PLANETARY CRASH

New insight into why hot Jupiters are so diverse

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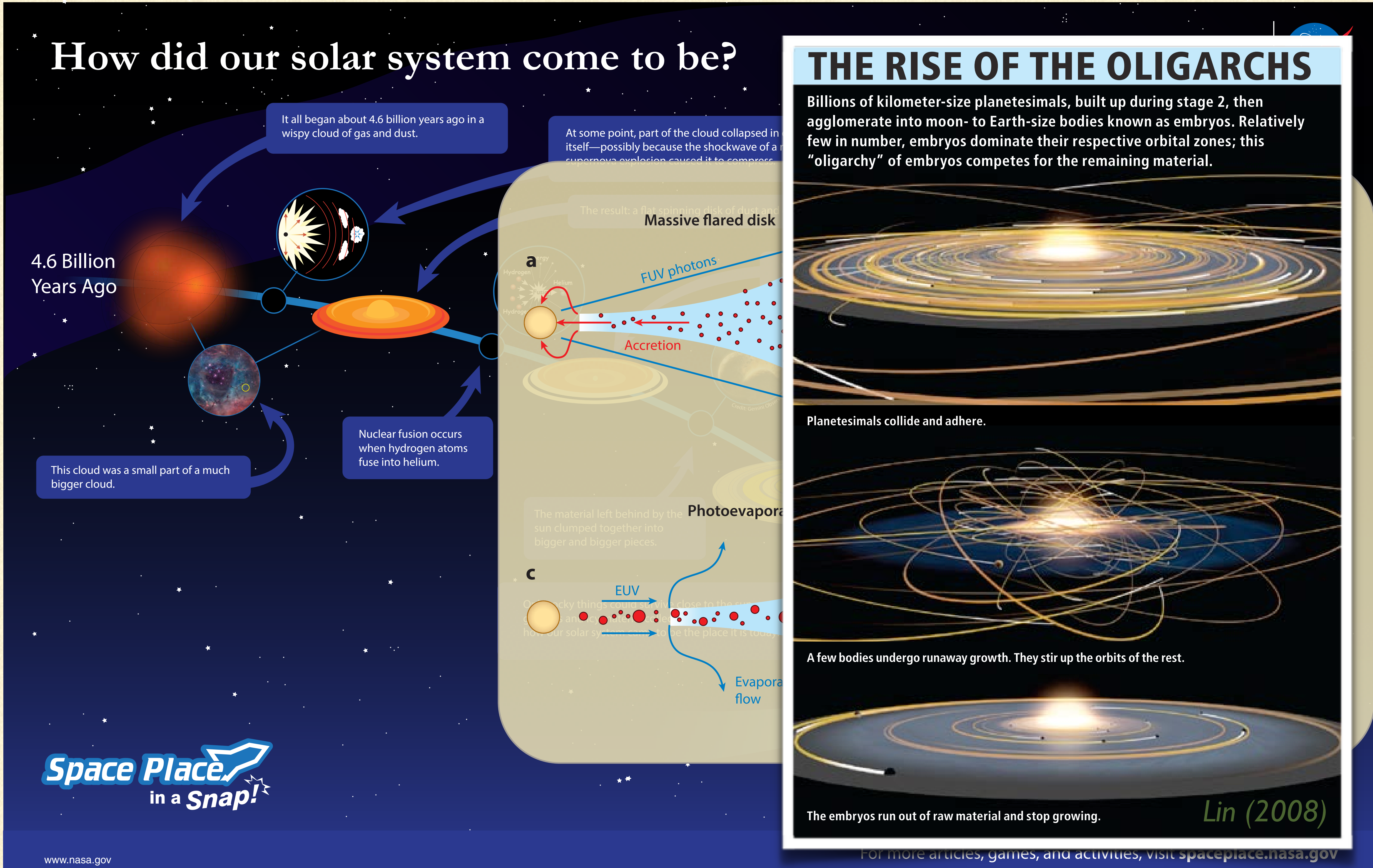
Planet Formation: the Big Picture



Planet Formation: the Big Picture (cont'd)

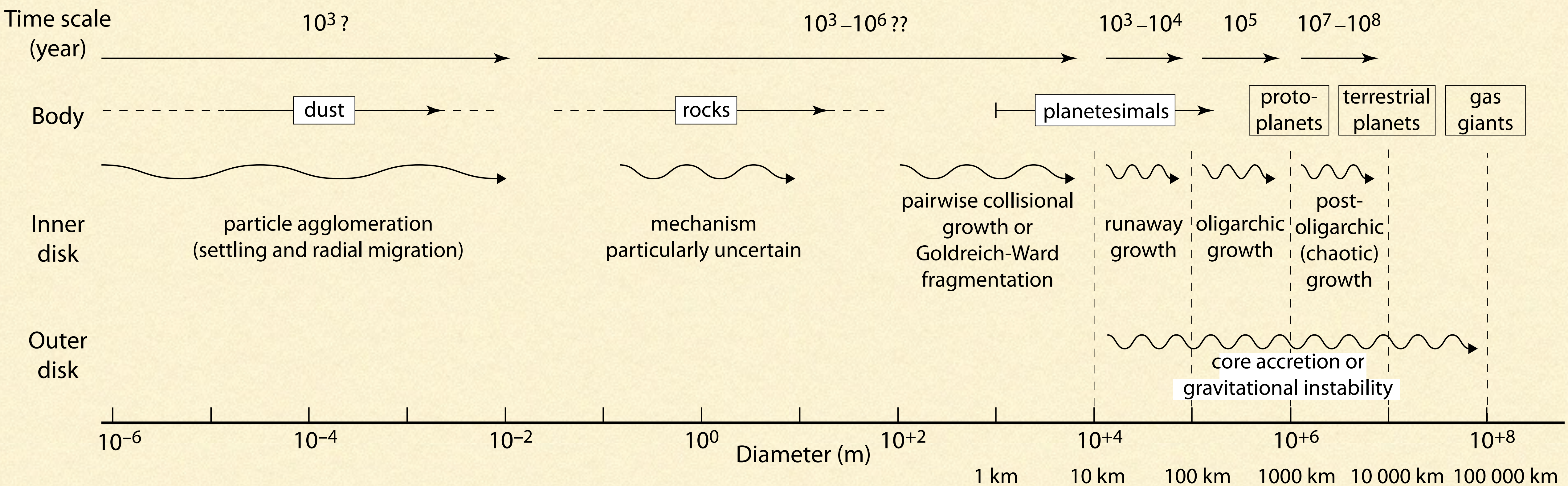


Figure 10.6: Schematic of the growth of planets, starting with sub-micron dust, and extending up to the terrestrial planets in the inner disk, and the gas giants in the outer disk. Some indicative time scales are given, although some intervals, especially around the meter-size barrier, remain highly uncertain.

Perryman (2011)

Outline

- Observational puzzles of Exoplanets
- Tidal Disruption of Gas Giant Planets
- Giant Impact and Merger Scenario
- Gravitational *N*-body Simulations

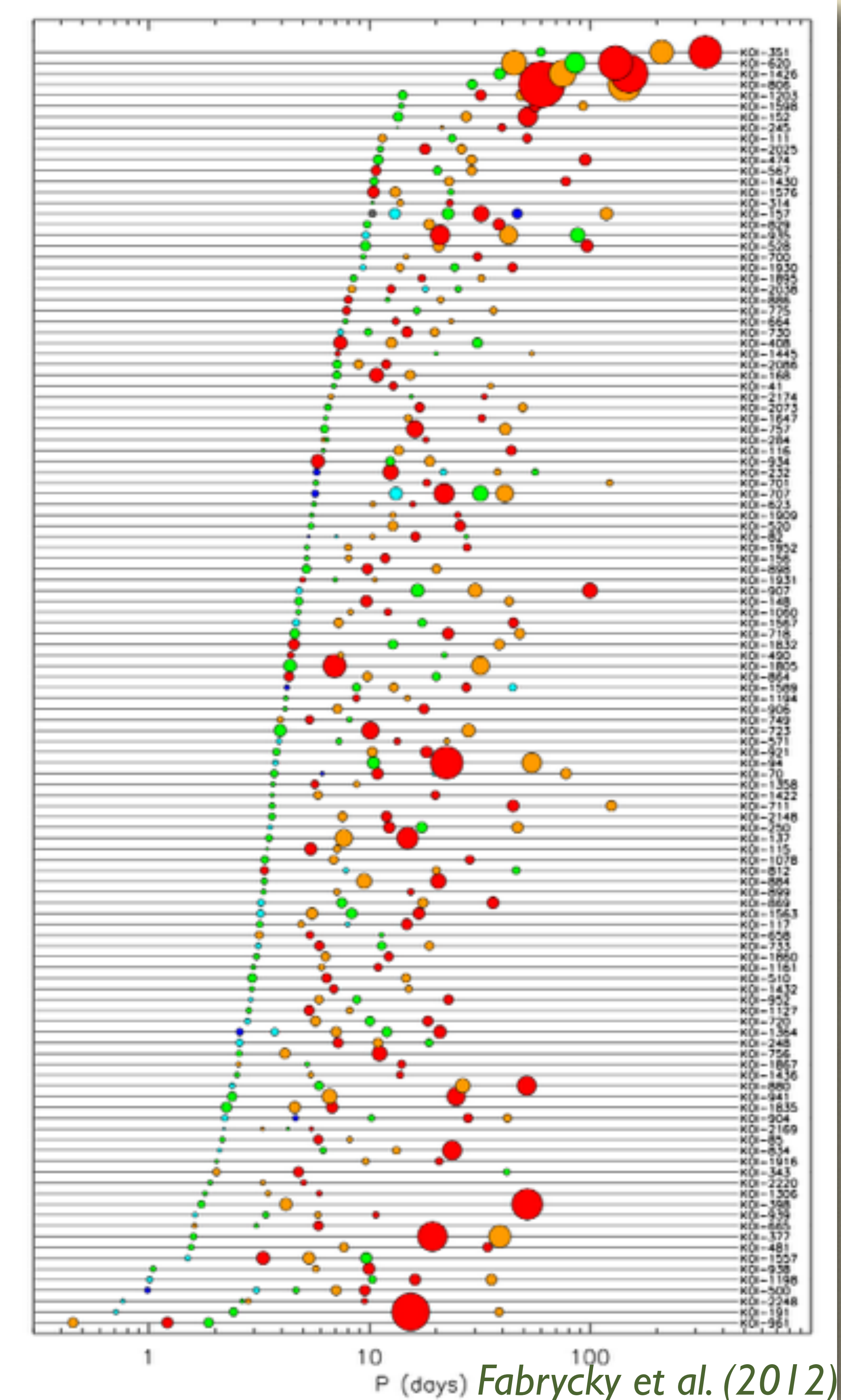
Solar System Analogues

Multiplicity in Kepler Catalogue:

17% (Borucki+2011) -> 20% (Batalha+2013) -> 23% (Burke +2014)

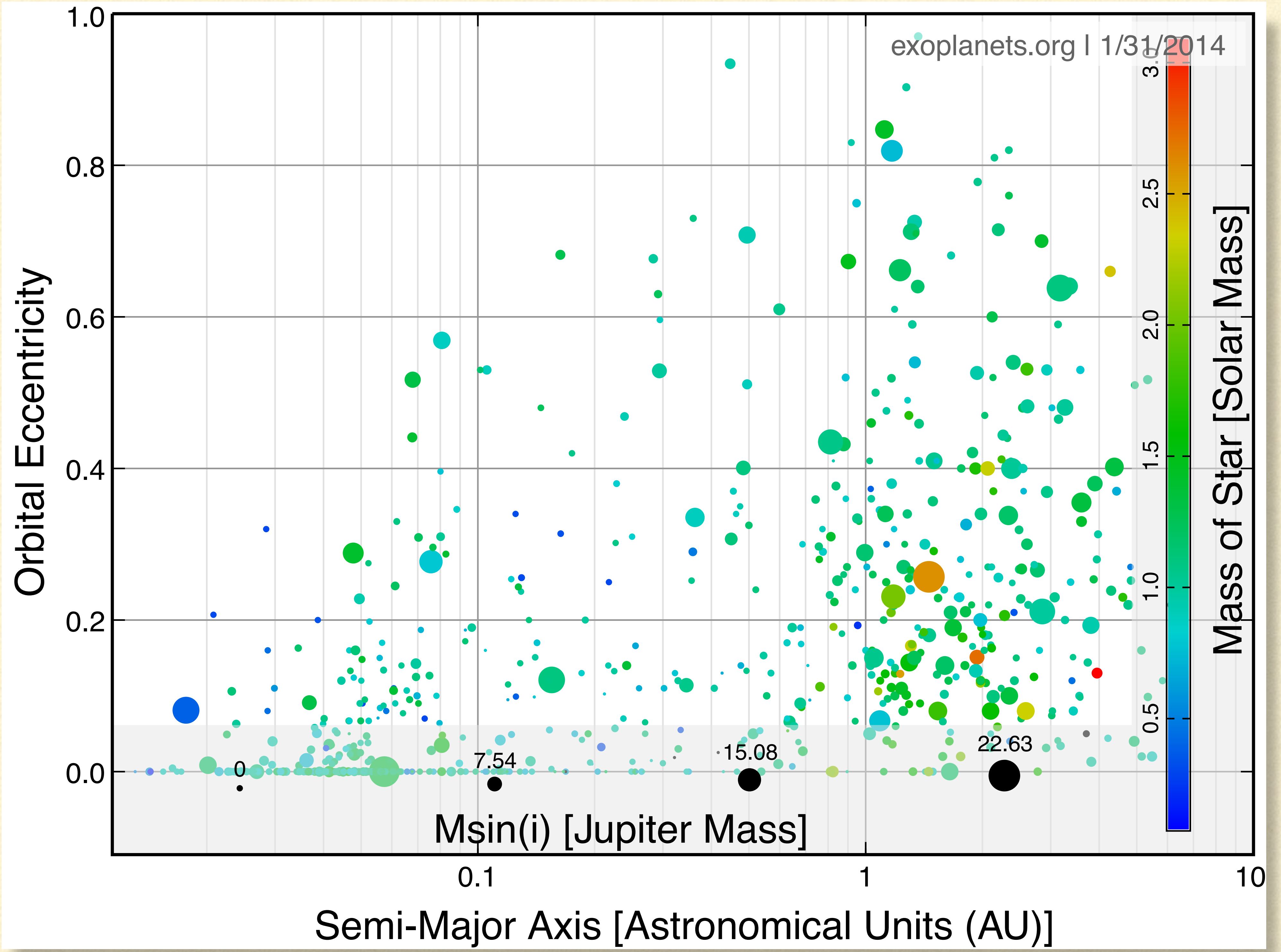
Coplanar, close to resonances

However, …

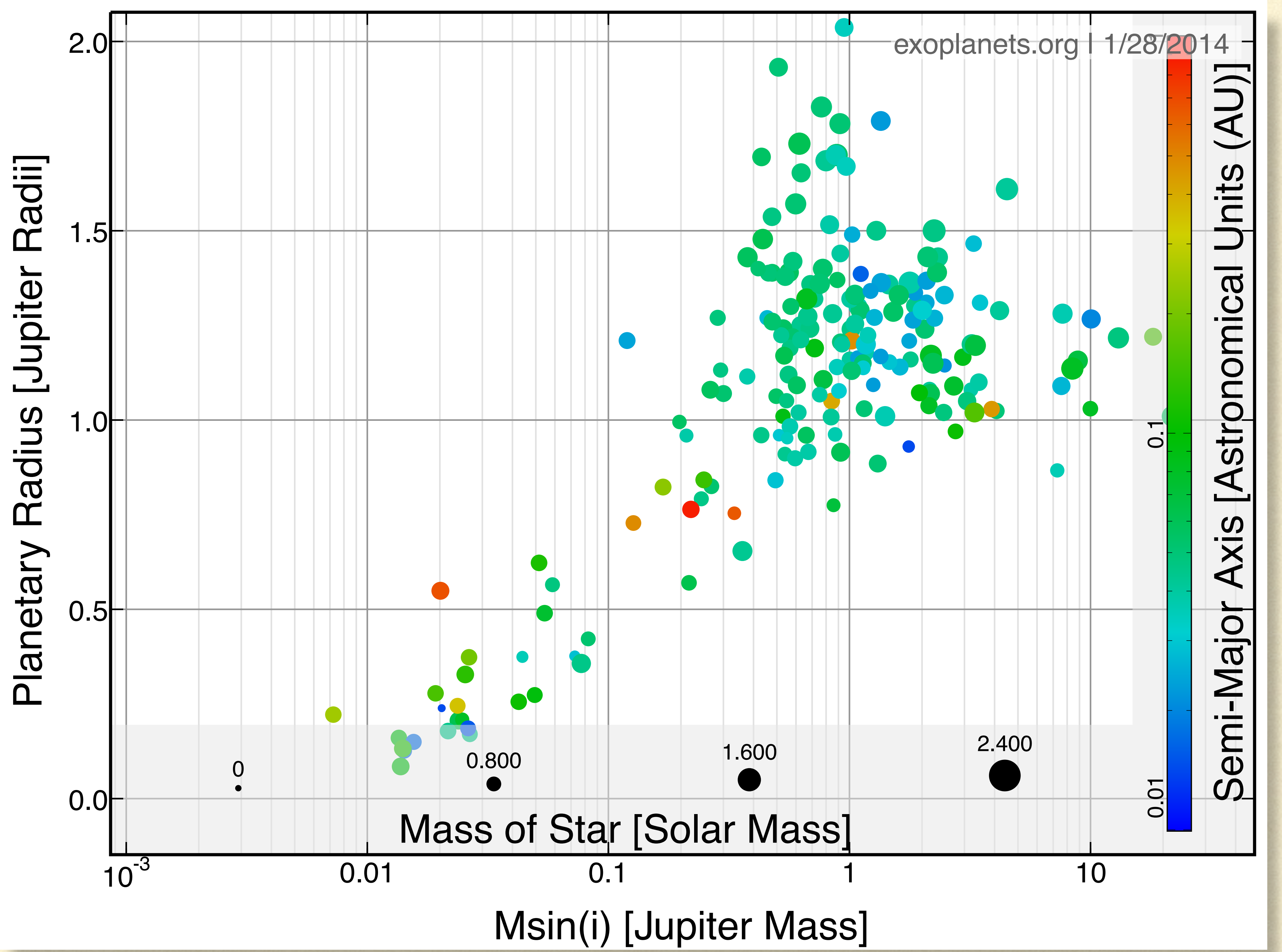


Fabrycky et al. (2012)

a-e Distribution of Confirmed Exoplanets

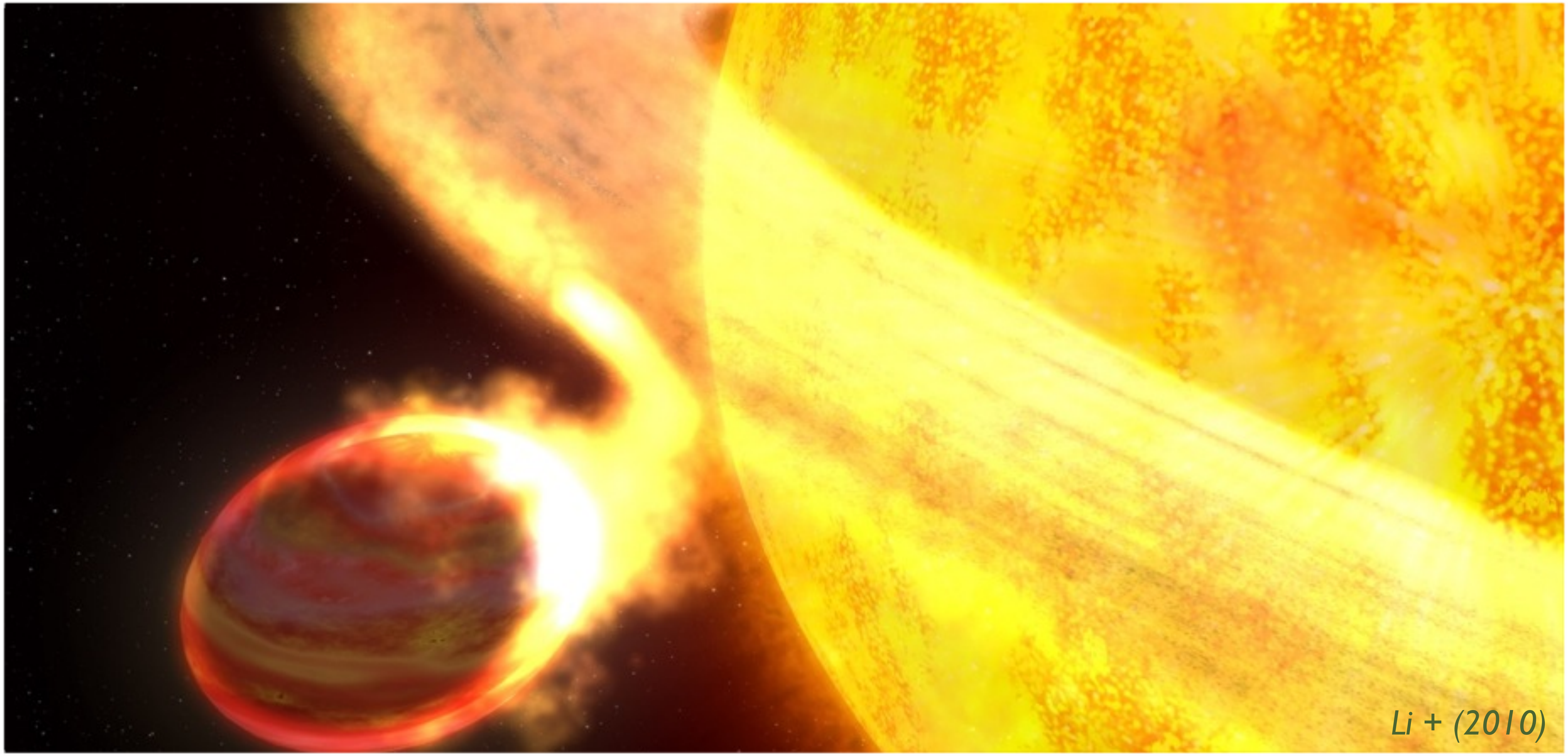


Diverse Hot Jupiters



Scenarios of Forming Hot Jupiters

- Orbital migration due to planet-disk interactions (Lin et al. 1996)
  - Smooth
  - Resonant systems
  - coplanarity
- Dynamical migration due to the interactions with a third body (Socrates et al. 2012)
  - High e
  - Random inclination



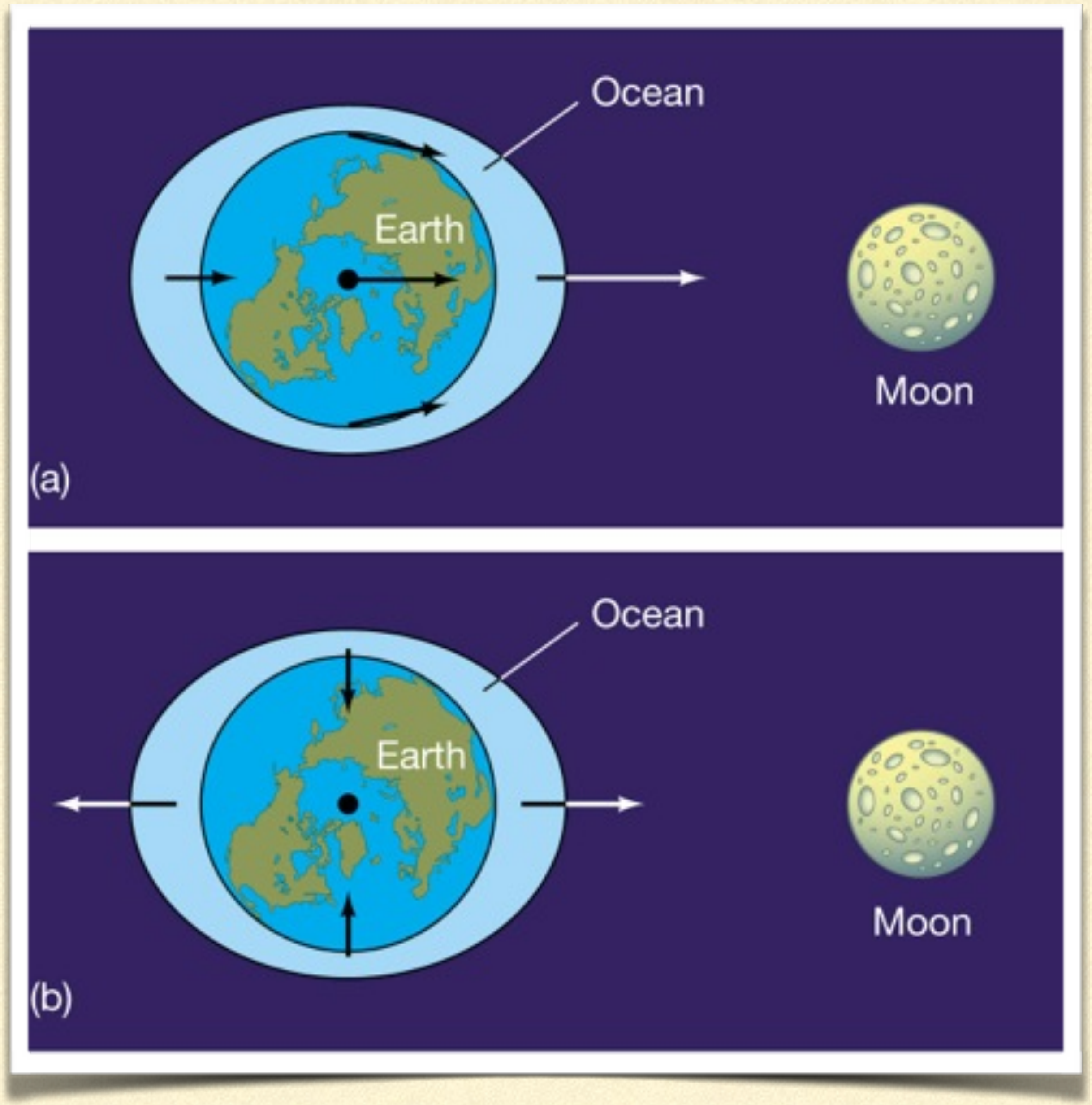
Tidal Disruption of Giant Planets

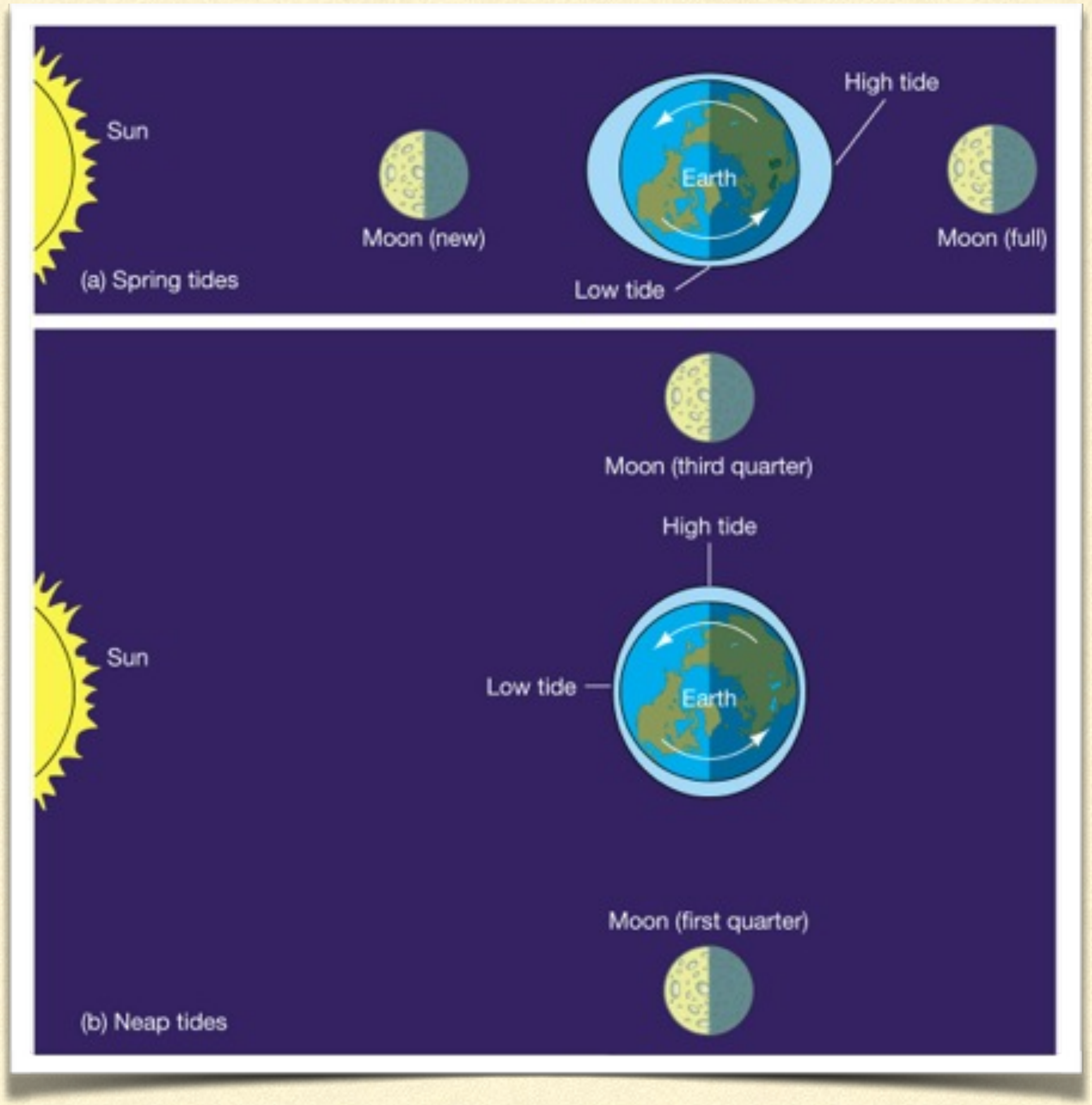
Lidov-Kozai mechanism

gaseous disk depleted —> Planet-planet scattering —> e excitation —> close encounter with host stars

Secular chaos, …

Tides are important

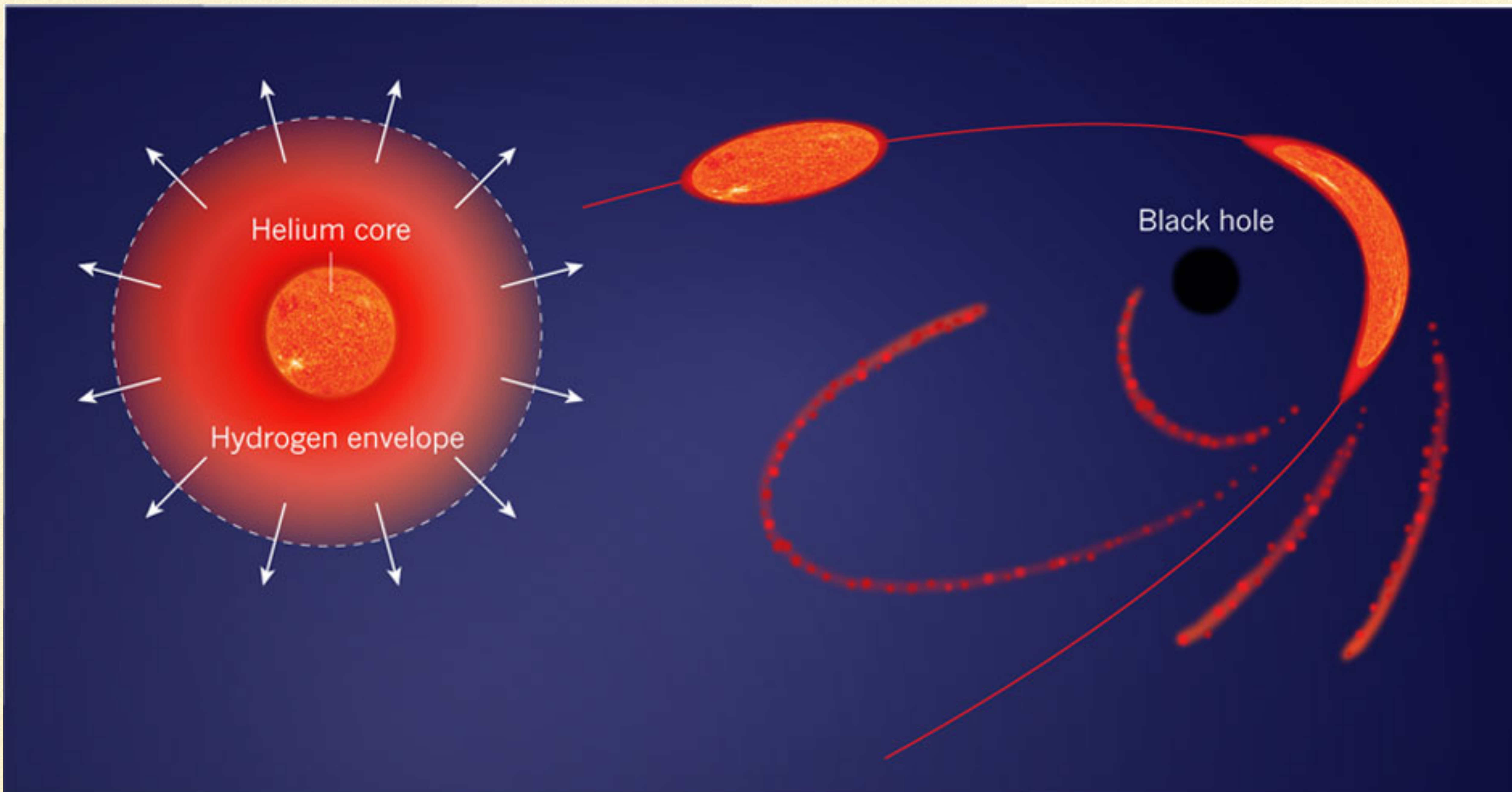




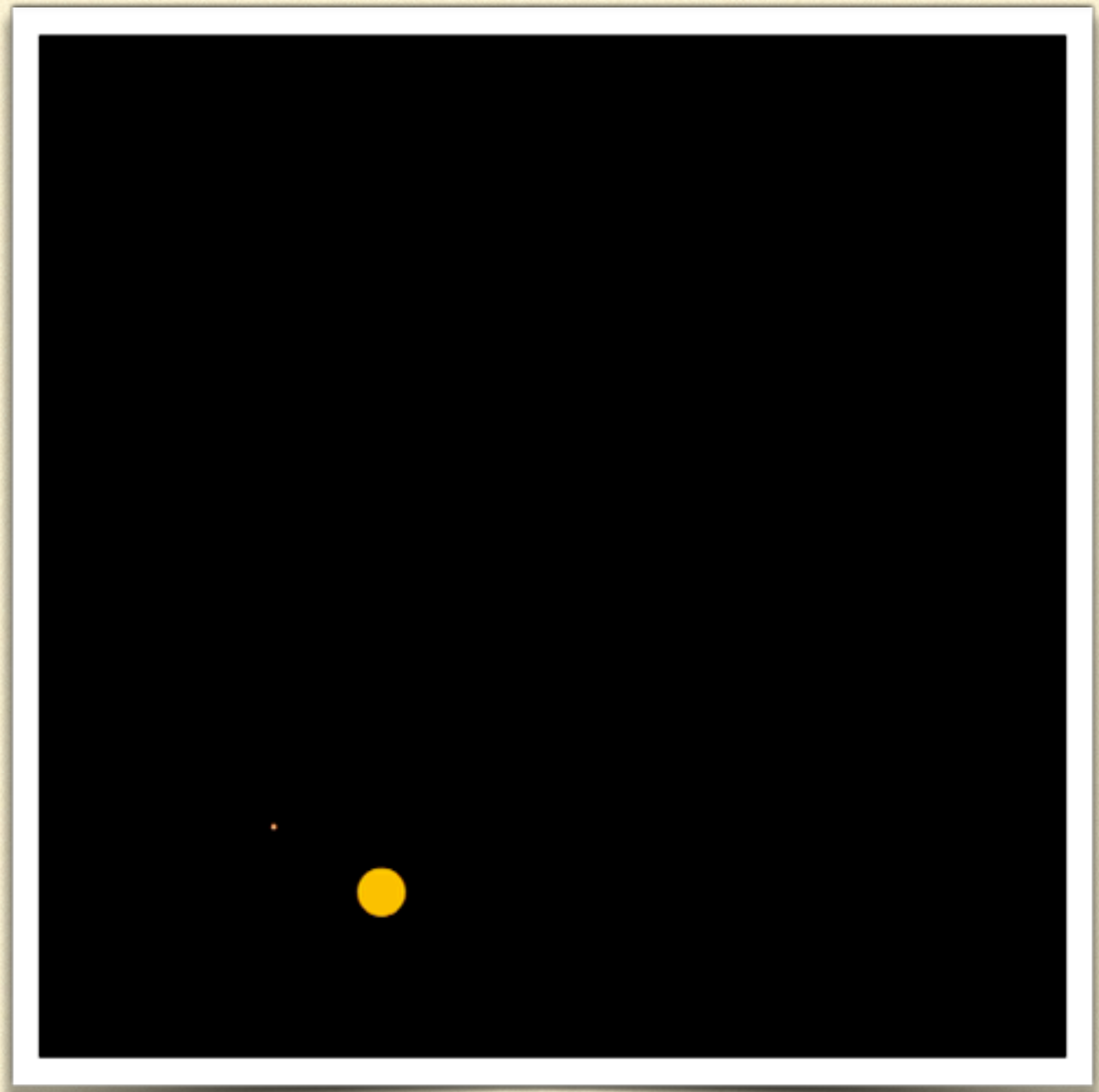
Terminology

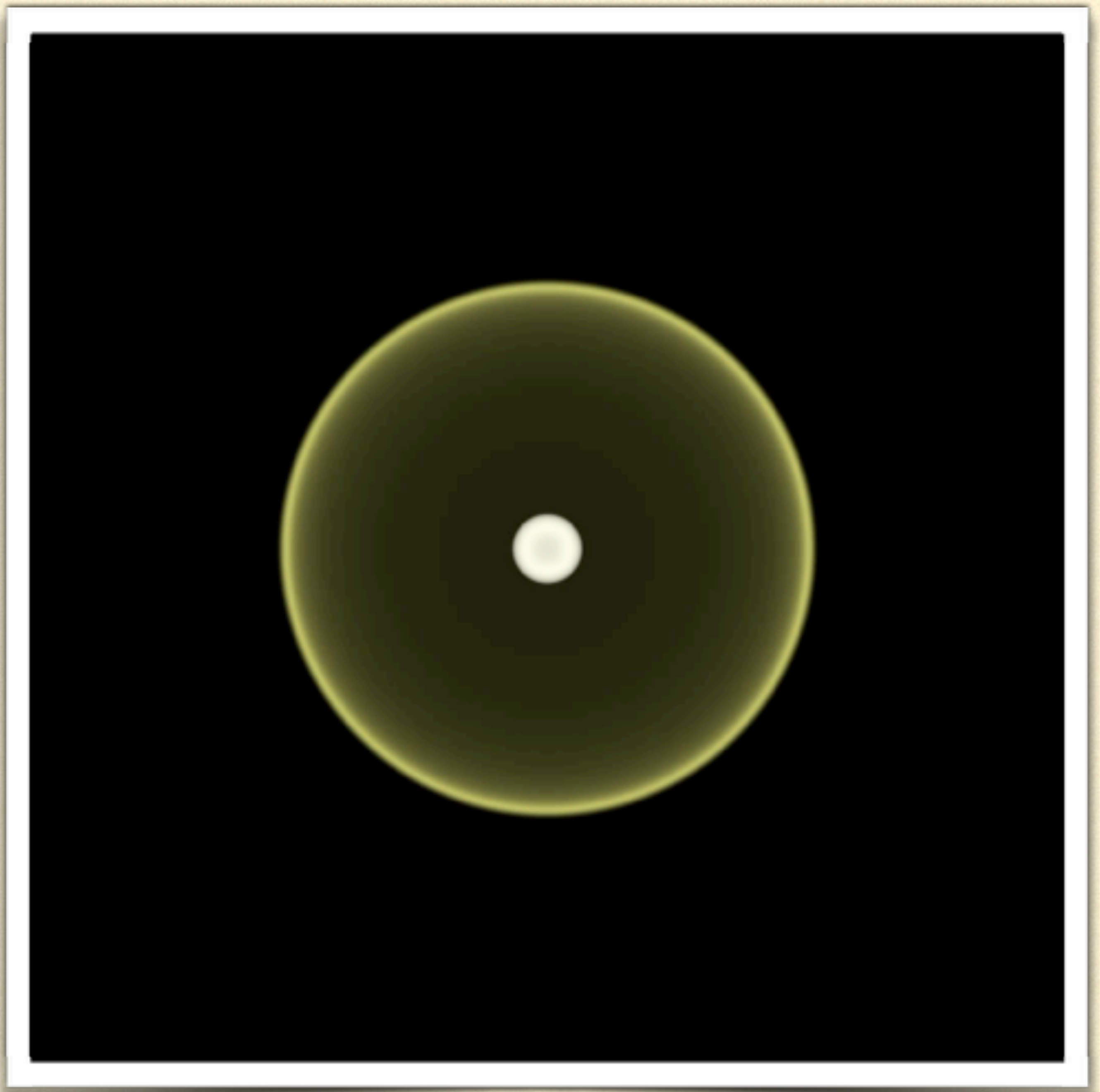
Tidal radius: $r_{\mathrm{t}} \equiv \left(\frac{M_*}{M_{\mathrm{P}}}\right)^{1/3} R_{\mathrm{P}}$

Roche radius: $r_R = 0.462 q^{1/3} a$



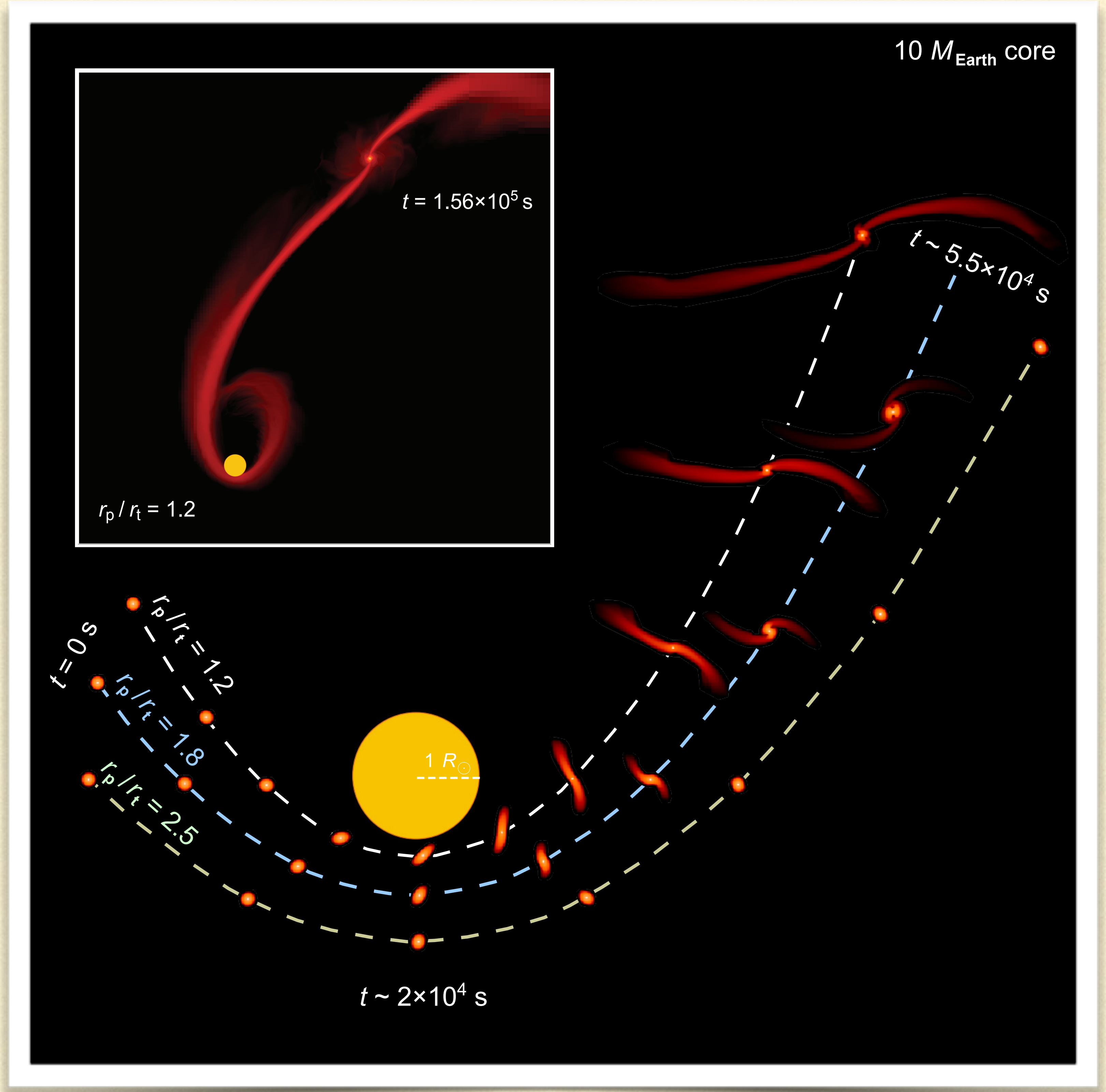
A Tidally Disrupted Gas Giant



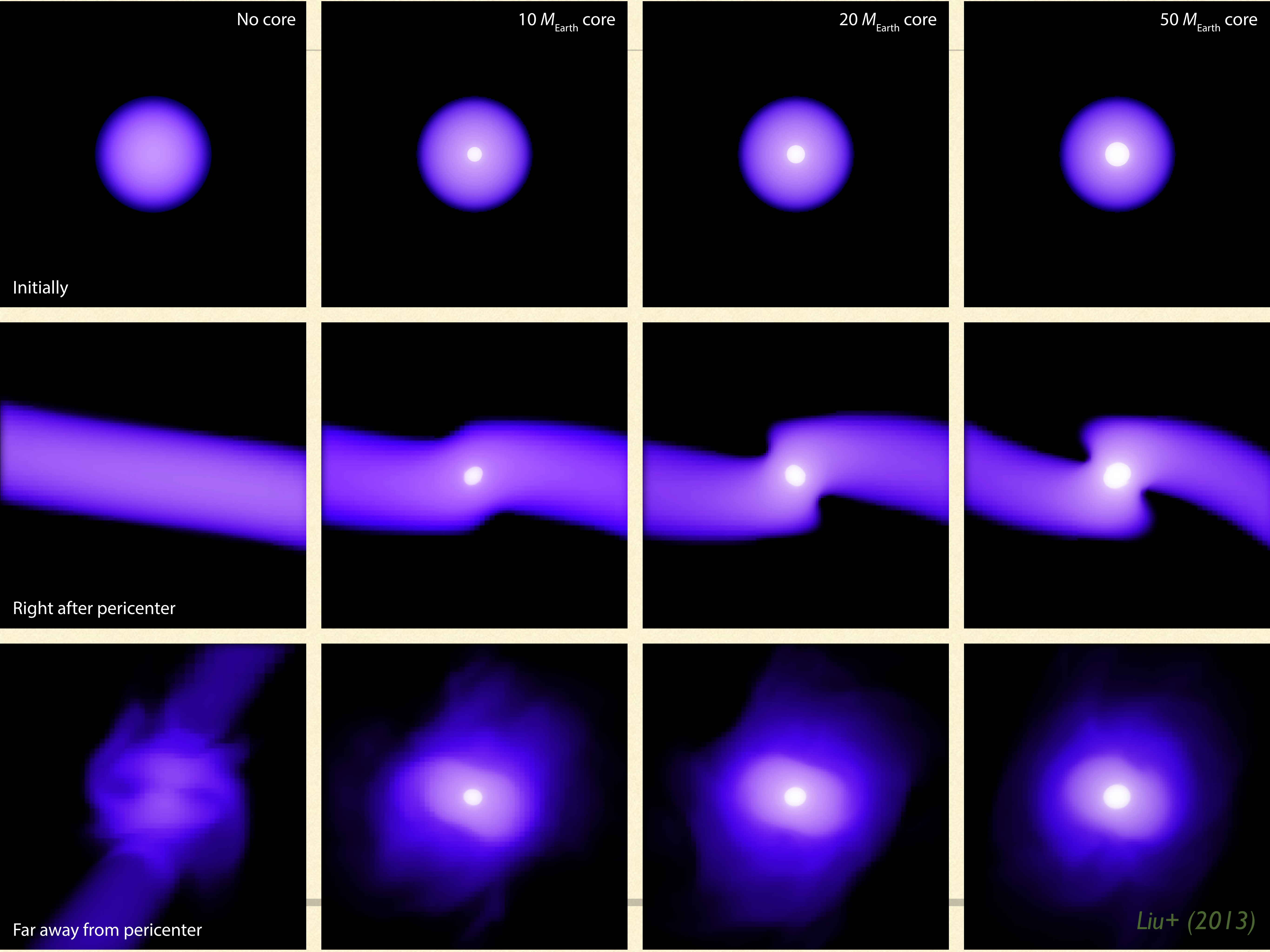


Liu+ (2013)

Tidally Disrupted Gas Giants

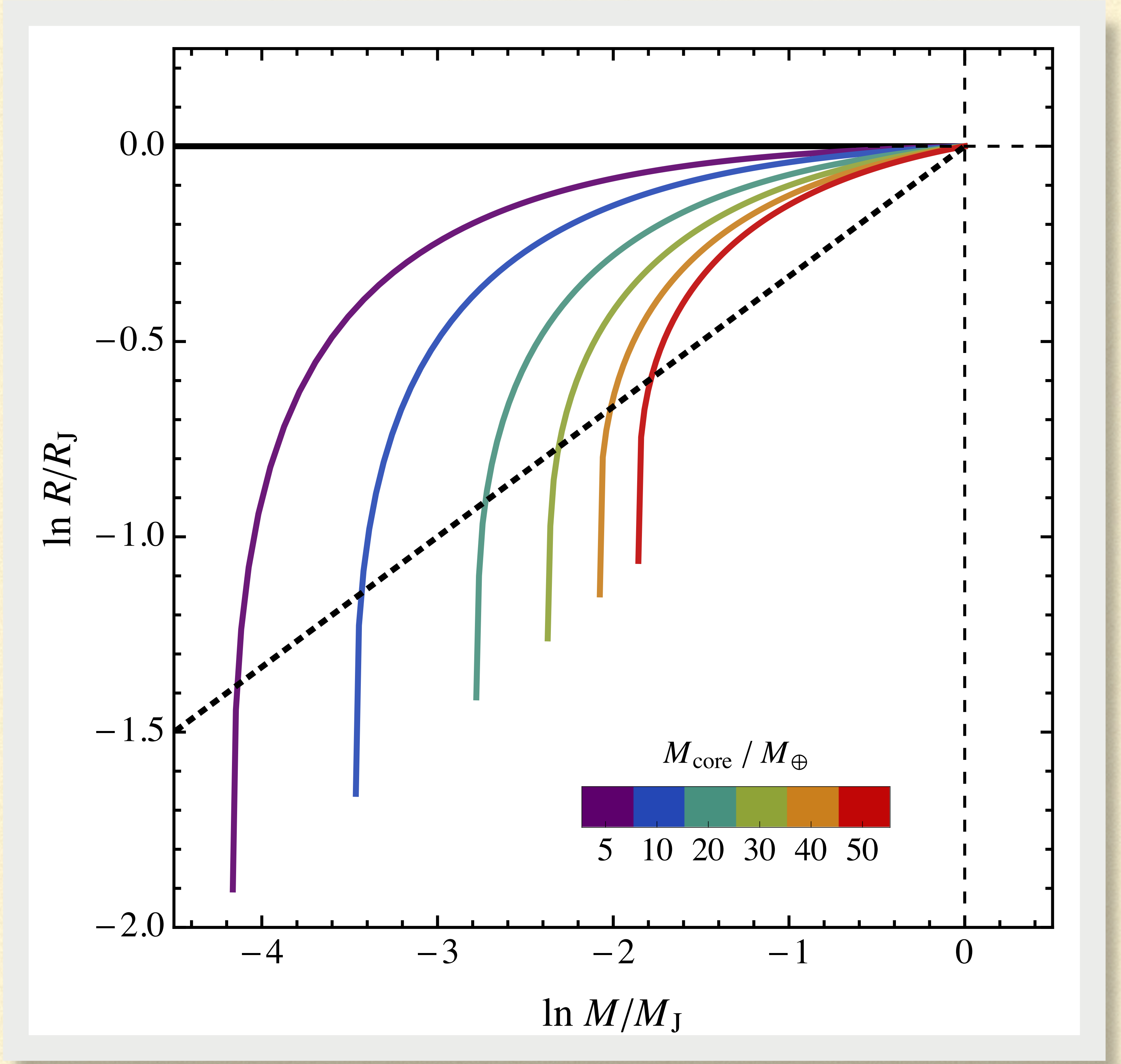


Liu+ (2013)



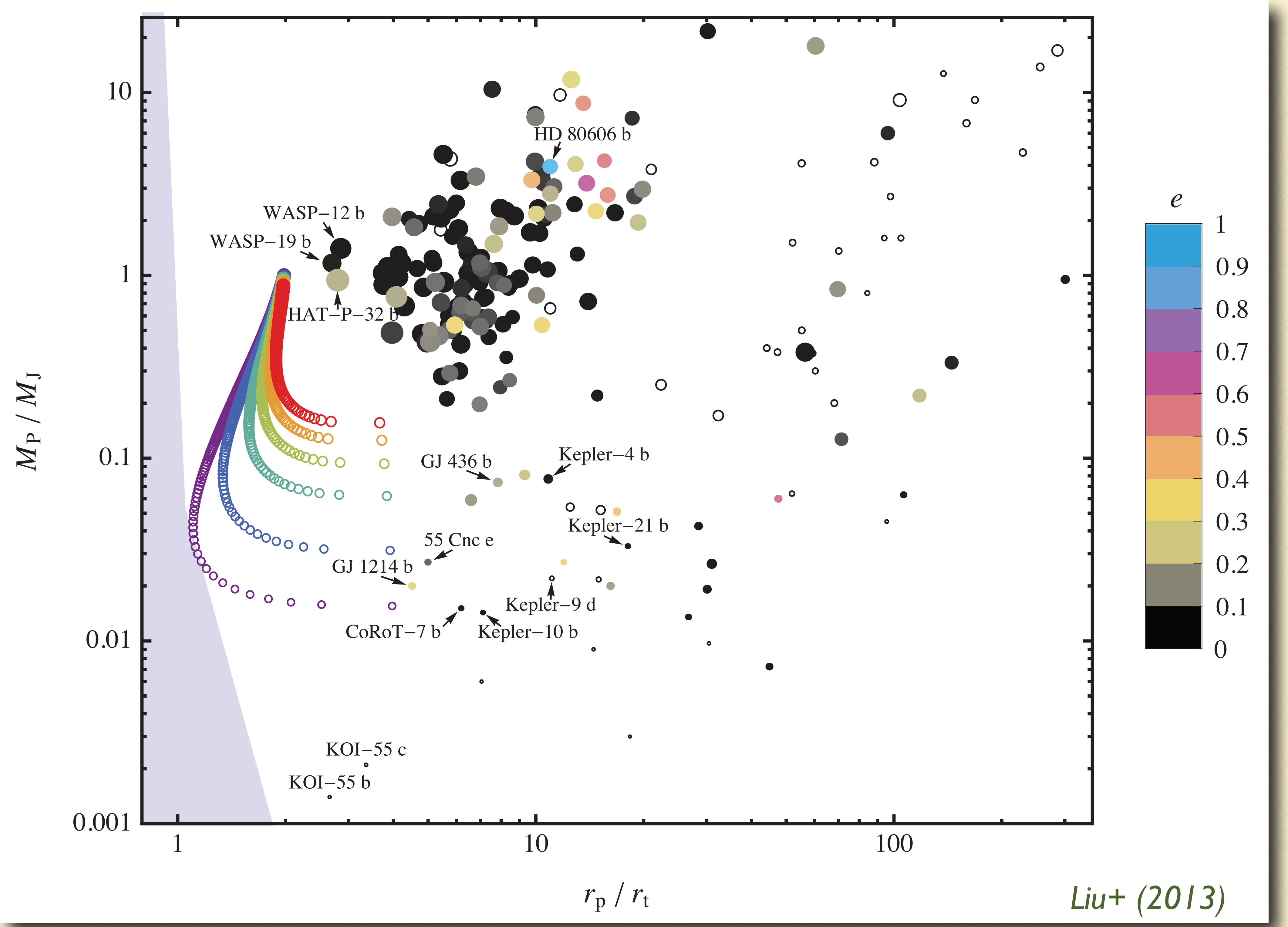
No core
10 M_{Earth} core
20 M_{Earth} core
50 M_{Earth} core
Initially
Right after pericenter
Far away from pericenter
Liu+ (2013)

Adiabatic Evolution of Mass-losing Gas Giants



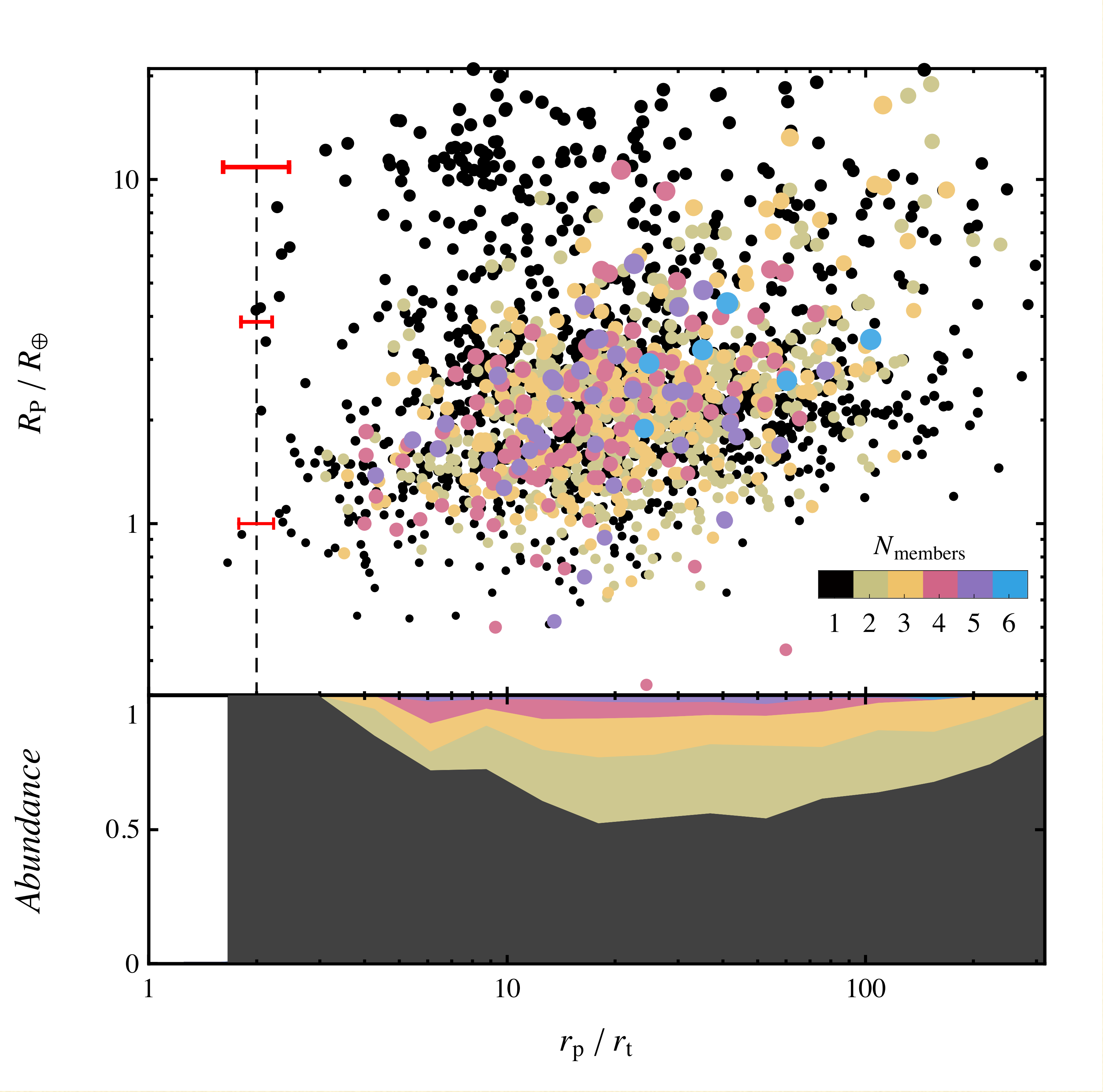
Liu+ (2013)

A Census of Possible Candidates



Liu+ (2013)

A Census of Possible Candidates

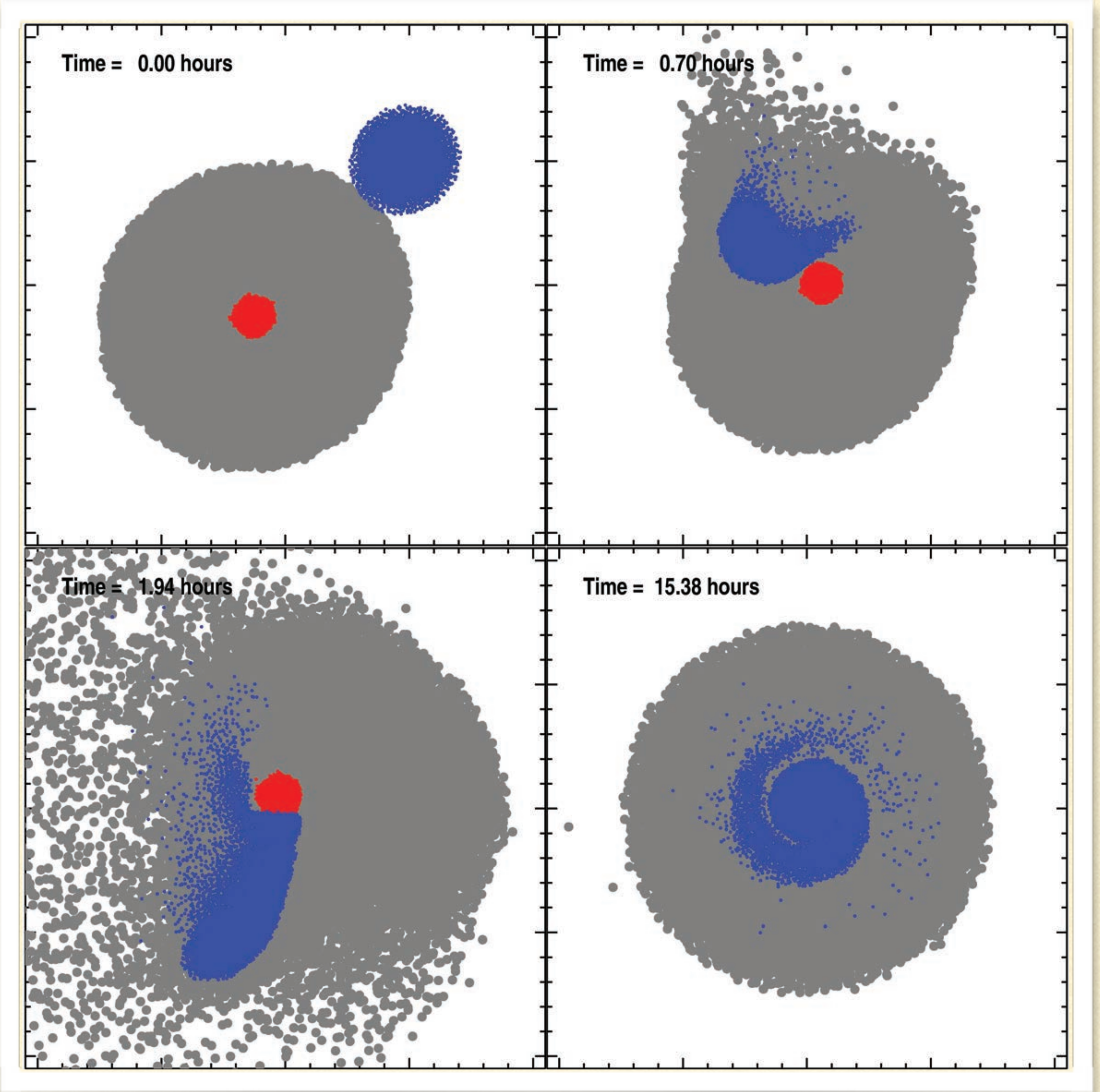


Liu+ (2013)

Giant Impacts

Applications in the Solar System: origin of Earth's Moon, stripping of Mercury's primordial mantle, Uranus' large obliquity, and the differences in the core mass between Jupiter and Saturn (Li+ 2010)

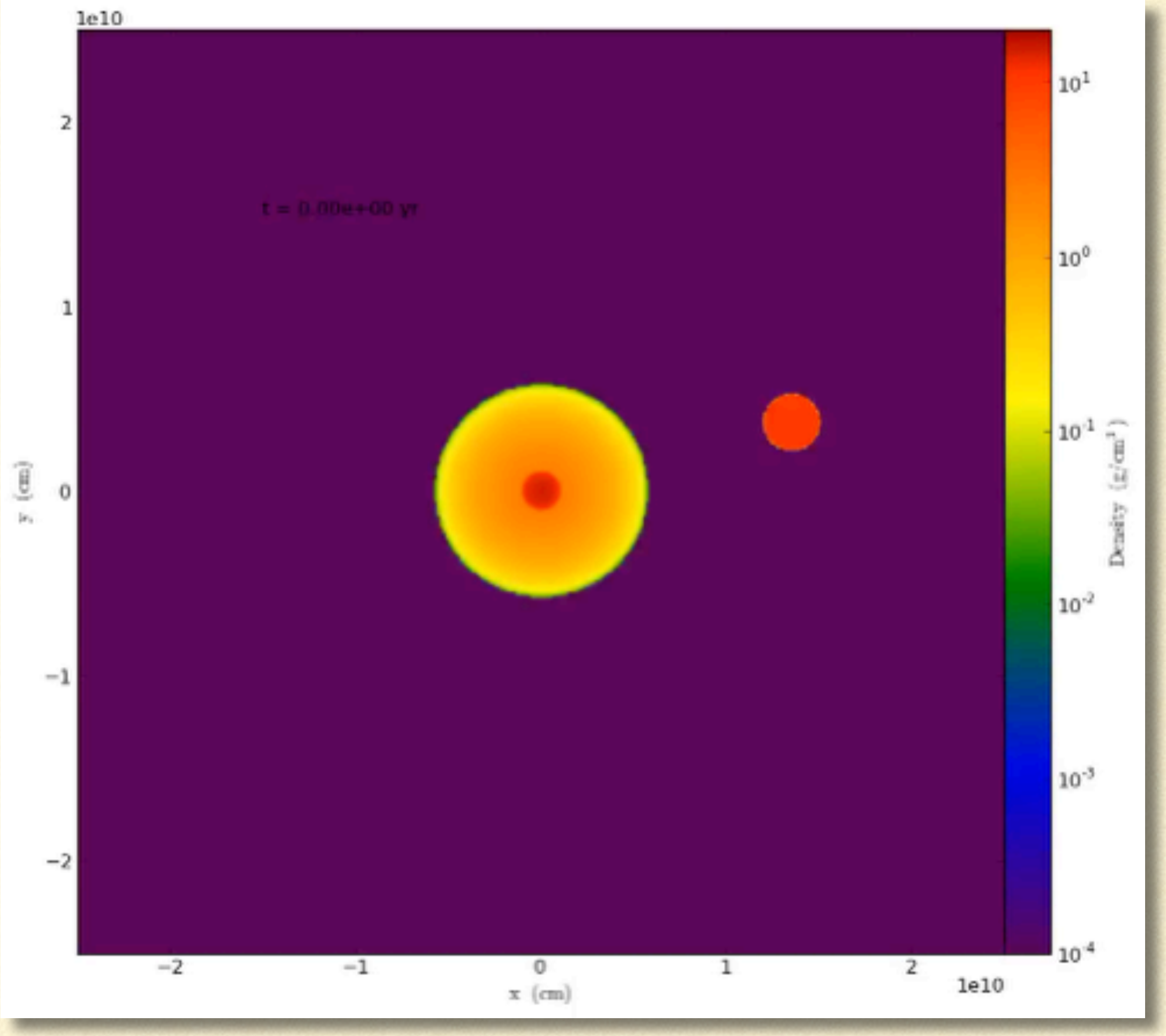
Low Speed Oblique Collisions (SPH)



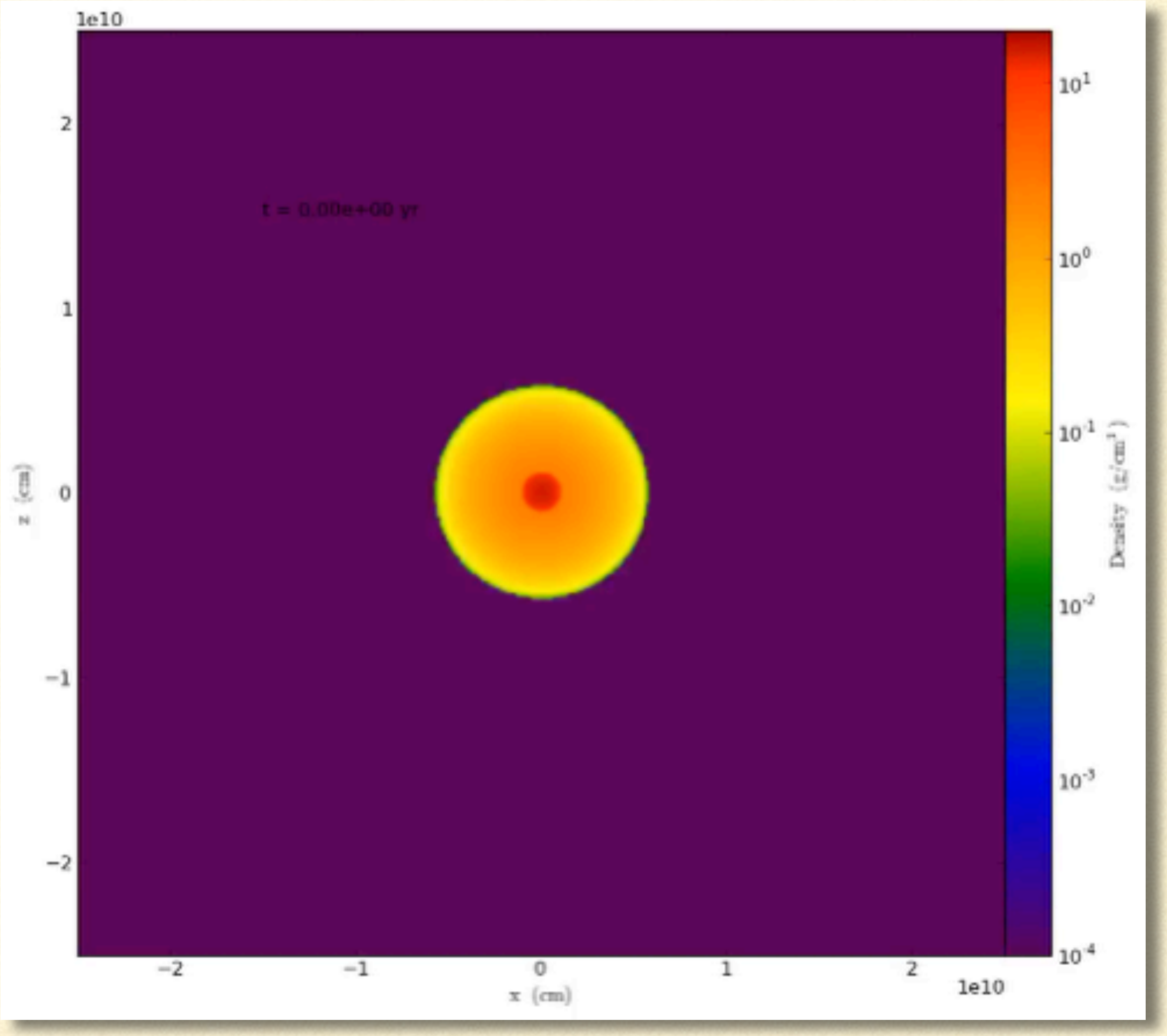
Liu+ (2014)

Low Speed Oblique Collisions (FLASH)

X-Y plane

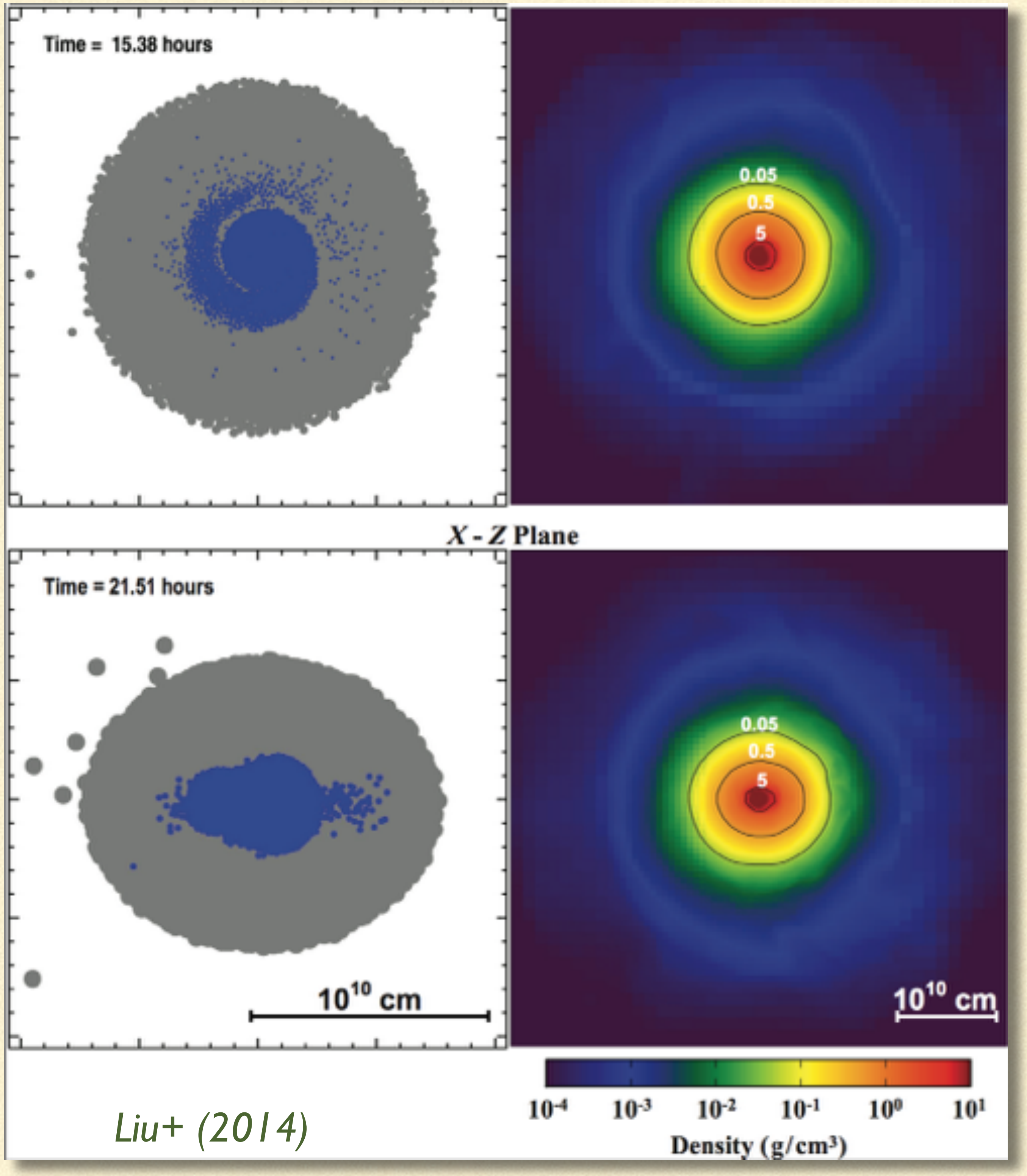


X-Z plane



Liu+ (2014)

Low Speed Oblique Impact (Summary)



Liu+ (2014)

Low speed impacts generally lead to mergers.

Energy injections inflate the gas giant substantially.

A rotational flattening structure is observed after the impact.

Discrepancies between the two methods

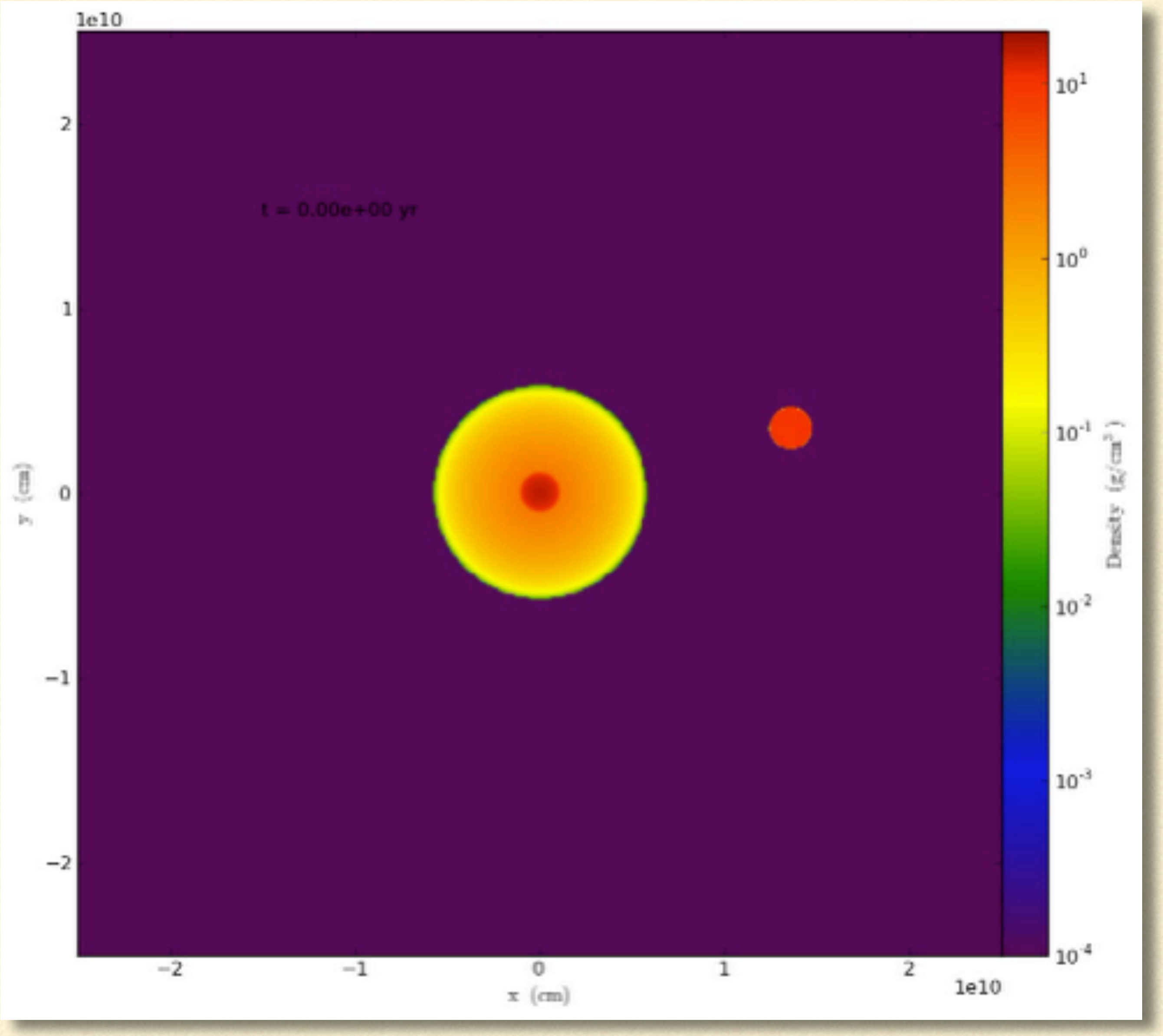
25 Earth Mass Impactor

Model	ξ	$v_{imp}/v_{esc,2}$	M_{bm}	$M_{bm,c}$	R_{bm}/R_T	M_{cc}	$M_{cc,c}$	R_{cc}/R_T	J_{cc}/J_*
SPH									
SA1a	0	1.0	125.0	35.0	1.08	107.9	35.0	0.95	0.001
SA1b	21	1.0	124.7	35.0	1.08	104.2	35.0	0.92	0.168
SA1c	30	1.0	124.7	35.0	1.08	101.9	35.0	0.90	0.219
SA1d	45	1.0	124.7	35.0	1.09	96.3	34.3	0.88	0.261
SA1e	60	1.0	125.1	35.0	1.03	90.5	10.4	0.94	0.069
SA2a	0	1.4	123.1	35.0	1.09	102.8	35.0	0.93	0.001
SA2b	21	1.4	122.9	35.0	1.09	97.2	35.0	0.89	0.210
SA2c	30	1.4	123.0	35.0	1.10	93.8	34.6	0.87	0.263
SA2d	45	1.4	99.1	10.8	1.02	88.5	10.4	0.93	0.065
SA2e	60	1.4	99.9	10.2	1.01	93.2	10.1	0.95	0.034
SA3a	0	3.0	87.9	35.0	0.84	80.3	34.7	0.78	0.001
SA3b	21	3.0	85.5	11.5	1.00	67.6	11.1	0.84	0.070
SA3c	30	3.0	92.6	10.5	1.03	74.6	10.3	0.88	0.064
SA3d	45	3.0	98.2	10.2	1.03	85.2	10.0	0.92	0.048
SA3e	60	3.0	99.8	10.0	1.01	92.8	10.0	0.95	0.021
SA4a	0	5.0	0.4	0.3	0.11	0.1	0.1	0.07	0.229
SA4b	21	5.0	69.5	10.3	0.90	58.0	10.1	0.79	0.059
SA4c	30	5.0	85.5	10.2	1.01	67.8	10.1	0.85	0.051
SA4d	45	5.0	96.4	10.1	1.04	80.7	10.0	0.91	0.048
SA4e	60	5.0	99.5	10.0	1.02	89.9	10.0	0.94	0.026
FLASH									
FA1c	30	1.0	121.1	34.4	12.67	117.1	34.4	3.34	0.066
FA2a	0	1.4	115.3	34.3	7.09	108.6	34.3	2.58	5×10^{-5}
FA3a	0	3.0	8.5	5.4	6.49	8.5	5.4	6.49	10^{-4}
FA3c	30	3.0	83.2	10.0	8.44	76.9	10.0	2.34	0.003

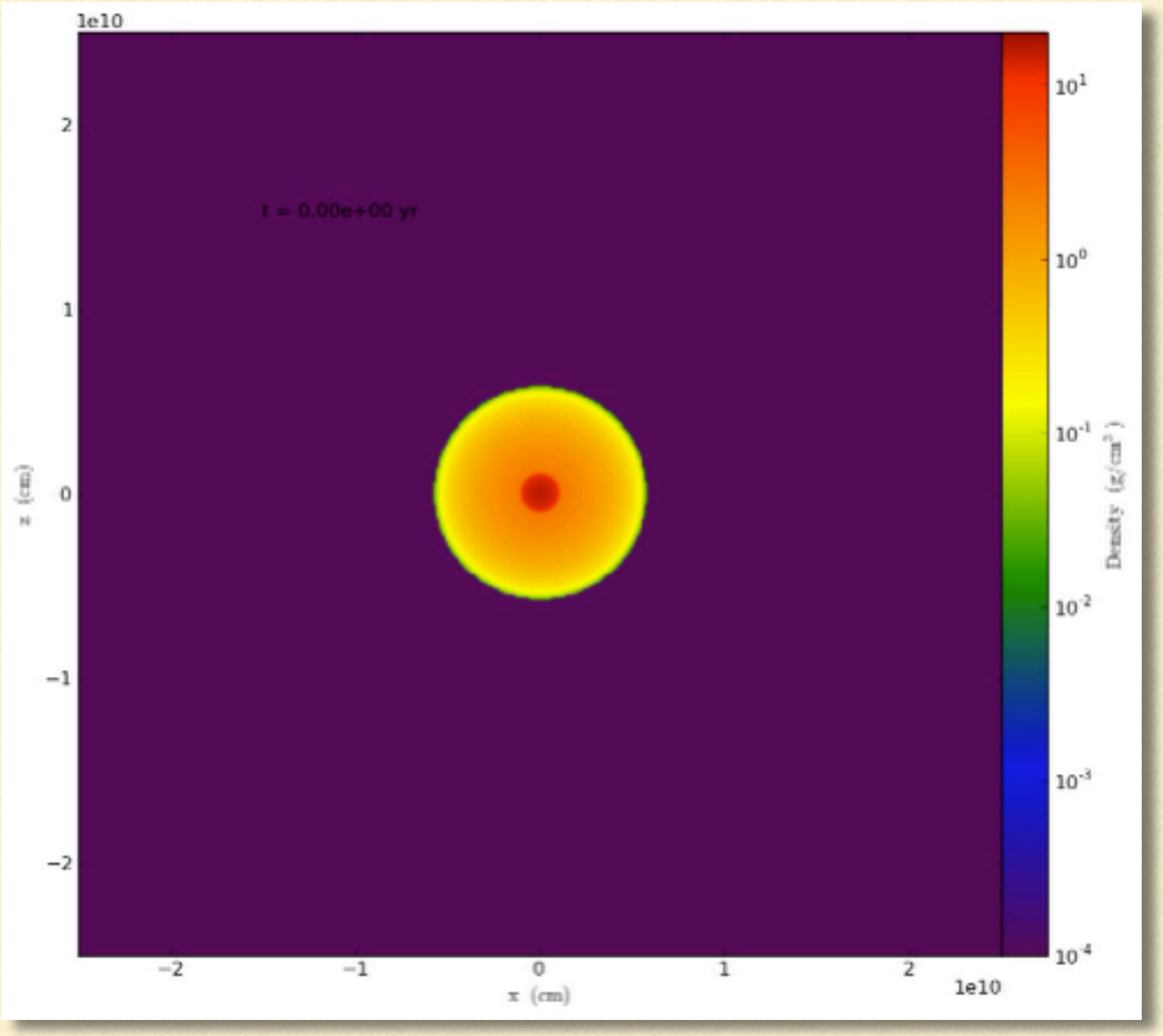
Liu+ (2014)

High Speed Oblique Impact (FLASH)

X-Y plane

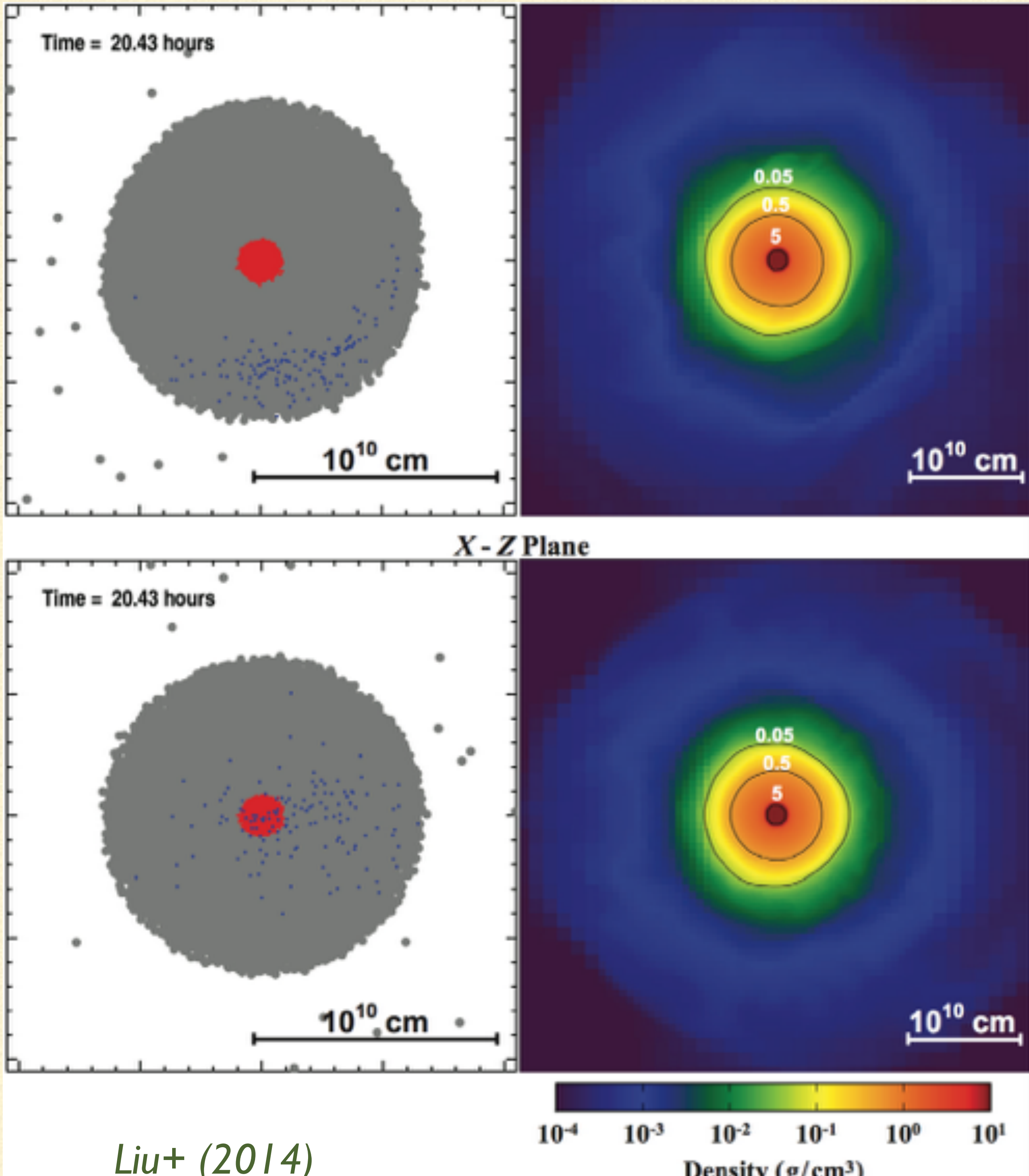


X-Z plane



Liu+ (2014)

High Speed Oblique Collisions (Summary)



Liu+ (2014)

The fly-by impactor may leave gas giant's core unaltered.

Energy injections inflate the gas giant substantially.

The impactor does not deposit much angular momentum

Discrepancies between the two methods

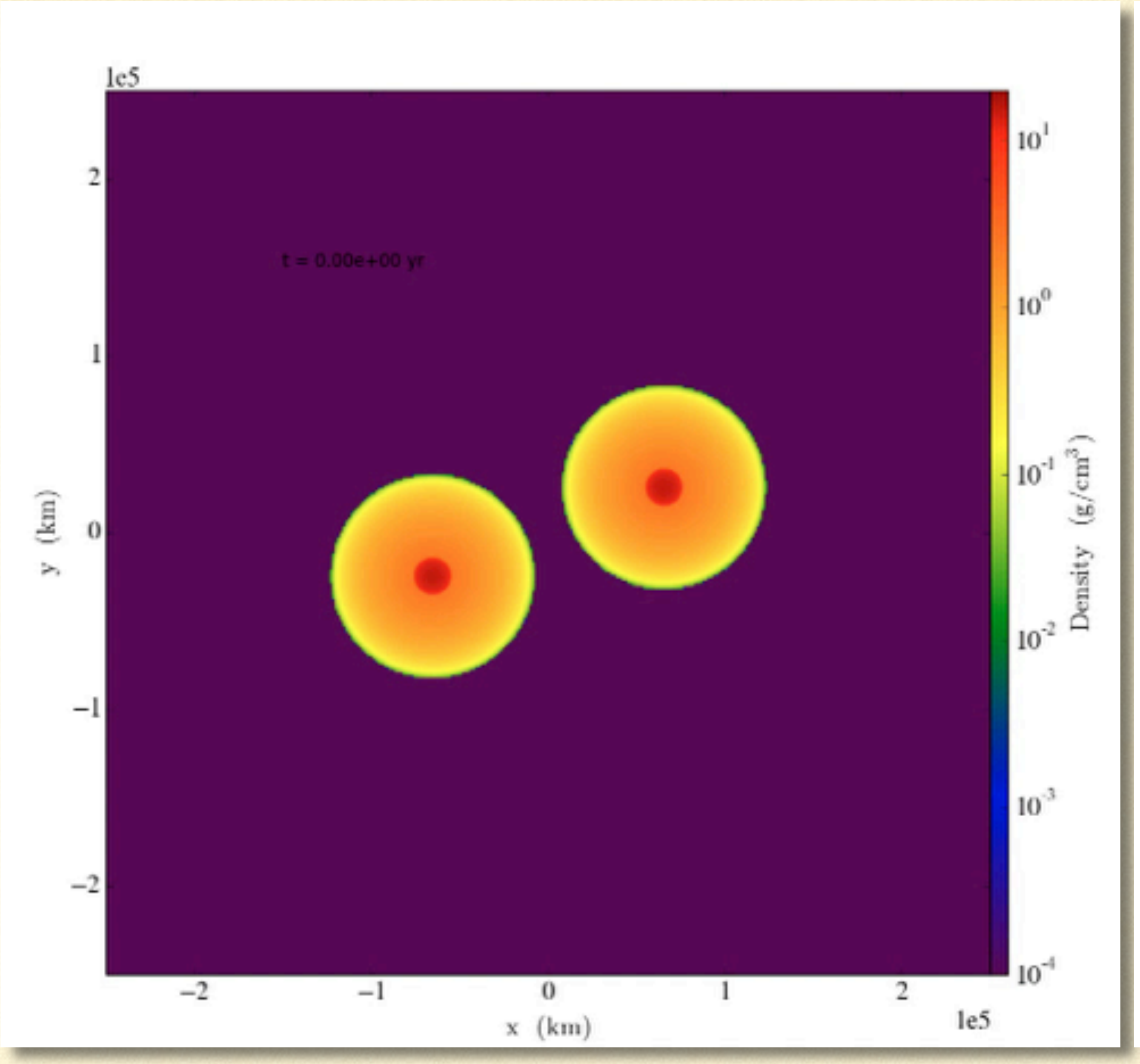
10 Earth Mass Impactor

Model	ξ	$v_{imp}/v_{esc,2}$	M_{bm}	$M_{bm,c}$	R_{bm}/R_T	M_{cc}	$M_{cc,c}$	R_{cc}/R_T	J_{cc}/J_*
SPH									
SB1a	0	1.0	110.1	20.0	1.06	96.9	20.0	0.95	0.001
SB1b	21	1.0	110.1	20.0	1.05	97.0	20.0	0.95	0.097
SB1c	30	1.0	110.0	20.0	1.05	96.2	20.0	0.94	0.132
SB1d	45	1.0	109.7	20.0	1.05	94.3	18.7	0.93	0.155
SB1e	60	1.0	109.8	20.0	1.03	100.2	19.6	0.96	0.246
SB2a	0	1.4	110.1	20.0	1.07	92.8	20.0	0.94	0.001
SB2b	21	1.4	109.5	20.0	1.07	92.2	20.0	0.93	0.122
SB2c	30	1.4	109.1	20.0	1.06	91.0	19.7	0.92	0.163
SB2d	45	1.4	100.3	11.4	1.02	91.2	11.0	0.94	0.056
SB2e	60	1.4	100.2	10.4	1.00	94.0	10.1	0.95	0.023
SB3a	0	3.0	100.5	20.0	1.06	79.4	20.0	0.89	0.002
SB3b	21	3.0	93.3	11.6	1.04	73.7	11.1	0.88	0.070
SB3c	30	3.0	95.6	10.6	1.04	79.8	10.3	0.91	0.061
SB3d	45	3.0	98.7	10.1	1.02	87.3	10.0	0.93	0.038
SB3e	60	3.0	99.9	10.1	1.01	93.2	10.0	0.95	0.017
SB4a	0	5.0	64.9	19.7	0.78	55.7	19.3	0.69	0.003
SB4b	21	5.0	82.0	10.5	0.99	64.5	10.2	0.83	0.049
SB4c	30	5.0	90.8	10.2	1.03	72.4	10.1	0.88	0.049
SB4d	45	5.0	97.5	10.0	1.03	83.6	10.0	0.92	0.042
SB4e	60	5.0	99.6	10.0	1.01	91.4	10.0	0.95	0.022
FLASH									
FB3a	0	3.0	65.9	14.9	4.52	65.9	14.9	4.52	10^{-4}
FB3c	30	3.0	88.9	10.1	8.42	80.5	10.0	1.55	0.004
FB4a	0	5.0	-	-	-	-	-	-	-

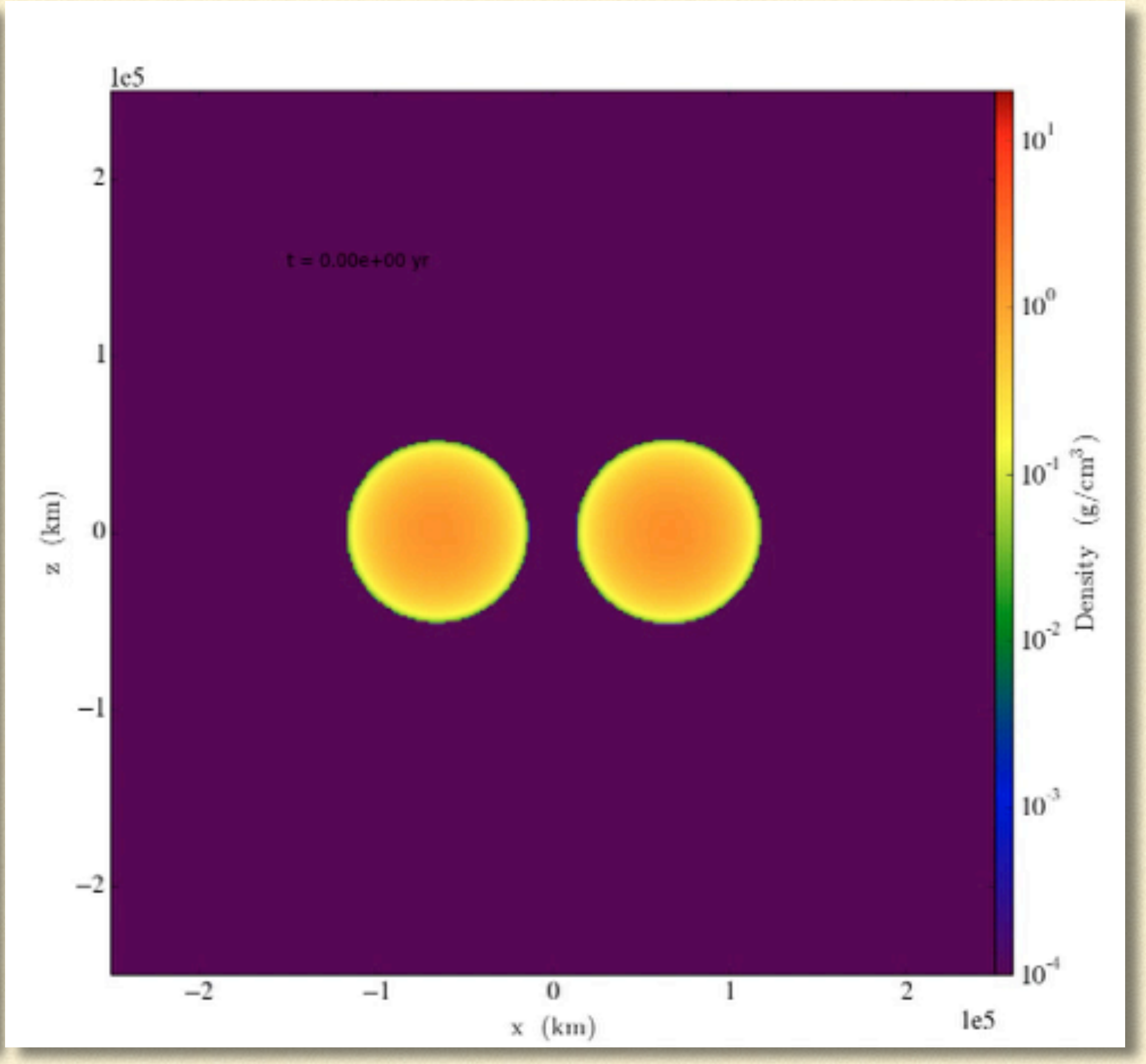
Liu+ (2014)

Merger of Two Gas Giants (FLASH)

X-Y plane



X-Z plane



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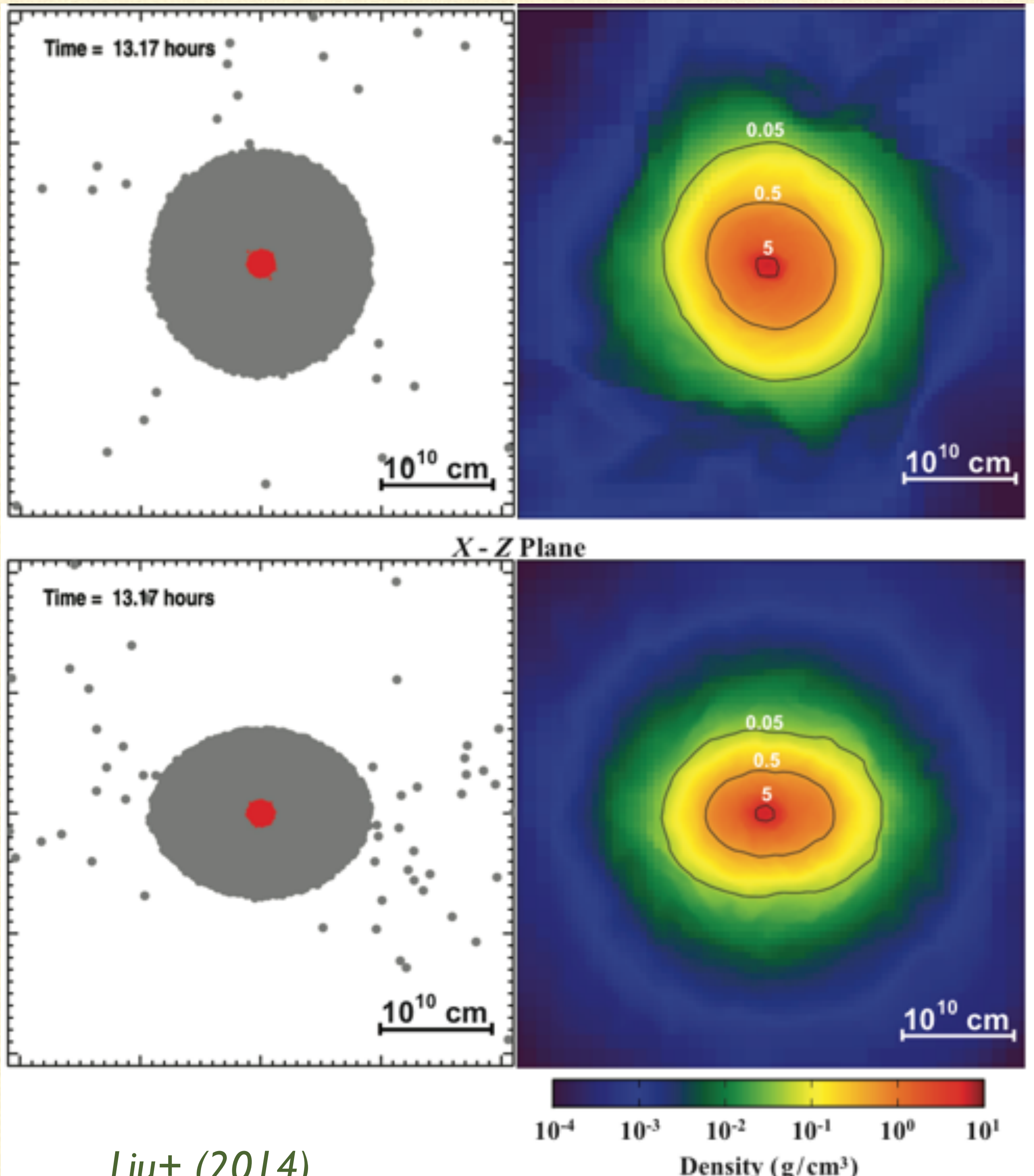
Merger of Two Gas Giants (Summary)



Liu+ (2014)

In order to merger, both the collision speed and impact parameter have to be small

Energy injections inflate the gas giant substantially.

The merger product gains a lot of angular momentum

Discrepancies between the two methods

Two Gas Giant Merger

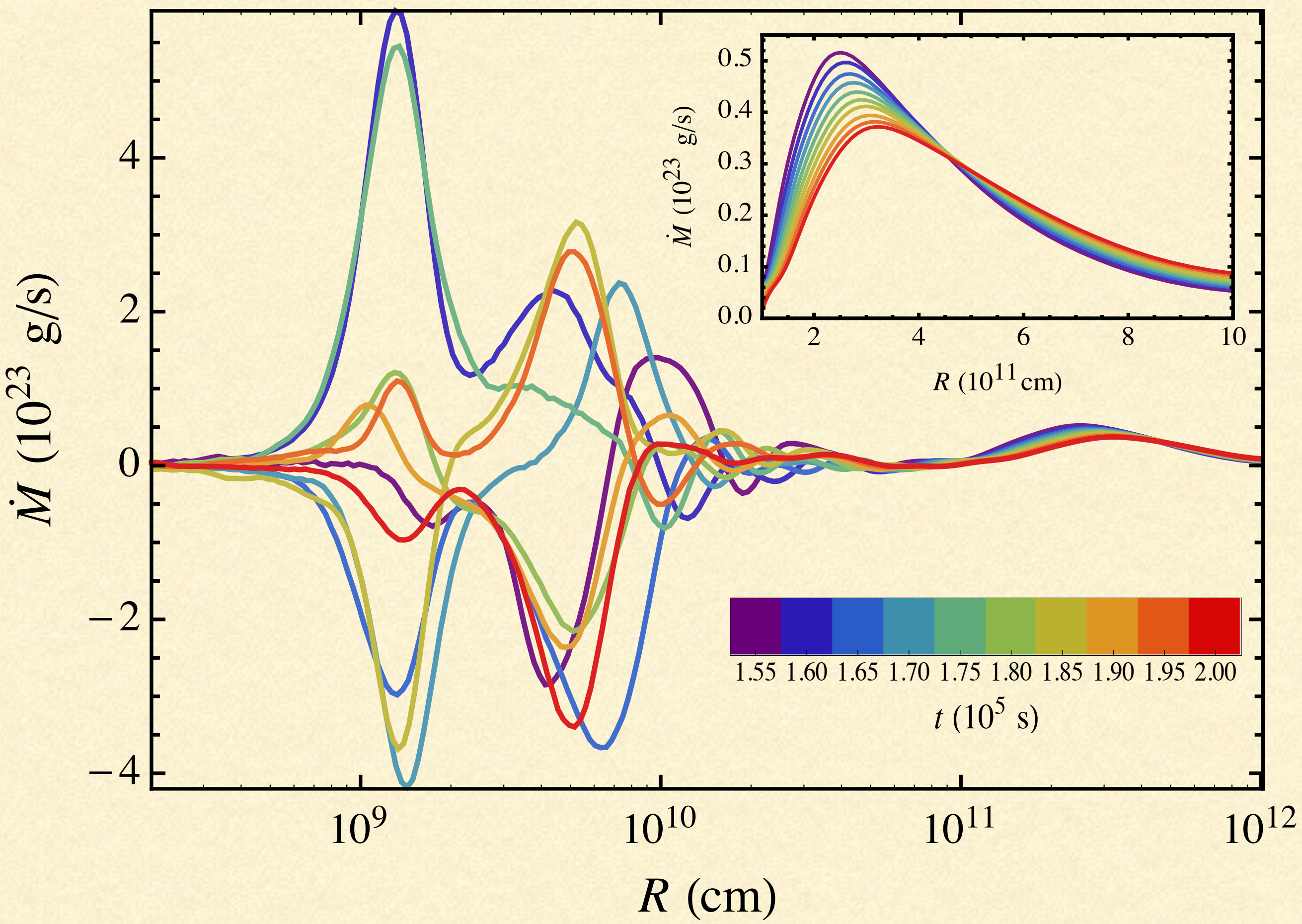
Model	ξ	$v_{imp}/v_{esc,2}$	M_{bm}	$M_{bm,c}$	R_{bm}/R_T	M_{cc}	$M_{cc,c}$	R_{cc}/R_T	J_{cc}/J_*
SPH									
SC1a	0	1.0	199.6	20.0	1.25	178.0	20.0	1.13	0.000
SC1b	21	1.0	200.1	20.0	1.27	159.8	20.0	1.05	0.258
SC1c	30	1.0	200.3	20.0	1.32	144.9	20.0	1.02	0.299
SC1d	45	1.0	200.3	20.0	1.27	151.5	20.0	1.02	0.744
SC1e	60	1.0	200.3	20.0	1.29	87.6	10.0	0.92	0.118
SC2a	0	1.4	197.8	20.0	1.27	168.0	20.0	1.11	0.001
SC2b	21	1.4	199.3	20.0	1.33	138.7	20.0	1.00	0.276
SC2c	30	1.4	199.9	20.0	1.34	77.3	10.0	0.88	0.150
SC2d	45	1.4	100.0	10.0	1.04	85.4	10.0	0.92	0.087
SC2e	60	1.4	100.0	10.0	1.02	91.0	10.0	0.94	0.063
SC3a	0	3.0	112.1	20.0	0.89	98.1	19.5	0.82	0.001
SC3b	21	3.0	69.2	10.0	0.84	62.1	10.0	0.77	0.155
SC3c	30	3.0	87.4	10.0	1.01	70.7	10.0	0.86	0.069
SC3d	45	3.0	97.5	10.0	1.04	81.0	10.0	0.91	0.061
SC3e	60	3.0	99.6	10.0	1.01	91.3	10.0	0.95	0.034
SC4a	0	5.0	41.7	13.1	0.55	36.3	12.4	0.51	0.005
SC4b	21	5.0	48.0	10.0	0.62	44.0	10.0	0.57	0.126
SC4c	30	5.0	70.0	10.0	0.87	62.9	10.0	0.80	0.084
SC4d	45	5.0	93.6	10.0	1.04	74.9	10.0	0.88	0.055
SC4e	60	5.0	99.2	10.0	1.03	87.3	10.0	0.93	0.037
FLASH									
FC1b	21	1.0	196.3	20.0	9.76	188.1	20.0	3.43	0.181
FC2a	0	1.4	169.2	20.0	12.47	148.0	20.0	3.49	2×10^{-4}

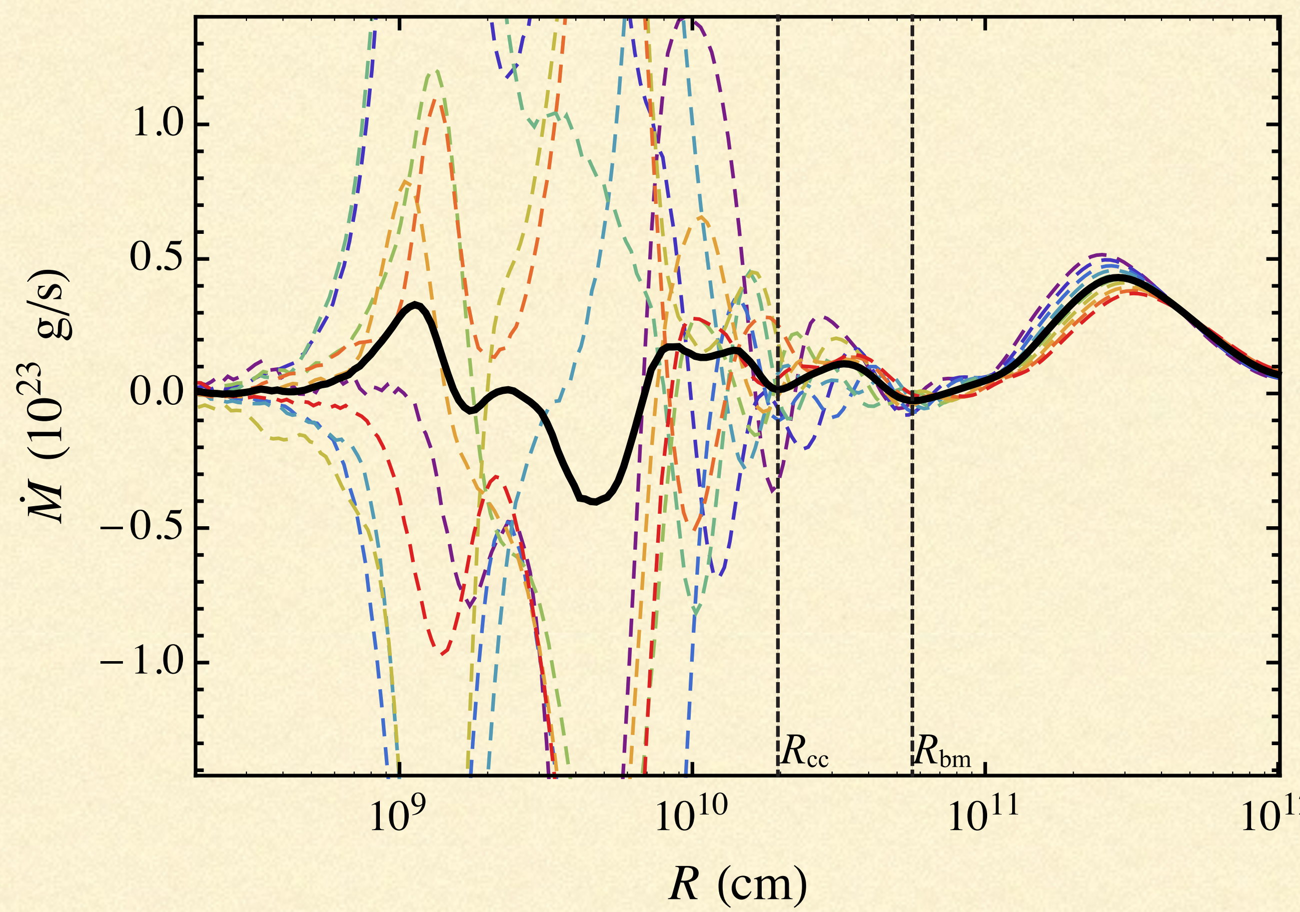
Liu+ (2014)

SPH vs FLASH (AMR)

	SPH	FLASH
HYDRO	Lagrangian	Eulerian
GRAVITY	Tree method	Multipole Expansion
EOS	Ideal gas + Tillotson	Composite polytropes
BOUNDARY	Lower density limit (external pressure)	OPEN

Boundary Determination in FLASH





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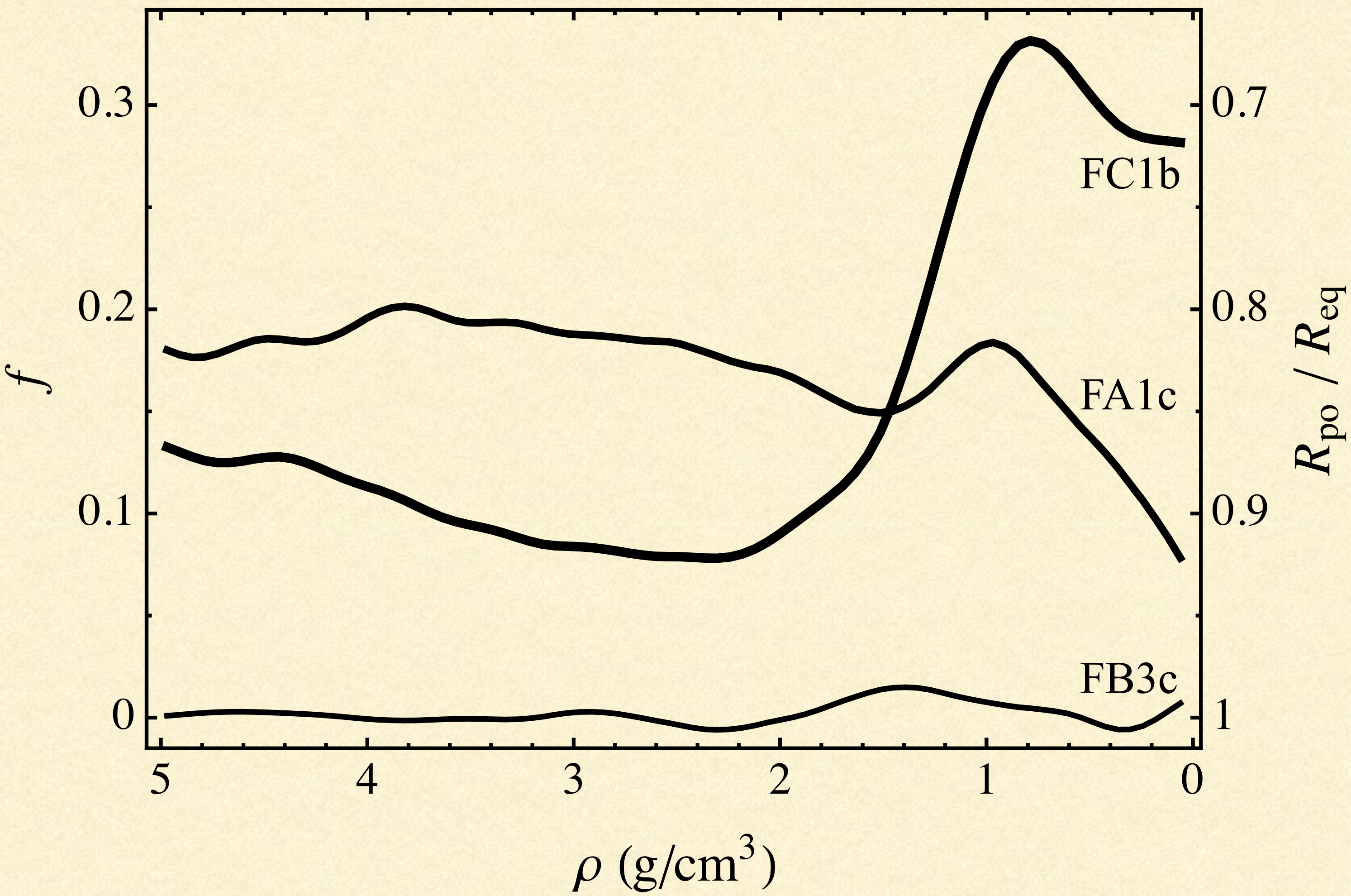
Oblateness caused by oblique collisions



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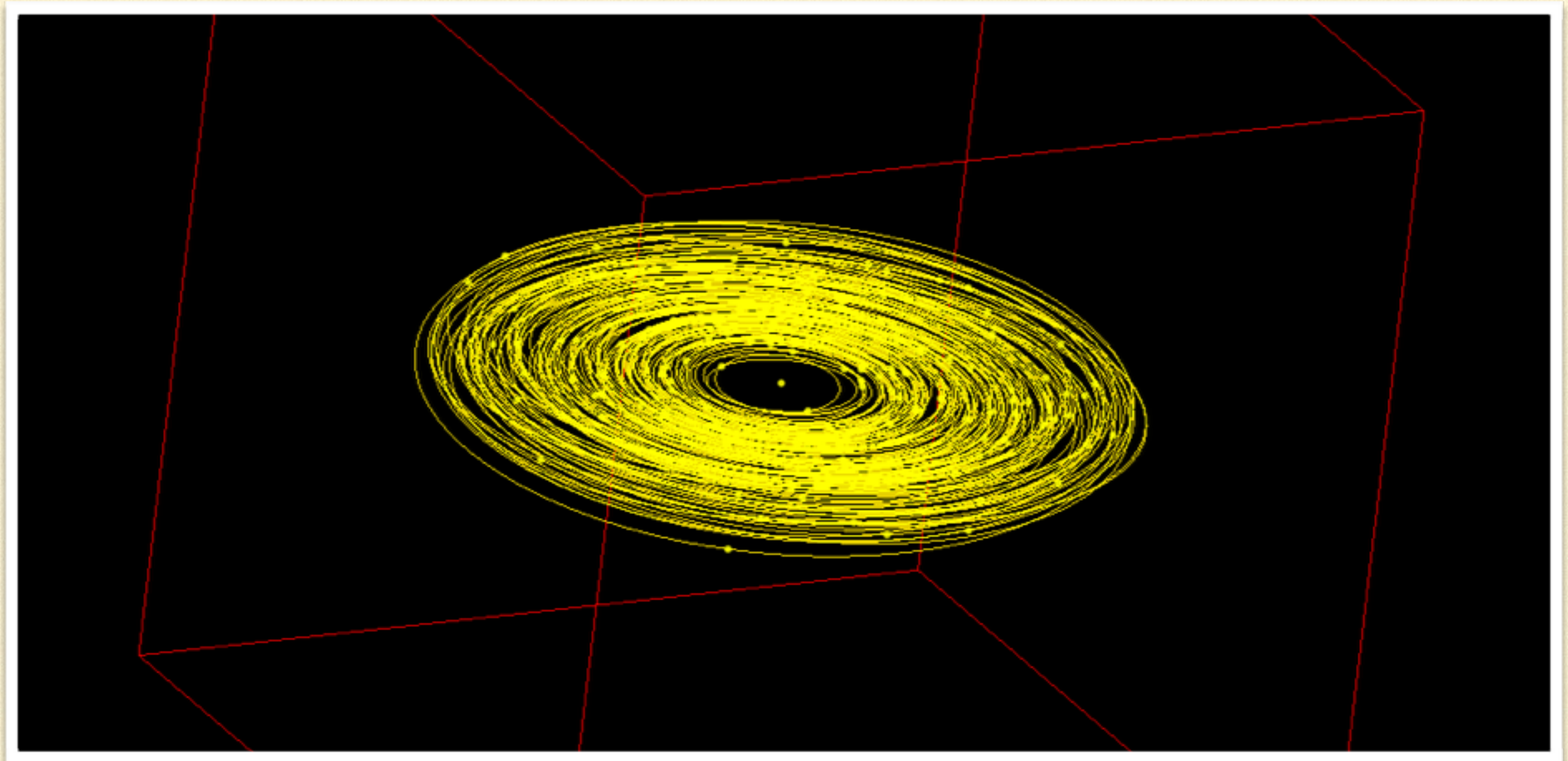
FA1c: Low speed embryo impact

FB3c: High speed embryo impact

FC1b: Low speed gas giant merger



Gravitational *N*-body Simulations including Collisions

A complementary method to study the long-term evolution and dynamical outcomes

Thank you!