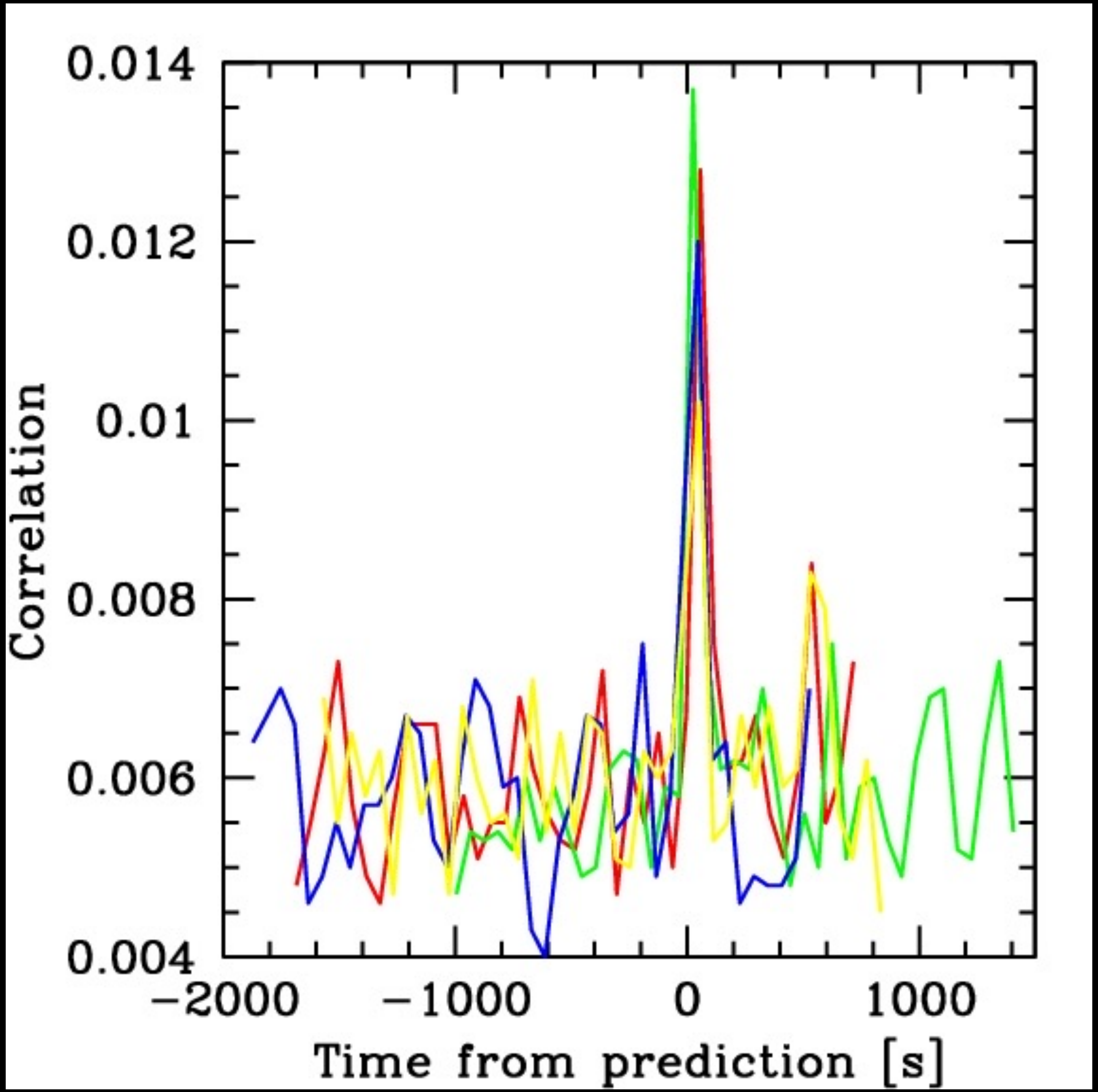
Venus Imaging



Campbell and Campbell, PSJ, 2022

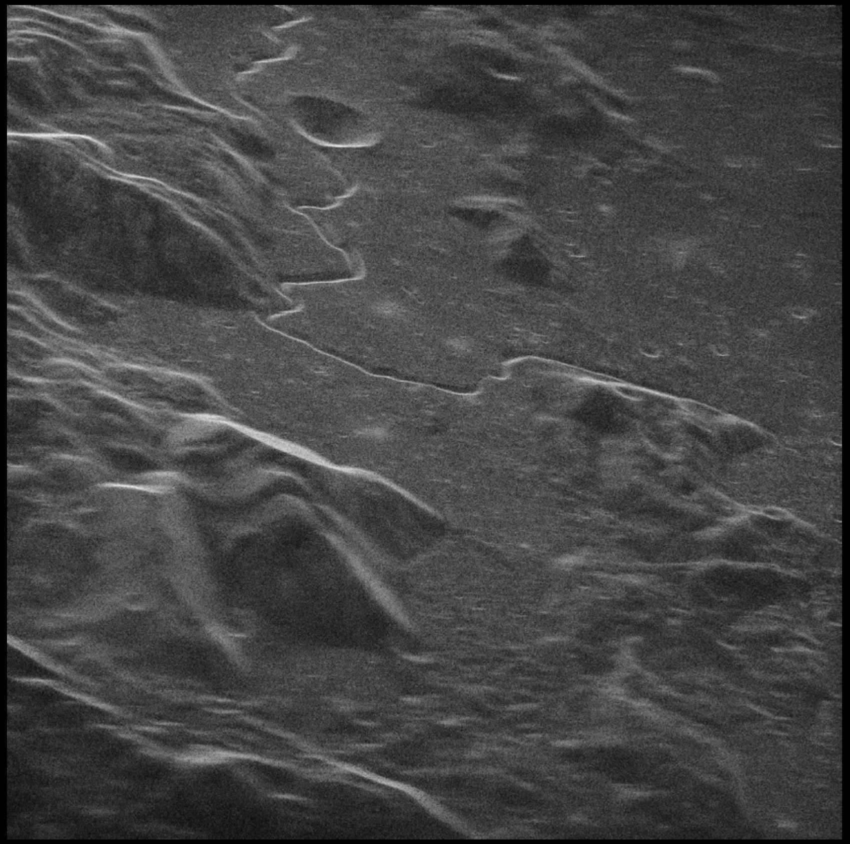
- Surface change
- Long-term spin rate monitoring
- Radar polarimetry

Europa and Ganymede

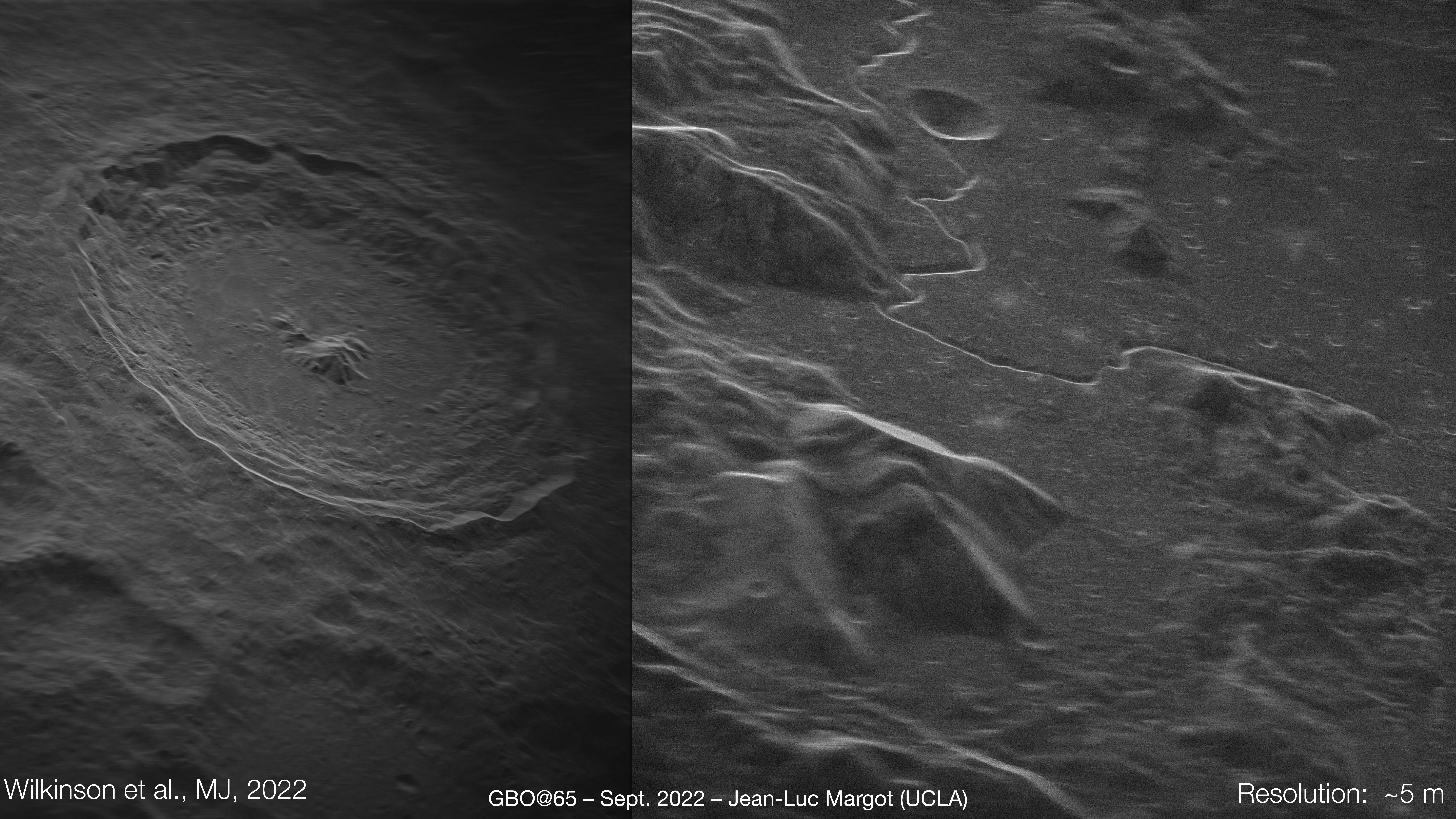


A New Era for Planetary Radar

Transmit from low-power (~1kW) Ku-band (13.9 GHz) prototype at GBT prime focus (with Raytheon) and receive at VLBA antenna in Hancock, NH.



Courtesy Flora Paganelli


Wilkinson et al., MJ, 2022
GBO@65 – Sept. 2022 – Jean-Luc Margot (UCLA)
Resolution: ~5 m

Conclusions

The Green Bank Observatory has enabled radar studies of the trajectories, spin states, surfaces, morphologies, and interiors of near-Earth asteroids, the Moon, Mercury, Venus, and Galilean Satellites.

The planned radar capability holds the promise of taking radar observations to new levels with notable increases in resolution and sensitivity.