# Following the Multicomponent Phase Diagram to the Origin of the Moon

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# Acknowledgements

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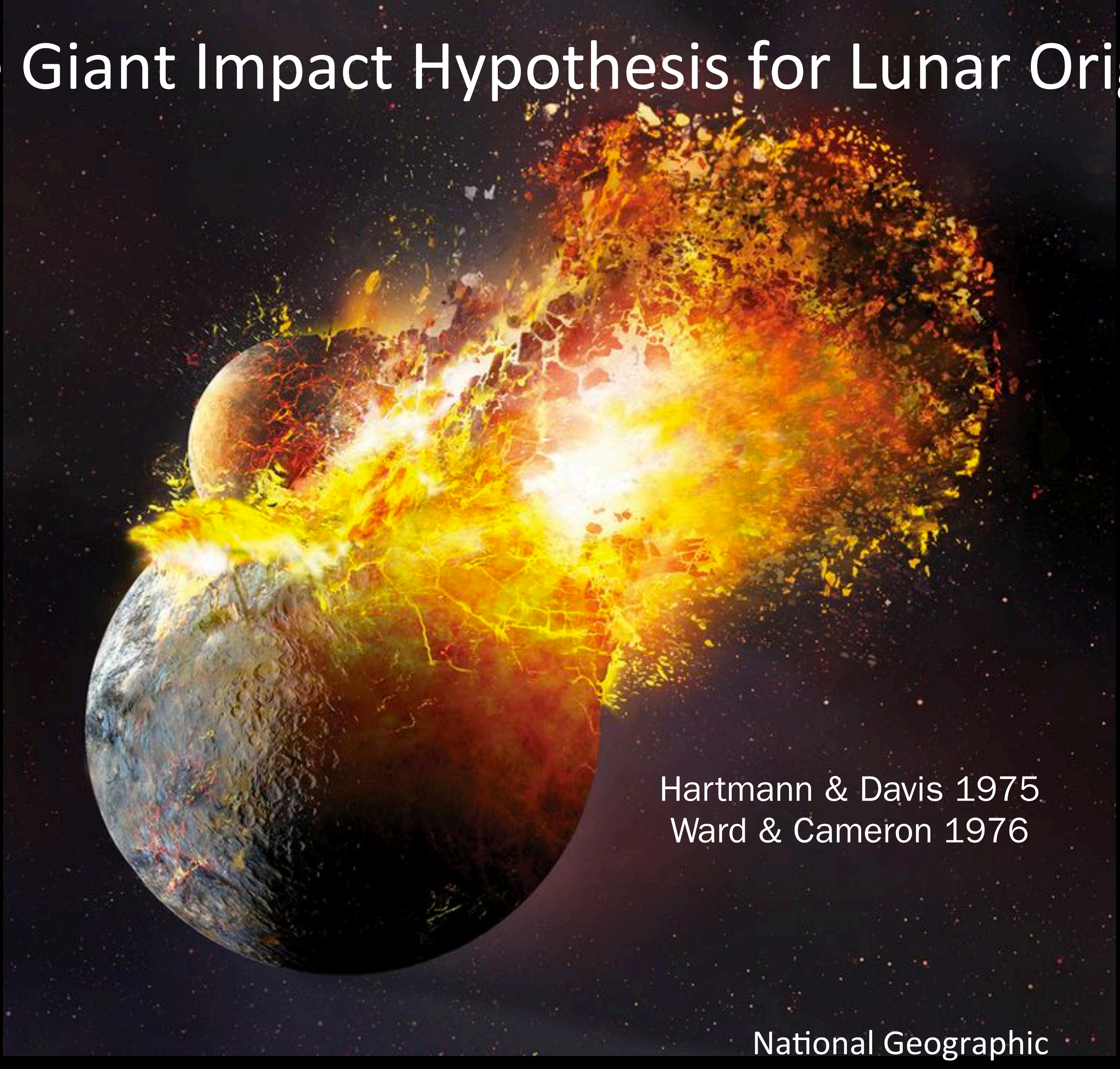
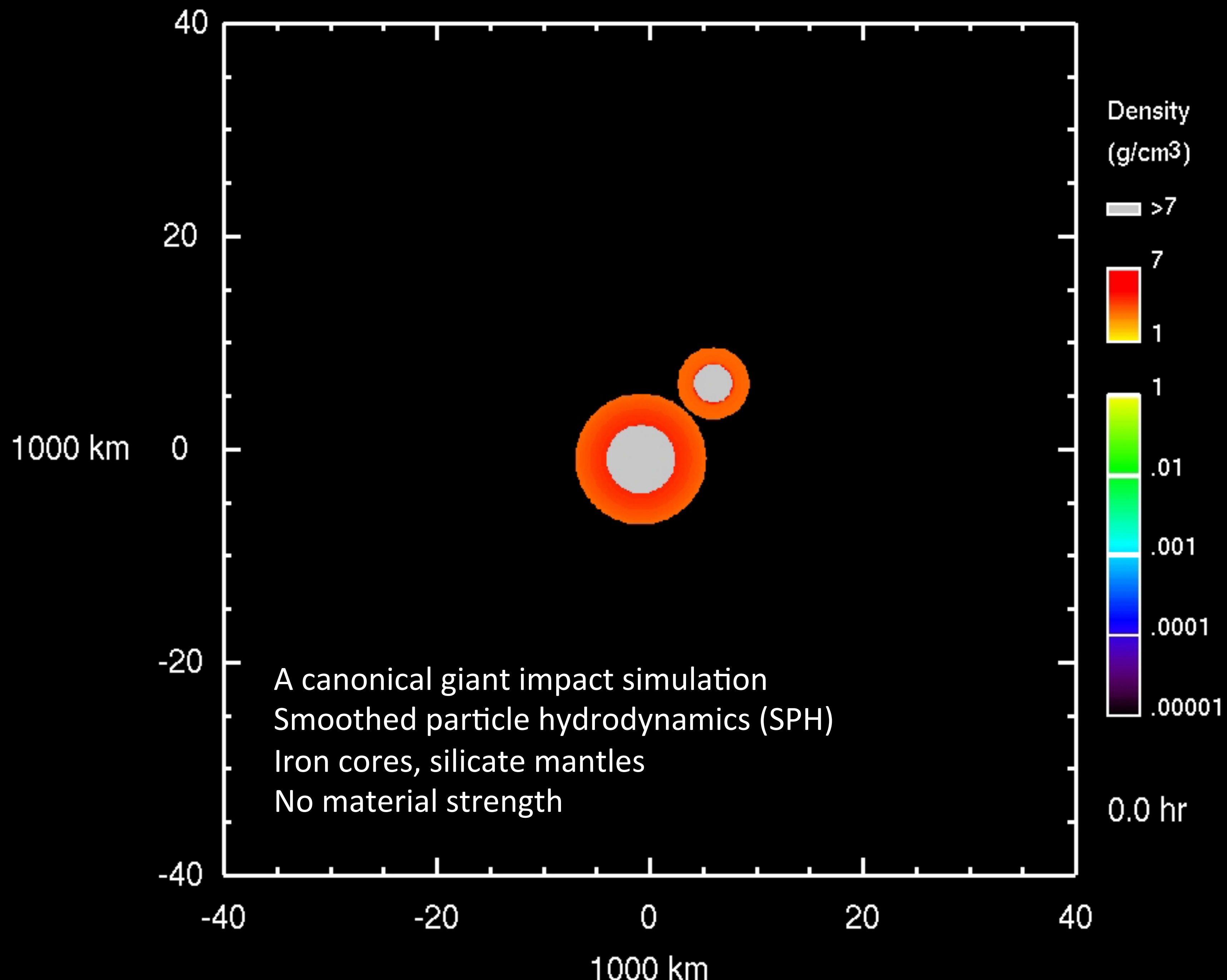
References

Simon J. Lock & Sarah T. Stewart, The structure of terrestrial bodies: Impact heating, corotation limits and synestias, J. Geophysical Research Planets, in press

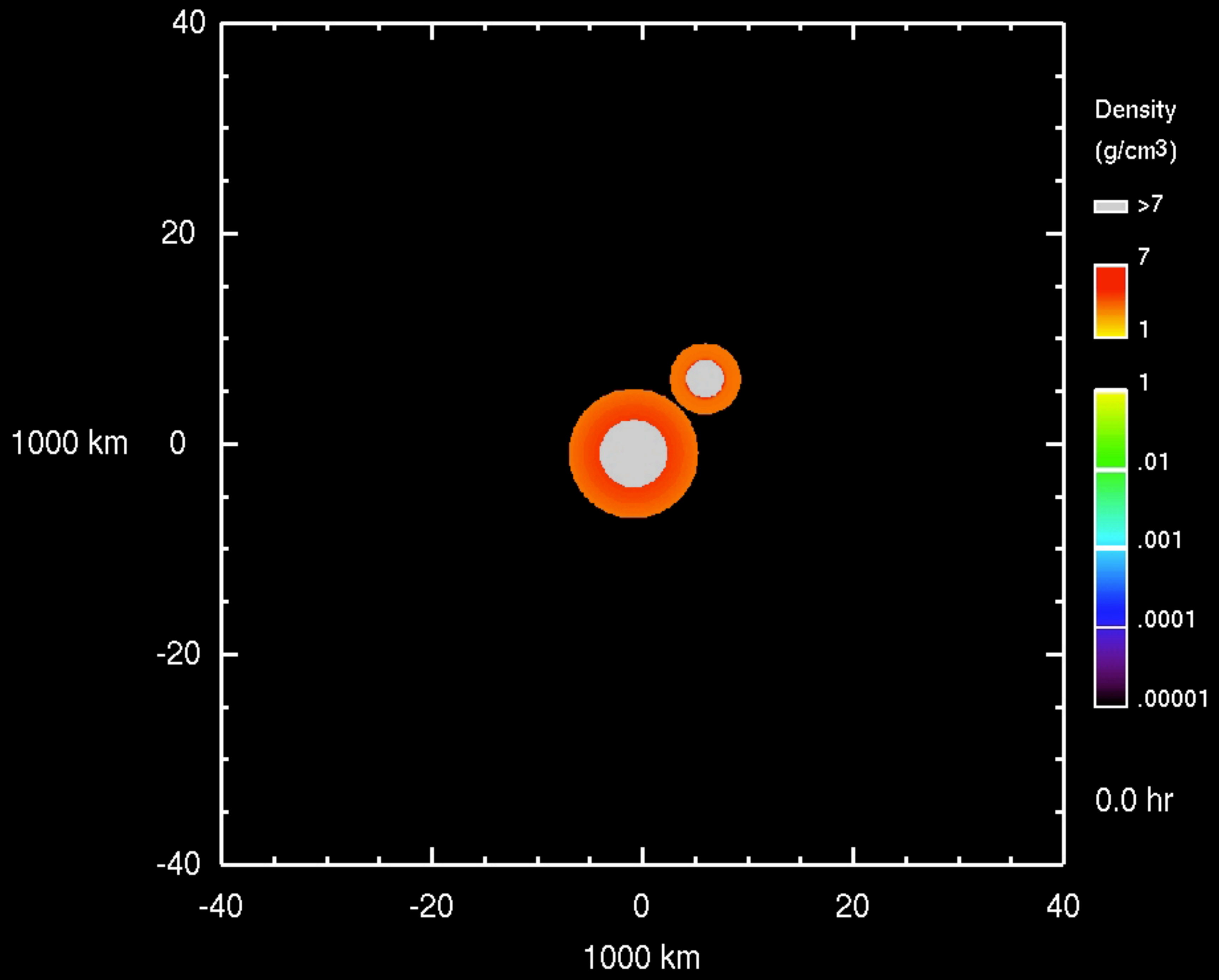
Simon J. Lock, Sarah T. Stewart, Michail I. Petaev, Zöe M. Leinhardt, Mia T. Mace, Stein B. Jacobsen, Matija Cuk, The origin of the Moon within a terrestrial synestia, J. Geophysical Research Planets, submitted

# The Giant Impact Hypothesis for Lunar Origin





Density
(g/cm3)
>7
7
1
1
.01
.001
.0001
.00001
0.0 hr
A canonical giant impact simulation
Smoothed particle hydrodynamics (SPH)
Iron cores, silicate mantles
No material strength
40
20
0
-20
-40
1000 km
-40
-20
0
20
40
1000 km



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.01
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0.0 hr
40
20
0
-20
-40
1000 km
-40
-20
0
20
40
1000 km

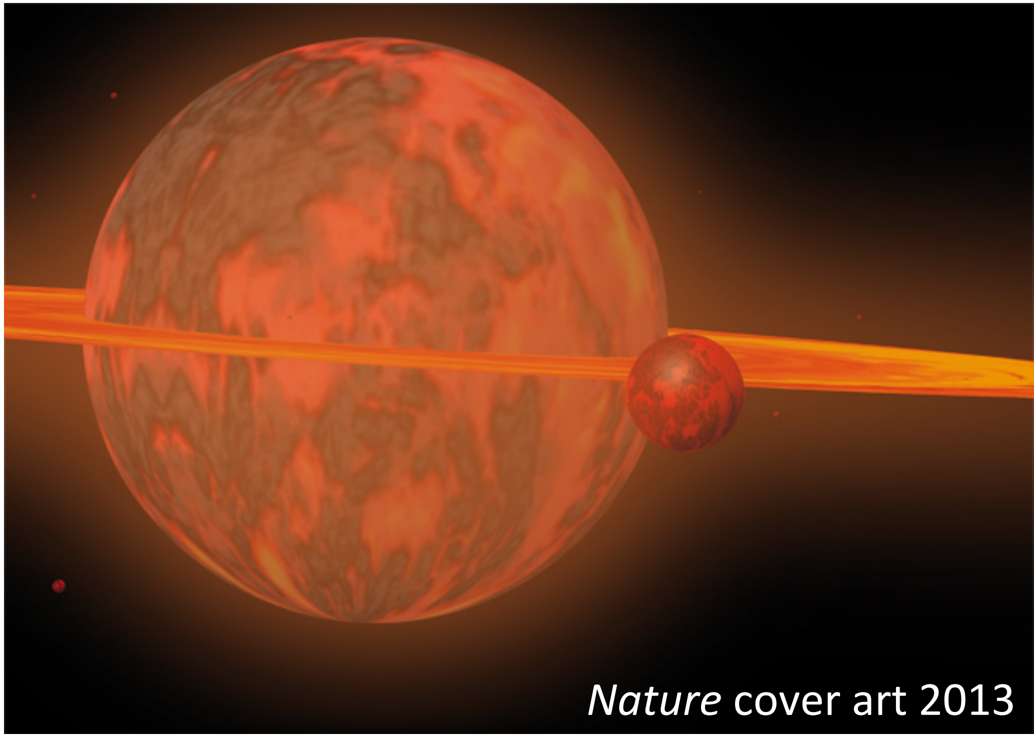
# Lunar Accretion from a Circumterrestrial Disk

Calculated moons are small. Hard to make lunar mass satellite from mixed phase disk.

(Salmon & Canup 2012, 2014)

Poorly understood physics in a vapor-rich disk.

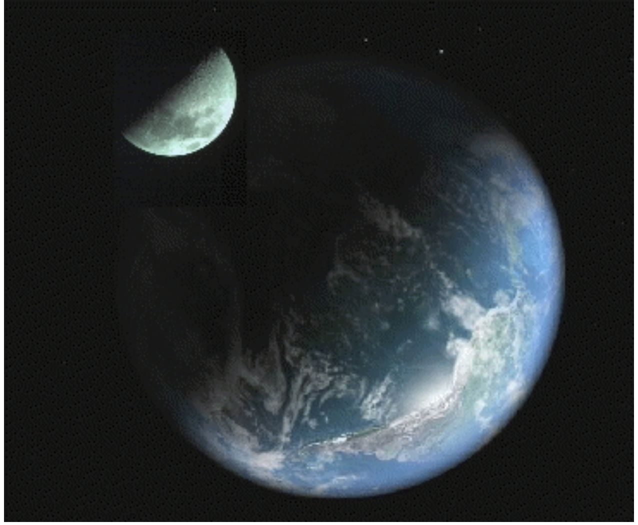
(Charnoz & Michaut 2015)




Misleading artist drawing!!

Disk is made mostly of impactor material.

# Earth and Moon are Isotopic Twins



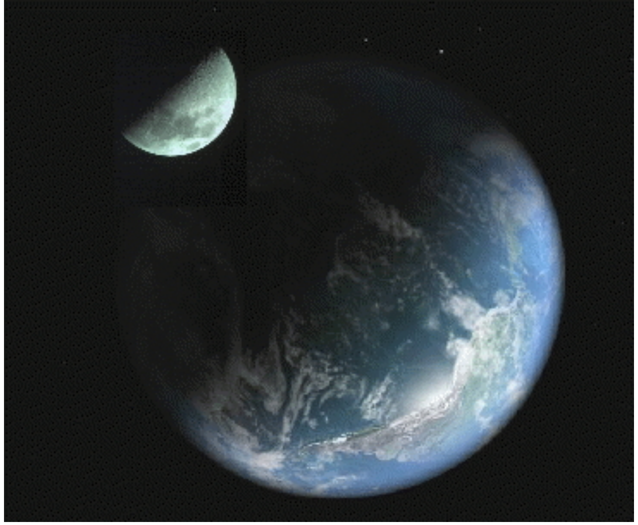
(Nearly) Identical Isotopes

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

Each planetary body has a different isotopic thumbprint*.

Lugmair & Shukolyukov 1998, Wiechert et al. 2001, Georg et al. 2007, Zhang et al. 2011, Saal et al. 2013
W: Touboul et al. 2015, Kruijer et al. 2015 *Dauphas et al. 2014, Dauphas 2017

# Earth and Moon are Isotopic Twins



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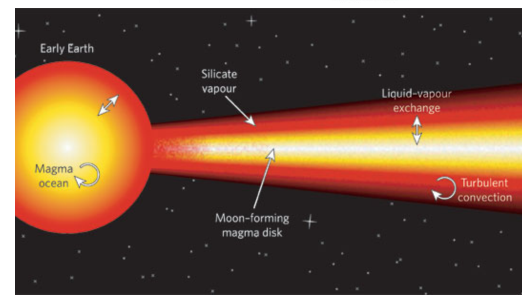
| W | radiogenic (8.9 Ma), core formation |

Minimalist interpretation:
Earth and the Moon are derived from the same material.

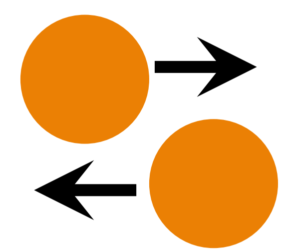
# Giant Impact Hypothesis in Crisis: Proposed Solutions

Enstatite chondrites

1. Impactor had same isotopes
   (Dauphas et al. 2014 but Dauphas 2017)




2. Mix after the impact
   (Pahlevan & Stevenson 2007 but Melosh 2014)



3. Mix during the impact
   with high angular momentum events
   (Ćuk & Stewart 2012; Canup 2012 but too special?)


4. The giant impact hypothesis is wrong
   (includes multiple moon hypothesis, Rufu et al. 2017)

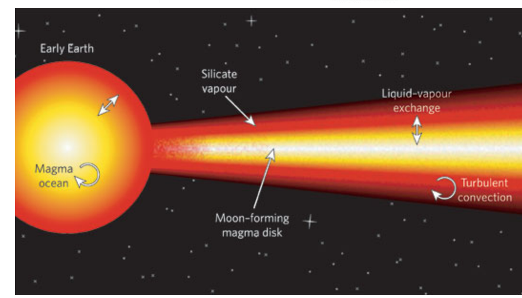
# Giant Impact Hypothesis in Crisis:

## New Solution (Lock et al., in review)

1. Impactor had same isotopes

Enstatite chondrites

2. Mix after the impact




3. Mix during the impact
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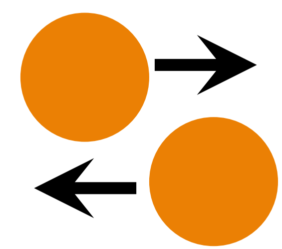
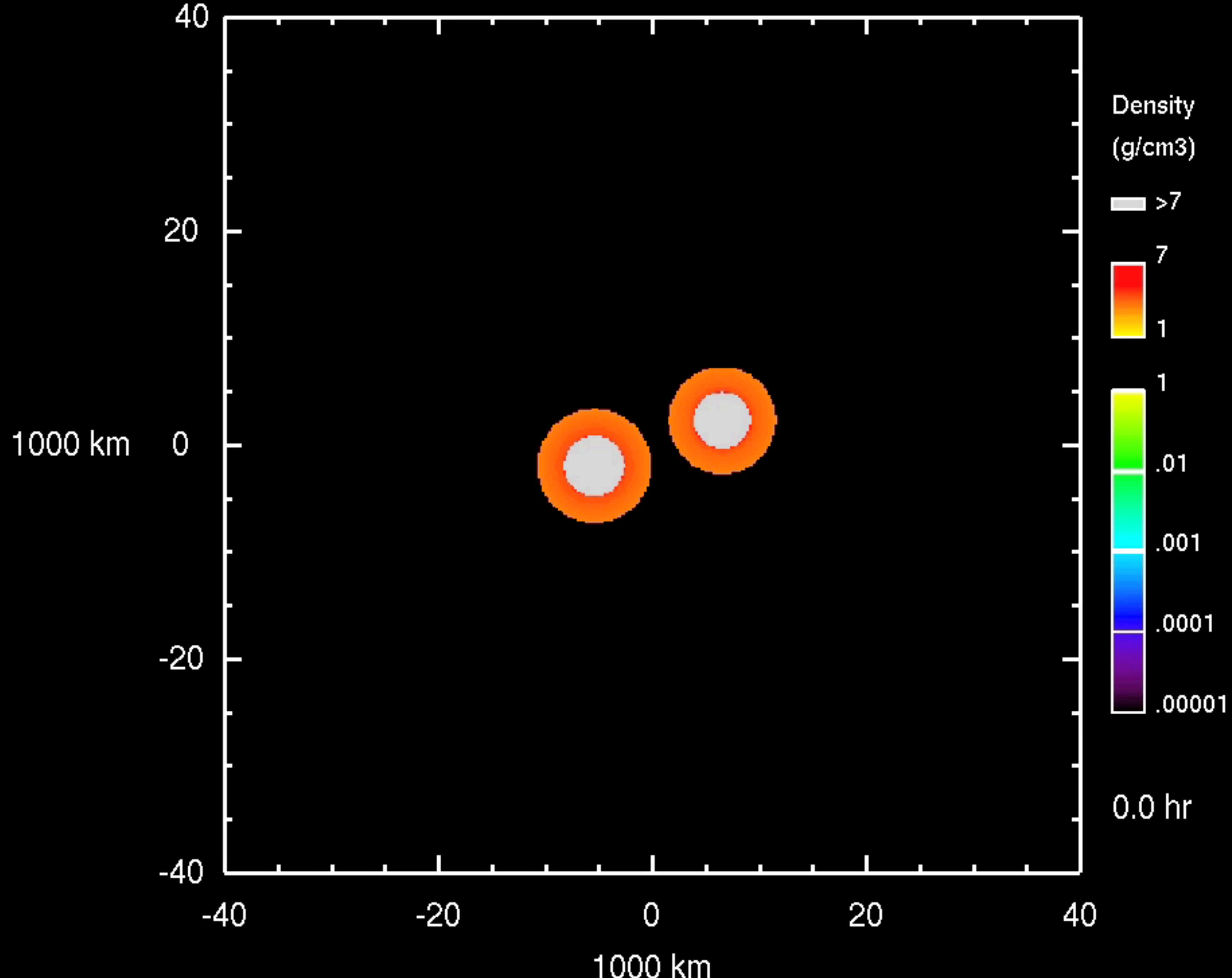


4. The giant impact hypothesis is wrong

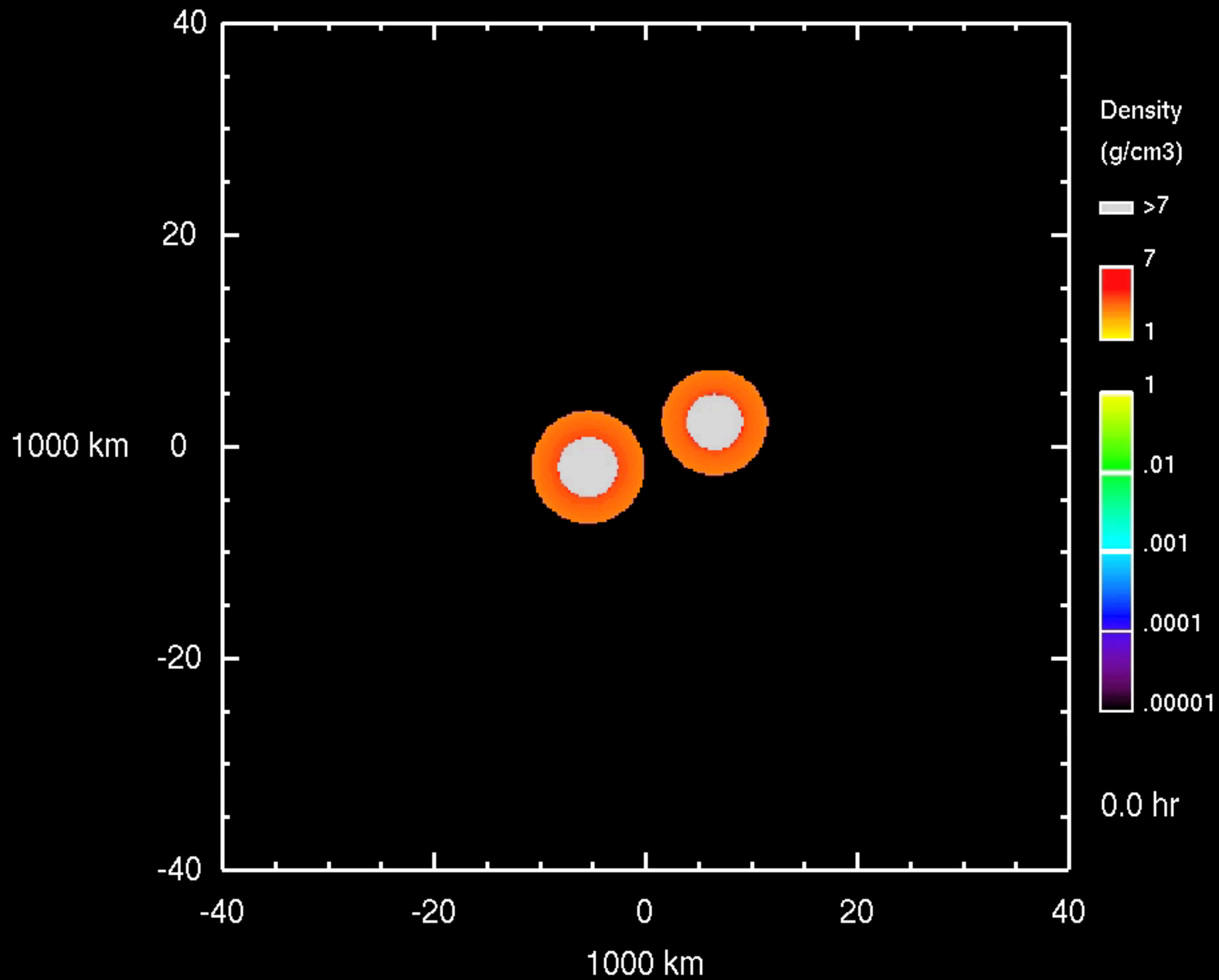
# A High-Energy, High-Angular-Momentum Giant Impact Makes a Hot, Fast-spinning Structure

?

What does it looks like?



40
20
0
-20
-40
1000 km
-40
-20
0
20
40
1000 km
Density
(g/cm3)
>7
7
1
1
.01
.001
.0001
.00001
0.0 hr



40
20
0
-20
-40
1000 km
-40
-20
0
20
40
1000 km
Density
(g/cm3)
>7
7
1
1
.01
.001
.0001
.00001
0.0 hr

# The Structure of Hot, Spinning Rocky Planets
# Numerically solve for the structure

## GADGET2 SPH code

Initialize planets with
- mass of mantle, core
- constant entropy mantle
- total ang. momentum

Solve for equilibrium
- size and shape

Code modified for tabulated EOS
- iron MANEOS core
- forsterite MANEOS mantle

## New HERCULES code

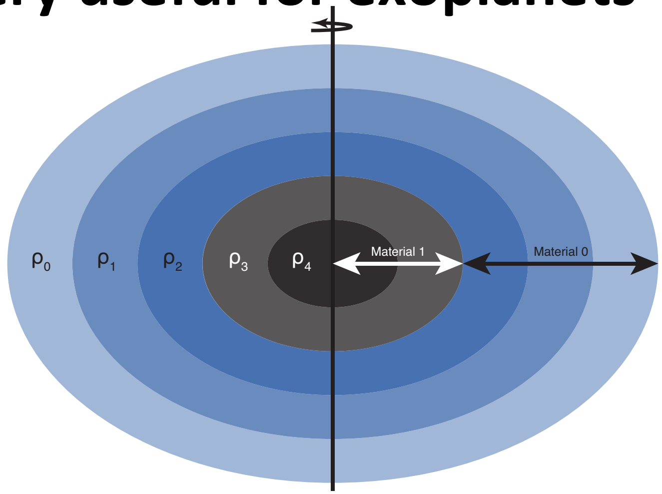
Concentric constant density layers

Iteratively solve for equipotential surfaces

Conserve AM, mass

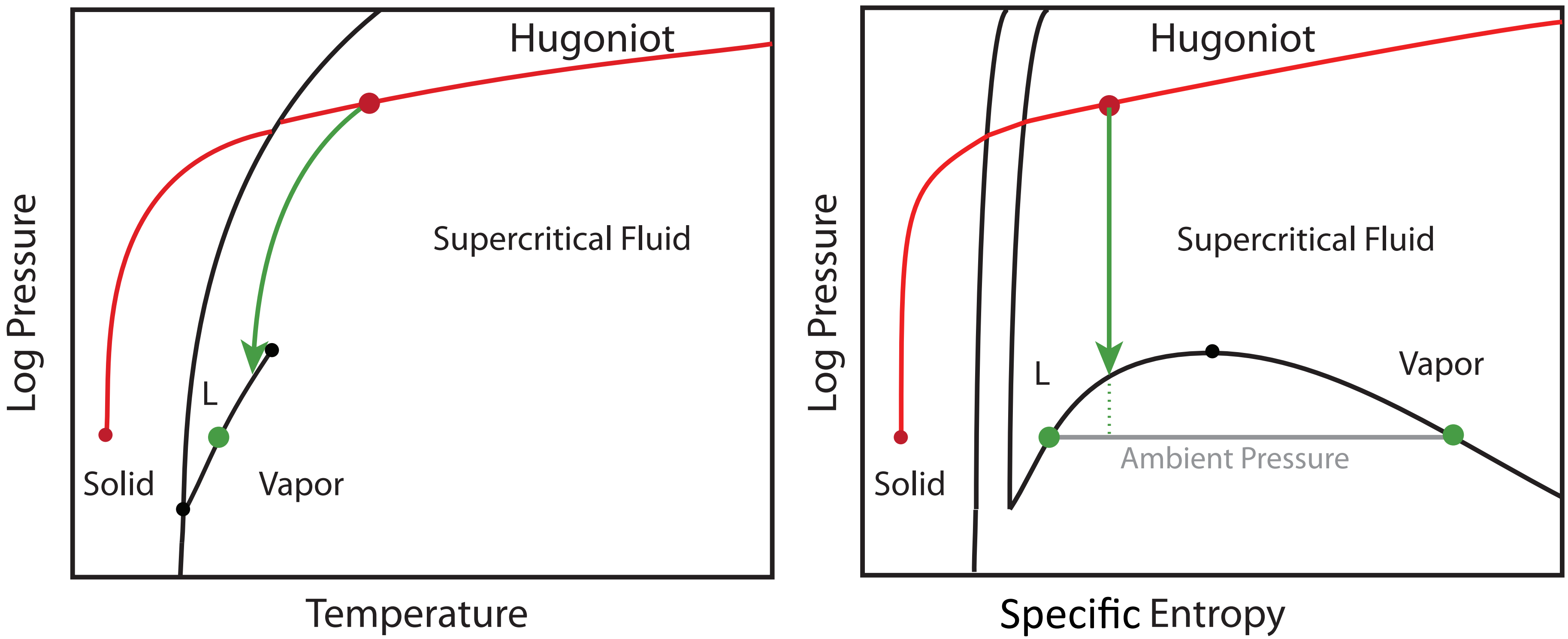
Expanded Hubbard 2013

**Very useful for exoplanets**



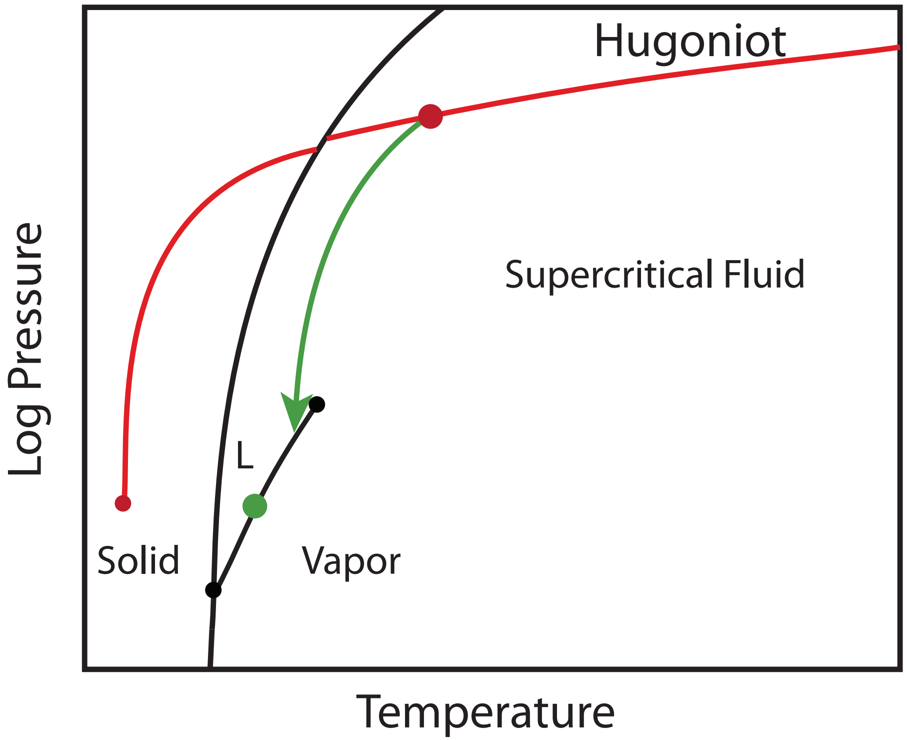

Lock & Stewart, JGR-Planets, in press.

# The Structure of Hot, Spinning Rocky Planets
# Thermodynamics

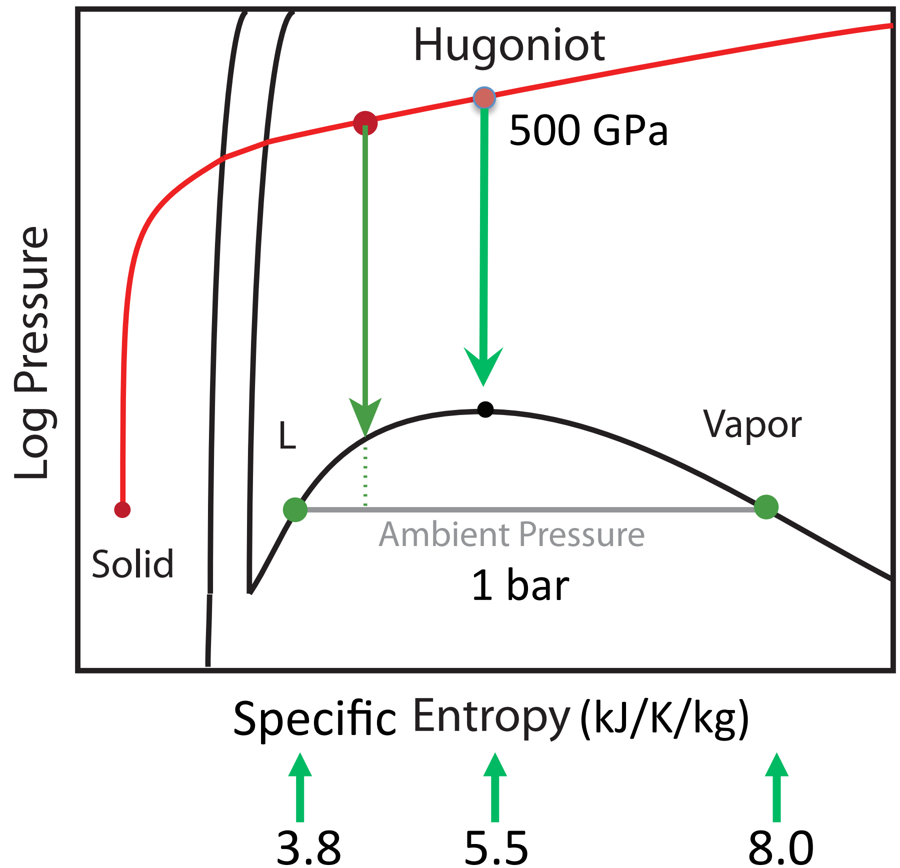



Specific entropy used to designate thermal state.

# The Structure of Hot, Spinning Rocky Planets Thermodynamics




Forsterite EOS for the mantle

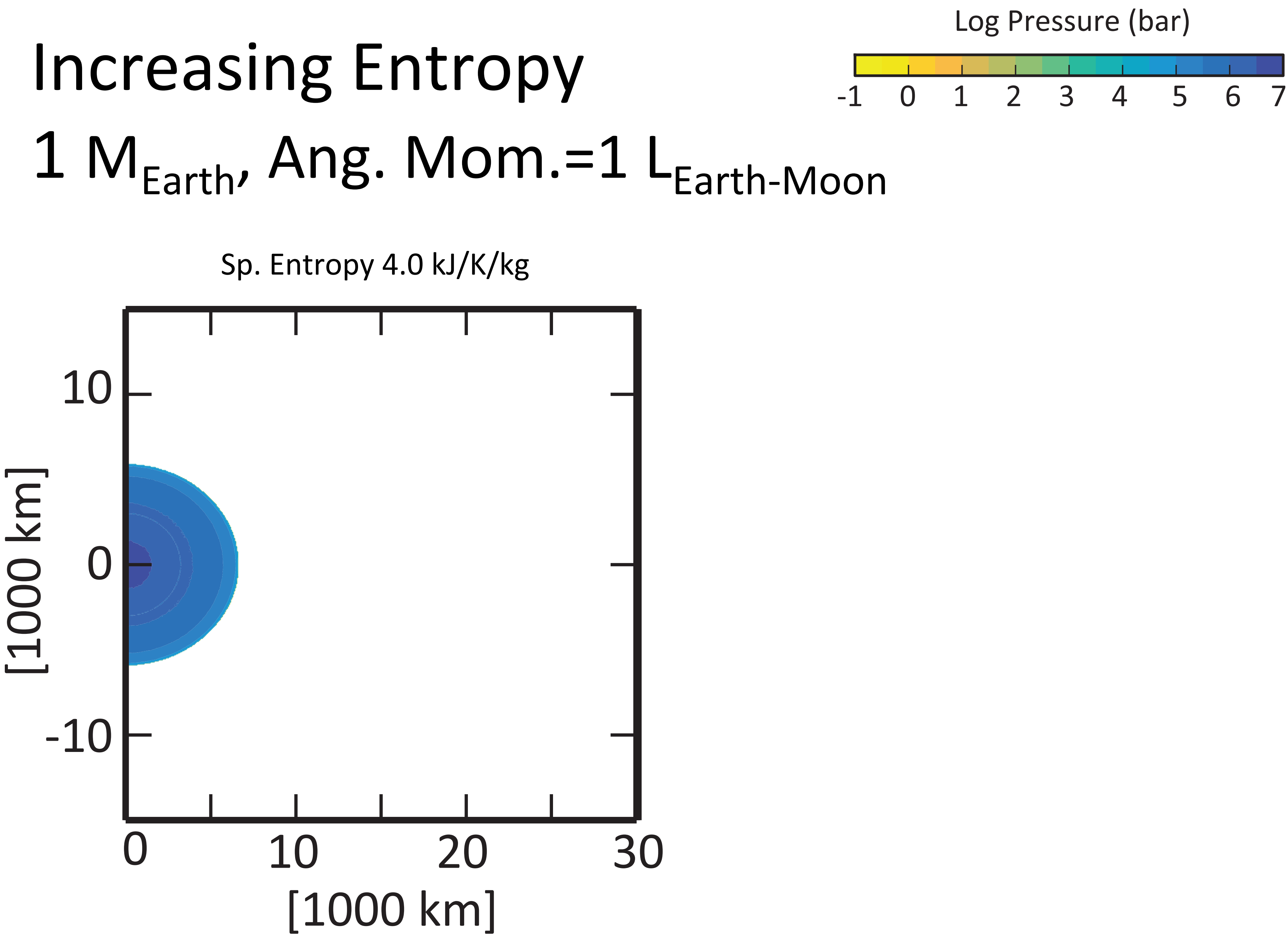



Specific entropy of outer layer of post-impact body is determined by the energy of the impact

Davies et al. LPSC 2017

# Increasing Entropy

## 1 $M_{Earth}$, Ang. Mom.=1 $L_{Earth\text{-}Moon}$



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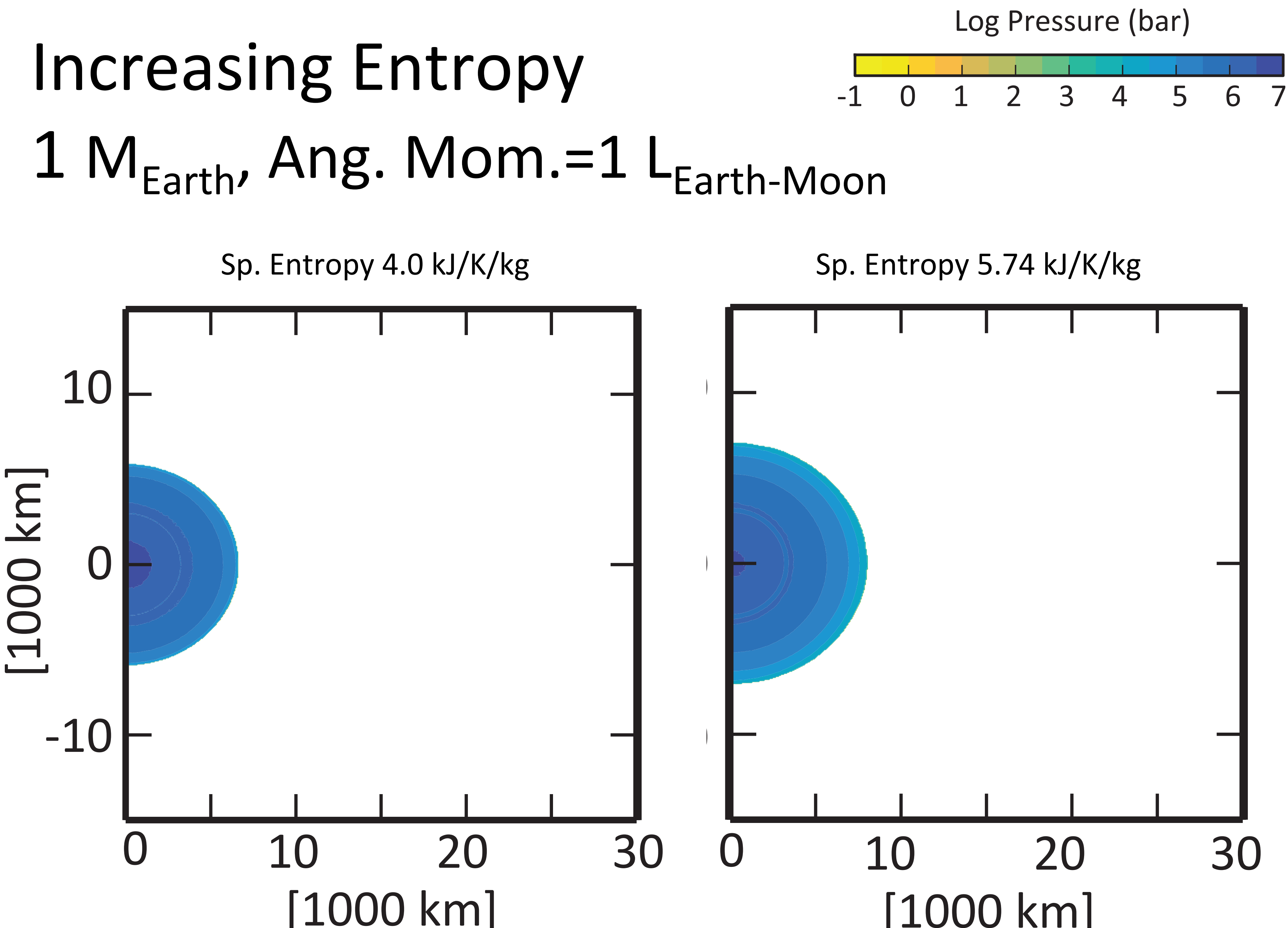

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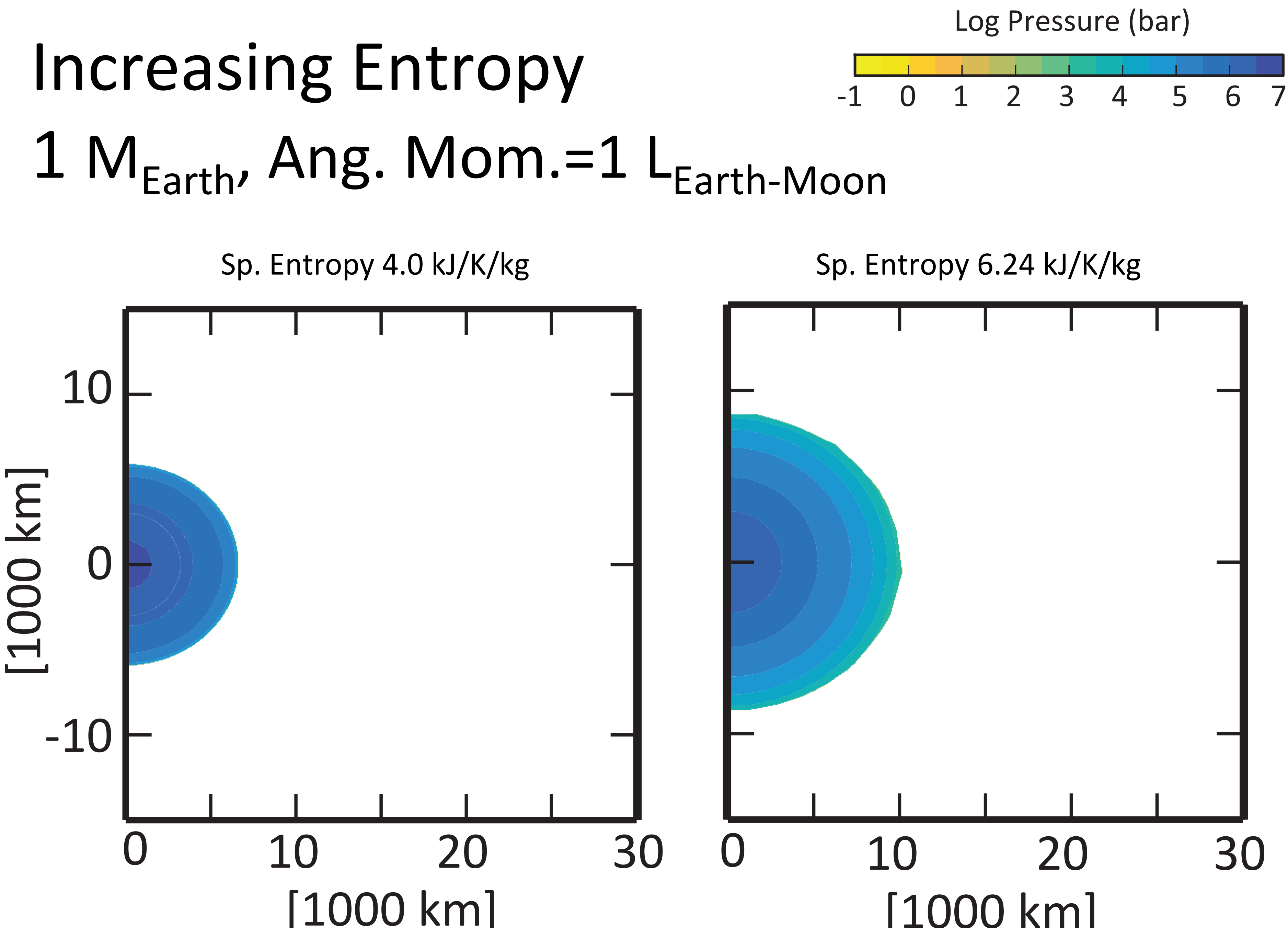
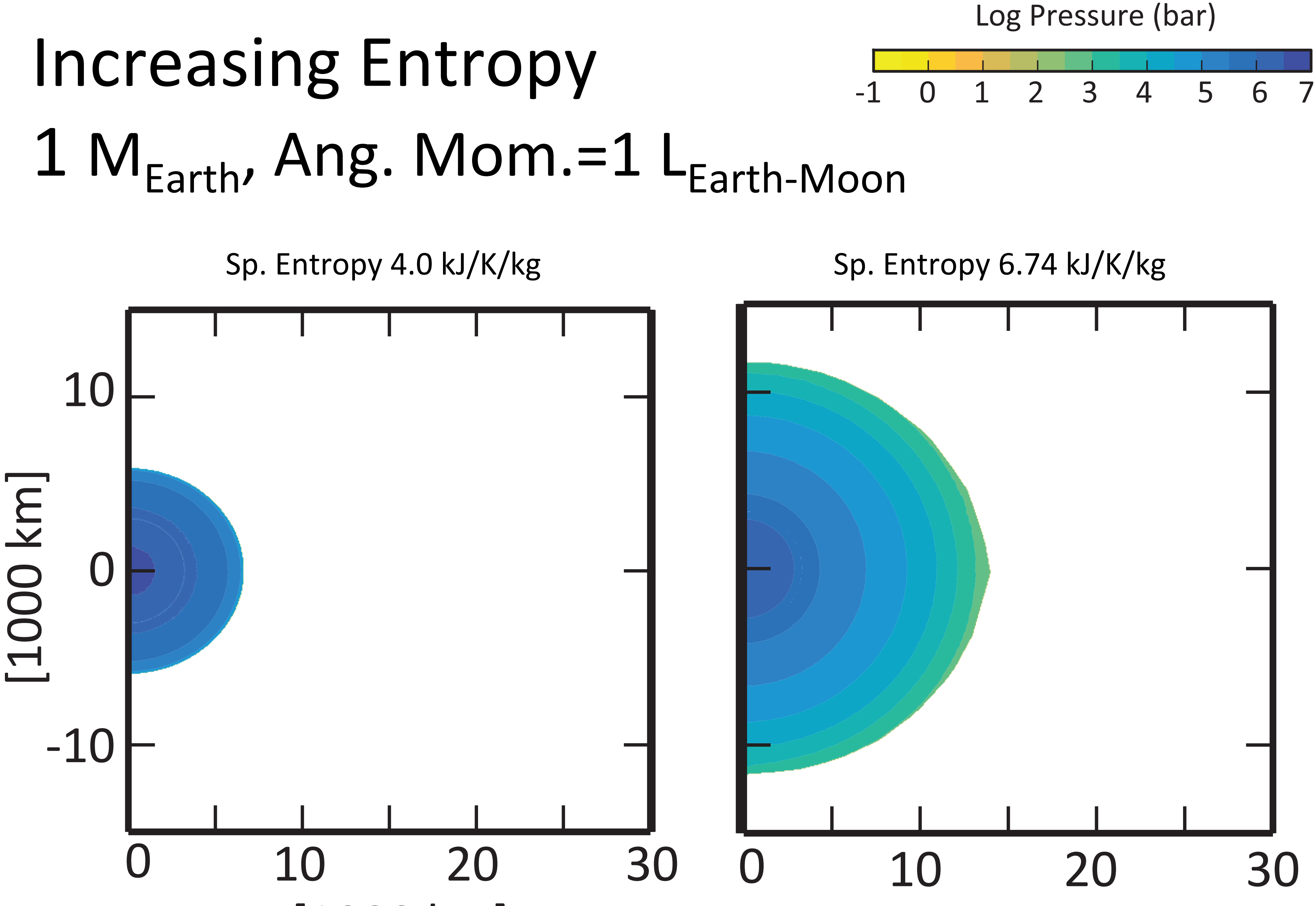


# Increasing Entropy

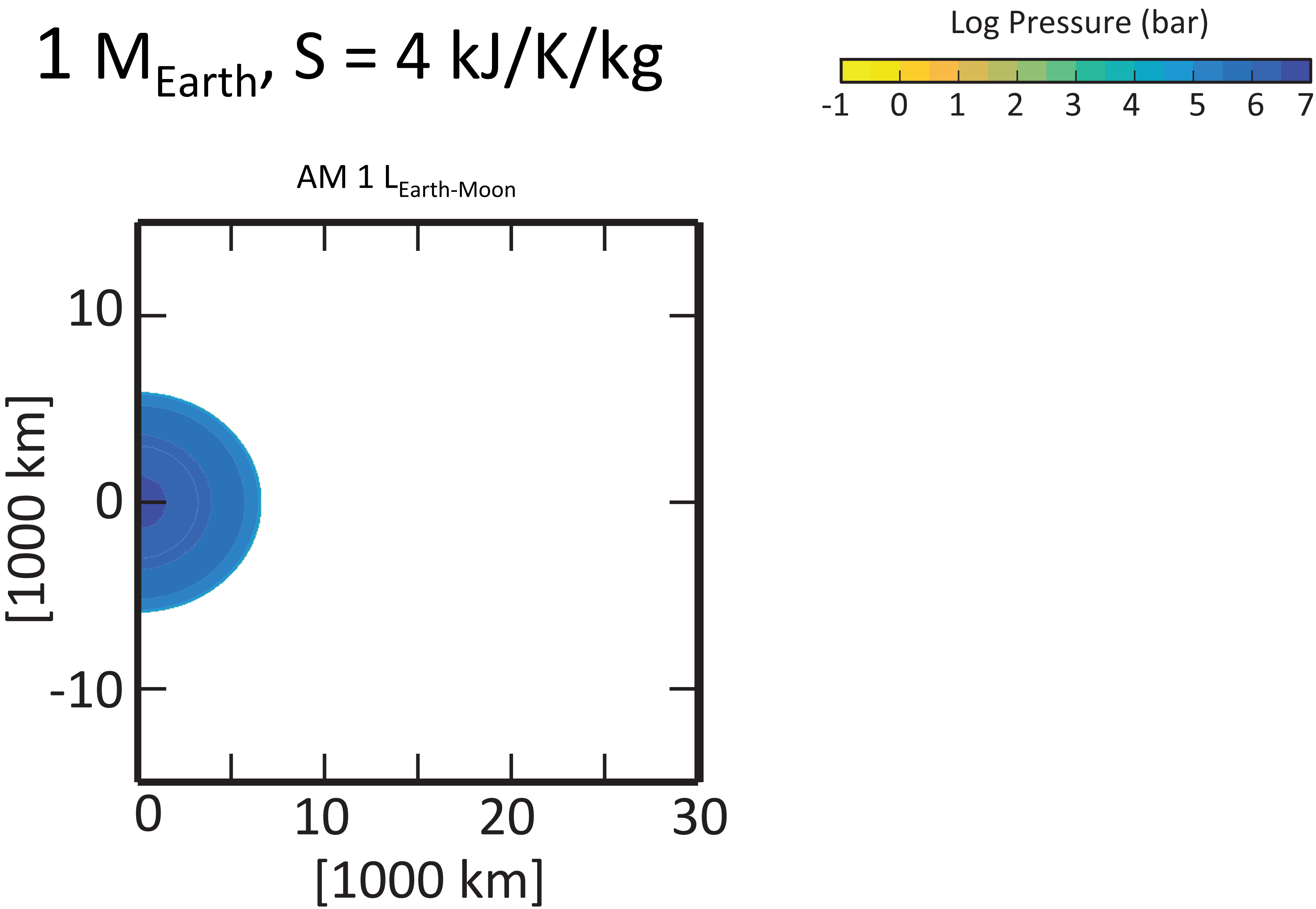
# 1 $M_{Earth}$, Ang. Mom.=1 $L_{Earth-Moon}$




Large radii, low mass exoplanets:
Hot rocky planet or sub-Neptune?

# Increasing Angular Momentum

## 1 $M_{Earth}$, S = 4 kJ/K/kg



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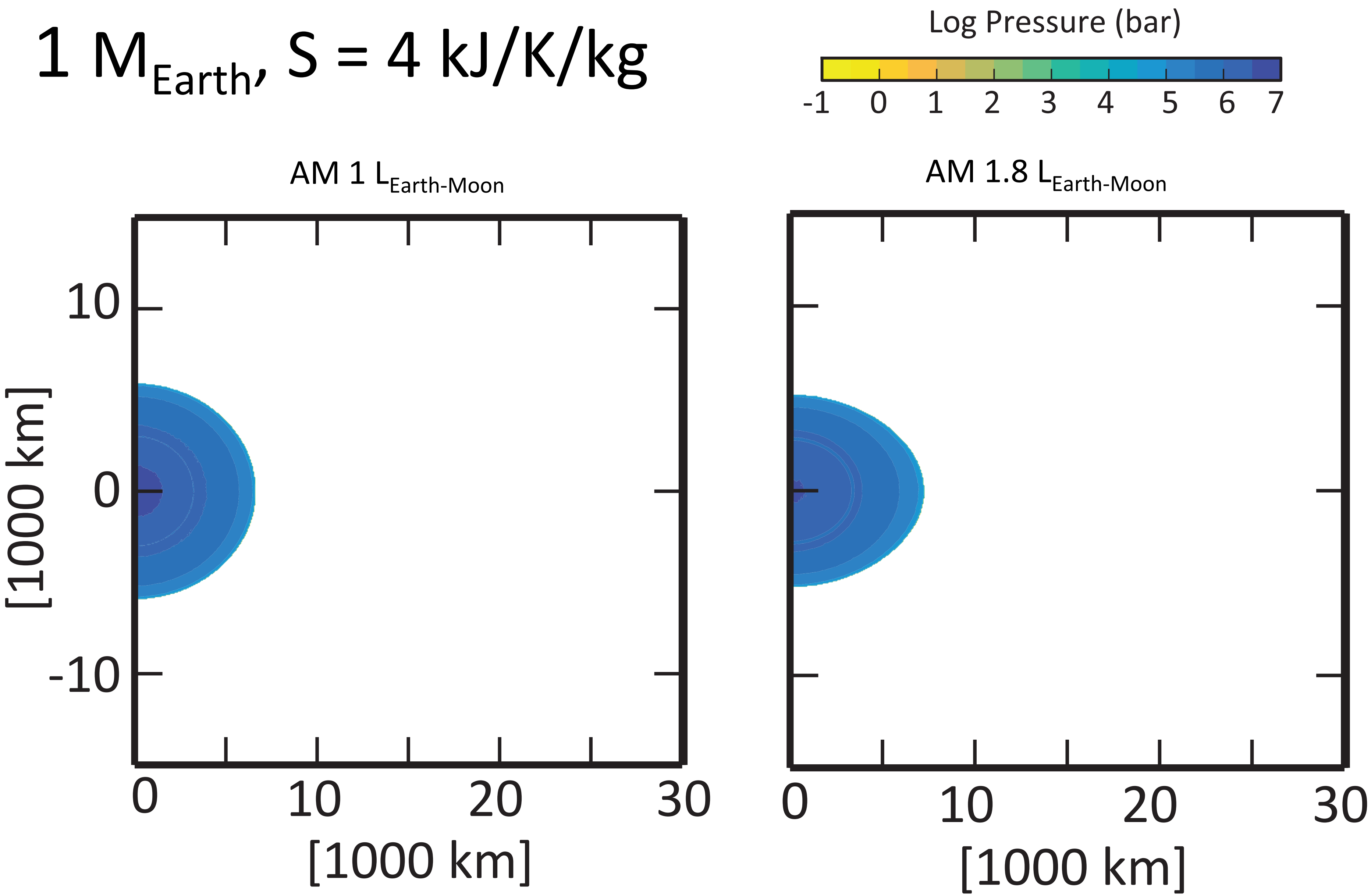

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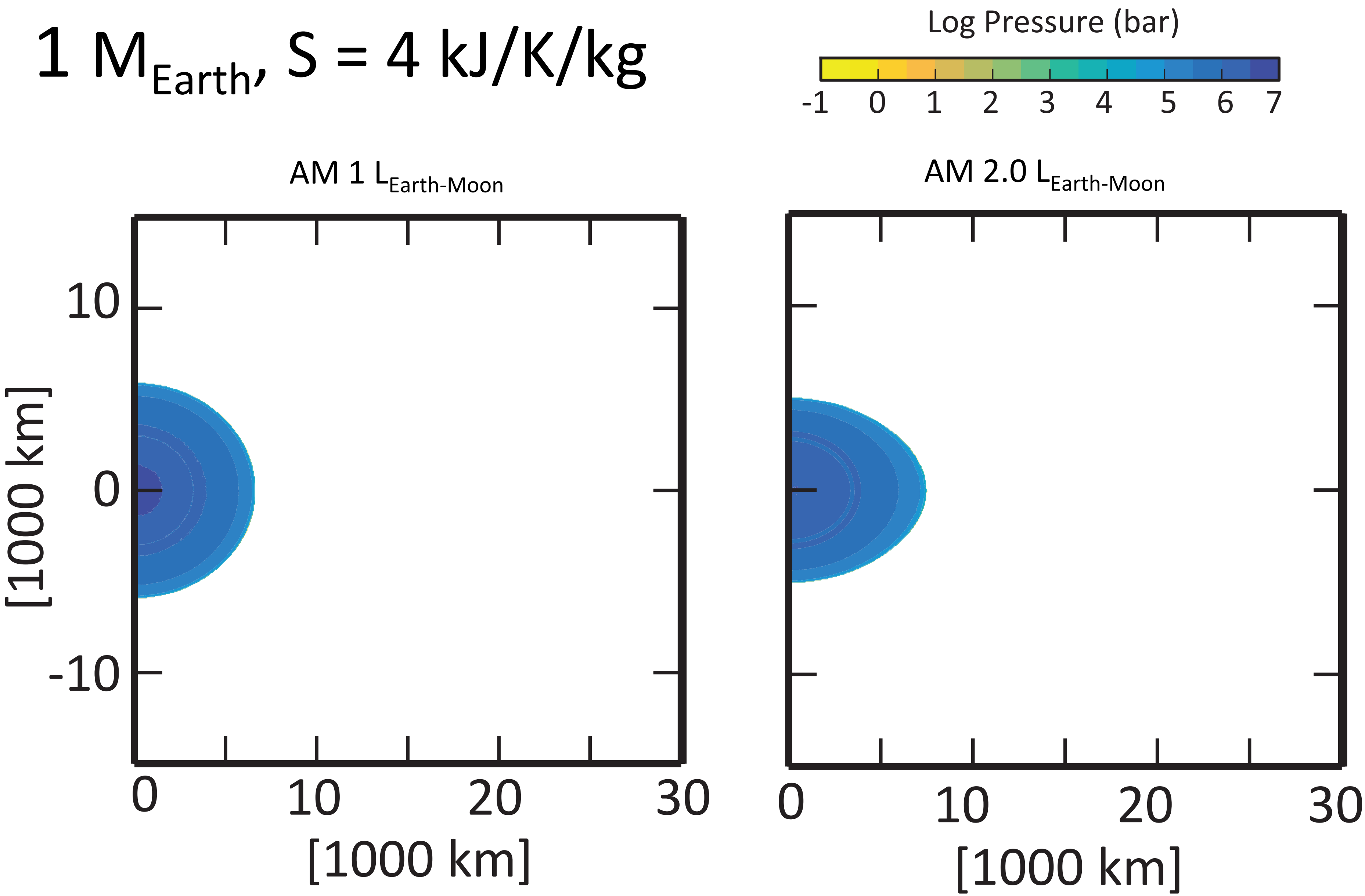

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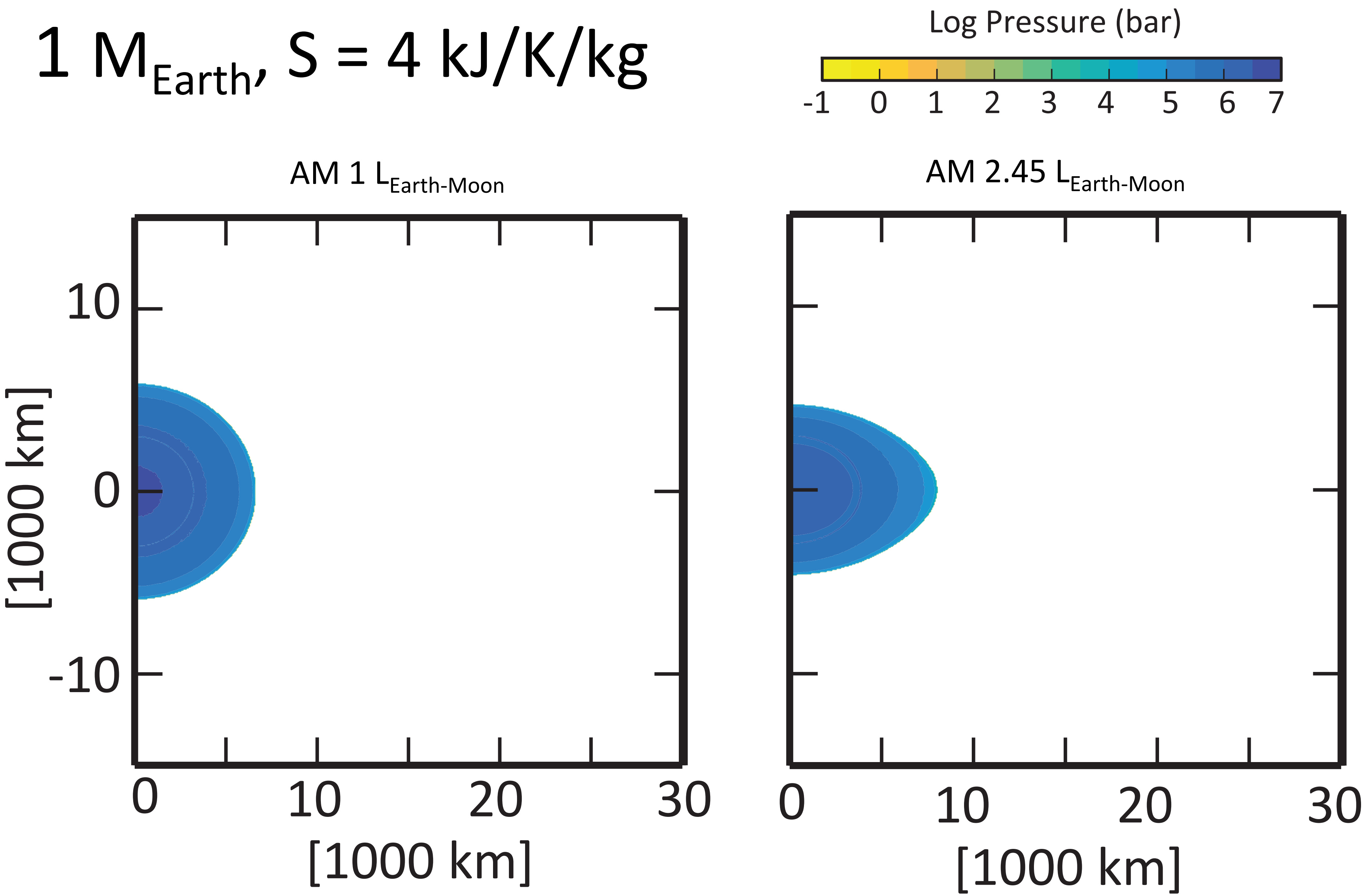
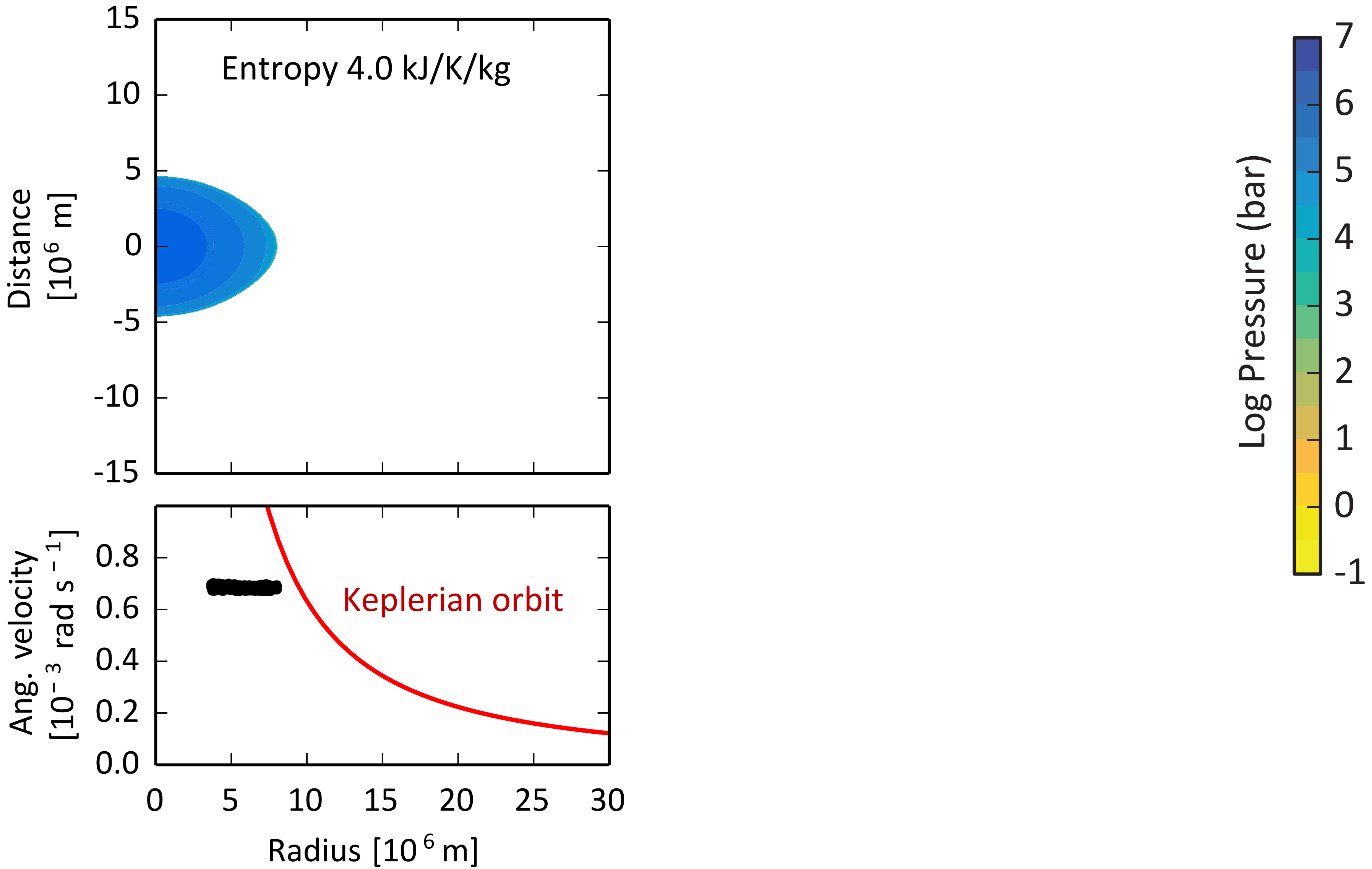


# High AM and High Entropy

# Ang. Mom.=2.45 $L_{Earth\text{-}Moon}$



# High AM and High Entropy

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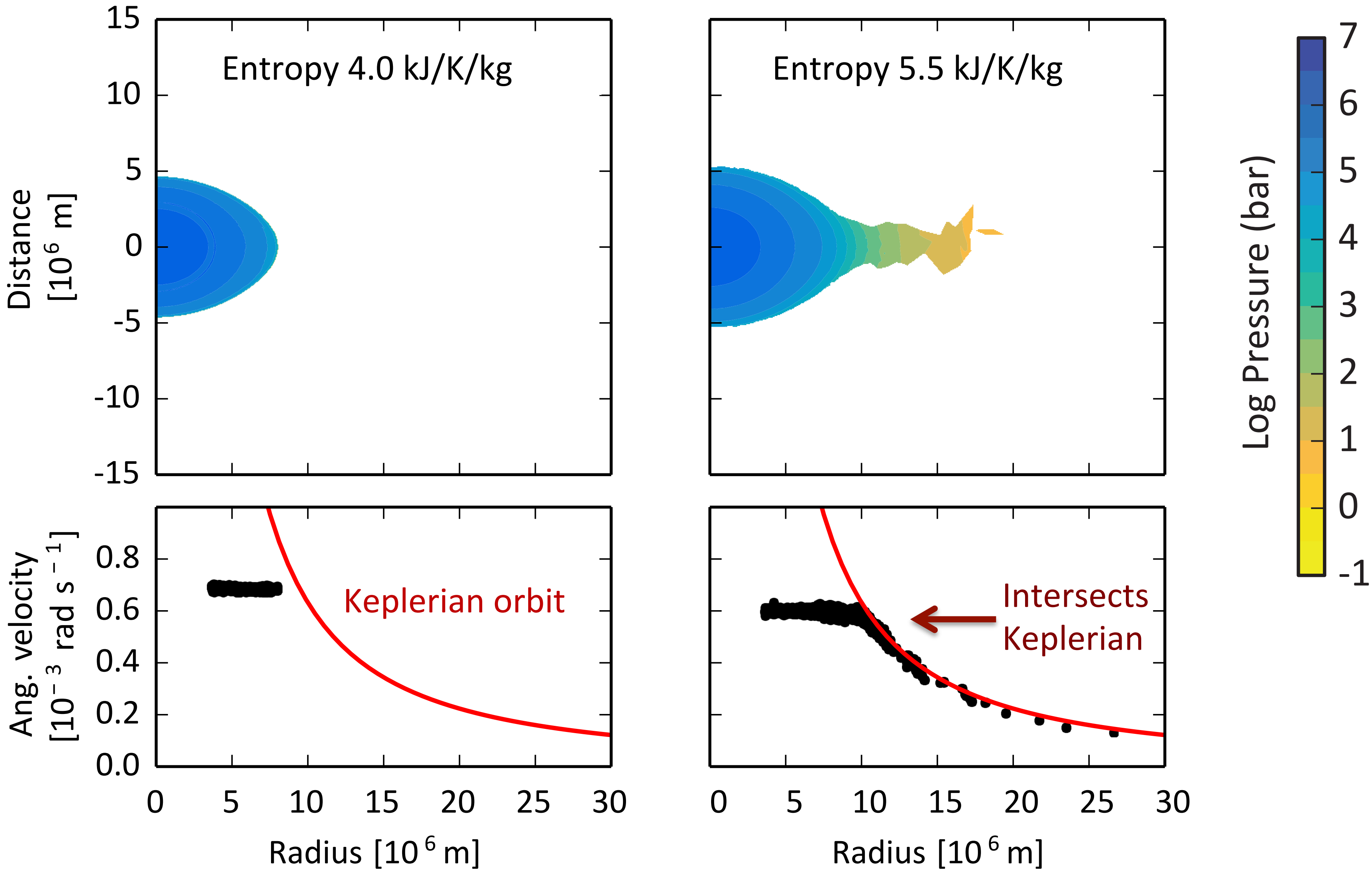
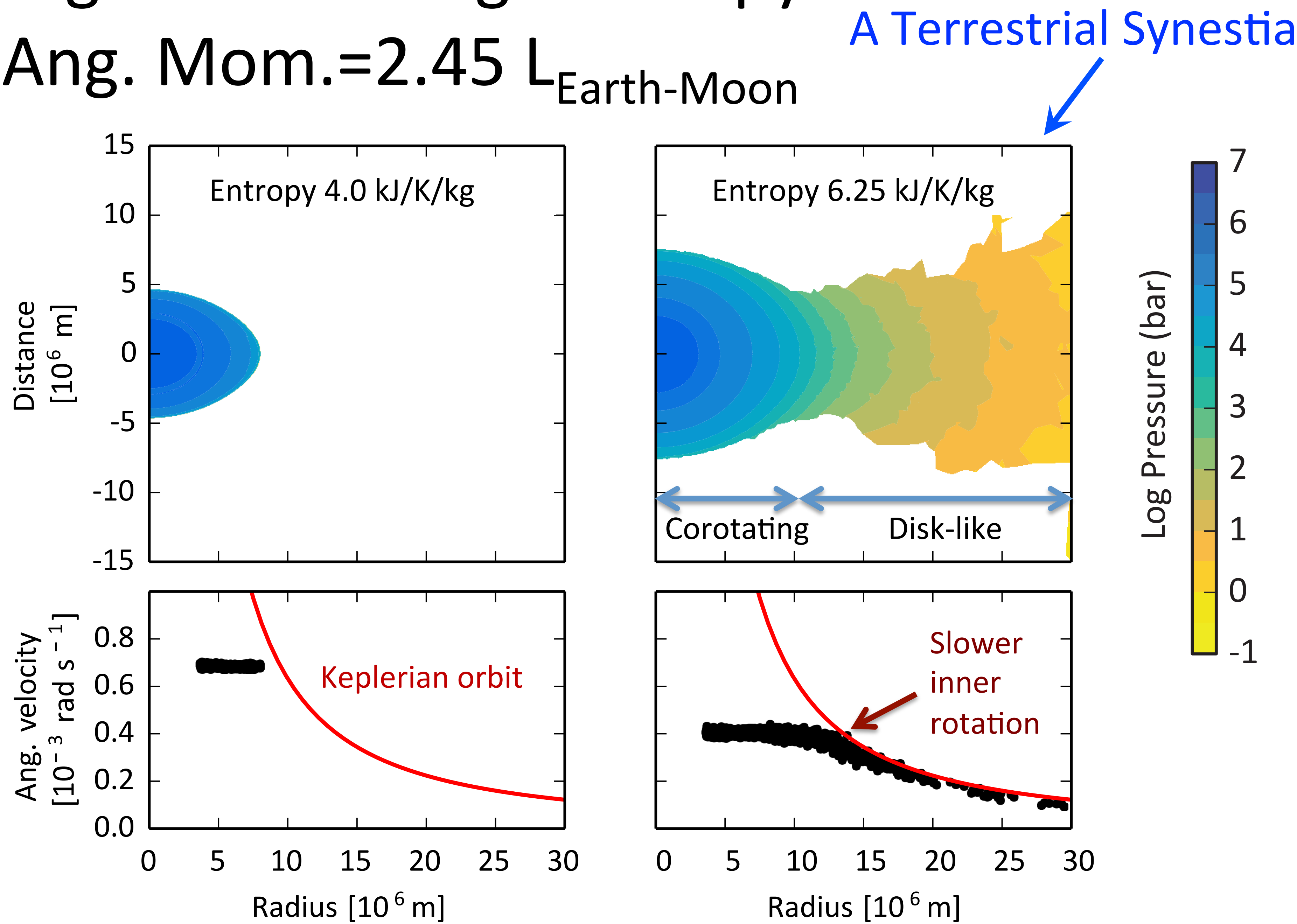
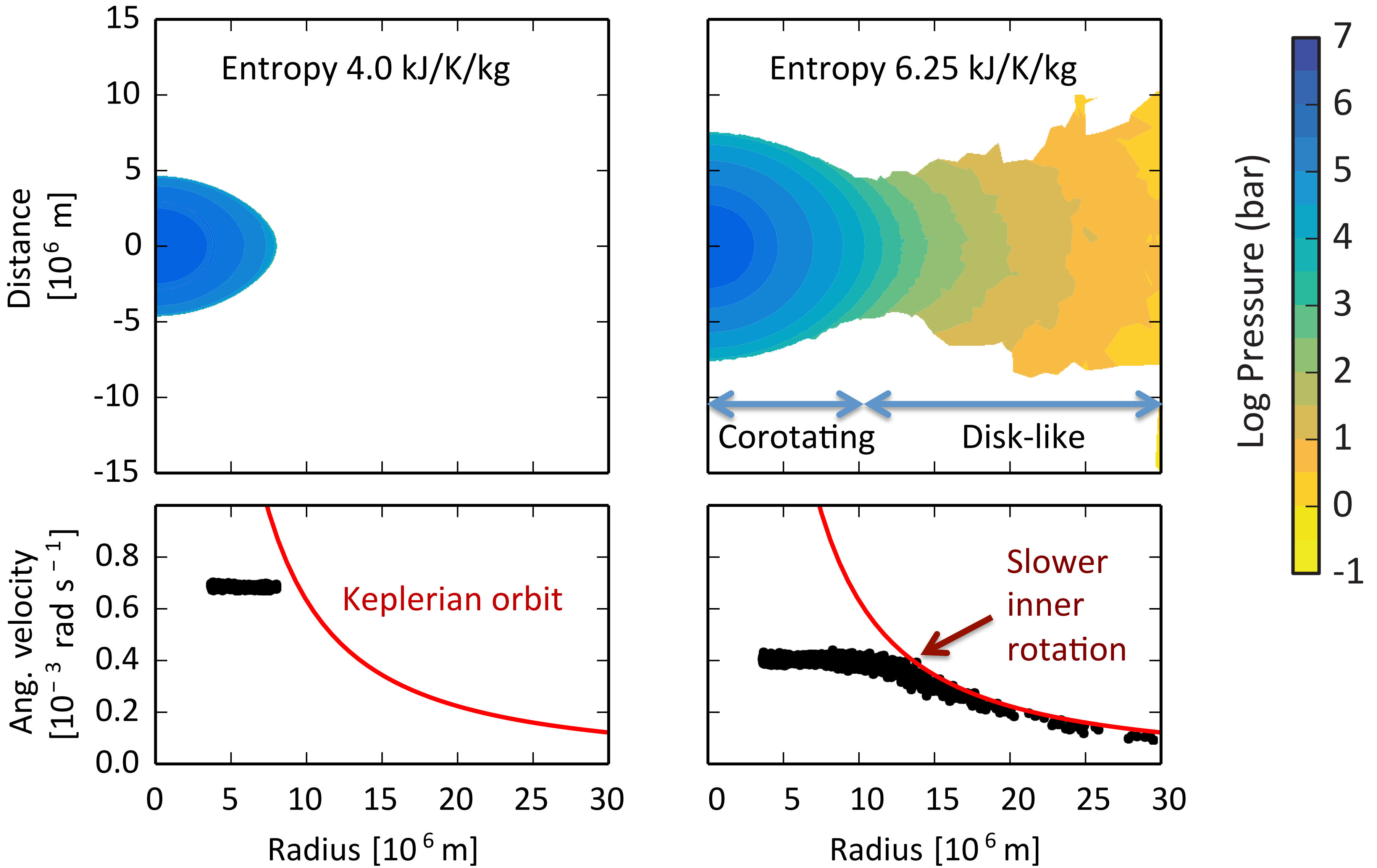


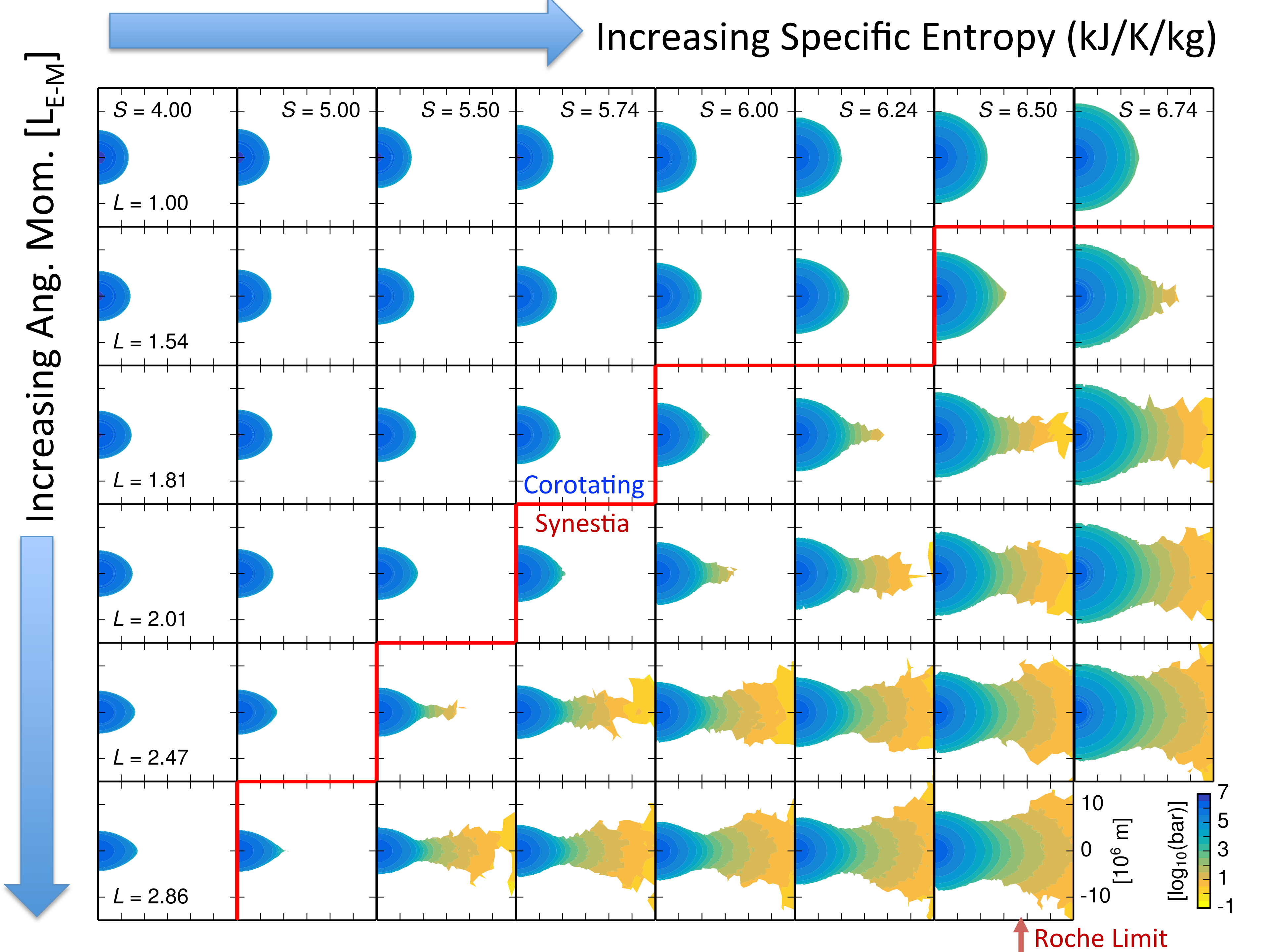
# High AM and High Entropy
# Ang. Mom.=2.45 $L_{Earth\text{-}Moon}$



# Synestia: Connected Structure

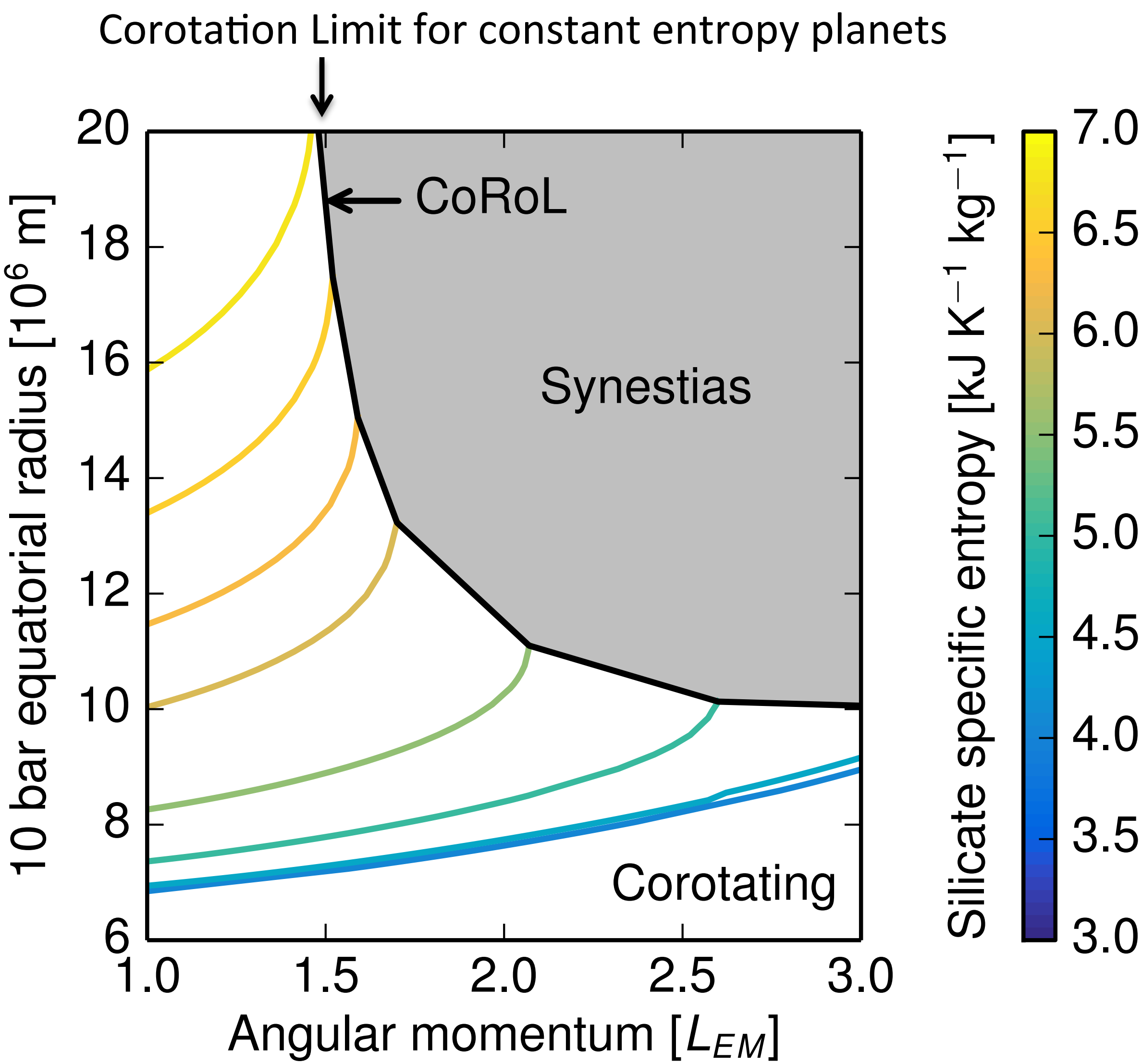
## syn + Hestia (goddess of architecture, hearth/home)





Increasing Specific Entropy (kJ/K/kg)
Increasing Ang. Mom. [L$_{E-M}$]
S = 4.00
S = 5.00
S = 5.50
S = 5.74
S = 6.00
S = 6.24
S = 6.50
S = 6.74
L = 1.00
L = 1.54
L = 1.81
L = 2.01
L = 2.47
L = 2.86
Corotating
Synestia
10
0
-10
[10$^6$ m]
[log$_{10}$(bar)]
7
5
3
1
-1
Roche Limit

# Corotating Planets and Synestias




Synestias are a new class of astronomical objects.

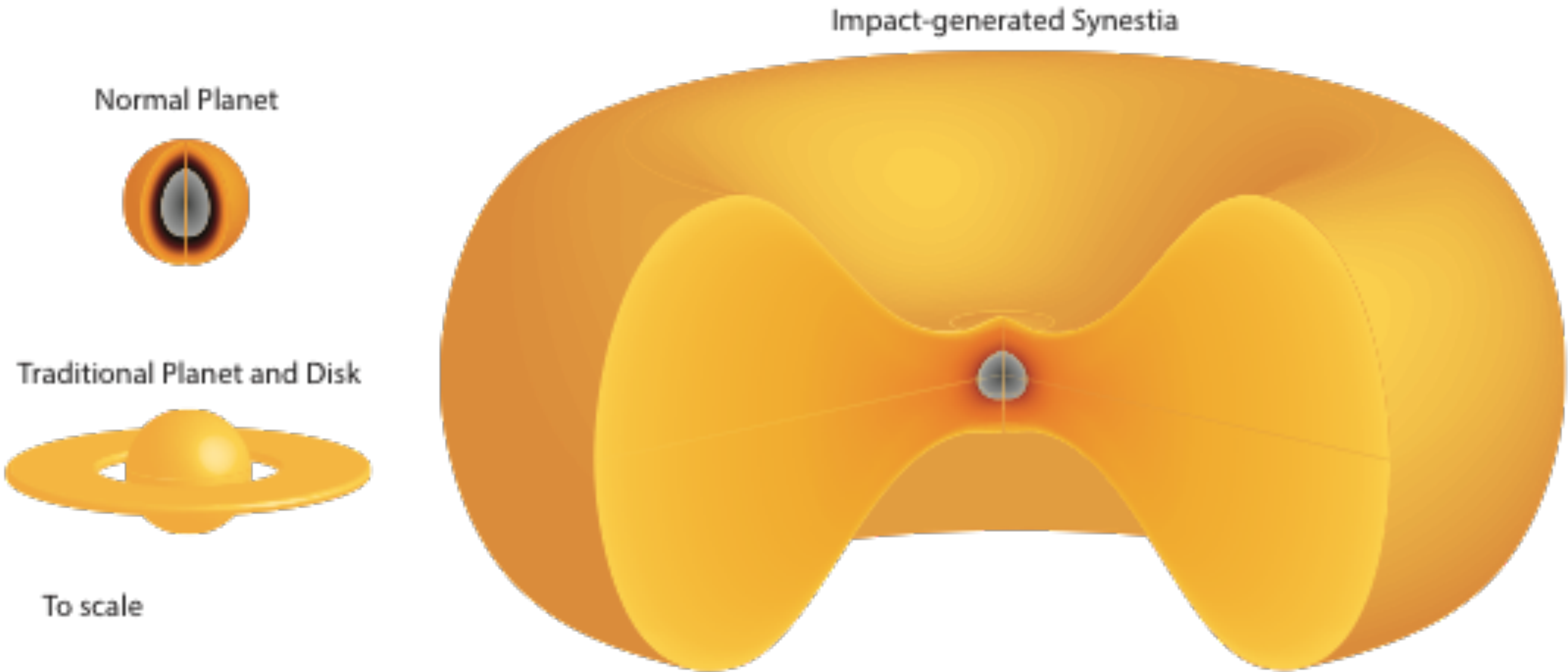
Dynamics are very different from corotating planets.

Important for rocky planet giant impacts, formation of gas giant planets and their satellites, and fast-spinning stars.

Expect multiple synestias during planet formation.

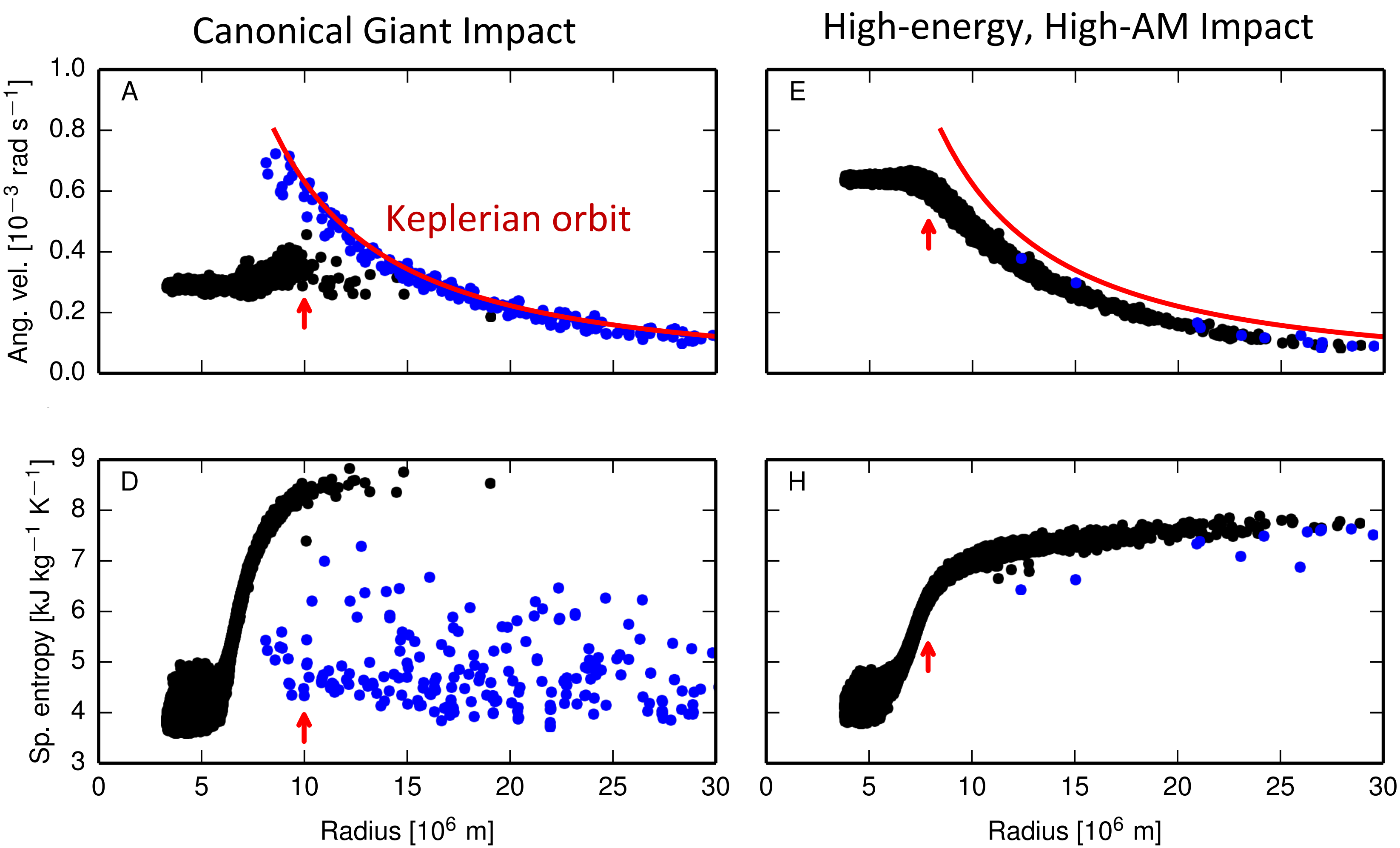
Lock & Stewart, JGR, in press

# Post-impact Synestia



# Example Post-Giant Impact Structures

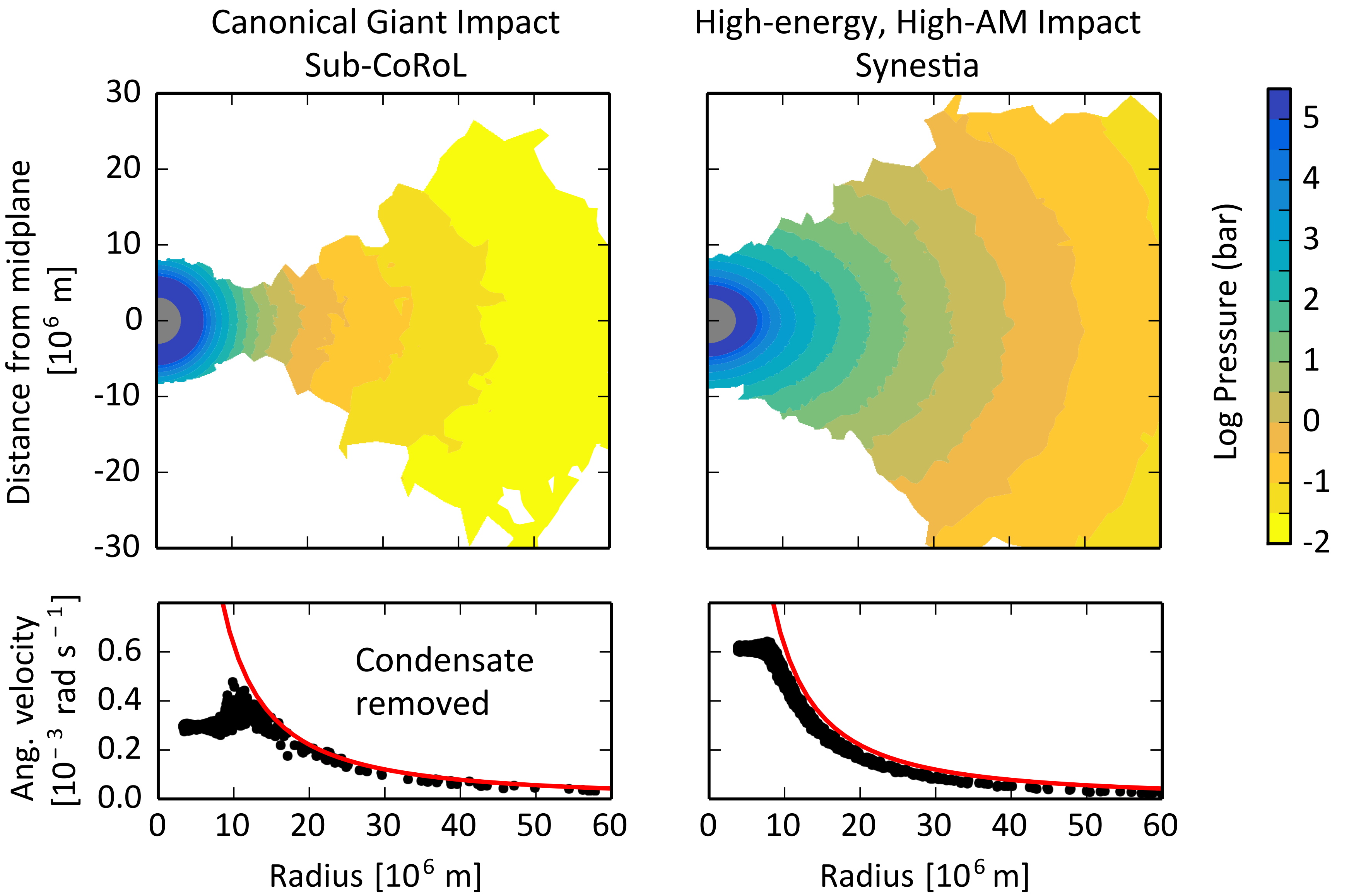
## Profile in the midplane



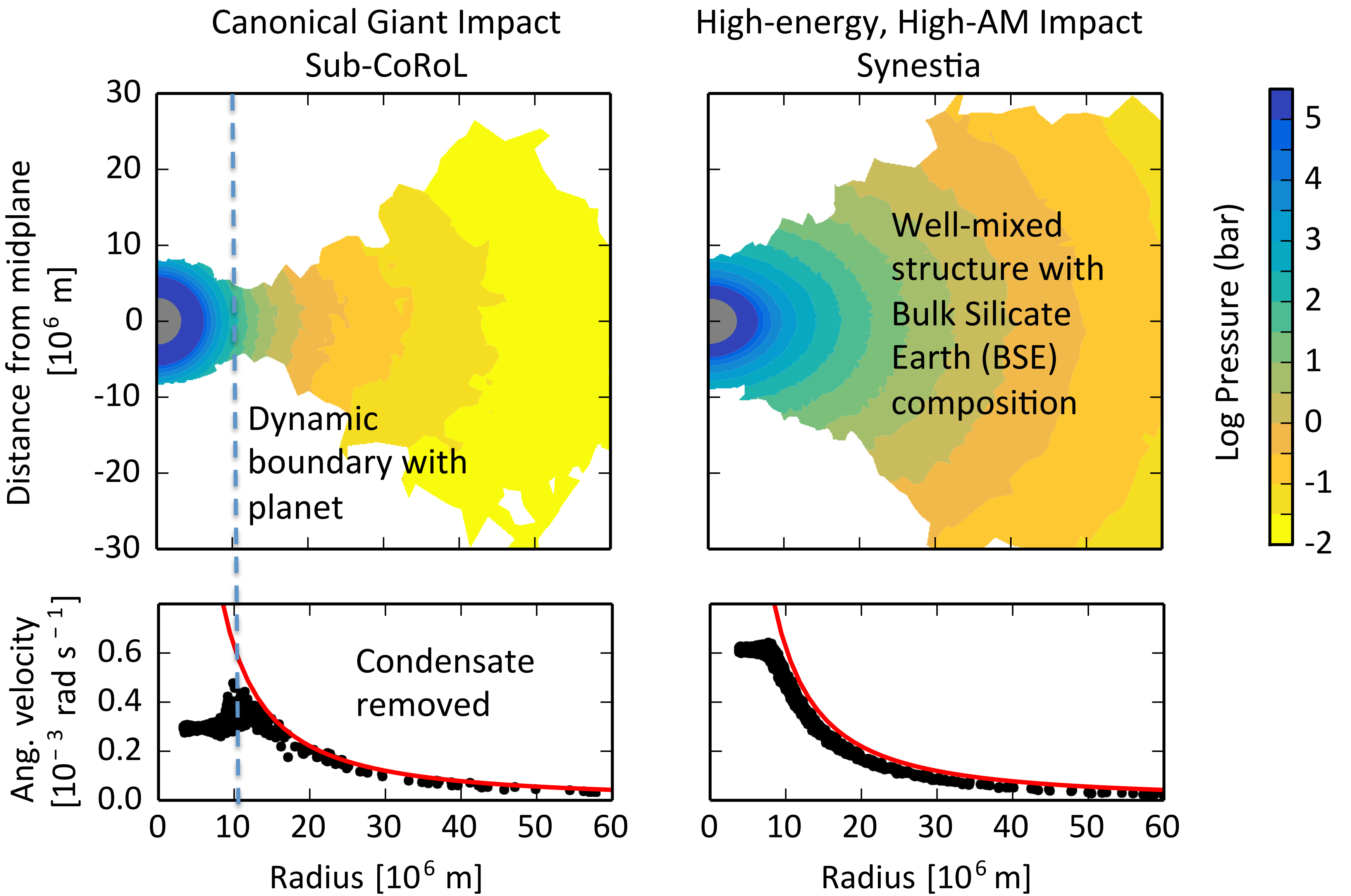

Blue is mixed liquid-vapor

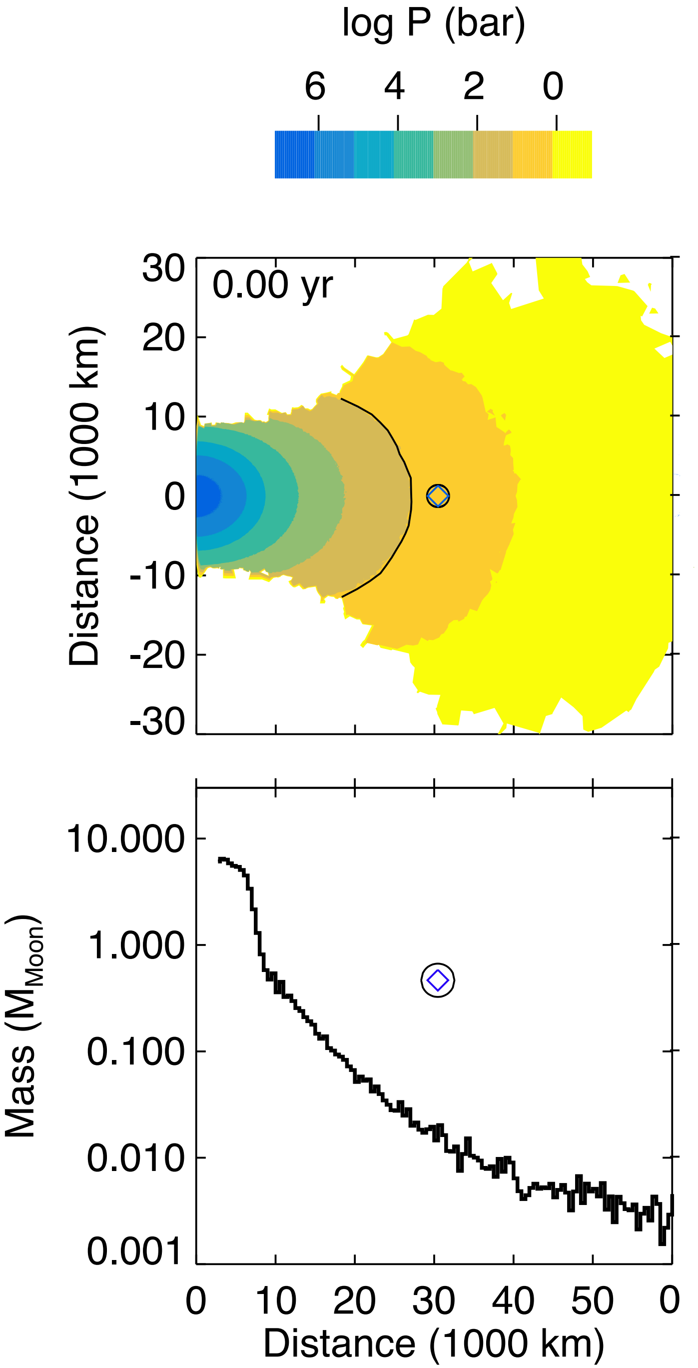
Black is pure vapor or pure liquid

# Example Post-Giant Impact Structures



# Example Post-Giant Impact Structures






# Cooling a synestia

Modified SPH code to simulate thermal equilibration and radiative cooling

No internal heating
Conservative estimate for FASTEST cooling

Condensates are extracted forming a 'lunar seed'

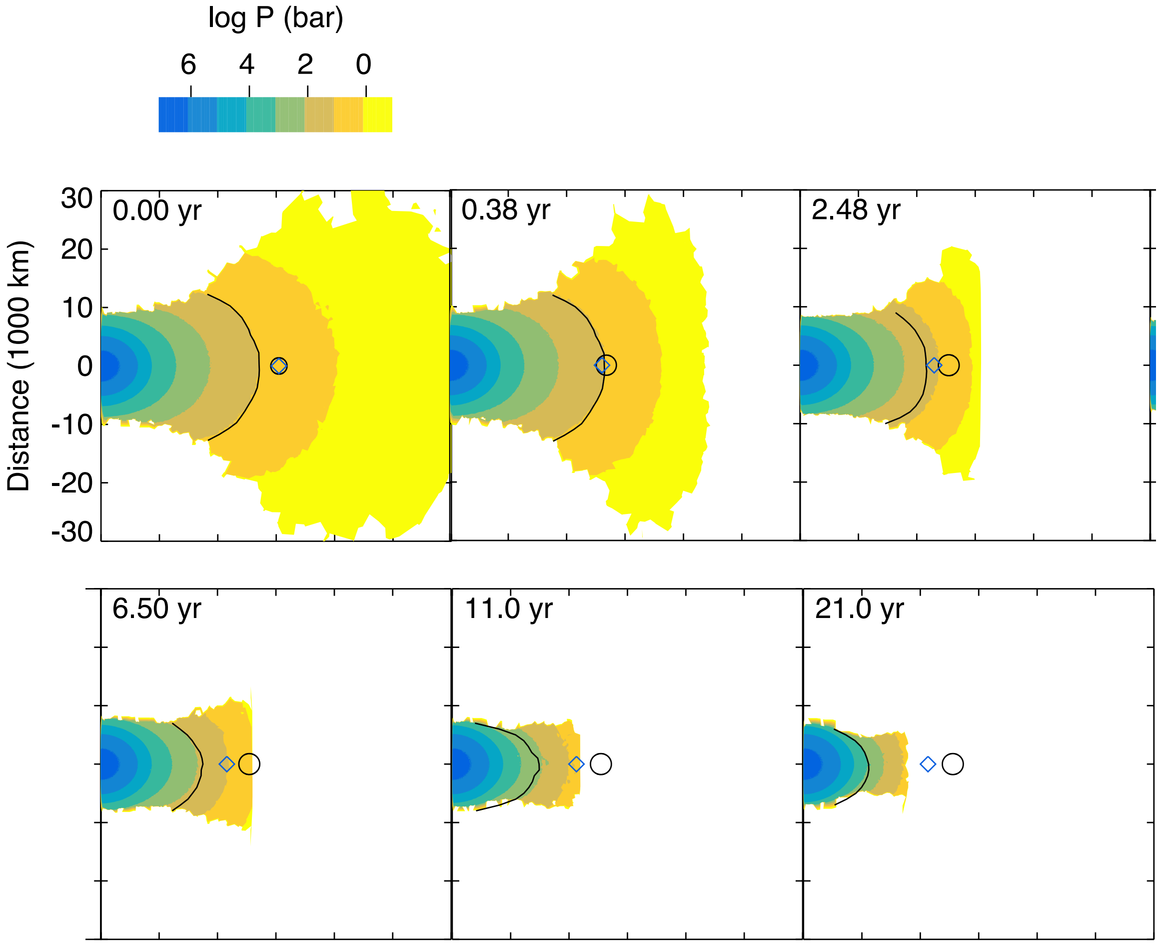
Structure condenses from outer radii inwards. Falling silicate 'raindrops' either re-vaporize or accrete into growing moonlets.

Condensates beyond Roche limit == growing moon

Two estimates for lunar mass and orbit

# Cooling a synestia

Canup 2012 style giant impact
$M_t$=0.572 $M_{Earth}$
$M_p$=0.468 $M_{Earth}$
V = 12.33 km/s, b = 0.4
Similar results for other impact scenarios




Black line is boundary between pure vapor and saturated vapor curve

# Cooling a synestia

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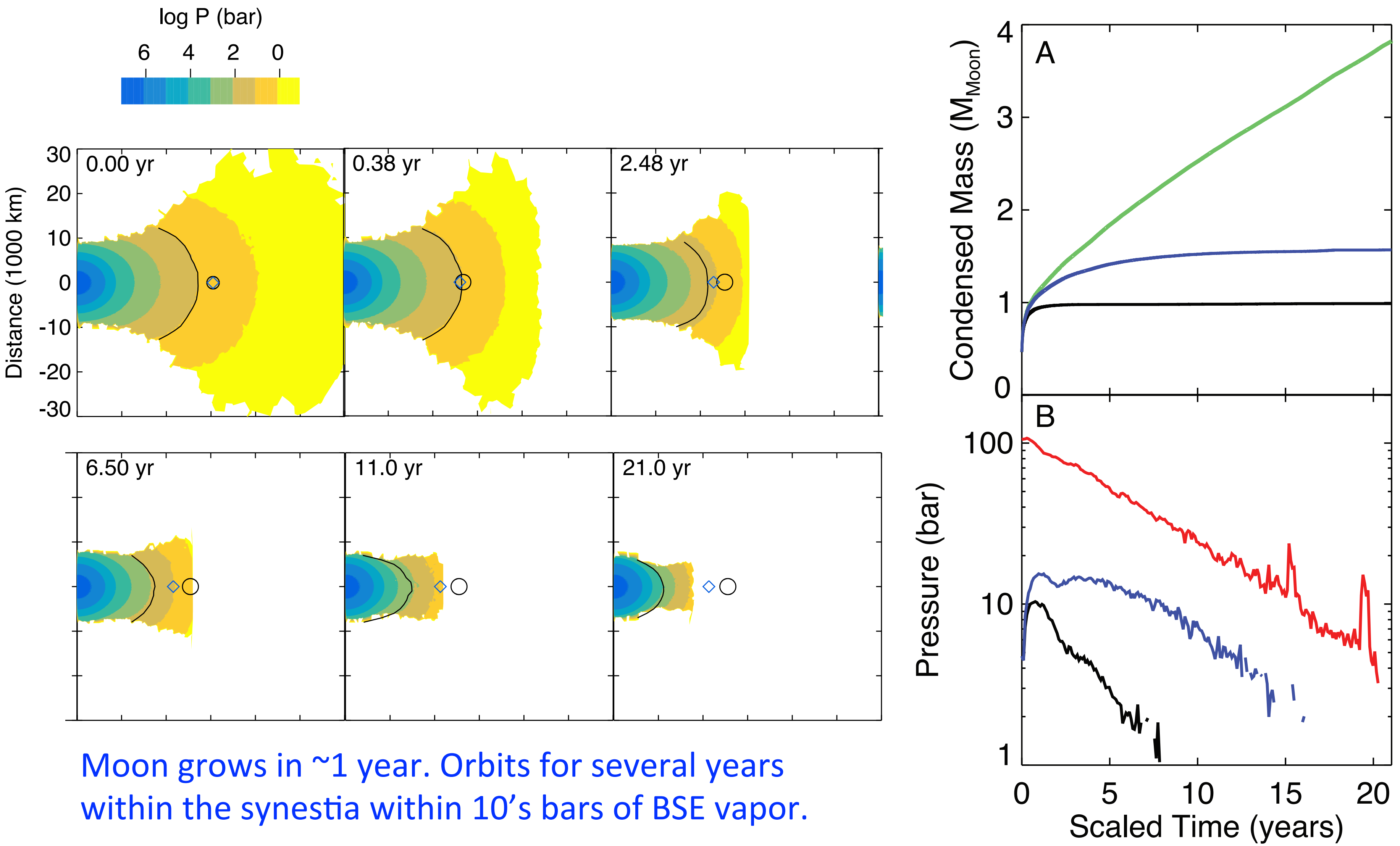


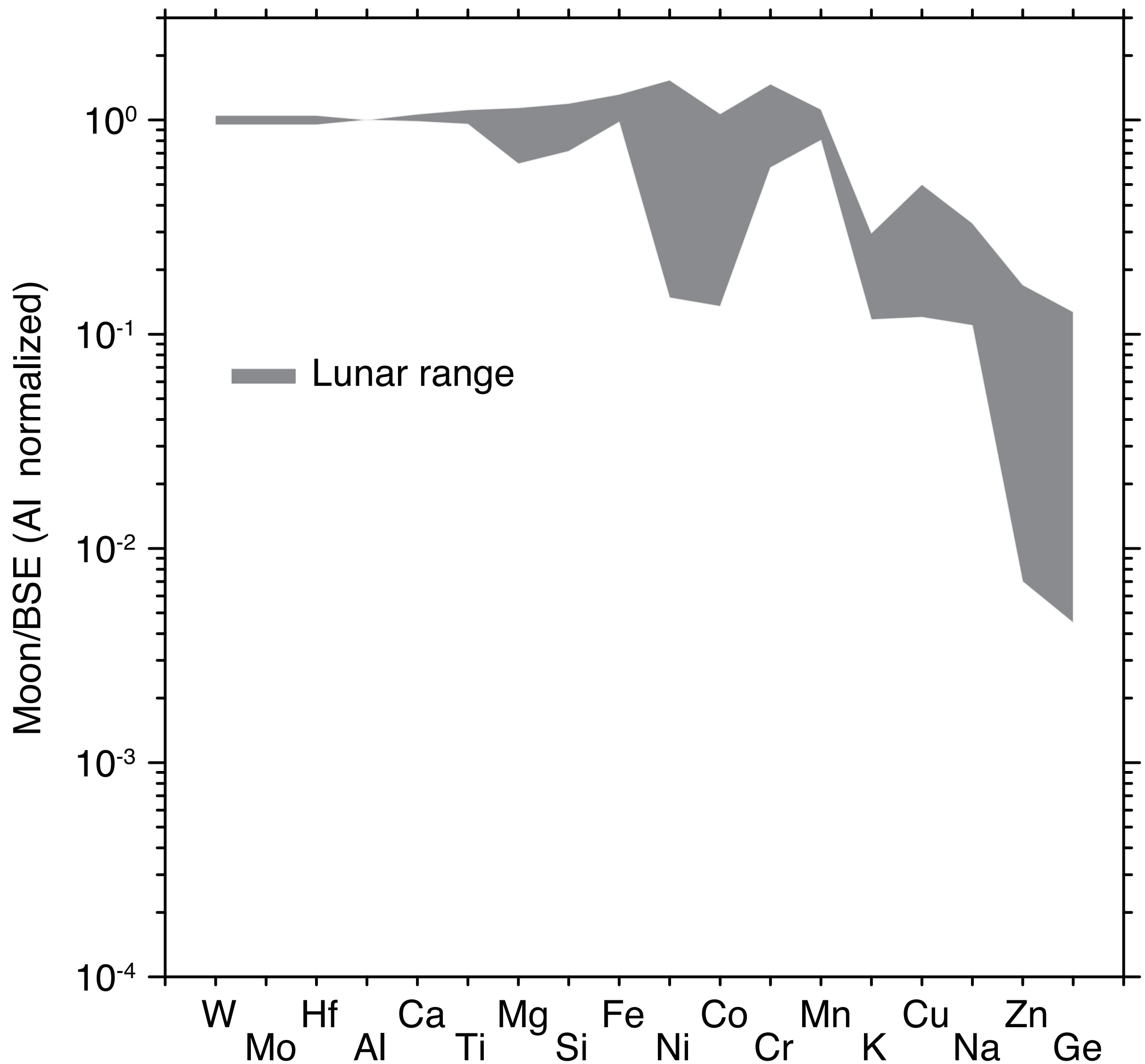

Moon grows in ~1 year. Orbits for several years within the synestia within 10's bars of BSE vapor.

# The Origin of the Moon within a Terrestrial Synestia

# The Origin of the Moon within a Terrestrial Synestia

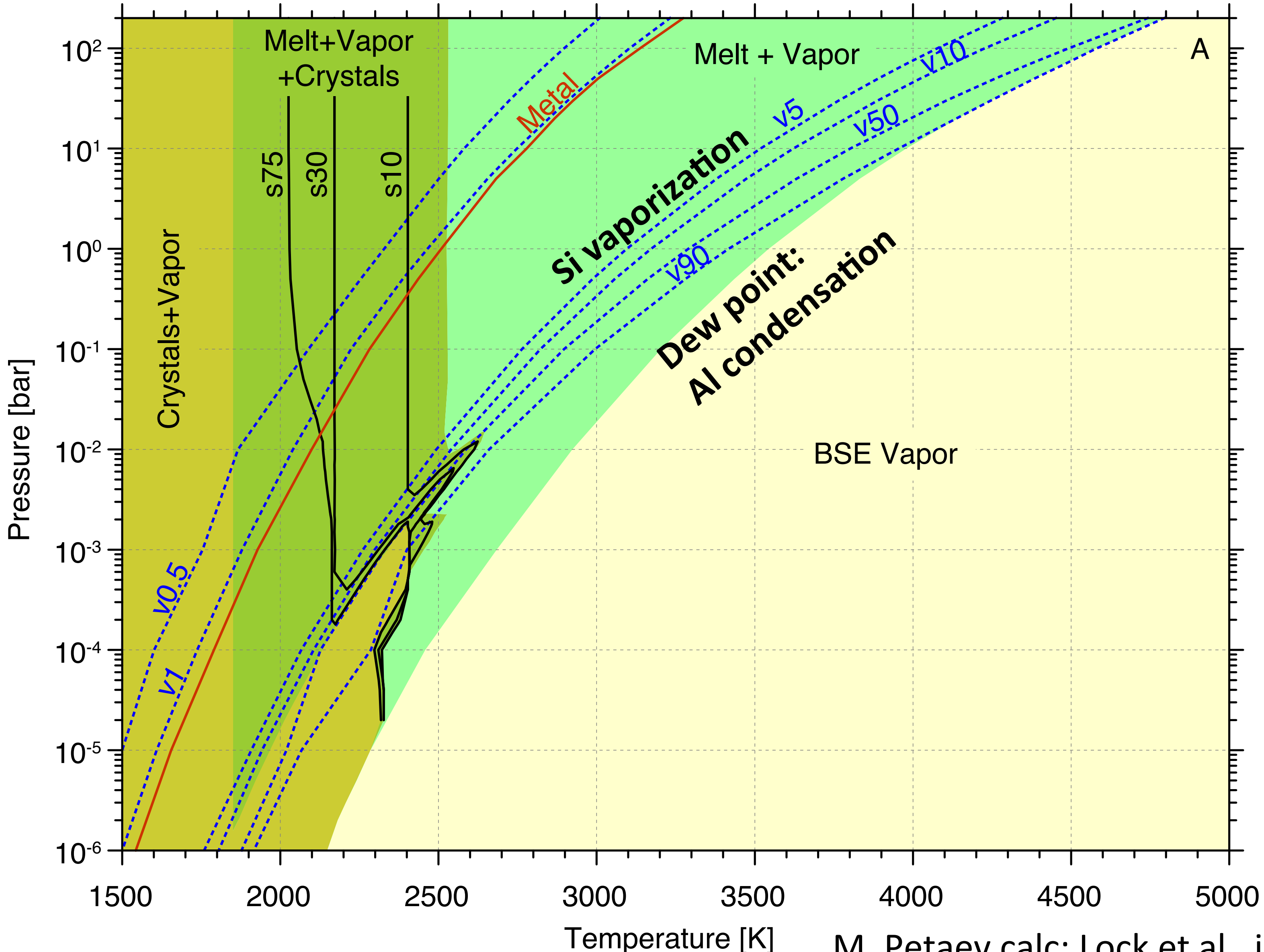
# The Origin of the Moon within a Terrestrial Synestia

# What is the composition of the Moon?

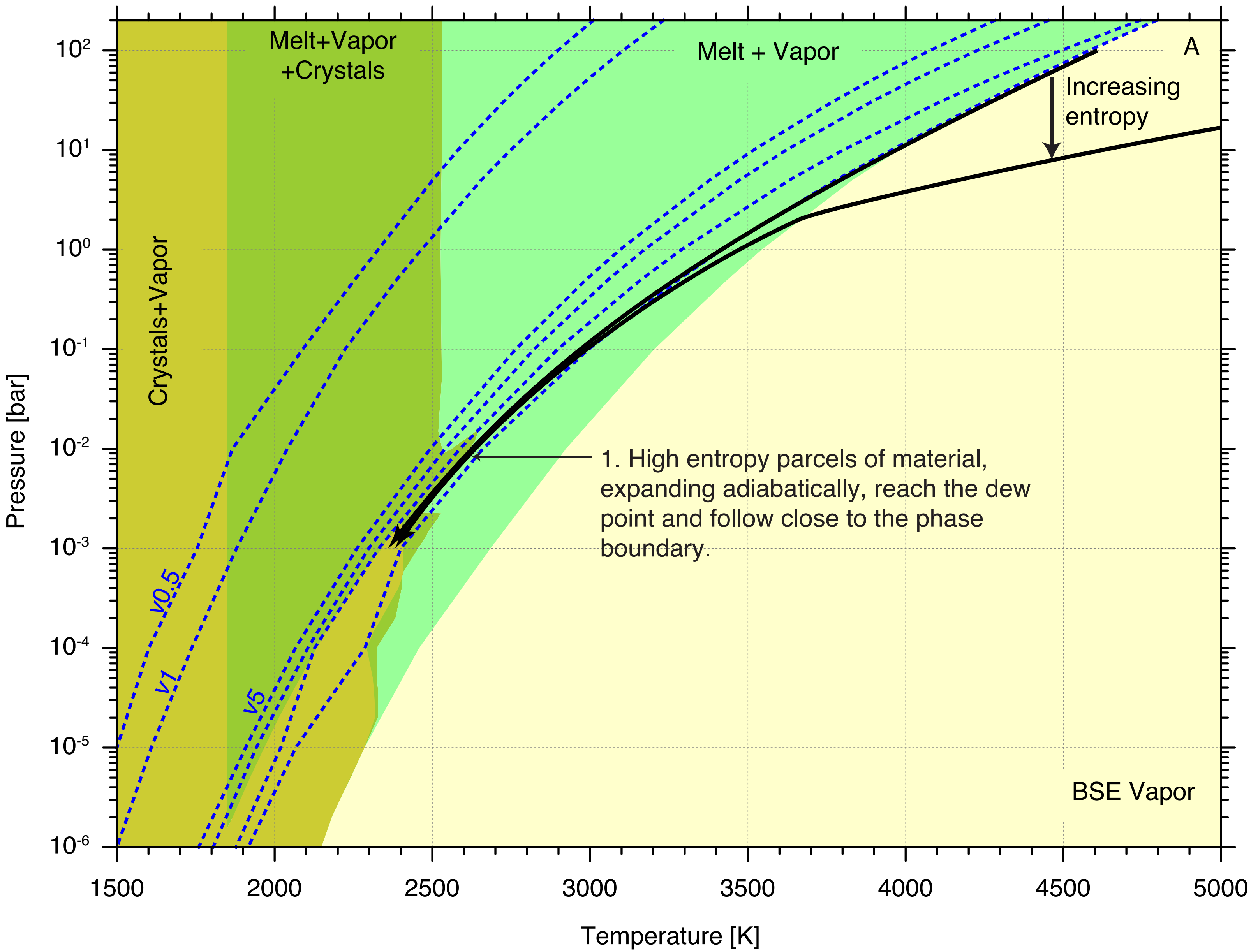



Moon is depleted in moderately volatile and volatile elements

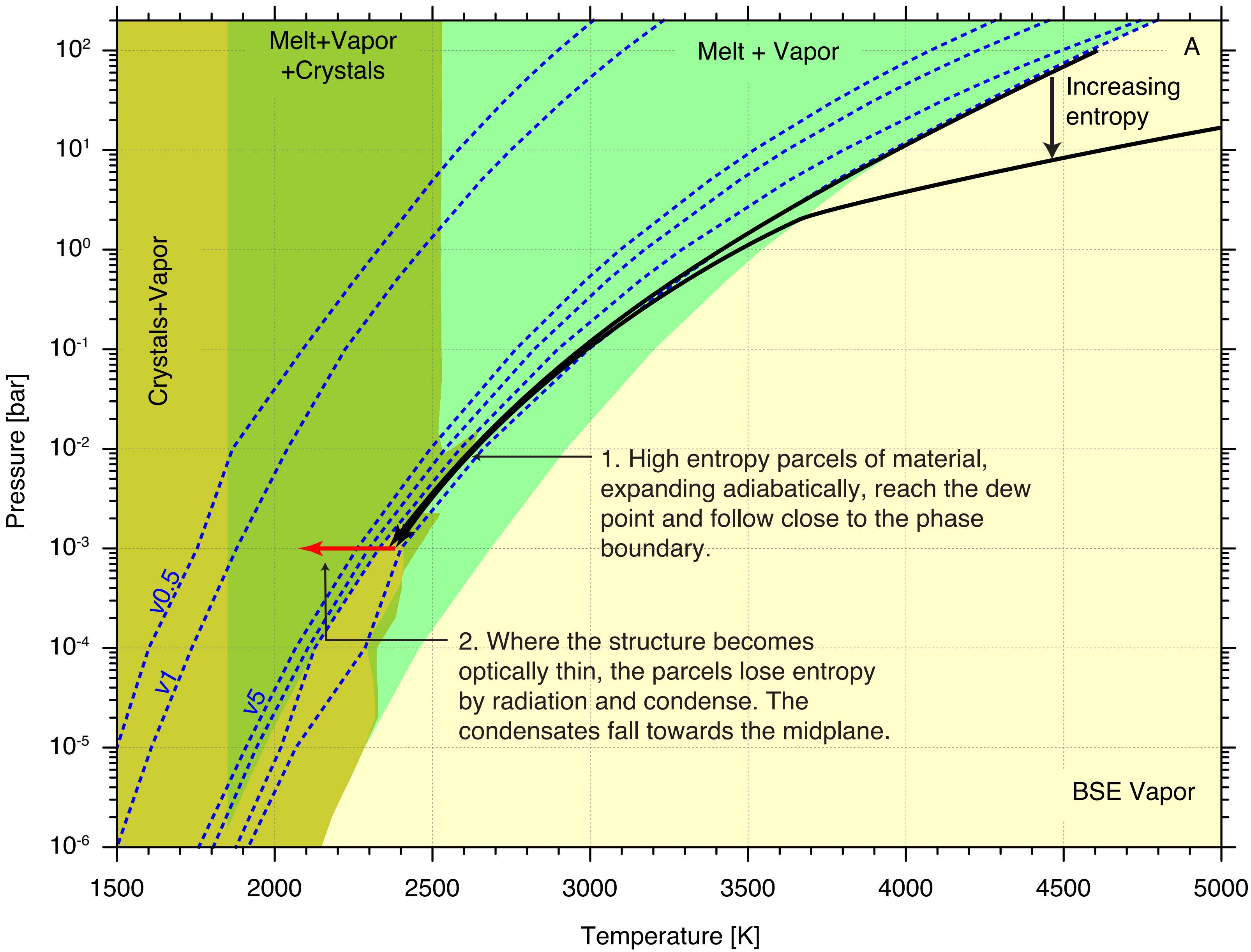
# Bulk Silicate Earth Phase Diagram



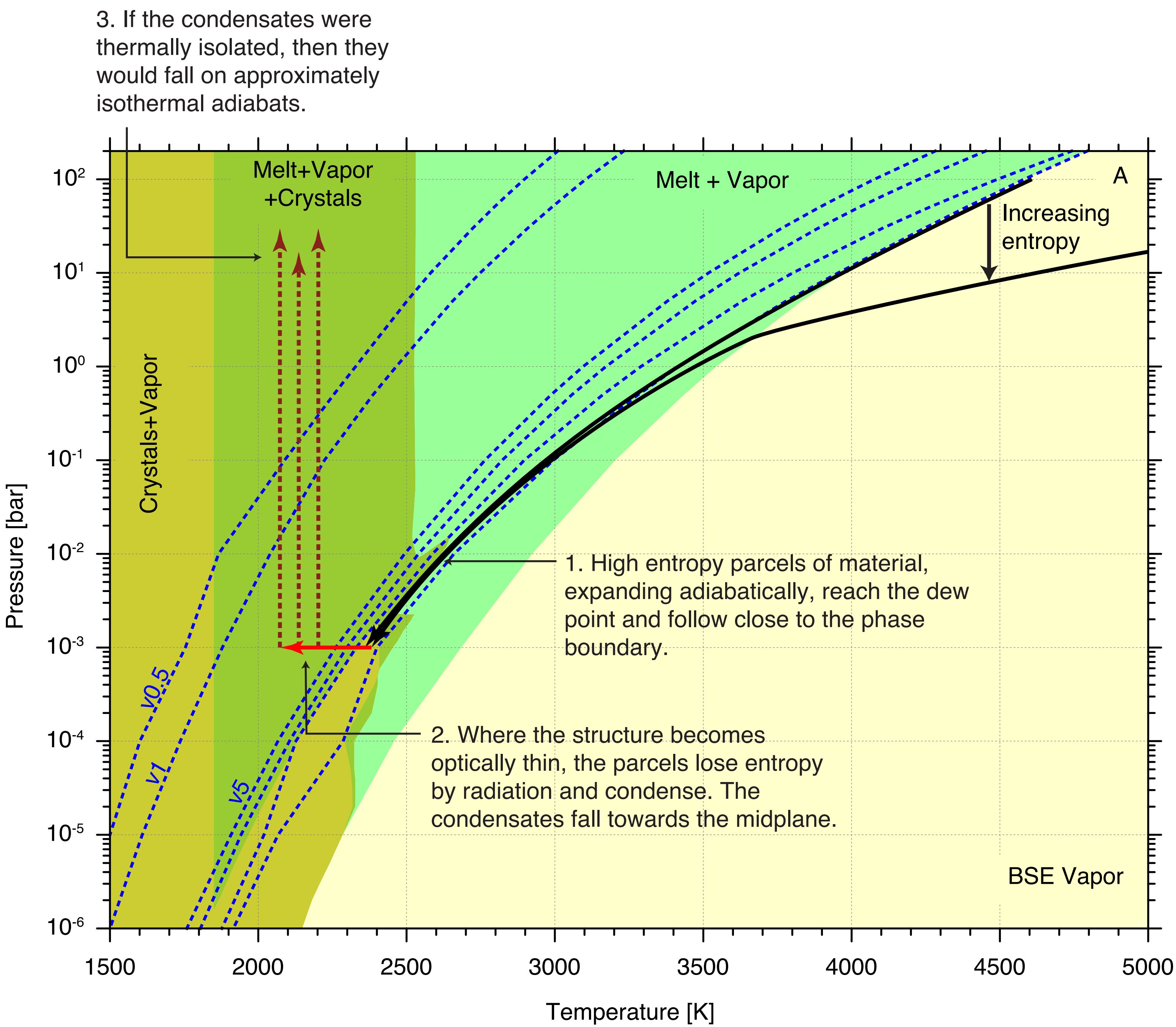

M. Petaev calc; Lock et al., in review



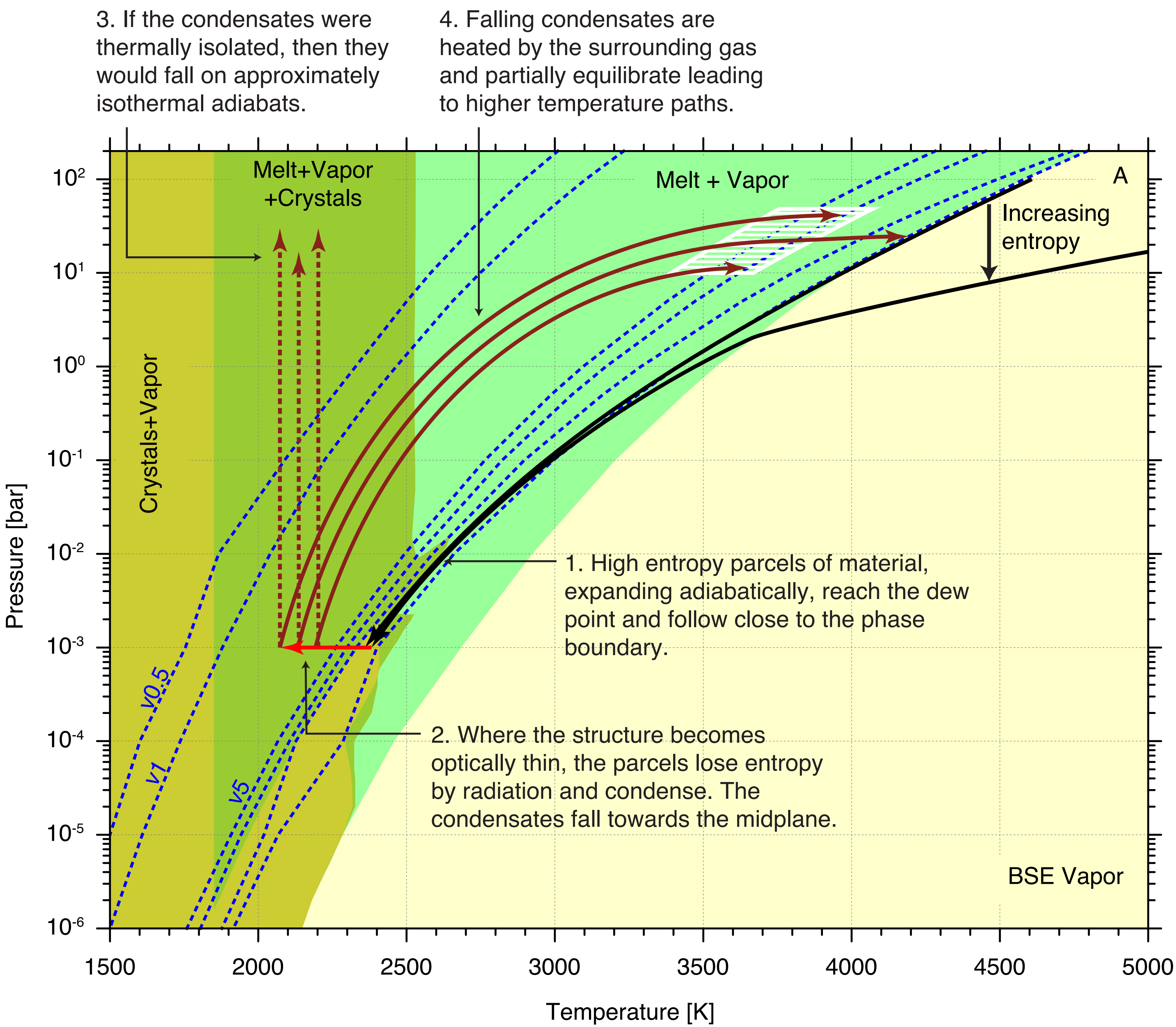
Melt+Vapor
+Crystals
Melt + Vapor
A
Increasing
entropy
Crystals+Vapor
1. High entropy parcels of material, expanding adiabatically, reach the dew point and follow close to the phase boundary.
v0.5
v1
v5
BSE Vapor
Pressure [bar]
Temperature [K]
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
1500
2000
2500
3000
3500
4000
4500
5000



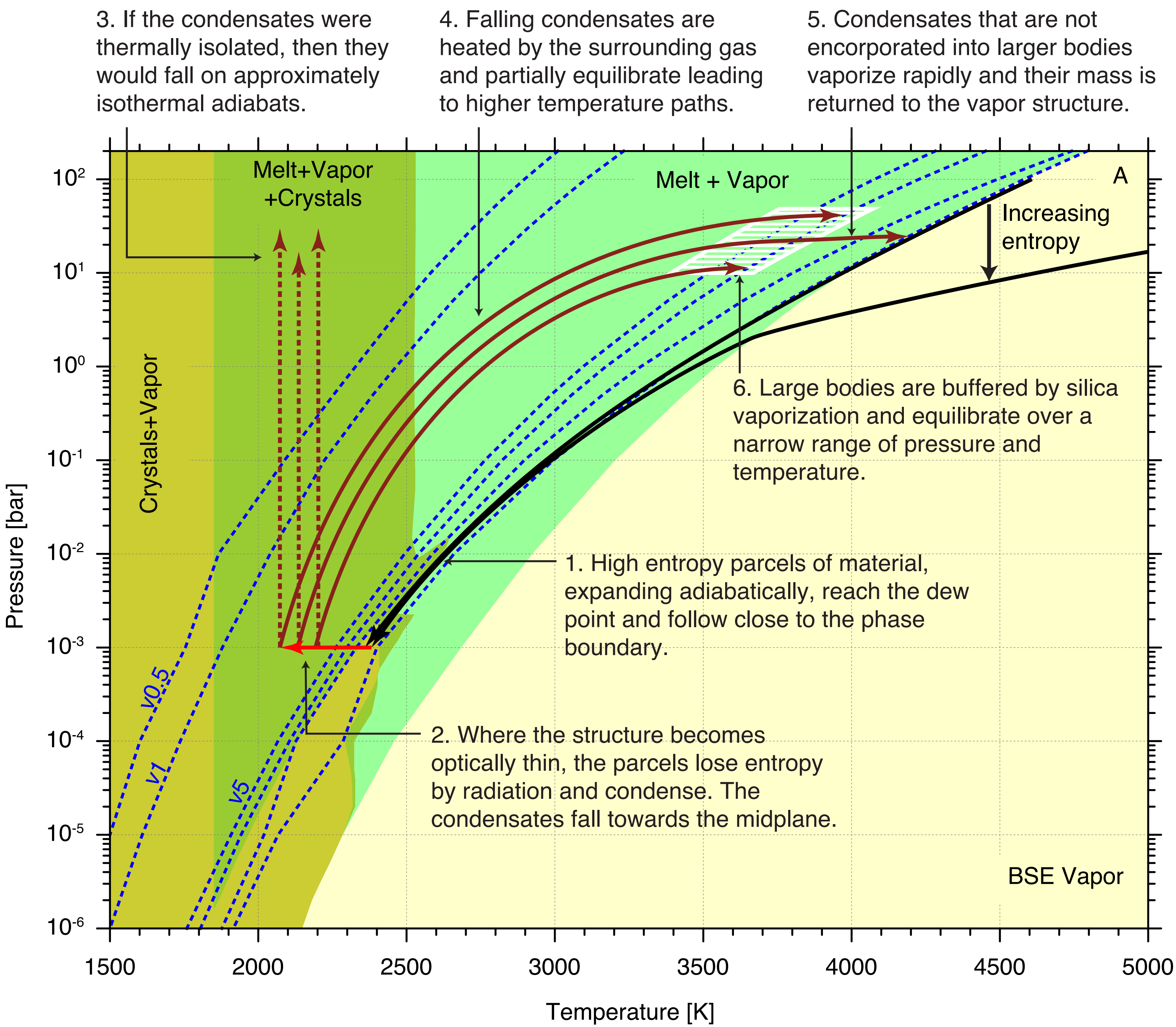
Melt+Vapor
+Crystals
Melt + Vapor
A
Increasing
entropy
Crystals+Vapor
1. High entropy parcels of material, expanding adiabatically, reach the dew point and follow close to the phase boundary.
2. Where the structure becomes optically thin, the parcels lose entropy by radiation and condense. The condensates fall towards the midplane.
v0.5
v1
v5
BSE Vapor
Pressure [bar]
Temperature [K]
$10^{2}$
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
1500
2000
2500
3000
3500
4000
4500
5000



3. If the condensates were thermally isolated, then they would fall on approximately isothermal adiabats.
Melt+Vapor +Crystals
Melt + Vapor
A
Increasing entropy
Crystals+Vapor
1. High entropy parcels of material, expanding adiabatically, reach the dew point and follow close to the phase boundary.
2. Where the structure becomes optically thin, the parcels lose entropy by radiation and condense. The condensates fall towards the midplane.
v0.5
v1
v5
BSE Vapor
Pressure [bar]
Temperature [K]

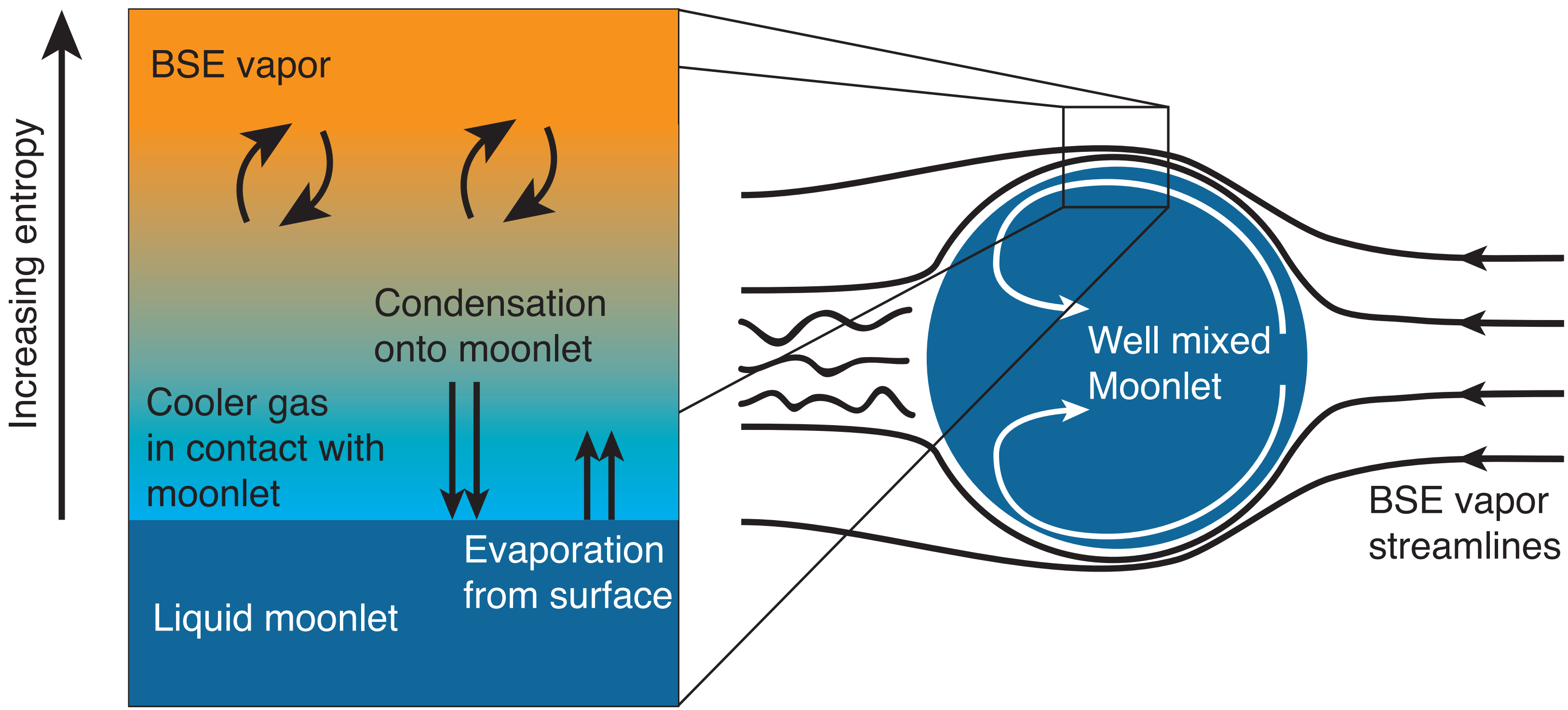


3. If the condensates were thermally isolated, then they would fall on approximately isothermal adiabats.
4. Falling condensates are heated by the surrounding gas and partially equilibrate leading to higher temperature paths.
Melt+Vapor +Crystals
Melt + Vapor
A
Increasing entropy
Crystals+Vapor
1. High entropy parcels of material, expanding adiabatically, reach the dew point and follow close to the phase boundary.
2. Where the structure becomes optically thin, the parcels lose entropy by radiation and condense. The condensates fall towards the midplane.
v0.5
v1
v5
BSE Vapor
Pressure [bar]
Temperature [K]



3. If the condensates were thermally isolated, then they would fall on approximately isothermal adiabats.
4. Falling condensates are heated by the surrounding gas and partially equilibrate leading to higher temperature paths.
5. Condensates that are not encorporated into larger bodies vaporize rapidly and their mass is returned to the vapor structure.
Melt+Vapor +Crystals
Melt + Vapor
A
Increasing entropy
Crystals+Vapor
6. Large bodies are buffered by silica vaporization and equilibrate over a narrow range of pressure and temperature.
1. High entropy parcels of material, expanding adiabatically, reach the dew point and follow close to the phase boundary.
2. Where the structure becomes optically thin, the parcels lose entropy by radiation and condense. The condensates fall towards the midplane.
v0.5
v1
v5
BSE Vapor
Pressure [bar]
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
1500
2000
2500
3000
3500
4000
4500
5000
Temperature [K]

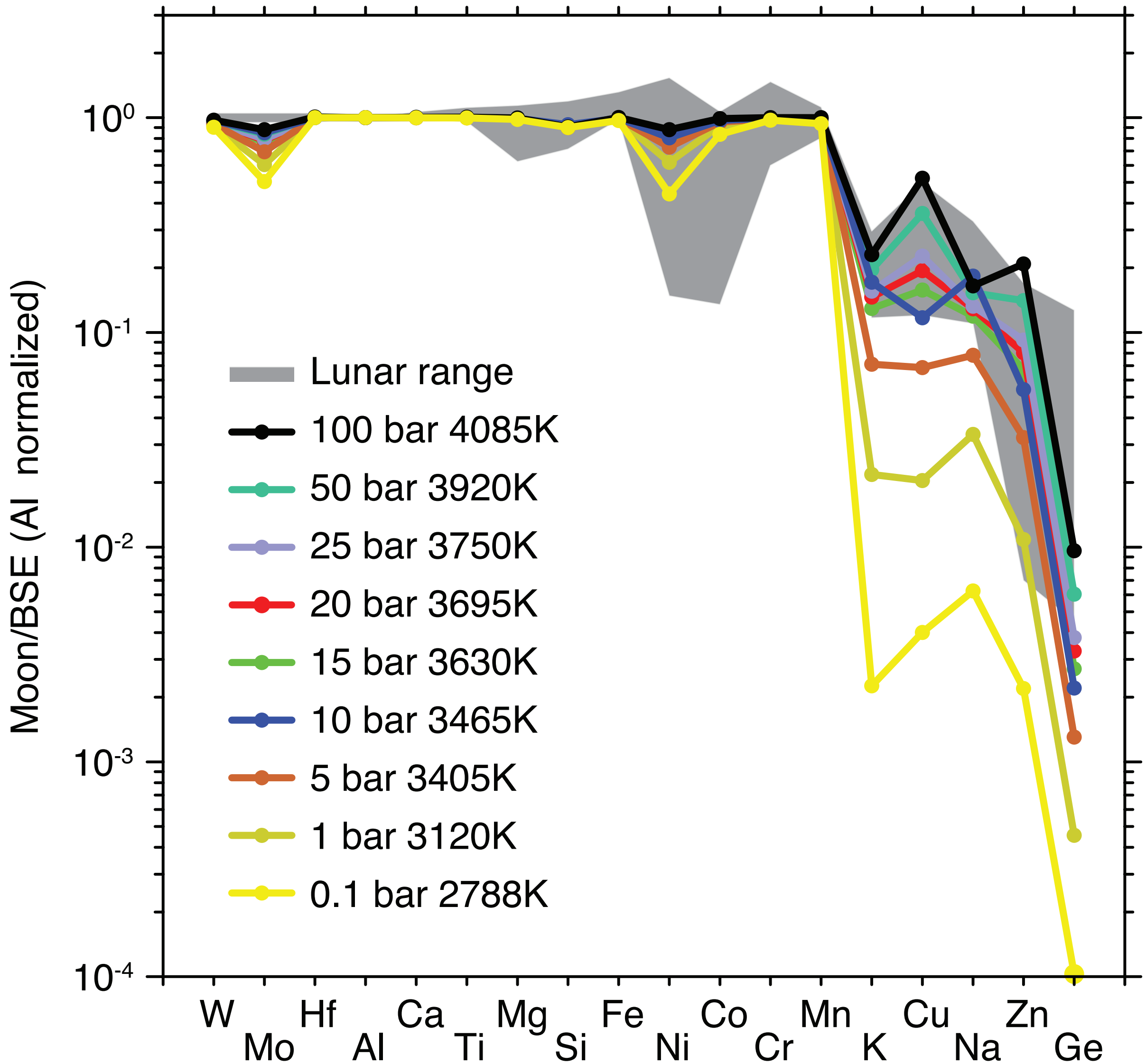
# Pressure & Temperature of Lunar Origin




High-energy, high-AM giant impacts generate BSE vapor pressures of 10's bars beyond the Roche limit. Well-mixed synestia and well-mixed Moon.

The liquid moon is surrounded by hotter BSE vapor. Moon is a cold trap. Moon heats to the boiling point of silicate (about 10% Si in the vapor).

# Predicted Lunar Chemistry

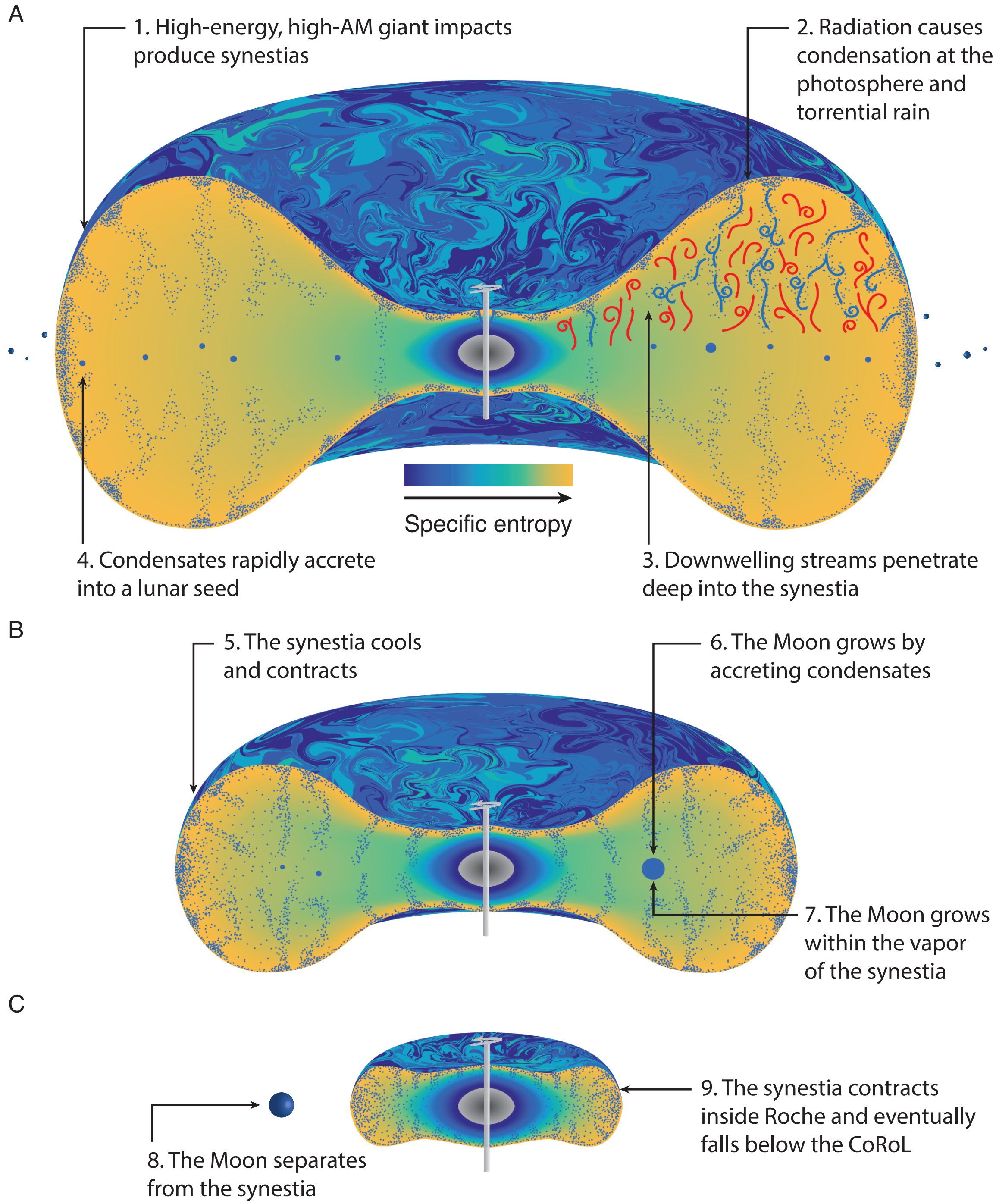



Predicted chemistry at 10's bar and 10% Si in vapor agrees very well with observations

W isotopes similar because well-mixed vapor structure (other isotopes TBD)

M. Petaev calculations using the GRAINS thermochemical code.

Lock et al., in review



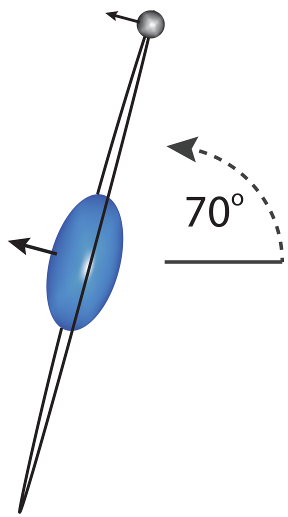

# Summary of Lunar Origin

Lock et al., submitted

# After making the Moon…….

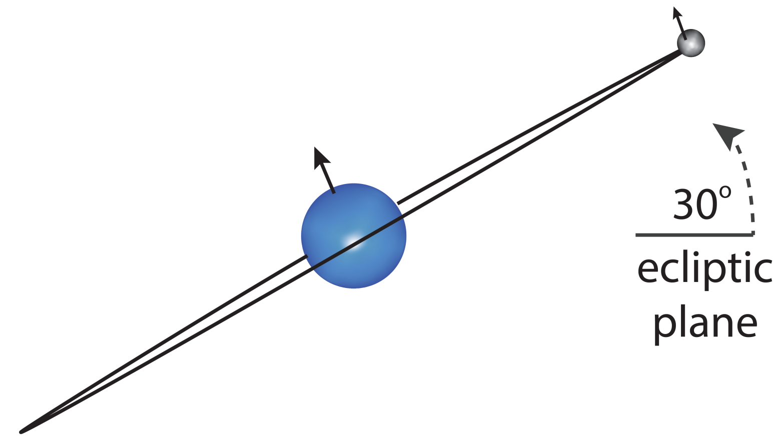
## Need to explain present-day orbit (AM and lunar inclination)

A




After impact, high-obliquity Earth

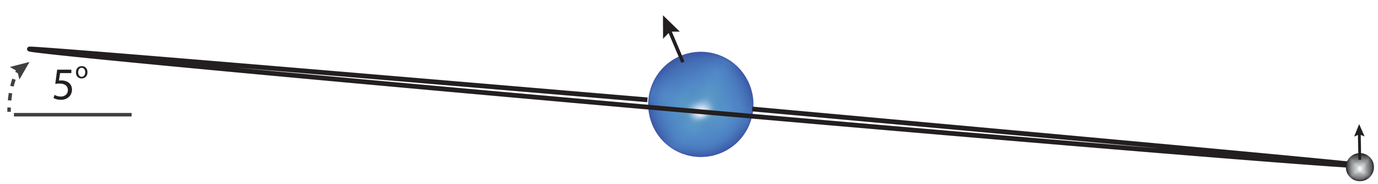
B




During LaPlace plane transition, remove AM

C

Residual inclination after Cassini State Transition




After lunar accretion, angular momentum transferred
from Earth-Moon to Sun-Earth system during tidal evolution of the Moon
Ćuk, Hamilton, Lock, Stewart, Nature, 2016