A constraint to thermal conductivity of Earth's core and CMB heat flow by assessment on stable region of Earth's core

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Key points of this presentation:

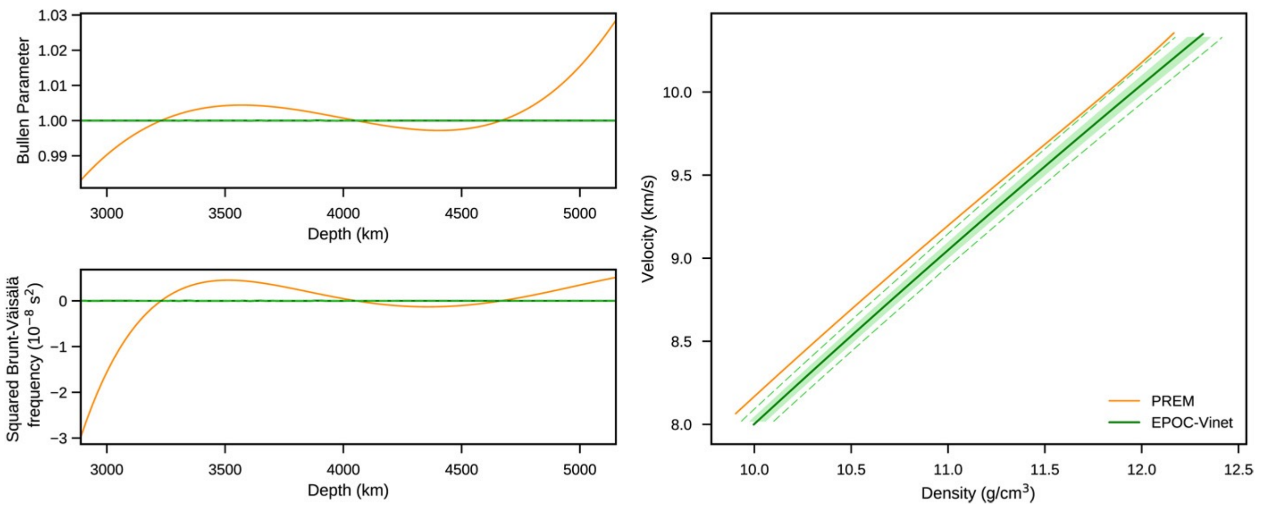
- Aim:
  1. Seek a compatibility of a stable region below the CMB at the present-day and long-term magnetic field generation.
  2. Look at how uncertainties on CMB heat flow and core thermal conductivity affects such a compatibility.
- Approach:
  1. Compute the convective flux in thermal and chemical evolution of Earth's core
  2. Stable region: Radial profile of the convective flux < 0
  3. Magnetic field: Dipole moment scaled by the convective flux as a function of time > 0
- Results:
  1. Stable region: Need a help of core-mantle chemical interaction.
  2. To find magnetic field and stable region simultaneously:

     Modern estimate: Q_{CMB}^{p} ~17.5 TW (Present-day CMB heat flow); k_c~212 W/m/K (Thermal conductivity); d_s~30 km (Thickness of a stable region)

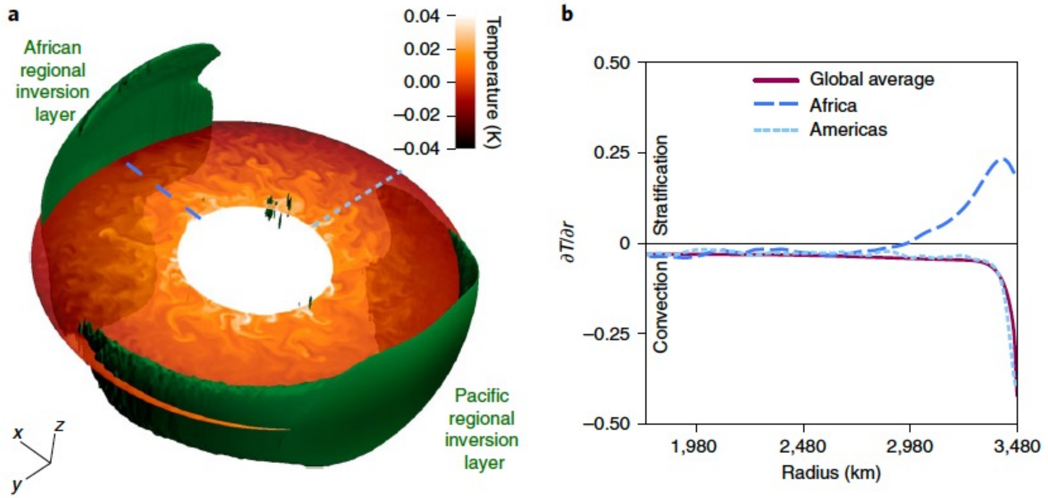
     Mantle convection: Q_{CMB}^{p}~10 TW; k_c~112 W/m/K; d_s~75 km
- Implications:
  - A stable region below the CMB <u>cannot be ruled out</u> but seems to be much <u>thinner than we thought</u>.

Motivations

- Controversial discussion on the stable region at the top of Earth's core
- Question: Can a stable region at the top of Earth's core be found from two views: Dynamics and evolution?
- How to answer the question – Develop an assessment scheme for emerging a stable region at the top of Earth's core and magnetic evolution simultaneously.

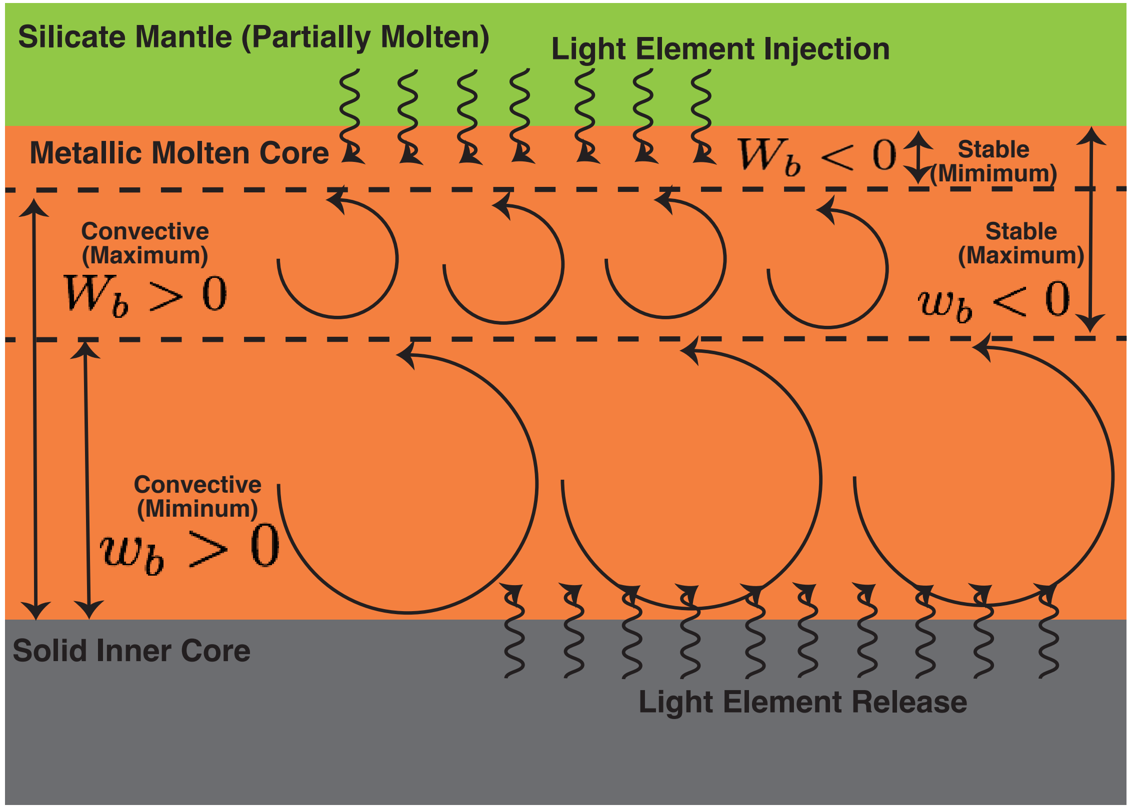


Irving et al. (2018): A seismic structure may explain convective properties without a stable region.



Mound et al. (2019): Stable region beneath the Africa LLSVP.

Model image: What we assume?

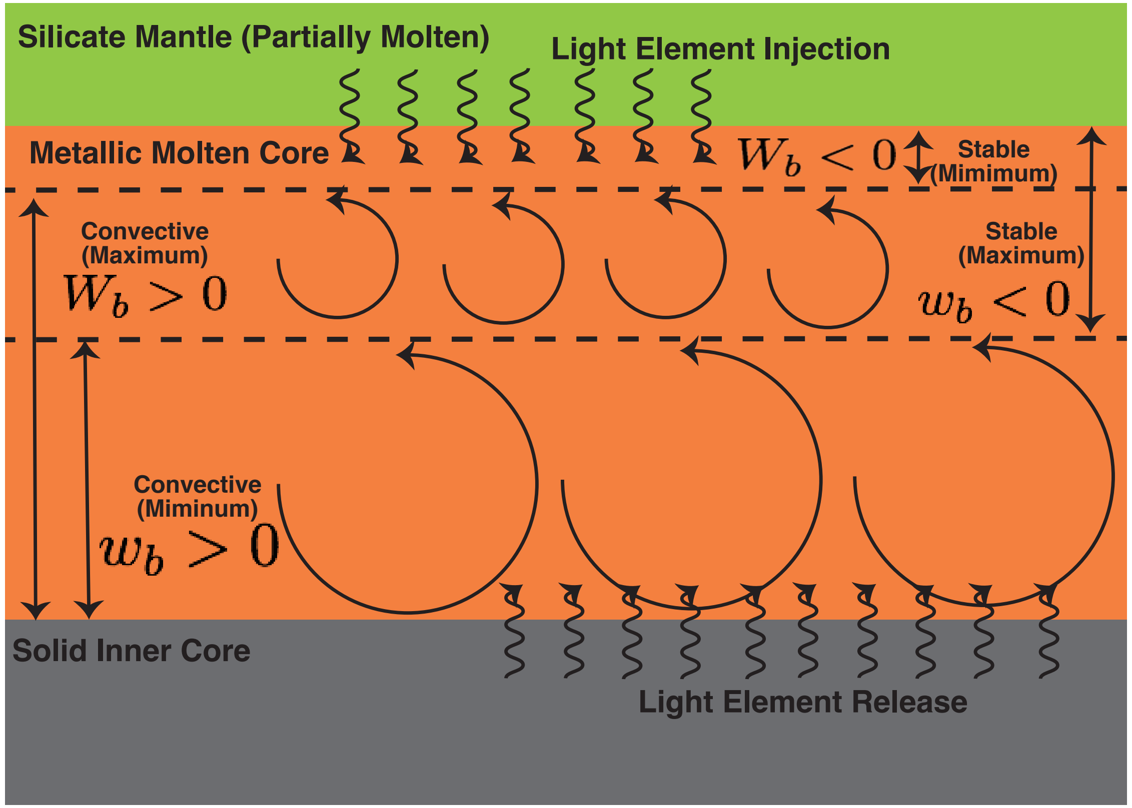


- Main concept: One-dimensional thermal and chemical evolution of Earth’s core.

- Earth’s outer core: Well-mixed convective region
- Chemical interaction
  - CMB: Metal-silicate reaction.
  - ICB: Add light element release caused by inner core growth.

- Thermal evolution: Follow Labrosse (2015).
- Chemical evolution: Follow Takehiro and Sasaki (2018) plus incorporating the core-mantle chemical coupling.
- Magnetic evolution: A scaling law of strength of dipole moment as a function of the convective flux (Christensen and Olson, 2006; Aubert et al., 2009; Driscoll and Bercovici, 2014).

Assessment scheme: Definition of the stable region below the CMB



Minimum thickness of convective region if $w_b(r,t) > 0$

Maximum thickness of convection region if $W_b(r,t) > 0$

$$w_b(r,t) = w_{b,s}(r,t) + w_{b,c}(r,t)$$
$$= g(r)\left(\underbrace{\frac{\alpha_T T_c(r,t)}{c_p} F_s(r,t)}_{\text{Thermal}} - \underbrace{\alpha_c F_C(r,t)}_{\text{Chemical}}\right)$$

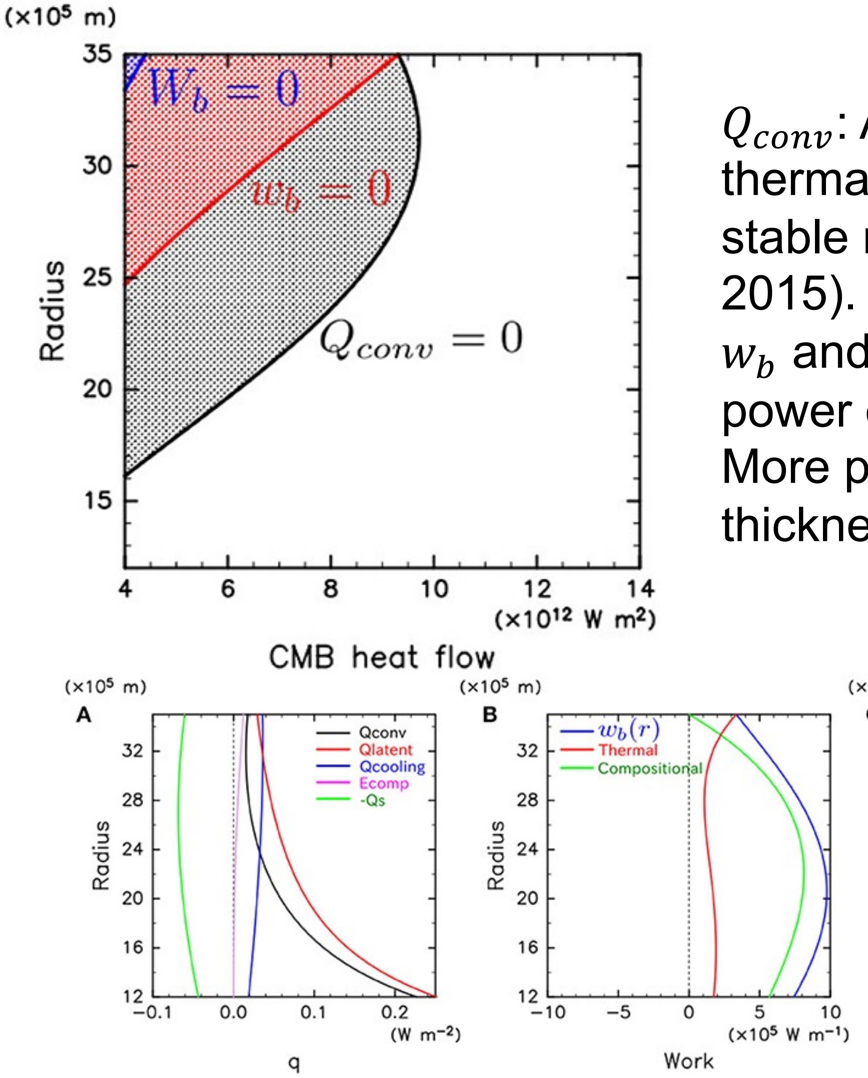
$$W_b(r,t) = \frac{1}{V(r)} \int_c^r 4\pi x^2 w_b(x,t)dx$$

Merit:

This scheme (use heat and mass budgets): More precise assessment on emergence of a stable region than others (Heat budget assessment)!

How the assessment scheme works out?

- Takehiro and Sasaki(2018): Light element release by the inner core growth – not likely to emerge the stable region in high Q_{CMB}^{p}
- Point: Use the convective flux incl. chemical convection
- Improvements in this study: **Incorporate the core-mantle chemical coupling.**



Q_{conv}: Available power of thermal convection – Thicker stable region (Labrosse, 2015).

w_b and W_b: Actual available power of core convection - More precise estimate of thickness of a stable region.

Takehiro and Sasaki (2018)

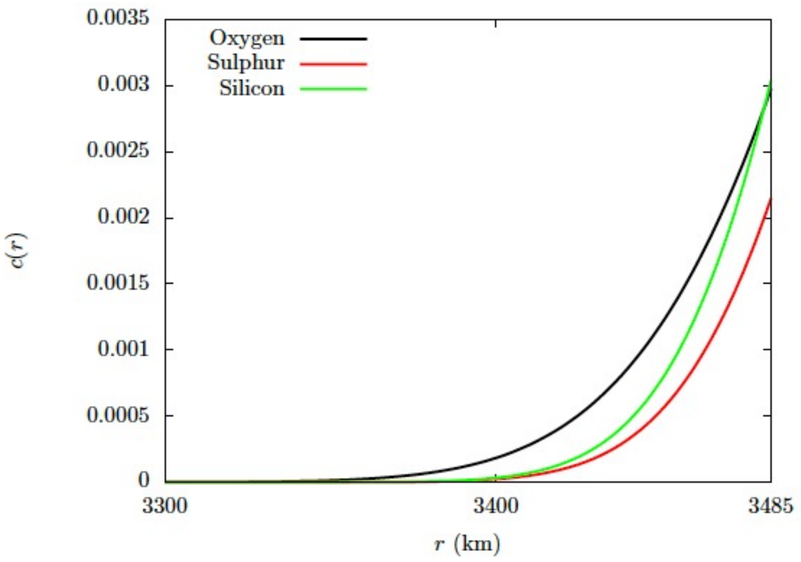
Core-mantle chemical coupling

- Assume that oxygen is a major type of light elements of Earth's core.
- Physical process of interaction – Baro-diffusion effects
- Other major candidates: Hydrogen, Silicon Sulphur and Carbon – Oxygen gives maximum effects of chemical stratification.

$$F_c = S_{ICB} - M_C(r)\frac{d\overline{X}}{dt}$$

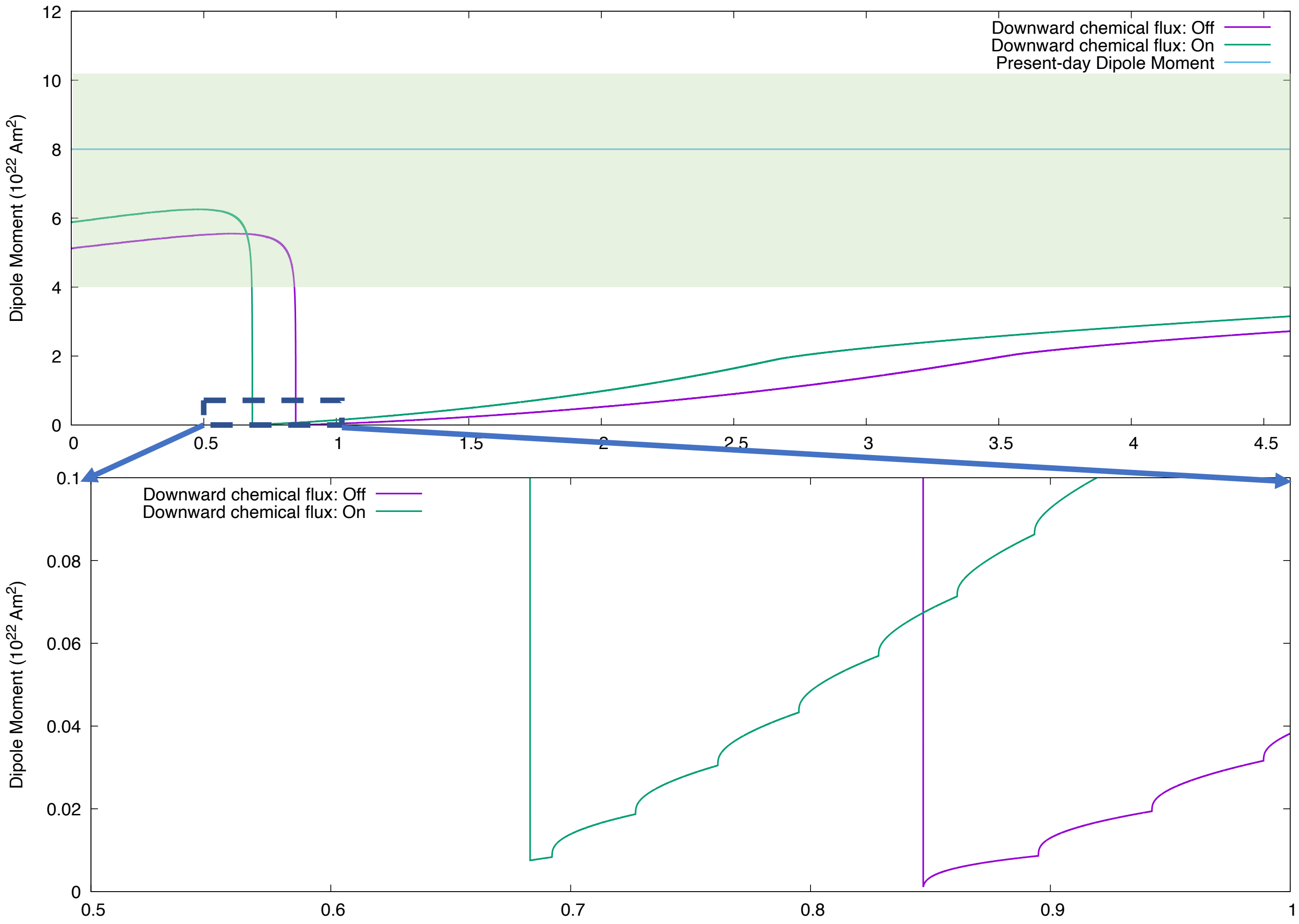
$$\frac{d\overline{X}}{dt} = \frac{dX_I}{dt} + \frac{dX_O}{dt} = \frac{4\pi c^2 X_0 \frac{dc}{dt} + S_{CMB}}{4\pi \int_c^b r^2 \rho_c(r)dr}$$

$$S_{CMB} = 4\pi b^2 \rho_c(b) D_c \frac{\alpha_{cO}}{H} g(b)$$



An expected chemical flux near the top of Earth's core taken from Gubbins and Davies (2013).

Long-term generation of magnetic field



$$M_{mag}(t) = 4\pi b^3 \frac{1}{D_c} \int_c^b \left(\frac{\rho(r)}{2\mu_0}\right)^{\frac{1}{2}} \left(\frac{(r-c)w_b(r,t)}{4\pi b^2 \rho(r)}\right)^{\frac{1}{3}} dr$$

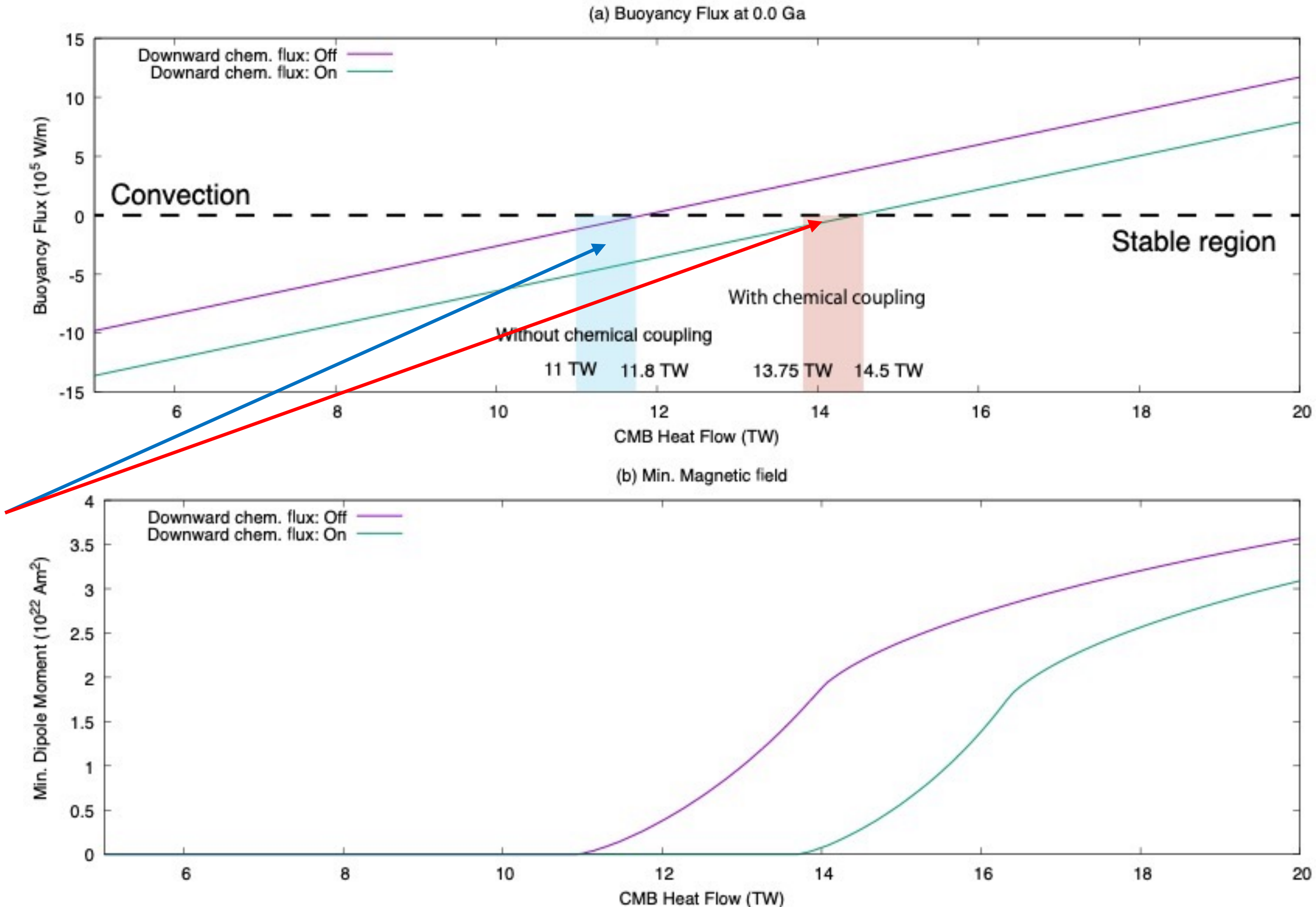
Driscoll and Bercovici (2014); Aubert et al. (2009)

$w_b(r,t)$: Convective flux (Equivalent to work by buoyancy)

Criteria for the long-term magnetic field generation:

$$\mathbf{min}\left(M_{mag}(t)\right) > 0$$

Stable region may satisfy the long-term magnetic field generation



Color shaded region: Co-existing stable region and long-term magnetic field

Nakagawa et al. (submitted)

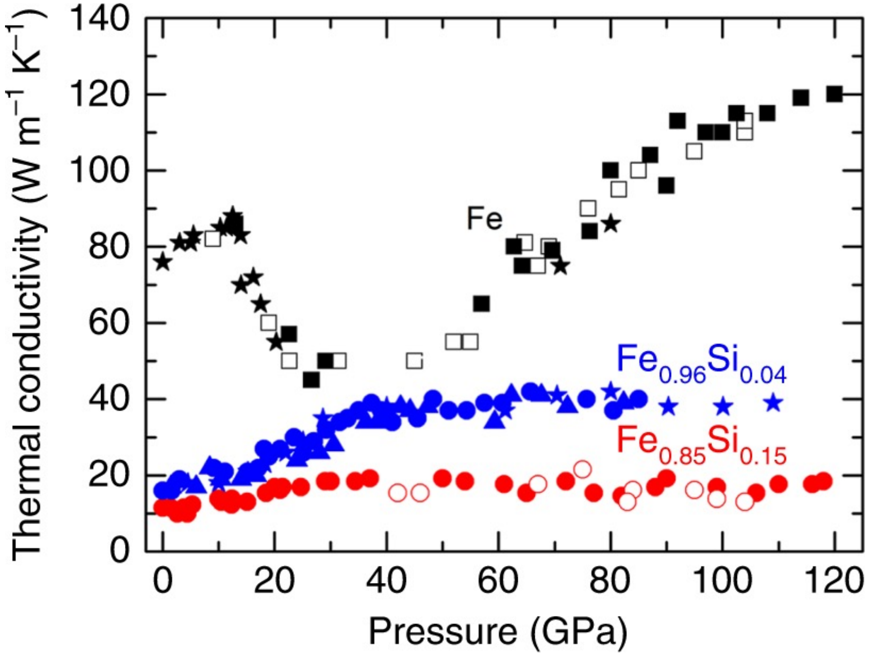
Uncertainty: CMB heat flow

- Heat budget and theoretical estimates: 5 to 17.5 TW (Lay et al., 2008; Labrosse, 2015).
- Thermal conductivity of silicate at the lower mantle condition: 6 to 17 TW (Manthilake et al., 2011; Tang et al., 2014; Dekura and Tsuchiya, 2019).
- Mantle convection model: 10 TW (Nakagawa and Tackley, 2010).
- Still very uncertain.
- Will show detailed results for Q_{CMB}^{p} =10 TW and 17.5 TW.

Additional uncertainty: Core conductivity

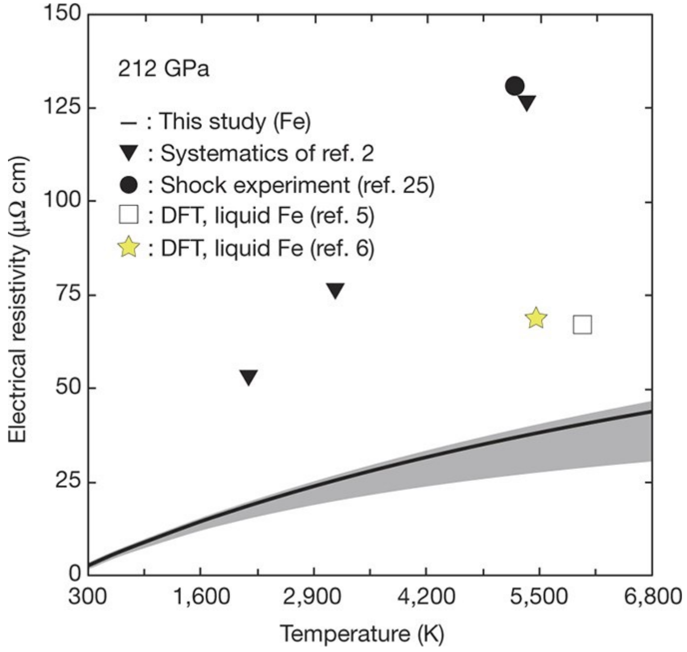
Main question: How can the core conductivity affect both an emergence of stable region and long-term magnetic field generation?

Direct measurements



Hsieh et al. (2020): Low (20 W/m/K)

Indirect measurements



Ohta et al. (2016): High (220 W/m/K converted from electorial resistivity)

Total heat flow for thermal convection

$$Q_{conv} = Q_C + Q_L + Q_G + Q_S$$

Isentropic heat flow

$$Q_S = 4\pi b^2 k_c \left(1 - A_k \left(\frac{r}{L_\rho}\right)^2\right) \frac{dT_c}{dr}$$

$$\frac{dT_c}{dr} < 0$$

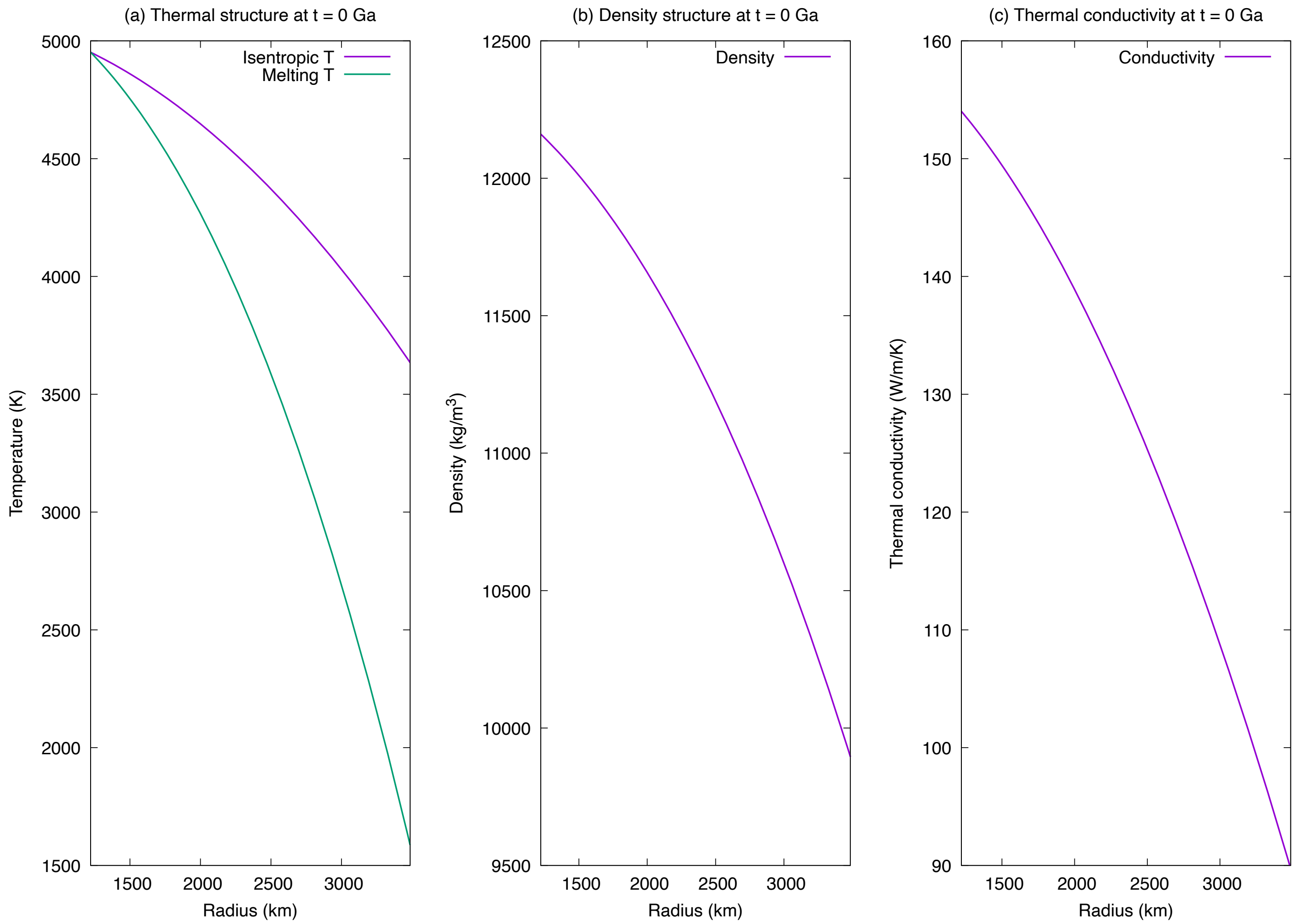
High conductivity – Reducing thermal convection

Low conductivity – Enhancing thermal convection

Analysis strategy

1. Start with the present-day convective structure – Assessing an emergence of stable region at the present time.
2. Back-tracing of the thermal, chemical and magnetic evolution of the Earth's core – Checking if the magnetic field can be generated over 4 billion years or not.
3. Parameter surveys – A reasonable range of Q^{p}_{CMB} (5 to 20 TW) and k_c (20 to 220 W/m/k)

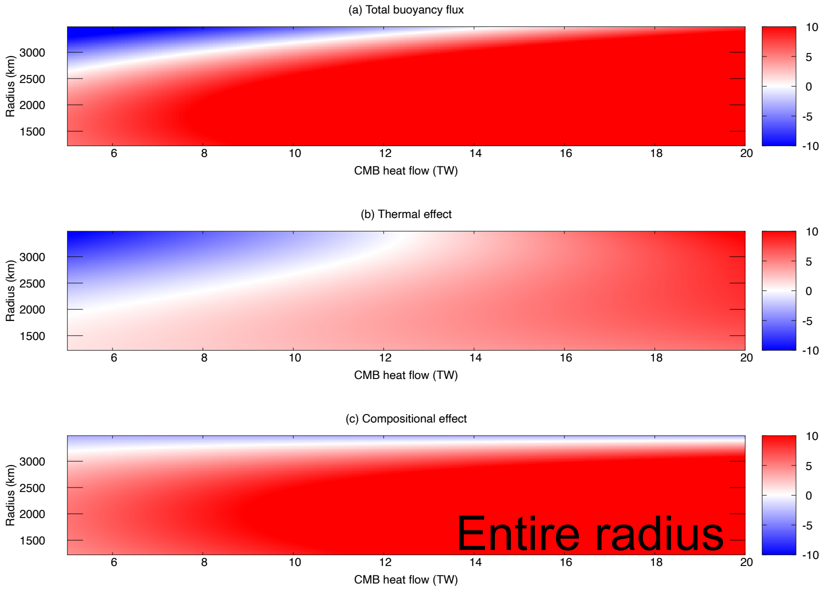
Reference structure of Earth's core ($k_c = 163$ W/m/K)



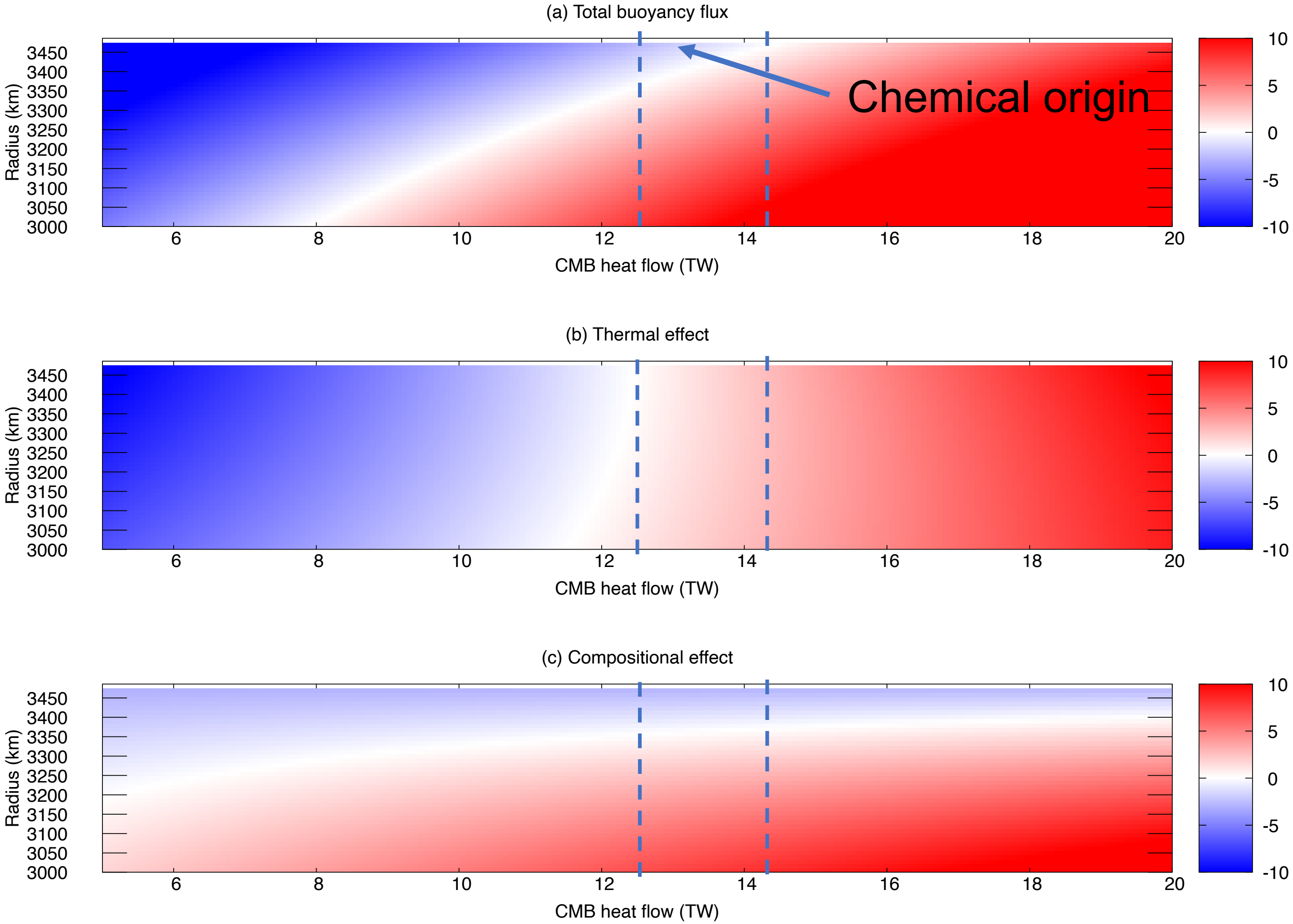
An example of result: a certain thermal conductivity case

$k_c = 163$ W/m/K

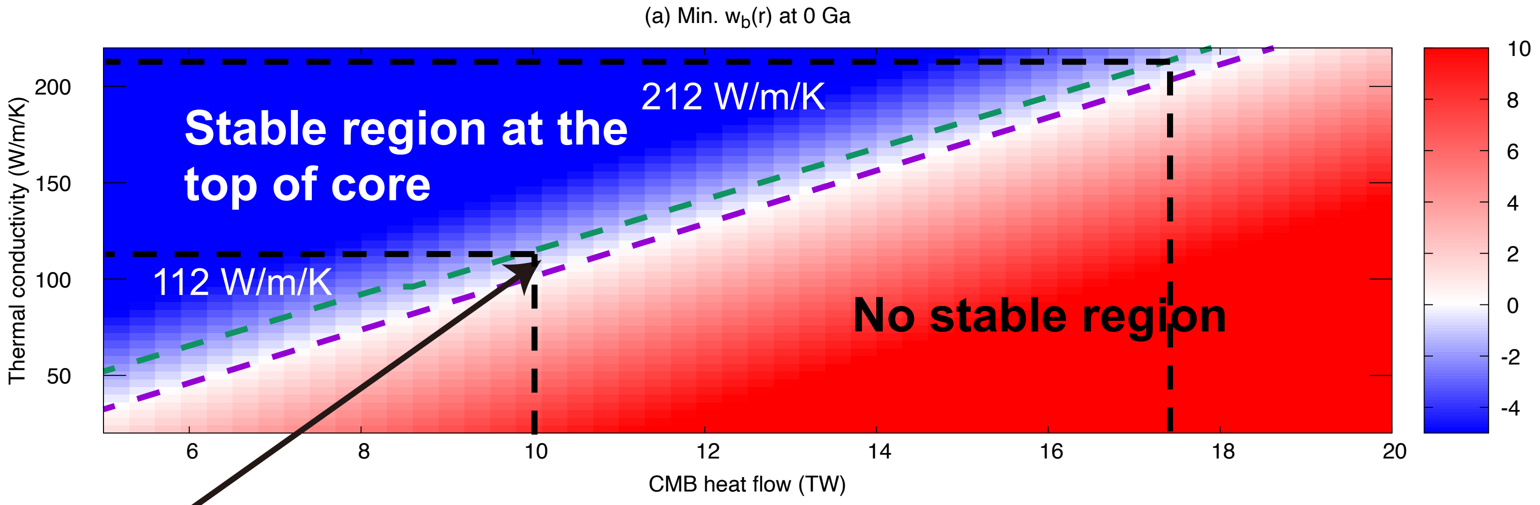
- Compositional convection enhances the core convection – Thermal stratification is reduced.
- Thickness of stratification: A position changing a sign of total $w_b(r)$.
- Chemical stratification - Q^p_{CMB}>12.5 TW



Zoom-up upper 500 km radius

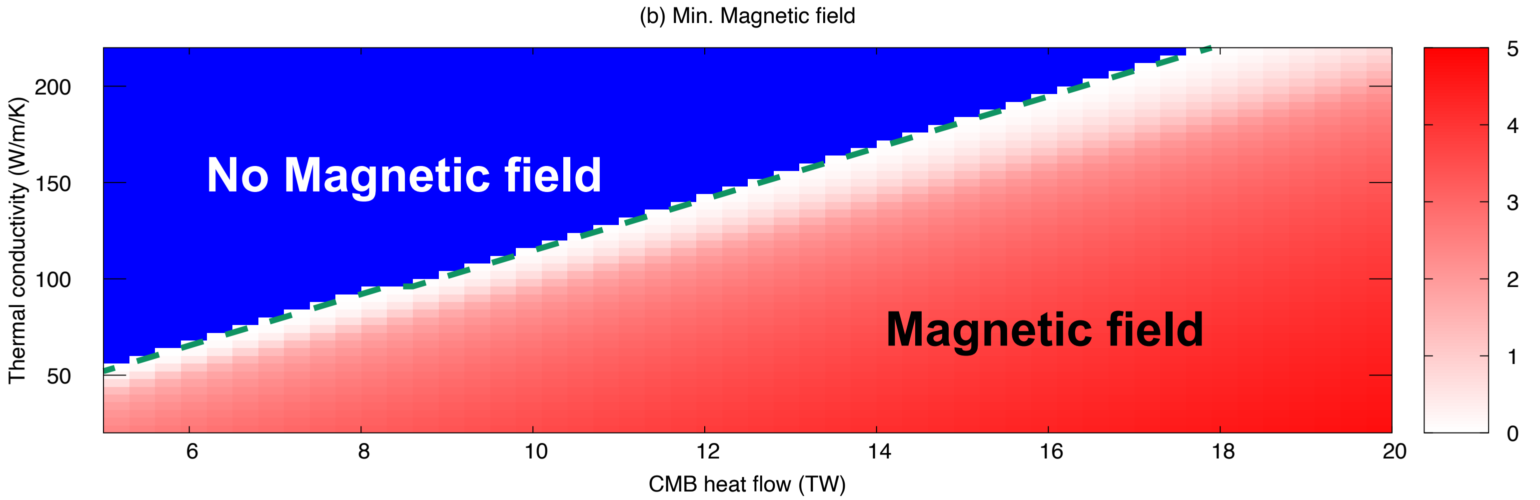


Solution regime diagram: Co-existing Stable region and long-term magnetic field



A boundary between 'no-magnetic field' and 'magnetic field can appear in the stable region at the top of core: Long-term magnetic field generation can co-exist with the stable region.

Possible solutions for both magnetic field and stable region



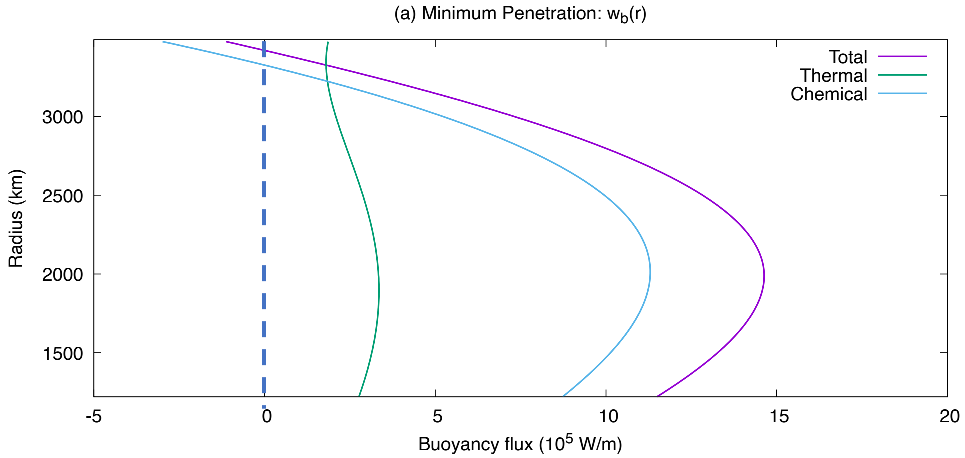
For getting both stable region and long-term magnetic field generation (A region between green and purple dashed lines) –

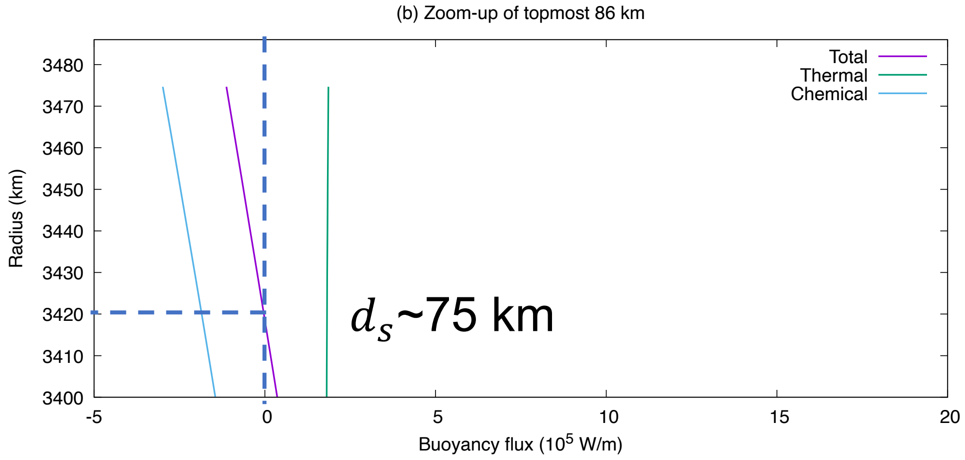
Lower limit of k_c~40 W/m/K
Upper limit of Q^p_{CMB}~18.5 TW

Stable region: Expected thickness from $w_b(r)$

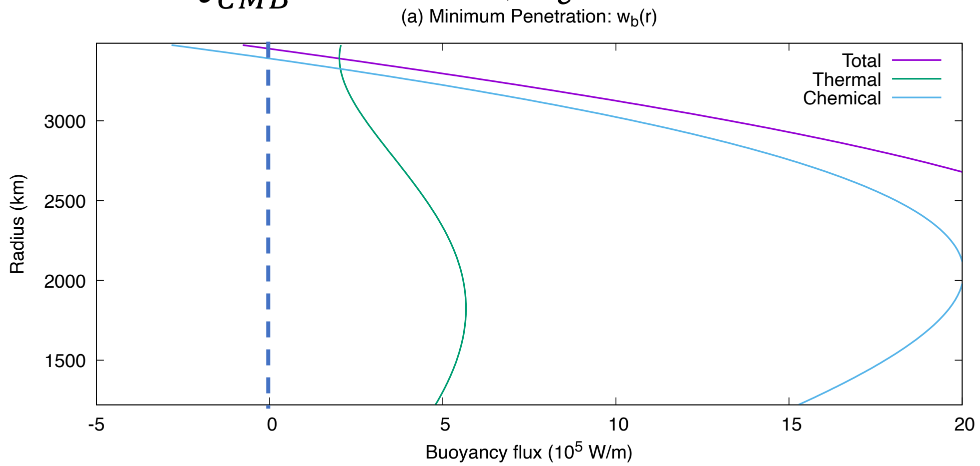
d_s: Thickness of stable region: A location changing a sign of $w_b(r)$.

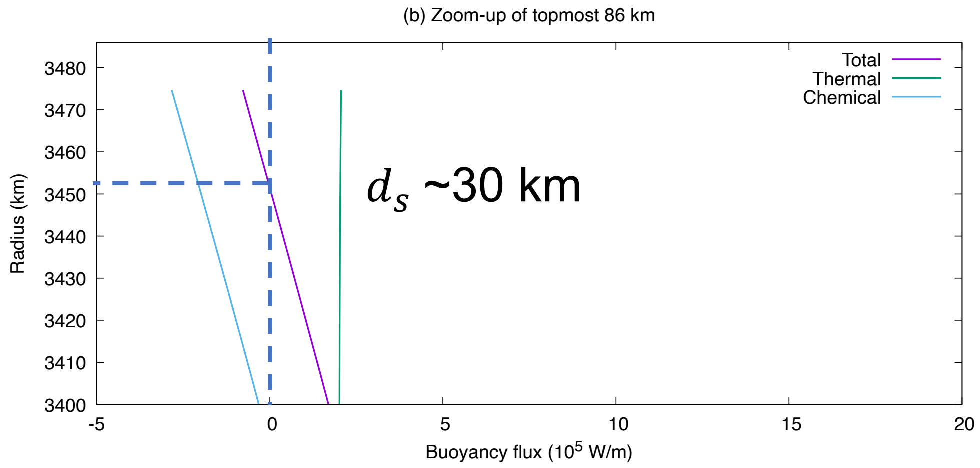
Q^p_{CMB}=10 TW; k_c=112 W/m/K





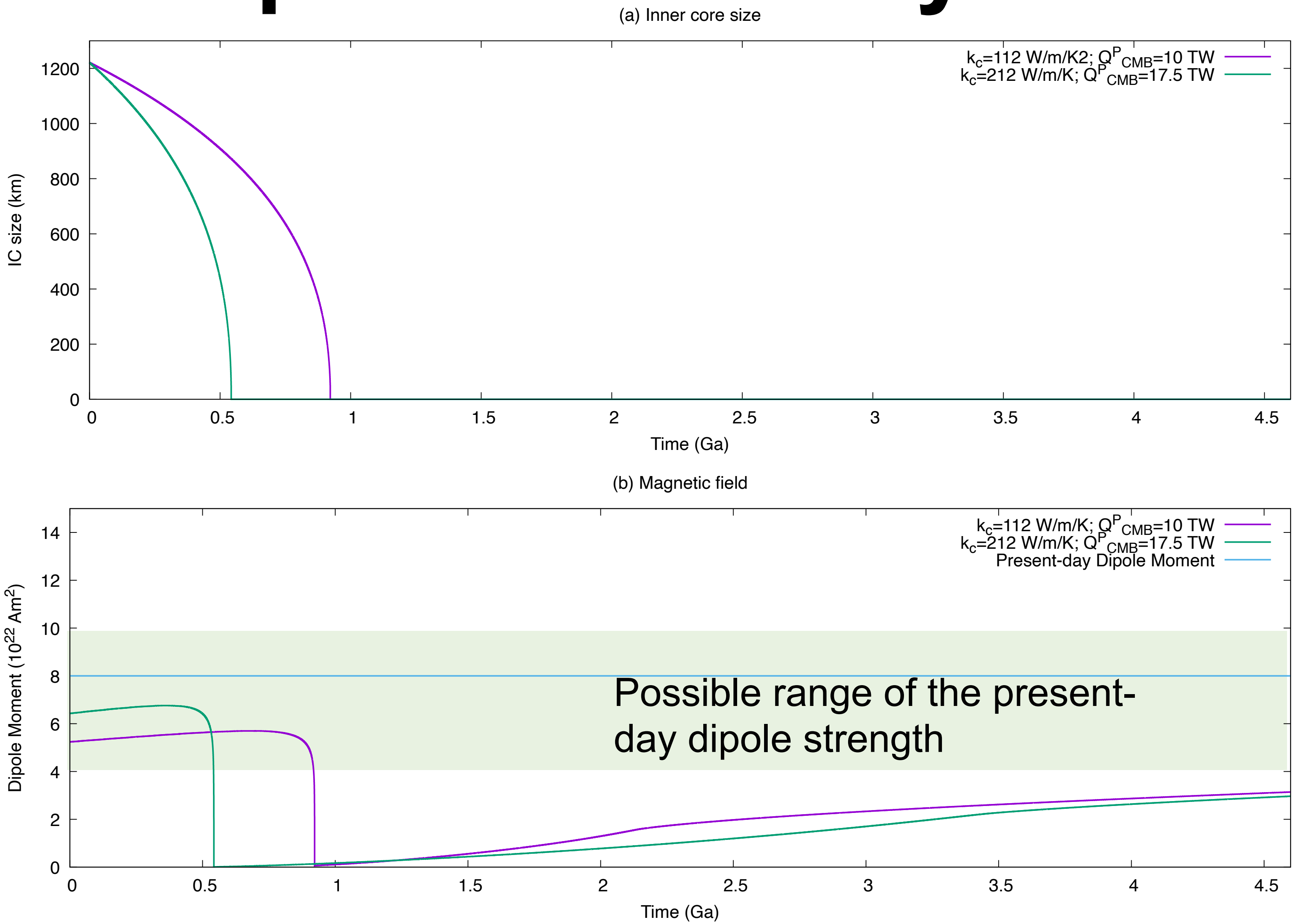
Q^p_{CMB}=17.5 TW; k_c=212 W/m/K





Back trace from present to early Earth

- Inner core age: less than 1 Ga.
- At the onset: Very weak magnetic field.
- Possible to co-exist a stably stratification at the top of Earth's core (30 to 75 km thickness)



Key points of this presentation:

- Finding from results:
  1. Stable region: Need a help of core-mantle chemical interaction.
  2. To find magnetic field and stable region simultaneously:

     Modern estimate: Q^{p}_{CMB} ~17.5 TW (Present-day CMB heat flow); k_c~212 W/m/K (Thermal conductivity); d_s~30 km (Thickness of a stable region)

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