

# ストレンジネスを含む強磁場原始中性子星内部 でのニュートリノ散乱、吸収および運動量移行

ストレンジ核物理2010 KEK

丸山 智幸	日大・生物資源	(Japan)
梶野 敏貴	国立天文台、東大	(Japan)
安武 伸俊	国立天文台	(Japan)
Cheoun, Myung-ki	Soongsil大学	(Korea)
Ryu, Chung-Yoe	Soongsil大学	(Korea)

# § 1. 導入

原始中性子星の内部構造      ハイペロン物質      強磁性  
どのように確かめられるか？      観測量      ニュートリノ

S.Reddy, M.Prakash and J.M. Lattimer, P.R.D58 #013009 (1998)

,      の影響を議論

強磁場中性子星      **Magnetar** :

表面  $\sim 10^{15}$  G , 内部  $\sim 10^{17} - 10^{19}$  G (?)      大きな異方性?

**磁場の影響**      P. Arras and D. Lai, P.R.D60, #043001 (1999)

S. Ando, P.R.D68 #063002 (2003)

星表面でのニュートリノ散乱、吸収

今回の研究      高温高密度中でのニュートリノ散乱、吸収

ニュートリノ伝搬

# パルサー・キック

A.G.Lyne, D.R.Lomier, Nature 369, 127 (94)

## 光速で移動するパルサー

平均 400 km/s , 最高 1500 km/s

## 爆発の非対称性

中性子星に並進速度

爆発のほとんどのエネルギーは  
ニュートリノとして放出  $\sim 10^{53}$  erg

1% の異方性で十分

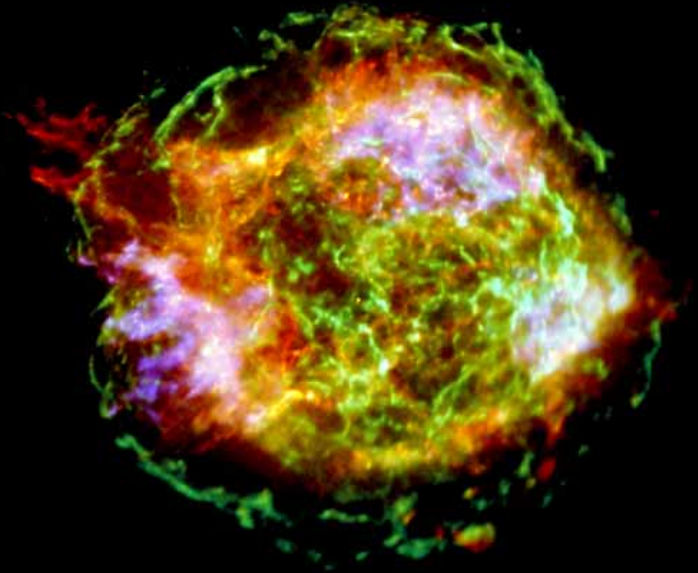
## 強磁場中でのニュートリノ散乱、吸収

マグネター(強磁場中性子星) 表面  $\sim 10^{15}$  G , 内部  $\sim 10^{17} - 10^{19}$  G (?)

$T = 20 \sim 40$  MeV      2 ~ 4 % の異方性      T.M., et al, arXiv:nucl-th/1009.0976

パルサー・キックをどの程度説明できるか？

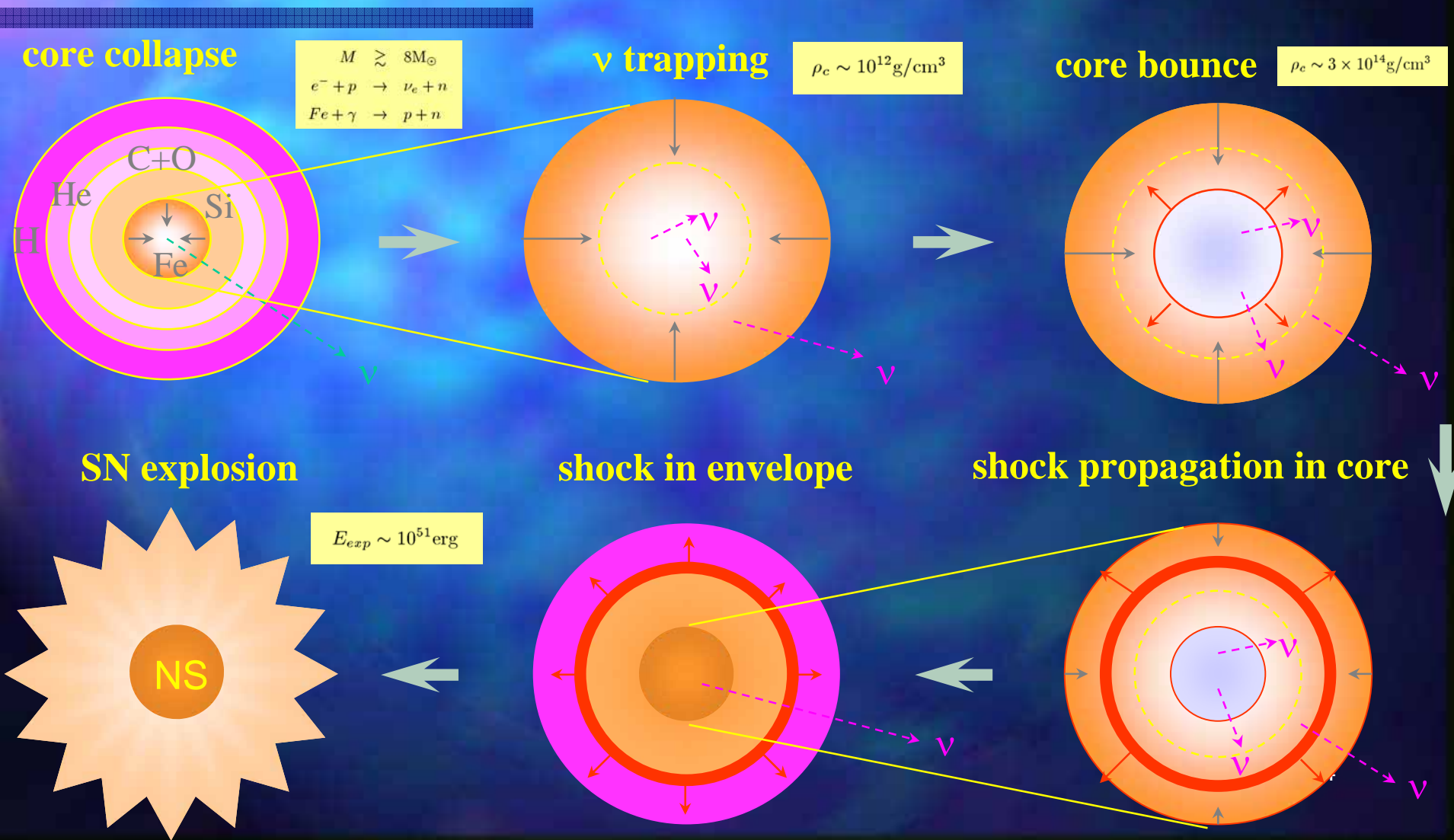
CasA



[http://chandra.harvard.edu/photo/2004/casa/casa\\_xray.jpg](http://chandra.harvard.edu/photo/2004/casa/casa_xray.jpg)



# Birth of Proto-neutron Star



## § 2. Formulation

**Magnetic Field :**  $\vec{B} = B\hat{z}.$

Lagrangian :  $\mathcal{L} = \mathcal{L}_{RMF} + \mathcal{L}_{lep.} + \mathcal{L}_{mag} + \mathcal{L}_{int}$

**Baryon**

**Lepton**

**B & L - Mag.**

**Weak Interaction**

$\nu_e + B$        $\nu_e + B$  : scattering

$\nu_e + B$        $e^- + B'$  : absorption

$$\mathcal{L}_{int} = G_F \{ \bar{\psi}_l \gamma_\mu (1 - \gamma_5) \psi_l \} \{ \bar{\psi}_{B'} \gamma^\mu (c_V - c_A \gamma_5) \psi_B \}$$

## § 2-1 Neutron-Star Matter in RMF Approach

RMF Lagrangian

$$\begin{aligned}\mathcal{L}_{RMF} = & \bar{\psi}_N(i\partial - M_N)\psi_N + \bar{\psi}_\Lambda(i\partial - M_\Lambda)\psi_\Lambda + g_\sigma\bar{\psi}_N\psi_N\sigma + g_\sigma^\Lambda\bar{\psi}_\Lambda\psi_\Lambda\sigma \\ & + g_\omega\bar{\psi}_N\gamma_\mu\psi_N\omega^\mu + g_\omega^\Lambda\bar{\psi}_\Lambda\gamma_\mu\psi_\Lambda\omega^\mu - \tilde{U}[\sigma] + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu\end{aligned}$$

$\psi_N$  (nucleon),  $\psi_\Lambda$  ( $\Lambda$ ),  $\sigma$  and  $\omega$  + **p-n Symmetry Force**

$\tilde{U}[\sigma]$  : the self-energy potential of the scalar mean-field.

$$[\not{p} - M_N^* - U_0(N)\gamma_0] u_N(p) = 0 \quad [\not{p} - M_\Lambda^* - U_0(\Lambda)\gamma_0] u_\Lambda(p) = 0$$

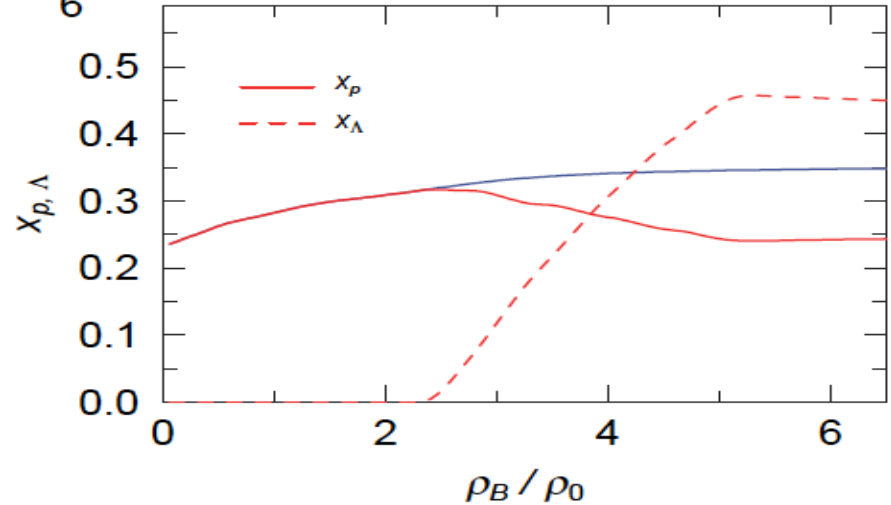
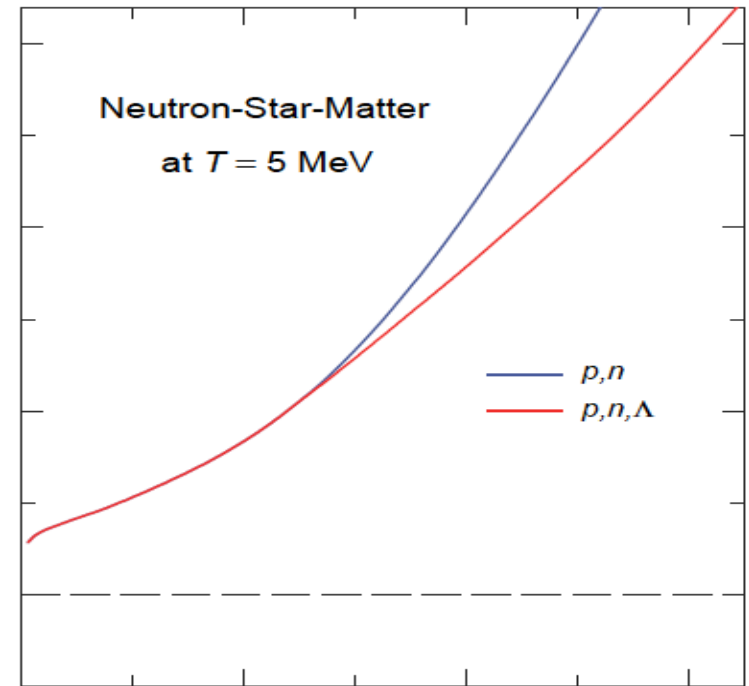
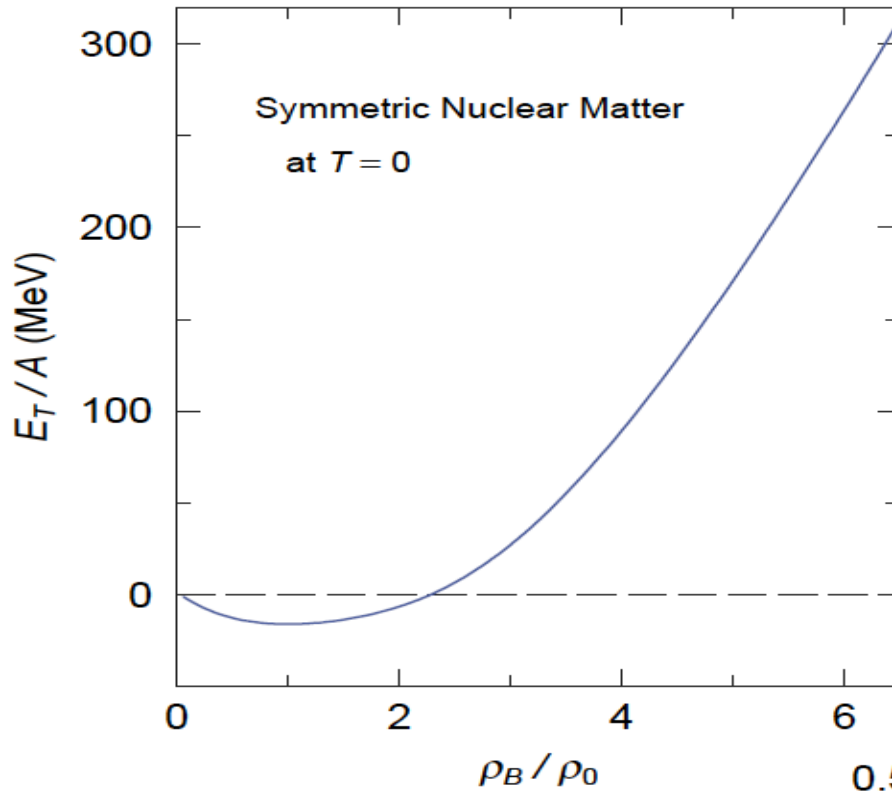
$$M_N^* = M_N - g_\sigma\sigma \quad M_\Lambda^* = M_\Lambda - g_\sigma^\Lambda\sigma$$

$$U_0(N) = \frac{g_\omega}{m_\omega^2}(g_\omega\rho(N) + g_\omega^\Lambda\rho_\Lambda) \quad U_0(\Lambda) = \frac{g_\omega^\Lambda}{m_\omega^2}(g_\omega\rho(N) + g_\omega^\Lambda\rho_\Lambda)$$

$$\frac{\partial}{\partial\sigma}\tilde{U}[\sigma] = g_\sigma\rho_s(N) + g_\sigma^\Lambda\rho_s(\Lambda)$$

# EOS of PM1-1

$BE = 16 \text{ MeV}$ ,  $M_N^* / M_N = 0.7$ ,  $K = 200 \text{ MeV}$  at  $\rho_0 = 0.17 \text{ fm}^{-3}$



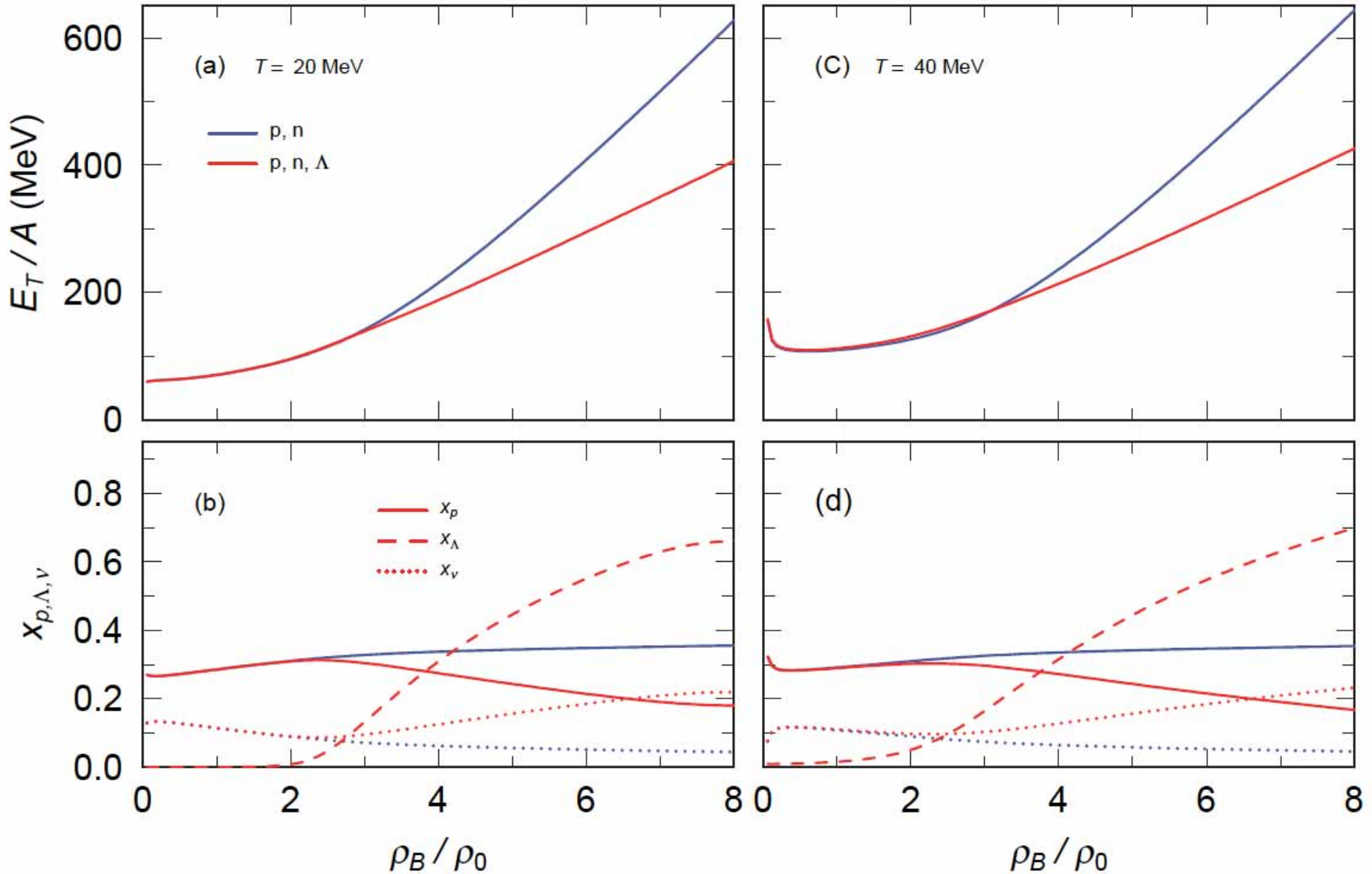
$$g_\sigma / g_\sigma^\Lambda = g_\omega / g_\omega^\Lambda = 2/3$$

T.M, H. Shin, H. Fujii, & T. Tatsumi,  
PTP. 102, P809

# EOS of Proto Neutron-Star-Matter at Finite Temperature

Charge Neutral ( $\rho_p = \rho_e$ ) & Lepton Fraction :  $Y_L = 0.4$

$$g_{\sigma,\omega}^{\Lambda} = \frac{2}{3} g_{\sigma,\omega}$$





## § 2-2 Dirac Equation under Magnetic Fields

$$\mu_N B \ll \mu_F \text{ (Chem. Pot)} \quad B \sim 10^{17} \text{ G}$$

Perturbative calculation, Ignoring Landau Level

*Magnetic Part  
of Lagrangian*

$$\begin{aligned} \mathcal{L}_{mag} &= \sum_n \mu_n \bar{\psi}_n \sigma_{\mu\nu} \psi_n F^{\mu\nu} = - \sum_n \mu_n B \bar{\psi}_n \sigma_z \psi_n \\ F^{\mu\nu} &= \partial^\mu A^\nu - \partial^\nu A^\mu \end{aligned} \quad (1)$$

**Dirac Eq.**  $\hat{h}(p)u(p) = (\not{p} - M^* - \mu B \sigma_z)u(p)$

Single Particle Energy :  $\det \hat{h}(p) = (p_0^2 - e^2(\mathbf{p}, +1))(p_0^2 - e^2(\mathbf{p}, -1))$

$$e(p, s) = \left[ \left( \sqrt{p_x^2 + M^{*2}} + s\mu B \right)^2 + p_z^2 \right]^{\frac{1}{2}} \approx E_p^* + s\mu B \frac{\sqrt{p_T^2 + M^{*2}}}{E_p^*} \quad E_p^* = \sqrt{p^2 + M^{*2}}$$

## Fermi Distribution

$$n(e(\mathbf{p}), s) \approx n(\varepsilon(\mathbf{p}, s)) + n'(\varepsilon(\mathbf{p}, s)) \frac{\sqrt{p_T^2 + M^{*2}}}{E_p^*} \mu B s.$$

Green-Funtion

$$S(p) = \sum_{s=\pm 1} \left\{ \frac{u(\mathbf{p}, s)\bar{u}(\mathbf{p}, s)}{p_0 - e(\mathbf{p}, s) + i\delta} + \frac{v(-\mathbf{p}, s)\bar{v}(-\mathbf{p}, s)}{p_0 + e(\mathbf{p}, s) - i\delta} \right\}$$

When  $\mu B \ll 1$ ,

$$u(\mathbf{p}, s)\bar{u}(\mathbf{p}, s) = [(p_0 - e(\mathbf{p}, s))S(p)] (p_0 = e(\mathbf{p}, s)) \approx \frac{1}{4E_p^*} (\not{p} + M^*)(1 + s\gamma_5 \not{p})$$

$$a_z = \frac{E_p^*}{\sqrt{p_T^2 + M^{*2}}} \quad \mathbf{a}_T = 0 \quad a_0 = \frac{p_z}{\sqrt{p_T^2 + M^{*2}}}$$

**Spin Vector**

**Dirac Spinor**

# The Cross-Section of Lepton-Baryon Scattering

$$\frac{d^2\sigma}{dk'd\Omega'_k} = \frac{G_F^2}{8\pi^2} k'^2 \sum_{s_i, s_f} \int \frac{d^3p}{(2\pi)^3} \tilde{W}_{BL} (2\pi) \delta(|\mathbf{k}| - |\mathbf{k}'| + e_i(\mathbf{p}) - e_f(\mathbf{k} + \mathbf{p} - \mathbf{k}'))$$

$$\times [1 - f'_l(\mathbf{k}')] n_B(e_i) [1 - n_{B'}(e_f)]$$

with

$$\tilde{W}_{BL} = \text{Tr} \left\{ \frac{(\not{k}' + m_f)(1 + \gamma_5 \not{p}')}{4|\mathbf{k}'|} \gamma^\mu (1 - \gamma_5) \frac{\not{k}}{2|\mathbf{k}|} \gamma^\nu (1 - \gamma_5) \right\}$$

$$\times \text{Tr} \left\{ \frac{(\not{p}' + M_f^*)(1 + \gamma_5 \not{p}')}{4E_f^*(\mathbf{p}')} \gamma_\mu (c_V - c_A \gamma_5) \frac{(\not{p} + M_i^*)(1 + \gamma_5 \not{p})}{4E_i^*(\mathbf{p})} \gamma_\nu (c_V - c_A \gamma_5) \right\}$$

$$m_f = 0 \quad \text{when } l_f = \nu \quad m_f = m_e \quad \text{when } l_f = e$$

$$\sigma = \sigma_0 + \Delta\sigma \quad \Delta\sigma \propto B$$

## Spin-indep. part

$$\frac{d^2 \sigma_0}{dk_f d\Omega_f} = \frac{G_F^2}{32\pi^5} \frac{|k_f|}{|k_i|} [1 - f_{l'}(|k_f|)] \int \frac{d^3 p}{E_i E_f} W_0 \times \delta(|k_i| - |k_f| + \varepsilon_i(p) - \varepsilon_f(p')) n_B(\varepsilon_i(p)) [1 - n_{B'}(\varepsilon_f(p'))]$$

$$\begin{aligned} W_0 &= c_V^2 [(k_f \cdot p)(k_i \cdot p') + (k_f \cdot p')(k_i \cdot p) - M_f M_i (k_f \cdot k)] \\ &+ c_A^2 [(k_f \cdot p)(k_i \cdot p') + (k_f \cdot p')(k_i \cdot p) + M_f M_i (k_i \cdot k_f)] - 2c_V c_A [(k_f \cdot p')(k_i \cdot p) - (k_f \cdot p)(k_i \cdot p')] \\ q &= k_i - k_f = p' - p \end{aligned}$$

## Spin-dep. Part

$$\frac{d^2 \Delta \sigma}{dk_f d\Omega_f} = \frac{G_F^2}{32\pi^5} B \frac{|k_f|}{|k|} [1 - f_{l'}(k_f)] (S_1 + S_2)$$

$$\begin{aligned} S_1 &= \frac{1}{Q} \int dE_i \int d\phi_p \{ n'_{B'}(\varepsilon_i) [1 - n_{B'}(\varepsilon_i + \omega)] W_i + n'_{B'}(\varepsilon_f) n_B(\varepsilon_i) (W_i - 2W_f) \}, \\ S_2 &= -\frac{1}{Q^2} \int dE_i \int d\phi_p (E_i + \omega) n_B(\varepsilon_i) [1 - n_{B'}(\varepsilon_i + \omega)] \frac{1}{p} \frac{\partial}{\partial t} (W_i - W_f). \end{aligned}$$

$$t = \frac{q \cdot p}{|q||p|}$$

$$\begin{aligned} W_i/\mu_i &= c_V^2 \{ [k_f \cdot (M_f p - M_i p')] (k_i \cdot b_i) - [k_i \cdot (M_f p - M_i p')] (k_f \cdot b_i) \} \\ &+ c_A^2 \{ [-k_f \cdot (M_f p + M_i p')] (k_i \cdot b_i) + [k_i \cdot (M_f p + M_i p')] (k_f \cdot b_i) \} \\ &- 2c_V c_A M_i \{ (k_f \cdot p')(k_i \cdot b_i) + (k_f \cdot b_i)(k_i \cdot p') \}, \end{aligned}$$

$$\begin{aligned} W_f/\mu_f &= c_V^2 \{ [k_f \cdot (M_f p - M_i p')] (k_i \cdot b_f) - [k_i \cdot (M_f p - M_i p')] (k_f \cdot b_f) \} \\ &+ c_A^2 \{ [k_f \cdot (M_f p + M_i p')] (k_i \cdot b_f) - [k_i \cdot (M_f p + M_i p')] (k_f \cdot b_f) \} \\ &- 2c_V c_A M_f \{ [(k_f \cdot b_f)(k_i \cdot p) + (k_f \cdot p)(k_i \cdot b_f)] \} \end{aligned}$$

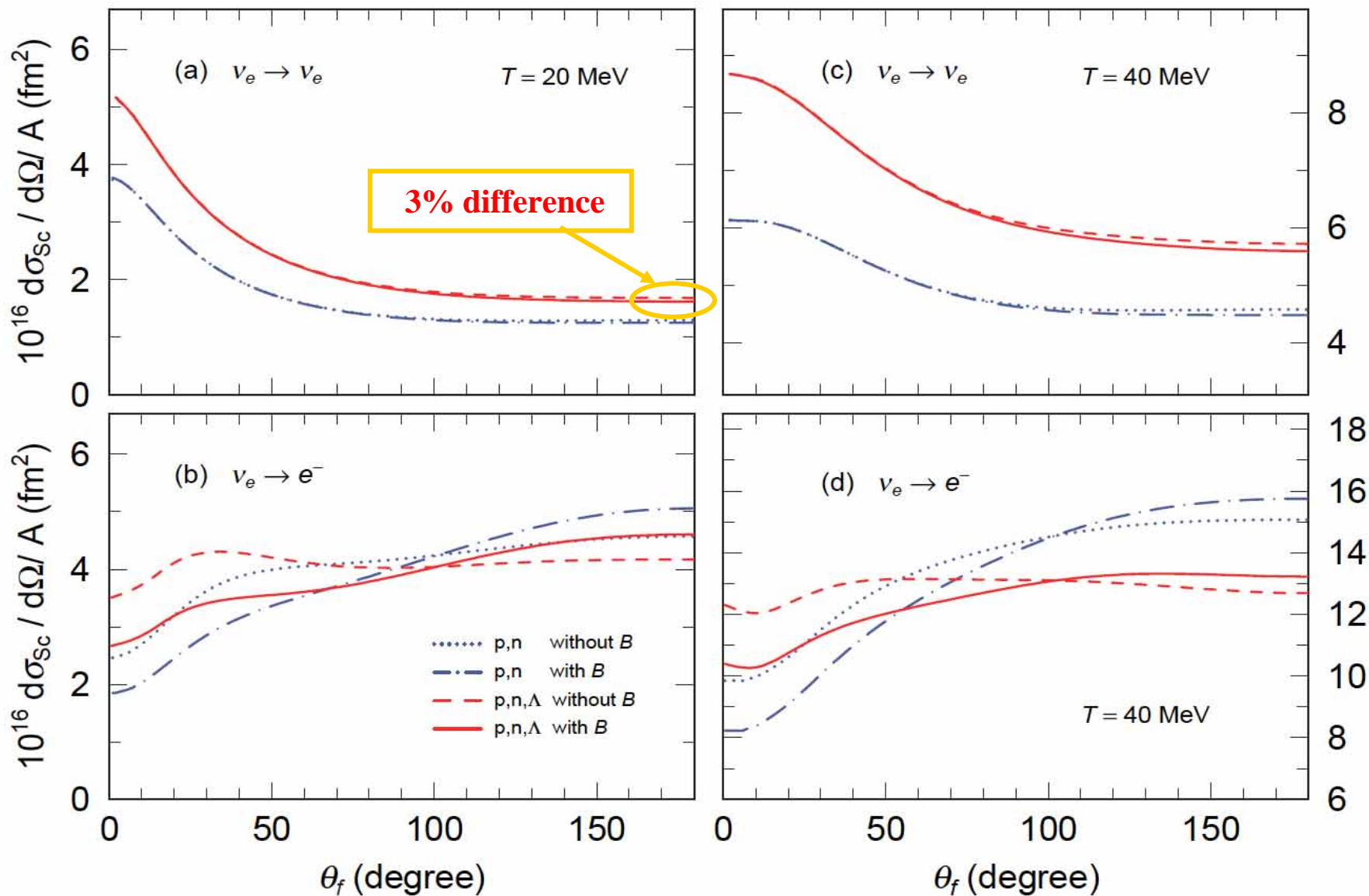
$$b_i = \frac{\sqrt{p_T^2 + M_i^2}}{E_i(p)} a_i,$$

$$b_f = \frac{\sqrt{p_T^2 + M_f^2}}{E_f(p')} a_f$$



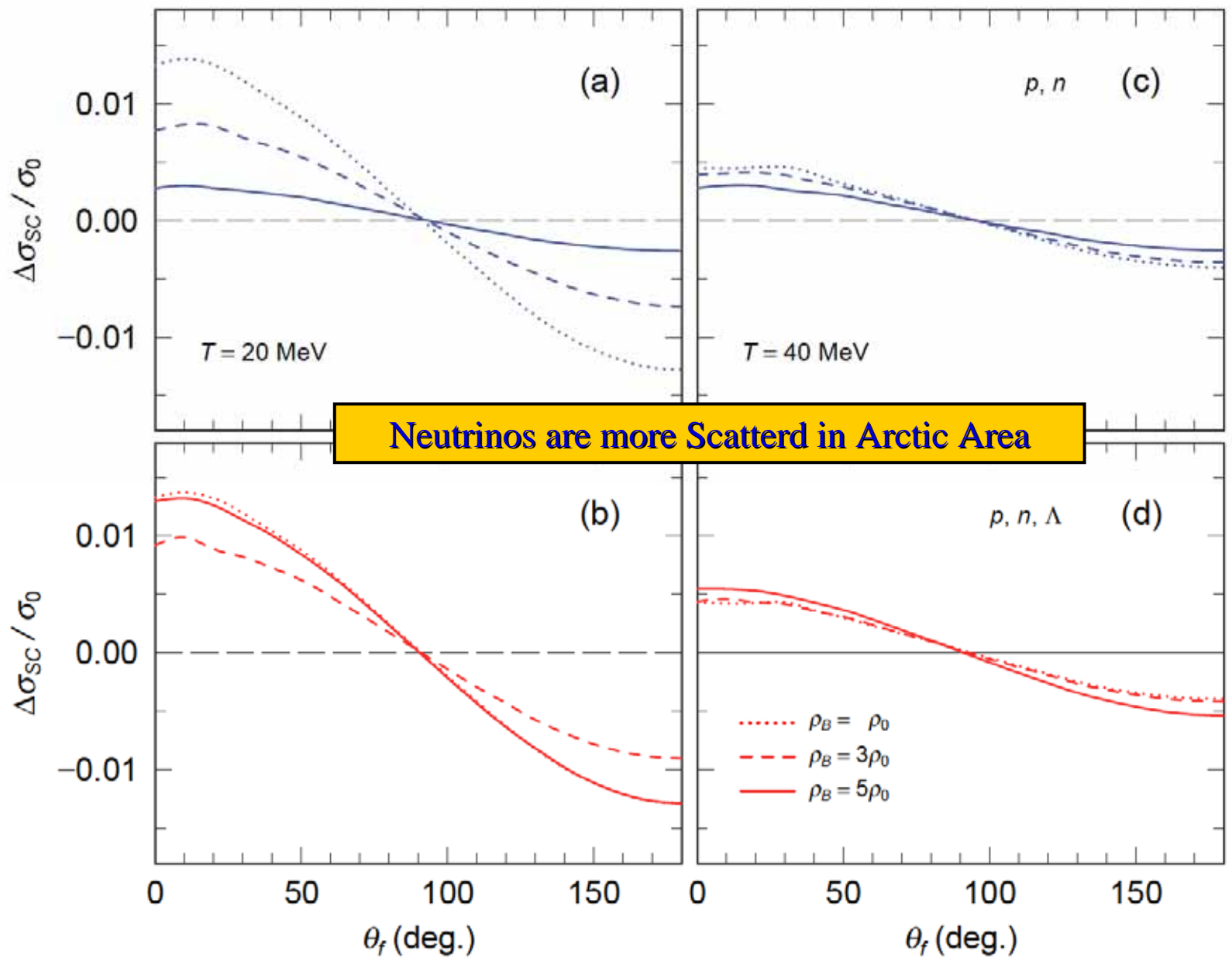
# § 3 Results

$k_i = \varepsilon_\nu$  (neutrino chem. pot.),  $B = 2 \times 10^{17}$  G and  $\theta_i = 0^\circ$



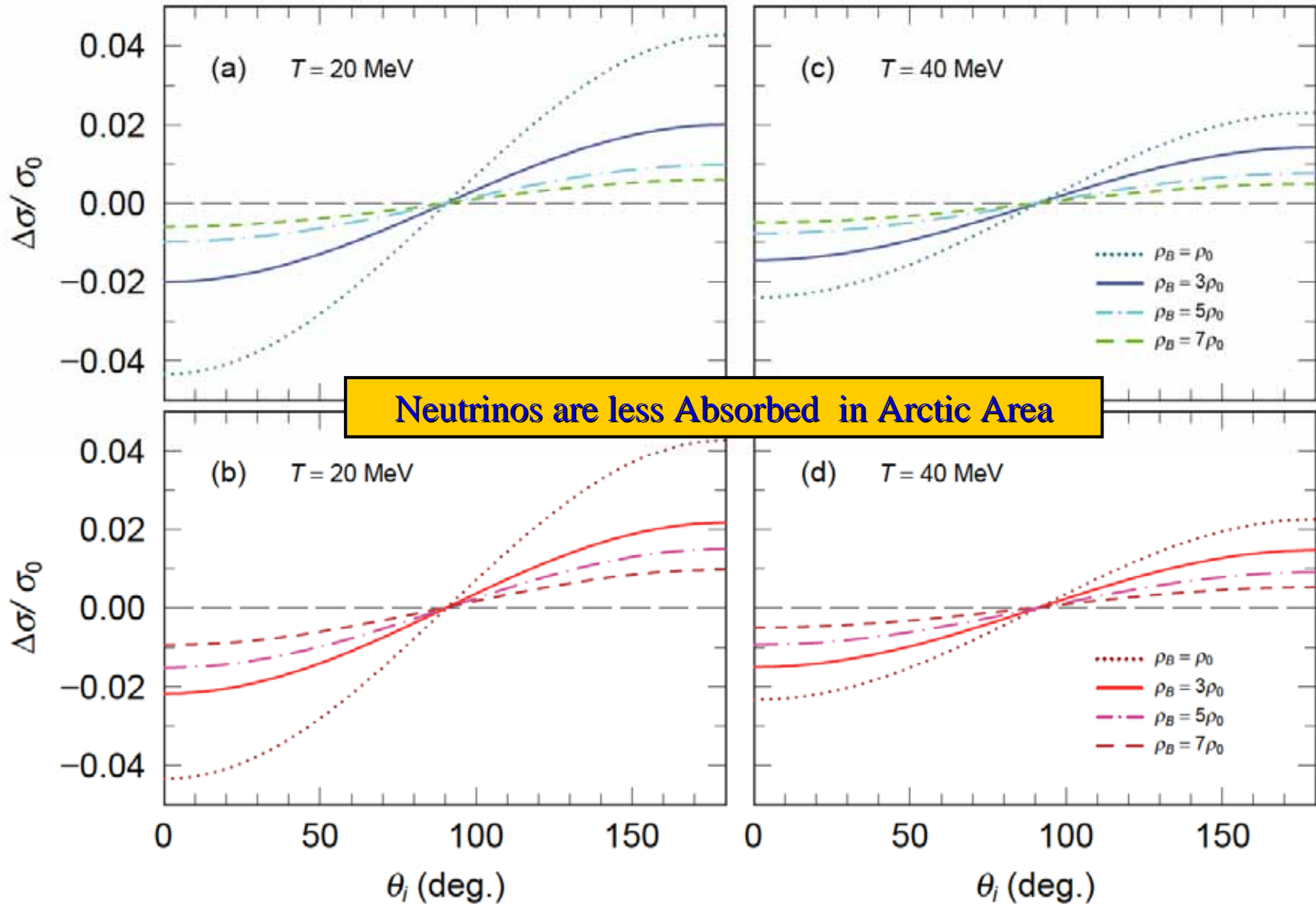
# Magnetic Parts of Scattering Cross-Sections

$$\sigma_{sc} = \int d\Omega_i \frac{d\sigma(v_e \rightarrow v_e)}{d\Omega_f}$$



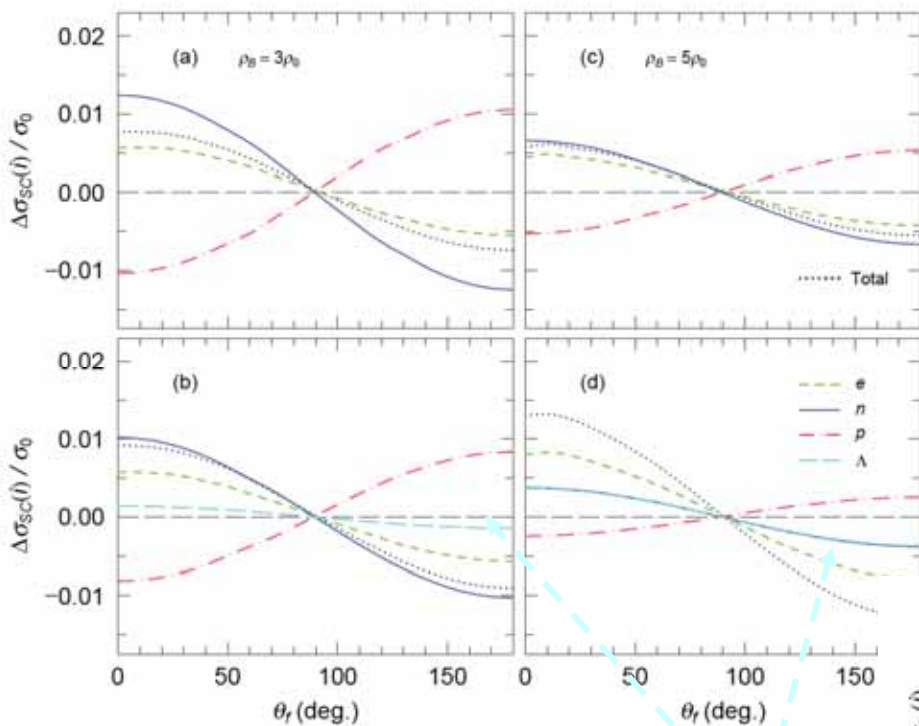
# Magnetic Parts of Absorption Cross-Sections

$$\sigma_{Ab} = \int d\Omega_f \frac{d\sigma(\nu_e \rightarrow e)}{d\Omega_f}$$



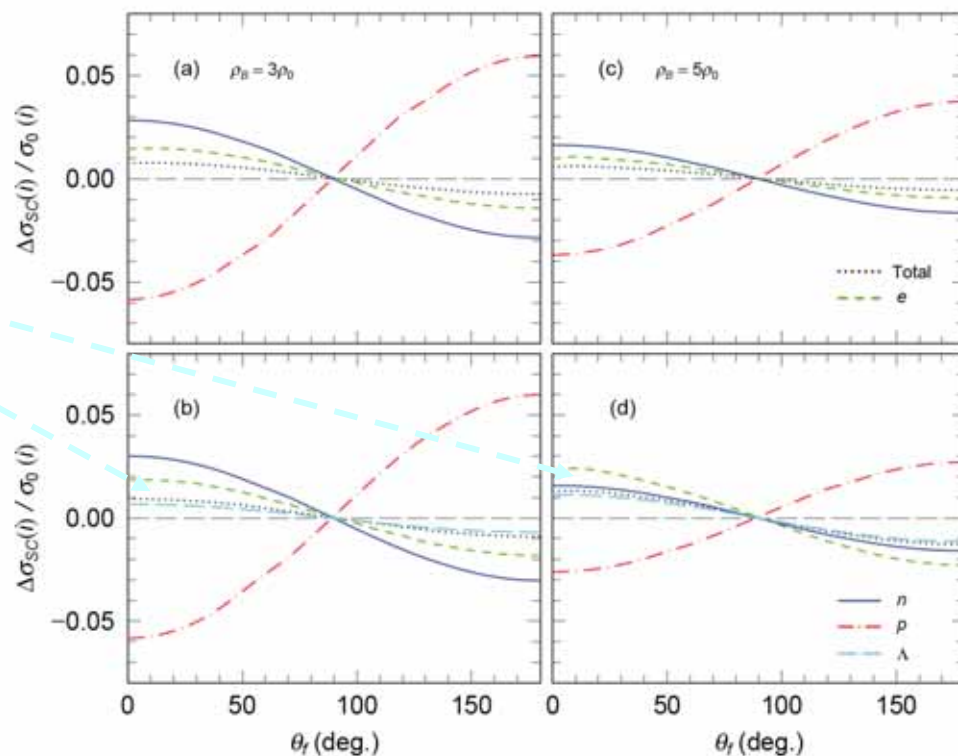
# Elements of Scattering Cross-Sections at $T = 20 \text{ MeV}$

各パートで規格化



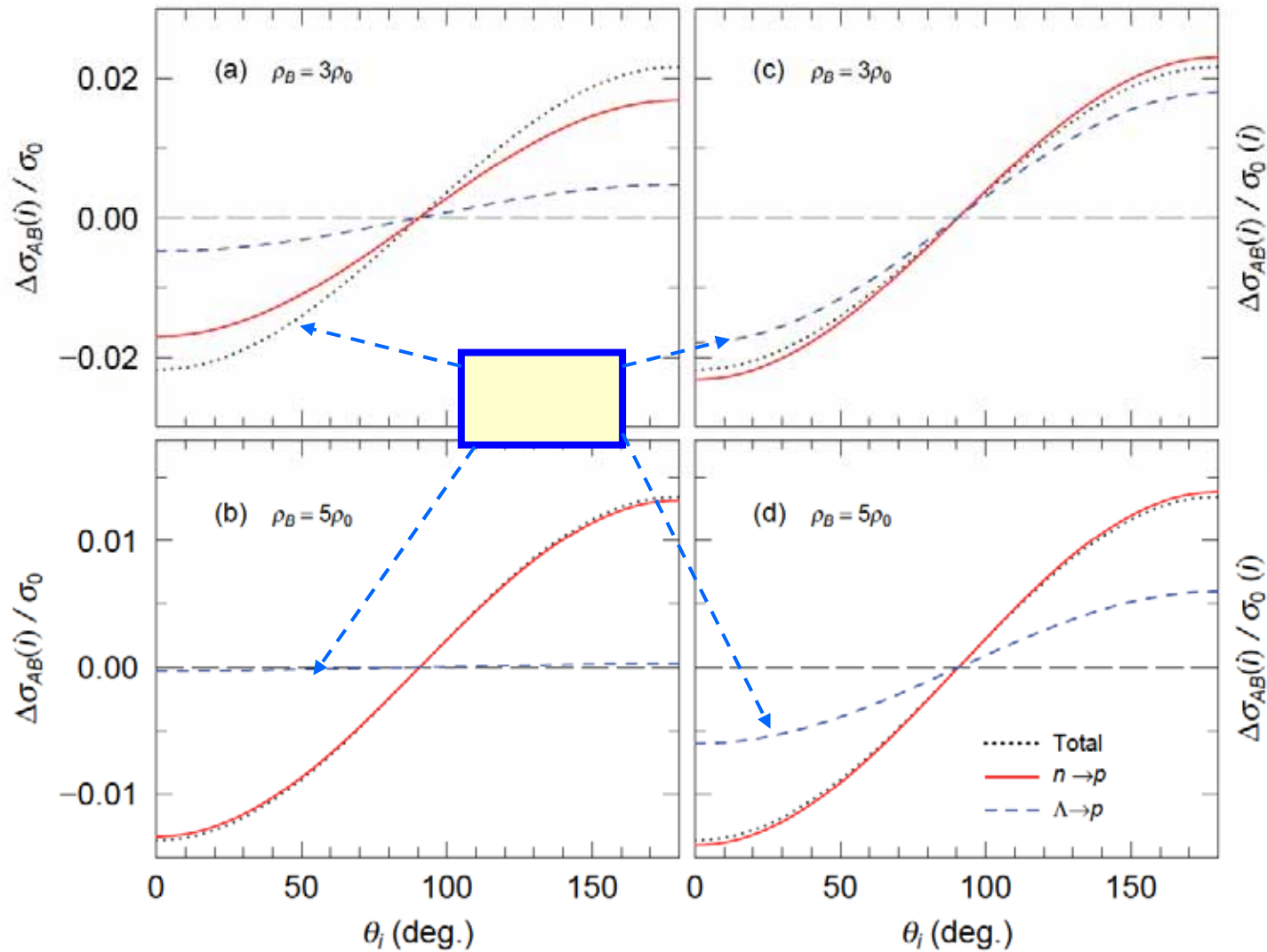
全断面積で規格化

寄与





# Elements of Absorption Cross-Sections



Contribution from  $\Lambda \rightarrow p$  is small

## § 4 Neutrino Absorption in Proto Neutron Star

### Neutrino Phase Space Distribution Function

$$f(\mathbf{p}, \mathbf{r}) \approx f_0(\mathbf{p}, \mathbf{r}) + \Delta f(\mathbf{p}, \mathbf{r}), \quad f_0(\mathbf{p}, \mathbf{r}) = 1 / \{1 + \exp[(|\mathbf{p}| - \varepsilon_\nu) / T]\}$$

Equip. Part

Non-Equip. Part

### Neutrino Propagation

### Boltzmann Eq.

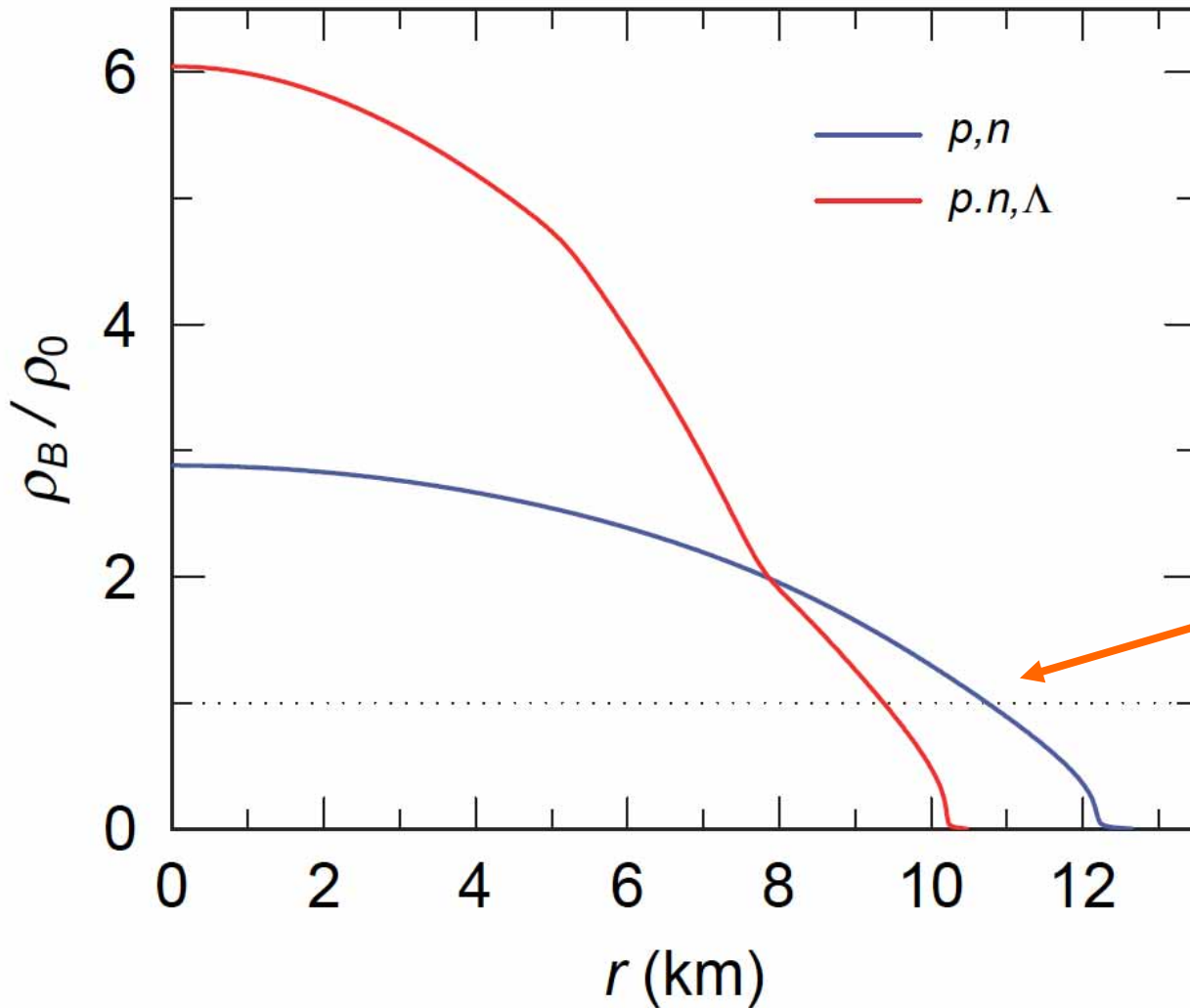
$$c \frac{d}{dx} f_0(\mathbf{p}, \mathbf{r}) + c \frac{d}{dx} \Delta f(\mathbf{p}, \mathbf{r}) = I_{coll} \approx -c b_\nu \Delta f(\mathbf{p}, \mathbf{r}), \quad b_\nu = \frac{\sigma_{ab}}{V}$$

Solution

$$\Delta f(\mathbf{p}, \mathbf{r}_T, z) = \int_0^z dx \left[ -\frac{\partial}{\partial x} f_0(p, r_T, x) \right] \exp \left[ -\frac{1}{c} \int_x^z dy b_\nu(y) \right],$$

$$z = \mathbf{r} \cdot \hat{\mathbf{p}}, \quad \frac{\partial}{\partial z} f_0(p, r_T, z) = \frac{d\varepsilon_\nu}{dz} \frac{\partial}{\partial \varepsilon_\nu} f_0(p, r_T, z)$$

# Baryon density in Proto-Neutron Star



$$M = 1.68M_{\text{solar}}$$

$$T = 30 \text{ MeV}$$

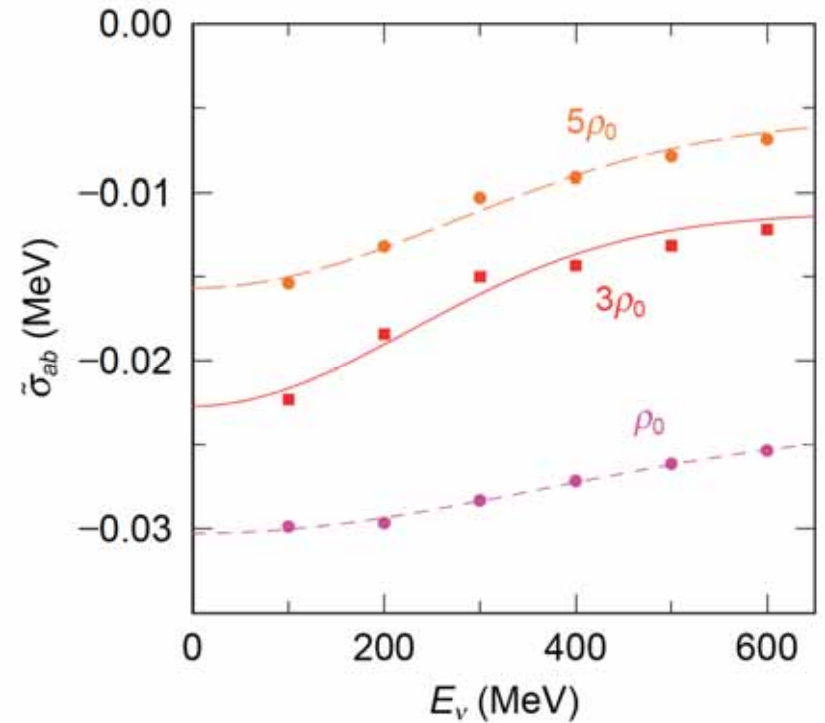
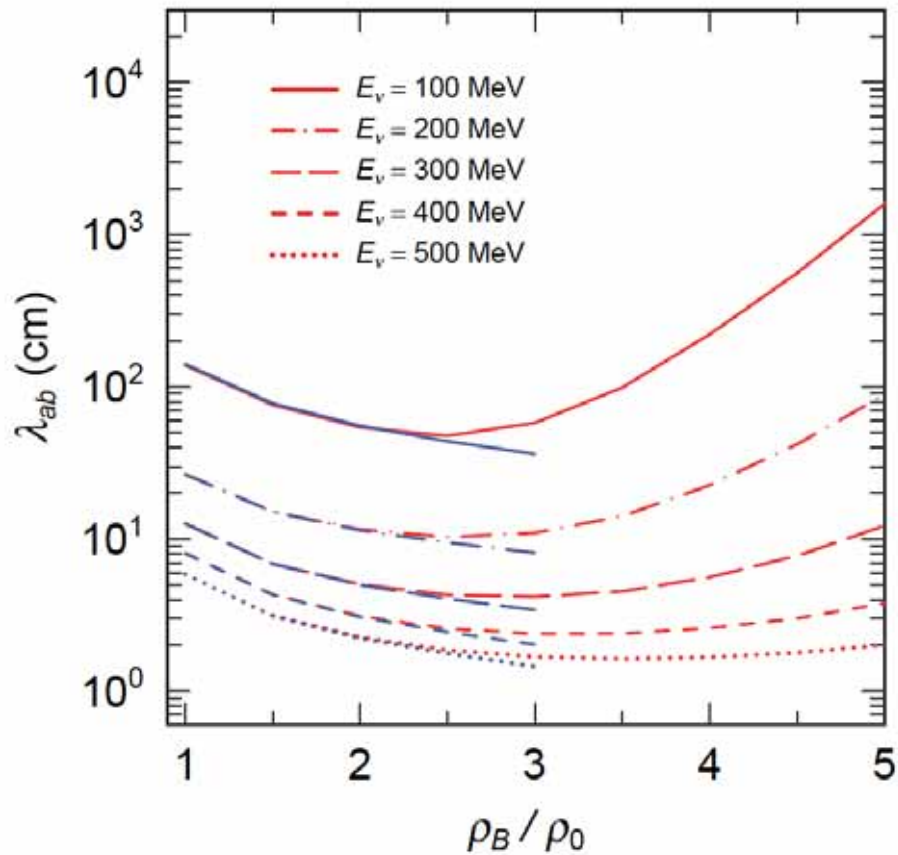
$$Y_L = 0.4$$

*Calculating  
Neutrino  
Propagation  
above*

$$\rho_B = \rho_0$$

# Mean-Free Path when $B=0$

$$\lambda_0^{ab} = \frac{1}{\sigma_o^{ab} / V}$$

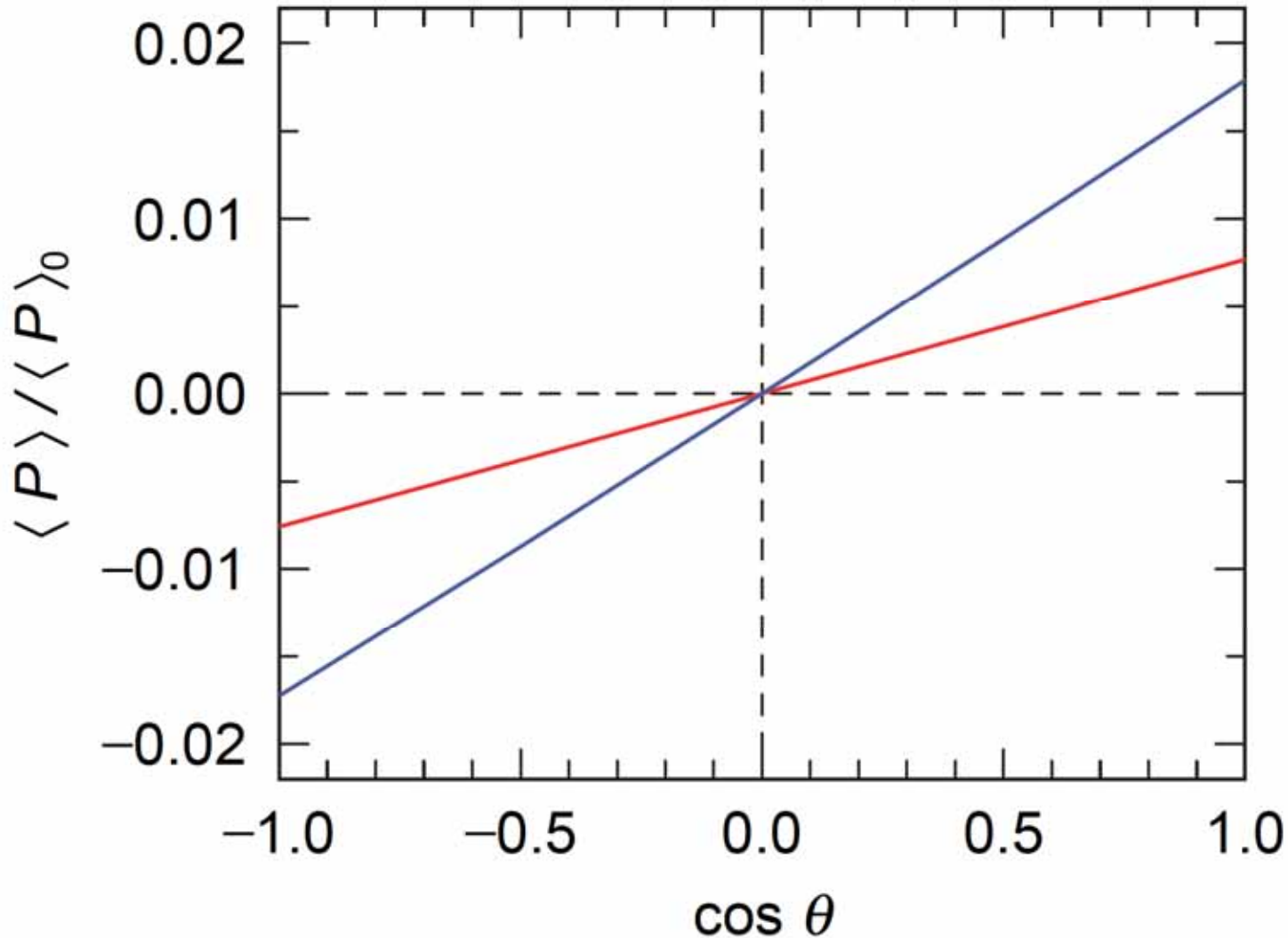


$$\sigma^{ab} = \sigma_o^{ab} (1 + \tilde{\sigma}_{ab} \cos \theta)$$



# Angular Dependence of Emitted Neutrino

$$\langle p \rangle = \int dr dp (\mathbf{p} \cdot \hat{\mathbf{u}}) \Delta f(\mathbf{p}, r)$$



Direction of  
Emitted  
Neutrino

# Kick Velocity

$$\langle \mathbf{p} \cdot \boldsymbol{\theta} \rangle = P_0 + P_1 \cos \theta$$

$$E_T = 4\pi R^2 P_0, \quad \langle p_z \rangle = \frac{4\pi}{3} P_1^2$$

$$\frac{\langle p_z \rangle}{E_T} = \frac{P_1}{3P_0} = 6.0 \times 10^{-3} \quad \text{p, n}$$

$$= 2.6 \times 10^{-3} \quad \text{p, n, } \Lambda$$

Assuming Neutrino Energy  $\sim 3 \times 10^{53}$  erg

D.Lai & Y.Z.Qian, *Astrophys.J.* 495 (1998) L103

$$M_{NS} = 1.68 M_{solar} [\text{g}], \quad E_T = 3 \times 10^{53}$$

$$v_{kick} = \frac{\langle p_z \rangle}{M} = 180 [\text{km/s}] \quad \text{p, n}$$

$$= 77 [\text{km/s}] \quad \text{p, n, } \Lambda$$

## § 4 Summary

- 中性子星物質のEOS RMFアプローチ ( p, n )
- 強磁場中でのニュートリノとバリオン物質の散乱・吸収断面積  
 $B \sim 10^{17} \text{G}$  摂動計算
- 散乱、吸収 ニュートリノ放出は磁場方向に増加  
(北極方向に多く放出される)  
散乱 **1.7 %**、吸収 **2.2 %** at  $B = 3 B_0$  and  $T = 20 \text{ MeV}$   
 $B = 2 \times 10^{17} \text{G}$   $B = 2 \times 10^{18} \text{G}$  で 10% 程度の変化
- 1%の変化で超新星爆発 対流, パルサー・キック

■ 強磁場原始中性子星でのパスサーキック速度を概算

■ EOS RMFアプローチ ( p, n ) ,

■  $B = 2 \times 10^{17} \text{G}$  ニュートリノ吸収断面積を摂動計算

$V_{\text{kick}} = 180 \text{ km/s ( p,n ) , 77 km/s ( p,n, )}$  南極方向  
400 km/s (観測), 280km/s (Lai & Qian)

無視した効果

散乱 北極側に放出 (1.7 % at  $\rho_B = 3\rho_0$  ,  $T = 20 \text{ MeV}$ ) 加速

温度  $T = 30 \text{ MeV}$  に固定 温度が低下 異方性の増大

低密度での寄与

ランダウ・レベル

バリオン物質の回転、対流

発展 スピン偏極バリオン物質、クォーク物質

極性(双極子)磁場

トロイダル磁場