Core-Mantle boundary heat flow

CIDER Geo-neutrino Working Group meeting
June 30 - July 1, 2014

CMB Heat flow estimates

Fourier's Law Approach

3D

$$\mathbf{q} = -k\, \nabla T$$

Heat flux

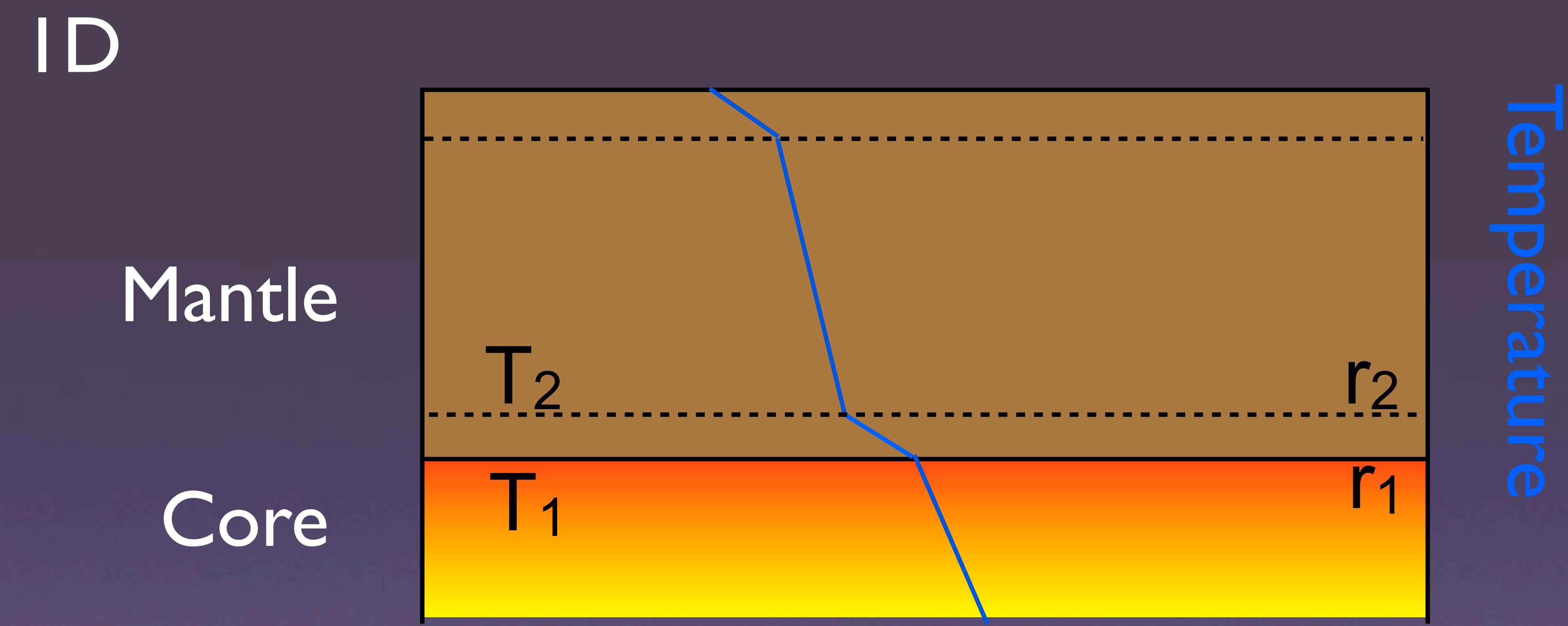
thermal conductivity

Spatial Temperature gradient

See review: Lay et al. 2008

CMB Heat flow estimates

Fourier's Law Approach



$$q = -k\ dT/dr$$

Heat flux

thermal conductivity

Temperature gradient

See review: Lay et al. 2008

CMB Heat flow estimates

Fourier's Law Approach

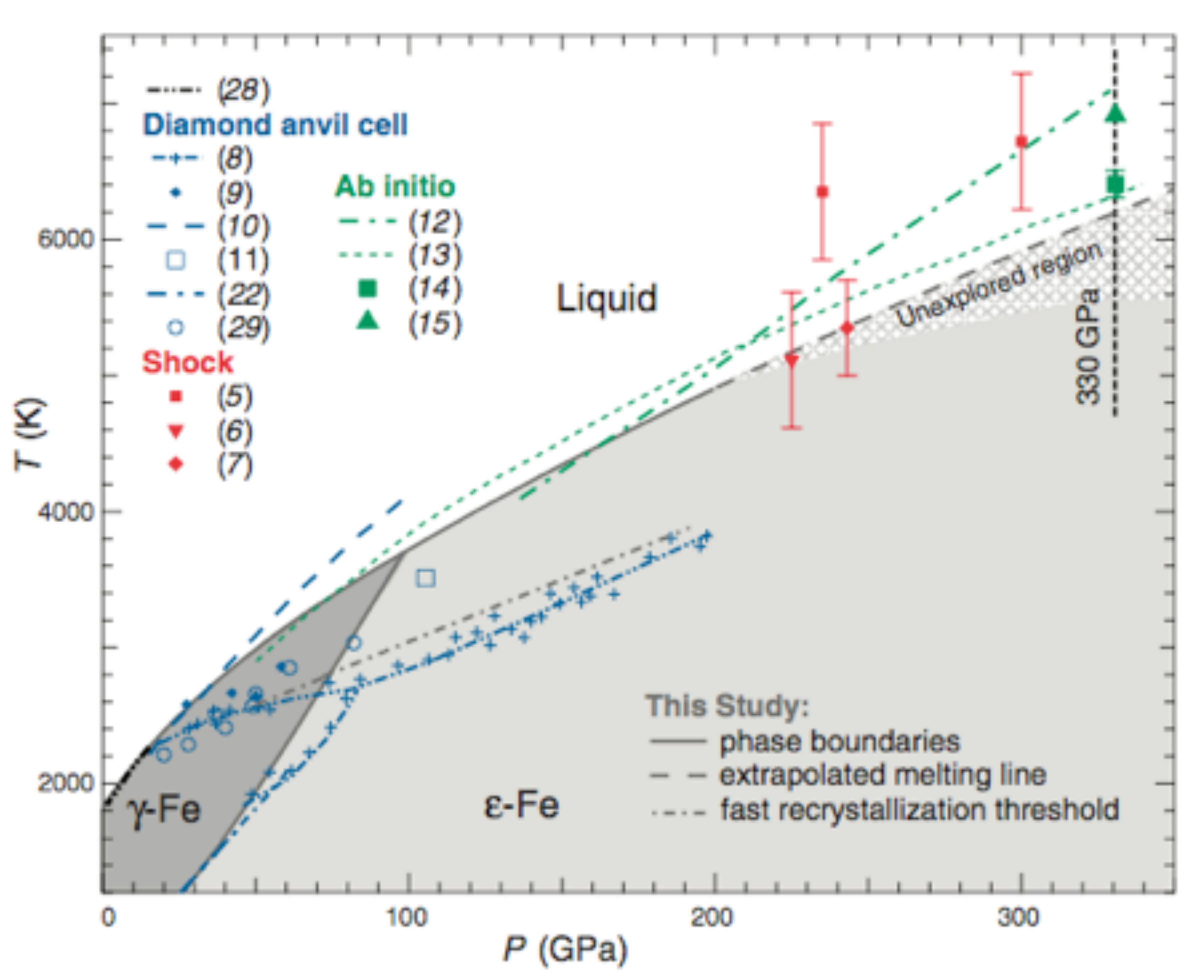
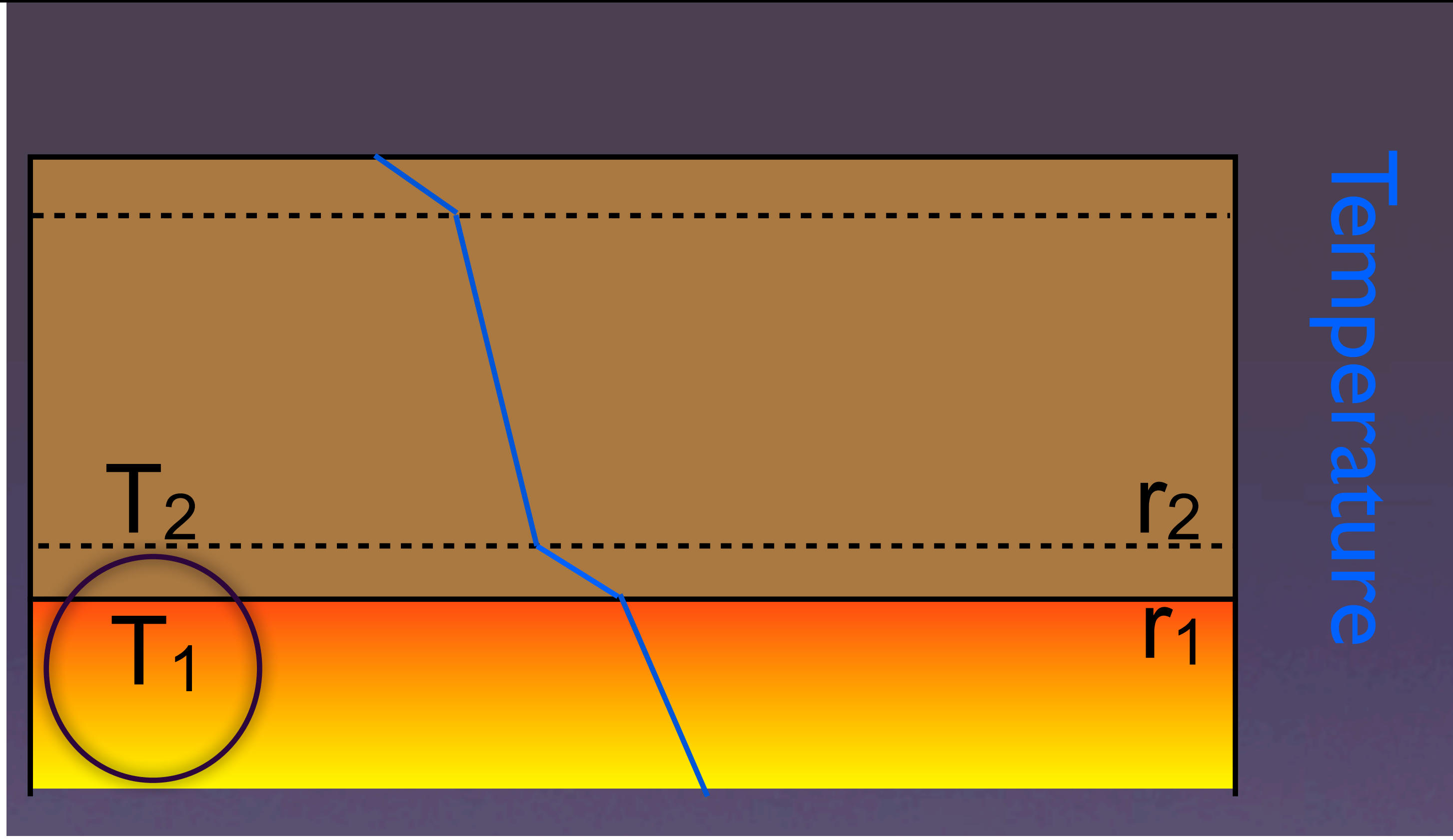


Fig. 3. Phase stability domains for Fe obtained in the literature and in this study. The stability field for ε-Fe is based on the current study data and data from (19).

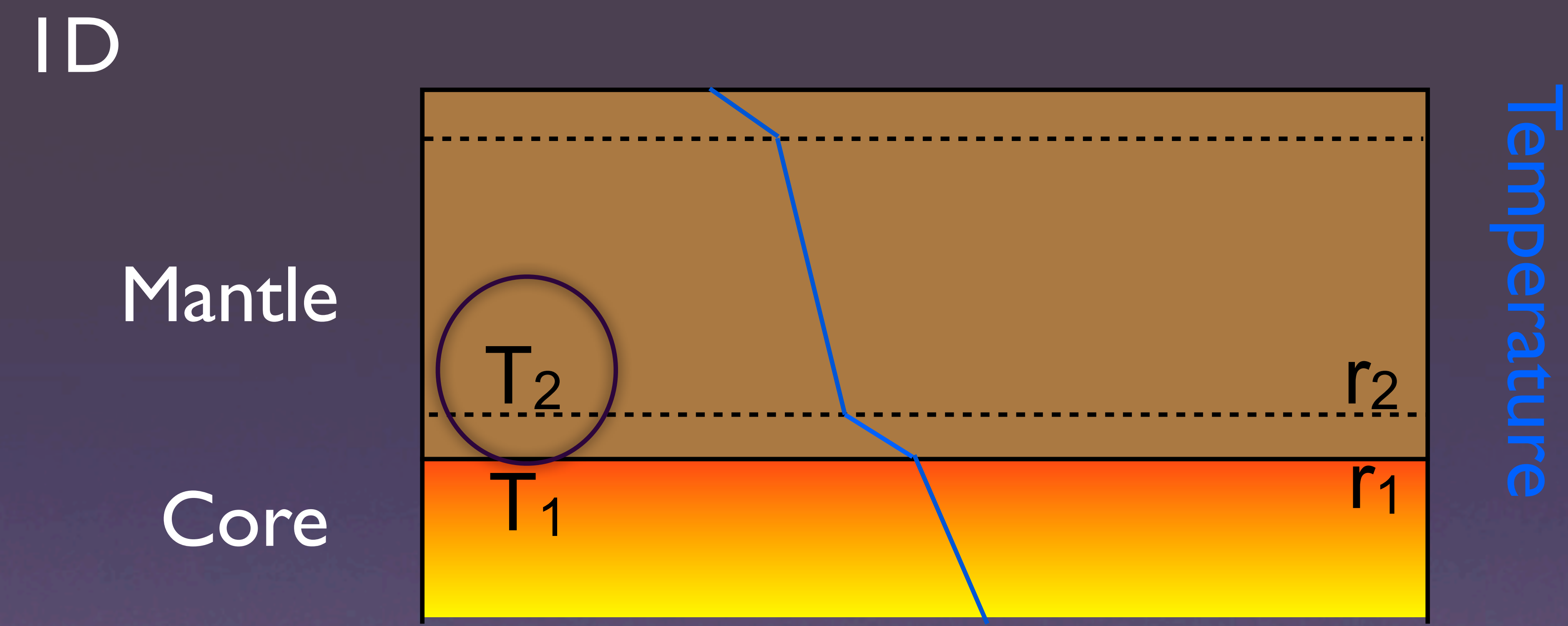


T_1: Core Temperature at top of Core

Anzellini et al 2013

- T of inner core boundary can be estimated by experimental determination of melting curve of Iron
- Extrapolate that T along the adiabat to the CMB
- T_{CMB} = 4050 +/- 500 K (Anzellini et al 2013)

CMB Heat flow estimates — Fourier's Law Approach

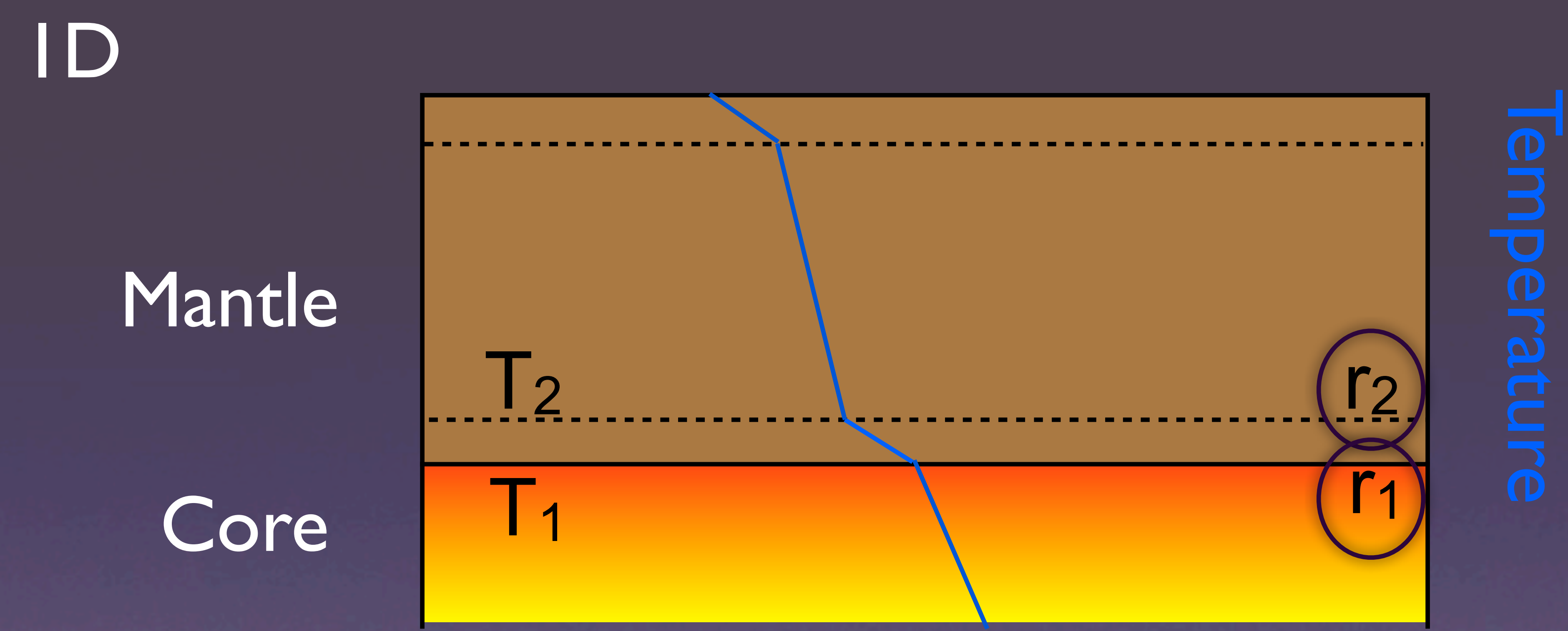


T_2: Mantle Temperature above CMB

- Similarly T at 660 phase transition and at post-perovskite transition can be estimated experimentally
- Extrapolate that T along the adiabat to the CMB gives 2,500-2,800 K

CMB Heat flow estimates

Fourier's Law Approach



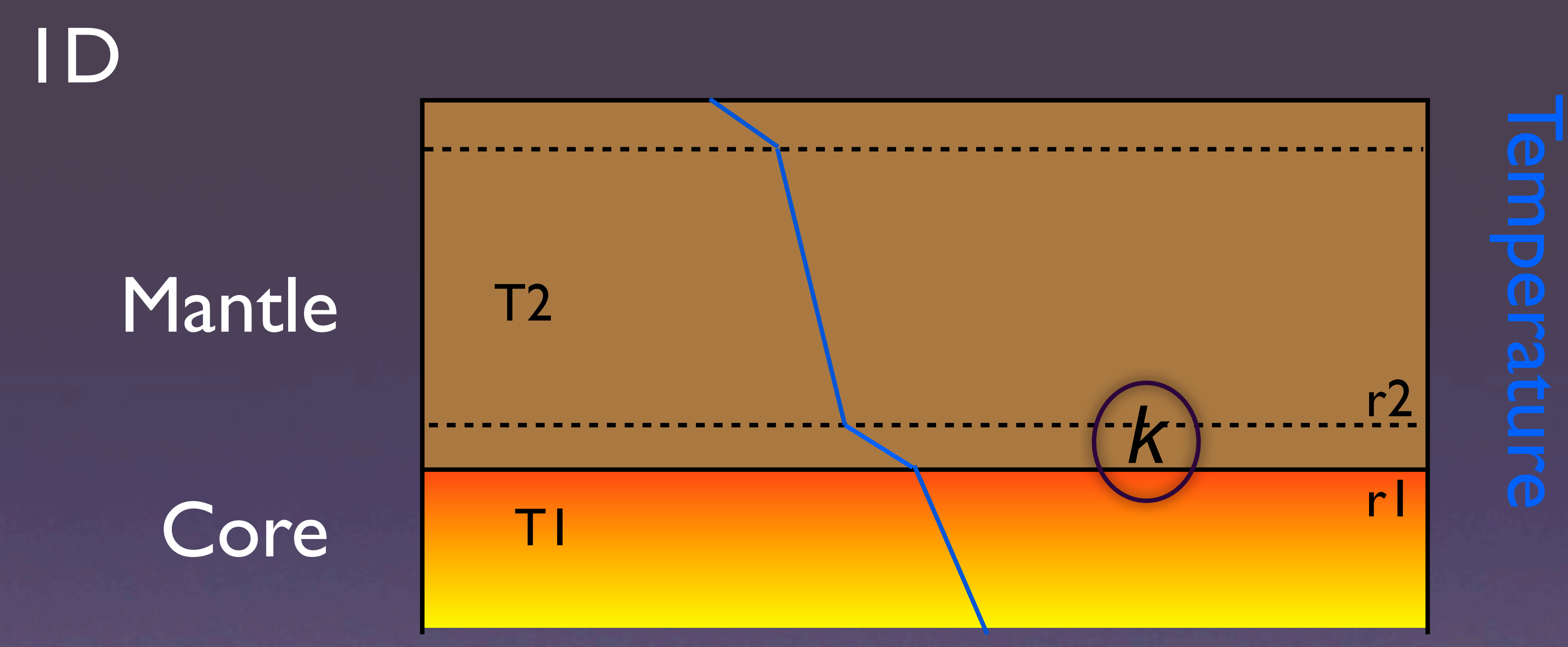
$r_2 - r_1$: Boundary Layer Thickness

- ~100-200 km

- For perspective, top thermal boundary layer is 90-100 km (taking the lithosphere to be the boundary layer)

CMB Heat flow estimates

Fourier's Law Approach

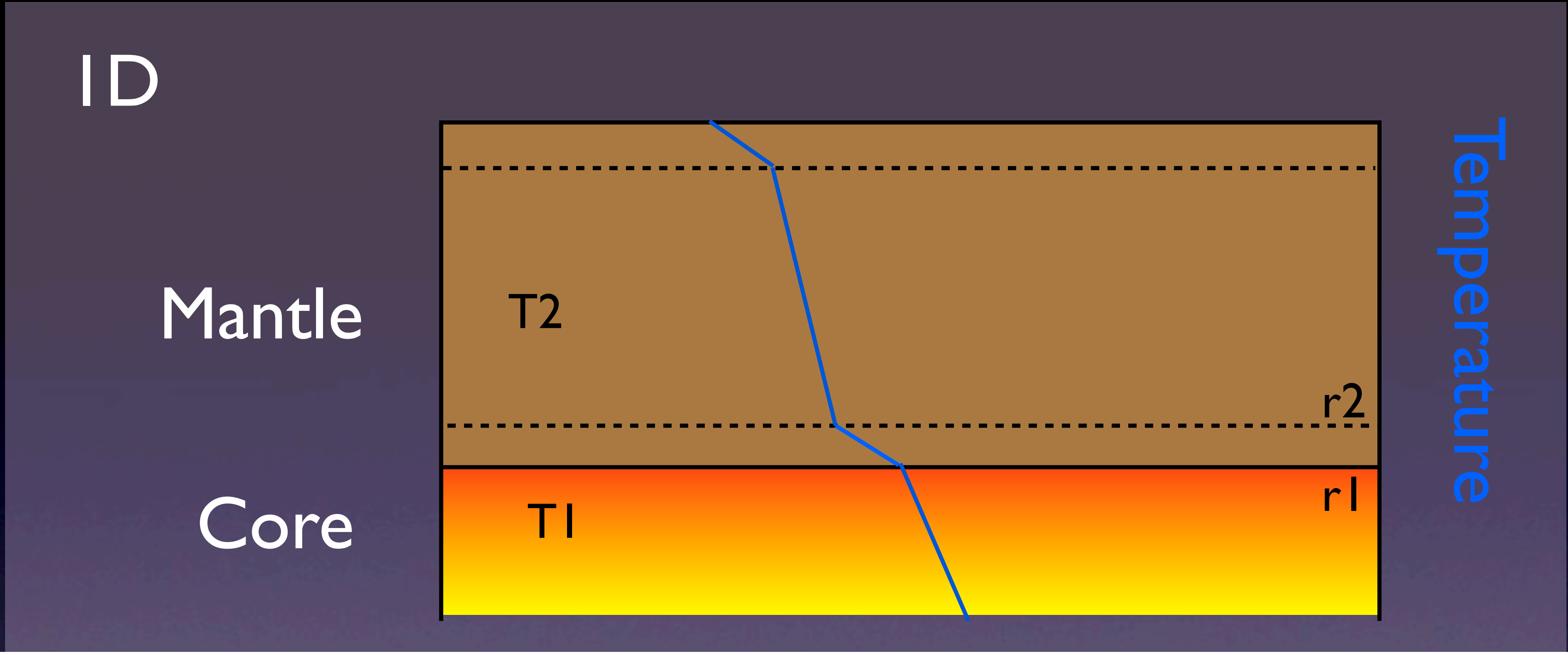


k: Thermal Conductivity of lower mantle material

- ~10 W/m/K
- could be laterally heterogeneous due to compositional and phase variability
- Ppv is anisotropic

CMB Heat flow estimates

Fourier's Law Approach



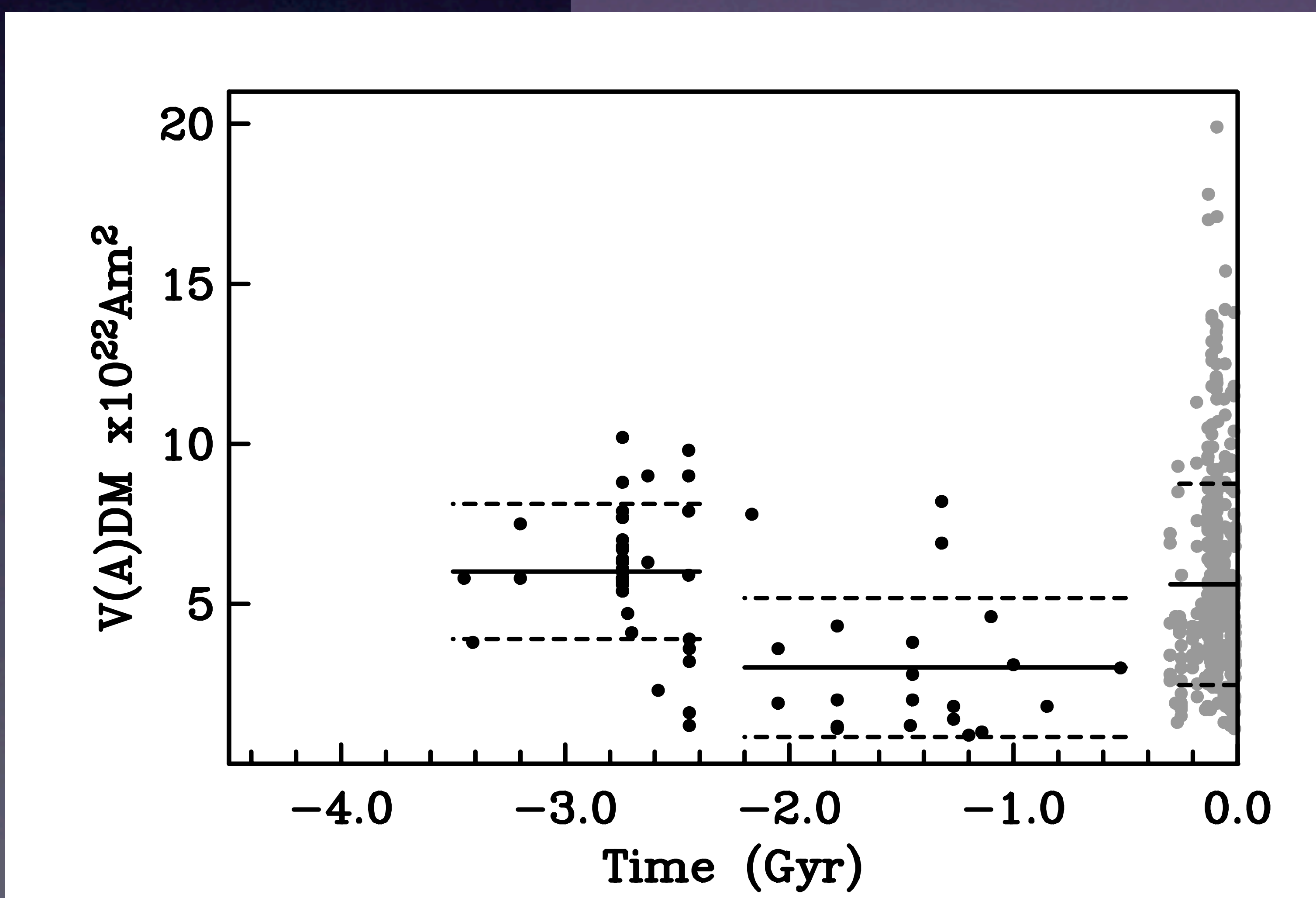
Result

- 10 - 15 TW
- 3-5 times larger than estimates pre-2008

CMB Heat flow estimates

Geomagnetic Constraints

- Core fluid motions strongly influenced by Q_{cmb}
- Fluid motions, in turn, drive a geodynamo which gives rise to a magnetic field observable at Earth's surface



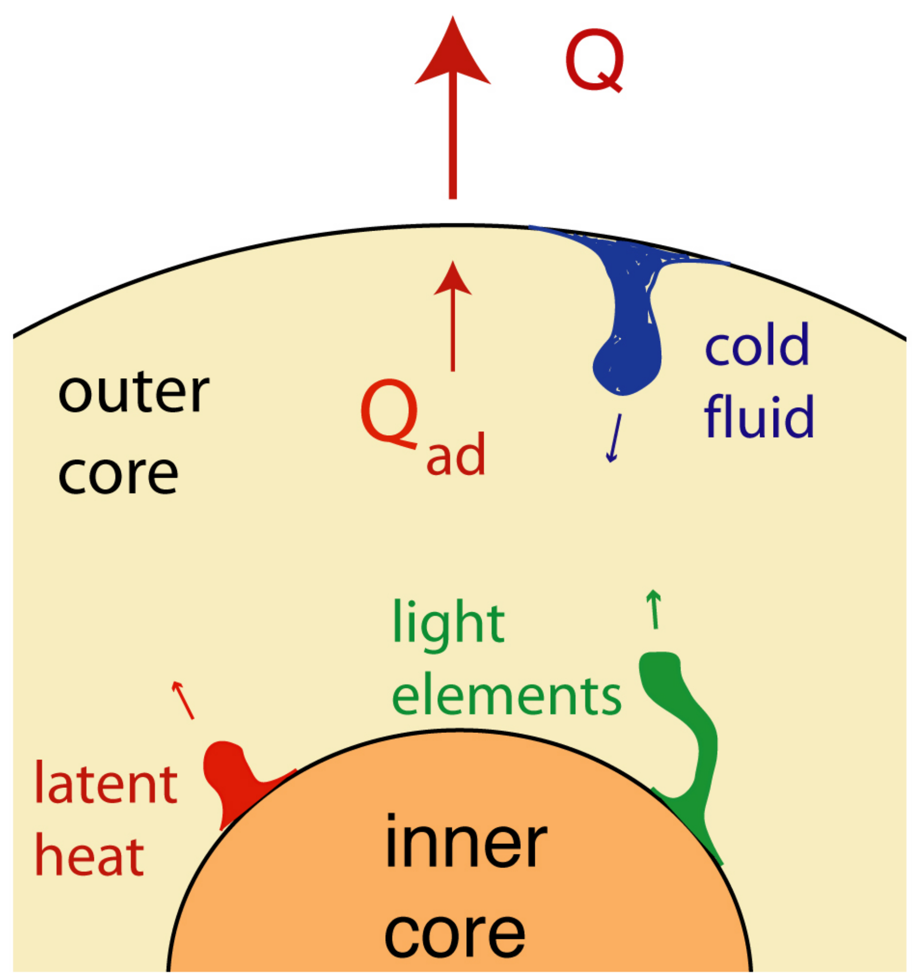
- Earth's magnetic field present at least 3.5 Gyr

CMB Heat flow estimates

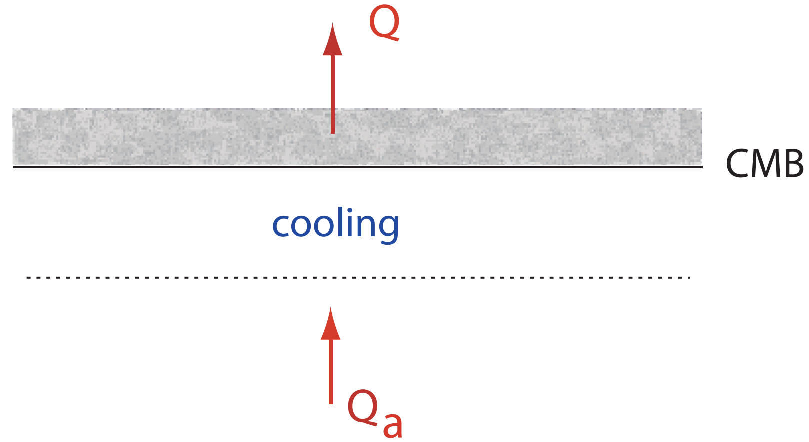
Geomagnetic Constraints

- If CMB heat flow *exceeds* core adiabatic heat flow, downwellings from the CMB are generated which facilitate whole layer stirring

Buffett 2012
CIDER presentation



Convective style for:
$Q_{cmb} > Q_{ad}$

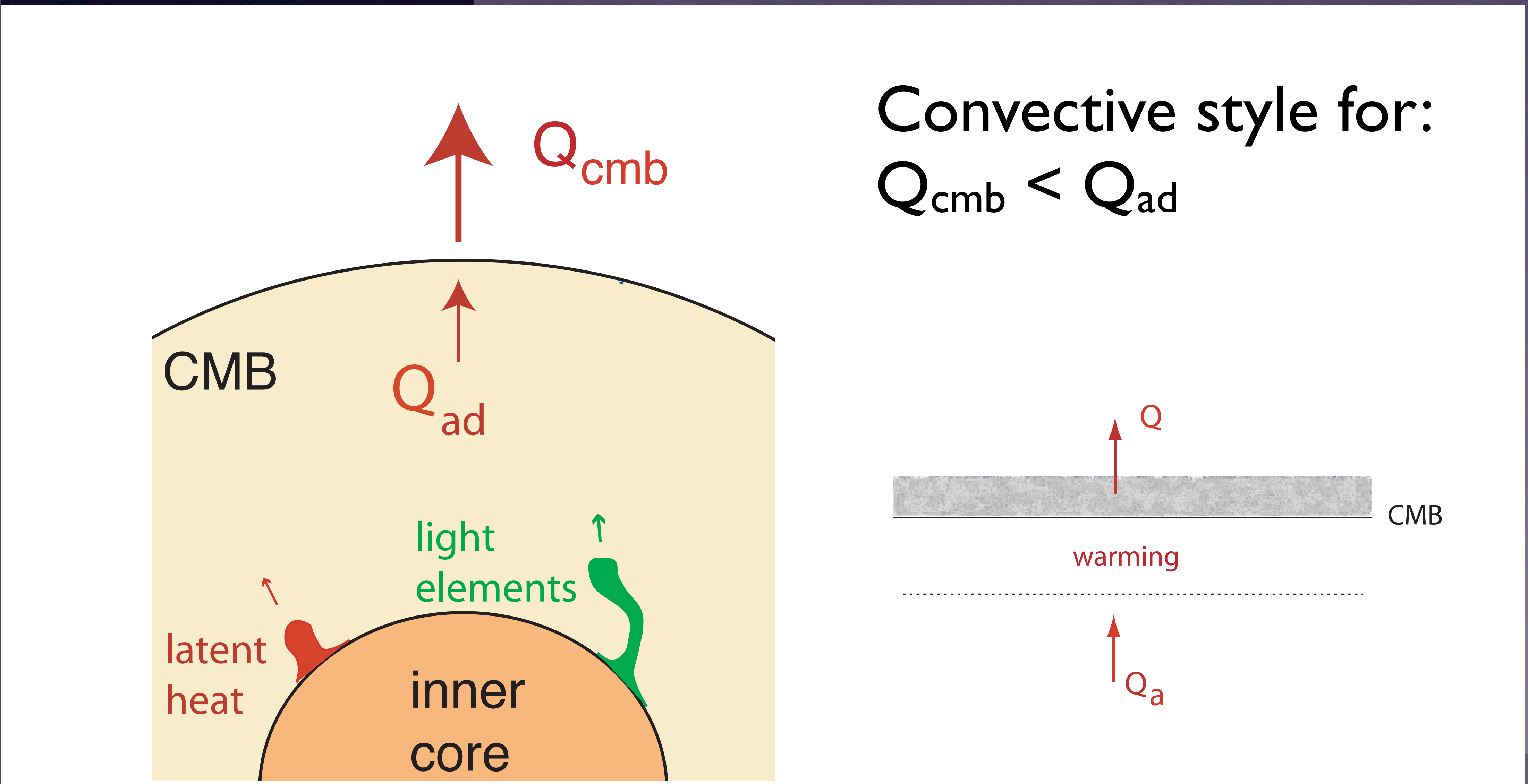


CMB Heat flow estimates

Geomagnetic Constraints

- If CMB heat flow is *less than* core adiabatic heat flow, core can develop thermal stratification at top; convection driven by inner core growth

Buffett 2012
CIDER presentation



CMB Heat flow estimates

Geomagnetic Constraints

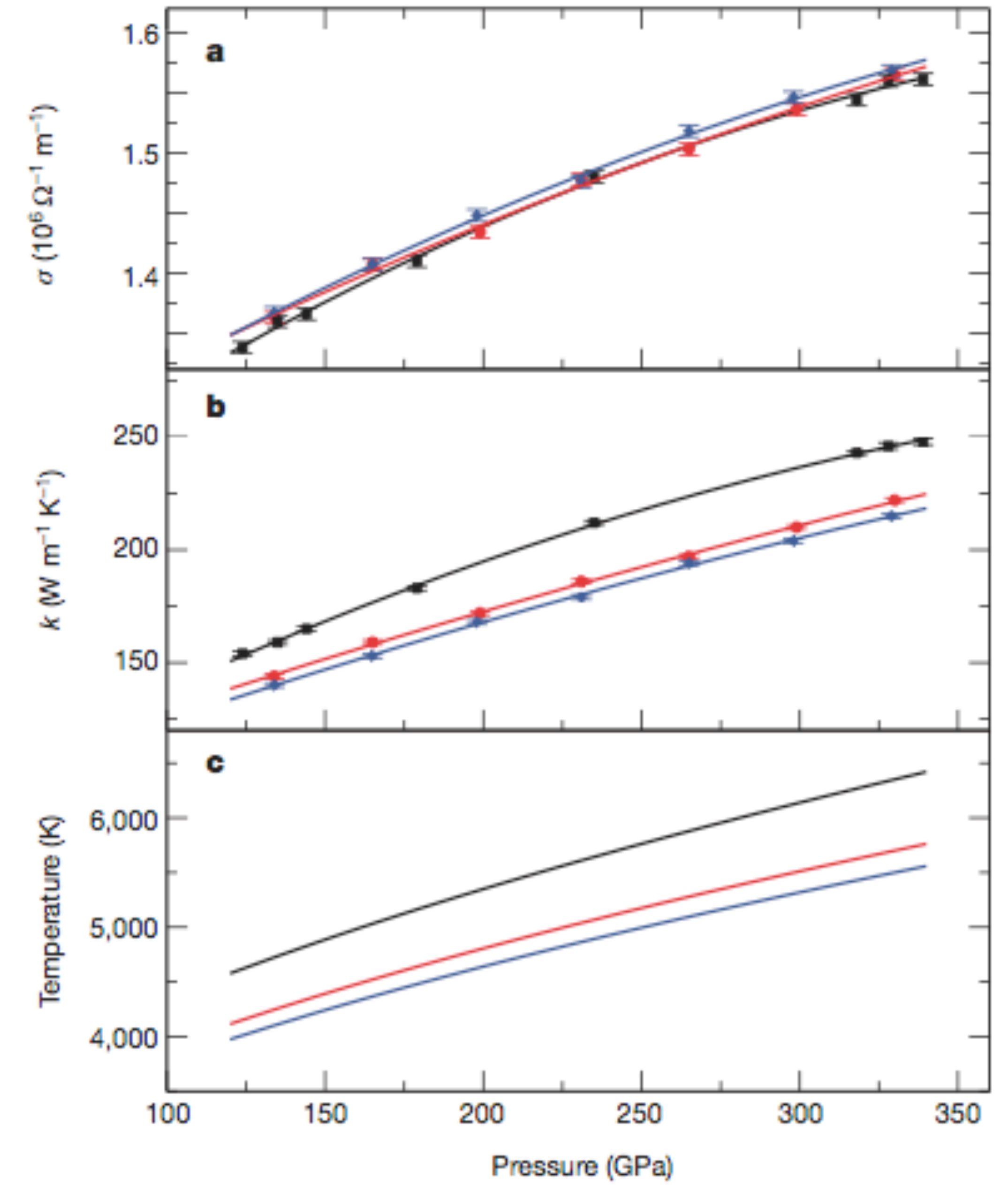


Figure 1 | **Electrical and thermal conductivity of iron at Earth's outer core conditions.** **a**–**c**, Electrical conductivity, σ (**a**), and electronic component of thermal conductivity, k (**b**), of pure iron corresponding to the three outer-core adiabatic profiles (adiabats) displayed in **c**. Black lines, adiabat corresponding to the melting temperature of pure iron at ICB pressure; red lines, that of the mixture containing 10% Si and 8% O; and blue lines, that of the mixture with 8% Si and 13% O. Lines are quadratic fits to the first principles raw data (symbols). Error bars (2 s.d.) are estimated from the scattering of the data obtained from 40 statistical independent configurations. Results are obtained with cells including 157 atoms and the single k-point (1/4,1/4,1/4), which are

Q_{ad}

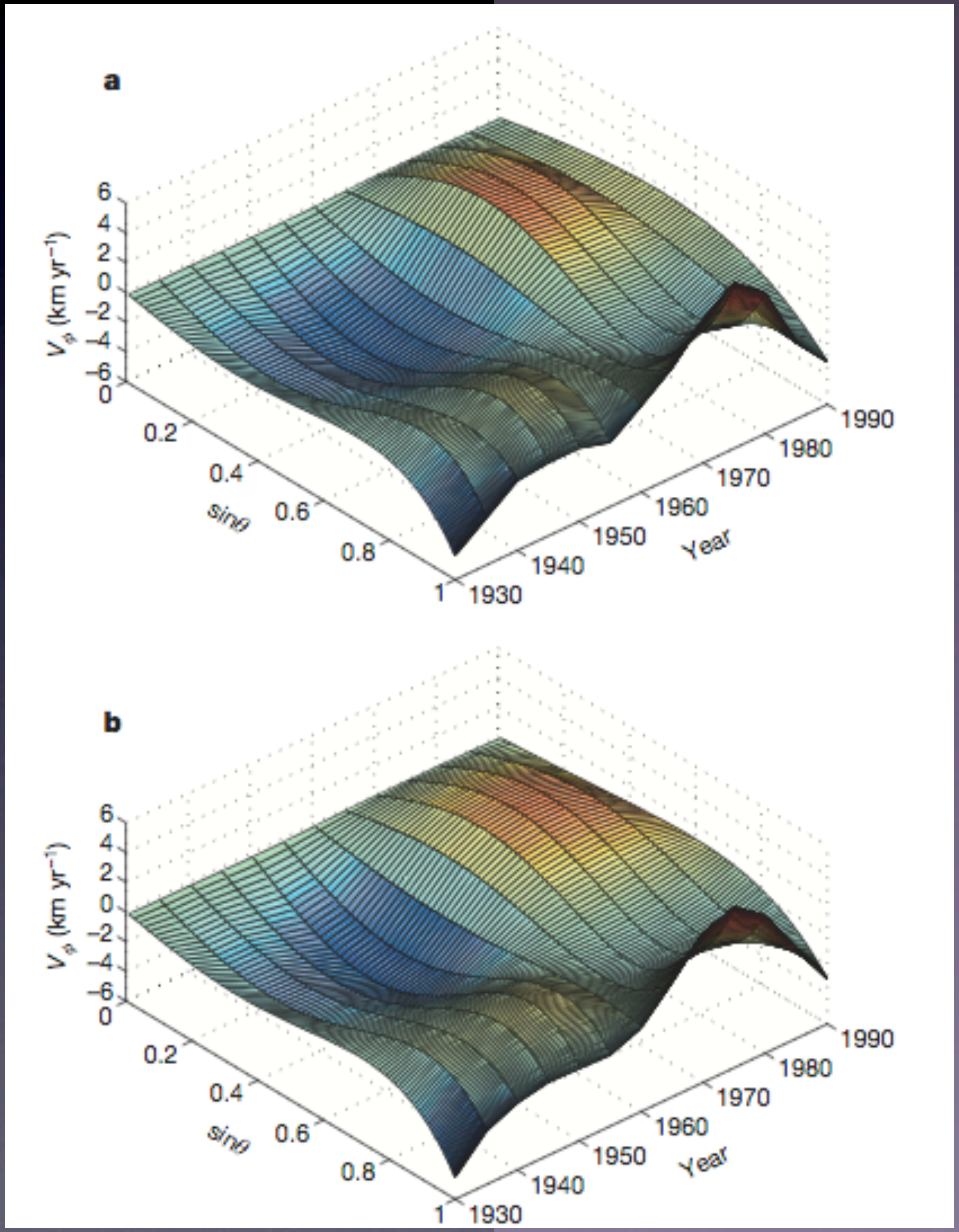
- 2012 results from ab initio calculations find thermal conductivity of core 2-3 times greater than previous estimates

- Q_{ad} = 15-16 TW
  - *higher than many estimates of* Q_{cmb}

Pozzo et al 2012

Geomagnetic Constraints

Evidence for stratified layer at top of Core?



- Decadal variations of magnetic field may show distinctive periodicities
- 140 km stratified layer at top of core can reproduce geomagnetic field observations
- Implication is 13TW (subadiabatic) Qcmb

Buffett 2014

CMB Heat flow estimates

Geomagnetic Constraints

CMB influence on geomagnetic field structure

Scalar magnetic field at Earth's surface:

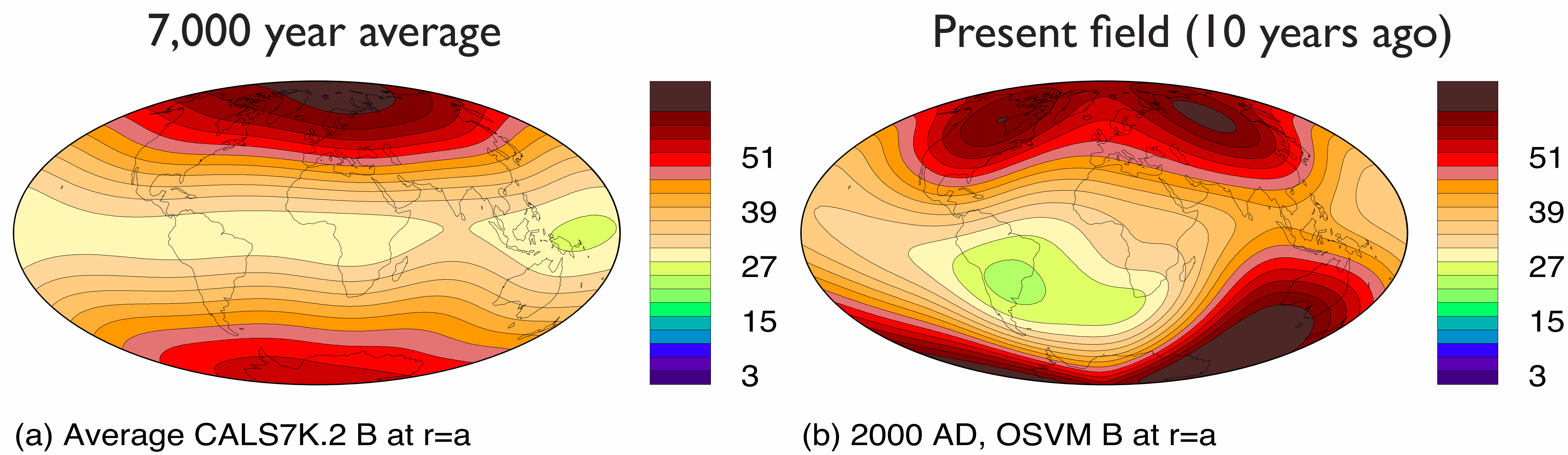
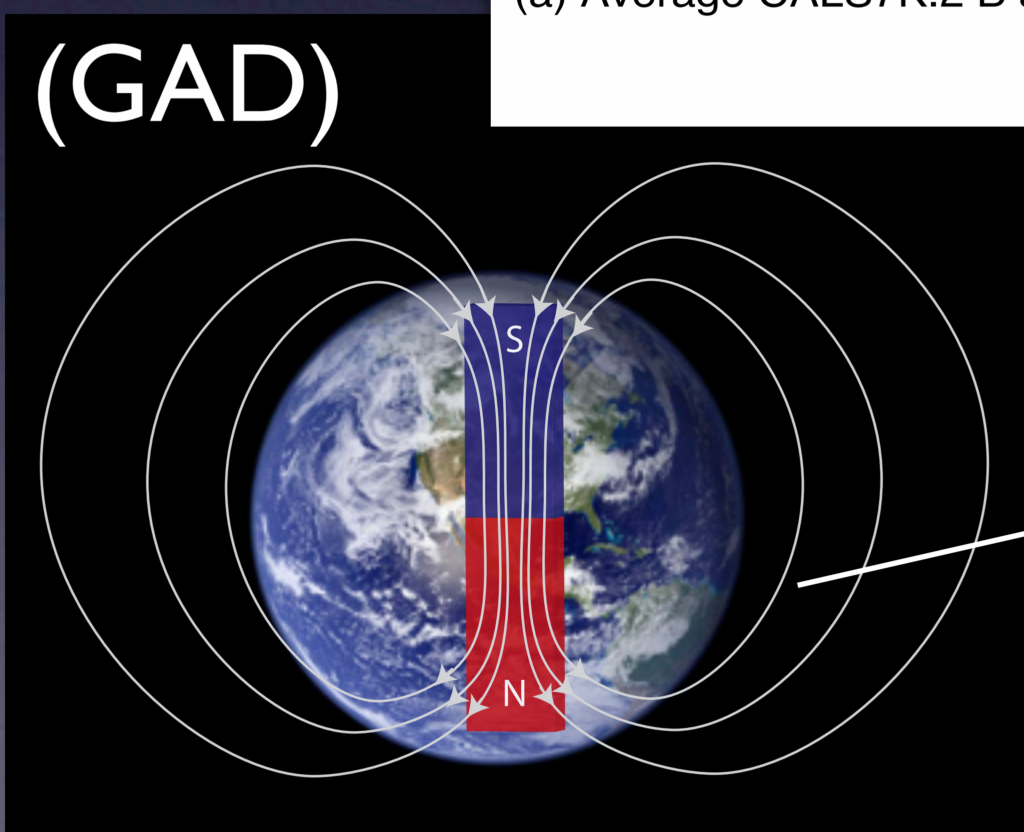
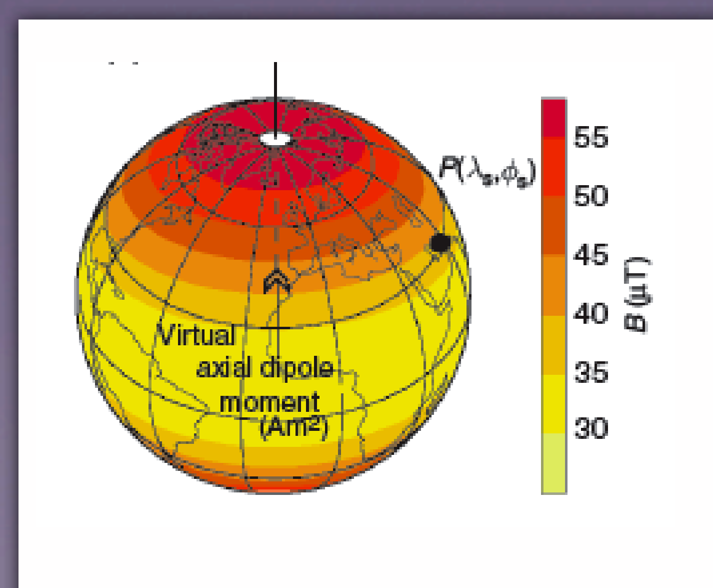


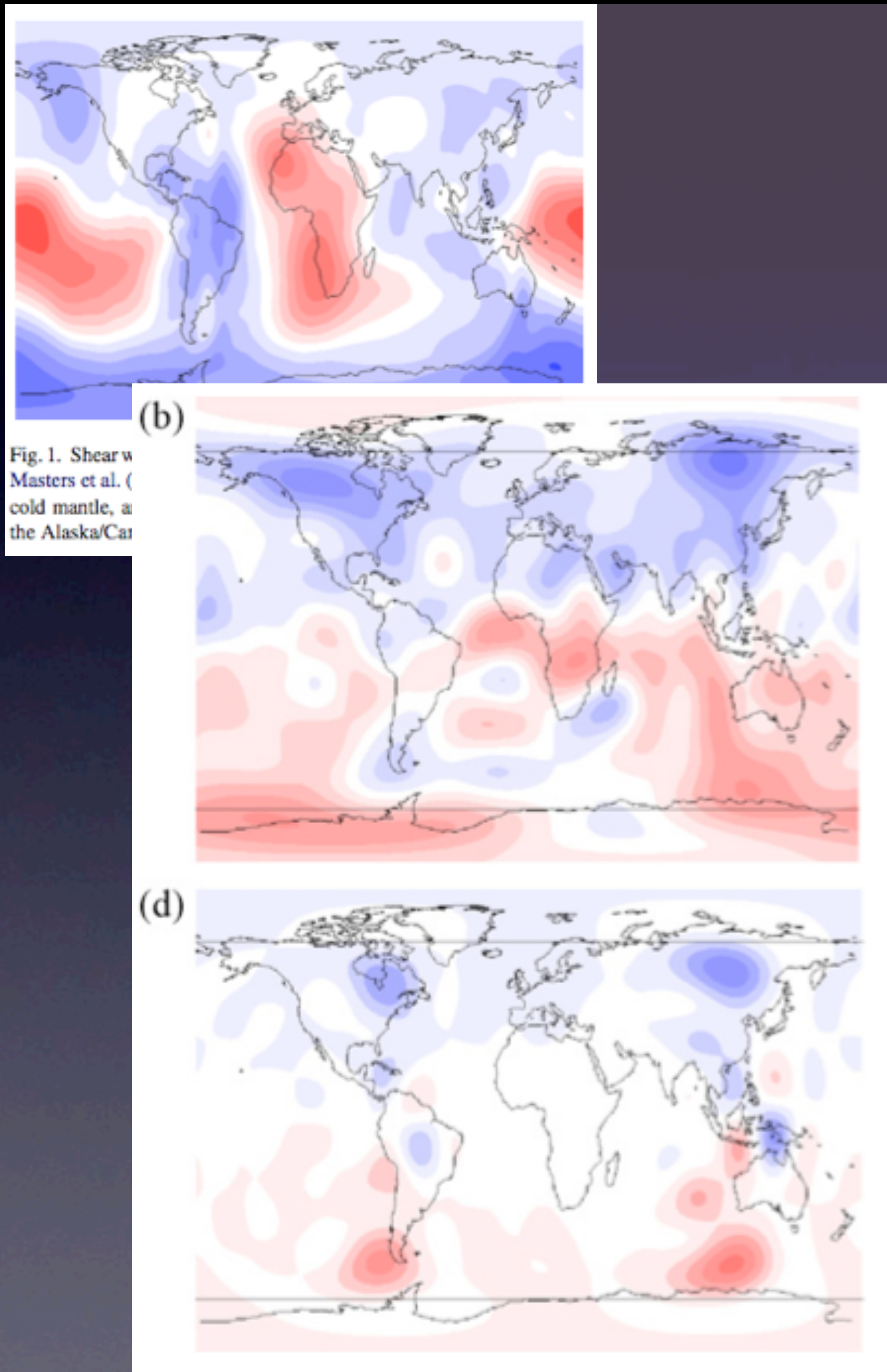
fig. from Constable (2007)





CMB Heat flow estimates

Geomagnetic Constraints



- Present day and historical magnetic field show high latitude flux lobes which move around but recur at preferred longitudes
- Could be explained by heterogeneous heat flow at CMB
- This result assumes/implies Vs at CMB is result of thermal variability

Observed Field in 1990 (Br plotted)

Dynamo model imposing heterogeneous CMB heat flow

Gubbins et al. 2007

CMB Heat flow estimates

Geomagnetic Constraints

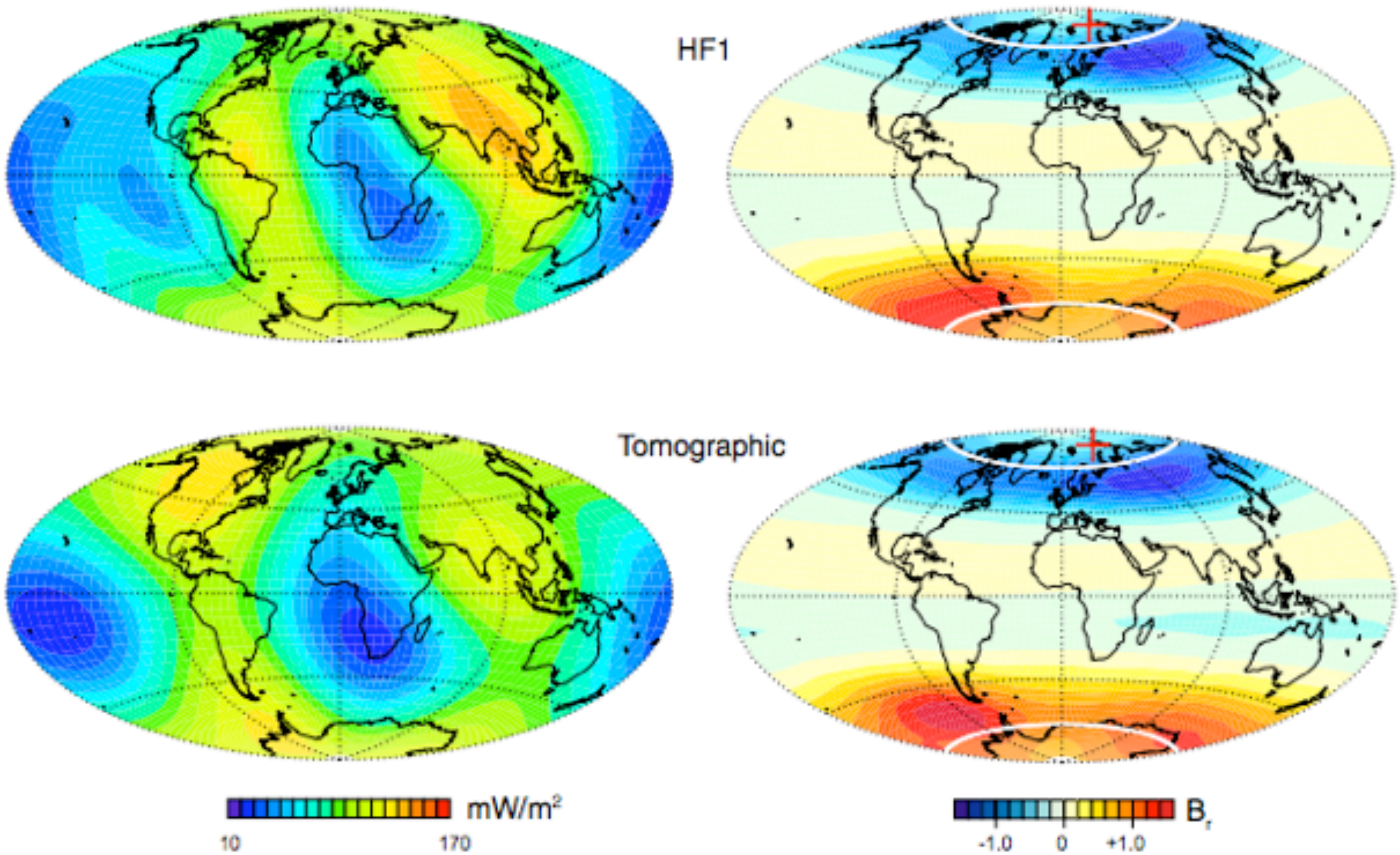


Fig. 4. Comparison of present-day CMB heat flux (left) and the corresponding time average dynamo radial magnetic field on the CMB during normal polarity times (right). HF1 = CMB heat flux from mantle history HF1 with spherical harmonic degree $l = 4$ truncation; Tomographic = CMB heat flux from lower mantle tomography with spherical harmonic degree $l = 3$ truncation. Magnetic intensity contours are in dimensionless Elsasser number units, red crosses mark the geomagnetic pole, white curves mark the inner core tangent cylinder.

Olson et al. 2013

- Siberian lobe dominant, leading to average dipole tilt (10 deg.)
- High heat flux regions lead to downwellings which concentrate magnetic field into high intensity patches

- Note: localized downwellings can lead to widespread core mixing in presence of average stratification

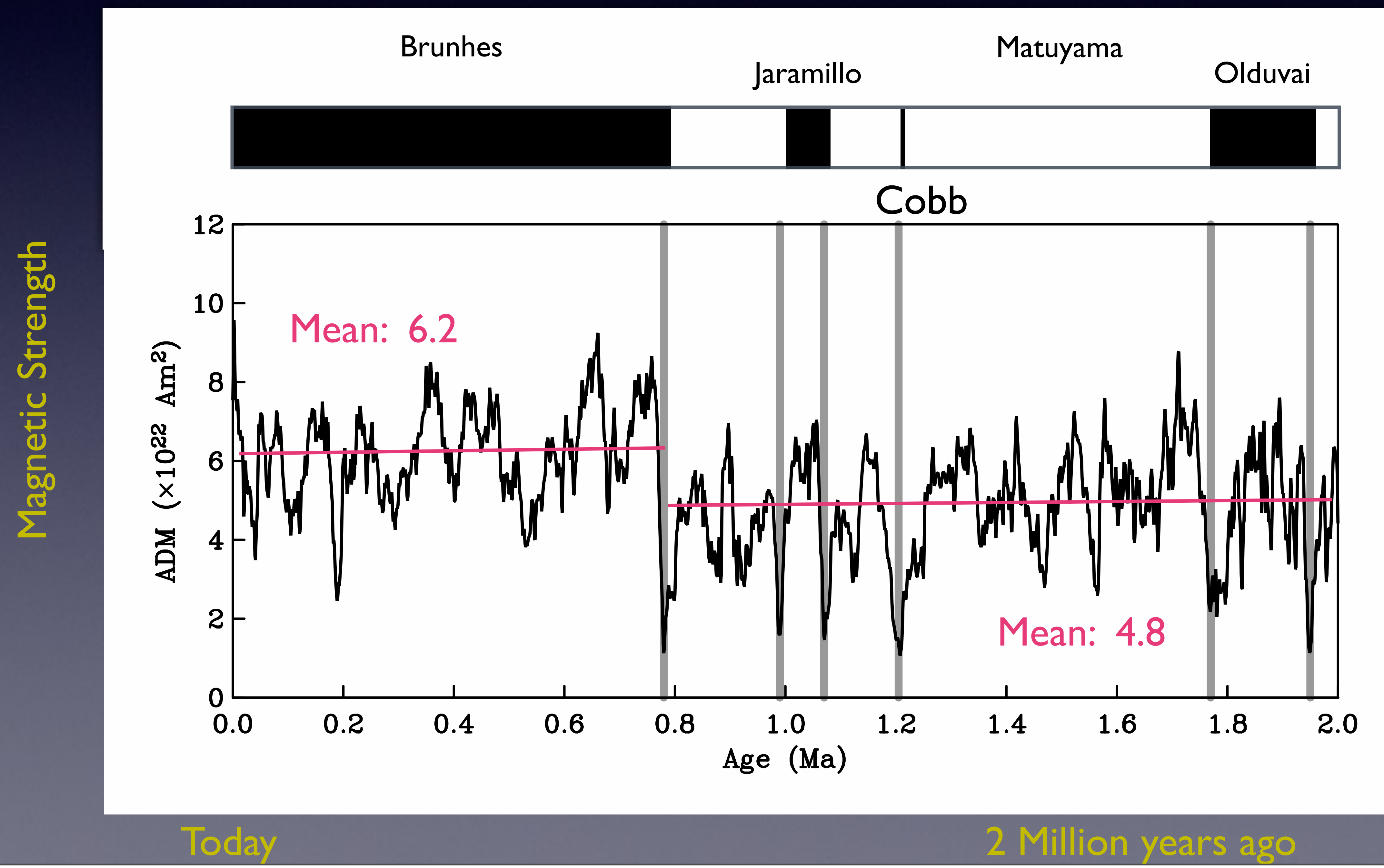
CMB Heat flow estimates

Geomagnetic Constraints

Olson et al. 2013

- Through time: GPTS reversal frequency indicates time dependent CMB heterogeneity
- Through time: magnetic field strength variations anti-correlated with kinematic energy of convection

Ziegler et al., GJI (2011)



CMB Heat flow

Discussion Points

- Geodynamic considerations give a plausible range for CMB heat flow of 10-15 TW for present day

- Total CMB heat flow estimates from geomagnetic considerations indicate present day values which are marginally subadiabatic

- Pattern of non-dipole geomagnetic field structure possibly explained by heterogeneous CMB heat flow

- Paleo-earth:
  - Is modern-day CMB seismic velocity (and/or heat flow) pattern the same as in the past?
  - Was the past CMB heat flow superadiabatic such that core convection and dynamo action could occur in the absence of the inner core? For 3 Gyr?