強磁場原始中性子星からの非等方ニュートリノ放出と関連現象

Asymmetric Neutrino Emission from Magnetized Proto-Neutron Stars and Its Related Astronomical Phenomena: Pulsar Kick and Spin-Deceleration

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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？

P. Arras and D. Lai, PRD60, #043001 (1999) , S. Ando, P.R.D68 #063002 (2003)）

（Non-Relativistic)

Our Works ⇒ Neutrino Reactions on High Density Matter wih Strong Mag. Fields in the Relativistic Mean-Field (RMF) Approach

TM et al., PRD83, 081303(R) (2011)

Application to Phenomena related with ν－Asymmetric Emission

Pulsar Kick in Poloidal Magnetic Field

Spin Deceleration in Toroidal Magnetic Field

§ 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

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

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

$\nu_e + B \rightarrow e^- + B'$ **: 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, Λ, σ, ω, ρ

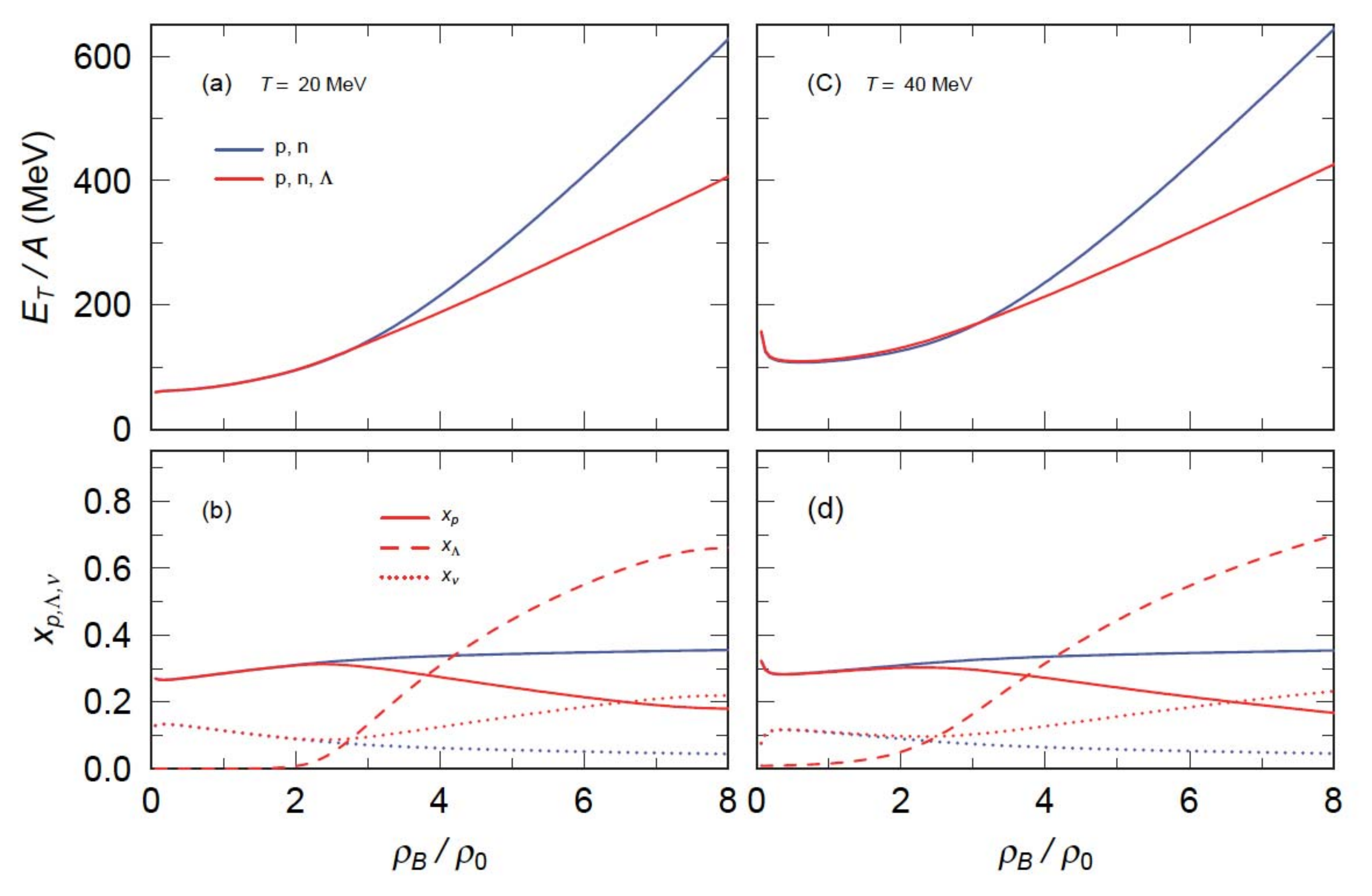
PM1-L1

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

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

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

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

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

Relativistic Effects of Magnetic Contributions

1) Mom.-Dep. of Spin Vector **2) Deformation of Fermi Distr.**

The Cross-Section of Lepton-Baryon Scattering

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

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

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

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 ⇒

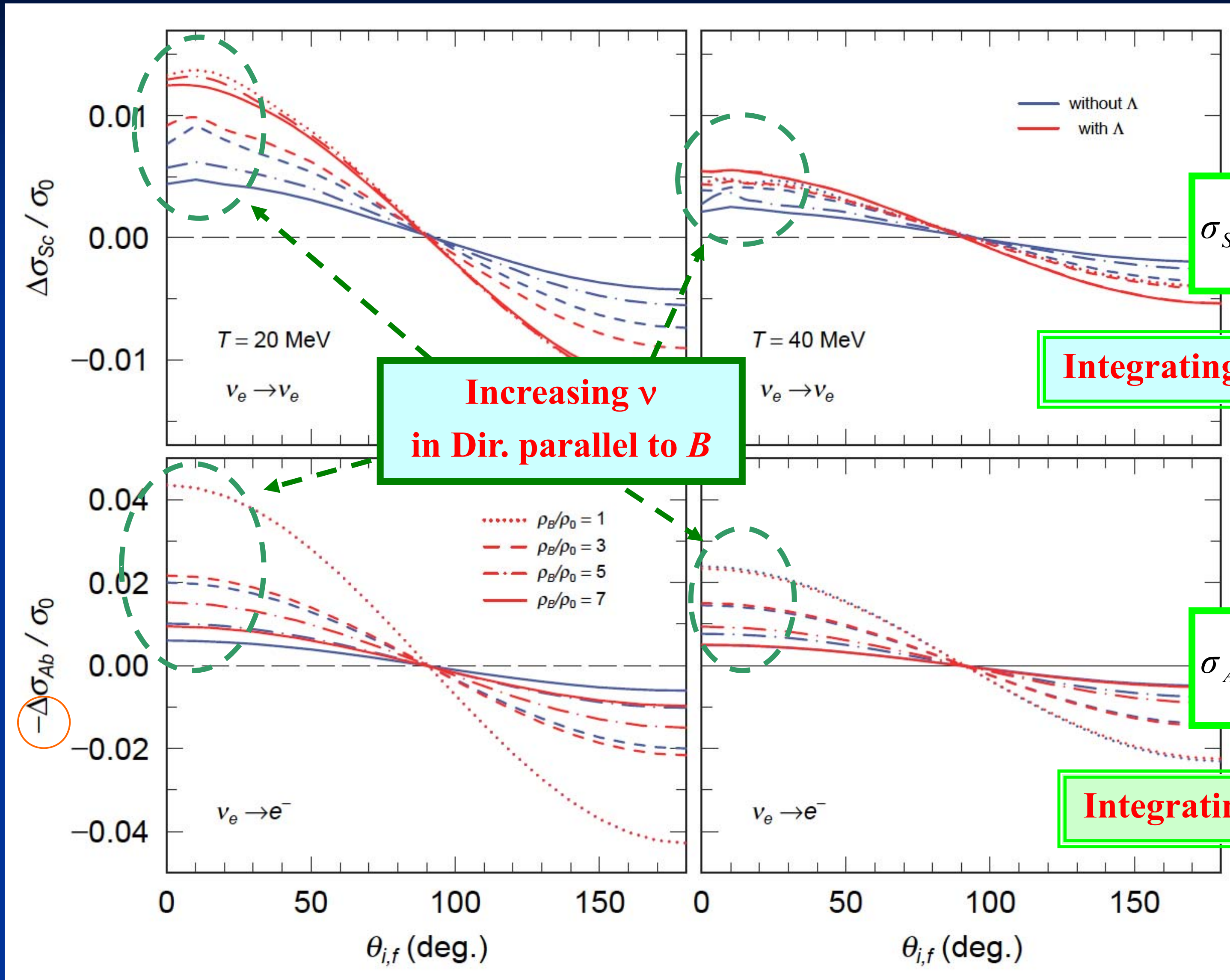
$$\sigma = \sigma_0 + \Delta\sigma \qquad \Delta\sigma \propto B$$

Non-Magnetic Part (σ_0)

Magnetic Part ($\Delta\sigma$)

§ 2-3 Magnetic parts of Cross-Sections

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



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

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

§ 2-4 Neutrino Transportation

Neutrino Phase Space Distribution Function

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

Equib. Part

Non-Equib. Part

Neutrino Propagation $\Rightarrow$ 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 $\Rightarrow$

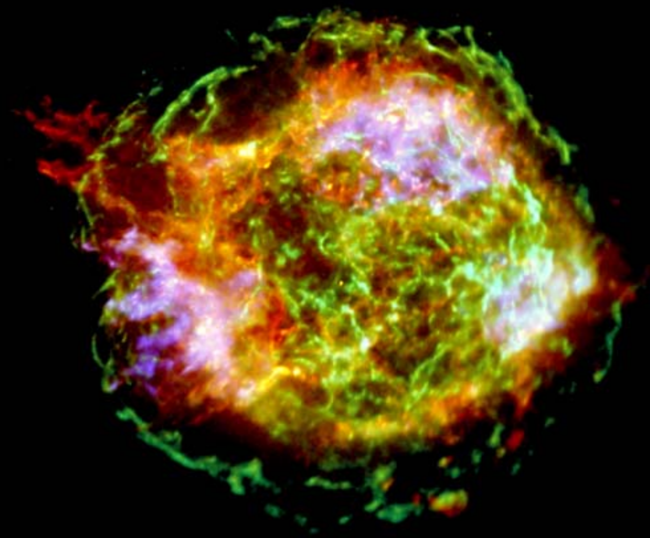
$$\Delta f(\boldsymbol{p},\boldsymbol{r}_T,z) = \int_0^z dx\left[-\frac{\partial}{\partial x} f_0(p,r_T,x)\right]\exp\left[-\frac{1}{c}\int_x^z dy\, b_\nu(y)\right],$$

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

§ 3 Estimating Pulsar Kick Velocities of Proto-Neutron Star

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

CasA



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

Asymmetry of Supernova Explosion

kick and translate Pulsar with

Kick Velocity: Average … 400km/s,

Highest … 1500km/s

Explosion Energy ~ 10^{53} erg

(almost Neutrino Emissions)

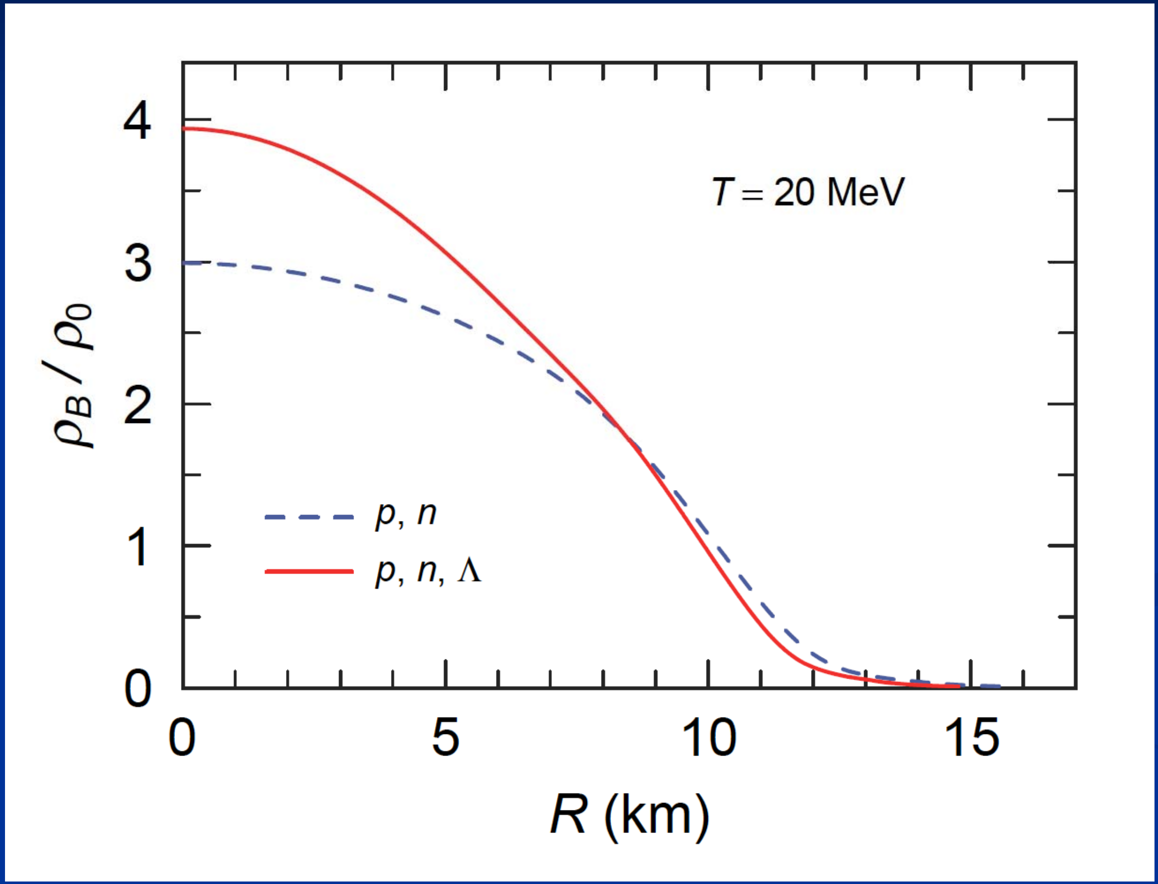
***1% Asymmetry* is sufficient to explain the Pulsar Kick**

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

Estimating Kick Velocity of PNS with $T = 20$ MeV and $B = 2\times 10^{17}$G

Poloidal Magnetic Field 2 - 3% Asymmetry in Absorption

Baryon density in Proto-Neutron Star



$M = 1.68 M_{solar}$

$Y_L = 0.4$

$$P_\alpha = \int_{S_N} d\boldsymbol{r} \int d\boldsymbol{p} p_\alpha \Delta f(\boldsymbol{r}, p_L, \boldsymbol{n}) / \int_{S_N} d\boldsymbol{r} \int d\boldsymbol{p} \Delta f(\boldsymbol{r}, p_L, \boldsymbol{n})$$

Calculating Neutrino Propagation above $\rho_B = \rho_0$

Angular Dep. of Emitted Neutrinos in Uniform Poloidal Mag. Field

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

$$< p(\boldsymbol{n}) > \approx P_0 + P_1 \cos\theta$$

$$B = 2\times 10^{17}\ [\mathrm{G}]$$

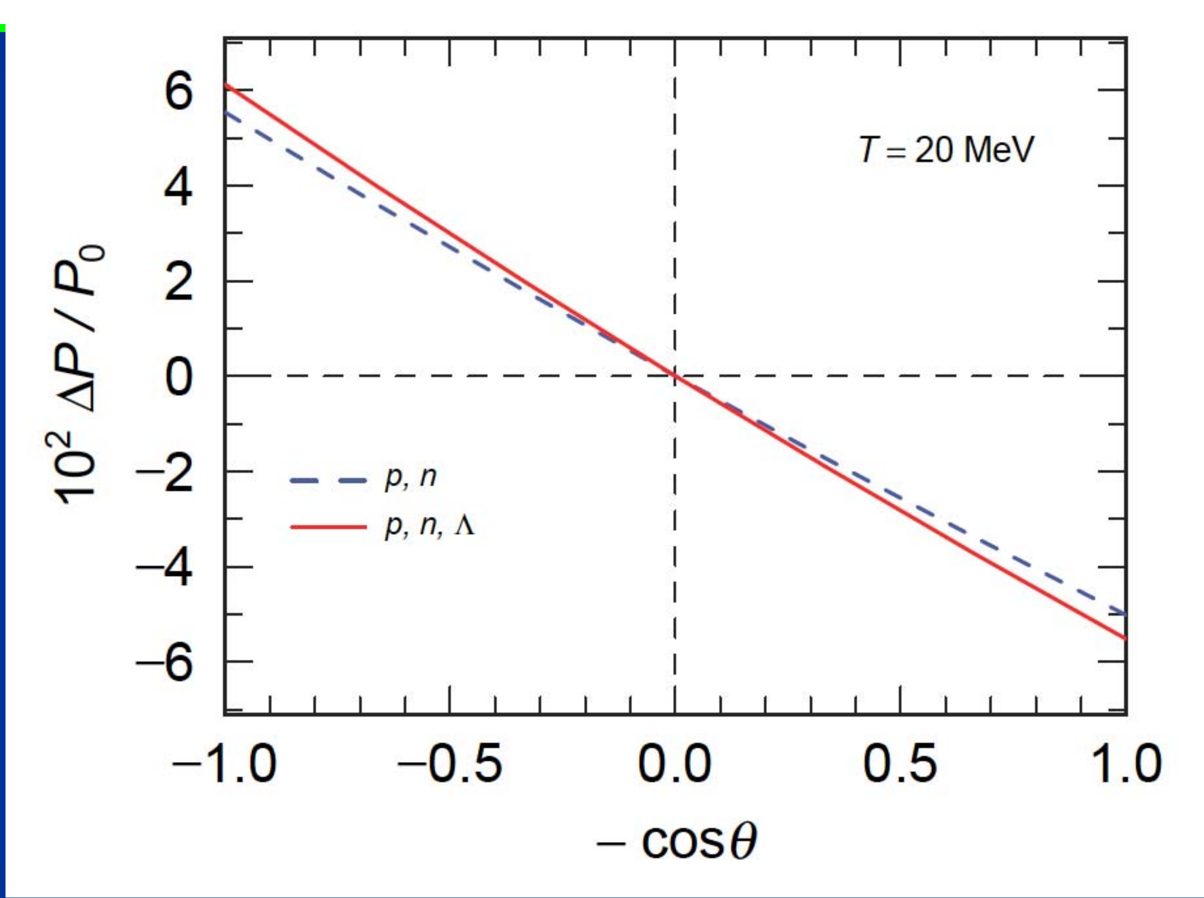
$$v_{kick} = \frac{\langle p_z \rangle}{M} \approx 600\,[\mathrm{km/s}]$$

T = 20 MeV

Observable Average

… 400km/s,

$$\frac{\langle p_z \rangle}{E_T} = \frac{P_1}{3P_0} = 1.76\times 10^{-2} \qquad p,\ n$$
$$= 1.94\times 10^{-2} \qquad p,\ n,\ \Lambda$$



§ 4 Angular Deceleration in Toroidal Magnetic Field

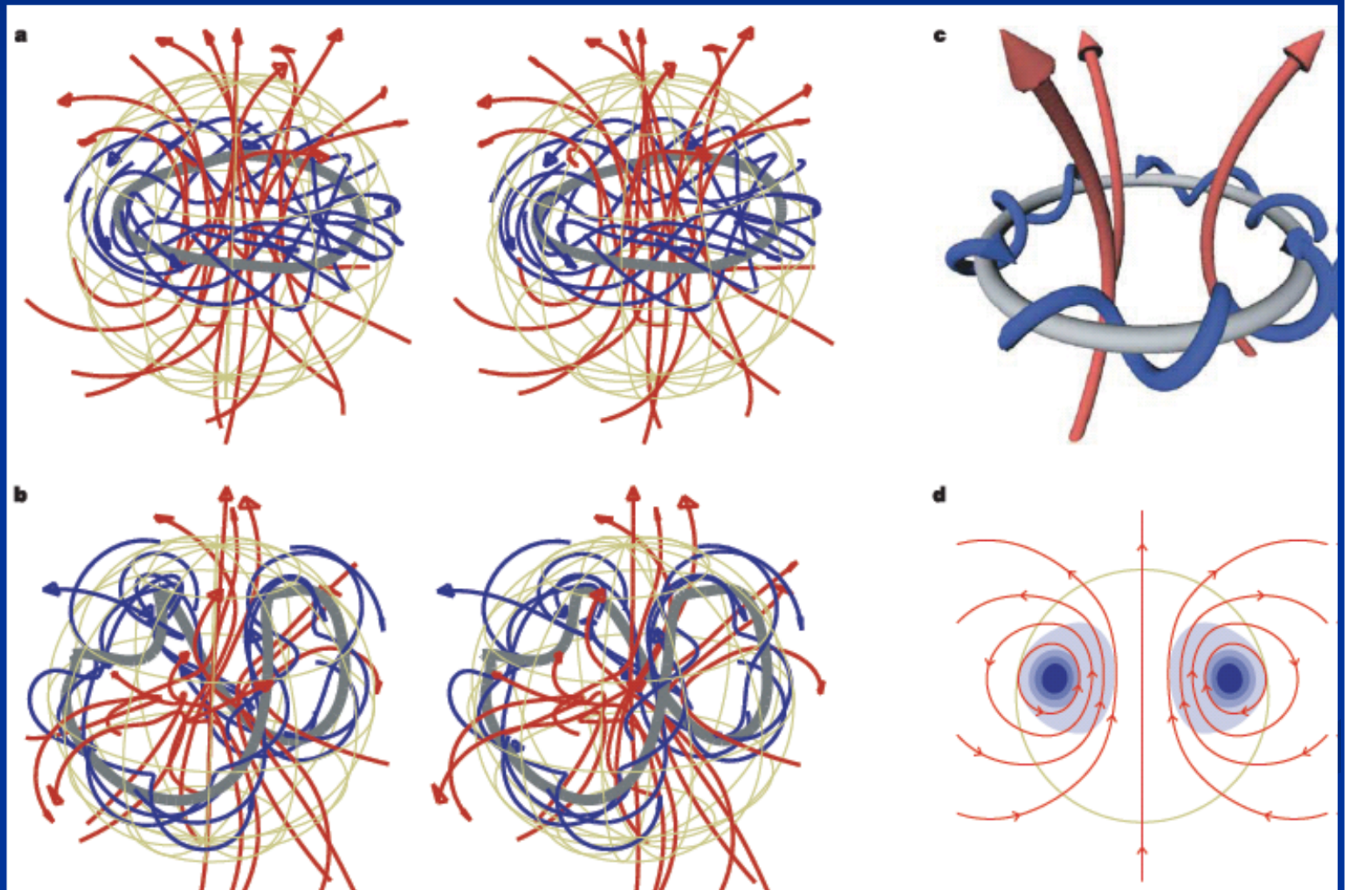
Stability of Magnetic Field in Compact Objects

(*Braithwaite & Spruit 2004*)

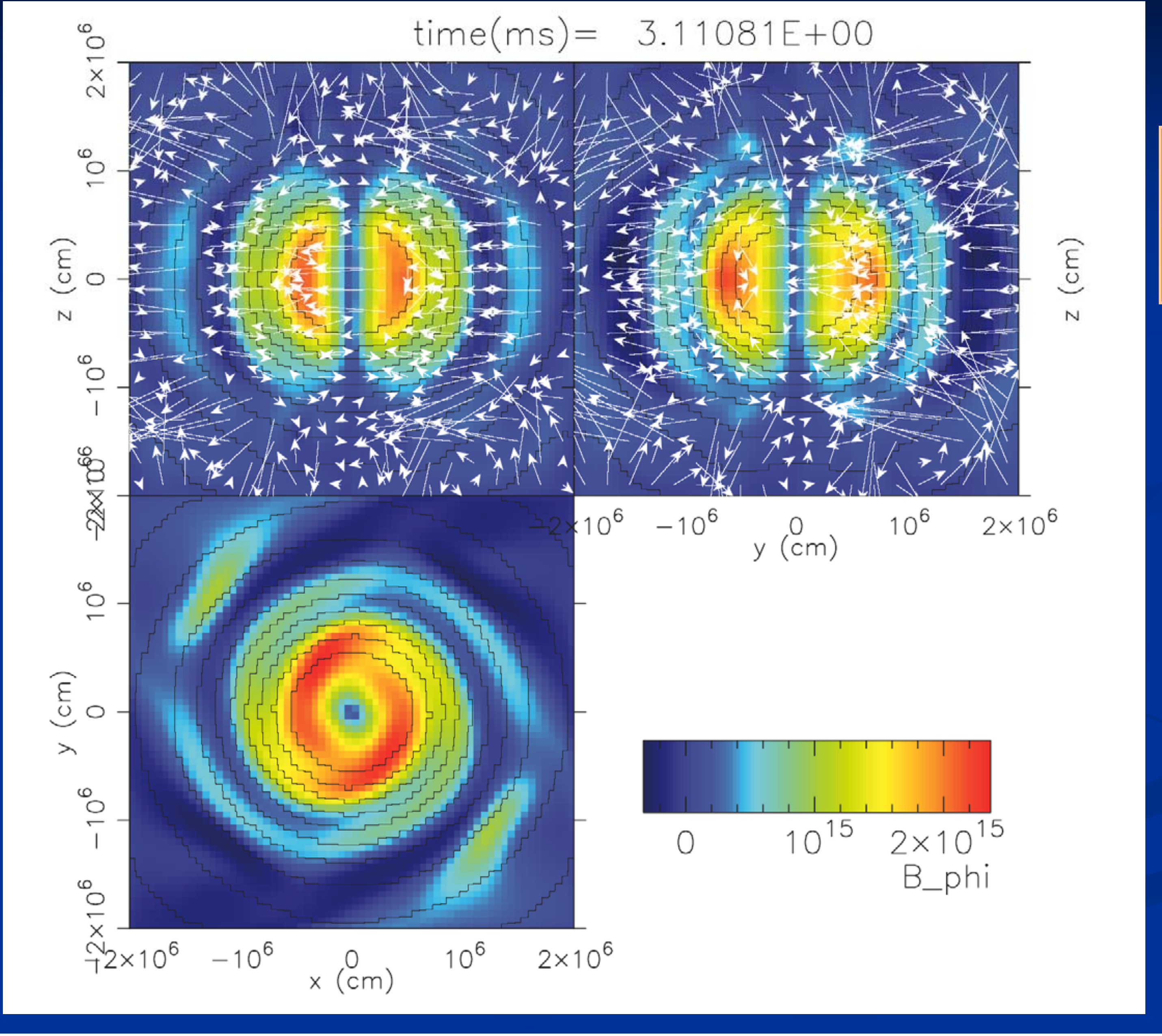
Toroidal Magnetic Field is stable !!

Mag. Field Parallel to Baryonic Flow

Assym. of ν-Emit. must decelerate PNS Spin



No poloidal Magnetic Field at the beginning



Single Toroidal

by T. Kuroda

Toroidal Magnetic Field

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

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

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

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

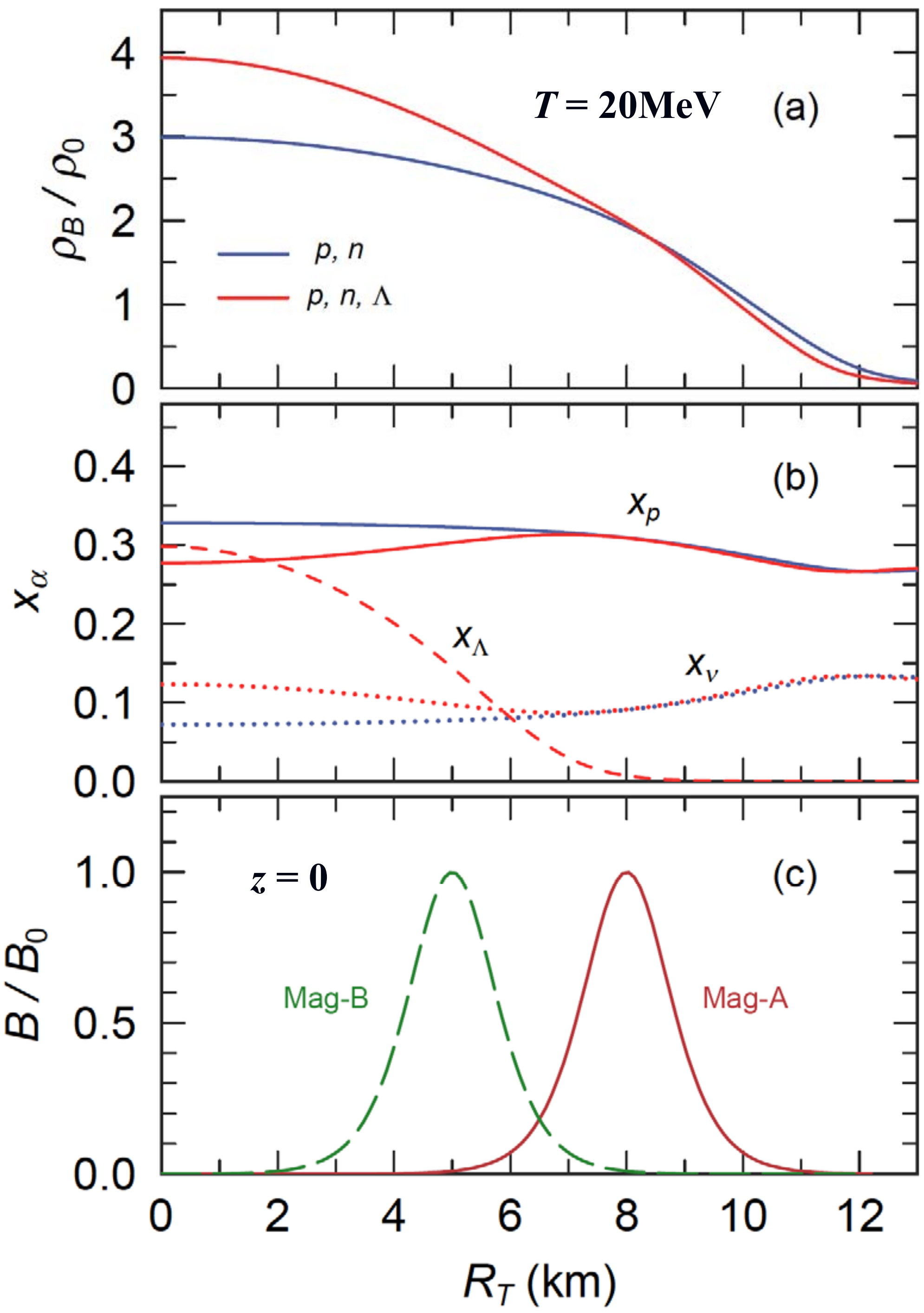
$\Delta r = 0.5$ (km)

$R_0 = 8$ (km)

Mag. - A

$R_0 = 5$ (km)

Mag. - B



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

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

$$\frac{-\dot{P}}{P} = \frac{\dot{\omega}}{\omega} = \frac{P}{2\pi I_{NS}}\left(\frac{dE_T}{dt}\right)_\nu \left(\frac{cdL_Z/dt}{dE_T/dt}\right) \propto P$$

Neutrino Luminosity

$(dE_T/dt)_\nu \sim 3\times 10^{52}$ erg/s

Magnetic Dipole Radiation (MDR)

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

$$B_{tro} \approx 100 B_{pol}$$

Results in Asymmetric Neutrino Emmision

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

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

Poloidal ($B_{pol} = 10^{14}$G) + Toroidal ($B_0 = 10^{16}$G)

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

Period $P = 10$ms

Mag Distr.	Bary.	$-\frac{cdL_Z/dt}{dE_T/dt}$ (cm)	$\dot{P}/P$ (ν **emis.**) $\rho_s = \rho_0$	$\dot{P}/P$ (ν **emis.**) $\rho_s = \rho_0/10$	$\dot{P}/P$ MDR
p,n	Mag-A	3.34	$\mathbf{3.45\times10^{-6}}$	$\mathbf{7.25\times10^{-7}}$	$\mathbf{9.86\times10^{-8}}$
	Mag-B		$\mathbf{4.97\times10^{-7}}$	$\mathbf{3.16\times10^{-7}}$	
p,n,Λ	Mag-A	5.45	$\mathbf{6.39\times10^{-6}}$	$\mathbf{1.02\times10^{-6}}$	$\mathbf{7.76\times10^{-8}}$
	Mag-B		$\mathbf{4.57\times10^{-7}}$	$\mathbf{2.01\times10^{-7}}$	

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

More Significantly than Magnetic Dipole γ-Radiation

§ 5 *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

- **Pulsar Kick in Poroidal Mag. Field B = 2 × 10^{17}G ⇒ Perturbative Cal.**

  v_{kick} = 580 km/s (p,n) , 610 km/s (p,n,Λ) at T = 20 MeV

  400 km/s (Average of Observed Values)

- **Estimating Spin-Down Rate of PNS with Toroidal Magnetic Field Config.**

  Mag. Field Poloidal 10^{14}G, Toroidal Max:**10^{16}G**

  Spin-Down Ratio P-dot/P ≈ 10^{-6} ~ 10^{-7} (1/s) for Asym. ν–Emit

  ≈ 10^{-8} (1/s) for MDR

Extension

Other Effects: ν-Scattering & ν-Production

Iso-Temp. ⇒ Iso-Entropy

Neutrino Propagation in Low Density $e^- + p \rightarrow \nu_e + n$

Examining Density-Dependence of Symmetry Energy

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

→ Landau Level at least for Electron

Gamma-Ray Emission in Strong Magnetic Field

$$p \rightarrow p + \pi^0$$