Some theoretical aspects of Magnetars

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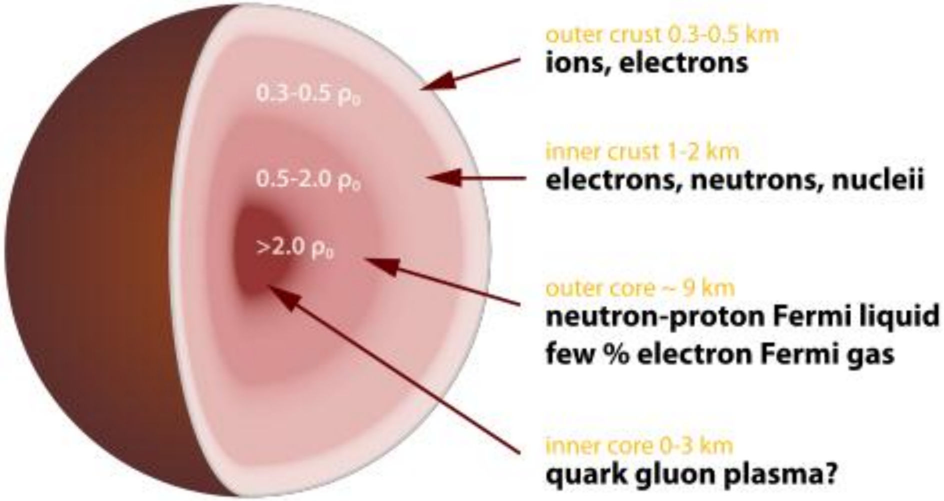
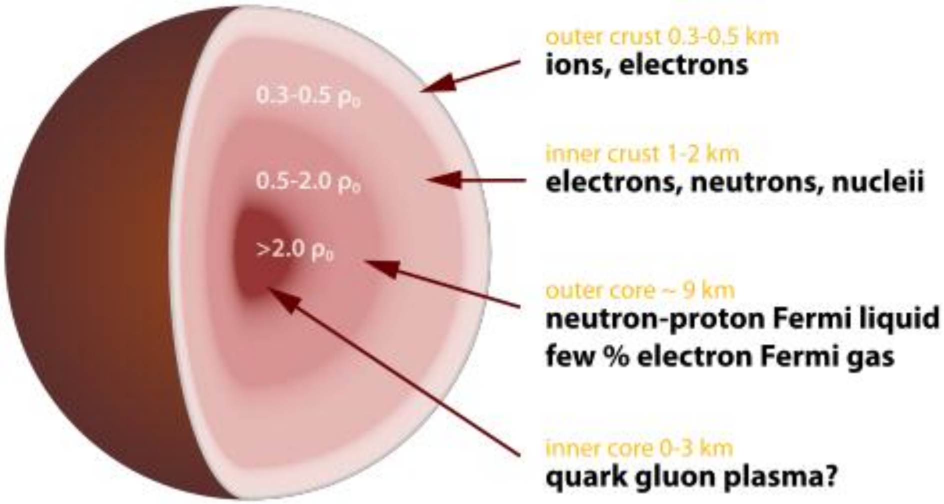
Structure of Neutron star

- Outer crust: ions + electrons a few hundred meters
- Inner crust: electrons + neutrons + neutron rich nuclei about one kilometer
- Outer core: **neutrons** + proton + electrons + muons
- Inner core: ? number of possibilities



Structure of Neutron star

- Nuclear matter
- Hyperon matter
- Pion condensate
- Kaon condendate
- Quark matter



Neutrons in the core could also be in superfluid state.

Theoretical model predicts

- Typical radius of NS is ~ 10 km and mass ~ 1.4 M_{sun}: very compact.
- As NSs are very compact in size, they can withstand fast rotation:

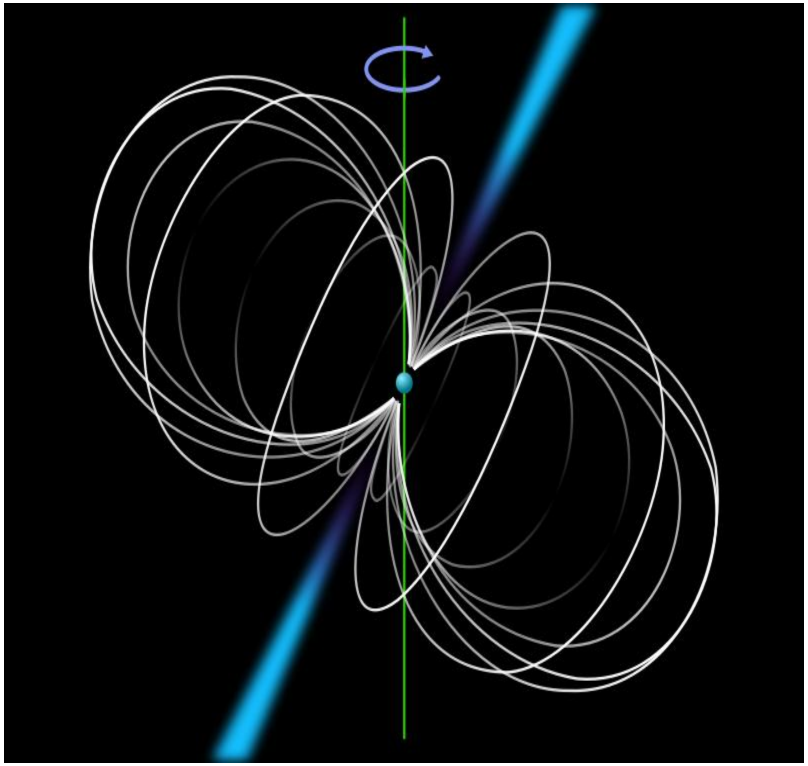
  P ~ ms – s.

- Pulsating stars discovered – PULSARS with pulse period ~ ms – s.
- Radiation from such object is emitted in some particular direction.
- The object is rotating
- When radiation comes into our line of sight we observe the radiation.

What is the cause of directional radiation?

Magnetic field

- Hence, pulsars are soon identified as magnetized rotating NS
- Pulsars are believed to be rotating NS with surface magnetic field $10^8 – 10^{12}$ G.
- Later on NSs were discovered with much higher surface magnetic field $10^{14} – 10^{15}$ G: **MAGNETAR**



Introduction

Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) :

- ➢ Very different from ordinary X-ray bursters and pulsars

- $L_{peak} \sim 10^{45}$ ergs/s, $L_x \sim 10^{35}$ ergs/s.
- Rotational period ~ 5 – 10 s, spin down rate ~ 10^{-11} s/s
- No evidence of binary companions: sometime association with supernova remnants:

Increasing number of common properties:

- ➢ Close relationship between SGRs and AXPs

Introduction

Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) :

- Very different from ordinary X-ray bursters and pulsars

- No correlation between energy and time interval since the previous burst:
  - Trigger of the bursts is not accretion.
- AXPs: Softer spectrum:
  - Neither accretion powered, nor rotation powered.

- Current model: Magnetar – Neutron stars with strong surface magnetic field ~ $10^{14} - 10^{15}$ G.
- The field in the interior of the NS may have higher value.

Effect of magnetic field on matter

Energy momentum tensor of the system:

$$T^{\mu\nu} = T_m^{\mu\nu} + T_f^{\mu\nu}$$

with

$$T_m^{\mu\nu} = \varepsilon_m u^\mu u^\nu - P(g^{\mu\nu} - u^\mu u^\nu) + \frac{1}{2}(M^{\mu\lambda} F_\lambda^\nu + M^{\nu\lambda} F_\lambda^\mu)$$

$$T_f^{\mu\nu} = -\frac{1}{4\pi} F^{\mu\lambda} F_\lambda^\nu + \frac{1}{16\pi} g^{\mu\nu} F^{\rho\sigma} F_{\rho\sigma}$$

$\varepsilon_m \longrightarrow$ Matter energy density

$P \longrightarrow$ Thermodynamic pressure

$M^{\mu\lambda} \longrightarrow$ Magnetization tensor

Effect of magnetic field on matter

- In the rest frame of matter, with the choice of magnetic field

$$\vec{\mathcal{B}} = \mathcal{B}\hat{z} \qquad \vec{E} = 0$$

$$T_m^{\mu\nu} = \begin{bmatrix} \varepsilon_m & 0 & 0 & 0 \\ 0 & P - M\mathcal{B} & 0 & 0 \\ 0 & 0 & P - M\mathcal{B} & 0 \\ 0 & 0 & 0 & P \end{bmatrix},$$

$$\mathcal{B}^\mu \mathcal{B}_\mu = -\mathcal{B}^2$$

$$T_f^{\mu\nu} = \begin{bmatrix} \frac{\mathcal{B}^2}{8\pi} & 0 & 0 & 0 \\ 0 & \frac{\mathcal{B}^2}{8\pi} & 0 & 0 \\ 0 & 0 & \frac{\mathcal{B}^2}{8\pi} & 0 \\ 0 & 0 & 0 & -\frac{\mathcal{B}^2}{8\pi} \end{bmatrix}.$$

$\mathcal{B} \longrightarrow$ Magnetic field

$M \longrightarrow$ Magnetization

$$\varepsilon = \varepsilon_m + \frac{\mathcal{B}^2}{8\pi} \qquad P_\perp = P - M\mathcal{B} + \frac{\mathcal{B}^2}{8\pi} \qquad P_\parallel = P - \frac{\mathcal{B}^2}{8\pi}$$

Effect of magnetic field on matter

$$\mathcal{E} = \mathcal{E}_k + \mathcal{E}_p$$

ε_p contribution from potential energy

In absence of magnetic field

$$\varepsilon_k = \int_0^{p_F} E_p d^3 p$$

$$E_p = \sqrt{p^2 + m^2}$$

In presence of magnetic field

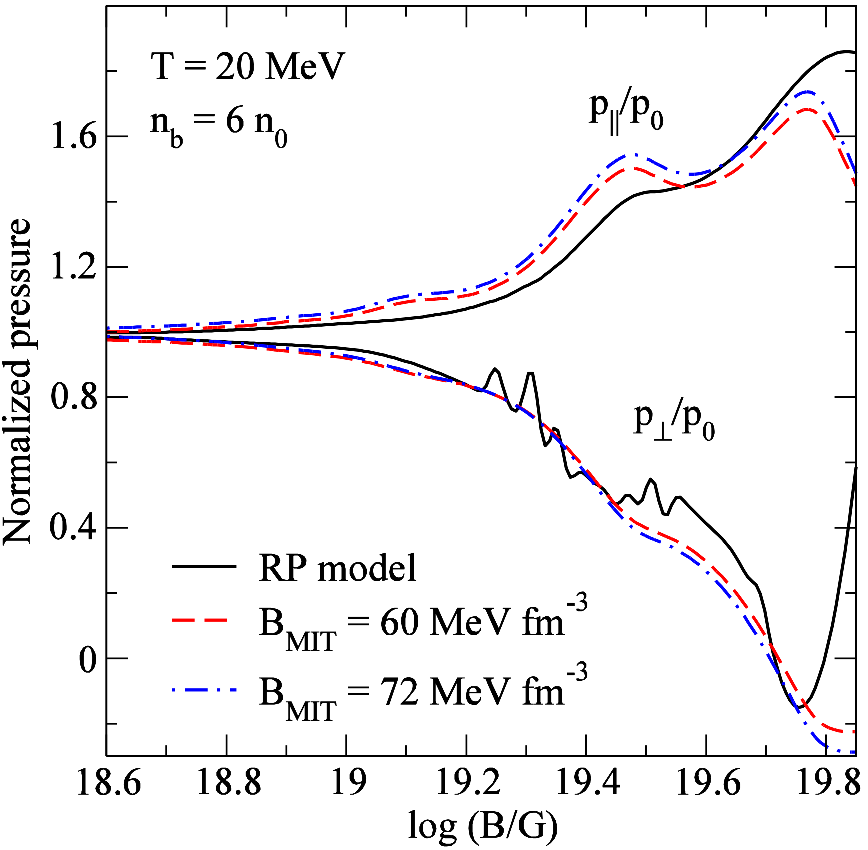
$$\mathbf{p} = (p_z, \mathbf{p}_\perp)$$

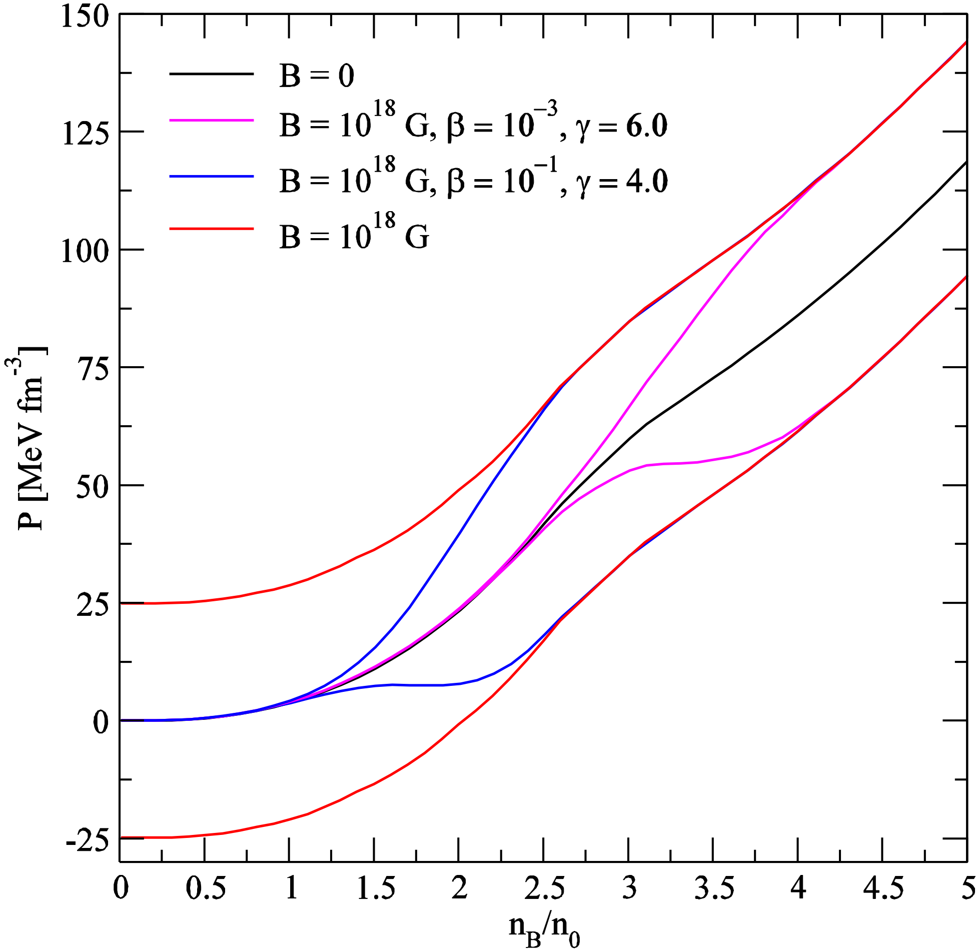
$$|\mathbf{p}_\perp| = 2ne|Q|\mathcal{B}$$

$$E_n = \sqrt{p_z^2 + m^2 + 2ne|Q|\mathcal{B}}.$$

$$\int d^3p \longrightarrow e|Q|\mathcal{B} \sum_n \int_{-p(n)}^{p(n)} dp_z \int_0^{2\phi} d\phi$$

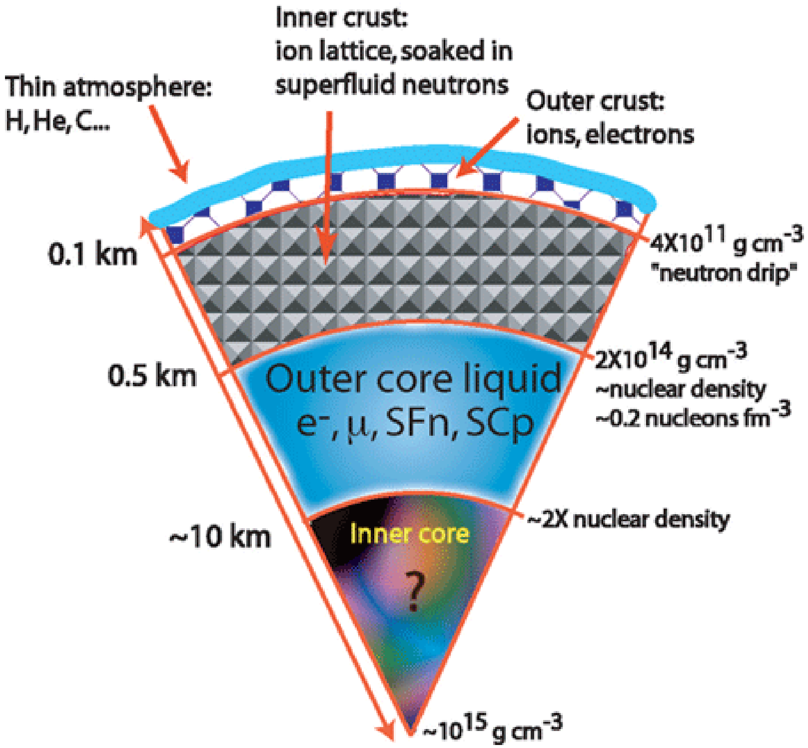
$$p(n) = \sqrt{p_F^2 - 2ne|Q|B}.$$


T = 20 MeV
$n_b = 6\ n_0$
$p_{\parallel}/p_0$
$p_{\perp}/p_0$
RP model
$B_{MIT} = 60$ MeV fm^{-3}
$B_{MIT} = 72$ MeV fm^{-3}
Normalized pressure
1.6
1.2
0.8
0.4
0
18.6
18.8
19
19.2
19.4
19.6
19.8
log (B/G)


B = 0
B = 10^{18} G, $\beta = 10^{-3}$, $\gamma = 6.0$
B = 10^{18} G, $\beta = 10^{-1}$, $\gamma = 4.0$
B = 10^{18} G
P [MeV fm^{-3}]
150
125
100
75
50
25
0
-25
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
n_B/n_0

Superconductivity inside neutron stars

- $B_s = 10^{14} - 10^{15}$ G
- Interior field even greater



Superconductivity inside magnetar **Quenched?**

Superconductivity inside neutron stars

Type-II superconductivity

$$\kappa > \frac{1}{\sqrt{2}}$$

$$\kappa = \frac{\delta_L}{\xi_p}$$

London's penetration depth

Coherence length

Type-II superconductivity exists if

$$H_{c1} < B < H_{c2}$$

$$H_{c2} = \frac{\Phi_0}{2\pi\xi_p^{\,2}}$$

$$\Phi_0 = \frac{nh}{2e}$$

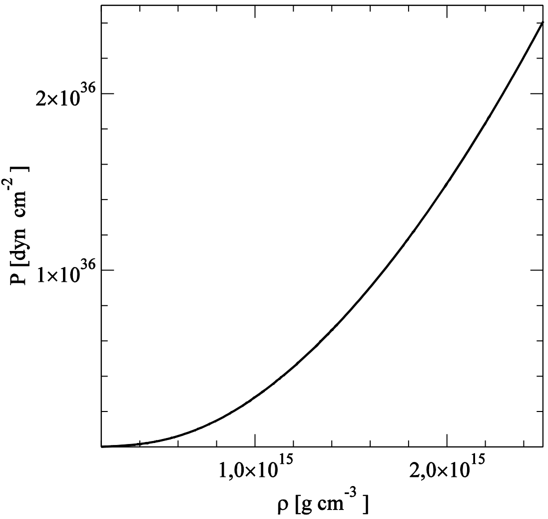
Quantum of flux

From virial theorem

$$B_{max} > H_{c2}$$

$$B_{max} = 10^{18}\ \mathrm{G}$$

Inputs…

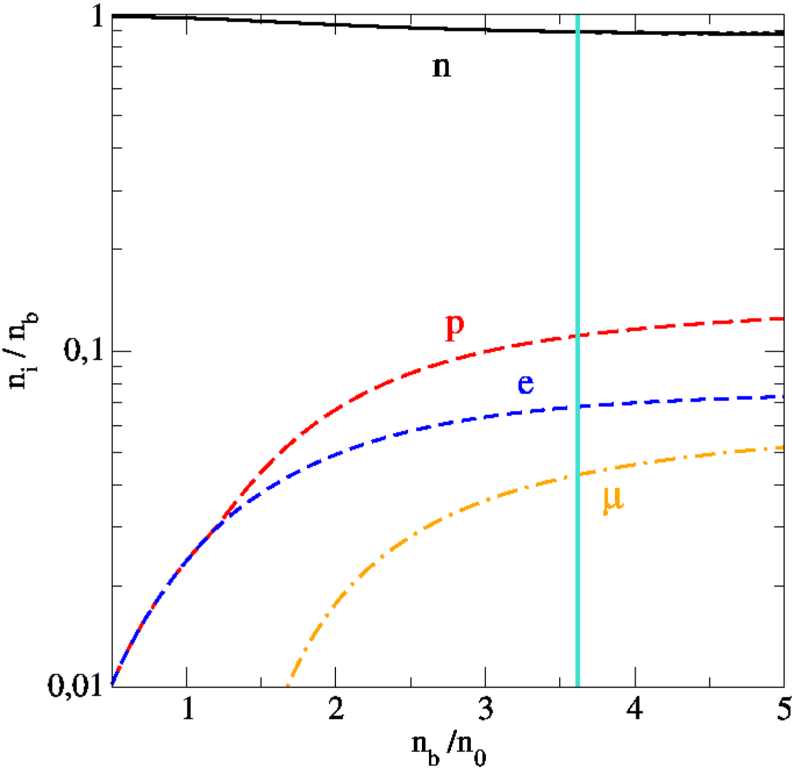


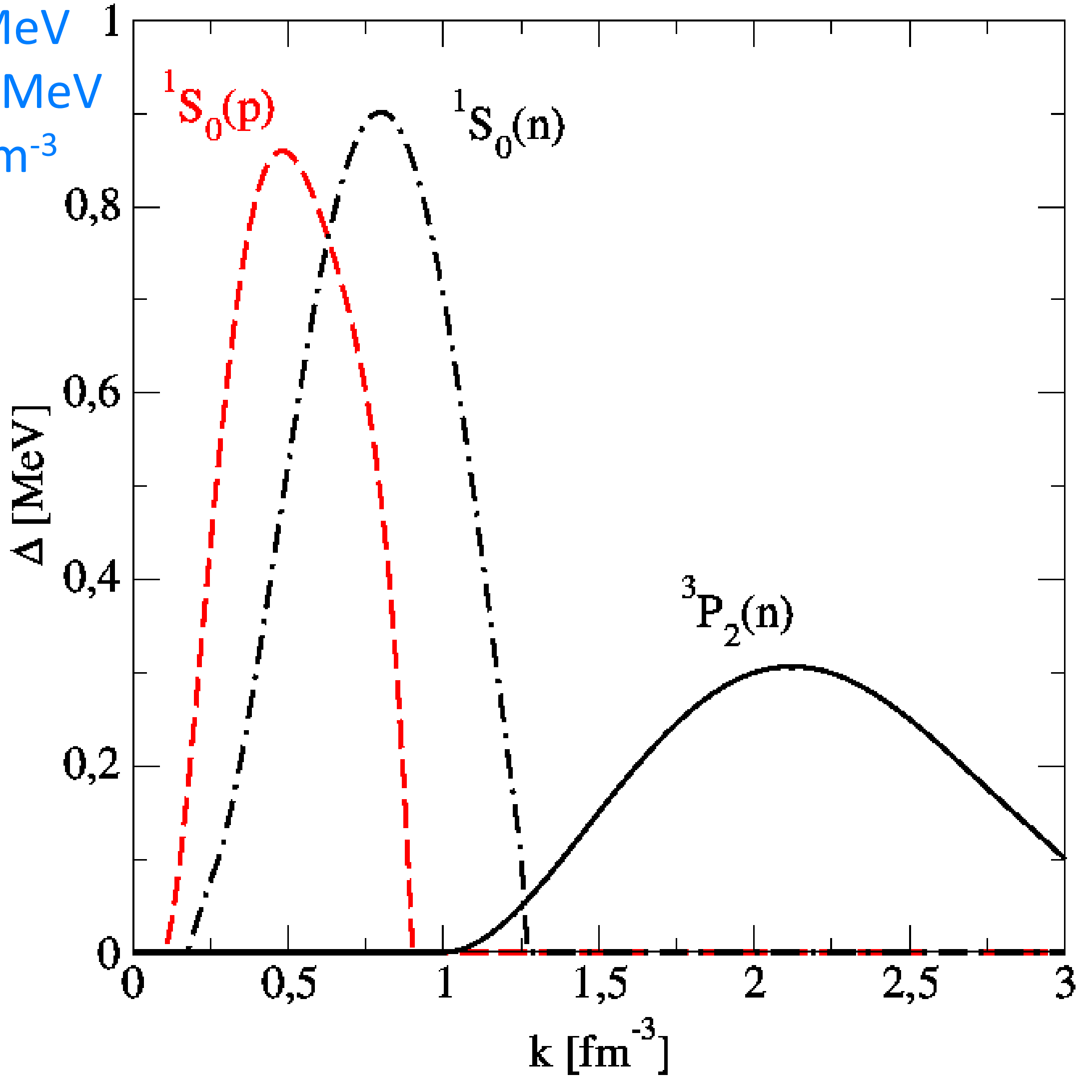
$E/A = -16.14$ MeV

E_s = 32.20 MeV

K_0 = 250.90 MeV

n_0 = 0.152 fm^{-3}





Wambach et al. NPA **555**, 128 (1993)

Baldo et al. PRC **58**, 1921 (1998)

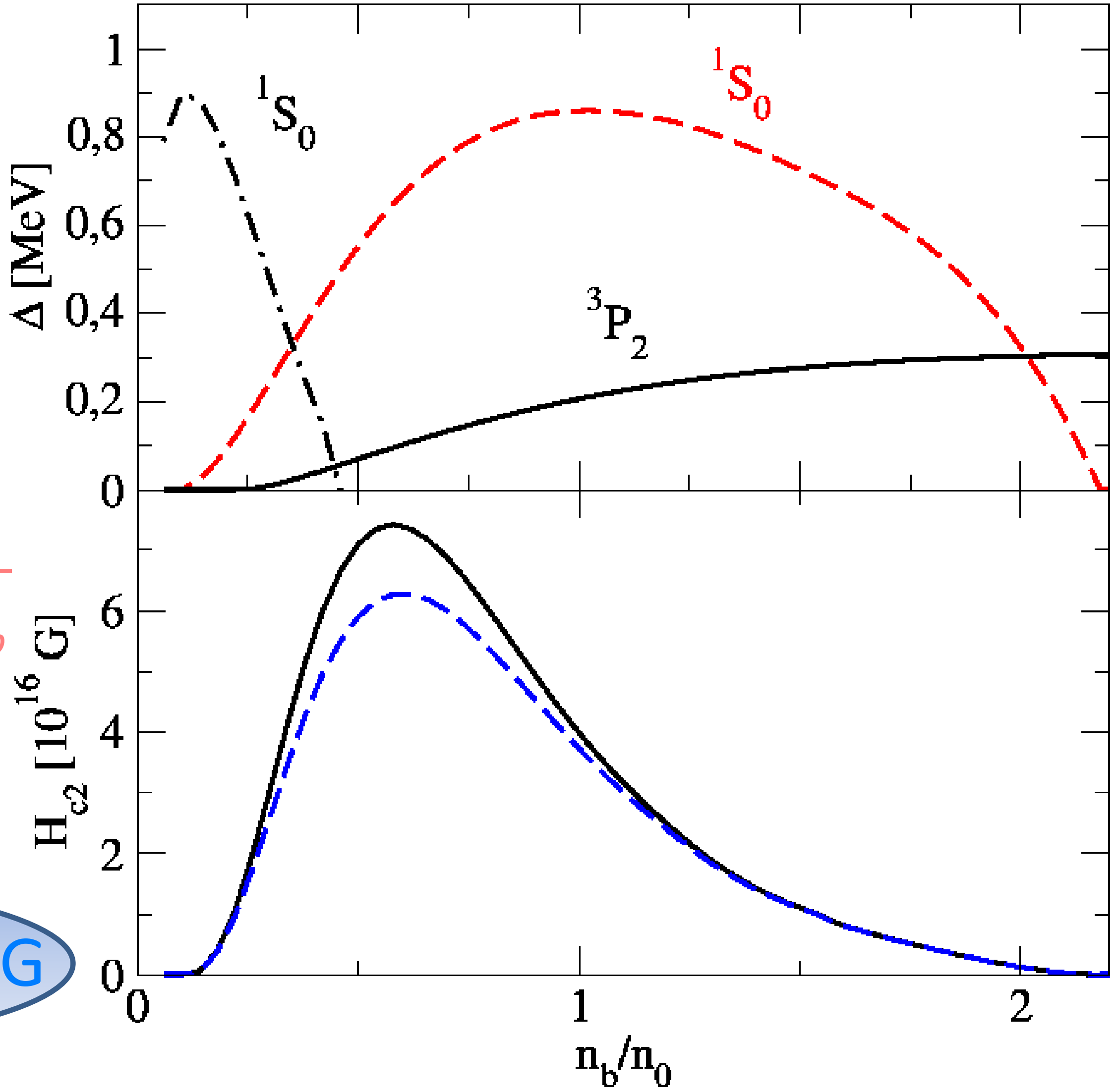
Superconductivity inside neutron stars

$$H_{c2} = \frac{\Phi_0}{2\pi\xi_p^{\,2}}\,[1+f]$$

$$\xi_p = \frac{k_p}{\pi m_{eff}\Delta_p}$$

$$f = \frac{27\pi^2}{8} G_{np} \frac{n_n^{\,2}}{\mu_p^{\,2}\mu_n^{\,2}} \frac{\Delta_p^{\,2}}{m_p k_{F_p}}$$

$\max H_{c2} \cong 6.25 \times 10^{16}$ G



Implications…

Neutrino emissivity

Field decay

Rotational dynamics

glitch

cooling

Reheating

Heat capacity

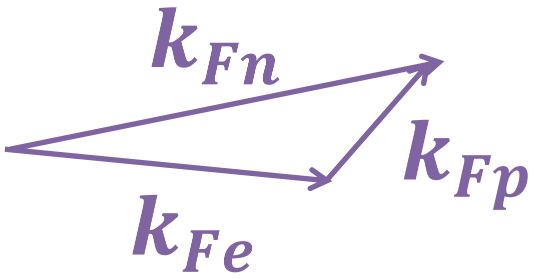
Electrical conductivity

Emissivity

Neutrino emissivity

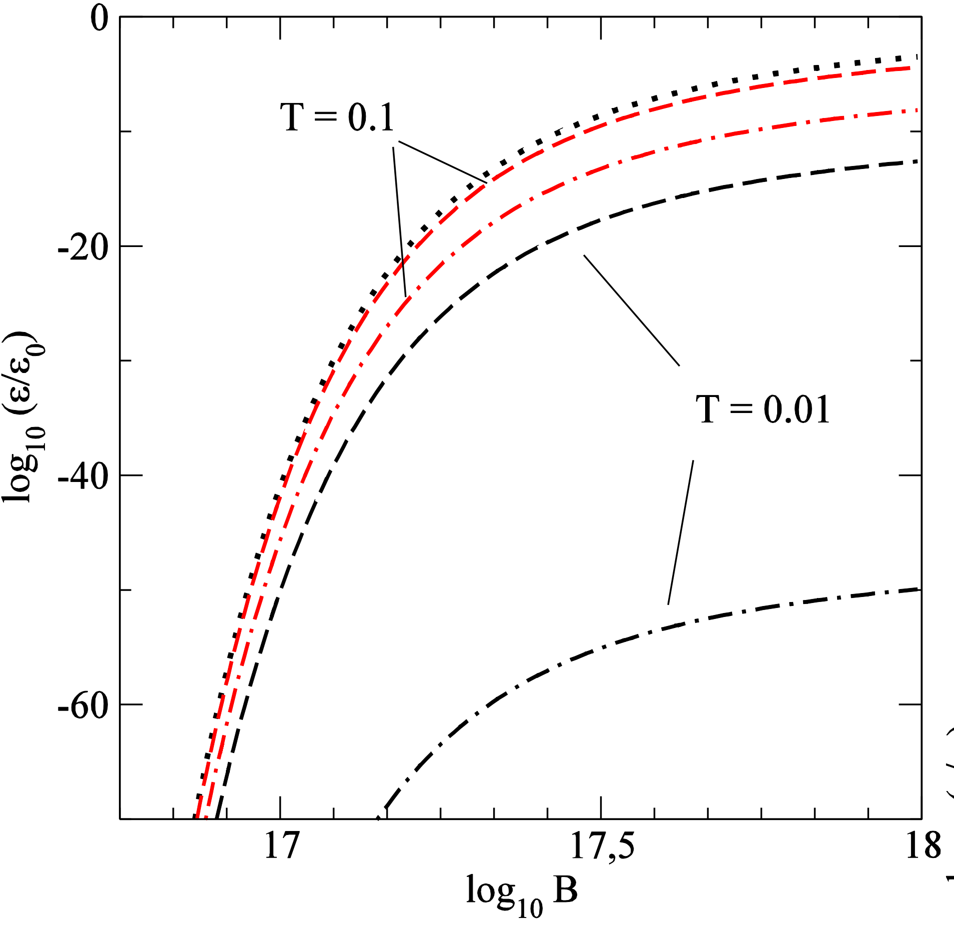
- Direct Urca process
- Pair-breaking process

$$n \rightarrow p + e + \bar{\nu}_e$$



$$x = \frac{{k_{Fn}}^2 - (k_{Fp} + k_{Fe})^2}{{k_{Fn}}^2} {N_{Fp}}^{2/3}$$

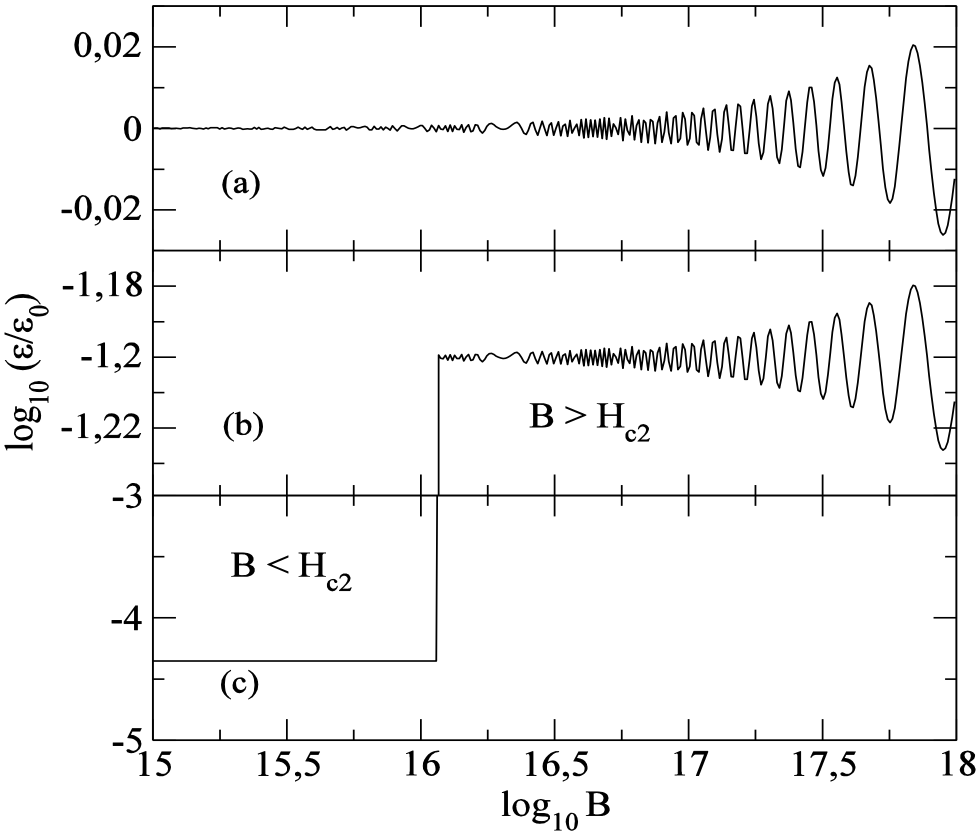
dUrca emissivity



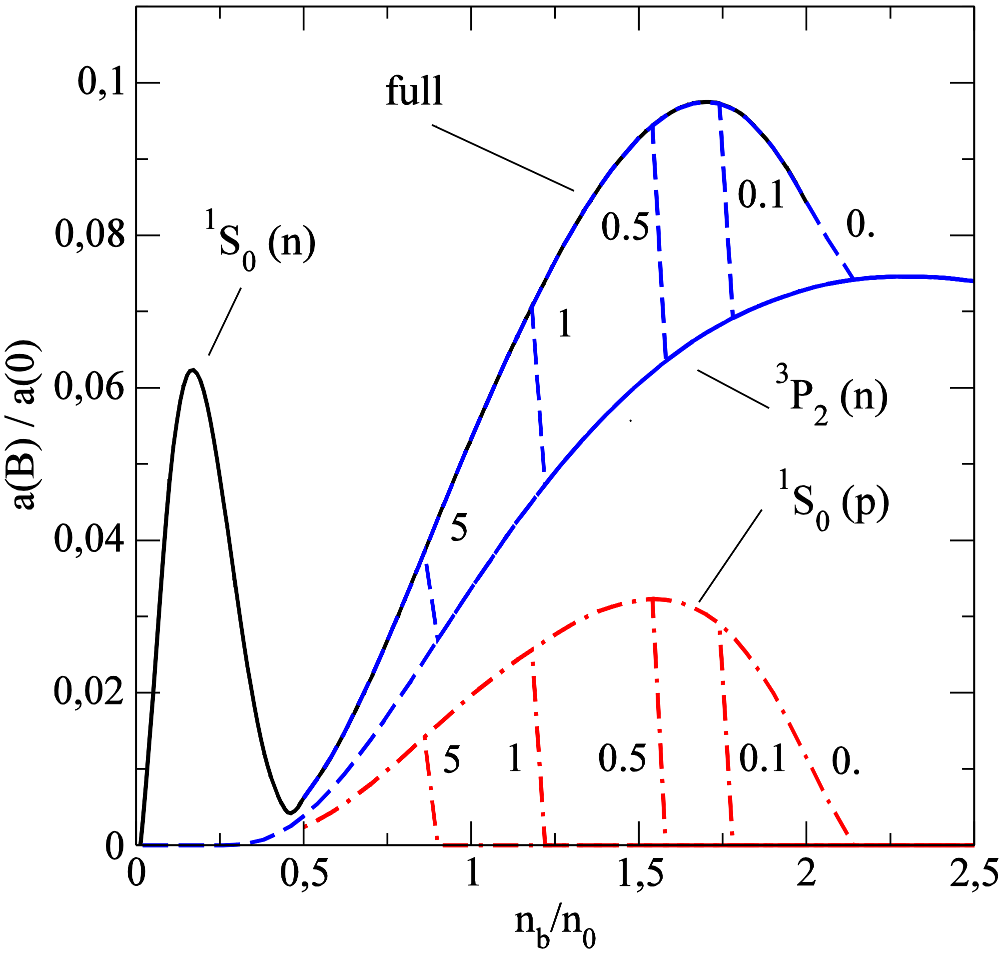
$e^{-(\Delta_n+\Delta_p)/T}$

$x > 0$

$x < 0$



Pair-breaking emissivity



$$\epsilon_{n/p} = =a_{n/p}{}^{S/P}(B)\,\frac{4G_F{}^2}{15\pi^2}T^7\boldsymbol{\mathcal{J}}$$

Summary

- Presence of magnetic field introduces the anisotropic pressure in the system.
- Negative contribution from field pressure of from interaction of matter with field to pressure leads to instability above a critical field.
- Magnetars are fully of partially free of proton superconductivity depending on strength of field inside the magnetars.
- Neutrino emissivity is affected due to unpairing effect.
- Detailed cooling simulations are needed to confront the theory of magnetar with quenched superconductivity with the observations.
- Heat capacity, reheating due to field decay are to be addressed under this condition.
- Electrical conductivity, field decay, rotational dynamic, coupling of normal matter to superfluid matter should be revisited with this result.

Thank you for your attention