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

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§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)

Λ，Σ　の影響を議論

強磁場中性子星　**Magnetar**：

表面　~ 10^{15} G，内部　~ 10^{17-19} 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

パスサー・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

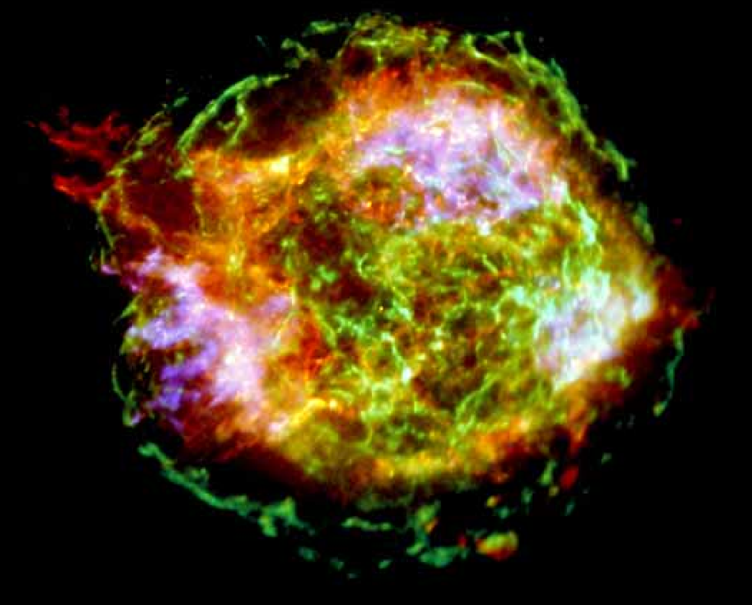
⇒　中性子星に並進速度

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 〜 10^{53} erg

1% の異方性で十分

CasA



http://chandra.harvard.edu/photo/2004/casa/casa_xray.jpg

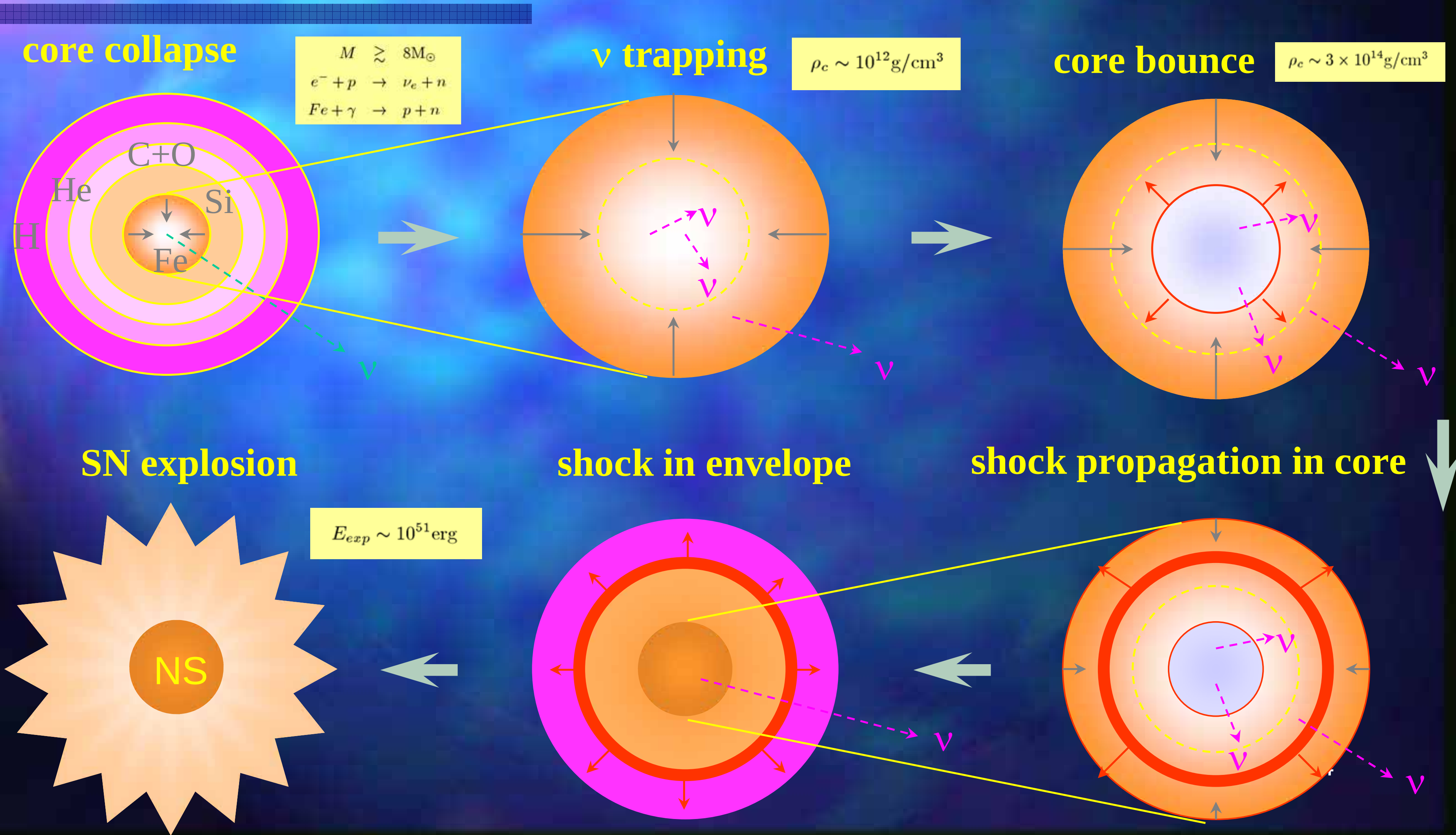
強磁場中でのニュートリノ散乱、吸収

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

Birth of Proto-neutron Star



§ 2. Formulation

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

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

Baryon | **Lepton** | B & L – Mag.

Weak Interaction

$\nu_e + B \rightarrow \nu_e + B$ **: scattering**

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

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

§2-1 Neutron-Star Matter in RMF Approach

RMF Lagrangian

$$\mathcal{L}_{RMF} = \bar{\psi}_N(i\not{\partial} - M_N)\psi_N + \bar{\psi}_\Lambda(i\not{\partial} - M_\Lambda)\psi_\Lambda + g_\sigma\bar{\psi}_N\psi_N\sigma + g_\sigma^\Lambda\bar{\psi}_\Lambda\psi_\Lambda\sigma$$
$$+g_\omega\bar{\psi}_N\gamma_\mu\psi_N\omega^\mu + g_\omega^\Lambda\bar{\psi}_\Lambda\gamma_\mu\psi_\Lambda\omega^\mu - \widetilde{U}[\sigma] + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu$$

ψ_N (nucleon), ψ_Λ (Λ), σ and ω **+ p-n Symmetry Force**

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

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

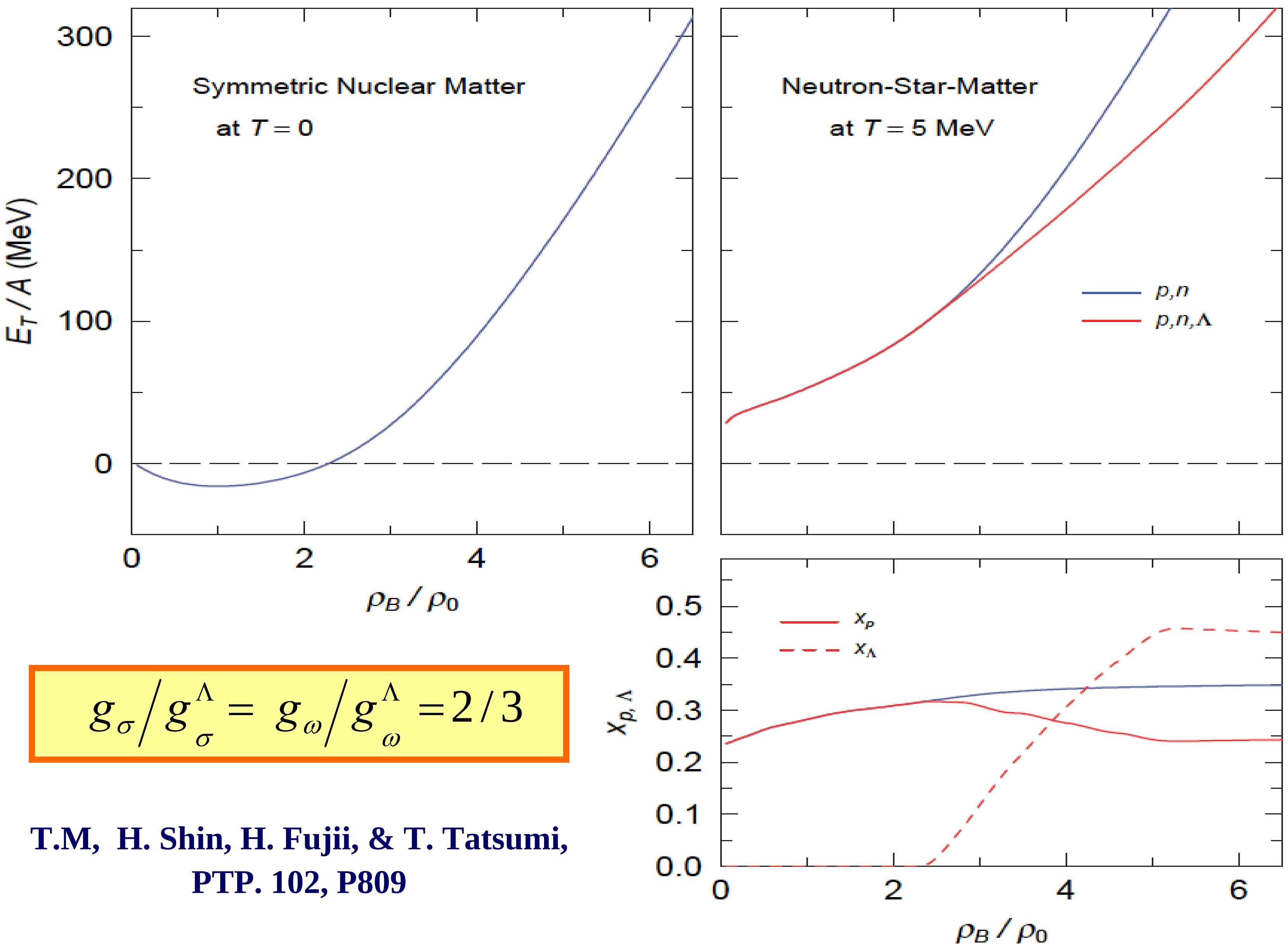
$$M_N^* = M_N - g_\sigma\sigma \qquad M_\Lambda^* = M_\Lambda - g_\sigma^\Lambda\sigma$$

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

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

EOS of PM1-1

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



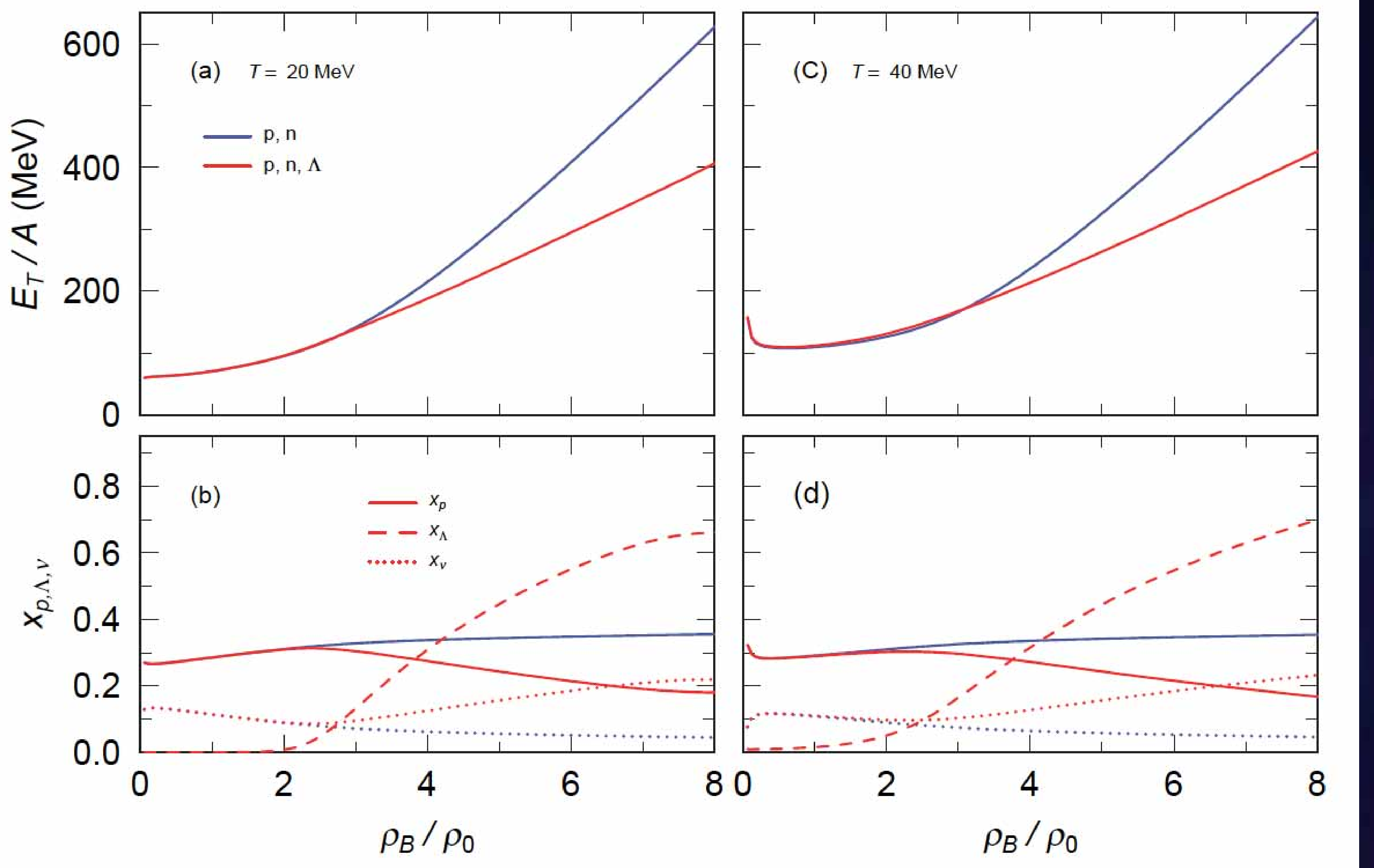
$$g_\sigma / g_\sigma^\Lambda = g_\omega / g_\omega^\Lambda = 2/3$$

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 :** $Y_L = 0.4$

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



§2-2 Dirac Equation under Magnetic Fields

$\mu_N B$ << ε_F (Chem. Pot) → B ~ 10^{17} G

Perturbative calculation, Ignoring Landau Level

Magnetic Part of Lagrangian

$$\mathcal{L}_{mag} = \sum_n \mu_n \bar{\psi}_n \sigma_{\mu\nu} \psi_n F^{\mu\nu} = -\sum_n \mu_n B \bar{\psi}_n \sigma_Z \psi_n$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu \qquad (1)$$

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

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

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

Fermi Distribution

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

Green-Funtion

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

When $\mu B << 1$,

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

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

Spin Vector

Dirac Spinor

The Cross-Section of Lepton-Baryon Scattering

$$\frac{d^2\sigma}{dk'd\Omega'_k} = \frac{G_F^2}{8\pi^2}\boldsymbol{k}'^2 \sum_{s_i,s_f}\int\frac{d^3p}{(2\pi)^3}\tilde{W}_{BL}(2\pi)\delta(|\boldsymbol{k}|-|\boldsymbol{k}'|+e_i(\boldsymbol{p})-e_f(\boldsymbol{k}+\boldsymbol{p}-\boldsymbol{k}'))$$
$$\times[1-f_l'(\boldsymbol{k}')]n_B(e_i)[1-n_{B'}(e_f)]$$

with

$$\tilde{W}_{BL} = \mathrm{Tr}\left\{\frac{(\not{k}'+m_f)(1+\gamma_5\not{a}_{l'})}{4|\boldsymbol{k}'|}\gamma^\mu(1-\gamma_5)\frac{\not{k}'}{2|\boldsymbol{k}|}\gamma^\nu(1-\gamma_5)\right\}$$
$$\times\ \mathrm{Tr}\left\{\frac{(\not{p}'+M_f^*)(1+\gamma_5\not{a}_f(p'))}{4E_f^*(\boldsymbol{p}')}\gamma_\mu(c_V-c_A\gamma_5)\frac{(\not{p}+M_i^*)(1+\gamma_5\not{a}_i(p))}{4E_i^*(\boldsymbol{p})}\gamma_\nu(c_V-c_A\gamma_5)\right\}$$

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

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

Spin-indep. part

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

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

Spin-dep. Part

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

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

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

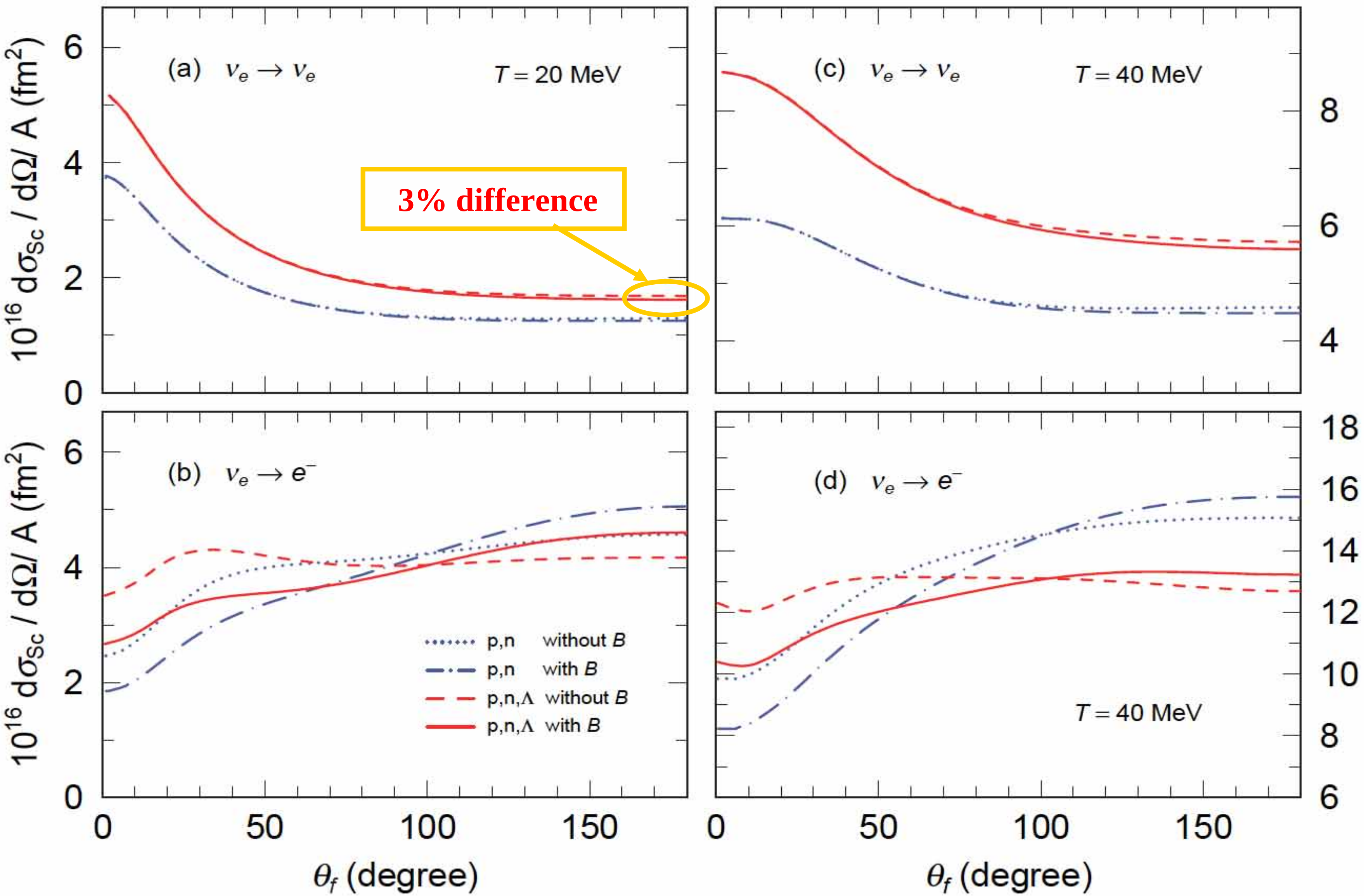
$$\begin{aligned} W_i/\mu_i &= c_V^2\left\{[k_f\cdot(M_f p - M_i p')](k_i\cdot b_i) - [k_i\cdot(M_f p - M_i p')](k_f\cdot b_i)\right\} \\ & + c_A^2\left\{[-k_f\cdot(M_f p + M_i p')](k_i\cdot b_i) + [k_i\cdot(M_f p + M_i p')\}(k_f\cdot b_i)\right] \\ & - 2c_V c_A M_i\left\{(k_f\cdot p')(k_i\cdot b_i)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

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

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

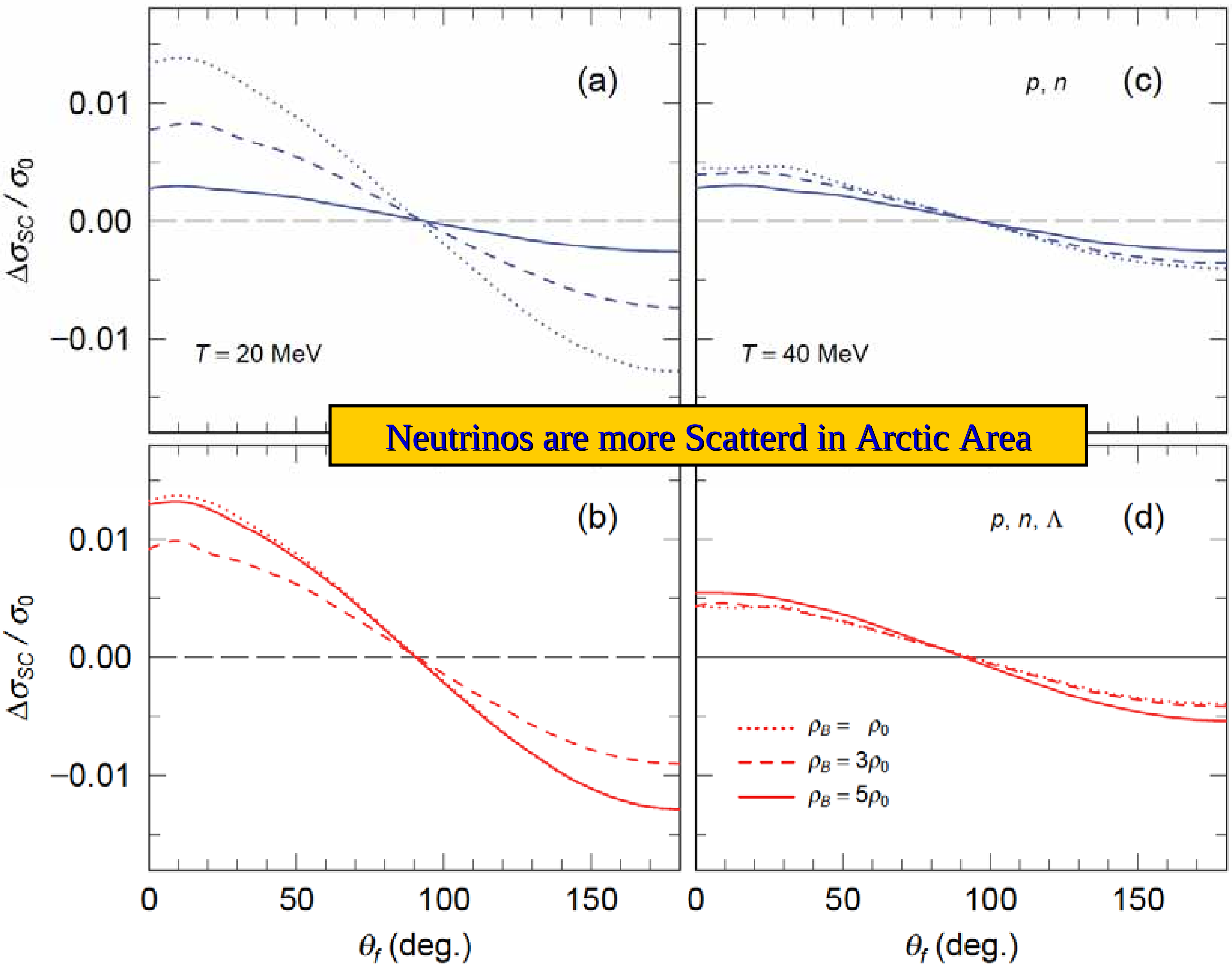
§ 3 Results

$k_i = \varepsilon_\nu$ (neutrino chem. pot.), $B = 2\times10^{17}$ G and $\theta_\mathrm{i} = 0^\circ$



Magnetic Parts of Scattering Cross-Sections

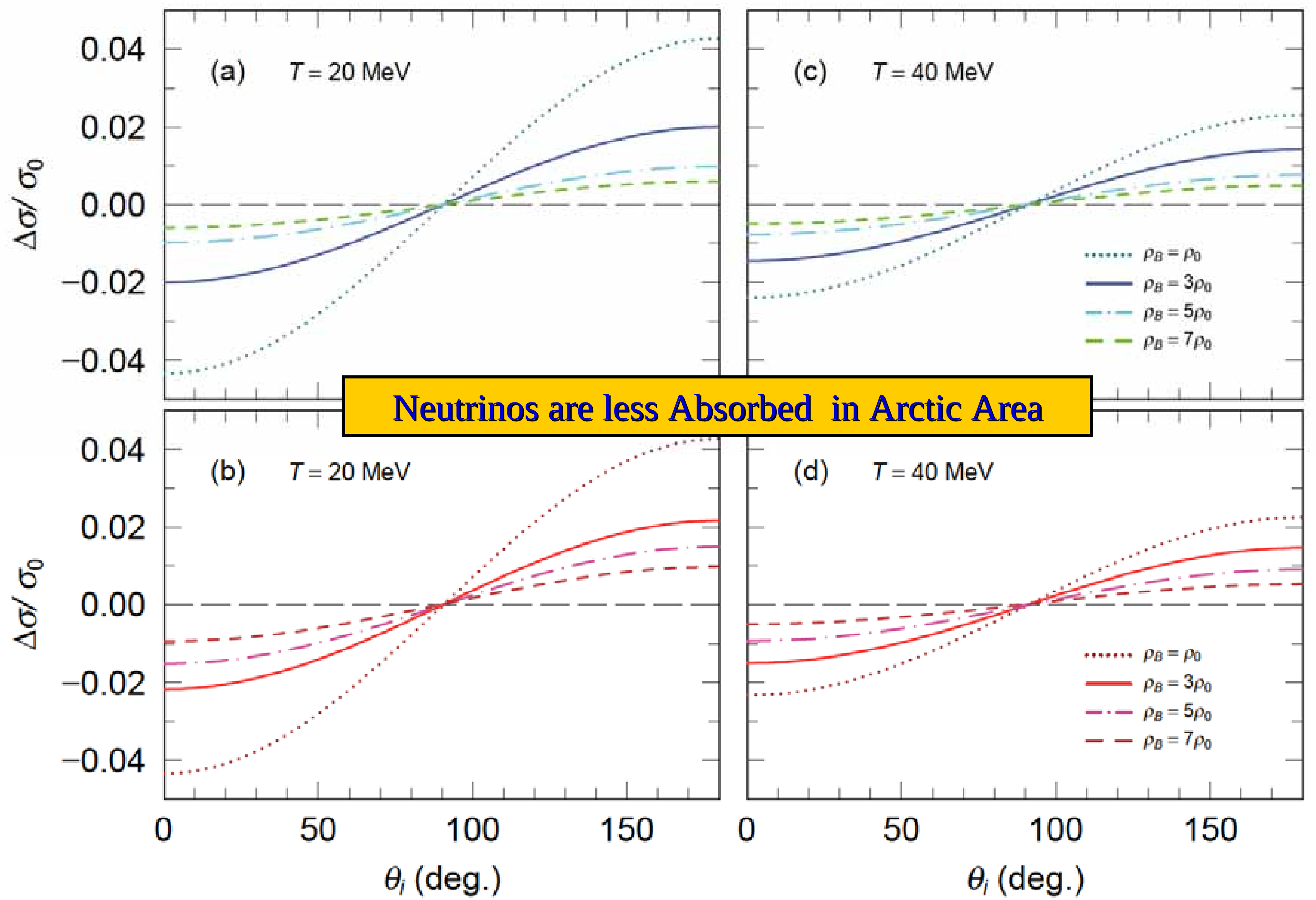
$$\sigma_{Sc} = \int d\Omega_i \frac{d\sigma(\nu_e \to \nu_e)}{d\Omega_f}$$



Neutrinos are more Scatterd in Arctic Area

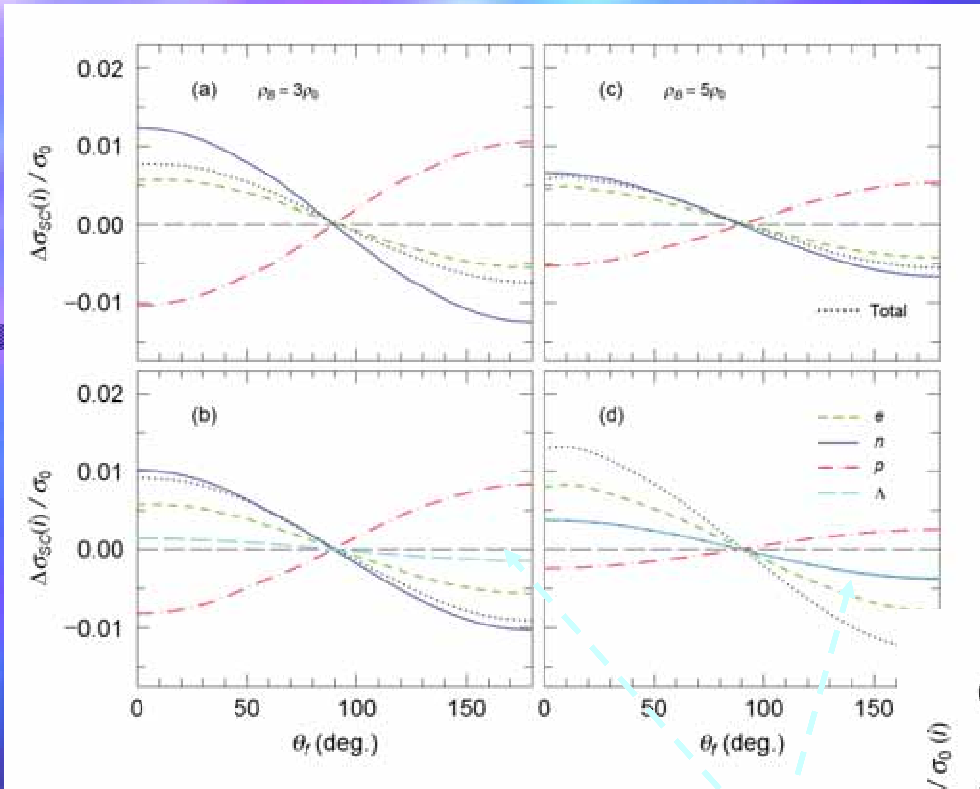
Magnetic Parts of Absorption Cross-Sections

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

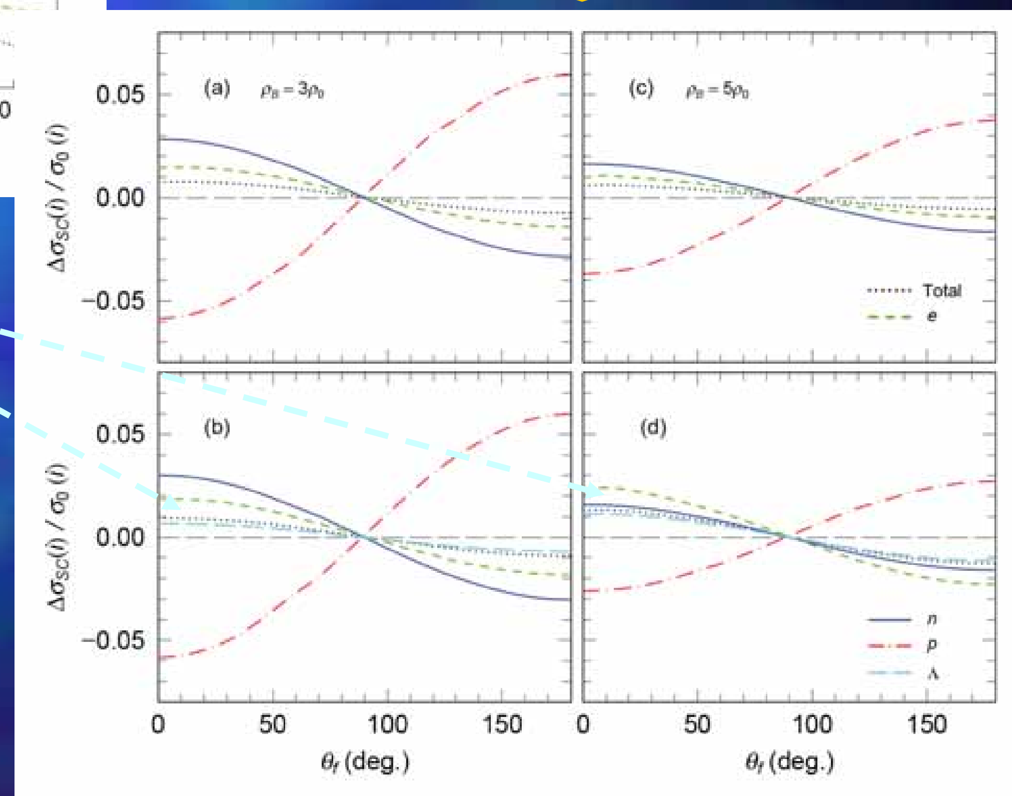


Neutrinos are less Absorbed in Arctic Area

Elements of Scattering Cross-Sections at $T = 20\ MeV$



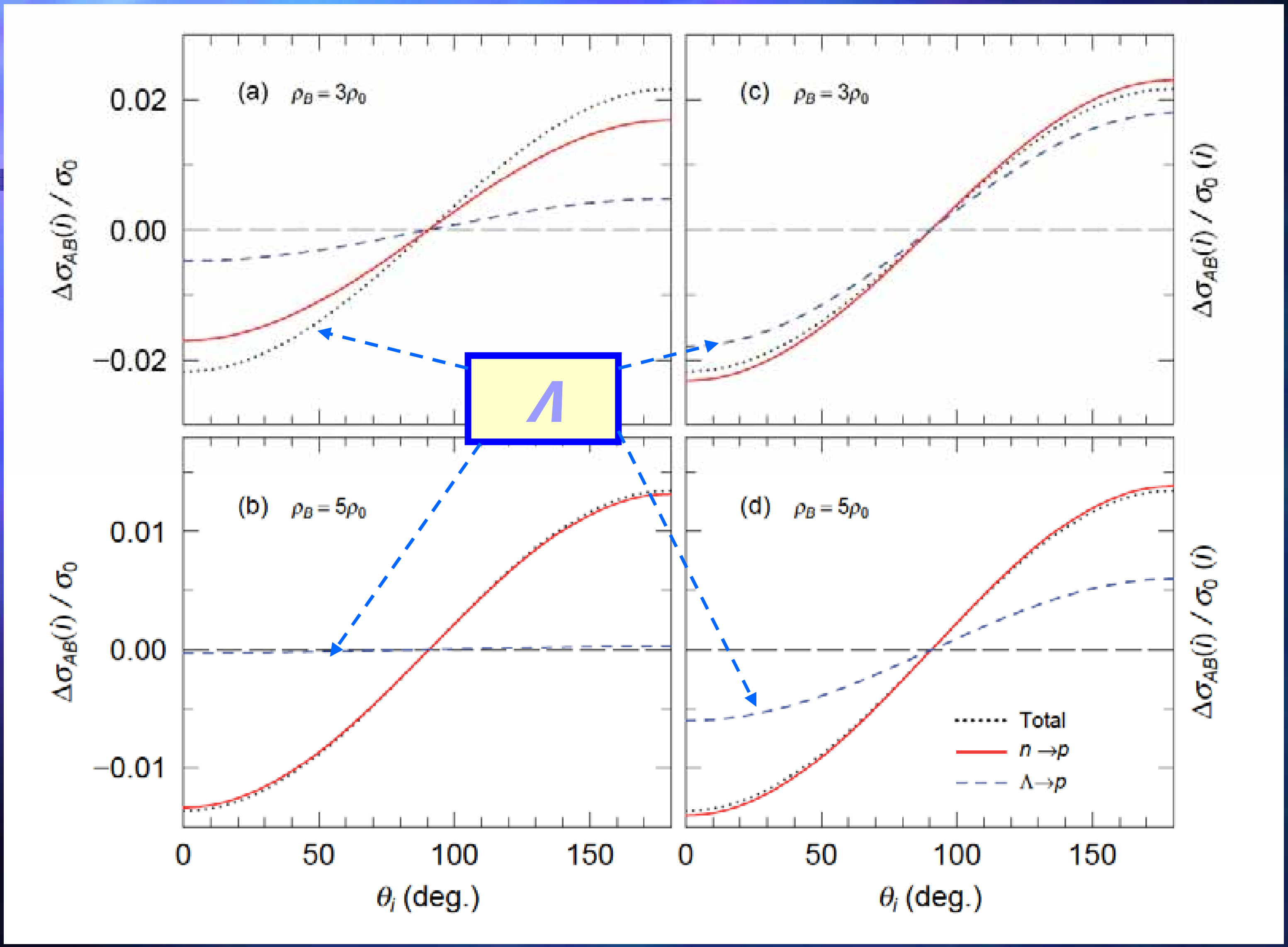
各パートで規格化



全断面積で規格化

Λ寄与

Elements of Absorption Cross-Sections



Contribution from Λ is small

§4 *Neutrino Absorption in Proto Neutron Star*

Neutrino Phase Space Distribution Function

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

Equib. Part (f_0) — Non-Equib. Part (Δf)

Neutrino Propagation ⇒ Boltzmann Eq.

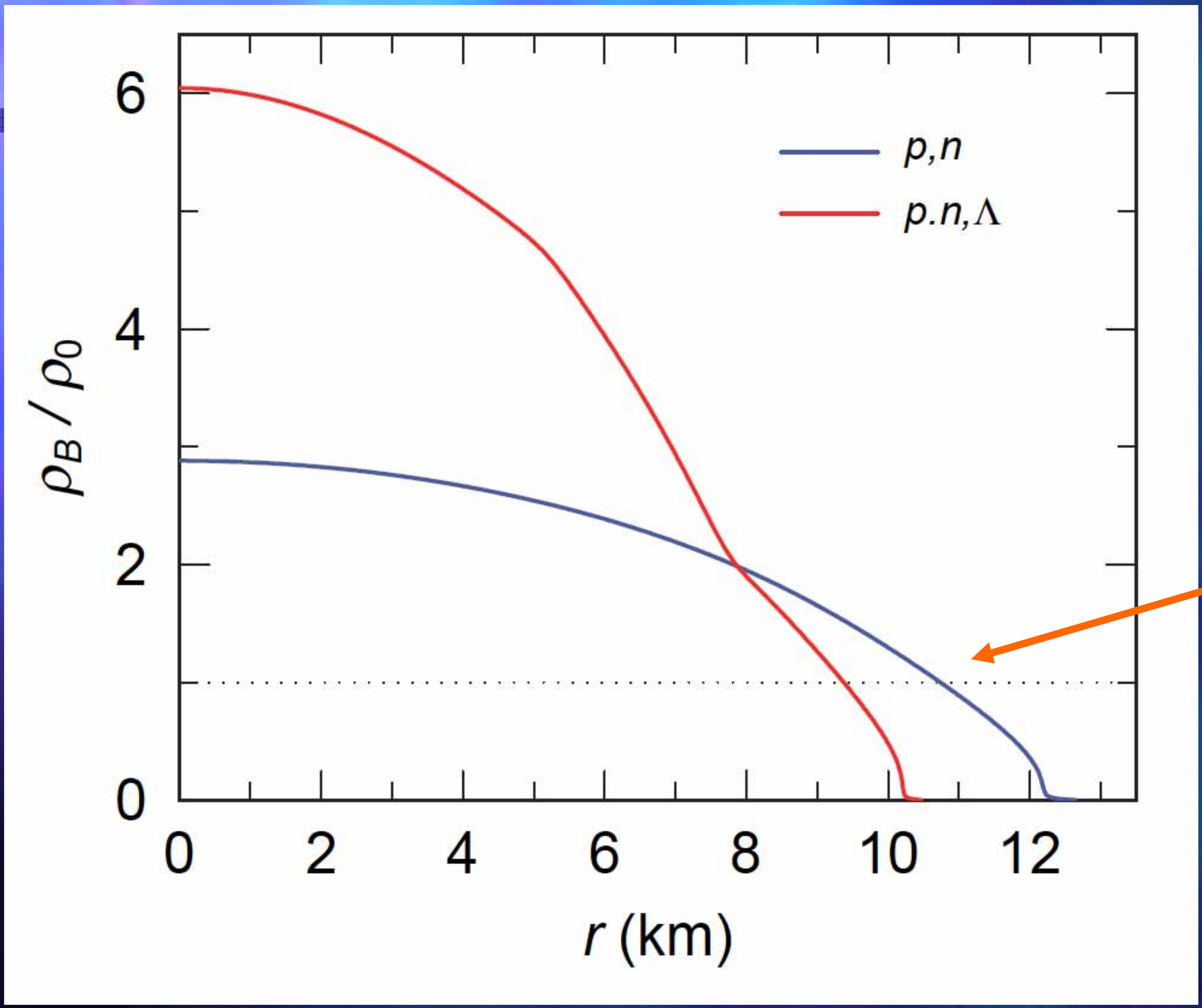
$$c\frac{d}{dx}f_0(\boldsymbol{p},\boldsymbol{r}) + c\frac{d}{dx}\Delta f(\boldsymbol{p},\boldsymbol{r}) = I_{coll} \approx -cb_\nu \Delta f(\boldsymbol{p},\boldsymbol{r}), \quad b_\nu = \frac{\sigma_{ab}}{V}$$

Solution ⇒

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

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

Baryon density in Proto-Neutron Star



$M = 1.68 M_{solar}$

T = 30 MeV

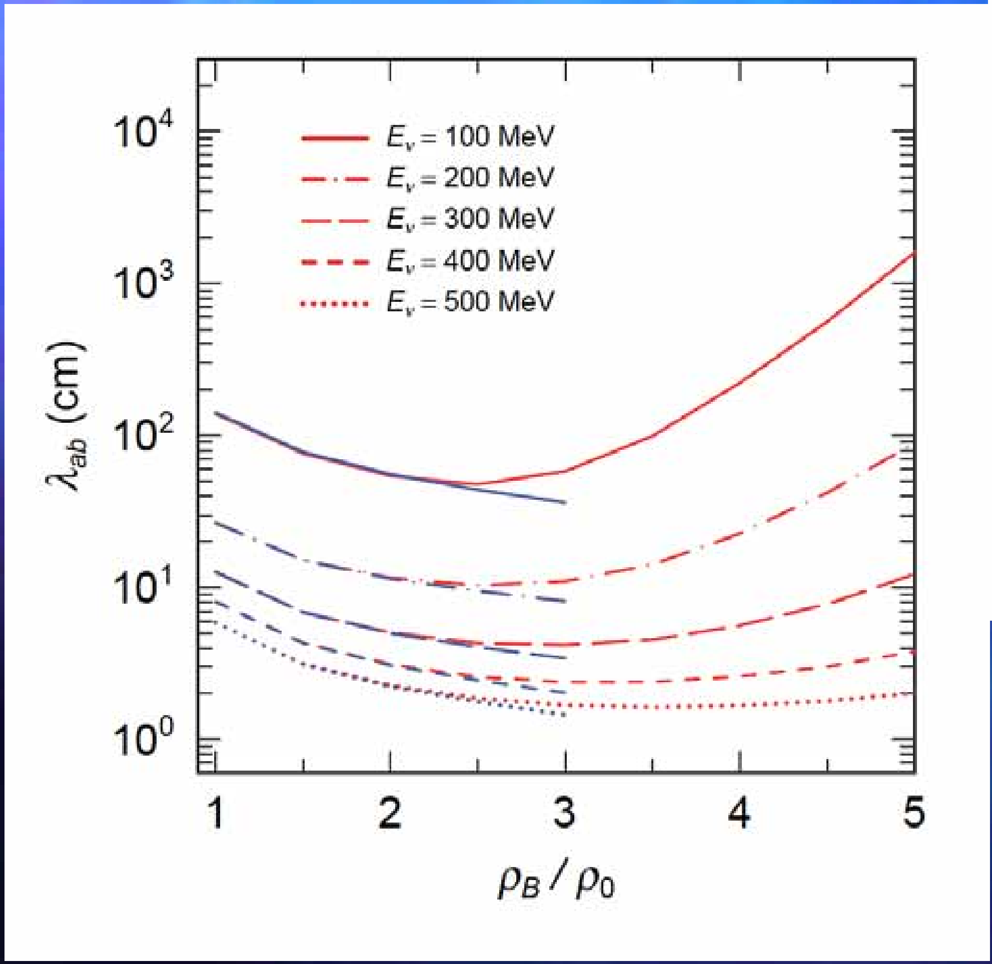
$Y_L = 0.4$

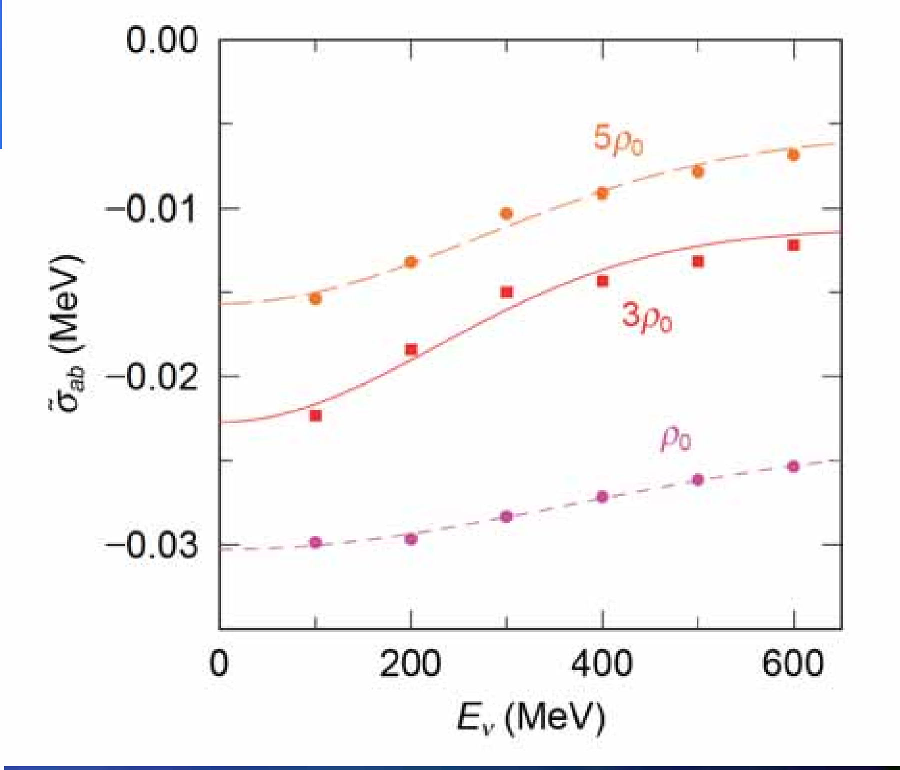
Calculating Neutrino Propagation above

$\rho_B = \rho_0$

Mean-Free Path when B =0

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



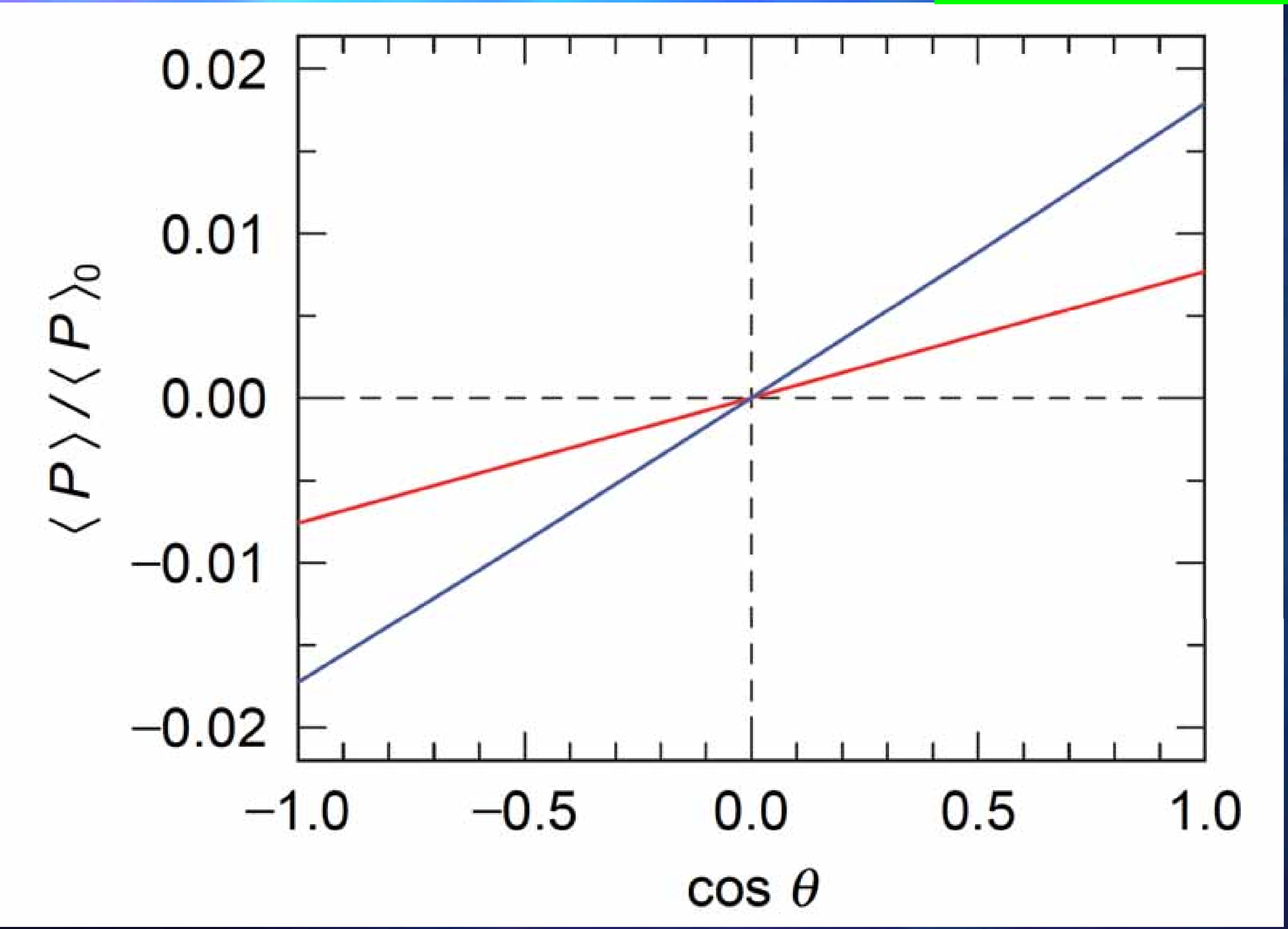


$$\sigma^{ab} = \sigma_o^{ab}\left(1 + \tilde{\sigma}_{ab}\cos\theta\right)$$

Angular Dependence of Emitted Neutrino

$$< p >= \int d\boldsymbol{r} d\boldsymbol{p} (\boldsymbol{p} \cdot \hat{\boldsymbol{u}}) \Delta f(\boldsymbol{p}, \boldsymbol{r})$$

Direction of Emitted Neutrino



Kick Velocity

$$< \boldsymbol{p} \cdot \boldsymbol{\theta} >= P_0 + P_1 \cos\theta$$

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

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

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

Assuming Nuetrino Energy ~ 3×10^{53} erg

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

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

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

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

§4 Summary

- 中性子星物質のEOS　RMFアプローチ（p, n Λ）
- 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 ～10^{17}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 $\rho_B = 3\rho_0$ and T = 20 MeV

⇒　$B = 2\times10^{17}$G　　$B = 2\times10^{18}$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 Λ）,
- $B = 2\times 10^{17}$G　⇒ ニュートリノ吸収断面積を摂動計算

V_{kick} = 180 km/s (p,n) , 77 km/s (p,n, Λ）　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 MeV)　⇒ 加速

温度 T = 30 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