Art by National Geographic

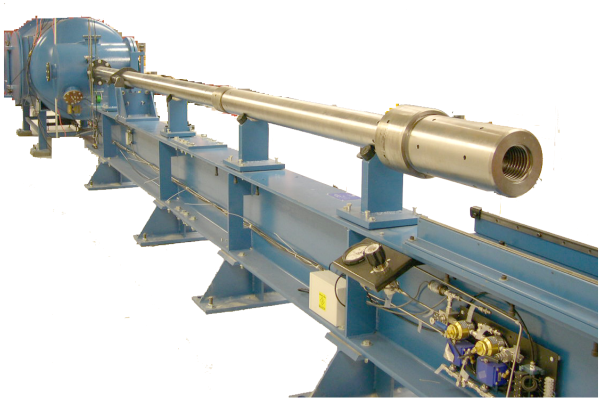
Growing Planets by Giant Impacts: A Diversity of Outcomes

Sarah T. Stewart

Dept. Earth & Planetary Sciences, UC Davis

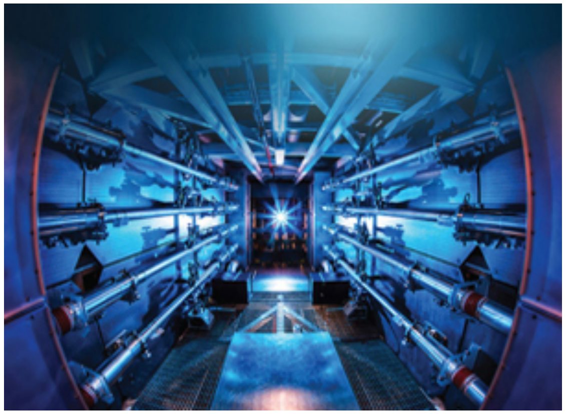
High Energy Density Science

Reaching the Extremes of Planet Formation in the Laboratory



Gas Guns

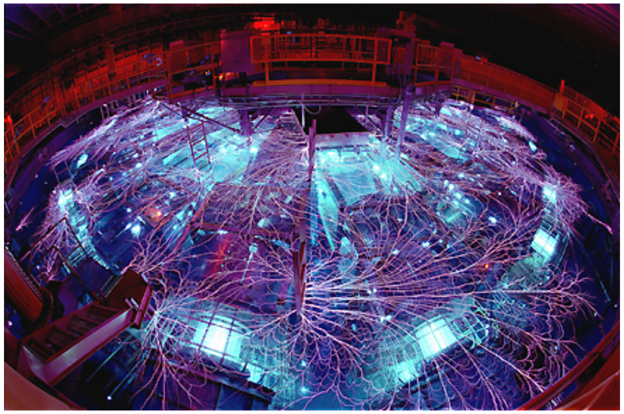
UC Davis
Shock Compression
Laboratory



LLNL NIF Laser

NIF Discovery
Science Program

Annual solicitations



Sandia Z Machine

Z Fundamental
Science Program

Next call in September

High Energy Density Science

Reaching the Extremes of Planet Formation in the Laboratory

Impact Vaporization

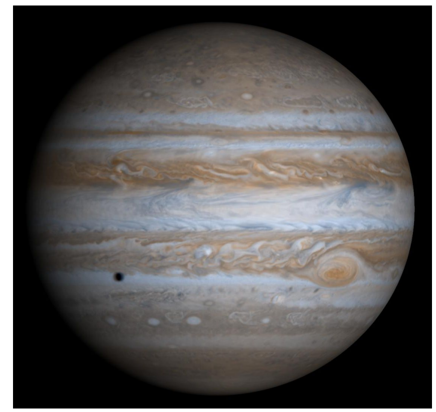
H_2O, SiO_2, Fe, MgO

Stewart et al. 2008
Kraus et al. 2012
Kraus et al. 2015
Kraus et al. in prep.

Melting Curves

MgO, SiO_2

McWilliams et al. Science 2012
Root et al. submitted (arxiv)
Millot et al. Science 2015



Internal Structure

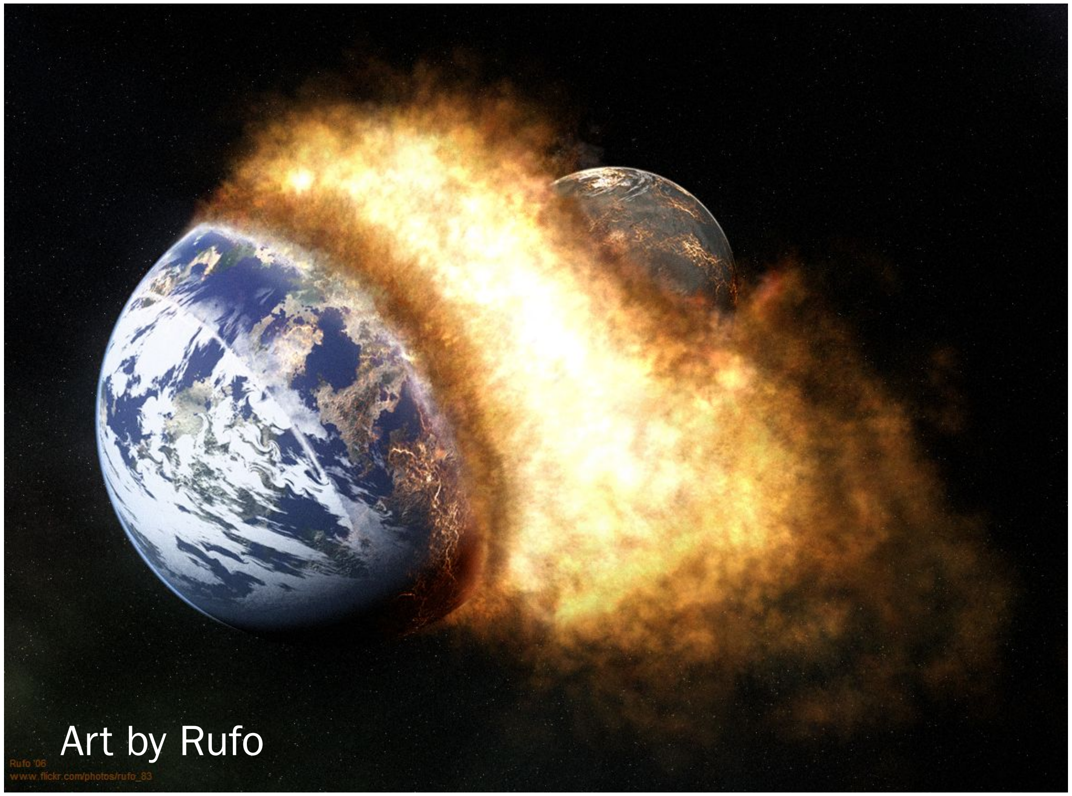
H, He, H_2O

Knudson et al. 2012
Millot et al. in prep
Knudson et al. submitted

How to think about giant impacts?
Is it something like an explosion?

Art by Industrial Light & Magic

Are volatiles lost during a giant impact?



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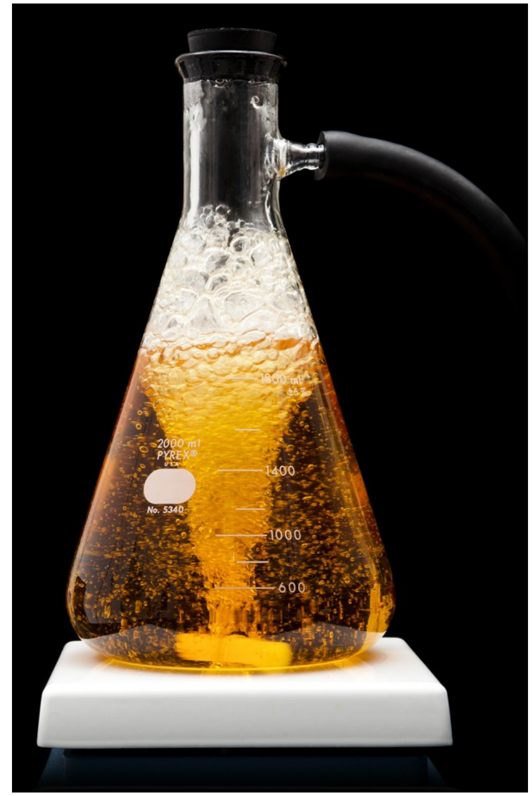
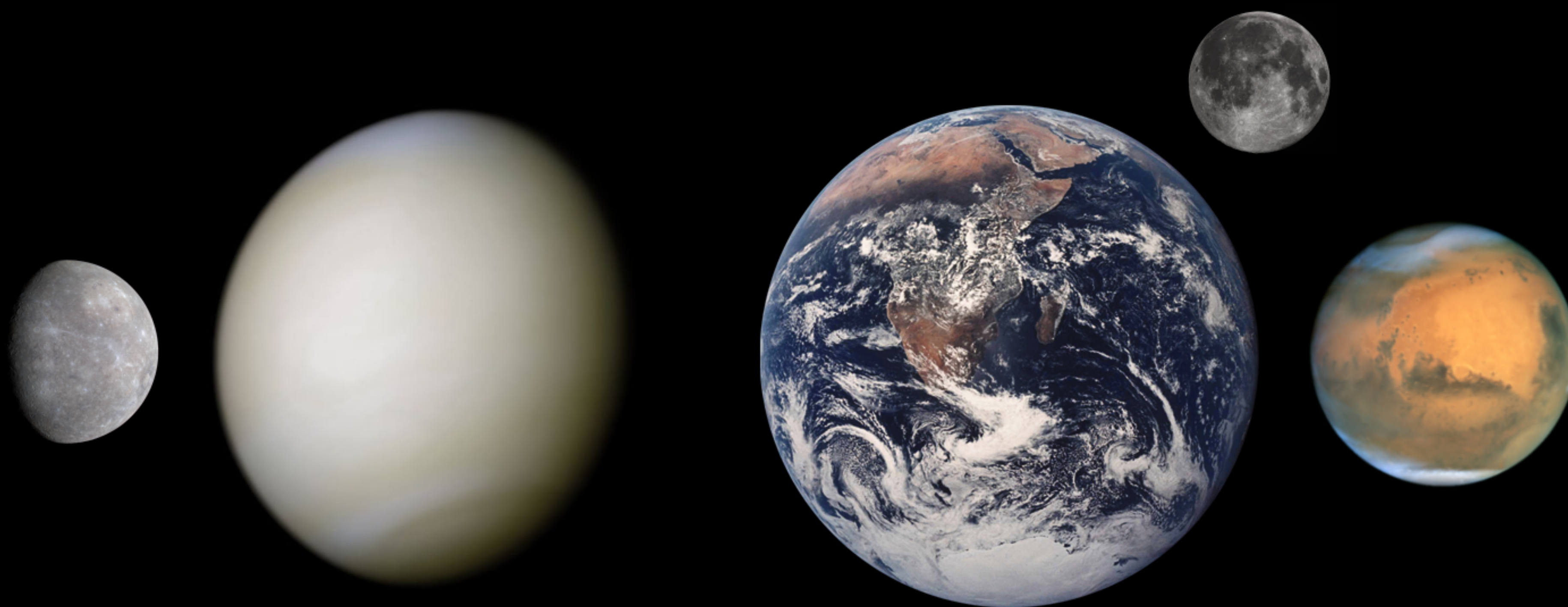


?

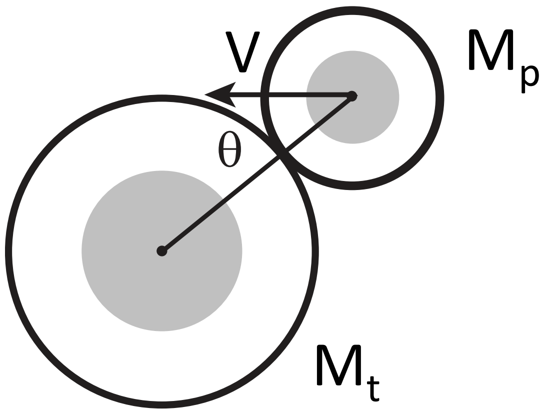
“One of the leading hypotheses on Earth’s formation is that it was so hot when it formed 4.6 billion years ago that any original water content should have boiled off.”
– ESA Rosetta Press release December 10, 2014

How did this happen?



Aspects of Giant Impacts

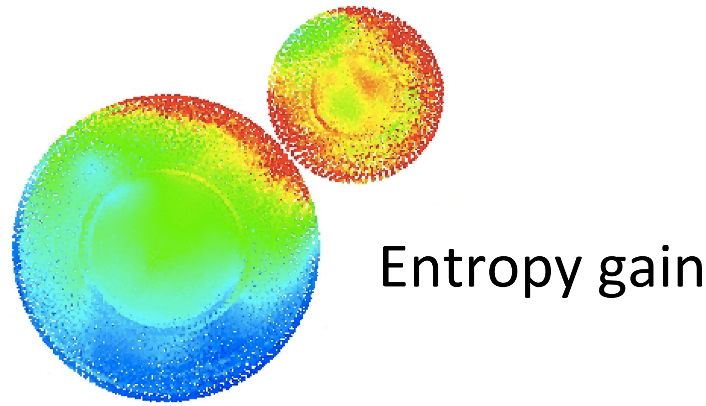
Mechanics



Largest post-impact mass
Size & velocity of fragments
Core/mantle ratio
Loss of atmosphere & ocean

Planet formation context gives probabilities of different impact outcomes.

Thermodynamics



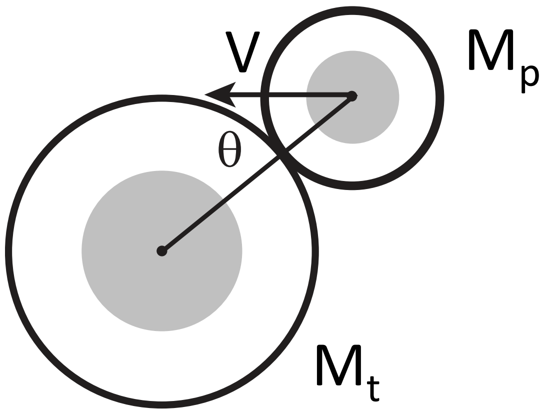
Mass of melt and vapor
Thermal states of final bodies

Implications for chemistry

What are the individual and cumulative effects of giant impacts on the physical and chemical properties of the final planets?

Aspects of Giant Impacts

Mechanics



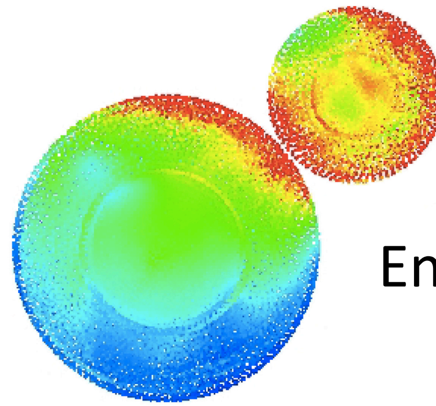
$$M_{lr} = F\left(M_t, M_p, V, \theta, c_{material}\right)$$

Leinhardt & Stewart 2012
and online calculator

$$L_{atm} = F\left(M_t, M_p, V, \theta, m_{atm} / m_{ocean}\right)$$

Lock, Stewart, Mukhopadhyay, in prep.

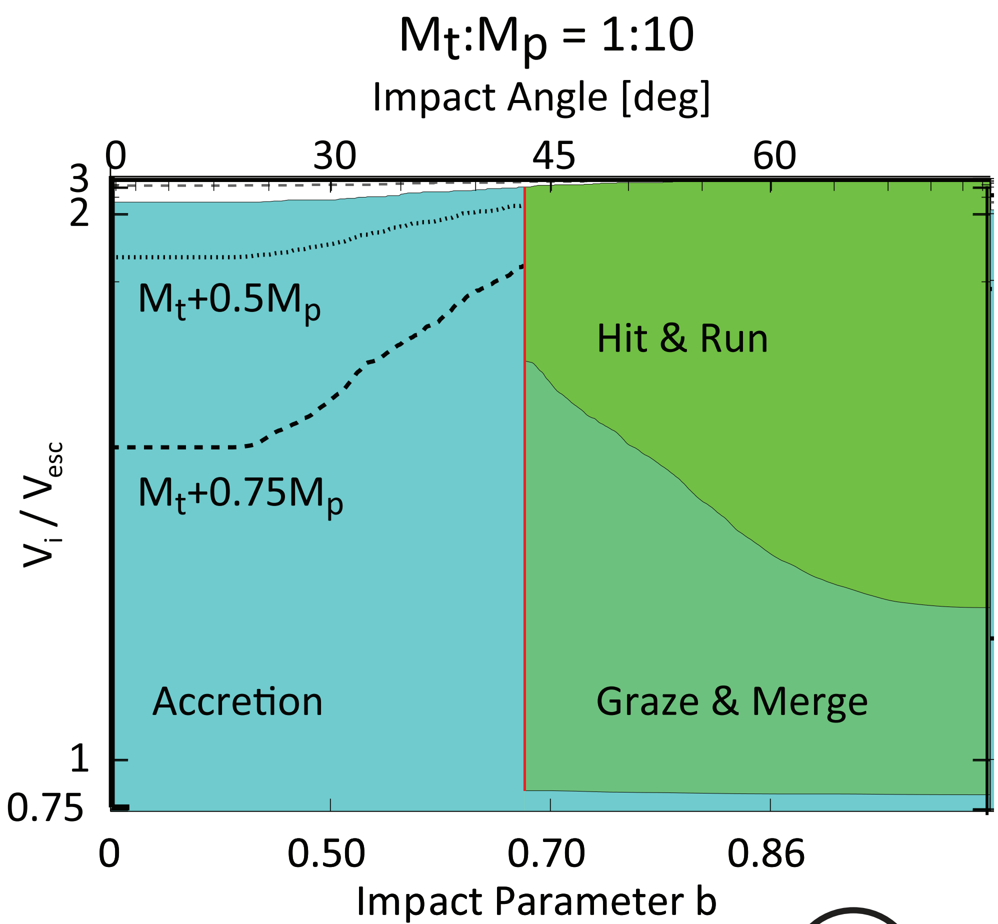
Thermodynamics



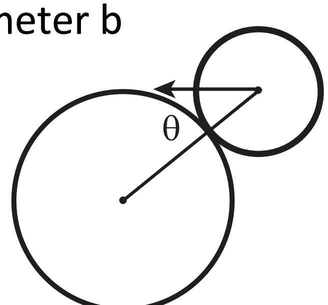
Entropy gain

$$dS = F\left(M_t, M_p, V, \theta, c_{material}\right)$$

Probability-scaled Collision Outcome Maps



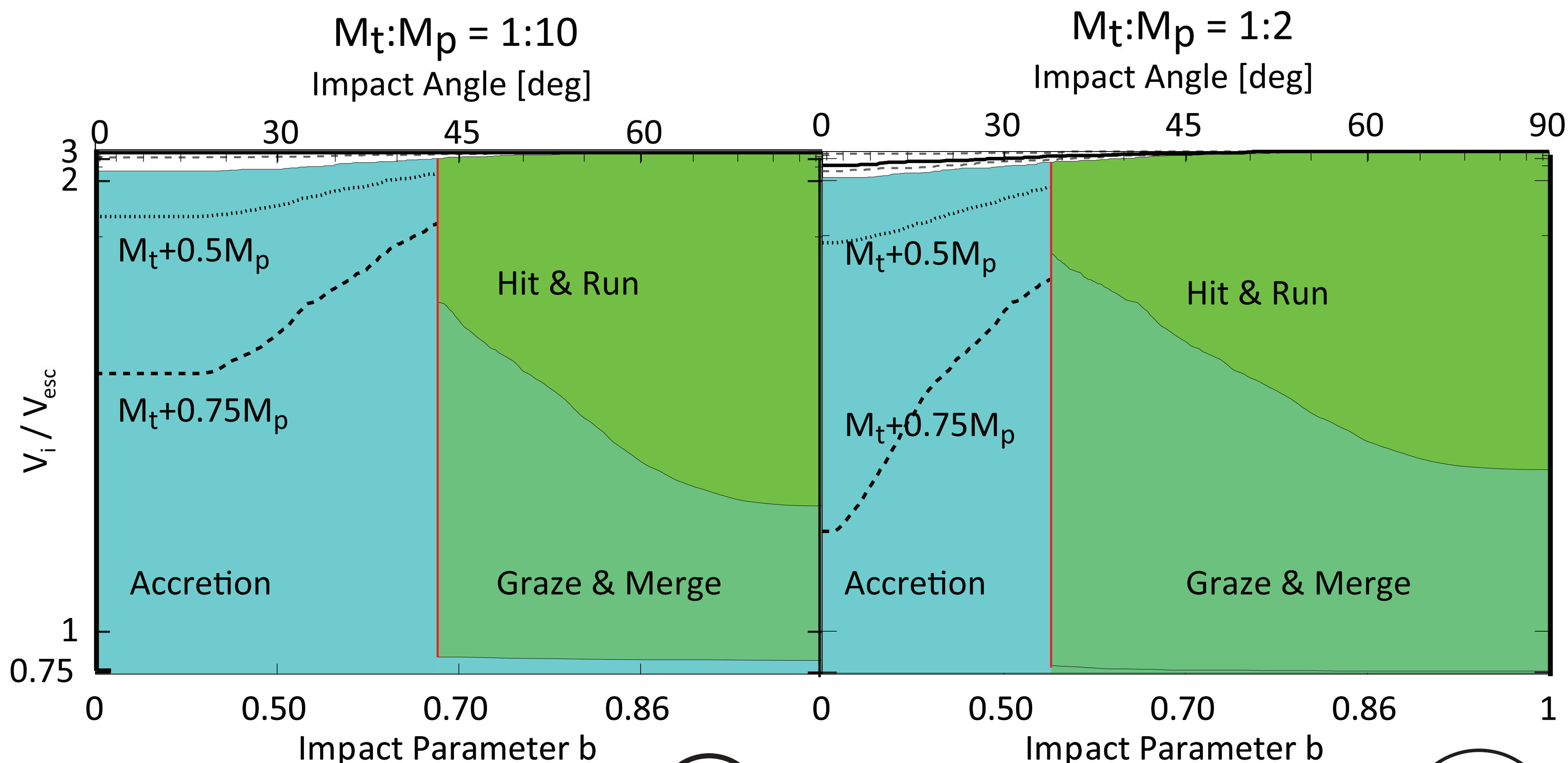
$$\frac{M_p}{M_t} = \frac{1}{10}$$



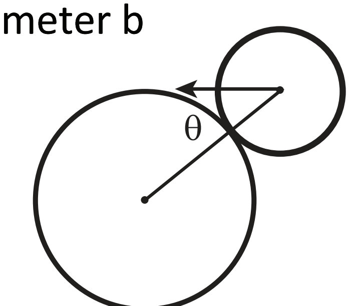
Stewart & Leinhardt 2012

online calculator mygeologypage.ucdavis.edu/stewart/resources/collision/

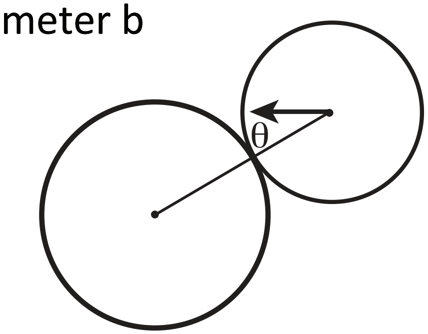
Probability-scaled Collision Outcome Maps



$$\frac{M_p}{M_t} = \frac{1}{10}$$



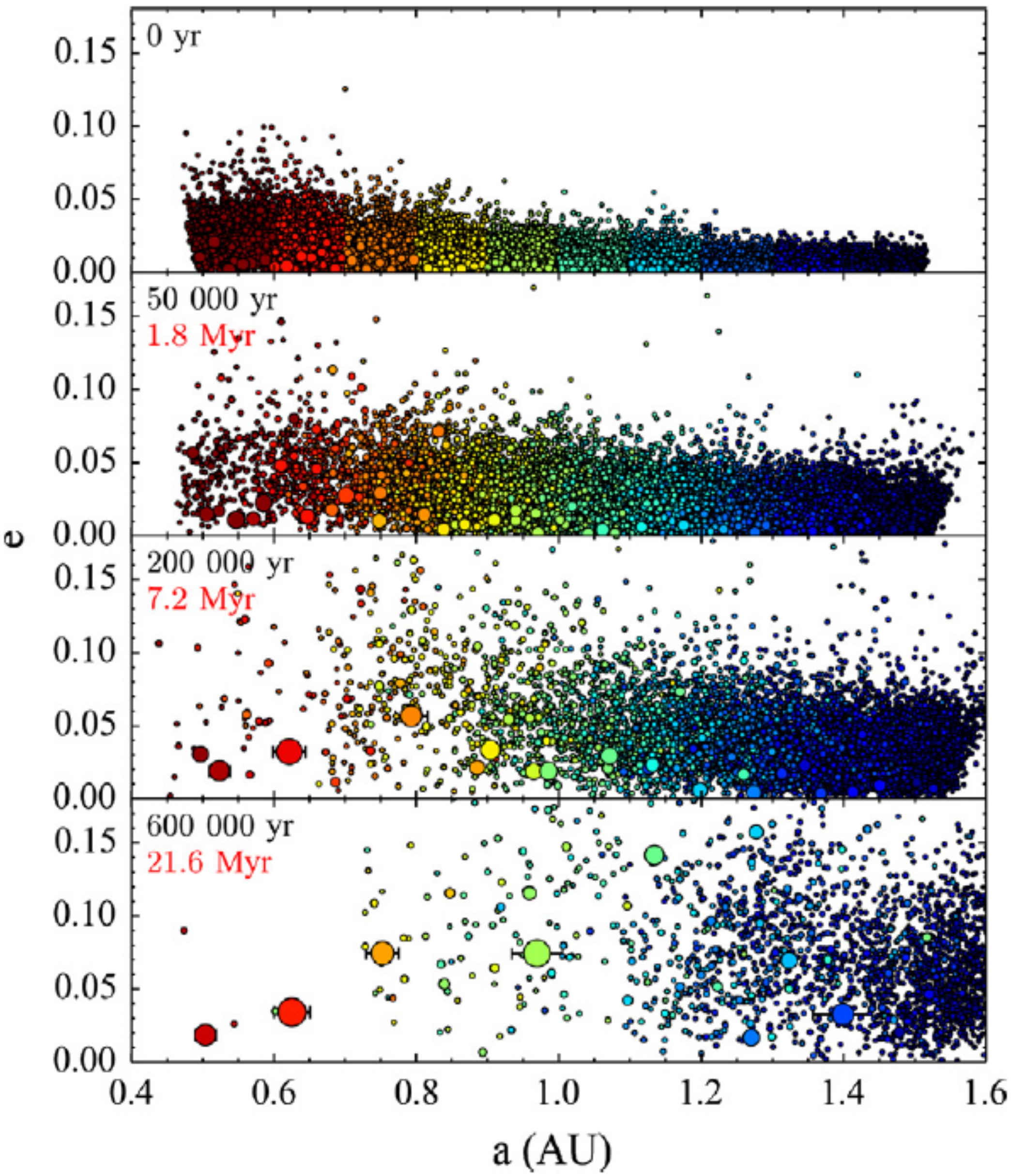
$$\frac{M_p}{M_t} = \frac{1}{2}$$

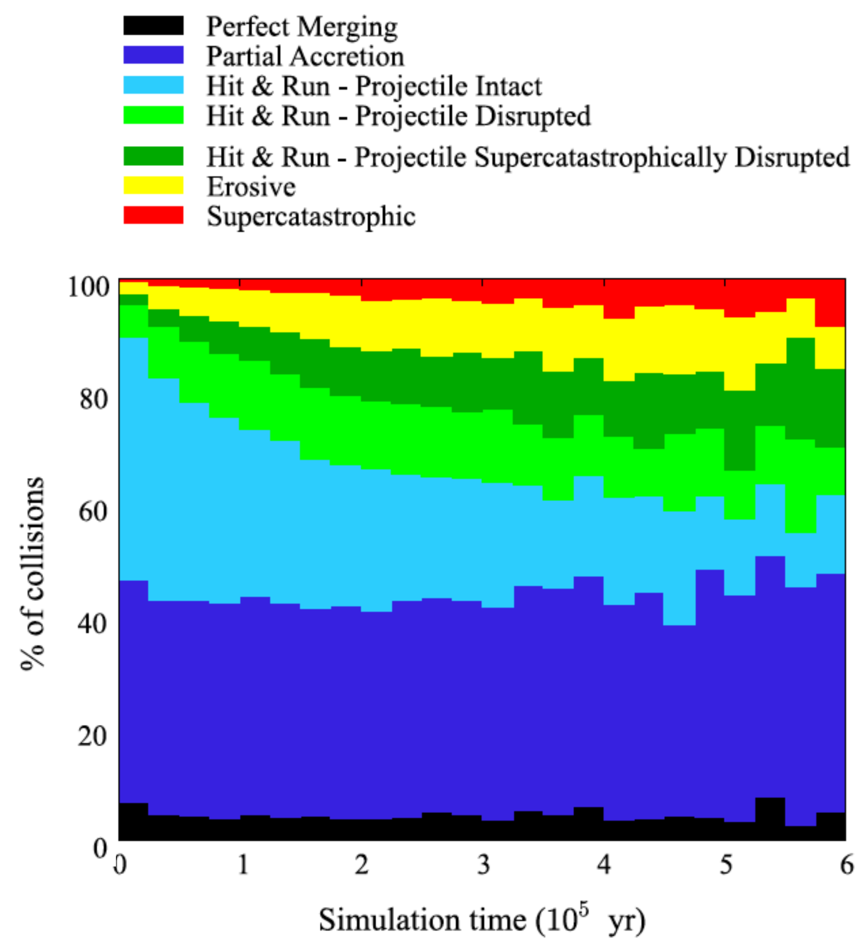


Stewart & Leinhardt 2012

online calculator mygeologypage.ucdavis.edu/stewart/resources/collision/

Accretion with Fragmentation



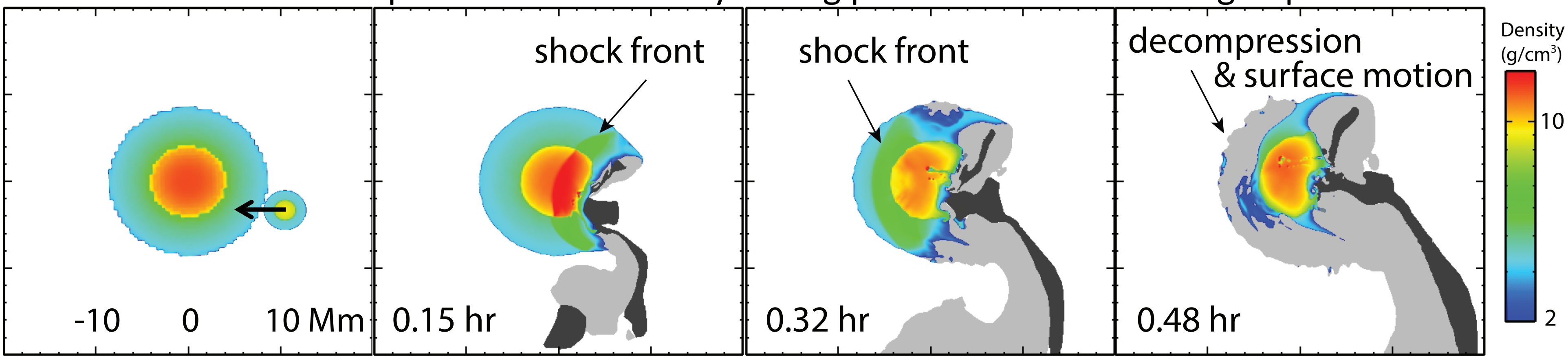


Equivalent to ~22 Myr

Bonsor, Leinhardt, Carter, Elliott, Walter, Stewart, Icarus 2015

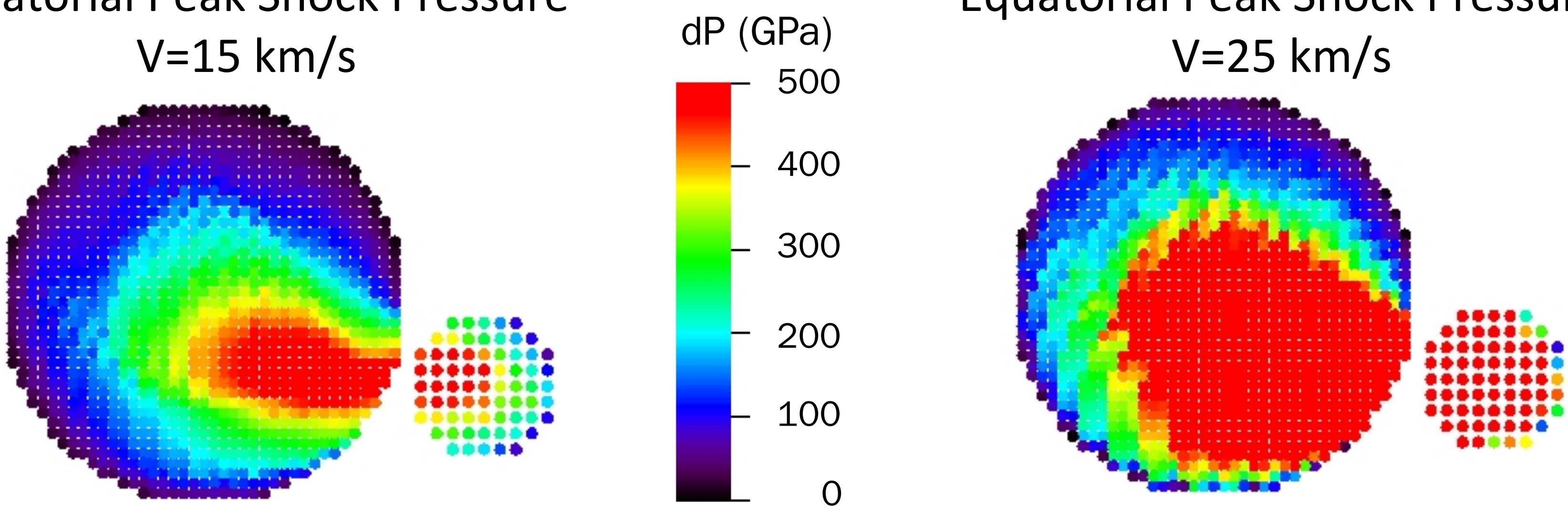
Atmospheric blowoff by a giant impact

Lower hemisphere view of density during potential Moon-forming impact



Equatorial Peak Shock Pressure
V=15 km/s

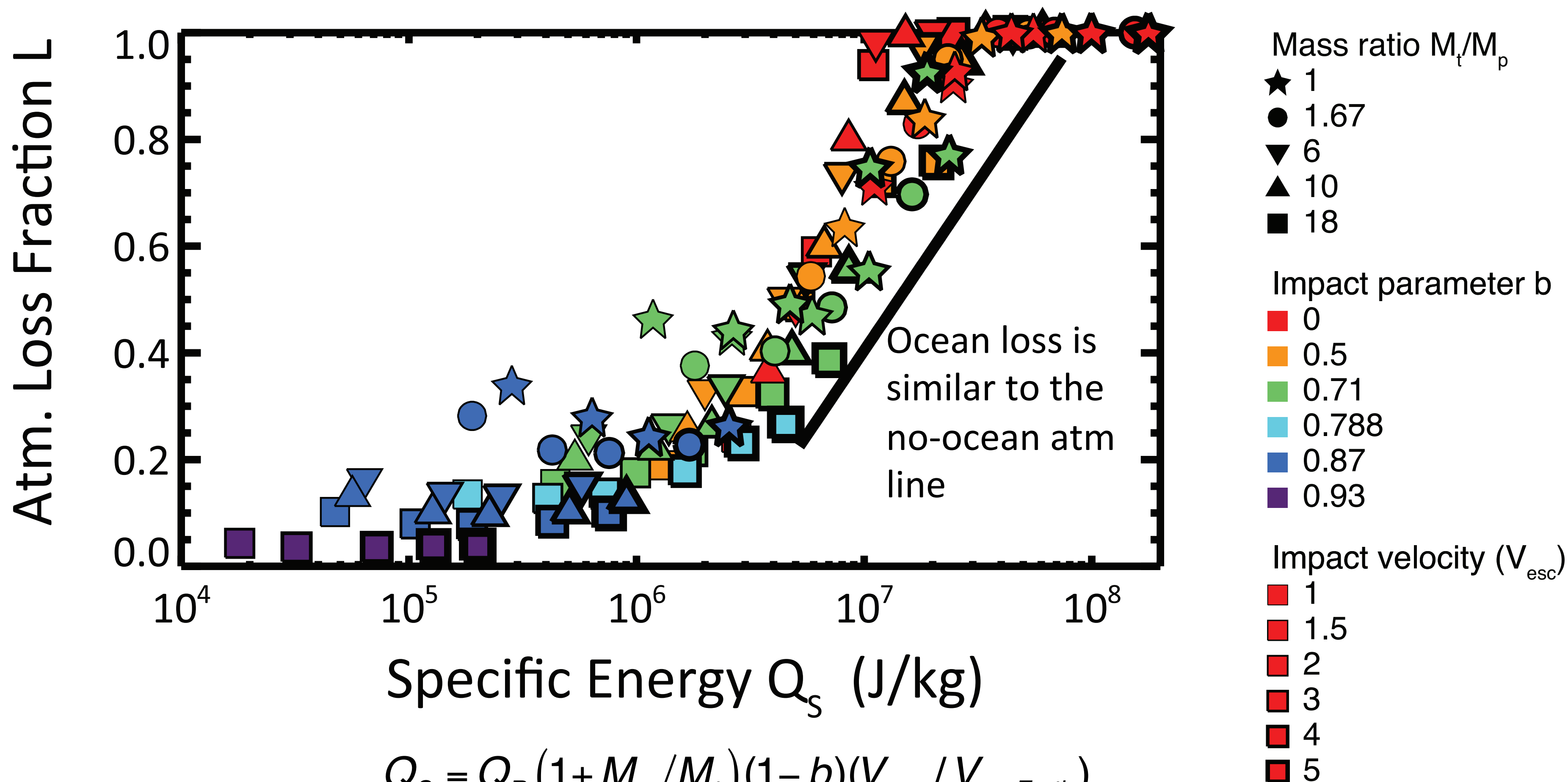
Equatorial Peak Shock Pressure
V=25 km/s



Atmospheric loss is related to the shock pressure field.

A total atmospheric loss function

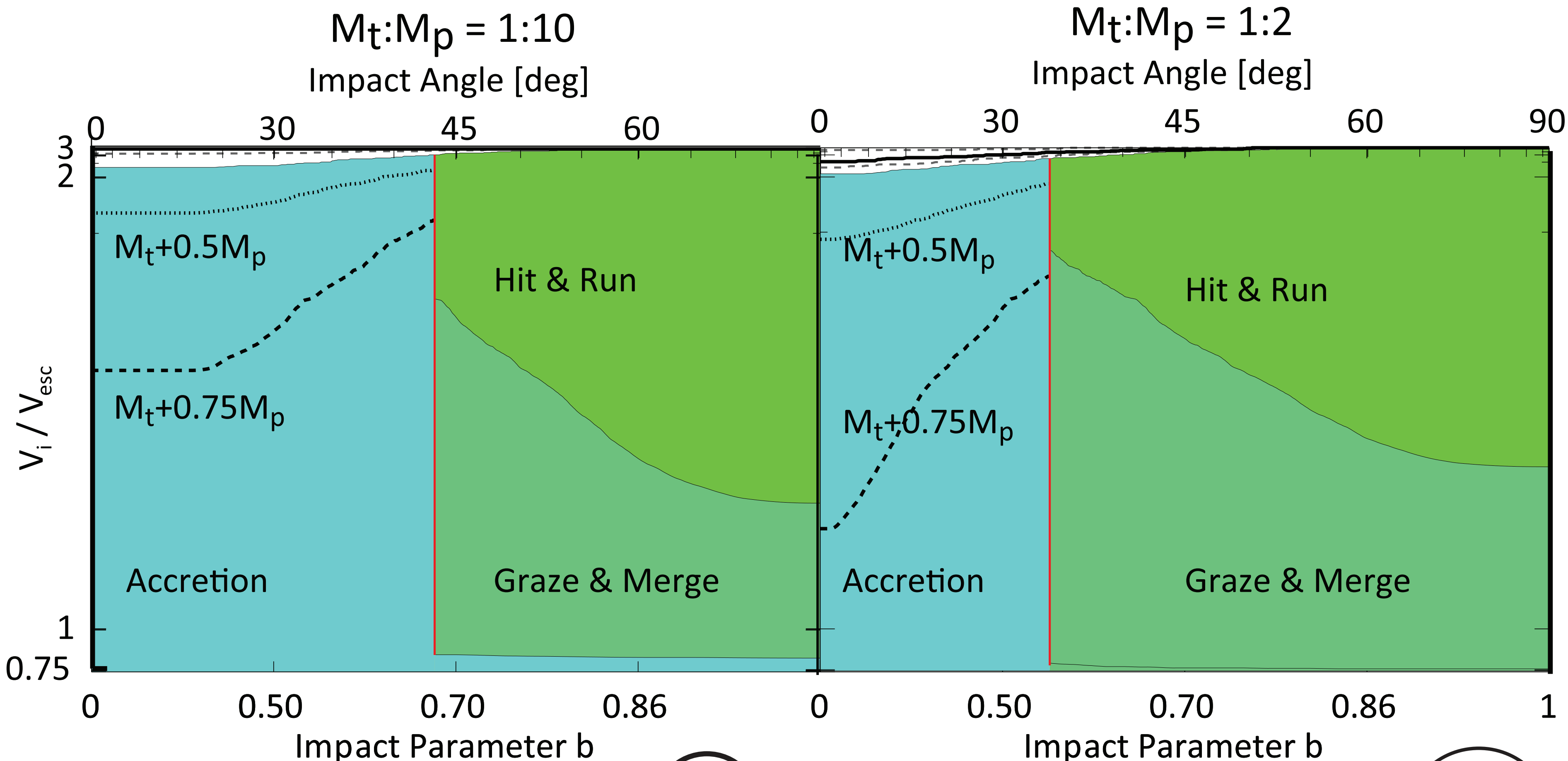
$L = \mathcal{F}(M_{targ}, M_{proj}, V_i, b, M_{atm}, M_{ocean})$



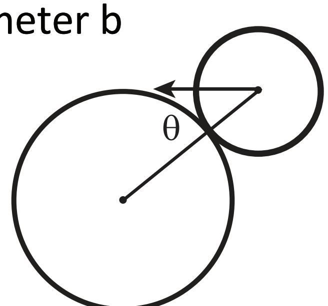
$$Q_S = Q_R\left(1 + M_p/M_t\right)(1-b)(V_{esc}/V_{escEarth})$$

$$Q_R = 0.5\mu V_I^2/(M_p + M_t)$$

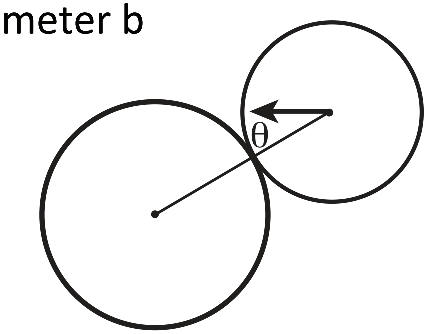
Probability-scaled Collision Outcome Maps



$$\frac{M_p}{M_t} = \frac{1}{10}$$



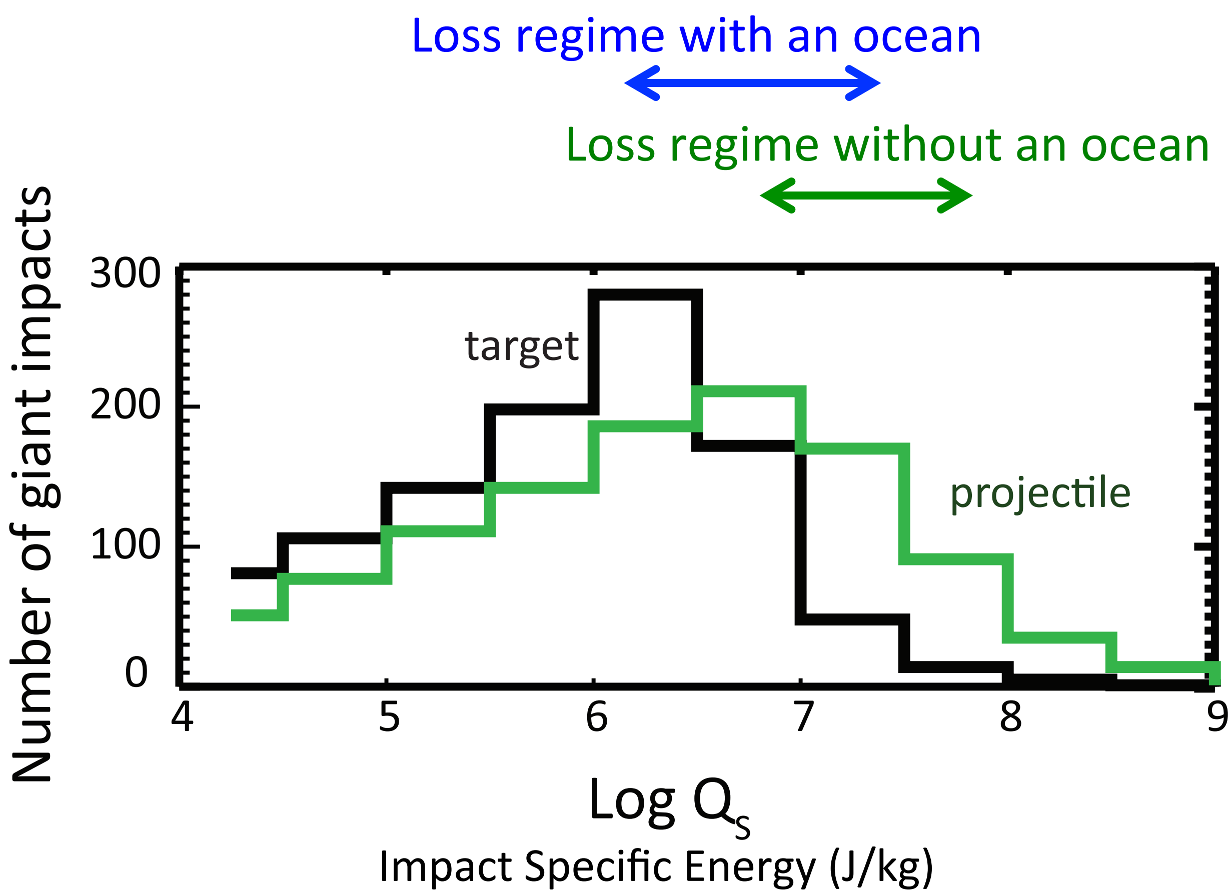
$$\frac{M_p}{M_t} = \frac{1}{2}$$



Stewart & Leinhardt 2012

online calculator mygeologypage.ucdavis.edu/stewart/resources/collision/

Giant impact atmospheric blowoff is a stochastic process during planet formation



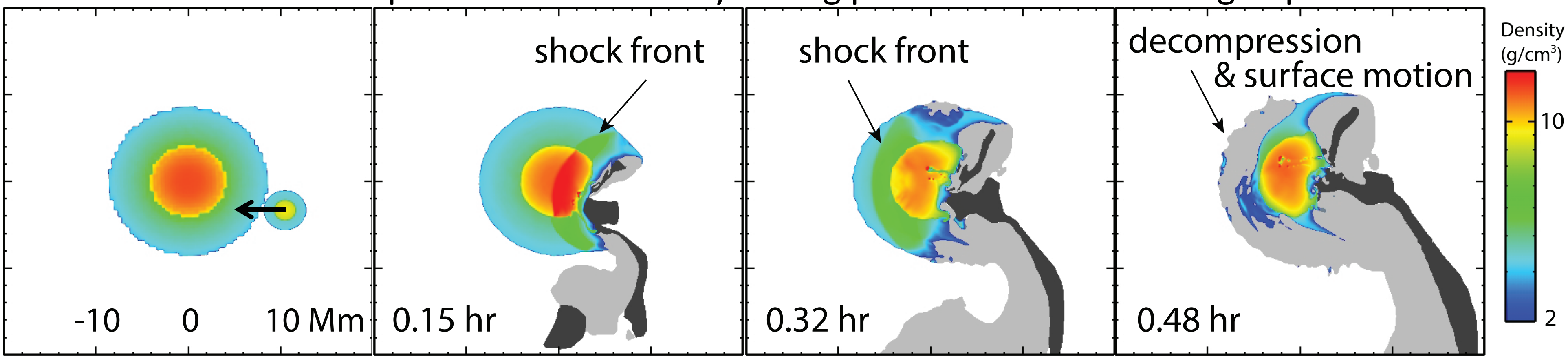
Giant impact specific energy distributions from N-body simulations (Raymond et al. 2009).

$$Q_S = Q_R\left(1 + M_p/M_t\right)(1-b)(V_{esc} / V_{escEarth})$$

$$Q_R = 0.5\mu V_I^2 / (M_p + M_t)$$

Are volatiles blown off by a giant impact?

Lower hemisphere view of density during potential Moon-forming impact



High energy impacts can remove a portion of the atmosphere.

It is difficult to remove all of the atmosphere in a single impact.

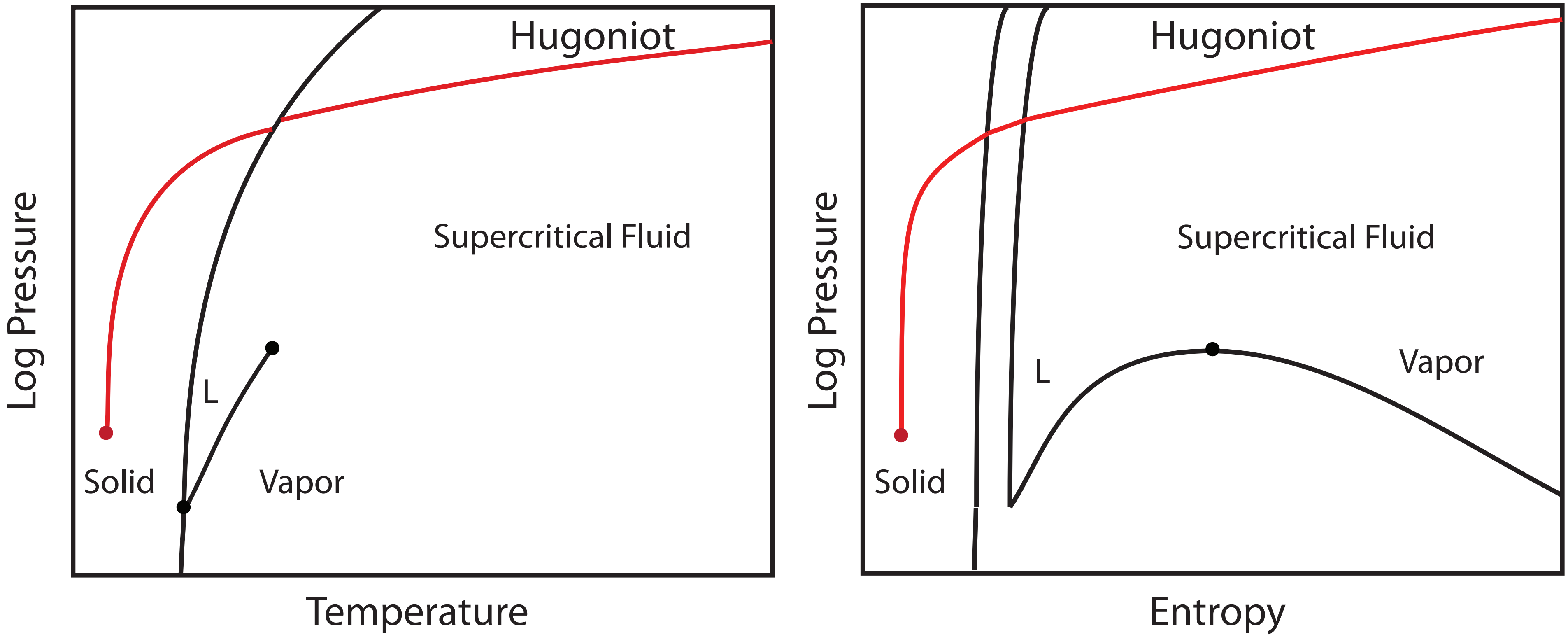
Oceans (condensed water) are not ejected.

Water vapor (and silicate vapor) is bound by gravity.

(Will add atmospheric loss to the online calculator)

Stewart et al. LPSC 2013, 2014; Lock et al. in prep.

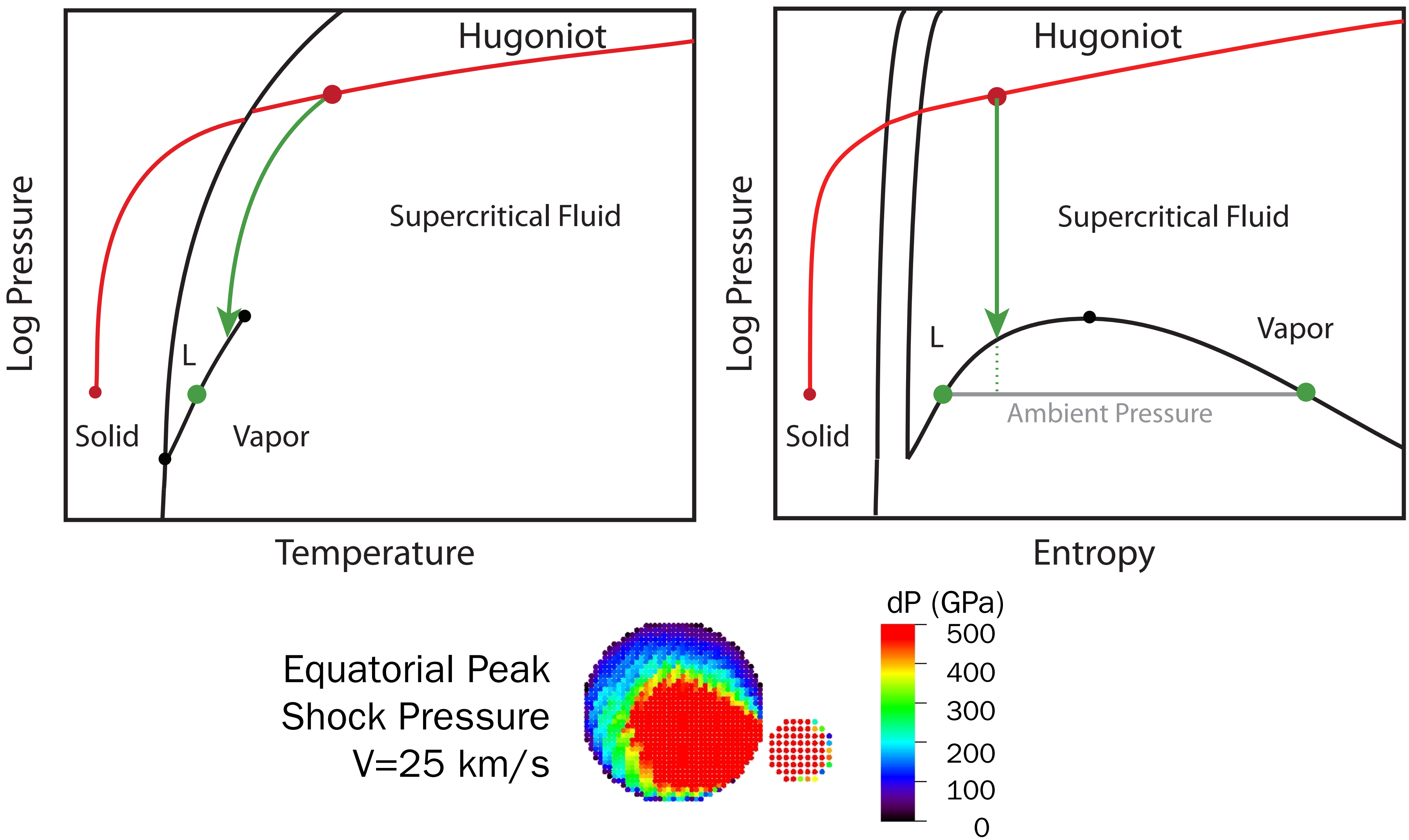
Thermodynamics of Giant Impacts



Model Critical Points

SiO_2	5130 K,	0.5 g/cm^3,	0.13 GPa
MgO	7900 K,	0.45 g/cm^3,	0.3 GPa
Fe	8800 K,	2.2 g/cm^3,	1.1 GPa

Thermodynamics of Giant Impacts



The Moon formed from the Earth

Observations

Lunar bulk composition and isotopes are similar to Bulk Silicate Earth

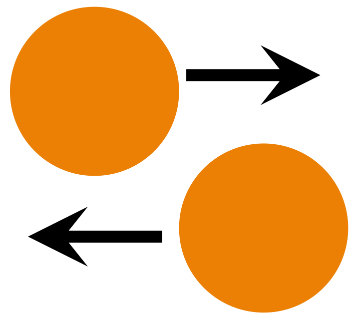
Moon is depleted in moderately volatile and volatile rock-forming elements (e.g., K, Rb, Cs, Na, F, Cl)

Interpretation

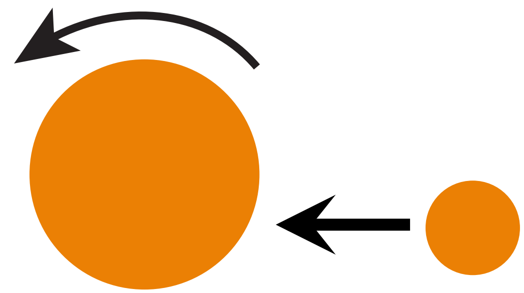
"the moon formed in earth-orbit by recondensation of material evaporated by the impact of a large planetesimal, from the earth's hot outer mantle subsequent to core formation" -- Ringwood & Kesson 1977

Apollo 11

A Moon-Forming Impact with High Angular Momentum



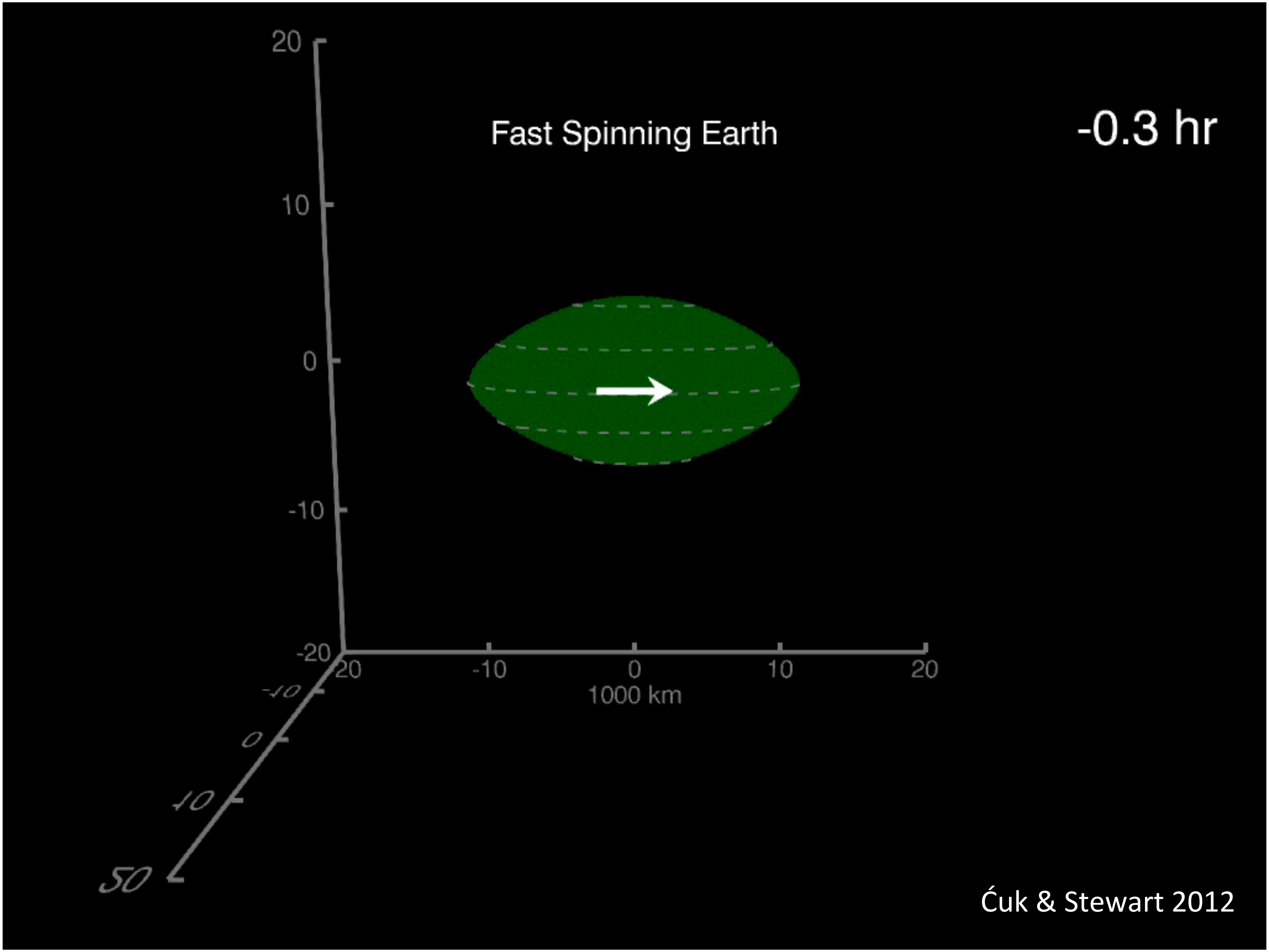
2 half-Earths
Oblique, near V_{esc}
(Canup 2012)



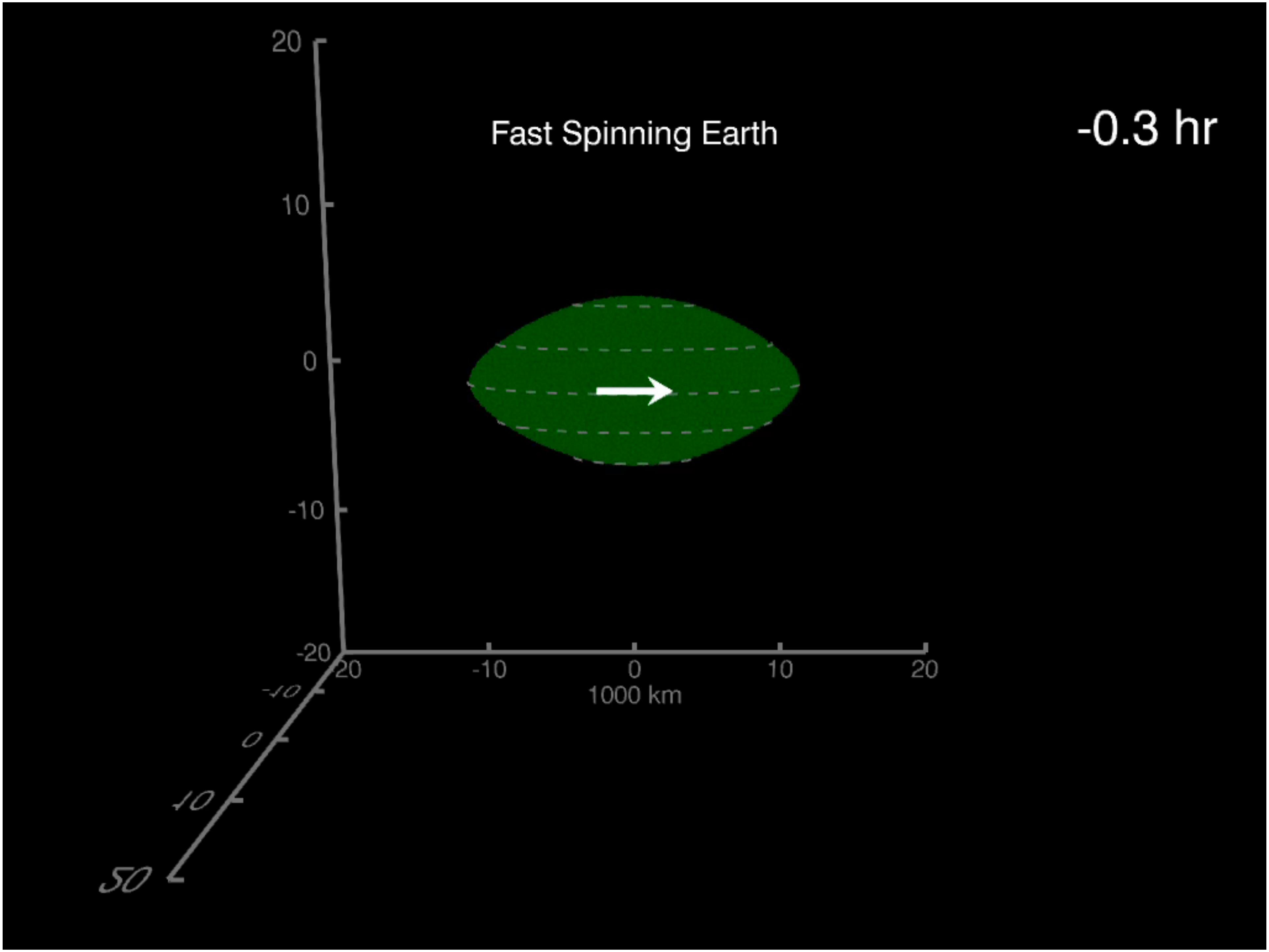
Fast-spinning Earth
Small, fast impactor, near head-on
(Ćuk & Stewart 2012)

Post-impact Earth and disk are made from the same material (similar proportions from each body).

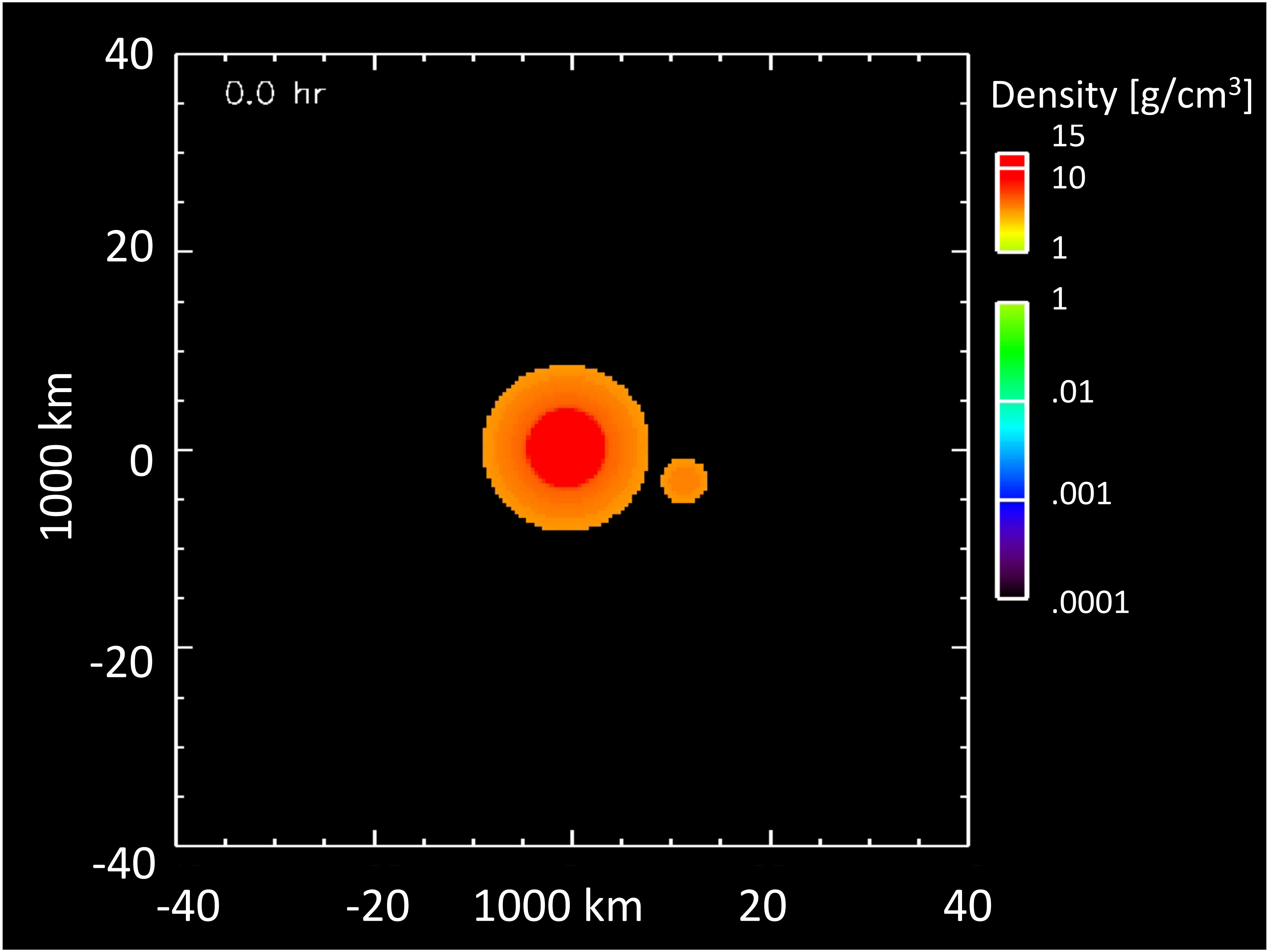
Both have post-impact Earth with 2 to 3-hr spin period.
An orbital resonance transfers AM to Sun after moon formation (Ćuk & Stewart 2012).

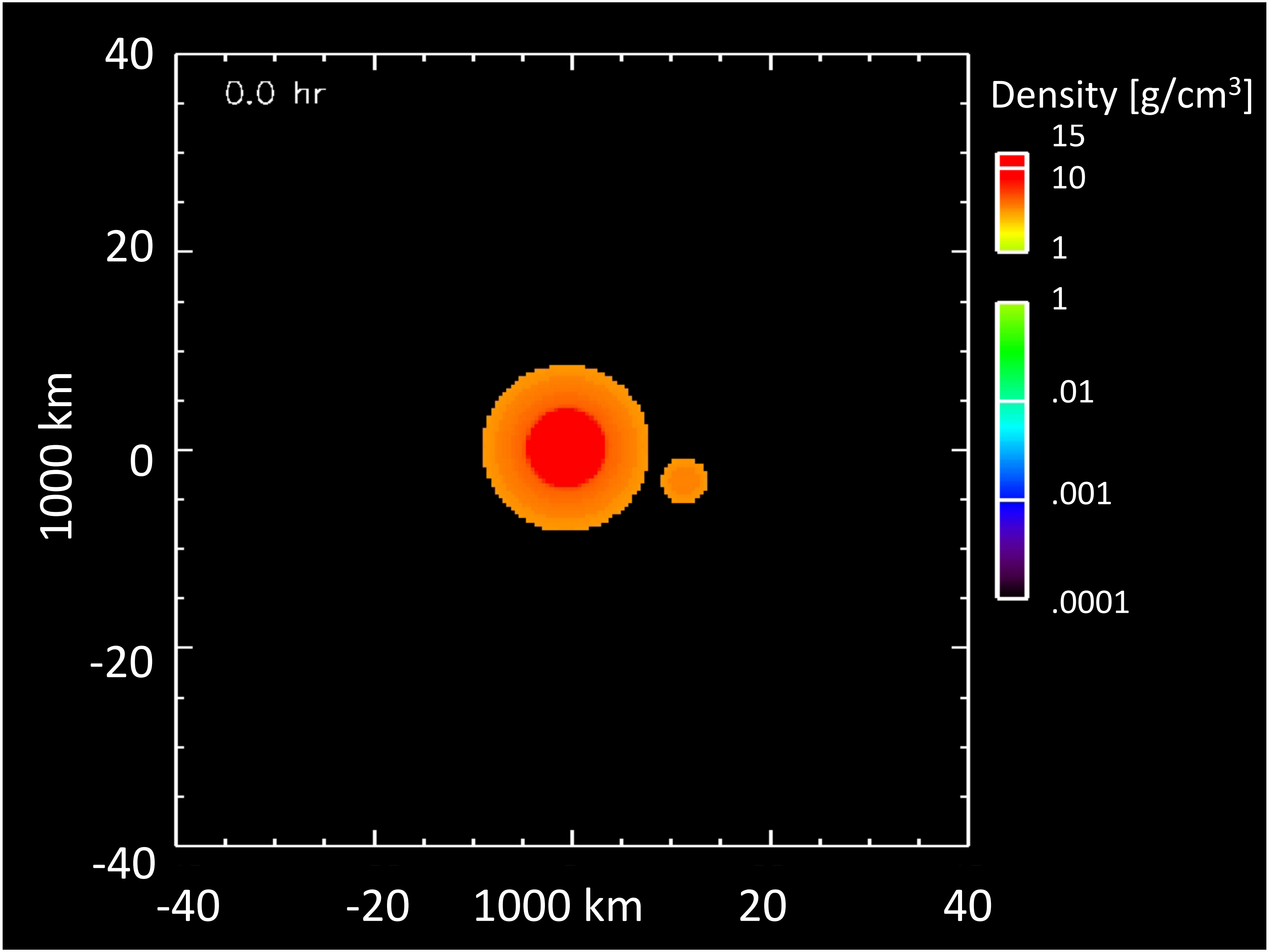


Fast Spinning Earth
-0.3 hr
20
10
0
-10
-20
-20
-10
0
10
20
1000 km
Ćuk & Stewart 2012

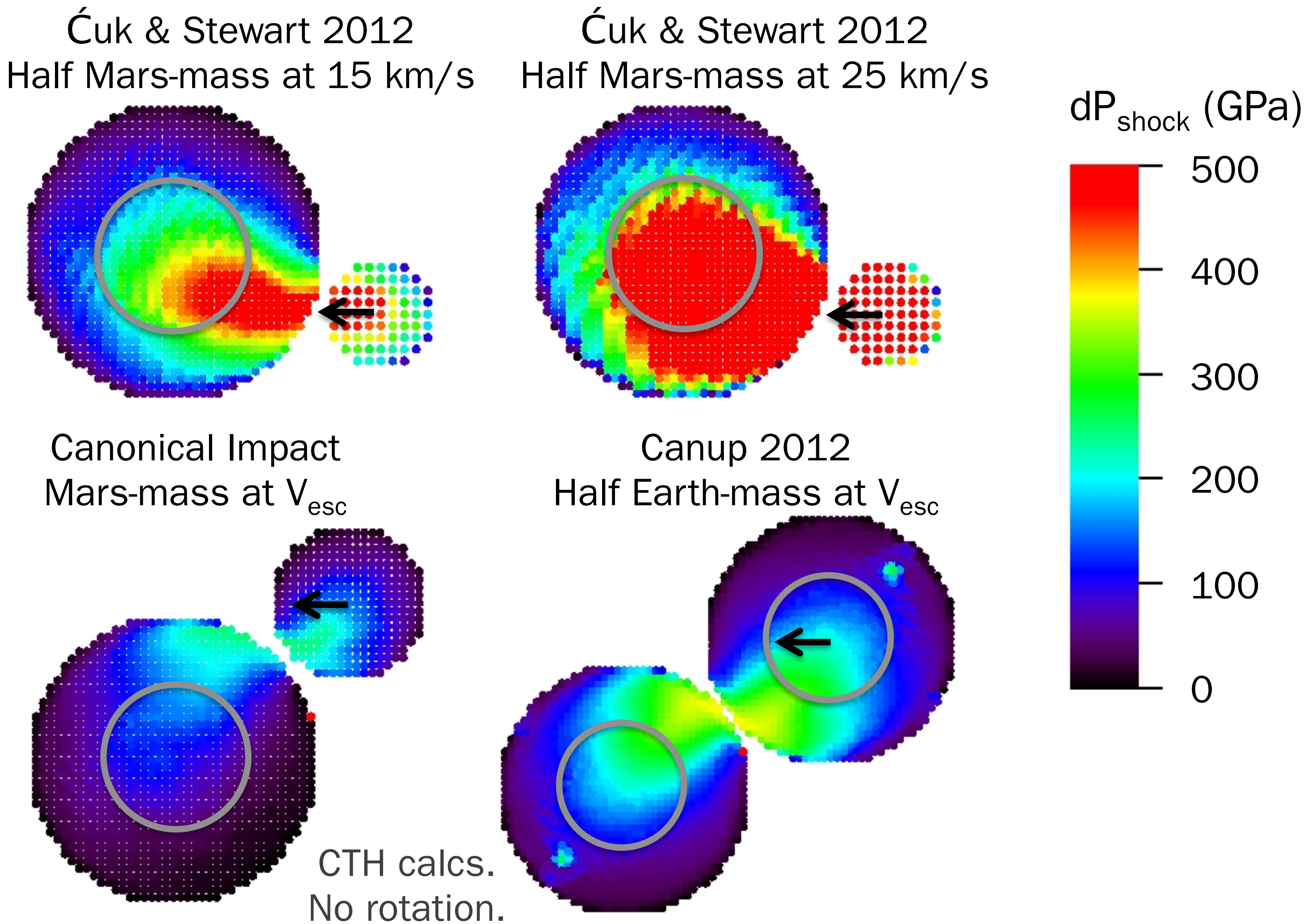


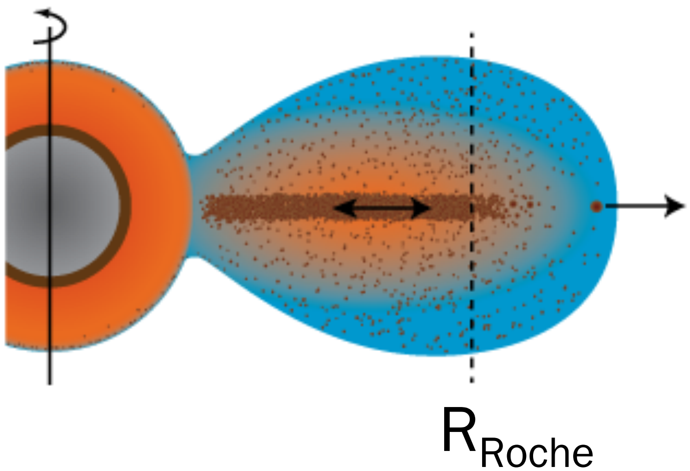
Fast Spinning Earth
-0.3 hr
20
10
0
-10
-20
-20
-10
0
10
20
1000 km
-10
0
10
50


0.0 hr
Density [g/cm^3]
15
10
1
1
.01
.001
.0001
40
20
0
-20
-40
1000 km
-40
-20
1000 km
20
40

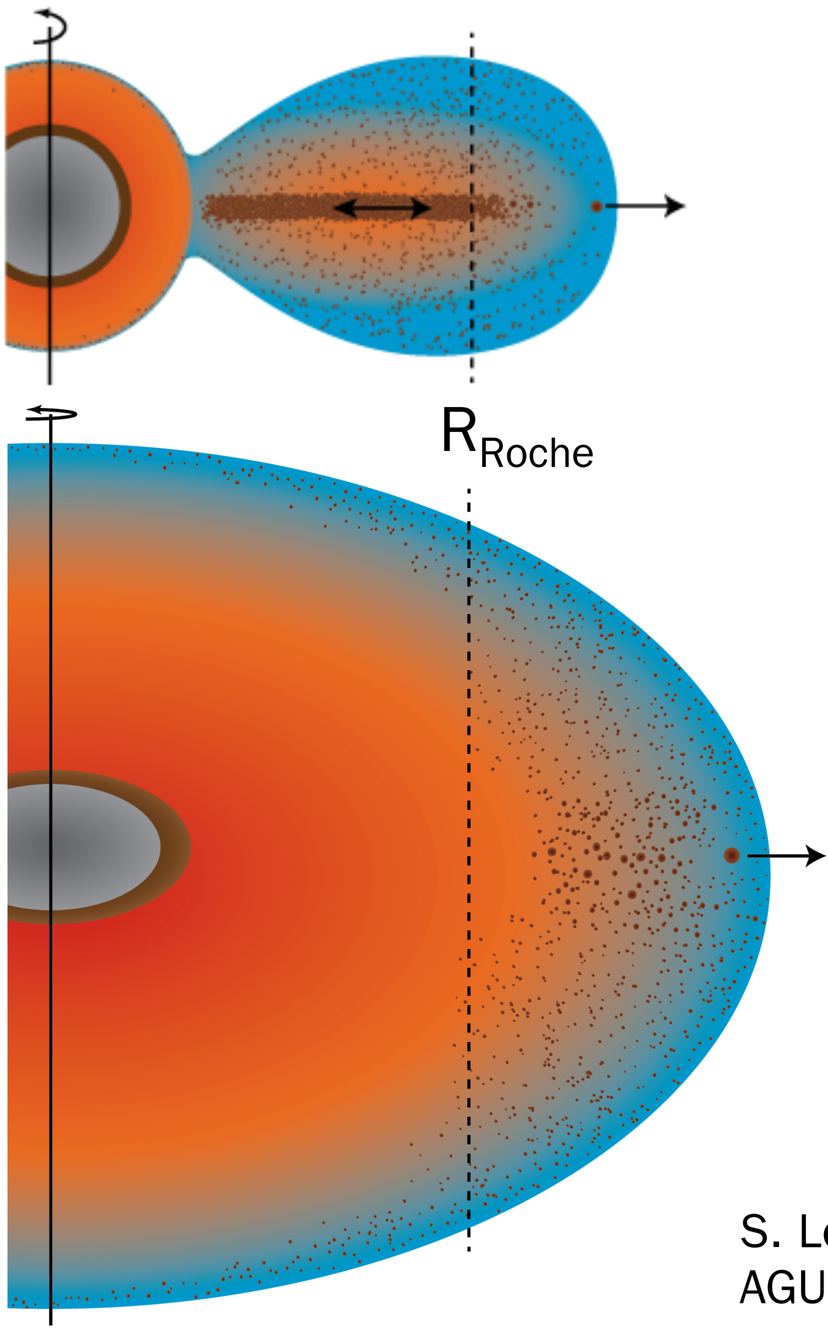

0.0 hr
Density [g/cm³]
15
10
1
1
.01
.001
.0001
40
20
0
-20
-40
1000 km
-40
-20
1000 km
20
40

Shock Pressures in Moon-Forming Impacts





Canonical impact planet and disk



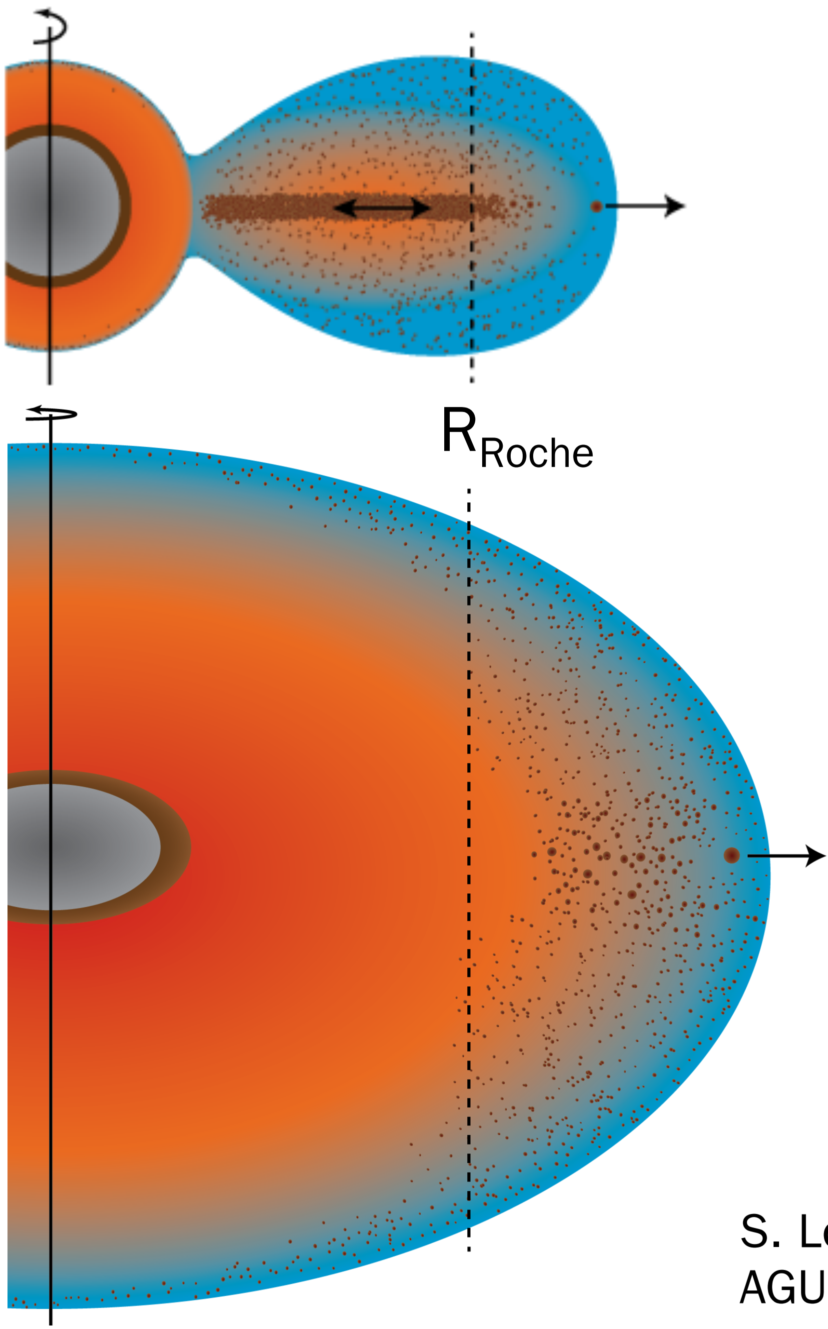
Canonical impact planet and disk

High angular momentum impact

Continuous

mantle-atmosphere-disk structure

S. Lock, S. Stewart, Z. Leinhardt, M. Mace, M. Ćuk, AGU 2014, LPSC 2015; in prep.



Canonical impact planet and disk

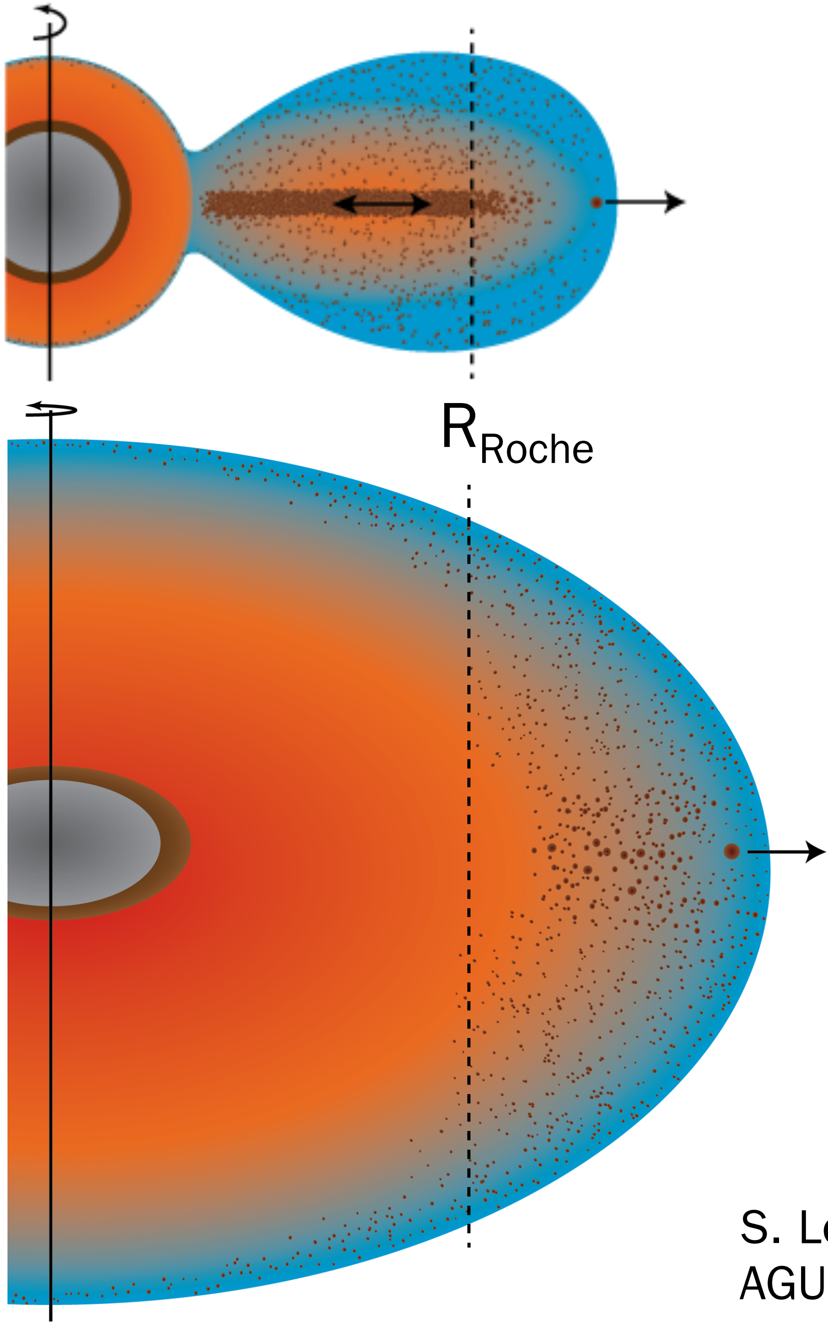
High angular momentum impact

Continuous

Mantle-Atmosphere-Disk structure

'MAD planet'

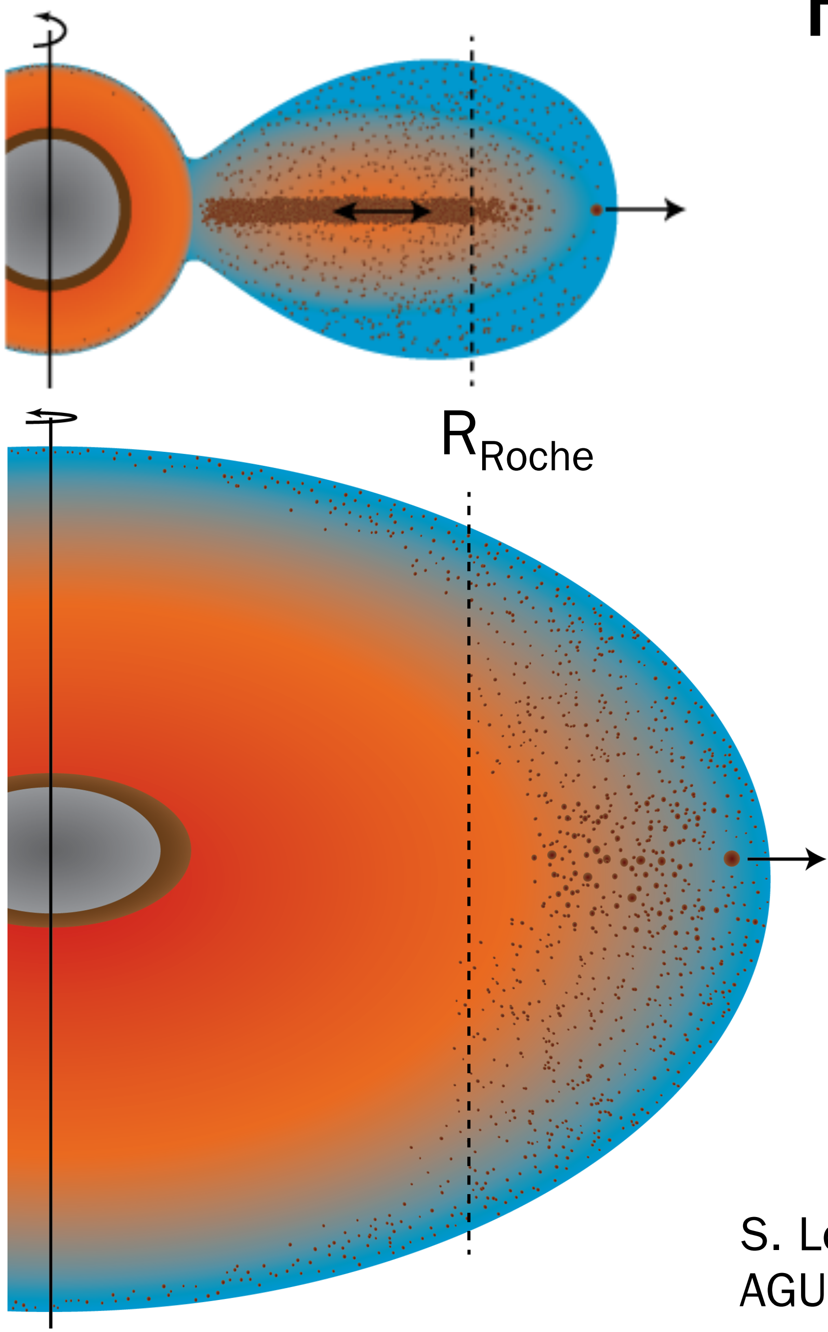
S. Lock, S. Stewart, Z. Leinhardt, M. Mace, M. Ćuk, AGU 2014, LPSC 2015; in prep.



Fundamentally different post-impact states

S. Lock, S. Stewart, Z. Leinhardt, M. Mace, M. Ćuk, AGU 2014, LPSC 2015; in prep.

Post-Impact States



Canonical impact planet and disk

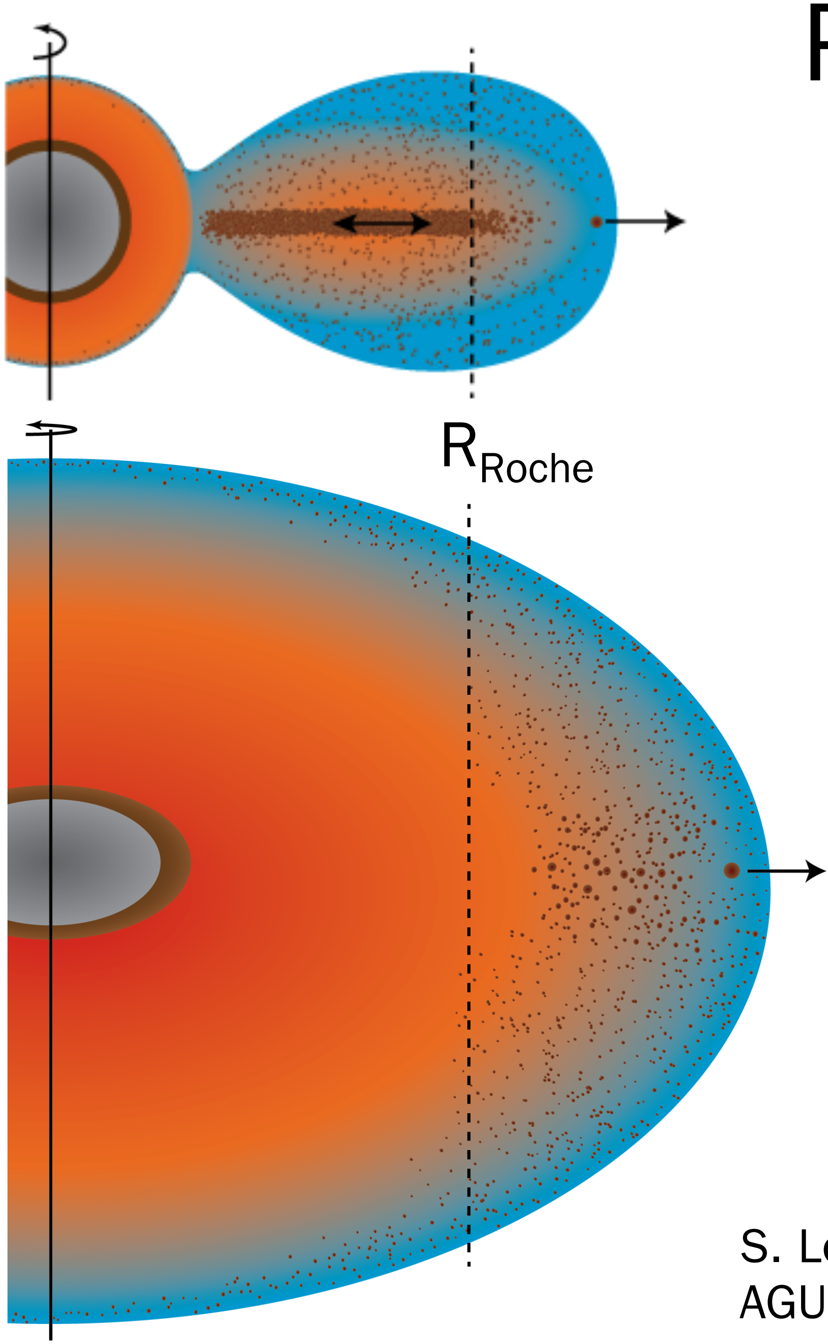
Dynamic and thermodynamic discontinuity.

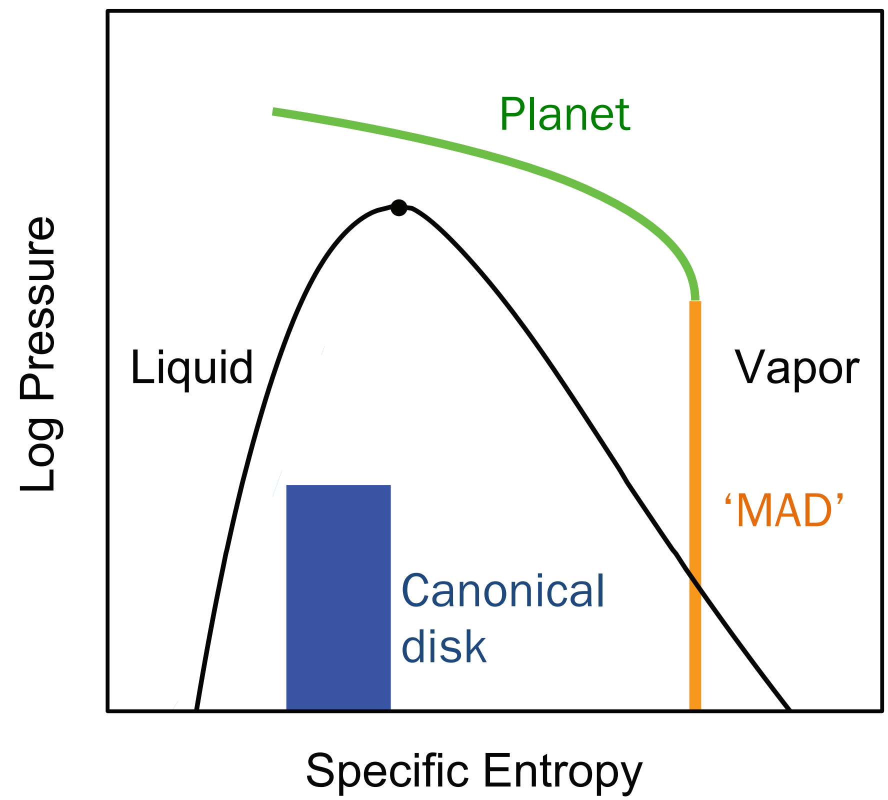
High angular momentum MAD planet

No dynamic and thermodynamic discontinuity.

S. Lock, S. Stewart, Z. Leinhardt, M. Mace, M. Ćuk, AGU 2014, LPSC 2015; in prep.

Post-Impact States





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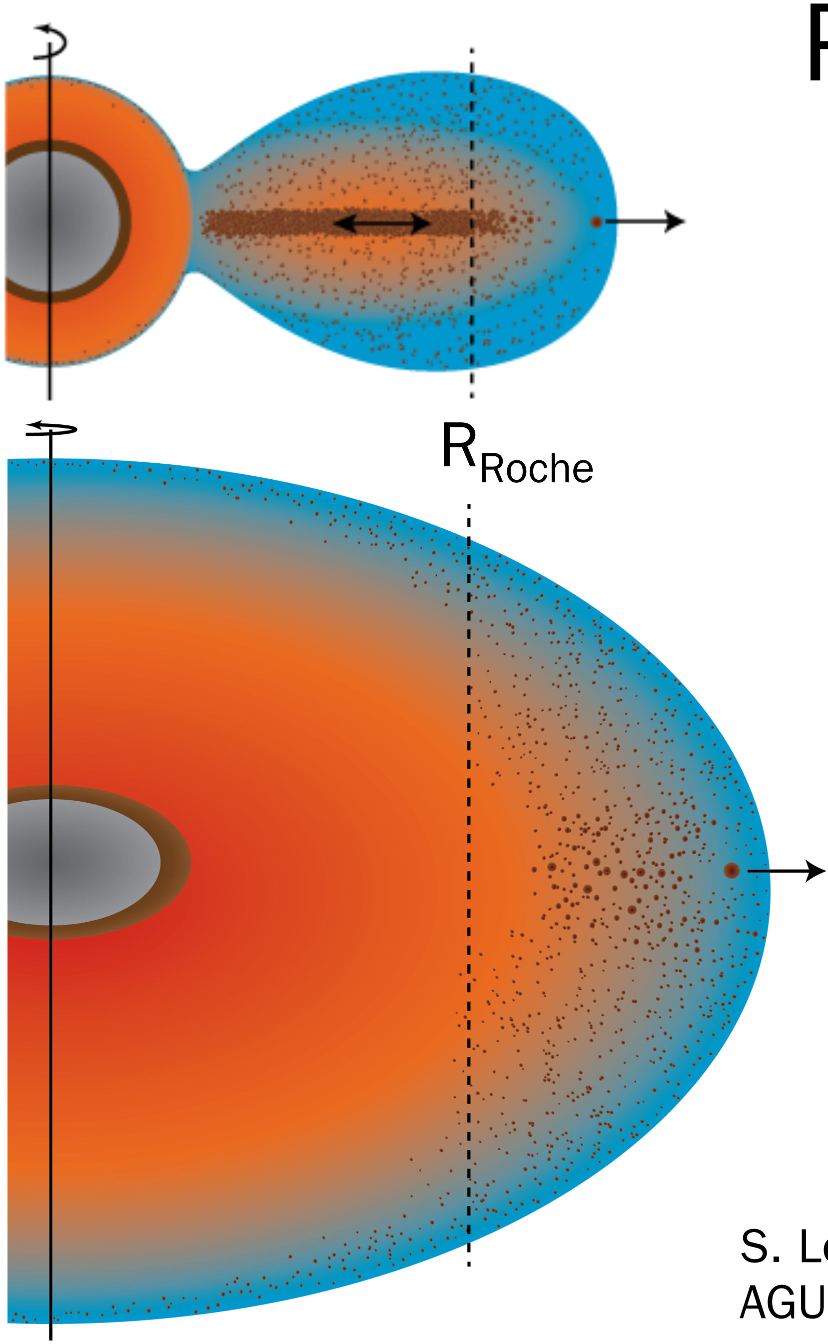

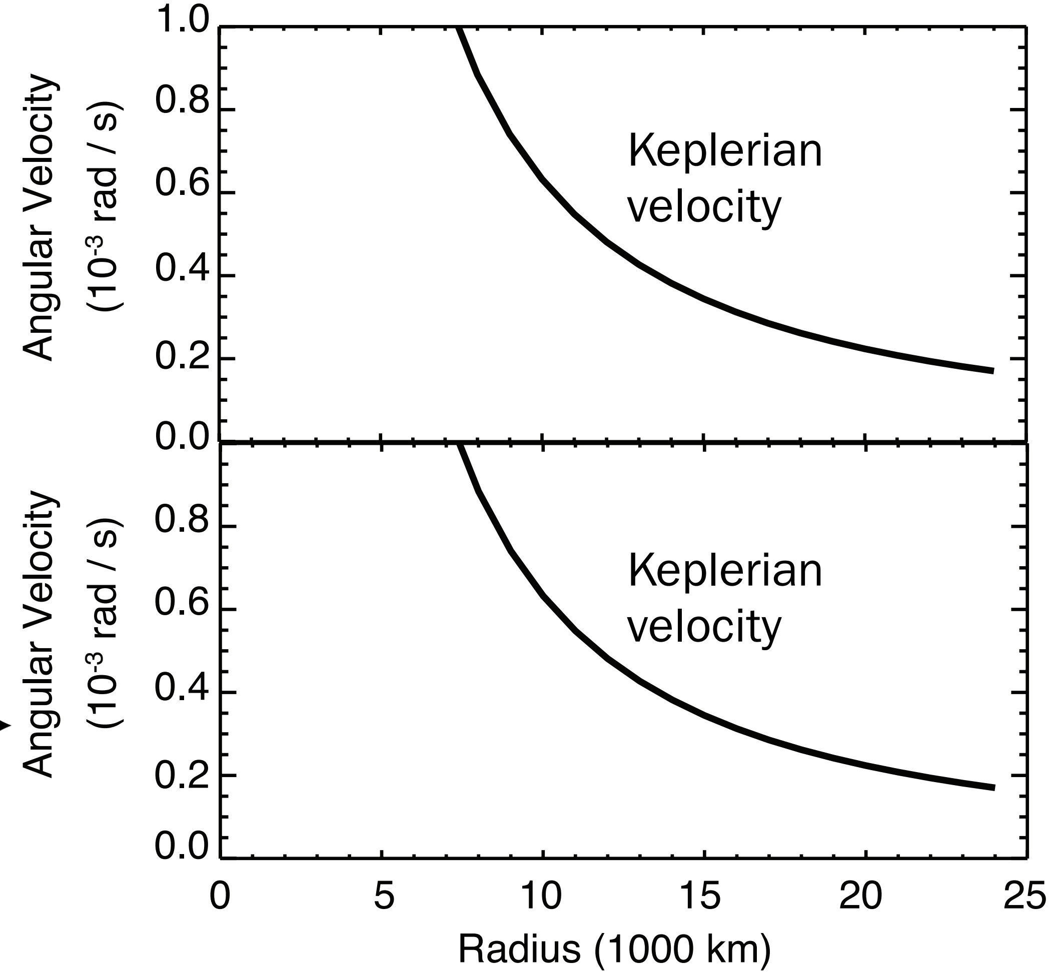

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AGU 2014, LPSC 2015; in prep.

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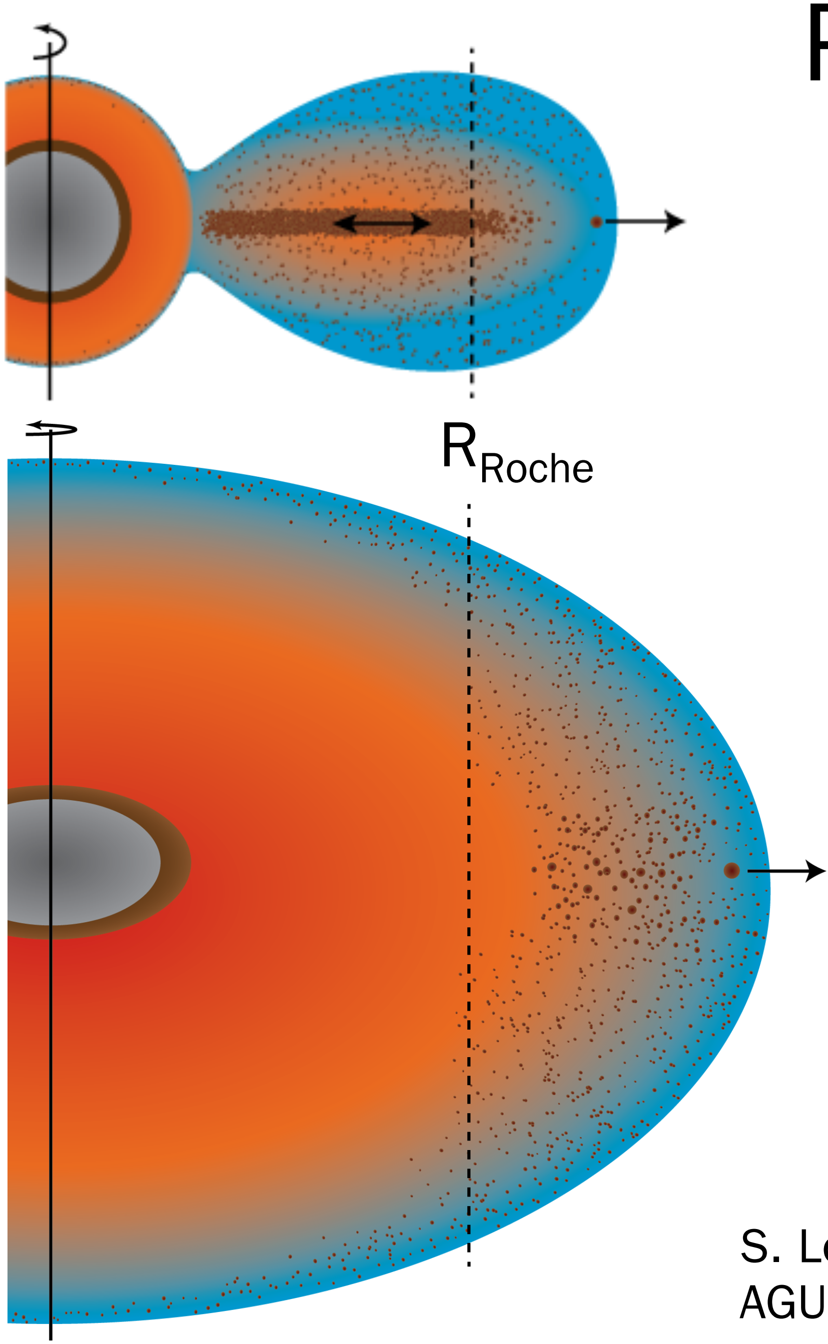

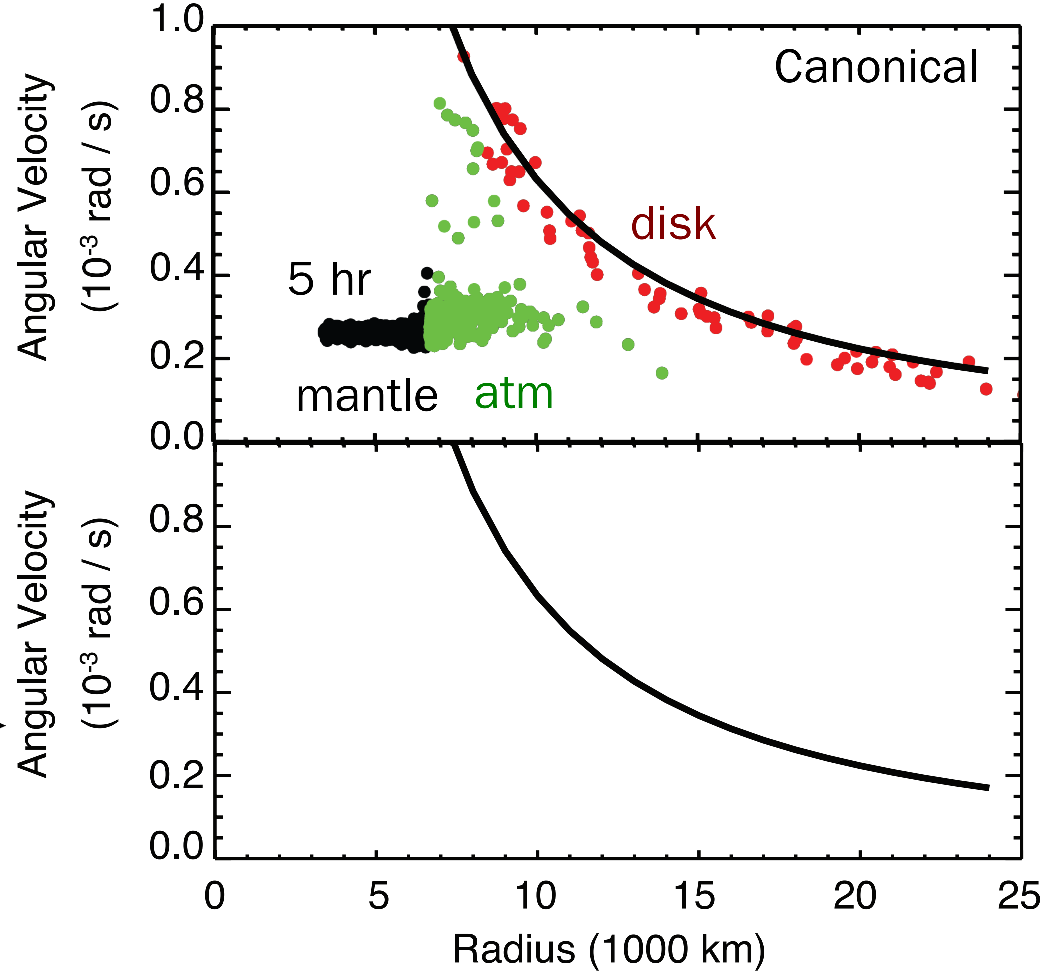

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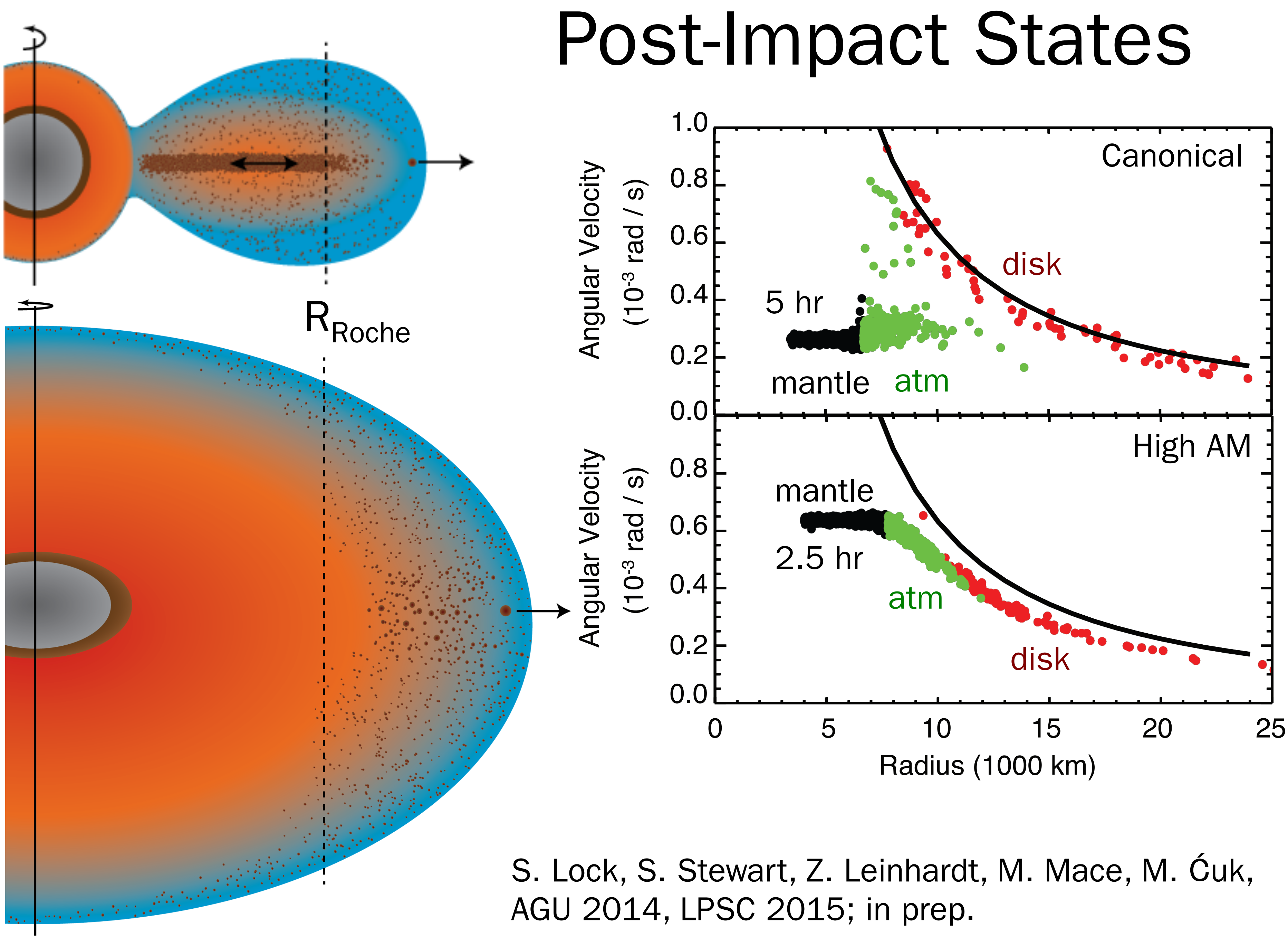

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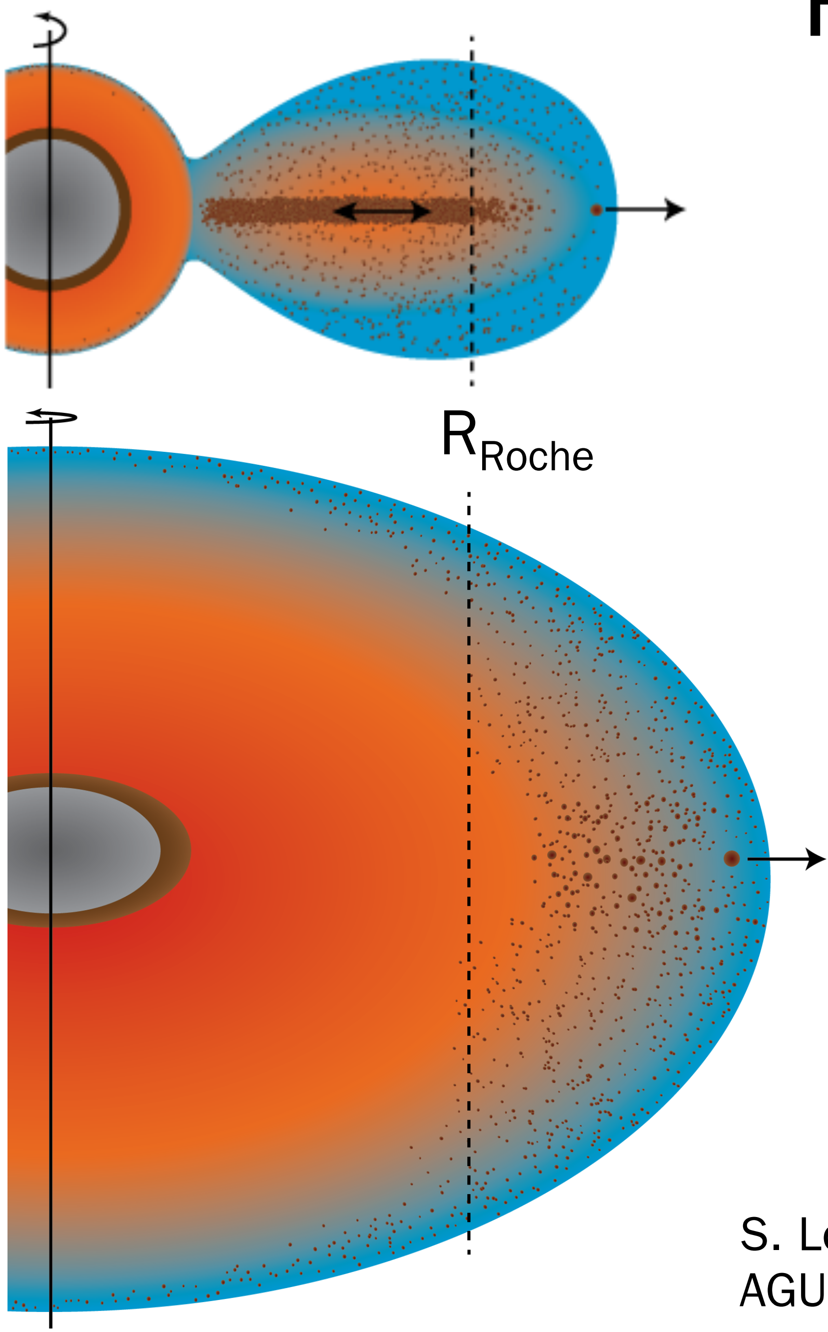


Canonical impact planet and disk

The disk can fall down.

Mixing difficult.

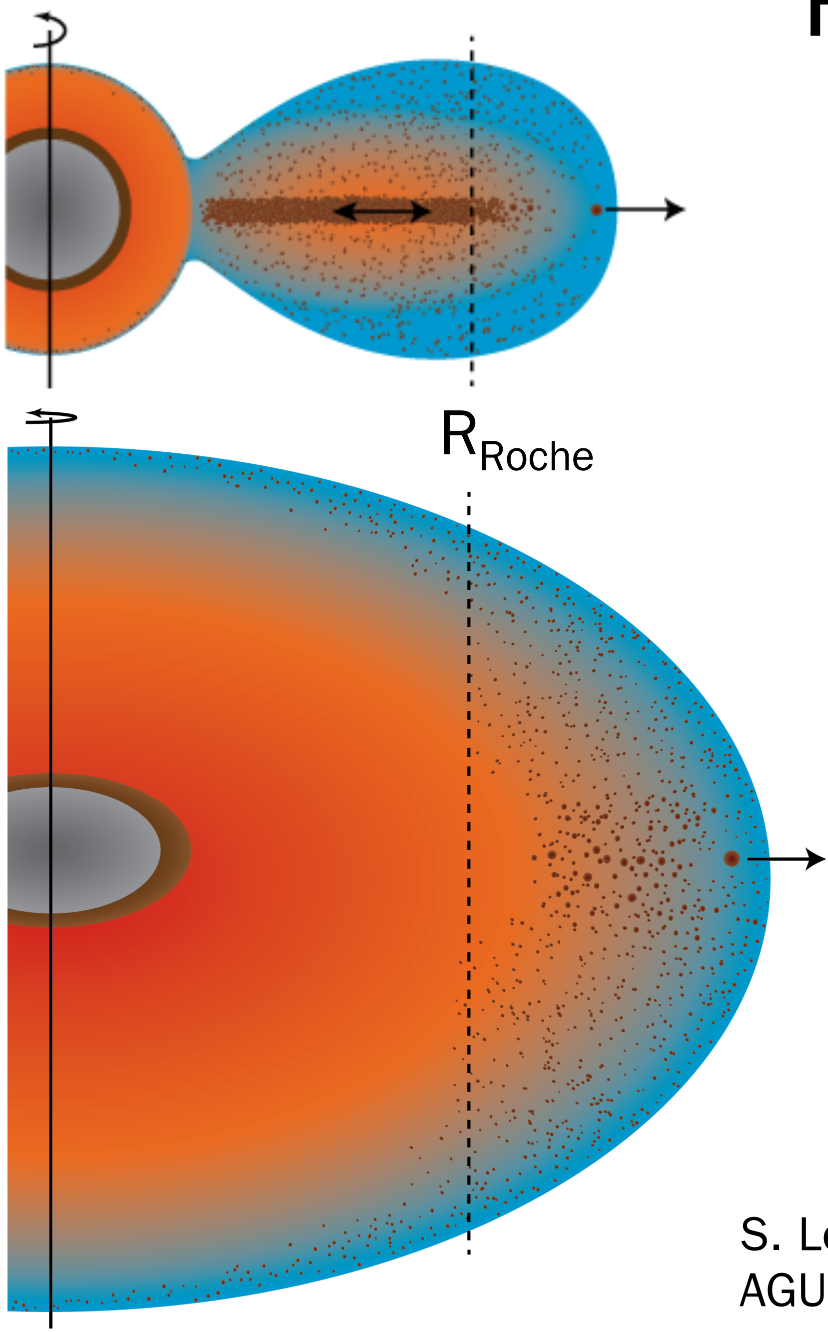
High angular momentum MAD planet

Structure supported by thermal pressure.

Mixing efficient.

S. Lock, S. Stewart, Z. Leinhardt, M. Mace, M. Ćuk, AGU 2014, LPSC 2015; in prep.

Post-Impact States



Canonical impact planet and disk

The disk can fall down.

Mixing difficult.

Inefficient lunar accretion.

High angular momentum MAD planet

Structure supported by thermal pressure.

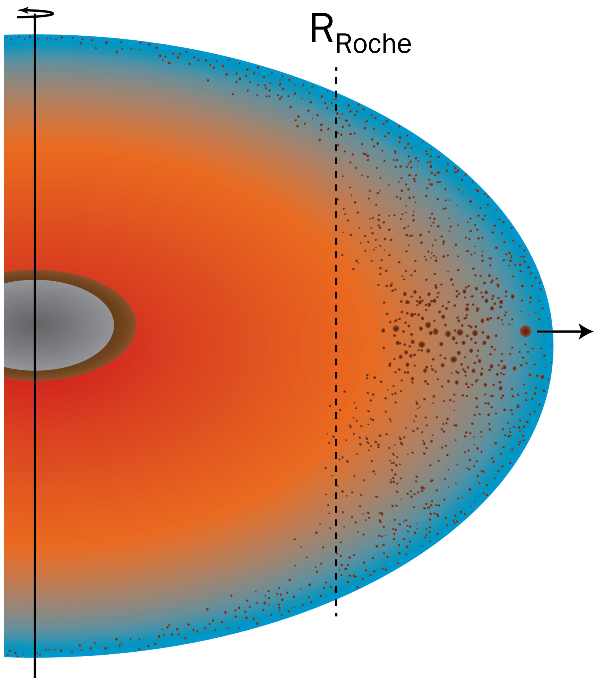
Mixing efficient.

Different lunar accretion process.

Partial condensate of the BSE.

S. Lock, S. Stewart, Z. Leinhardt, M. Mace, M. Ćuk, AGU 2014, LPSC 2015; in prep.

Are High Angular Momentum Moon-Forming Impacts Probable?



Necessary elements for a 'MAD' planet:

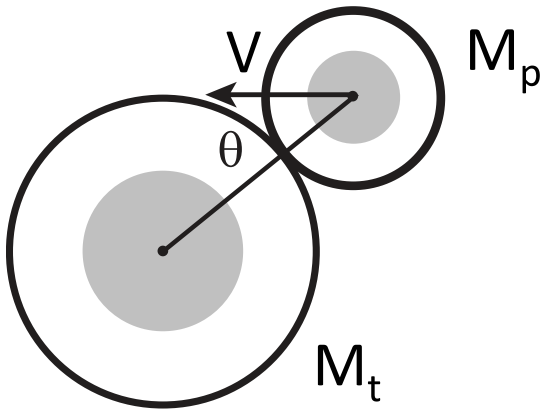
- Giant impact stage of planet formation generates fast-spinning planets.
  (Kokubo & Genda 2010)
- Giant impacts are energetic enough to vaporize several % of the planet.
  (thermodynamics and impact energy distribution)

Many impact geometries are possible:

- Ćuk & Stewart 2012 and Canup 2012 are special cases assuming no post-impact mixing.
- True probabilities need N-body simulations with spin, fragmentation and moon formation.
- Many impact sequences may generate a MAD planet.

Giant Impact Redux

Mechanics



Thermodynamics