強磁場原始中性子星での ニュートリノ反応断面積の非対称性と関連現象

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§ 1 *Introduction*

High Density Matter Study ⇒ Exotic Phases inside Neutron Stars

Strange Matter, Ferromagnetism, Meson Condensation, Quark matter

Observable Information ・・・・Neutrino Emissions

S.Reddy, et al., PRD58 #013009 (1998) Influence from Hyperons Λ, ∑

Magnetar 10^{15}G in surface $10^{17\text{-}19}$G inside (?) → Large Asymmetry of ν ?

Our Works : **Neutrino Scatt. and Absorp. under Strong Magnetic Field**

TM et al., PRD83, 081303(R) (11), PRD86,123003 (12)

Neutrinos are More Scattered and Less Absorbed

in Direction **Parallel to Magnetic Field**

⇒ More Neutrinos are Emitted in Arctic Area

Scattering 1.7 %

Absorption 2.2 % at $\rho_B = 3\rho_0$ and T = 20 MeV

Asymmetry of Supernova Explosion

kick and translate Pulsar with

Kick Velocity: Average … 400km/s,

Highest … 1500km/s

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

Explosion Energy ~ 10^{53} erg

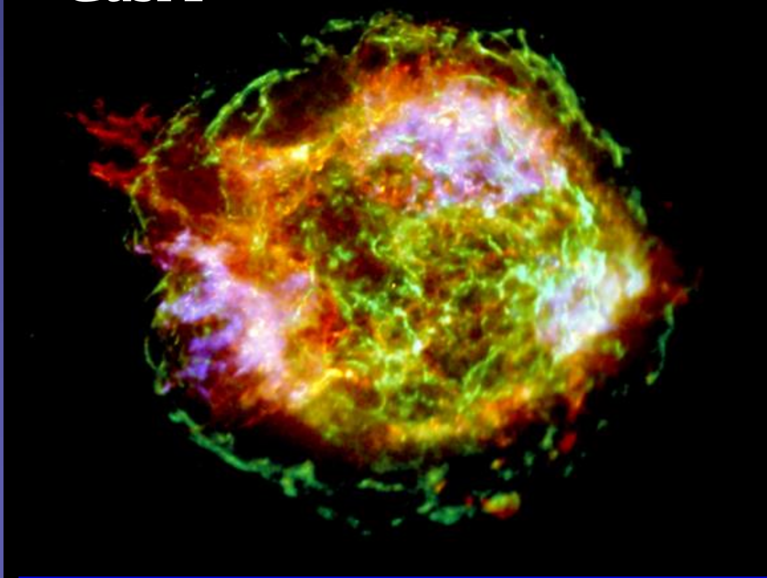
(almost Neutrino Emissions)

***1% Asymmetry* is sufficient**

to explain the Pulsar Kick

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

CasA



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

Our Works TM et al., PRD86,123003 (12)

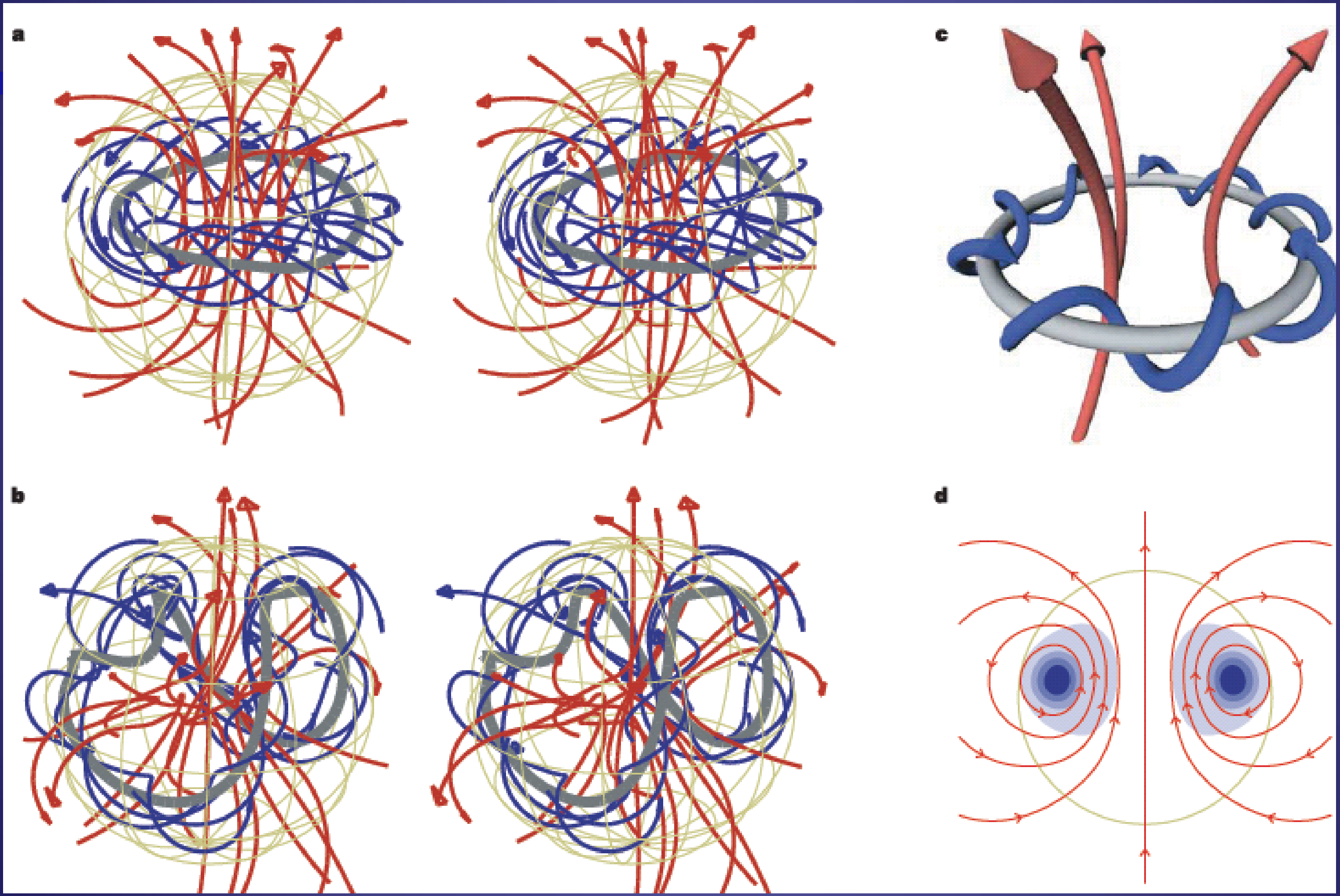
$B = 2\times 10^{17}$G Poloidal Configuration of Magnetic Field

$V_{\rm kick}$ = 580 km/s (p,n) , 610 km/s (p,n,Λ) at T = 20 MeV

Antarctic Direction

Stability of Magnetic Field in Compact Objects

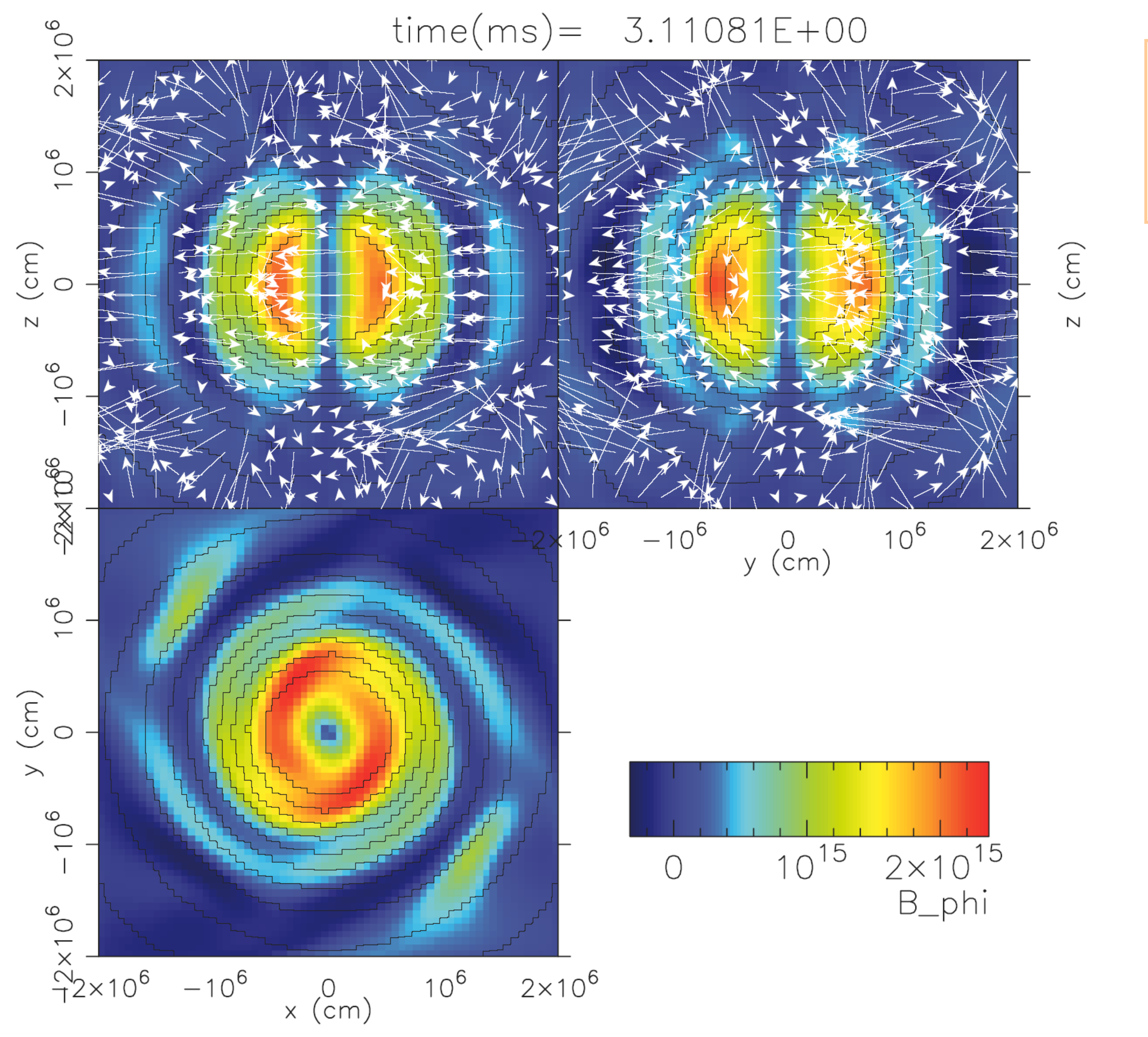
(Braithwaite & Spruit 2004)



Toroidal Magnetic Field is stable !!

T.Kuroda and H. Umeda, Astro. J. Suppl. 191, 439 (10)

Single Toroidal

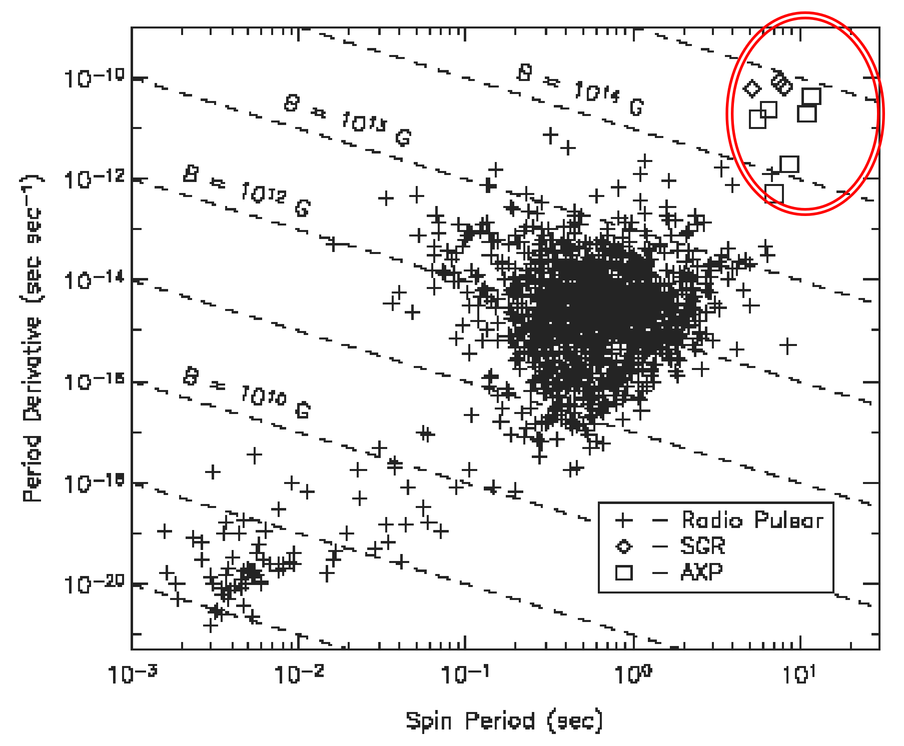


Magnetar Spin Period

2 ～ 12 s （Very Long)

Large Spin-down is necessary

in Process of NS production



Magnetic Field Confguration in PNS

Poloidal (10^{14}G) + Toroidal (10^{16}G) Magnetic Field

T. Takiwaki, K.Katake and K. Sato Astro. J 691, 1360 (2009)

Antisymmetric ν –Emission in Toloidal Configuration

⇒ Rapid Spin Deceleration

§ 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.

1. **Proto-Nuetron-Star (PNS) Matter without Mag. Field**
2. **Baryon Wave Function under Mag. Field in Perturbative Way**
3. **Cross-Sections for ν reactions**

Weak Interaction

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

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

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

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

§ 2-1 EOS of Proto Neutron-Star-Matter in RMF $N, \Lambda, \sigma, \omega, \rho$

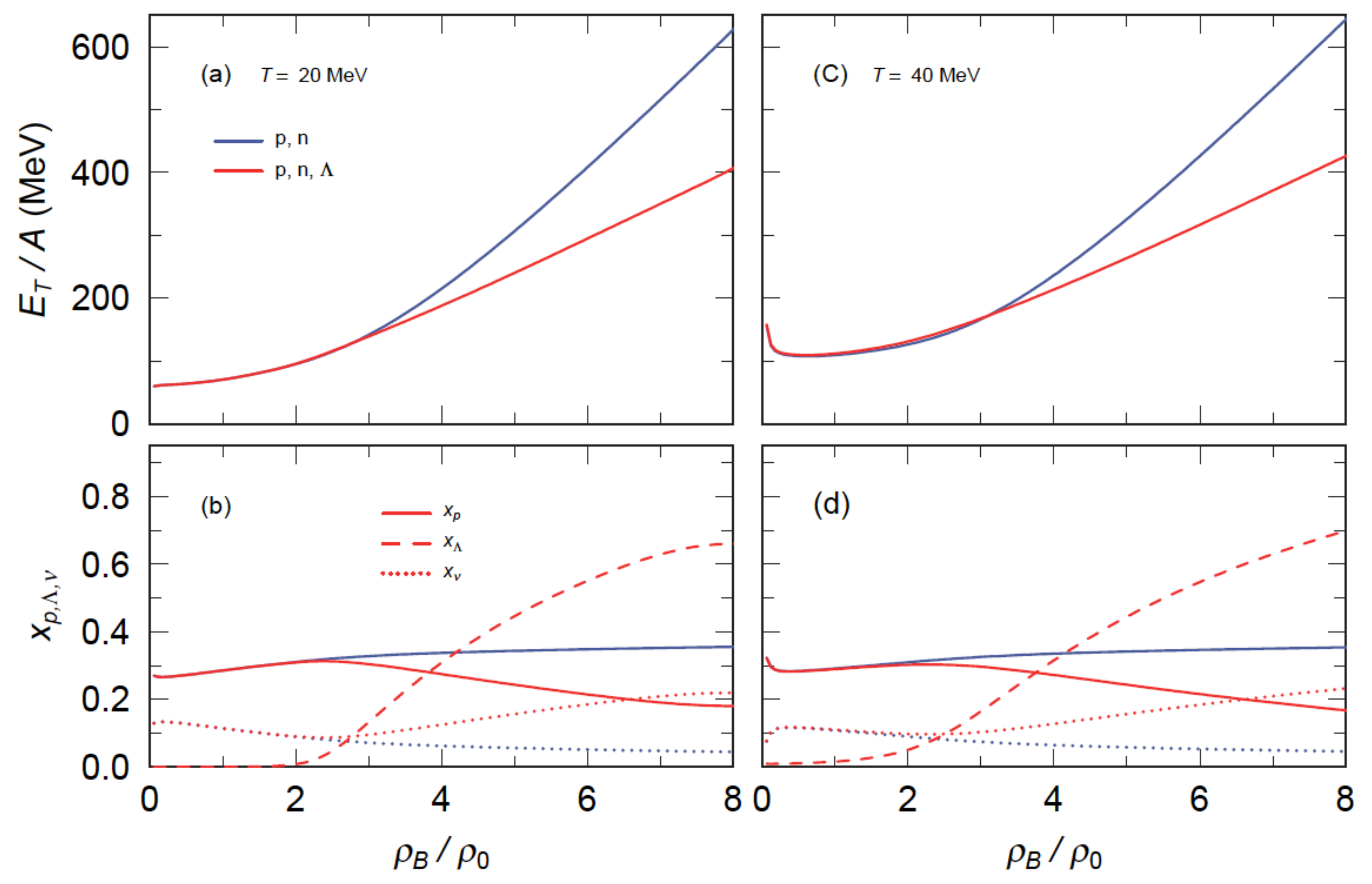
PM1-L1

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

$g_{\sigma,\omega}^{\Lambda} = \frac{2}{3} g_{\sigma,\omega}$ **SU(3)**

T.M, et al.
PTP. 102, p809
(1999)

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



§ 2-2 Dirac Equation under Magnetic Fields

$\mu_N B \ll \varepsilon_N$ (Chem. Pot) → B can be treated perturbatively

$B \sim 10^{17}$ G Landau Level can be ignored

Lagrangian

$$\mathcal{L}_{mag} \approx -\sum_b \mu_n B \bar{\psi}_b \sigma_z \psi_b$$

Dirac Eq.

$$\hat{K}(p)u(p) = \left[\gamma_\mu p^\mu - M^* - \mu B \sigma_z\right] u(p) = 0$$

Single Part. Eng.

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

Dirac Spinor

$$u(\boldsymbol{p},s)\bar{u}(\boldsymbol{p},s) \approx \frac{(\not{p} + M)(1 + \gamma_5 \not{a}(p) s)}{4E_p^*}$$

Spin Vector

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

The Cross-Section of Lepton-Baryon Scattering

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

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

$m_f = 0$ when $l_f = \nu$ $\quad$ $m_f = m_e$ when $l_f = e$

Fermi Distribution

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

Deformed Distribution

Perturbative Treatment

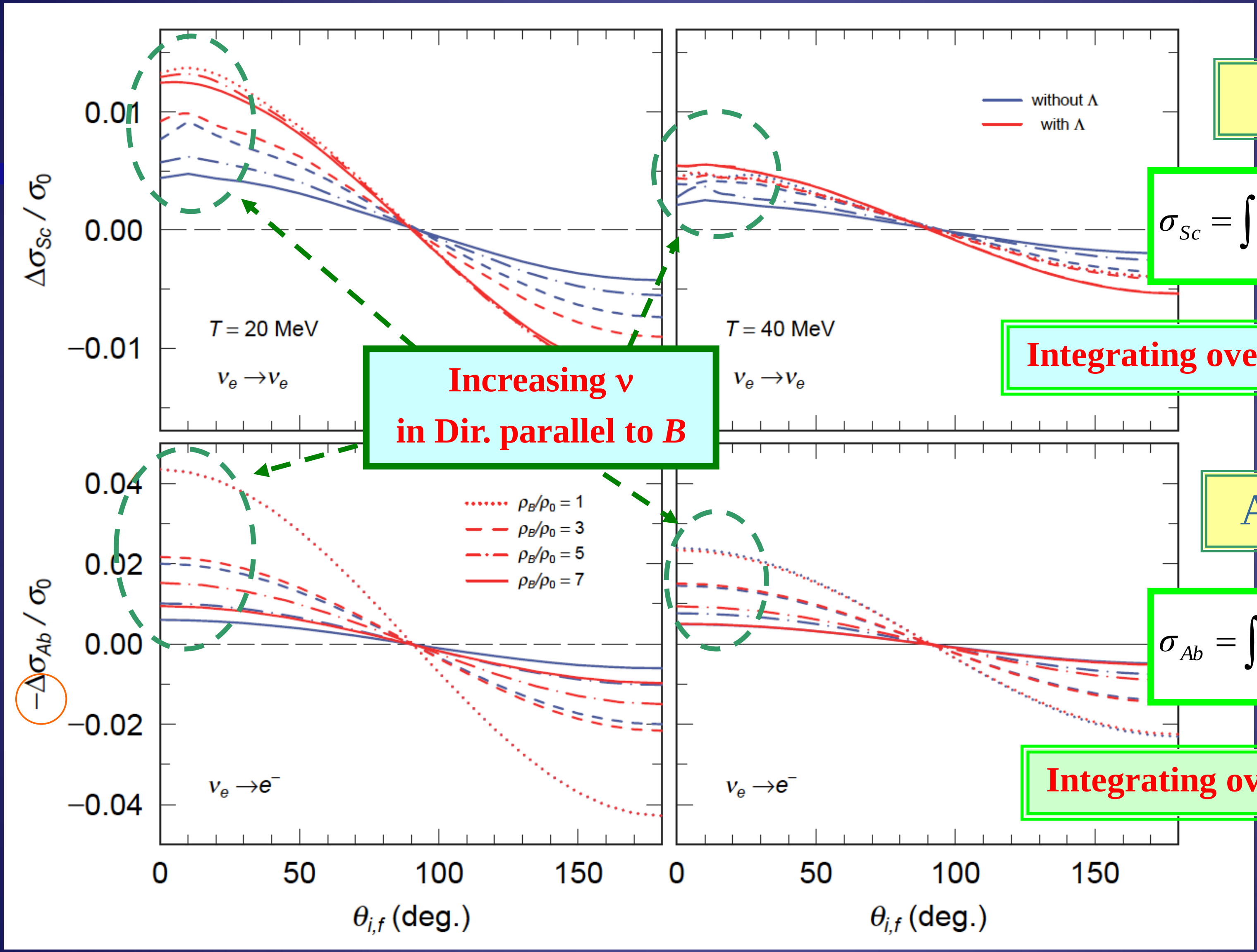
$$\sigma = \sigma_0 + \Delta\sigma \qquad \Delta\sigma \propto B$$

Non-Magnetic Part

Magnetic Part

§2-3 Magnetic parts of Cross-Sections

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



Increasing ν

in Dir. parallel to *B*

Scat.

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

Integrating over the initial angle

Absorp.

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

Integrating over the final angle

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

§ 3 Neutrino Transportation

Neutrino Phase Space Distribution Function

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

Equib. Part

Non-Equib. Part

Neutrino Propagation ⇒ Boltzmann Eq.

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

Neutrinos Propagate on **Strait Line**

only absorption

Solution ⇒

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

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

Toroidal Magnetic Field

$$\boldsymbol{B}(r_T, z) = B_0 G_T(r_T) G_L(z) \hat{e}_\phi$$

$$G_T(r_T) = \frac{16 \exp\left[-(r_T - R_0)/\Delta r\right]}{\left\{1 + \exp\left[-(r_T - R_0)/\Delta r\right]\right\}^2}$$

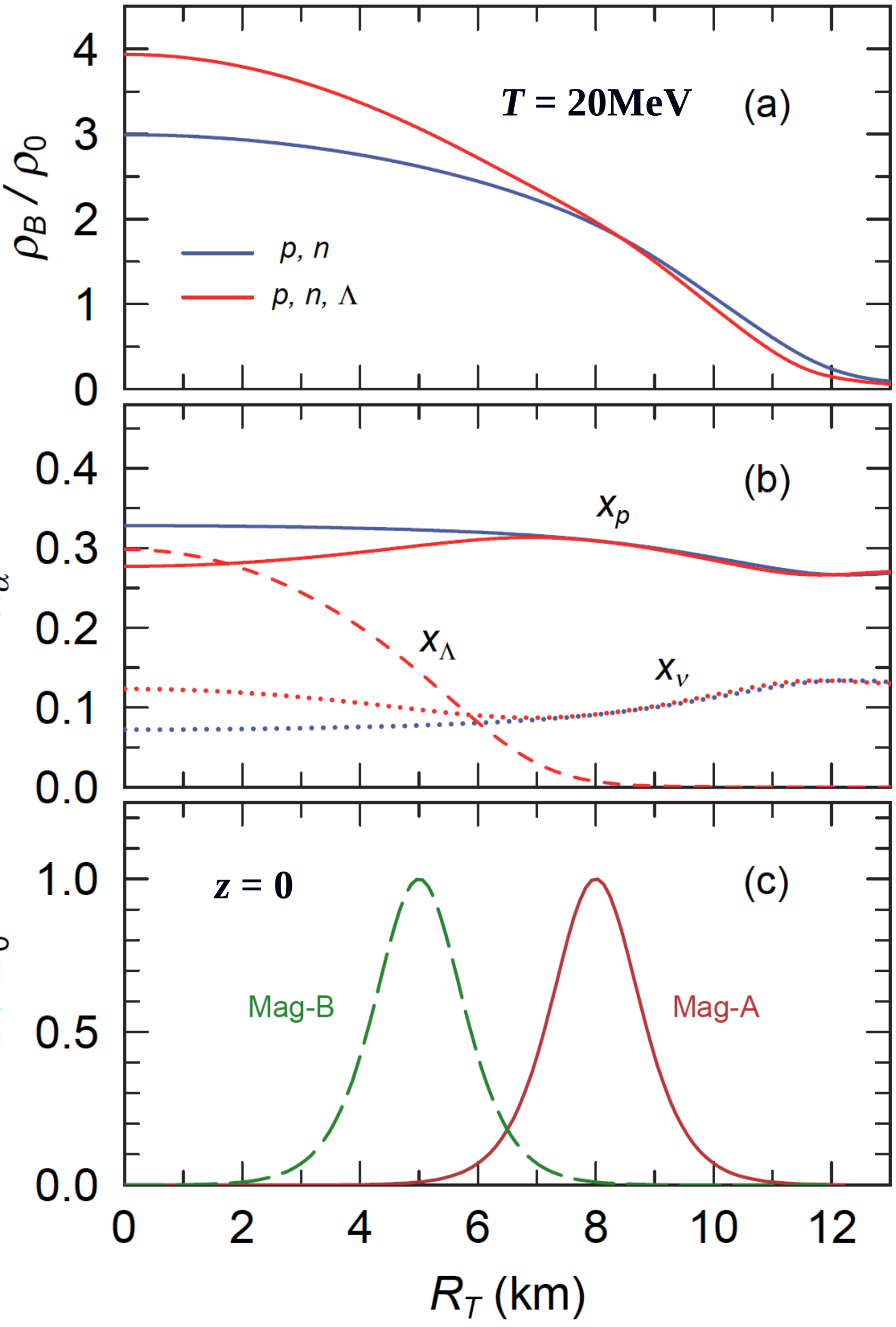
$$G_L(z) = \frac{\exp\left[-z/\Delta r\right]}{\left\{1 + \exp\left[-z/\Delta r\right]\right\}^2}$$

$$\hat{e}_\phi = (-\sin\varphi, \cos\varphi, 0)$$

$\mathit{\Delta r}$ = 0.5 (km)

R_0 = 8 (km)   (Mag-A)

R_0 = 5 (km)   (Mag-B)



§ 5 Spin Deceleration

Neutrino Luminosity

$(dE_T/dt)_\nu \sim 3\times10^{52}$ **erg/s**

$$\frac{dL_z}{dt} = c\int_{S_N} d\mathbf{r}\int d\mathbf{n}\int dp_L\, \Delta f(\mathbf{r}, p_L, \mathbf{n})(\mathbf{r}\times\mathbf{p})_z$$

$M_{NS} = 1.68 M_{solar}$

Period $P = 10$ms

$$\dot{\omega} = \frac{d\omega}{dt} = \frac{1}{I_{NS}}\frac{dL_z}{dt} = \frac{1}{I_{NS}}\left(\frac{dE_T}{dt}\right)_\nu \frac{cdL_z/dt}{dE_T/dt}$$

Magnetic Dipole Rad.

$$P\dot{P} = B^2\left(\frac{125\pi^2 I_{NS}^2}{3M_{NS}^2 c^3}\right)$$

Mag Distr.	Bary.	$-\frac{cdL_Z/dt}{dE_T/dt}$ (cm)	$\dot{P}/P$		
			(ν **emis.**)		MDR
			$\rho_s = \rho_0$	$\rho_s = \rho_0/10$	
p,n	Mag-A	3.34	**3.45×10^{-6}**	**7.25×10^{-7}**	**9.86×10^{-8}**
	Mag-B		**4.97×10^{-7}**	**3.16×10^{-7}**	
p,n,Λ	Mag-A	5.45	**6.39×10^{-6}**	**1.02×10^{-6}**	**7.76×10^{-8}**
	Mag-B		**4.57×10^{-7}**	**2.01×10^{-7}**	

In Early Stage (~ **10 s**) ν **Asymmetric** Emission must affect **PNS Spin**

More Significantly than Magnetic Dipole γ-Radiation

Present PNS Model

Uniform Matter, Iso-Thermal, Fixed Lepton Fraction
Strong Magnetic Field

Available in Inside Region

Surface Region

Past Structure, Low Temperature, Small Neutrino Fraction
Rather Weak magnetic Field

Larger Mean Free Path of Neutrino

We need to stop calculation at a Certain Radius
R_{C}, where $\rho_{\mathrm{B}} = \rho_{\mathrm{c}}$

§ 4 *Summary*

- **Asymmetry of Neutrino Absorption**

  4.3 % at $\rho_B = \rho_{0,}$ 2.2 % at $\rho_B = 3\rho_0$ when T = 20 MeV and B = 10^{17}G
- **Estimating Spin-Down Rate of PNS with Toroidal Magnetic Field Configuration**
- **Mag. Field Poloidal 10^{14}G, Toroidal** Max: **10^{16}G**
- **Asymmetry of Neutrino Absorption**

  4.3 % at $\rho_B = \rho_{0,}$ 2.2 % at $\rho_B = 3\rho_0$ when T = 20 MeV and B = 10^{17}G
- **Spin-Down Ratio P-dot/P = $10^{-6} \sim 10^{-7}$ (1/s) for Asym. ν–Emit**

  $\approx$ 10^{-7} (1/s) for MDR

Future Plans

Other Effects: ν-Scattering & ν-Production

Iso-Temp. ⇒ Iso-Entropy

Exact Solution of Dirac Eq. in Non-Perturbative Cal.

→ **Landau Level** at least for Electron

Neutrino Propagation in Low Density

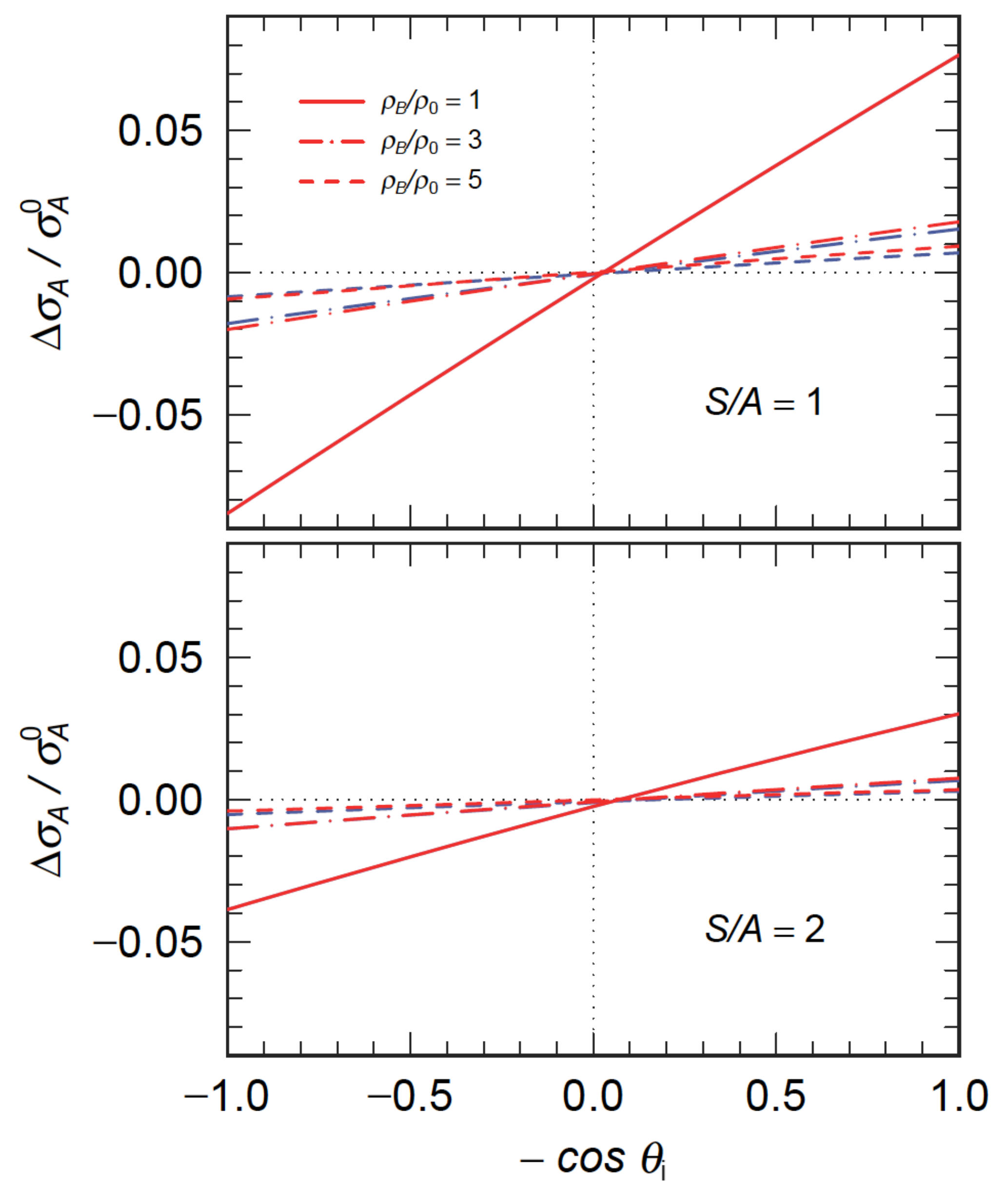
$$e^- + p \rightarrow \nu_e + n$$

Appling Our Method to *Double Toroidal Configuration*

Making Data Table and

Applying it to Supernovae Simulations

Magnetic parts of Absorption Cross-Sections



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

Integrating over the final angle

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

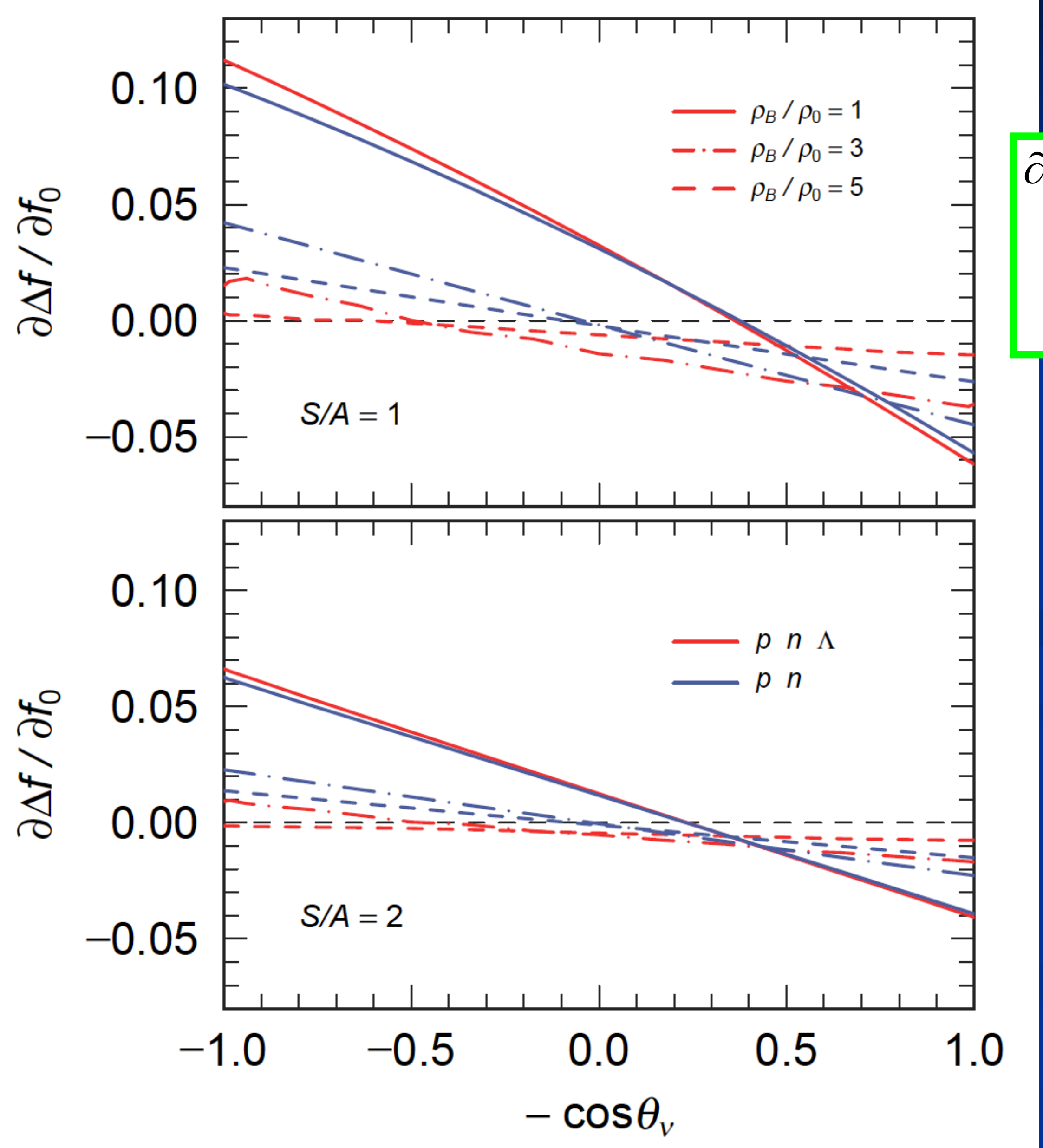
Less Absorption
&
Increasing ν
in Dir. parallel to *B*

$$k_i = \varepsilon_\nu \text{ (neutrino chem. pot.)},$$

$$Y_L = 0.4$$

$$B = 10^{17}\,\mathrm{G}$$

Magnetic parts of Neutrino Production



$$e^- + B \rightarrow \nu_e + B' \quad \text{(DU)}$$

$$\partial f_\nu(\mathbf{k}_\nu) = \partial f_0(\mathbf{k}_\nu) + \partial \Delta f(\mathbf{k}_\nu)$$
$$= \int \frac{d^3 p_e}{(2\pi)^3} n_e(\mathbf{p}_e) \frac{d^3\sigma(e^- \rightarrow \nu_e)}{d\mathbf{k}_\upsilon^3}$$

$$k_i = \varepsilon_\nu \text{ (neutrino chem. pot.)},$$
$$Y_L = 0.4$$
$$B = 10^{17}\,\mathrm{G}$$