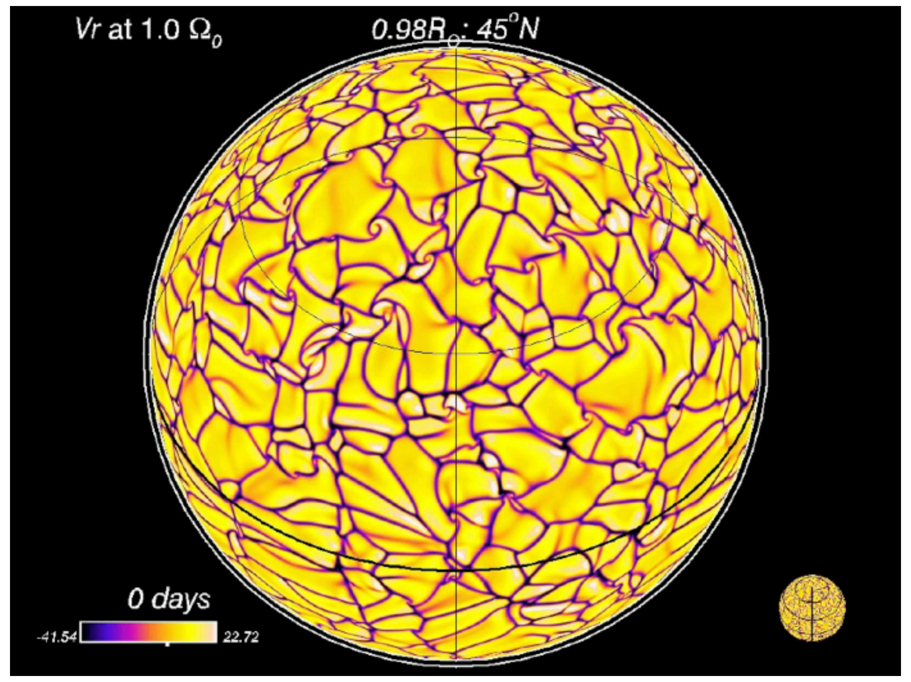
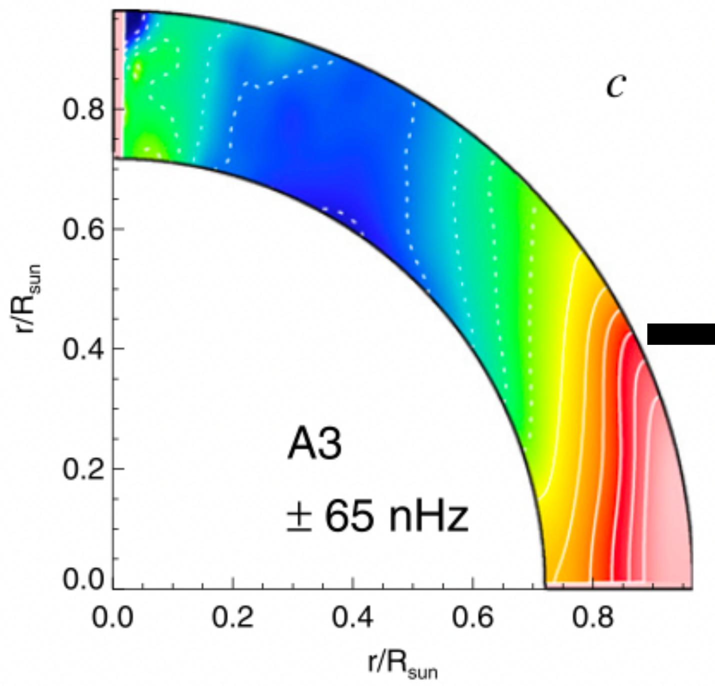
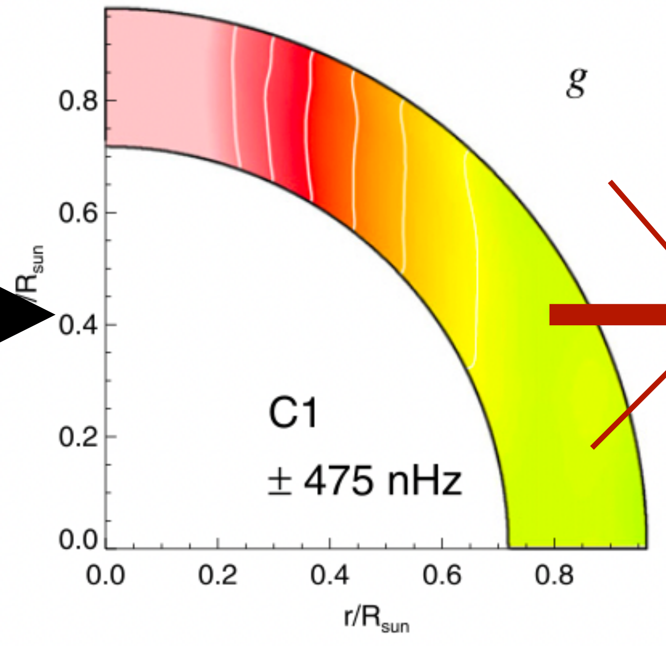
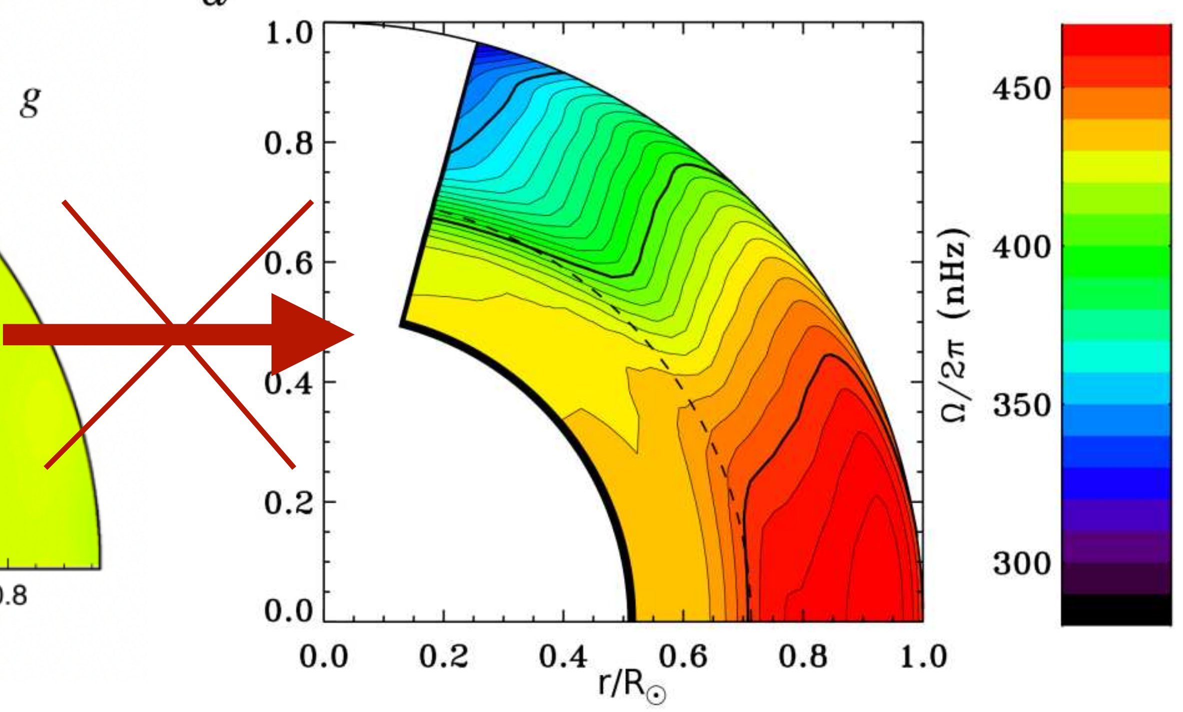
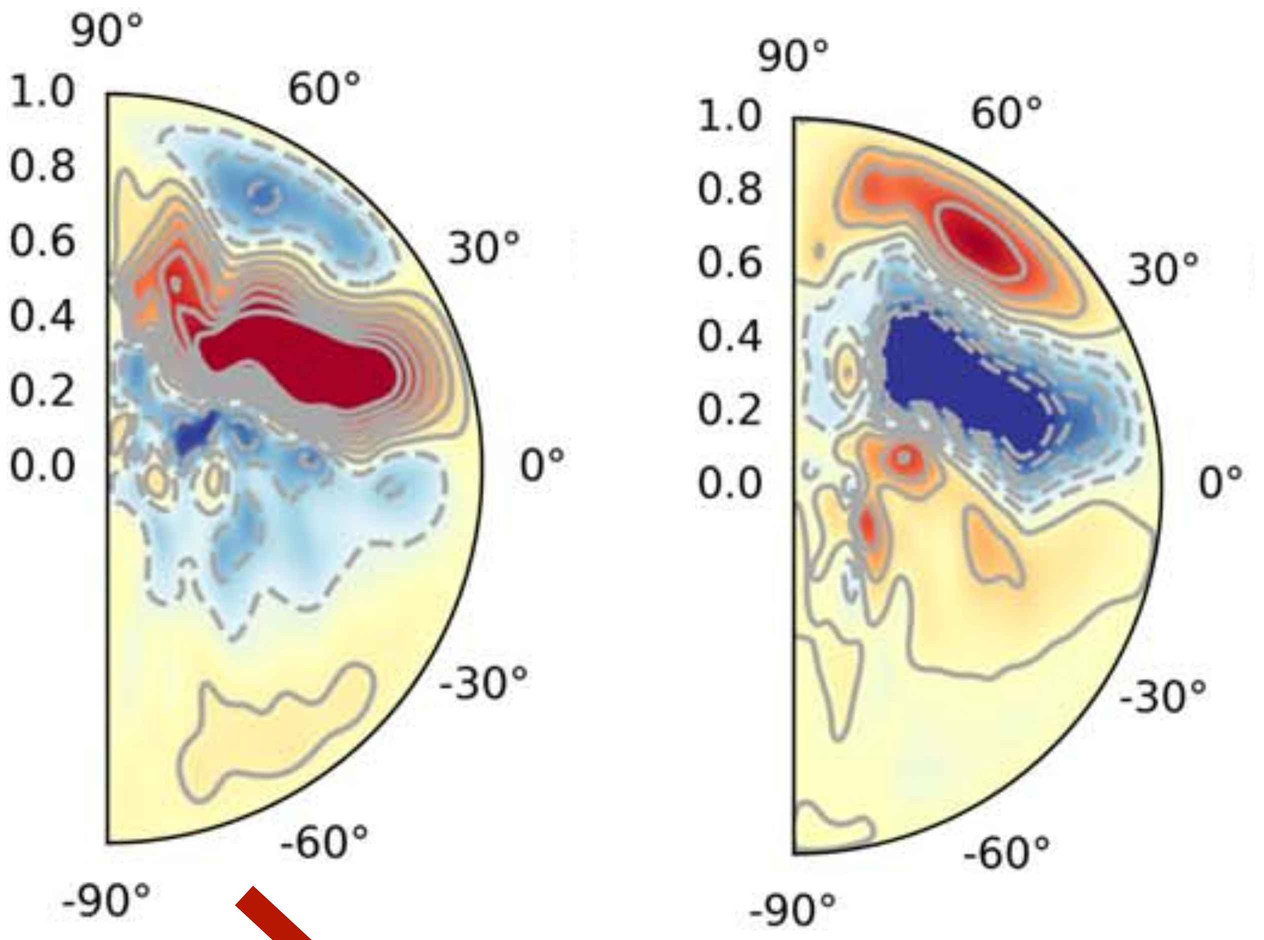






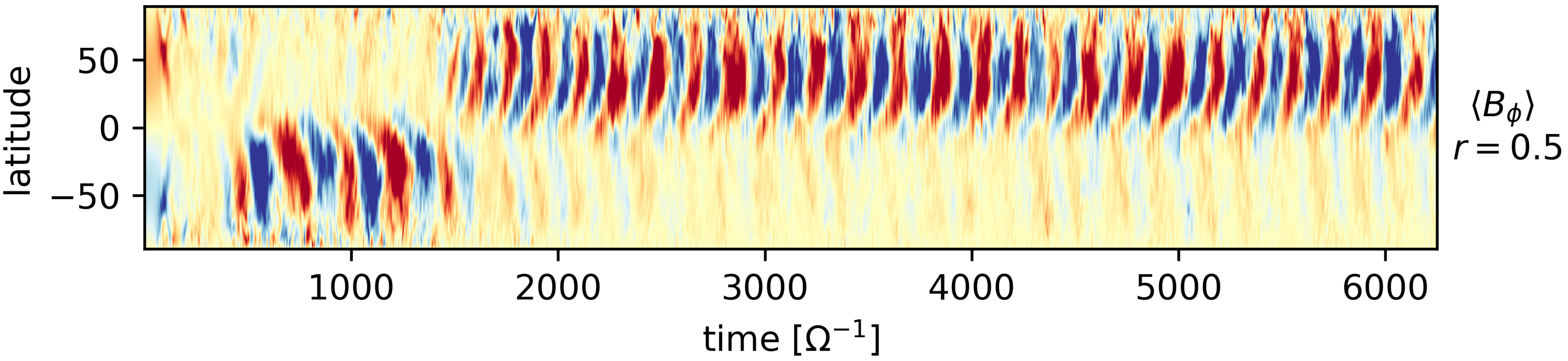




What can we learn from multi-D simulations anyways?

Benjamin Brown (University of Colorado),
with Jeffrey Oishi (Bates), Geoffrey Vasil (U Sydney),
Daniel Lecoanet (Northwestern), and Keaton Burns (MIT)

Toroidal magnetic field

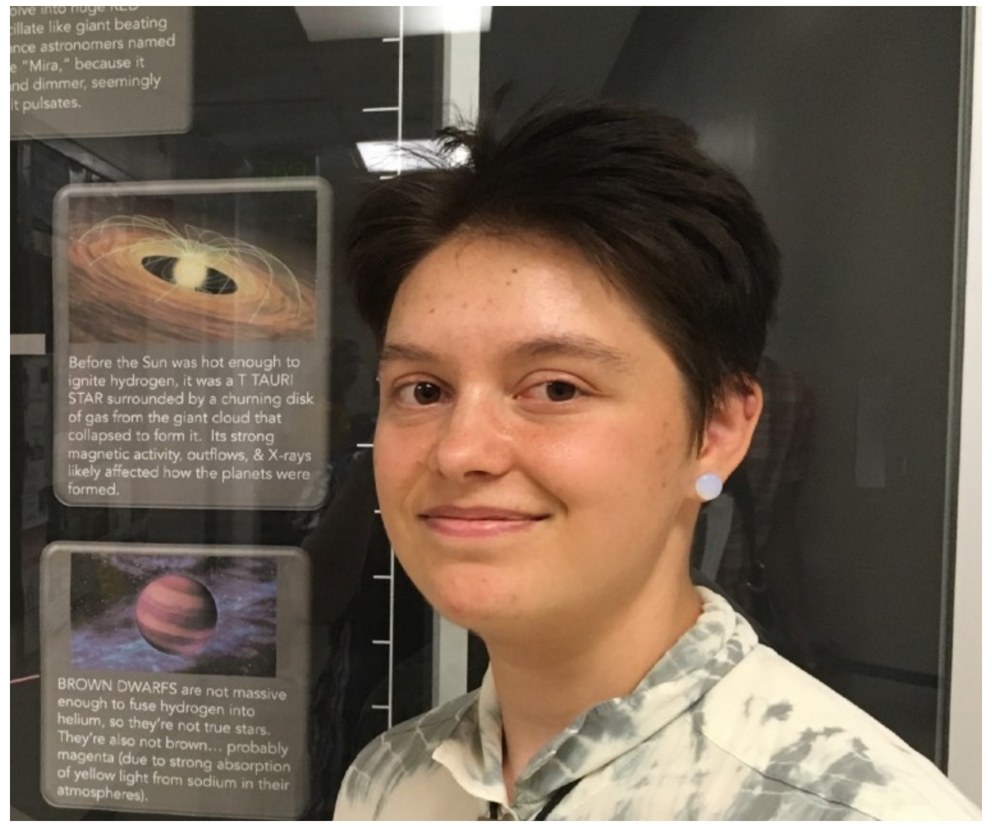


Brown, Oishi, Vasil, Lecoanet & Burns 2020, "Single-hemisphere dynamos in M-dwarf stars", ApJL

People do science

Exoweather group

Ryan Díaz-Pérez
Data Scientist
Los Angeles, CA



Jhett Bordwell
Myriad Genetics
San Francisco, CA

Evan Anders
CIERA Fellow
Northwestern

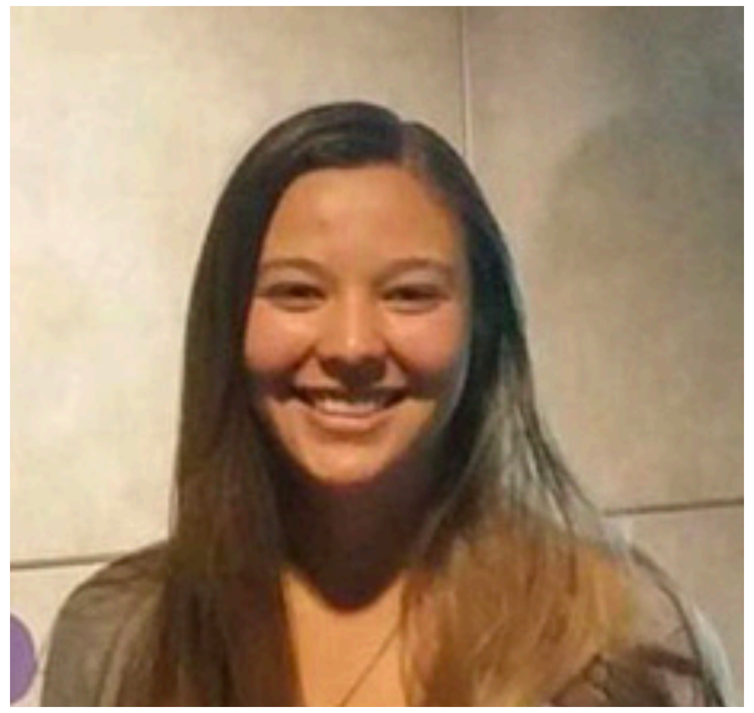
Whitney Powers

Imogen Cresswell

Linnea Wolniewicz
APS undergrad

Gabriel Ortiz-Peña
University lecturer
Guadalajara, Mexico

Katie Manduca
Boulder Labs
Boulder, CO



Tayler Quist
Applied Math
UC Santa Cruz

the Dedalus collaboration

Jeffrey Oishi
Bates College

Keaton Burns
MIT & CCA

Geoffrey Vasil
University of Sydney

Daniel Lecoanet
Northwestern

current and recent Hale postdoc fellows

Lydia Korre
APS/Applied Math

Benoit Tremblay
APS/NSO

Alicia Aarnio
UNC-Greensboro

Feng Chen
Nanjing University

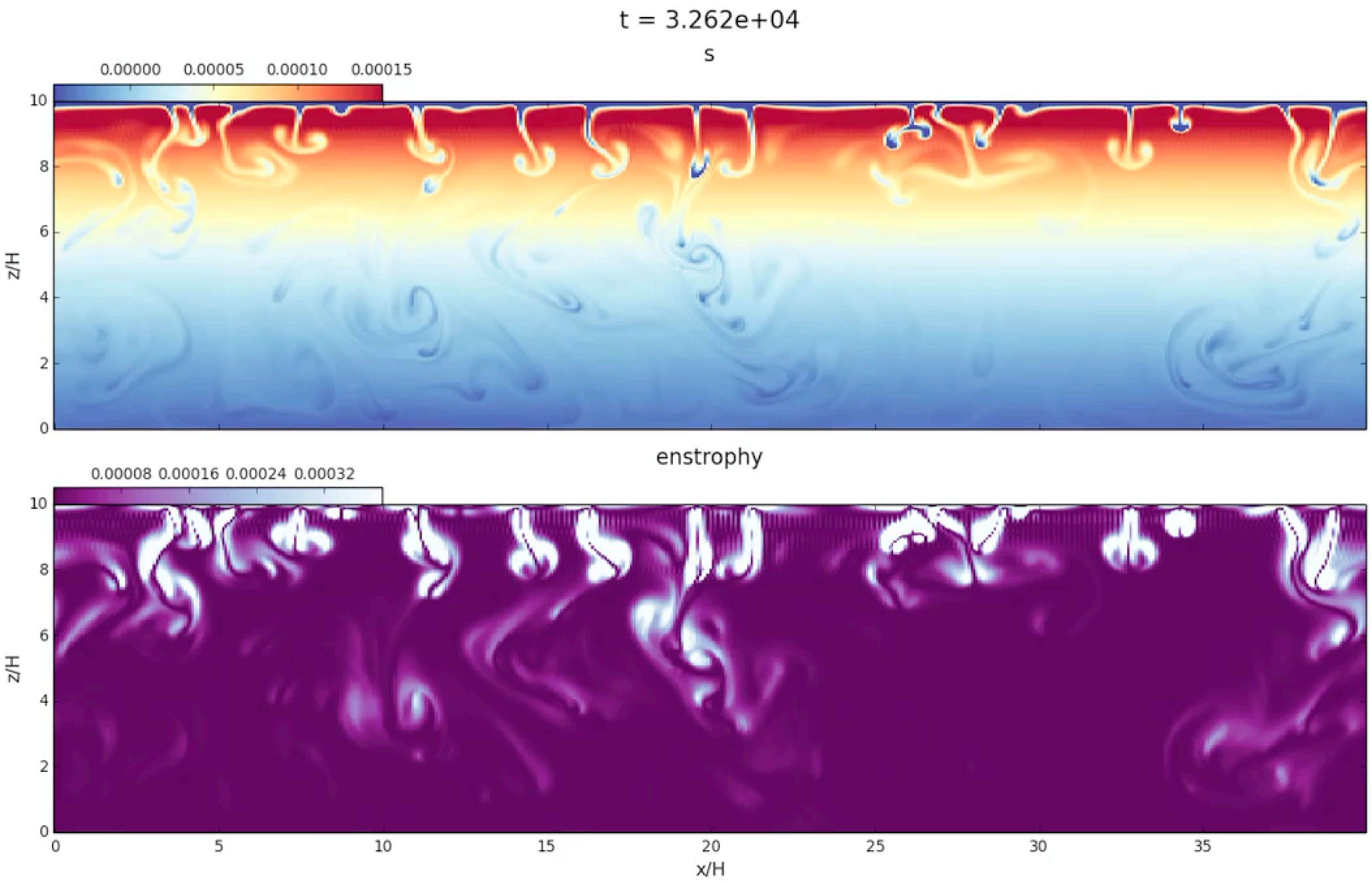
Personal views

- Simulations lie
- Sometimes you can catch them
- Sometimes you can’t
- So what do we do?

Some ways we can be wrong…

- Errors of numerics
  - you're solving the problem wrong on a computer; this one we can catch
- Errors of approximation/model
  - you're solving a different problem than the real one (deliberately, or not)
- Errors of application
  - you're not solving the problem you think that you're solving (this one's nasty…)

Errors of numerics



Here is a 2-D simulation of something. The mistake made is that the resolution is too low. Under-resolution can do a lot of things; most of them don't obey physics.

This is a spectral code, so when problems happen, they're O(1). That's a feature.

If you don't catch them, the sim may continue, but it's no good any more.

Errors of approximation/model

Now you’re changing the simulation. Maybe you’re doing 2-D rather than 3-D. Or maybe you’re solving a different set of equations (e.g., Boussinesq) rather than the real ones (e.g., fully compressible). Or you’re in the wrong geometry. This can be fine.

Or not.

But it’s a choice. And we can all discuss choices like civilized people.

An example: different models for low Mach flows

$$\nabla \cdot \boldsymbol{u} = 0$$

Boussinesq
(incompressible flow & buoyancy)

$$\nabla \cdot \boldsymbol{u} = -\boldsymbol{u} \cdot \nabla \ln \rho_0$$

Anelastic
(adds stratification)

$$\nabla \cdot \boldsymbol{u} = -\frac{\boldsymbol{u} \cdot \nabla \ln P_0}{\Gamma_1(P_0, \rho)}$$

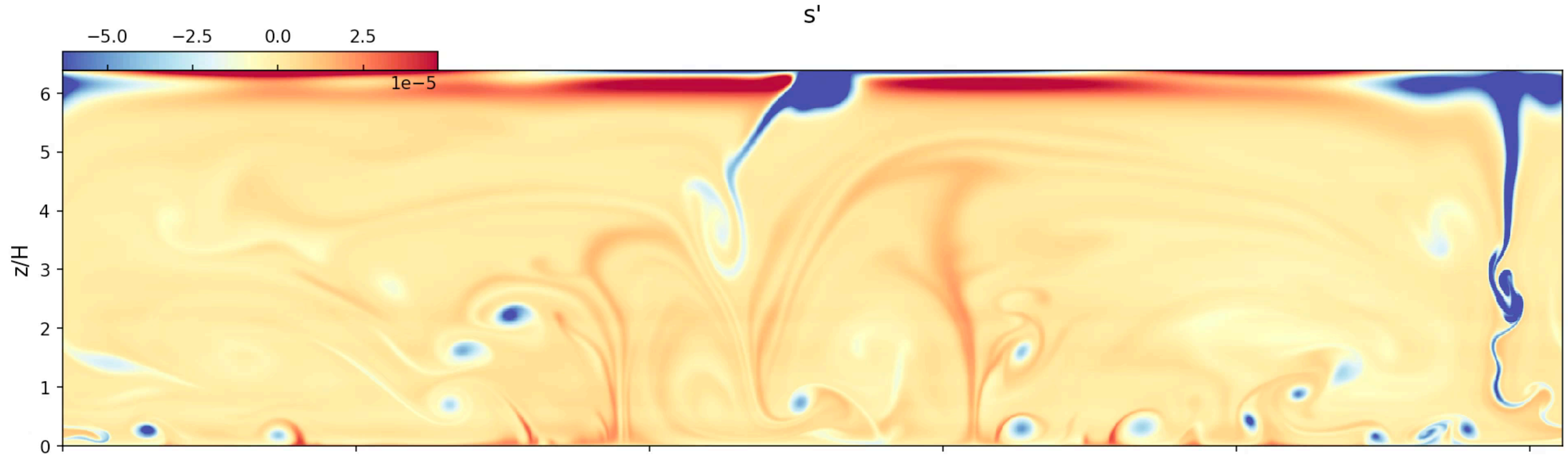
Generalized PI
(adds finite amplitude thermal perturbations; generalizes EOS)

$$\nabla \cdot \boldsymbol{u} = -\boldsymbol{u} \cdot \nabla \ln \rho - \partial_t \ln \rho$$

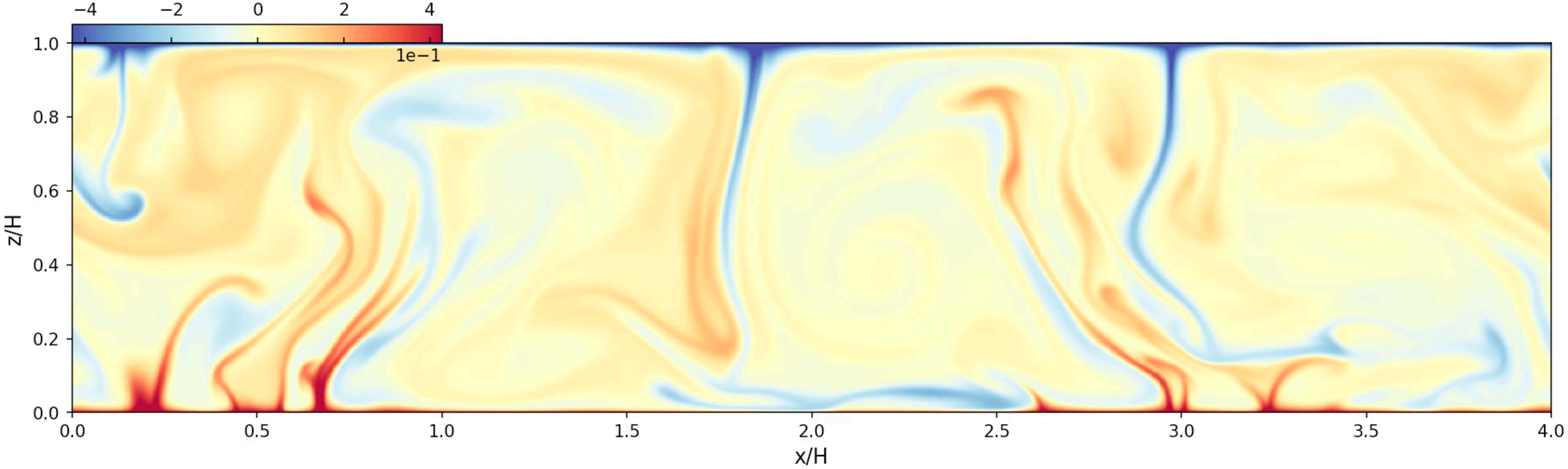
Fully compressible
(the real deal)

(Brown, Vasil & Zweibel 2012; Vasil, Lecoanet, Brown, Wood & Zweibel 2013)

Stratified, fully compressible convection



Non-stratified, boussinesq convection



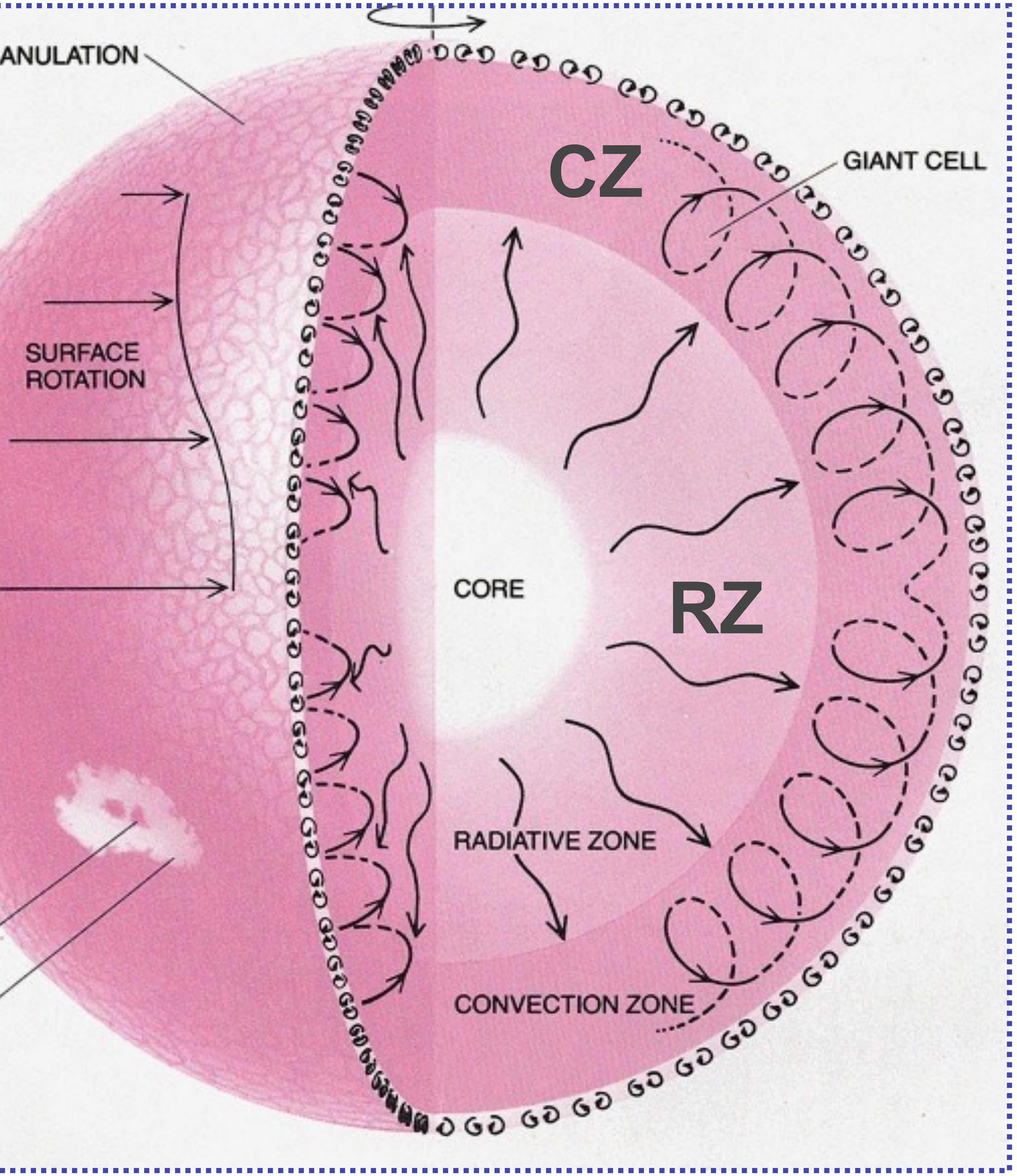
Both of these are 2-d.

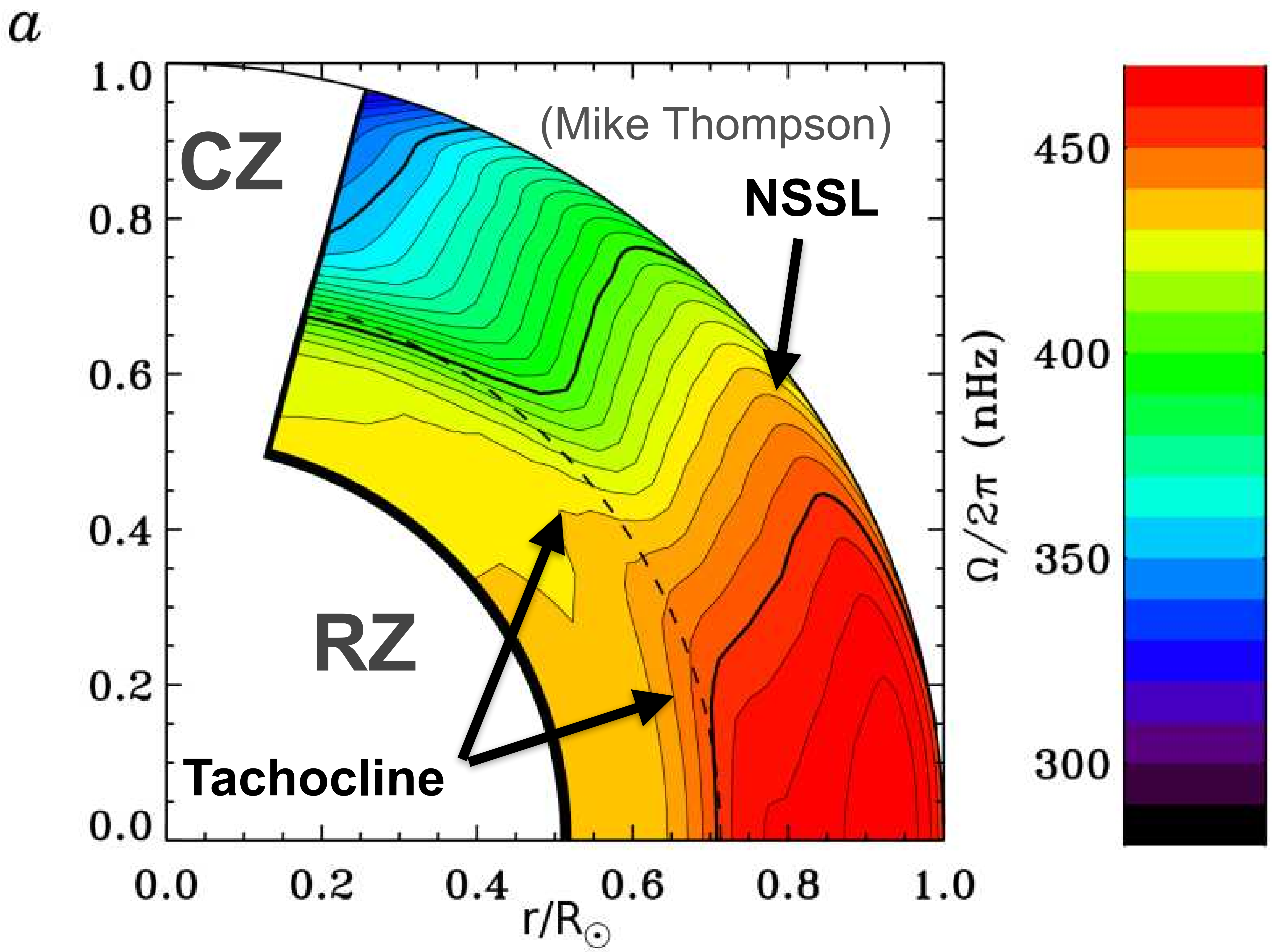
There are some shared similarities, and some differences. That may or may not matter.

If you're careful, you can learn from either of these.

$$\nabla \cdot u = 0$$

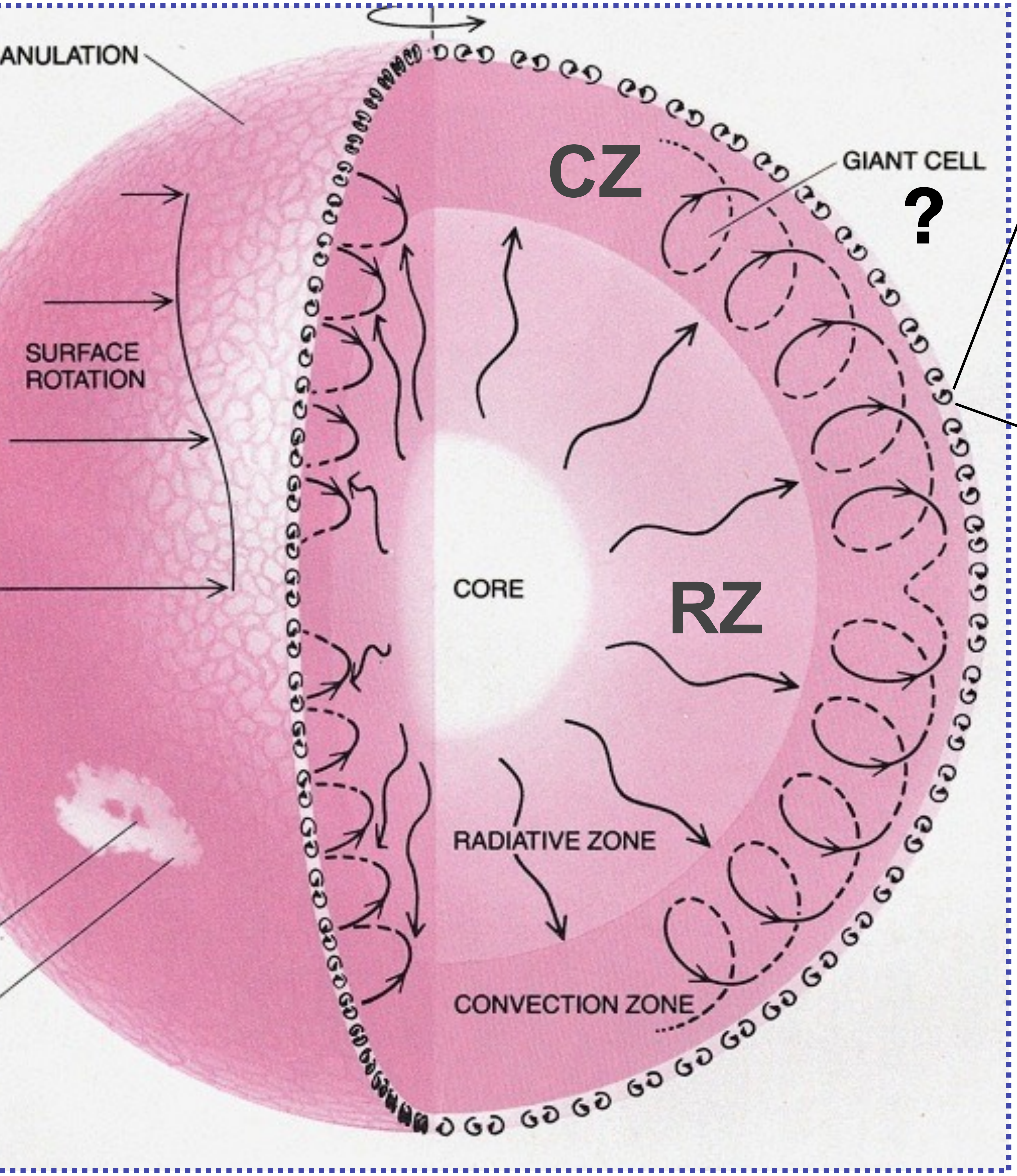
Inside our Sun: mysteries on the large scales

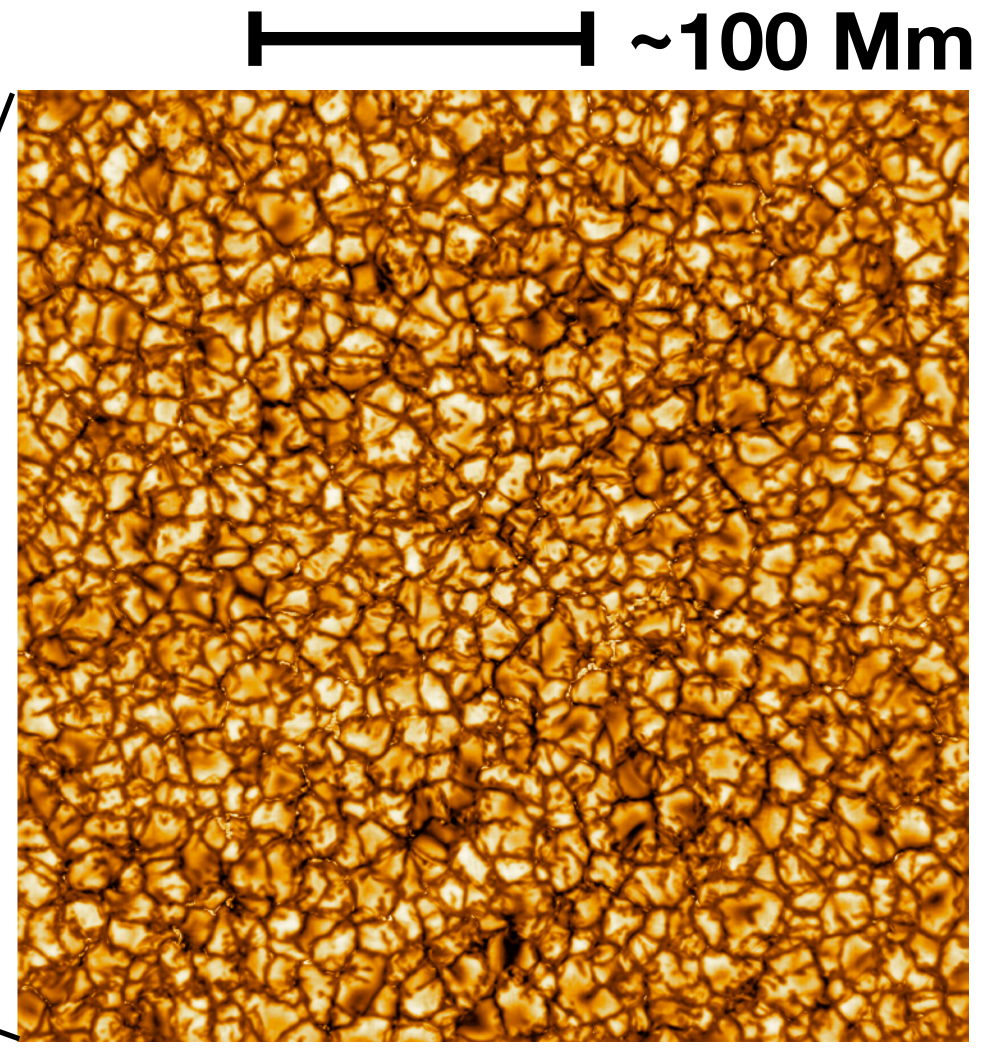




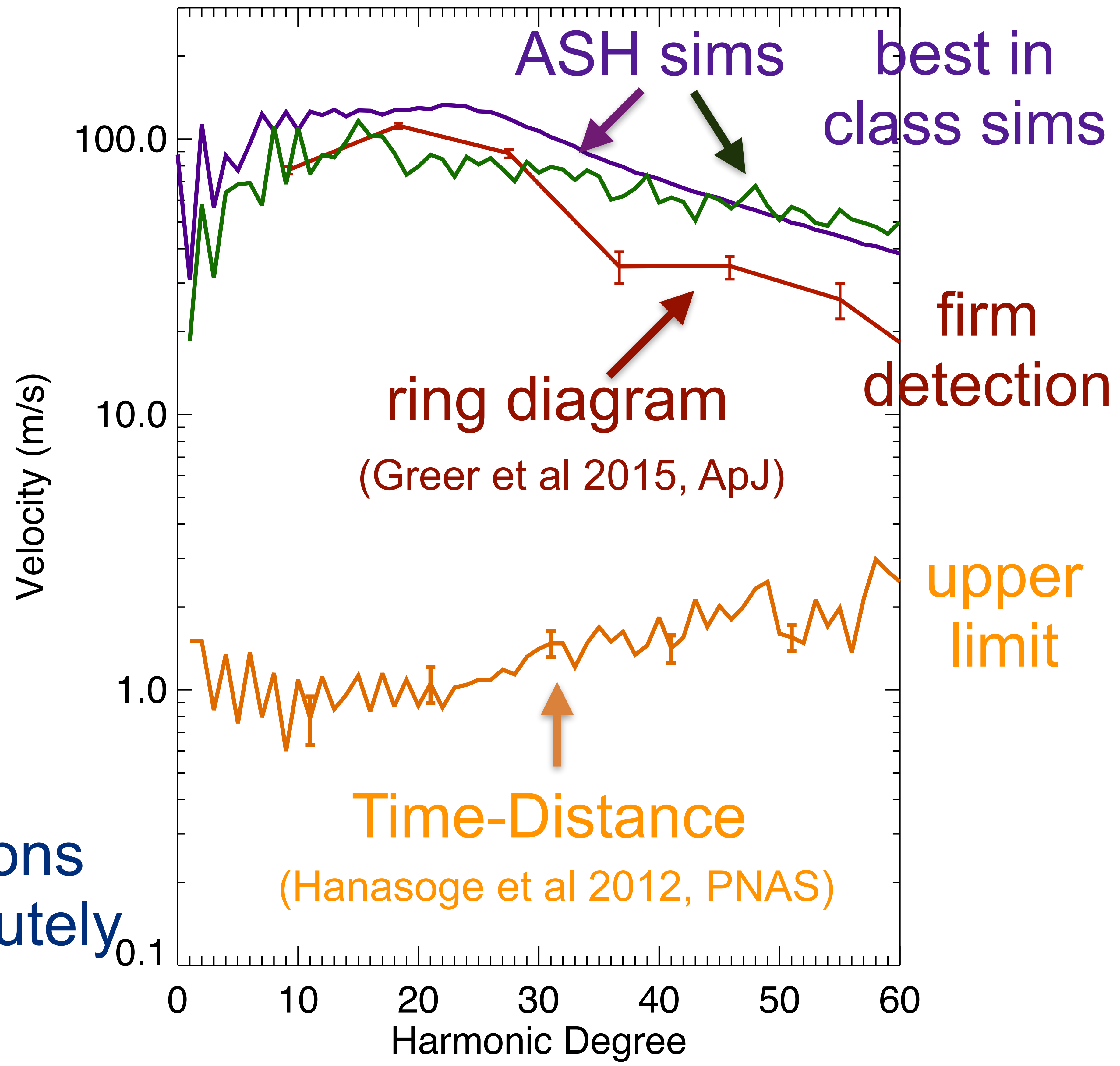
- Why does the interior of the Sun rotate like it does?
- The NSSL is MRI unstable; what does that mean?
- Where are the solar global-scale magnetic fields built?

Inside our Sun: mysteries on the large scales





DKIST, granulation



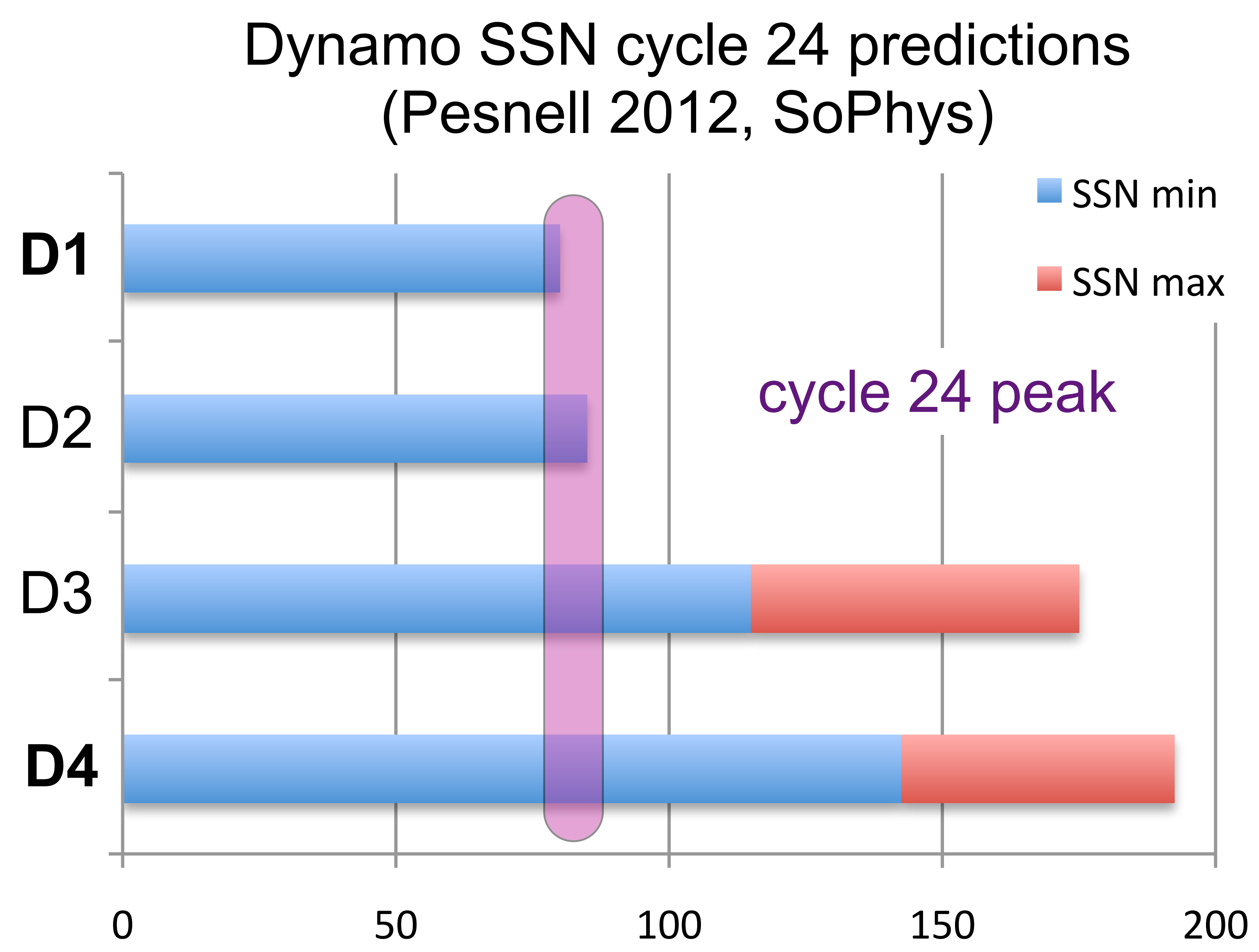
NASA SDO, giant cells

Helioseismic observations of giant cells have absolutely huge disagreement.

- **Why does the interior of the Sun rotate like it does?**
- **The NSSL is MRI unstable; what does that mean?**
- **Where are the solar global-scale magnetic fields built?**

- **Where are the giant cells of convection?**

Solar Dynamo Models: some history



2D: Mean-field models

- α-Ω type
- interface dynamos
- flux-transport and many variants (e.g. Babcock-Leighton)

Computationally inexpensive: simulate many cycles, try many ideas

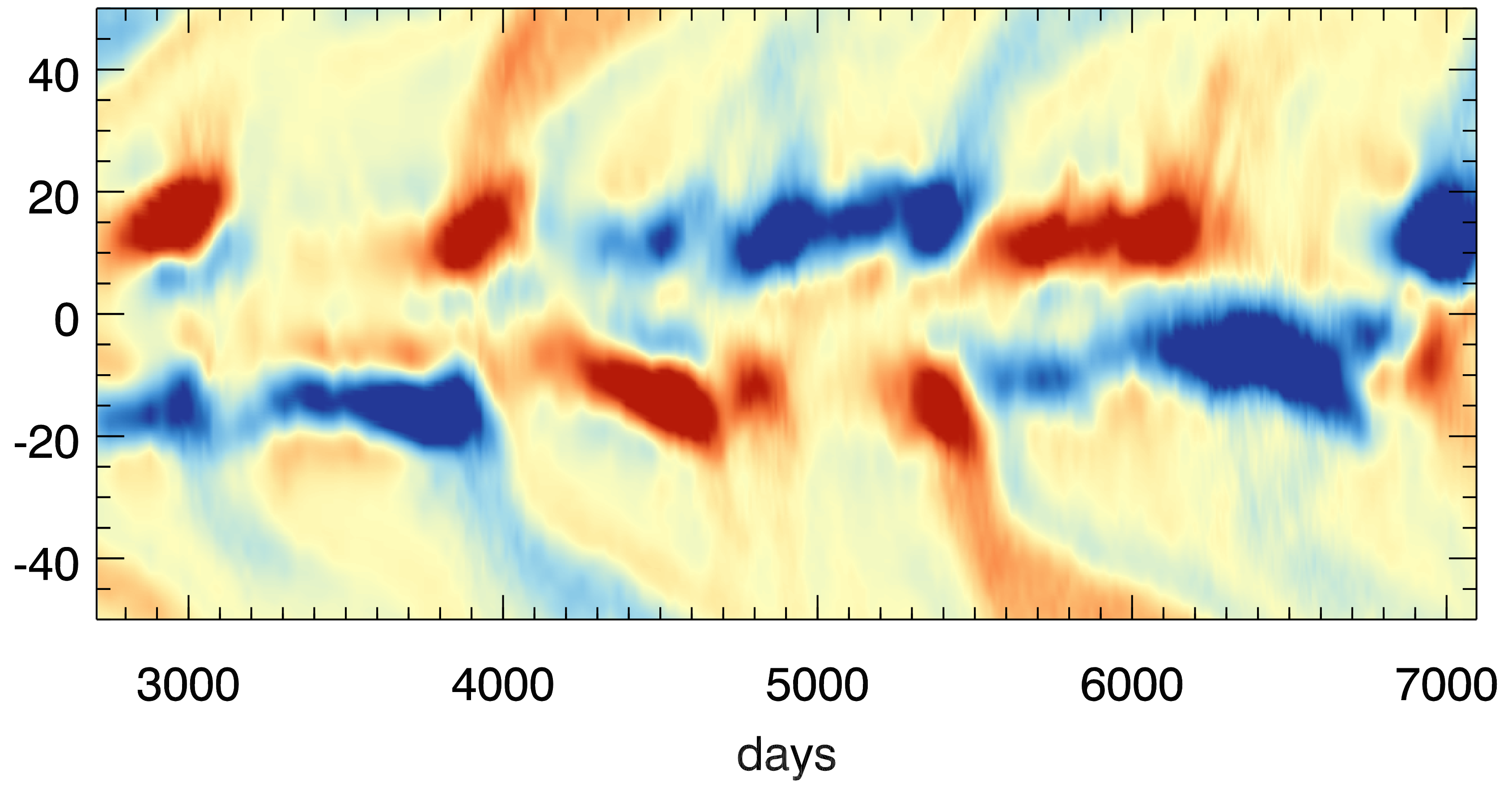
In a position to try solar predictions (but parameterize convection)

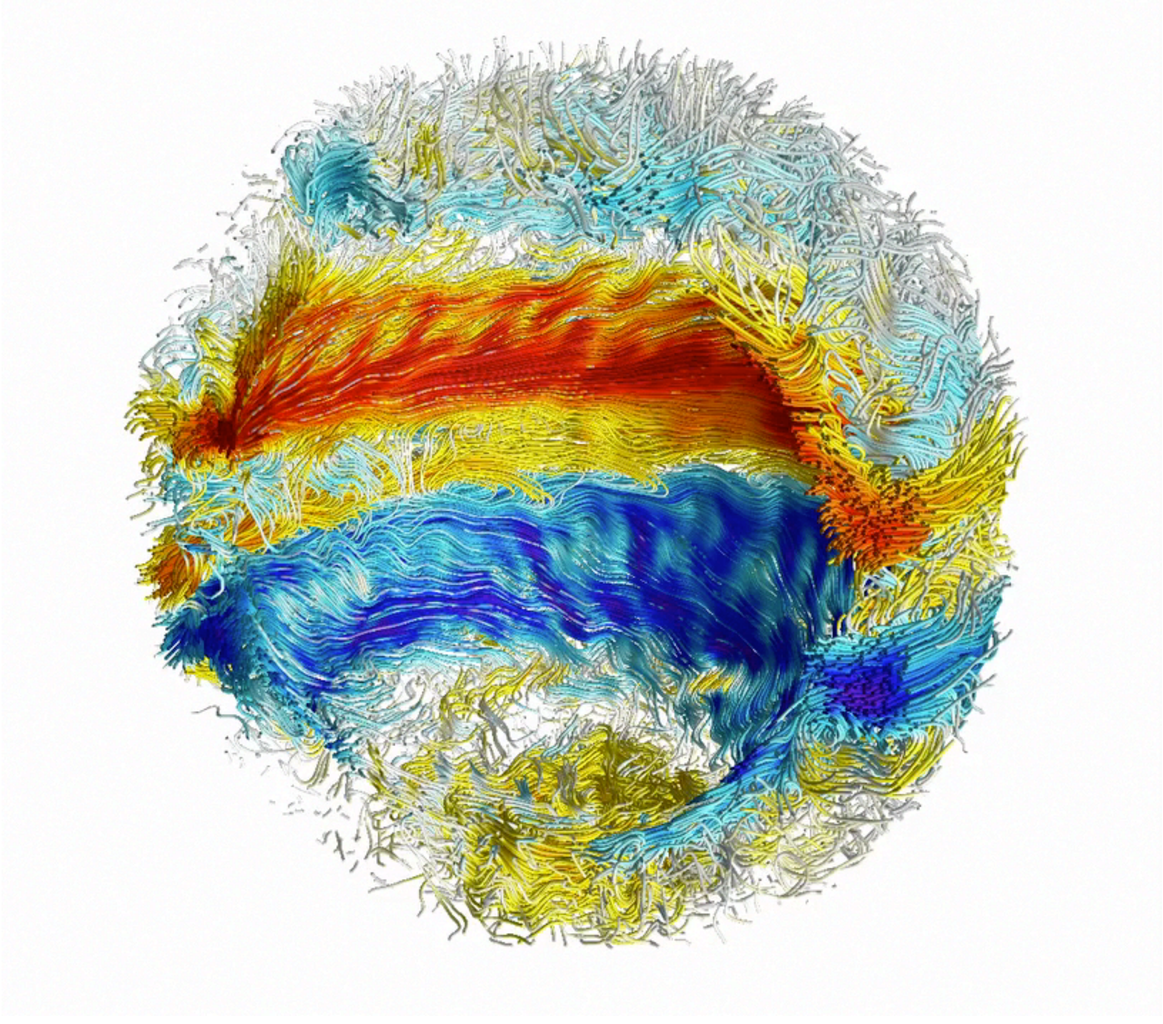
3D: Convection, Rotation & Magnetism

- global-scale flows, magnetism, coupling from first principles
- now achieving cyclic behavior, buoyant magnetic structures

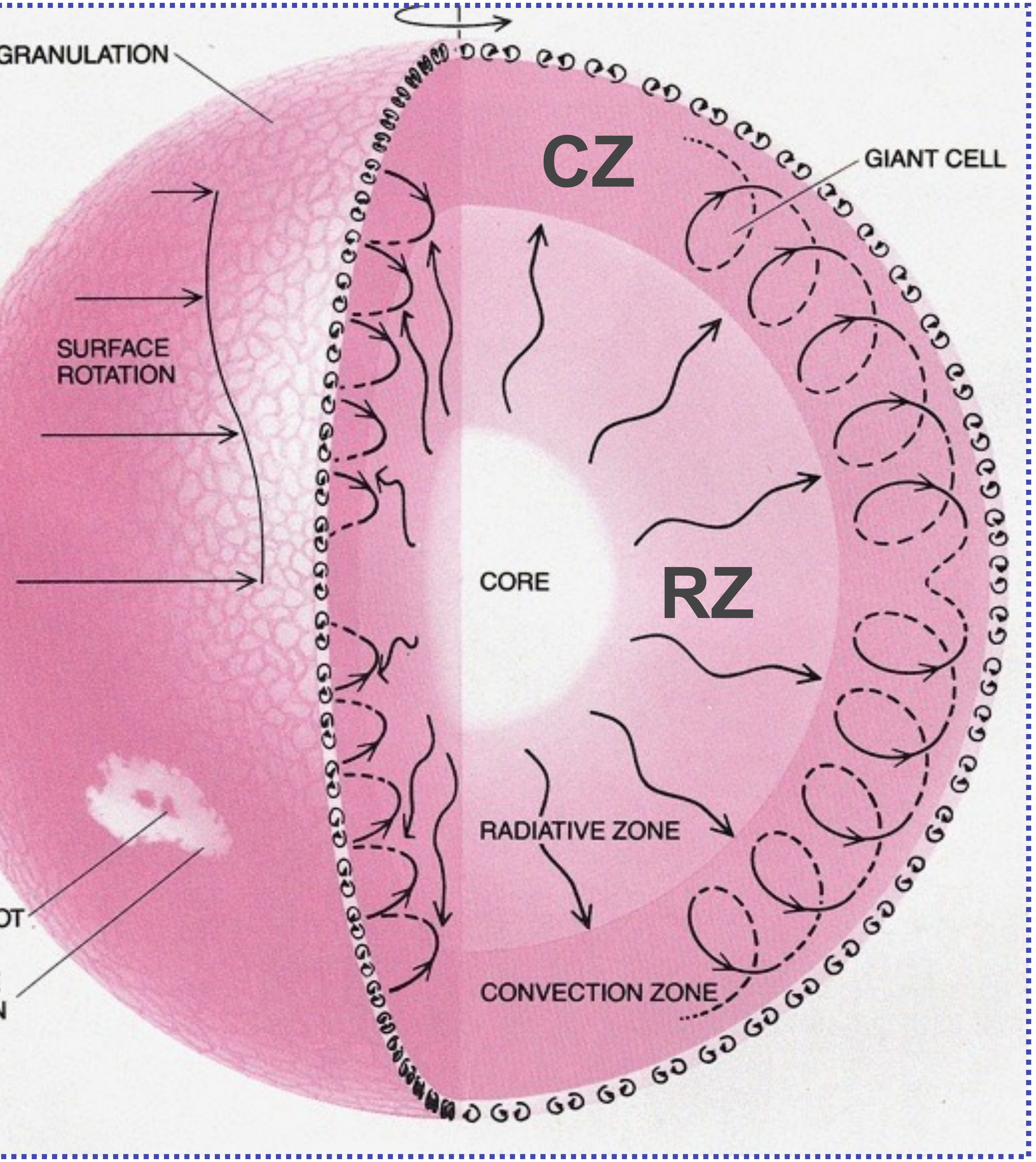
Computationally expensive

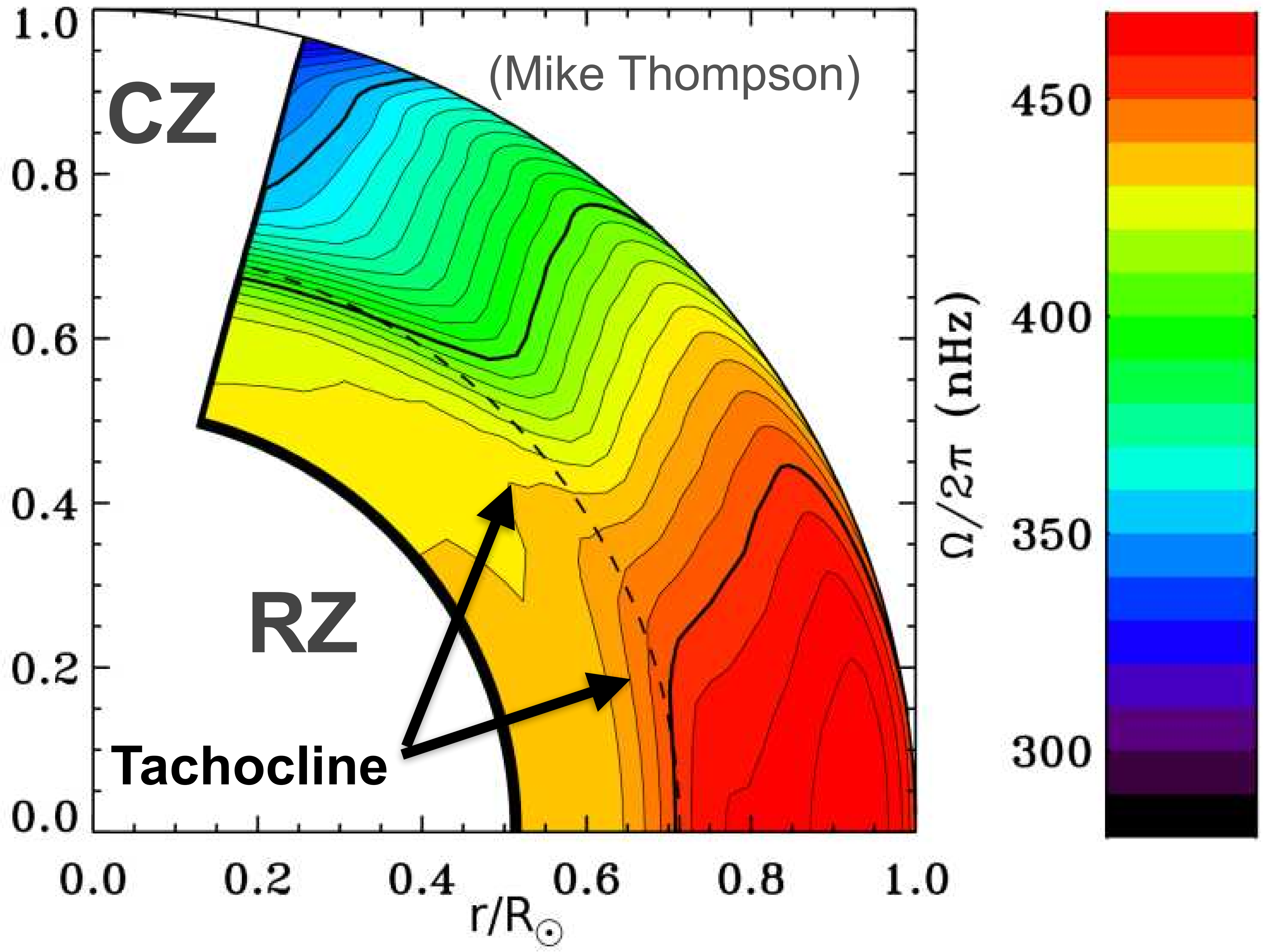
Solar parameters well out of reach





Inside the Sun





Properties of deep solar convection

(CZ depth of 200 Mm or 0.3R$_{sol}$)

Re ~ 10^{15} E ~ 10^{-15} Pr ~ 10^{-5} Pm ~ 10^{-2}

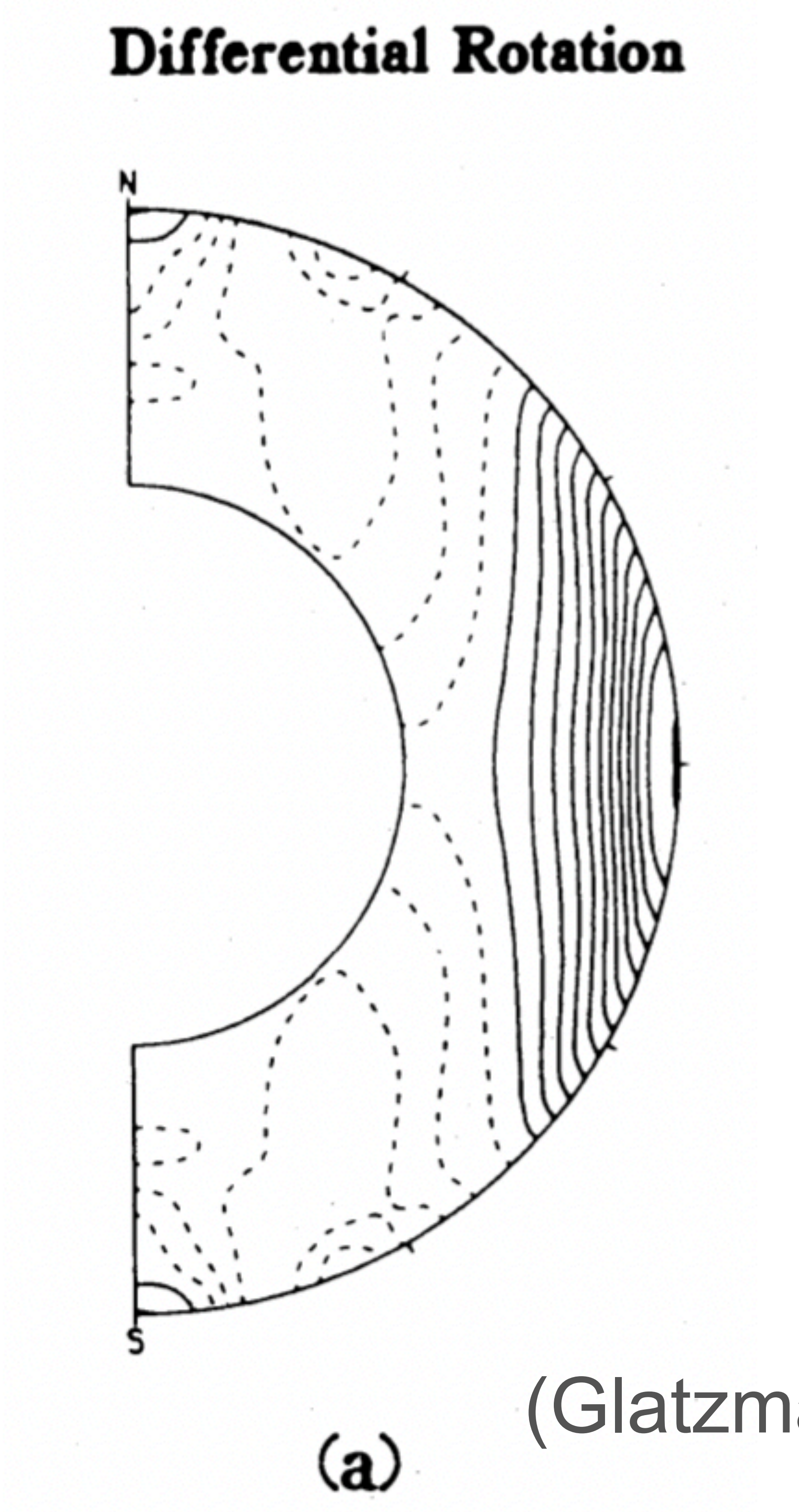
Ro ~ 1 (or maybe small!)

Tachocline is <5% thickness

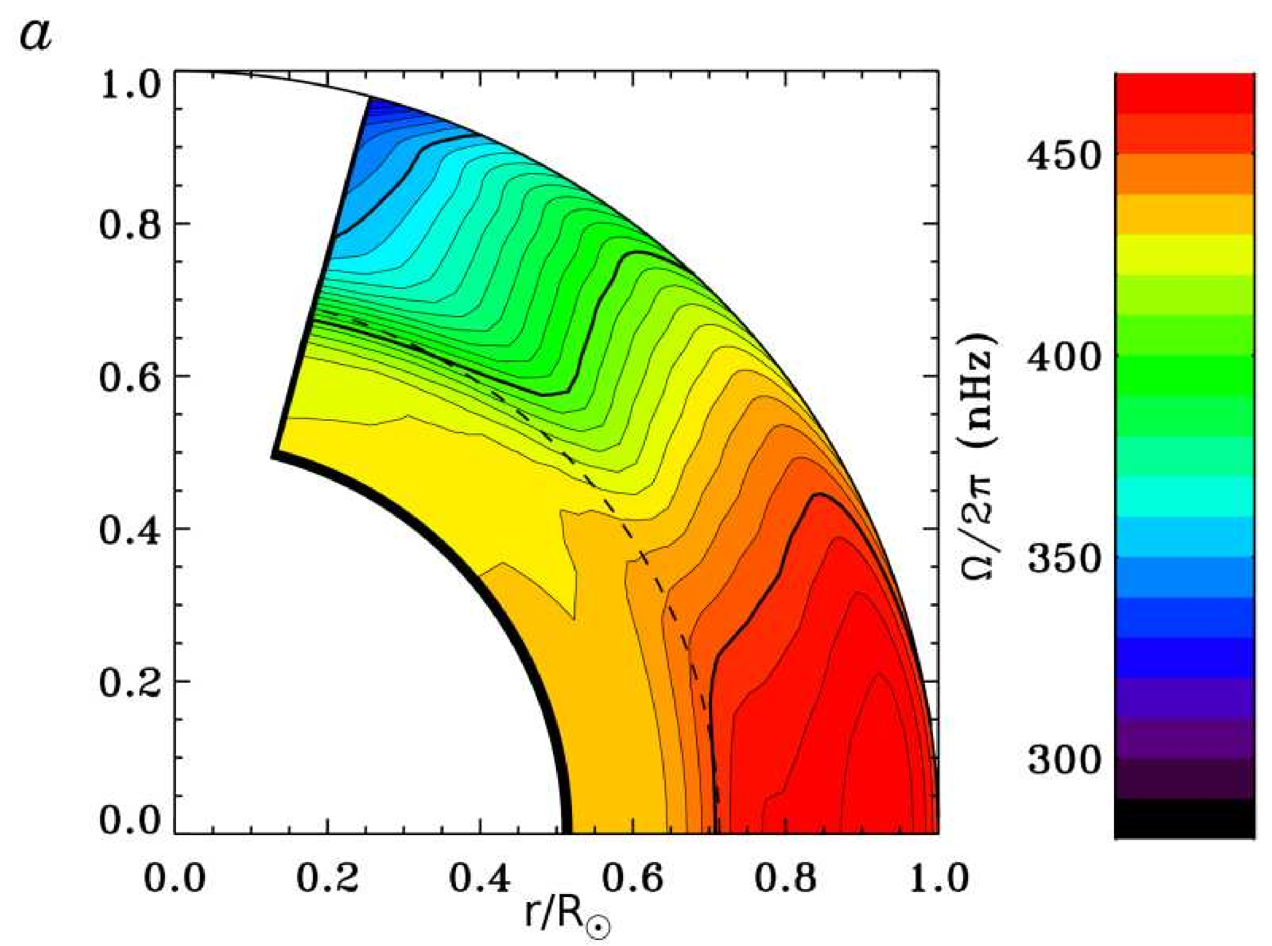
History

- **Gilman and Glatzmaier develop the first 3-D, spherical, global solar dynamo models (1980's). Boussinesq turned to anelastic, and Glatzmaier 1985 got anelastic dynamos.**

- **Resolutions were low, dynamics were limited, differential rotation was solar-like.**



(Glatzmaier 1985)



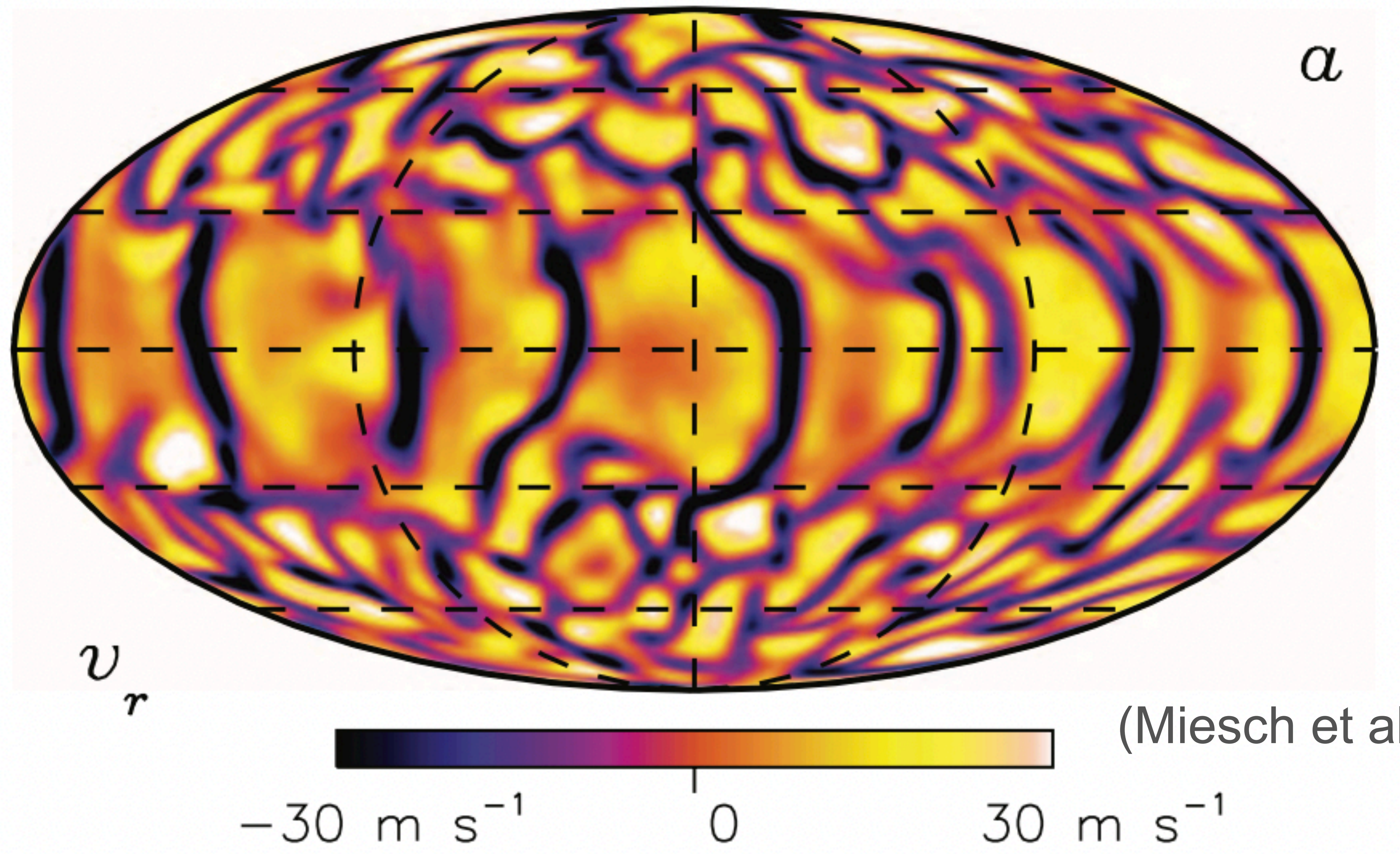
(Mike Thompson)

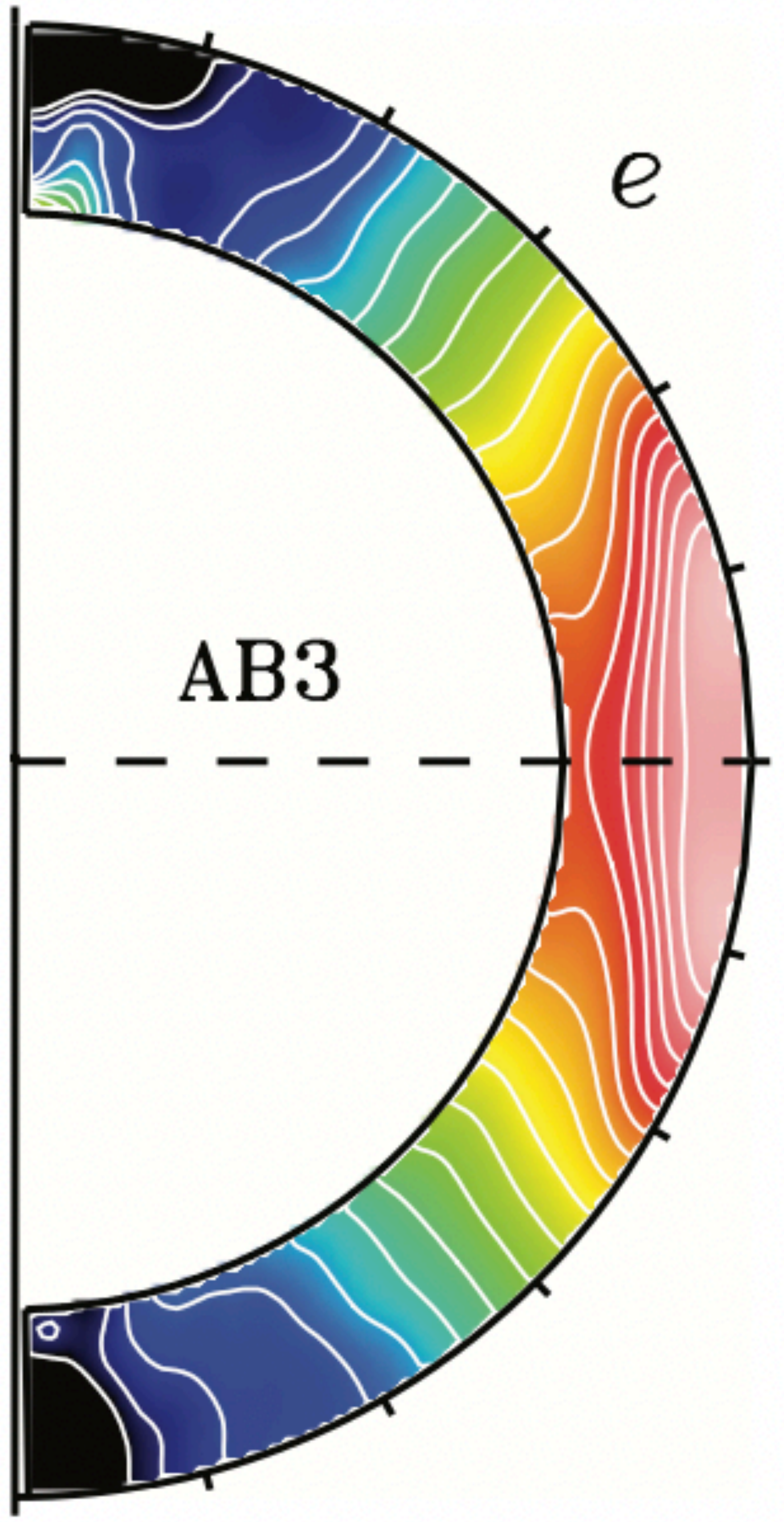
History

- **In the 2000's, Juri Toomre lead a re-building of anelastic spherical codes for modern computers. The ASH mob was born.**

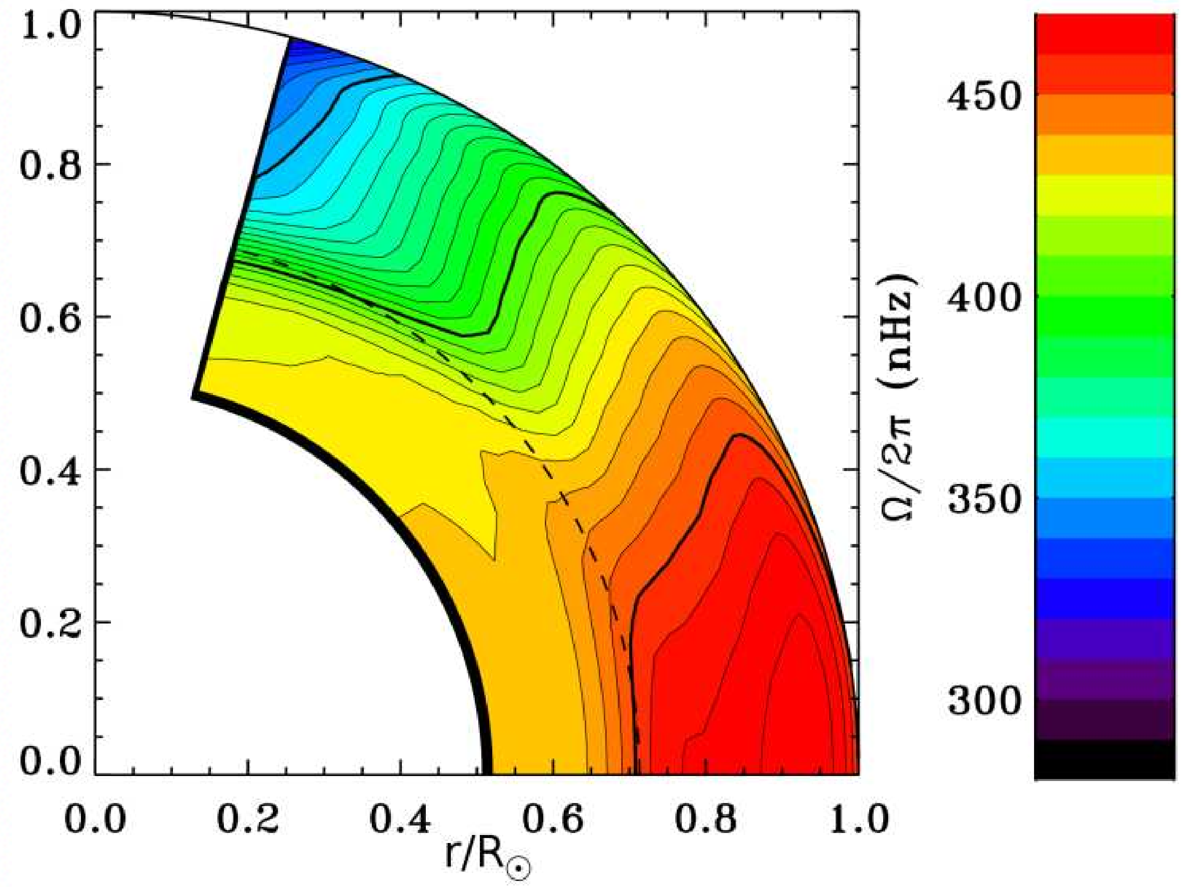
History

- ASH simulations of the Sun took off. First dynamo results (Brun, Miesch & Toomre 2004) lead to attempts to dial in the solar differential rotation (Miesch, Brun & Toomre 2006) guided by thermal wind theory by Rempel (2005). Resolutions were middling, time evolution was longish.





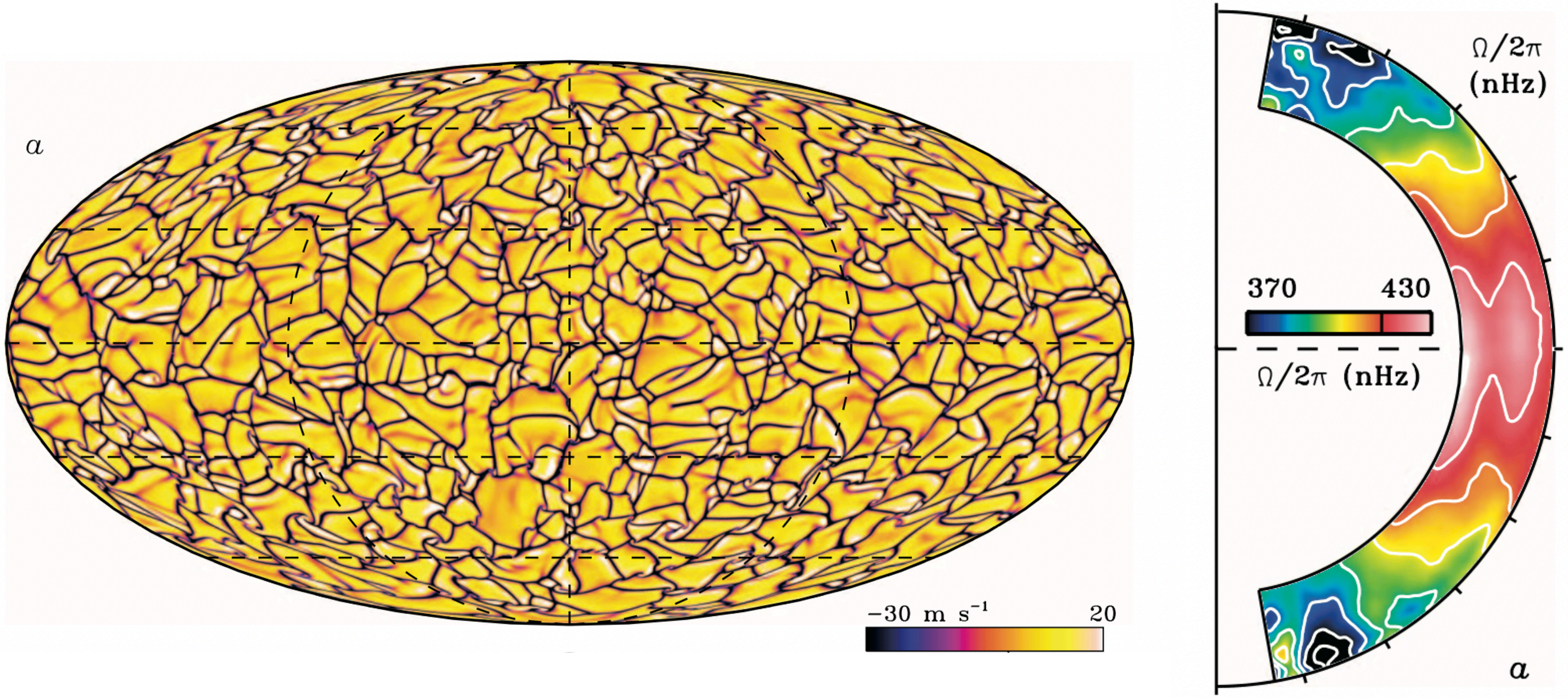
(Miesch et al 2006)



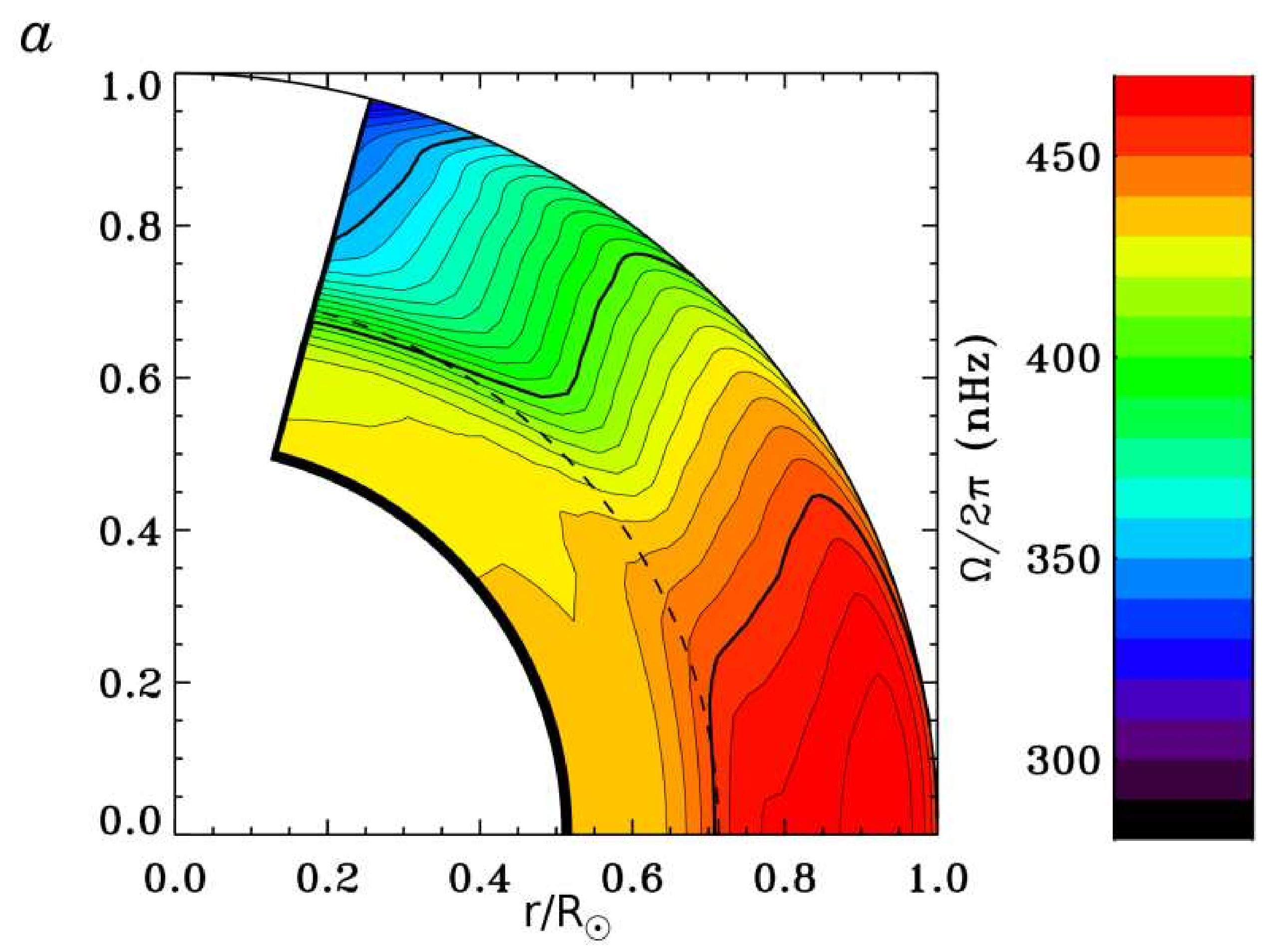
(Mike Thompson)

History

- Access to bigger computers meant bigger sims. Miesch et al (2008) was a high point (~1000³). Everything seemed fine. Sort of.



(Miesch et al 2008)



(Mike Thompson)

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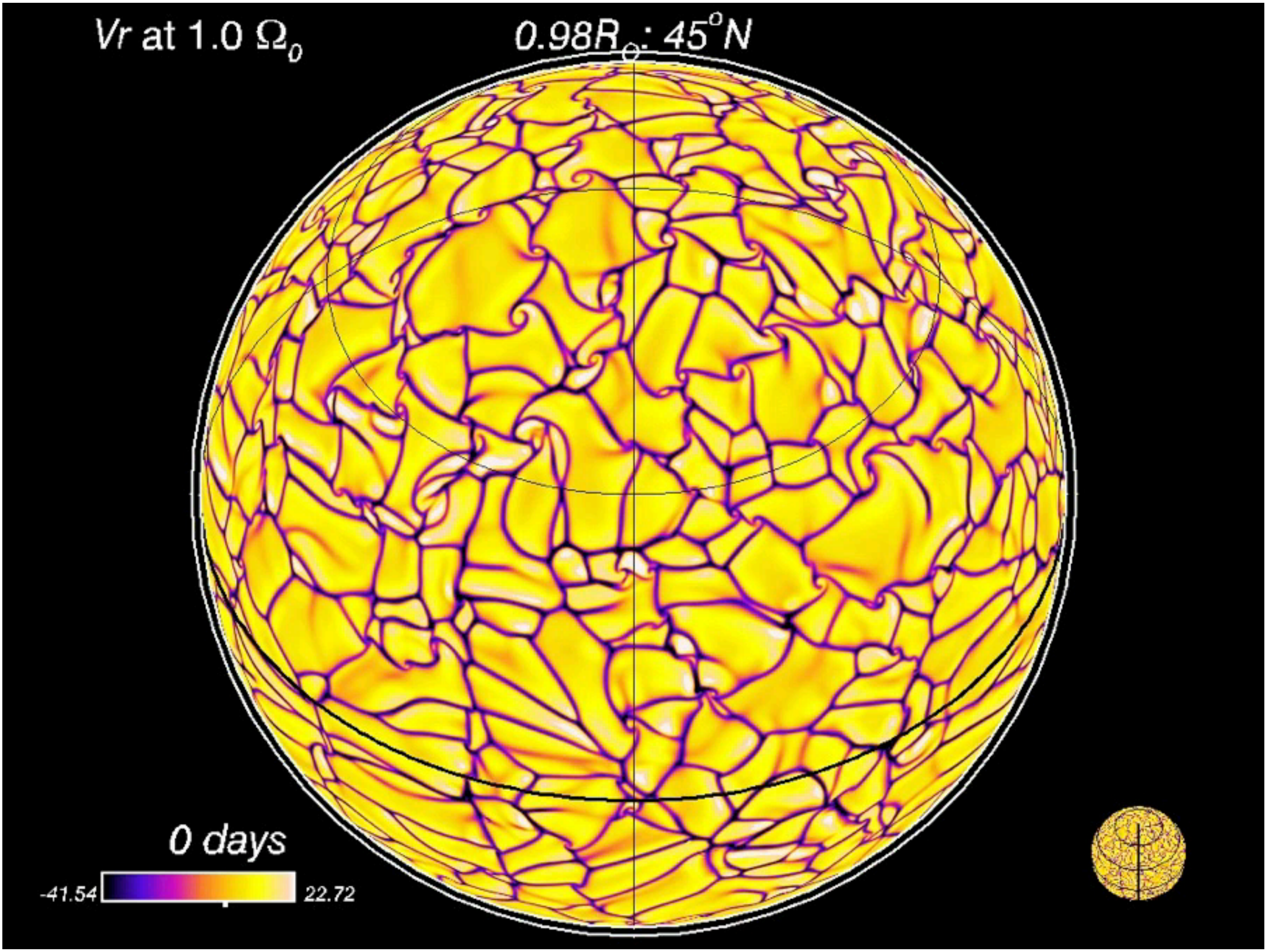
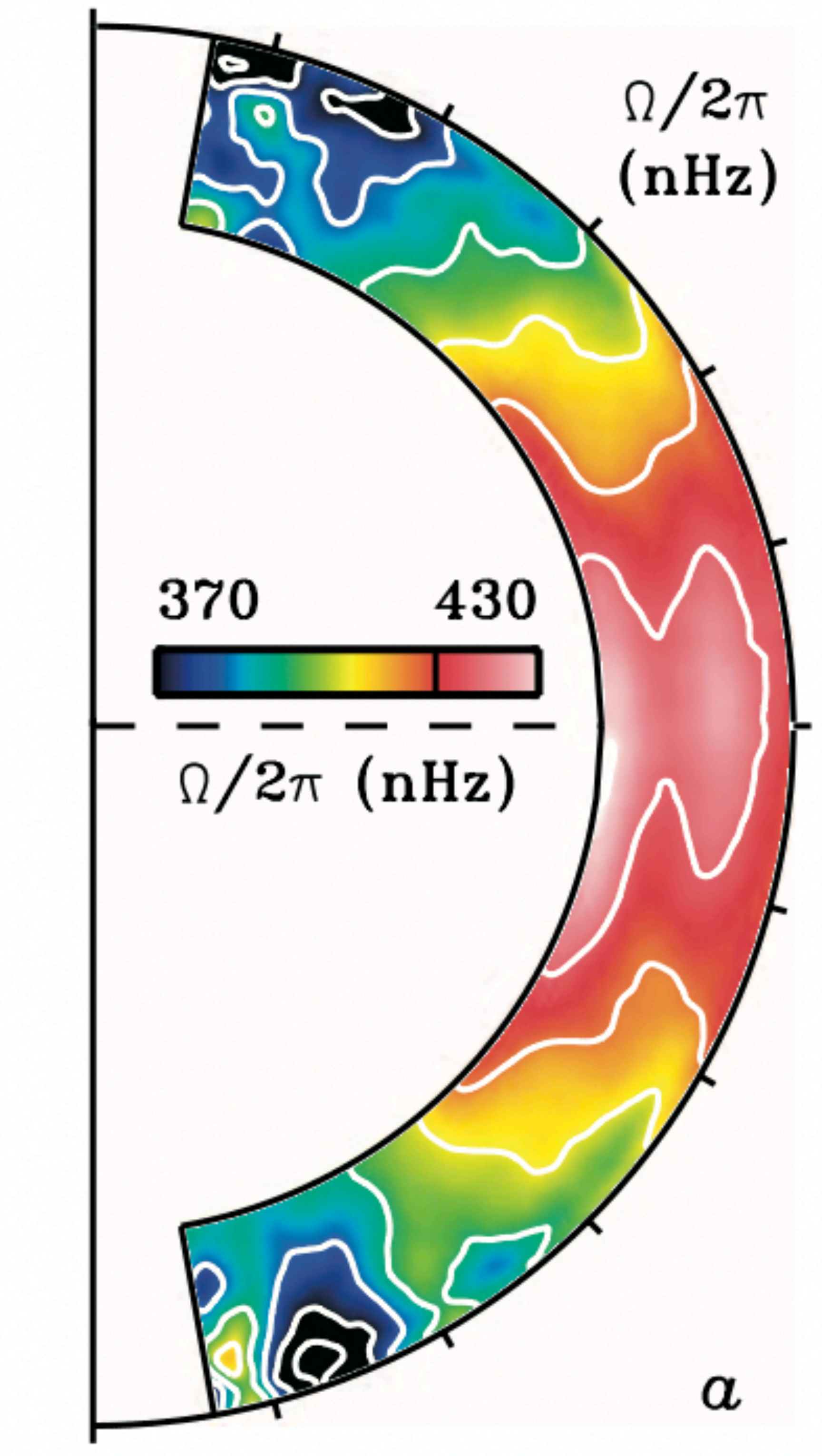
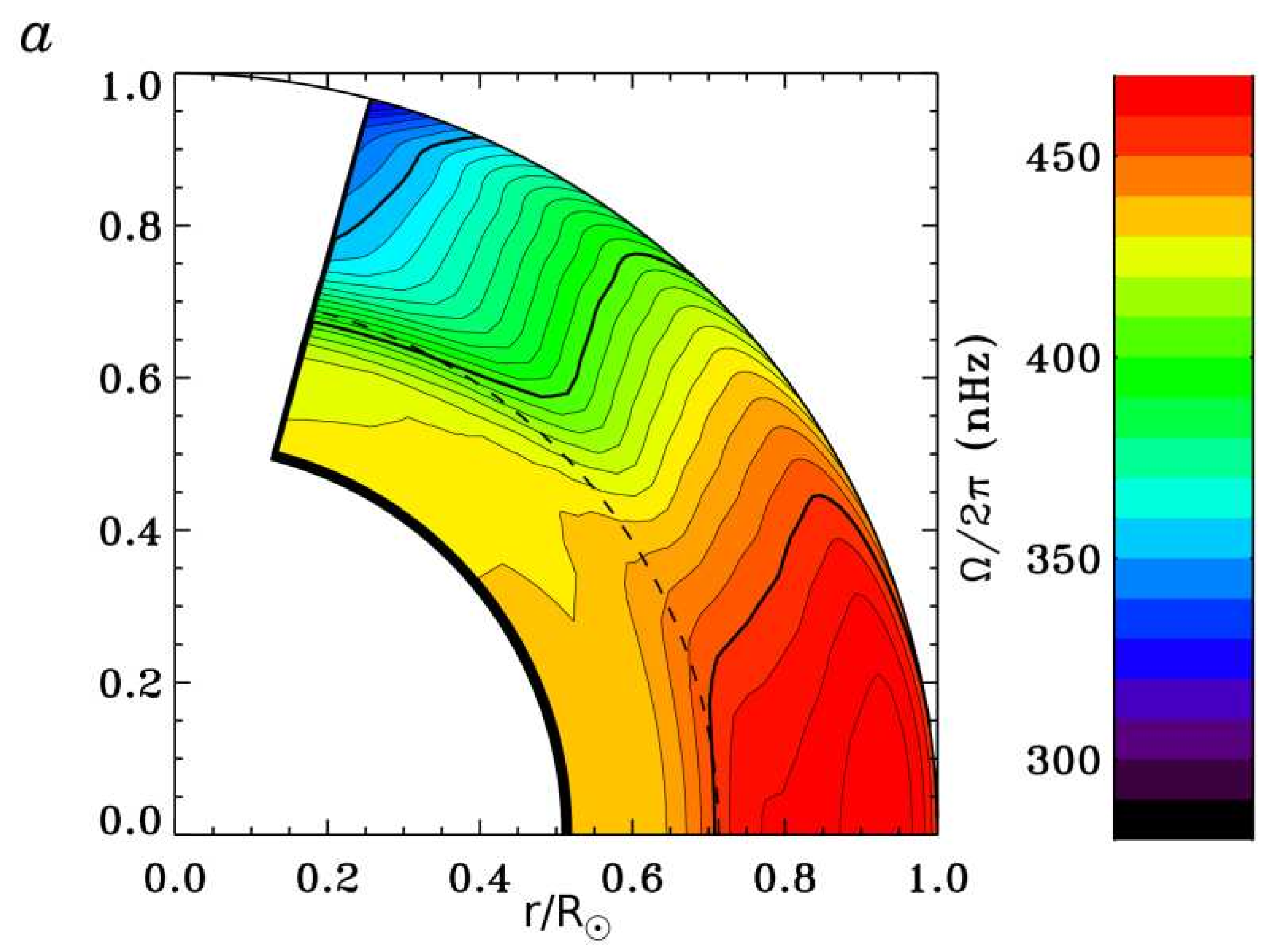




(Miesch et al 2008)



(Mike Thompson)

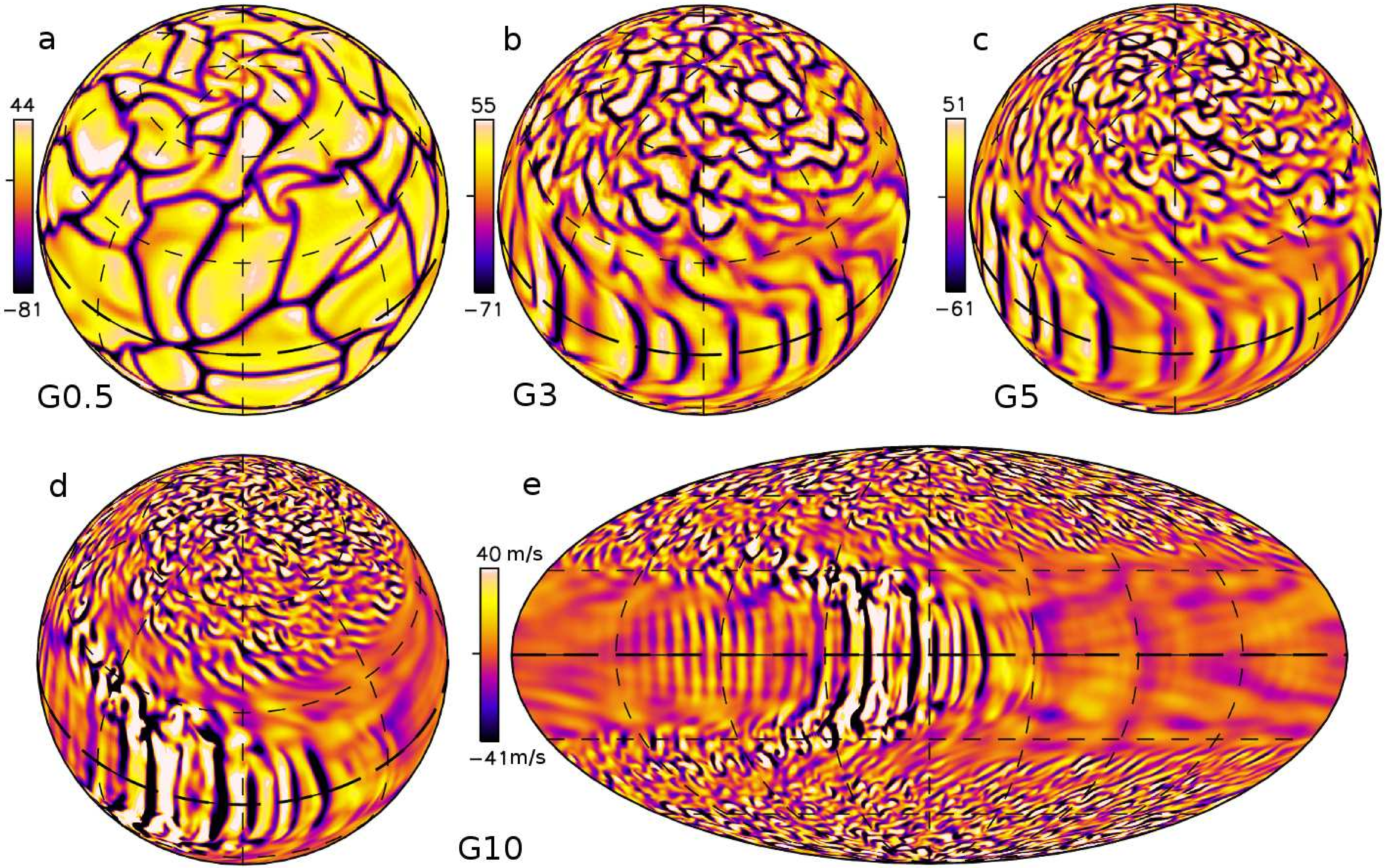
History

- At the same time, a bunch of (at the time) grad students started studying lots of other stars.

- Matt Browning: core convection in A-type stars, then M-dwarfs
- Ben Brown: rapidly rotating G-type stars
- Nick Featherstone: A-type stars with super-equipartition dynamos
- Kyle Augustson: F-type stars, then the Sun, then O & B-type stars
- Nick Nelson: G-type stars with fancy approaches to turbulence
- Jerome Ballot: young solar stars with deep CZs
- Laurene Jouve: magnetic flux ropes, babcock-leighton dynamos

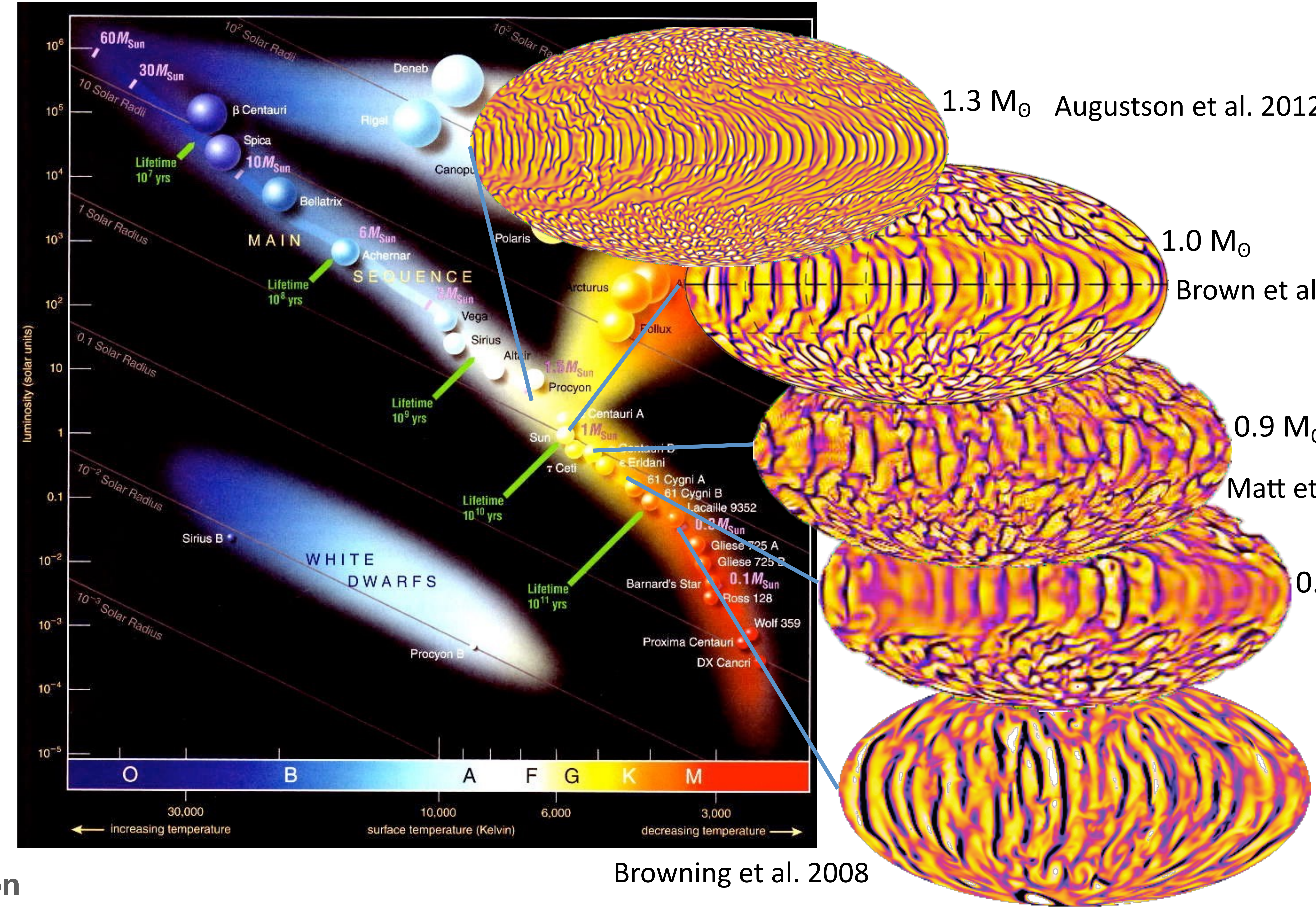
It was a bit of an industry. We learned lots of things.
Some of those still hold true.

Convection in G-type stars



(Brown et al. 2008)

Simulating the Main-Sequence



1.3 $M_\odot$ Augustson et al. 2012

1.0 $M_\odot$ Brown et al. 2008

0.9 $M_\odot$ Matt et al. 2011

0.5 $M_\odot$

0.3 $M_\odot$

Browning et al. 2008

Kyle Augustson

More history

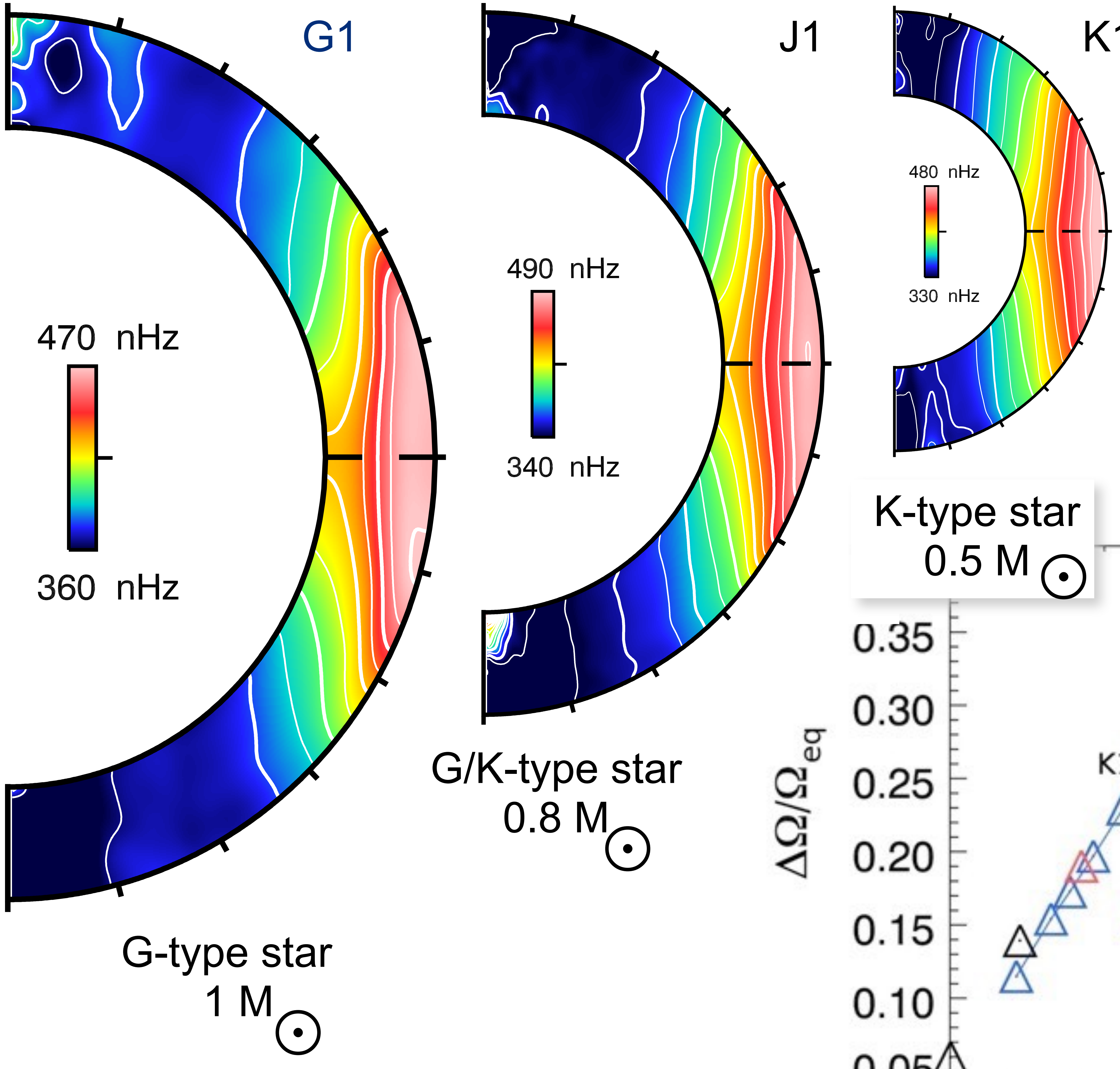
TCAN meeting
October 2013

Skyhouse,
San Luis Obispo

Ben waving arms,
Matteo taking photo,
Morro Rock in
background

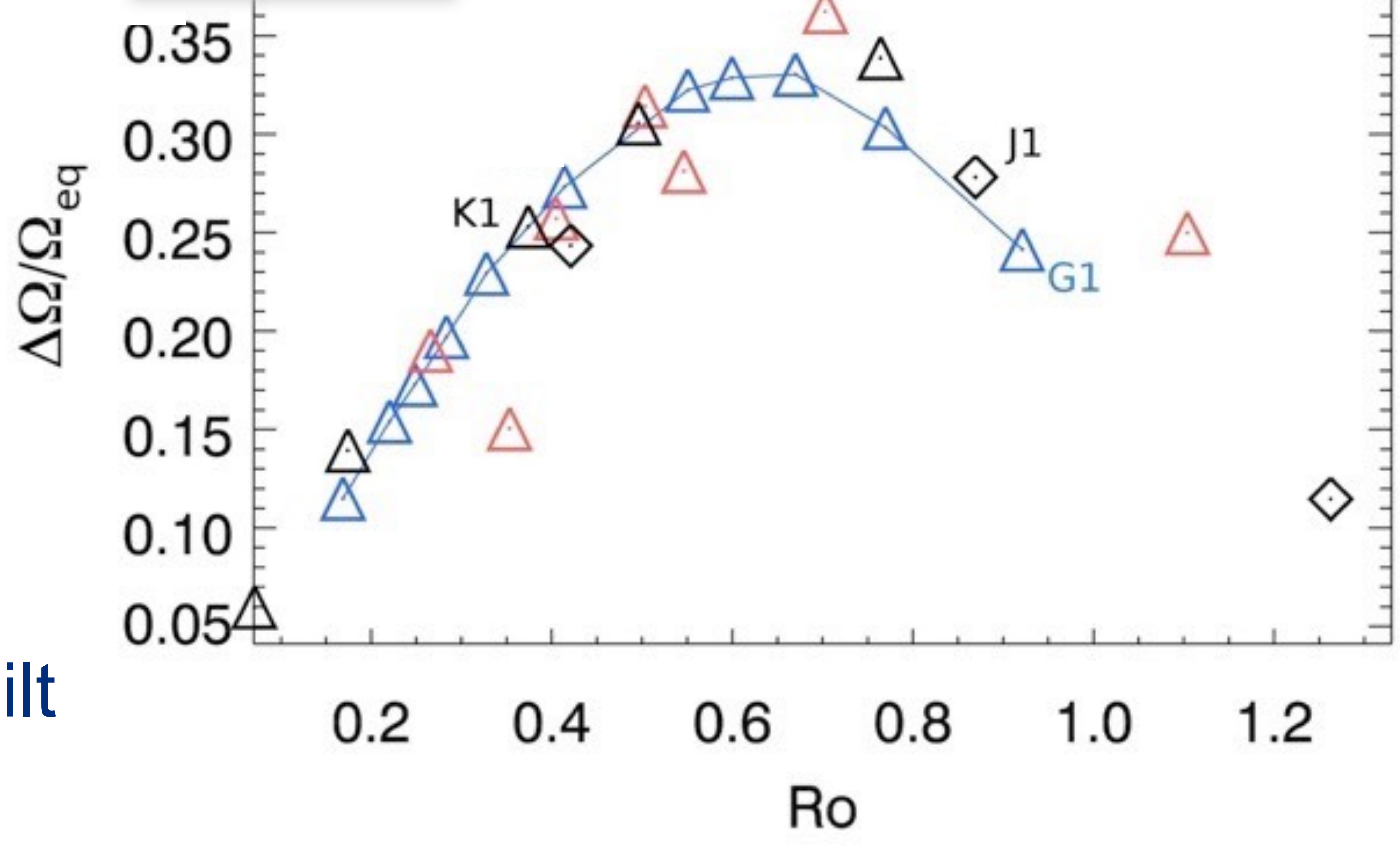
SPIDER

Differential Rotation in Other Stars



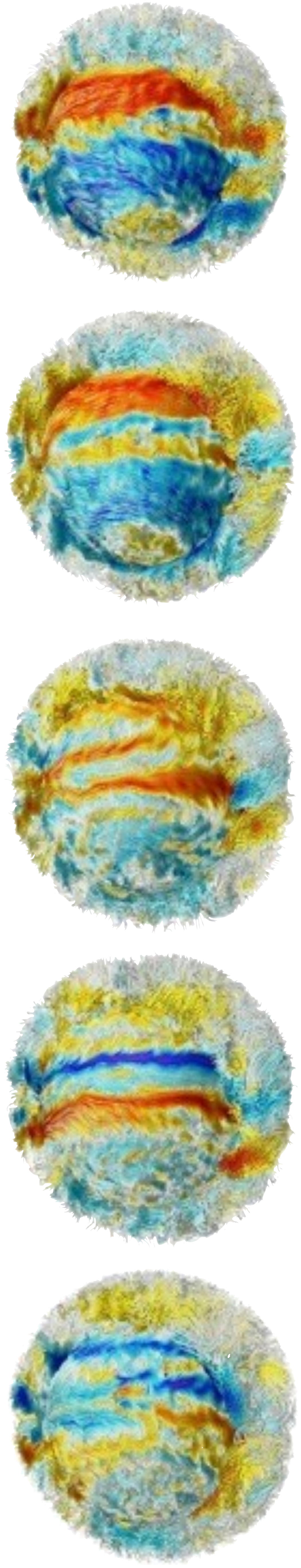
These models were attempting to be different stars, and to do it with "no free parameters" by using stellar structures, observed rotation rates, etc.

Rossby scaling



Stars of different masses, built off MESA structure models.

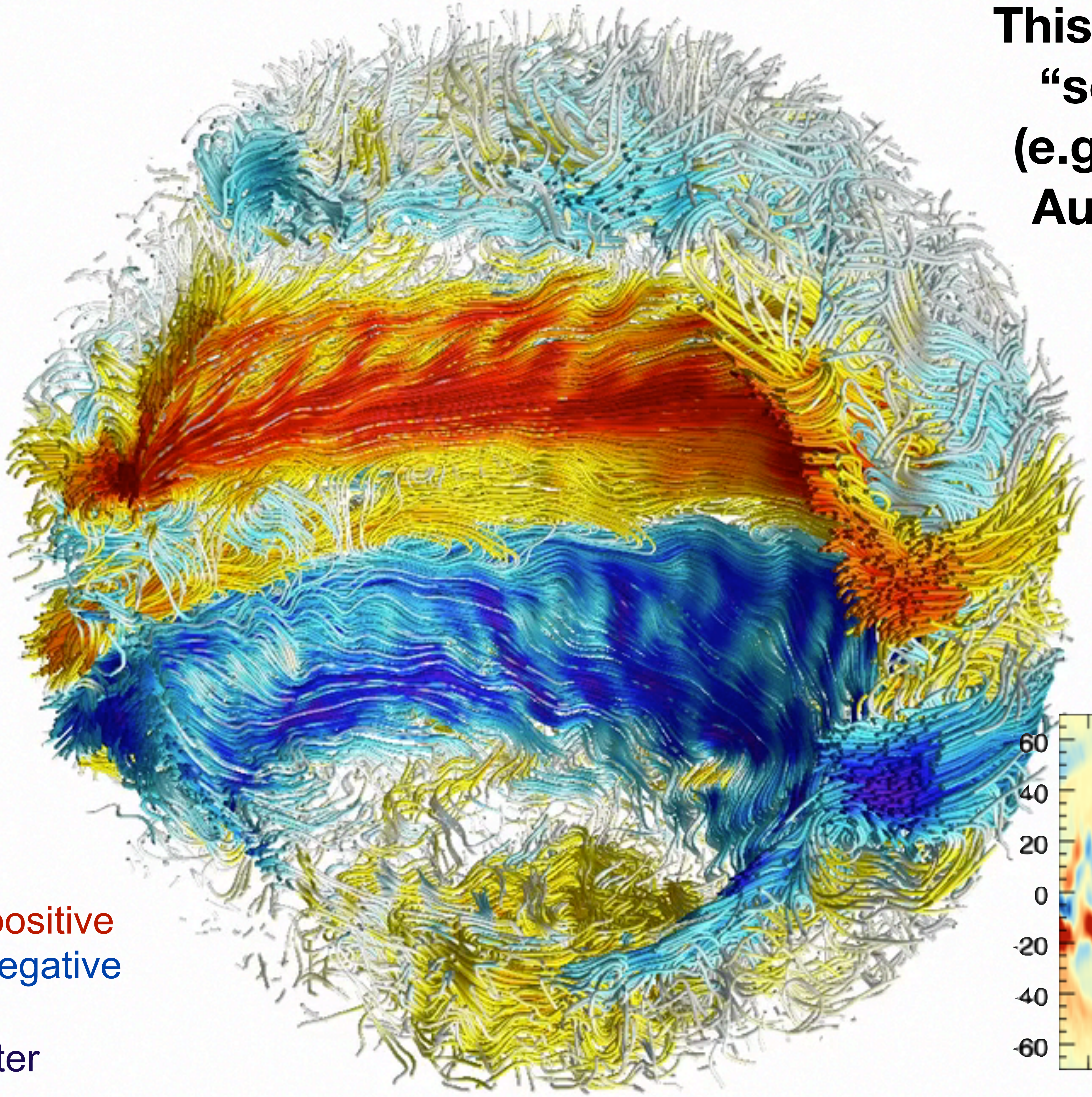
Convection zone dynamos with reversals



Shortly before

During reversal

Long after

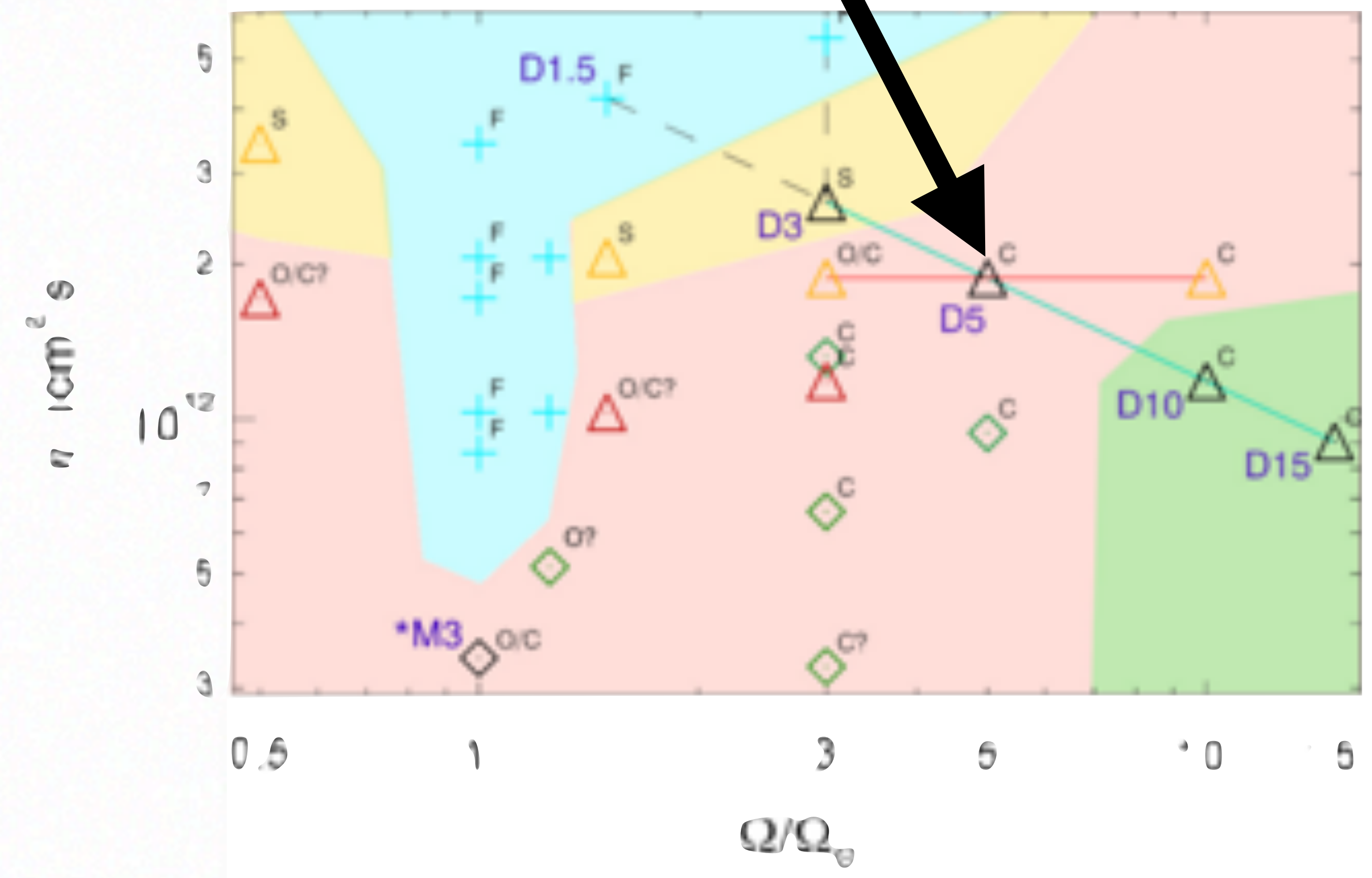


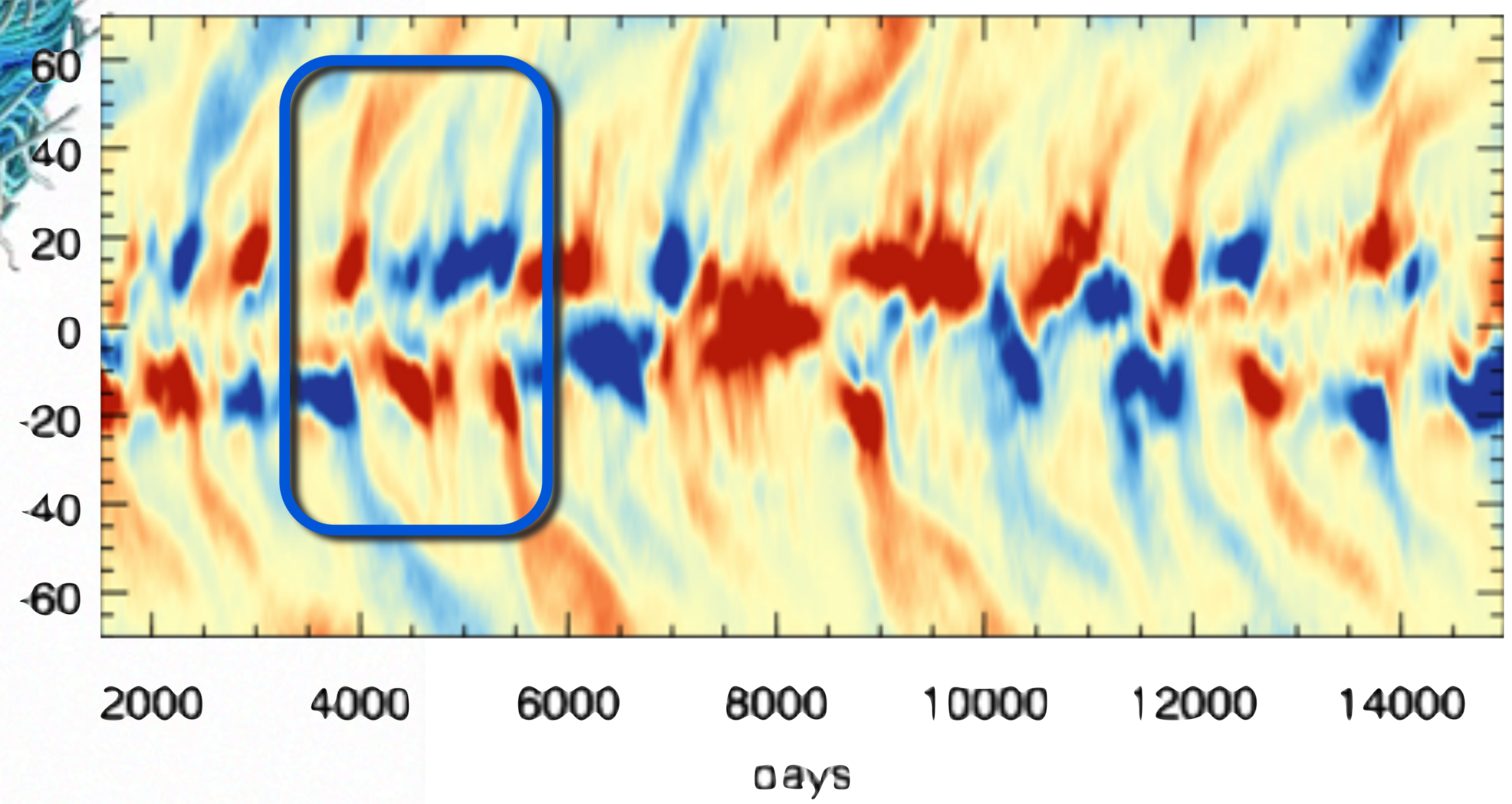
positive
negative

(Brown et al. 2011)

Ro ~ 0.25

This is one of many such “solar-like” dynamos (e.g., Nelson et al 2013, Augustson et al 2014)



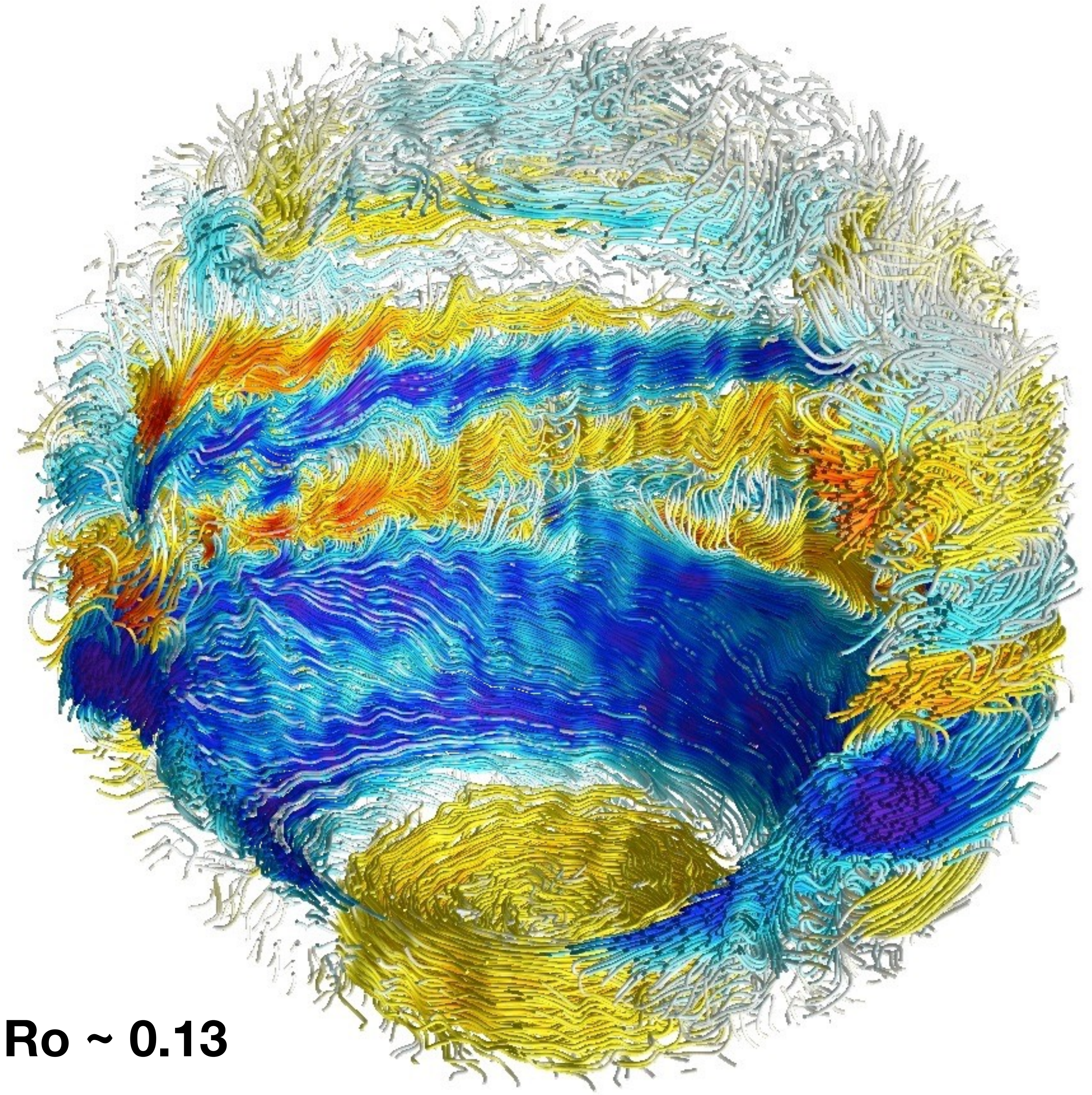


Lower Rossby numbers leads to hemispheric states

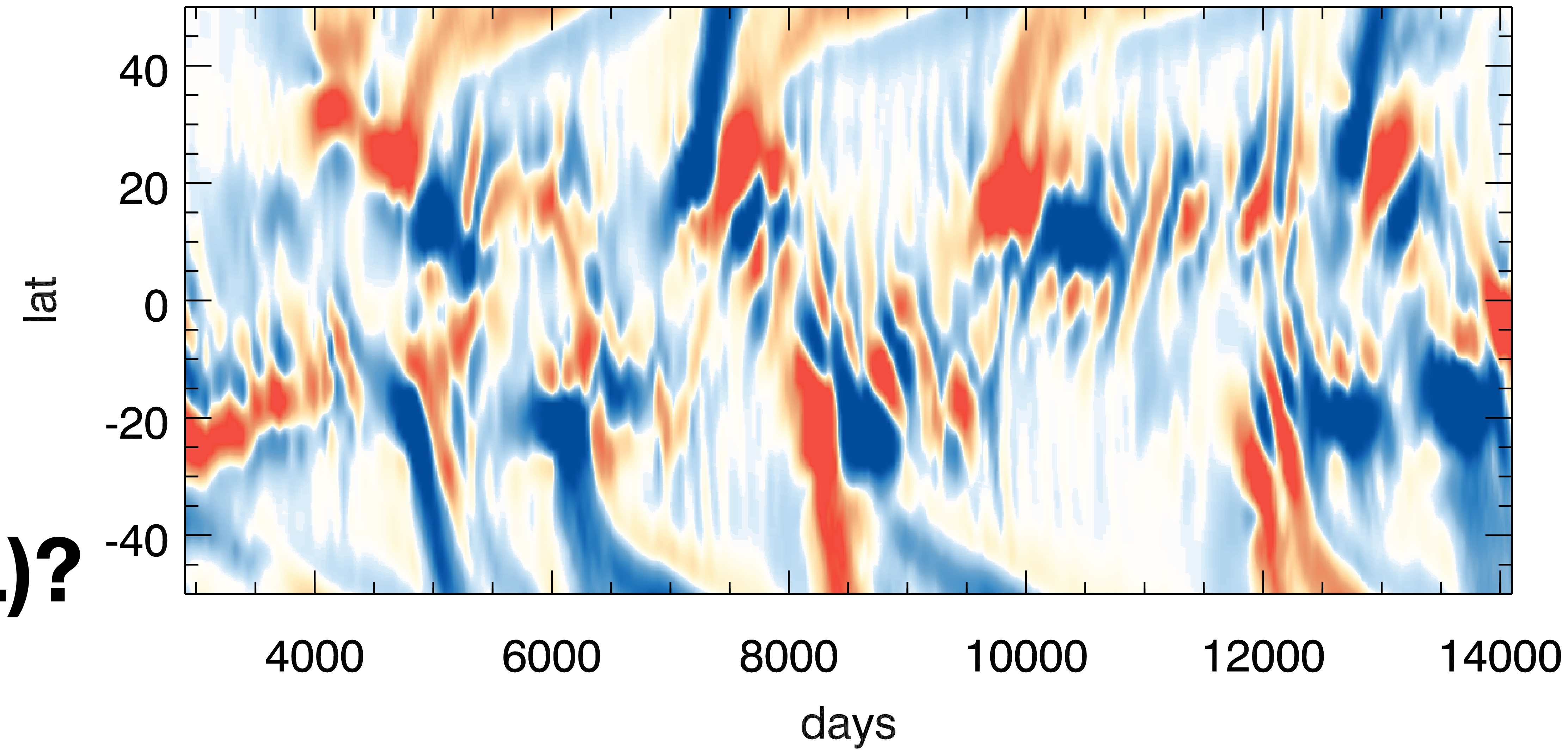
In shell-dynamos, we find globally-organized magnetic fields (and reversals) in lots of simulations that are at low values of the Rossby number. With or without tachoclines*.

This leaves a few very interesting questions:

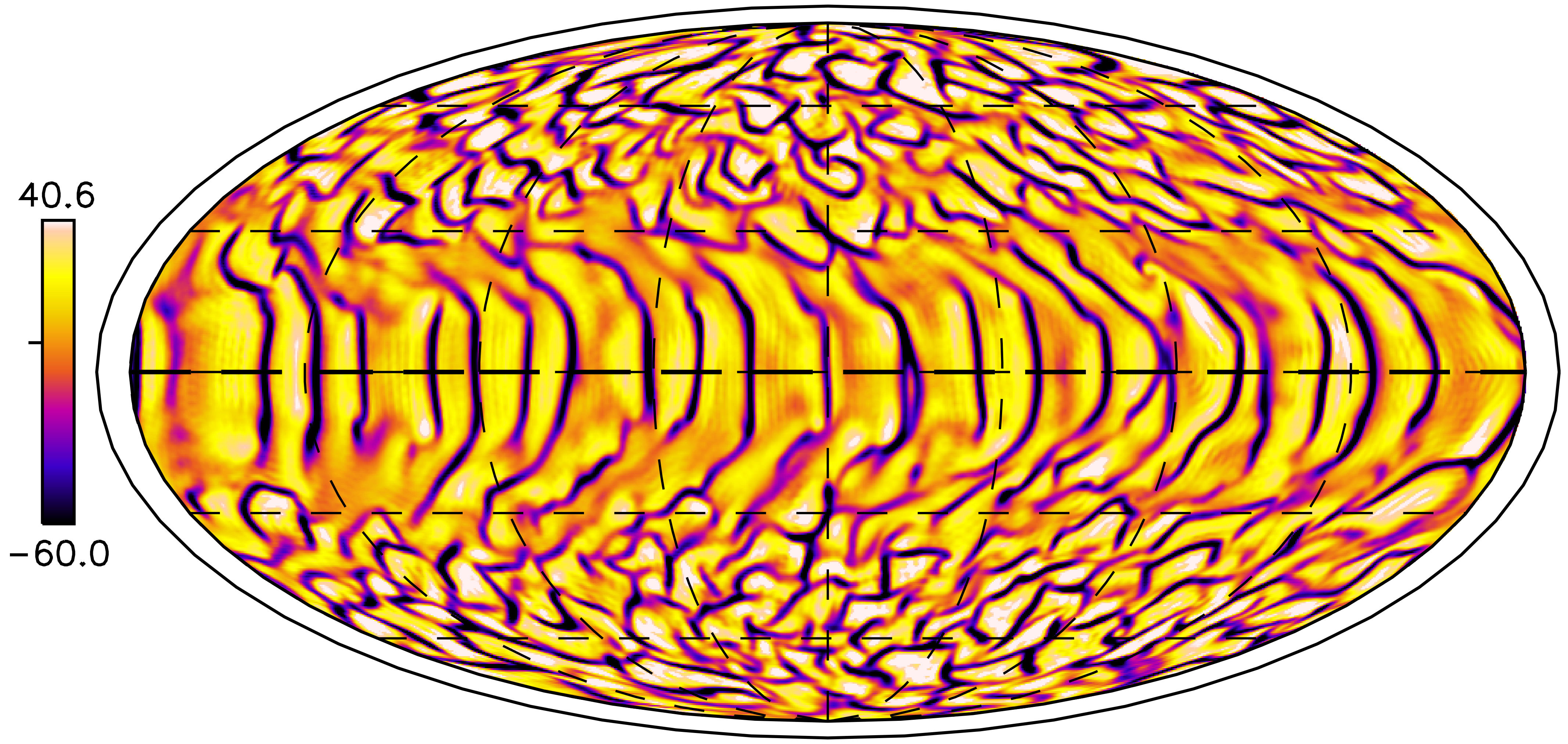
1) what's the Rossby number of the Sun?
2) What do you get if you really get rid of the tachocline*?
3) If the tachocline isn't doing anything, what about the other shear layer (NSSL)?

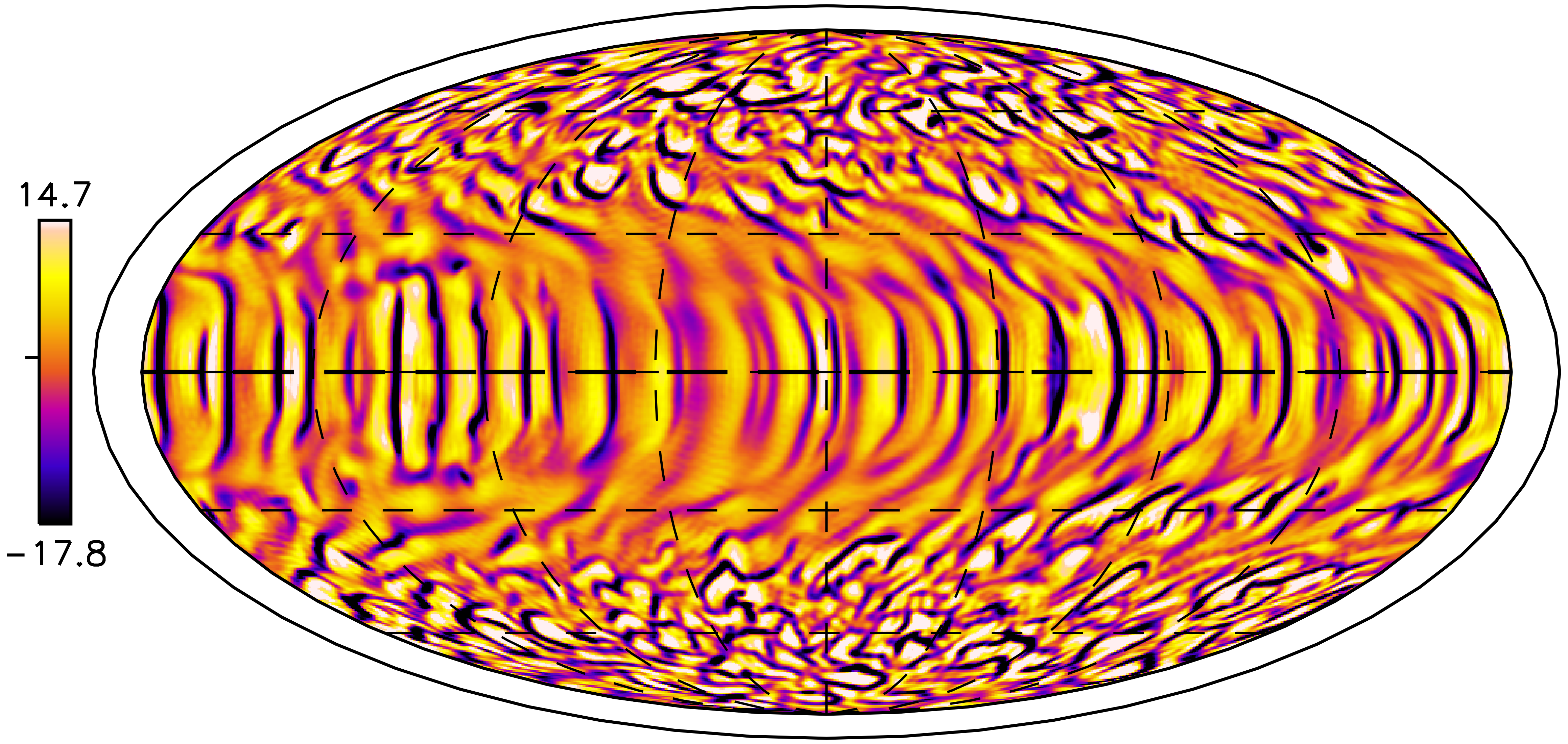


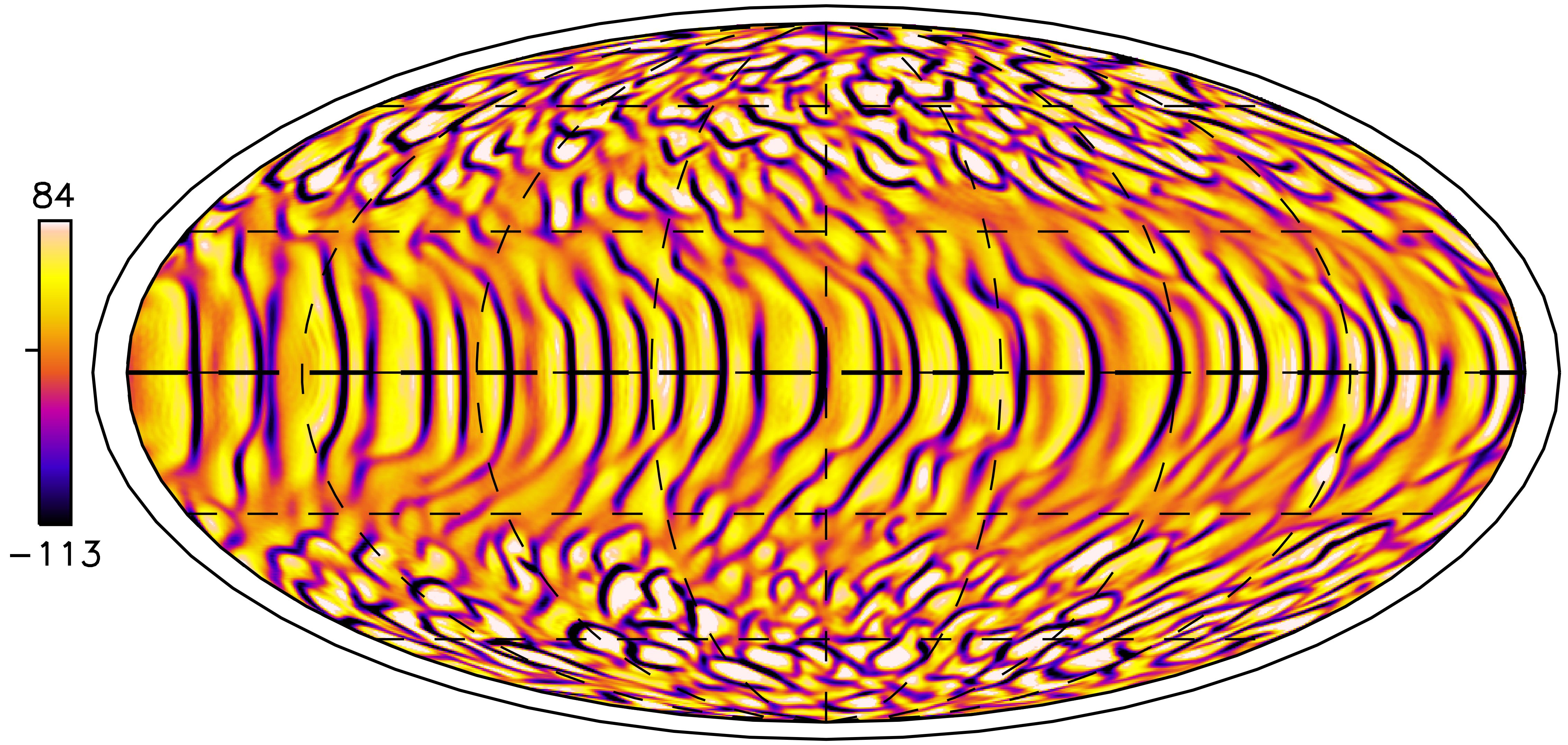
Ro ~ 0.13

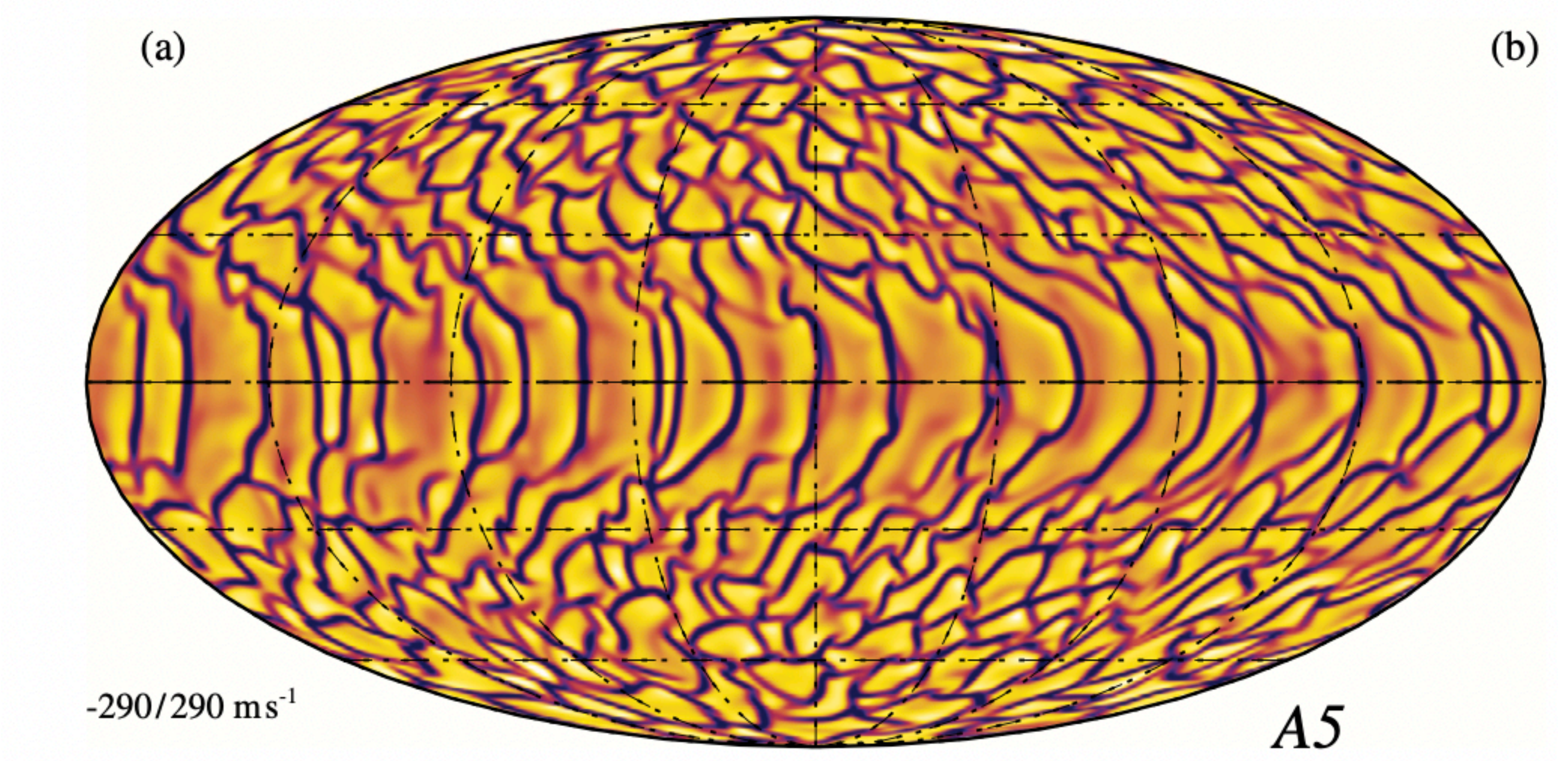


Wait… are these actually different stars?

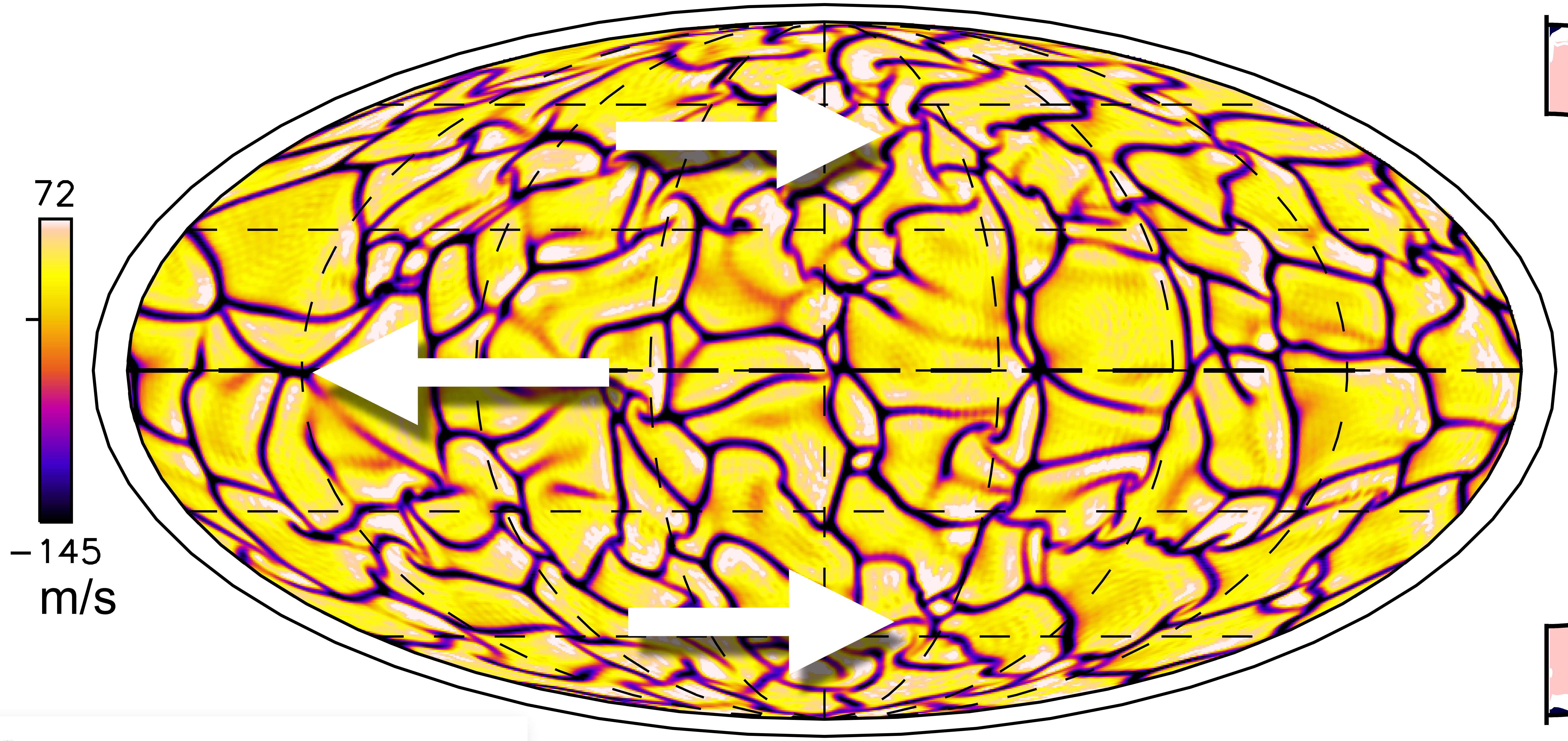


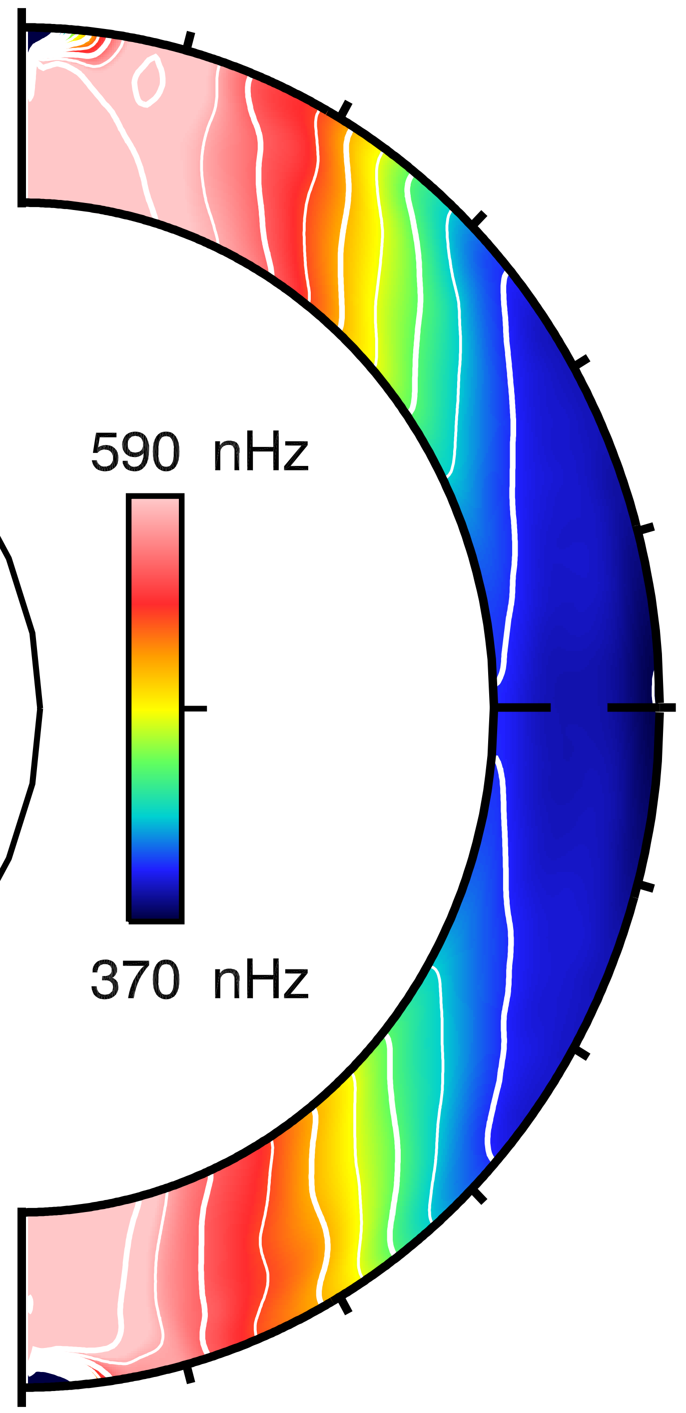


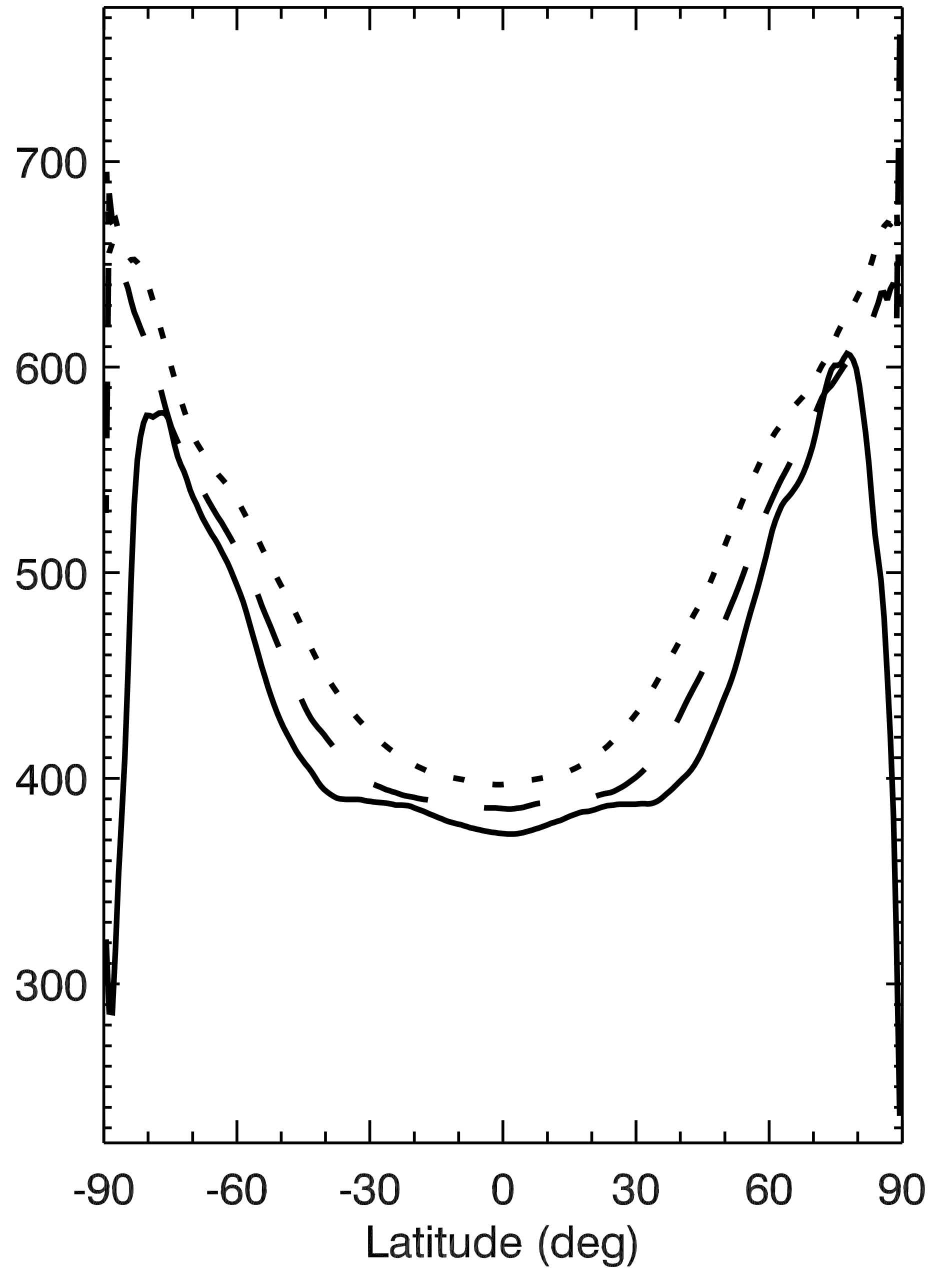


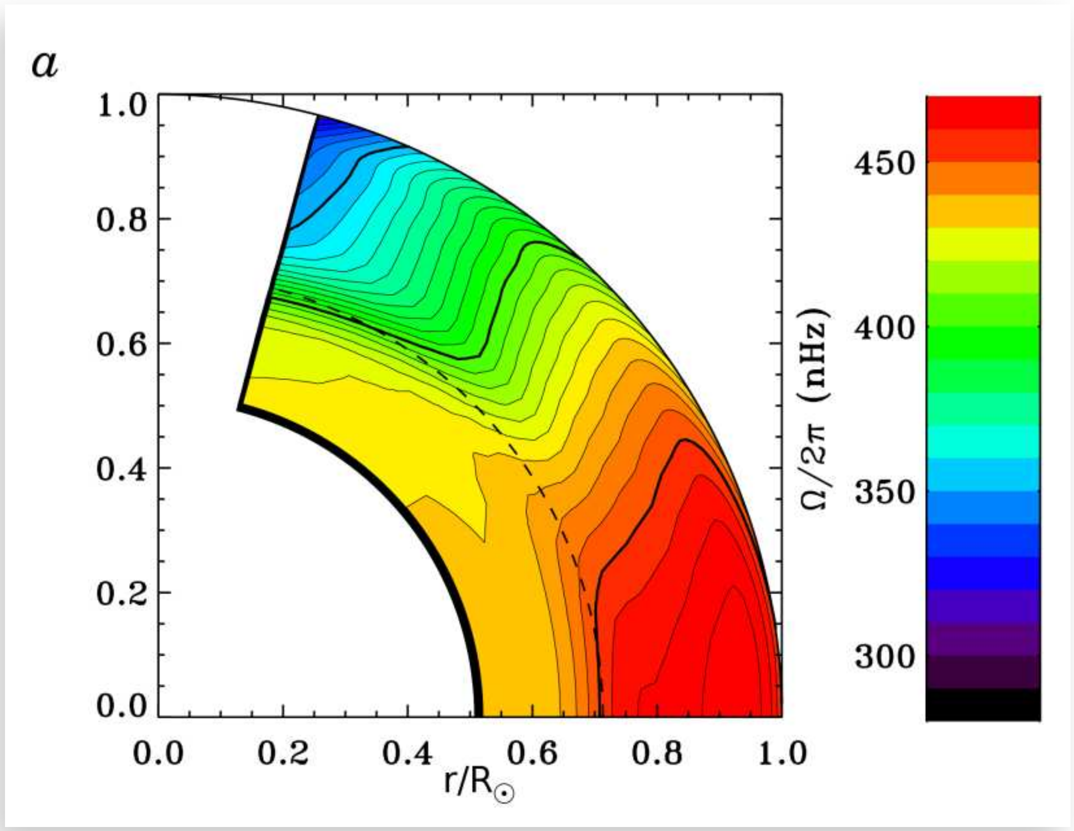


Back at the Sun: The problem of Anti-Solar DR





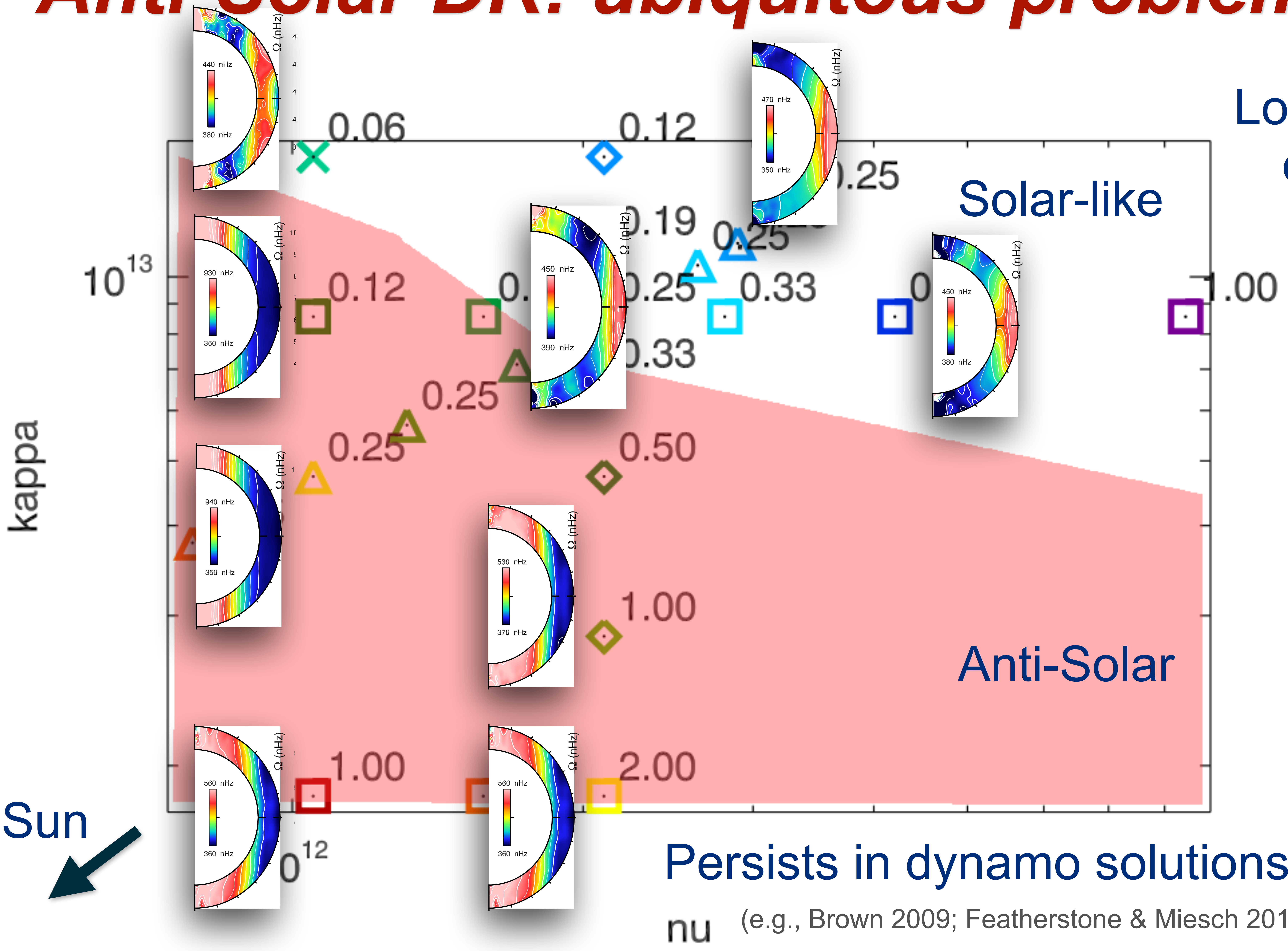




Here a convective ASH sim at solar parameters
(solar luminosity, solar rotation rate, etc.)
has distinct anti-solar differential rotation.

This is an extremely robust result.

Anti-Solar DR: ubiquitous problem



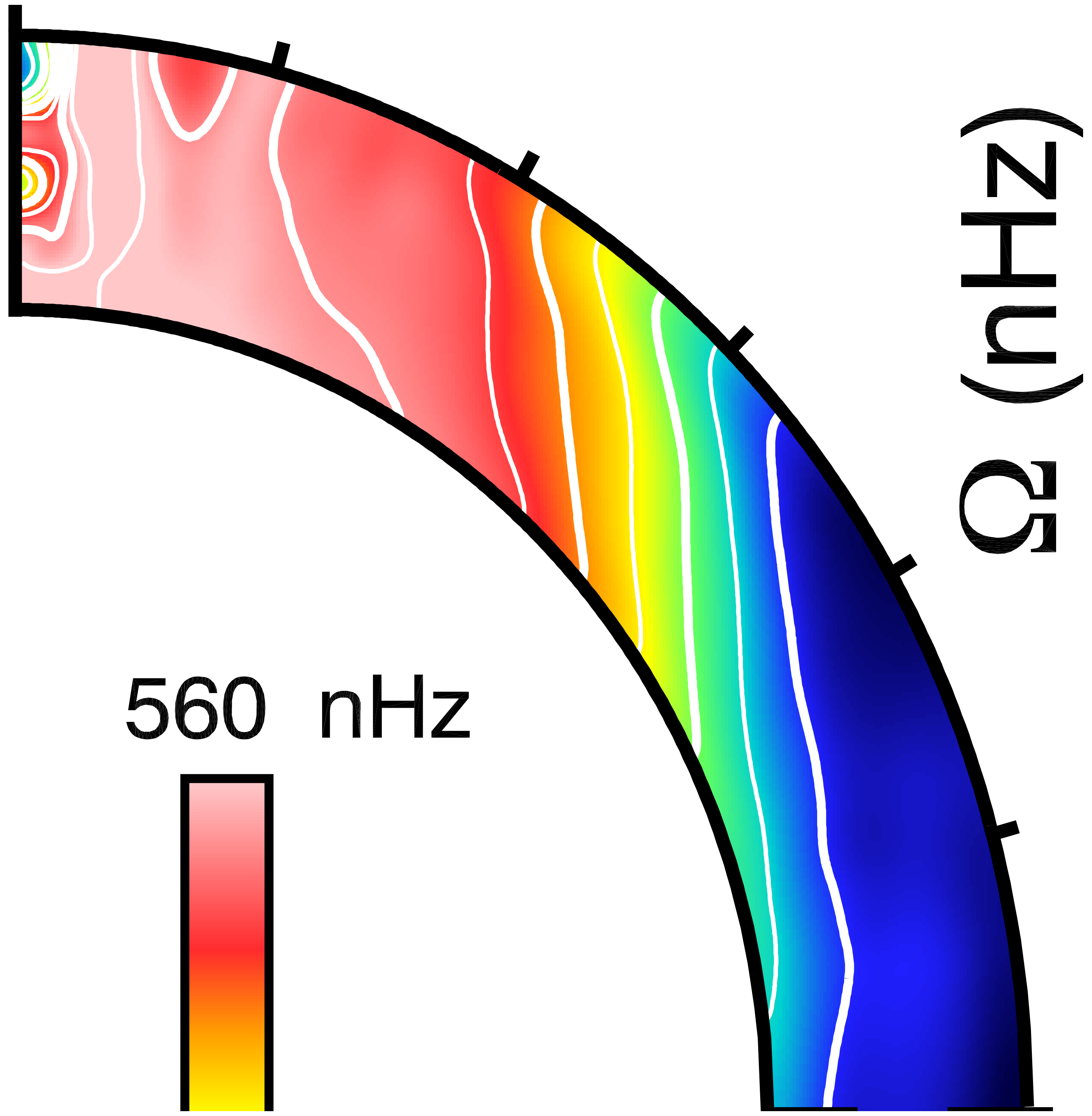
Low resolution early sims

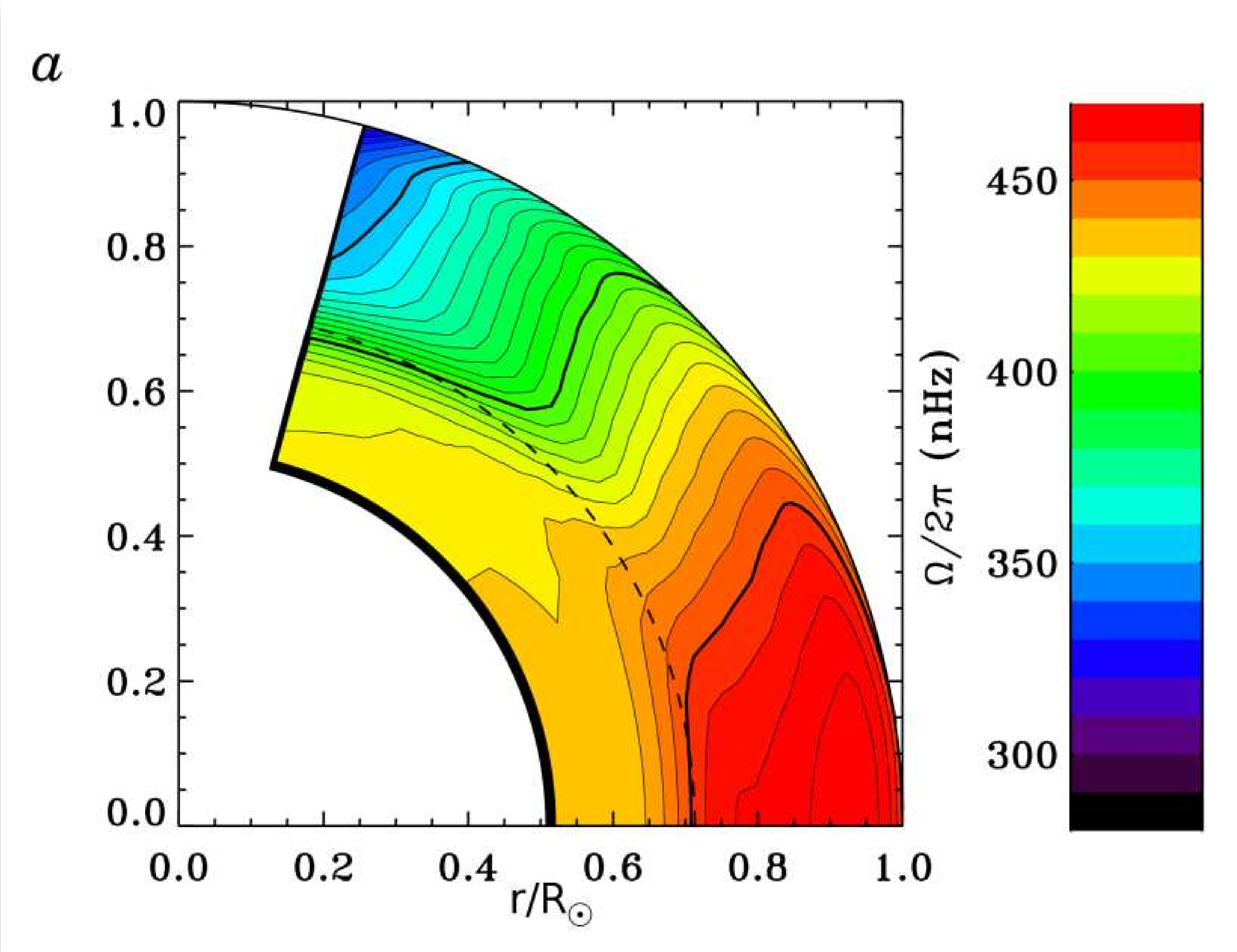
Sun

Persists in dynamo solutions

(e.g., Brown 2009; Featherstone & Miesch 2015)

When we learned we had a problem





We got real lucky here. This is an O(1) disagreement.
You can't just sweep this under the rug.

Our problem is that we thought we were simulating the Sun.
But we weren't. We got the non-dimensional parameters wrong.

So what can we do?

Simulations are a thing unto themselves.

At their best, they test our ideas, make us stop and think, and suggest new experiments or ways things work.

Studies of fundamental physical processes

CU students or postdocs

- Heat transport in fully compressible, stratified convection behaves like well-studied Rayleigh-Bénard (incompressible) convection.

  Anders & Brown 2017, "Convective heat transport in stratified atmospheres at low and high Mach number", PRF

- Disequilibrium chemical transport in planetary tropospheres can be described by a simple model; it's not mixing-length theory.

  Bordwell, Brown & Oishi 2018, "Convective Dynamics and Disequilibrium Chemistry in the Atmospheres of Giant Planets and Brown Dwarfs", ApJ

- Rotating convection experiments have a simple control parameter; it's not what we expected it to be.

  Anders, Manduca, Brown, Oishi & Vasil 2019, "Predicting the Rossby number in convective experiments", ApJ

- By understanding your system well, you can accelerate slow processes (like thermal evolution). Doing so matters, in surprising ways.

  Anders, Brown & Oishi 2018, "Accelerated evolution of convective simulations", PRF

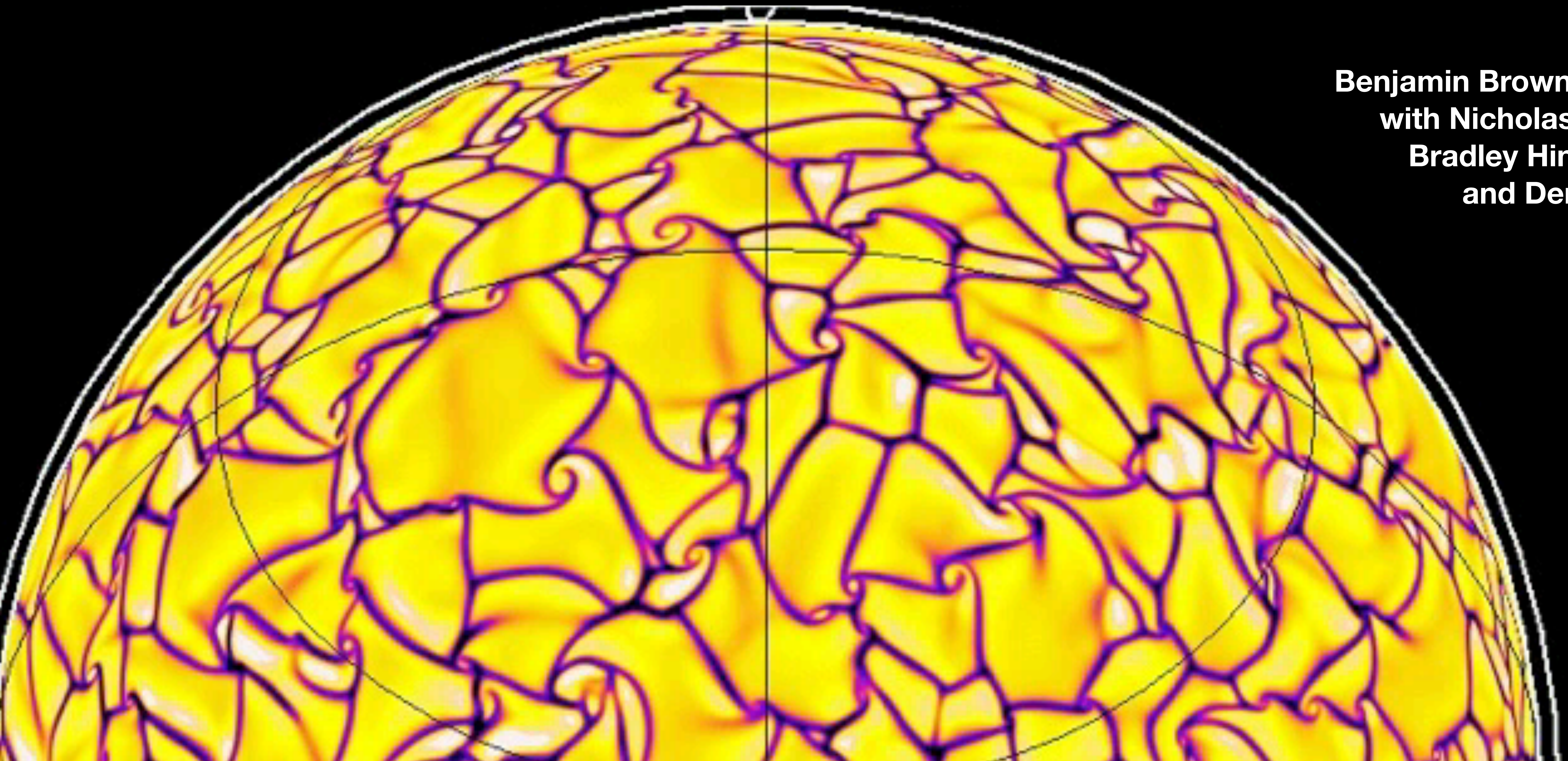
  Anders, Vasil, Brown & Korre 2020, "Convective dynamics with mixed temperature boundary conditions: why thermal relaxation matters and how to accelerate it ", PRF

- Plumes from the solar photosphere *might* make it all the way to the base of the solar convection zone. Solar entropy rain can't be ruled out (we tried).

  Anders, Brown & Lecoanet 2019, "Entropy Rain: dilution and compression of thermals in stratified domains", ApJ

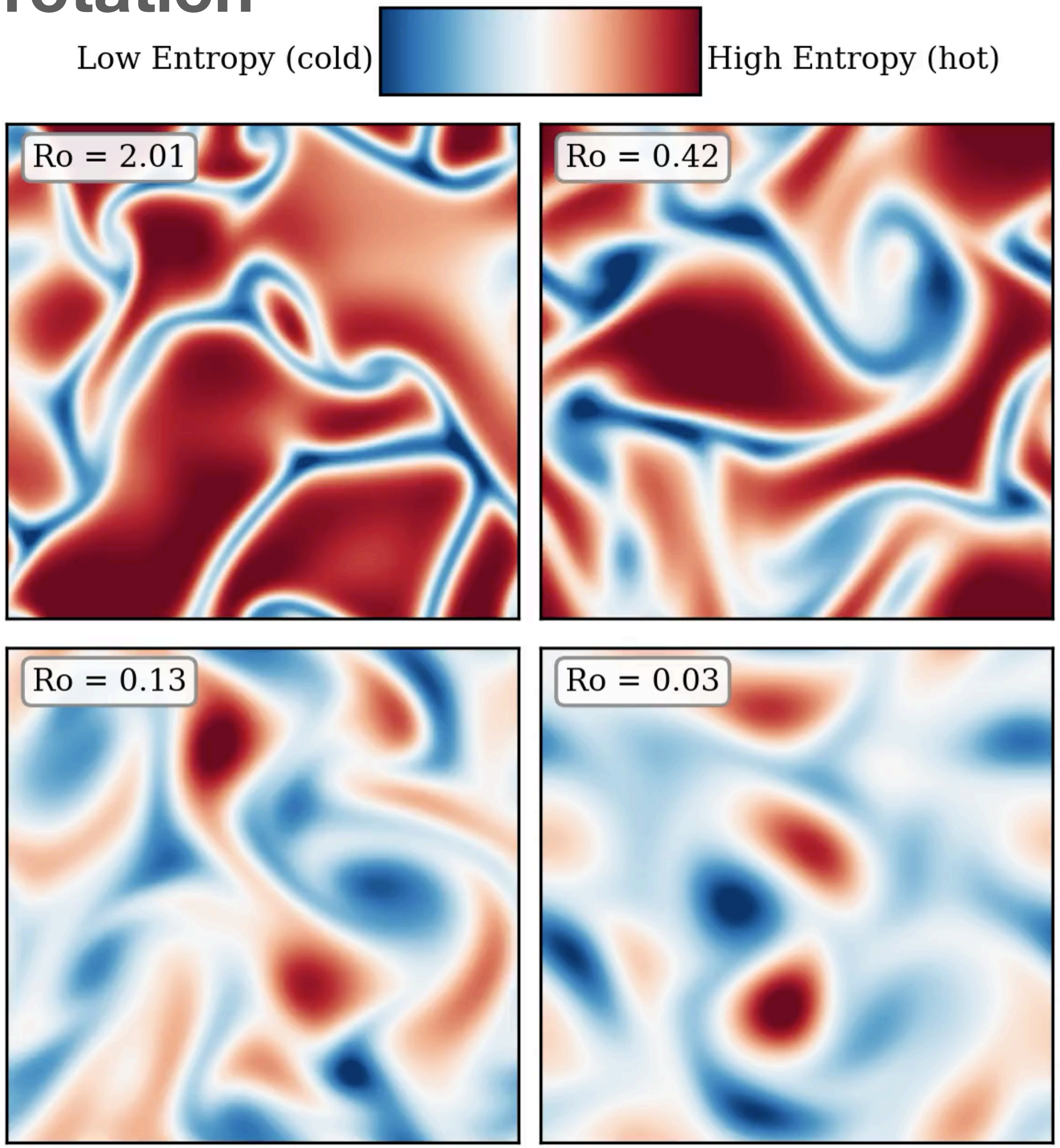
1. Hunting for Giant Cells at the Solar Poles

Benjamin Brown (University of Colorado), with Nicholas Featherstone (SwRI), Bradley Hindman (U Colorado), and Derek Lamb (SwRI)



What's missing?

Slow rotation

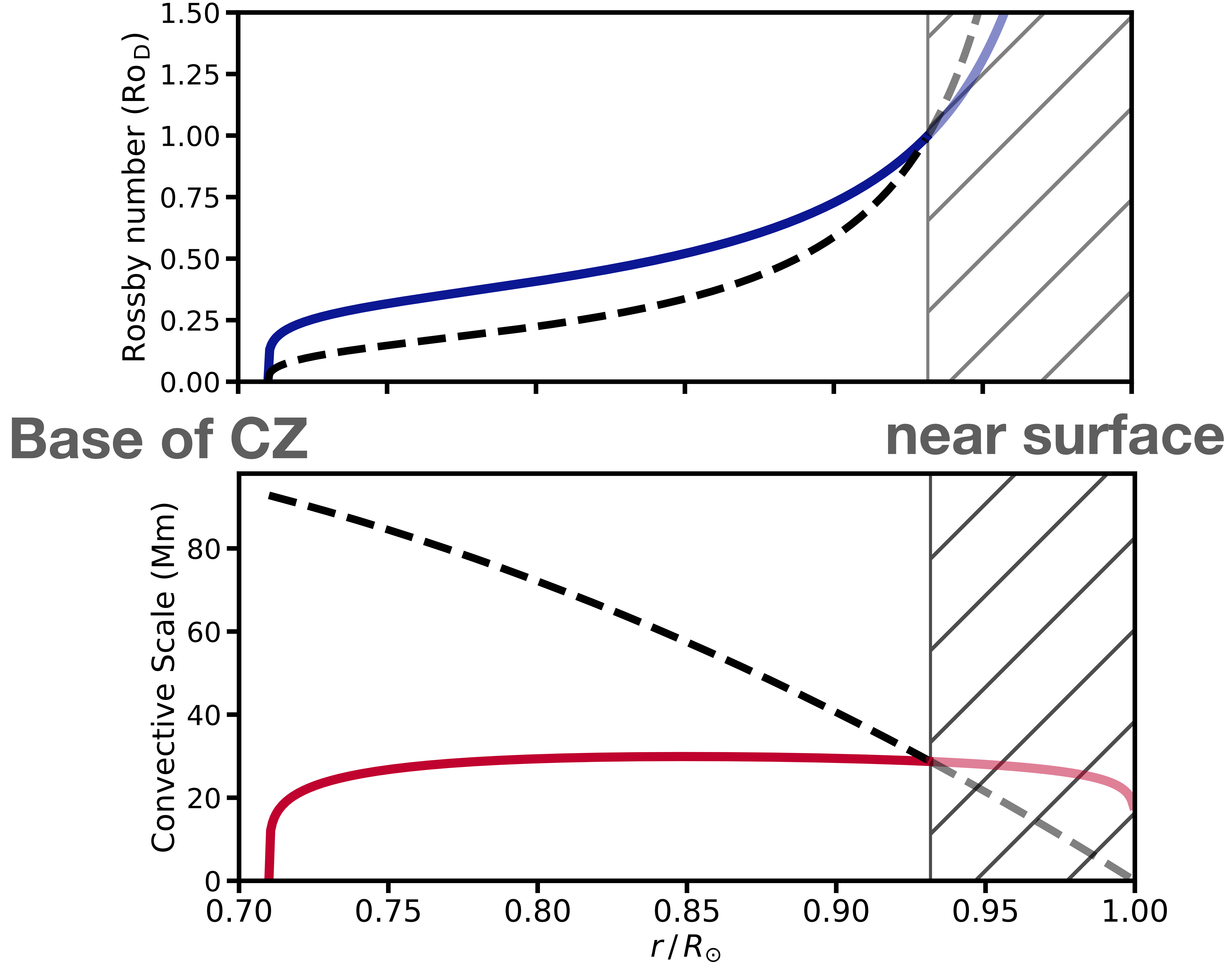


Rotation leads to fundamental changes in convective structures. They become columnar, and swirl, rather than spreading (diverging).

Fast rotation

(Anders et al 2019 ApJ: stratified, local models of rotating convection)

Importance of rotation



(Vasil, Julien & Featherstone 2021 PNAS)

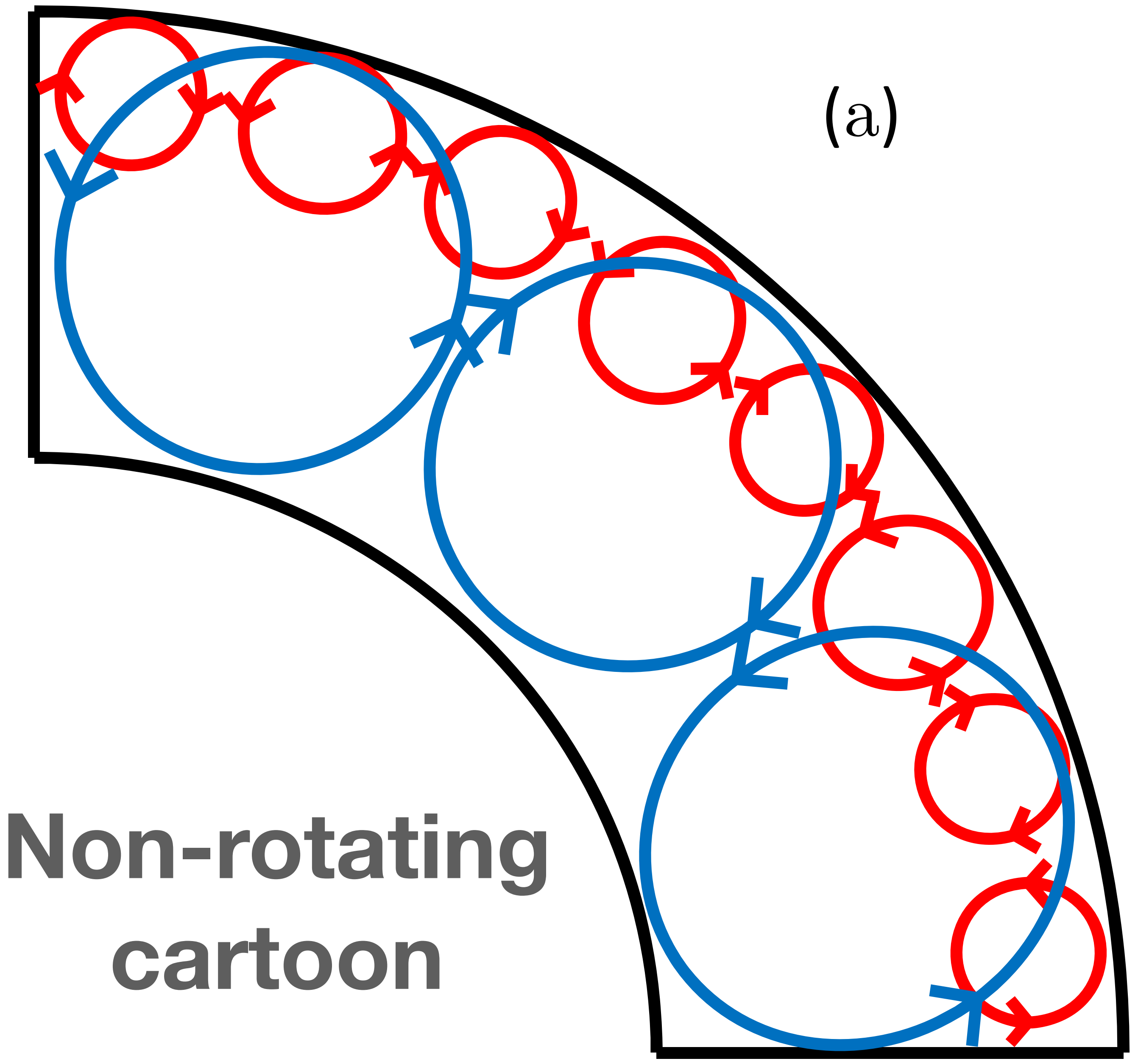
Best current estimates of solar interior dynamics (MLT w/ correct rotation)

Rossby is similar to "normal" versions of MLT and small below the NSSL

But length scales are much smaller. Closer to 30 Mm than 100's of Mm

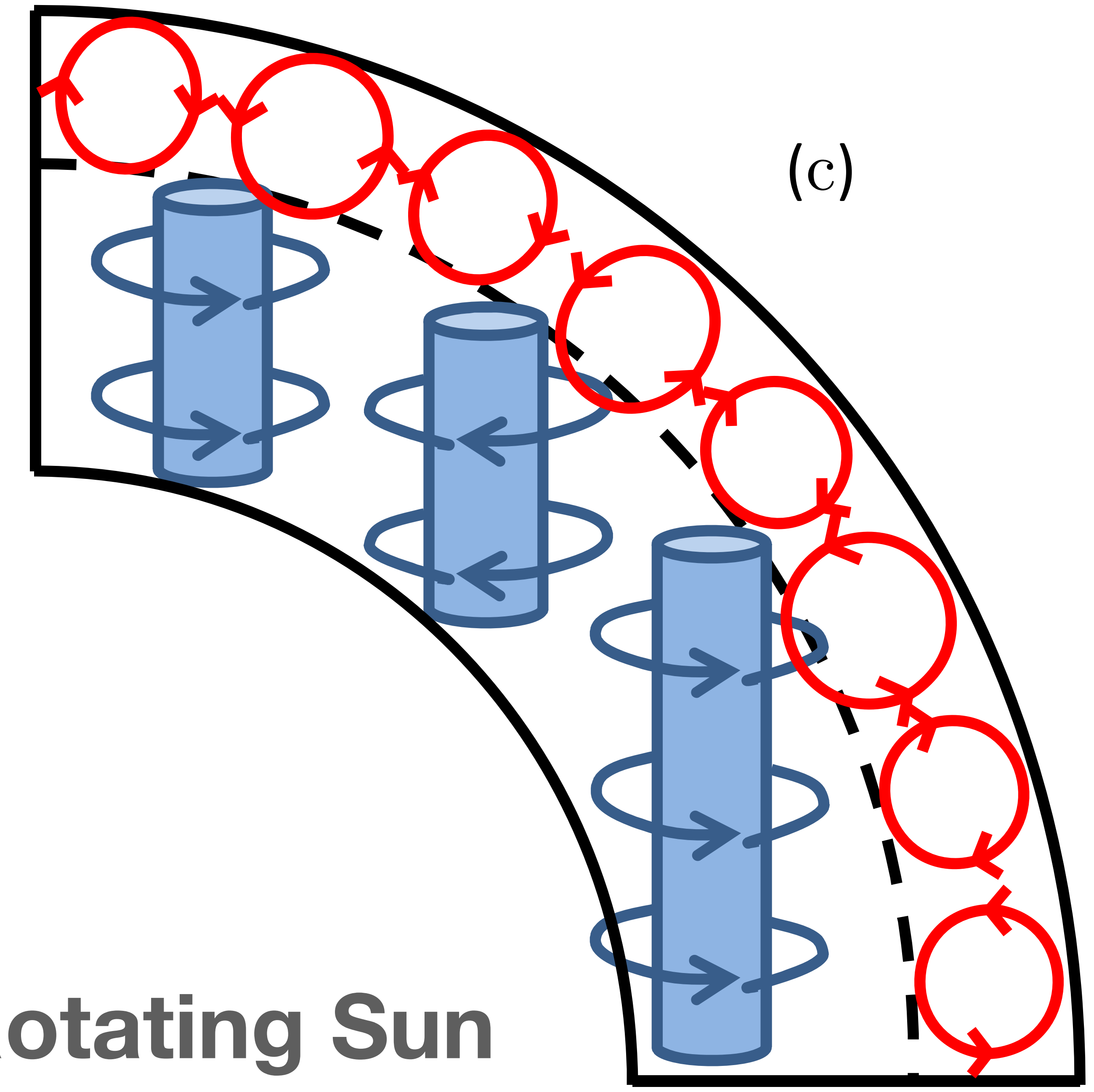
The poles are special
I: flow structures change at the poles

The surface noise is diverging flow (supergranules).



Non-rotating cartoon

Giant cells are large spreading cells with a divergence signature that is the same everywhere.



Rotating Sun

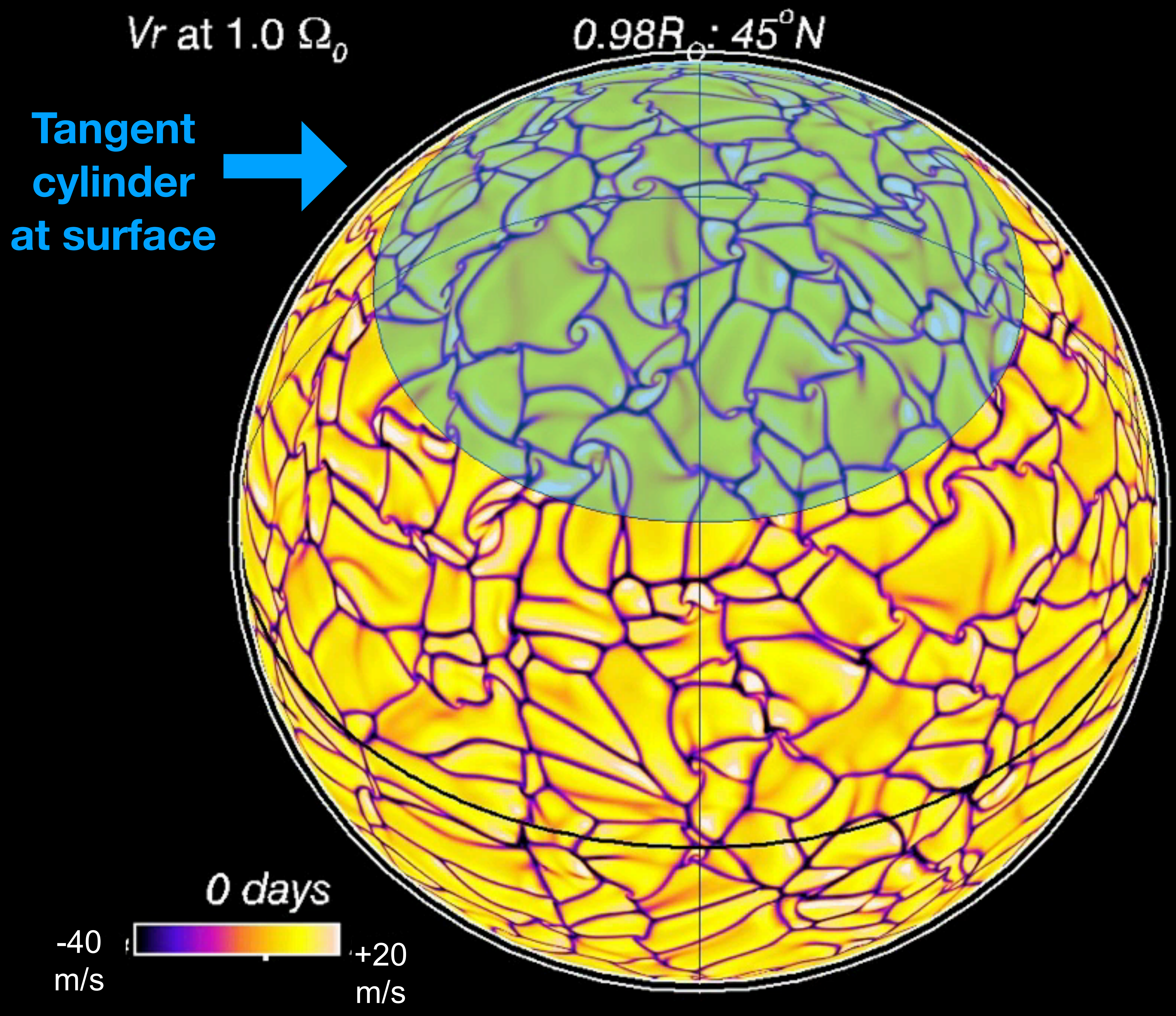
(Featherstone & Hindman 2016)

Giant cells are swirling columns, with high vorticity at the poles.

Reality is something like this

Hunting for Giant Cells at the Solar Poles

Benjamin Brown (University of Colorado), with Nicholas Featherstone (SwRI), Bradley Hindman (U Colorado), and Derek Lamb (SwRI)



(based on Miesch et al. 2008)

1. Giant cells of convection have not been conclusively observed; where are they?

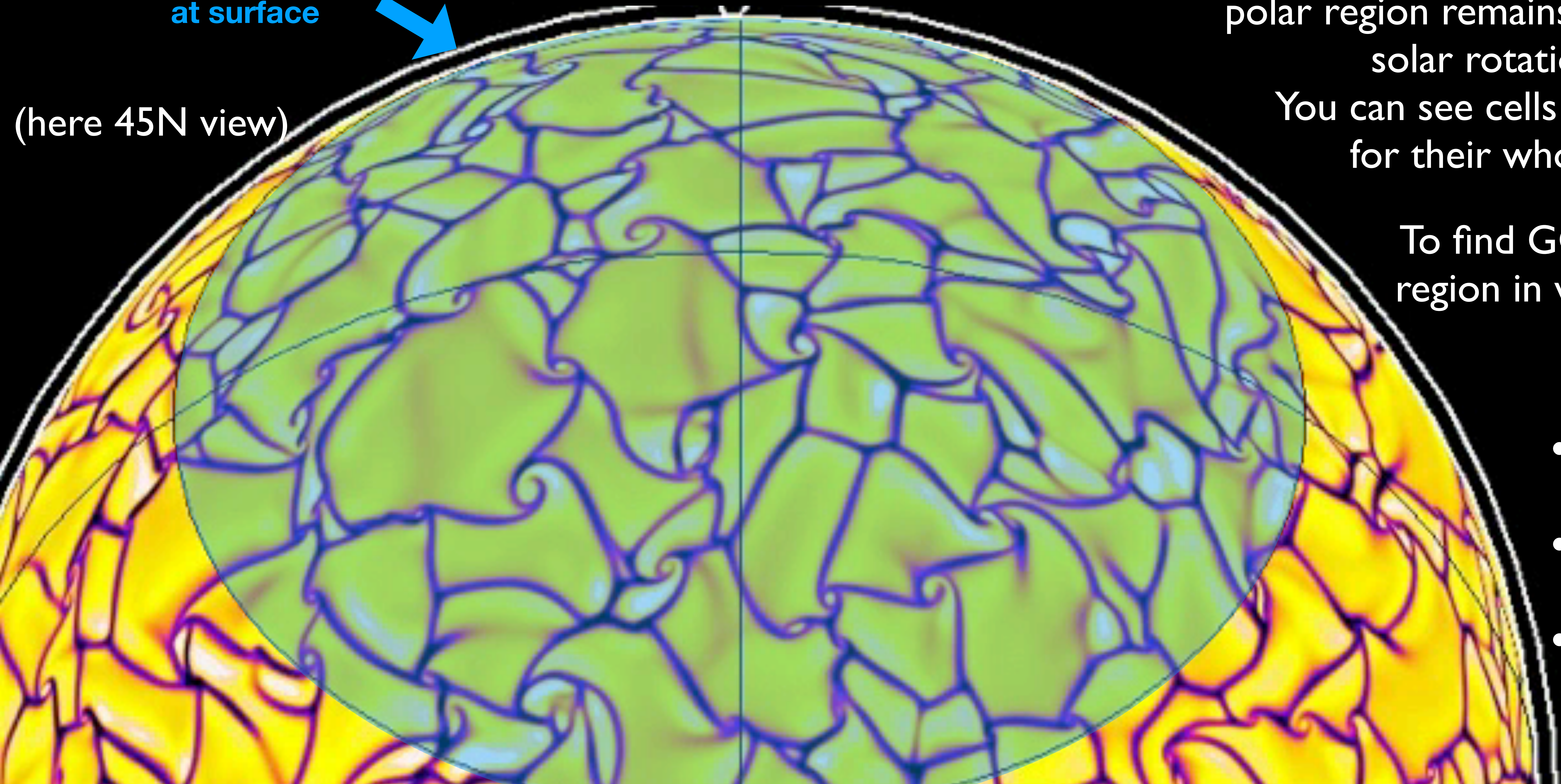
2. Rotating convection is surprising:
   a) Narrow columns aligned with rotation axis, rather than big overturning cells.

   b) Different dynamics within the tangent cylinder than equator.

3. Equatorial vantage points at 1AU have trouble: objects at the equator sweep out of view every 8 days, and you never see the whole equatorial region at once.

radial velocity structures
Downflows: fast, narrow
Upflows: slow, broad

The poles are special: structures stay in your FOV



At high latitude vantage points, the whole polar region remains in view for several solar rotation periods.
You can see cells as they circulate for their whole lifetimes.

To find GC: keep the whole polar region in view for several months.

How high in latitude?

- 45N is tangent cylinder at photosphere.
- In my mind, that's a min requirement.
- Higher is much better.

(based on Miesch et al 2008)

2. What happens if we have no tachocline? Dynamos in fully-convective M-dwarf stars

What are M-dwarf stars? (Astronomer perspective)

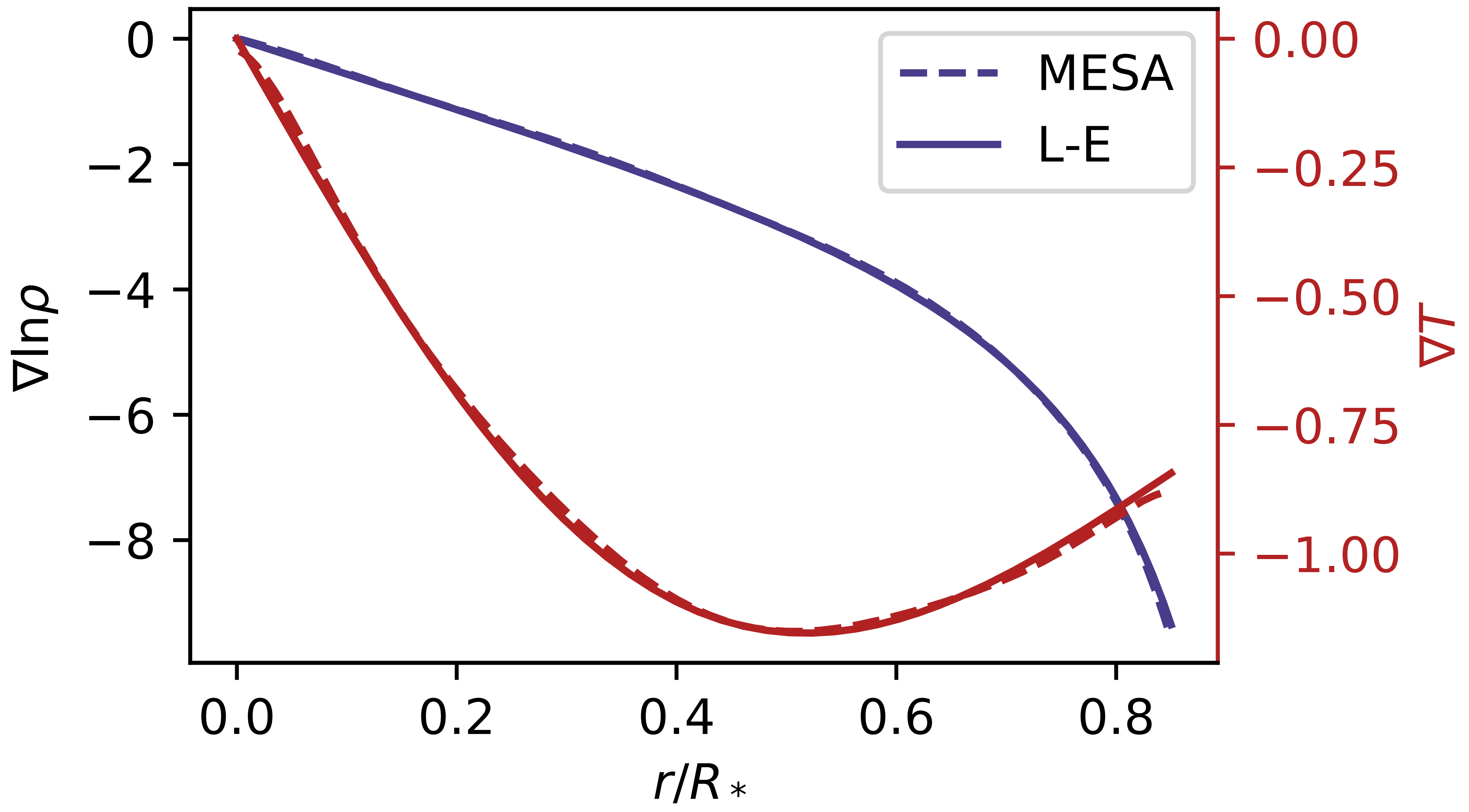
Compared to our Sun, M-dwarf stars are:

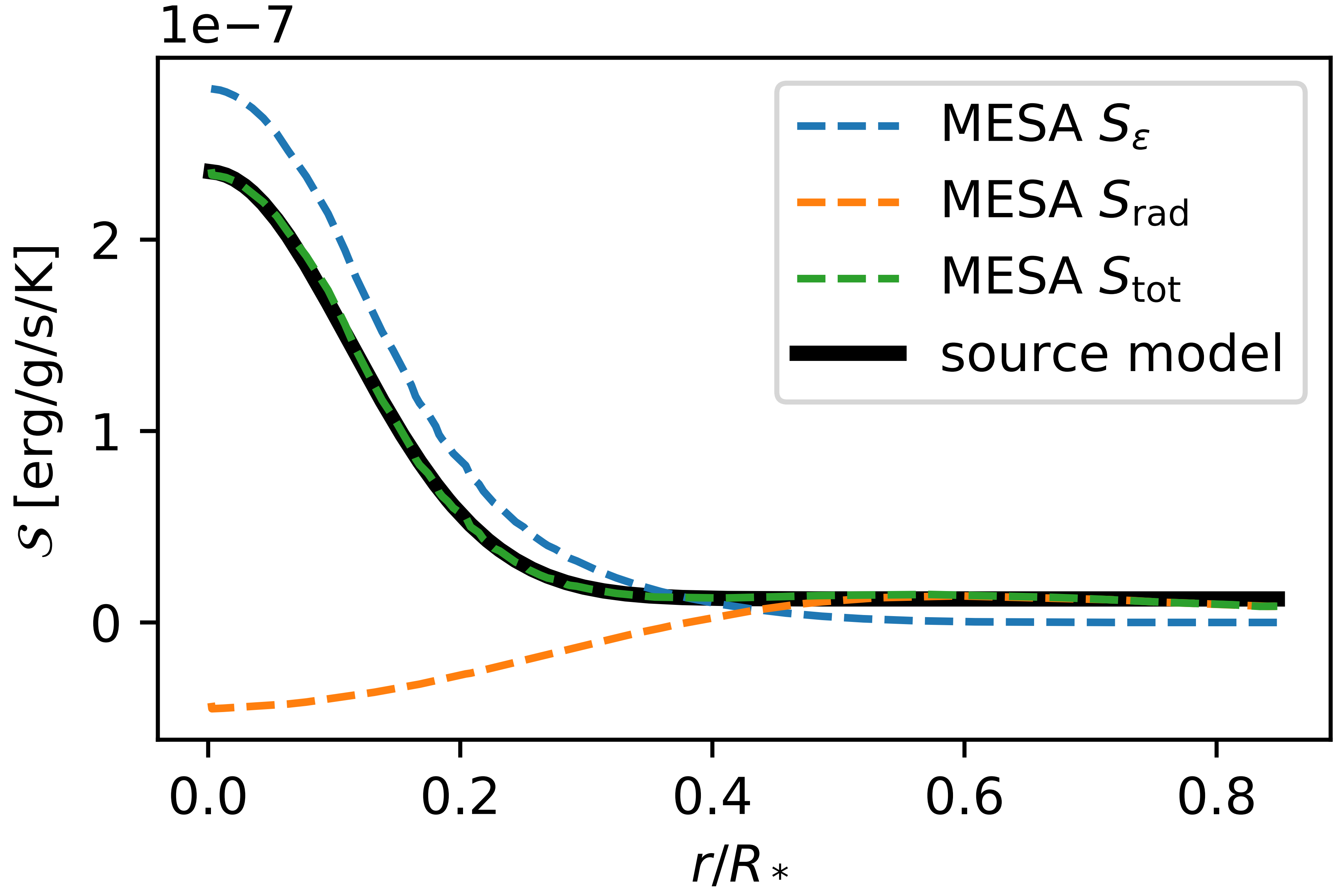
- **low mass (~0.3 solar masses)**
- **small (~0.1 solar radii)**
- **relatively cool (surface ~3500K, vs 5800K for Sun)**
- **often very magnetically active**
- **often fully convective**

“Powerful flare detected on M-dwarf star”
https://phys.org/news/2018-04-powerful-flare-m-dwarf-star.html

- **the most numerous stars in the universe**
- **the host stars of most of the planets, and possibly most of the *habitable* planets in our universe**

What makes an M-dwarf? (Fluids perspective)

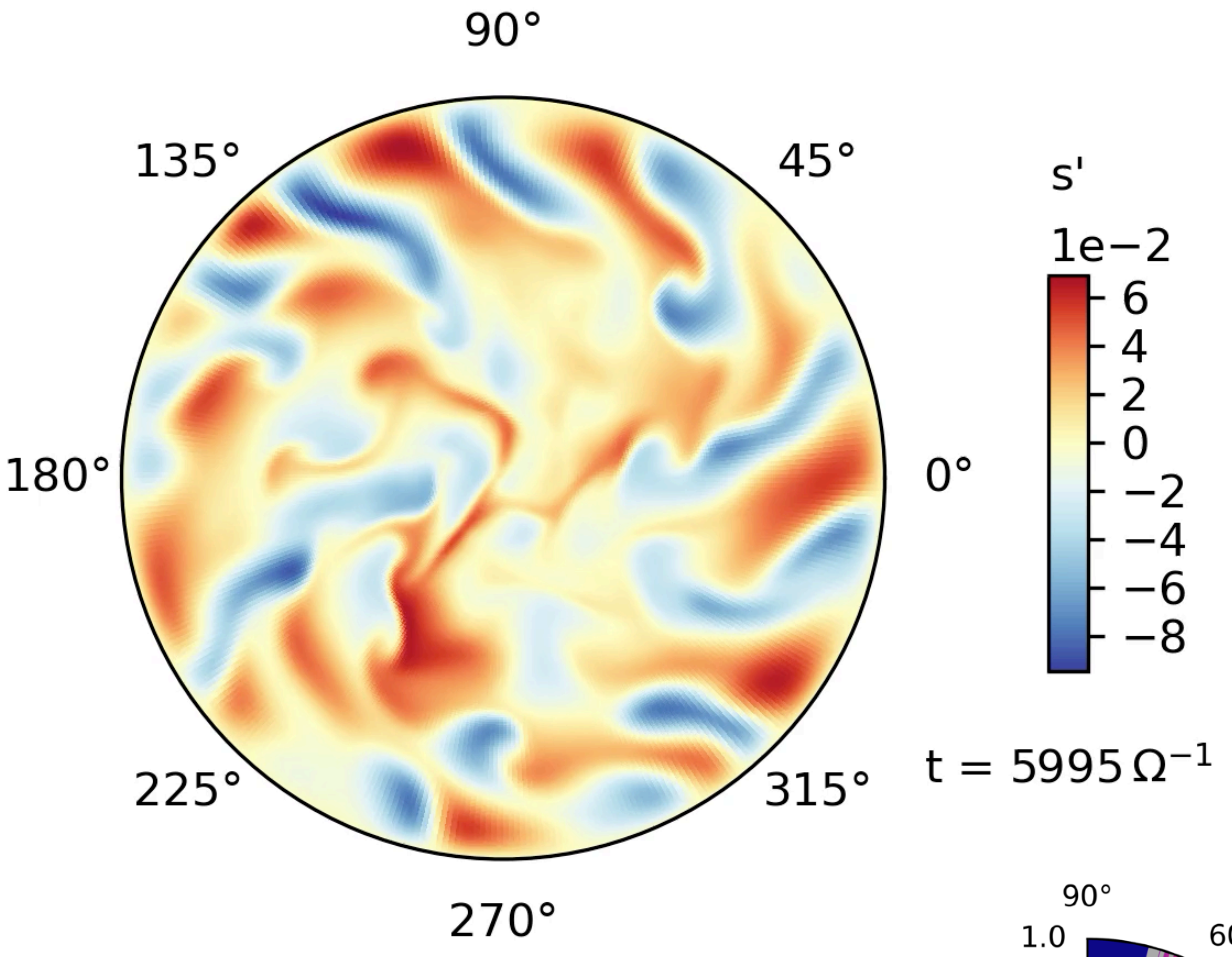


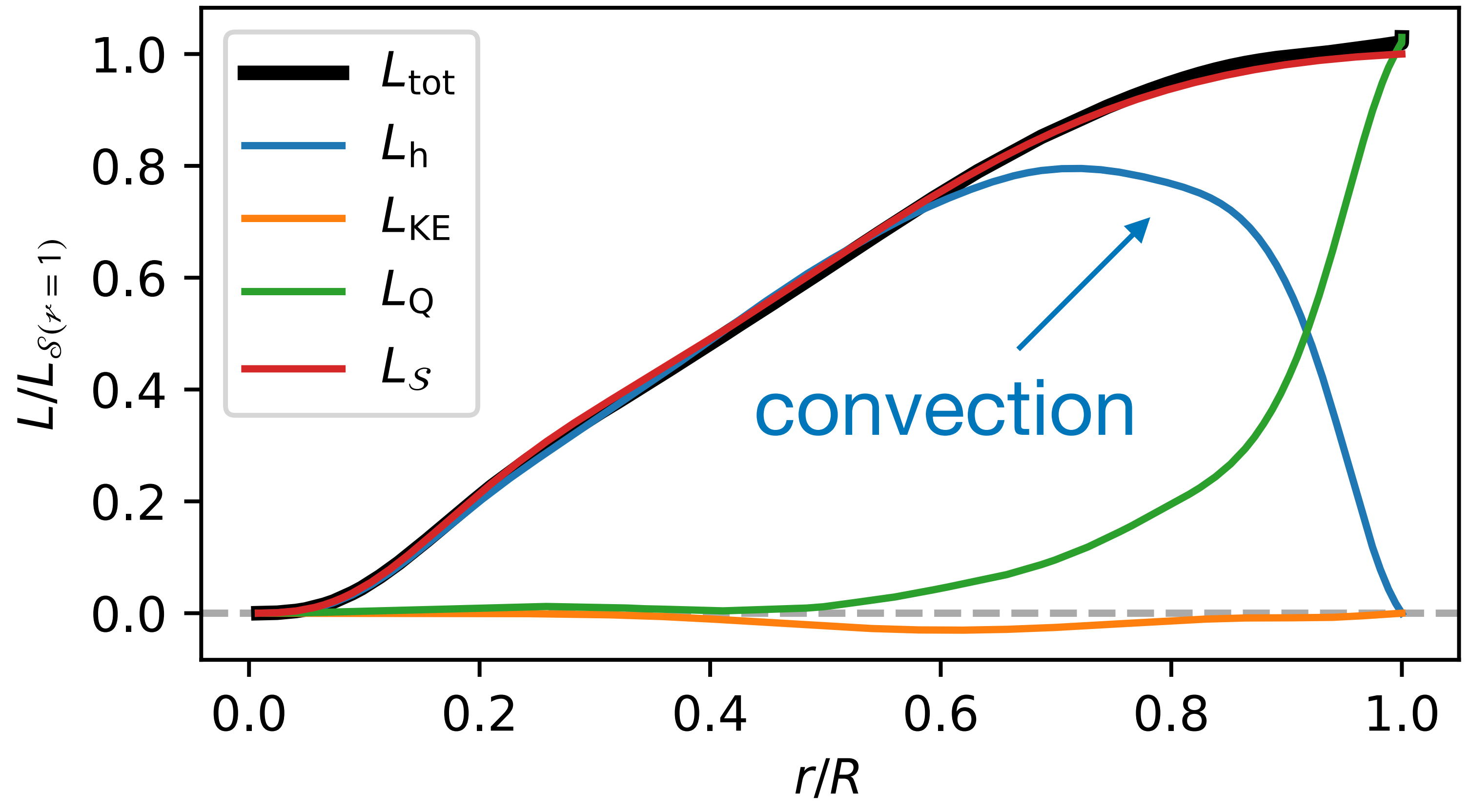


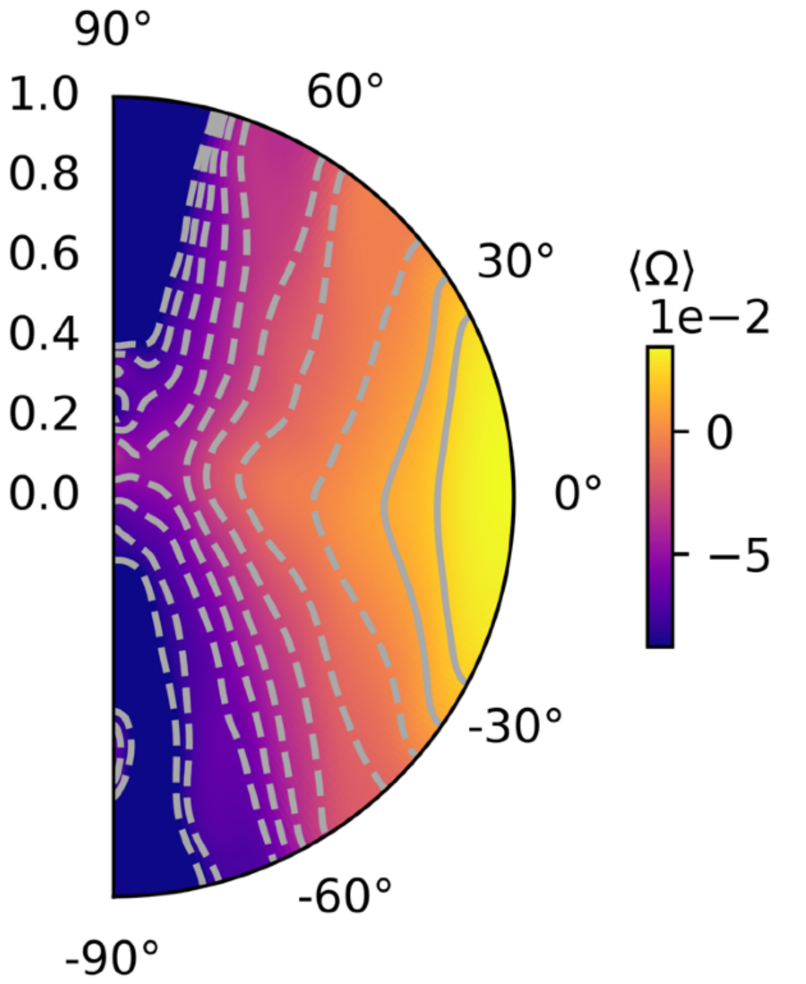
Low-Mach, fully convective objects with non-constant coefficients.
Density stratification — Lane-Emden solution
variable gravity — Lane-Emden solution
spatially inhomogeneous heating (mix of nuclear generation and radiative transport, leads to peak at core and distributed heating elsewhere; MESA)

Global dynamos in fully convective M-dwarf stars

- **Performed using the Dedalus framework: these are the first global-spherical simulations of fully-convective M-dwarfs.**
- **Anelastic, MHD, spectrally accurate.**
- **Flows at the center cross r=0 and rising plumes there are very different in character from the falling plumes at the outer boundary.**
- **Ro ~ 0.3, Re ~ 120-240**
- **Convection dominates the heat transport in the interior of the star, and builds a self-consistent, solar-like differential rotation (fast at the equator, slow at the poles)**

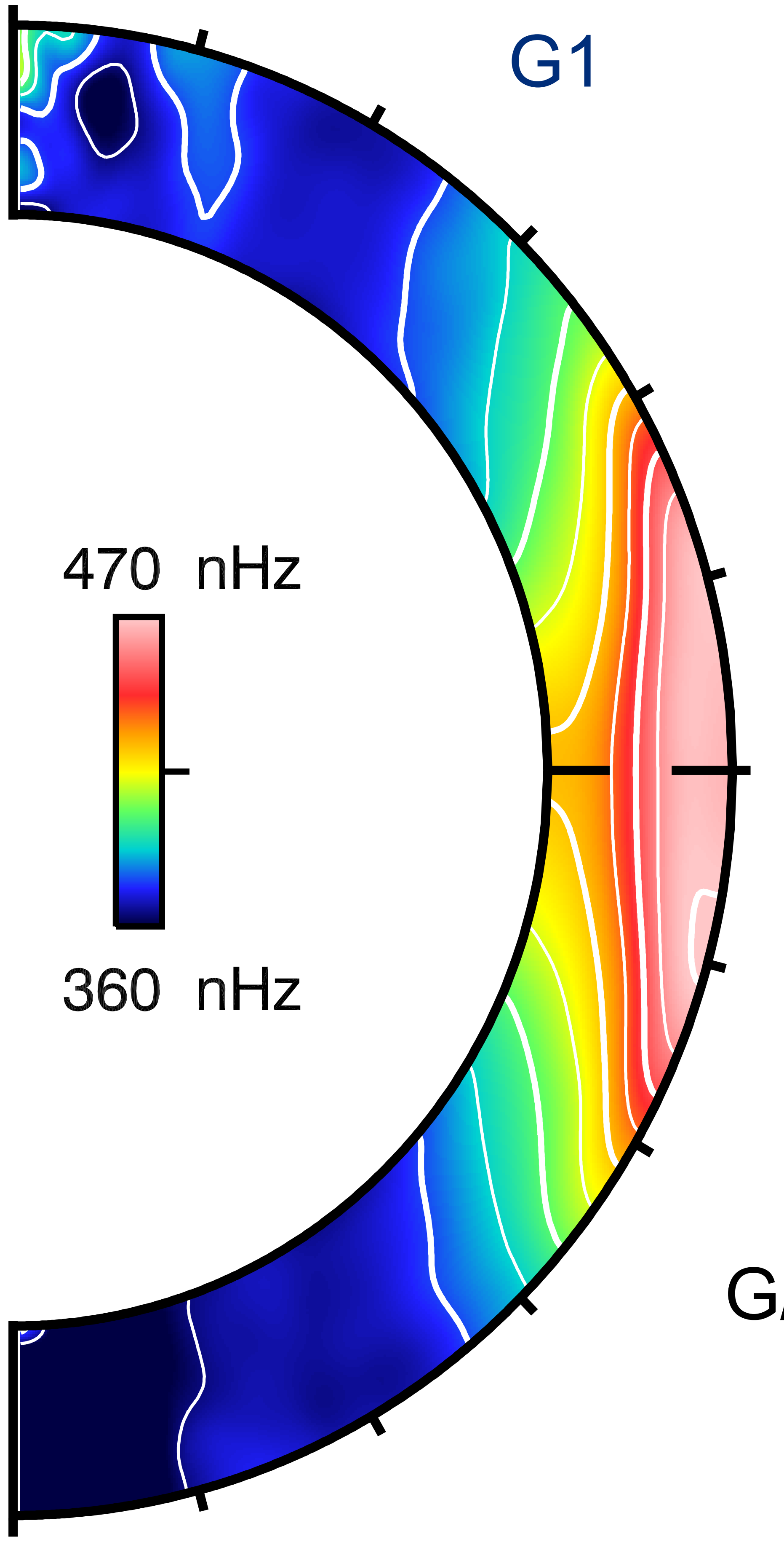




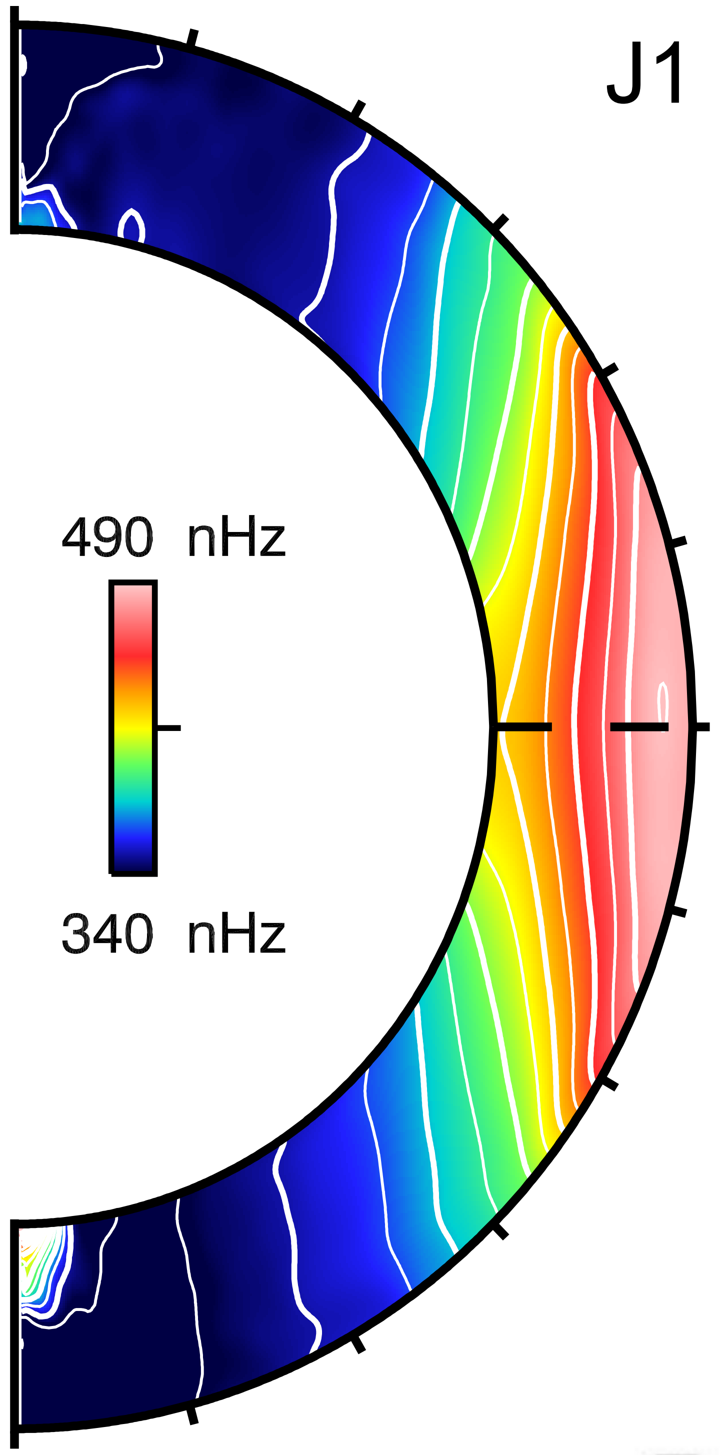


Brown, Oishi, Vasil, Lecoanet & Burns 2020, "Single-hemisphere dynamos in M-dwarf stars", ApJL

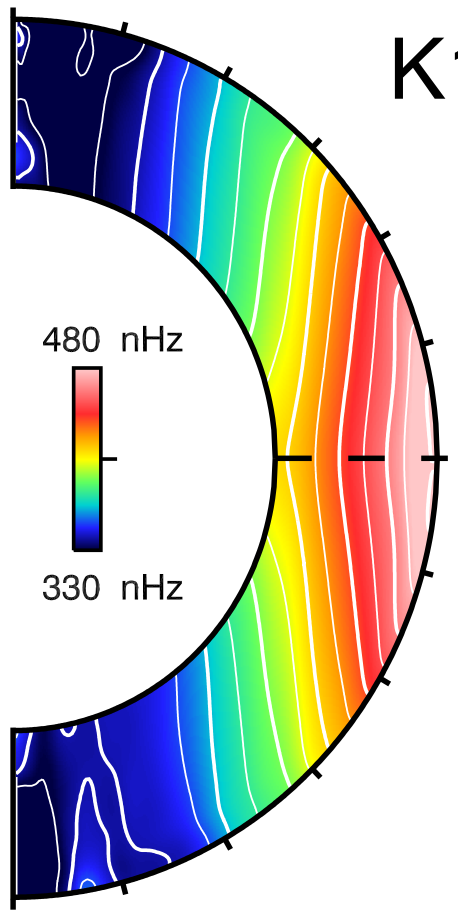
Differential Rotation in Other Stars



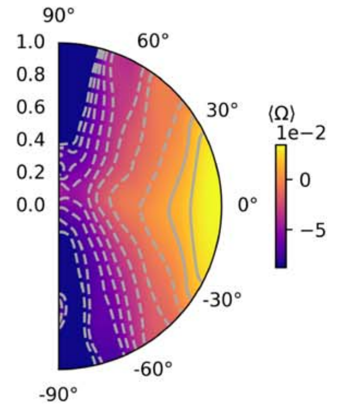
G-type star
1 M☉



G/K-type star
0.8 M☉

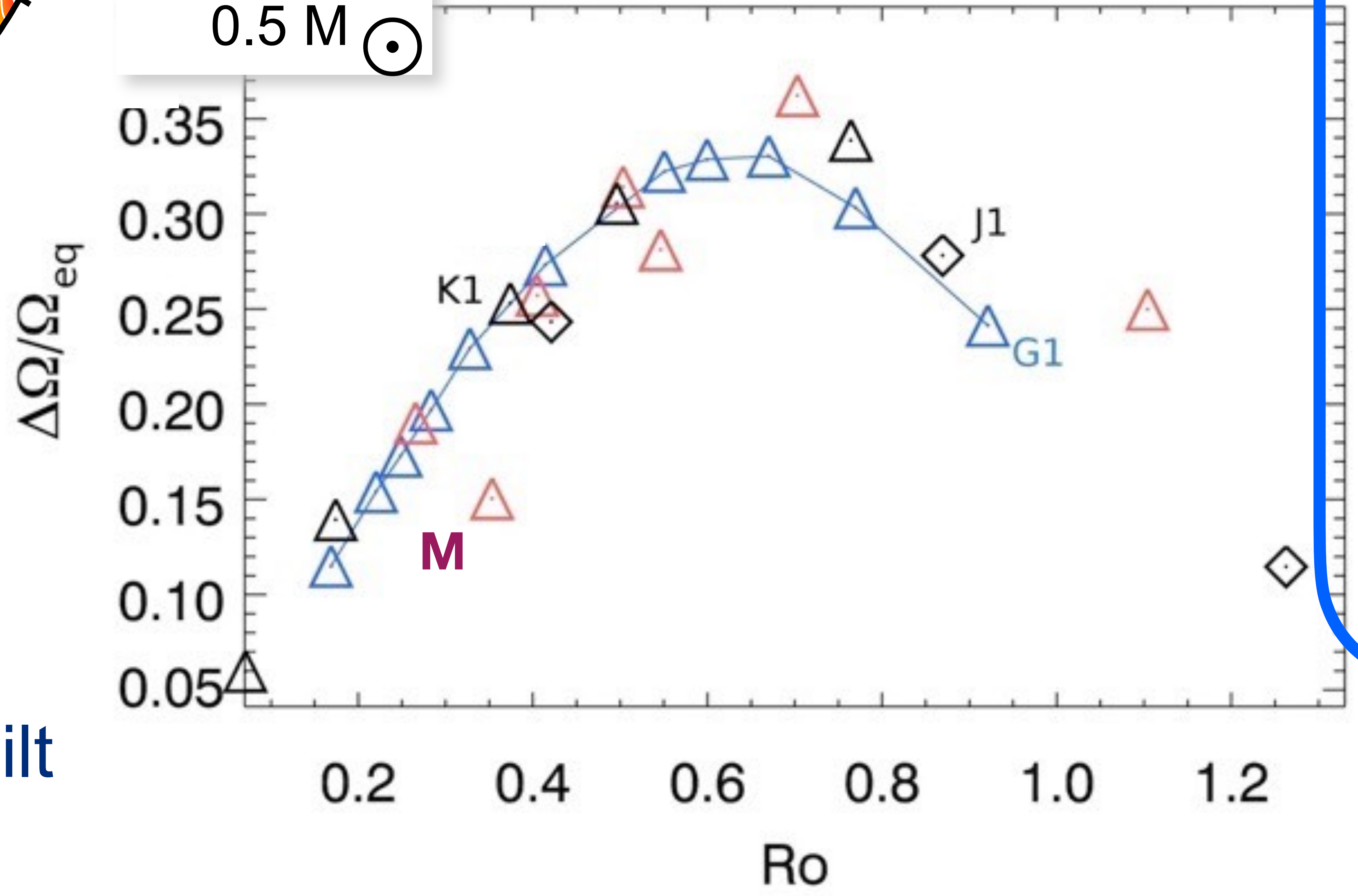


K-type star
0.5 M☉

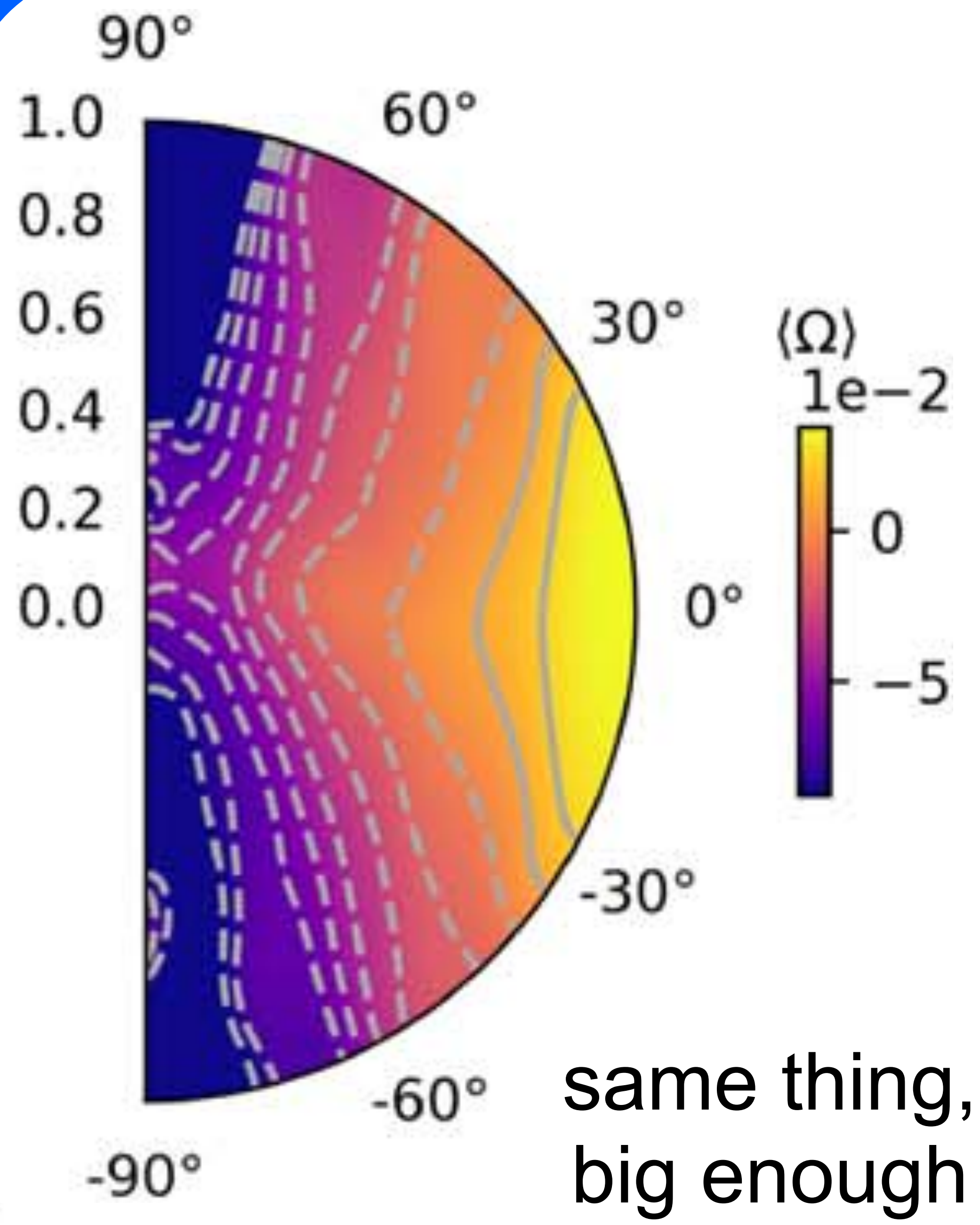


M-type star
0.3 M☉

Rossby scaling



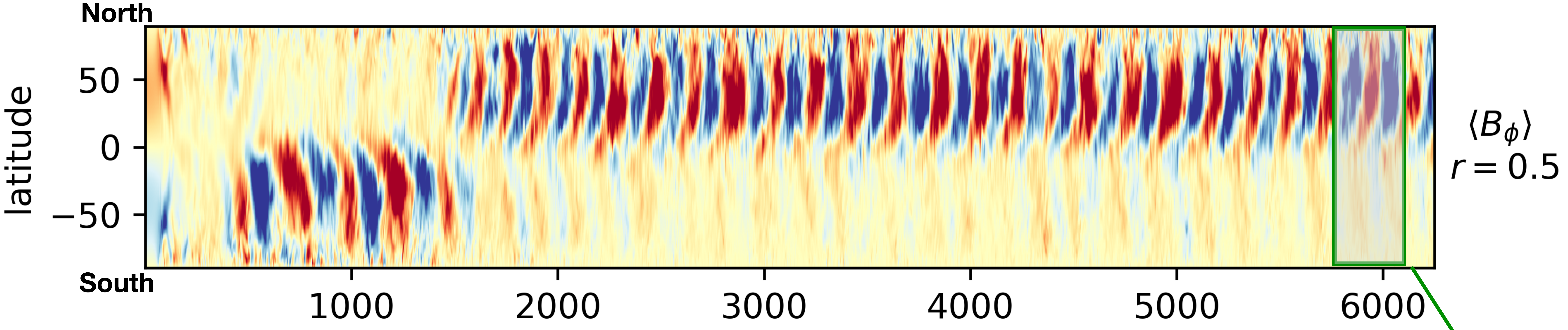
Stars of different masses, built off MESA structure models.



same thing, big enough to see

Fully convective M-dwarfs ~0.3 M☉ with Ro~0.3 (rotation periods of 80-130+ days)

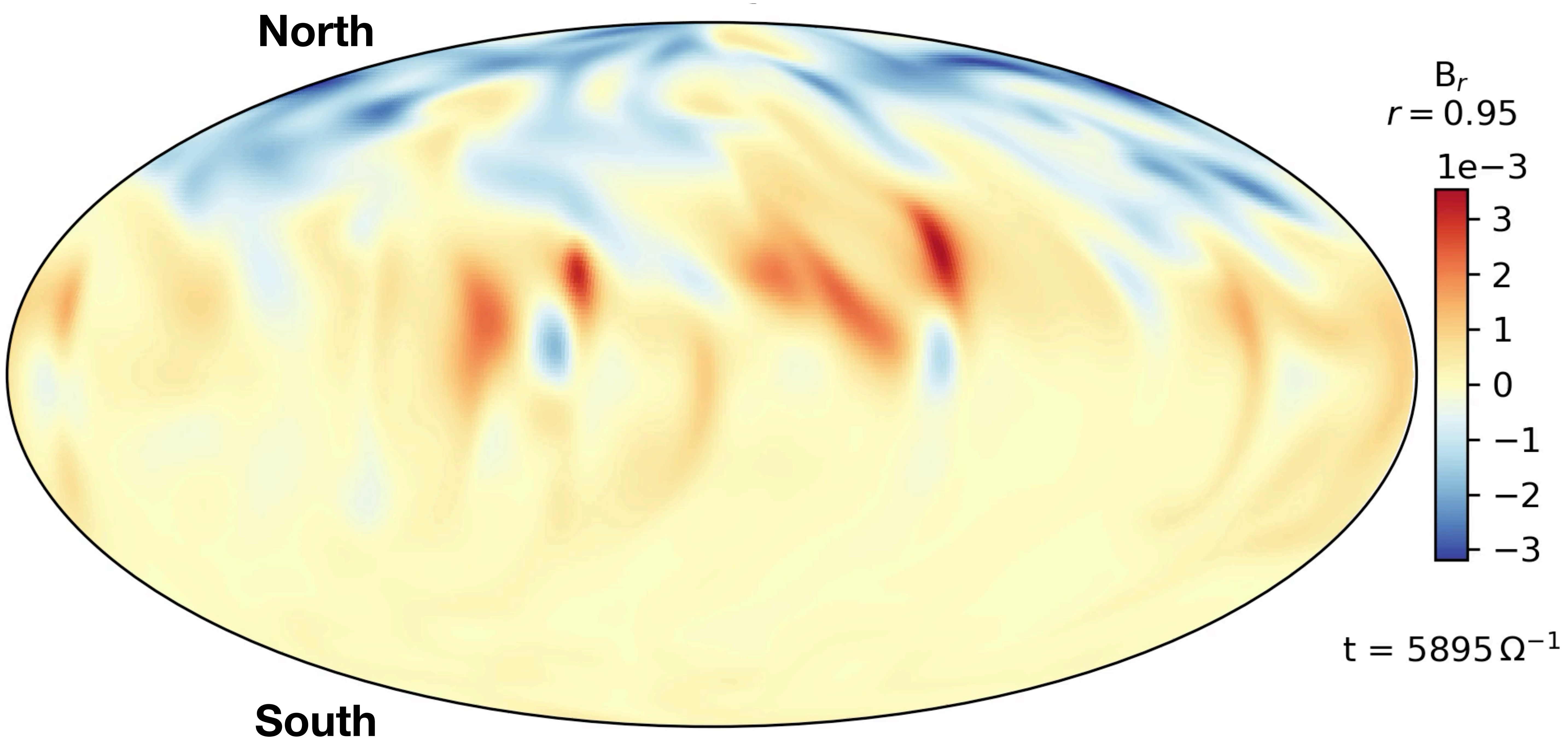
The magnetic fields cycle, in a single hemisphere



Movie spans this interval of time

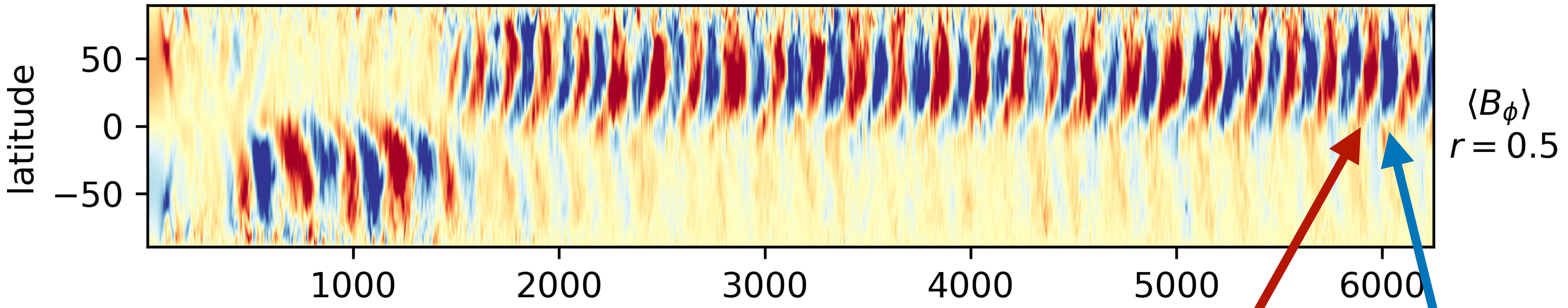
Radial magnetic field near the surface.

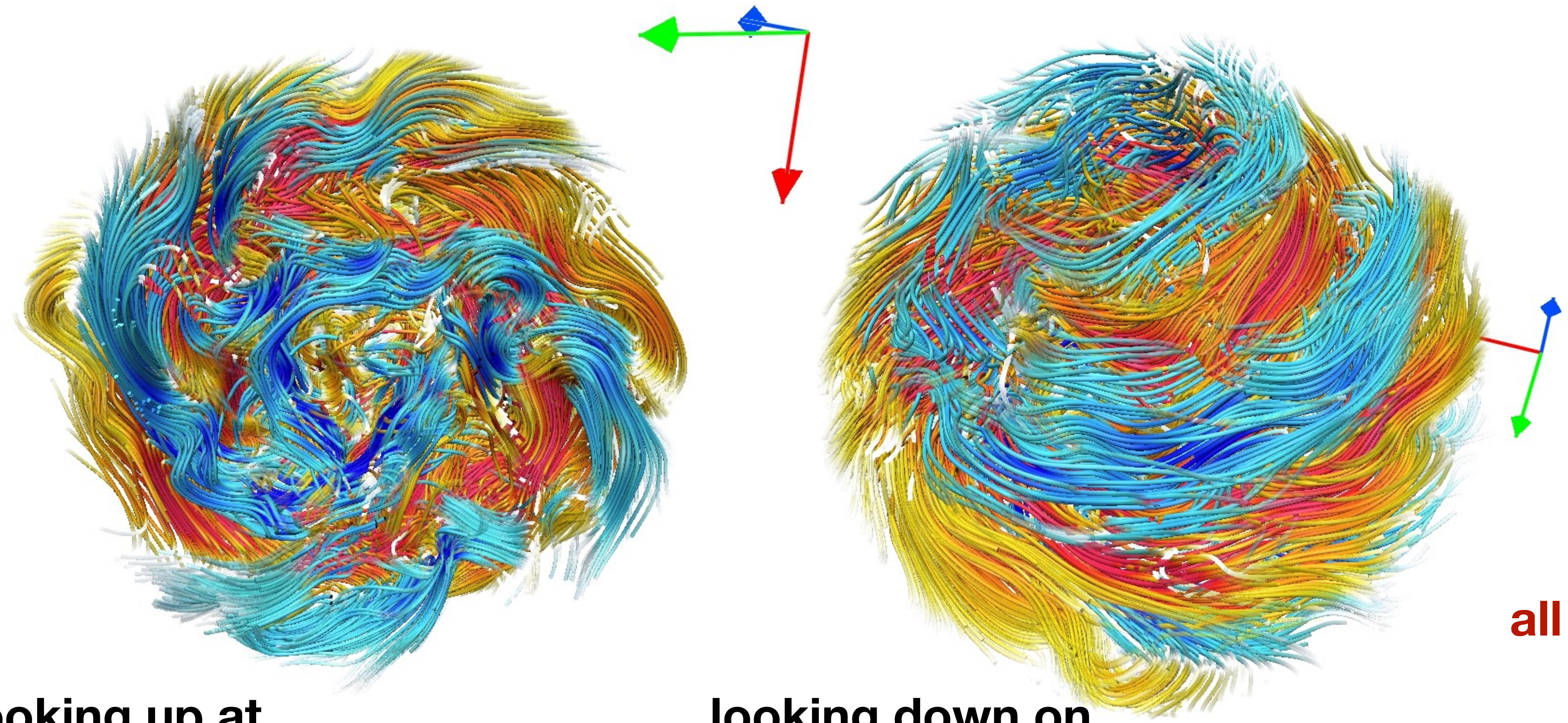
Globally-organized, reverses in polarity (color), but mostly in Northern hemisphere



Brown, Oishi, Vasil, Lecoanet & Burns 2020, "Single-hemisphere dynamos in M-dwarf stars", under review at ApJL

The magnetic fields fill the convection zone

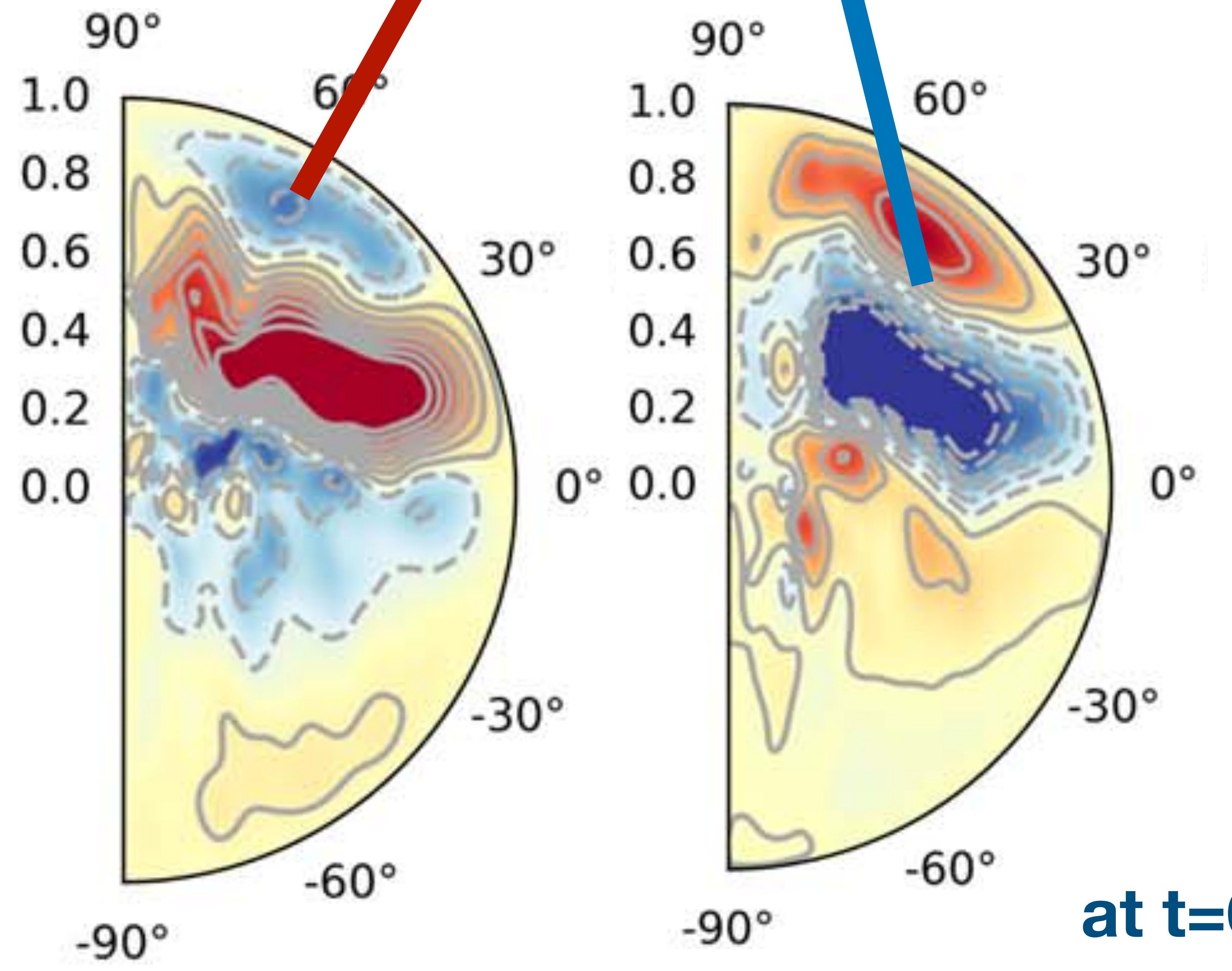




looking up at North hemisphere

looking down on North pole

all at t=5950



at t=6025

non-dipolar, hemispheric global fields that reverse polarity

Brown, Oishi, Vasil, Lecoanet & Burns 2020, “Single-hemisphere dynamos in M-dwarf stars”, ApJL

An analogy, with boats.

Here’s what we’re competent at doing.

An analogy, with boats.

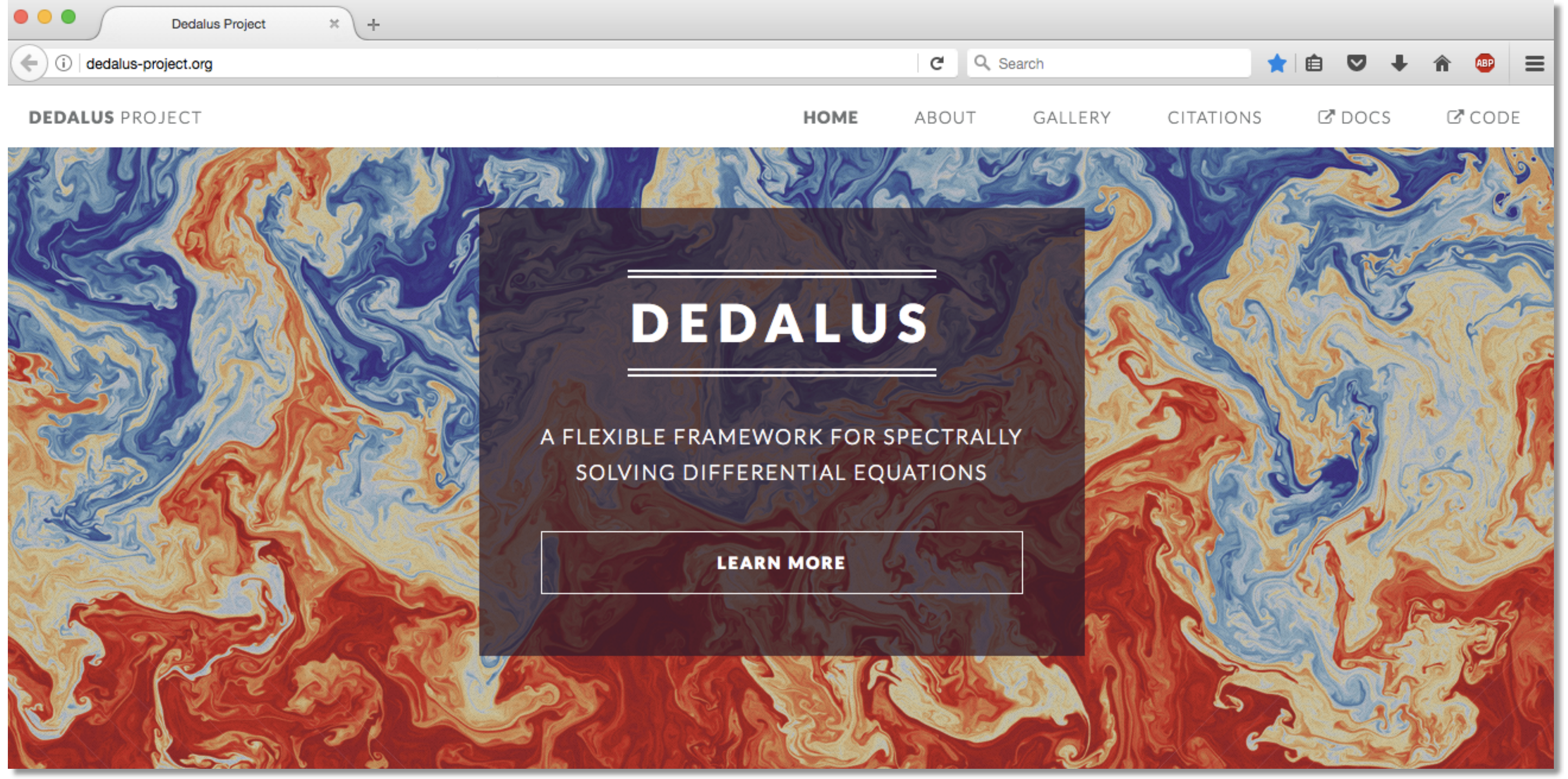
Here’s what we think we can do
(oh, we totally can! We’ve got this!)

An analogy, with boats.

Here’s what usually happens…

(but sometimes we don’t know we’re wrecked)

New tools for astrophysics and some parting thoughts



Reproducing existing numerical work is very hard.
This is crippling for science. Standards in Astro are lax.

Open source tools help ease this barrier to entry. But they're not enough.
It's important that the full toolchain be published in some fashion.

With modern practices, open source community tools can be built and maintained on the cheap.
Dedalus has cost ~$2M, vs. ~$100M+ for FLASH. There are downsides (no phone line).

Perspectives on Reproducibility and Sustainability of Open-Source Scientific Software from Seven Years of the Dedalus Project

A white paper submitted to the National Academies of Sciences, Engineering, and Medicine's Best Practices for a Future Open Code Policy for NASA Space Science

The Dedalus Collective
Jeffrey S. Oishi,[1] Benjamin P. Brown,[2] Keaton J. Burns,[3] Daniel Lecoanet,[4] and Geoffrey M. Vasil[5]

Oishi et al 2018 arxiv:1801.08200