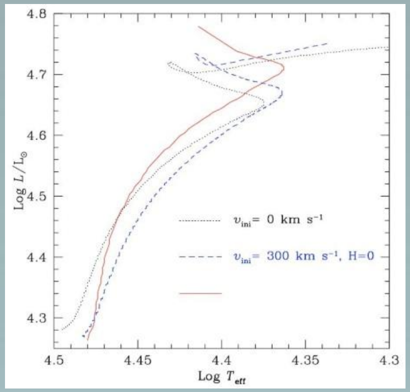
The B fields in OB stars (BOB) survey

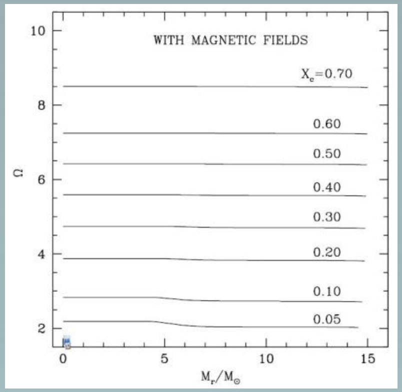
On behalf of the BOB collaboration:

Morel, T., Castro, N., Fossati, L., Hubrig, S., Langer, N., Schöller, M., Przybilla, N., González, J. F., Arlt, R., Barbá, R., Briquet, M., Carroll, T., de Koter, A., Dufton, P. L., Hamann, W.-R., Herrero, A., Ilyin, I., Irrgang, A., Kharchenko, N., Kholtygin, A., Maíz Apellaniz, J., Mathys, G., Nieva, M.-F., Oskinova, L., Piskunov, A., Reisenegger, A., Sana, H., Schneider, F., Scholz, R., Simon Díaz, S., Spruit, H., and Yoon, S.-C.

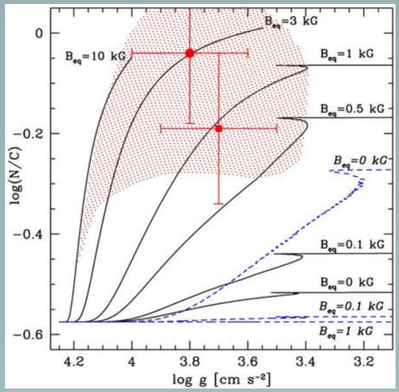
Effects of magnetic fields in massive stars



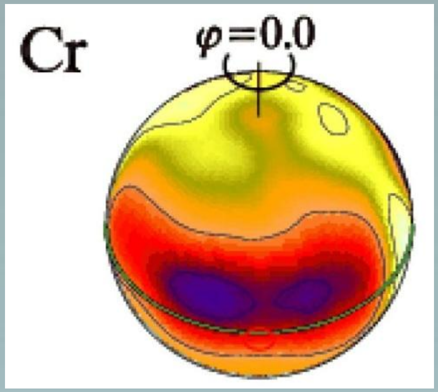
Evolution



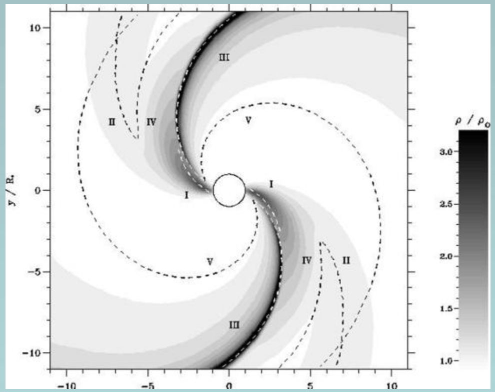
Magnetic braking
Rotational profile



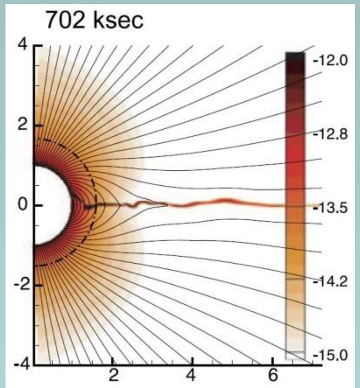
Internal mixing



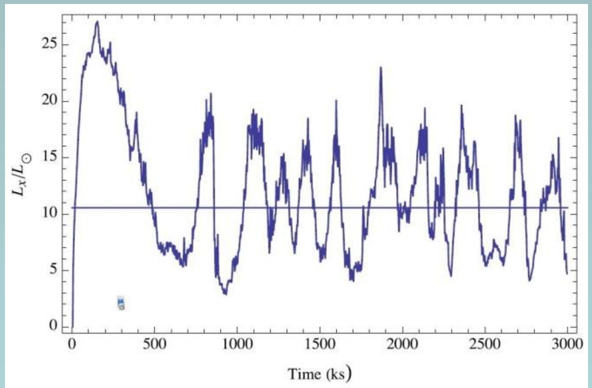
Inhomogeneous abundances
at the surface



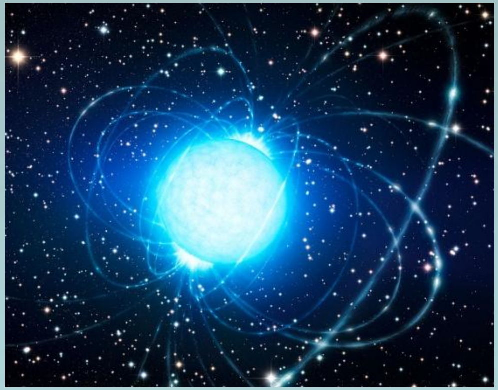
Seed perturbations for large-scale
wind structures (CIRs, …)



Channeling of
stellar wind



X-ray properties



End products
(magnetars, γ ray bursts, …)

The B fields in OB stars (BOB) project

A total of 35.5 nights allocated over two years (P93-P96) as an ESO Large Programme on FORS2 (*R*~2,000) and HARPSpol (*R*~115,000)

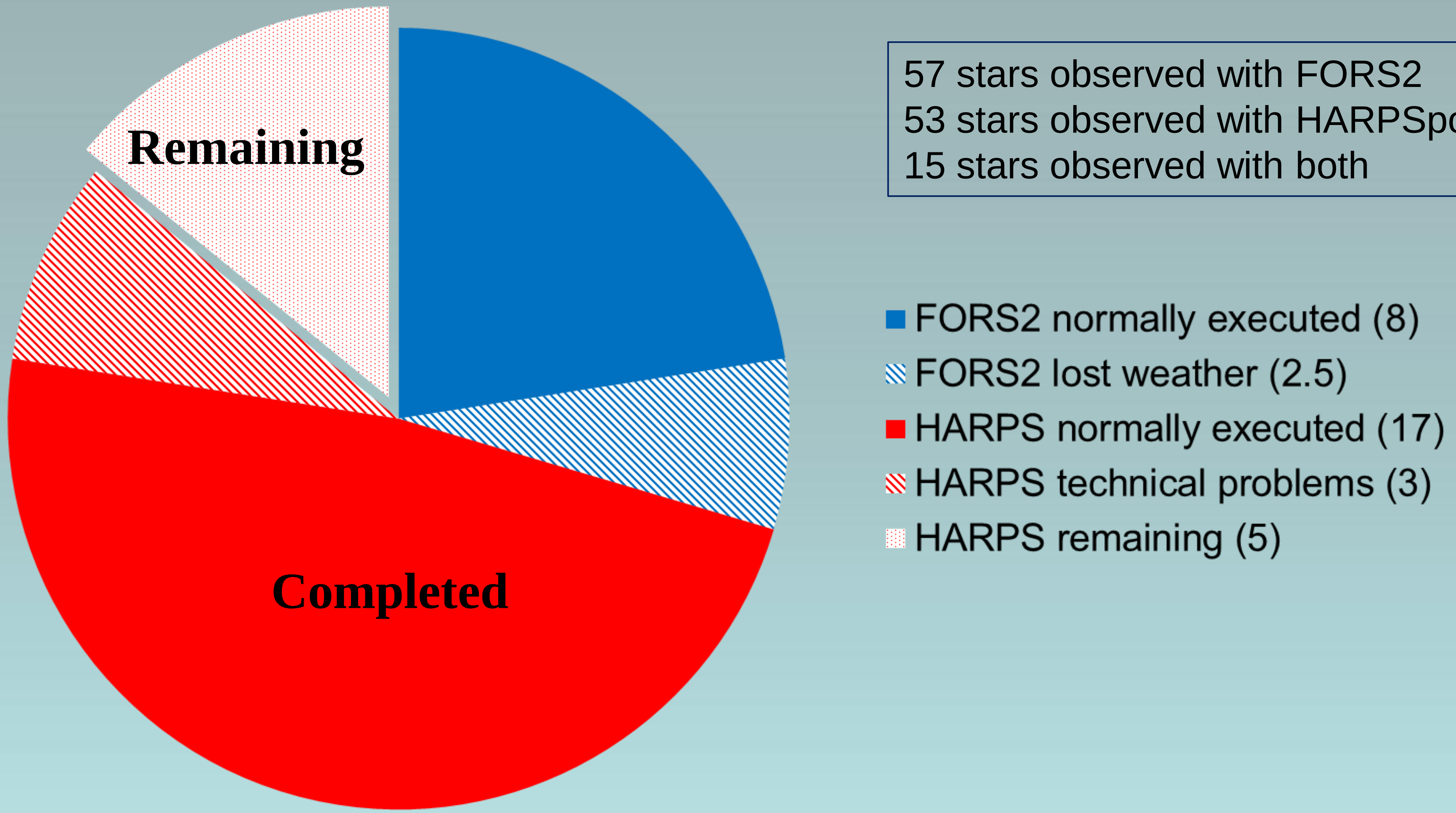
Survey biased towards slow rotators to enhance field detectability

For both FORS2 and HARPS, data reduction and analysis carried out completely independently by two groups (Bonn and Potsdam)

Field detection considered as real only if highly significant for both groups

Breakdown of observations
(35.5 nights awarded in total)

57 stars observed with FORS2
53 stars observed with HARPSpol
15 stars observed with both



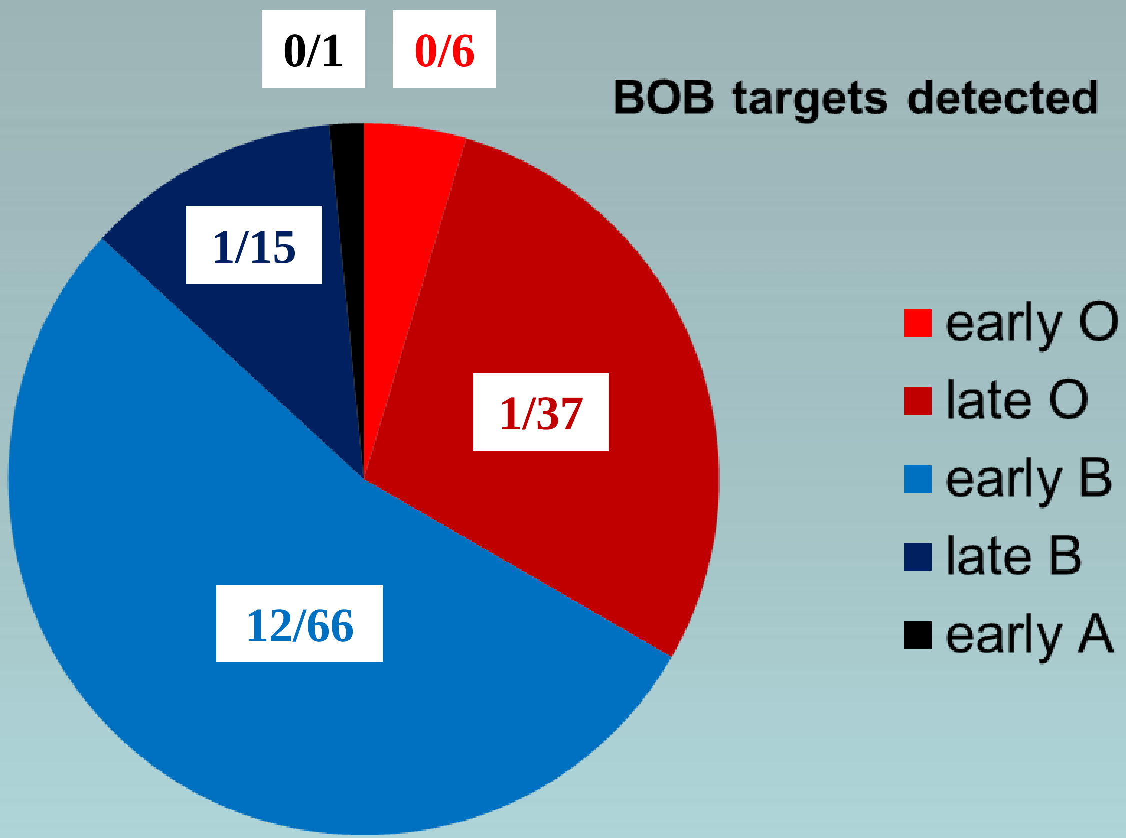
Incidence rate of magnetic fields in OB stars

	MiMeS	BOB
Number stars surveyed	~525	125
Number first detections	~35	14
Detection rate	7±1%	~11%

Figures not to be taken at face value:

A few BOB candidates still being followed up and analysis not fully completed

Selection effects of both surveys to be taken into account before comparison

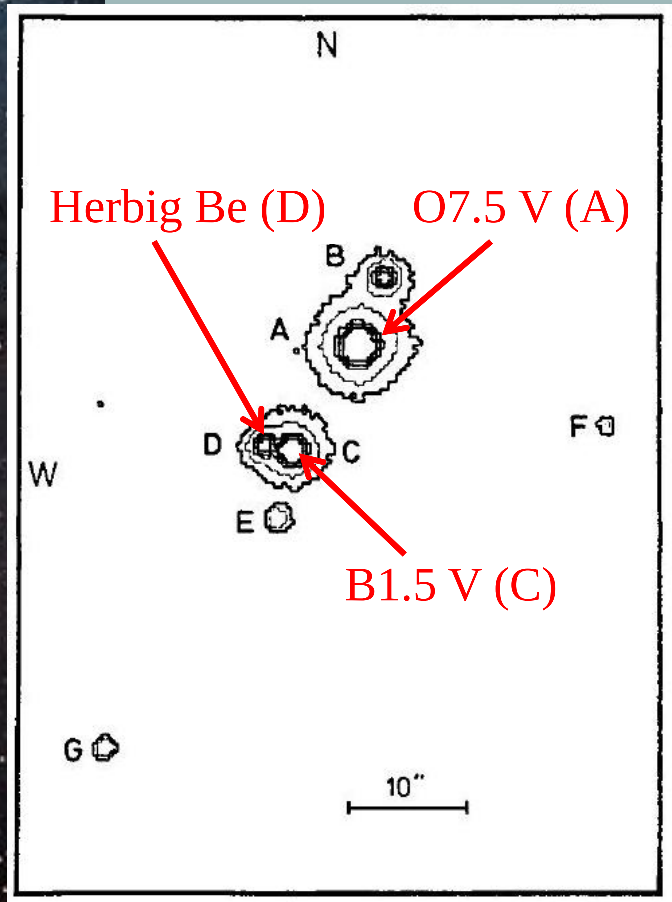


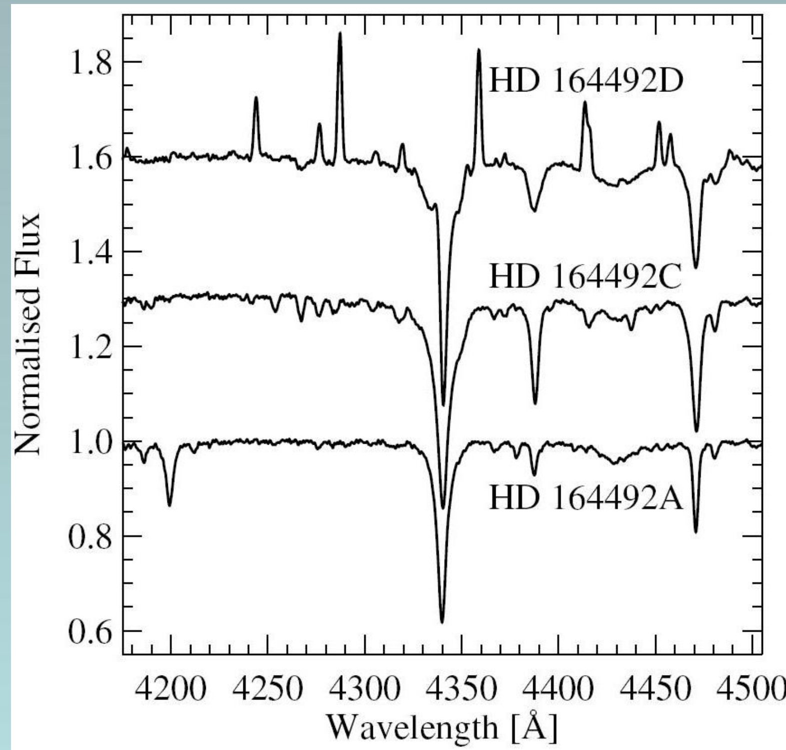
A young, magnetic binary in the Trifid Nebula

The Trifid Nebula is one of the youngest star forming regions.

Seven components identified in the central system HD 164492 (Kohoutek et al. 1999).

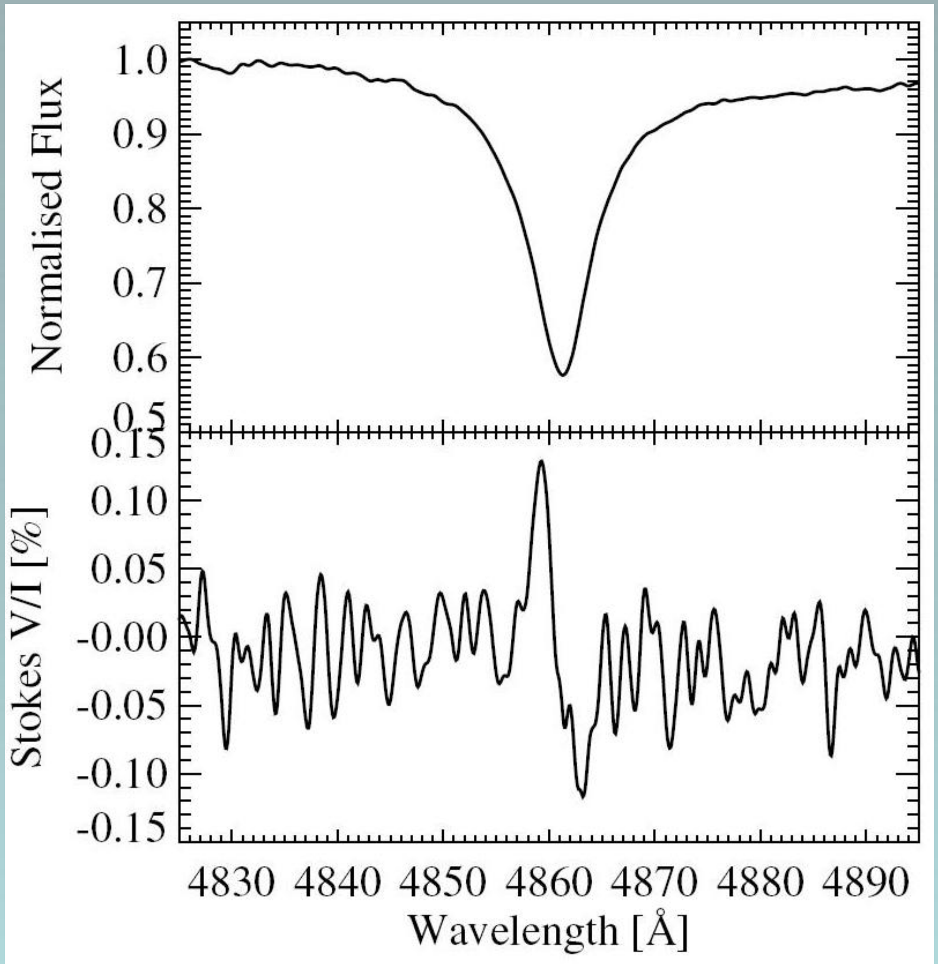
The three brightest components were observed: A, C, and D





Hubrig et al. (2014)

A young, magnetic binary in the Trifid Nebula



Hubrig et al. (2014)

Clear magnetic signal first detected in the FORS2 spectrum of HD 164492C obtained on 2013 April 9

Two fully independent (and consistent) magnetic field determinations:

Bonn:

$\langle B_z \rangle_{all} = 523 \pm 37$ G

$\langle B_z \rangle_{hyd} = 602 \pm 54$ G

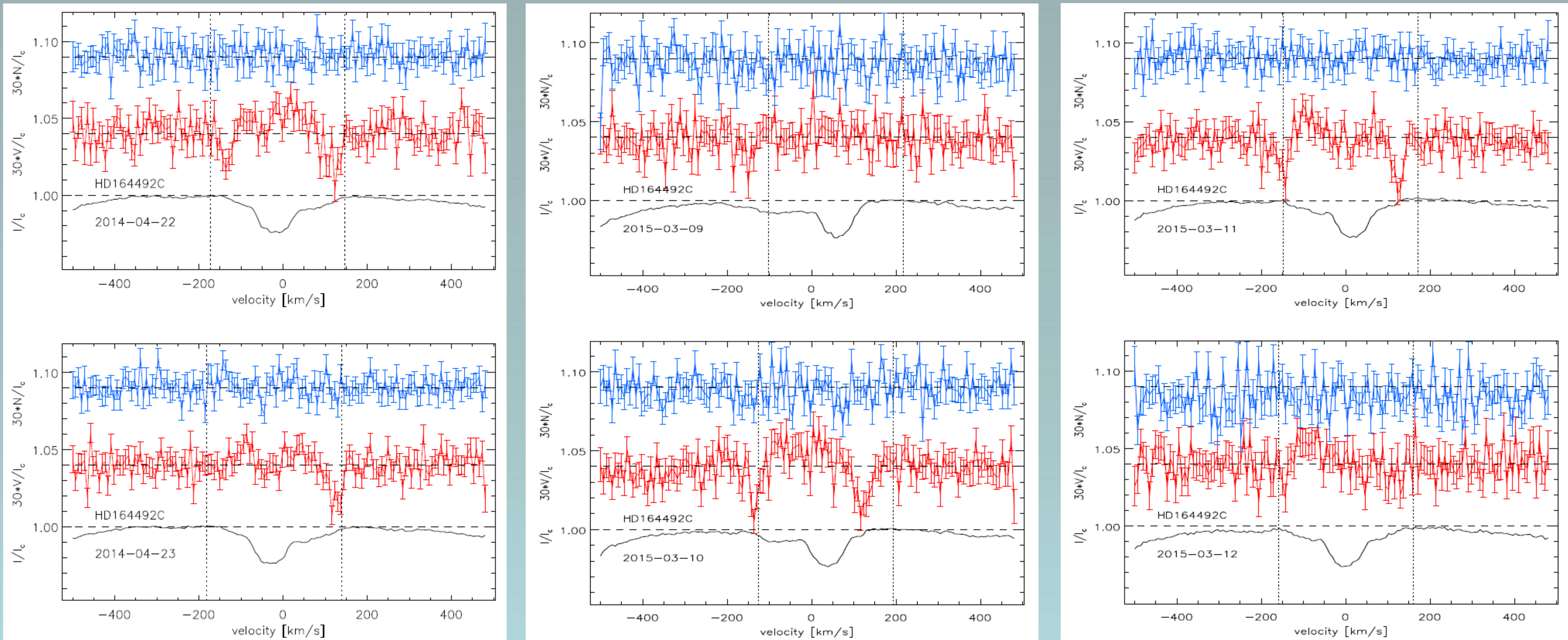
Potsdam:

$\langle B_z \rangle_{all} = 493 \pm 39$ G

$\langle B_z \rangle_{hyd} = 601 \pm 52$ G

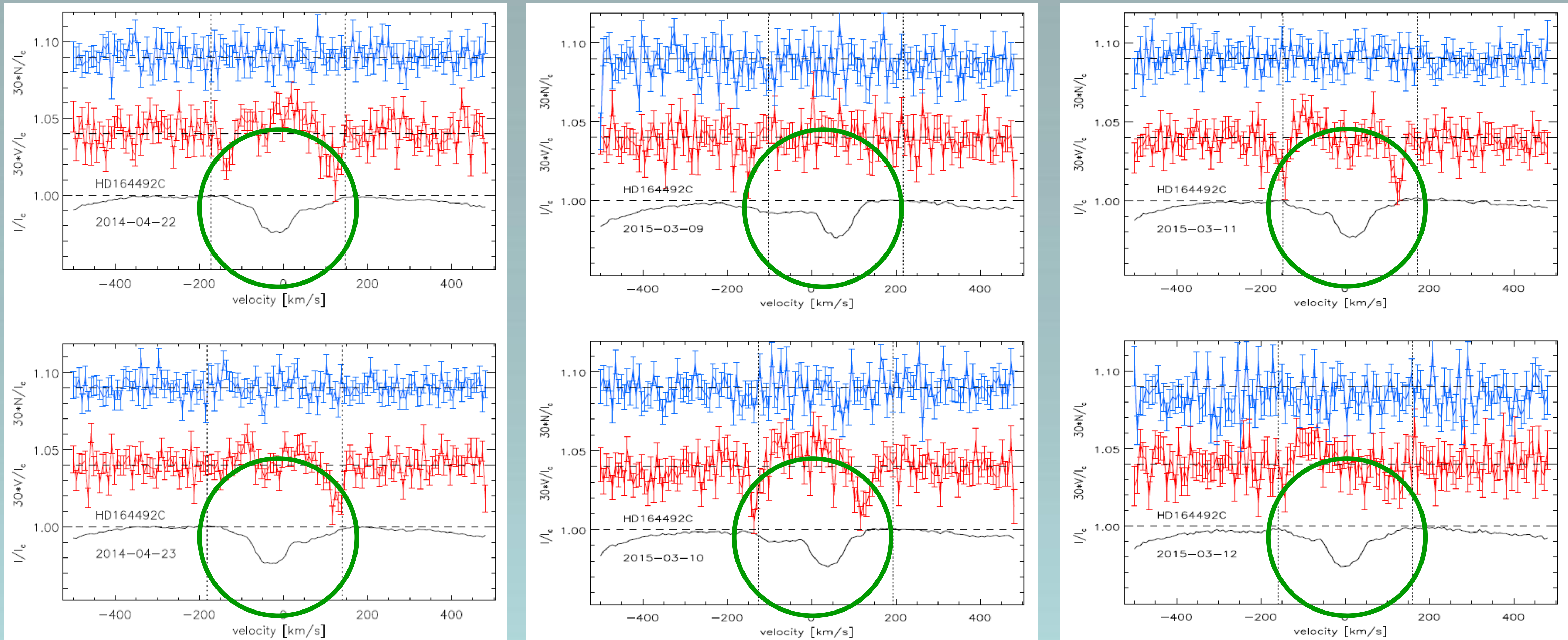
A young, magnetic binary in the Trifid Nebula

Detection repeatedly confirmed from subsequent FORS2 and HARPS observations



A young, magnetic binary in the Trifid Nebula

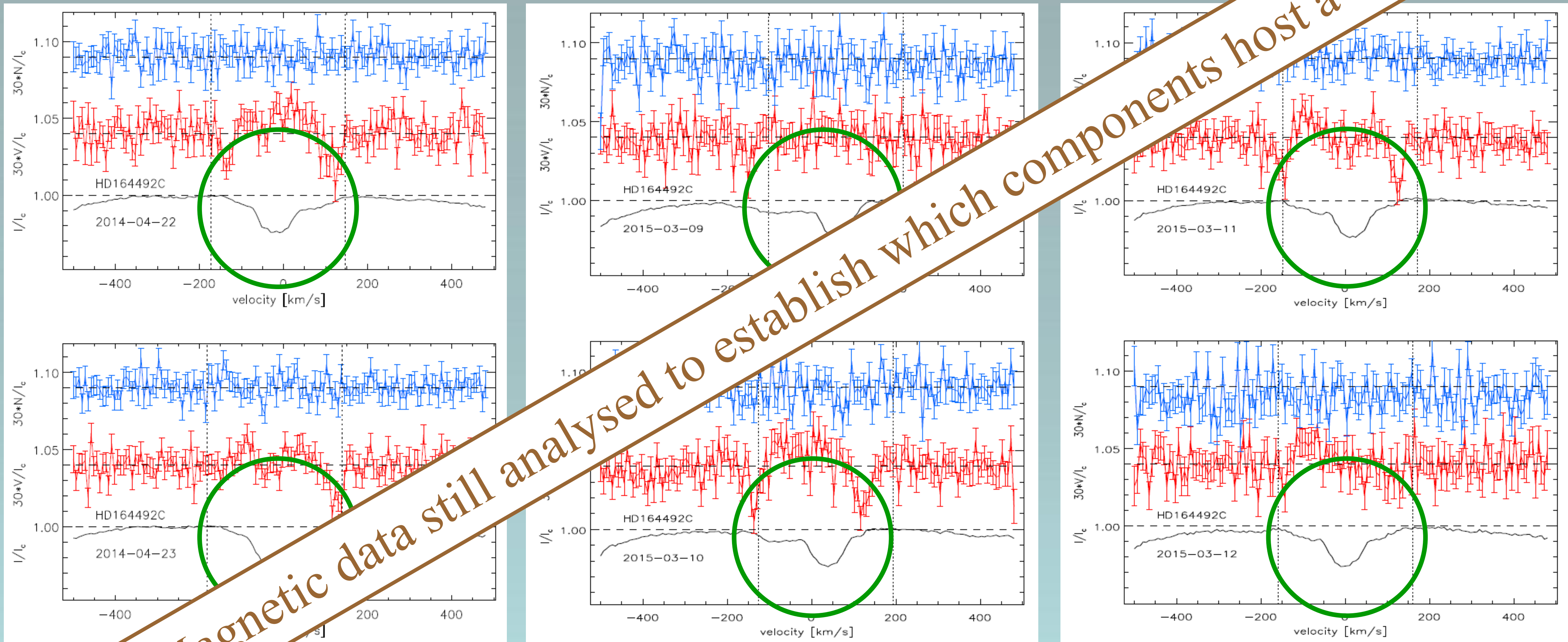
Detection repeatedly confirmed from subsequent FORS2 and HARPS observations



Strongly variable line profiles: turns out to be a triple system

A young, magnetic binary in the Trifid Nebula

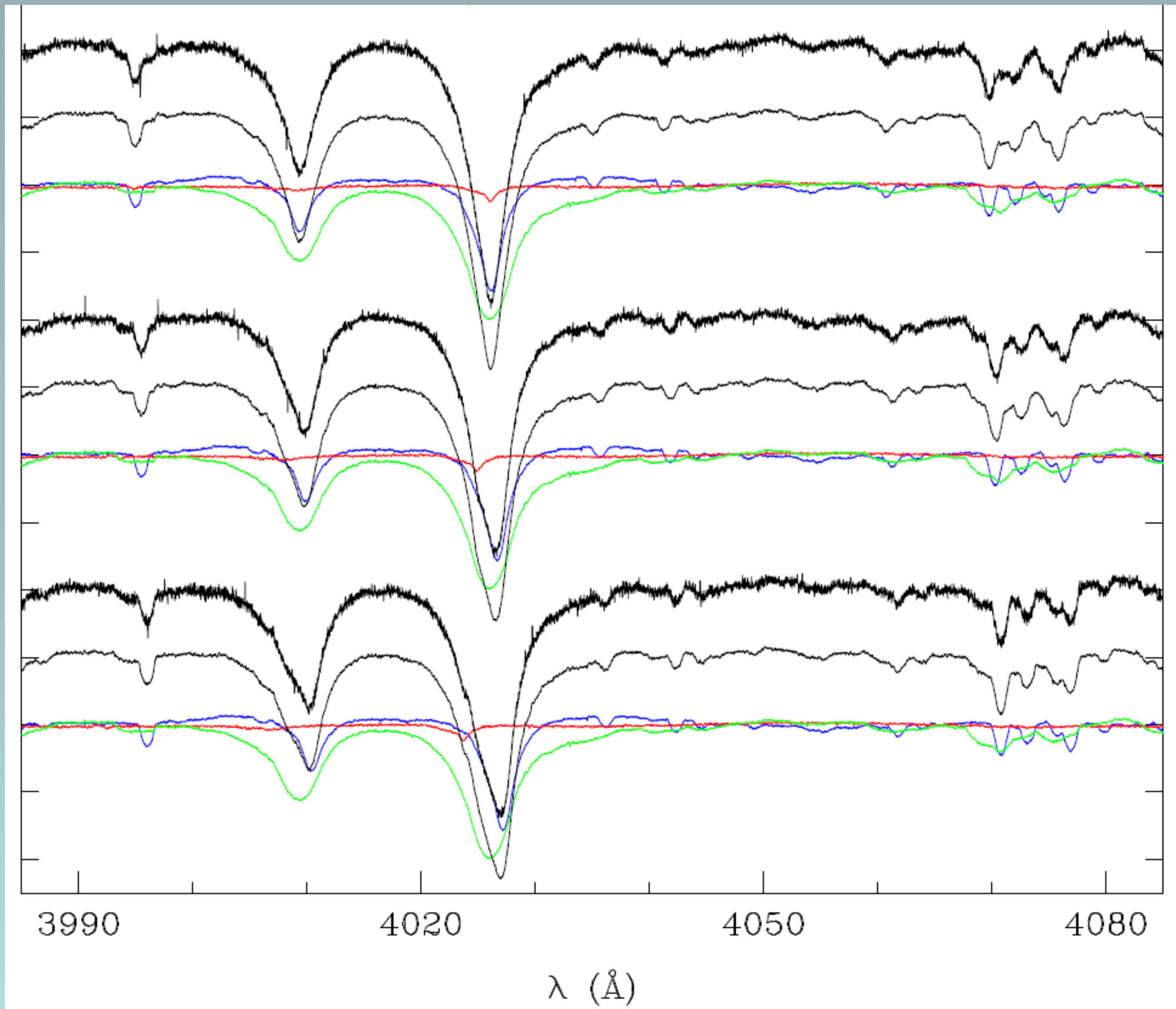
Detection repeatedly confirmed from subsequent FORS2 and HARPS observations



Magnetic data still analysed to establish which components host a field

Strongly variable line profiles: turns out to be a triple system

A young, magnetic binary in the Trifid Nebula



Observed spectrum

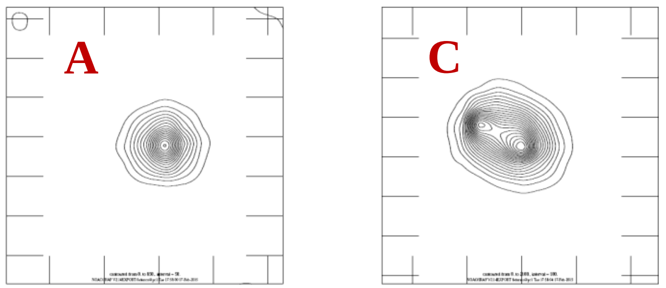
Reconstructed spectrum

Individual spectra

Three components can account for UVES observations:

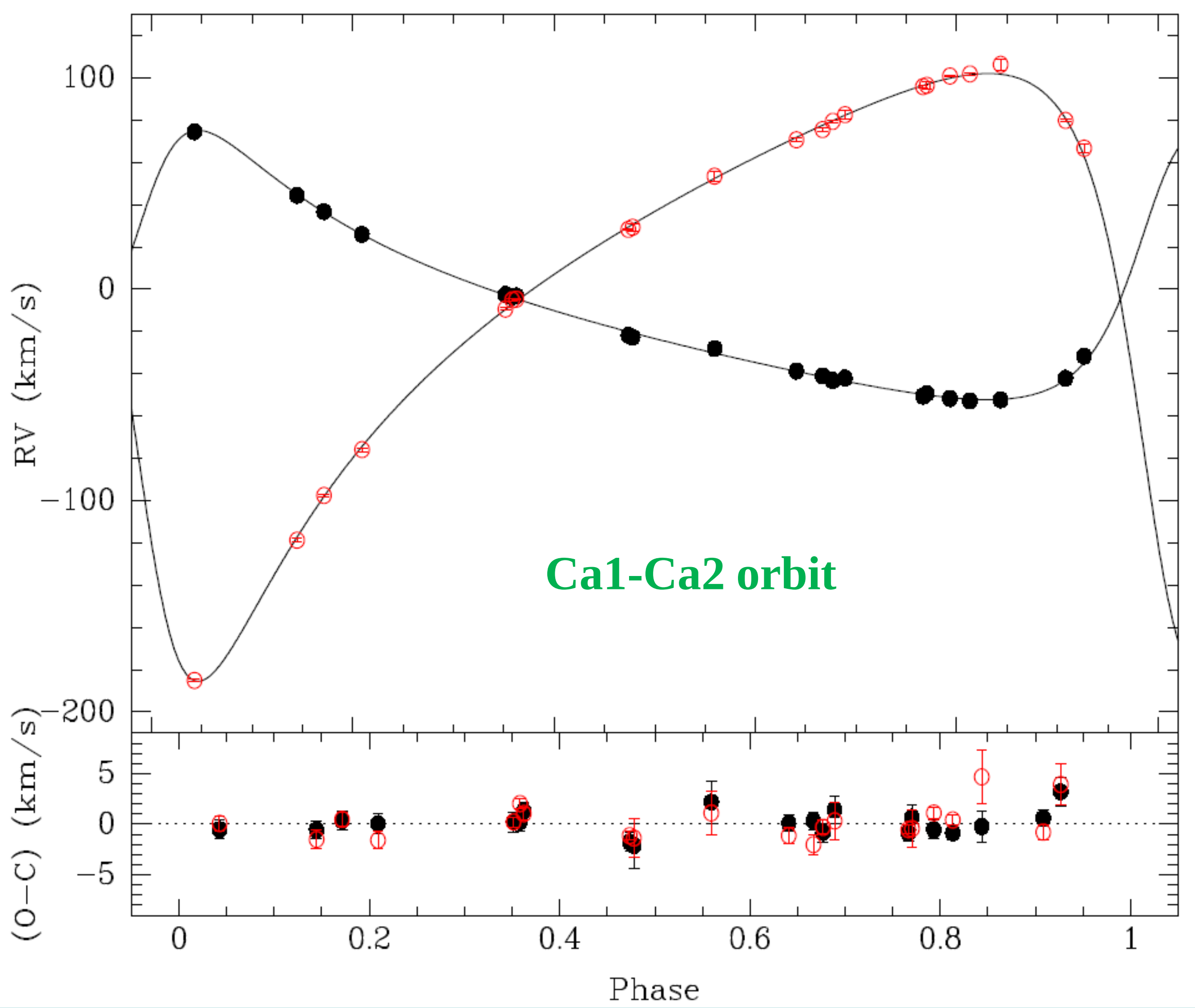
Ca1 (B1 V)
Ca2 (B4 V), about 1.7 mag fainter than Ca1
Cb (B1 V), faster rotator, He rich?

Triple system: Ca1-Ca2 in relatively close orbit (*P*~12.5 d) + distant tertiary (Cb)



González et al., in prep.

A young, magnetic binary in the Trifid Nebula



González et al., in prep.

HD 54879: A magnetic O9.7 V star

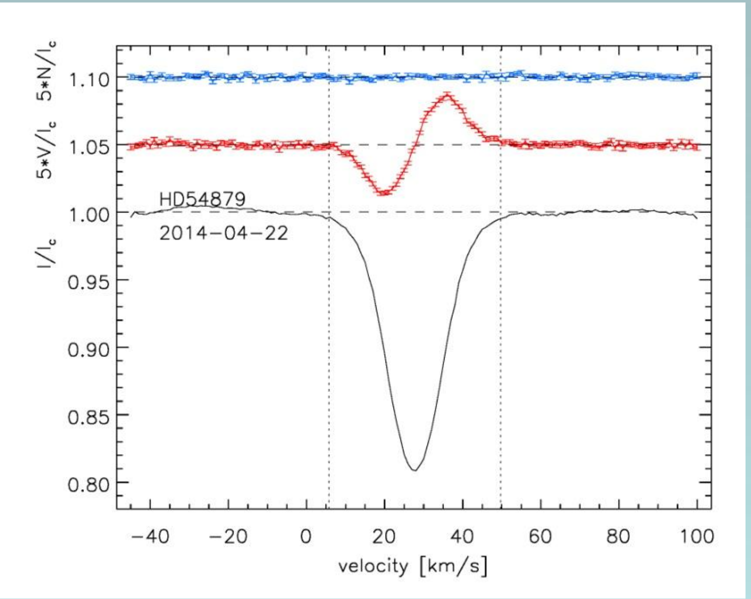
FORS2 observations

			Hydrogen lines		All lines	
			V	N	V	N
Detection	07 02 2014	Bonn	-655±109	22±8 1	-504±54	69±46
		Potsdam	-639±121	-16±119	-460±65	76±66
	08 02 2014	Bonn	-978±88	-36±76	-653±47	40±43
		Potsdam	-877±91	-102±105	-521±62	23±63
	17 03 2015	Bonn	-600±93	-1±71	-471±44	68±44
		Potsdam	-633±65	33±68	-527±45	52±45

HARPS observations

ND: FAP > 10^{-3} MD: 10^{-5} < FAP < 10^{-3} DD: FAP < 10^{-5}

		V		N
22 04 2014	Bonn	**-592±7**	**DD**	**ND**
	Potsdam	**-584±15**	**DD**	**ND**
10 03 2015	Bonn	**-268±10**	**DD**	**ND**
	Potsdam	**-431±25**	**DD**	**ND**
13 03 2015	Bonn	**-270±14**	**DD**	**ND**
	Potsdam	**-425±28**	**DD**	**ND**



Castro et al. (2015)

HD 54879: A magnetic O9.7 V star

FORS2 observations

			Hydrogen lines		All lines	
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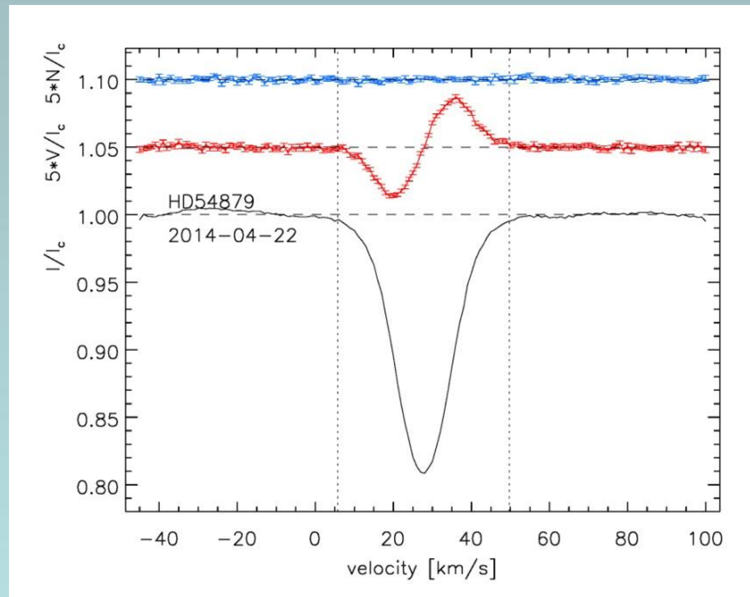
Detection	07 02 2014	Bonn	-655±109	22±8 1	-504 [illegible]	[illegible]
		Potsdam	-639±121	-16±119	[illegible]	[illegible]66
	08 02 2014	Bonn	-978±88	-36[illegible]	[illegible]	40±43
		Potsdam	-877±91	[illegible]	[illegible]21±62	23±63
	17 03 2015	Bonn	-600±[illegible]	[illegible]	-471±44	68±44
		Potsdam	[illegible]	[illegible]±68	-527±45	52±45

Dipolar field > 2.0 kG

HARPS observations

ND: FAP > 10^{-3} MD: 10^{-5} < FAP < [illegible] < 10^{-5}

		V		N
22 04 2014	Bonn	[illegible]	DD	ND
	Potsdam	[illegible]±15	DD	ND
10 03 2015	Bonn	-268±10	DD	ND
	Potsdam	-431±25	DD	ND
13 03 2015	Bonn	-270±14	DD	ND
	Potsdam	-425±28	DD	ND



Castro et al. (2015)

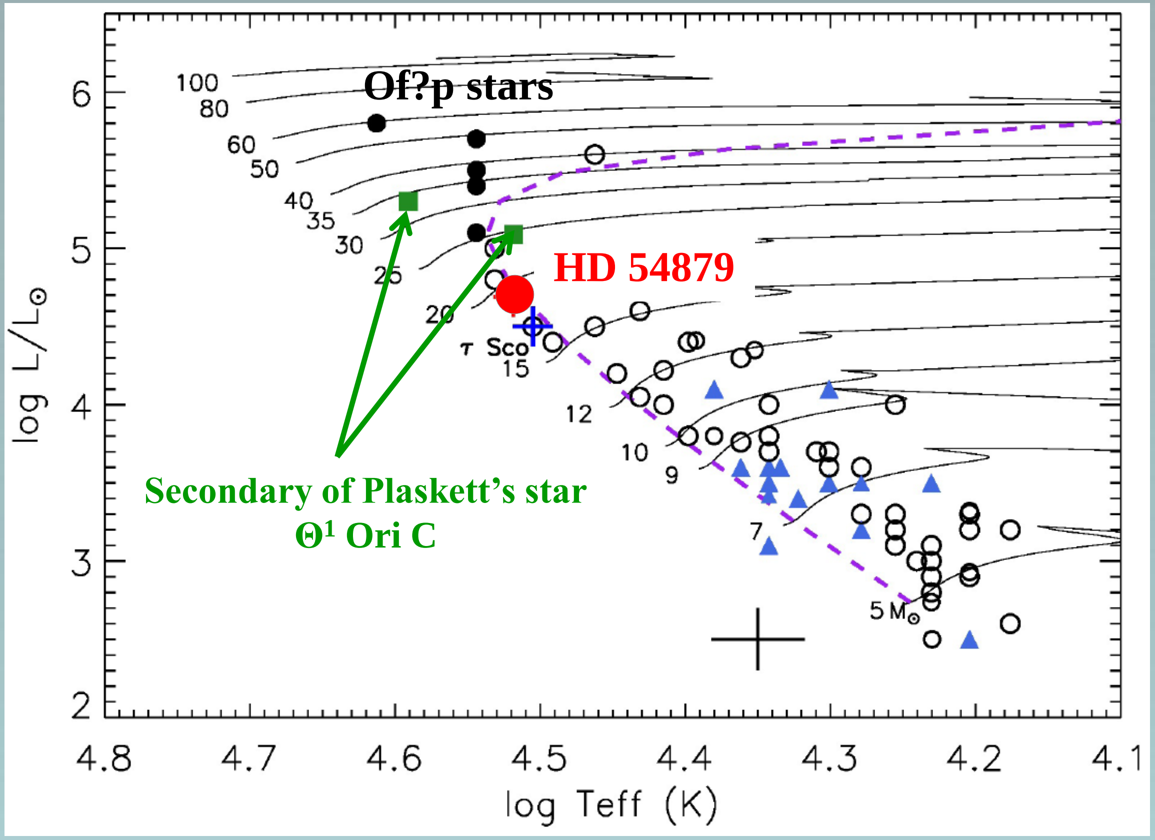
HD 54879: A magnetic O9.7 V star

Output of spectral synthesis with FASTWIND

Teff = 33000±1000 K
logg = 4.00±0.10
vsin*i* = 7±2 km s^{-1}
vmacro = 8±3 km s^{-1}
No abundance anomalies

Fundamental parameters and evolutionary stage from BONNSAI (Schneider et al. 2014)

logL/Lsun = 4.7±0.2
R/Rsun = 6.7±1.0
M/Msun = 18.6±2.0
Age = 4.0±1.0 Myrs



Castro et al. (2015)

Unusual lack of spectral peculiarities and variability for a magnetic OB star
But variable Hα emission line likely arising from a centrifugal magnetosphere

CPD −57° 3509: A He-rich star in NGC 3293

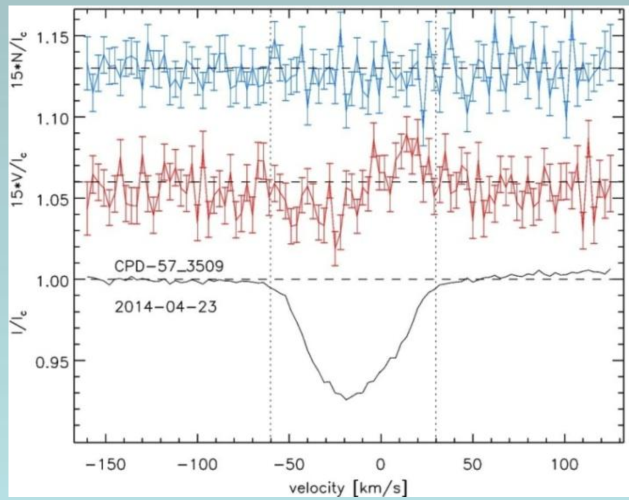
FORS2 observations

			Hydrogen lines		All lines	
			V	N	V	N
No detection	06 02 2014	Bonn	-356±125	-361±126	-143±78	-39±78
		Potsdam	-287±126	-377±139	-23±60	-101±64
Detection	07 02 2014	Bonn	659±109	-120±97	710±58	68±56
		Potsdam	694±108	-116±104	539±51	1±48
No detection	01 06 2014	Bonn	-71±75	-53±75	40±46	-51±47
		Potsdam	-19±71	-28±86	87±54	-45±59
Detection	02 06 2014	Bonn	1050±93	-85±61	943±43	2±39
		Potsdam	979±68	-108±77	920±48	2±50
	17 03 2015	Bonn	607±110	0±110	734±64	9±64
		Potsdam	582±99	-75±101	671±62	-33±61

HARPS observations

ND: FAP > 10^{-3} MD: 10^{-5} < FAP < 10^{-3} DD: FAP < 10^{-5}

		V		N	
23 04 2014	Bonn	**-557±73**	**DD**	**76±72**	**ND**
	Potsdam	**-492±78**	**DD**	**-59±59**	**ND**



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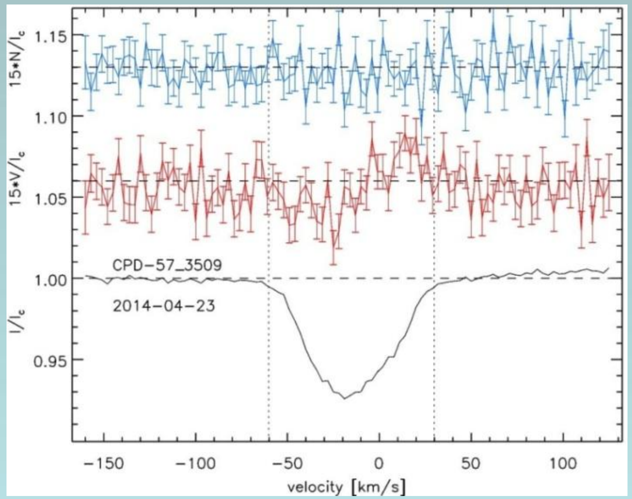
	17 03 2015	Bonn	607±110	0±110	734±64	9±64
		Potsdam	582±99	-75±101	671±62	-33±61

Strong, daily variations of the field

HARPS observations

ND: FAP > 10^{-3} MD: 10^{-5} < FAP < 10^{-3} DD: FAP < 10^{-5}

		V		N	
23 04 2014	Bonn	**-557±73**	**DD**	**76±72**	**ND**
	Potsdam	**-492±78**	**DD**	**-59±59**	**ND**



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		Potsdam	694±108	[illegible]	[illegible]	[illegible]
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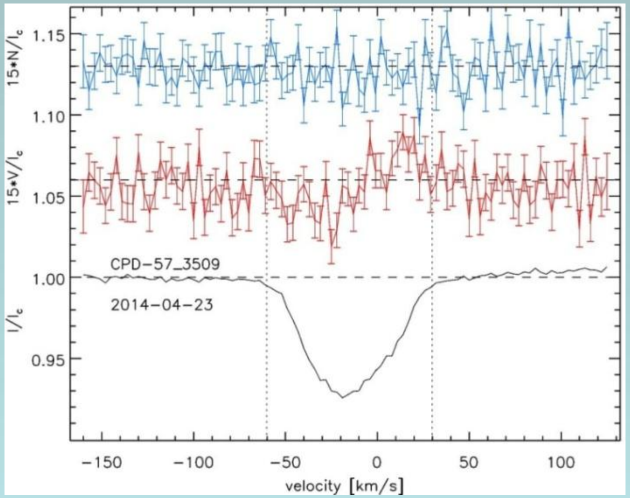
		Potsdam	-19±71	[illegible]	[illegible]	[illegible]
Detection	02 06 2014	Bonn	1050±93	[illegible]	[illegible]	[illegible]
		Potsdam	979±68	-108±77	920±48	2±50
	17 03 2015	Bonn	607±110	0±110	734±64	9±64
		Potsdam	582±99	-75±101	671±62	-33±61

High consistency of measurements

HARPS observations

ND: FAP > 10^{-3} MD: 10^{-5} < FAP < 10^{-3} DD: FAP < 10^{-5}

		V		N	
23 04 2014	Bonn	-557±73	DD	76±72	ND
	Potsdam	-492±78	DD	-59±59	ND



CPD −57° 3509: A He-rich star in NGC 3293

FORS2 observations

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		Potsdam	-287±126	-377±139	-2[illegible]	[illegible]
Detection	07 02 2014	Bonn	659±109	-120±97	[illegible]	[illegible]56
		Potsdam	694±108	-116[illegible]	[illegible]	1±48
No detection	01 06 2014	Bonn	-71±75	[illegible]	[illegible]±46	-51±47
		Potsdam	-19±7[illegible]	[illegible]	87±54	-45±59
Detection	02 06 2014	Bonn	1[illegible]	[illegible]61	943±43	2±39
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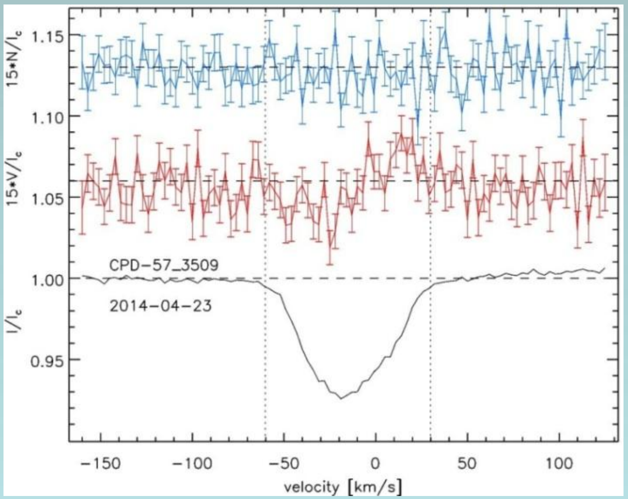
		[illegible]	[illegible]82±99	-75±101	671±62	-33±61

Dipolar field > 3.1 kG

HARPS o[illegible]

ND: FA[illegible] D: $10^{-5} < FAP < 10^{-3}$ DD: $FAP < 10^{-5}$

		V		N	
23 04 2014	Bonn	**-557±73**	**DD**	**76±72**	**ND**
	Potsdam	**-492±78**	**DD**	**-59±59**	**ND**



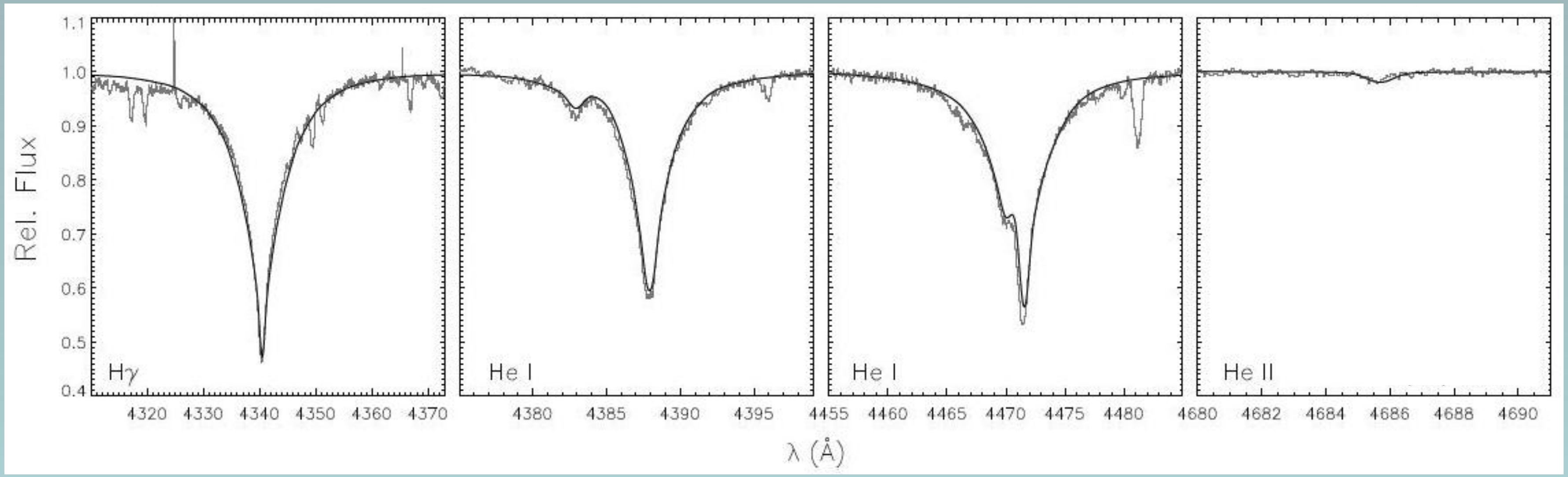
CPD −57° 3509: A He-rich star in NGC 3293

Age of NGC 3293 cluster: ~15 Myrs

Output of spectral synthesis with DETAIL/SURFACE

Teff ~ 23750 K logg ~ 4.05

vsini ~ 35 km s^{-1} **He/H ~ 0.28**

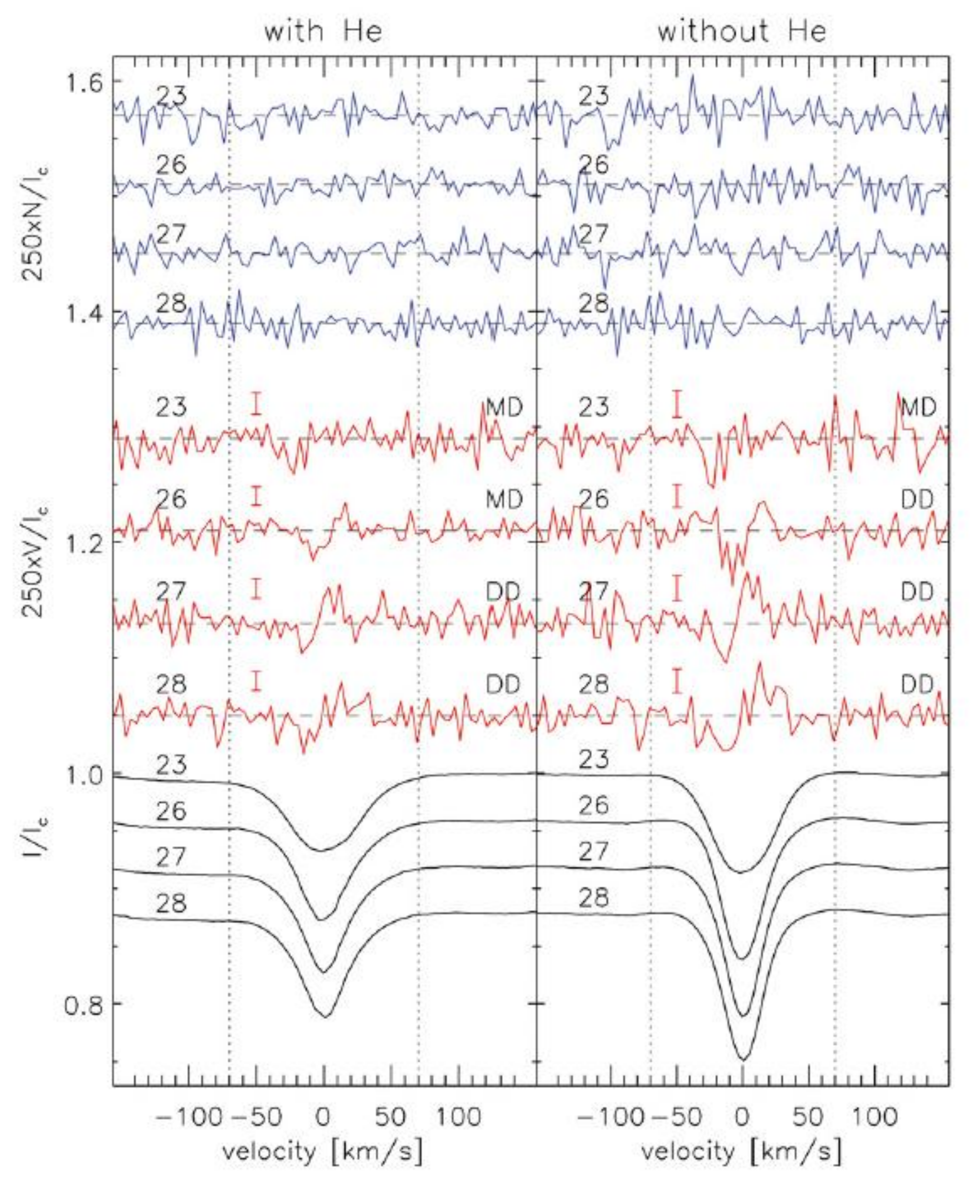


Przybilla et al., in prep.

Star has already spent ~half of its main-sequence lifetime
One of the most evolved He-rich stars with a well-constrained age estimate
Will provide constraints on the evolution of stars with magnetically-confined stellar winds

Detection of weak fields in early B-type stars

β CMa

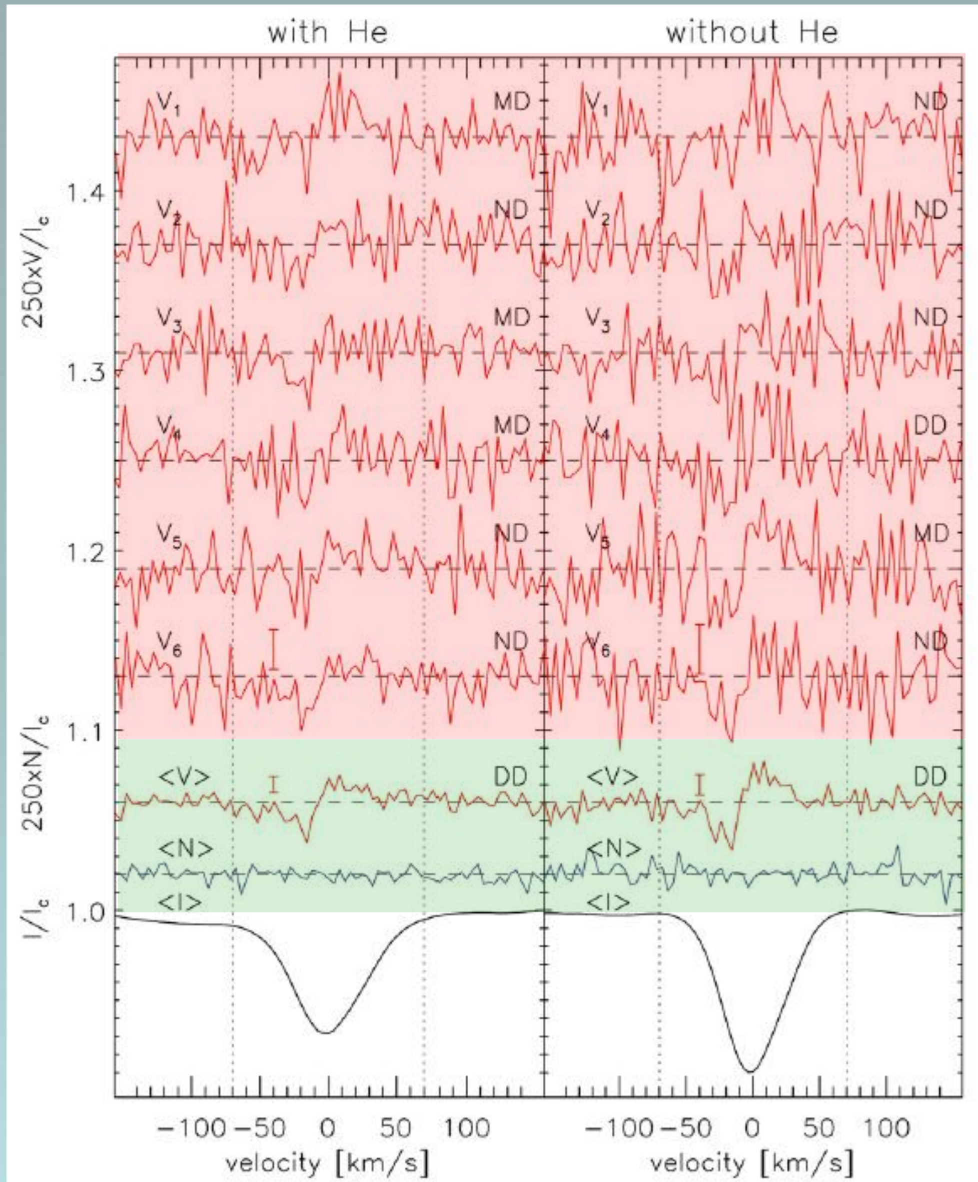


Observations in December 2013

Fossati et al. (2015)

Detection of weak fields in early B-type stars

β CMa



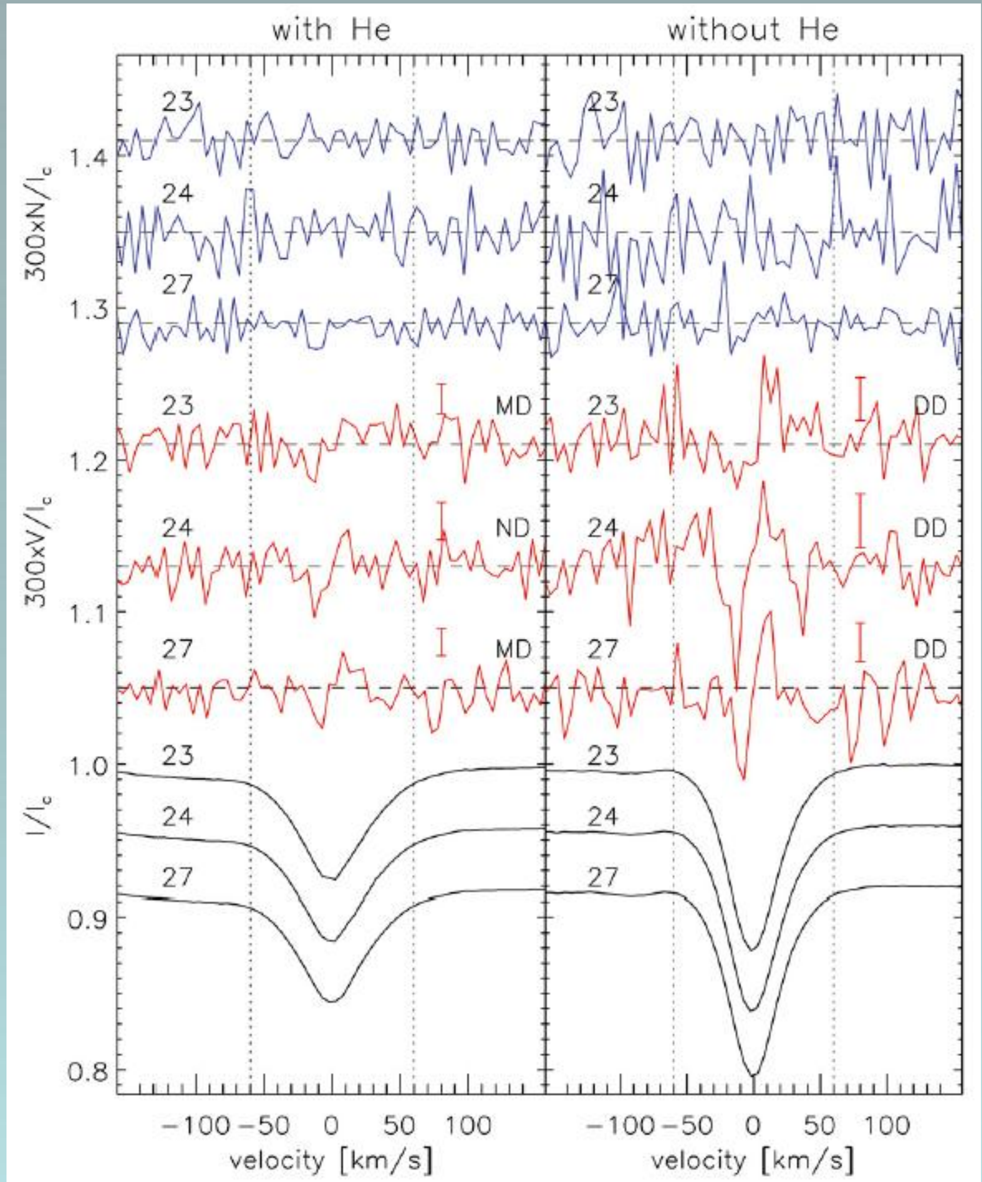
Pulsations may affect field measurements (e.g., Hubrig et al. 2011)

Consecutive observations in April 2014 (free from effects of pulsations)

Fossati et al. (2015)

Detection of weak fields in early B-type stars

ε CMa

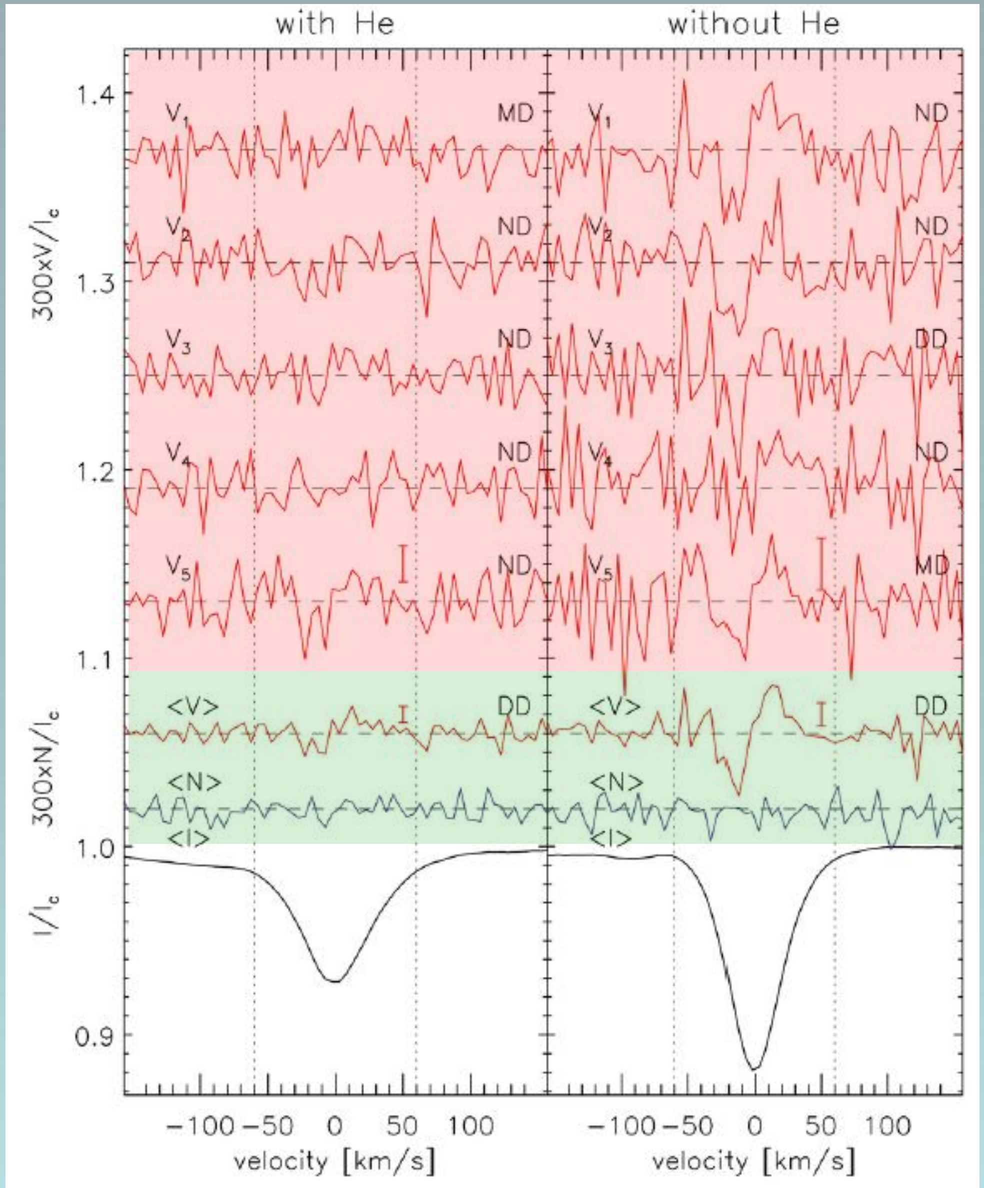


Observations in December 2013

Fossati et al. (2015)

Detection of weak fields in early B-type stars

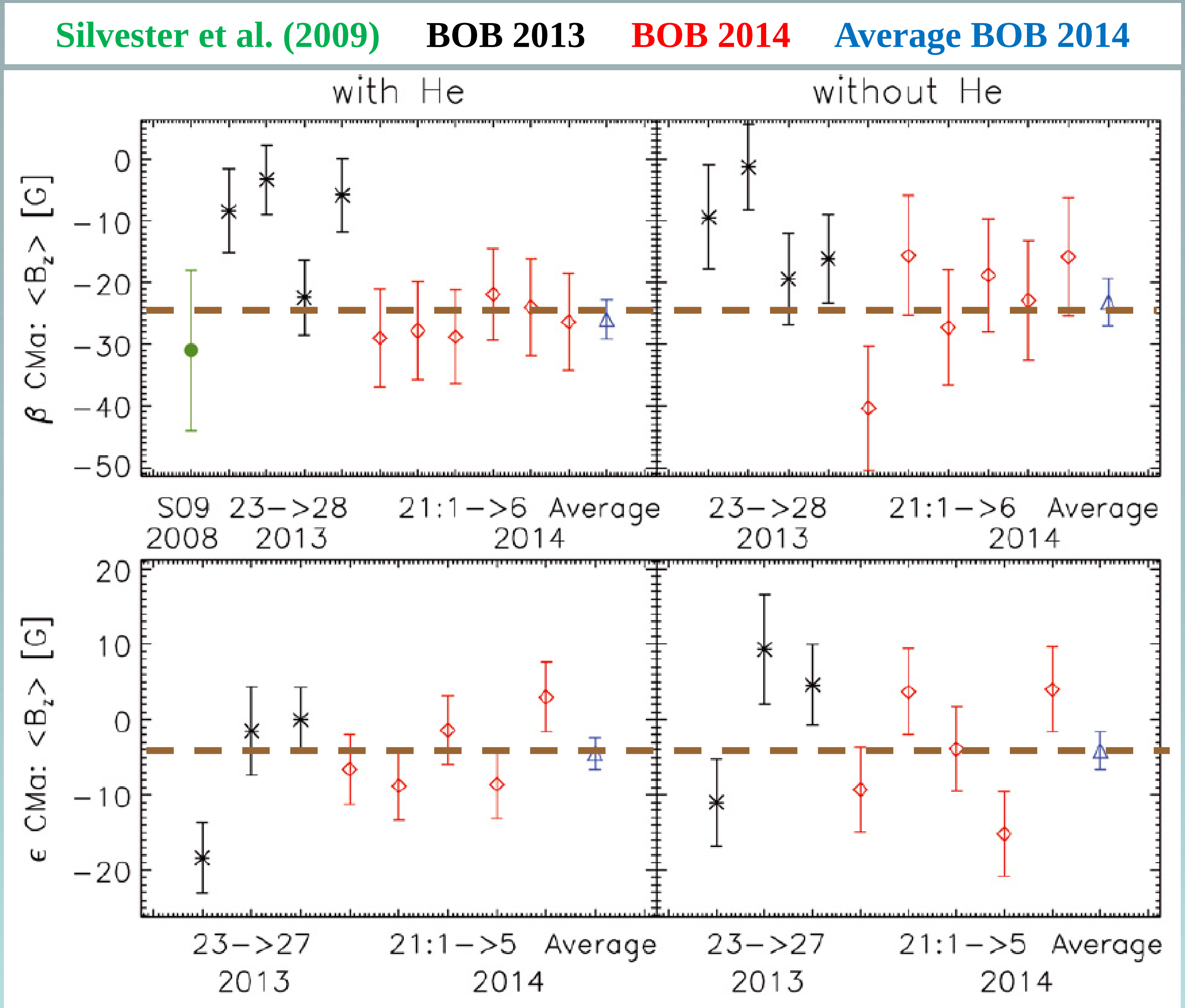
ε CMa



Consecutive observations in April 2014

Fossati et al. (2015)

Detection of weak fields in early B-type stars



β CMa: <Bz> ~ −25 G

Consistent with non detection (<1.5σ) with FORS1 by Hubrig et al. 2006)

ε CMa: <Bz> ~ −4 G

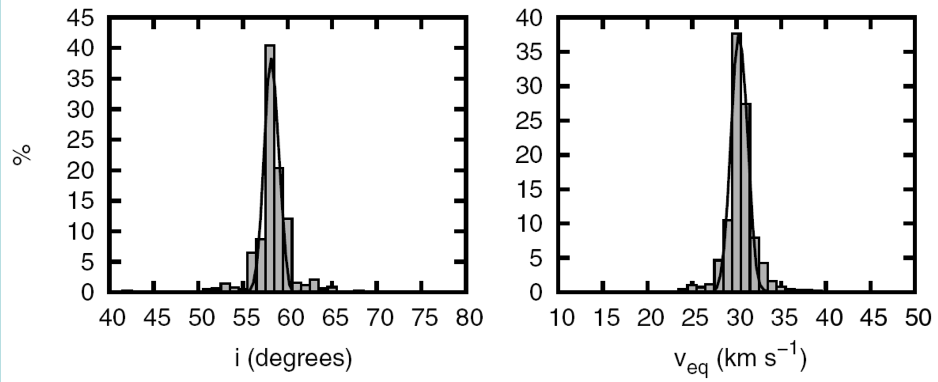
Re-analysis of FORS1 observations taken in 2006 and 2007 leads to a marginal detection (3-5σ): further observations warranted

Fossati et al. (2015)

Detection of weak fields in early B-type stars - Modelling of β CMa

Seismic study

v_{eq} = 30.6±0.9 km s^{-1}
i = 56.7±1.7°
P_{rot} = 13.6±1.2 days



Fossati et al. (2015)

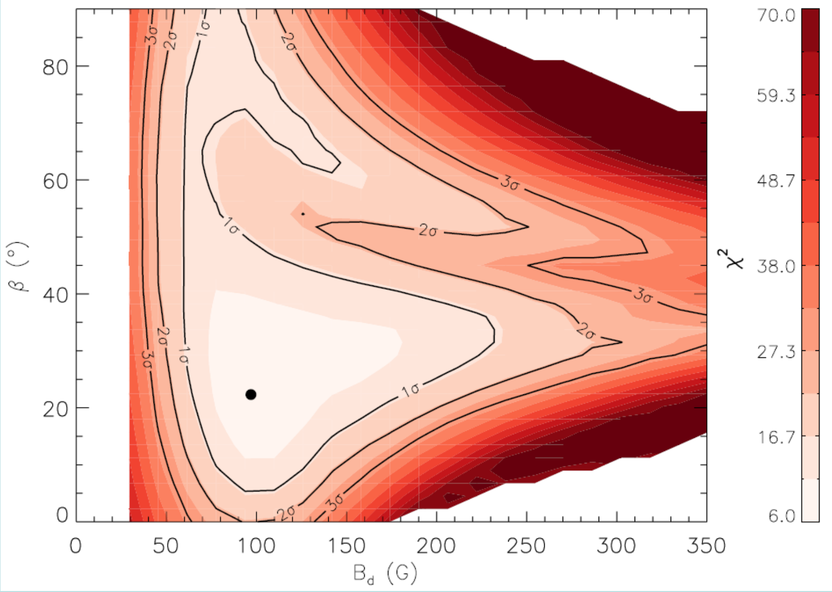
Preliminary modelling of magnetic data

Perfect dipole assumed
Period constrained within 13.6±1.2 days
i = 56.7° assumed

$$\langle B_z \rangle(t) = A \sin\left(\frac{2\pi t}{P} + \phi\right) + ZP$$

With ZP = −16.0 G, A = 10.0 G, P = 13.77 d, and φ = 92°

Best fit for β = 22.3° and B_d = 96.9 G
5 < β (°) < 90 and 60 < B_d (G) < 230 at 1σ level



Fossati et al. (2015)

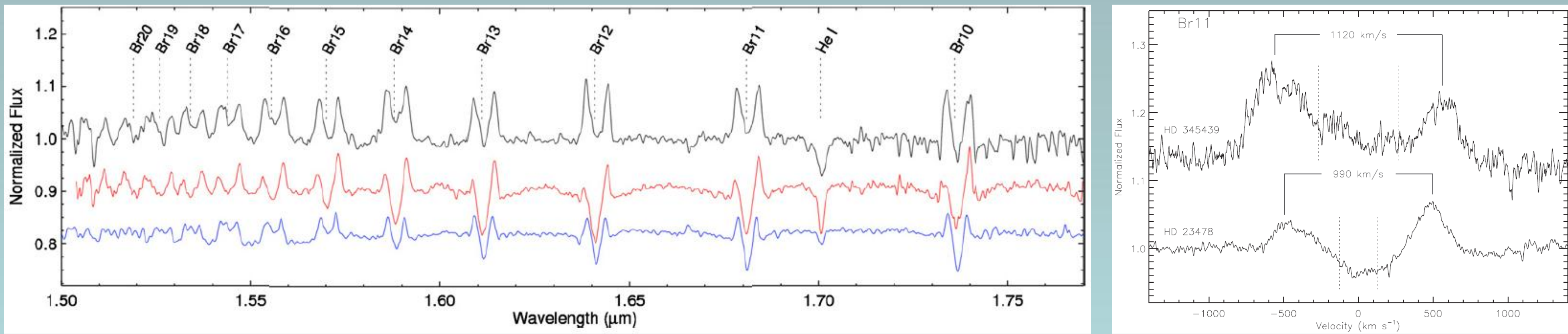
Model supported by further HARPS observations carried out in March 2015

σ Ori E analogues

σ Ori E analogues are early B-type stars with strong fields (B_d~10 kG) and fast rotation (P_{rot}~1 day or less). Problem: the expected spin-down timescale via magnetic braking is much shorter than their estimated ages.

The near-IR wavelength domain seems a powerful indicator for the identification of massive, fast-rotating stars hosting a rigidly rotating magnetosphere (e.g., Oksala et al. 2015). Two such candidates have recently been identified as part of the APOGEE survey (Eikenberry et al. 2014).

HD 345439 σ Ori E HD 23478

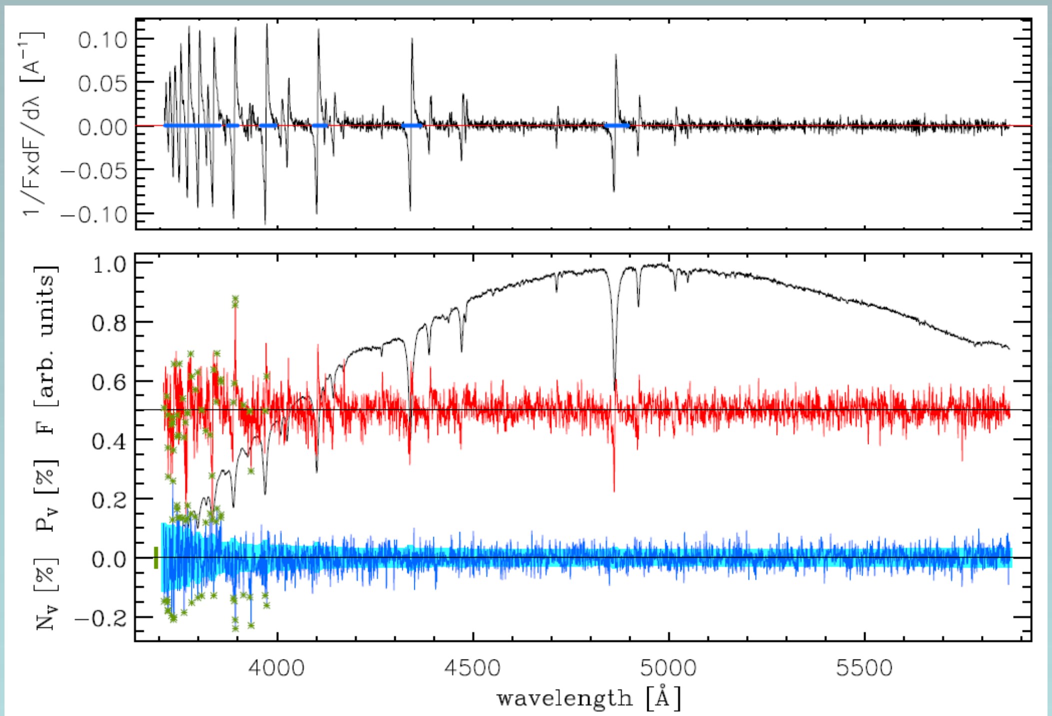


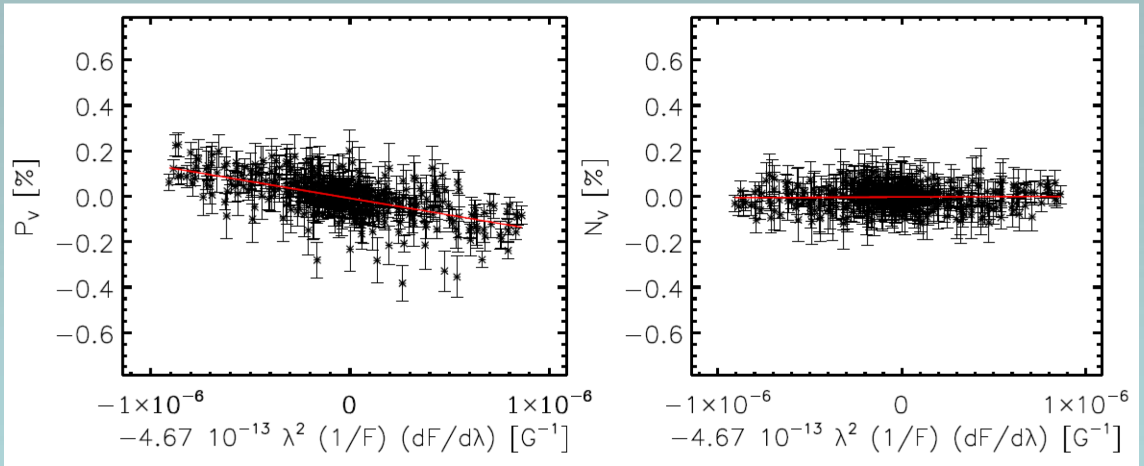
Eikenberry et al. (2014)

Both stars (HD 23478 and HD 345439) observed with FORS2 in June and November 2014

σ Ori E analogues – HD 23478

			Hydrogen lines		All lines	
FORS2 observations			V	N	V	N
Detection	17 11 2014	Bonn	-1477±95	30±64	-1302±59	74±49
		Potsdam	-1347±114	50±93	-1139±84	45±70

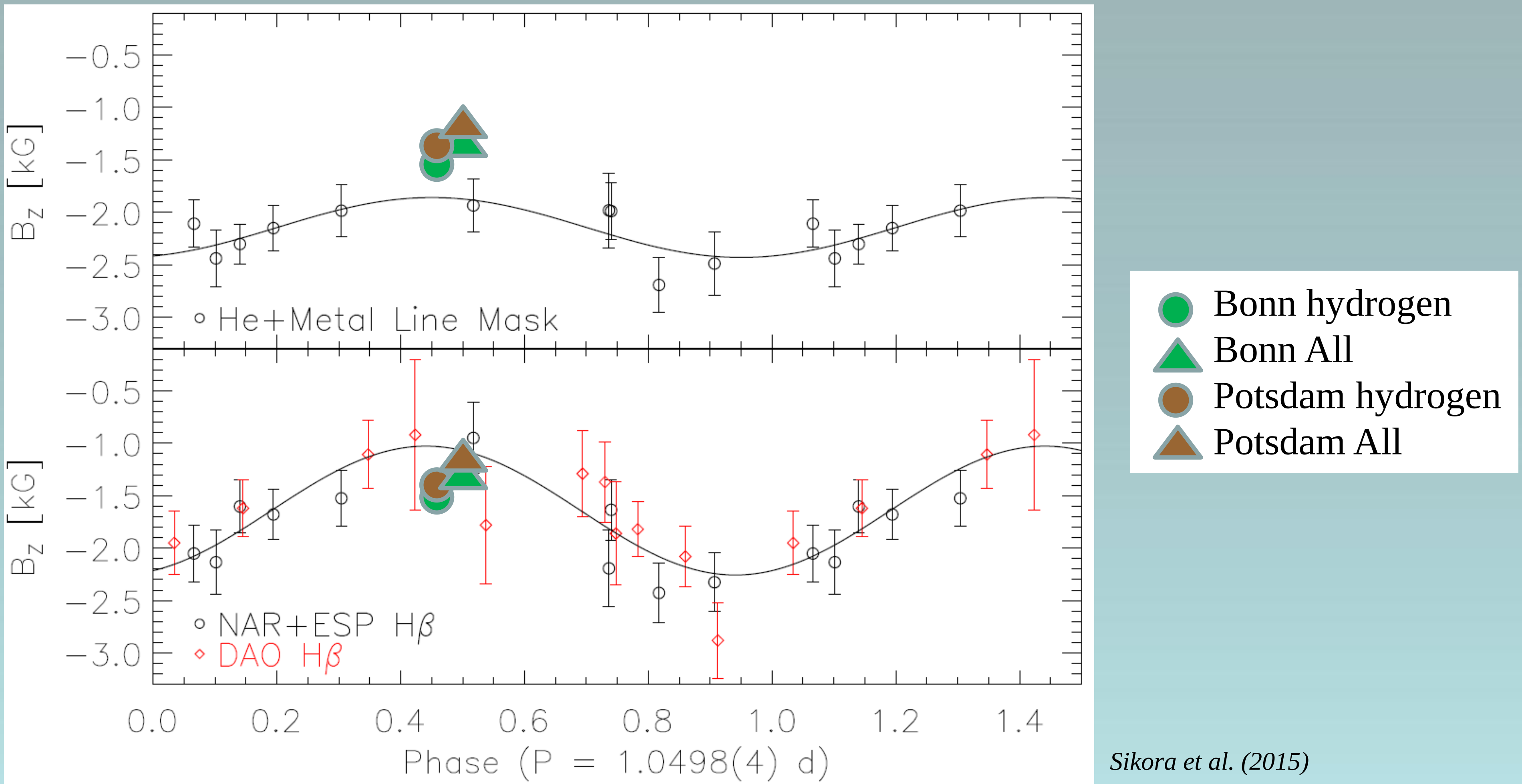




Hubrig et al. (2015)

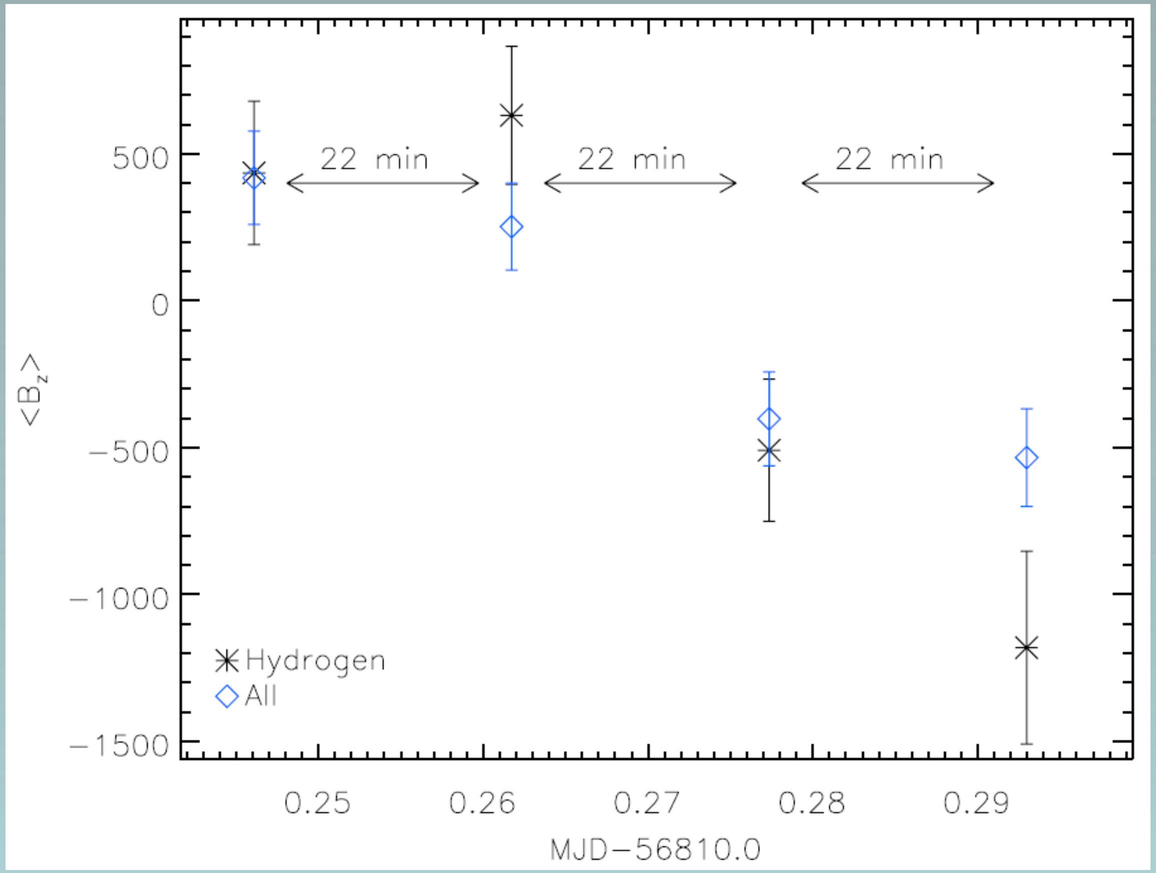
σ Ori E analogues – HD 23478

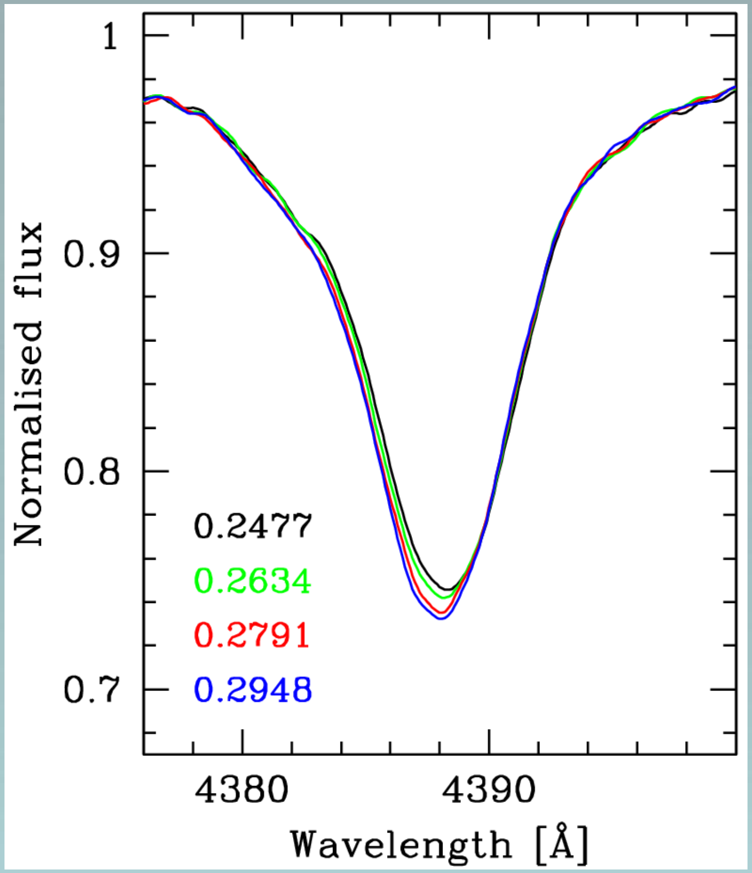
Field independently confirmed and evidence for rotational modulation of photometric/spectroscopic/magnetic data according to *P* ~ 1.05 d (Sikora et al. 2015)



Sikora et al. (2015)

σ Ori E analogues – HD 345439

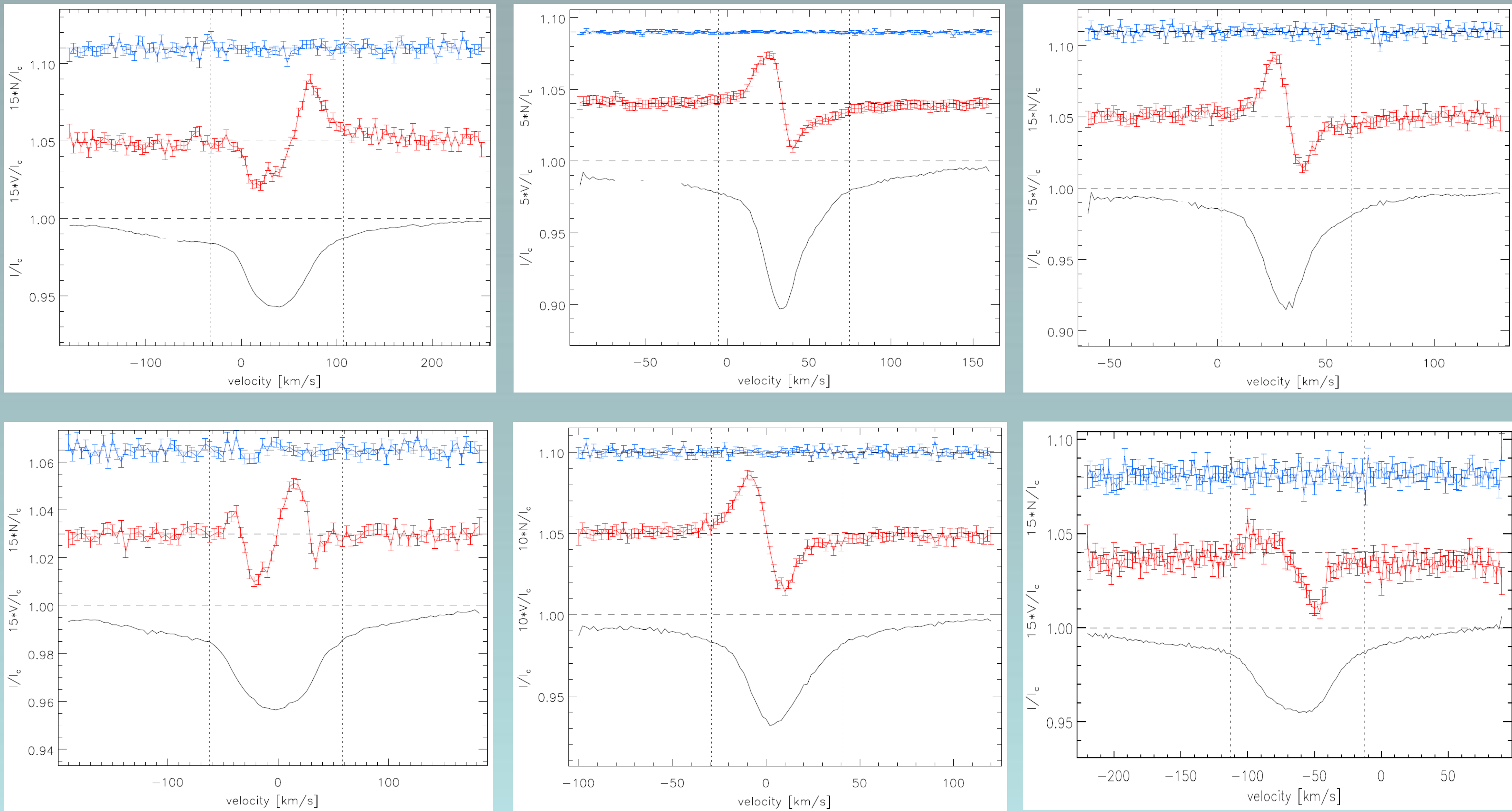




Hubrig et al. (2015)

Rapid line-profile and magnetic field variations because of fast rotation (vsini ~ 270 km s^{-1})
Reminiscent of variations of ~1 kG over 75 minutes in HR 7355 with *P* = 0.52 d (Rivinius et al. 2013)

Recent detection of He-rich B-type stars



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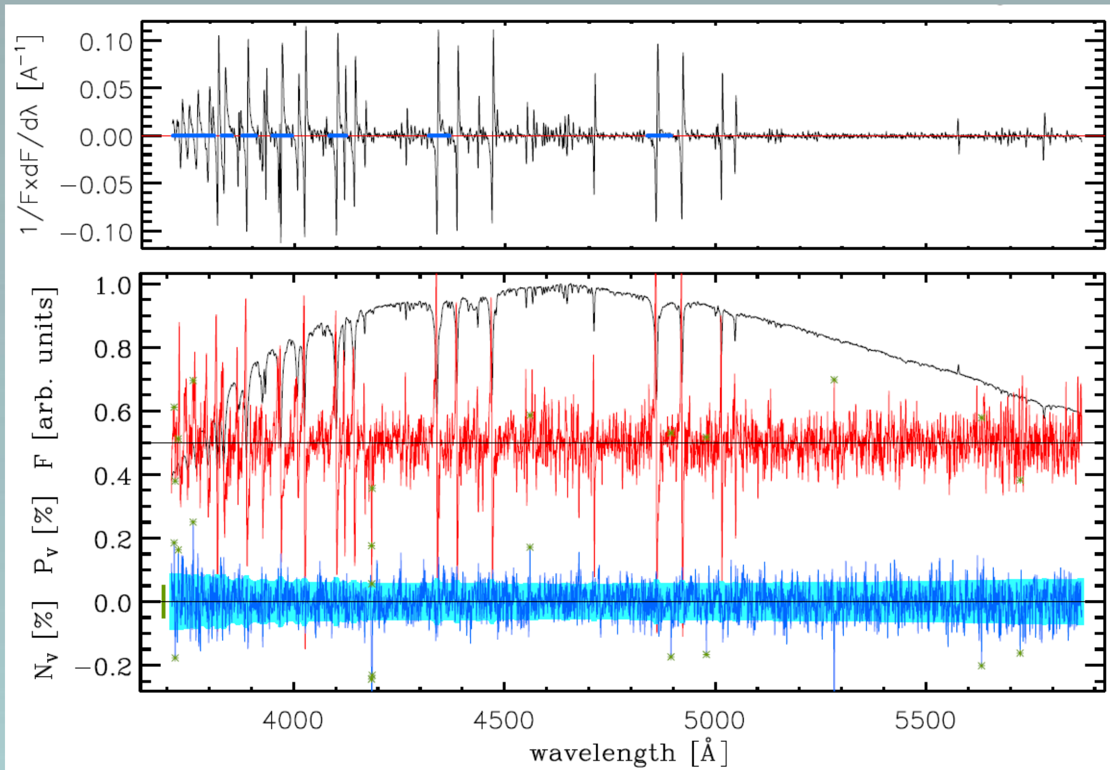

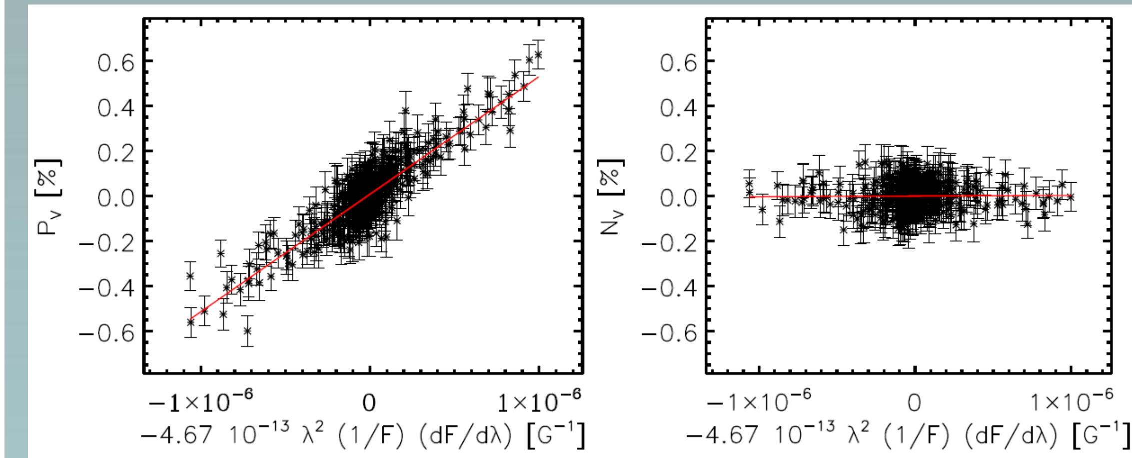

Longitudinal field from FORS2 = 5.2±0.3 kG (dipolar field > 16 kG)
Very strong field confirmed by subsequent HARPS observations
Third strongest magnetic field ever detected in a massive star

Conclusions

- Spectropolarimetric observations of 125 OB stars carried out so far with FORS2 and HARPS. Survey at ~85% complete.
- Only very few targets in common with MiMeS: complementary survey.
- Consistent detections using two completely different reduction and analysis techniques.

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- Spectropolarimetric observations of 125 OB stars carried out so far with FORS2 and HARPS. Survey at ~85% complete.
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- Consistent detections using two completely different reduction and analysis techniques.

- Evidence that the occurrence of relatively strong fields (typically above 100-200 G) is low in massive stars and is of the order of ~10%.

- Discovery of a magnetic, triple system in the young Trifid Nebula (Hubrig et al. 2014). Unclear at this stage whether only one or more components are magnetic.
- Indications for intrinsically weak fields ($B_d < 200$ G) in early B-type stars (Fossati et al. 2015).
- Confirmation that spectral diagnostics in the near-IR can be used to efficiently identify σ Ori E analogues (Hubrig et al. 2015).
- Discovery of a number of He-rich, magnetic B-type stars, among which one with one of the strongest fields ever detected in an OB star ($B_d > 16$ kG).