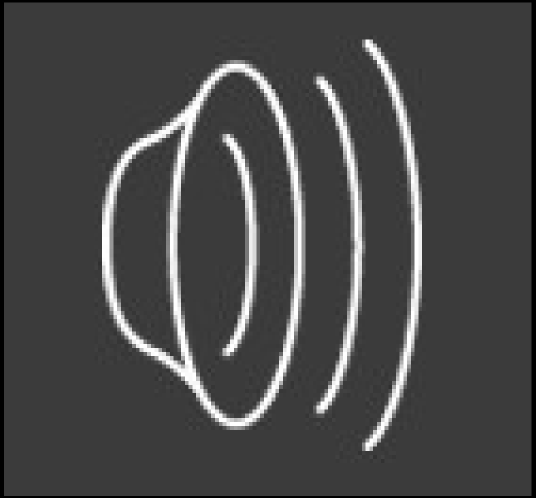
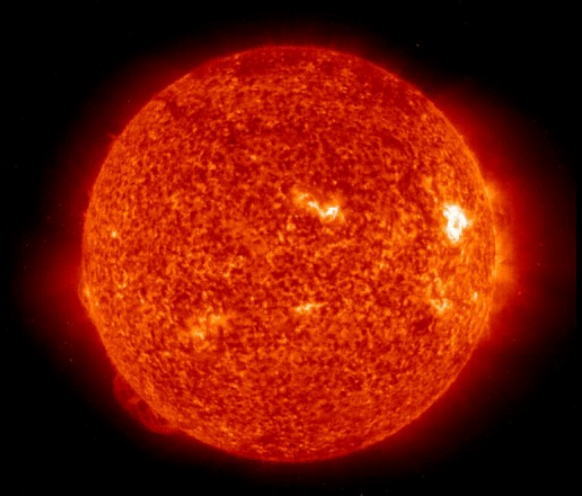
Simulations of Flux Emergence in Cool Stars: What’s Convection, Rotation, and Stellar Structure got to do with it?





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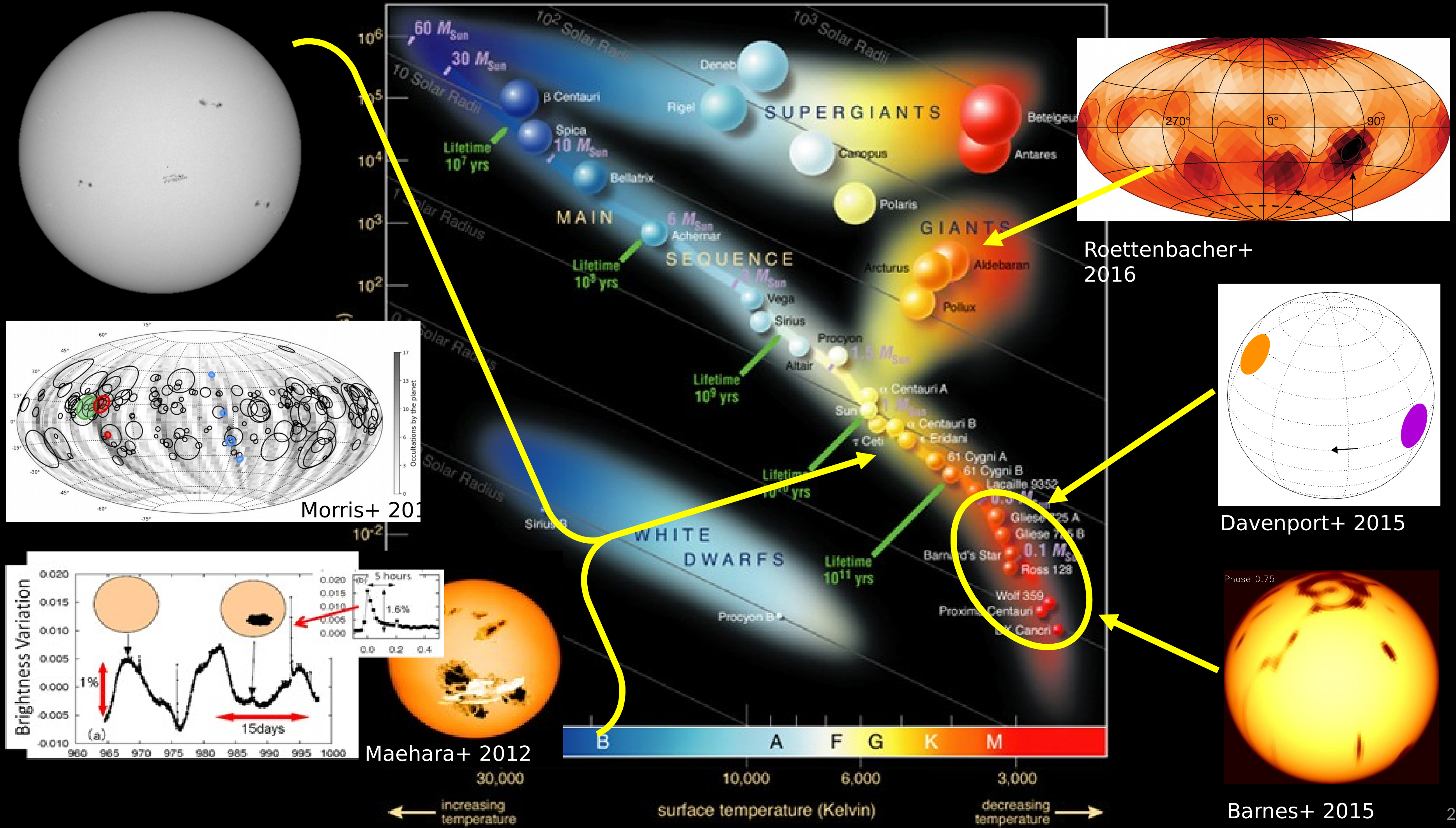
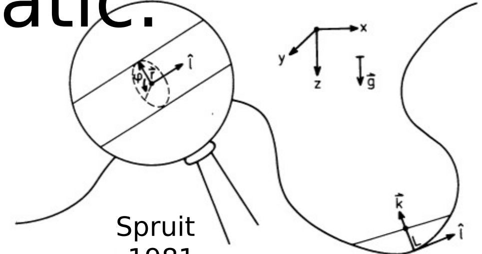


Roettenbacher+ 2016
Davenport+ 2015
Barnes+ 2015
Morris+ 201
Maehara+ 2012
Phase 0.75
270°
0°
90°
Brightness Variation
1%
15days
5 hours
1.6%
(a)
(b)
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
1.5 M_Sun
1 M_Sun
0.1 M_Sun
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Canopus
Polaris
Betelgeuse
Antares
Arcturus
Aldebaran
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
Sirius B
Procyon B
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Model Schematic:

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



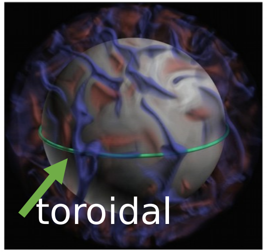
Spruit 1981

Equation of Motion:

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

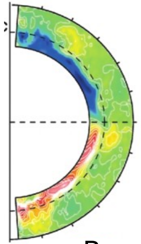
$$-C_d\frac{\rho_e|(v-v_e)_\perp|(v-v_e)_\perp}{(\pi\Phi/B)^{1/2}}$$

B_0
r_0
θ_0
Φ



Solar 1Ω⊙, 5Ω⊙

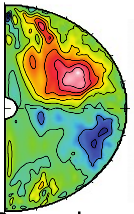
Tachocline interface dynamo



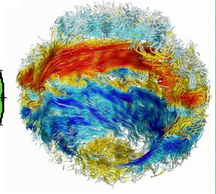
Browning+ 2006

M dwarf, Solar 3Ω⊙

Distributed dynamo

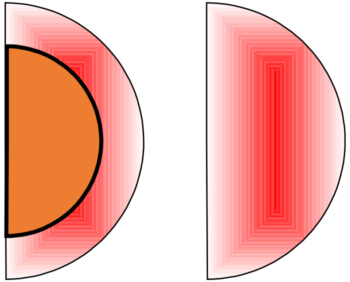


Browning 2008 M Dwarf

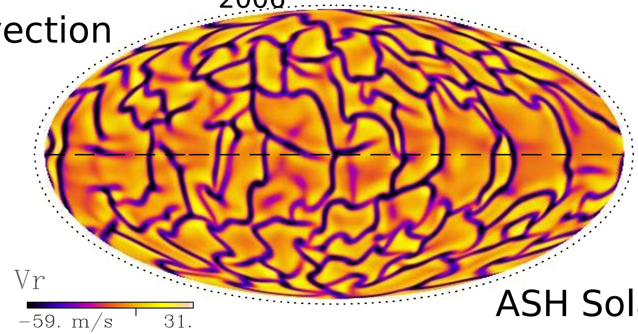


Rapid Ω0 Brown+ 2011

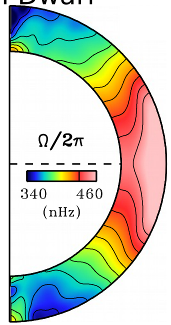
Sun 0.3M⊙ M Dwarf



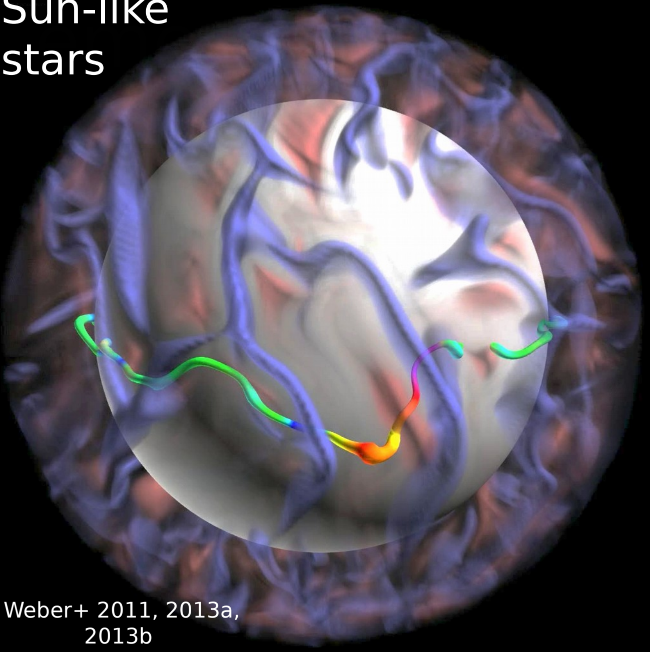
Convection

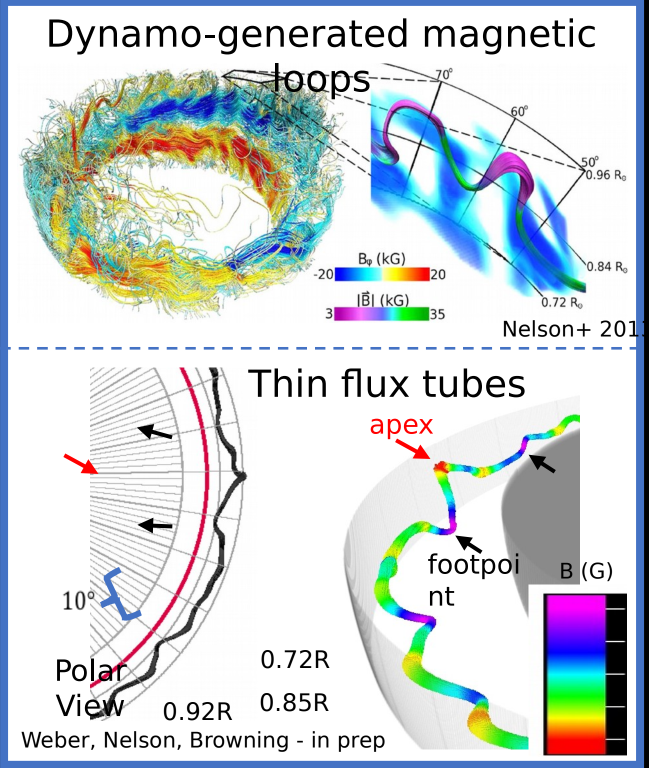


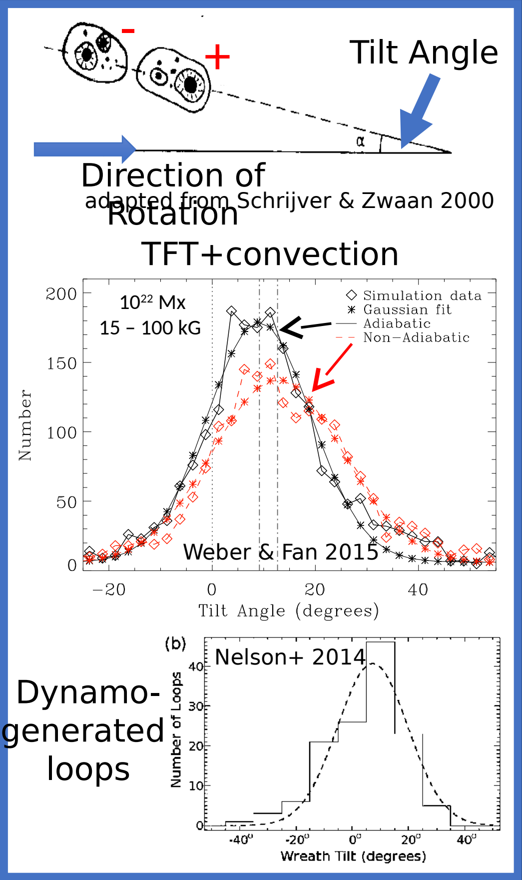
ASH Solar



Convection modulates flux





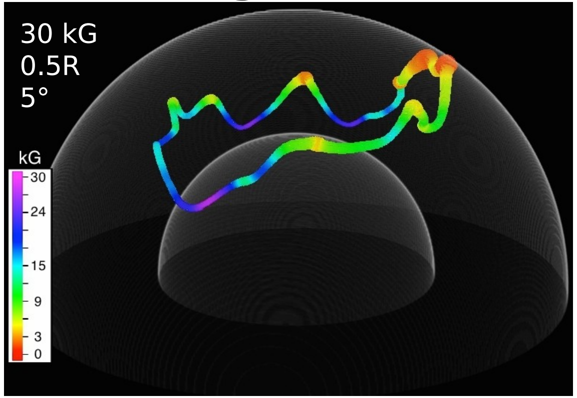


- Convection & magnetic buoyancy work in concert to promote flux emergence
- Downflows naturally induce loops ~15° – 20° apart
- Convection introduces a statistical spread in tilt angles

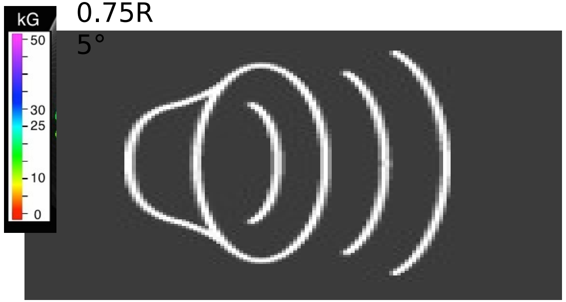
Downflows naturally induce loops apart

Convection can also suppress flux emergence

Fully convective M dwarf



30 kG
0.75R
5°

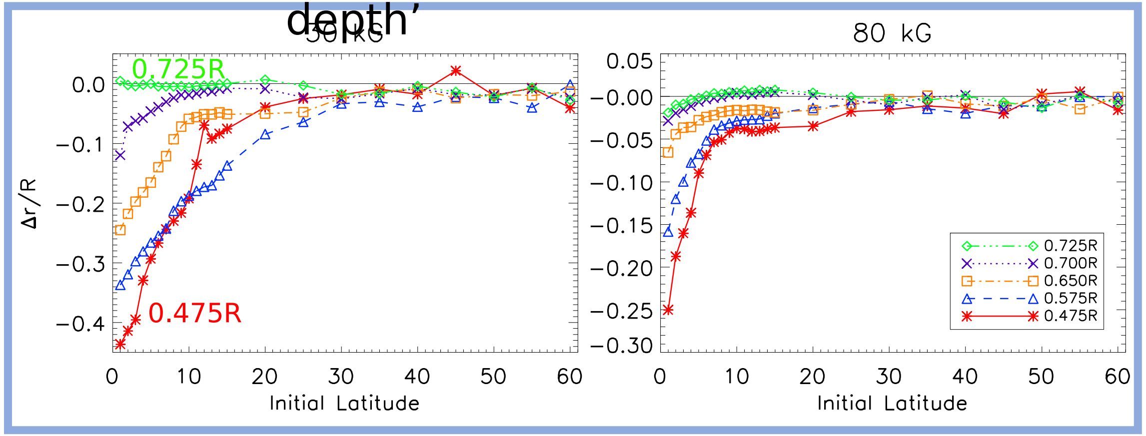


Weber & Browning 2016, Weber+ 2017

Average 'suppression depth' Δr

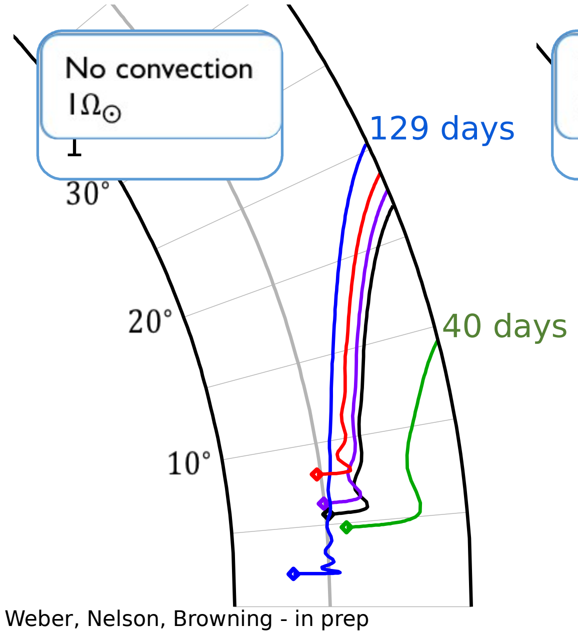
Average 'suppression depth'

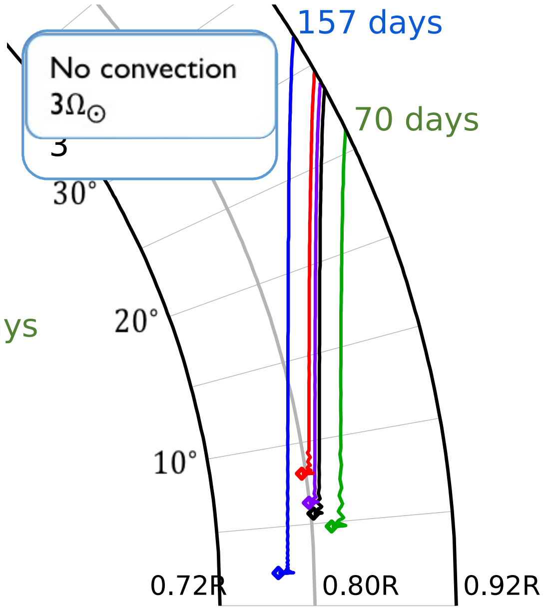
Weber+ 2017



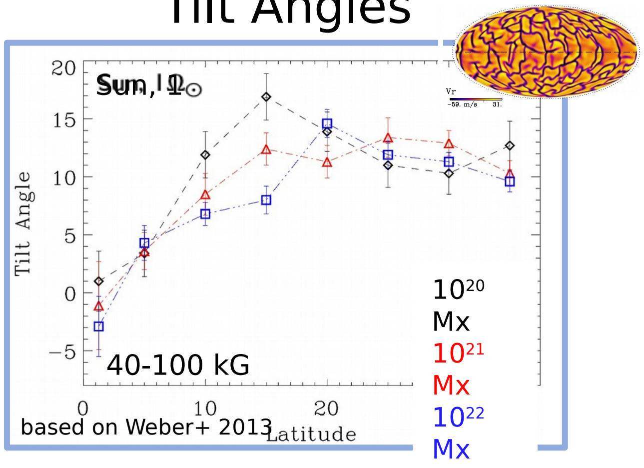
- The global rise of TFTs is more strongly suppressed by convective flows when the flux tube is initiated:
  - in the deeper interior
  - at lower latitudes
  - with a weaker magnetic field strength

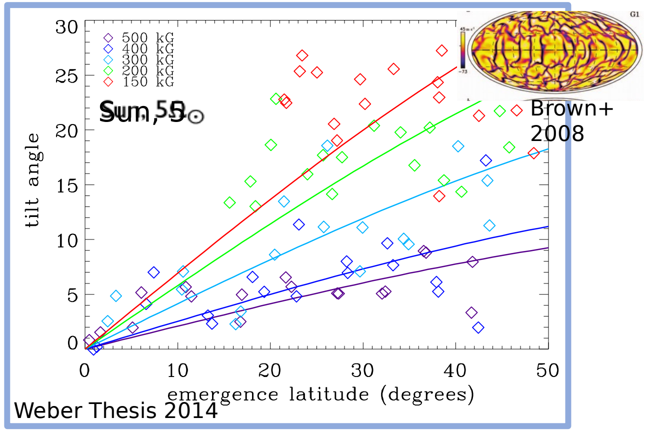
Rotation alters emergence properties





Tilt Angles

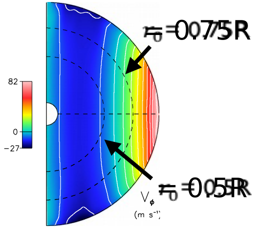


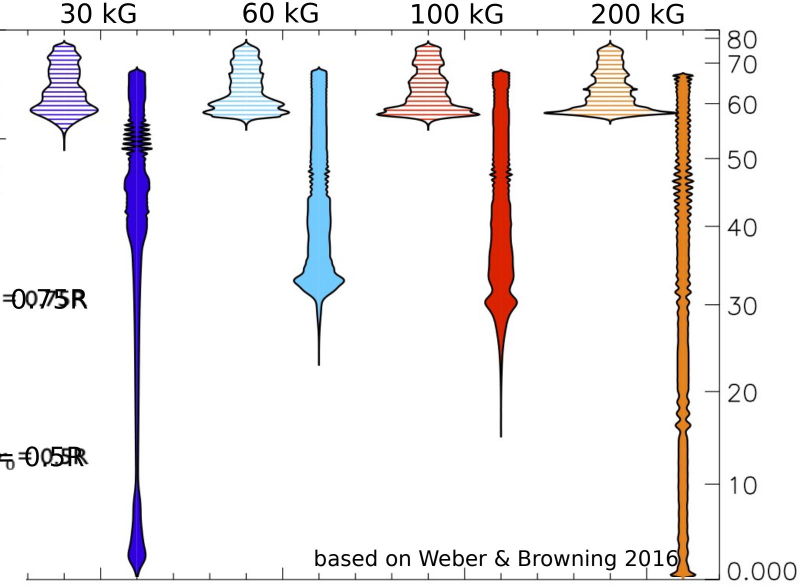


- Due to the Coriolis force, more rapid rotation:
  - Lengthens the rise time
  - Leads to poleward deflection
  - Increases tilt angles

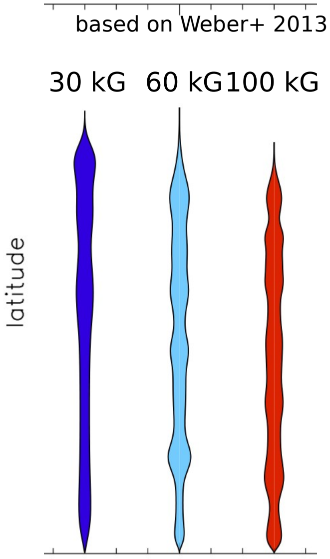
Stellar structure impacts emergence latitudes and more

Emergence Latitude Probability Functions



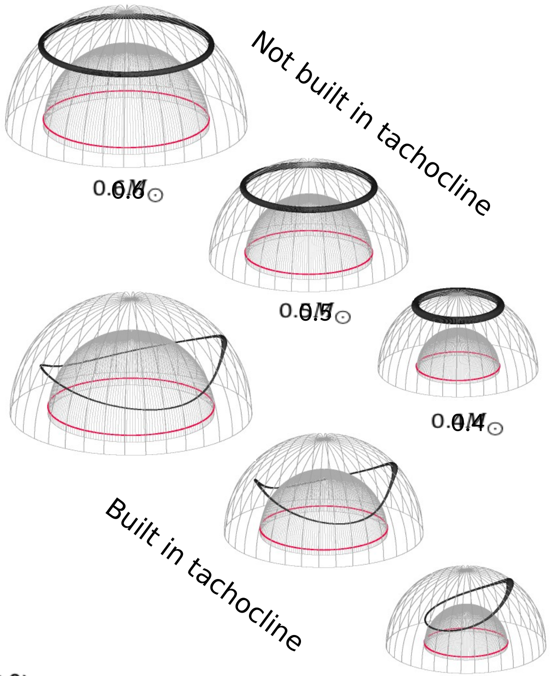


Fully Convective M Dwarf, $\theta_0 = 1° - 60°$



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)

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- 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 ≲ 10x
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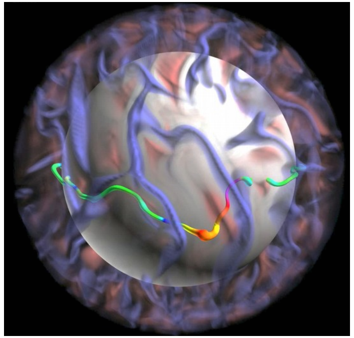
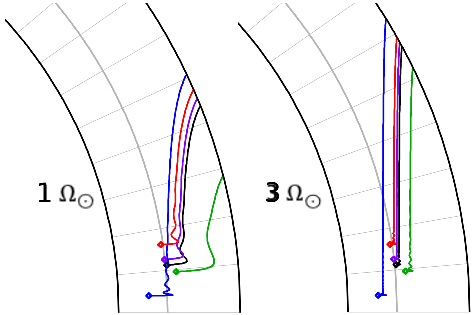
- Assumption of flux tube generating region, and thereby initial thermodynamic properties, matter

Summary

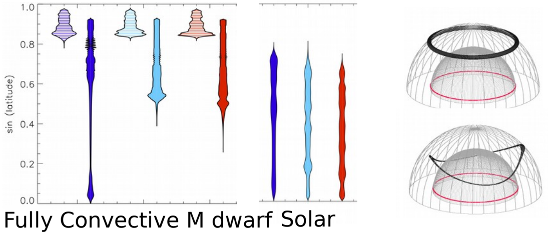
Convection, rotation, and stellar structure are all important contributing factors to the overall trend of flux emergence.



- 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.