# CHARACTERIZATION OF NEAR-EARTH OBJECTS USING PLANETARY RADAR OBSERVATIONS AND NUMERICAL MODELING

Anne Virkki[1,2]

[1]Department of Physics, University of Helsinki, Finland

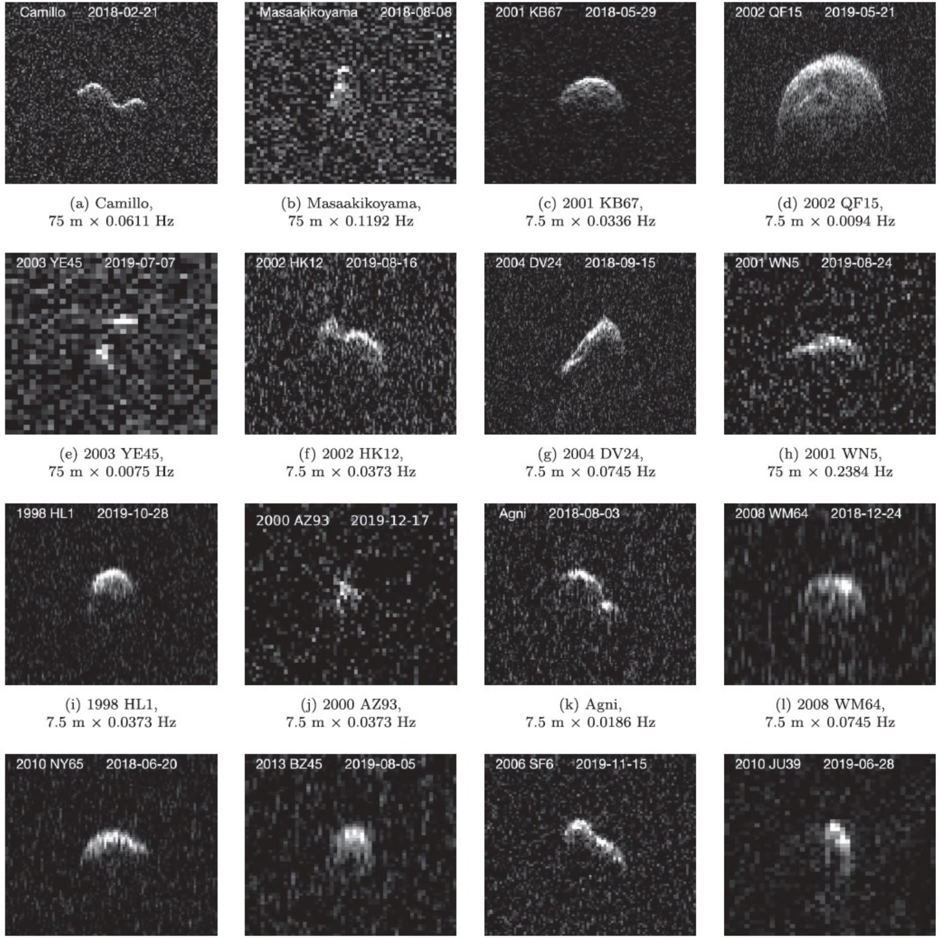
[2]Finnish Geospatial Research Institute (FGI), Masala, Finland

# Arecibo radar NEA observations
## Dec 2017 – Dec 2019

- We published
  - Radar cross sections (in two polarization) for nearly 200 NEOs
  - Spin periods and size estimates with a rough shape classification (rounded vs. contact binary vs. binary) for 37 asteroids
- ~30 % were contact binaries and ~10 % were binaries
- Two were reported possibly metal-rich and one possibly ice-rich
- A treasure chest for further analysis

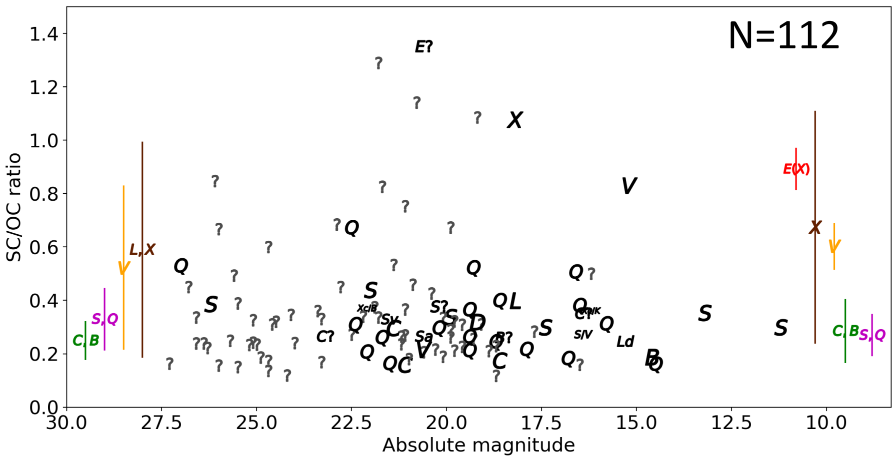
Virkki et al. (2022) PSJ 3:222

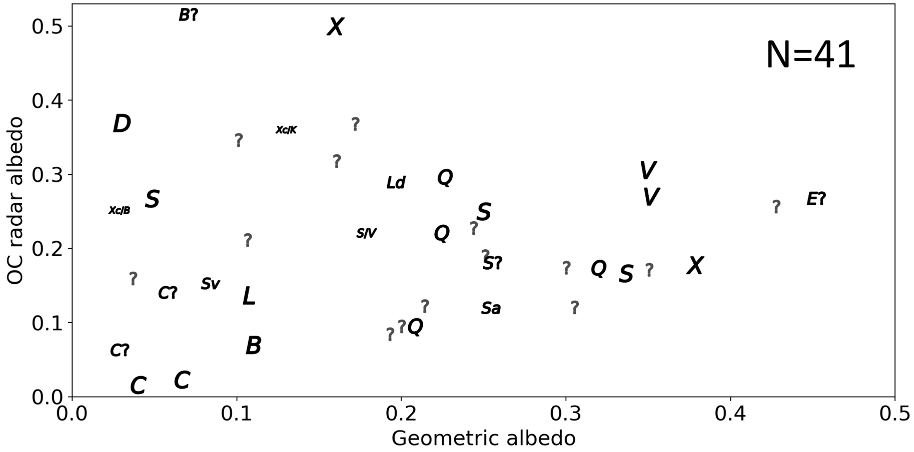
The Planetary Science Journal, 3:222 (36pp), 2022 September Virkki et al.



(a) Camillo, 75 m × 0.0611 Hz; (b) Masaakikoyama, 75 m × 0.1192 Hz; (c) 2001 KB67, 7.5 m × 0.0336 Hz; (d) 2002 QF15, 7.5 m × 0.0094 Hz; (e) 2003 YE45, 75 m × 0.0075 Hz; (f) 2002 HK12, 7.5 m × 0.0373 Hz; (g) 2004 DV24, 7.5 m × 0.0745 Hz; (h) 2001 WN5, 75 m × 0.2384 Hz; (i) 1998 HL1, 7.5 m × 0.0373 Hz; (j) 2000 AZ93, 7.5 m × 0.0373 Hz; (k) Agni, 7.5 m × 0.0186 Hz; (l) 2008 WM64, 7.5 m × 0.0745 Hz; (m) 2010 NY65, 7.5 m × 0.0373 Hz; (n) 2013 BZ45, 7.5 m × 0.0373 Hz; (o) 2006 SF6, 7.5 m × 0.0372 Hz; (p) 2010 JU39, 7.5 m × 0.0186 Hz

# Radar scattering properties




Virkki et al. (2022) PSJ 3:222

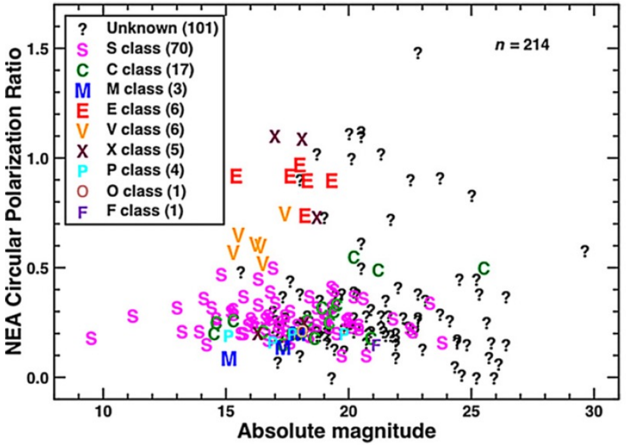



**Fig. 1.** Distribution of NEA SC/OC versus absolute magnitude. Spectral classes are indicated with different letters and colors. We adopt the classes described in Tholen and Barucci (1989), which identifies 14 groups based on the shape of their visible spectra and their albedos. S, Q, K, and L subclasses within the taxonomy in Bus et al. (2002) have been grouped into the S class. Dark C and B objects are labeled as "C." Of the 214 objects in the radar sample, estimates of VIS/IR spectral class are available for 113.

Benner et al. (2008)

# Polarization is indicative of the surface roughness

- **Smooth surfaces:** Specular reflection

–> All echo in the *opposite-circular* (OC) polarization than the transmitted signal

- **Rough surfaces (wavelength-scale surface roughness or boulders):** Quasi-specular + diffuse scattering

–> Echo partly in the OC polarization and partly in the *same-circular* (SC) polarization

**Radar cross section:**

$$\sigma_{Pol} = \frac{4\pi R^4 \lambda^2 P_{rx,Pol}}{P_{tx} A_{eff}^2}$$

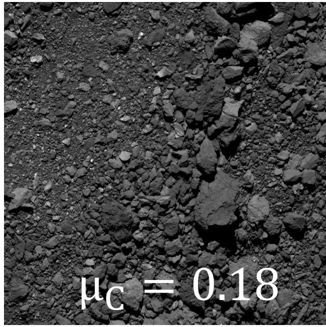
**Radar albedo:**

$$\hat{\sigma}_{Pol} = \frac{\sigma_{Pol}}{A_{proj}}$$

**SC/OC ratio:**

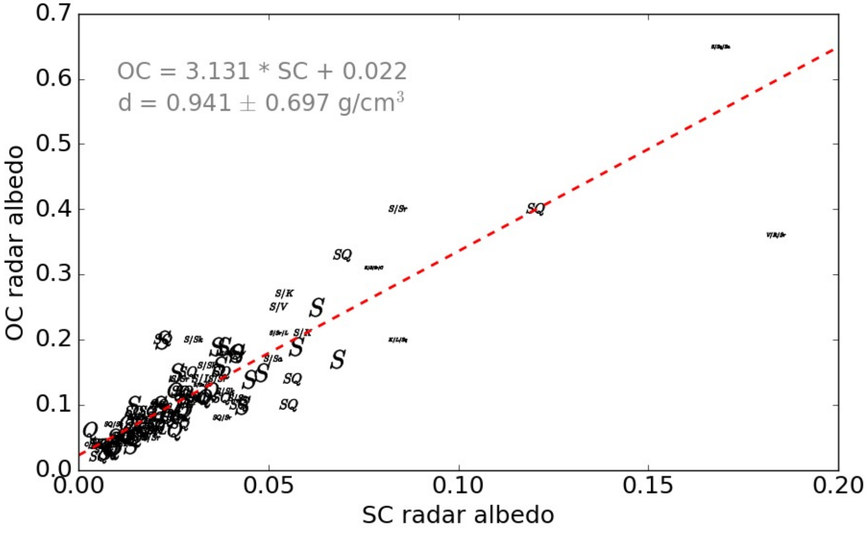
$$\mu_C = \frac{\sigma_{SC}}{\sigma_{OC}}$$

Bennu (39.5 m)

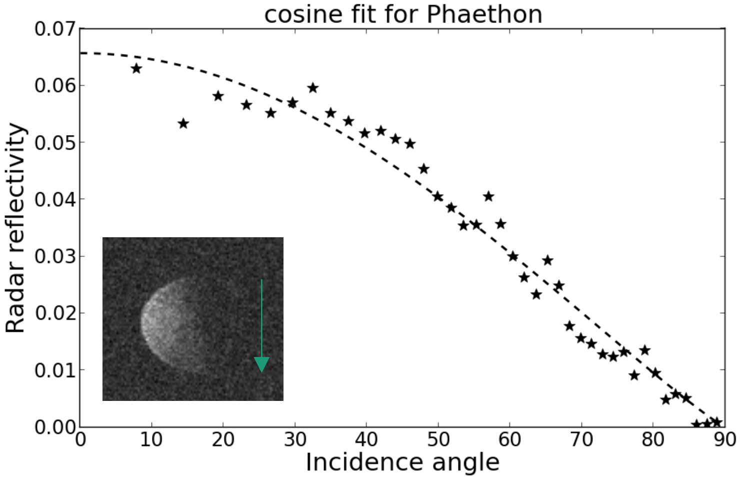


# The SC/OC ratio “hides” reflectivity information

Investigating the OC- and SC- polarized echoes separately is better…

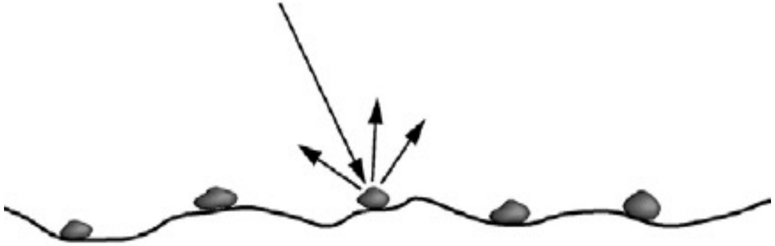


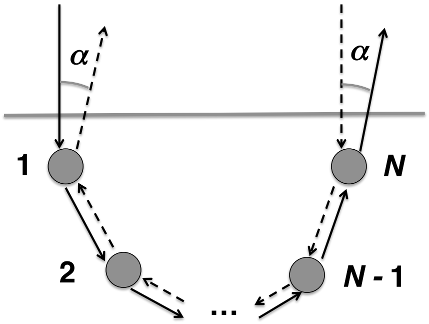

…whereas investigating the OC- and SC- polarized echoes as a function of incidence angle is the best approach!



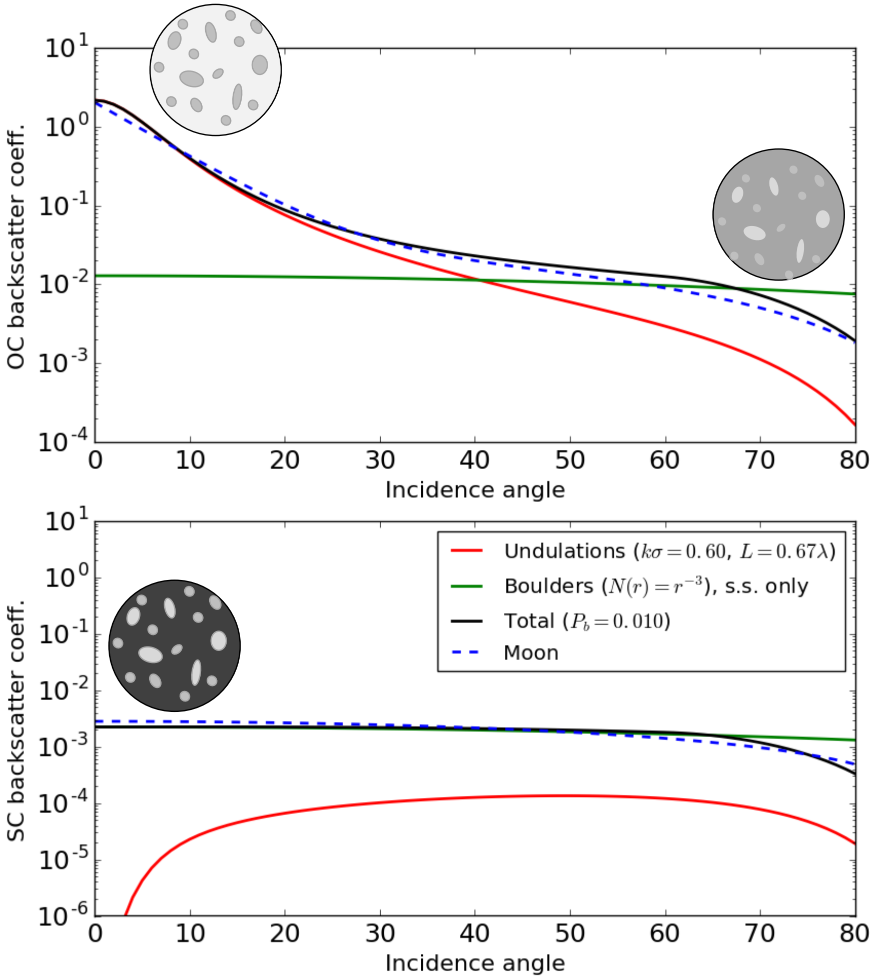

Virkki et al. (2017) EPSC2017-750

# Scattering by wavelength-scale particles

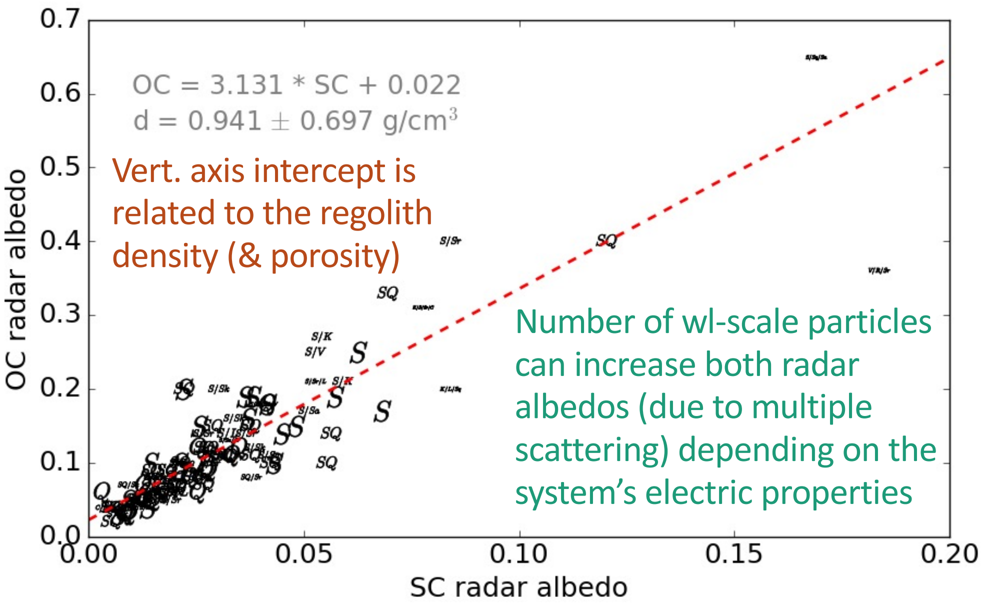





Forward scattering paths increase the apparent reflectivity compared to including only the Fresnel reflection.



# The wavelength-scale particles play a major role!




-> OC radar albedo is convolved with the roughness & SC/OC ratio with reflectivity

$\hat{\sigma}_C > \hat{\sigma}_s$ at high incidence angles

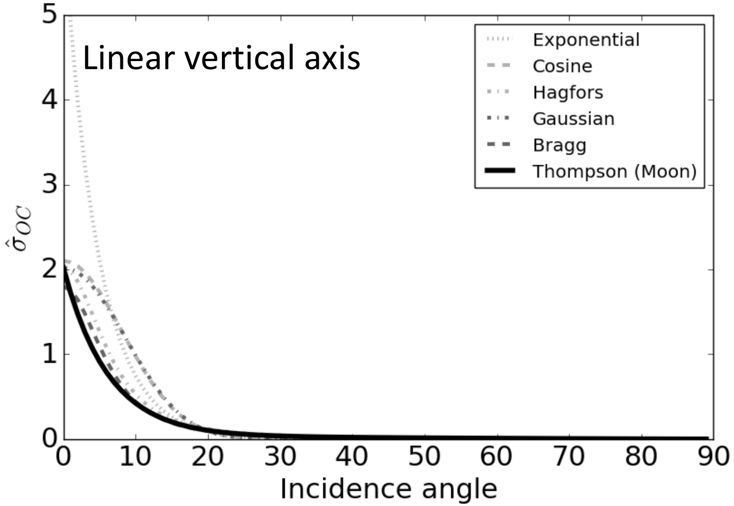
Effective radar BSC of wavelength-scale regolith

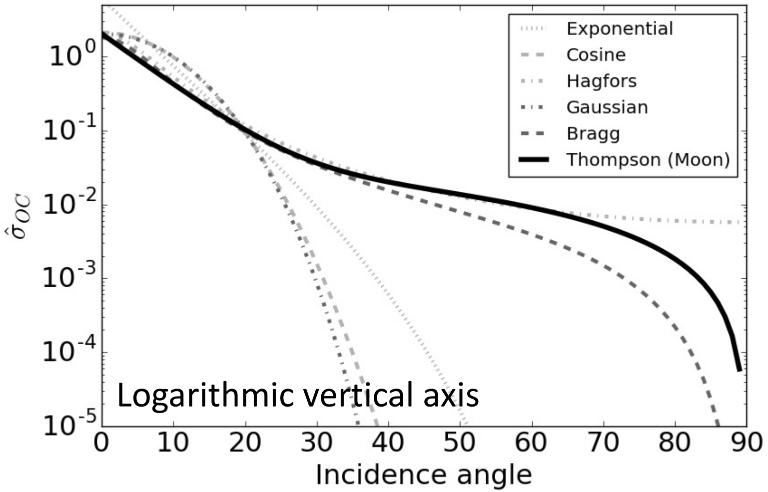
Effective radar BSC of fine-grained regolith

$$\hat{\sigma}(\theta) \sim P_C(\theta)\hat{\sigma}_C + [1 - P_C(\theta)]\hat{\sigma}_s(\theta)$$

Fraction of the received echo that is *non-specular*

Virkki & Bhiravarasu (2019) JGR Planets, 124, 11

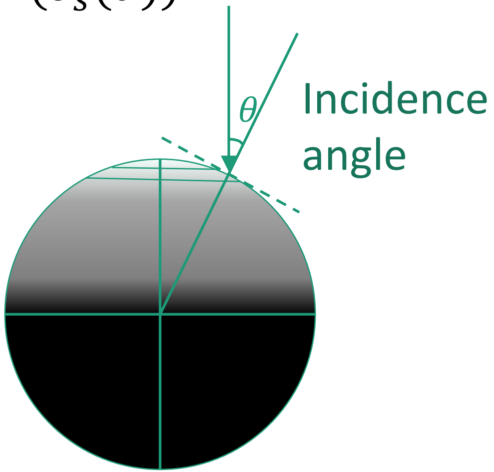



# Quasi-specular backscattering coefficient

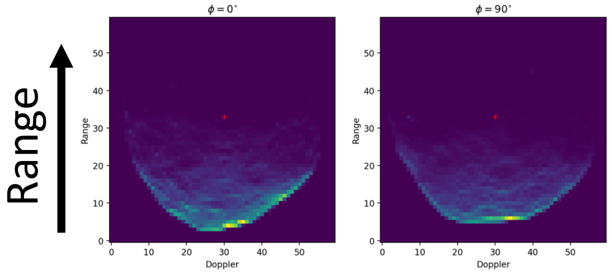
$(\hat{\sigma}_s(\theta))$

Several radar scattering laws have been developed (with different conditions), but only for undulating surfaces or empirically to fit the data.

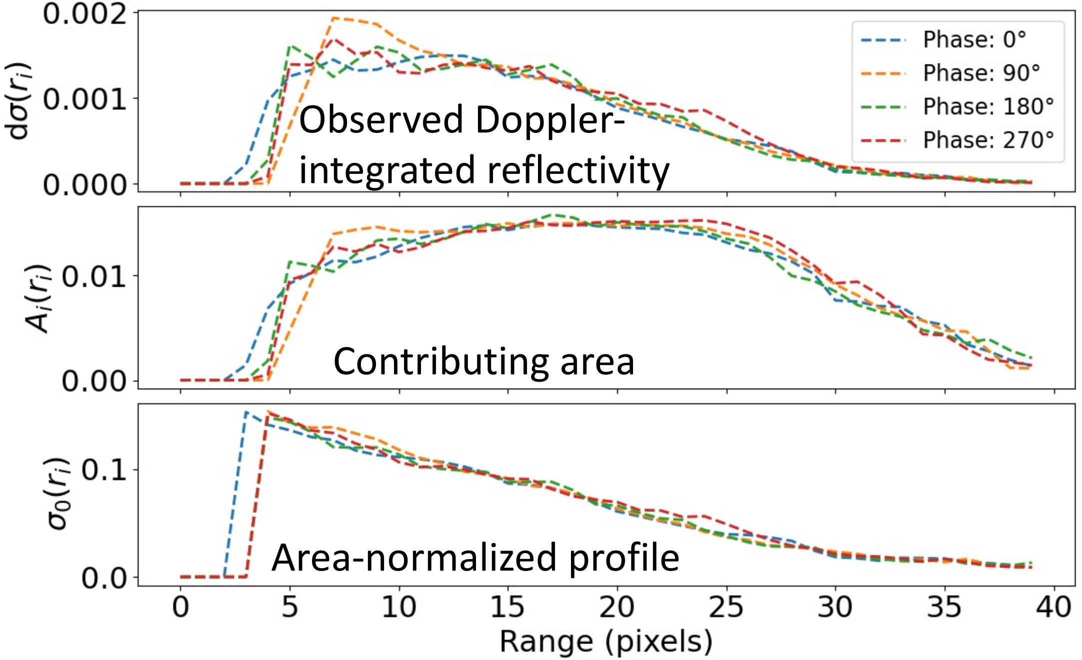



- Roughness parameter is ”r.m.s. slope”.
- Interpretation is at best hand-waving for high r.m.s. slopes.
- Better-established laws are work in progress.

# Radar scattering by Bennu




- For Bennu, SHAPE software gave R = 0.078 and C = 0.56
  (when $\frac{d\sigma}{dA} = RC\,(\cos\theta)^{2C}$)
- For C << 10, diffuse scattering by wavelength-scale regolith and structures with radii in the wavelength-scale dominate



# Near-surface densities

- Different empirical equations have been found for how the electric permittivity is related to the density
- Densities of 1-6 g/cm$^3$ using the radar-derived radar albedos and permittivities is a realistic range based on meteorite studies (preliminary results promising!)

$$\varepsilon \approx \left|\frac{1+\sqrt{R}}{1-\sqrt{R}}\right|^2$$

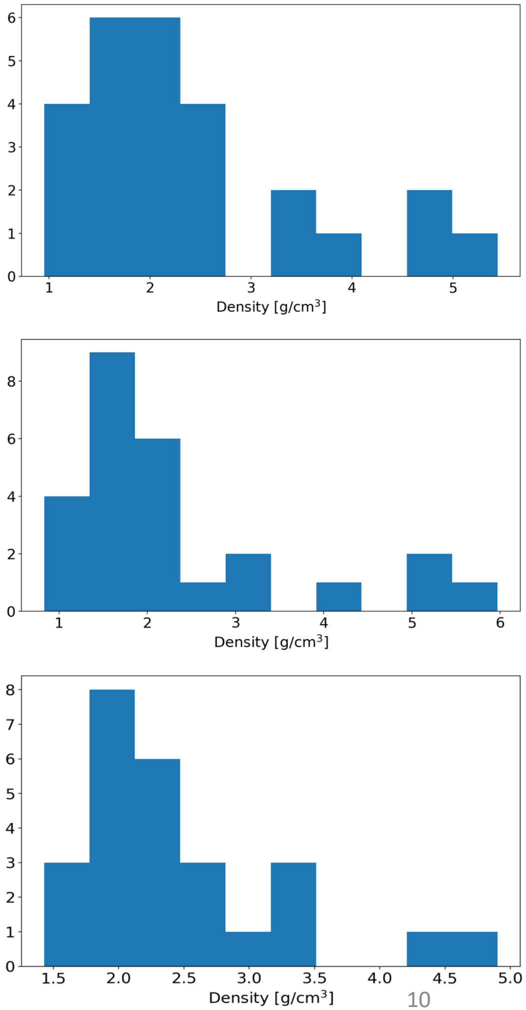
$$\rho = 3.26(\varepsilon^{\frac{1}{3}} - 1)$$

$$\rho = 1.77(\varepsilon^{\frac{1}{2}} - 1)$$

$$\rho = 6.95(\hat{\sigma}_{OC} + 0.156)$$

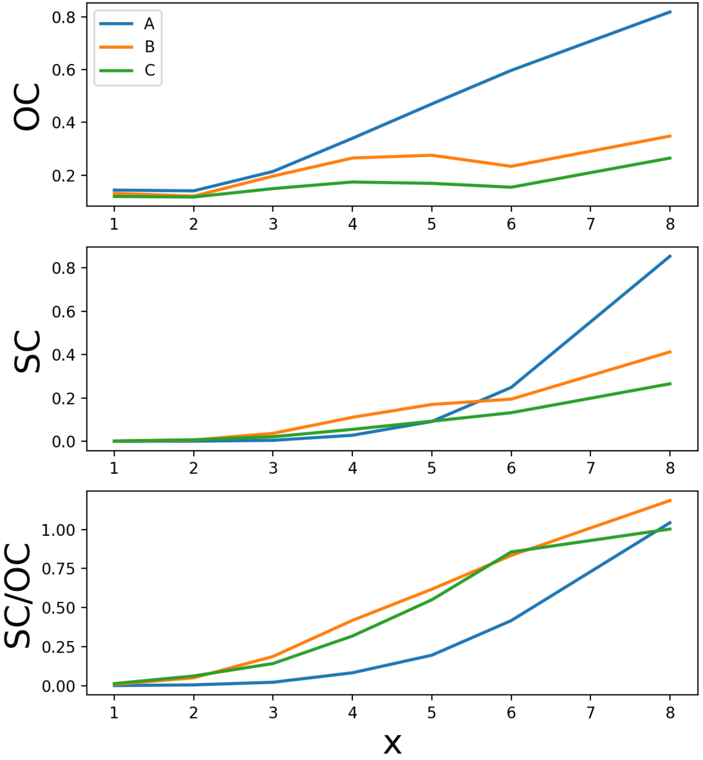
Hickson et al. (2018)
Shepard et al. (2008)
Garvin et al. (1985)

For Bennu,
$$\rho = 1.4 - 1.9\ \frac{\mathrm{g}}{\mathrm{cm}^{-3}}$$

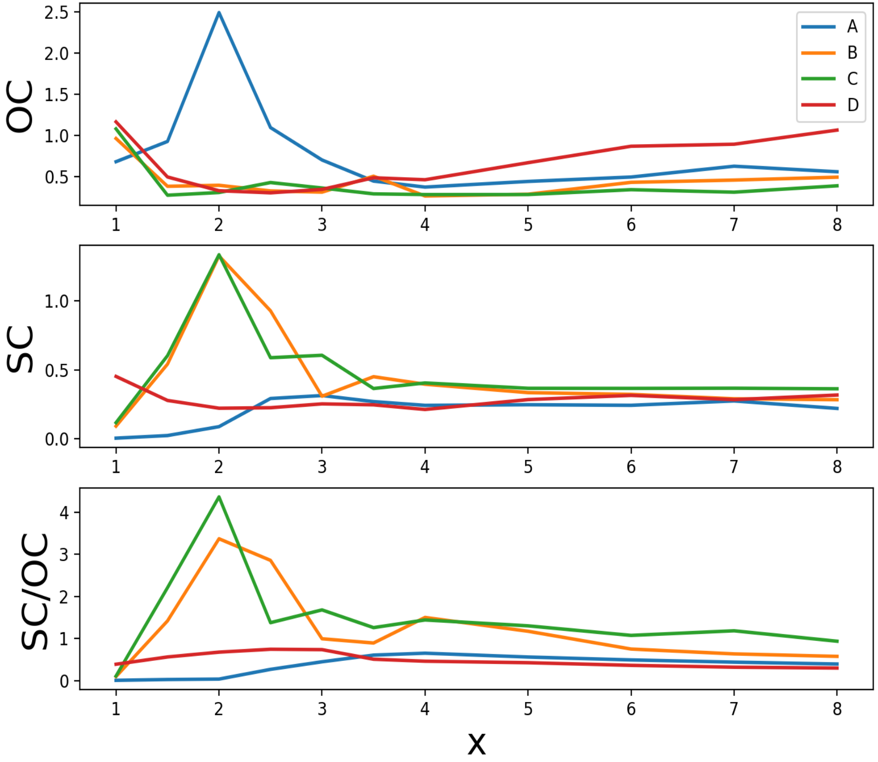


# Radar properties of wavelength-scale particles

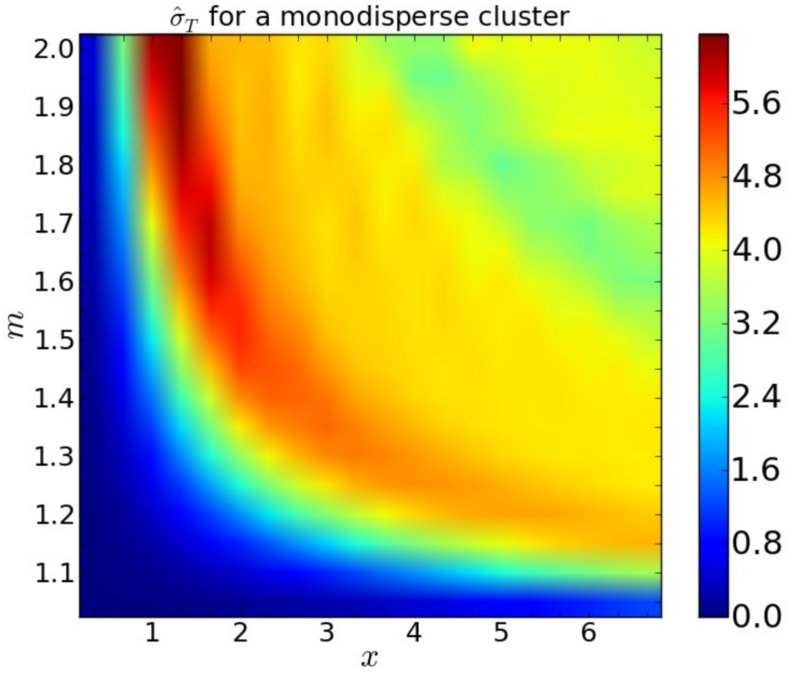
m = 1.43

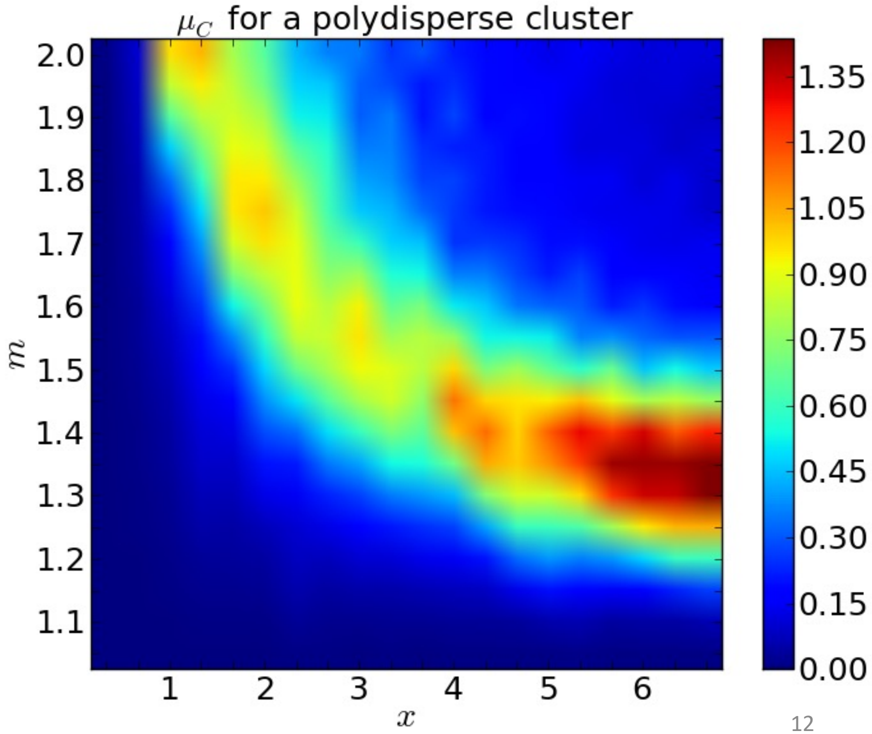



m = 2.54



# Backscattering as a function of size parameter and refractive index (using sphere clusters)



# Conclusions

- Radar is a powerful tool for characterizing the size, shape, and composition of NEOs
- The interpretation of the radar scattering properties of asteroids, for which the wavelength-scale particles may dominate the echo, is often hand-waving using the traditional interpretation that was suitable for the Moon and the planets
- New radar-scattering modeling work can move from less ambiguous surface-roughness parameters than the SC/OC ratio or rms slope to more reliable characterization
  - Deconvolves the reflectivity (electric properties) from the roughness
  - Furthermore, a distribution of near-surface densities of NEOs can be derived and size estimation's uncertainties can be better constrained