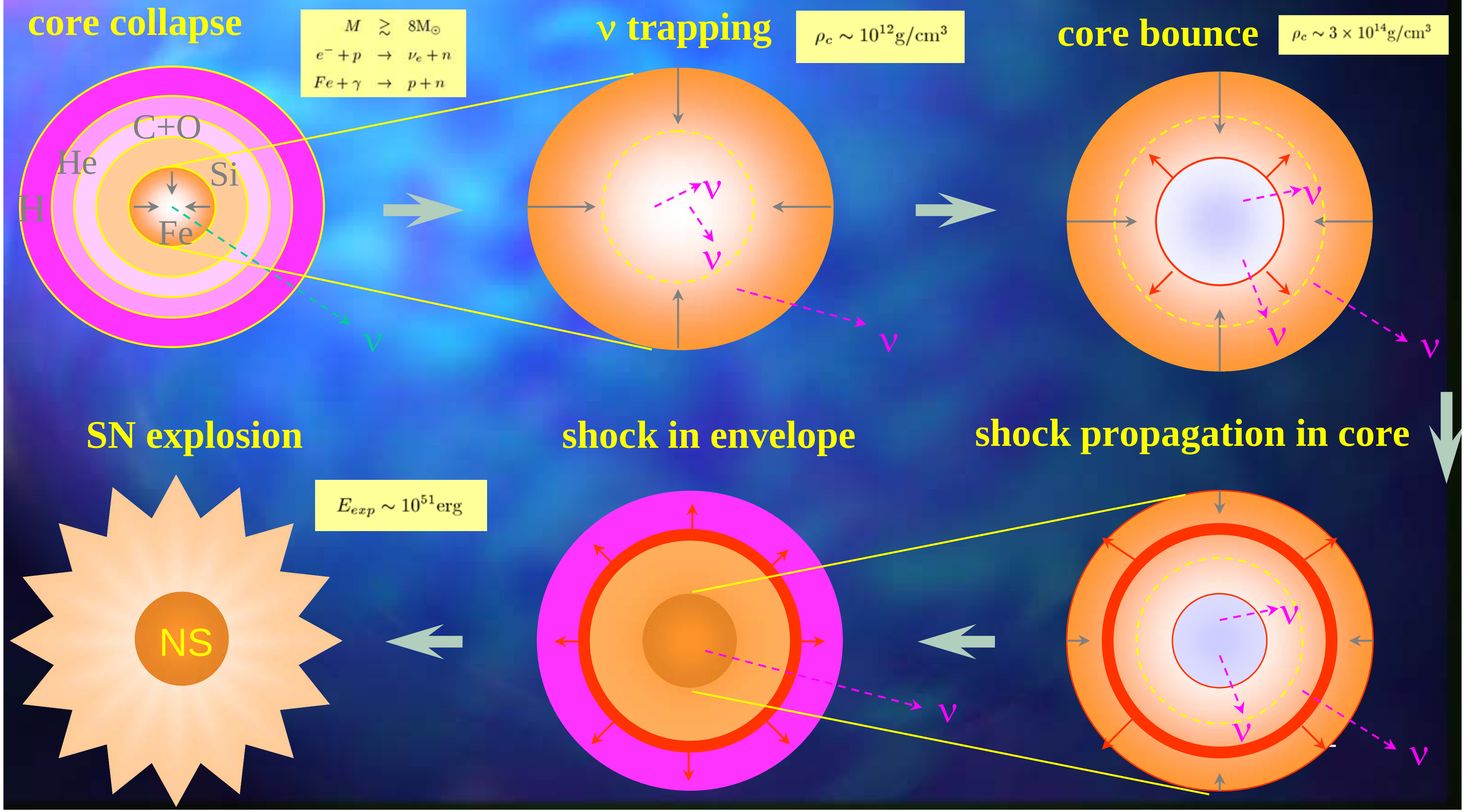
Neutrino Scattering in the protoneutron star with strong magnetic field

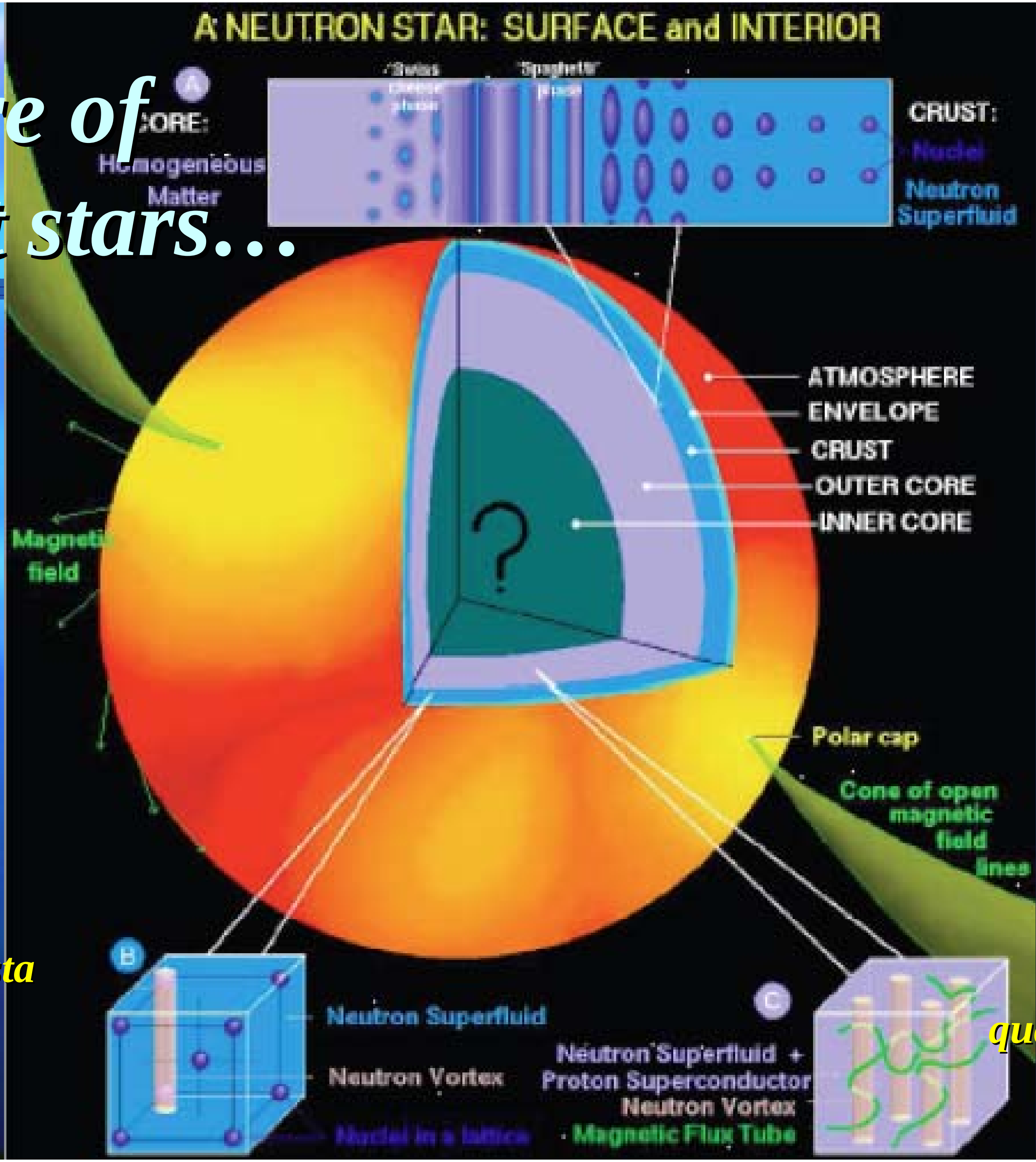
丸山　智幸　　日大生物資源
梶野　敏貴　　国立天文台
安武　伸俊　　国立天文台
Cheoun, Myun-ki　　Soongsil大学 (Korea)
Ryu, Chung-Yoe　　Soongsil大学 (Korea)

§ 1. 導入

Birth of Proto-neutron Star



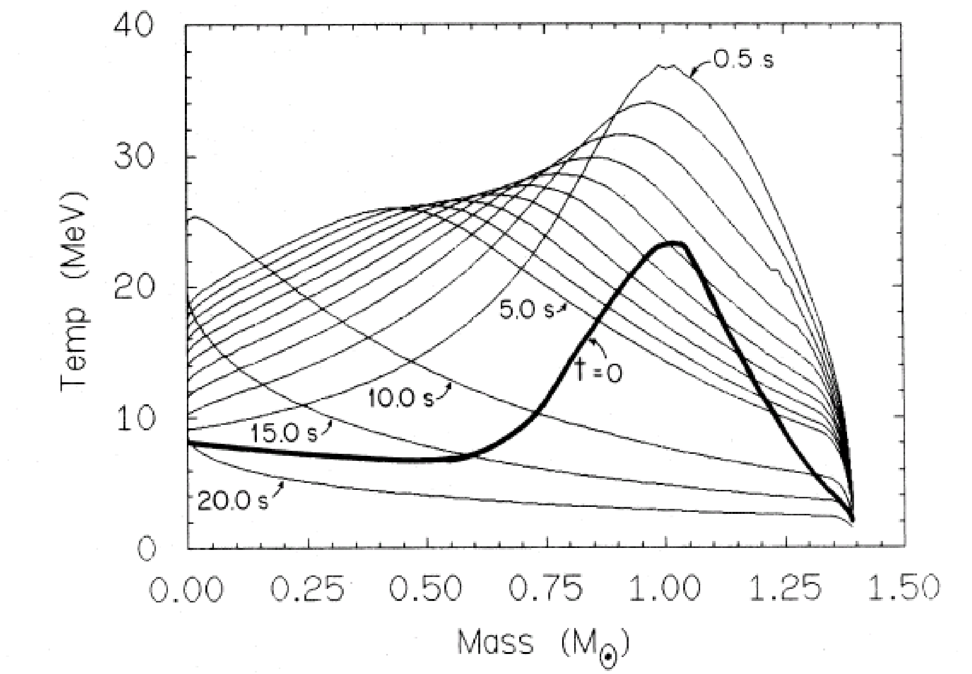
Structure of compact stars…

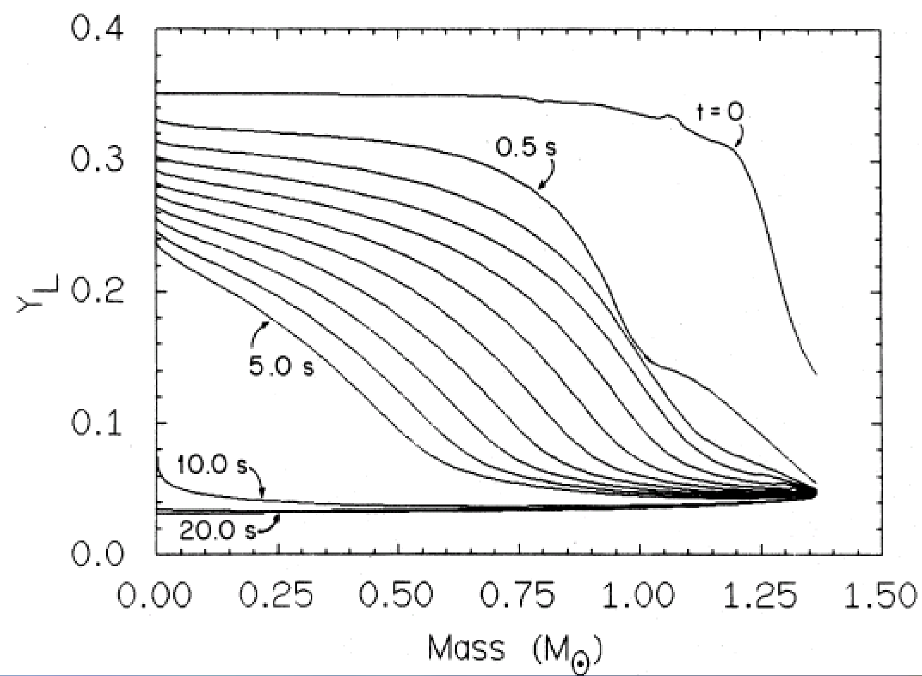


nucleon pasta

quark-had

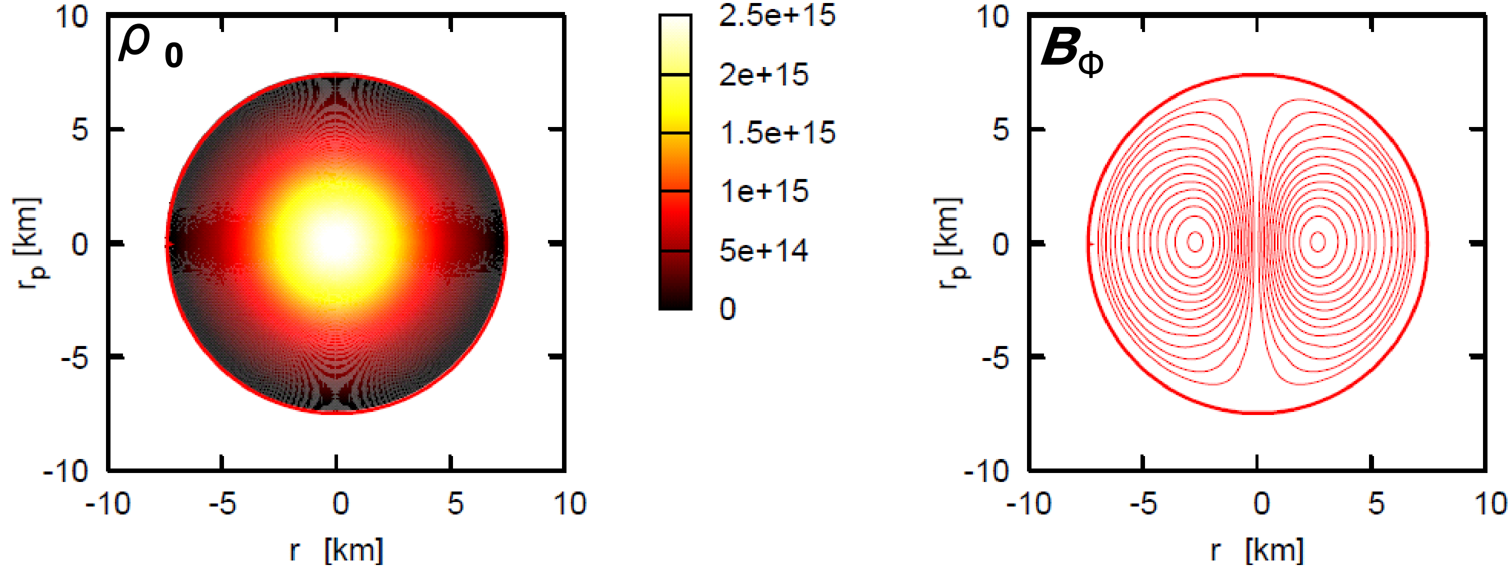
Temperature & lepton fraction in proto-neutron stars





T = 40 → 5 MeV, Y_L = 0.4→0.05

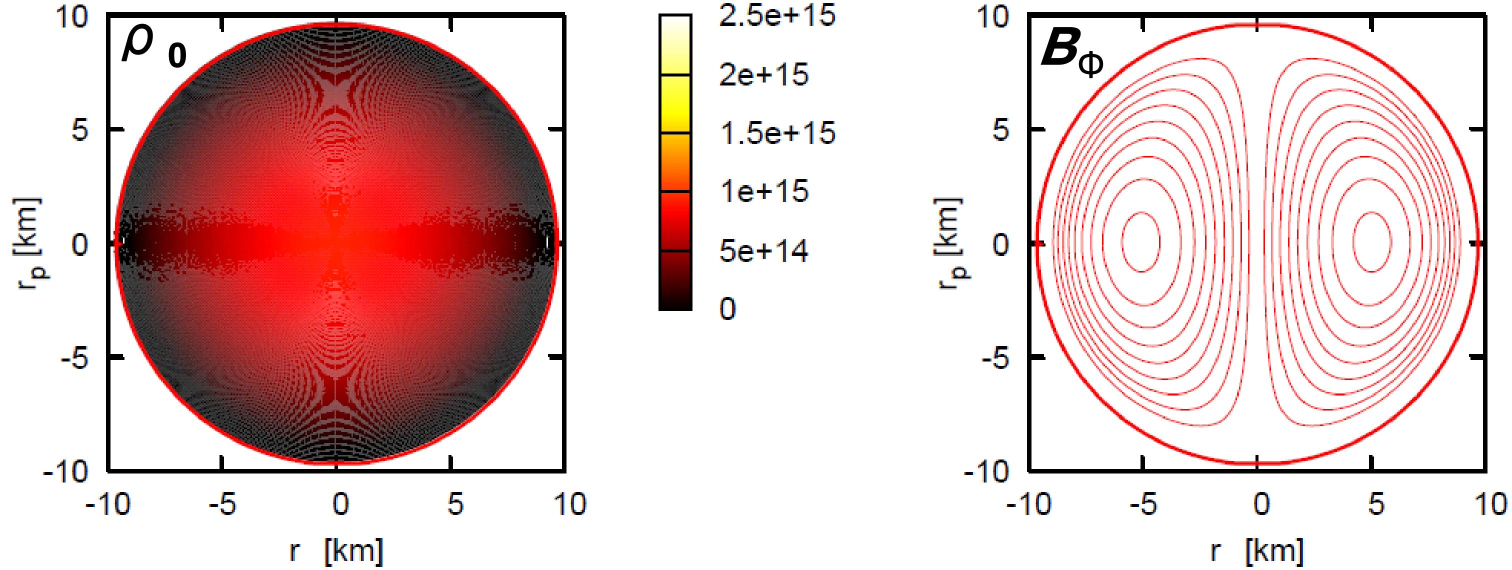
Neutron Stars with hyperons



M =1.31 Ms
B_{max}=7.1 × 10^{17}G

$$M_0=1.45Ms,\quad \Phi=5\times10^{29}\ \mathrm{G\ cm^2}$$

Neutron Stars without hyperons



M =1.32 Ms
B_{max}=4.6 × 10^{17}G

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

強磁性　→　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

§ 2. Formulation

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

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

Baryon | **Lepton** | Weak-int | B & L – Mag.

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

$\mu_N B$ << ε_F (Chem. Pot) → *B* を摂動、ランダウ・レベルは無視

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

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

Baryon : 相対論的平均場(RMF)模型

Lepton : free

$$\text{Dirac Eq. : } \hat{h}(p)u(p) = [\not{p} - M - \mu B \sigma_z]\, u(p) = 0$$

$$\text{Green Function } (S(p)) : \hat{h}(p)S(p) = 1$$

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

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

フェルミ面が横方向に広がる

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

When $\mu B << 1$,

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

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

Spin-indep. part

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

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

Spin-dep. Part

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

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

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

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

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

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

電子からの寄与

$$
\begin{aligned}
& \left[\frac{G_F^2}{32\pi^5}\frac{|\boldsymbol{k}_f|}{Q|\boldsymbol{k}_i|}\mu_e B\right]^{-1} \frac{d^2\Delta\sigma}{dk_f d\Omega_f} \\
\approx \quad & f'_{l'}(|\boldsymbol{k}_f|)\int dE_p d\phi_p W_e n_B(\varepsilon_i)[1-n_{B'}(\varepsilon_f)] + [1-f_{l'}(|\boldsymbol{k}_f|)]\int dE_p d\phi_p n_B(\varepsilon_i) n'_{B'}(\varepsilon_f) W_e \\
- \quad & [1-f_{l'}(|\boldsymbol{k}_f|)]\int dE_p d\phi_p (E_i+\omega) n_B(\varepsilon_i)[1-n_{B'}(\varepsilon_f)]\frac{1}{|\boldsymbol{p}|}\frac{\partial}{\partial t}W_e .
\end{aligned}
$$

§ 3 Results

状態方程式

非摂動1粒子エネルギー

$$\varepsilon_\alpha(\boldsymbol{p}) = \sqrt{\boldsymbol{p}^2 + (M - U_s(\alpha))^2} + U_0(\alpha)$$

Nuclear Matter PM1

***BE* = 16MeV,**
***K* = 200 MeV**
***M*/M* = 0.7**

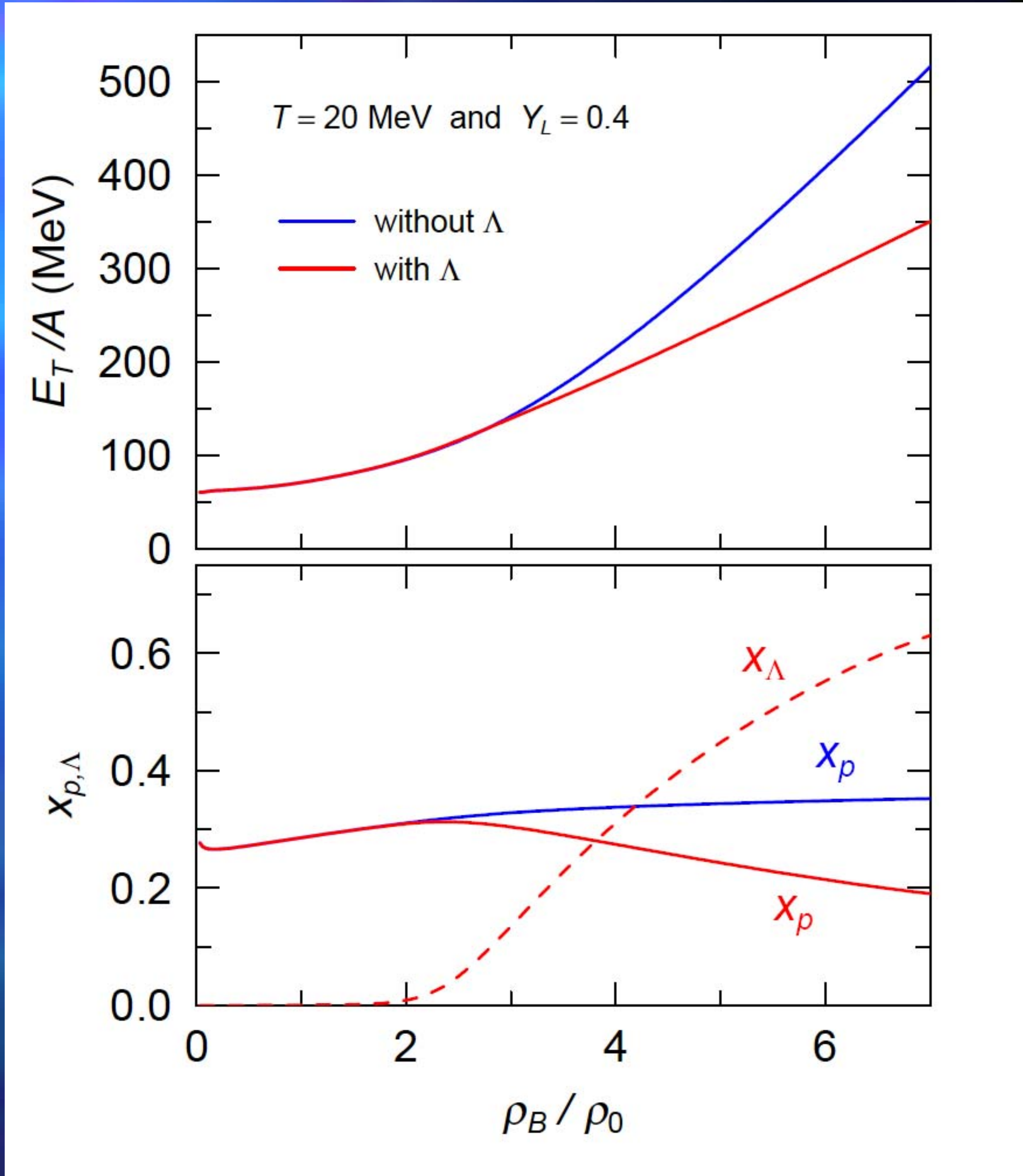
at ρ_0 = 0.17 (fm^{-3})

Λ – mean - fields

$$U_\alpha(\Lambda) = c_\alpha U_\alpha(N) \qquad (\alpha = s, 0)$$

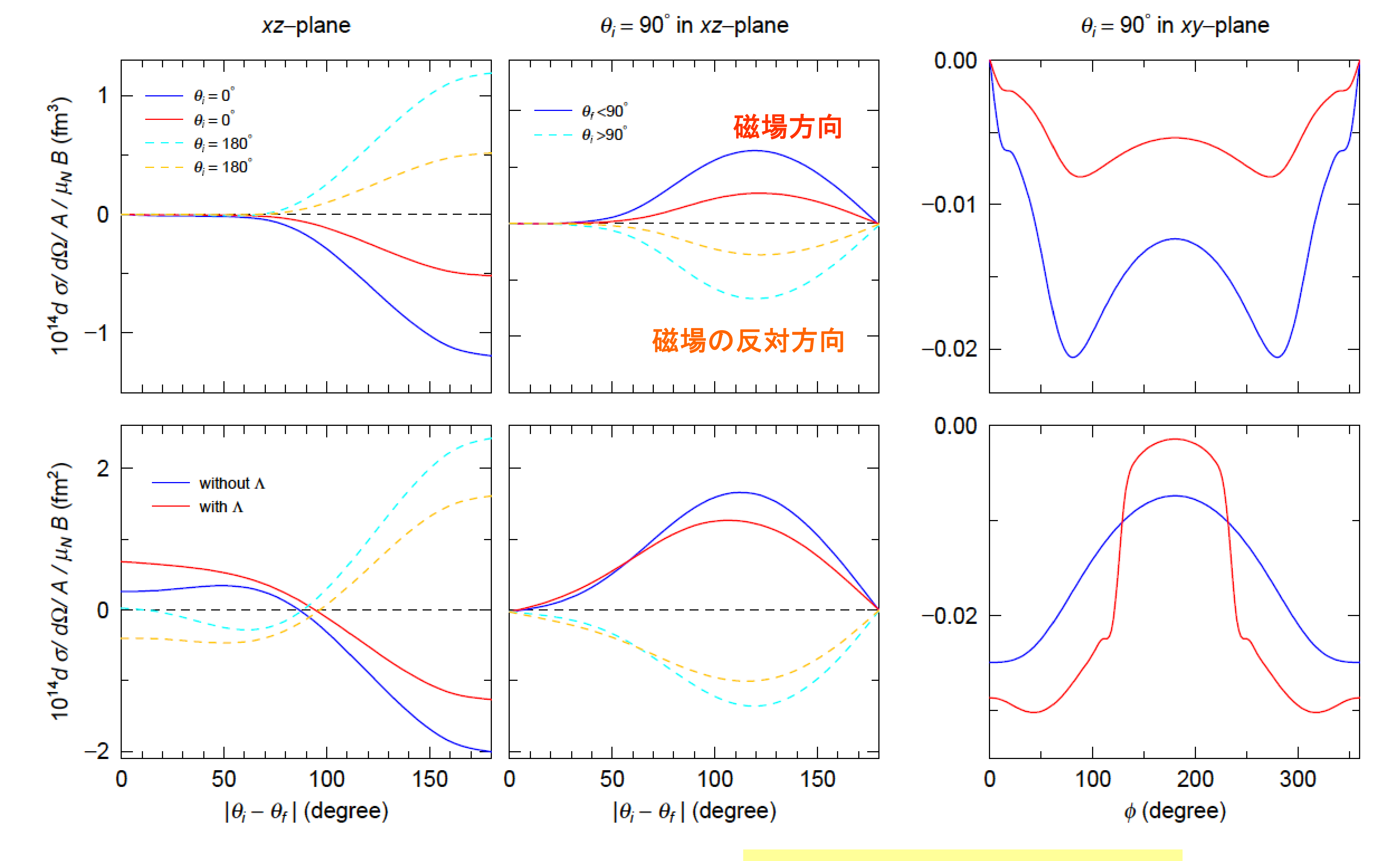
$$U_s(\Lambda) - U_0(\Lambda) = \frac{2}{3}\{U_s(N) - U_0(N)\}$$

C_s = C_0 = 2/3 L1



Spin-dep. Part of cross-section
with k_i=40 MeV T = 20 MeV

$\upsilon_e \rightarrow \upsilon_e$ scattering



$\upsilon_e \rightarrow$ e absorption

k_i=40 MeV

Actual Cross-Section

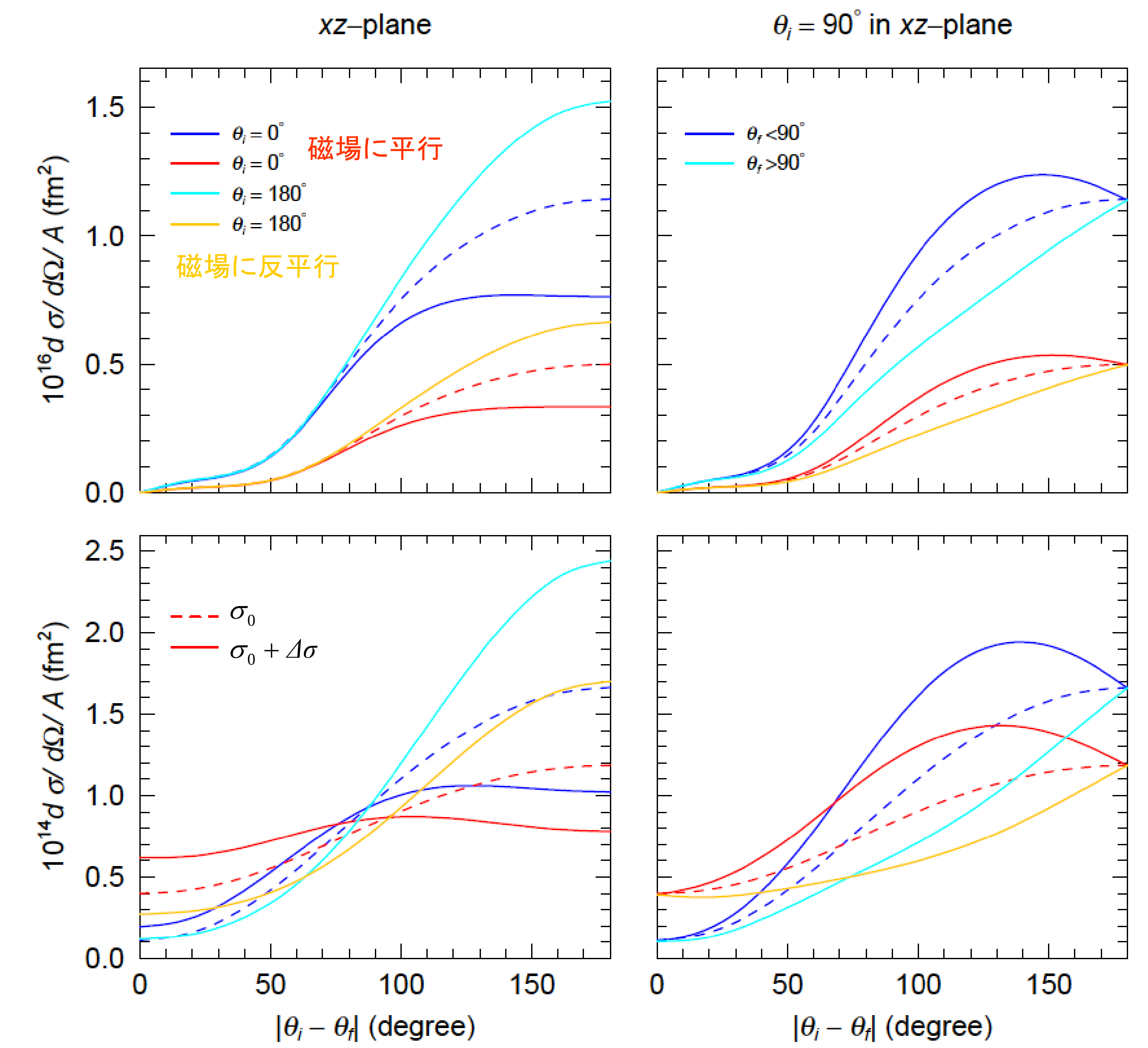
T = 20 MeV

磁場

$B=2\times10^{17}$ G

入射運動量

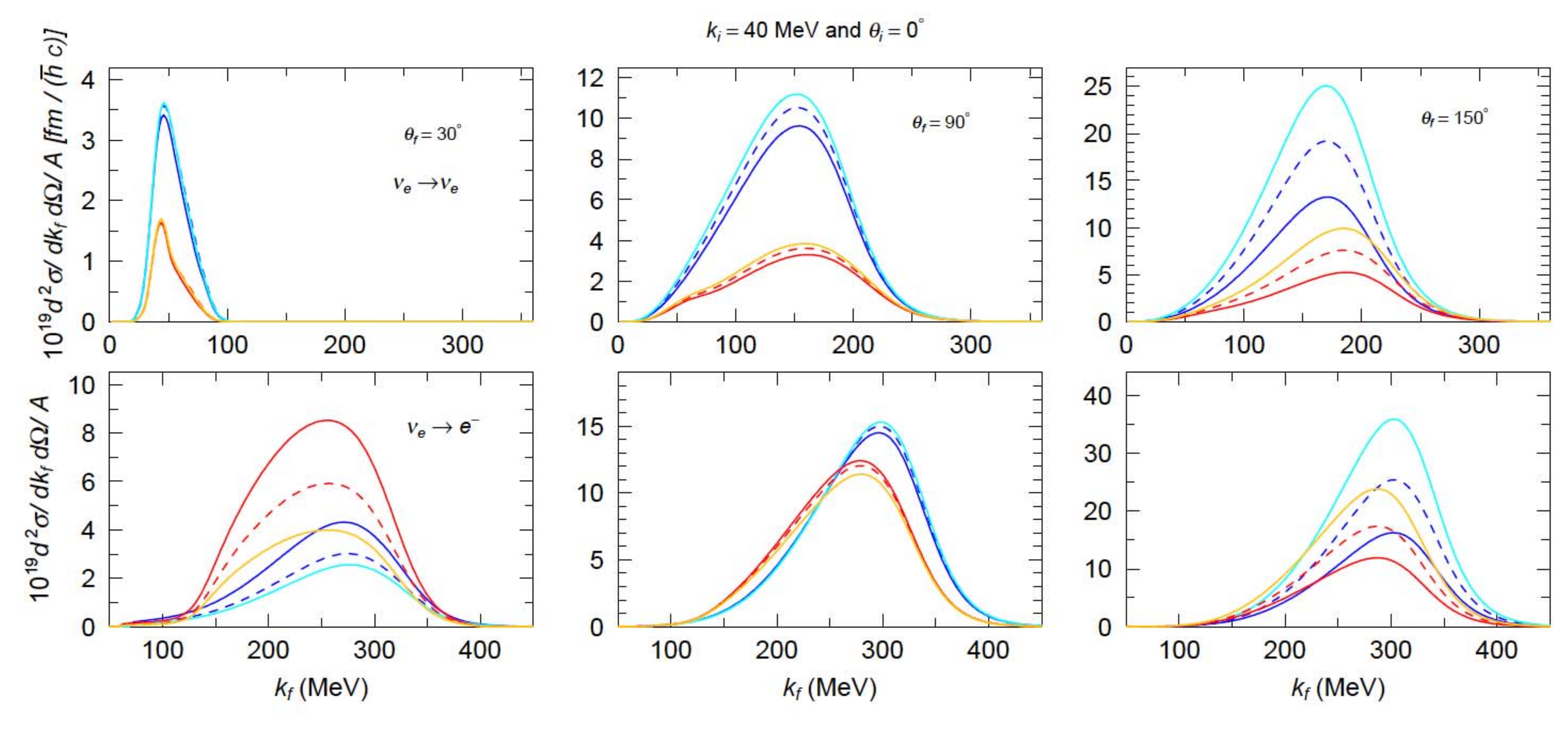
k_i=40 MeV



Energy Spectrum 磁場 $B=2\times10^{17}$ G

T = 20 MeV

入射運動量 k_i=40 MeV, θ_i = 0° & 180°



Cross-Section

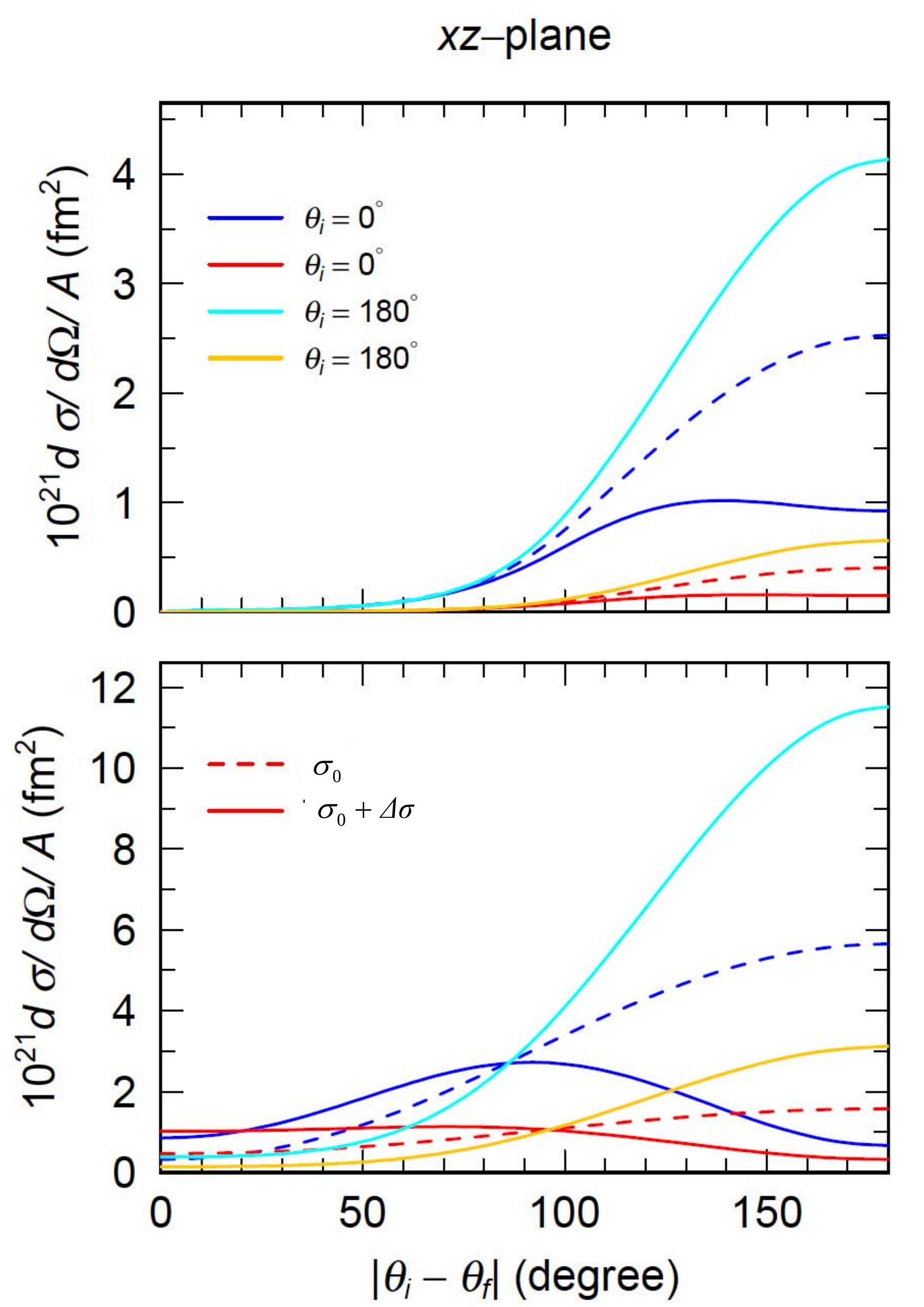
T = 10 MeV

磁場

$B=2\times10^{17}$ G

入射運動量

k_i=40 MeV



§4 まとめ

中性子物質内部でのニュートリノ散乱、吸収

$B \geqslant 10^{17}$**Gで磁場の効果が現れる** (摂動計算は$B < 10^{18}$G)

入射ニュートリノ　断面積は後方が大きい　← パウリ効果

磁場の効果　‥　平行は減少、反平行は増加

垂直→ 終状態は磁場方向に増加

将来計画

・$B > 10^{18}$Gでは構造に寄与　　Λ出現密度が変化

ランダウ・レベル

・スピンースピン相互作用　→　スピン偏極が変化

・**クォーク物質**

・Direct Urca Process in Cold Neutron Star Matter