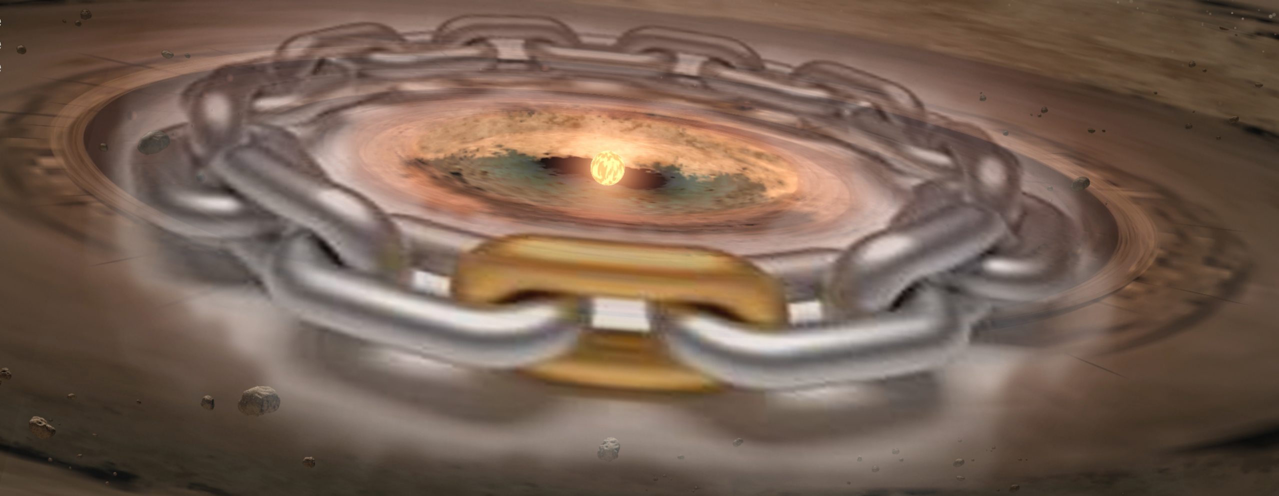

Surface, rotation, and interior of HAeBe stars

E. Alecian
IPAG – Observatoire de Grenoble

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Institut de Planétologie
et d'Astrophysique
de Grenoble

Surf
interior of HAeBe stars

E. Alecian
IPAG – Observatoire de Grenoble

Outline

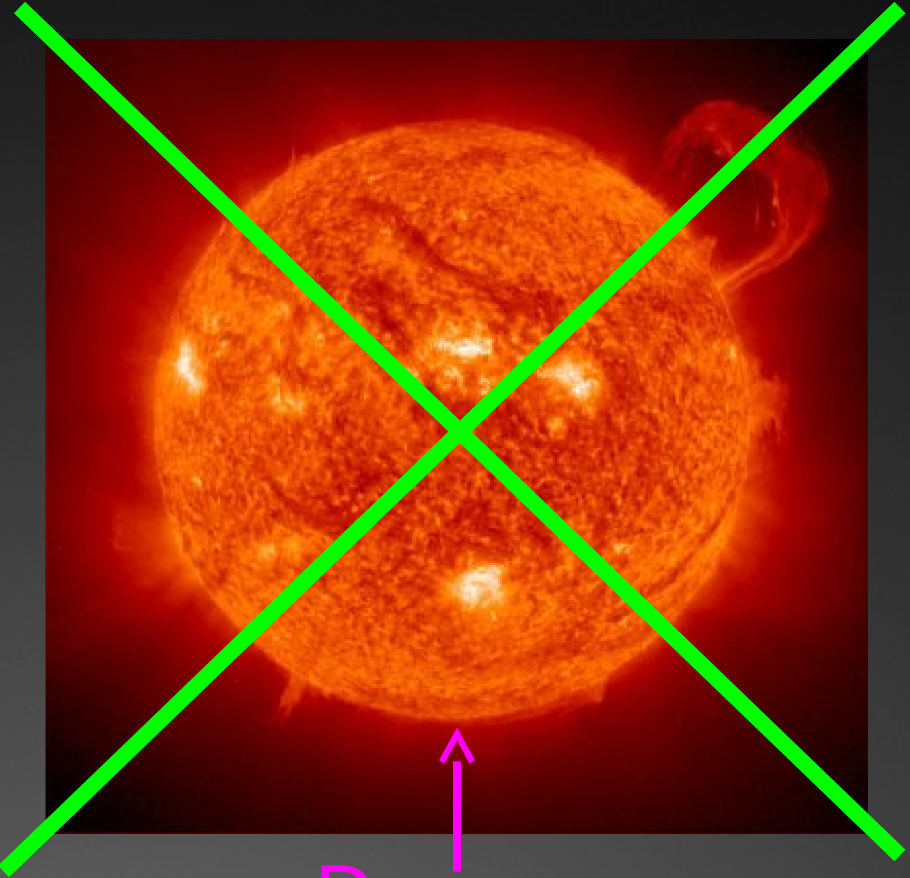
- Introduction
- Magnetic fields
- Rotation
- Chemical abundances
- Summary

Magnetic fields in the MS A/B stars

1.5 < M < 10 M

- Organised
- Strong
- Stable
- Uncorrelated
- Rare (< 10%)

Fossil field

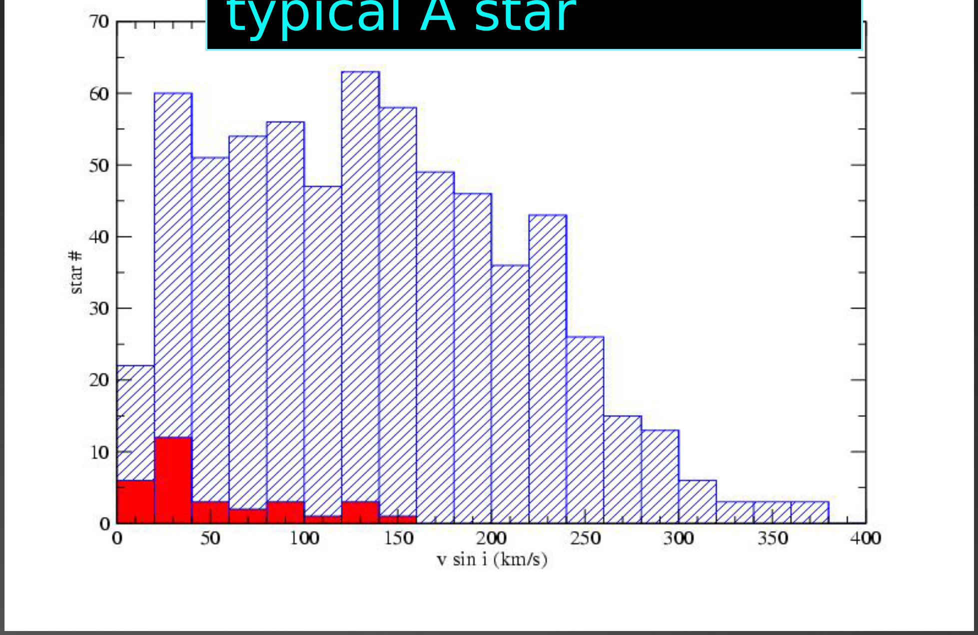


Magnetic fields in the MS A/B stars

1.5 < M < 10 M

- Organised
- Strong
- Stable
- Uncorrelated
- Rare (< 10%)
- In Ap/Bp stars only
- In the slowest rotators

Ultra-slow rotators with ~1% AM of typical A star



On the courtesy of F. Royer (Meudon)

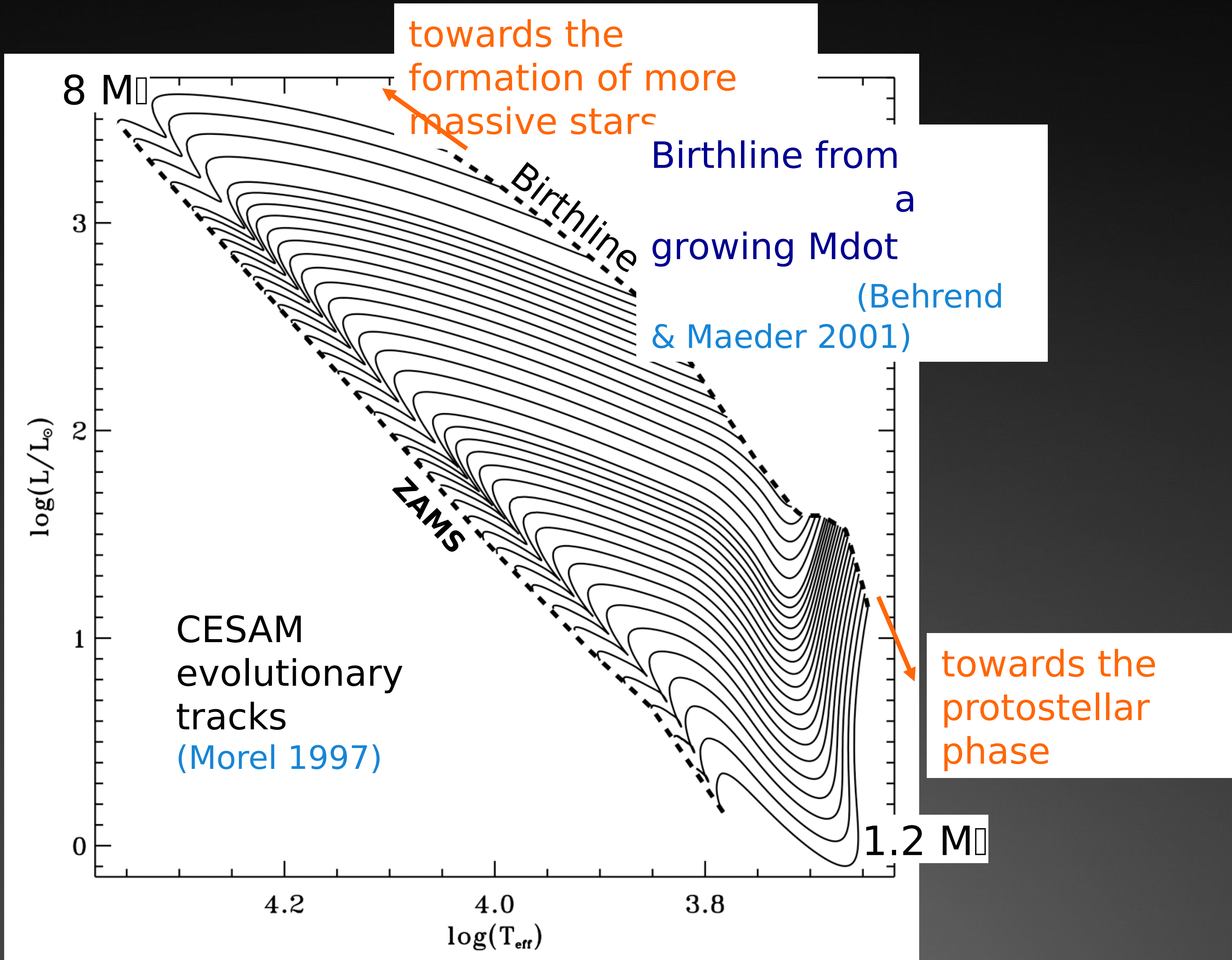
Origin of rotation, magnetic fields, chemical peculiarities in the Ap/Bp stars

- Magnetic fields
  - Fossil field => Accumulated or generated during the star formation (e.g. Borra et al. 1982, Moss 2001)
  - => PMS fossil fields ?
- Low Rotation
  - Magnetic braking during the PMS phase (Stepien 2002)
  - Selection effect during the star formation (e.g. Auriere et al. 2007)
  - => PMS magnetic braking ?
- Chemical peculiarities
  - Atomic diffusion (radiative levitation + gravitationnal settling, e.g. Michaud 1970)
  - => Time-scale ?

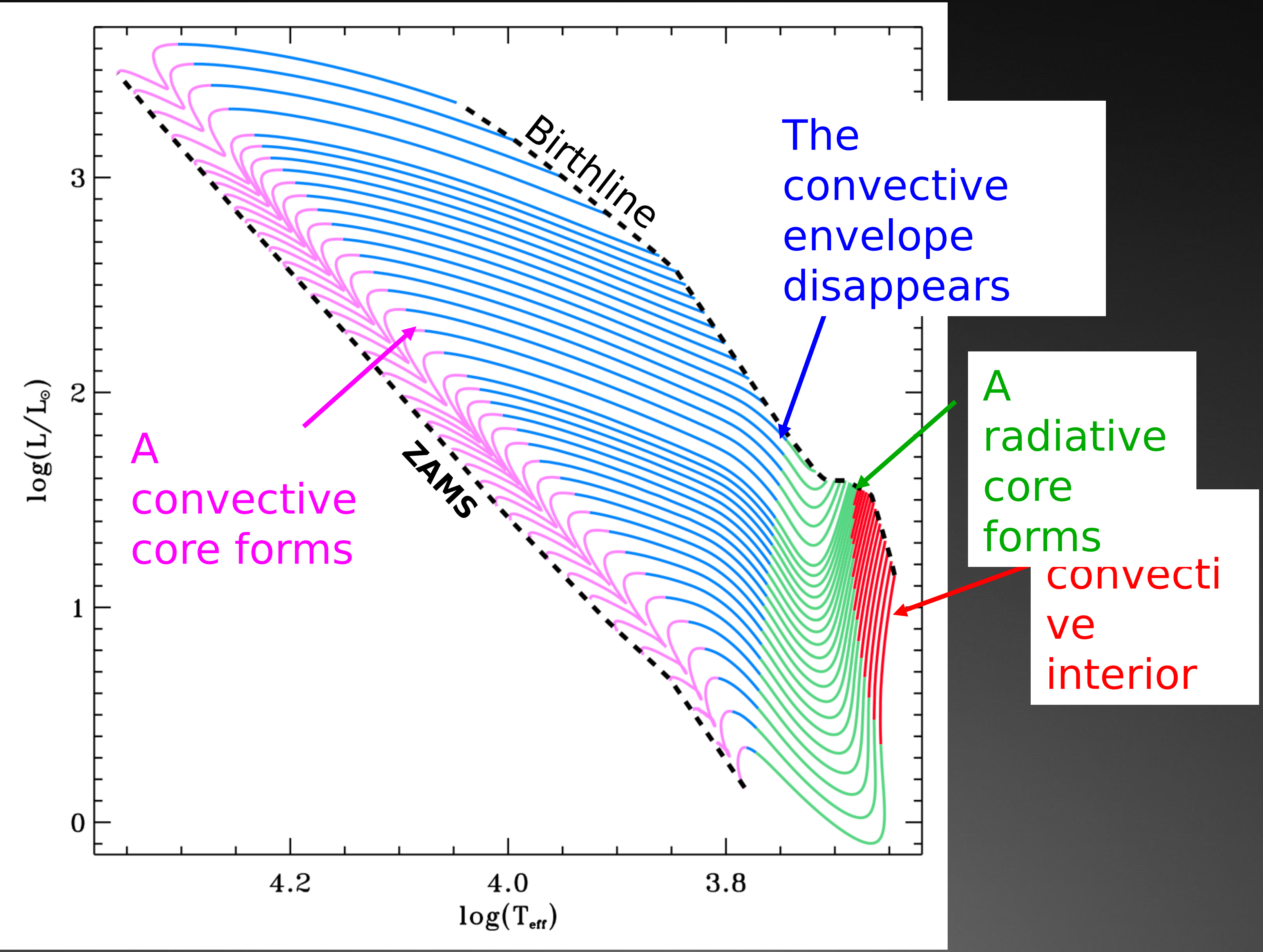
HAeBe stars and their surroundings

- Star-disk interaction
  - Magnetospheric accretion ?
  - X-winds ? Outflows ?
- Disk evolution
  - Accretion onto the star
  - Outflows
  - Photoevaporation
- Planetary formation
  - Migration
  - Stellar winds
- => necessity to study the surface/activity/interior of the HAeBe

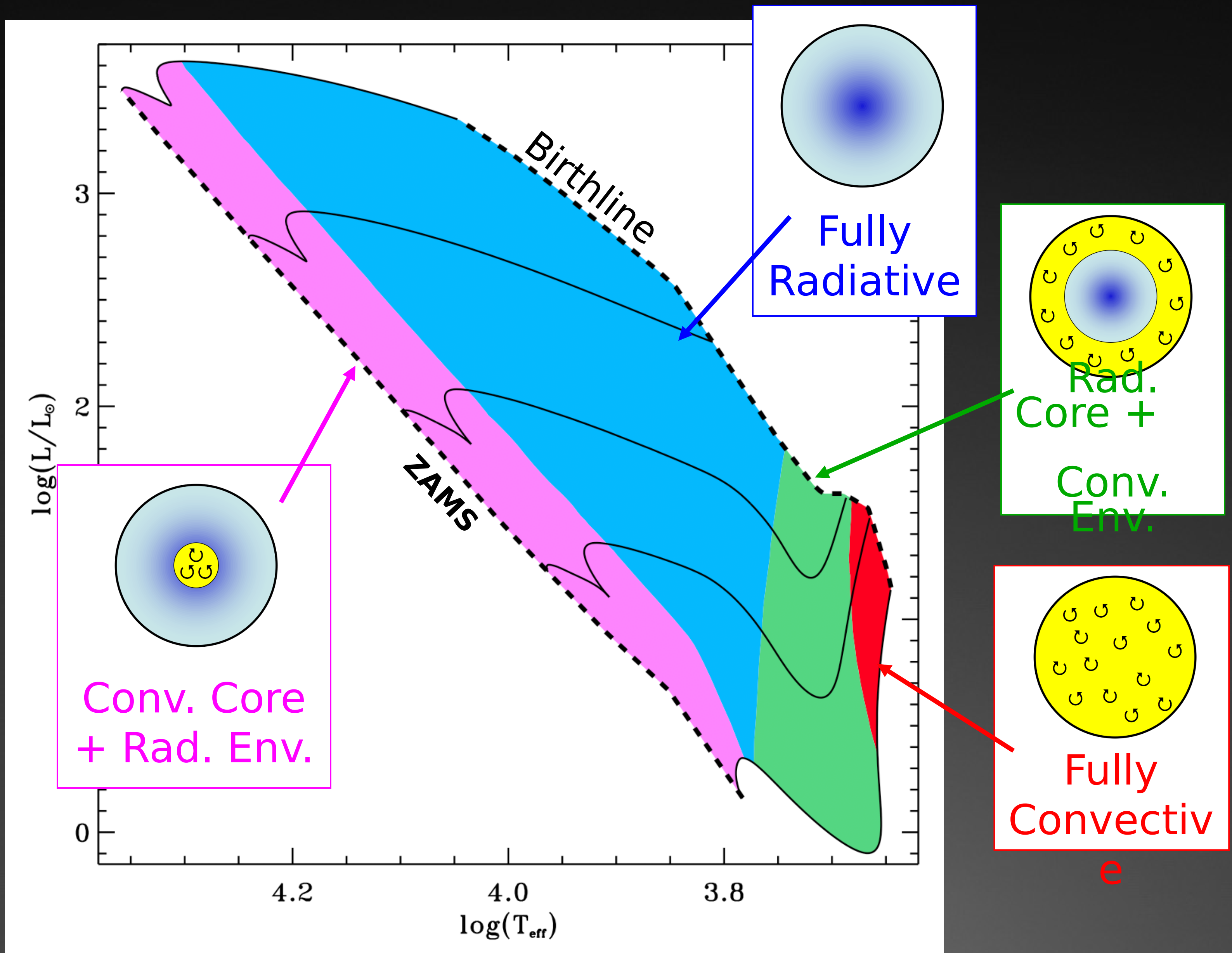
The PMS Evolution at intermediate-mass



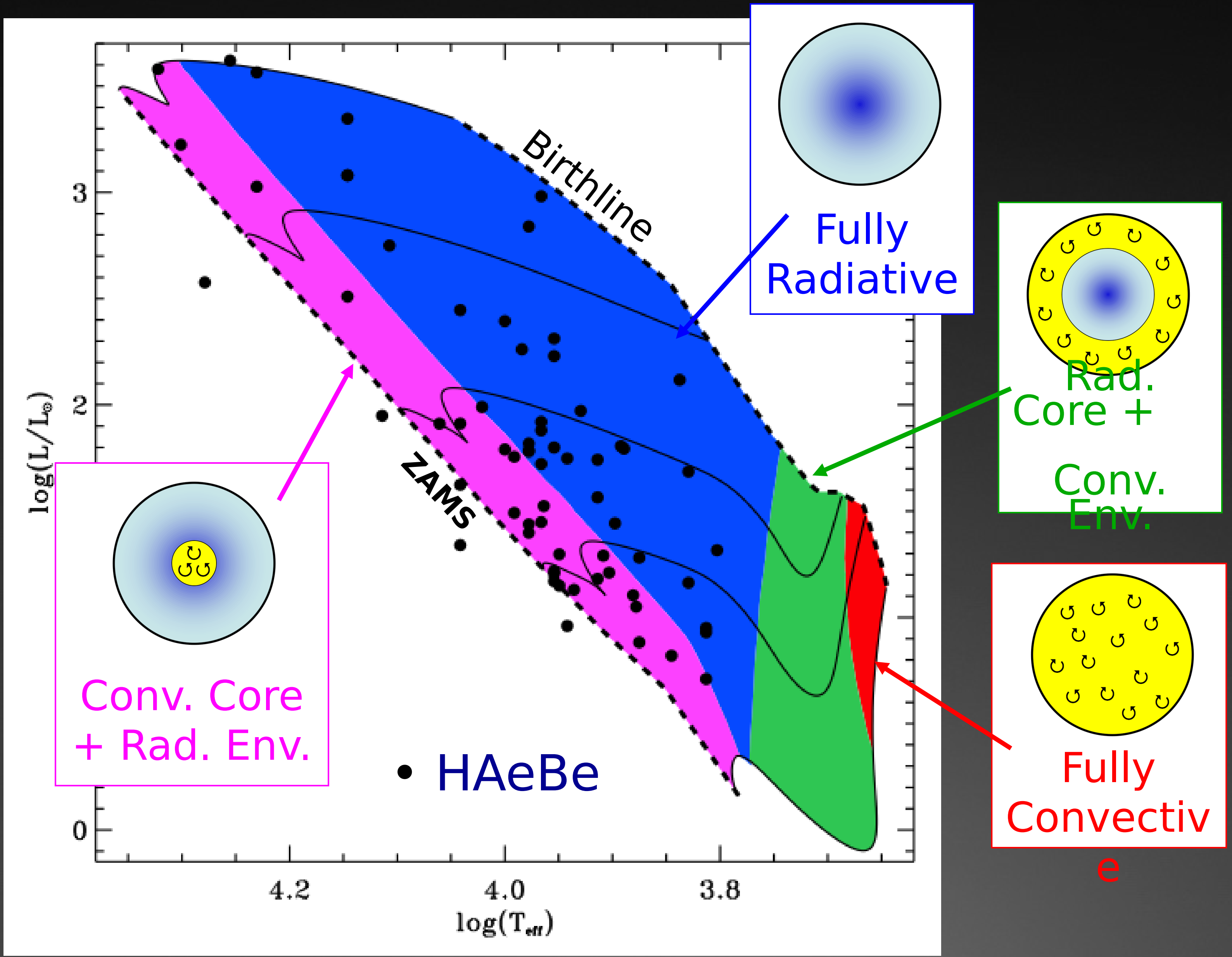
The PMS Evolution at high-mass



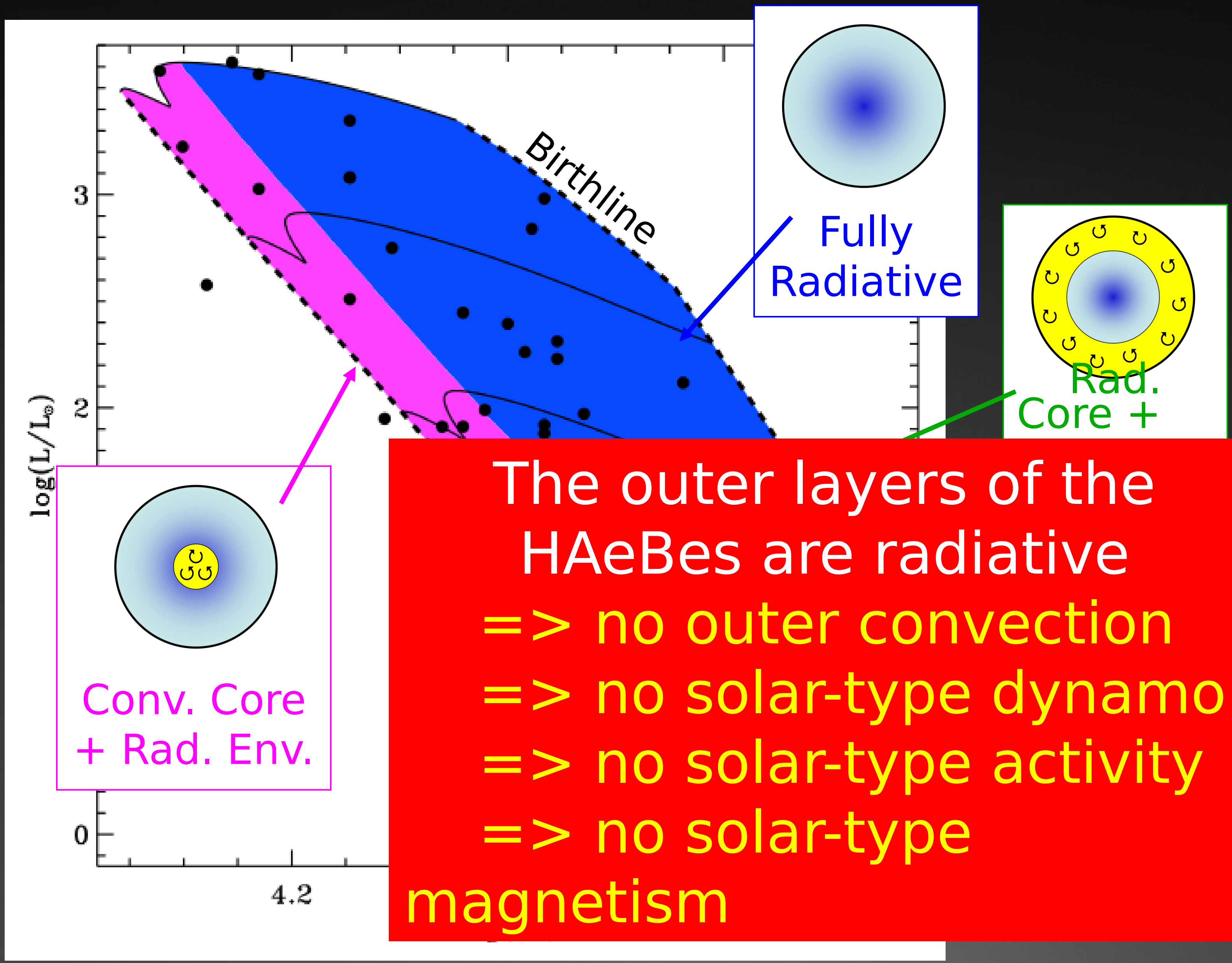
The PMS Evolution at high-mass



The PMS Evolution at high-mass



The PMS Evolution at high-mass



The outer layers of the HAeBes are radiative

=> no outer convection

=> no solar-type dynamo

=> no solar-type activity

=> no solar-type magnetism

Magnetic detections in the HAeBes

Zeeman effect

- if Bl ≠ 0

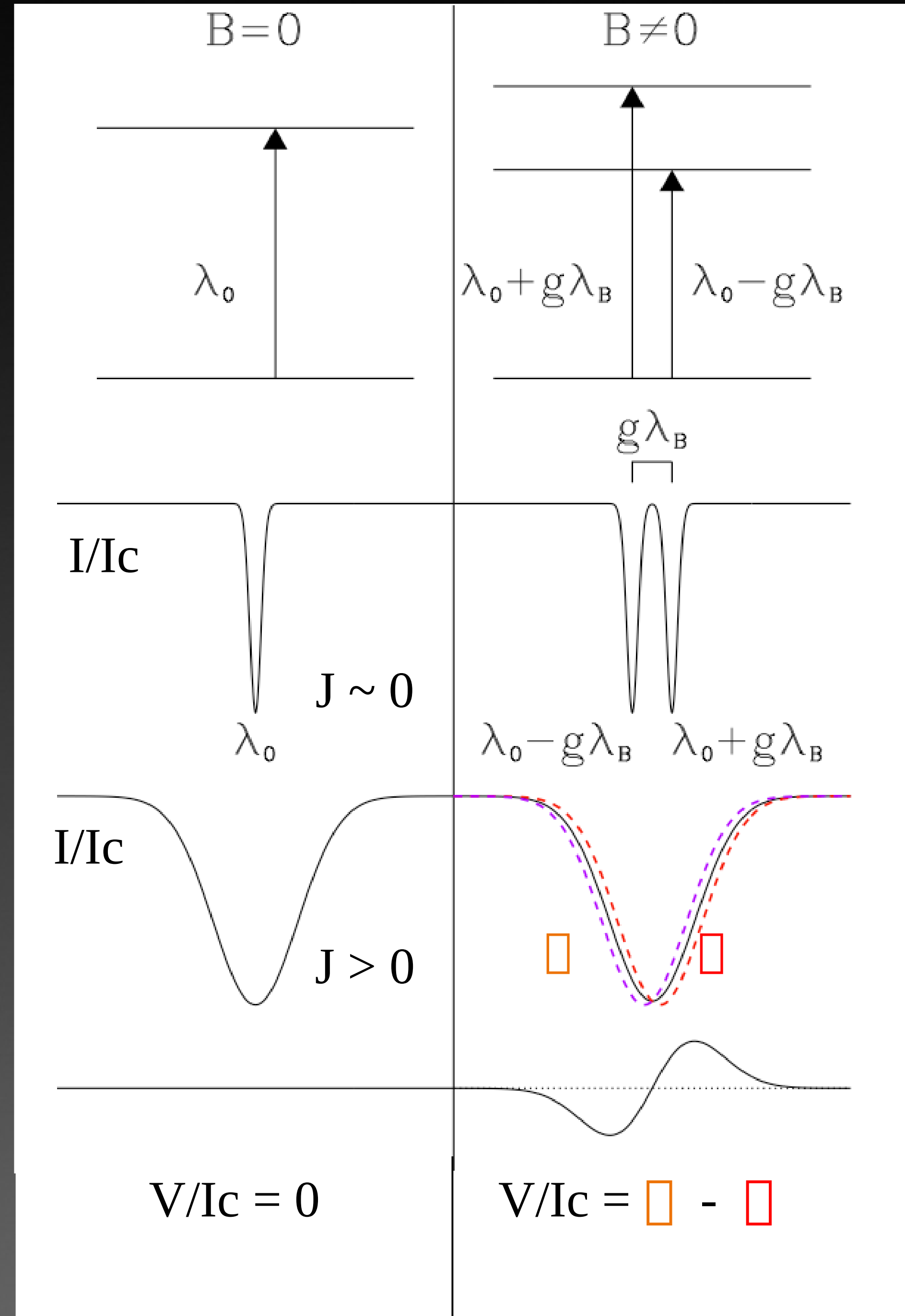
→ circular polarisation in the lines ≠ 0

→ Stokes V parameter ≠ 0

- In the weak field approx. (B<30kG):

$$V = -Cg\lambda (dI/d\lambda) B_l$$

Longitudinal magnetic field



Spectropolarimetric Observations

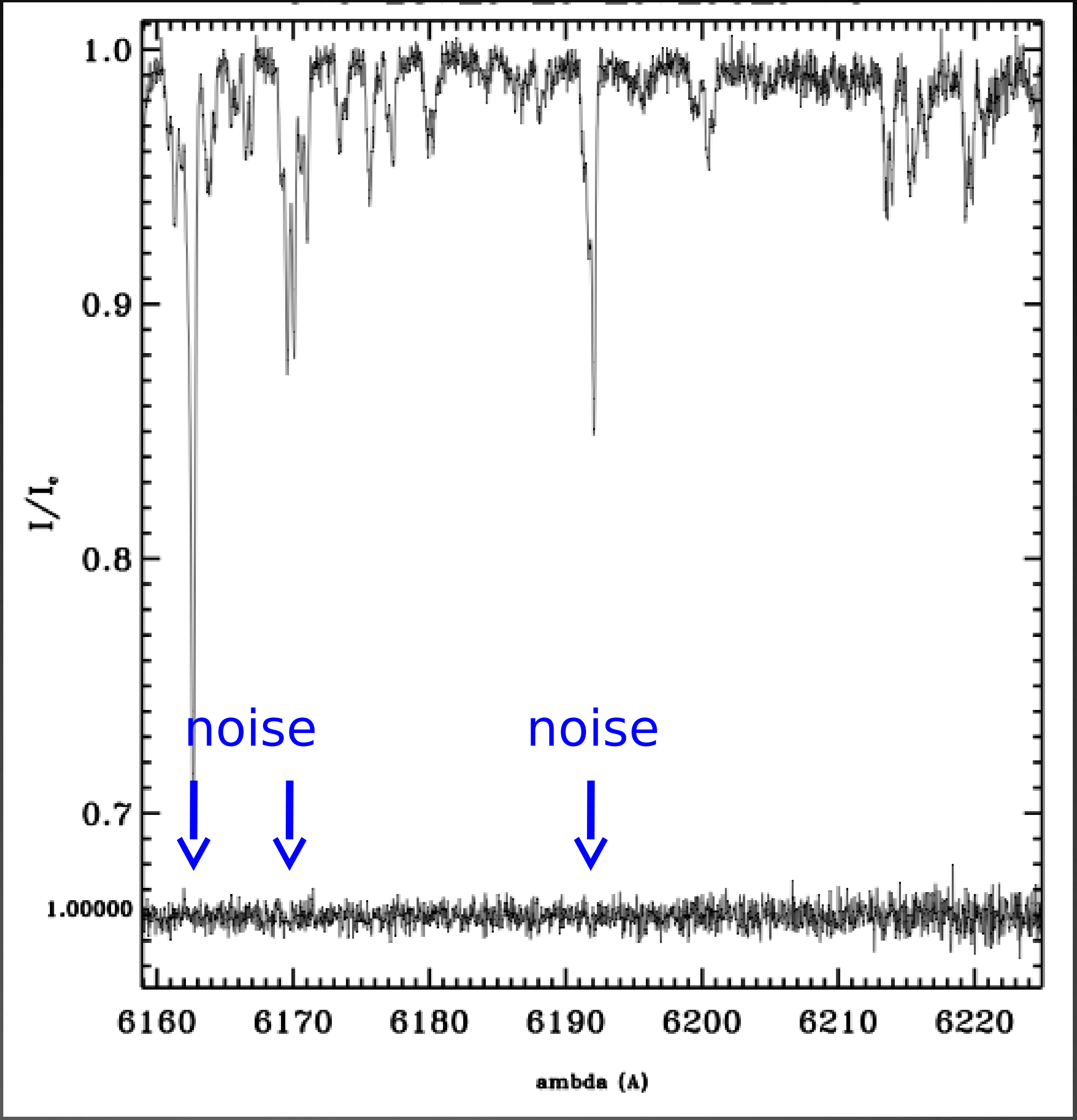
*Low-resolution spectropolarimeter:

FORS@VLT

*High-resolution spectropolarimeter:

~~SEMPOL @ AAT~~
ESPaDOnS @ CFHT
NARVAL @ TBL
HARPSpol @ ESO3.6m

=> Require multi-line analysis



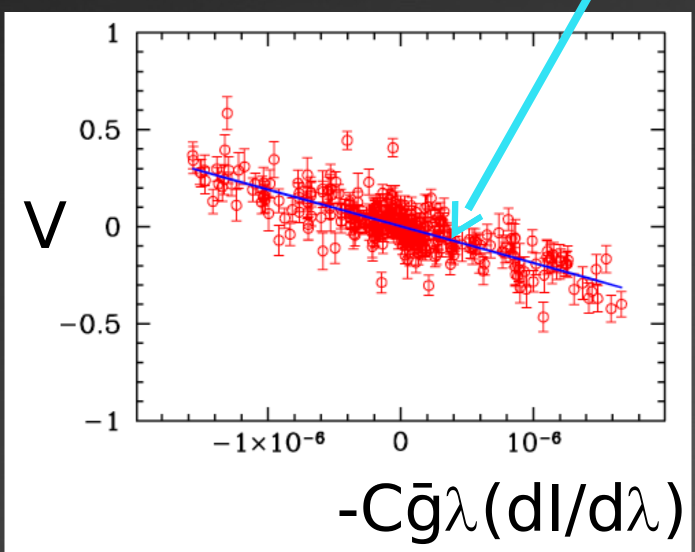
Fields detection techniques

Bl measurement

Moment technique (e.g.Mathys 1991, 1994)

Regression technique (Bagnulo et al. 2002, 2012):

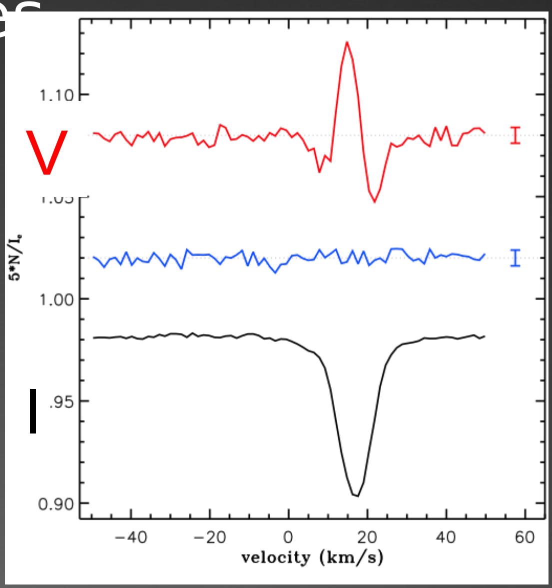
$$V = -C\bar{g}\lambda(dI/d\lambda)\mathbf{Bl}$$



Zeeman signature in V

- PCA (Semel et al. 2006), SVD (Carroll et al. 2012)
- LSD technique (Donati et al. 1997) :

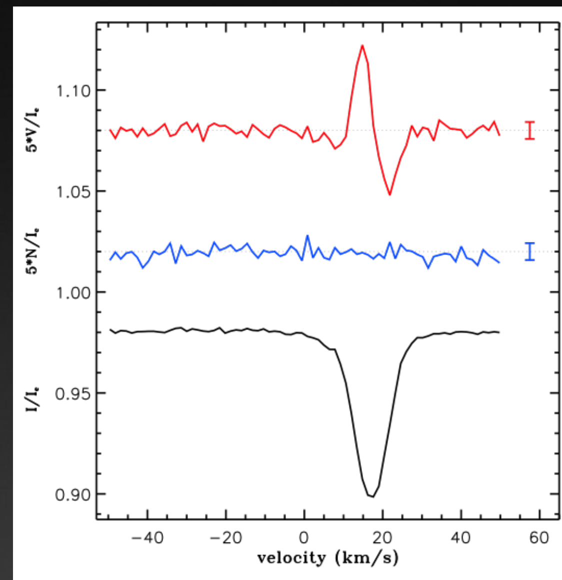
  weighted mean of the lines



Bl measurement vs Zeeman signature

Bl = 249 ± 49 G

Probably magnetic

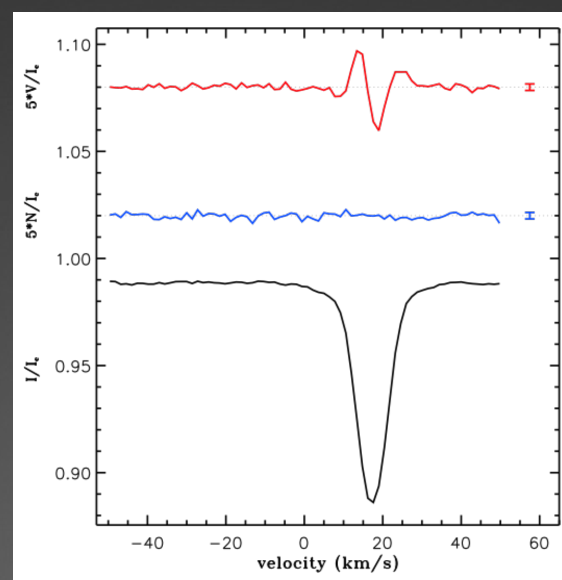


Typical Zeeman signature

No spurious polarisation

Bl = 15 G

Bl ≈ 0 G



Typical Zeeman signature

No spurious polarisation

Magnetic detection claims (1)

- Low-resolution spectropolarimeter
  - FORS/VLT
  - Regression technique => only Bl (Hubrig et al. 2004-2011, Wade et al. 2005, 2007)
  - Many detections not confirmed with high-resolution spectropolarimetry
  - Bagnulo et al. (2012) : reanalysed all FORS measurements
  - => FORS data measurements are ambiguous
  - => FORS error bares are underestimated by ≈50%
  - => FORS performs best for Bl > 300 G
  - list all confirmed, probable, and not confirmed magnetic HAeBe stars

Magnetic detection claims (2)

- High-resolution spectropolarimetric data
  - LSD technique => Zeeman signature (Donati et al. 1997, Wade et al. 2005, Catala et al. 2007, Alecian et al. 2008, 2013)
  - Moment technique => Bl only (Hubrig et al. 2013)

		Hubrig et al. (2013) Moment technique			Alecian et al. LSD	
ID	SNR	# lines	Bl (G)	sig(Bl) (G)	# lines	sig(Bl) (G)
HD 58647	437	18	218	60		
HD 98922	379	18	-131	42	541	155
HD 104237	170	18	65	15		
HD 190073	162	18	91	18	1051	21

Bl ≈ 0 G

nderestimated by a factor of 3 at least

ased on MT applied by other authors, e.g. Mathys 1994)

How to solve the controversies ?

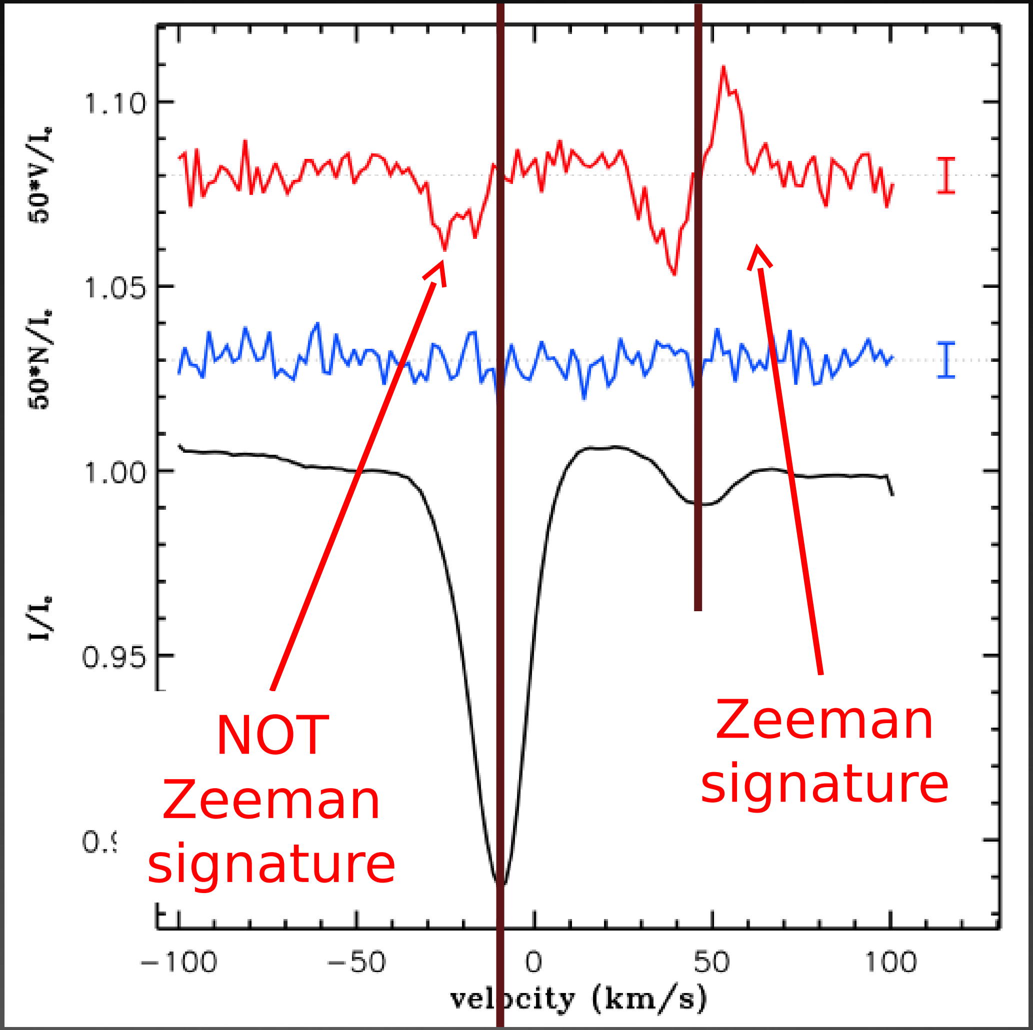
- Repeated detections using different instruments
- Confirmations by independent teams
- High-resolution Stokes V signatures + proper physical interpretation

HD 104237

V =
-Cḡλ(dI/dλ)BI

0th moment of V should be ≈0

Signature in the primary is most likely spurious (e.g. pulsations)



Confirmed magnetic HAeBe stars

- In the 'field' of the Galaxy
  - HD 104237 (=DX Cha) (Donati et al. 1997, Alecian et al. in prep.)
  - => Magnetic field in the IMTTS companion
  - => Magnetic field not yet confirmed in the primary Herbig Ae
  - HD 101412 (Wade et al. 2005, Bagnulo et al. 2012)
  - V380 Ori (Wade et al. 2005)
  - HD 72106 A (Wade et al. 2005)
  - => ZAMS star
  - HD 190073 (=V1295 Aql) (Catala et al. 2007)
  - HD 200775 (=MWC 361) (Alecian et al. 2008a)
  - => Magnetic field in the primary only
- In young clusters
  - NGC 6611 601 (Alecian et al. 2008b)
  - NGC 2244 201 (Alecian et al. 2008b)
  - NGC 2264 83 (= HD 47777) (Alecian et al. 2009)
  - LP Ori (= HD 36982) (Petit et al. 2008)

Magnetic properties of the HAeBes

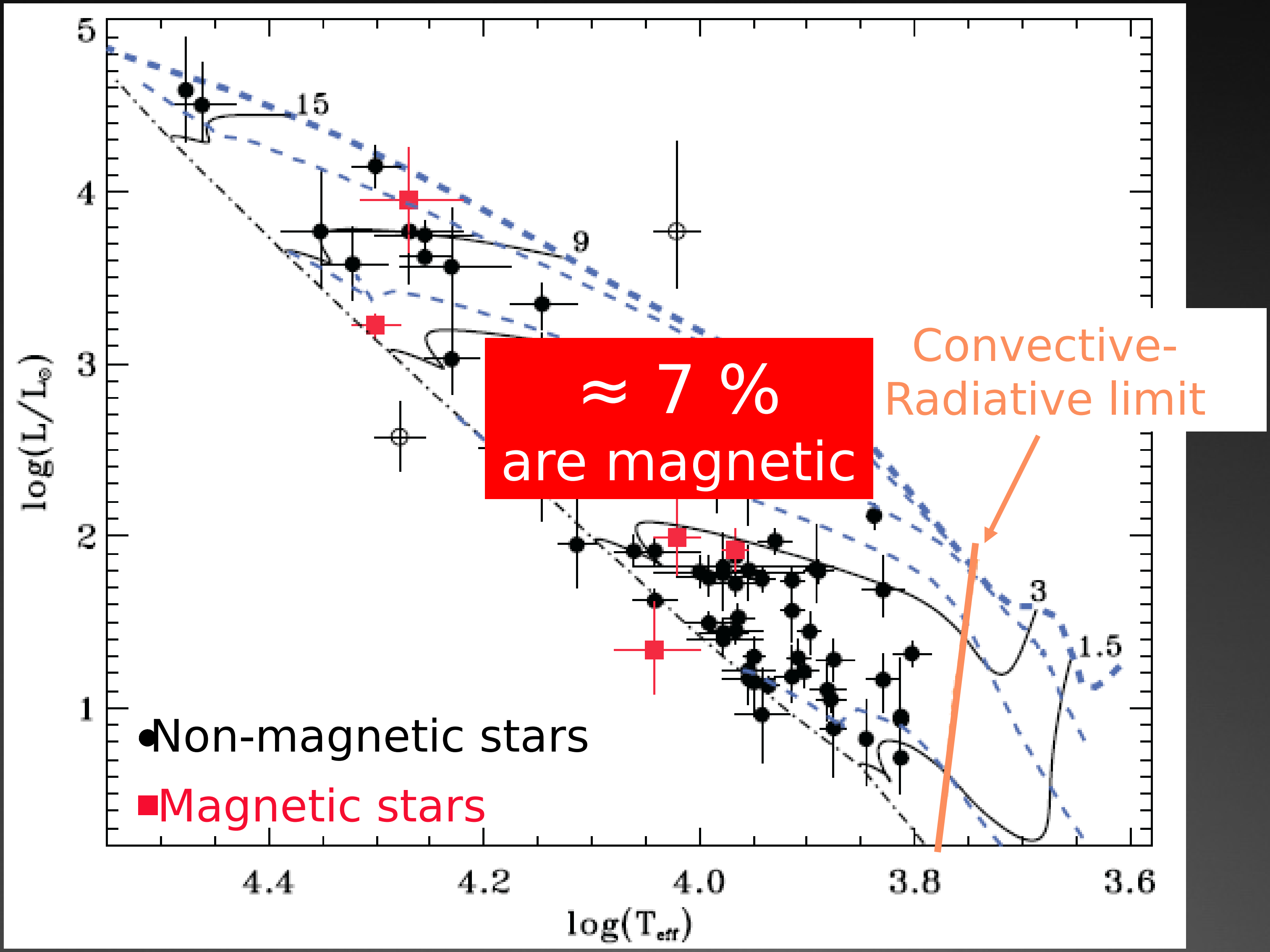
The Herbig Ae/Be survey

Alecian et al. 2013a

- The sample:
  - 70 HAeBe stars (from Thé et al. 1994, and Vieira et al. 2003)
  - Mass range: 1.5 – 15 $M_{\odot}$
- Observations:
  - ESPaDOnS @ CFHT
  - Narval @ TBL
  - ≈130 spectropolarimetric data
- Analysis
  - LSD technique => detection
  - Time series of the magnetic stars + fit => characterisation
- Results in: Wade et al. (2005), Catala et al. (2007), Alecian et al. (2008a), Folsom et al. (2008), Alecian et al. (2013a)

The Herbig Ae/Be survey

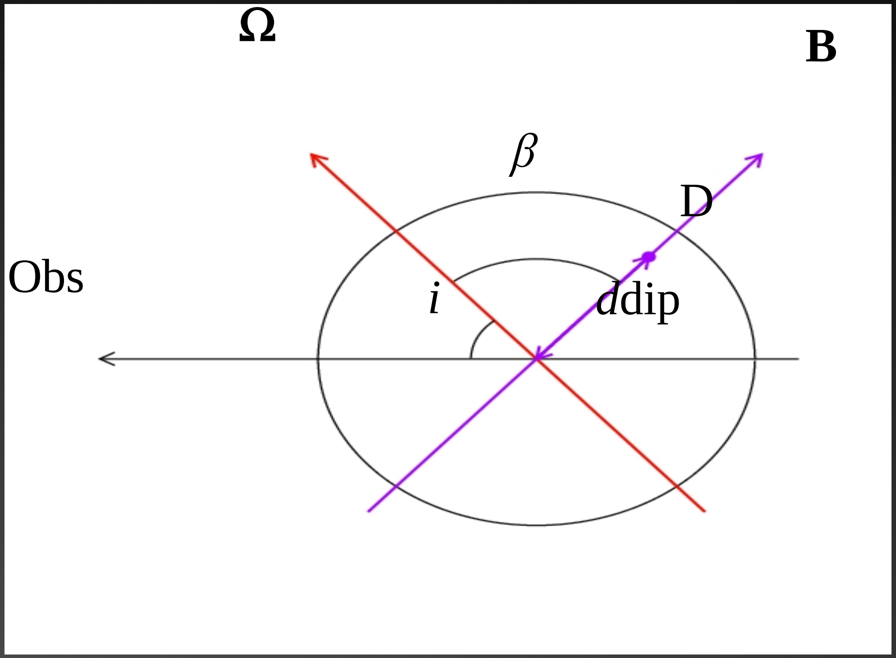
Alecian et al. 2013a



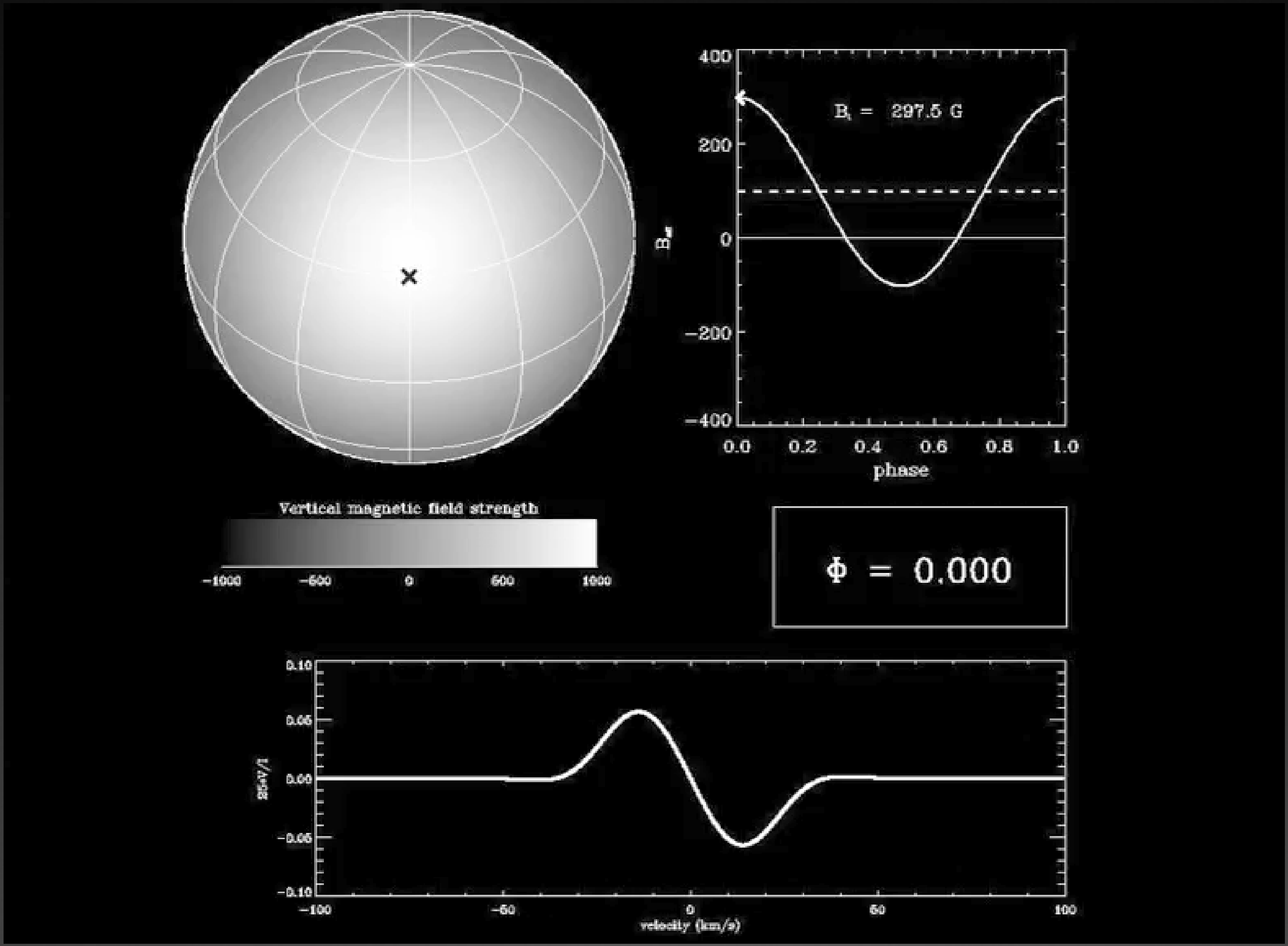
Oblique rotator model

Stibbs 1950

- Inclined dipole (at center D)
- Stokes V depends on:
  i, β, ϕrot, BP, ddip
- => grid of V profiles
- => χ2 minimisation



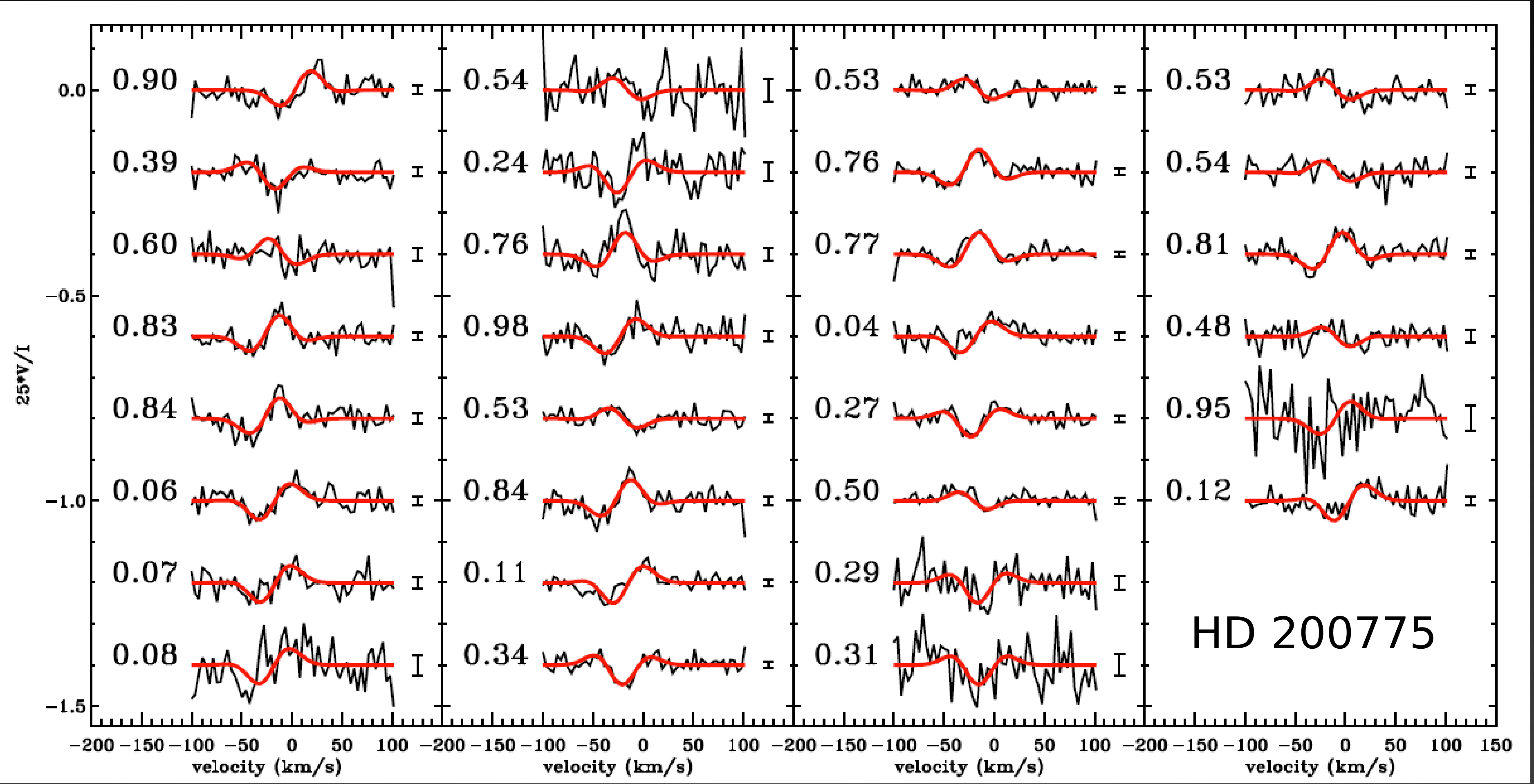
Oblique rotator model



Time series + fit

HD 200775

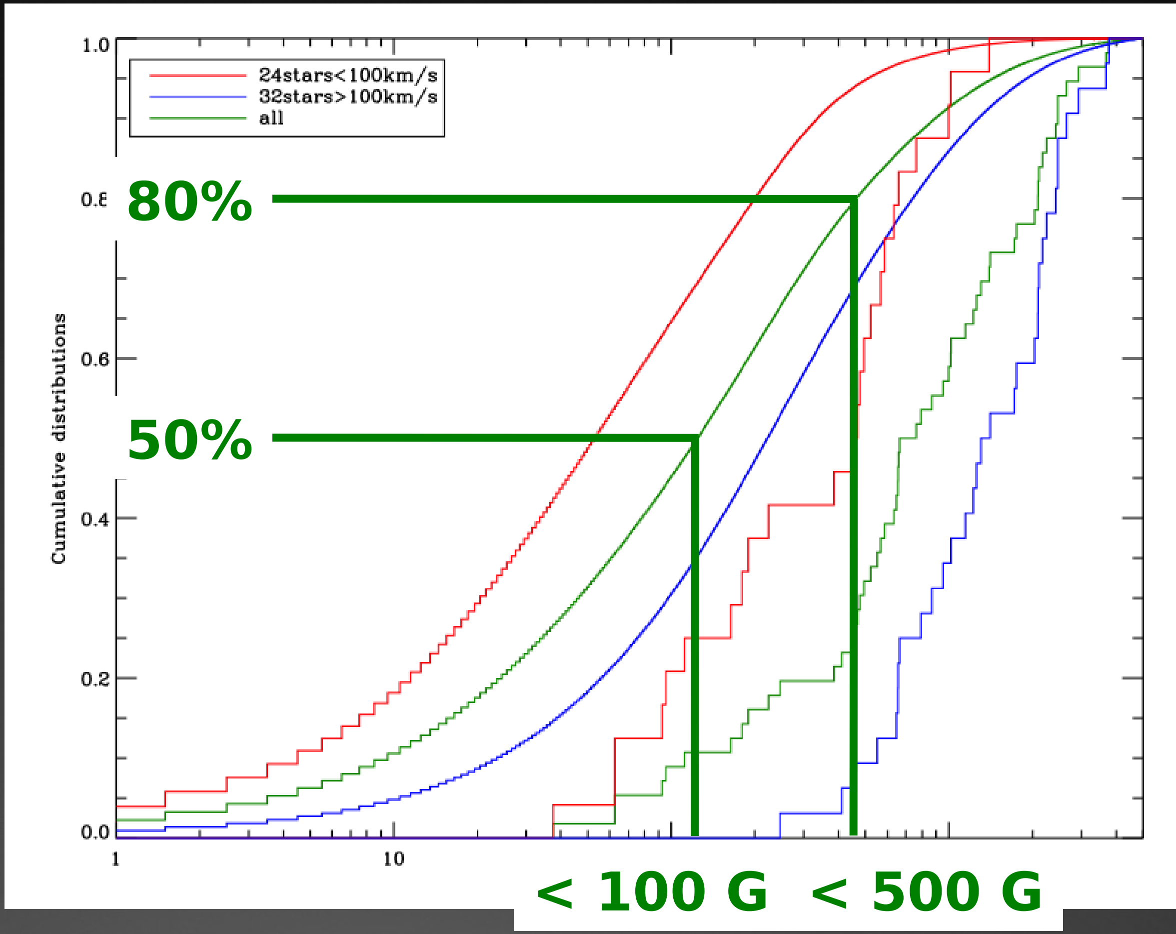
Alecian et al. (2008a)



P = 4.3281 d. i = 60 ° β = 125° Bd = 1000 G ddip = 0.05 R*

The non-magnetic stars
Bayesian analysis

- Hypotheses:
  - Large-scale fields
  - Random geometry
  - Random ϕrot
- =>Distributions of BP
- All vsini
  - BP < 500 G in 80%
  - BP < 100 G in 50%
- vsini < 100 km/s
  - BP < 200 G in 80%
  - BP < 50 G in 50%



Petit, Alecian, Wade et al., in prep.

HAeBe magnetic properties

- Dominantly dipolar
- Bp > 300 G, bulk at ≈ 1 kG
- Stable over few years
- => Fossil fields
- Magnetic flux in HAeBe ≈ Magnetic flux in Ap/Bp
- Rare (in about 7% of the HAeBe stars)
- => Fossil link established between the PMS and MS
- => Magnetic fileds originate in earlier phases
- 50% of the ‘non-magnetic’ stars have BP < 100 G

Rotation properties and evolution in the HAeBe stars

Previous studies

- Böhm et al. (1995) : *v*sin*i* Herbig vs *v*sin*i* MS stars

$\Omega(r) = cst$ → AM loss if $M < 2.6\ M_\odot$; AM cst if $2.6\ M_\odot < M < 4\ M_\odot$; AM gain if $M > 4\ M_\odot$

AM cst ∀M ← $\Omega(r) = r^{-2}$

- Wolff et al. (2004): *v*sin*i* of Orion stars

$M > 1.5\ M_\odot$: AM loss before PMS

AM cst on PMS radiative tracks

- Martayan et al. (2008): *v*sin*i* PMS vs MS B stars in NGC 6611

*v*sin*i* in MS is ≈ 20% lower than in PMS stars

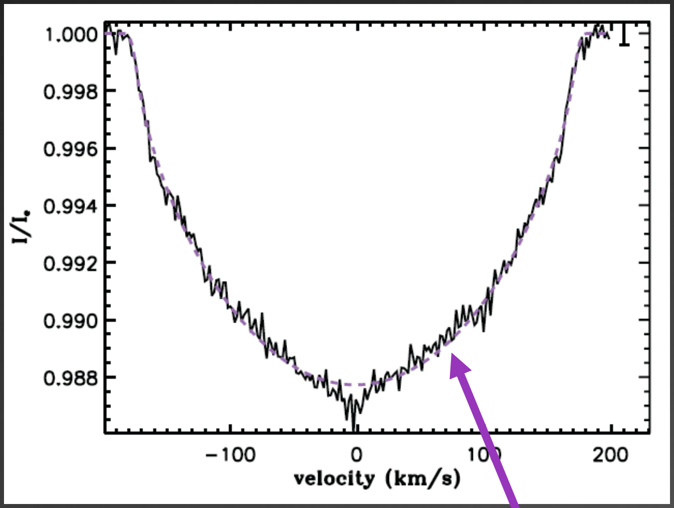
=> AM loss during the PMS phase for B stars

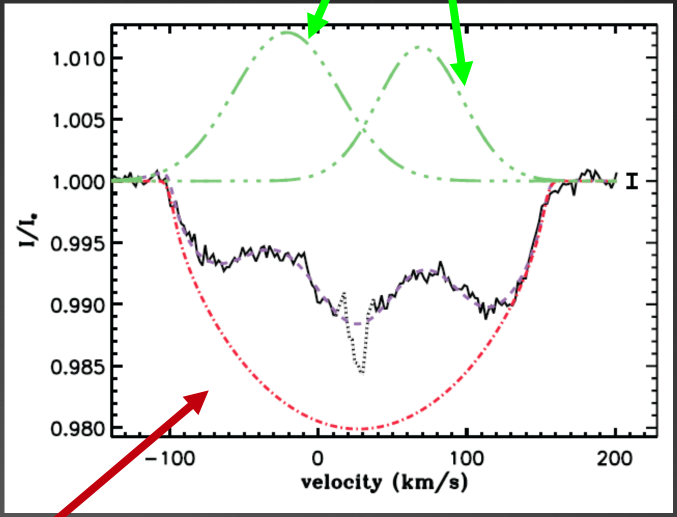
The Herbig Ae/Be survey

- Rotation analysis:
  - vsini from the LSD I profiles
  - Teff, Luminosity
  - Age, M, R, Rzams, from the HR diagram

Alecian et al. (2013a)

CS Gaussians



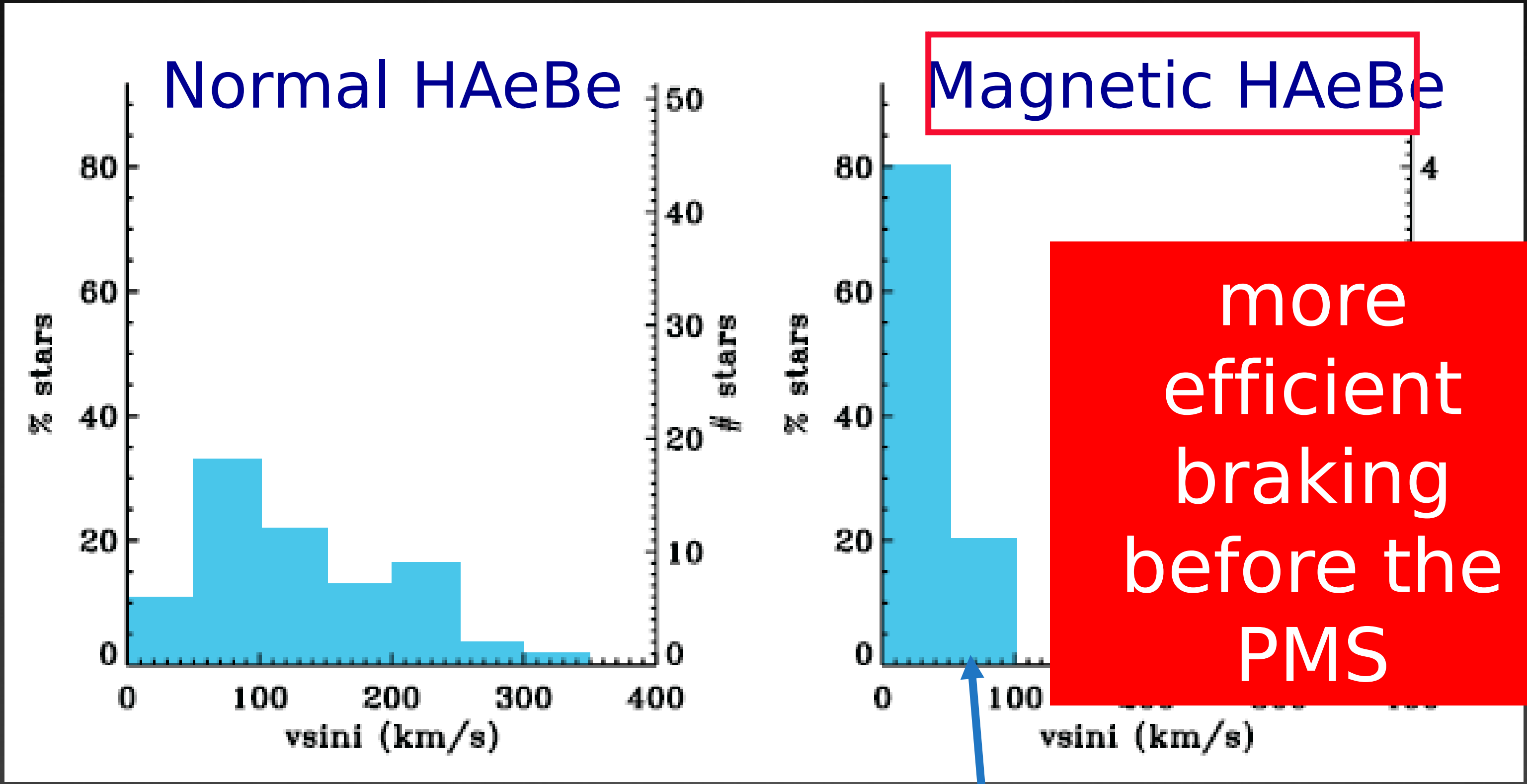


Photospheric profiles (Gray 1992)

Magnetic vs non-magnetic

Alecian et al. (2013b)

*v*sin*i* distributions



more efficient braking before the PMS

normal
=
non-magnetic and non-binary

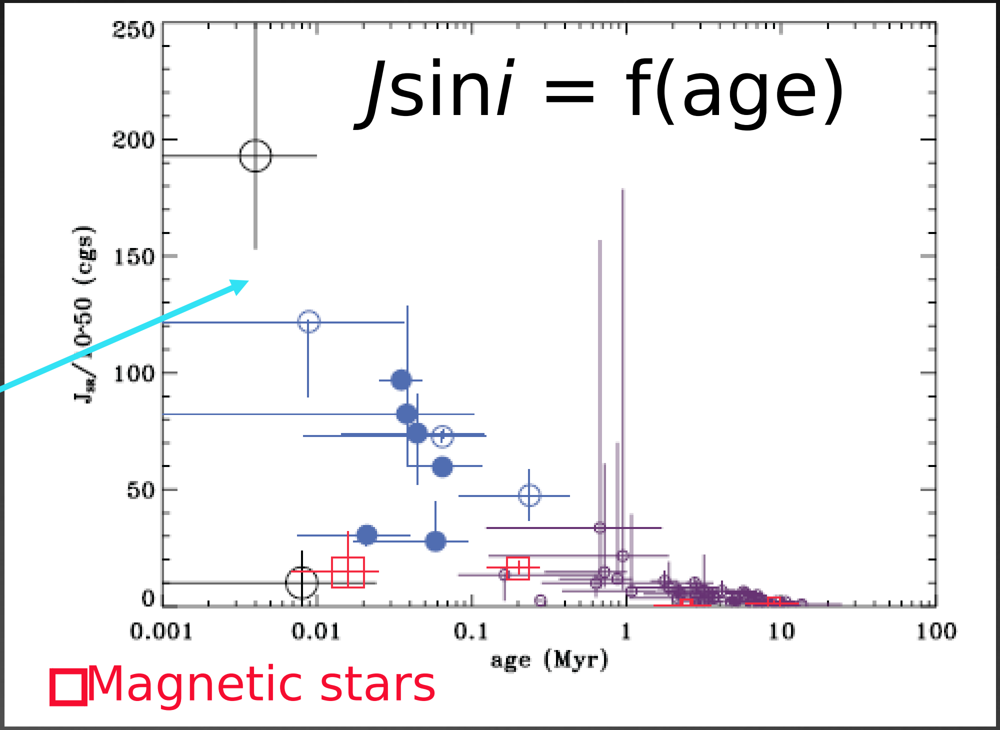
Prot > 1 d
⇒ no sin*i* effect

AM evolution
Normal sample

- Two hypotheses
  - Solid body rotation
  - Ω (r) = cst
  - Constant Specific AM
  - Ω (r) = r-2

⇒ both give similar results

- 0 < *J*sin*i* < max
- max = f(age)
  - M > 5 $M_\odot$
    real trend
  - M < 5 $M_\odot$
    not real (age-M relation)



Alecian et al. (2013b)

Rotation properties and evolution

- Magnetic HAeBe more efficiently braked than normal HAeBe
  - magnetised winds ? selection effect during the star formation ?
- Massive ($M > 5 M_\odot$) Normal sample:
  - evidence of AM loss
  - 70% show either P Cygni or strong blueshifted absorption components in wind sensitive lines in the optical or UV
  - winds in massive HAeBe can have a stronger effect than in low-mass HAeBe
- Low-mass ($M < 5 M_\odot$) Normal sample:
  - no evidence of AM loss
  - most of the sample have completed more than 50% of the PMS
  - too old to study their PMS AM evolution

Alecian et al. (2013b)

Chemical abundances

Previous studies

- Acke & Waelkens (2004) :
  - Analysis of 14 HAeBe stars
  - Method: equivalent width measurement
  - => One show clear λBoo patterns (HD 100546)
  - => One show probably λBoo patterns (AB Aur)
  - => One show depletion in many metals (HD 139614)
  - => All other ones have solar abundances

- Other studies
  - HD 101412 : λBoo patterns (Cowley et al. 2010)
  - HD 190073 : chemically normal (Cowley & Hubrig 2012)

The Herbig Ae/Be survey

- Folsom et al. (2012) :
  - Analysis of 20 HAeBe stars
  - Method: consistent spectral fitting of Teff, logg, and abundances
  - About 50% (11 stars) show λBoo patterns
  - One show weak Ap patterns
  - The others are chemically normal
  - No correlation between magnetic fields and λBoo patterns

λBoo Patterns:
Normal CNO abundances
Depleted iron-peak elements

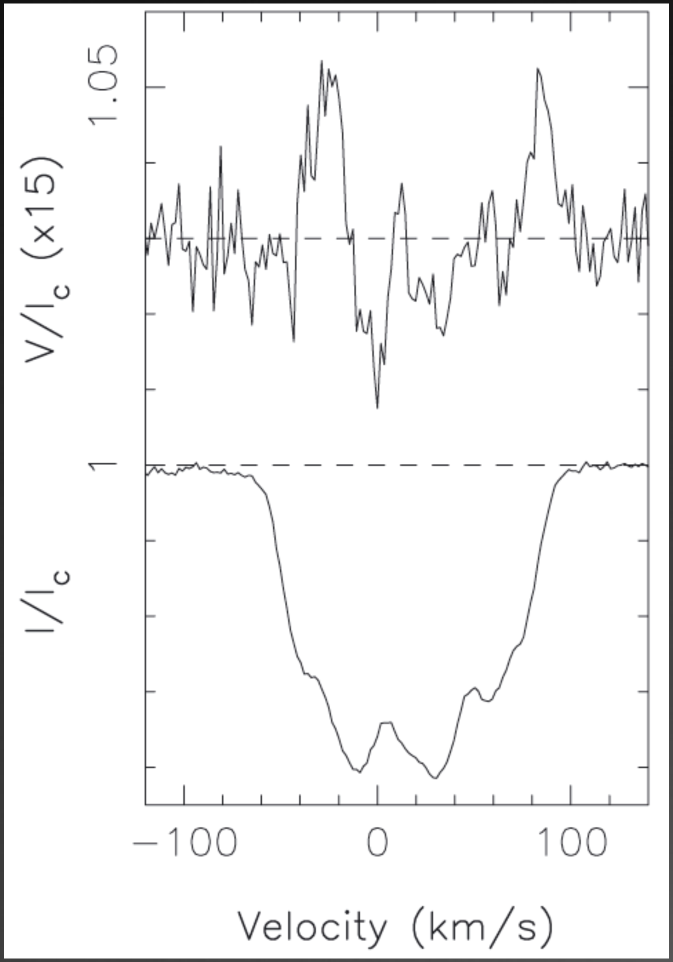
- => Arguments in favour of the selective accretion hypothesis (accretion onto the star of gas depletted in iron-peak elements)
- In MS stars: 2% λBoo
  - =>Transient PMS event

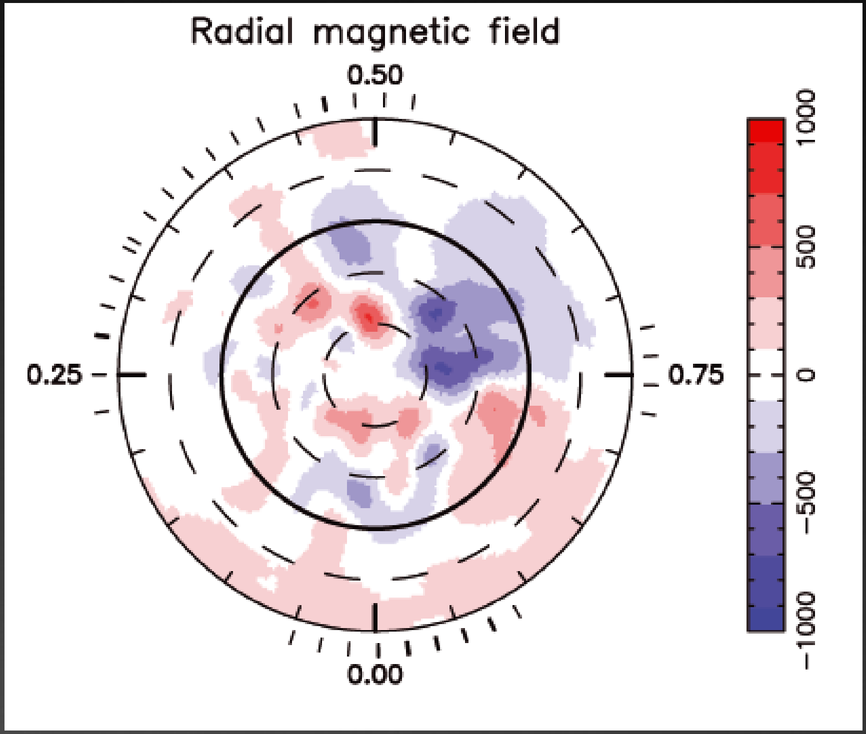
Summary

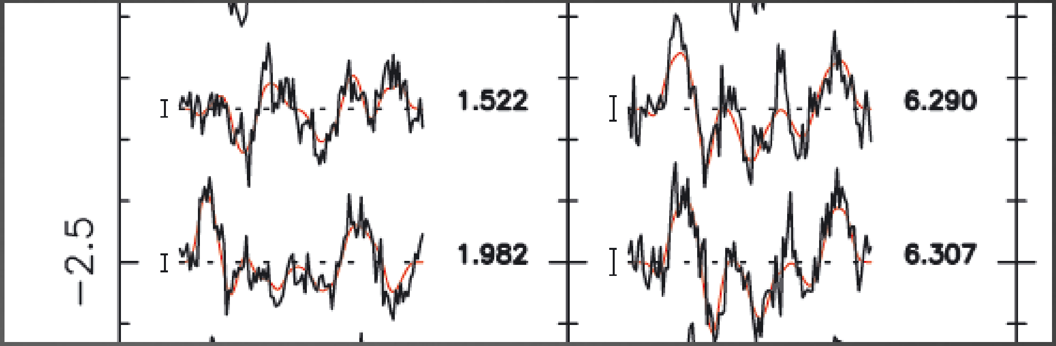
- HAeBe are predominantly radiative
  - => Surface activity ≠ TTS
- 7% HAeBe stars are magnetic
  - Fossil magnetic fields shaped during the star formation
- 50% ‘non-magnetic’ HAeBes have BP < 100 G
- Magnetic HAeBes are much slower rotators than non-magnetic HAeBes
- Normal HBes loose AM. Normal HAes ??
- Transient λBoo phenomenon during one part of the PMS

Complex magnetic fields

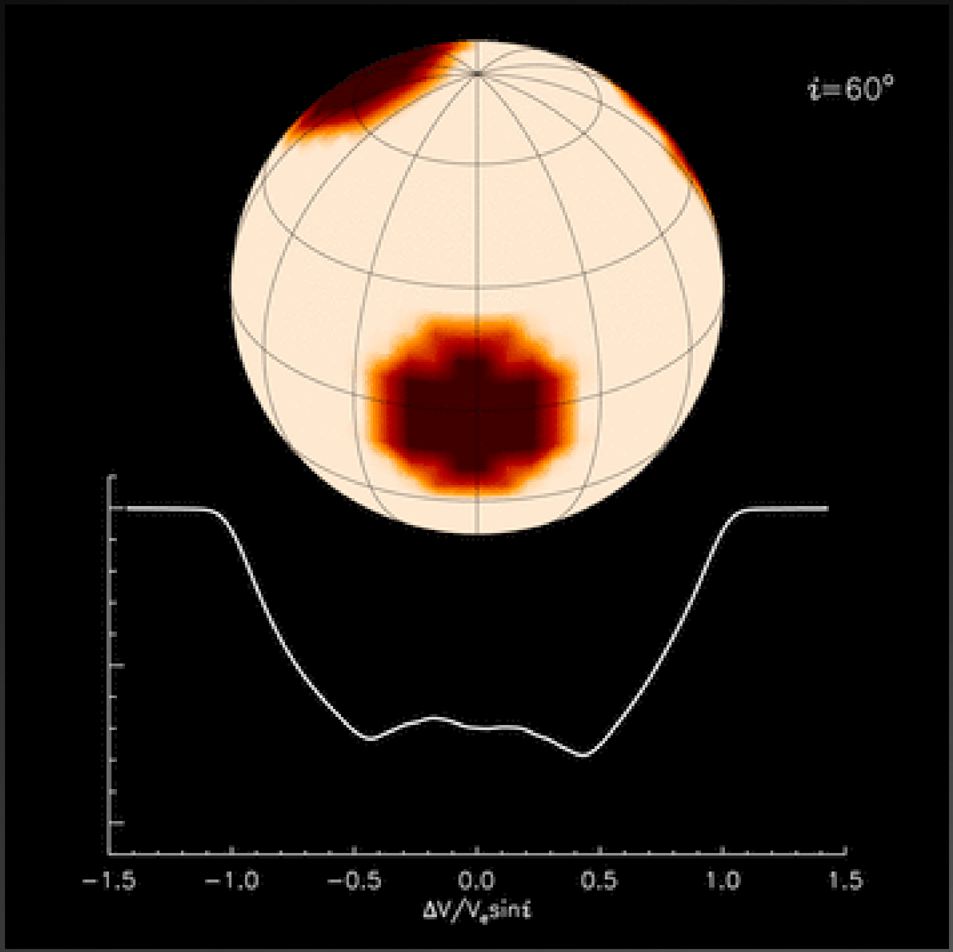
- V410 Tau = WTTS => Zeeman Doppler Imaging

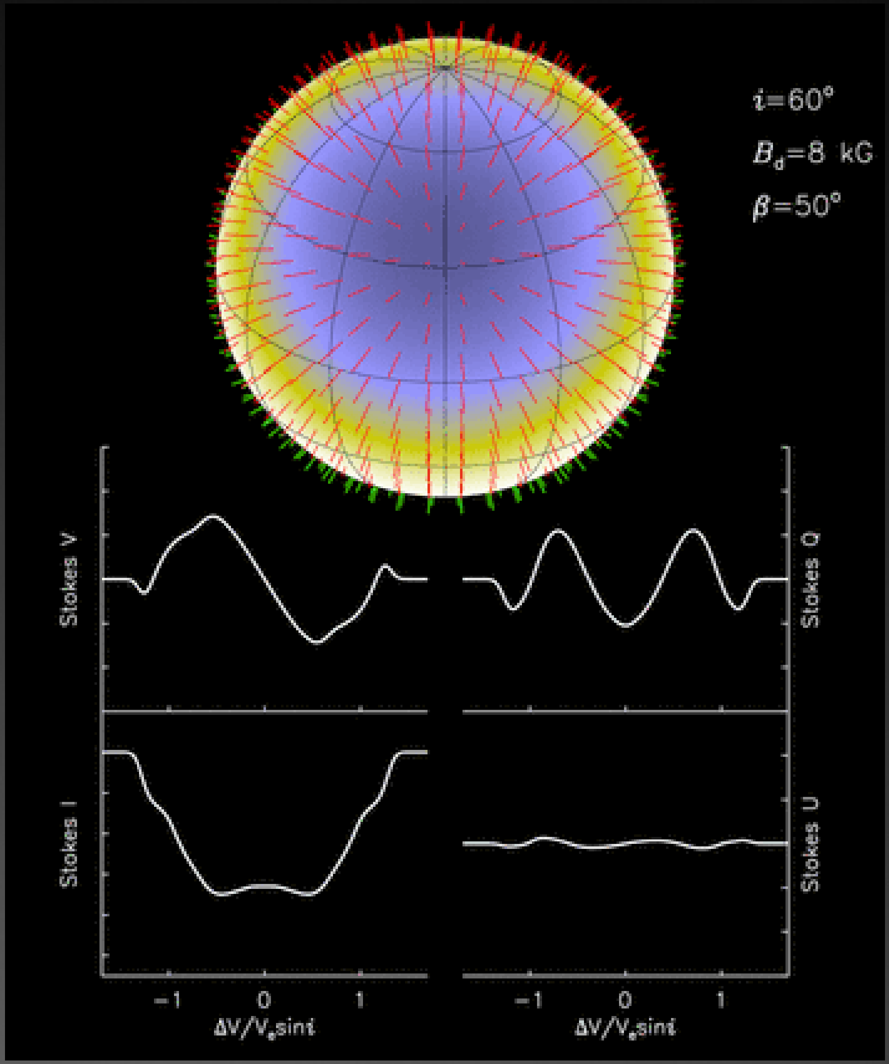






Zeeman Doppler Imaging





Introduction

- A/B stars: rotation, magnetic fields, chemical abundances (1 slide)
- Origin of rotation, magnetic fields, chemical peculiarities (1 slide)
  - => interest in studying their progenitors => HAeBe
- Star-disk interaction, disk evolution, planetary formation, star/planetary formation in the close surroundings (1 slide)
  - => interest in studying the surface/activity/interior of the HAeBe
- PMS evolution at intermediate mass => 3 slides (talk Moscou)
- Herbig Ae/Be stars in the HR diagram => 1 slide
  - Conclusion: HAeBe radiative stars
  - Mass and radius of HAeBe stars
  - Consequences: origin of magnetic fields, activity, rotation evolution

Magnetic fields

- Magnetic fields detection (1 slide)
  - Moment technique (Mathys 1991, 1994)
  - Regression technique (Bagnulo et al. 2002, 2012)
  - LSD technique (Donati et al. 1997)
- Bibliography (2 slides)
- Confirmed magnetic stars (1 slide)
- Magnetic fields charaterisation (3 slides)
  - Oblique rotator
  - Observing strategy + fits
  - Results : HR diagram
- Conclusion => origin of the fields

Rotation

- Bibliographic review: Böhm & Catala (1995), Wolff et al. (2004), Martayan et al. (2008), Alecian et al. (2013) (1 slide)
- Herbig survey + Analysis: LSD, profile fitting, vsini extraction (1 slide)
- Comparison with Böhm & Catala (1 slide)
- Results: vsini distributions (1 slide)
- Results: Amsini as a function of age (1 slide) + comparison with previous results
- Conclusions: AM loss above 5 Msun => winds (?), show some Pcygni profiles (1 slide) (Halpha profile: MWC 1080, Mg II h & k profile: BD+46 3471

Chemical abundances

- Bibliography
- Herbig survey
  - Selection (1 slide)
  - (Abundance analysis)
  - Results + comparison + interpretation (1 slide)

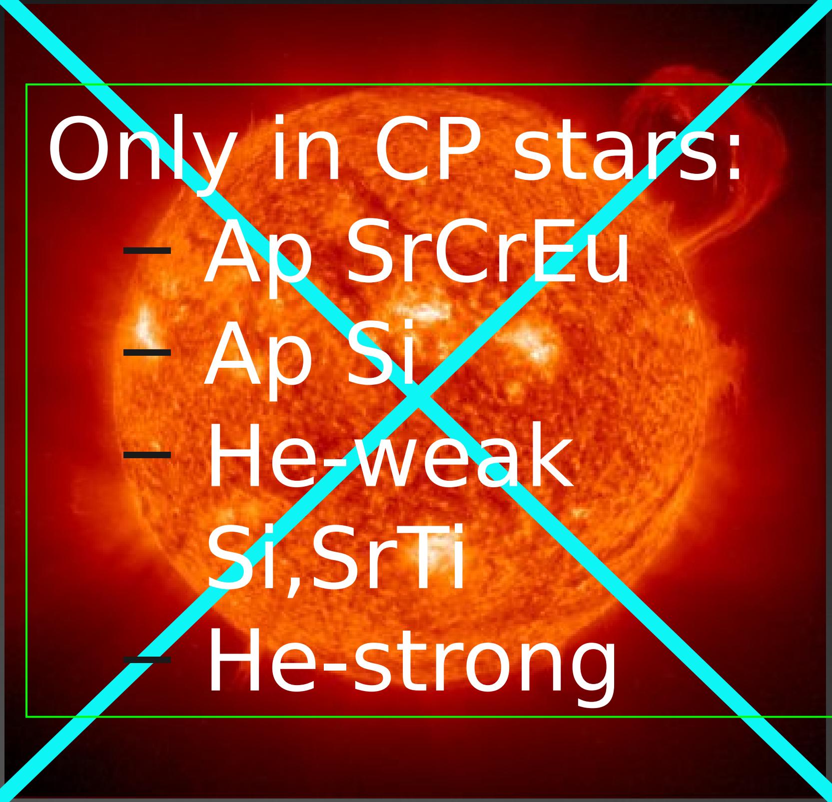
Pulsations

- Bibliography (1 slide)

Magnetic fields in the MS A/B stars

1.5 < M < 10 $M_\odot$

- “Ap star” paradigm
  - Organised
  - Strong
  - Stable
  - Uncorrelated
  - Rare
  - Slow rotator



Only in CP stars:
- Ap SrCrEu
- Ap Si
- He-weak Si,SrTi
- He-strong

e.g. Shorlin et al. (2002)

Magnetic fields in the MS A/B stars

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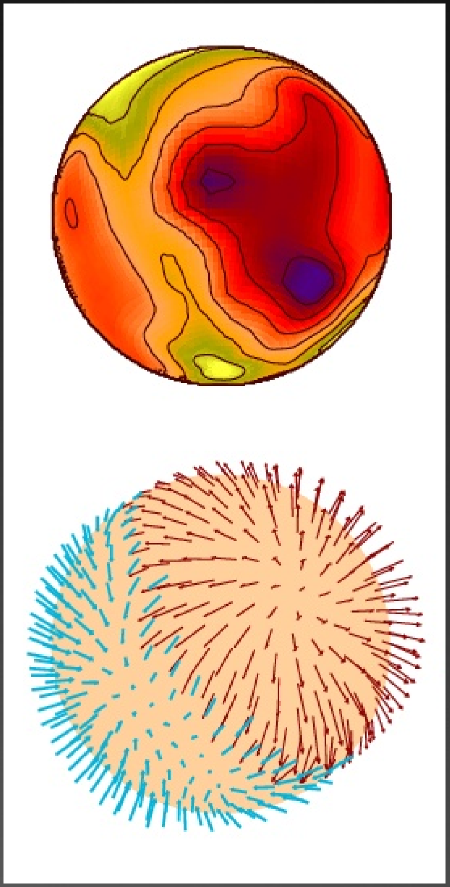

α2 CVn, Kochukhov & Wade 2010

Magnetic fields in the MS A/B stars

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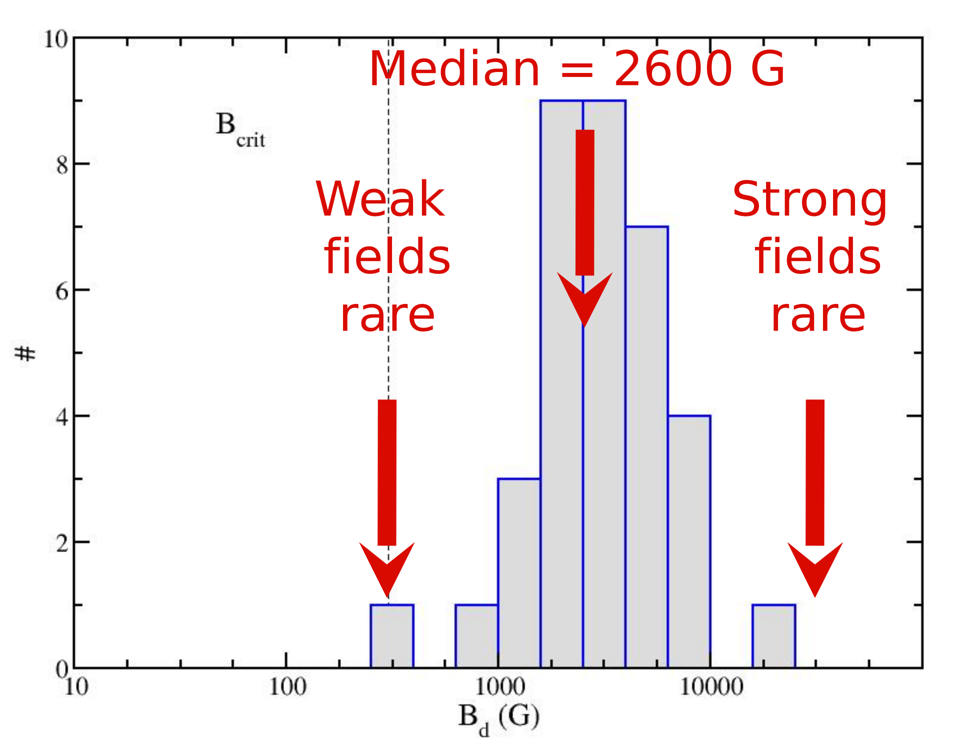

Power et al. (in preparation): The physical and magnetic properties of Ap stars: A volume-limited study

Magnetic fields in the MS A/B stars

$1.5 < M < 10\ M_{\odot}$

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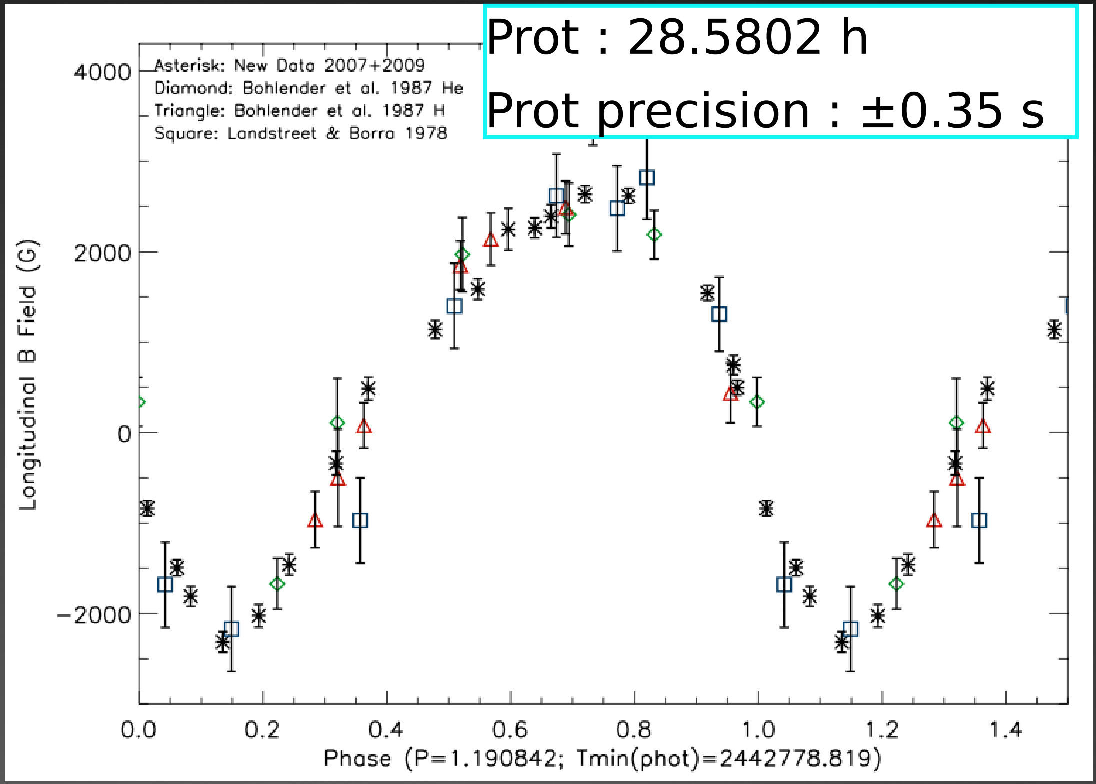
σ Ori E: 33 y time baseline



Prot : 28.5802 h

Prot precision : ±0.35 s

Oksala et al. (in
)

Magnetic fields in the MS A/B stars

$1.5 < M < 10 M_\odot$

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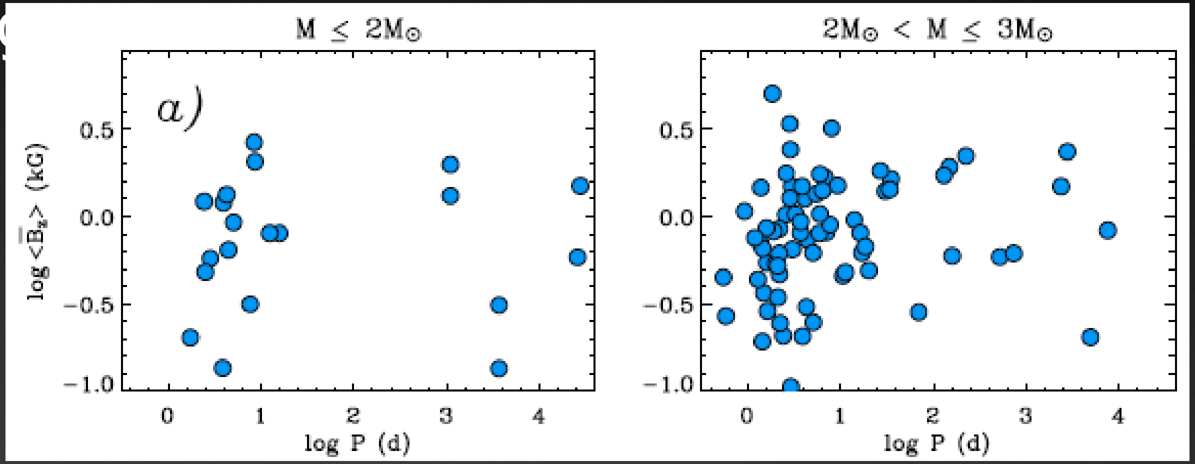
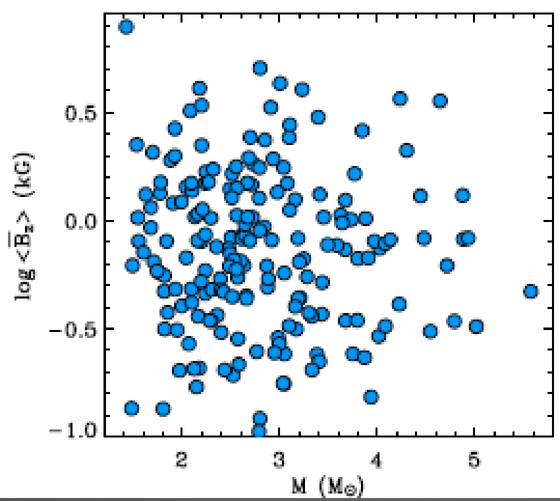




Kochukhov & Bagnulo (2006): Evolutionnary state of magnetic chemically peculiar stars

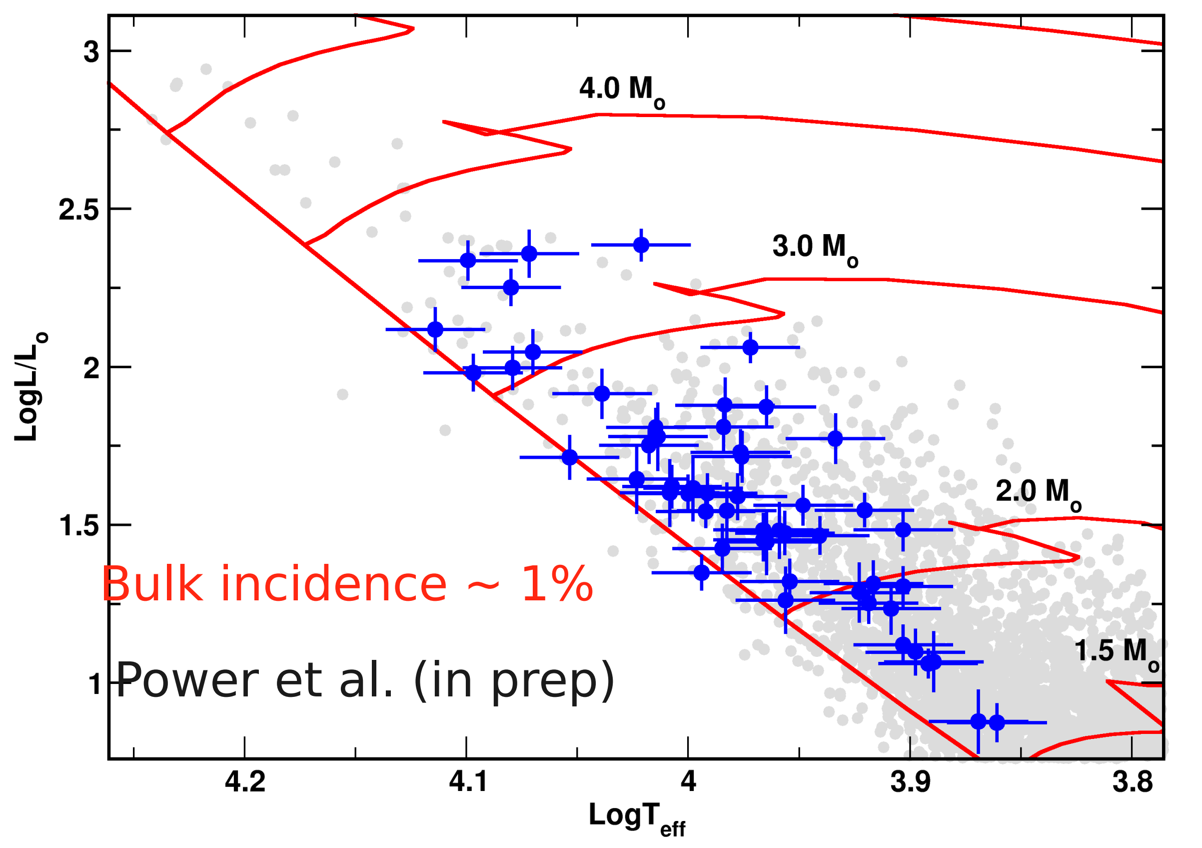
See also Mathys et al. (1997)

Magnetic fields in the MS A/B stars

1.5 < M < 10 M

- "Ap star" paradigm
- Organised
- Strong
- Stable
- Uncorrelated
- Rare
- Slow rotator

Power et al. (in prep.)



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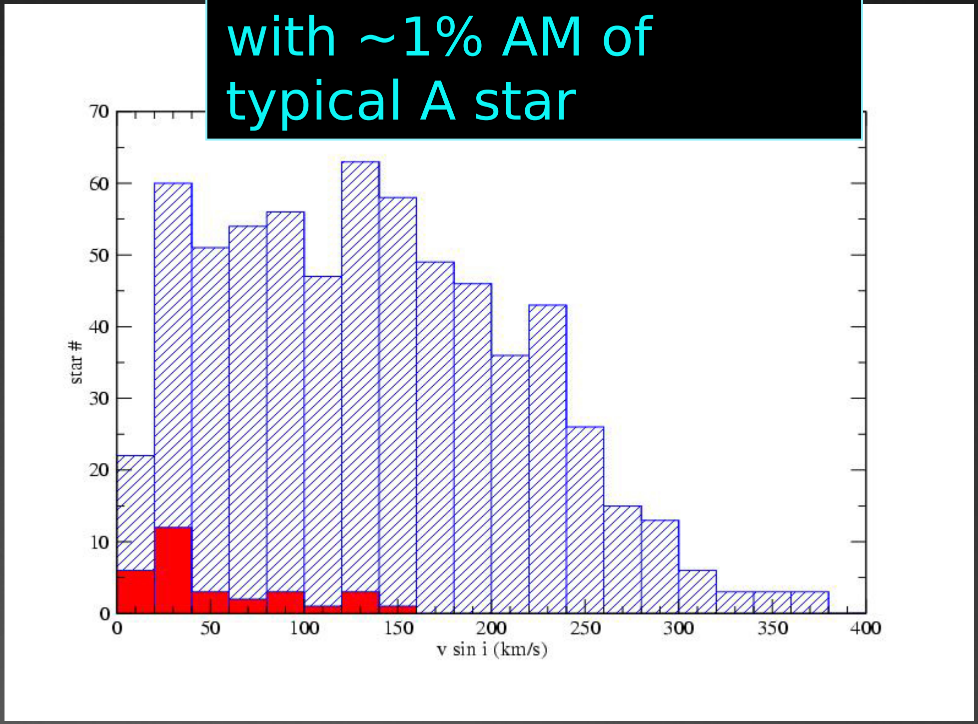
Ultra-slow rotators with ~1% AM of typical A star



On the courtesy of F. Royer (Meudon)

Hubrig et al. (2013)

				Hubrig et al. (2013)			Alecian et al.	
ID	SpT	vsini (km/s)	SNR	# lines	Bl (G)	sig(Bl) (G)	# lines	sig(Bl) (G)
HD 58647	B9	118	437	18	218	69		
HD 98922	B9	50	379	18	-131	42	541	155
HD 104237	A4	8	170	18	63	15		
HD 190073	A2	<8.6	162	18	91	18	1051	21

The PMS Evolution at high-mass