Towards a consistent modeling of magneto-rotating stellar evolution

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Outline

What are the evolutionary processes to form rotating & magnetized WDs/NSs?

No solid theoretical predictions have been made.

(Langer 2014)

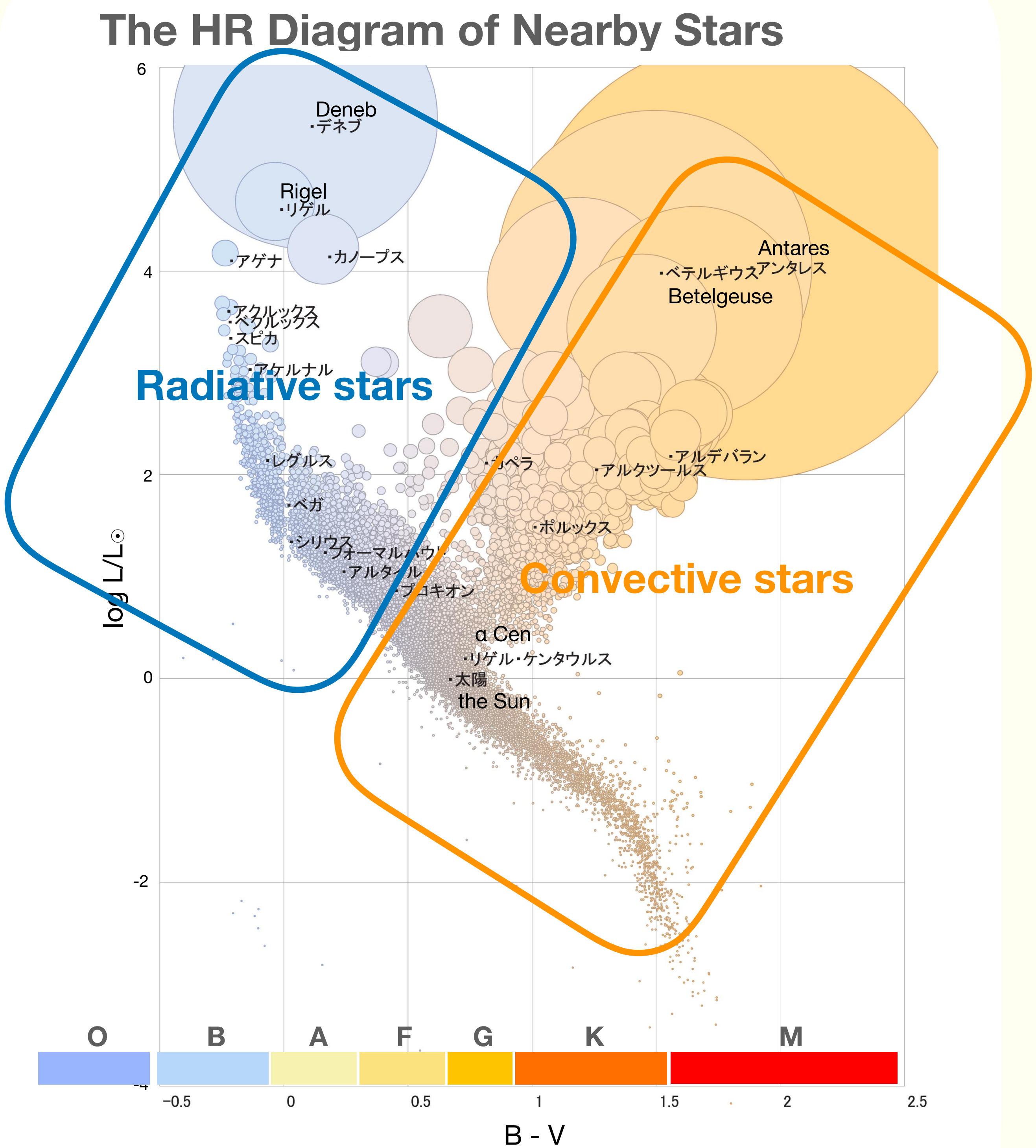
Because this is a tough work…

- **The evolutionary timescale is long.**
- **The structure change** affects **the magnetic field.**
- **Stellar magnetic field** will also affect **the evolution.**

I will report the current status of this field.

- A lot of studies have been done for specific topics.
  - **Many observational works**
  - Promising mechanisms of the interplay
- We are trying to construct a consistent method to follow the magneto-rotating stellar evolution.

Stars with convective/radiative envelopes



(http://www.geocities.jp/p451640/hr_diagram/hrdiagram5.html)

-Stars have different **envelope structures** due to different surface temperatures.

- -OBA stars are **radiative** stars.
- -FGK stars are **convective** stars.

-**Surface magnetic structures** are different between radiative stars and convective stars.

- -**'Fossil field'** for radiative stars
- -**'Dynamo field'** for convective stars

'fossil fields' just means 'stable fields'.

the origin of the 'fossil' field is unknown.
-flux conservation?
-core dynamo?
-stellar merger?

The sun and FGK convective stars

-Magnetic activities
- -sunspots
- -flares

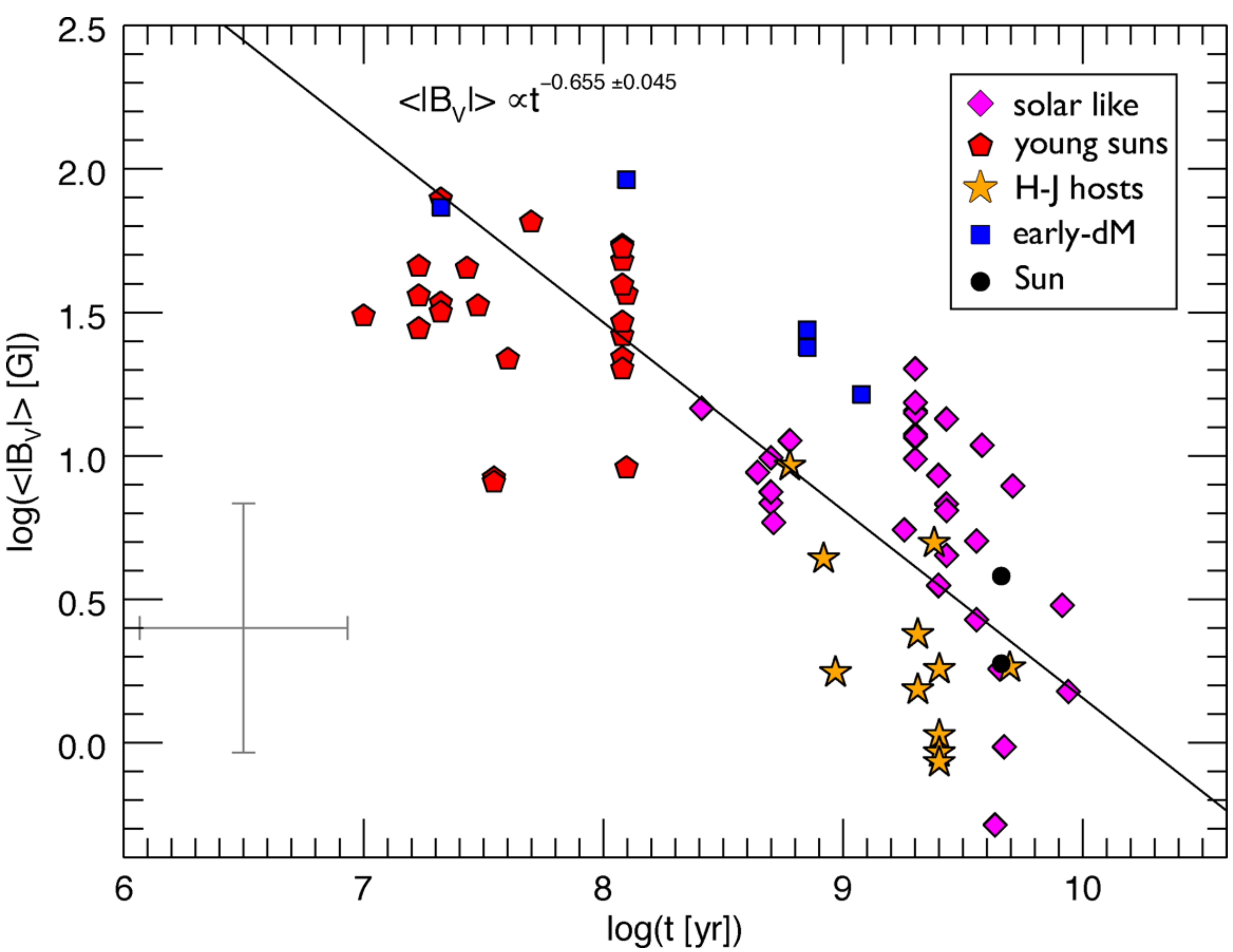
-Small & large scale fields
- ~1 kG at sunspots
- ~1 G for the dipole component

-**All the convective stars** likely have solar-like surface magnetic fields.

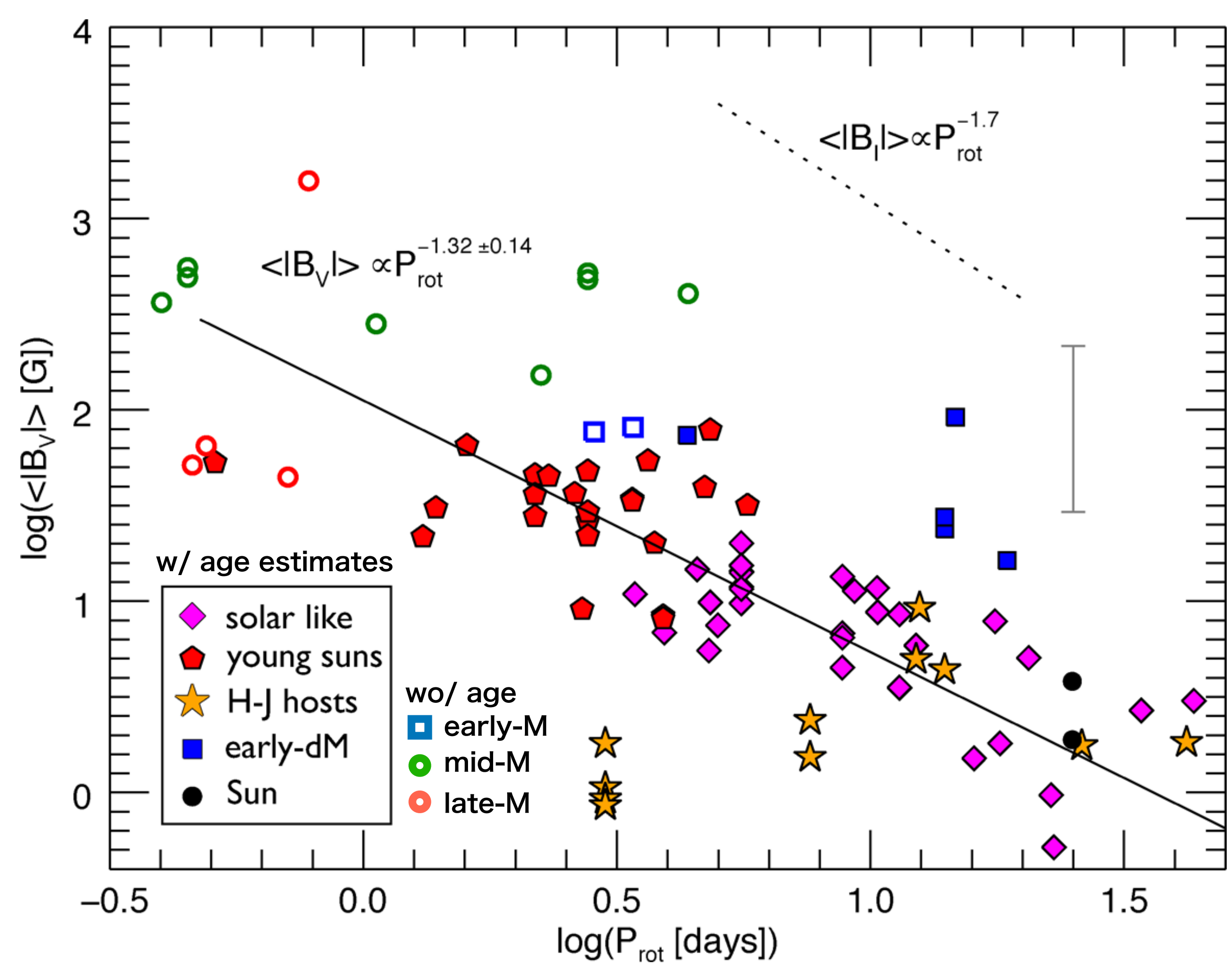
-Surface magnetic field in FGK stars show **strong correlation with the age and the rotation periods**.

-Magnetic amplification by **the α-Ω dynamo?**

Age vs field strength



Rotation vs field strength



(Vidotto et al. 2014)

Surface magnetic fields in radiative stars

Ap stars

-Chemically peculiar A type stars
-**~10%** of all A type stars

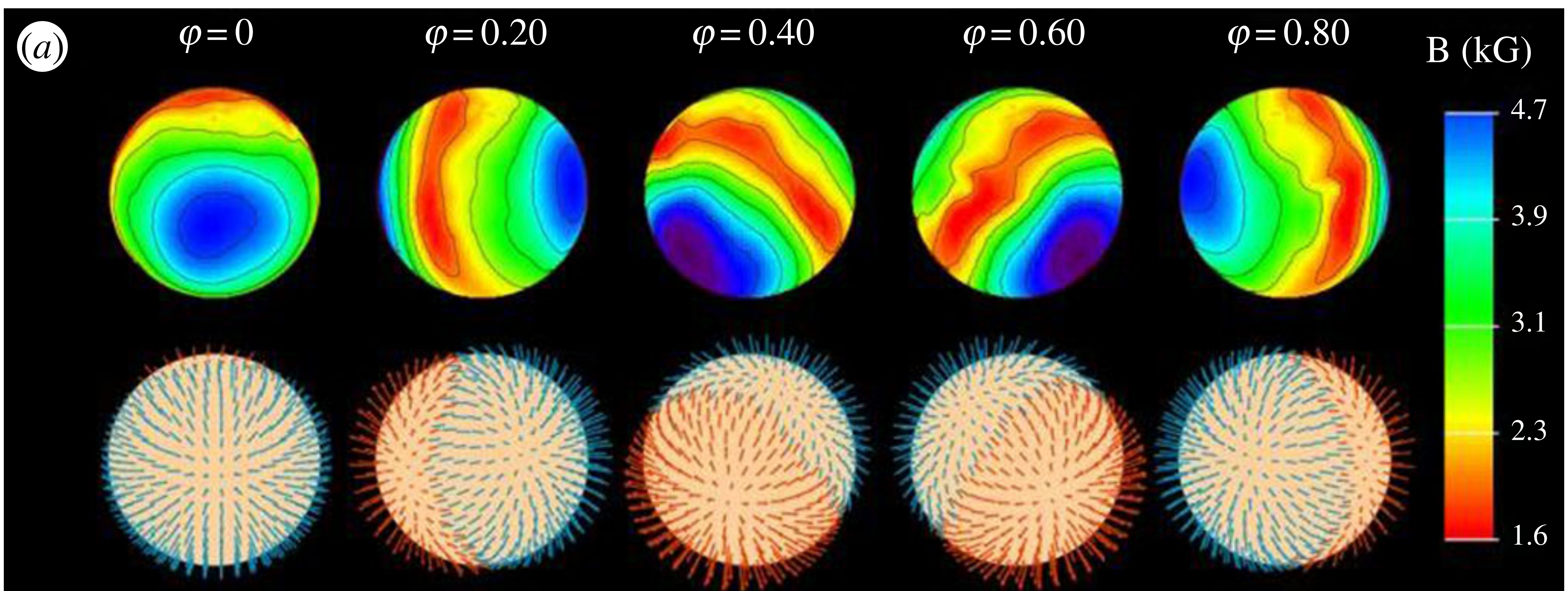
-B_l ~ **300-10k** G
-non-magnetic stars < ~1 G
-**Large-scale structure** (>~dipole)

(Badcock 1947,58; Landstreet 1992)

-Accumulating evidences indicate that **massive OB type stars share common magnetic features with less-massive A type stars.** (Wade et al. 2016; Wade & Neiner 2018)

Compatible with **a field in a stable equilibrium** **('Fossil' field)**.

Kochukhov et al. 2002: Magnetic field structure in α² CVn with 5 rotational phases



A fossil field in a stable stratified radiative zone

-**Strong, large-scale, and stable** surface magnetic fields observed in radiative stars are compatible with **the fossil field, i.e. a field in a stable equilibrium,** picture.

(Wade & Neiner 2018)

-A great number of investigations has been done to find the **static/stable magnetic configurations** in a radiative star.

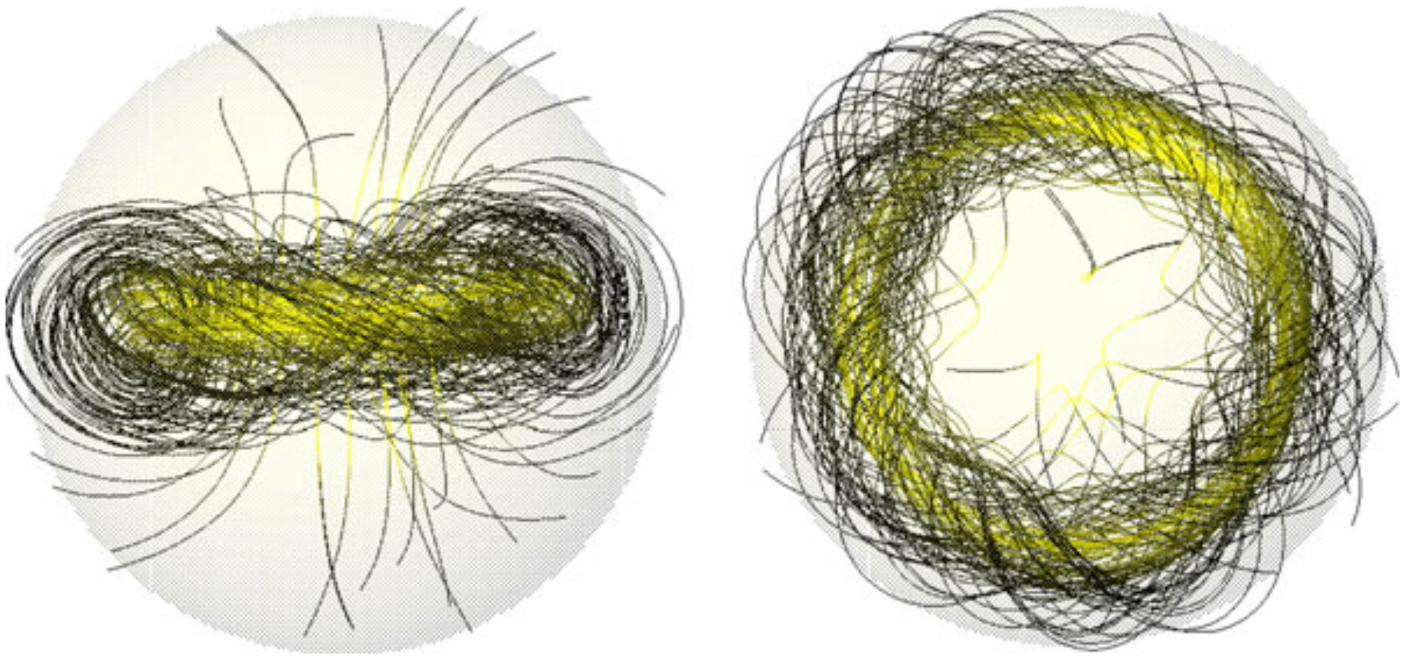
(Braithwaite & Spruit 2017 for a review)

-In an arbitrary configuration, magnetic fields move together with gases with the Alfvén velocity.

-With the short timescale **~ R/v_A** ~ 10 yr for a star with 10 kG, the magnetic field will find a stable configuration.

-The fossil field will persist with a long timescale **~ R^2/η** ~ 10^{10} yr for the sun.

A stable twisted-torus in equilibria



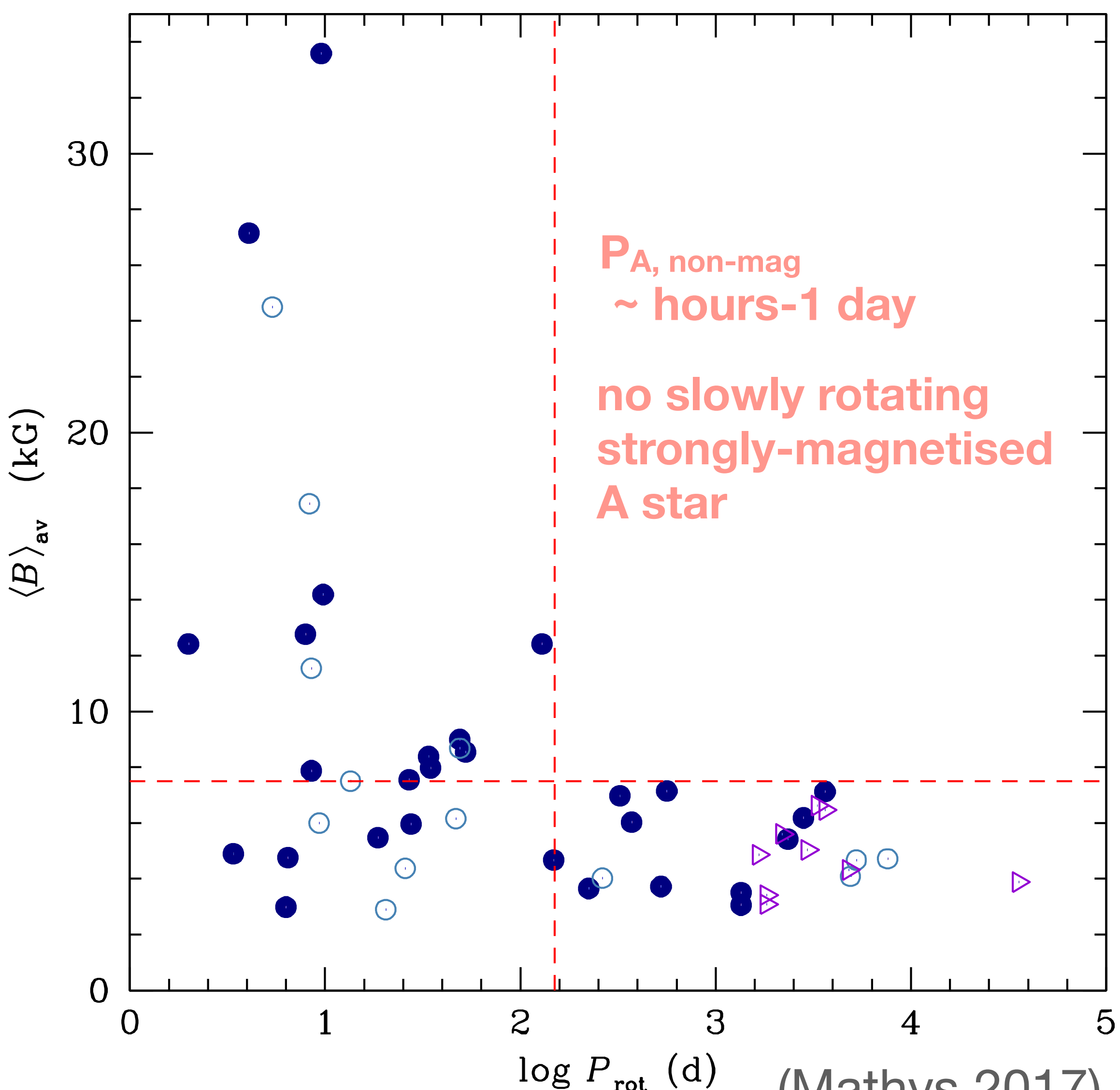
(Braithwaite & Nordlund 2006)

Interesting correlations in radiative stellar magnetism

-Correlations with fundamental parameters have been observed.

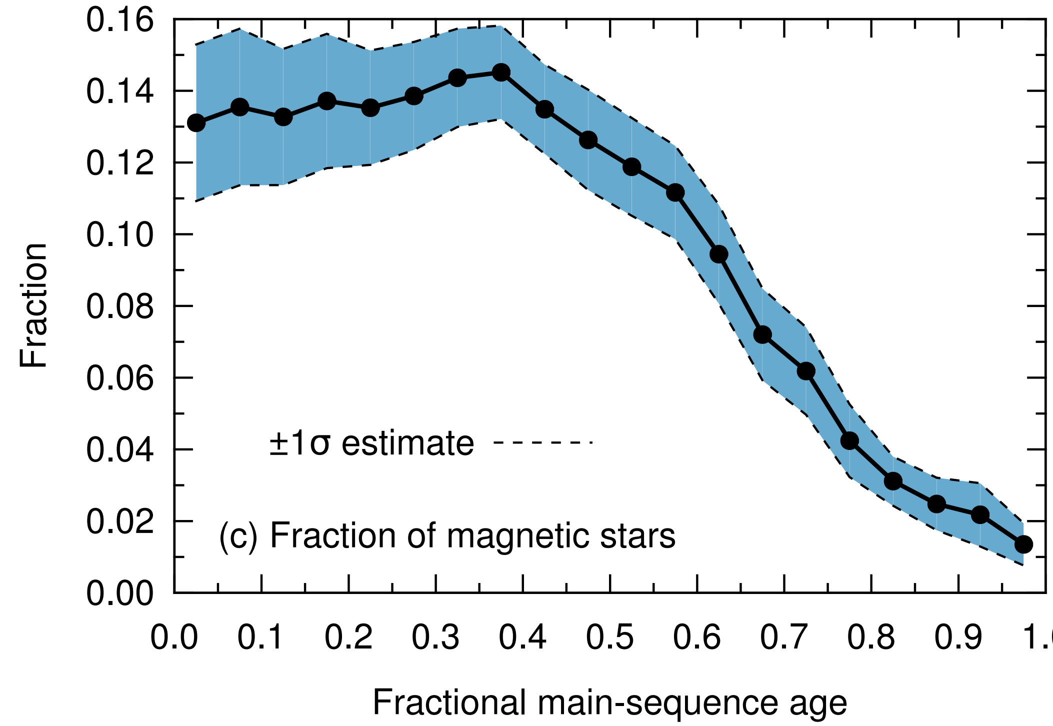
-age
-rotation
-binarity

Magnetic field modulus against P_{rot}

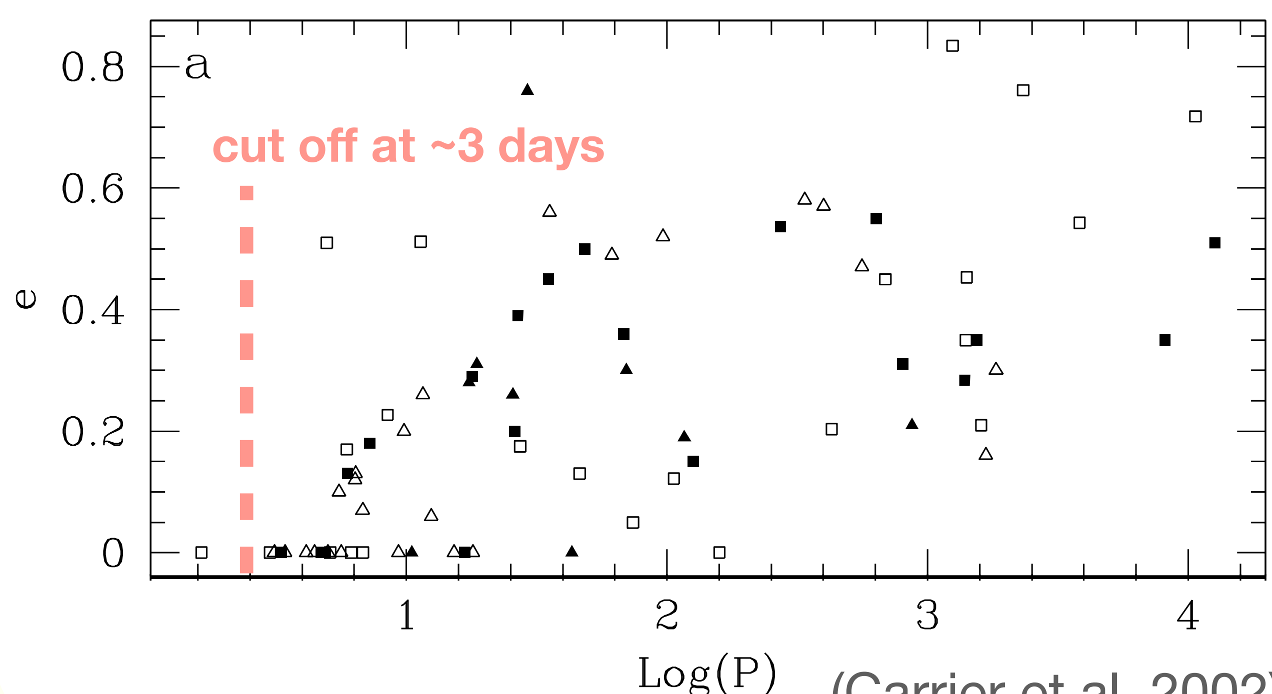


(Mathys 2017)

Time evolution (Fossati et al. 2016)



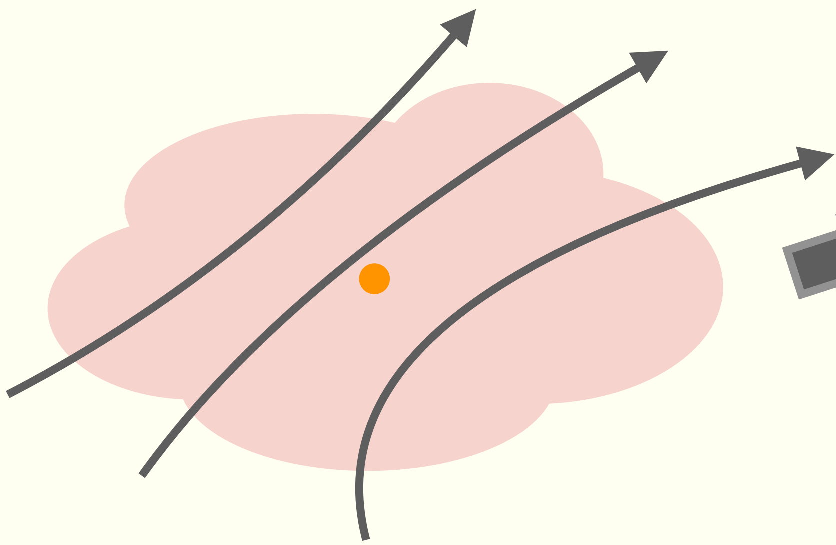
Binarity of Ap magnetic stars



(Carrier et al. 2002)

Stars retain magnetic fields from the birth to the death.

How can we model the interplay between structural changes and magnetic field evolution?



pre MS star (~**10%**):
B_{HAeBe} ~ 100 G,
R ~ 1-10 $R_\odot$
(Alecian et al. 2012)

MS star (~**10%**):
B_{ApBp} ~ 300-10k G,
R ~ 1-10 $R_\odot$
(Aurière et al. 2007)

Star forming cloud:
B_{MC} ~ 10^{-6} G,
R ~ 0.1-1 pc
(Crutcher 2012)

White dwarf (~**10%**):
B_{WD} ~ **10^3-10^9** G,
R ~ 0.01 $R_\odot$
(Ferrario et al. 2015)

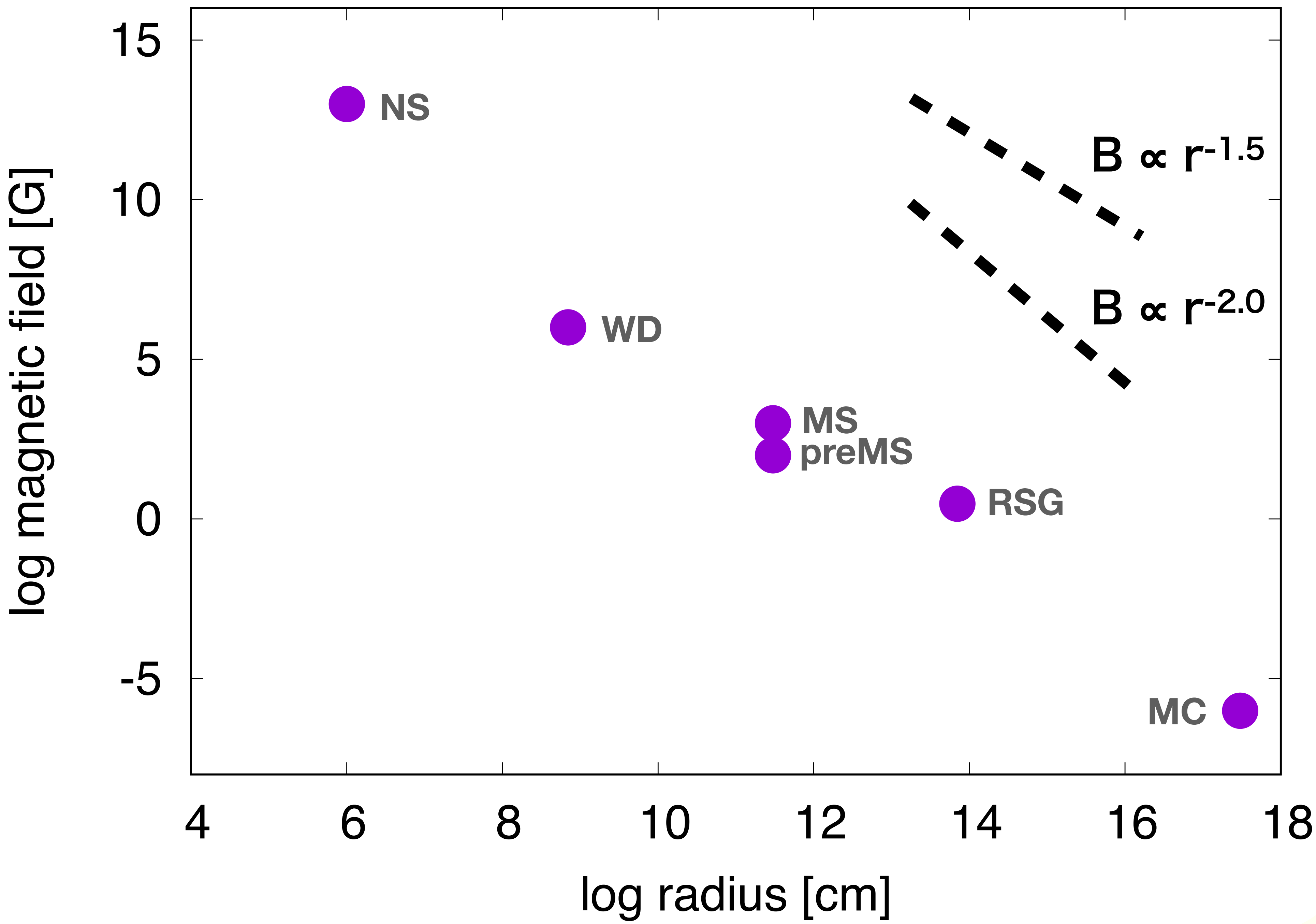
Red giants:
B_{RG} ~ 1-10 G,
R ~ 1000 $R_\odot$
(Grunhut et al. 2010; Tessore et al. 2017)

Neutron star:
B_{pulsar} ~ **10^{10}-10^{15}** G,
R ~ 10 km
(Tauris & van den Heuvel 2006)

Stars retain magnetic fields from the birth to the death.

How can we model the interplay between structural changes and magnetic field evolution?

Scaling relation

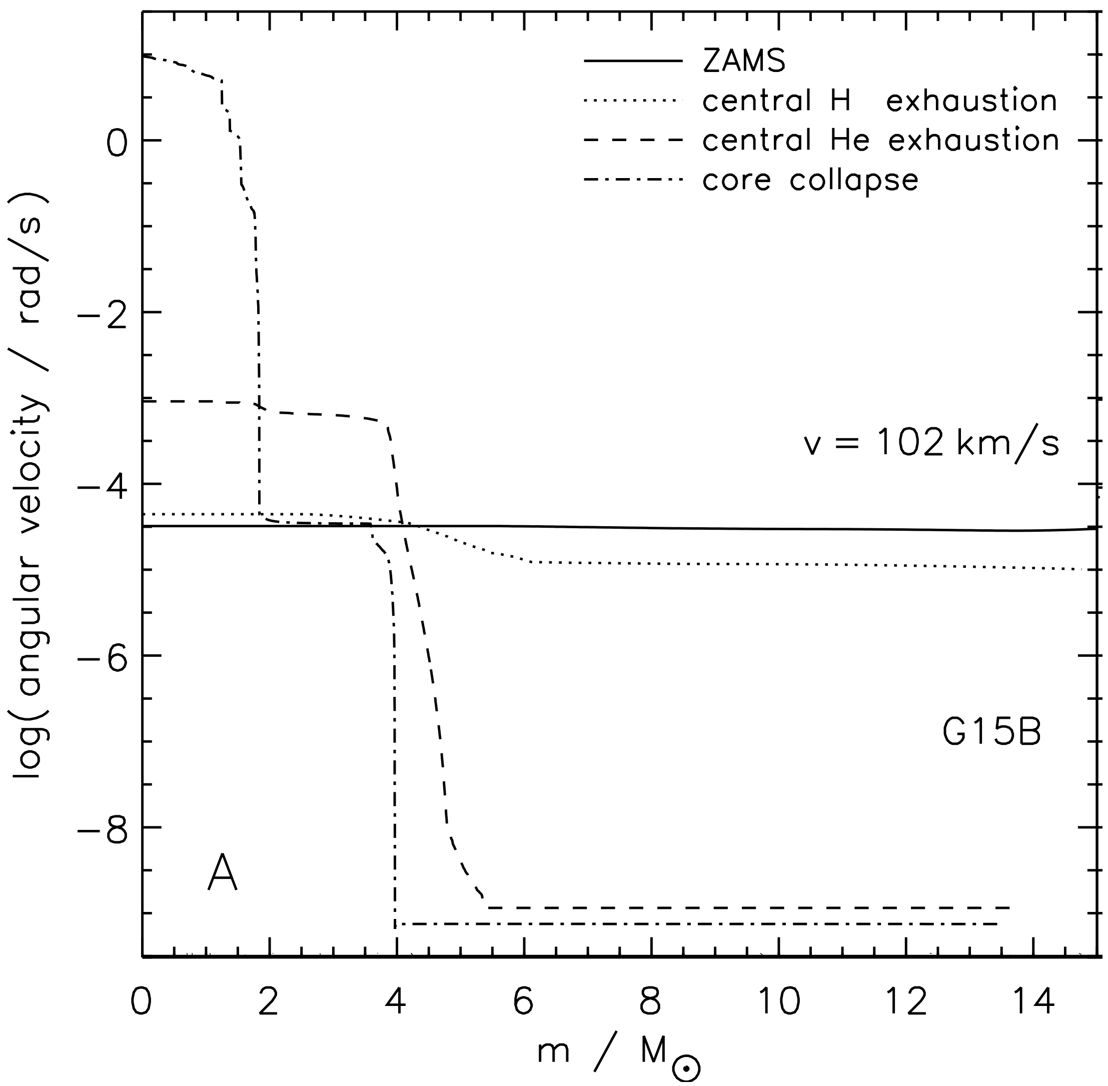


Sta
BMC
R ~
(Crut

l. 2017)

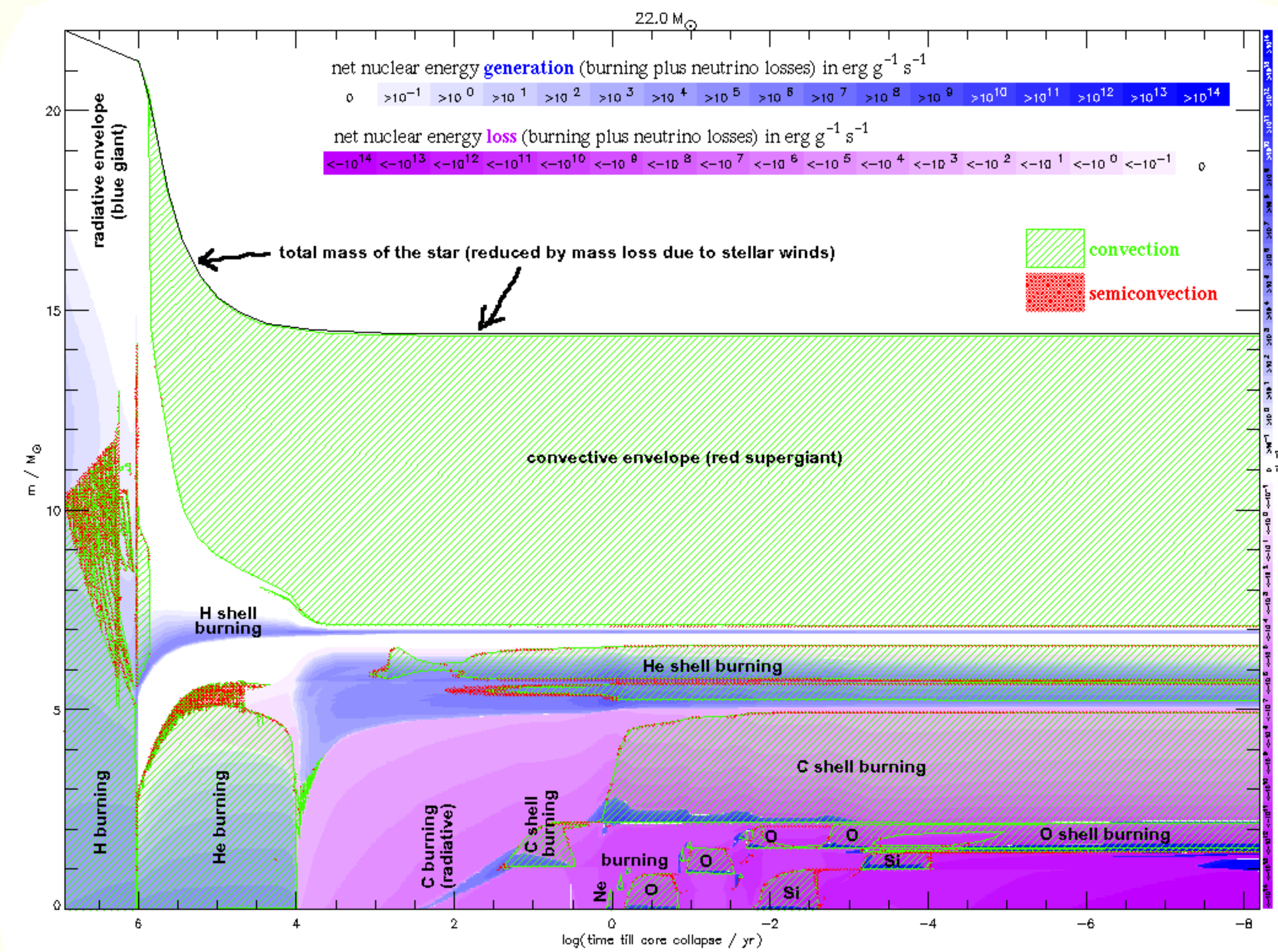
Magnetic field amplification in a massive star

Rotation profiles in a 15 M☉ model



(Heger et al. 2000)

Kippenhahn diagram of a 22 M☉ model



(A. Heger; https://2sn.org/stellarevolution/explain.gif)

Current status of magnetic evolution models

Works which consider magnetic field distributions

Tayler-Spruit dynamo:
-Maeder & Meynet 2003,04,05
-Heger et al. 2005
-Denissenkov & Pinsoneault 2007
and a lot of more…

Wind confinement:
-Petit et al. 2017
-Georgy et al. 2017

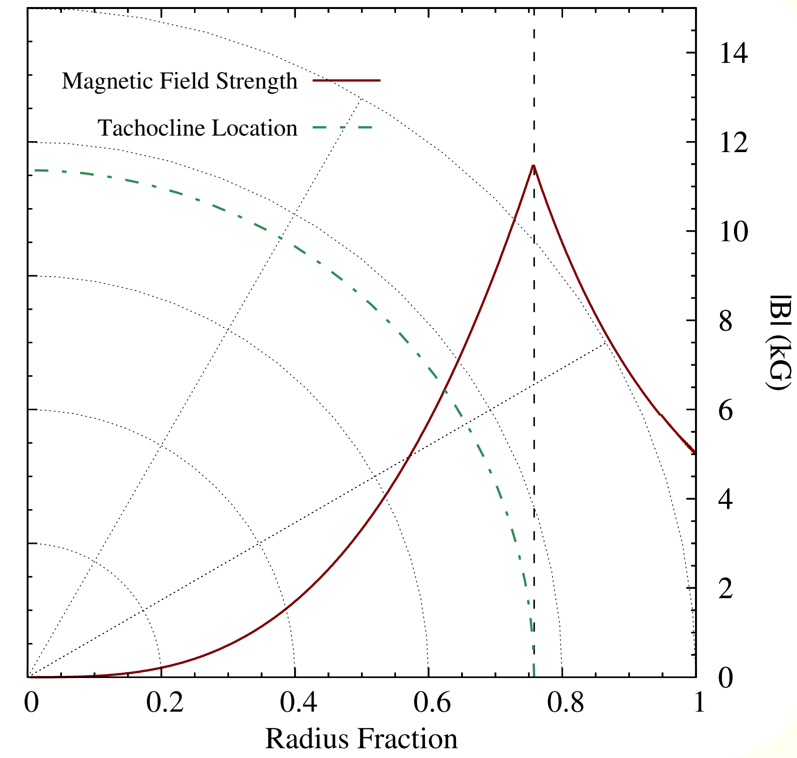
Magnetic breaking:
-Meynet et al. 2011

Convection inhibition:
-Petermann et al. 2015

Feiden & Chaboyer 2012,13,14

-low-mass stars
-magnetic pressure
-convective inhibition

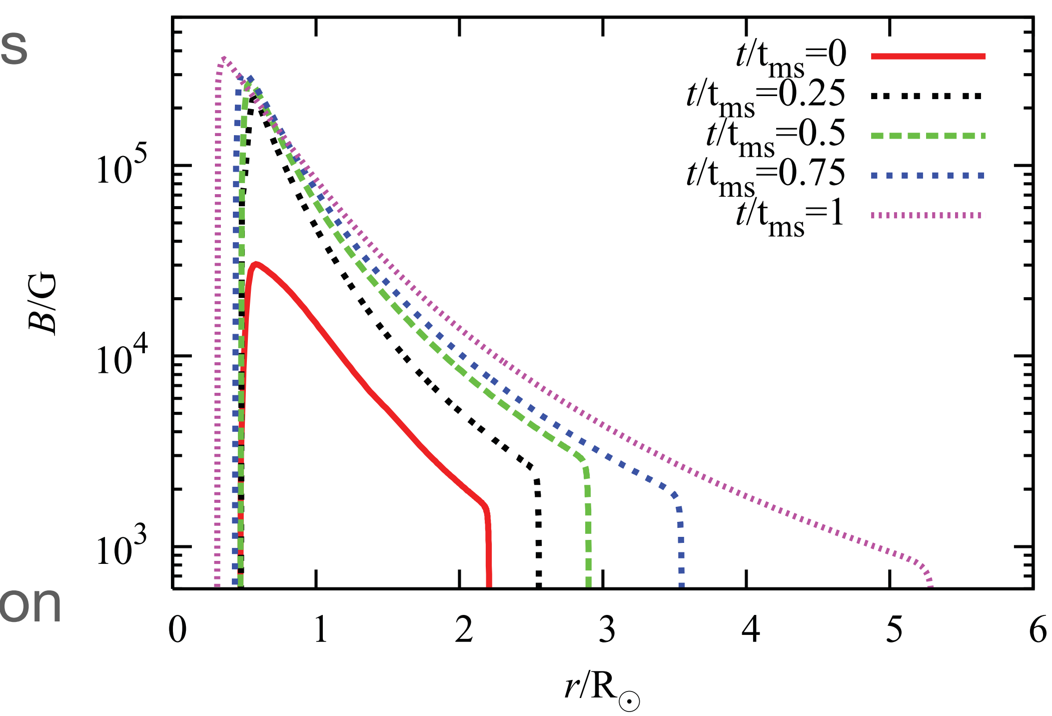
-no rotation
-no dynamo



Potter et al. 2012a,b,c

-intermediate-mass stars
-consider rotation
magnetic stress
αΩ dynamo
-magnetic breaking

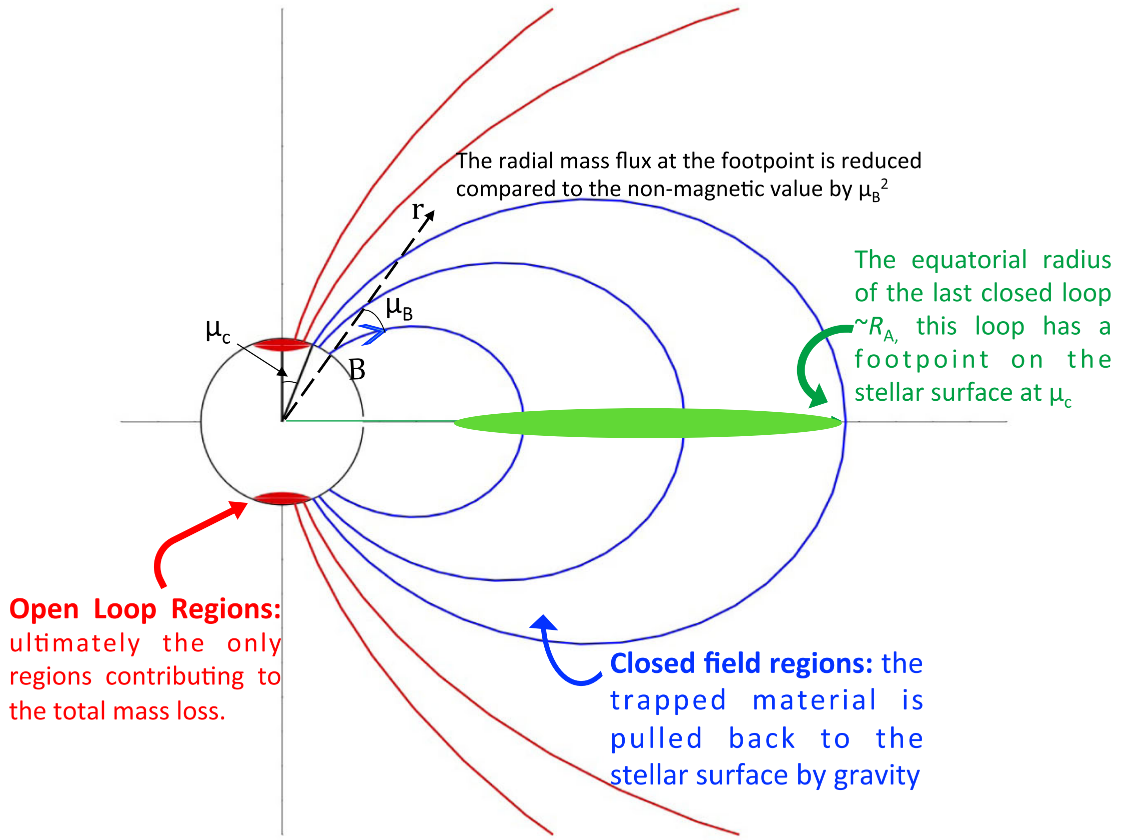
-no convective dynamo
-non-conservative form for angular momentum
-non-Lagrangian evolution equations



Wind-magnetic field interaction

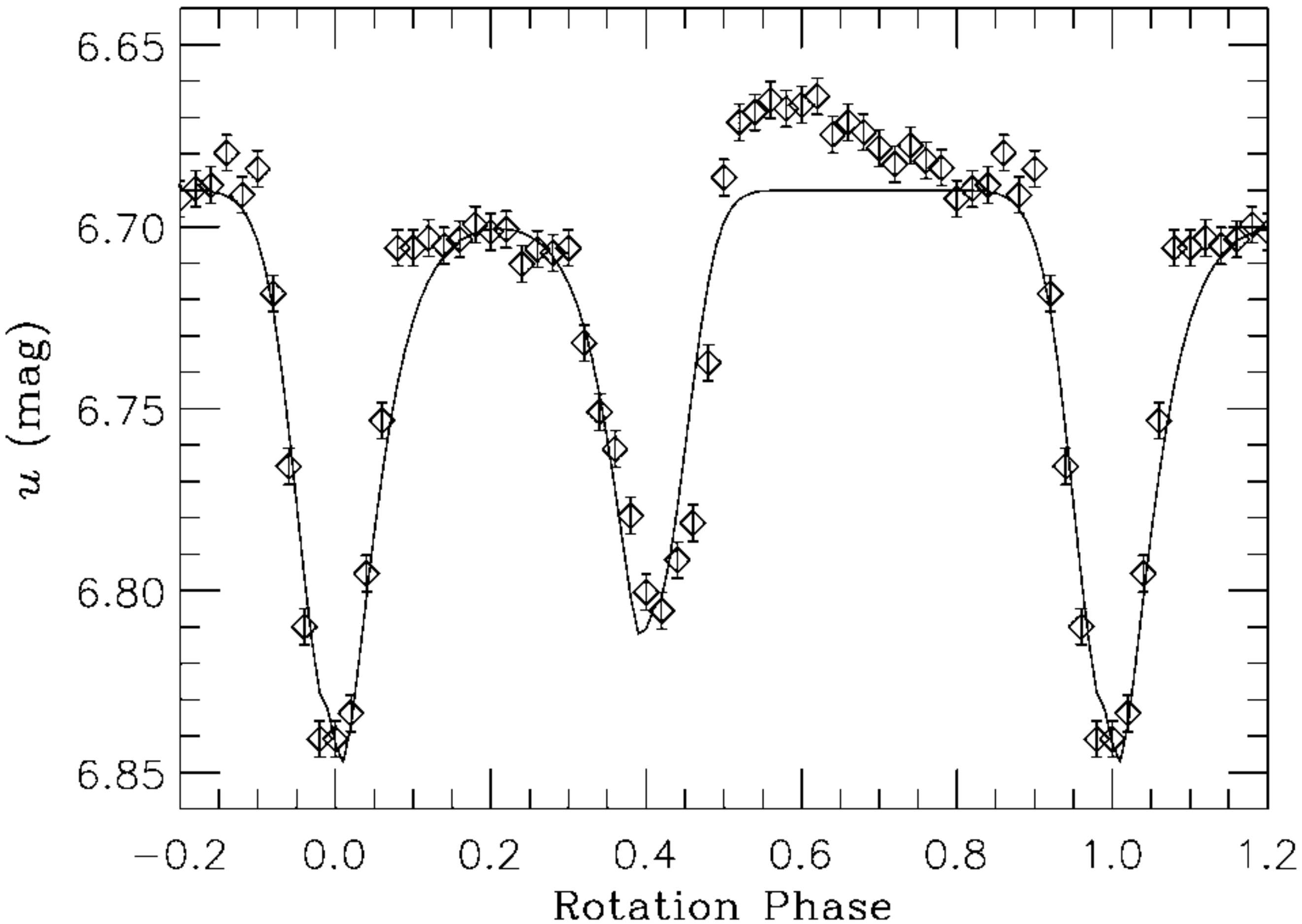
-Strong surface magnetic fields result in
- -**wind confinement** leading to a formation of rigidly rotating magnetosphere
- -**efficient angular momentum loss** by both the magnetic stress and by the gas

Magnetic wind confinement



(Donati et al. 2002; Petit et al. 2017)

Observed & modeled (solid line) light curves of σ Ori E



(Townsend et al. 2005)

Magnetic inhibition of convection

-Strong magnetic fields inside a star may **limit the size of convective zones**, which is one of the fundamental parameter of the massive star evolution.

-**Ap star**

-Chemically peculiar A type stars

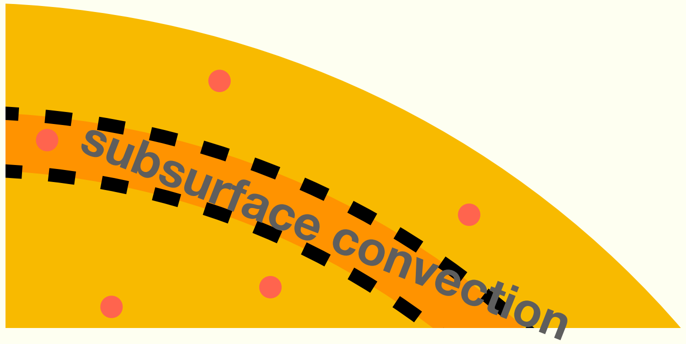
-enhancements in **Sr, Cr, Eu, Si**.

-**Subsurface convection** mixes the chemical profiles in the subsurface region.

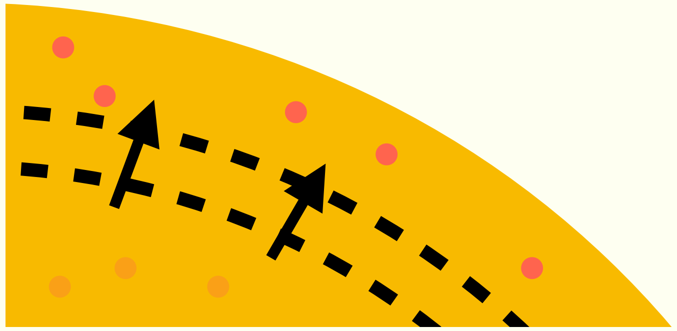
-In a magnetic star, the subsurface convection is **suppressed by the strong magnetic field**. Inside the stable medium, heavy elements which have a lot of lines is affected by the **radiative levitation**.

(Landstreet 1992)

Non-magnetic star



Magnetic star



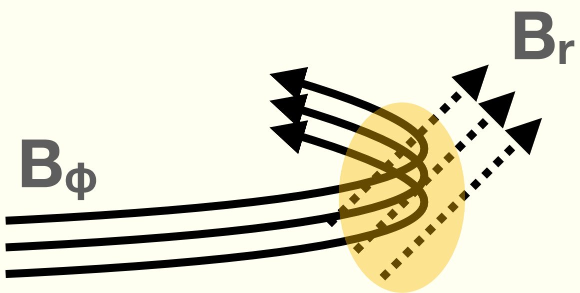
-The β Cep star V2052 Oph requires a small overshoot parameter.

(Briquet et al. 2012)

Angular momentum transport by the magnetic stress

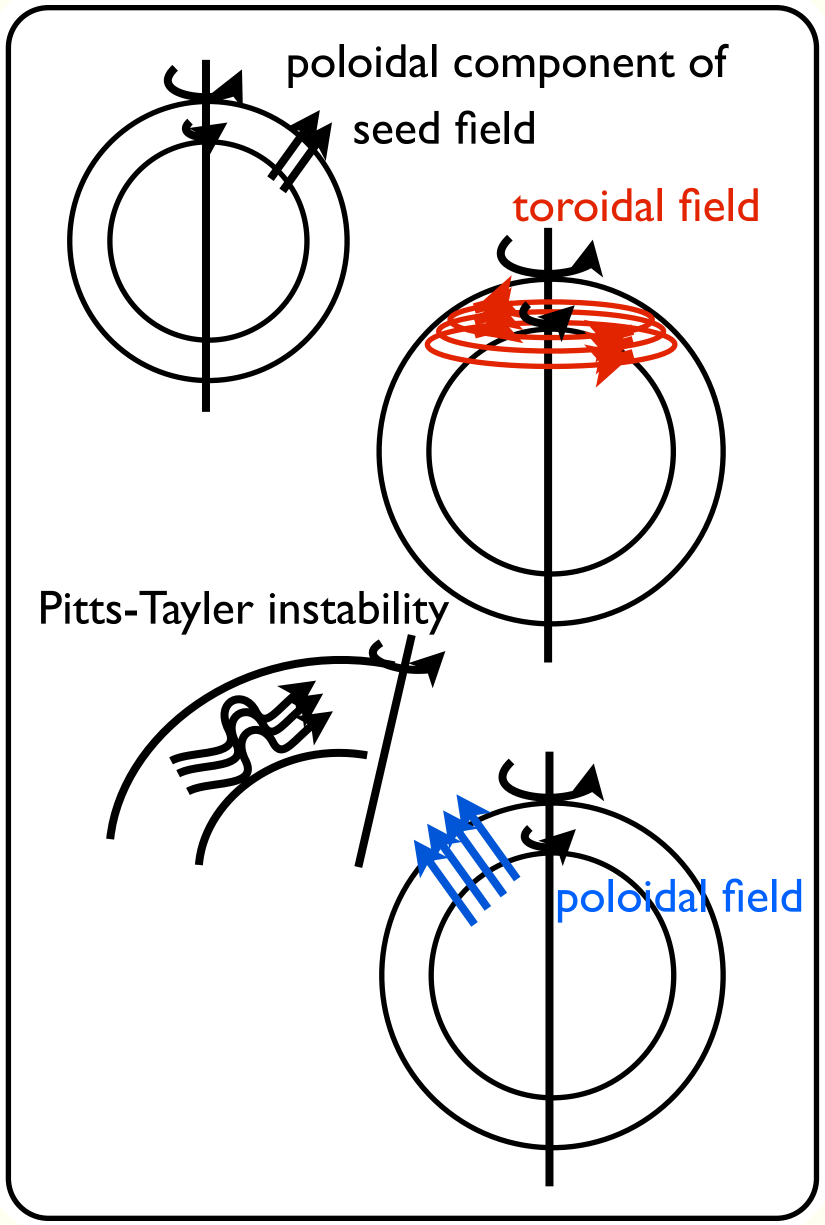
-**Magnetic stress** can transport angular momentum much more effectively than hydrodynamical processes.

$$S = \frac{B_r B_\phi}{4\pi}$$



-Most “magnetic” stellar evolution simulations estimate the magnetic stress based on the **Tayler-Spruit dynamo** theory. (Spruit 1999,2002; Maeder&Meynet 2003,04,05; Heger et al. 2005)

1. A poloidal field exists in the radiative layer.
2. **The Ω-dynamo**: the poloidal field is wound up to create the new toroidal component.
3. The strong toroidal magnetic field is unstable to the m=1 perturbation.
4. **The Pitts-Tayler instability in the toroidal field creates the new poloidal component.**
5. Saturation takes place when **turbulent diffusion by the Pitts-Tayler instability overcomes dynamo.**



No solid theoretical predictions have been made. **(Langer 2014)**

Our strategy

Goal:
-consistent calculation to estimate the **WD/NS rotation & magnetism**.

Requirements:
-long timescale evolution
-following conservation laws accurately

Method:
-new formalism based on the fundamental equations
-consistent evolutions among **structure, rotation, & magnetic field**

Confirmation:
-problems **known for rotating stellar evolution**
-**magnetic fields in stellar interiors**

Evolution of rotating massive stars

Rotation affects stellar structure and evolution. (Meynet & Maeder 2000; Heger et al. 2000)

Three rotational effects are treated in 1D stellar evolution codes.

1. **Deformation** by centrifugal force
   (Endal&Sofia 1976; Meynet&Maeder 1997)
2. **Matter mixing** by rotationally induced instabilities
   (Endal&Sofia 1978; Maeder&Meynet 1996)
3. **Mass loss enhancement**
   (Langer 1998, Maeder&Meynet 2000, Yoon et al. 2012)

The **shellular rotation** profile (Zahn 1992) evolves according to the radial transport equation of the angular momentum.

$$\rho \frac{\mathrm{d}}{\mathrm{d}t}(r^2\Omega) = \frac{1}{5r^2}\frac{\mathrm{d}}{\mathrm{d}r}(\rho r^4 \Omega U_2) + \frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(\rho r^4 \nu_{\mathrm{eff}} \frac{\mathrm{d}\Omega}{\mathrm{d}r}\right)$$

(Maeder & Zahn 1998)

U_2 : radial component of the meridional flow velocity

ν_{eff}: effective viscosity, most of which come from the Reynolds stress of turbulent flows induced by rotational instabilities.

Formulation: field evolution

Magnetic field configuration:
-toroidal+poloidal decomposition
-dipole approximation

$$
\begin{aligned}
\boldsymbol{B}(r,\theta) &\equiv \boldsymbol{B}_{\rm pol}(r,\theta) + \boldsymbol{B}_{\rm tor}(r,\theta) \\
\boldsymbol{B}_{\rm pol} &= B_r(r,\theta)\boldsymbol{e}_r + B_\theta(r,\theta)\boldsymbol{e}_\theta \\
\boldsymbol{B}_{\rm tor} &= B_\phi(r,\theta)\boldsymbol{e}_\phi,
\end{aligned}
$$

$$\boldsymbol{B}_{\rm pol} = \nabla \times \boldsymbol{A}_{\rm tor},$$

$$A_\phi(r,\theta) \equiv A(r)\sin\theta,$$

$$
\begin{aligned}
B_r(r,\theta) &= \frac{2A}{r}\cos\theta \\
B_\theta(r,\theta) &= -\frac{\sin\theta}{r}\frac{\partial(Ar)}{\partial r}.
\end{aligned}
$$

$$B_\phi(r,\theta) = B(r)\sin 2\theta.$$

Formulation: field evolution

Basic equations:

-Ohm's law + turbulent effects

-Induction equation

Mean-field MHD-dynamo equation

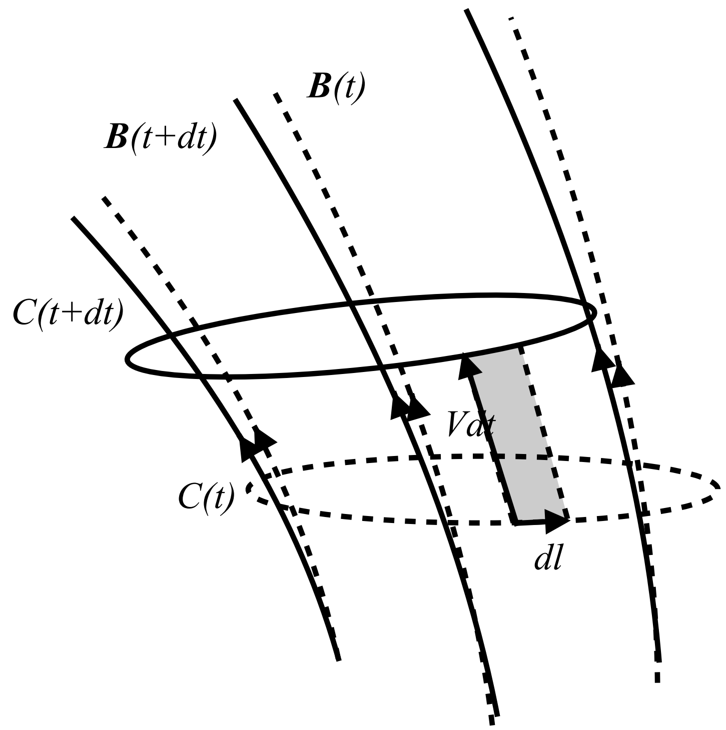
$$\boldsymbol{j} = \sigma \left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B} + \frac{\alpha}{c} \boldsymbol{B} + \frac{\eta_t}{c} \nabla \times \boldsymbol{B} \right)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B} + \alpha \boldsymbol{B}) - \nabla \times ((\eta + \eta_t) \nabla \times \boldsymbol{B})$$

1D averaging:

-Flux equation

$$\frac{\mathrm{d}\Phi_C}{\mathrm{d}t} = \int_C \left(\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) \right) \cdot \mathrm{d}\boldsymbol{S}$$



$$\frac{d(Ar)}{dt} = \eta r \frac{\partial}{\partial r} \left(\frac{1}{r^2} \frac{\partial}{\partial r} (Ar^2) \right) + r(\alpha \boldsymbol{B})_\phi (\theta = \pi/2).$$

$$\frac{d}{dt} \left(\frac{Br}{r^2 \rho} \right) = \frac{1}{r^2 \rho} \left(Ar \frac{\partial \Omega}{\partial r} + \eta r \frac{\partial}{\partial r} \left(\frac{1}{r^2} \frac{\partial}{\partial r} (Br^2) \right) + r \frac{\partial \eta}{\partial r} \frac{\partial Br}{\partial r} - \alpha r \frac{\partial}{\partial r} \left(\frac{1}{r^2} \frac{\partial}{\partial r} (Ar^2) \right) - r \frac{\partial \alpha}{\partial r} \frac{\partial Ar}{\partial r} \right)$$

Formulation: angular momentum transport

Basic equation:

-momentum conservation + Lorentz force → + Maxwell stress

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla P + \rho \boldsymbol{g} + \frac{1}{c}\boldsymbol{j} \times \boldsymbol{B} + (viscosity)$$

$$= -\nabla P + \rho \boldsymbol{g} + \nabla \cdot \boldsymbol{M} + (visc.)$$

1D averaging:

-Ang. mom. conservation + Maxwell stress

$$\rho\left(\frac{\partial}{\partial t} + v_r \frac{\partial}{\partial r} + \frac{v_\theta}{r}\frac{\partial}{\partial \theta} + \frac{v_\phi}{r\sin\theta}\frac{\partial}{\partial \phi}\right)(v_\phi r \sin\theta)$$

$$= \frac{1}{r^2}\frac{\partial}{\partial r}\left(\frac{r^3 \sin\theta B_r B_\phi}{4\pi}\right) + \frac{1}{\sin\theta}\frac{\partial}{\partial \theta}\left(\frac{\sin^2\theta B_\theta B_\phi}{4\pi}\right) + \frac{\partial}{\partial \phi}\left(\frac{B_\phi B_\phi}{4\pi}\right) - \frac{\partial}{\partial \phi}\left(\frac{B^2}{8\pi}\right) + (visc.)_\phi$$

$$\frac{d}{dt}(r^2\Omega) = \frac{1}{\rho r^2}\frac{\partial}{\partial r}\left(\frac{4}{5}\frac{r^2 AB}{4\pi}\right) + \frac{1}{\rho r^2}\frac{\partial}{\partial r}\left(\rho r^4 \nu_{\rm eff}\frac{\partial \Omega}{\partial r}\right)$$

Formulation

Magnetic field configuration:

-toroidal+poloidal decomposition
-dipole approximation

$$\begin{aligned} \boldsymbol{B}(r,\theta) &\equiv \boldsymbol{B}_{\rm pol}(r,\theta) + \boldsymbol{B}_{\rm tor}(r,\theta) \\ \boldsymbol{B}_{\rm pol} &= B_r(r,\theta)\boldsymbol{e}_r + B_\theta(r,\theta)\boldsymbol{e}_\theta \\ \boldsymbol{B}_{\rm tor} &= B_\phi(r,\theta)\boldsymbol{e}_\phi, \end{aligned}$$

$$\boldsymbol{B}_{\rm pol} = \nabla \times \boldsymbol{A}_{\rm tor},$$

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$$\begin{aligned} B_r(r,\theta) &= \frac{2A}{r}\cos\theta \\ B_\theta(r,\theta) &= -\frac{\sin\theta}{r}\frac{\partial(Ar)}{\partial r}. \end{aligned}$$

$$B_\phi(r,\theta) = B(r)\sin 2\theta.$$

Induction equation

-Ohm's law + turbulent effects
-evolution equation of magnetic flux

$$\frac{d(Ar)}{dt} = \eta r\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(Ar^2)\right) + r(\alpha\boldsymbol{B})_\phi(\theta = \pi/2).$$

$$\frac{d}{dt}\left(\frac{Br}{r^2\rho}\right) = \frac{1}{r^2\rho}\left(Ar\frac{\partial\Omega}{\partial r} + \eta r\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(Br^2)\right) + r\frac{\partial\eta}{\partial r}\frac{\partial Br}{\partial r} - \alpha r\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial}{\partial r}(Ar^2)\right) - r\frac{\partial\alpha}{\partial r}\frac{\partial Ar}{\partial r}\right)$$

Momentum conservation

-Lorentz force → Maxwell stress

$$\frac{d}{dt}(r^2\Omega) = \frac{1}{\rho r^2}\frac{\partial}{\partial r}\left(\frac{4}{5}\frac{r^2AB}{4\pi}\right) + \frac{1}{\rho r^2}\frac{\partial}{\partial r}\left(\rho r^4\nu_{\rm eff}\frac{\partial\Omega}{\partial r}\right)$$

Summary of the input physics

In the new formalization, we have achieved;

Satisfying ang. mom. conservation & flux conservation:
Adequate to follow a long-timescale evolution.

Ω effect is naturally introduced:
It comes from the induction equation.

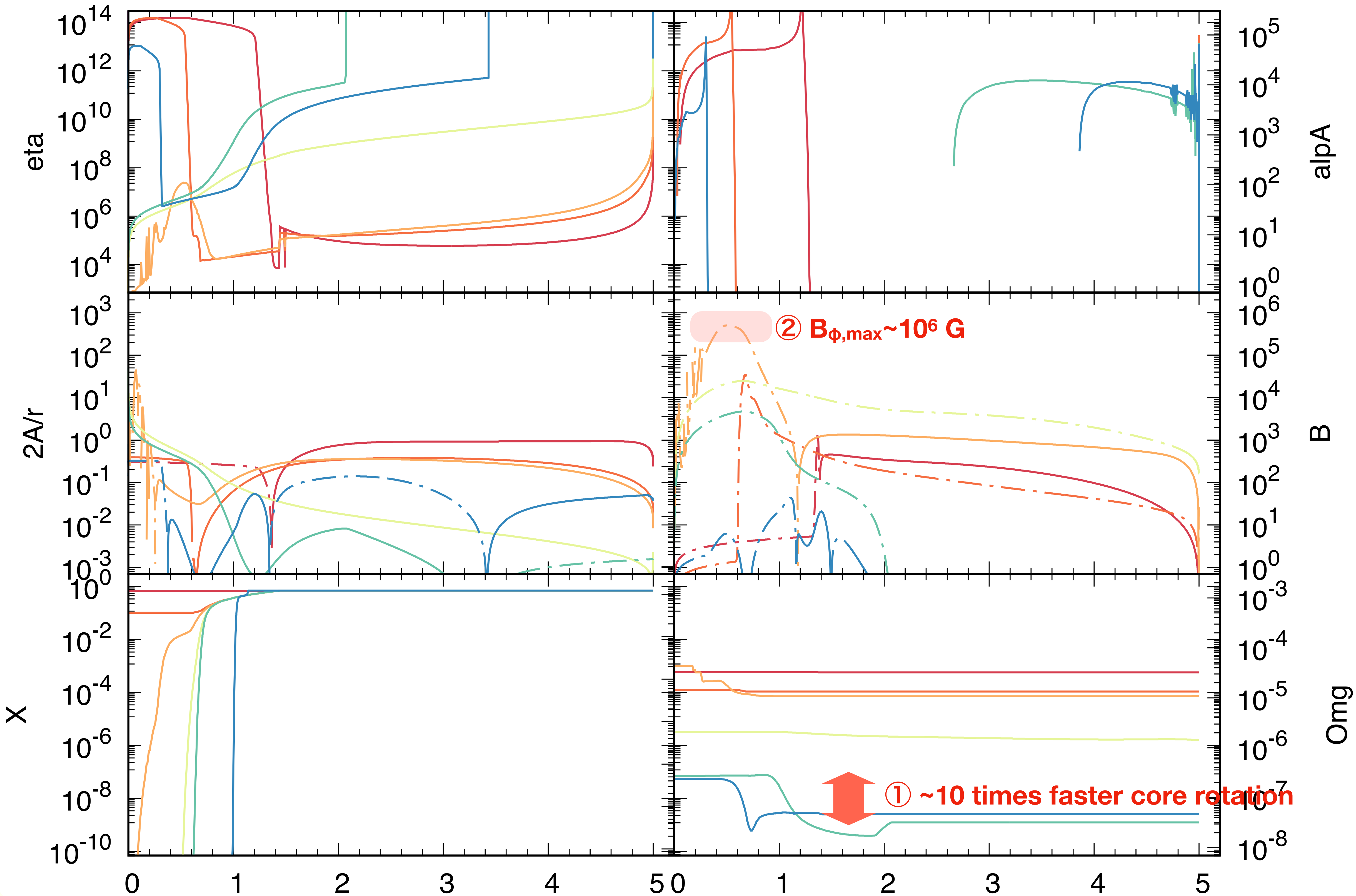
α effect taken from a mean-field dynamo theory:
Convective helical flow amplifies magnetic fields (Rudiger&Kichatinov 1993).
α-quenching is included.
Only $\alpha_{\phi\phi}$ is currently considered.

η_t of the Pitts-Tayler instability:
Strong toroidal fields introduce m=1 instability (Pitts&Tayler 1985).
No Tayler-Spruit dynamo included.

Tentatively omitted effects:
- -magnetic pressure
- -Joule heat
- -convective suppression
- -magnetic breaking
- -wind confinement

Internal rotation & magnetic field evolution

Very **preliminary** results for a ‘non-magnetic’ 5 $M_\odot$ model



Efficient angular momentum transportation

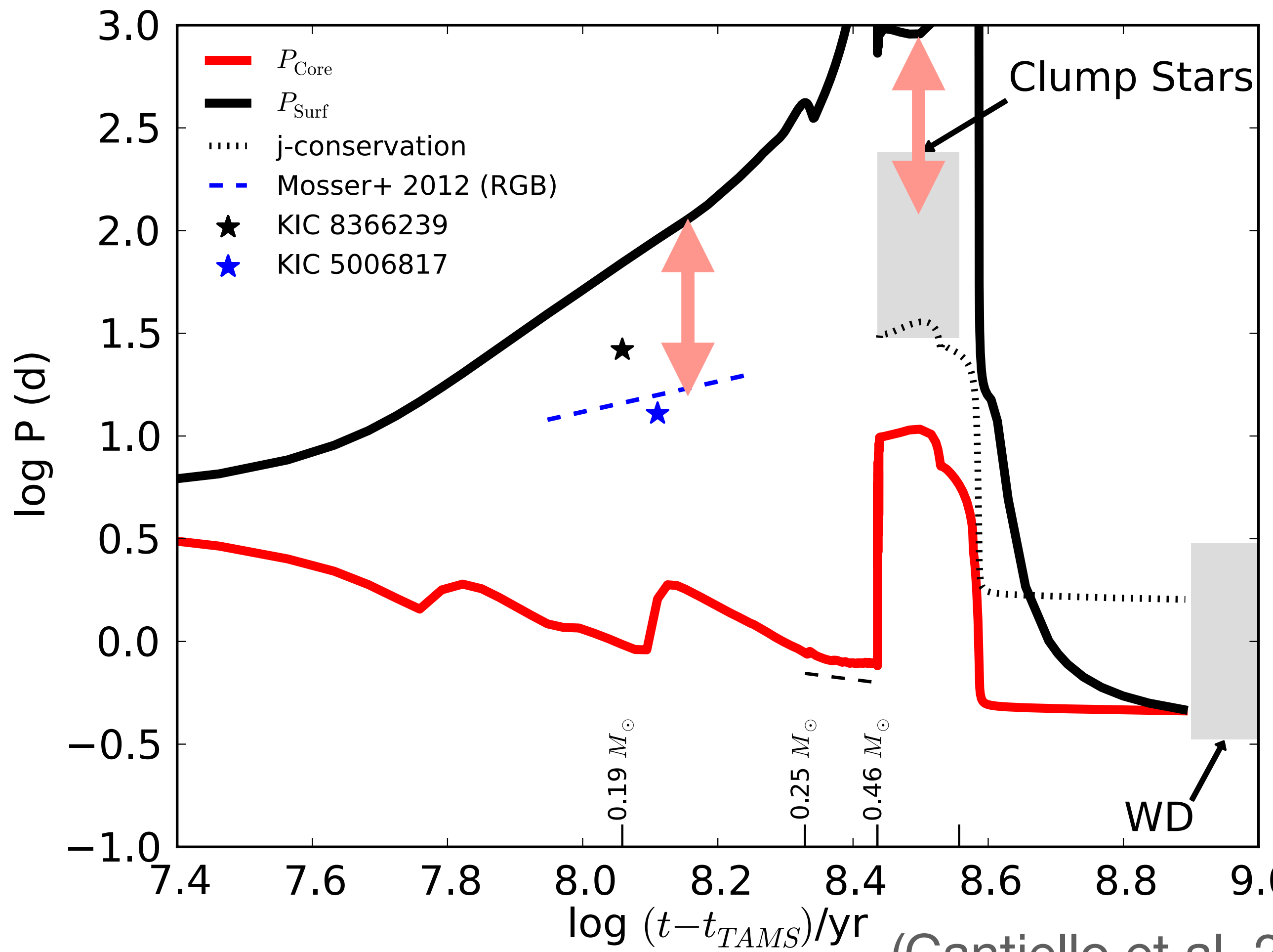
Stellar evolution calculation generally predicts **faster rotation periods** of stellar interior than observations.

- -**Compact remnants:**
  - -WDs for inter-mediate mass stars
  - -NSs for massive stars
- -**Red giant cores** for low-mass stars

(Mosser et al. 2012)

RG cores should rotate 10 times faster than their surfaces.

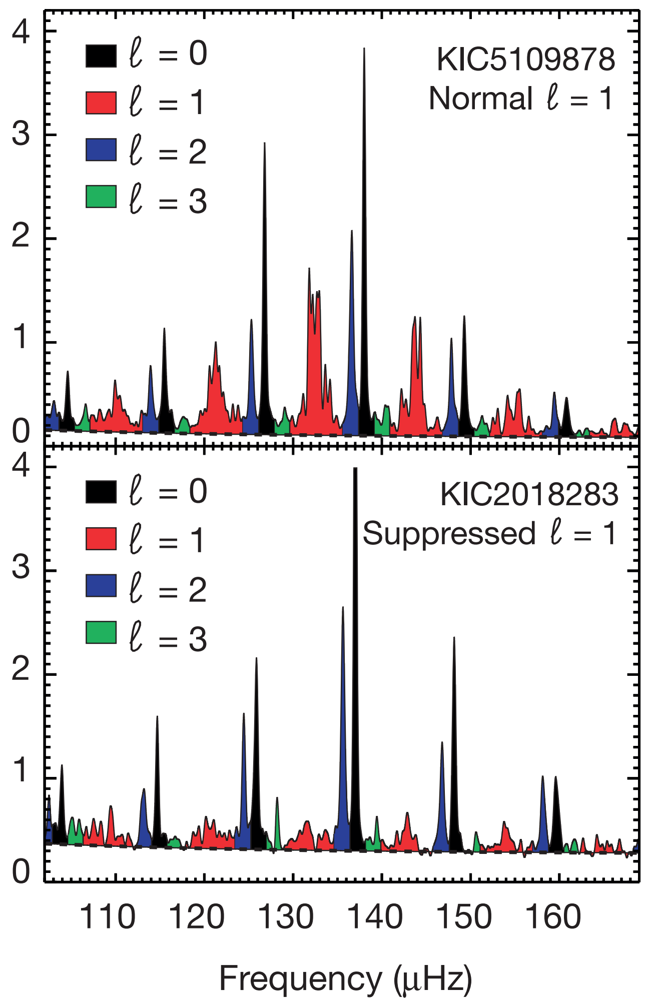
Evolution of the core rotation period



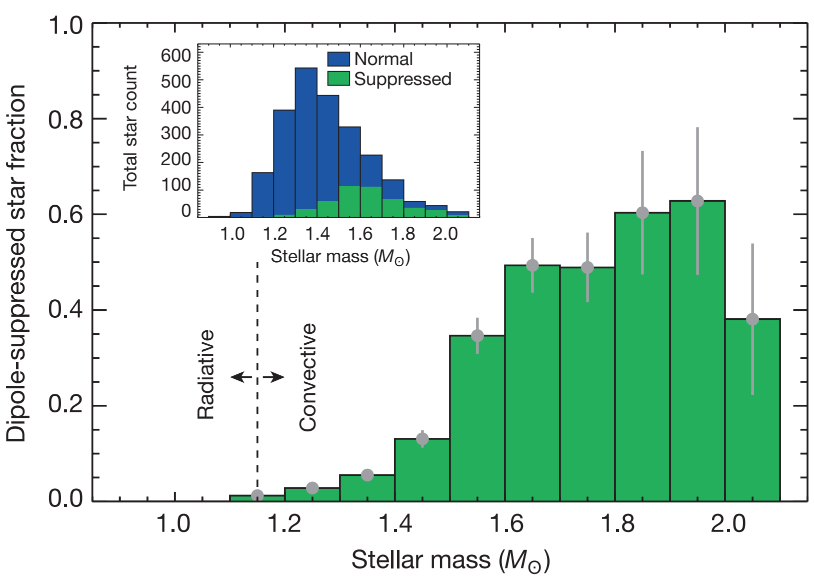
(Cantiello et al. 2014)

Constraint for the internal magnetic field

l=1 mode suppression



incidence rate vs mass

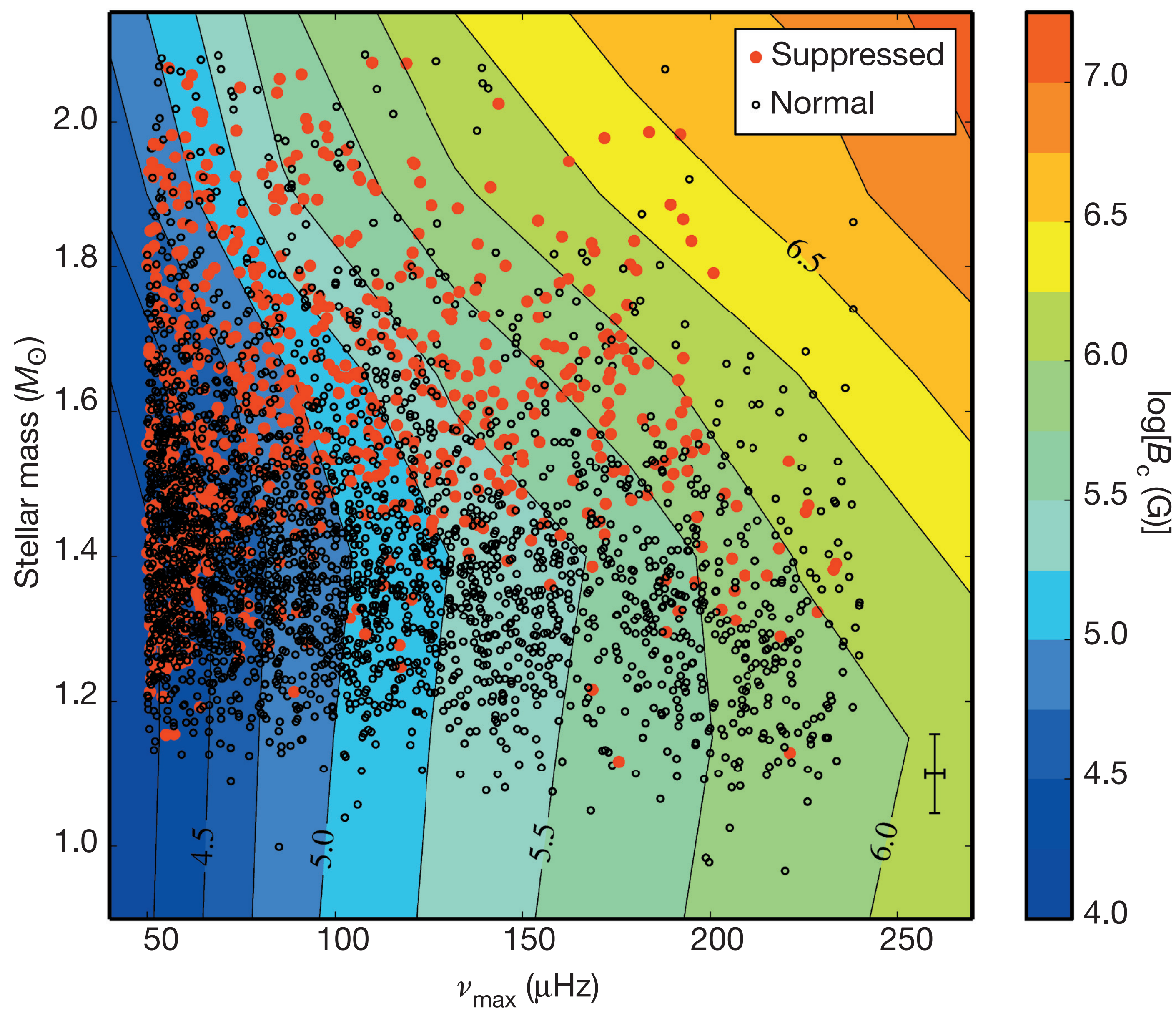


l=1 mode suppression in RGs would result from the wave trapping **due to strong magnetic field** in a He core.

-Fuller et al. 2015

-explain incidence rate

Stello et al 2016: Minimum magnetic field strength to explain the l=1 mode suppression



Conclusion

Current Status

-Stars, at least a fraction of them, in all evolutionary stages have surface magnetic fields.

- -pre-MS stars
- **-MS stars**
- **-radiative/convective stars**
- -red giants
- -WDs/NSs

-Indications of magnetic effects onto the stellar evolution

- **-angular momentum transport**
- -Wind-magnetic field interactions
- -inhibition of convection

A new model

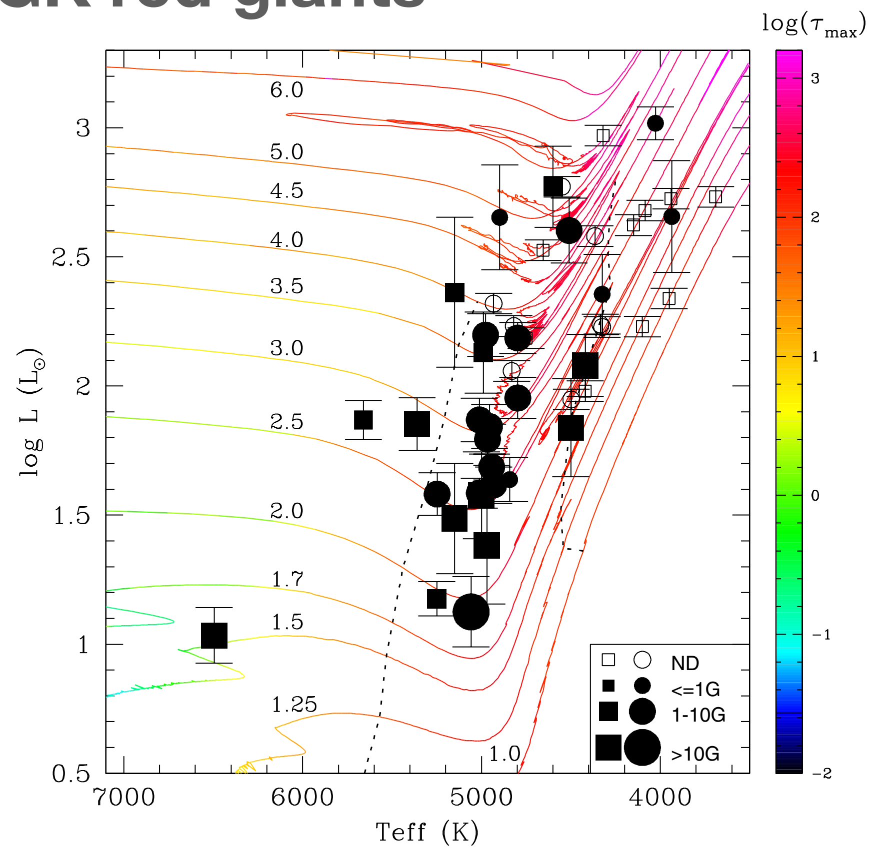
-Consistent treatments of **structure, rotation, & magnetic field** evolution

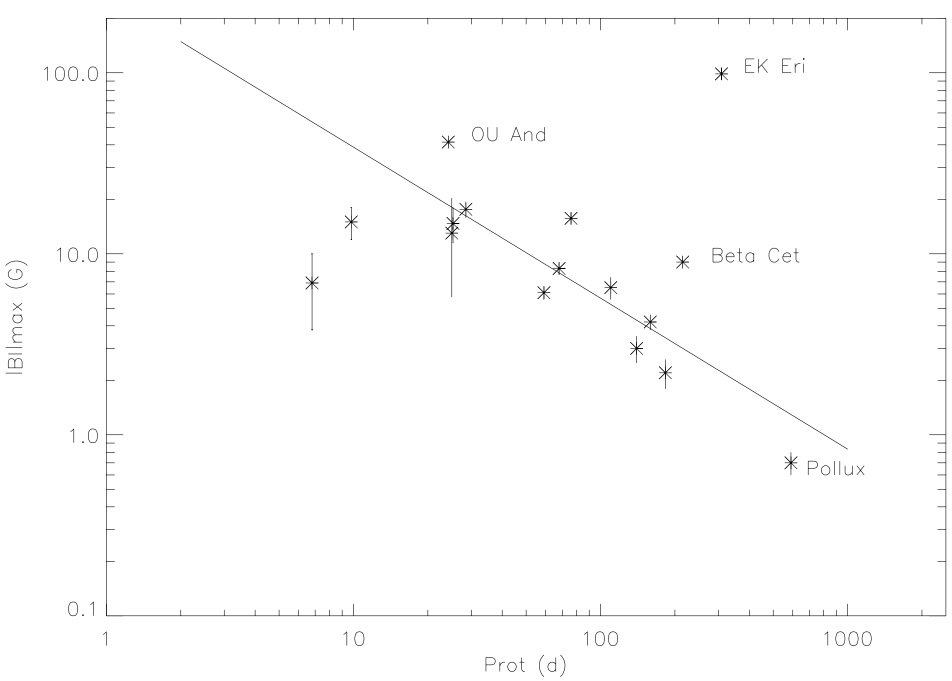
-Interesting agreements with observations

- **-core/surface rotation periods of factor of ~10 difference**
- **-internal magnetic field strength of ~10^6 G.**

Surface magnetic fields in convective stars

GK red giants





(Aurière et al. 2015)

-Fraction:

-29/48 (but with highly biased samples)

-Active giants

-Thermohaline deviants (Ap descendants)

-CFHT snapshot subsamples

-Properties:

-B_l ~ **1**-100 G

-**correlation with rotation periods**

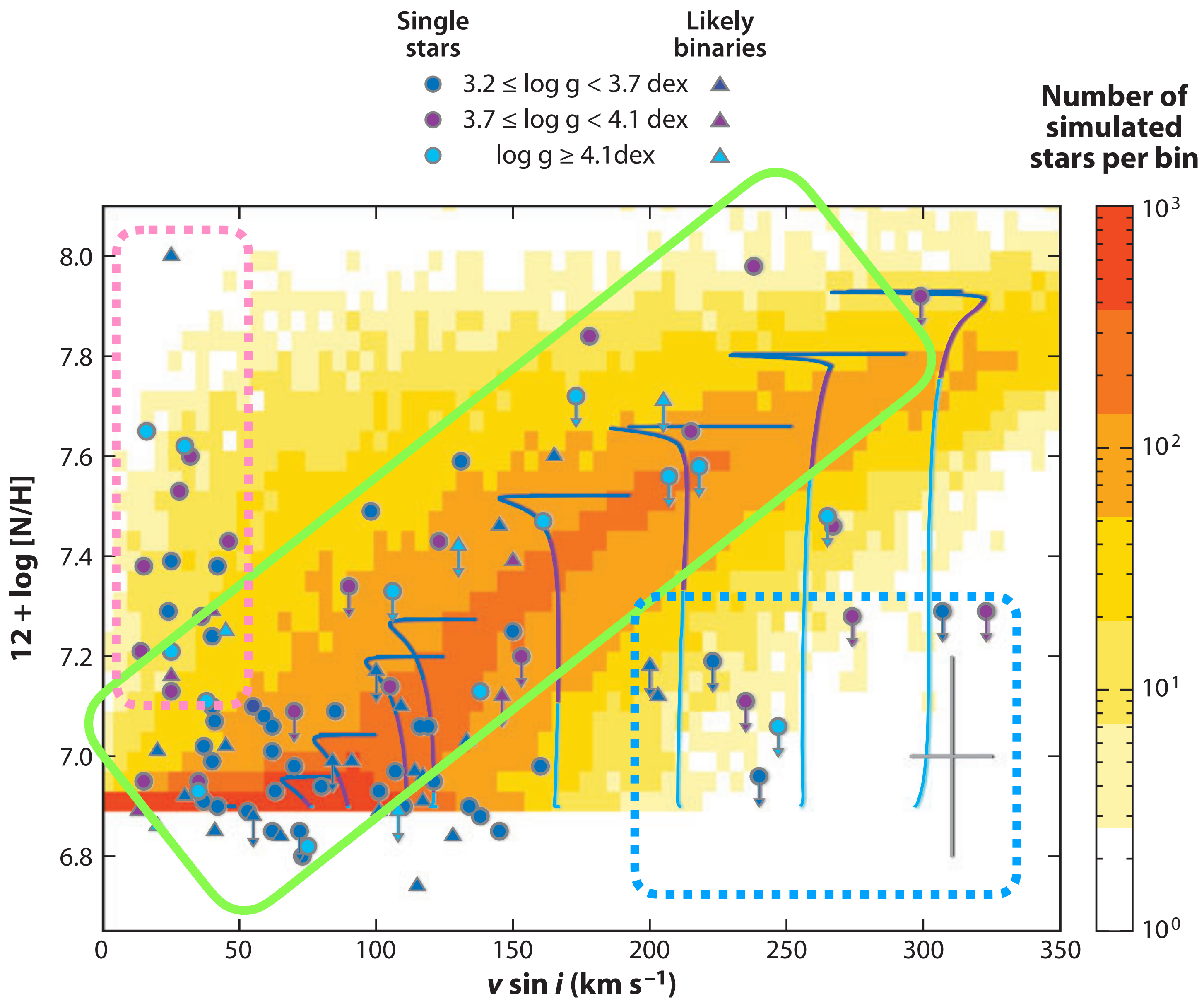
-The magnetic fields are likely to be produced by **the α-Ω dynamo**.

-GK giants are expected to have **weak surface magnetic fields** because of their large radii and slow rotations. (Landstreet 2004)

Hunter diagram

Rotational mixing can account for the **N enhancement in massive stars**.

Observed & modeled [N/H] vs v sin i relation



(Brott et al. 2011; Langer 2012)

-Majority of stars coincide with **the positive correlation** predicted by the theory.

-Meanwhile, two outliers exist; **slowly-rotating N-enhanced** stars and **fast-rotating N-normal** stars.

-The origins of these outliers are still debatable.

-Age/Mass effect?

-Binary?

-**Magnetic field**?

High magnetic incidence rate for galactic N-rich stars (Morel et al. 2008)