The magnetic properties of Main Sequence Stars, White Dwarfs and Neutron Stars

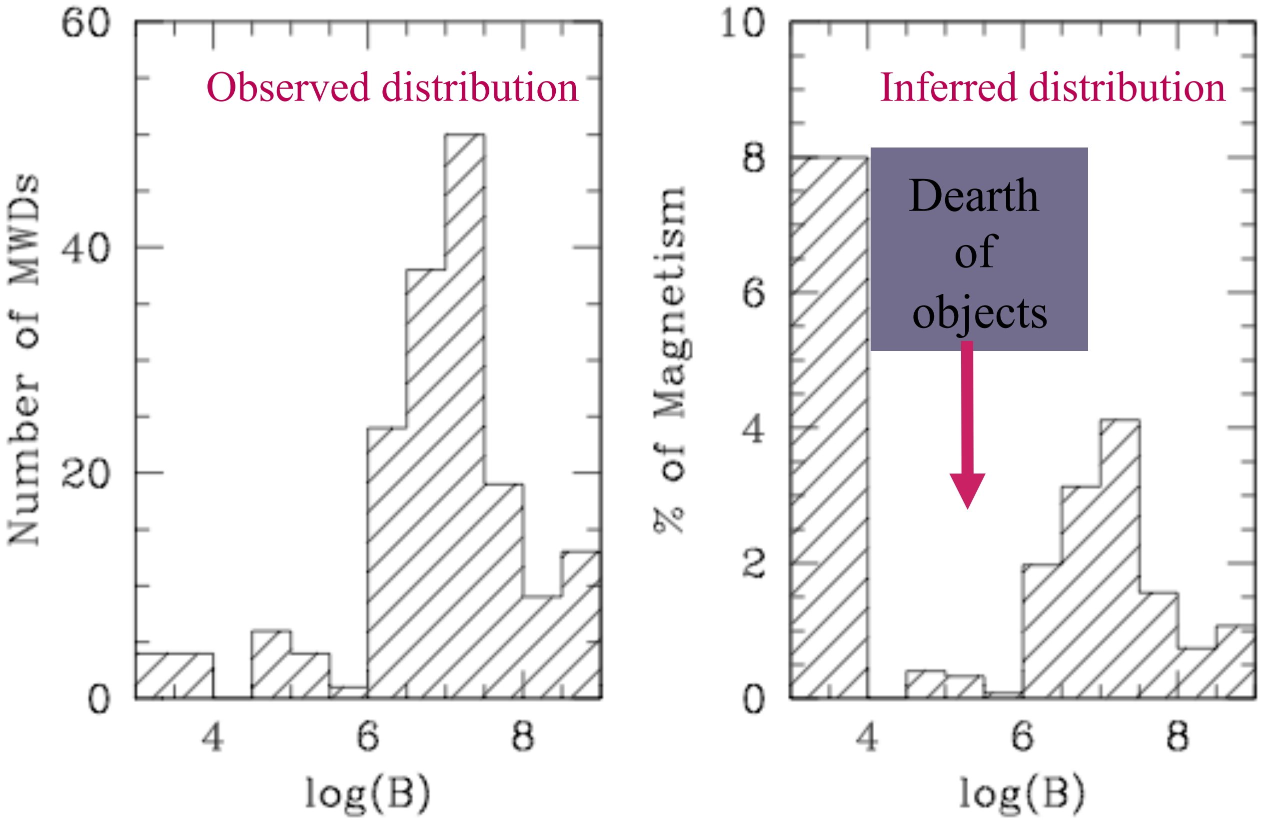
Lilia Ferrario

Mathematical Sciences Institute

Australian National University

Properties of MWDs

High Field MWDs ~ 10^6 - 10^9 G (~14% ,Liebert et al. `04)
Low Field MWDs ~ 10^3 - 10^5 G (~16%, Jordan et al. `06)
Spin of HFMWDs: ~ minutes - hundreds of years.



LFMWDs: 16% of of *apparently* non-magnetic WDs are weakly magnetic (10^3-10^4 G) Jordan et al. (2006). Incidence could approach ~100%

Magnetic Field Gap in MWDs

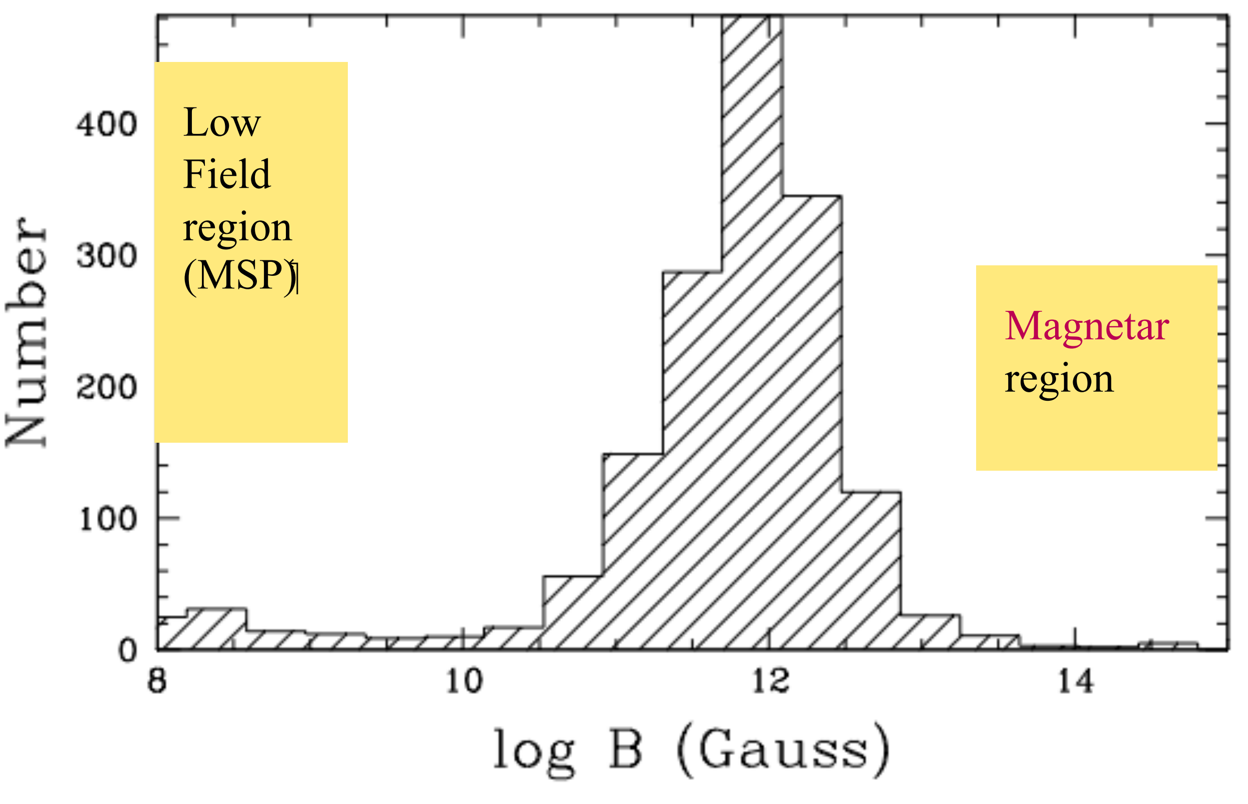
- Dearth of stars at B ~ 10^5 - 10^6 G is real.

- MWDs in this field range would have been discovered in the high-resolution Spy survey (Napiwotzki 2003).

- So far Spy has only yielded two or three new MWDs in this field range (Koester et al. 2001, 2005).

Properties of Neutron Stars

Data from ATNF Catalogue



- **Magnetic Fields:**

$\sim 10^{11}$ – a few 10^{13}G (RadioPulsars)

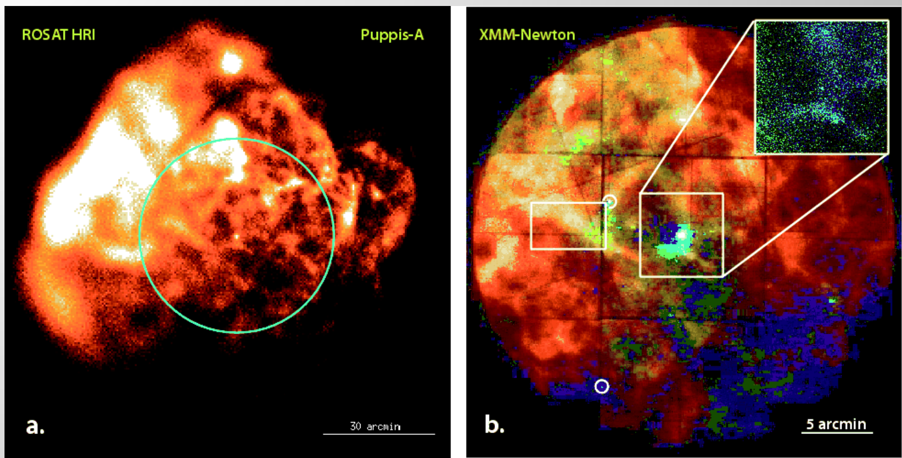
$\sim$ a few 10^{13} – 10^{15} G (Magnetars)

$\sim$

- **Incidence of Magnetism:** 100% (?)

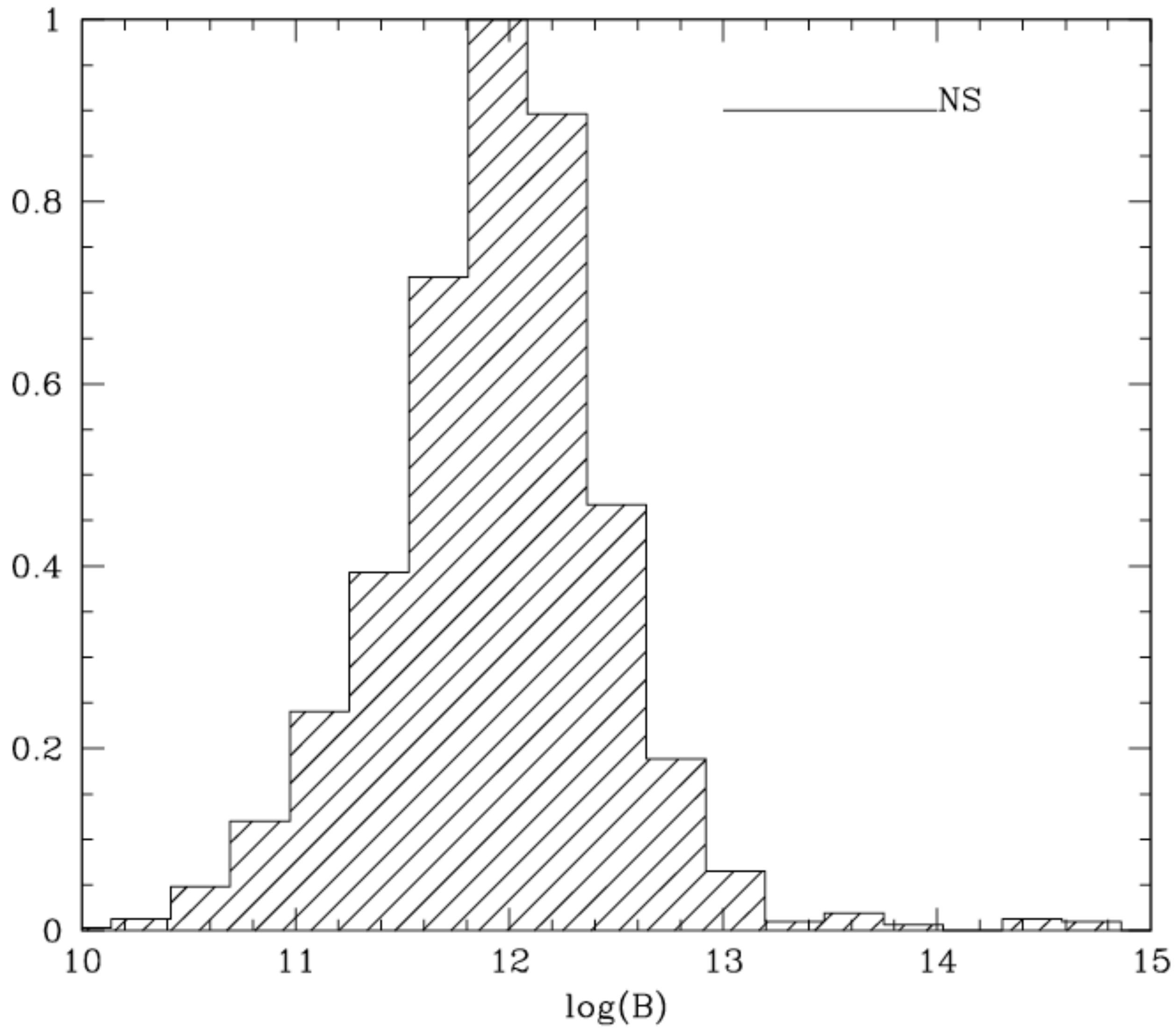
Evidence for weakly magnetic Neutron Stars: the CCO

- Central Compact Objects (CCOs) are found in young SNRs ($<10^4$ years).
- Characterised by:
  - •Thermal X-ray emission (0.4 keV BB, size< 1 km),
  - • Absence of optical or radio emission,
  - • Lack of a pulsar wind nebula.
- No measurable period derivatives implies $B<10^{11}$G.
- Incidence: 30% (De Luca 2008).

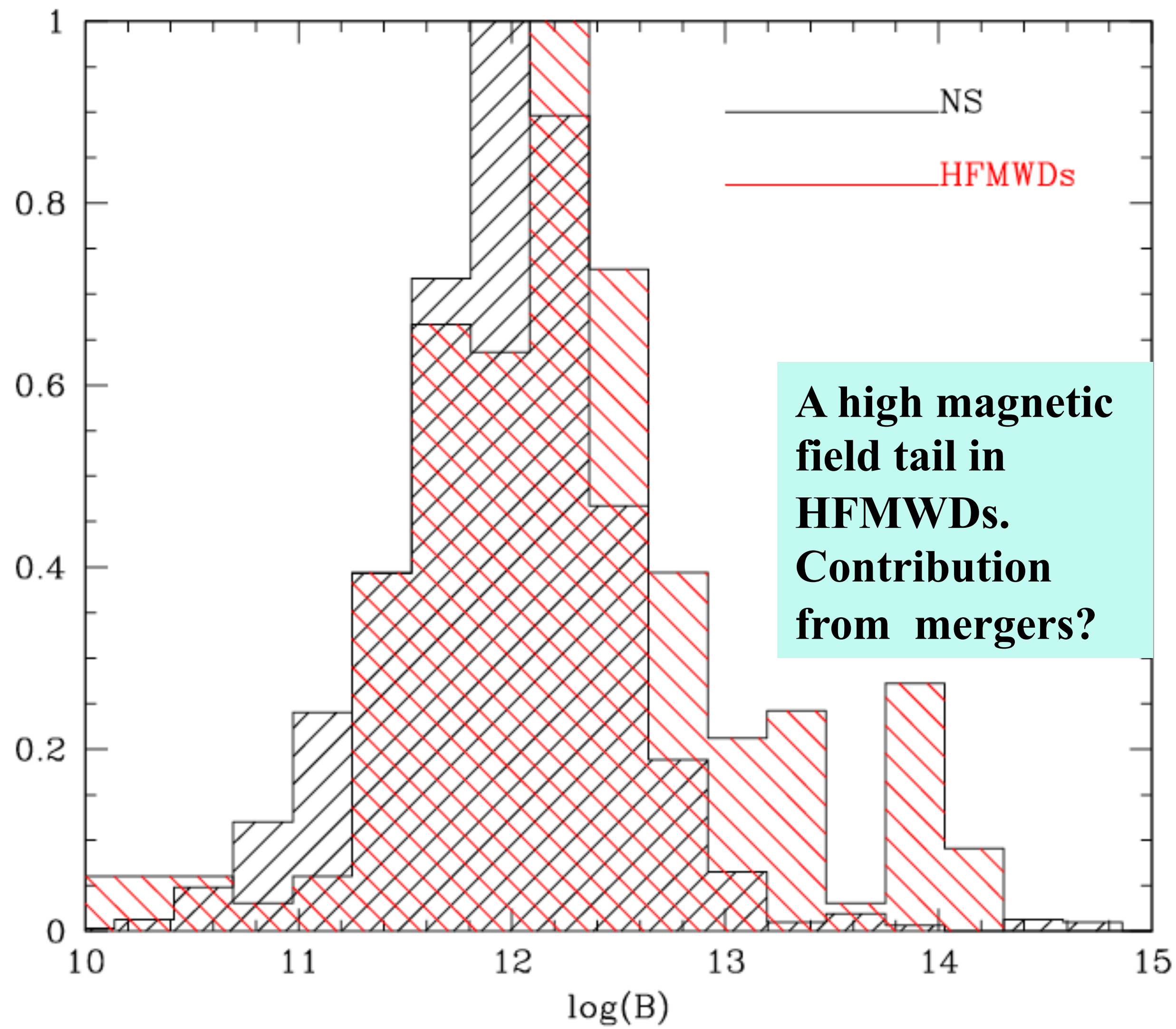


PupA (Hui & Becker 2006)

NS/HFMWDs: Field Comparison

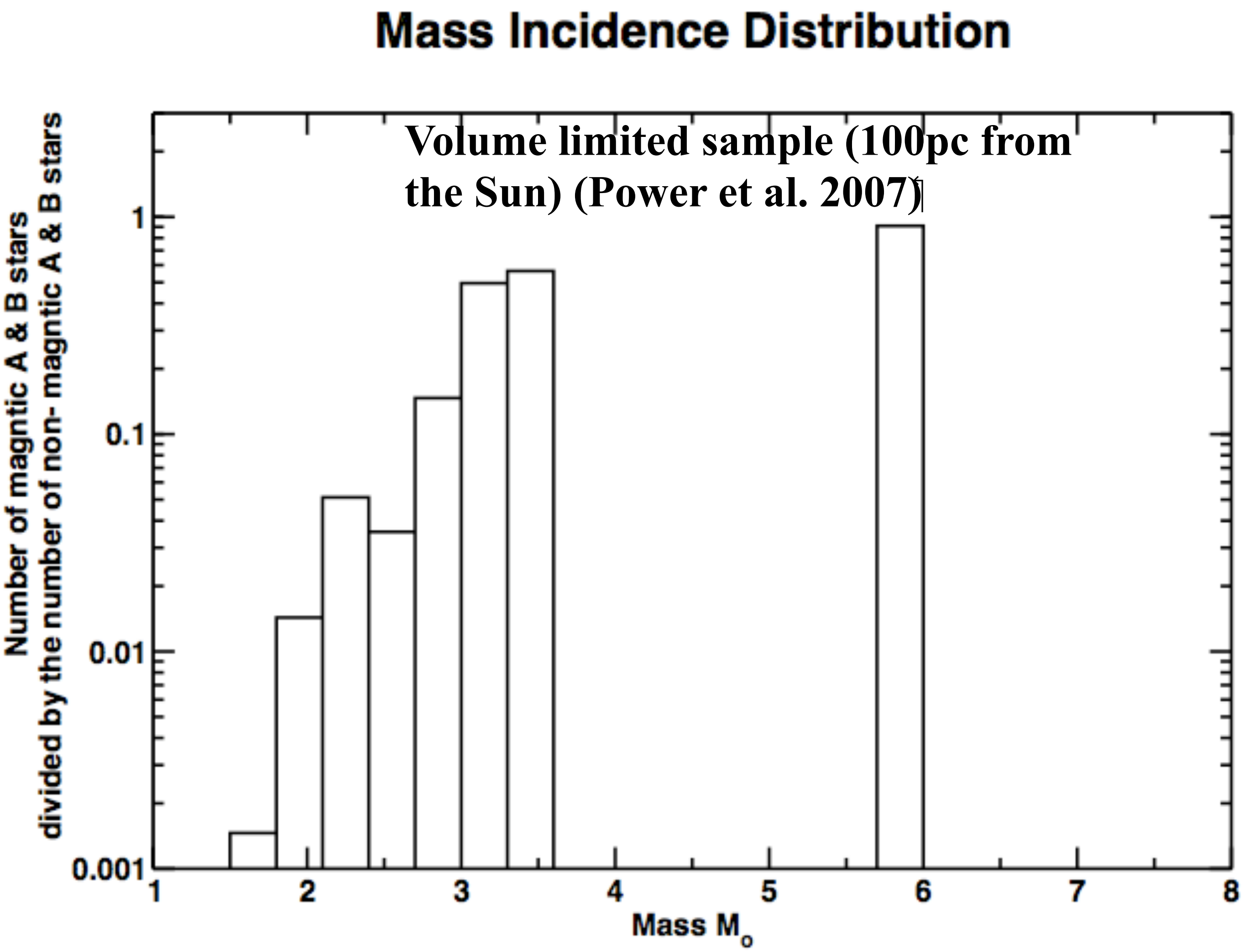


NS/HFMWDs: Field Comparison



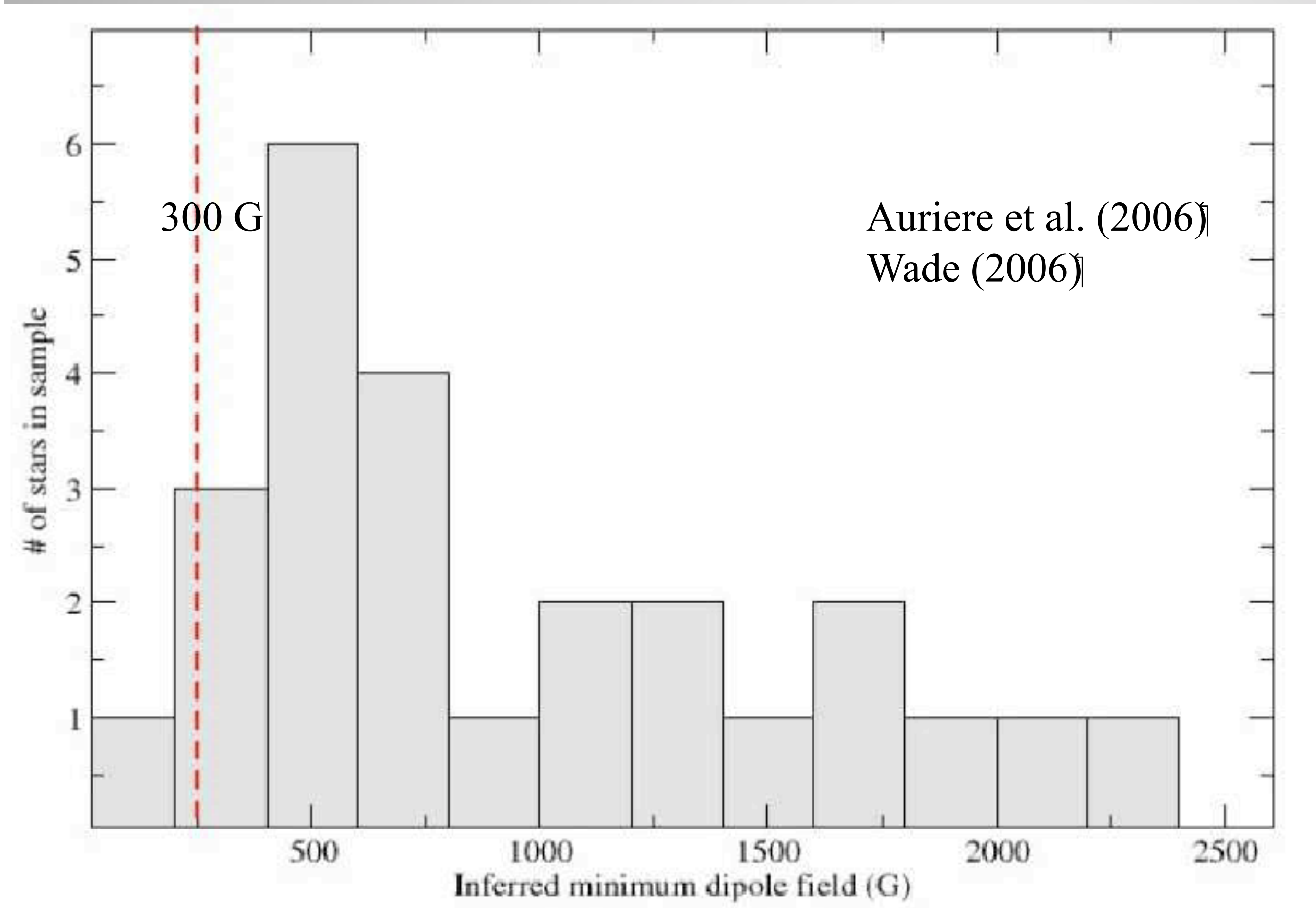
Magnetic field distribution of the HFMWDs compared to that of the NS when the WD radii are shrunk down to those typical of NS.

Main Sequence: Ap/Bp stars



- 10% of MS stars are magnetic with large scale dipolar fields.
- Highest incidence at B7, B8 and B9 (15.5%).

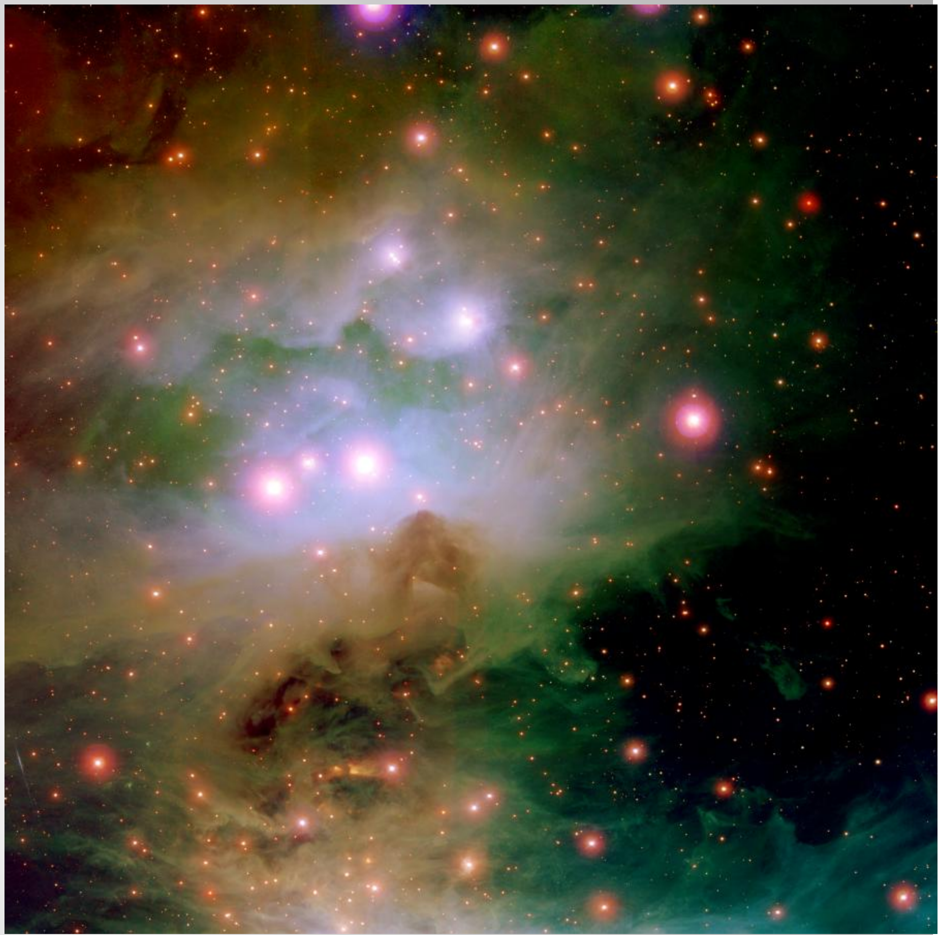
Magnetic fields in Ap/Bp stars: a dichotomy



Auriere et al (2006) discovered that A and *late* B stars have ordered dipolar fields with B >300 G or they are not magnetic down to an observational limit of ~30G.

Main Sequence: Op stars

- Petit et al. (2006) find 25% of stars with B>1 kG in the Orion Nebula. Highest fields: θ Ori C (1,100 G - Donati et al. 2002) and HD 191612: 1,500 G (Donati et al. 2006).
- Observations of other massive star regions → ~10%(Alecian & MiMes collaboration).



→ Orion has an unusually high % of highly magnetic stars. Orion also exhibits a highly abnormal massive-star mass function (Pflamm-Altenburg & Kroupa 2006)

Origin of magnetic fields

- Interstellar magnetic fields are trapped in collapsing protostars and survive to the compact star stage (***strong fossil field hypothesis***).
- Magnetic fields are created during the final stages of pre-main sequence evolution through mergers and survive to the compact star stage (***weak fossil field hypothesis***).
- Magnetic fields are destroyed and then created again in a fraction of stars during stellar evolution (***dynamo generated field hypothesis***).

Strong fossil hypothesis

- For $M > 2\,M_\odot$, stars continue to accrete mass and magnetic flux **after** they have developed a radiative envelope (Tout, Wickramasinghe, Ferrario '99).
- Stars with $M > 2M_\odot$ (Palla & Stahler 1990) - **do not go through a fully convective Hayashi phase** during which magnetic flux may be dissipated.
- Assuming that they form from a constant density cloud, the magnetic flux $\Phi \sim M^{2/3}$ (Tout, Wickramasinghe & Ferrario 2004).

Weak fossil hypothesis

- Ferrario et al (2009) have proposed that Ap/Bp stars acquired their fields through mergers occurring at the end of the pre-MS formation process → strong differential rotation → large scale fields that get "frozen" into the radiative envelopes.

- Such late mergers can also account for the lack of close binaries among Ap/Bp stars.

A fossil origin for HFMWDs & NS

- Magnetic Flux of O-type stars θ Ori C and HD 191612 : $\sim 10^{28}$G cm^2 ~similar to that of highest field magnetar SGR 1806-20.

- **Highest** magnetic fluxes of MS stars, MWDs, and NS are all of the same order of magnitude:

$$\Phi \approx 10^{28}\ \mathrm{G\ cm^2}$$

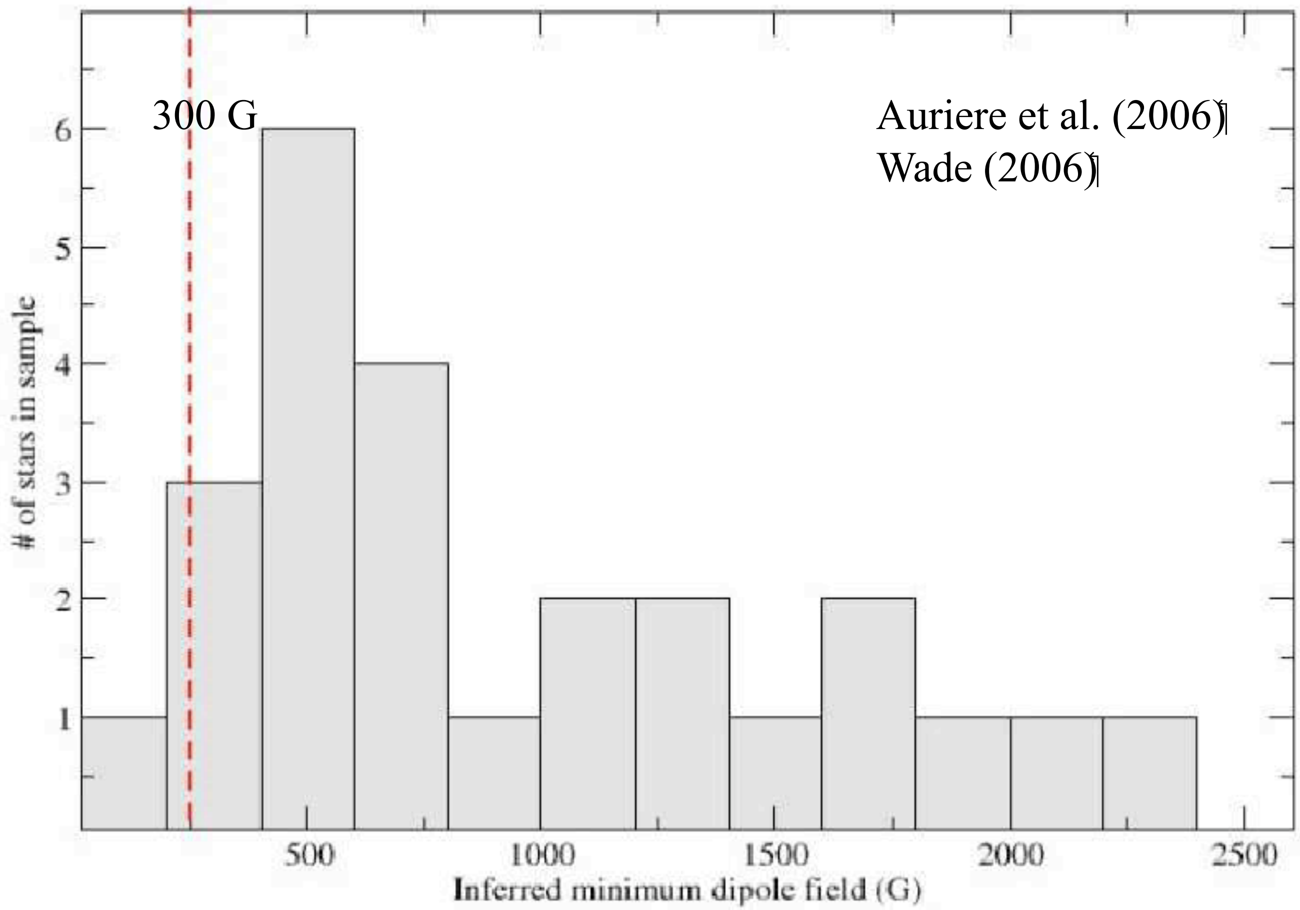
- Under flux conservation:

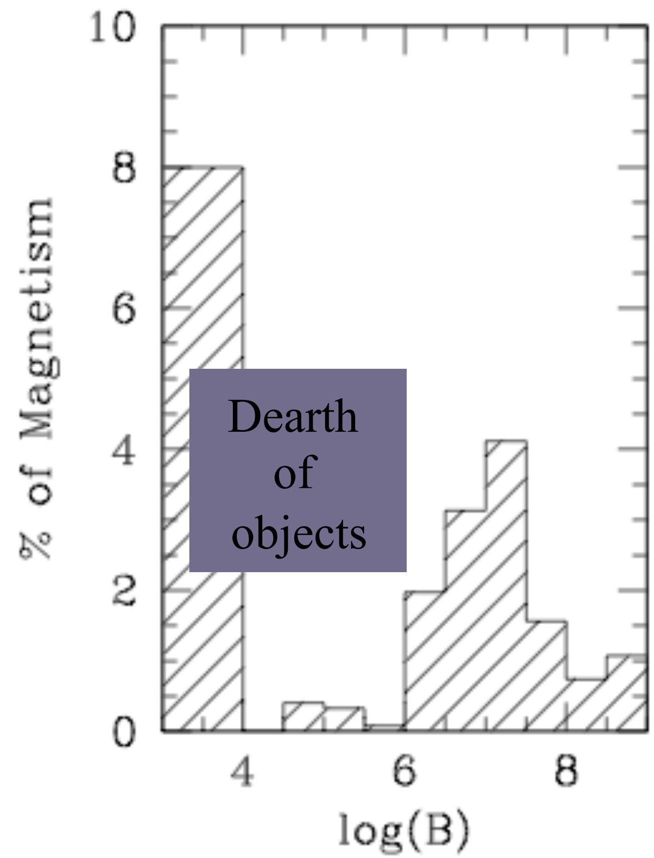
B(A-stars) ~ 300-30000 G → B (WD) ~ 10^6 - 10^9 G

B(O-stars) ~ ? - 2000 G → B (NS) ~ 10^{11} ~10^{15} G

Support for Fossil Hypothesis in WDs

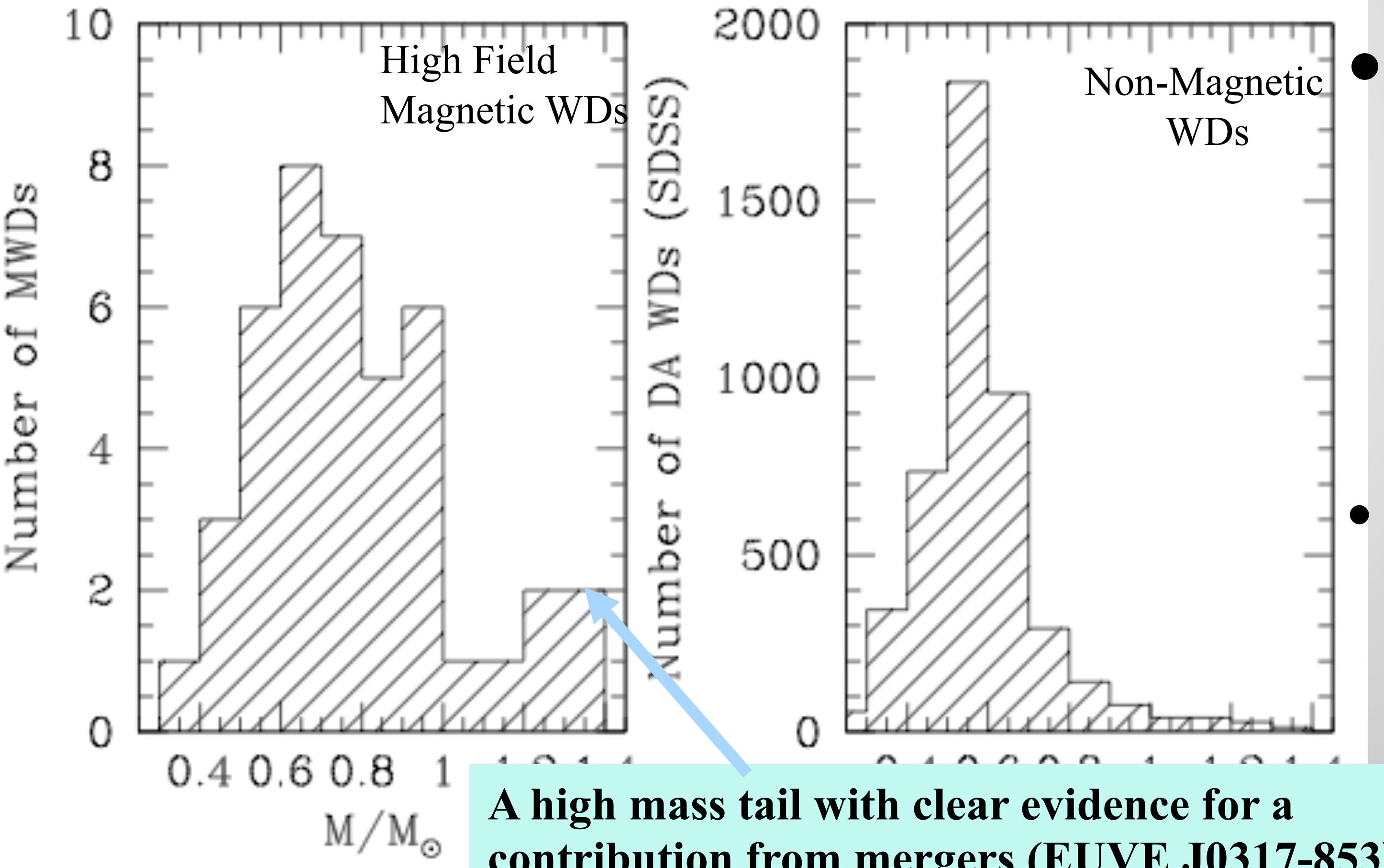
Dearth of Ap/Bp stars below 300 G: the magnetic flux matches the fields below which there is a dearth of MWDs.





Support for Fossil Hypothesis in WDs

- HFMWDs: mean mass ~ 0.82 M⊙ (c.f. 0.58 M⊙ for all WDs) ↰ of EUVE/Soft X-ray selected ultra-massive WDs (M>1.2 M⊙) are strongly magnetic (Vennes 1999).

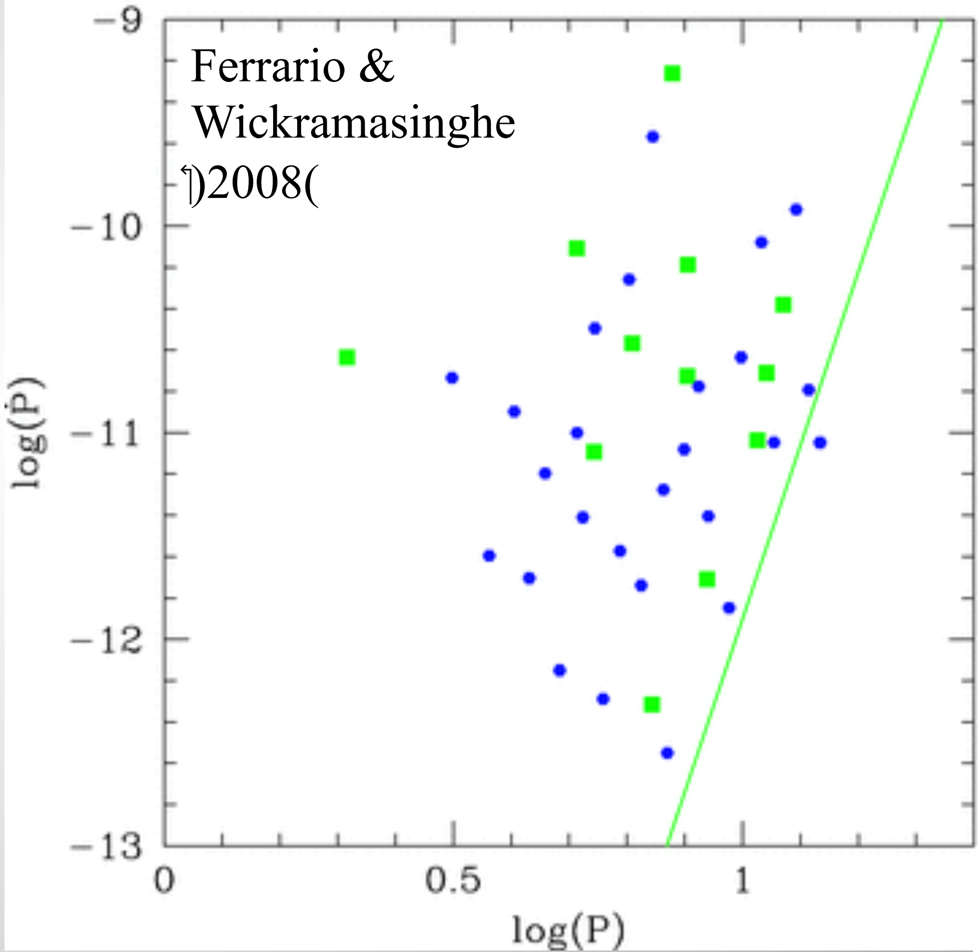


A high mass tail with clear evidence for a contribution from mergers (EUVE J0317-853)

- ⟶ Most MWDs have massive(>3M⊙) progenitors
- BUT many massive WDs are non-magnetic (e.g. GD50)

Population synthesis of magnetars on fossil field hypothesis.

- Used observations of 4 magnetars from *ROSAT All-Sky survey* .
- Objects are assigned two-components: power law and blackbody and are born according to Salpeter IMF.
- All ROSAT X-ray selection effects taken into account.
- If all $M_i > 20 M_\odot \rightarrow 26$ predicted with BR $3 \times 10^{-3} yr^{-1}$



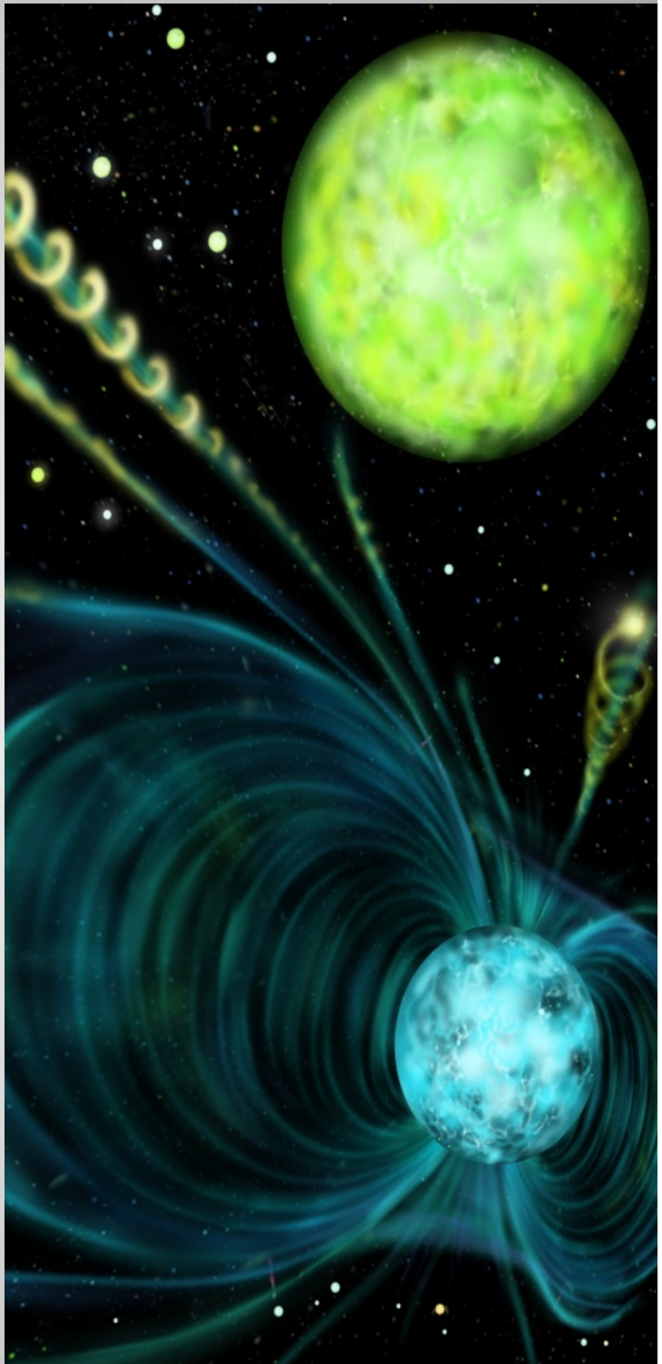
Green squares: observations.
Blue dots: synthetic population.

Major Problem with fossil field hypothesis?

- *How do fossil fields survive the red giant phase of stellar evolution?*
- **BUT** EK Eridani, a red giant with ~ 0.37 $M_\odot$ convective envelope, has a B~270 G large scale poloidal field, is *very* slowly rotating → compatible with being the descendant of a strongly magnetic Ap star (Auriere et al 2008).
- Currently, there are no stellar evolution calculations that include fossil fields in radiative regions and follow their evolution as the star evolves.

Merger hypothesis for field formation in HFMWDs

- Fields of HFMWDs come from mergers – like it has been proposed for Ap/Bp stars (Ferrario et al. 2009). EUVE0317-855 could be one of these objects.
- This would explain the complete absence of main sequence (M-dwarf) companions to HFMWDs (incidence in non-MWDs:25%)



Alternative scenario for field generation in NS

- Rapid rotation and differential motion in the proto-NS generates fields of (Duncan & Thompson 1992)

- Isolated radio-pulsars: $B \sim 10^{12}$ G $\rightarrow$ $P_i \sim 10$ ms
  Magnetars: $B \sim 10^{15}$G $\rightarrow$ $P_i < 3$ ms

- Magnetars fields form in <10 s with spin-down time scale of ~ 10-100 sec. With P ~ 1 ms, $E_{rot} = I\,\Omega^2/2 \sim 3\text{x}10^{52}$ 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

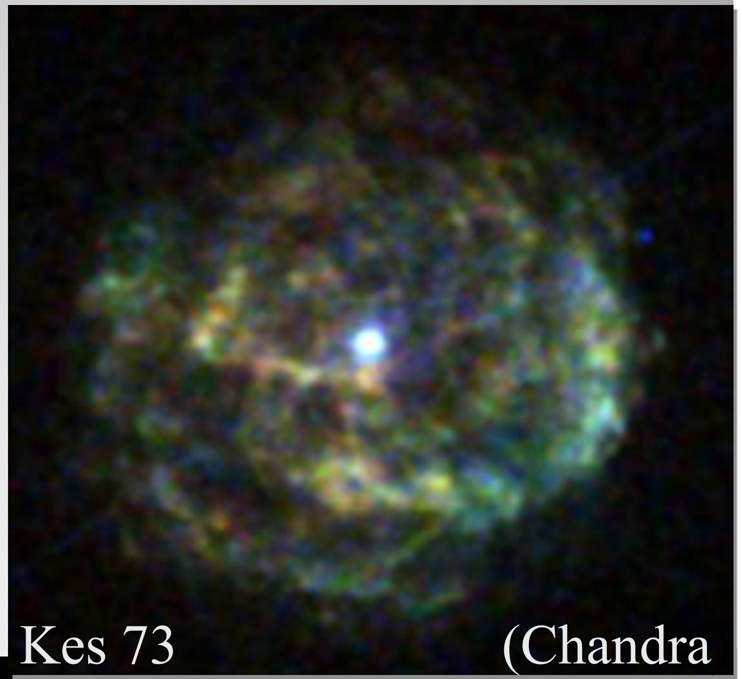
SNRs and magnetars

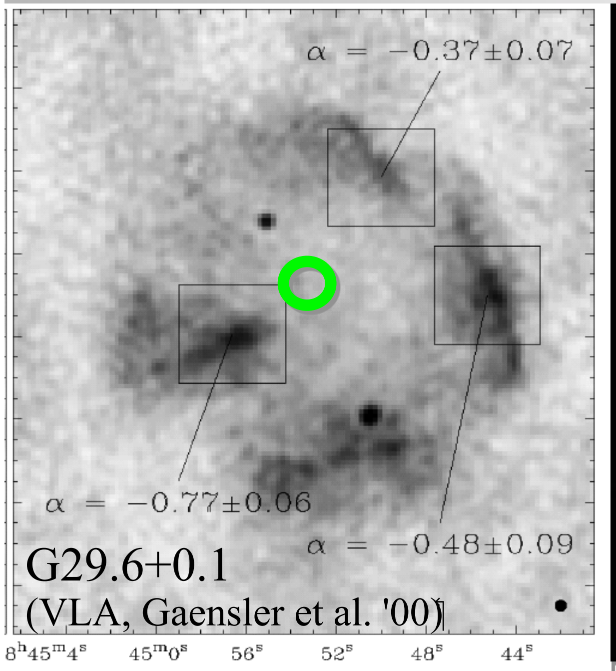
1 SGR in SNRs: N49 (LMC)

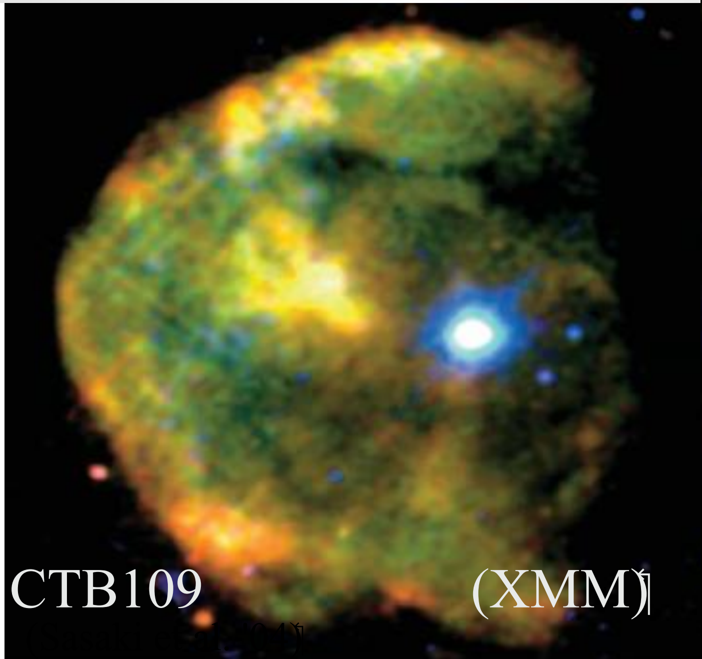
3 AXPs associated with SNRs:

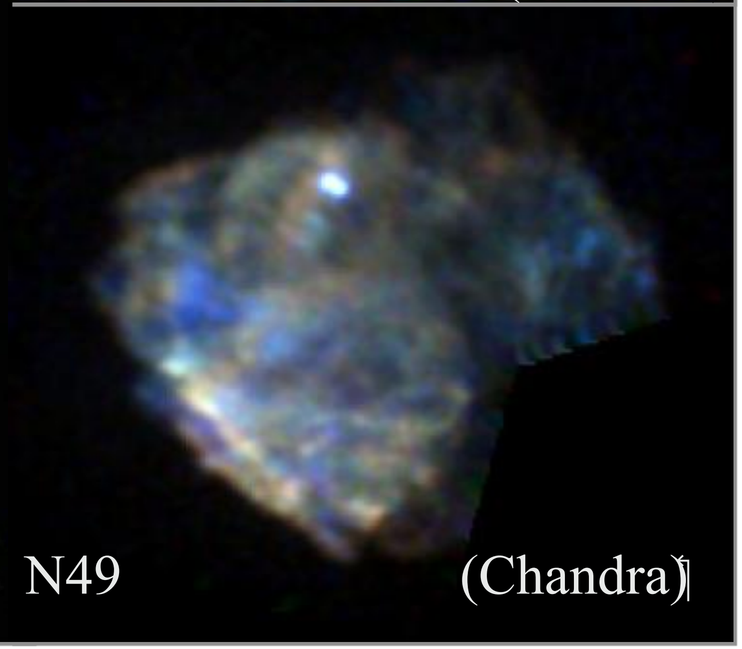
- Kes 73 (~ 7 kpc), CTB109 (~3 kpc)
  G29.6+0.1 (~3 kpc)

No more energetic than any other SN remnants → problem with dynamo.









Conclusions

- A fossil origin for the fields provides a natural explanation for the range of fields seen in Ap/Bp/Op stars, HFMWDs and Neutron Stars ***BUT*** it is not clear how these fields survive through the various stages of stellar evolution.

- If fields are destroyed by the onset of convection in the envelope at the end of the MS phase, then fields must be generated again to explain the existence of strong fields in compact stars.→ if all MWDS come from mergers, where do neutron star magnetic fields come from?