Evolution of magnetic field of massive stars

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Stars with a stable magnetic field: from pre-main sequence to compact remnants

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A fraction of magnetic stars

	MiMeS	BOB
Number stars surveyed	~525	138
Number fields detected	~35	14
Detection rate	**7±1%**	**~5-6%**
Magnetic field fraction at ZAMS?		

Only ~**5-7%** of OBA, HAEBE, WD stars are magnetic

We consider the magnetic field evolution

1) Before Main Sequence (MS)
2) at MS
3) from ZAMS to SN

Statistical characteristics of magnetic fields

Polarimetric observations give only values of B_l. These values strongly depends on the rotational phase and can not be used for the statistical analysis.

We use 3 characteristic of magnetic field weakly depending on the dates of observations

RMS magnetic field

$$\langle B \rangle = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(B_l^i\right)^2}$$

$$\sigma_B = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(B_l^i\right)^2}$$

Mean error of the magnetic field

$$\chi^2/n = \frac{1}{n}\sum_{i=1}^{n}(B_l^i)^2 \Big/ (\sigma_{B^i})^2$$

reduced χ^2 statistics

$$\begin{cases} \langle B \rangle > 2\sigma_B, \\ \chi^2/n > 1 \end{cases}$$

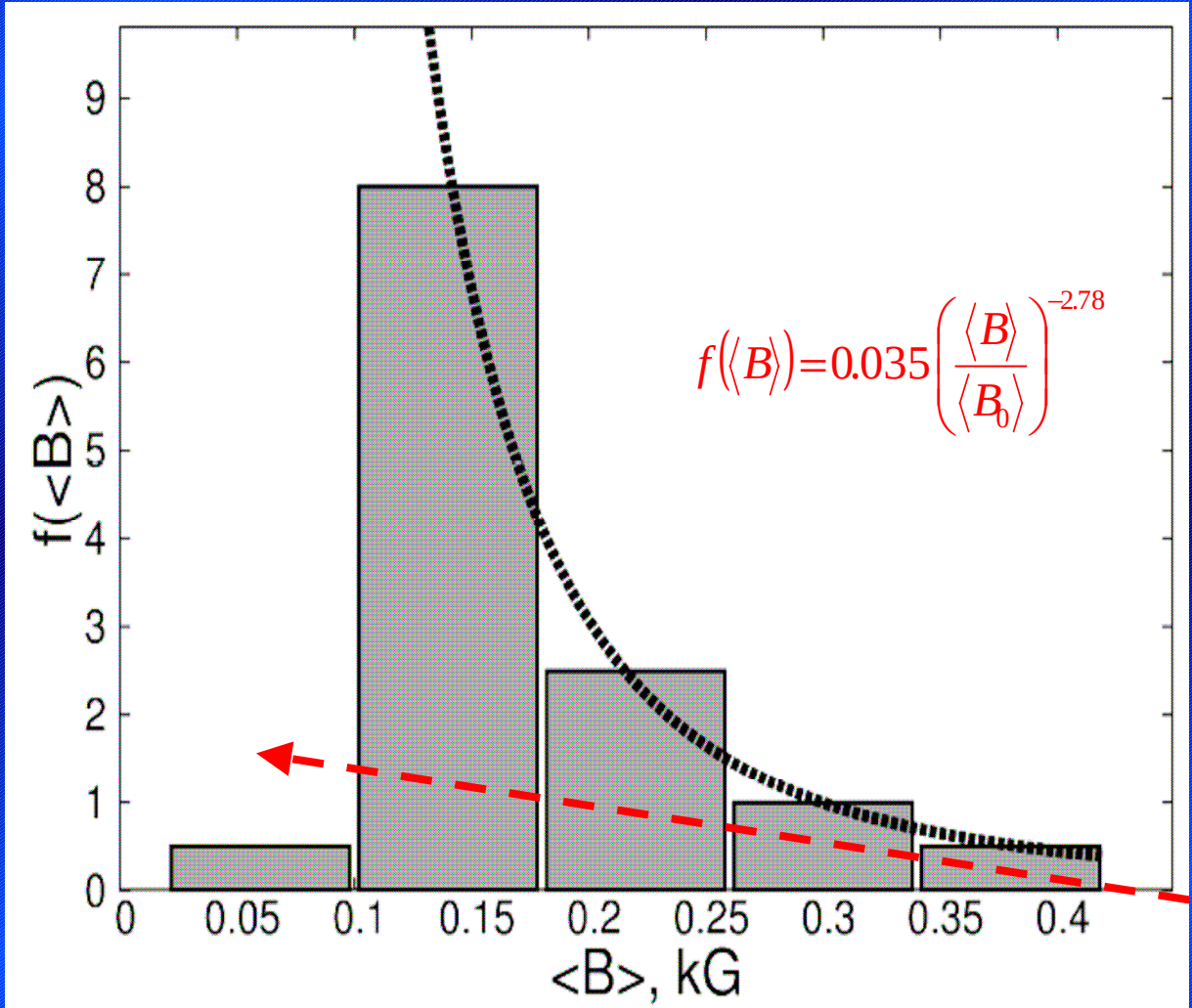
Criteria of real measurements (in this case at least one value $|B_l|>3\sigma_B$*)*

CPD-28 2561: $\langle B \rangle$= 239 G, σ_B=93 G, χ^2/n = 5

Net magnetic flux

$$F = 4\pi\langle B \rangle R^2$$

Magnetic field distribution for O stars

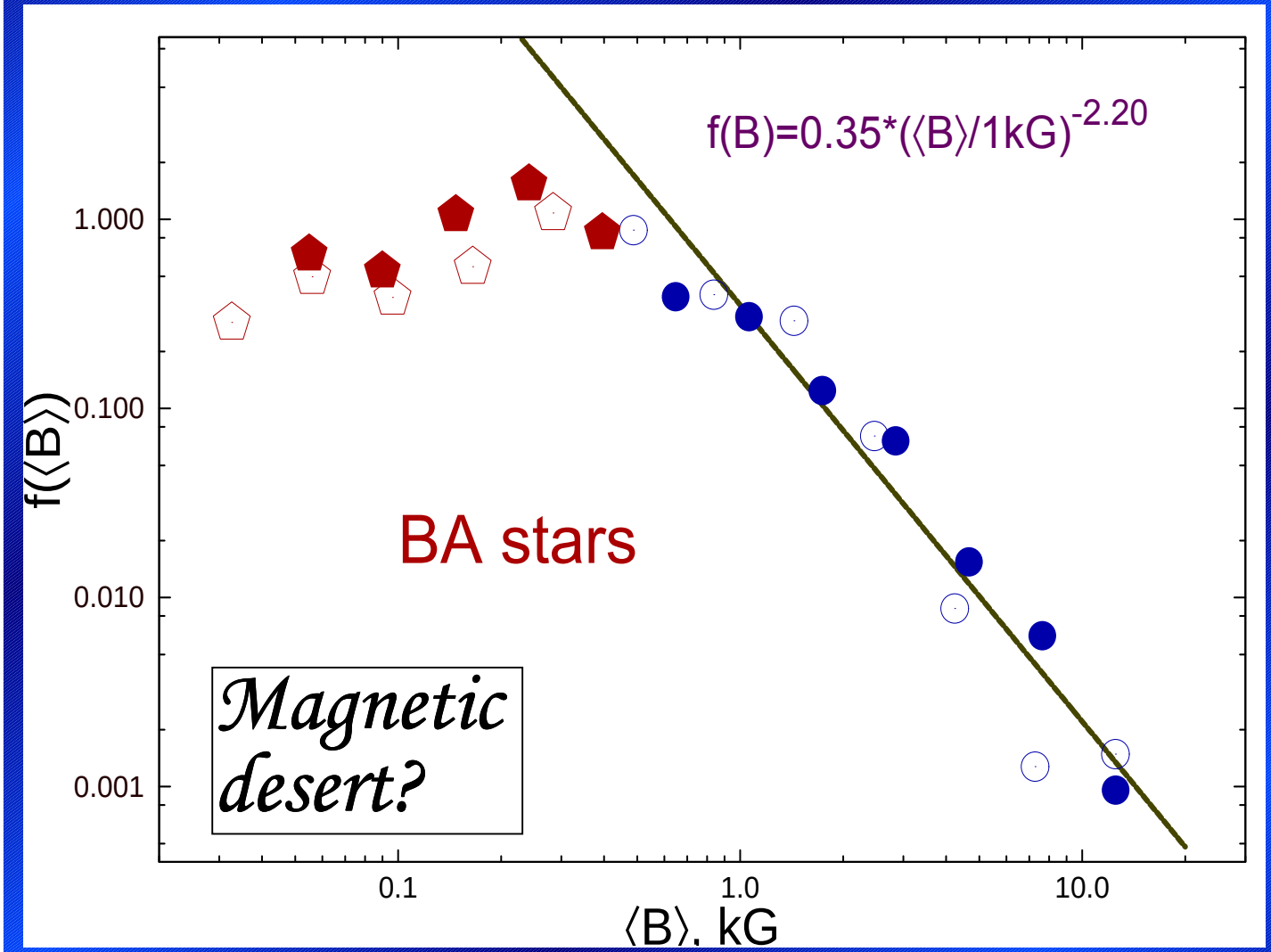


$$f^{obs}(B)=\frac{N(\mathbf{B},\mathbf{B}+\Delta\mathbf{B})}{N_0\Delta\mathbf{B}}$$

$$f(\langle B\rangle)=A_0\left(\frac{\langle B\rangle}{\langle B_0\rangle}\right)^{-\gamma}$$

Magnetic desert?

Magnetic field distribution for BA stars: the first view

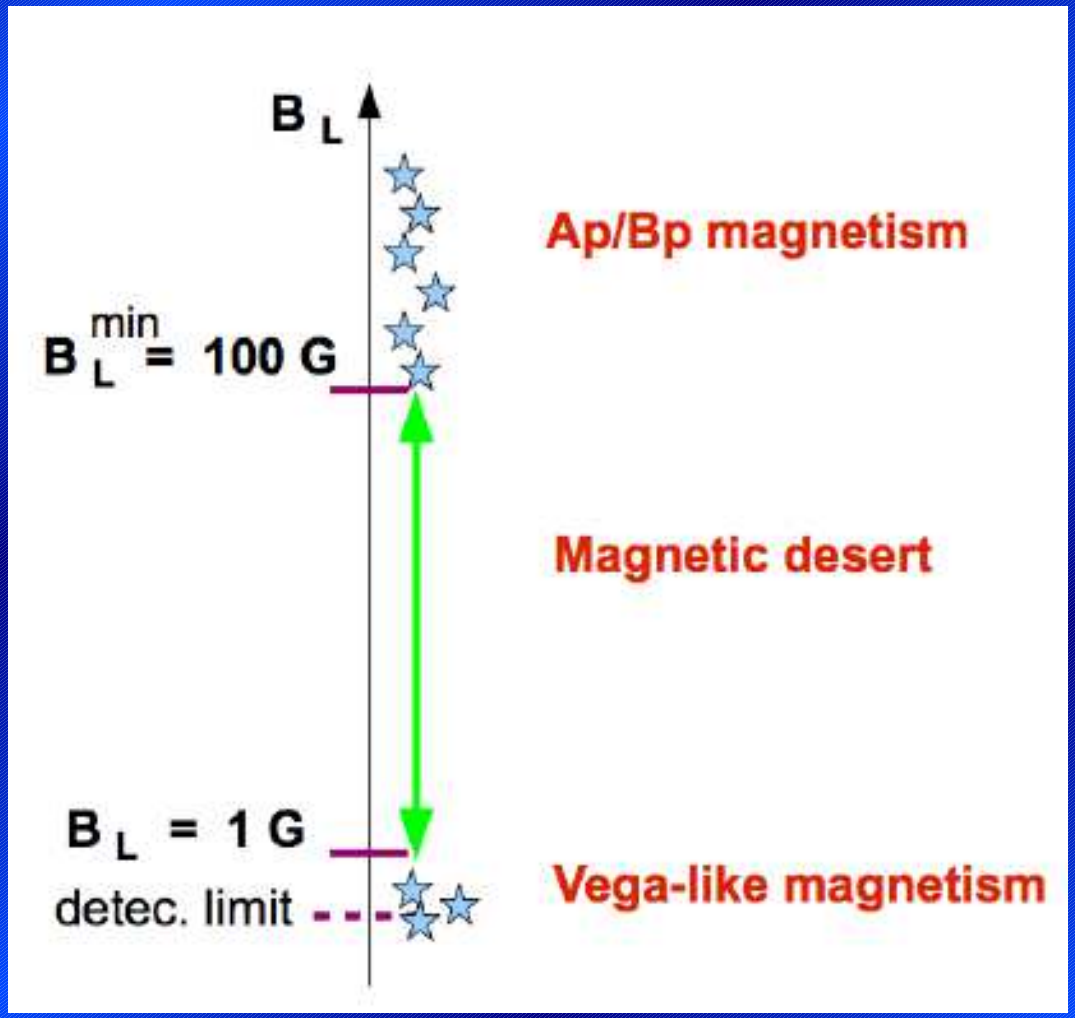


Magnetic field distribution for B (empty) and A (filled) symbols accordingly.

Power approximation is shown with dashed line. Pentagons mark data in the region $B < B^{th}$.

Is the gap at $B=B^{th} < 0.3$ kG (Magnetic Desert) real?

What means Magnetic Desert



Recent measurements:

Am stars.

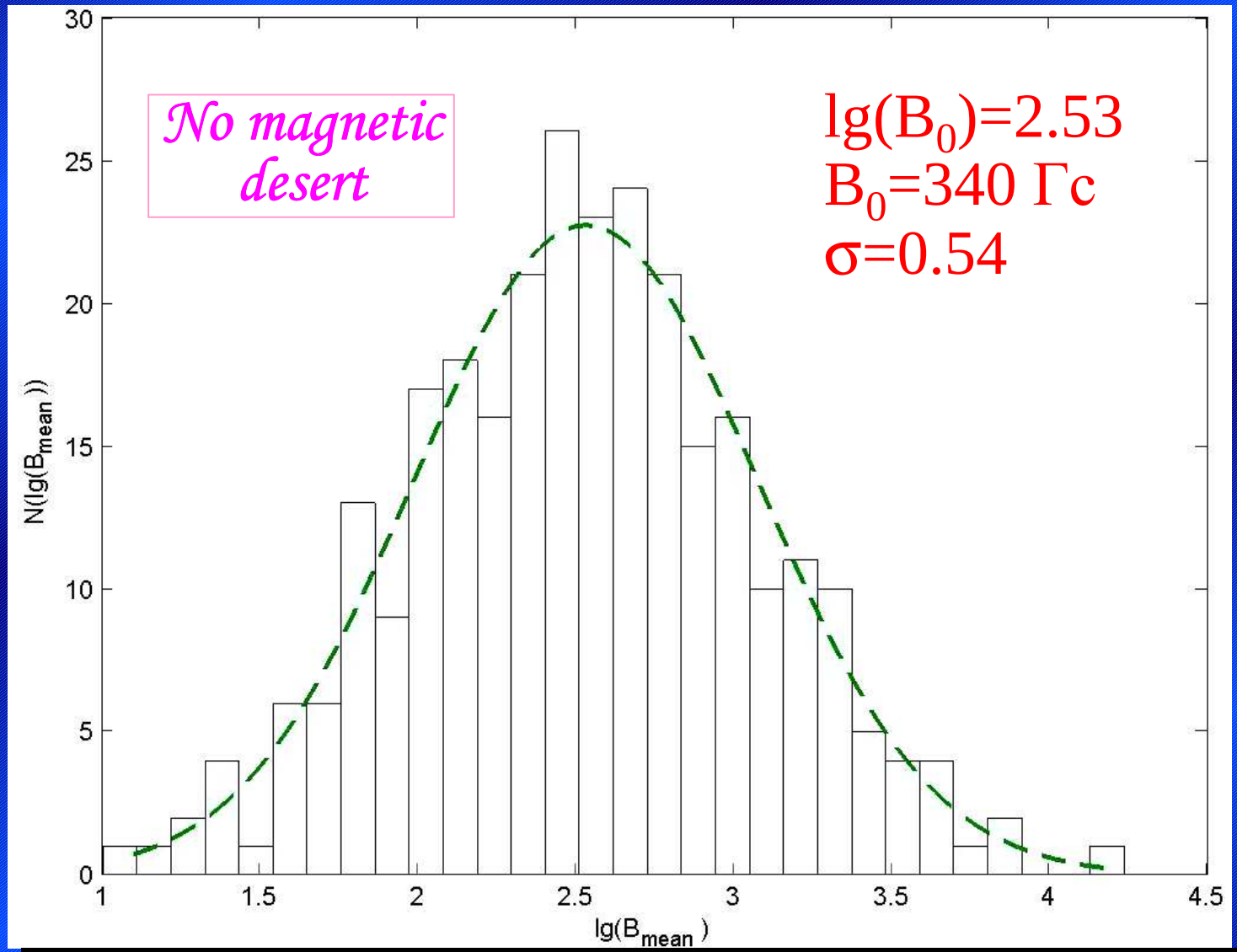
β UMa (A1Vm), B ~1G,

θLeo(A2Vm) B~0.4 G (Blazère et al. 2016a)

γ Gem (A0IVm) B~5G (Blazère et al. 2016b)

Lignières et al. (2014)

Magnetic field distribution for BA stars: the second view



Changing paradigm:

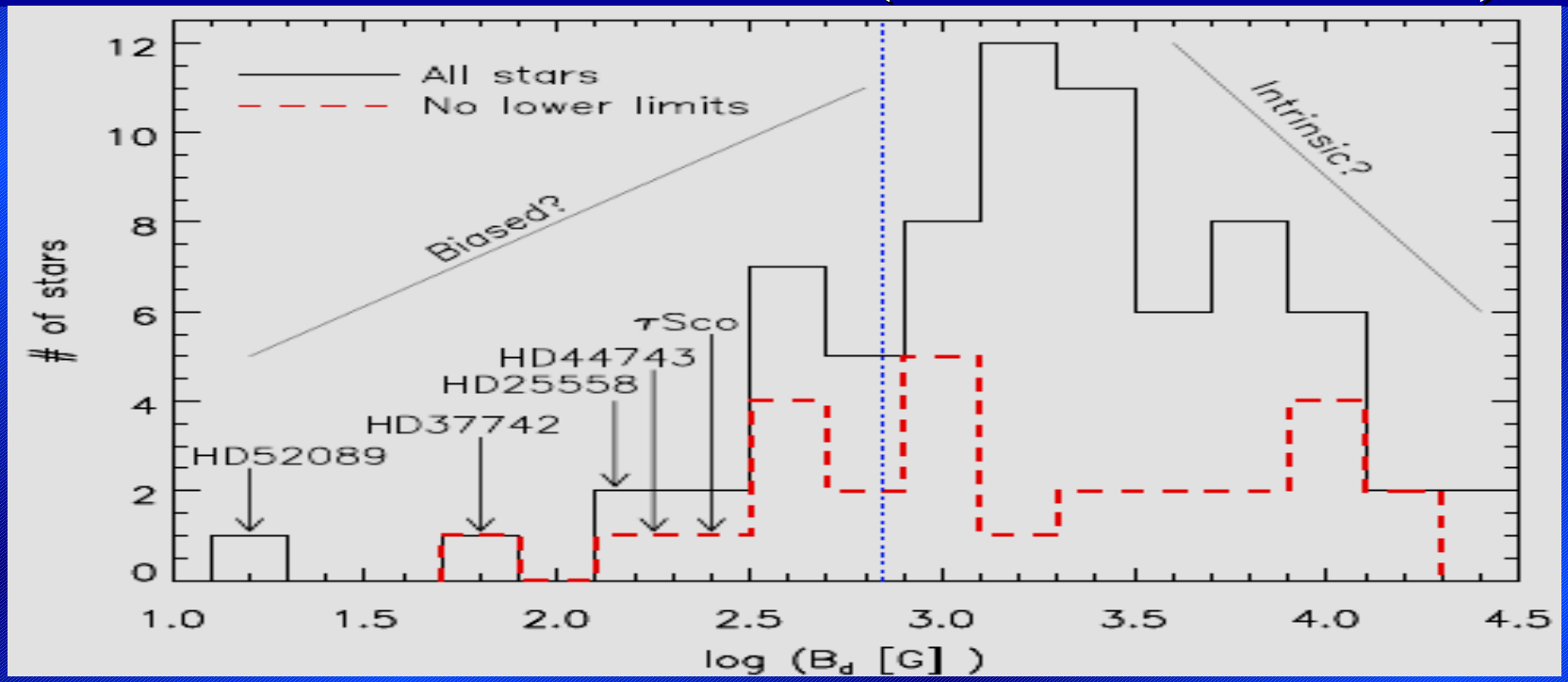
Log-normal distribution instead of power law

We use only data from

Bychkov (2009) catalog

$$x = \lg(B), \quad f(X) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-x_0)^2}{2\sigma^2}}, \quad x_0 = \lg(B_0)$$

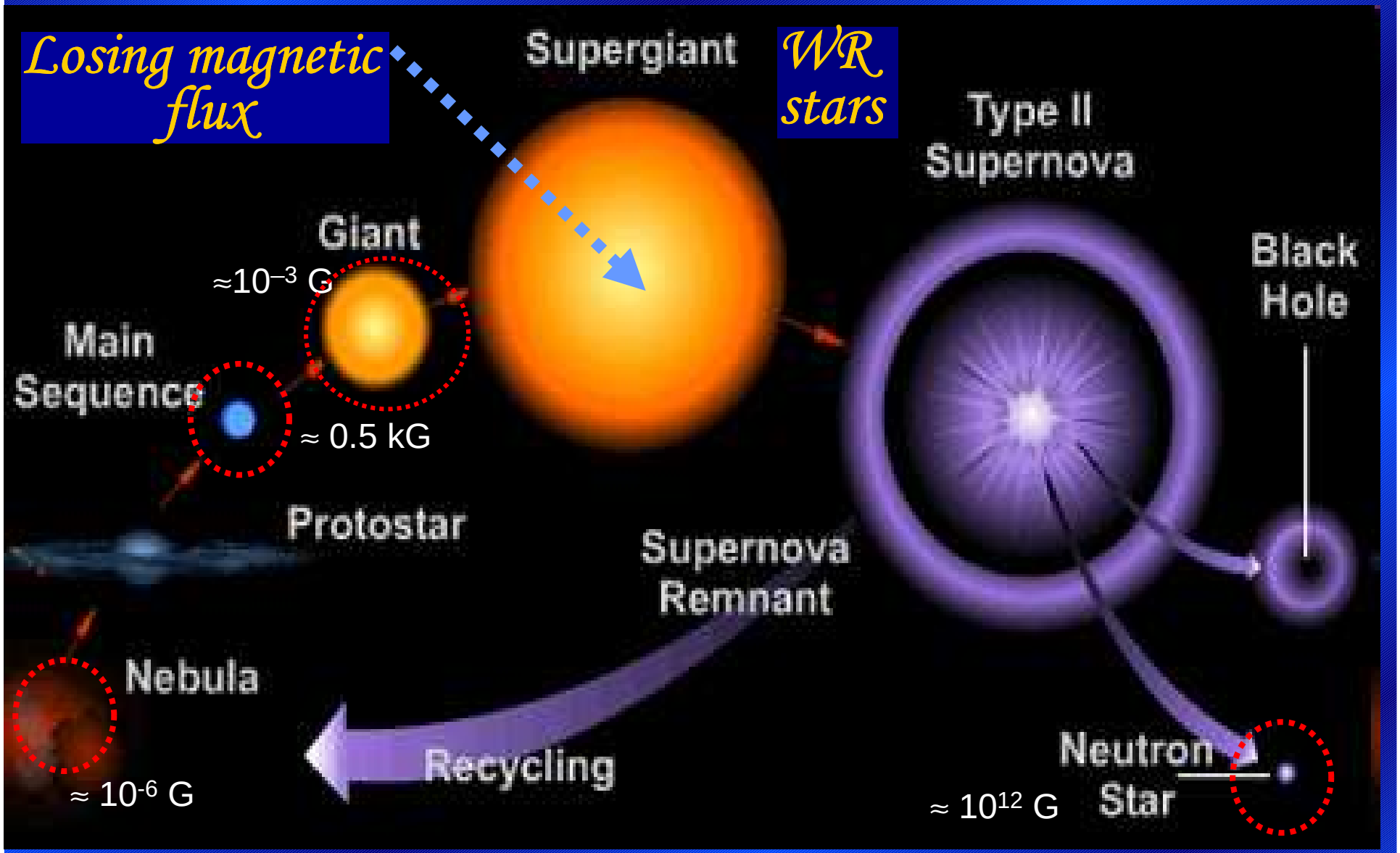
Statistics: BOB contribution (Fossati et al. 2015)



Number of magnetic massive stars as a function of the logarithm of the dipolar magnetic field strength B_d. A fixed bin size of $\log(B_d)=0.2$ dex. A red dashed line is that obtained considering only stars for which a definite value of B_d is available. The arrows show the position of the five stars with the weakest magnetic field. For HD52089 and HD25558 the B_d values are lower limits. The vertical blue dotted line indicates the FORS2 magnetic field detection threshold.

Lack of a “magnetic desert” in massive stars

The general scheme of the massive stars and **their magnetic field** evolution



Stages of evolution, about which we know the typical values of the magnetic field **are marked**

New population synthesis code

Medvedev & Kholtygin (2014, 2017)

Initial distribution of magnetic fluxes

$$f(\Phi_0) = \frac{1}{\Phi_0\sqrt{4\pi\sigma^2}} \exp\left\{-\frac{1}{2}\left(\frac{\log\Phi_0 - \langle\log\Phi_0\rangle}{\sigma}\right)^2\right\}$$

Magnetic flux evolution

$$\Phi_i = \Phi_{0,i} e^{-\tau_i/\tau_d}$$

τ_d is the dissipation parameter. $\tau_i = t/\tau_{MS}$

Magnetic flux and rms magnetic field

$$B_{\rm rms} = \frac{\Phi_i}{4\pi R_i^2}$$

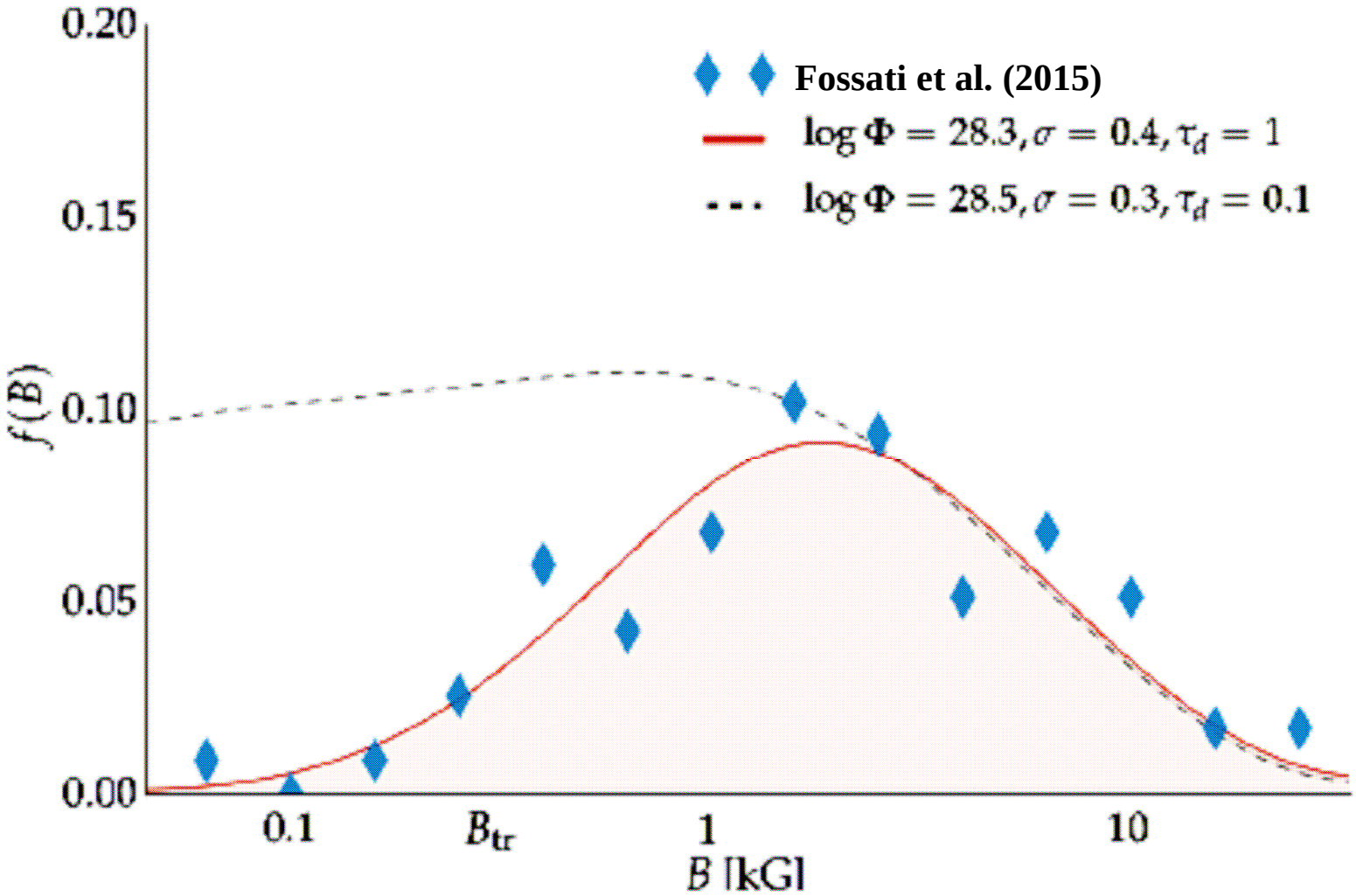
•Also we introduce a threshold value of the magnetic field B_{min} ~ 300 G (**Auriere et al. 2007**) as an optional parameter.

We use the AMUSE platform for the stellar evolution

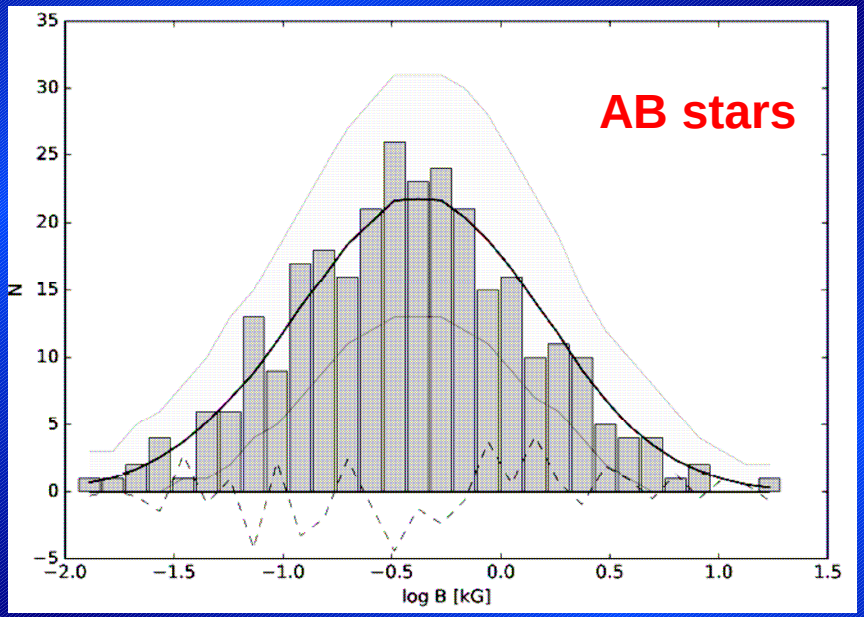
$f_1 = N_{magn}/N_{nomagn}$ (at ZAMS) $f_2 = N_{magn}/N_{nomagn}$ (at the present time)

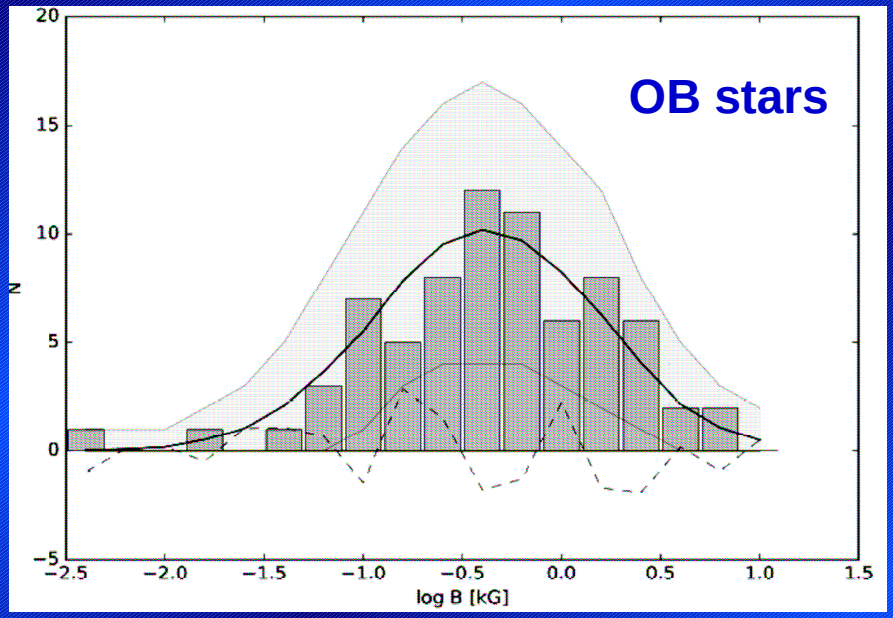
$f_1 = ?$ $f_2 \approx 0.07$

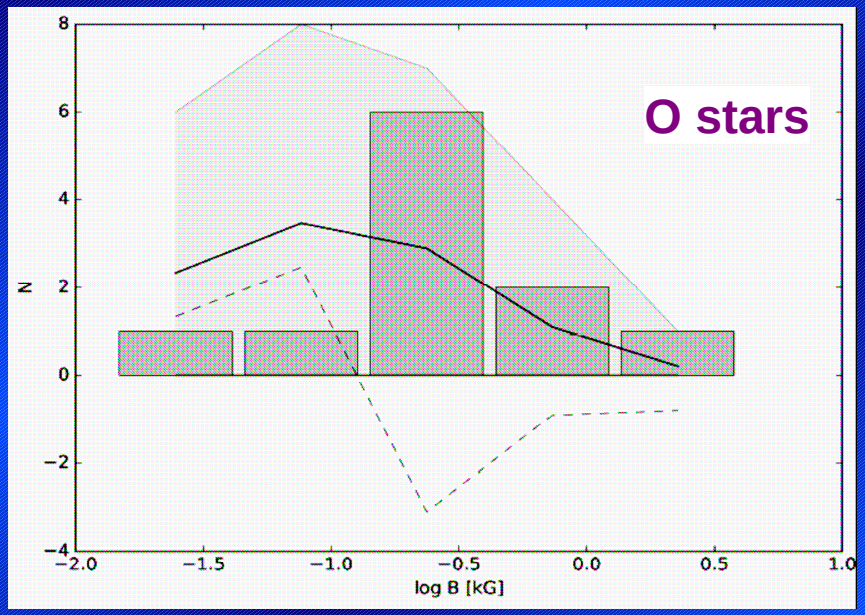
Magnetic field dissipation scale



Magnetic field distributions (No dissipation, Model **M0**)

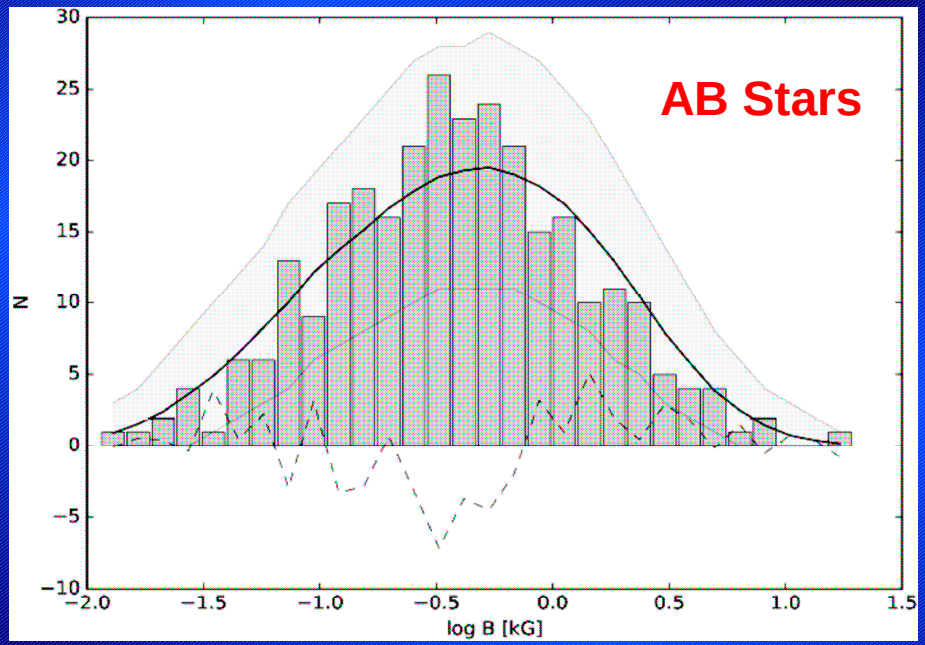


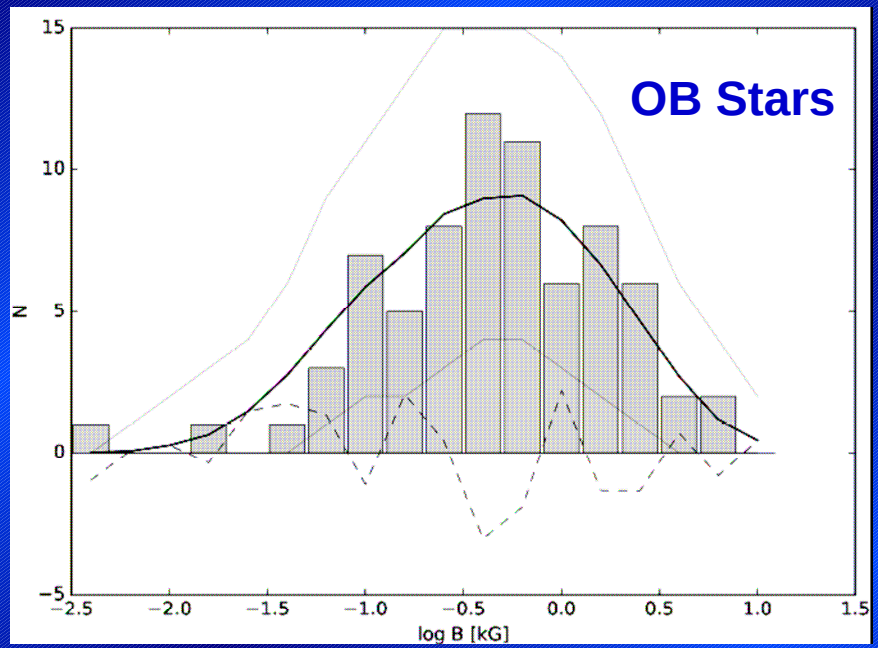


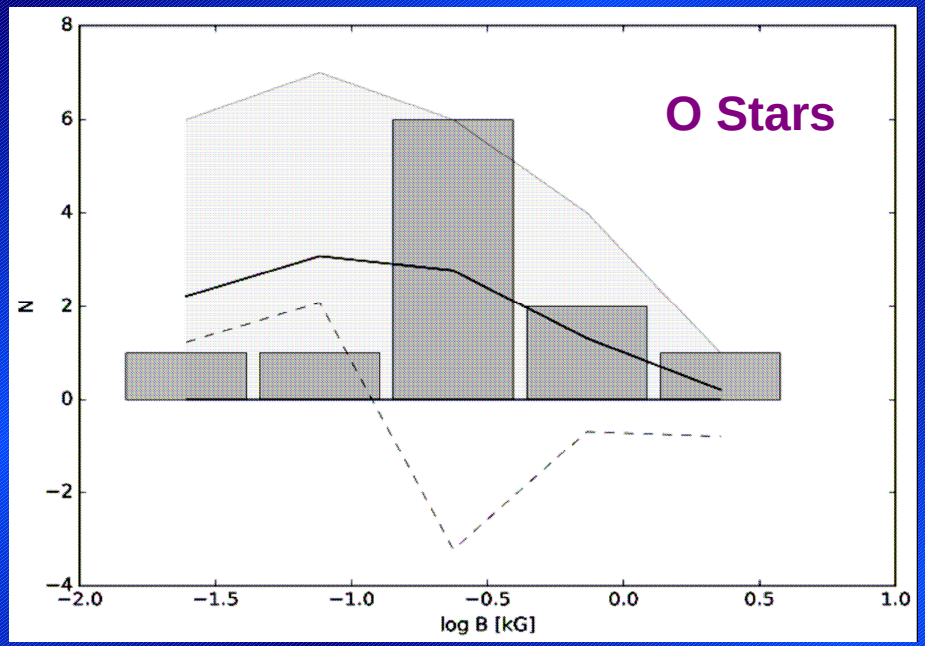


Magnetic field distributions for **AB**, **OB** and **O** stars (model without dissipation of the magnetic field). The gray histograms show the empirical data. The **black lines** and dashed lines show the mean model distribution and residuals. The gray filled area corresponds to the 95% confidence limits for Cash (1979) statistics.

Magnetic field distributions (τ_d=0.50, Model M1)







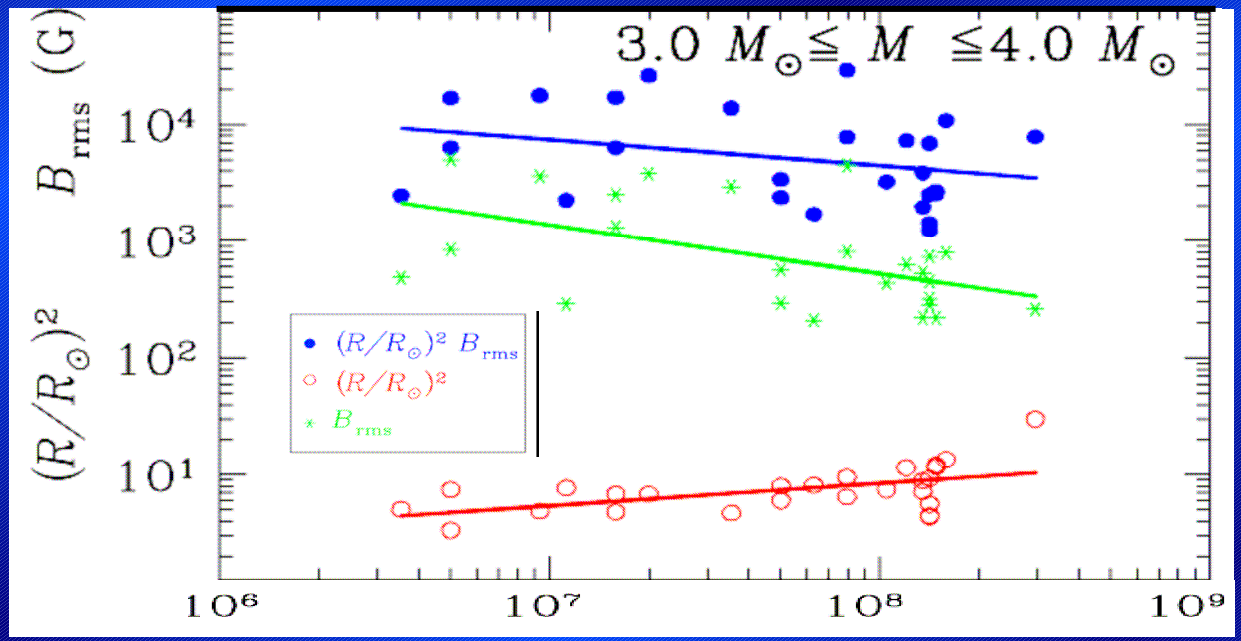
The same as in the previous slide but for the model with the dissipation parameter τ_d=0.5

$f_1 \approx 0.20$

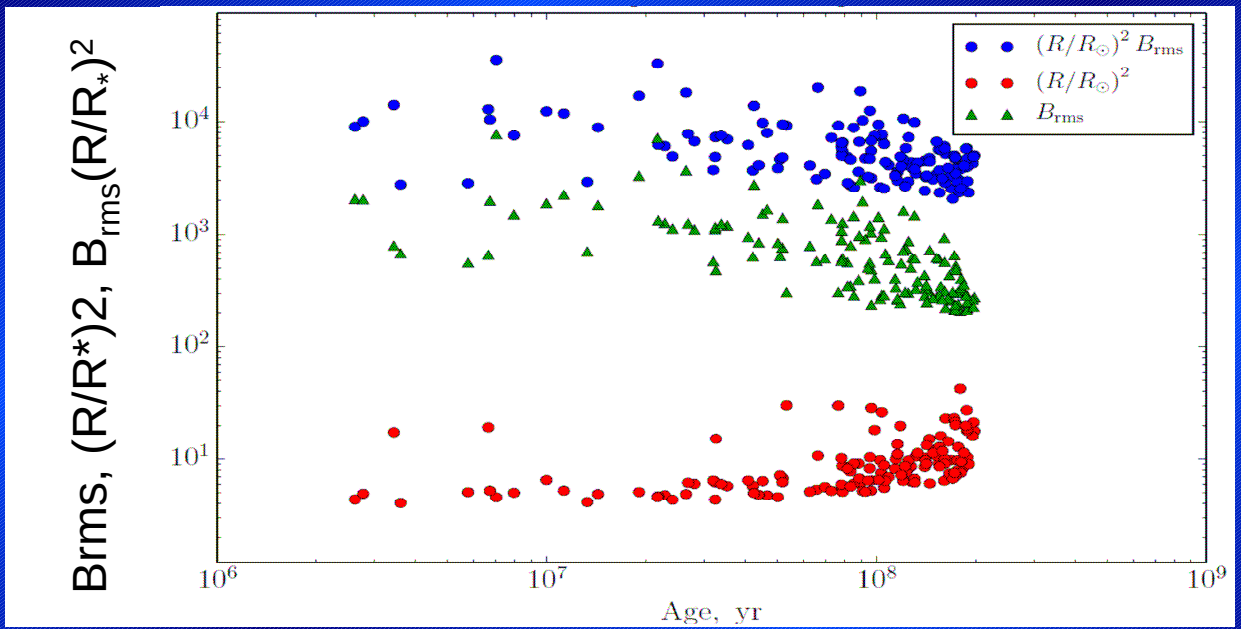
Parameters of the best fitting models for magnetic field distribution functions of BA and OB stars

Stars	Model	<logΦ>	σ
BA	M_0	26.42±0.04	**0.50±0.05**
	M_1	26.83±0.07	**0.33±0.07**
OB	M_0	26.51±0.11	**0.33±0.07**
	M_1	26.90±0.17	**0.53±0.09**
O	M_0	26.95±0.35	**0.53±0.35**
	M_1	27.29±0.47	**0.51±0.07**
OBA	**M_0**	**26.45±0.05**	**0.50±0.05**
	M_1	**26.87±0.07**	**0.35±0.06**

B_{rms}, $(R/R_*)^2$, and $B_{rms}(R/R_*)^2$ as functions of the stellar age

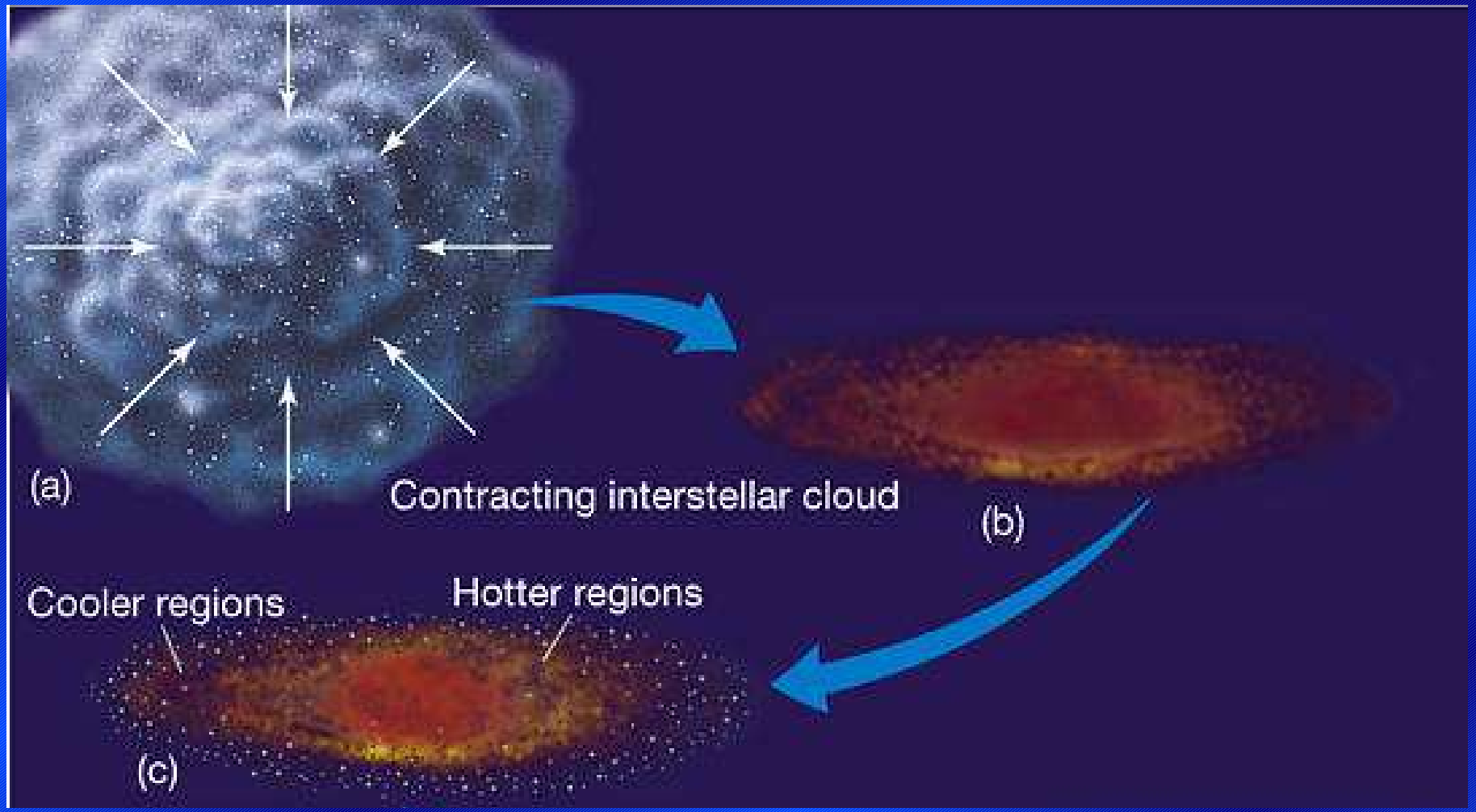


Landstreet et al. (2007)



Our model

Multiple merging in the proto-stellar cloud as the source of the magnetic field



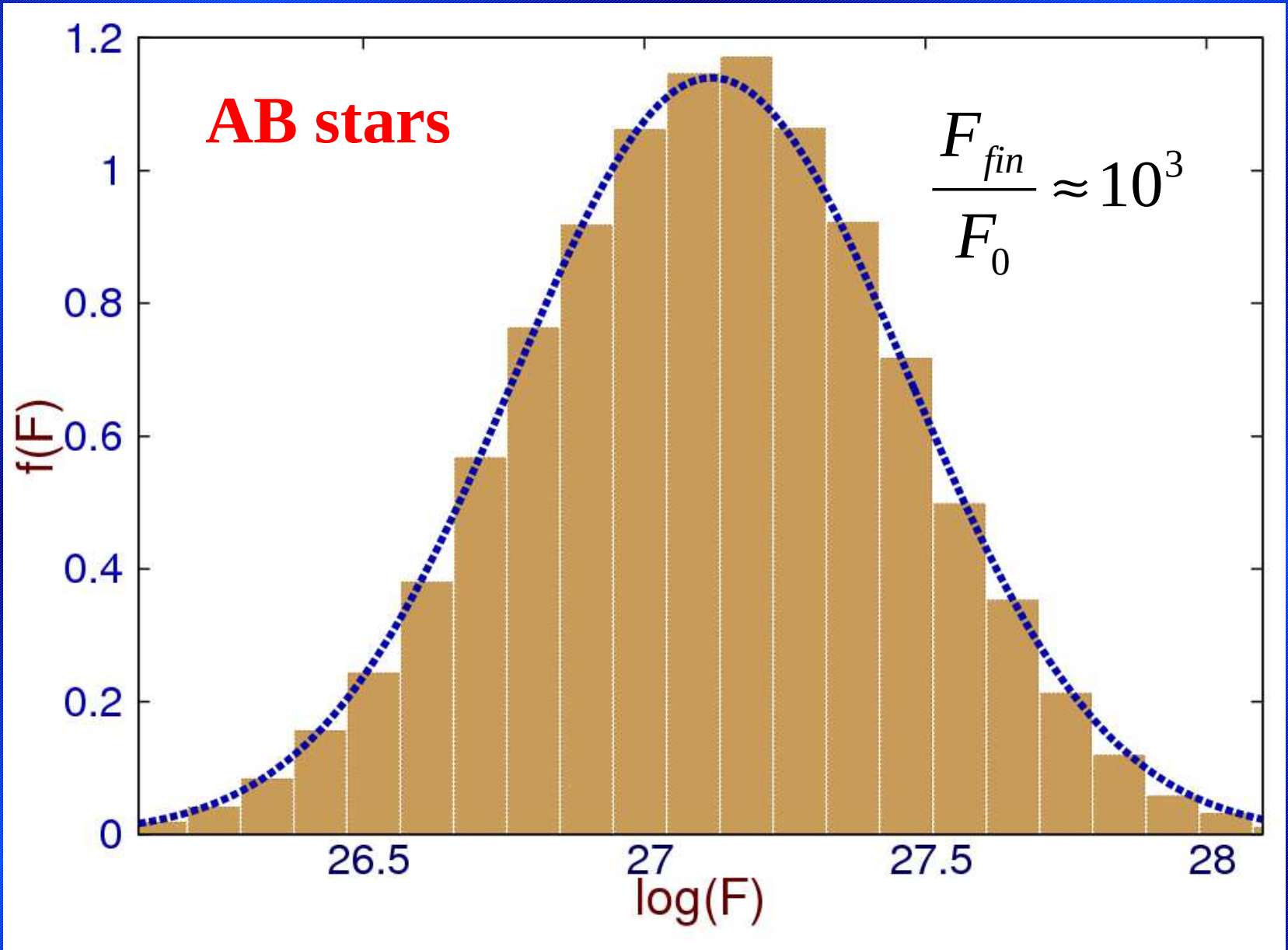
http://pages.uoregon.edu/jimbrau/BrauImNew/Chap15/FG15_01.jpg

Magnetic field before ZAMS

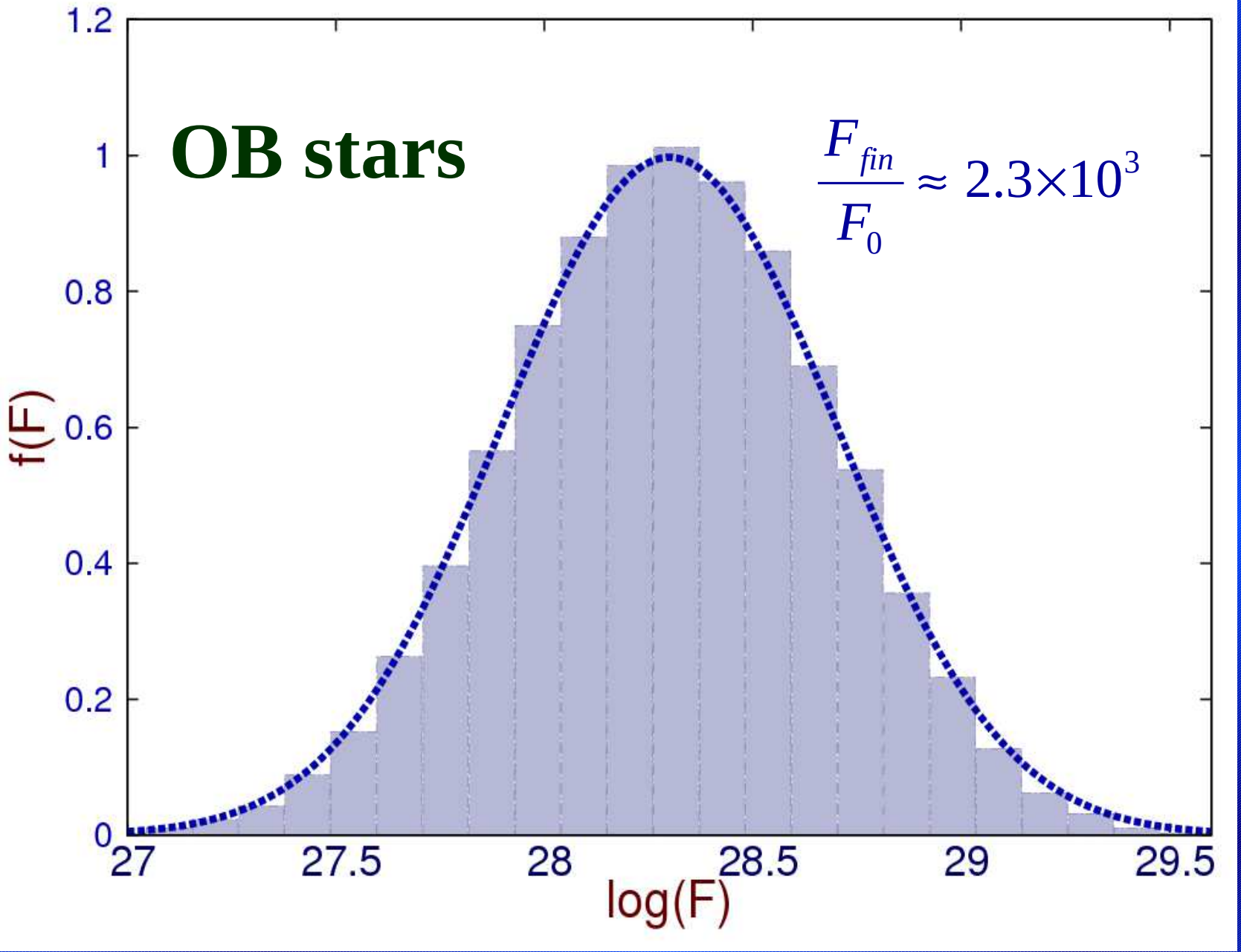
Toy model of the magnetic field and magnetic flux generation by dynamo-action

- All stars have the equal initial magnetic flux F_0
- **Magnetic field** is generated during the N cycles
- $B_{fin} = B_0 * \alpha_1 * \alpha_2 * \ldots \alpha_N$
- α_i – is the uniformly distributed random variable in an interval **[a,b]**
- **Magnetic flux** $F_i = 4\pi R_i^2 B_i$, R_i is the stellar radius at the cycle i,
- $F_{fin} = F_0 * \beta_1 * \beta_2 * \ldots \beta_N$, where $\beta_{i+1} = \beta i * (\alpha_{i+1} / \alpha_i) * (R_{i+1}/R_i)^2$
- $F_0 = B_0 * 4\pi R_0^2$

Parameters of the model: B_0 (or F_0), R_0, a, b, N



Parameters of the model $\log F_0 = 1.5 * 10^{24}$ G*cm^2, a=1.0, b=1.85, N=20



Parameters of the model: **$\log F_0$=8.8*10^{24} G*cm^2, a=1.0, b=2.00, N=20**

Last merging?

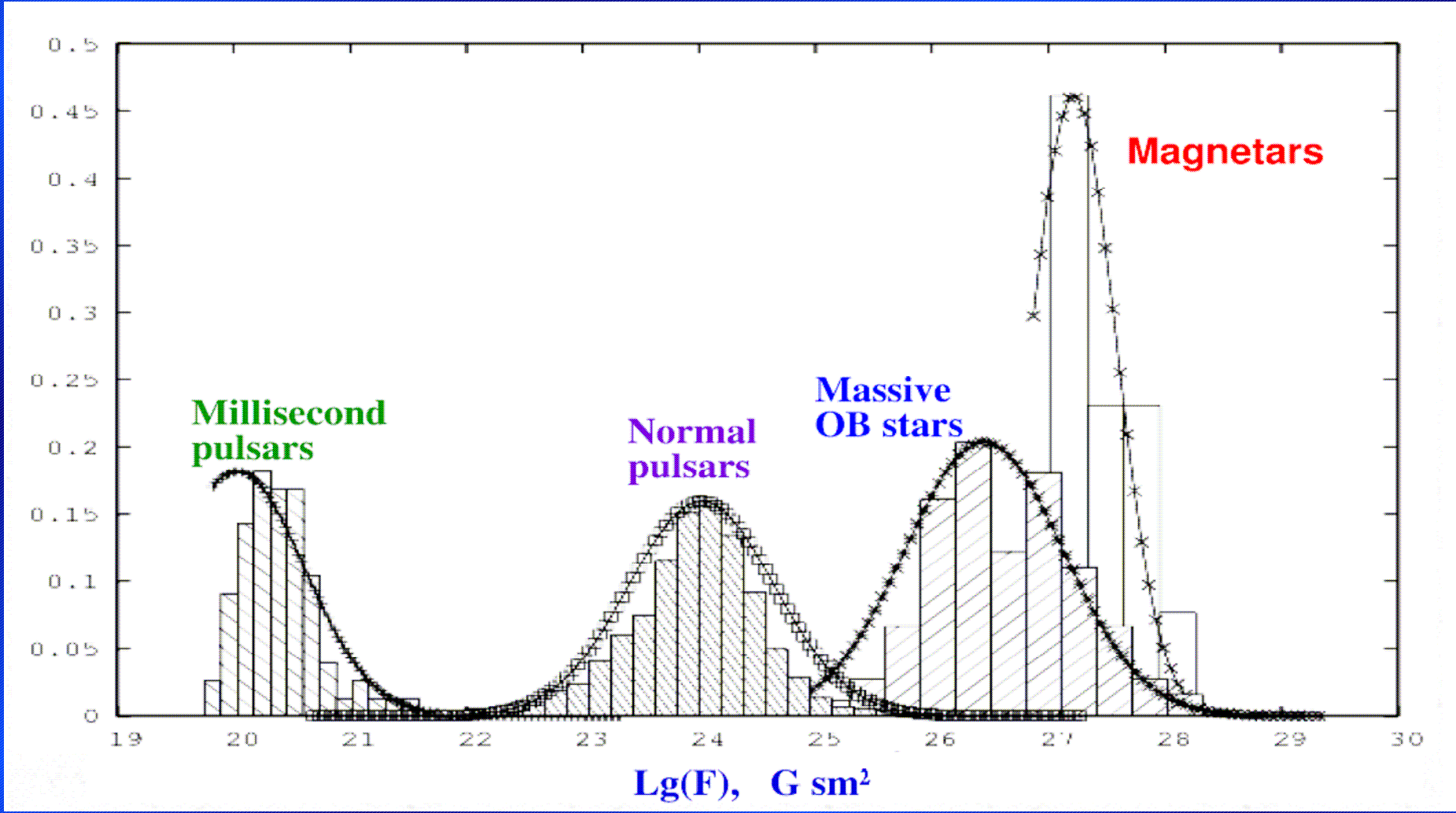
1) A fraction of magnetic stars in binary systems is small
2) There is no magnetic WD in binaries

This means that only in the case when all protostellar components (or planetesimals) are merged, the newborn star will have a sufficiently large magnetic field. In this case, the angular momentum of the entire protostellar cloud is converted into the magnetic moment of the star. The final merging of double protostars is one of the possible cases of such conversion.

Sun is non-magnetic stars (only 2% of the angular momentum)

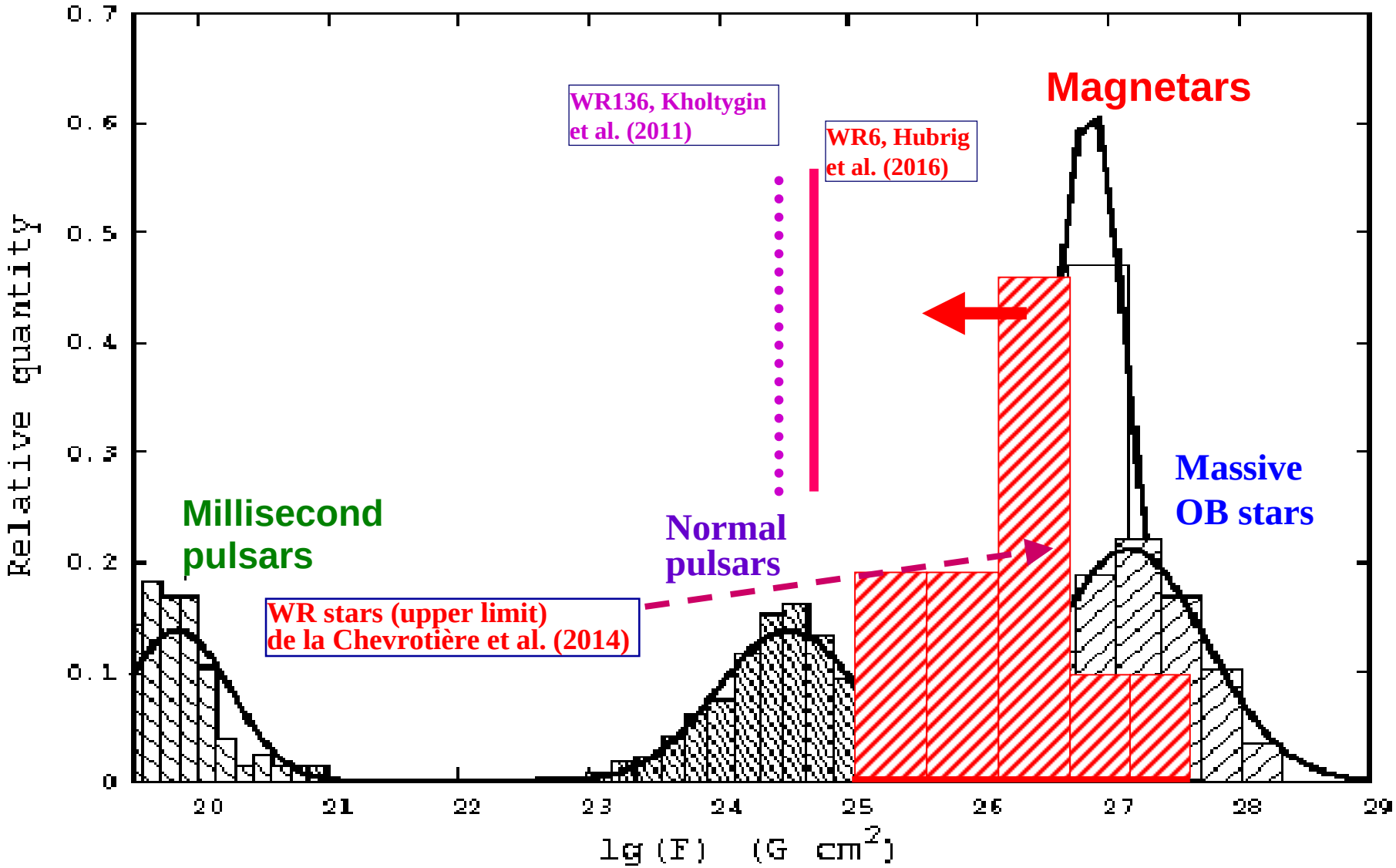
Magnetic evolution after the Main Sequence

Magnetic flux distribution for **massive OB stars** and **neutron stars**



Igoshev and Kholtygin (2011)

Magnetic flux distribution for massive OB stars, **WR stars**, pulsars and magnetars



Conclusions

1. **The main question is why only ~5-10% of OBA stars are magnetic is unanswered?**
2. **Dynamo multi-action can be responsible for the formation of magnetic field before the MS stage.**
3. Relic nature of the magnetic field in **OBA** stars is most likely. However, the contribution of local magnetic fields to the global magnetic field can be important.