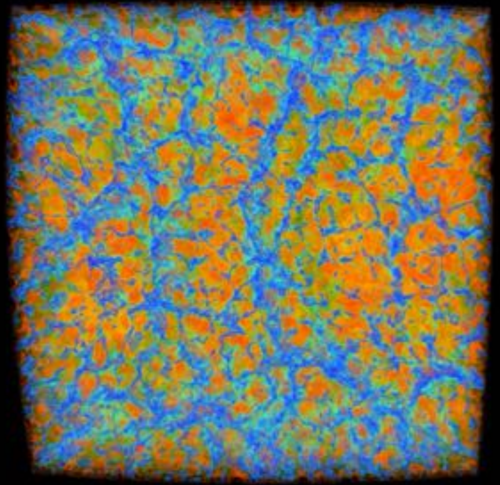
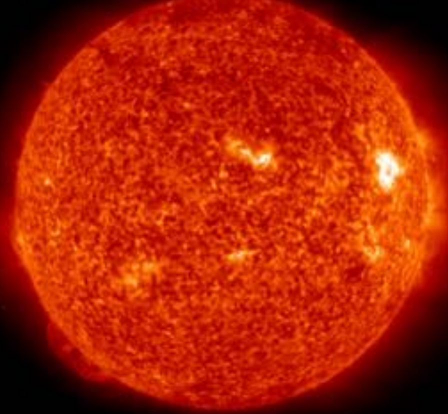
# Simulations of Flux Emergence in Cool Stars:
# What's Convection, Rotation, and Stellar Structure got to do with it?





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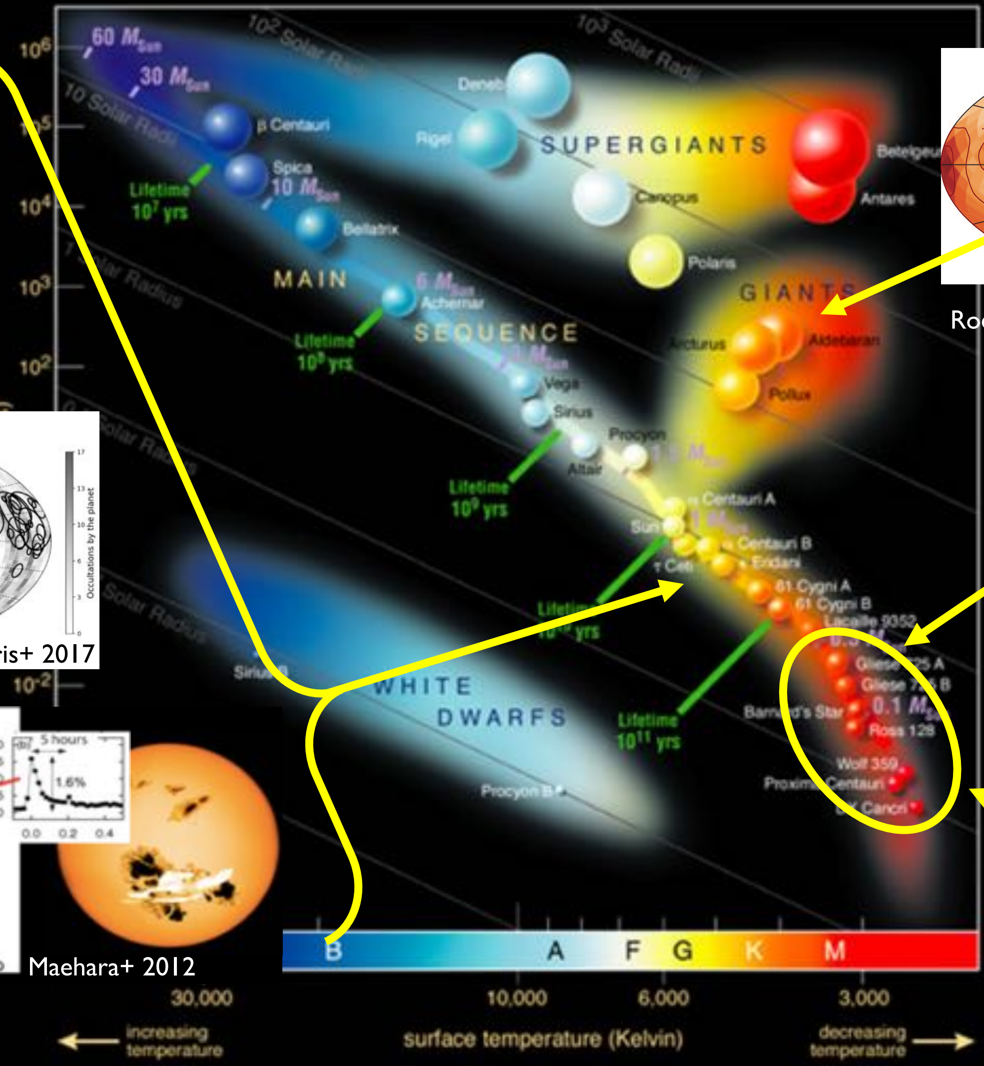
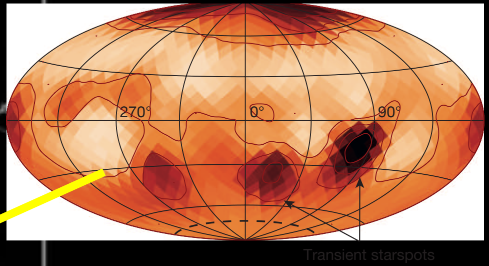
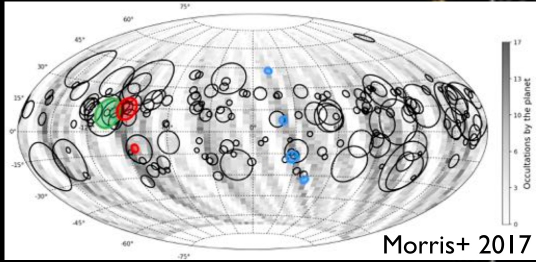
@SolarisMaria

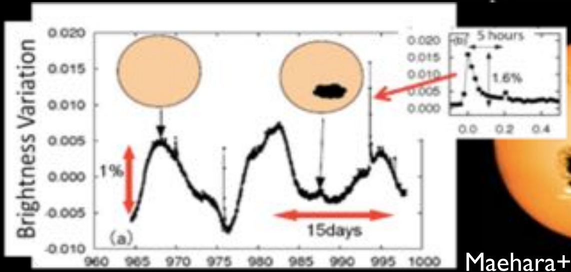


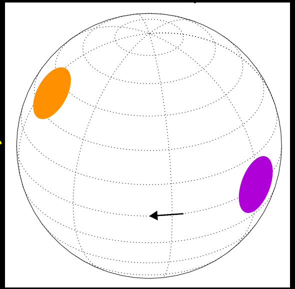

Roettenbacher+ 2016



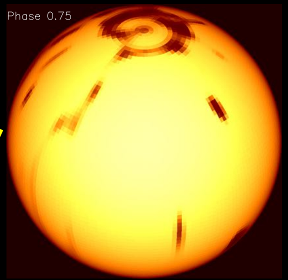
Morris+ 2017




Maehara+ 2012



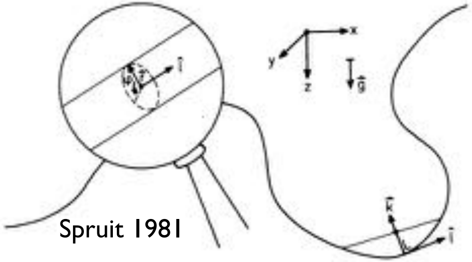
Davenport+ 2015




Barnes+ 2015

# Model Schematic:

TFT Approximation → Initial Conditions → Stellar Structure → Convective Velocity Field



Spruit 1981

**Equation of Motion:**

$$\rho\frac{d\mathbf{v}}{dt} = -2\rho(\mathbf{\Omega_0}\times\mathbf{v}) - (\rho_e - \rho)\mathbf{g} + \mathbf{l}\frac{\partial}{\partial s}\left(\frac{B^2}{8\pi}\right) + \frac{B^2}{4\pi}\mathbf{k}$$

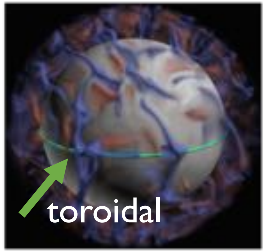
$$-C_d\frac{\rho_e|(\mathbf{v}-\mathbf{v}_e)_\perp|(\mathbf{v}-\mathbf{v}_e)_\perp}{(\pi\Phi/B)^{1/2}}$$

$B_0$

$r_0$

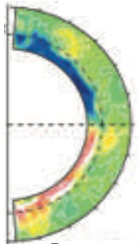
$\theta_0$

$\Phi$




Solar $1\Omega_\odot$, $5\Omega_\odot$

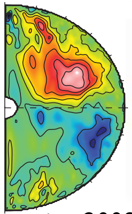
Tachocline interface dynamo



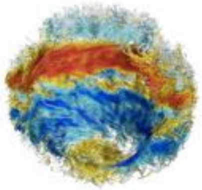
Browning+ 2006

M dwarf, Solar $3\Omega_\odot$

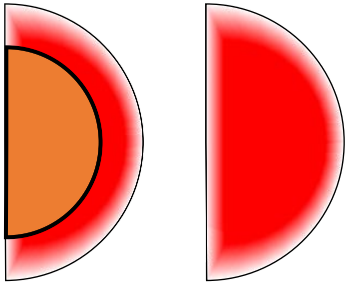
Distributed dynamo



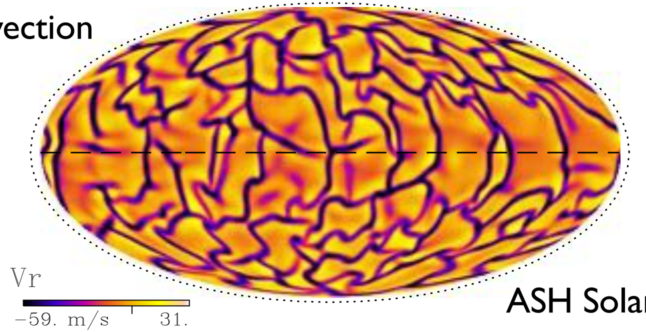
Browning 2008 M Dwarf



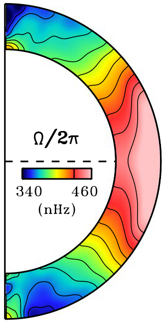
Rapid $\Omega_0$ Brown+ 2011




Convection

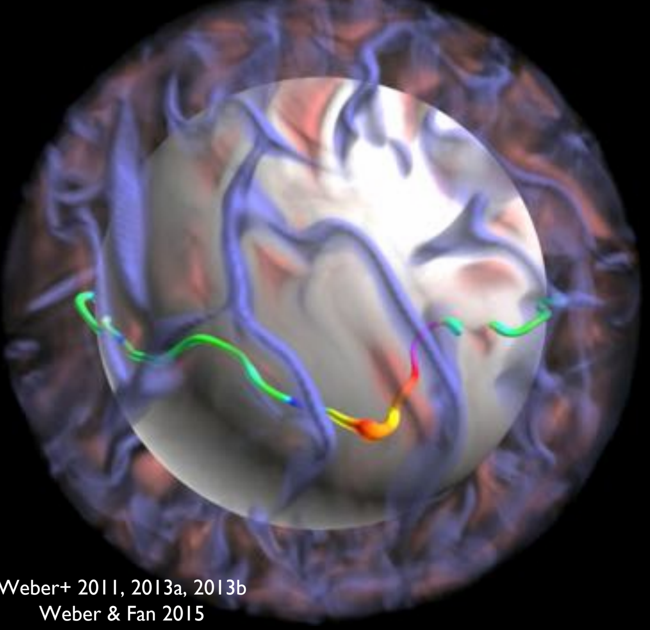



ASH Solar



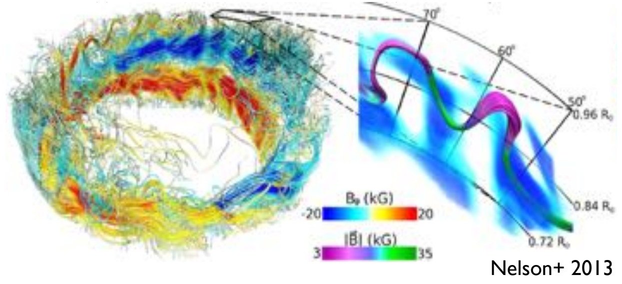
# Convection modulates flux emergence

## Sun-like stars



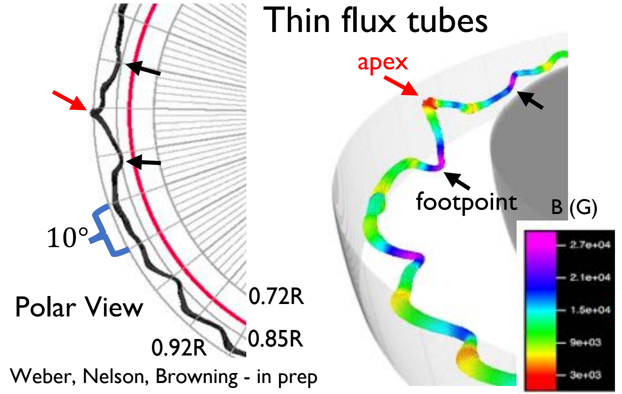
Weber+ 2011, 2013a, 2013b
Weber & Fan 2015

## Dynamo-generated magnetic loops

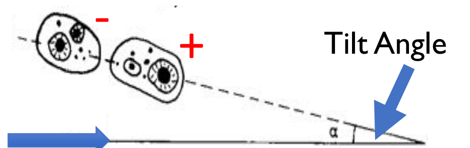



Nelson+ 2013

## Thin flux tubes

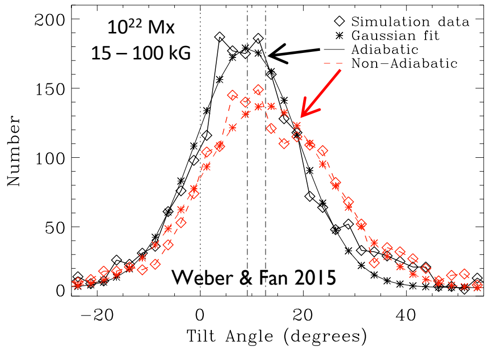



Weber, Nelson, Browning - in prep

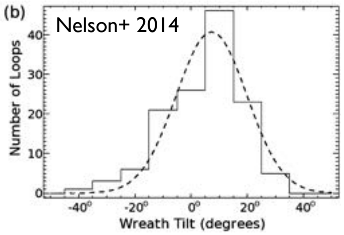



adapted from Schrijver & Zwaan 2000

## TFT+convection



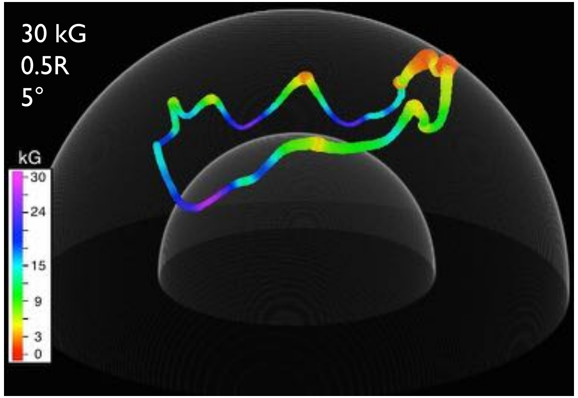

Dynamo-generated loops




- Convection & magnetic buoyancy work in concert to promote flux emergence
- Downflows naturally induce loops ~15° – 20° apart
- Convection introduces a statistical spread in tilt angles

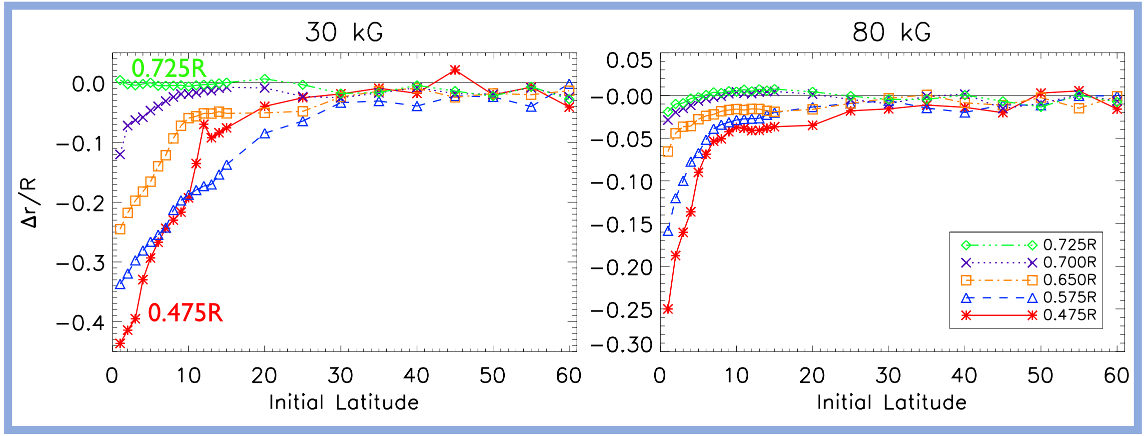
# Convection can also suppress flux emergence

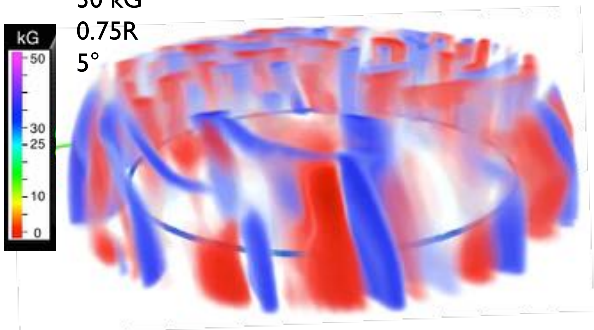
Fully convective M dwarf




Average 'suppression depth' $\Delta r$

Weber+ 2017

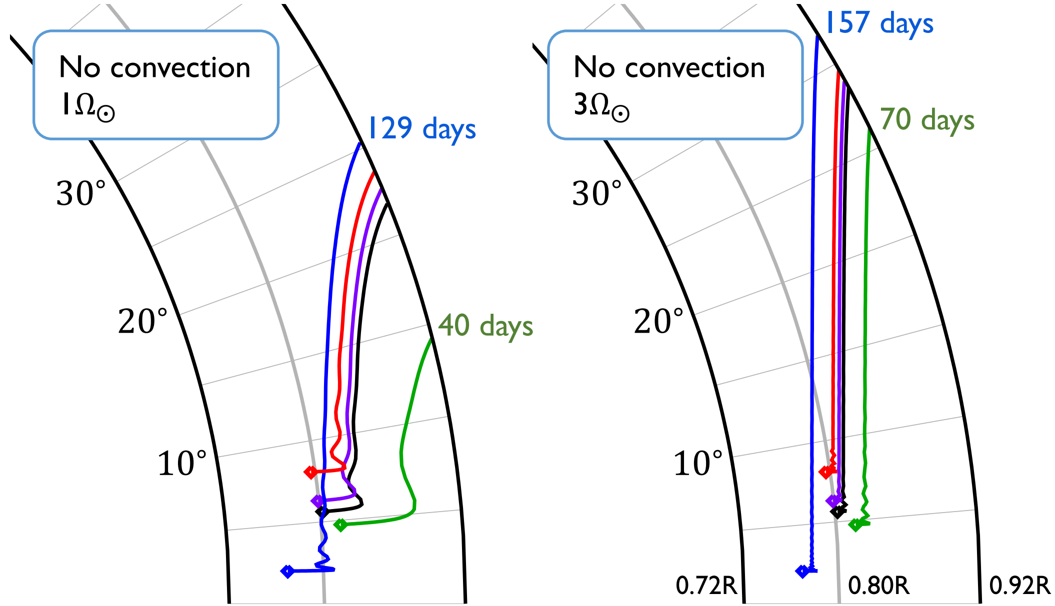



Weber & Browning 2016, Weber+ 2017

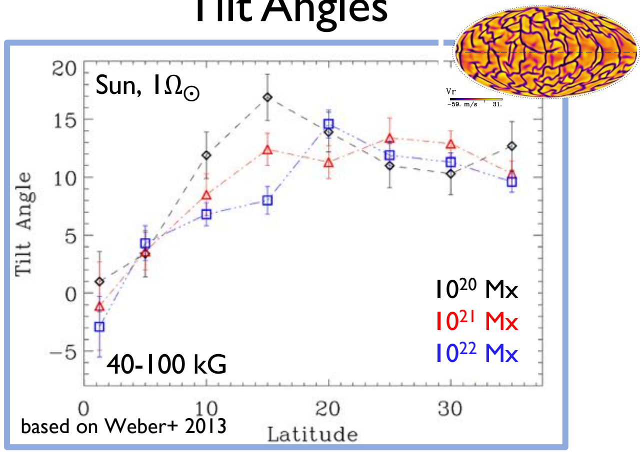
- The global rise of TFTs is more strongly suppressed by convective flows when the flux tube is initiated:
  - in the deeper interior
  - at lower latitudes
  - with a weaker magnetic field strength

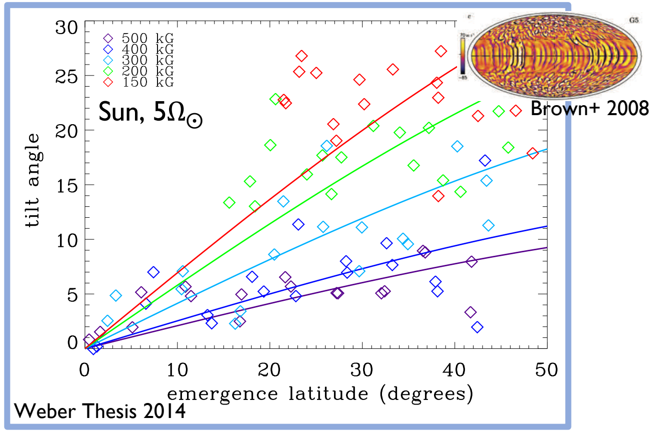
# Rotation alters emergence properties




Weber, Nelson, Browning - in prep

## Tilt Angles

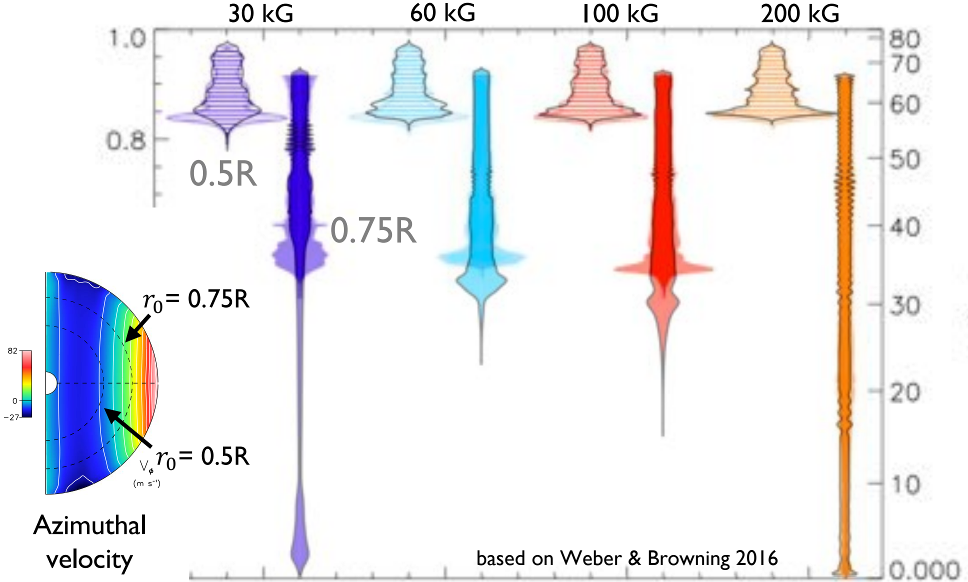


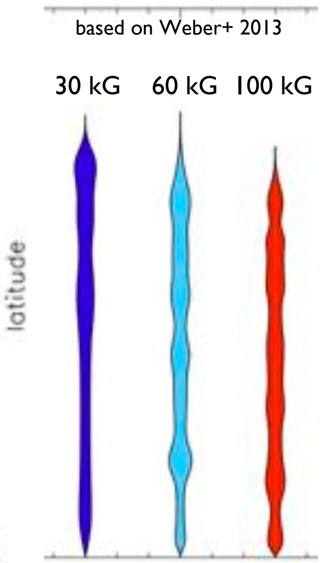

- Due to the Coriolis force, more rapid rotation:
  - Lengthens the rise time
  - Leads to poleward deflection
  - Increases tilt angles

# Stellar structure impacts emergence latitudes and more

## Emergence Latitude Probability Functions

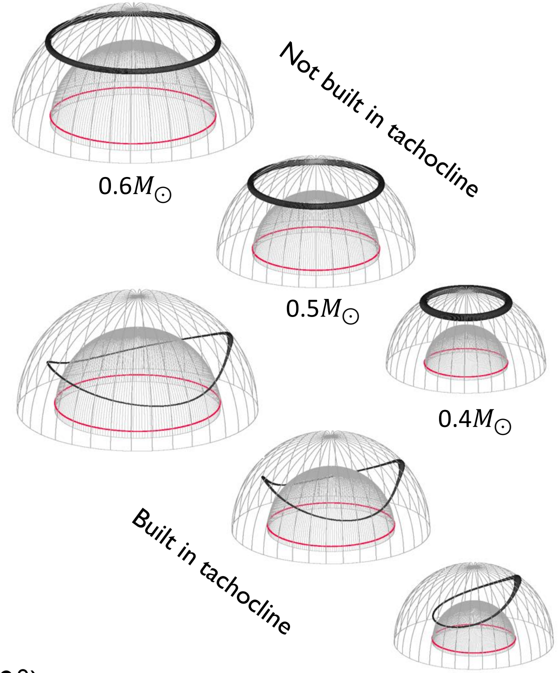



**Fully Convective M Dwarf**, $\theta_0 = 1° - 60°$




**Sun**, $\theta_0 = 2° - 40°$

## Tachocline or not?

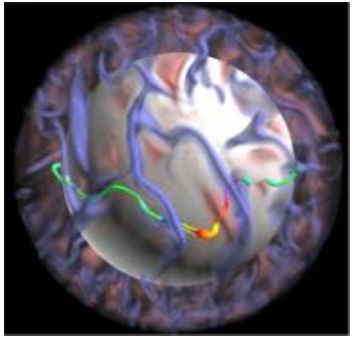



- Unlike solar case, in M dwarf there is a tendency for high latitude emergence (> 30°)
- Exceptions when flux tubes initiated closer to the surface and of sufficiently weak (≲30 kG) or strong field strengths (≳200 kG)
- Increased density in M dwarfs leads to longer flux tube rise times by $\lesssim 10$x

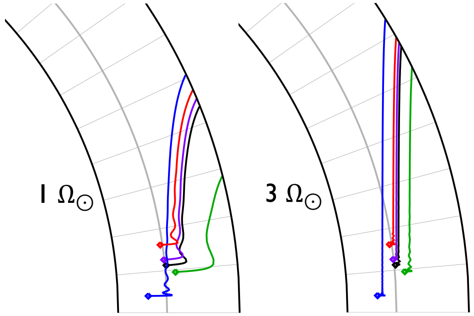
- Assumption of flux tube generating region, and thereby initial thermodynamic properties, matter

# Summary

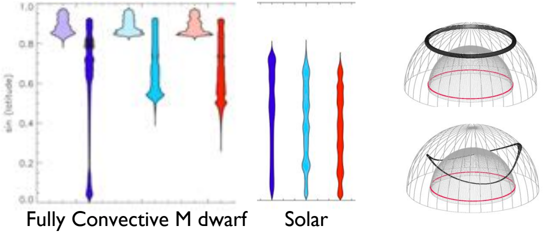
Convection, rotation, and stellar structure are all important contributing factors to the overall trend of flux emergence.



- Convection modulates flux emergence
- Fluid motions both suppress and promote the rise of magnetism
- Convection introduces a statistical spread in emergence properties




- Due to the Coriolis force, rapid rotation:
  - Lengthens the rise times
  - Leads to poleward emergence
  - Increases tilt angle




- Tendency for polar flux emergence in M dwarfs, unlike in solar-like stars
- Increased density in M dwarfs leads to longer rise times
- Assumptions about flux tube generating region (i.e. tachocline or not) has consequences for flux emergence

This work is a step toward linking magnetic flux emergence, convection, and dynamo action along the lower end of the main sequence.