



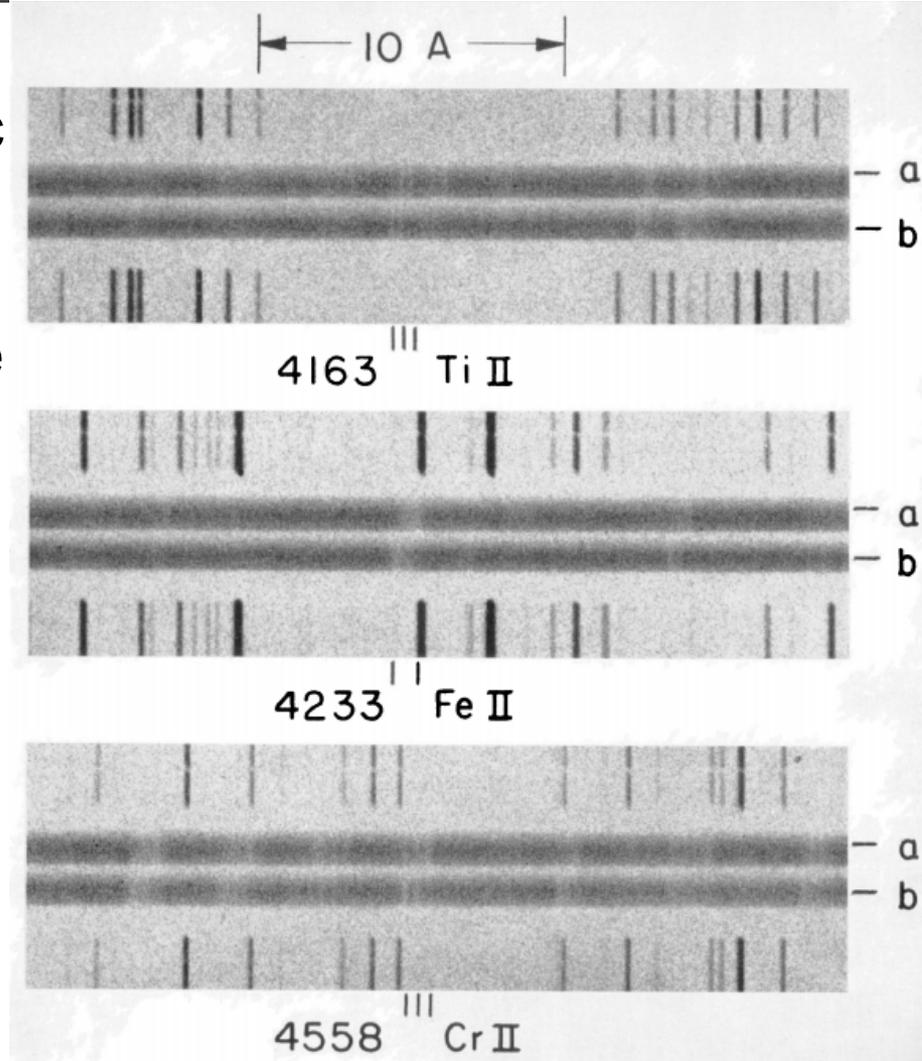
# The Magnetic Stars

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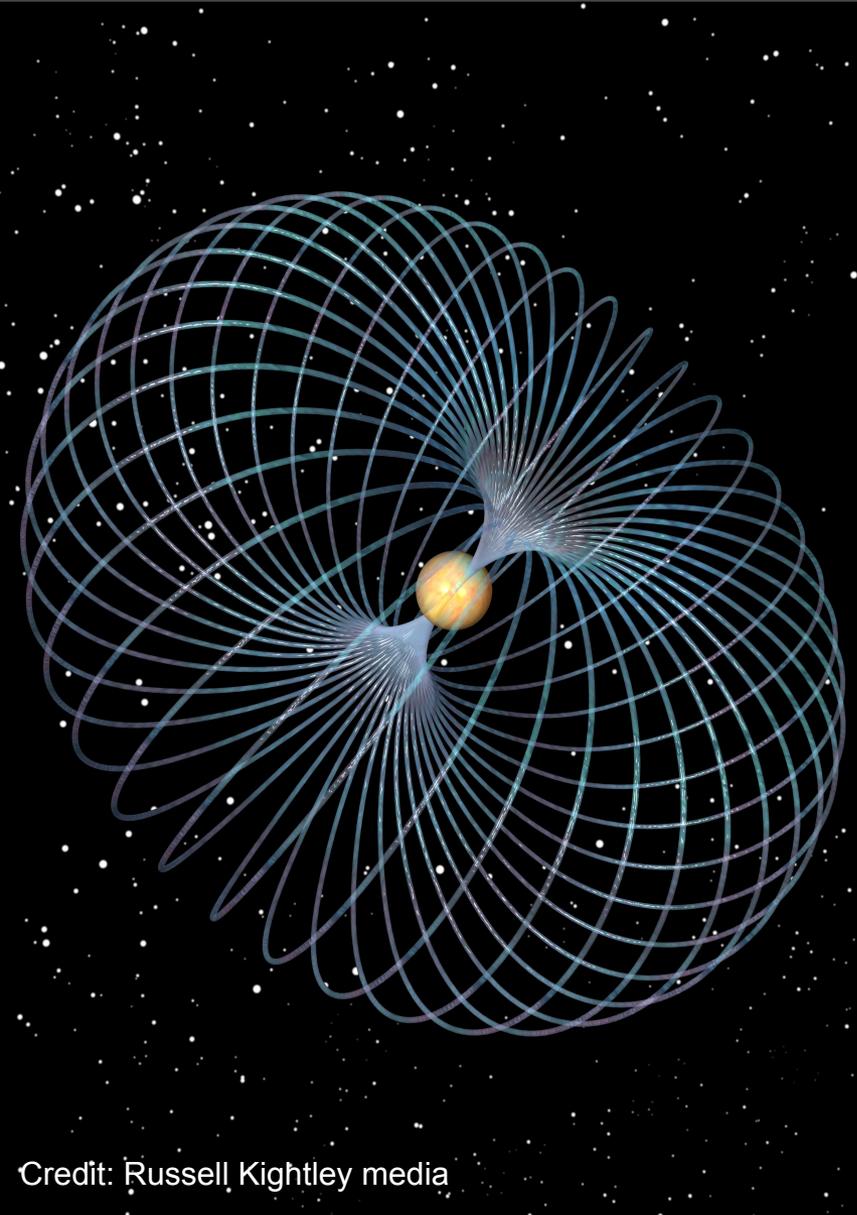
# Babcock's star

- The first detection of a magnetic field in a star, 78 Vir, was obtained by Babcock (1947).
- In 1960 Babcock discovered the most magnetic main sequence star known, HD 215441 ( $\sim 3.4 \times 10^4$  G). This became known as "Babcock's star".
- Now we know that about 5-10% of MS stars have fields in the range of  $\sim 300$ -30,000 G (Wade 2016, Hubrig et al. 2014; Bagnulo et al. 2012; Schöller et al. 2011; Aurière et al. 2007).



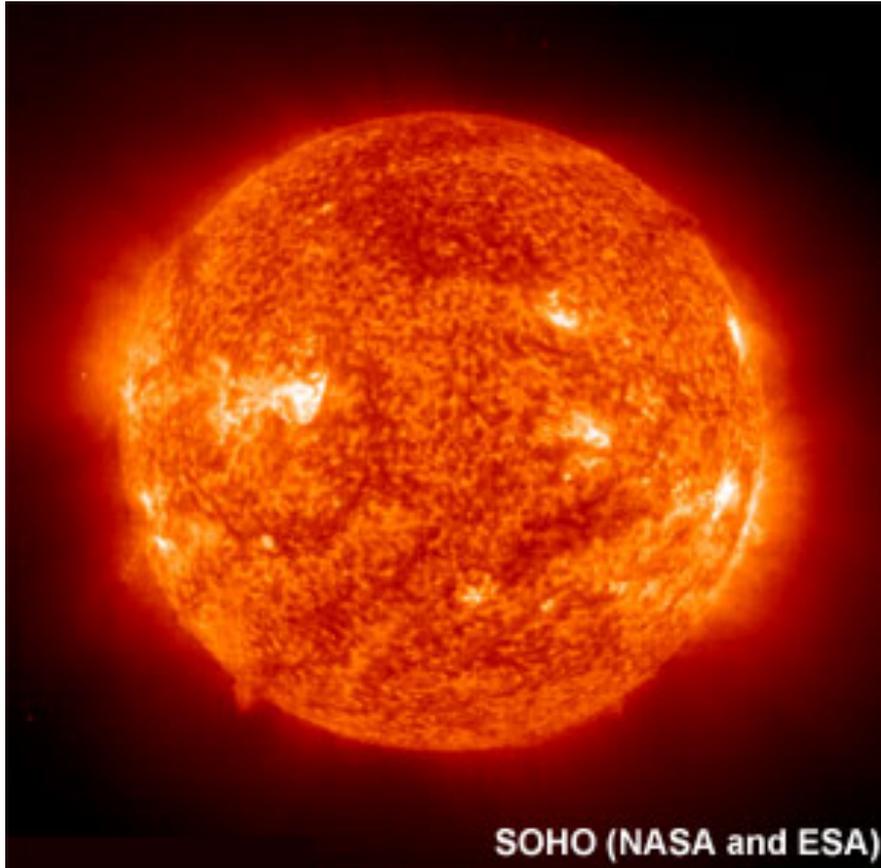
The spectra *a* and *b* were taken simultaneously through the left- and right-hand sections of a double circular analyzer.

# Magnetic fields in stars



In this talk I will summarise

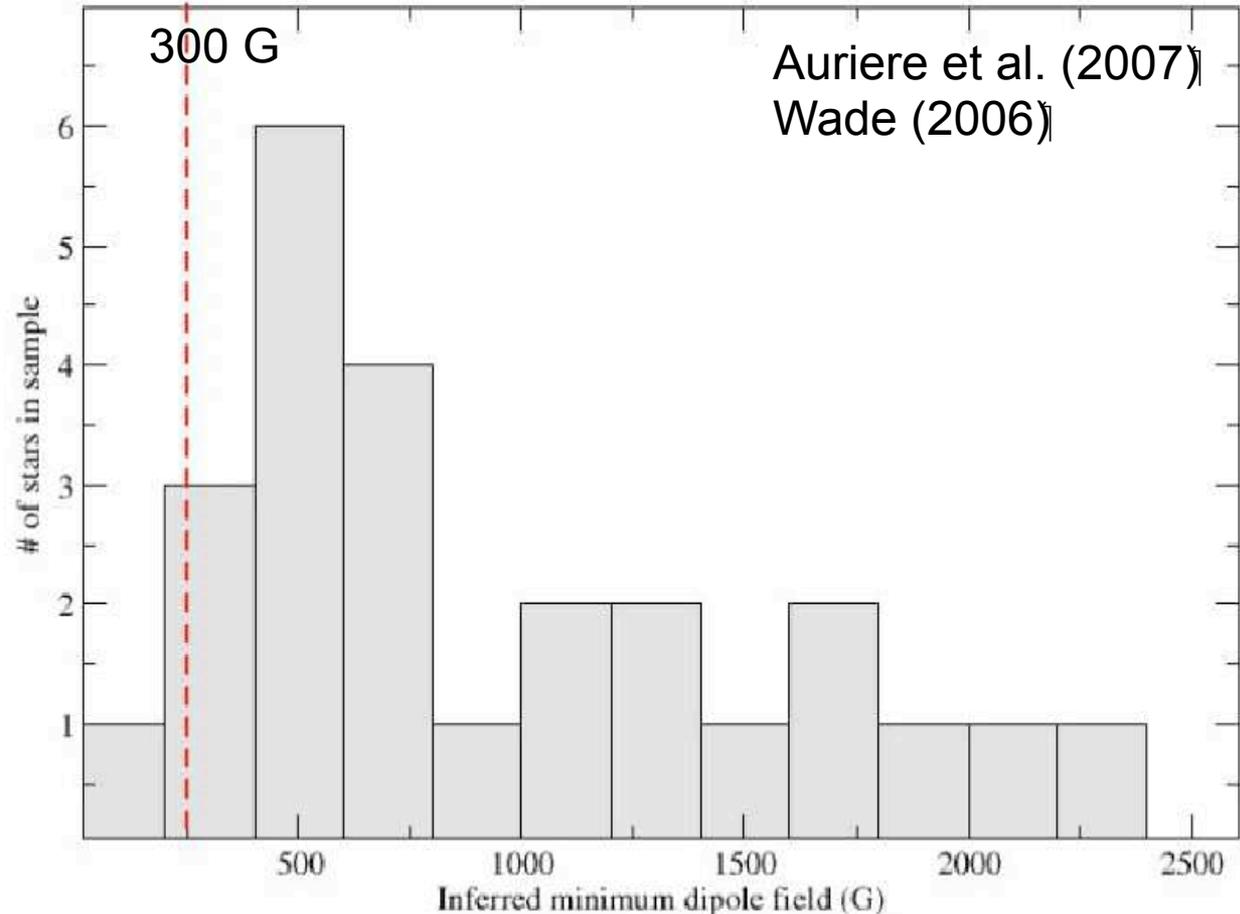
- What we know about magnetic fields in stars.
  - What the origin of stellar magnetic fields may be, and in particular:
    - Are stellar fields of fossil origin (magnetic flux is conserved from pre-Main Sequence to the compact star phase)?
- or
- Are fields dynamo generated during stellar evolution or perhaps via merging events?



## Magnetism on the Main Sequence

# Field Distribution of A/B stars

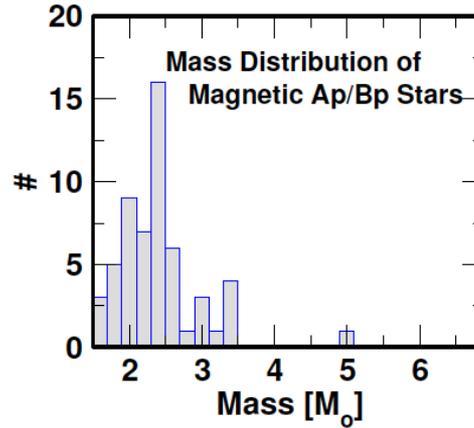
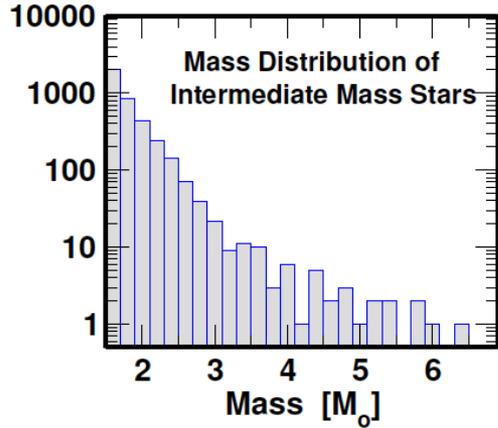
The highly sensitive survey of Auriere et al. (2007) has shown the existence of the following dichotomy: A and late B stars are either highly magnetic ( $>300$  G) with ordered dipolar fields or they are not magnetic at any detectable level (30 G).



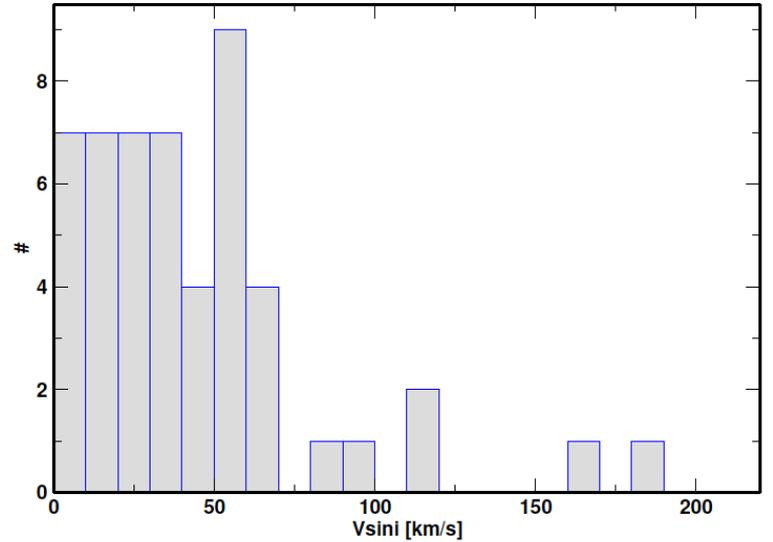
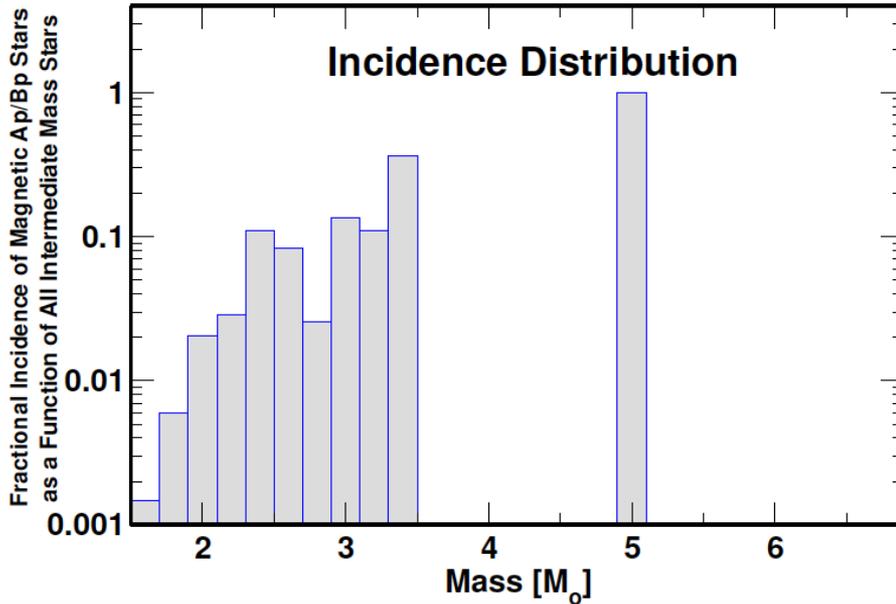
Absence of magnetic stars below the 300 G has been referred to as “the Ap/Bp magnetic desert”.



# Ap/Bp: 100pc volume limited sample



- ~10% of all stars of spectral type F0 and earlier are magnetic with large scale dipolar fields.
- Incidence of magnetism increases with mass. The least massive magnetic MS star has a mass of  $1.5M_{\odot}$ .
- 80% of stars have a rotational velocity slower than 60 km/s (non-magnetic A/B stars have typical velocities  $>100$  km/s).



Jennifer Power (MSc Thesis, 2007)  
(also James Sikora's talk)

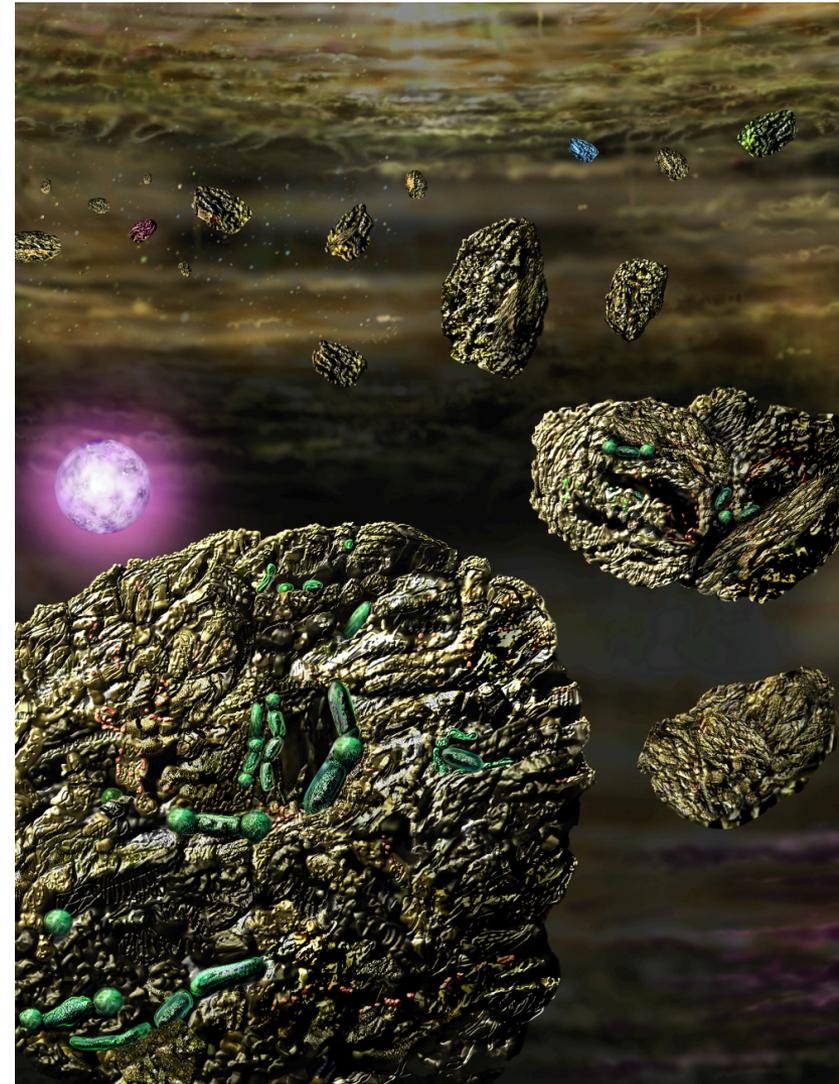


## Magnetism on the Pre-Main Sequence

Herbig-Haro 34 - Credit: FORS Team, 8.2-meter VLT, ESO

# Herbig AeBe (HAeBe) Stars

- HAeBe stars represent the late stages of the formation of intermediate-mass stars.
- They are pre-main sequence stars of  $2\text{--}15 M_{\odot}$  which are still embedded in their proto-stellar gas-dust envelope and exhibit emission lines of type A/B.
- Alecian et al. (2013) and Hubrig et al. (2013) conducted large spectro-polarimetric surveys of HAeBe stars to investigate magnetism and rotation in HAeBe stars and link their properties to the MS Ap/Bp stars (fossil field hypothesis).

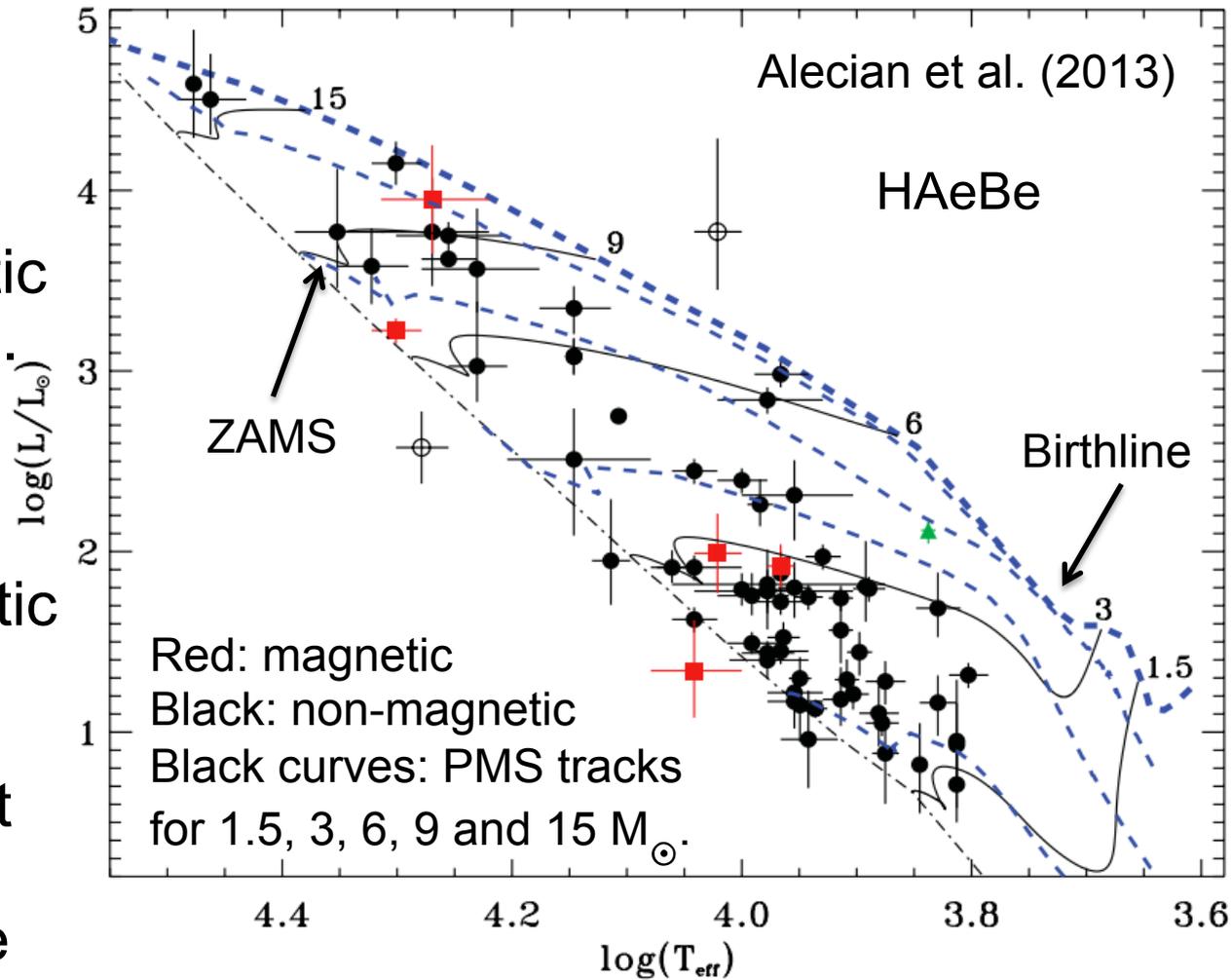


Credit: Russell Kightley media

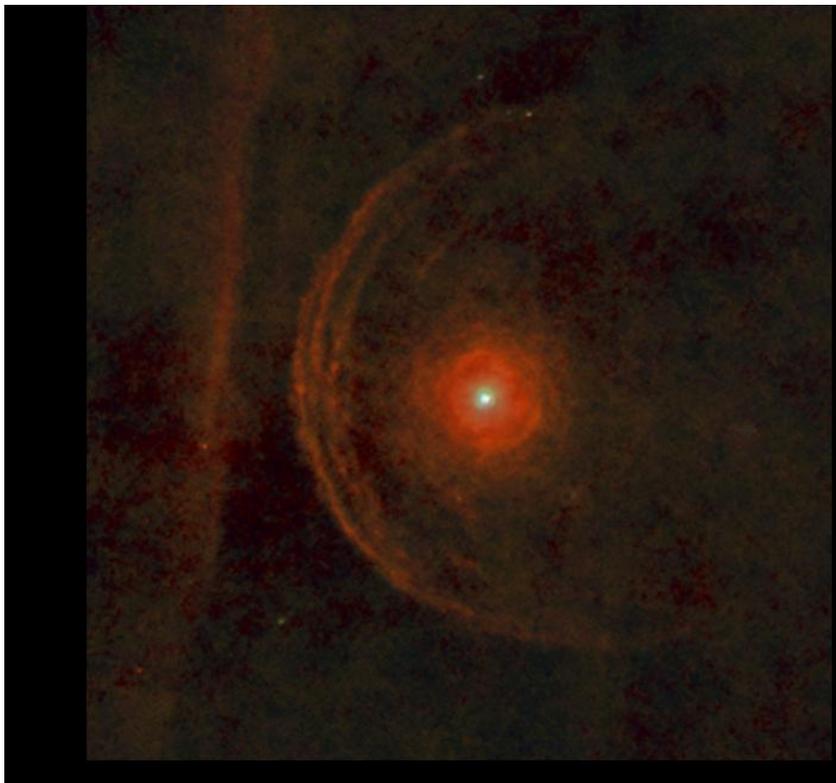
# Herbig AeBe (HAeBe) Stars

## Results:

- Large scale fields observed in magnetic field in HAeBe stars.
- Incidence of magnetism: 7%, in agreement with incidence of magnetic Ap/Bp stars.
- Magnetic flux in HAeBe is consistent with Ap/Bp stars.
- All magnetic HAeBe are slow rotators.



**These findings strongly support the fossil field hypothesis.**

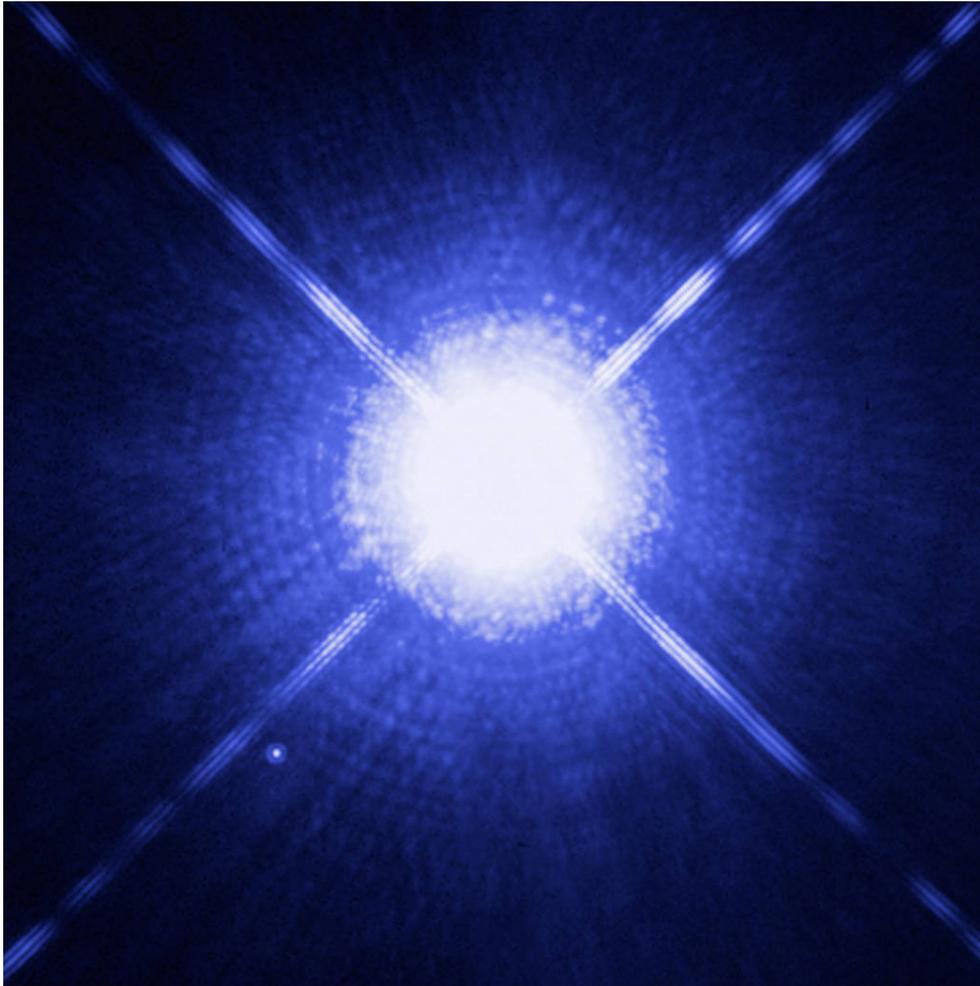


## Magnetism on the Post-Main Sequence

Betelgeuse – Credit: ESA/Herschel/PACS/L. Decin et al

# Can fields survive the post-MS phase?

- Magnetic decay seems to occur on the MS (Bagnulo et al. 2006; Landstreet et al. 2007, 2008; Fossati et al. 2016).
- Nonetheless fields have been observed in some post-MS stars
  - EK Eridani, a red giant with  $\sim 0.37 M_{\odot}$  convective envelope, has a  $B \sim 270$  G large scale poloidal field, is *very* slowly rotating  $\rightarrow$  compatible with being the descendant of a strongly magnetic Ap star (Aurriere et al 2008).
  - The O9.5 young supergiant  $\zeta$  Ori Aa has a dipolar field of 140G (Bouret et al. 2008; Blazère et al. 2015).
  - Neiner et al. (2017) detected magnetic fields in 2 hot evolved stars:  $\iota$  Car (either on its first crossing of the HR diagram or on a blue loop) and HR3890 (crossing of the HR diagram), and confirmed the Fossati et al. (2015) field in  $\epsilon$  CMa (near the end of the MS). Their field strength (a few G) is compatible with magnetic flux conservation during stellar evolution.
- There are no stellar evolution calculations that include fossil fields. Thus, these observational results provide important constraints for the construction of future evolutionary models.



Sirius A and B - Credit: NASA, ESA, H. Bond (STScI) and M. Barstow (University of Leicester)

## White Dwarfs

- Woltjer (1960) first suggested the existence of magnetic white dwarfs with fields of  $\sim 10^7$  G – the descendants of MS magnetic Ap/Bp stars (under magnetic flux conservation).
- Grw+70° 8247: First MWD discovered. Strongly circularly polarised (Kemp, Swedlund, Landstreet & Angel 1970).
- Magnetic fields of isolated MWDs are observed to lie in the range  $10^3$ – $10^9$  G. The upper limit cutoff near  $10^9$  G may be real, the lower limit is more difficult to investigate. The incidence of magnetism below a few  $10^3$  G still needs to be established (Landstreet et al. 2012).
- The number of MWDs has increased to  $\sim 300$  isolated and  $\sim 170$  in binaries (Ferrario et al. 2015).
- More on MWDs in Stefano Bagnulo's talk on Thursday and Adéla Kawka's talk on Friday.

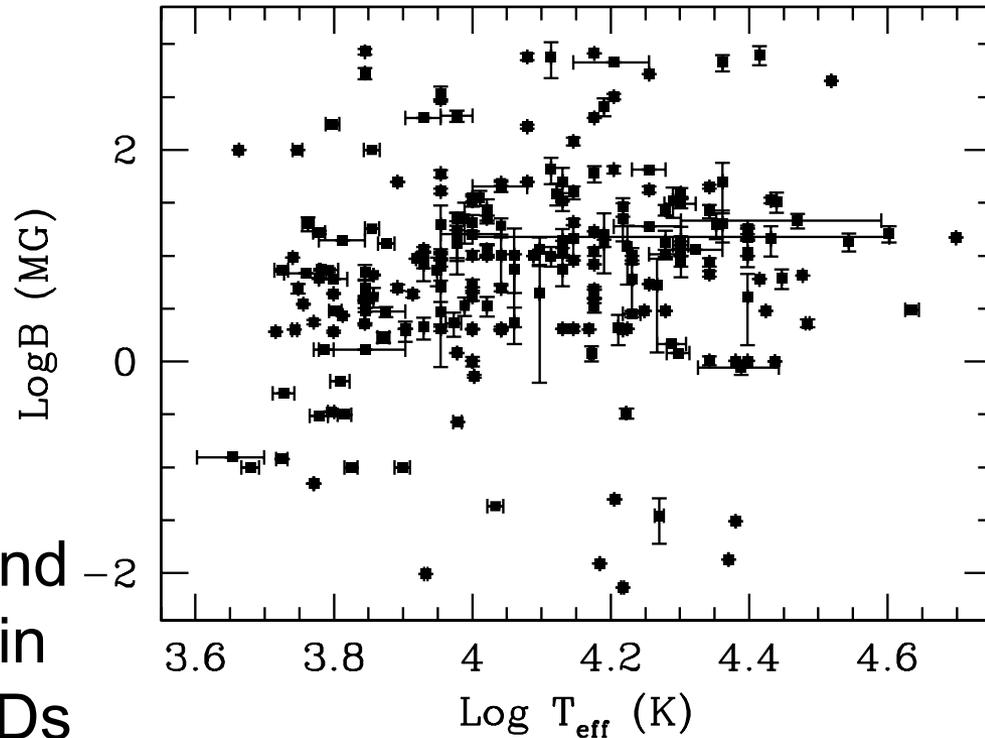
Free Ohmic decay time

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

L = length scale over which B changes

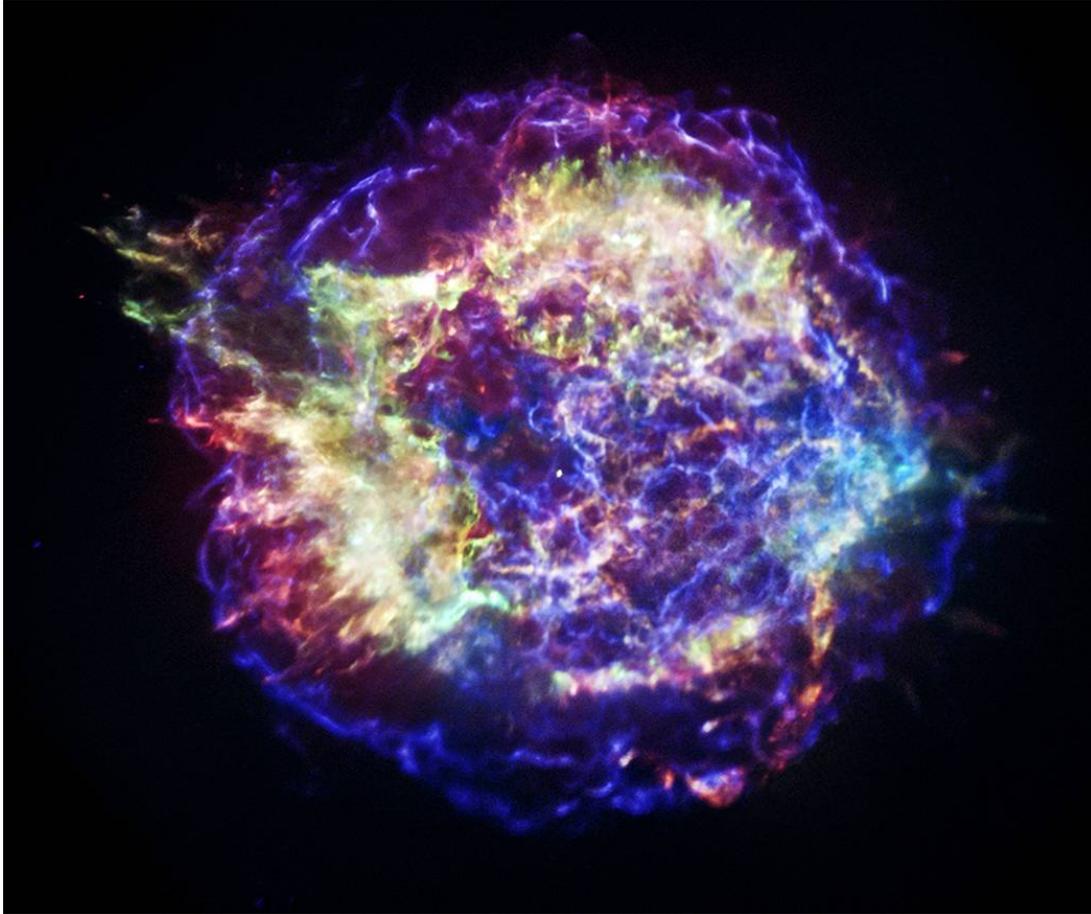
$\sigma$  = electrical conductivity.

Simplest estimates with  $L \approx R$  and  $\sigma$  equal to the values expected in the fully degenerate cores of WDs yield  $t_{ohm} \sim 2-6 \times 10^{11}$  yrs.



Ferrario, de Martino Gaensicke (2015)

Lack of evidence for the evolution of field strength with  $T_{eff}$  is consistent with these long decay time scales.



## Neutron stars

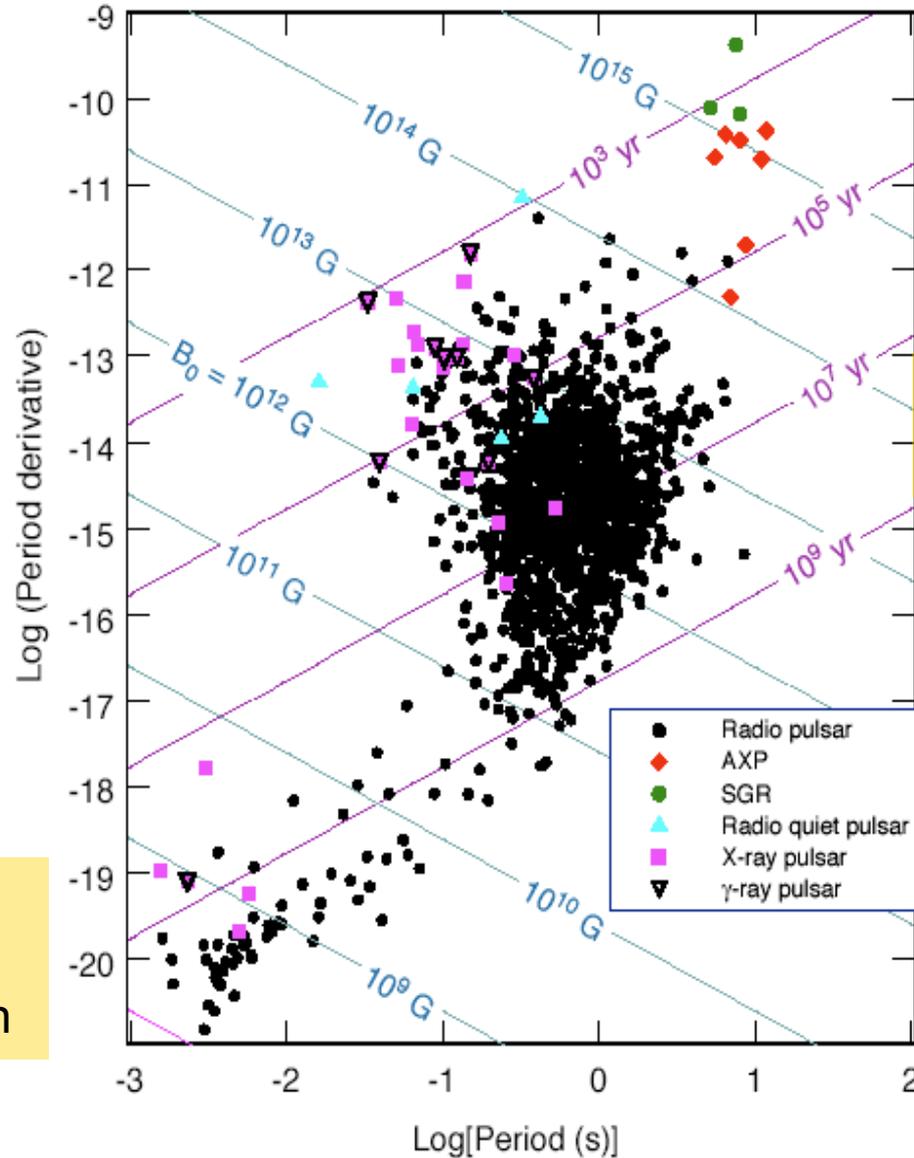
Cassiopeia A - Credit: NASA/CXC/SAO

# Fields in Neutron Stars

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

$$\tau = \frac{P}{2\dot{P}}$$

Millisecond  
(recycled)  
pulsars region



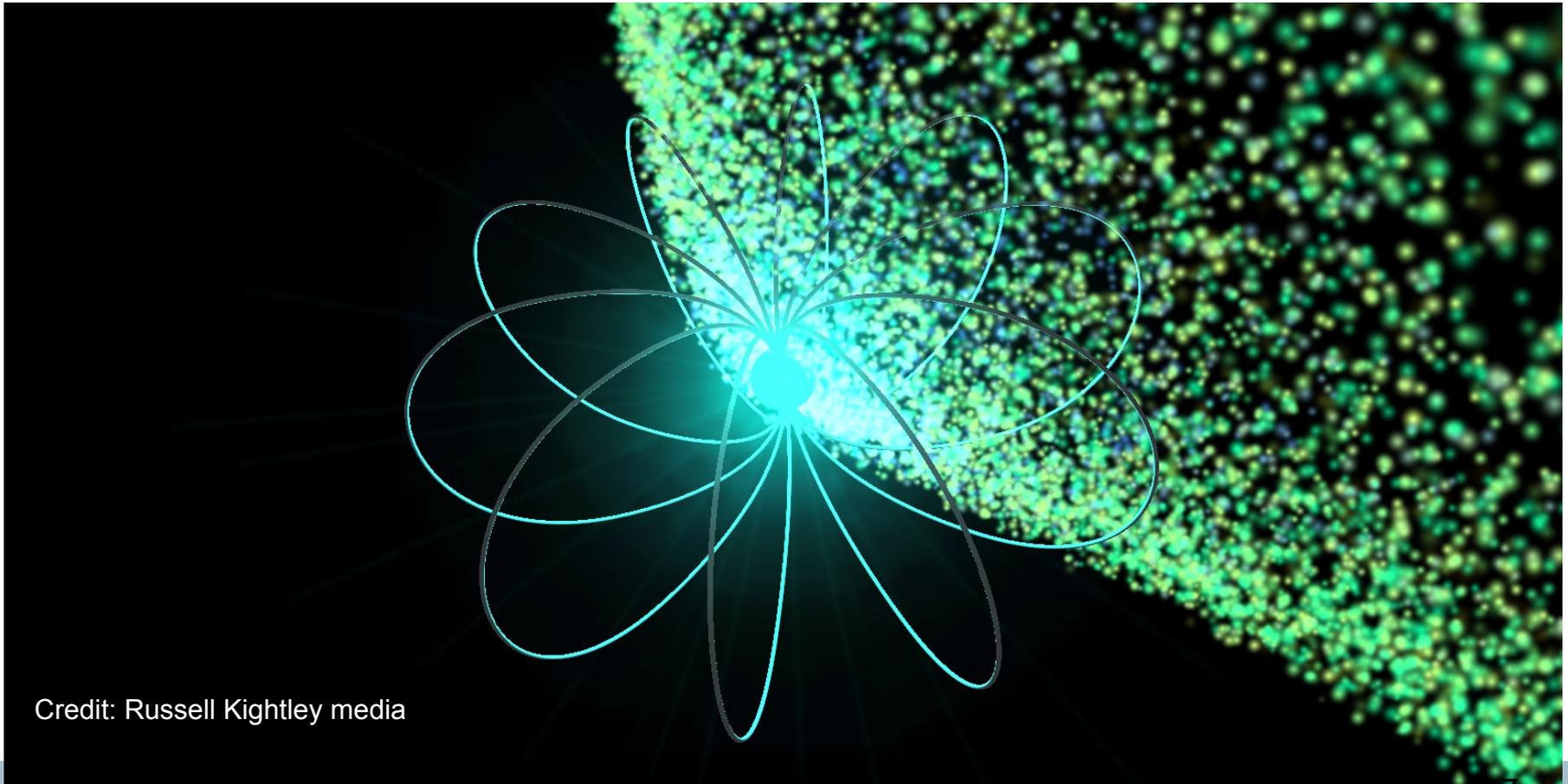
Magnetar (AXPs,  
SGRs) region

Radio-Pulsars  
region

Harding & Lai  
(2006)

# The Magnetars

The Anomalous X-ray Pulsars and the Soft Gamma Repeaters form a class of isolated and highly magnetic ( $>10^{13}\text{G}$ ) neutron stars called the “Magnetars”. Their (estimated) incidence among neutron stars is about 10% (see, e.g., Ferrario & Wickramasinghe 2006, 2008).

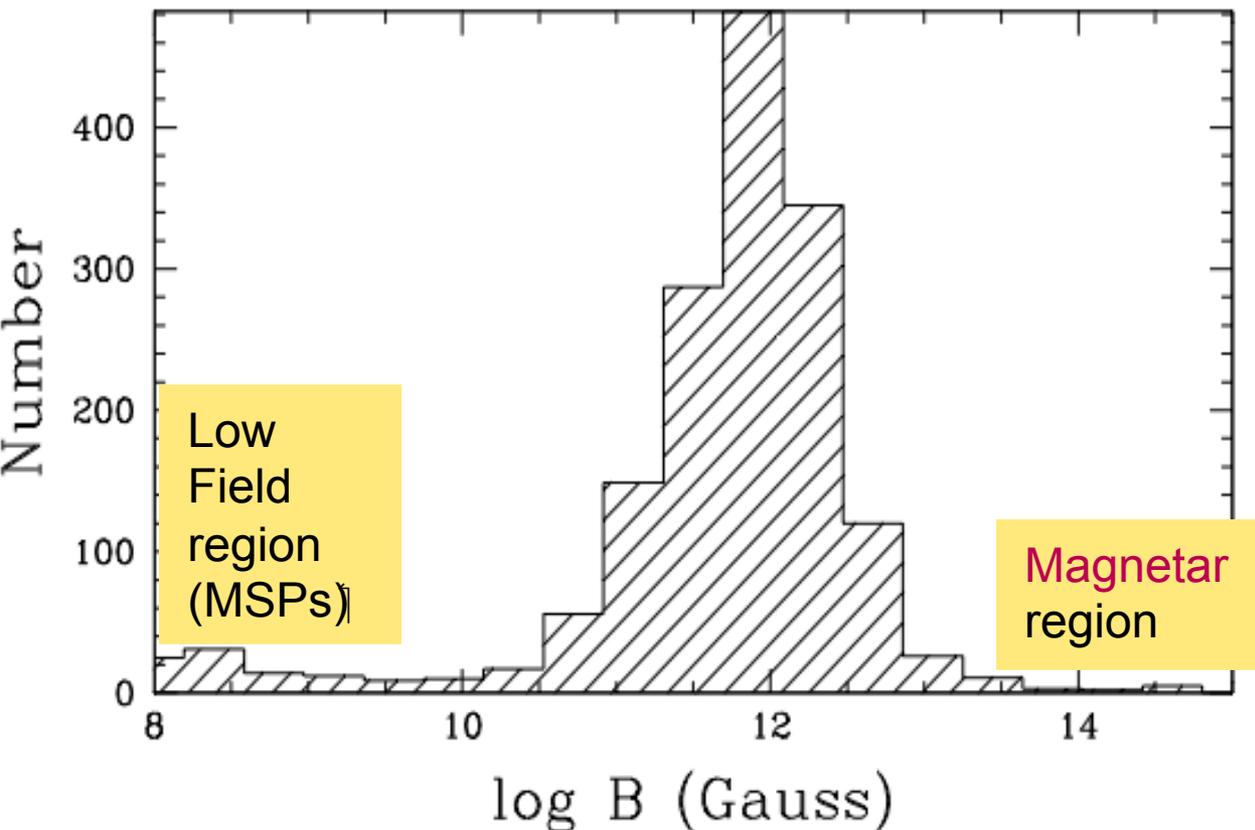


Credit: Russell Kightley media

# Properties of the Neutron Stars

**Magnetic Fields:**  $\sim 10^{11}$  - a few  $10^{13}$  G (Radio Pulsars)  
 $\sim$  a few  $10^{13}$  -  $10^{15}$  G (AXP/SGR Magnetars)  
 $\sim 10^8$  -  $10^9$  G (Millisecond Radio Pulsars)

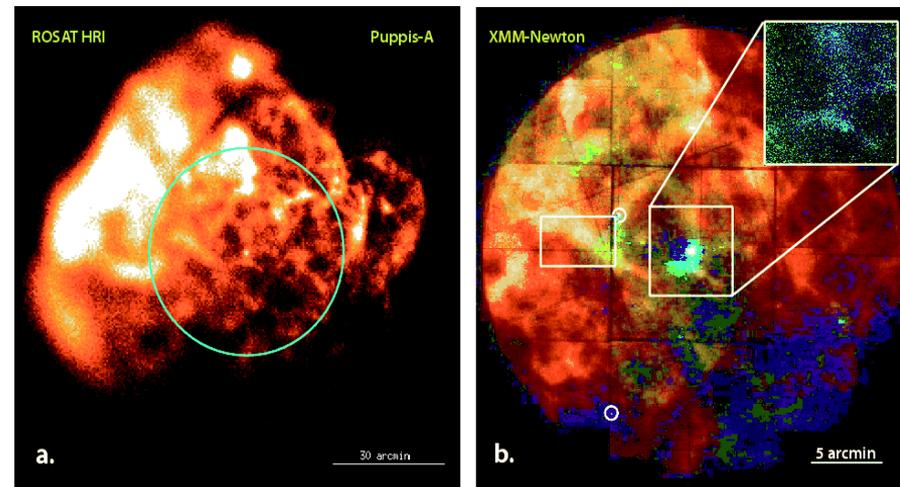
**Incidence of Magnetism:** 100% (probably!)



- **Mean Mass:**  $\sim 1.35M_{\odot}$
- **Rotation:** Milli-seconds to seconds. (*High Field Neutron Stars rotate more slowly*)
- Magnetars periods are in the range  $\sim 5$  - 11 sec, HFRPs  $\sim 3$ -5 sec; INs, RRATs  $\sim 3$  sec or longer

# Weakly Magnetic Neutron Stars

- Central Compact Objects (CCOs) are found in young SNRs ( $<10^4$  years).
- Characterised by: thermal X-ray emission (0.4 keV BB with dimensions of less than 1 km), absence of optical or radio emission, and lack of a pulsar wind nebula.
- Of the known SNRs within 5kpc, 14 harbour normal radio pulsars, 6 harbour CCOs and 1 an Anomalous X-ray Pulsar. Incidence: 30% (De Luca 2008).
- 6 confirmed CCOs: Cas A, PupA, Vela Junior, Kes79, PKS1209, G3473-05
- 3 CCOs have measured spin periods:  $\sim 100$ -400 ms
- No measurable period derivatives:  $B < 10^{11}$ .



■ PupA (Hui & Becker 2006)

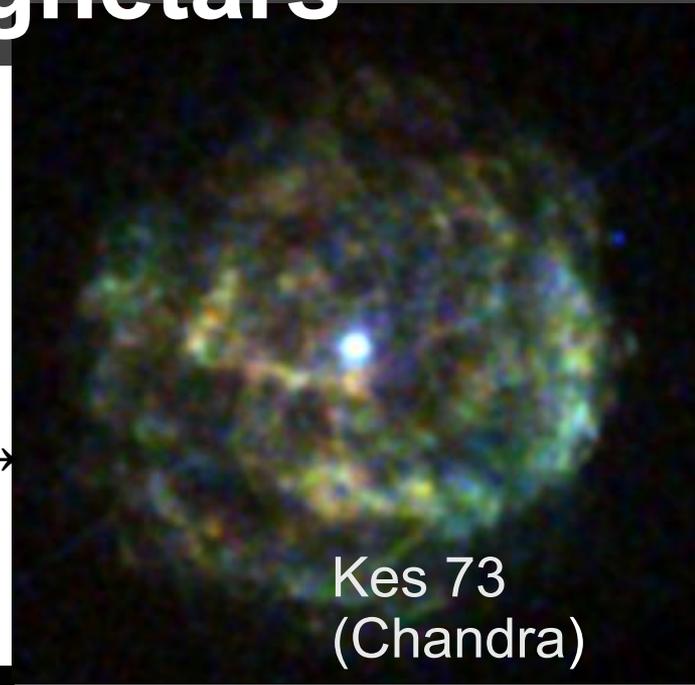
# Formation Scenario for NS

- Rapid rotation and differential motion in the proto-NS generates fields of (Duncan & Thompson 1992)
- Isolated radio-pulsars:  $B \sim 10^{12} \text{ G} \rightarrow P_i \sim 10 \text{ ms}$   
Magnetars:  $B \sim 10^{15} \text{ G} \rightarrow P_i < 3 \text{ ms}$
- Magnetars fields form in  $< 10 \text{ s}$  with spin-down time scale of  $\sim 10\text{-}100 \text{ sec}$ . With  $P \sim 1 \text{ ms}$ ,  $E_{\text{rot}} = I \Omega^2 / 2 \sim 3 \times 10^{52} \text{ erg}$  and magnetars should power **hypernovae** (T. Thompson et al. 2004). Vink & Kuiper (2006) have shown that SN remnants hosting magnetars are not more energetic than any other SN remnants.

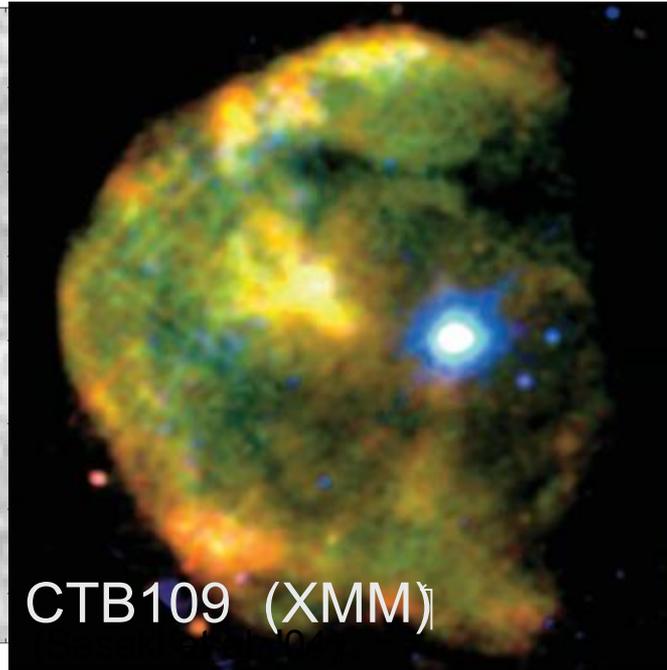
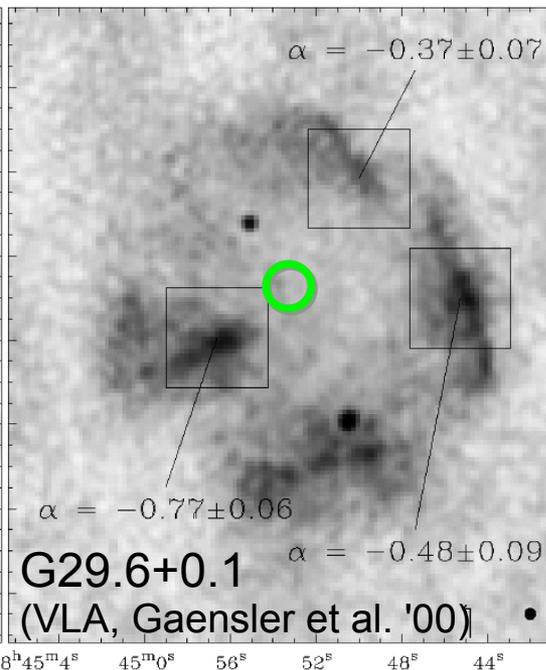
# SNRs and magnetars

- 1 SGR in SNRs: N49 (LMC)
- 3 AXPs associated with SNRs:
  - Kes 73 (~ 7 kpc), CTB109 (~3 kpc)
  - G29.6+0.1 (~3 kpc)

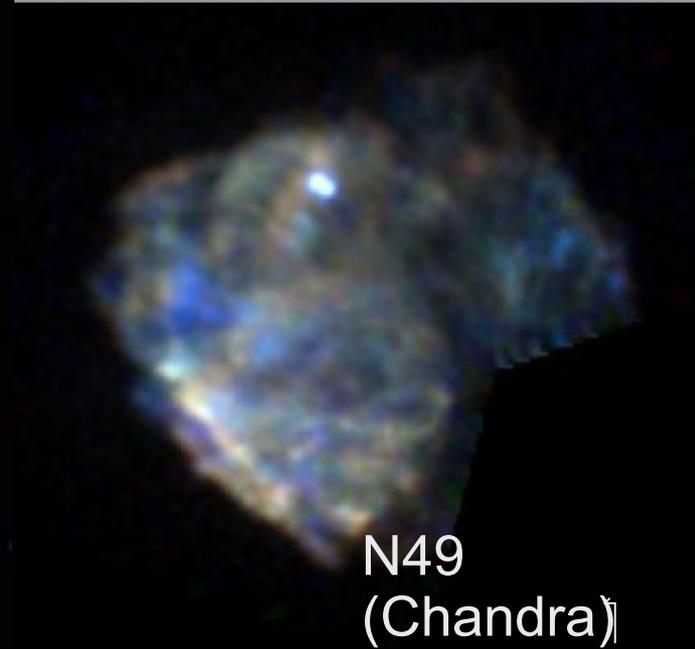
**Magnetars remnants are no more energetic than any other SN remnant → problem with dynamo-generated magnetar fields.**



Kes 73  
(Chandra)



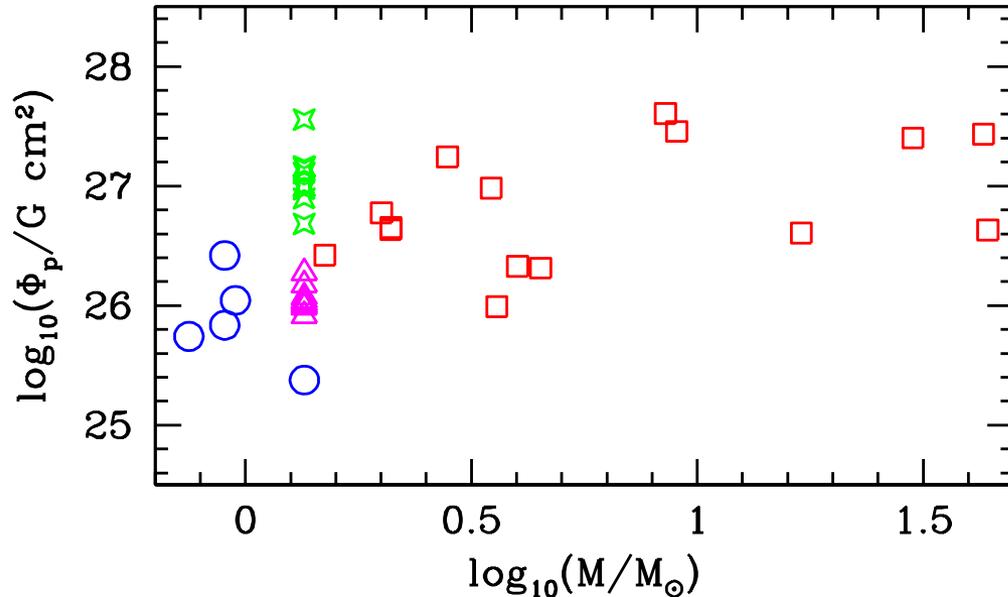
CTB109 (XMM)



N49  
(Chandra)

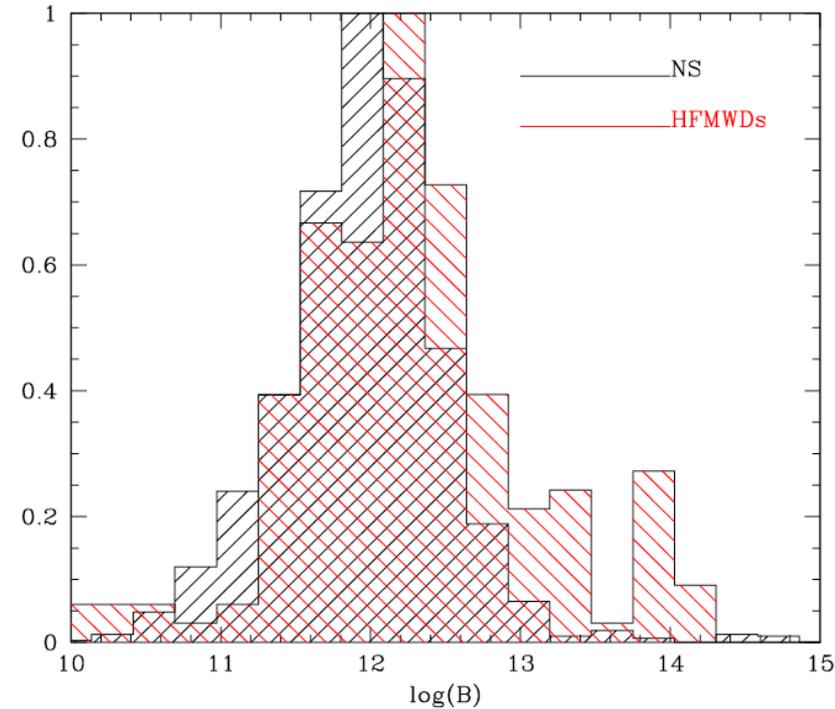
- Now I will talk about possible scenarios for the origin of magnetic fields in stars.
- I will start with the high field magnetic white dwarfs (HFMWDs).

# The most magnetic stars



The magnetic flux of the most magnetic MS stars (squares), MWDs (circles), high field radio pulsars (triangles) and magnetars (stars).

(“The most Magnetic Stars”,  
Wickramasinghe, Tout and Ferrario 2014)



Magnetic field distribution of the MWDs compared to that of the NS when the WD radii are shrunk to those typical of NS (Ferrario et al. 2010).

- Magnetic Fields present in the ISM become frozen into stars at formation.
- Magnetic flux is conserved as the star evolves.
- Ap/Bp stars are the progenitors of the High Field Magnetic White Dwarfs (HFMDWs, Wickramasinghe & Ferrario 2005).
- The Of?p Stars are the progenitors of the magnetars (Ferrario & Wickramasinghe 2006, 2008)

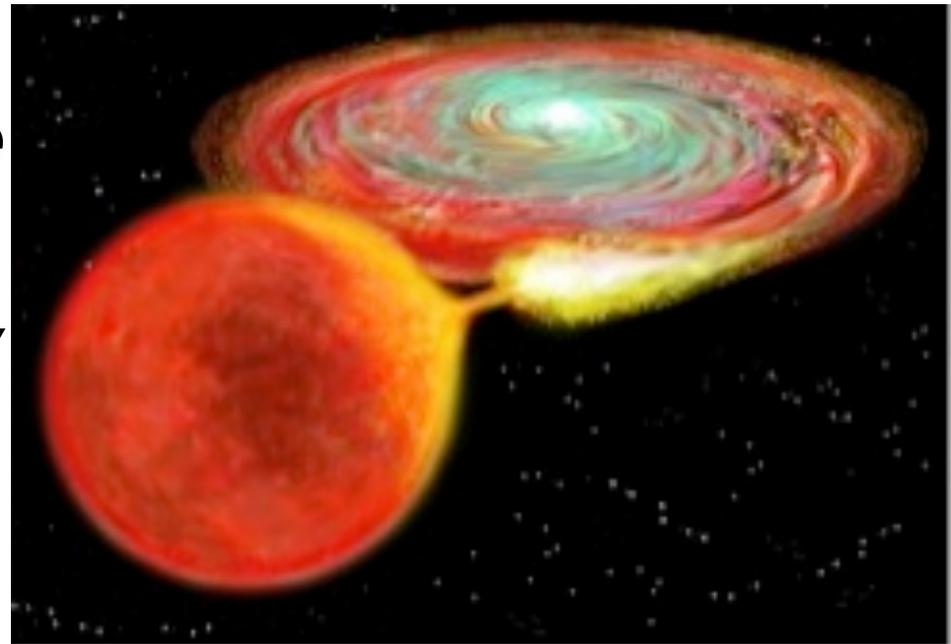
*Thus*

➤ *There should be the same fraction of HFMDWs in Binary Stars as in Single Stars.*

- Magnetic White Dwarfs ought to occur as often in *detached* binary stars as single stars.
- The Sloan Digital Sky Survey has identified thousands WD+M star detached spectroscopic binaries (e.g. Rebassa-Mansergas et al. 2012, 2013).
- None of these WDs has  $B >$  a few MG which could be seen by Zeeman Splitting.
- On the other hand, there are hundreds of isolated WDs known to have  $B >$  a few MG.

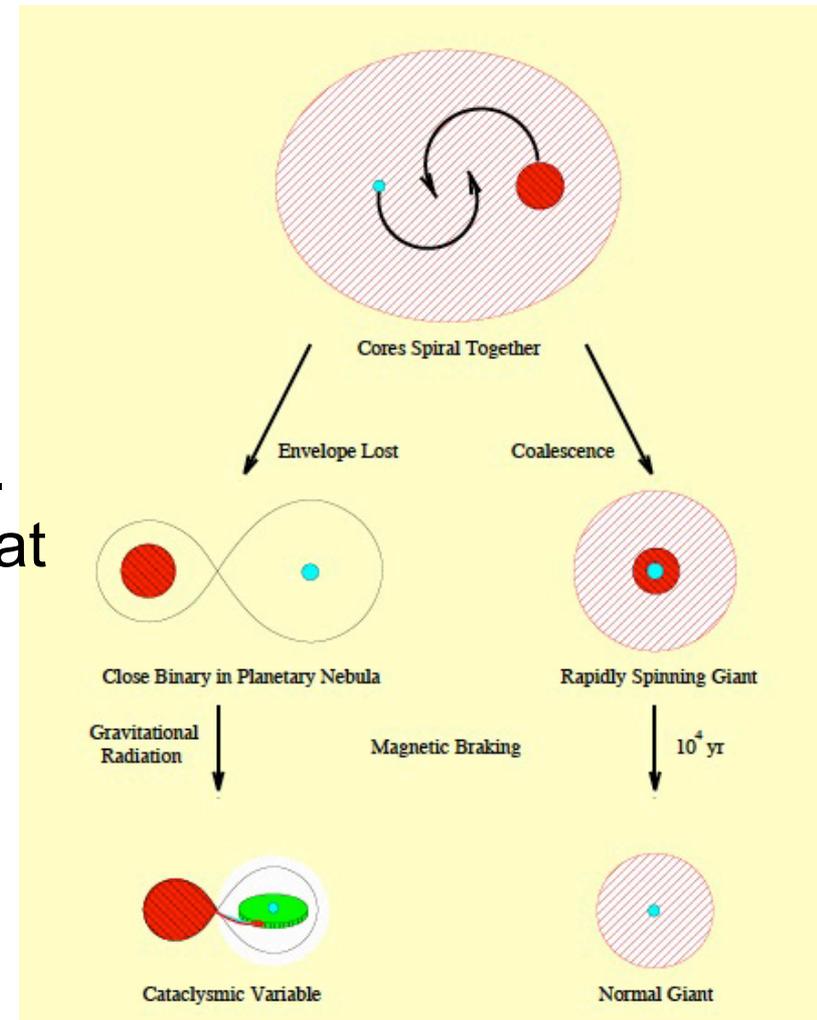
- The sample of WDs within 20 pc (Holberg et al. 2008) has shown that 19.6 (+/-4.5)% have MS companions.
- Thus, 14-24% of the ~300 MWDs (~40-70 WDs) should have such companions. There is none.
- The magnitude limited PG Survey has shown that 23-29% of hot WDs have cool companions.
- Thus, we expect 70–90 of the ~300 HFMWDs to have a companion.
- However, none has been found (Liebert et al. 2005, 2015)

*The origin of high magnetic fields in white dwarfs is intimately related to their duplicity (Tout et al. 2008).*



- Spiralling cores in CE create differential rotation.
- Dynamo generates field from differential rotation. The closer the cores get before the envelope is ejected the stronger the fields.
- Strongest fields when stars merge.
- Next strongest fields in systems that emerge from the CE about to transfer mass (MCVs).
- Systems that emerge widely separated do not have high fields. (Tout et al. 2008).

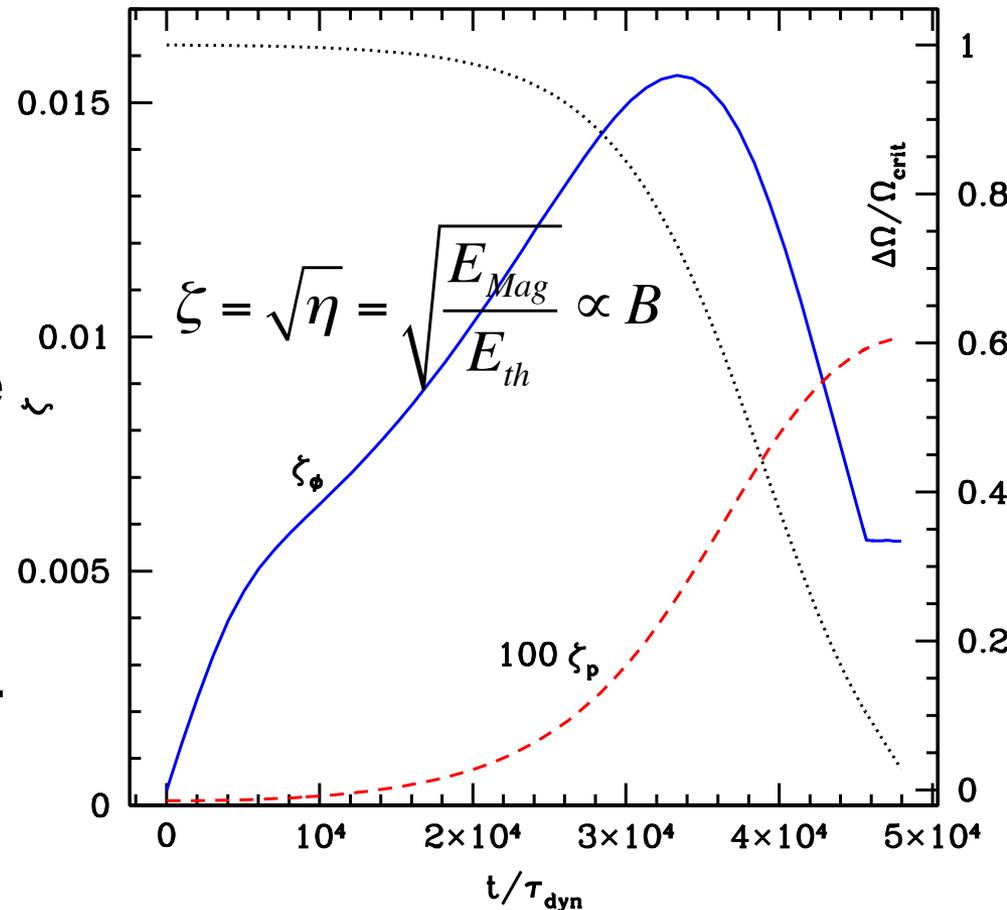
DD mergers would also give rise to HFMWDs.



Tout (2008)

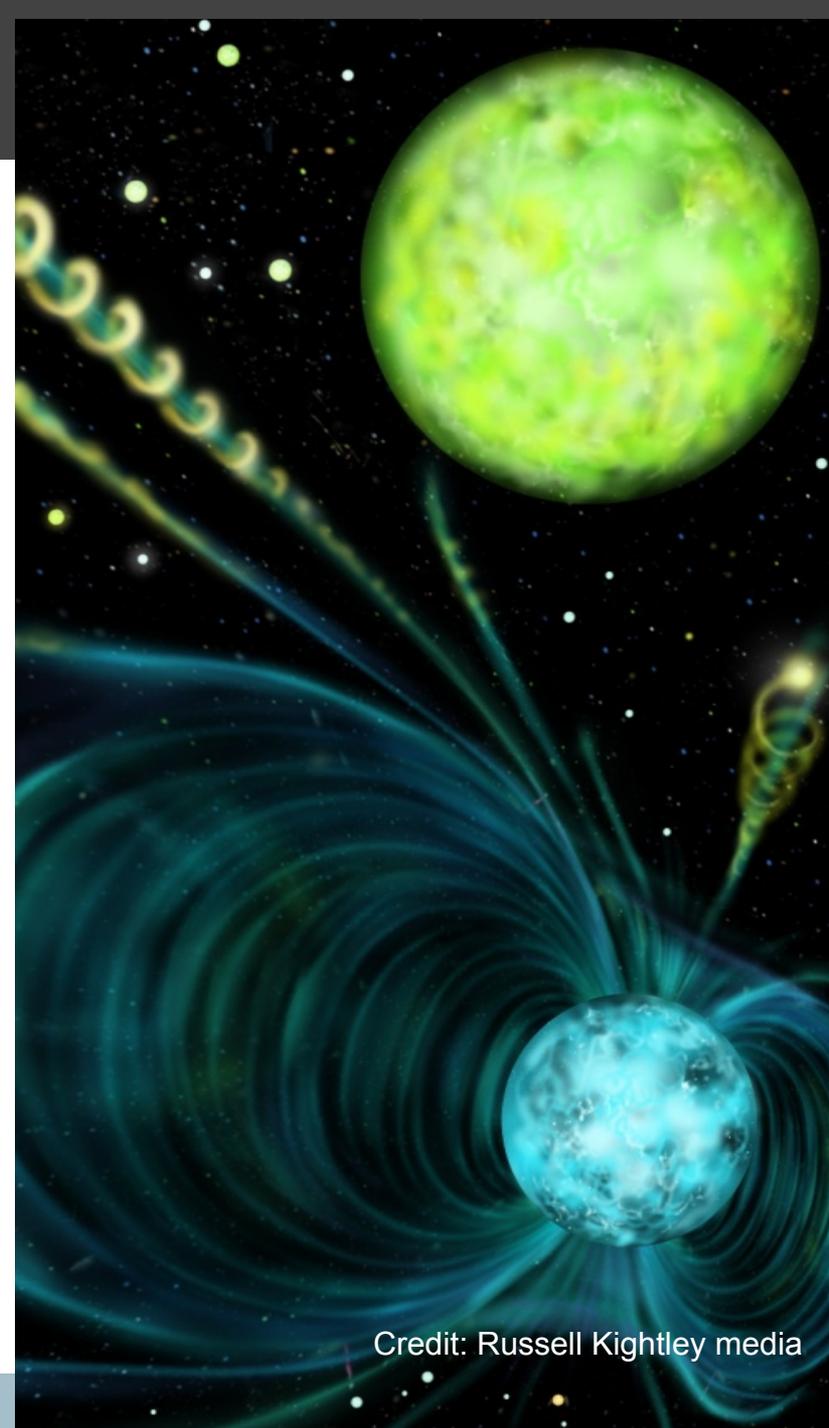
# Dynamo Evolution

- Dynamo generates  $B$  from differential rotation  $\Delta\Omega$
- $$0 \leq \Delta\Omega \leq \Omega_{crit} = \frac{1}{\tau_{dyn}} = \sqrt{\frac{GM}{R^3}}$$
- Toroidal and poloidal fields are unstable on their own (Braithwaite 2009). Poloidal stabilizes toroidal and viceversa, limiting field growth.
  - Poloidal and toroidal fields reach a stable configuration.
  - Final poloidal field is proportional to initial  $\Delta\Omega$ .



Wickramasinghe, Tout, Ferrario (2014)

- We know that some HFMWDs are the result of mergers.
- EUVE0317-855 is one of these objects (Ferrario et al. 1997, Vennes et al. 2003).
- DD mergers and CE mergers would explain the complete absence of main sequence (generally M-dwarf) companions to HFMWDs (incidence of such binaries among non-MWDs is  $\sim 25\%$ )



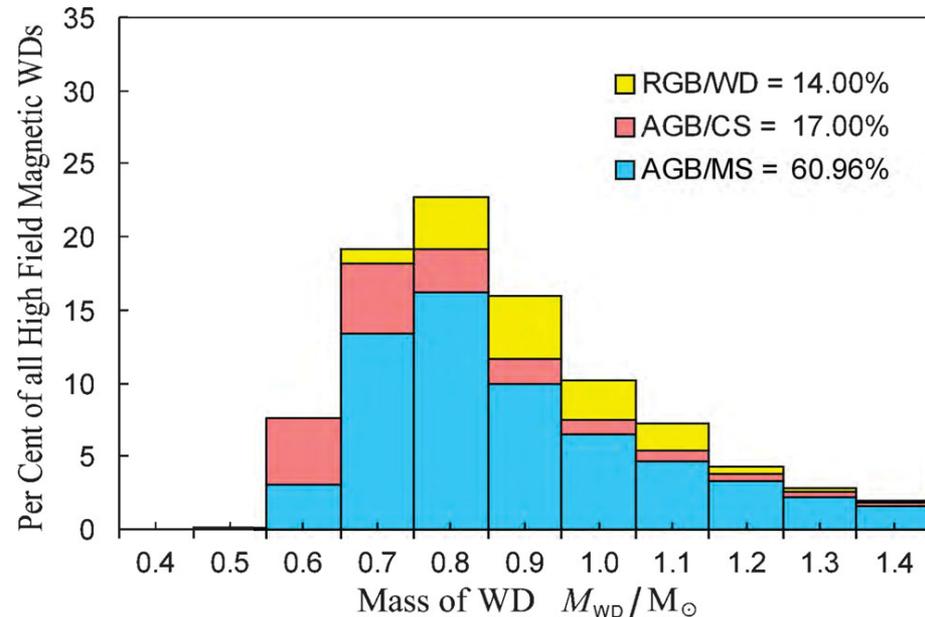
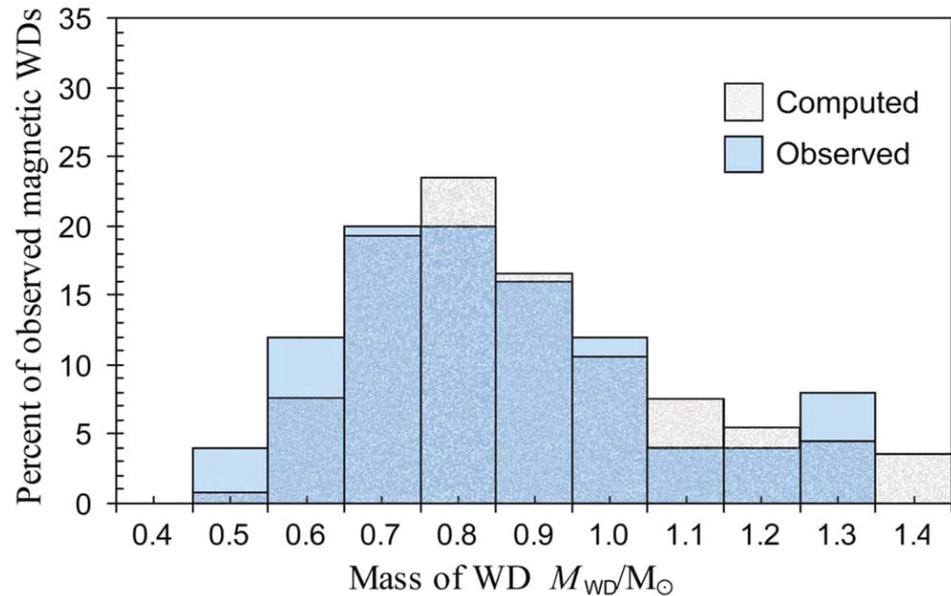
## Incidence of magnetism:

- PG sample: fraction of HFMWDs  $\sim 8\%$  (Liebert et al. 2003).
- Survey of WDs ( $<13\text{pc}$ ) by Kawka et al. (2007) shows that  $\sim 11.5\%$  are HFMWDs.

(Briggs et al. 2015)

<b>CE Efficiency Parameter <math>\alpha</math></b>	<b>Incidence of Magnetism</b>
0.1	19%
0.25	15%
0.3	14%
0.5	10%
0.7	8%
0.9	7%

- HFMWDs: mean mass  $\sim 0.78 M_{\odot}$  (c.f.  $\sim 0.66 M_{\odot}$  for non-Magnetic WDs, Tremblay et al. 2013).
- Best fit to incidence of magnetism and mass distribution requires  $\alpha < 0.3$



(Briggs et al. 2015)

- What can we say about magnetism in non-degenerate stars (pre-MS and MS)?

- Ferrario et al. (2009) proposed that the small fraction of magnetic MS stars can be explained if towards the end of the formation process (late Pre-MS) a small fraction of stars merge.
- Such late mergers would produce a brief period of strong differential rotation and give rise to the large-scale fields observed in the radiative envelopes of Ap, Bp, and Of?p stars.
- Such late mergers can also account for the lack of close binaries among MS magnetic stars.

# Magnetars

- Magnetar emission is powered by magnetic field decay.
- Magnetars differ from other neutron stars because of their ultra-strong fields and slow rotation.
- This magnetic field gives rise to very strong bursts of X-rays and gamma rays. Starquakes lead to extremely powerful gamma ray flares.
- The lifetime of a magnetar is only a few 10,000 years.
- The origin of these super-strong fields is uncertain.
- ***Could these objects, that are so different from normal pulsars, also be the result of mergers?***

- A 5-10% incidence of highly magnetic stars is observed at all evolutionary stages.
- Are these fields of fossil origin? Some observational results seem to support this hypothesis.
- **However**: No HFMWD paired with a non-degenerate companion has been found in a detached binary → HFMWDs could originate from systems that merge during the CE phase.
- A similar merging scenario could apply to magnetic pre-MS, explaining the dearth of short-period binaries among Ap/Bp stars. The BinaMlcS project (Alecian et al. 2014; Neiner & Alecian 2013) setup to investigate magnetism in close ( $P_{\text{orb}} < 20\text{d}$ ) binaries will shed some light on this issue.