Probing Physics with White Dwarfs and Neutron Stars

Jeremy Heyl

15 June 2015

Students: Elisa Antolini, Ryan Goldsbury, Alysa Obertas, Dan Mazur, Javiera Parada
Others: Ramandeep Gill, Jason Kalirai, Paola Marigo, Harvey Richer, Pier-Emmanuel Tremblay

Outline

White Dwarfs
- Magnetic White Dwarfs
- Cooling White Dwarfs

Neutron Stars
- Magnetic Neutron Stars
- Cooling Neutron Stars
- Superconducting Neutron Stars

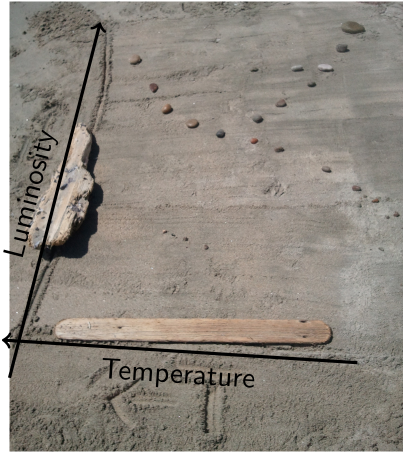
Stars

Stars are excellent, free laboratories.

Stars

Stars are excellent, free laboratories.

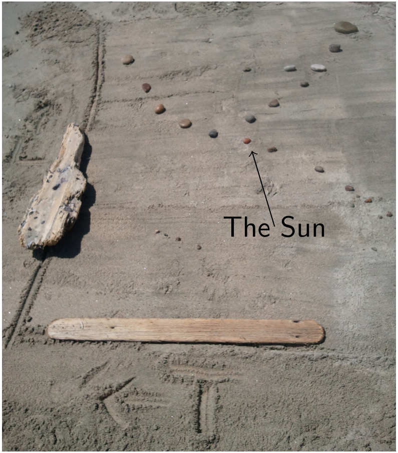
- Blue stars on the left and red on the right.



Stars

Stars are excellent, free laboratories.

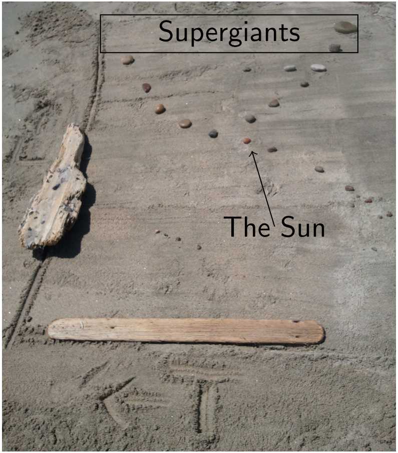
- Blue stars on the left and red on the right.
- The Sun consumes hydrogen in its core – main sequence.



Stars

Stars are excellent, free laboratories.

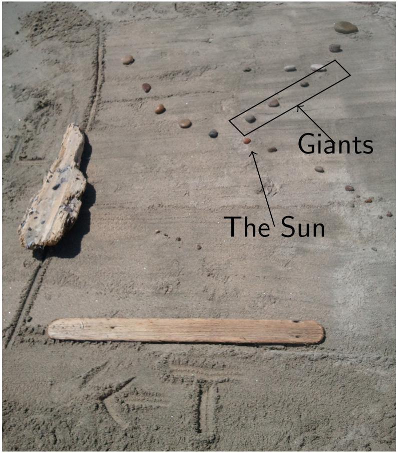
- Blue stars on the left and red on the right.
- The Sun consumes hydrogen in its core – main sequence.
- Supergiants become neutron stars.



Stars

Stars are excellent, free laboratories.

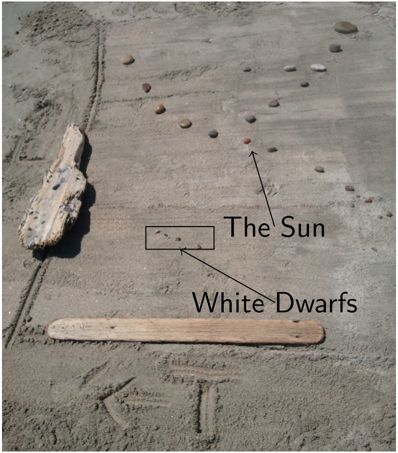
- Blue stars on the left and red on the right.
- The Sun consumes hydrogen in its core – main sequence.
- Supergiants become neutron stars.
- Giants consume hydrogen in a shell and helium in the core,



Stars

Stars are excellent, free laboratories.

- Blue stars on the left and red on the right.
- The Sun consumes hydrogen in its core – main sequence.
- Supergiants become neutron stars.
- Giants consume hydrogen in a shell and helium in the core,
- And become white dwarfs.



How big are compact objects?

White Dwarfs

Gravity yields: $P_0 \sim \frac{GM^2}{R^4}$
Relativistic degenerate electrons

$$P_0 \sim \frac{m_e c^2}{\lambda_e^3}, M = \frac{m_p}{\lambda_e^3} R^3$$

Solving yields

$$R = \lambda_e \frac{m_P}{m_p}, M = \frac{m_P^3}{m_p^2}$$

$$R \approx 10,000\mathrm{km}, M \approx 1.4\mathrm{M}_\odot$$

How big are compact objects?

White Dwarfs

Gravity yields: $P_0 \sim \frac{GM^2}{R^4}$
Relativistic degenerate electrons

$$P_0 \sim \frac{m_e c^2}{\lambda_e^3}, M = \frac{m_p}{\lambda_e^3} R^3$$

Solving yields

$$R = \lambda_e \frac{m_P}{m_p}, M = \frac{m_P^3}{m_p^2}$$

$$R \approx 10,000\mathrm{km}, M \approx 1.4\mathrm{M}_\odot$$

Neutron Stars

Gravity yields: $P_0 \sim \frac{GM^2}{R^4}$
Relativistic degenerate neutrons

$$P_0 \sim \frac{m_n c^2}{\lambda_n^3}, M = \frac{m_n}{\lambda_e^3} R^3$$

Solving yields

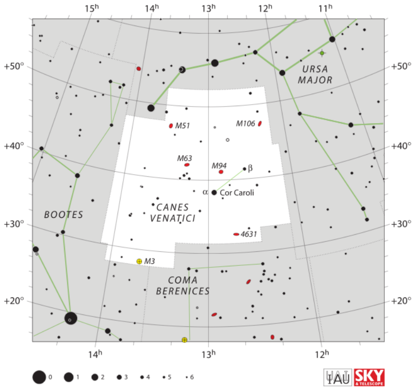
$$R = \lambda_n \frac{m_P}{m_n}, M = \frac{m_P^3}{m_n^2}$$

$$R \approx 17\mathrm{km}, M \approx 1.4\mathrm{M}_\odot$$

How strong can white-dwarf fields be?

Let's calculate the expected magnetic field of a white dwarf.

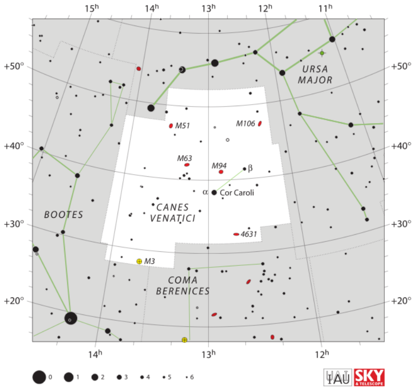
- The magnetic field of the Sun is about 50 Gauss.



How strong can white-dwarf fields be?

Let's calculate the expected magnetic field of a white dwarf.

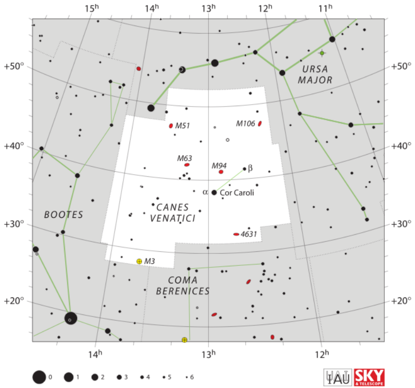
- The magnetic field of the Sun is about 50 Gauss.
- A white dwarf is the radius of the Earth.



How strong can white-dwarf fields be?

Let's calculate the expected magnetic field of a white dwarf.

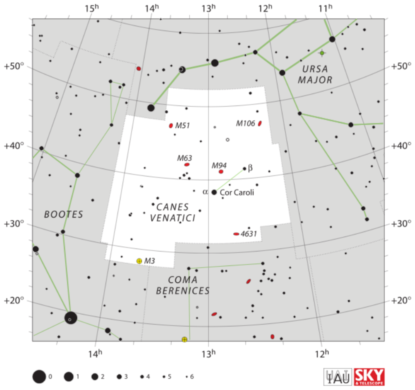
- The magnetic field of the Sun is about 50 Gauss.
- A white dwarf is the radius of the Earth.
- Flux freezing: $\Phi \propto BR^2$.



How strong can white-dwarf fields be?

Let's calculate the expected magnetic field of a white dwarf.

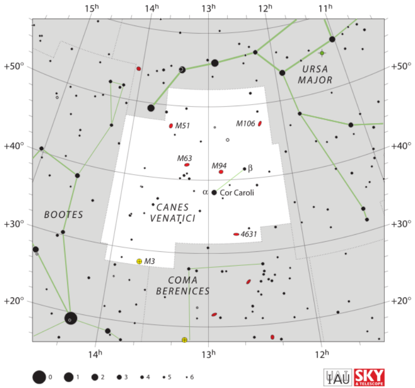
- The magnetic field of the Sun is about 50 Gauss.
- A white dwarf is the radius of the Earth.
- Flux freezing: $\Phi \propto BR^2$.
- $B \sim 50\mathrm{G}\ (109)^2 \sim 500\mathrm{kG} = 50\mathrm{T}$.



How strong can white-dwarf fields be?

Let's calculate the expected magnetic field of a white dwarf.

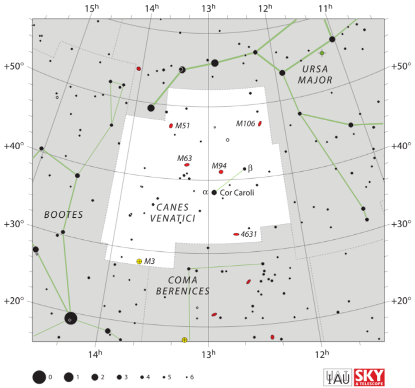
- The magnetic field of the Sun is about 50 Gauss.
- A white dwarf is the radius of the Earth.
- Flux freezing: $\Phi \propto BR^2$.
- $B \sim 50\mathrm{G}\ (109)^2 \sim 500\mathrm{kG} = 50\mathrm{T}$.
- Magnetic Ap stars have 1 kG fields and are bigger than the Sun.



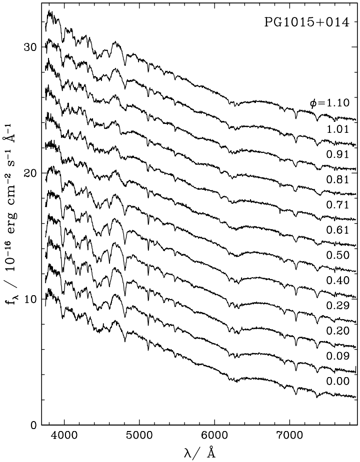
How strong can white-dwarf fields be?

Let's calculate the expected magnetic field of a white dwarf.

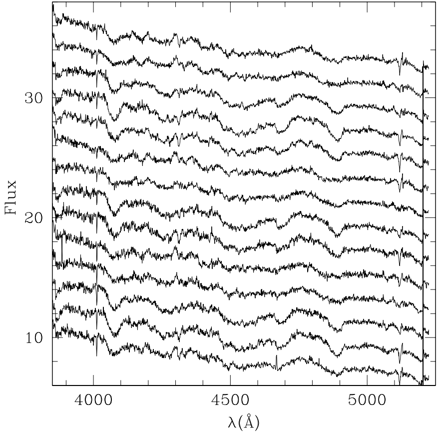
- The magnetic field of the Sun is about 50 Gauss.
- A white dwarf is the radius of the Earth.
- Flux freezing: $\Phi \propto BR^2$.
- $B \sim 50\mathrm{G} \ (109)^2 \sim 500\mathrm{kG} = 50\mathrm{T}$.
- Magnetic Ap stars have 1 kG fields and are bigger than the Sun.
- $B \sim 100\mathrm{MG} = 10^4\mathrm{T}$.



White Dwarf Spectra



PG1015+014 : Left (Euchner et al. 2006), Right (Keck;Heyl)



Axions and White Dwarfs

White dwarfs have exquisite polarimetric observations, finding no linear polarization to the few percent level.

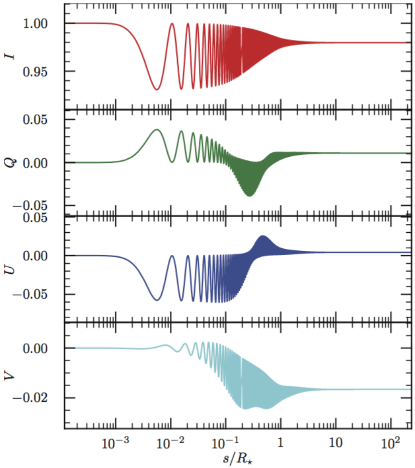
Their fields are weaker 10^{8-9} G, but the stars are bigger, and we know the field geometry.

Gill, Heyl 11

Axions and White Dwarfs

White dwarfs have exquisite polarimetric observations, finding no linear polarization to the few percent level.
Their fields are weaker 10^{8-9} G, but the stars are bigger, and we know the field geometry.

Gill, Heyl 11

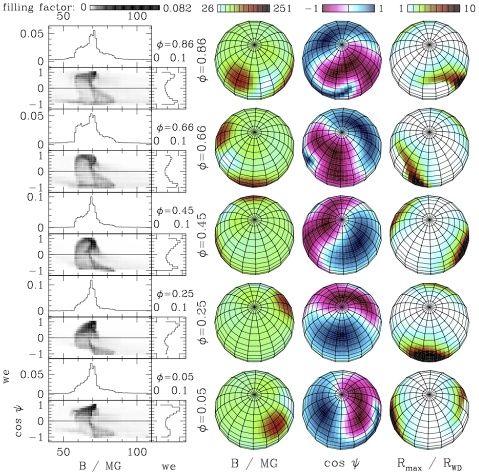


PG 1015+015

Spectropolarimetry constrains the structure of magnetic field.

PG 1015+015

Spectropolarimetry constrains the structure of magnetic field.



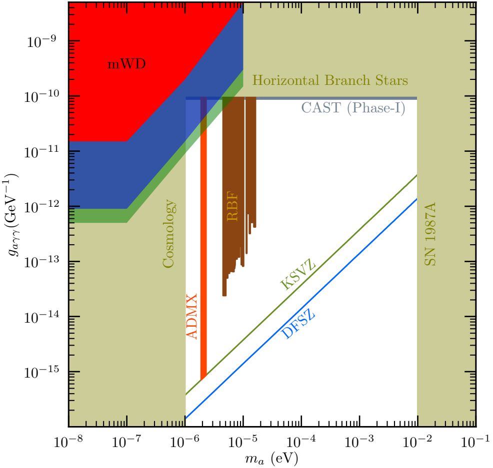
Euchner et al 06

Axions and White Dwarfs

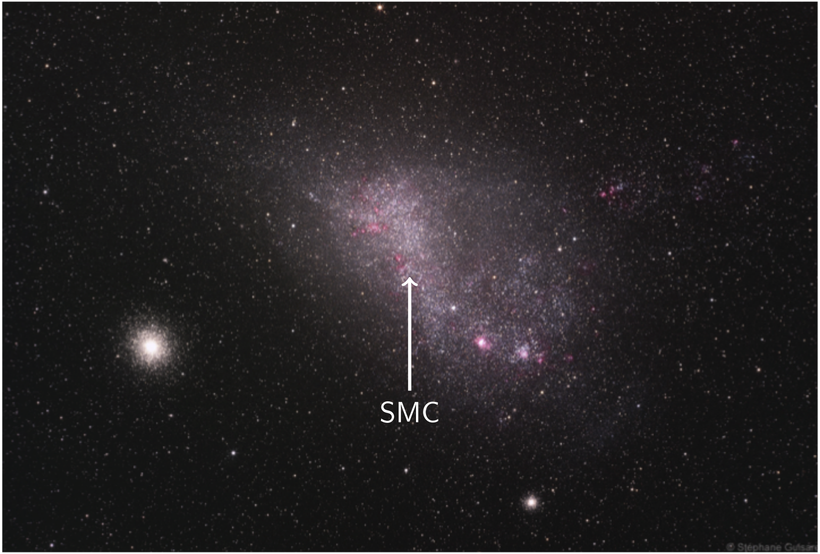
Let's look at more strongly magnetized white dwarfs: PG 1031+234 and SDSS J234605+385337. The observed minimum polarization of a few percent excludes some of the currently allowed region for axion-like particles.

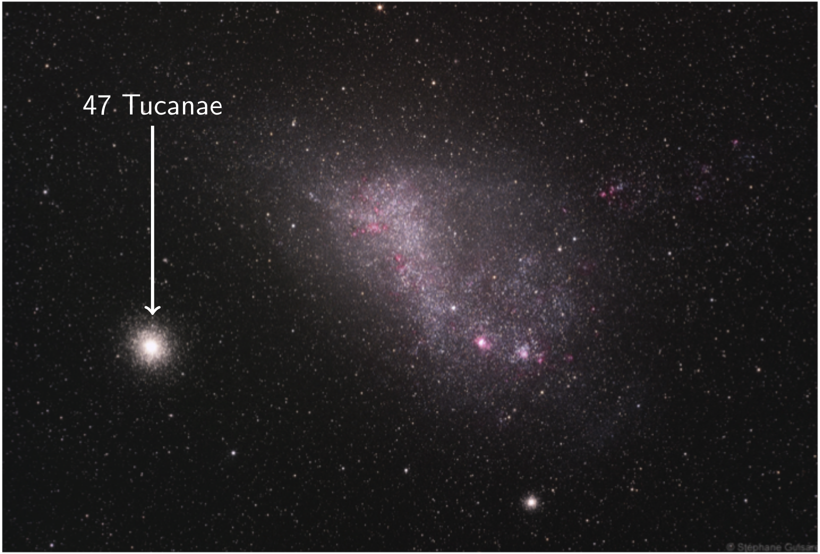
Axions and White Dwarfs

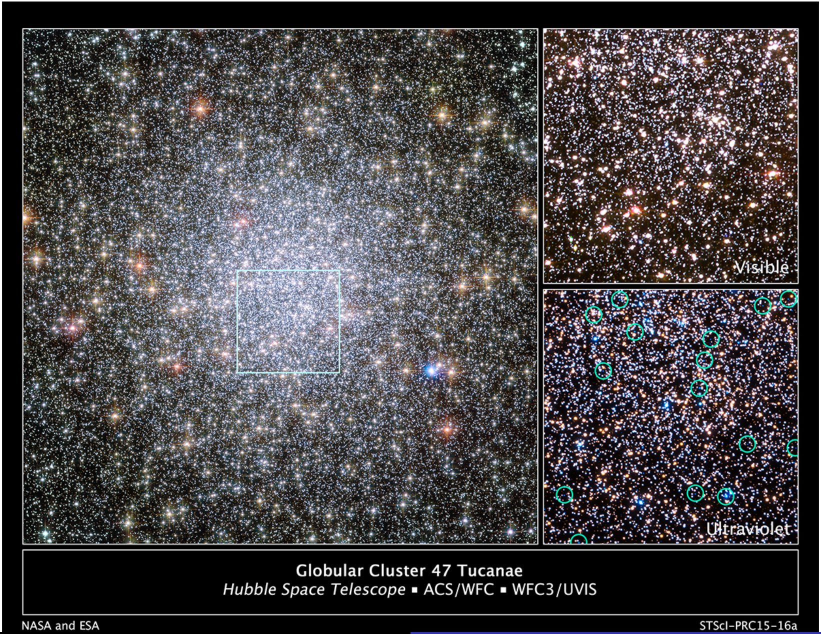
Let's look at more strongly magnetized white dwarfs: PG 1031+234 and SDSS J234605+385337. The observed minimum polarization of a few percent excludes some of the currently allowed region for axion-like particles.



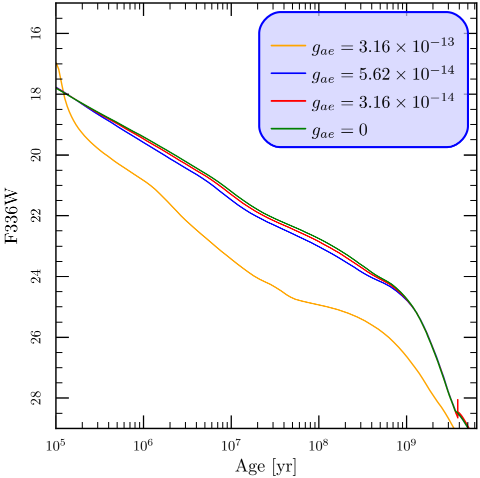
Gill, Heyl 11

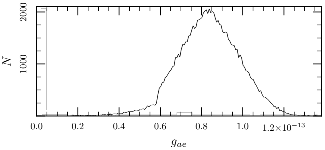

SMC
© Stephane Guisard

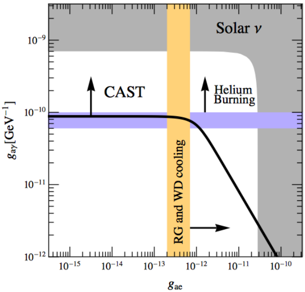

47 Tucanae
© Stéphane Guisard


Visible
Ultraviolet
Globular Cluster 47 Tucanae
Hubble Space Telescope ▪ ACS/WFC ▪ WFC3/UVIS
NASA and ESA
STScI-PRC15-16a

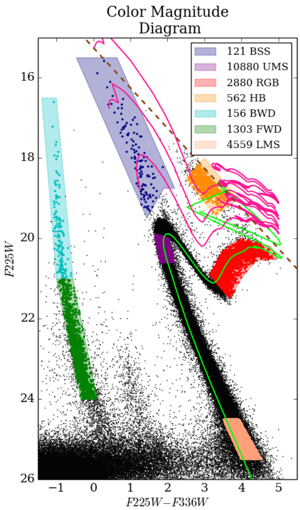
Cooling White Dwarfs

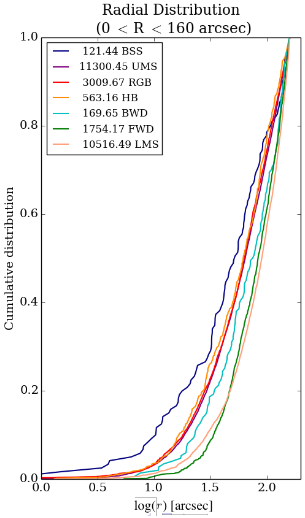






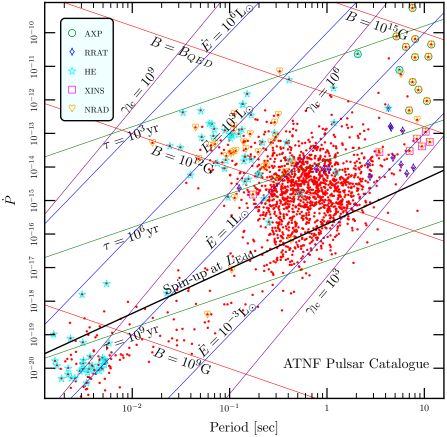
Relaxation


Color Magnitude
Diagram
121 BSS
10880 UMS
2880 RGB
562 HB
156 BWD
1303 FWD
4559 LMS
F225W
F225W−F336W
16
18
20
22
24
26
−1
0
1
2
3
4
5


Radial Distribution
(0 < R < 160 arcsec)
121.44 BSS
11300.45 UMS
3009.67 RGB
563.16 HB
169.65 BWD
1754.17 FWD
10516.49 LMS
Cumulative distribution
log(r) [arcsec]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0

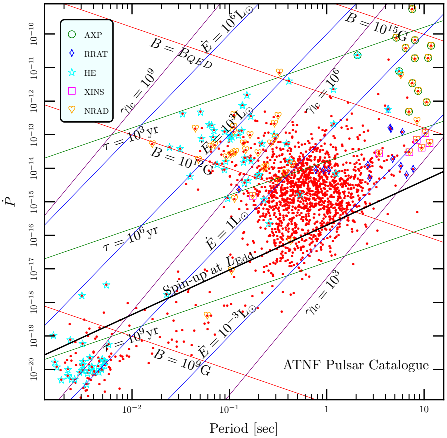
Neutron Stars

- The first neutron stars to be identified were radio pulsars.



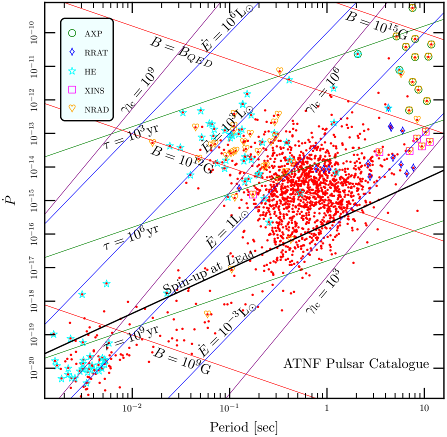
Neutron Stars

- The first neutron stars to be identified were radio pulsars.
- Over 2,000 are now known.

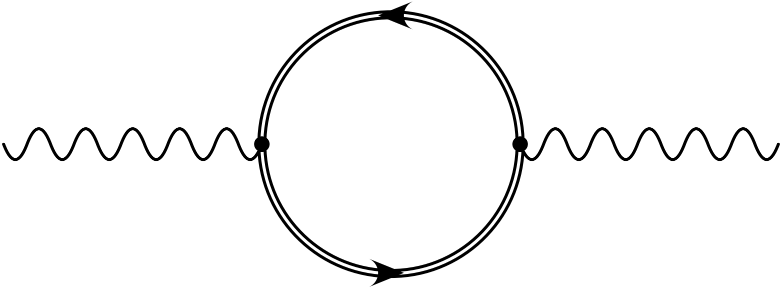


Neutron Stars

- The first neutron stars to be identified were radio pulsars.
- Over 2,000 are now known.
- Lots of flavours – not even including the accretors.

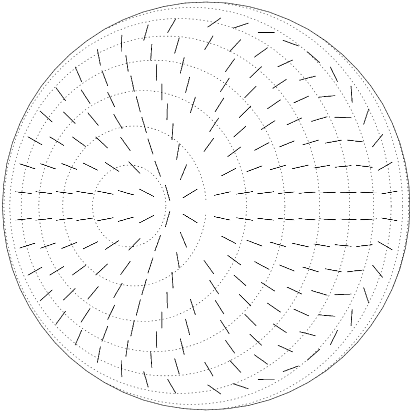


Magnetic Fields



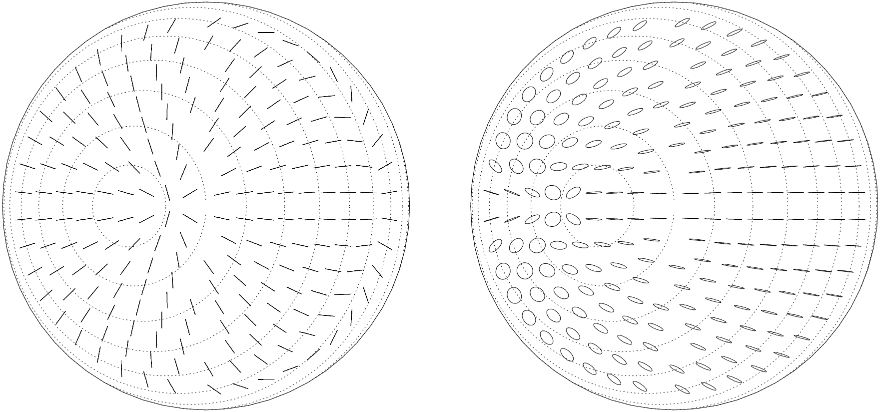
$$S = S_0 + \frac{1}{2} f^{\mu\nu} f^{\alpha\beta} \frac{\delta^2 S}{\delta f^{\mu\nu} \delta f^{\alpha\beta}}$$

Why does this matter?



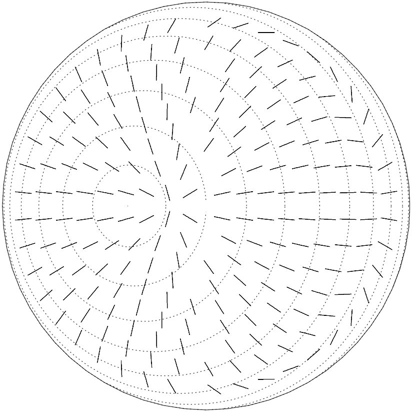
Heyl, Shaviv 02

Why does this matter?

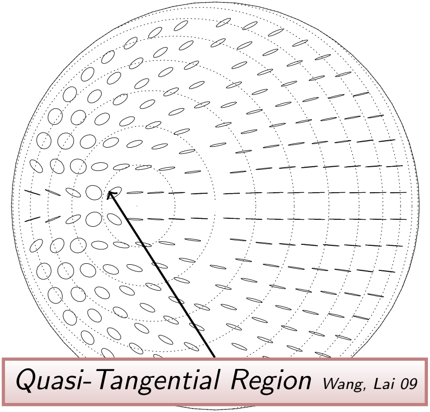


Heyl, Shaviv 02

Why does this matter?



Heyl, Shaviv 02



This is not subtle.

Let's recap.

- Neutron star atmospheres emit polarized light.

This is not subtle.

Let's recap.

- Neutron star atmospheres emit polarized light.
- The emission varies across the surface.

This is not subtle.

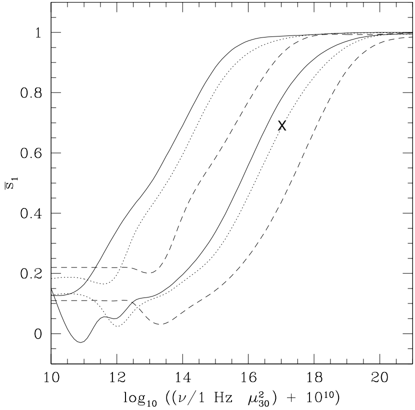
Let's recap.

- Neutron star atmospheres emit polarized light.
- The emission varies across the surface.
- The rotating magnetic field twists the polarization.

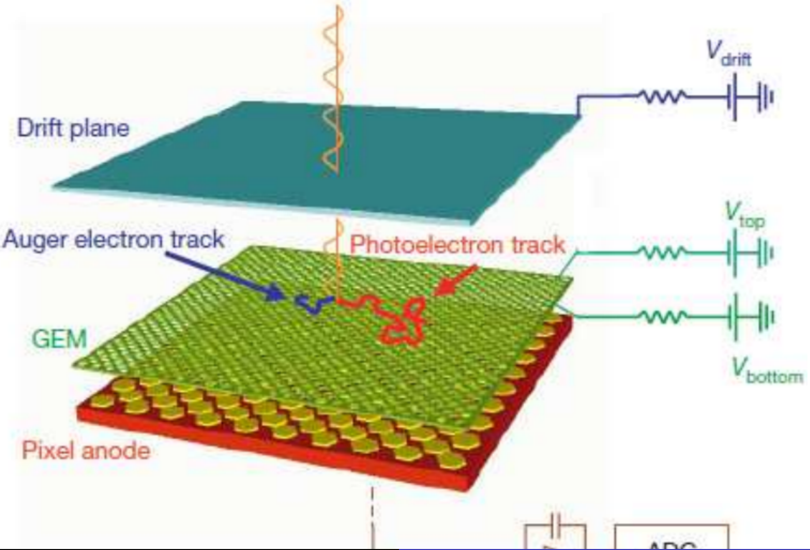
This is not subtle.

Let's recap.

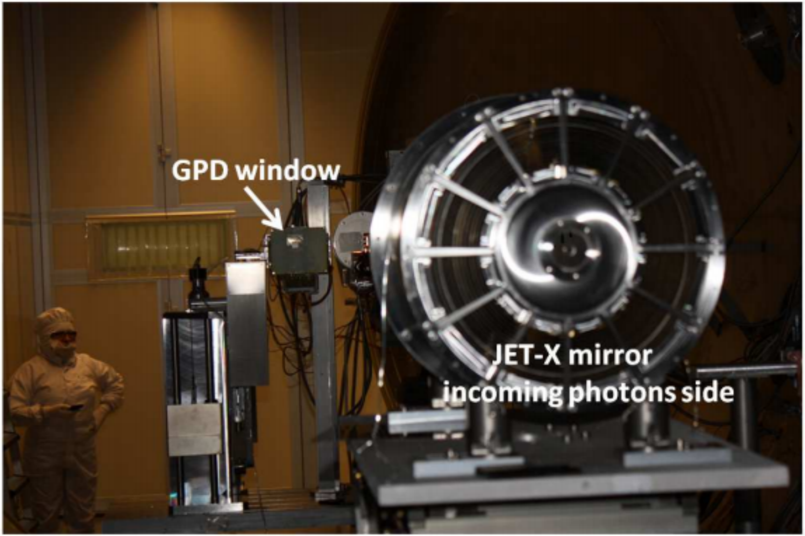
- Neutron star atmospheres emit polarized light.
- The emission varies across the surface.
- The rotating magnetic field twists the polarization.



XIPE


Drift plane
Auger electron track
Photoelectron track
GEM
Pixel anode
V_{drift}
V_{top}
V_{bottom}

XIPE



Neutron Stars

- The cumulative distribution is the ML estimate of the cooling curve.

Neutron Stars

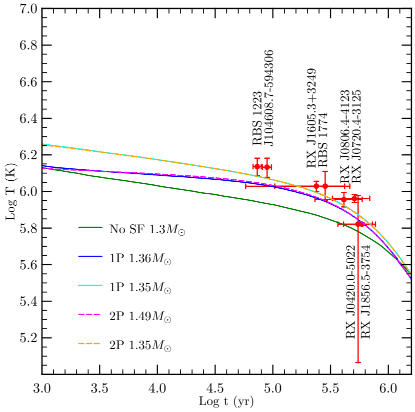
- The cumulative distribution is the ML estimate of the cooling curve.
- In a cluster the weight of a white dwarf is the reciprocal of the birthrate within the fields that form the sample.

Neutron Stars

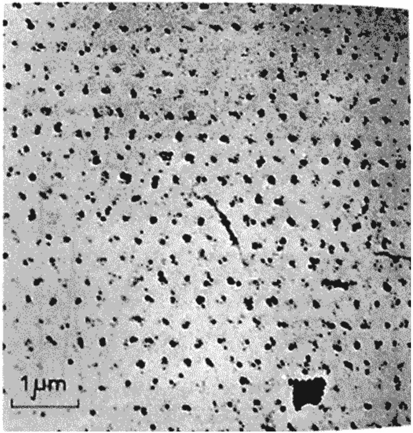
- The cumulative distribution is the ML estimate of the cooling curve.
- In a cluster the weight of a white dwarf is the reciprocal of the birthrate within the fields that form the sample.
- Weight each successive neutron star by the reciprocal of the birthrate within the volume from which it was found.

Neutron Stars

- The cumulative distribution is the ML estimate of the cooling curve.
- In a cluster the weight of a white dwarf is the reciprocal of the birthrate within the fields that form the sample.
- Weight each successive neutron star by the reciprocal of the birthrate within the volume from which it was found.



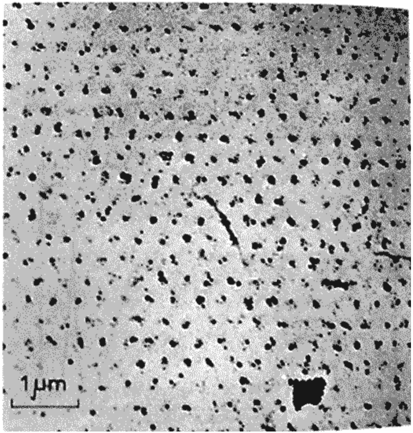
Superconductivity



Essmann & Träuble 1967

In a lab superconductor the distance between vortices is $\sim 1\mu$m, and their size is ~ 100nm.

Superconductivity



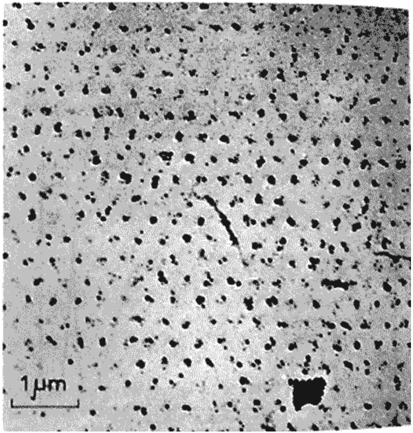
Essmann & Träuble 1967

In a lab superconductor the distance between vortices is $\sim 1\mu$m, and their size is ~ 100nm.

In a neutron star we have

$$a \sim \sqrt{\frac{4h}{\pi e B}} = 7 B_{12} \mathrm{pm} = 19 \bar{\lambda}_e$$

Superconductivity



Essmann & Träuble 1967

In a lab superconductor the distance between vortices is $\sim 1\mu$m, and their size is ~ 100nm.

In a neutron star we have

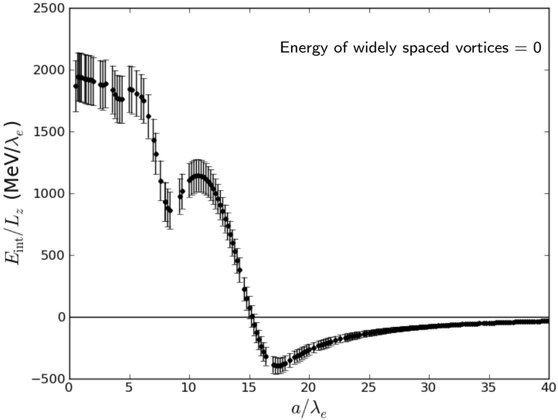
$$a \sim \sqrt{\frac{4h}{\pi eB}} = 7B_{12}\mathrm{pm} = 19\bar{\lambda}_e$$

and

$$\lambda_L = \sqrt{\frac{mc^2}{8\pi q^2 n_0}} = 7\rho_{15}\mathrm{fm}$$

Casimir Force

Discovery of an attractive Casimir interaction



Circle Packing

Circle Packing

Consequences

- For fields less than 10^{12} G the flux tubes will be about seventeen Compton wavelengths apart with large regions free of flux tubes.

Consequences

- For fields less than 10^{12} G the flux tubes will be about seventeen Compton wavelengths apart with large regions free of flux tubes.
- For fields between 10^{12} G and 2×10^{12} G, the tubes will be evenly and closely packed (like the conventional model).

Consequences

- For fields less than 10^{12} G the flux tubes will be about seventeen Compton wavelengths apart with large regions free of flux tubes.
- For fields between 10^{12} G and 2×10^{12} G, the tubes will be evenly and closely packed (like the conventional model).
- For fields between 2×10^{12} G and 5×10^{12} G the flux tubes will be either about eight or seventeen Compton wavelengths apart forming a (probably irregular) lattice filling the entire region.

Consequences

- For fields less than 10^{12} G the flux tubes will be about seventeen Compton wavelengths apart with large regions free of flux tubes.
- For fields between 10^{12} G and 2×10^{12} G, the tubes will be evenly and closely packed (like the conventional model).
- For fields between 2×10^{12} G and 5×10^{12} G the flux tubes will be either about eight or seventeen Compton wavelengths apart forming a (probably irregular) lattice filling the entire region.
- For stronger fields, the tubes will be evenly and closely packed (like the conventional model).

Consequences

- For fields less than 10^{12} G the flux tubes will be about seventeen Compton wavelengths apart with large regions free of flux tubes.
- For fields between 10^{12} G and 2×10^{12} G, the tubes will be evenly and closely packed (like the conventional model).
- For fields between 2×10^{12} G and 5×10^{12} G the flux tubes will be either about eight or seventeen Compton wavelengths apart forming a (probably irregular) lattice filling the entire region.
- For stronger fields, the tubes will be evenly and closely packed (like the conventional model).
- These bounds are qualitative as we need to model the superconductor more accurately.