Dynamos and Differential Rotation

Advances at the crossroads of analytics, observations, and numerics

Kyle Augustson

CEA – Saclay Service d'Astrophysique

Seismology of the Sun and the Distant Stars

Session 8, Wednesday 13 July 2016

Whence the Crossroads?

Which stellar observations currently provide the best constraints on analytical and numerical dynamo models?

- The Sun
  - Activity cycles and detailed dynamics
- A selection of active Kepler and Mt Wilson stars, among a few others
  - Sensitivity of activity cycles to fundamental parameters
- Red Giants
  - Convective Core Dynamos
- M dwarfs
  - Impact of a stable interior, fully convective dynamics, proxy for pre-main sequence stars

The puzzling magnetism of the Sun and Sun-like stars

- What interplay of mechanisms set the cycle period and permit polarity reversals?

- What is the internal state of the Sun’s convection?

- What role does a tachocline play?

Essential Dynamo Processes

Evolution of Mean Magnetic Fields

$$\frac{\partial A}{\partial t} = \overbrace{\eta\left(\nabla^2 - \frac{1}{\lambda^2}\right)A}^{\text{magnetic diffusion}} - \overbrace{\frac{1}{\lambda}\mathbf{u}_m \cdot \nabla(\lambda A)}^{\text{meridional advection}} + \overbrace{\hat{\phi}\cdot\overline{\mathbf{u}' \times \mathbf{B}'}}^{\text{poloidal generation}}$$

$$\frac{\partial B}{\partial t} = \underbrace{\eta\left(\nabla^2 - \frac{1}{\lambda^2}\right)B}_{\text{magnetic diffusion}} + \underbrace{\frac{1}{\lambda}\frac{\partial \eta}{\partial r}\frac{\partial \lambda B}{\partial r}}_{\text{diffusive transport}} - \underbrace{\lambda \mathbf{u}_m \cdot \nabla \frac{B}{\lambda}}_{\text{meridional advection}}$$

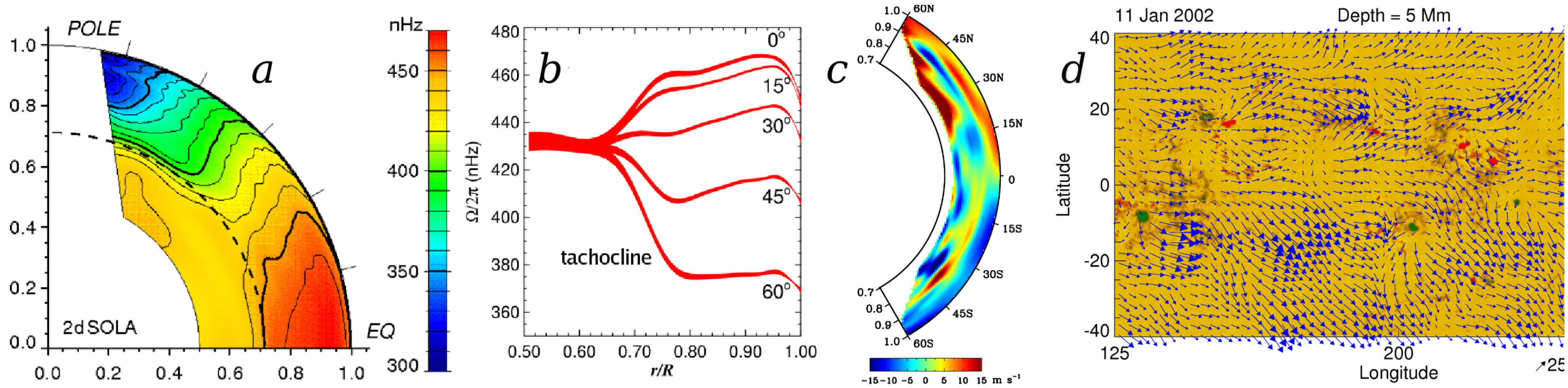
$$- \underbrace{B\nabla\cdot\mathbf{u}_m}_{\text{compression}} + \underbrace{\lambda\nabla\Omega\cdot\nabla\times A\hat{\phi}}_{\text{stretching}} + \underbrace{\hat{\phi}\cdot\nabla\times\overline{\mathbf{u}'\times\mathbf{B}'}}_{\text{toroidal generation}}$$

Turbulent Correlations

Rotation

- Fully resolved nonlocal 3D MHD
  Self-consistent flow and field
- Flux-transport dynamo (e.g., BL)
  Prescribed flows & model EMF
- Delta-correlated turbulence (MFT)
  Prescribed flows & model EMF
- Parametrically asymptotic models
  A way of reaching more stellar-like parameter regimes

Essential Dynamo Processes



Differential Rotation

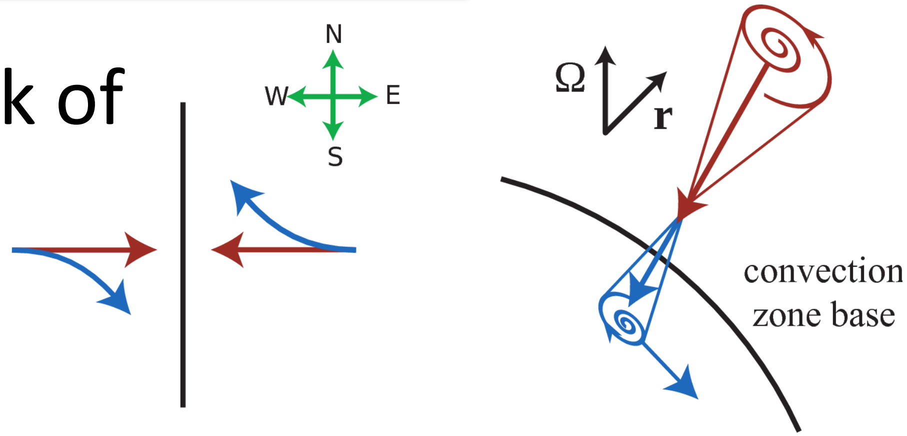
Howe 2009

Meridional Circulation

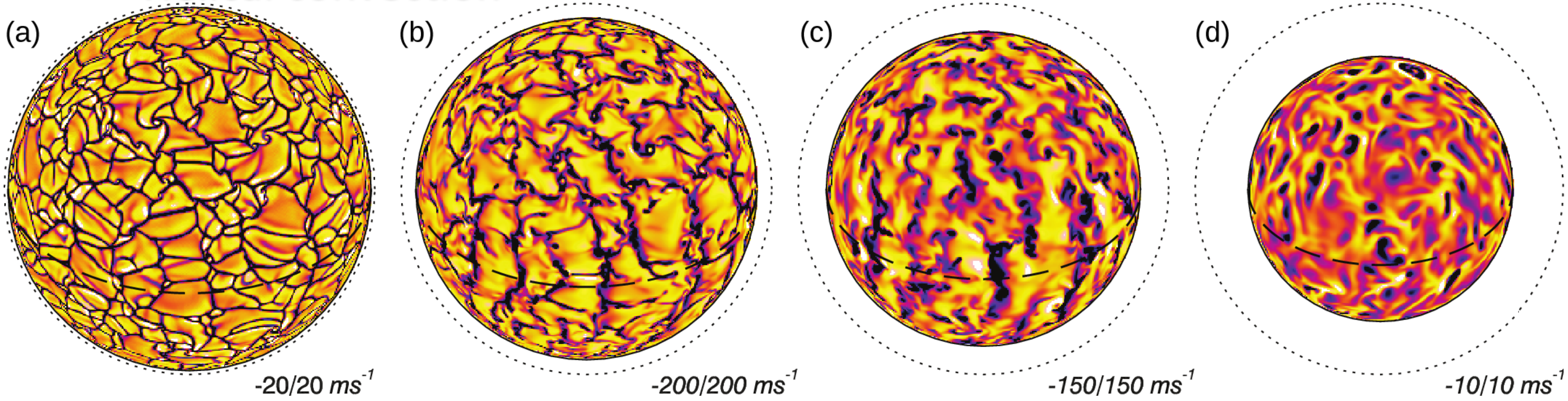
Zhao et al 2013

Elements of Stellar Magnetic Variability

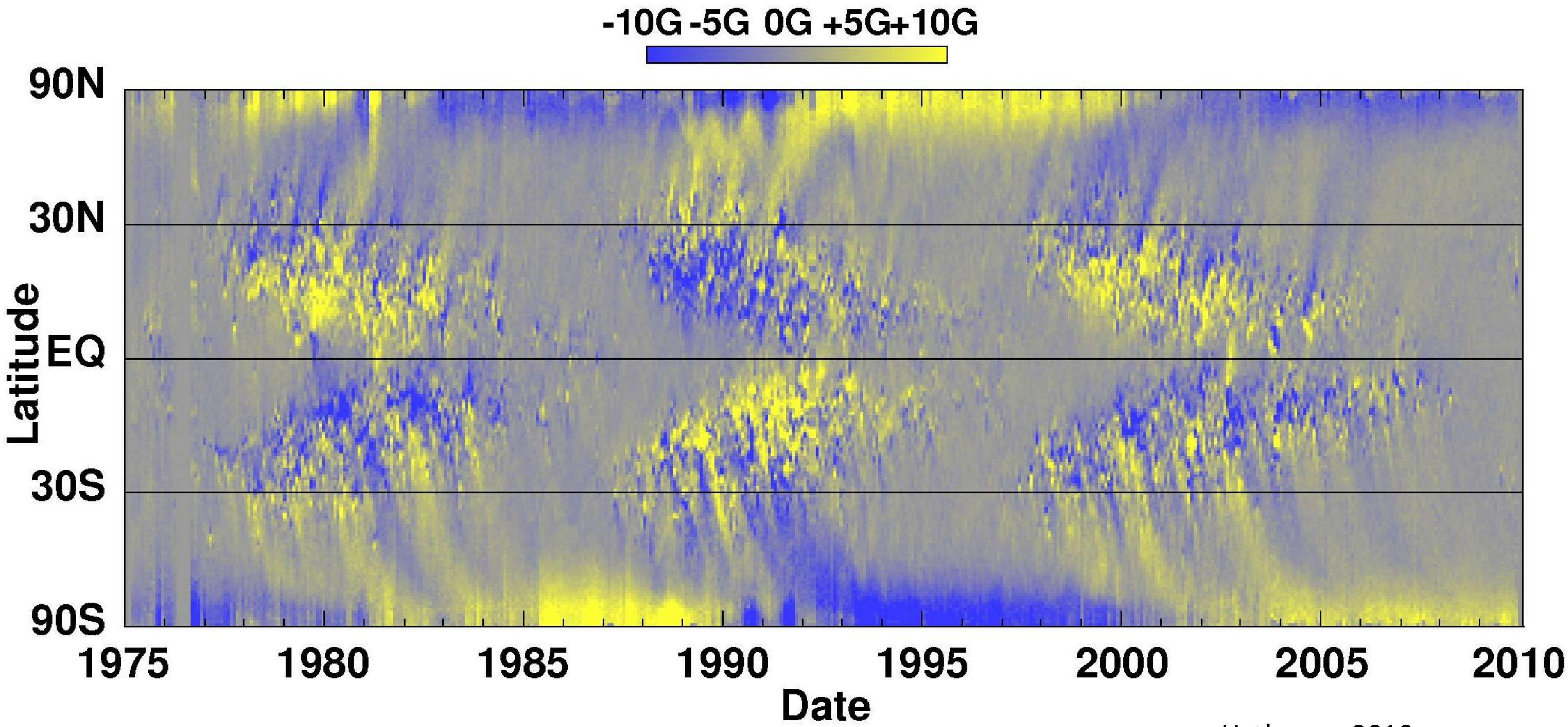
The other basic building block of stellar dynamos:



Helical convection

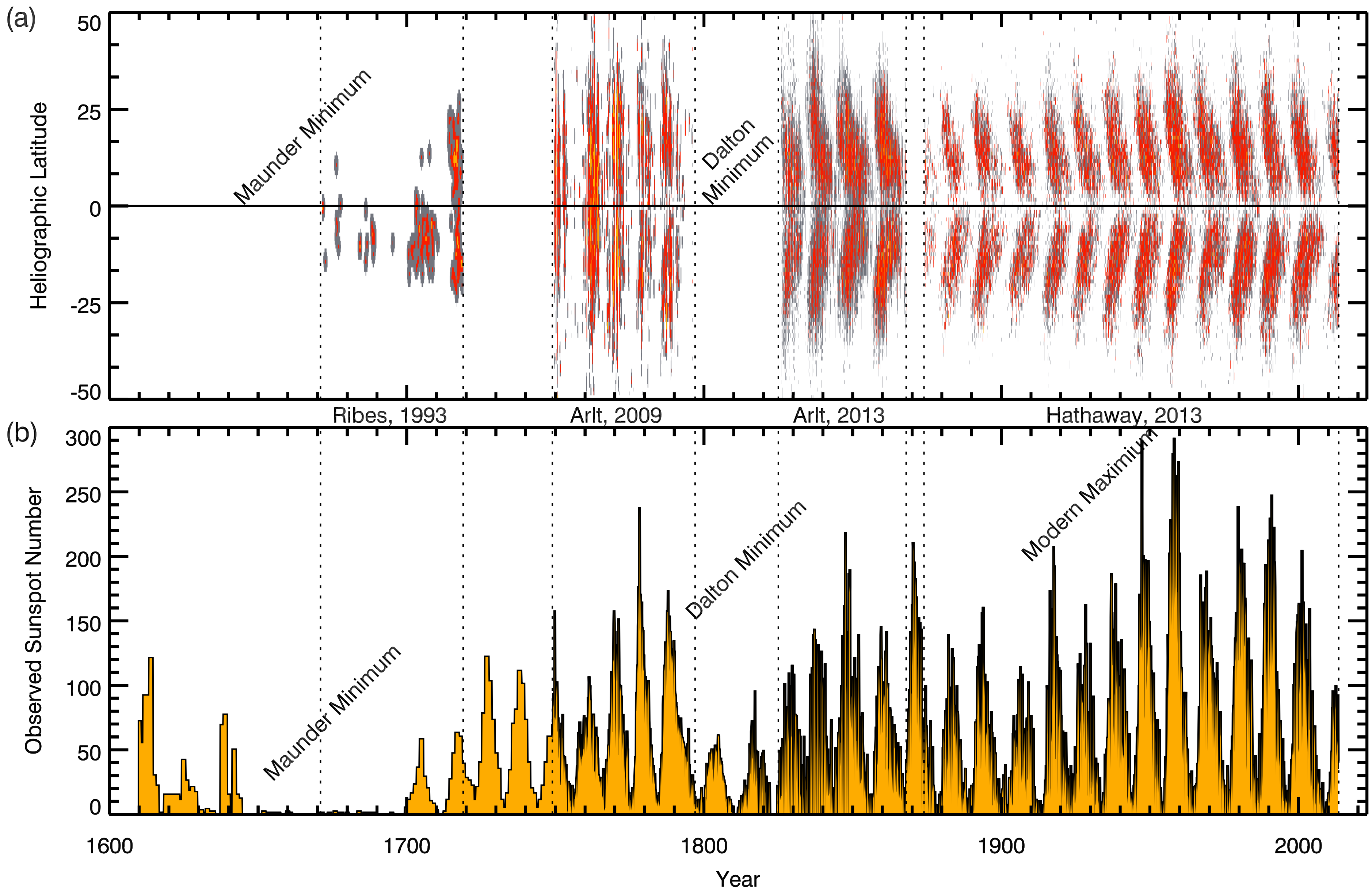


Basic Aspects of Solar Magnetism

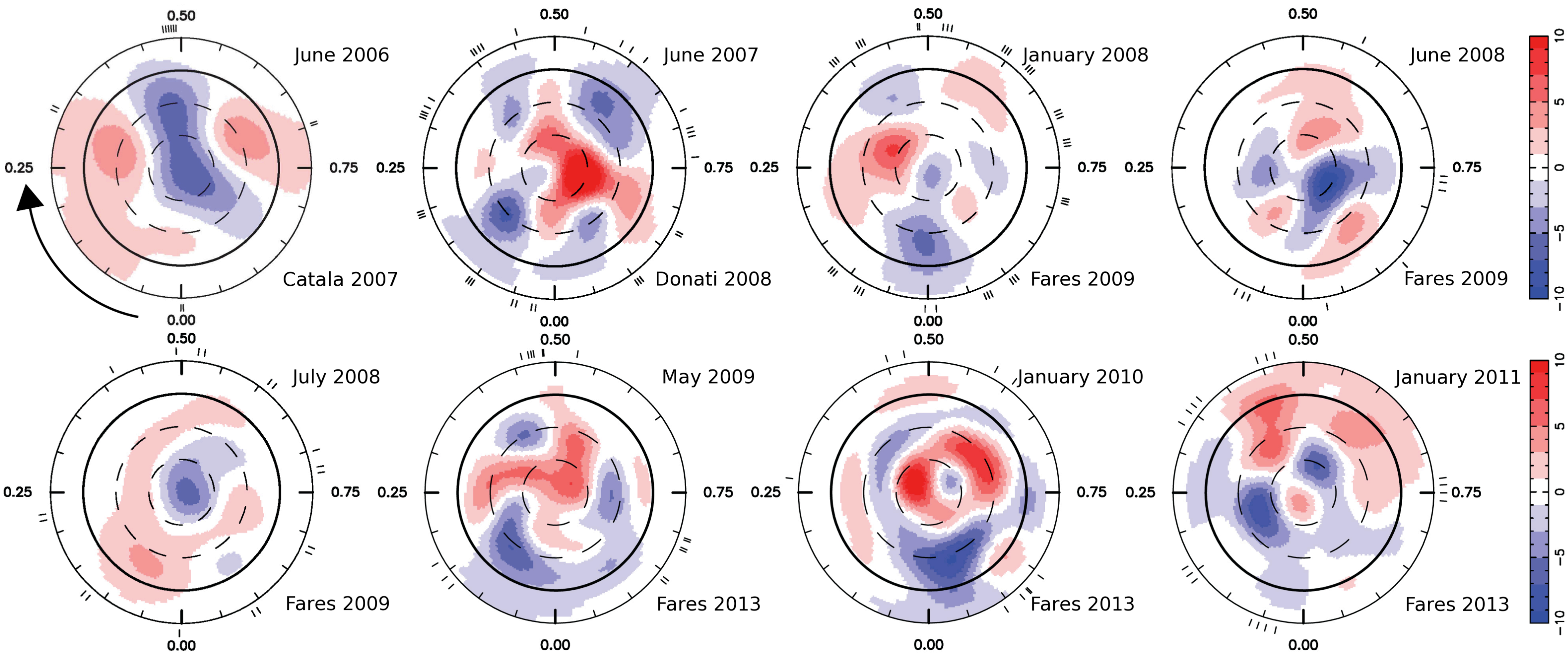


Hathaway 2010

Basic Aspects of Solar Magnetism



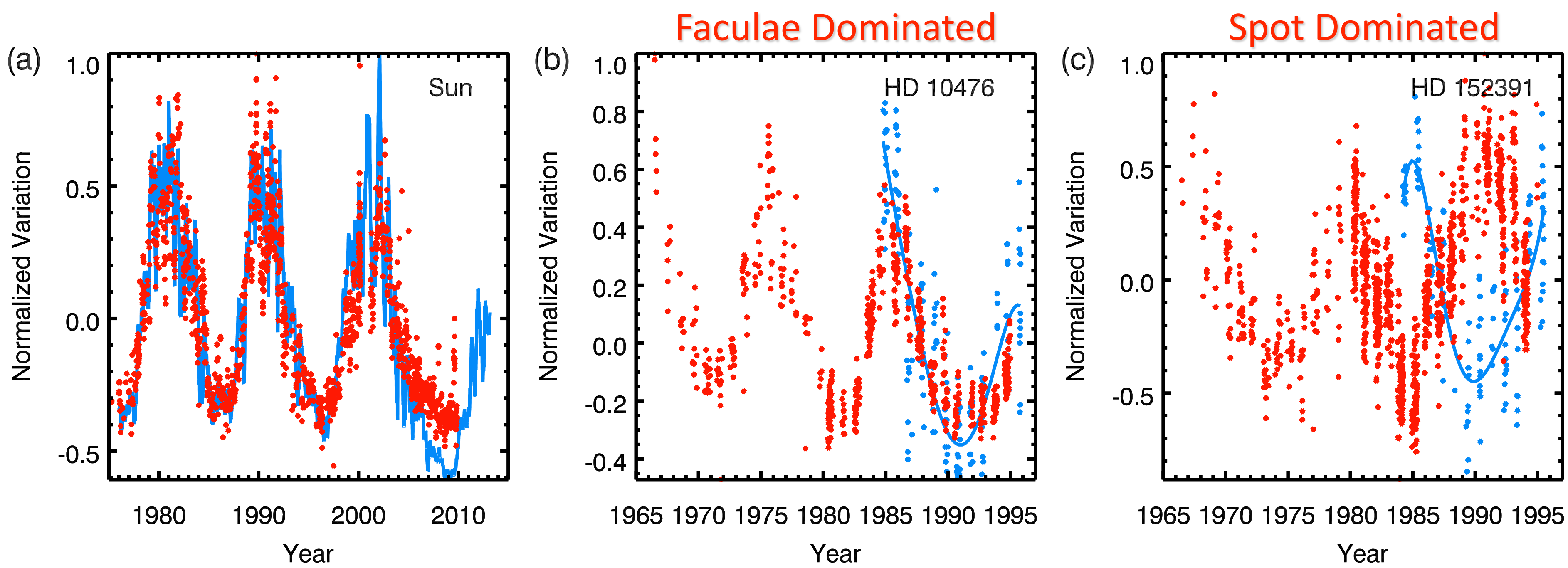
Stellar Cycles & Magnetism



Spectropolarimetry

Tau-Bootis F-type Star

Stellar Cycles & Magnetism



Froehlich 2013,
Livingston 2007

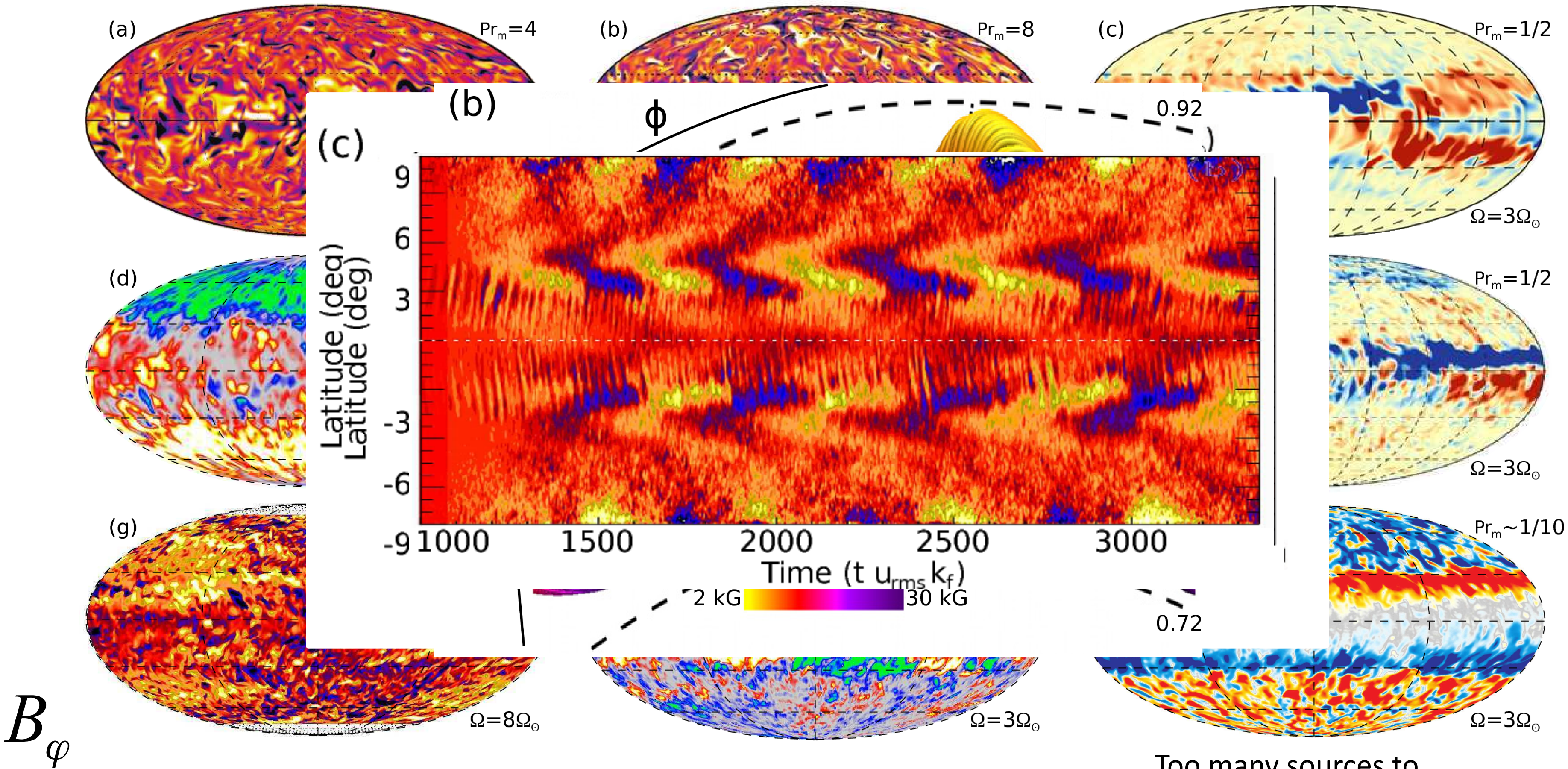
Radick 1998

Ca H & K Emission

Long-term Activity Cycles

And of course new cycle period data from a set of Kepler targets (e.g. Mathur et al), as well as the work that we heard about yesterday (e.g., Metcalf et al 2016).

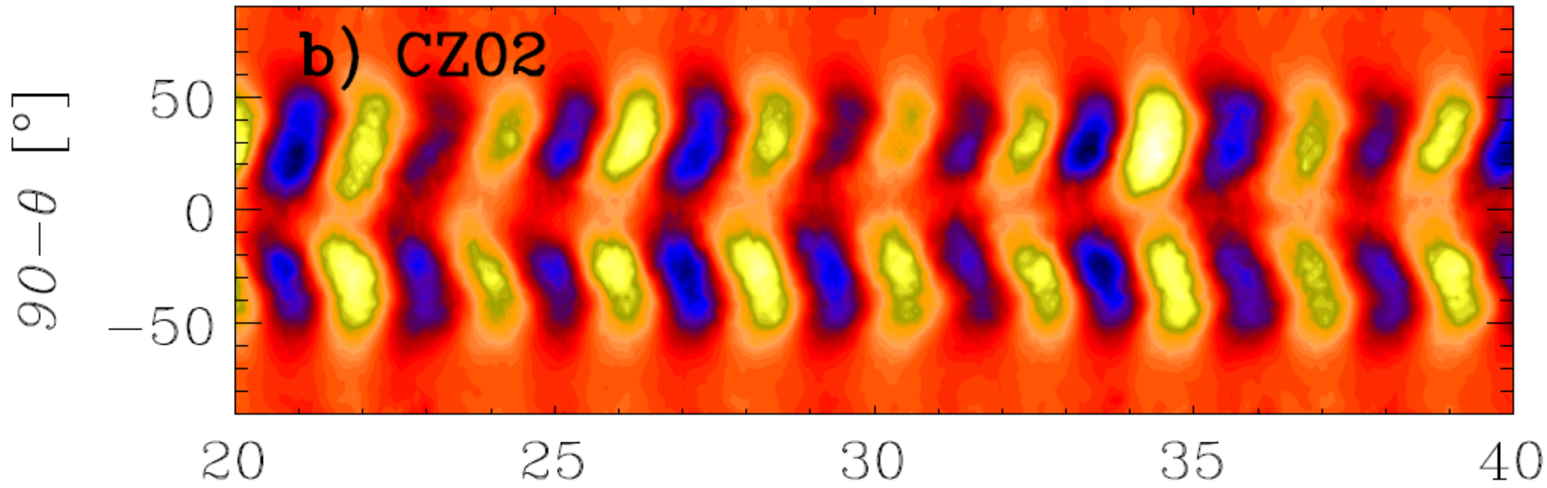
Progress in Stellar Dynamo Theory



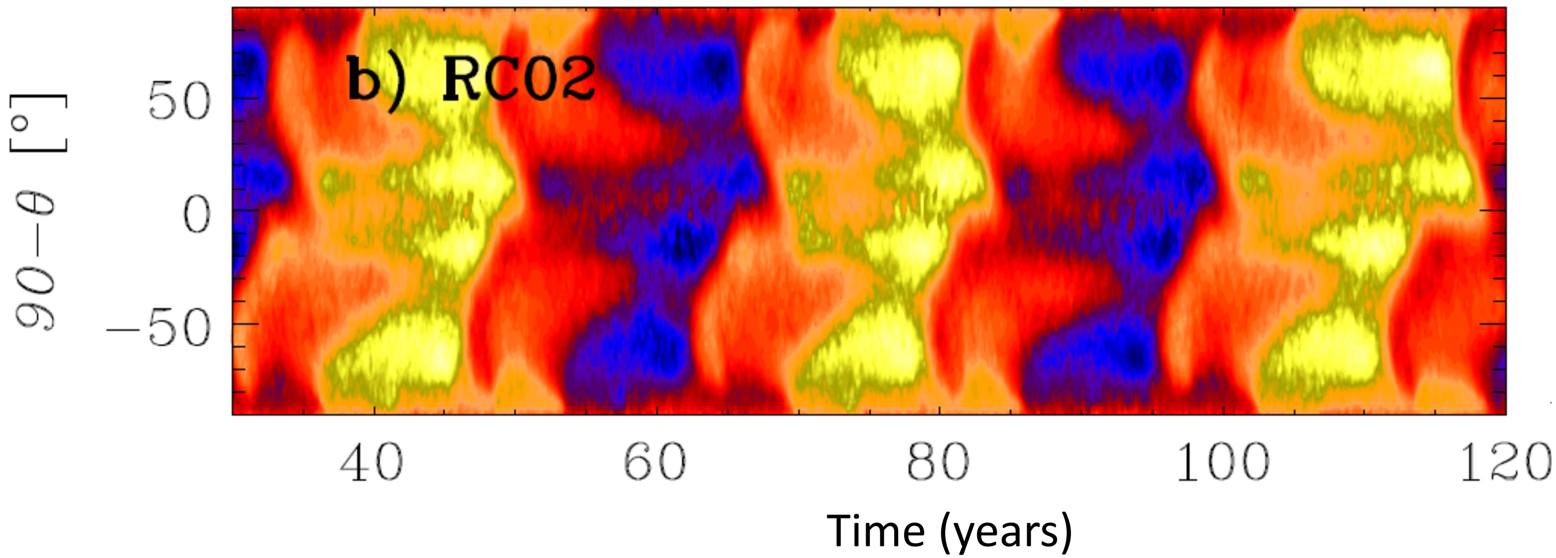
Too many sources to list!

Solar-like stars

Impacts of a convectively stable region on cycle period



Fast Cycles, Convection Zone Only

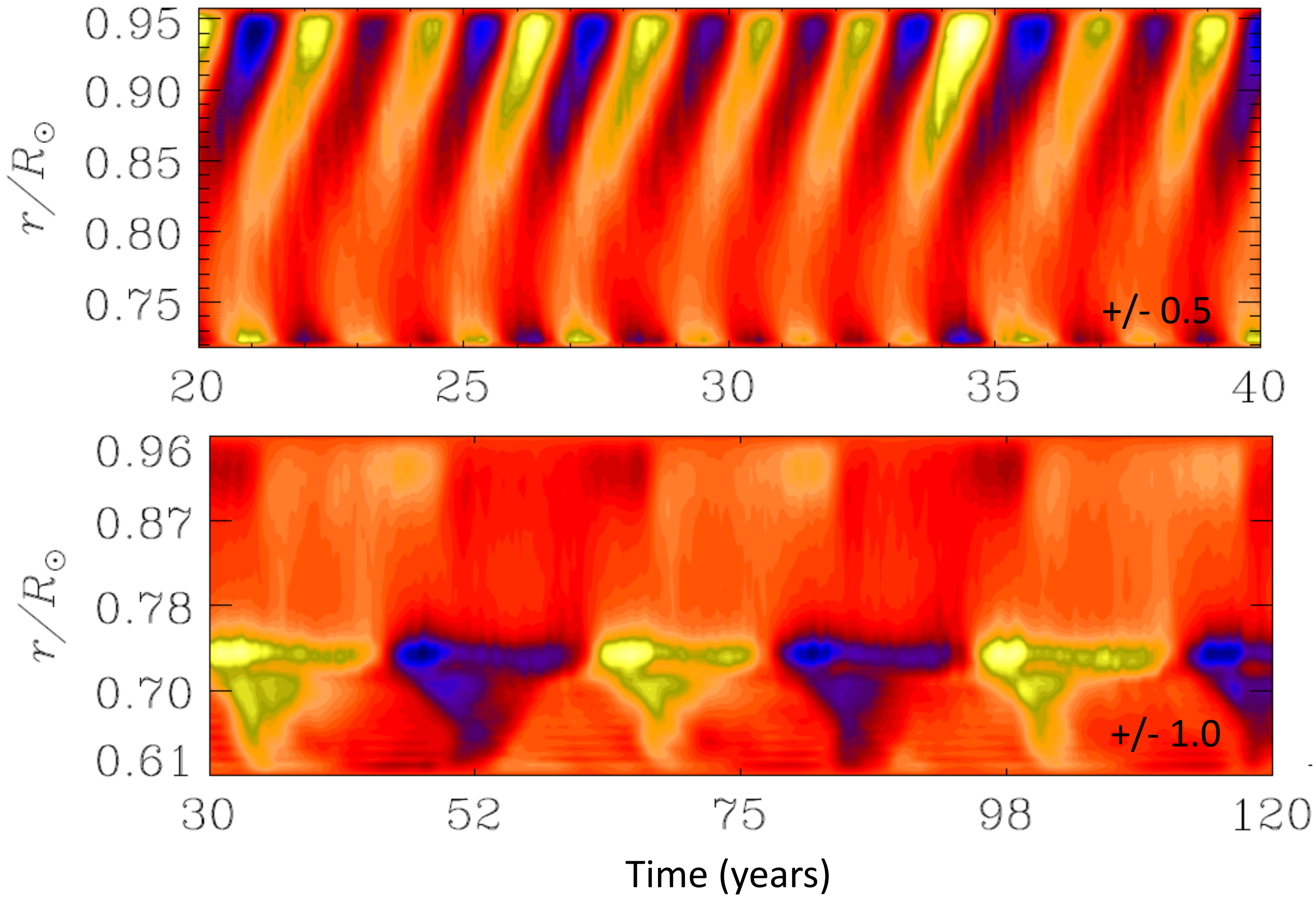


Slow Cycles, Both Zones

Guerrero et al. 2016

Solar-like stars

Impacts of a convectively stable region on cycle period



Fast Cycles, Convection Zone Only

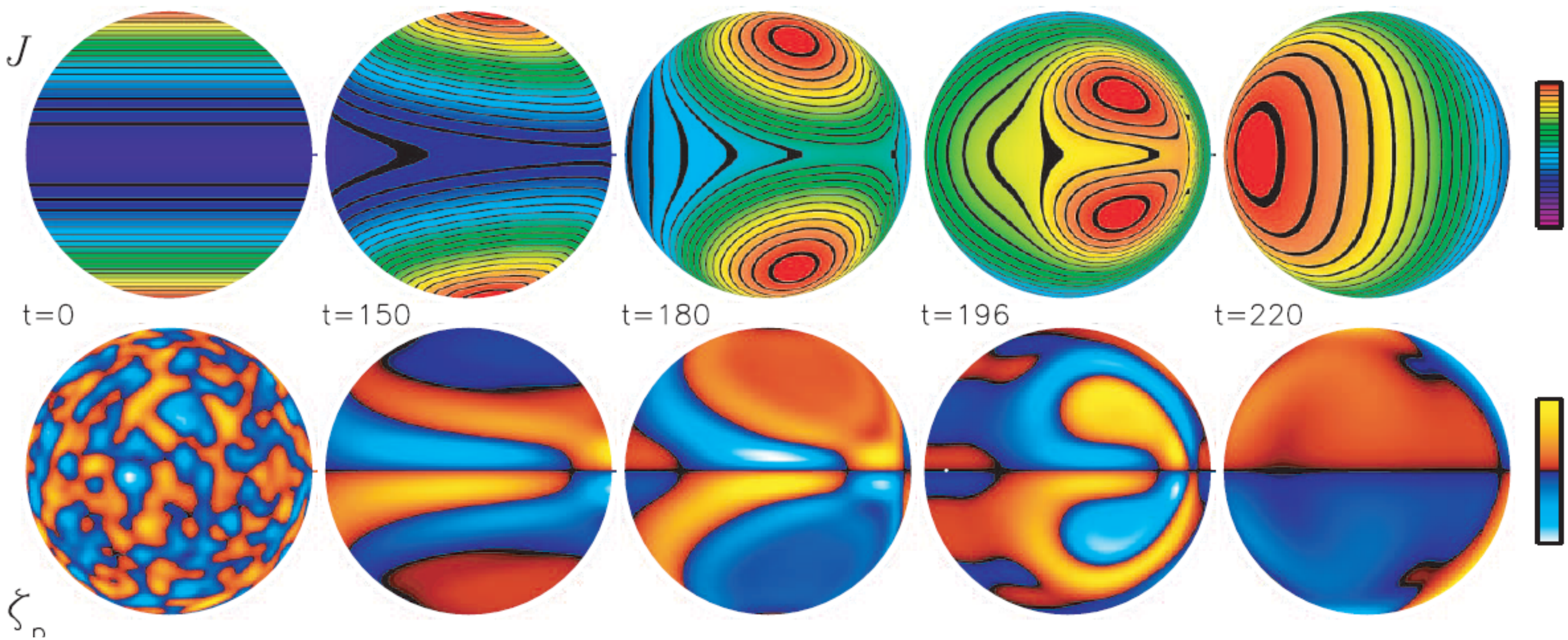
Slow Cycles, Both Zones

Guerrero et al. 2016

Solar-like stars

Impacts of a convectively stable region: MHD instabilities

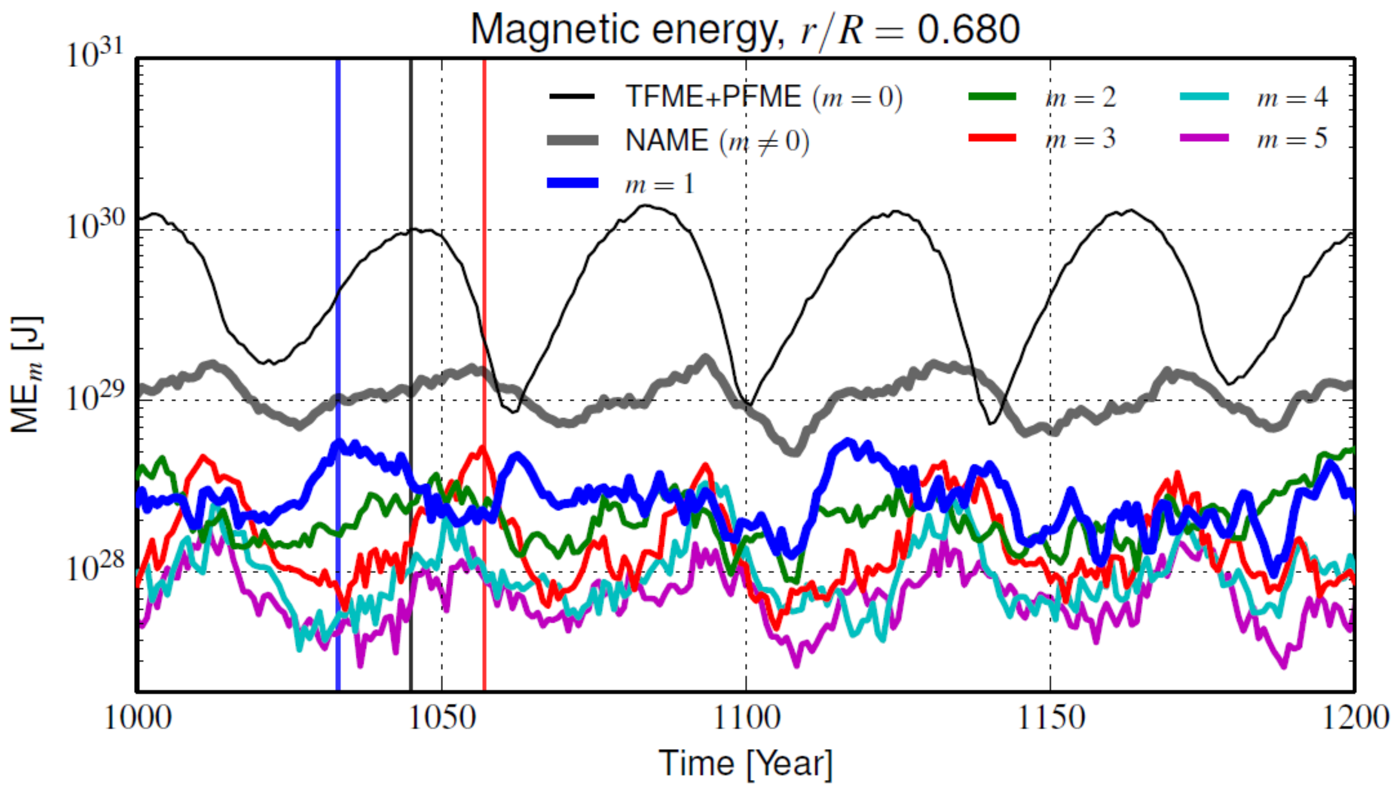
Magneto-shear instability (e.g., Miesch 2007)



Solar-like stars

Impacts of a convectively stable region: MHD instabilities

Magneto-shear instability (e.g., Miesch 2007)

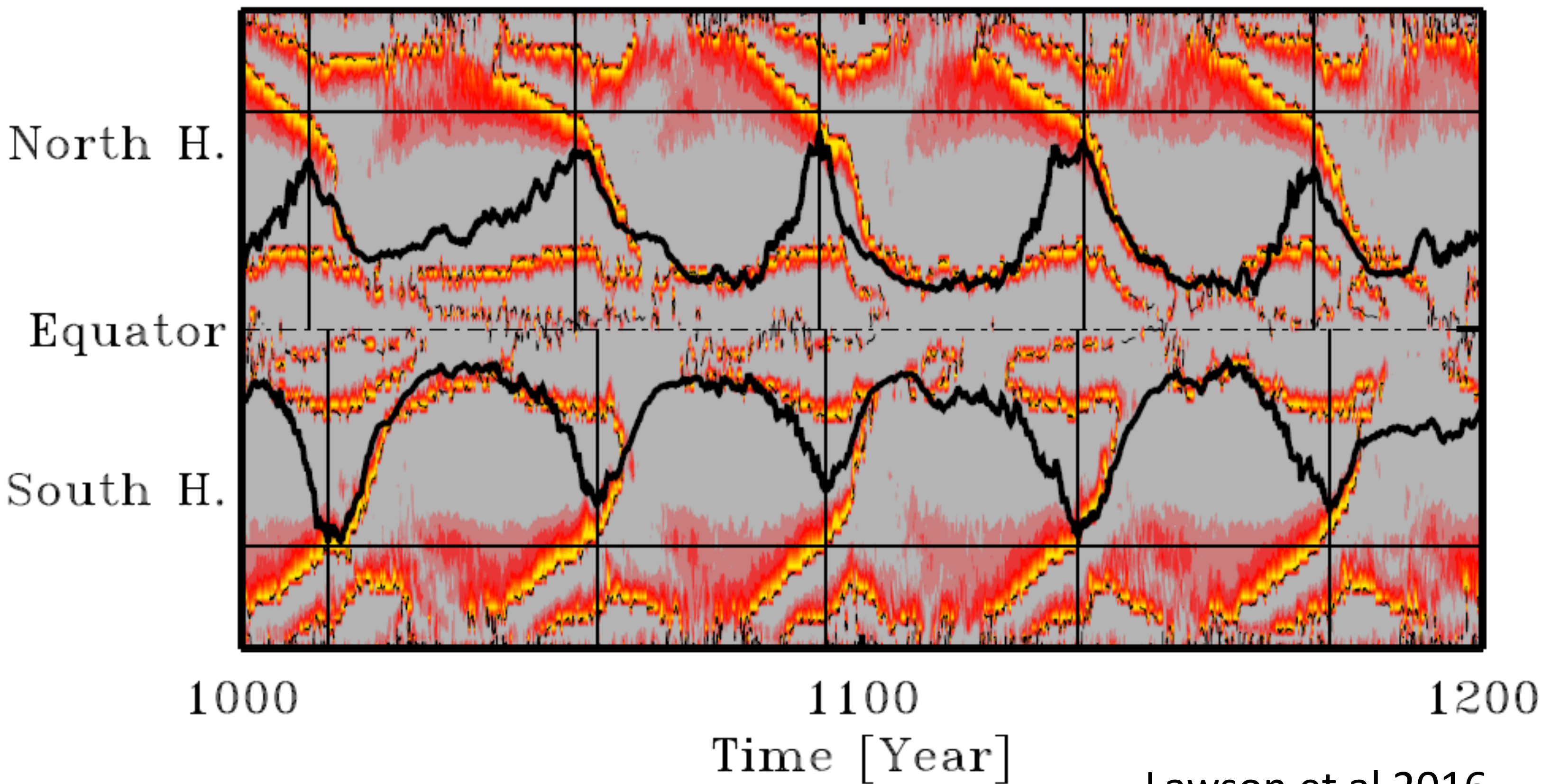


Lawson et al 2016

Solar-like stars

Impacts of a convectively stable region: MHD instabilities

Tayler instability (e.g., Tayler 1973)

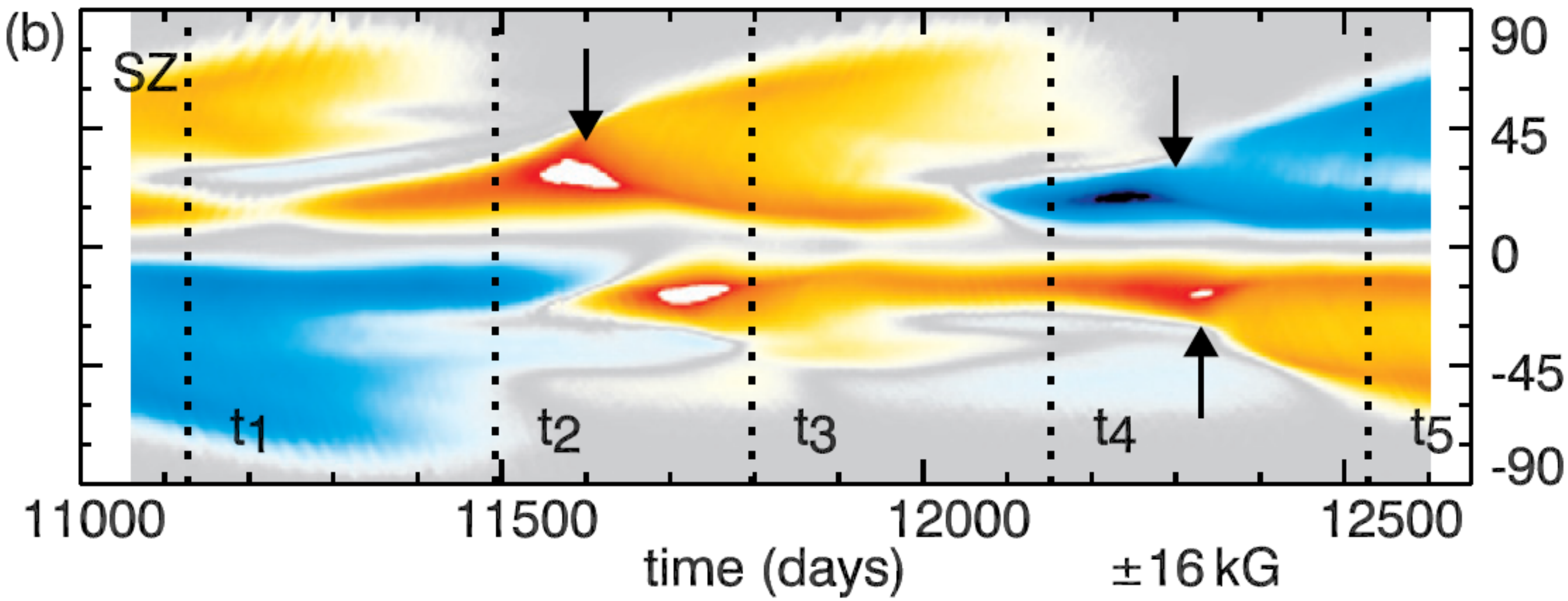


Lawson et al 2016

Solar-like stars

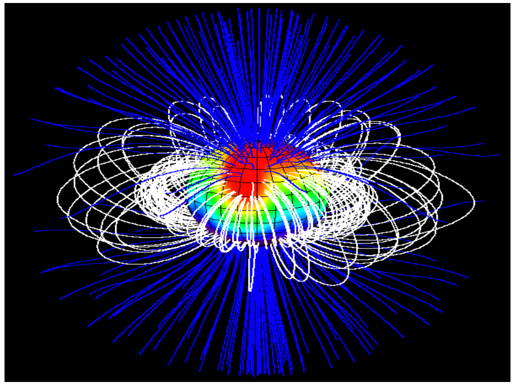
Impacts of a convectively stable region: MHD instabilities

Polar-slip instability (e.g., Spruit et al 1982)

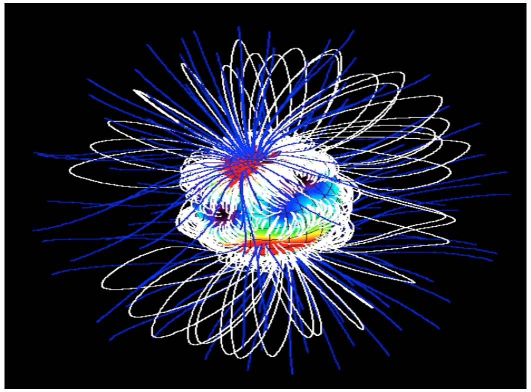


Augustson et al 2013

Before we leave stable zones behind… consider: Tiny Stars with Strong Fields



ultra-cool star V374 Pegasi
(Donati et al.)



Young star V2129 Oph
(Donati et al.)

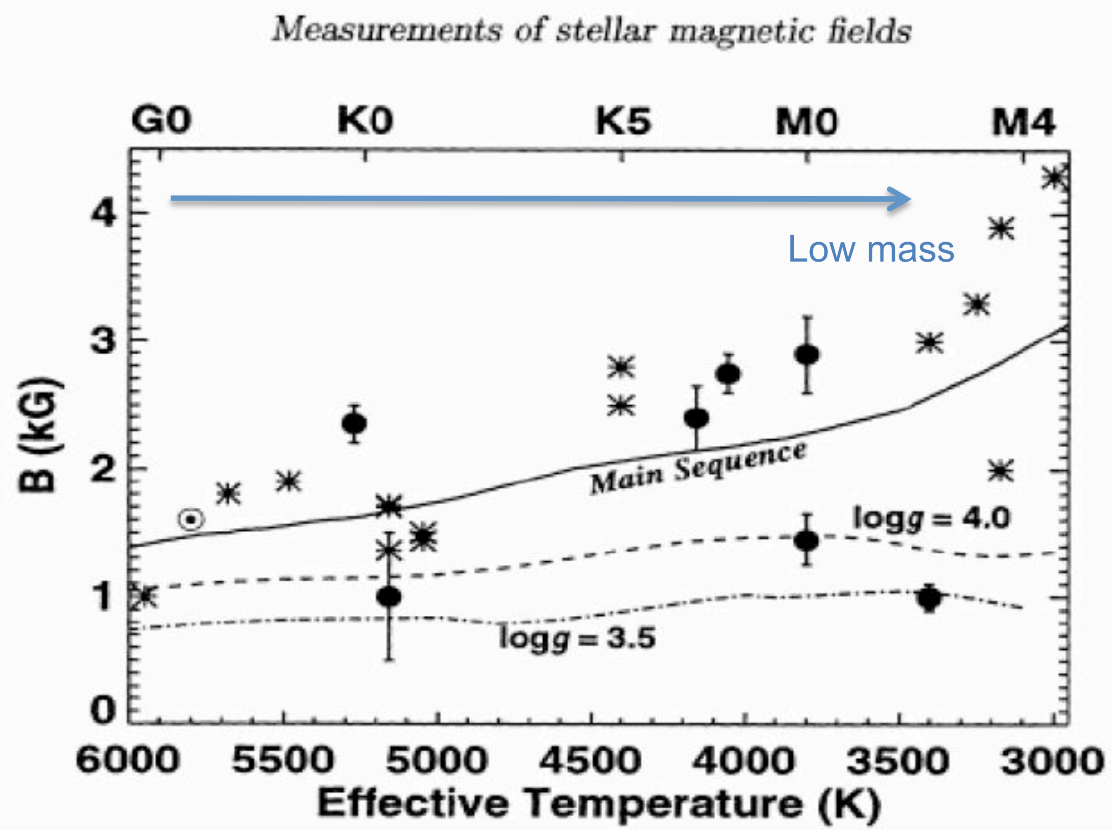
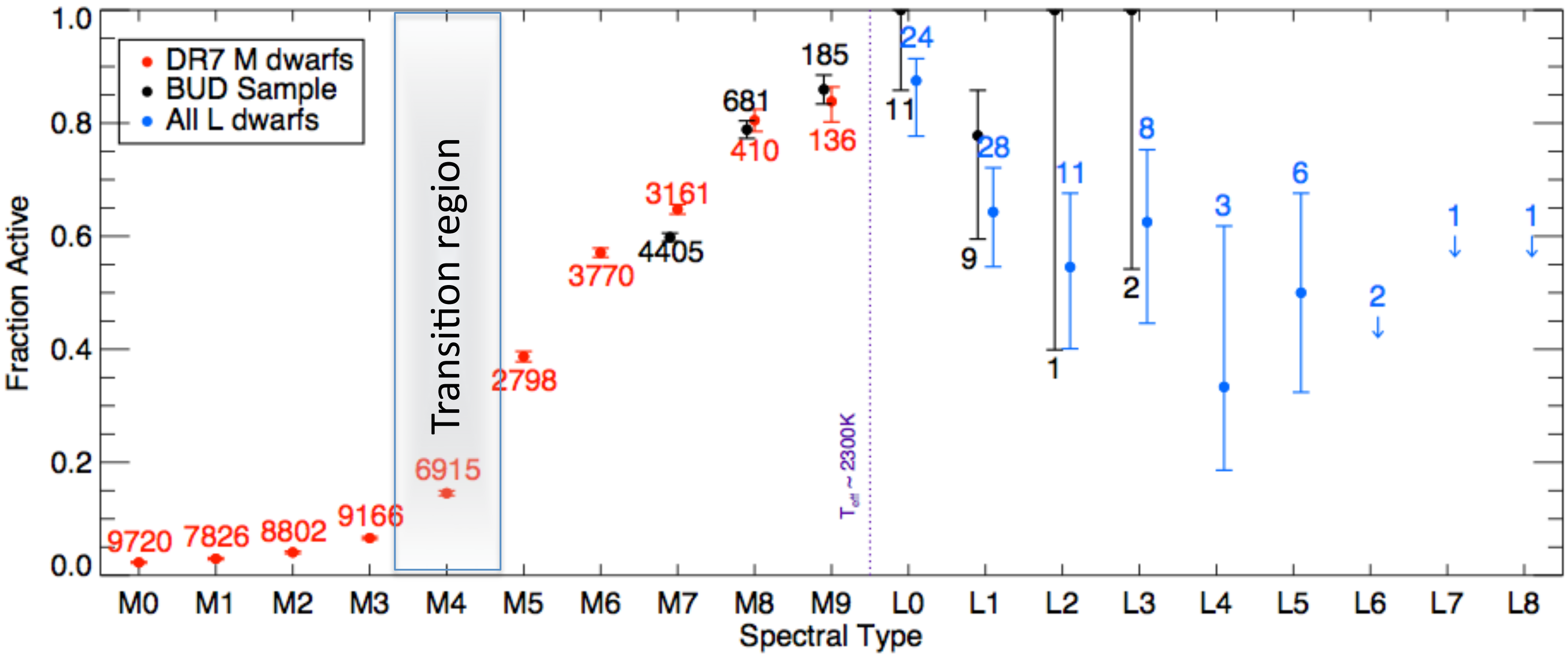


Figure 5. Predicted surface "equipartition" magnetic fields for cool stars. Also shown are measurements of main sequence stars (asterisks) and TTS (solid circles). The sun is shown by an encircled dot.

(J. Schmitt, 2003, IAU S219) From Johns-Krull & Valenti

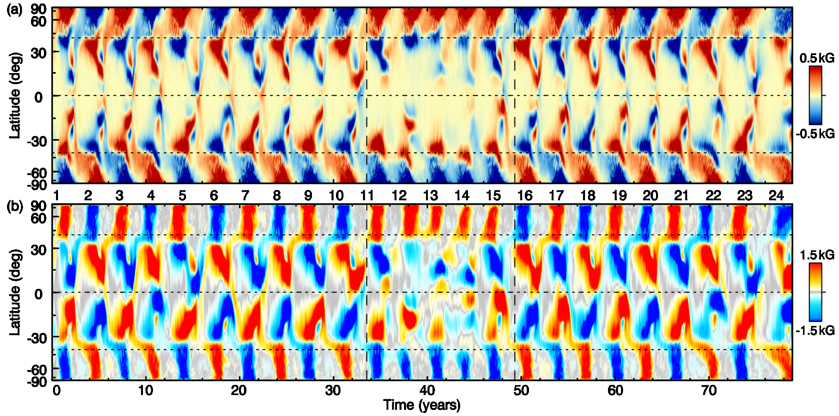
Interface Dynamo Transition?



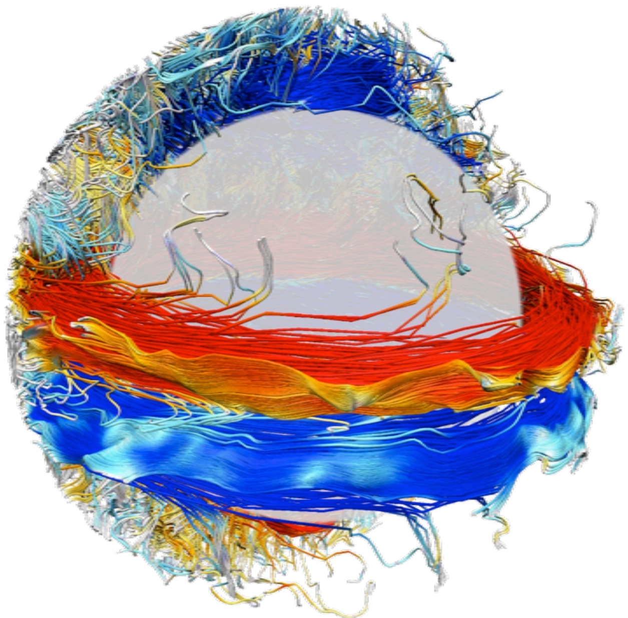
Schmidt 2014

Implications of a convectively stable region

- Stable regions act as storage of magnetic energy, significantly lengthening the cycle period
- In addition to convective pumping, instabilities play a role in eroding that stored field
- Potentially reduces the magnetically-active lifetime of the star, relative to fully convective stars



Cycling Wreaths of Magnetism



Magnetic Field Lines

Features similar to the observed solar dynamo:

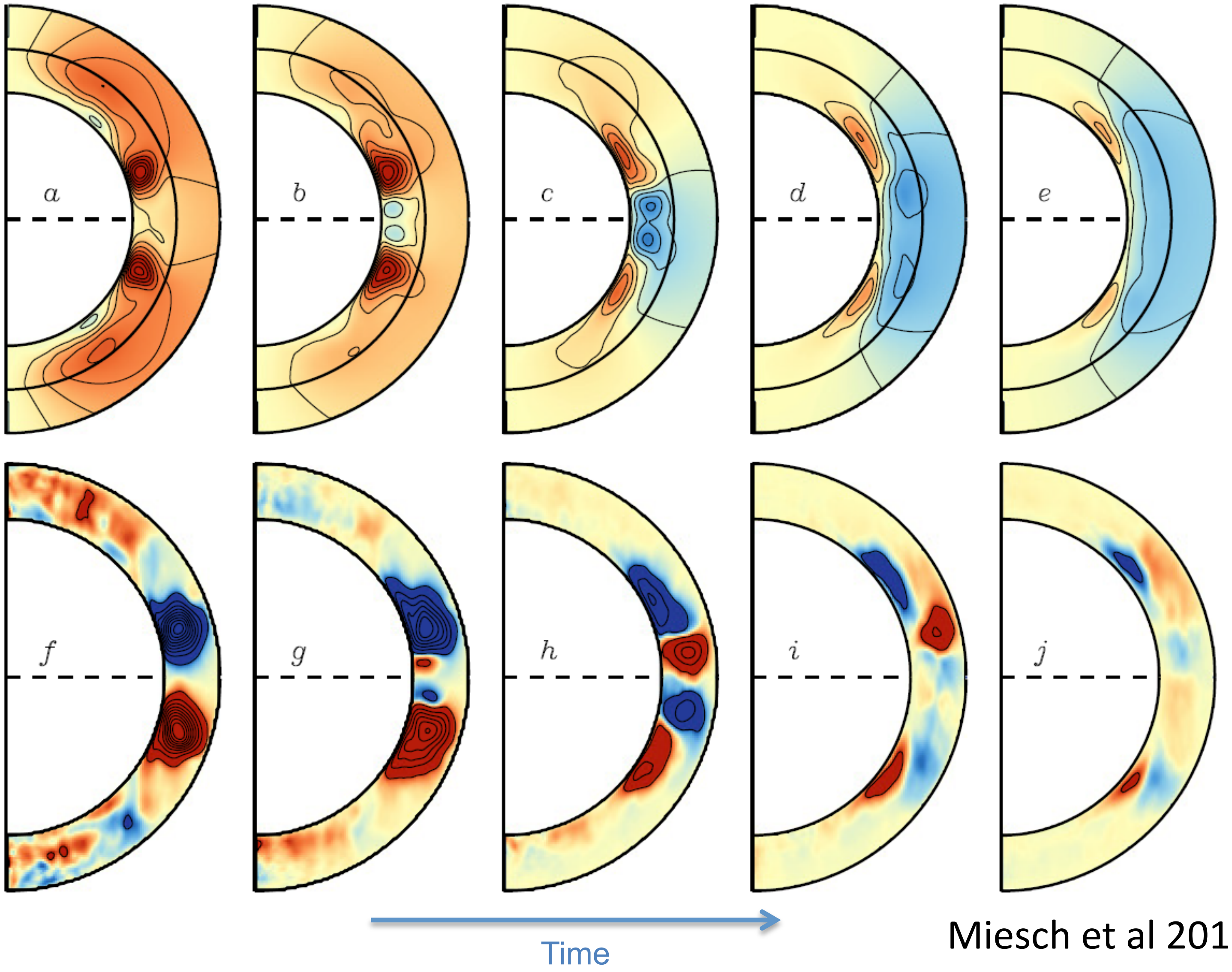
- Magnetic energy (activity) cycles
- Regular polarity reversals
- Equatorward propagation of magnetic structures
- Grand minimum

Physical processes at work
(Augustson et al., 2013, 2014, & 2015):

- Polarity cycle arising from
  - Strong Lorentz-force feedback
  - Low-latitude poloidal field generation, topological reorganization
  - Resistive collapse
- Equatorward propagation through a nonlinear dynamo wave
- Grand minimum arising from disrupted phase correlation

Solar-like stars

On the role of helicity in the dynamo

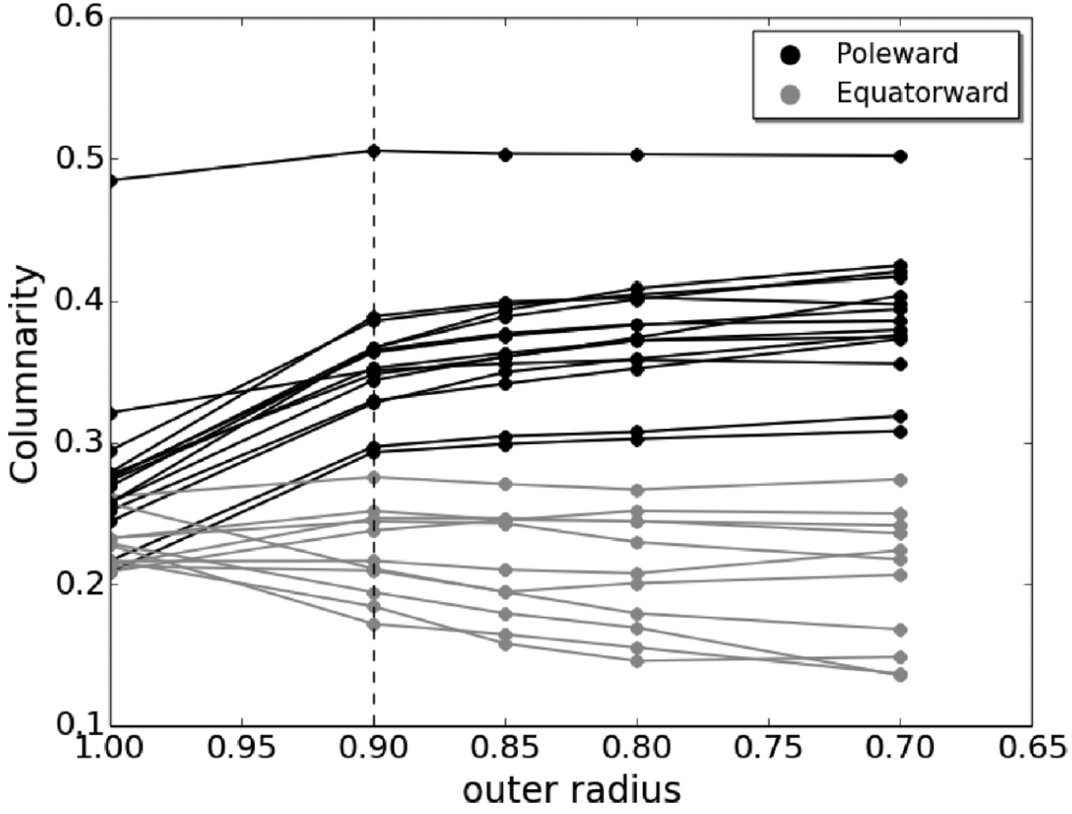


Miesch et al 2016

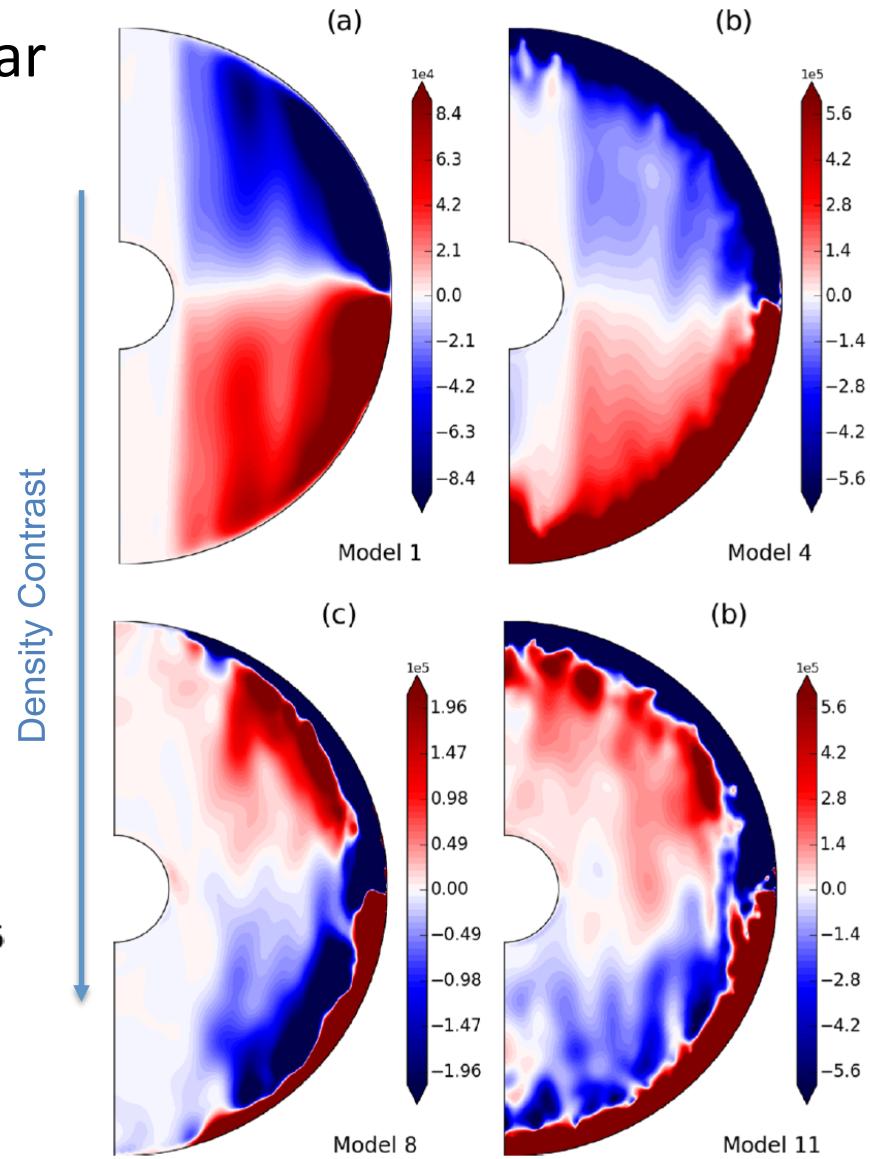
Solar-like stars

On the role of helicity in the dynamo:

Equatorward propagation of a nonlinear dynamo wave



Duarte et al 2016



Two paths to equatorward propagation

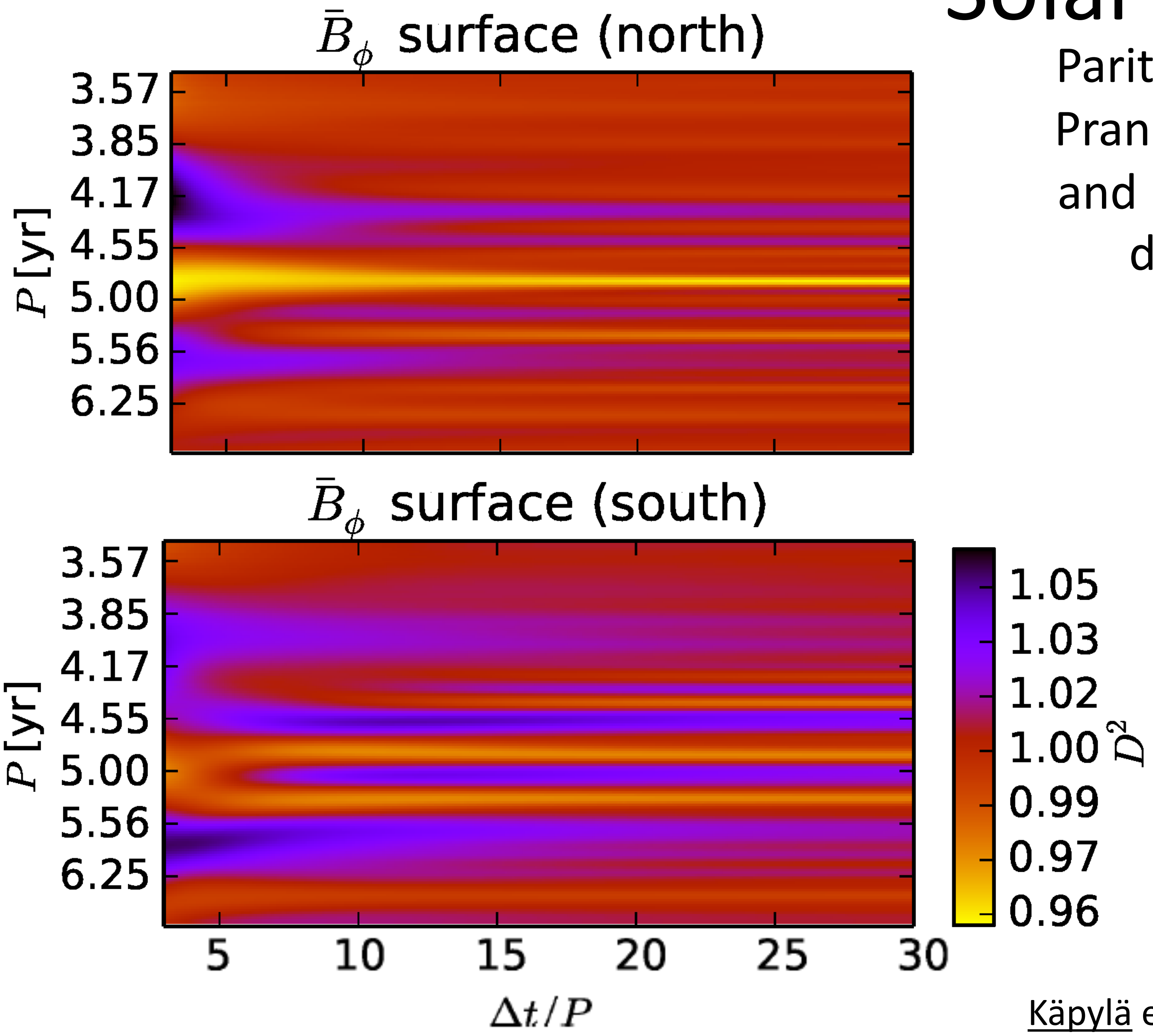
- Structure of the differential rotation and kinetic helicity lead to a dynamo wave that follows Parker-Yoshimura
  - (e.g., Duarte et al 2016 and Wernicke et al 2014)

$$\boldsymbol{s} = \alpha \nabla \Omega \times \boldsymbol{e}_\phi$$

- Nonlinear Lorentz force feedback
  - (e.g., Augustson et al 2015 and Guerrero et al 2016)

Solar-like stars

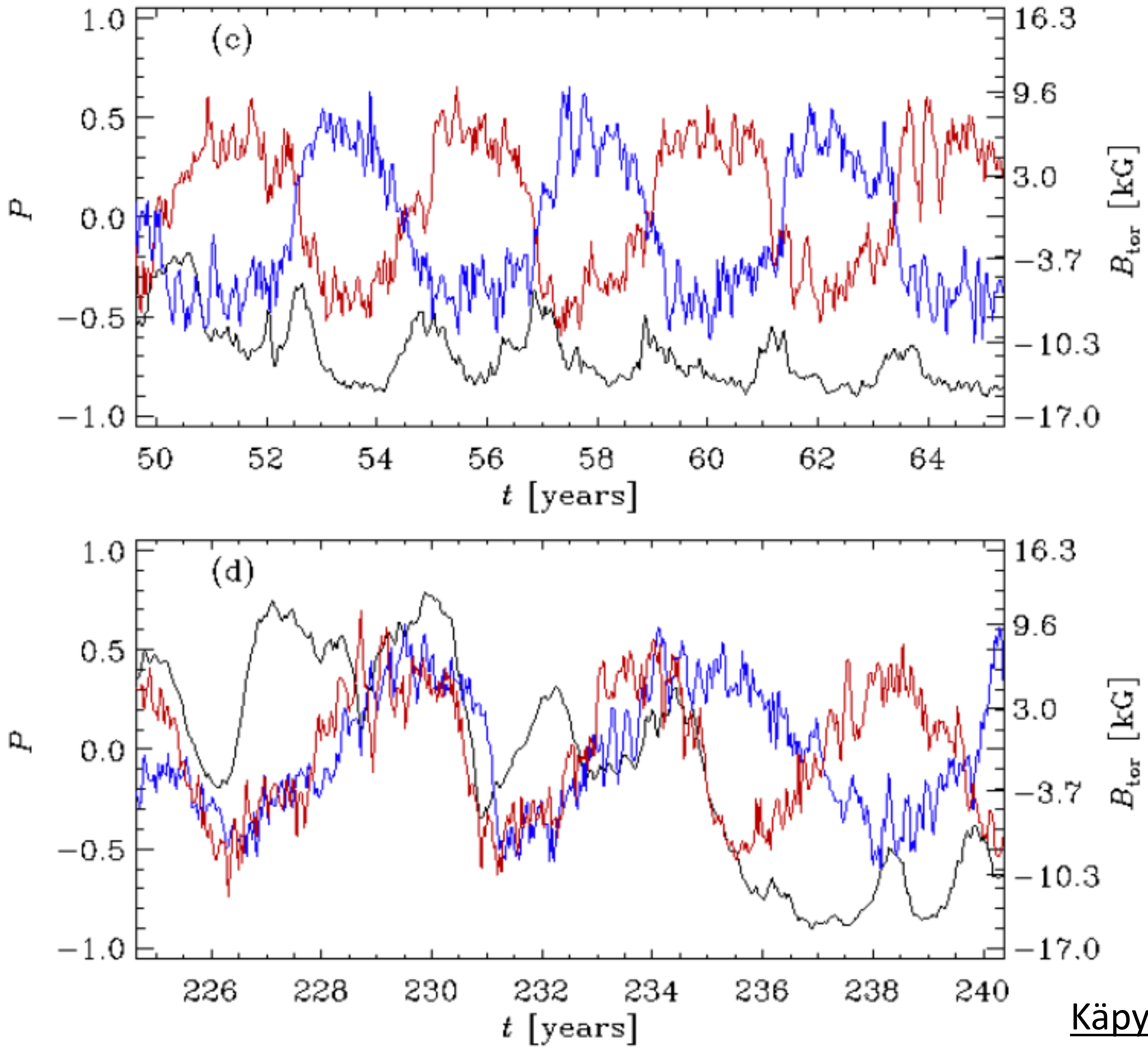
Parity, magnetic Prandtl number, and multimodal dynamos



Käpylä et al 2016

Solar-like stars

Parity, magnetic Prandtl number, and multimodal dynamos



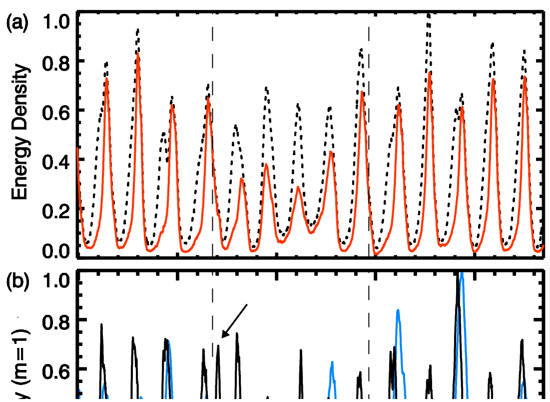
Käpylä et al 2016

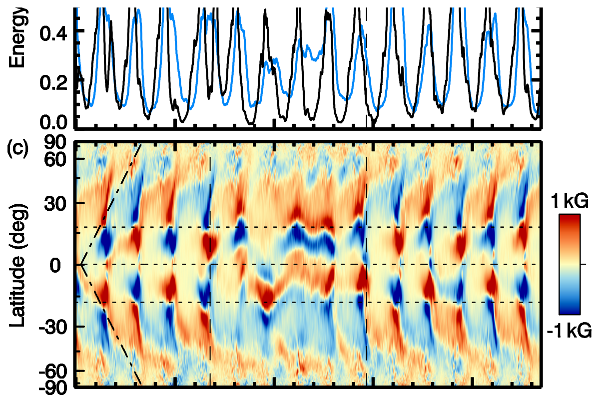
Solar-like stars

Parity, magnetic Prandtl number, and multimodal dynamos

20 30 40 50 60
Time (years)

20 30 40 50 60
Time (years)

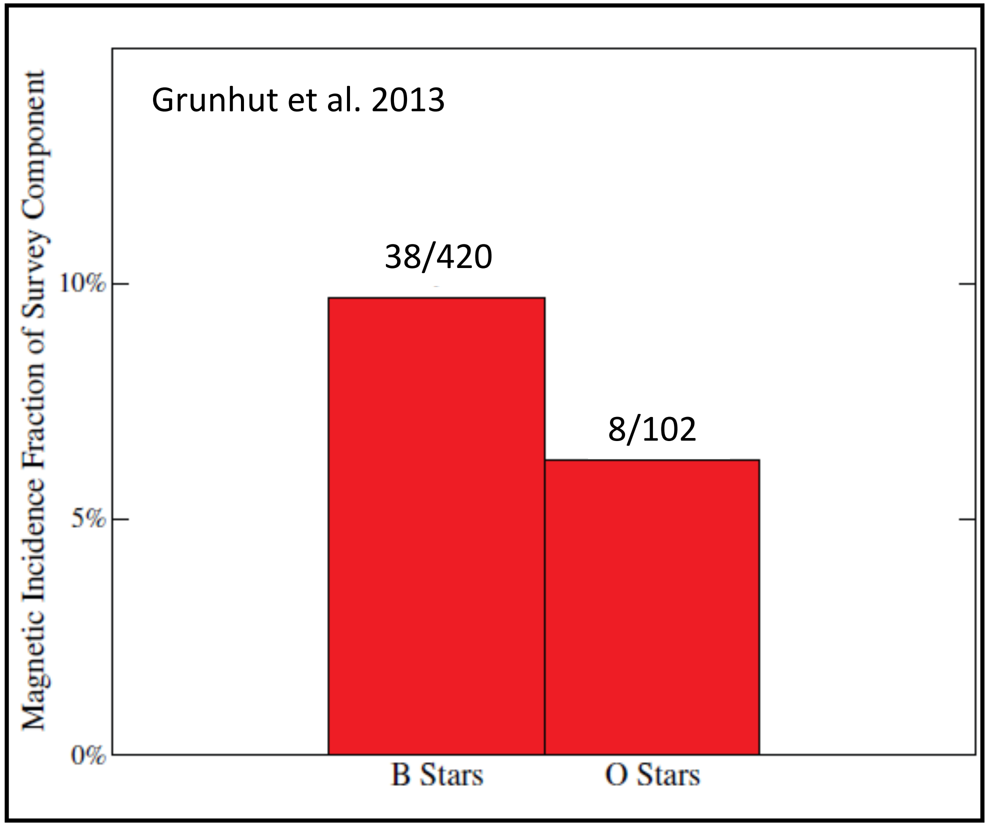


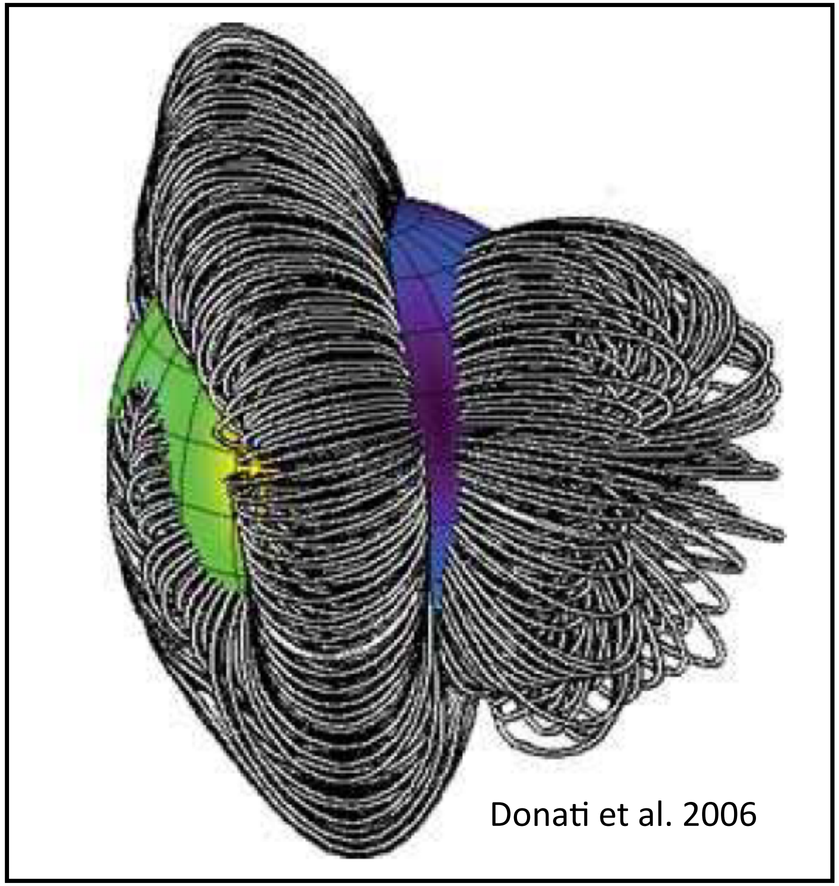


Augustson et al 2015

Massive Star Magnetism

And its implications for lower mass stars





Origins of Observed Massive Star Magnetism

- Dynamo-generated or frozen-in fields from PMS
  - Lead to stable fossil fields in radiative regions

    (e.g. Braithwaite et al. 2006, Duez & Mathis 2010, Emeriau & Mathis 2015)

  - Potential instability driving dynamo in radiative regions

    (e.g. Spruit 2002, Mullan et al. 2005)

- Core dynamo-generated fields from convective regions
  - Influences later stages of evolution

    (e.g. Moss et al. 1989, Brun et al. 2005, Featherstone et al. 2009)

- Evolution of a Massive Star
  - Pre-Main Sequence
    - Either convective or radiative depending upon mass
  - Main Sequence
    - Convective core and surface region, generate field how does this link to fossil field?
  - Helium Burning
    - Like the main-sequence, with a more compact core, stronger fields (geometry + density)!
  - Mixed Element Burning
    - Shellular burning with an even more compact core -> even stronger fields!
  - Silicon Burning
    - End-stage with shellular burning and extremely compact core -> strongest fields!

The magnetic field at each stage depends upon the topological evolution of the previous one!

Some Simple Considerations for Scaling Laws

- Consider a statistically steady state with the following force balance for a non-rotating system:

$$\rho \mathbf{v} \cdot \nabla \mathbf{v} \approx \frac{1}{4\pi} \boldsymbol{\nabla} \times \mathbf{B} \times \mathbf{B}.$$

- Further, let

$$= Pm\ell_B. \text{ Ꞁ}$$

- Then, the equipartition magnetic field should roughly be

$$\frac{4\pi\ell_B}{\ell_\nu}\rho v^2 \approx B^2 \implies B_{\mathrm{eq}} \approx \left[\frac{4\pi\rho v^2}{Pm}\right]^{1/2}$$

Some Simple Considerations for Scaling Laws

- Extend this statistically-steady force balance to a rotating system:

$$\alpha\rho\mathbf{v}\cdot\nabla\mathbf{v}+2\rho\mathbf{v}\times\hat{\Omega}_0\approx\frac{1}{4\pi}\nabla\times\mathbf{B}\times\mathbf{B},$$

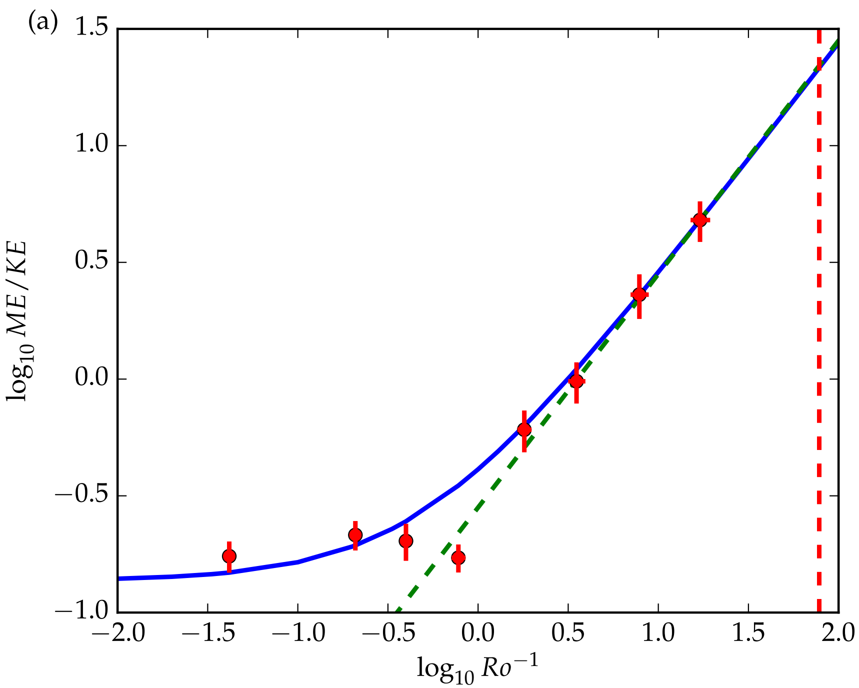
$$\Longrightarrow\frac{\alpha}{\ell}\rho v^2+2\rho v\Omega_0\approx\frac{B^2}{4\pi\ell},$$

- Then, the super-equipartition magnetic field may scale as

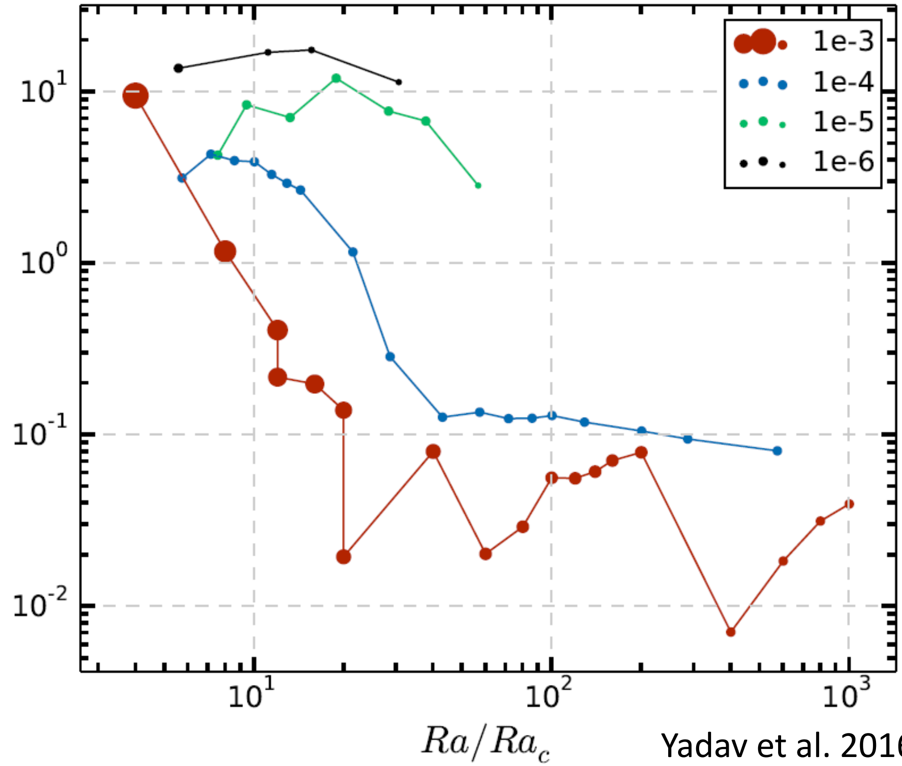
$$\Longrightarrow\frac{B^2}{8\pi}\approx\frac{1}{2}\rho v^2\left(\alpha+2\ell\Omega_0/v\right),$$

$$\Longrightarrow\frac{ME}{KE}\approx\alpha+Ro^{-1}.$$

Some Simple Considerations for Scaling Laws

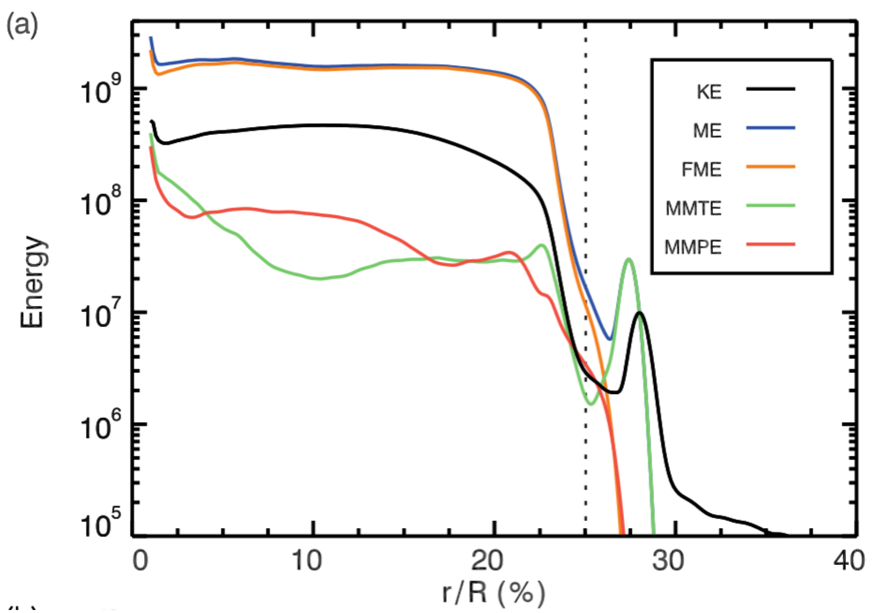


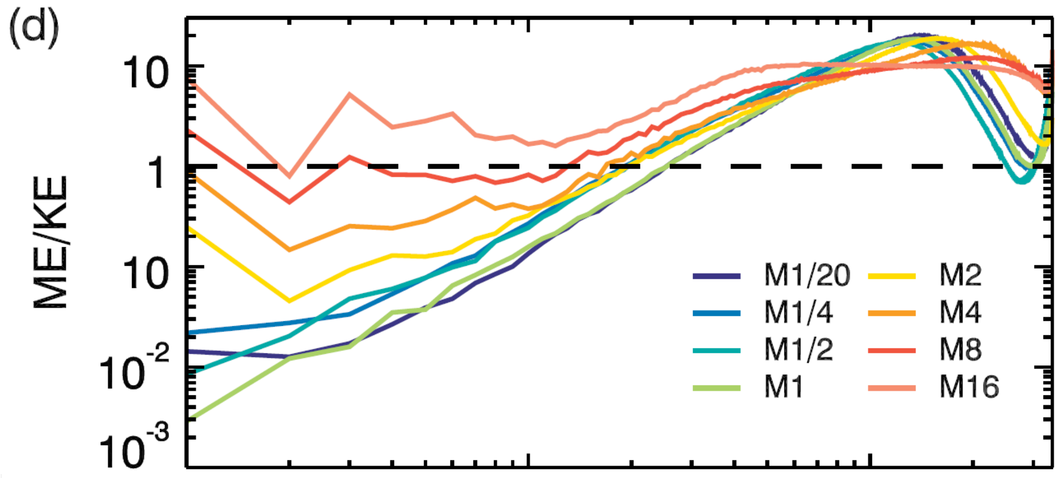
Augustson et al. 2016



Yadav et al. 2016

Superequipartition Across Resolved Scales

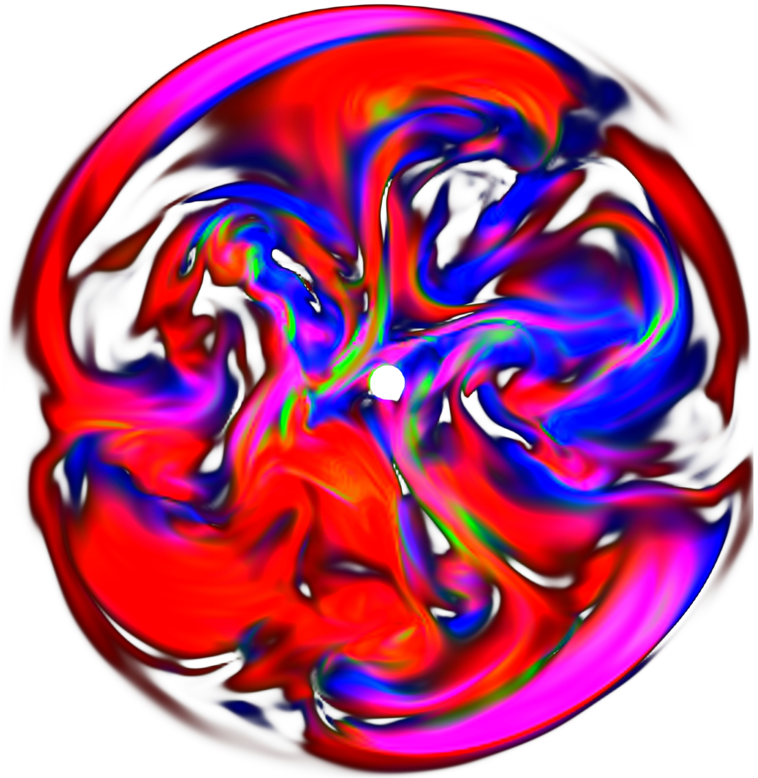




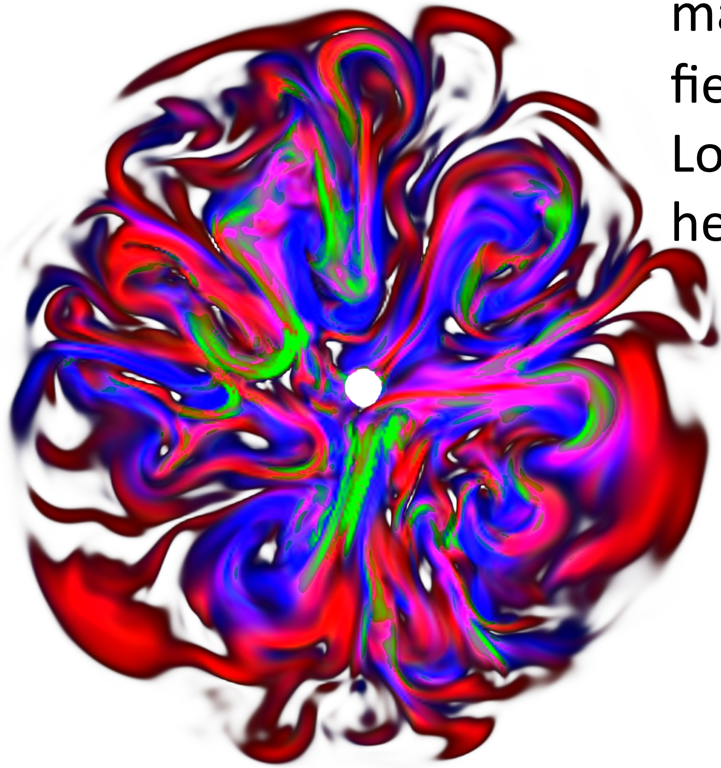
Augustson et al. 2016

How can such states exist?

In these simulations, displacement of magnetic and velocity fields minimizes Lorentz forces on heat-carrying flows.

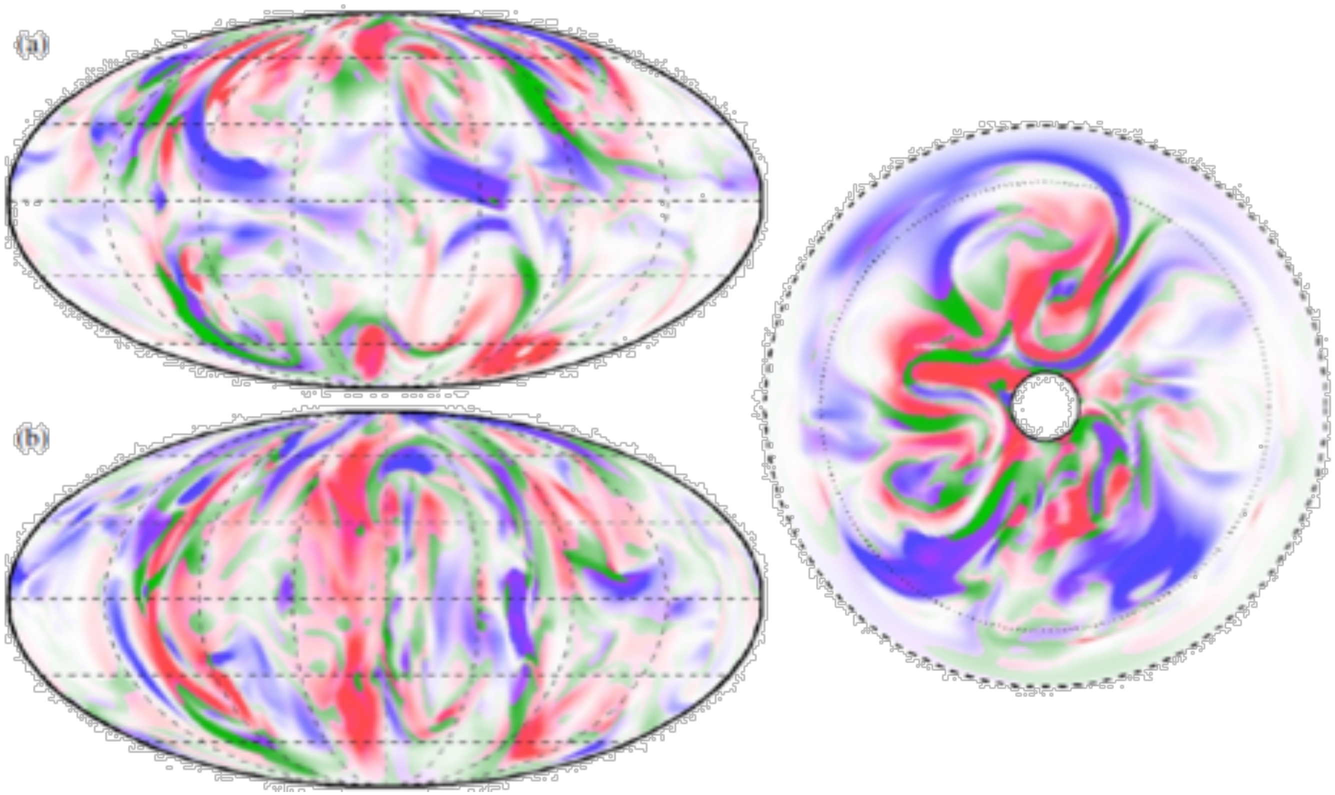


Strong-Field Initial Condition



Weak-Field Initial Condition

How can such states exist?



The displaced fields have weak generation, while generation occurs largely in the overlap regions, namely at the edges of the magnetic structures.

Featherstone et al. 2009

Implications for Stars with low Rossby number

Superequipartition convective dynamos are likely to occur above a threshold Rossby number

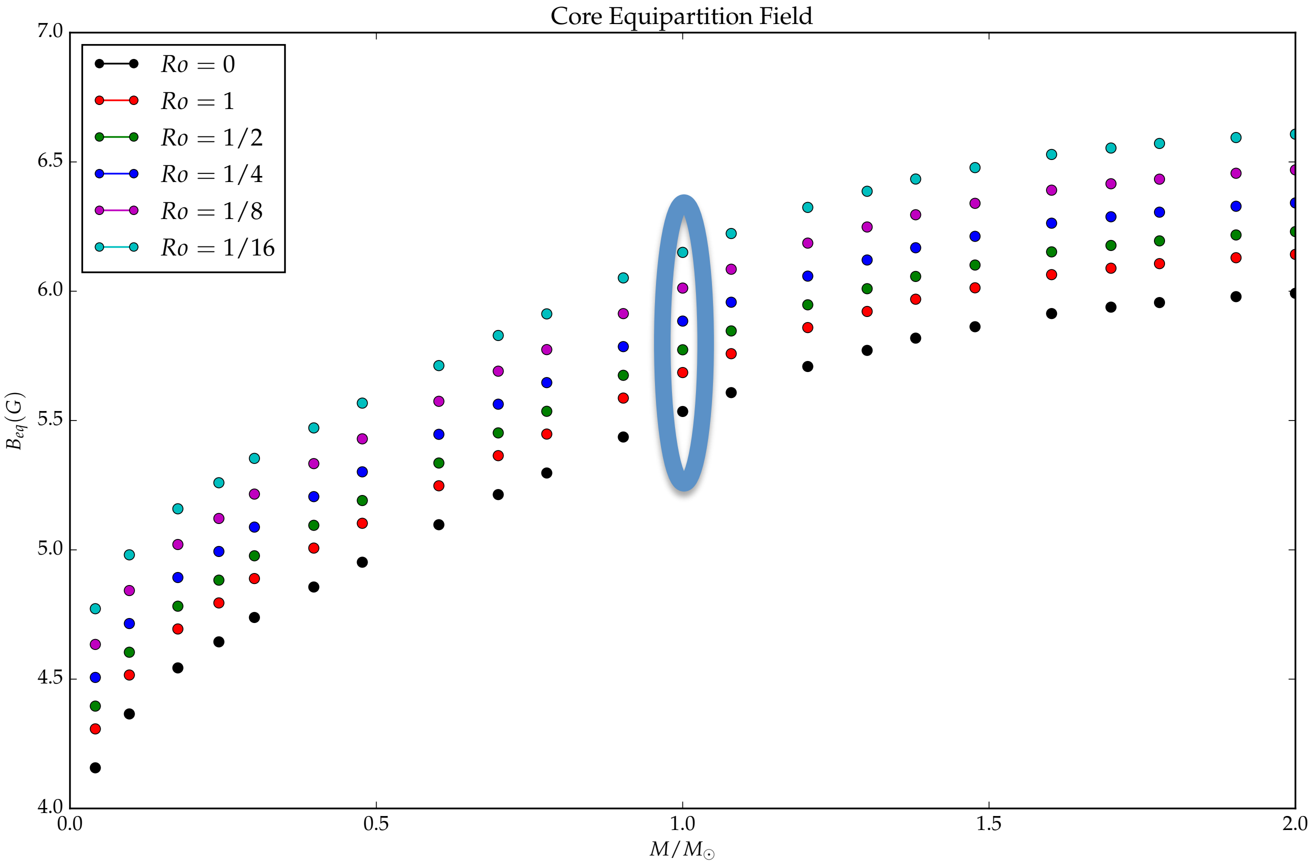
Such dynamos avoid magnetic quenching through non-local interactions

- Minimizing the Lorentz force
- Optimizing the induction

Stars with low Rossby number

Strong magnetic fields, for these 10 Msun stars, imply they are likely for most core convective stars.

For more see the talk's after the coffee break!



Summary

- Solar-like stars:
  - The last six years have been fruitful in finding cycling dynamos in self-consistent 3D simulations.
  - Stable regions play an important role in the solar-like dynamos, lengthening cycle periods by storing magnetic field.
  - MHD instabilities also promote cycling by eroding those stored fields.
  - Topological reconnection and magnetic helicity conservation may play a role in for cycling dynamos.
  - Spatial propagation of the mean magnetic field is well described either by nonlinear feedback or by dynamo waves.
  - Still missing how to form sunspots though!
- Core dynamos:
  - Superequipartion states easily achieved (also true for rapidly rotating low mass stars)
  - Nonlocal dynamics allow such states, with the magnetic and kinetic energy (as well as thermal) structures being spatially displaced.
  - Room left to explore more turbulent states with potentially higher levels of superequipartition magnetic energy.