Core Constraints on Deep Earth Evolution

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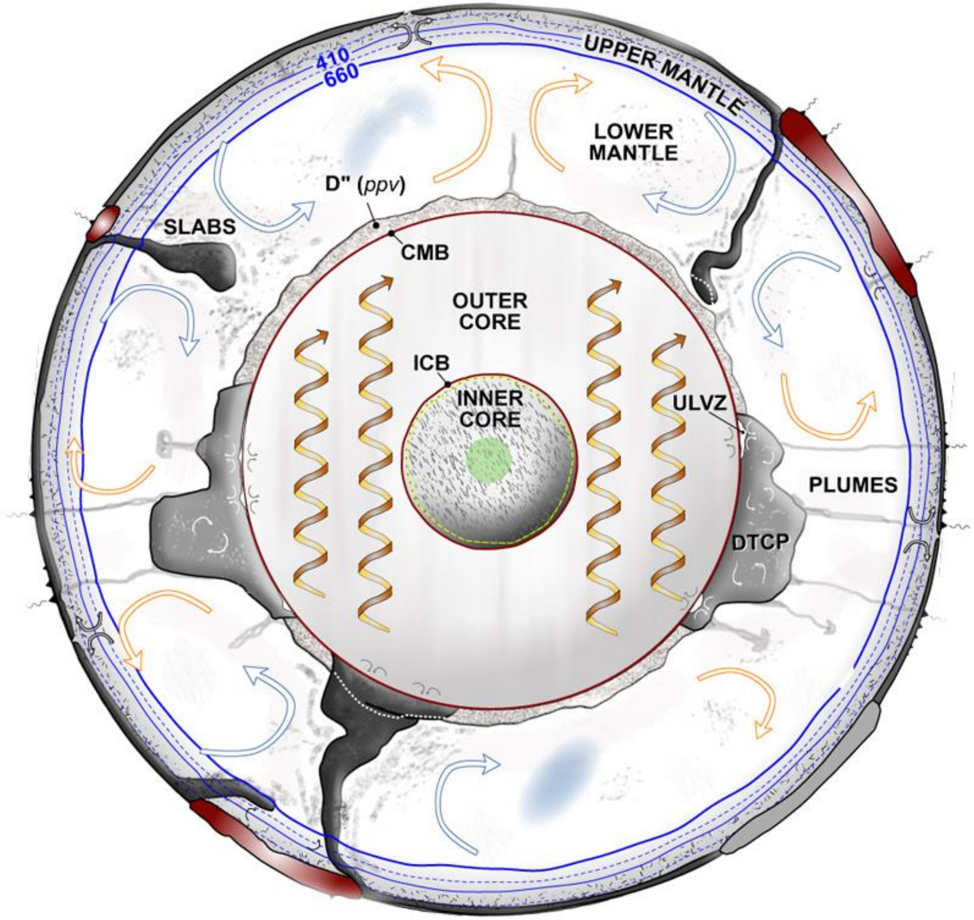

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Ed Garnero

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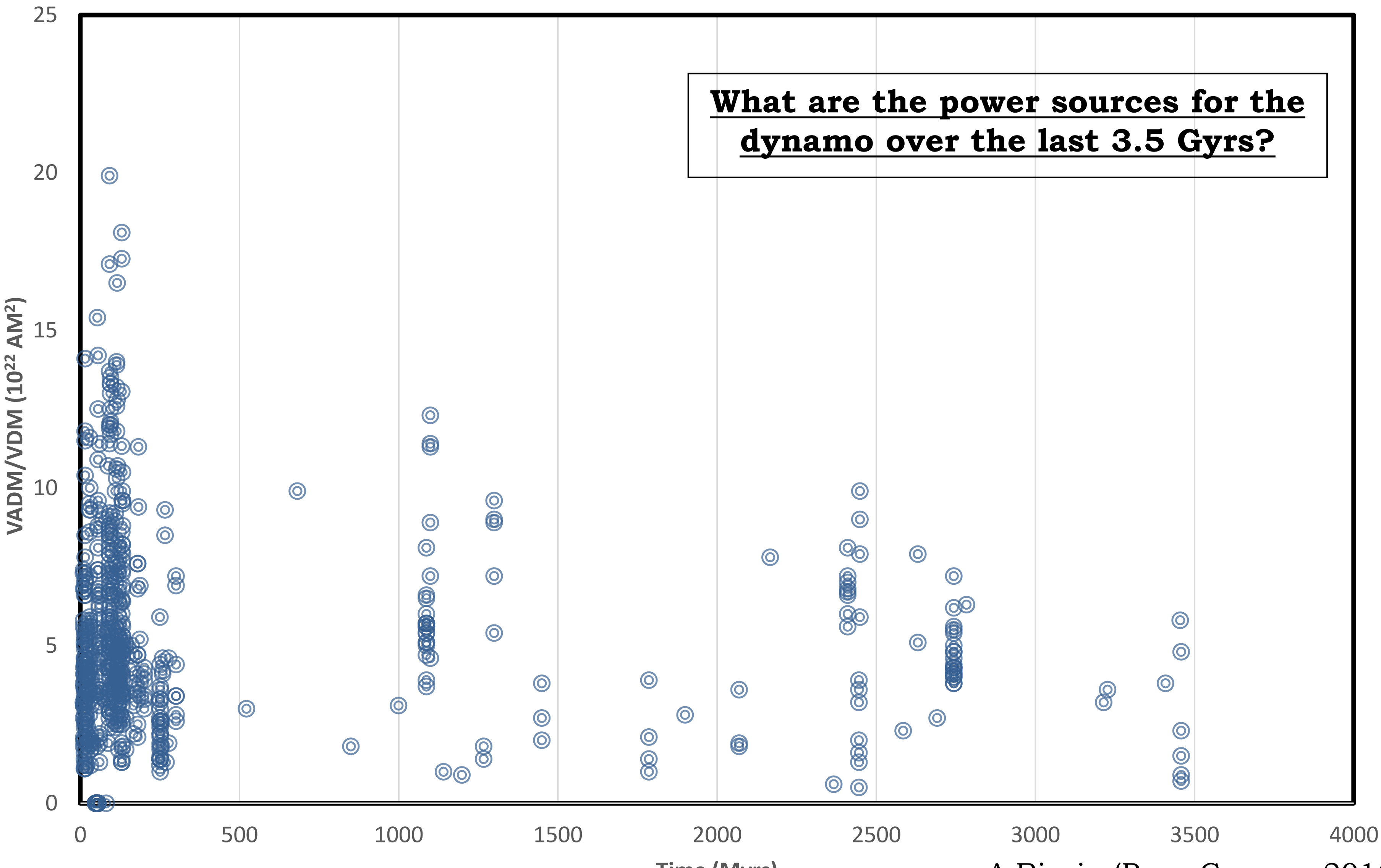
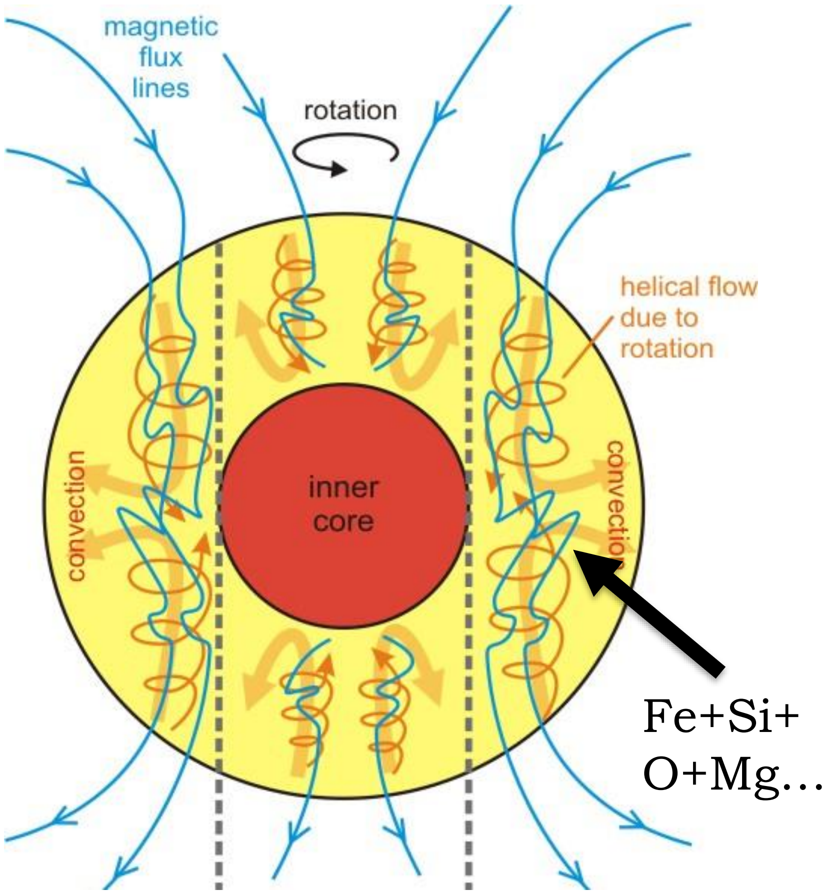
Fluctuations of Earth's Magnetic Field

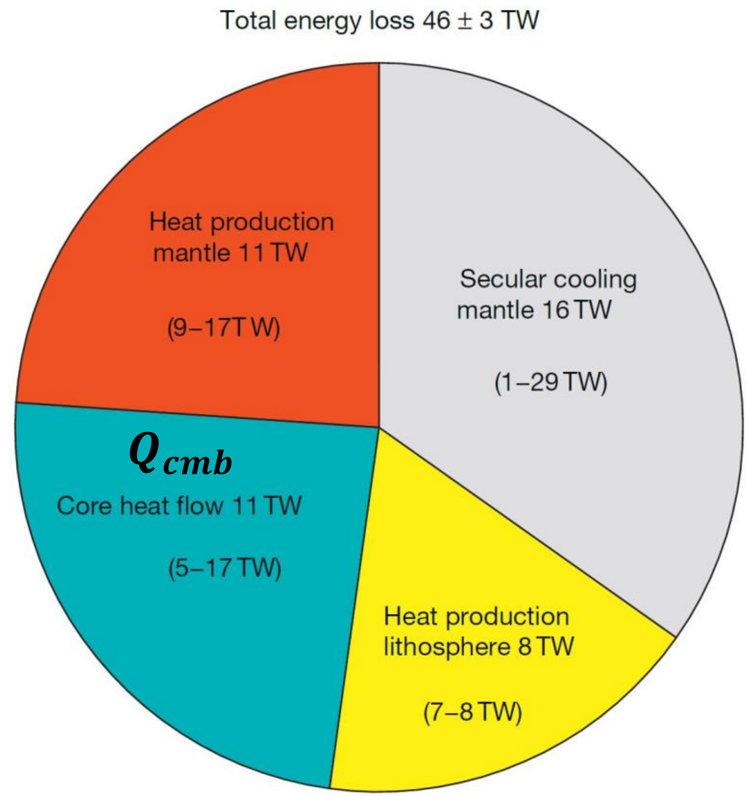


A.Biggin (Pers. Comms, 2016)

Generating the Geomagnetic Field



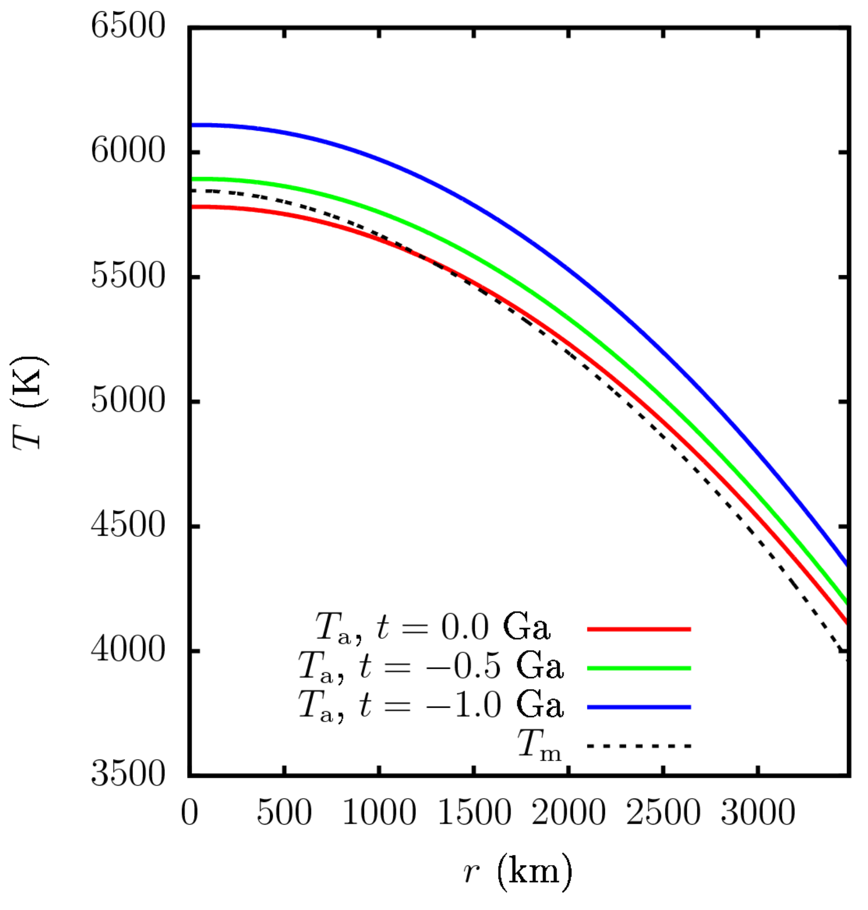
Glatzmaier & Roberts (1997)

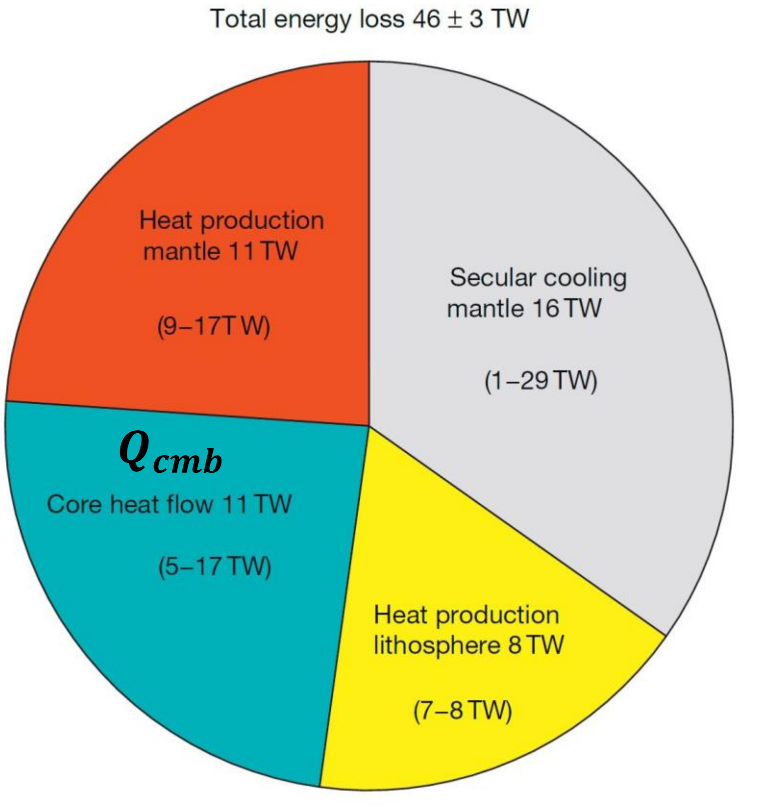


Jaupart et al (2015)

- Dynamo is powered by cooling – heat flow Q_{cmb} across core-mantle boundary
- Power needed to sustain the dynamo constrains Q_{cmb}

Cooling – Inner Core Growth

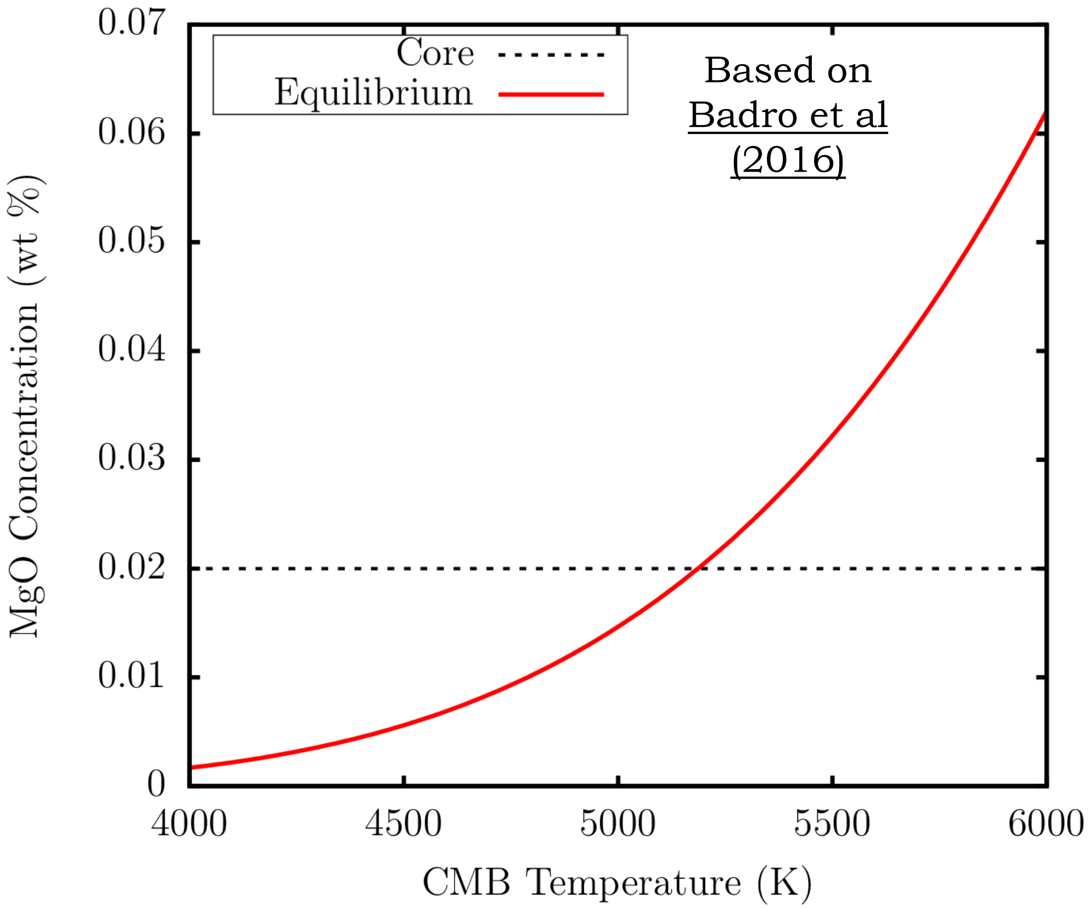


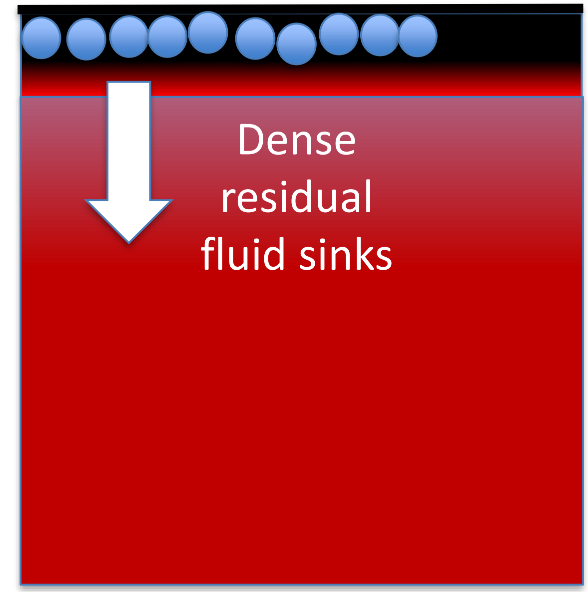


Jaupart et al (2015)

Power to sustain the dynamo constrains rate of core cooling and inner core growth

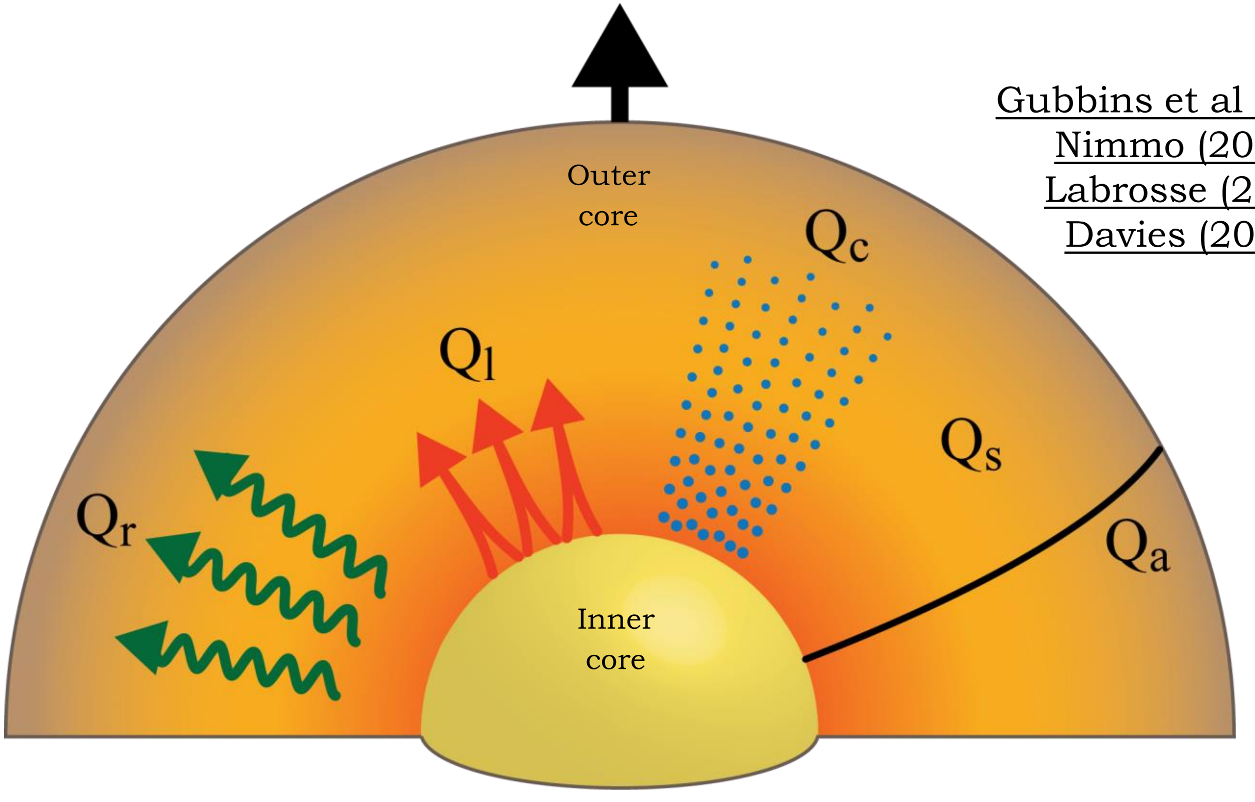
Cooling - Precipitation of MgO?





Precipitation may occur from core formation and could significantly lower core cooling rate (O'Rourke & Stevenson (2016); Badro et al (2016, 2018); Du et al (2017, 2019))
[NB – SiO_2 and FeO could also precipitate (e.g. Hirose et al, 2017)]

Q_{CMB} and Temperature in Time



Gubbins et al (2004);
Nimmo (2015);
Labrosse (2015)
Davies (2015)

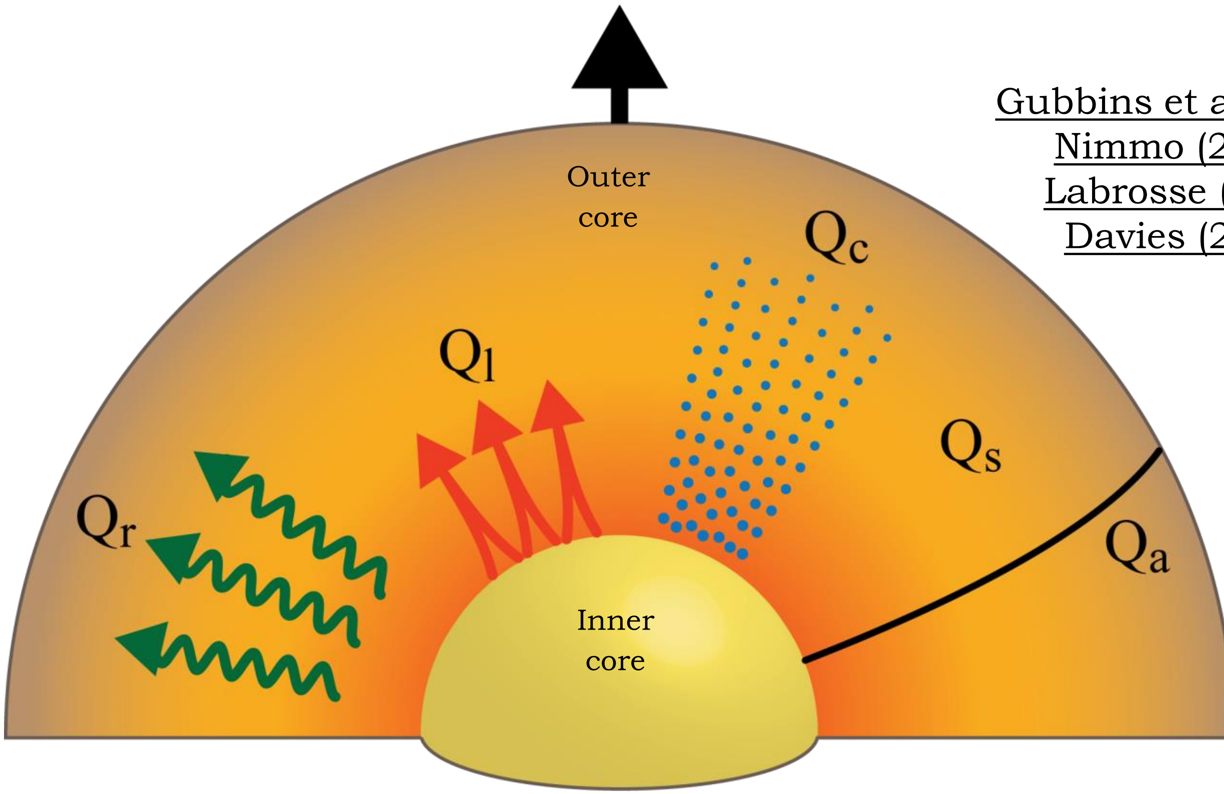
secular gravitational precipitation

$$Q_{cmb} = Q_s + Q_L + Q_c + Q_r + Q_P = A\frac{dT_c}{dt} + Q_r + Q_p$$

latent radiogenic

- Core cooling rate (dT_c/dt) determined from Q_{cmb} (imposed by mantle convection)

Q_{CMB} and Temperature in Time



Gubbins et al (2004); Nimmo (2015); Labrosse (2015) Davies (2015)

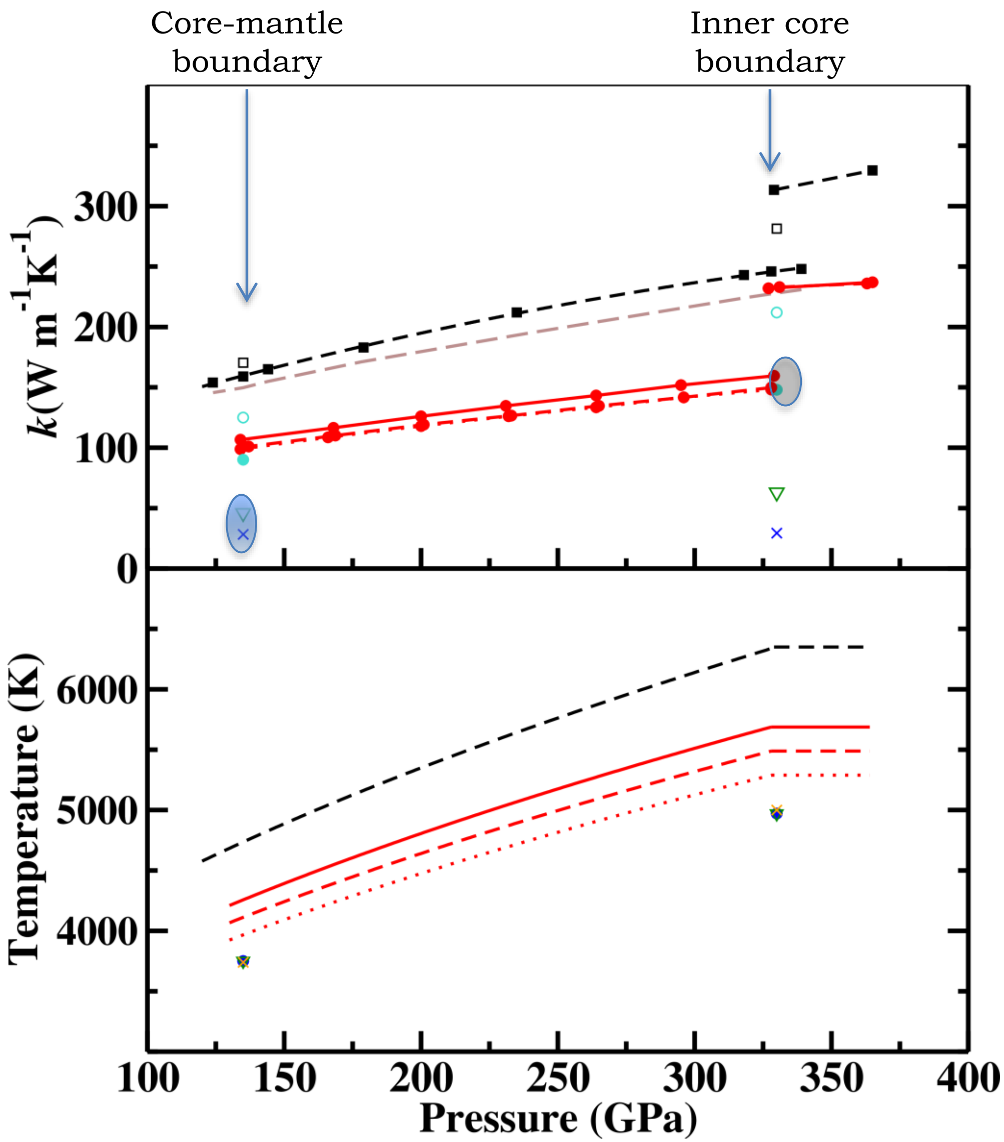
secular, gravitational, precipitation

$$Q_{cmb} = Q_s + Q_L + Q_c + Q_r + Q_P = A\frac{dT_c}{dt} + Q_r + Q_p$$

latent, radiogenic

$$E_J(\boldsymbol{B}) + E_a(k) = E_s + E_L + E_g + E_r + E_P = B\frac{dT_c}{dt} + E_r + E_P$$

Thermal Conductivity (k)



Pure Fe:
Pozzo et al (2012) [Also Gomi et al (2013); Ohta et al (2016)]
De Koker et al (2012)

Mixtures:
Pozzo et al (2013);
76.8%Fe–23.2%O Gomi et al (2013, Open)
77.5%Fe–22.5%Si Gomi et al (2013, Closed)

"Low" values
Stacey & Anderson (2001)
Stacey & Loper (2007)
Konopkova et al (2016)
Xu et al (2018, hcp iron)

- *'High' k values are 2-3 times larger than 'low' values*
- *k varies significantly with depth*

Aims and Basic Setup

Model core in isolation

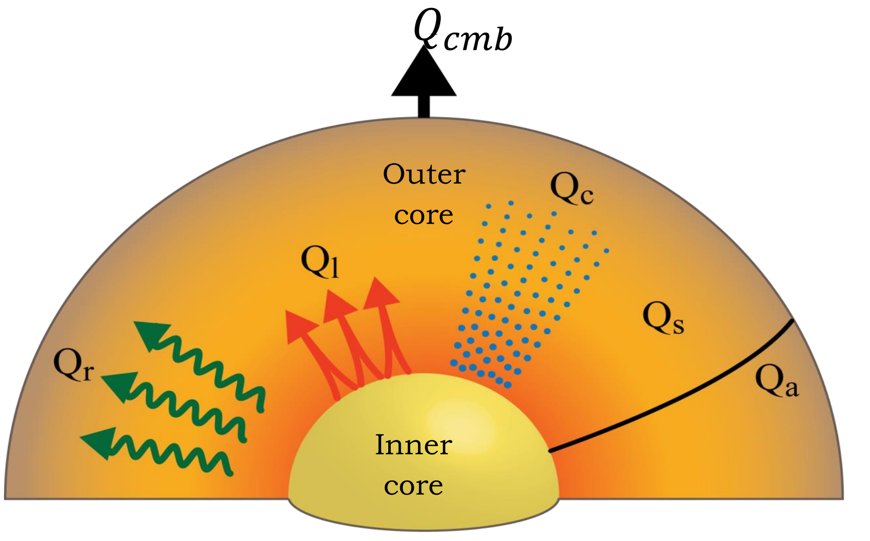
Constraint: $E_J > 0$ for last 3.5 Gyrs

Lower(ish) bound on cooling rate: set $E_J = 0$ before inner core formation

How do the high conductivity estimates affect models of Earth's core evolution?

- Inner core evolution
- Core temperatures
- CMB heat flow

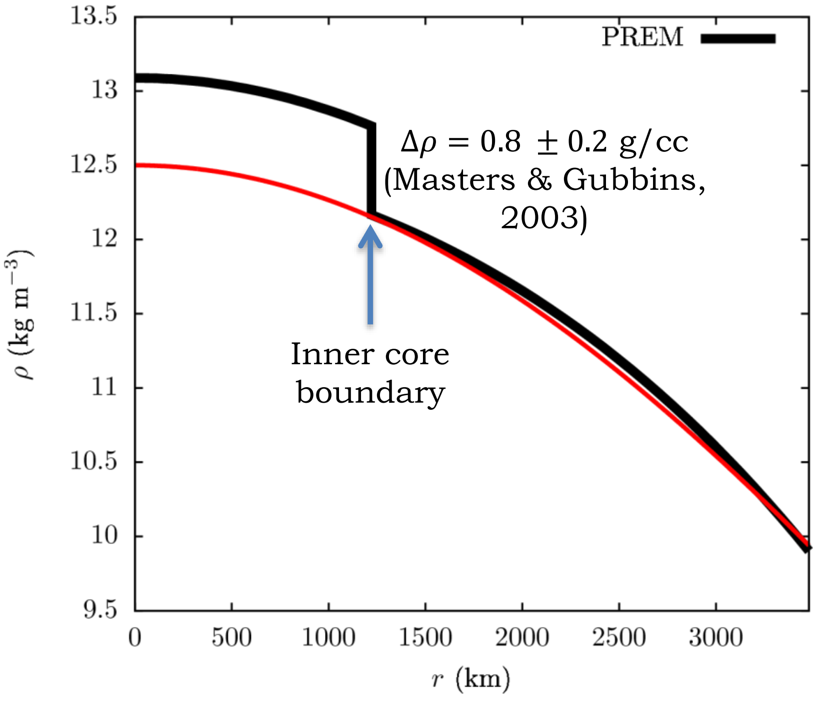
Omit precipitation at first..



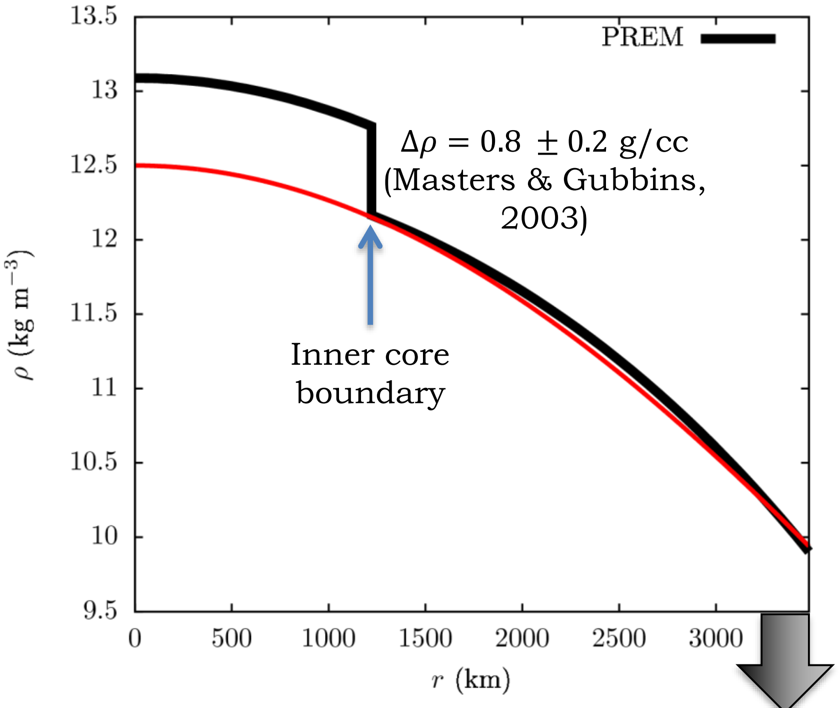
$$Q_{cmb} = A\frac{dT_c}{dt} + Q_r + Q_P$$

$$E_J(\boldsymbol{B}) + E_a(k) = B\frac{dT_c}{dt} + E_r + E_P$$

The Core Model



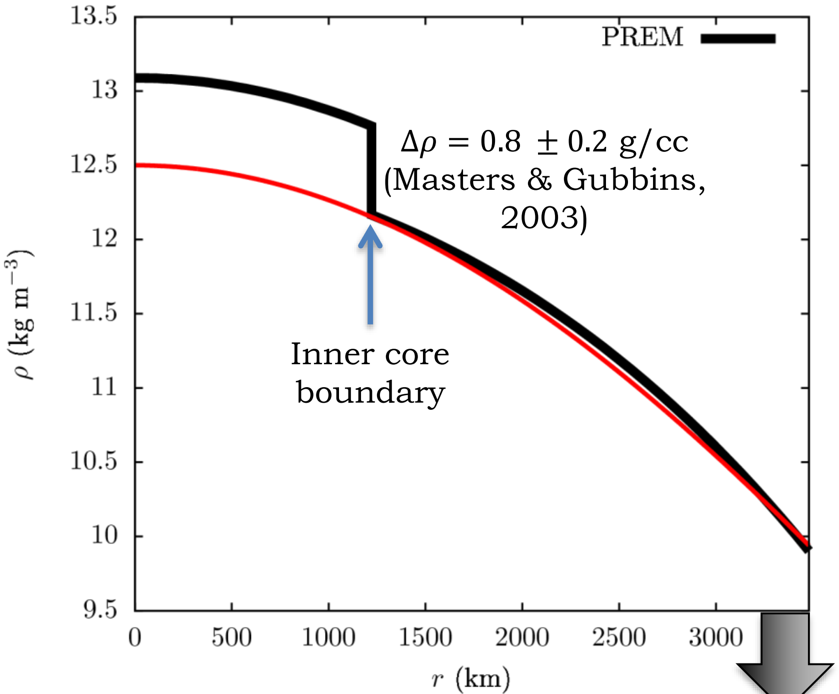
The Core Model



$\Delta\rho$ (kg/m³)	%Fe	%O	%Si	T_i
0.6	82	8	10	5900
0.8	79	13	8	5580
1.0	81	17	2	5320

Alfe et al (2002); Gubbins et al (2015)

The Core Model



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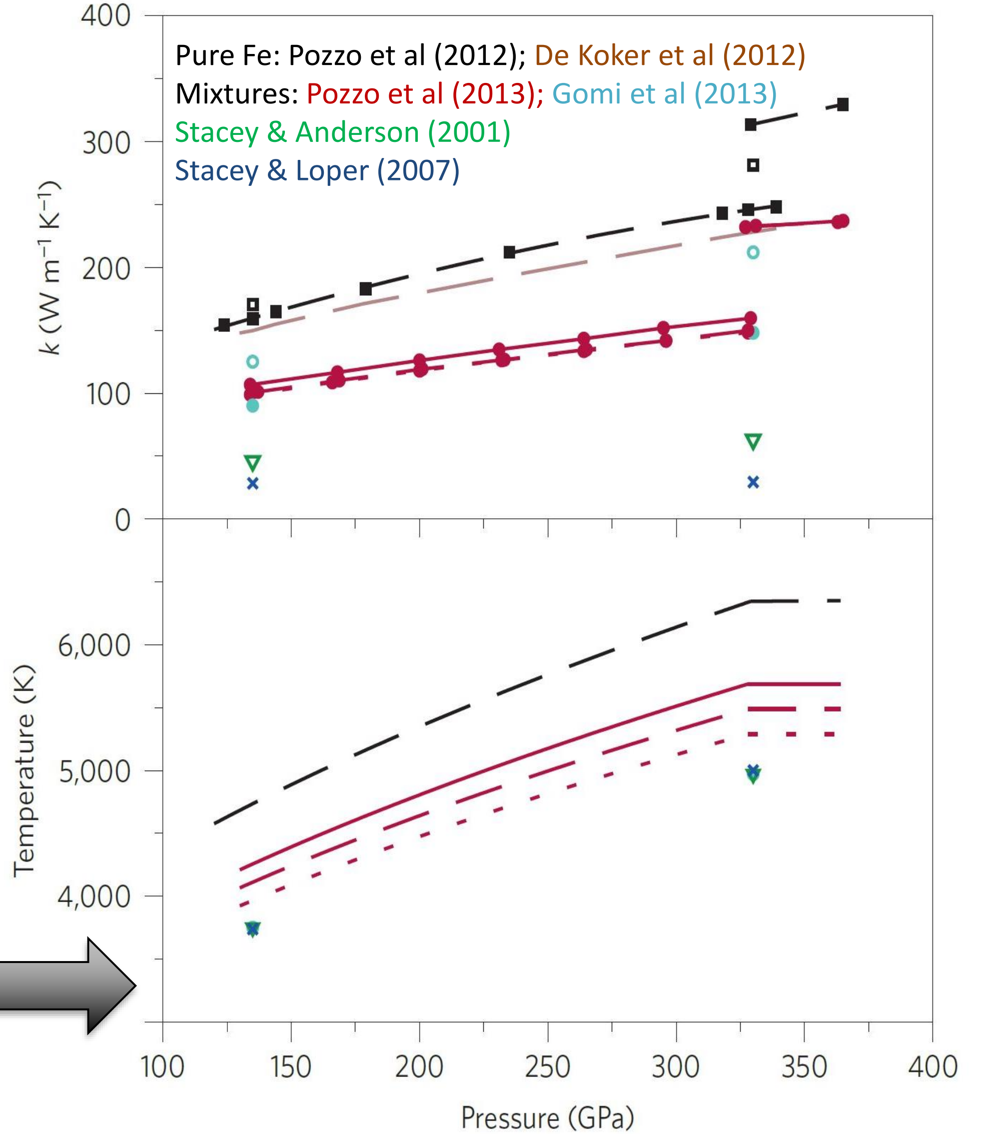
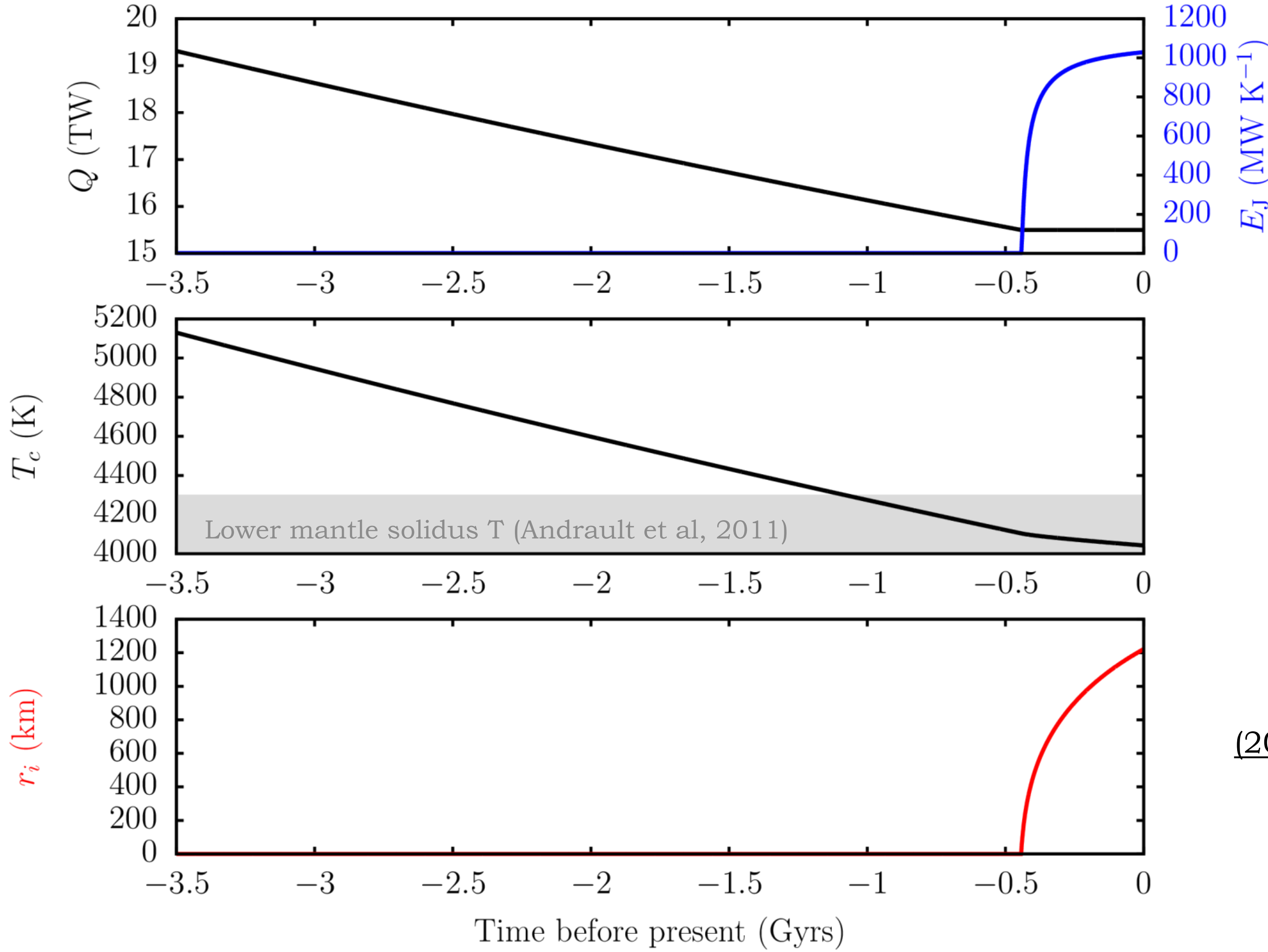
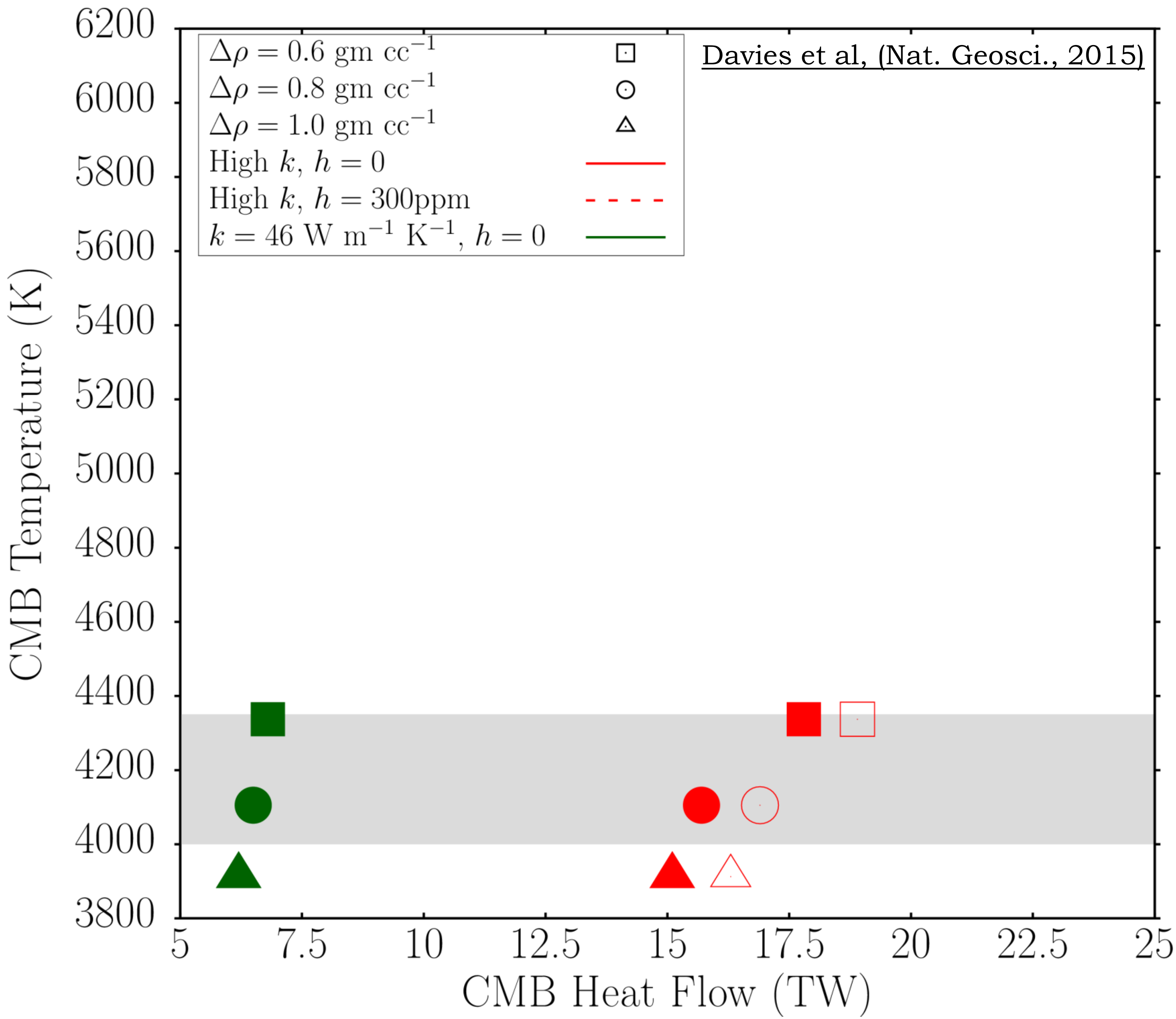


Alfe et al (2002); Gubbins et al (2015)

Example

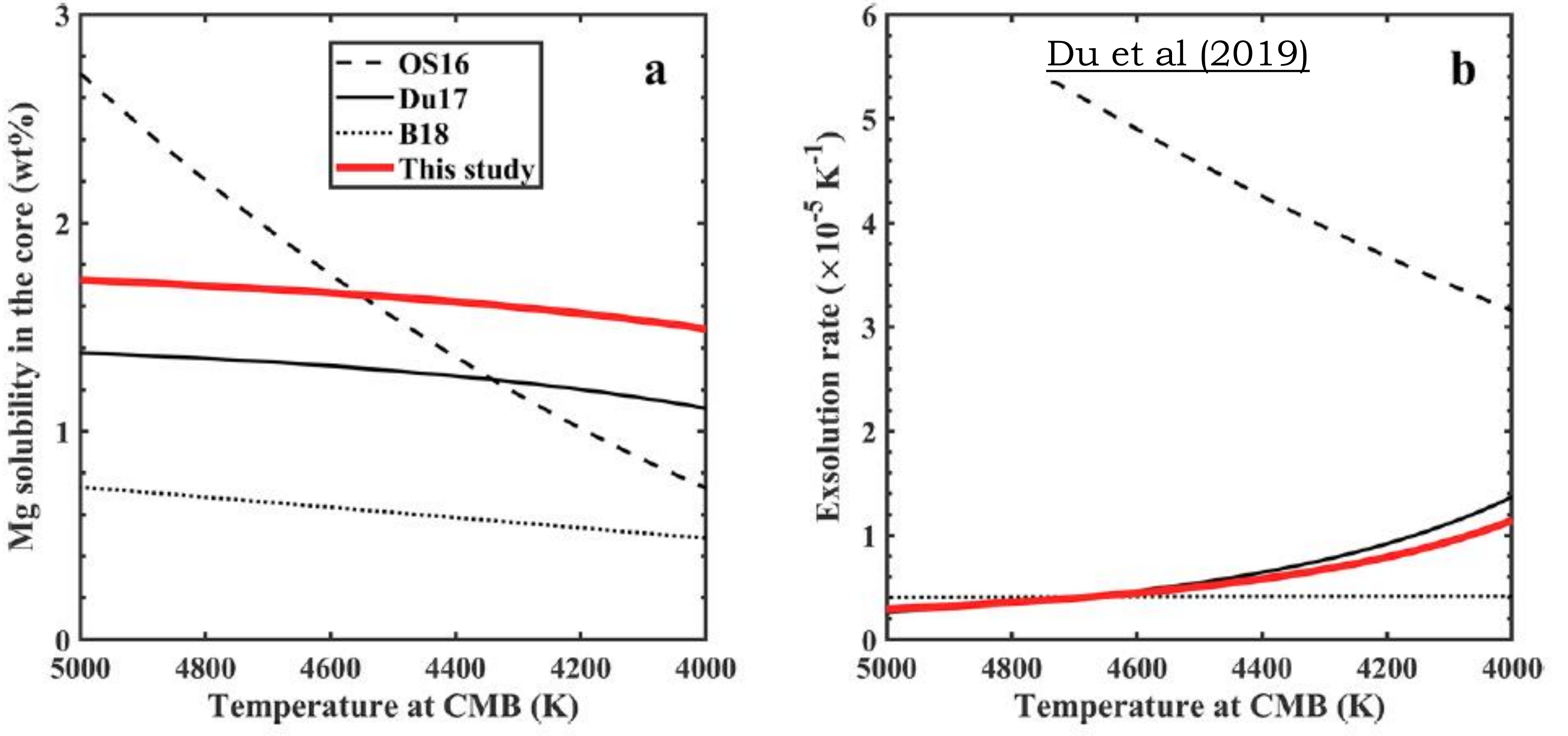


Davies (2015, PEPI)



Davies et al, (Nat. Geosci., 2015)
$\Delta\rho = 0.6$ gm cc^{-1}
$\Delta\rho = 0.8$ gm cc^{-1}
$\Delta\rho = 1.0$ gm cc^{-1}
High k, $h = 0$
High k, $h = 300$ppm
$k = 46$ W m^{-1} K^{-1}, $h = 0$
CMB Temperature (K)
CMB Heat Flow (TW)
6200
6000
5800
5600
5400
5200
5000
4800
4600
4400
4200
4000
3800
5
7.5
10
12.5
15
17.5
20
22.5
25

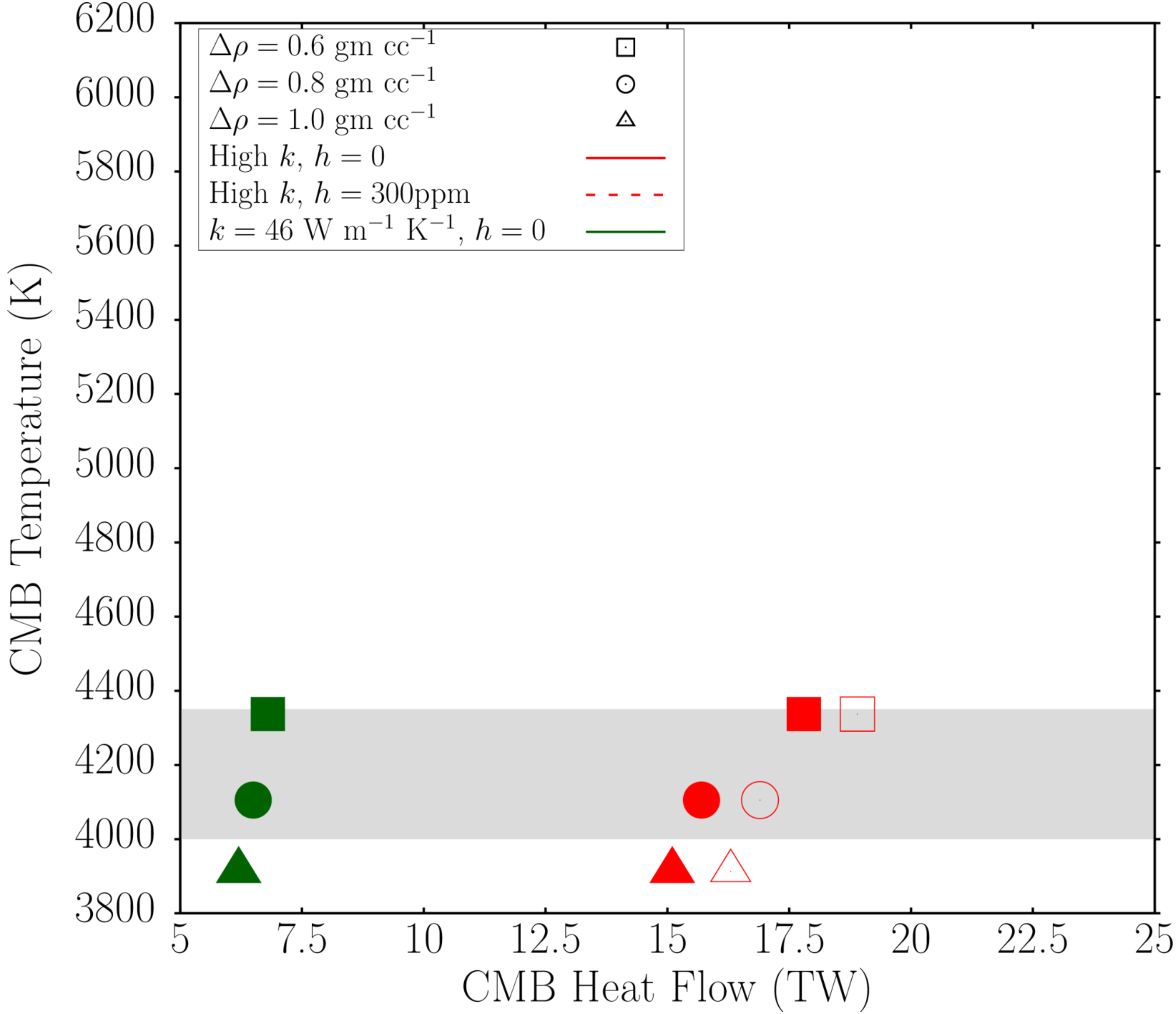
Precipitation



Gravitational energy released depends on C_m, mass precipitated per unit T drop

Add precipitation with $C_m = 0.6{,}1 \times 10^{-5}/\mathrm{K}$ to previous models.

Assume precipitation occurs over last 3.5 Gyrs



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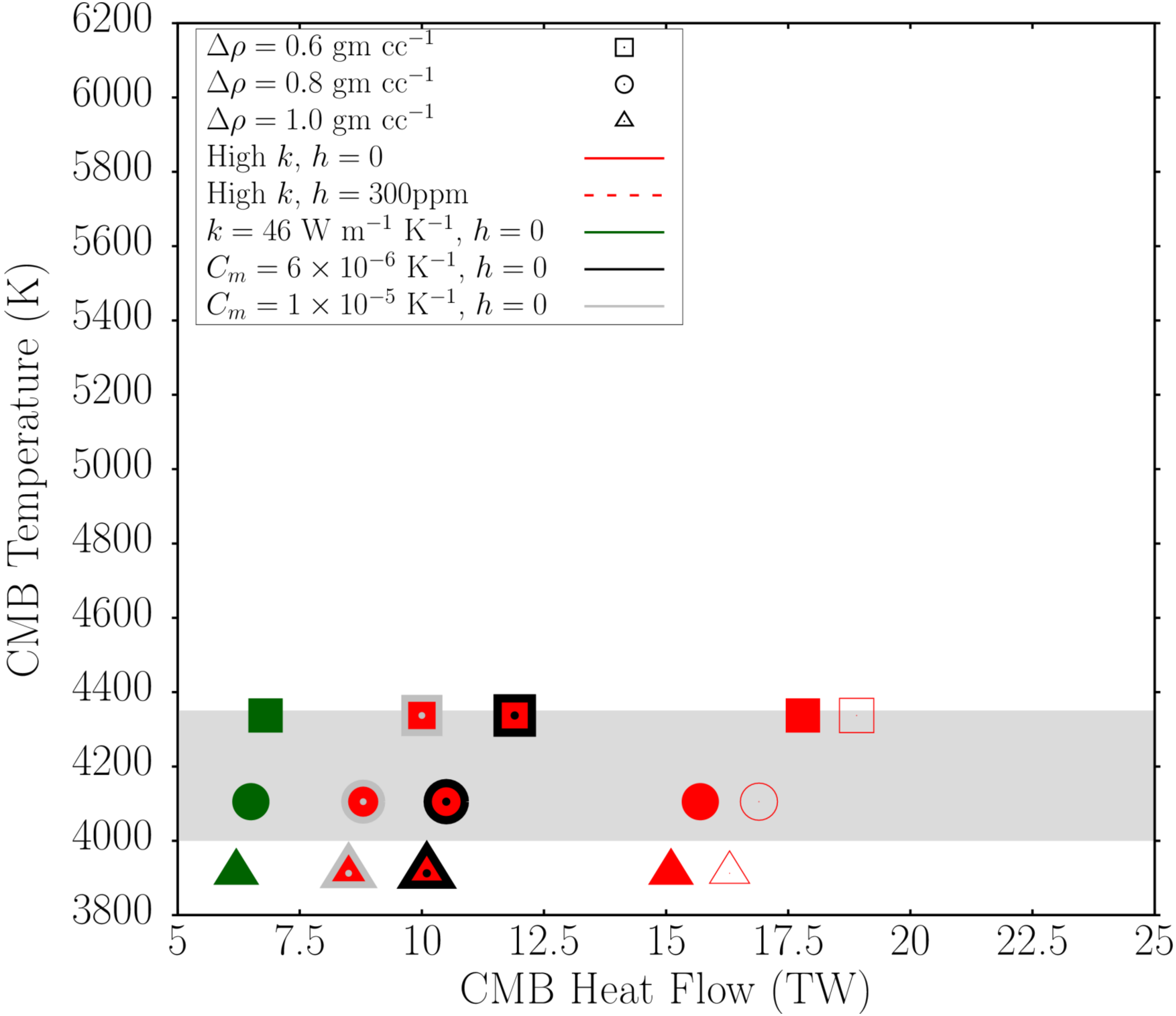

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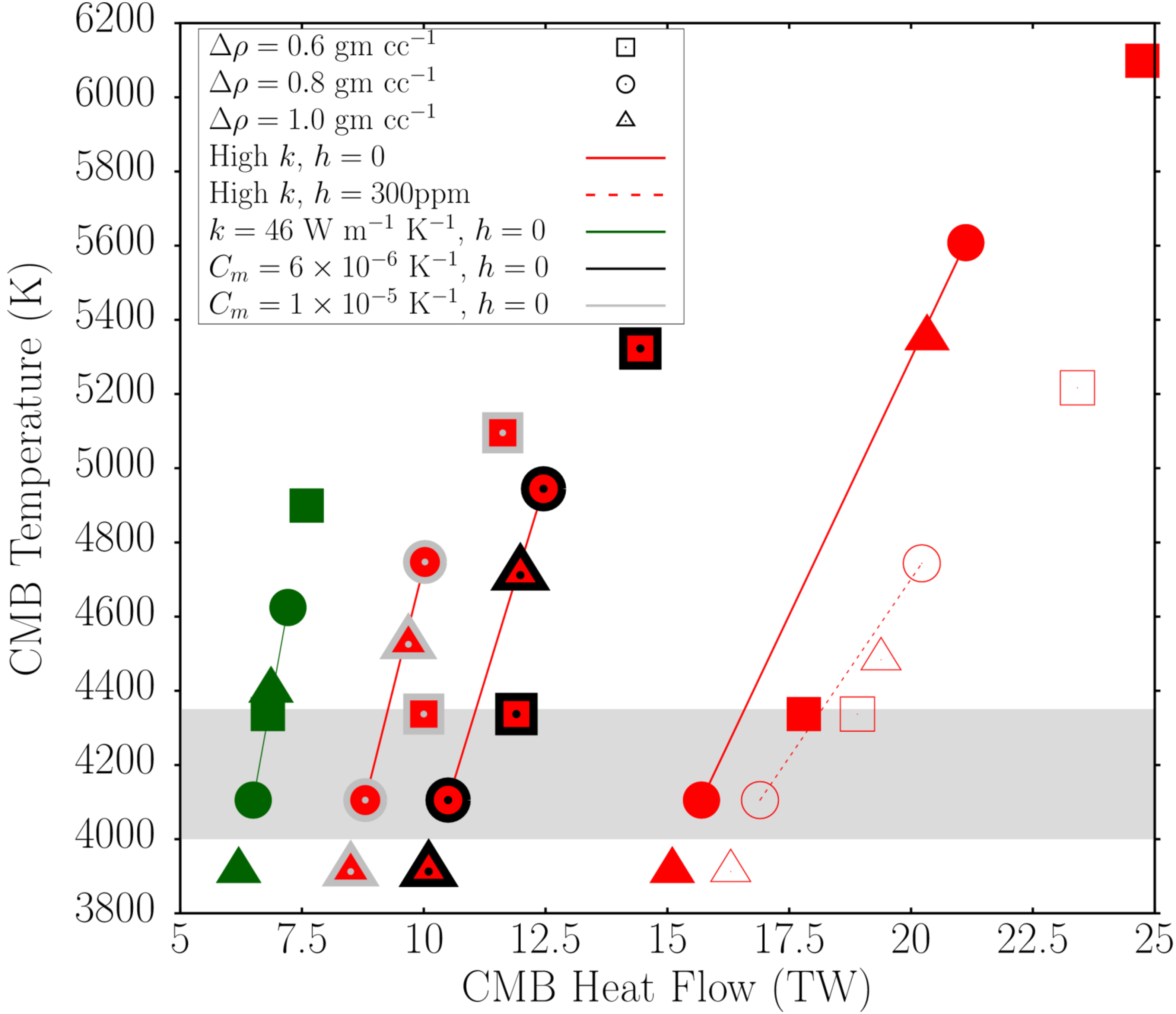
CMB Heat Flow (TW)



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Conclusions

Maintaining a marginal dynamo prior to inner core formation with high k requires

- Primordial core temperature > present estimates of lower mantle solidus
- Inner core age < 1 Gyr (300-500 Myrs without precipitation; 500-800 Myr with precipitation)

Minimum changes over 4.5 Gyrs:

- T_{cmb}: 600-1800 K
- Q_{cmb}: 2-7 TW

Minimum present-day $Q_{cmb} \sim 8-9$ TW

ICB density jump and C_m are main uncertainties in current models