Extrapolating from the Geodynamo to Exodynamos

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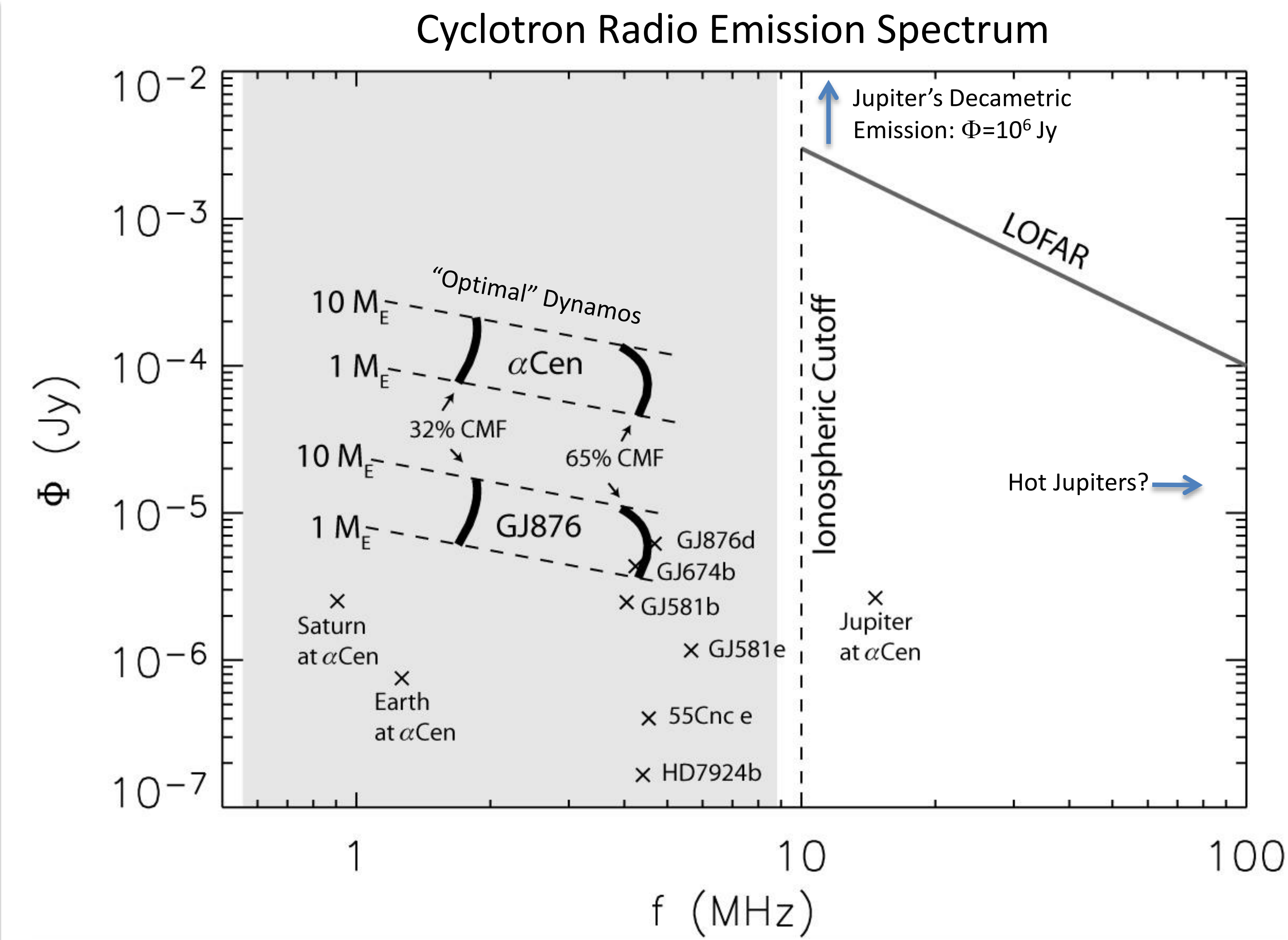
Motivation

- How do we make predictions for terrestrial exodynamos?
- Can we extrapolate from the geodynamo?
- What do we know about the geodynamo through time?

Outline

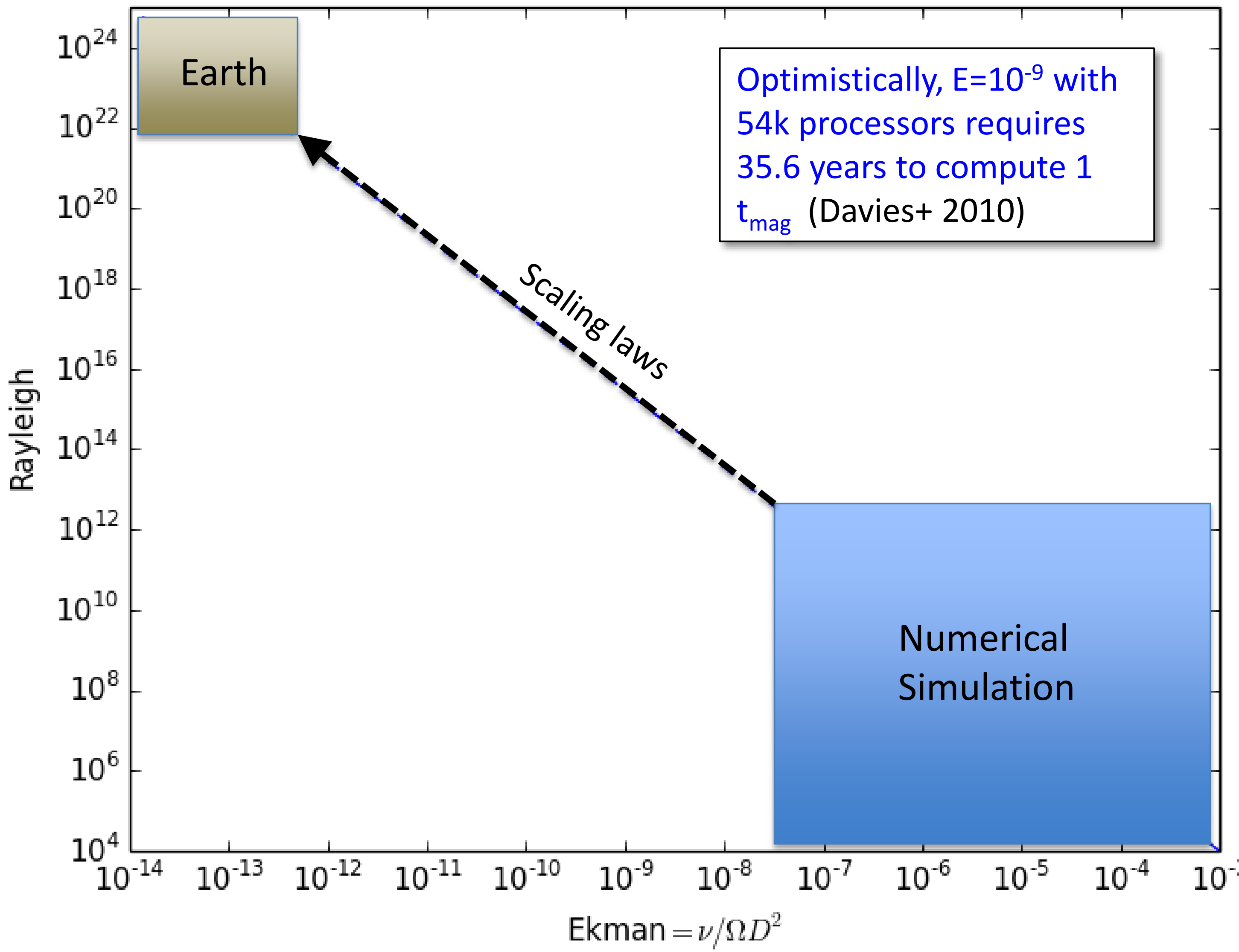
1. Magnetic scaling laws
2. Dynamo regimes
3. Paleomagnetic observations
4. Numerical geodynamo evolution
5. Mantle effects



Φ Scaling law (Farrell, 1999)

Driscoll+Olson 2011

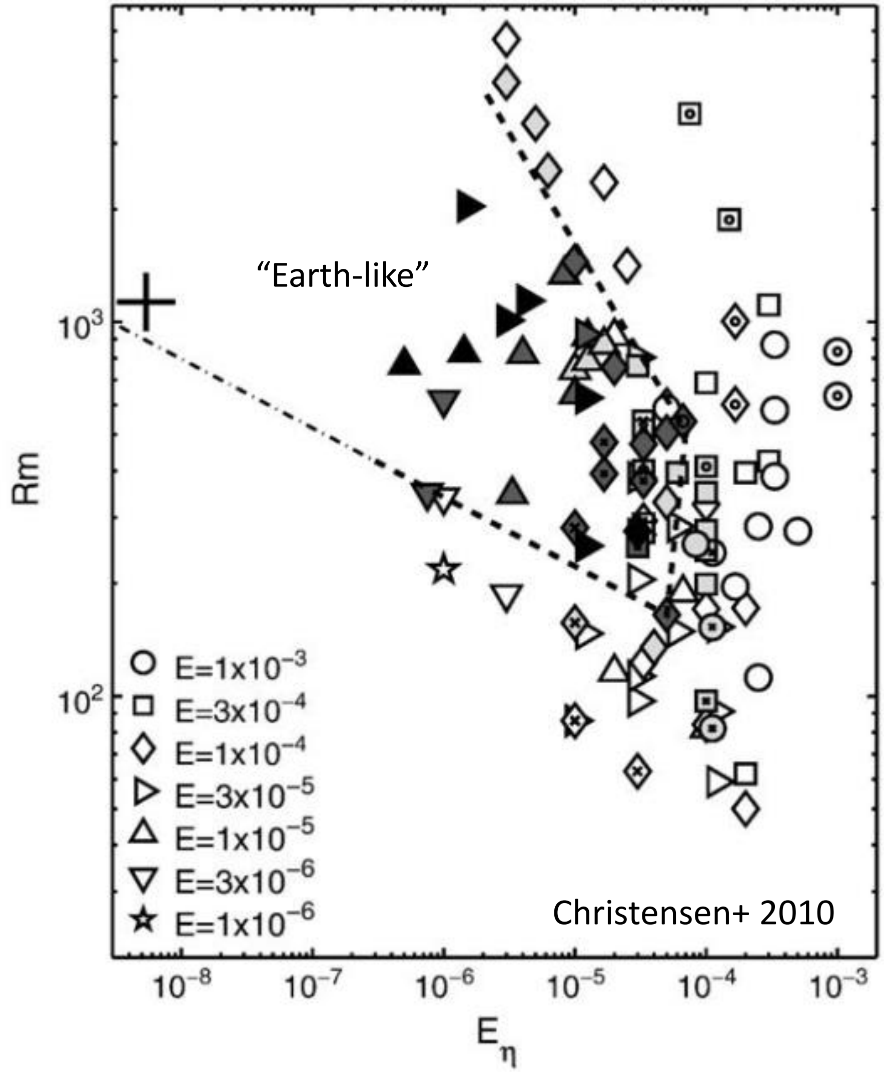
Numerical Limitations



Dynamic Similarity

- “Earth-like” dynamo criteria (Christensen+ 2010): AD/NAD, O/E, Z/NZ, Flux concentration (FCF)
- Derived from 0-7 kyr time average
- But … is modern field typical?
- Look at paleomagnetic record

How to extrapolate?



Christensen+ 2010

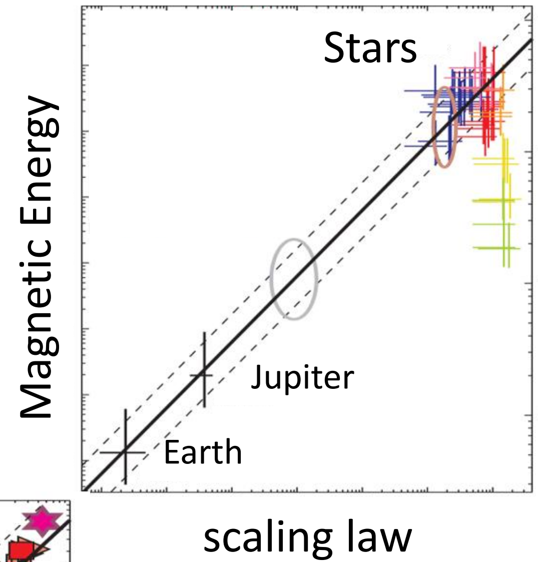
Magnetic Scaling Laws

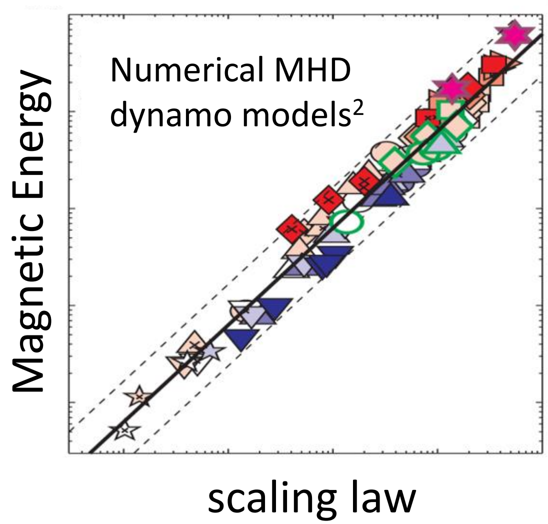
Dipole Moment Scaling Law[1] $\mathcal{M} = 4\pi R_c^3 \gamma_{dip} \sqrt{\rho_c / 2\mu_0}\, (D_c F_c)^{1/3}$

Buoyancy Flux $F_c = \frac{\alpha_c g_c}{\rho_c c_c} q_{conv} + g_i \frac{\Delta\rho}{\rho_c} \left(\frac{R_i}{R_c}\right)^2 \dot{R}_i$

Convective Heat Flux $q_{c,conv} = q_{cmb} - q_{ad}$

But… all dipolar!
At high *F_c* expect: $\gamma_{dip} \propto F_c^{-\alpha}$



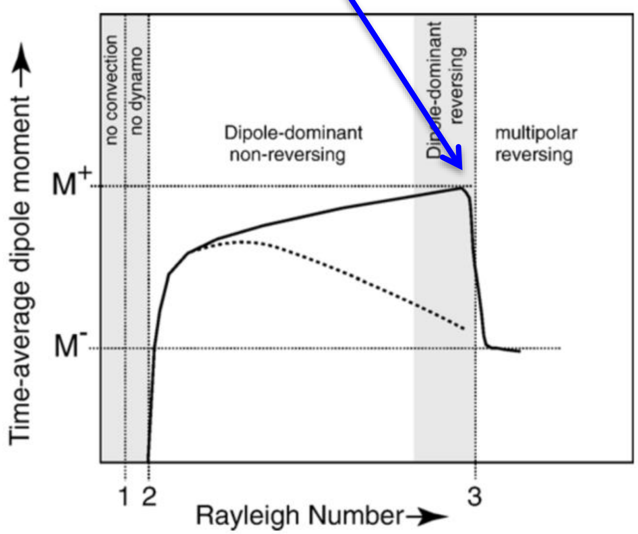


Is a dipolar dynamo expected?

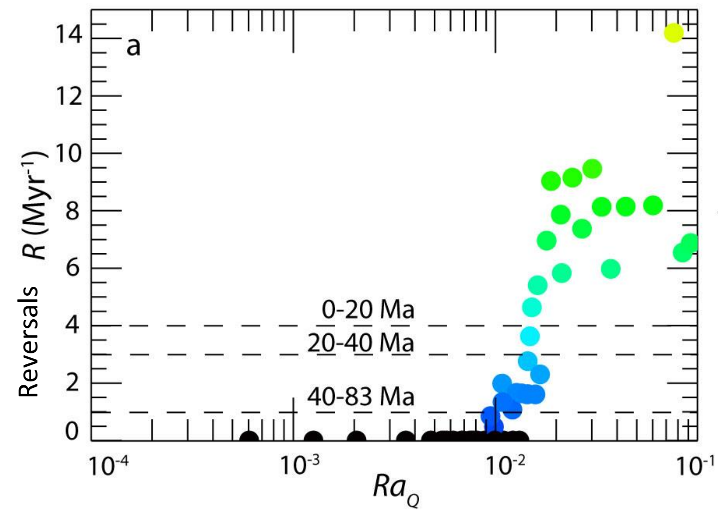
[1] Olson and Christensen (2006)
[2] Christensen *et al.* (2009)

Magnetic Regimes

Maximum dipole intensity
& Earth-like field structure
& Magnetic field reversals!



Olson and Christensen (2006)

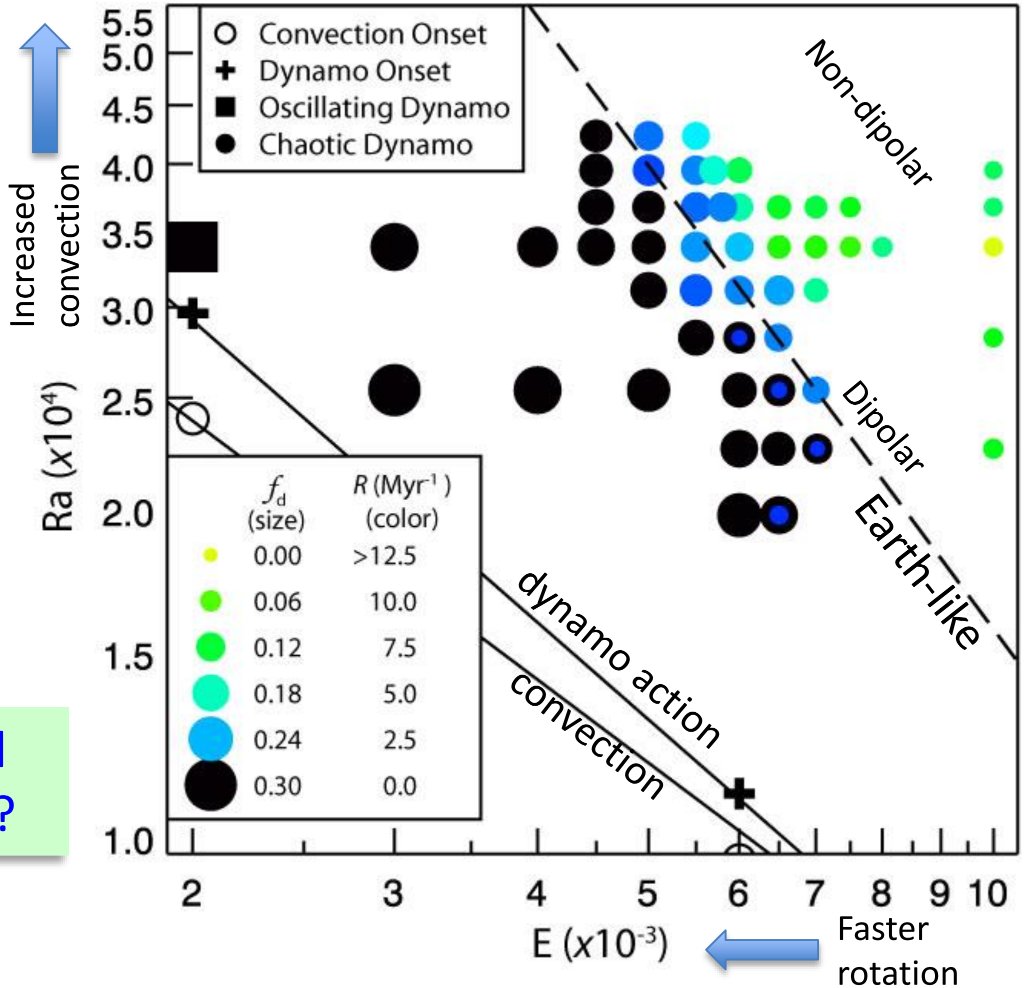


Driscoll+Olson (2009)

Dynamo Regimes

Dynamo regimes:

- Weak-field: steady/oscillating
- Strong-field: chaotic
- Dipolar
- Multipolar

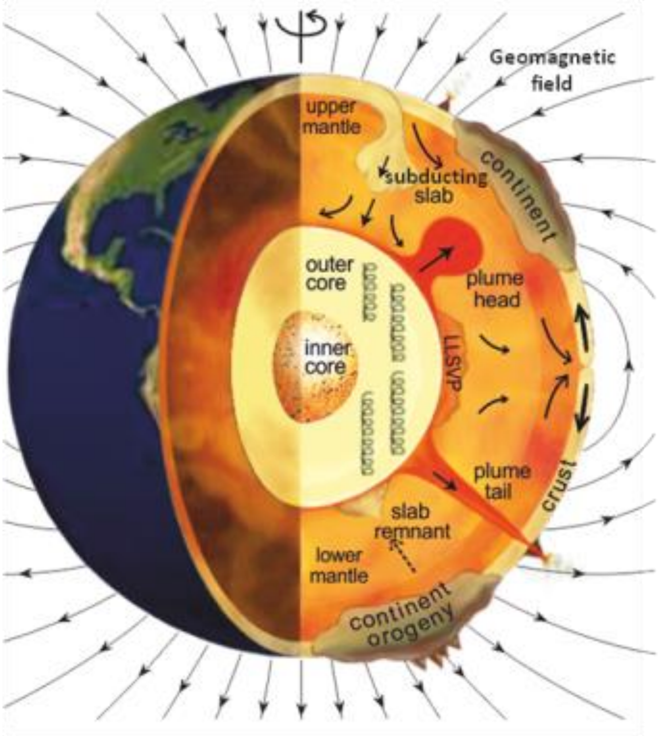


Has the geodynamo moved through regimes over time?

Driscoll and Olson, 2009

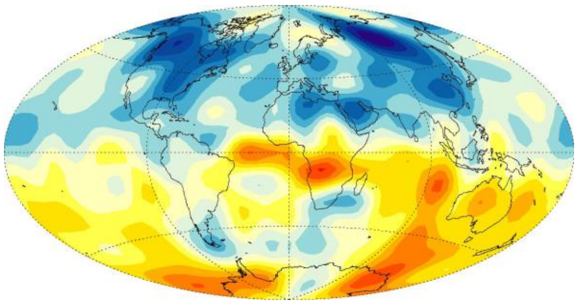
Geodynamo Timescales

- Viscous mantle (τ~100 Myr) controls core cooling rate
- Dipole decay time scale ~50 kyr
- Geodynamo contains both mantle (imposed) and core (intrinsic) timescales
- Maintained for 3-4 Gyr!
- Thousands of polarity reversals



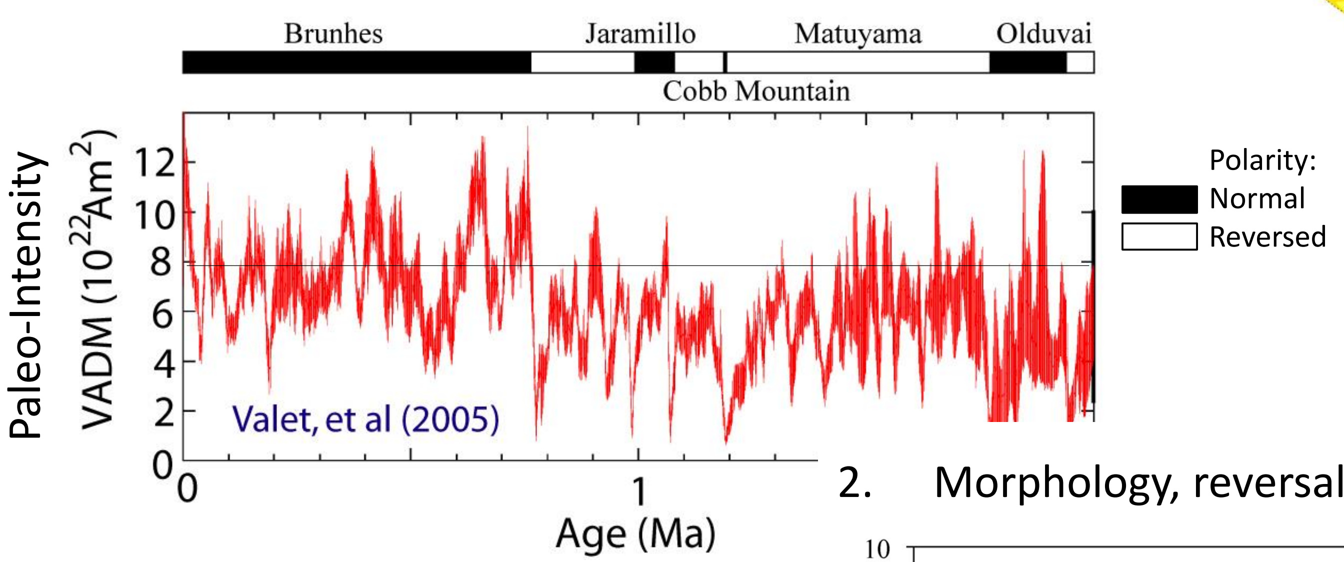
geomagnetism.org

Probing Geodynamo Evolution:

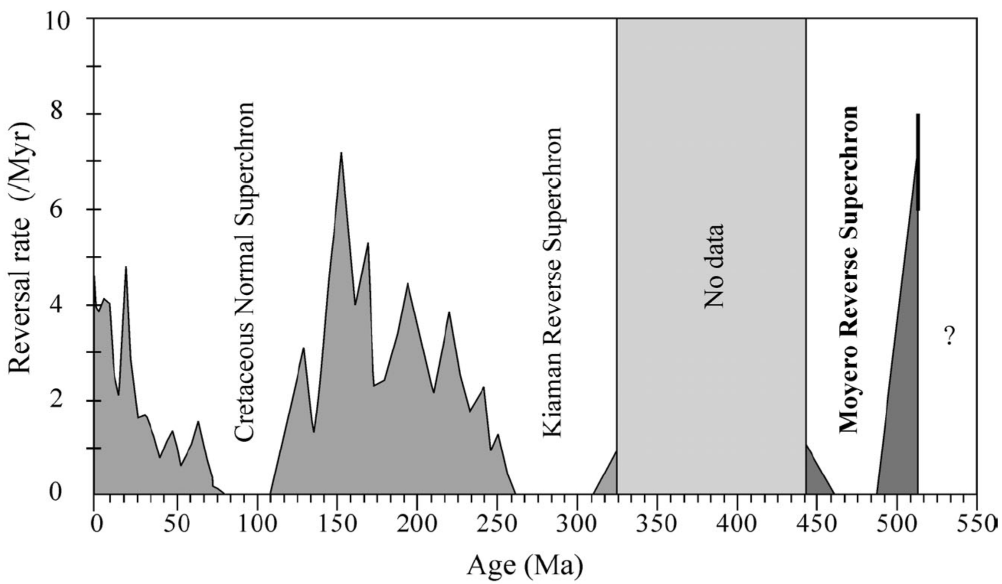


Modern B_r^{CMB}

1. Magnetic field intensity ("paleointensity")

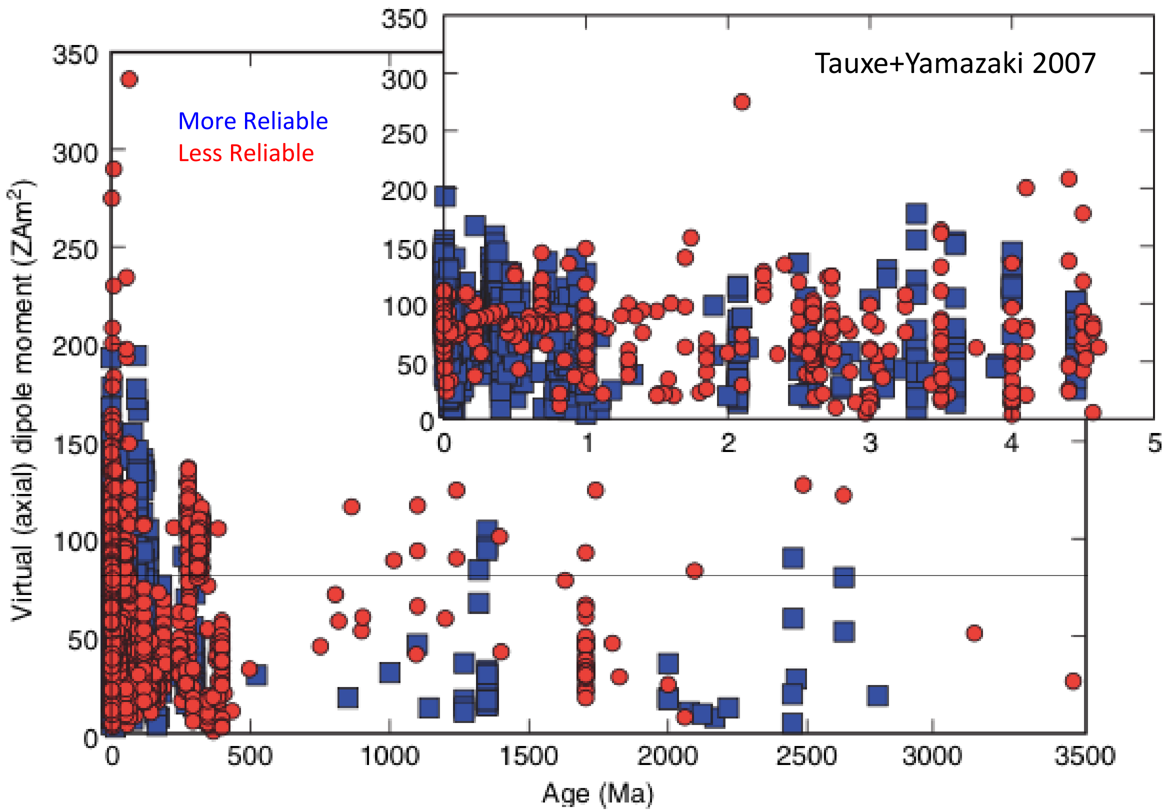


2. Morphology, reversal frequency



Paleointensity Record

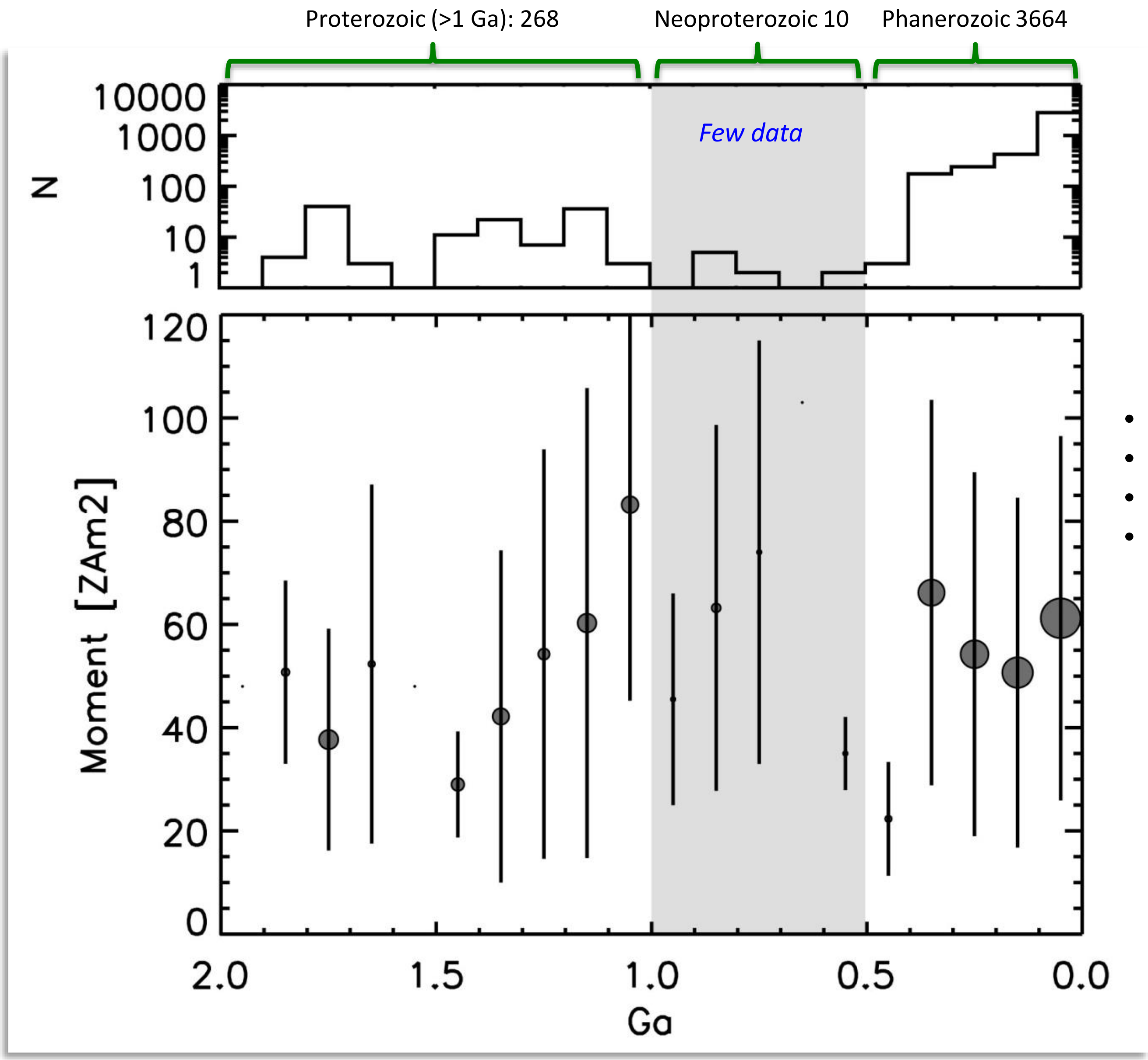
- Oldest 4.2 Ga! (possibly older than plate tectonics)
- Up to > 3x stronger than modern field
- Trend ~ flat?
- **Inner core nucleation effects?**



Is the mean paleointensity stationary??

PINT Paleointensity

Biggin et al. 2015, 2009



- Highest quality data
- 100 Myr bins
- Size proportional to N
- Error bar=stdev

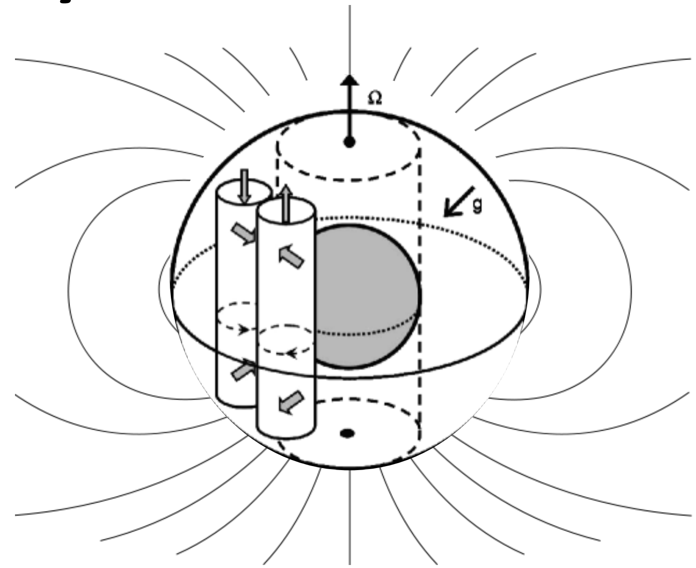
Is there a signature of inner core nucleation?

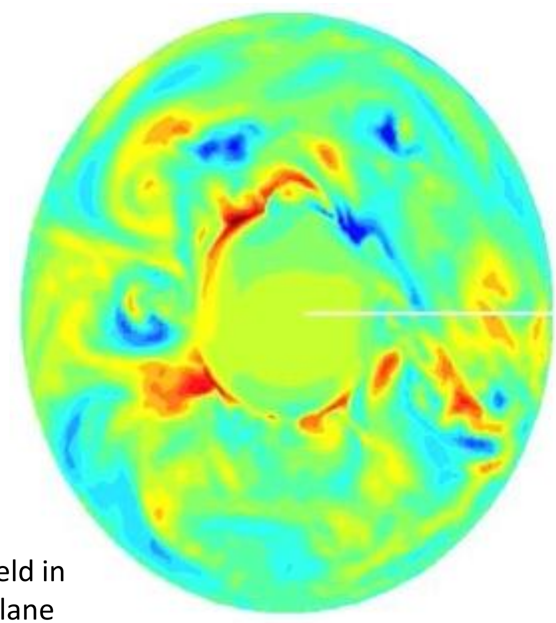
Driving the Geodynamo

1. Thermal convection:
   - CMB heat flow is super-adiabatic ($Q_{cmb}>Q_{ad}$)
   - CMB heat flow determined by *lower mantle*
   - High Fe thermal conductivity implies Q_{ad}~14 TW

2. Compositional convection:
   - Phase change (e.g. inner core growth) releases buoyancy (latent heat + light elements)
   - Requires cooling and must overcome any stratification

3. Driving Forces
   - **a.** **Top driven**: secular cooling, favors small scales
   - **b.** **Bottom driven**: inner core growth, favors large scales





Vertical Magnetic Field in Equatorial Plane

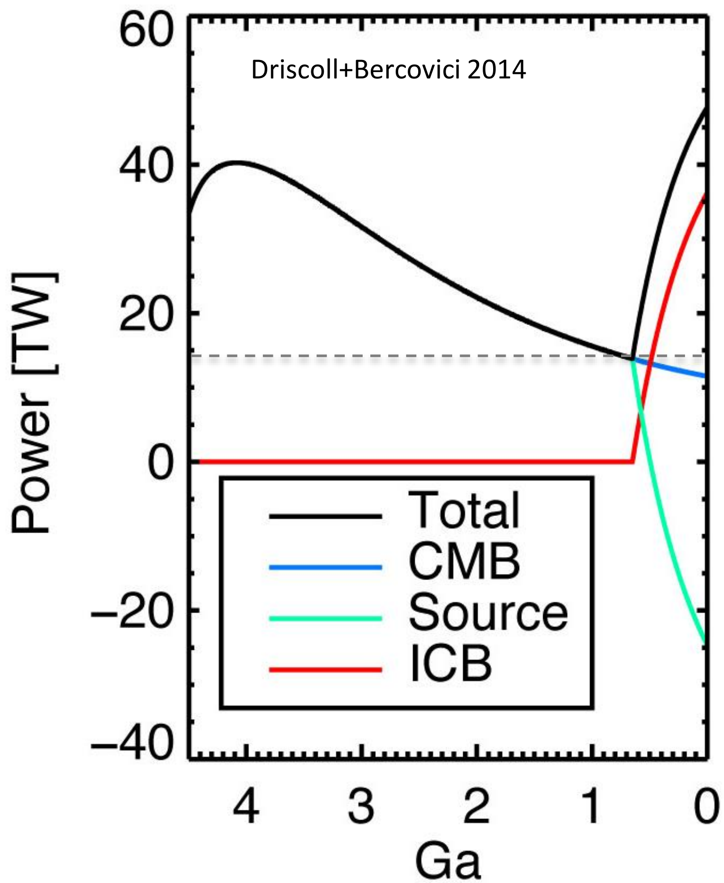
1D Thermal Evolution

- Invoke 3.5 TW radioactivity in core
- Core is thermally convective for 4.5 Gyr
- Inner core ~650 Myr old

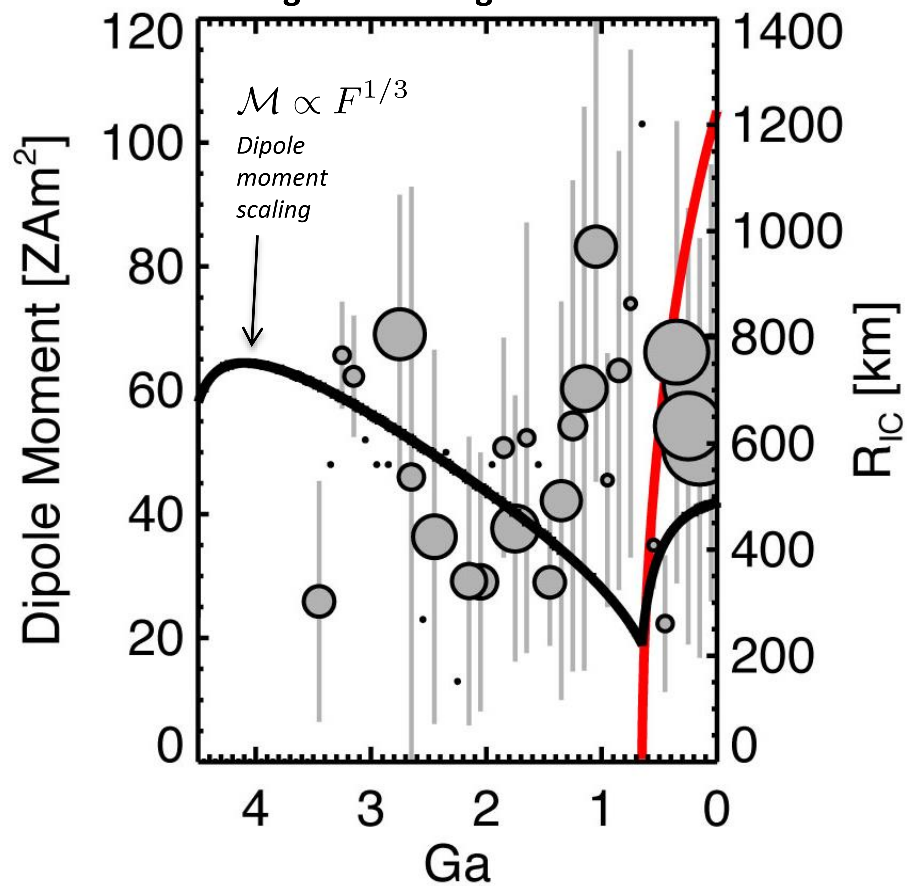
New problems:

1. Observations inconsistent with model prediction
2. Magnetic scaling *assumes* dipolar dominant field

Thermal Evolution

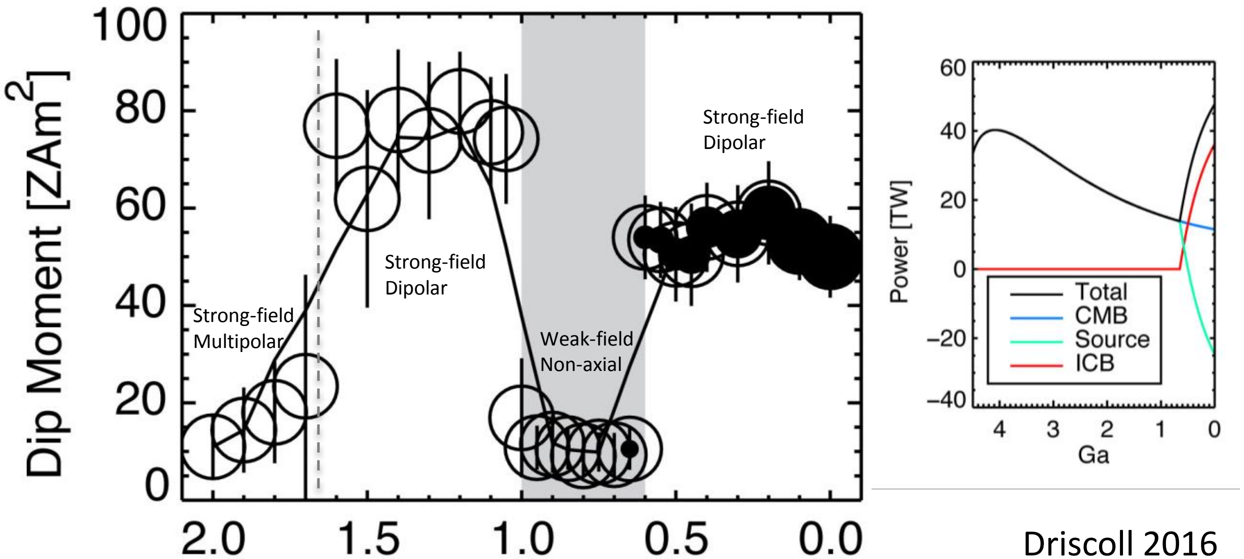


Magnetic Scaling Prediction



Evolving Numerical Dynamos

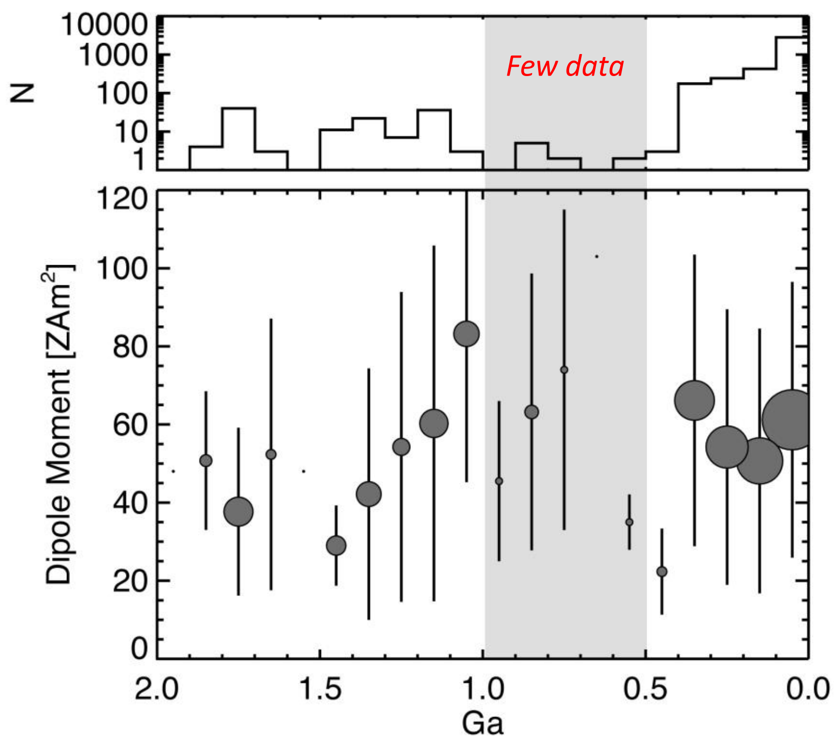
- Every 80 Myr compute numerical dynamo for 1-2 Myr
- Energetics from thermal history model
- 500 Myr long regimes



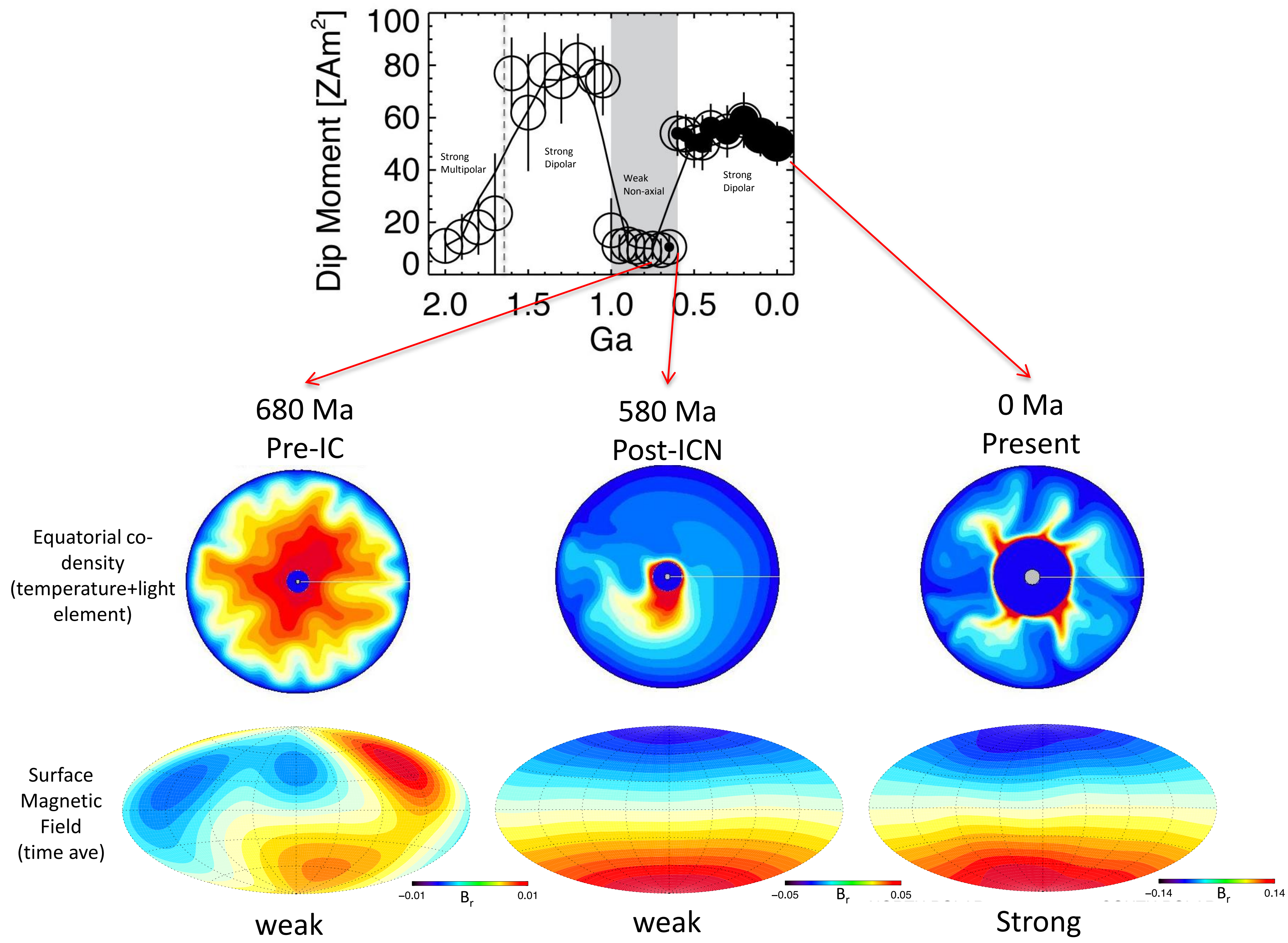
Driscoll 2016

Paleointensity

- Highest quality data
- 100 Myr bins
- Gap 0.5-1.0 Ga

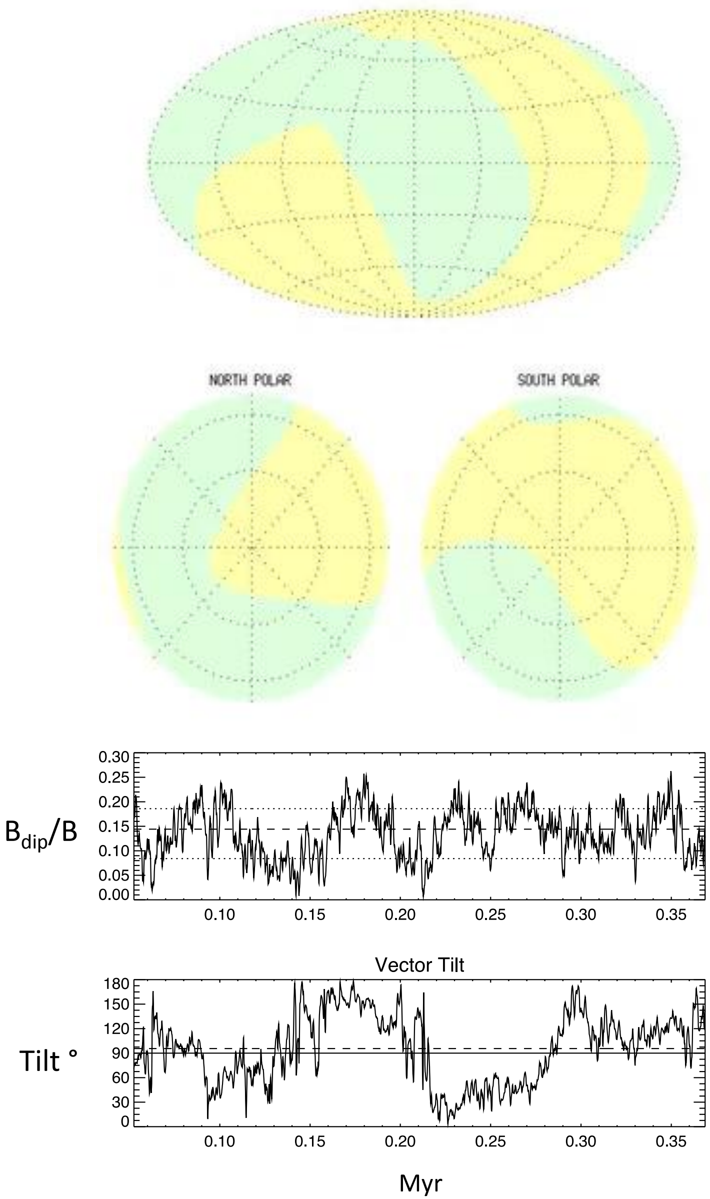


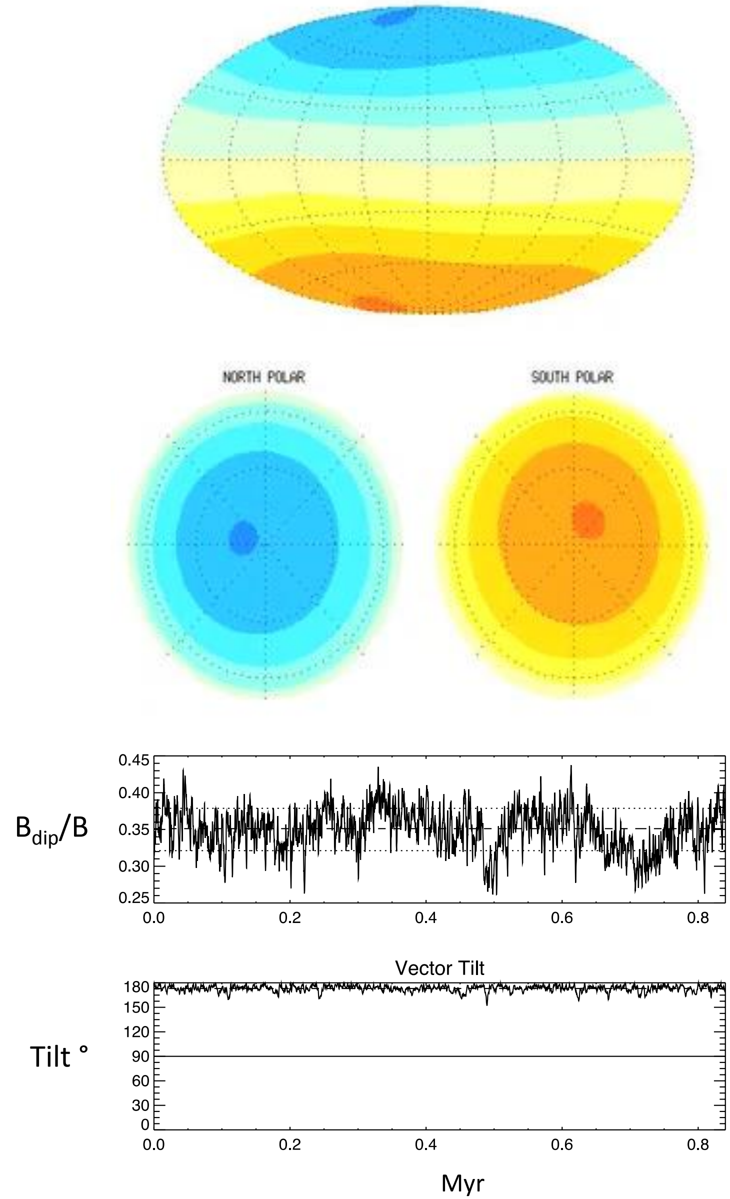
Biggin+ 2015, 2009



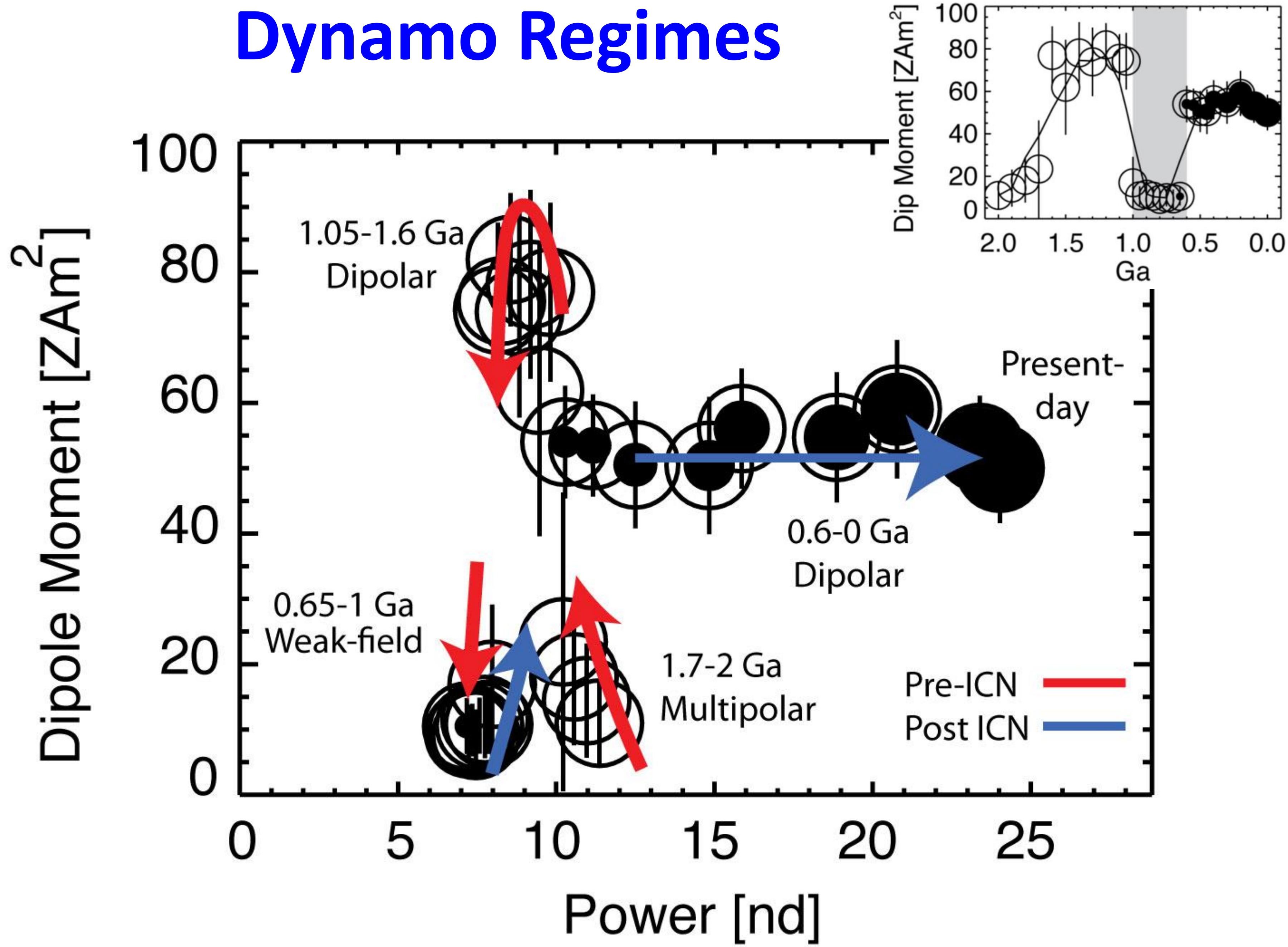
Dip Moment [ZAm^2]
100
80
60
40
20
0
2.0
1.5
1.0
0.5
0.0
Ga
Strong Multipolar
Strong Dipolar
Weak Non-axial
Strong Dipolar
680 Ma
Pre-IC
580 Ma
Post-ICN
0 Ma
Present
Equatorial co-density (temperature+light element)
Surface Magnetic Field (time ave)
−0.01
B_r
0.01
−0.05
B_r
0.05
−0.14
B_r
0.14
weak
weak
Strong

680 Ga, Prior to ICN | B_r^{SUR} | **Present-day**





Dynamo Regimes



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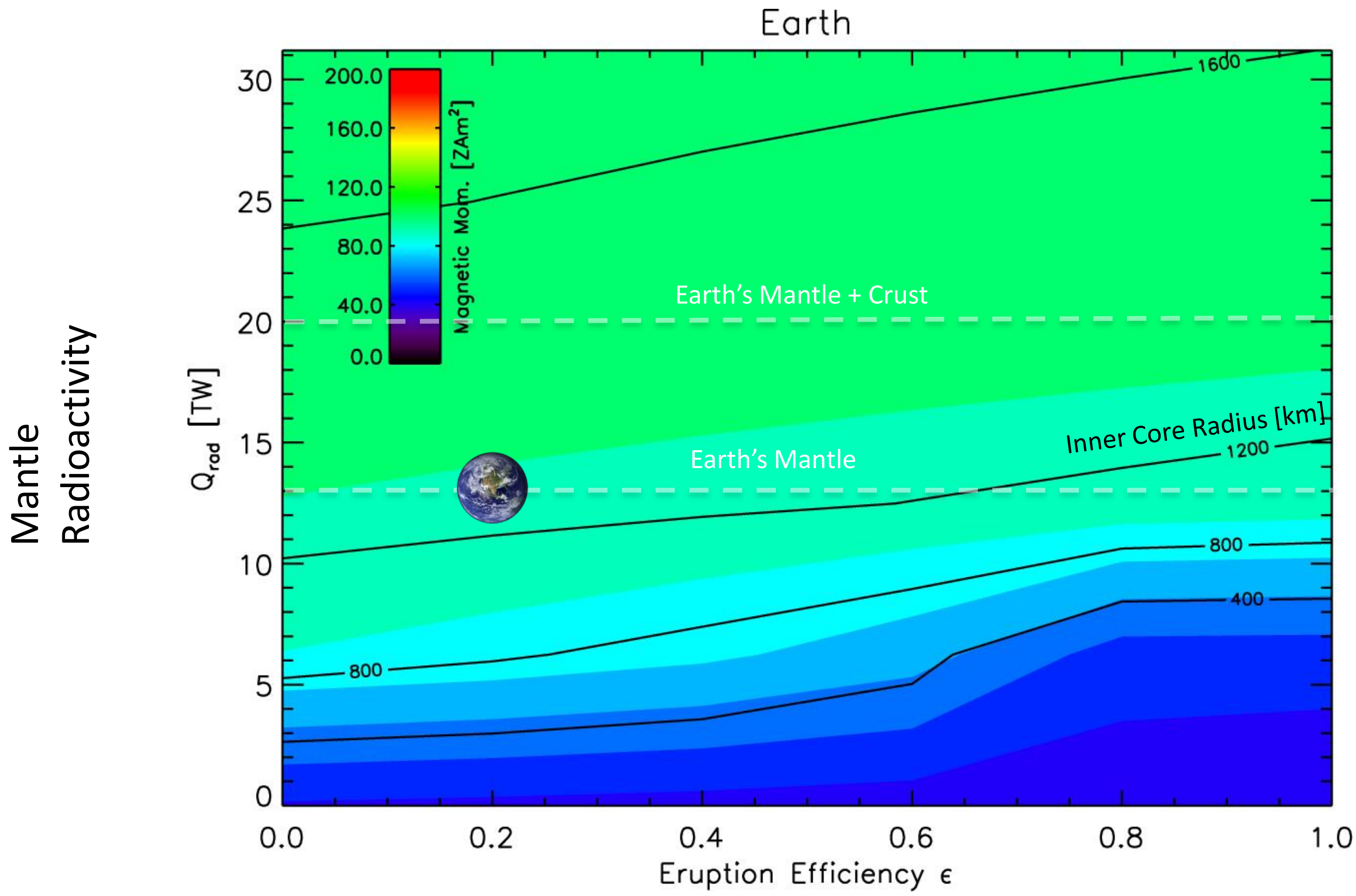
Mantle Control

How is core affected by

1. Volcanic cooling of mantle
2. Radioactivity
3. Tidal heating in mantle

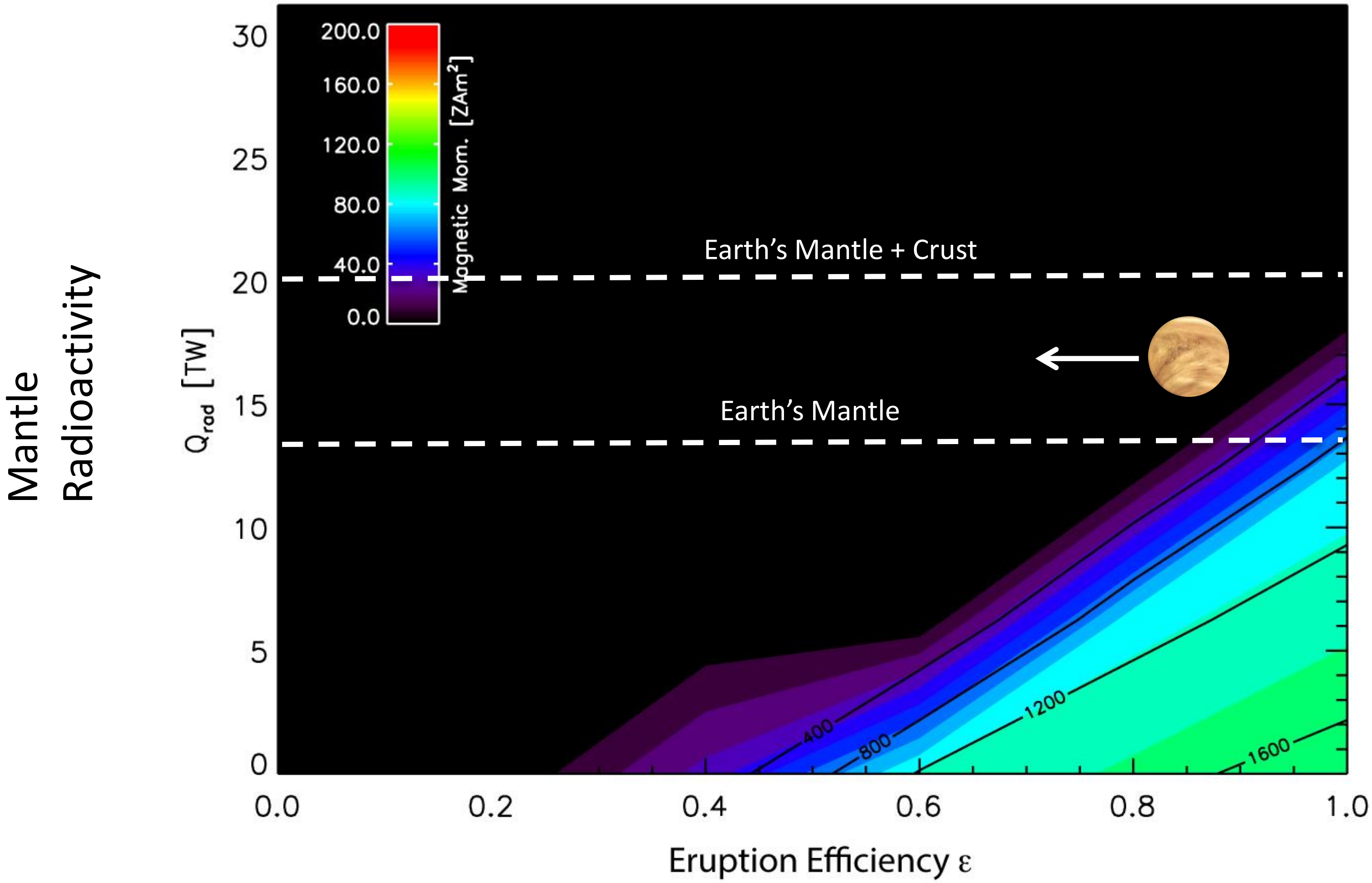
For mobile lid mantle



- Mobile lid little dependence on volcanic cooling

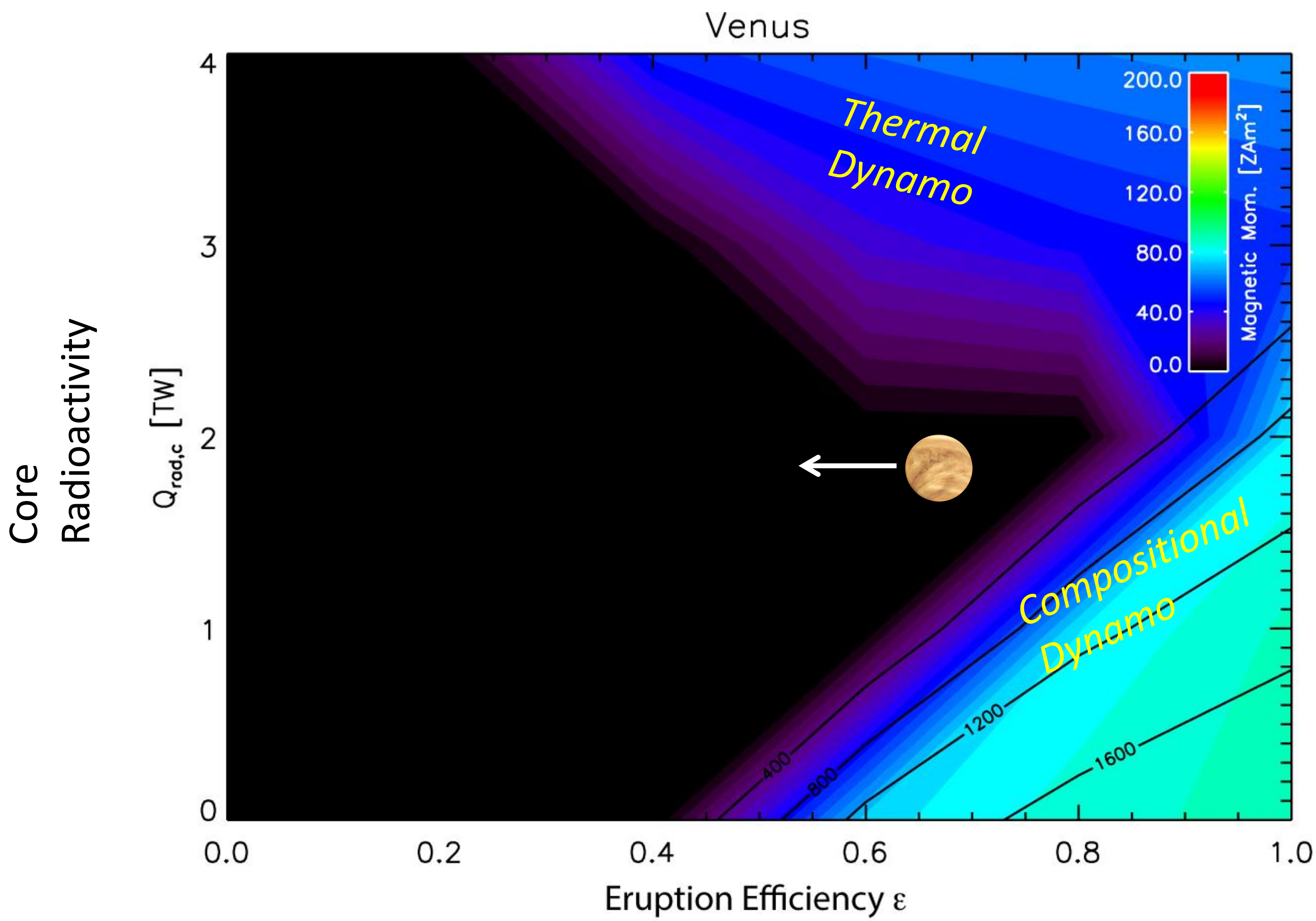
Driscoll+Bercovici (2014)

Stagnant lid mantle
(e.g. Venus)



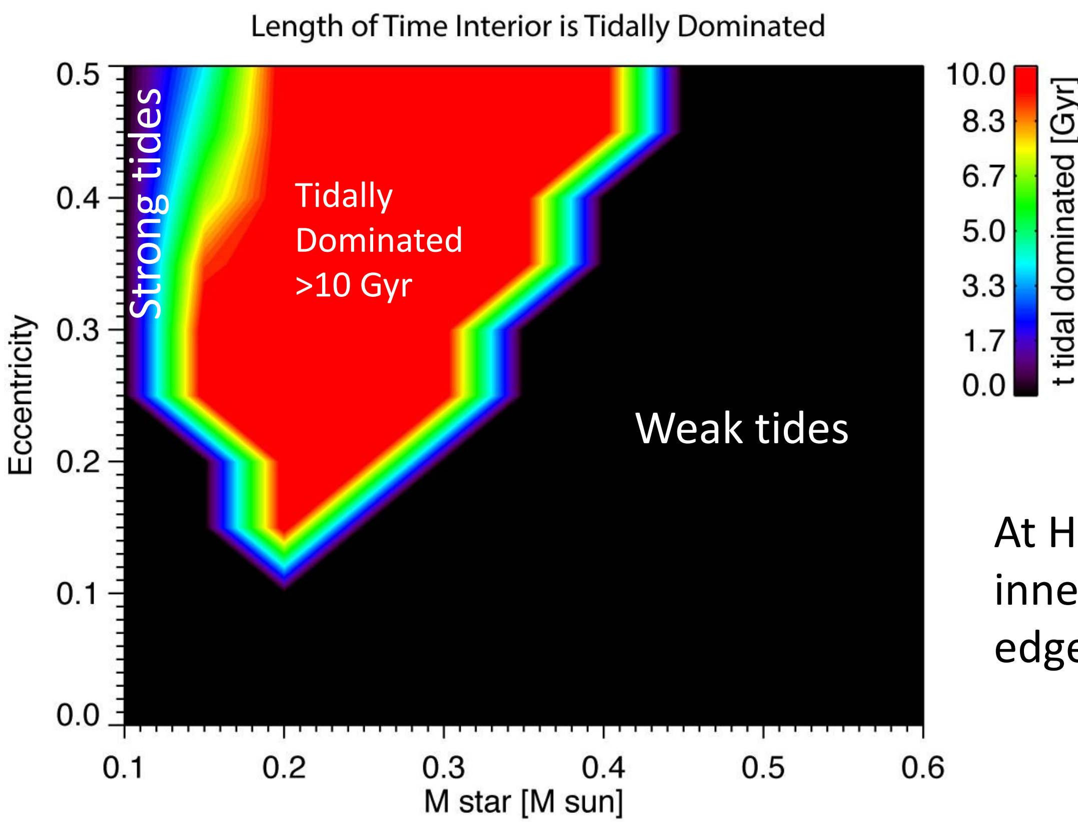
Driscoll+Bercovici (2014)

Stagnant Lid, Radioactive Core



Driscoll+Bercovici (2014)

Tidal heating in mantle:
How long is inner edge of HZ tidally dominated?

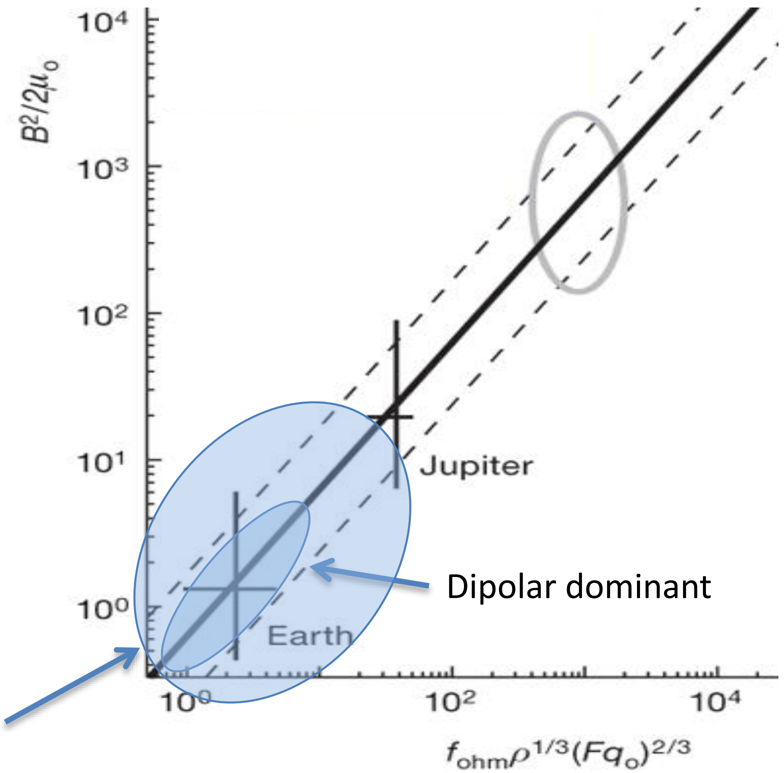


At HZ inner edge

- Tidal dissipation is stronger function of orbital distance (α $a^{-15/2}$) than stellar mass (α $M_*^{+5/2}$)
- So inner edge around low mass stars experiences stronger tides, fast circularization
- Tides are stronger function of M_{star} and *a* than circularization rate
- Tides dominate for 0.15-0.4 M_{sun} and e>0.1!

Driscoll+Barnes (2015)

Terrestrial Exodynamo Speculation



Magnetic Energy

Energy Flux

Multiple regimes
Time variable

Summary

1. Scaling laws predict dipole dominated dynamos depend only on energy flux
2. Multiple dynamo regimes exist around dipolar state
3. Geodynamo may have passed through weak-field state
4. Long-lived dynamo may rely on compositional convection
5. Volcanic heat loss can power a core dynamo beneath a stagnant lid
6. Tidal heating in mantle can stymie dynamos around 0.3 M_s stars
7. Expect *exodynamos* to occupy a myriad of dynamo states, difficult to infer tectonics