A Planetesimal Pas de Deux or the Clash of the Titans: A Model for Collisions in Planet Formation

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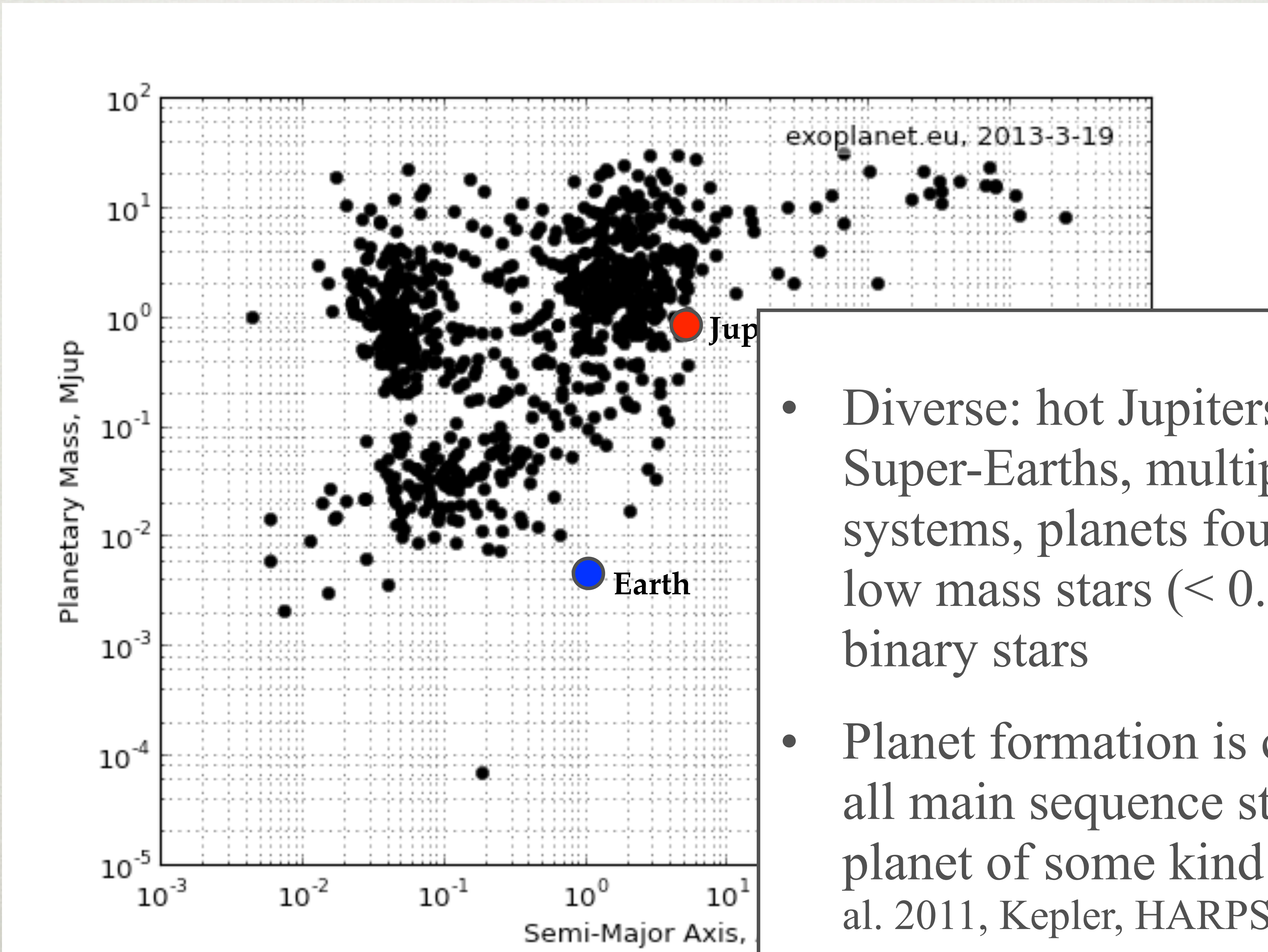
Exoplanets



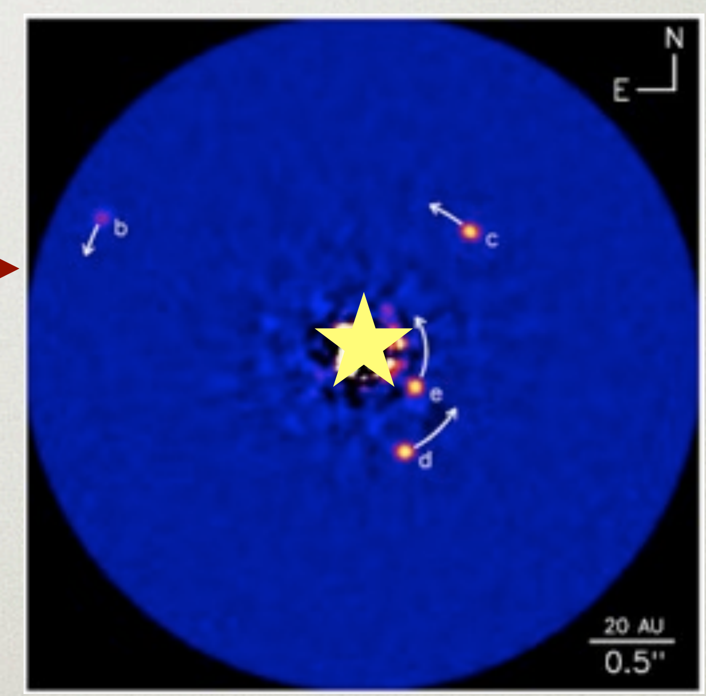
- Diverse: hot Jupiters, hot Super-Earths, multiple systems, planets found around low mass stars (< 0.5 M_{sun}) & binary stars
- Planet formation is common: all main sequence stars have a planet of some kind (Borucki et al. 2011, Kepler, HARPS)

Planet Formation

- Number of observed planets increases daily (919 on 13.08.13), drives planet formation theory
- Observations provide snapshots of protoplanetary disks or stable planetary systems. Little info. to connect two stages. Leaves numerical sims. But diversity still a surprise.

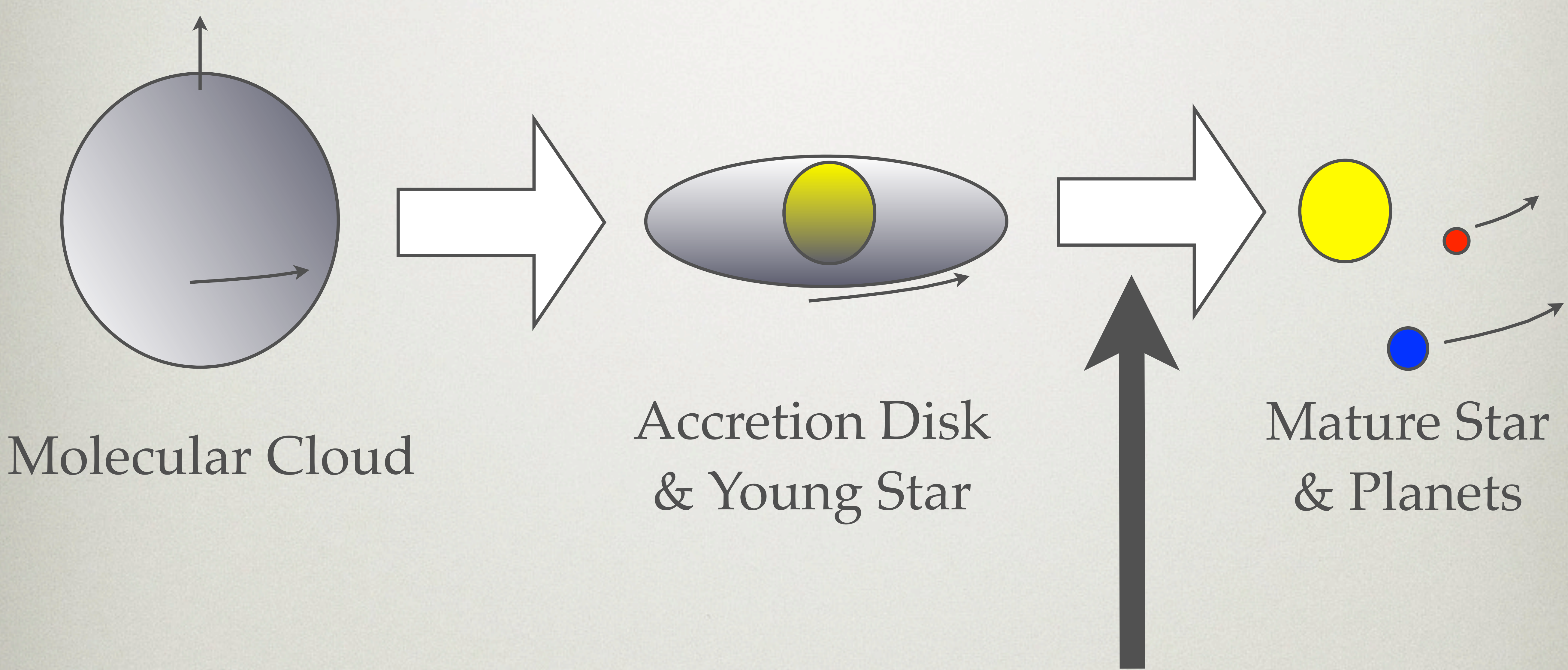
HH 30, Watson (2000)

Bluecrystal Supercomputer UoB



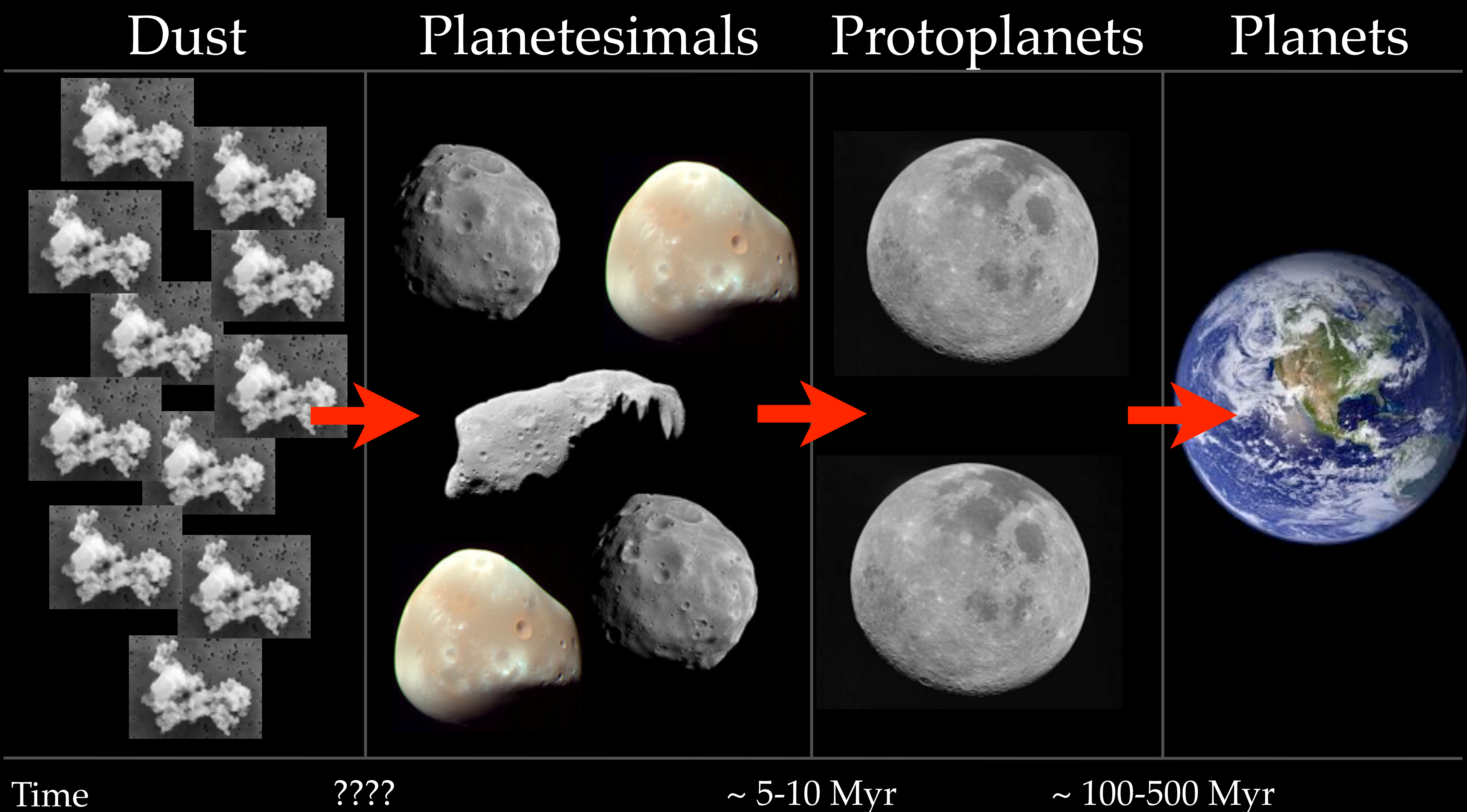
HR 8799, Marois et al. (2010)

Planet Formation Cartoon



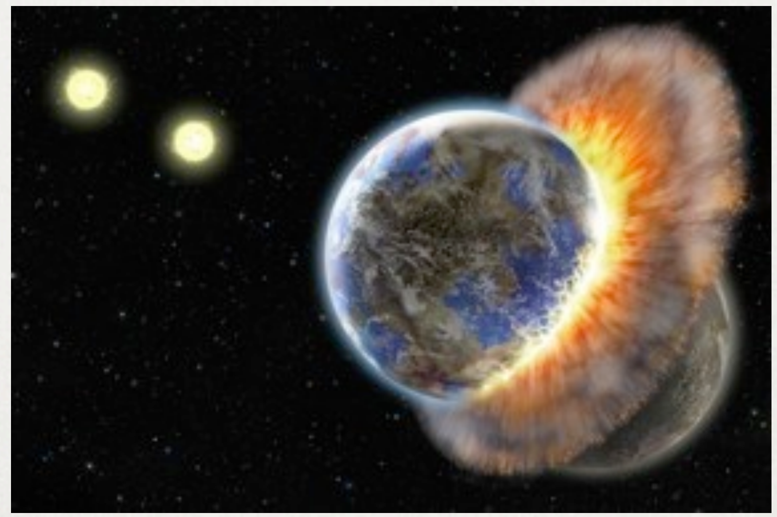
This is the process we would like to understand. It is effectively invisible.

Phases of Planet Formation



Collisions within a Solar System

Planetesimal Collisions

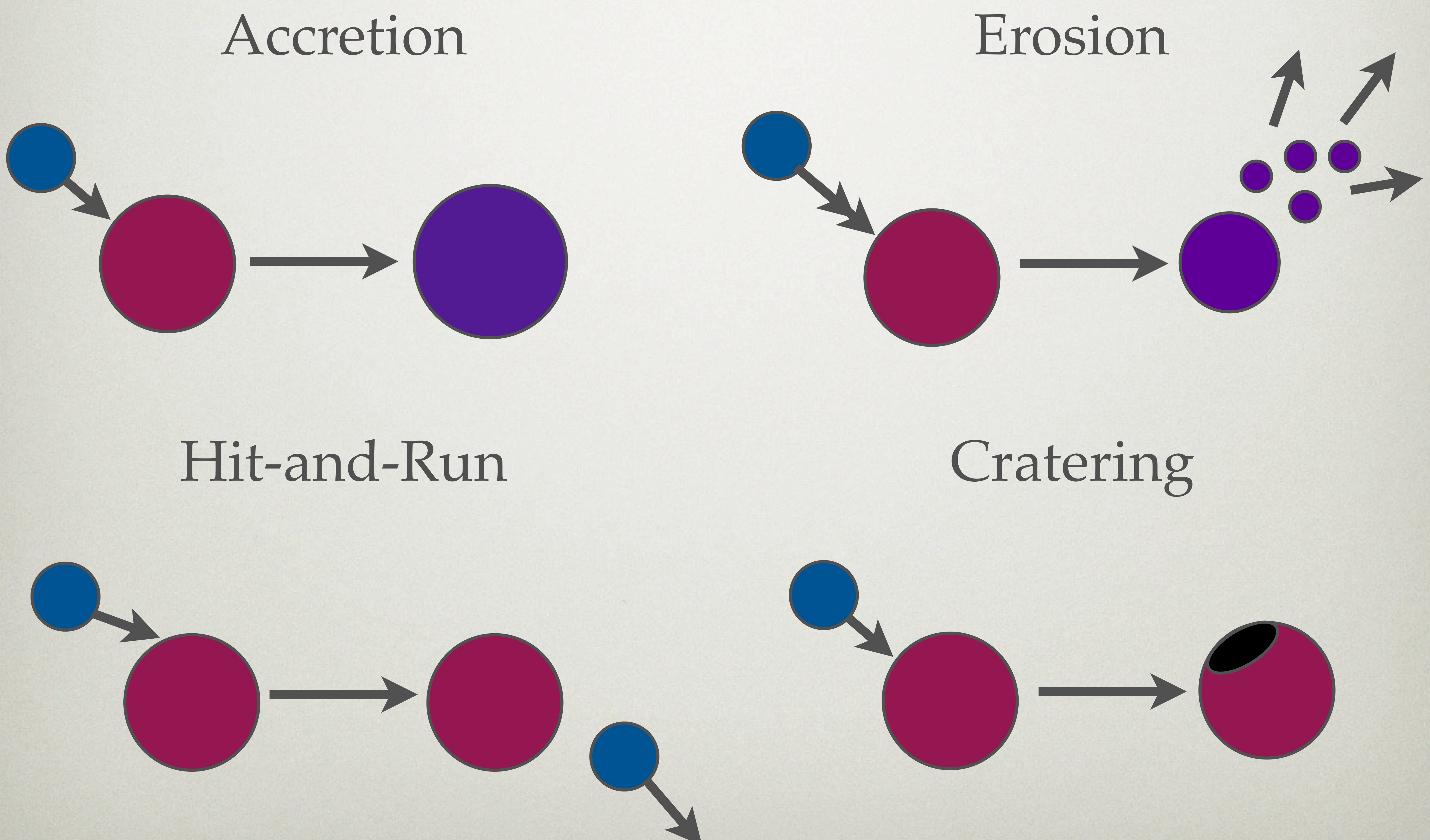


Giant Impacts

Family Formation

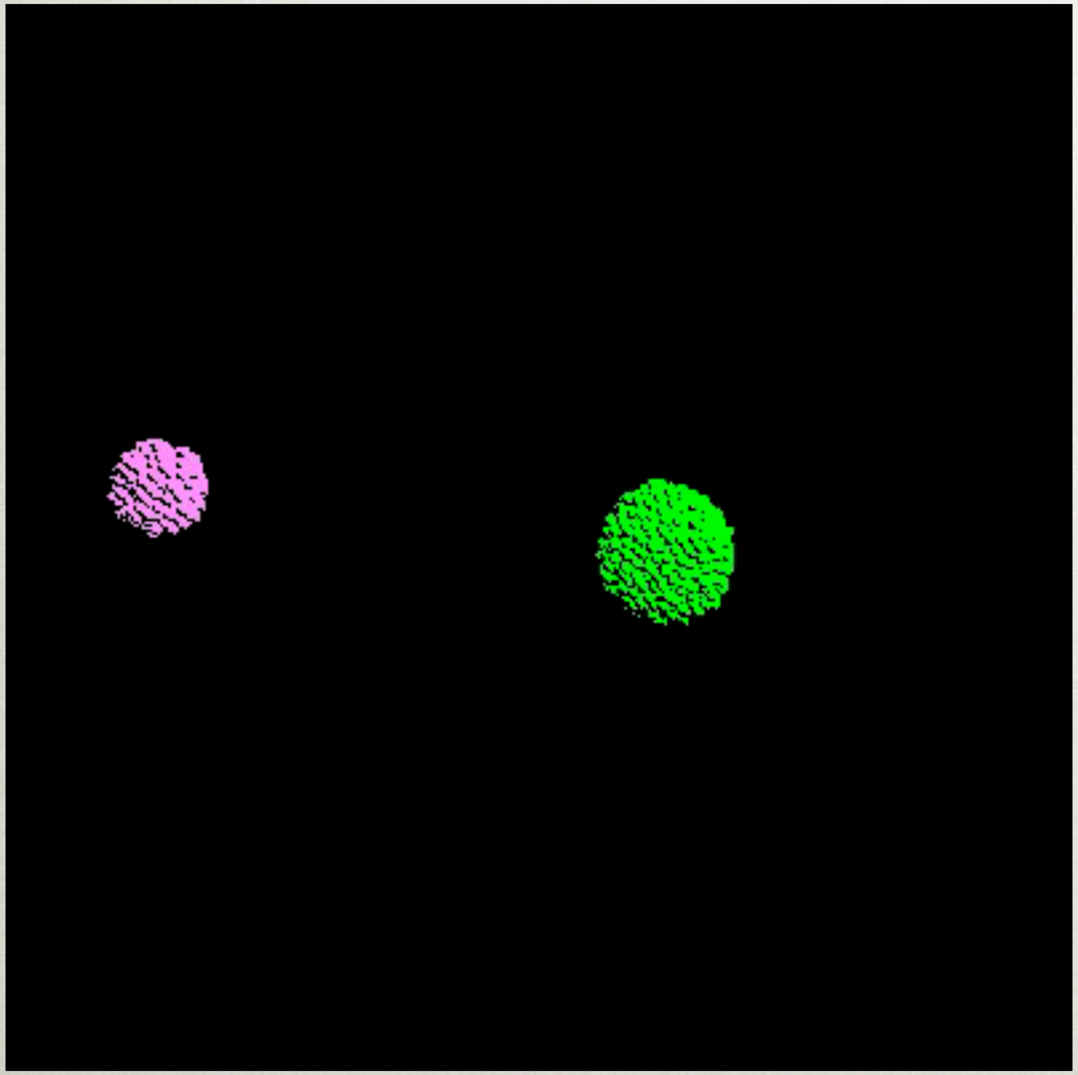
- Collisions are fundamental to the evolution of solar systems: planetesimal evolution, giant impact phase, late evolution
- Many phenomena require that we understand collisions and have a model to describe them
- Previous collision models cannot constrain the models: simplistic (assume a simple collision outcome), slow (directly model the collision), apply to a narrow regime of phase space

Possible Collision Regimes

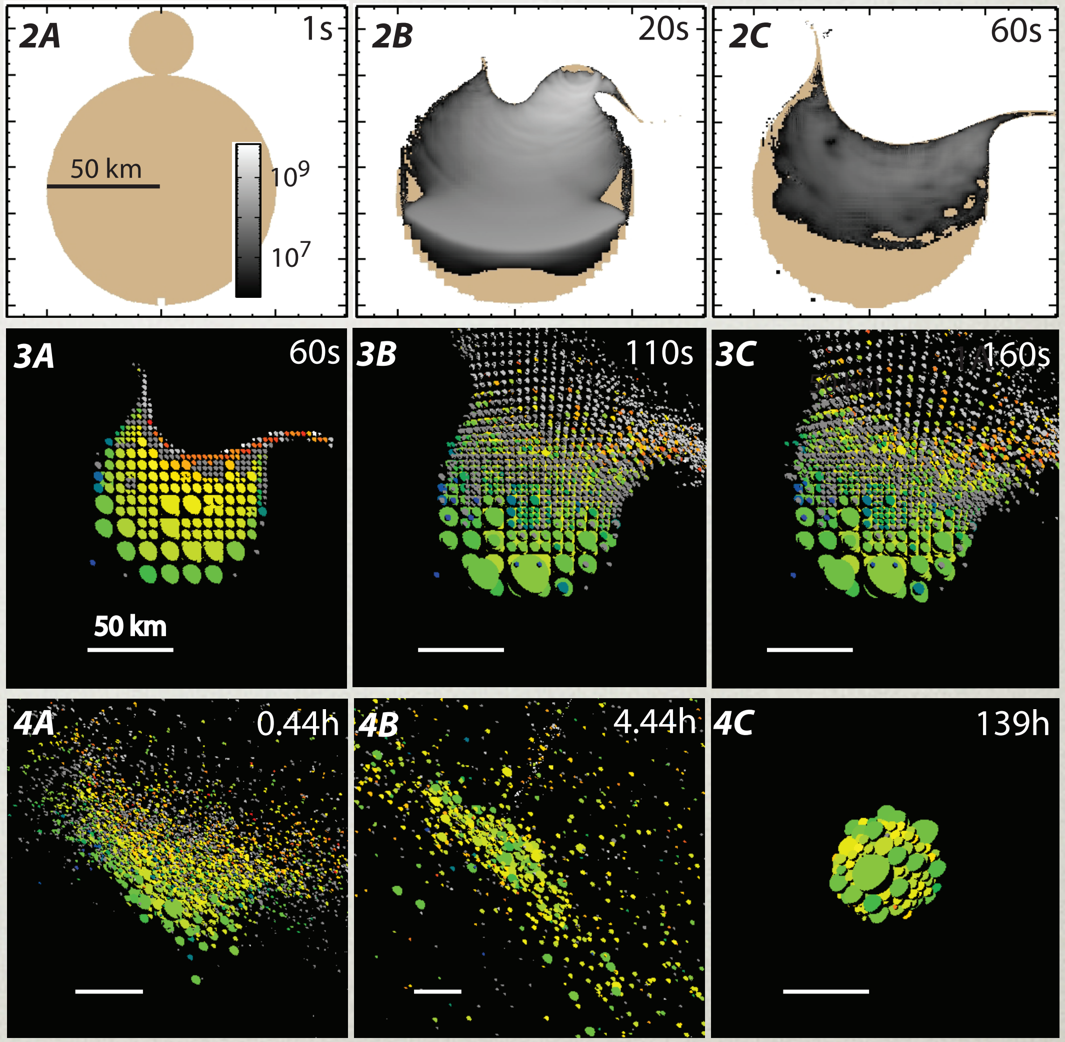


Numerical Simulations of Collisions

Method: Numerically simulate collisions in isolation. Fit scaling-laws to collision outcomes and regime transitions.



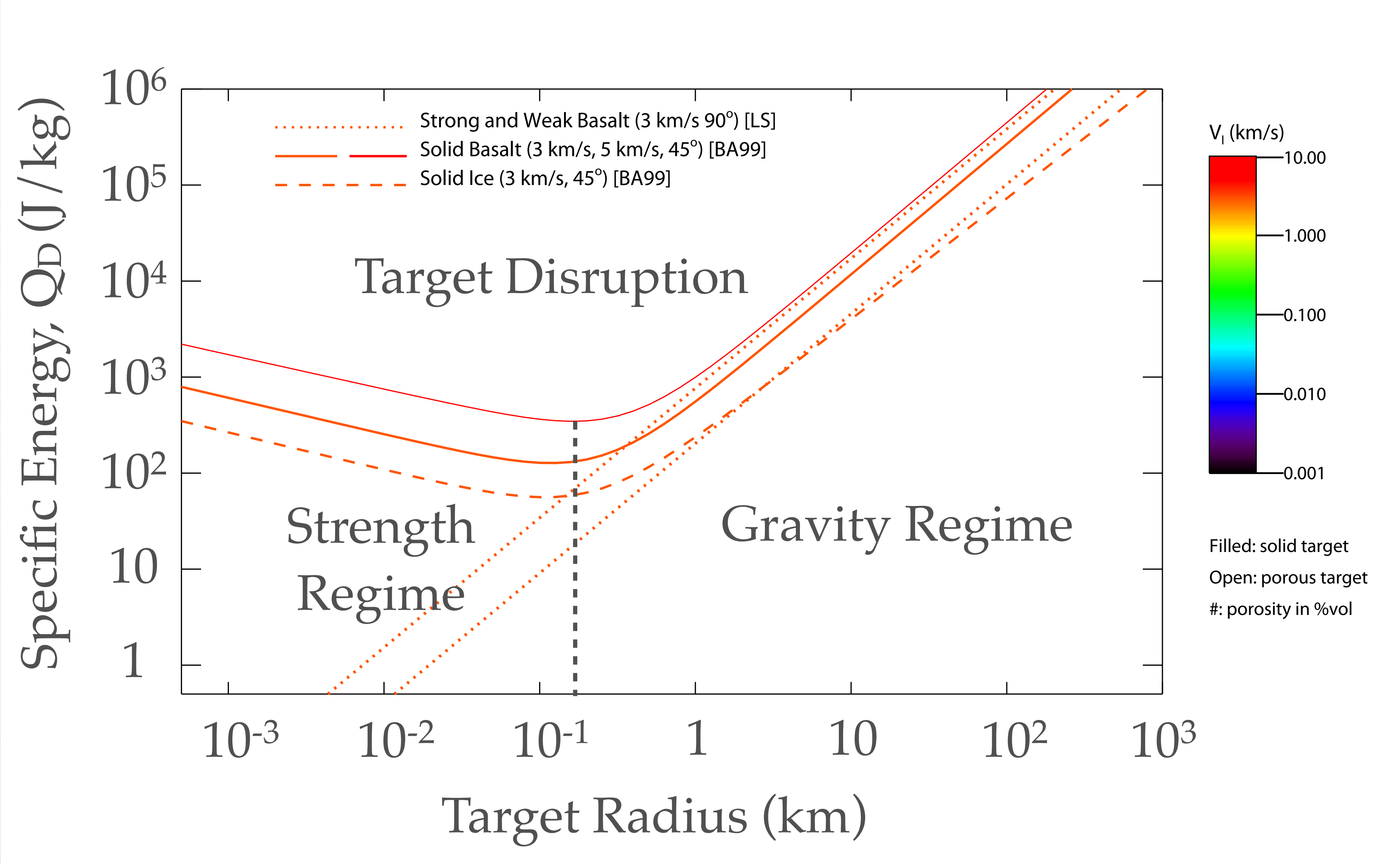
Leinhardt & Richardson 2002



Leinhardt & Stewart 2009

Old Collision Model

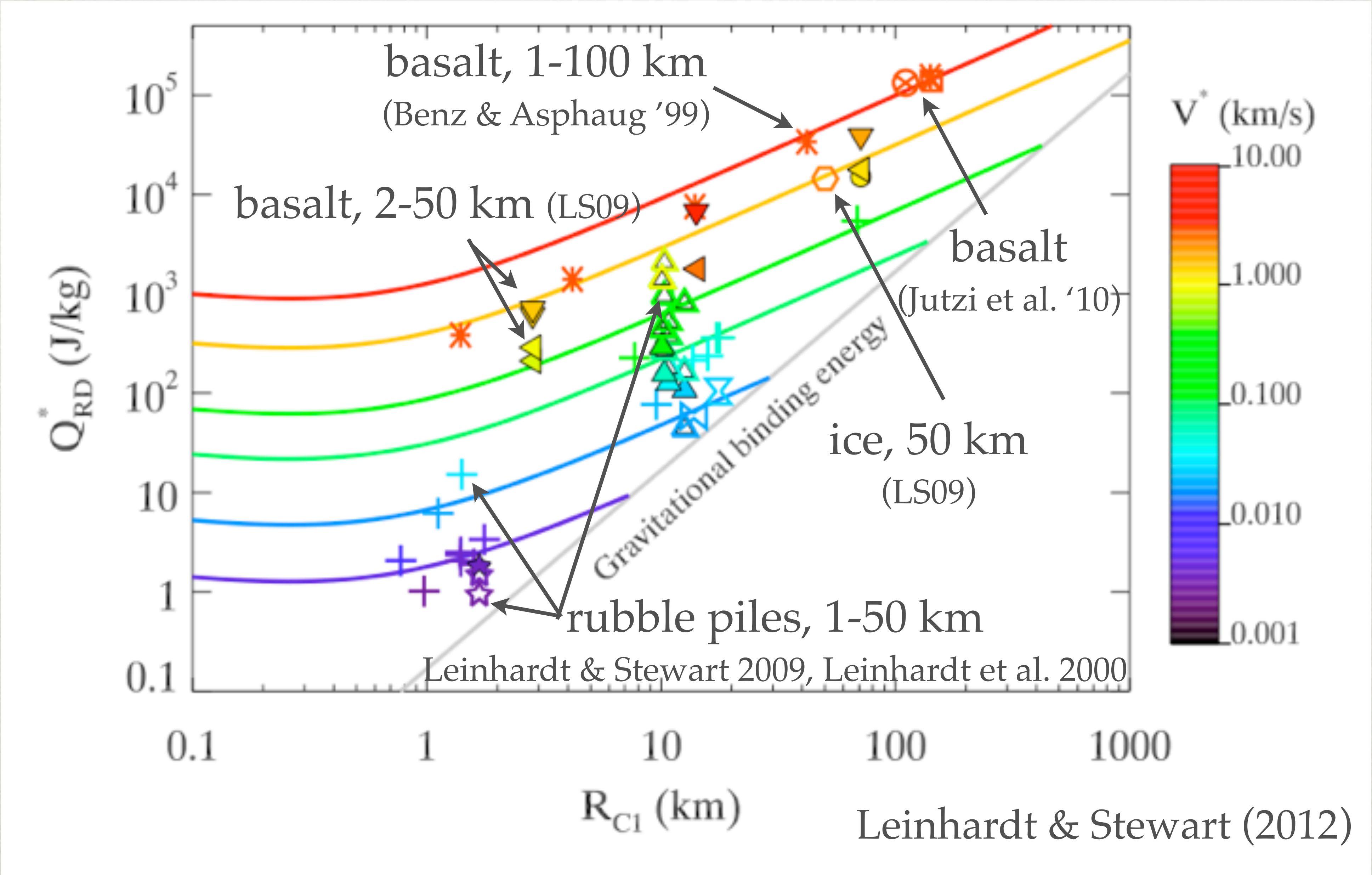
Benz & Asphaug 1999



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

Model was used well outside of range

Empirical Scaling Laws



Wednesday, 14 August 13

Empirical Scaling Laws

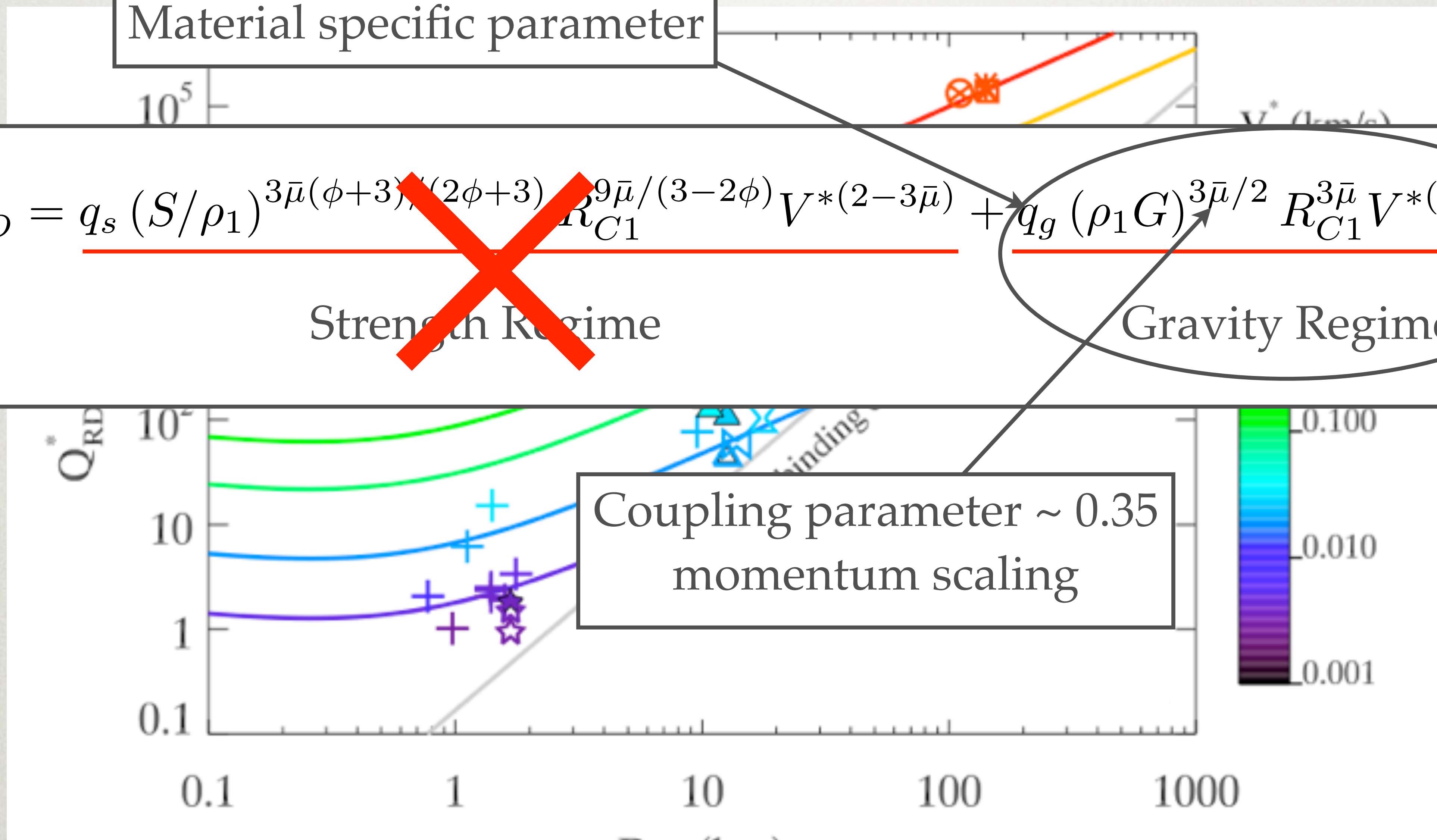
$$Q^*_{RD} = q_s\,(S/\rho_1)^{3\bar{\mu}(\phi+3)/(2\phi+3)}\,R_{C1}^{9\bar{\mu}/(3-2\phi)}\,V^{*(2-3\bar{\mu})} + q_g\,(\rho_1 G)^{3\bar{\mu}/2}\,R_{C1}^{3\bar{\mu}}\,V^{*(2-3\bar{\mu})}$$

Strength Regime

Gravity Regime

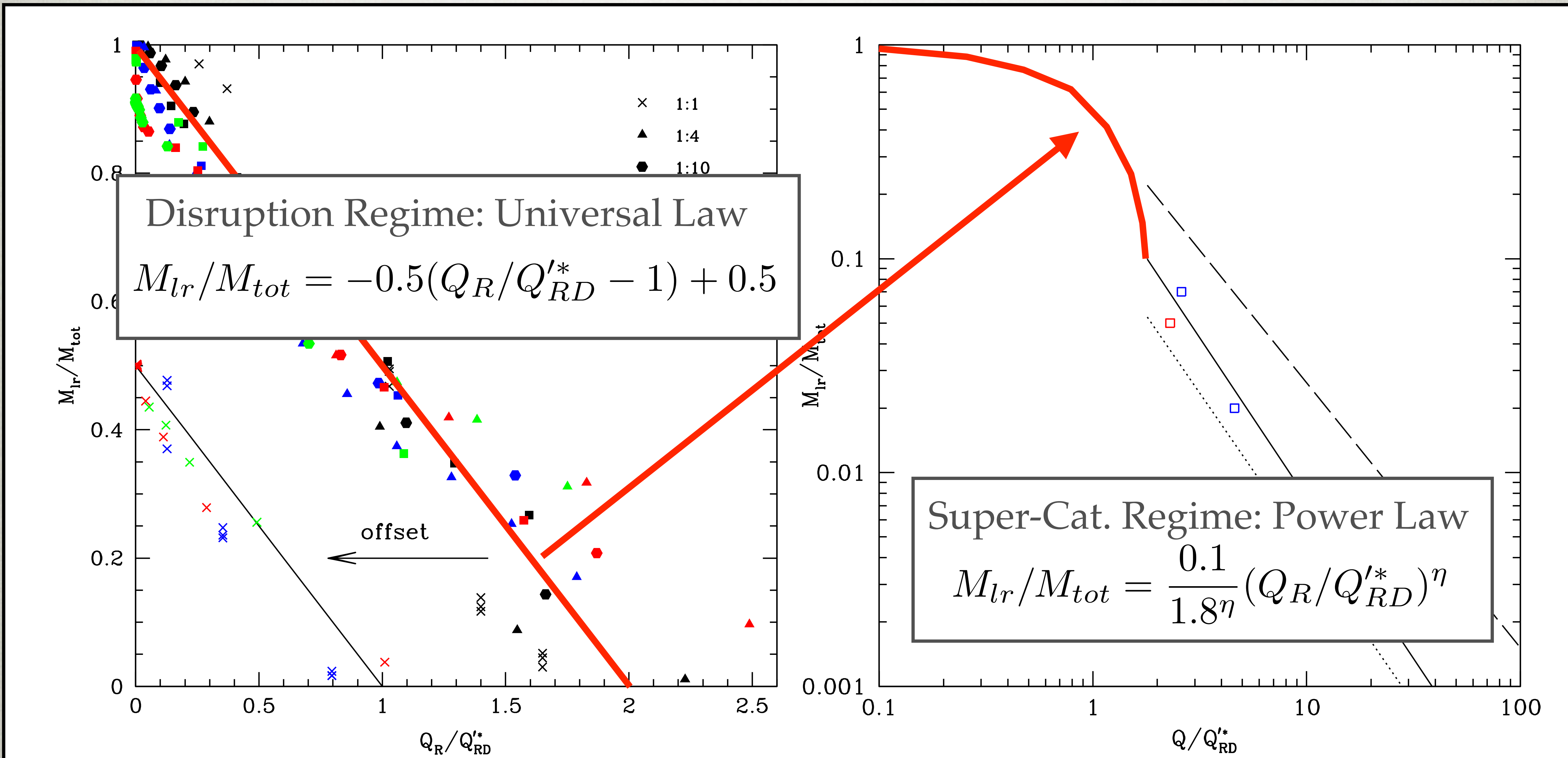
Material specific parameter

Coupling parameter ~ 0.35
momentum scaling



Leinhardt & Stewart (2012)

Disruption & Super-catastrophic Regime



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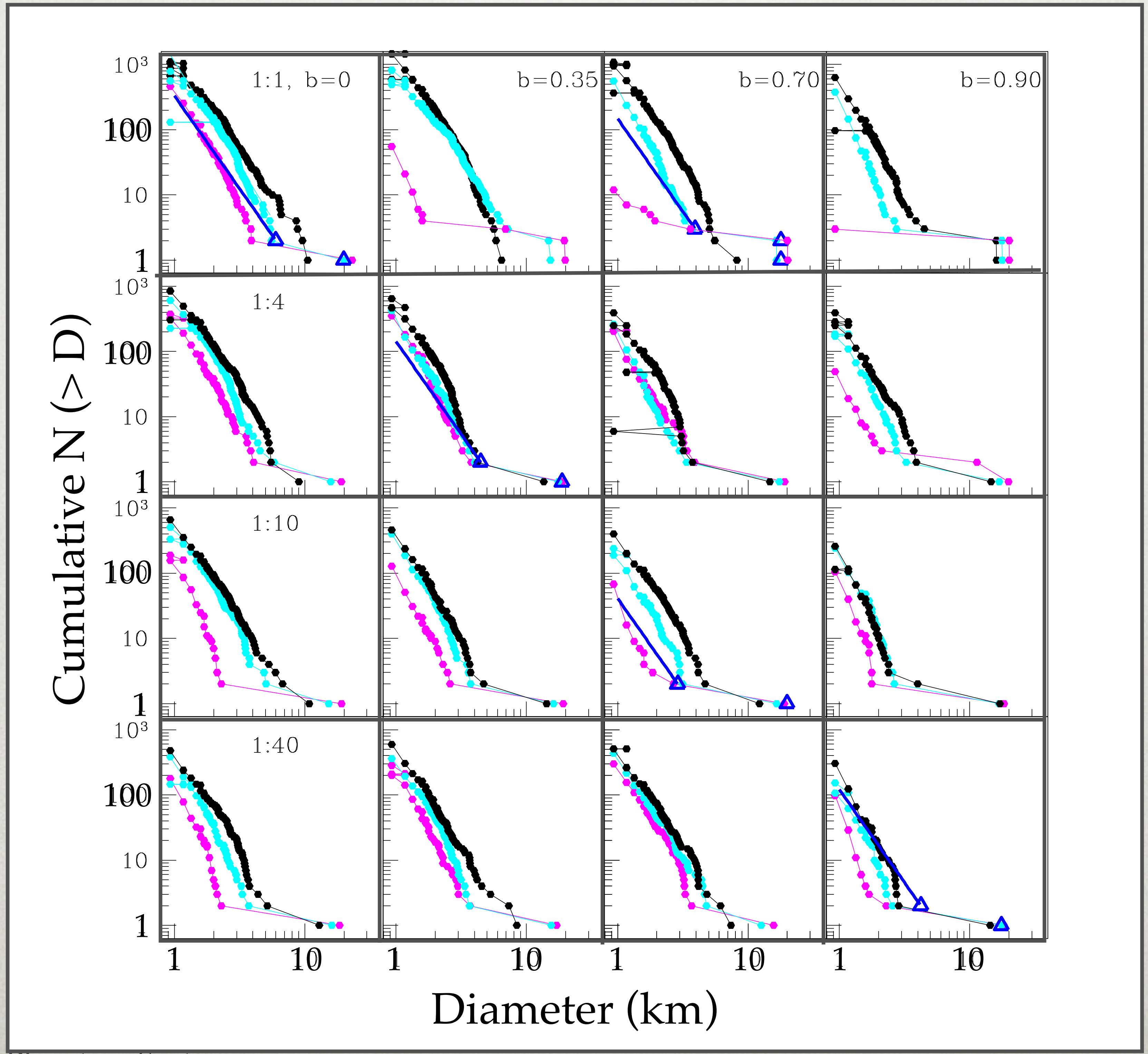
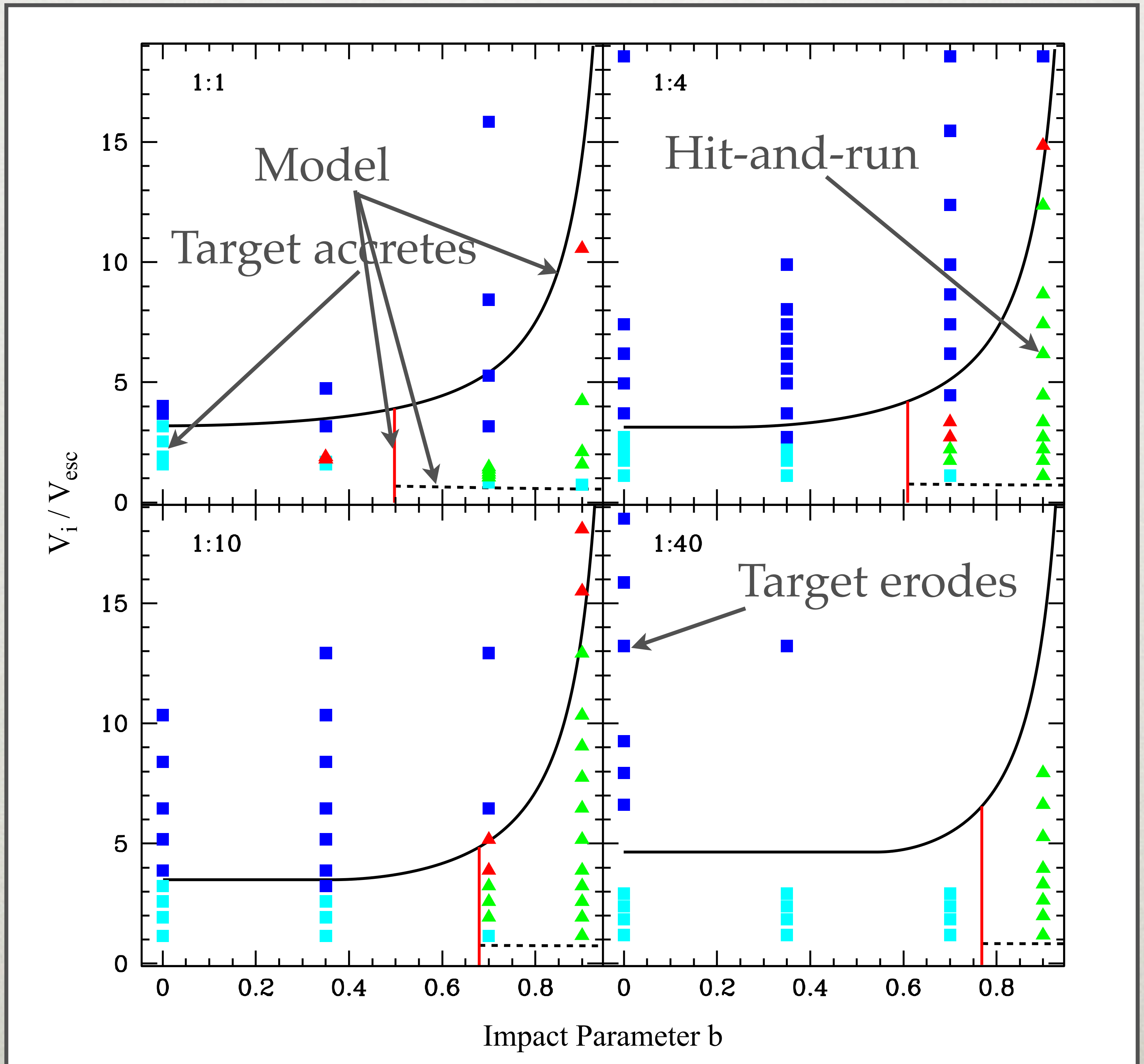
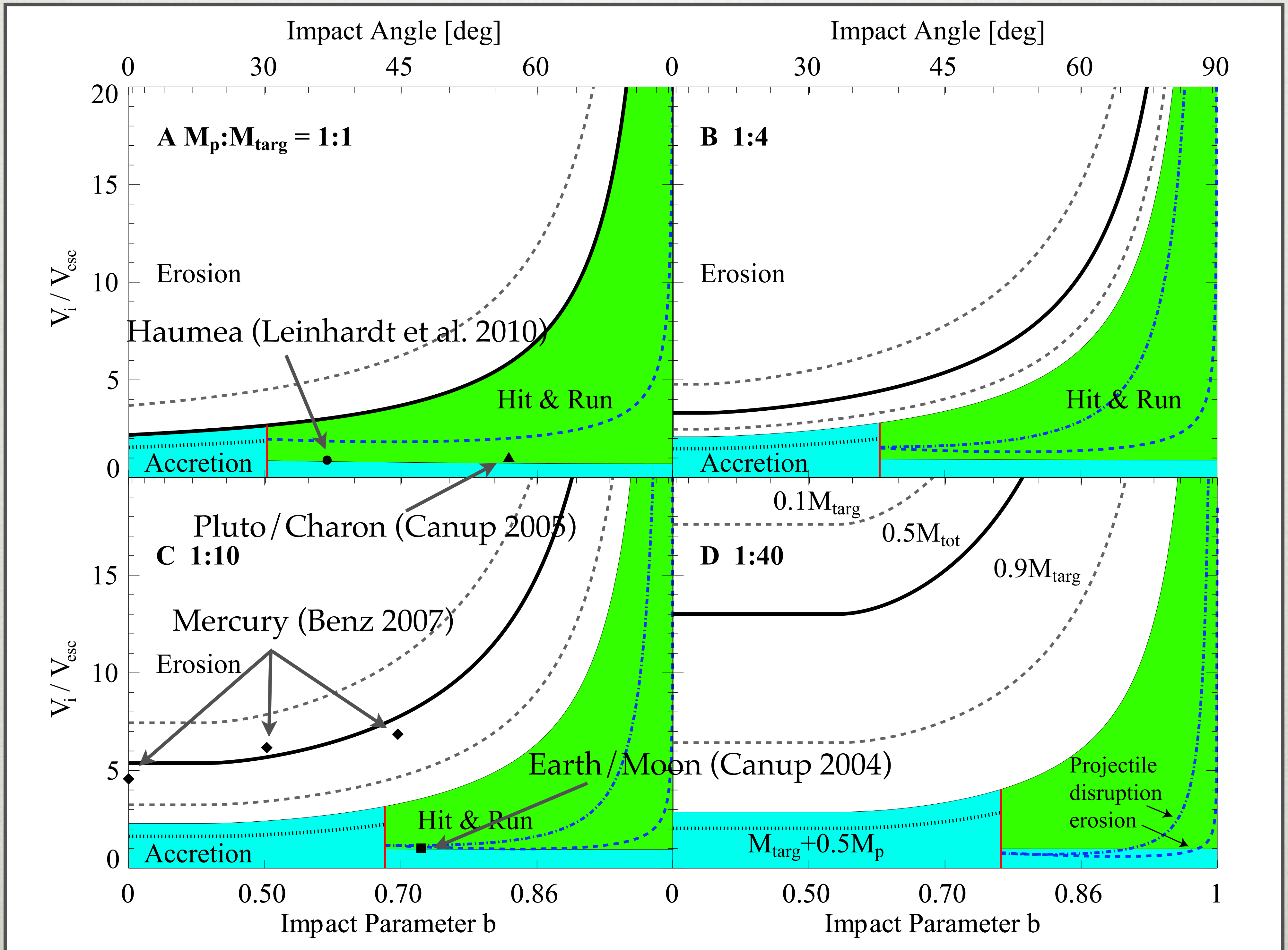
Collision Model for Planet Formation



Outcome Regimes



Outcome Regimes

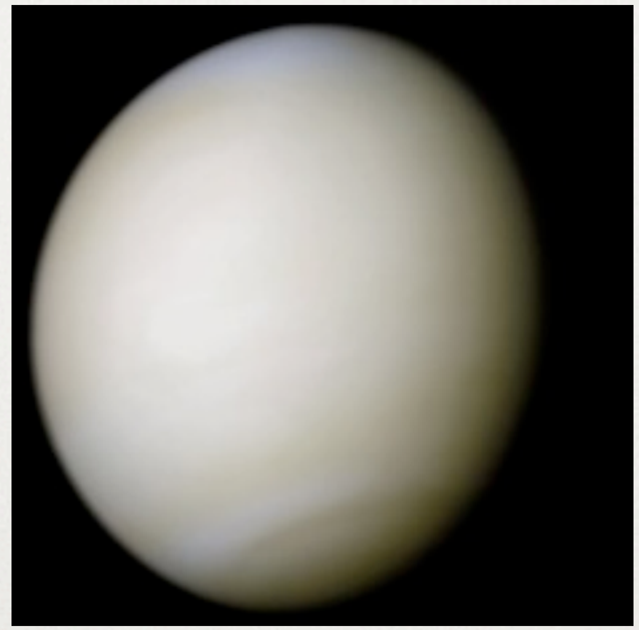


Summary of Collision Model

- New collision model provides largest remnant, size & velocity distributions for collisions of any mass ratio, impact parameter, impact speed.
- Collision model from Benz & Asphaug ’99 applies to a very limited range of collision parameters. Collisions between planetesimals, asteroids, protoplanets 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). But the process is more complex. New collision model increases possible outcomes and thus diversity.

Evidence of Giant Impacts in The Solar System

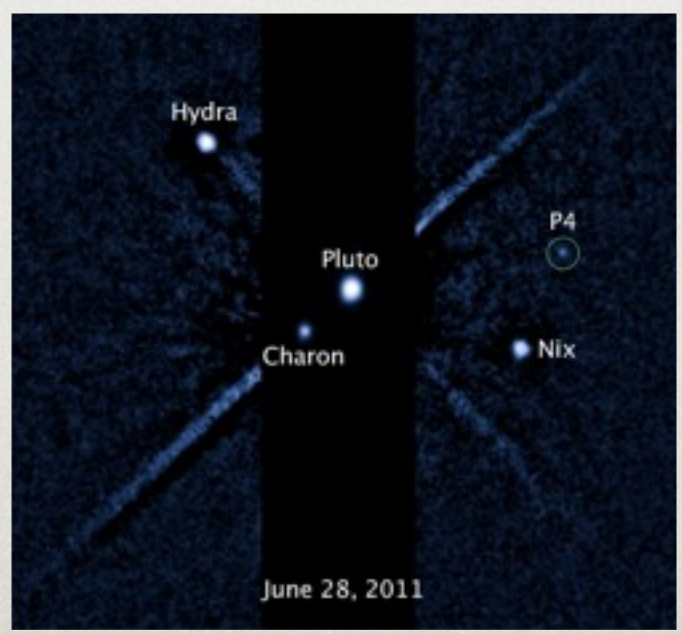
Mercury: Large Core



Venus: Retrograde Rotation

Moon: Formation

Mars: Crustal Dichotomy



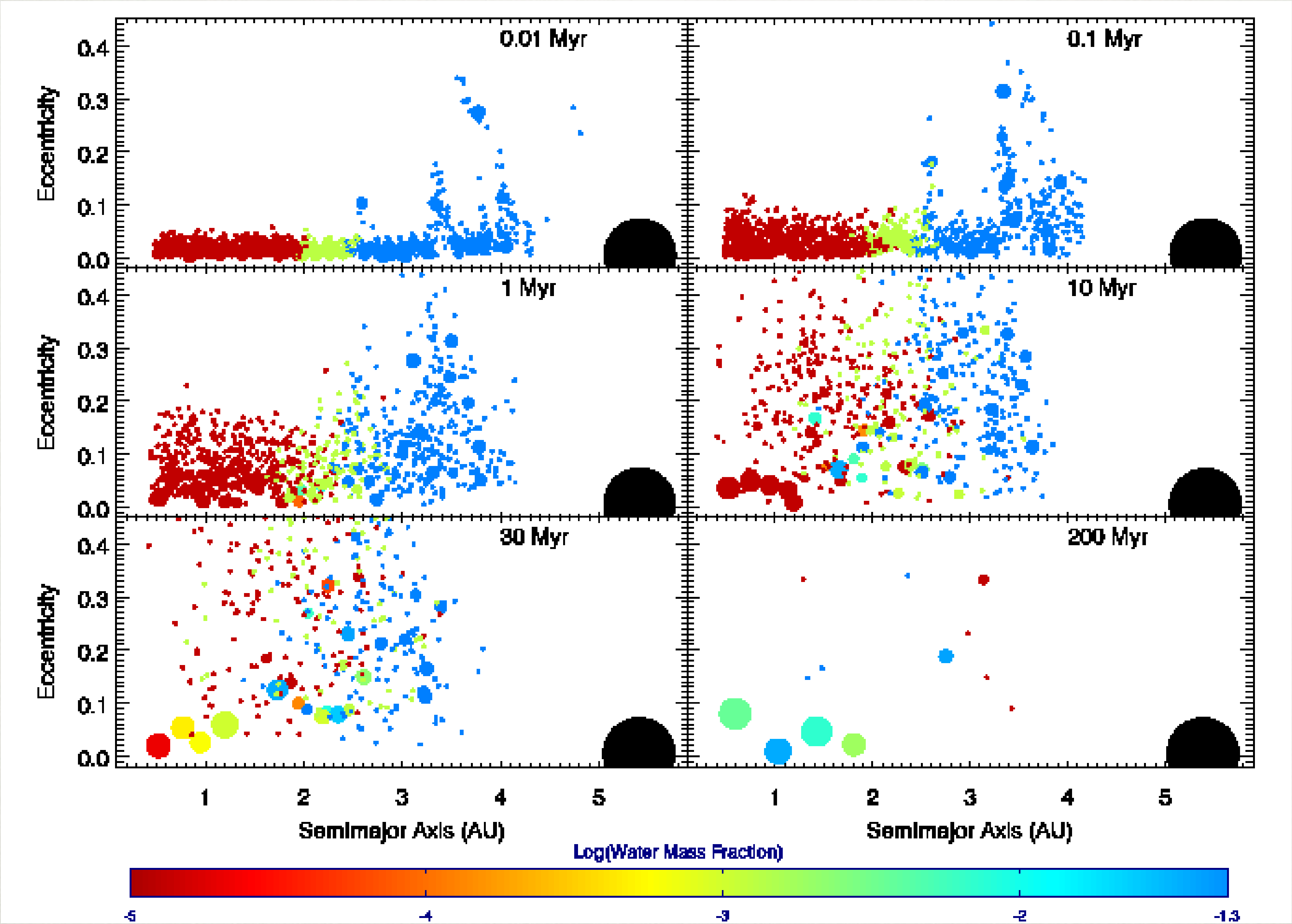
Pluto: Satellite System

Haumea: Spin and Moons

Impact of New Collision Model?

- What kind of impacts really occur in planet formation?
- Retrospective analysis of impacts between planetary embryos from published N-body simulations of giant impact stage from Raymond et al. (2009) & O'Brien et al. (2006)
- Original simulations used 25 - 90 embryos and 1000 planetesimals at beginning of last stage of growth - the stochastic giant impact phase
- Impacts between embryos are "giant" impacts - all impacts originally resulted in a perfect merging event (both for embryo-embryo and embryo-planetesimal)

Original Raymond et al. 2009



Implications of Collision Model from Individual Collisions

	Group 1 O'Brien et al. 2006 15 Large Planets from 8 Sims. $0.74 - 1.58 M_{\mathrm{Earth}}$				Group 2 Raymond et al. 2009 52 Large Planets from 40 Sims. $0.70 - 1.45 M_{\mathrm{Earth}}$			
	Planetesimal		Giant		Planetesimal		Giant	
Collision outcome	$N = 1140$	%	$N = 67$	%	$N = 3142$	%	$N = 544$	%
Super-catastrophic	0	0	1	1	0	0	0	0
Partial erosion	8	< 1	1	1	61	2	3	< 1
Partial accretion	820	72	18	27	2180	69	213	39
Perfect merging	0	0	0	0	18	< 1	4	< 1
Graze-and-merge	43	4	26	39	85	3	173	32
Hit-and-run	269	24	21	31	798	25	151	28
Special cases								
H&R with proj. erosion	265	23	3	4	778	25	75	14
$5 - 10\%$ increase in f_{core}	0	0	5	7	0	0	132	24
$> 10\%$ increase in f_{core}	0	0	6	9	2	< 1	90	17

- Found giant impacts are evenly split between accretion, graze-and-merge, and hit-and-run events. Few true perfect merging events.
- Individual giant collisions can change core to mantle ratio by > 10%

Testing the Cumulative Effect of the Collision Model

To explore the cumulative effects of more realistic collision model on the growth of an individual planet we developed a Monte Carlo technique using the impact parameter distributions from the late stage N-body simulations

1. Choose an initial mass from N-body distribution
2. Choose number of giant impacts from N-body distribution
3. For each giant impact choose impact parameters from N-body distributions
4. Choose mass contribution from planetesimals from N-body distributions

Implications of Collision Model
Model from Multiple Collisions

Collision outcome	Group A: No hit-and-run return; 13 Planets $0.7 - 1.26 M_{\mathrm{Earth}}$; 200 Planets $N = 1455$	%	$\geq 0.7 M_{\mathrm{Earth}}$ $N = 162$	%	Group B: With hit-and-run return; 30 Planets $0.7 - 1.53 M_{\mathrm{Earth}}$; 200 Planets $N = 1809$	%	$\geq 0.7 M_{\mathrm{Earth}}$ $N = 508$	%
Super-catastrophic	3	< 1	0	0	5	< 1	0	0
Partial erosion	16	1	2	1	28	2	9	2
Partial accretion	487	33	57	35	617	34	168	33
Perfect merging	105	7	14	9	103	6	31	6
Graze-and-merge	571	39	48	29	668	37	142	28
Hit-and-run	273	19	28	17	388	21	128	25
Special cases								
H&R with proj. erosion	117	8	14	9	182	10	71	14
$5 - 10\%$ increase in final f_{core}	39/200	20	2/13	15	47/200	24	7/30	23
$> 10\%$ increase in final f_{core}	65/200	33	9/13	69	79/200	40	18/30	60

- Fewer planets reached Earth mass and of those that did a majority were enriched in core metals and deficient in mantle
- Fragmentation was significant - partial accretion and hit-and-run events of the projectile - accretion of iron core - ejection of mantle material from both projectile and target

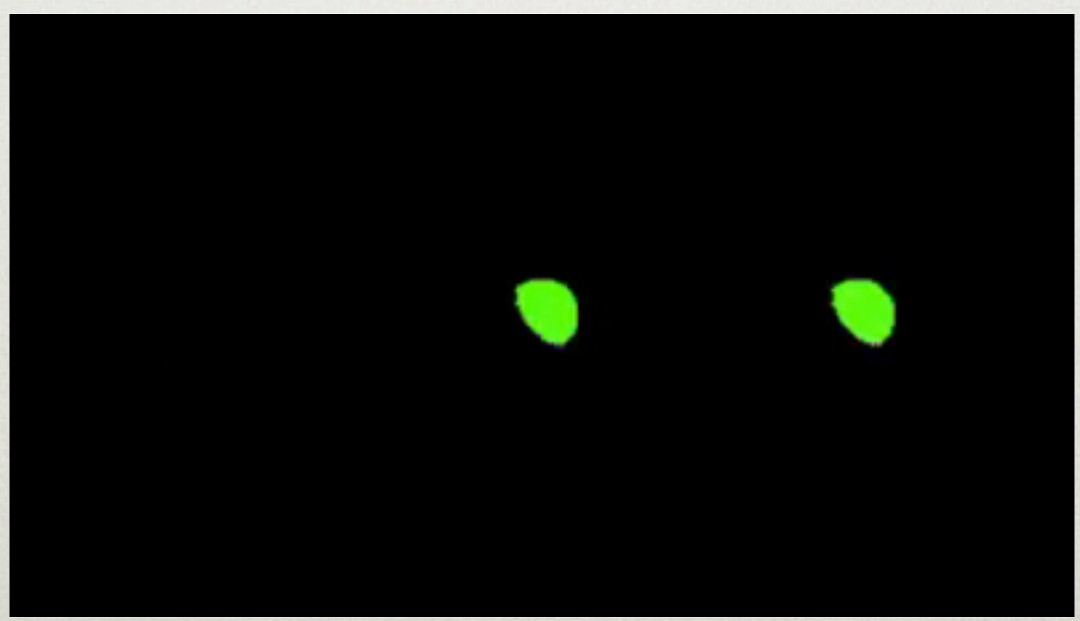
Conclusions

- Outcomes of giant impacts span all possible collision regimes including hit-and-run, accretion, erosion, and catastrophic disruption
- Fragmentation during giant impacts is also significant - the majority of the ejected material is mantle from partial accretion events - if ejected material is not totally re-accreted giant impacts can create planets depleted in volatiles and mantle (including water and atmosphere) compared to initial embryos
- Our new model was only applied retrospectively to the last stage - we predict a significant change in outcome distribution but will probably be more significant if model is included from the beginning

EDA-CM Collision Outcomes
(LS12 collision model in PKDGRAV)

Merge

Bounce

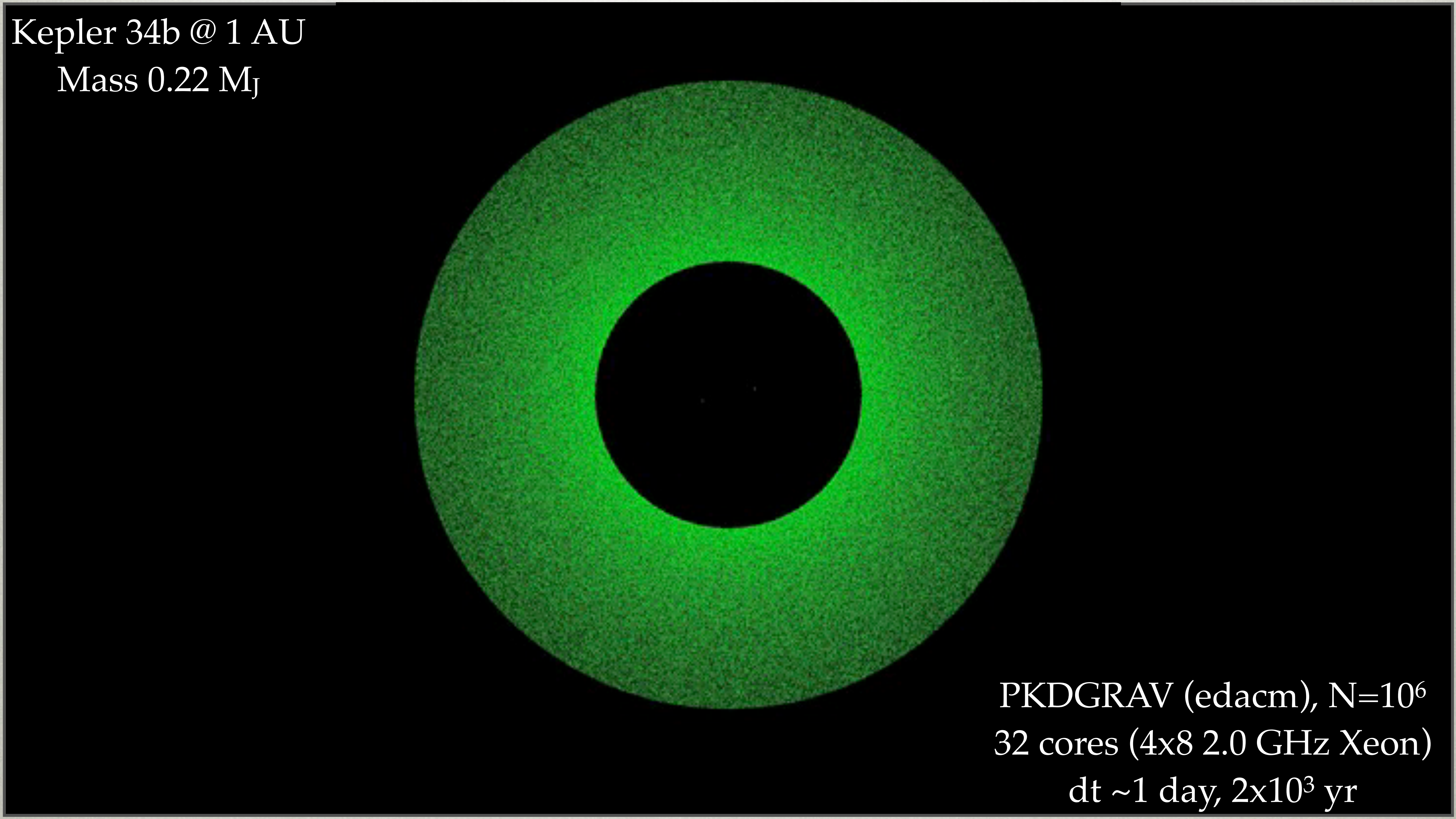


Fragment

Work in Progress: Circumbinary Planet Formation

- Several circumbinary planetary systems: Kepler 16, 34, 35, 38, 47, PH1, disagreement in community about where planets could have formed (Paardekooper, Leinhardt et al. 2012 vs. Meschiari 2012)
- Gravitational perturbations from the second star introduce high impact velocities close to the binary but the effect of the second star drops off quickly with distance so need a collision model that can accurately model both scenarios (Lines, Leinhardt, et al. in prep.)

Kepler 34
(Equal-Mass Stars, a = 0.2, e = 0.5)



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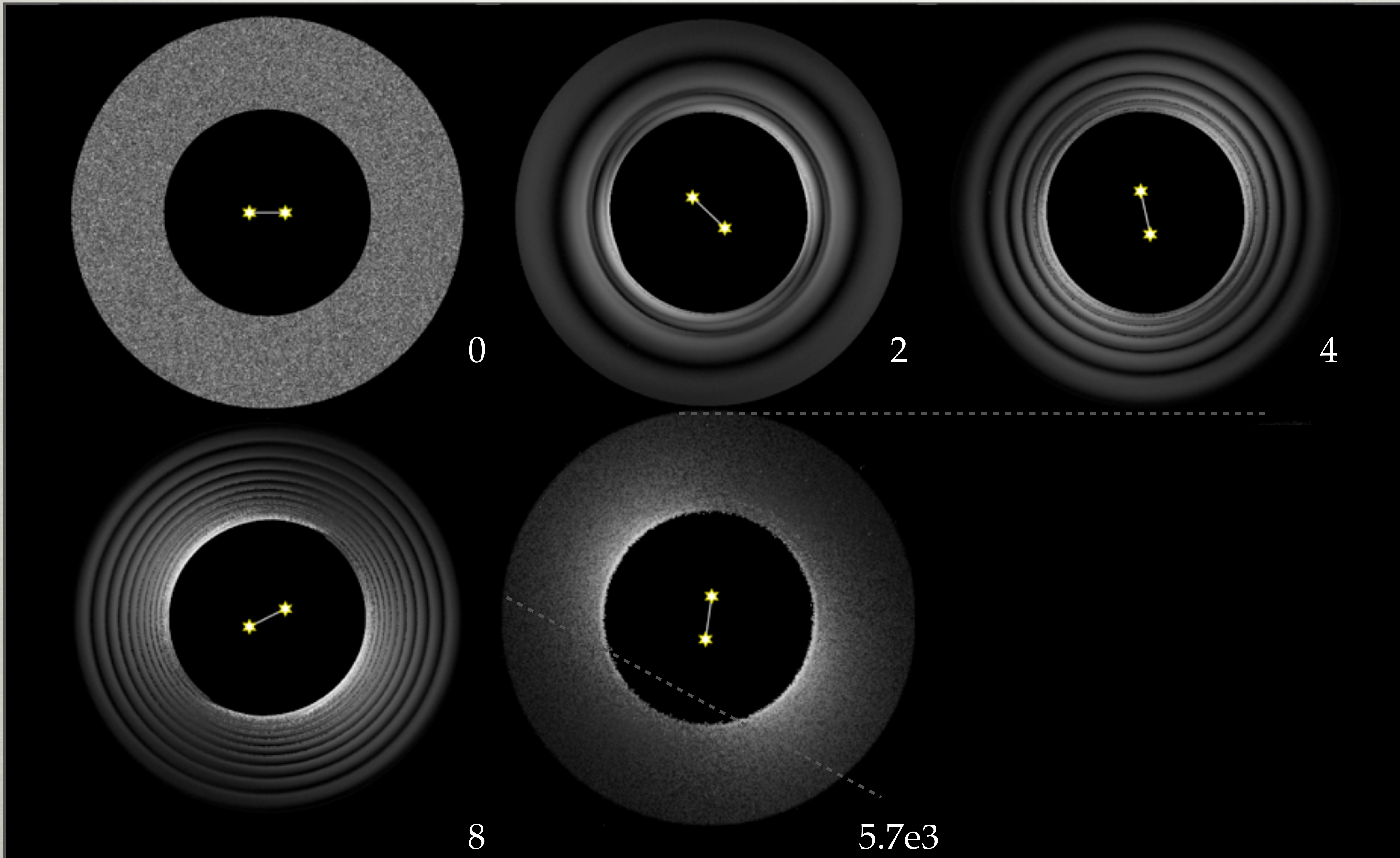
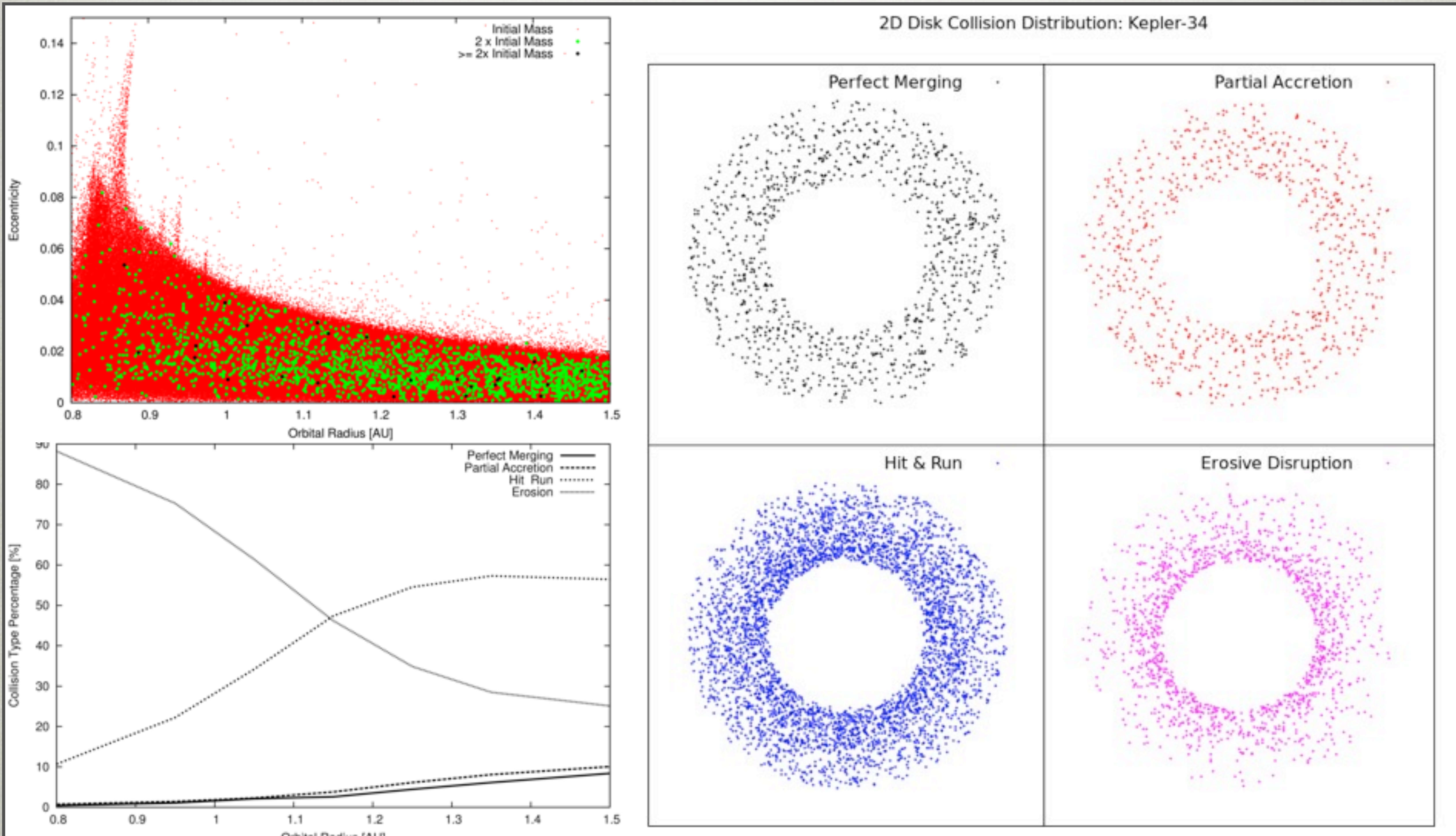
K34 Eccentricity Evolution



K34 Collision Outcomes

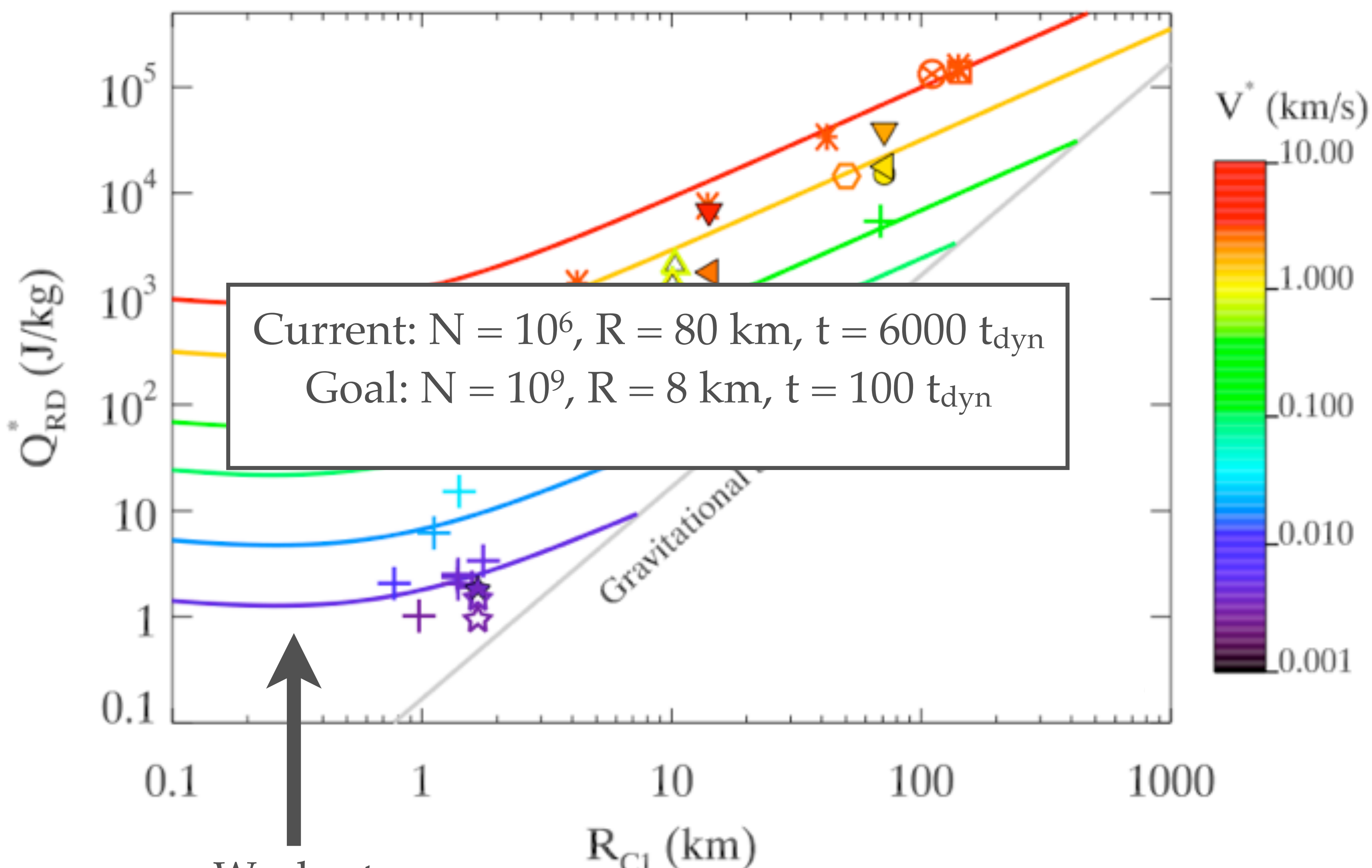


Lines, Leinhardt et al. in prep.

K34 Conclusions

- In situ growth of K34b seems unlikely ...
- High impact velocities up to 5 km/s
- Erosive collisions dominate for a < 1.1 AU
- No evidence for new type of runaway growth in inner erosive region - no dust run away growth
- To Do:
  a) Compare with single star simulation including edacm
  b) Include gravity of gas disk (non-axisymmetric)
  c) Planetesimal generation (Paardekooper & Leinhardt, 2010)?
  d) Do all of the Kepler circumbinary planets similar?

Whats next?



Current: $N = 10^6$, R = 80 km, $t = 6000\ t_{dyn}$
Goal: $N = 10^9$, R = 8 km, $t = 100\ t_{dyn}$

Weakest

Leinhardt & Stewart (2012)

UoB High Performance Machines

Platform	Total nodes	Cores per node	Processor	Memory per node	Memory per core	Network
Cray XE6	16	32 cores	2x AMD Opteron 6272 @ 2.1GHz	32 GB	1GB	Cray Gemini
Intel test machine	1	16 cores	2x Intel E5 2687W @ 3.1GHz	32 GB	2GB	N/A
Bluecrystal Phase 2	416	8 cores	2x Intel E5642 @ 2.8GHz	8 GB	1GB	QLogic Infinipath
Bluecrystal Phase 3	-	16 cores	2x Intel E5 2670 @ 2.6GHz	128 GB	8GB	-

Currently in testing phase - will be available Oct/Nov 2013

Biggest Problem - Memory

- Never a problem before but for $N = 10^9$ need a few 10^6 particles/core
- Hierarchical tree itself takes up considerable space (our version of PKDGRAV has two - one for gravity, one for collisions)
- Test: Changing bucket size, $N = 1.6 \times 10^6$, inelastic collisions, 100 steps

Bucket size	Time taken	Nodes in tree (per process)	Tree memory allocated (MB per process)	% of total	Relative tree memory use	Relative speed
8	577	32768	14.75	56.3%	100%	100%
32	587	8192	3.68	14.5%	25.7%	98.2%
64	660	4096	1.84	7.02%	12.5%	87.5%
128	875	2048	0.9	3.44%	6.1%	65.9%
256	1251	1024	0.46	1.78%	3.1%	46.1%

Other Problems

- Input/Output - generating and reading files
- Data processing & storage - moving the data, visualising the data, storing the data
- Time to complete simulation - simulation will be more than 1000 times slower:
  a) PKDGRAV scales as NlogN but collision rate should increase a lot too and collision search is expensive
  b) Can PKDGRAV be optimised further? (only useful if efficiency is increased by ~10s%)
- Generating an appropriate initial condition - needed 10s of dynamical times to get to steady state for $N=10^6$