Chemically peculiar A and B stars

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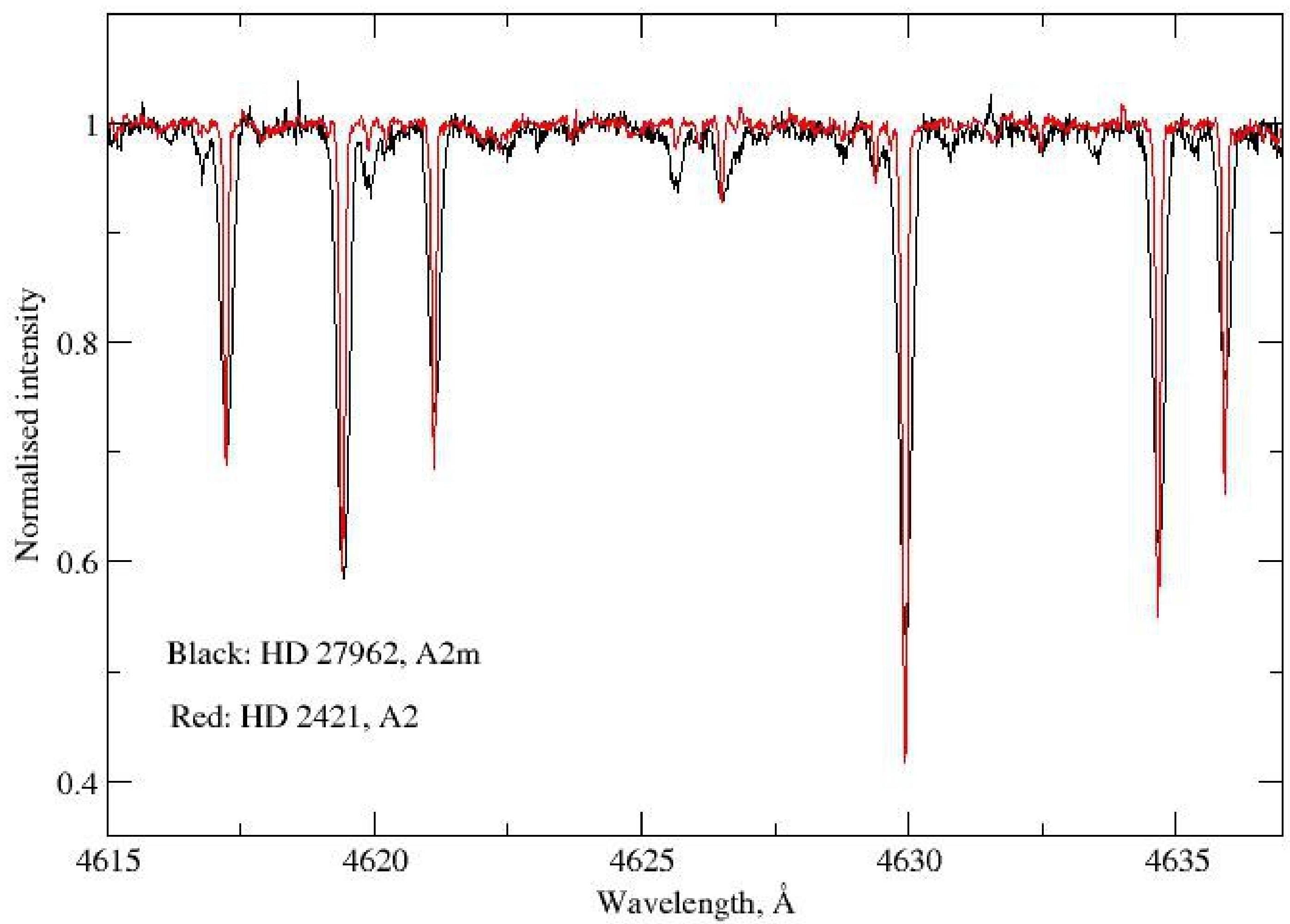
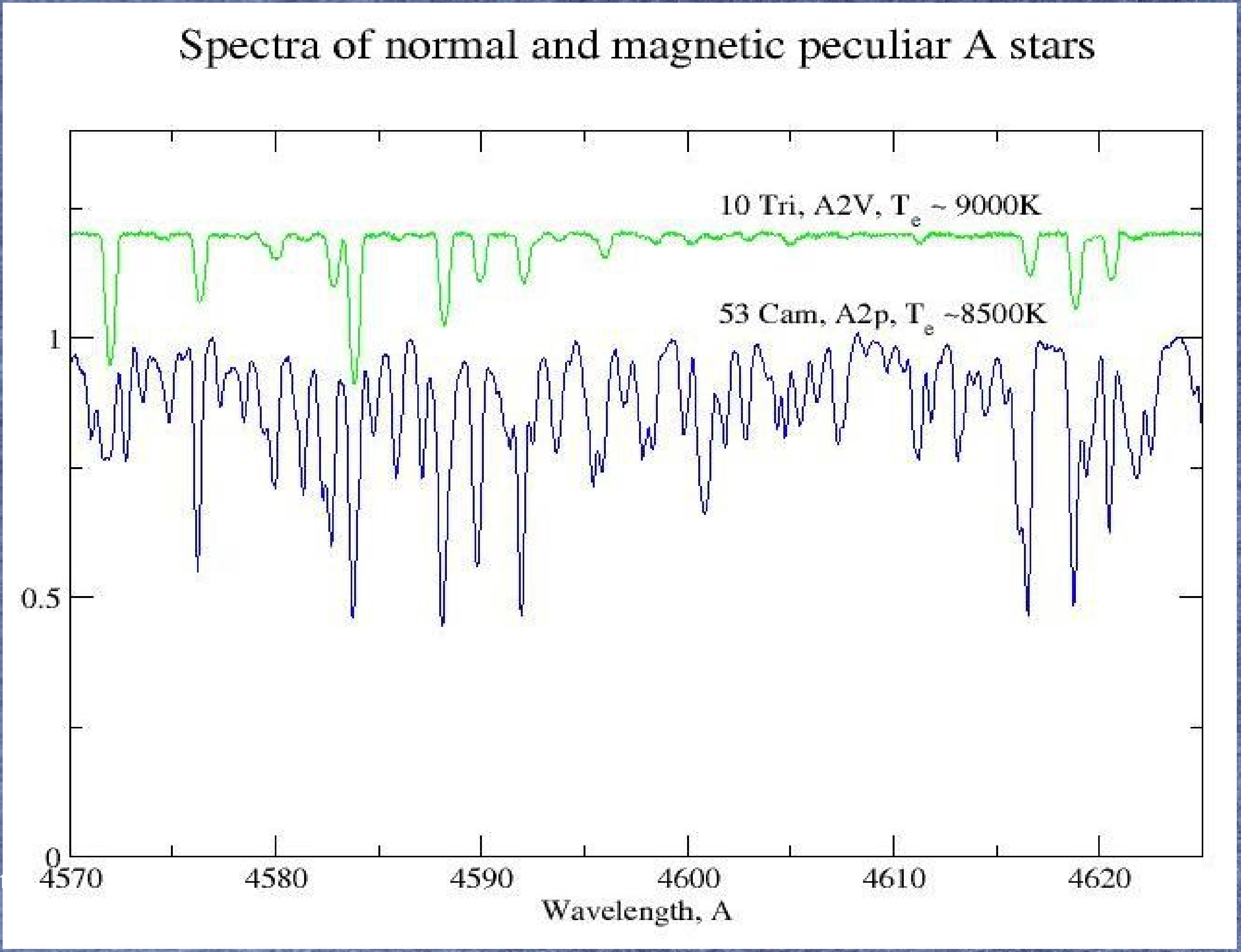
Some peculiars aren't very



And some peculiars <u>are</u> very



Do peculiar stars matter ?

- Most main sequence spectra depend strongly **only** on bulk composition, Teff and v sin i
- In Teff range ~7000 to ~20000 K, a few % have very « peculiar » spectra
- For a long time, peculiar stars were weird and unimportant, a niche interest
- Now we recognise that they provide valuable information about internal stellar physics

Physical processes ??

- Michaud (1970) and the Vauclairs argued that many strange abundance patterns are due to atomic diffusion, driven by gravity (down) and radiative forces (up)
- In stars of low Teff <~ 6000 K, deep mixing keeps surface chemistry similar to interior
- In star of high Teff >~ 20000 K, rapid mass loss brings interior chemistry to surface faster than competing processes can alter it

Diffusion in A/B stars

- In A and B MS stars, no process overwhelms diffusion, but convection layers, large-scale circulation, and mass loss modify results =>
- Various patterns of peculiarity allow us to test & constrain theories of these largely invisible internal and external processes
- Thus peculiar A/B stars emerge as bright and valuable labs for studying internal stellar physics

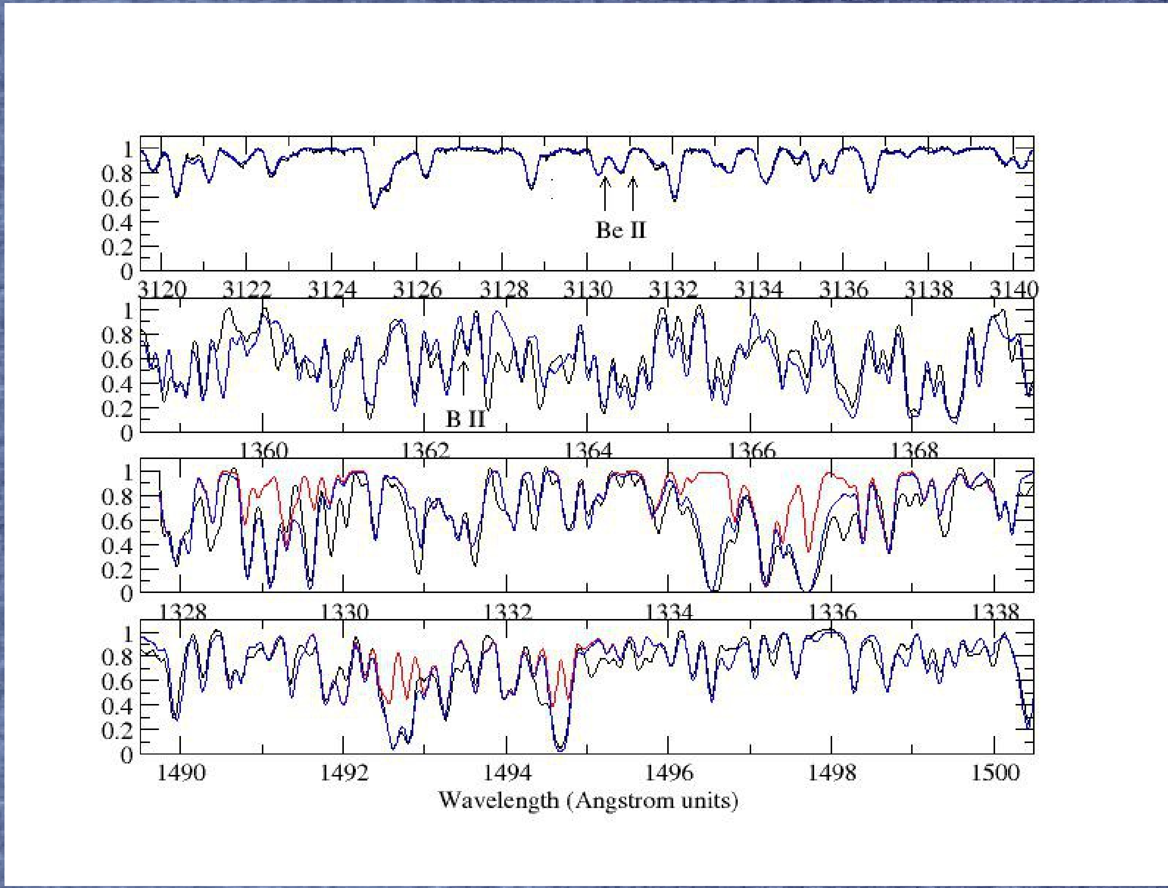
Types of peculiarity

- 2+ quite distinct families of peculiarities
- Magnetic Ap/Bp stars : single, slow rotators, distinctive chemical signatures as approximate function of Teff (SrCrEu - Cr - Si - Hewk)
- Non-magnetic (or very weak field) Am/HgMn stars : close binaries, slow rotators, chemical signatures vary with Teff (Am - HgMn - PGa)
- Lambda Boo stars : low abundance of Fe-peak

Simplest case = Am stars ?

- Am stars show mildly overabundant Fe peak, excess heavy elements, low abundance Ca
- If one tries to model such stars using only diffusion, the model star quickly develops much stronger abundance anomalies than are seen in observations (Michaud).
- Even in Am stars, physical effects must compete with diffusion – very weak fields (Neiner, Blazere), winds, deep turbulence ?

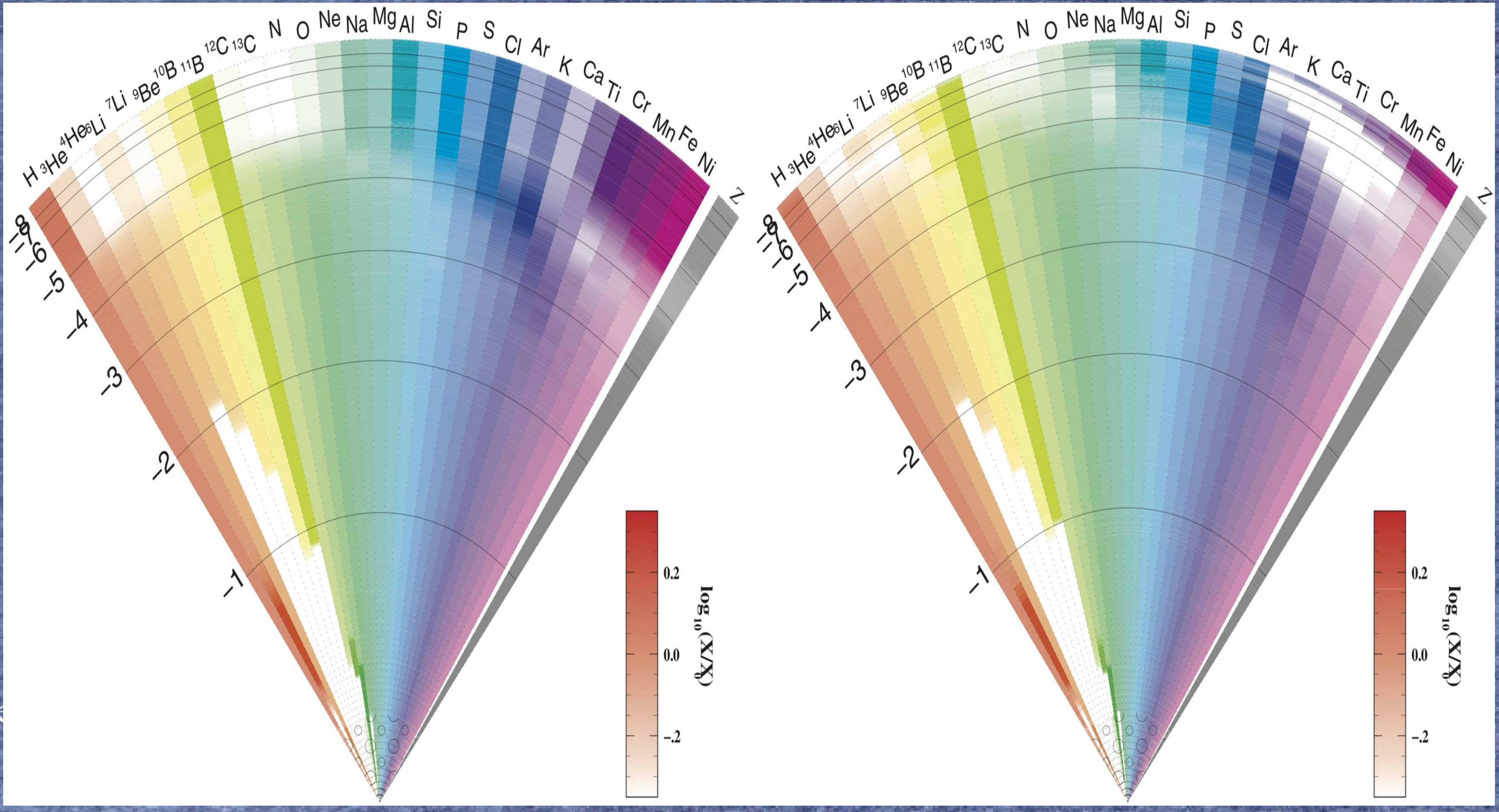
Precise abundances are essential



- Sirius, abundance of Be, B, C, N using spectrum synthesis (Landstreet 2011) … a practical method thanks to VALD !!

Modelling abundance evolution

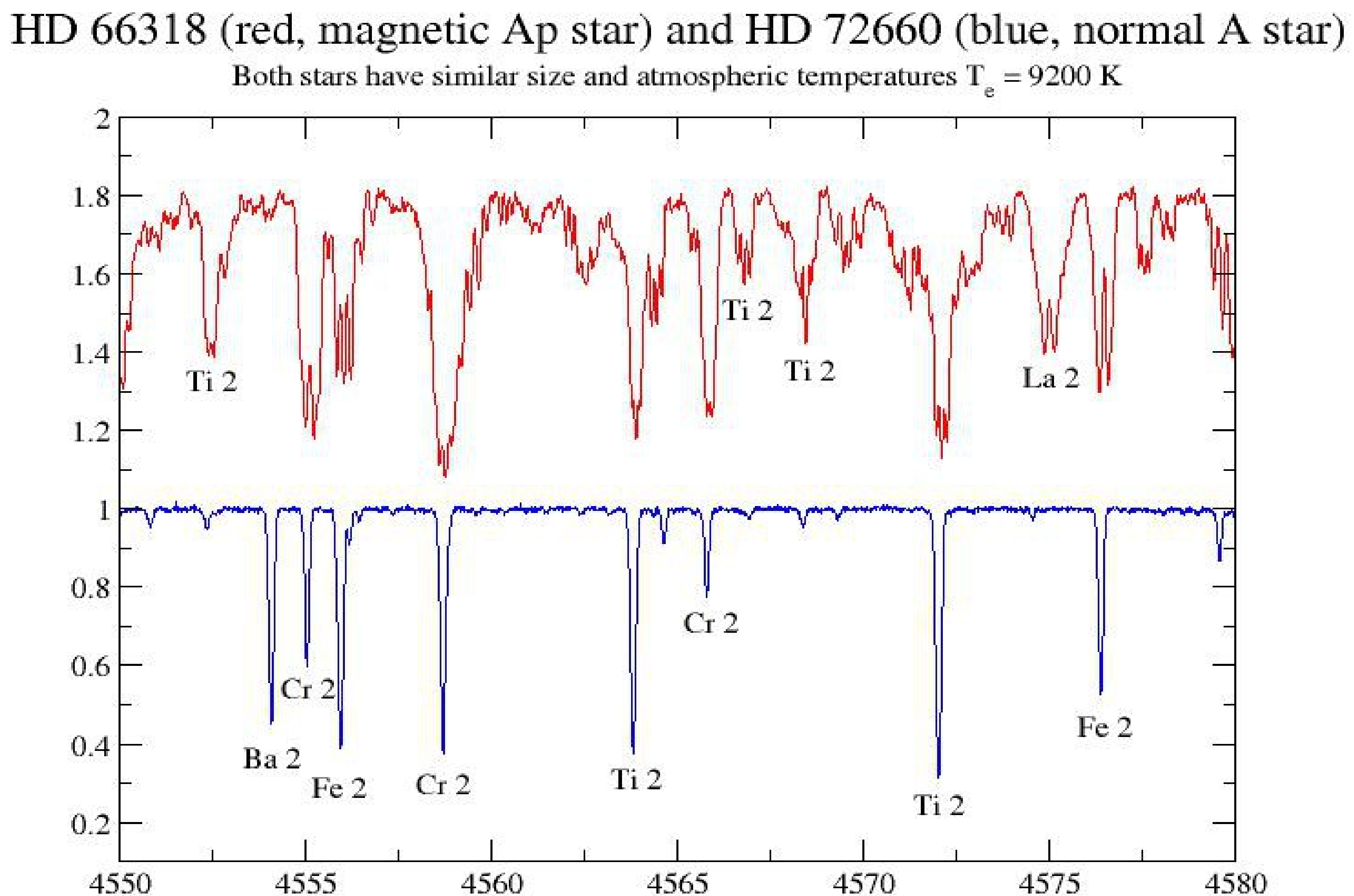
- Models of hot Am star Sirius abundances (at 233 Myr) with turbulent mixing (left) OR mass loss (right) from Michaud et al (2011)



Magnetic stars even more complex

- Some peculiar A/B stars have strong magnetic fields, ~300 G <~ <|B|> <~ 30 kG
- Fields usually have ~dipolar topology
- Abundances are often *very* non-solar, & also *quite* non-uniform over surface.
- Modelling and mapping such patchiness provides further constraint on underlying physics (Landstreet, Kochukhov, Donati, Stift...)

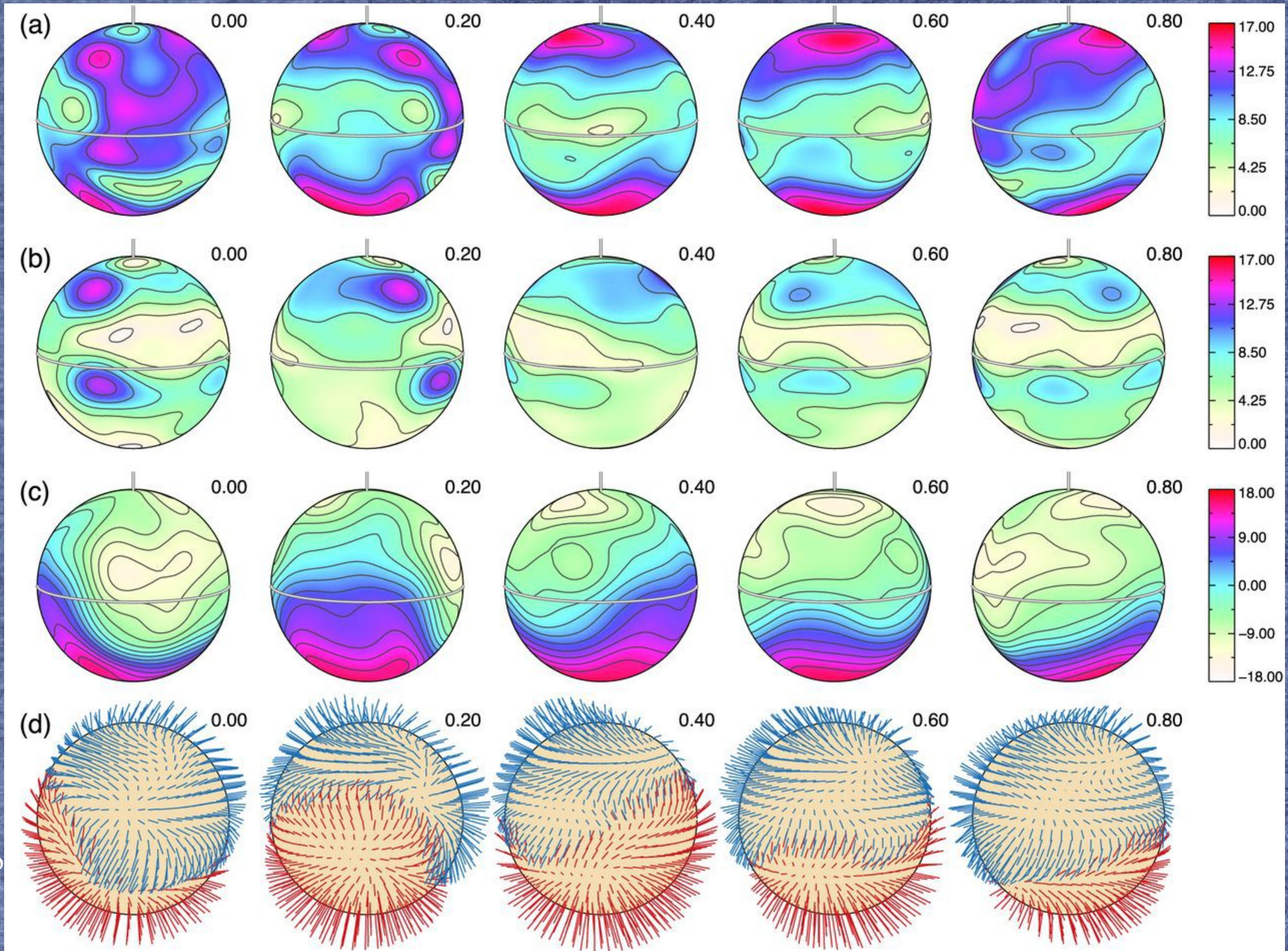
Magnetic Ap star vs normal star



Observing magnetic Ap/Bp stars

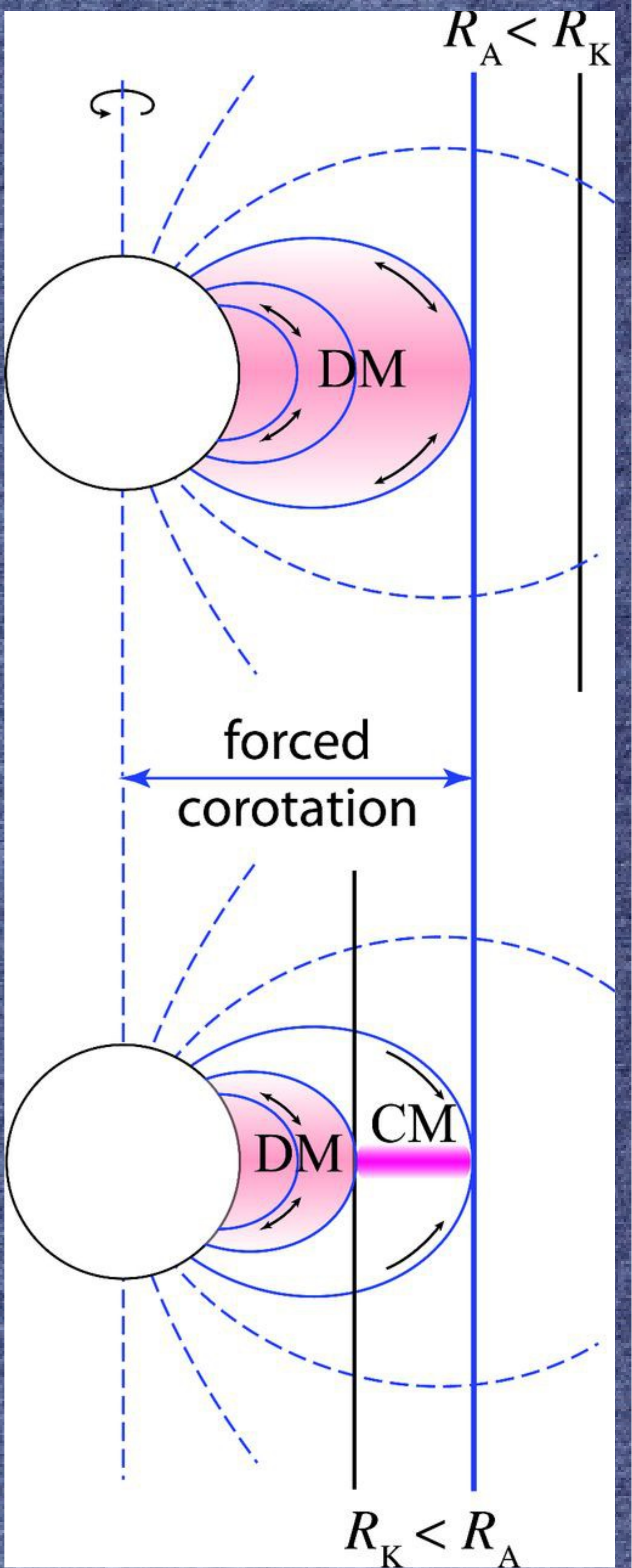
- Field detection thresholds have fallen by 1-2 orders of magnitude (ESPaDOnS, NARVAL, HARPSpol)
- Precise measurements possible down to V ~ 10 (or even 13 or 15, FORS regime)
- Can now obtain spectra in four Stokes parameters for many stars
- Possible to do accurate and detailed mapping of magnetic field from series of IQUV spectra

Magnetic map of HD 32633
(Silvester, Kochukhov, Wade 2016)

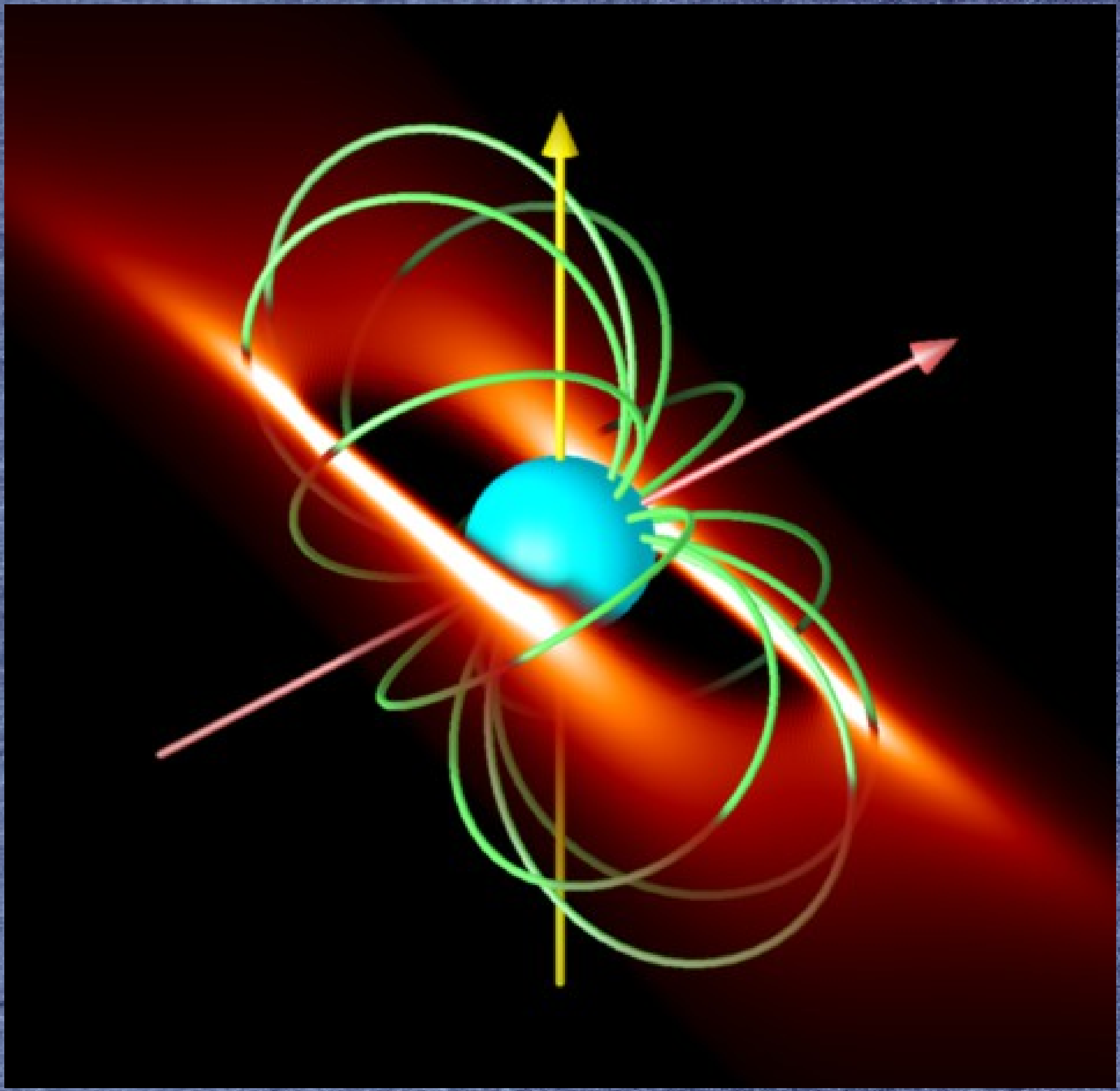


OB stars

- Trapped magnetosphere around He str B star sigma Ori E found long ago (Landstreet, Borra 78)
- MiMeS survey found many such objects among magnetic O, early B stars (Petit et al 2013)
- Some stars have centrifugally supported clouds, others have dynamic magnetospheres



Magnetosphere of sigma Ori E



- Owocki, Townsend, Ud Doula…

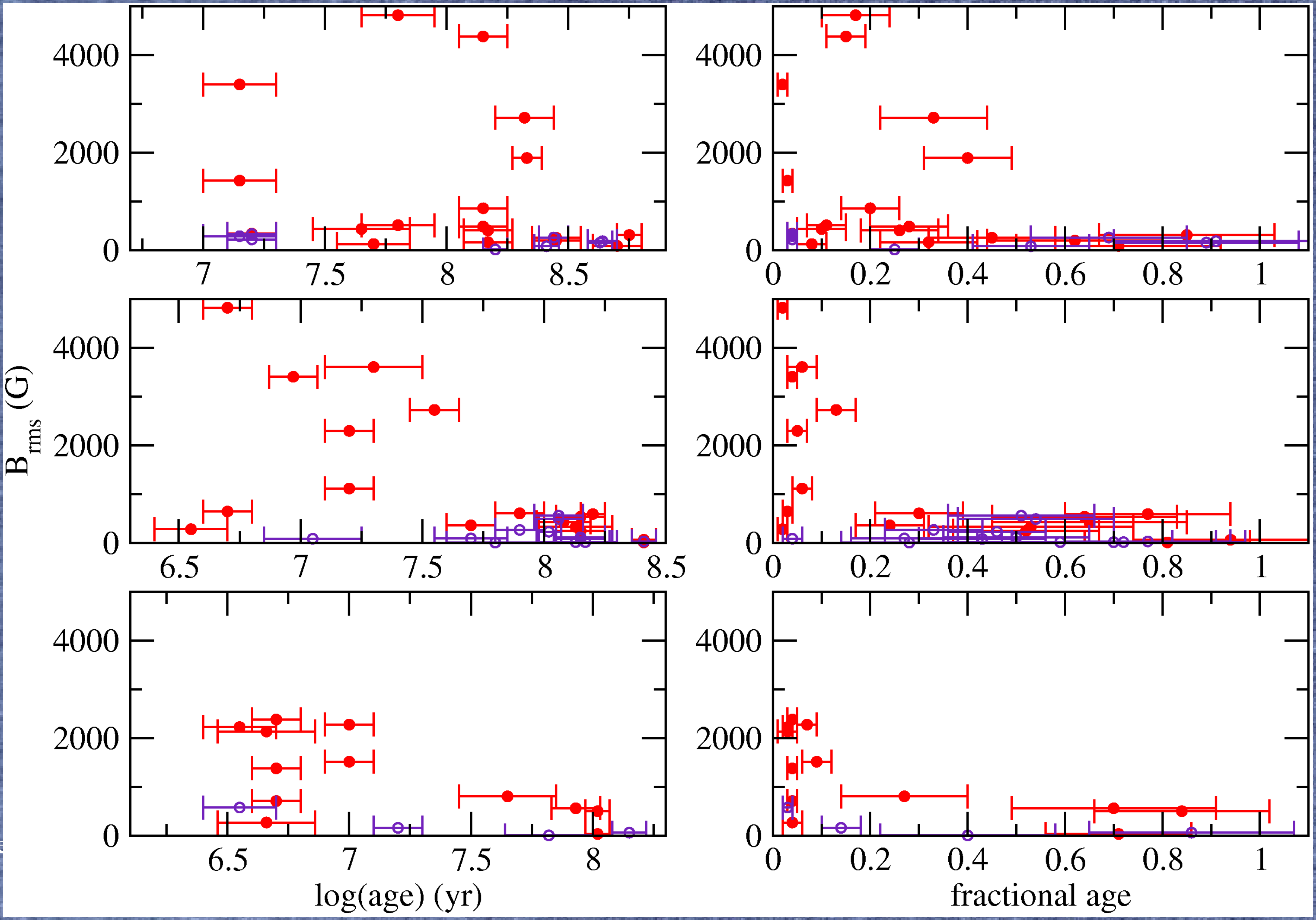
Evolution of abundances, magnetic fields

- Expect chemical abundance variations due to diffusion to vary during evolution as atoms brought to surface and lost to space
- Models of Am stars, hot HB stars by Michaud-Richer group show this clearly
- But it is usually very hard to determine accurate evolutionary age of an isolated field peculiar star because of uncertain Teff, log L/Lo

Evolution – cluster members

- We expect magnetic fields to evolve due to evolutionary changes in stellar structure, internal flows and motions, ohmic decay
- If a star is member of open cluster, can use age of cluster to get accurate stellar age
- Now possible to study many cluster peculiars
- Use cluster Ap/Bp stars to study field and abundance evolution (Bagnulo, Landstreet, et al 2006 and later ; now moving to mapping)

Evolution of B fields



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Evolution - larger context

- For abundances, expect current surface abundances to depend on bulk chemistry and time since last deep mixing (e.g. on PMS)
- However, magnetic fields may persist from stage to stage
- Now have detected magnetic fields in most major stages of stellar evolution - PMS, MS, RG, AGB, WD/NS ...

Evolution of fields

- Structure & evolution during radiative periods (MS, WD) of fossil fields is beginning to be modelled & understood (Braithwaite, Mathis...)
- Not so for evolution through deep convection
- Formation of Ap/Bp fields from deeply convective PMS epoch still very mysterious
- Strange dependences of magnetic fields on binarity => importance of binarity in formation of MS magnetic stars (Binamics, Mathys ...) ??

Further evolution

- MS Ap fields seem to persist for a while in RGs, but how could these fields survive to WD ?
- Formation of WD fields still mysterious – retention of Ap fields ?? Creation (re-creation) during common envelope phase of close binary ??
- Still plenty of questions left to answer about UMS peculiar stars ....

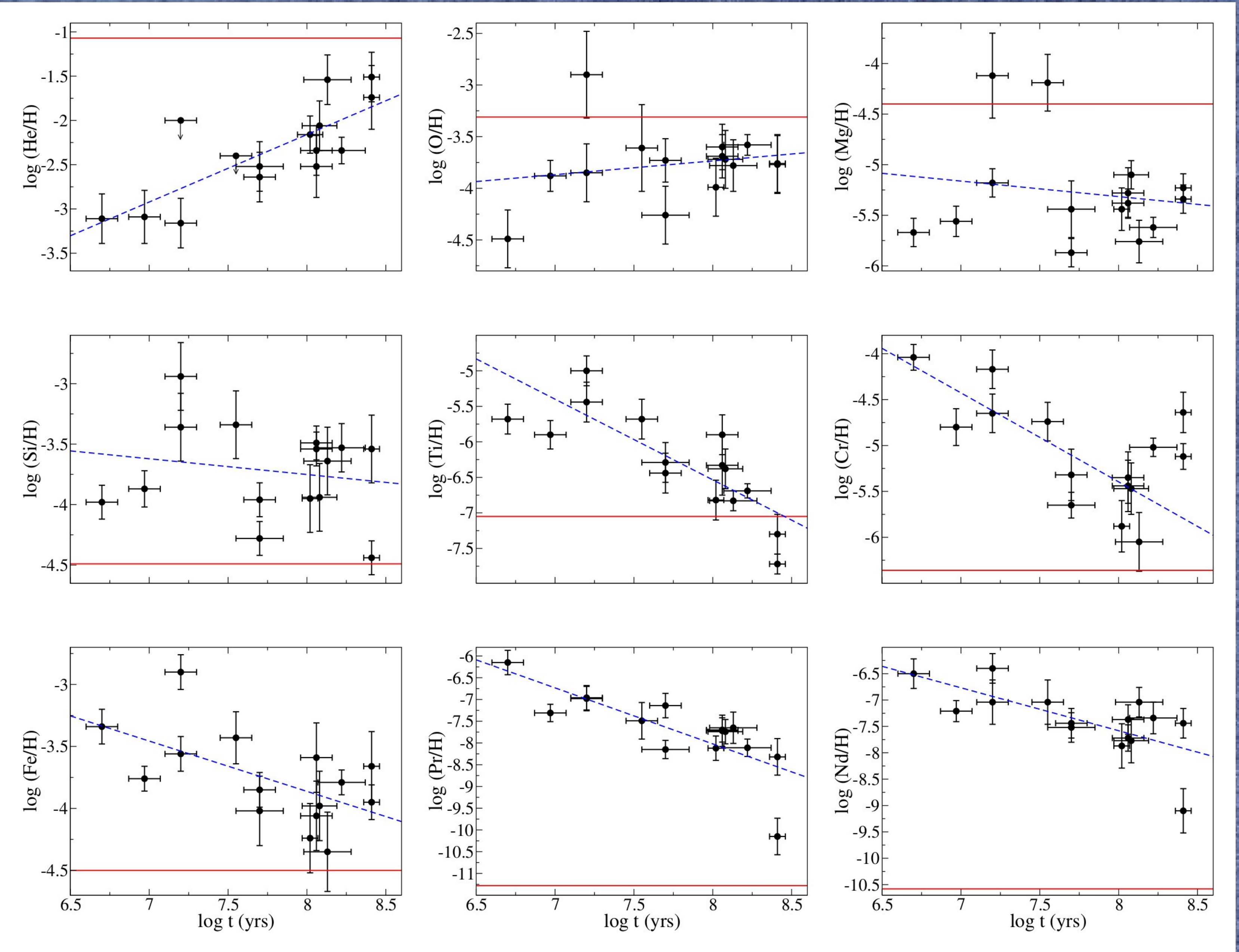
Oops, I almost forgot

- Some peculiar magnetic A stars pulsate !!
- This will allow us to access (gradually) a LOT of information about the interior, beautifully complementing the information that comes from what we see directly in the atmosphere.
- THANK YOU DON KURTZ
- But that is another story that you will hear from other people.

Thanks

- To many collaborators and to other for inspiration (Stefano Bagnulo, Gregg Wade, Coralie Neiner, Georges Michaud, Silvie Vauclair, Jeff Bailey, Oleg Kochukhov, etc.)
- And thank you for your attention

Evolution of chemical peculiarity



Why study magnetic fields in stars ?

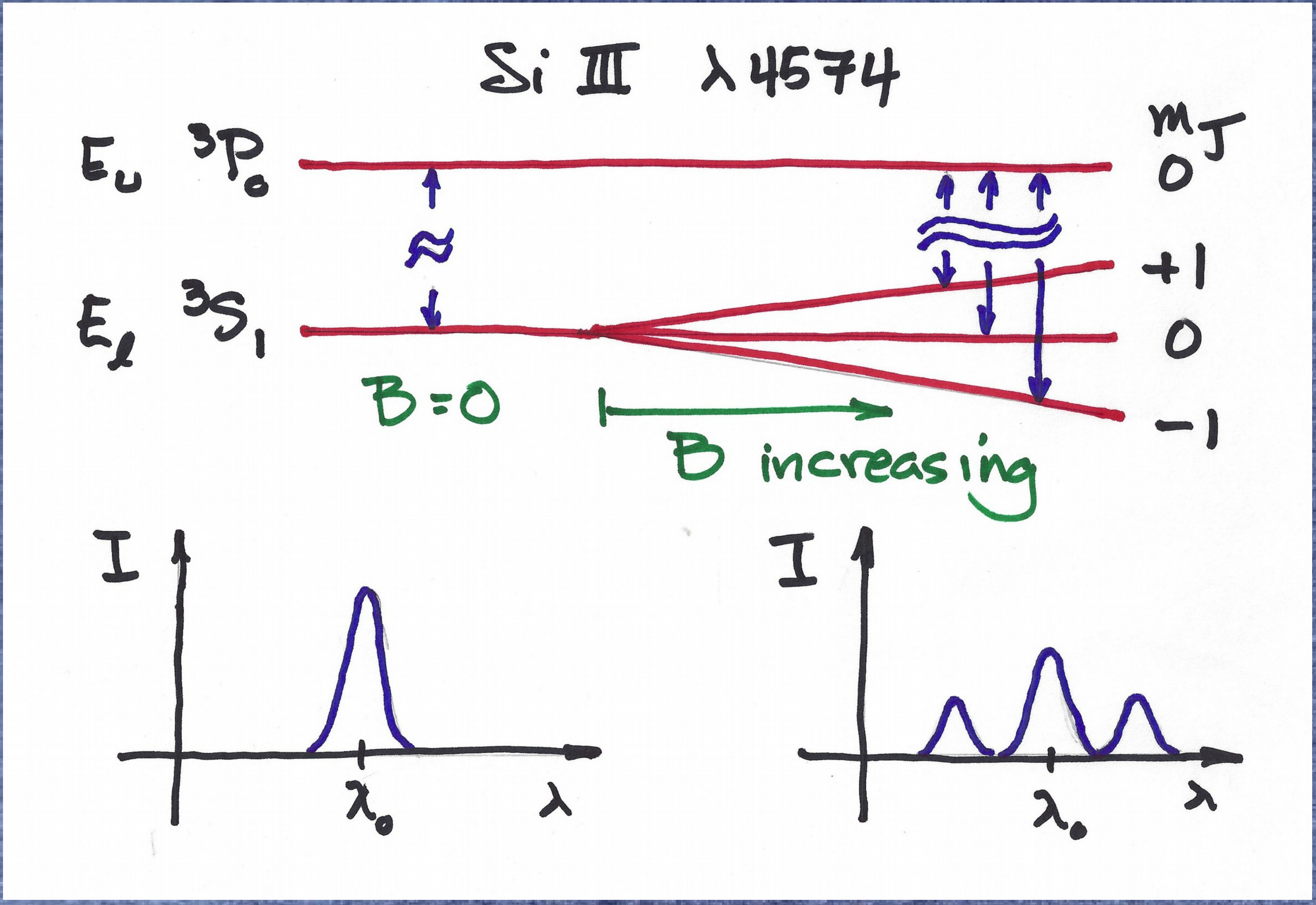
- Magnetic fields alter spectral lines, greatly change pulsation modes, and produce « activity », strongly affecting interpretation of observations
- A magnetic field can stabilise a stellar atmosphere and substantially alter its physical structure (e.g. by supressing convection)
- Fields greatly affect transport of angular momentum and mixing – during accretion or mass loss phases, and inside the star at any time

How are magnetic fields detected and measured ?

- To detect magnetic fields, we use the **Zeeman effect**. In many hot stars, this is the **only** directly detectable symptom of a field.
- Zeeman effect splits a single line into multiple components, separated in wavelength and polarised
- Components are separated by roughly

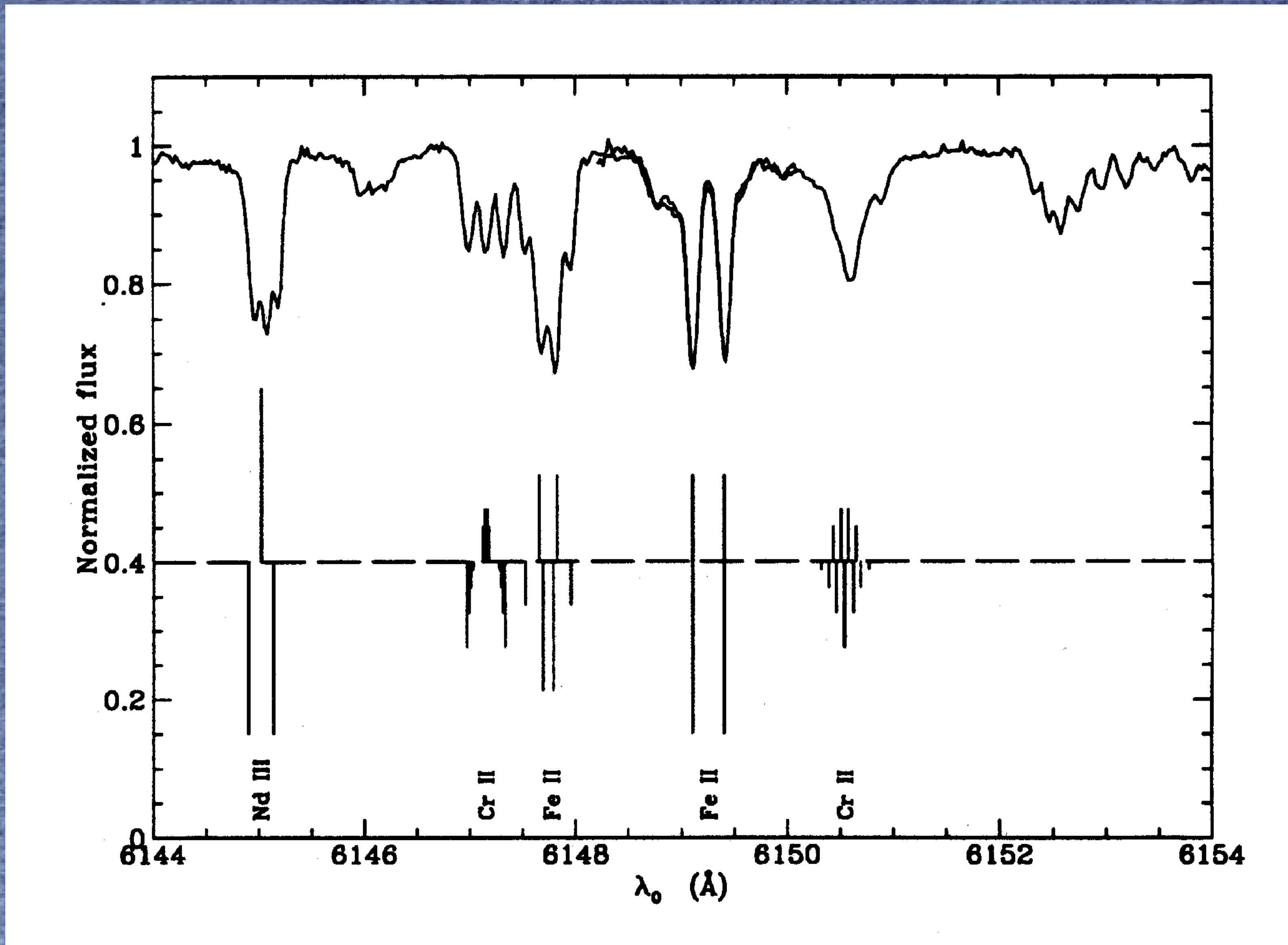
$$\Delta\lambda(A) \sim 5\ 10^{-13}\ B(G)\ \lambda^{2}(A) \sim 0.013\ A/kG$$

Zeeman effect in the intensity spectrum

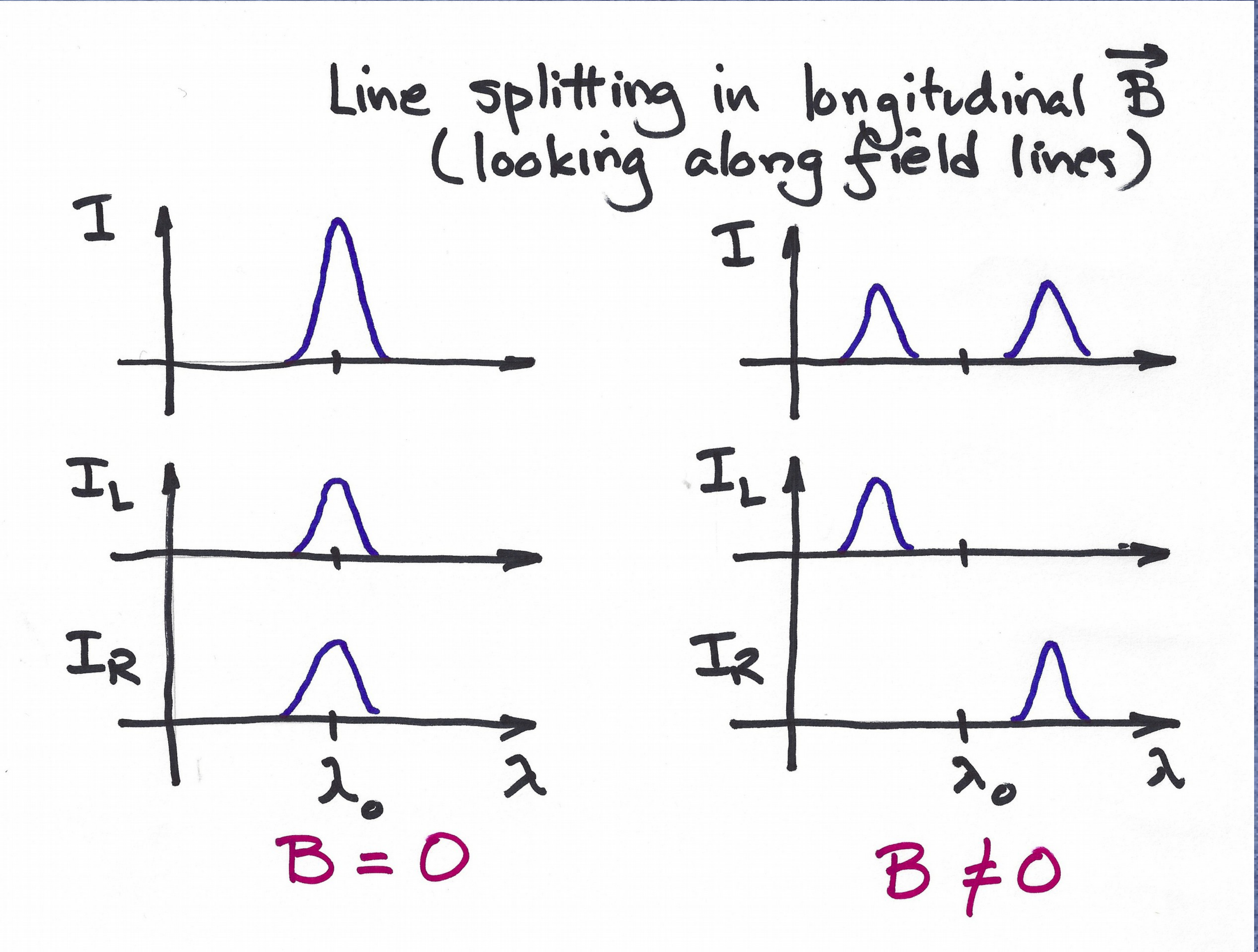


Zeeman splitting in 6kG field of magnetic Ap star HD 94660

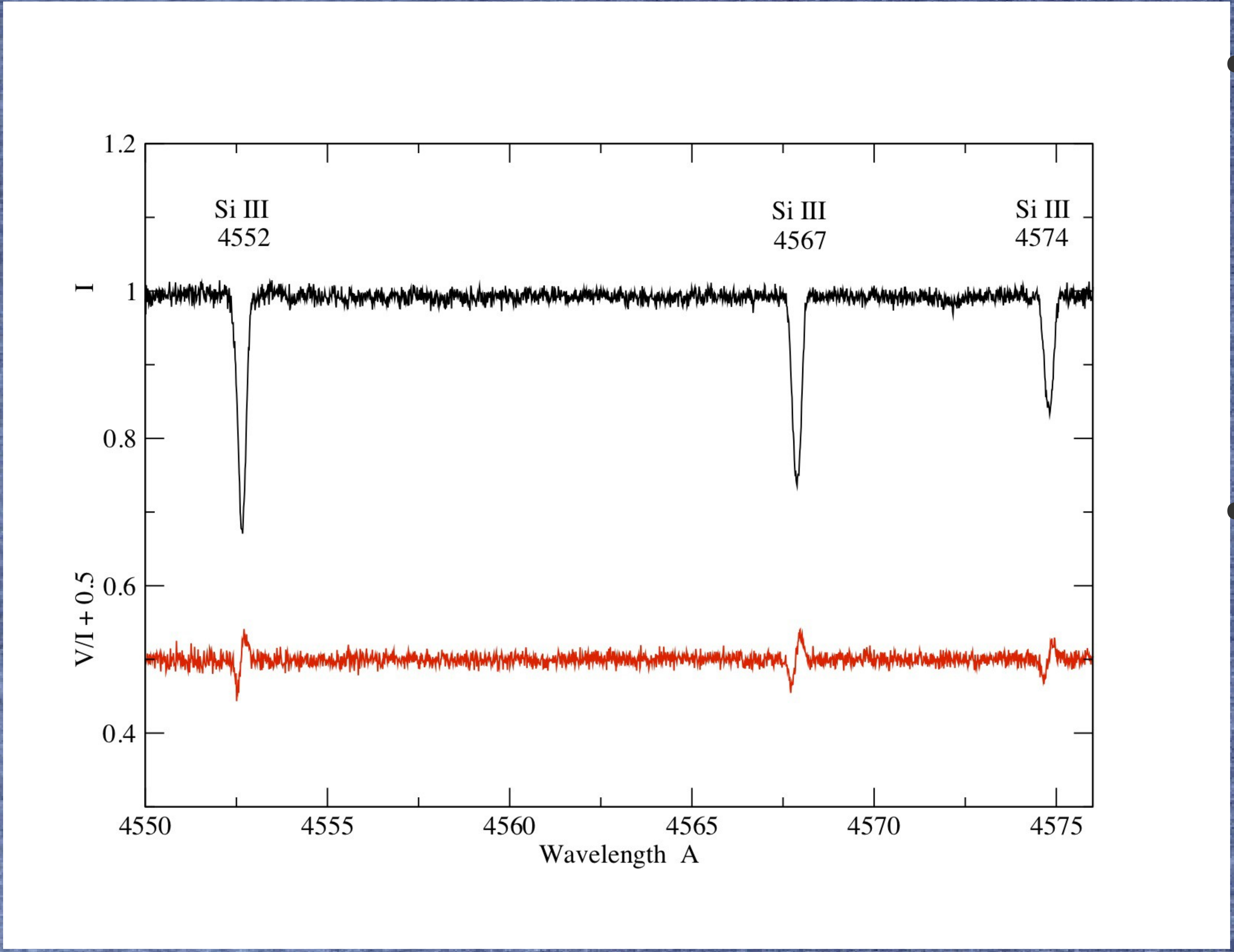
- Figure : Mathys



Zeeman effect also leads to line polarisation



Weaker fields (HD 96446) show polarisation, but no splitting



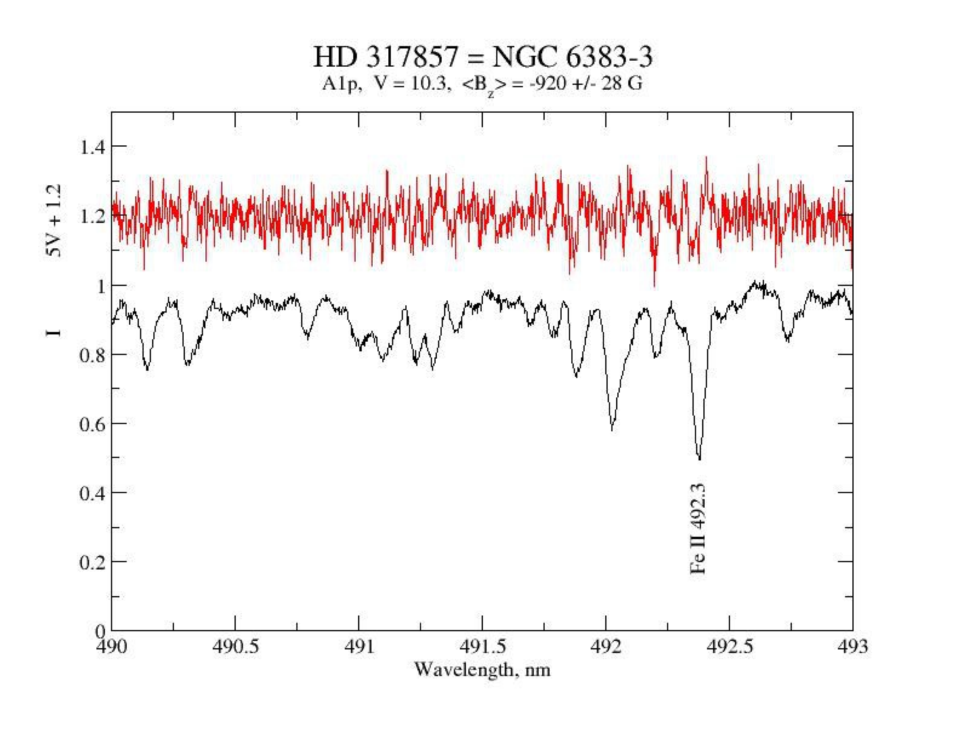
- Data from Neiner et al (2012)
- Notice similar profile shapes

Recent advances in instruments

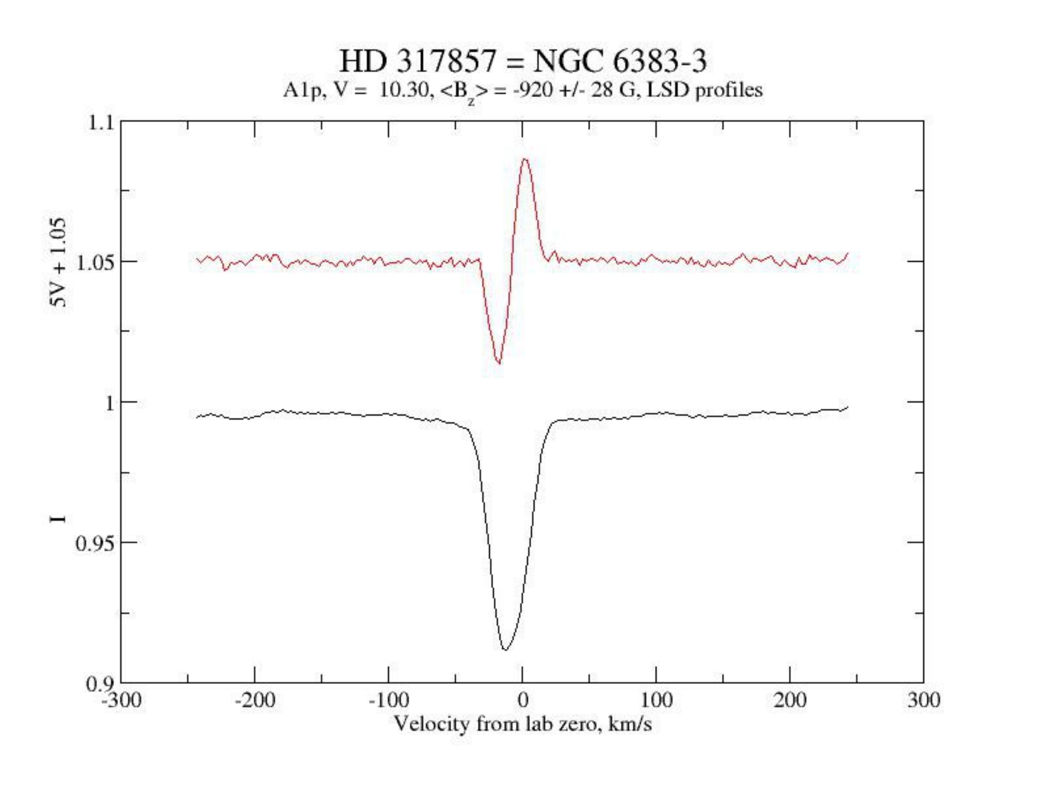
- Recent advances in instruments make most of HRD accesible to useful measurement !
  - MUCH higher throughput
  - Polarimetric sensitivity over wide spectrum
  - Huge spectral range, e.g. all of optical window
- Several excellent spectropolarimeters are facility instruments (ESPaDOnS at CFHT, NARVAL at PdM , HARPSpol at ESO, FORS at ESO, ISIS at WHT...)

Improved analysis too!

- Notice that (circular) *V/I* polarisation signals are very similar from line to line. Averaging can greatly increase signal-to-noise ratio.
- Sensitivity to **very small** fields depends on
  - efficient spectropolarimetry over broad wavelength band
  - high density of fairly strong spectral lines
  - small v sin i (narrow spectral lines)
  - Useful polarimetric sensitivity to 3 10^{-6}



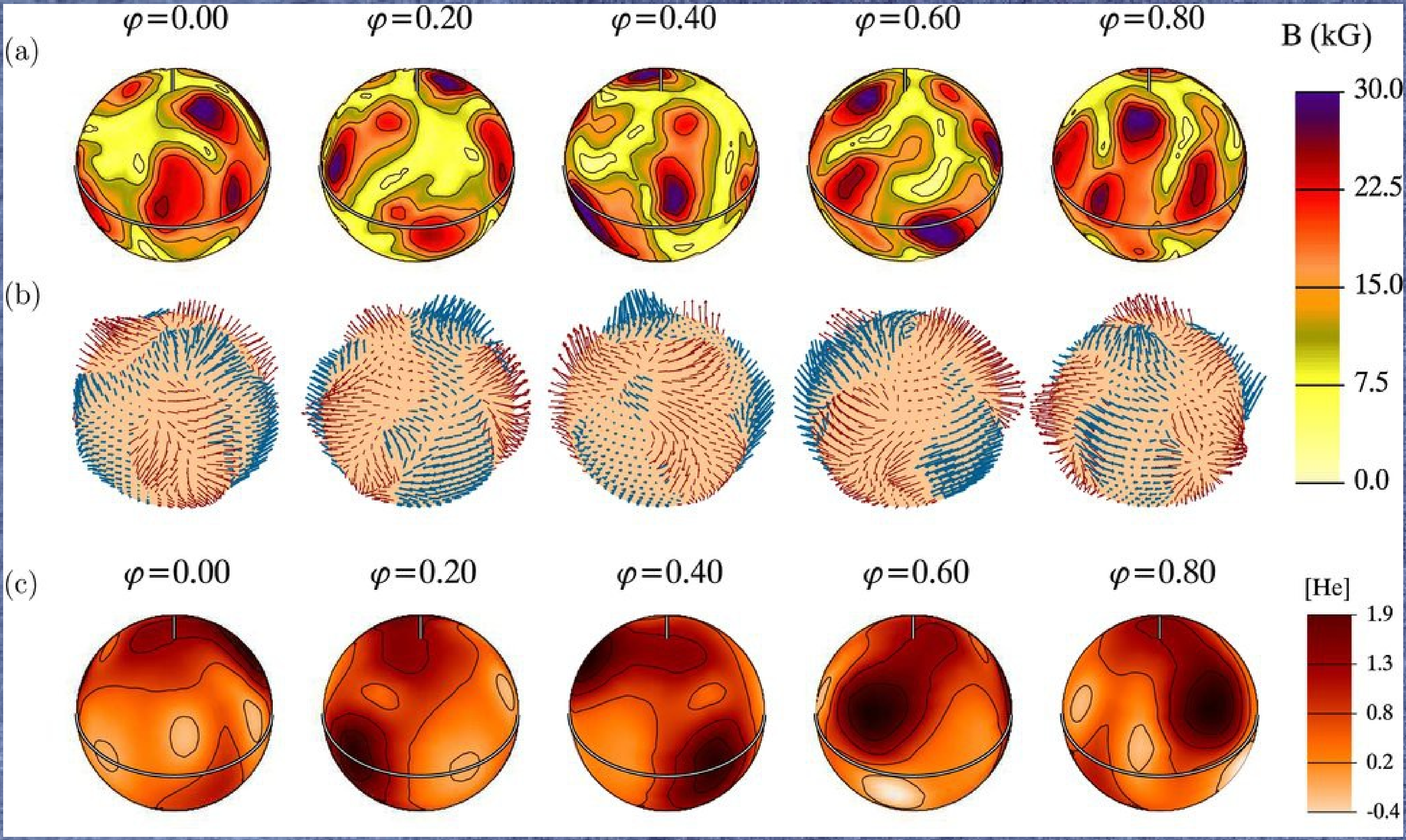
- Example of increased S/N produced by averaging over many lines (from Bagnulo & Landstreet open cluster survey)



Mapping

- We find that many stars have fields with static or slowly changing structure.
- Series of polarimetric spectra in all Stokes components, taken as a star rotates, make **mapping** possible (Piskunov, Kochukhov, Donati, P. Petit, etc).
- Such maps reveal magnetic field structure at moderate spatial resolution, and often can uncover associated temperature or local abundance variations

Map of B2V magnetic star HD 37776 (Kochukhov et al 11)



The overall picture today

- Improvement of instrumentation has led to many major surveys and at least some field detections all major phases in HR diagram!!
  - PMS stars: T Taus and a few Herbig AeBe stars
  - Main sequence (MS): rapidly rotating low mass stars, small fraction of O, B, A (Ap/Bp) stars
  - Giant stars: a few Ap descendant(?) fields, weak dynamo fields in both red giant & AGB stars
  - Small fraction of white dwarfs, all(?) neutron stars

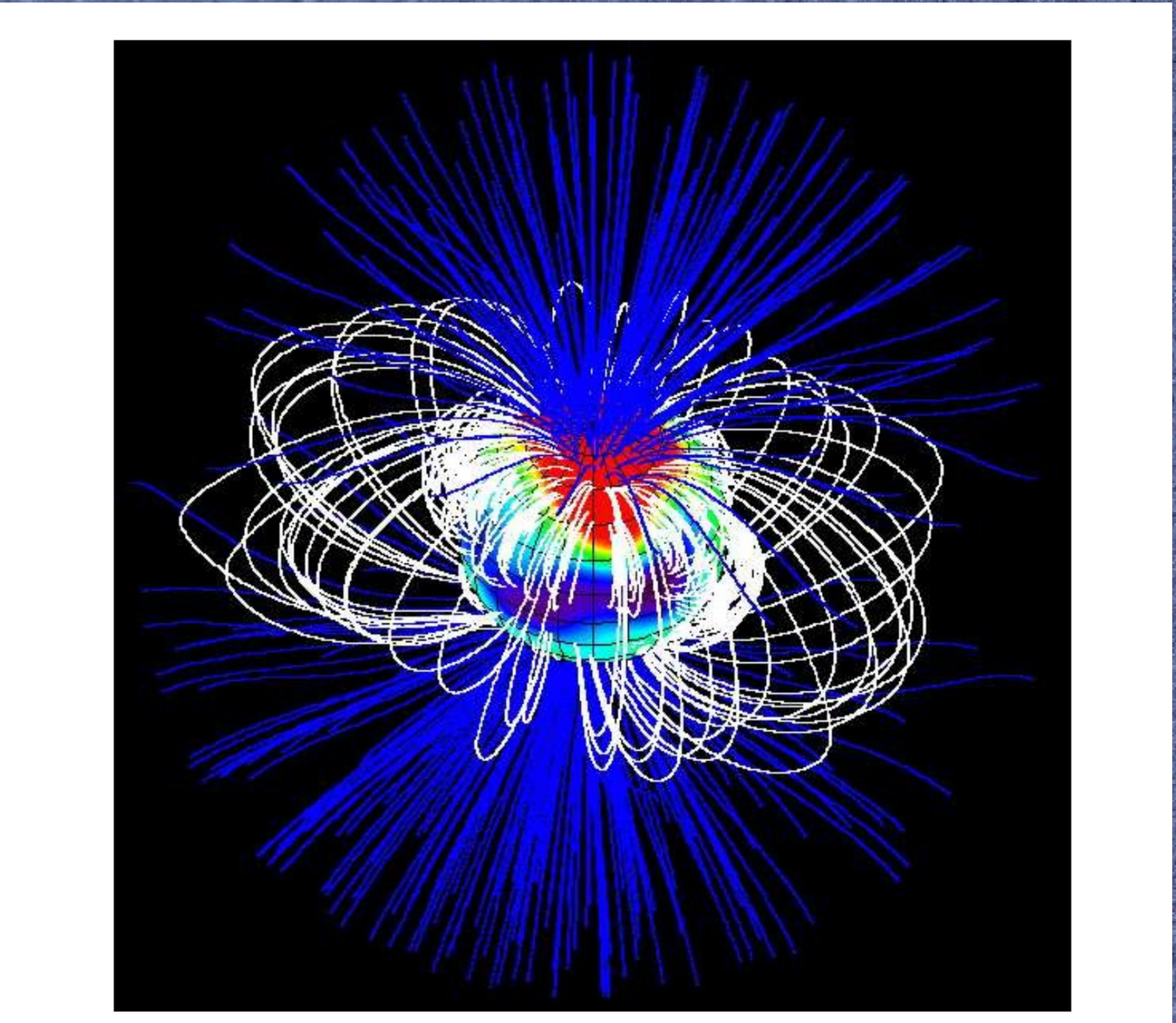
Field structures

- Studying the magnetic fields found, we recognise two main types:
  - **dynamo (solar-type) fields**, in cool stars. Complex topology, changing structure on many short timescales, activity, field strength correlated with rapid rotation. Field is currently being generated by a dynamo.
  - **fossil fields**, in hot stars. Roughly dipolar topology, structure ~constant over >tens of years, field strength independent of rotation rate. Remnant (fossil) from earlier phase.

Fields in pre-main sequence stars

- Both low and intermediate mass PMS stars pass through "T Tau" (deep convection) phase: rapid rotation, strong dynamo fields, up to ~3 kG (Johns-Krull et al, Donati et al)
- Intermediate and high mass stars may then pass into Herbig AeBe (mostly radiative) phase. Dynamo fields vanish, a few % show weak fossil fields, 10s or 100s of G at surface (Catala et al, Wade et al, Alecian et al)

Classical T Tau star BP Tau: surface & magnetosphere field

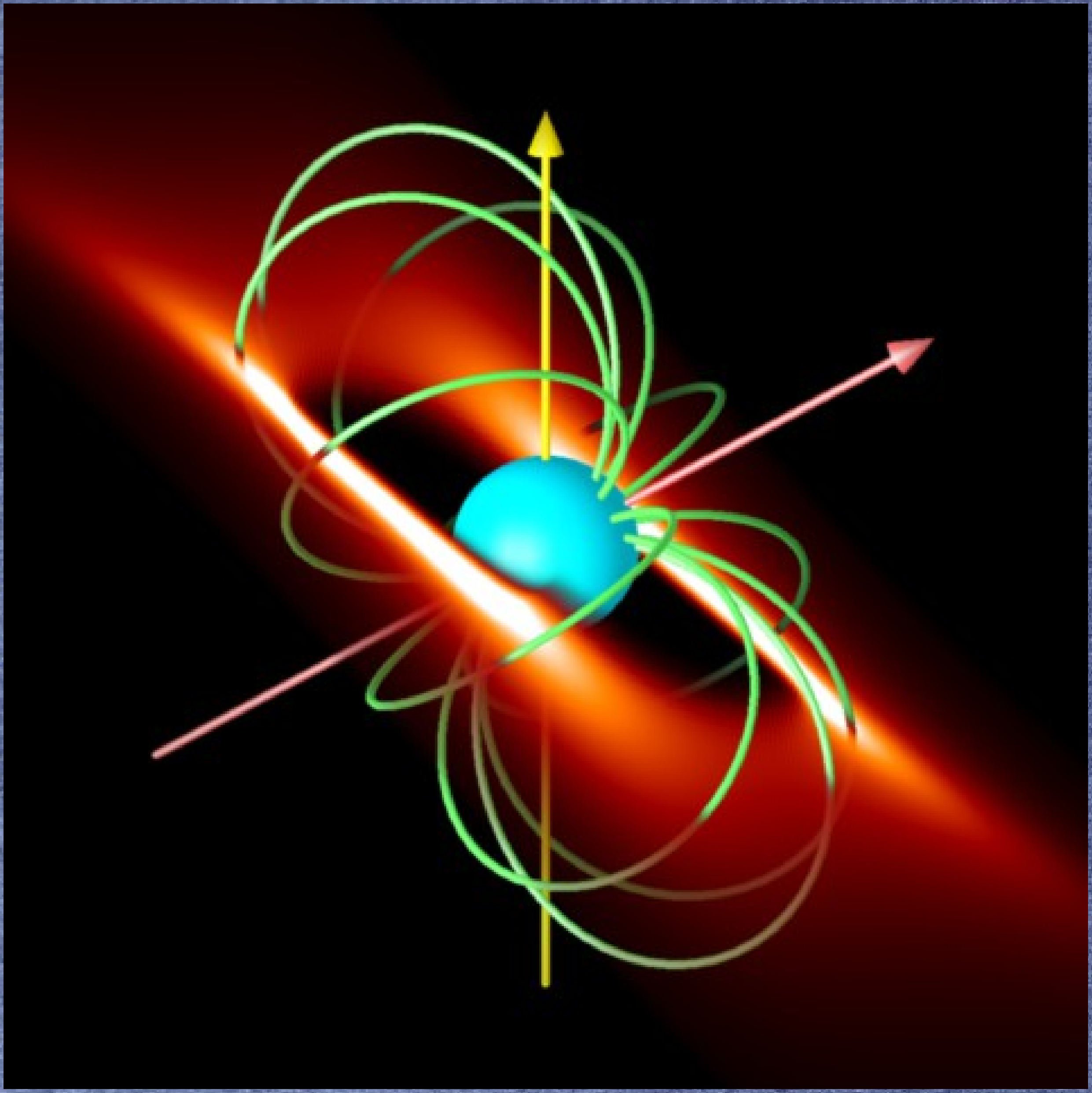


- Donati et al (2008)

Main sequence and evolved stars

- Low mass main sequence stars have dynamos that depend strongly on rotation rate, <~ 3 kG (Donati et al, P. Petit et al, Morin et al,...)
- Small fraction of intermediate and high mass MS stars have fossil fields, B_z ~ 0.1 - 10 kG (Babcock, Preston, Landstreet et al, Mathys, Wade et al (especially MiMeS), SAO group...)
- Massive stars can trap stellar wind in closed fields lines - produce emission lines, eclipses...

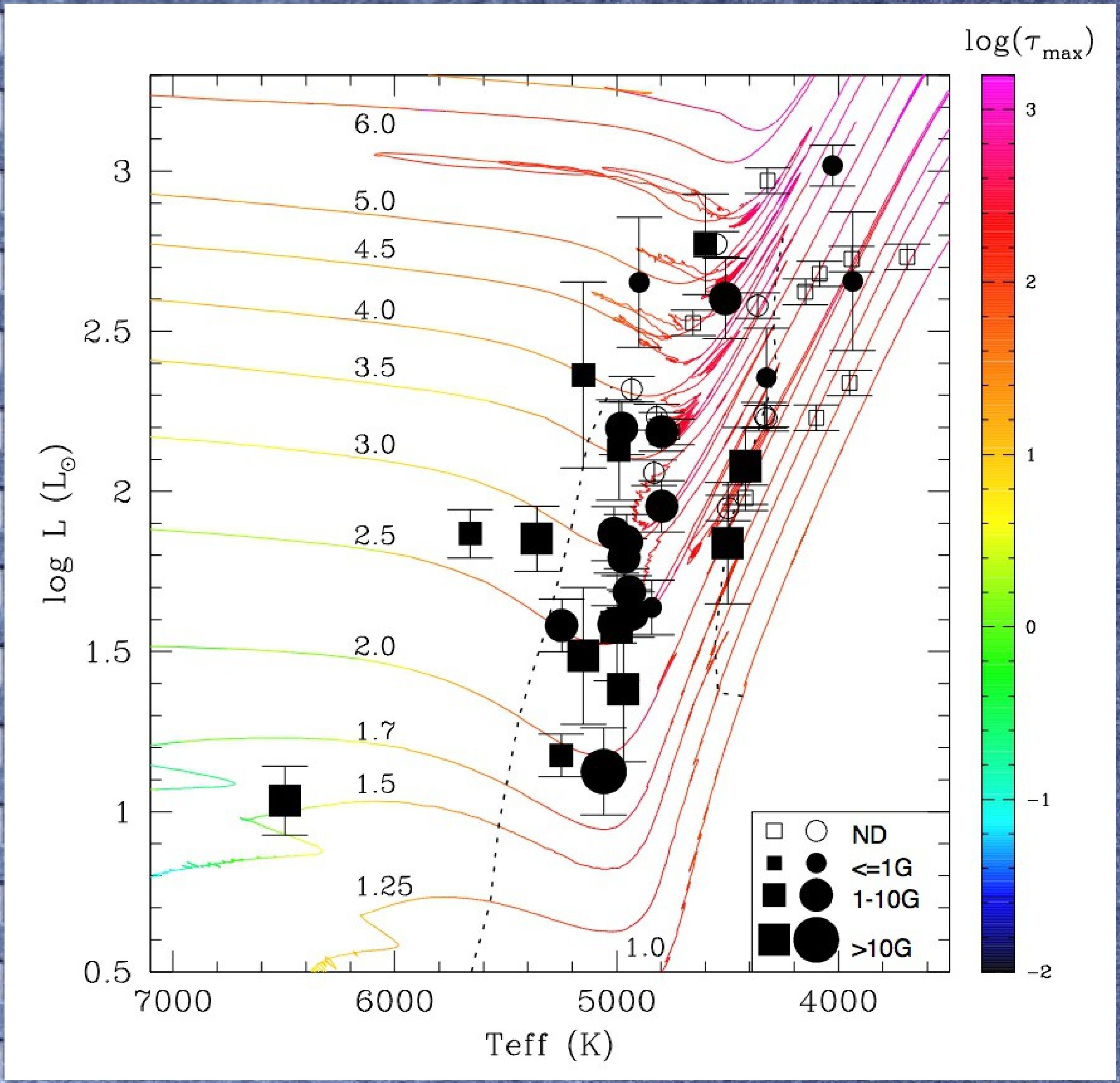
Trapped magnetosphere in σ Ori E



- Phenomenon identified by Landstreet & Borra (1978)
- Recent modelling by Owocki & Townsend

- Red giants have dynamo fields of a few G or less, depending on rotation, but magnetic Ap star descendants have fields of ~10 - 100 G even when rotation is very slow (Auriere et al, Konstantinova-Antova et al)
- Many massive AGB stars have dynamo fields of ~ 1G (Grunhut et al). N.B.: detected giant star fields might be ~1% of local fields...
- Fields **are** detected in most giants that show indirect indicators of magnetism - Ca II H & K line emission, strong X-rays, "rapid" rotation

Magnetic fields in red giants



- Auriere, Konstaninova-Antova, Charbonnel et al (2015)

Collapsed stars

- White dwarfs reveal fields via usual Zeeman effect and/or **continuum** polarisation
- Fields are found in a few % of all white dwarfs. Fields range 10^4 to 10^9 G.
- Field structure roughly dipolar, and the fields are fossils, like those of hot MS stars
- Most or all neutron stars have fossil fields for a while (as pulsars), ranging from 10^9 to 10^{15} G

Global evolution of fields

- Now have observational evidence that (some) fields occur in most major evolution stages
- In low mass stars, current dynamos seem to occur at most stages until final collapse to white dwarf
- In more massive stars, situation is very interesting! T Tau (dynamo) -> Herbig (fossil) -> MS (fossil) -> RG, AGB (dynamo) -> white dwarf or neutron star (fossil). This complex evolution is FAR FROM UNDERSTOOD.

Theoretical framework - 1

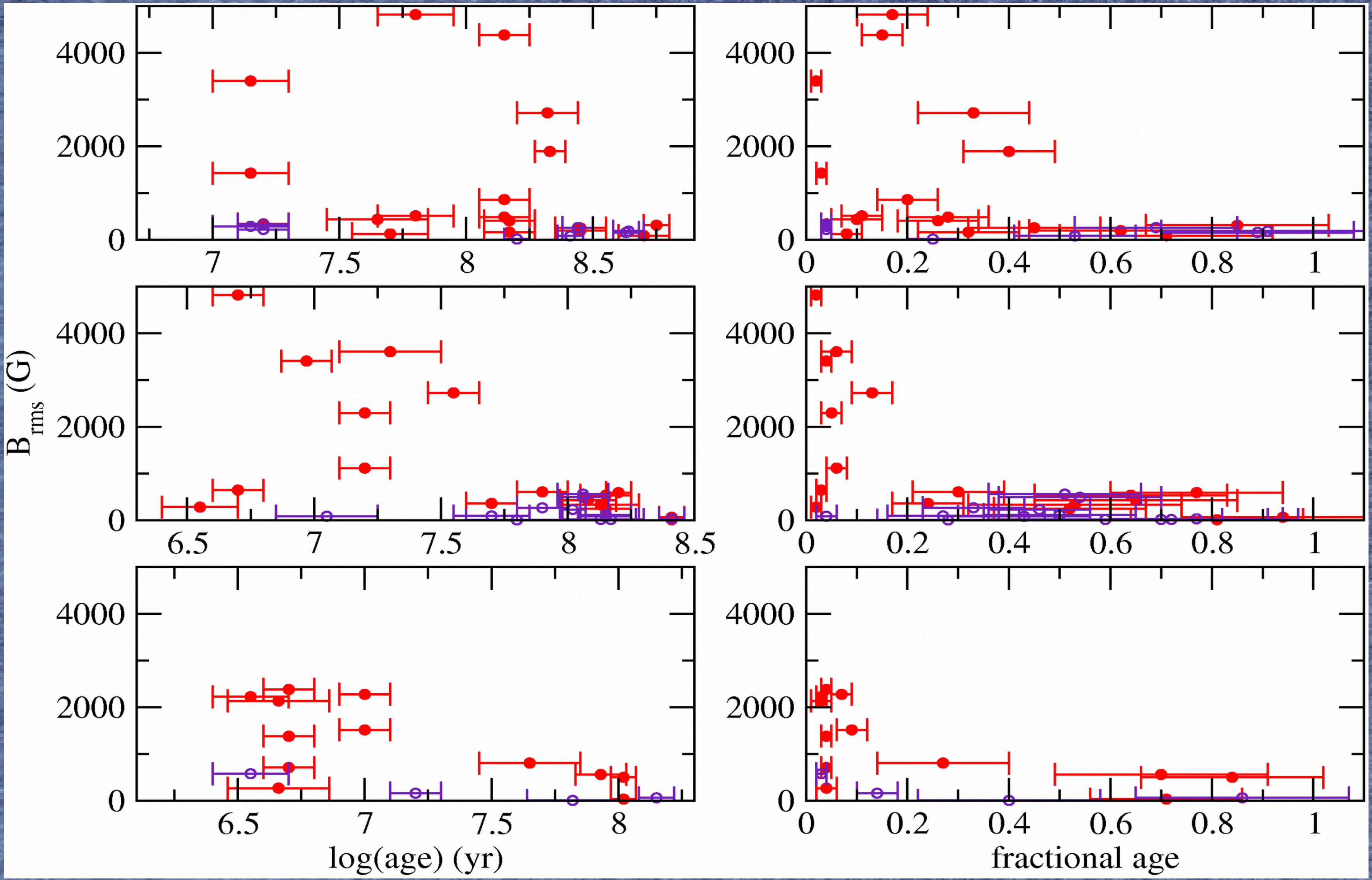
- Surface fields are a consequence of internal electric currents and motions
- In cool stars observed fields may be mainly determined by present convection zone and distribution of angular momentum
- But we see from strong field red giants, thought to be descendants of magnetic Ap stars, that earlier field affects – for a time ? - the current field
- What happens when giant -> hot white dwarf?

Theoretical framework - 2

- In massive stars, high T_{eff} phases clearly lack contemporary dynamo - insufficient convection
- Today's (surface) field is the fossil that results from the field left in star by earlier evolution phases, modified by Ohmic decay, field relaxation, instabilities, stellar structure changes and internal shear flows (Mestel, Moss, Braithwaite, Mathis, Brun...)
- (Some?) fossil fields may be due to evolution in close binary systems

Can we observe field evolution within a single phase?

- With sample of stars of given mass with well-determined relative ages (e.g. fraction of main sequence completed, or evolution position on giant branch) we can observe field evolution **statistically**
- Magnetic evolution of main sequence stars of 2 - 5 M_0 has been found, using a sample of magnetic stars in open clusters of known age



- Using a cluster Ap star sample, Landstreet et al (2008) showed that RMS magnetic field declines with stellar age during MS. top: 2-3 Mo; middle 3-4Mo, bottom 4-5Mo.

Summary

- Magnetic fields affect stellar structure and evolution, and what we observe, so we need to study them
- Fields are now observed in (some) stars in almost all major stages of stellar evolution
- Field evolution during some stages (e.g. MS) can be observed statistically
- Field evolution during single evolution stages, and over stellar lifetime, is NOT WELL UNDERSTOOD – a challenge to theorists