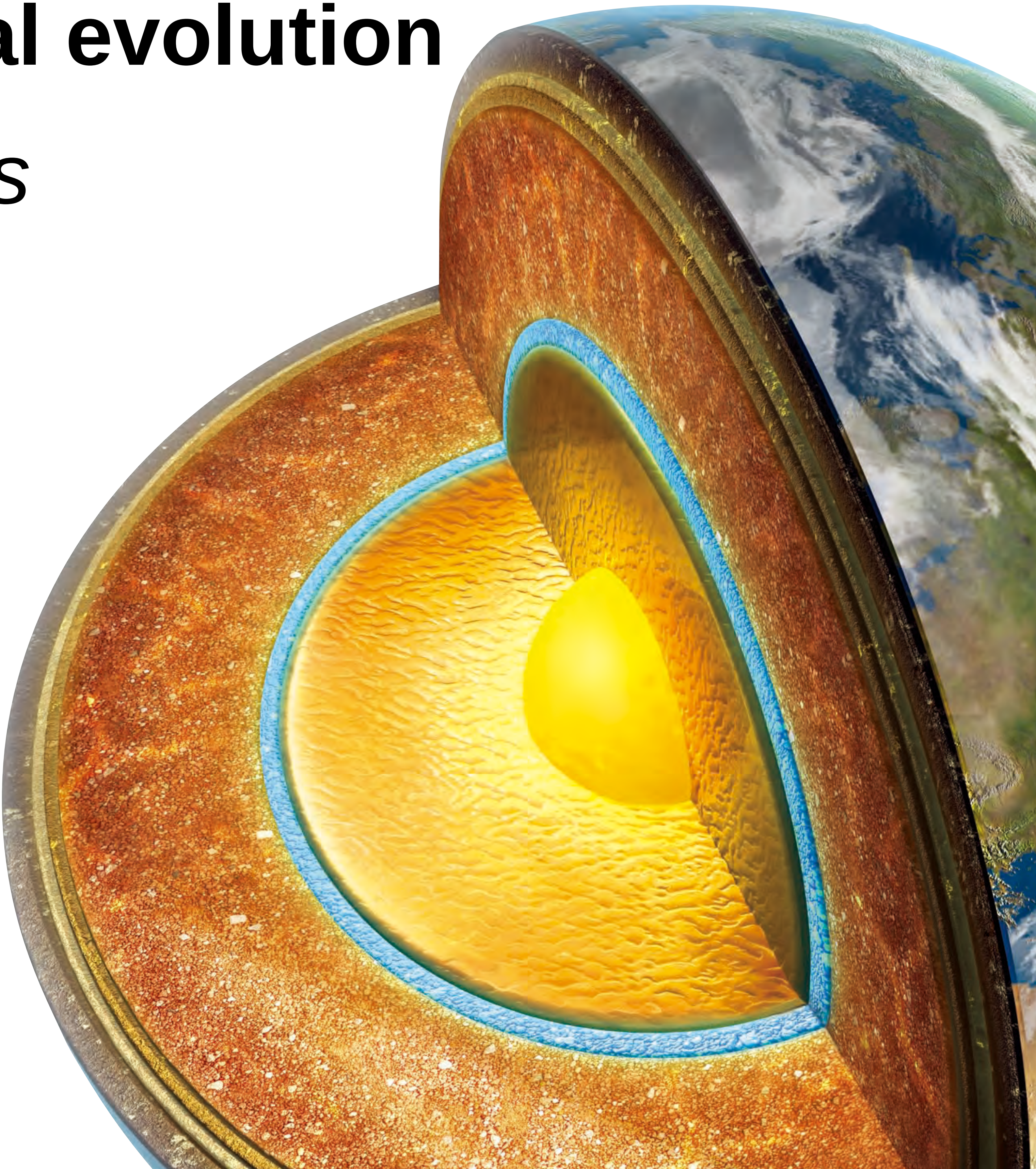
The Earth’s thermal evolution

from mineral physics perspective



Kenji Ohta

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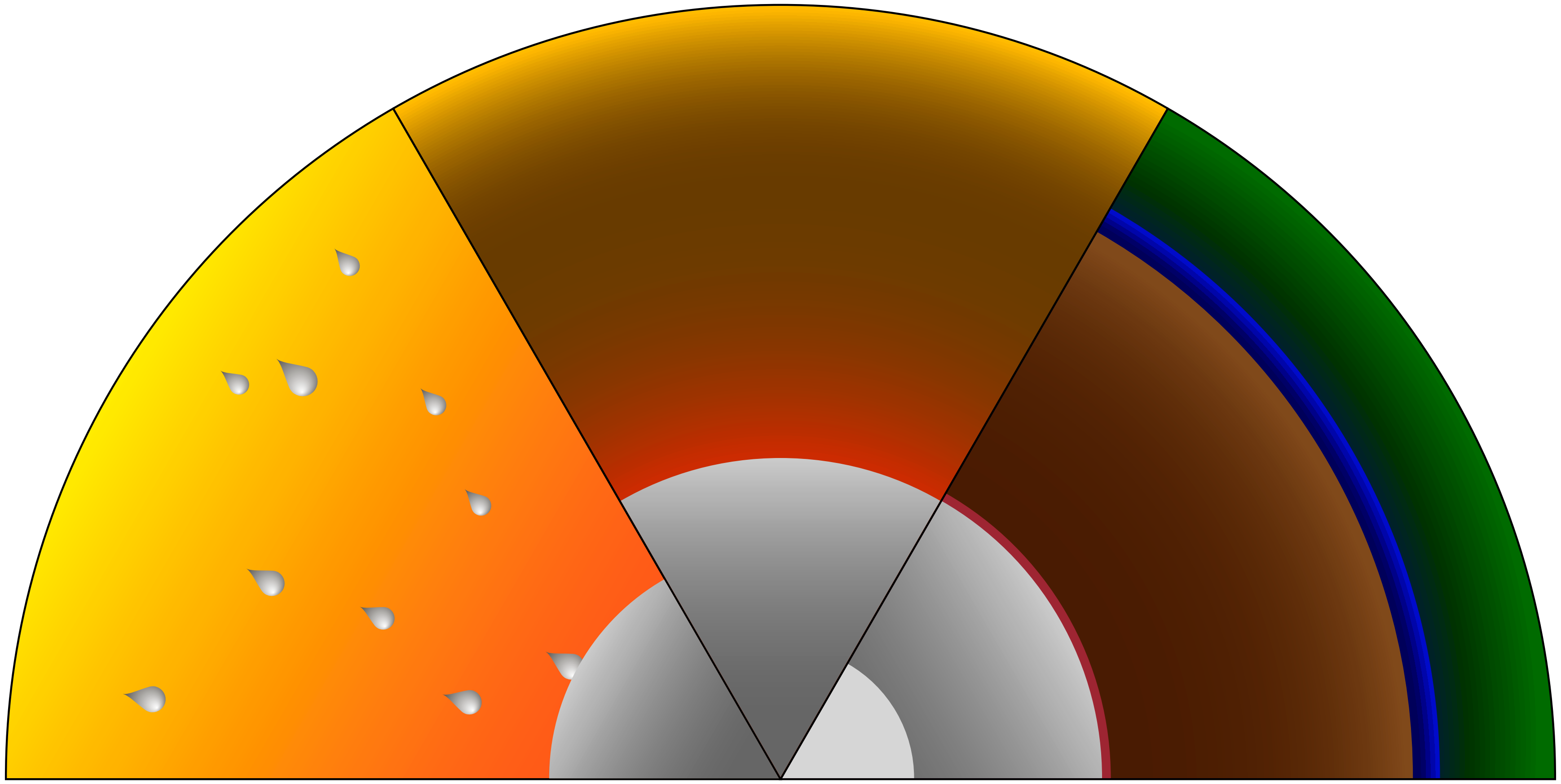
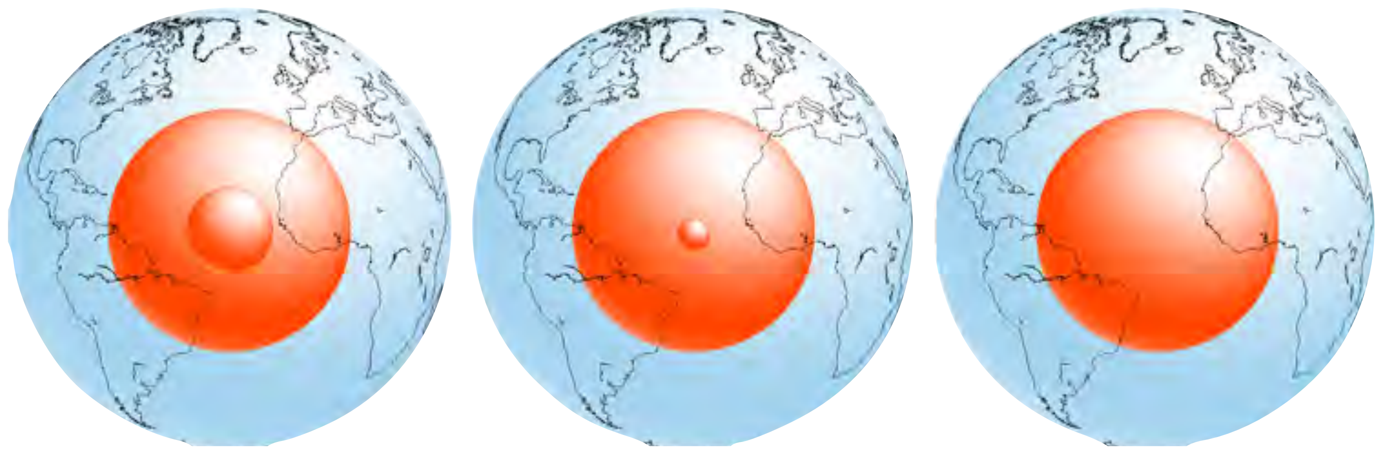
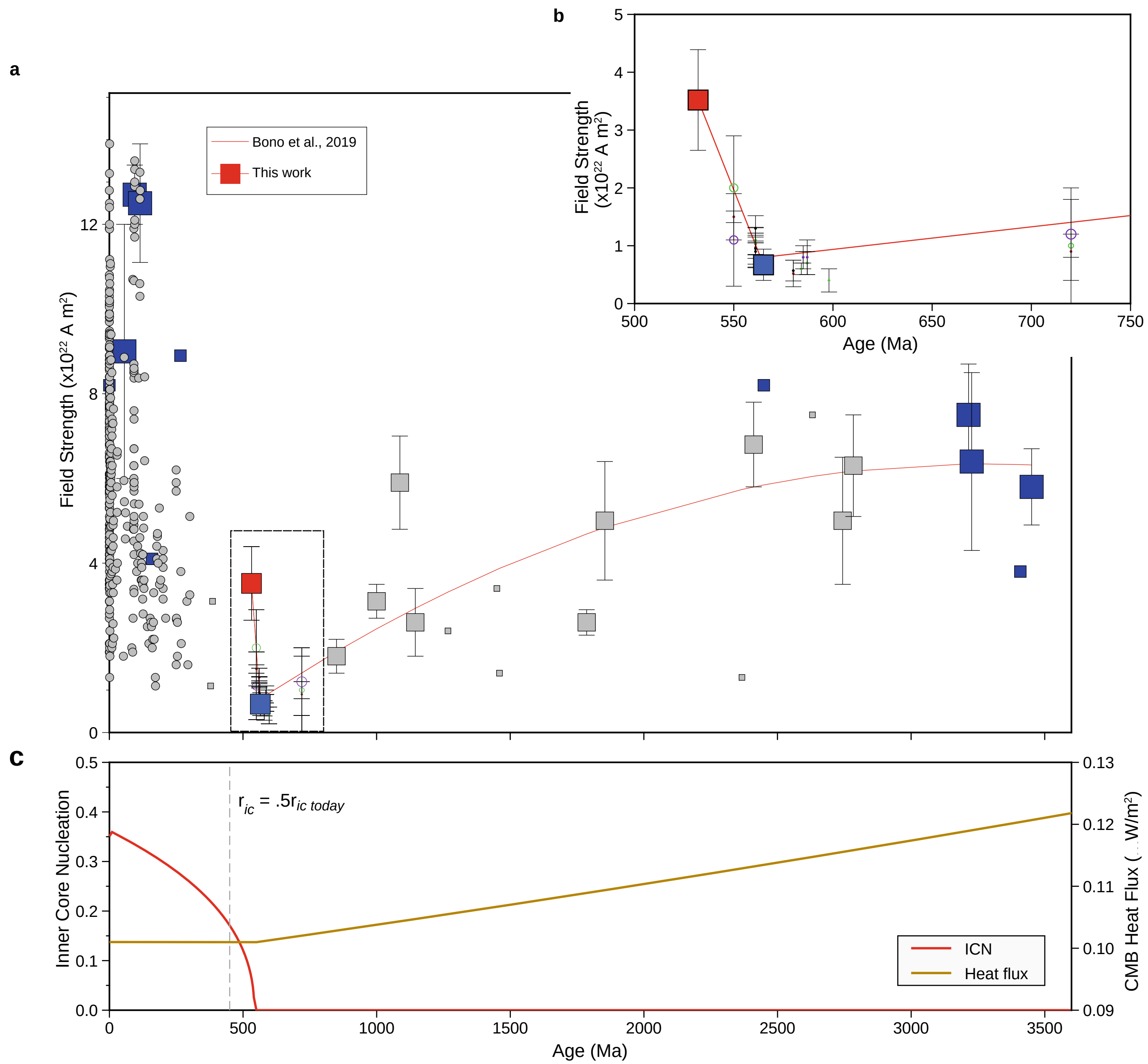
Cooling Earth's evolution

- Accumulation and core formation
- Solidification of magma ocean
- Birth and growth of the inner core
- Core and mantle dynamics and plate tectonics



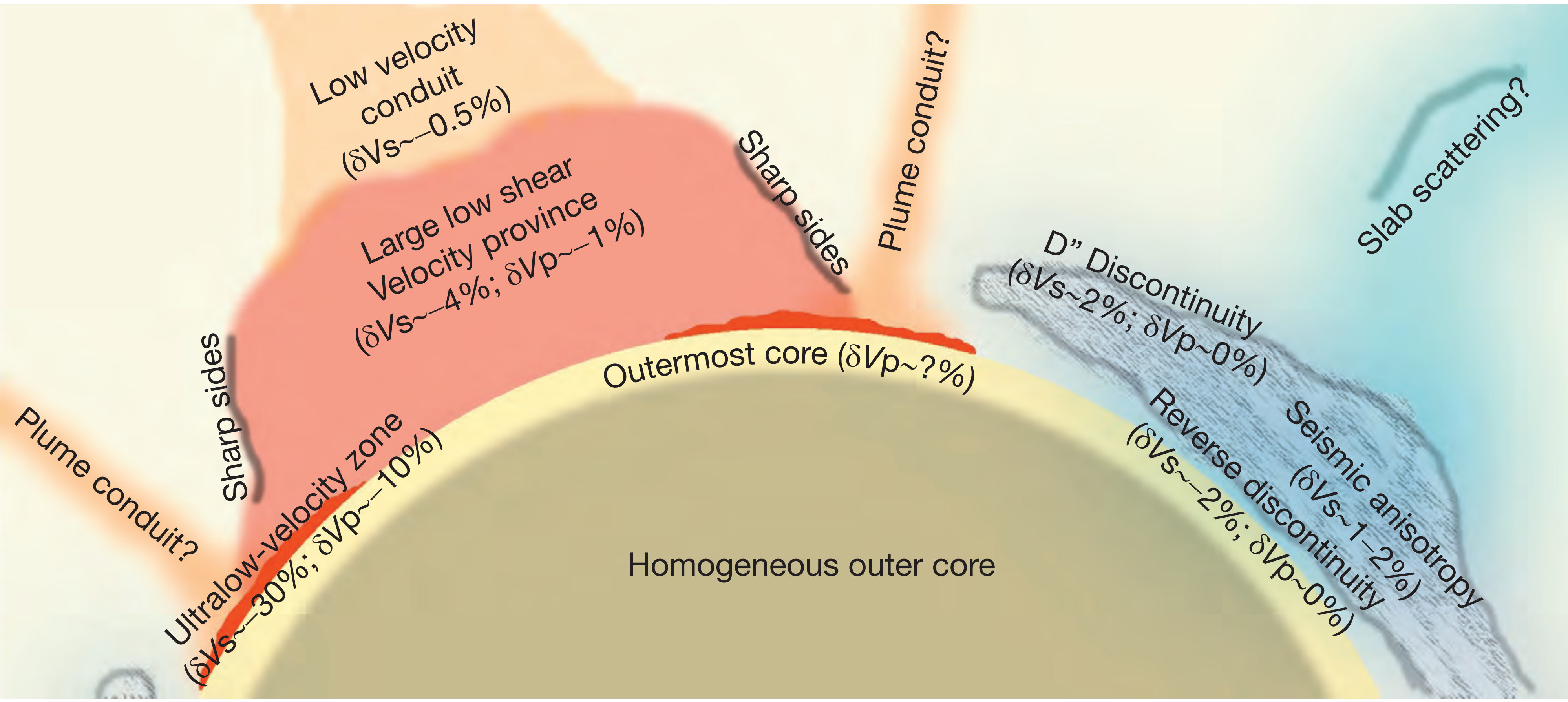
The birth of inner core and geodynamo





Zhou et al., 2022 Nature Communications

Core-mantle "thermal" interaction and coevolution



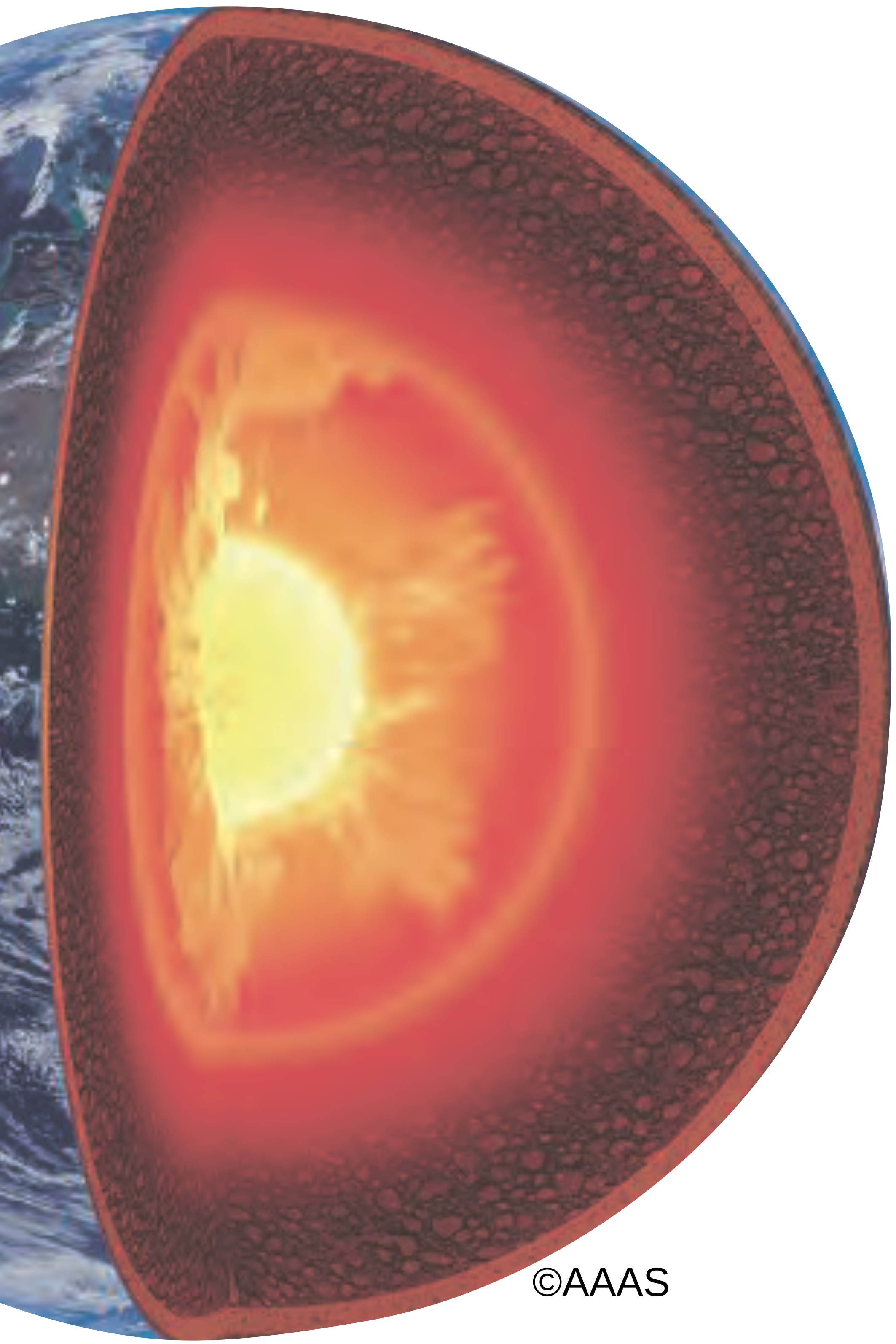
Hernlund & McNamara, 2015 Treatise on Geophys.

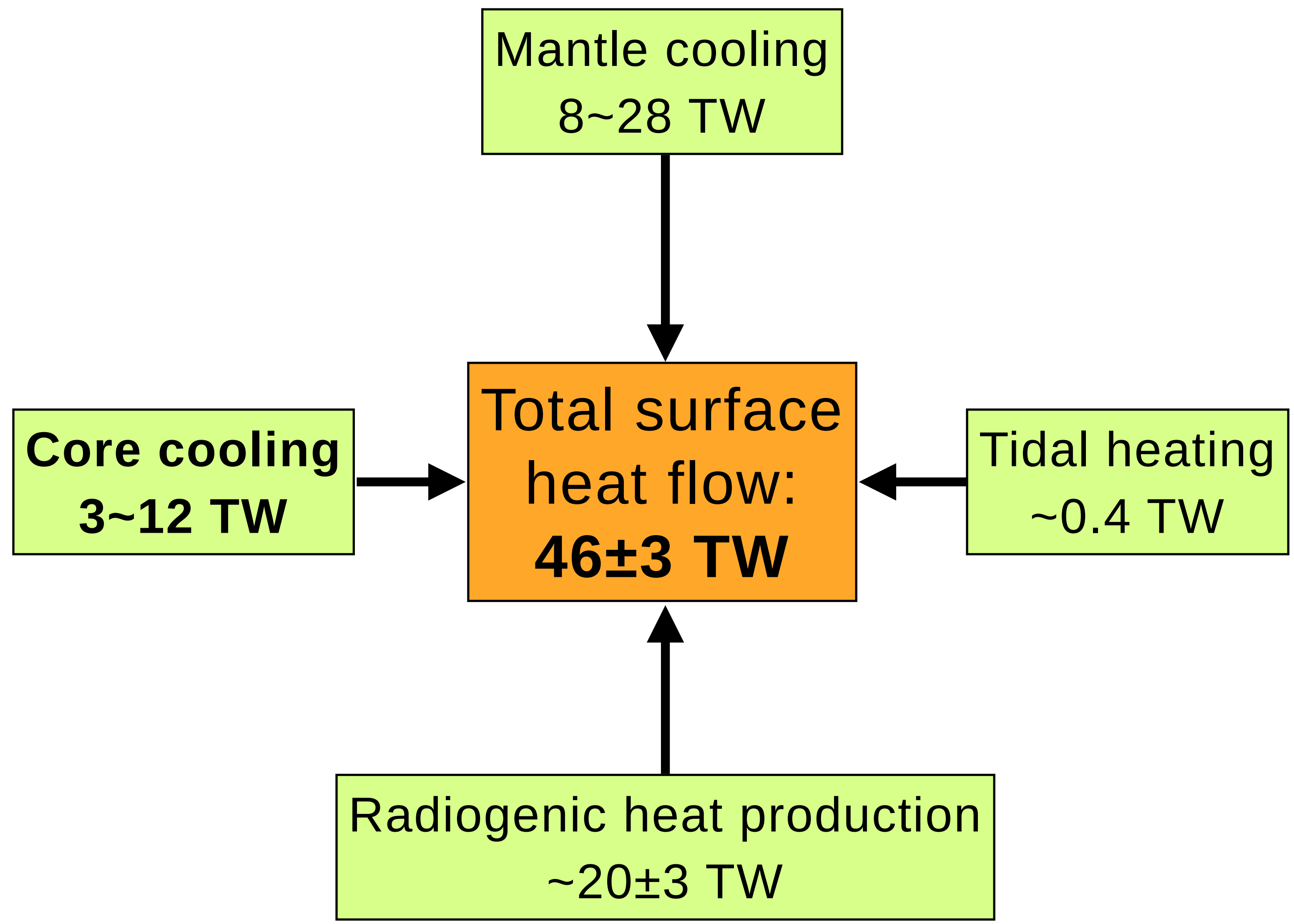
Mantle heat flow
- Mantle dynamics
- Plate tectonics

CMB thermal interaction and evolution
- Structure of thermal boundary layer (thickness of PPv layer)
- Mantle plume generation

Predominant driving force: heat inside the Earth

Earth’s heat budget and heat flow from the core





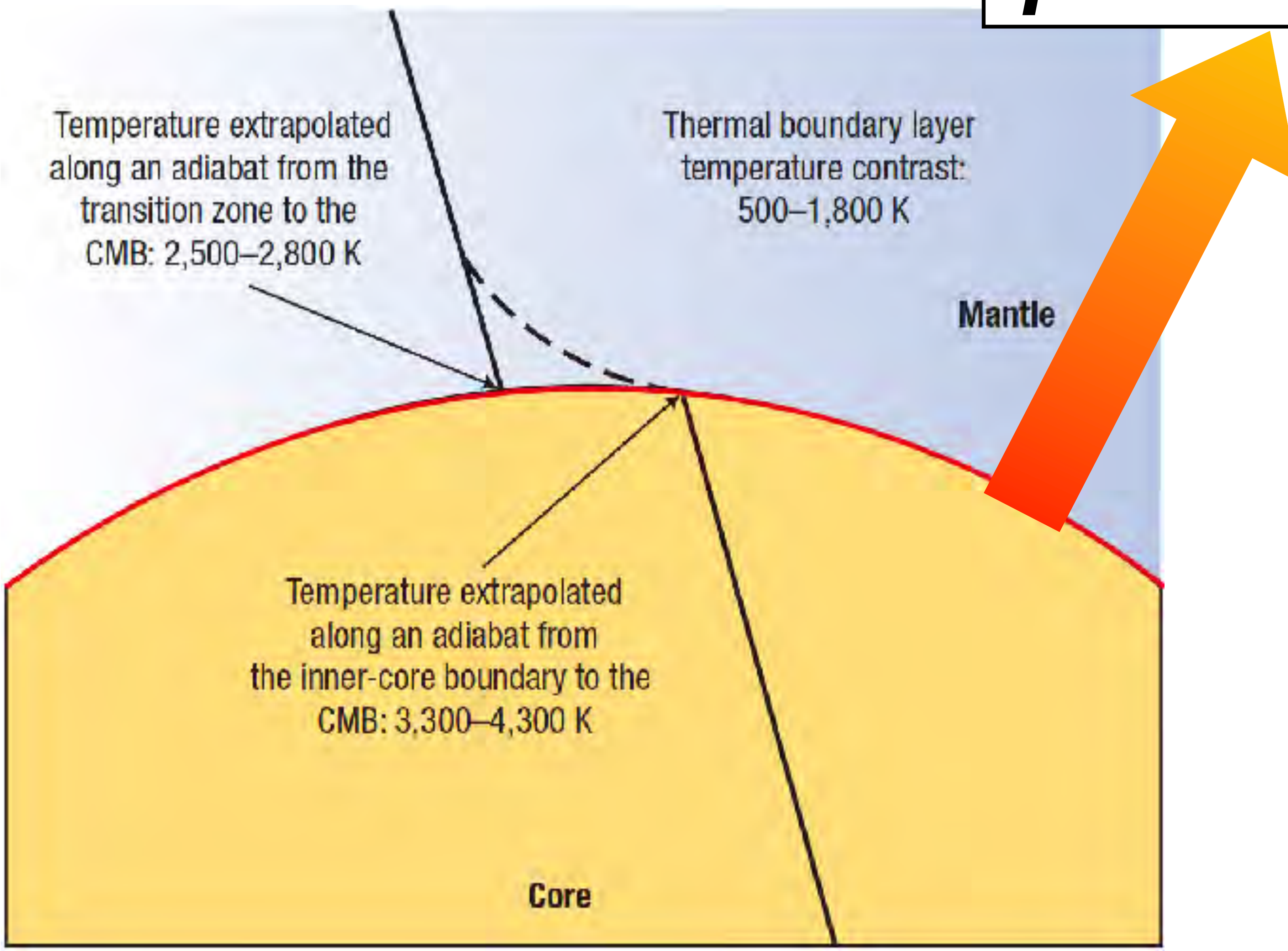
Modified after Lay et al., 2008

Large uncertainty in the estimate of mantle and core cooling

Core cooling

$$q = -\kappa \cdot \mathrm{d}T/\mathrm{d}z$$

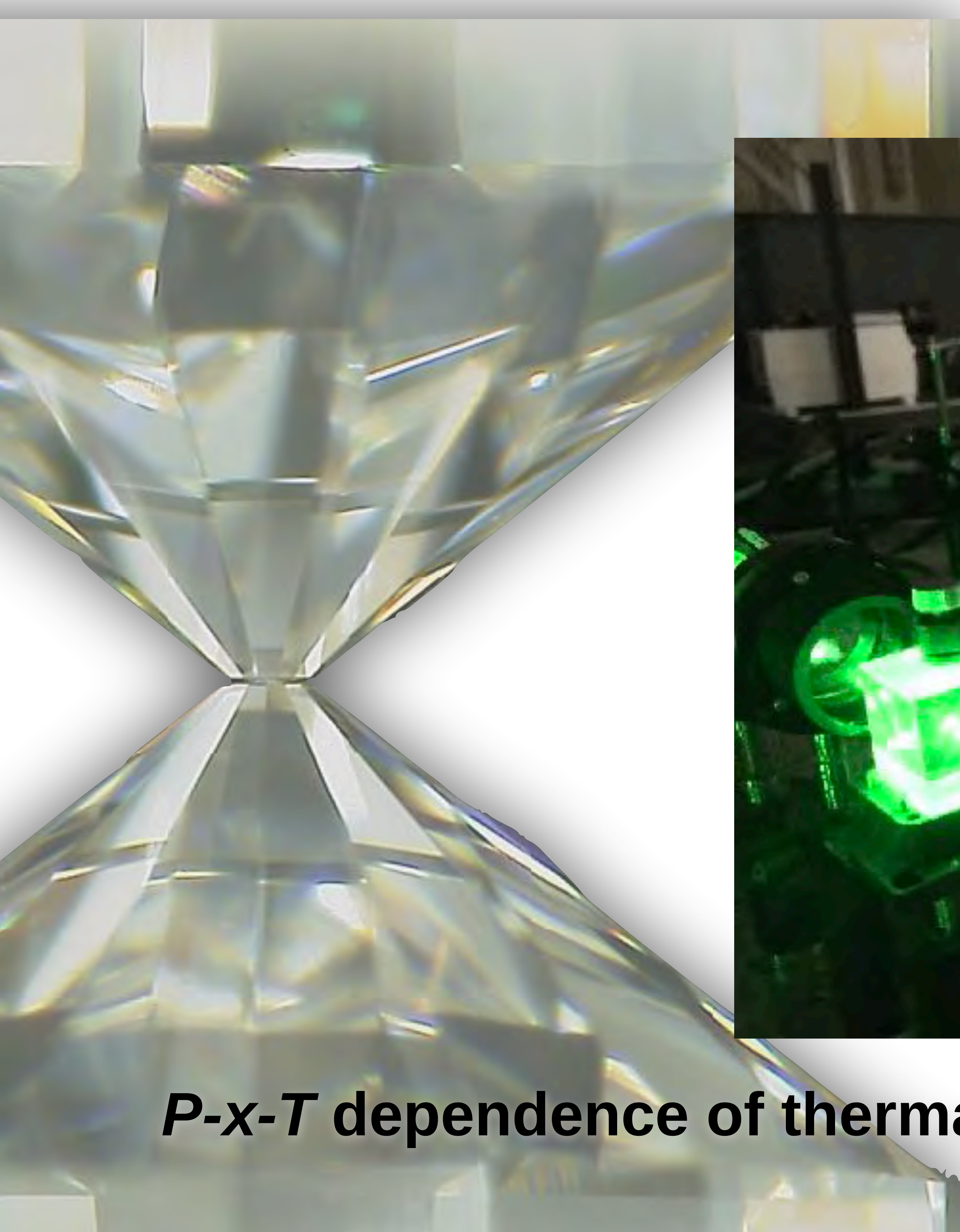
Core-mantle boundary
Pressure (P): 135 GPa

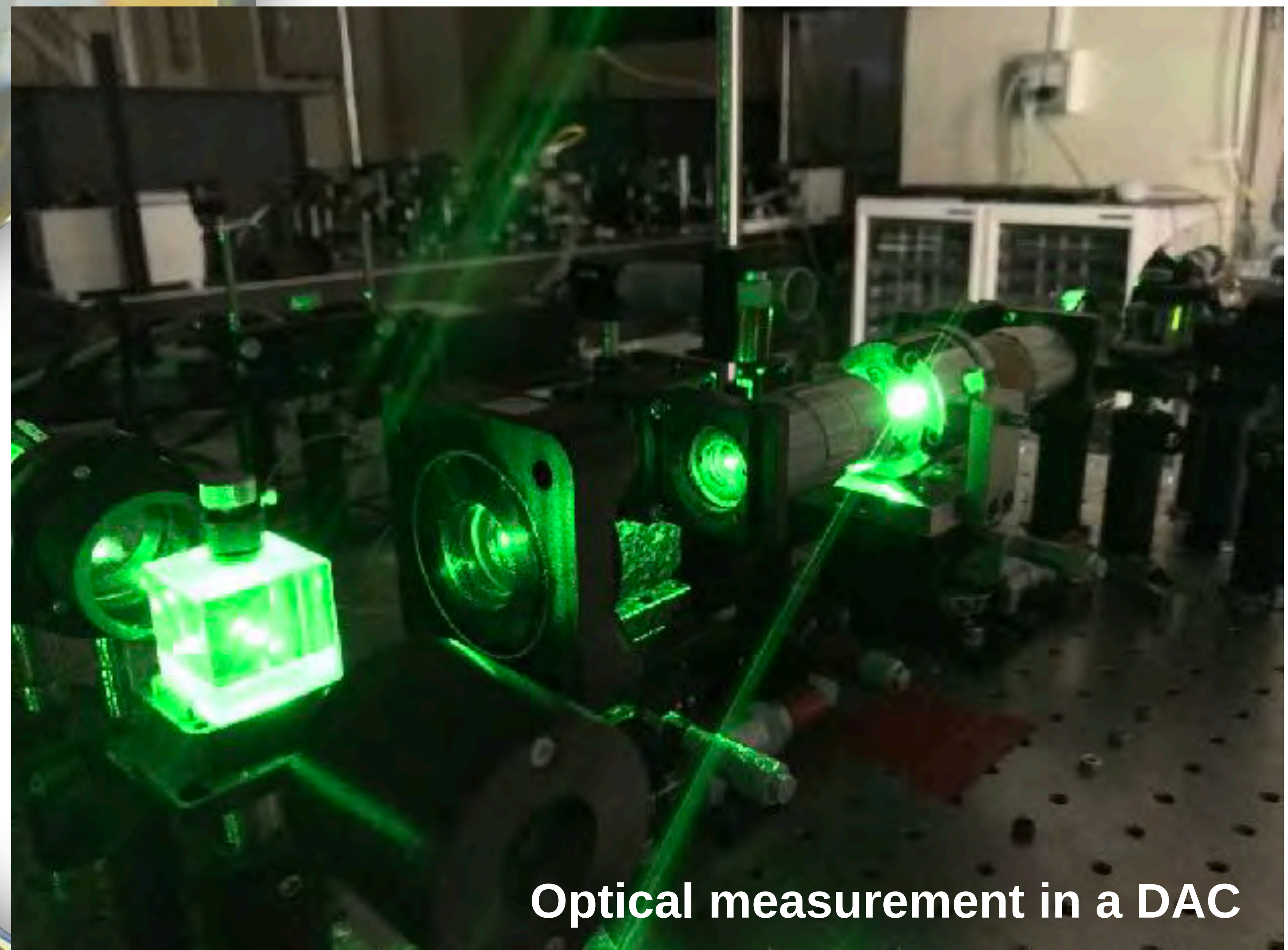


Lay et al., 2008 Nature Geo.

***P-x-T* dependence of thermal conductivity (*κ*) of mantle?**

High-pressure experiments using diamond anvil cell (DAC)





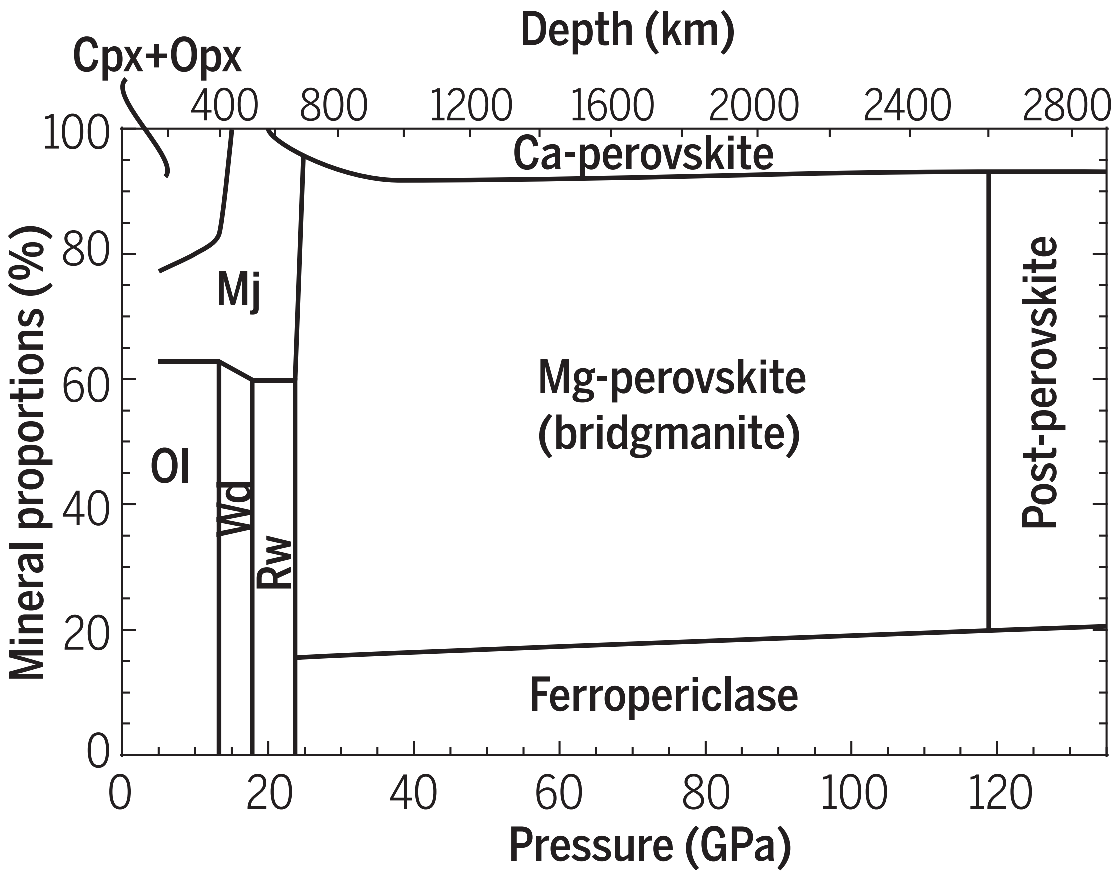
Optical measurement in a DAC

P-x-T **dependence of thermal conductivity (*κ*) of mantle?**

Mineralogy in the Earth's lower mantle

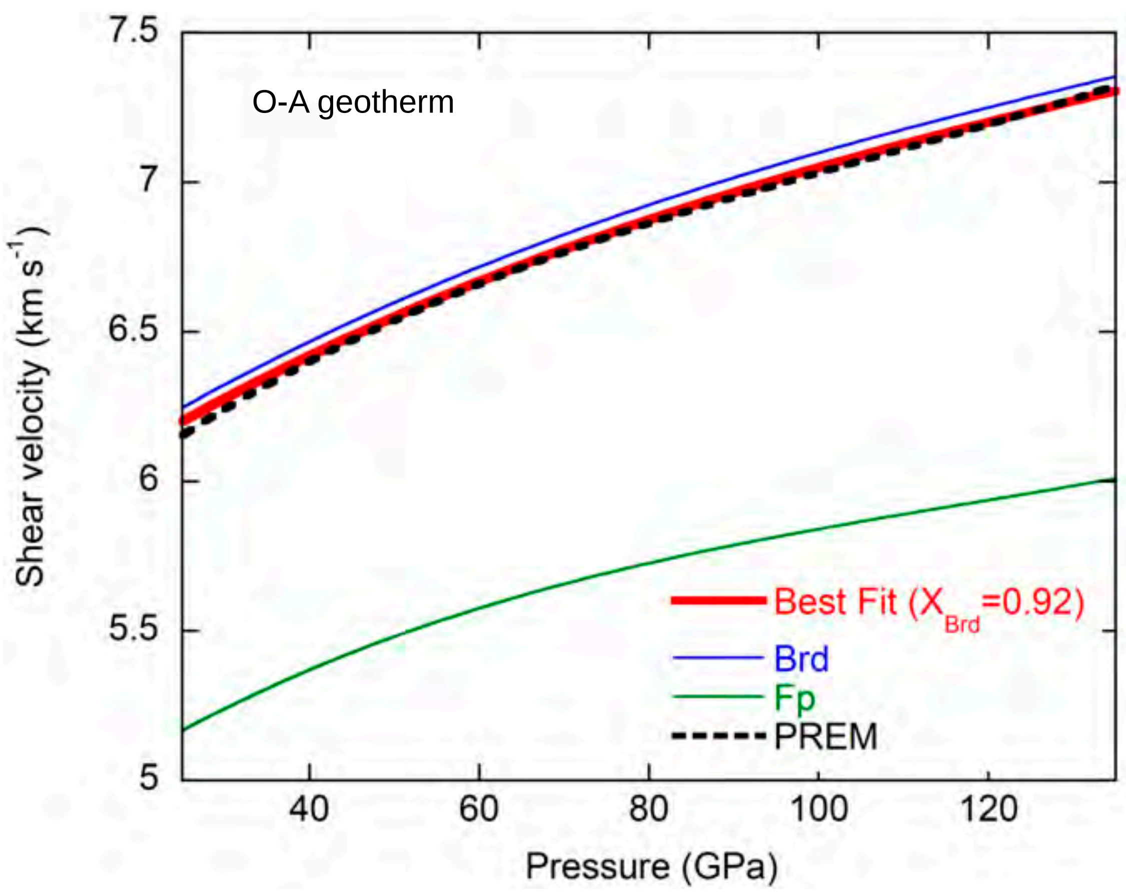
- $(Mg,Fe)(Al,Si)O_3$ bridgmanite (bdg), post-perovskite (PPv)
- $(Mg,Fe)O$ ferropericlase (fp)
- $CaSiO_3$ davemaoite* (dvm)   *named at the end of 2021

Pyrolitic lower mantle



Hirose et al., 2017Science

Bdg-enriched lower mantle

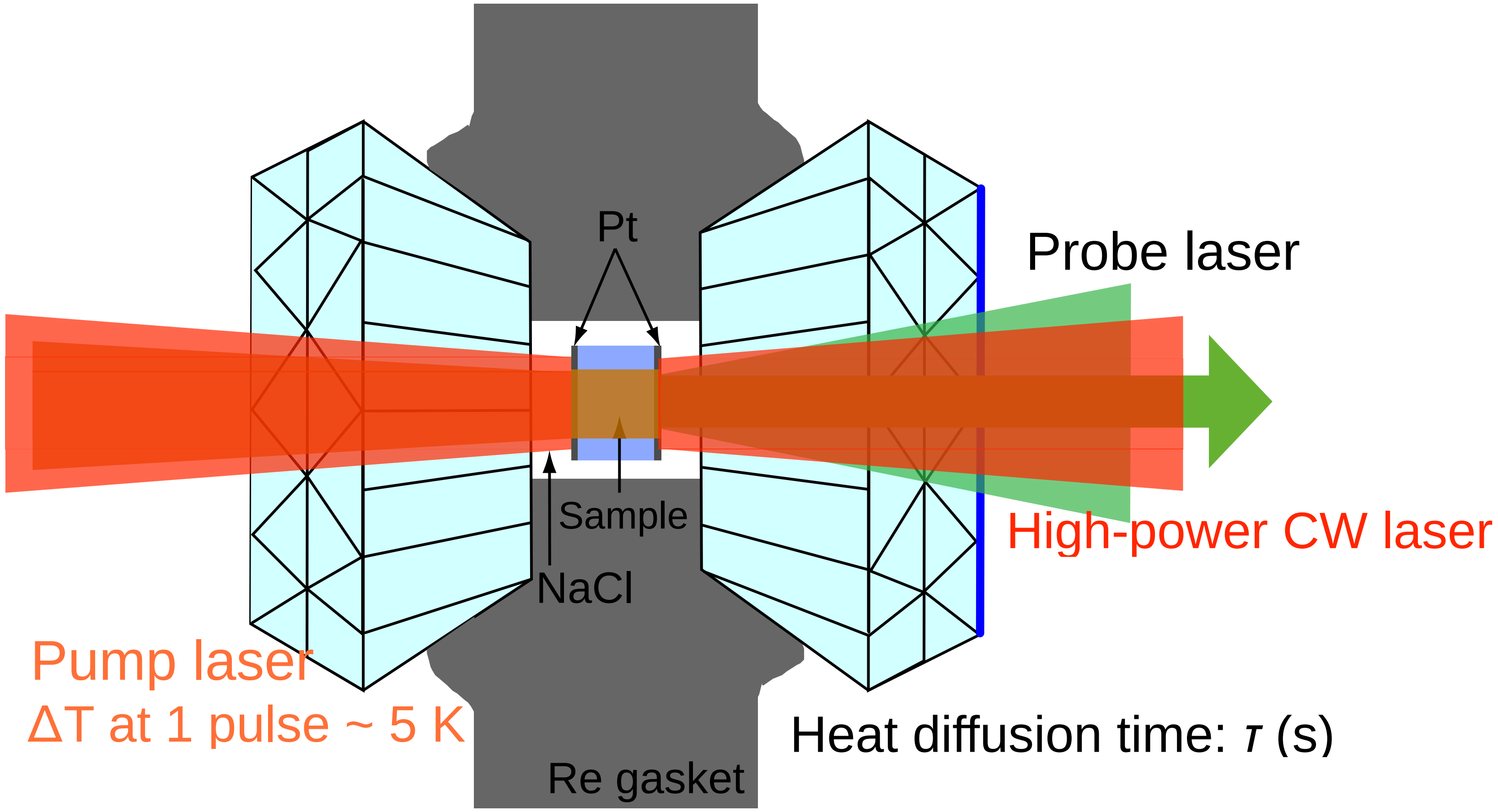


Mashino et al., 2020PNAS

Method
High *P*–*T* thermoreflectance technique in DAC

Thermal conductivity： $\kappa = \rho Cp(d^2/\tau)$

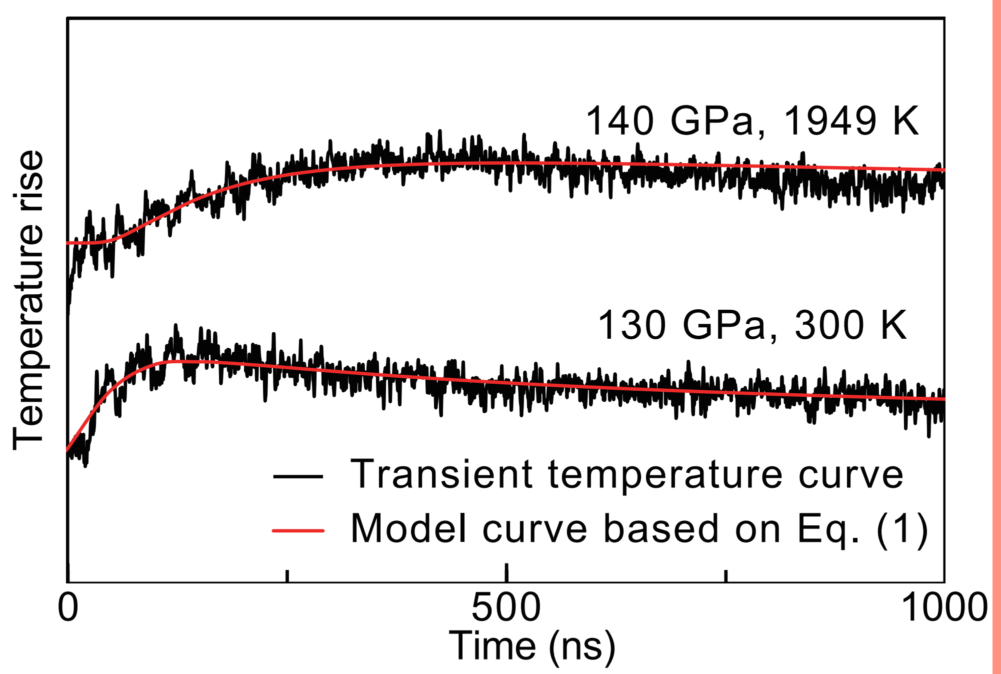
ρ: density, Cp: heat capacity at constant P,
d: sample thickness, τ: heat diffusion time



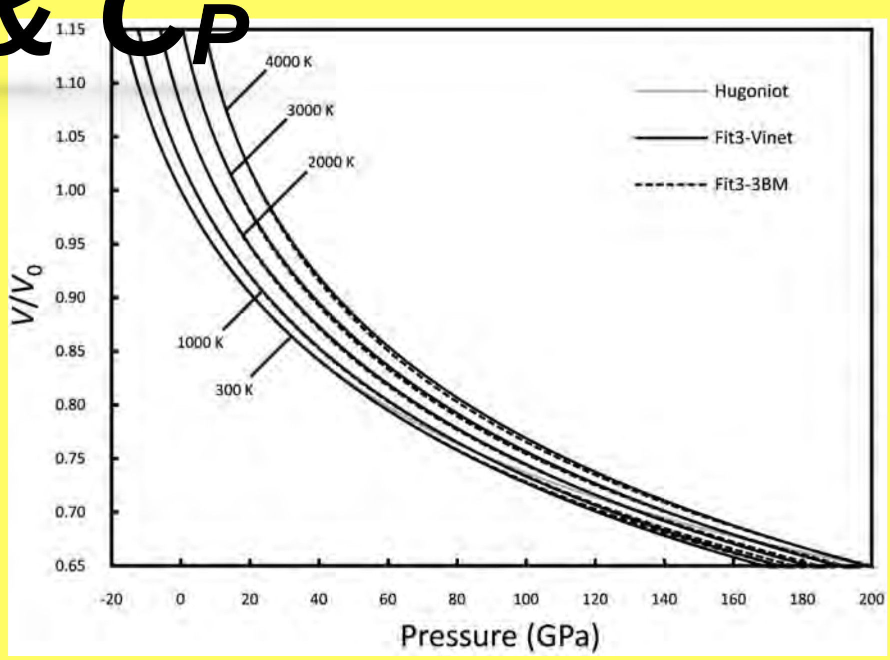
High *P*–*T* thermoreflectance technique in DAC

Thermal conductivity： $\kappa = (d^2/\tau)\rho Cp$

τ



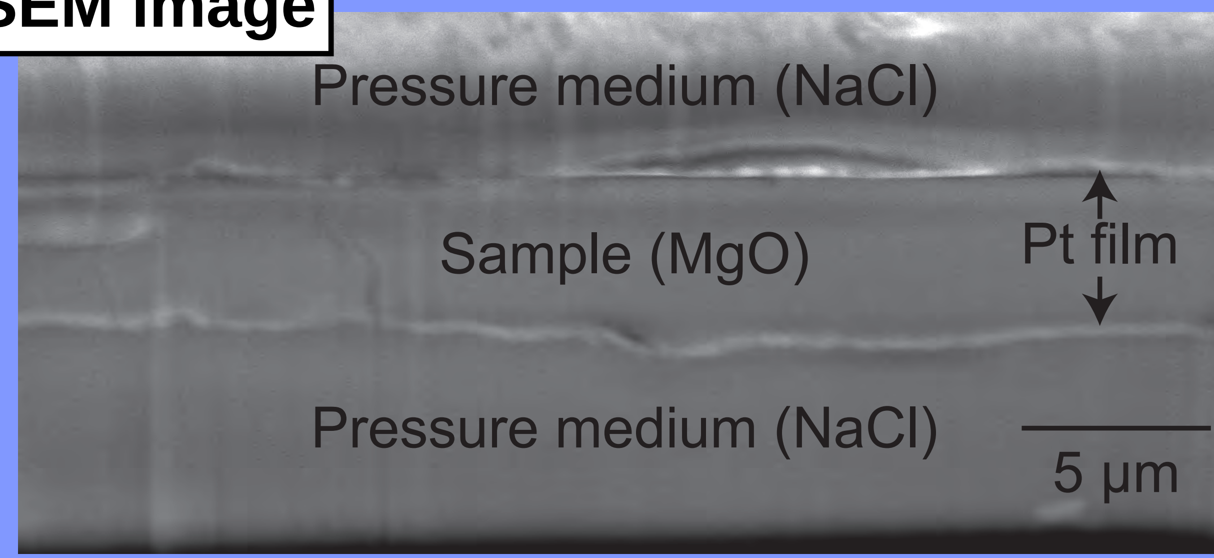
ρ & C_P



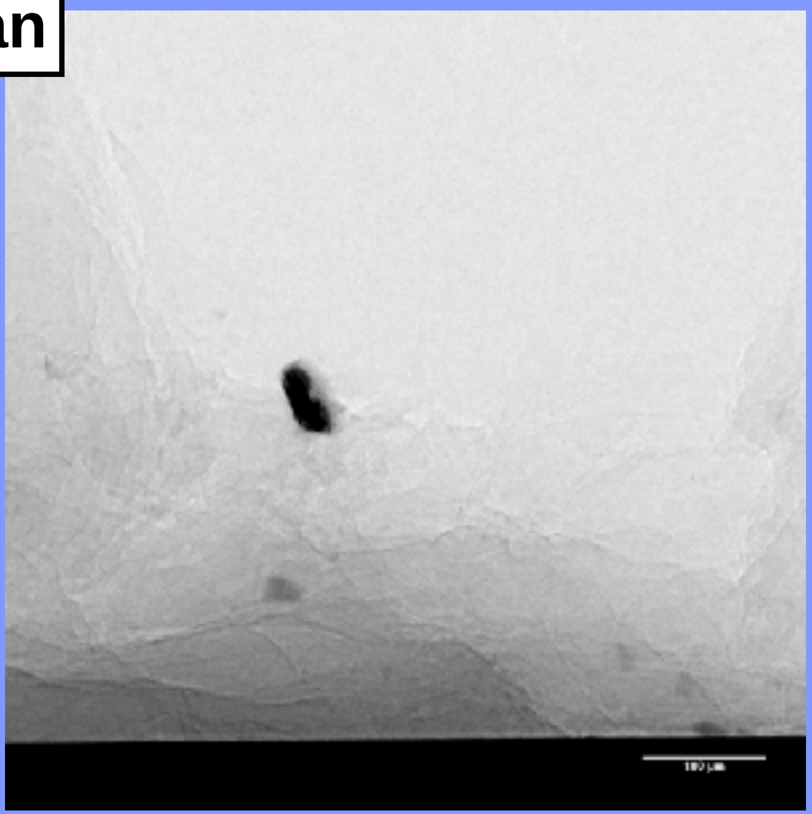
Tange et al., 2009JGR

d

SEM image

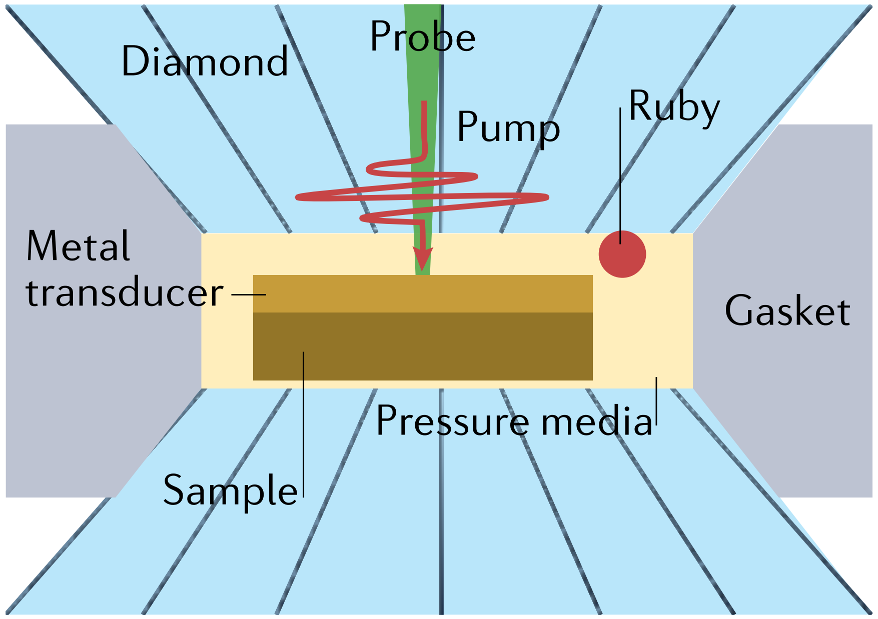


XCT scan



Other methods for measuring κ at high P and T

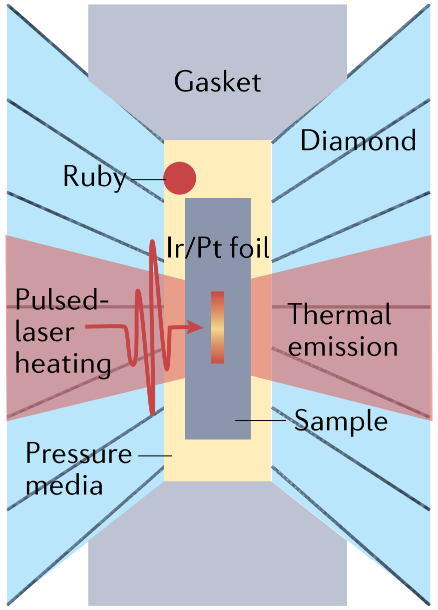
<u>Time-domain thermoreflectance method</u>



e.g., Hsieh et al., 2017JGR

- Similar to ours but front-heat & front-probe
- Measurements for some lower mantle minerals up to 133 GPa and 300 K
- High-T measurement is not feasible so far

<u>Pulsed-laser transient heating method</u>



e.g., Geballe et al., 2020EPSL

- Fast detection of thermal radiation from sample
- Measurements for pyrolite up to 124 GPa and 2460 K
- Large uncertainty in T
- Low-T measurement is not feasible

Advantage in our method: κ with small T error in a wide P–T range

Experimental techniques are developing

before ~2011	now
bdg: 26 GPa and to 1200 K	bdg: 140 GPa and to 450 K
PPv: none	PPv: 180 GPa, and to 1500 K
Fp: 14 GPa, <1300 K	Fp: 127 GPa, to 2000 K
dvm: none	dvm: 70 GPa, to 2000 K
κ_{CMB} ~ 10 W/m/K (Stacey, 1992 Physics of the Earth)	**following slides**

Some fruits of our studies

Earth and Planetary Science Letters 349–350 (2012) 109–115

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Lattice thermal conductivity of $MgSiO_3$ perovskite and post-perovskite at the core–mantle boundary

Kenji Ohta[a,*,1], Takashi Yagi[b], Naoyuki Taketoshi[b], Kei Hirose[a,c], Tetsuya Komabayashi[a], Tetsuya Baba[b], Yasuo Ohishi[d], John Hernlund[e]

Earth and Planetary Science Letters 465 (2017) 29–37

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Thermal conductivity of ferropericlase in the Earth's lower mantle

Kenji Ohta[a,*], Takashi Yagi[b], Kei Hirose[c], Yasuo Ohishi[d]

Earth and Planetary Science Letters 520 (2019) 188–198

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Effect of spin transition of iron on the thermal conductivity of (Fe, Al)-bearing bridgmanite

Yoshiyuki Okuda[a,*], Kenji Ohta[a], Ryosuke Sinmyo[b], Kei Hirose[b,c], Takashi Yagi[d], Yasuo Ohishi[e]

C. R. Geoscience 351 (2019) 229–235

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Internal Geophysics (Physics of Earth's Interior)

Composition and pressure dependence of lattice thermal conductivity of (Mg,Fe)O solid solutions

Akira Hasegawa[a,b,*], Kenji Ohta[a,*], Takashi Yagi[b], Kei Hirose[c], Yoshiyuki Okuda[a], Tadashi Kondo[d]

Earth and Planetary Science Letters 547 (2020) 116466

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Thermal conductivity of Fe-bearing post-perovskite in the Earth's lowermost mantle

Yoshiyuki Okuda[a,*], Kenji Ohta[a], Akira Hasegawa[a,b], Takashi Yagi[b], Kei Hirose[c,d], Saori I. Kawaguchi[e], Yasuo Ohishi[e]

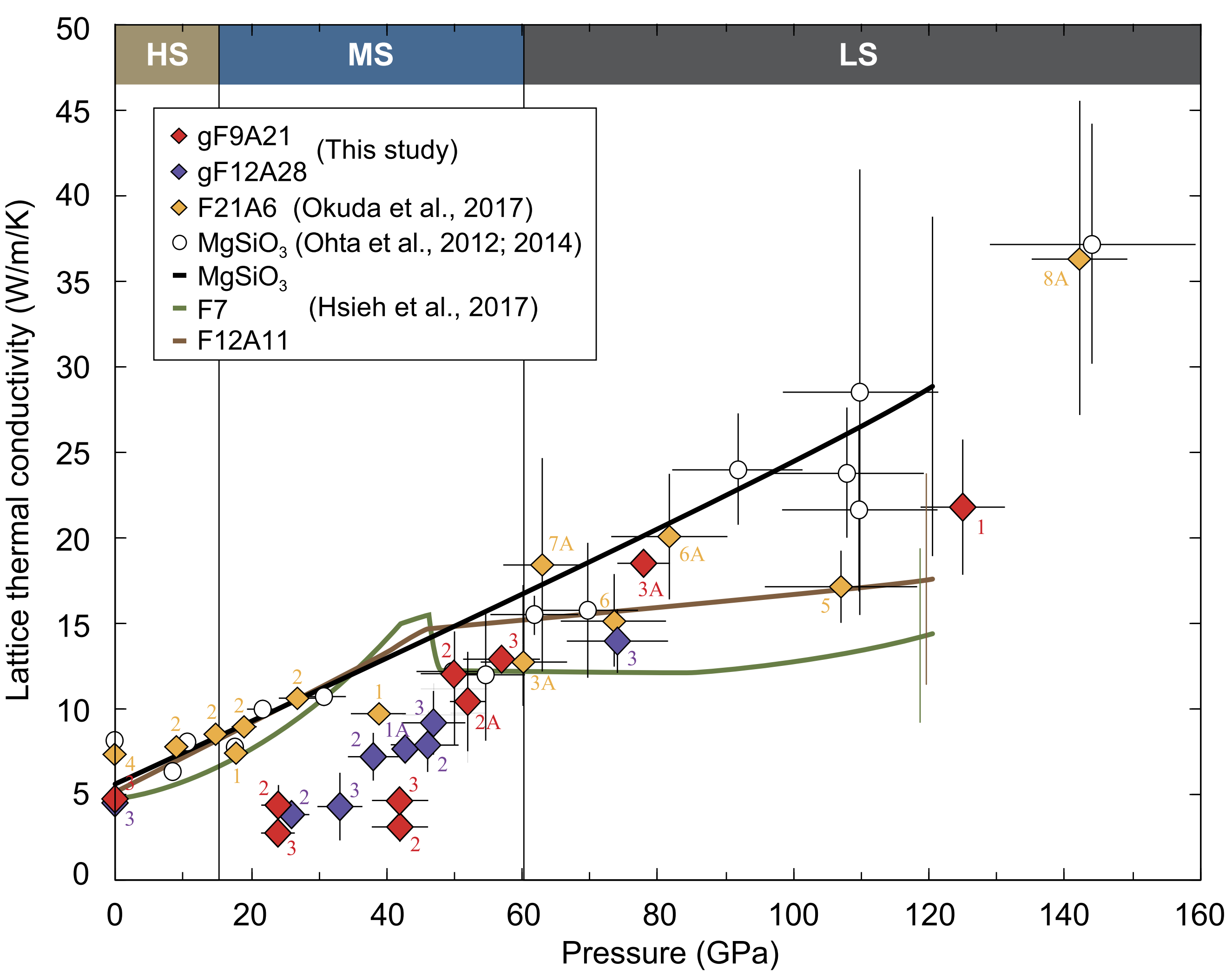
PHYSICAL REVIEW B **104**, 184101 (2021)

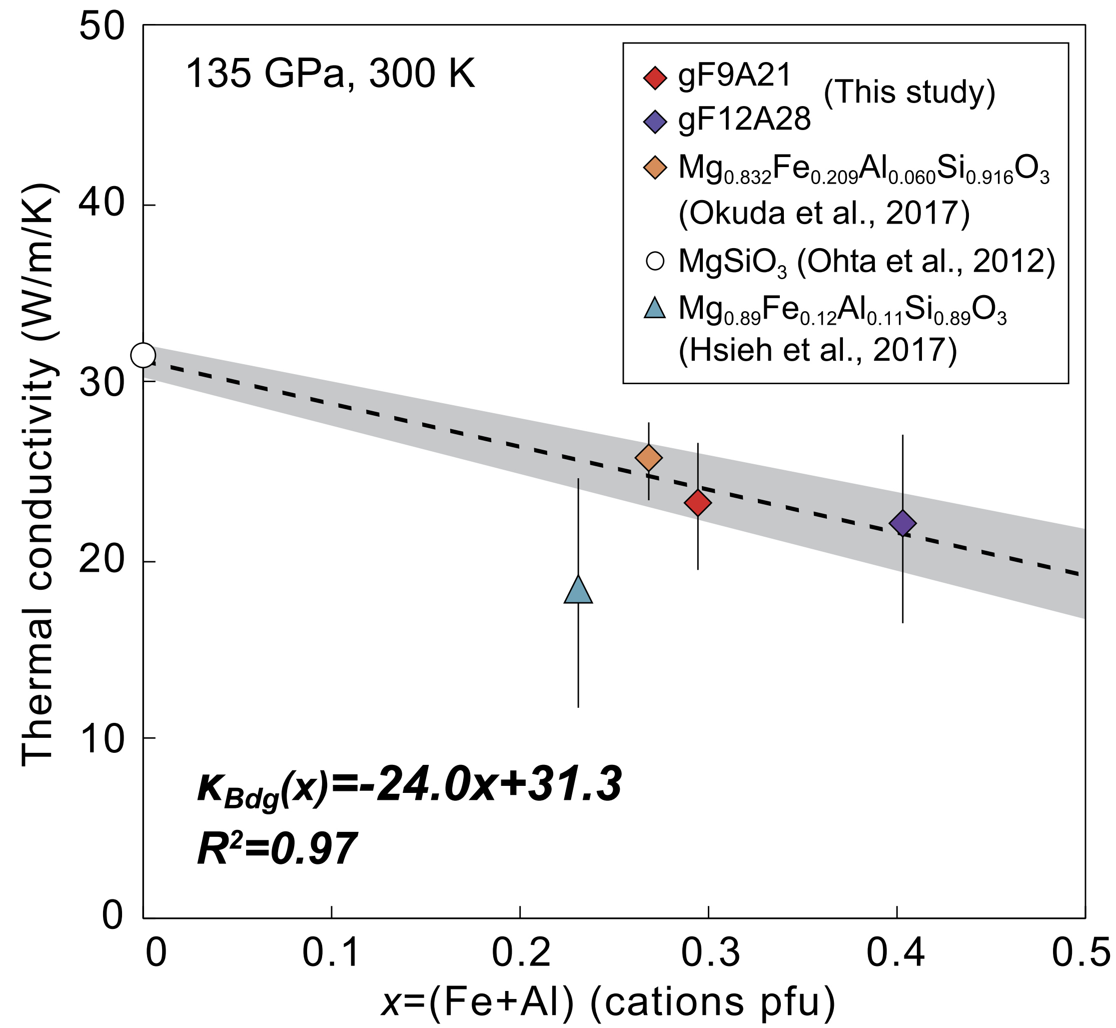
Thermal conductivity of $CaSiO_3$ perovskite at lower mantle conditions

Zhen Zhang,[1] Dong-Bo Zhang,[2,3] Kotaro Onga,[4] Akira Hasegawa,[4,5] Kenji Ohta,[4] Kei Hirose,[6,7] and Renata M. Wentzcovitch[1,8,9,*]

Results: Thermal conductivity of bridgmanite

- *P*–*x* dependence of $\kappa_{\mathrm{bridgmanite}}$ is constrained
- *T* effect is not yet examined

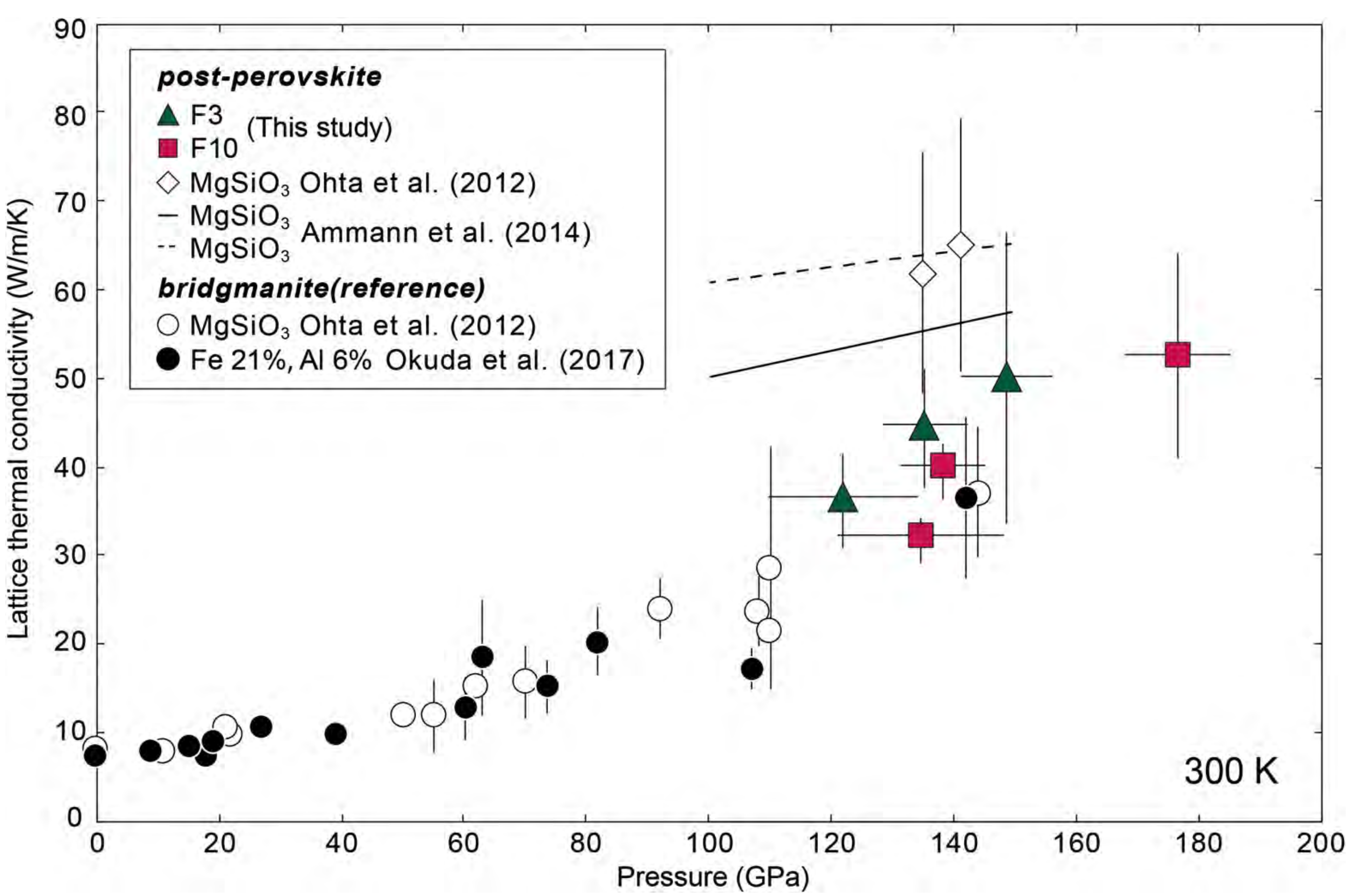


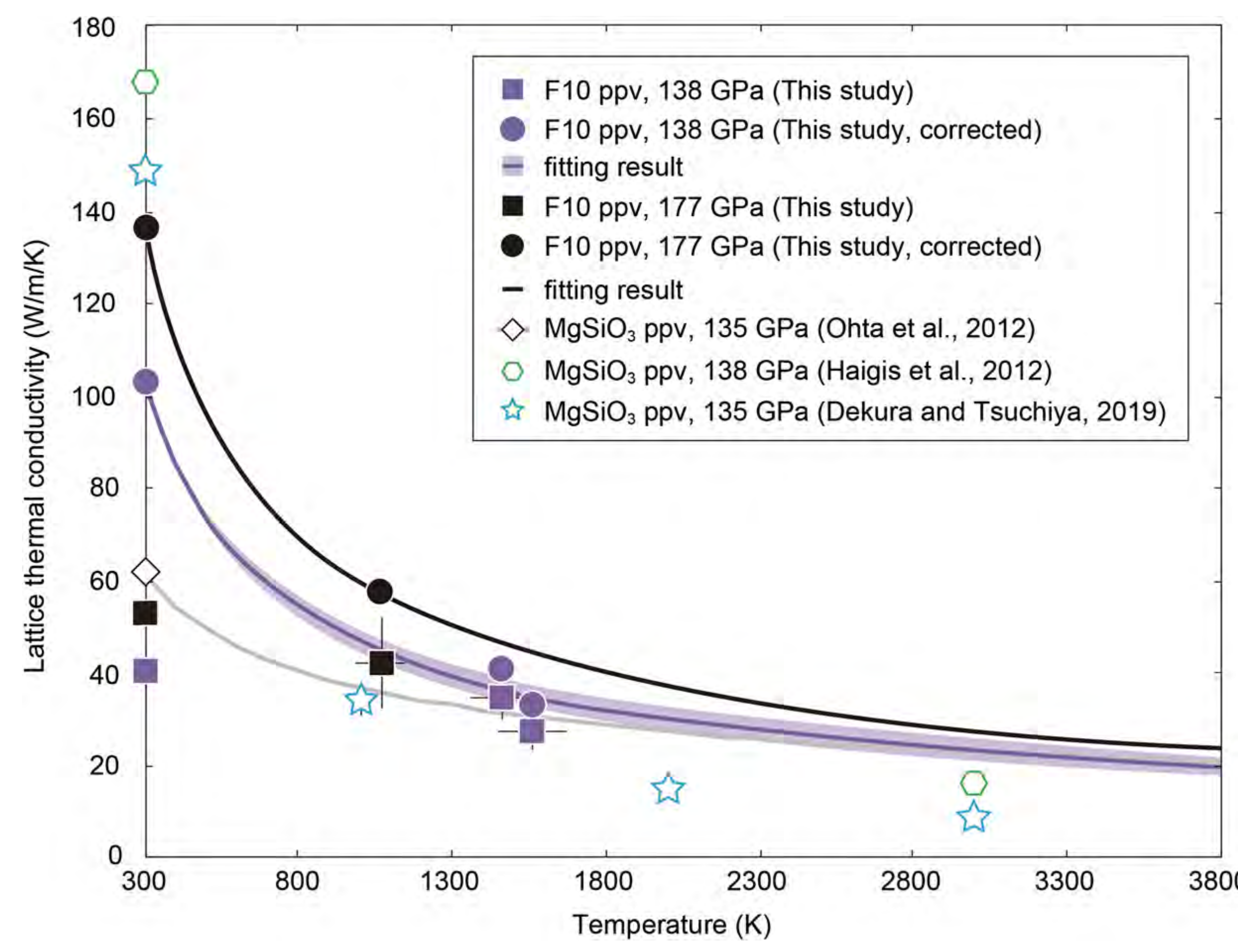


Okuda et al., 2019EPSL

Results: Thermal conductivity of post-perovskite

P–T–x dependence of κ_{PPv} is constrained

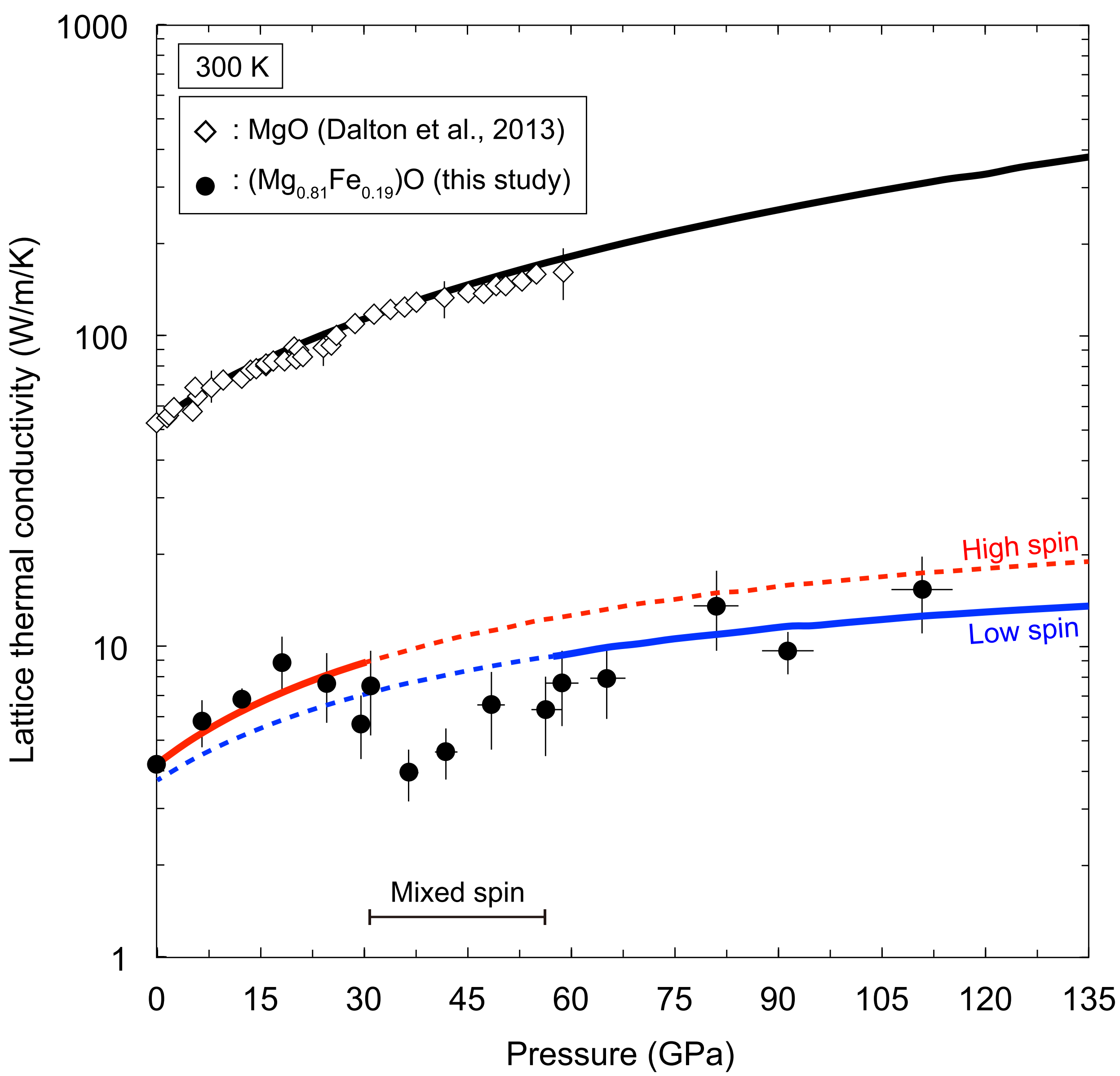


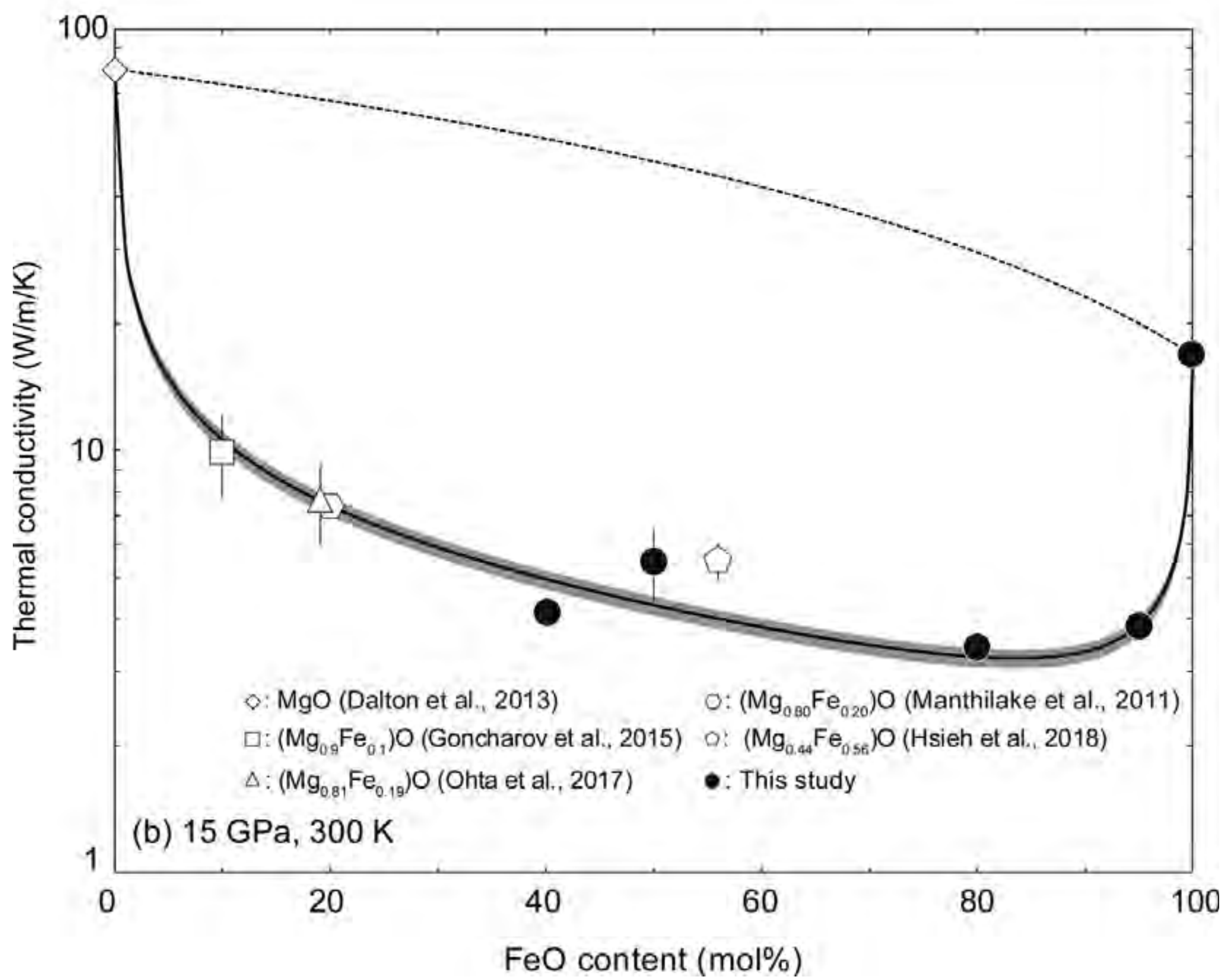


Okuda et al., 2020EPSL

Thermal conductivity of (Mg,Fe)O

- *P*–*x* dependence of $\kappa_{(Mg,Fe)O}$ is well constrained
- Fe spin transition decreases $\kappa_{(Mg,Fe)O}$



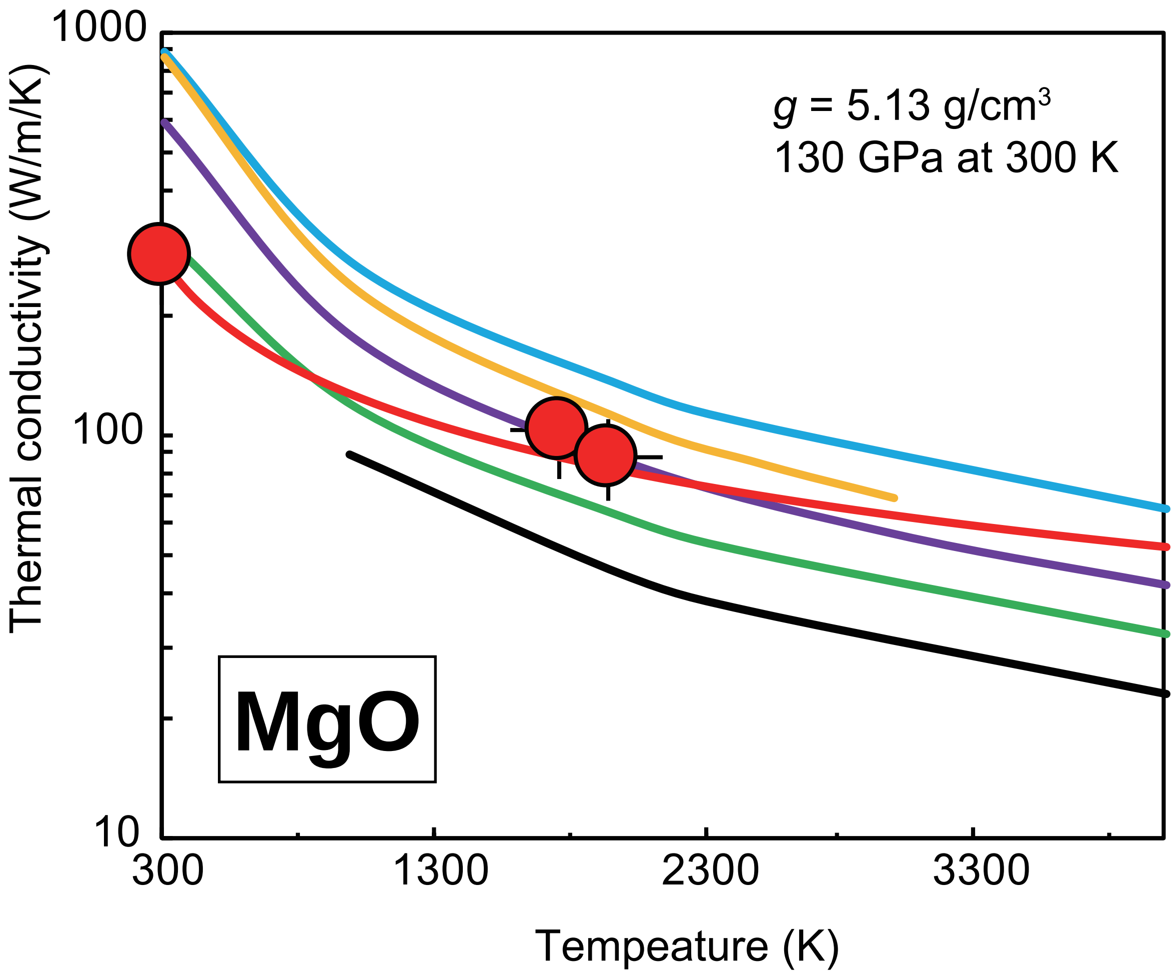


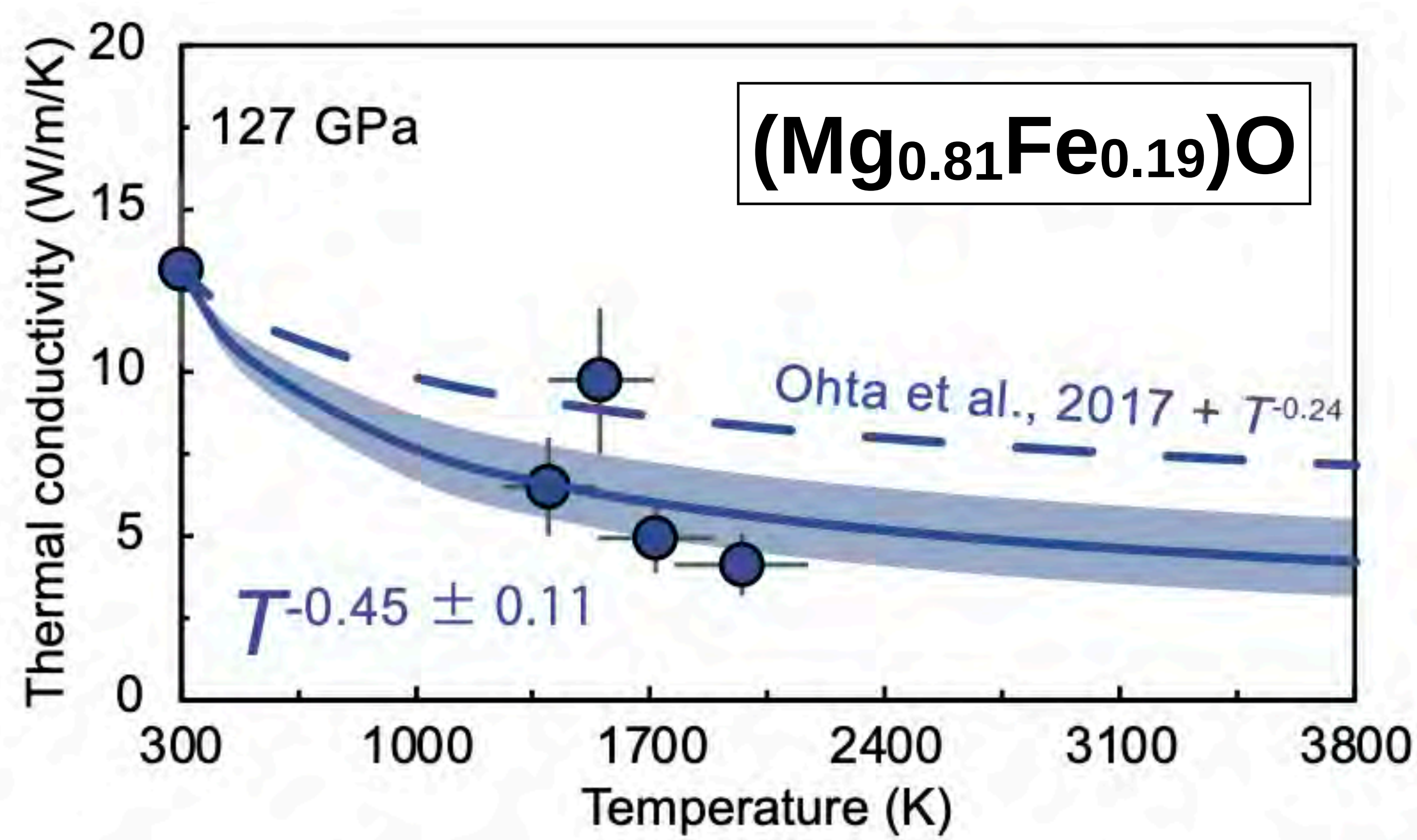
Hasegawa et al., 2019CRG

Ohta et al., 2017EPSL

Thermal conductivity of (Mg,Fe)O at high *P* & *T*

- High *P*–*T* $\kappa_{(Mg,Fe)O}$ is examined
- $\kappa_{(Mg,Fe)O}$ at lowermost mantle = ~5 W/m/K

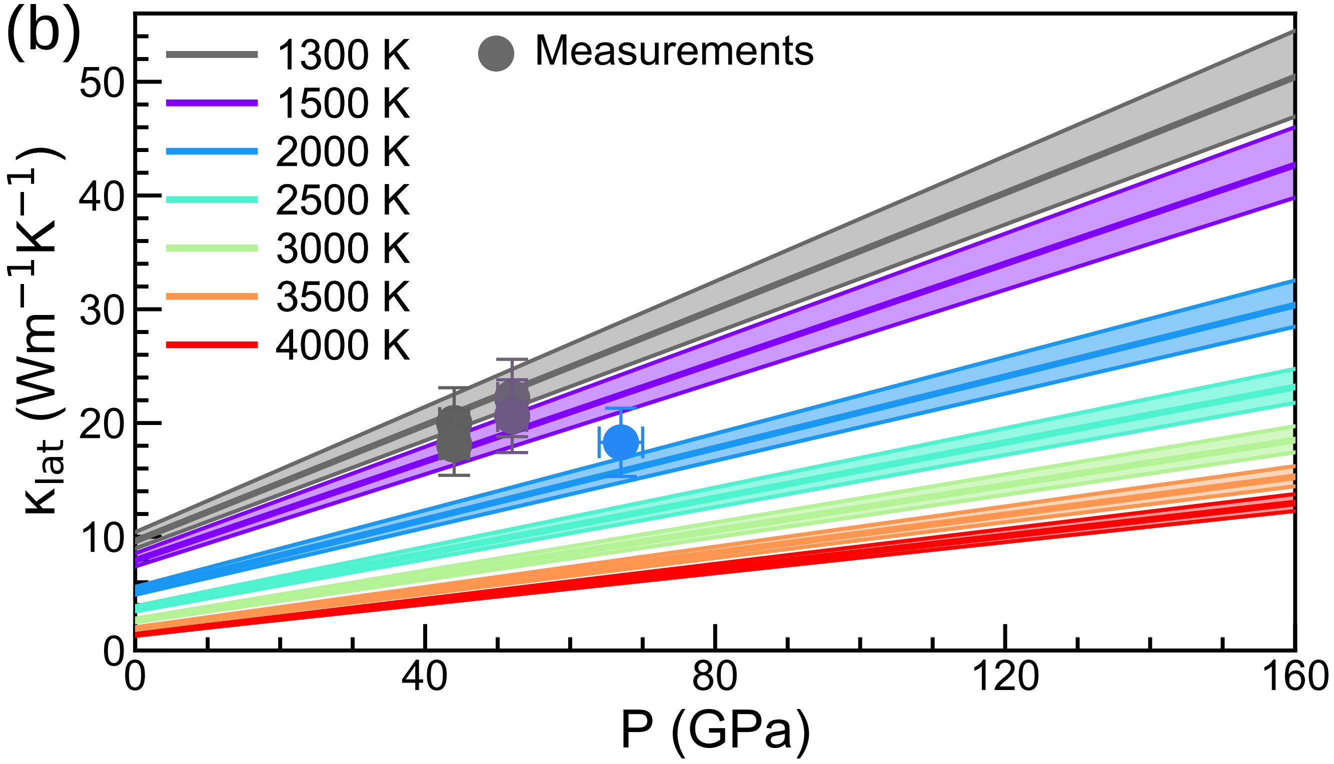




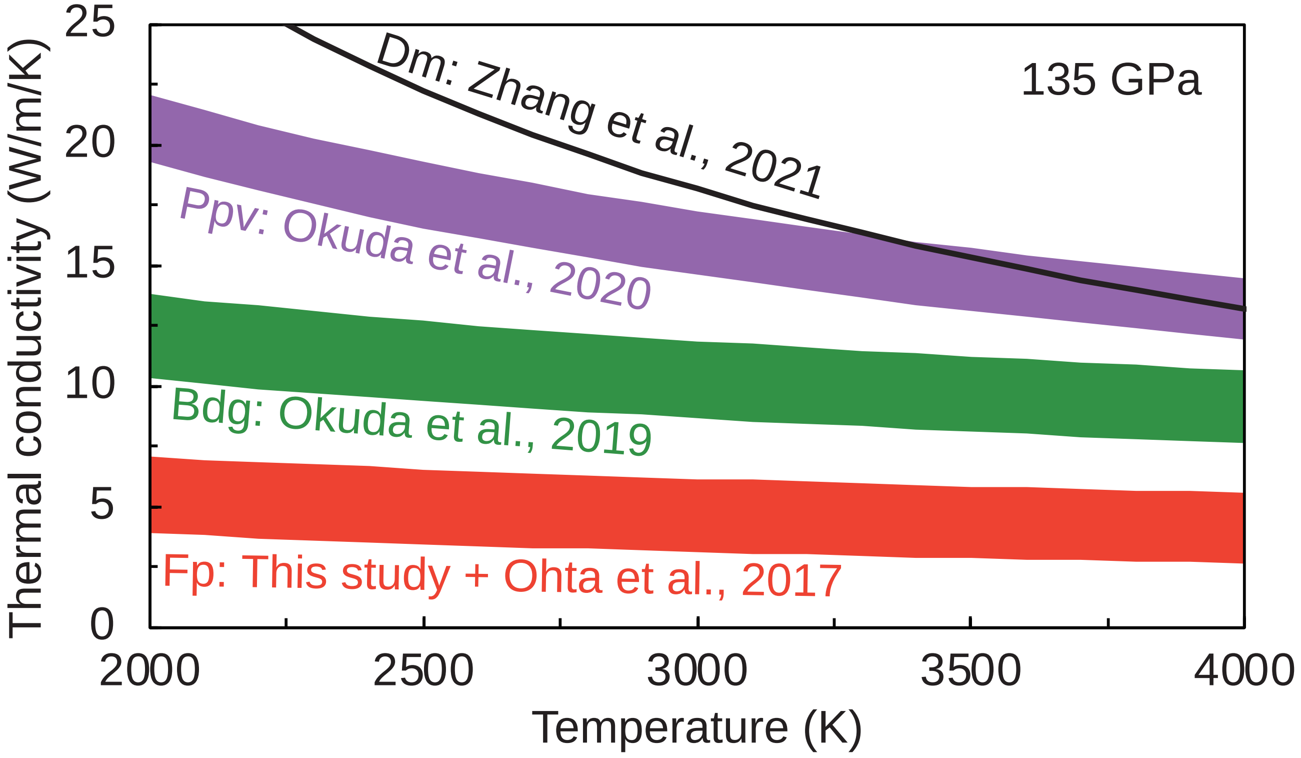
Hasegawa et al., in prep.

Thermal conductivity of davemaoite

- Combination of exp. and *ab initio*
- Davemaoite with cubic structure
- Similar κ to PPv

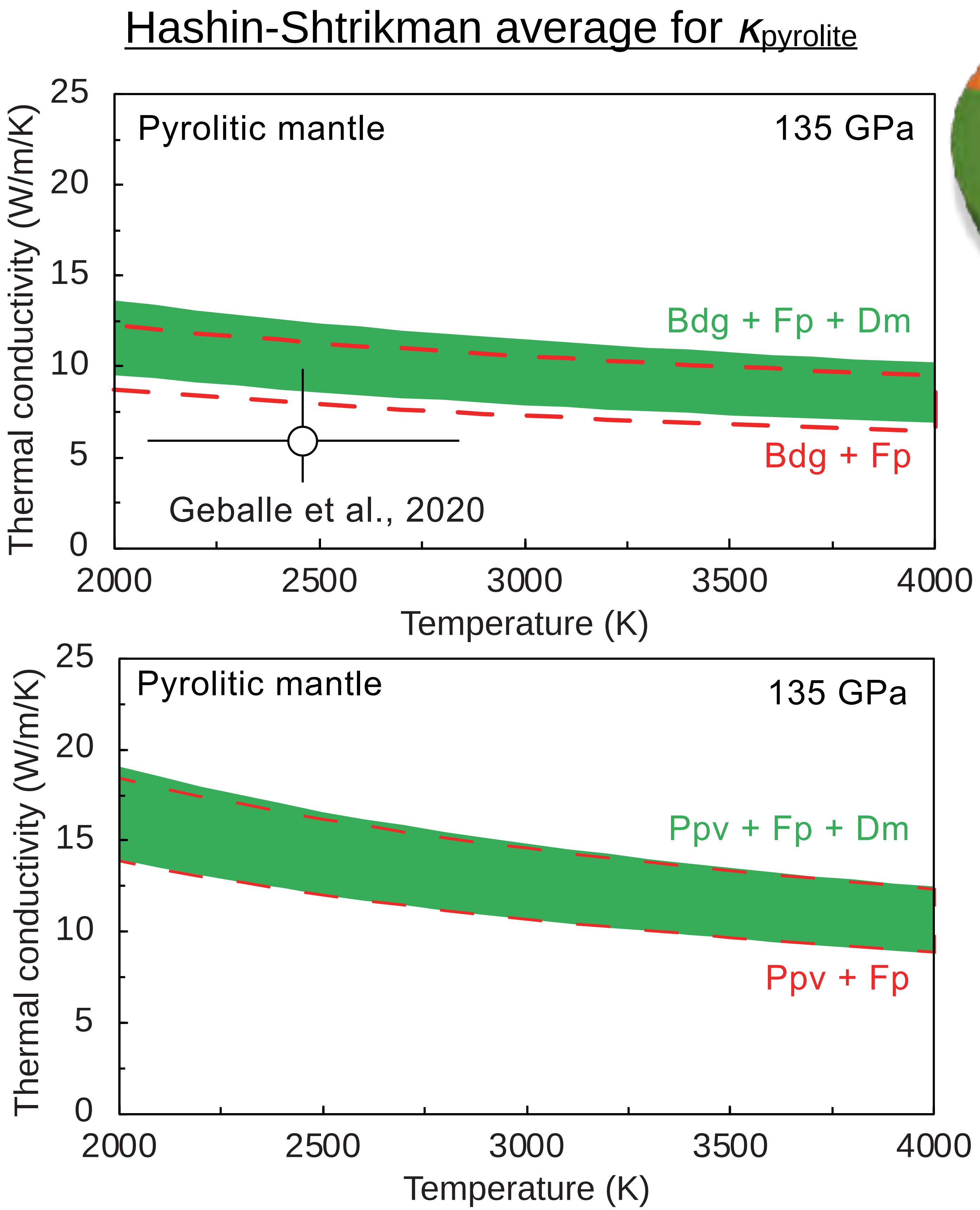


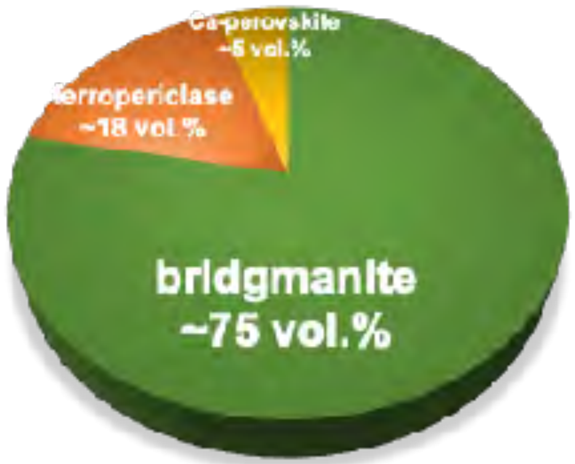
Zhang et al., 2021PRB



Hasegawa et al., in prep.

Thermal conductivity of pyrolite





Calculations of *T* profiles at the lowermost mantle

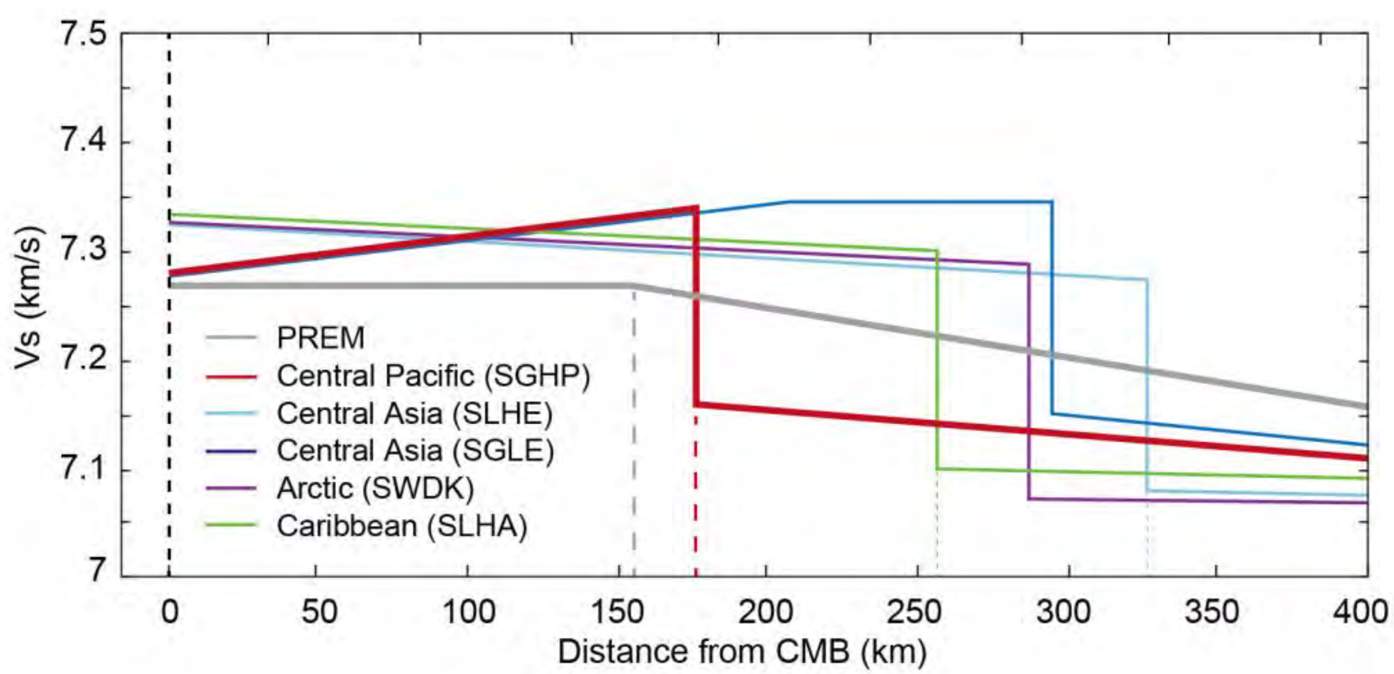
$$\frac{\partial T(z(P),t)}{\partial t} = \frac{1}{C_P(z(P,T))\rho(z(P,T))}\frac{\partial}{\partial z}\left[\kappa(z(P),T)\frac{\partial T(z(P),t)}{\partial z}\right]$$

κ: from our experiments

C_P: 1300 J/kg/K (fix)

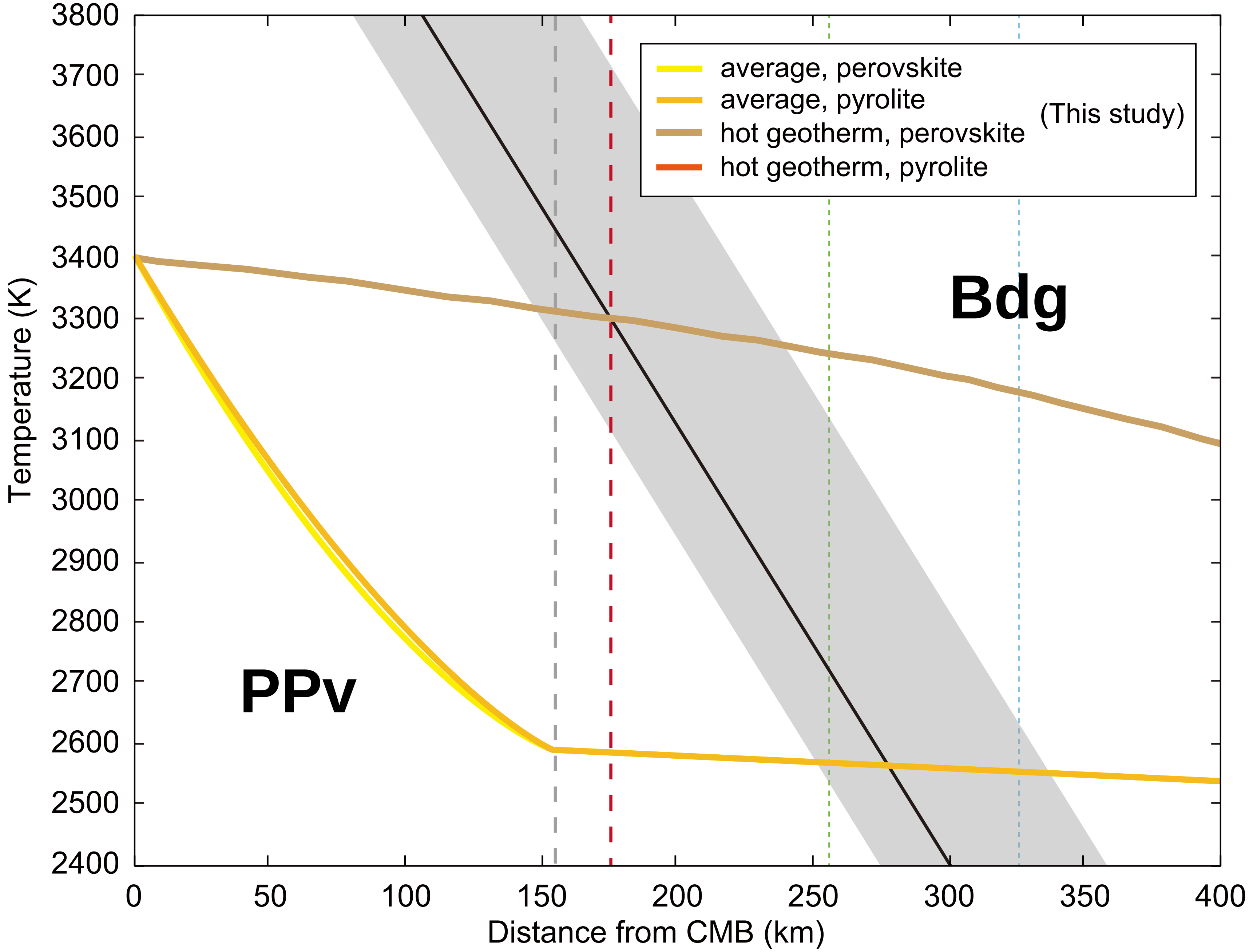
ρ: 0.51z+4094 $\mathrm{kg/m_3}$ from PREM (Dziewonski & Anderson 1981)

T_{CMB} = 3400 K (Kim et al., 2020GRL)



- “Average geotherm”: T > 155 km above CMB ≒ $T_{adiabat}$
- “Hot geotherm”: Top of TBL corresponds to D” discontinuity under central Pacific

Calculations of *T* profiles at the lowermost mantle

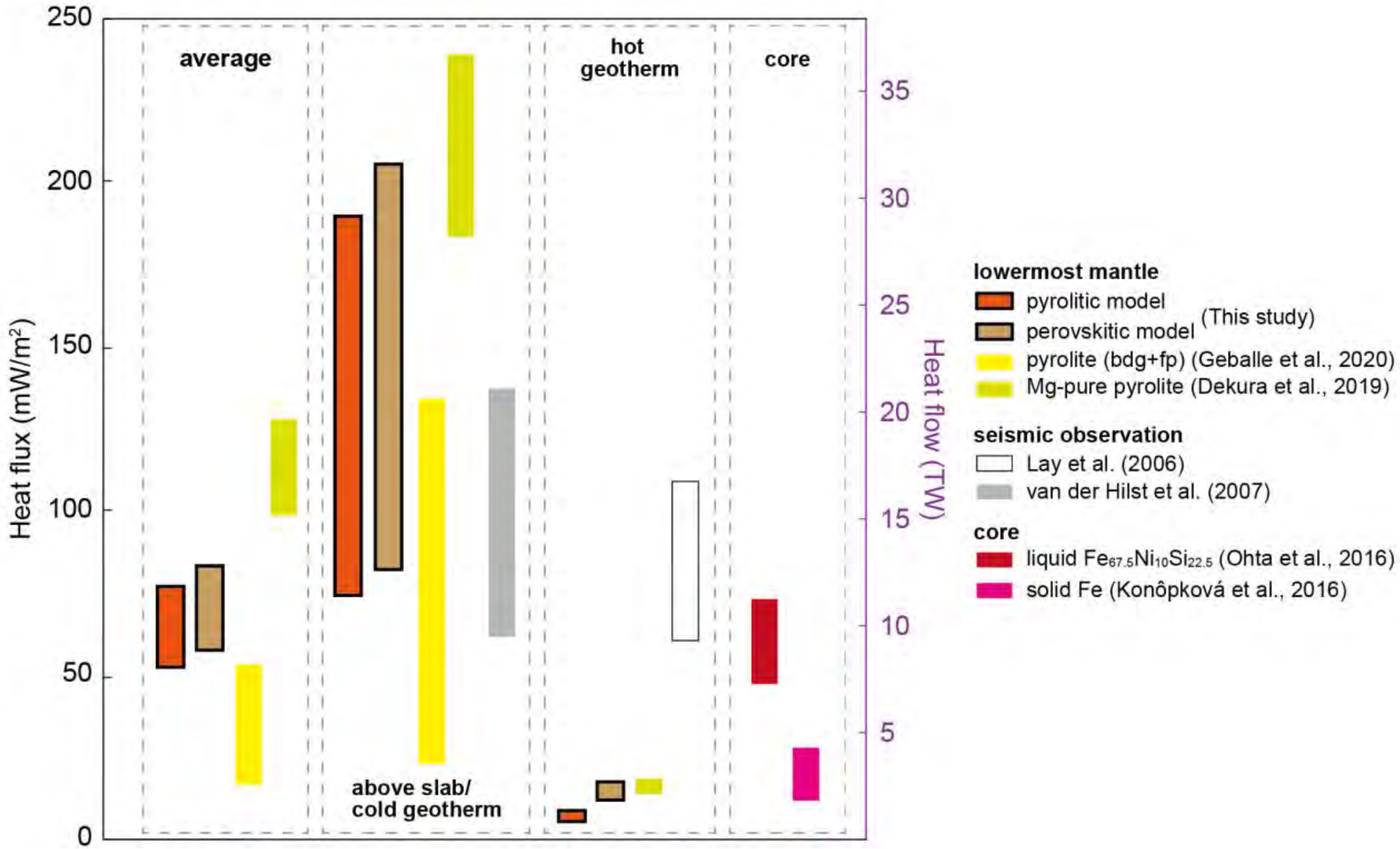


Okuda & Ohta, AGU books in press.

Very similar thermal structure between pyrolite and perovskitite

Heat flux from the core

$$\underline{Q = -A_{CMB} \bullet \kappa \bullet dT/dz}$$

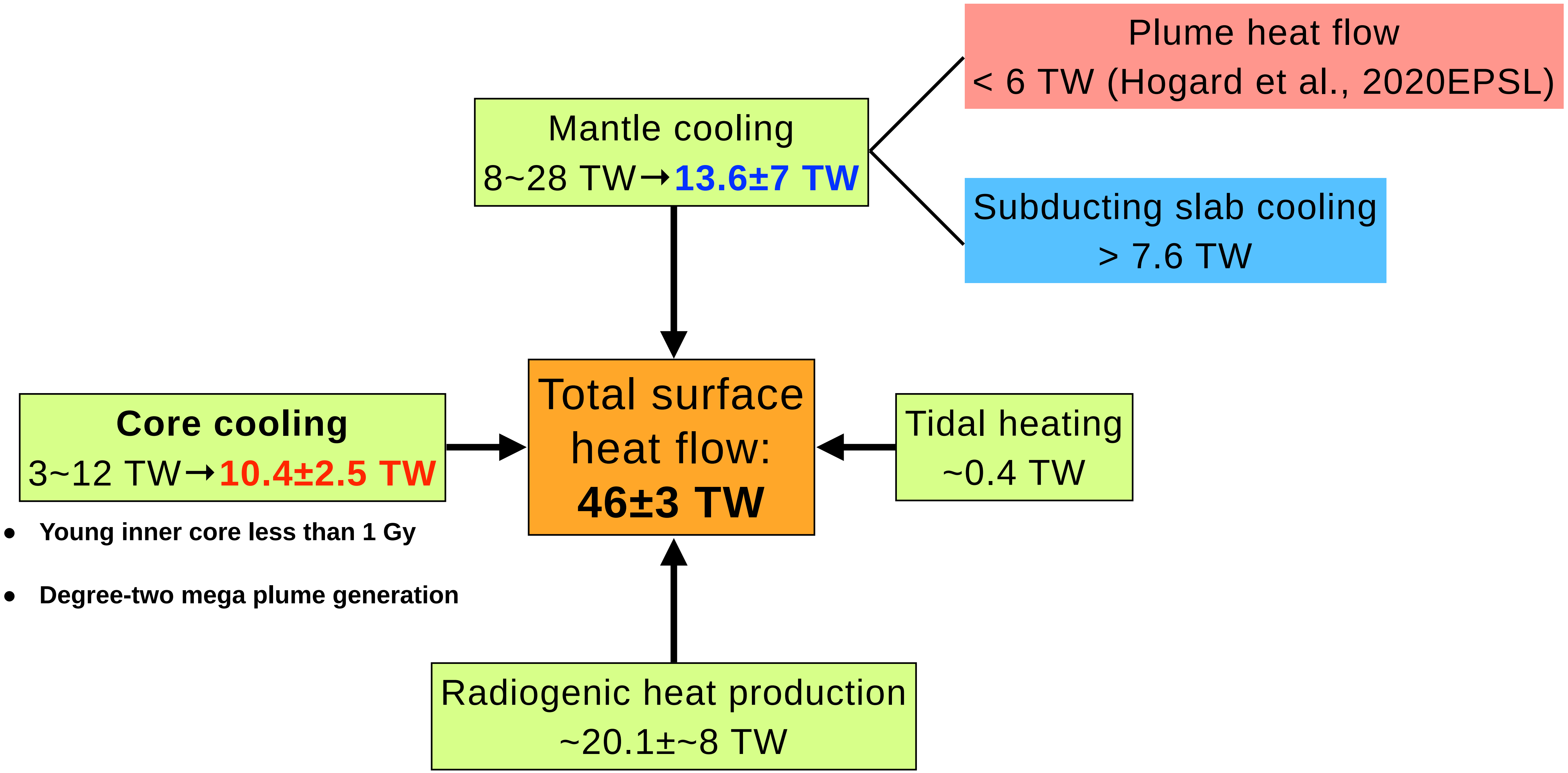


Okuda & Ohta, AGU books in press.

$Q_{\text{CMB, average}}$ = 10.4±2.5 TW

Large regional variation in Q_{CMB}

Earth’s heat budget revisited

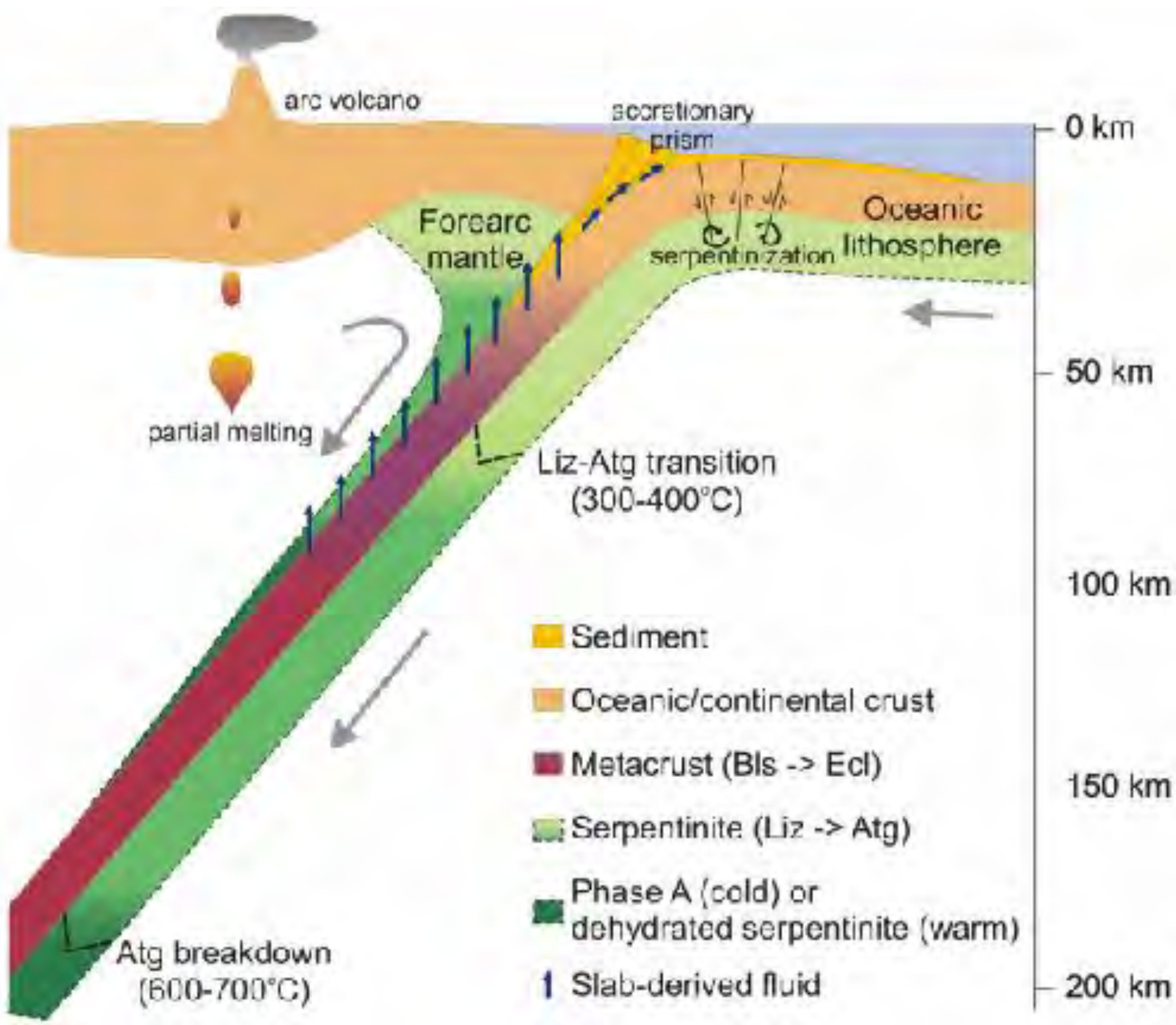


From talks in this symposium

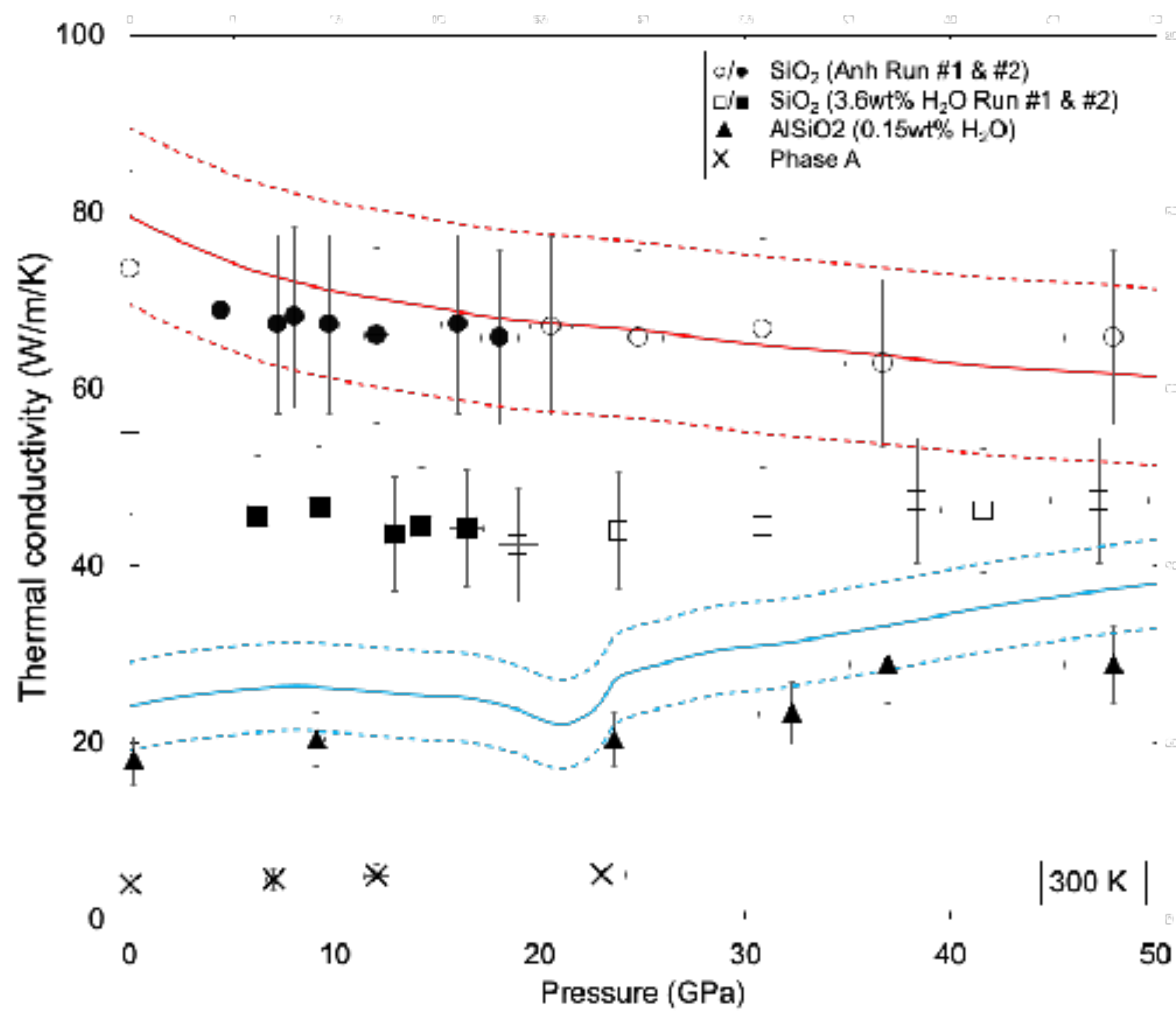
Similar magnitude of core and mantle cooling

Subjecting slab efficiently cools Earth

Inference of cooling history of slab



Page & Hattori, 2019



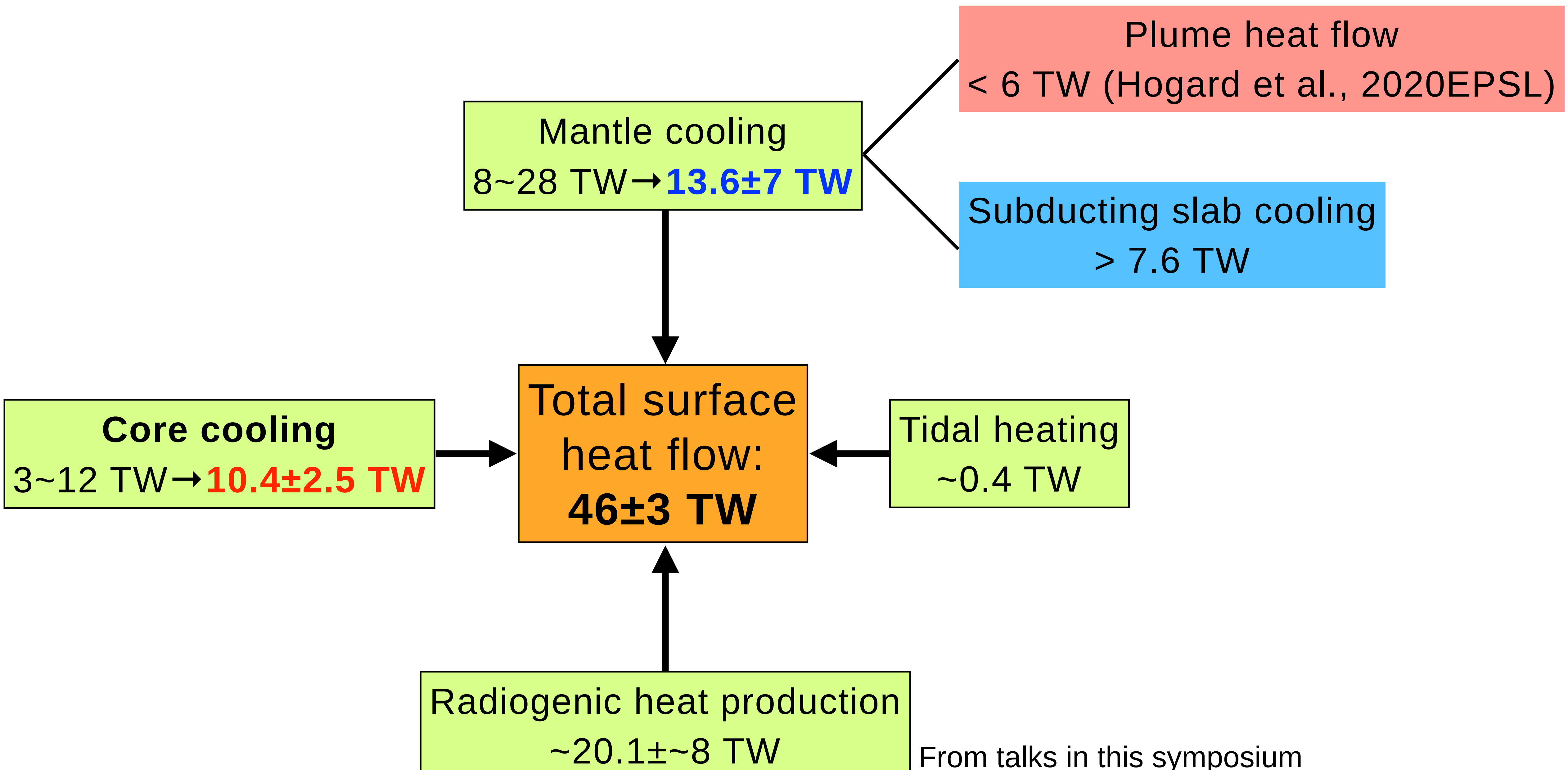
Sweidan et al. poster here

On going collection of κ of slab material under pressure

Simulations of slab warming (in future)

Points for discussion

- How much water do slab contain?
- How precise can we determine the mantle temperature?
- How precise can geoneutrino obs. constrain radiogenic heat?



From talks in this symposium

Acknowledgements

- Yoshiyuki Okuda
- Akira Hasegawa
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- Bill Sweidan
- Takashi Yagi (AIST Tsukuba)
- Kei Hirose (The University of Tokyo)
- M. Kodama & S. Hirai (Tokyo Tech)
- and so many