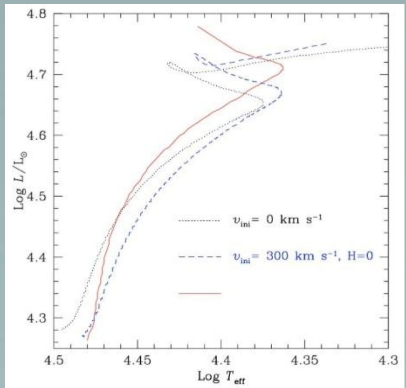
The B fields in OB stars (BOB) survey

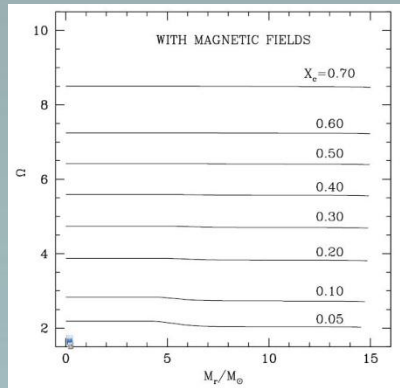
On behalf of the BOB collaboration:

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., Järvinen, S., Kharchenko, N., Kholtygin, A., Liermann, 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.

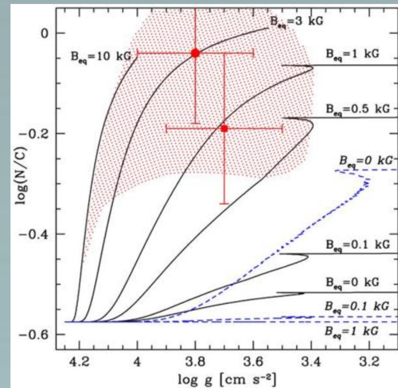
Effects of magnetic fields in massive stars



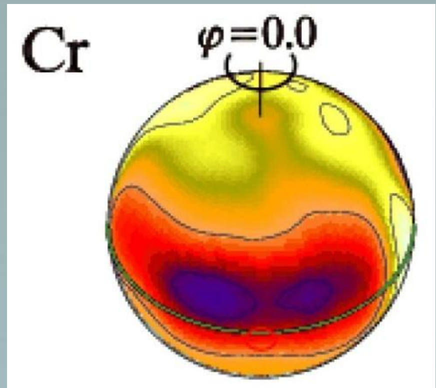
Evolution



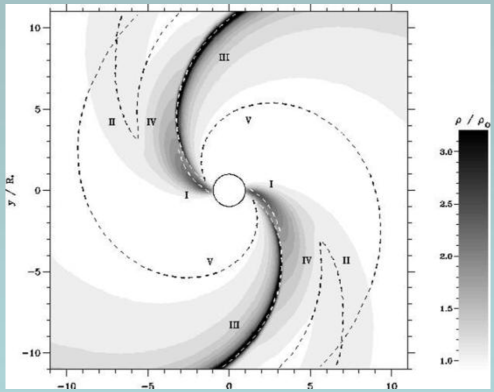
Magnetic braking
Rotational profile



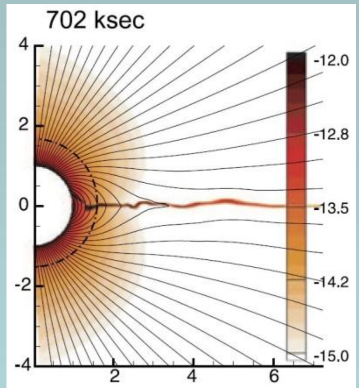
Internal mixing



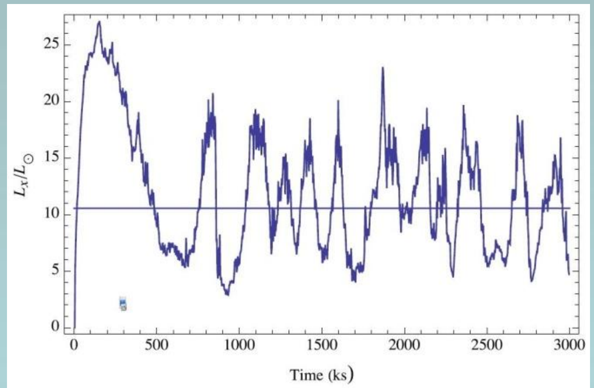
Inhomogeneous abundances
at the surface



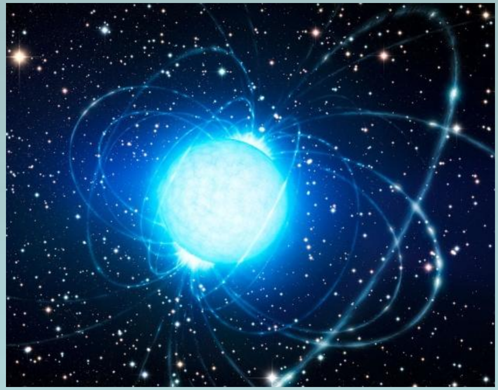
Seed perturbations for large-scale
wind structures (CIRs, …)



Channeling of
stellar wind



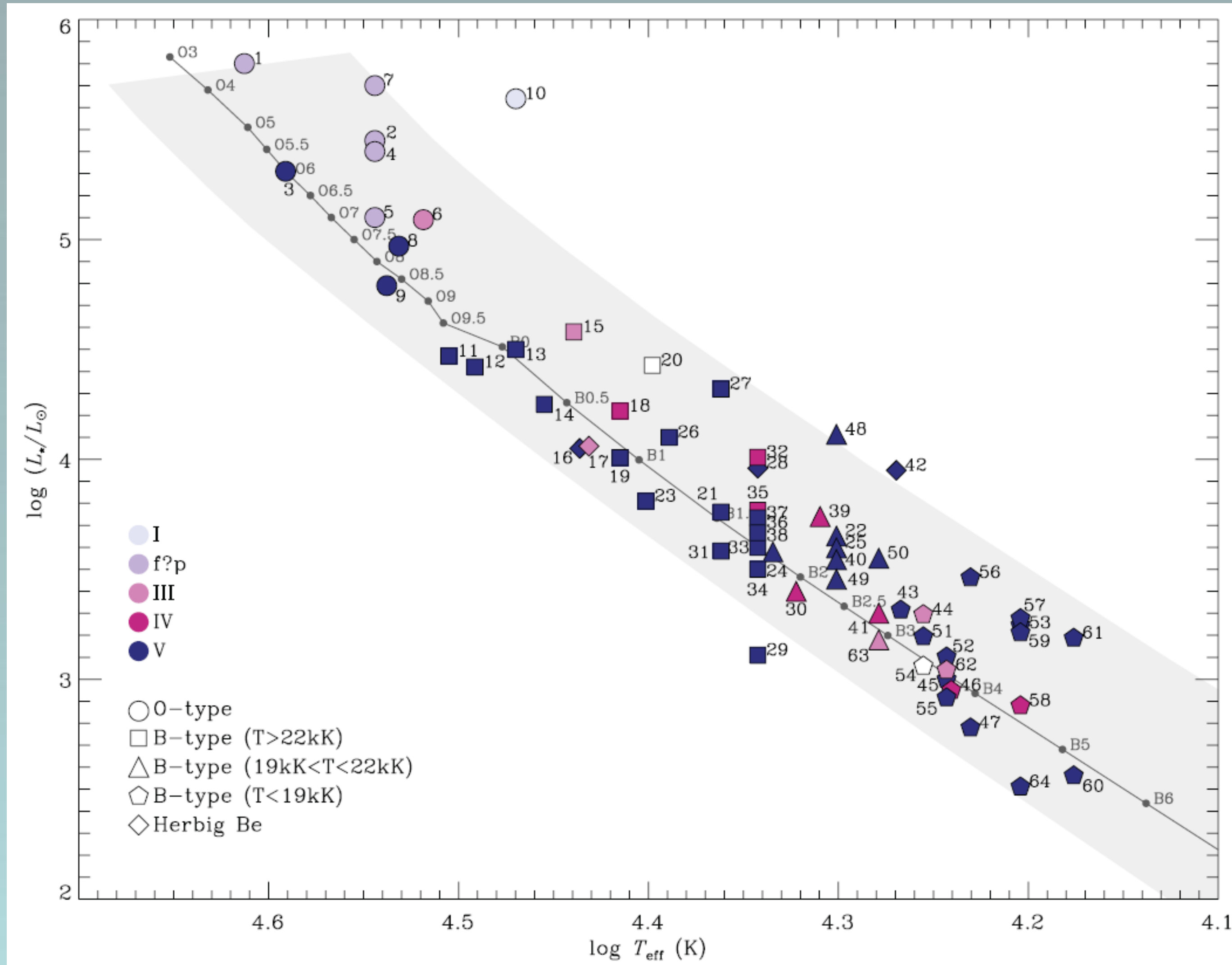
X-ray properties



End products
(magnetars, γ ray bursts, …)

Magnetism in massive stars: some observational facts

Magnetic OB stars are *rare*



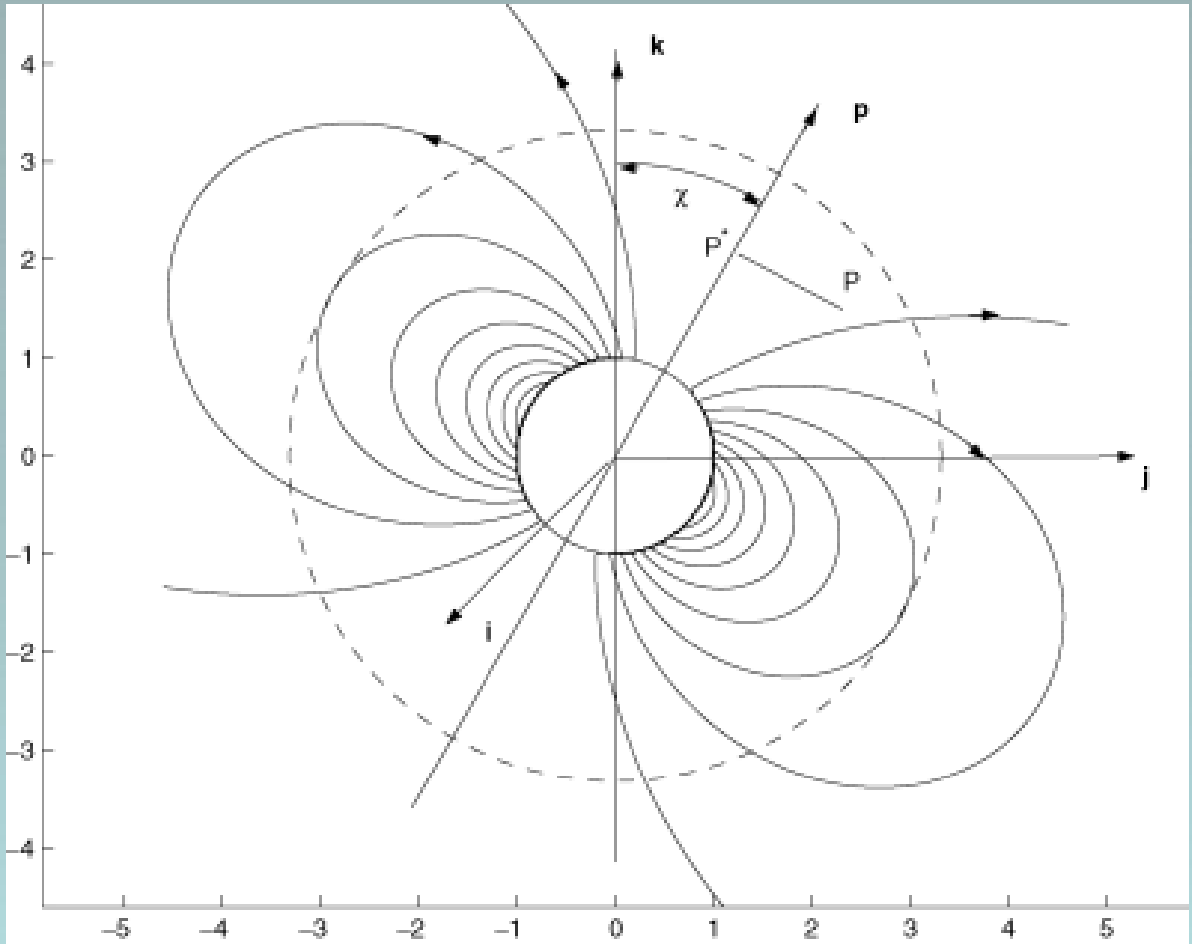
Petit et al. (2013)

Magnetism in massive stars: some observational facts

The detected field is generally *long-lived, strong* (~kG) and predominantly *dipolar*

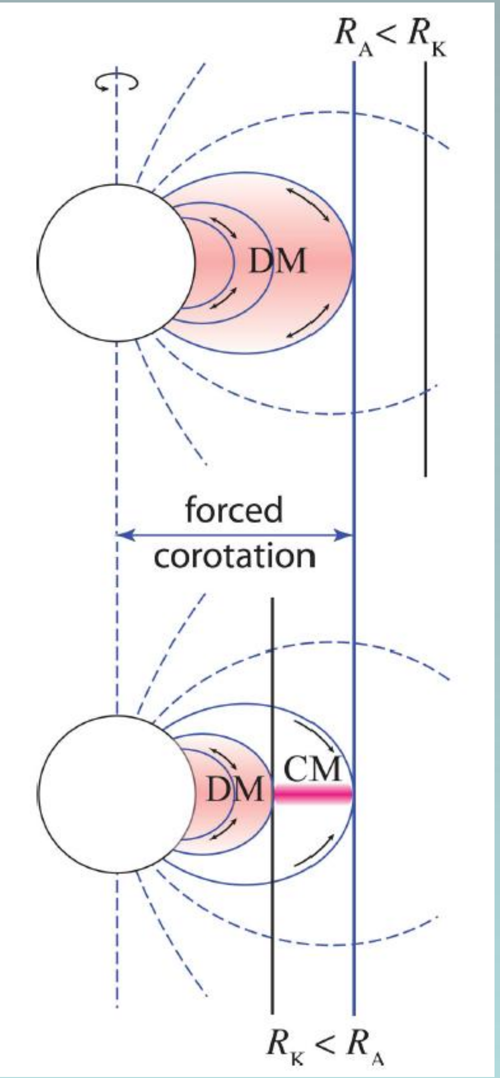
The magnetic and rotational axes are often *tilted* relative to each other

No dependence between field strength and rotation rate

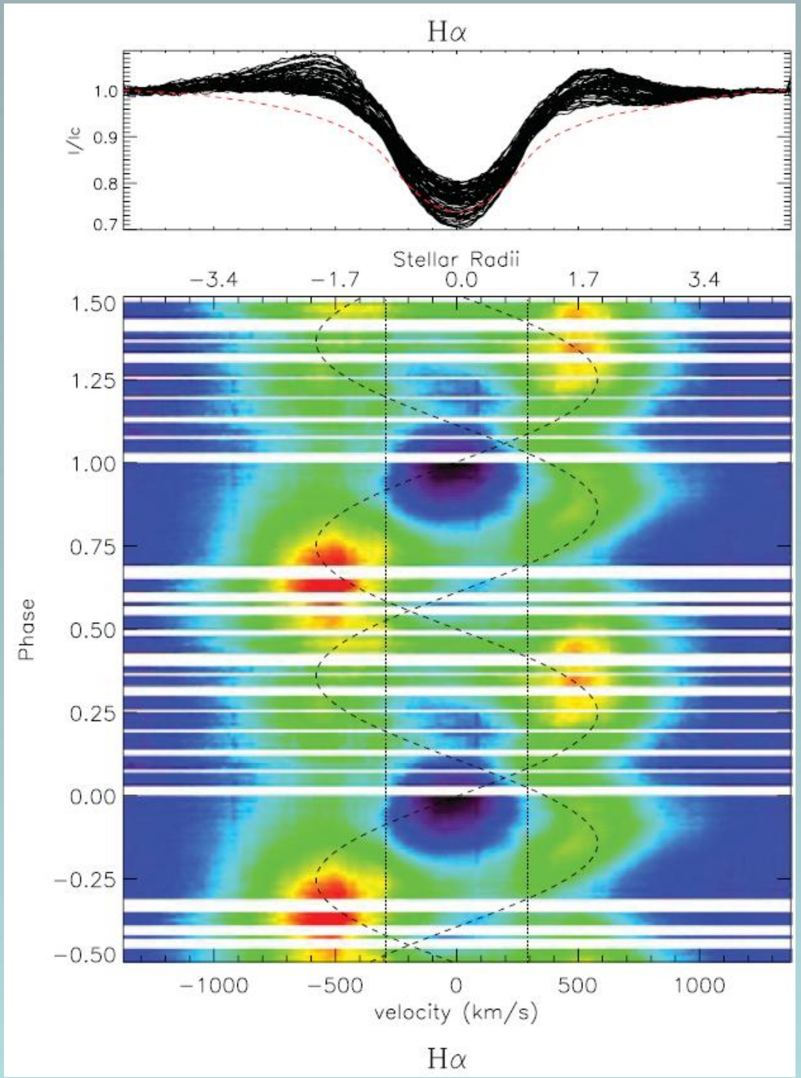


Magnetism in massive stars: some observational facts

They can host a *magnetosphere*



Petit et al. (2013)



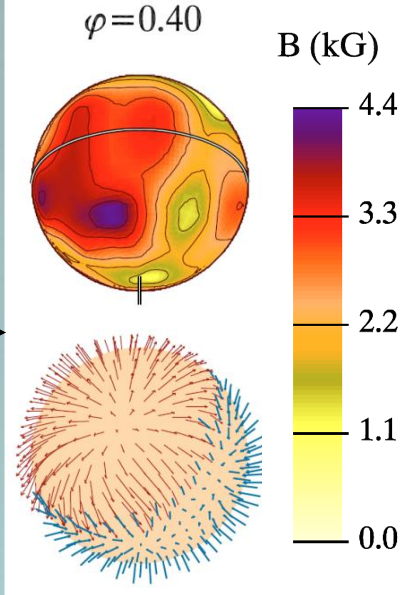
Grunhut et al. (2012)

Origin of *stable, large-scale* magnetic fields in massive stars

Dynamo currently acting in radiative envelope

- ✗ *Difficulties to match field properties (stability, topology, strength, incidence)*
- ✗ *Some dependence with rotation rate expected*
- ✗ *Really at work (Zahn et al. 2007)?*

?



Kochukhov & Wade (2010)

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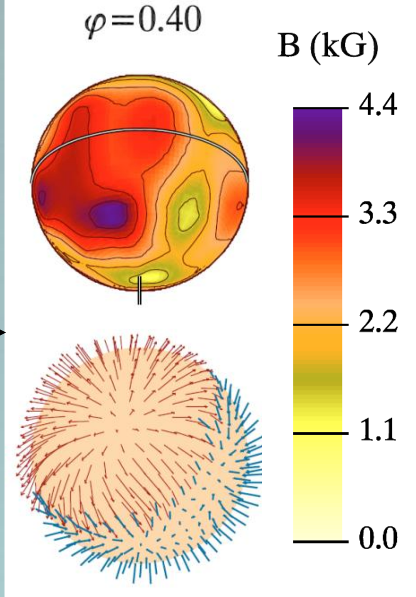

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Merger event during the (pre-)MS phase

- ✓ *Field incidence rate broadly consistent with expected number of mergers during MS (Sana et al. 2012)*
- ✓ *Dearth of magnetic stars in close SB2 systems (<2%; BinaMIcS survey)*
- ✗ *Can hardly explain pairs of magnetic B-type stars (ε Lupi; Shultz et al. 2015)*
- ✗ *Cannot be confronted with observations (lack of simulations)*

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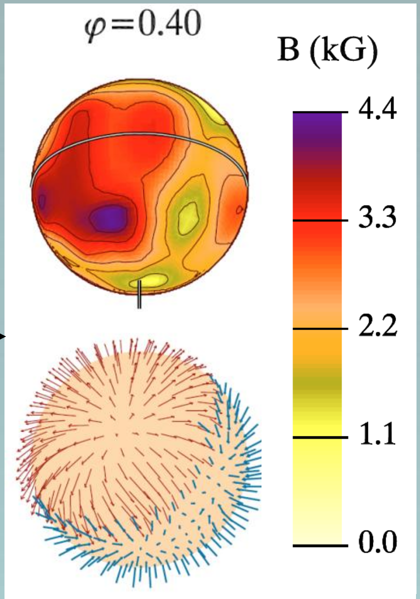

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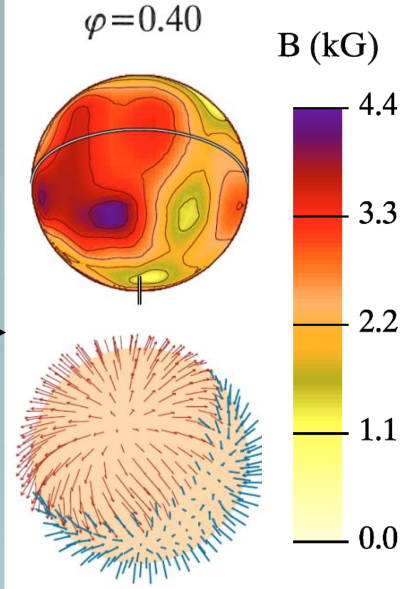
Inherited from collapse of natal molecular cloud ('fossil field')

- ✓ *Field properties natural outcome of MHD simulations (Braithwaite & Spruit 2004)*
- ✓ *Magnetic fields of MS OB stars with similar incidence and properties as progenitors (Herbig Ae/Be stars)*
- ✓ *No dependence field strength vs mass and rotation speed as observed*
- ✓ *Might be consistent under certain conditions with incidence rate*
- ✗ *Close binaries with only one magnetic component*

?



Kochukhov & Wade (2010)

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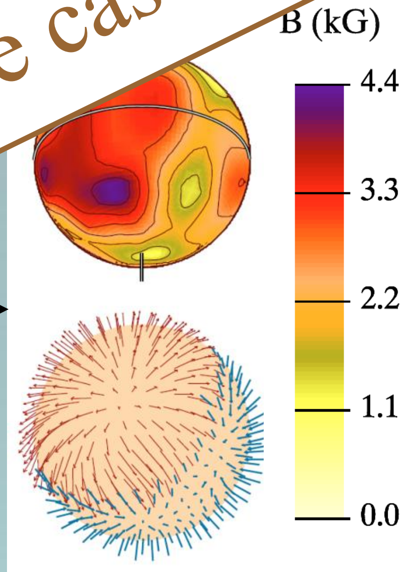
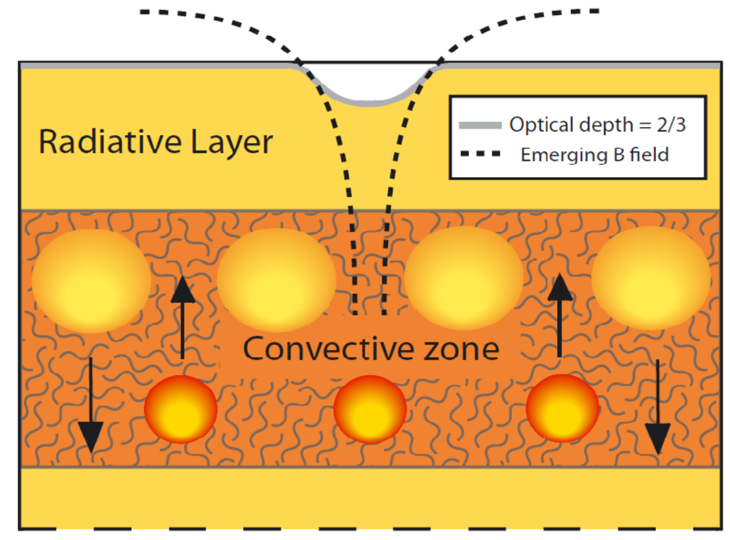
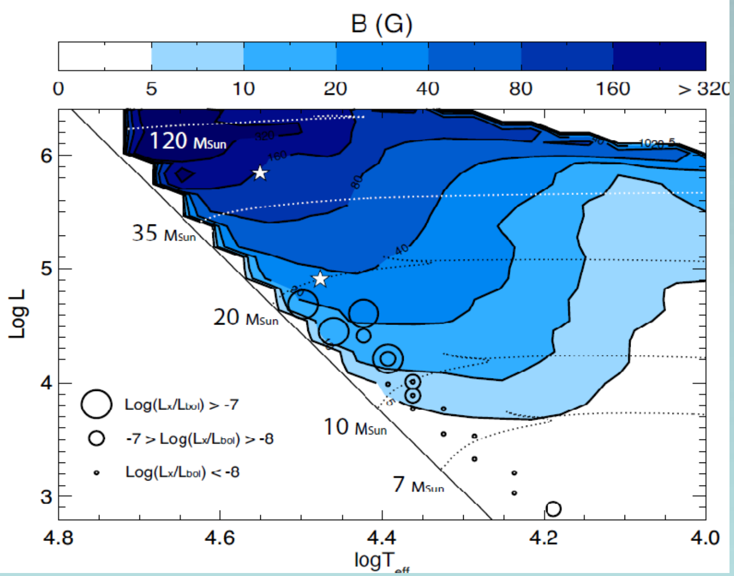


Kochukhov & Wade (2010)

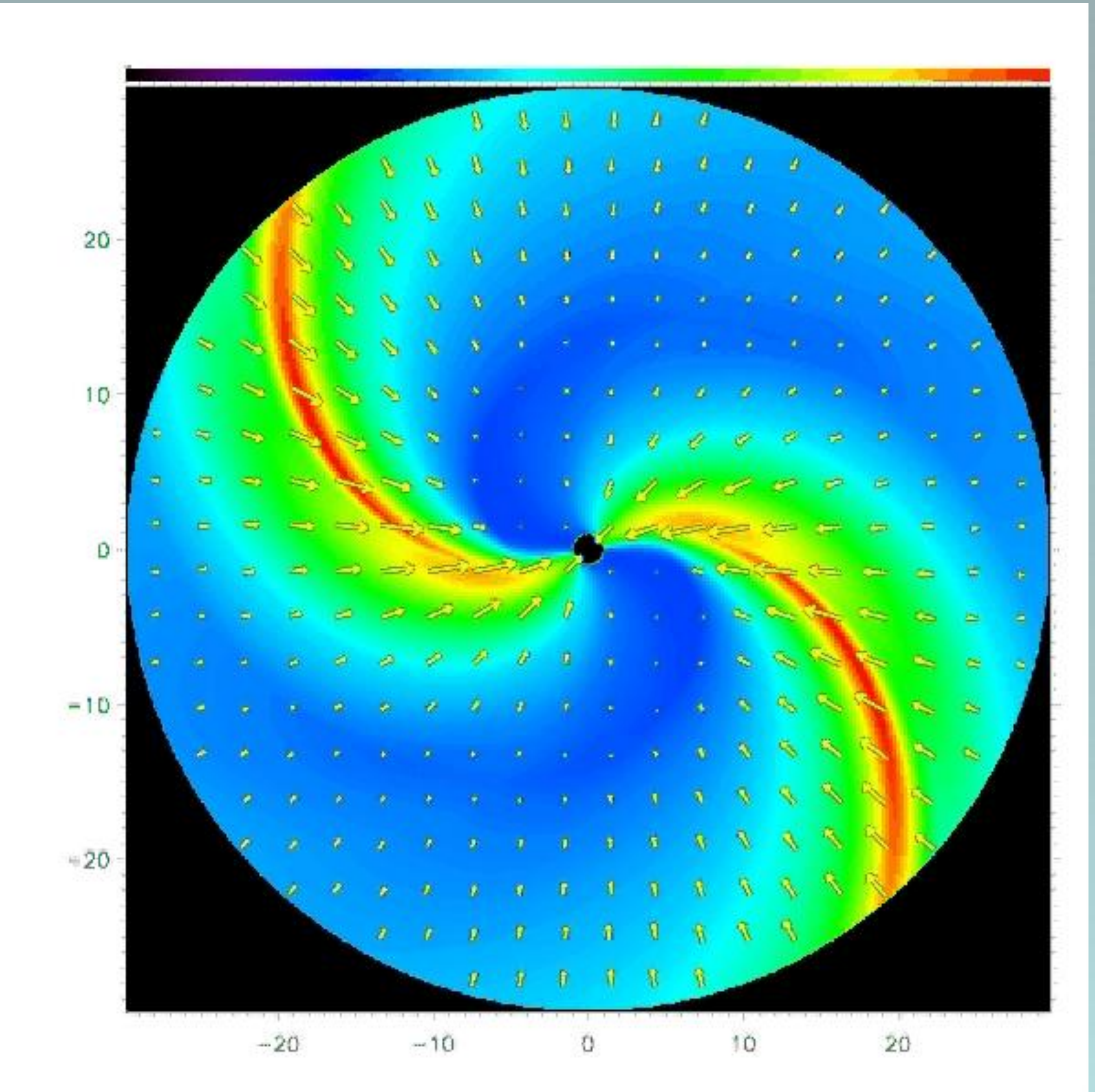
Fossil field scenario preferred, but field production through stellar mergers may occur in some cases

Possible existence of *dynamic, small-scale* magnetic fields in massive stars



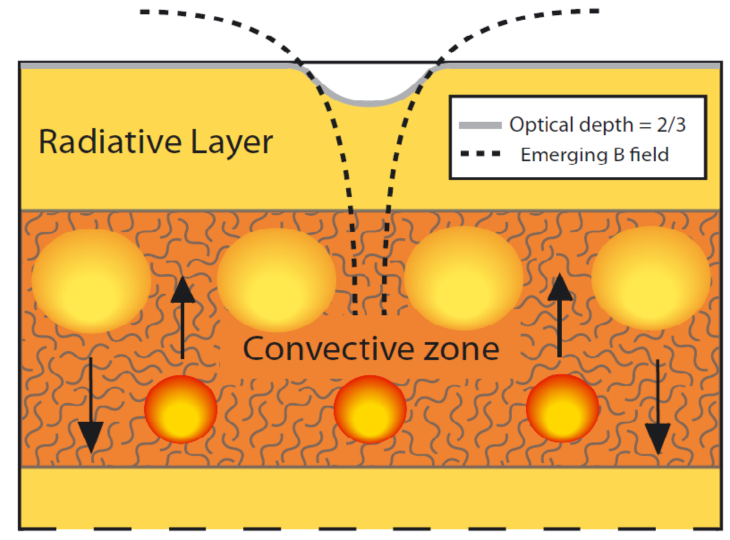


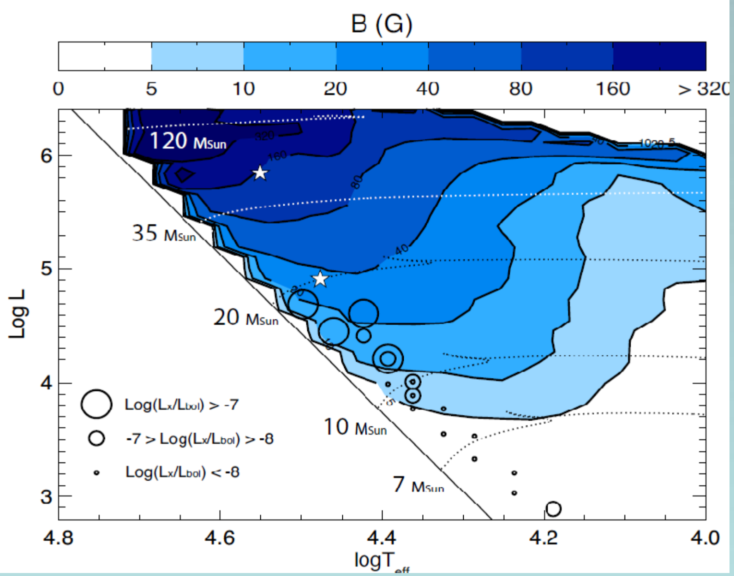
Cantiello & Braithwaite (2011)



Courtesy: Alex Lobel & Ronny Blomme (ROB)

Possible existence of *dynamic, small-scale* magnetic fields in massive stars





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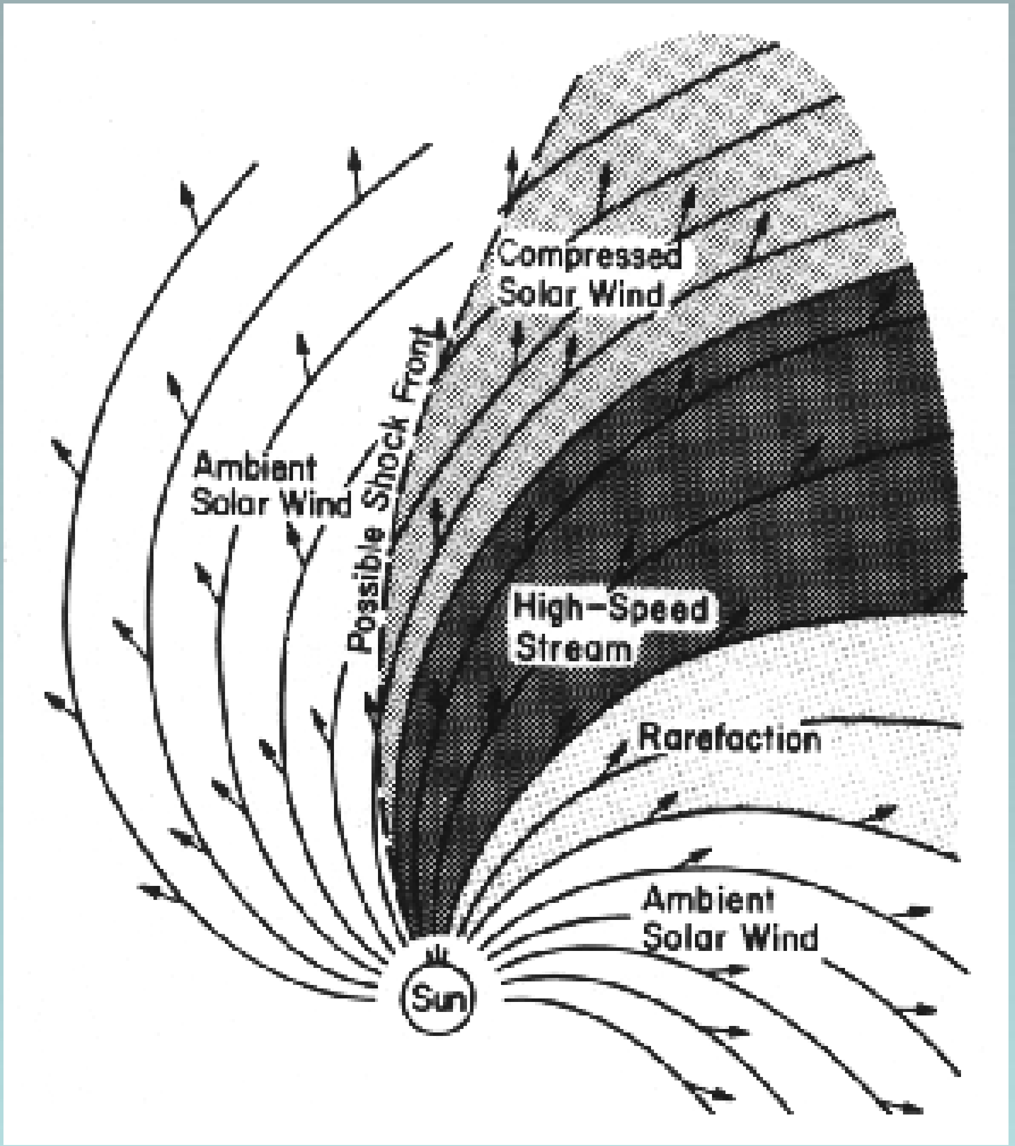


Hundhausen (1972)

The B fields in OB stars (BOB) project

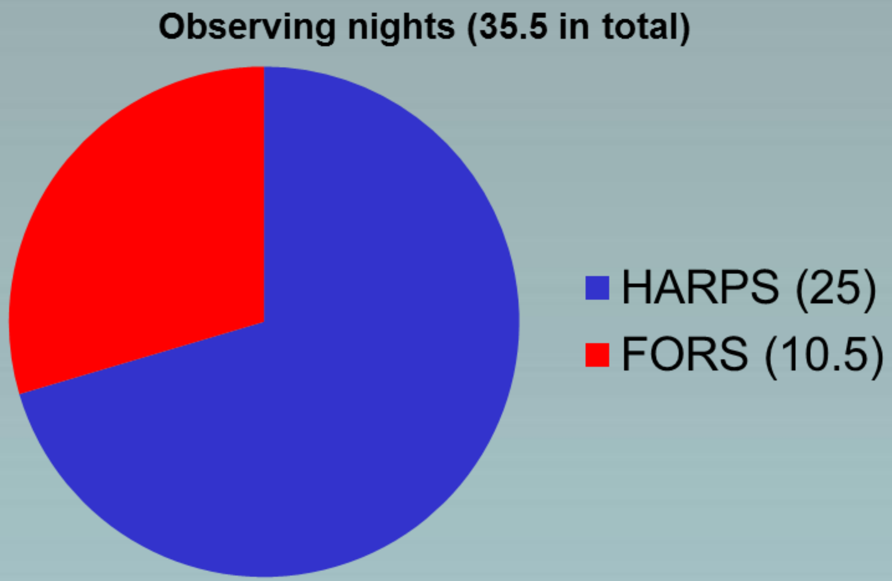
A total of 35.5 nights allocated over three years (2013-2016) as an ESO Large Programme on FORS2 (*R*~2000) and HARPSpol (*R*~115,000)

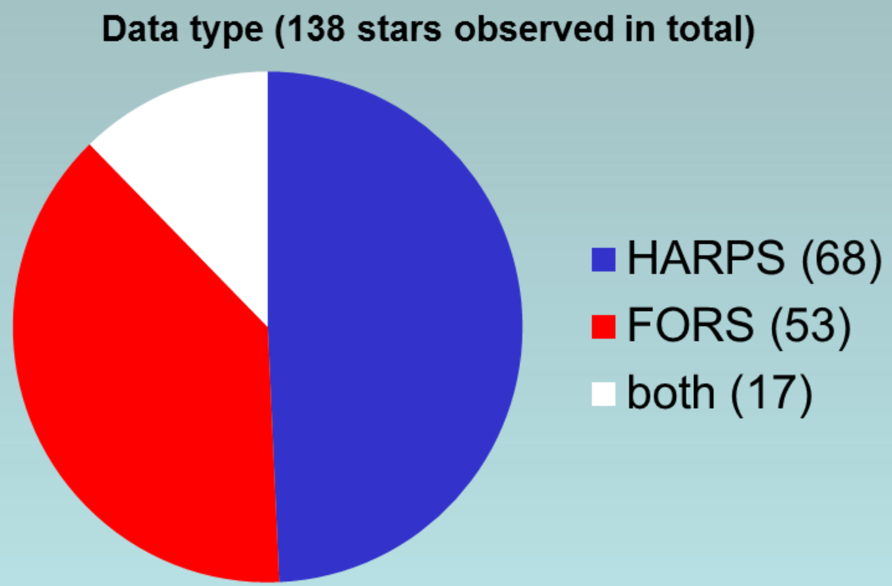
Survey biased towards slow rotators to enhance field detectability

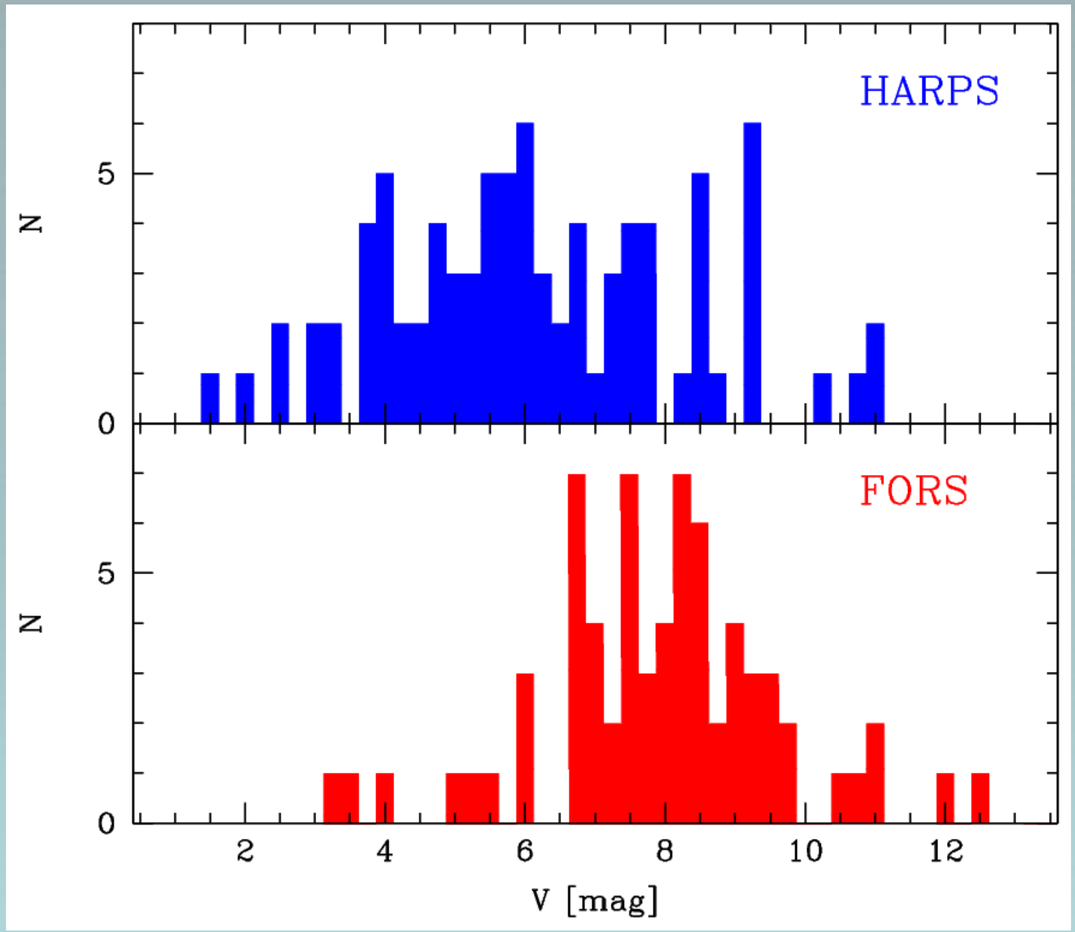
For both FORS2 and HARPS, data reduction and analysis carried out completely independently by two groups (Bonn and Potsdam)

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

Breakdown of observations







Incidence rate of magnetic fields in OB stars

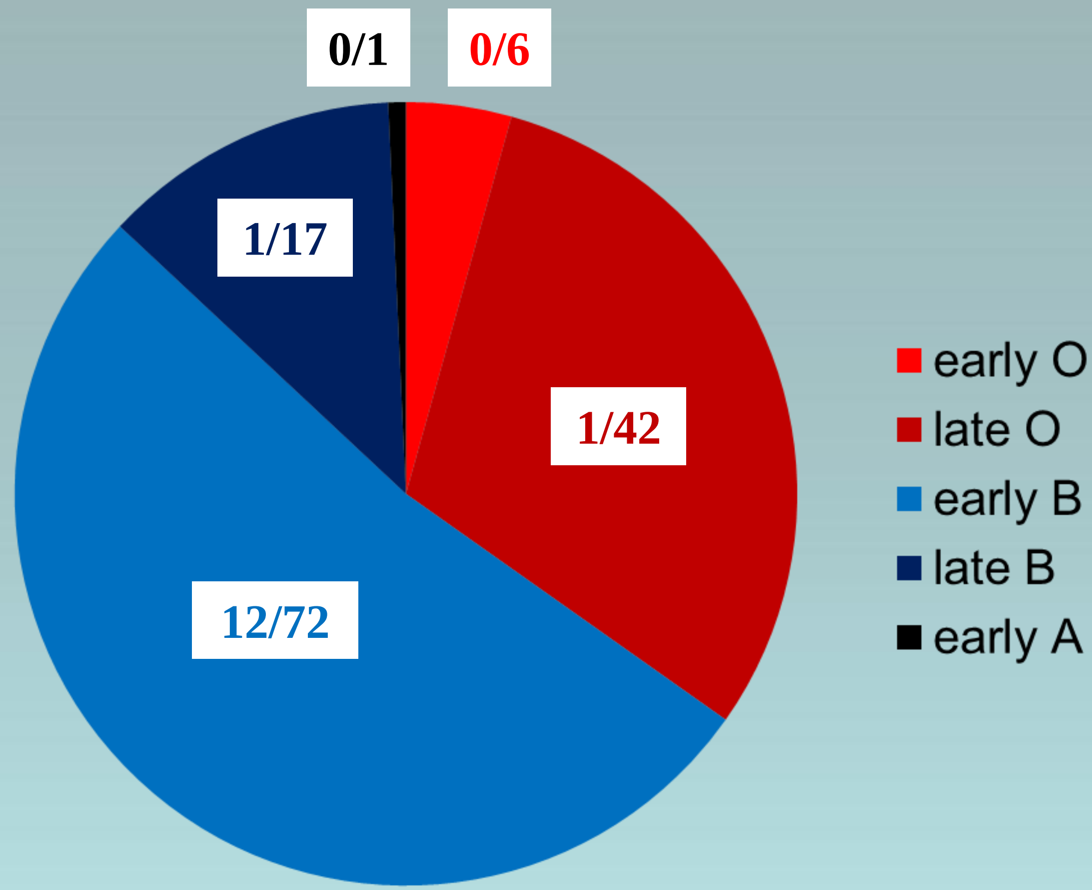
	MiMeS	BOB
Number stars surveyed	~525	138
Number first detections	~35	14
Detection rate	**7±1%**	**~10%**

Figures not to be taken at face value:

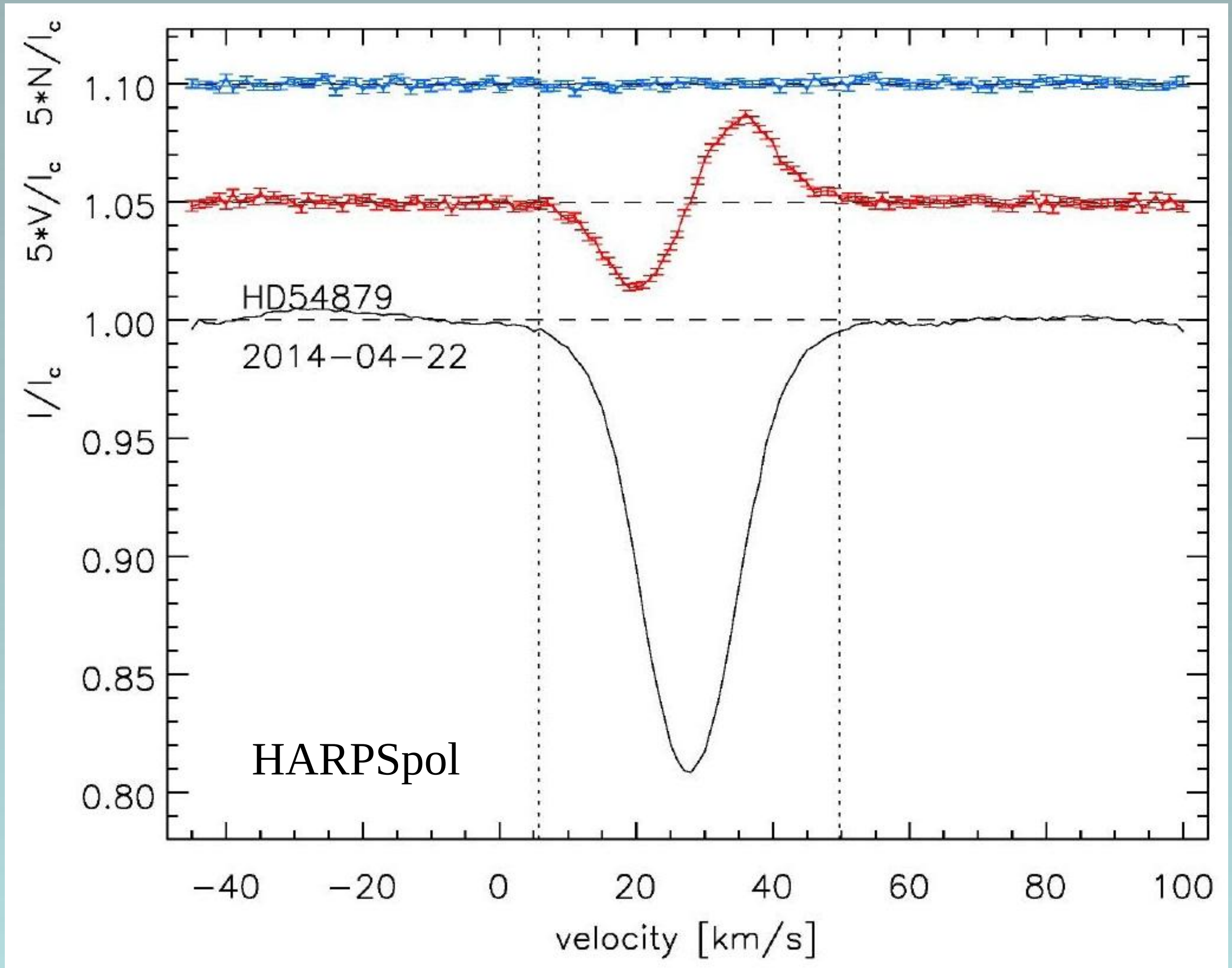
Some HARPS observations still not fully analysed

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

BOB targets detected/observed



Detecting a field in a massive star
An example from *high-resolution* observations



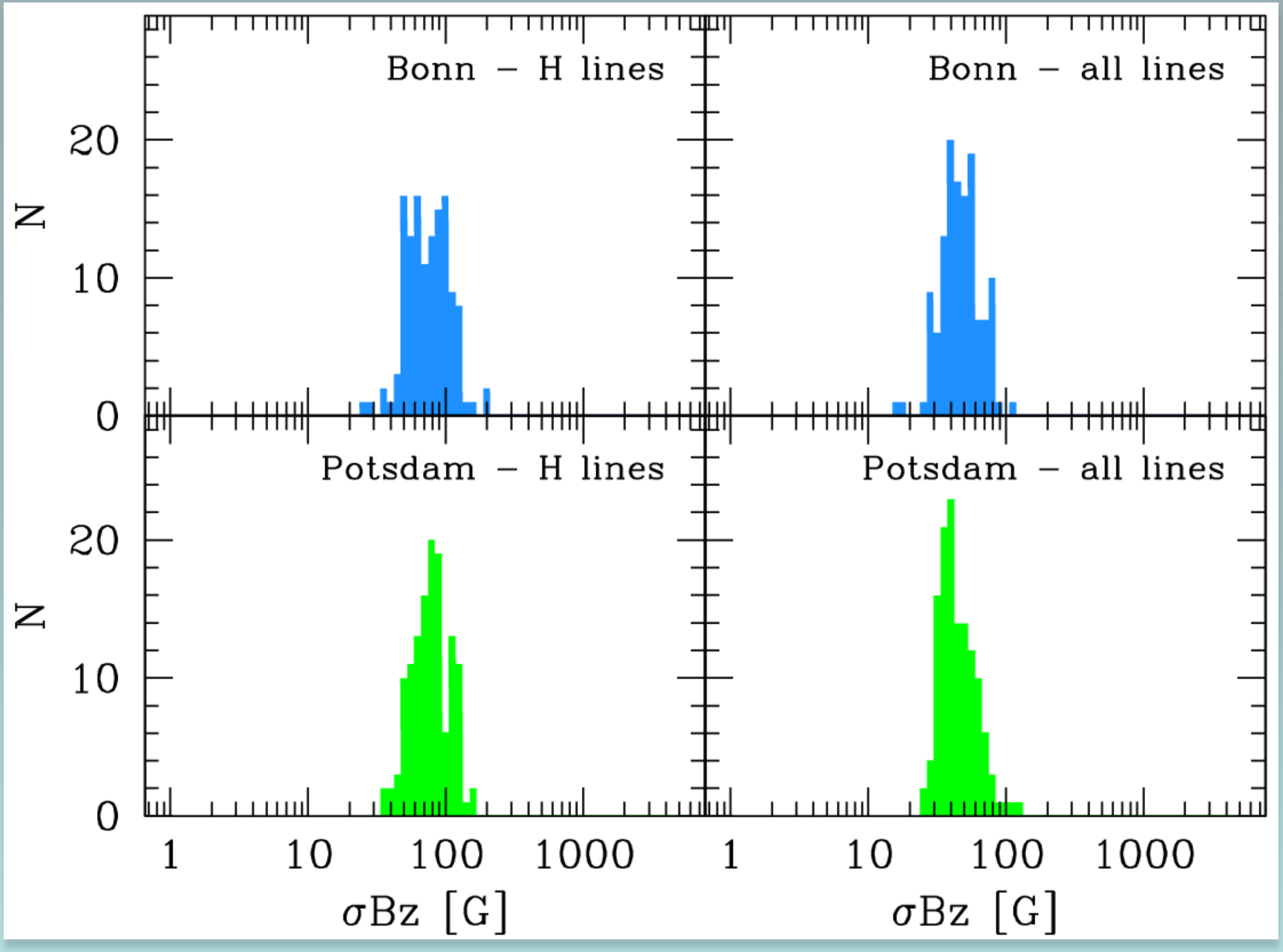
Null profile: FAP > 0.7

Stokes *V*: ‹Bz› = −592±7 G
FAP~10^{-15}

Unpolarised Stokes *I* profile

Castro et al. (2015)

Overview of FORS2 results



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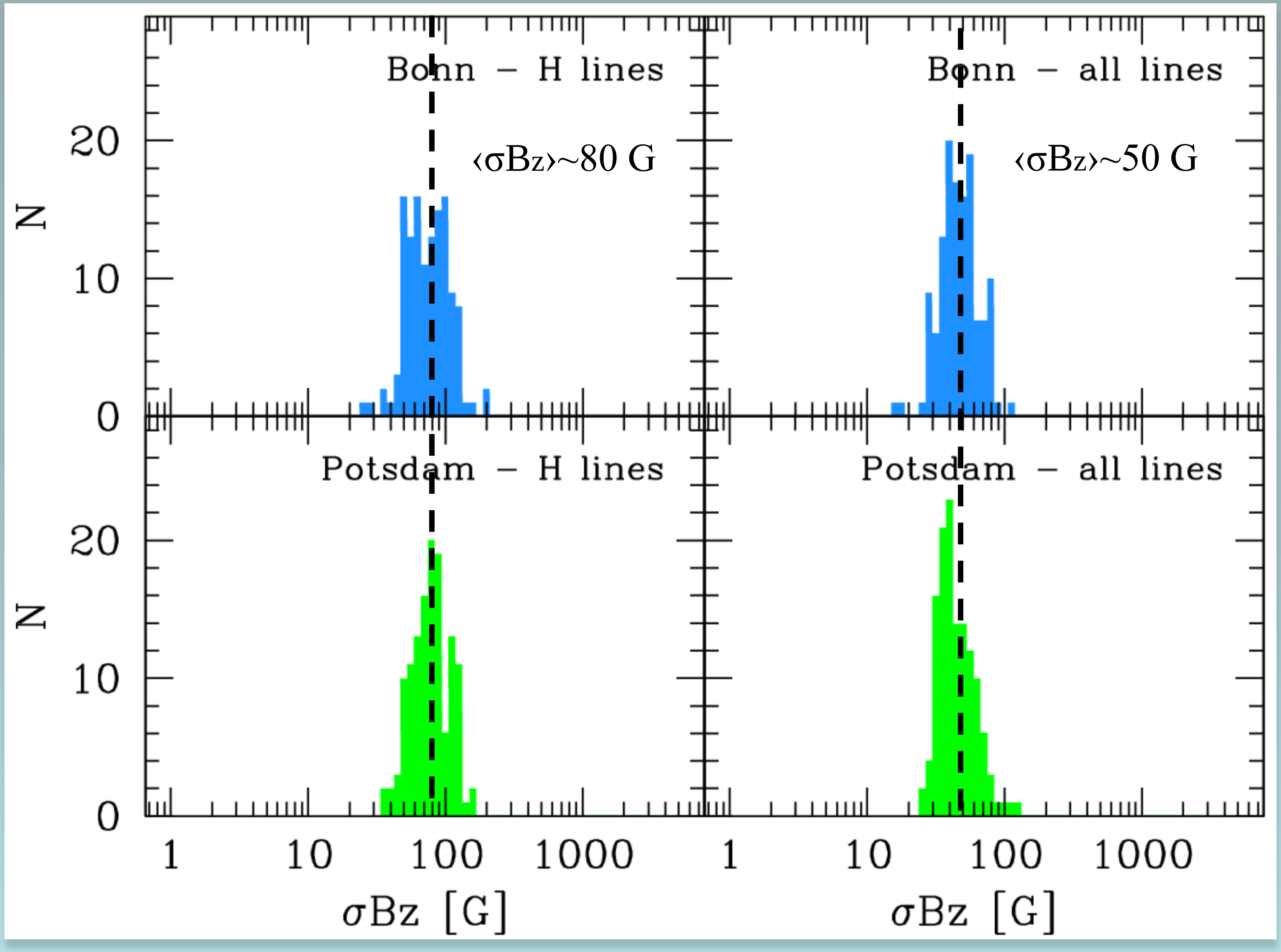

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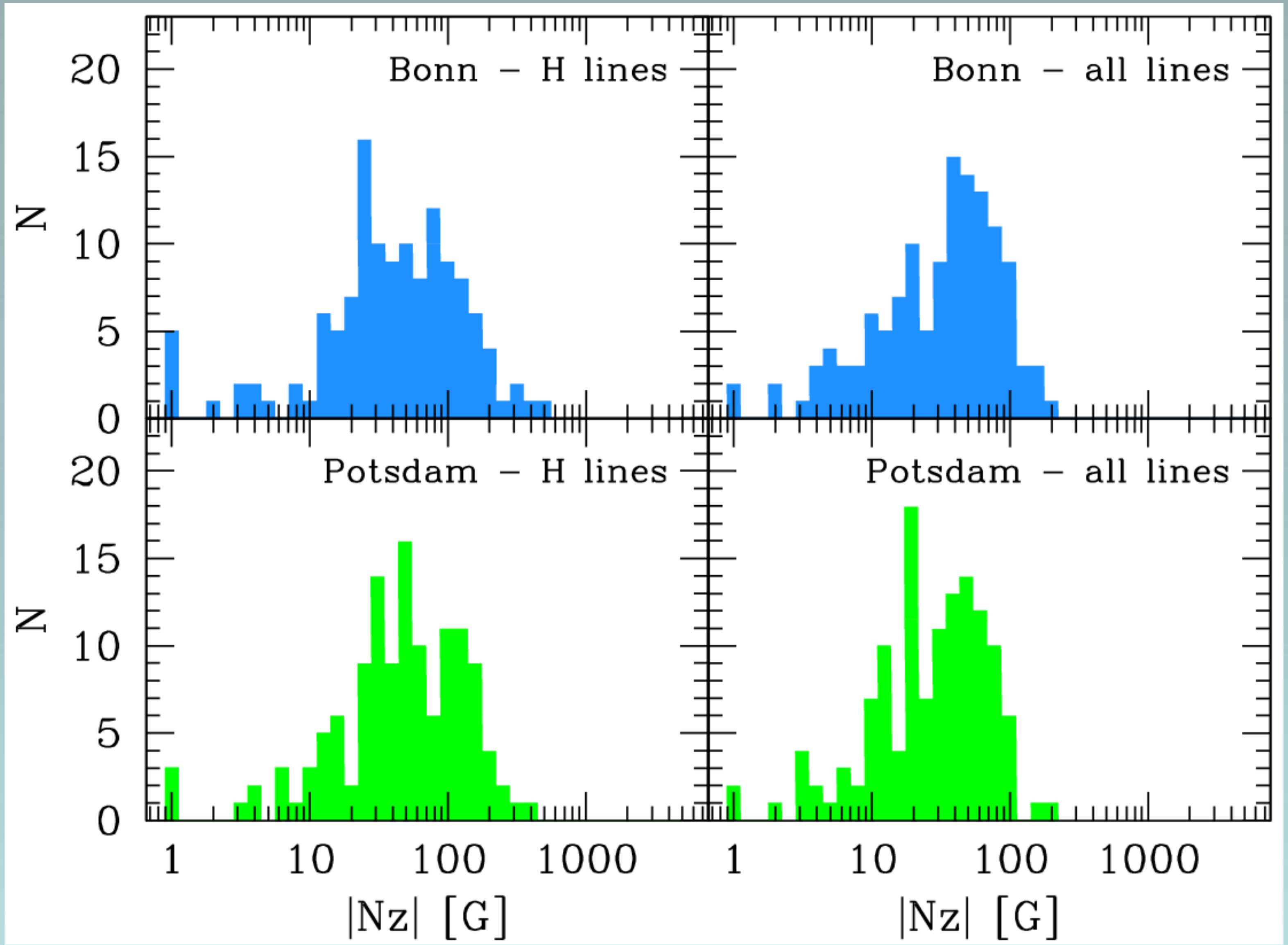

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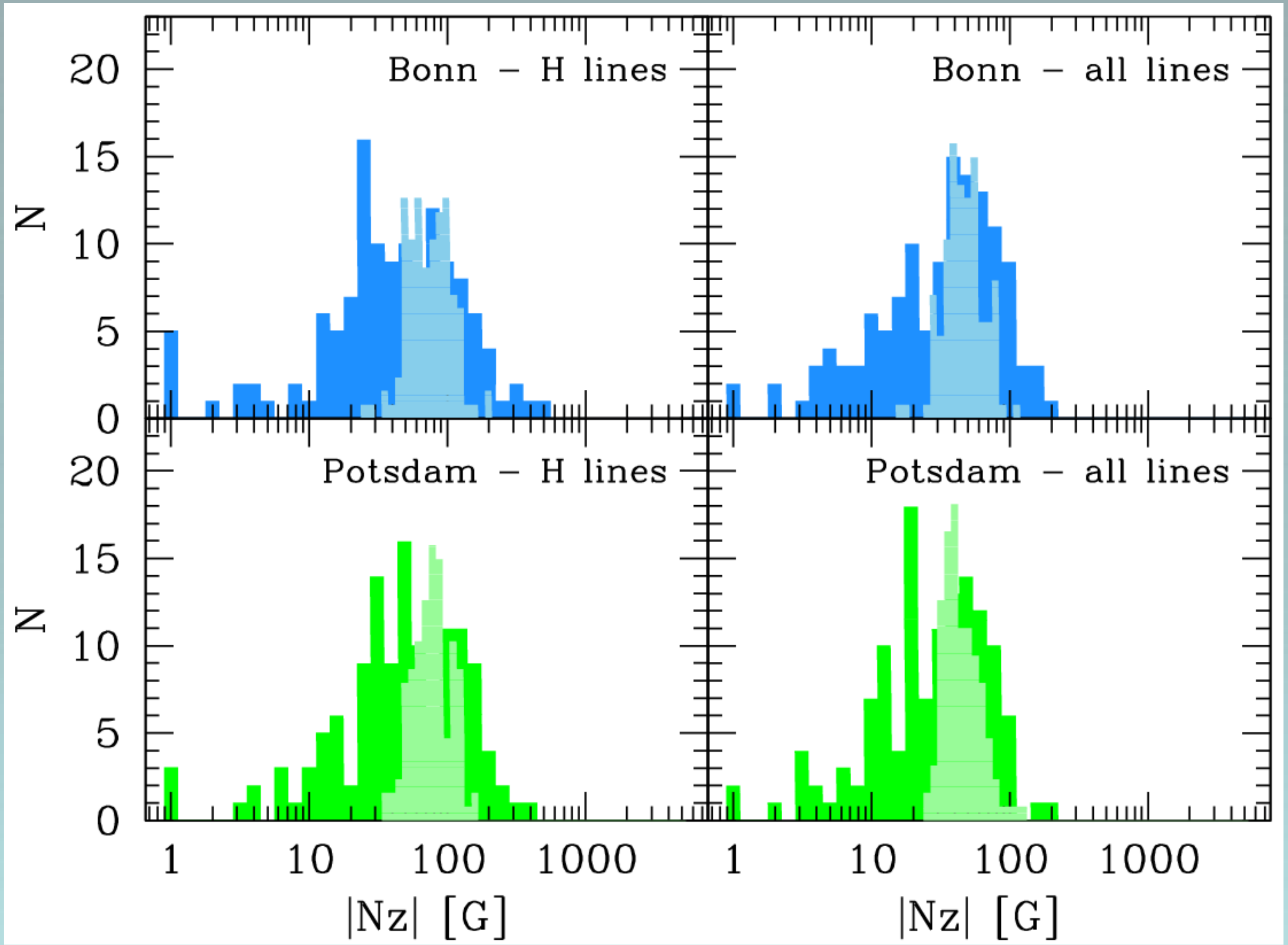

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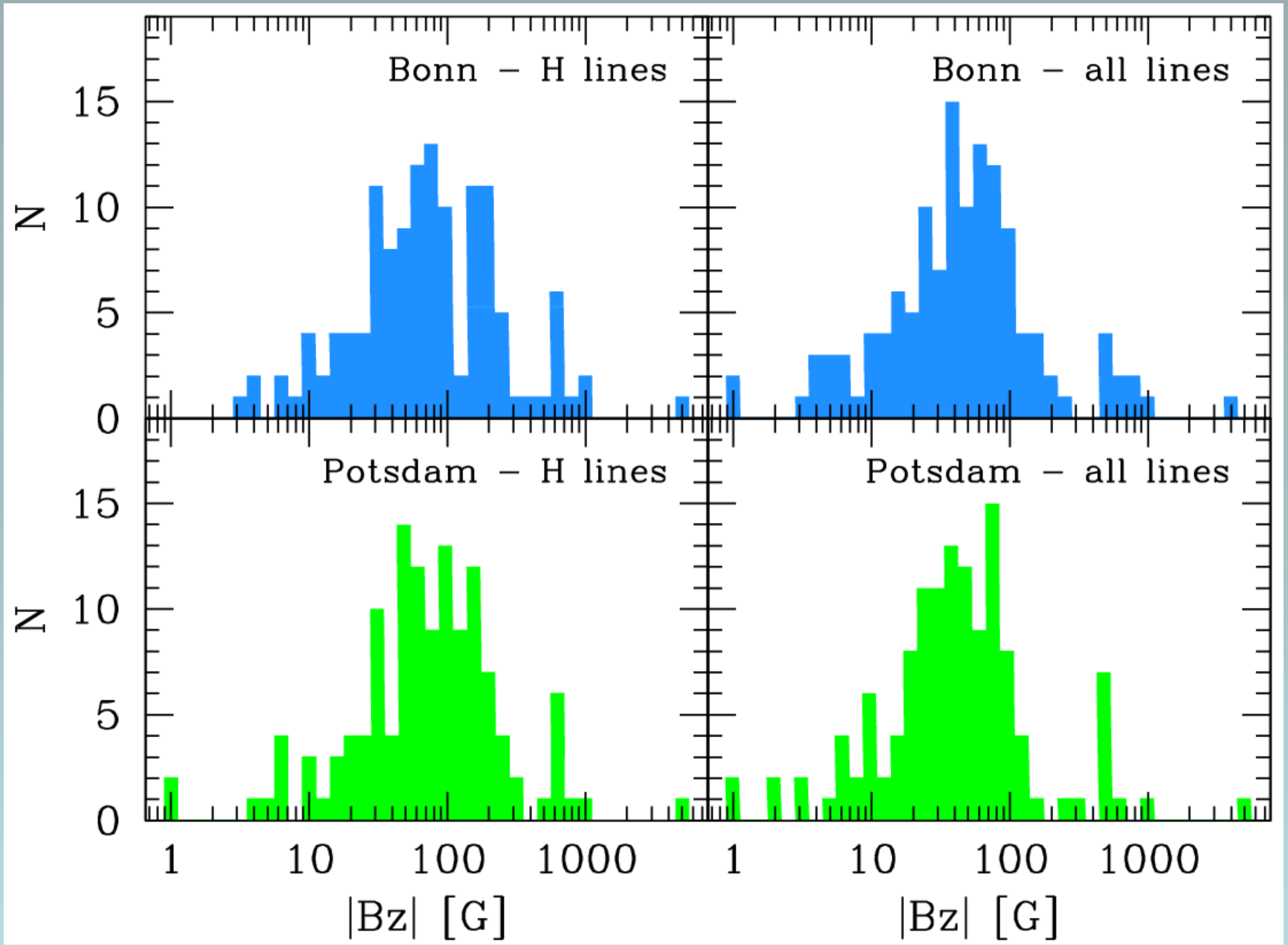

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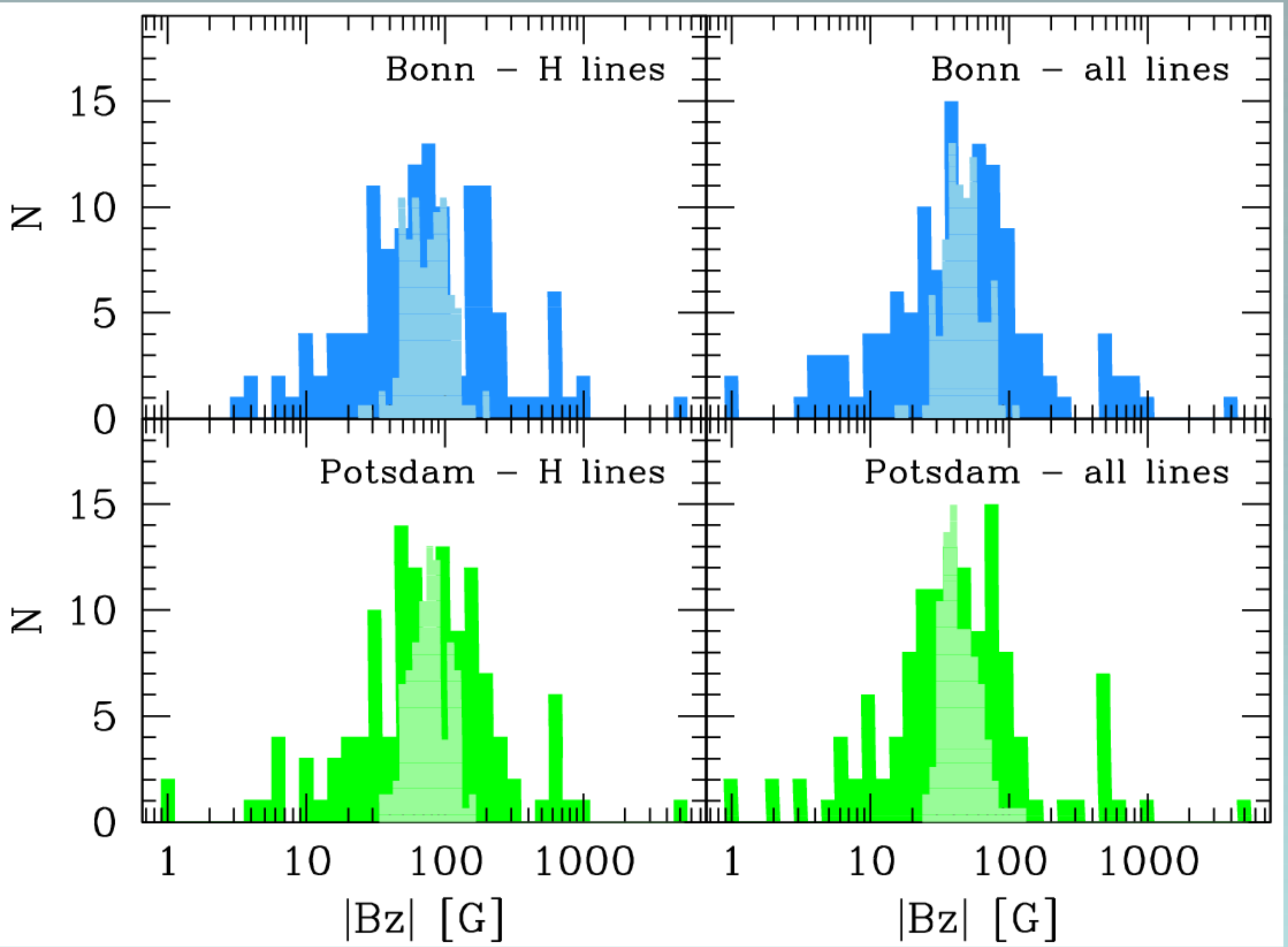

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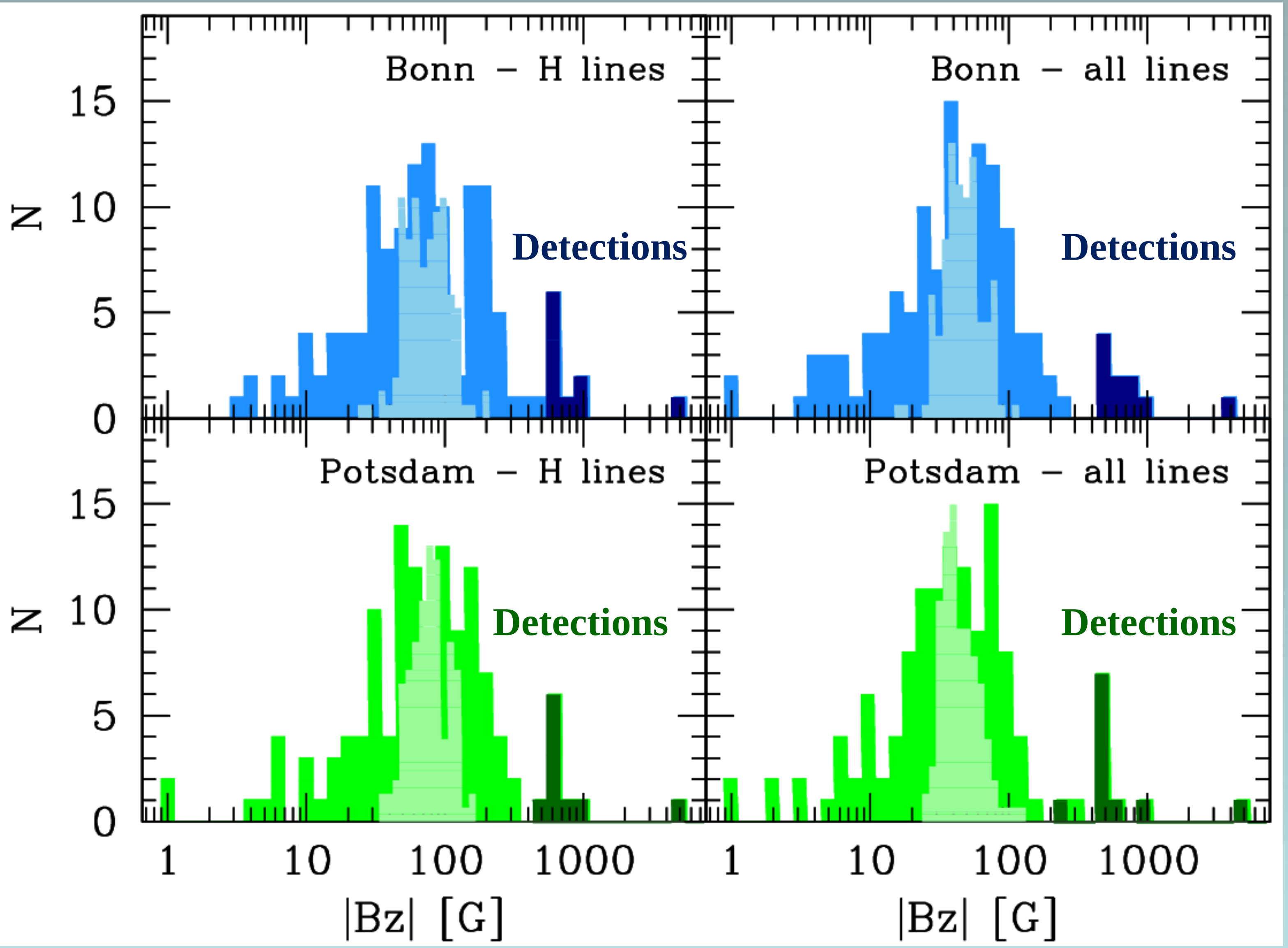

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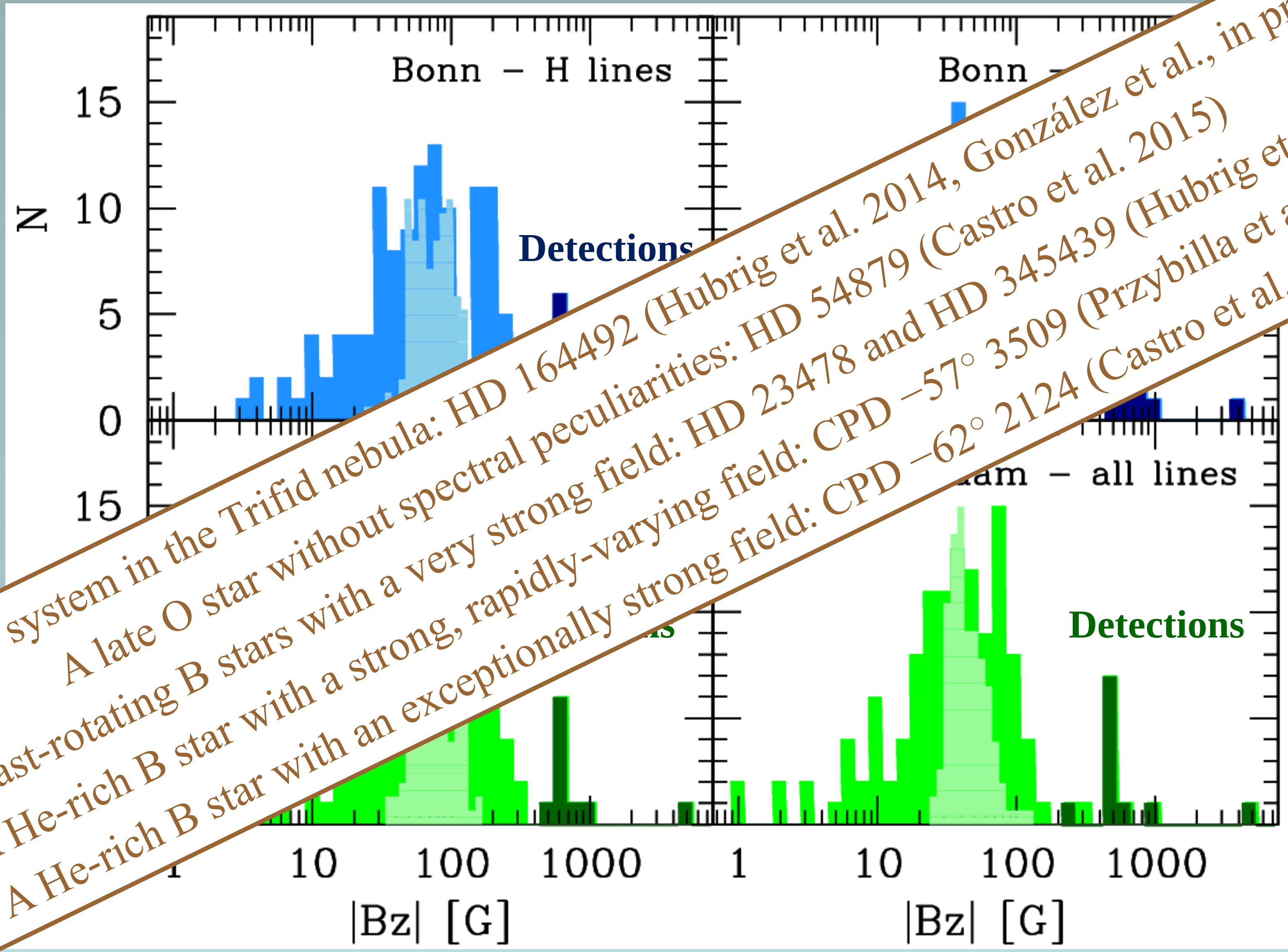


A triple system in the Trifid nebula: HD 164492 (Hubrig et al. 2014, González et al., in prep.)

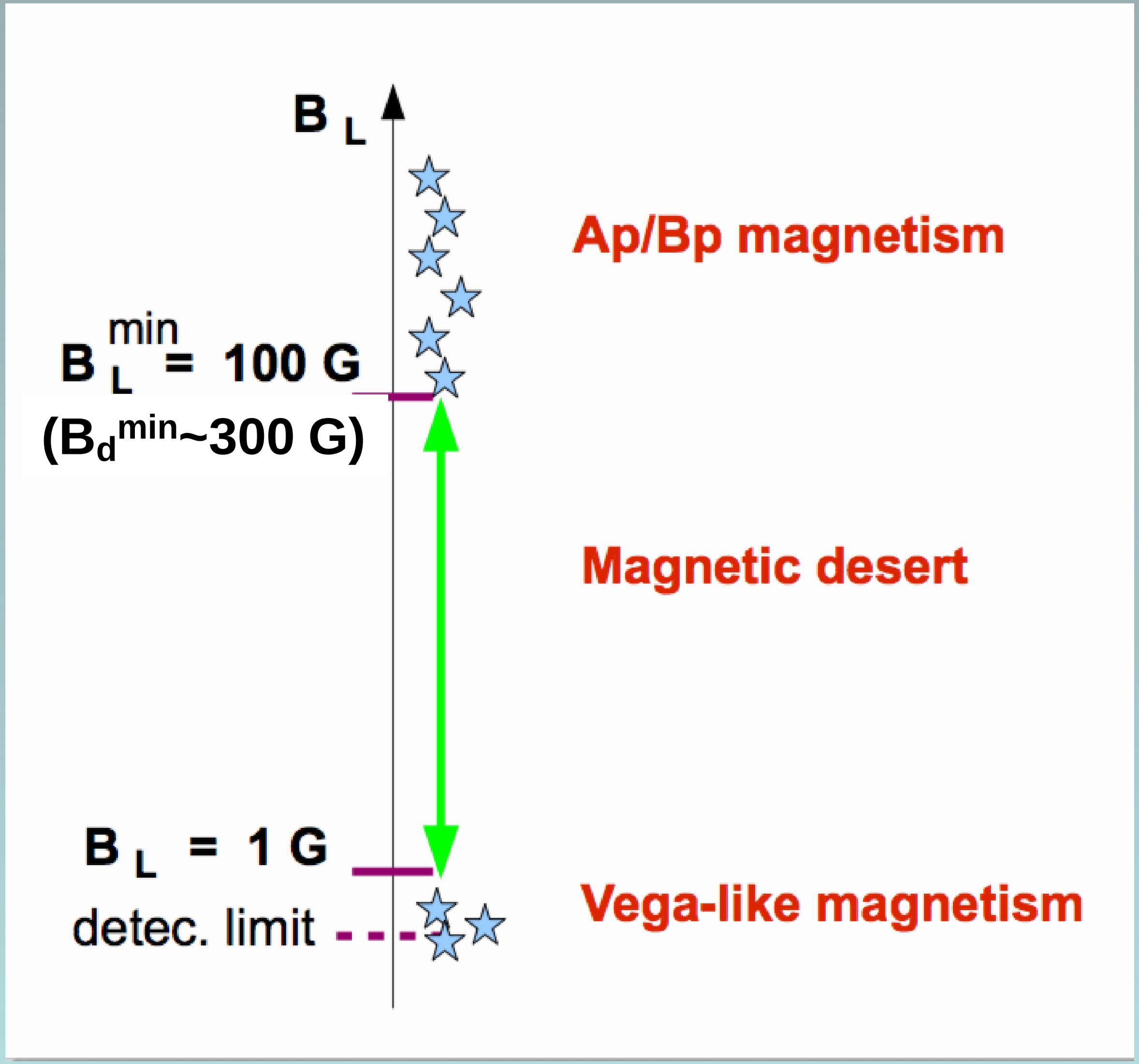
A late O star without spectral peculiarities: HD 54879 (Castro et al. 2015)

Two fast-rotating B stars with a very strong field: HD 23478 and HD 345439 (Hubrig et al. 2015)

A He-rich B star with a strong, rapidly-varying field: CPD -57° 3509 (Przybilla et al. 2016)

A He-rich B star with an exceptionally strong field: CPD -62° 2124 (Castro et al., in prep.)

A ‘magnetic desert’ in massive OB stars?

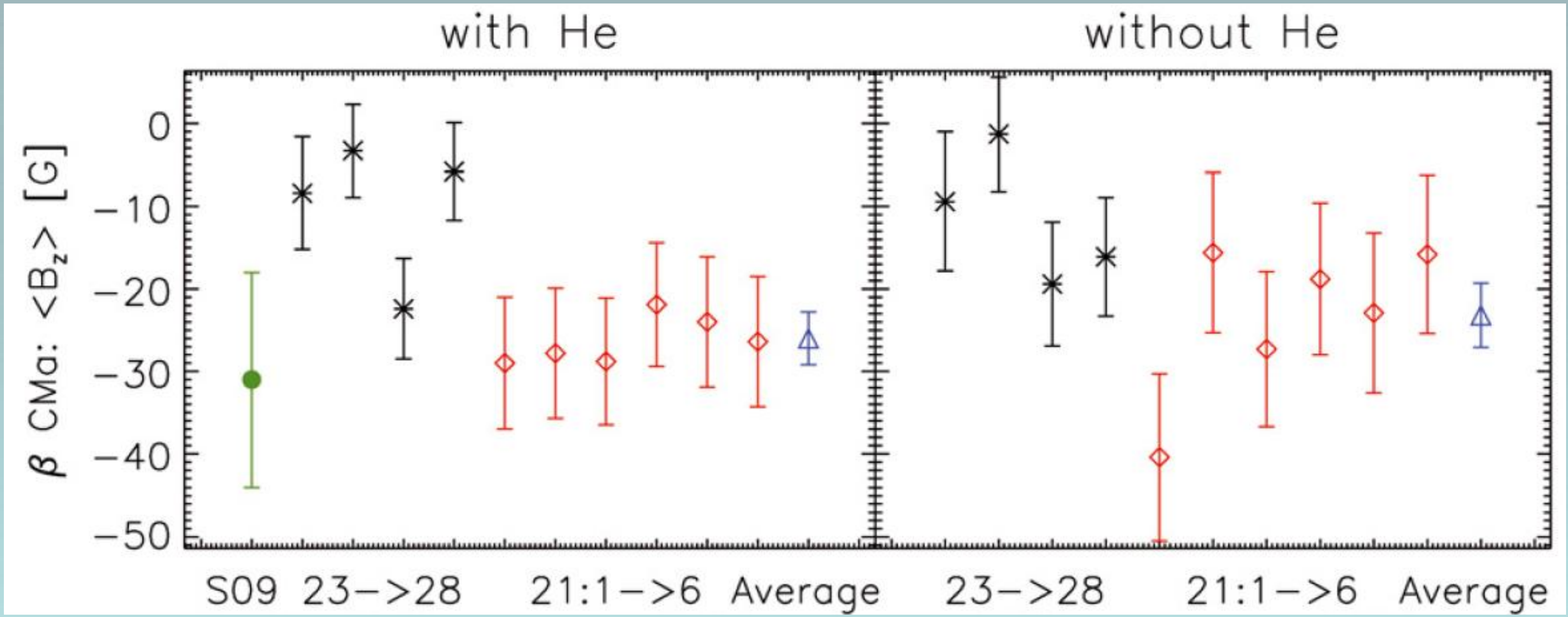


Lignières et al. (2014)

A ‘magnetic desert’ in massive OB stars?

Very high S/N HARPSpol observations of β CMa (B1 III)

Silvester et al. (2009) **BOB 2013** BOB 2014 Average BOB 2014



Fossati et al. (2015)

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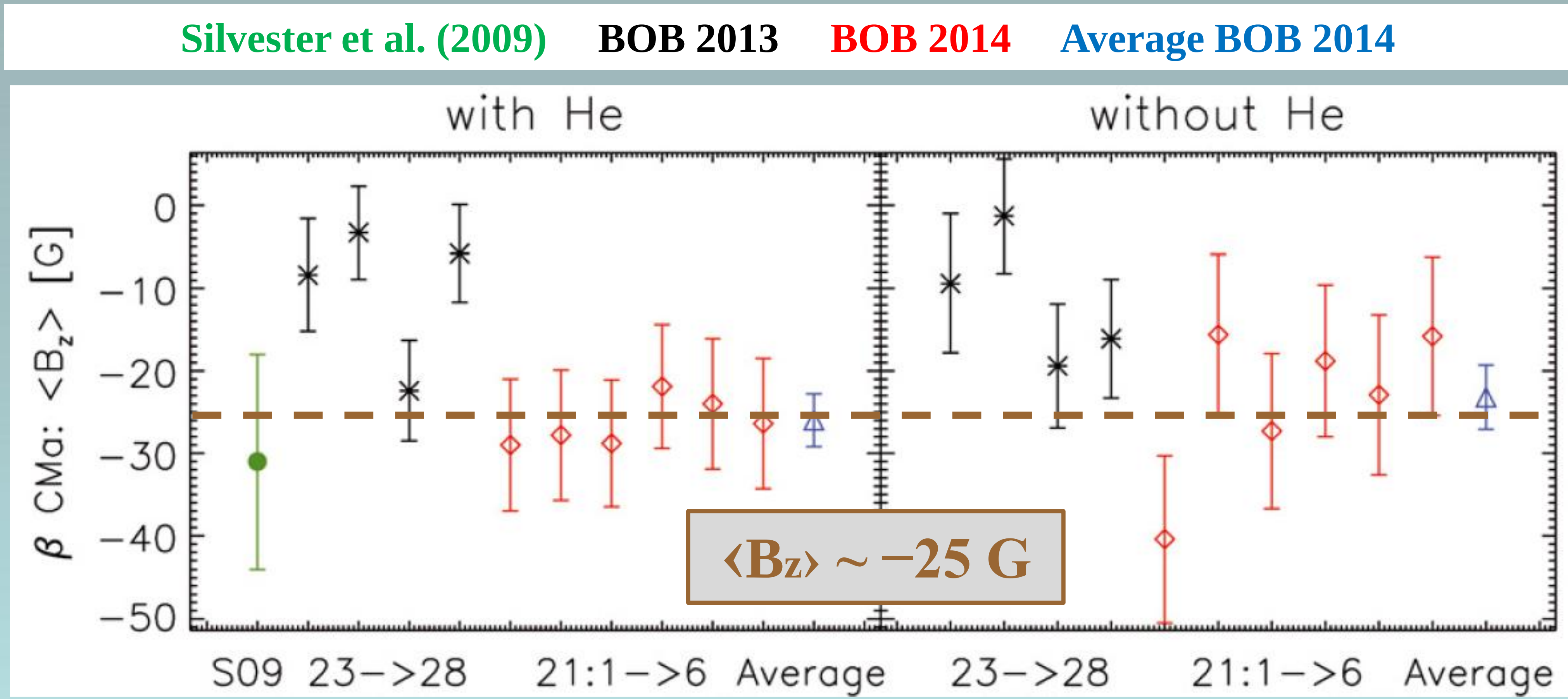
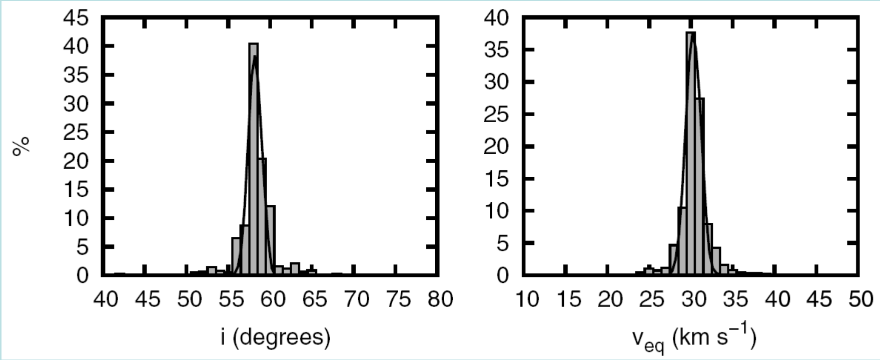


Fossati et al. (2015)

A 'magnetic desert' in massive OB stars?

Asteroseismic 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)

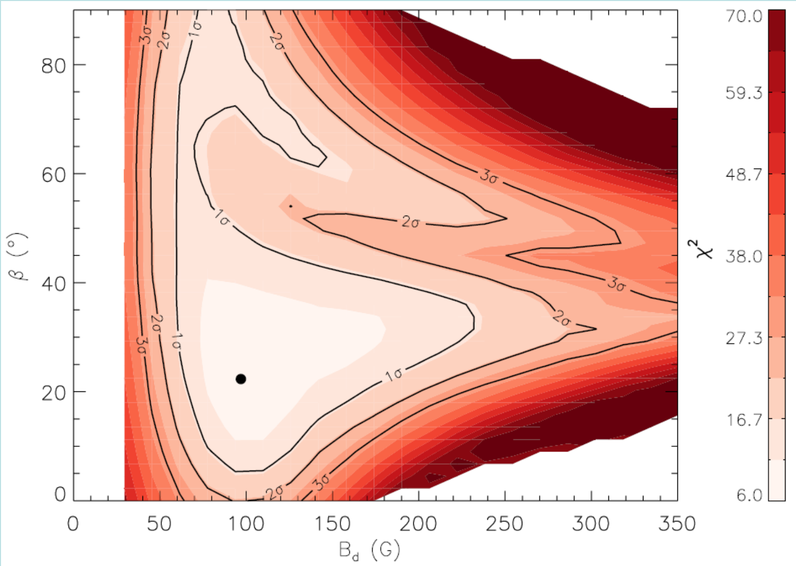
Preliminary modelling of magnetic data

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

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

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 ($^{\circ}$) < 90 and 60 < B_d (G) < 230 at 1σ level



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Model supported by further HARPS observations carried out in March 2015

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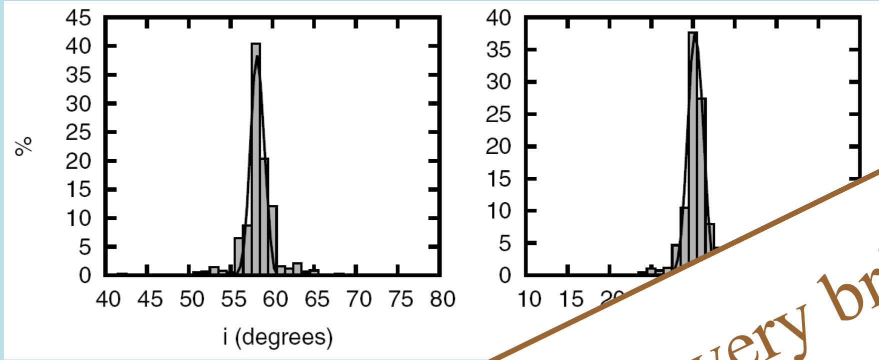

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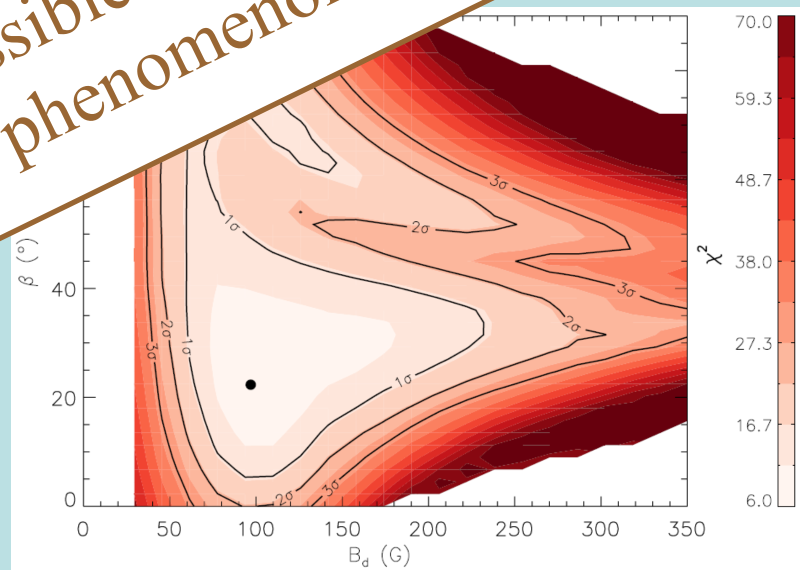


Fossati et al. (2015)

Model supported by further HARPS observations carried out in March 2015

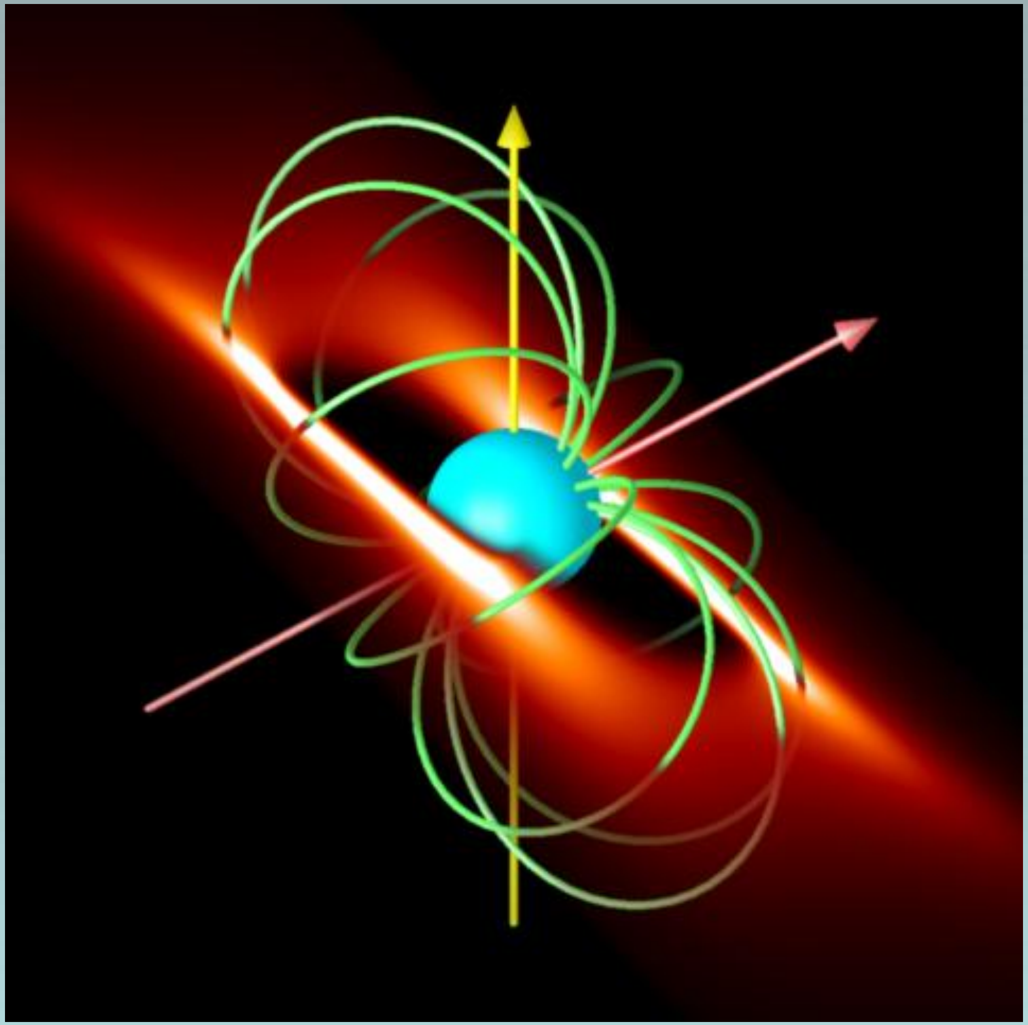
Such high-quality observations only possible for very bright stars:
weak fields a widespread phenomenon?

σ Ori E analogues

Early B-type stars with very strong fields (B_d~10 kG) and fast rotation (P_{rot}~1 day or less)

The most rapidly rotating, non-degenerate magnetic stars known!

Ideal testbeds for theories about the formation and physics of stellar magnetospheres

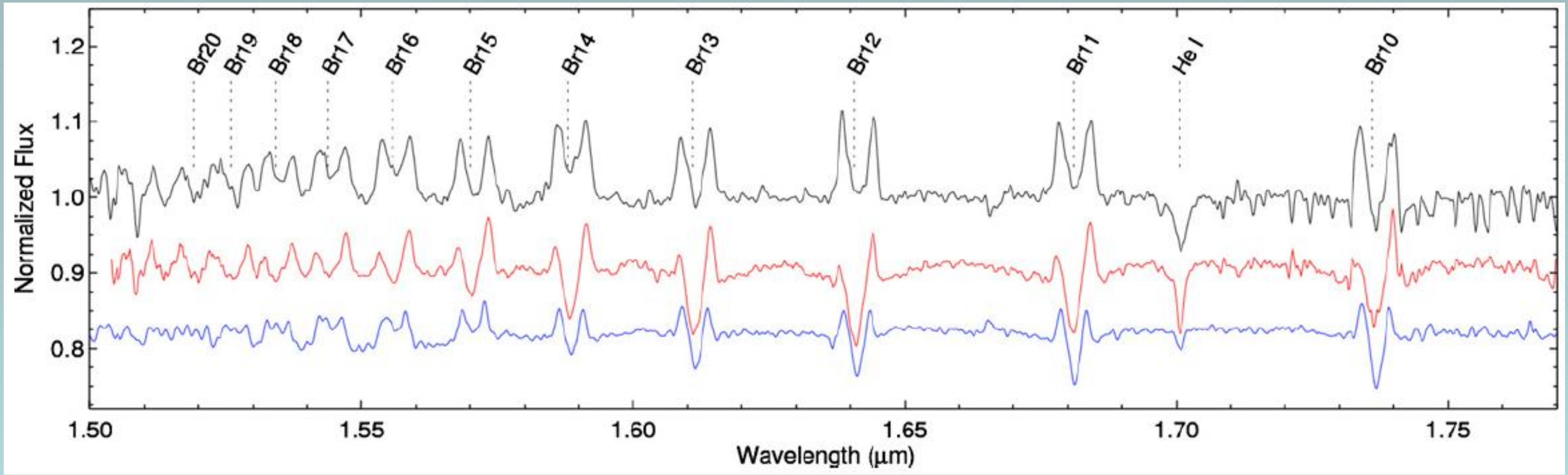


Courtesy: Rich Townsend (UW-Madison)

σ Ori E analogues

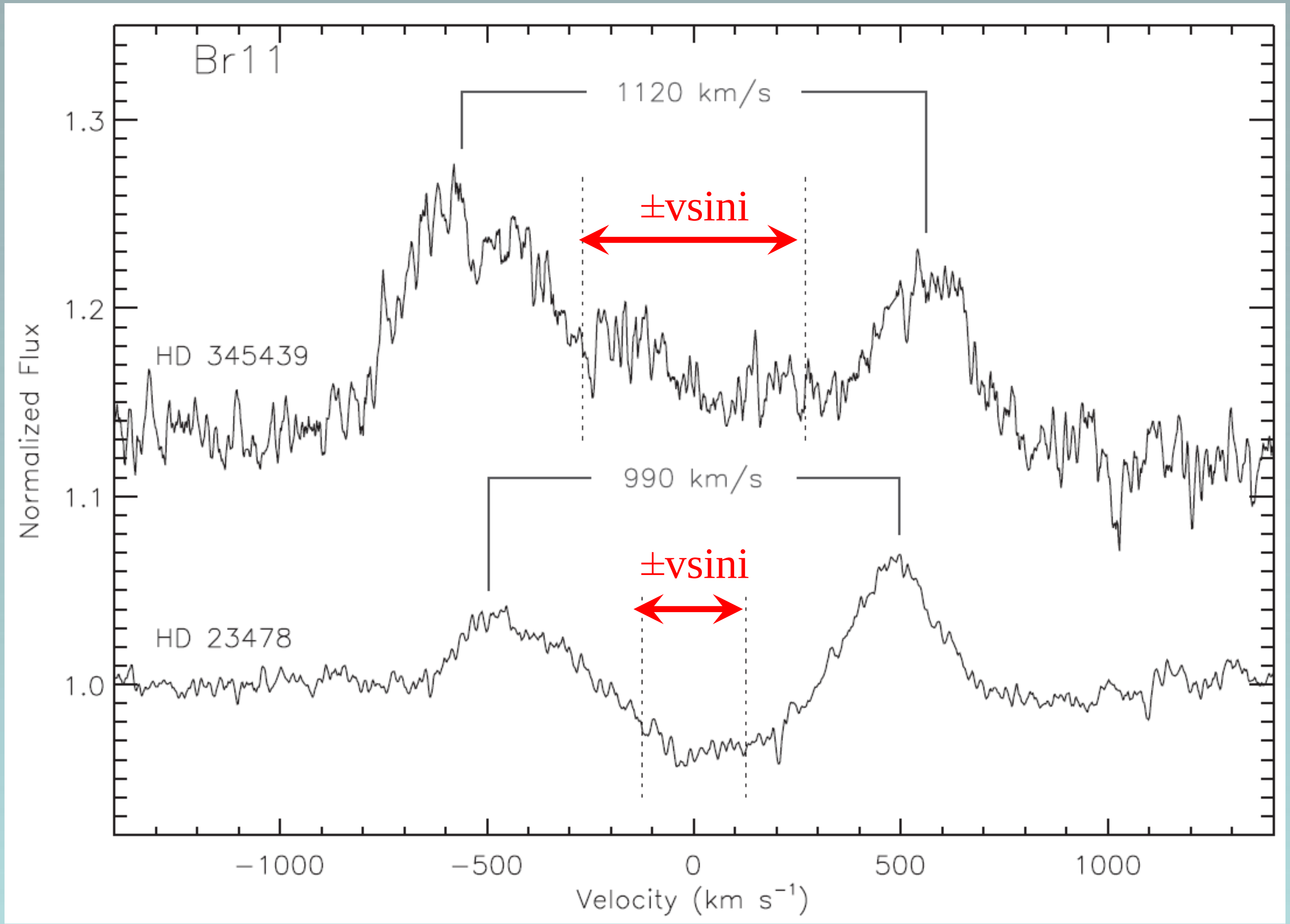
Two candidates for hosting a rigidly-rotating magnetosphere identified by the APOGEE survey from their spectral peculiarities in the near-IR (HD 23478 and HD 345439)

HD 345439 σ Ori E HD 23478



Eikenberry et al. (2014)

σ Ori E analogues

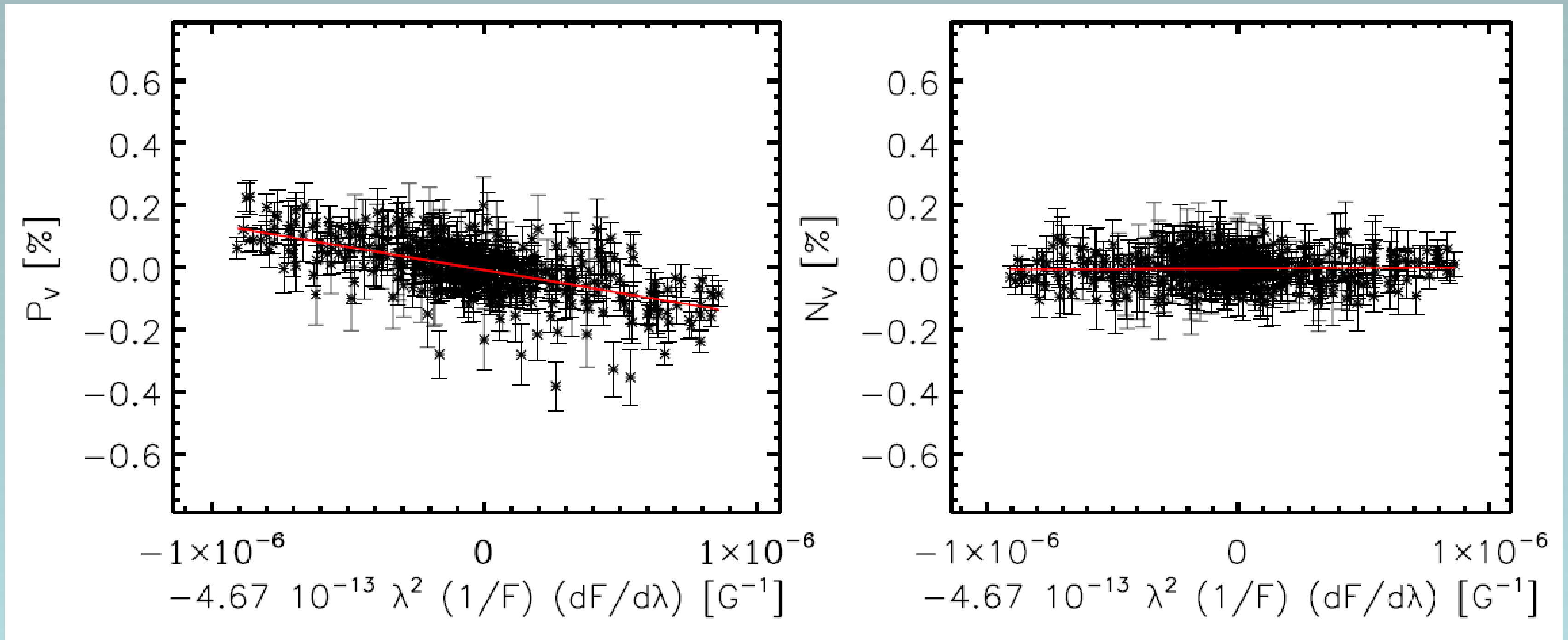


Eikenberry et al. (2014)

σ Ori E analogues – HD 23478

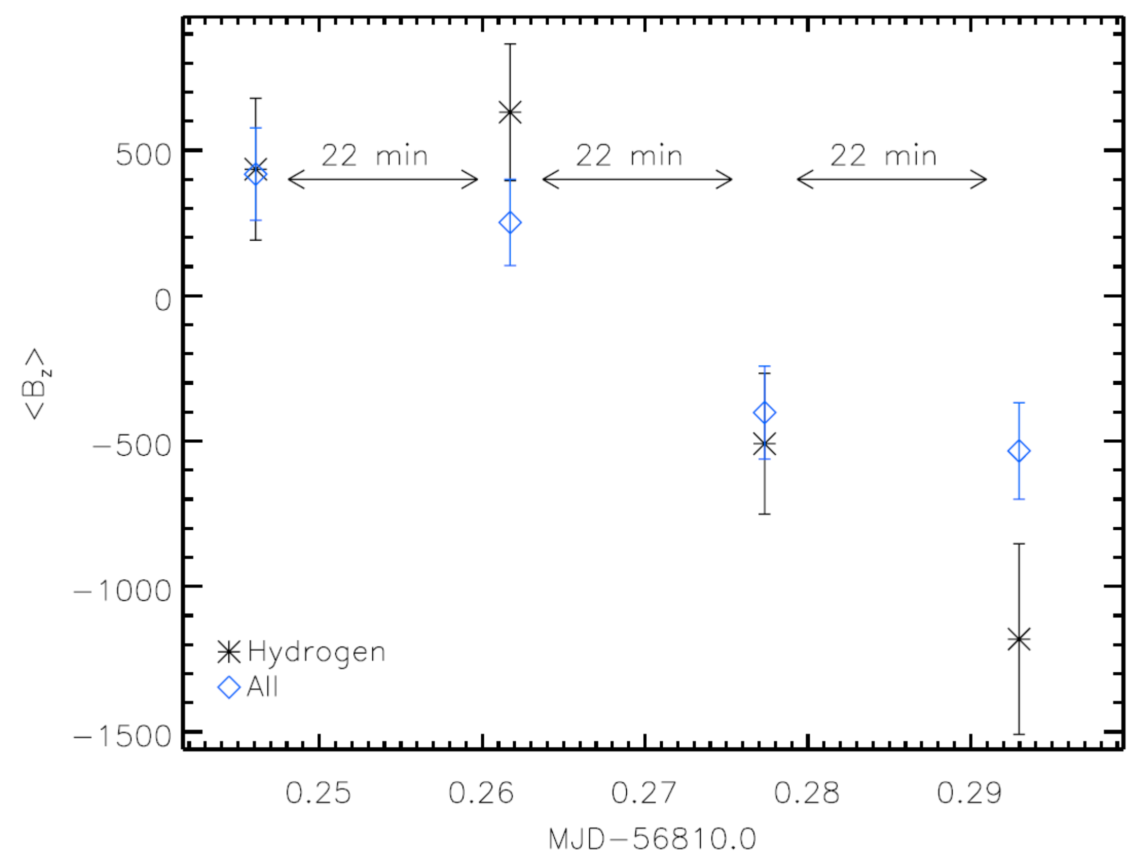
⟨Bz⟩ from FORS2 observations

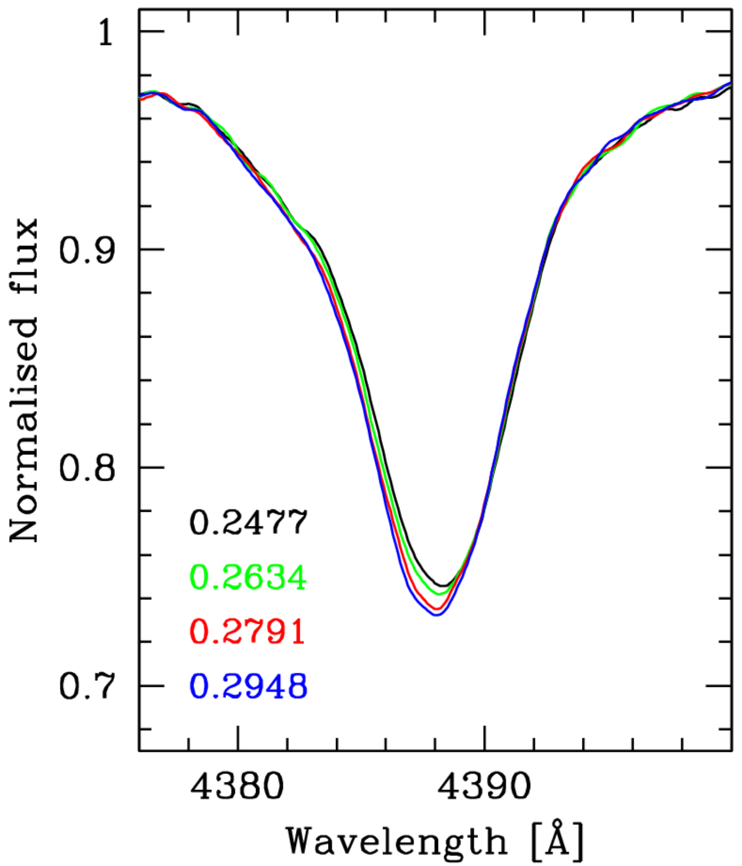
			Hydrogen lines		All lines	
			V	N	V	N
Detection	17 11 2014	Bonn	−1477±95	30±64	−1302±59	74±49
		Potsdam	−1347±114	50±93	−1139±84	45±70



Hubrig et al. (2015)

σ Ori E analogues – HD 345439

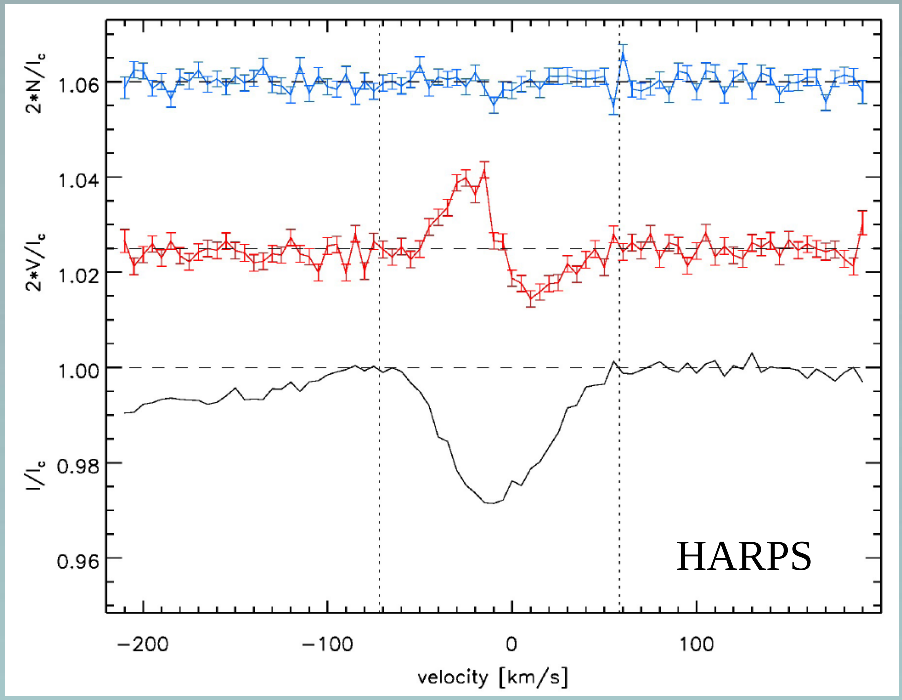


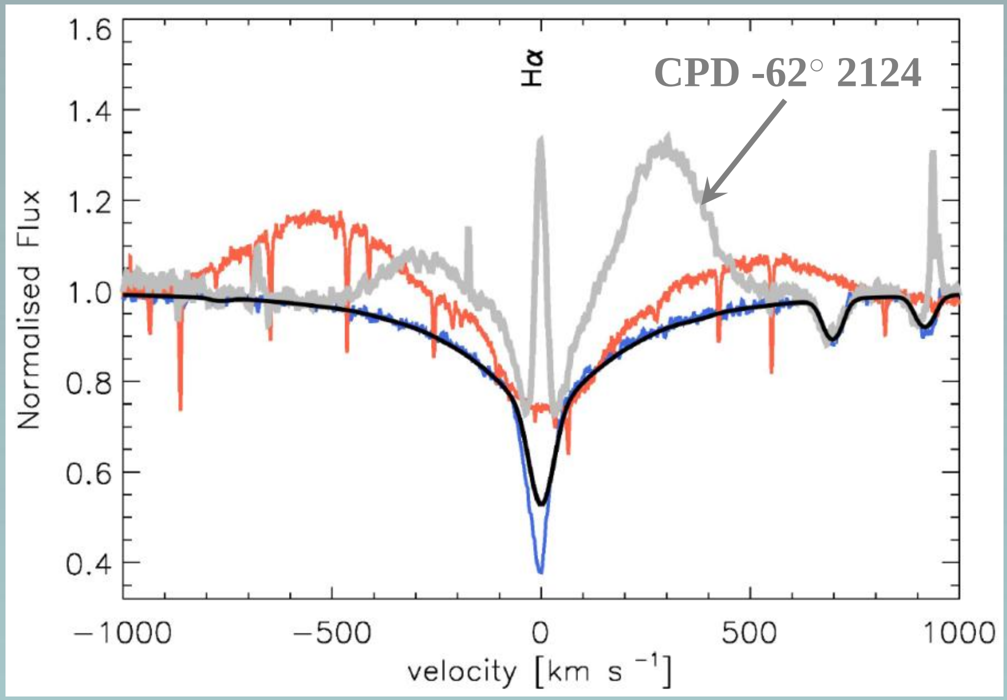


Hubrig et al. (2015)

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)

Other detection of He-rich, B-type stars: CPD −62° 2124





Castro et al., in prep.

Strong He overabundance at the surface: $y \sim 0.35$
Centrifugal magnetosphere revealed by broad emission in Hα

Very strong longitudinal field in the range 3-5 kG (dipolar field > 12 kG)
Star quite evolved, yet has one of the strongest magnetic fields ever detected in a massive star

Conclusions

- Spectropolarimetric observations of 138 OB stars carried out over 3 years with FORS2 and HARPS. Survey now completed.
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- Consistent detections using two completely different reduction and analysis techniques.
- Evidence that the occurrence of relatively strong fields (longitudinal component typically above 100-200 G) is low in massive stars and is of the order of ~10%.
- Indications for intrinsically weak fields ($B_d < 200$ G) in early B-type stars. Possible existence of an undetected, large population of weakly magnetic stars.
- Discovery of a number of strongly magnetic B-type stars hosting a magnetosphere including one with one of the strongest fields ever detected in a massive star ($B_d > 12$ kG).