Main Belt collisional evolution
and family formation

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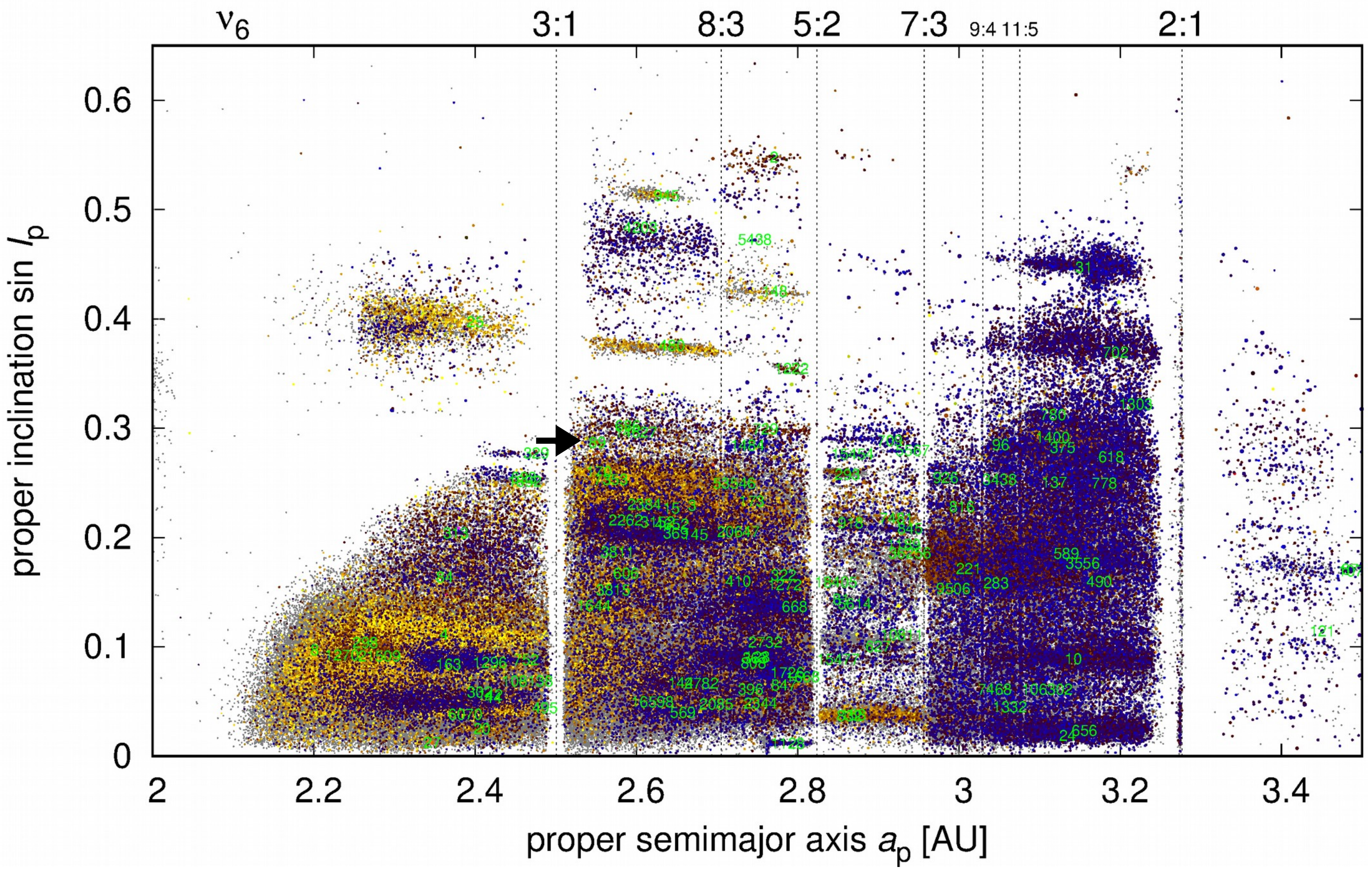
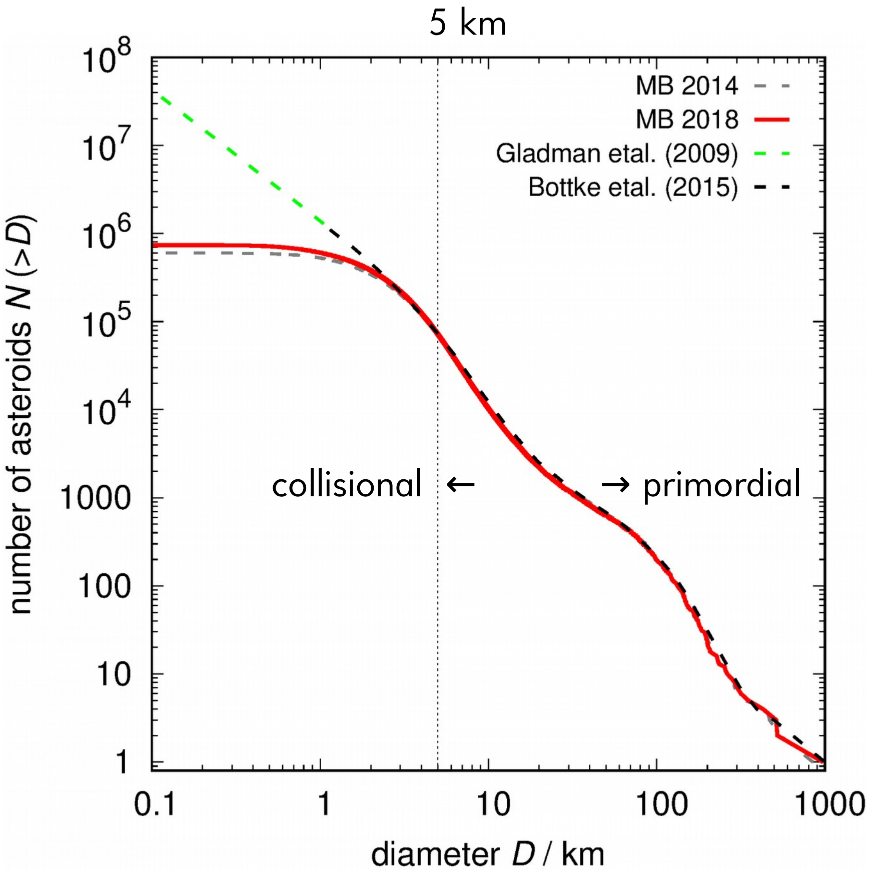
Family statistics

- **140** collisional families (Nesvorny etal. 2015, Vinogradova 2019, ...)
- old? (Bolin etal. 2017, Delbo etal. 2019)
- 20 LR/PB < 0.5, $D > 100$km
- synthetic proper elements (Knezevic & Milani 2003)
- WISE + Akari albedos (Nugent etal. 2015, Usui etal. 2011)
- SDSS colours (Ivezic etal. 2002)



Observed SFD (completeness)

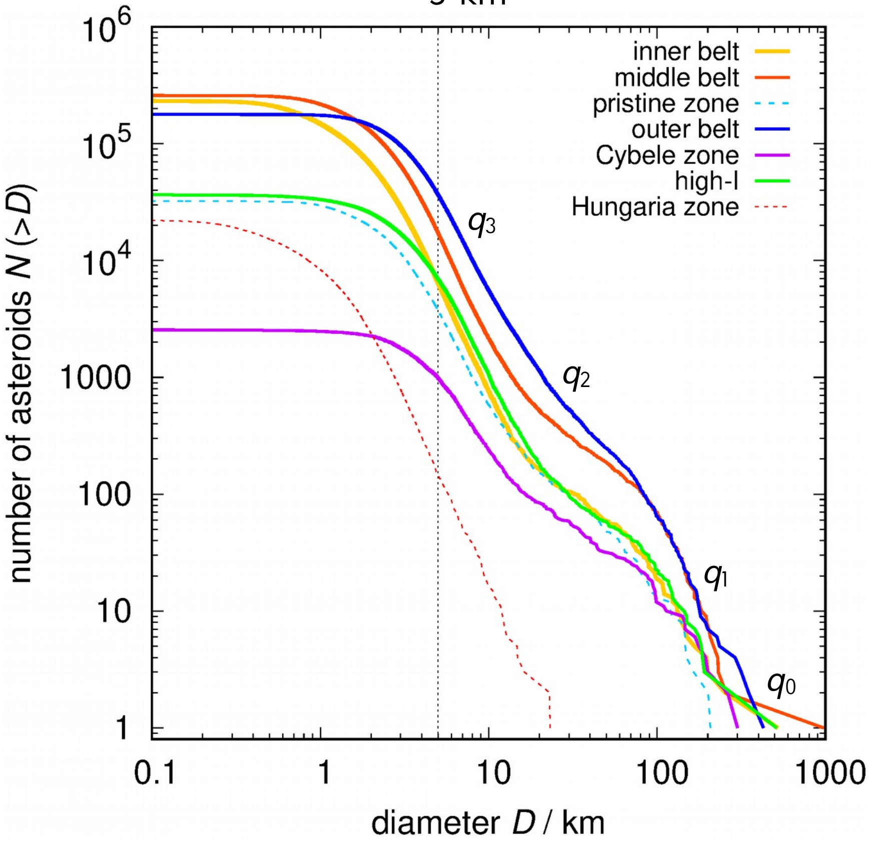
- minor revisions (cf. Cibulkova etal. 2014)
- completeness already at $D < 5$ km, but randomly assigned p_V
- debiased SFD (Bottke etal. 2005, 2015)
- $D < 2$ km shallower than collisional equilibrium, $q = -2.5$ (Dohnanyi 1969)



Observed SFDs (for 7 parts)

`knee'

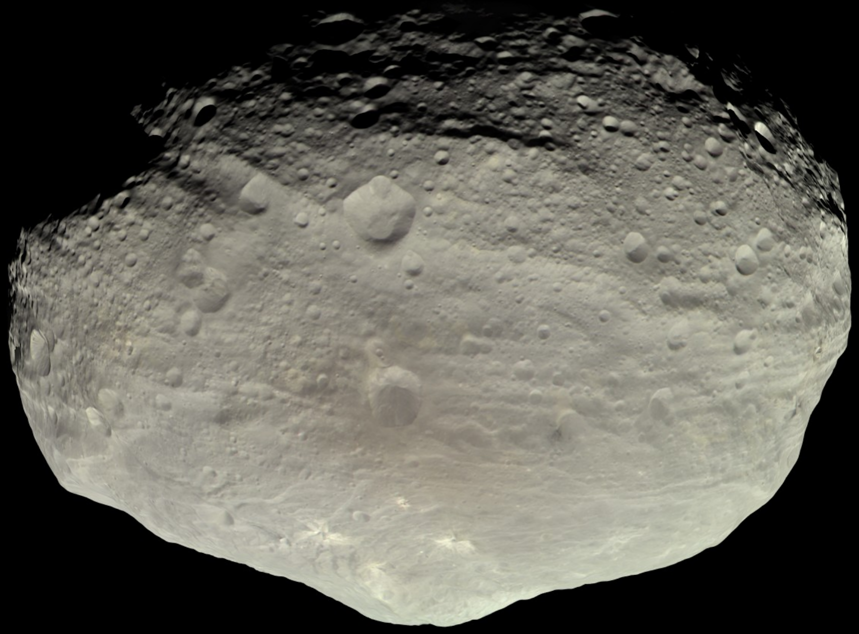
- characteristic slopes q_0, q_1, q_2, q_3
- different q_1, q_2 (middle–outer), i.e. IC or rheology?
- different P_i, v_{imp} → `environments'
- N in agreement with # of families; catastrophic disruptions D_{PB} > 100 km



Observed craterings (*in situ*)

- Gaspra, Ida (Chapman etal. 1996),
  Mathilde (Chapman etal. 1999),
  Eros (Chapman etal. 2002),
  Lutetia (Marchi etal. 2012),
  Vesta (Marchi etal. 2012),
  Ceres (Marchi etal. 2016), ...

- Itokawa (Hirata etal. 2009), Bennu, Ryugu, ...



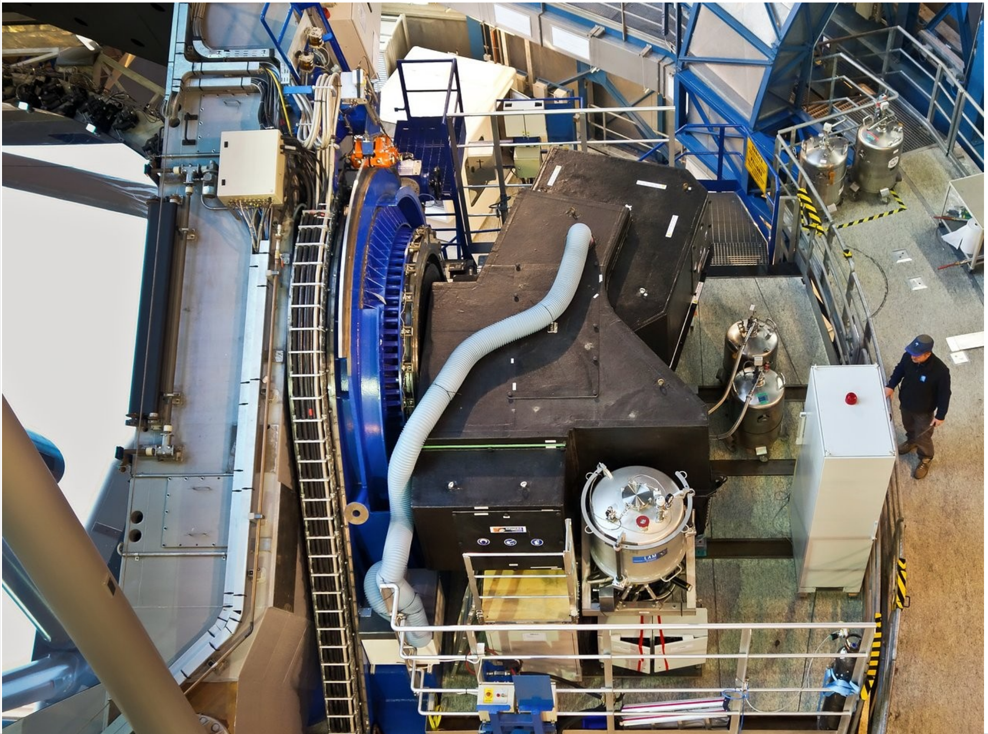
Images: NASA / JPL / MPS / DLR / IDA
Dawn 2011-07-24 08:35 to 2011-07-24 09:36
Image processing: Björn Jónsson

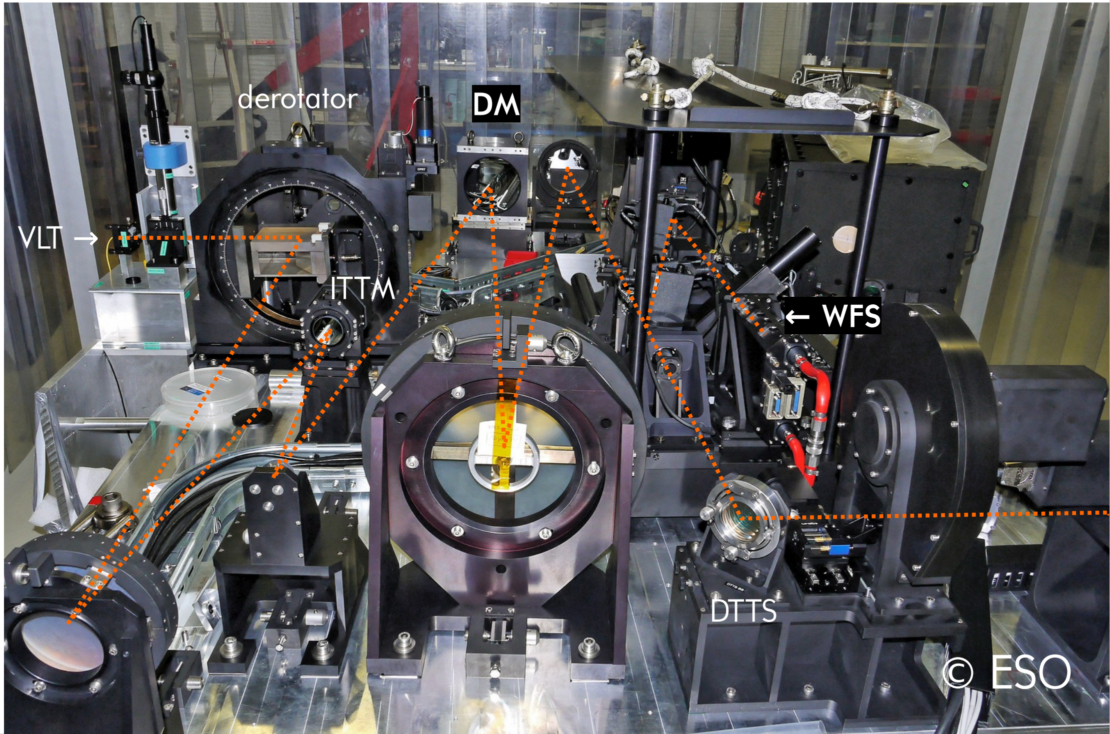
Q: Adaptive-optics imaging?

Extreme Adaptive Optics

f = 1.2 kHz, 40×40 lens & actuators ↑

- **VLT/SPHERE/ZIMPOL** instrument (Schmid etal. 2018), 8m-diffraction-limited imaging, designed for exoplanets (M_J), but also suitable for $D \geq 100$ km asteroids...



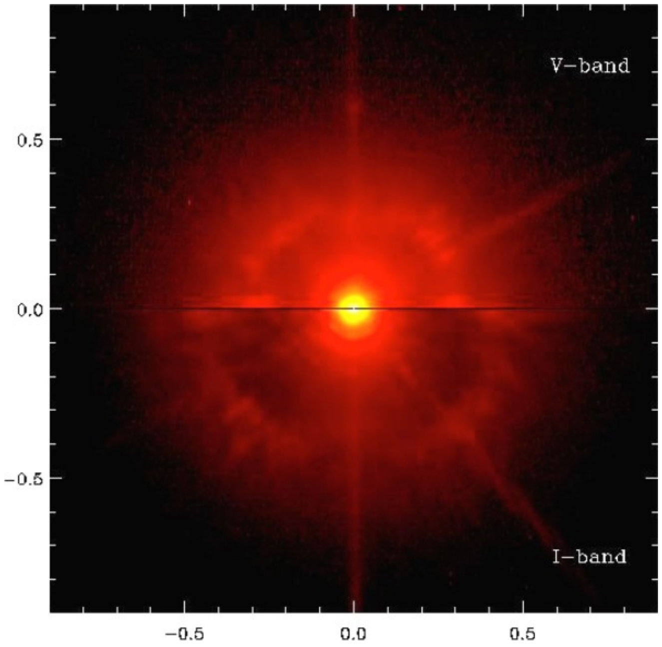


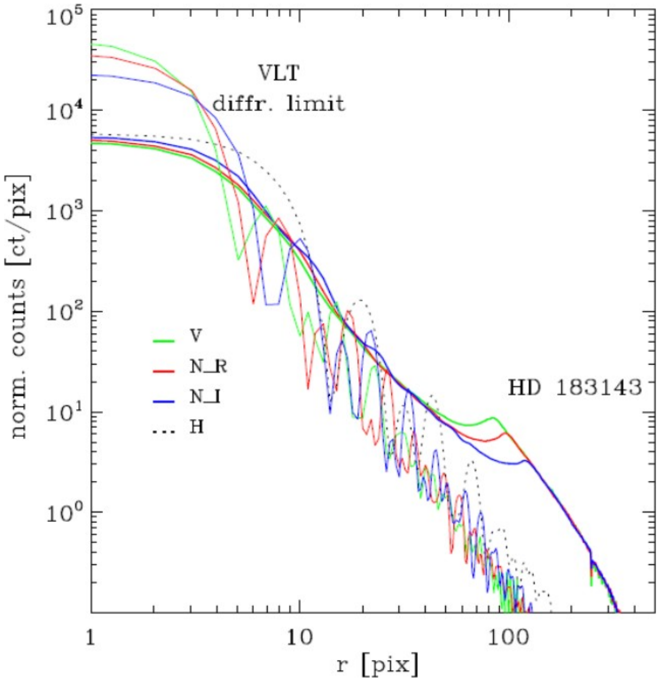
Point Spread Function (PSF)

- in N_R filter (645 ± 28 nm), dependence on λ and seeing conditions (<0.8'')
- asteroid as NGS, nearby * as PSF, 5 series of 10-s exposures @ epoch

1''

cf.





Schmid etal. (2018)

← Strehl 0.095 (V)

3.6 mas per pxl

Myopic deconvolution*

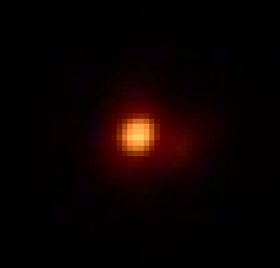
of (89) Julia (Vernazza etal. 2018)

degraded image

=

or Moffat (Fetick etal. 2018; Vesta)

stellar PSF



*

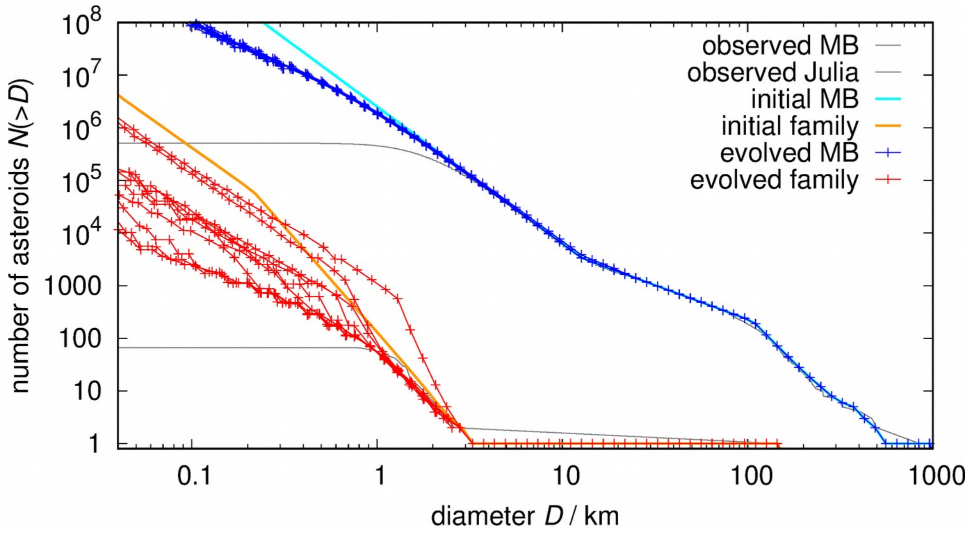
deconvolved image

*| **MISTRAL algoritm** (Conan etal. 2000), additional priors (edge, seeing), but still problems w. “darkness”↑

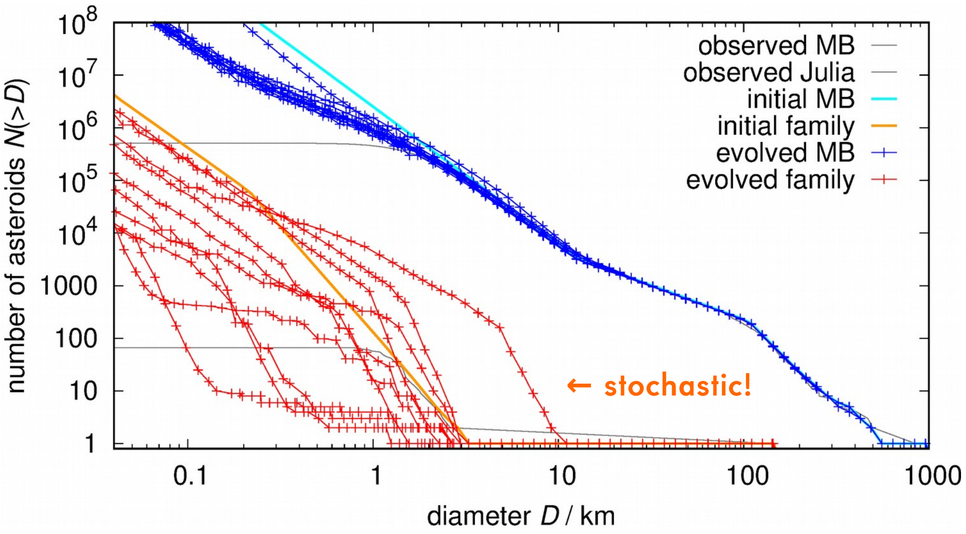
Julia family evolution (Vernazza etal. 2018)

- **crater ↔ family** identification; importance of small projectiles ($D \simeq 2$ km)!
- MC model with (89) Julia → number of events: 1 to 10 per 4 Gyr (100 runs)
- if ≫ 1 then possible **resurfacing**? irregular shape?

30 Myr



~~520 Myr~~



Monte-Carlo collisional models

(e.g. Boulder code, Morbidelli et al. 2009)

- Monte-Carlo approach
- number of disruptions
- parametric relations (from SPH)
- largest remnant
- largest fragment
- SFD slope of fragments
- dynamical decay

pseudo-random-number generator for rare collisions

specific energy $Q = \frac{1}{2}\, m_i v^2 / M_{tot}$, $Q_D{}^*$ ... scaling law

focussing

$$n_{ij} = p_{\rm i}(t) f_{\rm g} \frac{(D_i + d_j)^2}{4} n_i n_j \Delta t$$

$$M_{\rm LR} = \left[-\frac{1}{2}\left(\frac{Q}{Q_D^\star} - 1\right) + \frac{1}{2}\right] M_{\rm tot} \quad \text{for } Q < Q_D^\star$$

$$M_{\rm LR} = \left[-0.35\left(\frac{Q}{Q_D^\star} - 1\right) + \frac{1}{2}\right] M_{\rm tot} \quad \text{for } Q > Q_D^\star$$

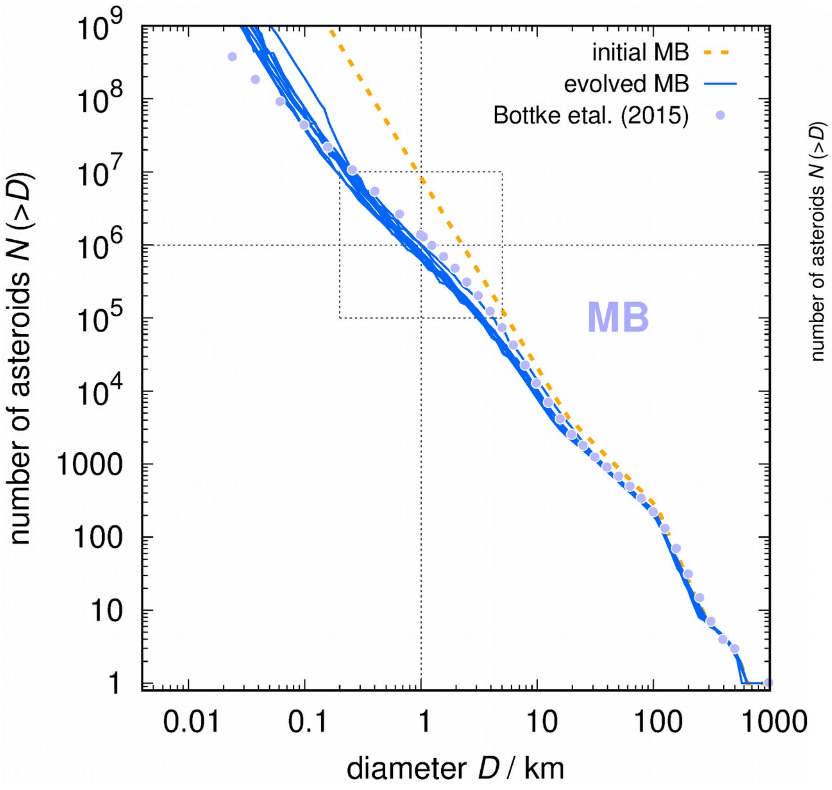
$$M_{\rm LF} = 8 \times 10^{-3} \left[\frac{Q}{Q_D^\star} \exp\left(-\left(\frac{Q}{4Q_D^\star}\right)^2\right)\right] M_{\rm tot}$$

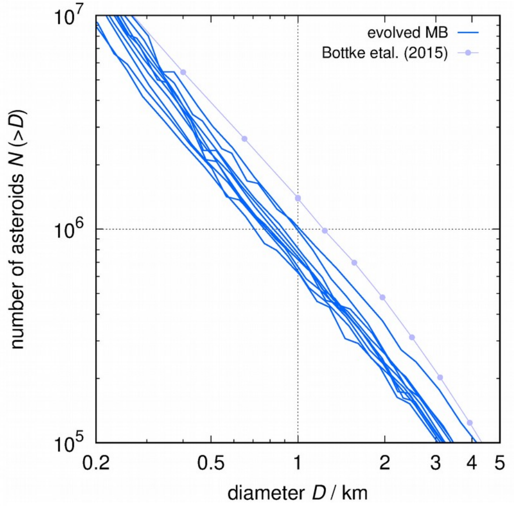
$$q = -10 + 7\left(\frac{Q}{Q_D^\star}\right)^{0.4} \exp\left(-\frac{Q}{7Q_D^\star}\right)$$

Standard MB collisional model?

- P_i, v_{imp} constant, but not N
- nominal time scale 4 Gy
- scaling: Benz & Asphaug (1999), monolith, basalt, ...
- YE dynamical removal (Bottke etal. 2005)

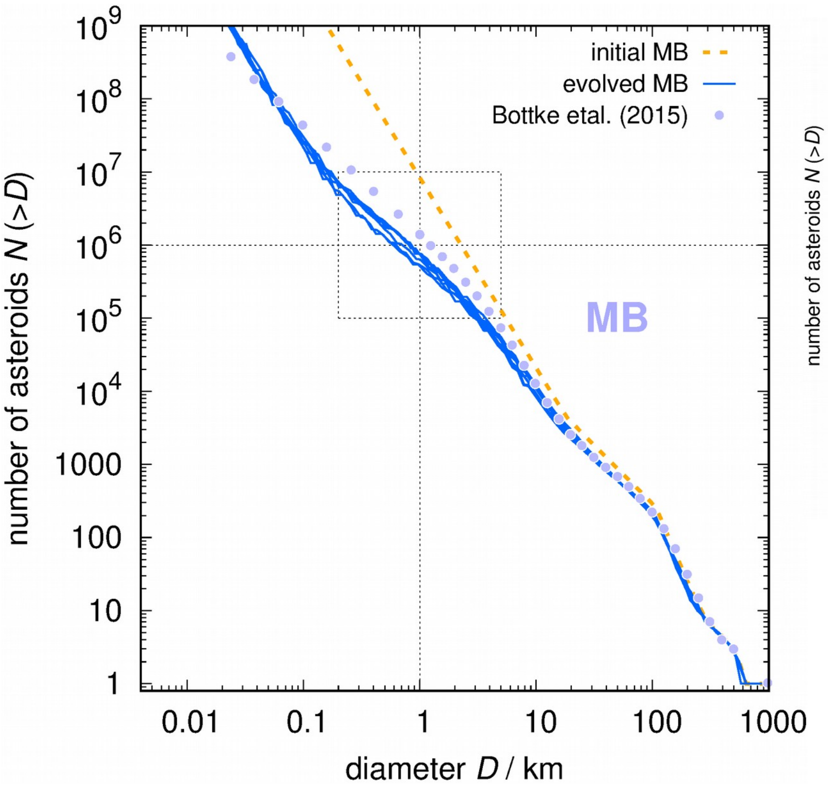
- usually, SFD $N_{syn} < N_{obs}$ for $D \simeq 1$ km bodies
- a trivial problem...

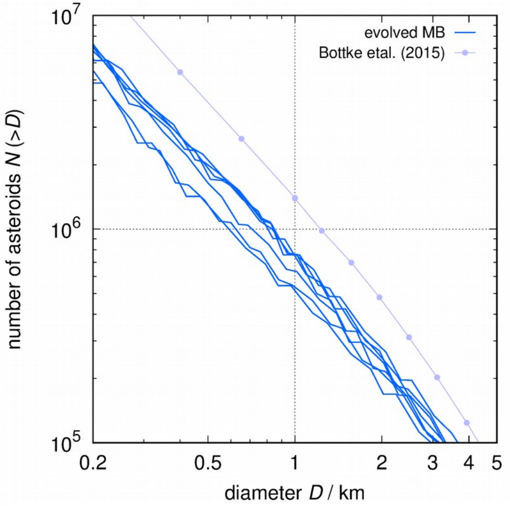




Test 1: 10-km parametric relations

- M_{LR}, M_{LF}, q relations (Sevecek etal. 2017)
- linear interpolation for $D = 10 \leftrightarrow 100$ km
- super-catastrophic impacts not computed
- not so trivial...

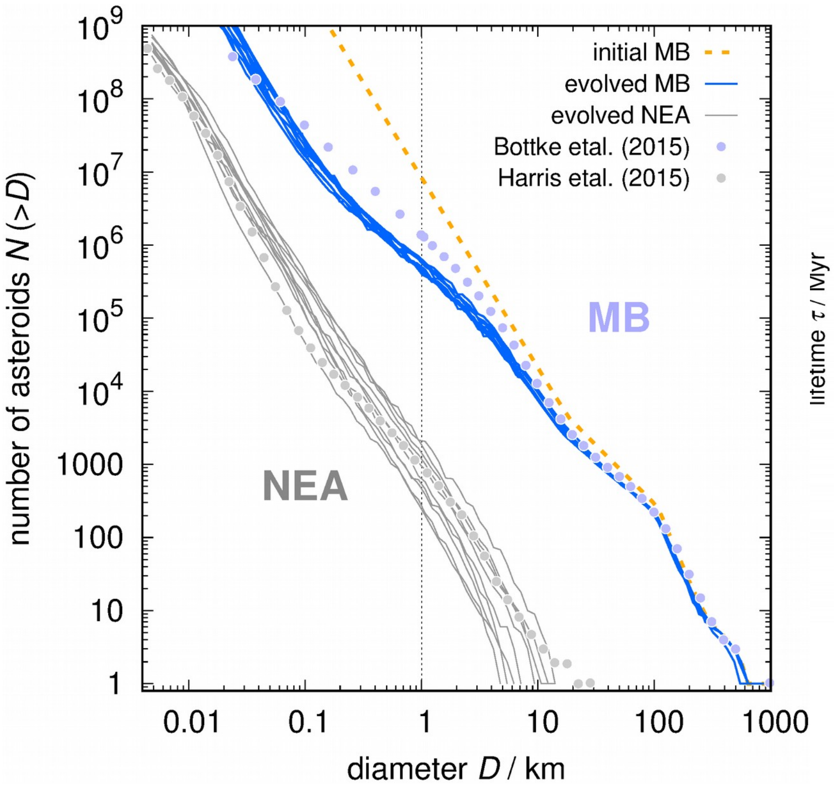


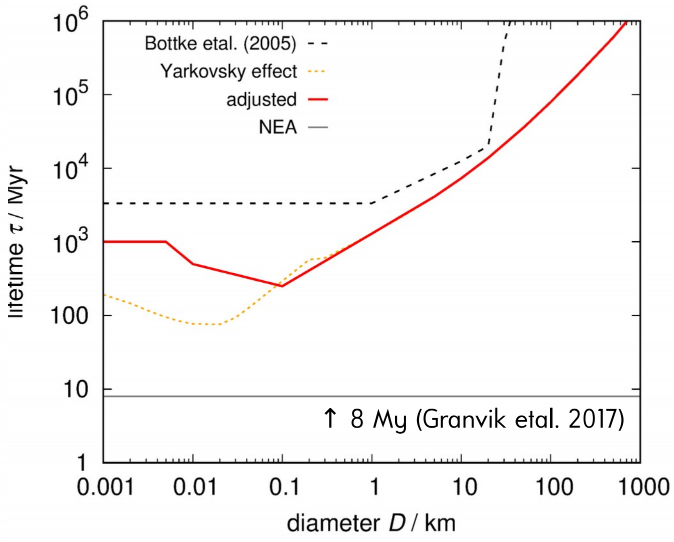


Test 2: Dynamical removal

- Yarkovsky effect
- *ω*, *K* … *f* (*D*), or transitions (Delbo etal. 2007)
- YORP → YE
- must fit **NEA**!

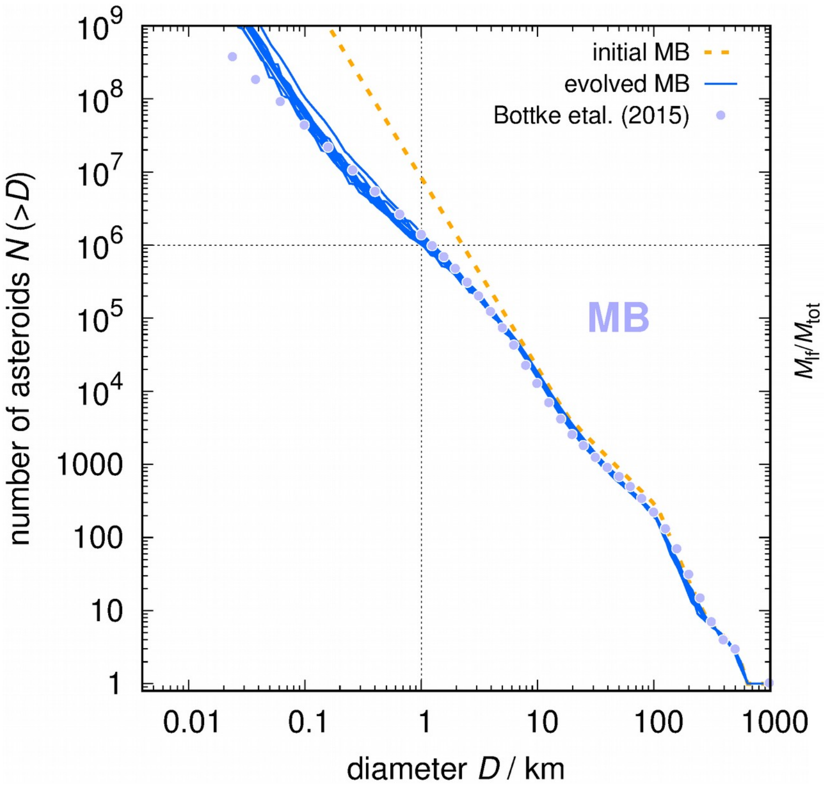
- alternatively, YORP disruptions? (Marzari etal. 2011, Jacobson etal. 2014)



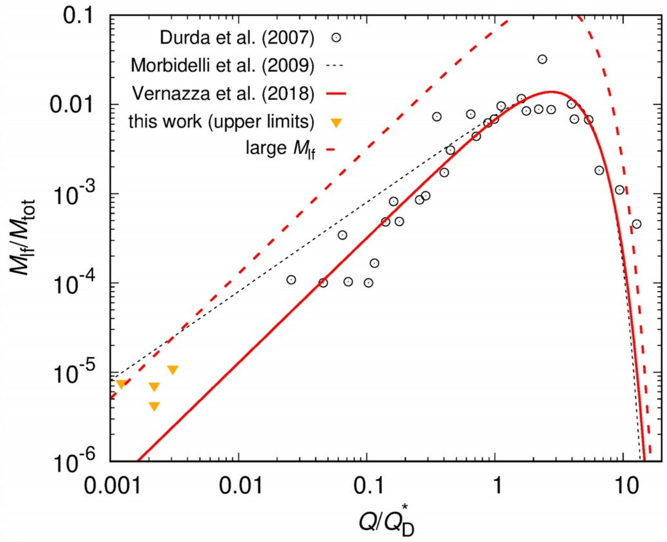


Test 3: SPH input (LF/PB mass)

- different rheology?
- cf. friction, crushing (Jutzi 2015)

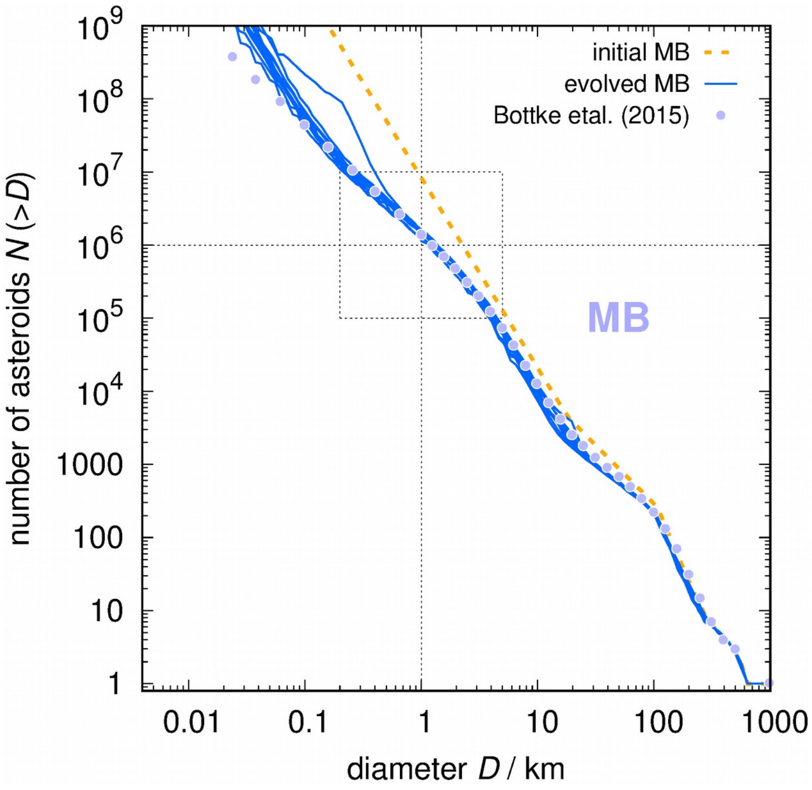


factor 10 in M → 2 in D
i.e. 2nd largest fragment

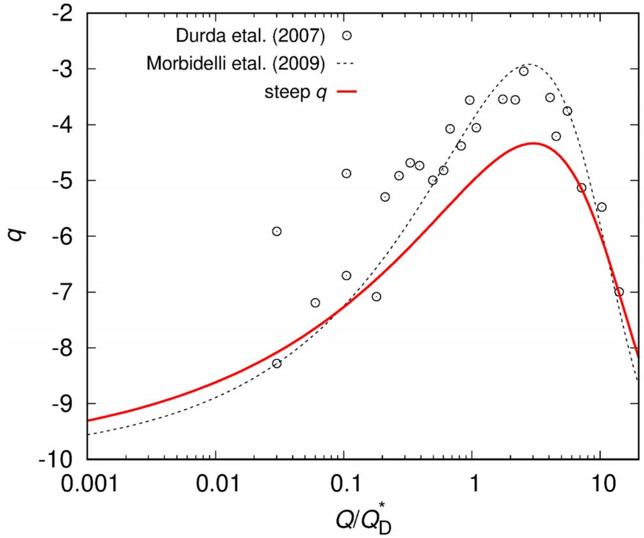


Test 4: SPH input (fragment slope)

- dtto



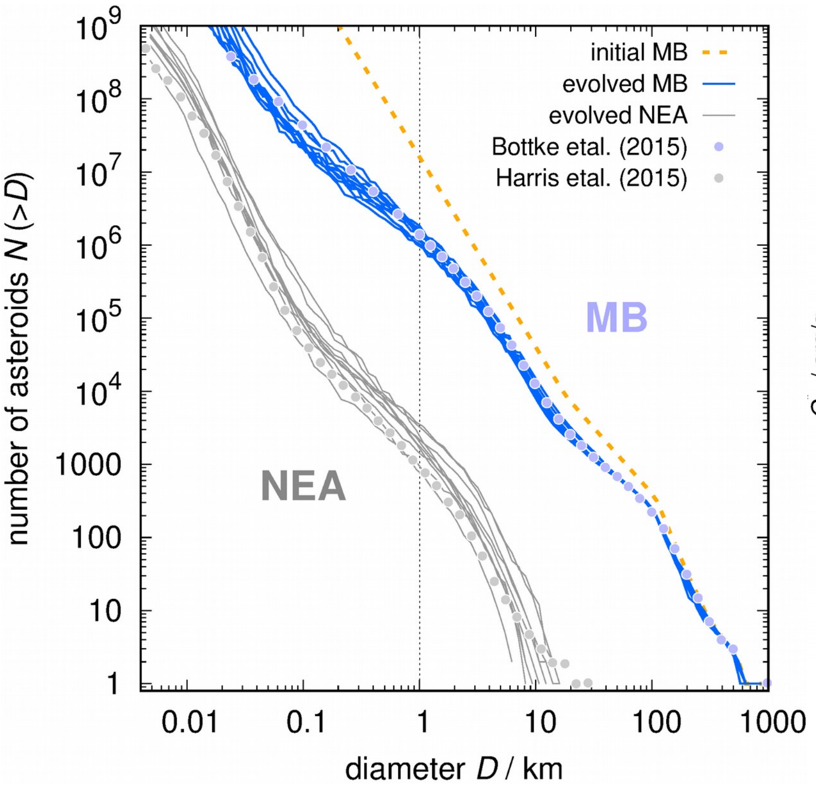
q steeper by −2

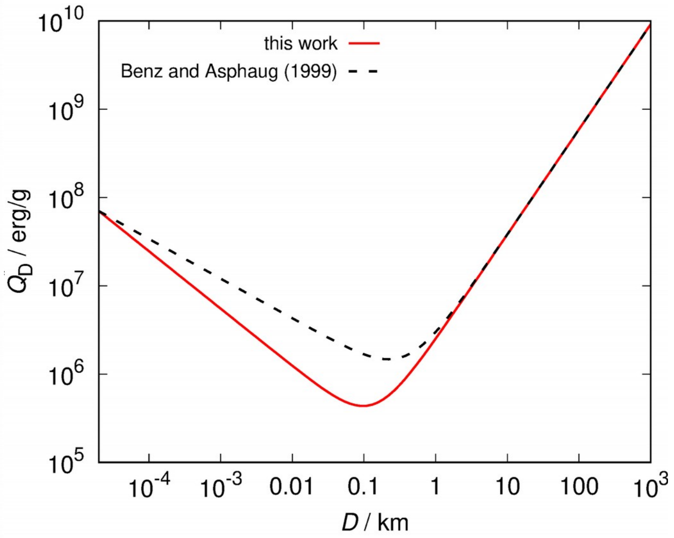


Test 5: Scaling law

- lower strength, and a shift 200→100 m (O'Brien & Greenberg 2003)
- verify by SPH?

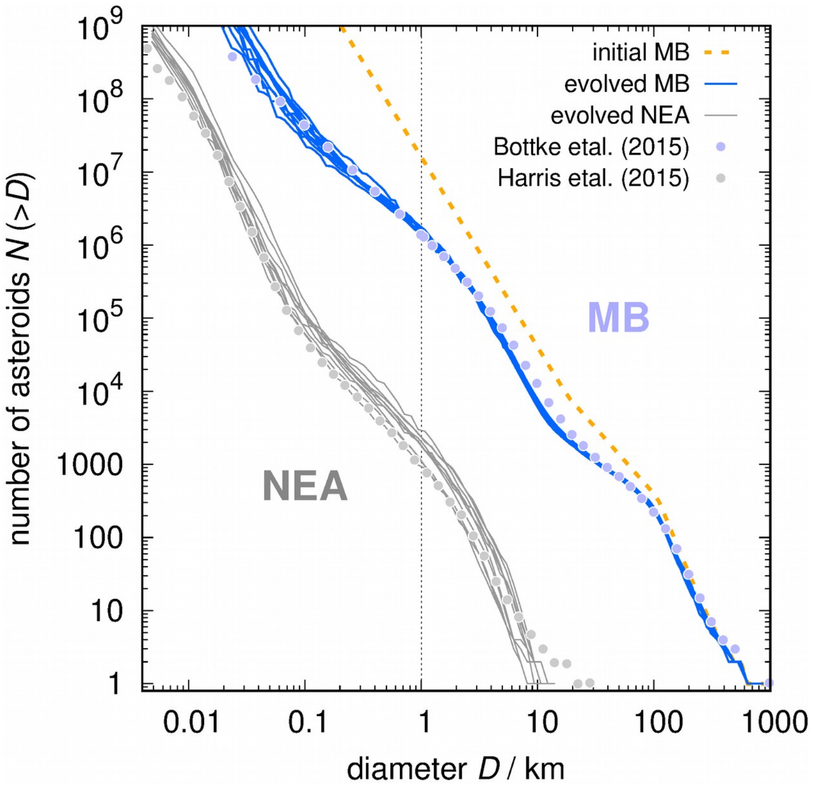
- alternatively, YORP

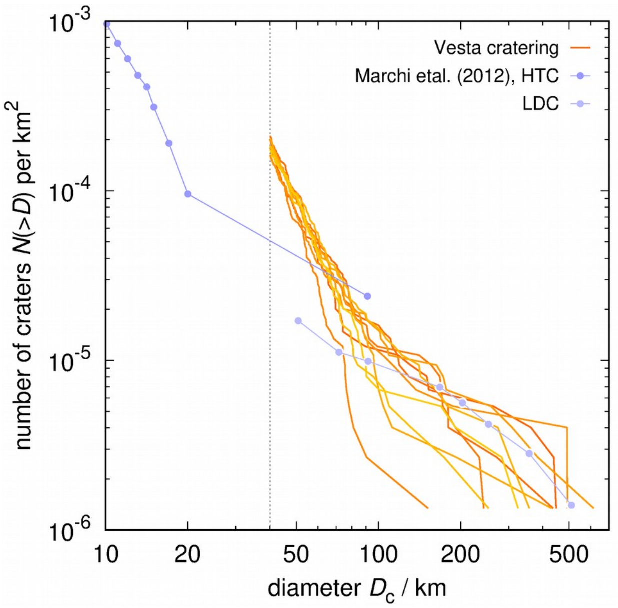




Test 6: Initial conditions

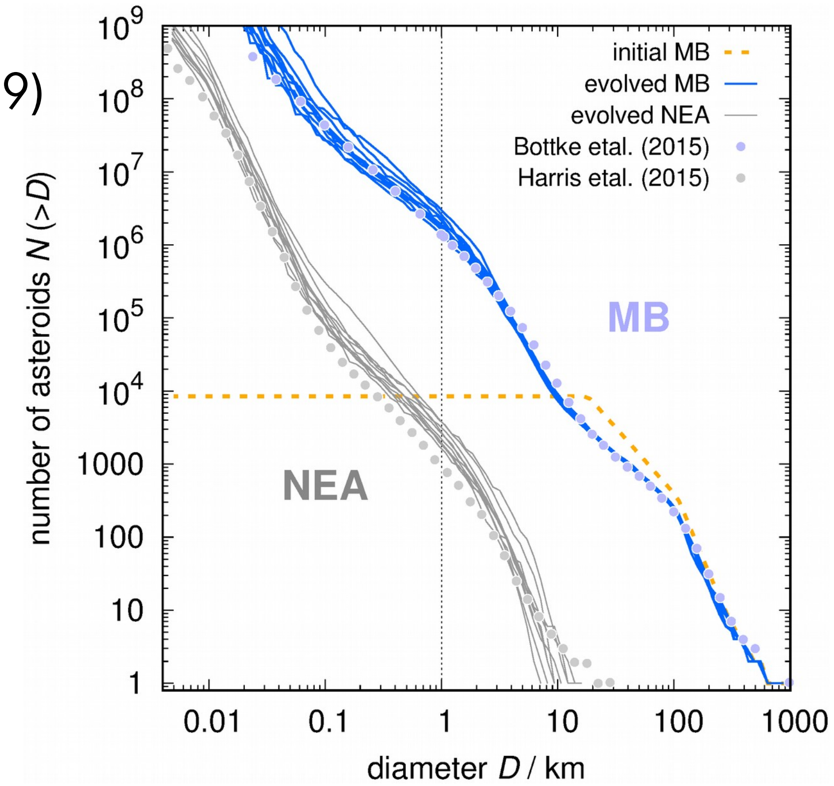
- e.g. Vesta cratering
- $\int dt$ sensitive to the initial population! (Marchi etal. 2012)
- N_{syn} too steep, but...
- scaling law is also modified here
- crater erasure *not* included (O'Brien etal. 2006)

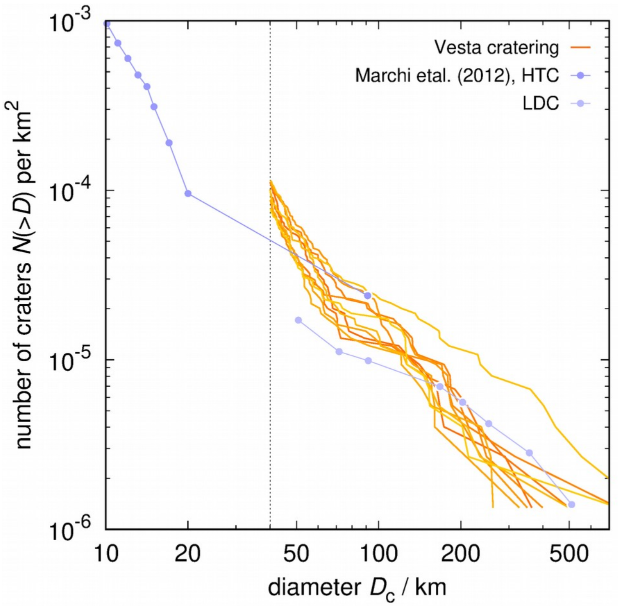




Test 6: Initial conditions

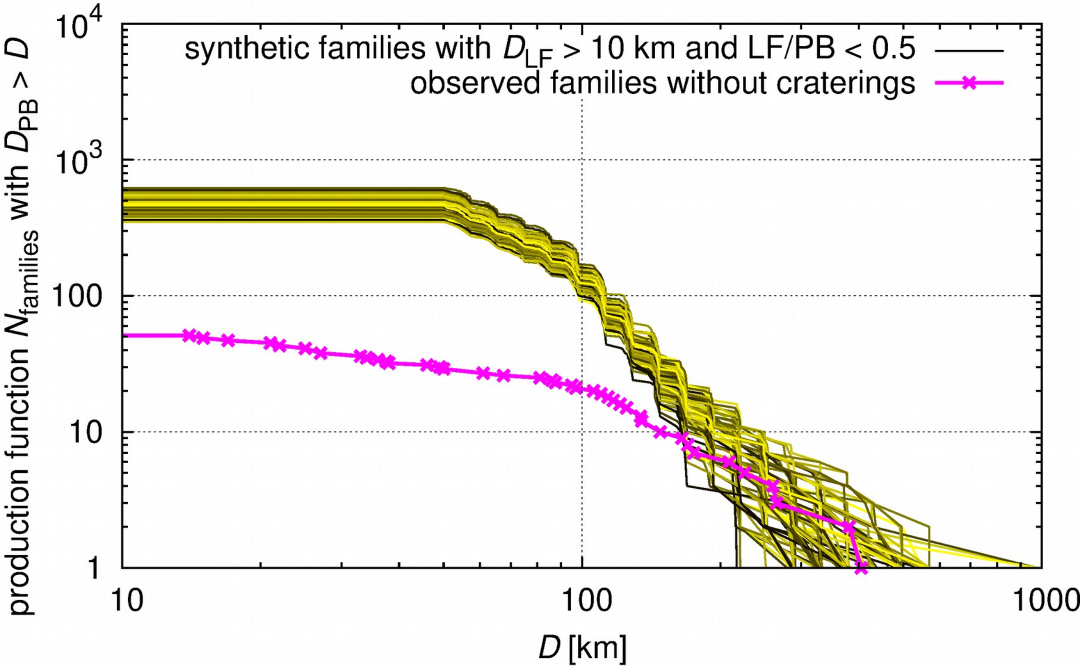
- flat SFD (a.k.a. Morbidelli etal. 2009)
- N_{syn} shallow(er)





Note: High velocities?

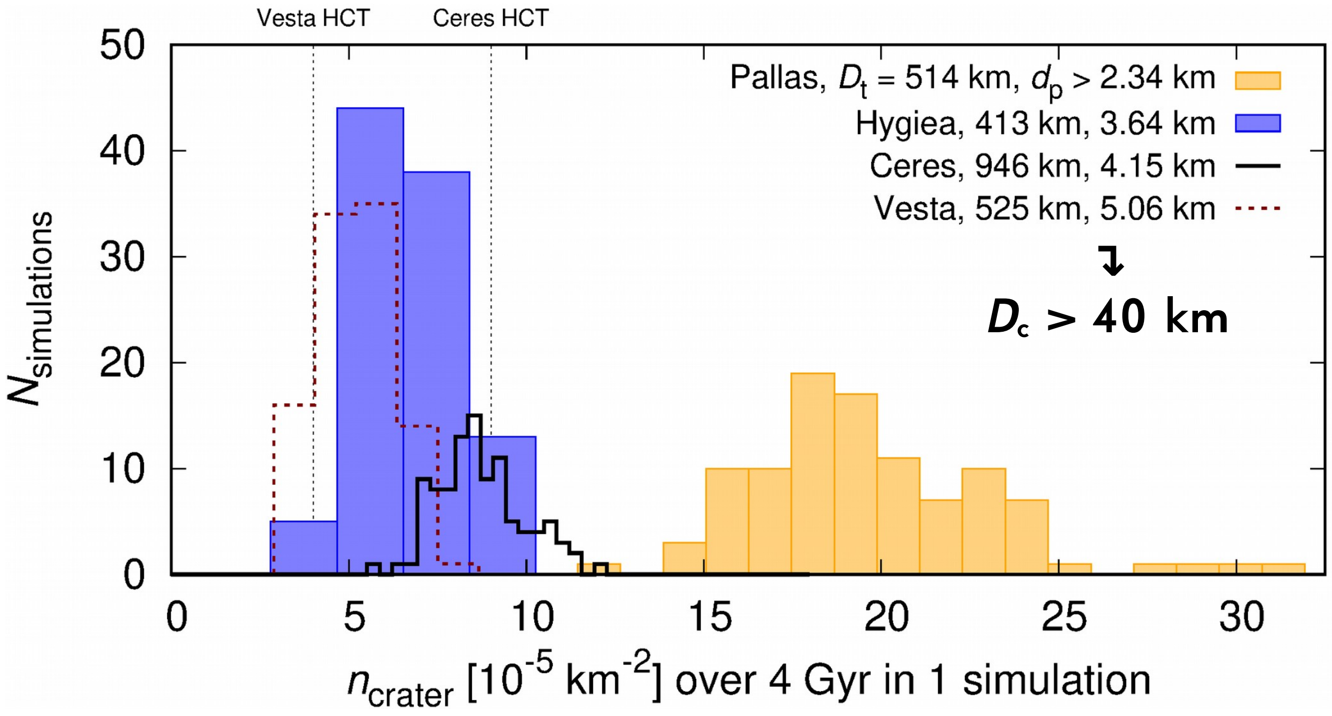
- p. r. suitable for cometary bombardment (LHB; Brož etal. 2013)
- dynamical evolution not included in nominal simulations



Collisional environment(s) in MB

↓talk P. S.

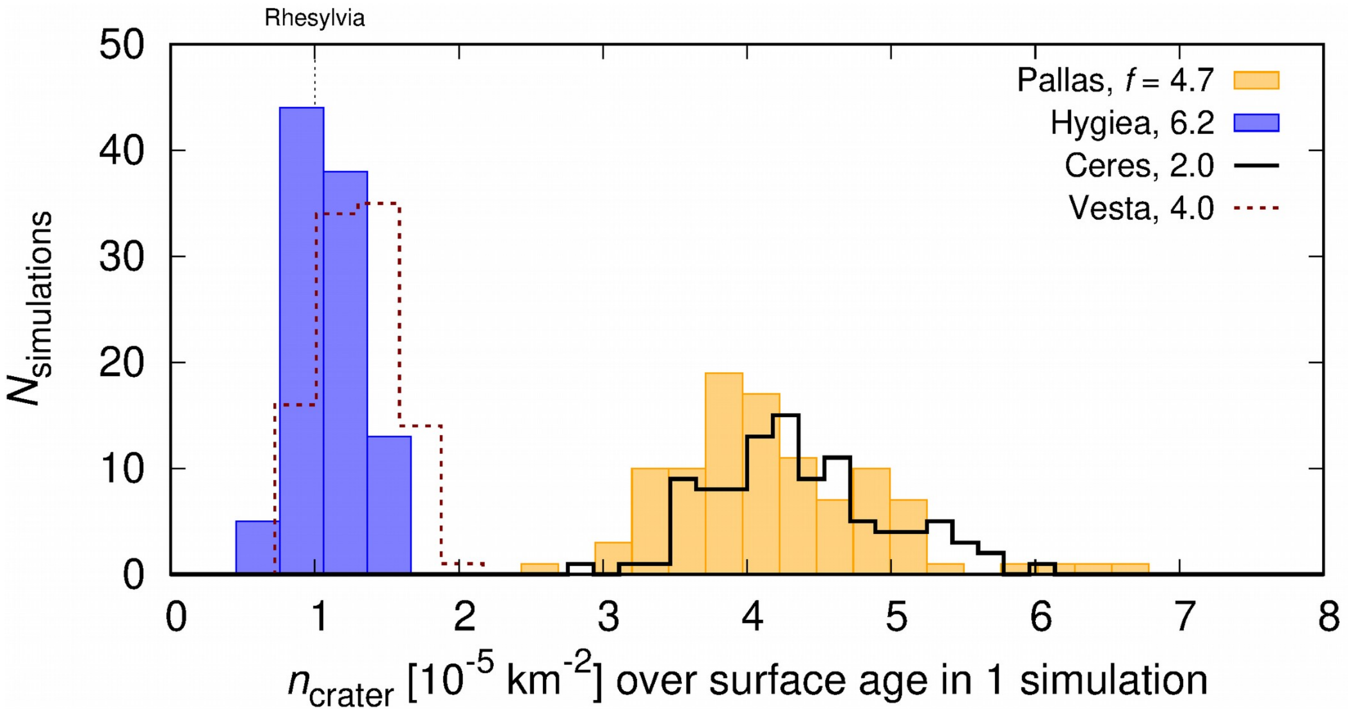
- Pallas, Hygiea vs Ceres, Vesta ← different P_i, v_{imp}, g (gravity), π-scaling



Collisional environment(s) in MB

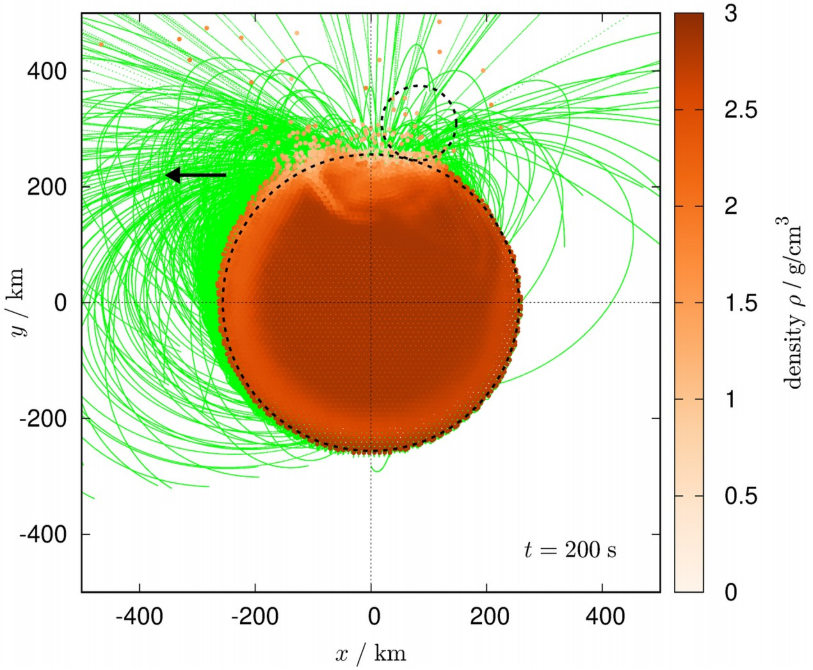
for relative comparison, see Fetick etal. (2018) ↓

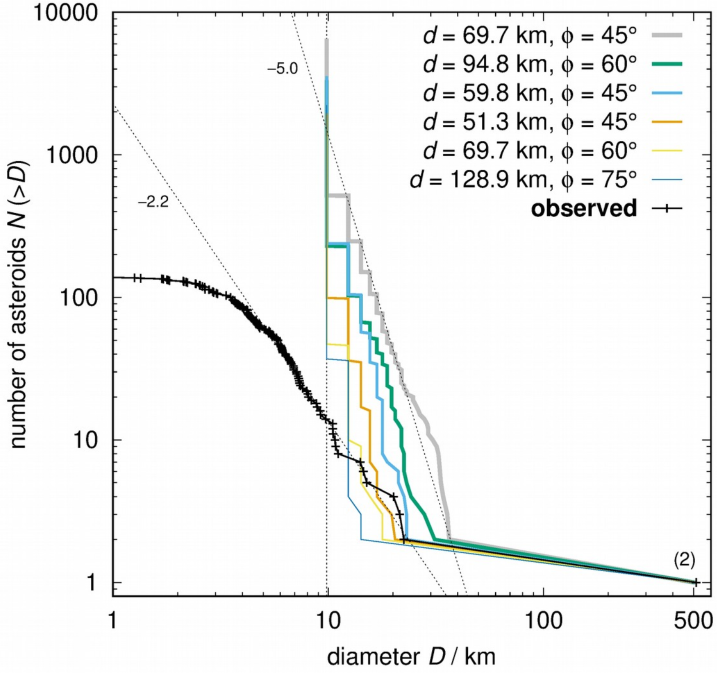
- Pallas, Hygiea vs Ceres, Vesta → absolute w. factor $f = f_{visible} f_{bias} f_{resurf} f_{age}$



Pallas family origin

- SFD: Q/Q_D^* = 0.024 (↓) to 0.106 (reaccumulative); dynamical age (1.6 ± 0.3) Gyr
- *but* 2 observed features? (Marssett etal. in prep.)





Goal!

- standard? well, not yet...
- equilibrium? not exactly (CRE spikes, ^{3}He data, ...)
- *prescribed* dated-family-formation events?
- more rheologies? (monolith ↔ rubble-pile, S/C, friction, crushing)
- SFD of YORP disruptions? (cf. Walsh etal. 2008; Cotto-Figueroa etal. 2015)
- fit also spin rates? ← diffuse spin barrier!

- statistical sample: **30 targets** (ESO LP), MC model convergence, incl. rare cases, catastrophic/reaccumulative/cratering, direct, hit-and-run, low-*v*, ...
- development of deconvolution algorithms (ELT)