Survey of Planetary Interior Geophysics

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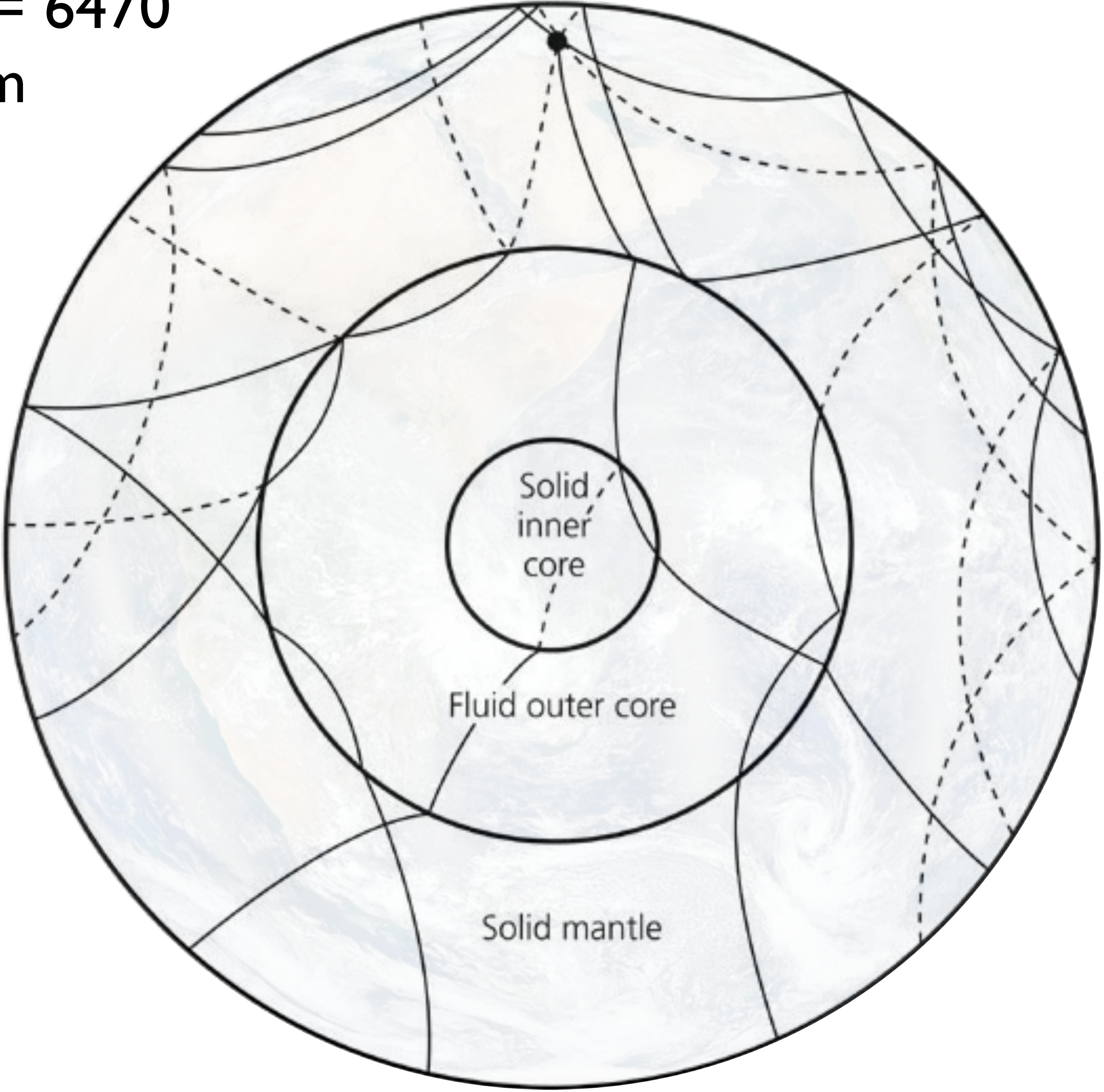
Talk Outline

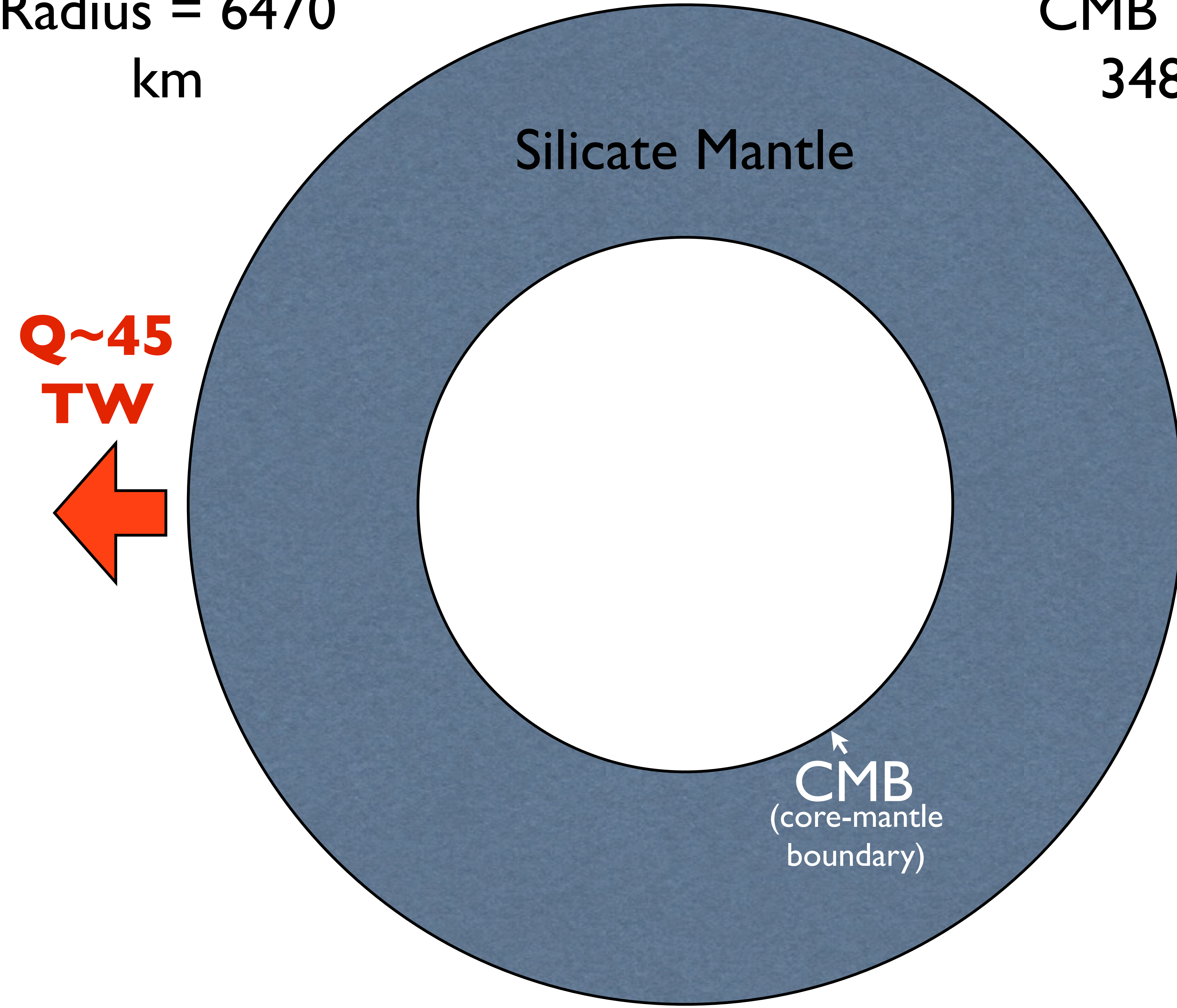
- Interior of the Earth
  - mantle to core
- Dynamo Fundamentals
- Open Questions

Radius = 6470 km



Radius = 6470 km

CMB radius = 3485 km



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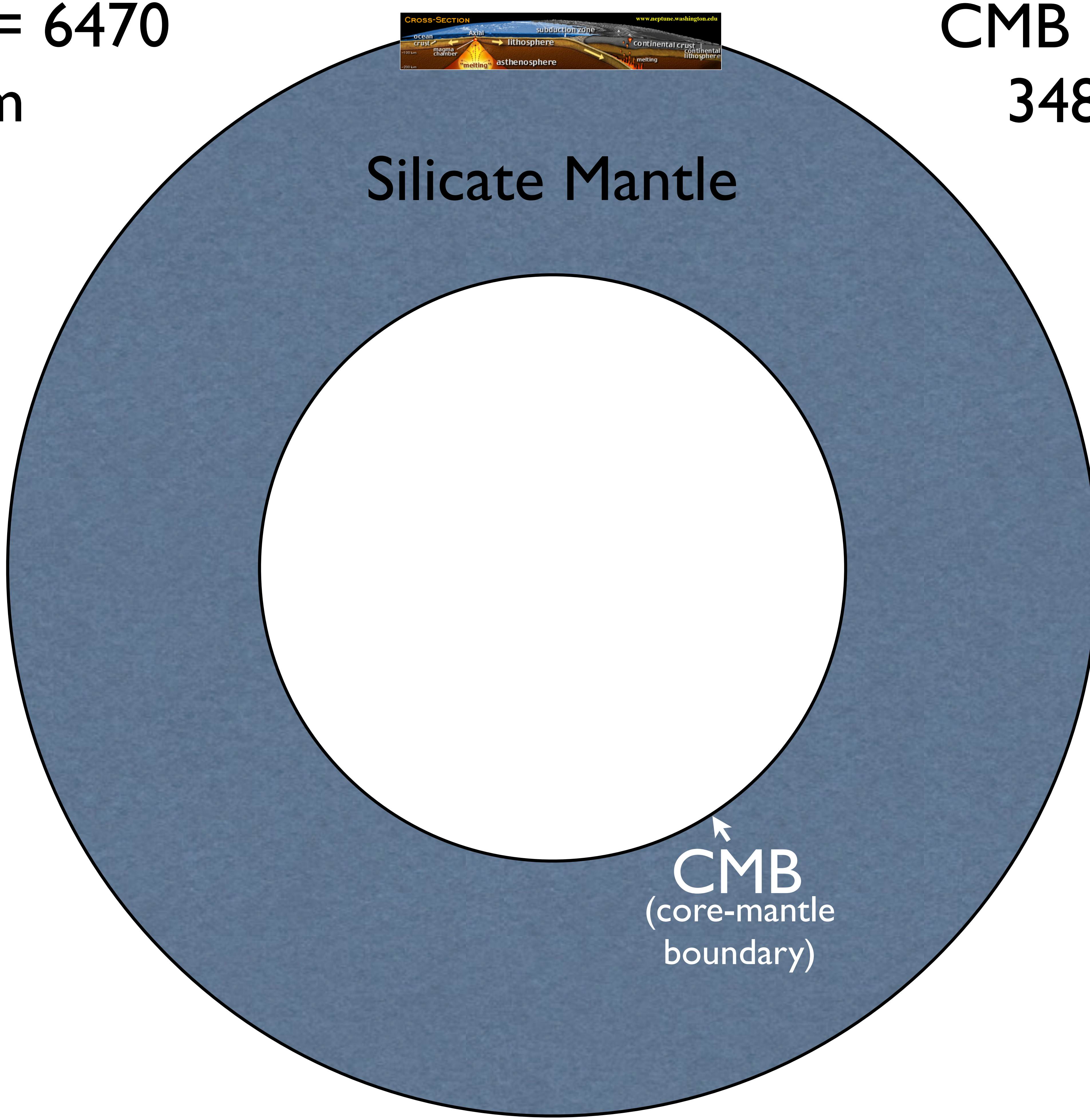
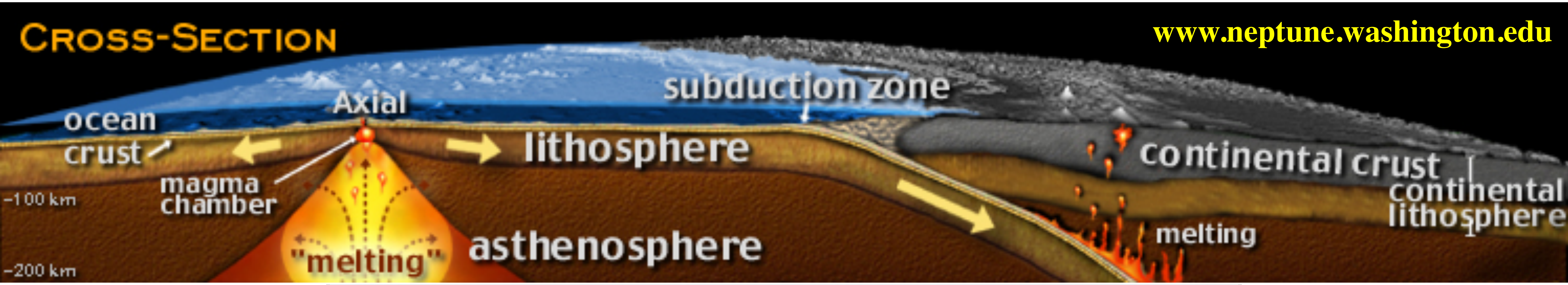
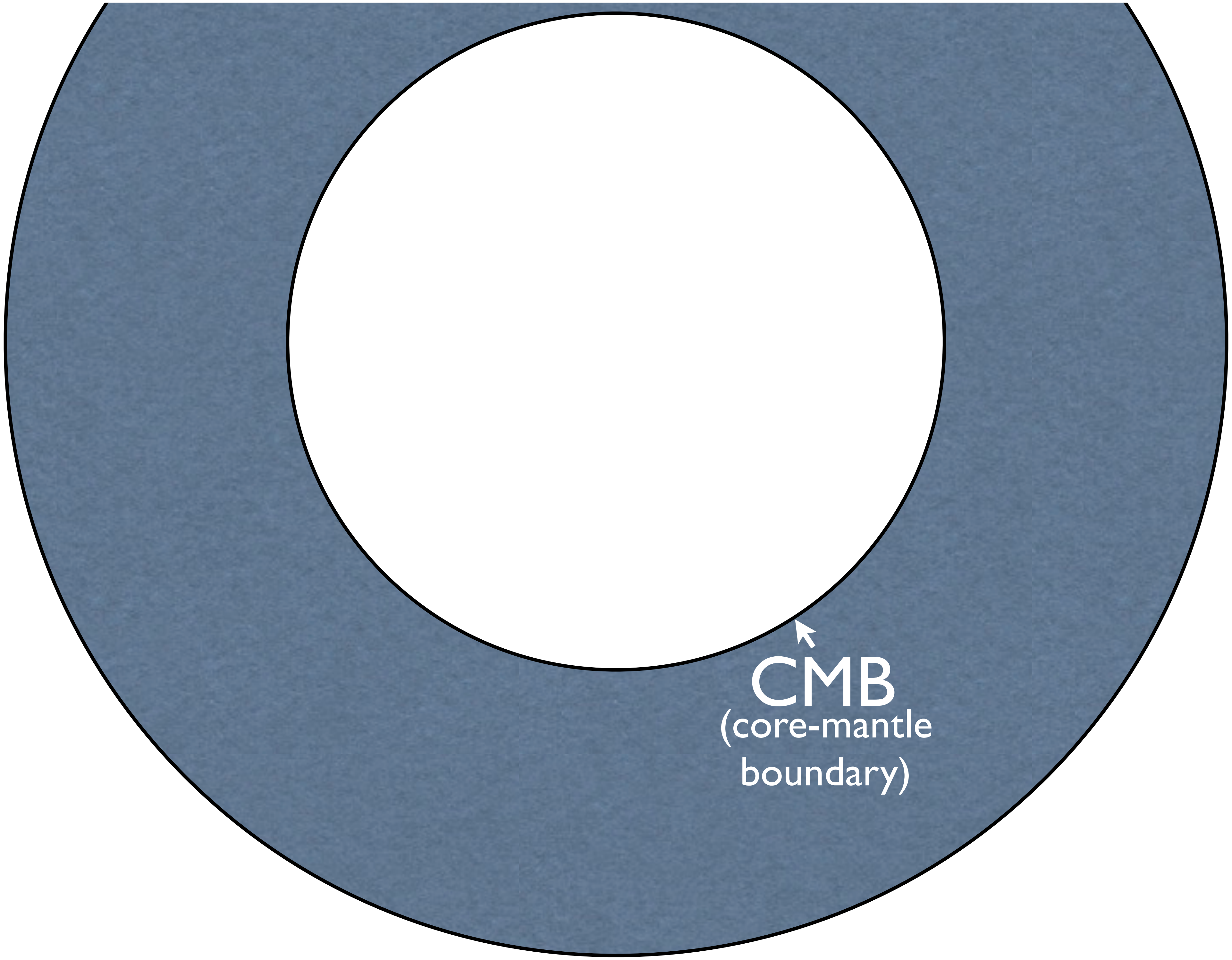
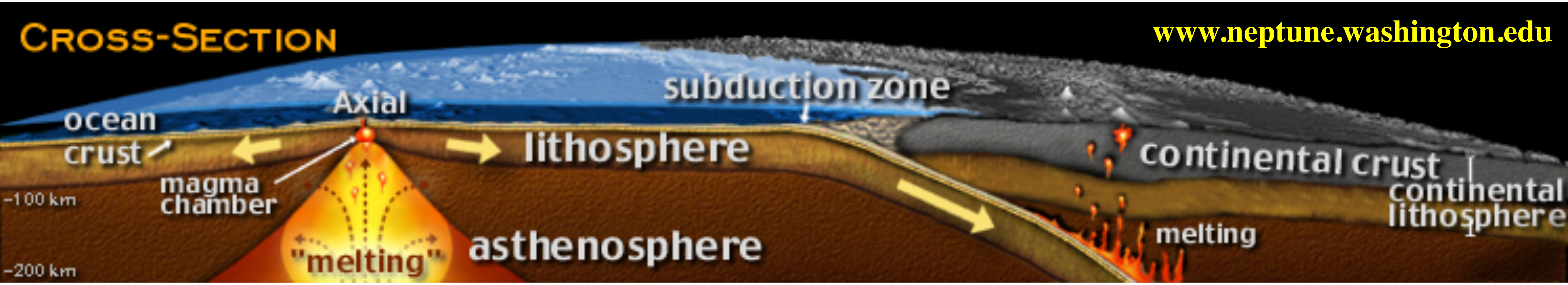
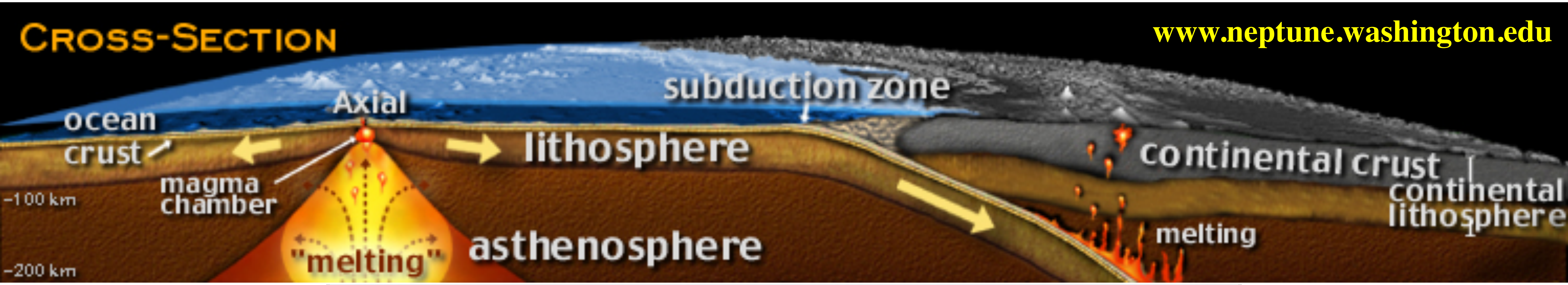



Cross-Section
www.neptune.washington.edu
ocean
crust
Axial
magma chamber
subduction zone
lithosphere
continental crust
continental lithosphere
-100 km
-200 km
"melting"
asthenosphere
melting

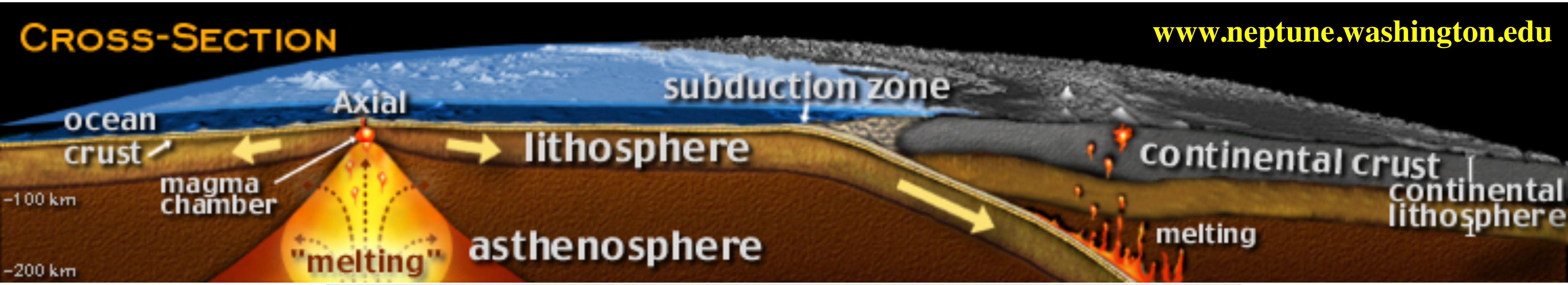

CMB
(core-mantle boundary)



- Oceanic lithosphere: thinner and denser
- Continental lithosphere: Thicker, less dense
  - Continents float higher on mantle
  - Well-defined ocean basins



- Recycling oceanic lithosphere
  - Top boundary layer of convecting mantle
  - Overturn timescale ~ 100 Myrs



- Recycling oceanic lithosphere
- Drives plate tectonics
  - Successful kinematic model

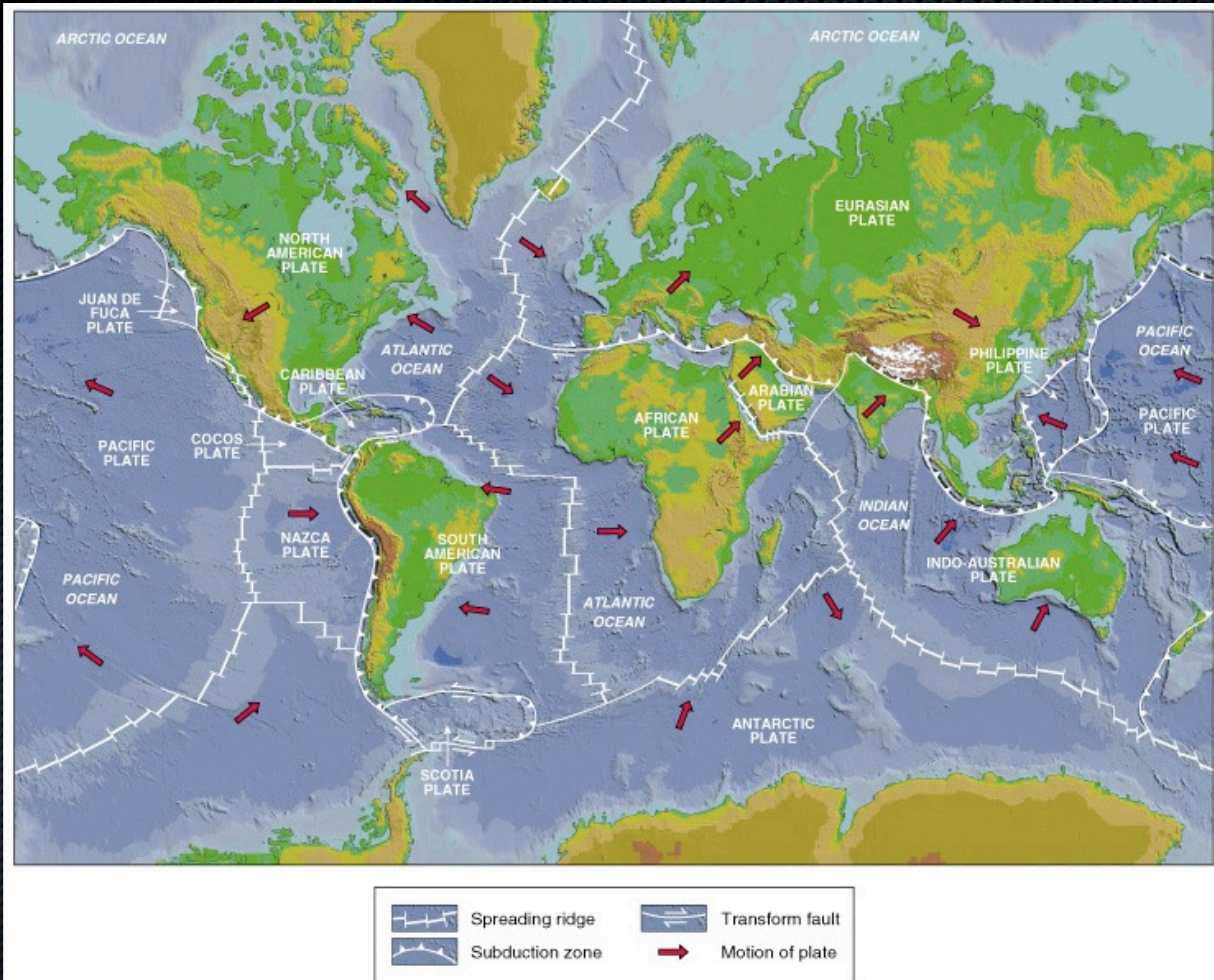
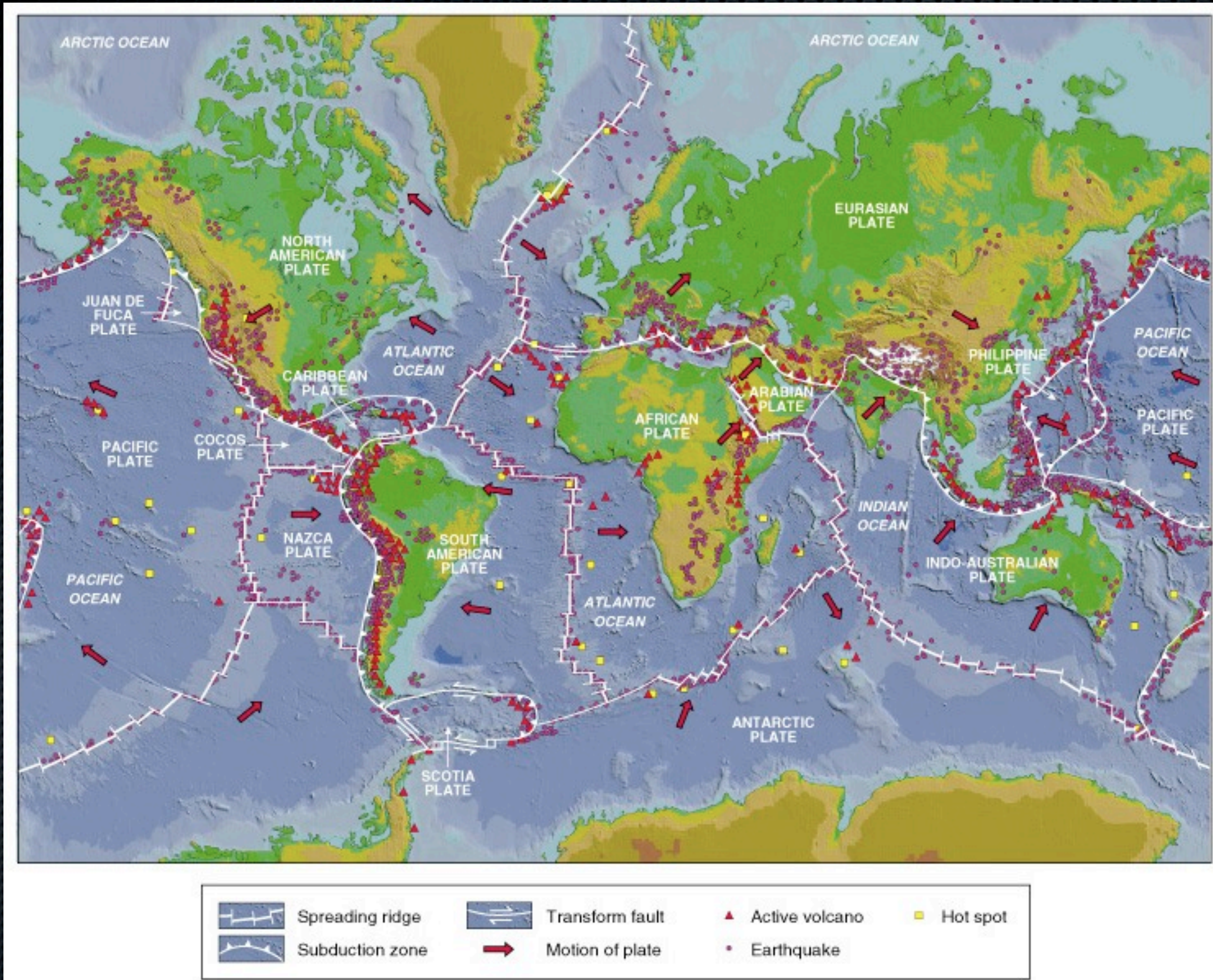


Image: P. Davis



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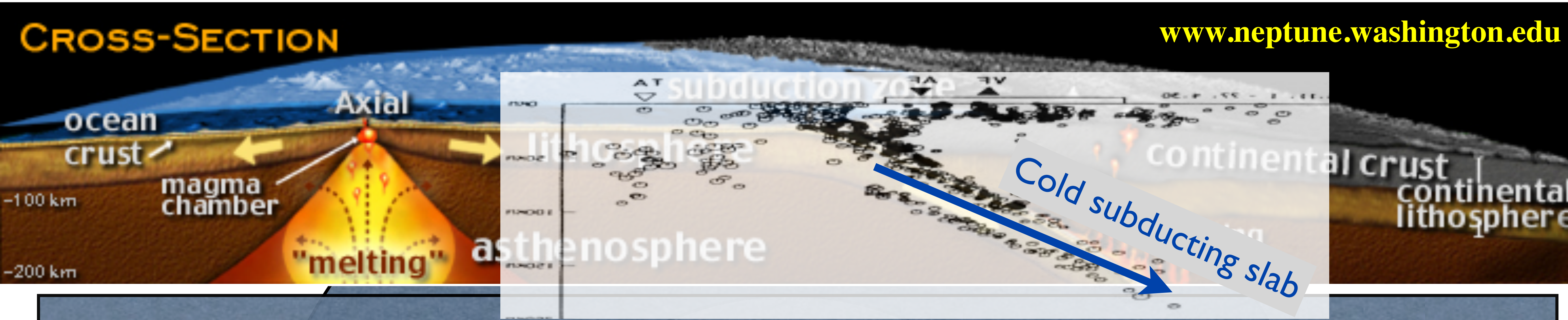

- Recycling oceanic lithosphere
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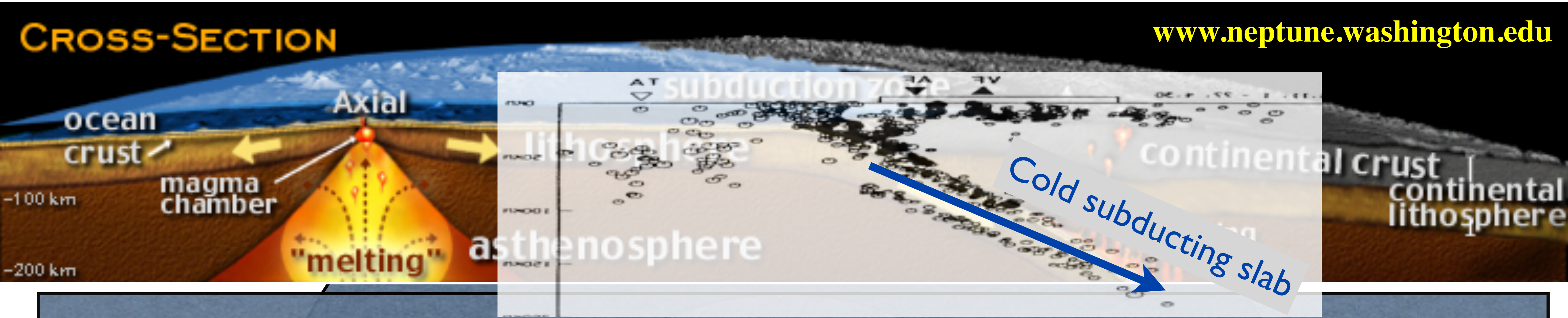
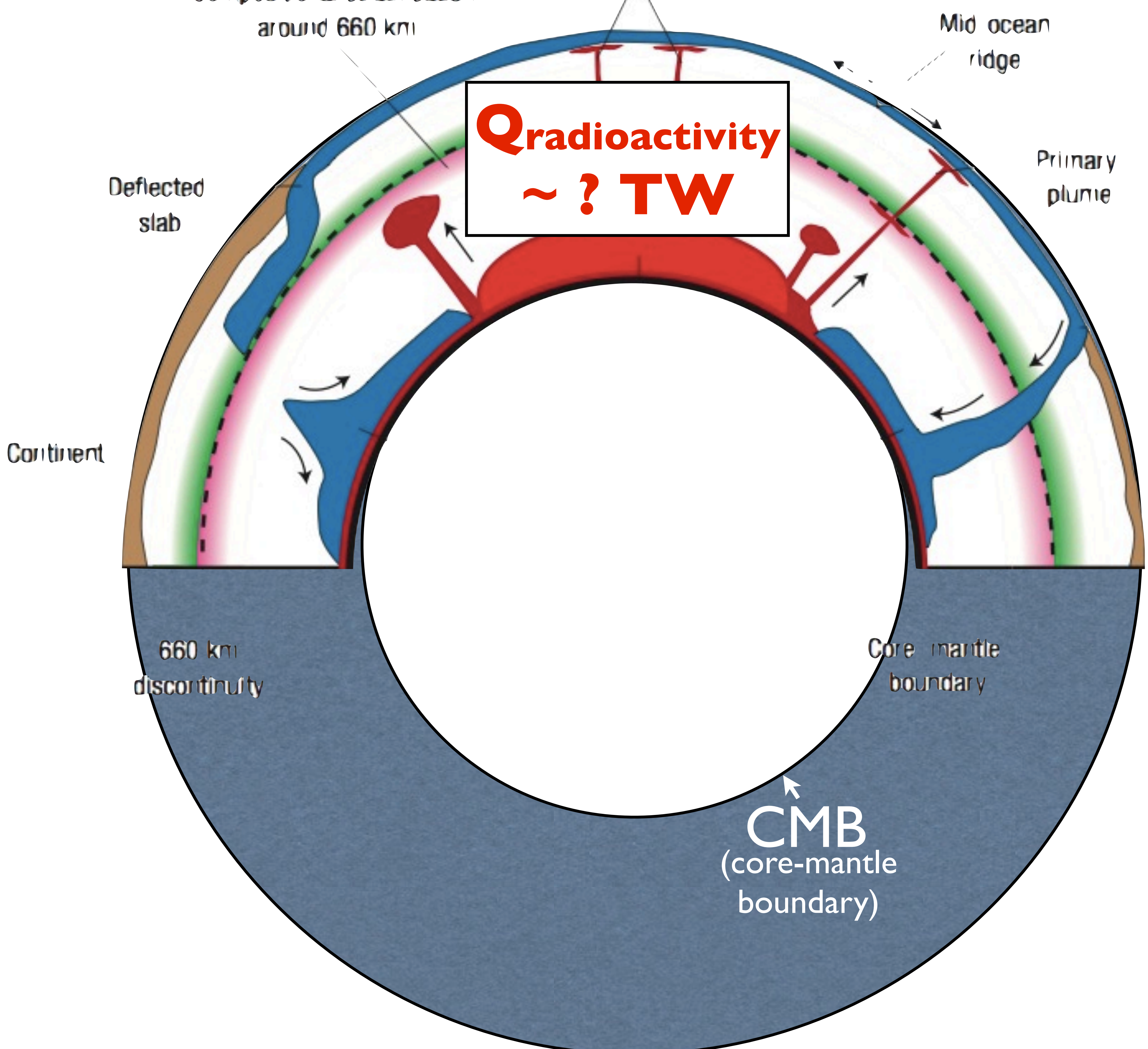
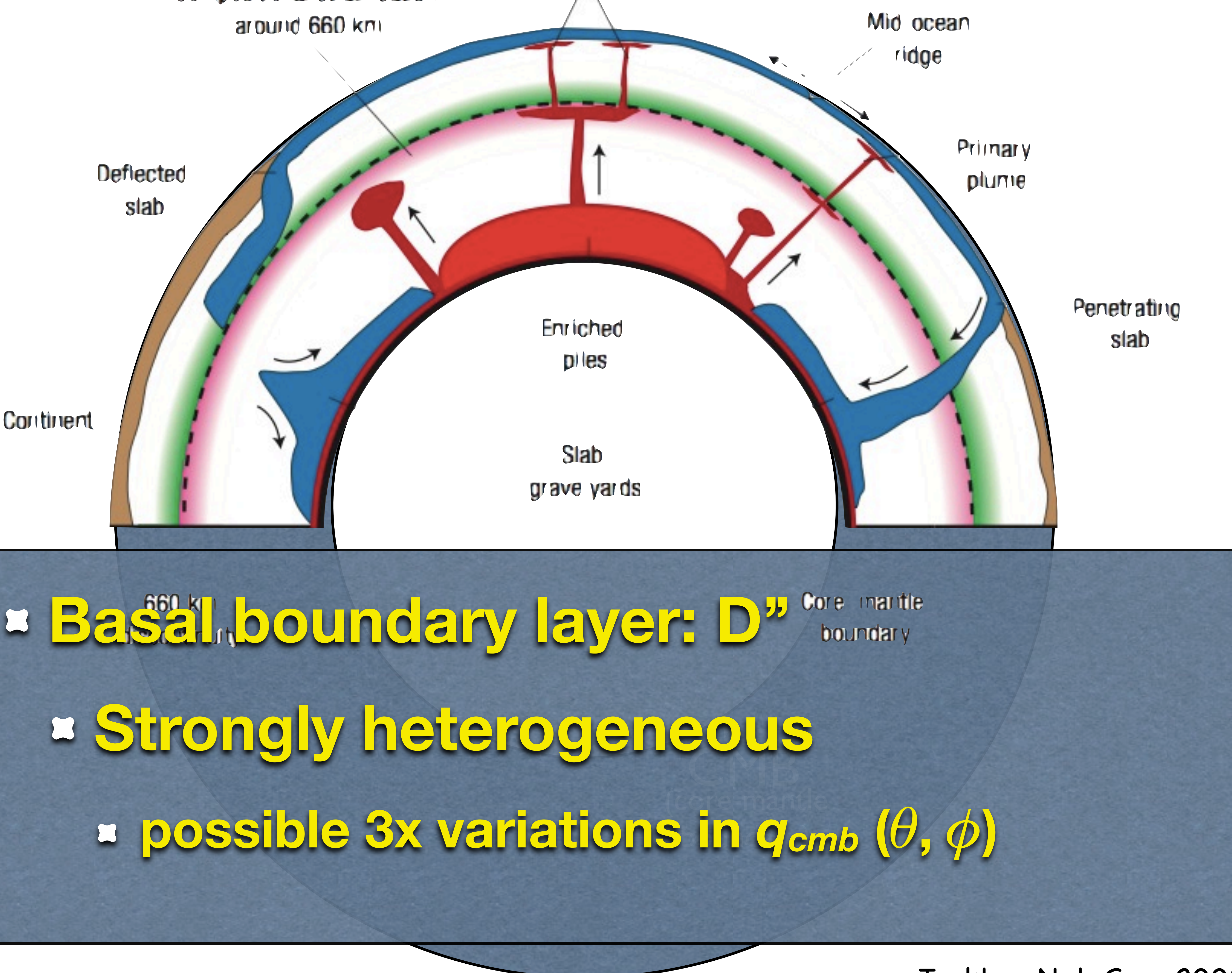
  - Successful kinematic model



- **Recycling oceanic lithosphere**
- **Drives plate tectonics**
  - **Successful kinematic model**
  - **No fully dynamical model yet**
    - ***<u>Subduction process</u>***

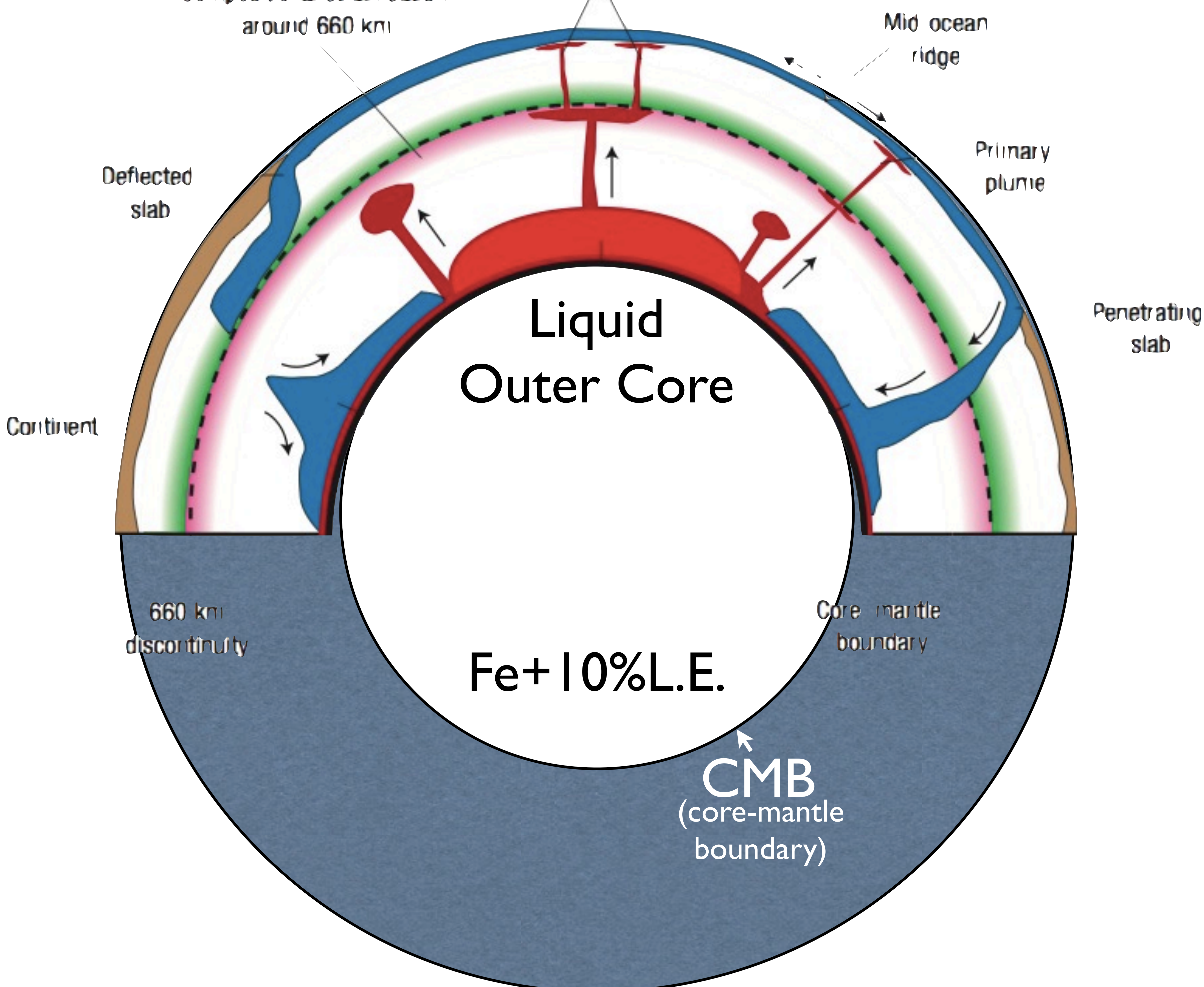


Tackley, *Nat. Geo.* 2008



- **Basal boundary layer: D”**
  - **Strongly heterogeneous**
    - **possible 3x variations in q_{cmb} (θ, ϕ)**

Tackley, Nat. Geo. 2008



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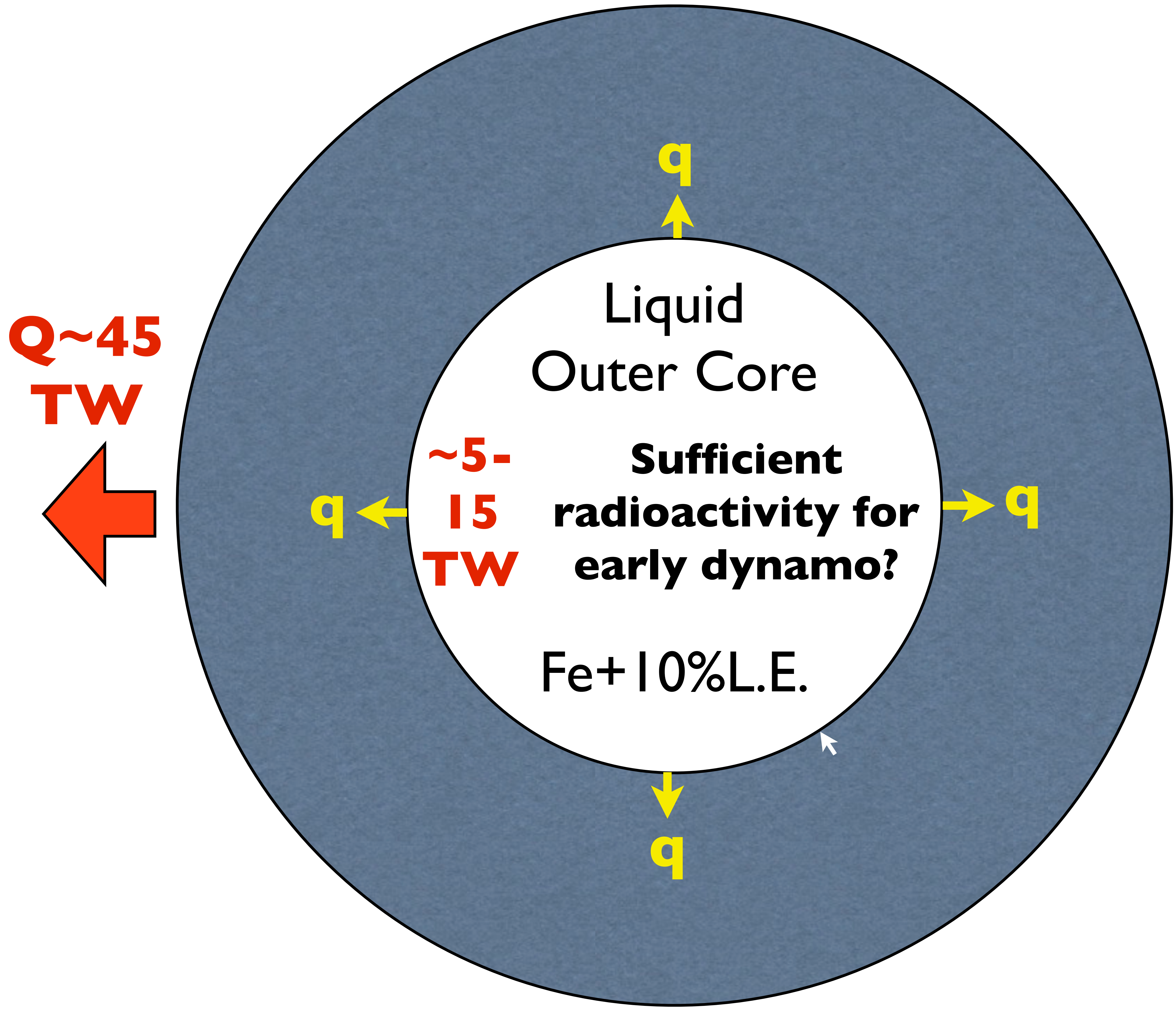
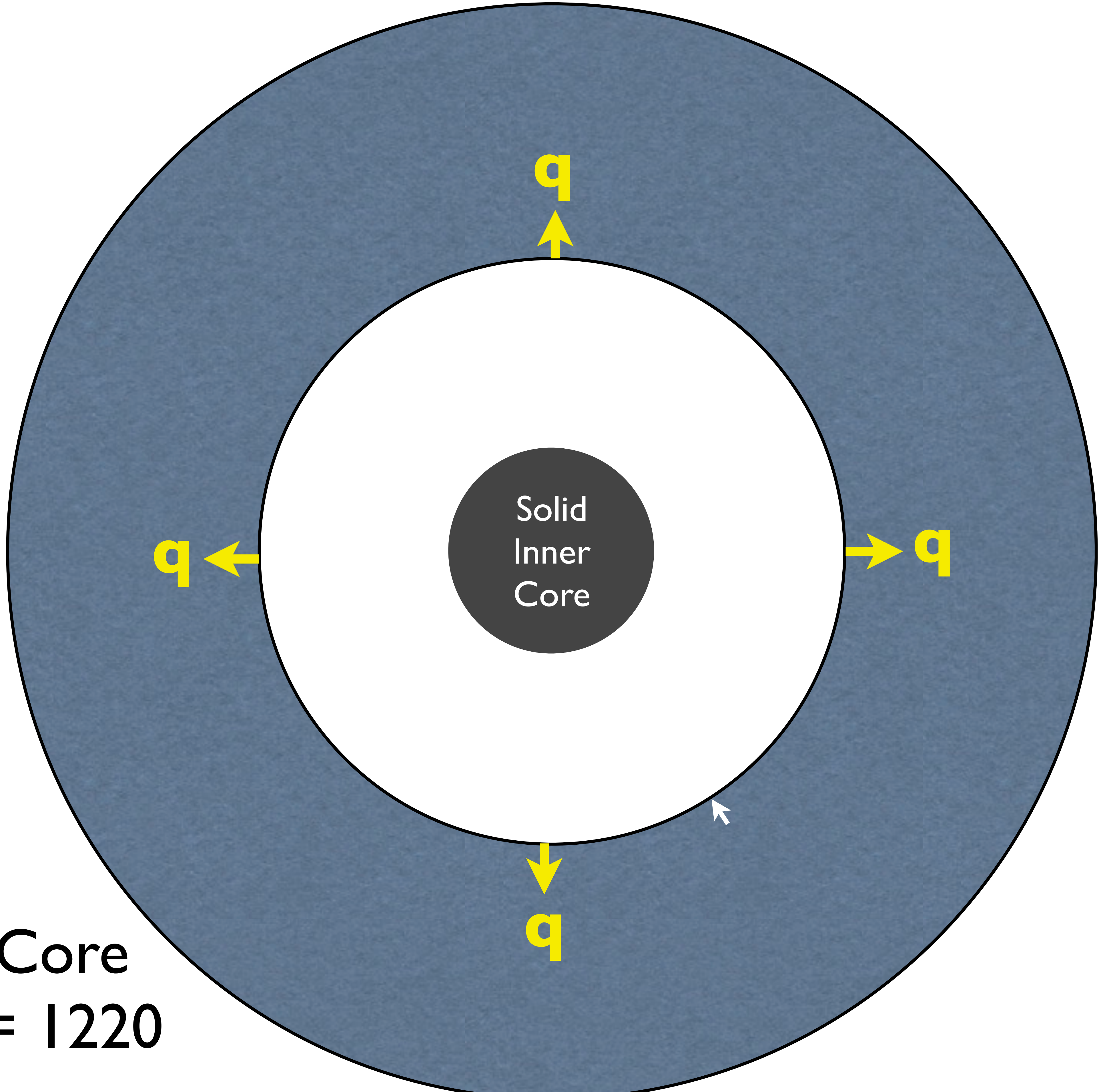
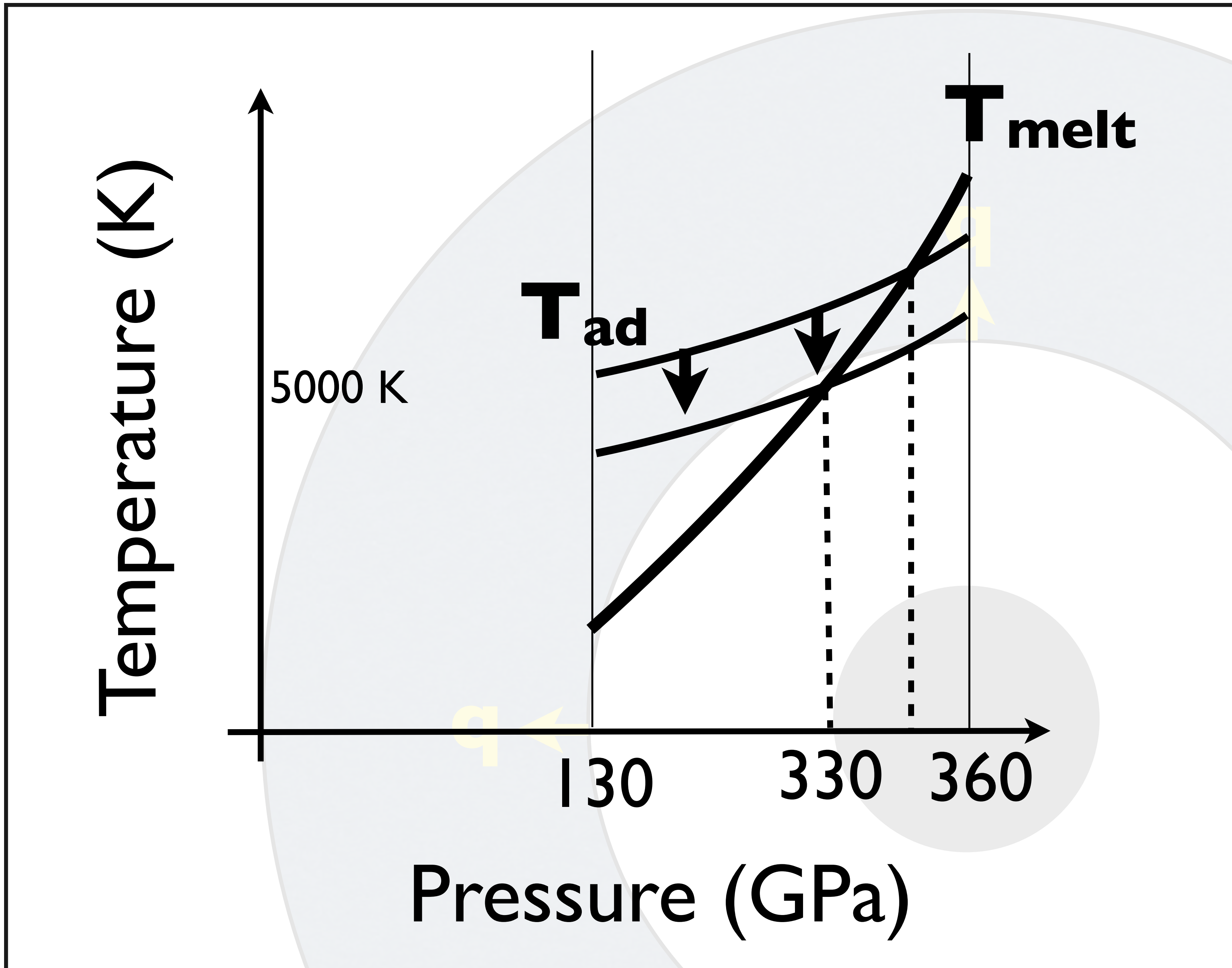

Q~45 TW
Liquid Outer Core
~5-15 TW
Sufficient radioactivity for early dynamo?
q
q
q
q
Fe+10%L.E.



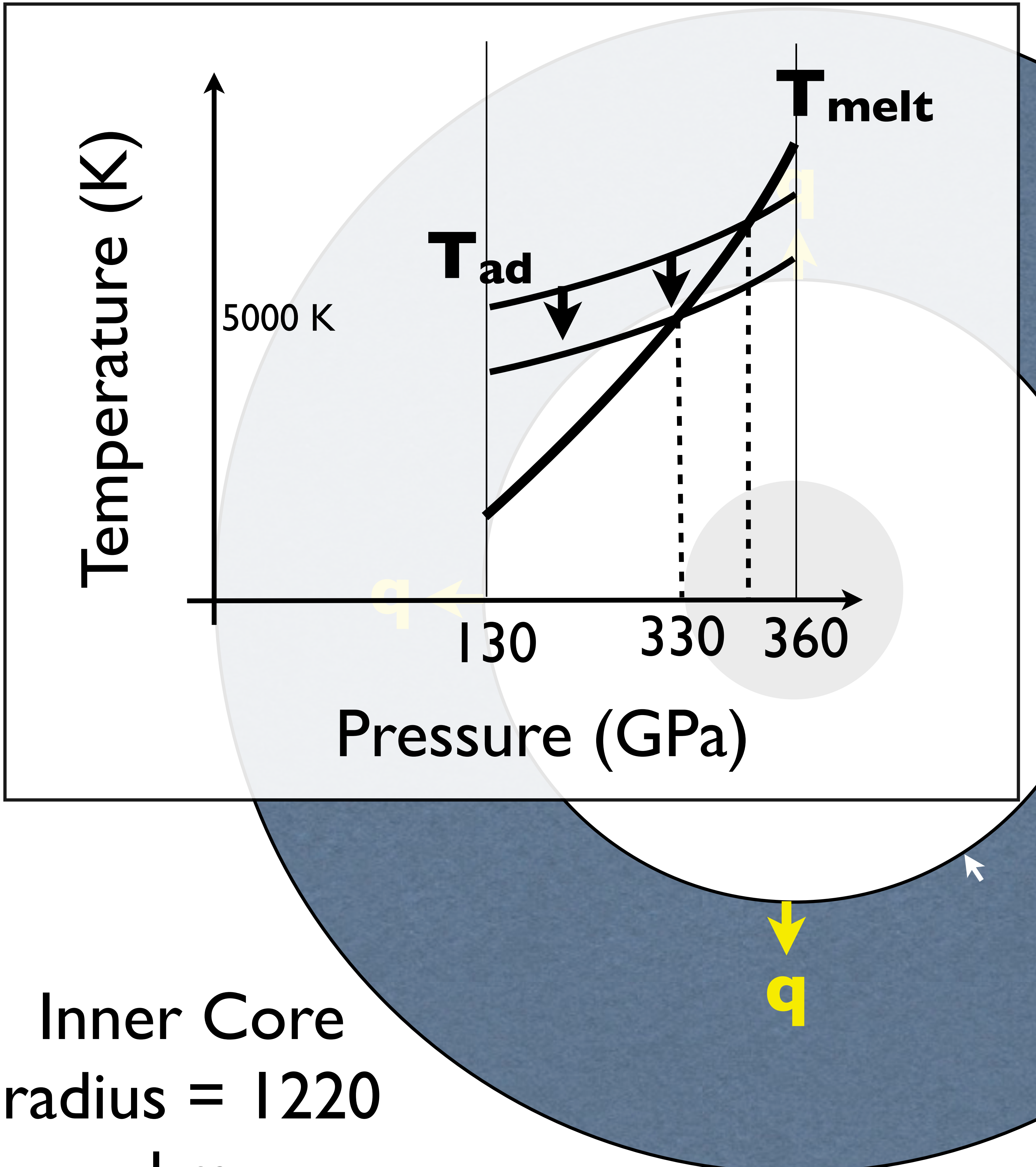
Inner Core
radius = 1220
km



- **Growing Fe inner core**
  - **Latent heat source**
  - **Chemical buoyancy source**
- **Thermo-chemical convection**
  - ***Tight energy budget***

$$B \simeq \left(\frac{\delta \rho_{ic}}{\rho} + \frac{\alpha L}{C_p} \right) g_{ic} \frac{dR_{ic}}{dt}$$

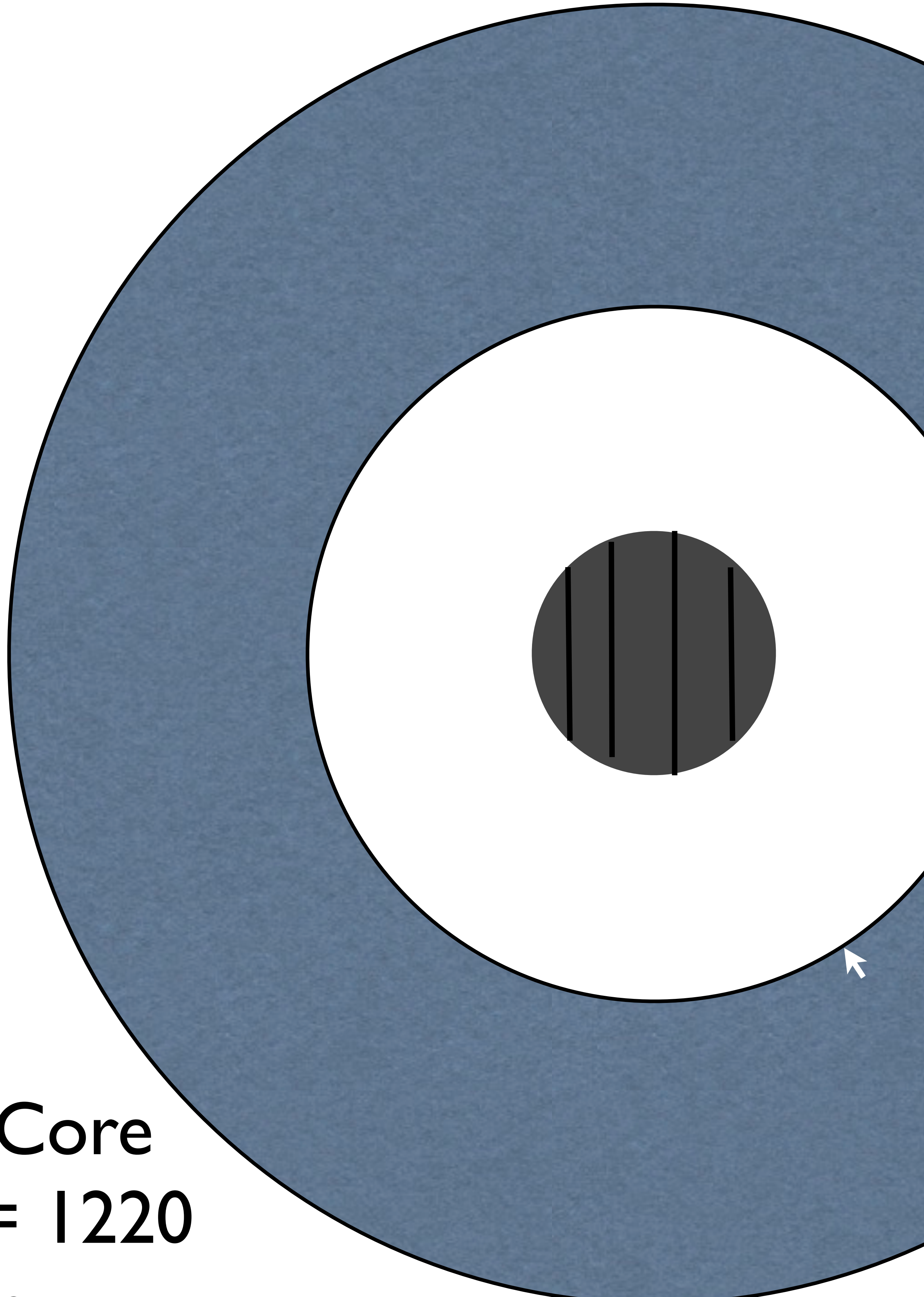
radius = 1220 km



Inner Core radius = 1220 km

- **Growing Fe inner core**
  - **Leading idea for what fuels core dynamo**

- **IC seismics**
  - **fast along axial direction**



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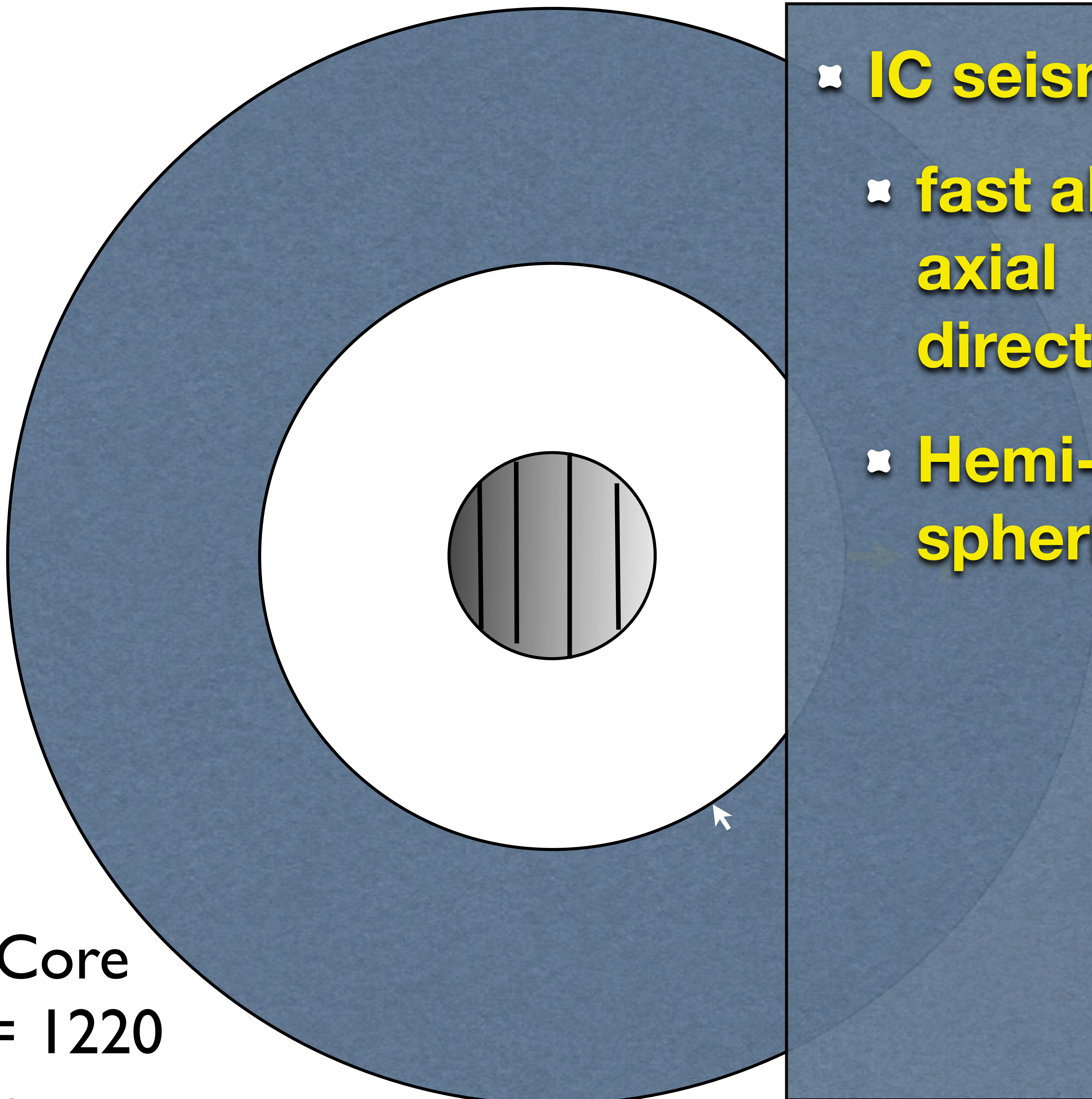
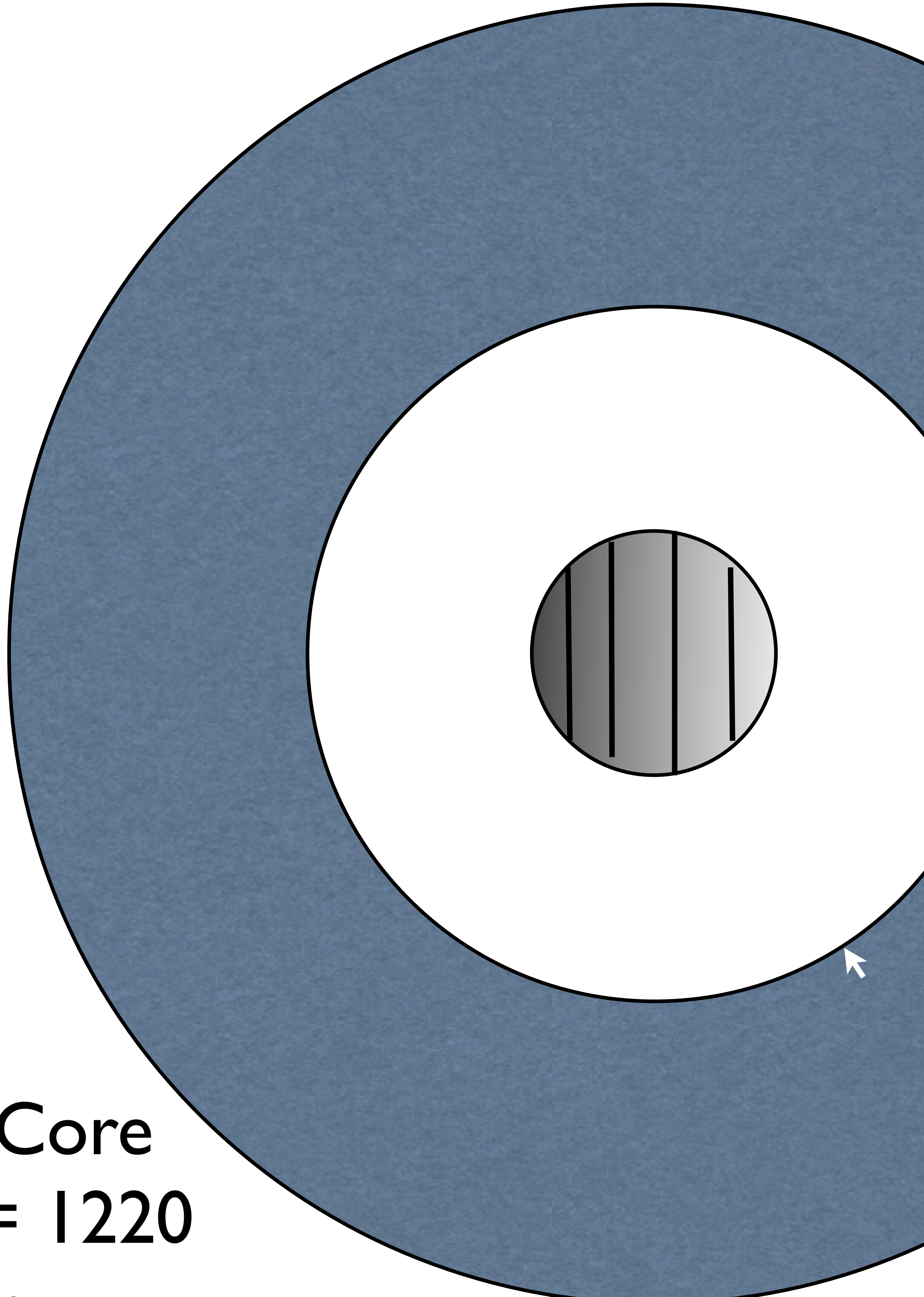


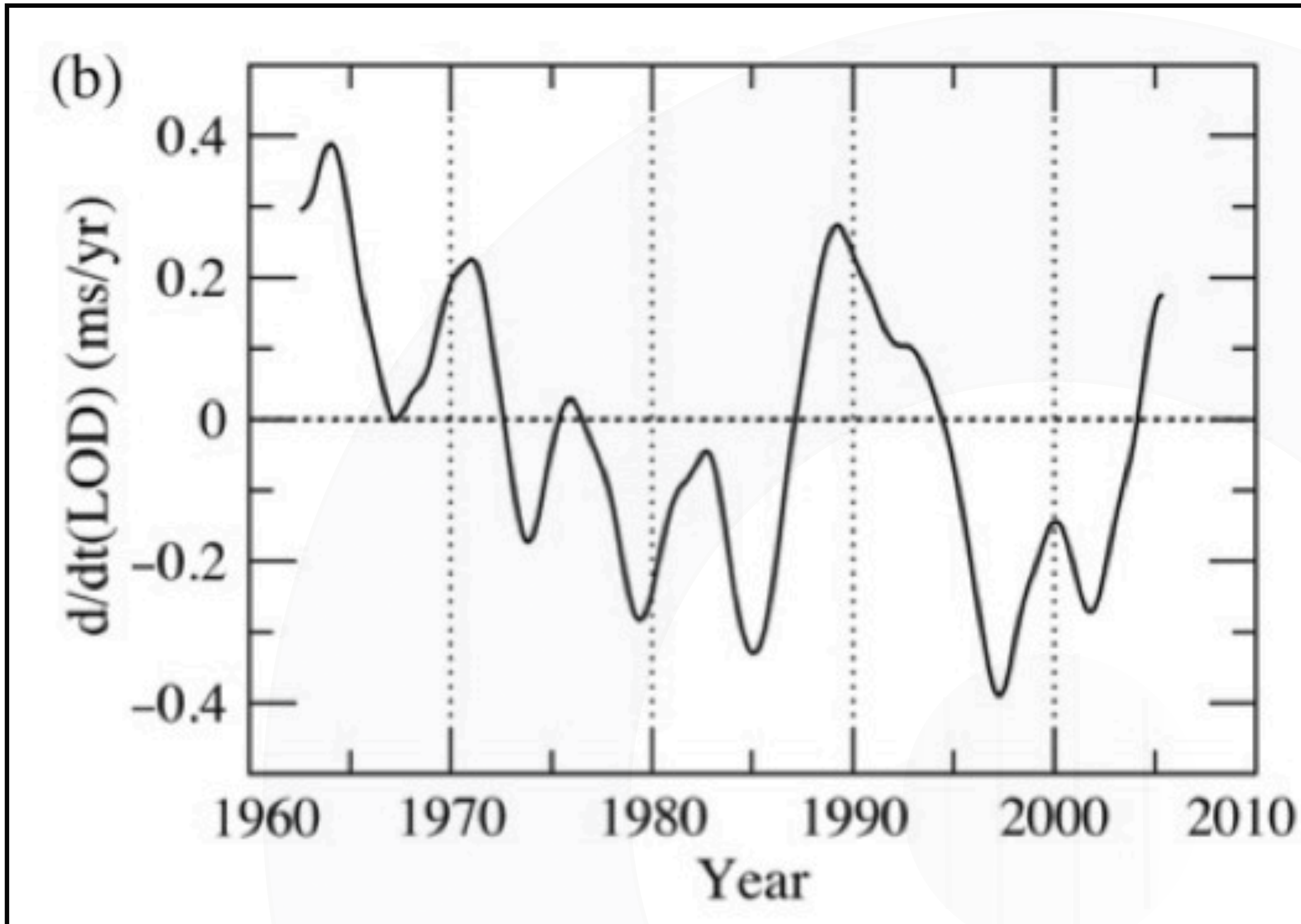
- IC seismics
  - fast along axial direction
  - Hemi-sphericity

Inner Core radius = 1220 km

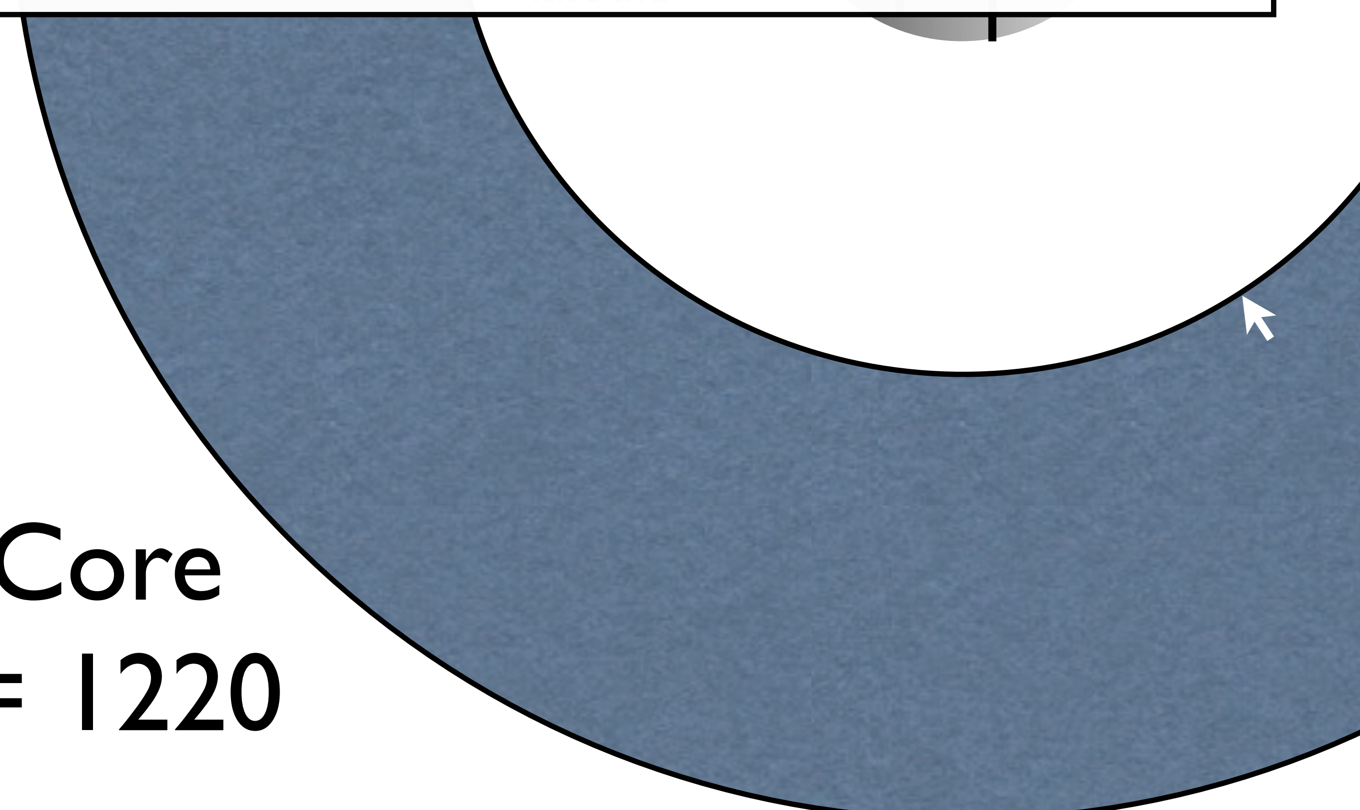


- IC seismics
  - fast along axial direction
  - Hemi-sphericity
- Dynamics
  - Translation?
  - Anomalous rotation

Inner Core radius = 1220 km

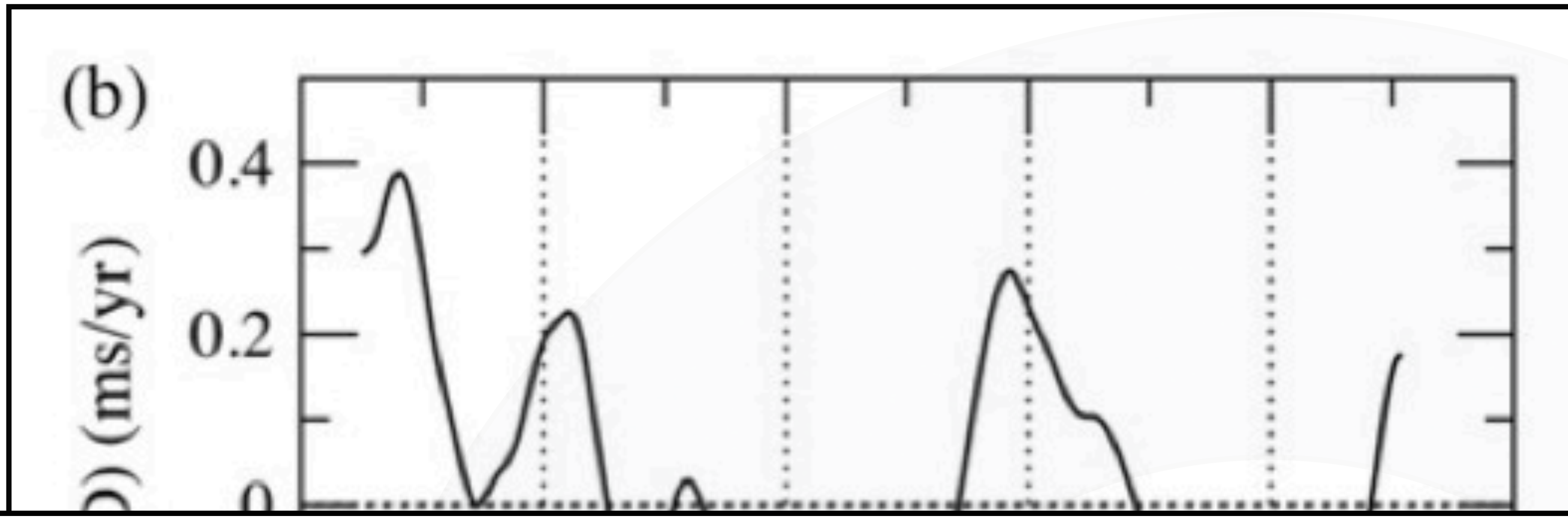


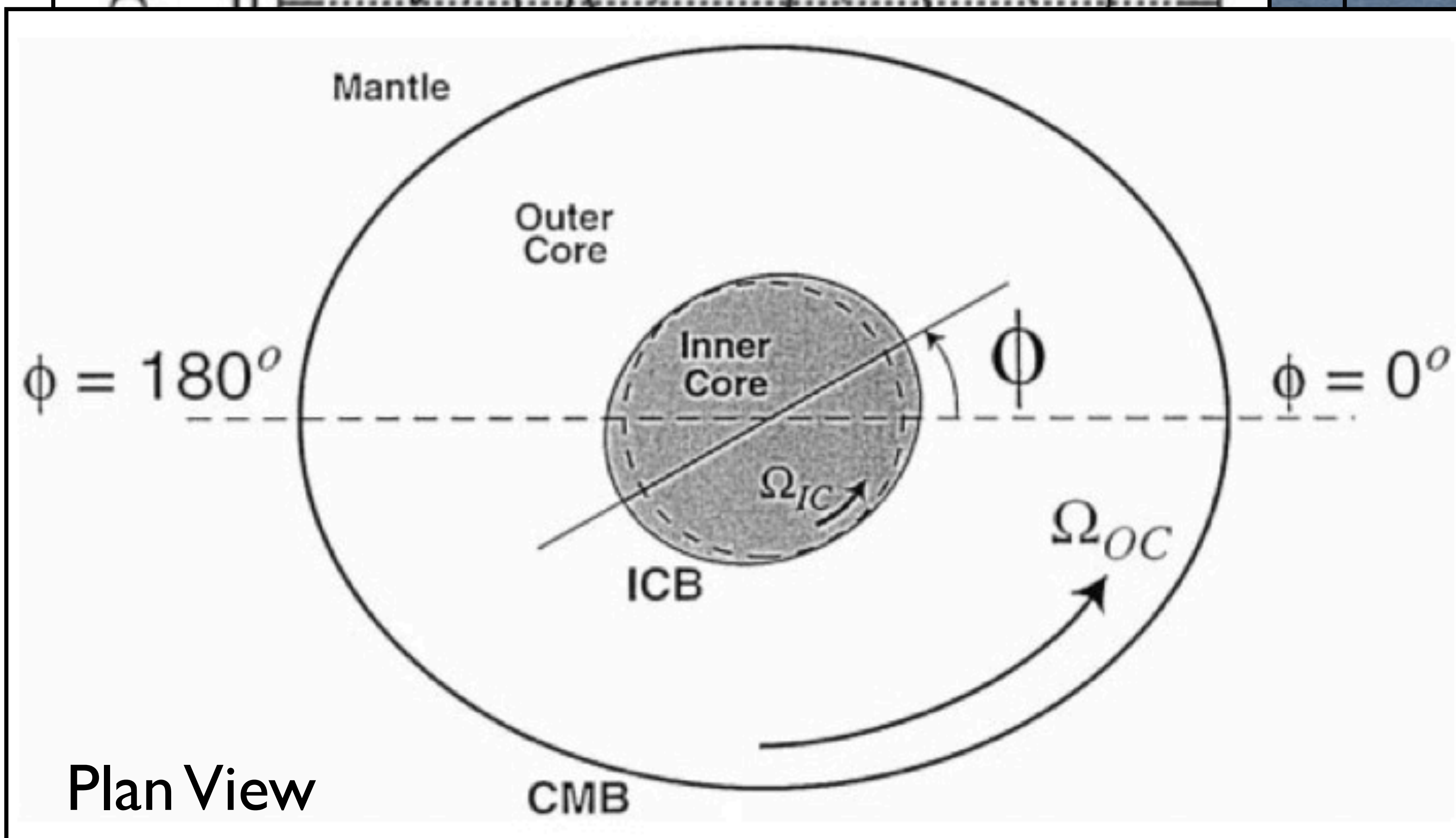
- **Length of day**
  - **C-M coupling ~ 10^18 N.m**



Inner Core radius = 1220

LOD data: Holme & de Viron GJI'05



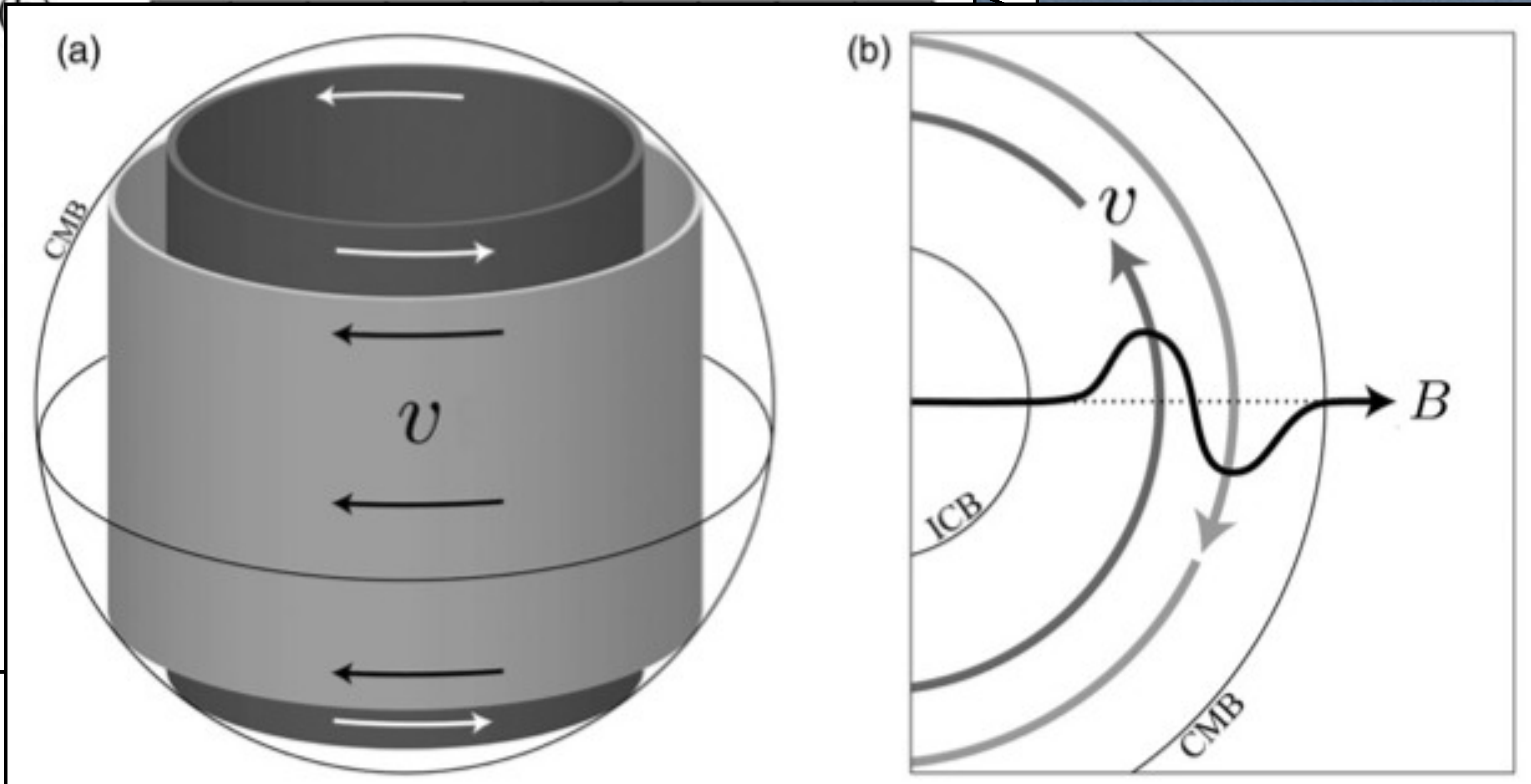


- **Length of day**
  - **C-M coupling ~ 10^18 N.m**
    - **IC grav'l oscilla-tion?**

Inner Core radius = 1220

.

LOD data: Holme & de Viron GJI'05

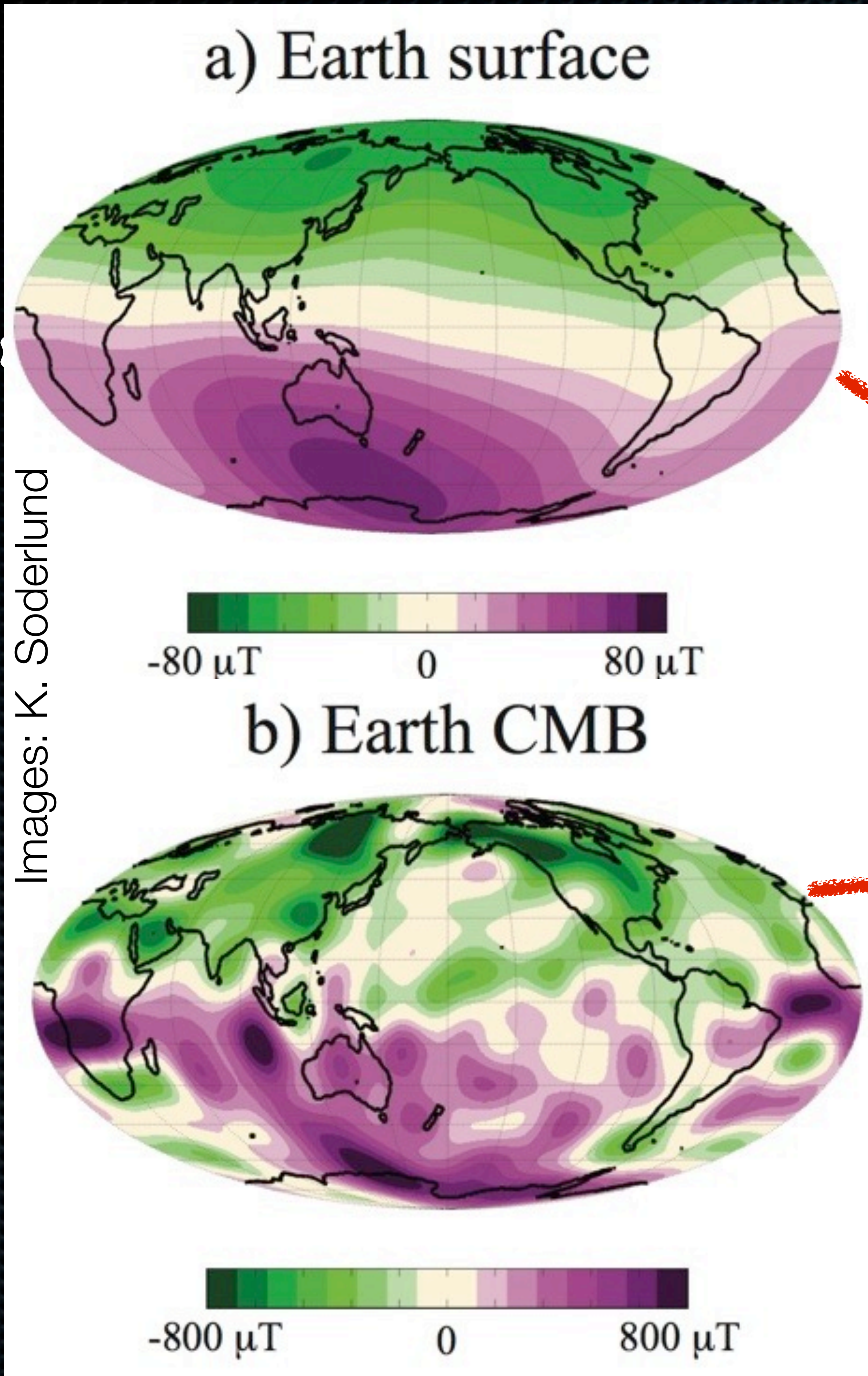


- **Torsional waves in the core?**

Inner Core radius = 1220

LOD data: Holme & de Viron GJI'05

etic Field



Images: K. Soderlund

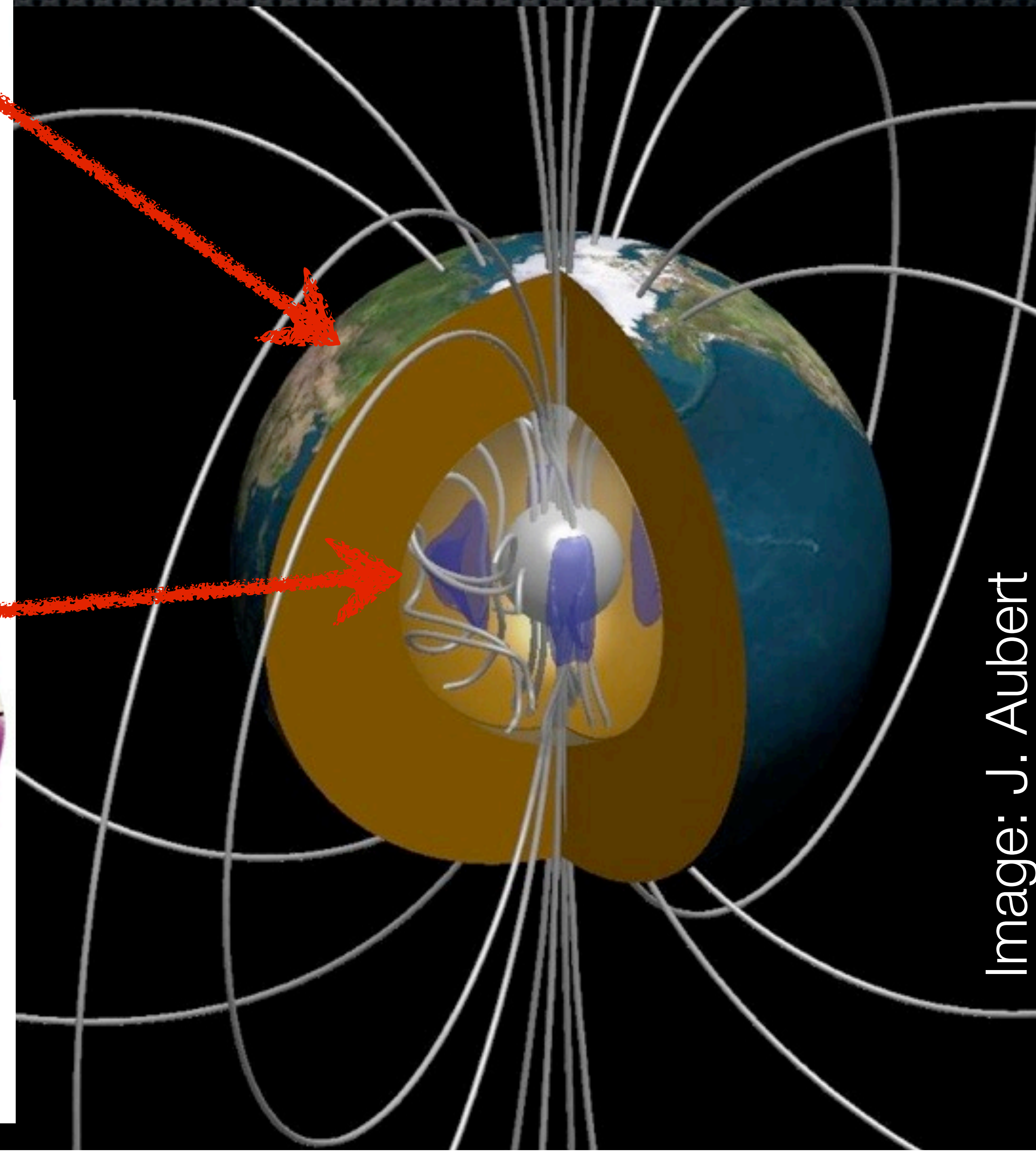


Image: J. Aubert

Earth's Magnetic Field

- Surface field extrapolation
- Outside of core, current density is ~zero:

$$\nabla \times \vec{B} \simeq \mu_o \vec{J} = 0\,; \;\; \nabla \cdot \vec{B} = 0$$

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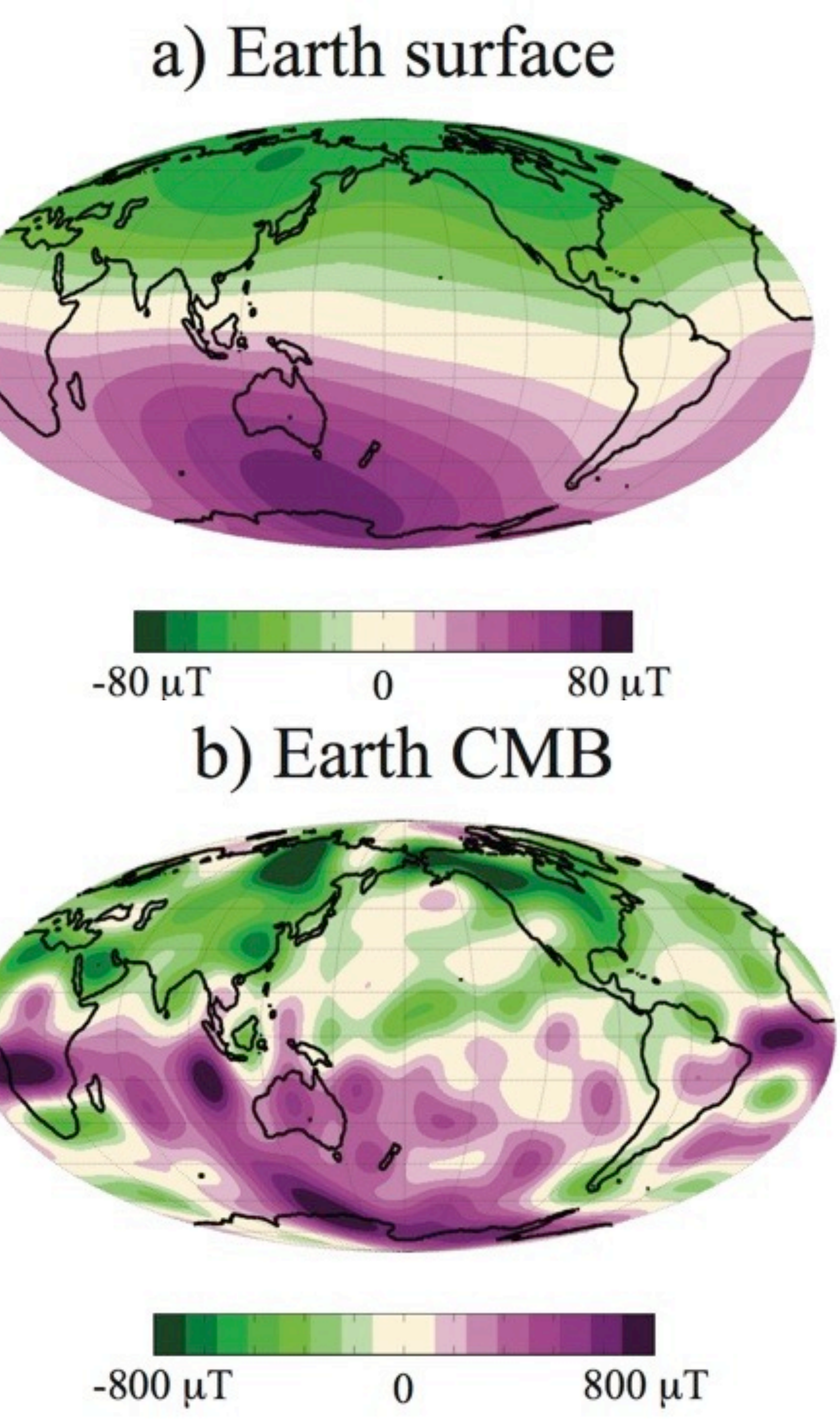
- Solution to Laplacian:

$$W(r,\,\theta,\,\phi,\,t) = a \sum_{l=1}^{l_{max}} \sum_{m=0}^{l} (a/r)^{l+1} \; g_l^m(t)\; Y_l^m(\theta,\,\phi)$$

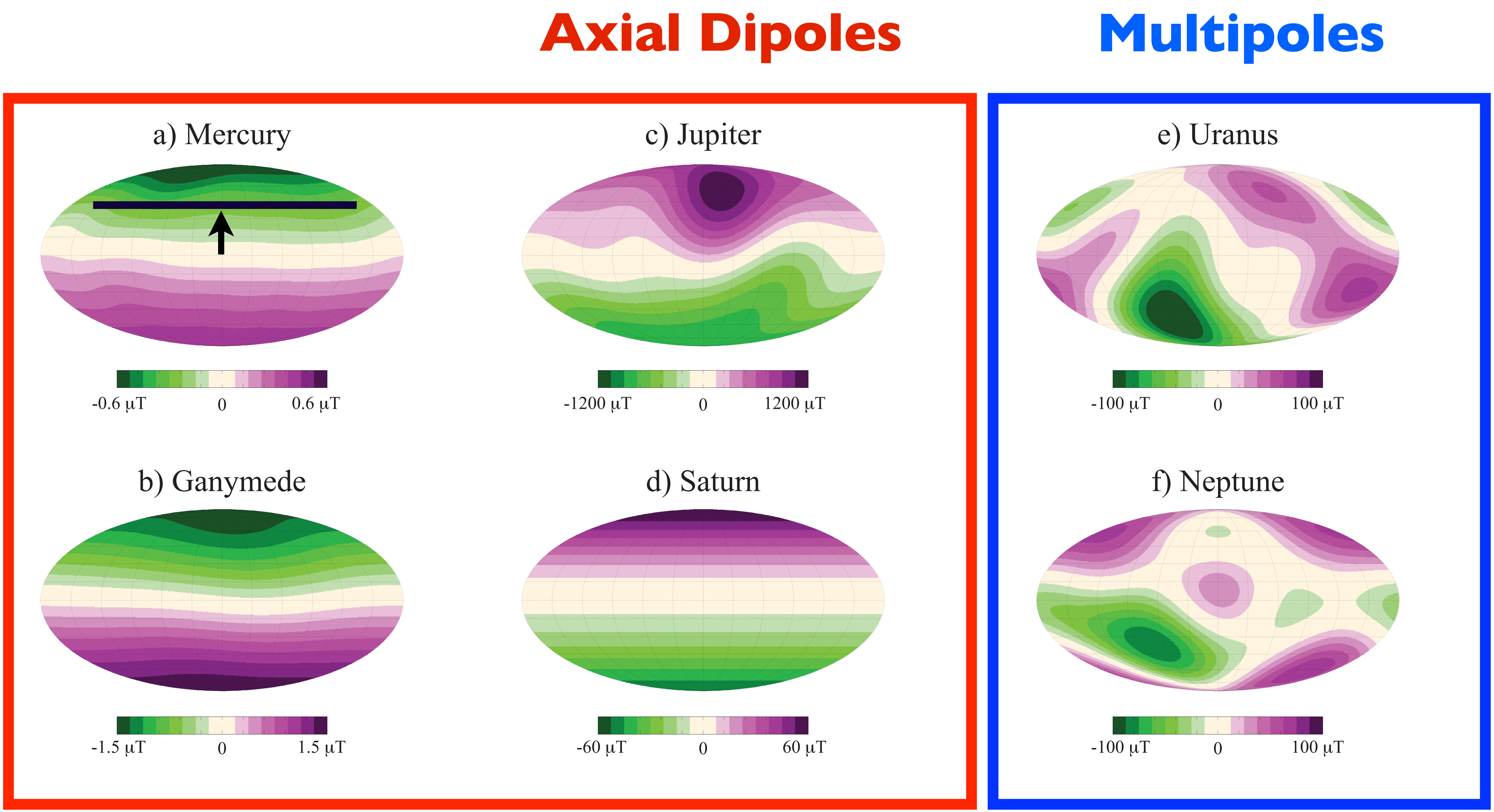
etic Field



Images: K. Soderlund

- Potential field can be extrapolated from surface down to CMB
- But not possible to extrapolate ***INSIDE*** the core
- Very low resolution view of the geomagnetic field
- Crustal field swamps out core field so that L_{max} ~ 15

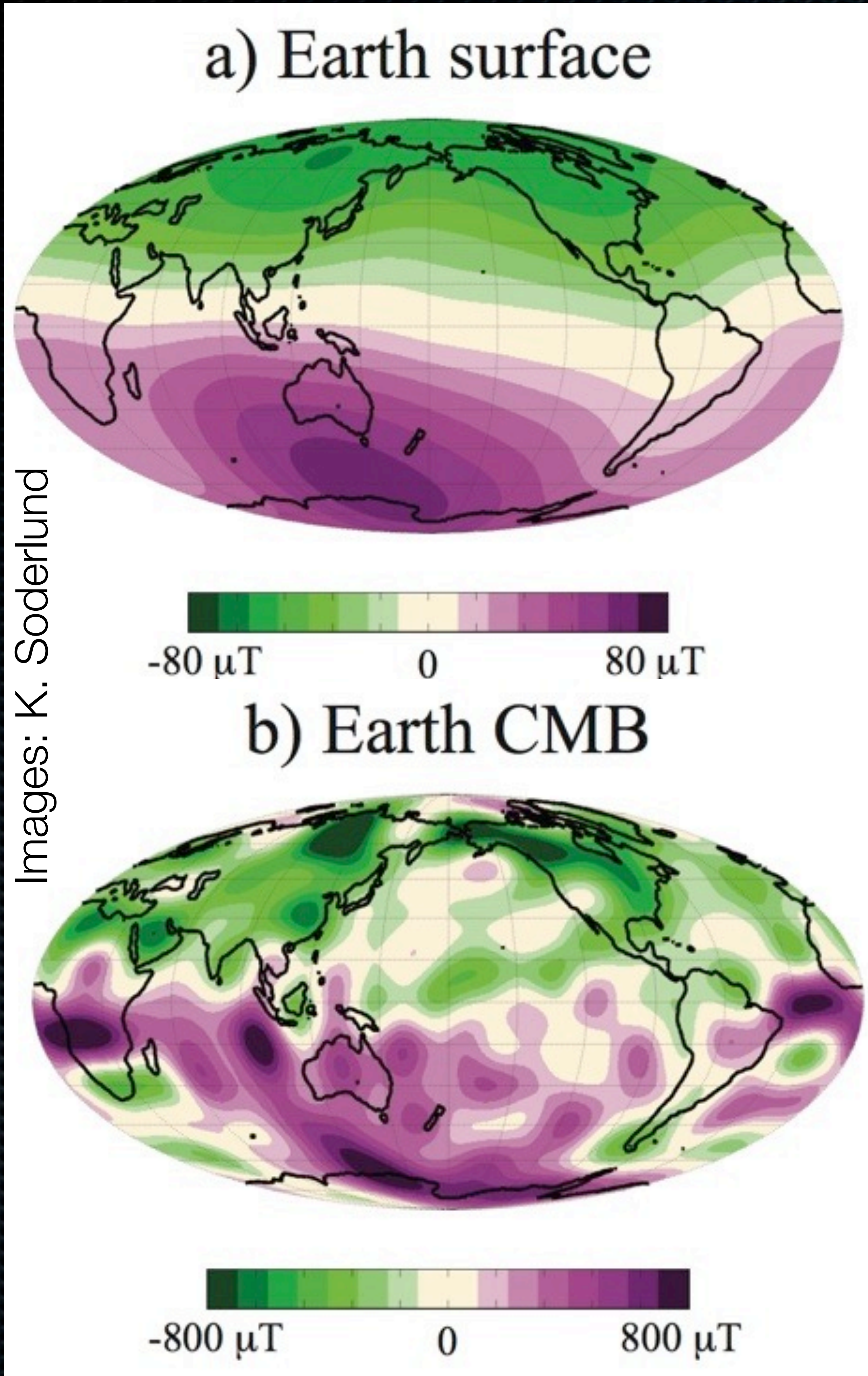
Other Planetary *B*-Fields



Data taken from Uno et al. (2009), Kivelson et al. (2002), Yu et al. (2010), Burton et al. (2009), and Holme and Bloxham (1996).

Image: K. Soderlund

etic Field



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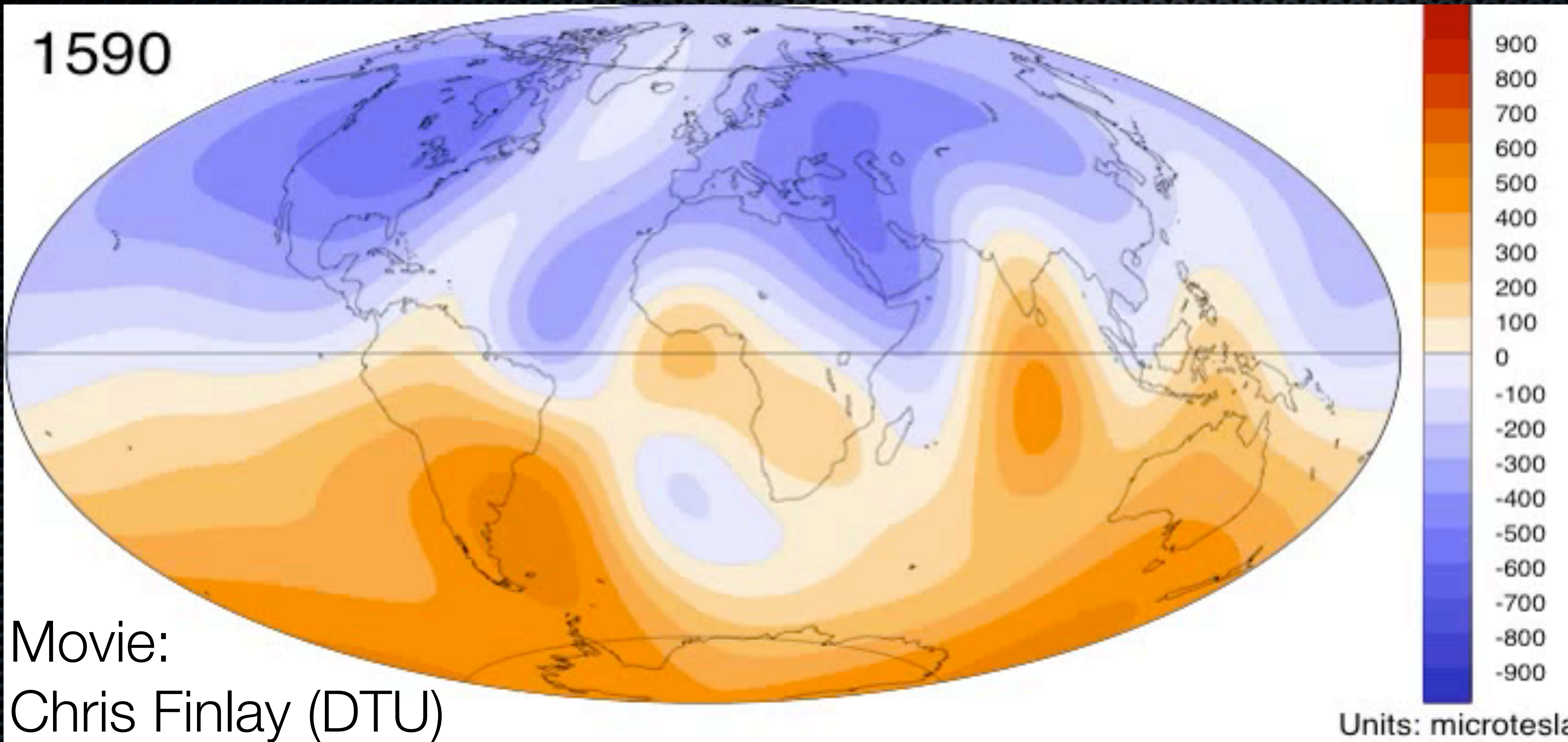
Core-Mantle Boundary $B_r(t)$



- Large-scale flux patches
- Field changes over relatively short times

The Induction Equation

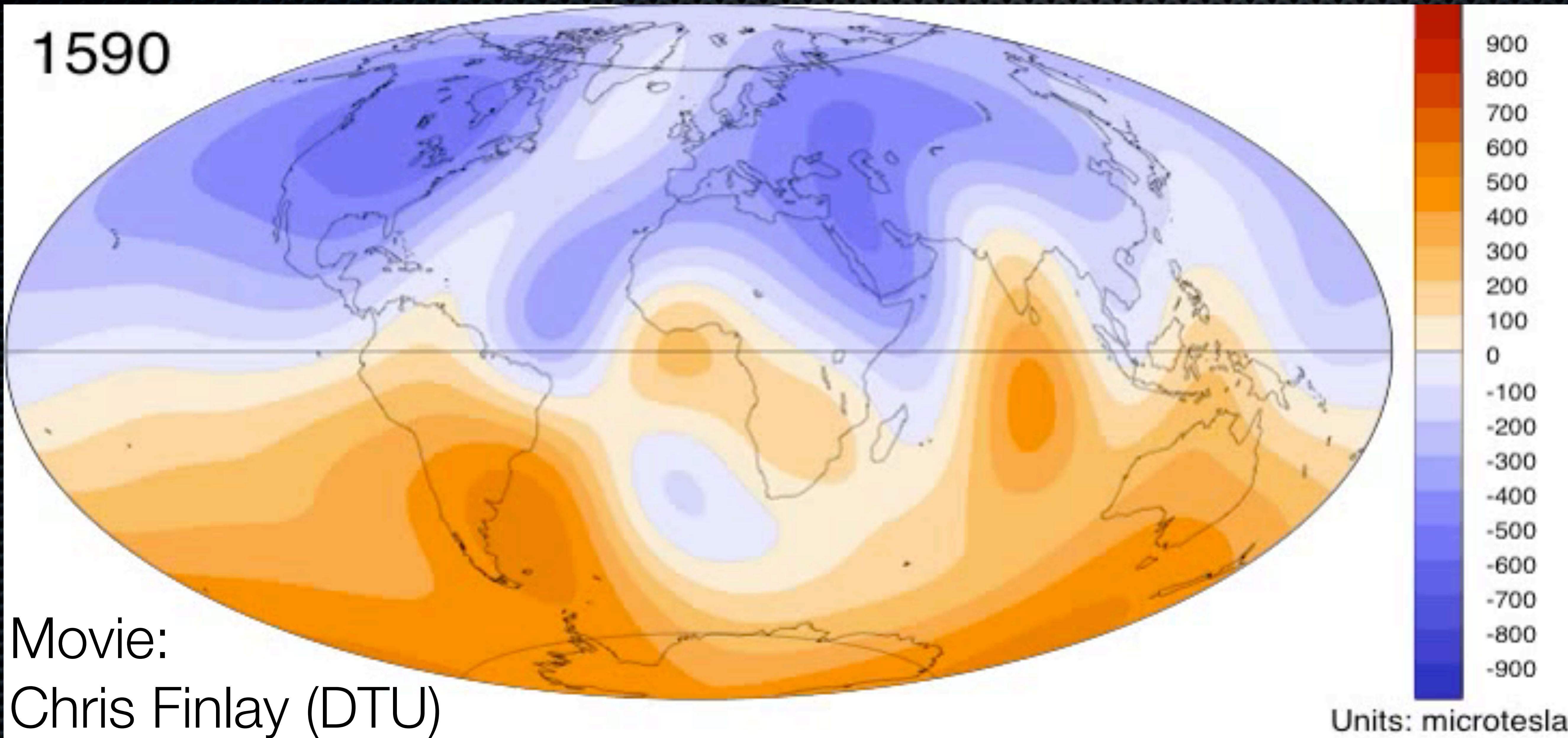
- Induction Equation:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \wedge \vec{u} \wedge \vec{B} + \frac{1}{Re_M} \nabla^2 \vec{B}$$

$$Re_M = \frac{UD}{\eta} = \frac{\text{induction}}{\text{diffusion}}$$

  - Relatively simple equation for *B*-evolution
  - *Rm* must be ~ 100 for dynamo action

Core-Mantle Boundary $B_r(t)$



Movie:
Chris Finlay (DTU)

- Field changes over relatively short times
  - **Infer core flows with Re ~ 10^8; Ro ~ 10^-7**

Complex Flows

Magnetic Fields in the Core

- Poloidal-Toroidal Decompositions
  - Break up ***B*** (and ***u***) into poloidal and toroidal vector fields

$$\mathbf{B_T} = \nabla \times (T\mathbf{r})$$

$$\mathbf{B_P} = \nabla \times \nabla \times (P\mathbf{r})$$

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    - $\boldsymbol{B_P}$ lies in plane containing ***r***
    - $\boldsymbol{B_T}$ on surfaces perpendicular to ***r***

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    - $\boldsymbol{B_T}$ on surfaces perpendicular to ***r***

      - ***NB:*** Curl of a *T* gives a *P;* Curl of a *P* gives a *T*

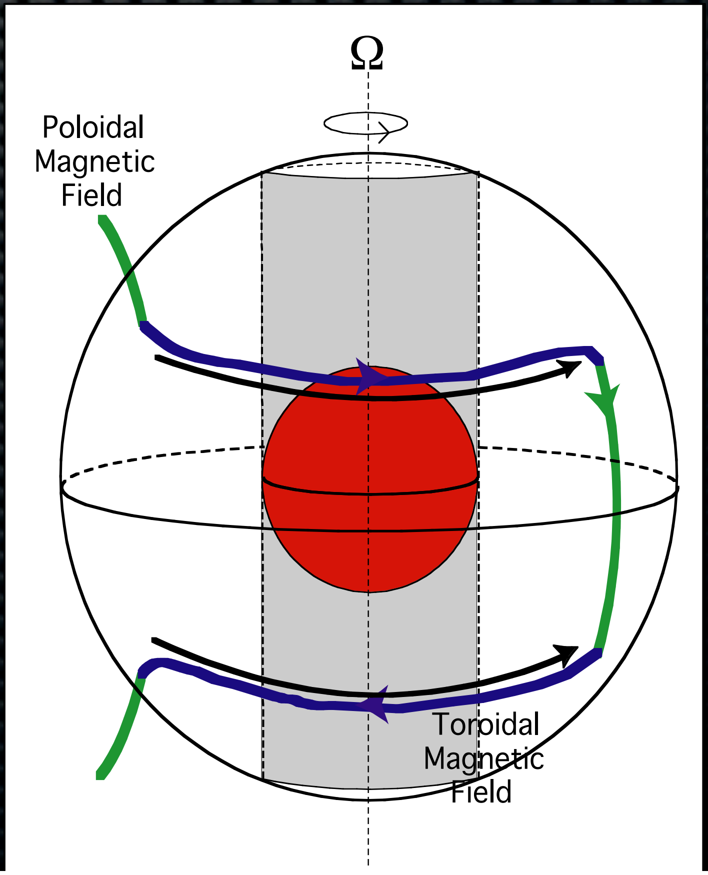
Axisymmetric Fields

- For **axisymmetric** fields & only **s-varying zonal velocities**:

$$\partial B_p / \partial t = \eta \nabla^2 B_p$$

$$\partial B_\phi / \partial t = s B_s \underline{(\partial \omega / \partial s)} + \eta \nabla^2 B_\phi$$

- **The ω-effect**: angular *T*-shears convert *P* field (here B_s) into *T* field (B_ϕ)



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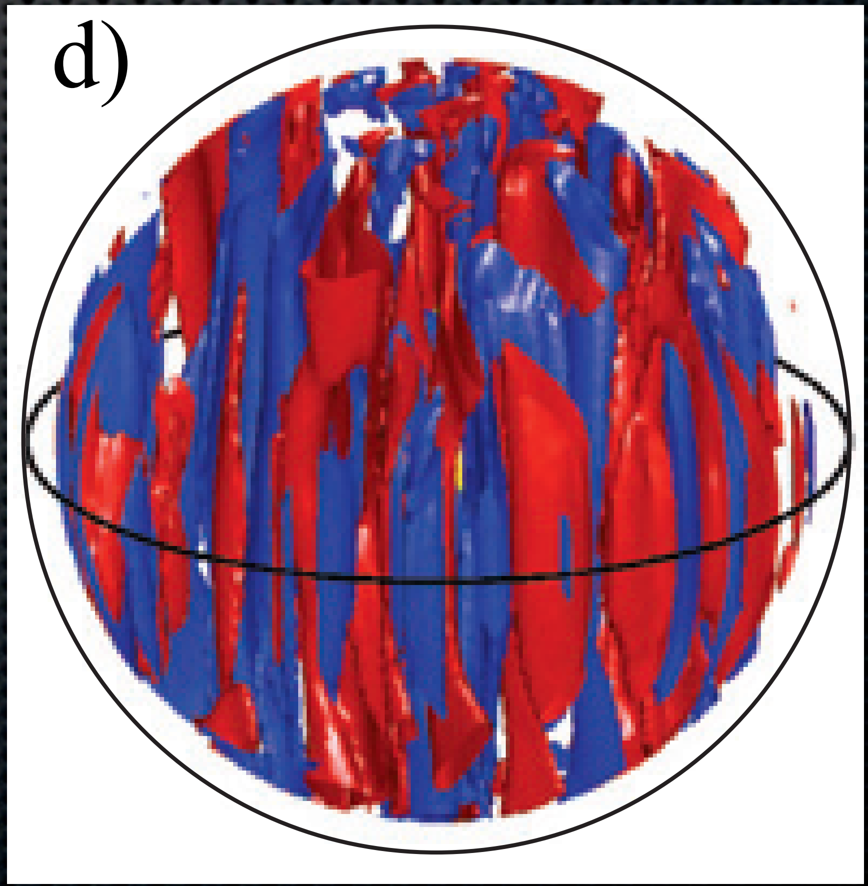
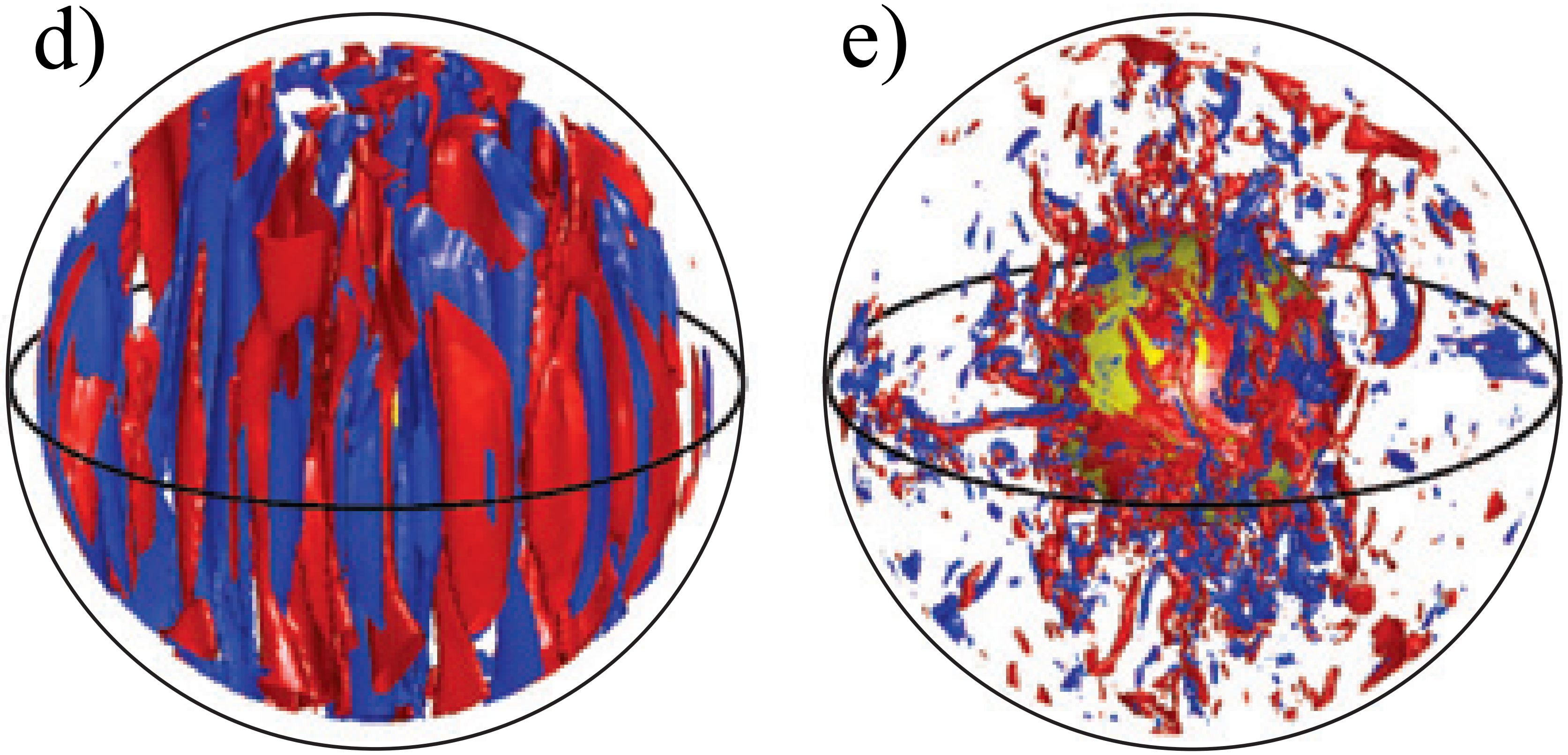
- **The ω-effect**: angular *T*-shears convert *P* field (here B_s) into *T* field (B_ϕ)
  - However, axisymmetric flows do not convert *T* into *P* fields
    - *Any initial B_p will eventually decay away and the axisymmetric dynamo field will fail*

Oversimple dynamos fail: Requires complex flows

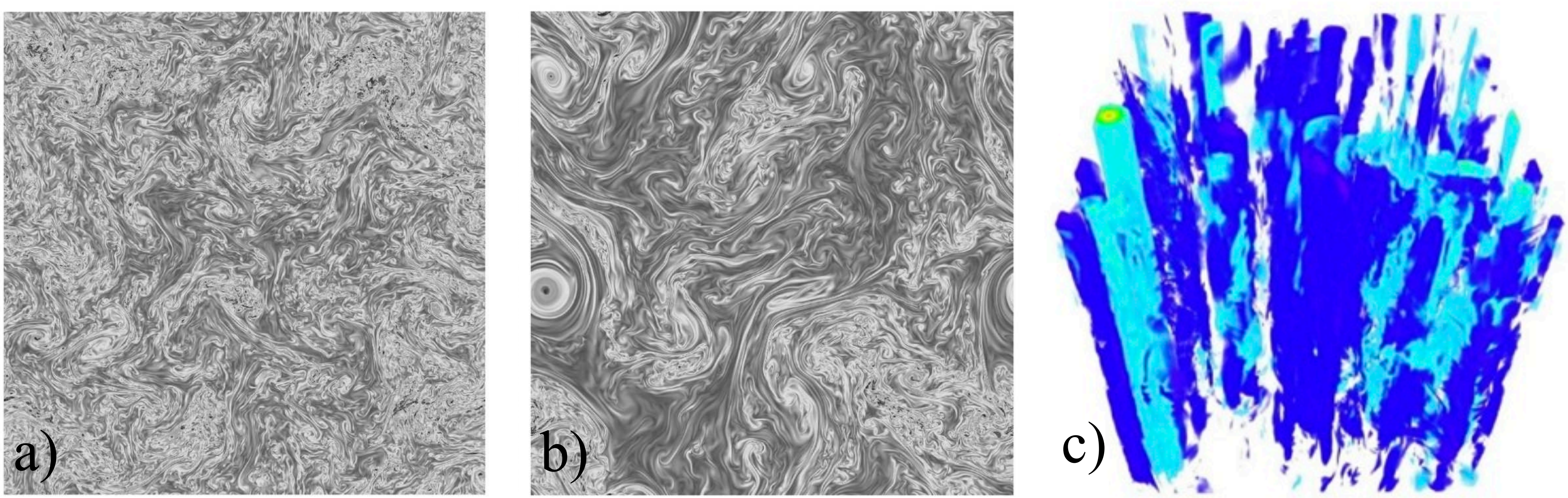
Complex Dynamics

- Earth's core parameters:
  - ***Re* ~ 10^8; *Ro* ~ 10-7 (thus, *E* ~ 10^-15)**
  - *Pr* ~ 10^-2; *Pm* ~ 10^-6
  - *Rm* ~ 10^3, *Elsasser* ~ 0.1
- Laminar present day dynamos
  - Earth-like *Rm*, Earth-like *B*
    - Low *Re*, high *Pm* and high *E* thermal convection models
      - Are they accurate?





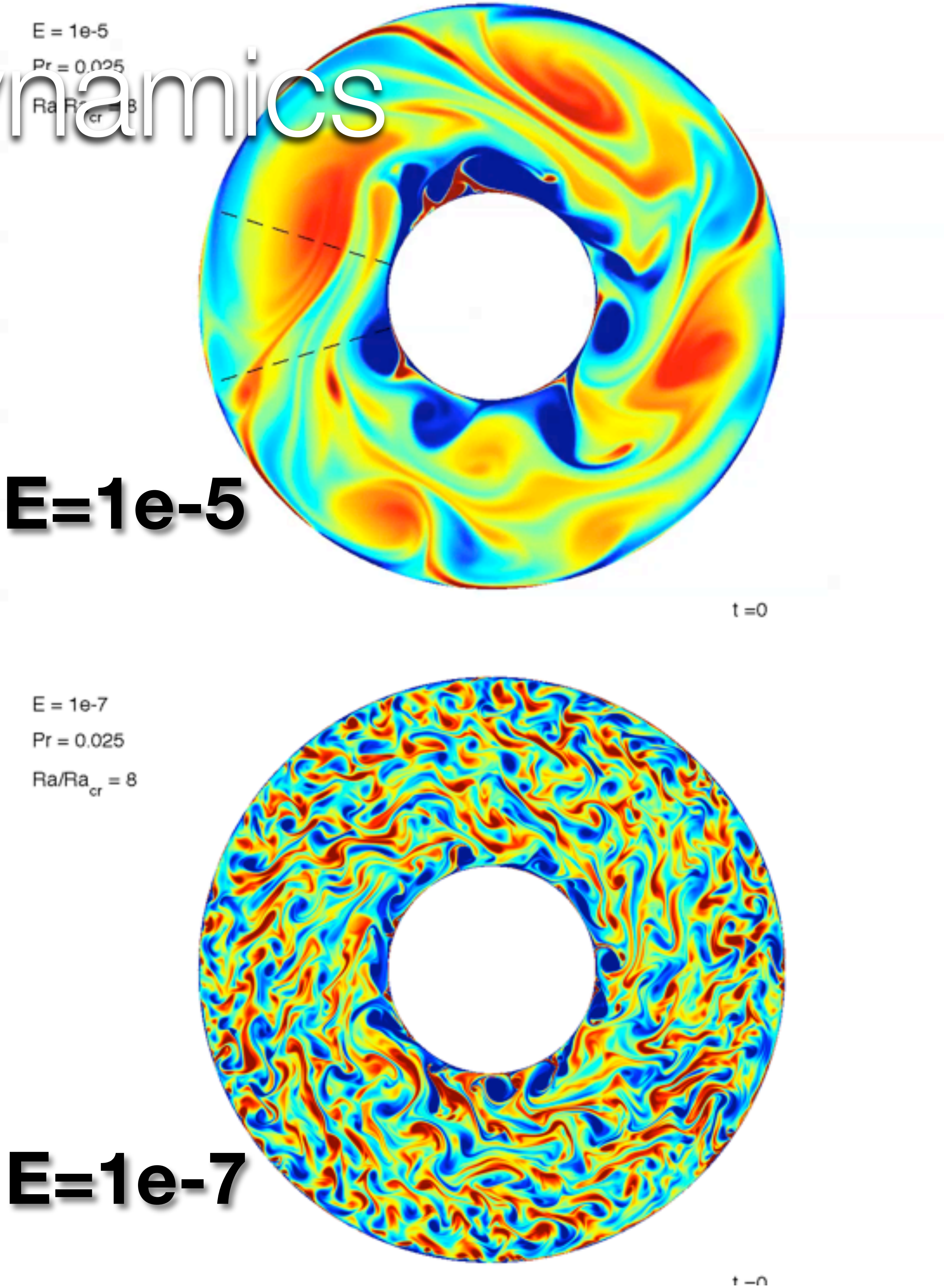
Vorticity in 3D Dynamo Simulations:
d) E = 1e-4; Re = 95, Ra/RaC = 4.9.
e) E = 1e-4; Re = 2014, Ra/RaC = 562.



Vorticity in 3D Rotating Turbulence: a) initial horizontal slice; b) after 30 overturn times; c) 3D rendering also after 30 overturn times. Parameters: Ekman E = 1e-5; Reynolds Re = 5100.

Complex Dynamics

- Laminar present day dynamos
  - Earth-like *Rm*, Earth-like *B*
  - Possibly kinematically accurate; but dynamically inaccurate
- Limited predictability
- Or bulk turbulence is 2nd fiddle, i.e., BCs

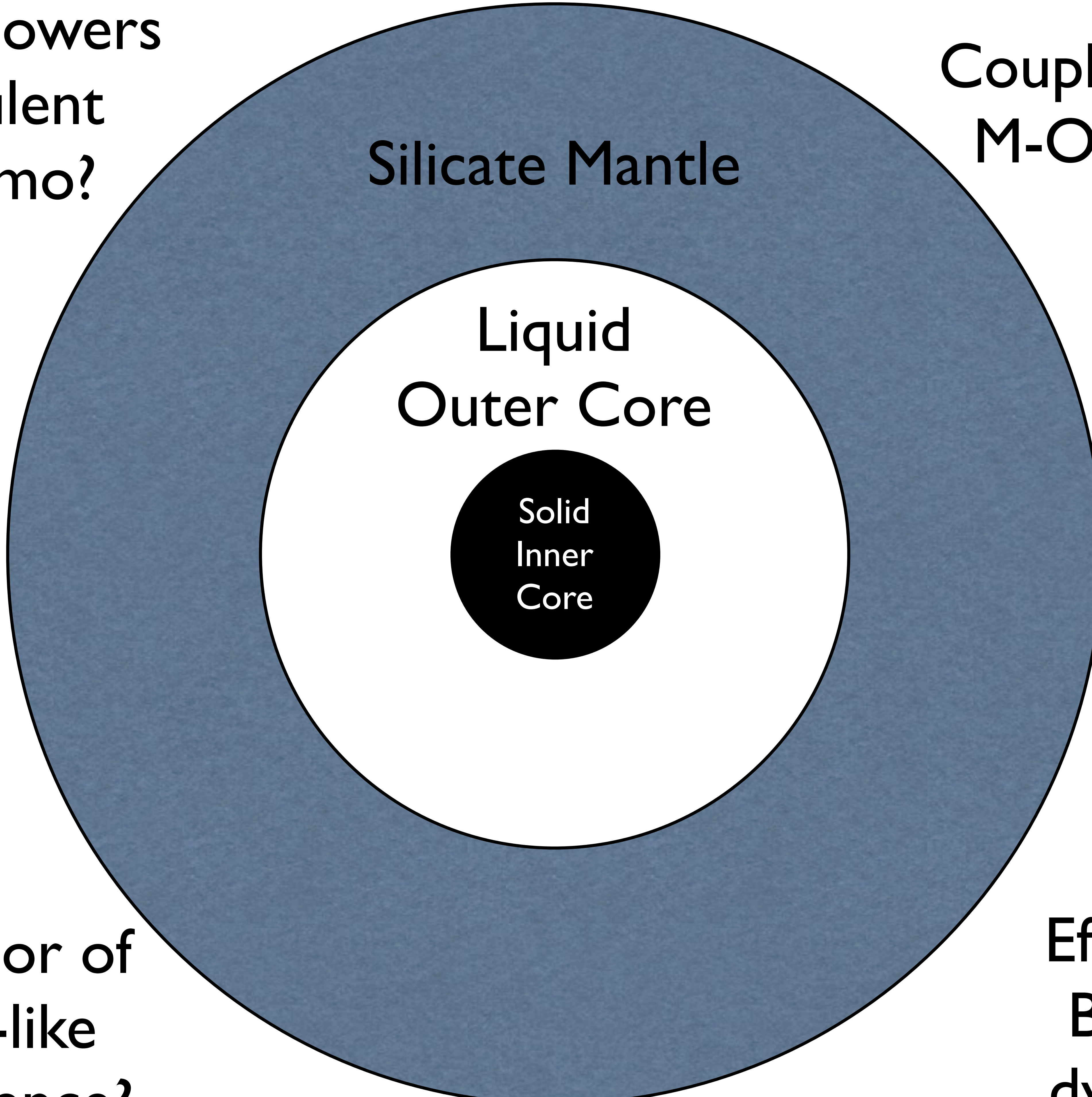


Complex Dynamics

- Thermochemical convection: not obviously superadiabatic in terrestrial planets
  - **Mechanically-forced core flows?**
- Mechanical driving: Precession, nutation, libration
  - Can possibly tap into massive resevoirs of planetary rotational energy

What powers turbulent dynamo?

Couplings b/w M-OC-SIC?

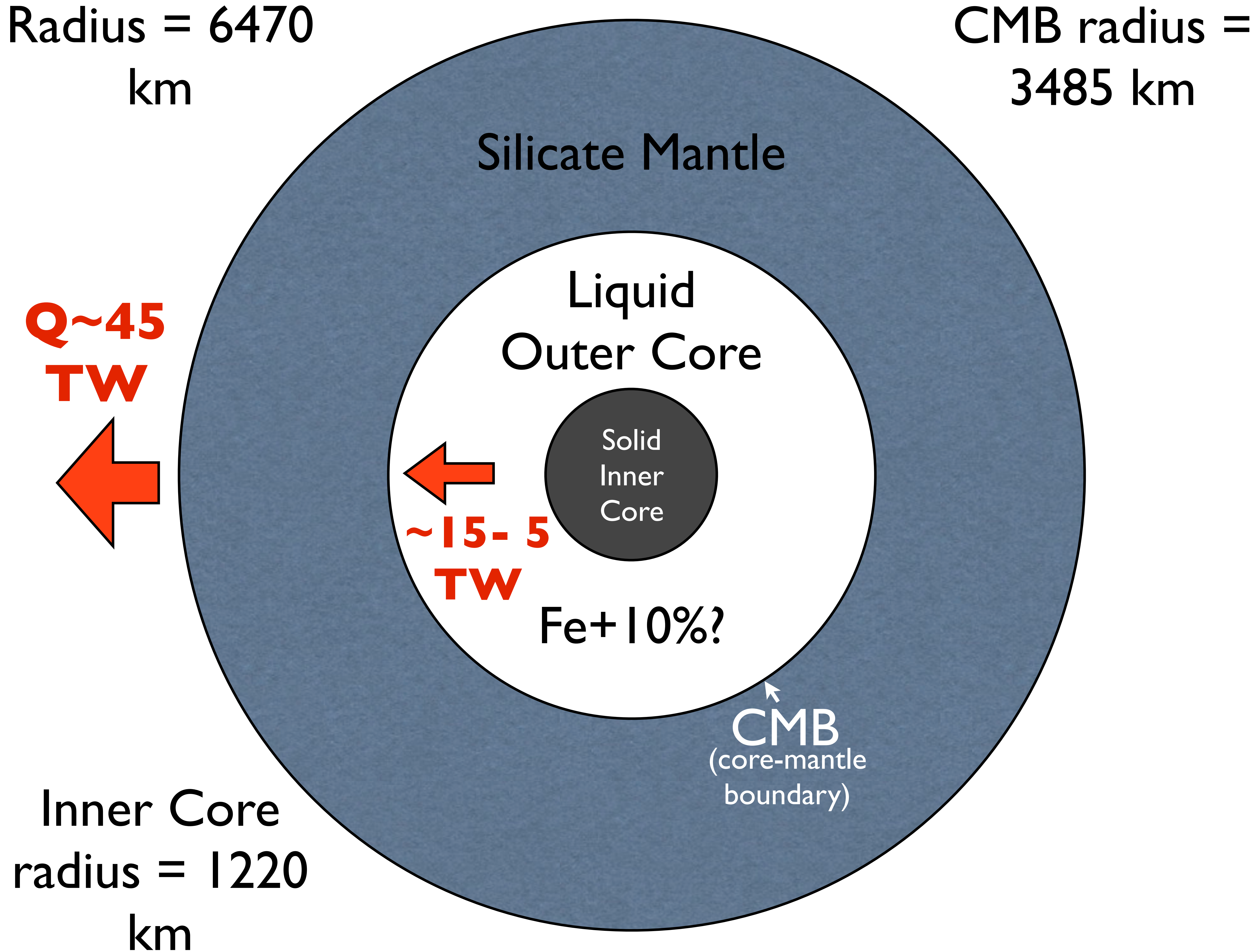


Behavior of core-like turbulence?

Effects of BCs on dynamos

APPENDIX SLIDES


Silicate Mantle
Liquid
Outer Core
Solid
Inner
Core
CMB
(core-mantle
boundary)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Silicate Mantle
Liquid Outer Core
Solid Inner Core
Q~45 TW
~15- 5 TW
Fe+10%?
CMB (core-mantle boundary)
Inner Core radius = 1220 km

P-waves

- Primary waves: Compressional (or dilatational) waves
- Solution:

$$\Theta = \Theta_o(\vec{x} - V_p t) + \hat{\Theta}_o(\vec{x} + V_p t)$$

$$V_p = \left[\frac{K + 4/3\,\mu}{\rho}\right]^{1/2}$$

- Non-dispersive, propagating dilatations in the form of longitudinal waves (wave velocity parallel to displacements)

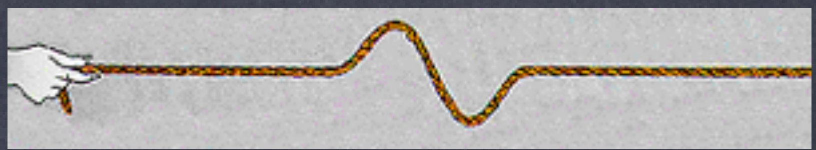
S-waves

- Secondary waves: Shear waves (only in "solids")
- Solution:

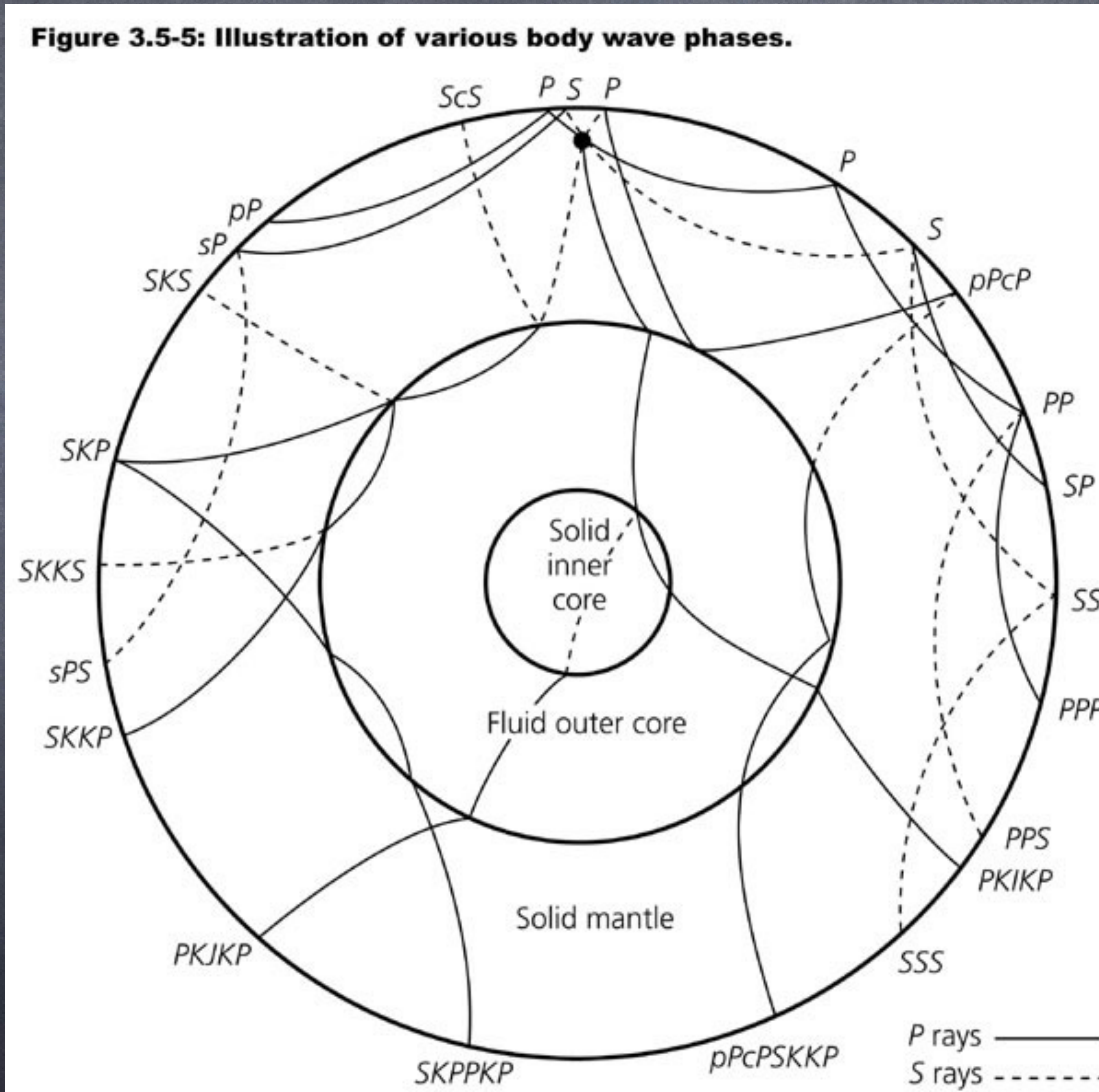
$$\vec{\Omega} = \vec{\Omega}(\vec{x} - V_s t) + \vec{\hat{\Omega}}_o(\vec{x} + V_s t)$$

$$V_s = \left[\frac{\mu}{\rho}\right]^{1/2}$$

- Non-dispersive, propagating "shears" in the form of transverse waves (wave velocity perpendicular to displacements)



Seismic Phases



Citation: http://epsc.wustl.edu/seismology/michael/web/teaching.html

Adams-Williamson Equation

- Adiabitic radial density gradient

$$\frac{d\rho}{dr} = \left(\frac{\partial \rho}{\partial p}\bigg|_s \frac{dp}{dr} = \left(\frac{1}{K/\rho}\right) \frac{dp}{dr} \boxed{= -\frac{\rho g}{\phi}}$$

- Seismic Parameter, phi:

$$\phi(r) = K/\rho = V_p^2 - 4/3 V_s^2$$

- Hydrostatic pressure gradient:

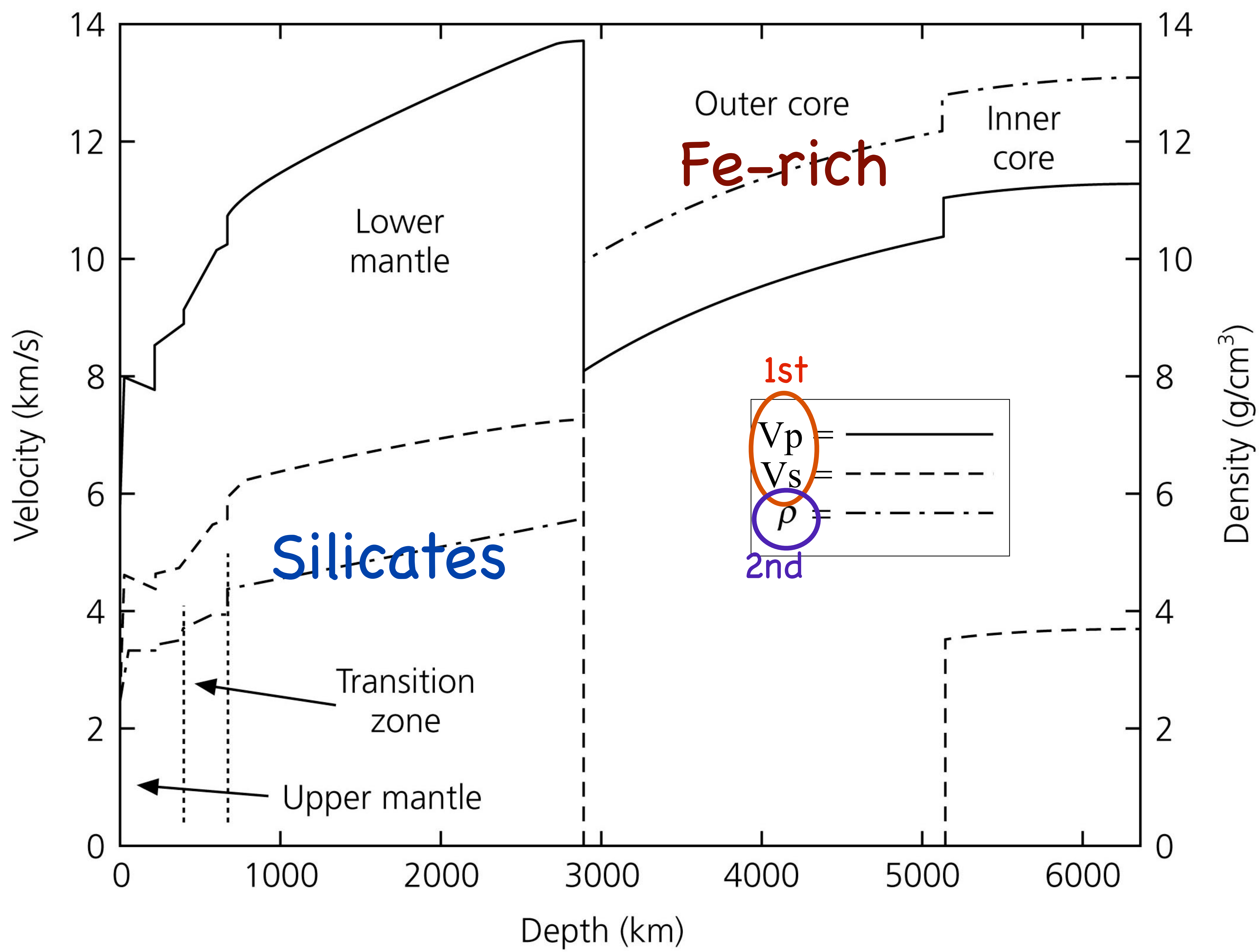
$$\frac{dp}{dr} = -\rho g$$

- Lastly, we need a g(r) equation:

$$\frac{dg}{dr} + \frac{2g}{r} = -4\pi G\rho$$

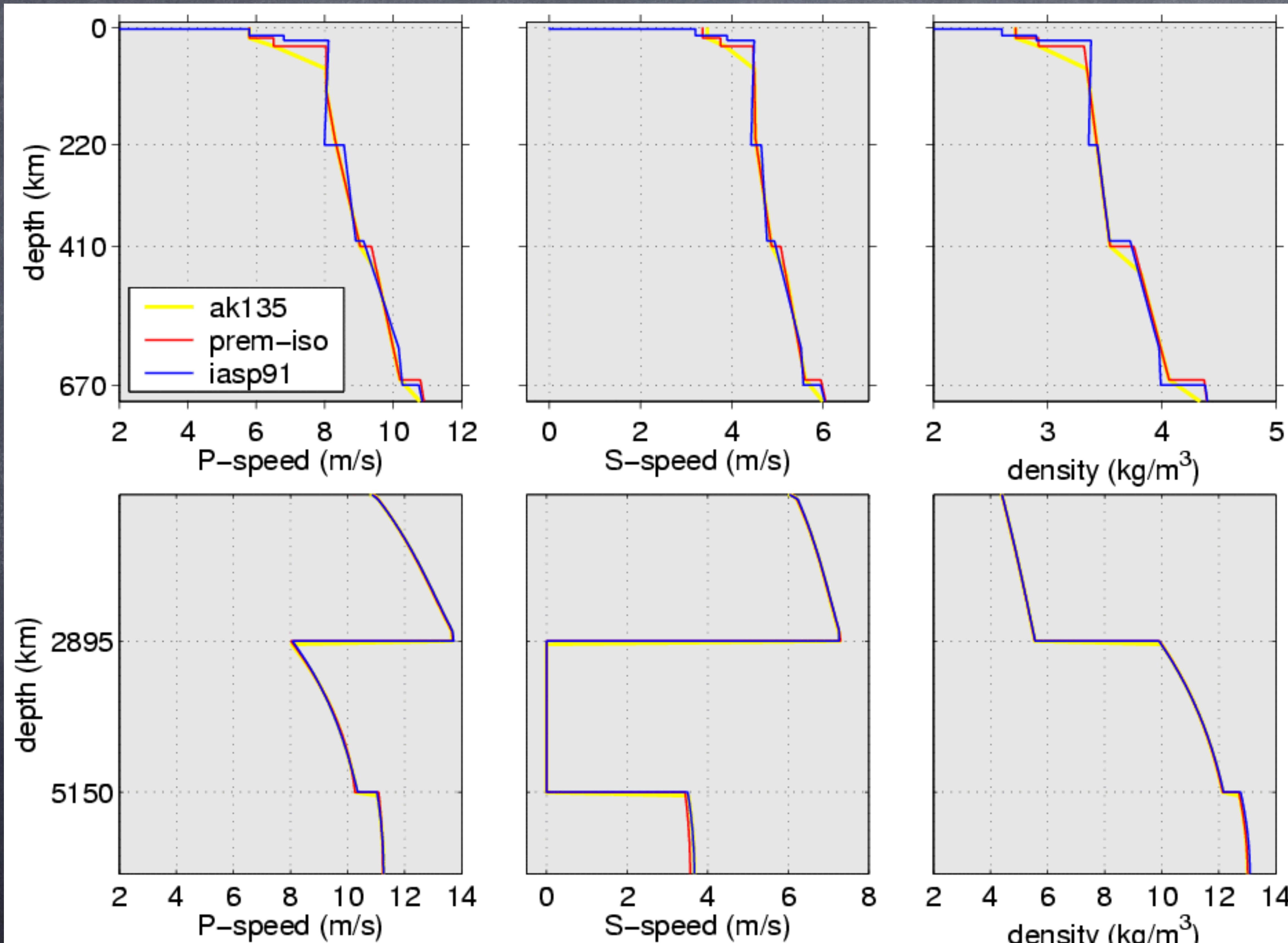
Earth Structure - 1D

Figure 3.8-4: Preliminary Reference Earth Model.



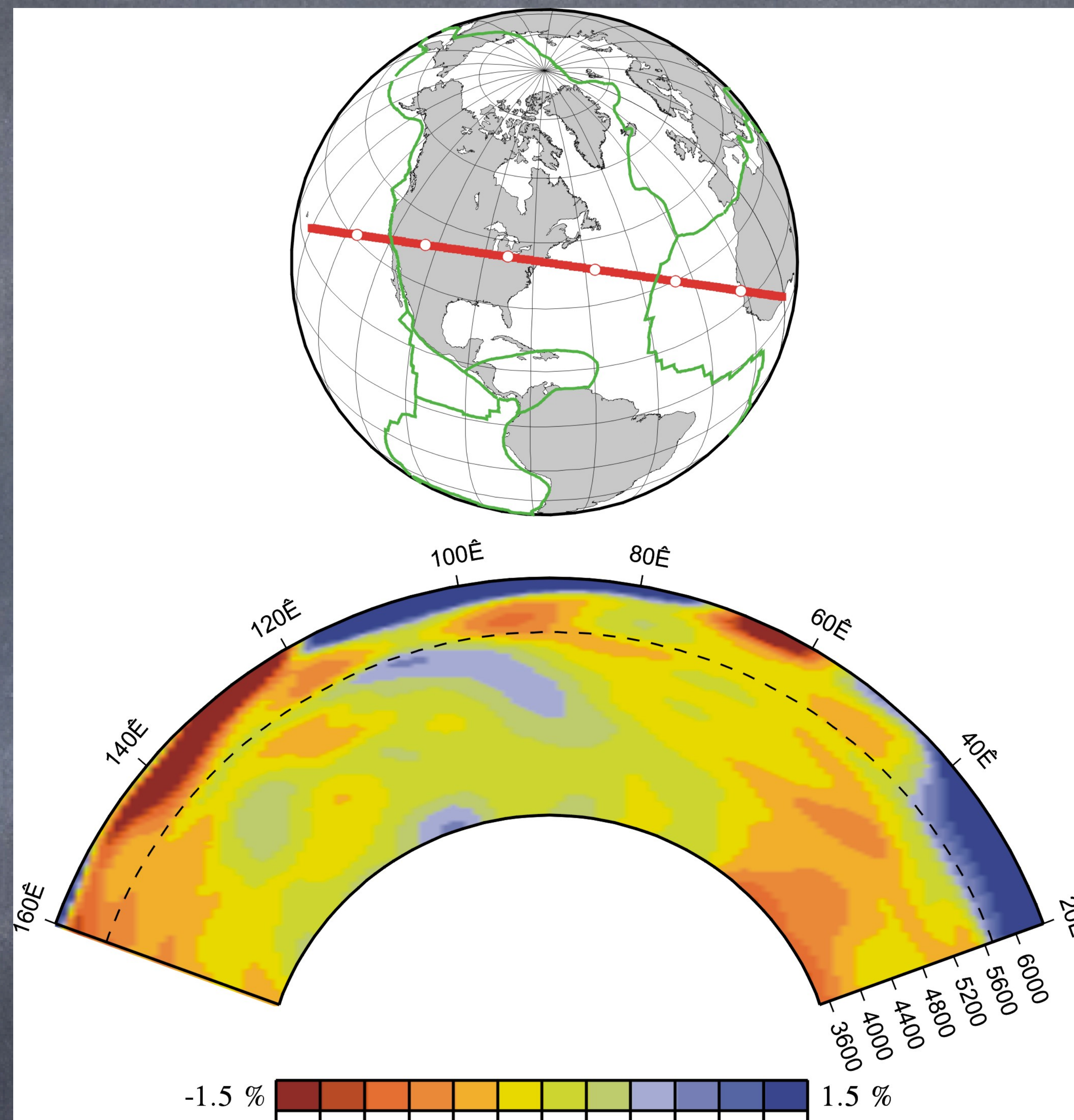
Citation: http://epsc.wustl.edu/seismology/michael/web/teaching.html

Earth Structure - 1D



Earth Structure - 2D/3D

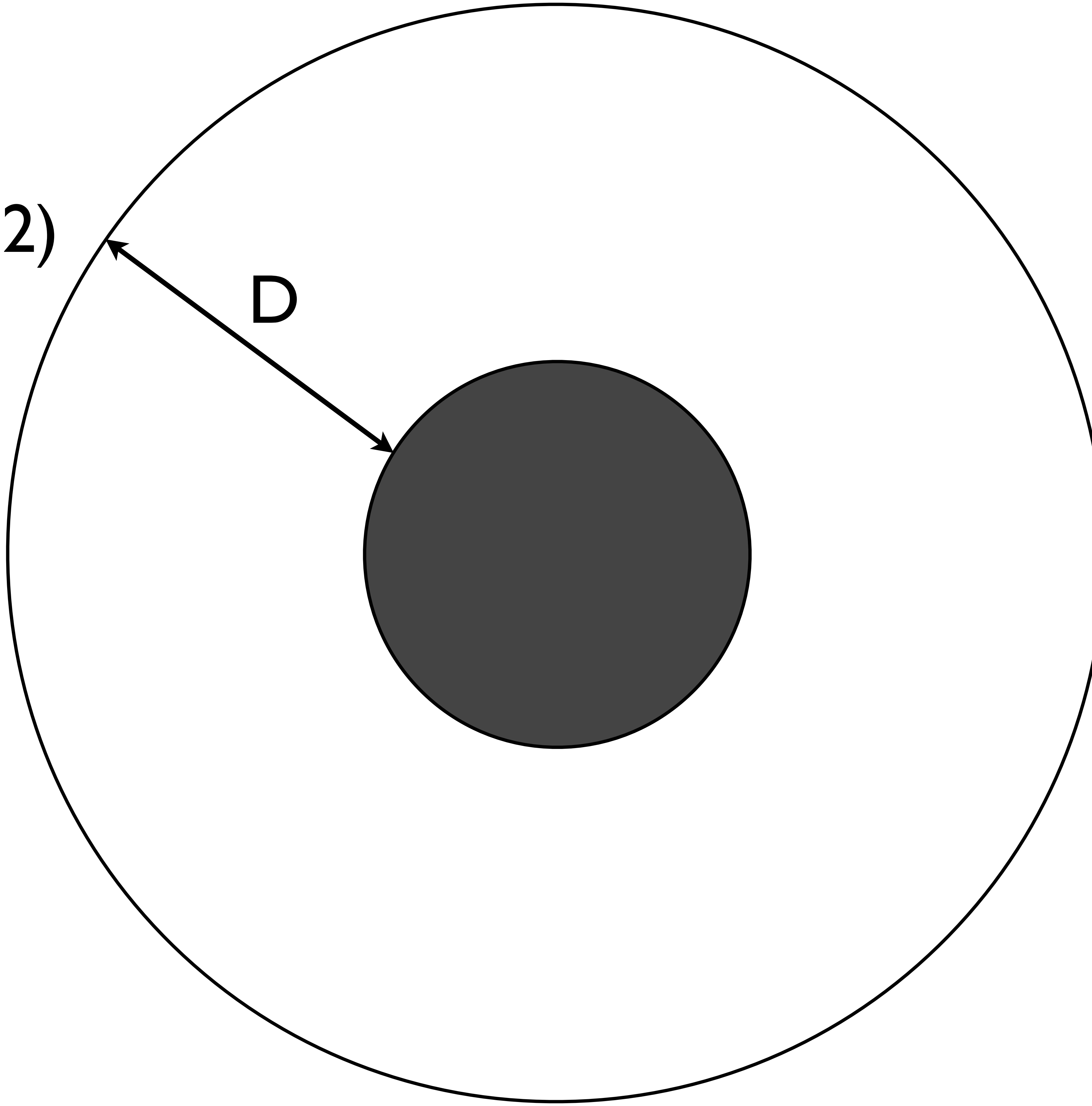
- Can carry out 3D inversions for best fitting seismic velocities to fit modern, massively overlapping data sets
- Shows anomalies of S-wave velocities relative to 1D PREM model



Van Heijst, Ritsema, and Woodhouse [1999]

D = Fluid Shell thickness

Ekman $E = \nu/(\Omega D^2)$



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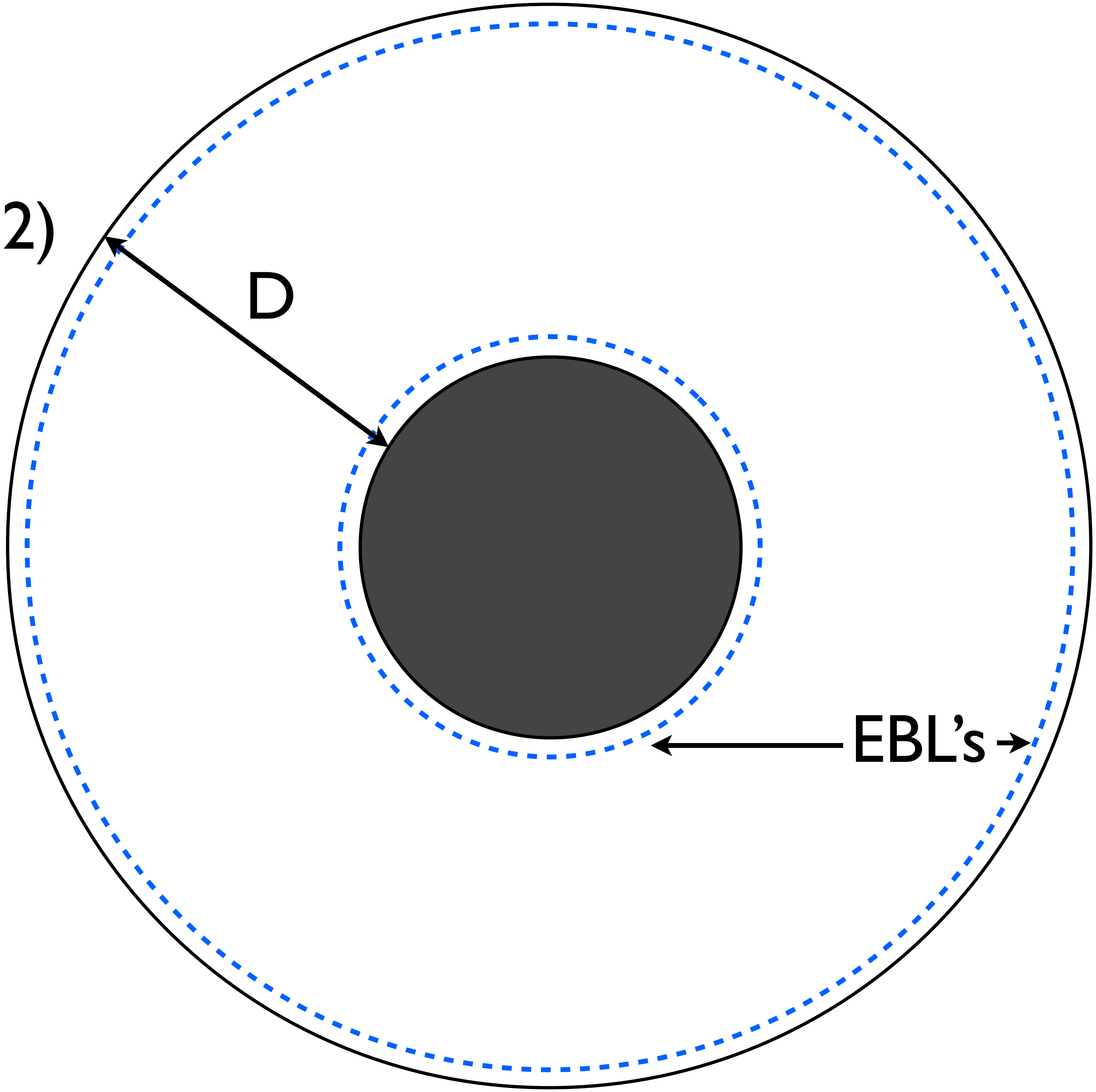
Ekman boundary Layers (EBL) $\sim E^{1/2} D$



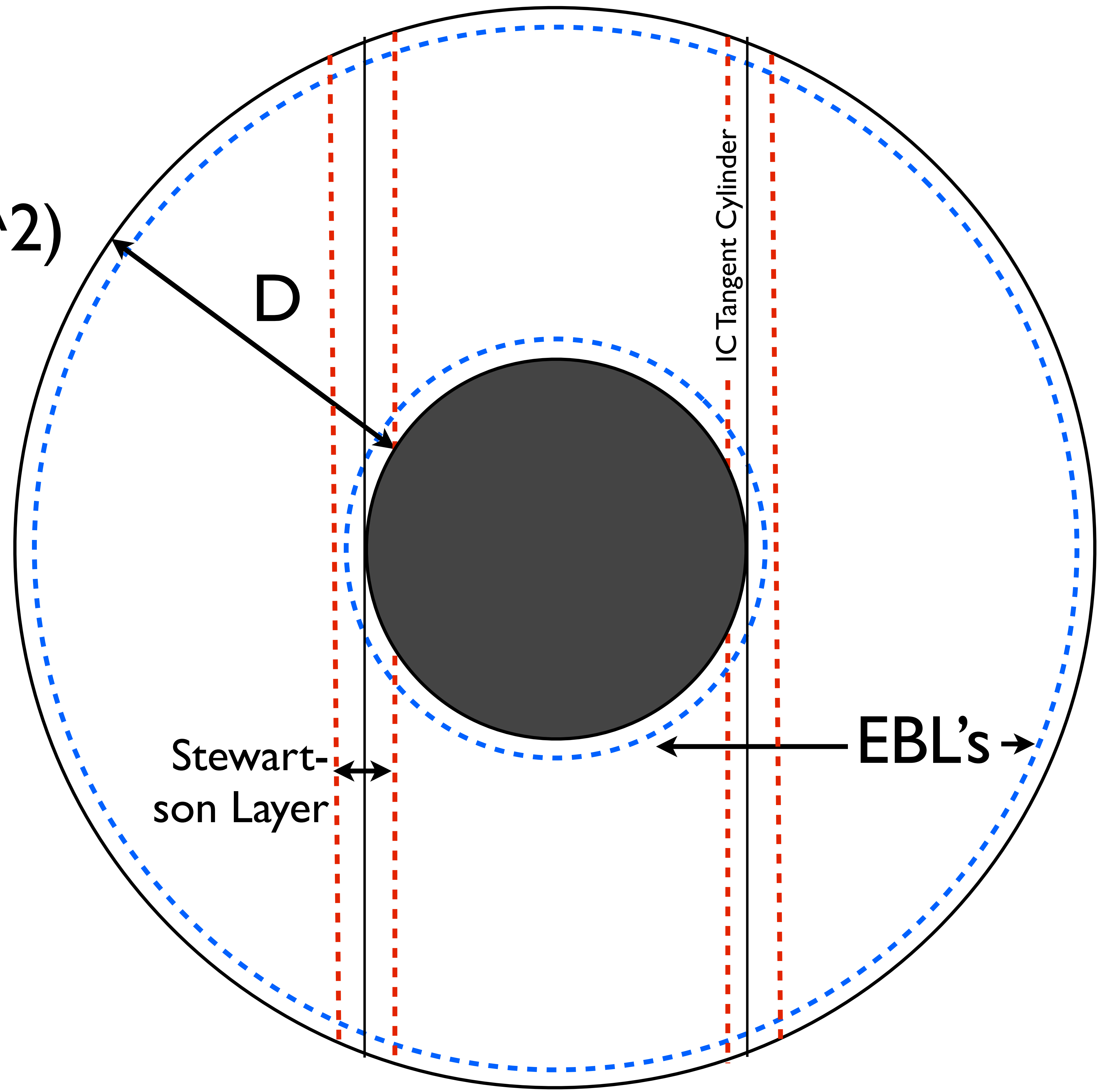
D = Fluid Shell thickness

Ekman $E = \nu/(\Omega D^2)$

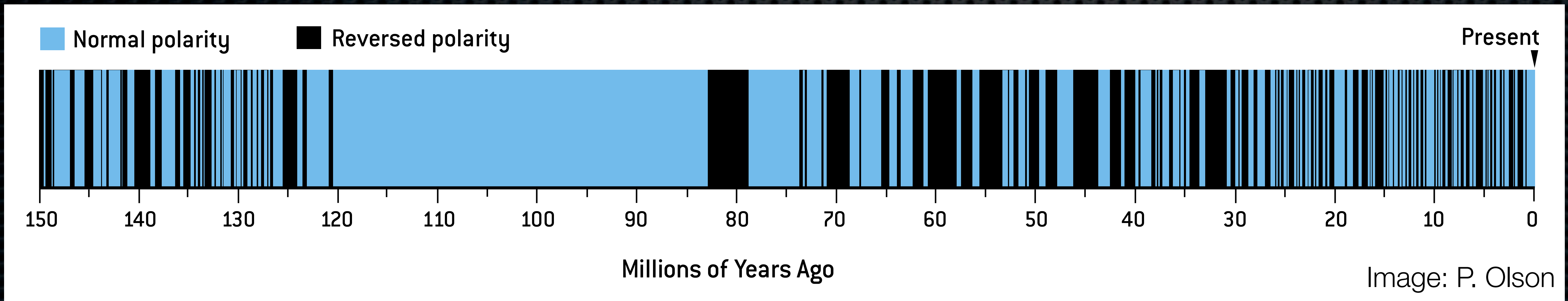
Ekman boundary Layers (EBL) $\sim c1\ E^{1/2}\ D$

Stewartson Layer $\sim c2\ E^{1/3}\ D$

$c1 \sim c2 \sim 1$



Magnetic Polarity Reversals



- Reversals ~ 5 kyr event, every ~ 0.25 Myrs
- How & why do reversals happen?
    - **Boundary conditions *AND/OR* core turbulence**

The MHD Approximation

$$\frac{1}{\mu_o}\nabla \times \vec{B} = \vec{J} + \epsilon_o \frac{\partial \vec{E}}{\partial t}$$

$$\simeq \vec{J} + \frac{\epsilon_o}{\sigma}\frac{\partial \vec{J}}{\partial t}$$

$$\simeq \vec{J} + \epsilon_o \mu_o \eta \frac{\partial \vec{J}}{\partial t}$$

$$\simeq \vec{J} + \frac{\eta}{c^2}\frac{\partial \vec{J}}{\partial t}$$

$$\simeq \vec{J}$$

Magnetic Fields in the Core

- Poloidal-Toroidal Decompositions
  - Break up ***B*** (and ***u***) into poloidal and toroidal vector fields

$$\mathbf{B_T} = \nabla \times (T\mathbf{r})$$

$$\mathbf{B_P} = \nabla \times \nabla \times (P\mathbf{r})$$

    - $\boldsymbol{B_P}$ lies in plane containing ***r***
    - $\boldsymbol{B_T}$ on surfaces perpendicular to ***r***

Axisymmetric Fields

- Inserting ***axisymmetric*** *P*-*T* vectors into Induction eq:

$$\partial B_p/\partial t = \nabla \times (u_p \times B_p) + \eta \nabla^2 B_p$$

$$\partial B_T/\partial t = \nabla \times (u_p \times B_T + u_T \times B_p) + \eta \nabla^2 B_T$$

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- Now, let's let $\mathbf{u} = u_T = U_\phi(s)$

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- Now, let's let $\mathbf{u} = u_T = U_\phi(s)$

$$\partial B_p/\partial t = \nabla \times (0) + \eta \nabla^2 B_p$$

$$\partial B_T/\partial t = \boxed{\nabla \times U_\phi(s) \times B_p} + \eta \nabla^2 B_T$$

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$$= (B_p \cdot \nabla) U_\phi(s)$$

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$$\partial B_T/\partial t = \nabla \times U_\phi(s) \times B_p + \eta \nabla^2 B_T$$

$$= (B_p \cdot \nabla) U_\phi(s) = s B_s \left(\partial [U_\phi/s]/\partial s\right) \hat{\phi}$$

Axisymmetric Fields

- Inserting <u>***axisymmetric***</u> *P-T* vectors into Induction eq:

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- Now, let's let $\mathbf{u} = u_T = U_\phi(s)$

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$$= (B_p \cdot \nabla) U_\phi(s) = s B_s \left(\partial [U_\phi/s]/\partial s\right) \hat{\phi}$$

$$= \boxed{s B_s \, \partial \omega / \partial s \hat{\phi}} \quad \text{where } U_\phi = \omega \, s$$