Occultations and the Size and Density of Asteroids

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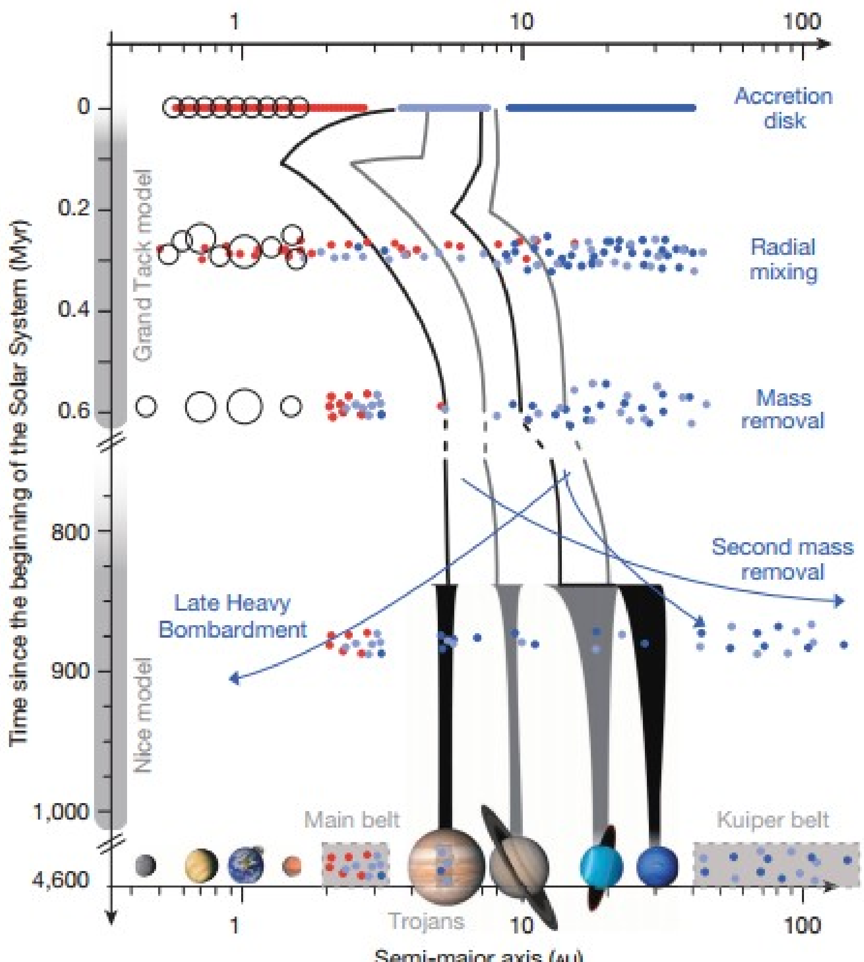
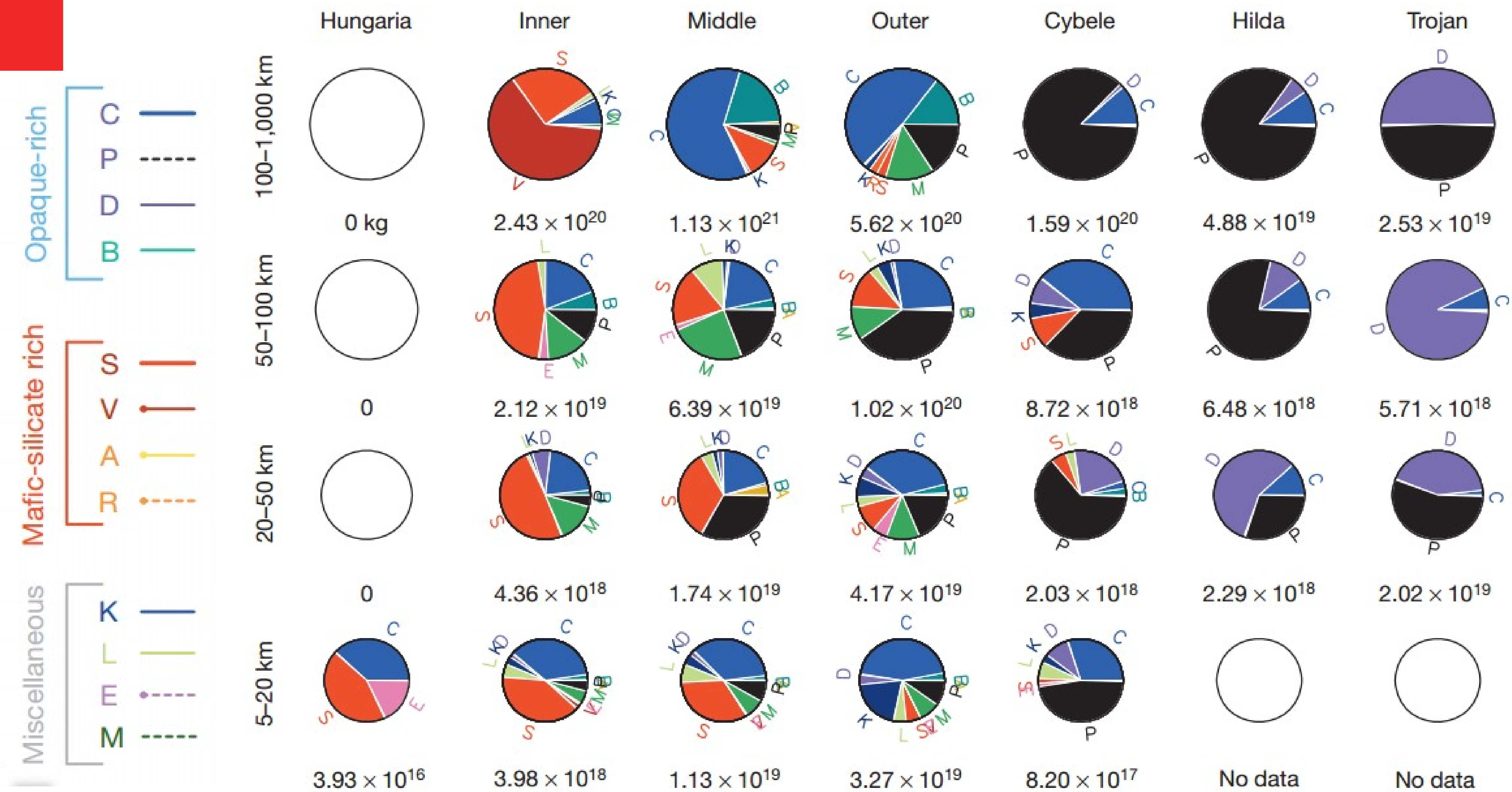
Small bodies in the Solar System formation context



DeMeo & Carry (2014)

- SB are remnants of the early stages of planetary formation.
- They contain information about these processes.
- Trigger (new/revised) theories on the formation and evolution of our Solar System (GTM, NM).
- SS history more dynamic than thought 20+ yrs before.

Compositional mass distribution as function of size



From: DeMeo & Carry (2014)

Based on TC to (diameter, mass) calculation. Wish: statistic sample based on real estimates.

SB: different but related domains

- Orbit and spin state
- Composition
- Physical parameter (size, mass, bulk density, macro porosity, etc.)

→ Dynamical (LT) studies, YE,...

→ In situ, spectra (VIS/VNIR) => TC, meteorites

→ Size: multi-domain (e.g. occultations)

→ Mass: dito (e.g. astrometric)

Density of asteroids

- Fundamental property for the understanding of the composition and internal structure.
- Directly: (mean bulk) density = mass / volume.
- Indirectly: Mutual events of binary systems.
- Deduce it from TC associated density.

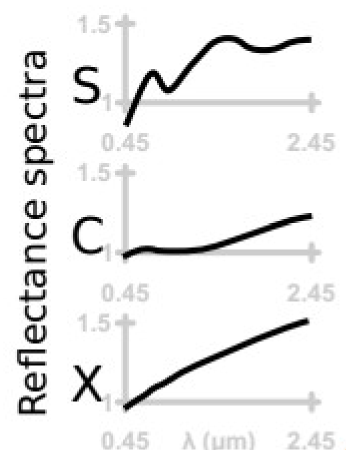
Asteroids – TC – Meteorites - Link

- **Taxonomic Classes** (TC): classicifcation scheme based on VIS and VNIR spectra
  - Chapman, Morrison, Zellner (1975)
  - Tholen (1984): 3 groups (C/S/X), 14 types
  - Bus-DeMeo (2009): 24 classes
  - SMASS,S3OS2,...

Typical values for density:

  - C = 1.38 g/cm^3
  - S = 2.71 g/cm^3
  - M = 5.32 g/cm^3

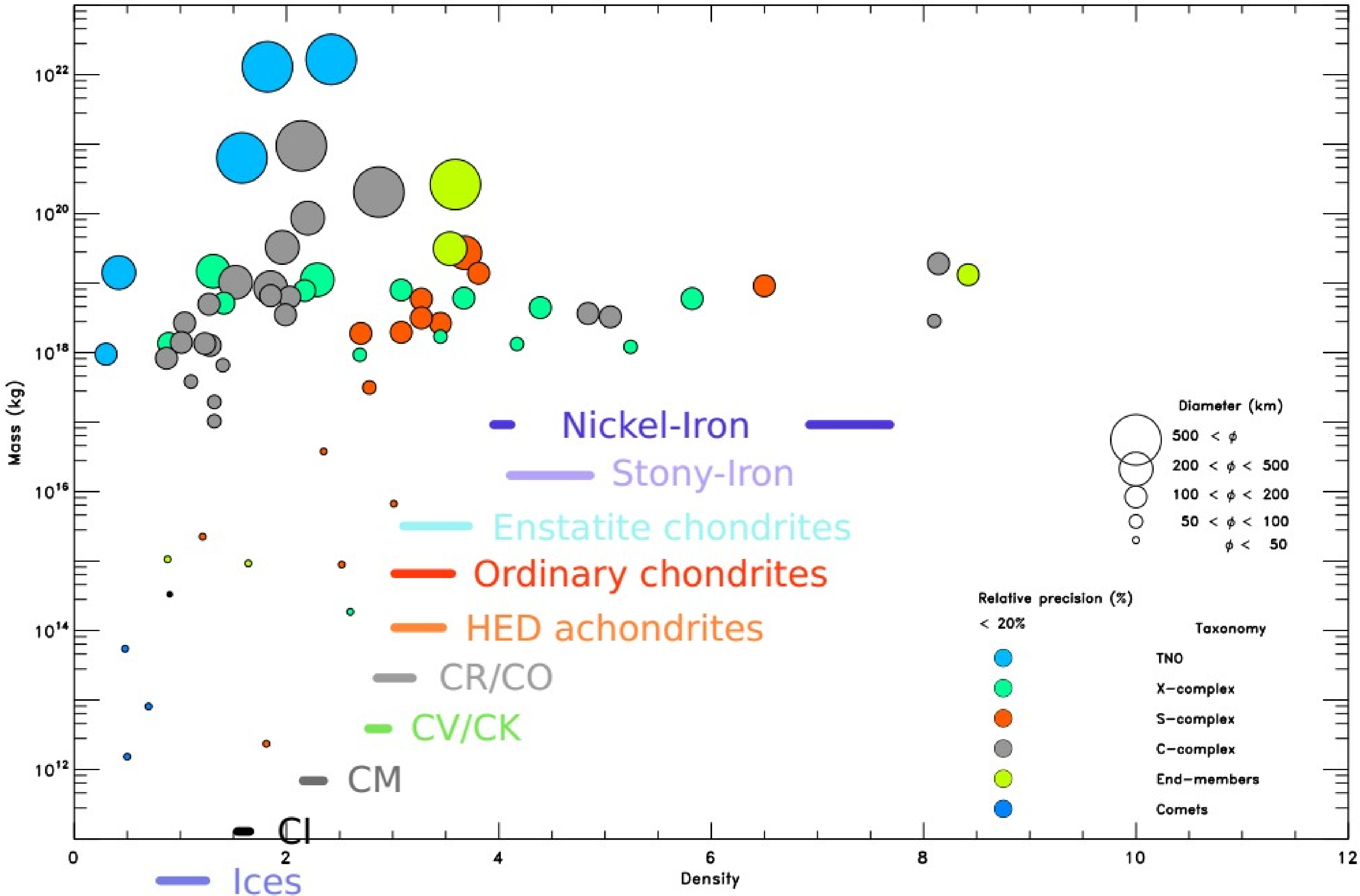
  (Krasinsky et al. 2002)



Meteorites

- Typical densities (g/cm^3):
  - Chondrites : 3.2-3.4
  - Carbonaceous chondrites: 2.1-3.5
  - Stony irons: 4.3 – 4.8
  - Iron: 7-8
  - + lot of sub-types !

Find link between TC and meteorites. Then you can examine this piece of asteroid in the laboratory.



From Carry (2012)

Volume / Size / (mean,eff.,equiv.) Diameter

- Volume (Sphere, MacLaurin, Jacobi) = f(1-3 param.), e.g. V = V(D) = 4/3 π (D/2)^3
- Non-spherical body: define a mean/equivalent/effective diameter D for it, where:
  - a sphere with that diameter has the same volume as the body.
  - a sphere with that diameter has the same surface as the body.
- Density => $D_{equiv(V)}$ is needed.
- Caution: check radiometric diameter if $D_{equiv(V)}$ or $D_{equiv(A)}$ is given.
- I will use the terms diameter, size, volume interchangeable for the same concept.

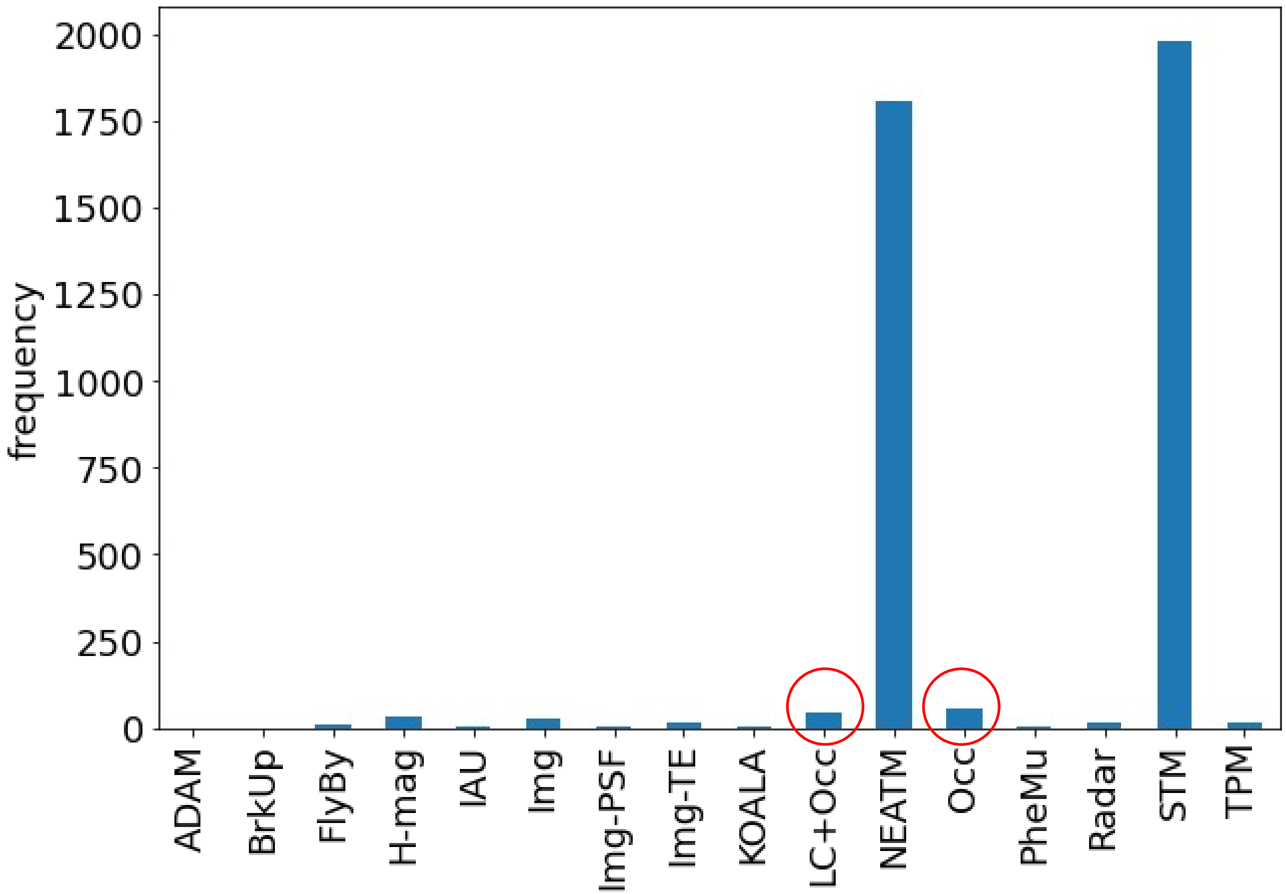
Diameter/Size/Volume estimates

- Crude estimate from H and assumed (TC) geometric albedo p : D (km) = 1329 $p^{-0.5}10^{-0.2H}$
- Radiometric (thermal modeling, e.g. STM and NEATM): IRAS, AKARI, Spitzer, WISE.

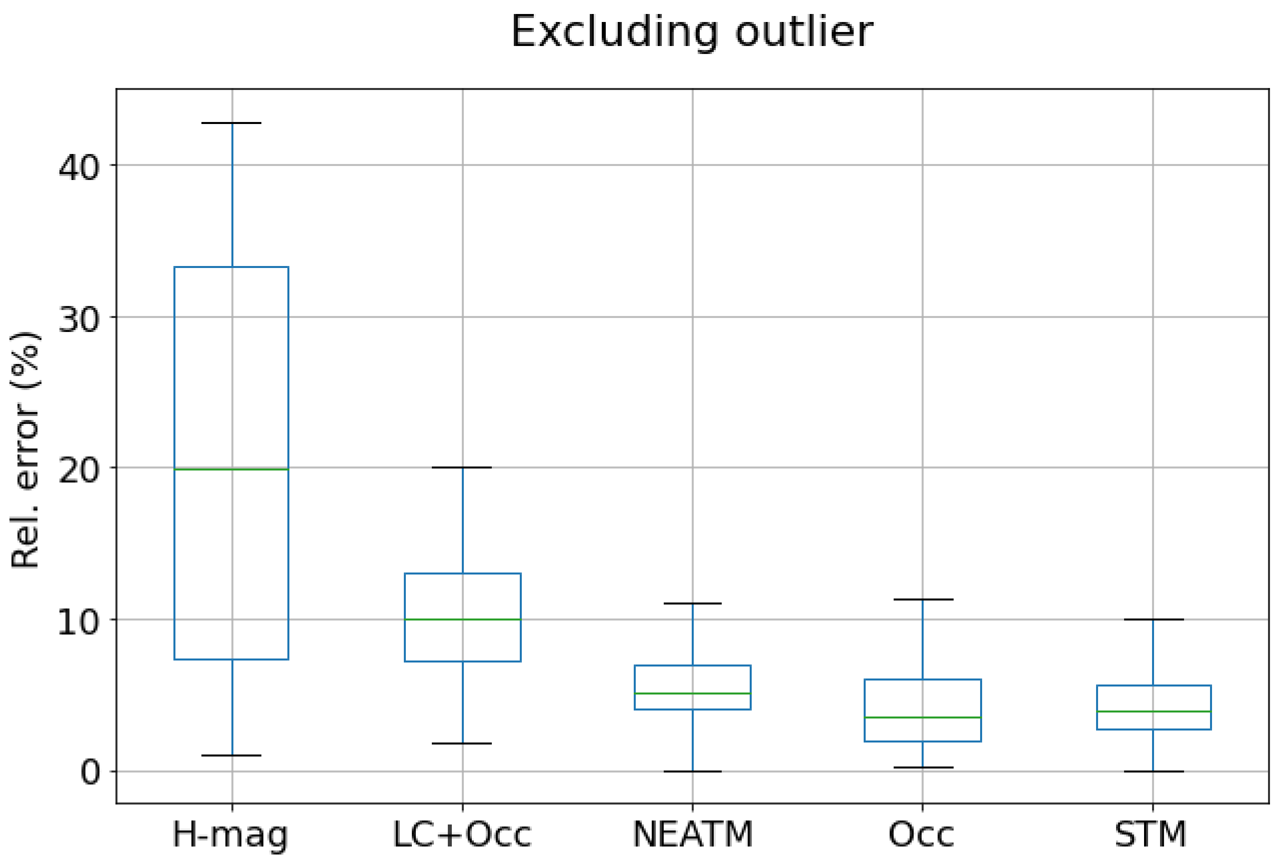
- 2D from occultations.
- 3D model from LC inversion (ADAM, KOALA, SAGE) need to be scaled for physical size => OCC's !

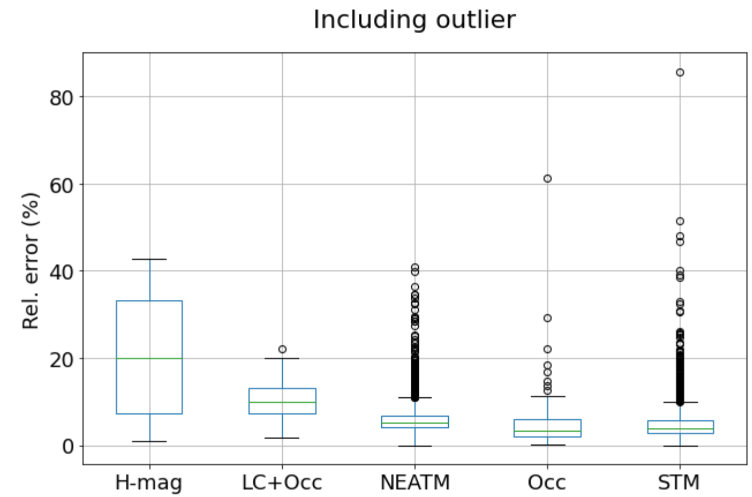
  Multi-data: LC, OCC, direct imaging, radar (NEO).

Diameter estimate methods



Relative error for diameter estimates



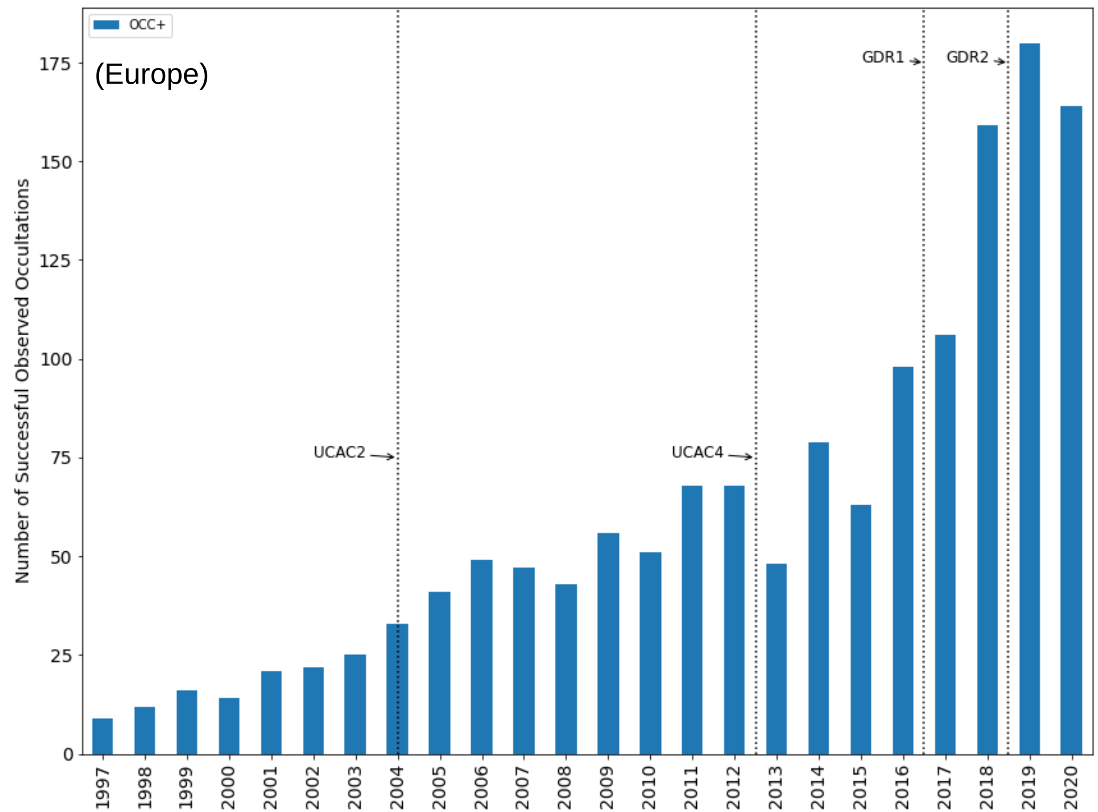


Sample: ~ 4000 estimates

Benefit of asteroidal occultation observations

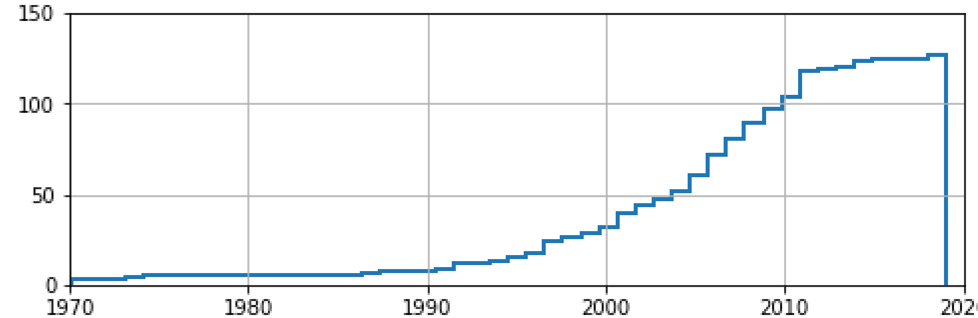
- Size (directly or via multi-data). (sub-)km level !
- 2D-Profile / Shape
- (sub-) mas astrometry
- Binary, moons, rings etc.
- Increasing data set:

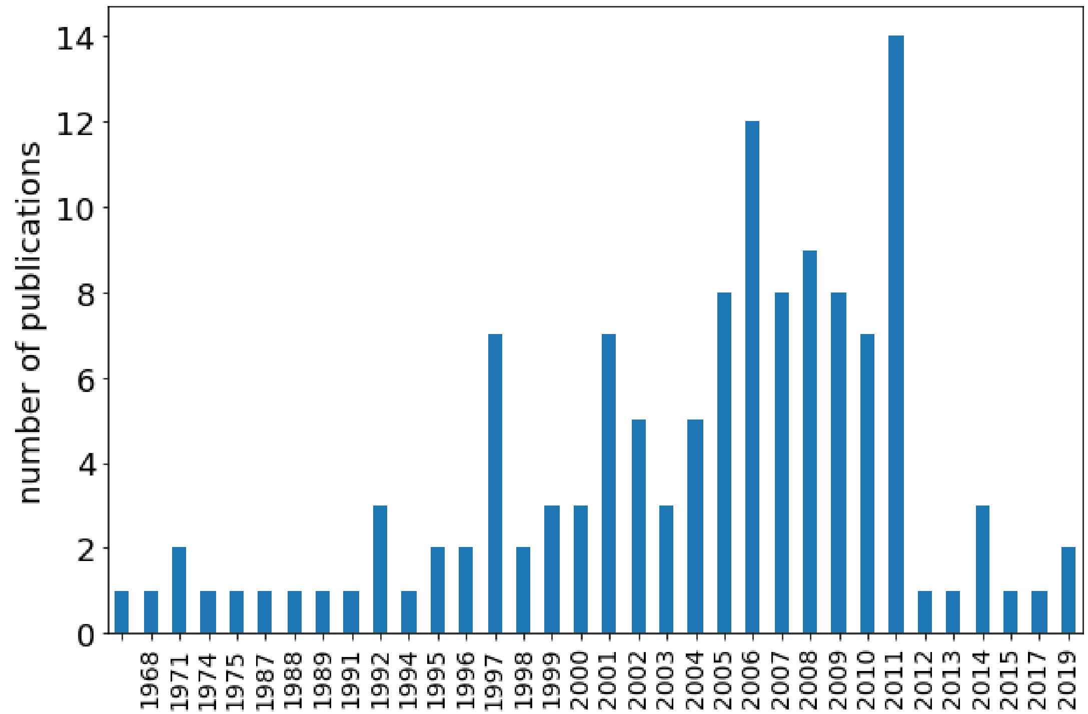
  Number of OCC+ is growing significantly (not only since Gaia, but boosted by Gaia).



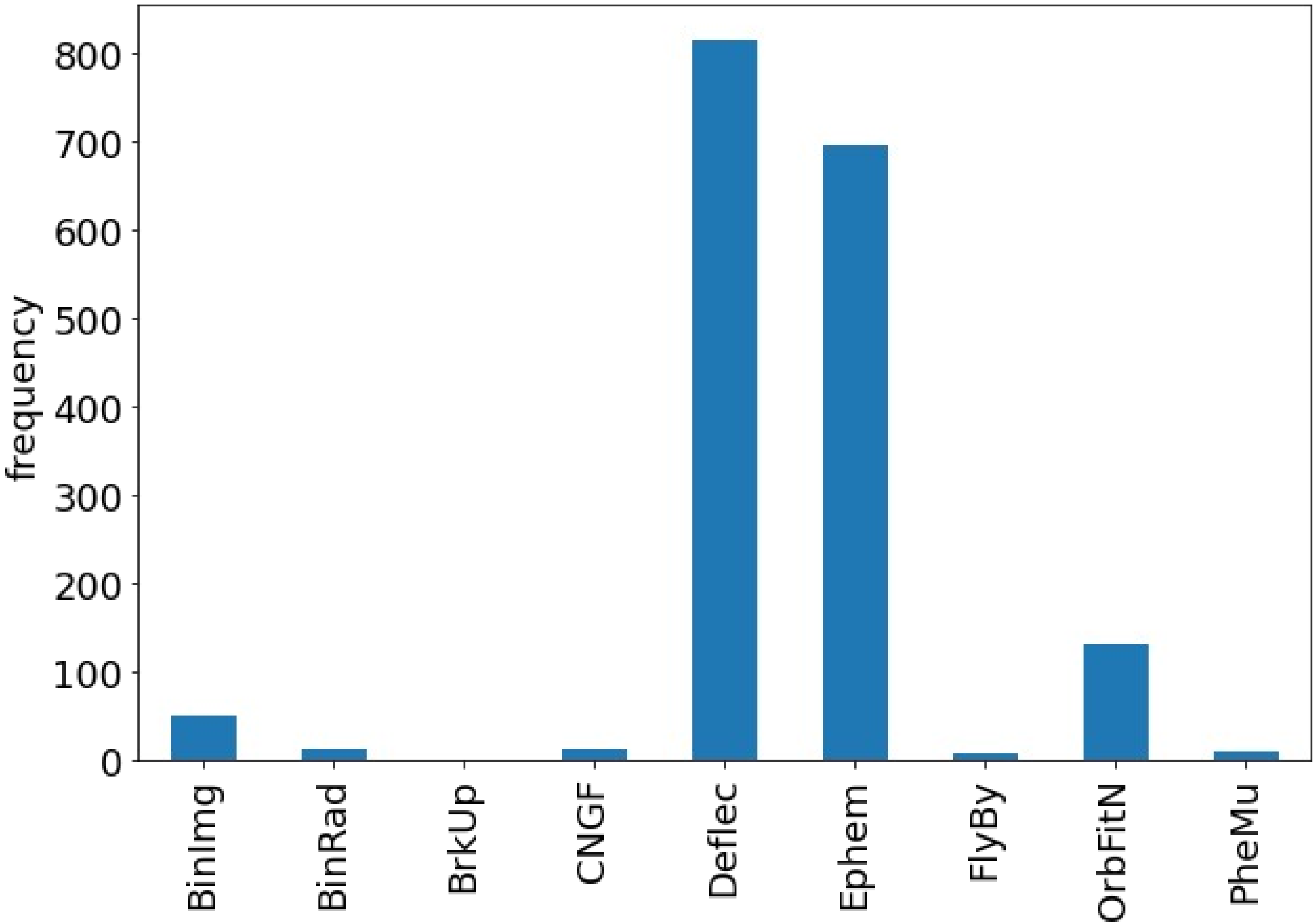
Mass estimates

- Methodically usually harder to derive as size.
- More data needed (more objects, more estimates per object).
- Gaia prospects:
  - ~ 36 < 10%
  - ~ 150 < 50%





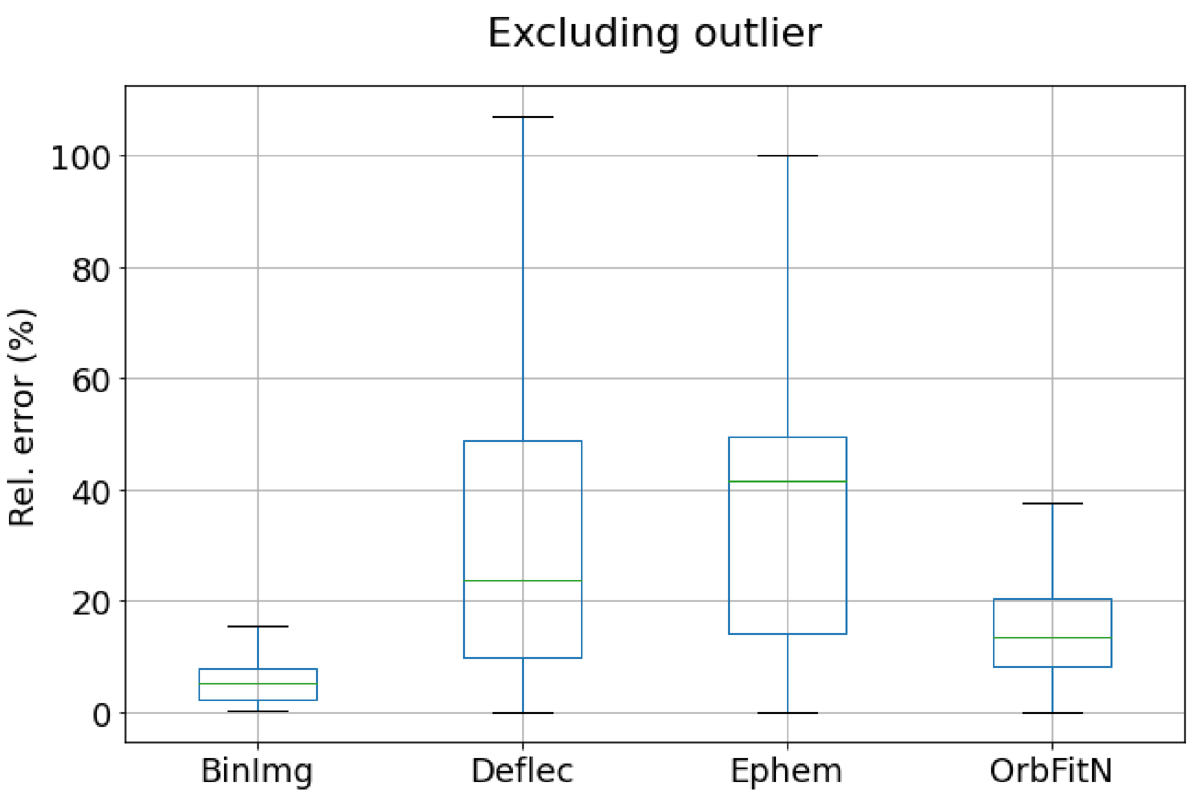
Mass estimates

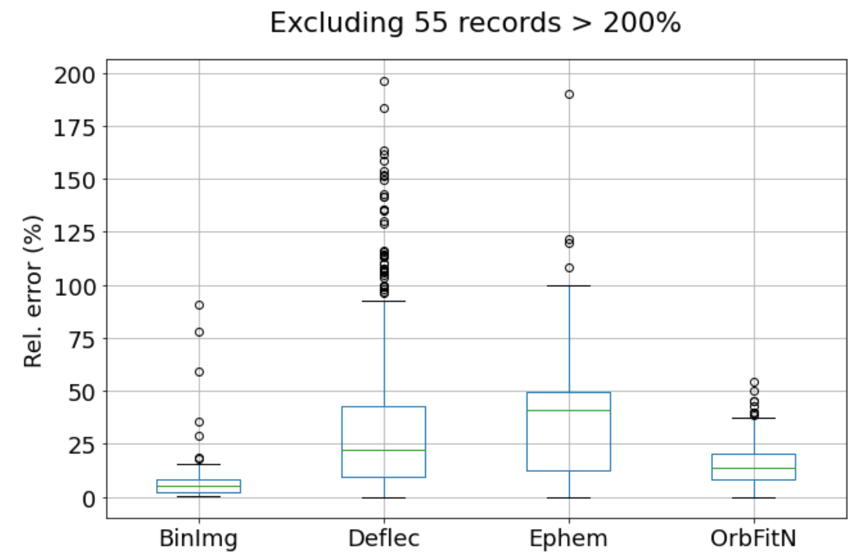


Deflec : Mutual encounter
Ephem: JPL DE, INPOP

astrometric methods

Relative error for mass estimates

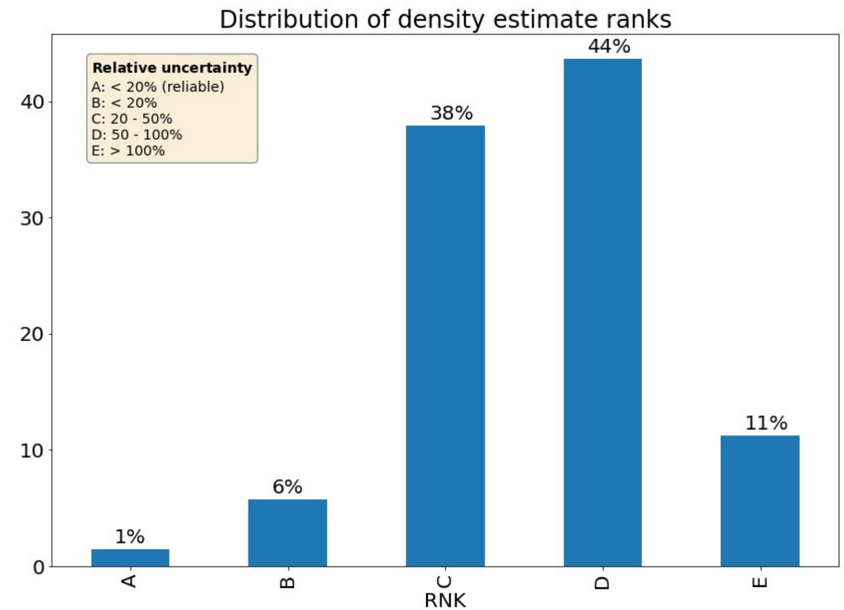




Sample: ~ 1700 estimates

SiMDA catalog of densities

ROW	NUM	DESIGNATION	DYN	B.D.	ERR	RNK	T.T	T.B	L.T	L.B	T.D	DIAM	ERR	MASS	ERR	B.D (C12)	ERR (C12)	TAX (C12)
1		10P/Tempel 2	COM	0.76	0.46	D	-	-	-	-	-	9.6	1.4	3.50e+14	1.50e+14	0.75	0.46	-
2		1999 OJ4	TNO	0.34	0.35	E	-	-	-	-	-	130.0	45.0	3.91e+17	2.20e+16	0.33	0.35	-
3		19P/Borrely	COM	0.05	0.04	D	-	-	-	-	-	4.8	0.4	2.70e+12	2.10e+12	0.12	0.09	-
4		1P/Halley	COM	0.54	0.38	D	-	-	-	-	-	10.4	2.0	3.20e+14	1.20e+14	0.54	0.37	-
5		2000 QL251	TNO	1.76	1.76	E	-	-	-	-	-	150.0	50.0	3.11e+18	5.10e+16	1.75	1.76	-
6		2000 UG11	NEA	0.66	0.67	E	-	-	-	-	-	0.3	0.1	9.35e+09	1.59e+09	0.66	0.67	-
7		2001 QC298	TNO	1.42	0.96	D	-	-	-	-	-	244.0	55.0	1.08e+19	7.00e+17	1.41	0.96	-
8		2001 XR254	TNO	0.67	0.67	E	-	-	-	-	-	225.0	75.0	4.00e+18	1.70e+17	0.67	0.67	-
9		2003 QY90	TNO	0.57	0.72	E	-	-	-	-	-	150.0	50.0	1.01e+18	7.85e+17	0.57	0.72	-
10		2003 TJ58	TNO	1.02	1.02	E	-	-	-	-	-	75.0	25.0	2.25e+17	1.50e+16	1.01	1.02	-
11		2004 PB108	TNO	6.74	7.23	E	-	-	-	-	-	140.0	50.0	9.68e+18	5.70e+17	6.73	7.22	-
12		22P/Kopff	COM	0.22	0.12	D	-	-	-	-	-	3.6	0.4	5.30e+12	2.20e+12	0.21	0.11	-
13		2P/Encke	COM	1.71	1.39	D	-	-	-	-	-	4.7	0.8	9.20e+13	5.80e+13	1.67	1.36	-
14		45P/H-M-P	COM	1.26	2.59	E	-	-	-	-	-	0.7	0.2	1.90e+11	3.50e+11	1.26	2.59	-
15		46P/Wirtanen	COM	0.41	0.30	D	-	-	-	-	-	1.1	0.1	3.30e+11	2.30e+11	0.4	0.28	-
16		67P/C-G	COM	1.10	0.45	C	-	-	-	-	-	3.0	0.1	1.50e+13	6.00e+12	0.43	0.37	-
17		6P/dArrest	COM	1.09	0.49	C	-	-	-	-	-	1.7	0.2	2.80e+12	8.00e+11	1.08	0.49	-
18		81P/Wild 2	COM	1.72	0.23	B	-	-	-	-	-	2.1	0.1	8.10e+12	8.10e+11	0.7	0.1	-
19		9P/Tempel 1	COM	0.45	0.23	C	-	-	-	-	-	5.6	0.5	4.21e+13	1.81e+13	0.48	0.06	-
20		SL9	COM	0.51	0.16	C	-	-	-	-	-	1.8	0.2	1.53e+12	1.53e+11	0.5	0.05	-
21	1	Ceres	MBA	2.14	0.15	A	G	C	C	C	C	944.3	21.6	9.43e+20	6.16e+18	2.13	0.15	C
22	2	Pallas	MBA	2.97	0.45	A	B	B	-	-	B	516.2	17.1	2.14e+20	2.42e+19	2.86	0.32	B
23	3	Juno	MBA	3.29	0.59	A	S	Sk	S	Sk	Sq	250.0	8.2	2.69e+19	4.03e+18	3.68	0.62	Sq
24	4	Vesta	MBA	3.56	0.14	A	V	V	-	-	V	519.3	5.9	2.61e+20	5.55e+18	3.58	0.15	V
25	5	Astraea	MBA	4.27	2.20	D	S	S	-	-	S	114.9	9.7	3.40e+18	1.52e+18	3.45	0.66	S
26	6	Hebe	MBA	3.88	0.86	C	S	S	-	-	-	188.4	8.5	1.36e+19	2.36e+18	3.81	0.5	S
27	7	Iris	MBA	3.19	0.91	C	S	S	-	-	S	203.8	12.4	1.41e+19	3.08e+18	2.14	0.81	S
28	8	Flora	MBA	5.41	1.25	C	S	-	-	-	Sw	138.3	5.6	7.50e+18	1.47e+18	6.5	1.28	S
29	9	Metis	MBA	3.87	1.17	C	S	-	T	T	-	161.1	12.2	8.47e+18	1.71e+18	3.6	0.87	S
30	10	Hygiea	MBA	2.21	0.55	C	C	C	-	-	C	423.2	29.9	8.77e+19	1.14e+19	2.19	0.42	C
31	11	Parthenope	MBA	3.12	0.74	C	S	Sk	-	-	Sq	147.9	9.7	5.28e+18	6.96e+17	3.27	0.41	Sq
32	12	Victoria	MBA	2.14	1.25	D	S	L	D	D	-	128.2	5.6	2.36e+18	1.34e+18	2.45	0.67	L
33	13	Egeria	MBA	1.48	0.70	C	G	Ch	-	-	Ch	222.8	6.9	8.55e+18	3.98e+18	1.7	0.86	Ch
34	14	Irene	MBA	3.00	0.80	C	S	S	-	-	S	147.5	5.2	5.04e+18	1.24e+18	1.72	1.12	S
35	15	Eunomia	MBA	3.59	0.60	A	S	S	-	-	K	255.0	13.1	3.12e+19	2.02e+18	3.54	0.2	K
36	16	Psyche	MBA	3.00	0.73	C	M	X	-	-	Xk	243.5	18.6	2.27e+19	1.87e+18	3.38	1.16	Xk



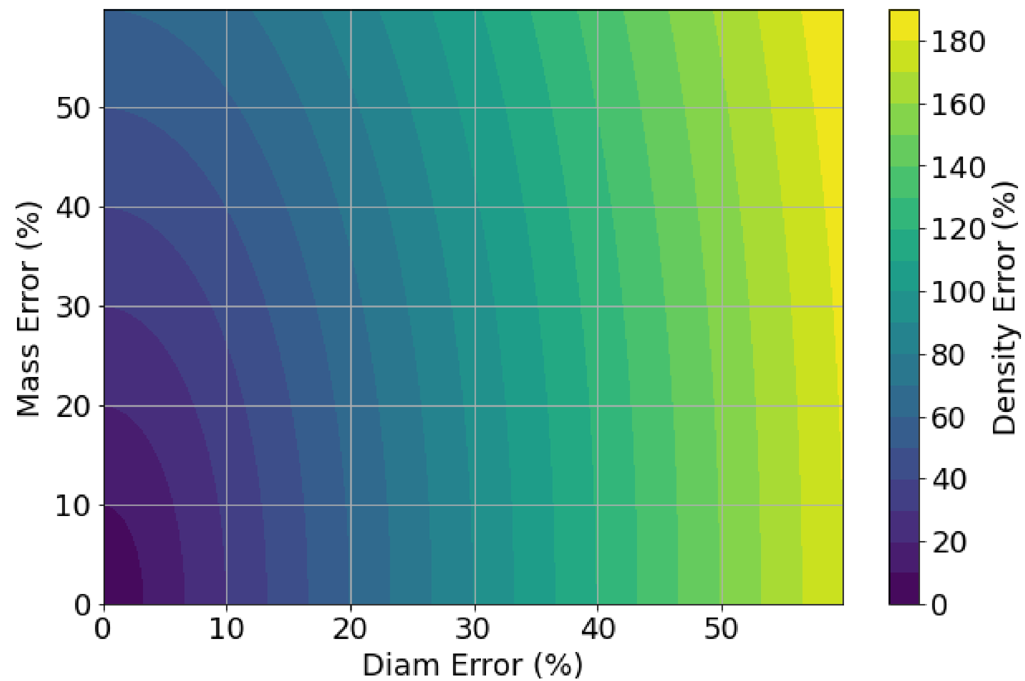
SiMDA ‘plain’: no individual D,M selection for a ‘best value’ estimate (TBD and/or by user), just outlier rejection. EVM tend to larger standard errors.

But: only ~ 300 estimates

Uncertainty of derived density

- The contribution of diameter uncertainty easily overwhelms that of the mass :

  $\Delta\rho/\rho = \mathrm{sqrt}((\Delta M/M)^2 + 9(\Delta D/D)^2)$



Main conclusion

- We need more and more accurate and reliable densities !
- => Volumes (diameters)
  - Occultations
  - Light Curves
- => Mass estimates

- Formal (post fit) errors can be underestimated (wrt to mass and diameter).
- Diameter / mass / density data probably biased by used methods and also by observational constraints.

Research: where are the (individual) data !?

- No machine-readable compilation of individual mass estimates including errors.
- Diameter: different (often machine-ready) data sets available, but many individual results only in literature. Need to be evaluated, joined in data set including error estimates, etc.
- No machine-readable compilation of all densities including the individual diameter and mass estimates and their errors.
- Hard to get a (quick and easy) overview / common picture about all diameter, mass and density including error estimates publications for an object.

Existing work on densities

- Asteroid I-IV.
- Some individual research and compilations on asteroid masses.
- Several data set on diameters.
- Latest compilation: paper by Carry 2012.

(Incomplete list)

SiMDA – Data Archive and Web Portal

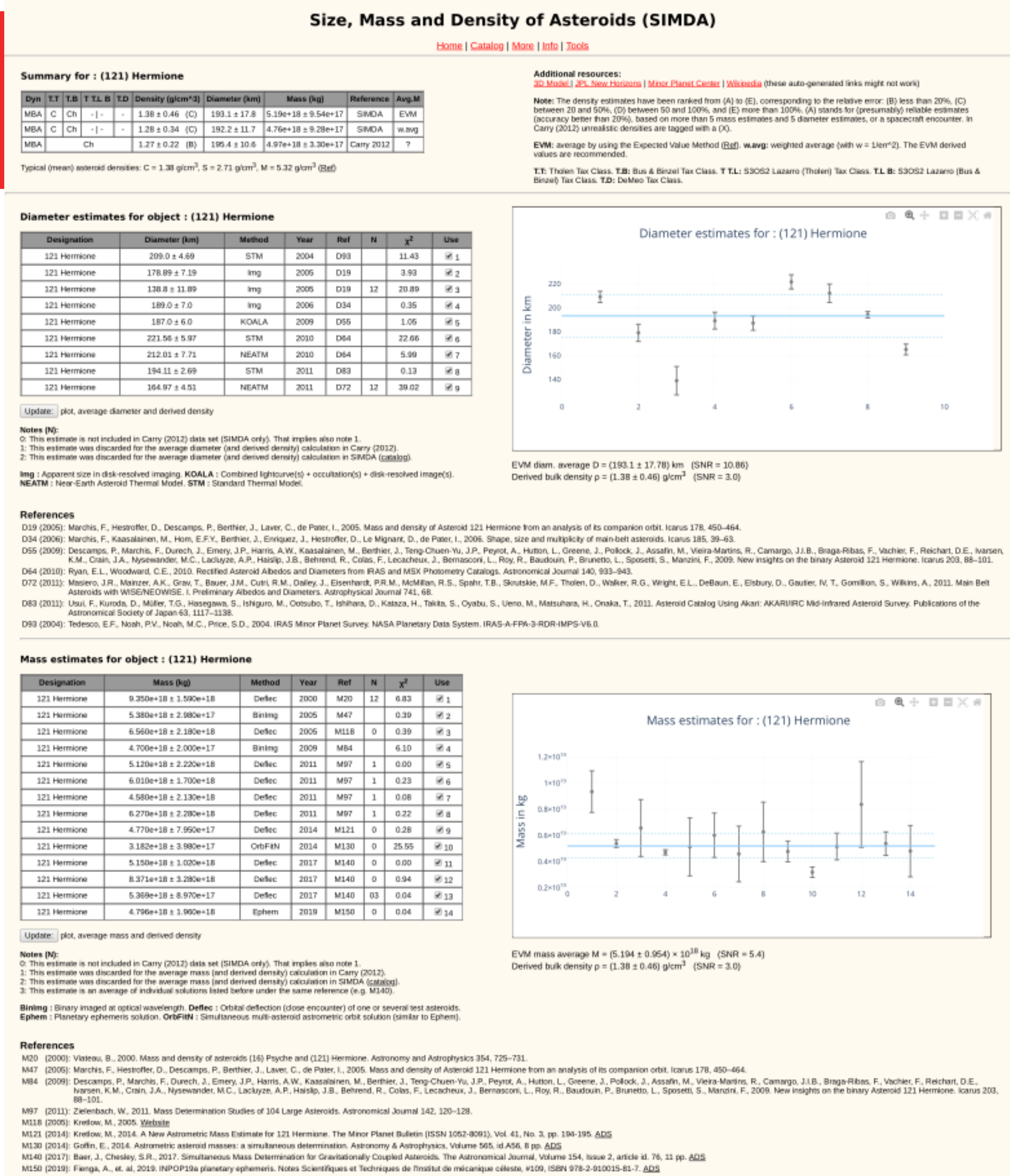
At present

- Initial motivation: own mass determination of asteroids
  => get an overview about status quo.
- Data: Manual, scripted (parser) and OCR based acquisition of ~4000 diameters, ~1750 mass estimates, ~2600 tax and dyn. classes, ~230 references.
- Application: Django (Python) web application.
- Note: SiMDA is still in early state.

Roadmap

- Reach v1.0 until EPSC 2020 ... ;-)
- More data (still incomplete).
- Dynamical (sub)classes.
- Catalog: improve ‘Best value’ .
- --
- Additional online (on the fly) analysis features.
- Other data exchange formats (VO tables etc.).
- User suggestions ...

SiMDA – Size, Mass and Density of Asteroids (but also TNOs, Comets, ...)



Size, Mass and Density of Asteroids (SIMDA)

Home | Catalog | More | Info | Tools

Summary for : (121) Hermione

Dyn	T.T	T.B	T T.L B	T.D	Density (g/cm^3)	Diameter (km)	Mass (kg)	Reference	Avg.M
MBA	C	Ch	- | -	-	1.38 ± 0.46 (C)	193.1 ± 17.8	5.19e+18 ± 9.54e+17	SIMDA	EVM
MBA	C	Ch	- | -	-	1.28 ± 0.34 (C)	192.2 ± 11.7	4.76e+18 ± 9.28e+17	SIMDA	w.avg
MBA	Ch				1.27 ± 0.22 (B)	195.4 ± 10.6	4.97e+18 ± 3.30e+17	Carry 2012	?

Typical (mean) asteroid densities: C = 1.38 g/cm^3, S = 2.71 g/cm^3, M = 5.32 g/cm^3 (Ref)

Additional resources: 3D Model | JPL New Horizons | Minor Planet Center | Wikipedia (these auto-generated links might not work)

Note: The density estimates have been ranked from (A) to (E), corresponding to the relative error: (B) less than 20%, (C) between 20 and 50%, (D) between 50 and 100%, and (E) more than 100%. (A) stands for (presumably) reliable estimates (accuracy better than 20%), based on more than 5 mass estimates and 5 diameter estimates, or a spacecraft encounter. In Carry (2012) unrealistic densities are tagged with a (X).

EVM: average by using the Expected Value Method (Ref), **w.avg:** weighted average (with w = 1/err^2). The EVM derived values are recommended.

T.T: Tholen Tax Class. **T.B:** Bus & Binzel Tax Class. **T T.L:** S3OS2 Lazarro (Tholen) Tax Class. **T.L B:** S3OS2 Lazarro (Bus & Binzel) Tax Class. **T.D:** DeMeo Tax Class.

Diameter estimates for object : (121) Hermione

Designation	Diameter (km)	Method	Year	Ref	N	χ^2	Use
121 Hermione	209.0 ± 4.69	STM	2004	D93		11.43	☑ 1
121 Hermione	178.89 ± 7.19	Img	2005	D19		3.93	☑ 2
121 Hermione	138.8 ± 11.89	Img	2005	D19	12	20.89	☑ 3
121 Hermione	189.0 ± 7.0	Img	2006	D34		0.35	☑ 4
121 Hermione	187.0 ± 6.0	KOALA	2009	D55		1.05	☑ 5
121 Hermione	221.56 ± 5.97	STM	2010	D64		22.66	☑ 6
121 Hermione	212.01 ± 7.71	NEATM	2010	D64		5.99	☑ 7
121 Hermione	194.11 ± 2.69	STM	2011	D83		0.13	☑ 8
121 Hermione	164.97 ± 4.51	NEATM	2011	D72	12	39.02	☑ 9

Update: plot, average diameter and derived density

Notes (N):
0: This estimate is not included in Carry (2012) data set (SIMDA only). That implies also note 1.
1: This estimate was discarded for the average diameter (and derived density) calculation in Carry (2012).
2: This estimate was discarded for the average diameter (and derived density) calculation in SIMDA (catalog).

Img : Apparent size in disk-resolved imaging. **KOALA** : Combined lightcurve(s) + occultation(s) + disk-resolved image(s). **NEATM** : Near-Earth Asteroid Thermal Model. **STM** : Standard Thermal Model.

EVM diam. average D = (193.1 ± 17.78) km (SNR = 10.86)
Derived bulk density ρ = (1.38 ± 0.46) g/cm^3 (SNR = 3.0)

References

D19 (2005): Marchis, F., Hestroffer, D., Descamps, P., Berthier, J., Laver, C., de Pater, I., 2005. Mass and density of Asteroid 121 Hermione from an analysis of its companion orbit. Icarus 178, 450–464.
D34 (2006): Marchis, F., Kaasalainen, M., Hom, E.F.Y., Berthier, J., Enriquez, J., Hestroffer, D., Le Mignant, D., de Pater, I., 2006. Shape, size and multiplicity of main-belt asteroids. Icarus 185, 39–63.
D55 (2009): Descamps, P., Marchis, F., Durech, J., Emery, J.P., Harris, A.W., Kaasalainen, M., Berthier, J., Teng-Chuen-Yu, J.P., Peyrot, A., Hutton, L., Greene, J., Pollock, J., Assafin, M., Vieira-Martins, R., Camargo, J.I.B., Braga-Ribas, F., Vachier, F., Reichart, D.E., Ivarsen, K.M., Crain, J.A., Nysewander, M.C., Lacluyze, A.P., Haislip, J.B., Behrend, R., Colas, F., Lecacheux, J., Bernasconi, L., Roy, R., Baudouin, P., Brunetto, L., Sposetti, S., Manzini, F., 2009. New insights on the binary Asteroid 121 Hermione. Icarus 203, 88–101.
D64 (2010): Ryan, E.L., Woodward, C.E., 2010. Rectified Asteroid Albedos and Diameters from IRAS and MSX Photometry Catalogs. Astronomical Journal 140, 933–943.
D72 (2011): Masiero, J.R., Mainzer, A.K., Grav, T., Bauer, J.M., Cutri, R.M., Dailey, J., Eisenhardt, P.R.M., McMillan, R.S., Spahr, T.B., Skrutskie, M.F., Tholen, D., Walker, R.G., Wright, E.L., DeBaun, E., Elsbury, D., Gautier, IV, T., Gomillion, S., Wilkins, A., 2011. Main Belt Asteroids with WISE/NEOWISE. I. Preliminary Albedos and Diameters. Astrophysical Journal 741, 68.
D83 (2011): Usui, F., Kuroda, D., Müller, T.G., Hasegawa, S., Ishiguro, M., Ootsubo, T., Ishihara, D., Kataza, H., Takita, S., Oyabu, S., Ueno, M., Matsuhara, H., Onaka, T., 2011. Asteroid Catalog Using Akari: AKARI/IRC Mid-Infrared Asteroid Survey. Publications of the Astronomical Society of Japan 63, 1117–1138.
D93 (2004): Tedesco, E.F., Noah, P.V., Noah, M.C., Price, S.D., 2004. IRAS Minor Planet Survey. NASA Planetary Data System. IRAS-A-FPA-3-RDR-IMPS-V6.0.

Mass estimates for object : (121) Hermione

Designation	Mass (kg)	Method	Year	Ref	N	χ^2	Use
121 Hermione	9.350e+18 ± 1.590e+18	Deflec	2000	M20	12	6.83	☑ 1
121 Hermione	5.380e+18 ± 2.980e+17	BinImg	2005	M47		0.39	☑ 2
121 Hermione	6.560e+18 ± 2.180e+18	Deflec	2005	M118	0	0.39	☑ 3
121 Hermione	4.700e+18 ± 2.000e+17	BinImg	2009	M84		6.10	☑ 4
121 Hermione	5.120e+18 ± 2.220e+18	Deflec	2011	M97	1	0.00	☑ 5
121 Hermione	6.010e+18 ± 1.700e+18	Deflec	2011	M97	1	0.23	☑ 6
121 Hermione	4.580e+18 ± 2.130e+18	Deflec	2011	M97	1	0.08	☑ 7
121 Hermione	6.270e+18 ± 2.280e+18	Deflec	2011	M97	1	0.22	☑ 8
121 Hermione	4.770e+18 ± 7.950e+17	Deflec	2014	M121	0	0.28	☑ 9
121 Hermione	3.182e+18 ± 3.980e+17	OrbFitN	2014	M130	0	25.55	☑ 10
121 Hermione	5.150e+18 ± 1.020e+18	Deflec	2017	M140	0	0.00	☑ 11
121 Hermione	8.371e+18 ± 3.280e+18	Deflec	2017	M140	0	0.94	☑ 12
121 Hermione	5.369e+18 ± 8.970e+17	Deflec	2017	M140	03	0.04	☑ 13
121 Hermione	4.796e+18 ± 1.960e+18	Ephem	2019	M150	0	0.04	☑ 14

Update: plot, average mass and derived density

Notes (N):
0: This estimate is not included in Carry (2012) data set (SIMDA only). That implies also note 1.
1: This estimate was discarded for the average mass (and derived density) calculation in Carry (2012).
2: This estimate was discarded for the average mass (and derived density) calculation in SIMDA (catalog).
3: This estimate is an average of individual solutions listed before under the same reference (e.g. M140).

BinImg : Binary imaged at optical wavelength. **Deflec** : Orbital deflection (close encounter) of one or several test asteroids. **Ephem** : Planetary ephemeris solution. **OrbFitN** : Simultaneous multi-asteroid astrometric orbit solution (similar to Ephem).

EVM mass average M = (5.194 ± 0.954) × 10^{18} kg (SNR = 5.4)
Derived bulk density ρ = (1.38 ± 0.46) g/cm^3 (SNR = 3.0)

References

M20 (2000): Viateau, B., 2000. Mass and density of asteroids (16) Psyche and (121) Hermione. Astronomy and Astrophysics 354, 725–731.
M47 (2005): Marchis, F., Hestroffer, D., Descamps, P., Berthier, J., Laver, C., de Pater, I., 2005. Mass and density of Asteroid 121 Hermione from an analysis of its companion orbit. Icarus 178, 450–464.
M84 (2009): Descamps, P., Marchis, F., Durech, J., Emery, J.P., Harris, A.W., Kaasalainen, M., Berthier, J., Teng-Chuen-Yu, J.P., Peyrot, A., Hutton, L., Greene, J., Pollock, J., Assafin, M., Vieira-Martins, R., Camargo, J.I.B., Braga-Ribas, F., Vachier, F., Reichart, D.E., Ivarsen, K.M., Crain, J.A., Nysewander, M.C., Lacluyze, A.P., Haislip, J.B., Behrend, R., Colas, F., Lecacheux, J., Bernasconi, L., Roy, R., Baudouin, P., Brunetto, L., Sposetti, S., Manzini, F., 2009. New insights on the binary Asteroid 121 Hermione. Icarus 203, 88–101.
M97 (2011): Zielenbach, W., 2011. Mass Determination Studies of 104 Large Asteroids. Astronomical Journal 142, 120–128.
M118 (2005): Kretlow, M., 2005. Website
M121 (2014): Kretlow, M., 2014. A New Astrometric Mass Estimate for 121 Hermione. The Minor Planet Bulletin (ISSN 1052-8091). Vol. 41, No. 3, pp. 194-195. ADS
M130 (2014): Goffin, E., 2014. Astrometric asteroid masses: a simultaneous determination. Astronomy & Astrophysics, Volume 565, id.A56, 8 pp. ADS
M140 (2017): Baer, J., Chesley, S.R., 2017. Simultaneous Mass Determination for Gravitationally Coupled Asteroids. The Astronomical Journal, Volume 154, Issue 2, article id. 76, 11 pp. ADS
M150 (2019): Fienga, A., et. al, 2019. INPOP19a planetary ephemeris. Notes Scientifiques et Techniques de l'Institut de mécanique céleste, #109, ISBN 978-2-910015-81-7. ADS

Short live preview / presentation ...

Summary / Takeaway

- Number of diameter, mass and density estimates has grown about one order of magnitude since *Asteroids III.*
- Still just a tiny fraction (and biased?).
- Mass estimates were crucial in the past in terms of quantity but also quality (u.e. errors). Can / will improve due to:
  - better astrometry (talk by J. Fereirra)
  - better errors models
  - more data (surveys)
  - Gaia observations of asteroids
- As consequence the diameter estimates will become (more) crucial for the density accuracy in many cases.
- Radiometric method may have significant (systematic) errors.
- LC+OCCs reliable independent method, significant (continuous) amateur contribution is possible (photometry and occultations).
- Dedicated data archives and analysis tools like SiMDA help to reveal issues and to find ‘best values’.

Thank you for ...

- your work on asteroidal occultations. Accurate and reliable diameter values are very important for SB science!
- your work on asteroidal (rotation) light curves.
- your astrometry (+ sparse photometry).
- using SiMDA and helping to improve it.
- **your attention !**