Magnetic field generation in hybrid stars

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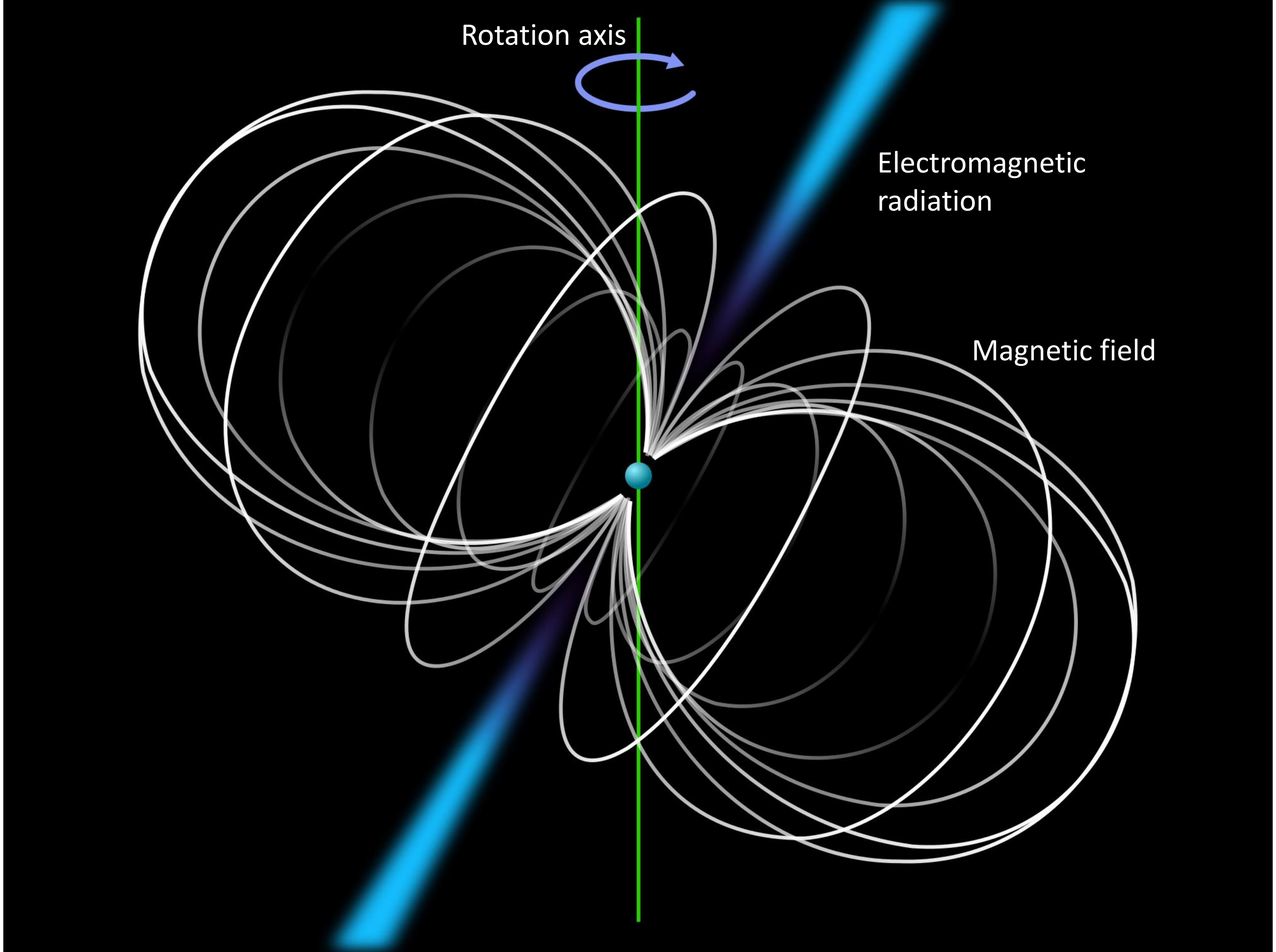
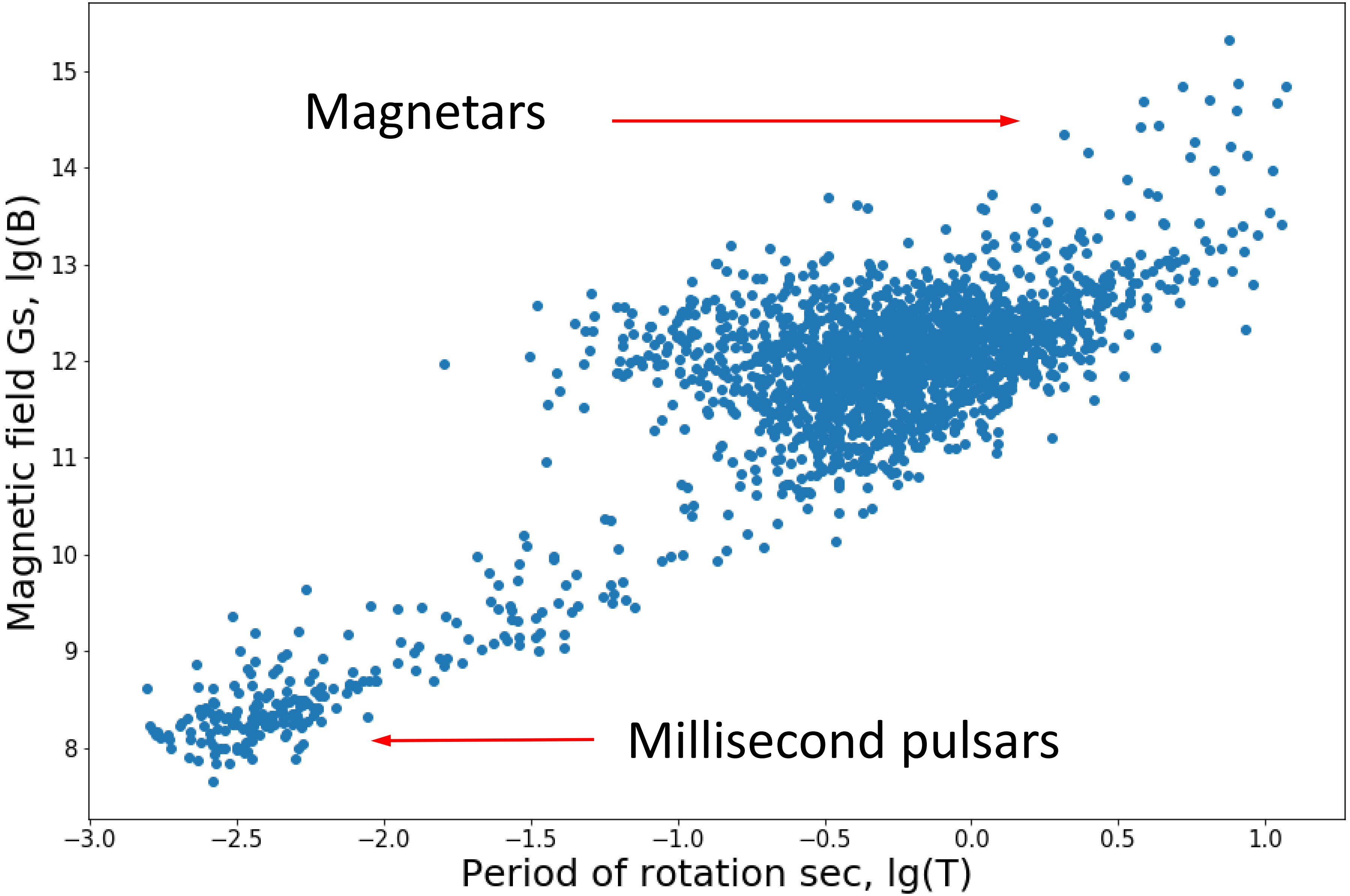
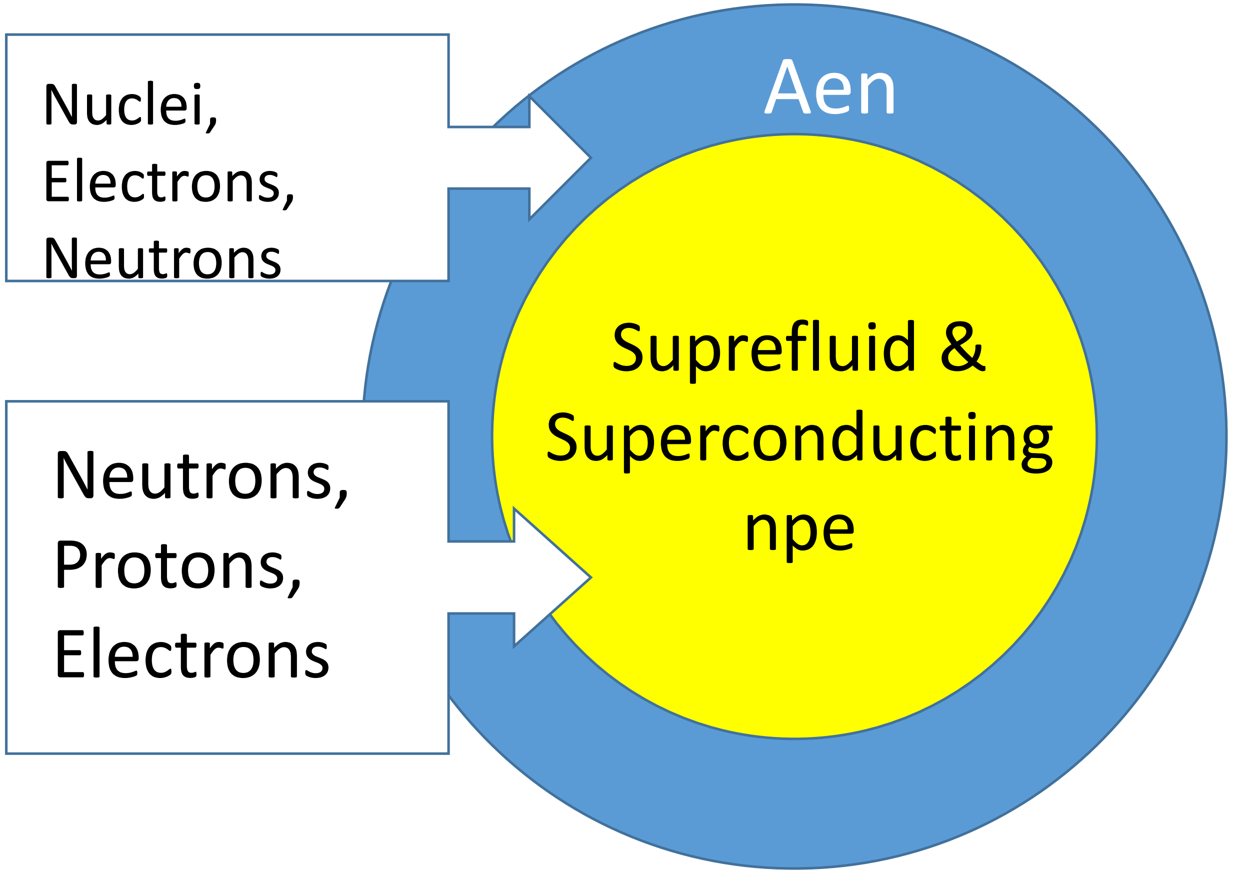

Rotation axis
Electromagnetic radiation
Magnetic field

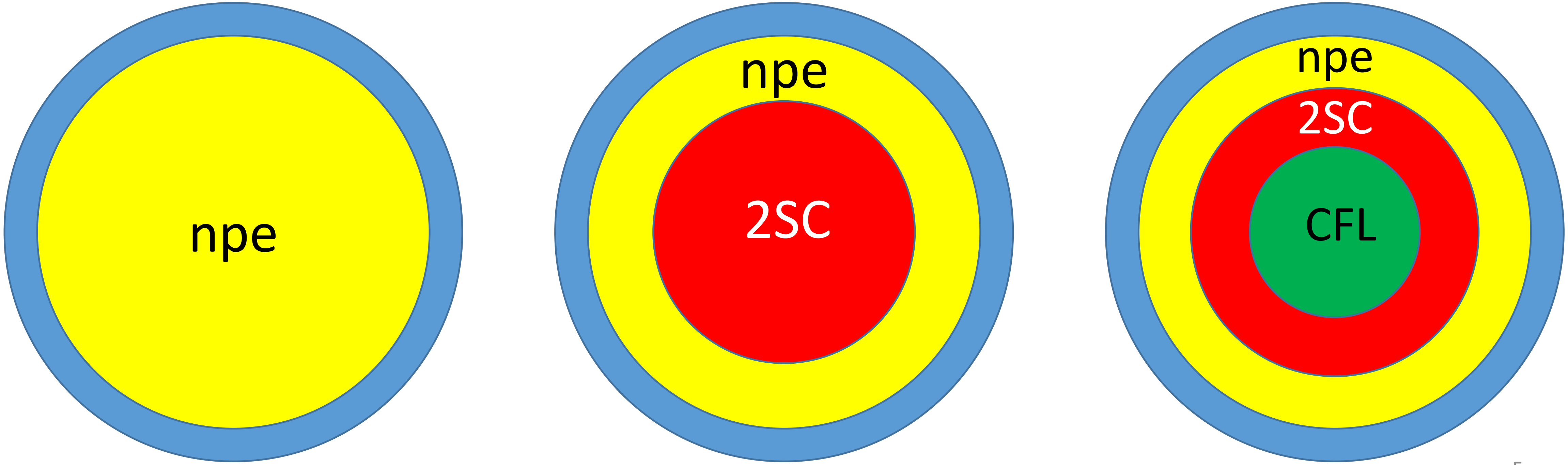

Magnetars
Millisecond pulsars
15
14
13
12
11
10
9
8
−3.0
−2.5
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
Magnetic field Gs, lg(B)
Period of rotation sec, lg(T)

Two-component NS

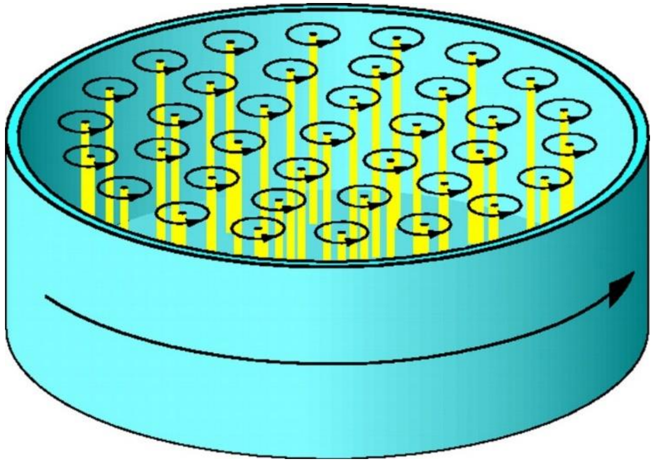


Quark matter phases in hybrid stars

2SC – two-flavor superconducting u, d, e
CFL – color-flavor locking u, d, s



Magnetic field generation in "npe"-phase



Due to superfluidity of rotating star, neutron rotational vortices appear like in HeII.

Due to strong interaction, superfluid neutrons entrain superconducting protons in vortex motion.

This leads to entrainment currents, which eventually leads to magnetic field generation.

Vortices in “npe”-phase

Velocity near vortex core $v = \frac{\chi}{r}$ $\chi = \frac{\hbar}{2m}$, m – neutron mass

$n = \frac{2\Omega}{\chi}$ vortices density, $b = \sqrt{\frac{\hbar}{2m\Omega}}$ vortex radius

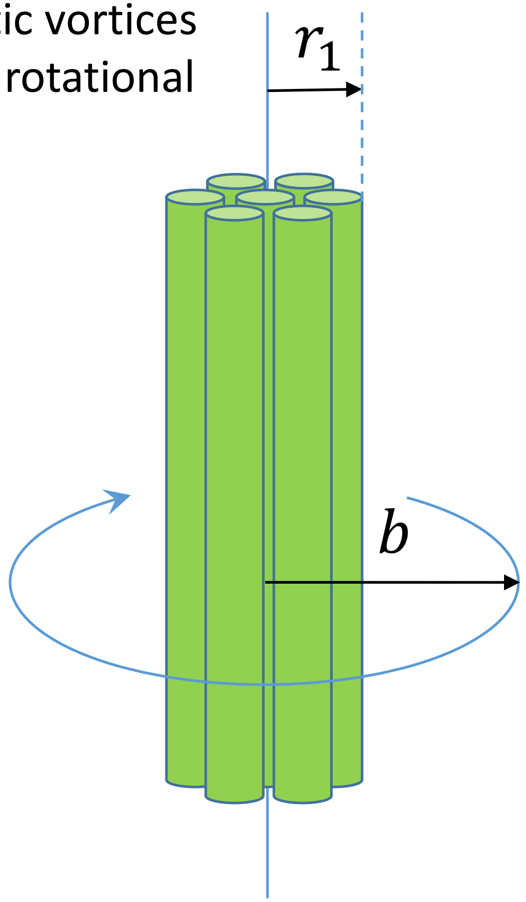
$\vec{j}_p = \frac{e}{m} k \rho_p \vec{v}$ entrainment currents, $k = 0.5$ – entrainment coefficient

$\mathrm{rot}\vec{H} = \frac{4\pi}{c} \vec{j}_p$ Maxwell′s equation

Around a rotational vortex, where the magnetic field of entrainment currents is greater than the first critical field of proton superconductor H_{c1}, proton magnetic vortices appear

Vortex cluster

Cluster of magnetic vortices around rotational vortex



Solution of Maxwell's equation:

$$H = \frac{k\Phi_0}{2\pi\lambda_p^2} \ln\frac{b}{r} \qquad \lambda_p^2 = \frac{m^2c^2}{4\pi e^2\rho_p} \qquad \Phi_0 = \frac{\pi\hbar c}{e} = 2\cdot 10^{-7}\,\mathrm{Gs.\,cm^2}$$

λ_p - magnetic field penetration depth

First critical field of a sferic proton superconductor:

$$H_{c1} = \frac{\Phi_0}{6\pi\lambda_p^2} \ln\frac{\lambda_p}{\xi_p} \qquad H(r_1) = H_{c1} \Rightarrow \frac{r_1}{b} = \left(\frac{\xi_p}{\lambda_p}\right)^{\frac{1}{3|k|}}$$

ξ_p - coherence length

r_1 - radius of magnetic vortex cluster

Mean value of magnetic induction of rotational vortex:

$$\bar{B} = \frac{1}{\pi b^2}\int_0^{r_1}(H(r) - H_{c1})2\pi r dr = \frac{k\Phi_0}{4\pi\lambda_p^2}\left(\frac{\xi_p}{\lambda_p}\right)^{\frac{1}{|k|}}$$

For “npe”-phase:

$$\xi_p = 10^{-12} - 2\cdot 10^{-12}\mathrm{cm}, \qquad \lambda_p = 10^{-11}\mathrm{cm}$$

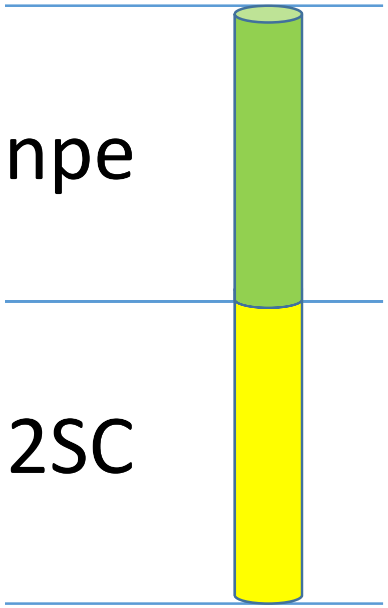
$\bar{B} \sim 10^{12} - 10^{13}$Gs   Coresponds to magnetic field of common radiopulsars

Magnetic field generation in quark phase

Suppose that in case of hybrid star, rotational vortices of “npe”-phase

continue in “2SC”-phase and entrainment currents appear as well

Magnetic field in “2SC”-phase



$$\vec{j}_q = \frac{e}{6m_q}\rho_q \vec{v} \qquad H(r) = \frac{\Phi_0}{\pi\lambda_q^2}\ln\frac{b}{r} \qquad \lambda_q^2 = \frac{\left(2m_q\right)^2 c^2}{4\pi(e/3)^2\rho_q}$$

$$H_{c1} = \frac{\Phi_q}{6\pi\lambda_q^2}\ln\frac{\lambda_q}{\xi_q} \qquad \frac{r_1}{b} = \left(\frac{\xi_q}{\lambda_q}\right)^{\Phi_q/\Phi_0}$$

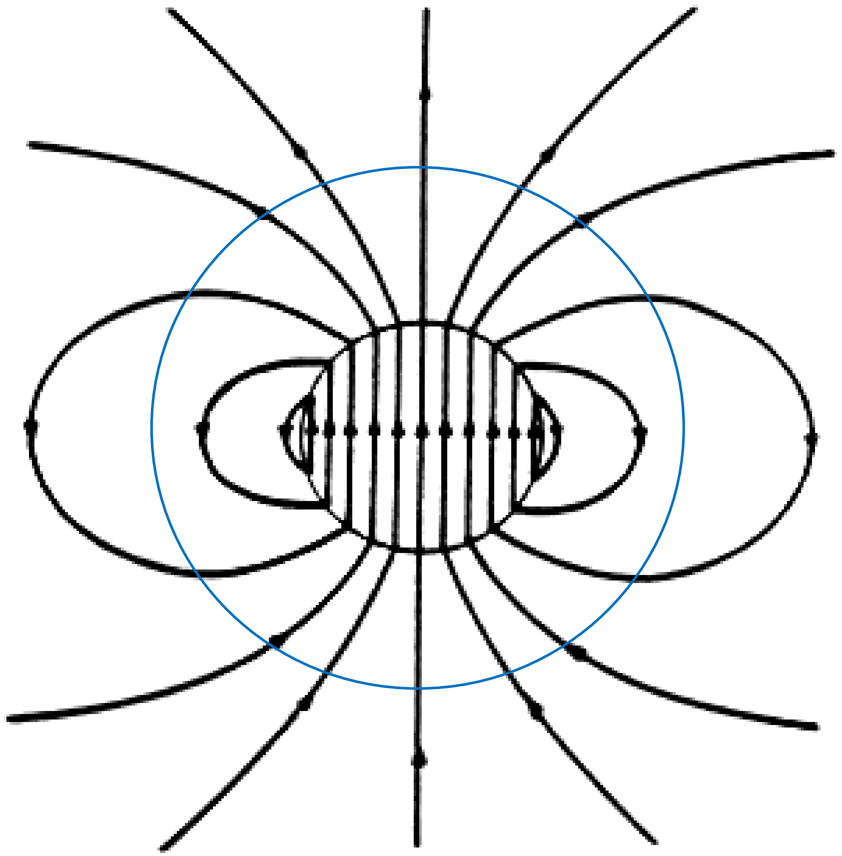
$\Phi_q = 6\Phi_0$ - flux carried by each magnetic quark vortex

$$\bar{B} = \frac{\Phi_0}{2\pi\lambda_q^2}\left(\frac{r_1}{b}\right)^2 = \frac{\Phi_0}{2\pi\lambda_q^2}\left(\frac{\xi_q}{\lambda_q}\right)^2 \quad \xi_q = 10^{-13}\mathrm{cm}, \qquad \lambda_q = 5\cdot 10^{-13} - 10^{-12}\mathrm{cm}$$

$$\bar{B} \sim 5\cdot 10^{14}\mathrm{G} - 5\cdot 10^{15}\mathrm{G}.$$

Cluster field $\bar{B}_c = \frac{\Phi_0}{2\pi\lambda_q^2} \approx 3\cdot 10^{16} - 1.5\cdot 10^{17}\mathrm{G} > H_{c2}\ for\ protons$

Magnetic field on the surface



If proton superconductivity is destroyed in "npe"-phase, the magnetic field is dipolar outside a quark core.

Magnetic momentum of quark core: $M = \frac{\bar{B} R_q^3}{2}$

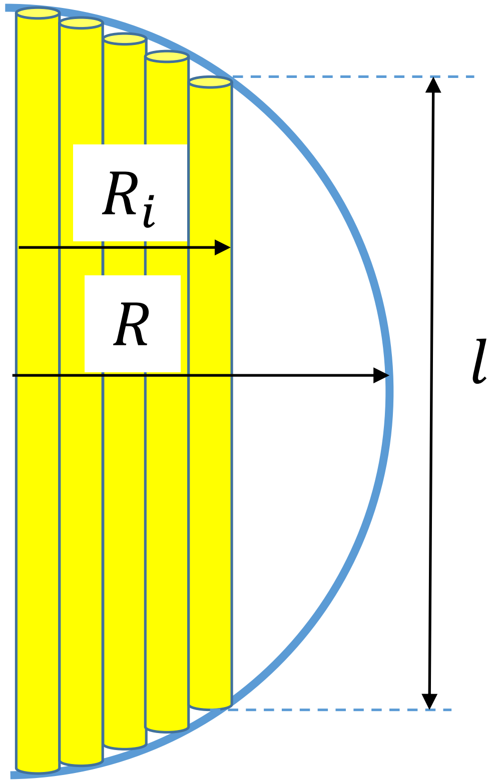
Possible configuration of hybrid star:

$R = 11km, \qquad R_q = 6.5km$

Magnetic field on the surface corresponds to magnetic field of magnetars:

$$B_{ext} \approx \frac{M}{R^3} = \frac{\bar{B}}{2}\left(\frac{R_q}{R}\right)^3 \approx 5 \cdot 10^{13} - 5 \cdot 10^{14}\mathrm{Gs}$$

Vortex-free zone



Due to magnetization of rotational vortex, the vortex-free zone can be formed. The radius of vortex-free zone is defined by ratio of magnetic and mechanical energy densities:

$$\frac{R}{R_i} - \frac{R_i}{R} \approx \left(\frac{\bar{B}^2/8\pi}{\rho_q \Omega^2 R^2/2}\right)^{\frac{1}{2}} = \delta^{1/2}$$

During slow-down of star, vortices move away from rotational axis and annihilate reaching vortex-free zone. Magnetic energy of annihilating vortex can be the source of energy radiation ($l -$ the length of the last vortex):

$$\frac{dE}{dt} = \frac{\bar{B}^2}{8\pi}\left|\frac{\dot{\Omega}}{\Omega}\right| R_i \cdot 2\pi R_i l = 2.5 \cdot 10^{35} \bar{B}_{15}^2 \left|\frac{\dot{\Omega}}{\Omega}\right|_{-12} R_{i6}^2 l_6$$

Energy release in NS

For neutron star

$\text{vortex} - \text{free zone width: } R - R_i \sim 5m$

$\text{last vortex length: } l \sim 100m$

Energy lose $\frac{dE}{dt} \sim 10^{25} - 10^{30} erg/s$=>radioluminosity of pulsars

For hybrid star

Possible model: $R = 6.5km$ $B = 5 \cdot 10^{14} Gs$ $\Omega \sim 5s^{-1}$

$R - R_i \sim 1.5km$ $l \sim 8km$ $\frac{dE}{dt} \sim 10^{34} erg/s \Rightarrow$ X-ray power

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