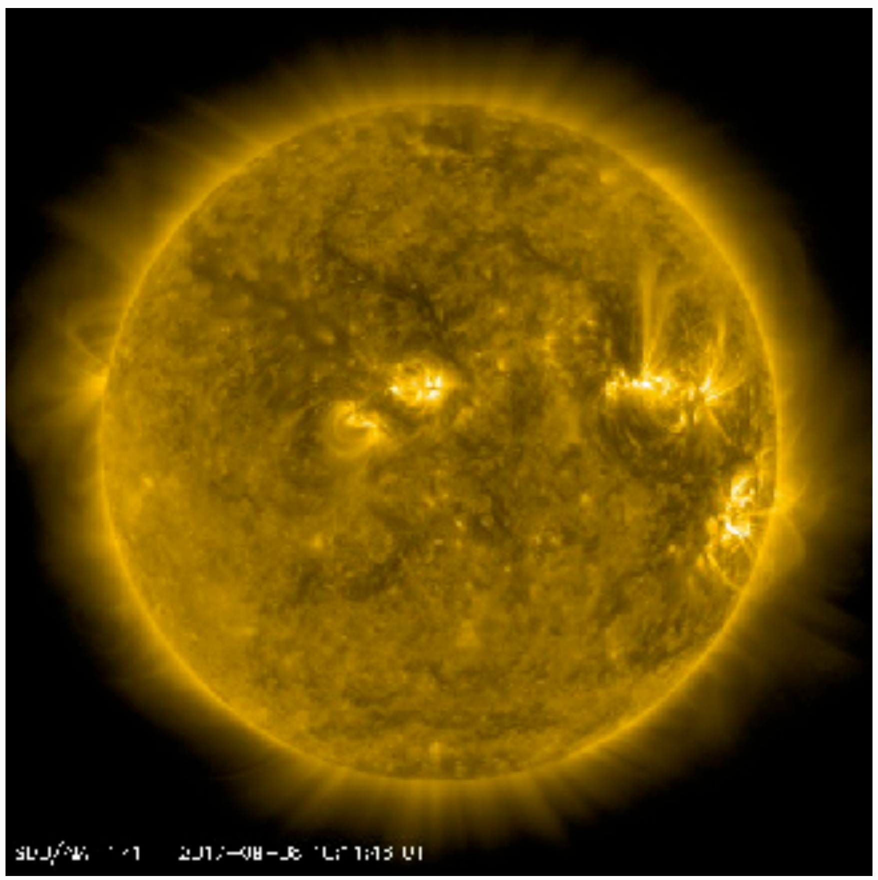
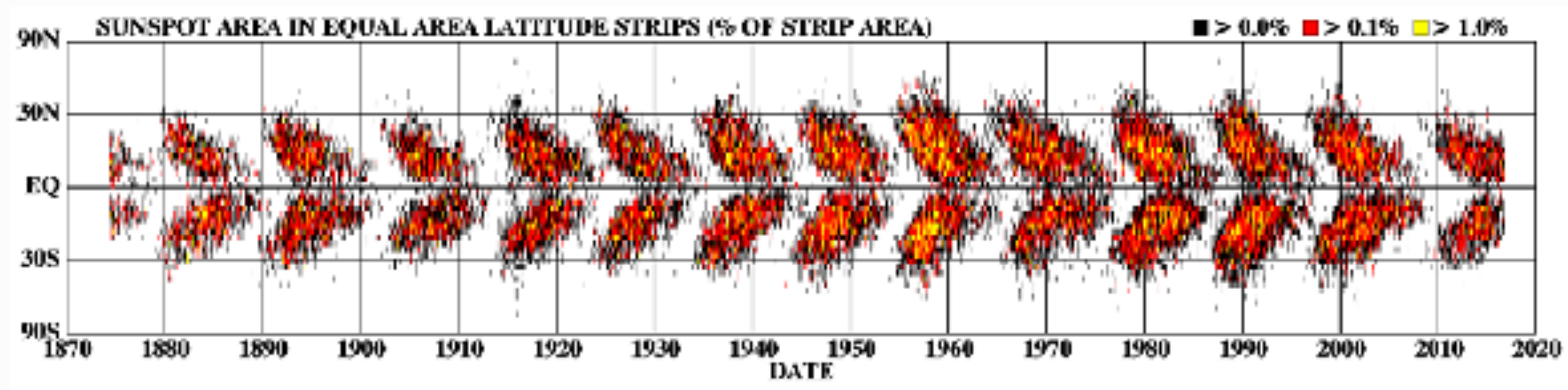
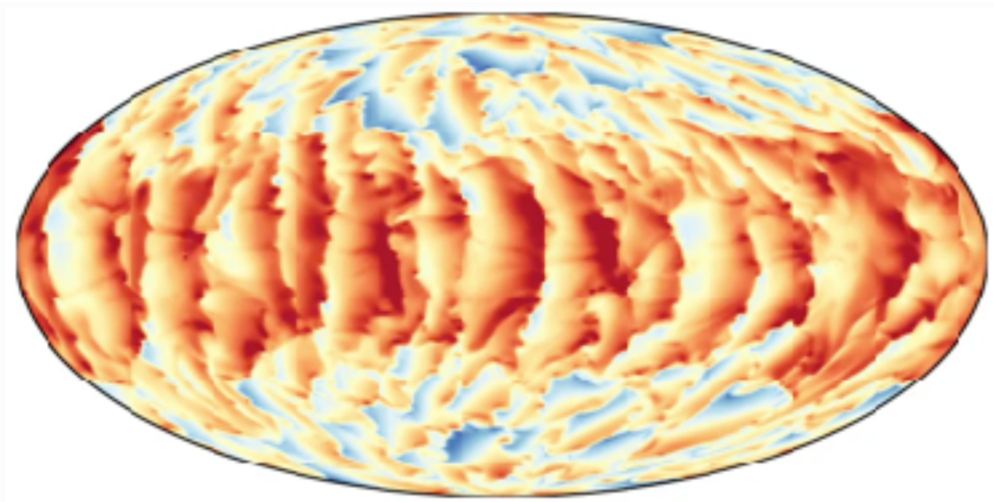
STELLAR MAGNETISM: ORIGINS, EFFECTS, ENIGMAS







MATTHEW BROWNING, LAURA CURRIE, LUCIA DUARTE, MARIA WEBER, FELIX SAINSBURY-MARTINEZ, LEWIS IRELAND

+ FRIENDS ELSEWHERE (NICK FEATHERSTONE, MARK MIESCH, SACHA BRUN...)

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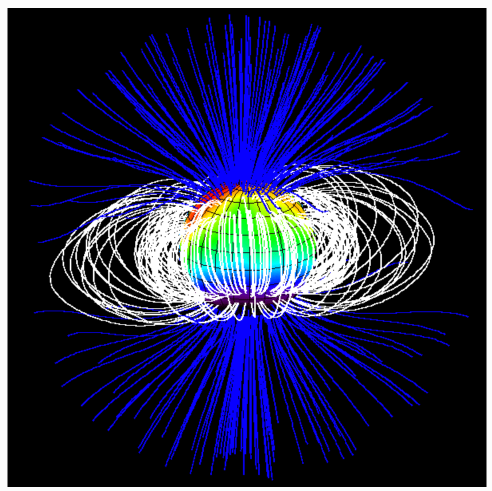
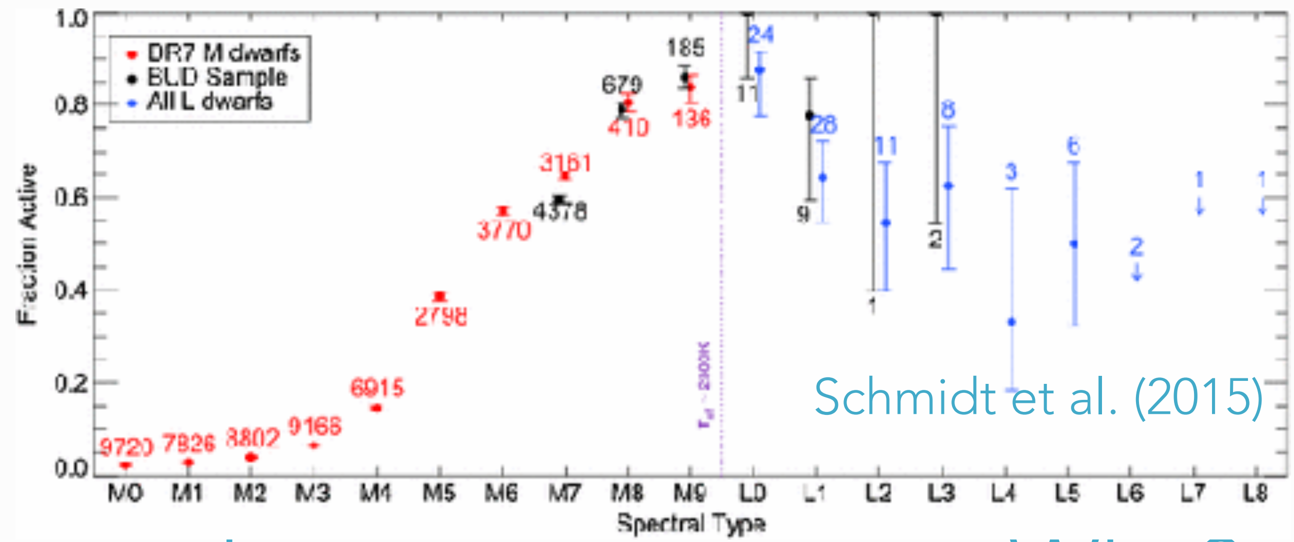
SOME MOTIVATING QUESTIONS FOR TODAY

Some stars have strong B fields; others don't. Why?

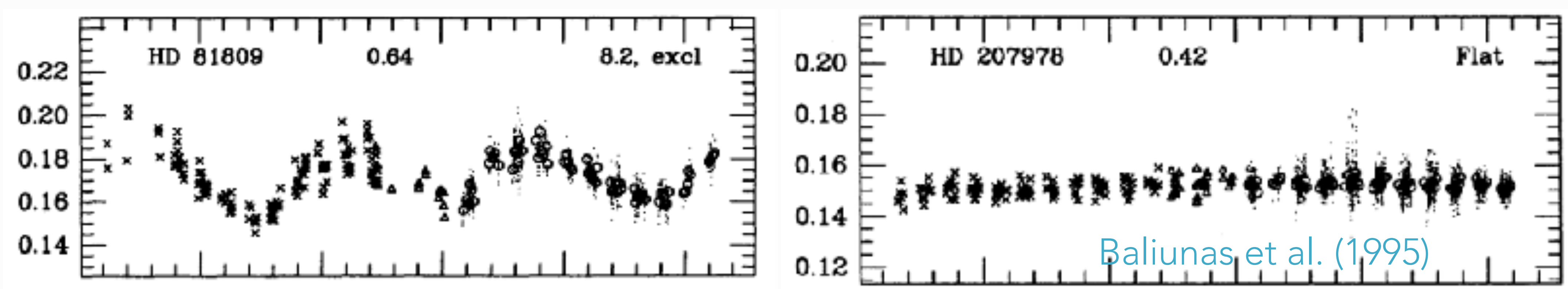


Donati et al. (2006)



Schmidt et al. (2015)

Some stars have clear cycles; others seem not to. Why?



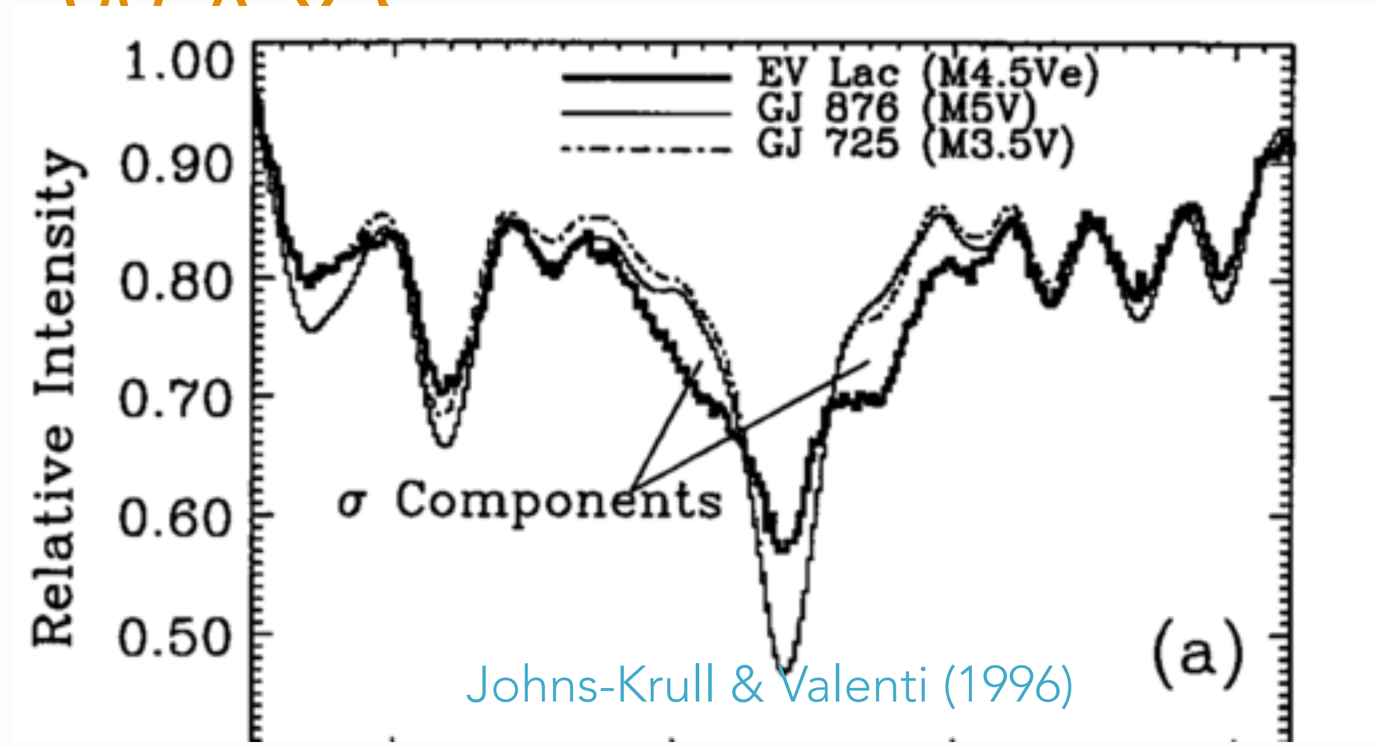
Baliunas et al. (1995)

How is a star's life shaped by magnetism?

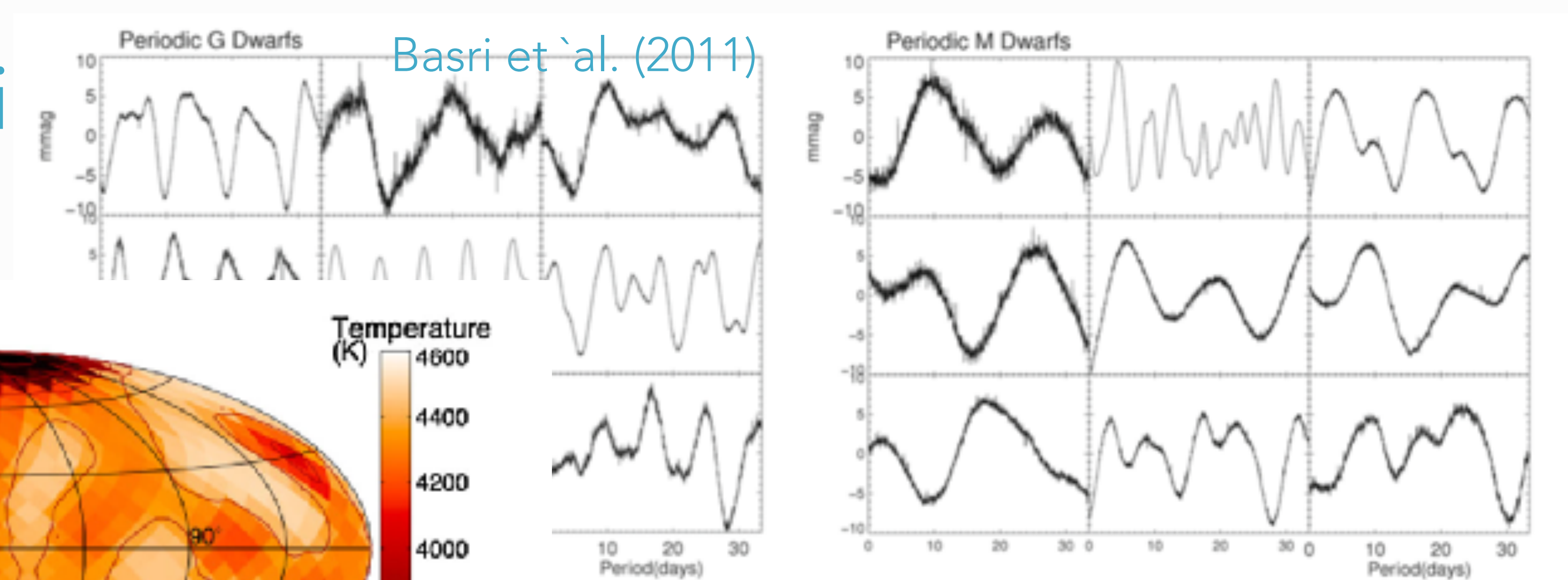
YOU CAN DETECT MAGNETISM IN A VARIETY OF WAYS

Astro 101: measure flux

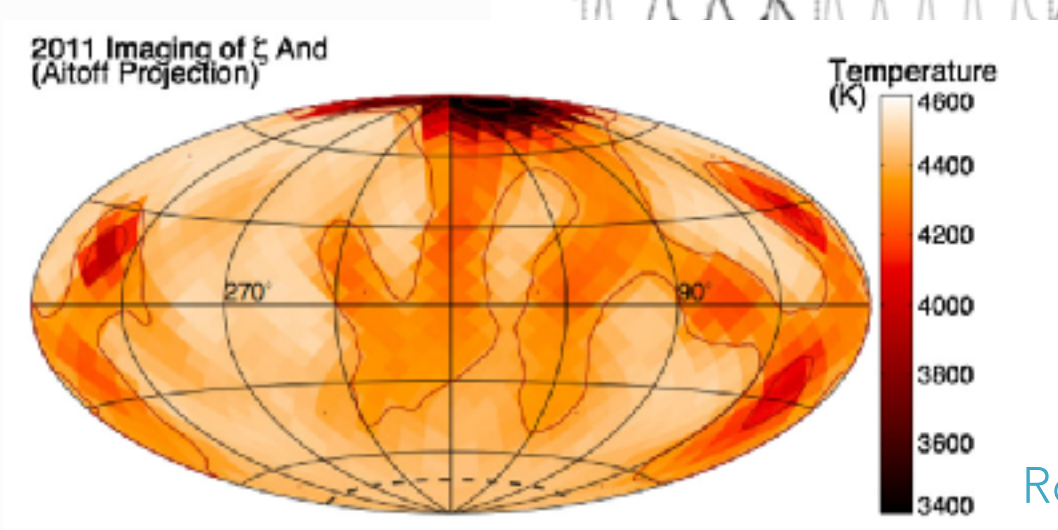
- as function of wavelength
- as function of time
- as function of positi
- (plus po



Johns-Krull & Valenti (1996)

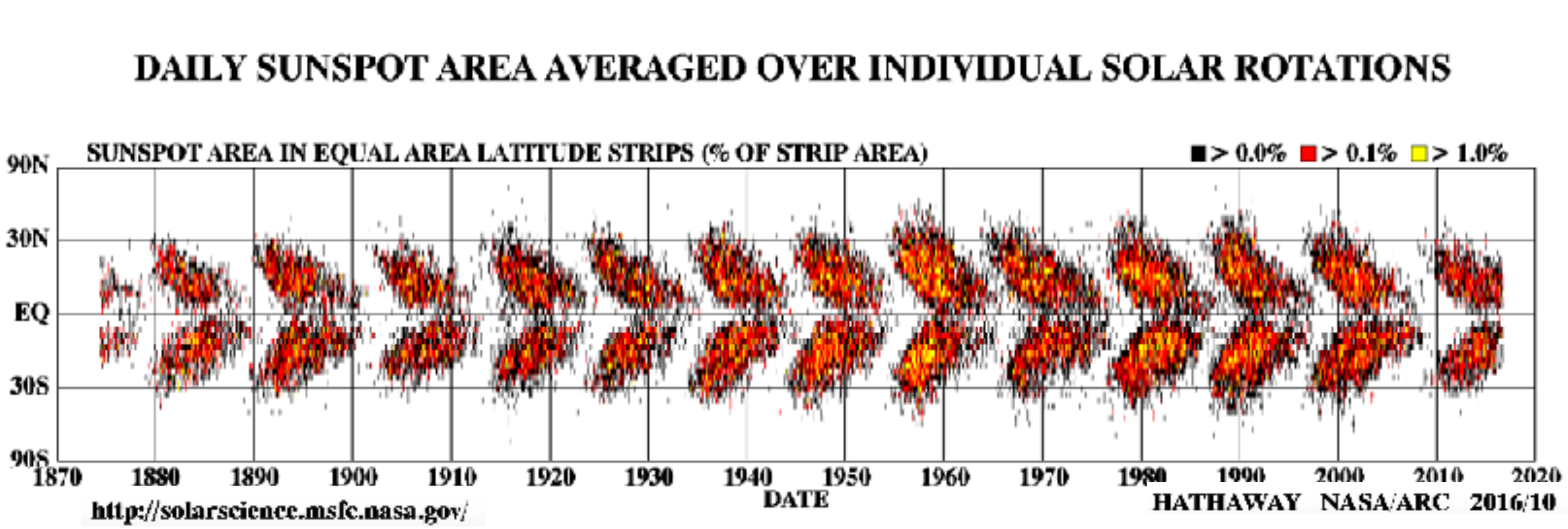


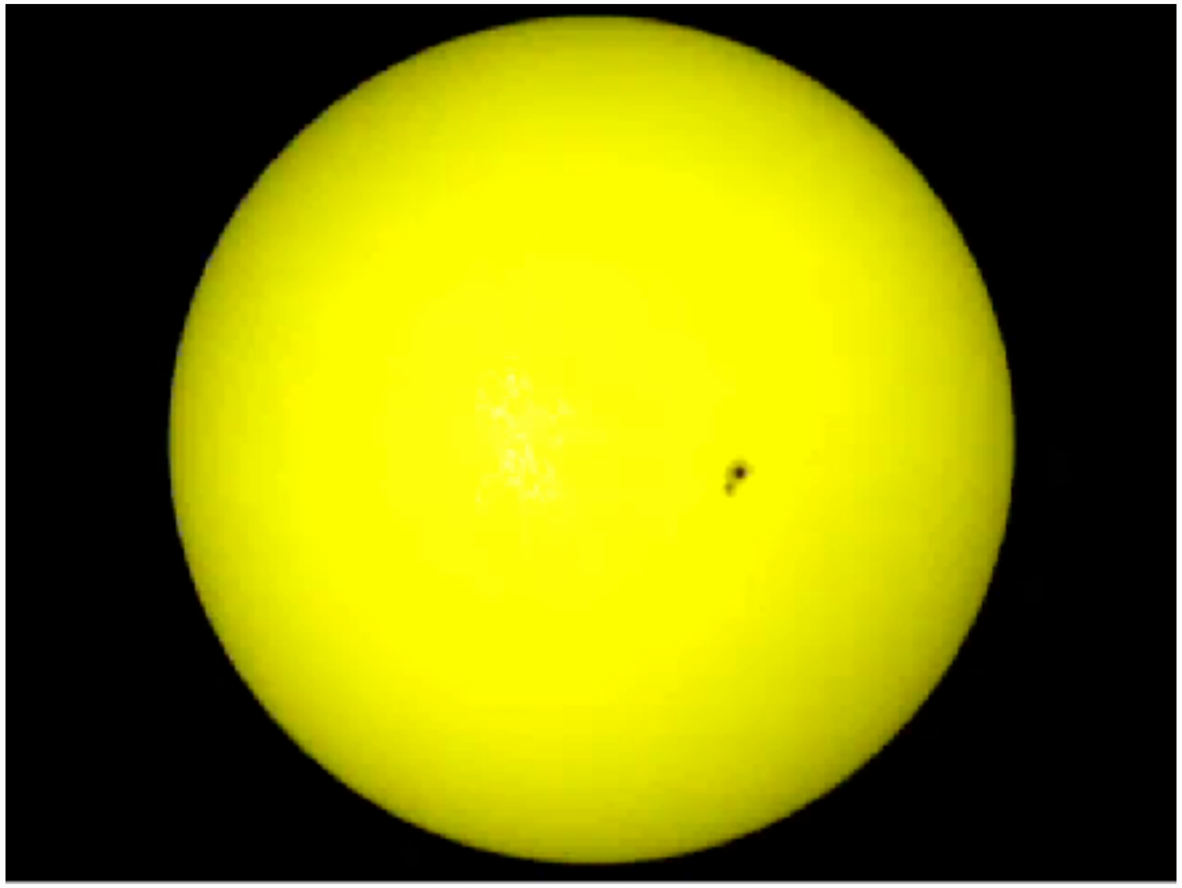
Basri et `al. (2011)



Roettenbacher et al. (2016)

THE SUN: ORDER AMIDST CHAOS





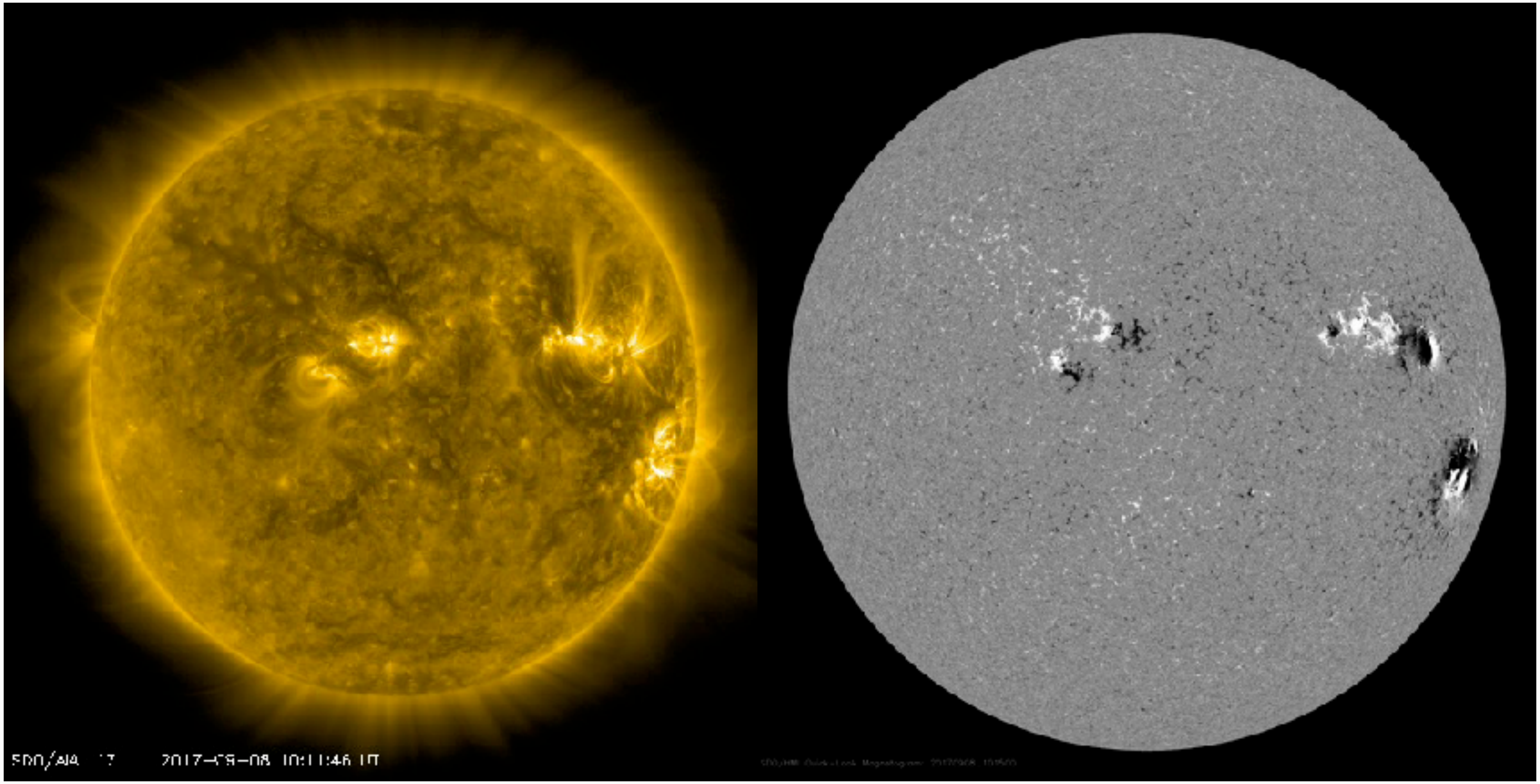
Solar interior is turbulent

(anything/diffusivity = big)

How do you build *ordered* fields?

Full disk: SOHO/MDI. Close-up: Hinode (SOT)

MAGNETIC FIELDS CONTRIBUTE TO HEATING OF STELLAR ATMOSPHERES



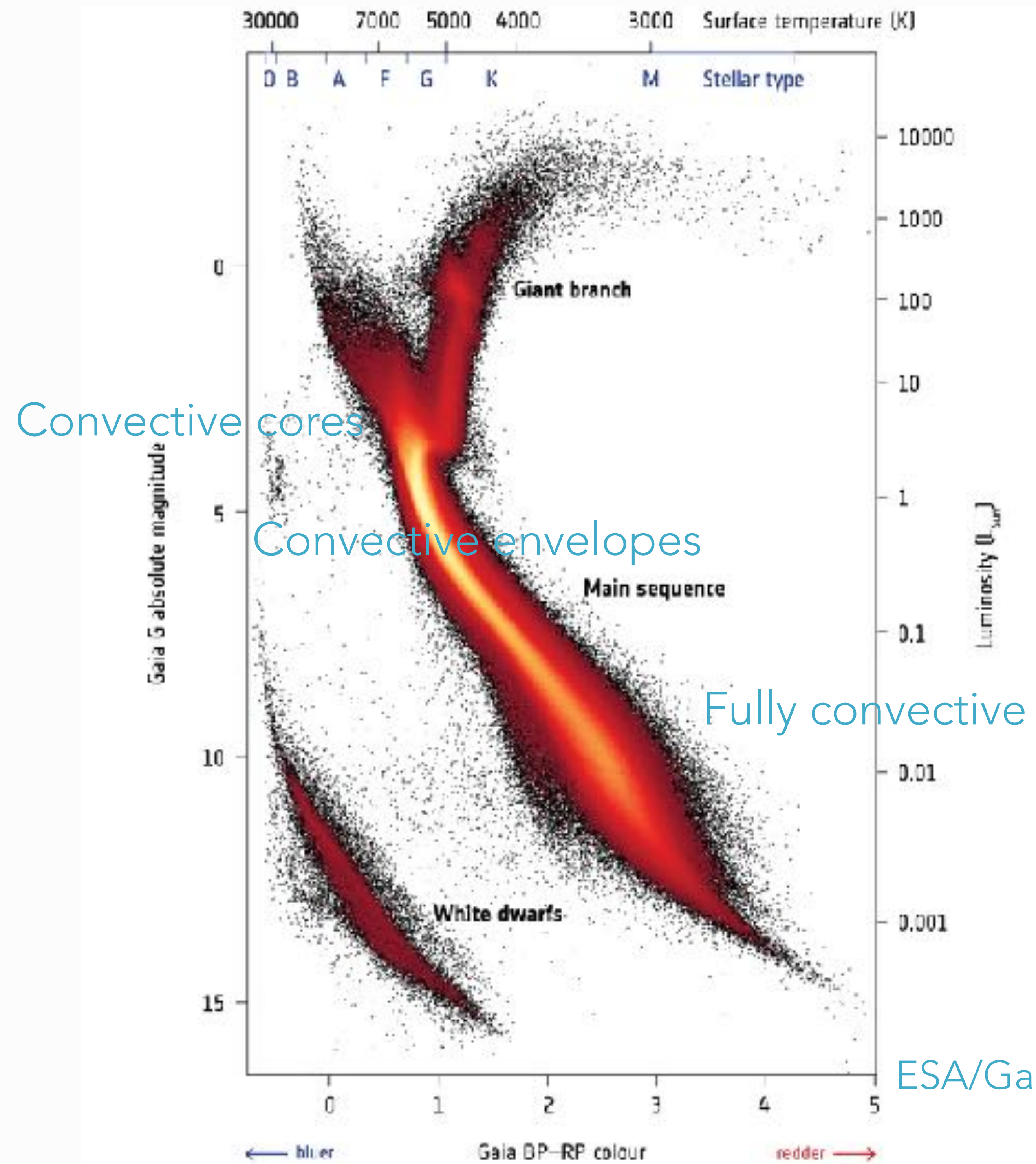
High-energy emission magnetogram

(Solar Dynamics Observatory: AIA 171, HMI, Sept 8-10, 2017)

Physical picture: fields linked to heating

SURFACE CONVECTION AND MAGNETISM ARE LINKED

- Convection in envelopes, cores, or full interiors
- Magnetism often found where you have surface convection (exceptions: Ap/Bp)

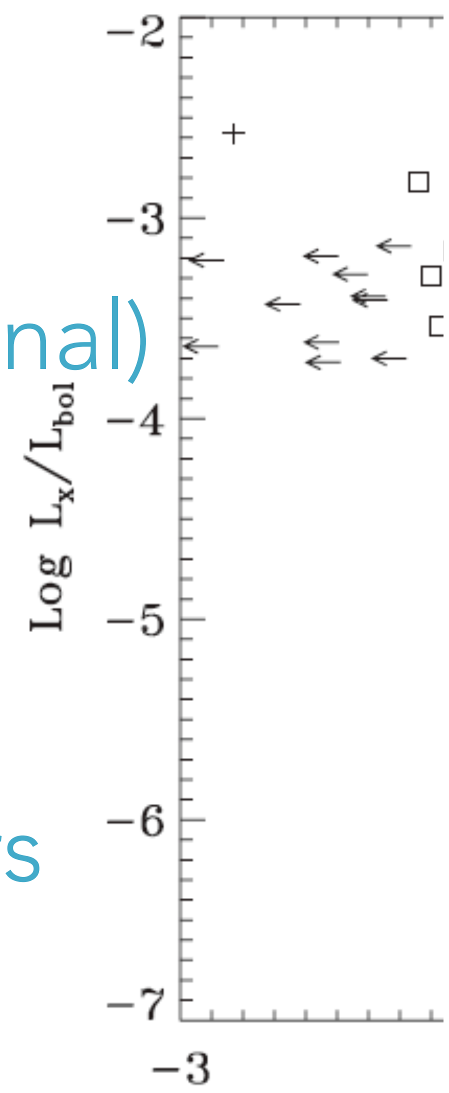


ESA/Gaia/DPAC

SURFACE MAGNETISM IS RELATED TO STELLAR ROTATION RATE

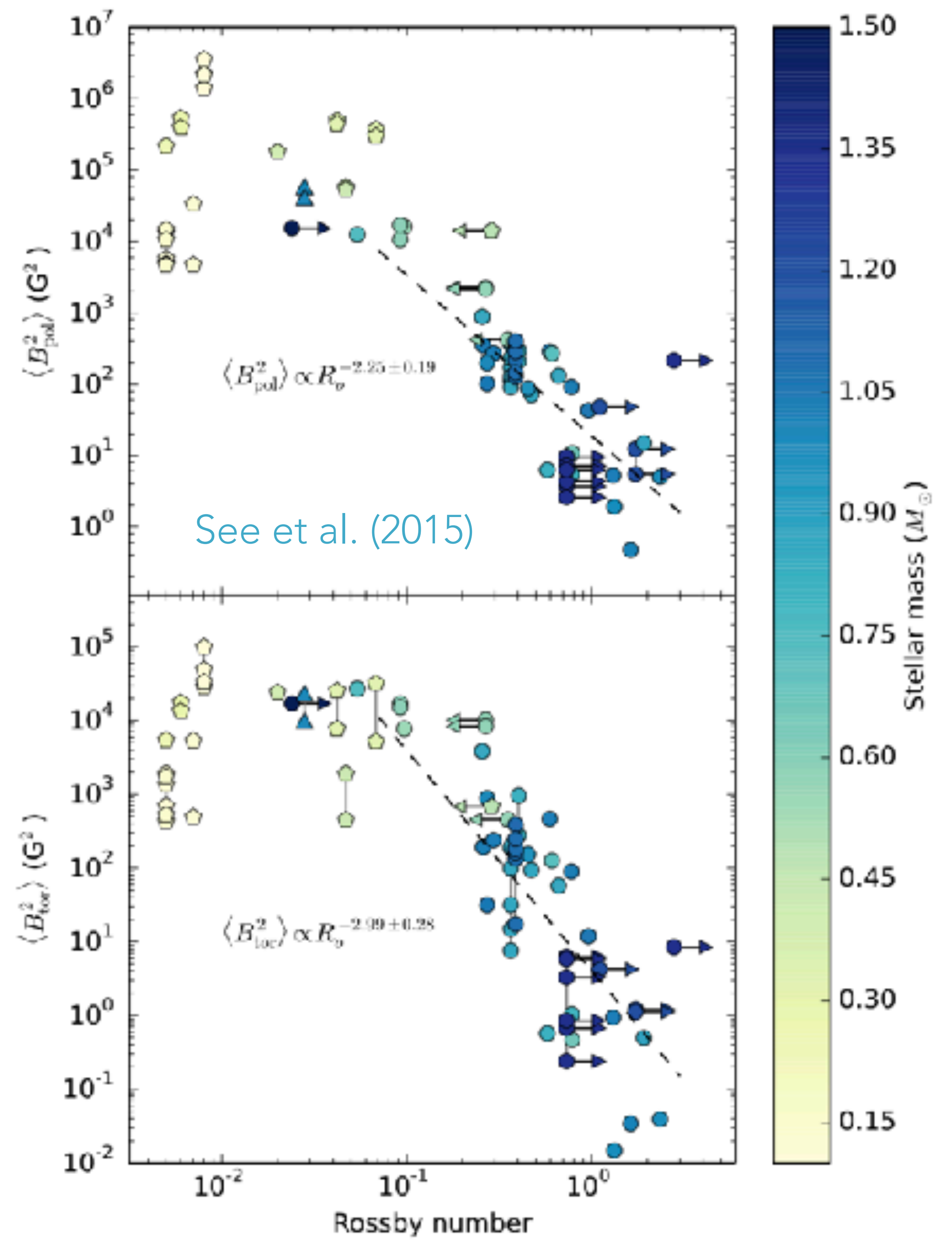
Activity

(here, coronal)



Observed in many stars

More rapid rotation=
more activity (to a point)



See et al. (2015)

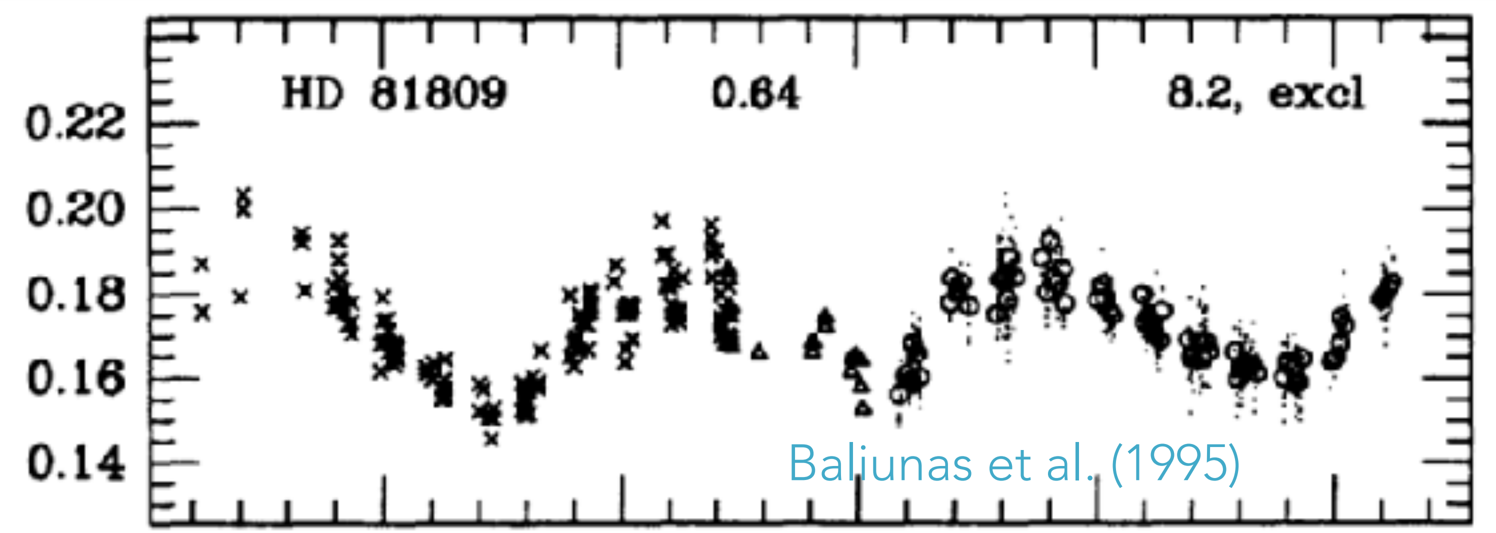
SOME STARS EXHIBIT MAGNETIC CYCLES, WITH (ROTATION-DEPENDENT) PERIODS

Long-term monitoring needed!

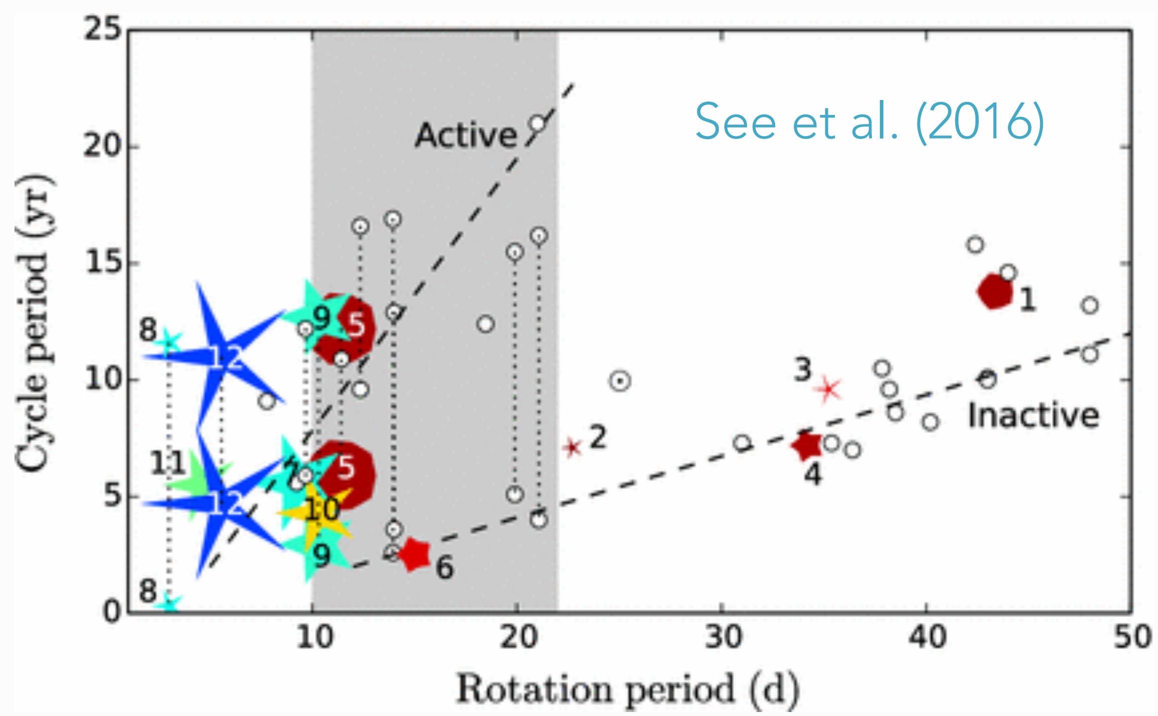
Mt Wilson Observatory HK project

Lowell Observatory SSS project

see, e.g., review in Hall (2008)



Baliunas et al. (1995)



See et al. (2016)

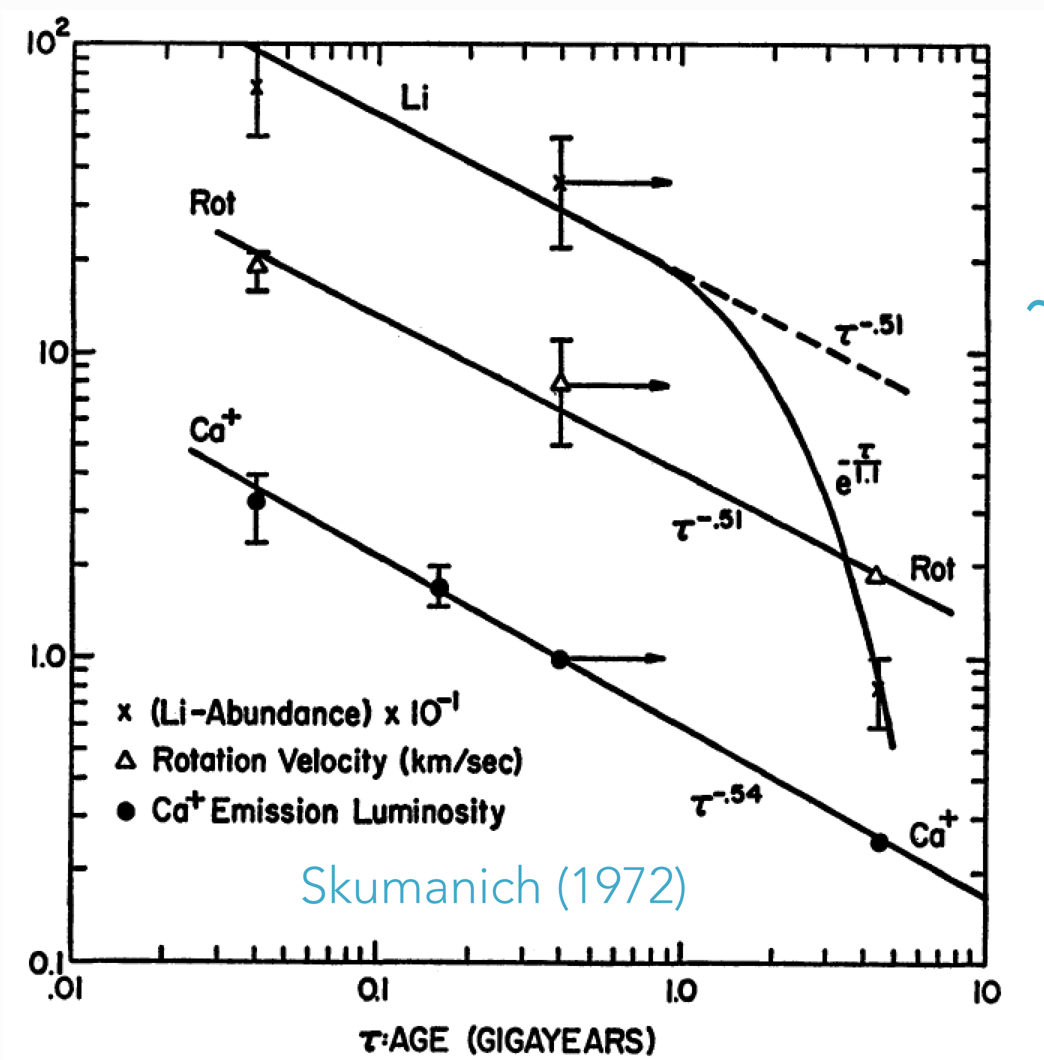
Relation between cycle period and rotation rate: it's complicated (see Egeland talk)

see, e.g., Saar & Brandenburg (1999); Bohm-Vitense (2007); Reinhold et al. (2017); Egeland (2017)

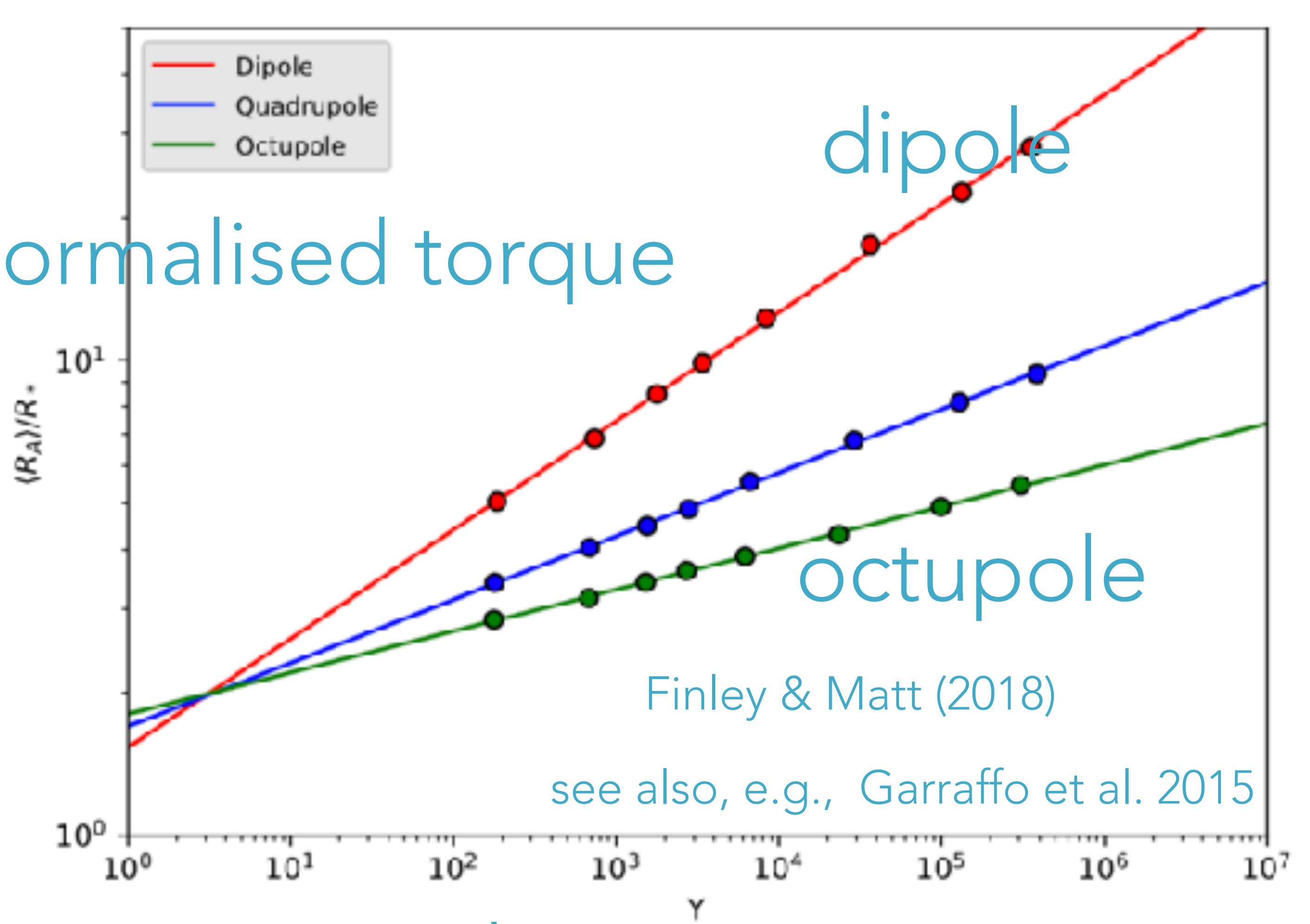
MAGNETISM FEEDS BACK ON A STAR'S ROTATIONAL EVOLUTION

Stars lose mass and angular momentum over time

Magnetic field strength and morphology both affect this



Skumanich (1972)



~Normalised torque

dipole

octupole

Finley & Matt (2018)

see also, e.g., Garraffo et al. 2015

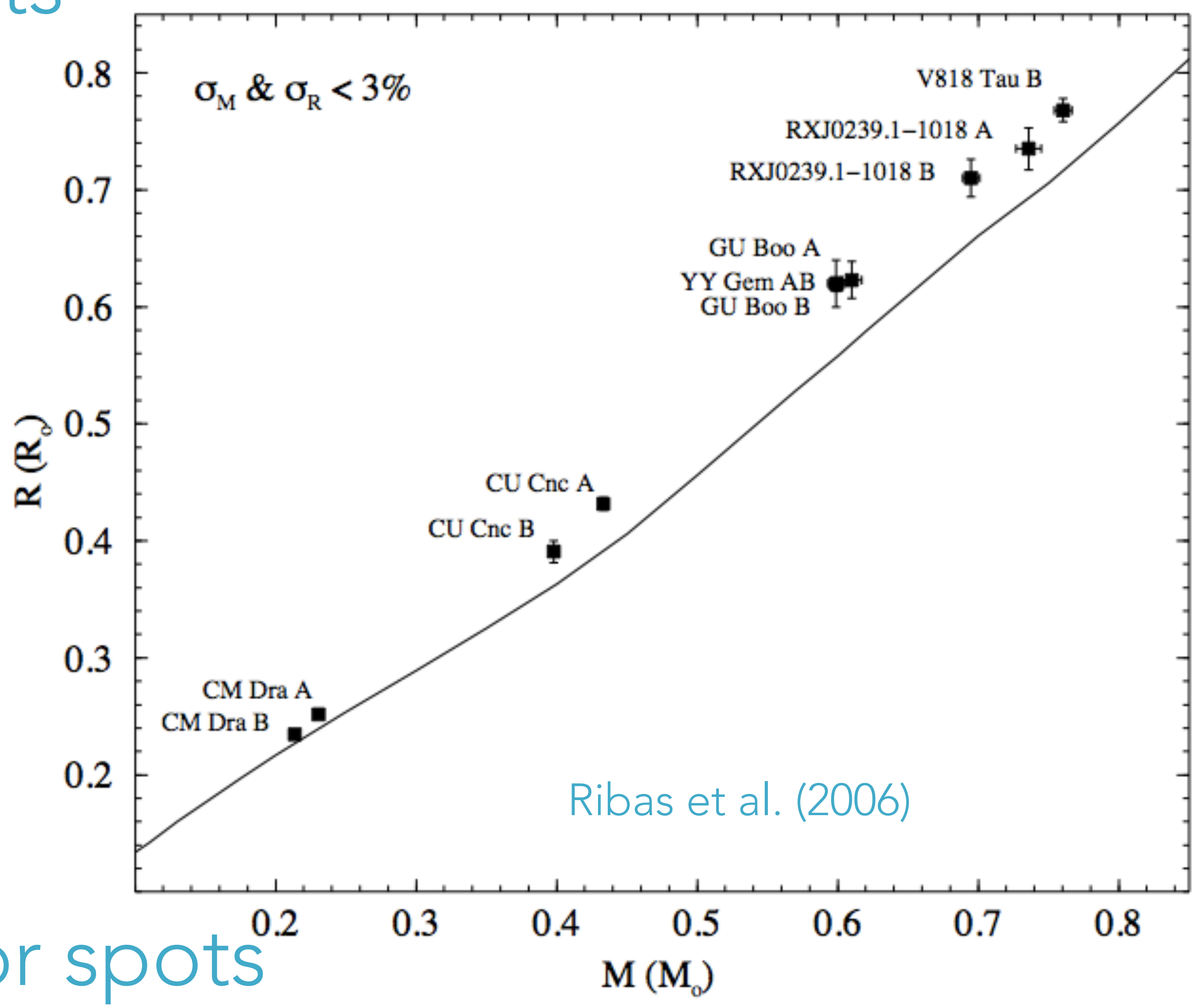
"wind magnetization"

COULD B (OR ROTATION) AFFECT STELLAR RADII?

Eclipsing binary measurements of stellar radii

Radii "inflated" w/r/t models (by 3-15 percent)

(Teff lower, L~const)

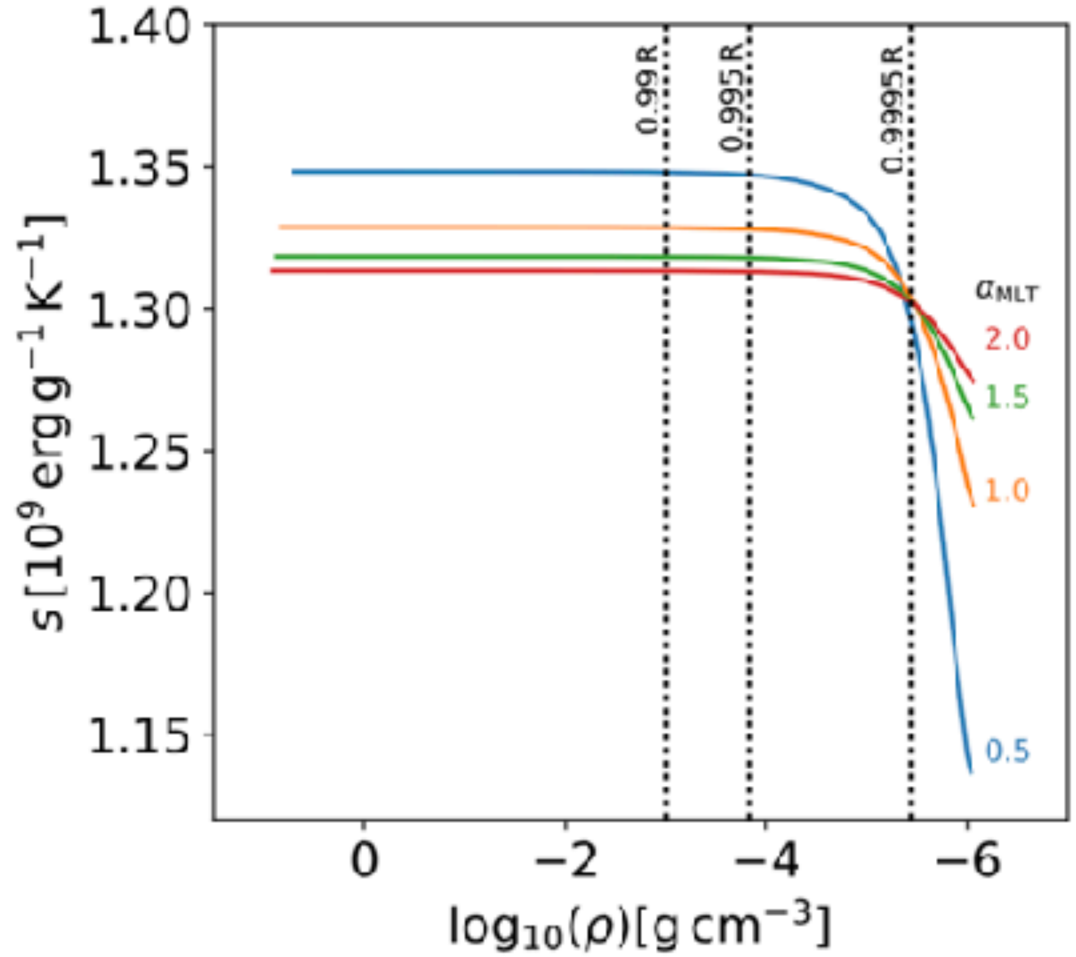


Ribas et al. (2006)

Convective inefficiency and/or spots frequently invoked

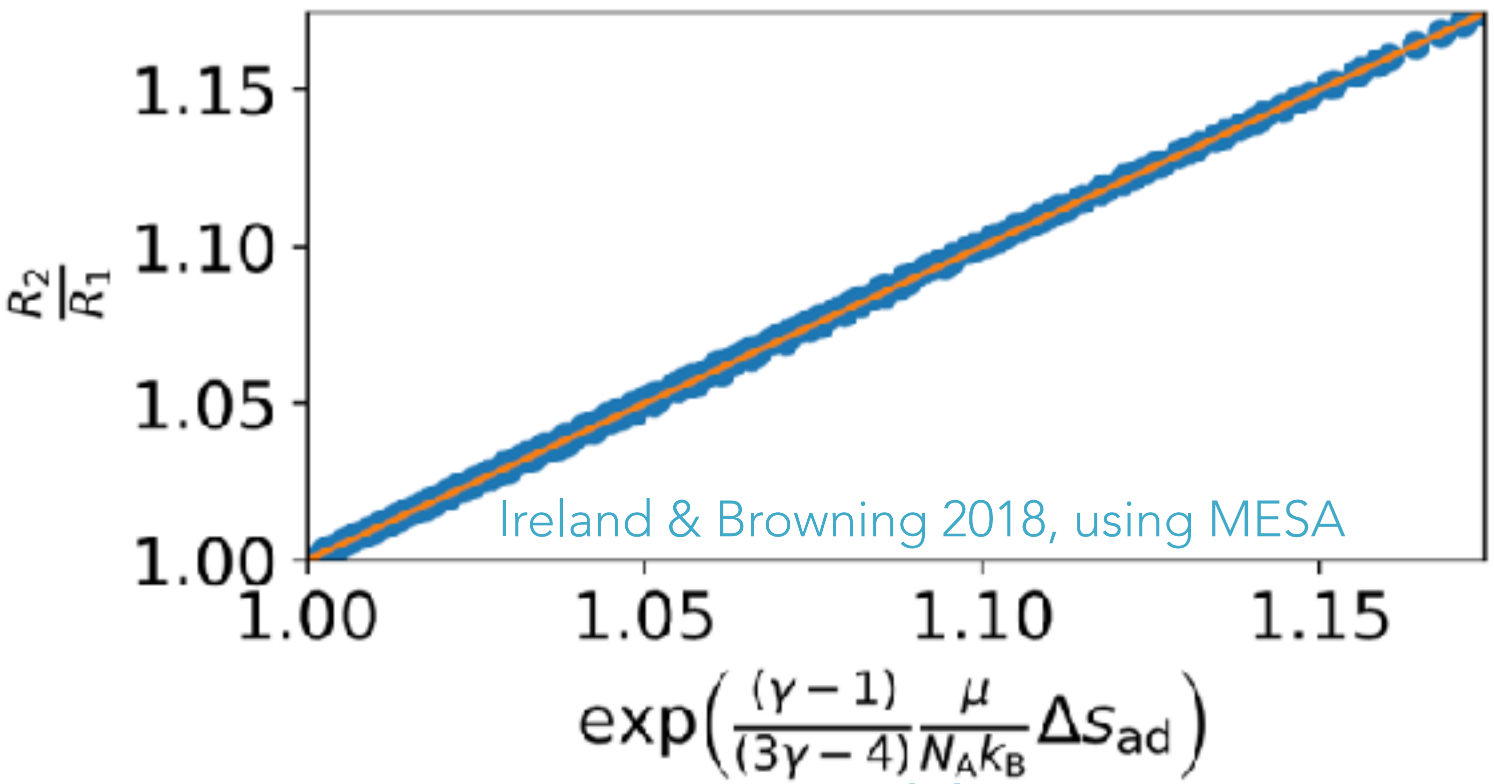
see, e.g., Feiden & Chaboyer (2014), Feiden (2016)
MacDonald & Mullan (2013, 2015, 2017,…)
Chabrier et al. (2007)

THE RADIUS OF A STELLAR MODEL IS PROPORTIONAL TO ITS ENTROPY



Standard MLT: S~const in interior

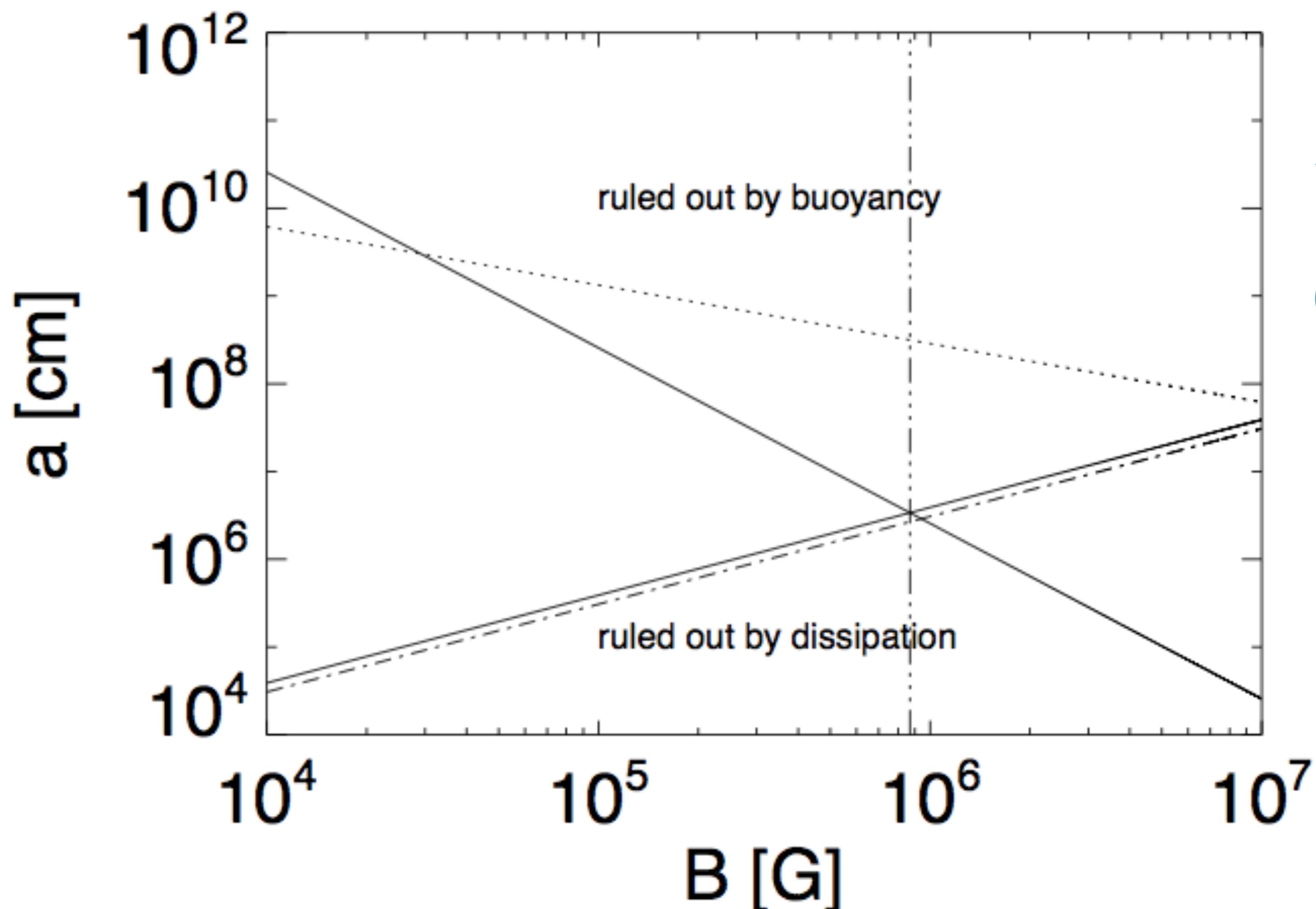
R increases with S see, e.g., Stahler (1988)



If B is big enough, will affect P/T/S in interior, and hence R

Extreme case: stably stratified (Mullan & MacDonald 2001)

BUT *THERMALLY RELEVANT* FIELDS ARE PROBABLY UNREALISTICALLY STRONG



Browning et al. (2016). See also Feiden & Chaboyer (2014)

Strong, *small-scale* B:

Ohmic dissipation>> L

Strong, *large-scale* B:

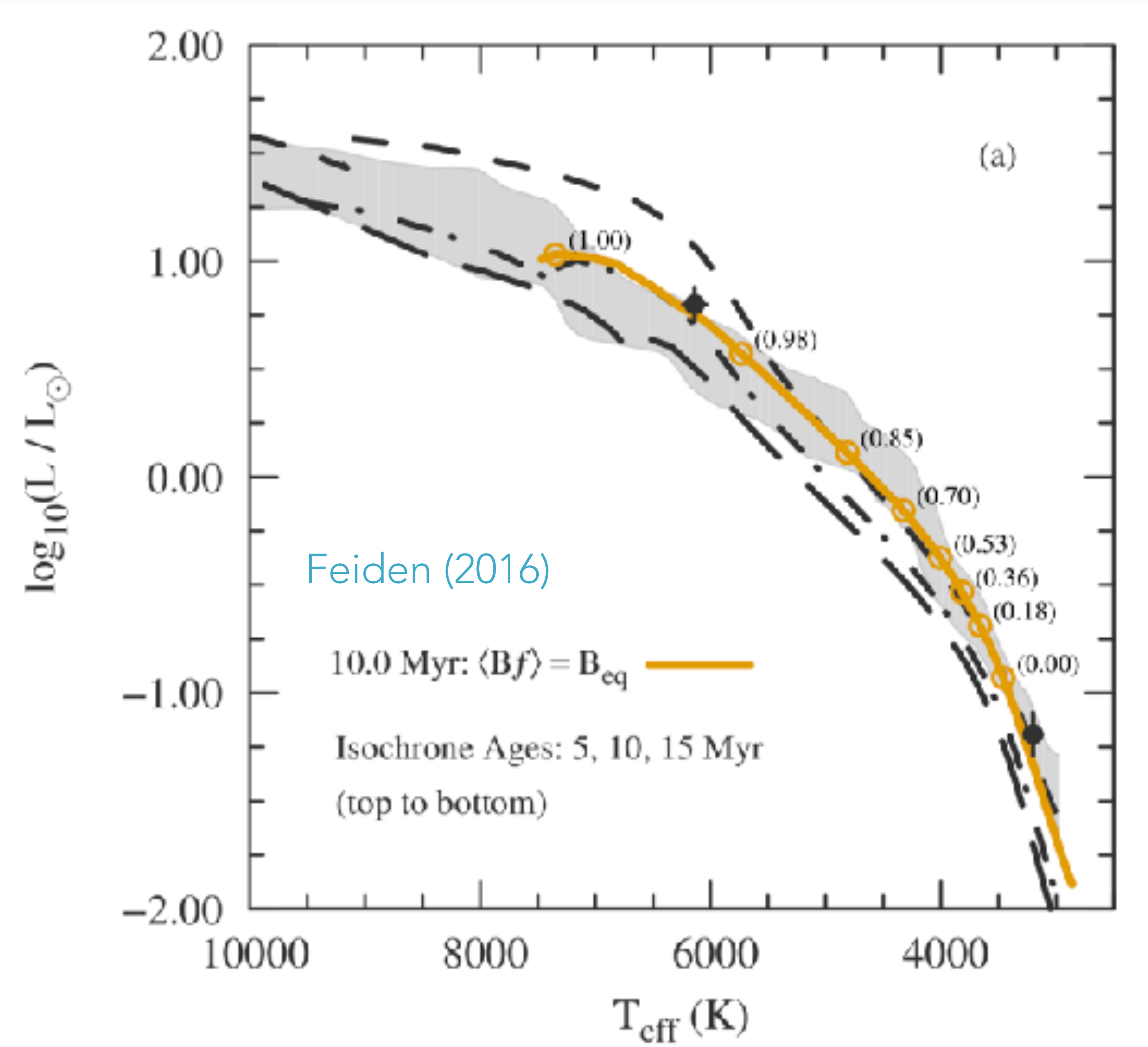
Rise faster than can be regenerated*

Beyond a certain (really high!) strength,

no* field can satisfy both constraints

WHAT DO WEAKER FIELDS DO? (DEPENDS A BIT ON MODEL)

No universally-agreed way of incorporating B in 1-D



But various models try to do so in plausible ways, e.g.:

a) model mag. pressure

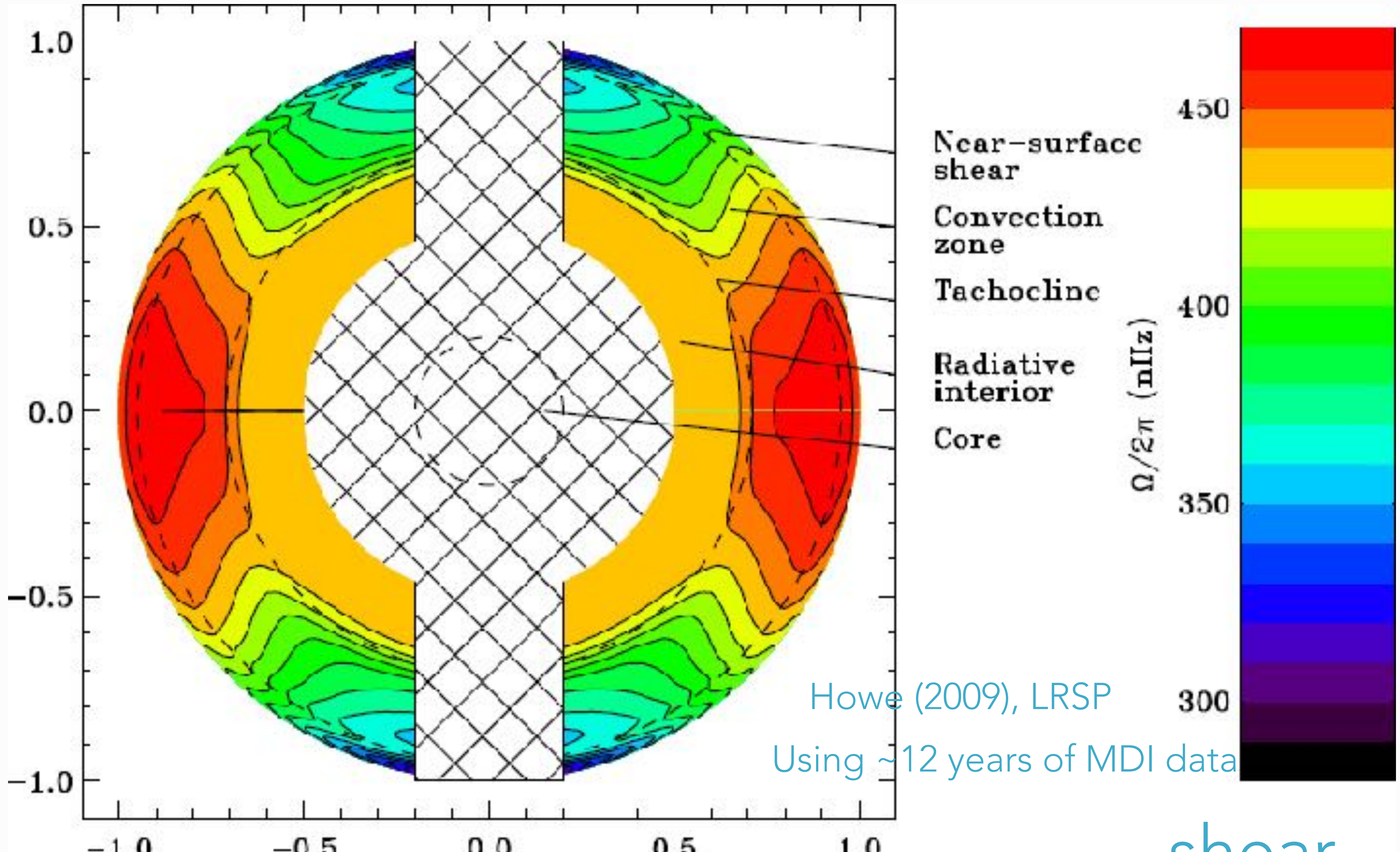
b) model ds/dr as f(B)

If you affect layers near surface -> overall structure adjusts

May lead to "inflation," (particularly on pre-MS)

See also MacDonald & Mullan (2016-2018), Ireland & Browning (2018)

HELIOSEISMOLOGY REVEALS SUN HAS TWO SHEARING BOUNDARY LAYERS



Howe (2009), LRSP

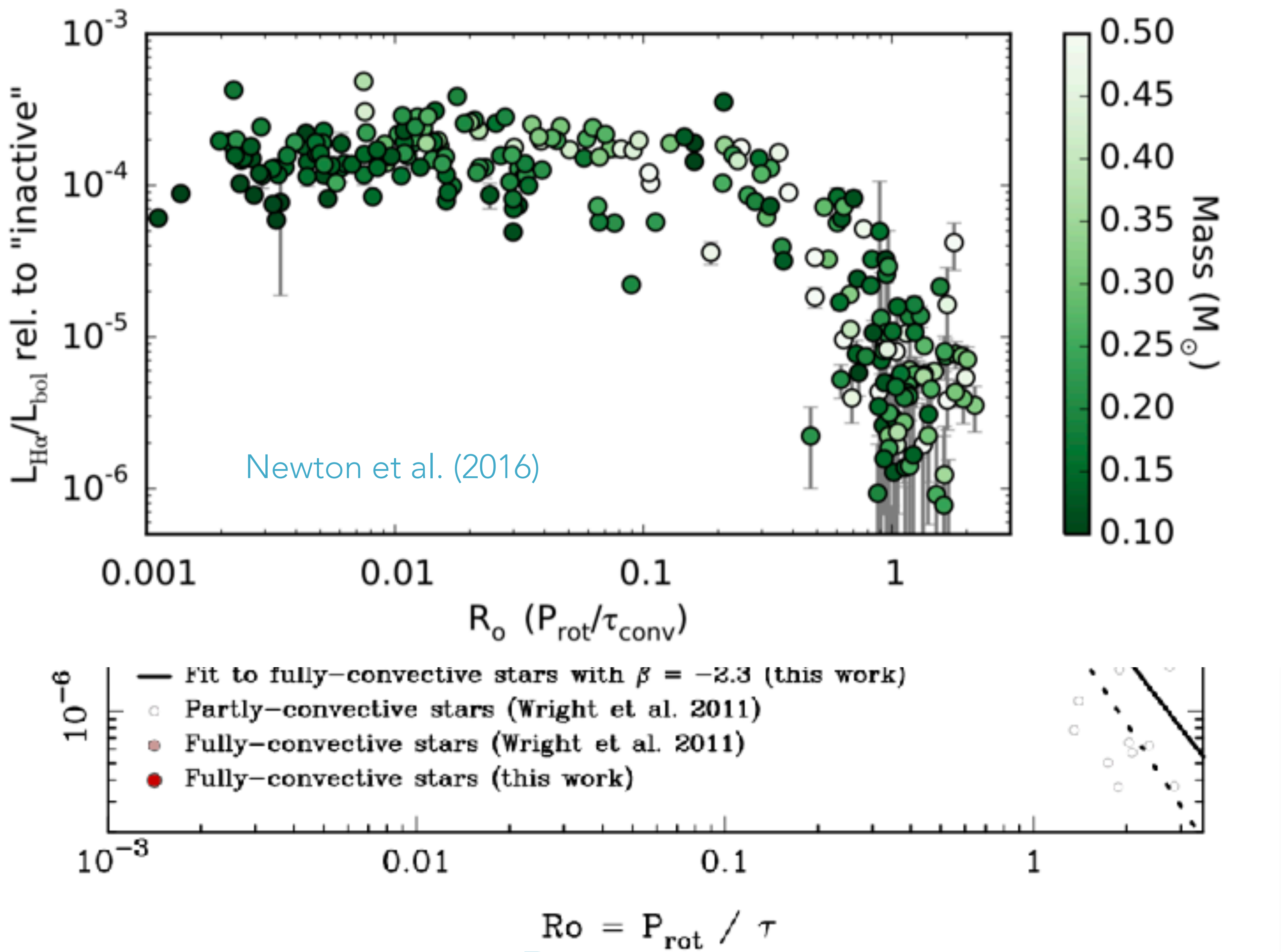
Using ~12 years of MDI data

In classic "interface" Solar dynamo models, tachocline long thought to play a crucial role

shear
stratification
helicity

FULLY CONVECTIVE STARS ALSO SHOW ROTATION-ACTIVITY CORRELATION

Activity



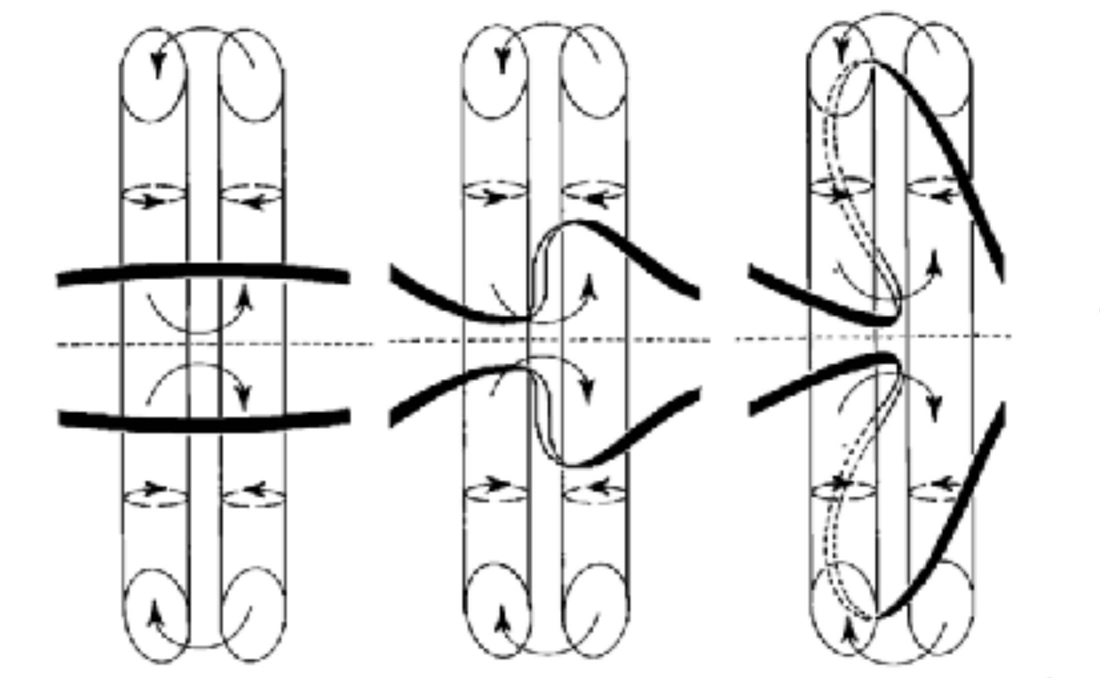
Rotation

WHAT ARE "BUILDING BLOCKS" OF DYNAMO ACTION?

For "small-scale" fields: complex flow, high conductivity

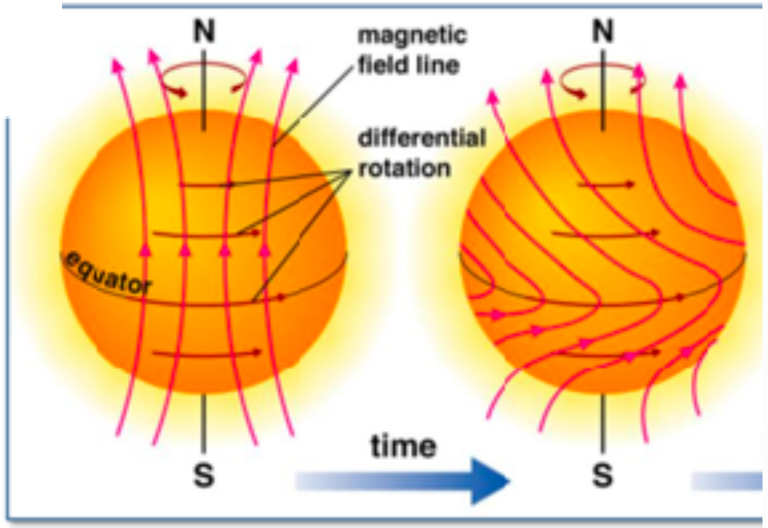
For ordered fields: need more (symmetry-breaking)

"Alpha" effect: helical convection



Olson et al. (1999)

"Omega" effect: shear



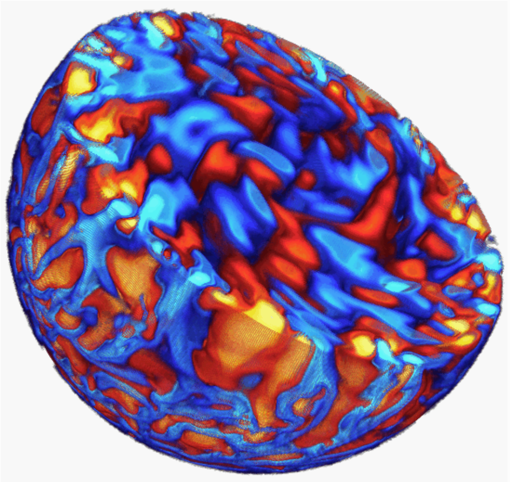
+ potentially many other effects

(meridional circulation, Babcock-Leighton,…)

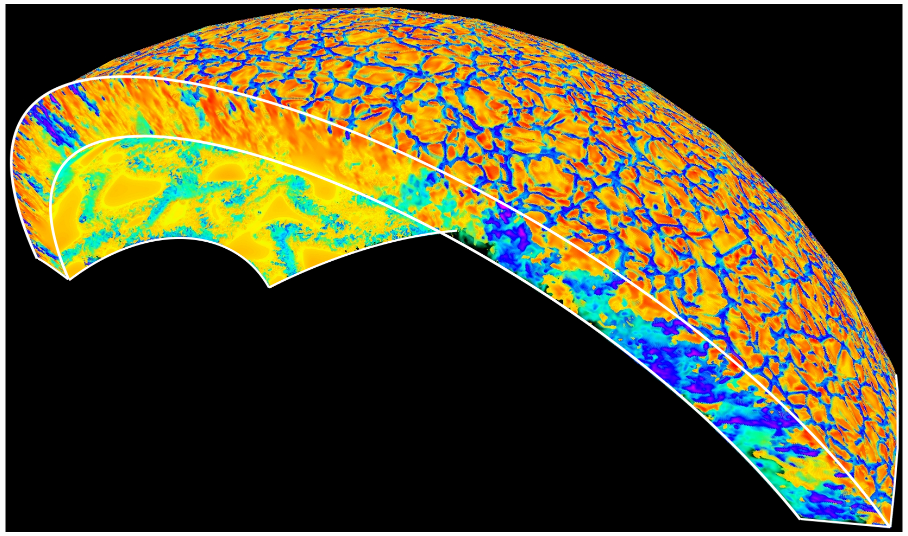
Bennett et al. (2003)

HIERARCHY OF APPROACHES (EACH WITH PROS/CONS)

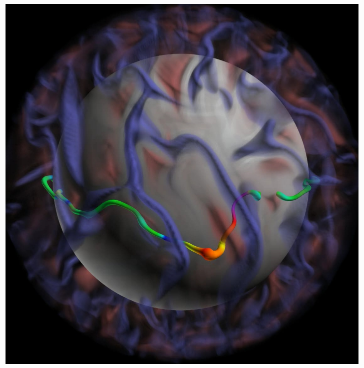
Global models:
Resolve largest scales, ignore (or parameterise) smallest

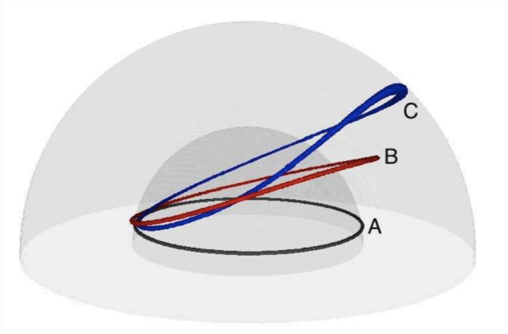


More local 2D/3D models:
higher local resolution,
(but boundaries, geometry)



1D-like: evolution models, MFT,…
Cheaper to compute, can build intuition



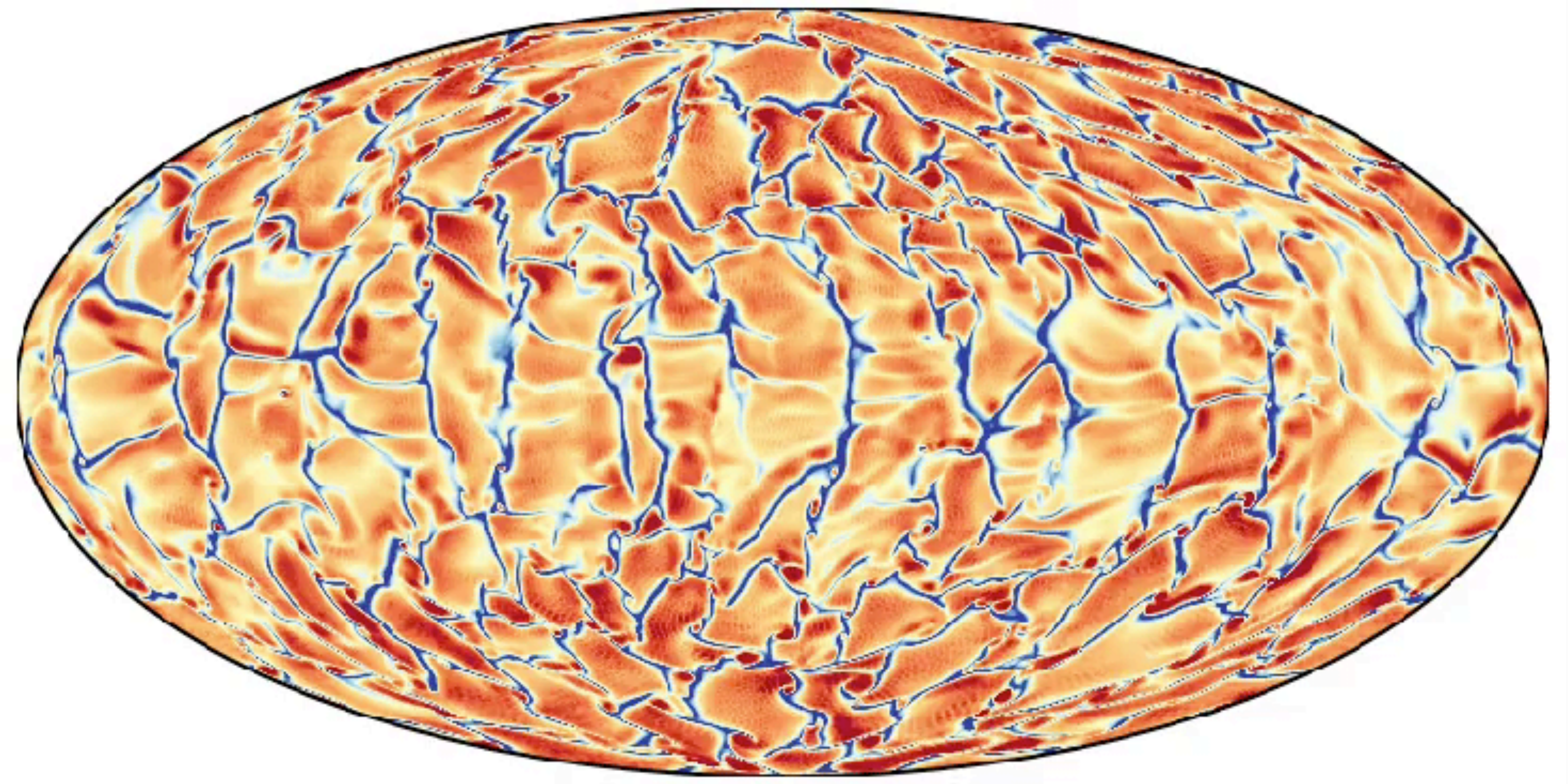


ASIDE: YOU CAN DO THIS, TOO

Many of these codes are publicly available, e.g.

Rayleigh: geodynamics.org/cig/software/rayleigh/
Magic: magic-sph.github.io
Dedalus: dedalus-project.org
(+ many others: MESA, Pencil, …)

FLOWS THAT FEEL ROTATION, STRATIFICATION, MAGNETISM



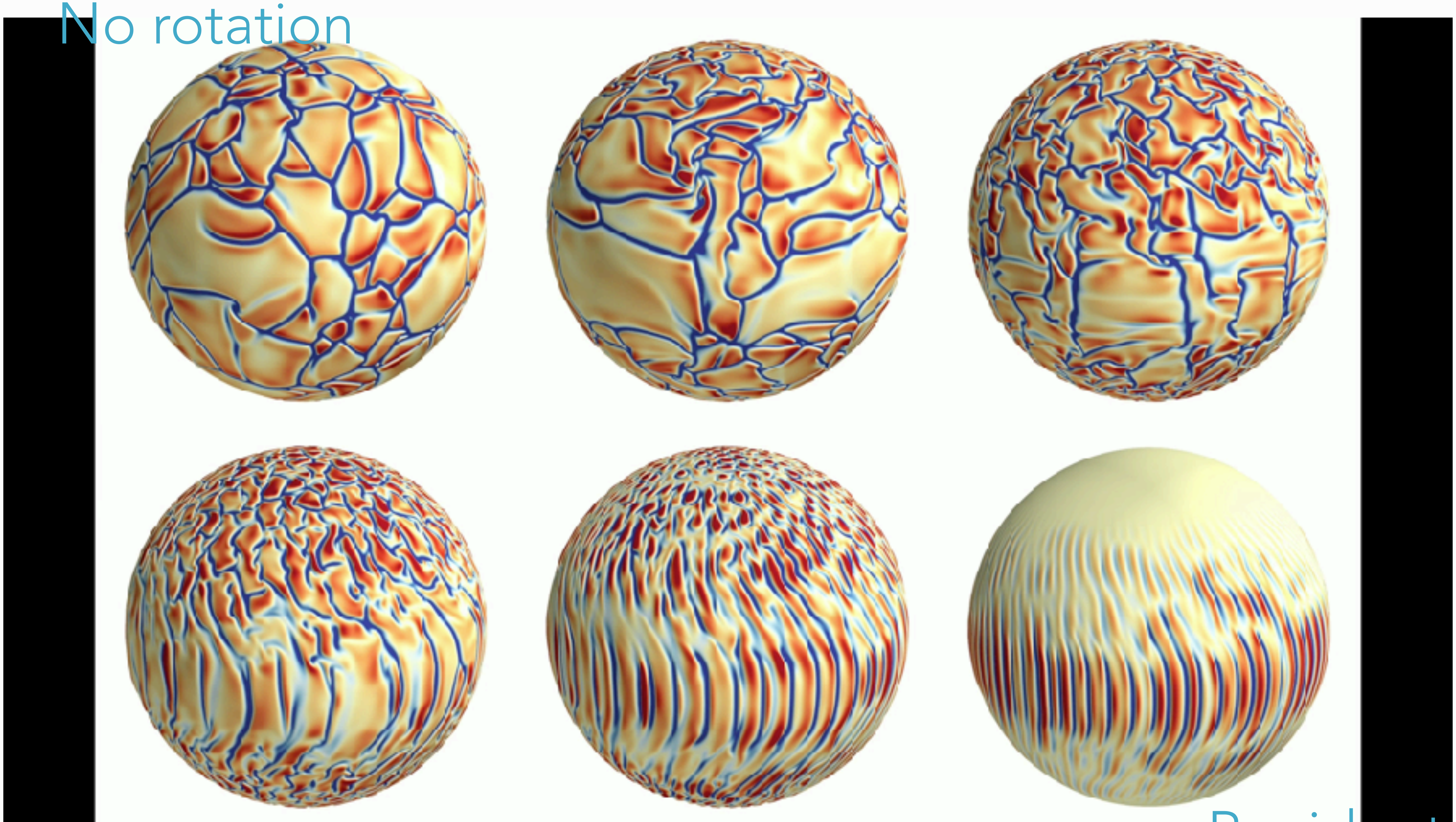
3D deep-shell simulation by Lucia Duarte (Duarte et al. 2016)

Radial velocity on a particular shell near the upper surface

Upflows are red; down flows are blue

ROTATION MATTERS …
FOR CONVECTIVE FLOWS

No rotation

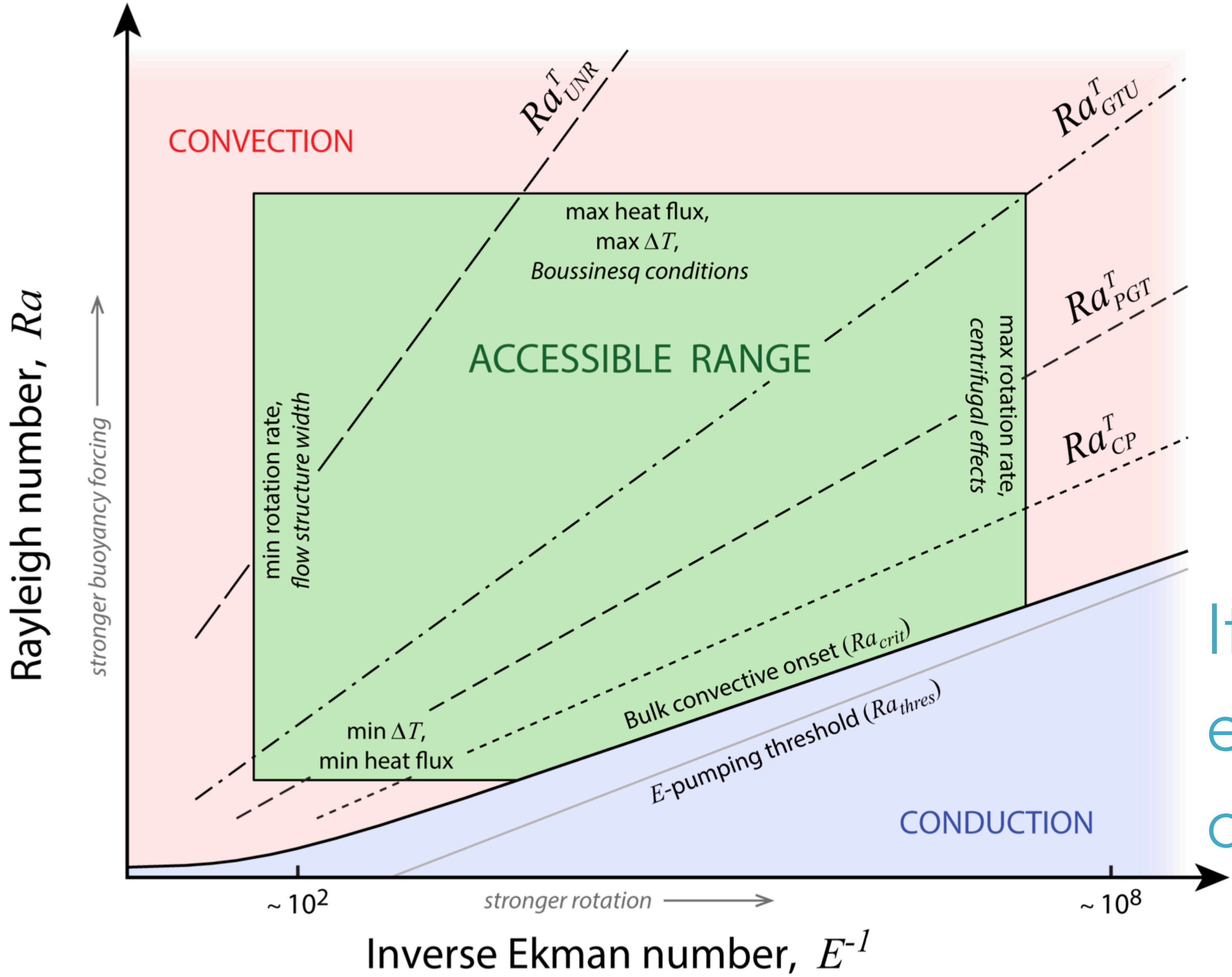


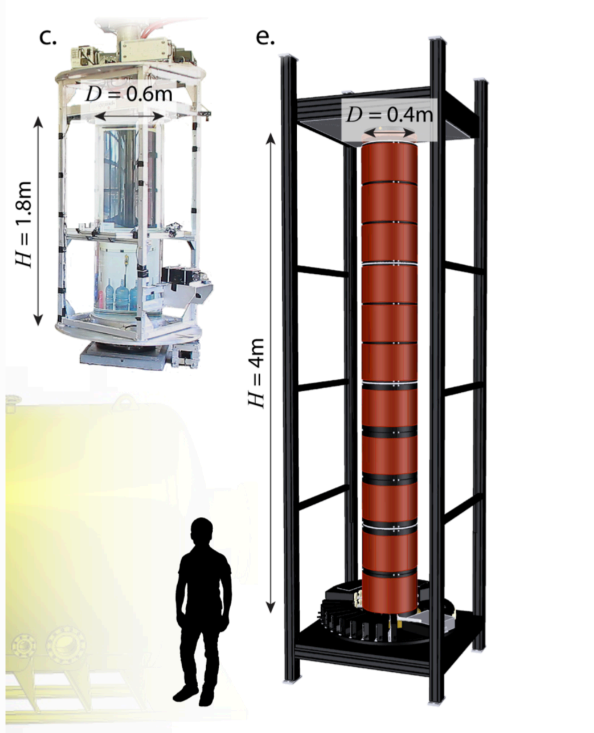
Rapid rotation

Visualisations and simulations by Nick Featherstone with Rayleigh

Rotation shapes the convective flows

ROTATION STABILISES CONVECTION IN THE LAB, TOO



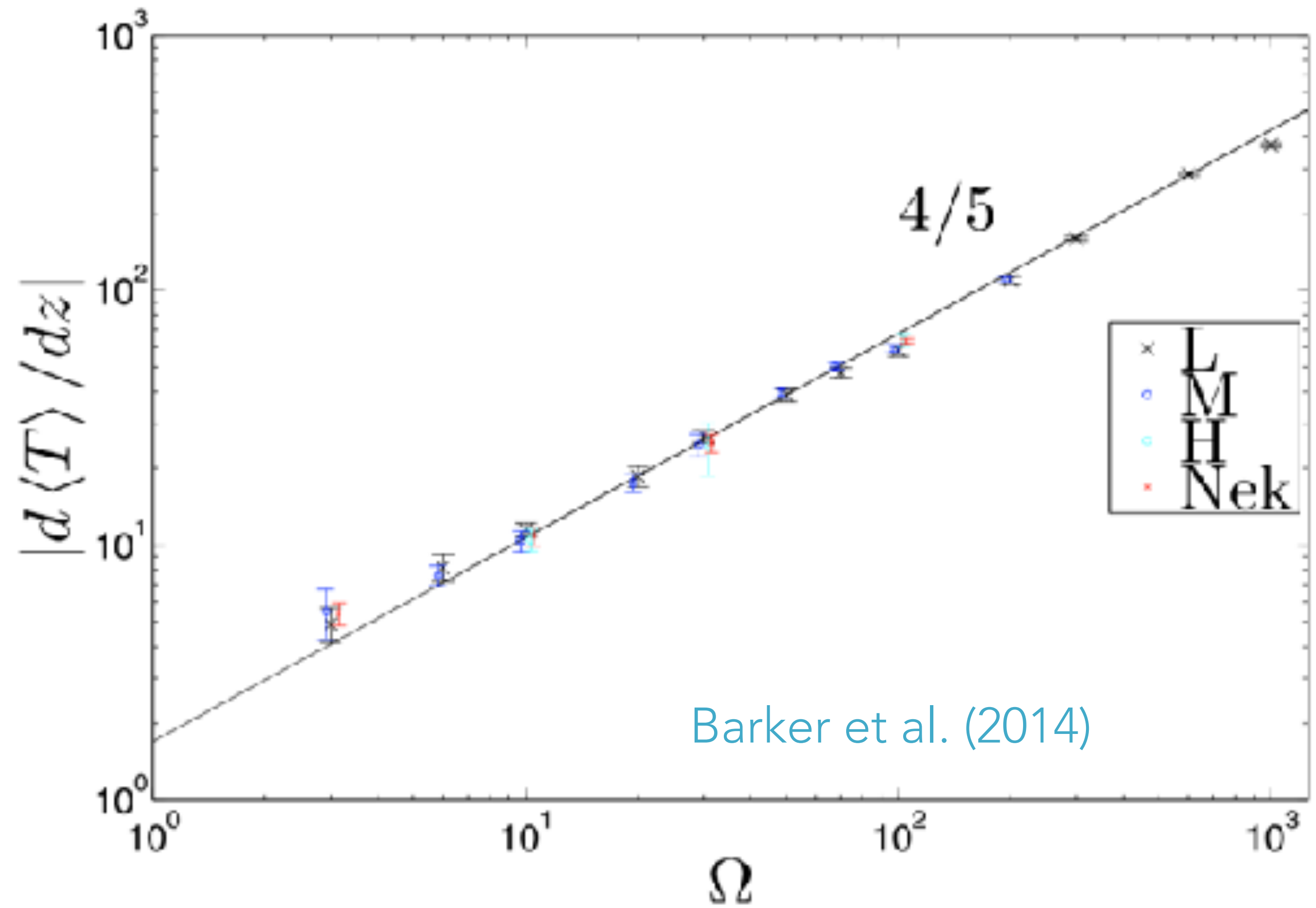


If you spin rapidly enough, eventually convection stops

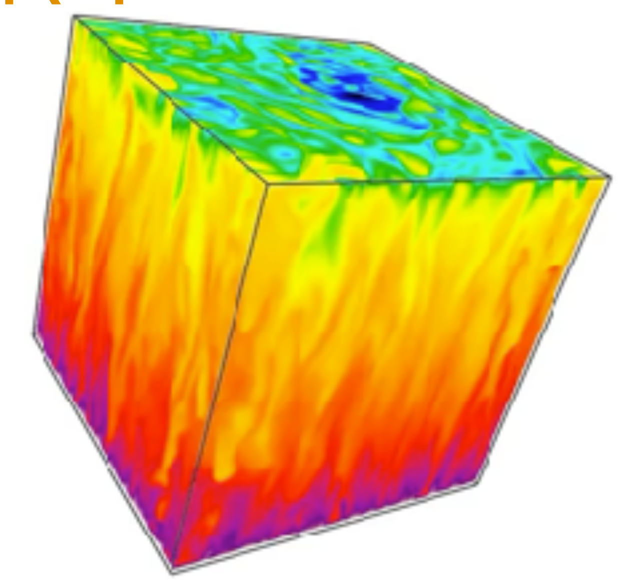
(for fixed driving/flux/dT/etc)

Cheng et al. 2017

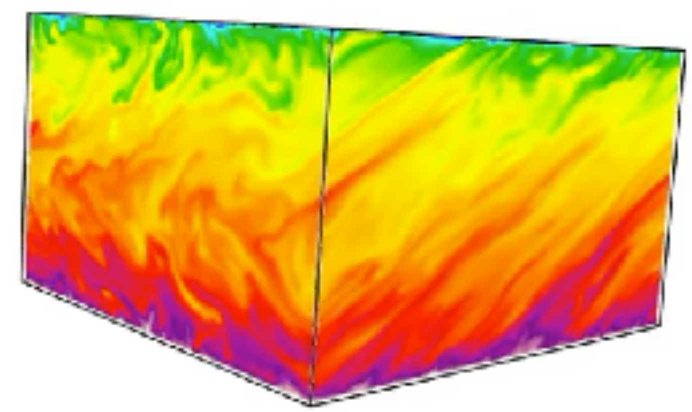
ROTATION MATTERS … FOR HEAT TRANSPORT



Barker et al. (2014)



Simulations by Laura Currie, Adrian Barker, et al., using Dedalus



Need stronger dT/dz at higher rotation rates (for given flux)

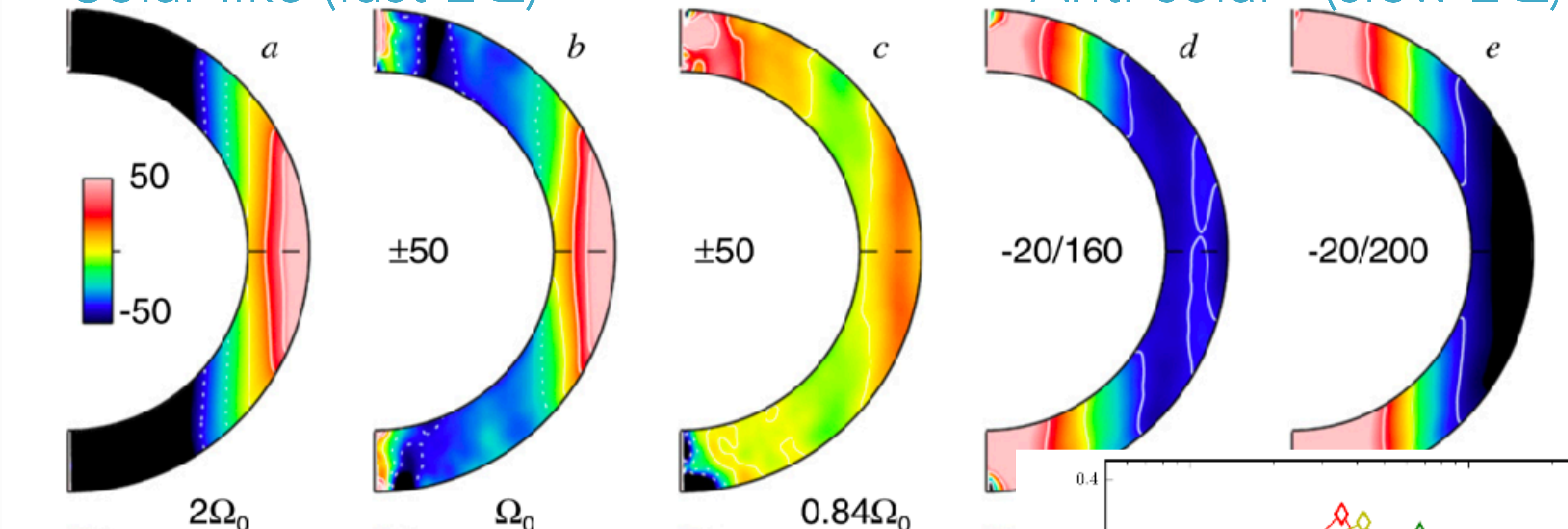
Theory and simulations give similar scalings

e.g., Stevenson (1979), Julien et al. (2012), …

ROTATION MATTERS ...
FOR DIFFERENTIAL ROTATION

Solar-like (fast EQ)

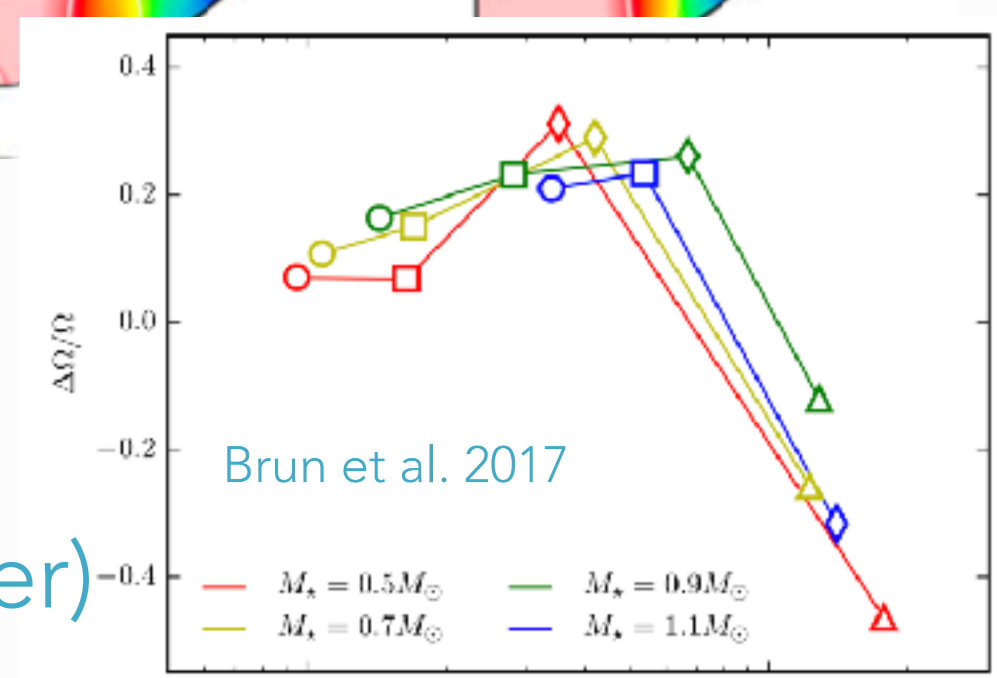
"Anti-solar" (slow EQ)



Rotation rate

Featherstone & Miesch (2015)

(+ many prior papers: e.g., Gilman (1976-1978); Gastine et al. 2014)



Brun et al. 2017

+ eventually, banded zonal flows (Jupiter)

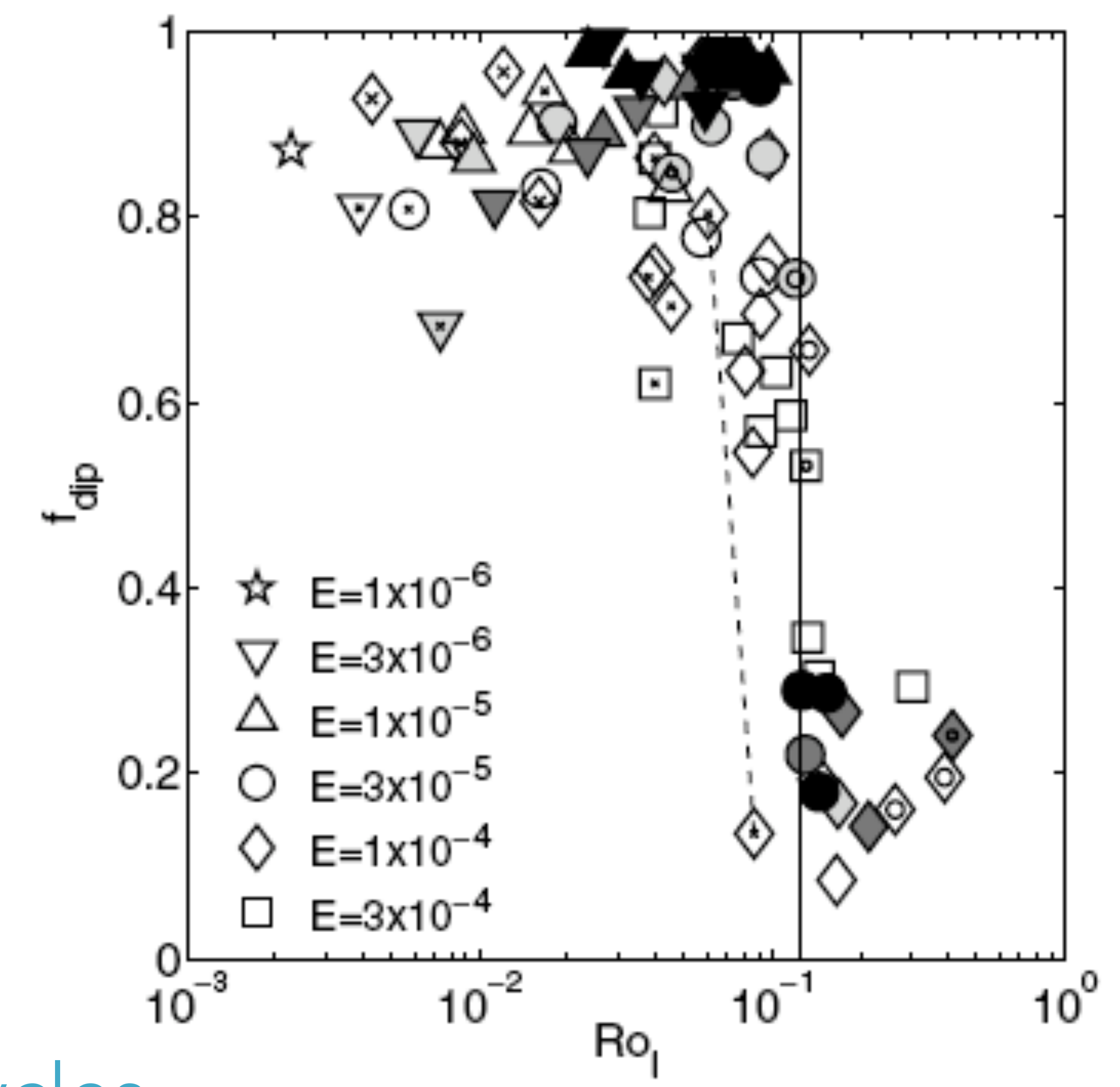
ROTATION MATTERS …
FOR FIELD GENERATION

Rotation typically favours the generation of more ordered fields

Here ("planetary" simulations), more rapid rotation-> more dipolar

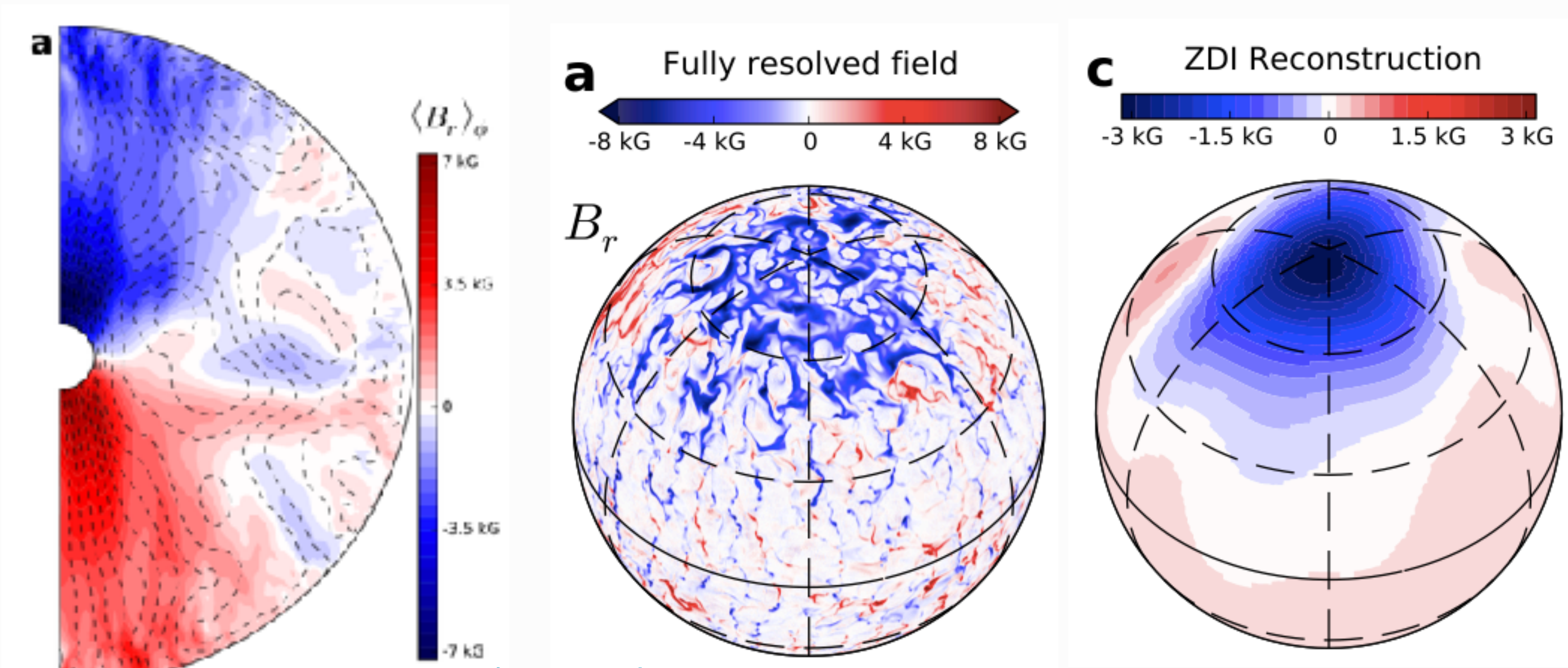
Many outcomes possible:

Steady dipoles, "wreaths," cycles…

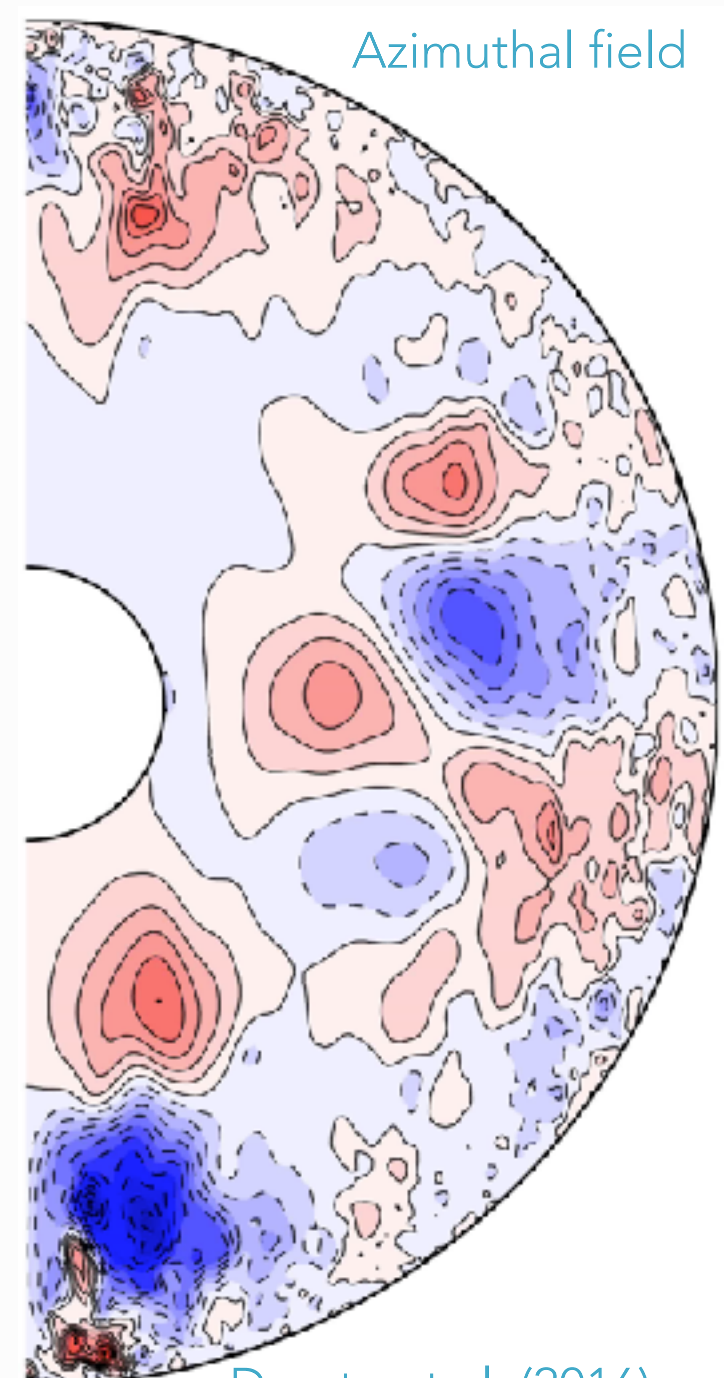


Christensen & Aubert (2006)

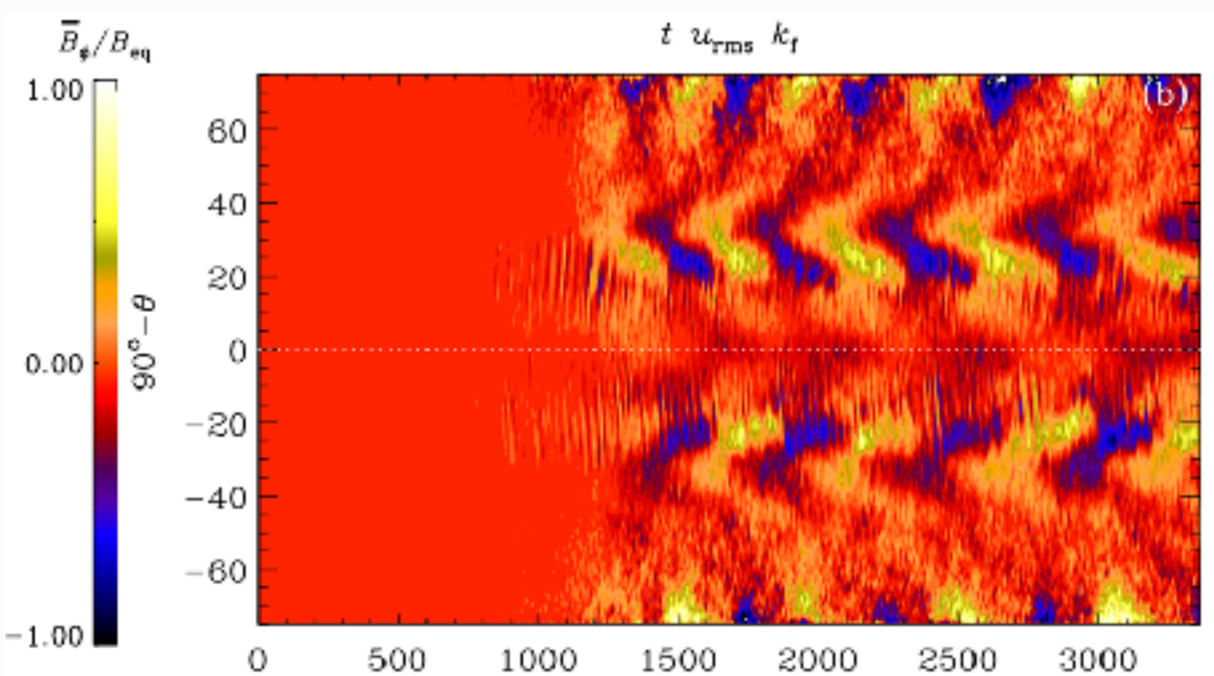
ORDERED AND CYCLICAL FIELDS CAN BE GENERATED WITHOUT A TACHOCLINE



Yadav et al. (2015)



Duarte et al. (2016)



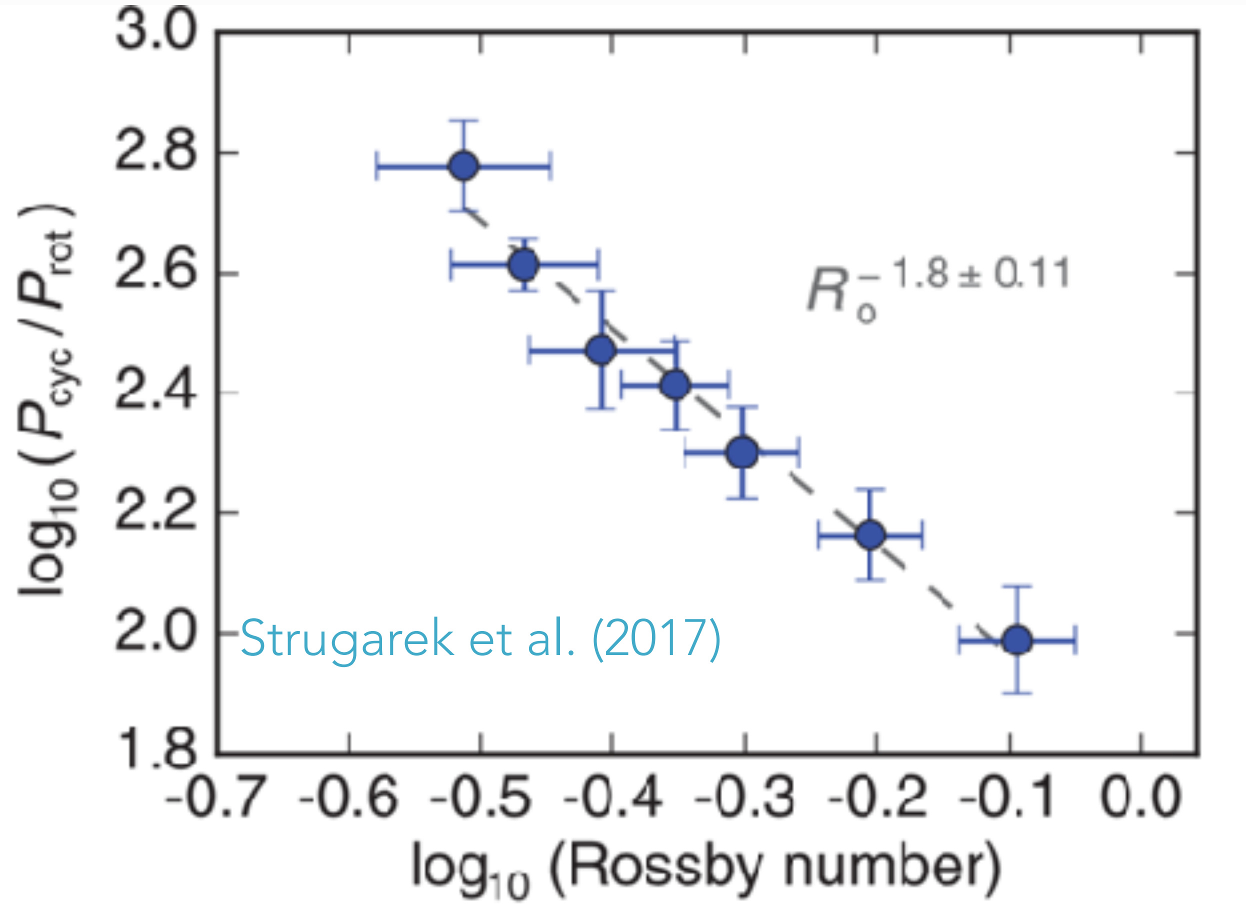
Kapyla et al. (2012)

+ many other examples!

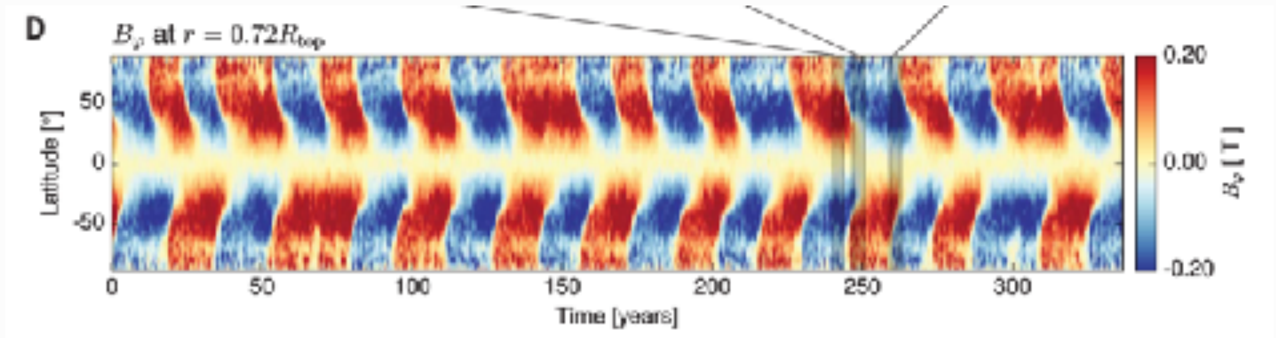
e.g., Brown et al. (2011), Augustson et al. (2015)

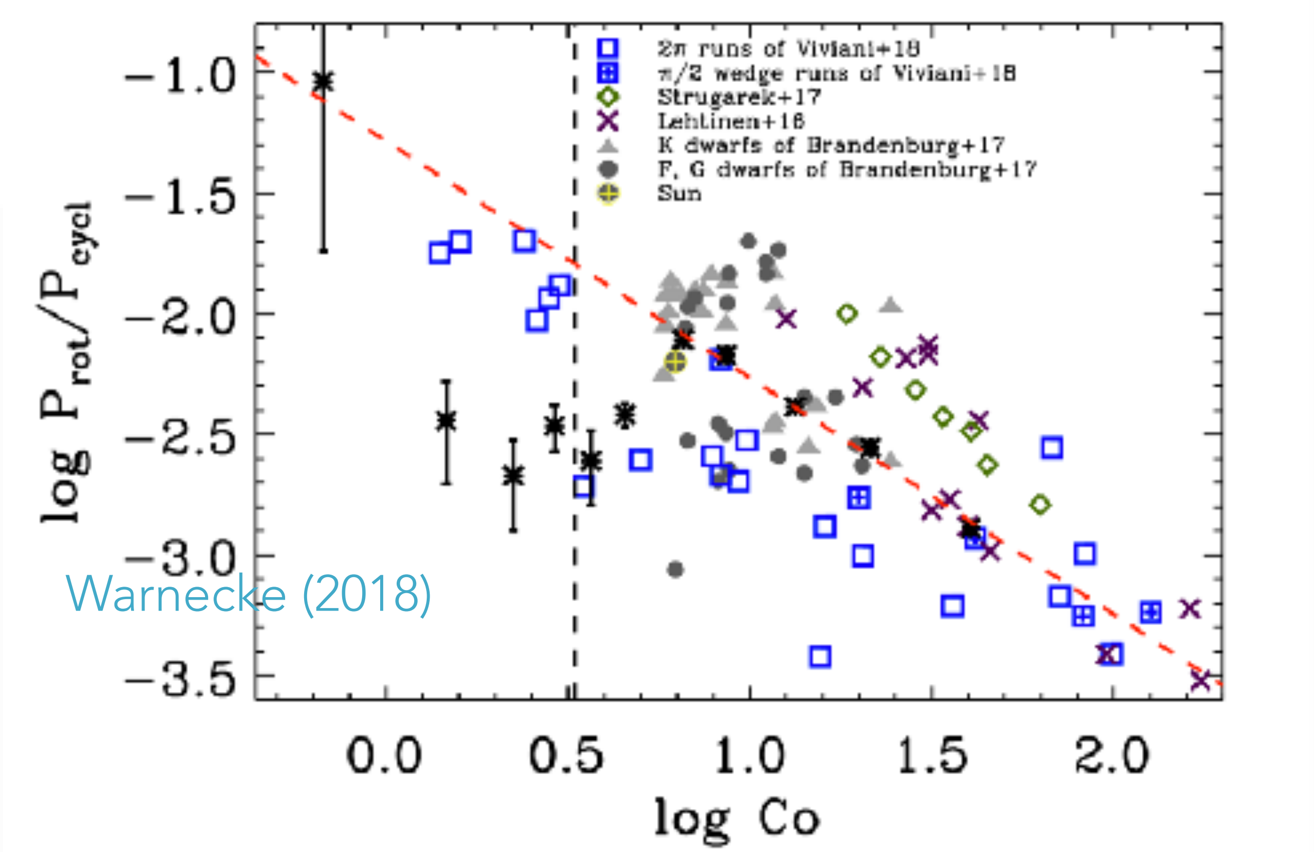
(this does not *necessarily* mean tachocline plays no role in Sun)

RELATIONS BETWEEN CYCLE PERIOD AND ROTATION IN SIMULATIONS



Here, more rapid rotation yields *longer* cycles

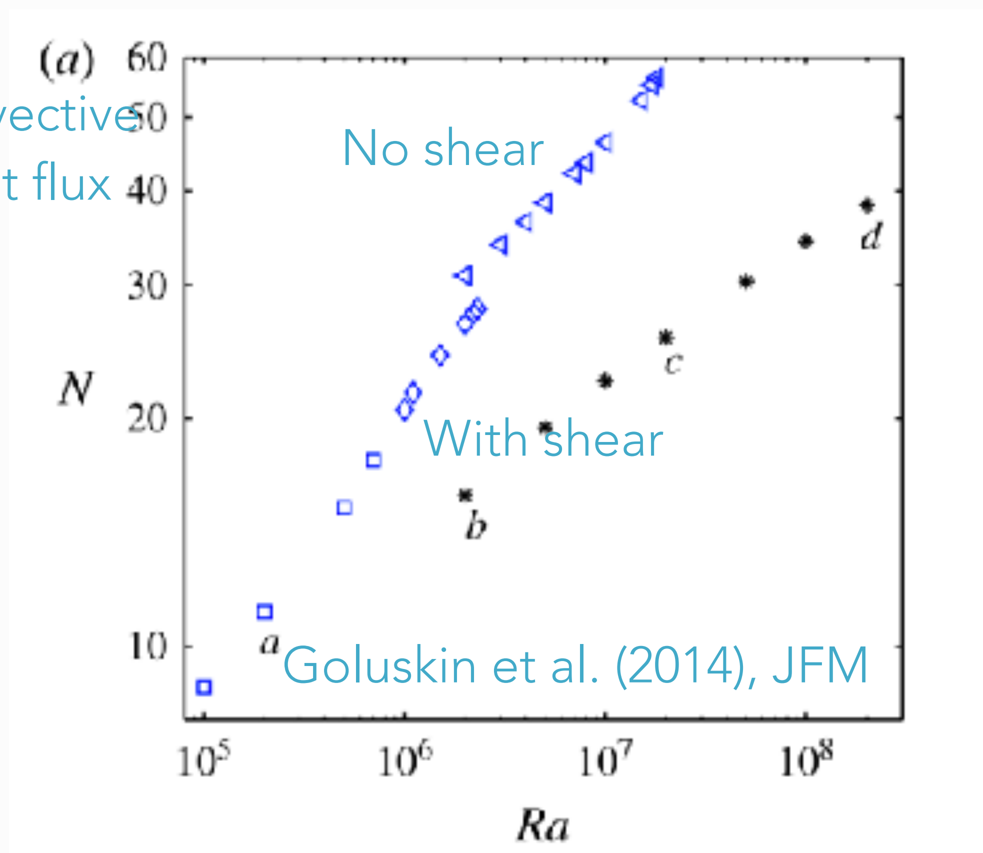




More on this in later talks + splinters

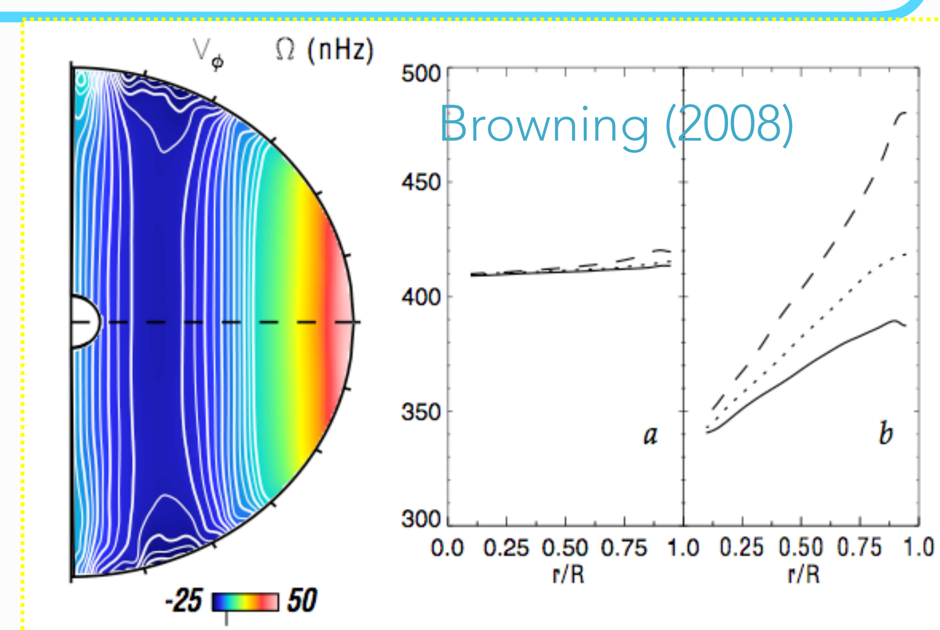
THE INTERACTION BETWEEN CONVECTION, MAGNETISM, AND SHEAR CAN BE COMPLEX

In some regimes, B may *increase* convective heat transport



Shear reduces convective F

Magnetism reduces shear



Net effect of B can be increased F

see, e.g., Yadav et al. (2016), GJI

IN SEARCH OF A PRIVATE ISLAND

Where we'd like to go

Necker Island, BVI

vs.

What we can afford

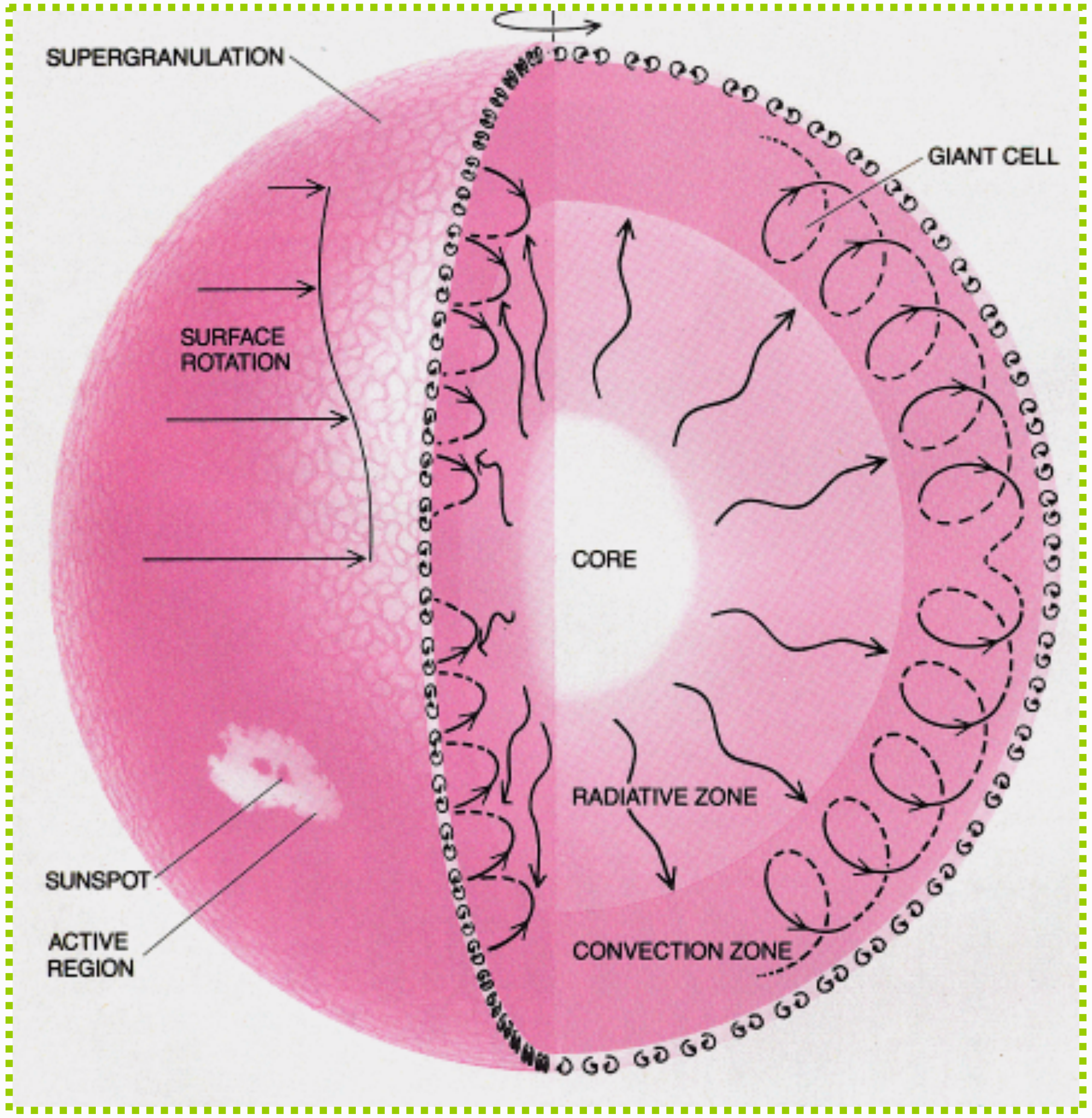
Images: Rebecca Anthony (DevonLive); Luca Galuzzi — www.galuzzi.it

SUMMARY: THE MAGNETIC LIVES OF ROTATING STARS

Magnetism shapes the lives of stars in a variety of ways

The magnetism is built by dynamo action, usually involving convection.

The character of the fields is influenced by rotation.



We still don't have a comprehensive theory of how this all works (or what the fields do), but lots of clues!