Planet Formation in Binaries

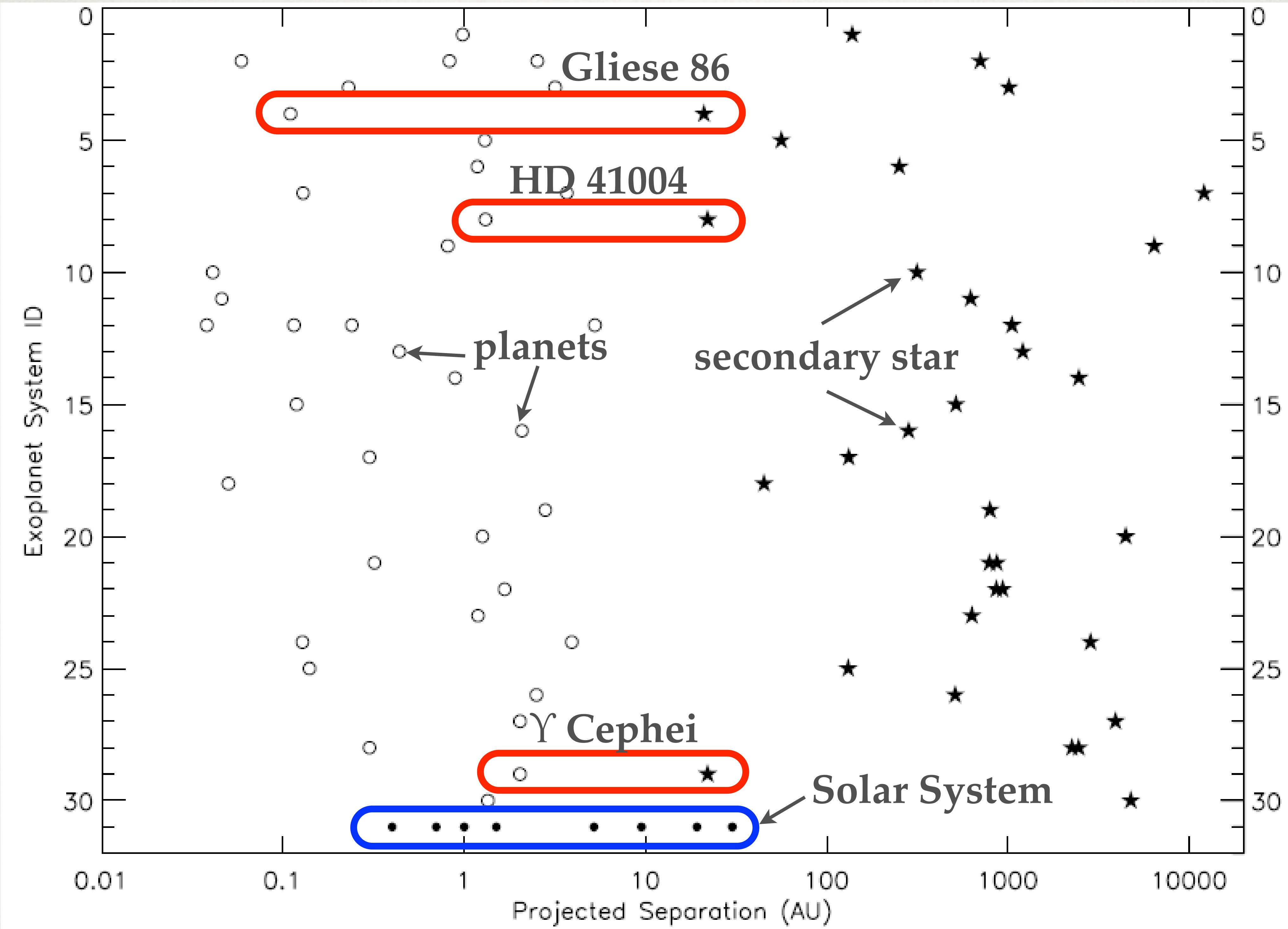
Dr. Zoë Malka Leinhardt
School of Physics, University of Bristol

Sarah T. Stewart, Sijme-Jan Paardekooper, Philippe Thébault

Overview

- 685 extrasolar planets 15.9.11
- 10-20% of planets in binary systems
- Few percent in tight binaries (a_b ~ 20 AU)
  (ϒ Cephei, GL 86, HD 41004, HD 196885)
- Binaries are a testbed for planet formation:
  - What are the most extreme scenarios that our models allow? Do these constraints match observations?
  - Can numerical/theoretical models form the most extreme observed systems?

Exoplanets in Binaries



Raghavan et al., 2006

What we know about planet formation in binaries.

inclination < 25^{o}	phase II, moderate	Fragner et al. 2011
accret. hard (a~20 AU)	phase I, tight	Zsom et al. 2011
accretion ok	phase II, distant inclined	Batygin et al. 2011
HD196885 no acct.	phase II, tight	Thébault 2011
accret. ok in outer disk	phase II, tight	Beaugé et al. 2010
inclination 1-5^{o} helps	phase II, tight	Xie et al. 2009
harder than Thébault '06	phase II, tight	Paardekooper et al. '08
accretion ok (mostly)	phase II, tight circumb.	Scholl et al. 2007
planet formation ok	phase III, m & t	Quintana et al. 2007
growth at 1 AU unlikely	phase II, m & t	Thébault et al. 2006

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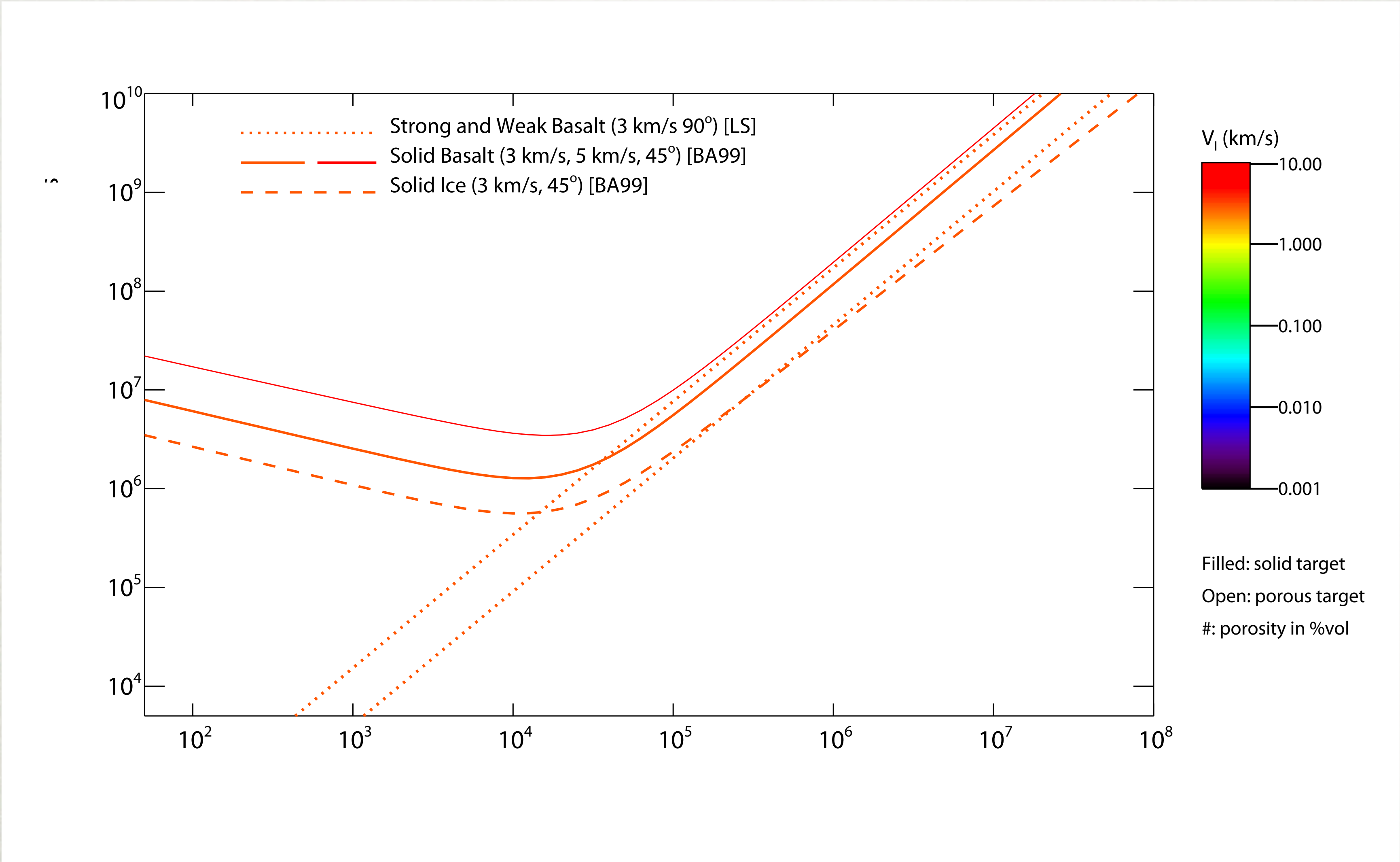
All work depends on collision model. When do the planetesimals grow and when do they erode?

Old Collision Model

Benz & Asphaug 1999



Model applies to $M_p << M_{targ}$, narrow range of V_i 3-5 km/s

Model was used well outside of range

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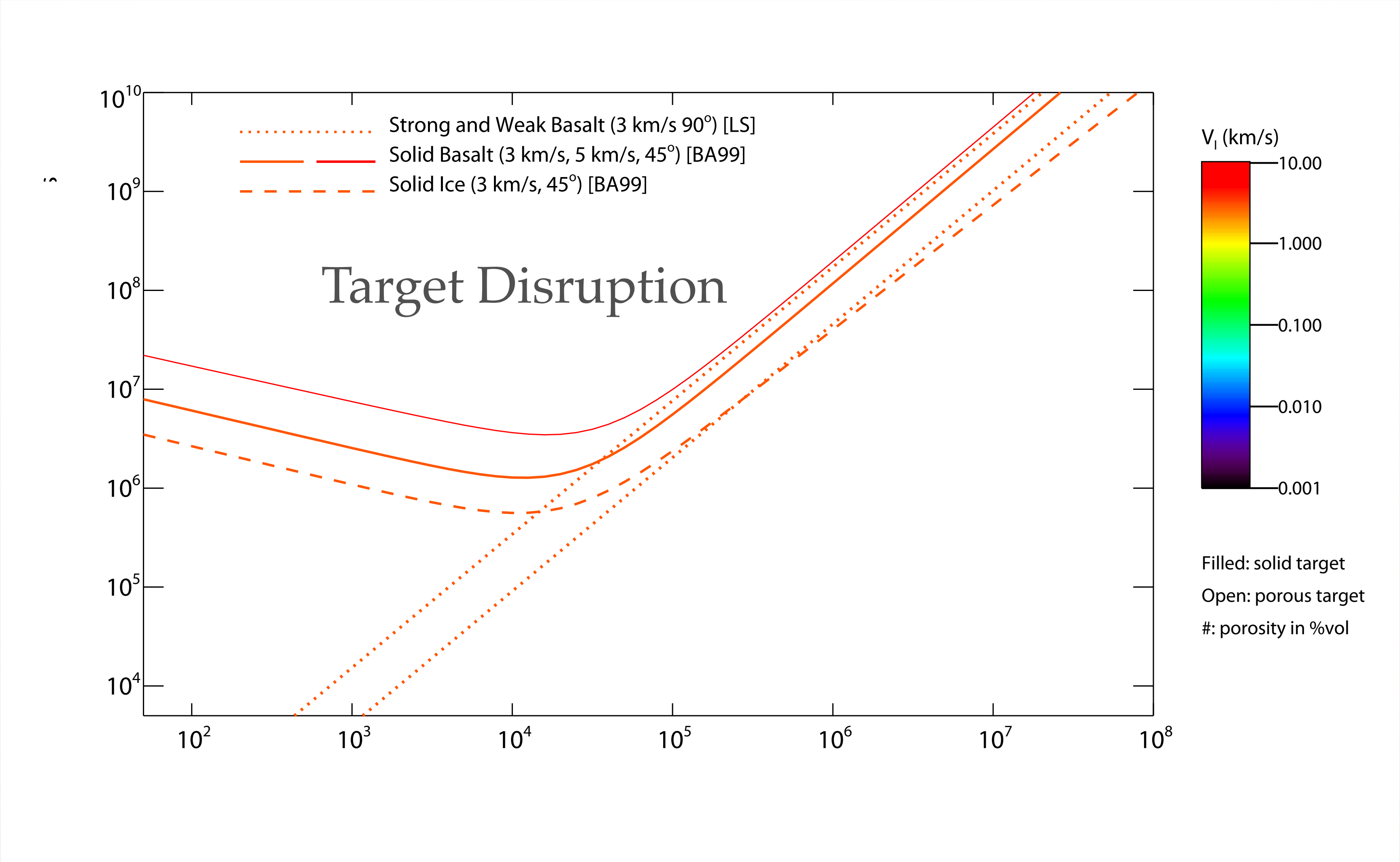

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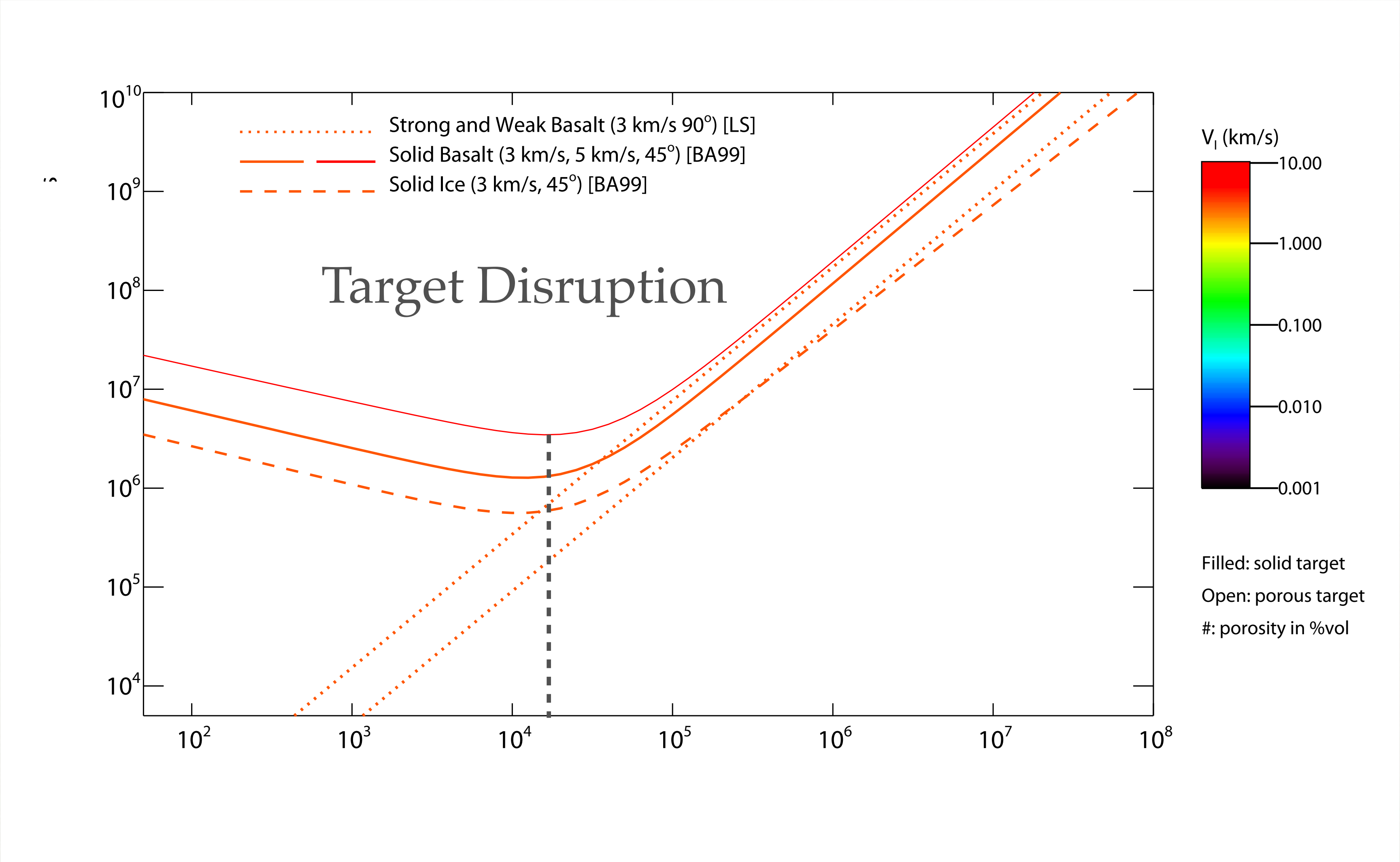

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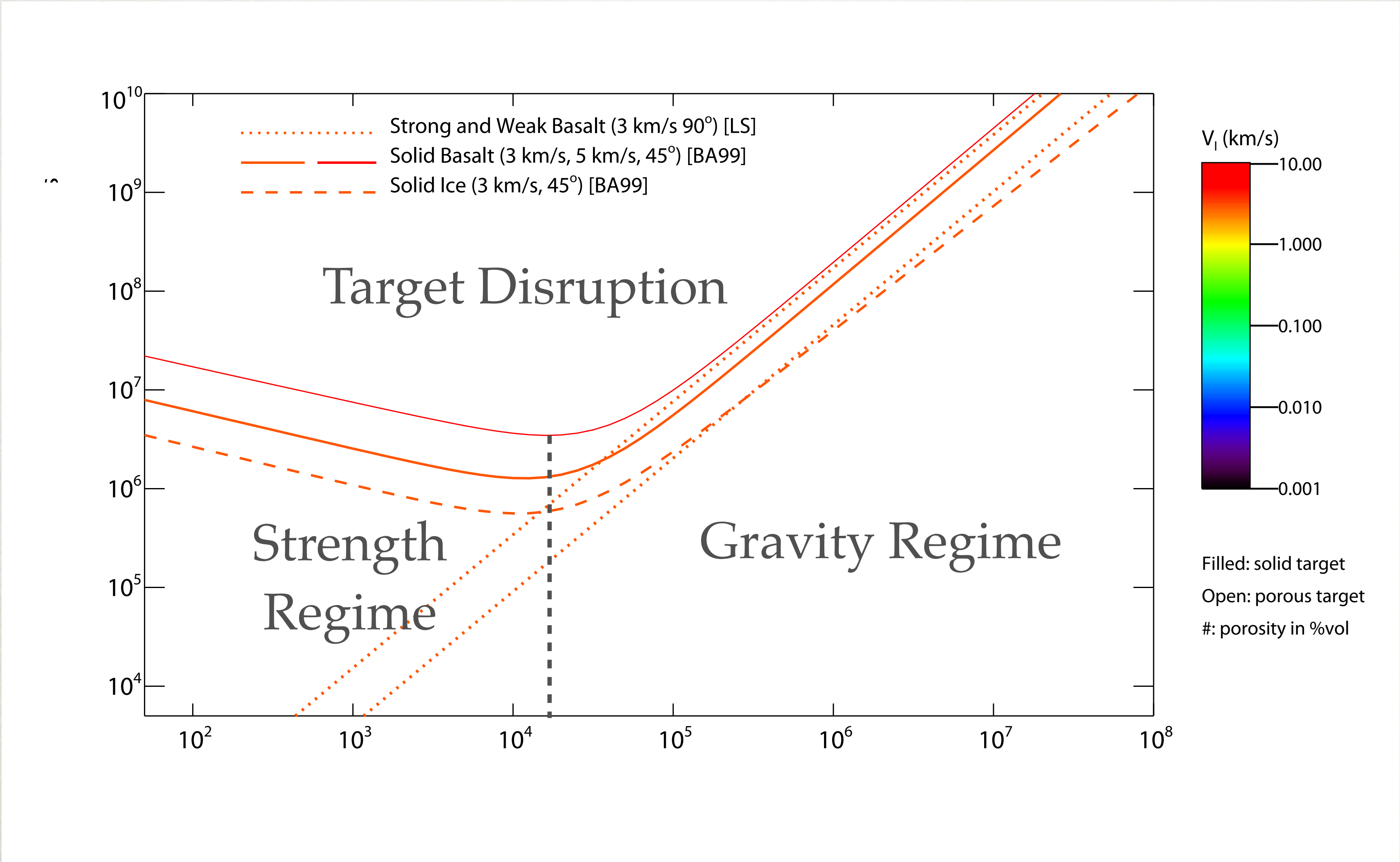

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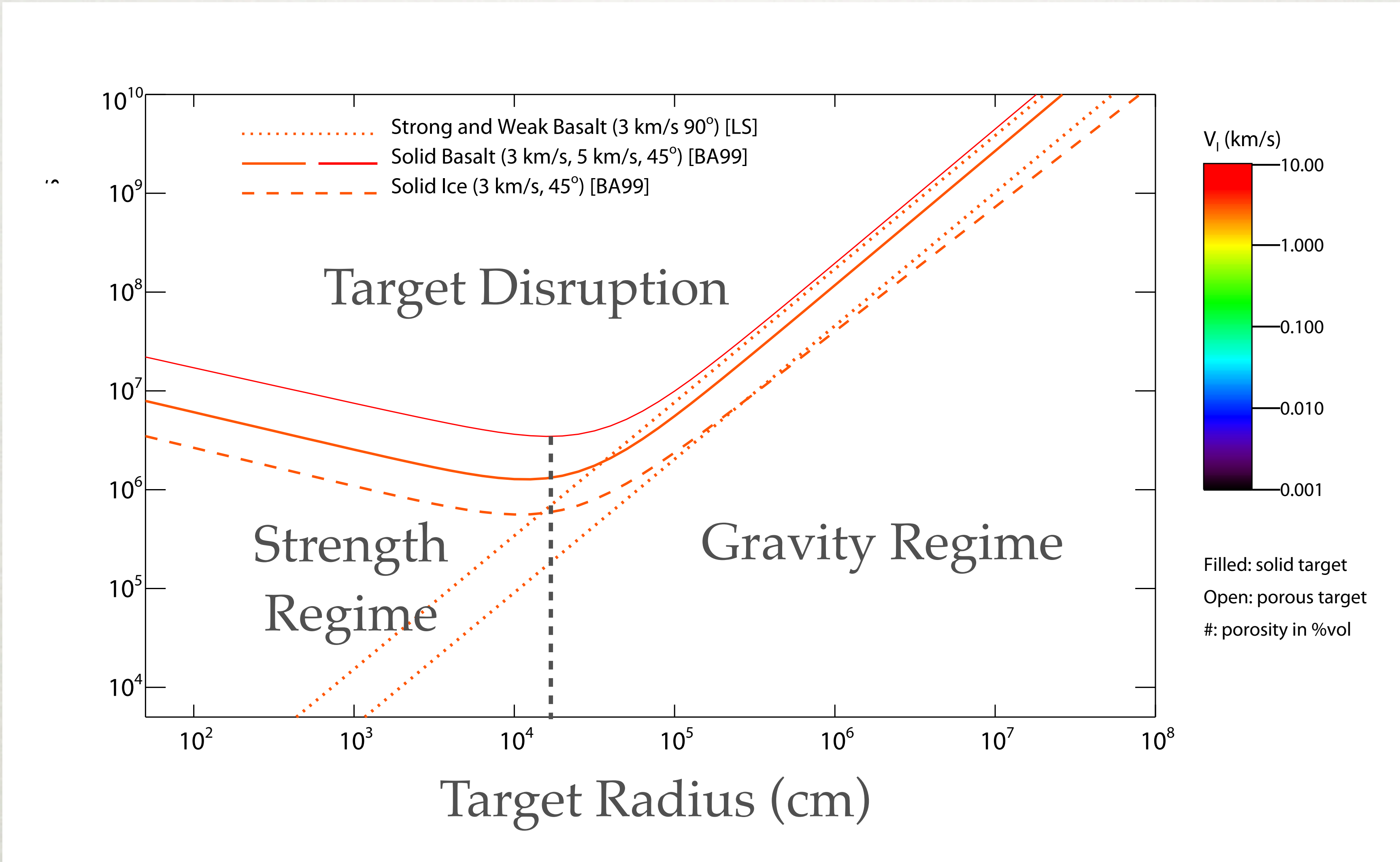

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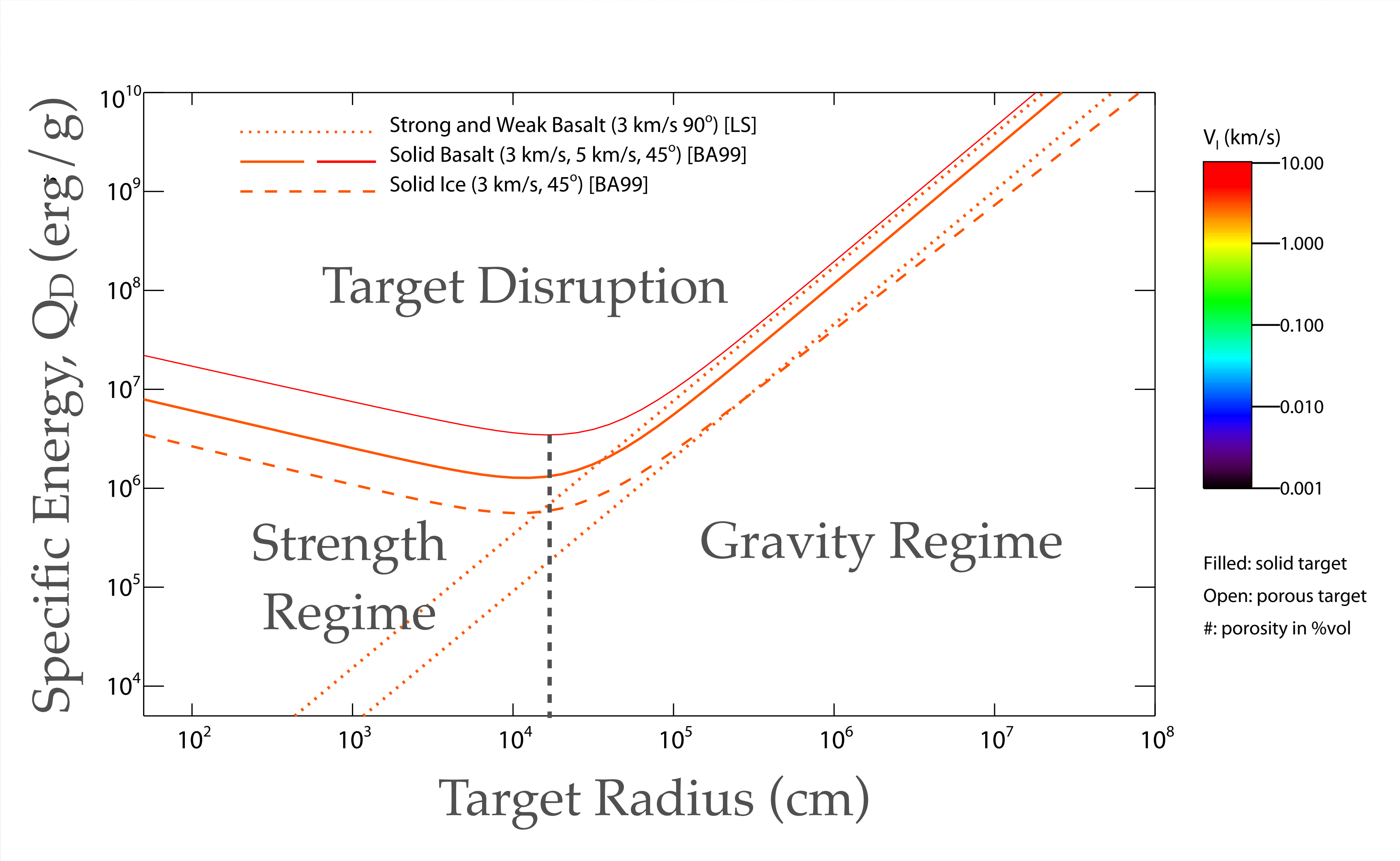

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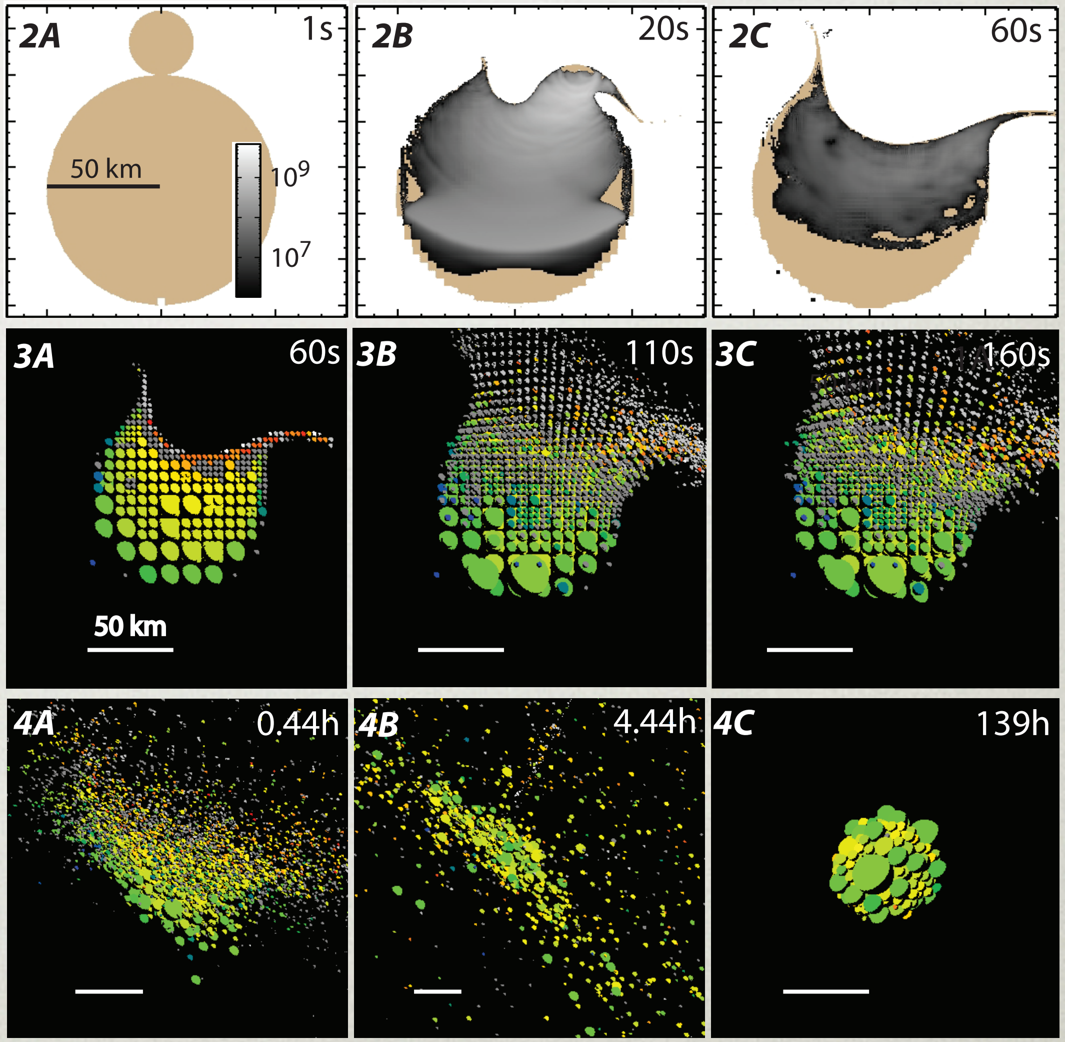
Numerical Simulations of Collisions

Idea: Study collisions in isolation. Find a way to empirically describe results and then apply within planetary formation simulations.



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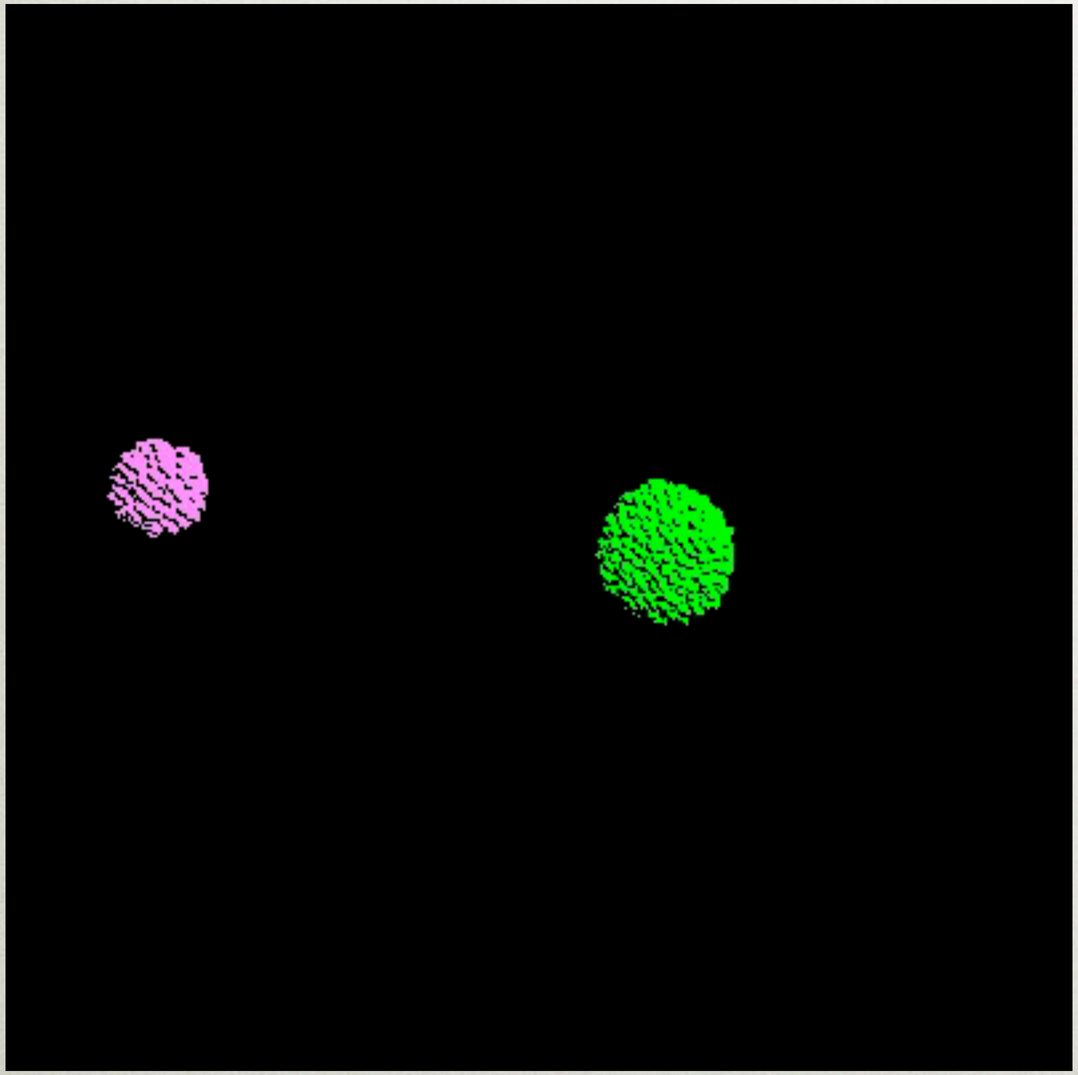
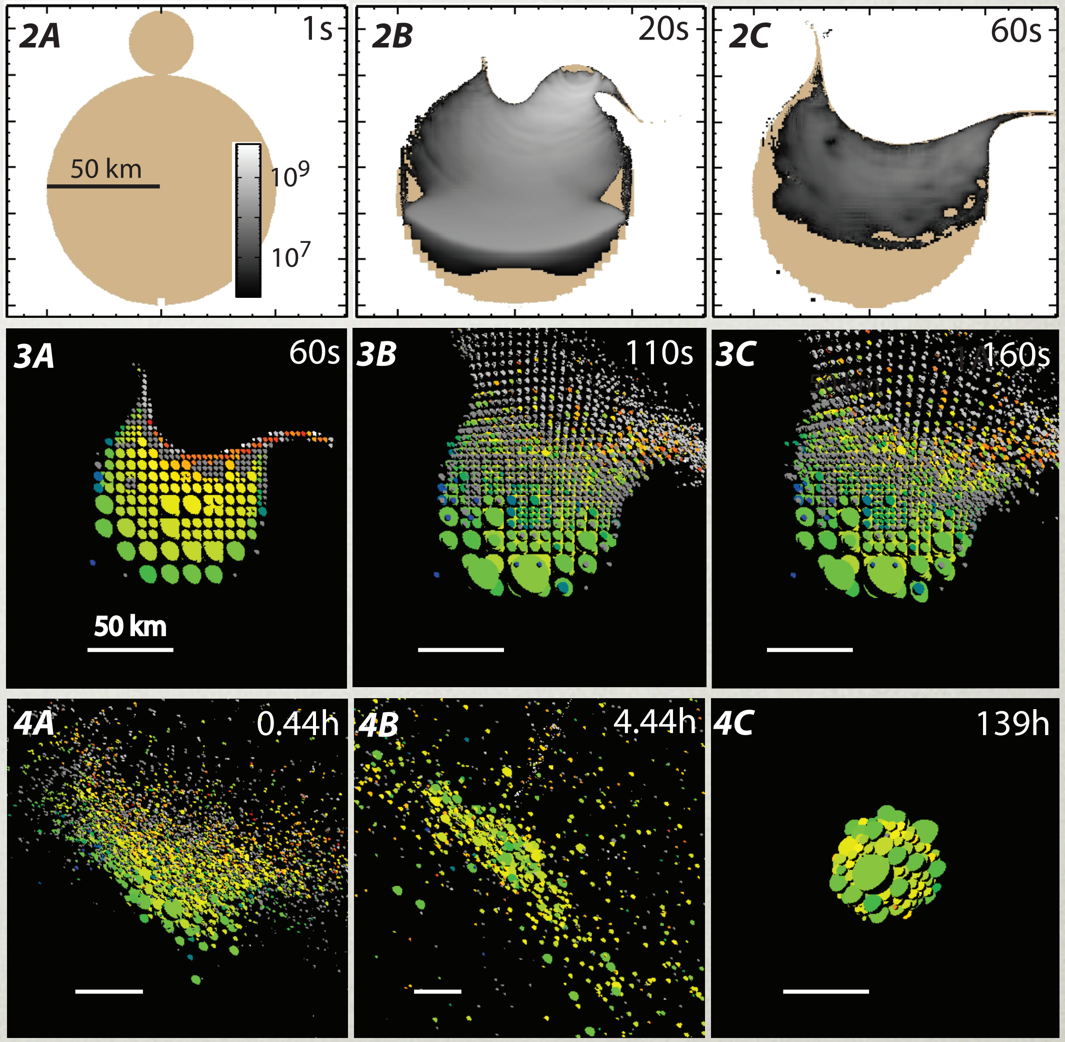
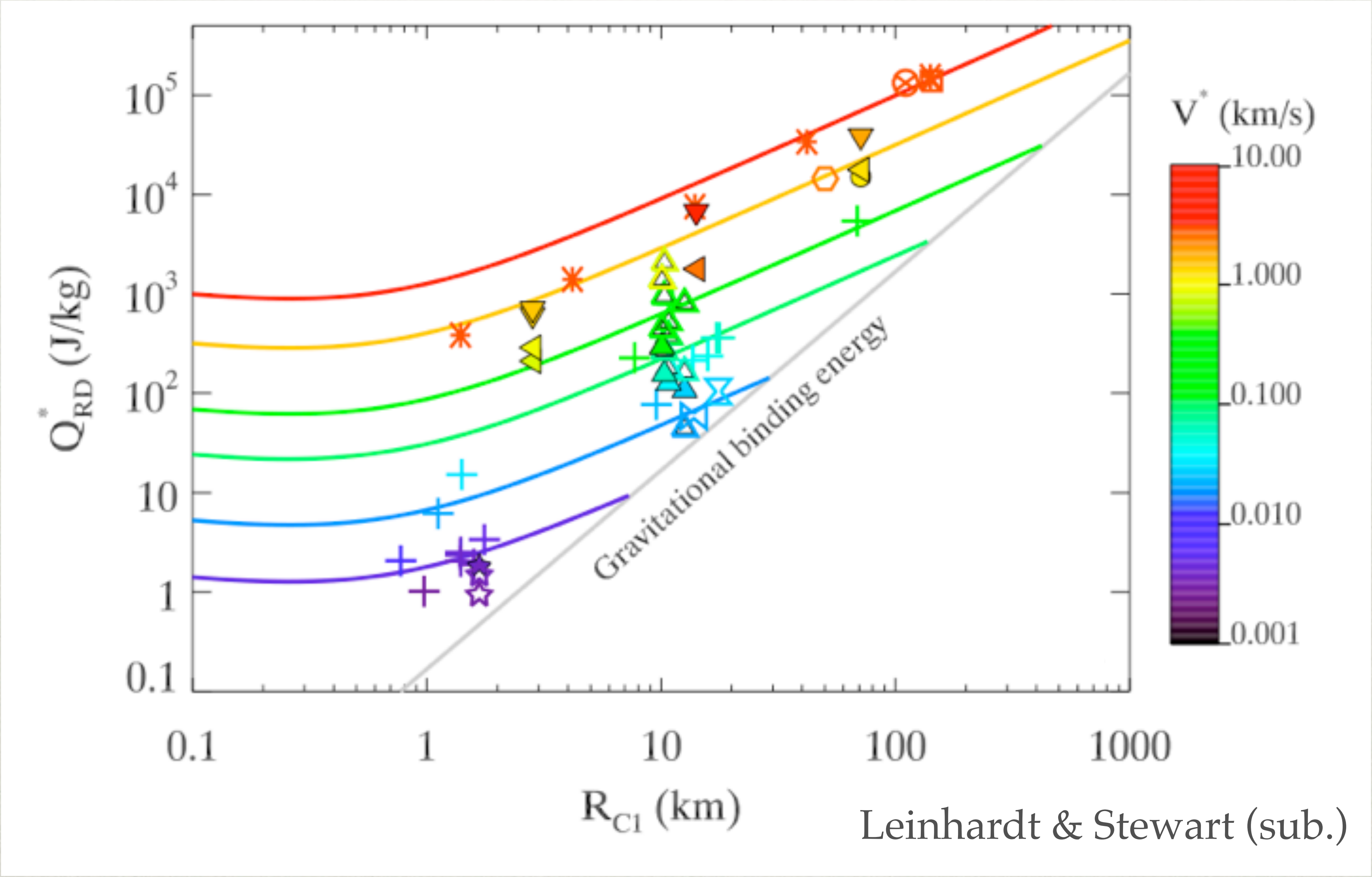




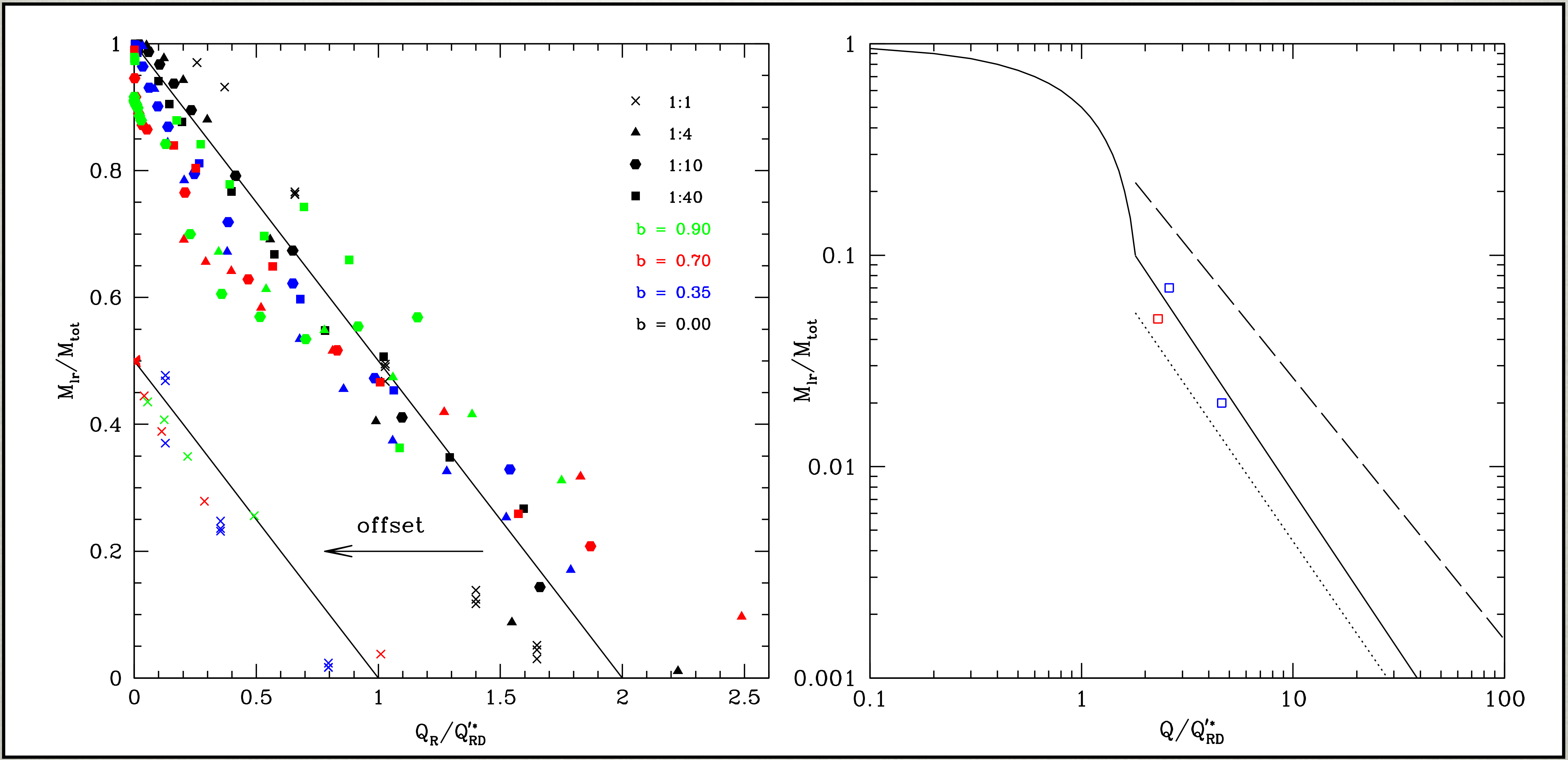
Leinhardt & Stewart 2009

Empirical Scaling Laws



$$Q^*_{RD} = q_s \left(S/\rho_1\right)^{3\bar{\mu}(\phi+3)/(2\phi+3)} R_{C1}^{9\bar{\mu}/(3-2\phi)} V^{*(2-3\bar{\mu})} + q_g \left(\rho_1 G\right)^{3\bar{\mu}/2} R_{C1}^{3\bar{\mu}} V^{*(2-3\bar{\mu})}$$

Disruption & Super-catastrophic Regime



$$M_{lr}/M_{tot} = -0.5(Q_R/Q'^*_{RD} - 1) + 0.5$$

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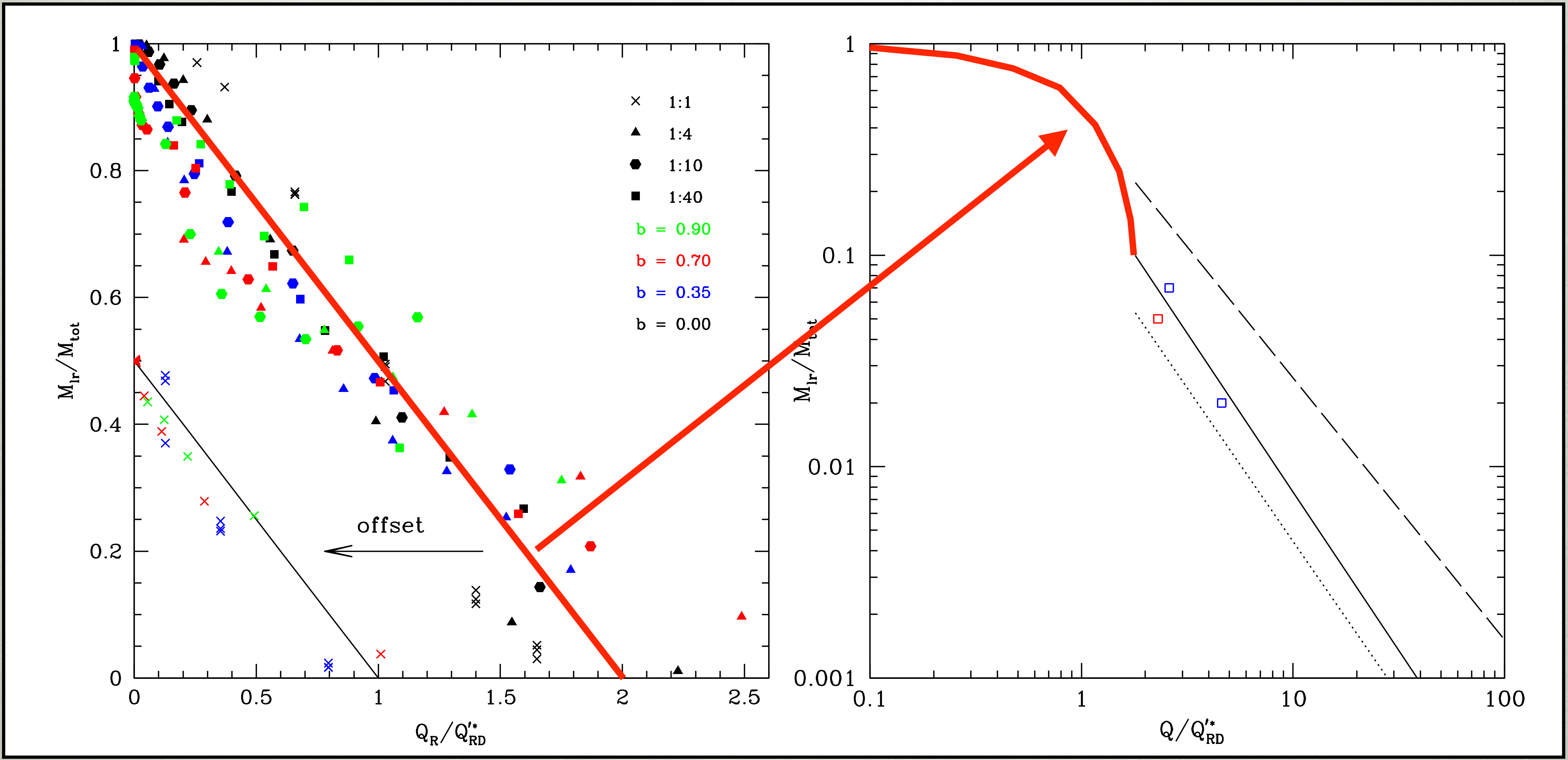

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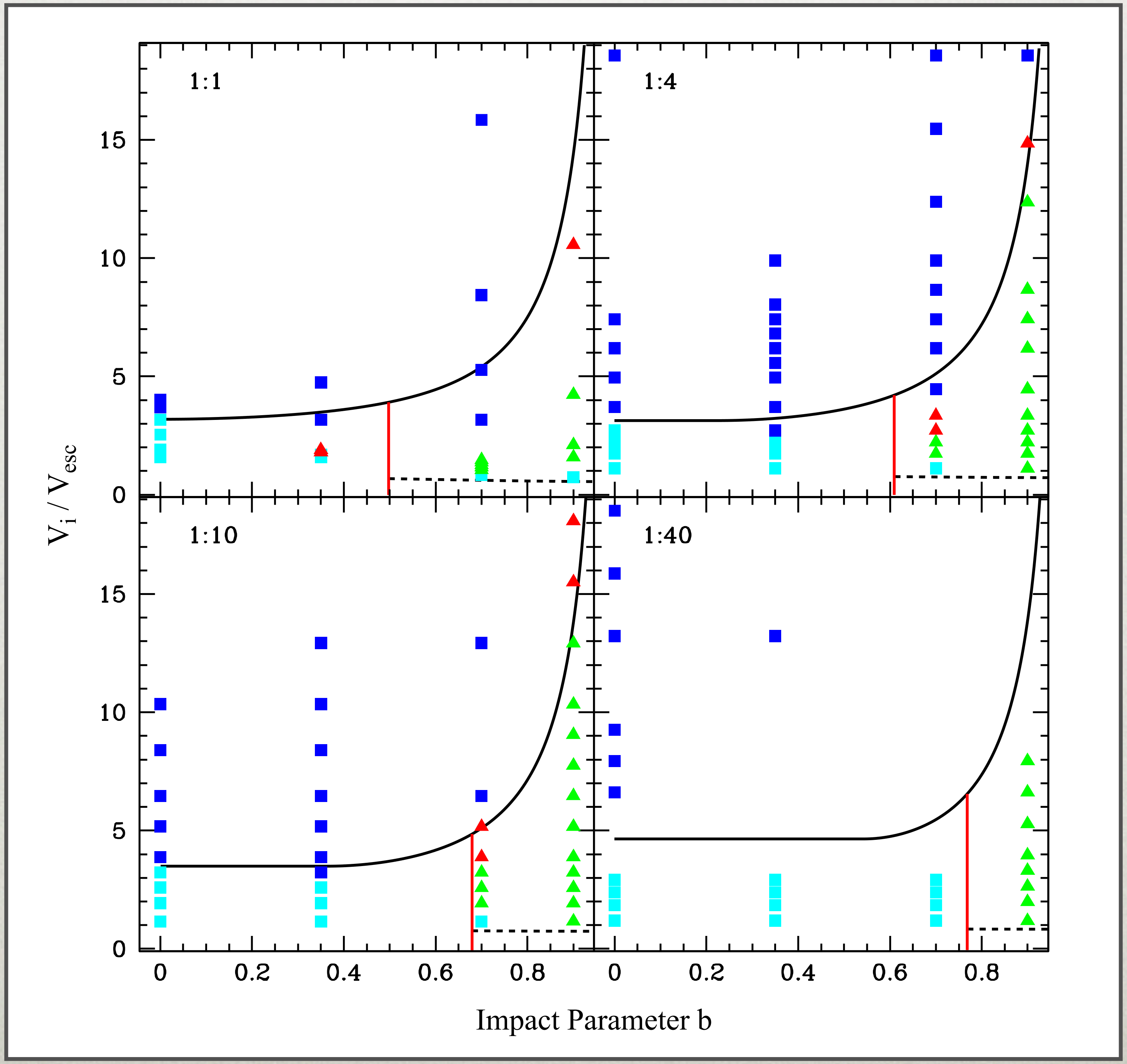

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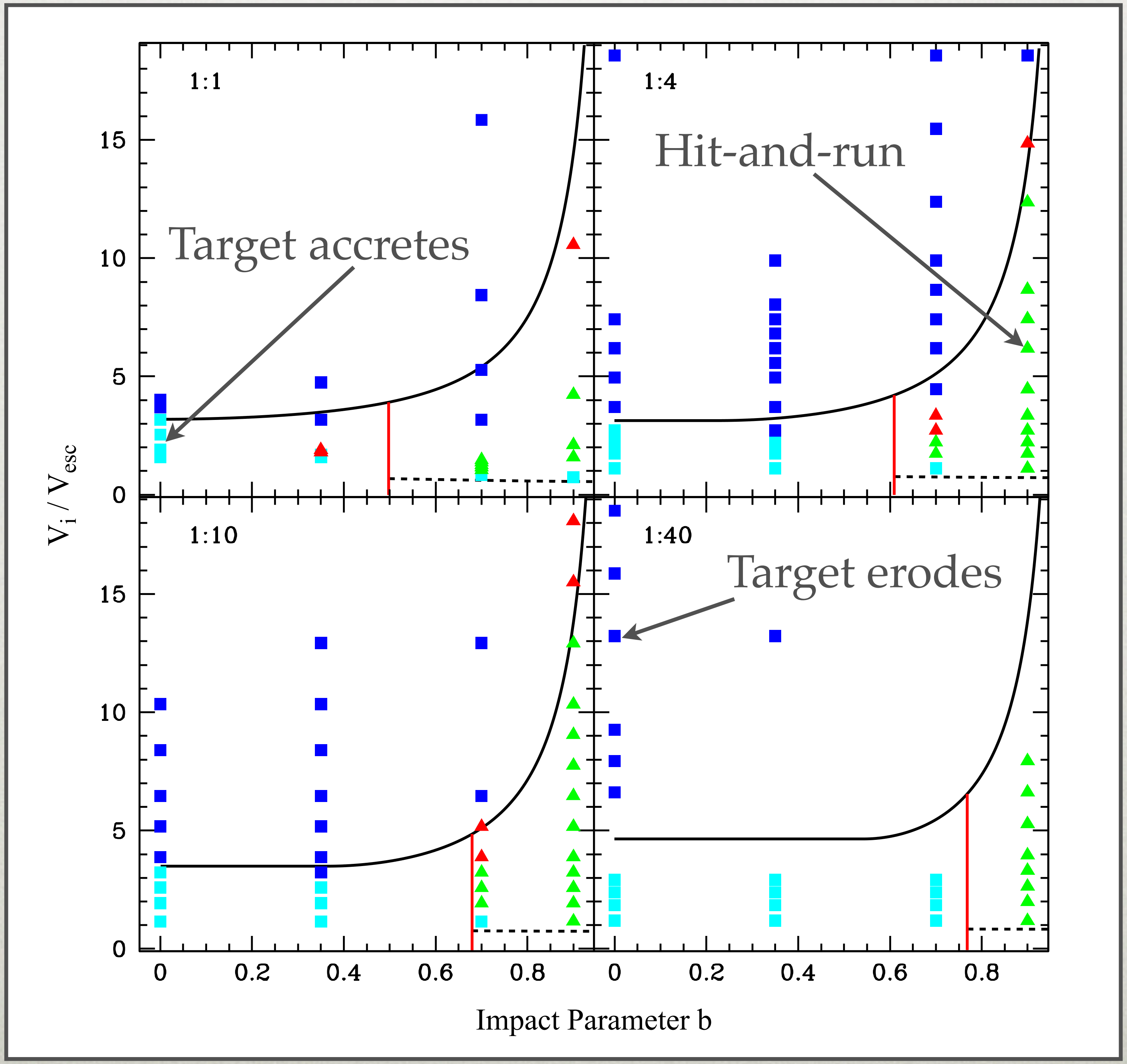

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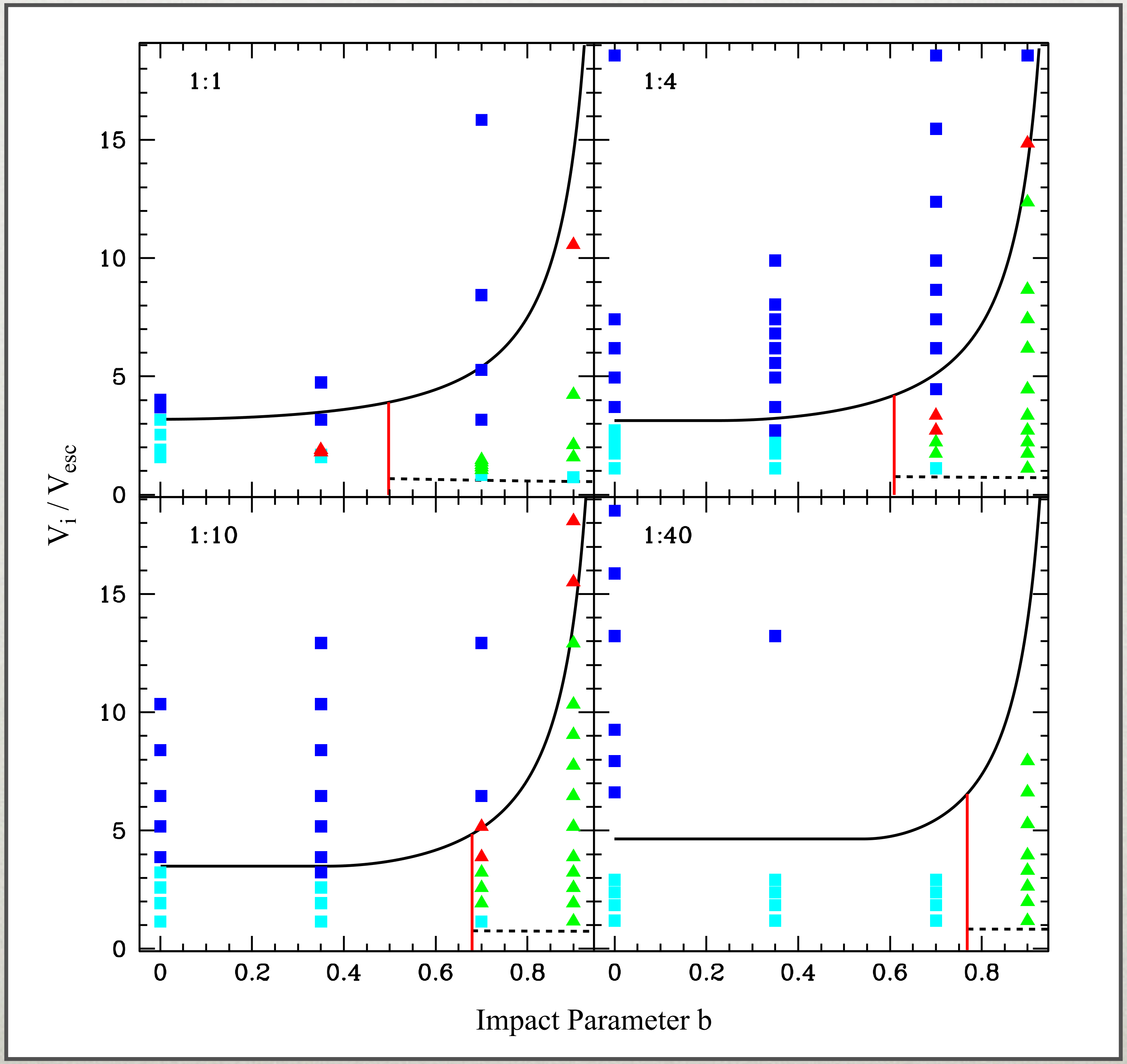

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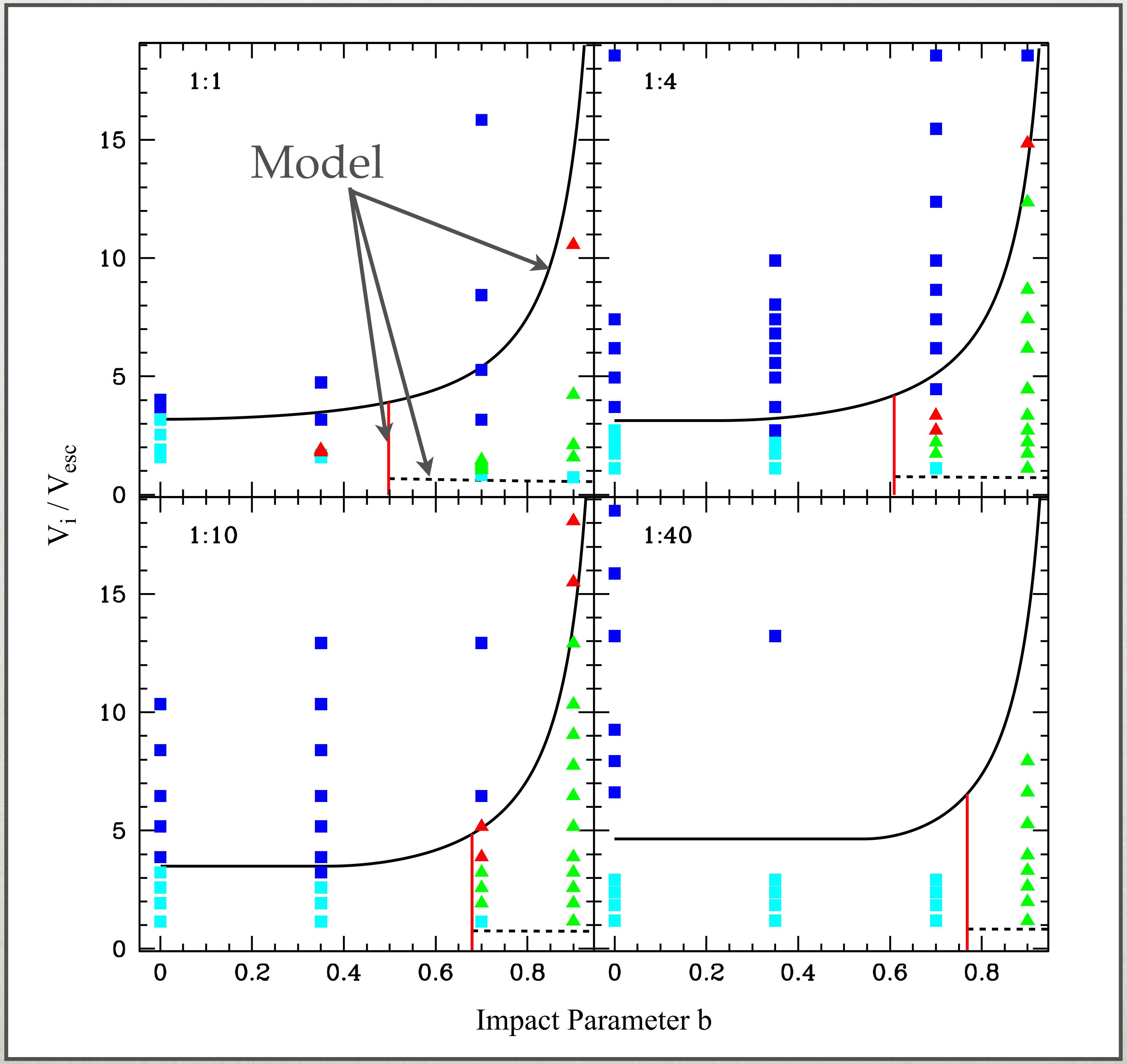

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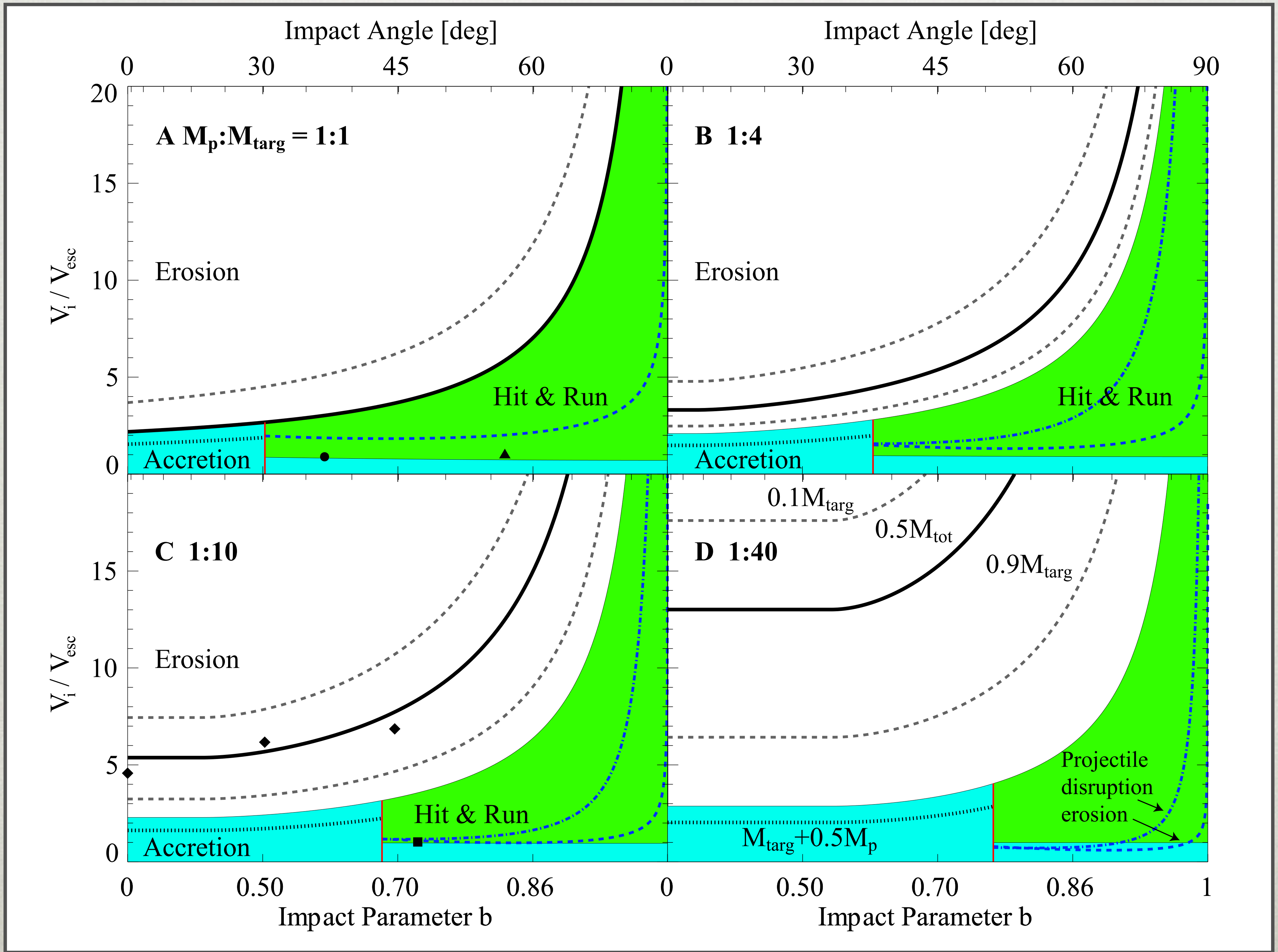

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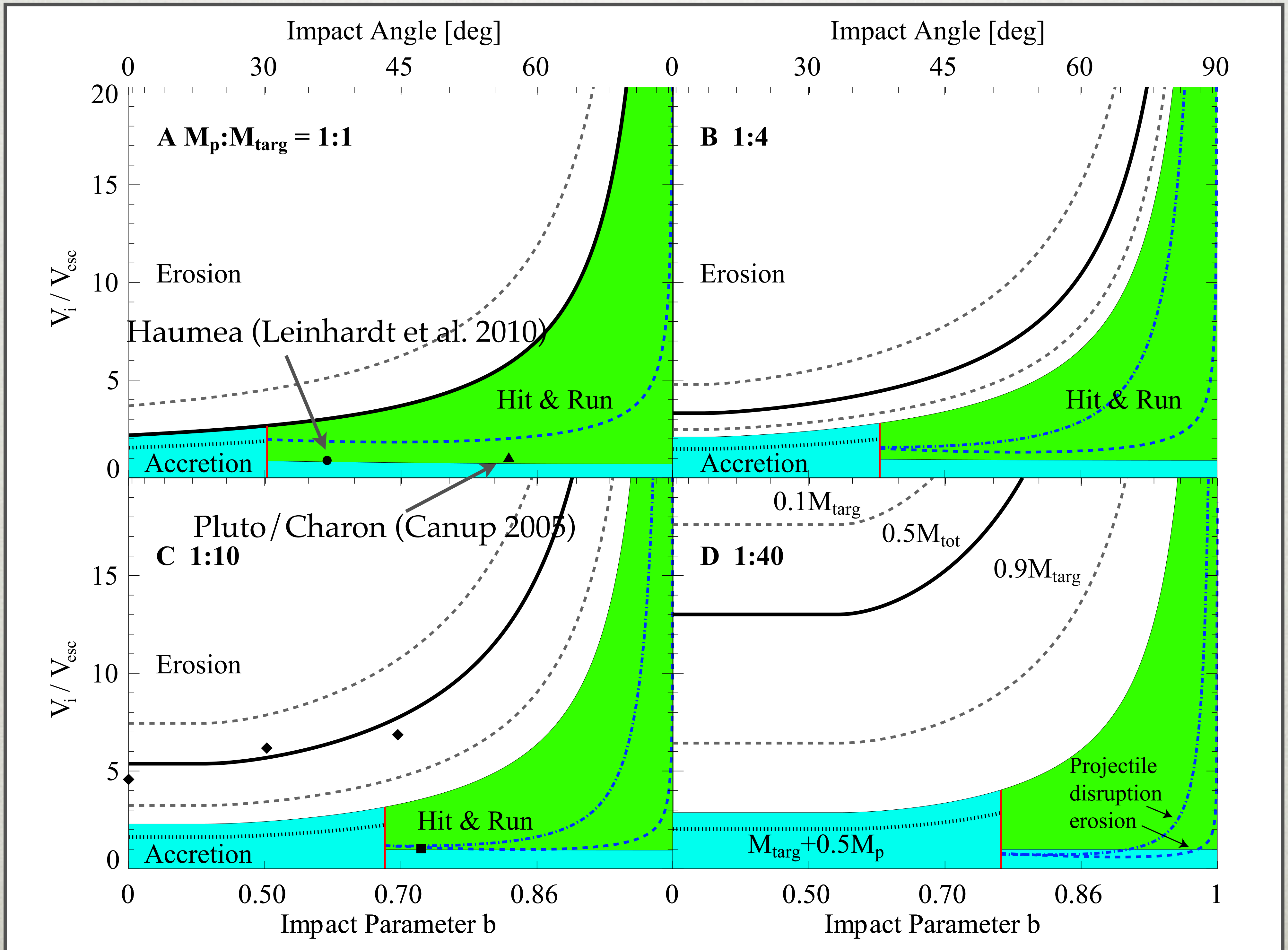

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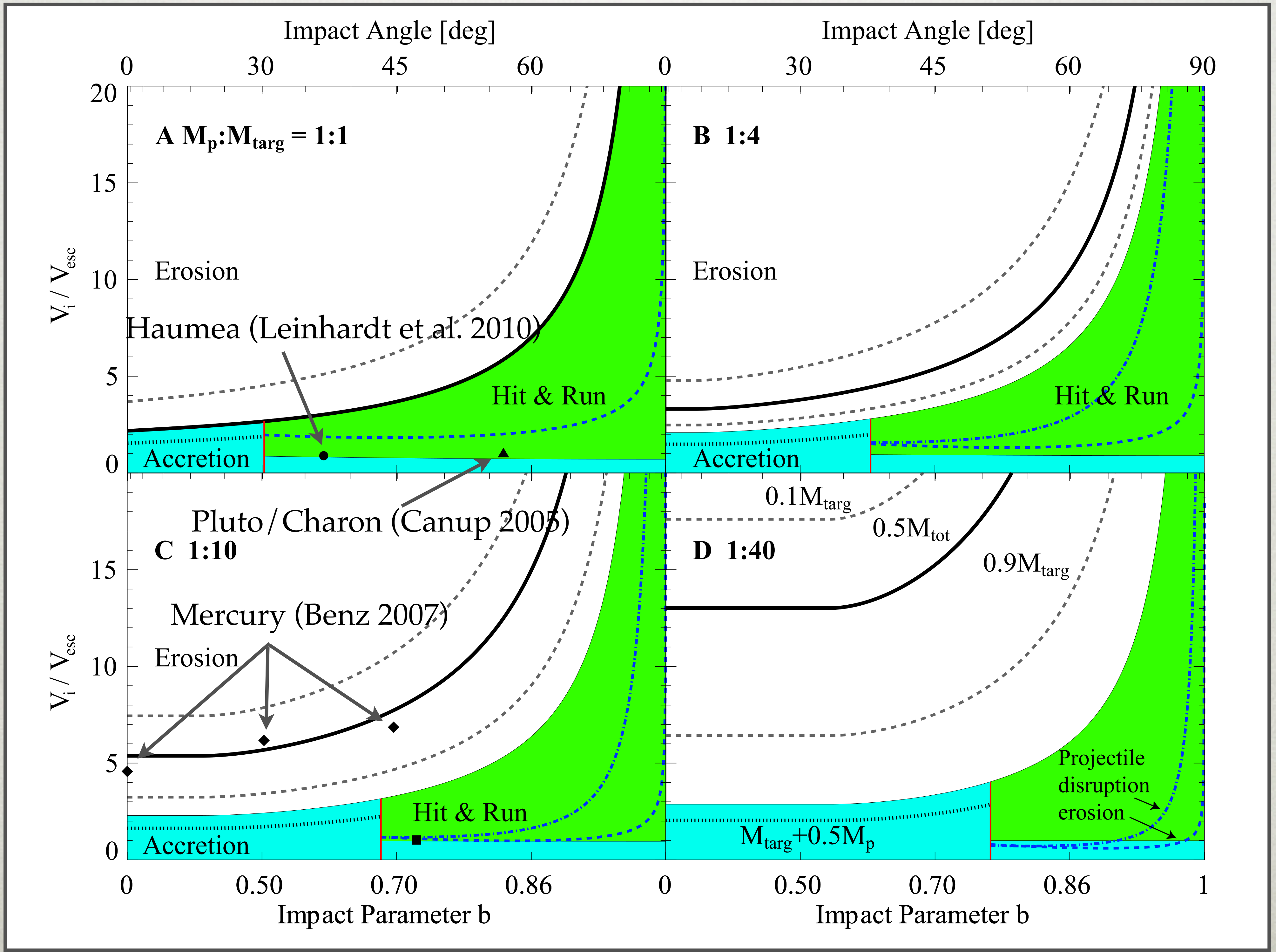

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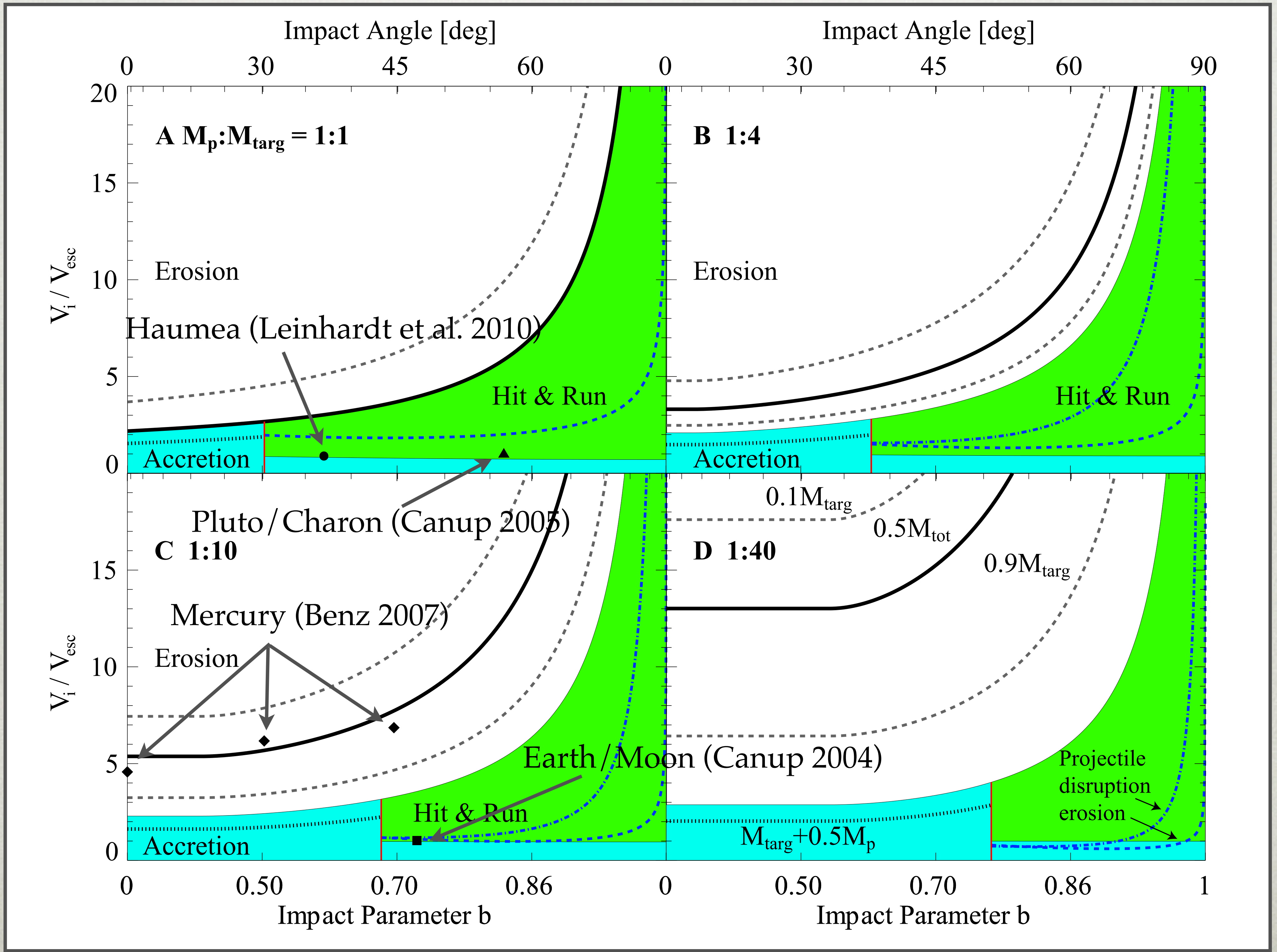


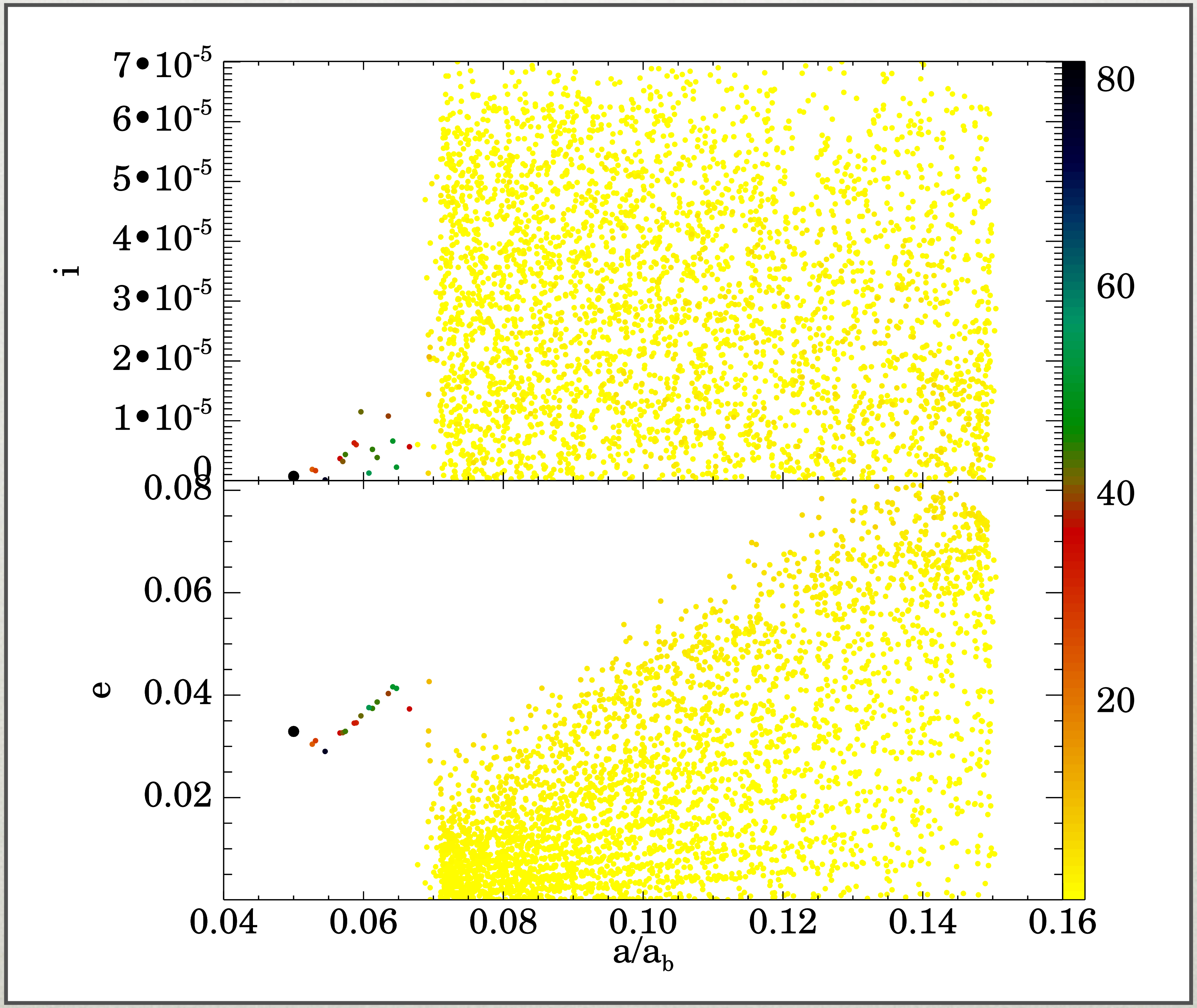
Summary

- New collision model provides largest remnant, size & velocity distributions for collisions of any mass ratio, impact parameter, impact speed.
- Old collision model being used in all work on binaries applies to a very limited range of collision parameters. Collisions between planetesimals in a binary star system should have a broad range of impact speeds, mass ratios, and impact angles.
- Old collision model would have over predicted the amount of energy needed to disrupt a planetesimal in a equal mass collision. Doesn't necessarily mean that it is even harder to grow (considerable feedback from additional debris). See next bit ...

Numerical Model of Planetesimal Evolution in ϒ Cep

- Swarm of planetesimals (10^6) moving in gravitational field of binary, static circular gas disk, & unresolved debris.
- Detect collisions, evolve sizes and velocities using simplified collision model from Stewart & Leinhardt (2009) & Leinhardt & Stewart (submitted).
- Dust component can be accreted onto larger planetesimals or can be used to make new planetesimals (1 km).
- Gas disk can potentially damp eccentricities but gas-drag is size-dependent. Still have high impact speeds between planetesimals of different sizes.
- Destructive collisions increase collision timescale, making it more likely remaining bodies will survive.

3D Results



Planetesimal Size

Paardekooper, Leinhardt & Thébault (in prep.)

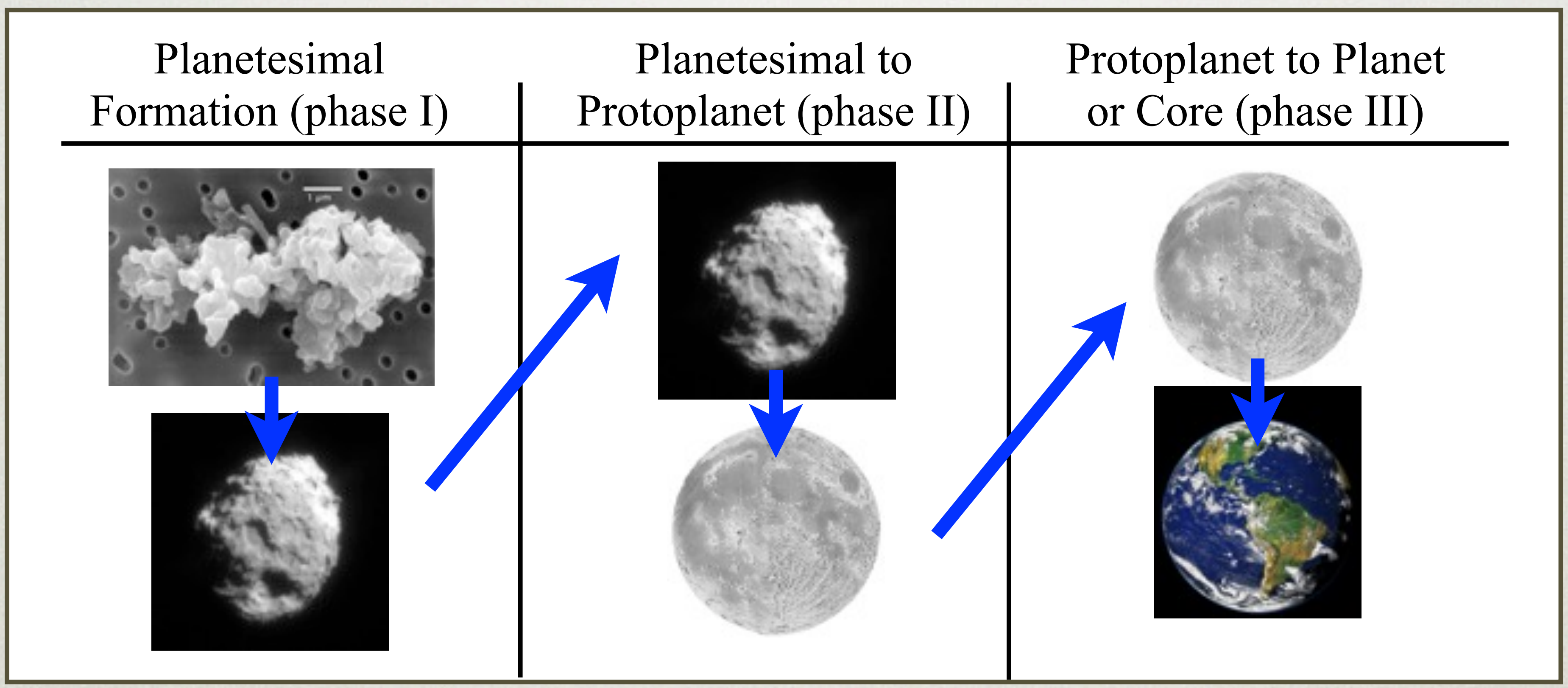
Summary

- Fully 3D simulations still allow growth but it is slower and the growth region is narrower than our earlier 2D sim. results.
- Forming planets in tight binaries is hard. It is essential to include collisions in a self-consistent way. Planetesimals can grow if they can accrete small debris.
- Caveat: Impact speed of dust onto planetesimals may be far too fast for accretion.
- New collision model is available on astro-ph: Leinhardt & Stewart arXiv:1106.6084.

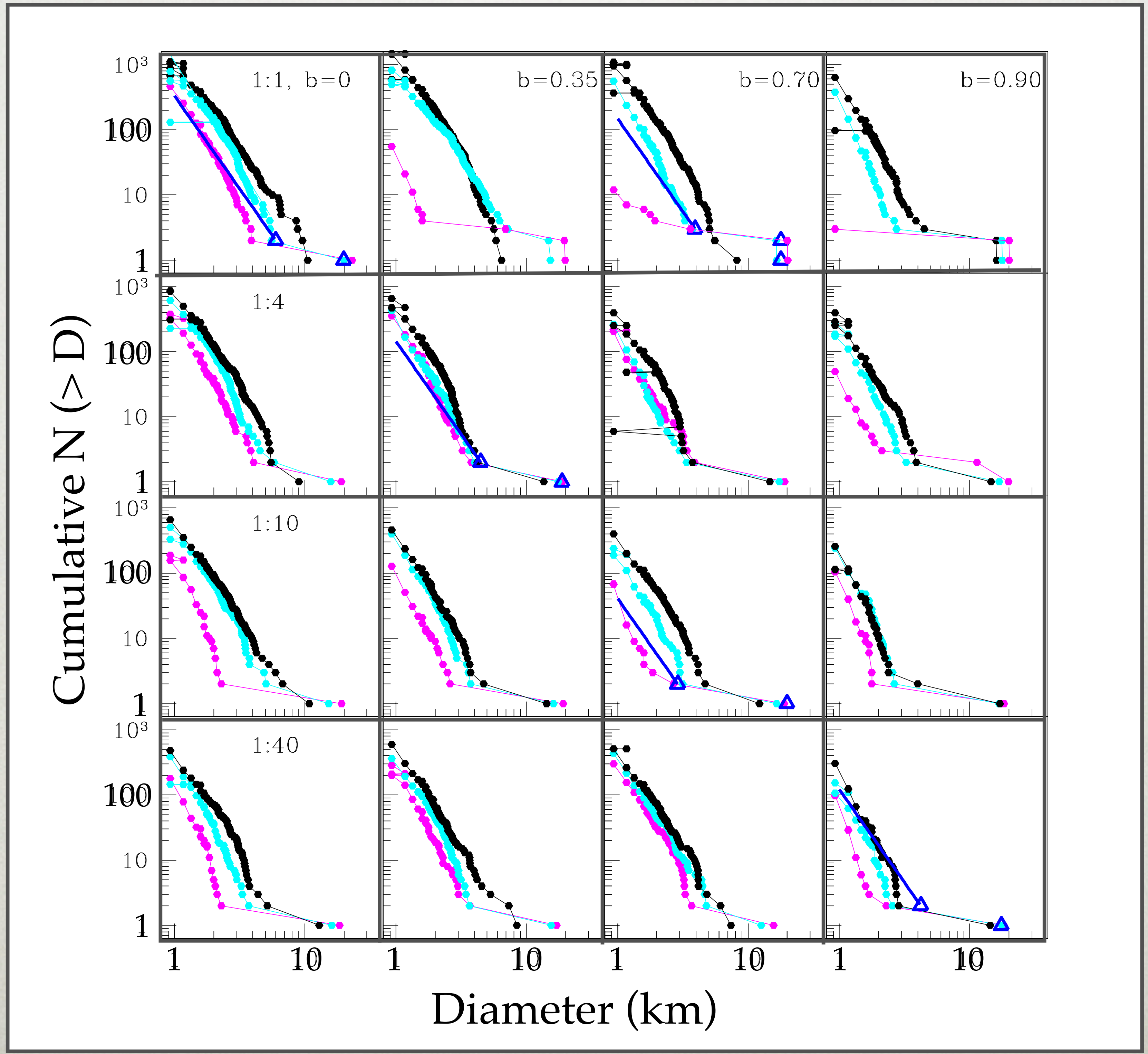
Recent Work

- What are the most extreme systems that can still support planet formation?
  No clear answers here but recent work on phase II (p to pp)
  separation distances (between stars): ~50-100 AU
  (e.g. Paardekooper et al. 2008, Fragner et al. 2011)
  inclinations (of stars): modest 10 - 20
  (e.g. Xie & Zhou 2009, Fragner et al. 2011)
  work on phase I is also less than definitive
  Zsom et al. (2011) find that dust aggregate growth becomes very difficult for tight binary configurations
- All work depends on collision model. When do the planetesimals grow and when do they erode?

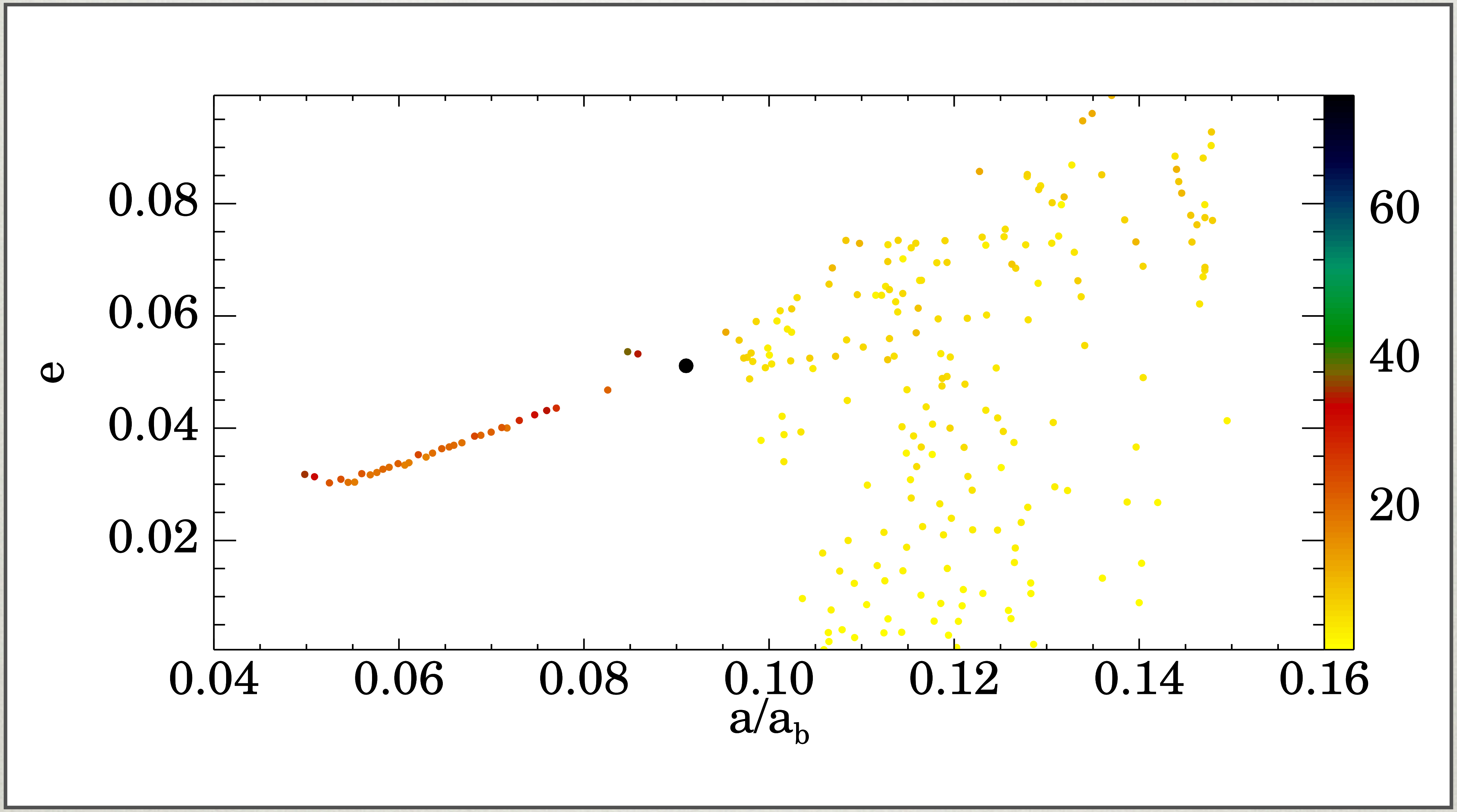
Core Accretion Cartoon



Collision Model for Planet Formation



2D Results



Paardekooper & Leinhardt (2010): planetesimals can grow if allowed to accrete debris from disrupted planetesimals. Assumed no velocity evolution of M_{lr} as result of collision (stayed on the same orbit).