相対論的量子論による強磁場中性子星でのシンクロトロン放射の研究

PS-Boson Production in Magnetar

丸山智幸

日本大学生物資源

共同研究者

梶野敏貴, 国立天文台

千　明起, 崇実大

G.J.Mathews Univ. of Notre Dome, USA

***Baha* Balantekin** Univ. of Wisconsin-Madison, USA

http://www.space.com/21347-strange-magnetar-neutron-star-glitch.html

§ 1 Introduction

Magnetar　Neutron-Star with Strong Magnetic-Field

B.C.Duncan & C.Thompson ApJL 392, L9 (1992)
S.Merghetti, A&AR 15, 225 (2008)

1)　Very Strong Magnetic Field

$B \sim 10^{15}$ G　　(surface)

$B \sim 10^{17-19}$ G　(insides)

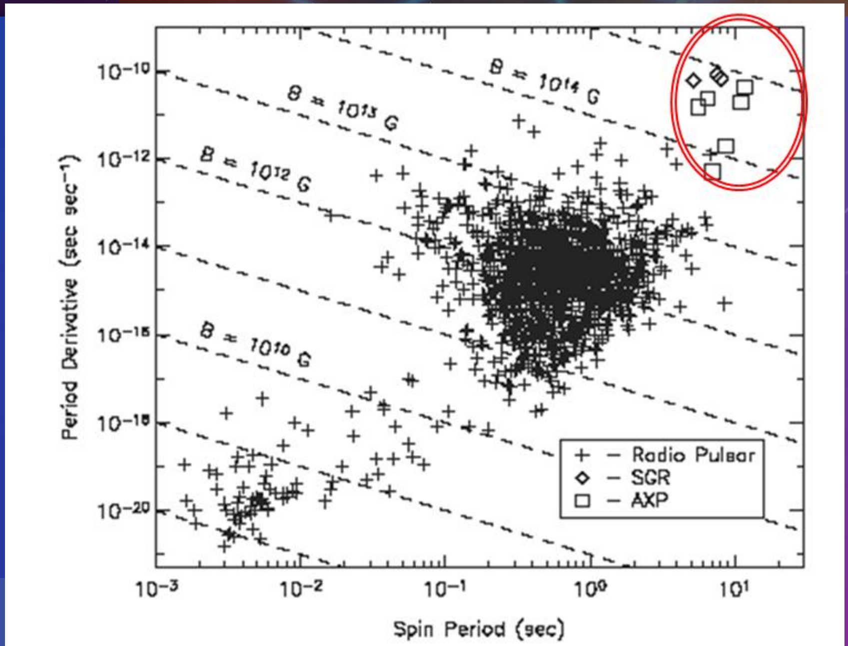
Normal Neutron Star　$B \sim 10^{12-13}$ G

2)　Long Spin Period

$P = 2 \sim 12$ s

Losing Ang. Mom. very Rapidly

Strong Magnetic Field disappear about 10,000 years



3) Higher Temperature

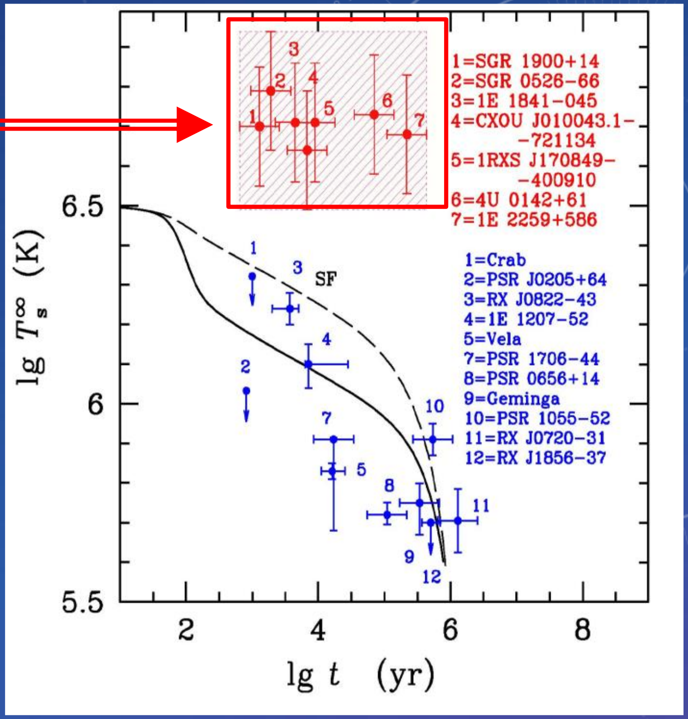
Heating Source ?

Magnetic Energy

-> Thermal Energy

A. D. Kaminker et al. MNRAS 2009;395:2257-2267

Magnetar Zone

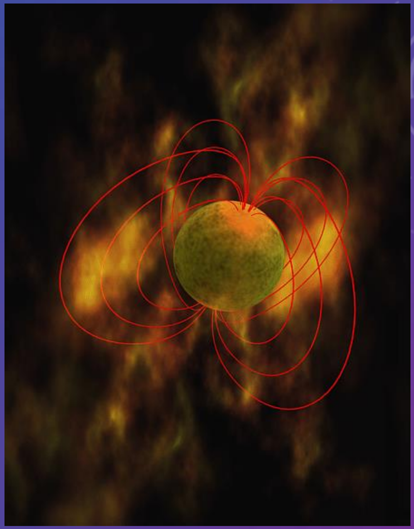


http://www.pd.infn.it/astro/pers/aspen2009/presentations/yakovlev.pdf

4) Emitting High Energy Photons

Soft Gamma Repeater (SGR)

Anomalous Xray pulsar (AXP)



http://commons.wikimedia.

Effects of Strong magnetic Fields in Magnetar

Strong Mag. Fld. ⇒ Neutrino Scat. & Abs. in Highly Dense Matter

TM et al., PRD83, 081303(R) ('11) , PRD86,123003 ('12), PRC89, 035801 '(14)

Perturbative Calculation with respect to Magnetic Field

- **Asymmetry of Neutrino Absorption**

  4.2 % at $\rho_B=\rho_0$, 2.2 % at $\rho_B=3\rho_0$ when T = 20 MeV and B = 10^{17}G

- **Poloidal Magnetic Field Configuration → Kick Velocity**

  v_{kick} **≈ 500 ー600 [km/s] when T = 20 MeV and $B = 2 \times 10^{17}$G**

- **Toroidal Magnetic Field Cation → Spin-Down Rate of PNS**

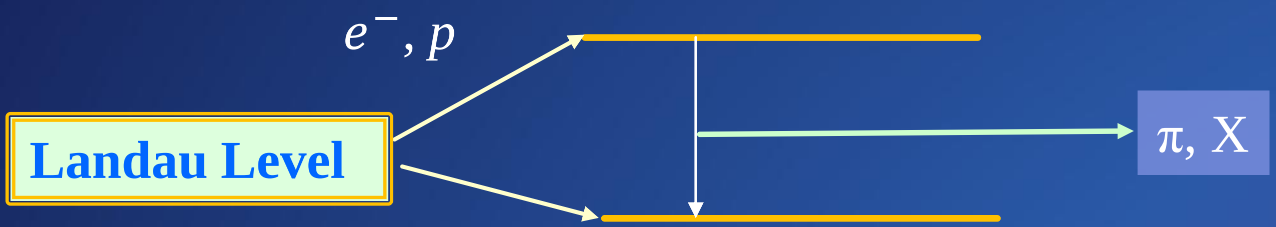
  Spin-Down Ratio $\dot{P}/P \approx 10^{-6} \sim 10^{-7}$ **(1/s) for Asym. ν–Emit**

  $\approx 10^{-8}$ **(1/s) for MDR**

No Landau Level Effects

Present Subjects :

Synchrotron Radiation of Pseudo-Scalar Particles from Charged Particles (Proton, Electron)



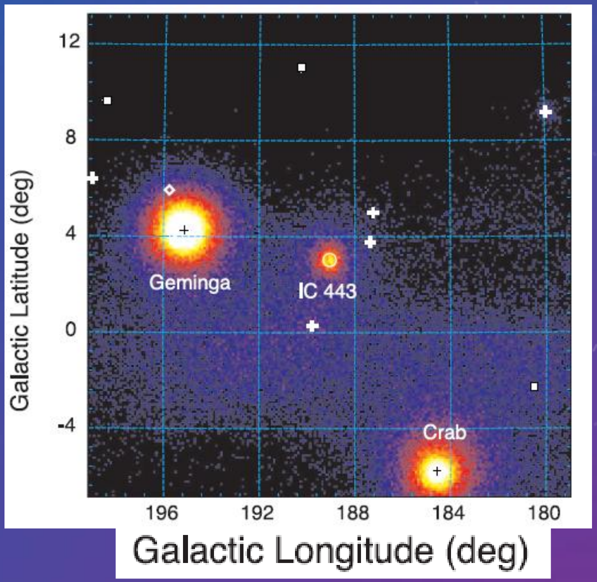
1) Pion Production

Ultra High Energy Cosmic Ray

Origin of TeV Photon

Observed from Sepur Nova Remnant

M. Ackermann, et al. Science Vol. 339, 807 (13)



2) Axion Production

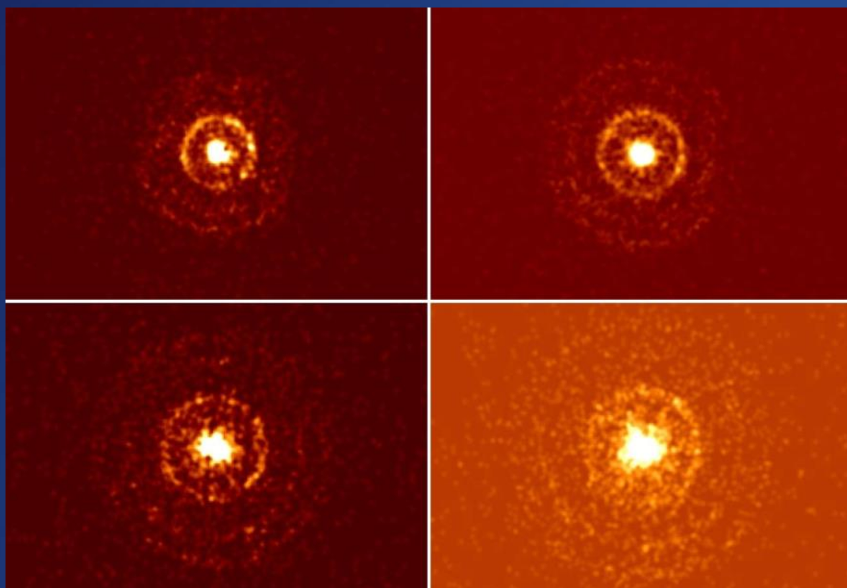
Axion Cooling for Magnetar

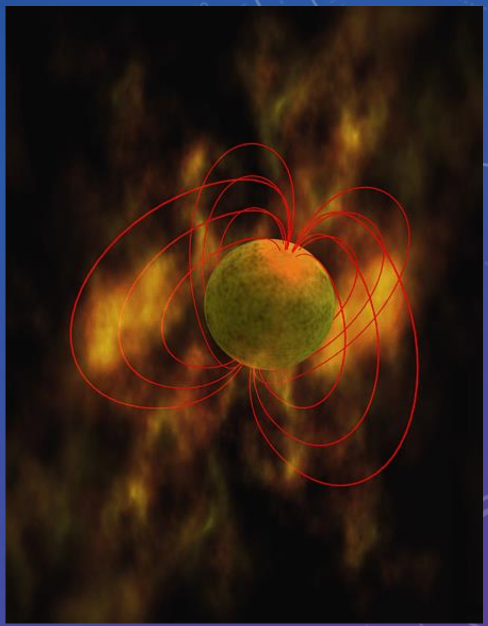
Decay to Photon in Strong Magnetic Field

§ 2 Pion Production via Proton Synchrotron Radiation

T.Maruyama et al., PR D91, 123007 (15). PLB757, 125 (16).

Soft Gamma Repeater (SGR) , Anomalous Xray pulsar (AXP)





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⇒ Magnetar 10^{15}G in surface $10^{17\text{-}19}$G inside

B.C.Duncan & C.Thompson ApJL 392, L9 (1992)

S.Merghetti, A&AR 15, 225 (2008)

Observation of γ-ray → Study of Magnetar Structure

γ-ray Radiation

Proton is accelerate

up to 1GeV〜1TeV

⇒ Synchtotron Radiation

・・・ Meson Prod （$\boldsymbol{Str. > El.Mag.}$）

All Theories are Semi-Classical

V.L.Ginzburg et al., UsFiN 87, 65, ARA&A 3, 297 (65)

G.F. Zharkov, Sov. J. Nucl. Phys., 1, 17314 (65)

V. Berezinsky, et al., Phys. Lett. B 351, 261 (95)

A. Tokushita and T. Kajino, ApJ. 525, L117 (99) ⟶

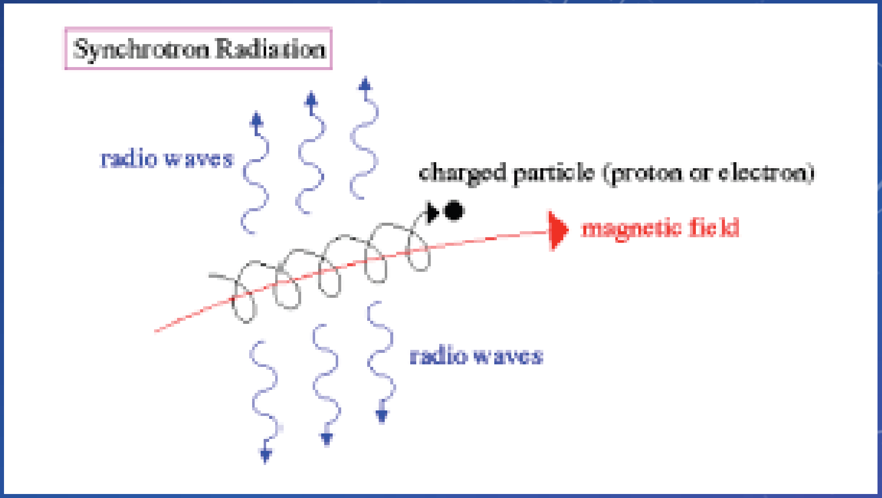
T.Kajino et al., ApJ 782, 70 (2014)

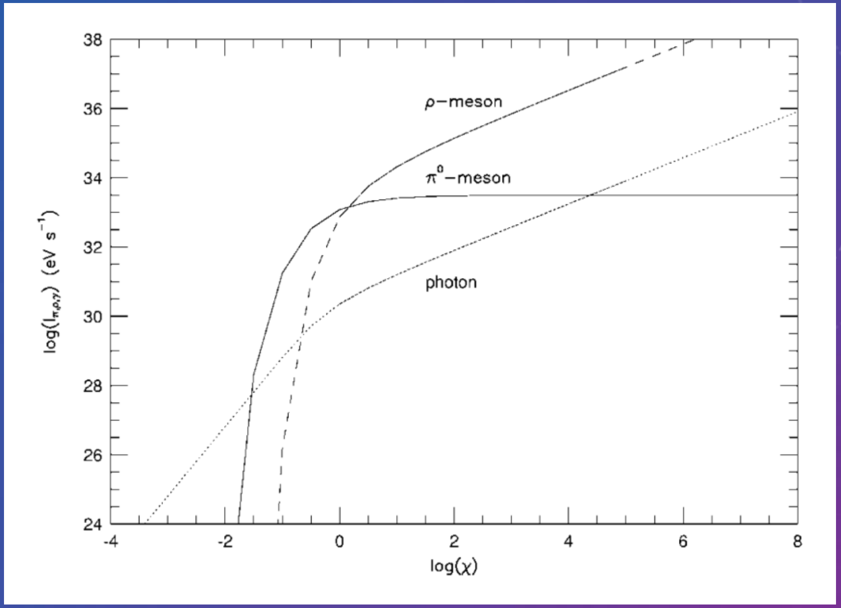
Many Assumption and Approxs.

Mom.-Dist. cannot be calculated

Quantum Calulations.

⇒ Exact Information





§ 2-2 Formulation in Relativistic Quantum Approach

Magnetic Field : $\vec{B} = B\hat{z}.$ $\vec{A} = (0, xB, 0)$

Dirac Equation

$$\left\{\vec{\alpha}(-i\vec{\nabla}_r - e\vec{A}) + \beta m_N + \frac{e\kappa}{2m_N} B\beta\Sigma_z\right\}\tilde{\psi}(\boldsymbol{r}) = \varepsilon\tilde{\psi}(\boldsymbol{r})$$

$$\Sigma_z = \begin{pmatrix} \sigma_z & 0 \\ 0 & -\sigma_z \end{pmatrix} = -\sigma_{12} = \frac{i}{2}[\gamma_1, \gamma_2]$$

Anomalous Mag. Moment
Tensor-Type Mean-Field

Scale Transformation : $M_N = m_N/\sqrt{eB},\ P_i \equiv p/\sqrt{eB},\ X_i = \sqrt{eB}x_i.$

Def: $U_T = \kappa\sqrt{eB}/2m_N = \kappa/2M_N.$

Dirac Eq.

$$\{-i\alpha_x\nabla_x+\alpha_y\left[-i\nabla_y-eBx\right]-i\alpha_z\nabla_z+\beta m_N+U_T\Sigma_z\}\,\tilde{\psi}(\boldsymbol{r})=\varepsilon\tilde{\psi}(\boldsymbol{r})$$

Wave Function

$$\psi\equiv(eB)^{-3/2}\tilde{\psi}\quad=\begin{pmatrix}\lambda_1 f_{n+1}(X-P_y)\\ \lambda_2 f_n\ \ (X-P_y)\\ \lambda_3 f_{n+1}(X-P_y)\\ \lambda_4 f_n\ \ (X-P_y)\end{pmatrix}e^{iP_yY+iP_zZ-iEX_0}$$

P_z is kept $\quad$ P_y : Central Position of Wave Function

Dirac Spinor

$$\begin{pmatrix}E-M_N-\kappa_p/2M_N & 0 & -P_z & -i\sqrt{2(n+1)}\\ 0 & E-M_N+\kappa_p/2M_N & i\sqrt{2(n+1)} & P_z\\ -P_z & -i\sqrt{2(n+1)} & E+M_N+\kappa_p/2M_N & 0\\ i\sqrt{2(n+1)} & P_z & 0 & E+M_N-\kappa_p/2M_N\end{pmatrix}\begin{pmatrix}\lambda_1\\ \lambda_2\\ \lambda_3\\ \lambda_4\end{pmatrix}=0.$$

Proton Green Functionl

$$G(X,X',P_yP_z;P_0)=\sum_{n=0}\sum_{s=\pm1}\tilde{F}(X-P_y)\left[\frac{\rho_M^{(+)}(n,s,P_z)}{P_0-E(n,s,P_z)+i\delta}+\frac{\rho_M^{(-)}(n.x.P_z)}{P_0+E(n,s,P_z)+i\delta}\right]\tilde{F}(X'-P_y)$$

$$\rho_M^{(+)}(n,s,P_z)=[E\gamma_0-\boldsymbol{\gamma P}+M_N+\Sigma_z(\kappa_p/2M_N)]\left[1+\frac{s(\kappa_p/2M_N)}{\sqrt{2n+M_N^2}}+s\gamma_5(a_0\gamma^0-a_z\gamma^3)\right]$$

$$\rho_M^{(-)}(n,s,P_z)=-[-E\gamma_0-\boldsymbol{\gamma P}+M_N+\Sigma_z(\kappa_p/2M_N)]\left[1+\frac{s(\kappa_p/2M_N)}{\sqrt{2n+M_N^2}}-s\gamma_5(a_0\gamma^0-a_z\gamma^3)\right]$$

$$\tilde{F}=\mathrm{diag}\,(f_n,f_{n-1},f_n,f_{n-1})=f_n\frac{1+\Sigma_z}{2}+f_{n-1}\frac{1-\Sigma_z}{2}.$$

$$\boldsymbol{P}=(0,\,-P_{\mathrm{T}},\ P_{\mathrm{z}})$$

$$\boldsymbol{P}_T^2=\sqrt{2n+1}$$

$$a_0=\frac{P_z}{\sqrt{2n+M_N^2}}\;,\quad a_z=\frac{E}{\sqrt{2n+M_N^2}}.$$

$$E_T=\sqrt{P_z^2+\left(\sqrt{2n+M_N^2}-s\kappa/M_N\right)^2}$$

$$\frac{1}{2}\left(-\nabla_x^2+x^2\right)f_n(x)=\left(n+\frac{1}{2}\right)f_n(x),$$

Decay Width of p to $p + \pi^0$, X

πN interaction $\mathcal{L} = \frac{i f_\pi}{m_\pi} \psi \gamma_5 \gamma_\mu \tau_a \psi \partial^\mu \phi_a$

PV coupling

$$\frac{d^3\Gamma_{p\pi}}{dQ^3} = \frac{1}{8\pi^2 E_\pi}\left(\frac{f_\pi}{M_\pi}\right)^2 \sum_{n_f, s_f} \frac{\delta(E_f + E_\pi - E_i)}{4E_i E_f} R_E$$

$$R_E = 4E_i E_f \mathrm{Tr}\left\{\mathcal{O}_\pi \rho_M^{(+)}(n_f, s_f, P_z - Q_z)\mathcal{O}_\pi^\dagger \rho_M^{(+)}(n_i, s_i, P_z)\right\},$$

$$\boldsymbol{Q} = (0, Q_T, Q_z) = \mathbf{q}/\sqrt{eB}$$

$$\begin{aligned}\mathcal{O}_\pi = \gamma_5 \Bigg\{ &\left[\mathcal{M}(n_i, n_f)\frac{1+\Sigma_z}{2} + \mathcal{M}(n_i - 1, n_f - 1)\frac{1-\Sigma_z}{2}\right][\gamma_0 Q_0 - \gamma^3 Q_z] \\ &- \left[\mathcal{M}(n_i, n_f - 1)\frac{1+\Sigma_z}{2} + \mathcal{M}(n_i - 1, n_f)\frac{1-\Sigma_z}{2}\right]\gamma^2 Q_T \Bigg\}\end{aligned}$$

$$\begin{aligned} M(n_1, n_2) &= \int dx f_{n_1}\left(x + \frac{Q_y}{2}\right) f_{n_2}\left(x - \frac{Q_y}{2}\right). \\ &= (2^{n_1+n_2}\pi n_1! n_2!)^{-1/2} e^{-Q_T^2/4} \int dx e^{-x^2} H_{n_1}\left(x + \frac{Q_T}{2}\right) H_{n_2}\left(x - \frac{Q_T}{2}\right) \\ &= \sqrt{\frac{n_2!}{n_1!}}\left(-\frac{Q_T^2}{\sqrt{2}}\right)^{n_1-n_2} e^{-\frac{Q_T^2}{4}} L_{n_2}^{n_1-n_2}\left(\frac{Q_T^2}{2}\right) \qquad (n_1 \le n_2) \\ &= \sqrt{\frac{n_1!}{n_2!}}\left(\frac{Q_T^2}{\sqrt{2}}\right)^{n_2-n_1} e^{-\frac{Q_T^2}{4}} L_{n_1}^{n_2-n_1}\left(\frac{Q_T^2}{2}\right) \qquad (n_1 \ge n_2) \end{aligned}$$

$H_n(x)$: Hermit Polynomial

$L_n^m(x)$: Associated Laguerre Polynomlal

§ 2-3 Results of π^0 Production

Decay Width

$$E_i = 1\,\text{GeV},\ B = 5\times10^{18}\ \text{G}$$

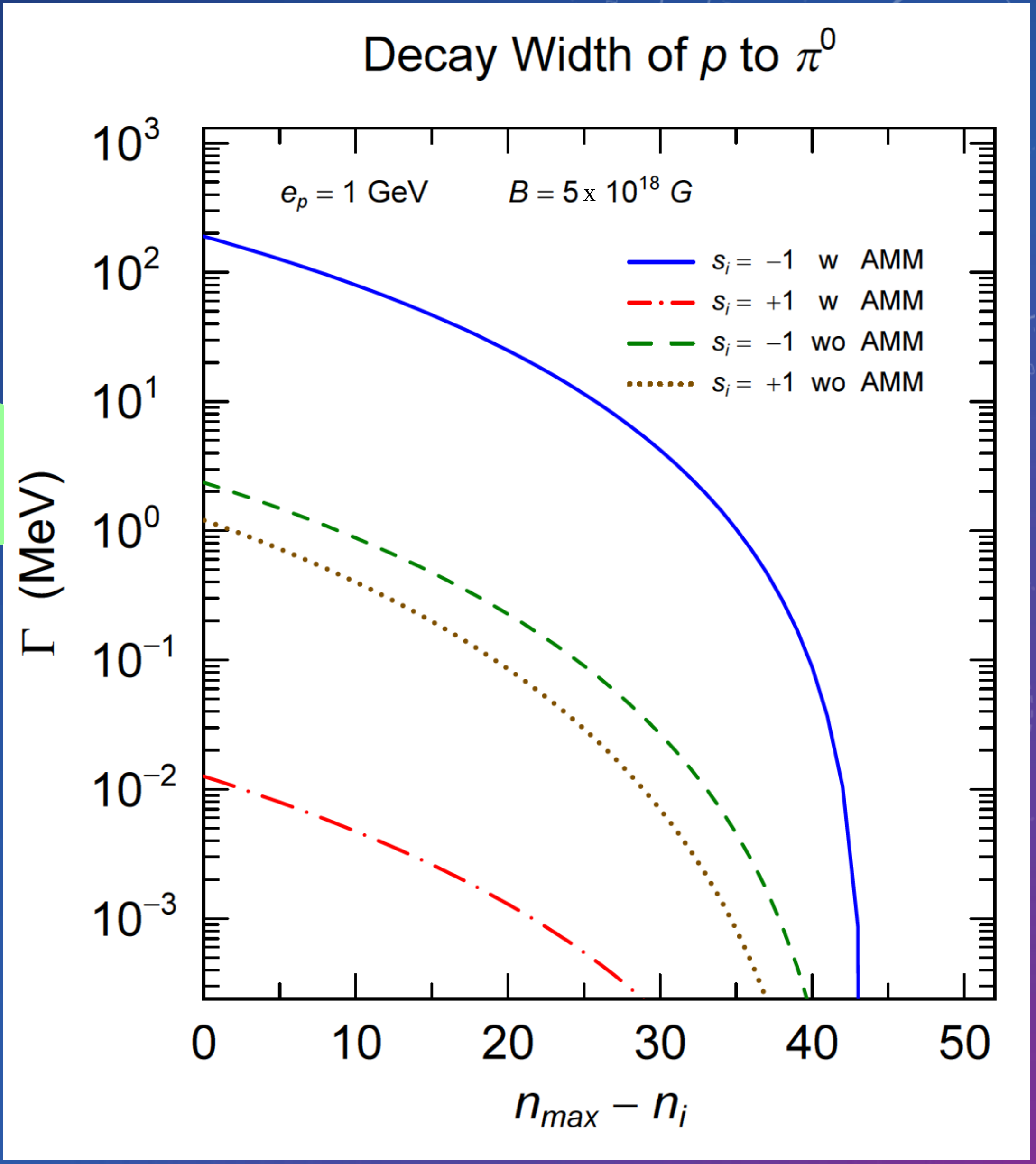
$$\chi = e_i^2 / m_N^3 R_C = eBe_p / m_N^3 = 0.069$$

$$\chi \approx 0.01 - 1 \quad \pi\text{-Prod. Dominant}$$

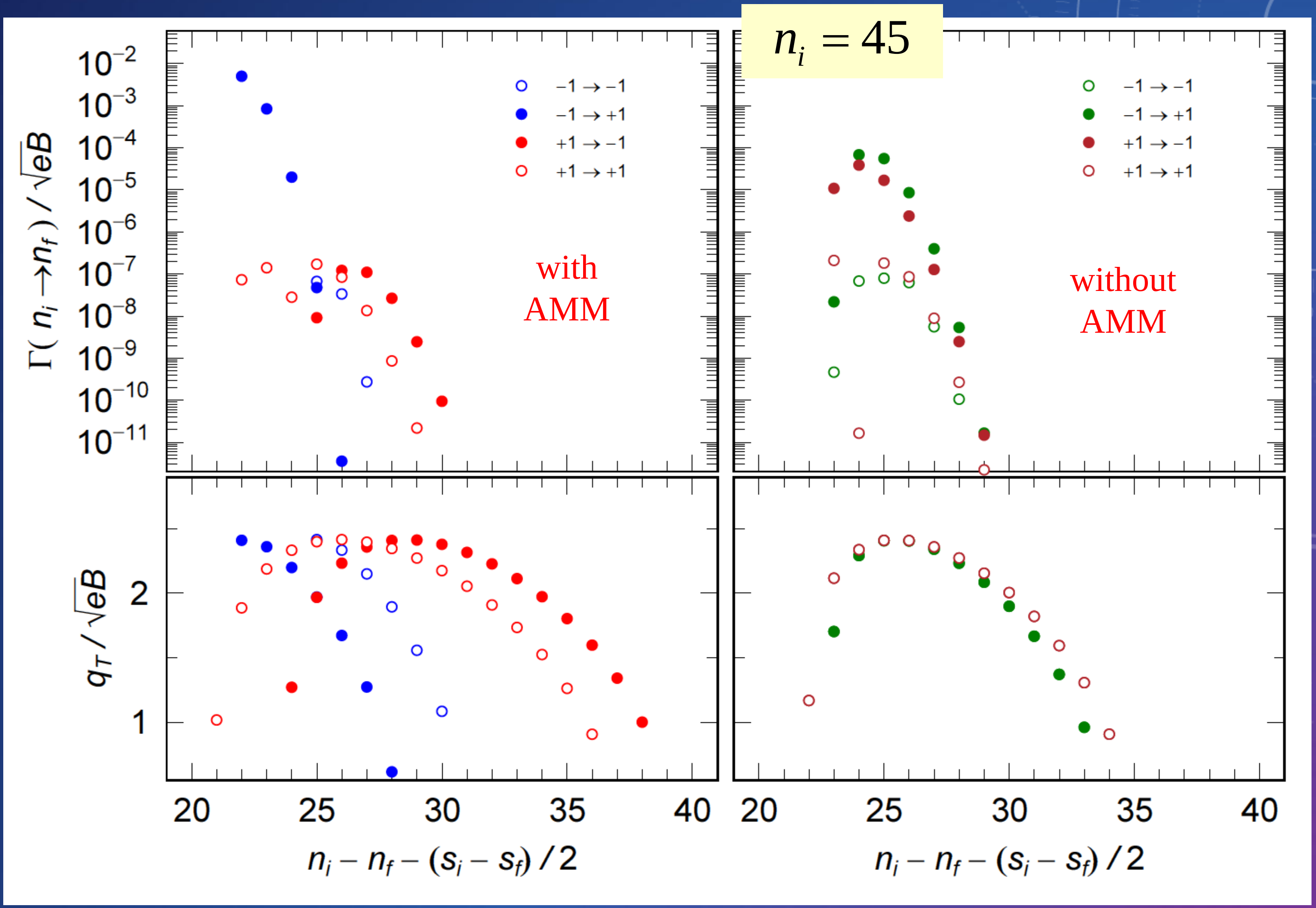
$$\sqrt{eB} = 17.2\,\text{MeV}, \quad \frac{e\kappa_p}{2m_N} B = 28.3\,\text{MeV}$$

$$n_{\max} + \frac{s_i + 1}{2} = 50 \ \text{for}\ s_i = -1$$
$$= 45 \ \text{for}\ s_i = +1$$

no AM $\quad n_{\max} + \frac{s_i + 1}{2} = 47$



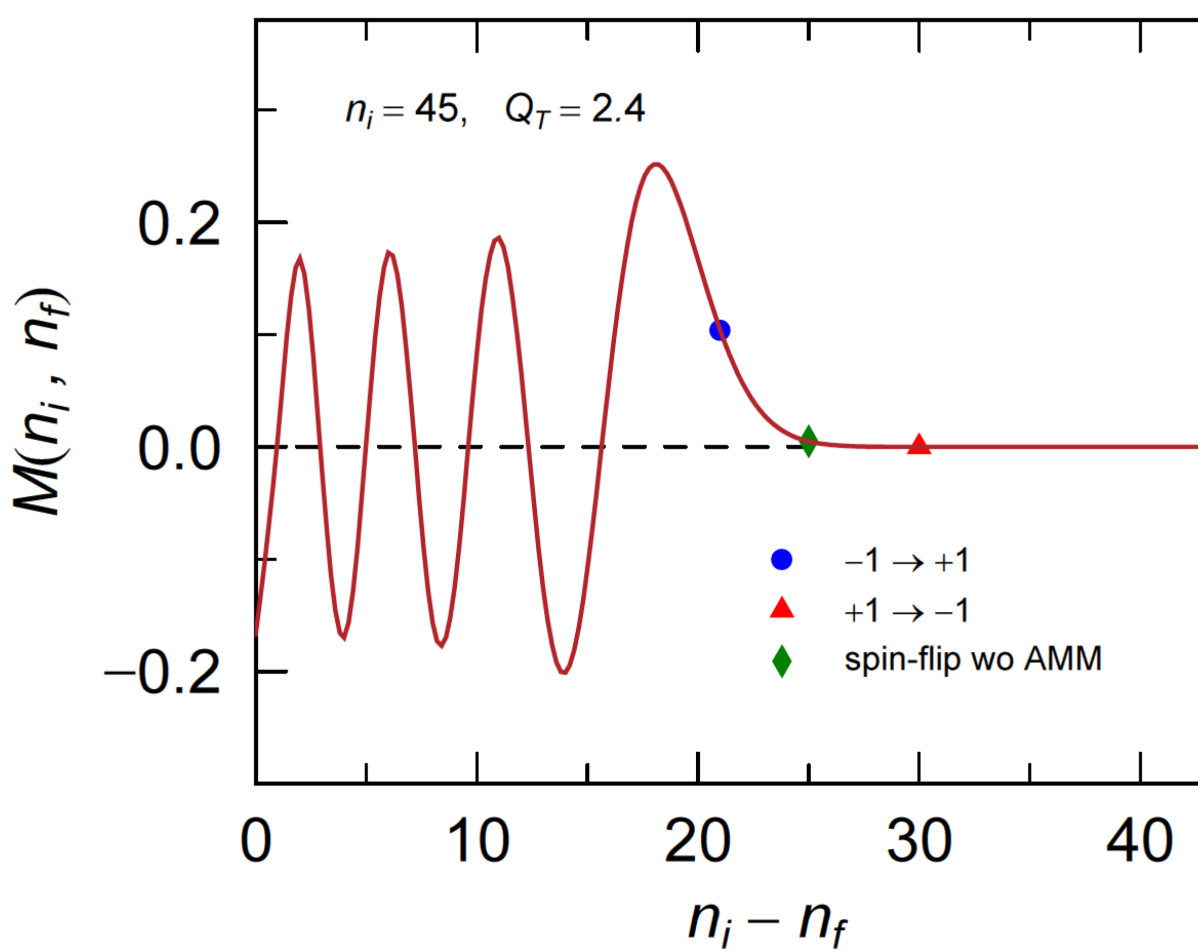
Transition Strengths between two Landau Levels

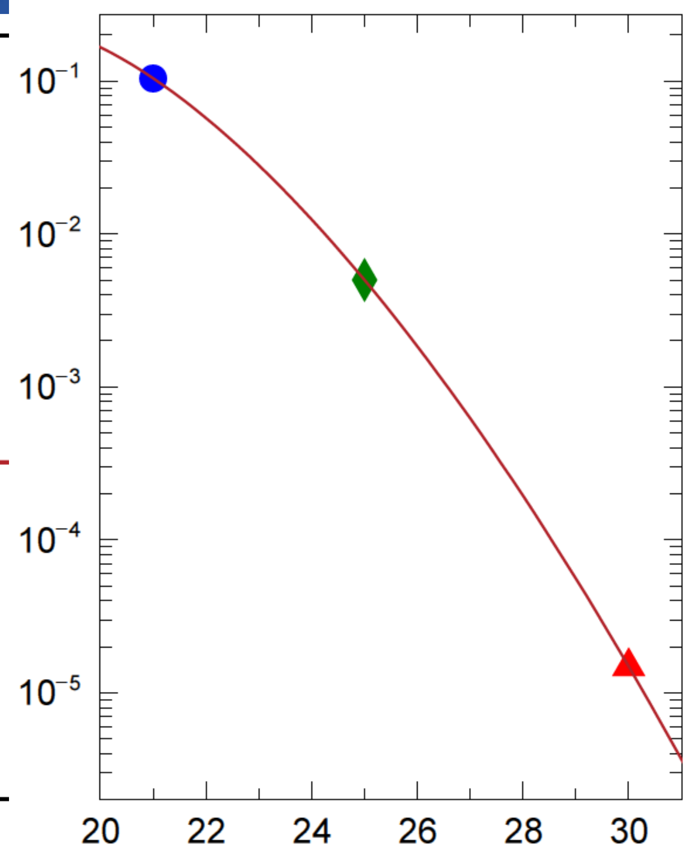


–1 —> +1 small Landau-level difference

Transition Strength 2

$$\begin{aligned} M(n_1,n_2) &= \int dx f_{n_1}\left(x+\frac{Q_y}{2}\right) f_{n_2}\left(x-\frac{Q_y}{2}\right). \\ &= (2^{n_1+n_2}\pi n_1! n_2!)^{-1/2} e^{-Q_T^2/4} \int dx e^{-x^2} H_{n_1}\left(x+\frac{Q_T}{2}\right) H_{n_2}\left(x-\frac{Q_T}{2}\right) \\ &= \sqrt{\frac{n_2!}{n_1!}} \left(-\frac{Q_T^2}{\sqrt{2}}\right)^{n_1-n_2} e^{-\frac{Q_T^2}{4}} L_{n_2}^{n_1-n_2}\left(\frac{Q_T^2}{2}\right) \qquad (n_1 \le n_2) \\ &= \sqrt{\frac{n_1!}{n_2!}} \left(\frac{Q_T^2}{\sqrt{2}}\right)^{n_2-n_1} e^{-\frac{Q_T^2}{4}} L_{n_1}^{n_2-n_1}\left(\frac{Q_T^2}{2}\right) \qquad (n_1 \ge n_2) \end{aligned}$$





Very Large AMM Effects

$p \rightarrow p + \pi^0$ **Energy Momentum Conservation is not satisfied in the free kinematics**

Mag. Fld.＋AMM　Tensor Type Mean-Field

$s = -1$ **(repulsive),** $s = +1$ **(attractive)**

Level Interval of Transition $n_i - n_f$

$s_i = -1 \rightarrow s_f = +1$ **Smaller Intervals**

$\Rightarrow$ **Enhances Transition Strength**

$s_i = +1 \rightarrow s_f = -1$ **Larger Intervals**

$\Rightarrow$ **Reduces Transition StrengthV**

Small Shifts $n_i - n_f$ **make Large change of Transition Strength**

§ 2-3 Realistic System

Pion Production Dominant Energy Region

$\chi = eBe_p / m_N^3 \approx 0.01 - 1$

$B = 10^{15}$ G   Landau Number : $n_{\mathrm{i}} \approx 10^{12} - 10^{13}$

Actual calculations are almost impossible

Problem : HO overlap

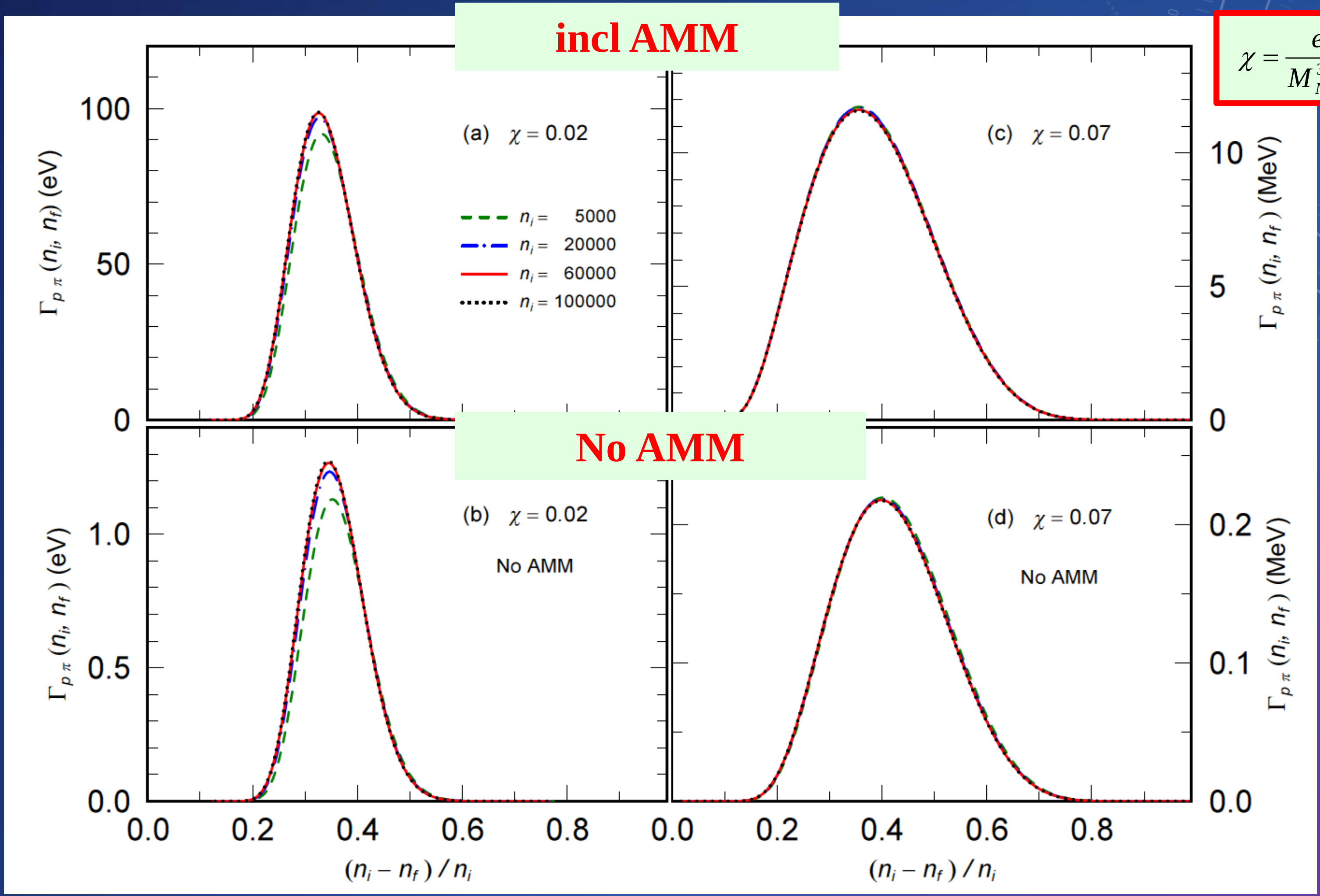
$$\mathcal{M}(n_1, n_2) = \int dx f_{n_1}\left(x - \frac{Q_T}{2}\right) f_{n_2}\left(x + \frac{Q_T}{2}\right) = \sqrt{\frac{n_2!}{n_1!}} \left(\frac{Q_T}{\sqrt{2}}\right)^{n_1 - n_2} e^{-\frac{Q_T^2}{4}} L_{n_2}^{n_1 - n_2}\left(\frac{Q_T^2}{2}\right)$$

It is possible to make a Lorentz Transportation along z-direction

$$\Gamma(n_i, P_{iz}) = \frac{\sqrt{E_i^2 - P_{iz}^2}}{E_i} \Gamma(n_i, P_{iz} = 0)$$

Semi-Classical Theory ⇒ Scaling, Dep. Only on χ

Contribution at Fixed Final Landau Number



$$\chi = \frac{e_i^3}{M_N^3 R_L} = \frac{eBe_i}{M_N^3}$$

Scaling Law **Function of χ, $(n_i - n_f)/n_i$**

Prediction Results $n_i \approx 10^4$ $\Rightarrow$ Results $n_i \approx 10^{12-13}$ (B ~ 10^{15}G)

Huge Effects of AMM remain even in B ~ 10^{15}G

Small χ

Larger n_i → Scaling

Total Decay Width

Scaling Relation

(All Semi-Classial Theoryies Show)

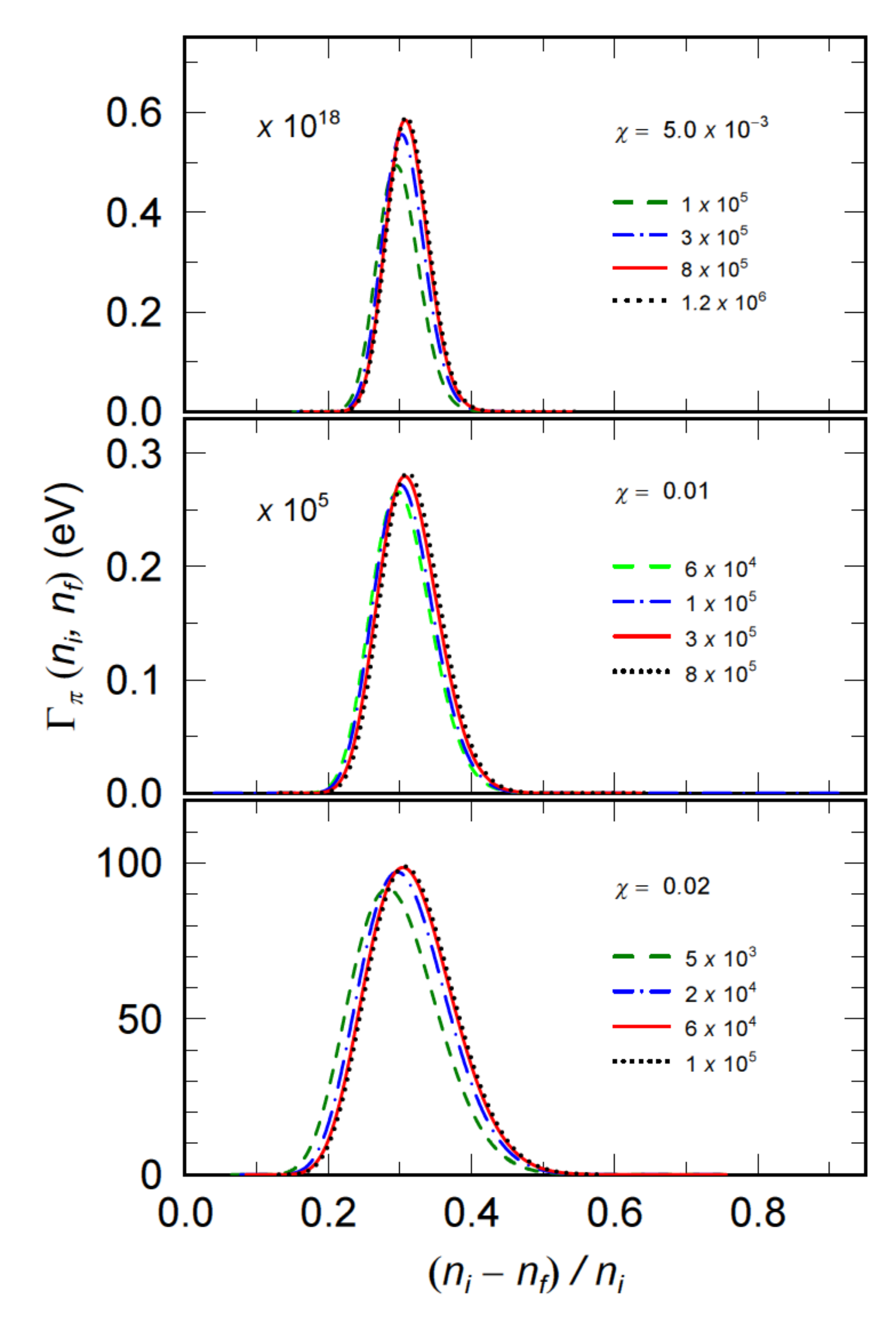
3 Variables B, n_i, n_f

⇒ 2 Variables

$$\chi = eBE e_i / m_N^3, \quad (n_i - n_f)/n_i$$

Peak position

$(n_i - n_f) / n_i \rightarrow 0.3$



Adiabatic Limit

Relative Momentum between Final **Proton** and Pion is Zero,

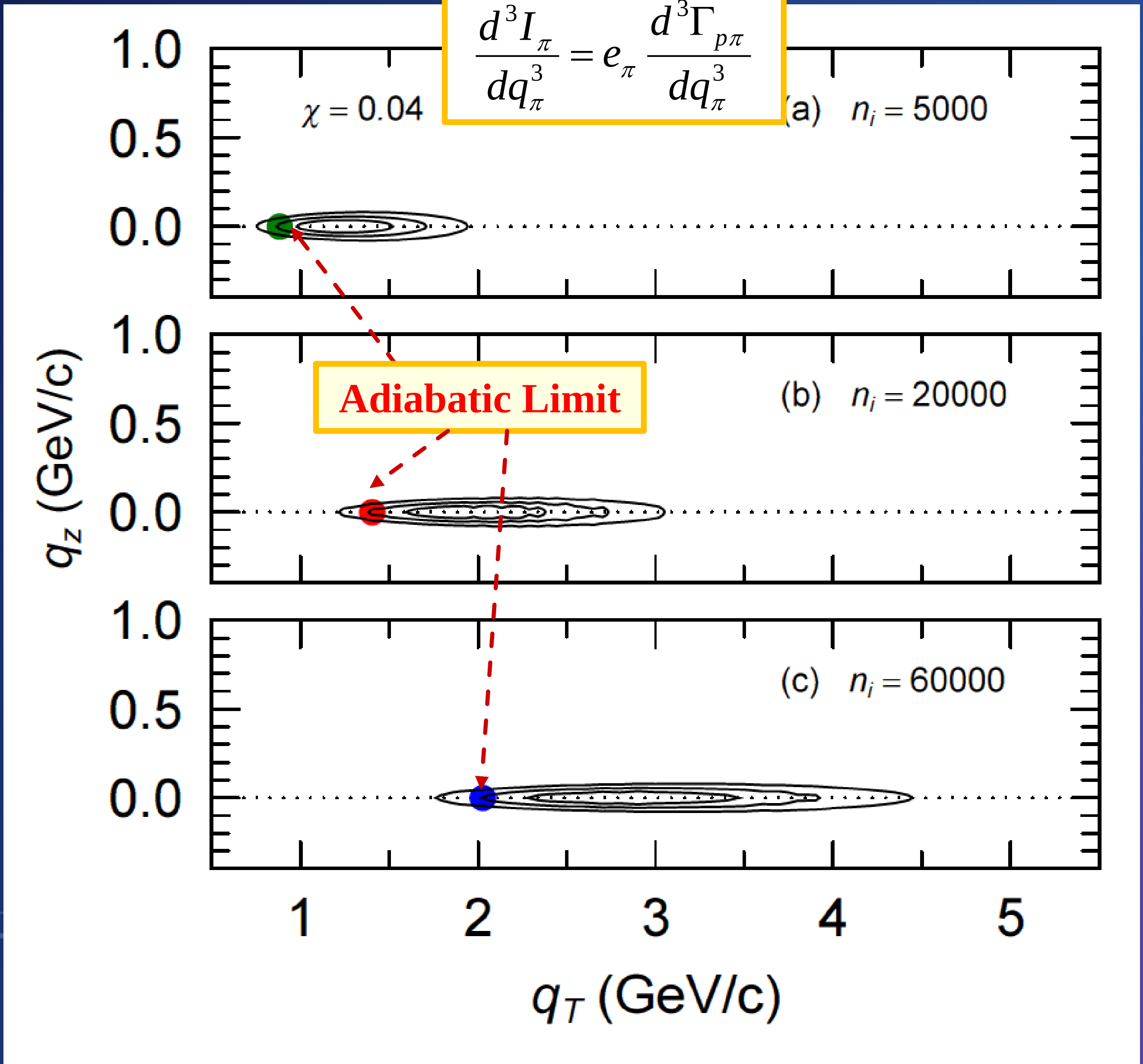
Same Velocity

$$e_\pi = \frac{m_\pi}{m_p + m_\pi} e_i, \quad e_f = \frac{m_p}{m_p + m_\pi} e_i \quad \left(e_{i,f} \approx \sqrt{2n_{i,f}} \right)$$

$$\rightarrow \boxed{\frac{n_i - n_f}{n_i} \approx 0.28} \quad \Leftrightarrow \quad \text{Semi-Classical}: \frac{n_i - n_f}{n_i} << 1$$

Angular Distrbution at $p_{\mathrm{iz}} = 0$

$$\frac{d^3 I_\pi}{dq_\pi^3} = e_\pi \frac{d^3 \Gamma_{p\pi}}{dq_\pi^3}$$

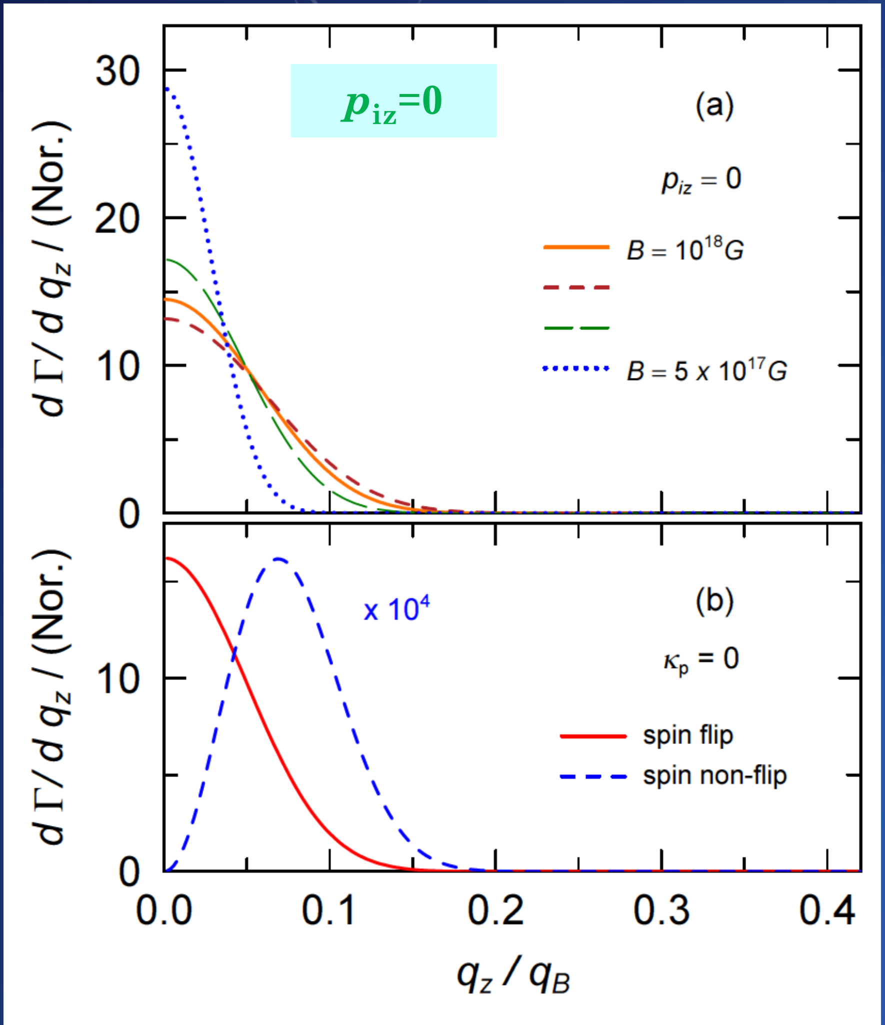


Δq_z indep. on I Incidet Energy

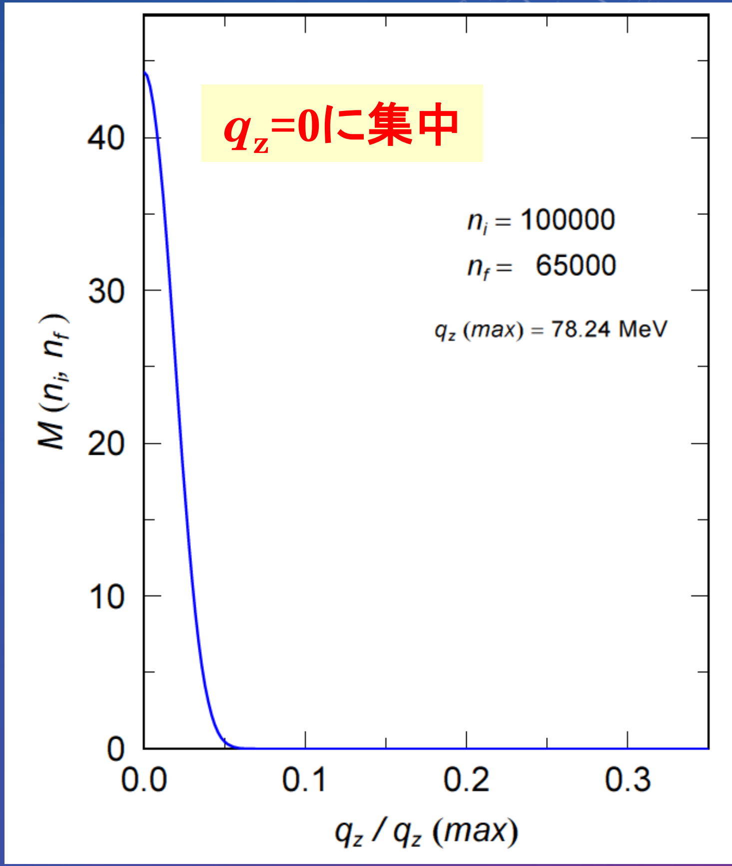
Norrow Angular Ditsr.

$$\Gamma(n_i, n_f; P_{iz} = 0) \propto \delta(Q_z)$$

Lorentz Trans. along z-direction



磁場の現象とともに
分布が狭くなる



Spin-nonflipでは
$p_{iz} = 0$ でゼロ

崩壊幅への寄与が小さい

Angular Distribution of Pion Luminocity

$$\frac{d^3 I_\pi}{dq_\pi^3} = e_\pi \frac{d^3 \Gamma_{p\pi}}{dq_\pi^3}$$

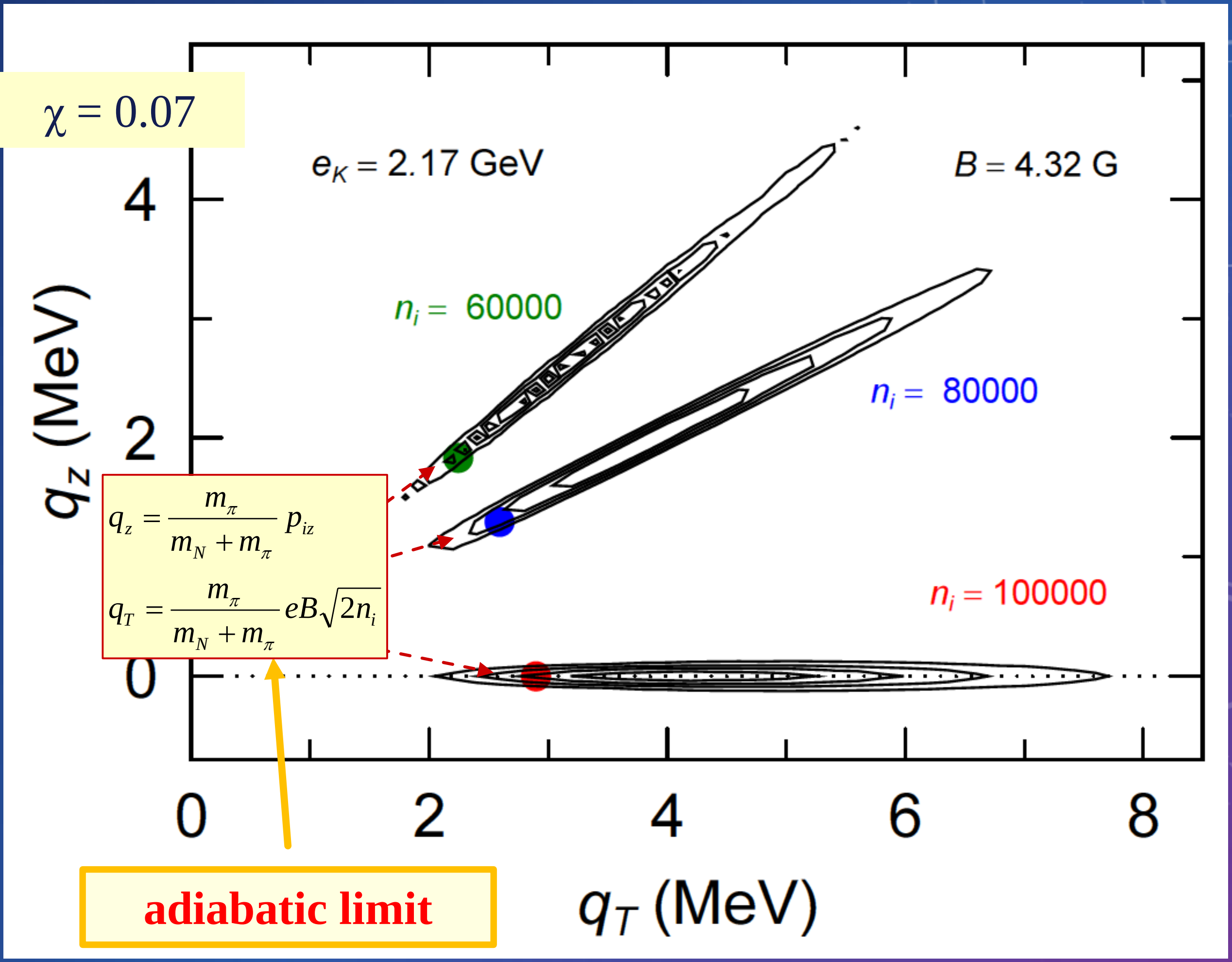
when $n_i >> 1$,

$\boldsymbol{q}_T \,//\, \boldsymbol{p}_f \,//\, \boldsymbol{p}_i$

Same Polar Angle

Width is very small

$\chi = 0.07$



$$q_z = \frac{m_\pi}{m_N + m_\pi} p_{iz}$$

$$q_T = \frac{m_\pi}{m_N + m_\pi} eB\sqrt{2n_i}$$

adiabatic limit

Proton Decay Width $n_\mathrm{i} >> 1$

$p_{\mathrm{iz}} = 0$

$$\frac{d\Gamma_{p\pi}(p_{iz}=0,s_i)}{dq^3} = \frac{1}{e_\pi}\sum_{n_f}\Gamma_{p\pi}(n_i,n_f)\delta\left(e_i - e_f - q_0\right)\delta(q_z)$$

⇓ Lorentz Transformation

$p_{\mathrm{iz}} \neq 0$

$$\frac{d\Gamma_{p\pi}(p_{iz},s_i)}{dq^3} = \frac{1}{e_\pi}\frac{e_{iT}}{e_i}\sum_{n_f}\Gamma_{p\pi}(n_i,n_f)\delta\left(e_i - e_f - q_0\right)\delta\left(q_z - \frac{e_\pi}{e_i}p_z\right)$$

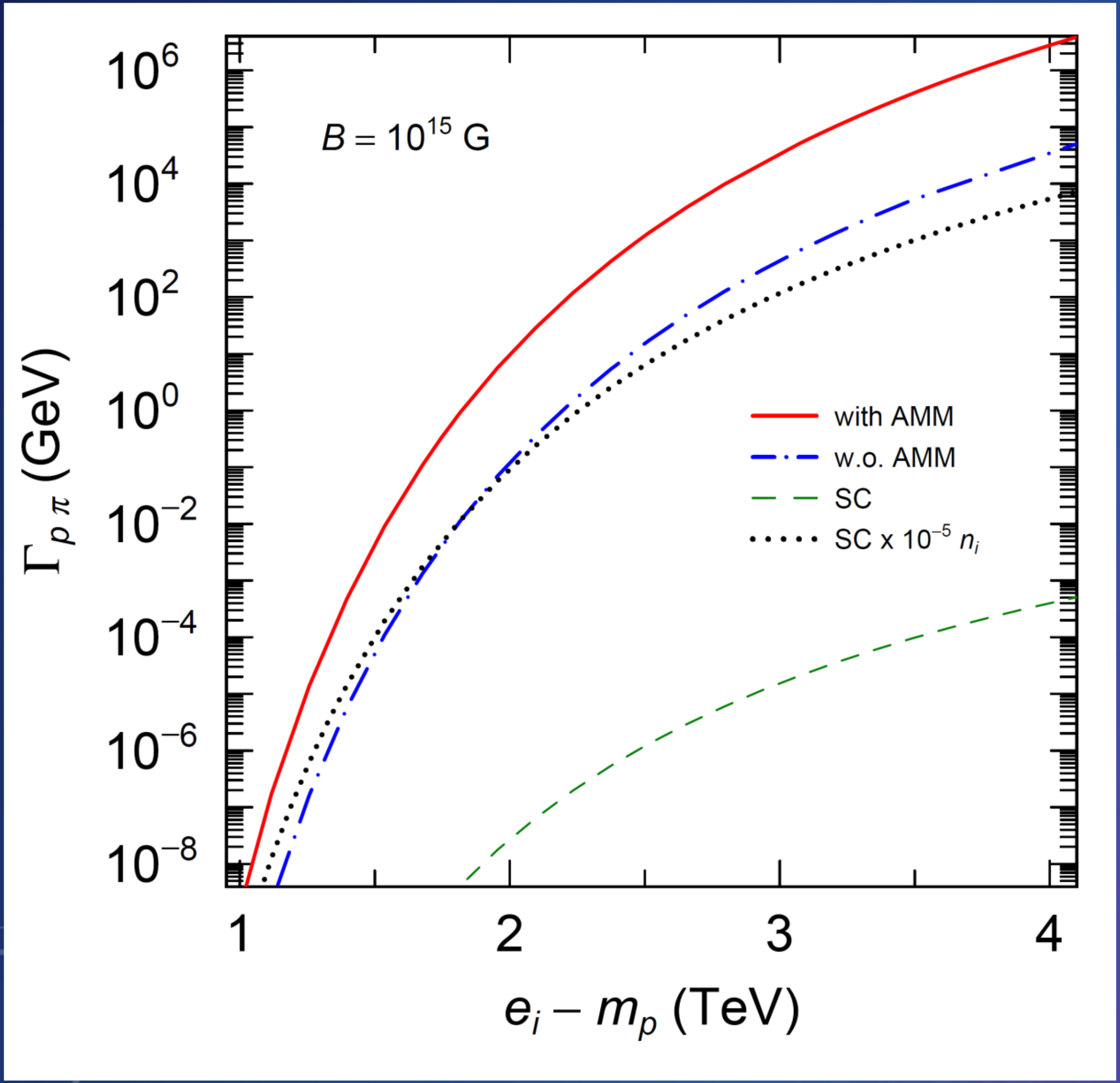
Scaling **Results with n_i, n_f ~ 10^4 ⇒** Results with 10^{12}

Semi-Classical Approximation assume $n_\mathrm{i} - n_\mathrm{f} << n_\mathrm{i}$

π has mass **This Assumpyion is wrong**

$$\sqrt{n_i} - \sqrt{n_f} > \frac{m_\pi}{m_N + m_\pi}\sqrt{n_i}$$

Total Decay Width



$$\Gamma(n_i, \chi; P_{iz} = 0) \propto n_i$$

Semi-Classical
A.Tokushita and T. Kajino,
ApJ. 525, L117 (99).

$$\Gamma(n_i, \chi; P_{iz} = 0)$$
$$\text{indep.of } n_i$$

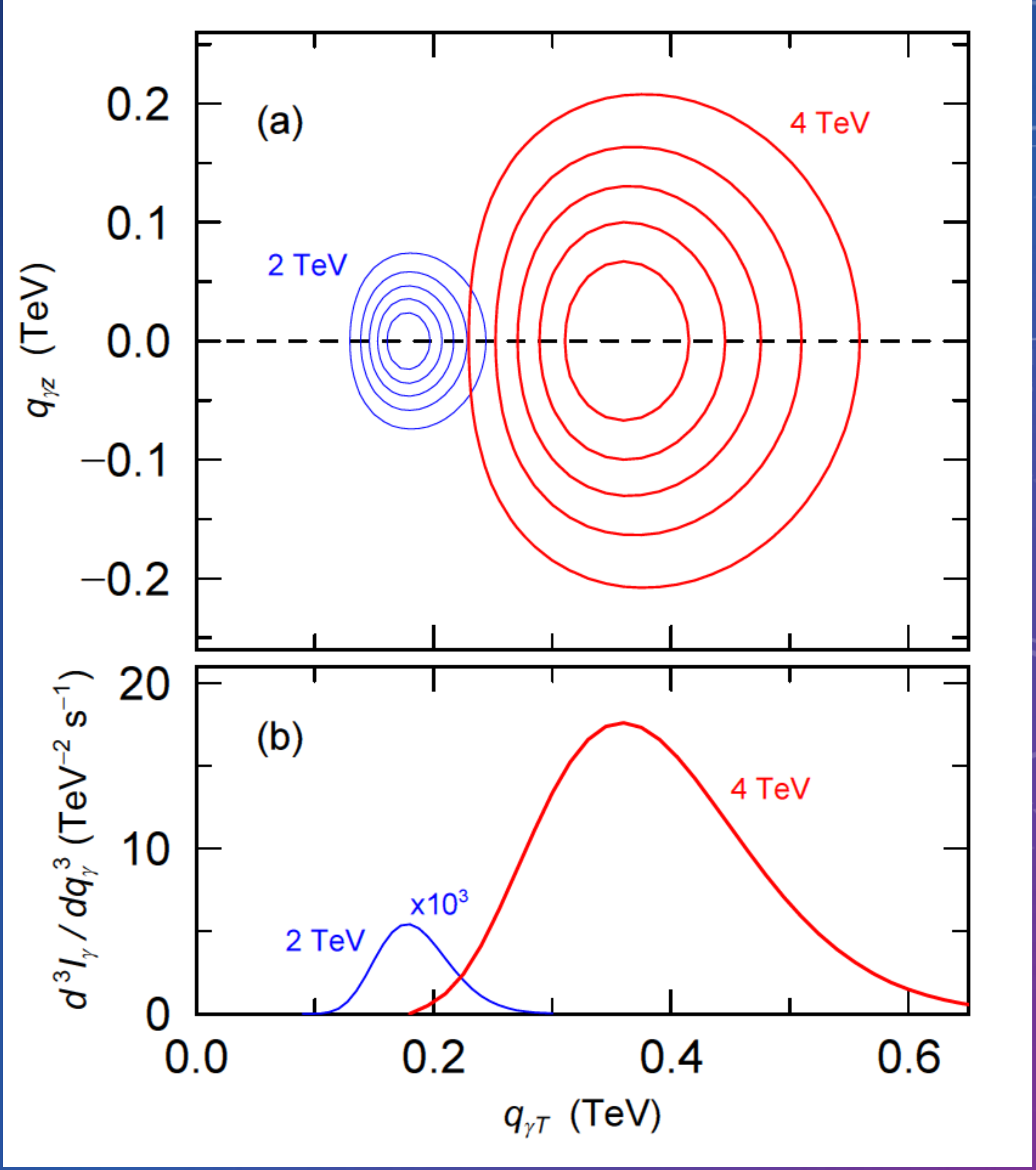
Luminocity-Distribution of Emitted Photons

$$p \longrightarrow p + \pi^0$$

$$\pi^0 \longrightarrow 2\,\gamma$$

Average over Initial Proton Angle

Distribution is Spherical



§ 2-4 Summary

- π^0 emission from Proton Transition between two Landau Levels

  $n_i, n_f \sim 10^5 \Rightarrow B \sim 10^{17}$ G

  AMM effect −1→+1 Dccay widths become 50 – 100 times larger

- Scaling Law, predicted by the Semi-Classical theory

  3 Variables $B, n_i, n_f \Rightarrow$ 2 Variables $\chi = eBE e_i / m_N^3$, $(n_i - n_f)/n_i$

  $B \sim 10^{17}$ G $\Rightarrow B \sim 10^{15}$ G (Magnetar)

  Results with $n_i, n_f \sim 10^4 \Rightarrow$ Results with 10^{12}

- Angular Dist $\theta_i \approx \theta_f \approx \theta_\pi$

$$\frac{d\Gamma_{p\pi}(n_i, p_{iz})}{dq^3} \,\alpha\, \delta\left(q_z - \frac{e_\pi}{e_i} p_z\right)$$

- Pion Energies are distributed in Broad Region

$$\sqrt{n_i} - \sqrt{n_f} > \frac{m_\pi}{m_N + m_\pi}\sqrt{n_i}$$

⇔

Semi-Classical Approx.

$n_i - n_f << n_i$

The Results come from HO overlap Integral

$$\mathcal{M}(n_1, n_2) = \int dx f_{n_1}\left(x - \frac{Q_T}{2}\right) f_{n_2}\left(x + \frac{Q_T}{2}\right) = \frac{2\pi}{\sqrt{n_i}} \mathcal{W}(n_i, n_f)\delta(Q_z)$$

It is a function of Q_T and very rapidly change when $n_{i,f} >> 1$

$$\mathcal{W}(n_i, n_f) \propto \frac{1}{\sqrt{n_i}} (\text{Function of } \chi)$$

Generally

$$\Gamma(n_i, P_{iz} = 0) = \mathcal{W}(n_i, n_f) \times F(P_{iz} = P_{fz} = Q_z = 0)$$

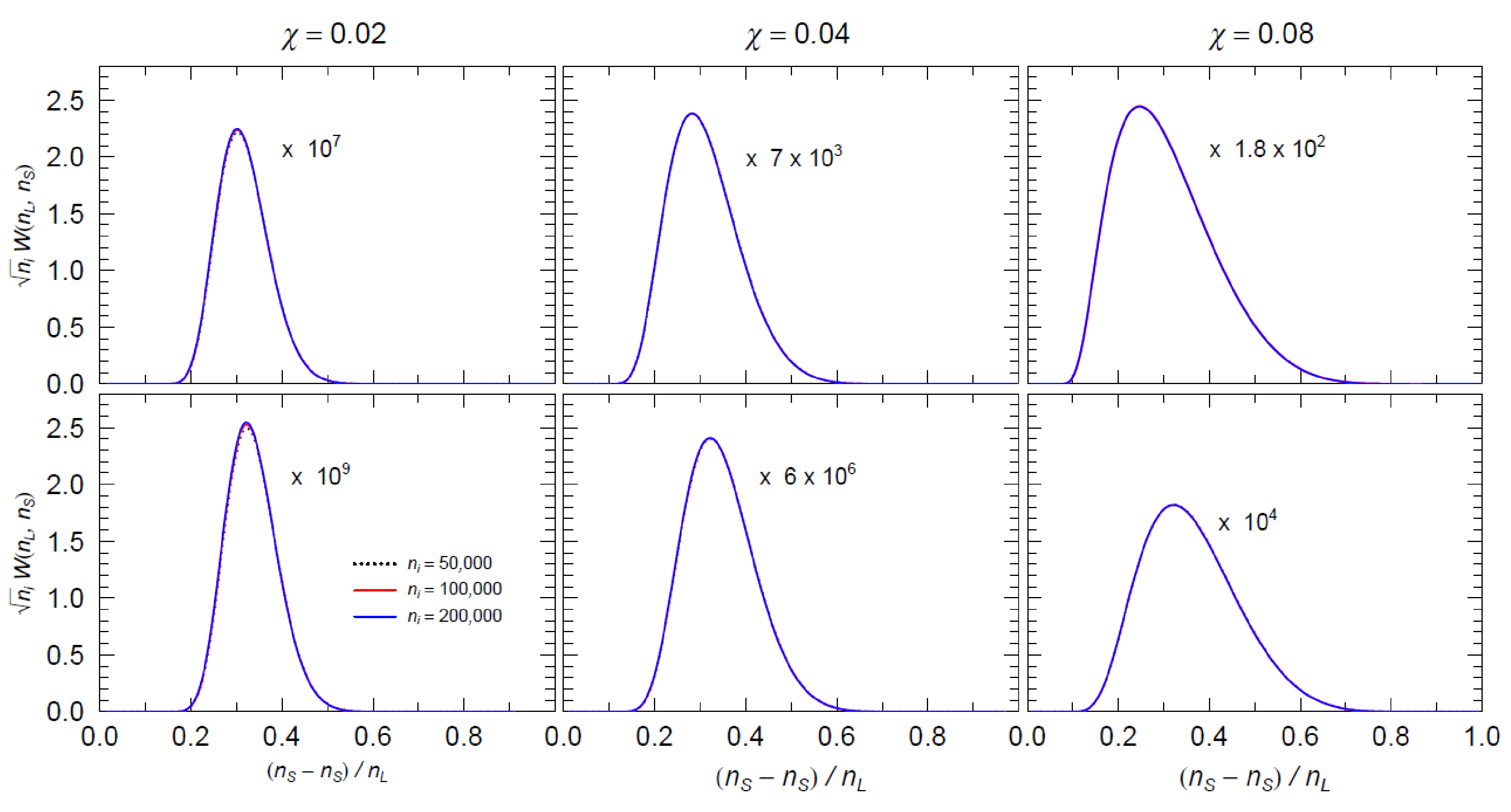
$\Rightarrow$ Other Particle Productions

$\Rightarrow$ **Magnetic Structure in Magnetars**

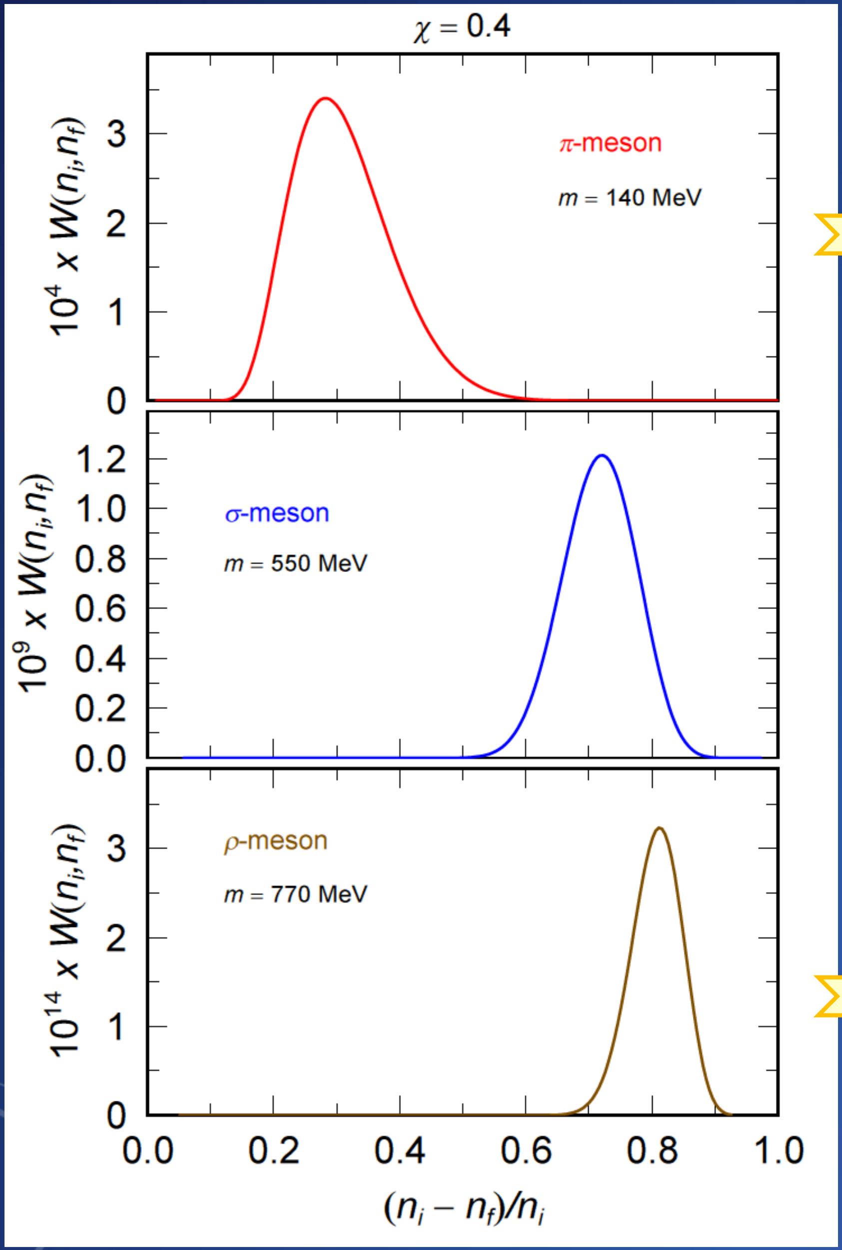
HO Overlap Integral

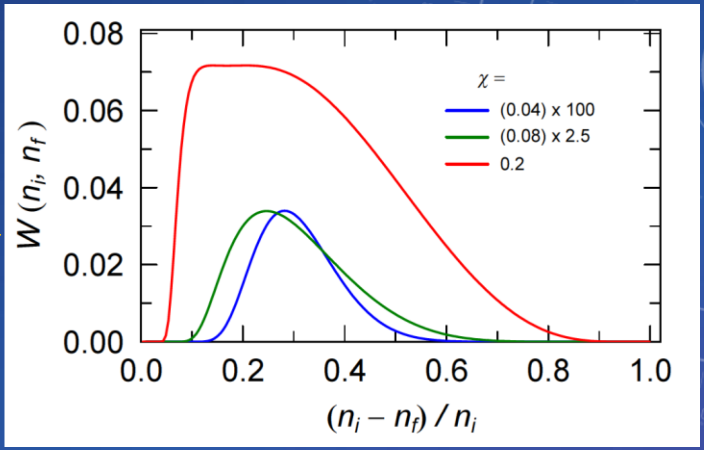
$$\mathcal{W}(n_1, n_2) = \sqrt{n_i} \int \frac{Q_z}{2\pi} \int dx f_{n_1} \left(x - \frac{Q_T}{2}\right) f_{n_2} \left(x + \frac{Q_T}{2}\right)$$

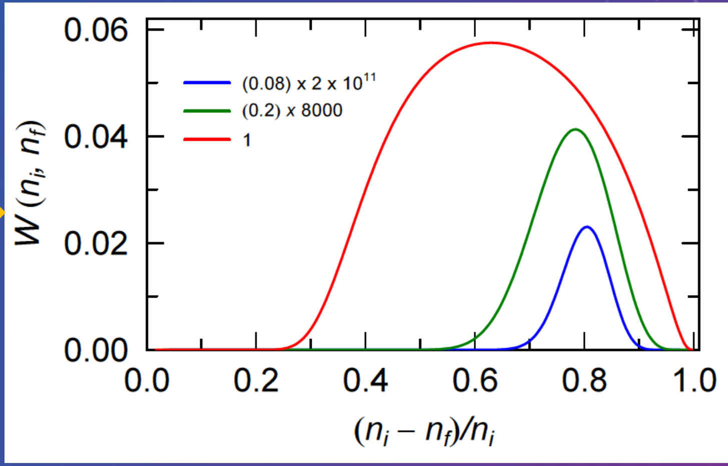
$$\mathcal{M}(n_1, n_2) = \int dx f_{n_1} \left(x - \frac{Q_T}{2}\right) f_{n_2} \left(x + \frac{Q_T}{2}\right) = \frac{2\pi}{\sqrt{n_i}} \mathcal{W}(n_i, n_f) \delta(Q_z)$$



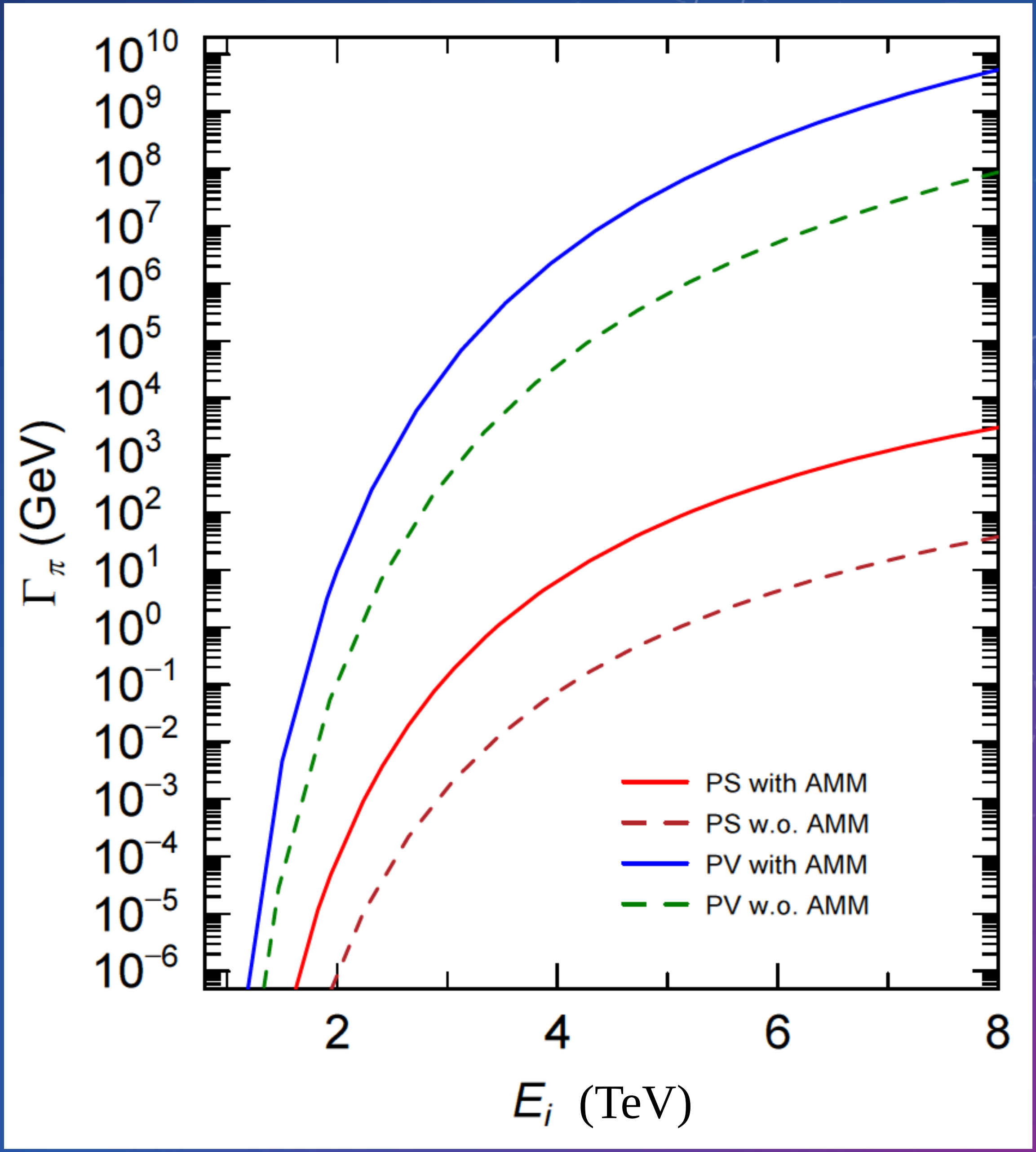
Meson Mass Dependence







PS-Coupling of Pion-Production



§ 3 Axion Cooling

Axion ： Hypothetical Particle postulated by the **Peccei–Quinn theory**

Solution to the strong CP-violation problem of QCD

R. D. Peccei and H. R. Quinn, PRL 38, 1440 (1977); PRD16, 1791 (1977).

Possible Component of Cold Dark Matter.

F. Wilczek, PRL 40, 279 (1978).

In Strong Magnetic Field $X + \gamma^*(B) \rightarrow \gamma$

axion helioscope **（アクシオン太陽望遠鏡）**

秋本祐希、蓑輪眞: 日本物理学会誌, Vol. 65, 2010 年1 月号25 – 29

Searches for solar Kaluza–Klein axions with Gas TPCs

B. Morgan et al., Astroparticle Physics 23, 287 (05)

Astrophysical Observation ⇒ Constraints of Axion Properties

J.E. Kim, Phys. Rep. 150, 1 (87) ,

SN1987A A. Payez, et al., JCAP02, 006 (15)

$e^- \rightarrow e^- + X$ in magnetized white dwarfs and Neutron Stars

M. Kachelrieß, C. Wilke, and G. Wunner, PRD 56, 1313 (97)

Neutron Star Cooling

1) Direct Urca $n \to p + e^- + \bar{\nu}$

Proton Fraction $x_p > \frac{1}{9}$ ($k_n < k_p + k_e$: Fermi Mom.)

Neutrino Luminosity $L \propto T^6$

2) Modified Urca $n + B \to p + B + e^- + \bar{\nu}$

Neutrino Luminosity $L \propto T^8$

3) neutrino-antineutrino paid production

$e^- + B \to e^- + B + \nu + \bar{\nu}$ (Crust, Low Density Region)

Conditions are determined by **Energy Momentum Conservation**

In Strong Magnetic Field

Mometum Conservation is not necessary

Decay Width

$$\frac{d^3\Gamma}{dq^3} = \frac{g_X^2}{8\pi^2 e_X} \sum_{n_f, s_f} \frac{\delta(E_f + e_X - E_i)}{4E_i E_f} W_{if} \boxed{f(E_i)\left[1 - f(E_f)\right]}$$

Landau Level Transition Energy is kept to be a few MeV

$$\sqrt{eB} = 2.43\text{MeV} \quad \text{when } B = 10^{15}\text{G}$$

Low Temperature Expansion ($T << 1$)

$$f(e) = \frac{1}{1 + \exp\left[(e-\mu)/T\right]} \approx \Theta(e-\mu) + a_C T \delta'(e-\mu)$$

Unavailable!

Emitted Particle Energy ~ T (Temperature)

Medium-Effect Relativistic Mean-Field Theory

Effective Mass $M_N \rightarrow M^*$ **except AMM**

§ 3-2 Results

EOS of Neutron-Star-Matter in RMF ***N, e, σ, ω, ρ***

$$BE = 16\,\mathrm{MeV},$$

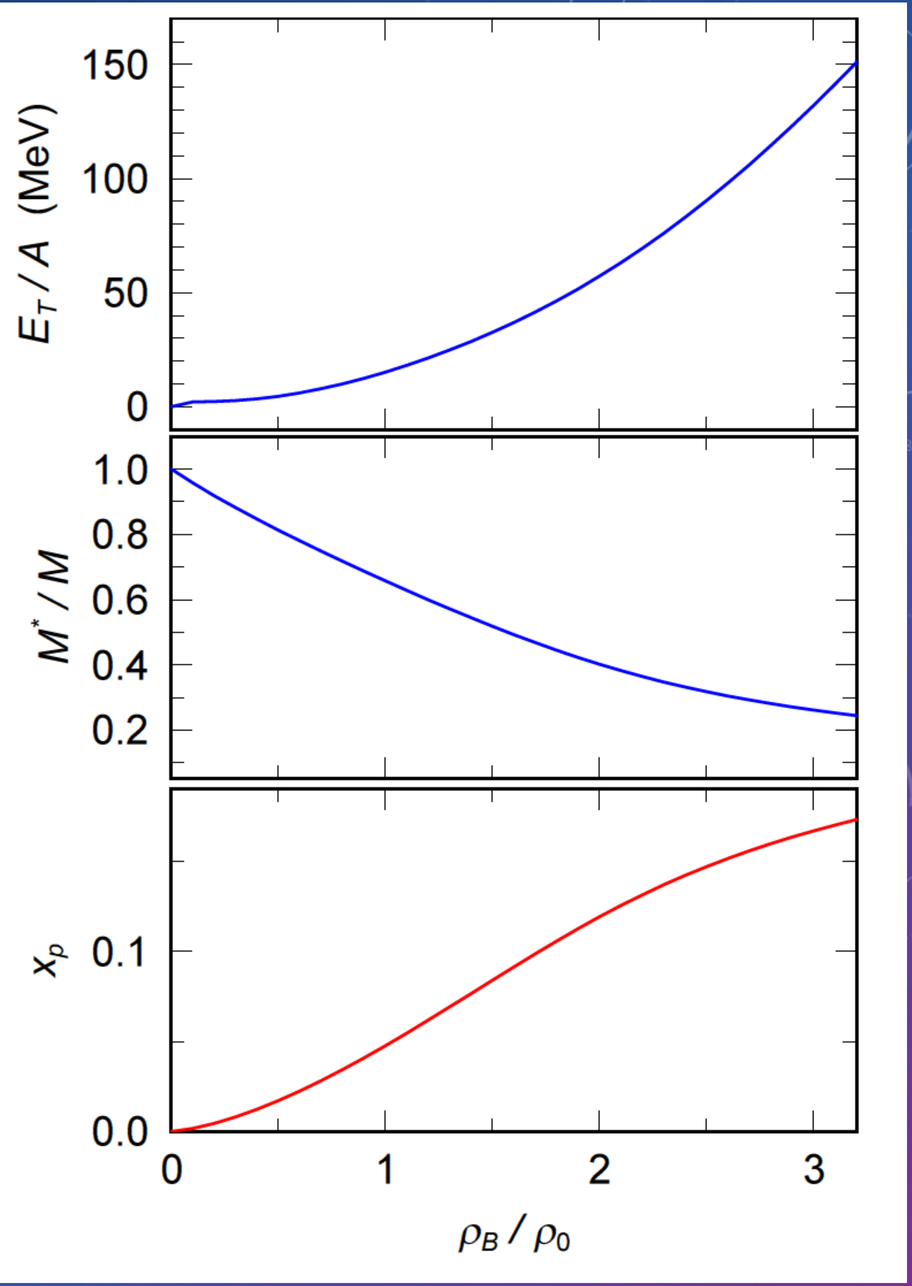
$$M_N^* / M_N = 0.65,$$

$$K = 200\,\mathrm{MeV}$$

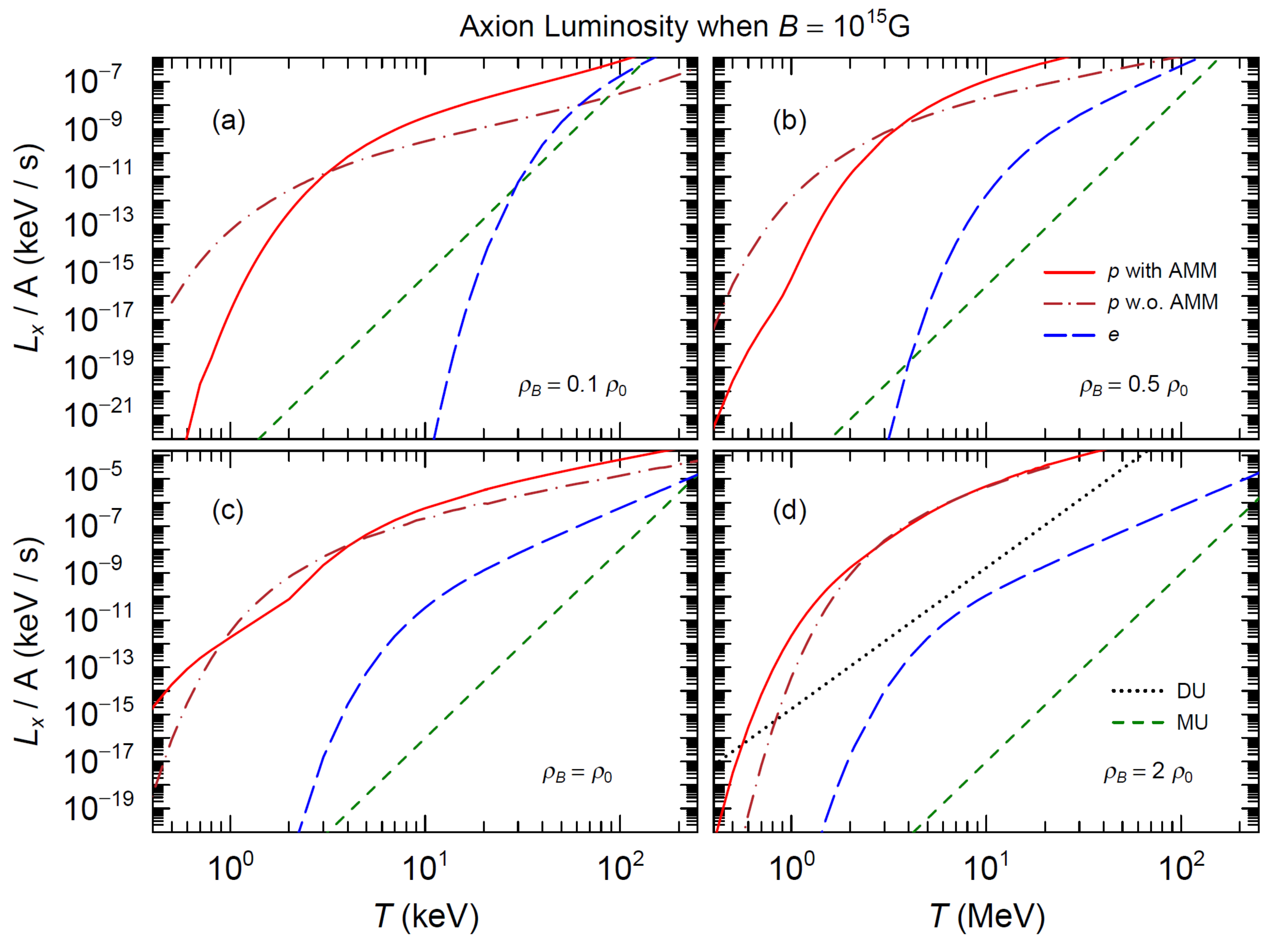
$$e_{sym} = 32\mathrm{MeV} \quad \text{at} \quad \rho_0 = 0.17\,\mathrm{fm}^{-3}$$

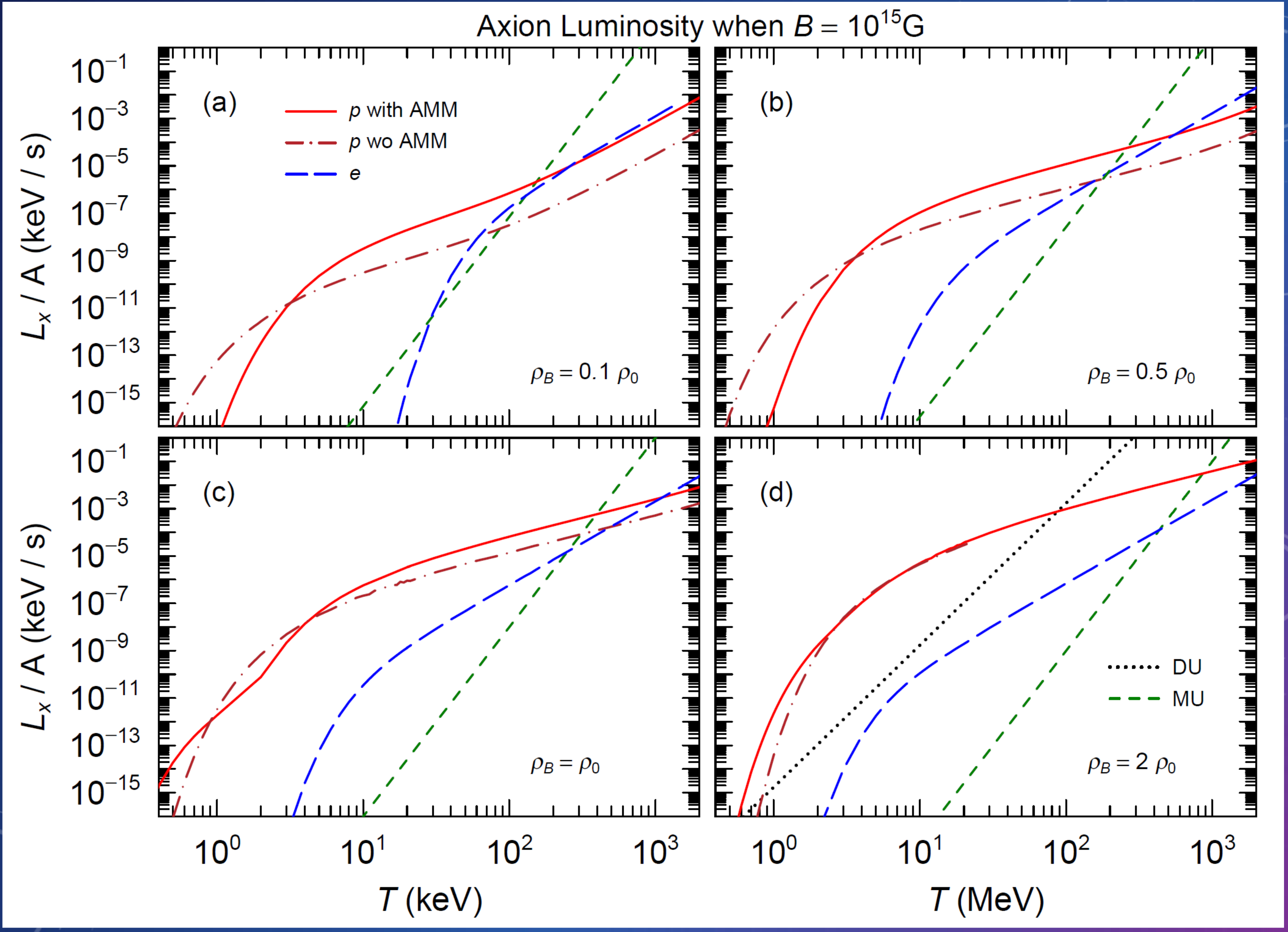
Axion–N, e Coupling

$$g_{XNN} = 4\times10^{-10},\ g_{Xee} = 9\times10^{-13}$$



Temperature Dependence of Axion Luminosity





Axion Luminosity when $B = 10^{15}$G
(a)
(b)
(c)
(d)
p with AMM
p wo AMM
e
DU
MU
$\rho_B = 0.1\ \rho_0$
$\rho_B = 0.5\ \rho_0$
$\rho_B = \rho_0$
$\rho_B = 2\ \rho_0$
L_x / A (keV / s)
T (keV)
T (MeV)

Axion Production in Proton Transition

PS-Particle $X \rightarrow$ **emitted to Transverse Dir.**

$$\Rightarrow \qquad p_{iz} = p_{fz} = q_z = 0$$

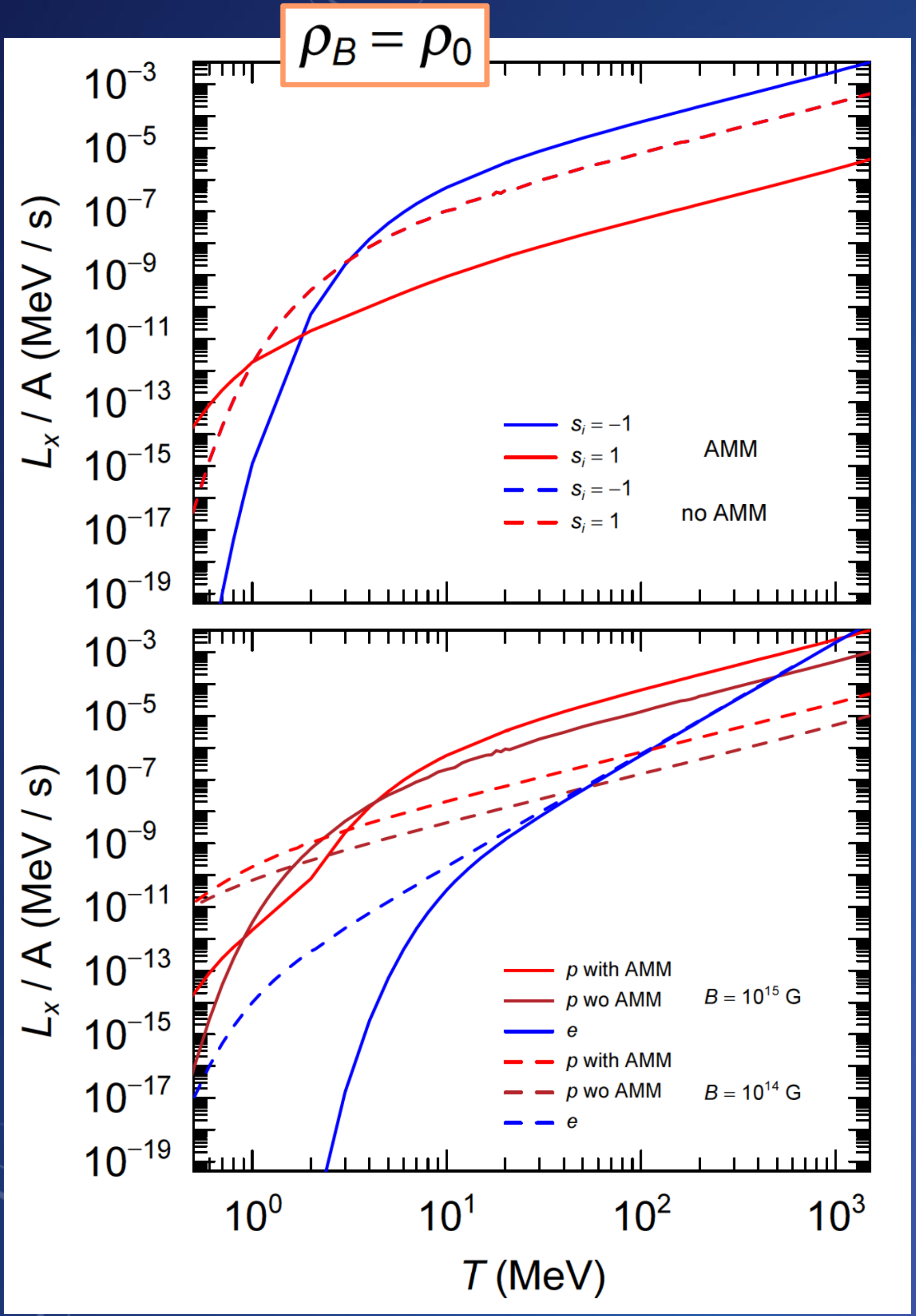
Very Small Mass $\Rightarrow \quad \Delta n_{if} = n_i - n_f \approx 1$

Spin-Flip Dominant $\Rightarrow \quad \Delta s_{if} = (s_i - s_f)/2 = \pm 1$

$$q_0 = e_i - e_f = \sqrt{2eBn_i + M^{*2}} - \sqrt{2eB(n_i - \Delta n_{if}) + M^{*2}} - \frac{eB\kappa}{M}\Delta s_{if}$$
$$\approx \frac{eB}{\sqrt{2n_i eB + M^{*2}}}\Delta n_{if} + \frac{eB\kappa}{M}\Delta s_{if}.$$

Energy Step:

$$\Delta e \approx \frac{eB}{E_F^*} + \frac{eB\kappa}{M}\Delta s_{if}$$



Energy-Interval

$$\Delta e \approx \frac{eB}{E_F^*} + \frac{eB\kappa}{M}\Delta s_{if}$$

$$\sqrt{eB} = 2.43\text{MeV} \quad \text{when } B = 10^{15}\,\text{G}$$

$$\sqrt{eB} = 0.77\text{MeV} \quad \text{when } B = 10^{14}\,\text{G}$$

$$e\kappa_p / M_N = 7.43\text{keV} \quad \text{when } B = 10^{15}\,\text{G}$$

$$e\kappa_p / M_N = 0.74\text{keV} \quad \text{when } B = 10^{14}\,\text{G}$$

$$\frac{eB}{E_F^*} \approx 9.4\text{keV} \;\; (p)$$

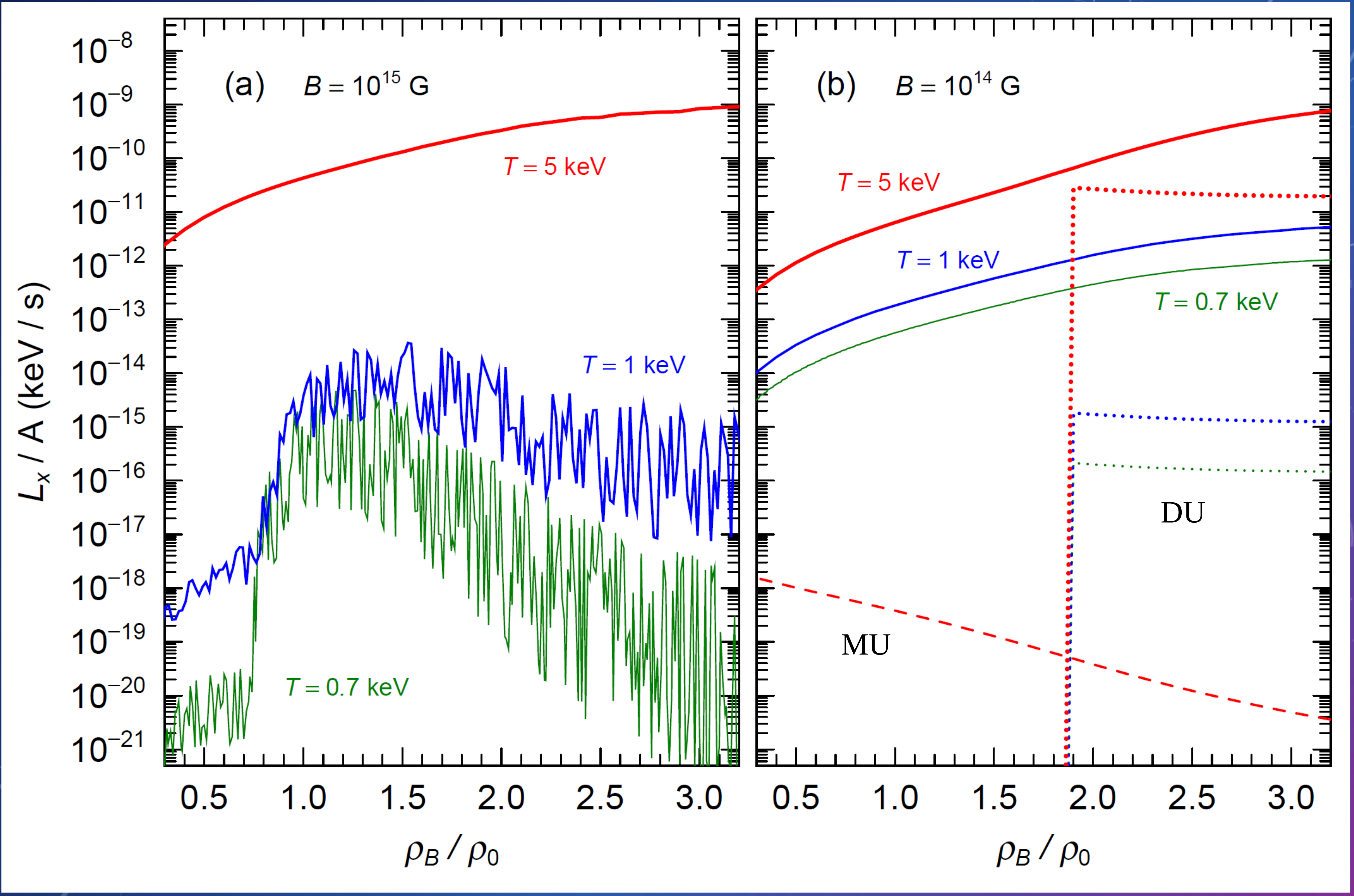
$$\frac{eB}{E_F^*} \approx 48.3\text{keV} \;\; (e) \qquad \text{when } B = 10^{15}\,\text{G}$$

$$\frac{eB}{E_F^*} \approx 0.04\text{keV} \;\; (p)$$

$$\frac{eB}{E_F^*} \approx 4.8\text{keV} \;\; (e) \qquad \text{when } B = 10^{14}\,\text{G}$$

Density Dependence of Axion Luminosity

$\times 10^{-3}$



§ 3-3 Summary of Axion Production

Axion Luminosity $L_X \propto T^a$ $a \approx 1.6$ **when T > 10 keV**

Low Tempearture Expansion

$f(E)\,[\,1-f(E)\,] \Rightarrow$ Narrow Peak **Energy Level** with Width T …. **Reagion A**

N + N → N+N+X ⇒ $L_X \propto T^6$ **A.Sedrakian, PRD 93, 065044 (16)**

Neutrino Luminosity a = 6 (DU), = 8 (MU)

Present Calculation

Very Low Temp. (T < 5 keV) **Energy Shift $\Delta e > T$**

Both Initial and Final States do not locate in Region A

Discrete Energy Levels affect Strength Distribution

$$X + \gamma^*(B) \rightarrow \gamma$$

Are All Axions are Emitted to Outside of Magnetar?

§ 4 Summary

PS-Boson Productions from Synchortron Radiation
in Strong Magnetic Fieldin Relativistic Quantum Approach
Landau Level & **Anomalous Magnetic Moment**

1) Pion Production

- **Scaling Law** ⇒ TeV Energy Production **Landau Level ~ 10^{12}**
- **Semi-Classical Calculation is not Available** $n_i - n_f \cong n_i$
- **Too Large Luminosity inconsistent to Cosmic Ray**

⇒ Photon is not Stable

$\gamma \to 2\gamma$ **K.Hattori, K.Itakura , Ann. Phys.**

$\gamma \to e^- + e^+$

2) Axion Production

- **Same Method of Pion Production**
- **Quantum Effects are Clearly seen in Low Temperature**

  ($T < 1$ keV)
- **Very Large Luminosity**

  though the Axion coupling is unclear
- **$X \rightarrow \gamma$ in Stong Magnetic Field $\Rightarrow$ Observables**

Project

Magnetar Cooling

1) $\nu\bar{\nu}$ **- Pair** Production from Transition of Electron (Proton)
2) Direct Urca $n \rightarrow p + e^- + \bar{\nu}$ Even if $x_p < \frac{1}{9}$,
3) **High Energy Photon Production**

$\Rightarrow$ Information of **Magnetic Structure** in Magnetar