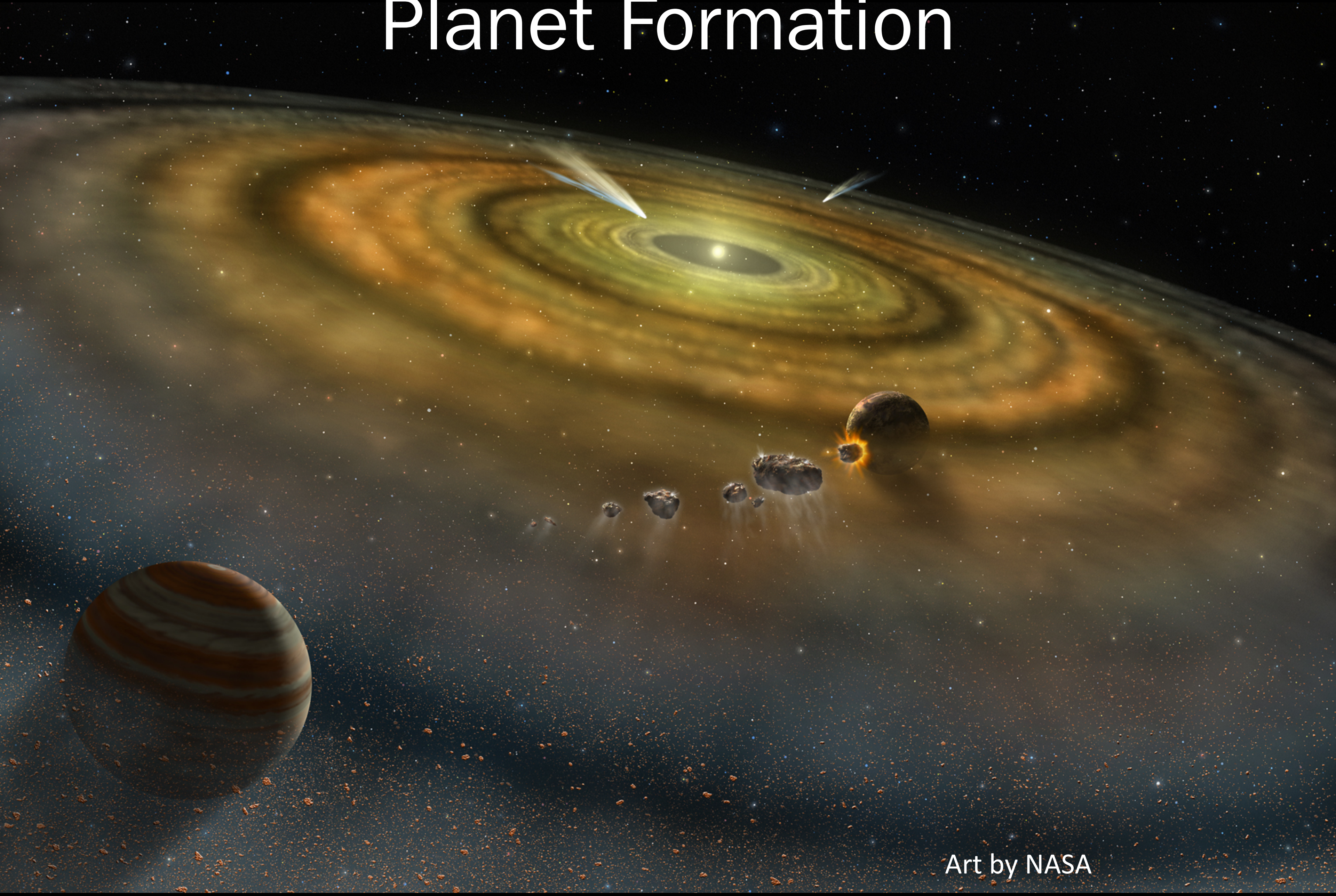
Reaching the Extremes of Planet Formation

Shockwave Experiments in the Giant Impact Regime

Sarah T. Stewart

Dept. Earth & Planetary Sciences, UC Davis

Planet Formation

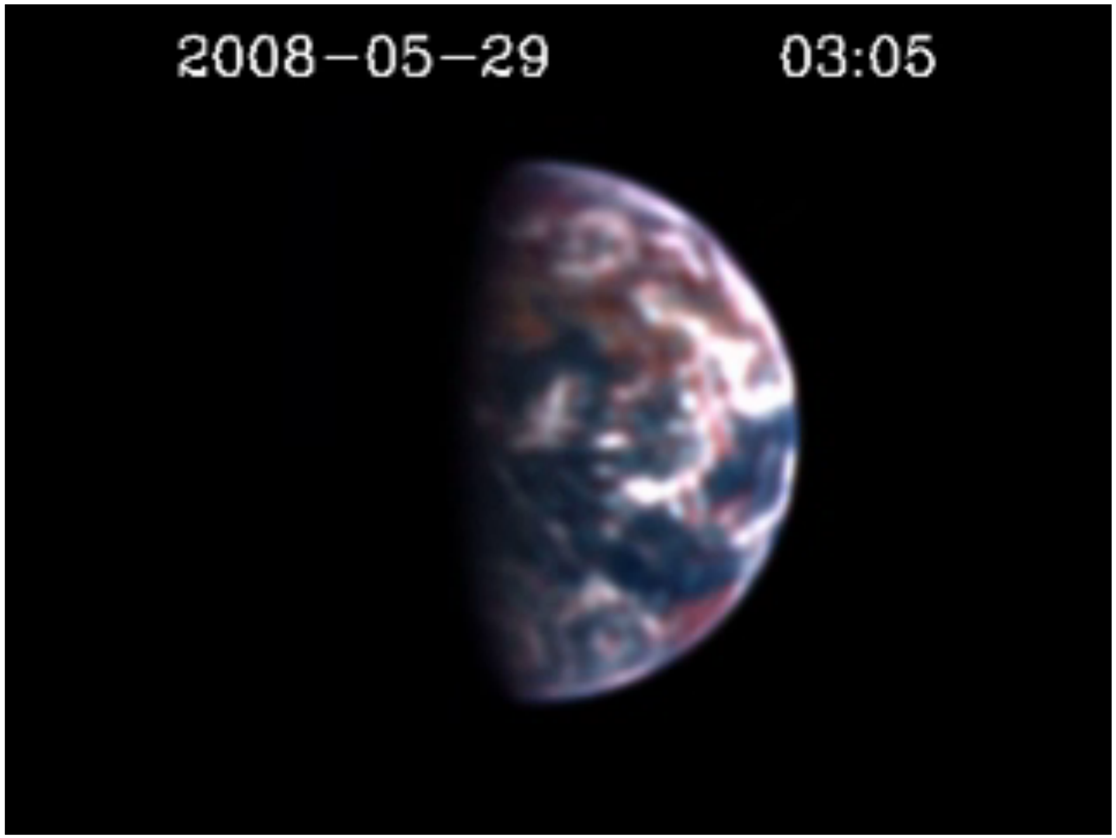


Art by NASA

Giant Impacts

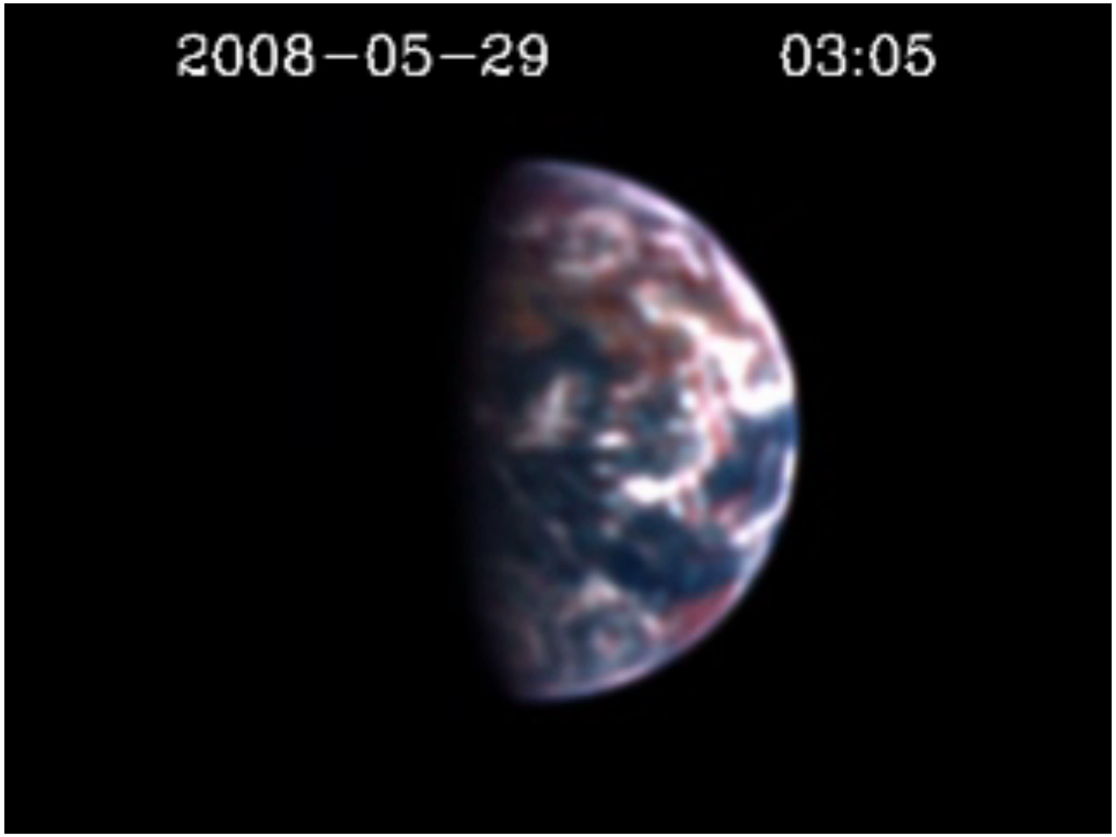
Art by National Geographic

The Origin of the Moon

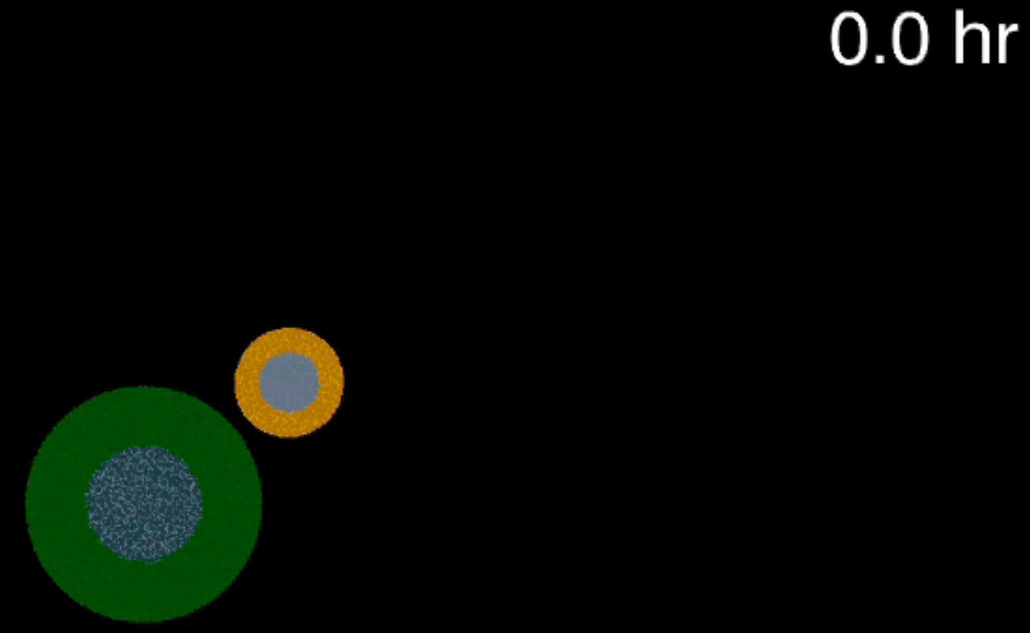


Lunar transit
NASA EPOXI

We don’t know how to make the Moon

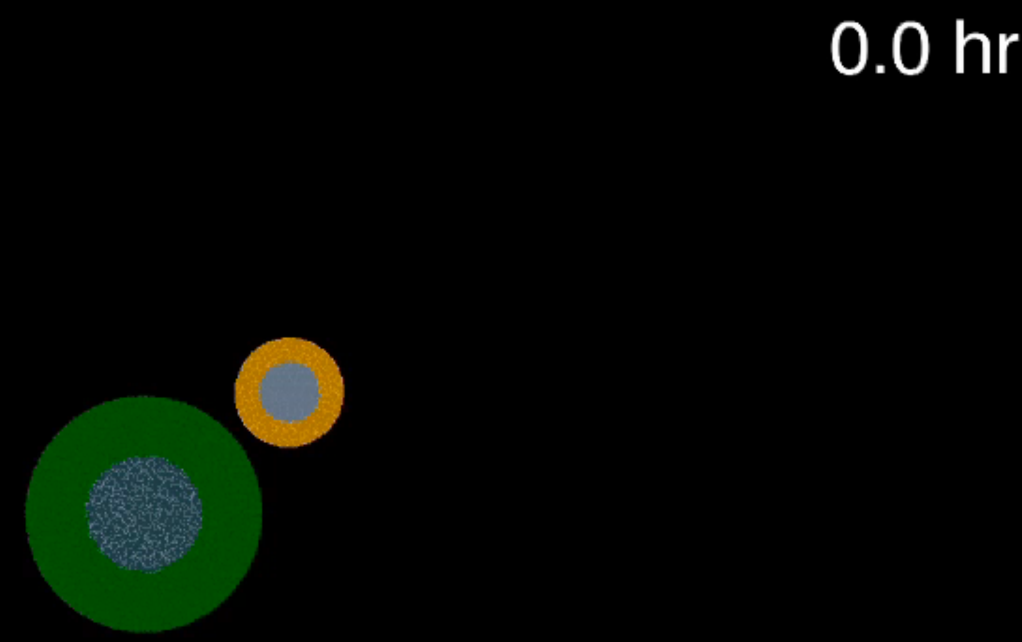


Lunar transit
NASA EPOXI



A canonical giant impact simulation: Oblique Mars mass impact at escape velocity (Asphaug & Canup 2001; Canup 2004, 2008)

Smoothed particle hydrodynamics (SPH)
Iron cores, silicate mantles; phase changes included in equation of state
Gravity-dominated events; no material strength


0.0 hr

Accretion of the Moon from a Disk

Timescale: 1 to 100's yr

Accretion efficiency is low:

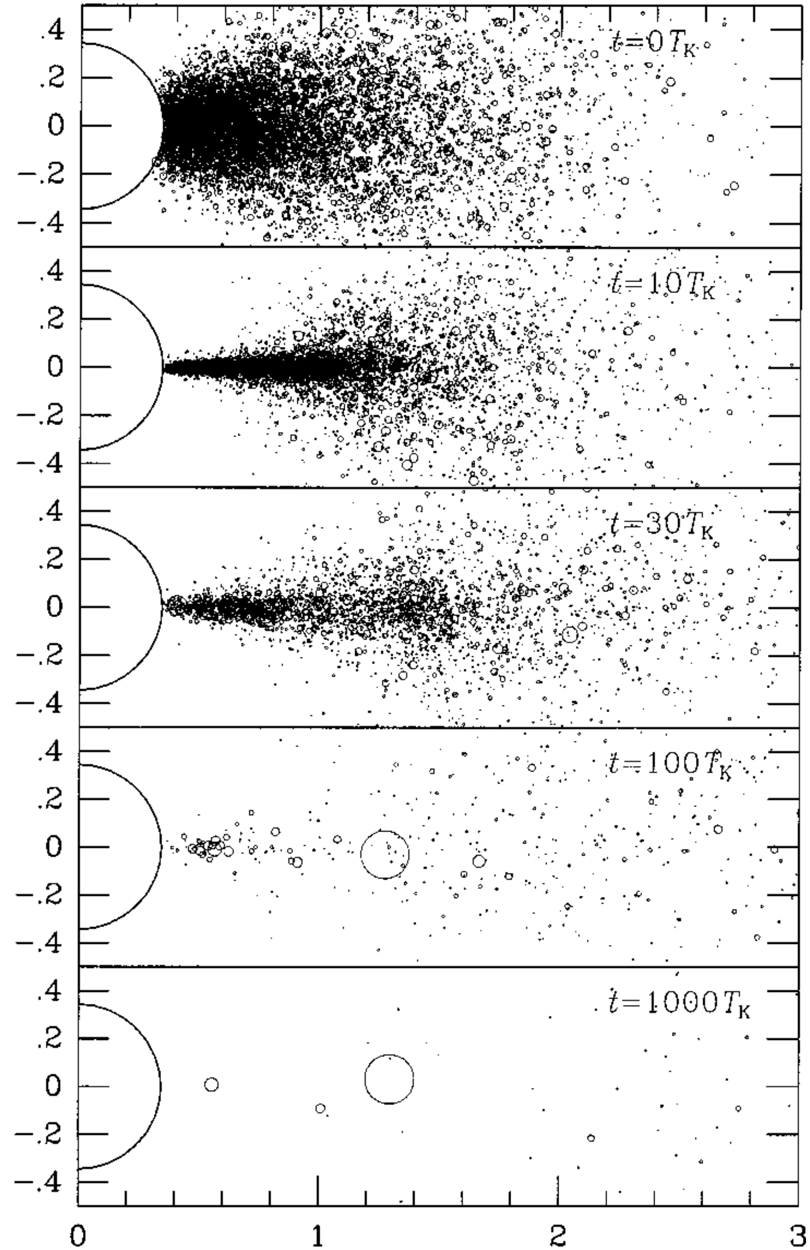
10-50% M_{disk}

Main problem:

angular momentum out

mass in

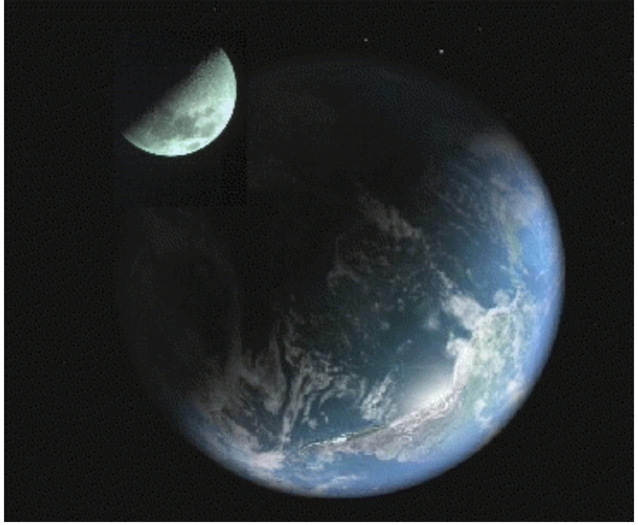
The calculated Moons are too small.



Distance (Roche radii ≈ $3R_{Earth}$)

Kokubo et al. 2010; Salmon & Canup 2012, 2015

Earth and Moon are Isotopic Twins



Identical isotopes

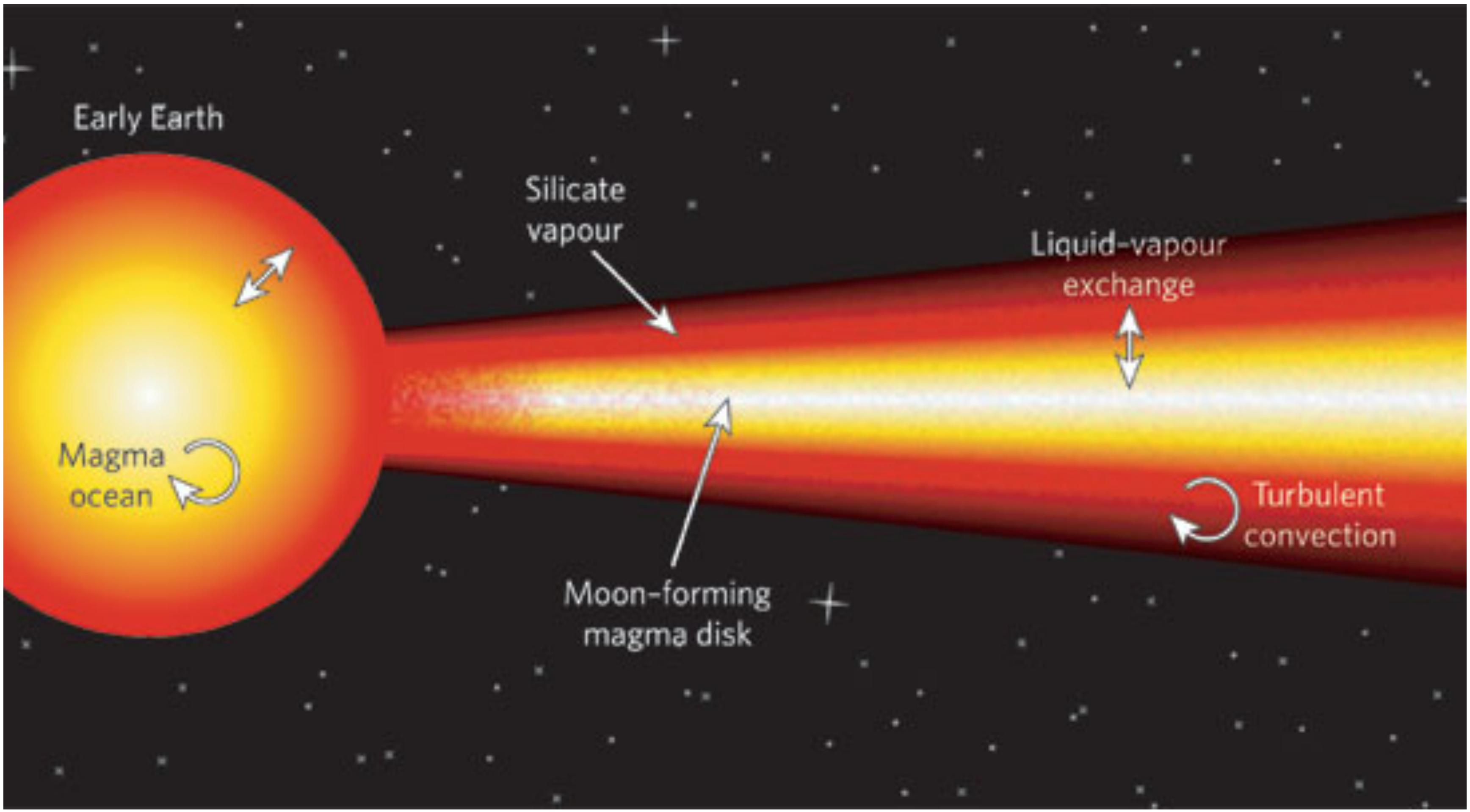
O	volatile, large variations in solar nebula
Ti	refractory, nucleosynthetic anomalies
W	radiogenic (8.9 Ma), core formation
Cr	radiogenic (3.7 Ma), variations in nebula
Si	moderately refractory, core formation
H	volatile, large variations in solar nebula

Each planetary body has a different isotopic signature.

Lugmair & Shukolyukov 1998, Wiechert et al. 2001, Georg et al. 2007, Zhang et al. 2011, Saal et al. 2013
W: Touboul et al. 2007 but now Touboul et al. LPSC 2014 & Kleine et al. LPSC 2014

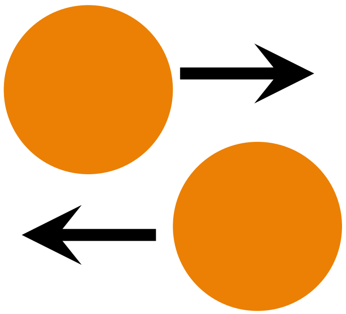
A Proposed Solution: Mix after the impact

Pahlevan & Stevenson 2007

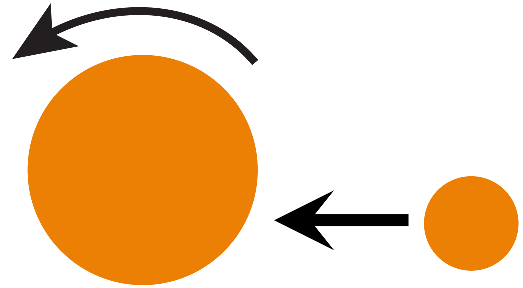


Why not reject the giant impact hypothesis for lunar origin?

A Giant Impact with High Angular Momentum



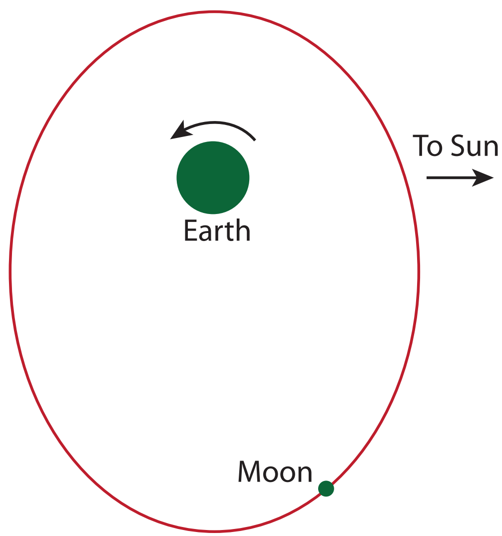
2 half-Earths
Oblique, near V_{esc}
(Canup 2012)

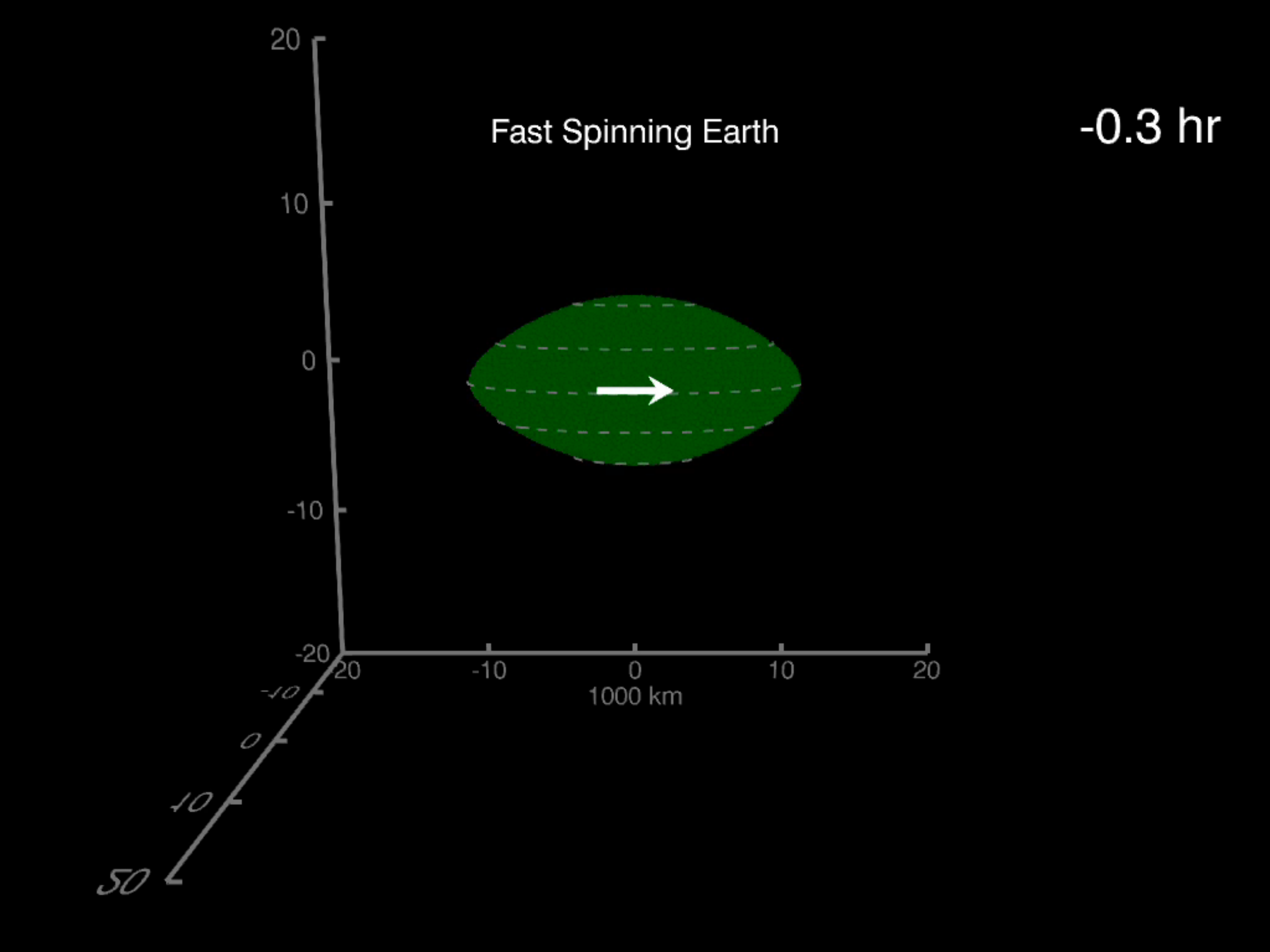


Fast-spinning Earth
Small, fast impactor, near head-on
(Ćuk & Stewart 2012)

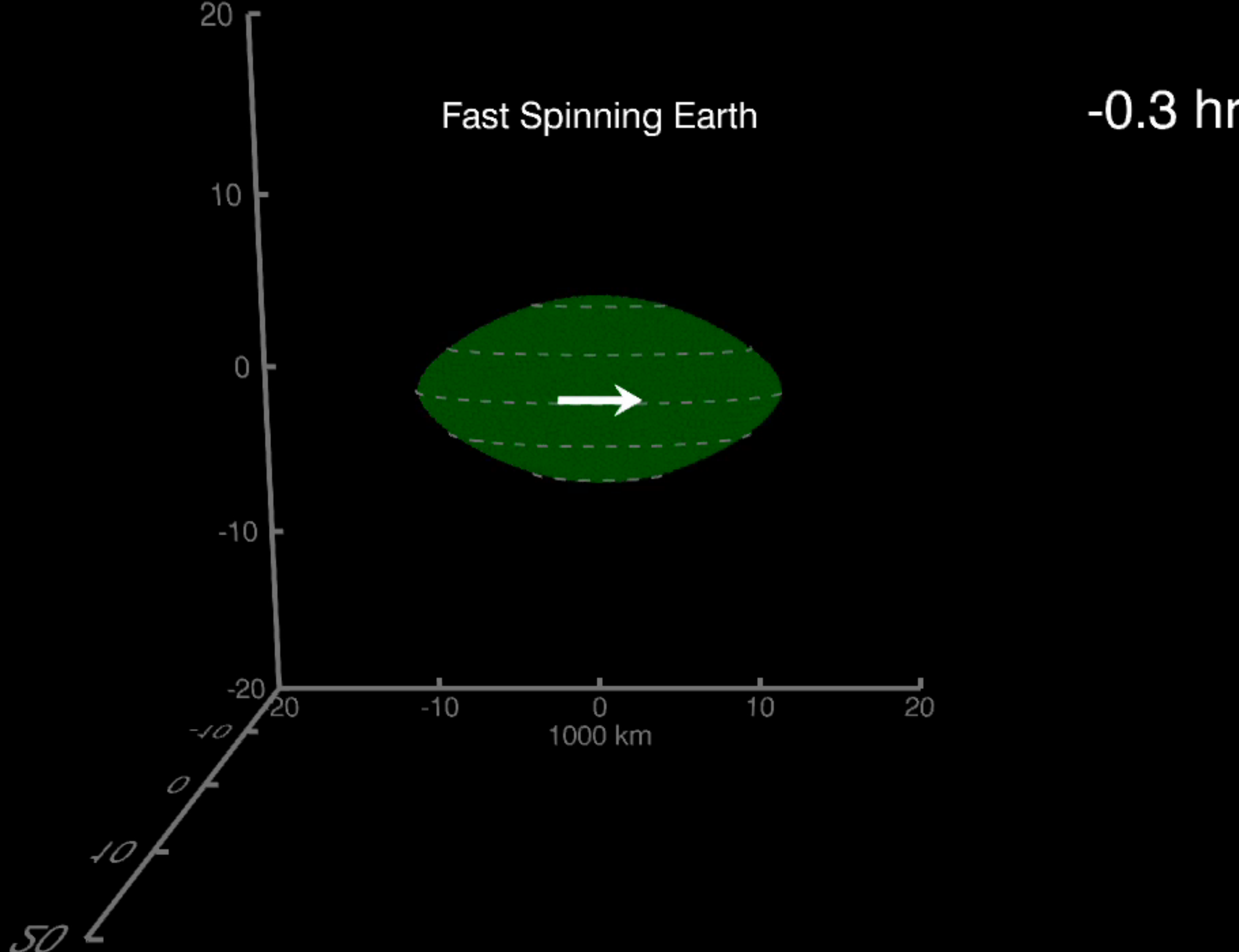
Both have post-impact Earth with 2 to 3-hr spin period.

After Moon formation, an orbital resonance transfers angular momentum to the Sun.
(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



Fast Spinning Earth
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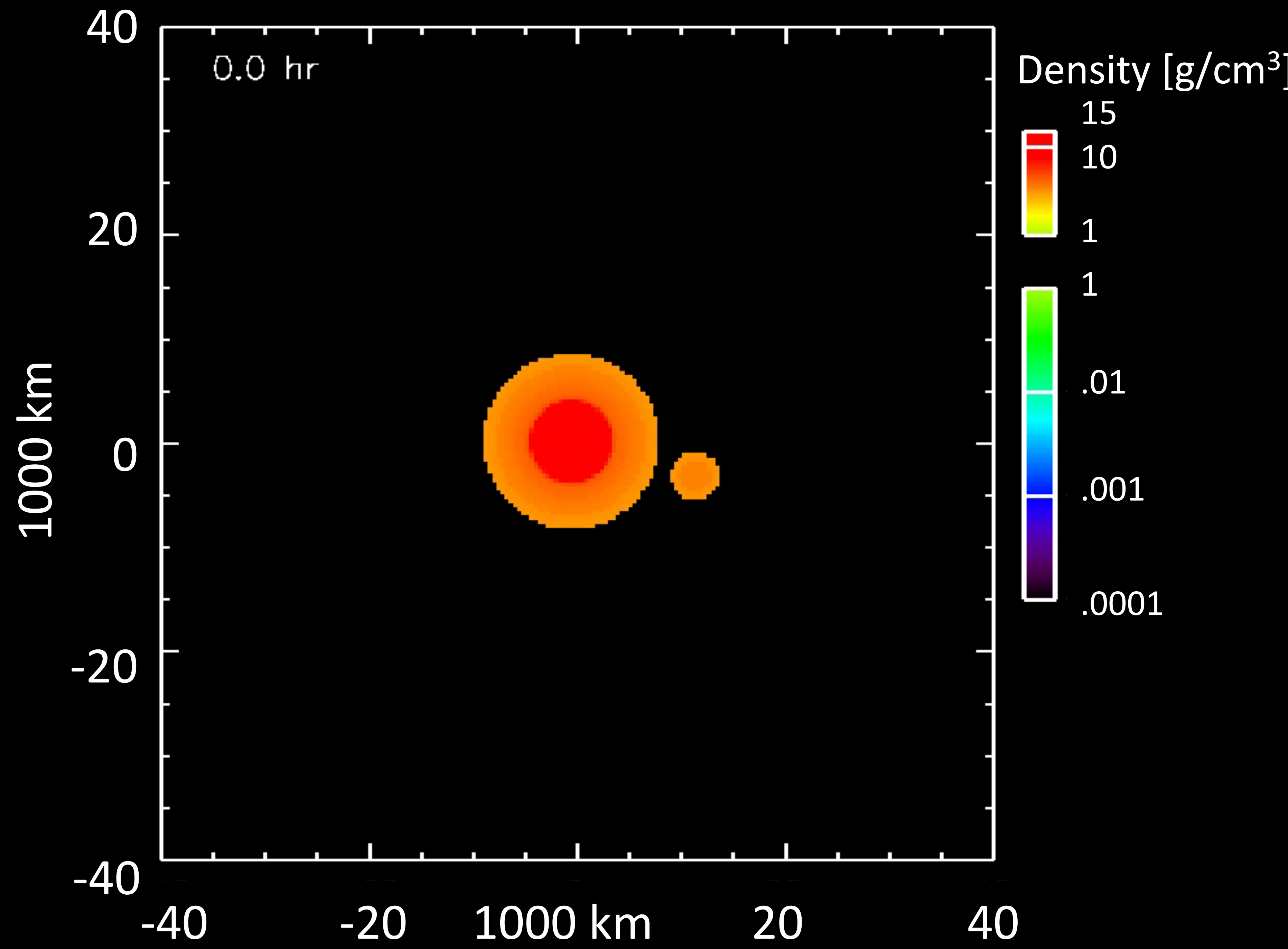
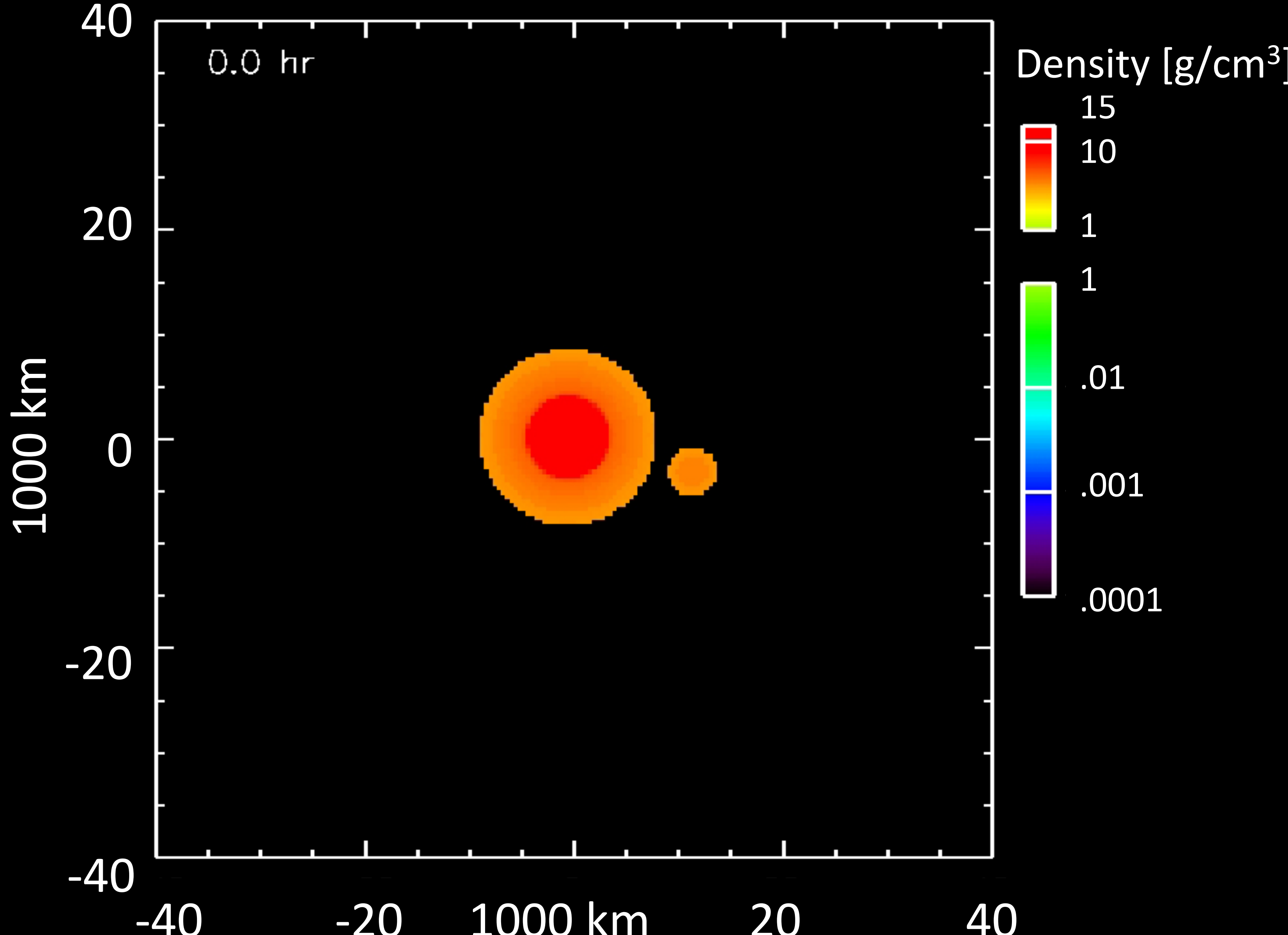
1000 km
-10
0
10
50


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


0.0 hr
Density [g/cm3]
15
10
1
1
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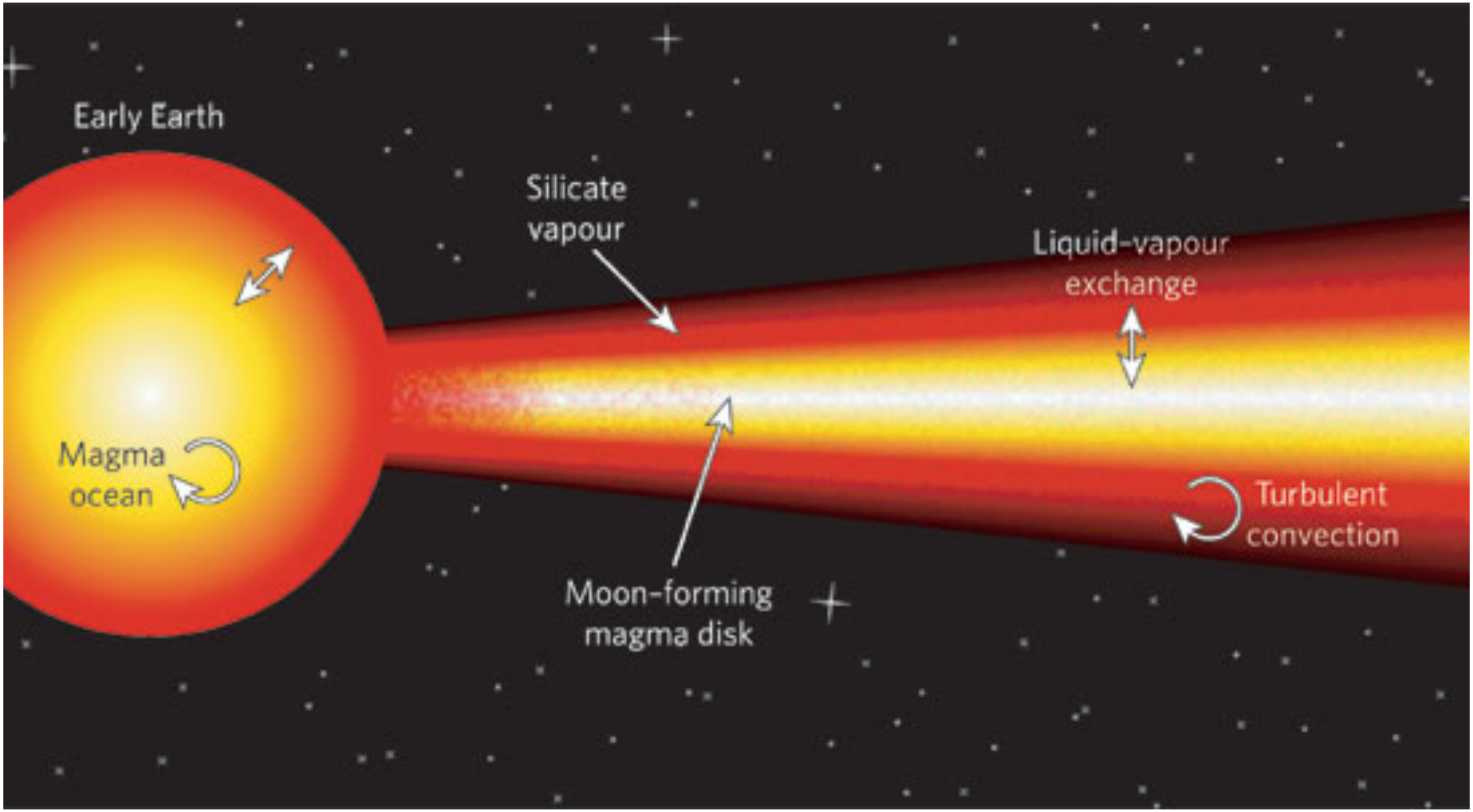
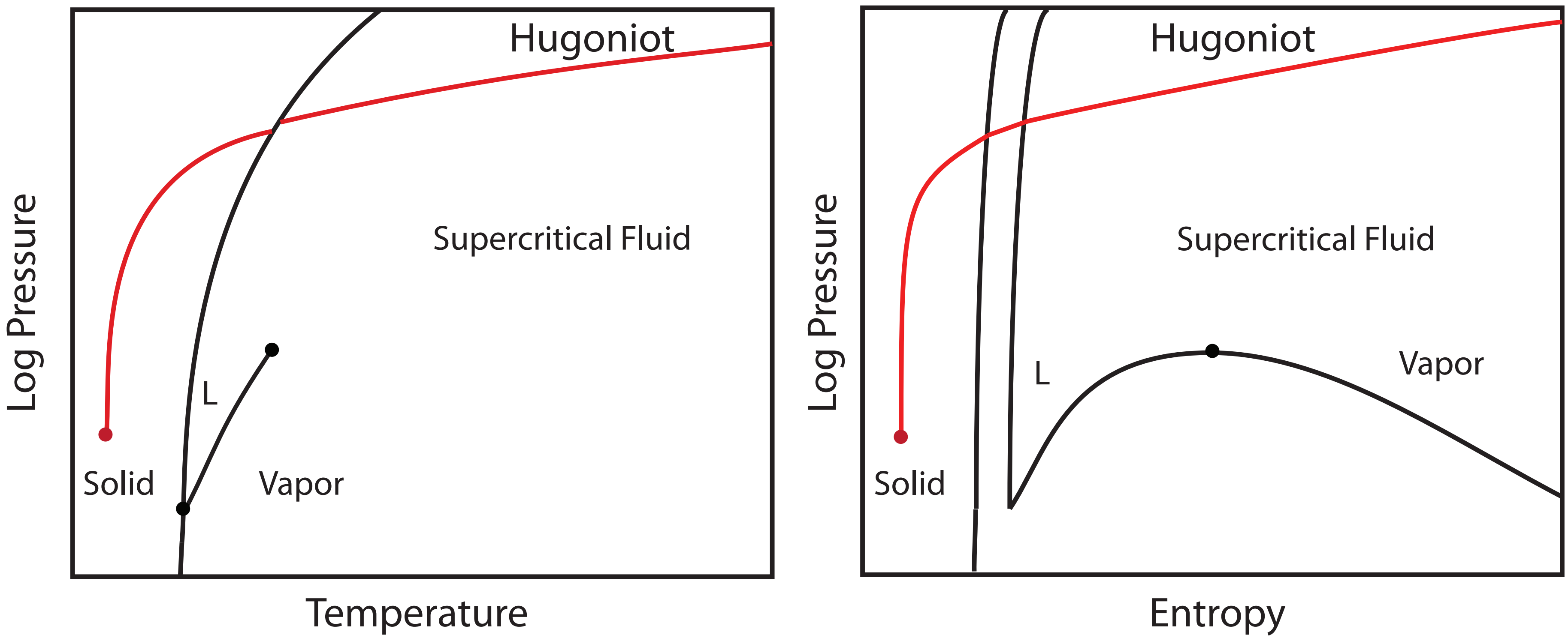
1000 km
-40
-20
1000 km
20
40

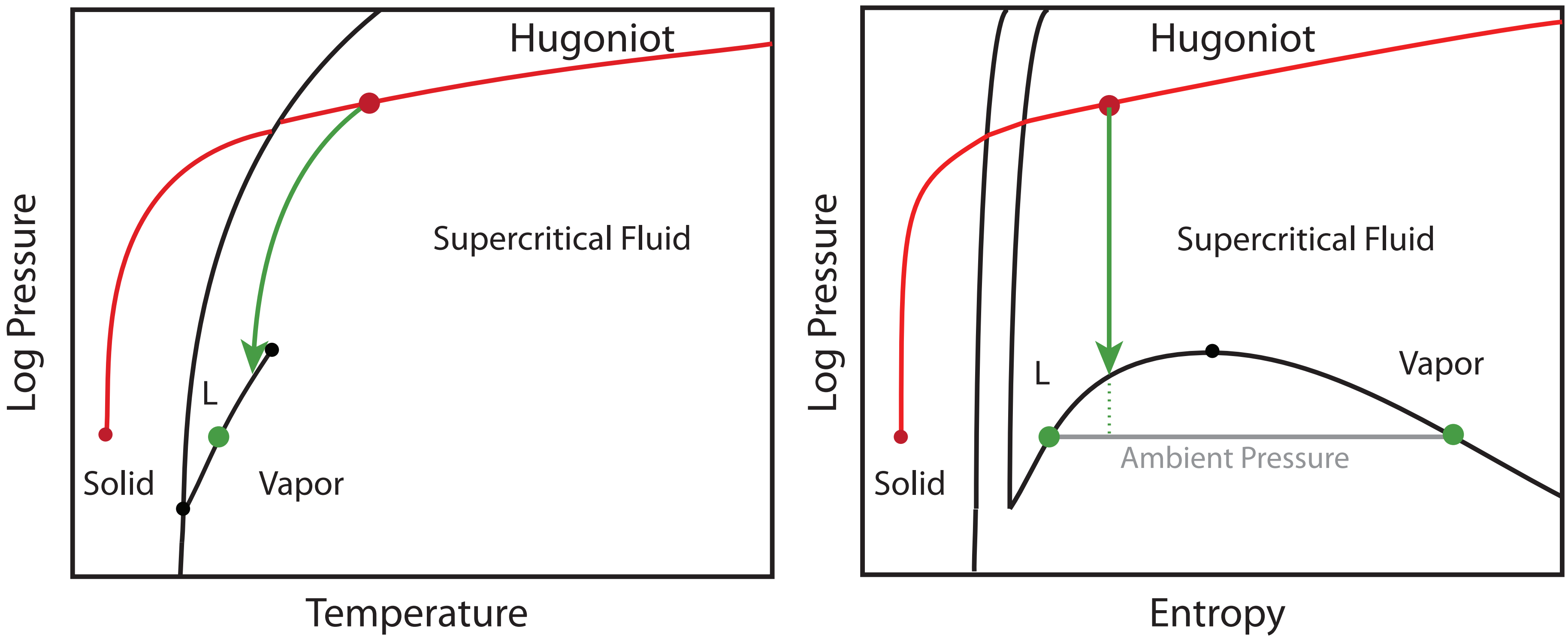
What was the physical state of the Earth and Lunar Disk?



Thermodynamics of Giant Impacts

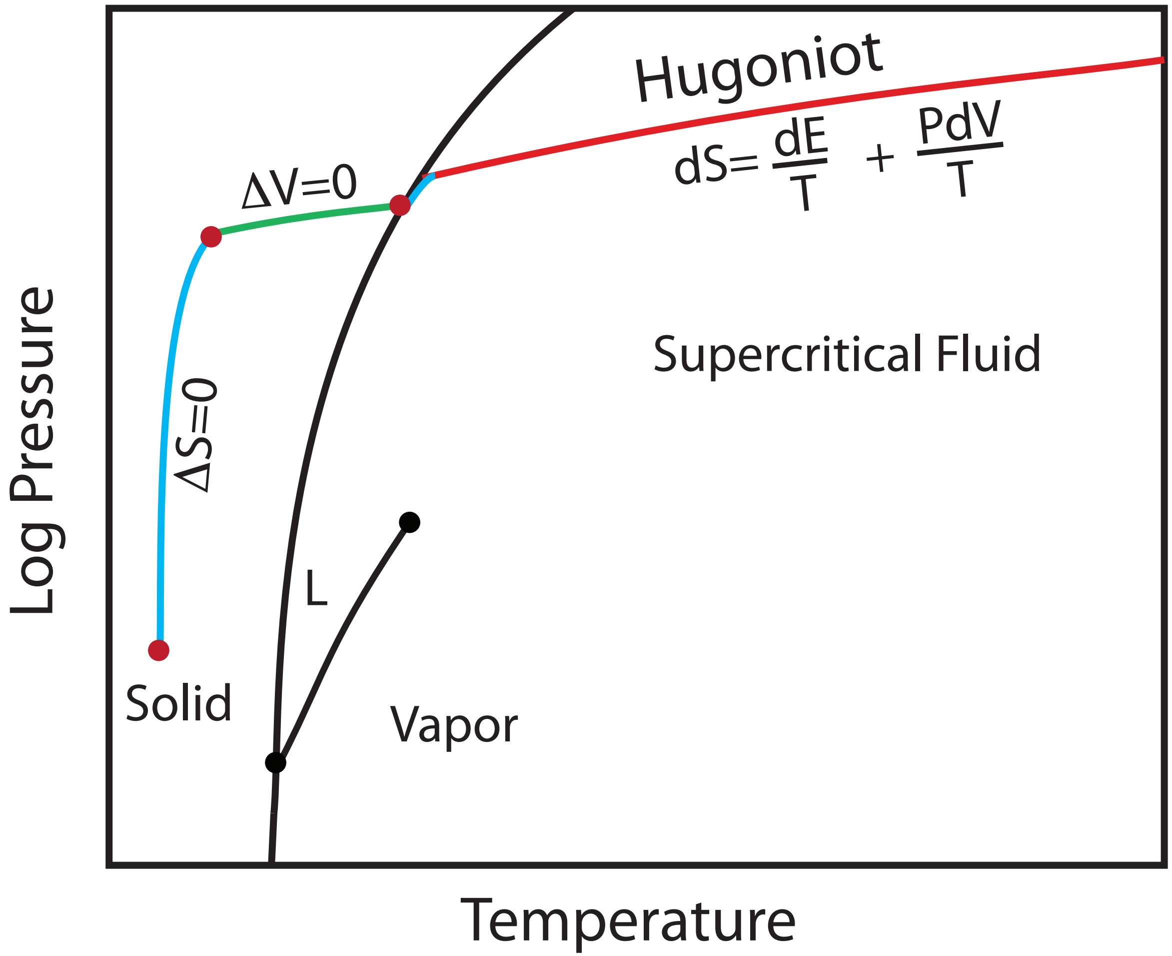


Thermodynamics of Giant Impacts



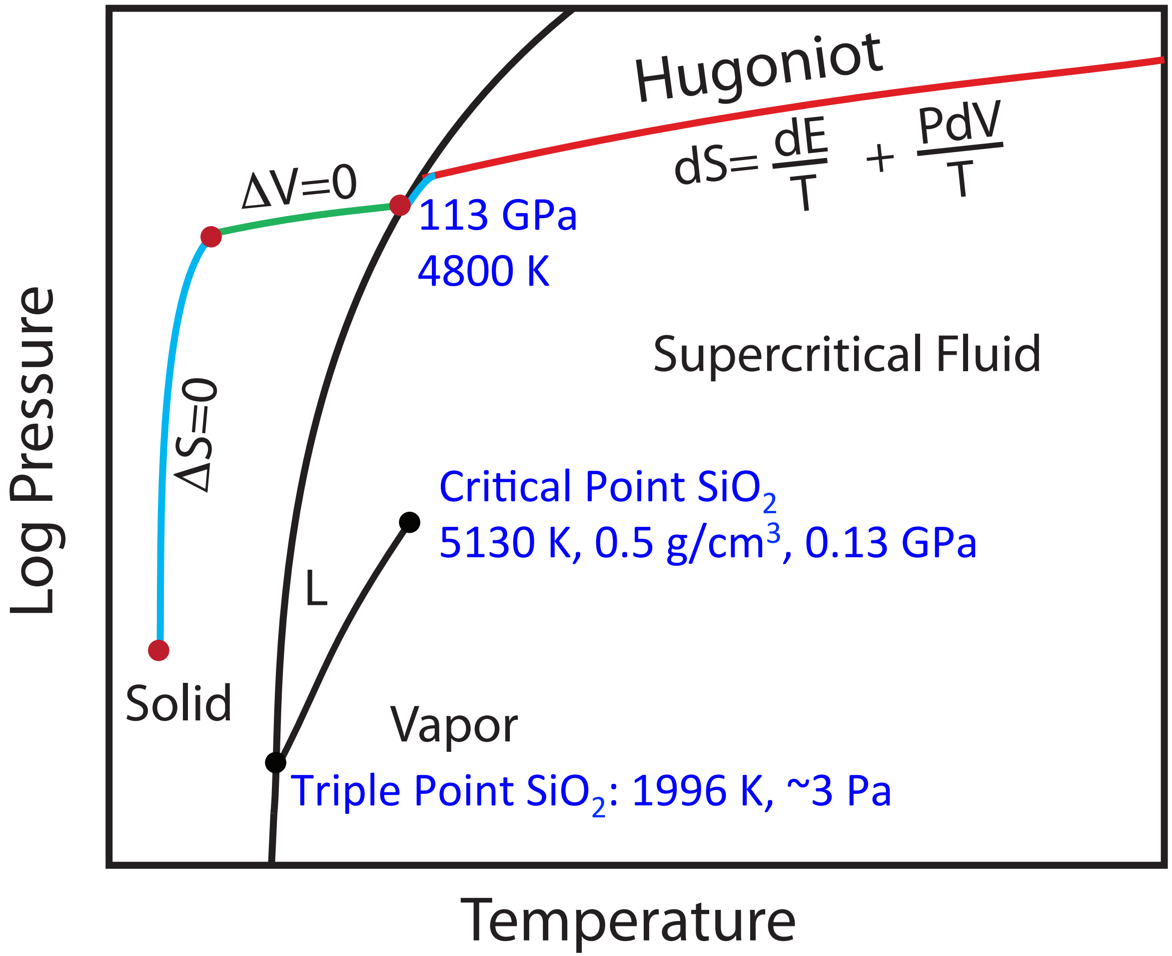
How much material melts or vaporizes?

Calculating Entropy on the Hugoniot with Static Data and Shock Temperatures



SiO_2 quartz   Temperature (Hicks et al. 2006) → Entropy (Kraus et al. 2012)

Calculating Entropy on the Hugoniot with Static Data and Shock Temperatures



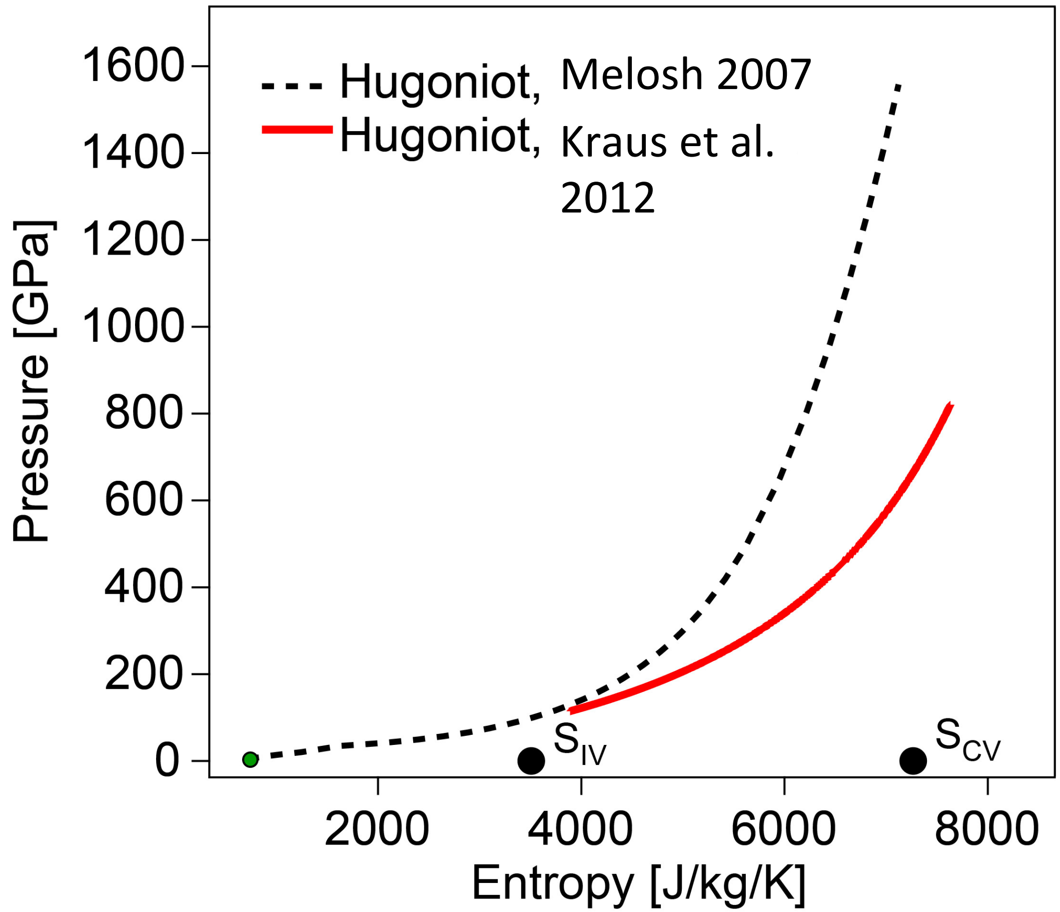
Other Critical Points

MgO (SESAME)
7900 K
0.45 g/cm^3
0.3 GPa

Fe (Fortov & Lomonosov 2010)
8800 K
2.2 g/cm^3
1.1 GPa

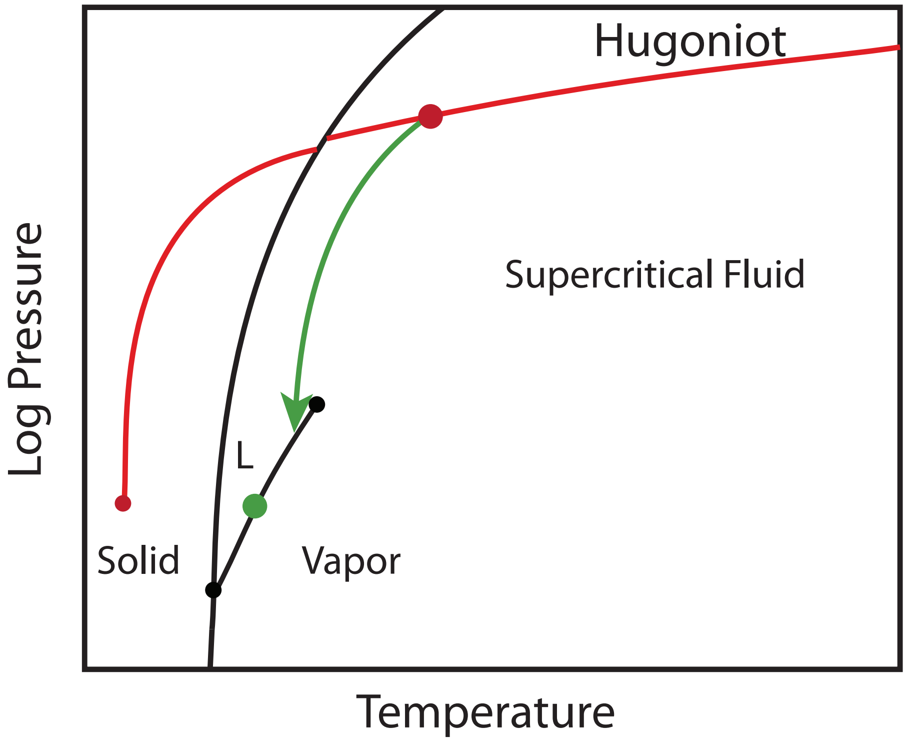
SiO_2 quartz   Temperature (Hicks et al. 2006) → Entropy (Kraus et al. 2012)

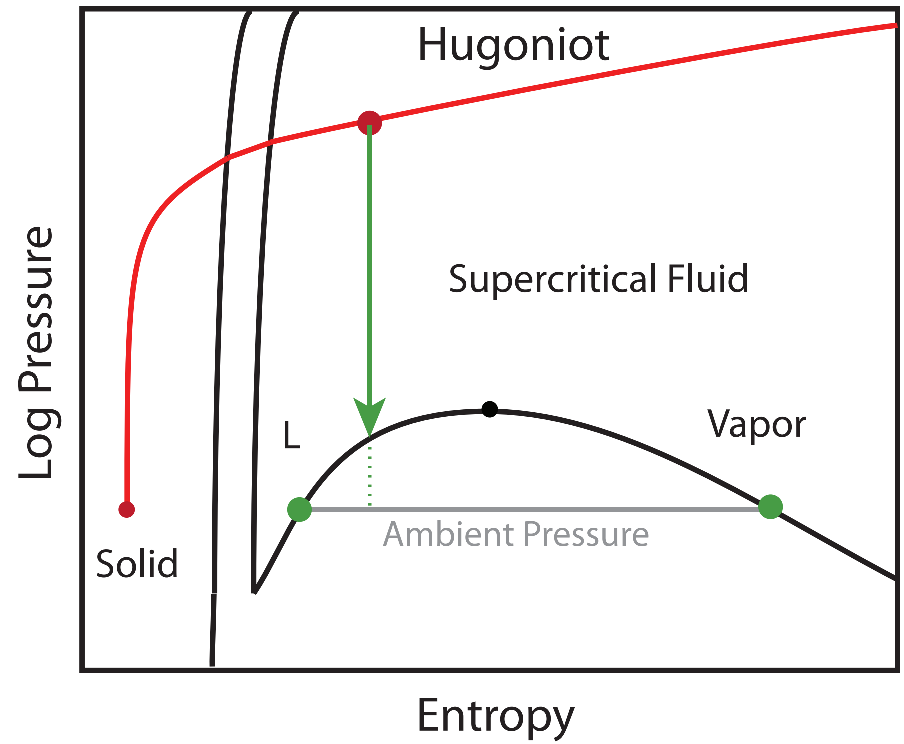
Simple Equation of State Models Do Not Predict the Correct Entropy



New critical pressure for complete vaporization: 715 GPa (Kraus et al. 2012)
Old value from M-ANEOS model: 1650 GPa (Melosh 2007)
Onset of vaporization at impact velocities of only 7 km/s.

How to measure the liquid-vapor curve?

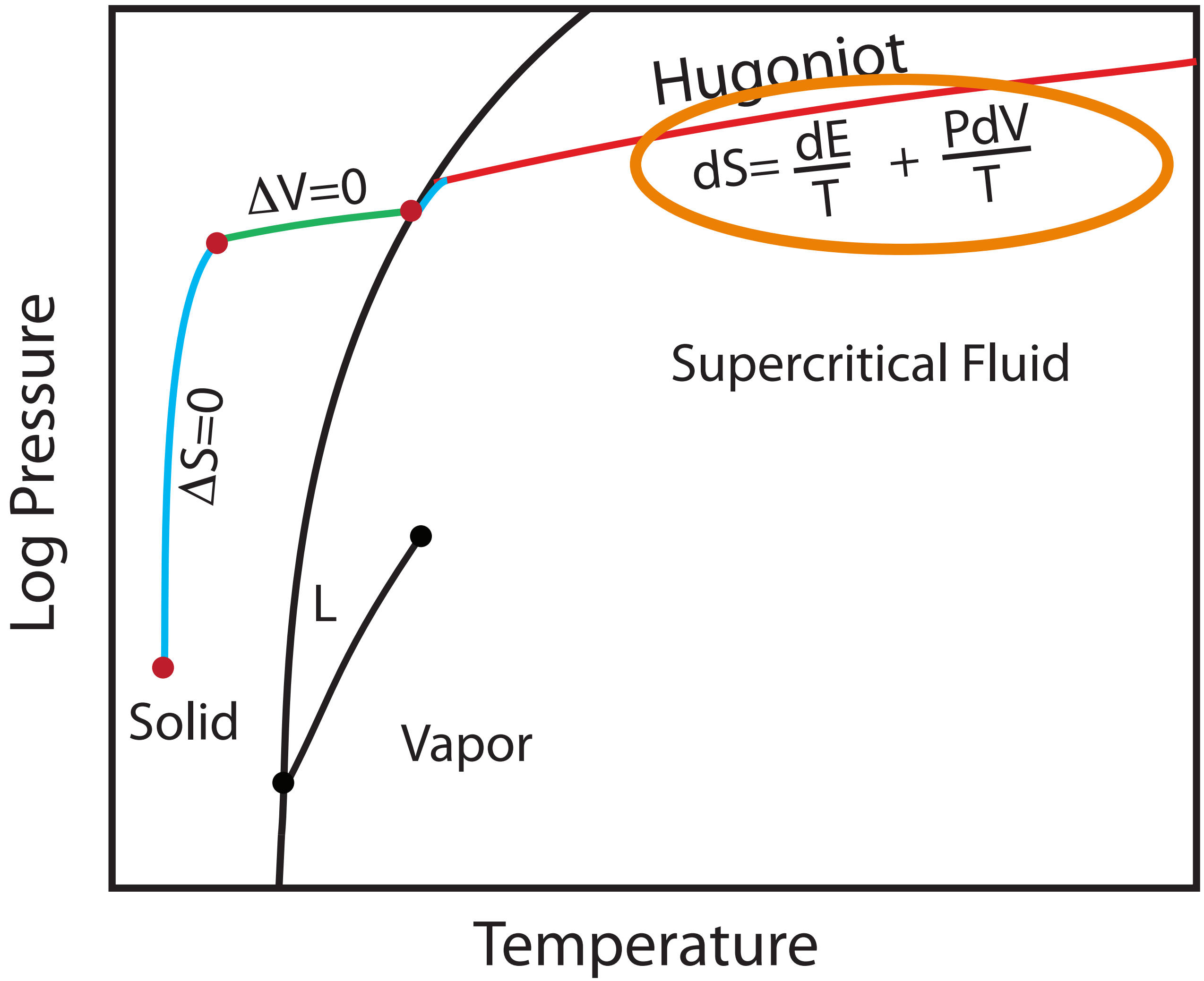




Model Critical Points

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

How to determine entropy when cannot measure shock temperature directly?

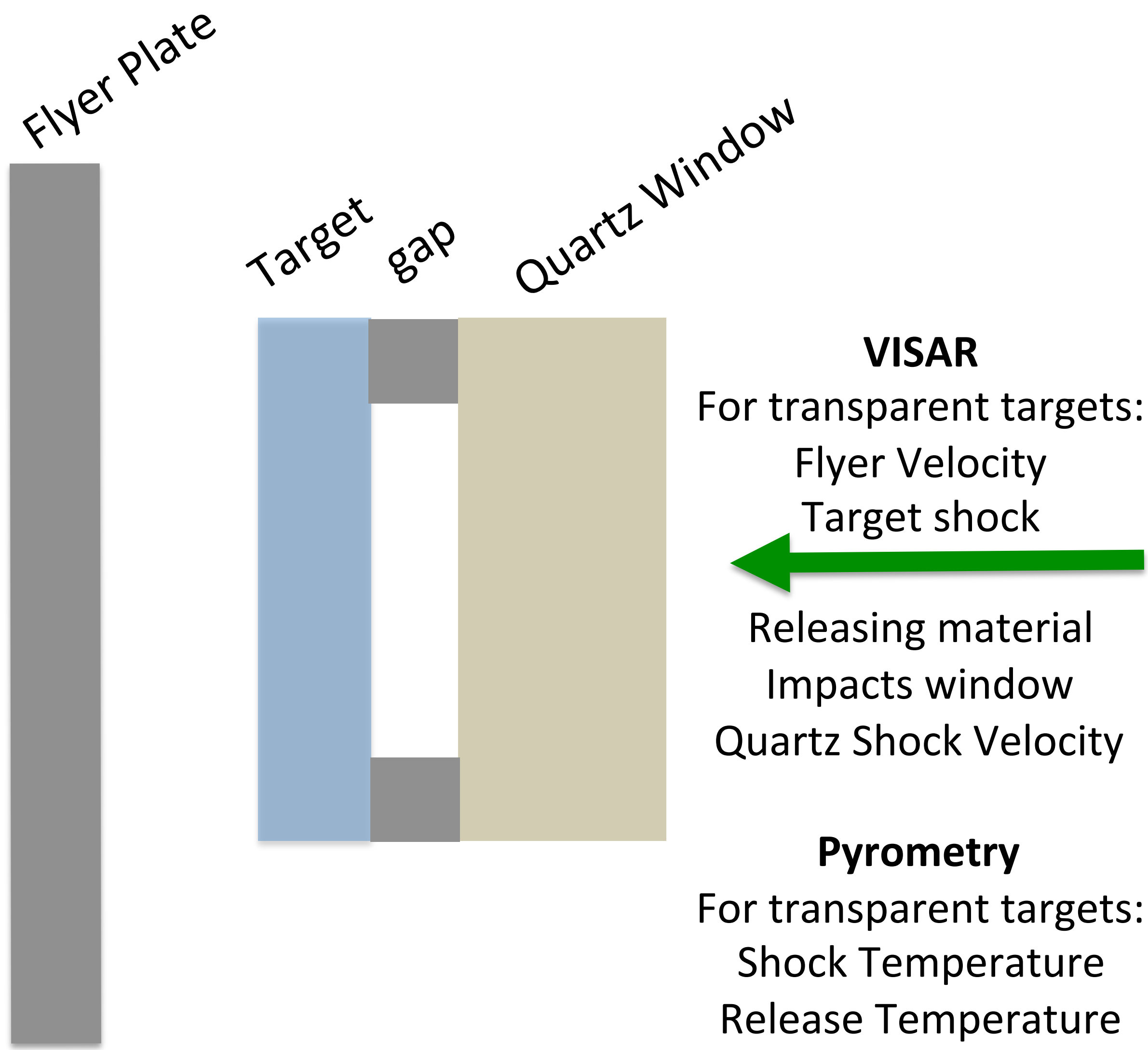


A general technique is needed for opaque materials.

Planar Geometry Shock-and-Release Experiments

Flyer Plate Velocities
> several km/s

Laser drive
>100's J



VISAR
For transparent targets:
Flyer Velocity
Target shock

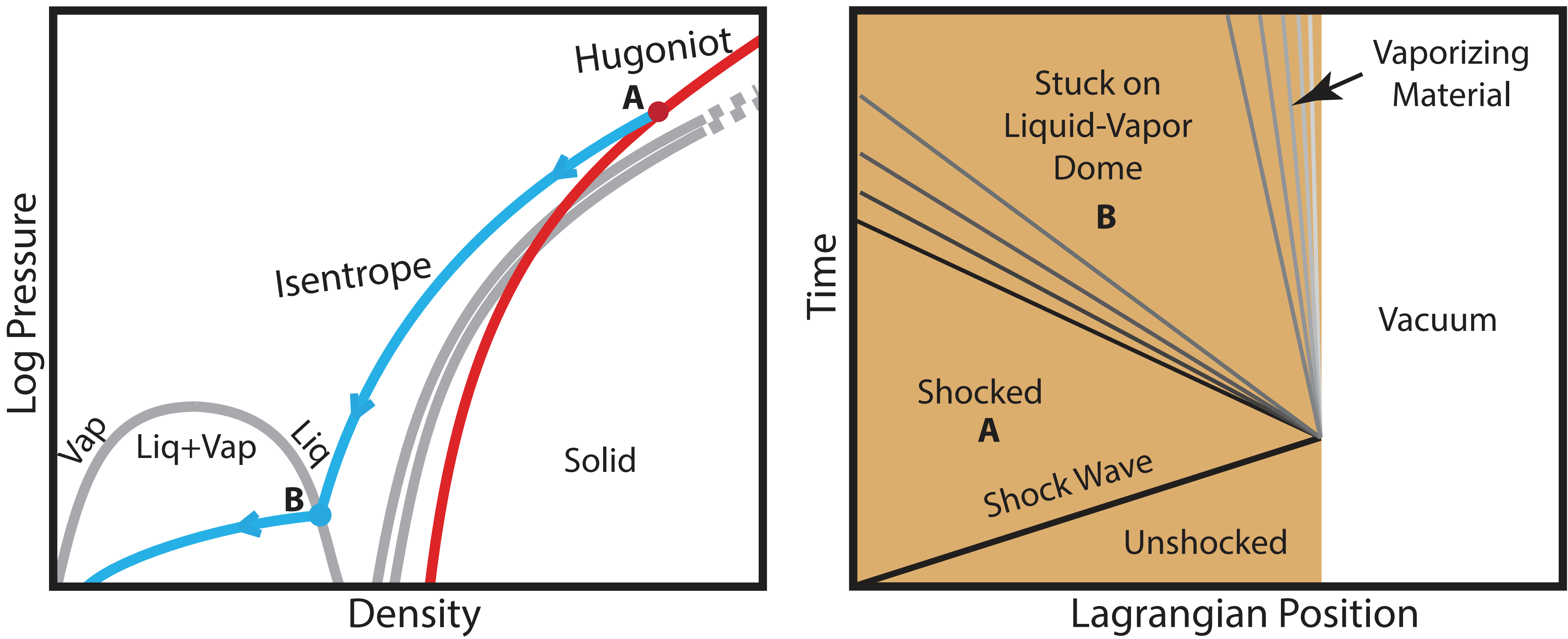
Releasing material
Impacts window
Quartz Shock Velocity

Pyrometry
For transparent targets:
Shock Temperature
Release Temperature

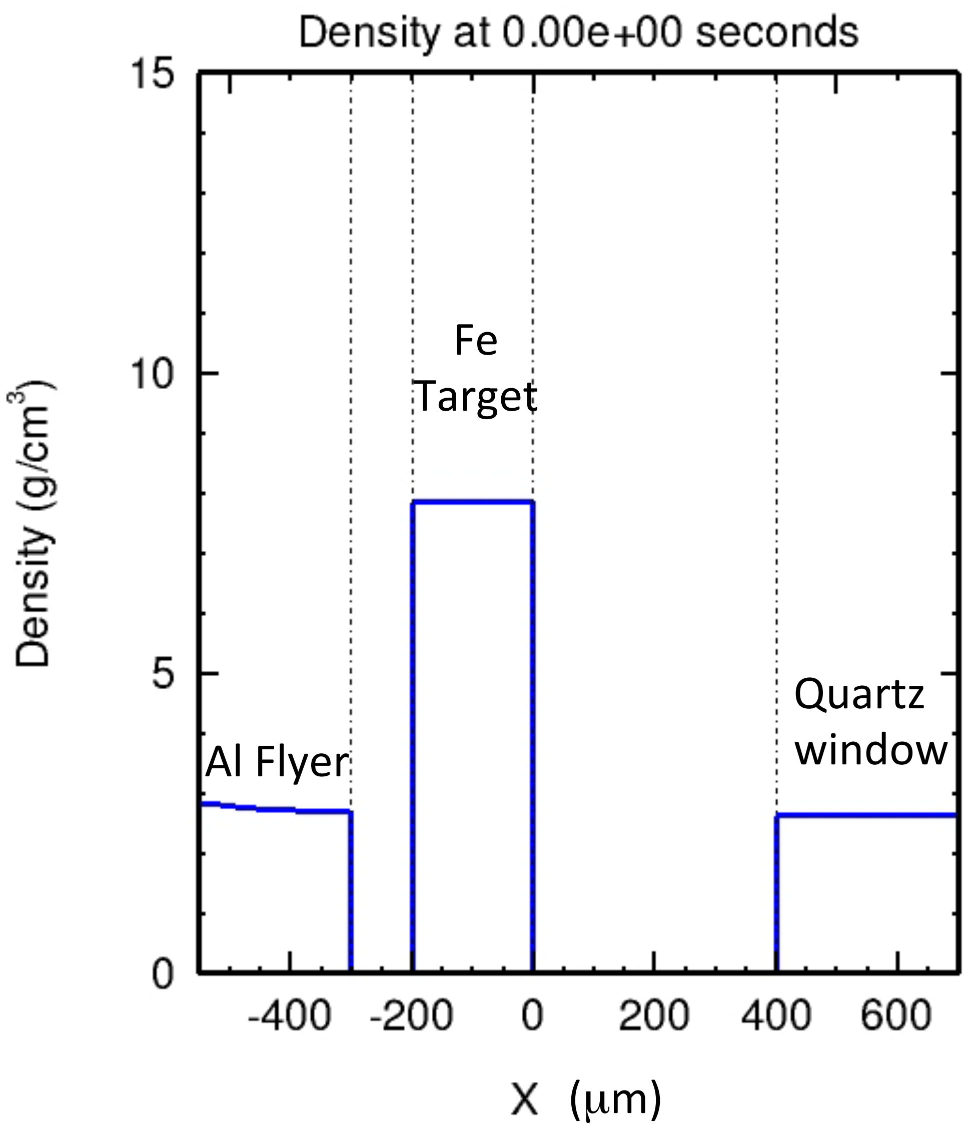
Technique development in Kraus et al. 2012.

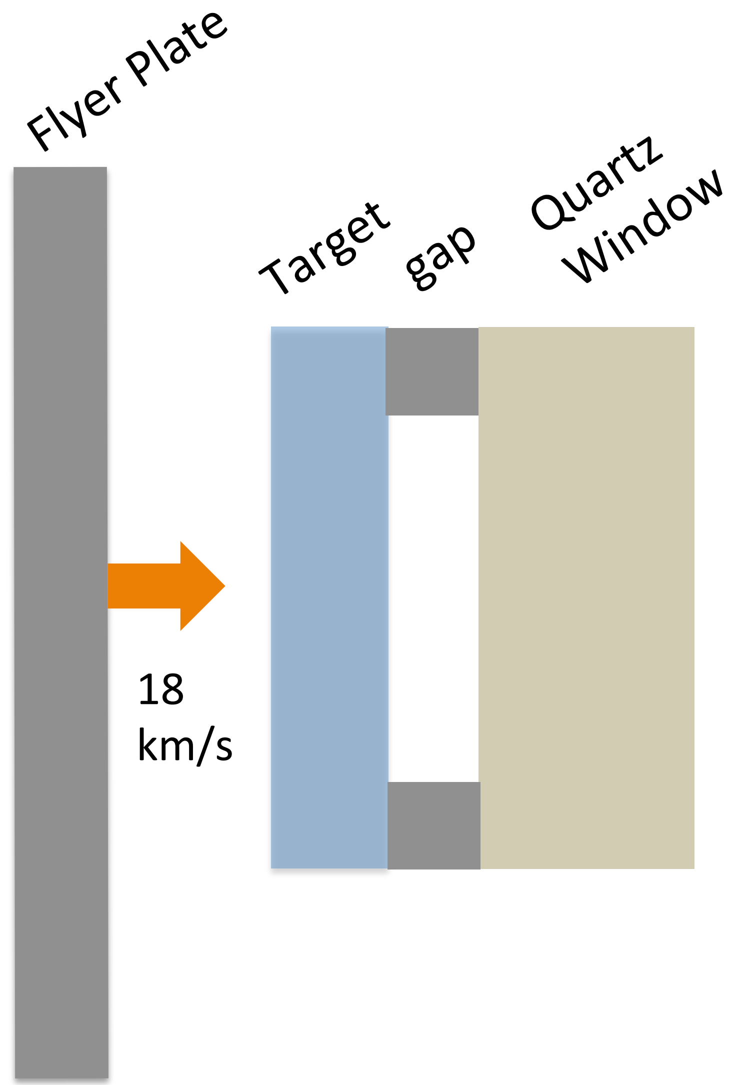
Gas gun: Boslough 1988, Stewart et al. 2008; **Laser**: Kraus et al. 2012; **Z-machine**: Kraus et al. revised

Shock-and-Release Experiments to Measure the Liquid-Vapor Boundary

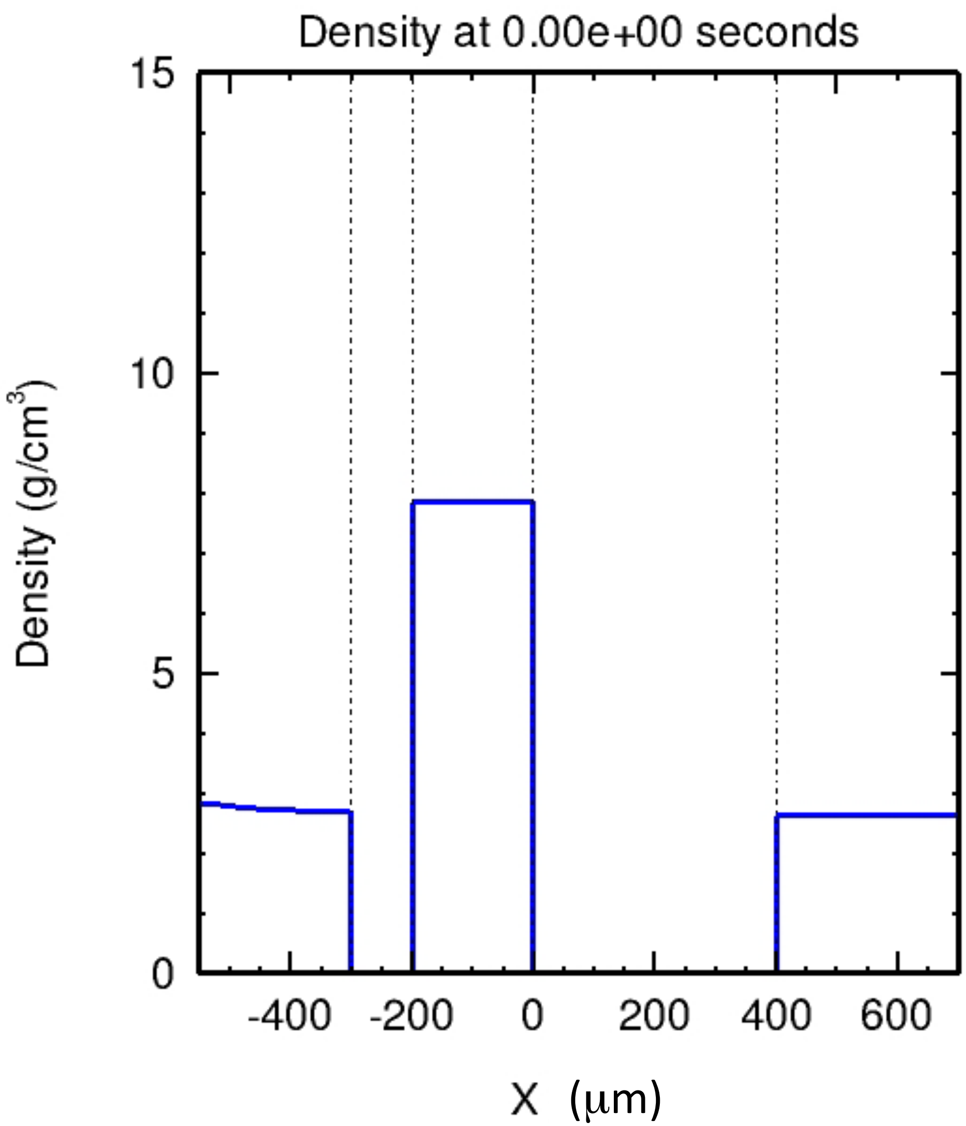


Shock-and-Release Experiment

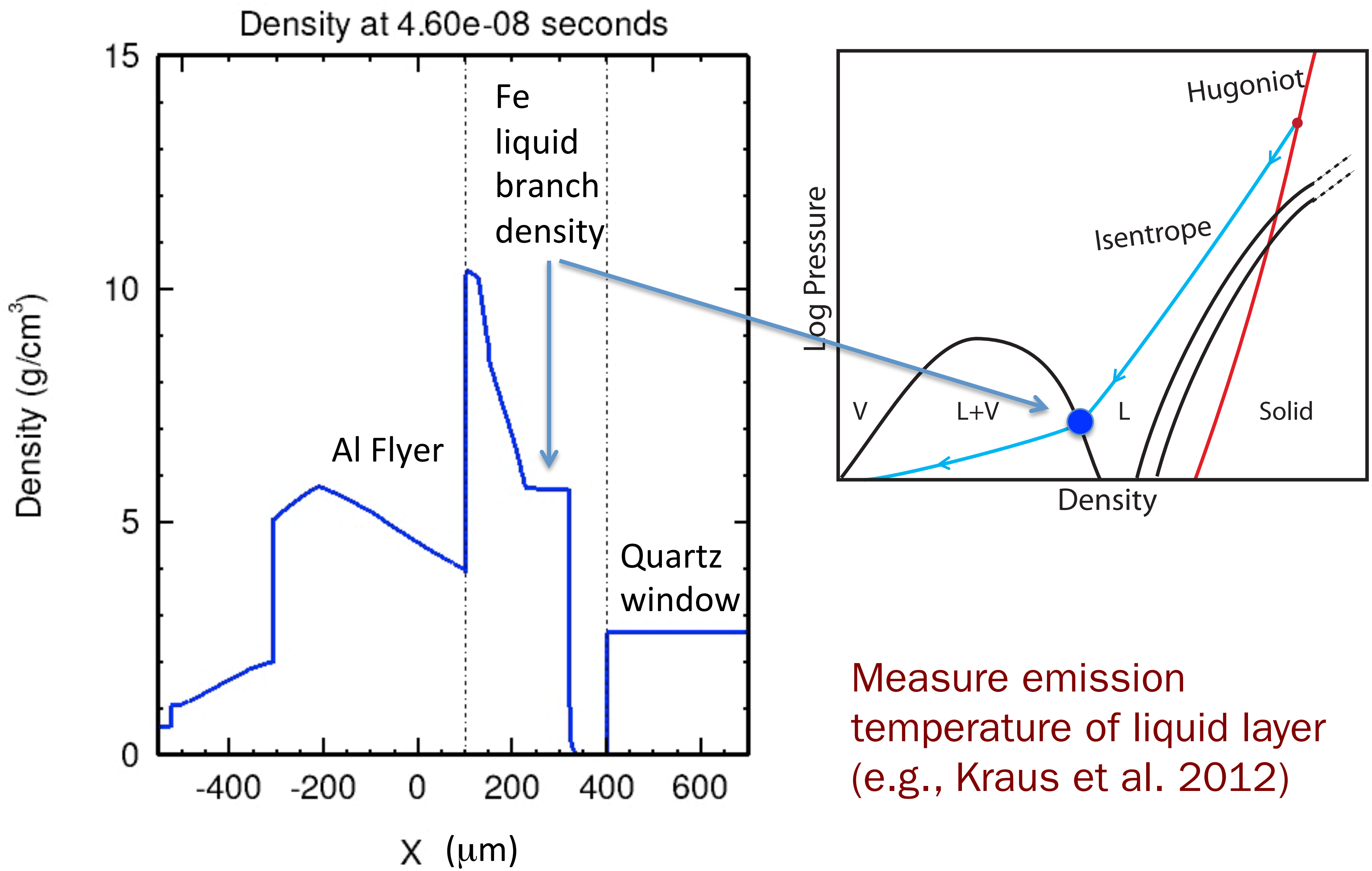




Shock-and-Release Experiment

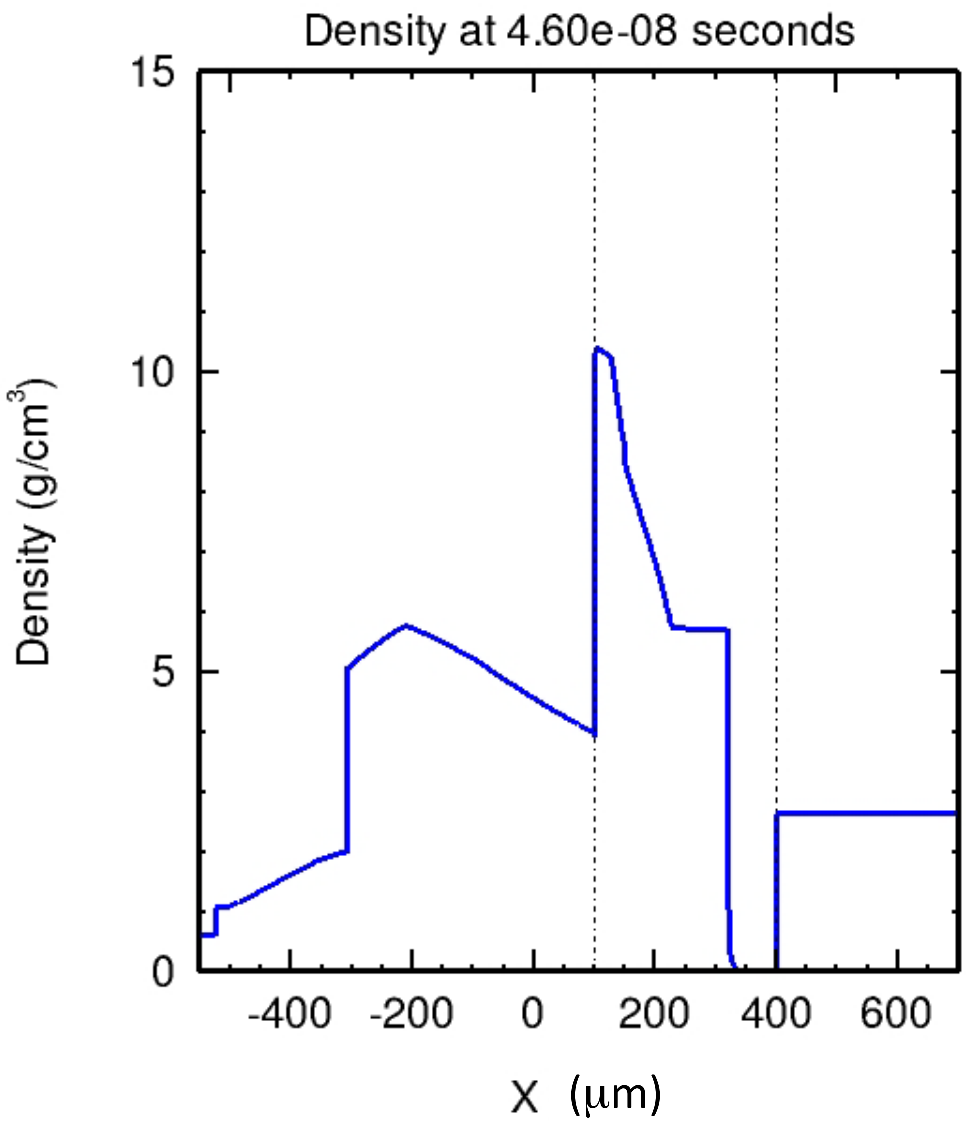


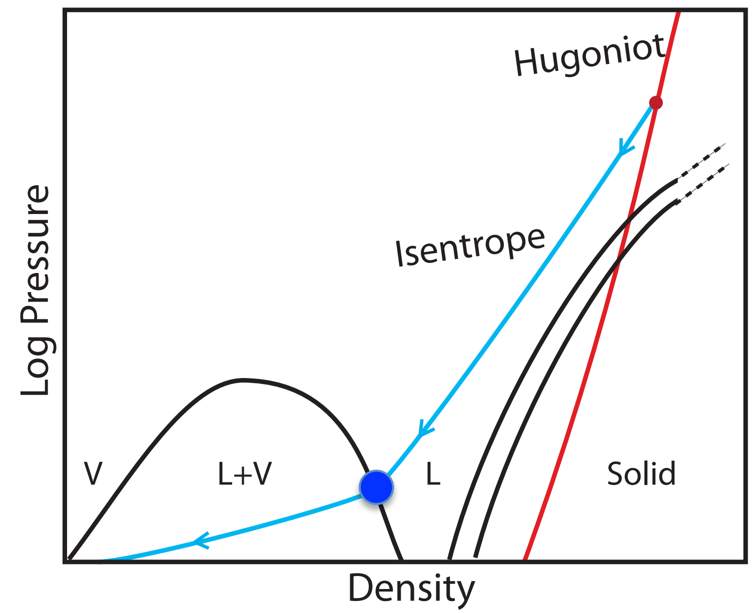
Shock-and-Release Experiment



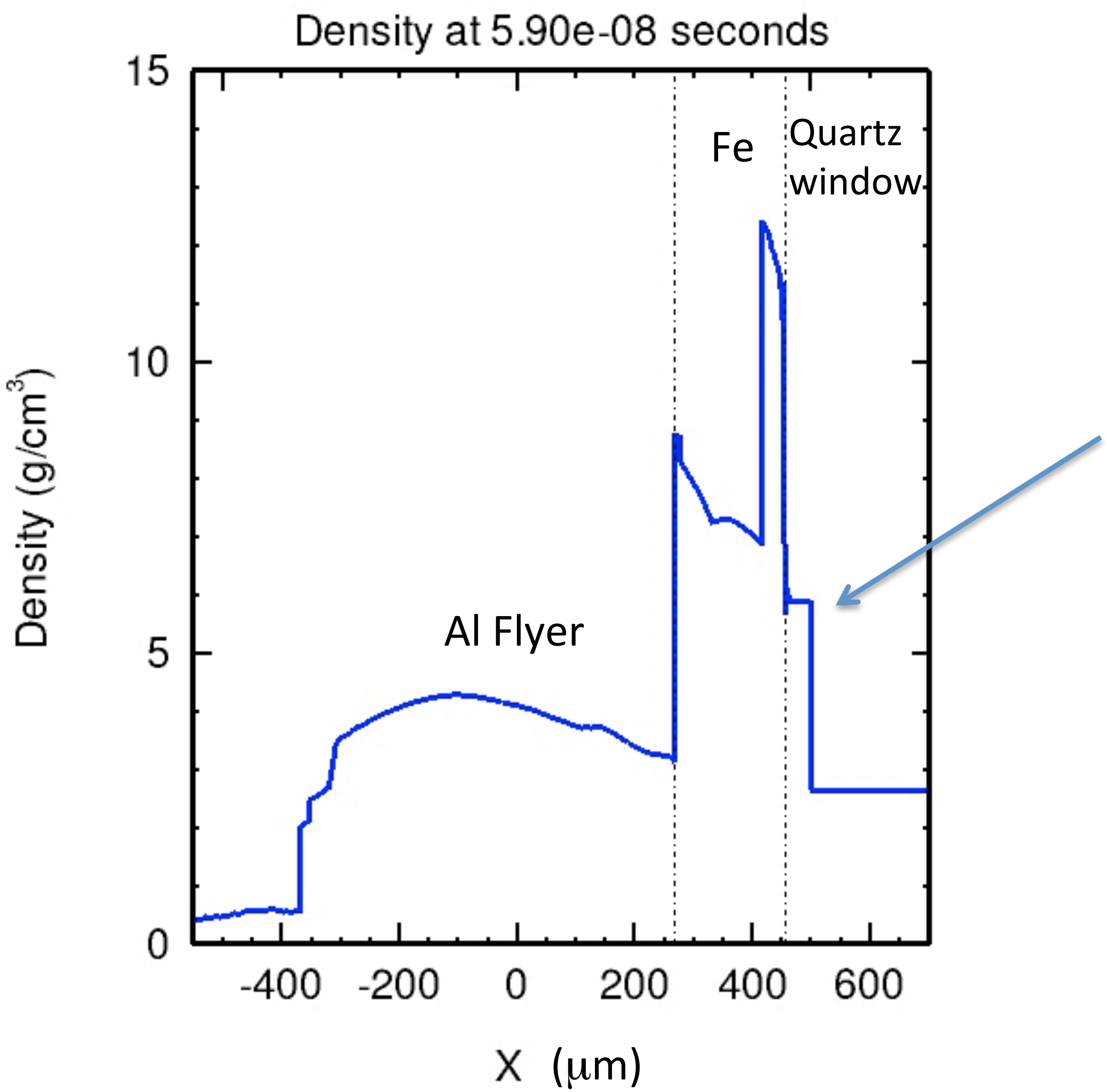
Measure emission temperature of liquid layer (e.g., Kraus et al. 2012)

Shock-and-Release Experiment





Shock-and-Release Experiment



Measure steady shock in quartz window.

Solve for density of the liquid iron as in a reverse impact experiment.

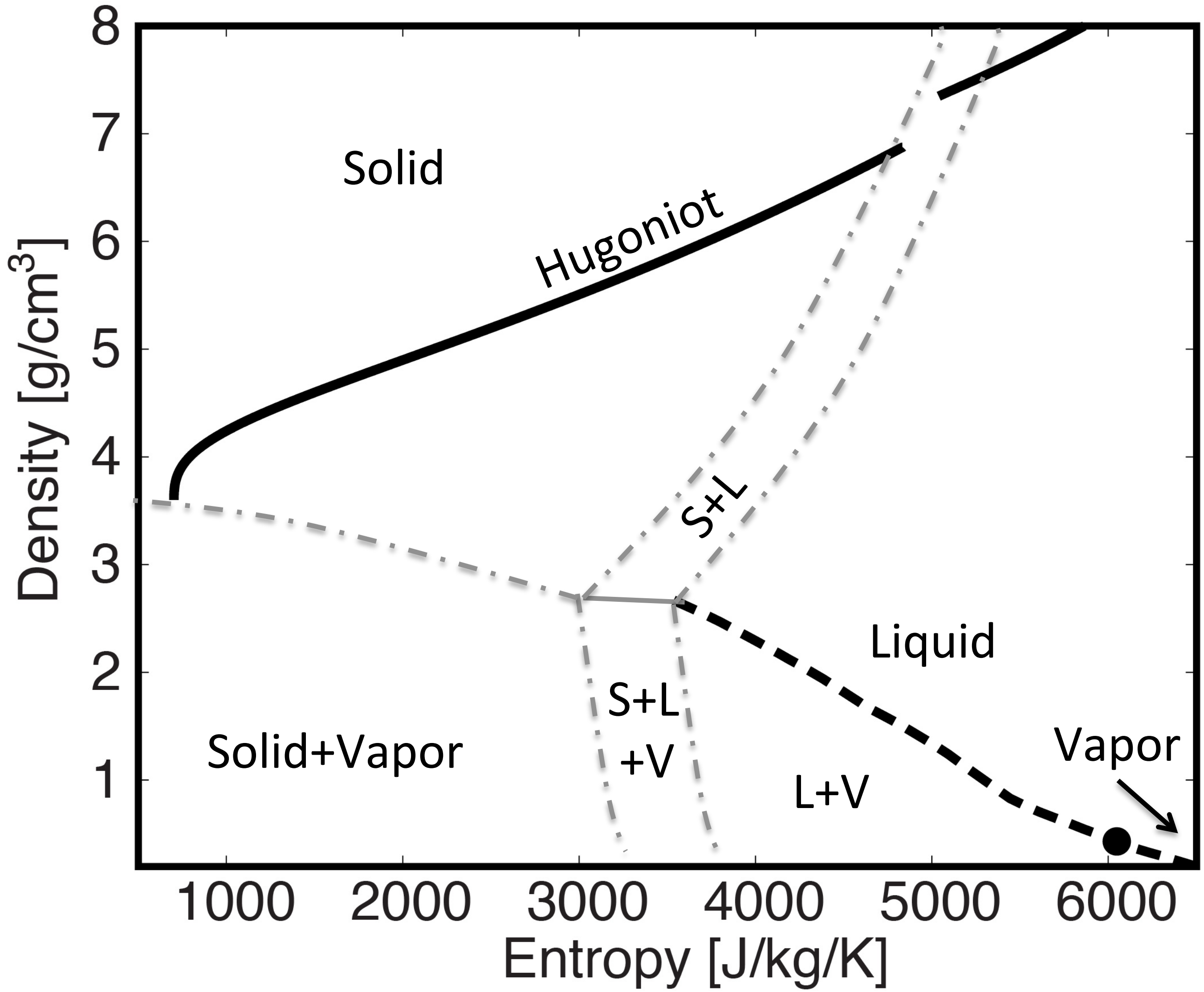
First Shock-and-Release Density Measurements

Fundamental Science Program at the Sandia Z Machine & NNSA HEDLP

Richard G. Kraus, Seth Root, Raymond W. Lemke,
Sarah T. Stewart, Stein B. Jacobsen, and Thomas R. Mattsson

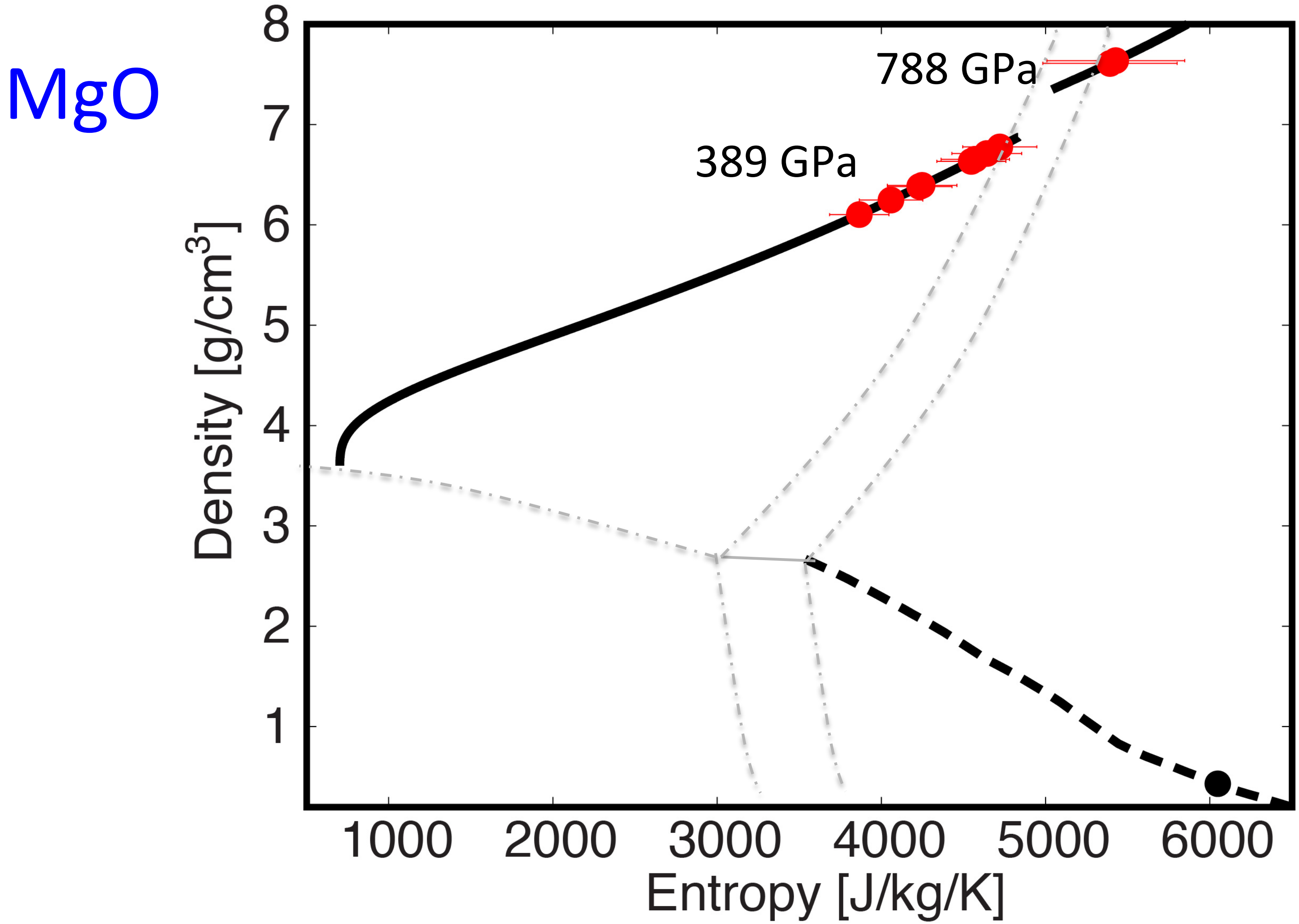
Shock and Release in Entropy-Density Space

MgO



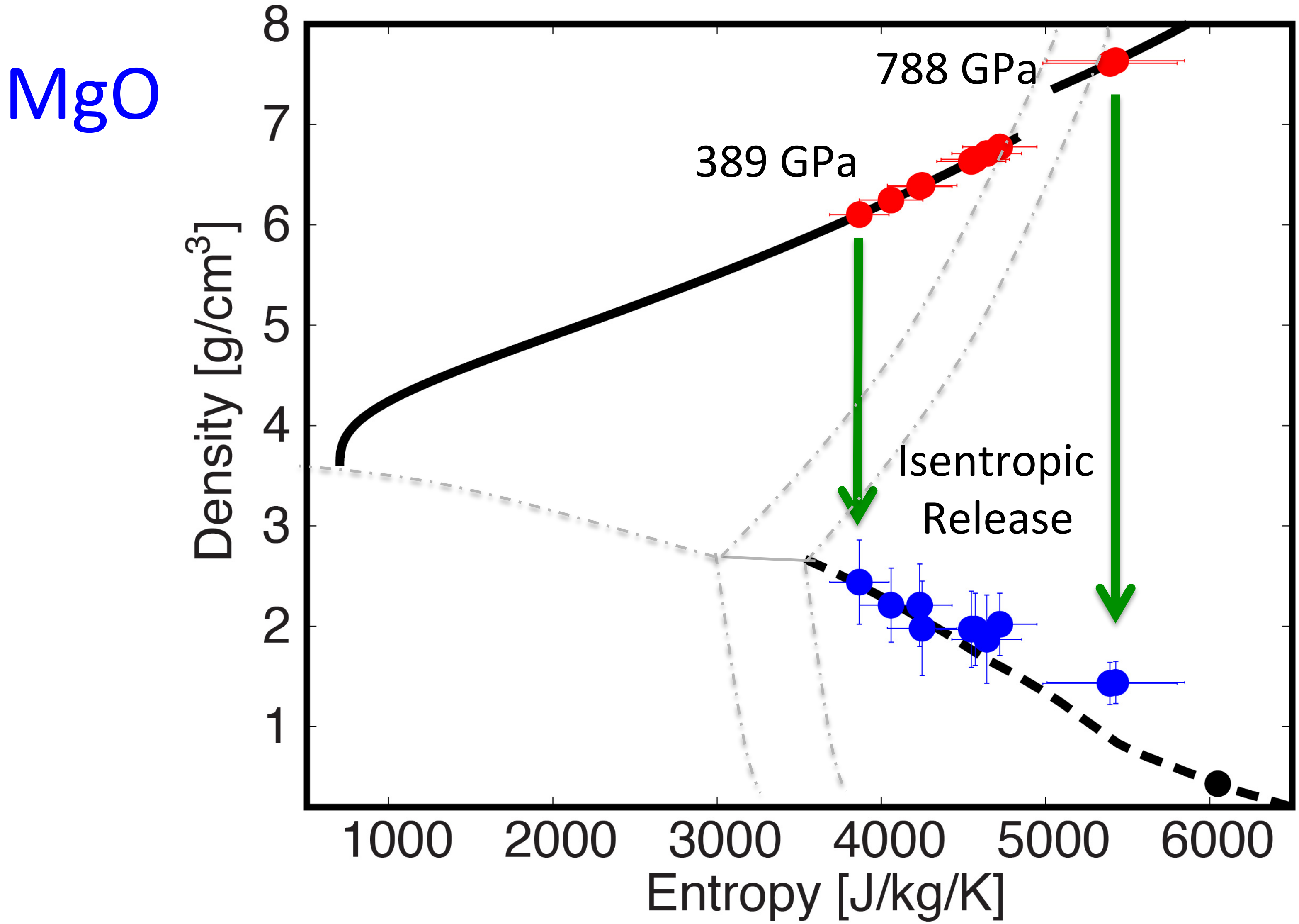
Kraus et al., in prep.

Shock and Release in Entropy-Density Space



Kraus et al., in prep.

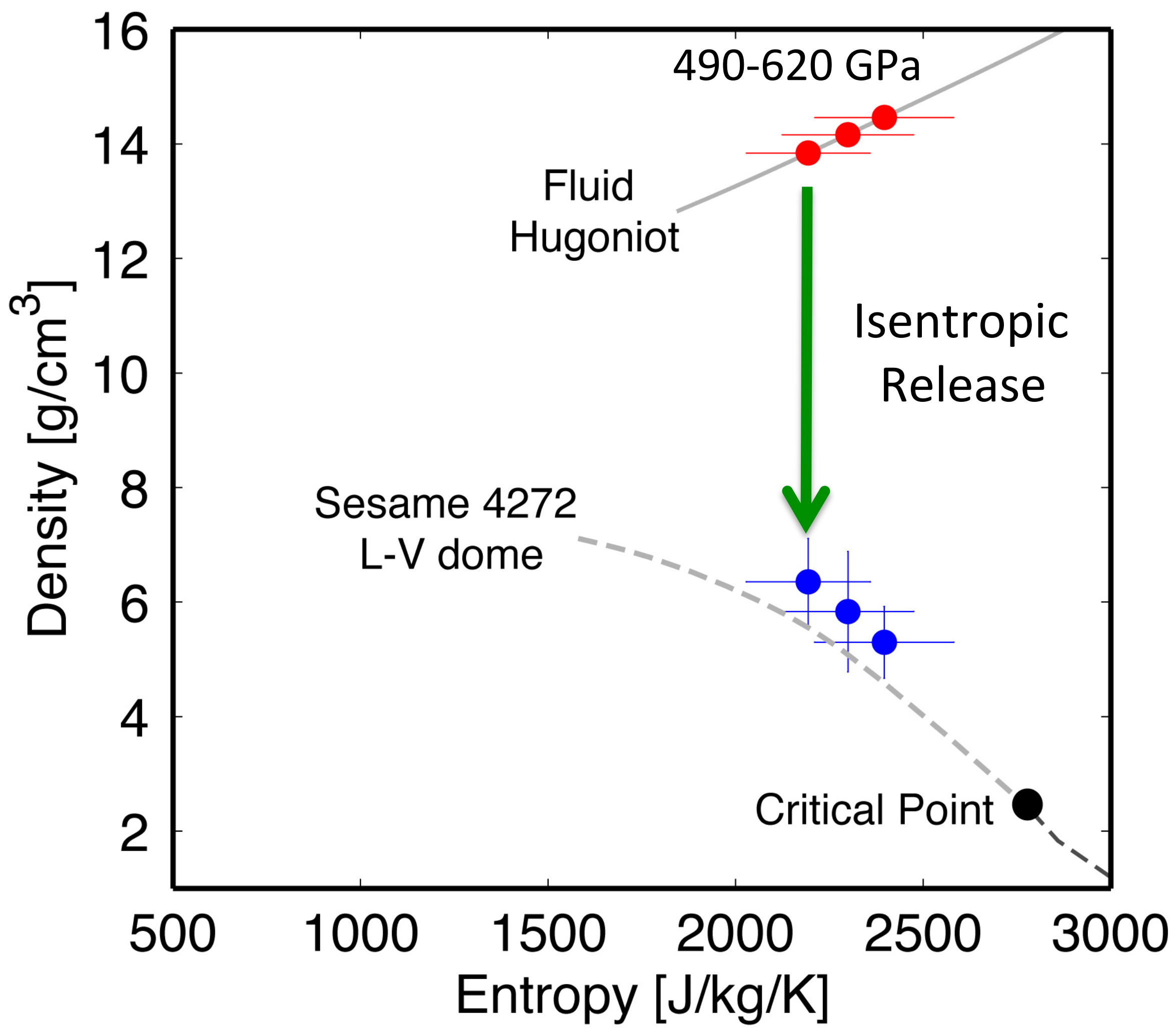
Shock and Release in Entropy-Density Space



MgO SESAME 7460 liquid-vapor curve

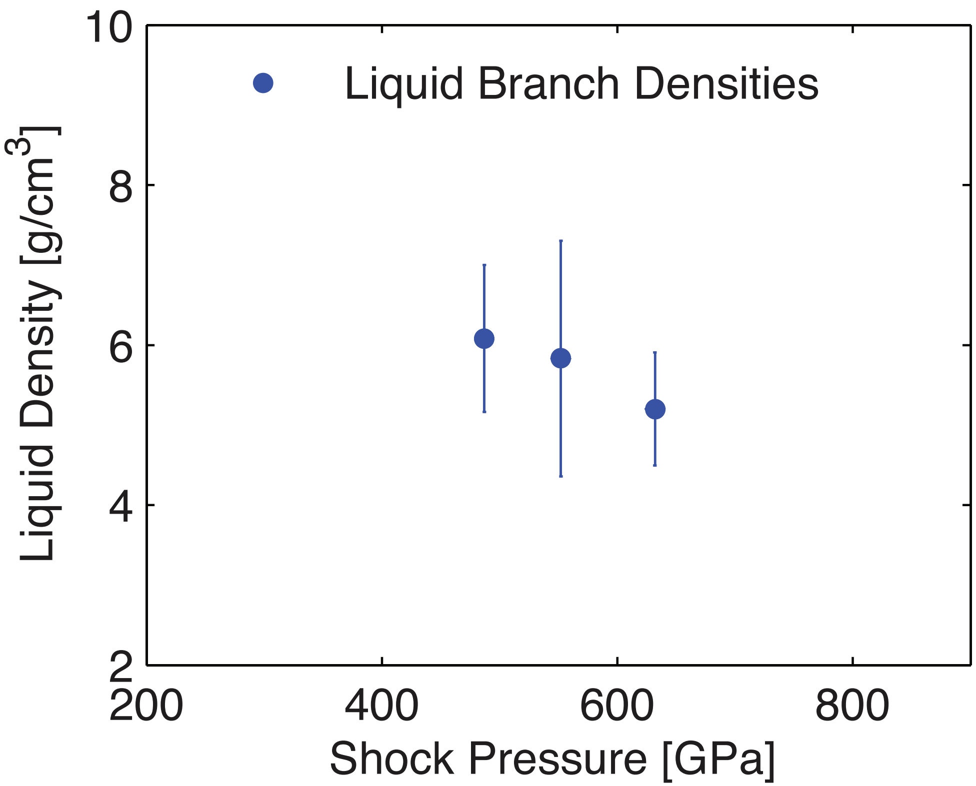
Kraus et al., in prep.

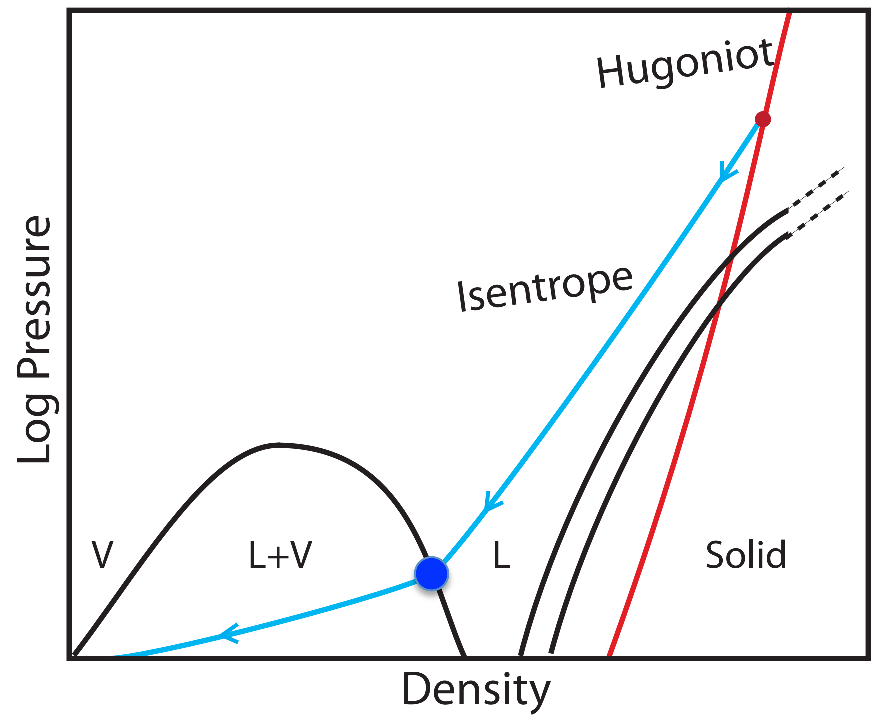
Iron Shock and Release Density Data



Kraus et al., revised.

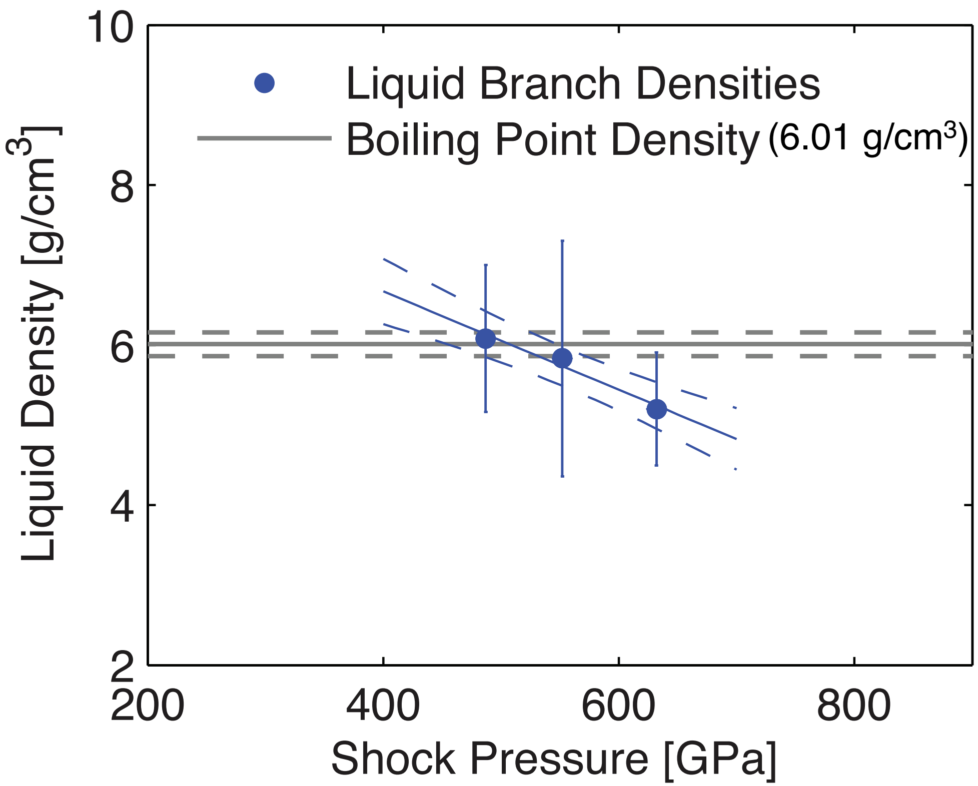
Iron Density Data
Liquid Branch of Liquid-Vapor Curve

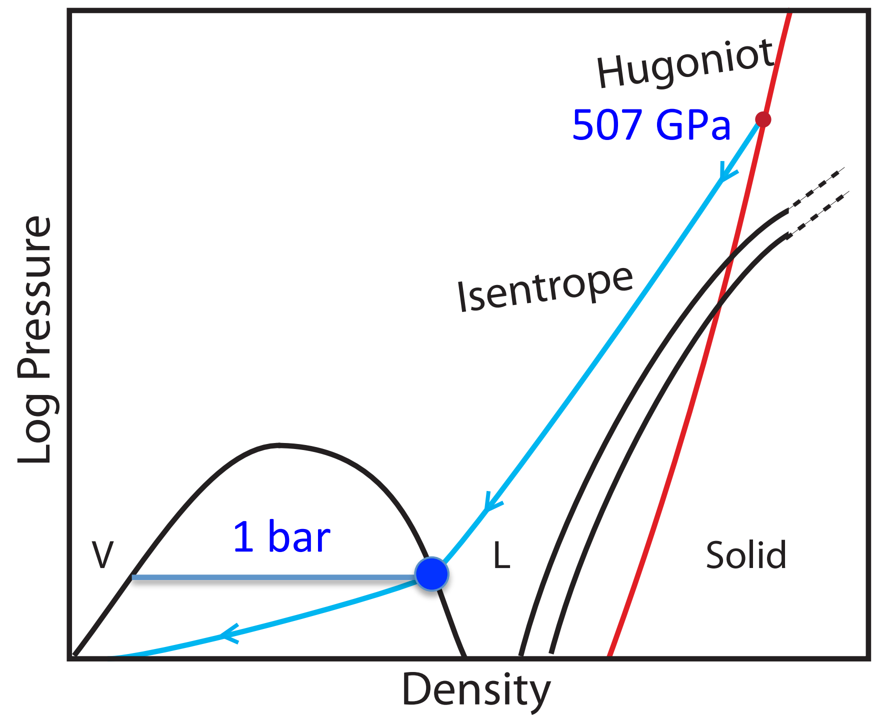




Kraus et al., revised.

Iron Liquid Branch Density Data Constrains Entropy on the Hugoniot



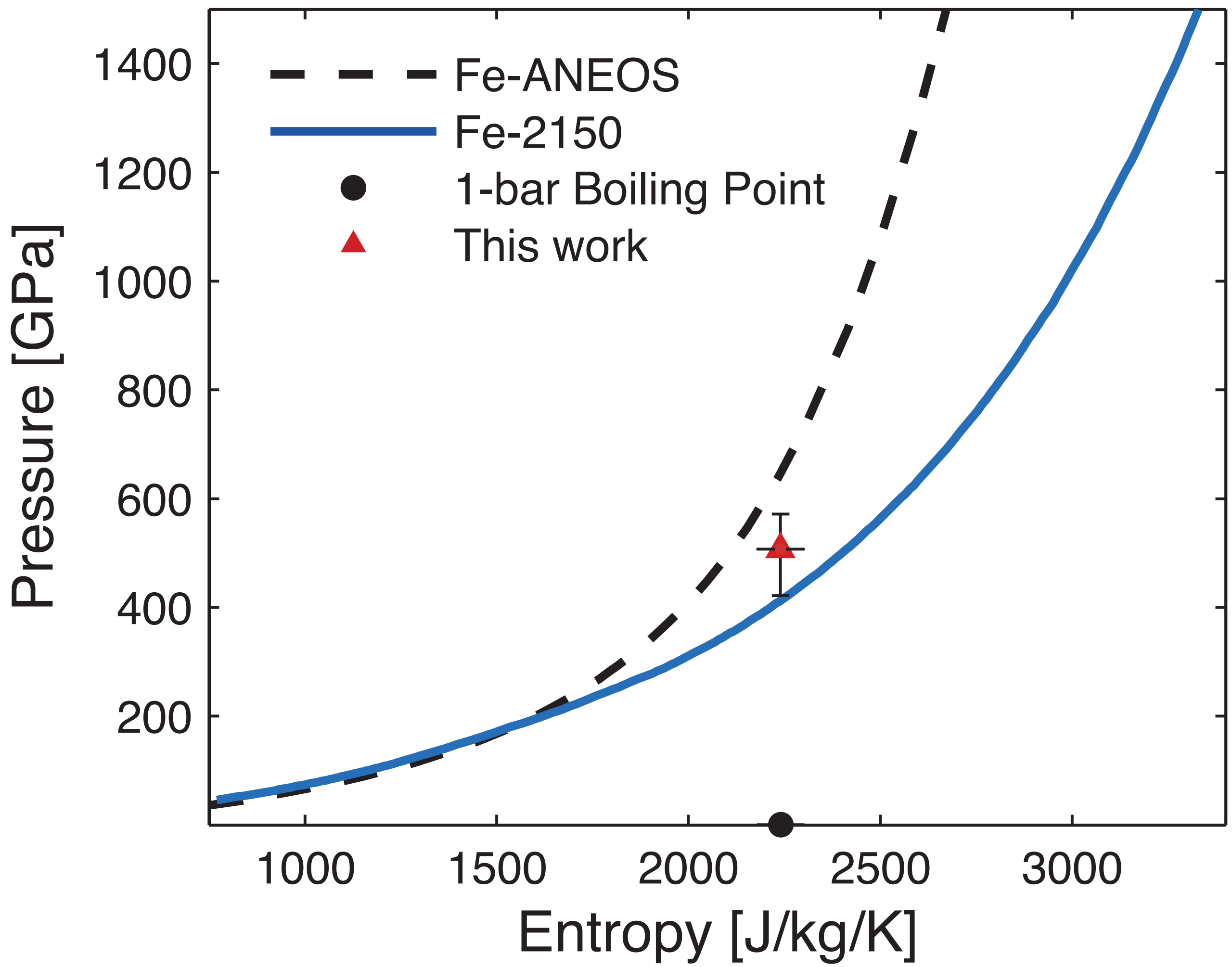


Post-shock densities tie the 1 bar boiling point to the shock state

Shock pressure to induce vaporization: 507 GPa
(13 km/s impact by a differentiated asteroid)

Kraus et al., revised.

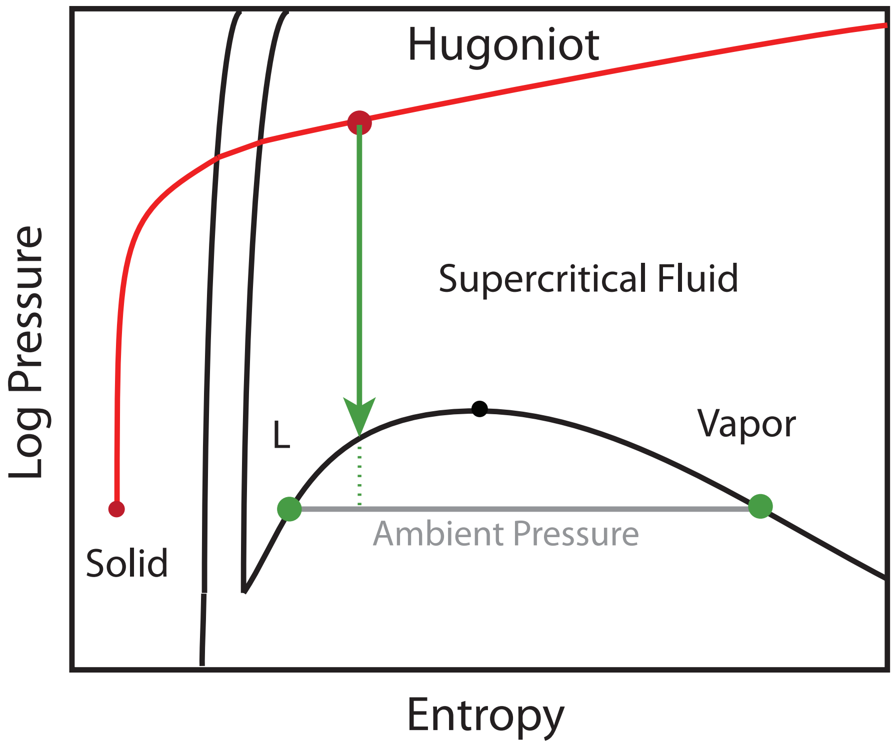
Thermal State on the Hugoniot of an Opaque Material

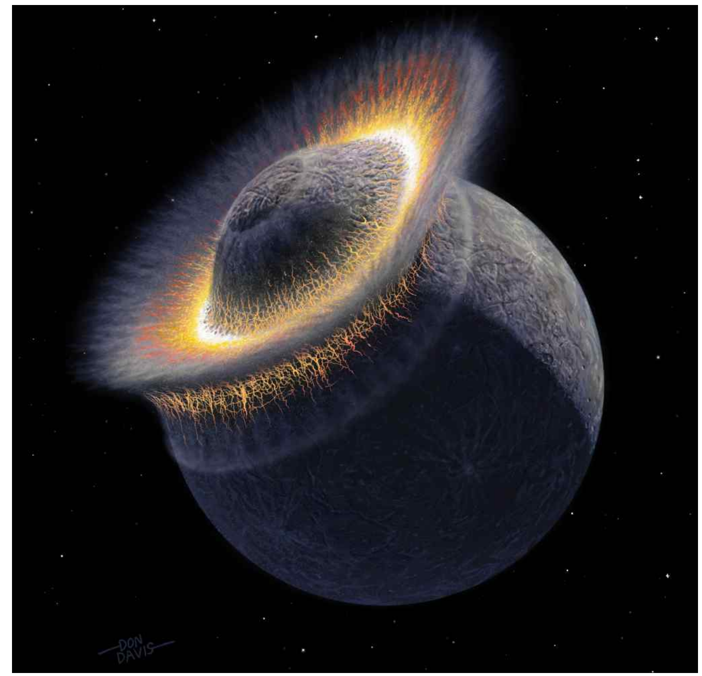


Method for Hugoniot entropy is completely general.

Kraus et al., revised.

Shock-induced Phase Changes: A Planetary Process

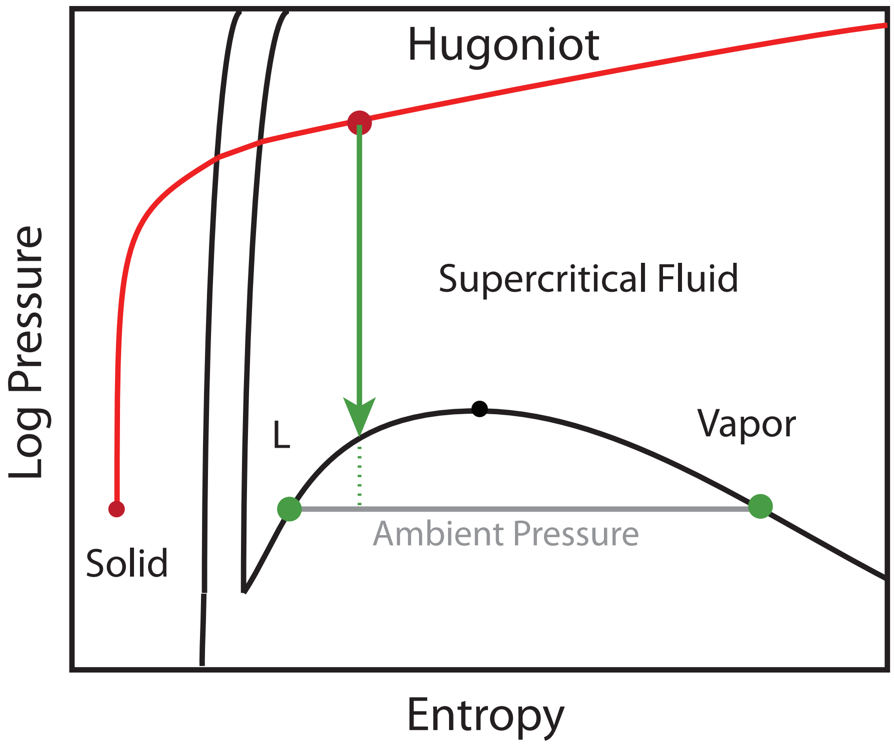


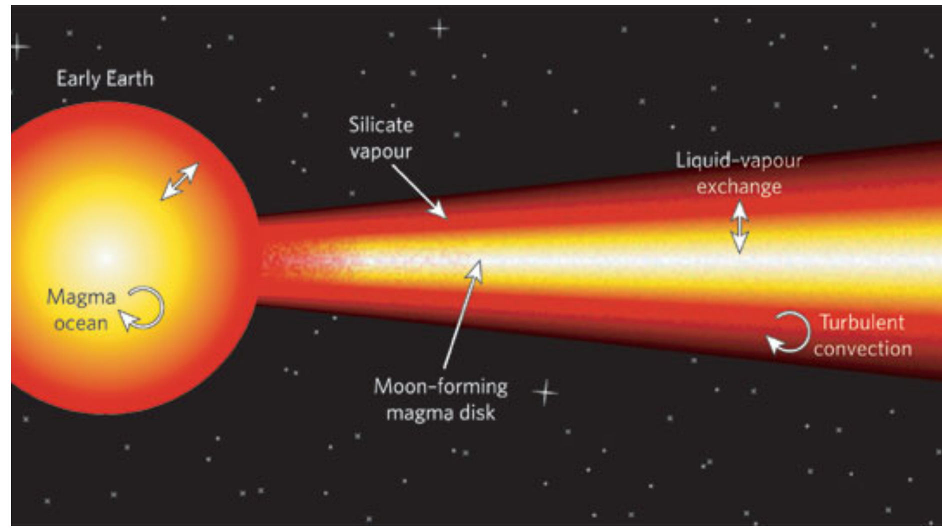


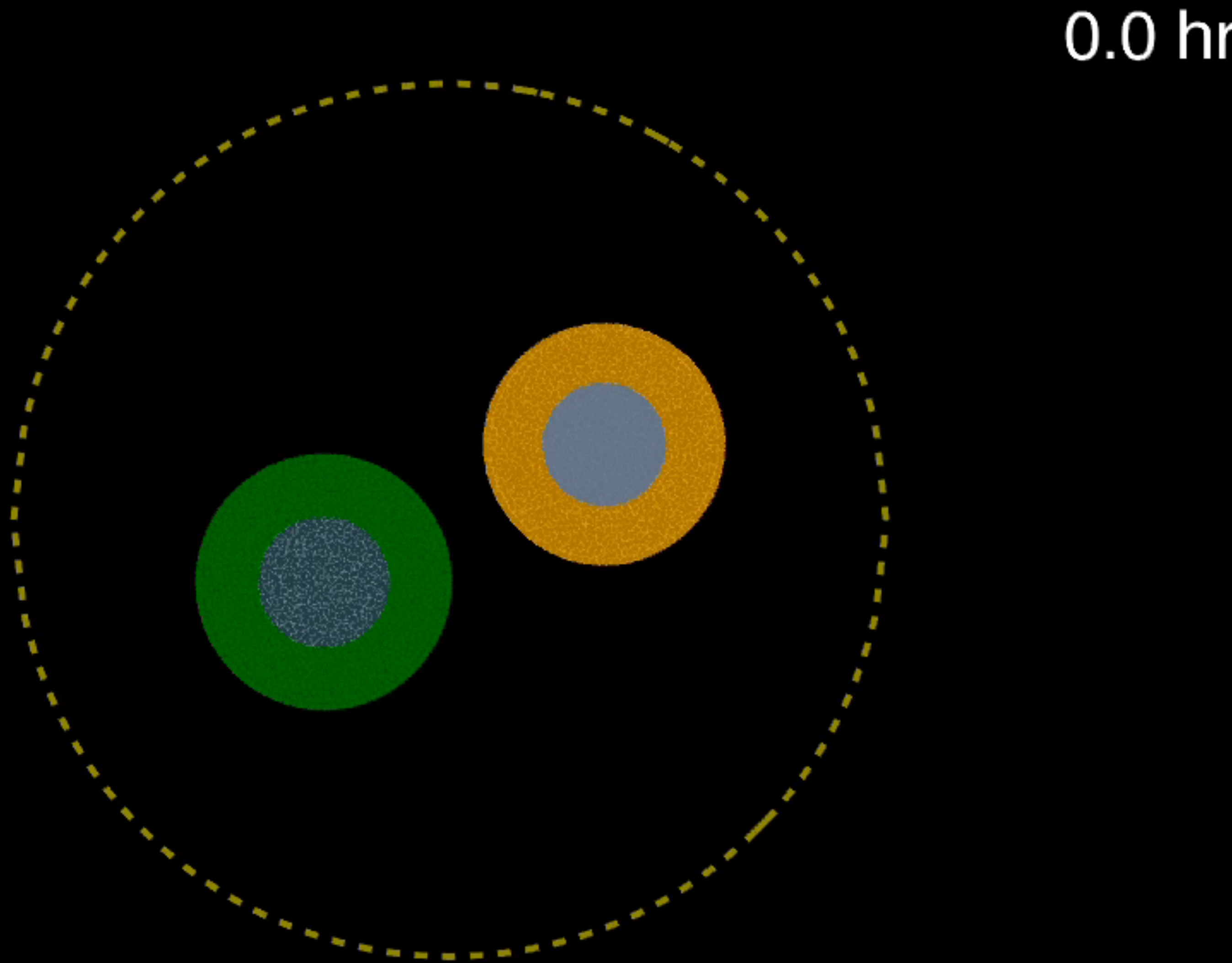
New experimental techniques to measure states of the liquid-vapor curve

Impact-induced vaporization is a common process during planet formation.

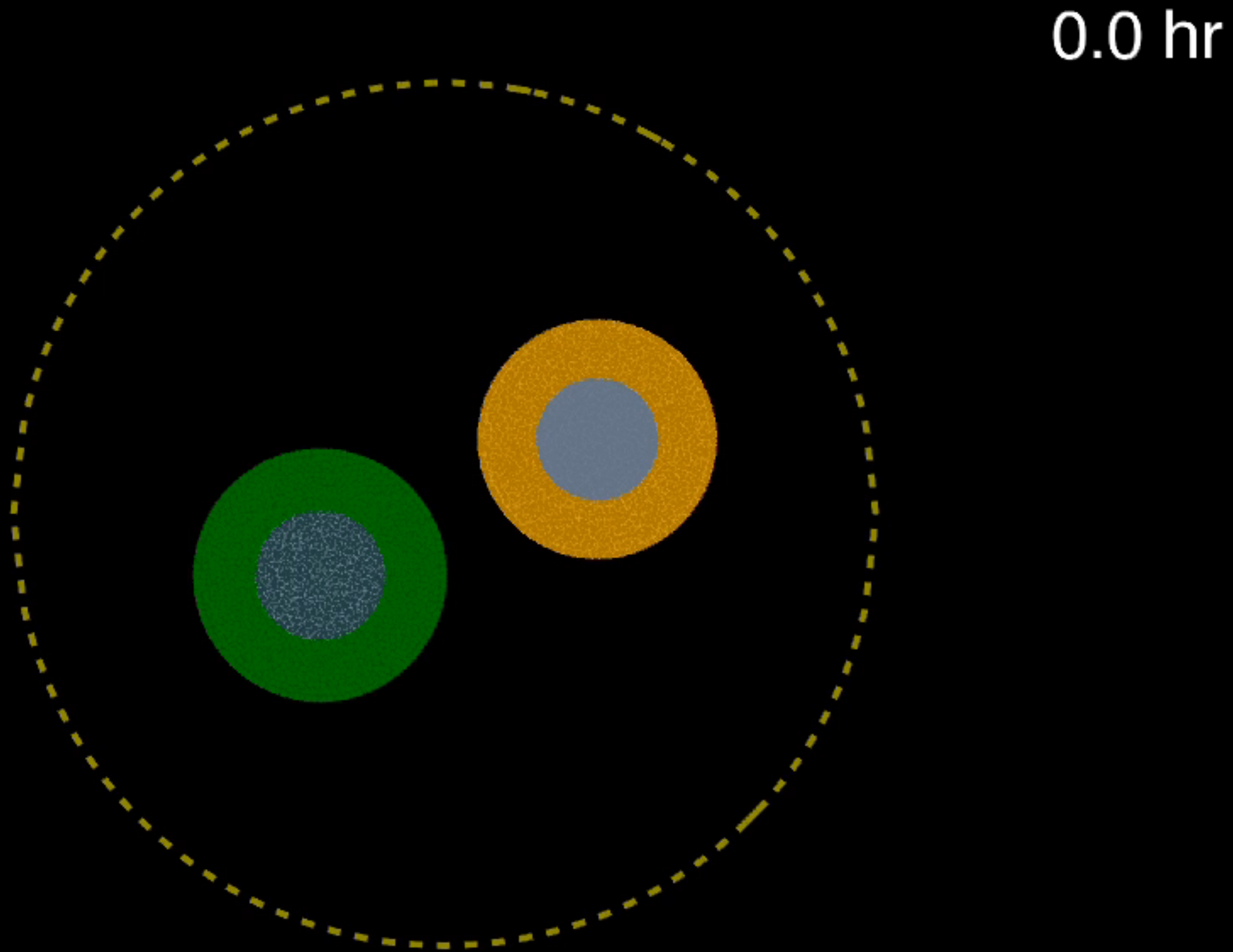
What was the physical state of the Earth and Lunar Disk?



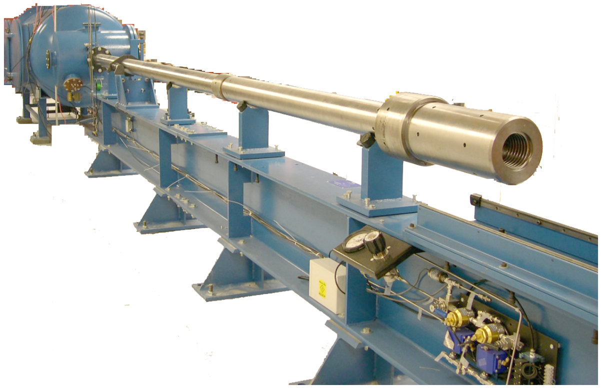




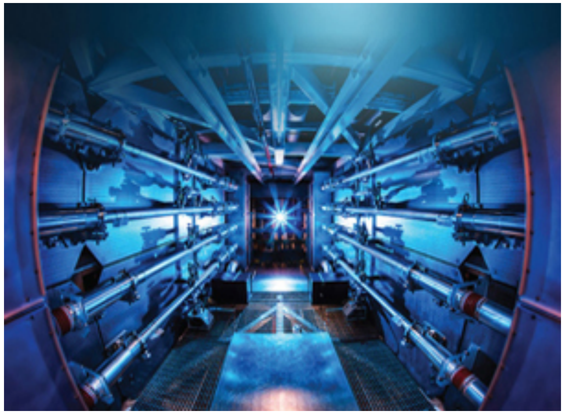
Collision of 2 half-Earths (Canup 2012)


0.0 hr

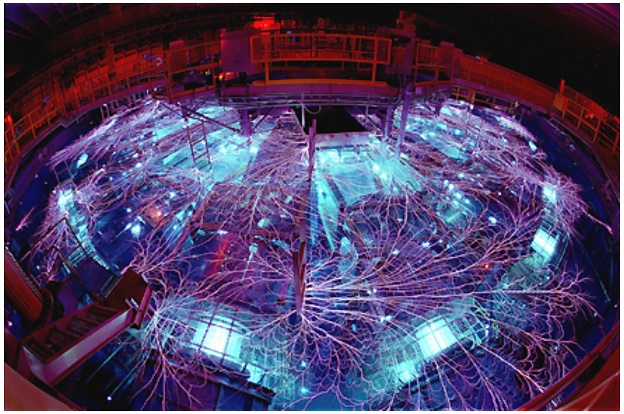
Reaching the Extremes of Planet Formation



Gas Guns



LLNL NIF Laser



Sandia Z Machine

View on Oct 30 by
Chang’e 4 spacecraft

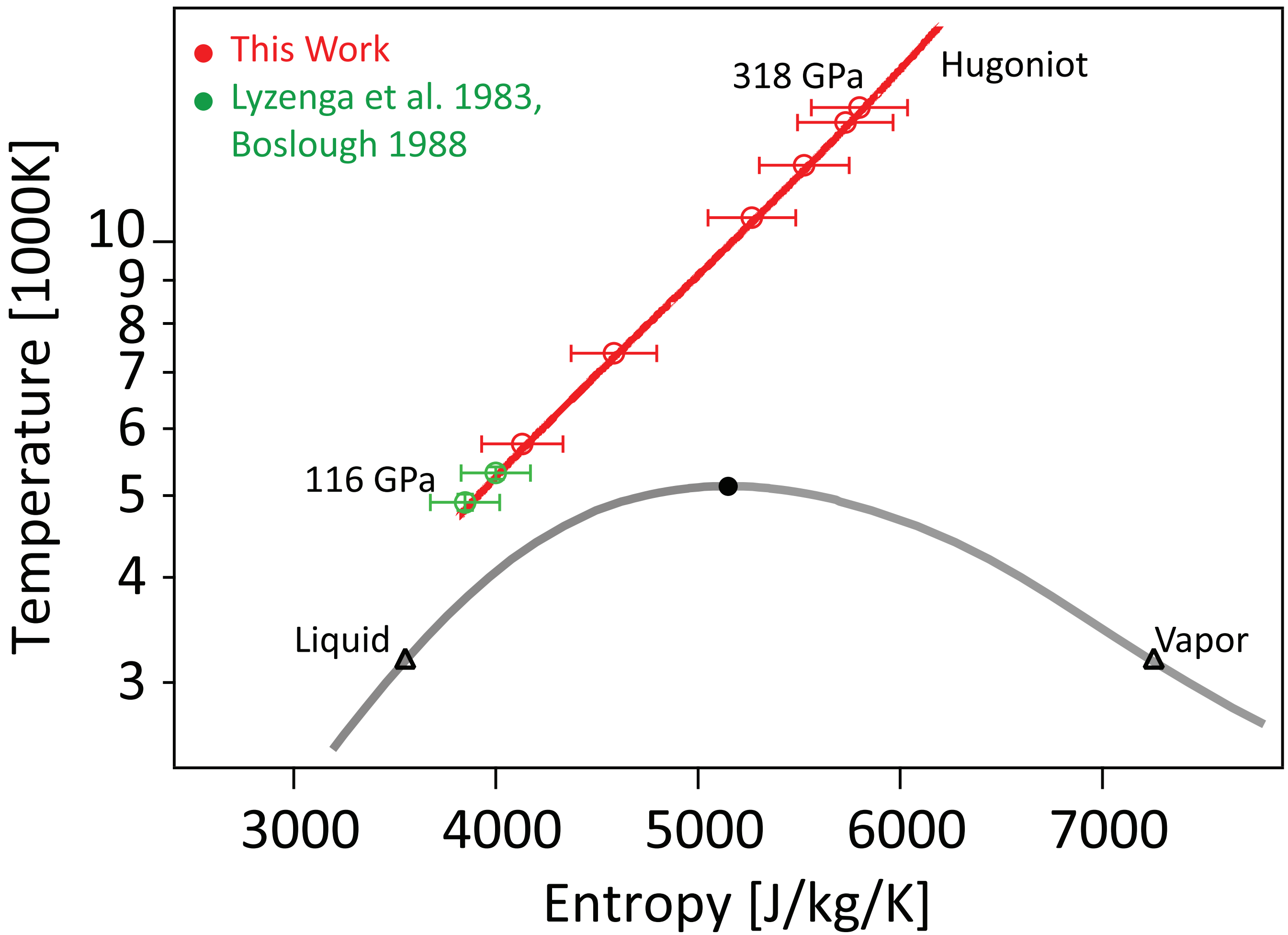
Shock-and-Release Temperature Measurements

LLNL Jupiter Laser Facility User Program and NNSA SSGF

R. G. Kraus, S. T. Stewart, D. C. Swift, C. A. Bolme, R. F. Smith, S. Hamel, B. D. Hammel, D. K. Spaulding, D. G. Hicks, J. H. Eggert, and G. W. Collins

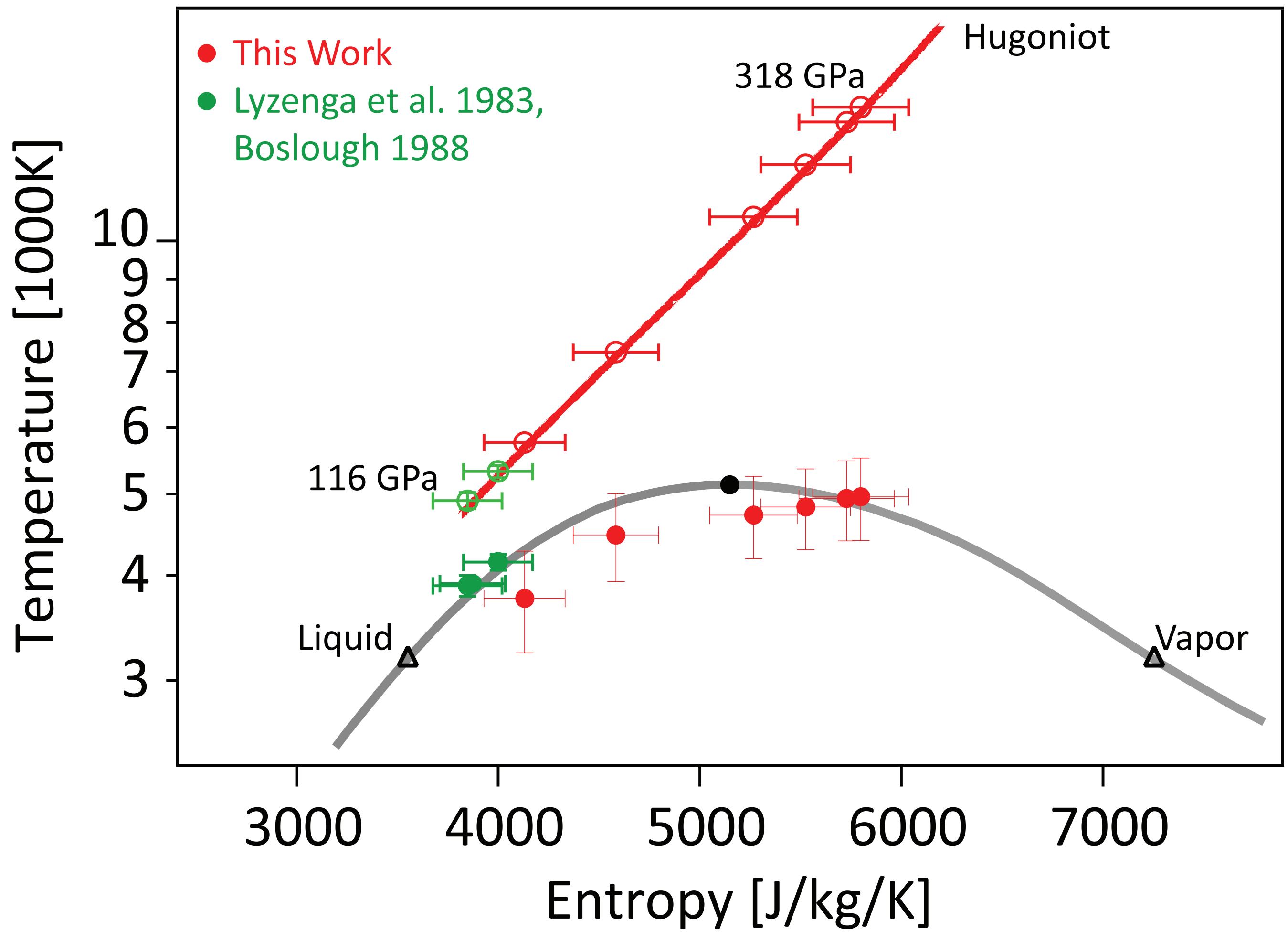
J. Geophysical Research Planets, 2012

Quartz Shock Vaporization Experiments



Kraus et al. 2012

Quartz Shock Vaporization Experiments



Kraus et al. 2012

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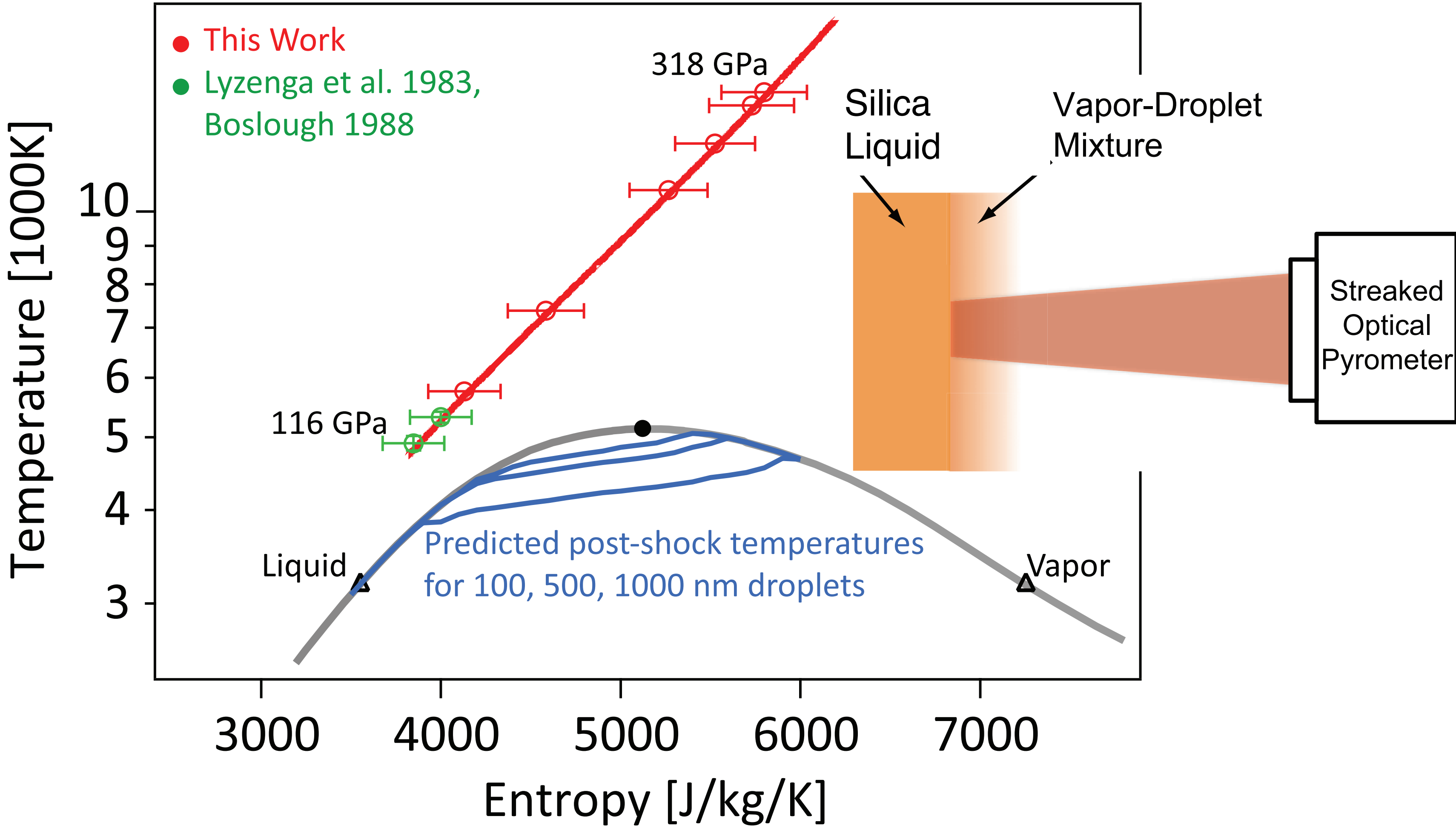
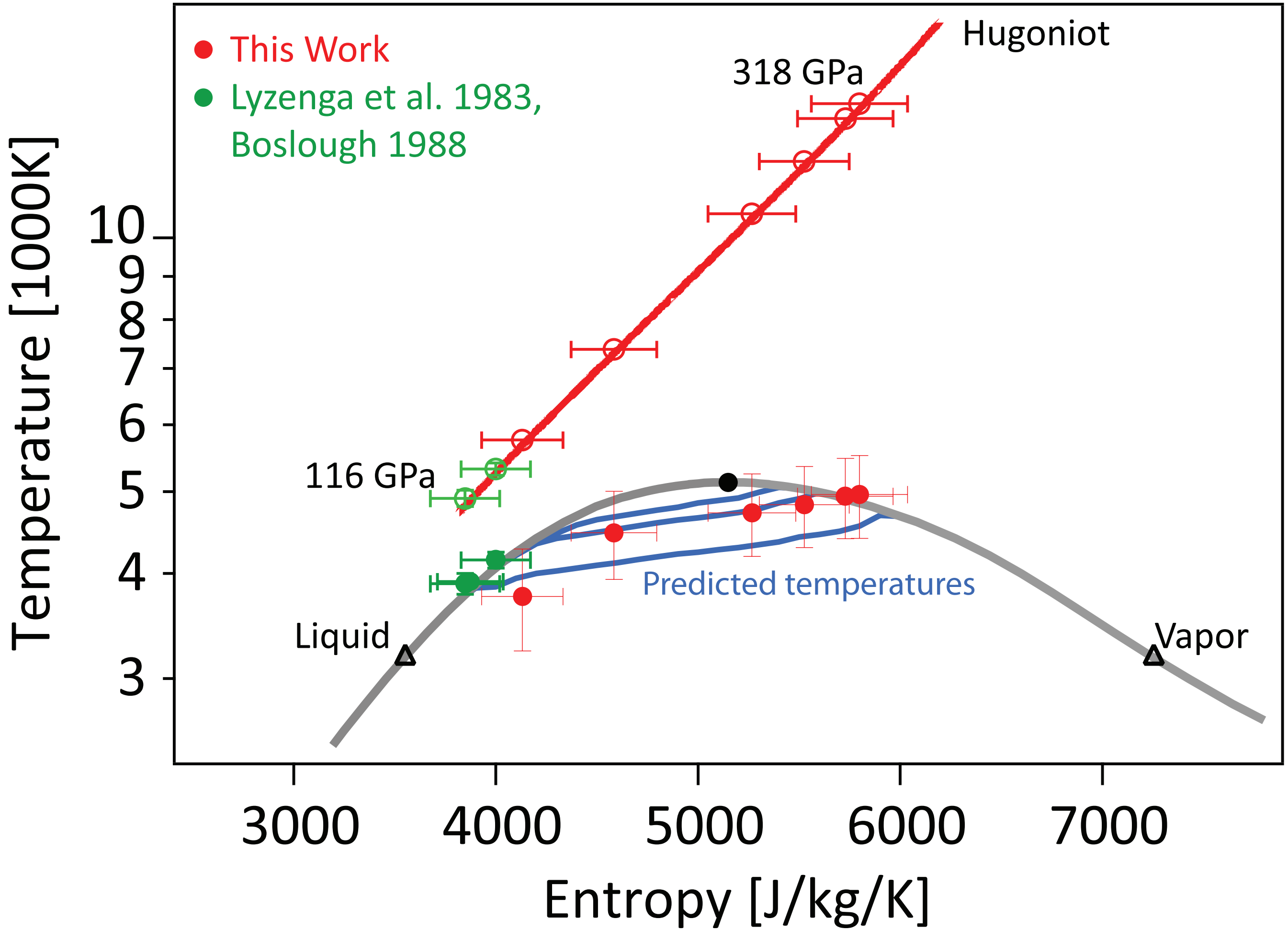


Kraus et al. 2012

Quartz Shock Vaporization Experiments



Critical point for SiO_2: 5130 K and 0.13 Gpa
Impact-induced vaporization starts at 7 km/s

Kraus et al. 2012