Toward a better understanding of the thermochemical evolution in Earth and planetary interiors

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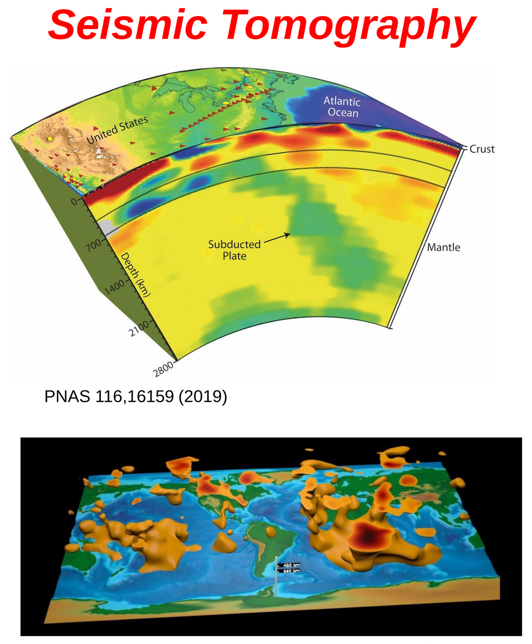
Introduction

Transport properties of constituting materials in Earth and planetary interiors play critical roles in controlling their thermochemical evolution and dynamics. Thermal conductivity is one of the key transport properties, in particular around the regions where heat is predominantly transferred by conduction, such as near the thermal boundary layers. Recent successful coupling of an ultrafast optical pump-probe method with externally- and laser-heated diamond anvil cells have enabled us to systematically and precisely measured the thermal conductivity of deep Earth materials, from upper mantle all the way down to the core. Combined with data modelling, we have created the first deep Earth thermal conductivity anatomy, including pyrolitic mantle, subducting slab, and heterogeneous structures in Earth's deep interior, which has critical impacts on the thermochemical evolution and geodynamics in different regions.

A journey to the center of the Earth

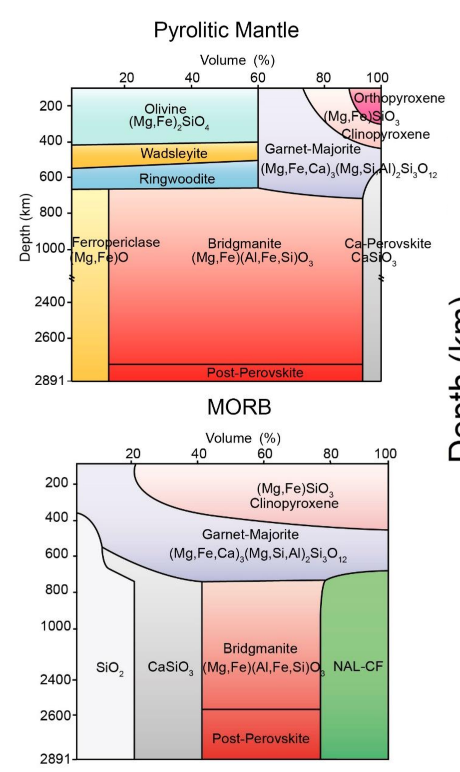
Mapping the thermal profile in Earth's interior: Deep Earth Thermal Conductivity Anatomy (DETCA)

Seismic Tomography

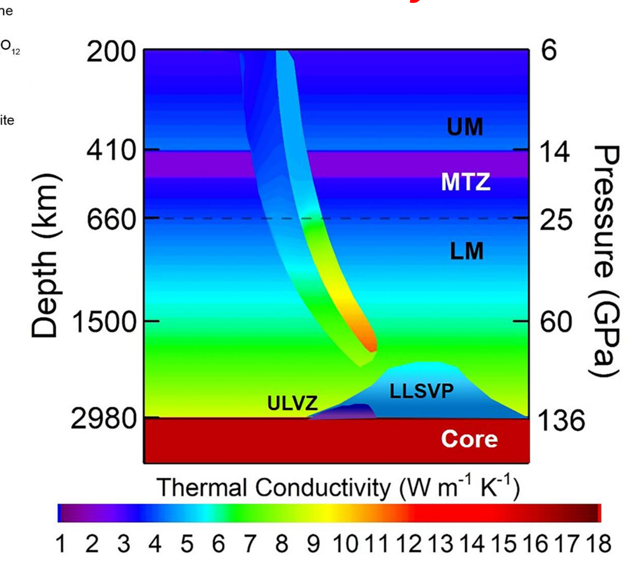


PNAS 116,16159 (2019)

www.olcf.ornl.gov/2017/03/28/a-seismic-mapping-milestone



Thermal Conductivity Anatomy

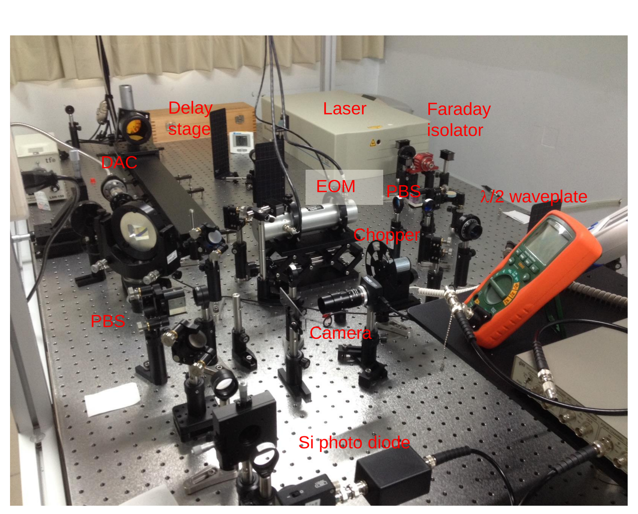


As of December 2023

Thermal conductivity of Earth materials is key to control the temperature profile, thermal evolution, thermochemical structures, and dynamics of Earth interior.

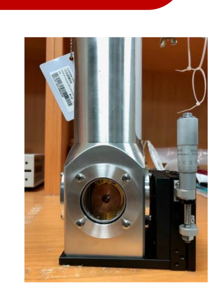
Ultrafast optical pump-probe spectroscopy coupled with high-pressure diamond cells and high-temperature heating or low-temperature cooling

Ultrafast optical pump-probe measurements at Academia Sinica

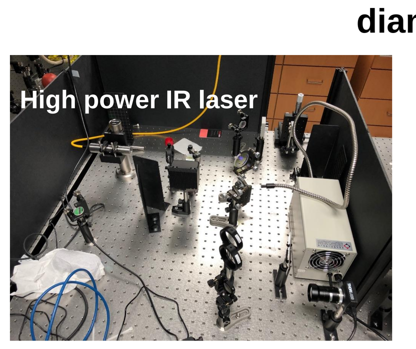


Diamond anvil cell

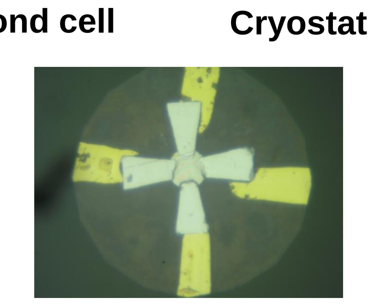
Externally-heated diamond cell



Cryostat



Laser heating



Four point probe measurements

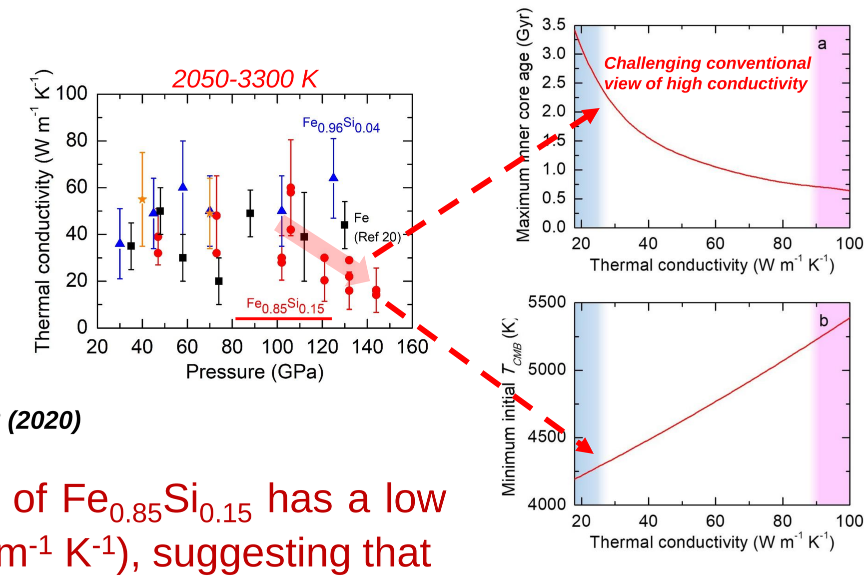
Time-domain thermoreflectance, four point probe technique + diamond cell with heating/cooling

enable measurements of thermal and electrical conductivity and elastic constants at high pressures and variable temperatures

- ***General*** *for almost* ***all samples/minerals***
- *Measurements at* ***extreme P, T, t,*** *and* ***chemical compositions***

Discovering anomalous thermal structures in deep Earth, fundamentally changing our understanding of Earth's thermochemical structure and evolution history

Earth's core

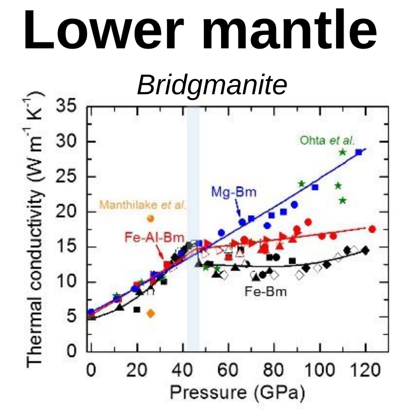


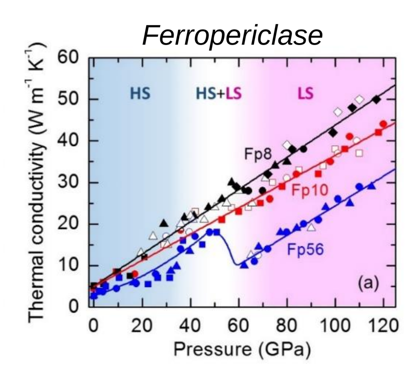
Hsieh et al., Nat. Commun. 11, 3332 (2020)

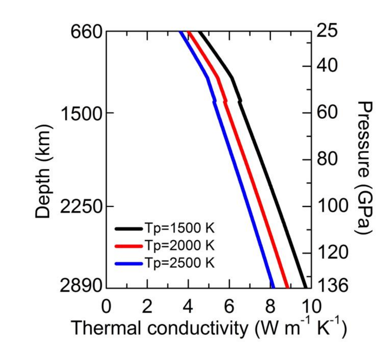
The core with a composition of $Fe_{0.85}Si_{0.15}$ has a low thermal conductivity (~20 W m⁻¹ K⁻¹), suggesting that

- the max age of inner core could be 2 Gyrs, much older than previously thought.
- the thermal energy alone could be enough to operate the geodynamo and sustain Earth's magnetic field: Q_{CMB}, ~10 TW, is larger than Q_a, the isentropic heat flow through the core.

Lower mantle





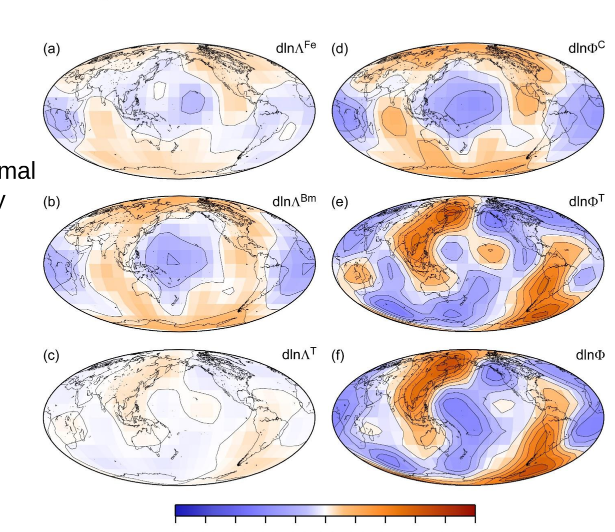


Integrating P, T, K_D, spin transition, lattice distortion

Hsieh et al., JGR 122, 4900 (2017) *Hsieh et al., PNAS 115, 4099 (2018)*

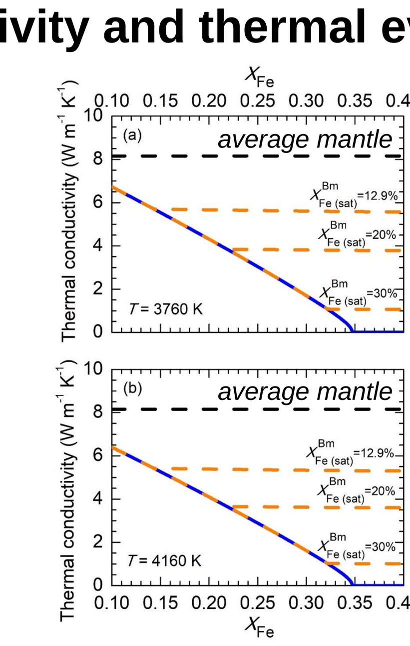
Impacting lower mantle thermal conductivity and thermal evolution

LLVPs thermal conductivity anomalies



CMB heat flux anomalies due to *Compositional anomalies*

Temperature anomalies

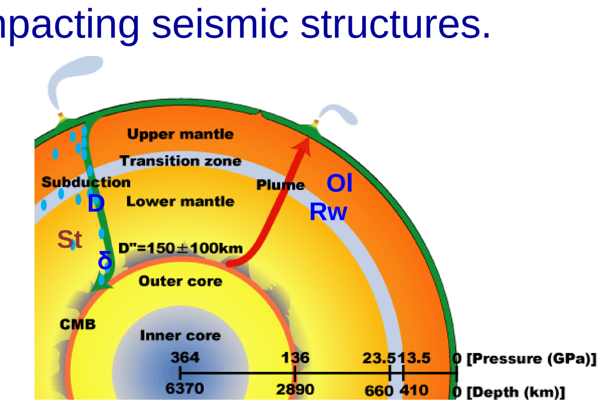


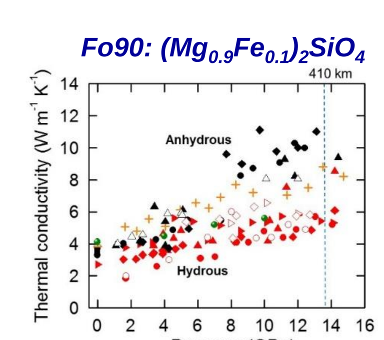
Modelling the thermal conductivity of a hot, iron-enriched ULVZ

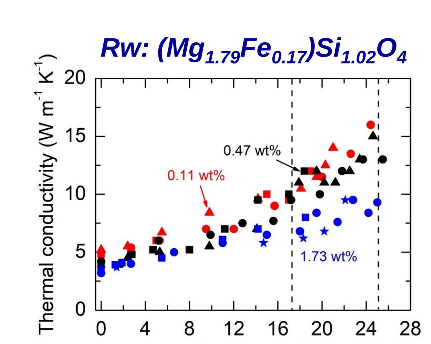
- Presence of Fe and Al has strong effects on the thermal conductivity of bridgmanite and ferropericlase under relevant high *P-T* conditions.
- The LLVPs' thermal conductivity and CMB heat flux are influenced accordingly.
- Above the CMB, iron-enriched mantle aggregates not only have ultra-low seismic velocity, but also ultra-low thermal conductivity (~30% to 80% lower than the average mantle). This would lead to a high temperature anomaly, affecting the rheology and dynamics at both sides of the CMB.

Upper mantle

Earth's deep water cycle makes some minerals hydrated, resulting in poor heat conduction and low temperature anomaly, preserving hydrous minerals and impacting seismic structures.







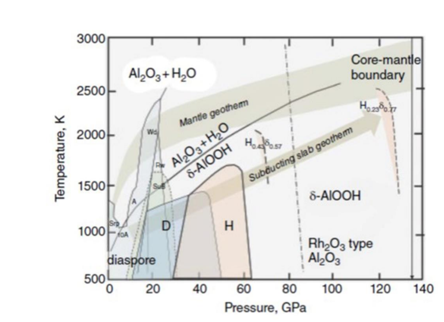
Chang et al., PNAS 114, 4078 (2017) *Marzotto et al., GRL (2020)*

Acknowledgements

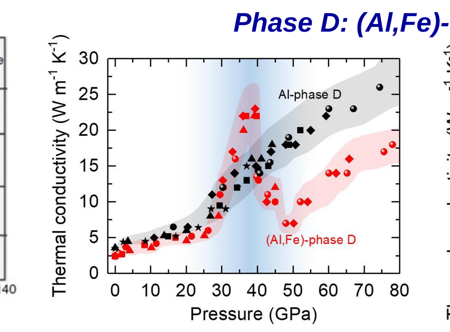
We acknowledge funding support from the Academia Sinica and the National Science and Technology Council of Taiwan, Republic of China, under Contract AS-IA-111-M02, 107-2628-M-001-004-MY3, and 110-2628-M-001-001-MY3. The works presented here are co-authored with F. Deschamps (*Academia Sinica, Taiwan)*, E. Ohtani *(Tohoku U, Japan)*, Jung-Fu Lin (*U Texas, Austin, USA*), E. Marzotto (*GFZ, Germany)*, T. Ishii (*Okayama, Japan*), S. Labrosse (*CNRS, France)*, T. Okuchi (*Kyoto U, Japan*), J. Tsuchiya (*Ehime U, Japan),* A. Goncharov (*Carnegie Inst., USA), and* S. Shieh (*Western U, Canada), etc.*

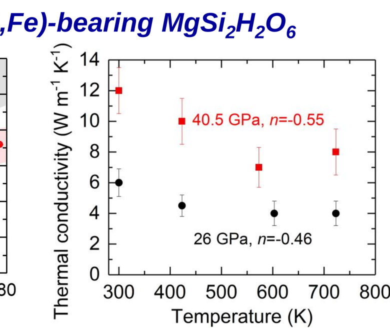
Phase D is a potential water carrier to transition zone and shallow lower mantle

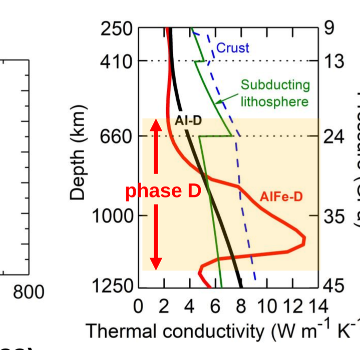
Phase D: (Al,Fe)-bearing $MgSi_2H_2O_6$



Ohtani et al. in *Deep Earth* (2016)

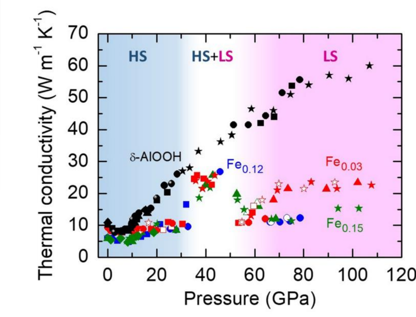


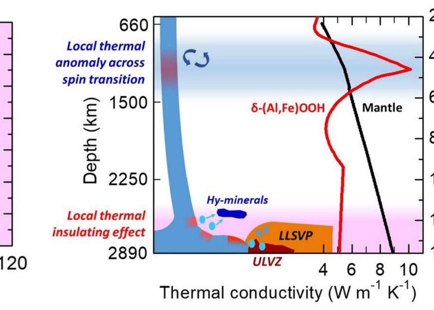




Hsieh et al., JGR (2022)

δ-(Al,Fe)OOH is stable at lowermost mantle conditions: a candidate to transport water to the bottom of the mantle

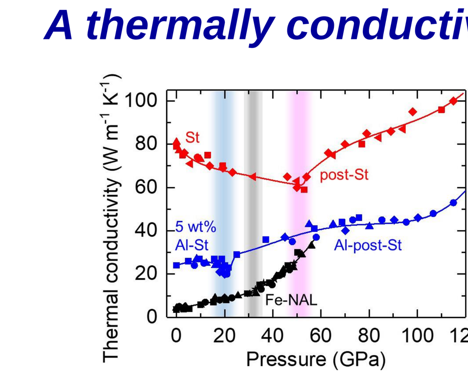


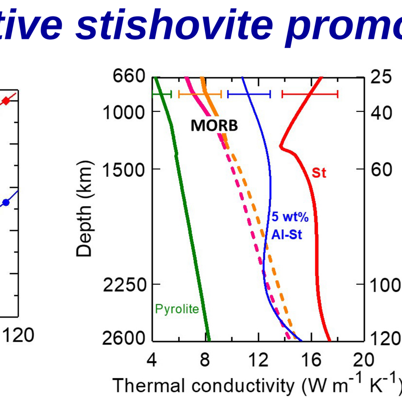


Hsieh et al., GRL (2020)

- An iron spin transition leads to a thermal blanket effect that promotes heating and dehydration.
- Water released from δ-(Al,Fe)OOH facilitates partial melting of minerals for seismic ULVZ. It also serves as a water source for deep-mantle hydrous minerals, e.g., hydrous Al-bearing bridgmanite.

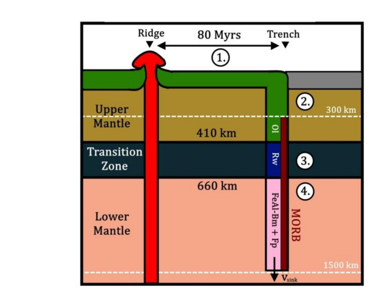
A thermally conductive stishovite promotes rapid warming of a sinking slab

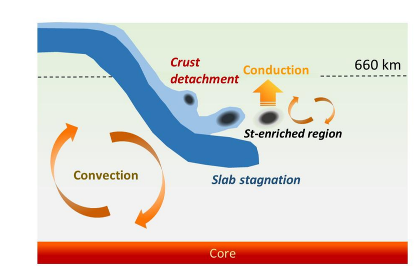


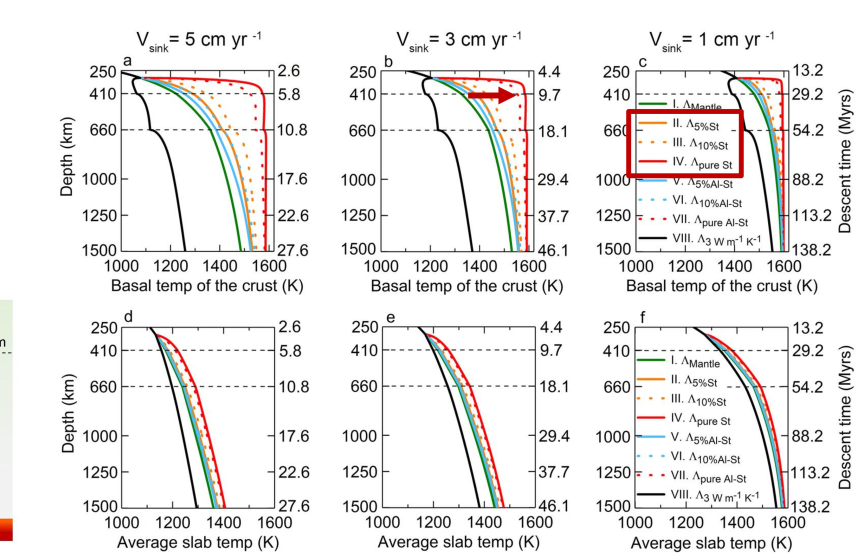


The high thermal conductivity of stishovite in basaltic crust results in a local high T anomaly, facilitating crust detachment, and slab stagnation at shallow lower mantle.

Hsieh et al., EPSL 584, 117477 (2022)

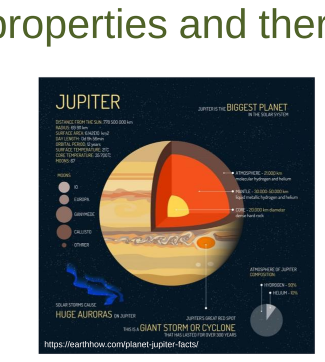




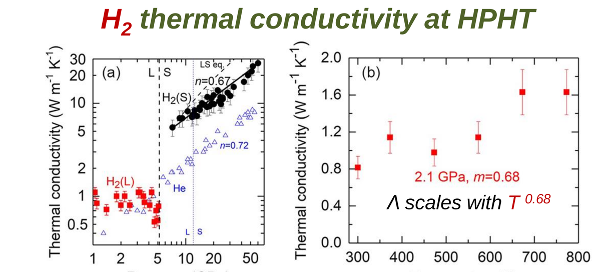


Planetary interiors

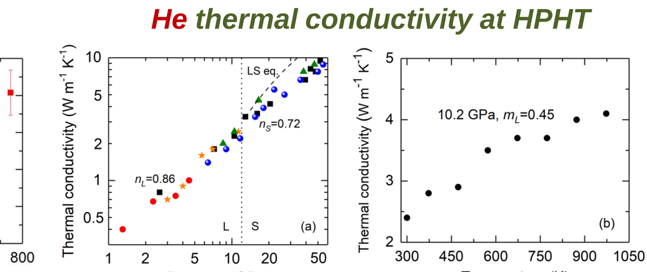
Volatiles in giant planets and icy bodies critically affect their physical and chemical properties and thermochemical evolution



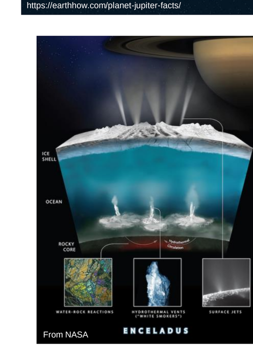
H_2 thermal conductivity at HPHT



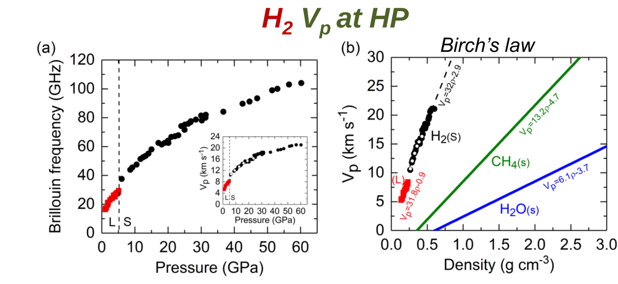
He thermal conductivity at HPHT



Hsieh, et al., Materials 15, 6681 (2022)

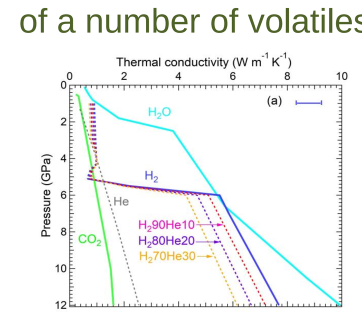


H_2 V_p at HP

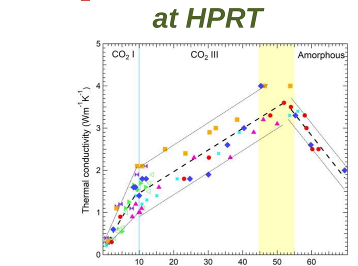


Shieh et al., GRL 50, e2023GL103994 (2023)

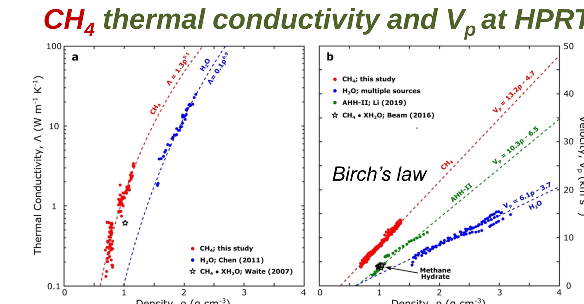
Modelling thermal conductivity of a number of volatiles



CO_2 thermal conductivity at HPHT



CH_4 thermal conductivity and V_p at HPRT



Shieh et al., JGR Planets (2022) *Meyer et al., JGR Planets (2022)*

Low thermal conductivity of H_2–He mixtures makes large temperature gradient at the shallow layers of giant planets.

Summary

- Thermal conductivity of materials in Earth and planetary interiors plays key roles in influencing their thermochemical evolution.
- Future HPHT and HPLT data are required to further pin down the thermal transport properties with relevant applications.
- Further combinations of transport properties and numerical modelling will offer novel insights to the dynamics and evolution in Earth and planetary interiors.