Refining Asteroid Mass Uncertainty via Volume, and Bulk Density Constraints for Optimal Flyby Mission Design

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Introduction

- Refining the physical properties of asteroids is crucial for designing asteroid mitigation missions and assessing the consequences of possible impacts as part of disaster management and impact response efforts.
- Asteroid shape, density, strength, and internal structure significantly affect how a body will respond to mitigation efforts.
- In a planetary defense scenario—depending on how far in advance the asteroid is discovered—flyby missions may be the only practical option for narrowing uncertainty in physical parameters.

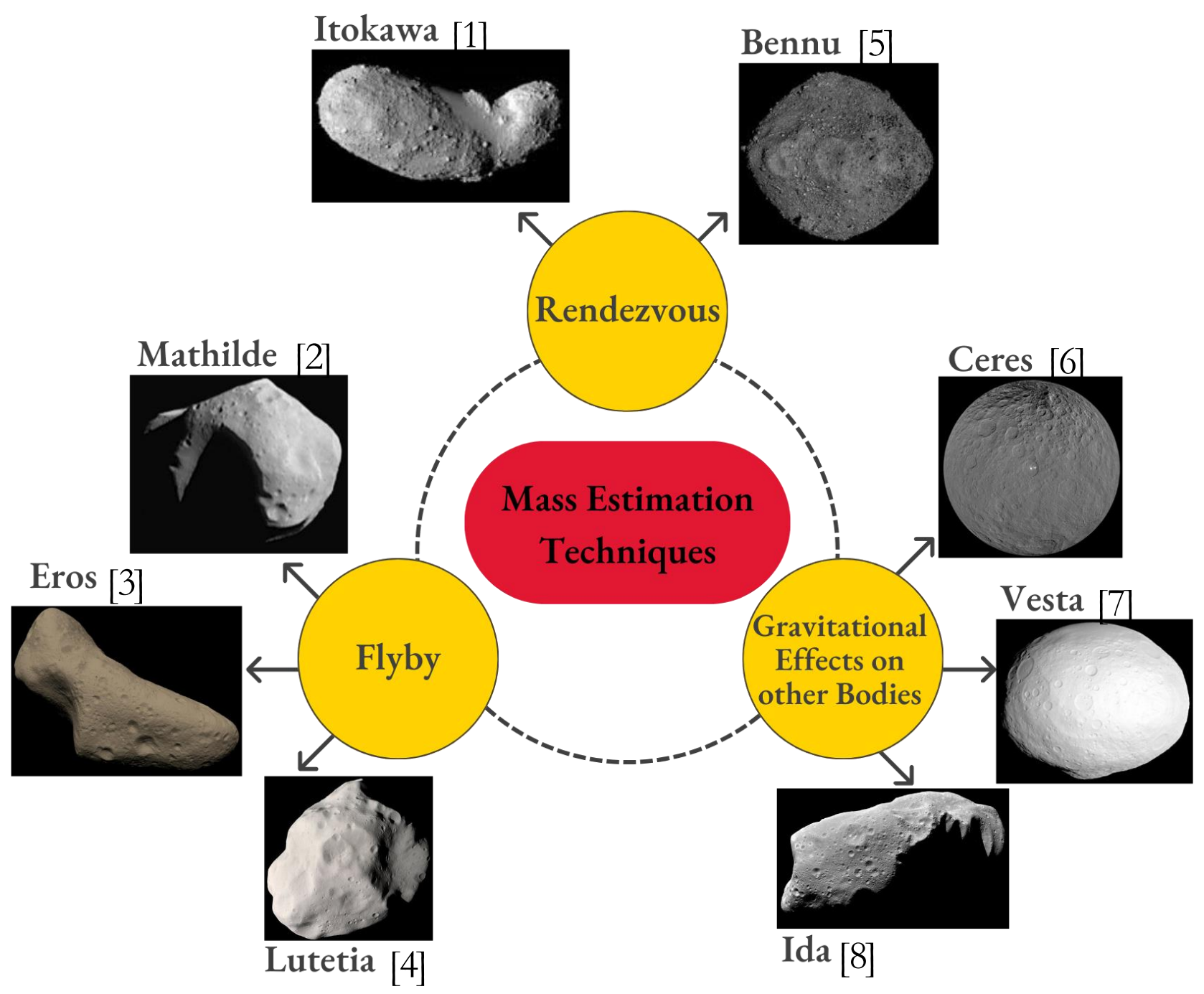

Figure 1: **Examples of bodies whose masses have been determined with various mass estimation techniques**

Table 1: Post flyby uncertainty ranges of asteroid physical parameters

	Uncertainty
Volume	10% - 30% [9, 10]
Mass	10% - 15% [10]
Porosity	10% - 20%

A Quantitative Approach to Mass Uncertainty

Mass as a Function of Volume and Density

- Asteroid mass can be modeled as a function of volume (v), and bulk density (ρ)

$$m = f(v, \rho)$$

- To understand how uncertainty in volume and density affects mass estimates, we can differentiate this relationship and simplify it using standard deviations

$$\sigma_m = \sqrt{\rho^2 \sigma_v^2 + v^2 \sigma_\rho^2}$$

Percentage Uncertainty

- Volume Uncertainty: $p_v = {}^{\sigma_v}/_{v}$
- Density Uncertainty: $p_\rho = {}^{\sigma_\rho}/_{\rho}$
- Mass Uncertainty: $p_m = {}^{\sigma_m}/_{m}$

$$\boxed{p_m = \sqrt{p_v^2 + p_\rho^2}}$$

Target Mass Uncertainty

- Evaluate how volume and density uncertainties contribute to total mass uncertainty – critical for mission planning and asteroid characterization
- Given that volume uncertainty can be minimized via flyby imaging, the key challenge becomes identifying how well bulk density must be constrained to meet a desired mass uncertainty.

Table 2: Mass, Volume, and Density uncertainty relations

Mass (p_m)	Volume (p_v)	Density (p_ρ)
0.1	0.05	0.087
	0.1	0
0.25	0.05	0.24
	0.1	0.23
	0.2	0.15
	0.25	0
0.5	0.05	0.5
	0.1	0.49
	0.2	0.46
	0.3	0.4
	0.5	0

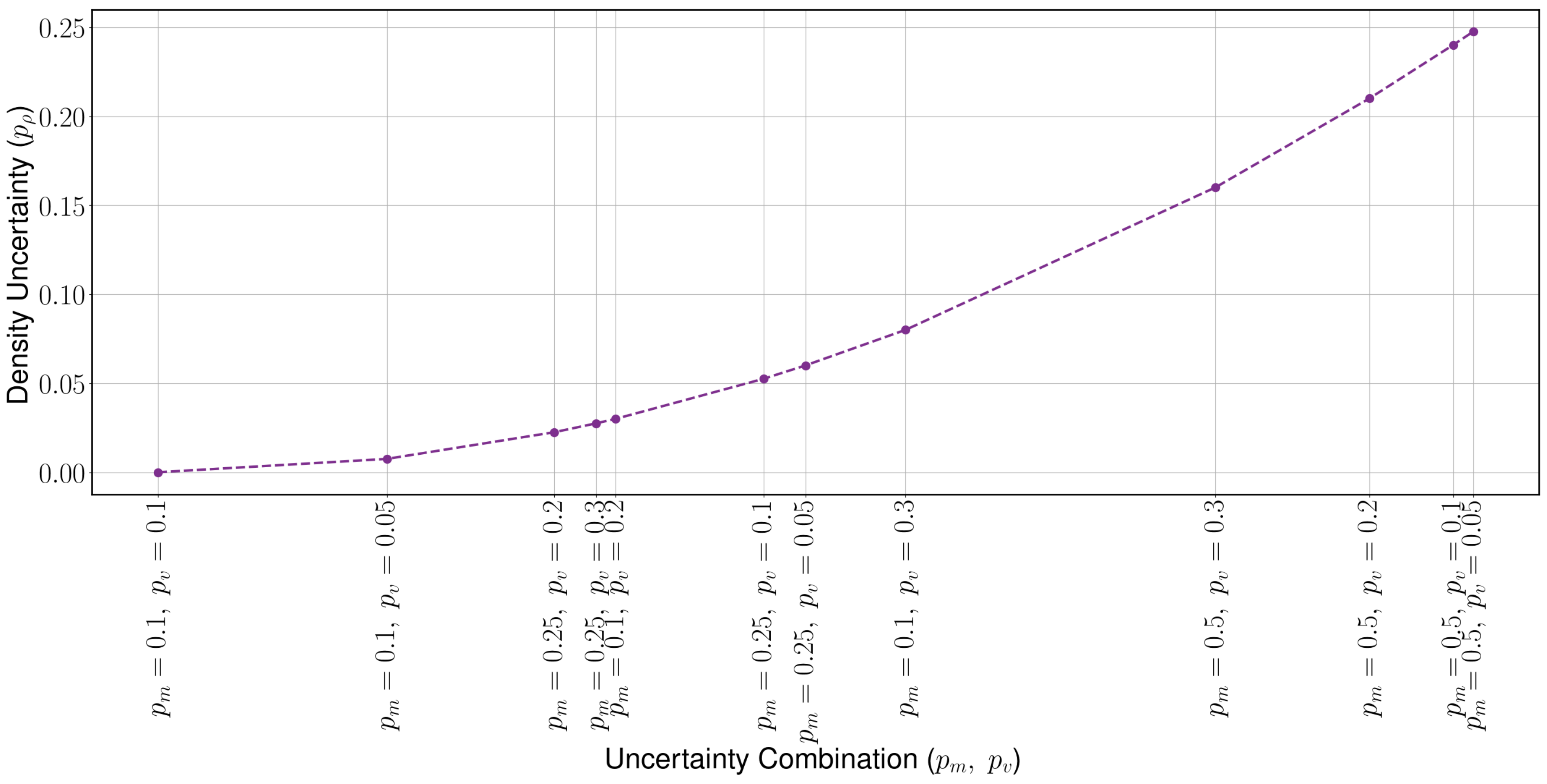

Figure 2: Relationship between mass, volume, and bulk density uncertainty.

References

[1] NASA, "25143 Itokawa - NASA Science." Accessed: Apr. 28, 2025. [Online]. Available: https://science.nasa.gov/solar-system/asteroids/25143-itokawa/
[2] NASA, "253 Mathilde - NASA Science." Accessed: Apr. 28, 2025. [Online]. Available: https://science.nasa.gov/solar-system/asteroids/253-mathilde/
[3] The Planetary Society, "Asteroid Eros reconstructed," Accessed: Apr. 28, 2025. [Online]. Available: https://www.planetary.org/space-images/asteroid-eros-reconstructed
[4] The Planetary Society, "Pretty Pictures: Amazing Asteroid Lutetia," Accessed: Apr. 28, 2025. [Online]. Available: https://www.planetary.org/articles/3448
[5] NASA, "Bennu - NASA Science." Accessed: Apr. 28, 2025. [Online]. Available: https://science.nasa.gov/solar-system/asteroids/101955-bennu/
[6] NASA, "Ceres: Facts - NASA Science." Accessed: Apr. 28, 2025. [Online]. Available: https://science.nasa.gov/dwarf-planets/ceres/facts/
[7] NASA, "4 Vesta - NASA Science." Accessed: Apr. 28, 2025. [Online]. Available: https://science.nasa.gov/solar-system/asteroids/4-vesta/
[8] NASA, "Asteroid Ida - Five Frame Mosaic - NASA Science." Accessed: Apr. 28, 2025. [Online]. Available: https://science.nasa.gov/resource/asteroid-ida-five-frame-mosaic/
[9] R. Schulz et al. "Rosetta fly-by at asteroid (21) Lutetia: An overview". In: Planetary and Space Science 66.1 (2012), pp. 2–8. ISSN: 00320633. DOI: 10.1016/j.pss.2011.11.013.
[10] J. Hanus et al. "Volumes and bulk densities of forty asteroids from ADAM shape modeling". In: Astronomy & Astrophysics 601 (2017), A114. ISSN: 0004-6361, 1432-0746. DOI: 10.1051/0004-6361/201629956.
[11] J. B. Carry. "Density of asteroids". In: Planetary and Space Science. Solar System science before and after Gaia 73.1 (2012), pp. 98–118. ISSN: 0032-0633. DOI: 10.1016/j.pss.2012.03.009.
[12] A. S. Rivkin et al. "JWST Observations of Potentially Hazardous Asteroid 2024 YR4". In: Research Notes of the AAS 9.4 (2025), p. 70. ISSN: 2515-5172. DOI: 10.3847/2515-5172/adc6f0.
[13] M. Devogele et al. Physical characterization of 2024 YR4. Near Earth Coordination Center ESA ESRIN Frascati Italy, 2025. URL: https://iawn.net/documents/20250204_20th_Vienna/ESA-S2P-PD-HO-0262.pdf.
[14] P. Pravec et al. "Absolute magnitudes of asteroids and a revision of asteroid albedo estimates from WISE thermal observations". In: Icarus 221.1 (2012), pp. 365–387. ISSN: 0019-1035. DOI: 10.1016/j.icarus.2012.07.026.
[15] A.W. Harris. "On the Revision of Radiometric Albedos and Diameters of Asteroids". In: Icarus 126.2 (Apr. 1, 1997), pp. 450–454. ISSN: 0019-1035. DOI: 10.1006/icar.1996.5664.
[16] A.S. Rivkin et al. JWST Observations of Potential Impactor 2024 YR4. Unpublished technical memo. Mar. 27, 2025

Implications for Flyby Mission Design

Bulk density baseline by taxonomic class identification:

Table 3: Bulk density ranges by taxonomic classes of near-Earth asteroids

Taxonomic Class	Bulk Density (Mean ±1σ)	Uncertainty (%)	Examples
S-type	2.70 ± 0.69 g/cm^3 [11]	± 25.6%	433 Eros, 25143 Itokawa
C-type	1.41 ± 0.69 g/cm^3 [11]	± 48.9%	253 Mathilde, 101955 Bennu
X-type	1.99 ± 0.99 g/cm^3 [11]	± 49.7%	87 Sylvia
M-type	3.85 ± 1.27 g/cm^3 [11]	± 33.0%	16 Psyche, 216 Kleopatra

Expected ranges of reduced uncertainty by included instrument category:

Table 4: Approximate uncertainty ranges to be expected from varying satellite instrumentation for a flyby reconnaissance mission

Instrument Configuration	Volumetric Uncertainty (%)	Bulk Density Uncertainty (%)
Camera/IR spectrometer	15–20	25–50 (class-dependent)
IR radiometry/Radar	–	10–20
Combined Instrumentation	~≤15 - 20	10–20

* Values assembled from historic flyby spreads and published estimation exercises – assumes asteroid is largely homogeneous and largest portion of bulk density uncertainty from porosity

Model Evaluation Using Asteroid 2024 YR4

Using the presently known properties and distributions as a baseline:

Table 5: Physical Properties of 2024 YR4

	Value	Note
H-Magnitude	24.05 ± 0.15 [12, 13]	After rotation lightcurve correction [13]
Albedo	0.197 ± 0.051 [14]	Mean albedo for S/A/L types of size 0.6 - 200 km [14]
Density [g/cm^3]	2.70 ± 0.69 [11]	Based on 28 estimates with a 50% accuracy [11]

Gaussian albedo and absolute magnitude create right-skewed diameter distribution:

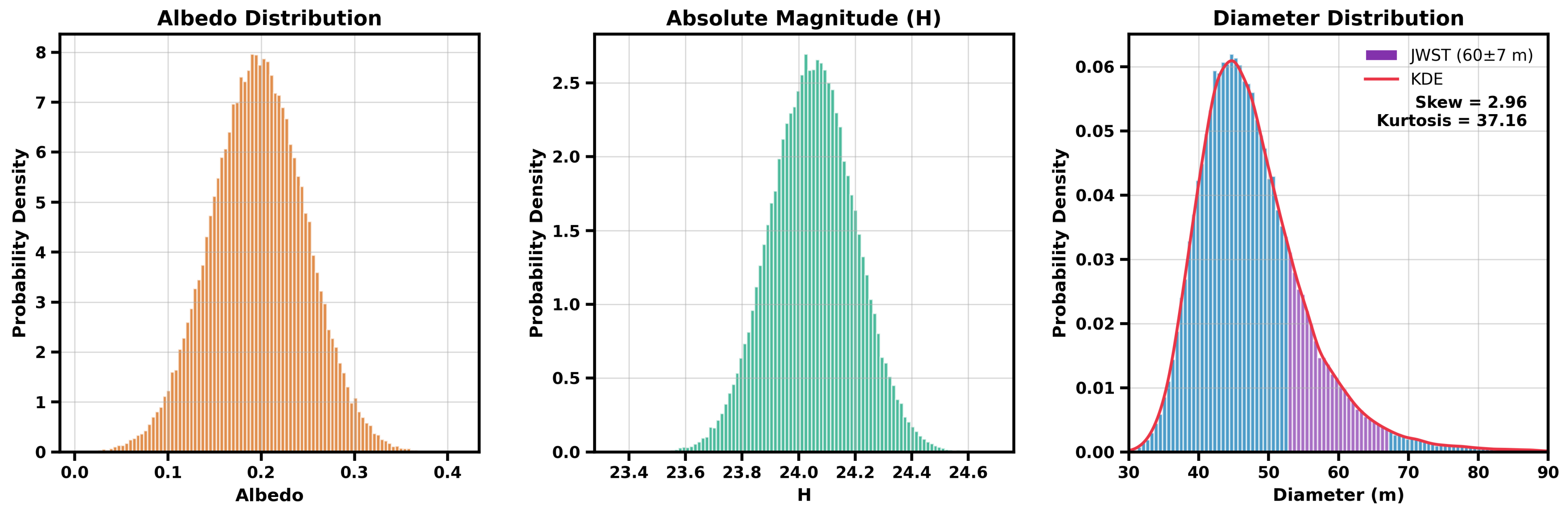

Figure 3: Physical property distribution with diameter estimation using empirical relations from Harris (1997) [15]
* JWST observation-based 1-σ bounds highlighted within traditional diameter distribution

Set of flyby-based reduced uncertainties show respective impact on mass distribution:

Table 6: Selected example uncertainty resultants for instruments on flyby missions, improvements taken as median values from Table 5

Instrument Configuration	Volumetric Uncertainty (%)	Bulk Density Uncertainty (%)
No Flyby Baseline	149.04	25.6
Camera/IR spectrometer	17.5	25.6
IR radiometry/Radar	149.04	15.0
Combined Instrumentation	17.5	15.0

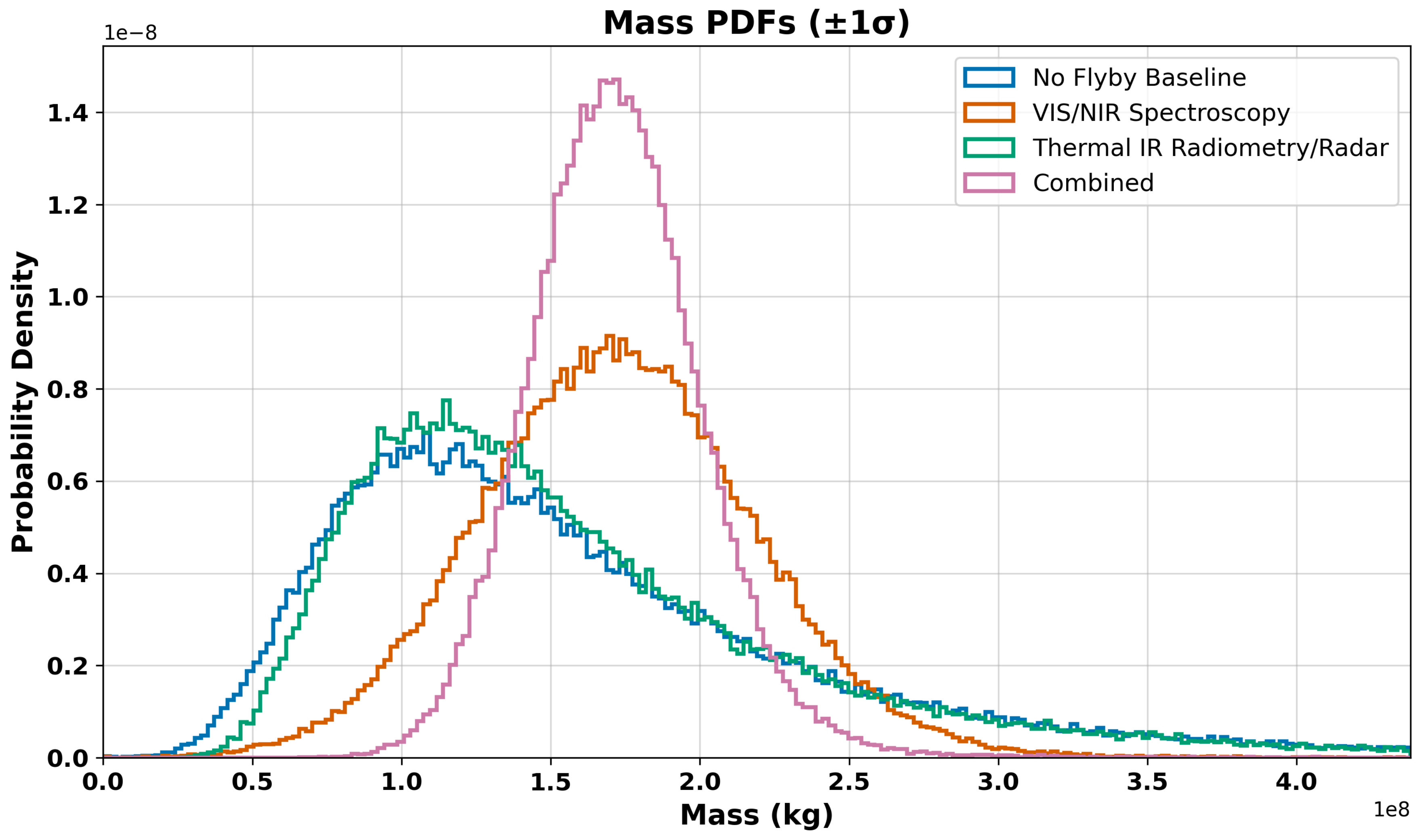

Figure 4: Resulting probability distribution functions for the resultants as outlined in Table 6

Sobol indices - fractional uncertainty contribution for each scenario:

$$S_v = \frac{p_v^2}{p_v^2 + p_\rho^2} \qquad S_{v,\text{prior}} = \frac{1.49^2}{1.49^2 + 0.256^2} \approx 0.97$$

$$S_\rho = \frac{p_\rho^2}{p_v^2 + p_\rho^2} \qquad S_{\rho,\text{prior}} = \frac{0.256^2}{1.49^2 + 0.256^2} \approx 0.03$$

Instrument Configuration	S_v (%)	S_ρ (%)
No Flyby Baseline	97	3
VIS +NIR Spectroscopy	32	68
Thermal IR Radiometry/Radar	99	1
Combined Instruments	58	42

Conclusion

- By deriving a quantitative relationship between volume, bulk density, and mass, we show that spacecraft imaging alone can significantly reduce mass uncertainty with sufficient resolution and flyby geometry, but without data from infrared spectroscopy, thermal radiometry, or radar, uncertainties in bulk density will dominate the residual mass uncertainty.
- Significant reductions in mass uncertainty only come once volume is constrained significantly below traditional ground-based observation and current telescope-based estimates ($\sigma_v \sim\leq \pm 20\%$)
- Applying this framework to asteroid 2024 YR4 showed pre-flyby mass uncertainty overwhelmingly driven by large volume uncertainties derived from albedo, and absolute magnitude estimates.