Neutron Star Cooling n Strong Magnetic Field : Neutrino -Antineutrino Pair Emission and Diret Urca Porcesses

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T.M. et al., PLB805 (2020) 135413, T.M. et al., arXiv:2103.01703

Collaborators

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Magnetar Neutron-Star with Strong Magnetic-Field

1) Very Strong Magnetic Field $B \sim 10^{14-15}$ G (surface)

$B \sim 10^{17-19}$ G (insides)

Normal Neutron Star $B \sim 10^{12-13}$ G

2) Long Spin Period

$P = 2 \sim 12$ s

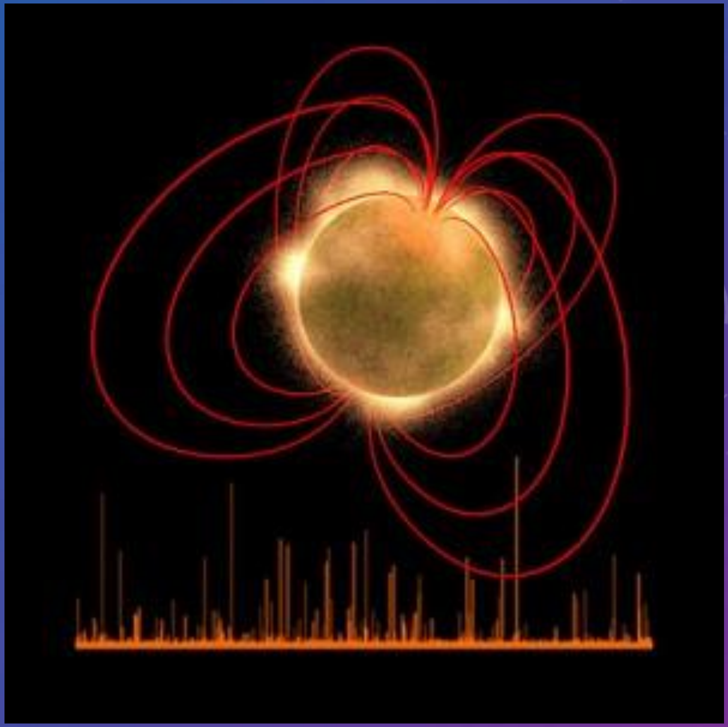
3) Higher Temperature

Magnetic Eng. -> Thermal Eng.

4) Emitting High Energy Photons

Soft Gamma Repeater (SGR)

Anomalous Xray pulsar (AXP)



Neutron Star Cooling

Neutrino Emission → Information on Inside of NSs

1) Modified Urca $n + B \rightarrow p + B + e^- + \bar{\nu}$

Neutrino Luminosity $L \propto T^8$

2) Direct Urca $n \rightarrow p + e^- + \bar{\nu}, \quad p + e^- \rightarrow n + \nu$

Proton Fraction $x_p > \frac{1}{9}$ ($k_n < k_p + k_e = 2\,k_p$: Fermi Mom.)

Neutrino Luminosity $L \propto T^6$

3) neutrino-antineutrino pair emission

$e^- + B \rightarrow e^- + B + \nu + \bar{\nu}$ (Crust, Low Density Region)

Conditions are determined by **Energy Momentum Conservation**

In Strong Magnetic Field

Momentum Conservation is not necessary

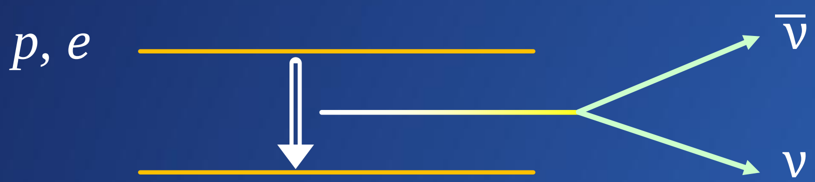
Trans. bet. Two Landau Levels give Additional Momentum

The Present Work

In Strong Magnetic Field

Transition Between Different Landau Level States

1) $e^- \rightarrow e^- + \nu + \bar{\nu}, \quad p^+ \rightarrow p^+ + \nu + \bar{\nu}$ ($\nu\bar{\nu}$ - ***pair Emission***)



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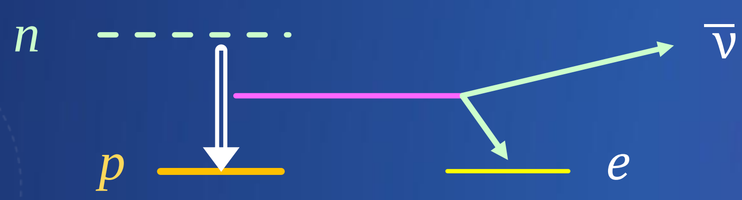
Inner Crust ~ Core

2) $n \rightarrow p + e^- + \bar{\nu}$ (DU) Core



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Neutron-Star Matter with Strong Mag. Field

Nucleon Mean-Fields RMF Theory

Magnetic Field : $\vec{B} = B\hat{z}.$ $\vec{A} = (0, xB, 0)$

Dirac Eq. $$\left\{\boldsymbol{\alpha}\cdot(-i\boldsymbol{\nabla} - q\boldsymbol{A}) + \beta(M - U_s) + U_0 + \frac{e\kappa B}{2M}\right\}\psi(\boldsymbol{r}) = E\psi(\boldsymbol{r})$$

U_s:Scalar Mean-Field

U_0:Vector Mean-Field

AMM

$BE = 16$ MeV, $M_N^*/M_N = 0.70$,

$K = 200$ MeV , $e_{sym} = 32$MeV

at $\rho_0 = 0.17$ fm^{-3}

Single Particle Energies and Wave-Functions

Single Pariicle Energy

Landau Level Number

p & e

$$E(n, p_z, s) = E^* + U_0 = \sqrt{p_z^2 + (\sqrt{2eBn} + M^{*2} + se\kappa B/2M)^2} + U_0$$

n

$$E(n, p_z, s) = E^* + U_0 = \sqrt{p_z^2 + (\sqrt{\boldsymbol{p}_T^2 + M^{*2}} + se\kappa B/2M)^2} + U_0,$$

Wave-Fuction

p & e

$$\psi_{n,s,p_z}(\boldsymbol{r}_1)\overline{\psi}_{n,s,p_z}(\boldsymbol{r}_2) = \frac{e^{i(p_y y + p_z z)}}{\sqrt{R_y R_z}} \hat{F}\left(x_1 - p_y/eB\right) \frac{\rho_M}{4E} \hat{F}\left(x_2 - p_y/eB\right)$$

$$\rho_M(n, s, P_z) = \left[E^*\gamma_0 - \zeta\sqrt{2neB}\gamma_2 - p_z\gamma_z + M^* + \frac{e\kappa B}{2M}\Sigma_z\right]\left[1 + \frac{s}{\sqrt{2neB + M^{*2}}}\left(\frac{e\kappa B}{2M} + p_z\gamma_5\gamma^0 - E^*\gamma_5\gamma^3\right)\right]$$

$\tilde{F} = \mathrm{diag}(f_n, f_{n-1}, f_n, f_{n-1})$ **p**

$= \mathrm{diag}(f_n, f_{n-1}, f_{n-1}, f_n)$ **e**

Neutron

$$\psi_{\mathbf{p},\mathbf{s}}(\boldsymbol{r}_1)\overline{\psi}_{\mathbf{p},\mathbf{s}}(\boldsymbol{r}_2) = \frac{e^{i\mathbf{p}\cdot(\mathbf{r}_1 - \mathbf{r}_2)}}{\sqrt{\Omega}}\left[E^*\gamma_0 - \boldsymbol{p}\cdot\cdot\boldsymbol{\gamma} + M^* + \frac{e\kappa B}{2M}\Sigma_z\right]\left\{1 + \frac{s}{\sqrt{\boldsymbol{p}_T^2 + M^{*2}}}\left[\frac{e\kappa B}{2M} + \gamma_5\left(p_z\gamma^0 - E^*\gamma^3\right)\right]\right\}$$

Decay Width of *νν̄ - pair Emission*

Total Luminosity

$$L_{\nu\bar{\nu}} = \frac{\pi G_F^2}{8} \sum_{n_i,s_i} \sum_{n_f,s_f} \int \frac{dp_{iz}}{2\pi} \frac{d^3k_{iz}}{(2\pi)^3} \frac{d^3k_{fz}}{(2\pi)^3} \frac{N_{\mu\nu}L^{\mu\nu}}{|\boldsymbol{k}_i||\boldsymbol{k}_f|e_i e_f} (|\boldsymbol{k}_i| + |\boldsymbol{k}_f|) f(e_i)[1 - f(e_f)] \delta(e_i - e_f - |\boldsymbol{k}_i| - |\boldsymbol{k}_f|)$$

Landau Level Transition Energy is kept to be a few MeV

$$\sqrt{eB} = 2.43\text{MeV} \quad \text{when } B = 10^{15}\text{G}$$

Low Temperature Expansion ($T << 1$)

$$f(e) = \frac{1}{1 + \exp[(e-\mu)/T]} \approx \Theta(e-\mu) + a_C T^2 \delta'(e-\mu)$$

Unavailable!

Emitted Particle Energy ~ T (Temperature)

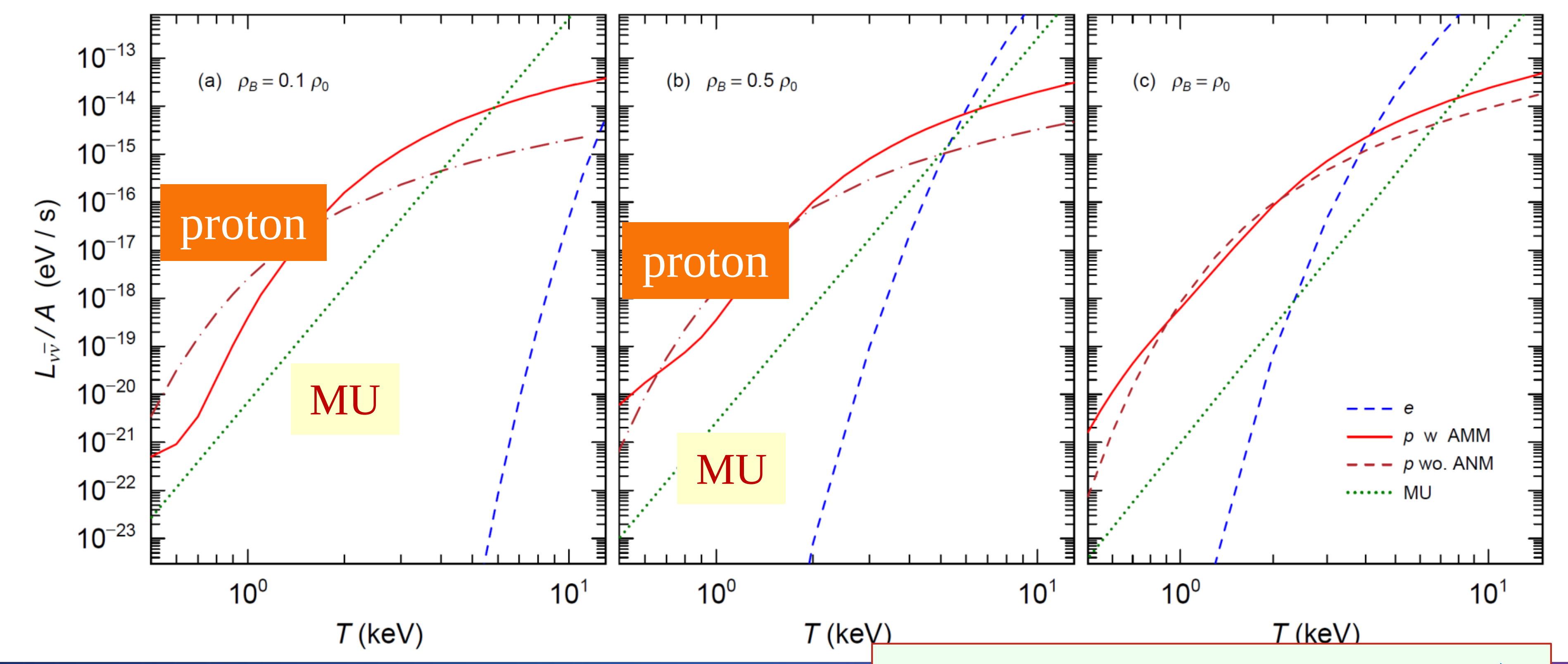
In Strong Mag. Fld. $f(e_i) \sim (1 - f(e_f)) << 1$

$(e_i - e_f) >> T$

Neutrino Luminosity in $\nu\bar{\nu}$ - *pair Emission*

Temperature Dependence

$B = 10^{15}$ G

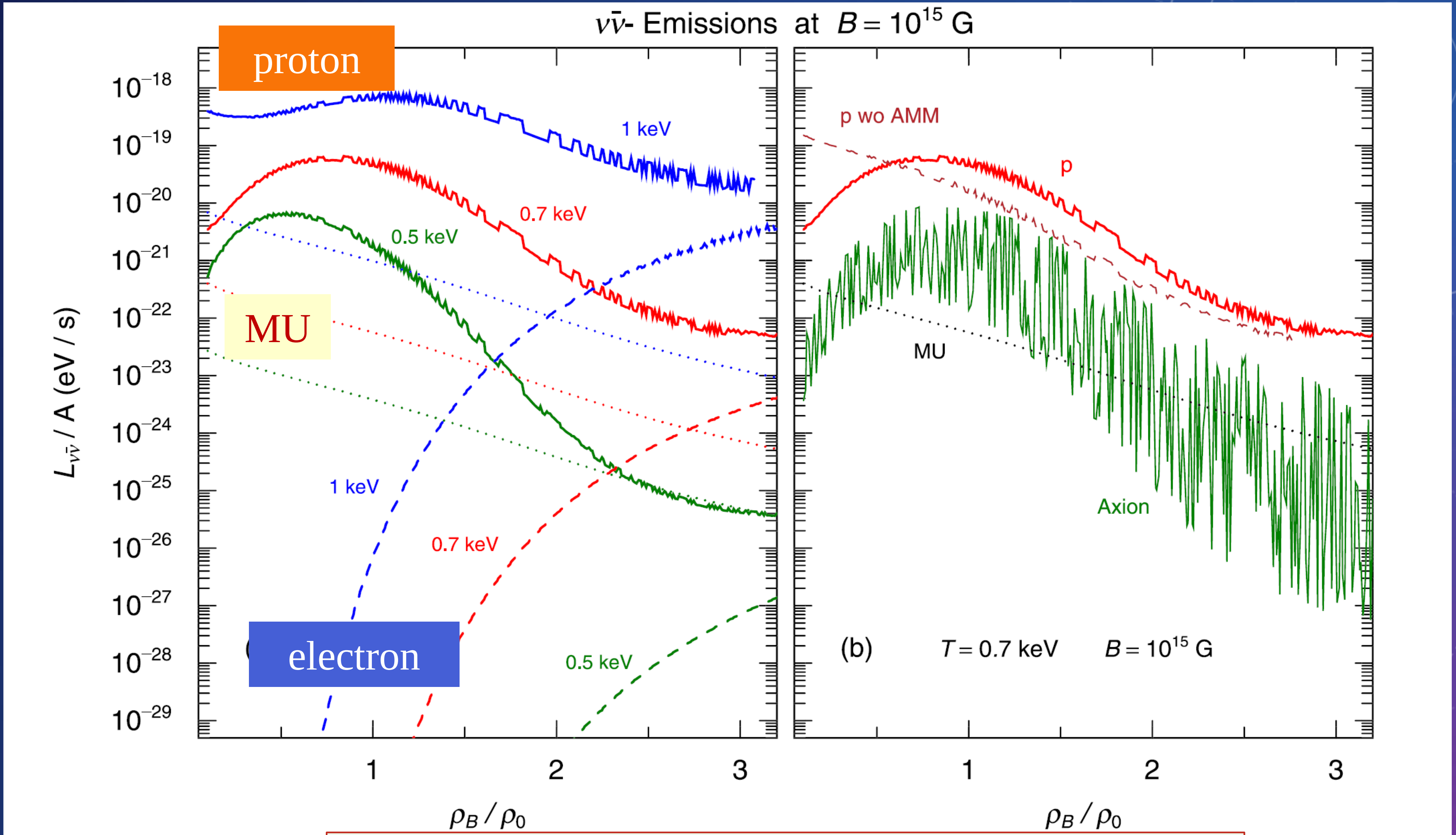


($\nu\bar{\nu}$-Pair) >> (Modified Urca)

EOS: $BE = 16$ MeV, $M_N^*/M_N = 0.70$,

$K = 200$ MeV , $e_{sym} = 32$MeV at $\rho_0 = 0.17$ fm^{-3}

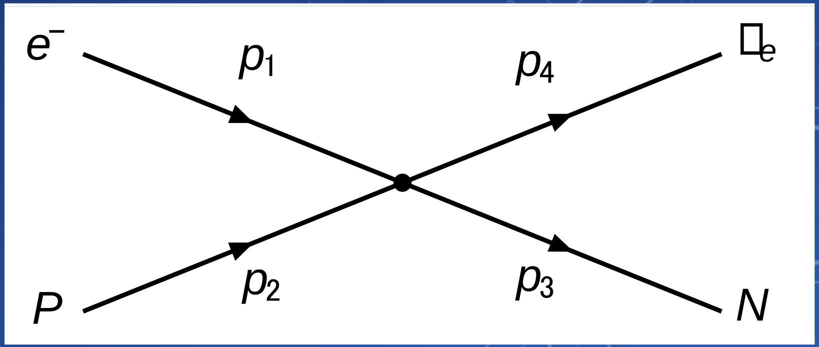
Density Dependence



($\nu\bar{\nu}$-Pair) >> (Modified Urca)

Effects of Magnetic Fields are Very Large

Direct Urca Process



Low Temperature Limit

$T \to 0$

$$e_\nu^3 n_n(E_n)[1-n_p(E_p)]n_e(e_z) = \mathcal{I}_{DU}\delta(E_n-\mu_n)\delta(E_p-\mu_p)\delta(e_e-\mu_e).$$

$$\mathcal{I}_{DU} = \int dE_n dE_p dE_e (E_n - E_p - E_e)^3 n_n(E_n)[1-n_p(E_p)][1-n_e(E_e)] = \frac{457}{5040}\pi^6 T^6.$$

All Particles on Fermi Surface

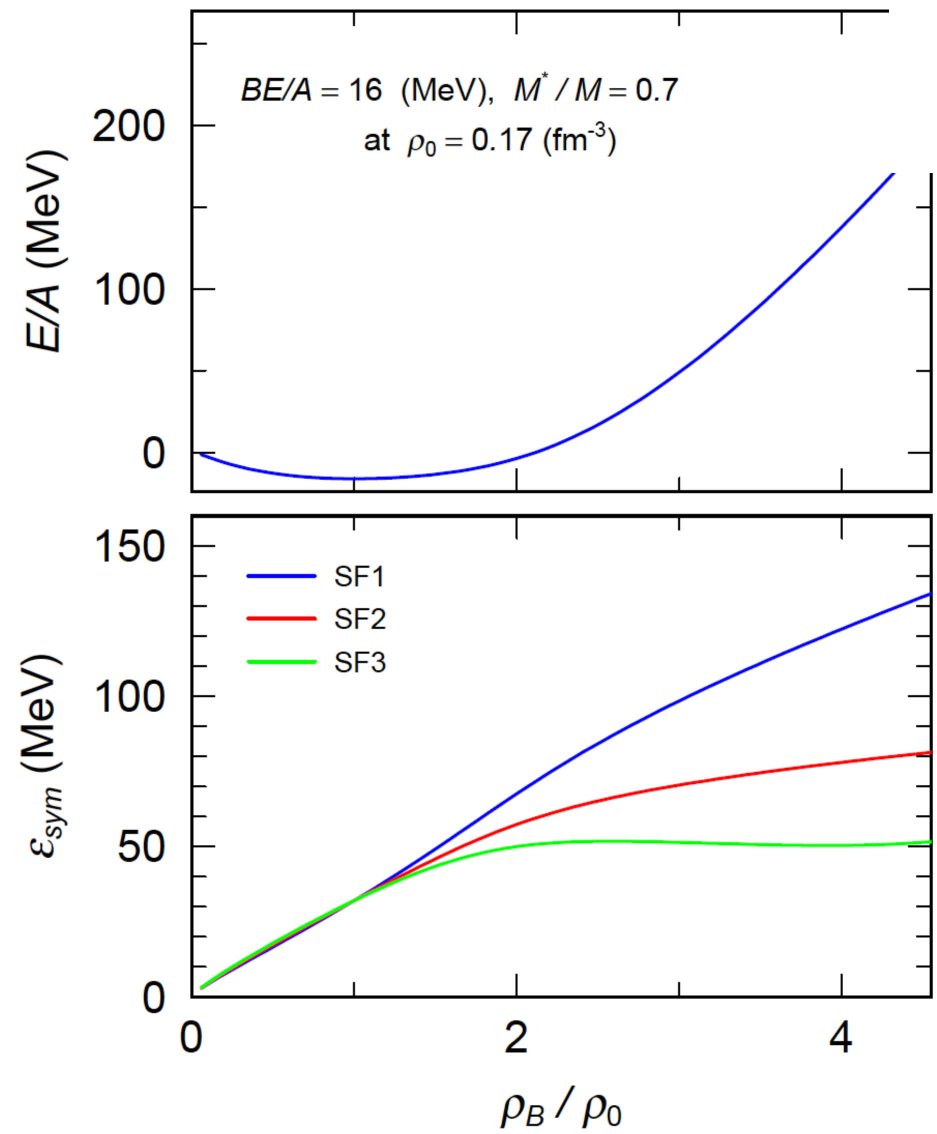
Neutrino Emissivity

$$\epsilon_{DU} = \frac{457\pi G_F^2}{2^7 \cdot 5040} T^6 \sum_{n_e,n_p} \frac{p_{nT}}{p_{pz}p_{ez}\sqrt{p_{nT}^2 + M_n^{*2}}} \sum_s \sum_{i,j} \int \frac{d\Omega_4}{4\pi} \mathcal{M}(j_1,i_1)\mathcal{M}^*(j_2,i_2)\frac{L_{\mu\nu}N^{\mu\nu}}{e_\nu}.$$

$$\mathcal{M}(j_p,j_l) = \int dx f_{n_e+(j_l-1)/2}\left(x + \frac{p_{nT}}{\sqrt{2eB}}\right) f_{n_p+(j_p-1)/2}\left(x - \frac{p_{nT}}{\sqrt{2eB}}\right),$$

$f_n(x)$: 1dim. HO Wave-Function

Nuclear Matter RMF Equations of State



$$
\begin{aligned}
\mathcal{L} &= \bar{\psi}_N(i\partial\!\!\!/ - M)\psi_N + g_\sigma\bar{\psi}_N\psi_N\sigma + g_\omega\bar{\psi}_N\gamma_\mu\psi_N\omega^\mu \\
&\quad -\frac{C_s^{IV}}{2M^2}(\bar{\psi}_N\tau\psi_N)^2 - \frac{C_v^{IV}}{2M^2}(\bar{\psi}_N\gamma_\mu\tau\psi_N)^2 \\
&\quad -\widetilde{U}[\sigma] + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu .
\end{aligned}
$$

Two kinds of symmetric force

Lorenz Vector & Scalar

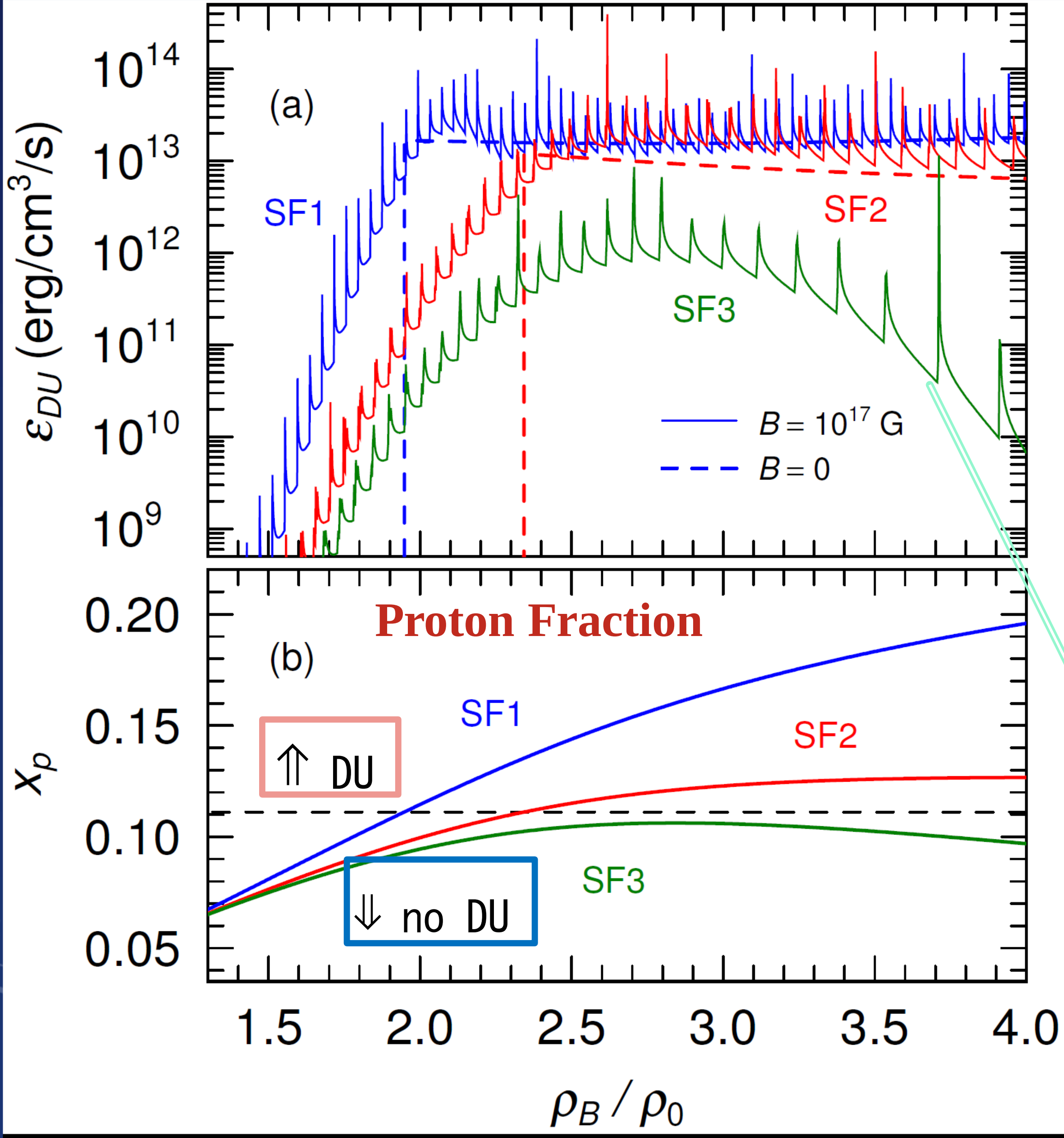
Parameter-Set	C_s^{IV}	C_v^{IV}	L (MeV)
SF1	0	20.42	92.7
SF2	23.61	0	84.1
SF3	33.02	-8.154	81.0

SF1 : Vector Type Sym. Force

SF2 : Scalar Type Sy, Force

SF3: Negative Vector

Density-Dependence of the Neutrino Emissivity in DU



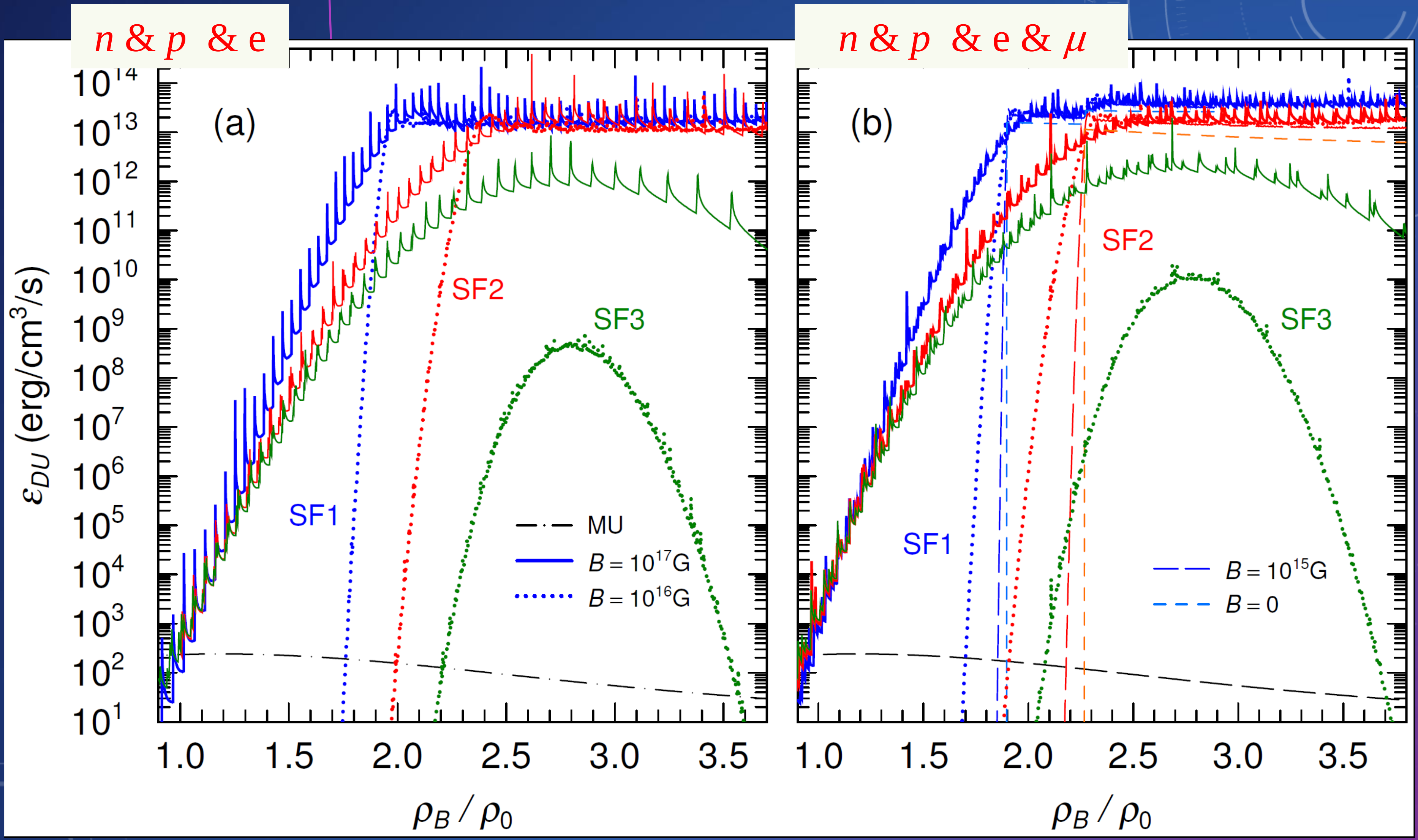
NS matter consistss of
n & *p* & e

Spikes reflect the density of states given by the Landau levels

Neutrinos emitted through Transitions between Landau levels

DU does not appear when B=0

Density & Mag. Fld. Dep. of the Neutrino Emissivity



Summary

Laudau Levels are introduced into Calculations
of Neutrino Emissions in Strong Magnetic Field

$\nu\bar{\nu}$ - Pair Emission	**Energy Loss ≫ MU**

DU process from NS matter

Three Parameter-sets for Symmetry Energy

Proton Fraction ⟷ the Neutrino Emissivity.

In the forbidden region $x_p < 1/9$ ⇨ Mag. Fld. make DU

At Low Temp. Limit, **Mag. Effect** in DU is **not very Large** when $x_p < 1/9$.

Because of Low Temperature Approximation (?) .

ν-Emissivity may become Larger in Exact Calculations

Matter include MuonEmissivity