The evolution of magnetic fields from the main-sequence to very late stages

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Introduction

- Magnetic fields are observed in many if not all types of star
- Where present these magnetic fields influence the evolution of their host star
- However, they themselves change as the host stars undergo significant structural changes during their evolution

Dynamo Field

- Continuously generated
- Can be dynamically evolving
- Flux conservation

Fossil Field

- Formed in previous evolutionary stages
- Stable large scale fields
- Ohmic decay
- Flux conservation

Ohmic decay

$$t_{\text{ohm}} \sim \frac{4\pi\sigma L^2}{c^2}$$

- t_{ohm} = ohmic decay time
- L = Magnetic field Length scale
- c = speed of light
- σ = electrical conductivity

- Ohmic decay timescale is the time for which a magnetic field will decay in the absence of any other effects

- Likely to effect fossil fields, since dynamo fields are continuously generated.

Magnetic flux conservation

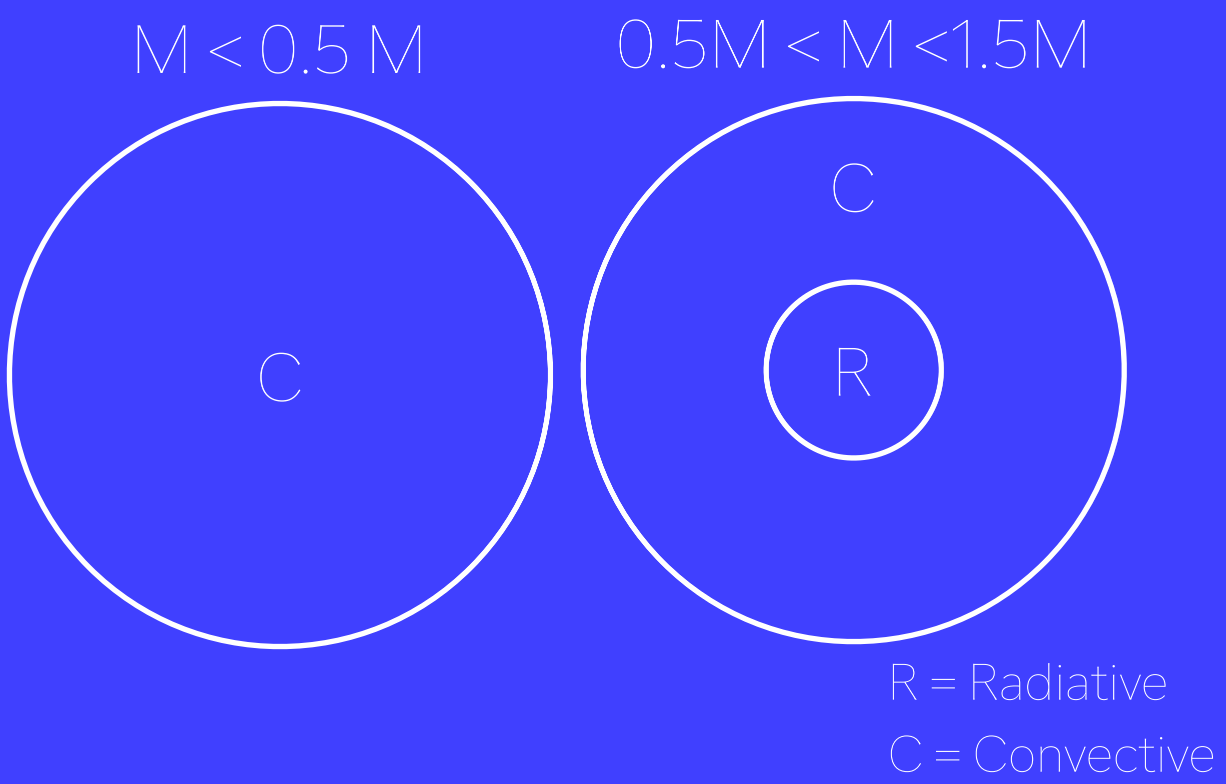
$$B_\mathrm{d}(t_2) = B_\mathrm{d}(t_1)\left[\frac{R(t_1)}{R(t_2)}\right]^2$$

- B_d = Dipole field strength
- R = Stellar radius

- As the radius of a star increases the surface magnetic field strength decreases
- As the radius of a star decreases the surface magnetic field strength increase

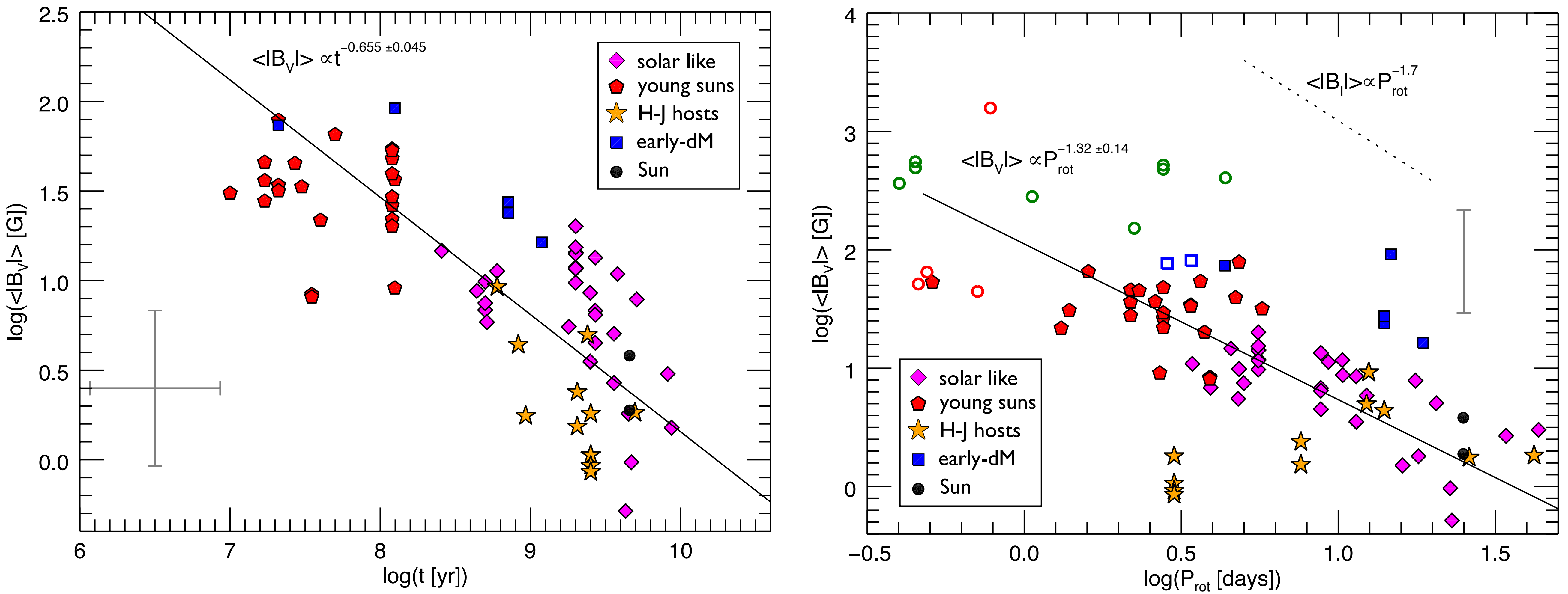
Main-Sequence Stars

Low-mass stars



- Dynamo fields
- $\sim 0.1 < M/M_\odot < \sim 1.5$
- **$M = 0.1\ M_\odot$**: MS Lifetime = $\sim 3 \times 10^{12}$ yr
  MS radius expansion = ~1
- **$M = 1.5\ M_\odot$**: MS Lifetime = $\sim 2 \times 10^{9}$ yr
  MS radius expansion = ~1.5

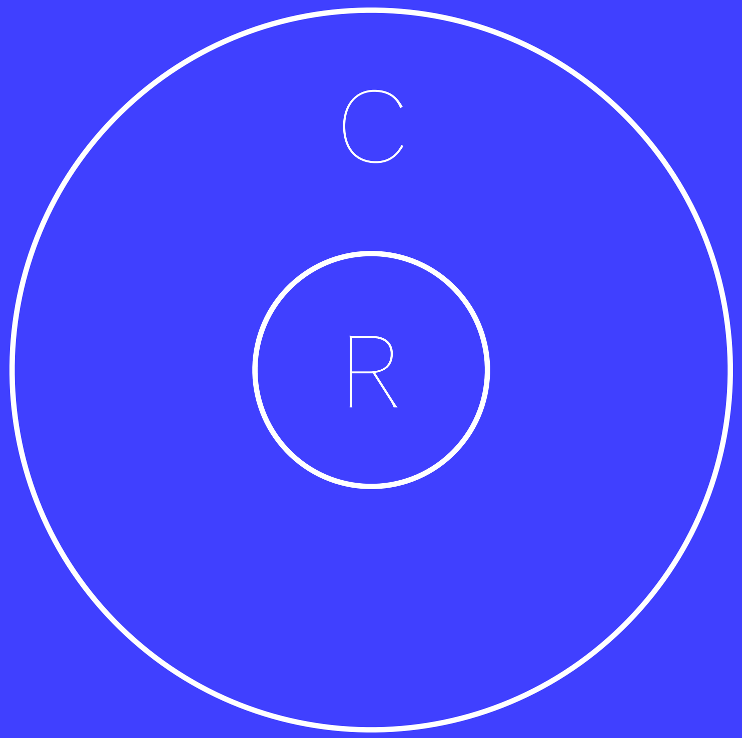
Low-mass stars



- 73 late-F, G, K and M stars from the pre-main sequence and main sequence
- $<|B_V|> \propto t^{-0.655\pm0.045}$, $\Phi_V \propto t^{-0.622\pm0.042}$
- Gives good evidence for Skumanich law

Vidotto et al., 2014, MNRAS, 441, 2361

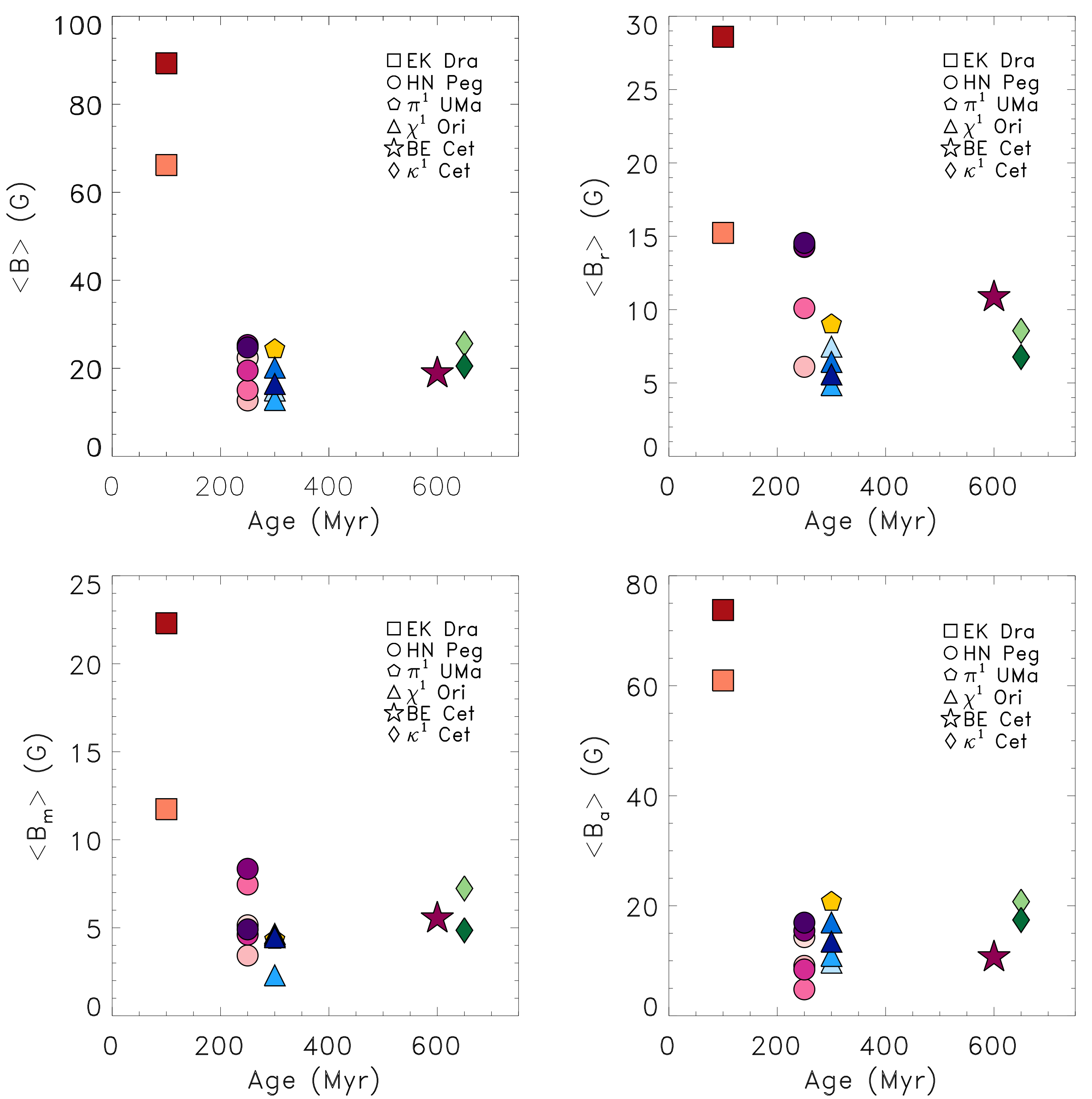
Solar Twins



R = Radiative
C = Convective

- Dynamo field
- Mass very close to 1 $M_\odot$
- Approximate MS Lifetime = ~ 8.5 x 10^9 yr
- Radius expansion during MS = ~1.4

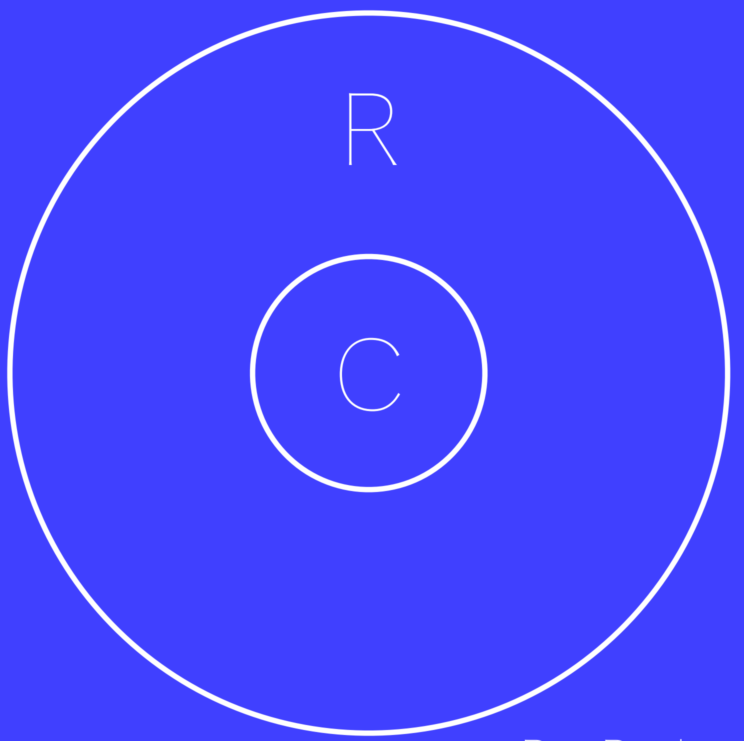
Solar Twins



- 6 Solar analog stars
- 100-650 Myr
- Significant decrease in <B> only from 100-250 Myr
- Small sample

Rosén et al., 2016, A&A, 593, A35

Intermediate Mass stars



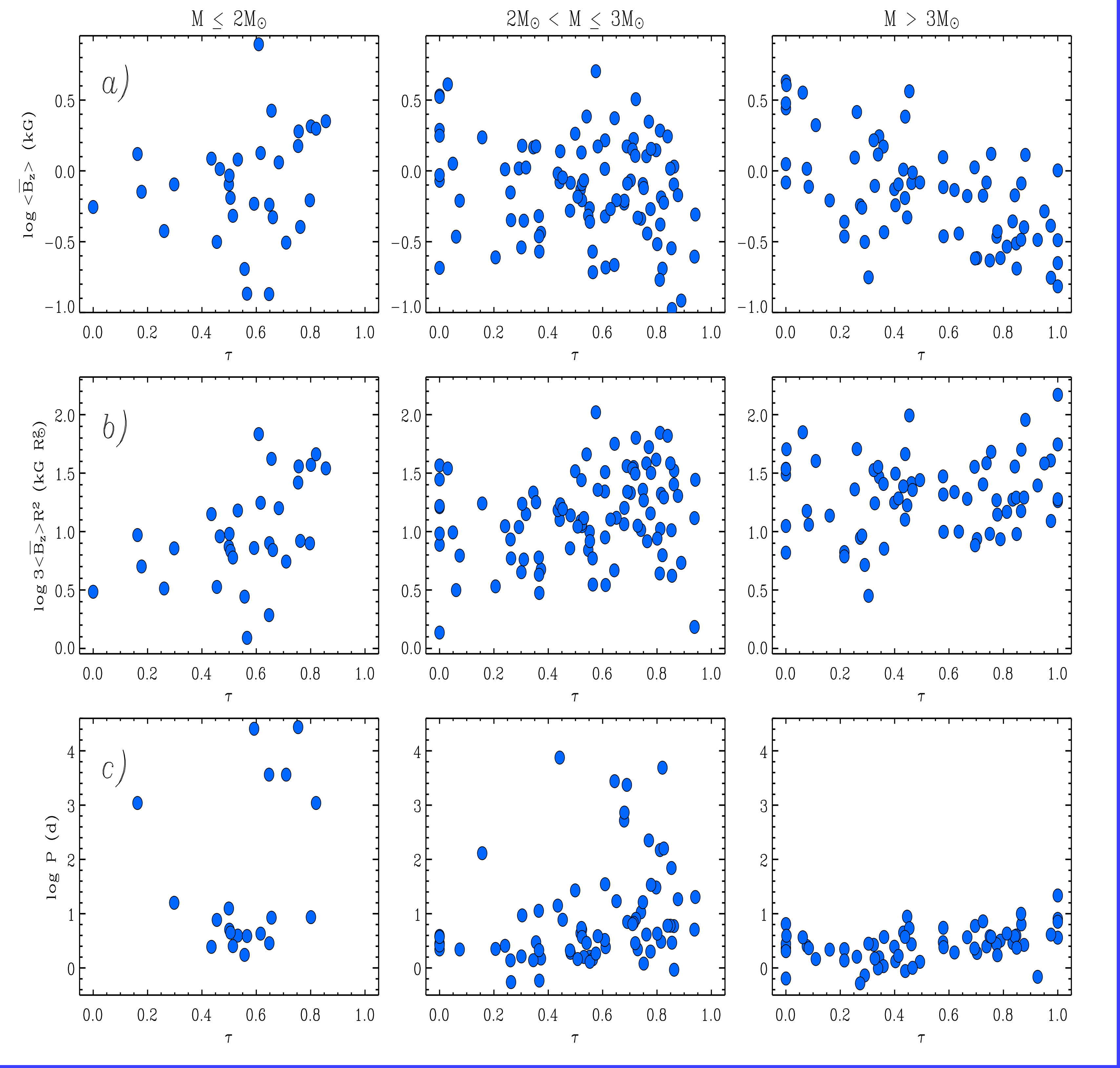
R = Radiative
C = Convective

- Fossil field
- $\sim 1.5 < M/M_\odot <\sim 8$
- Approximately 10%
- **$M = 1.5\ M_\odot$:** MS Lifetime $= \sim 2 \times 10^9$ yr

  MS radius expansion = ~1.5
- **$M = 8\ M_\odot$:** MS Lifetime $= \sim 3 \times 10^7$ yr

  MS radius expansion = ~2

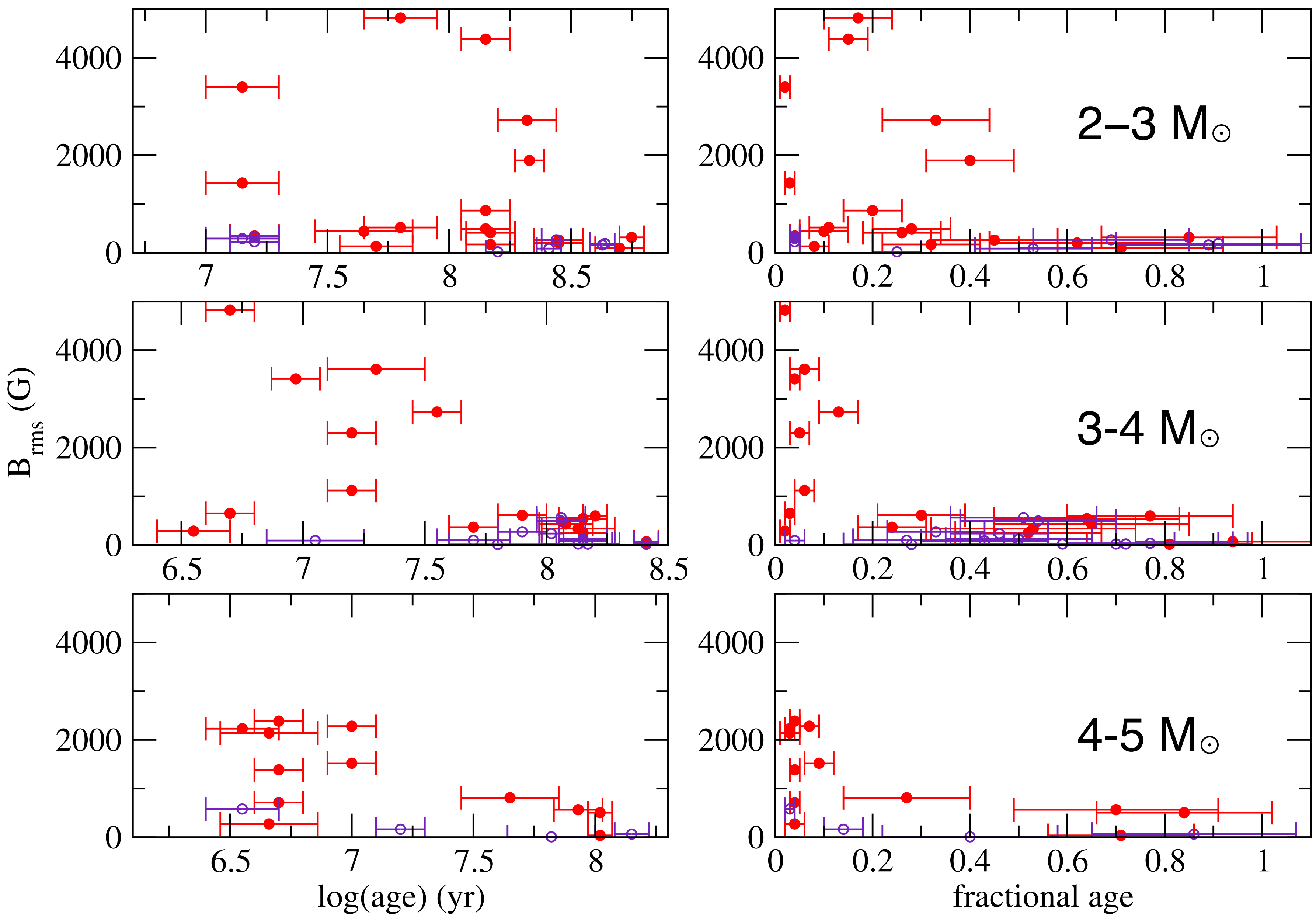
Intermediate Mass stars



- Average surface field strength decreases with time for stars with M > 2M⊙
- Results show that the magnetic flux of stars with M < 3M⊙ increases with time.
- Marginal trend between magnetic flux and time for M > 3M⊙

Kochukhov and Bagnulo, 2006, 450, 763

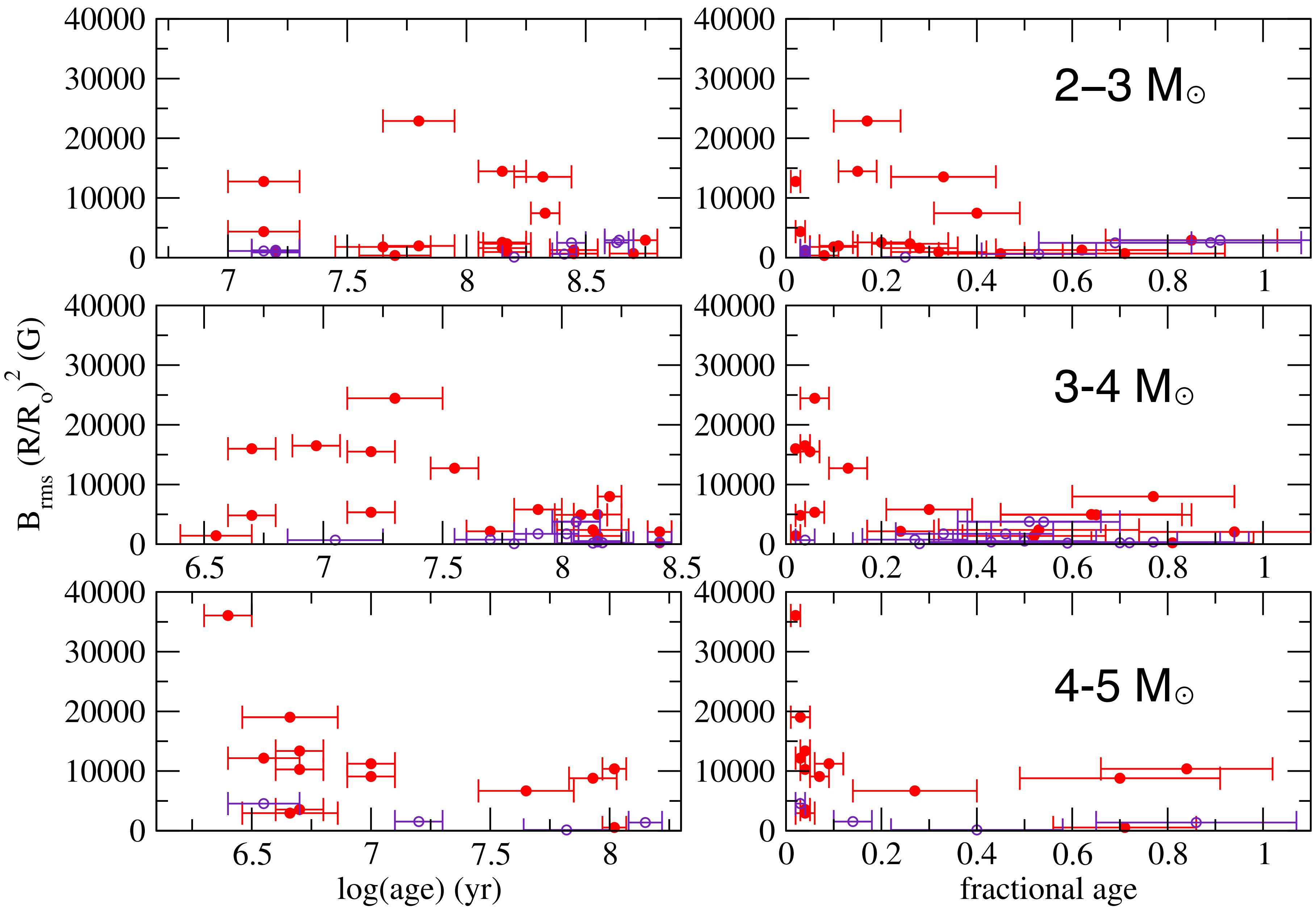
Intermediate Mass stars



- 2–3 $M_\odot$ field decline after about 2.5×10^8 yr.
- 3-4 $M_\odot$ field decline after about 4×10^7 yr
- 4-5 $M_\odot$ field decline after about 1.5×10^7 yr

Landstreet et al., 2008, A&A, 481, 465

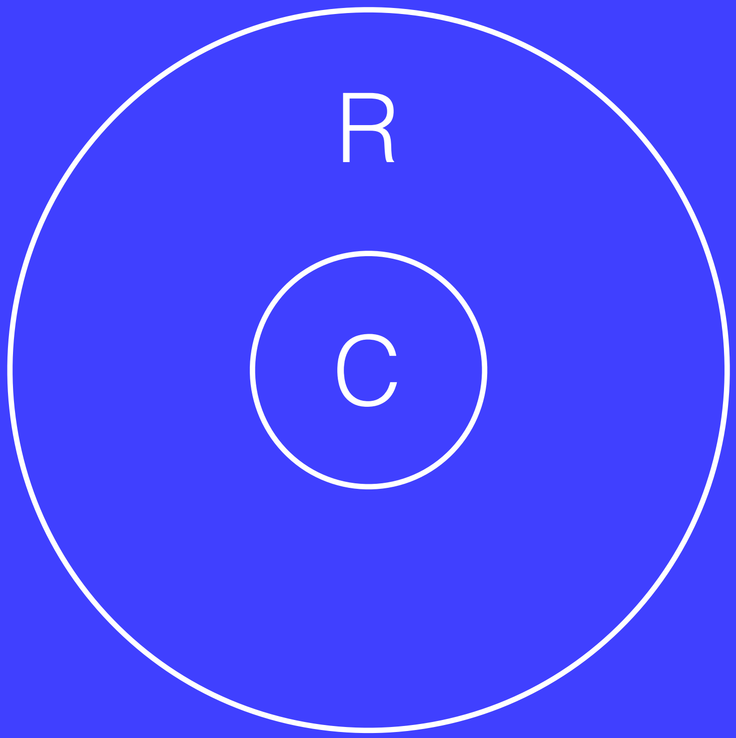
Intermediate Mass stars



- Magnetic flux either declines in all stars through the main sequence lifetime, or
- Magnetic flux in the more strongly magnetic stars found at young fractional ages is somehow reduced

Landstreet et al., 2008, A&A, 481, 465

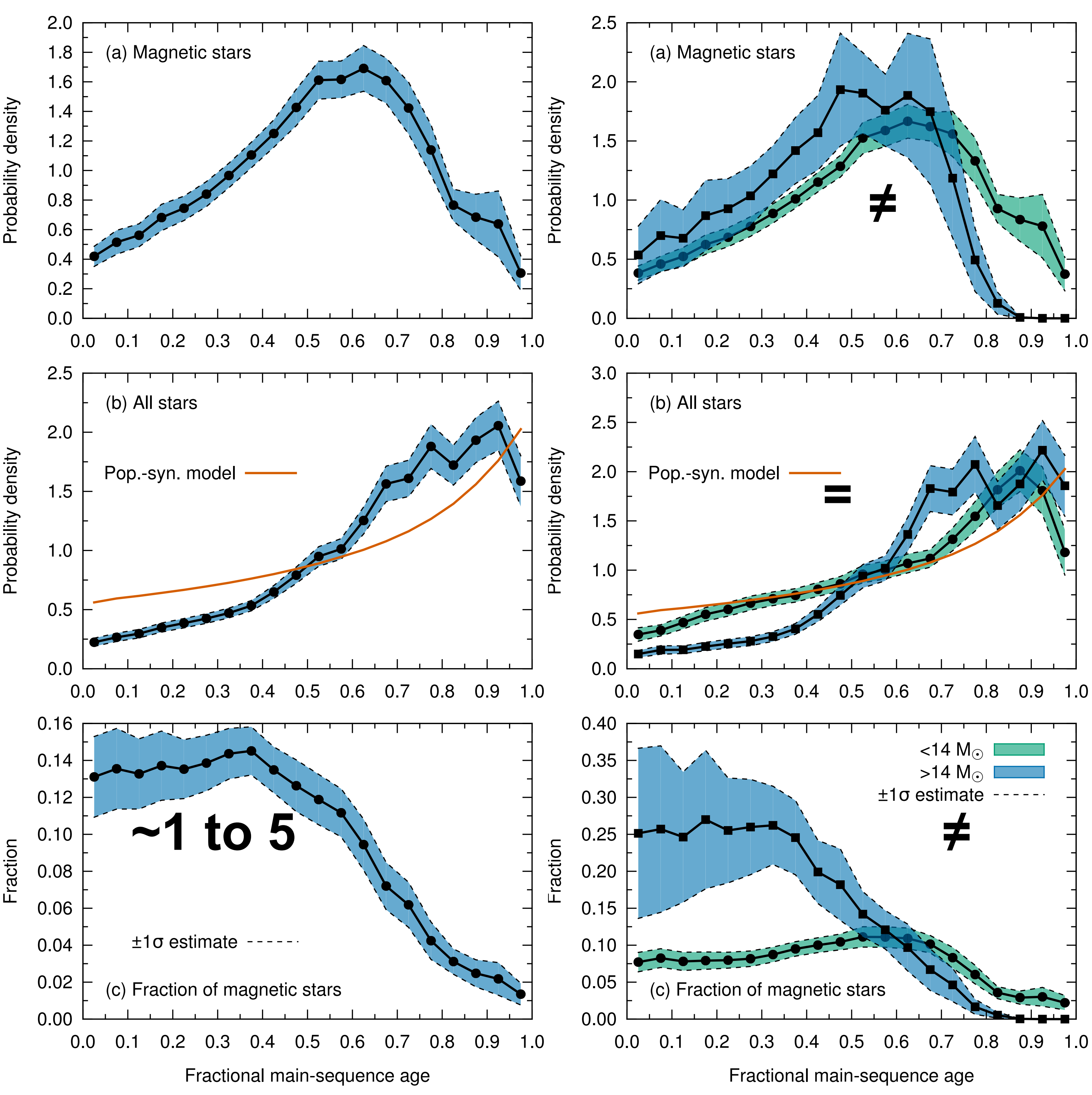
Massive Stars



R = Radiative
C = Convective

- Fossil fields
- ~8 < $M/M_\odot$
- **M = 8 $M_\odot$**: MS Lifetime = ~3 x 10^7 yr
  MS radius expansion = ~2
- **M = 50 $M_\odot$**: MS Lifetime = ~ 4 x 10^6 yr
  MS radius expansion = ~6

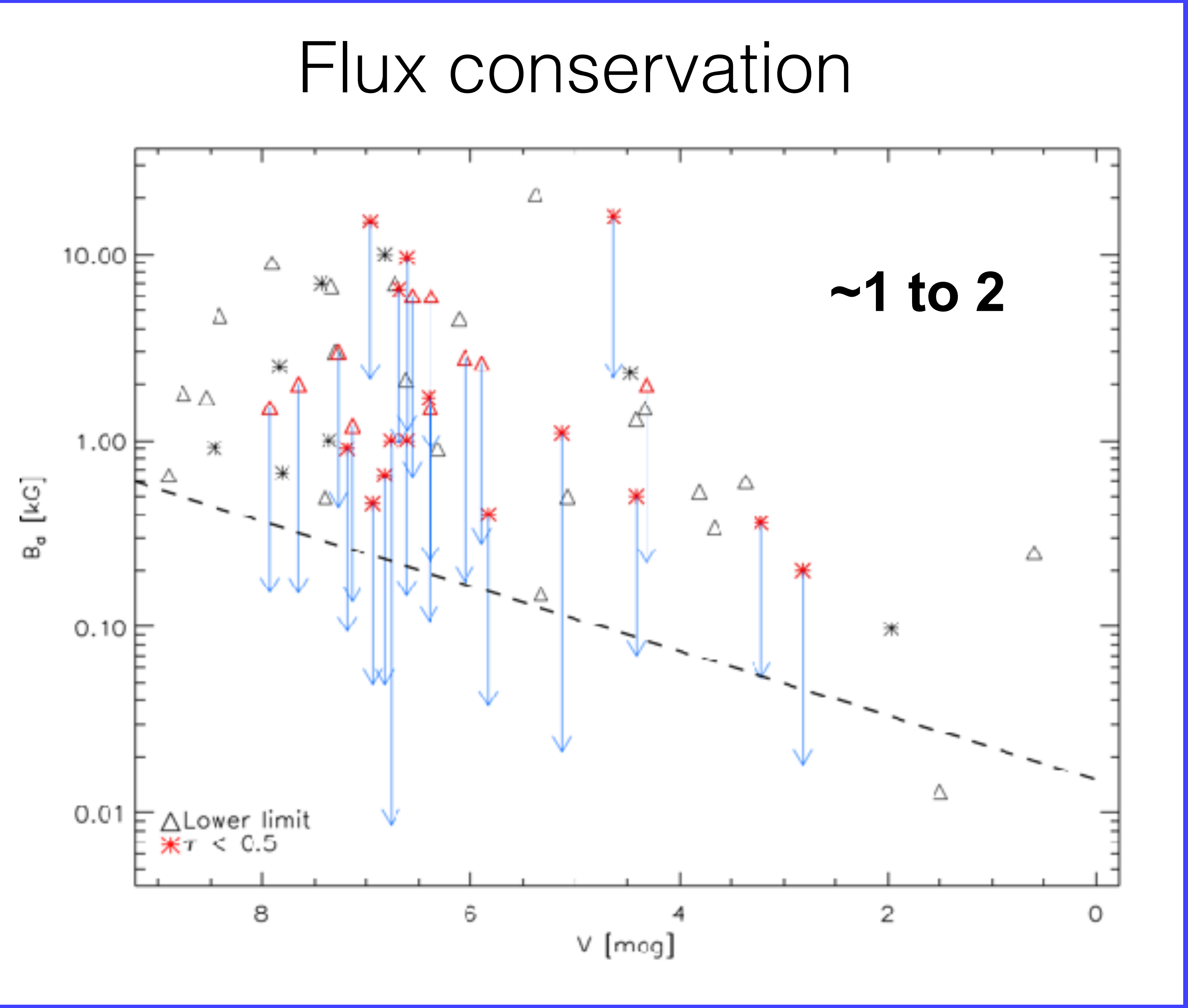
Massive Stars



- 205 non-magnetic massive stars
- 53 magnetic massive stars
- V < 9 mag
- M: 5 – 50 $M_\odot$
- Fossati et al. (2016) found that Binary rejuvenation and suppression of core convection cannot explain the observed distributions

Fossati et al., 2016, A&A, 592, A84

Massive Stars



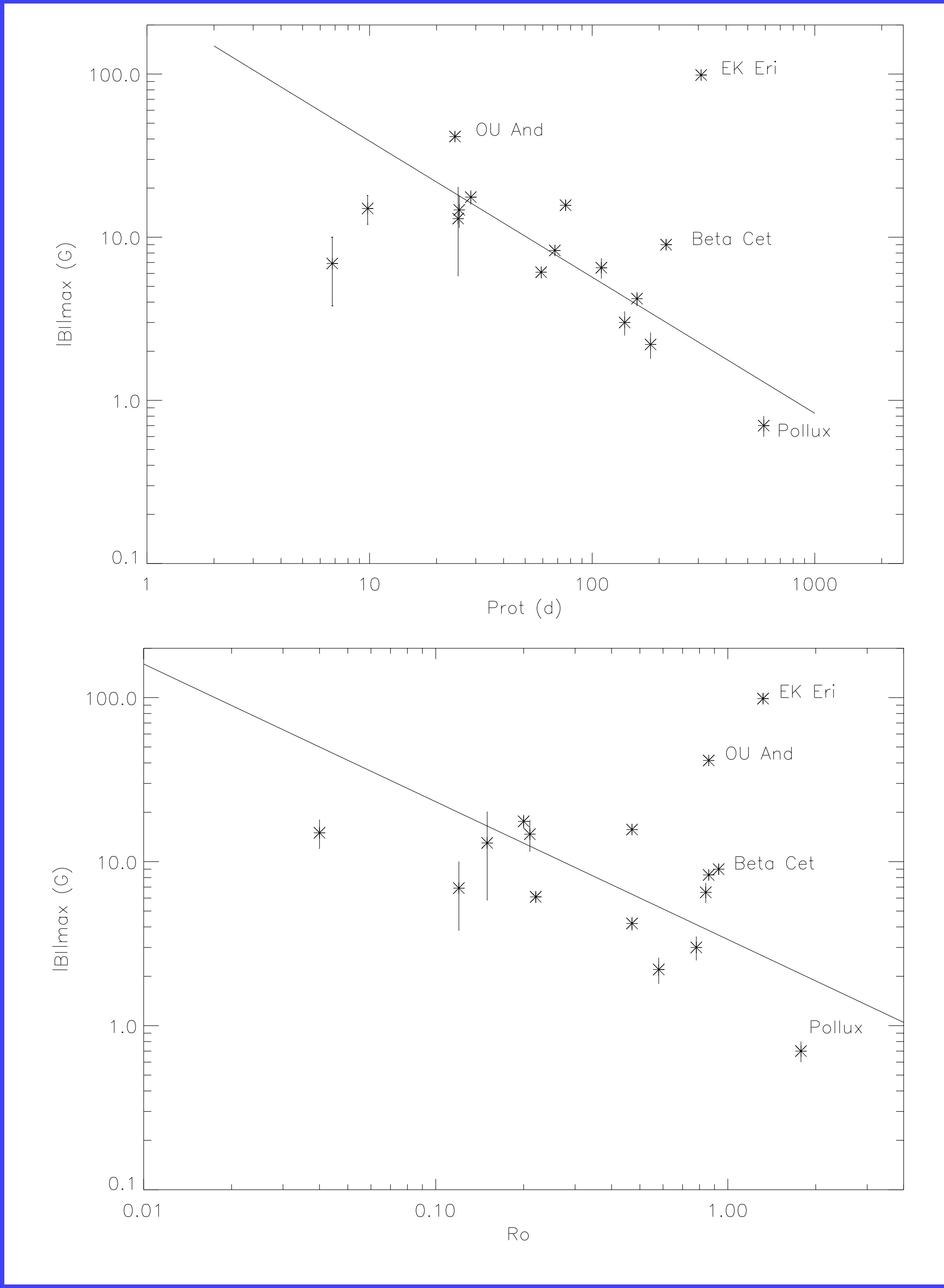
- If the magnetic field decreased only through flux conservation, half of the stars detectable to be magnetic on the ZAMS would be still detected as magnetic on the TAMS
- Flux conservation alone unlikely to be responsible for rapid decrease in fraction of magnetic stars at fractional ages > 0.6
- Therefore it it likely that a mass dependent field decay is the cause.

Fossati et al., 2016, A&A, 592, A84

Post main-sequence stars

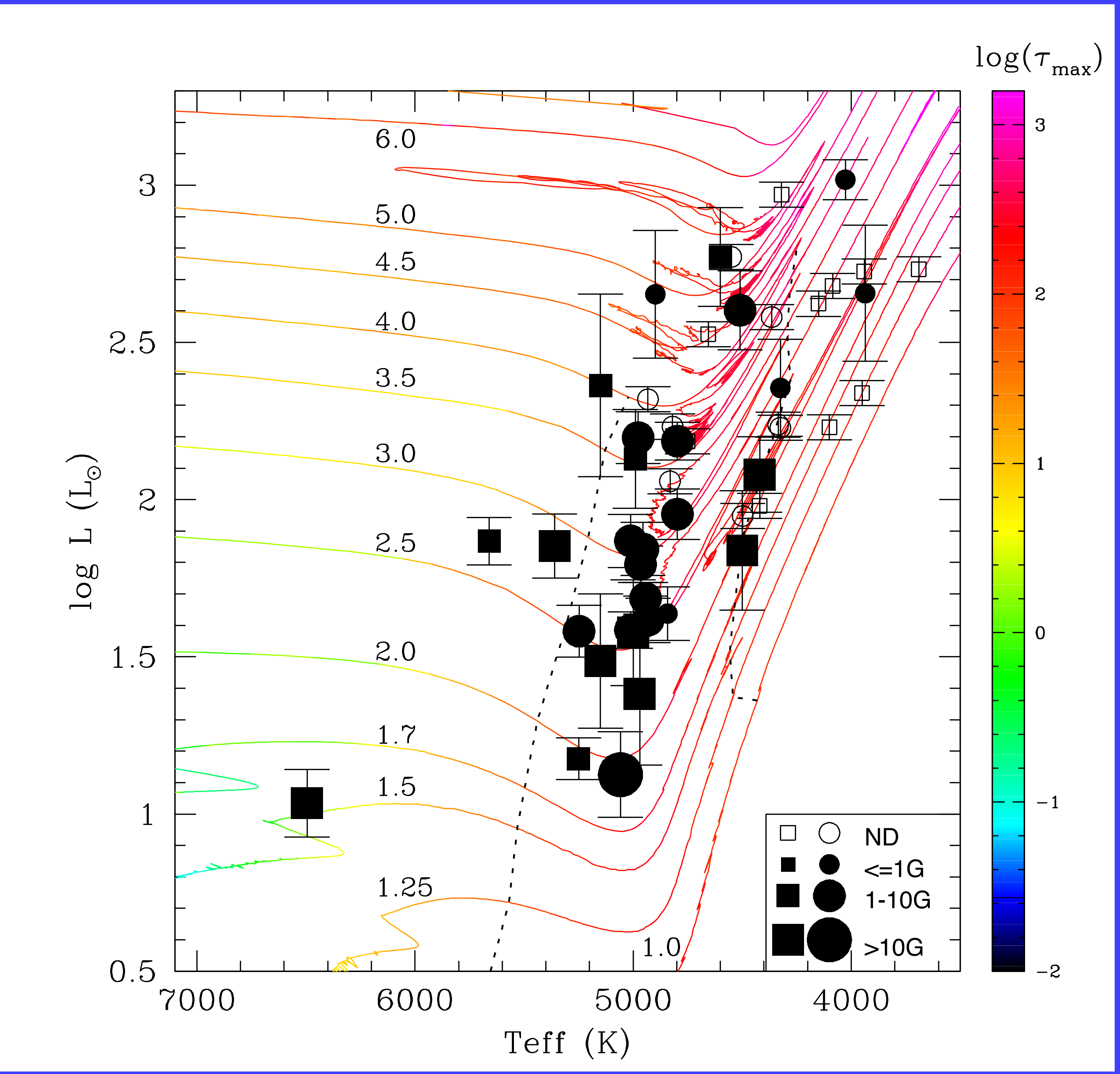
Post MS FGK stars

- Weak surface dynamo fields
- ZAMS masses between 1.25 $M_\odot$ and 6.0 $M_\odot$



Aurière et al., 2015, A&A, 574, A90

Post MS FGK stars

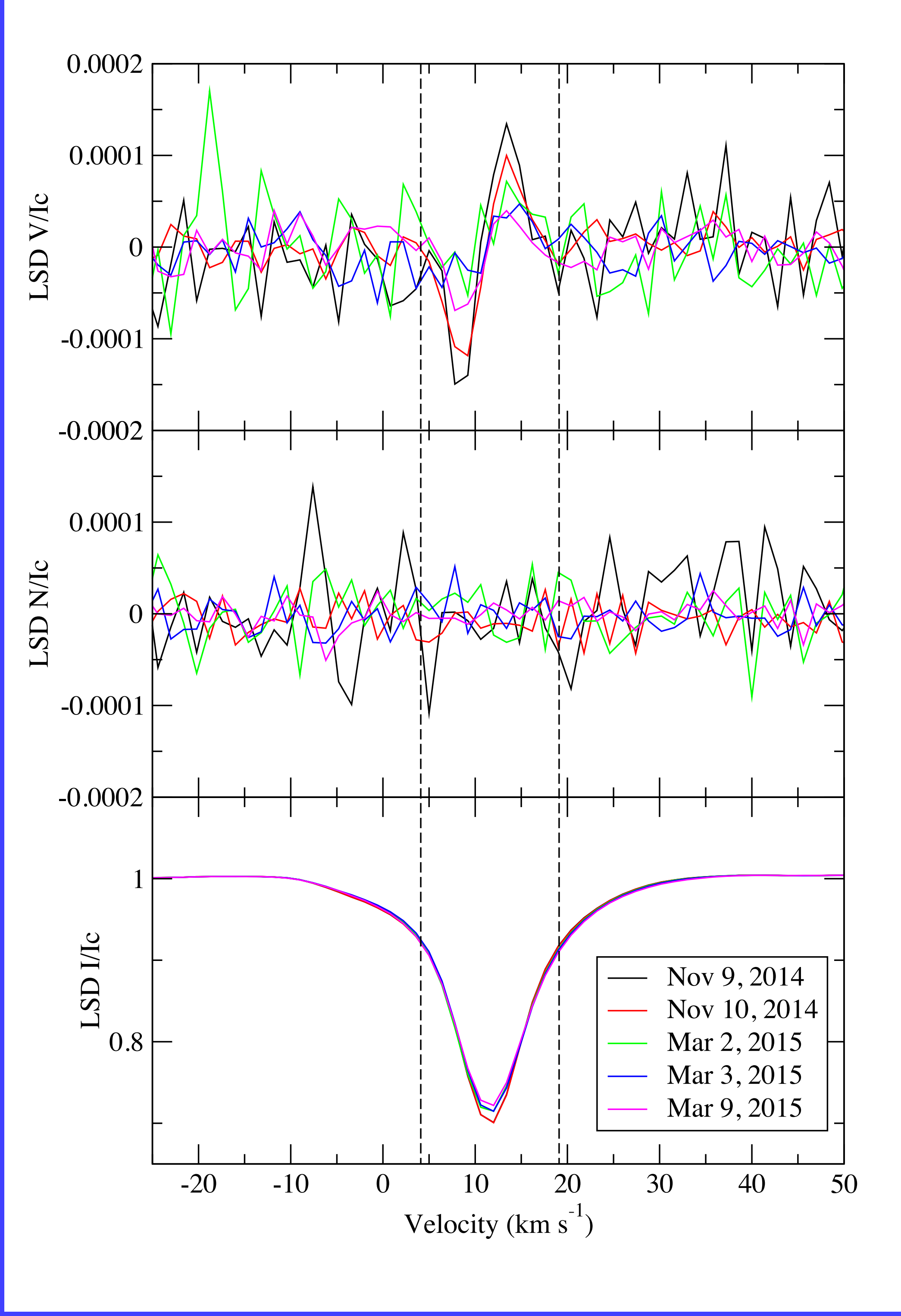


- Most stars in the first dredge-up phase or core helium-burning phase
- Could point towards a magnetic strip of the most active stars.

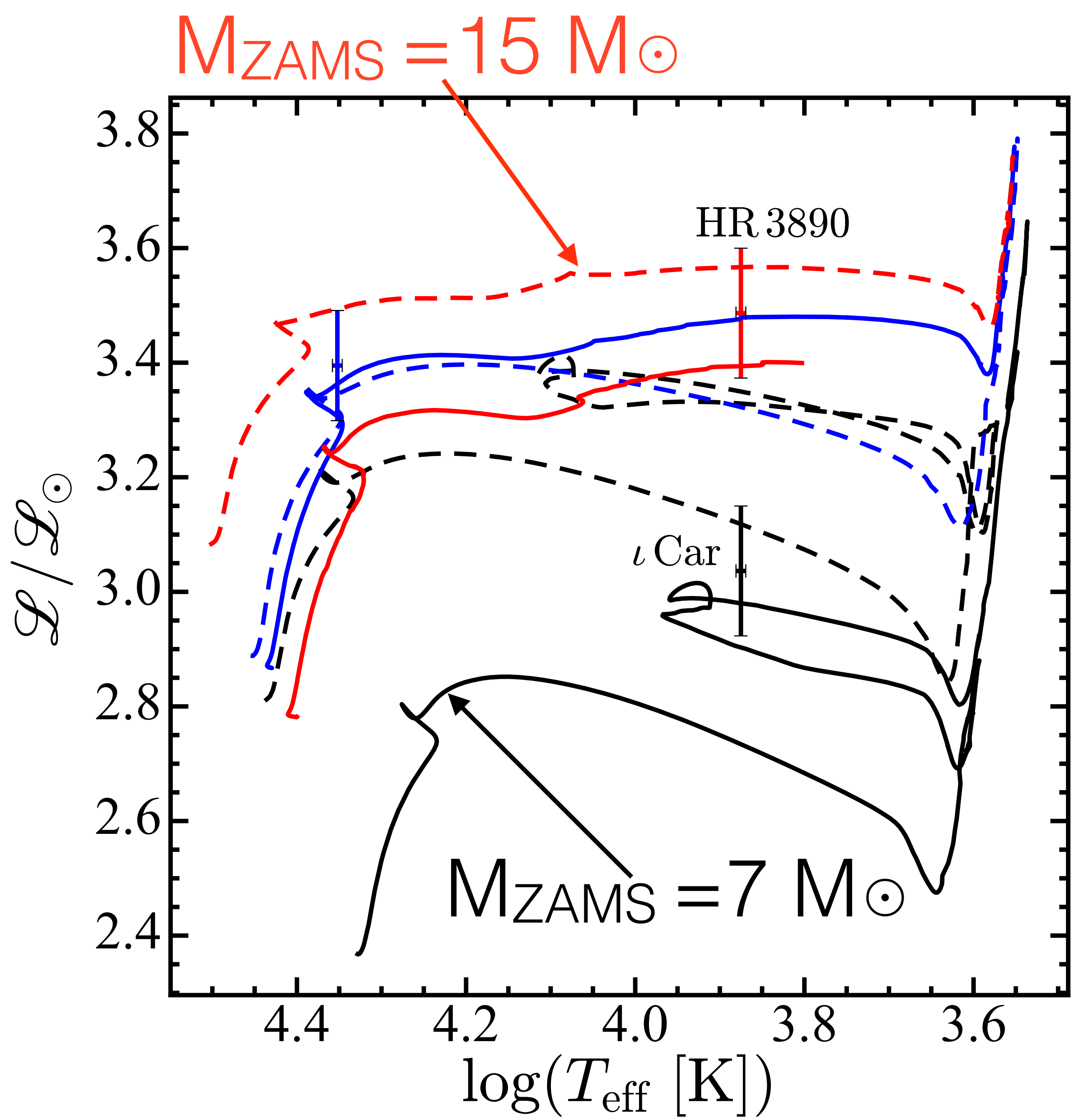
Aurière et al., 2015, A&A, 574, A90

Post MS OBA stars

- Fossil field may remain from MS
- Large radius expansion as the star evolves through the post-MS
- SNR 2360 to 5300 in Stokes I
- SNR 15000 to 44000 in Stokes V



Post MS OBA stars



BRITEpol

(BRIght Target Explorer spectropolarimetric survey)

HR 3890

- Longitudinal Field = ~2G
- Dipole Field = 6G
- ZAMS Dipole Field = 3000-6000G
- $R_{current}/R_{ZAMS}$ = ~30-20

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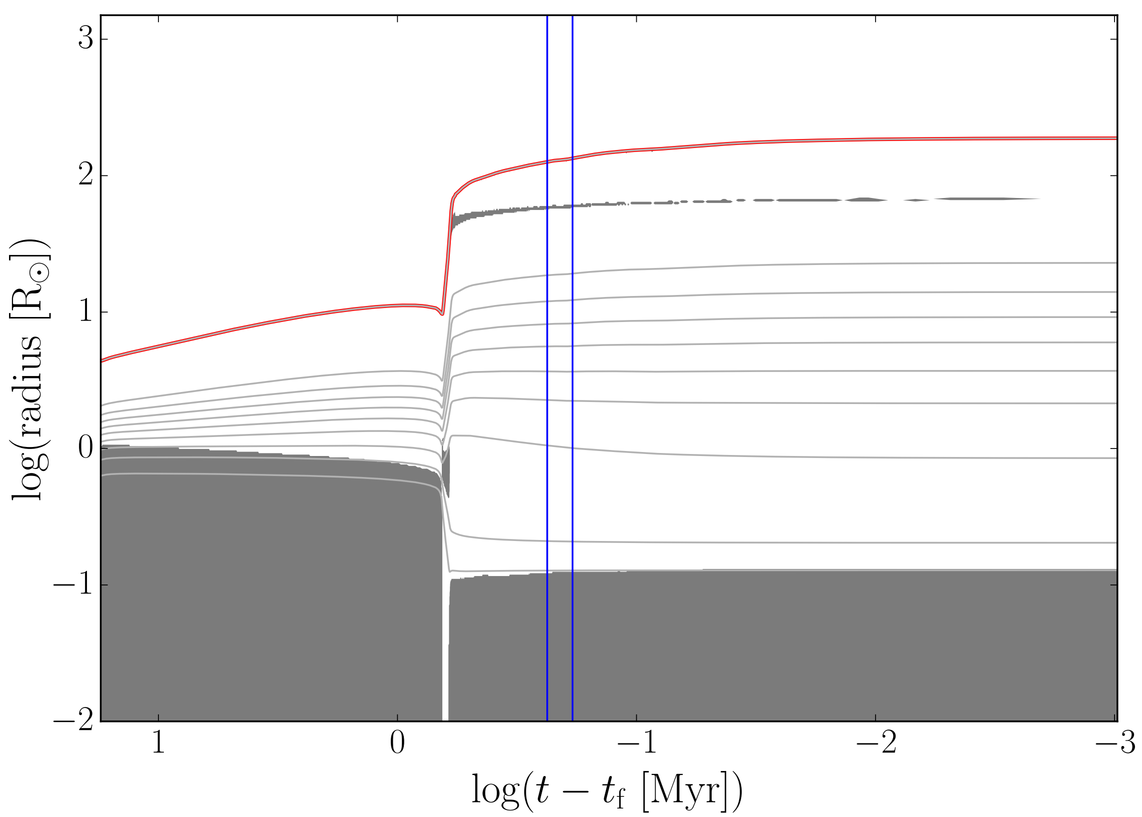
- Longitudinal Field = ~1G
- Dipole Field = 3G
- ZAMS Dipole Field = 700-1100G
- R/R = ~25-20

Neiner et al., 2017, MNRAS, 471, 1926

Post MS OBA stars

HR 3890



- Thin upper convective region
- Currently unlikely to form dynamo

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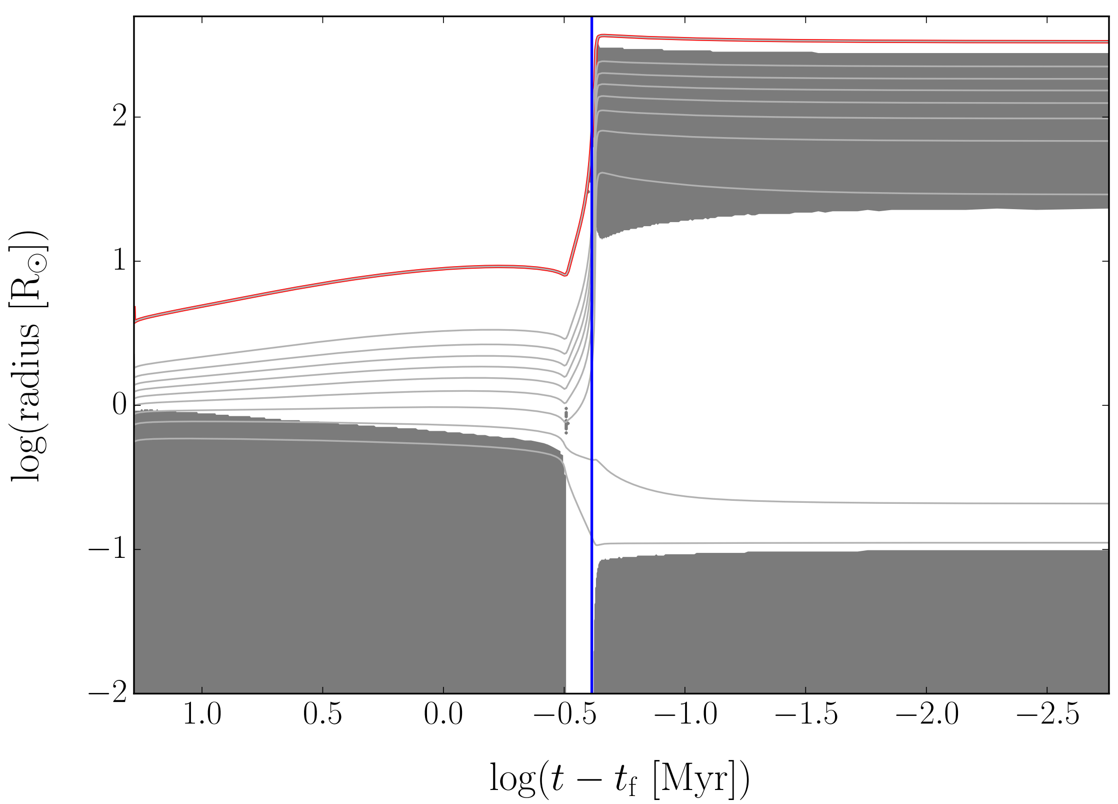


- Beginning of Transition
- Currently unlikely to form dynamo

Neiner et al., 2017, MNRAS, 471, 1926

The LIFE project

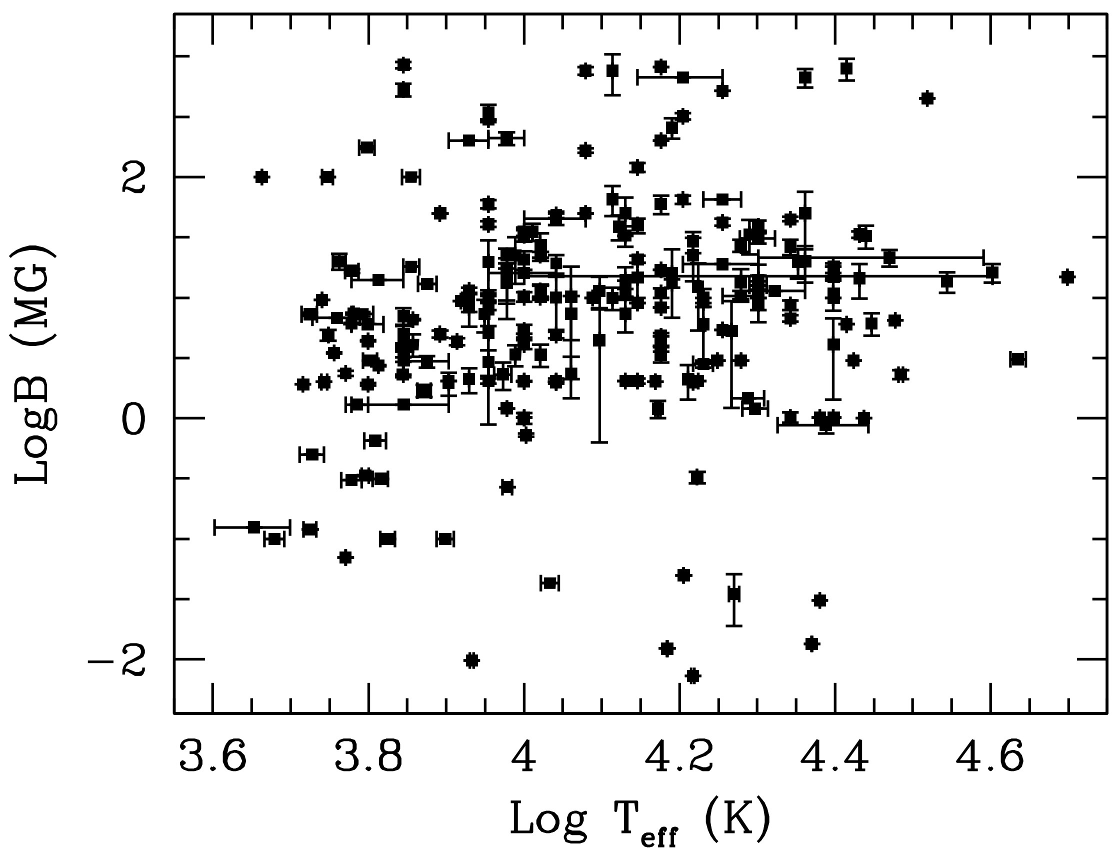
- The Large Impact of magnetic Fields on the Evolution of hot stars
- Surveying giant and supergiant OBA stars
- Extends the evolutionary baseline of study
- Each magnetic star we find will be fully characterised

Martin, Neiner, Oksala, Wade, Keszthelyi, et al., 2017, in prep.

White dwarf stars

- Fossil field origin
- End phase of most stars: those with mass less than about $8M_{\odot}$
- Ohmic decay timescale of $\sim 2\text{–}6 \times 10^{11}$ yr
- $\sim$10% host strong magnetic fields
    - These could be fossils somehow preserved from main sequence fields
    - Fossil fields of strong convective core fields of red giants that are revealed as the outer layers of the star are stripped off during late evolution
    - Fossil fields of dynamo fields generated in former close binaries that merged and went through a common envelope phase

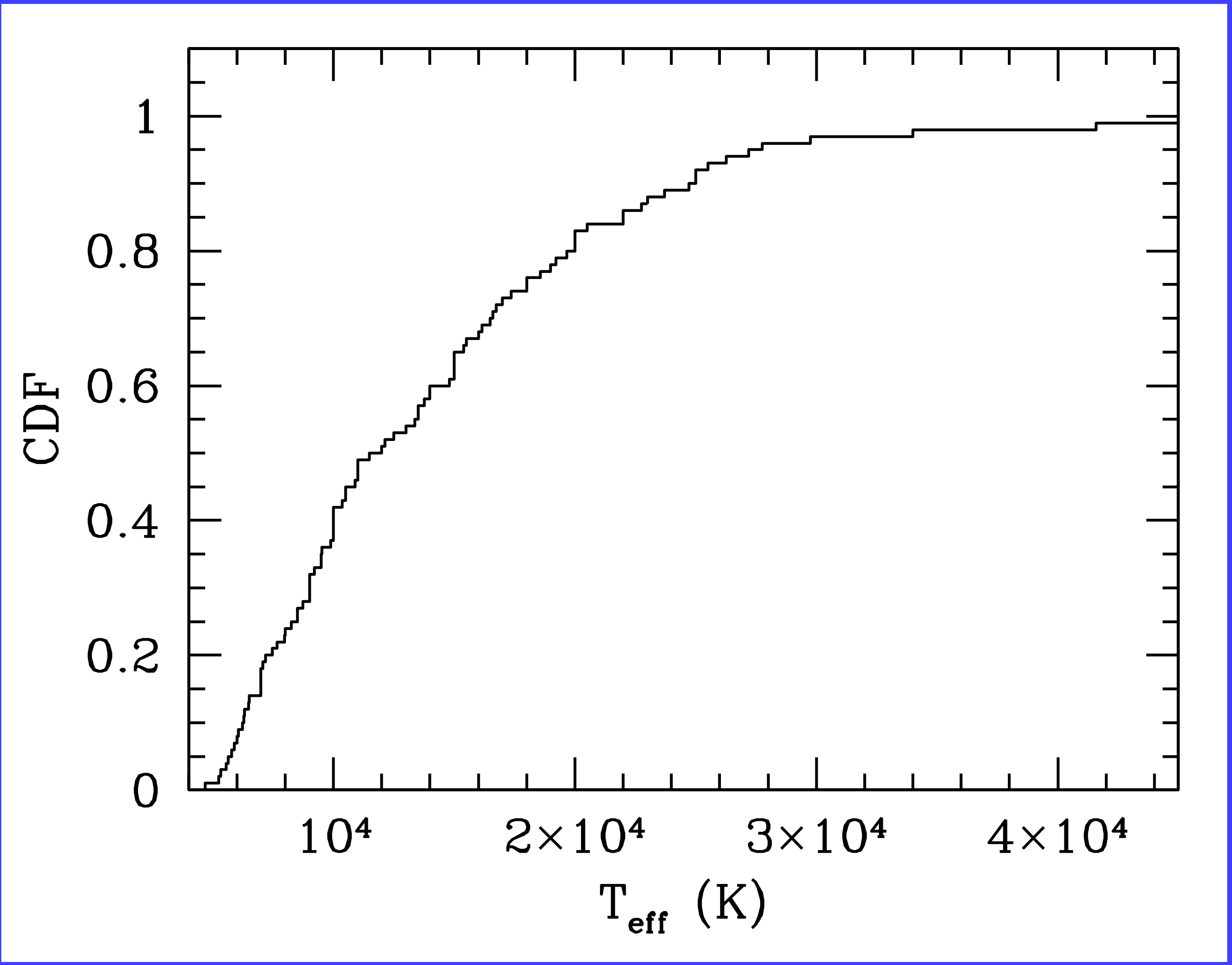
White dwarf stars



- No evidence for field evolution along the cooling curve
- Consistent with the long ohmic decay timescale

Ferrario et al., 2015, Space Science Reviews, 191, 111

White dwarf stars

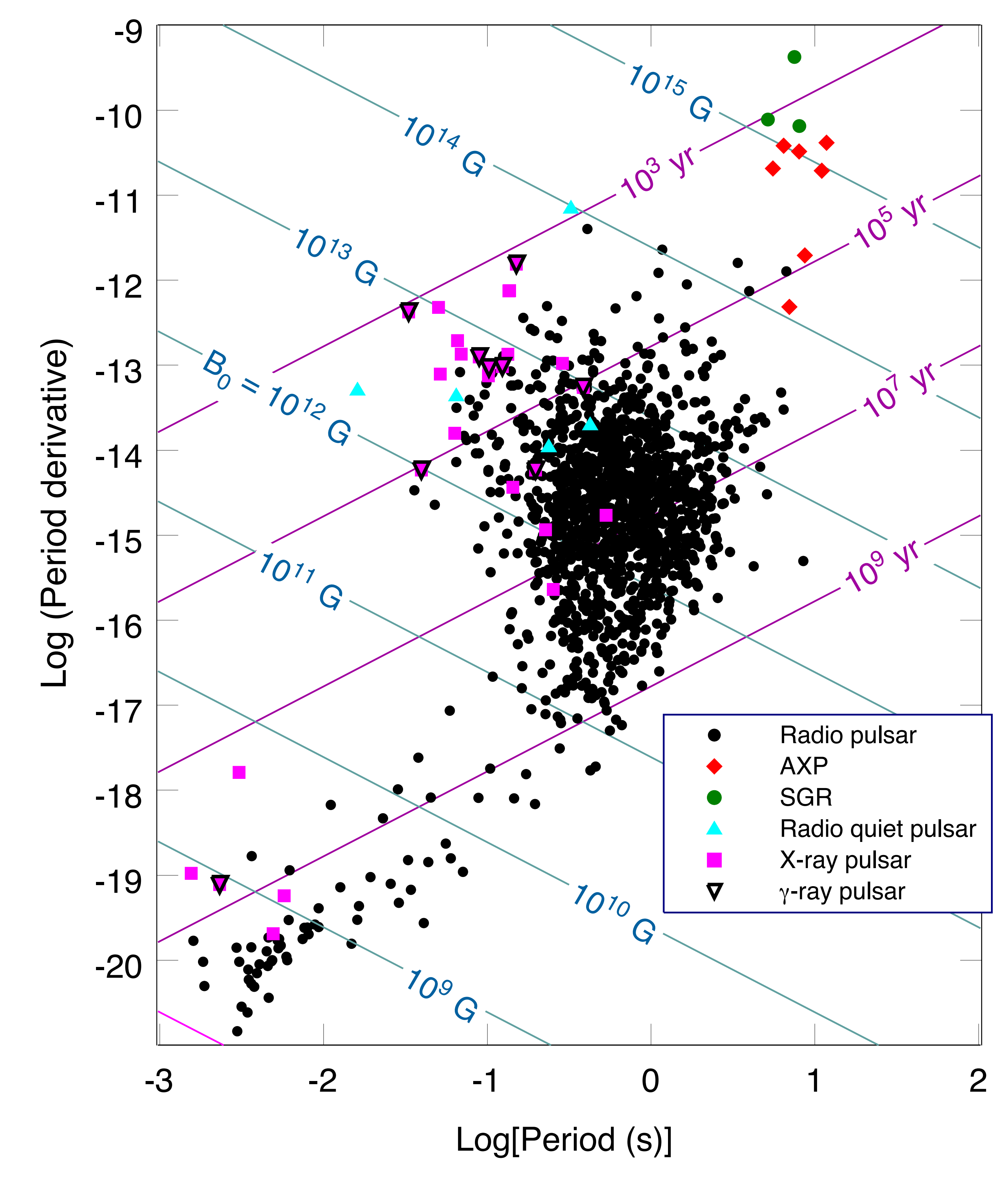


- Liebert & Sion (1979) and Fabrika & Valyavin (1999) reported a higher incidence of magnetism in cool WDs than hot WDs

- CDF containing a much larger sample of WDs has a smooth gradient suggesting that birthrate of MWDs has not significantly changed over the age of the Galactic disk.

Ferrario et al., 2015, Space Science Reviews, 191, 111

Neutron stars



$$B \propto \sqrt{P\dot{P}}$$

$$t \propto \frac{P}{2\dot{P}}$$

- P = Rotational period
- $\dot{P}$ = Spin-down rate
- Magnetic field reduces with age

Harding & Lai, 2006, Reports on Progress in Physics, 69, 2631

Summary

Main Sequence

Low-mass stars

- Trends between magnetic field strength and flux consistent with the inverse of the Skumanich law
- Decrease in magnetic field strength with rotational period

Solar twins

- Significant decrease in <B> only from 100-250 Myr
- Small sample

Intermediate mass stars

- Stars with $M > 3M_\odot$ fields decline substantially over an age ~1.5-4 x 10^7 yr
- Stars with $M = 2\text{-}3M_\odot$ fields decline over an age ~2.5 x 10^8 yr
- Magnetic flux declines in all stars ($M = 2\text{-}5M_\odot$) through the main sequence lifetime

Massive stars

- Instance of detected magnetic fields drops off rapidly for massive stars with fractional age greater than 0.6
- More significant for stars $M > 14\ M_\odot$
- Likely caused by a mass dependant field decay since flux conservation, suppression of core convection and binary rejuvenation do not explain this

Summary

Post MS and Late Stages

Post-MS FGK stars

- Most magnetic stars in the first dredge-up phase or core helium-burning phase, pointing to a magnetic strip of the most active post-main sequence FGK stars

Post-MS OBA stars

- Only 2 magnetic Post MS OBA stars found
- Evolution of magnetic field consistent with flux conservation
- Potential for dynamo to form in newly formed upper convective regions, however no observational evidence yet

White dwarfs

- No evidence of evolution of magnetic field with temperature, which is consistent with the long ohmic decay time

Neutron Stars

- The magnetic field reduces with the stellar age.

Thank You

Any Questions?