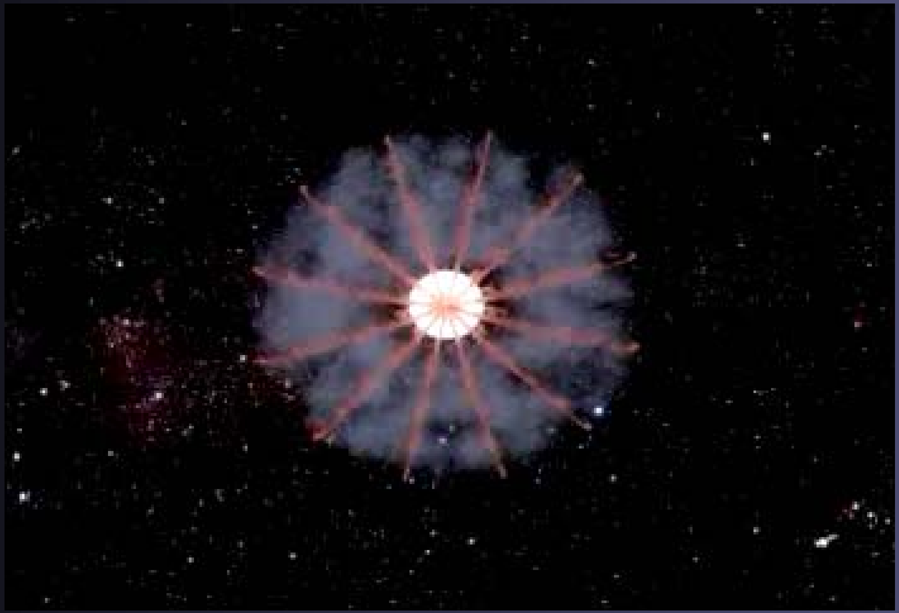
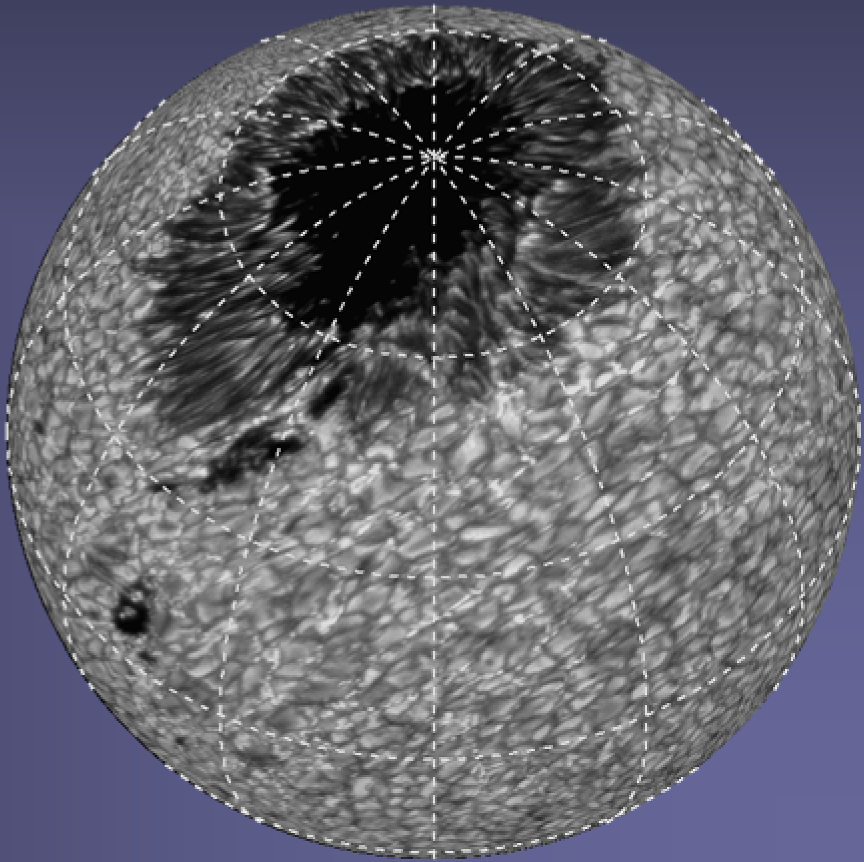
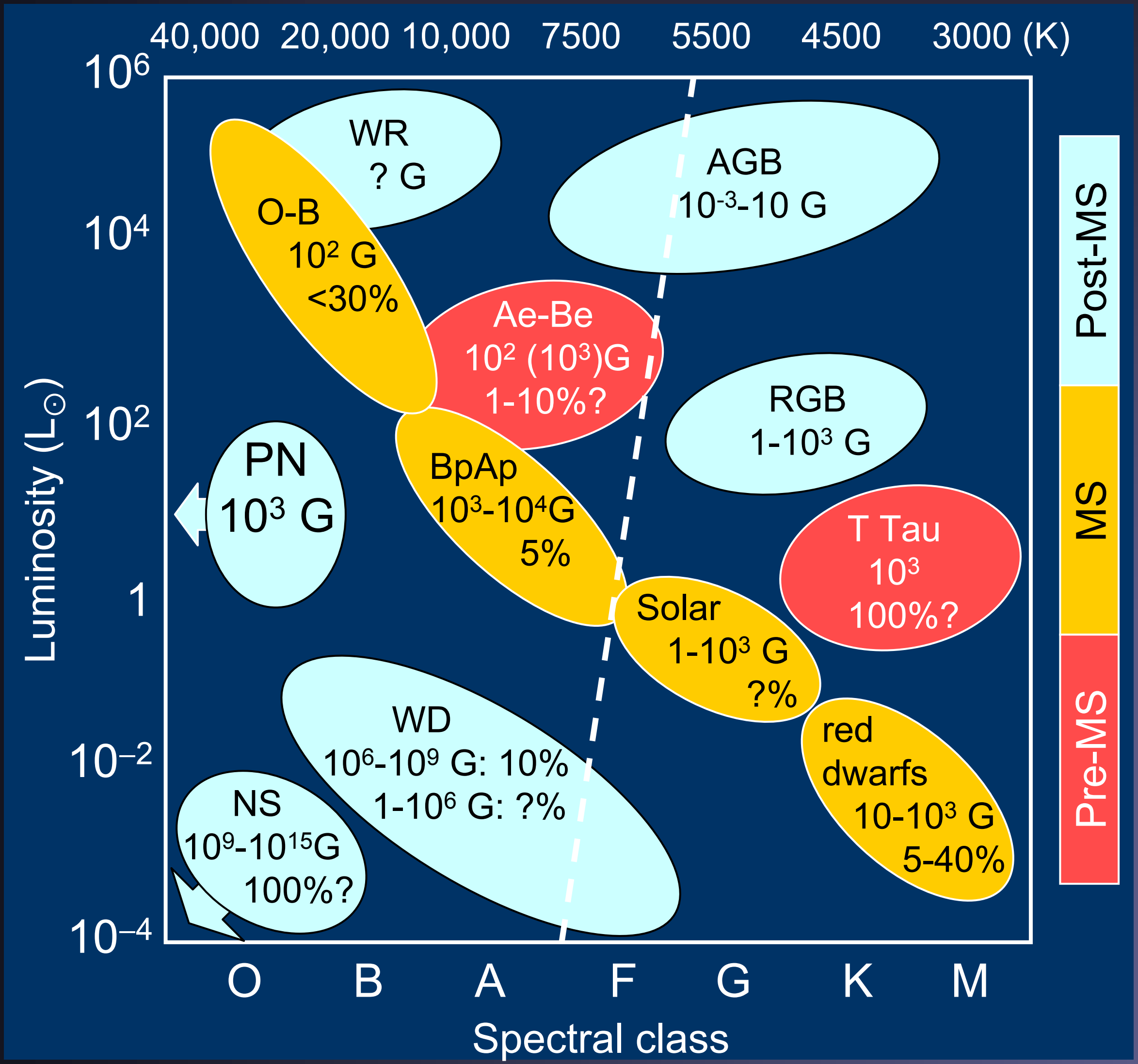
Magnetic fields in the Herzsprung-Russell diagram





Stellar magnetic fields



Magnetic fields are found on stars throughout the HR-diagram

Often they produce activity on the star or influence its evolution (e.g. of stellar rotation). See next lecture

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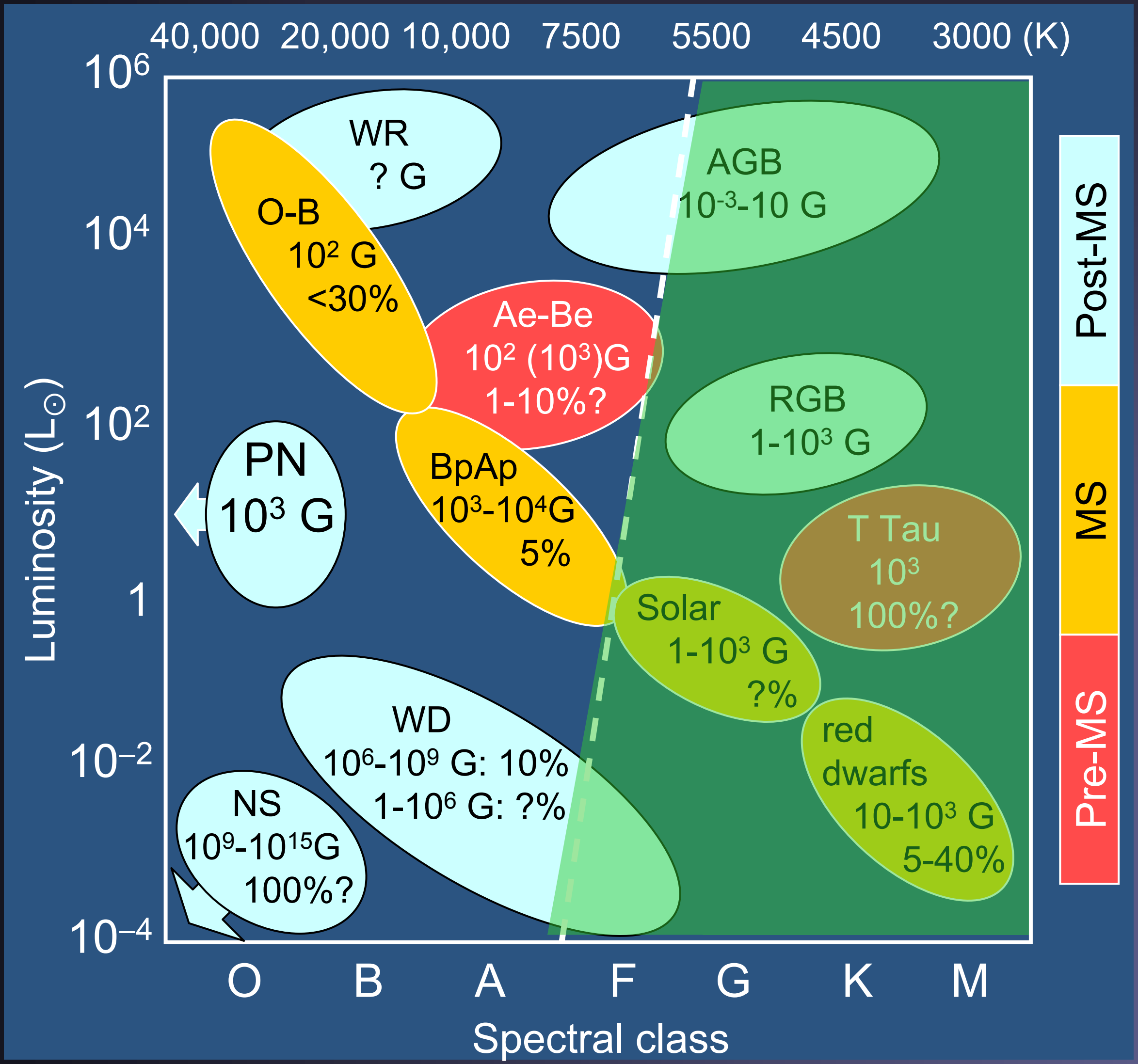
Stellar magnetic fields



Magnetic fields in green shaded part of HR diagram are likely produced by a dynamo and have a complex structure

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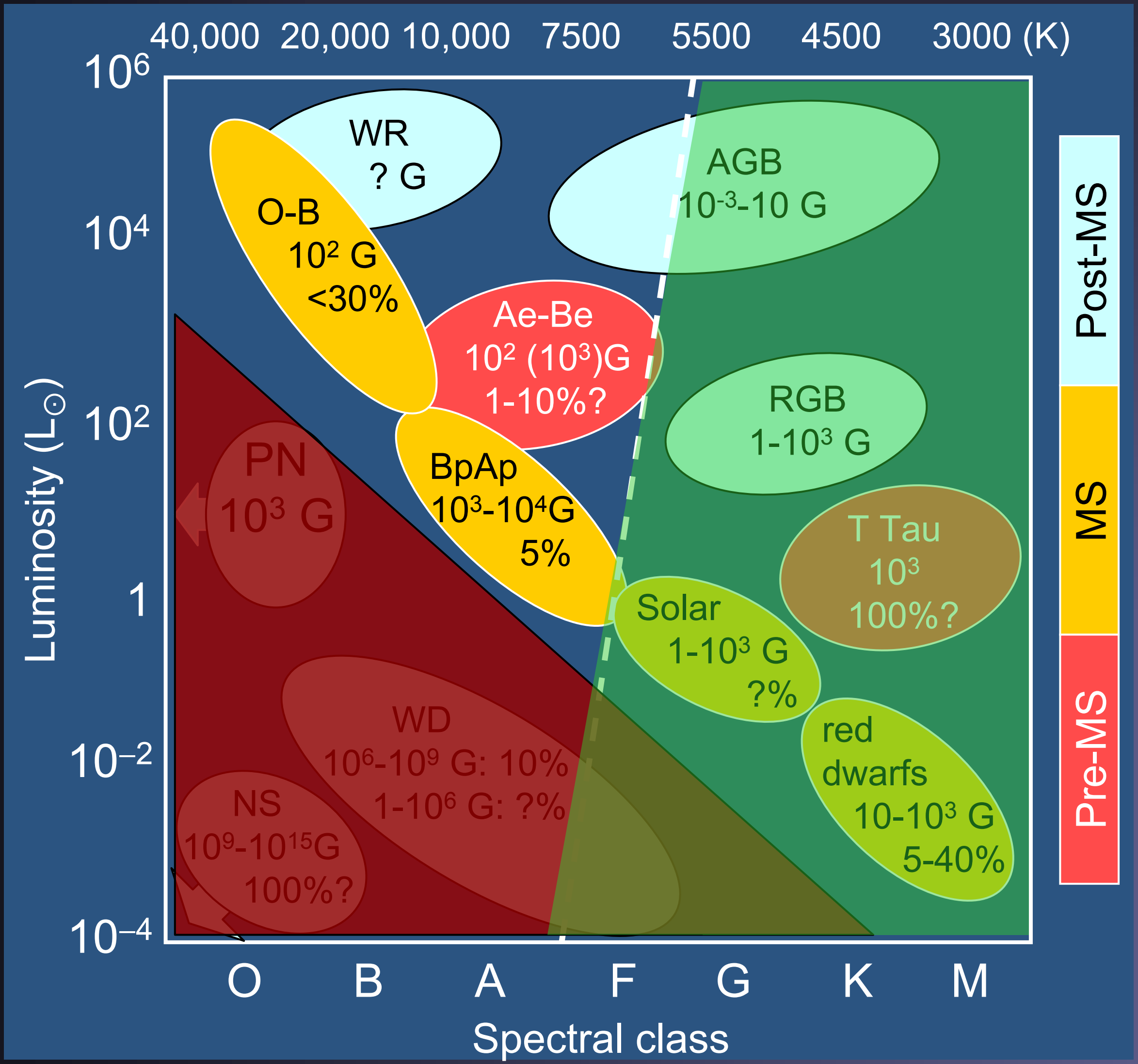
Stellar magnetic fields



Magnetic fields in degenerate stars and those on the path to degeneracy are not discussed here

Randomly discuss a few other parts of HR diagram

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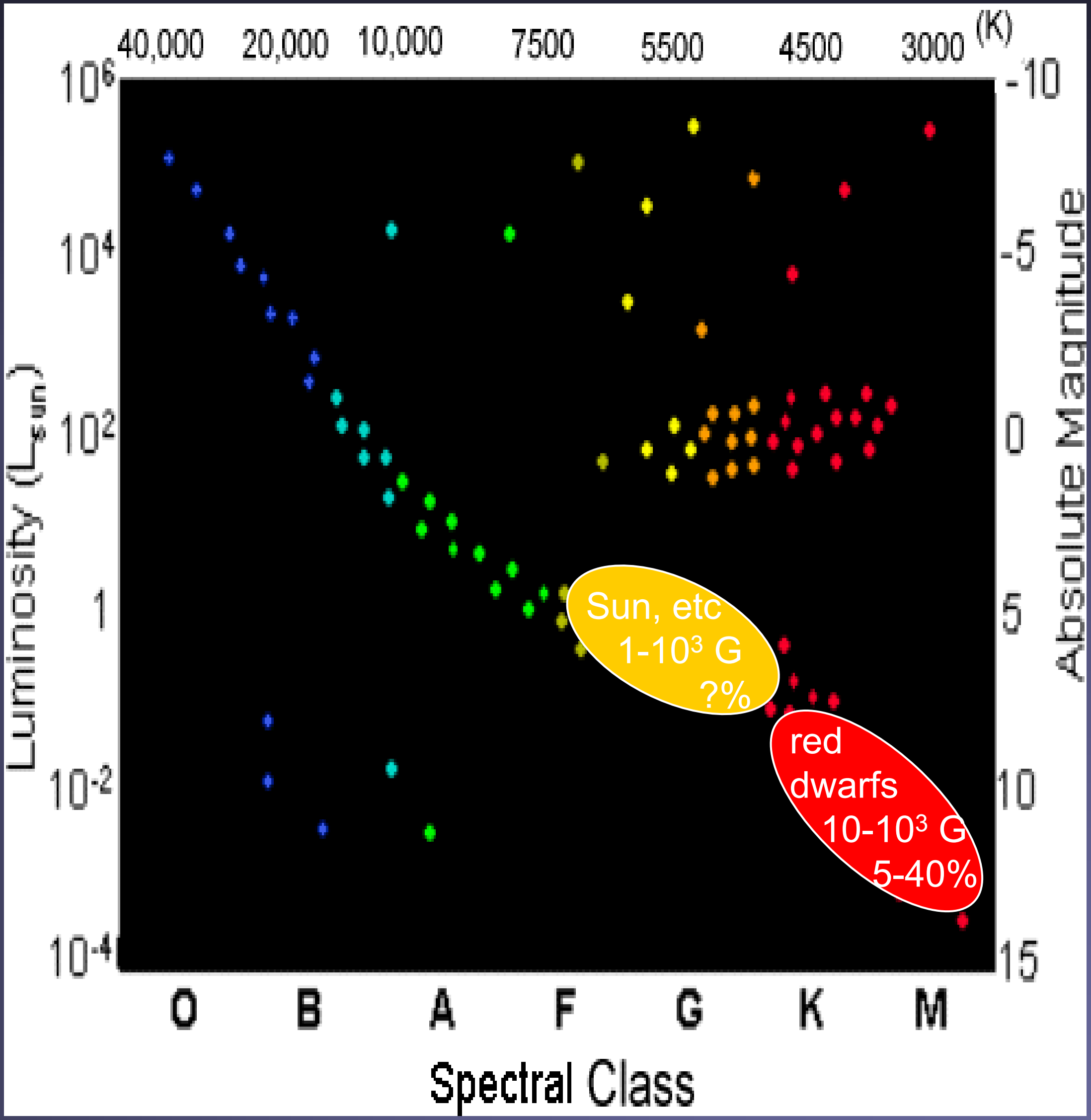
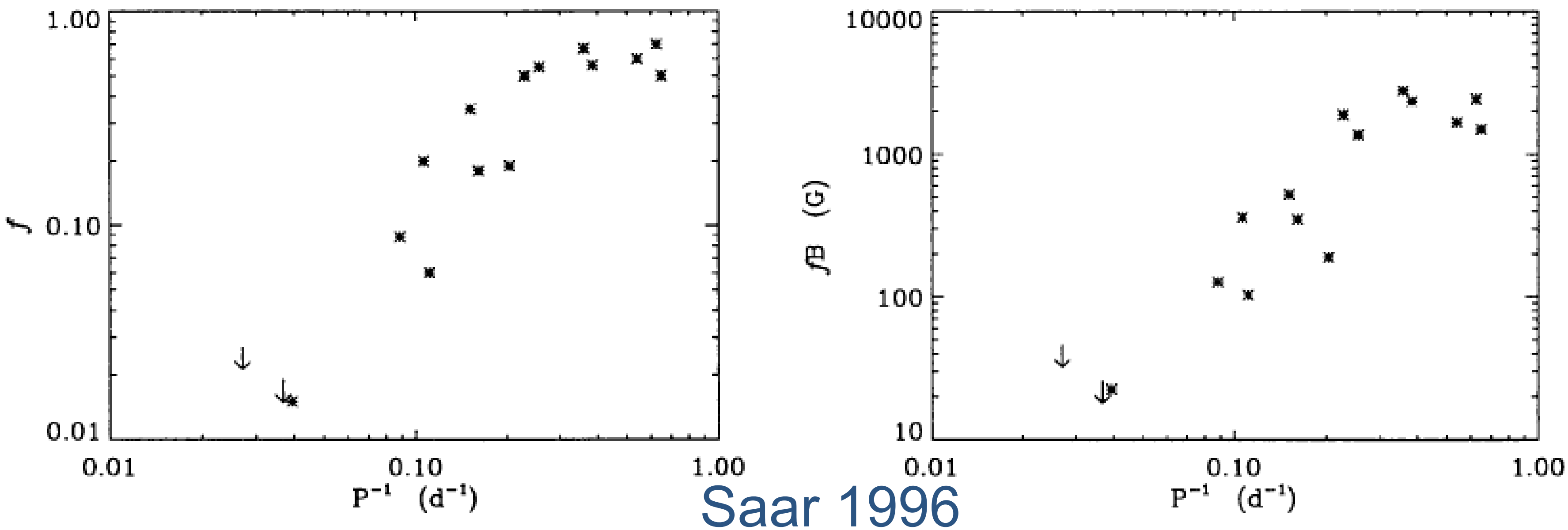
Cool stars

- Bf ≤ 10G – 10^3G
  |**B**| ~ 10^3 G
- Magnetic field complex on small scales
- Produced by dynamo in or below convection zone



Dependence of measured cool star fields on rotation rate



Saar 1996

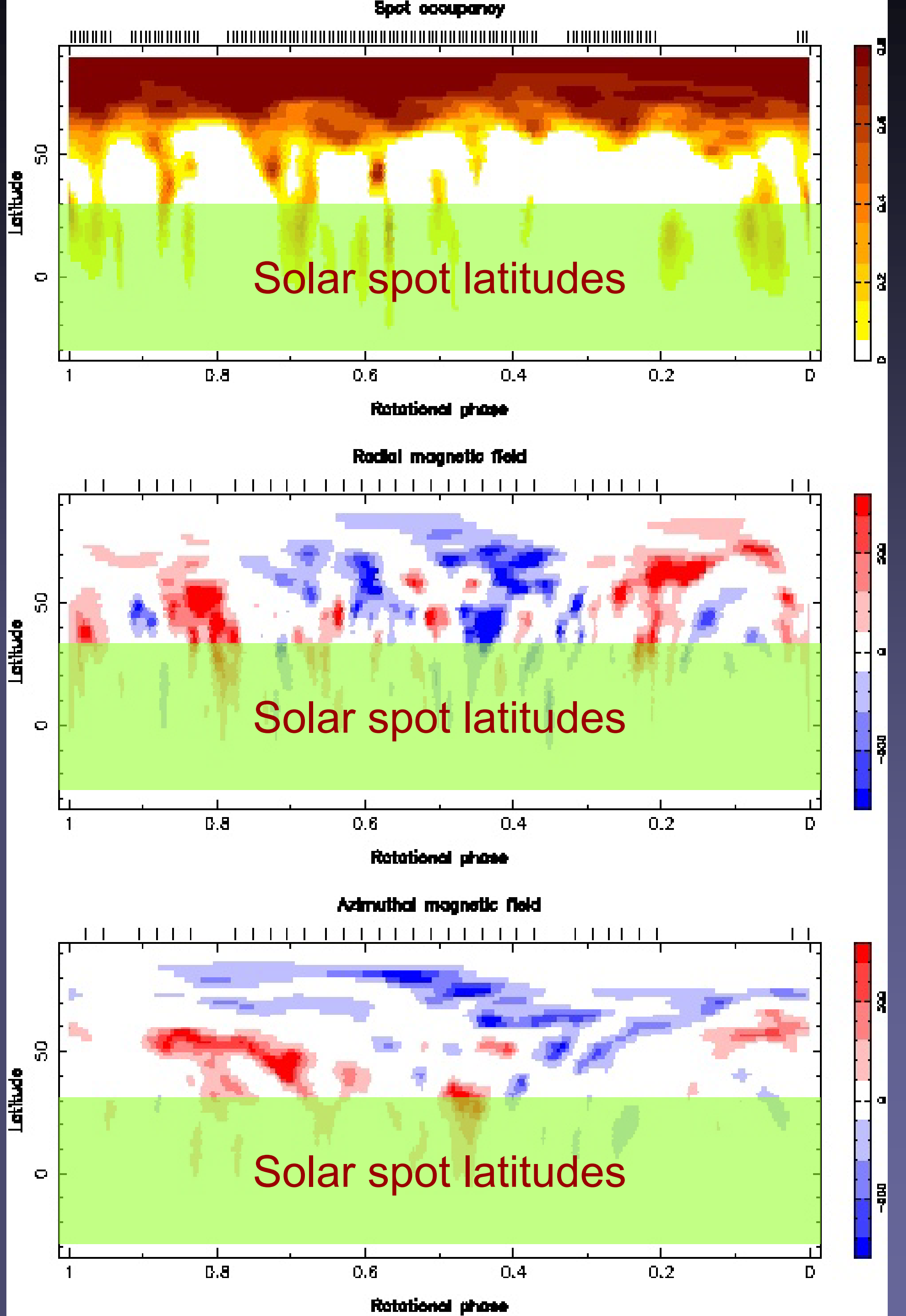
- Rotation rate has a dominant influence, just as it does for X-rays.
- f ~ fB ~ $P^{-1.8}$, with saturation for P < 3 days (?) (not all data show saturation)

Polar spots on active stars

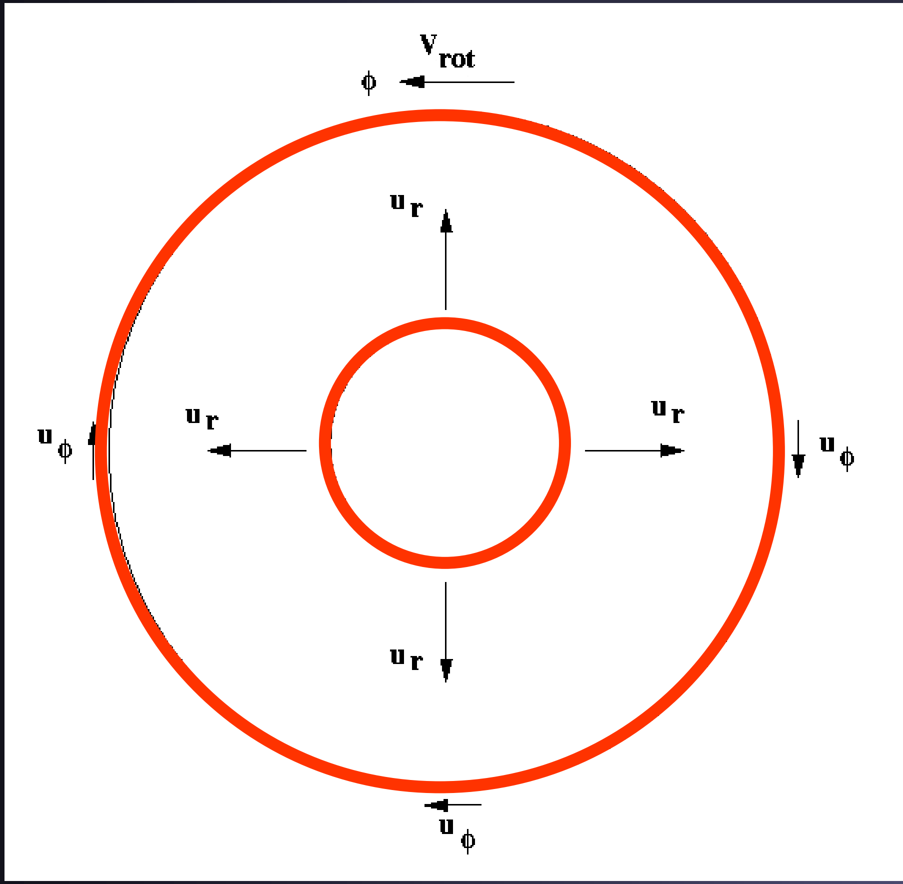
- Rapid rotators: E.g. AB Dor: Major spot at poles
- RS CVn stars: Large spots at or near poles

➔ Situation for rapid rotators is quite different than for sun

Donati et al.



The effect of rotation on buoyant flux tube



Buoyantly expanding flux ring

$$\mathbf{F}_{\text{Coriolis}} = 2\rho\Omega\,(u_\phi, -u_R, 0)$$

➔ restoring force

$$\dot{u}_\phi = -2\,\Omega\,u_R$$
$$\dot{u}_R = 2\,\Omega\,u_\phi$$
$$\rightarrow\; u_R, u_\phi \propto \sin(2\,\Omega\,t)$$

➔ inertial oscillations perpendicular to rotation axis

➔ amplitude depends on the strength of the buoyancy force

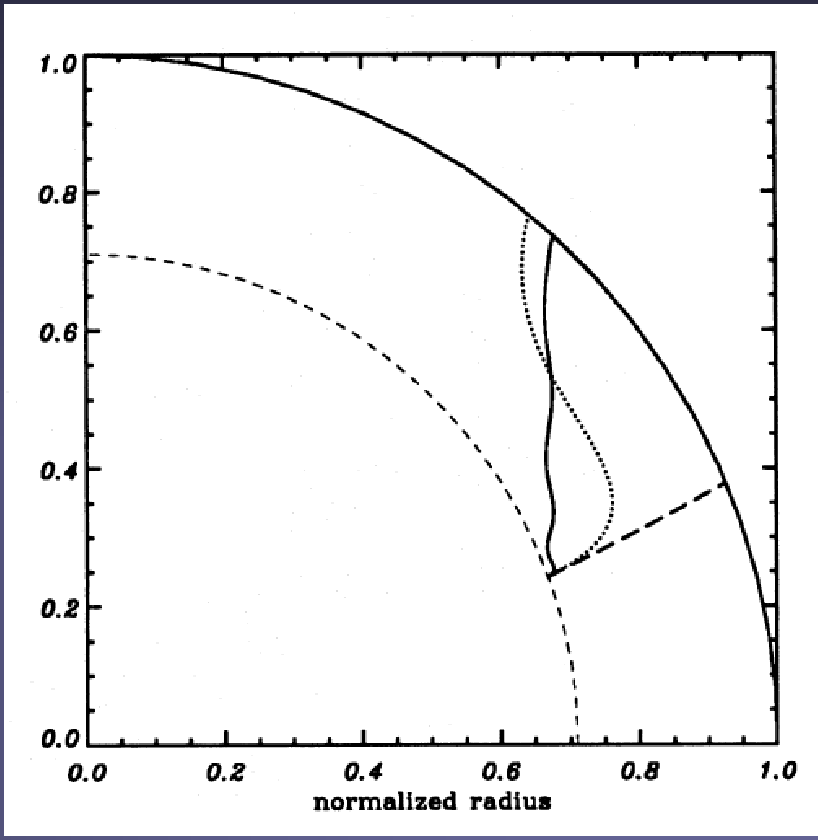
Polar spots

- Whether tube travels radially in the CZ or is deflected to poles depends on ratio of Coriolis frorce, F_C, to Buoyancy, F_B

$$\frac{|\ \mathbf{F}_\mathrm{C}\ |}{|\ \mathbf{F}_\mathrm{B}\ |} = \frac{2\rho\,\upsilon_\mathrm{rise}\,\Omega}{B^2\ /(8\pi H_p)} \propto \frac{2\Omega H_p}{\upsilon_\mathrm{A}}$$

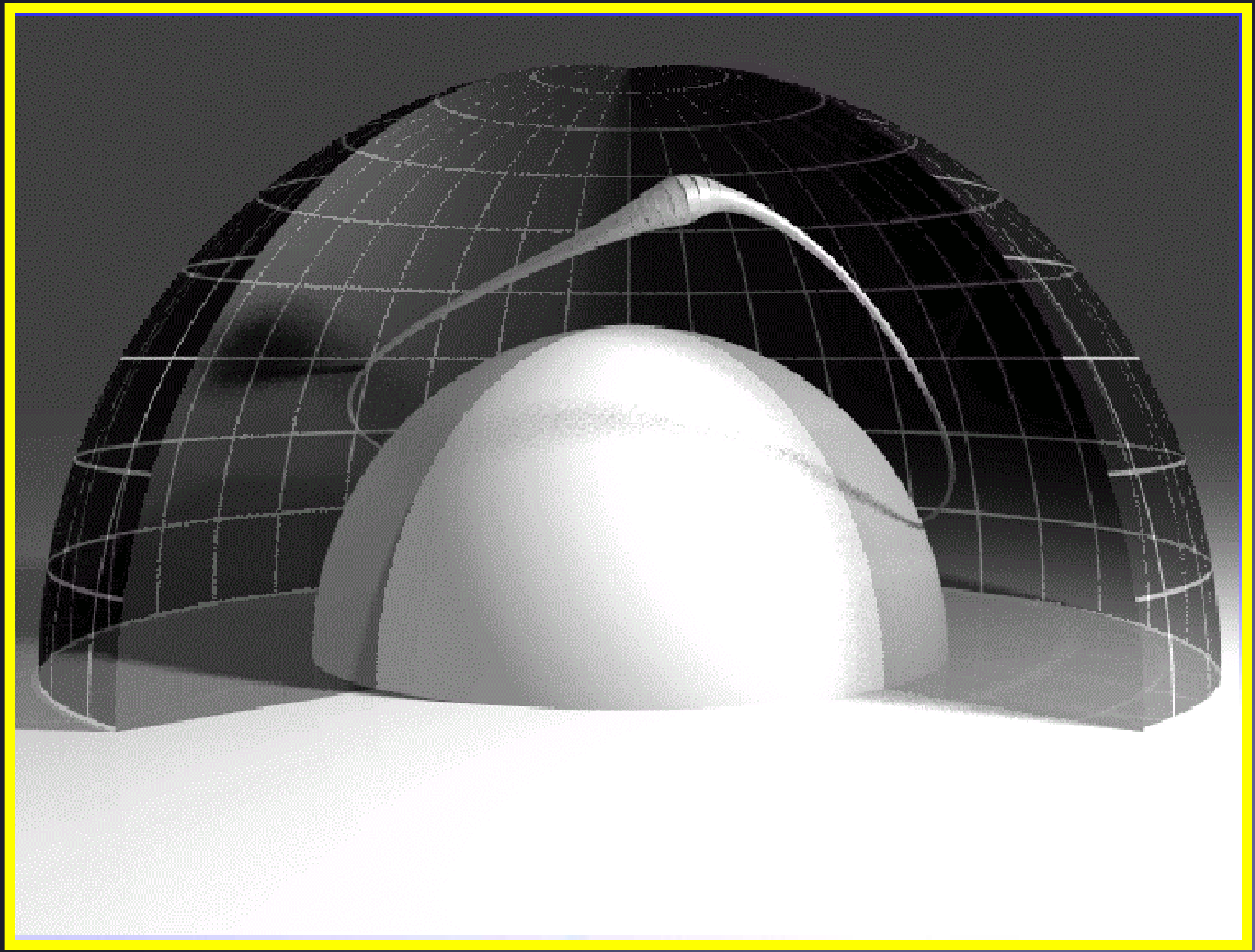
ρ = density in tube, H_p = pressure scale height, Ω = rotation rate

- For $\Omega = \Omega_\odot$: $F_C < F_B$ – – – – -
- For $\Omega = 3\Omega_\odot$: $F_C > F_B$ ....
- For $\Omega = 10\Omega_\odot$: $F_C >> F_B$ ———



Schüssler & Solanki 1992

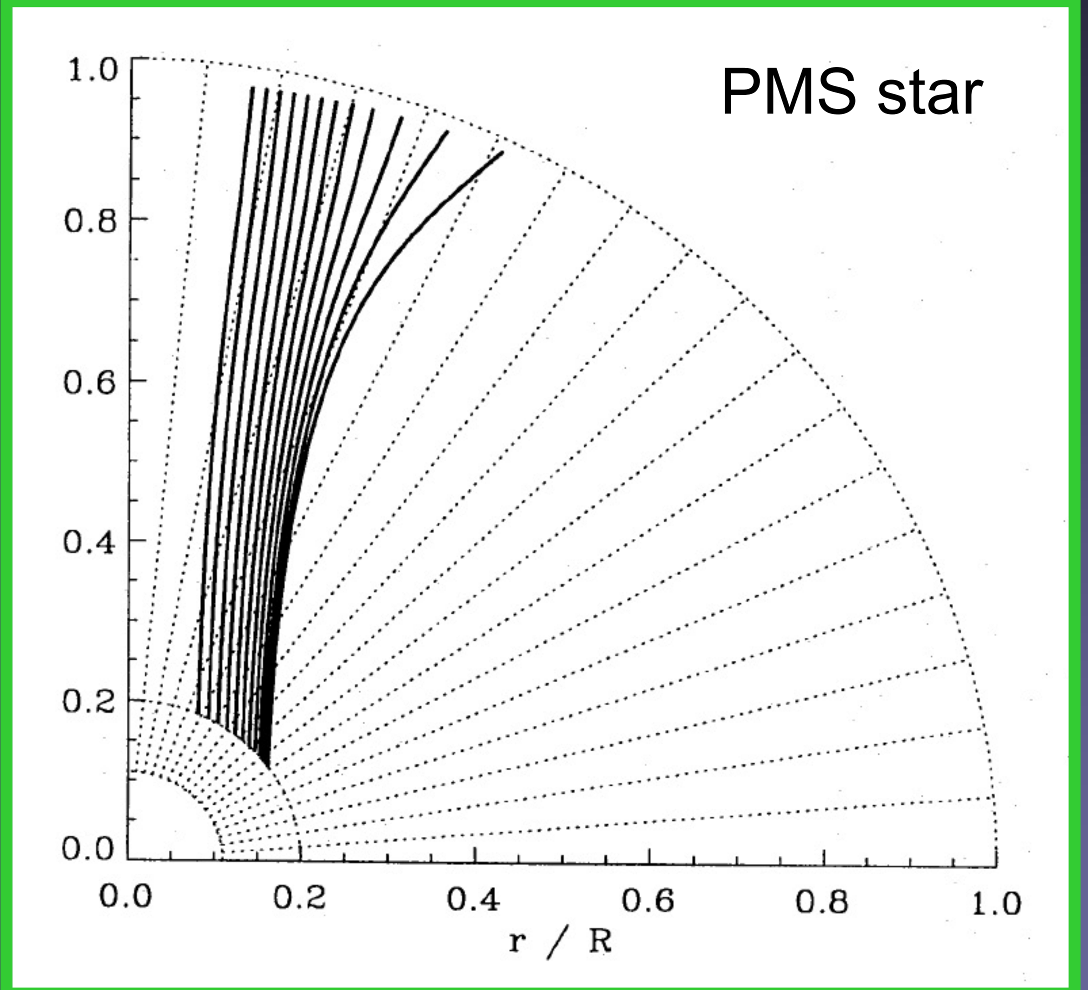
A sources of high latitude spots



Schüssler & Solanki 1992; Schüssler et al. 1996; Granzer et al.

Truly polar spots only for stars with very deep convection zones

- Assumption: dynamo resides at interface to radiative zone also for deep convective envelopes
- Flux tubes rising || to rotation axis appear very close to pole



Schüssler et al. 1996

What determines the emergence latitude?

Multiplicity

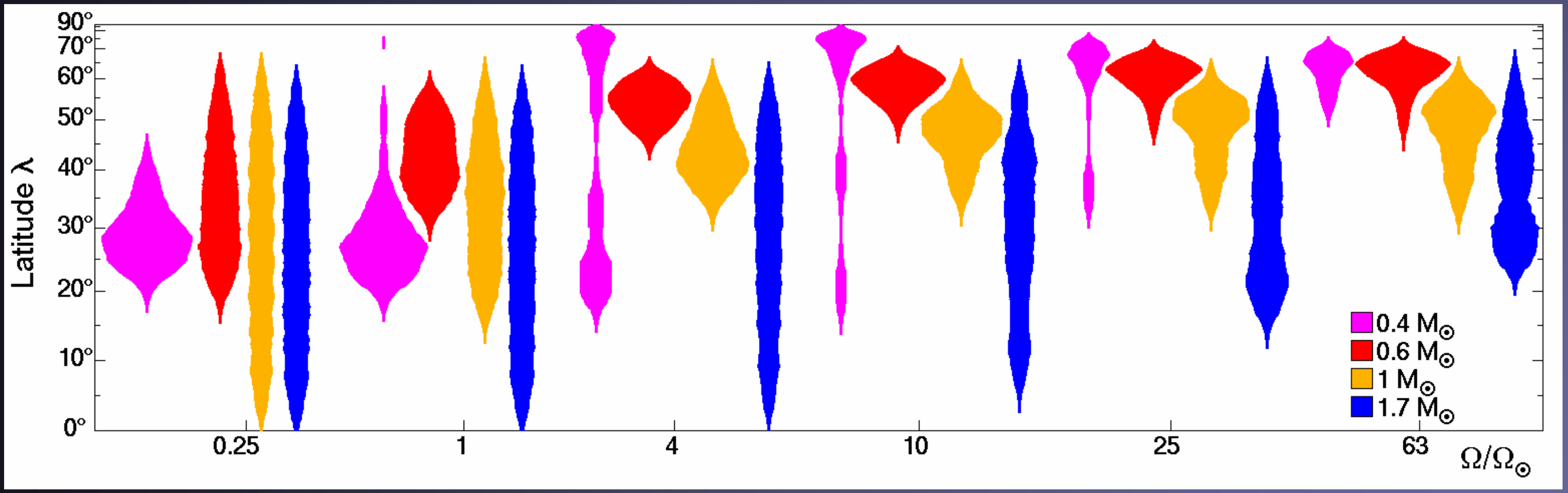
Age

Mass

Rotation
➔ Coriolis force

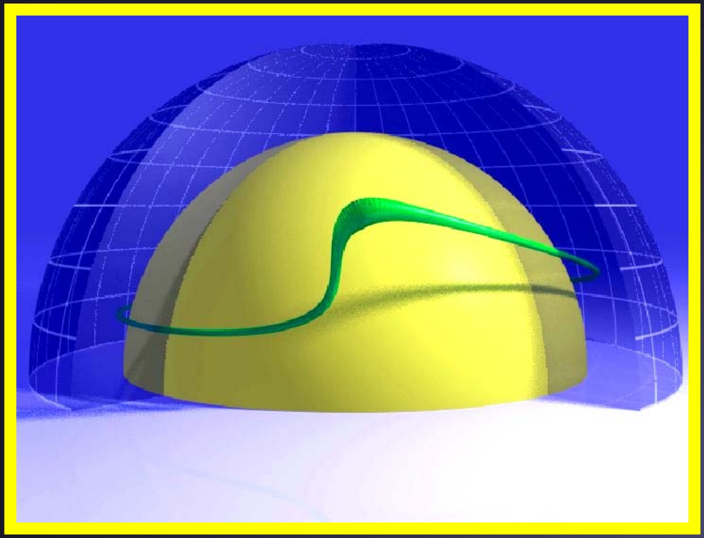
Core size & B
➔ curvature force

Gravity
➔ buoyancy force



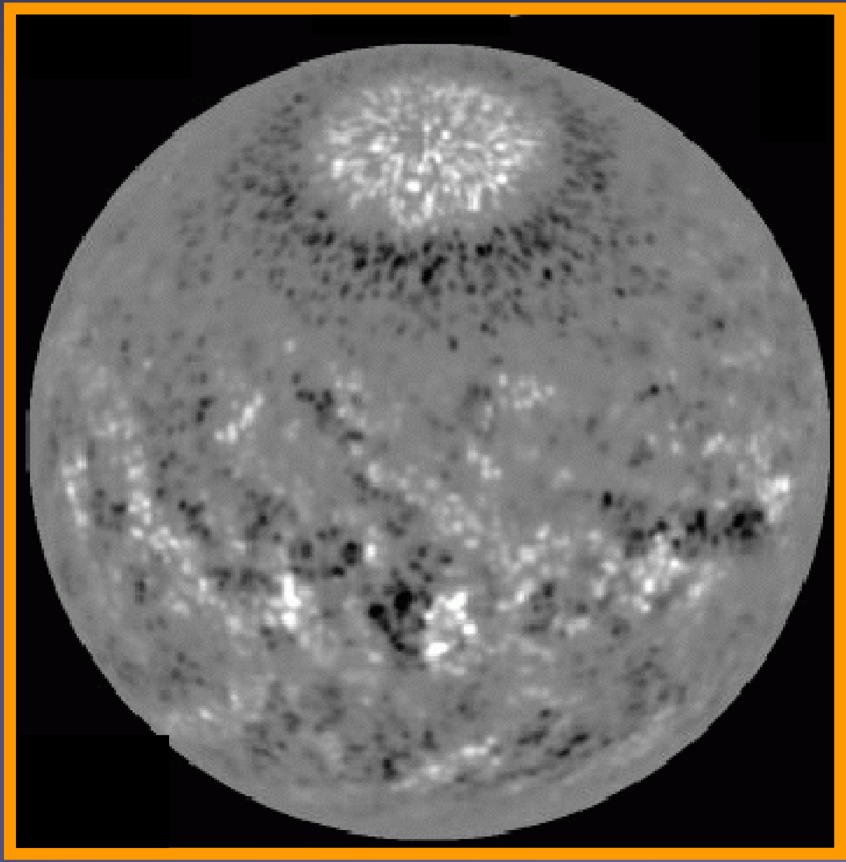
Pre-main-sequence stars (Granzer, 2000)

Alternative sources of high latitude spots

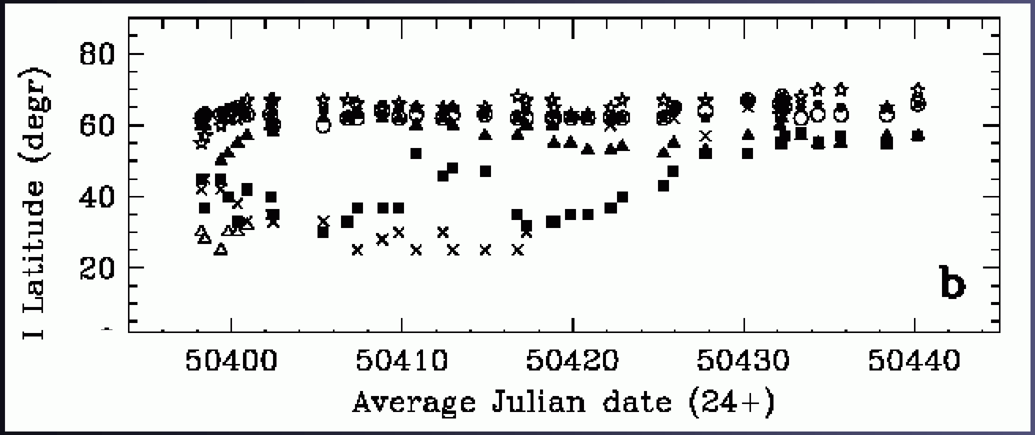


Schrijver & Title 2001

Meridional flow

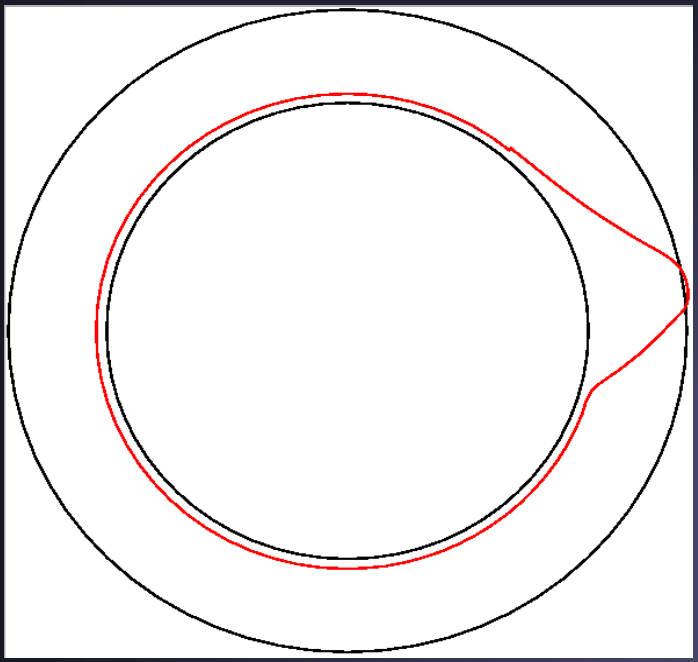


Latitudinal spot drift on HR1099

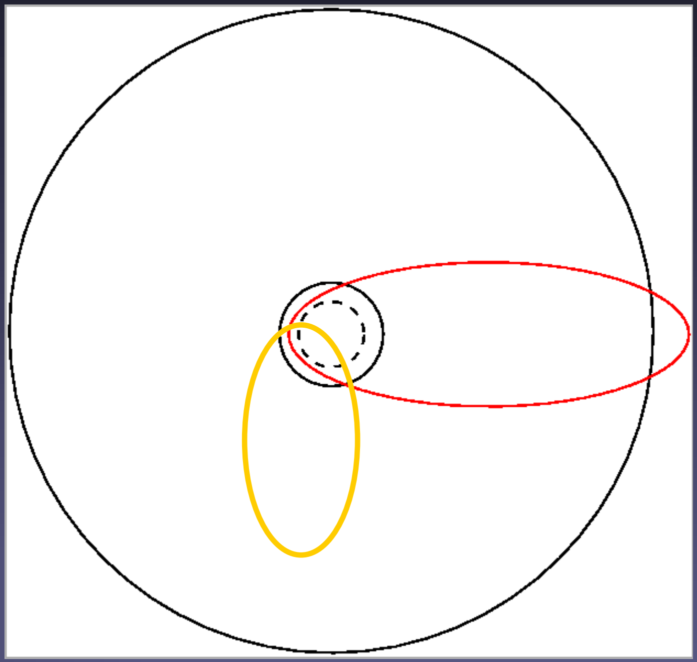


(Strassmeier & Bartus, 2000)

Eruption vs. trapping: buoyancy vs. curvature



Main-sequence star



Giant

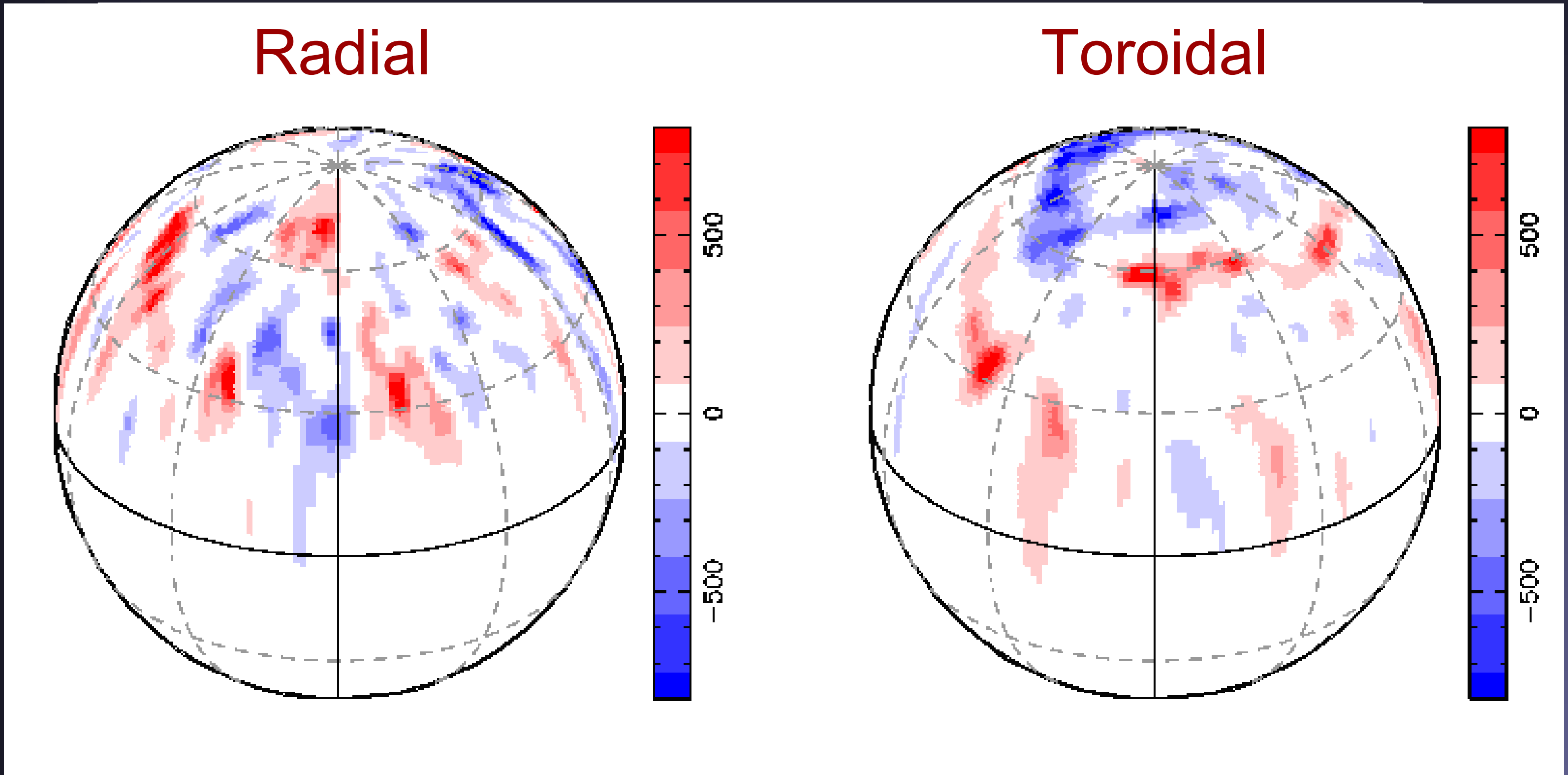
Sufficiently small initial radius:

➔ curvature force increases more rapidly than buoyancy force

➔ new equilibrium within the convection zone

Trapping for $R_{tube} / R_{star} \lesssim 0.2$

Radial vs. toroidal magnetic field



AB Dor: toroidal field > radial and meridional field

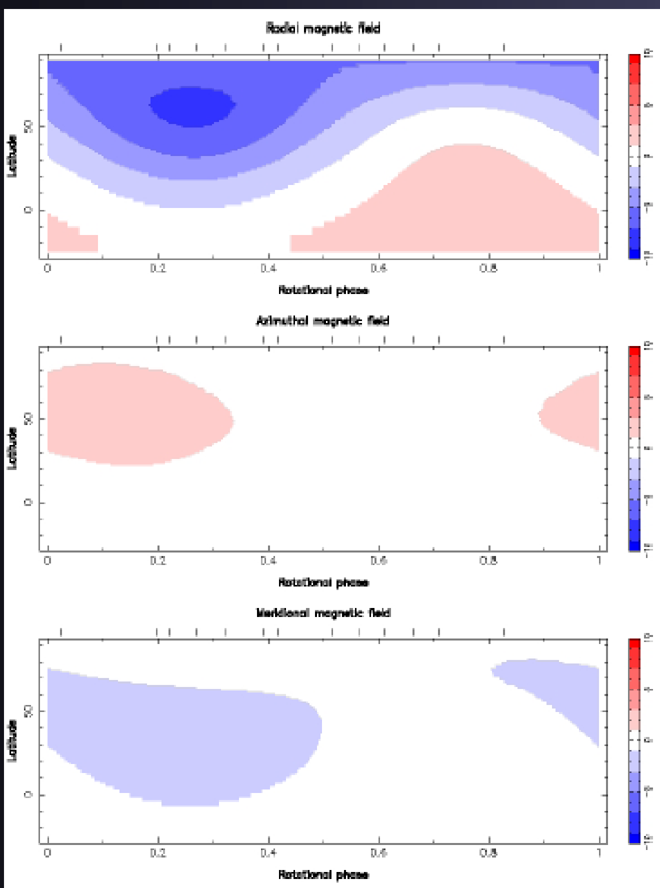
Typical of ZDI images of rapid rotators.

BUT: Solar field is dominantly radial.

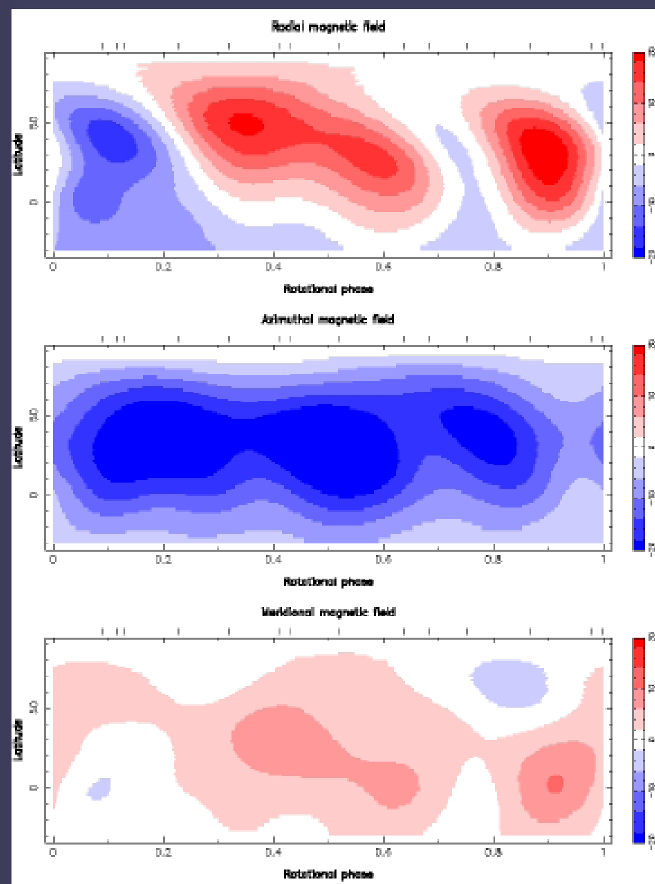
Lower MS stars

The Sun displays mainly a radial field (due to evacuation, FTs are buoyant and vertical). Are the large toroidal fields found in ZD Images of cool stars real or an artifact?

Poloidal (P~20d)



Toroidal (P~10d)



Radial

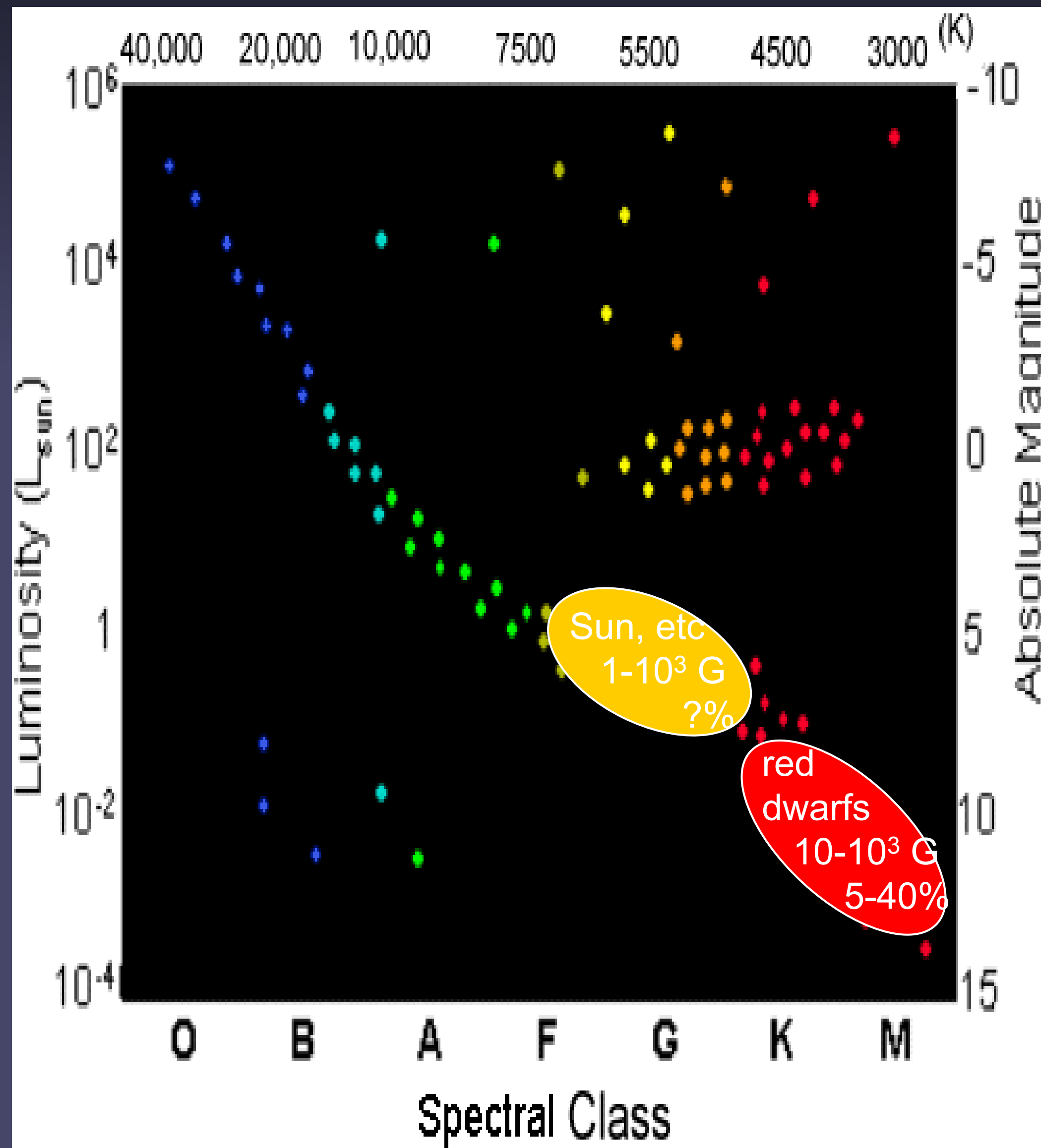
Toroidal

Meridional

(Petit et al. 2008)

Lower MS stars: M,L,T dwarfs

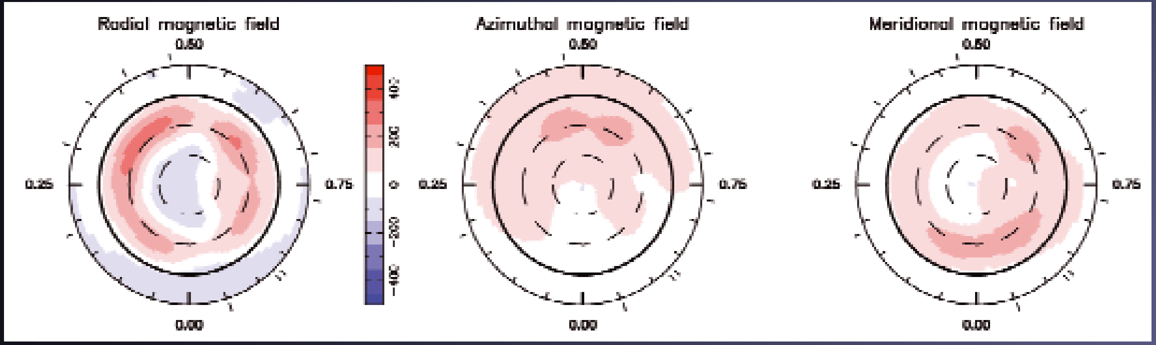
- Zeeman effect Fe I (IV)
- FeH, TiO, CaH, etc. (IV)
- Onset of distributed dynamo
  - M4 (expected), M8 (observed?)



M dwarfs: topology

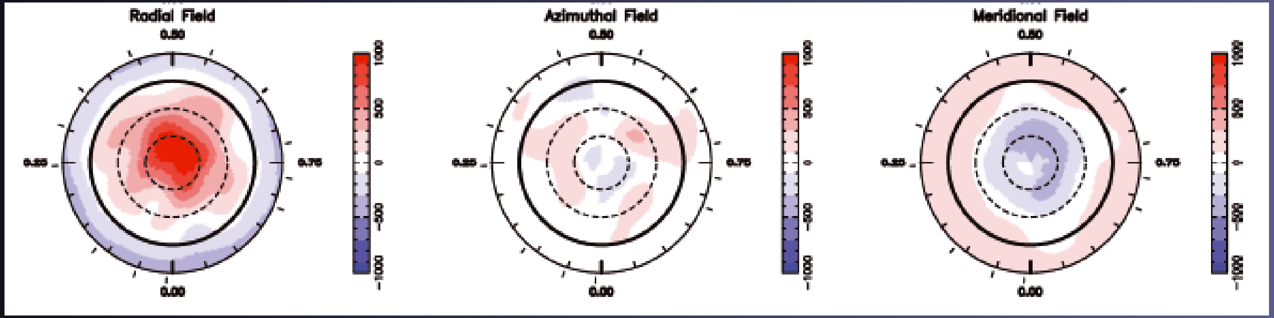
- Main question: what changes when going to a fully convective star? Can't have an overshoot layer dynamo!
- ZDI with LSD IV (Donati et al. 2008; Morin et al. 2008)

M1: toroidal (+non-axi-symm-poloidal)



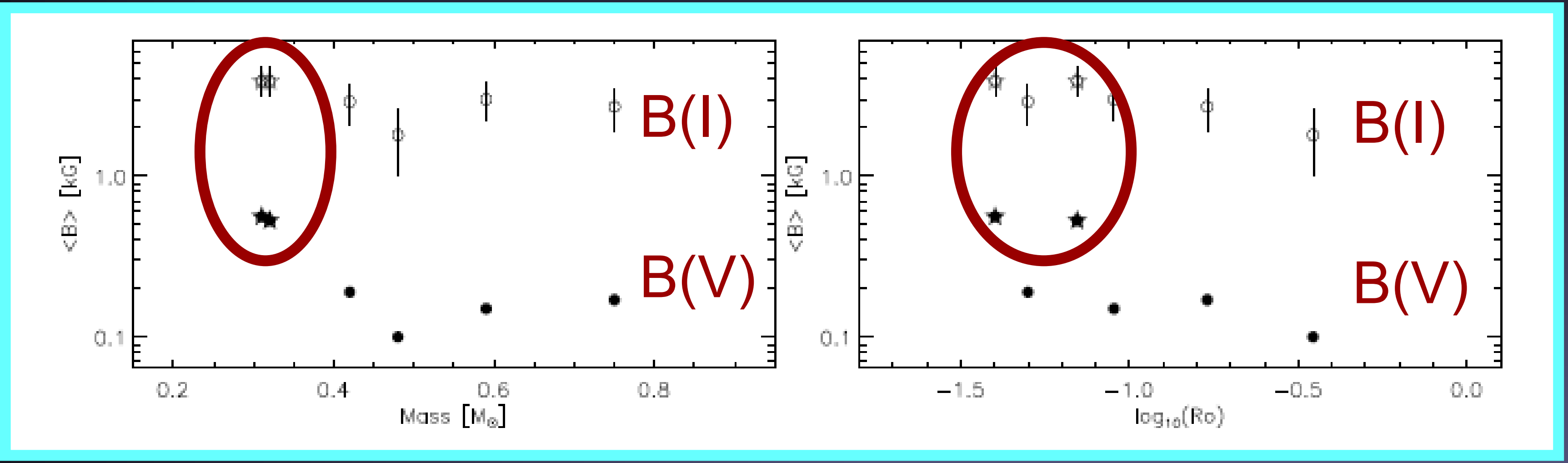
M1: T_{eff}=3950K bipolar region with B_r in cool spots

M4: axisymmetric poloidal



M4: T_{eff}=3750K bipolar region with B_r in cool spots

How much flux does ZDI miss?



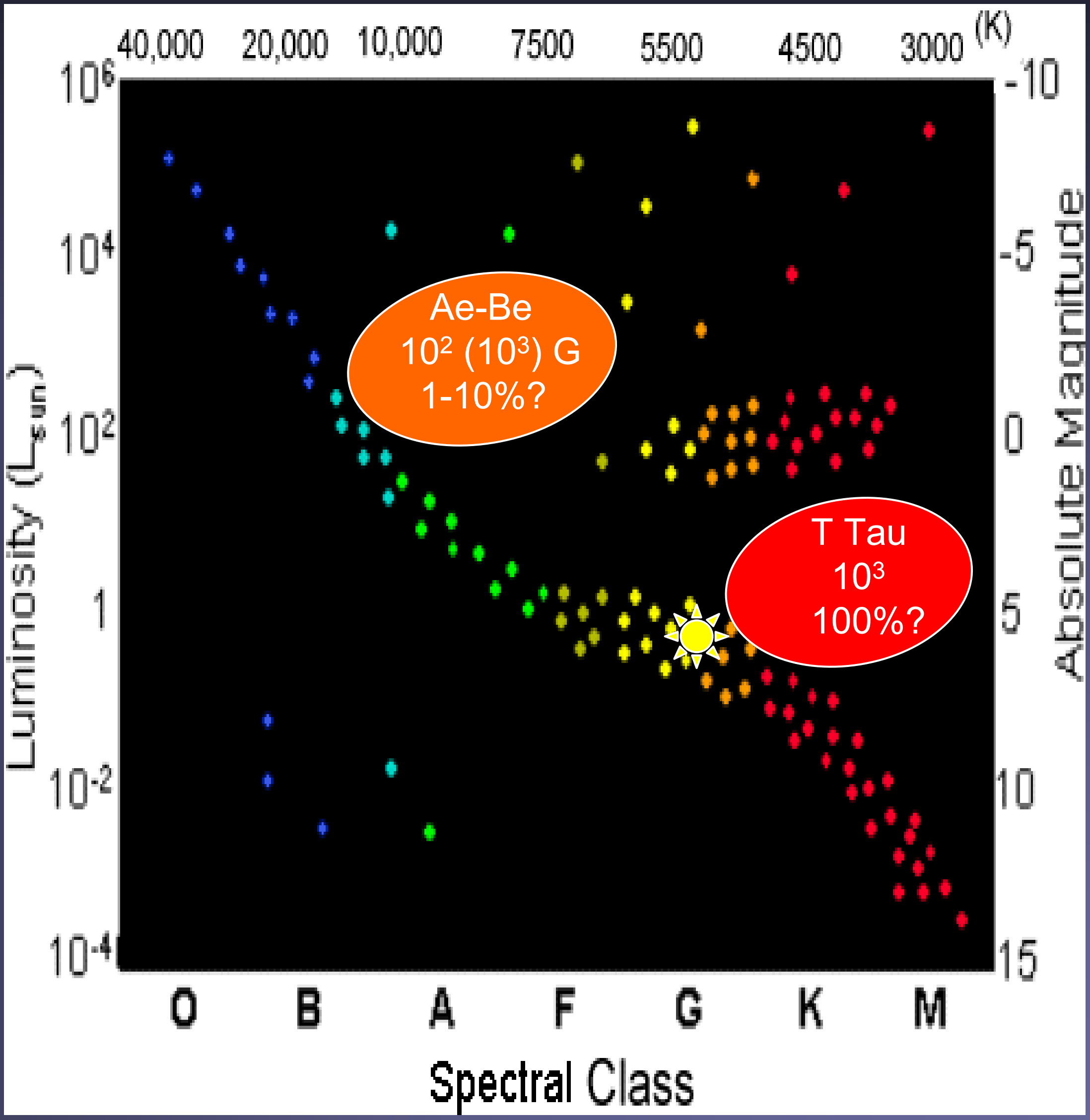
Stars: fully convective stars

A. Reiners

- For G, K and early M stars ZDI missed up to 95% of magnetic flux
- For fully convective M dwarfs this fraction drops to 85%: signs of a structuring on larger scales?

Pre-MS stars: T Tauri stars

- Dynamo action (distributed?)
- activity & kG B-fields with filling factor of almost unity. Diff. from sun-like stars (C.Johns-Krull)
- topology of field from ZDI with LSD

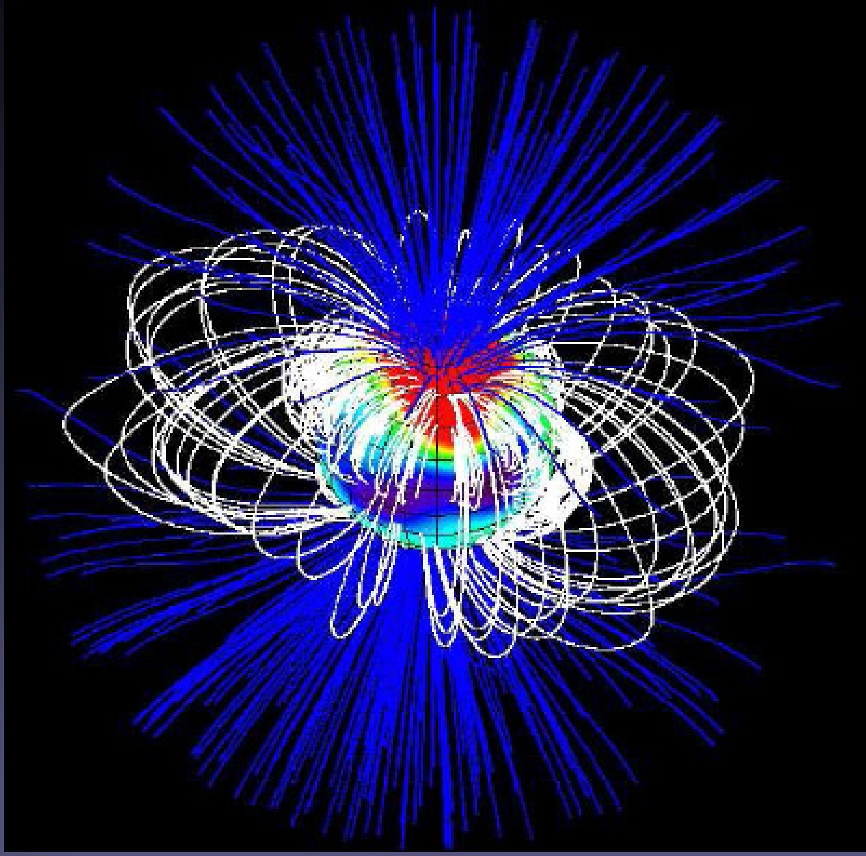


Imaging a cTTS

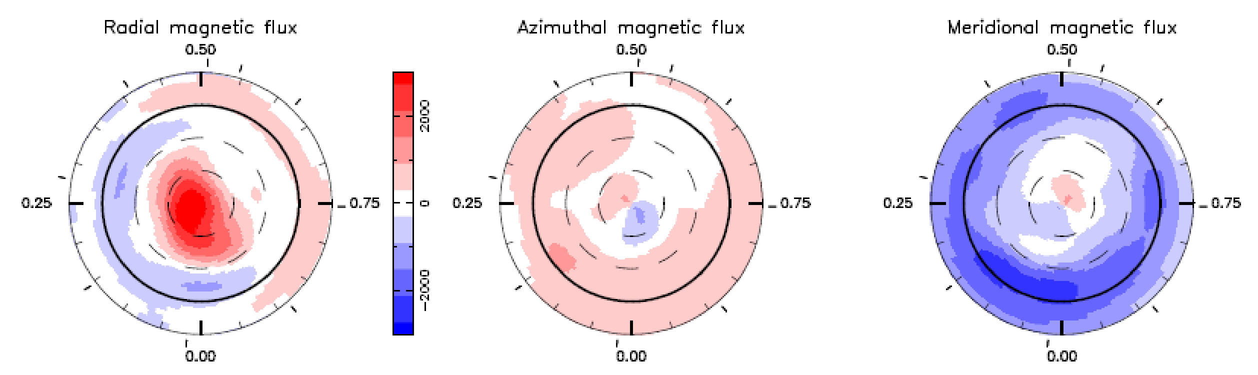
Clear bipolar signature (1.2 kG) with an additional 1.6 kG octupole.

Explains large filling factors deduced from Stokes I spectra

Accretion takes place over the pole

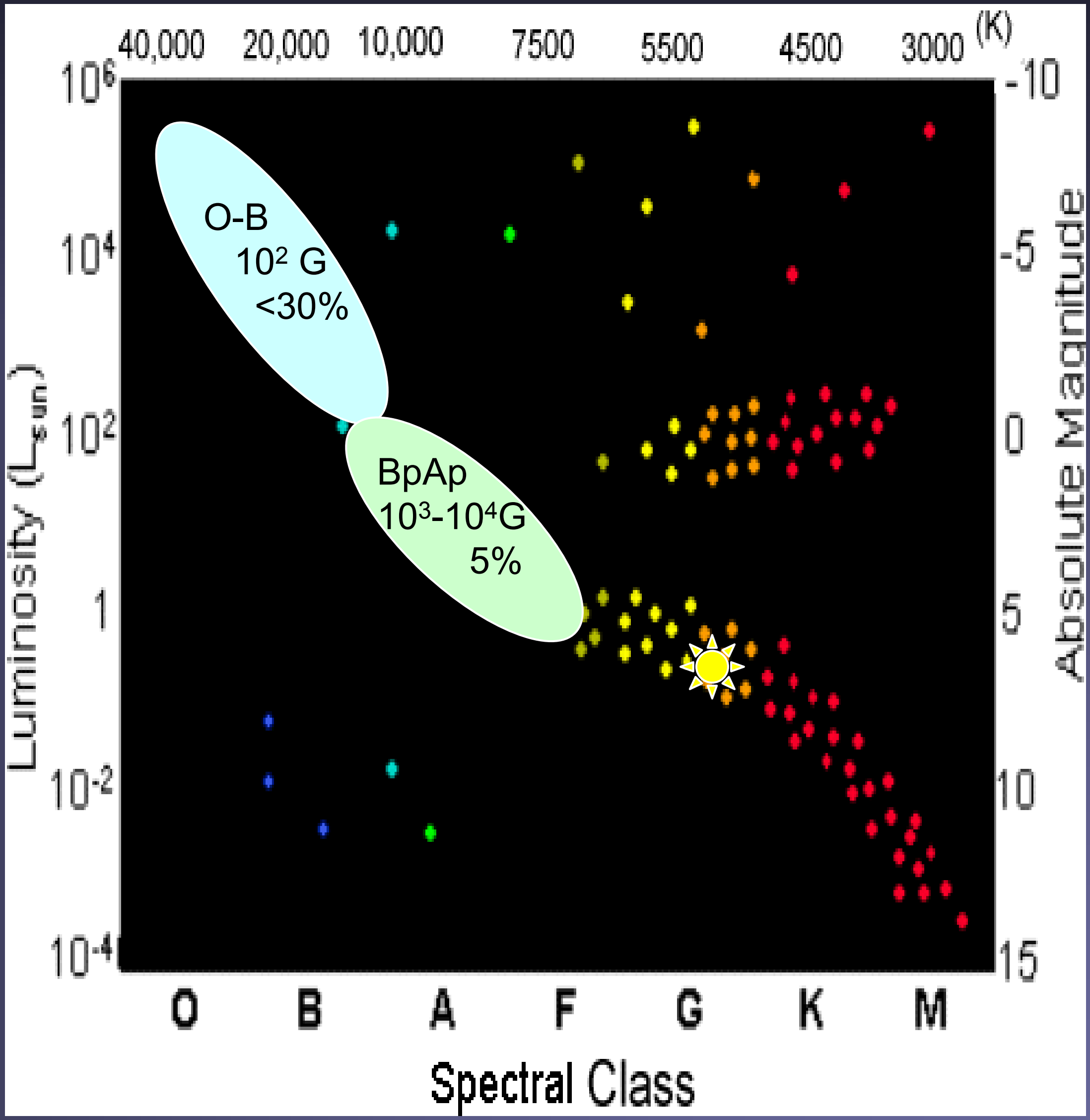


Low mass cTTS BP Tau (Donati et al. 2008) $M=0.7M_{\odot}$



Upper MS stars: Ap and Bp stars

- Bf~|**B**|~10^3–10^4 G
- Dipoles (some multipoles)
- Fossil fields?
- Progenitors of magnetic WDs?



Ap and Bp stars

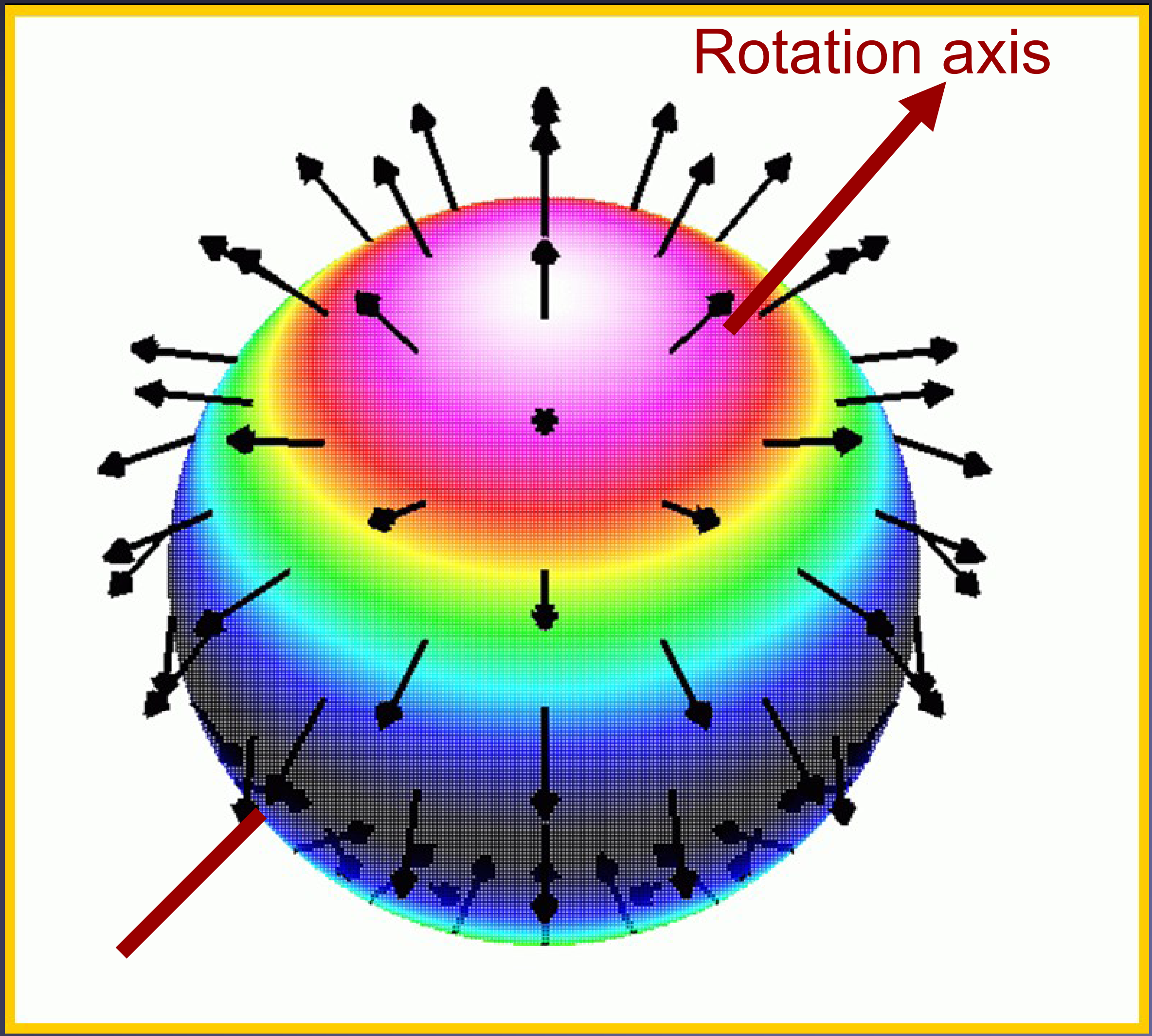
- A few % of stars with 2-3 $M_\odot$ show (static) magnetic fields ranging from 60 G to 30,000 G in different stars (lower limit is detection limit)
- These “magnetic Ap stars” show very unusual atmospheric chemistry – underabundant He, O; overabundant Si, Cr, Sr, rare earths....
- Surface abundances vary over surface and with height in atmosphere!
- Ap stars rotate unusually slowly for these spectral types, with periods of 0.5d to many years

Oblique rotator model

Arrows show field vectors of roughly axi-symmetric field

Coloured bands indicate field strength variations over surface

Star rotates about axis not aligned with dipole axis



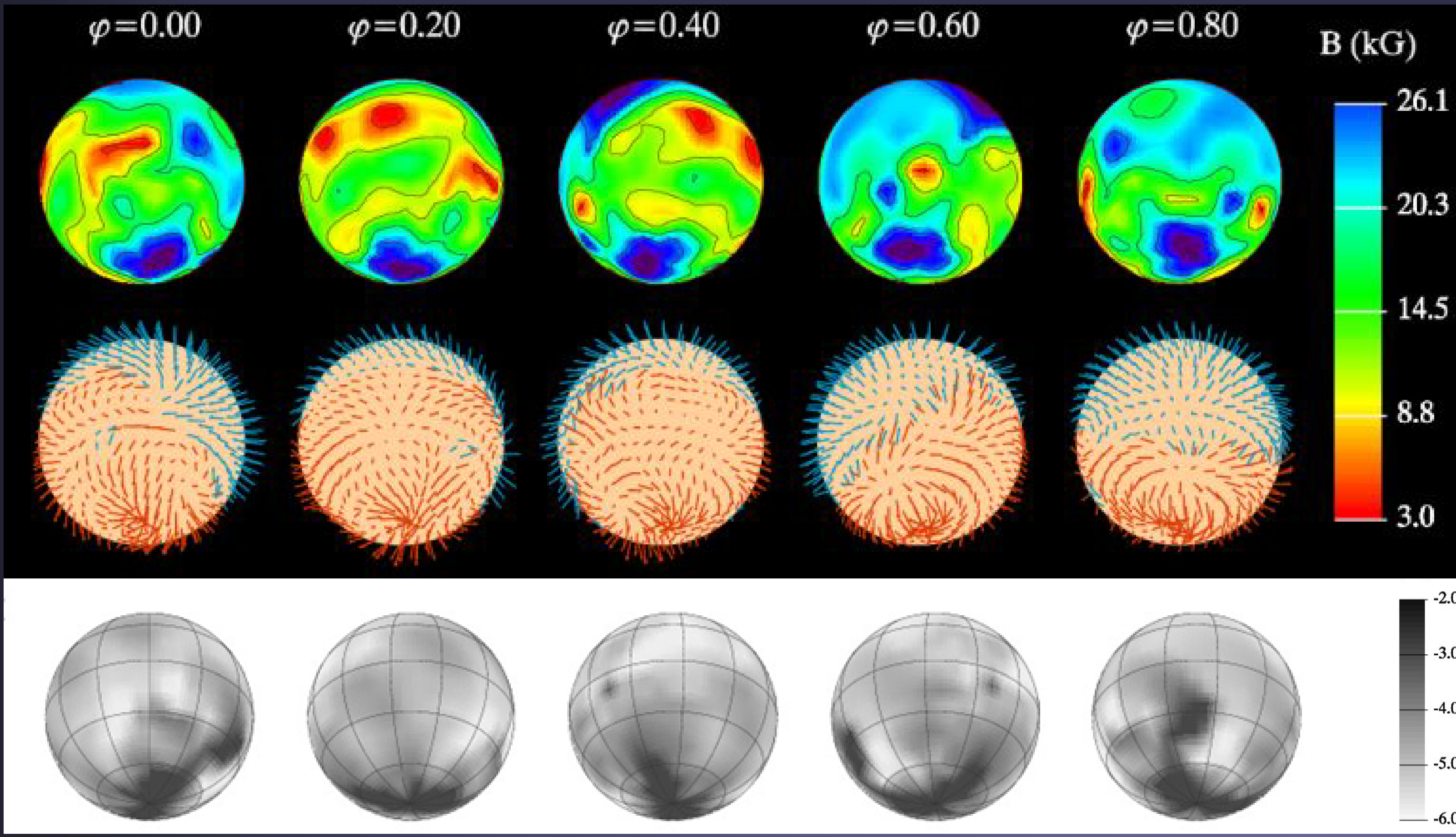
Zeeman Doppler map of 53 Cam

- ZDI based on IQUV. Also determine abundance map

B

Direction of **B**

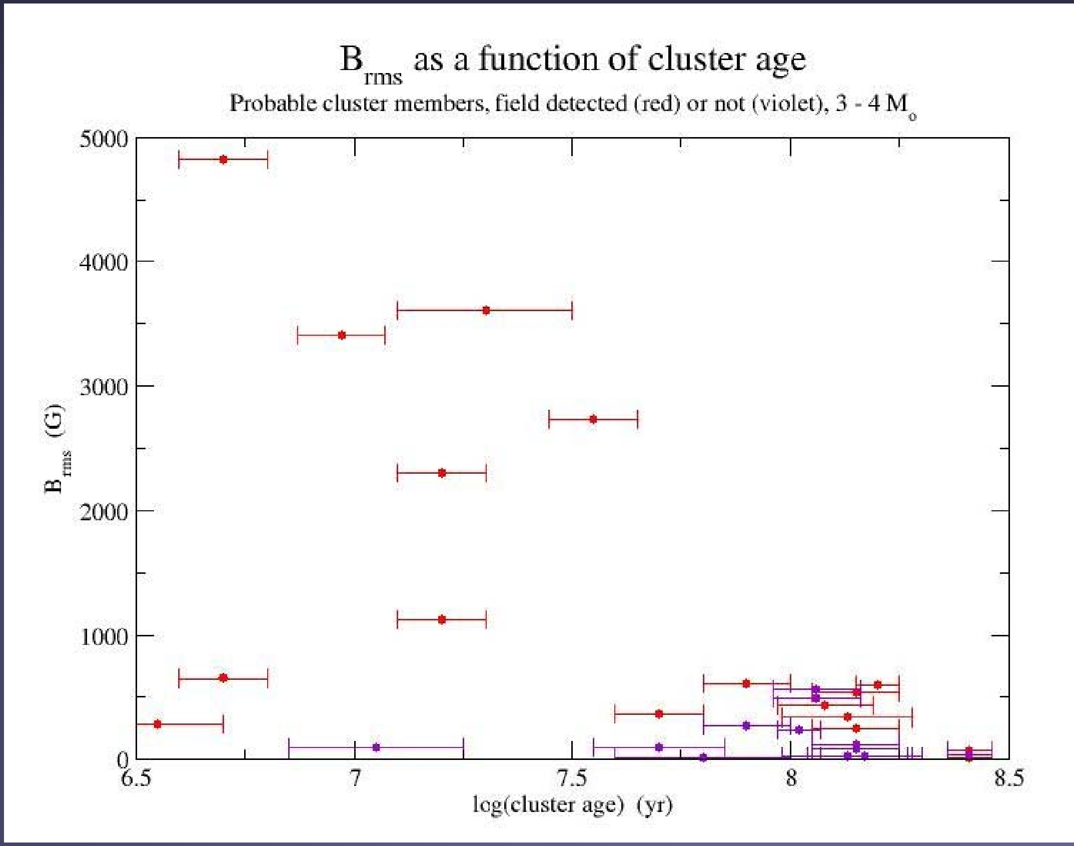
Fe I abund.



(Kochukhov et al. 2004)

Evolution of field strength in Ap stars

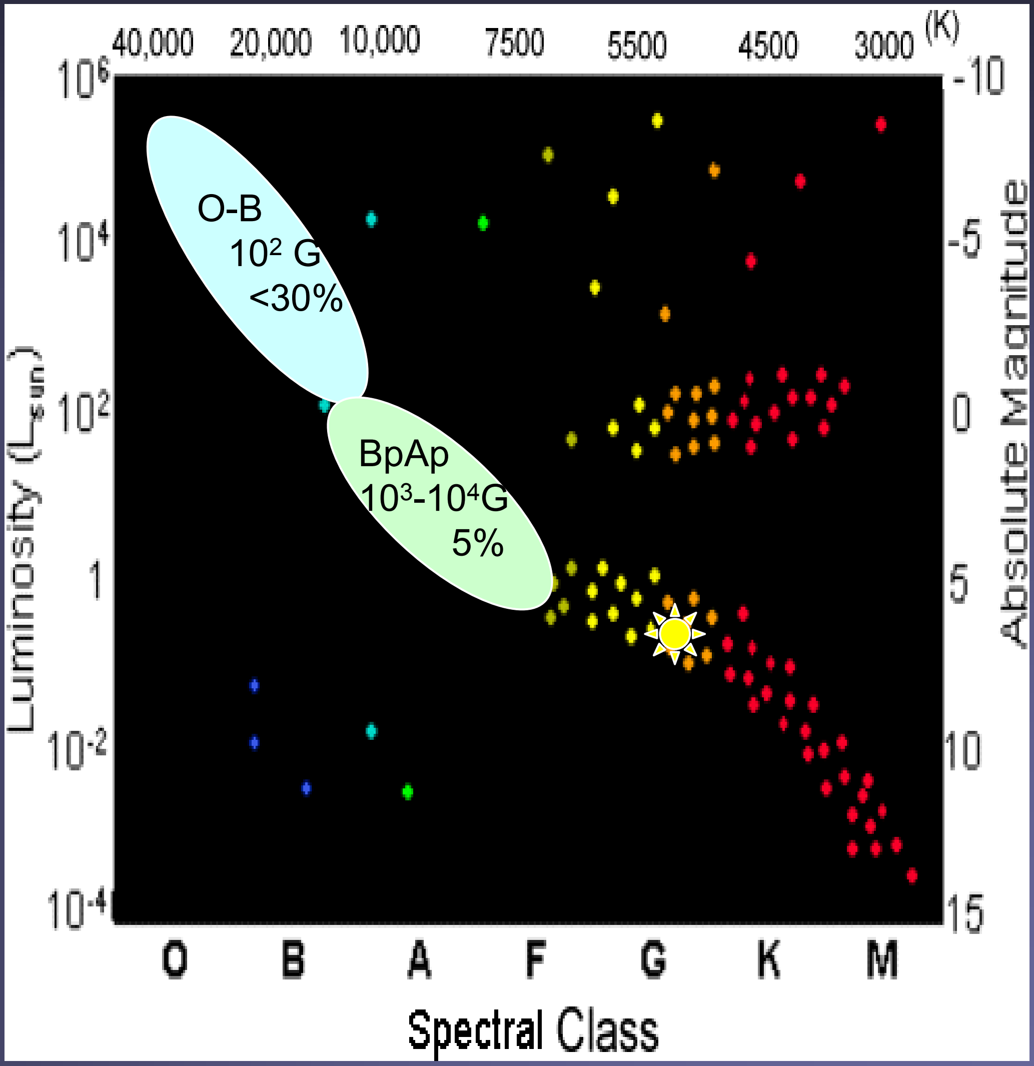
- Sample of magnetic stars in associations and clusters spanning the full main sequence lifetime from ZAMS to TAMS
- At right, field strengths in 3-4$M_\odot$ Ap stars seem to decline after an age of about 40 Myr



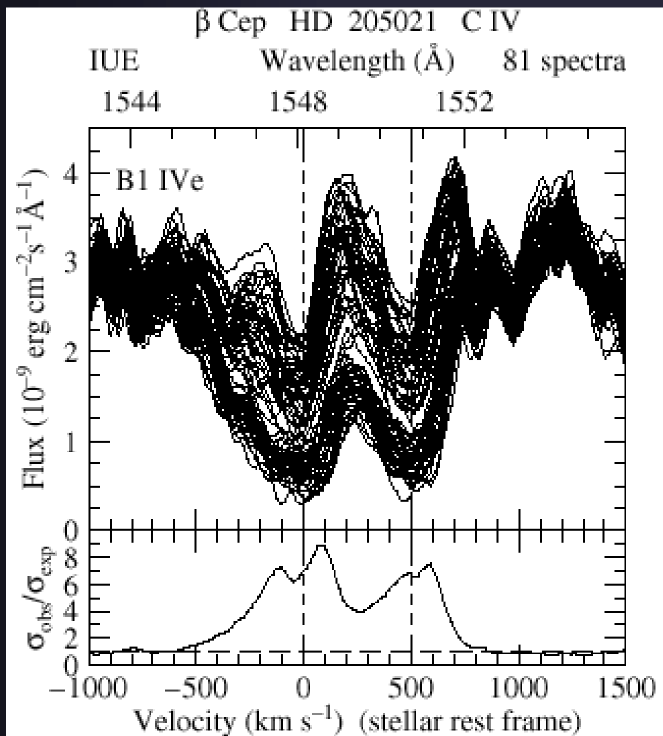
Landstreet et al.

Upper MS stars: O - B stars

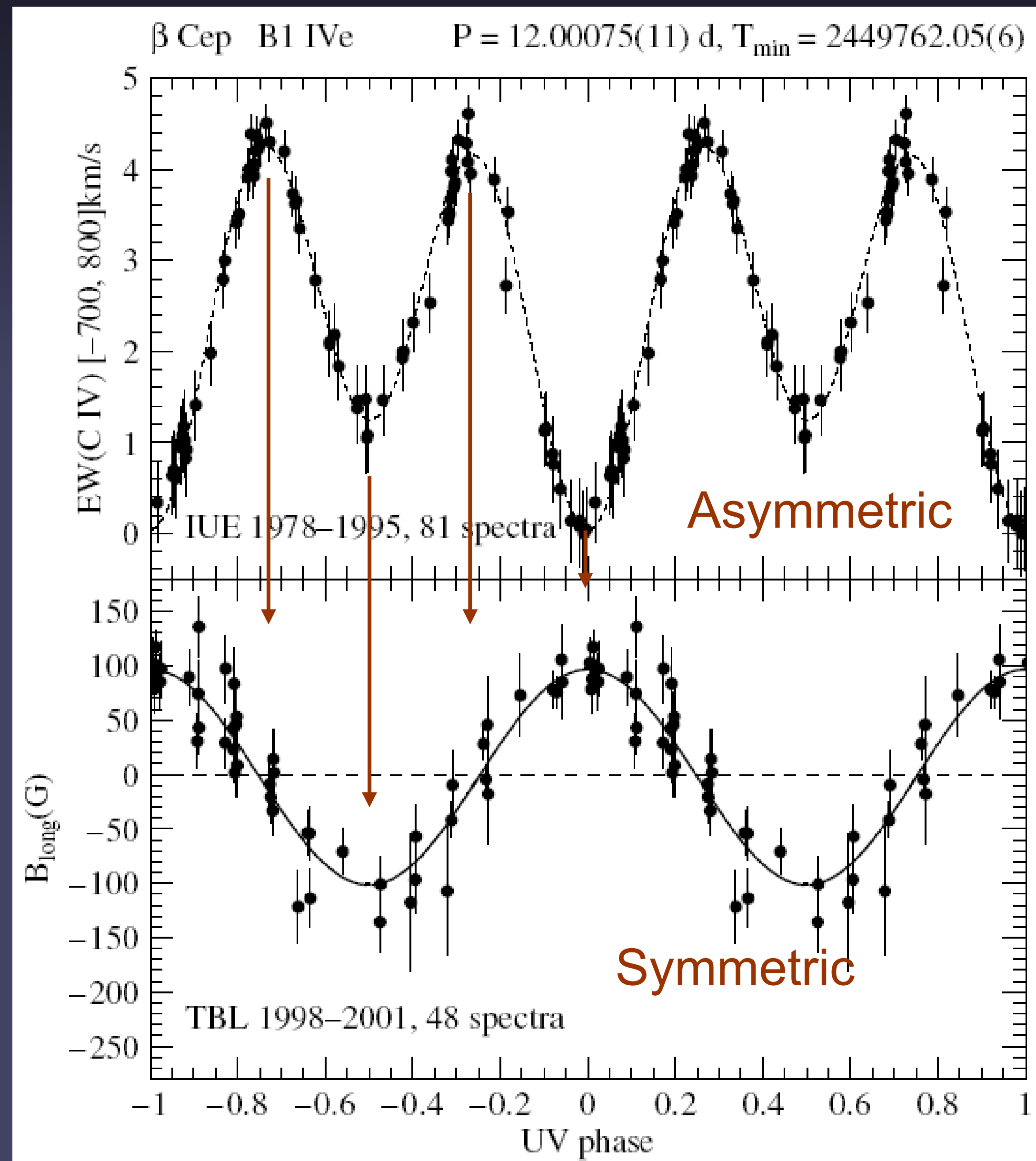
- $\langle B_z \rangle \sim 10^2$ G
- Range of field strengths: 100-1500 G
- Hottest MS star with field: O4-6V
- Occurrence ≤ 30%
- topology: simple
- No dependence on rotation rate
- Most have some abundance anomaly



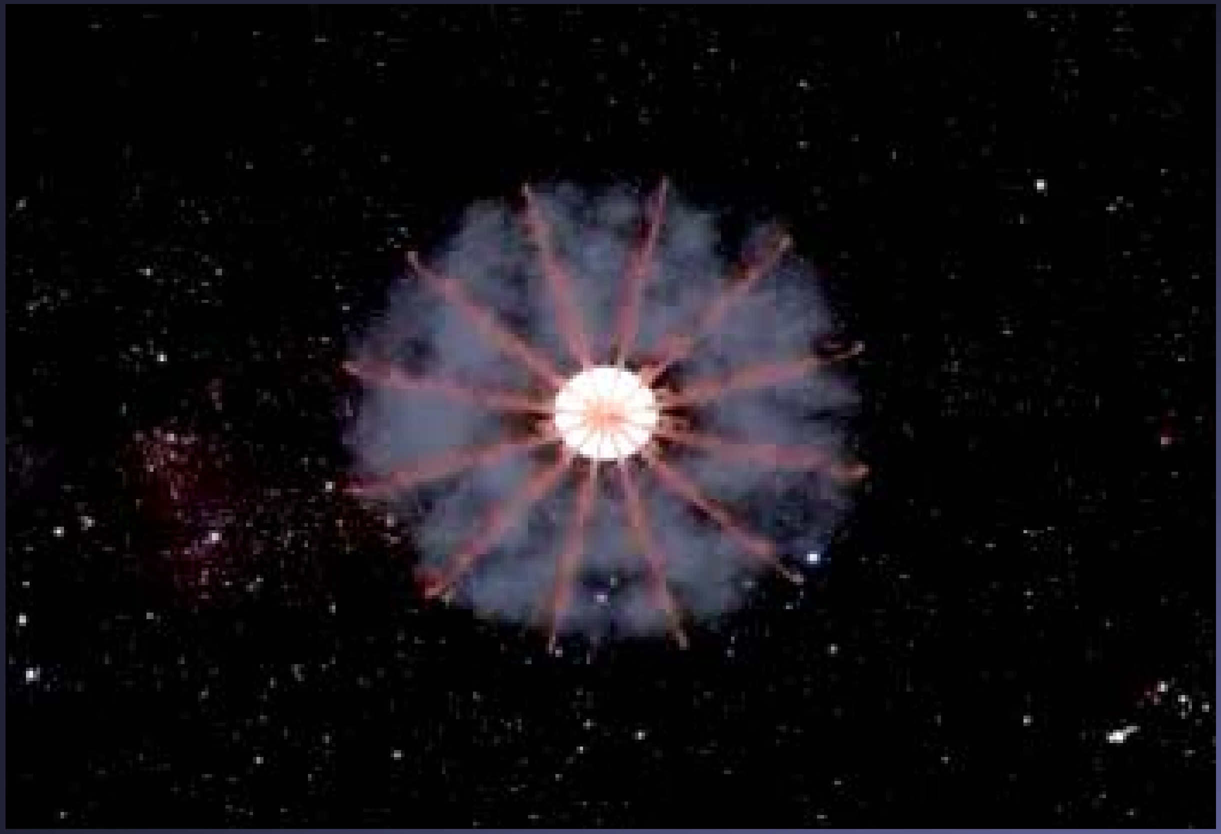
β Cep: UV absorption in phase with magnetic field



For all observed stars: Maximum CIV wind absorption occurs in magnetic equator



Magnetically confined wind of β Cep

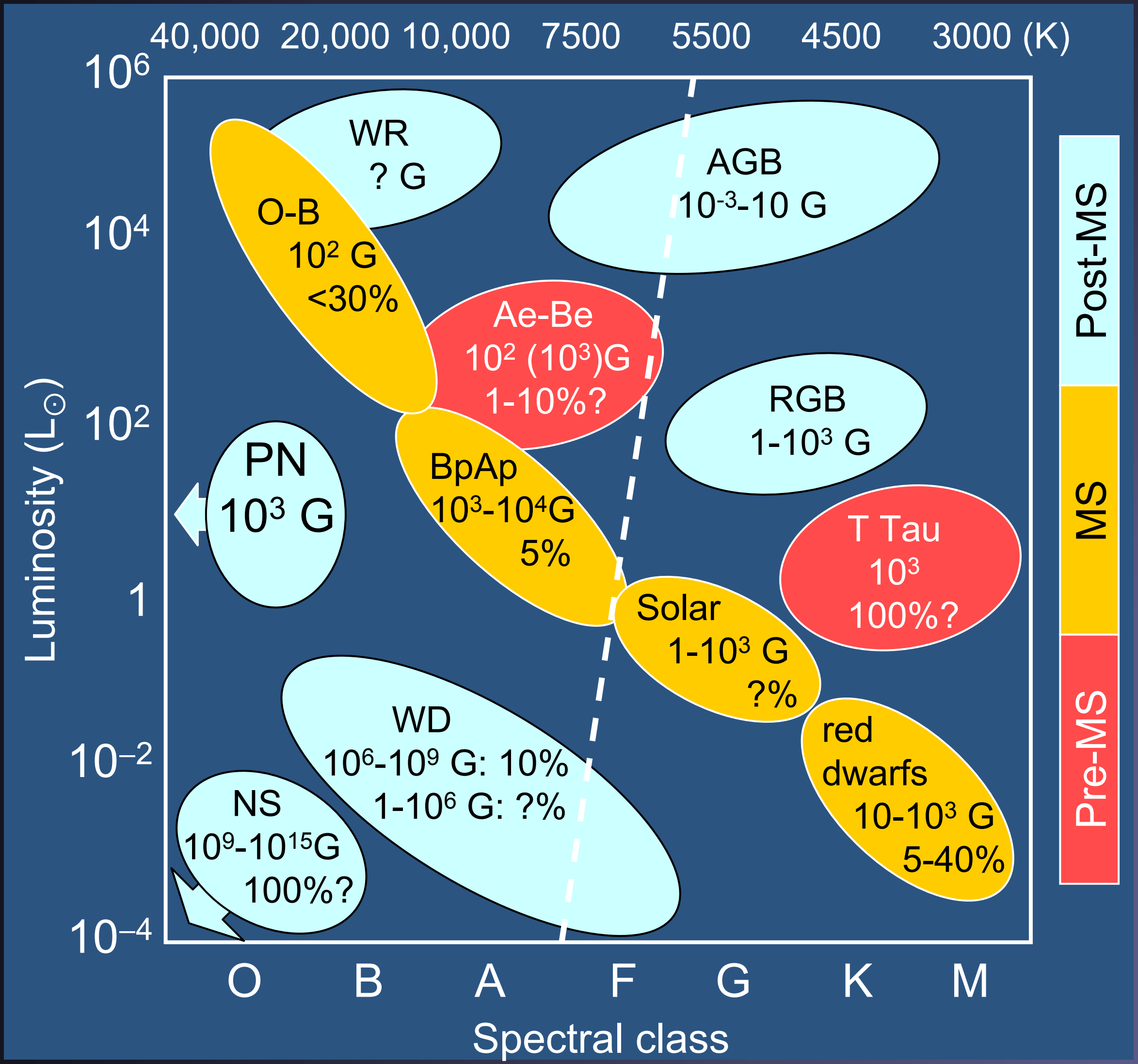


This and previous slide kindly provided by Huib Henrichts

Pulsating B-star with magnetic field of ~100 G

In all magnetic stars: Maximum CIV wind absorption in magnetic equator (predicted: also minimum X-ray flux)

Stellar magnetic fields



So many stars

so little time...

Berdyugina 2009