High energy neutrinos from curvature pions in magnetars

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Motivation

Neutrino physics plays an important role in astrophysics

At very high energy, only the neutrinos reach the earth in their "original form" $\Longrightarrow$ Only neutrinos can provide us information about very high energy astrophysical processes

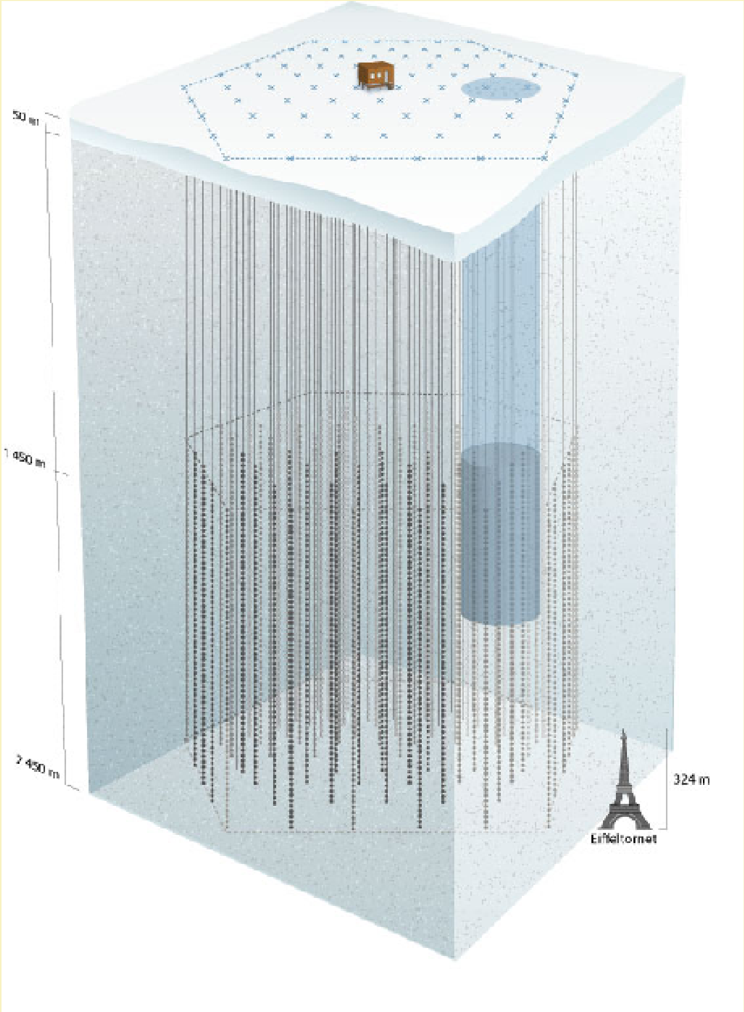
Detecting these high energy neutrinos can give us a chance to test the different models for dark matter, supernovas, gamma ray burst, neutron stars, magnetars. . .

We investigated the pion (subsequent neutrino) radiation by protons accelerated in very strong electromagnetic field of magnetars.

Overview

- The possible sources of neutrino flux detected on earth
- Curvature and synchrotron pion radiation in electromagnetic field by protons
- Different models for the electromagnetic field of magnatars
- Consideration of the back reaction force by pion and photon radiation in the equation of motion of protons
- The solution of the equation of motion and the intensity of the corresponding pion(neutrino) radiation
- Conclusion

Neutrinos sources and energy scales



At low energy:

Big bang	10^{-3}eV
Radioactive decays	10^{3} eV
Reactors, fusion (Sun)	10^{6} eV

At high energy:

Cosmic rays in the atmosphere	10^{9} eV
?? WIMP annihilation ??	??
Active Galactic Nuclei (AGN)	10^{12} eV
Magnetars	10^{12} eV
Gamma Ray Burst (GRB)	10^{15} eV

KM3NET
ICECUBE

ICECUBE detector can detect neutrinos up to 10^{17} eV

Processes of neutrino emission

- Charged pion decays:

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}), \quad \mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_{\mu}(\nu_{\mu})$$

- Inverse β decay in magnetic field (B):

$$p + B \to n + e^{+} + \bar{\nu}_e$$

- Proton $\longrightarrow$ pion processes:

$\to$ photomeson interaction:

$$p + \gamma \longrightarrow \Delta^{+} \longrightarrow n + \pi^{+}$$

$\to$ proton–neutron collision:

$$p + n \longrightarrow n + n + \pi^{+}$$

$\to$ in magnetic field

synchrotron type radiation:

$$p + B \longrightarrow \begin{cases} p + \pi^{0} + B \\ n + \pi^{+} + B \\ (p + \gamma + B) \end{cases}$$

Pion emission in magnetic field

$$p + B \longrightarrow \begin{cases} p + \pi^0 + B \; [1] \\ n + \pi^+ + B \; [2] \end{cases}$$

Photon radiation:

$p + B \longrightarrow p + \gamma + B$

Pion–nucleon interaction:

$\mathcal{H}_I^{N\pi} = g\vec{\rho}_{5N}\vec{\pi}$, source: $\vec{\rho}_{5N} = \bar{N}\vec{\tau}\gamma_5 N$

proton–photon interaction:

$\mathcal{H}_I^{p\gamma} = e j_\mu A^\mu$, source: $j_\mu = \bar{p}\gamma_\mu p$

Semiclassical treatment of the synchrotron radiation in homogenous magnetic field:

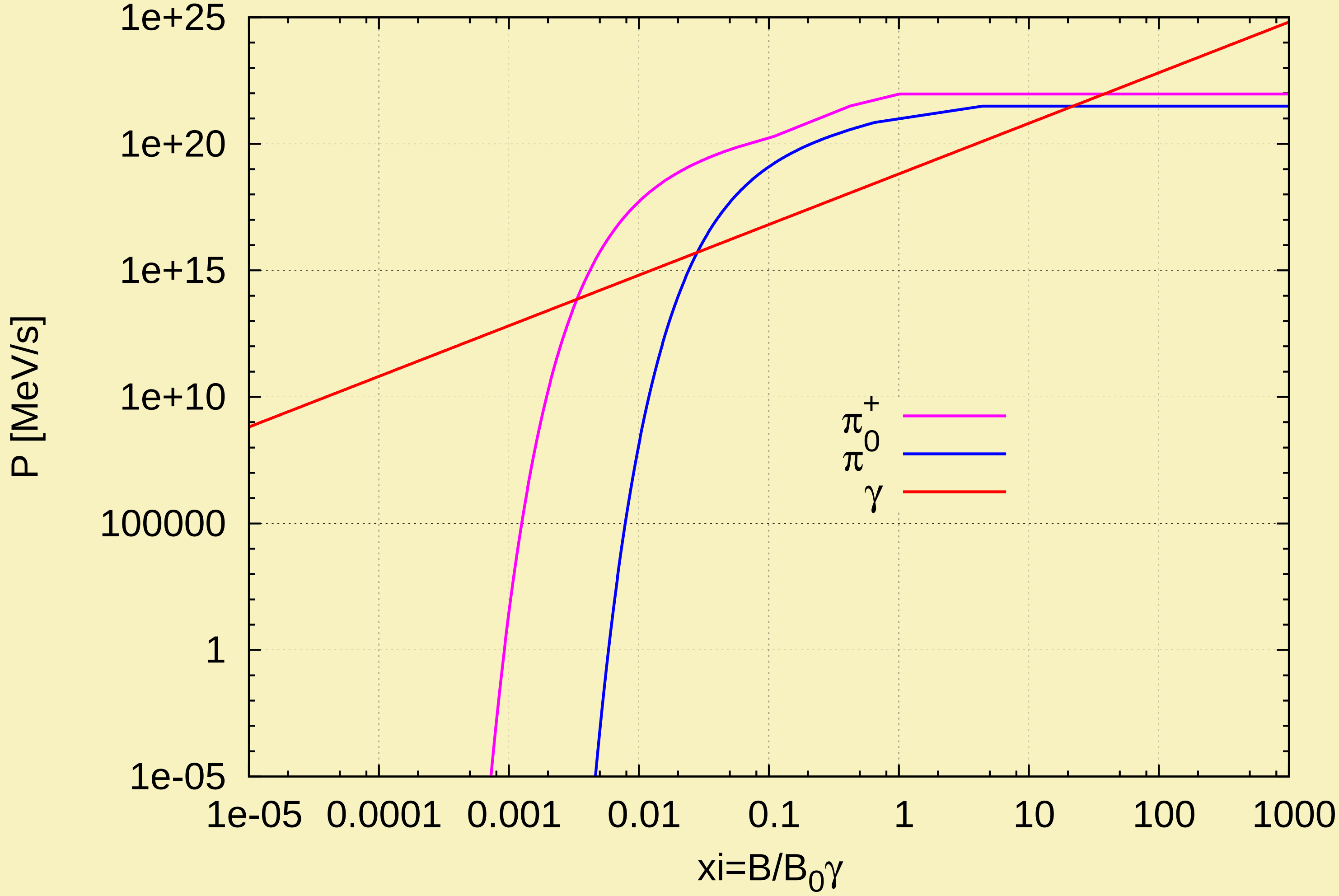
The constant source of photon radiation is the j_μ current of protons

$\Longrightarrow$ analogous description can be used for the pion radiation.

The photon radiation is dominant in week magnetic field, however at very high B the pions dominates the radiation. Especially, B can reach 10^{15} Gauss on the surface of magnetars.

[1] V. L. Ginzburg and G. F. Zharkov (1964); A. Tokuhisa and T. Kajino (1999)
[2] G. F. Zharkov (1965); T. Herpay and A. Patkós (2007)

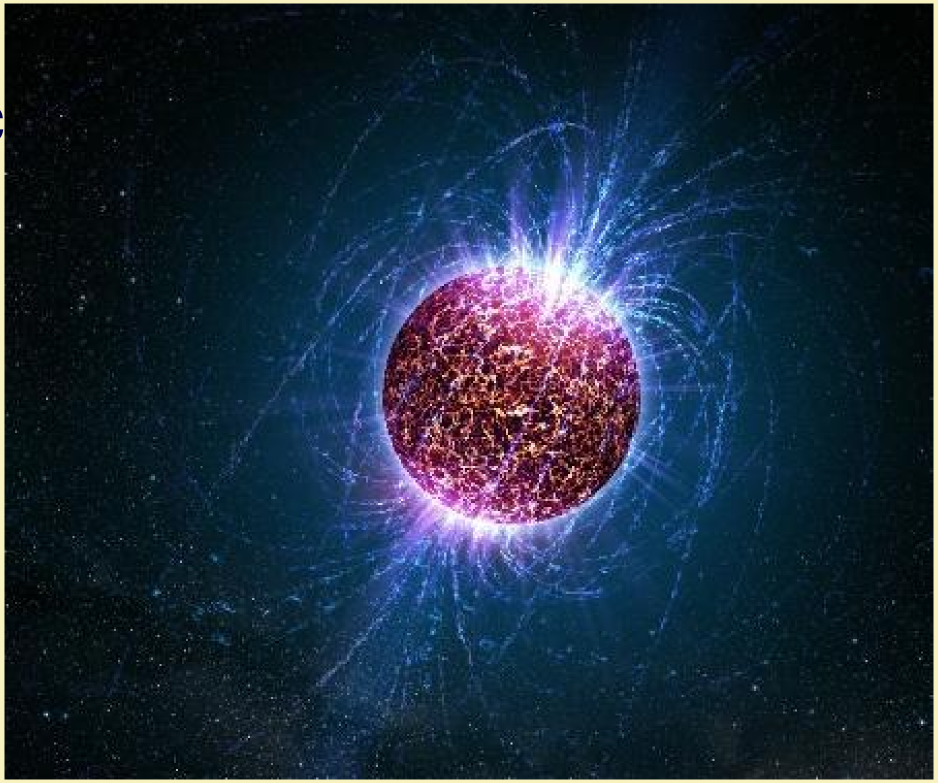
Synchrotron type pion/photon radiation



$\chi = \frac{B}{B_0}\gamma,\ \gamma = \frac{E_p}{m_p},\ B_0 = 1.5 \cdot 10^{20}$ G $\Longrightarrow$ π^+ radiation dominates if $B\gamma \gtrsim 10^{18}$ G

$\Longrightarrow$ Large magnetic and accelerating field is neccessary

Magnetars



Casey Reed, Pennstate University

Nuetron stars with strong magnetic field $\longrightarrow$ magnetars

Very compact objects:

mass: $M \approx 1.4$ solar mass
radius: $R \approx 10\,$km
strong magnetic field: $B \approx 10^{12-15}\,$G
fast rotation: $P = 2\pi/\Omega \approx 1$–$100\,$ms

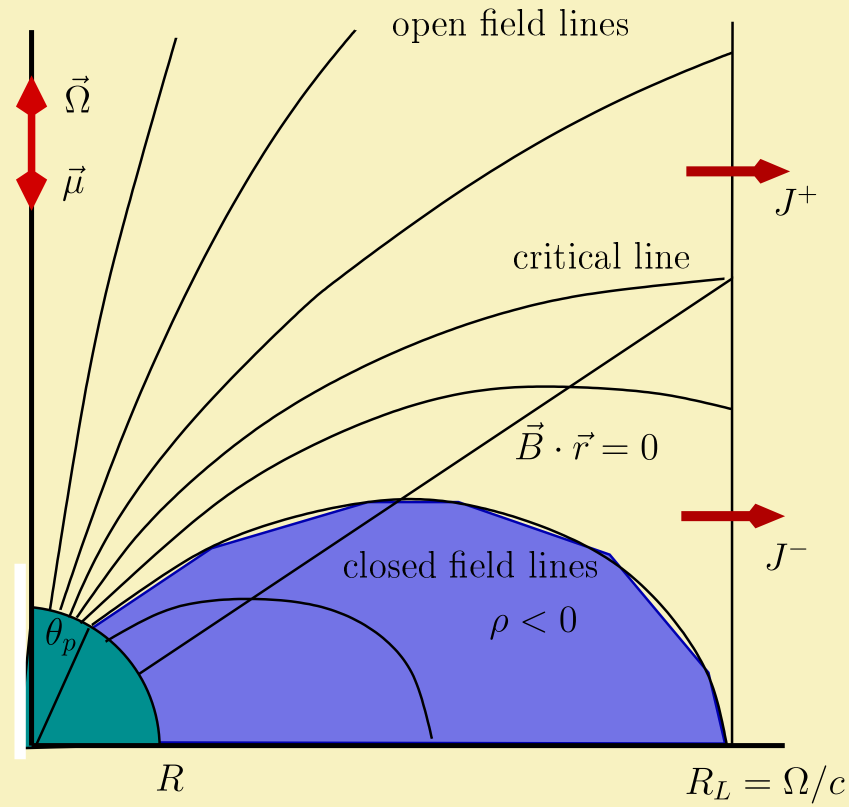
Strong gamma and X-ray emission $\Longrightarrow$ magnetars are loosing their rotation energy very quickly (about 10000 years).

Fast rotation and strong magnetic field $\Longrightarrow$ strong electric field $\Longrightarrow$ protons/ions can reach very high energy in the magnetosphere

The standard model of the magnetosphere

Assumptions:

- Magnetic dipole field
- In our case the rotation axis and dipol vector are anti parelell
- The surface is perfect conductor



P. Goldrich, W. H. Julian (1969)

Consequences:

- The Lorentz force acts on the free surface charges: $\vec{F} \sim \vec{v}/c \times \vec{B}$
- In the corotating reference frame, $E'_\theta = E_\theta + v_\phi B_r/c = 0$

Laplace eq. plus boundary conditions $\Longrightarrow$ electric quadrupole field
The corotating reference frame is limited by the speed of light (c), at the so–called light cylinder $R_L = \Omega/c \Longrightarrow$ closed field region

Models of the magnetosphere

• Space charge evolves in the closed field lines region, which corotating with the magnetar and screens the electric field

• In the open field region the quadrupole electric field almost paralallel with the magnetic field lines $E_{\parallel}\Big|_R \cong \frac{R\Omega}{c} B_0$ (at the surface) and so the protons/ions are accelerated from the surface

This simple model doesn't take into account the back reaction of current and the interactions of the accelerated charged particles.

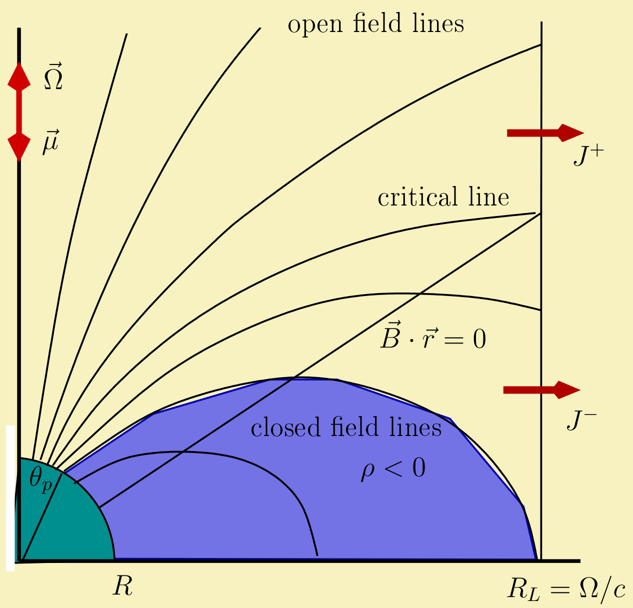
Modern models make attempt to the selfconsistent description:

(1) vacuum–gap model

$\Longrightarrow$ acceleration near the light cylinder

(2) space charge–gap model

$\Longrightarrow$ acceleration near the surface



[1] Medin, Lai 2008; [2] Harding, Muslimov 2002;

Curvature radiation

The common properties of magnetar models:

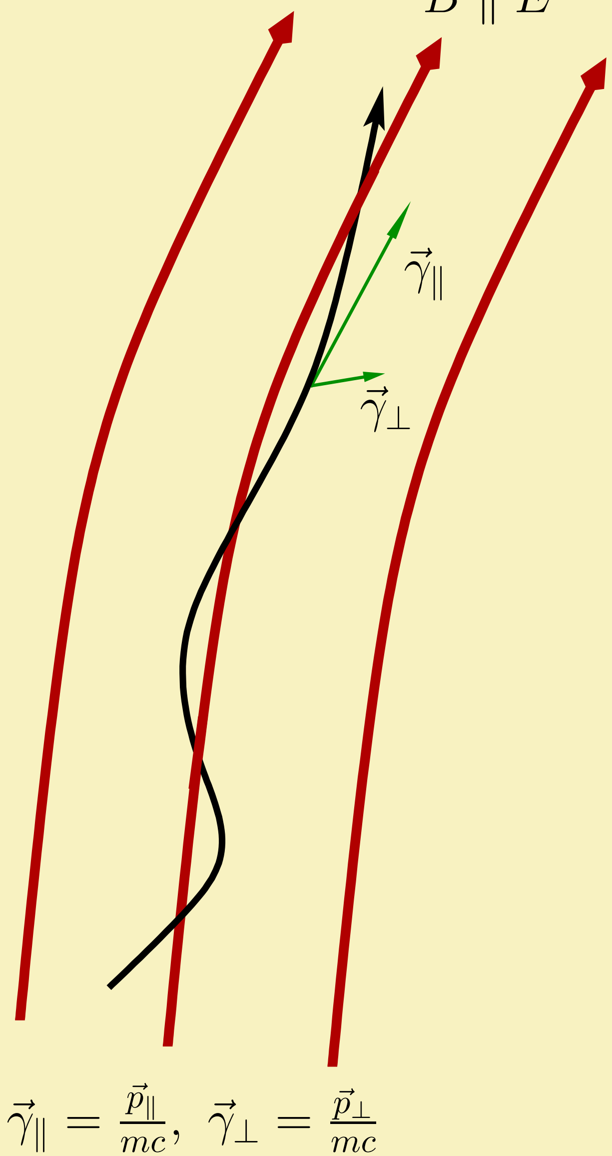
- The magnitude of the electric field: $\boxed{\cong \frac{R\Omega}{c}B}$

- The parallel component of the electric field to the magnetic field is much larger than the perpendicular component,

$$\boxed{\vec{E}\cdot\vec{B}\neq 0 \text{ and } E_{\|}\gg E_{\perp}}$$

Simple physical picture:

$p_{\|}$ decreasing quickly due to synchrtotron radiation $\Longrightarrow$ acceleration along the $\vec{B}$ lines $\Longrightarrow$ the main part of the high enegry radiation corresponds to the curvature of the B field.



Synchrotron vs. curvature radiation

Synchrotron radiation ($\vec{v} \perp \vec{B}$):

$$\mathcal{P}_\gamma = \frac{2}{3}e^2m^2\left(\frac{eB\gamma}{m^2}\right)^2 \equiv \frac{2}{3}e^2m^2\chi^2$$

Curvature radiation:

$$\mathcal{P}_{c\gamma} = \frac{2}{3}e^2m^2\left(\frac{\gamma^2}{mR_c}\right)^2, \quad R_c : \text{ curv.radius}$$

In both cases the radiation arises from the curvature of trajajectory. The effect of the magnetic field is only the determination of the curvature radius,

$$R = \frac{m\gamma}{eB}$$

One can define the "curvature χ" parameter:

$$\boxed{\chi = \frac{eB\gamma}{m^2}} \qquad \boxed{\chi_c = \frac{\gamma^2}{mR_c}}$$

The above explanation remains true for the π^0 and π^+ radiation by protons (V. Berezinsky, 1987)

Curvature radiation as a back reaction force

Lorentz force $\Longrightarrow$ trajectory of protons without radiation

photon, π^0 and π^+ rdiadiation $\Longrightarrow$ decreasing the energy of protons:

$$\mathcal{P} = \sum_i \mathcal{P}_i = \sum_i \frac{\mathrm{d}E_i}{\mathrm{d}t} = -\frac{\mathrm{d}E_p}{\mathrm{d}t}, \ i = \text{photon}, \ \pi^0, \ \pi^+$$

$\Longrightarrow$ assuming that the radiation is a dissipative force in the e.o.m.,

$$\dot{\vec{\gamma}} = \frac{e}{mc}\left(\vec{E} + \frac{1}{\sqrt{1+\vec{\gamma}^2}}\vec{\gamma} \times \vec{B}\right) - \frac{\mathcal{P}}{mc^2}\frac{\sqrt{\vec{\gamma}^2+1}}{|\vec{\gamma}|}\frac{\vec{\gamma}}{|\vec{\gamma}|}, \qquad \vec{\gamma} = \frac{\vec{p}}{mc},$$

$\vec{B}(\vec{r})$: dipole field; $\vec{E}(\vec{r})$: SCLF electric field (Harding, 2002)

$\vec{E}(\vec{r})$ has both parallel and perpendicular component to the magnetic field, and $\mathcal{P}$ depends on the curvature radius R_c and γ.

Equation of motion

$$\boxed{\chi = \frac{\gamma^2}{mR_c}}$$

$\mathcal{P}$ depends on χ and it depends on the curvature radius which can be written as

$$\frac{1}{R_c} = \frac{\sqrt{1+\vec{\gamma}^2}}{|\vec{\gamma}|^3}\left|\dot{\vec{\gamma}} \times \vec{\gamma}\right| = \frac{\sqrt{1+\vec{\gamma}^2}}{|\vec{\gamma}|^3}\sqrt{\vec{\gamma}^2\dot{\vec{\gamma}}^2 - (\vec{\gamma}\dot{\vec{\gamma}})^2}$$

and so $\mathcal{P} \equiv \mathcal{P}[|\vec{\gamma}|, \chi(\vec{\gamma}, \dot{\vec{\gamma}})] \Longrightarrow$ both side of the e.o.m. depend on $\dot{\vec{\gamma}}$

Fortunately $\dot{\vec{\gamma}}$ appears only in the $\dot{\vec{\gamma}} \times \vec{\gamma}$ combination, which can be calculated directly from the e.o.m.: $\dot{\vec{\gamma}} \times \vec{\gamma} \sim \left(\vec{E} + \frac{1}{\sqrt{1+\vec{\gamma}^2}}\vec{\gamma} \times \vec{B}\right) \times \vec{\gamma}$

$$\chi = \frac{e}{m^3}\frac{1}{|\vec{\gamma}|}\left|\vec{\gamma} \times \left(\sqrt{1+\vec{\gamma}^2}\,\vec{E}(\vec{r}) + \vec{\gamma} \times \vec{B}(\vec{r})\right)\right|$$

and finally $\mathcal{P}$ depends on only $\vec{\gamma}$: $\mathcal{P} = \mathcal{P}_{ph} + \mathcal{P}_{\pi^0} + \mathcal{P}_{\pi^+} \equiv \mathcal{P}[|\vec{\gamma}|, \chi(\vec{\gamma})]$

The equations

The six coupled differential equations:

$$\dot{\vec{\mathbf{r}}} = \frac{\vec{\gamma}}{\sqrt{1+\vec{\gamma}^2}},$$

$$\dot{\vec{\gamma}} = \frac{e}{m}\left(\vec{E}(\vec{\mathbf{r}}) + \frac{1}{\sqrt{1+\vec{\gamma}^2}}\vec{\gamma}\times\vec{B}(\vec{\mathbf{r}})\right) - \frac{P(|\vec{\gamma}|, \bar{\chi}(\vec{\gamma}, \vec{\mathbf{r}}))}{m}\frac{\sqrt{\vec{\gamma}^2+1}}{|\vec{\gamma}|}\frac{\vec{\gamma}}{|\vec{\gamma}|}$$

The expressions of the radiation intensity for $\chi < 1$:

$$\mathcal{P}_{photon} = \frac{2}{3}em^2\chi^2, \qquad \mathcal{P}_{\pi^0} = g^2 m m_\pi \chi \exp\left[-\frac{\sqrt{3}}{\chi}\frac{m_\pi}{m}\right]$$

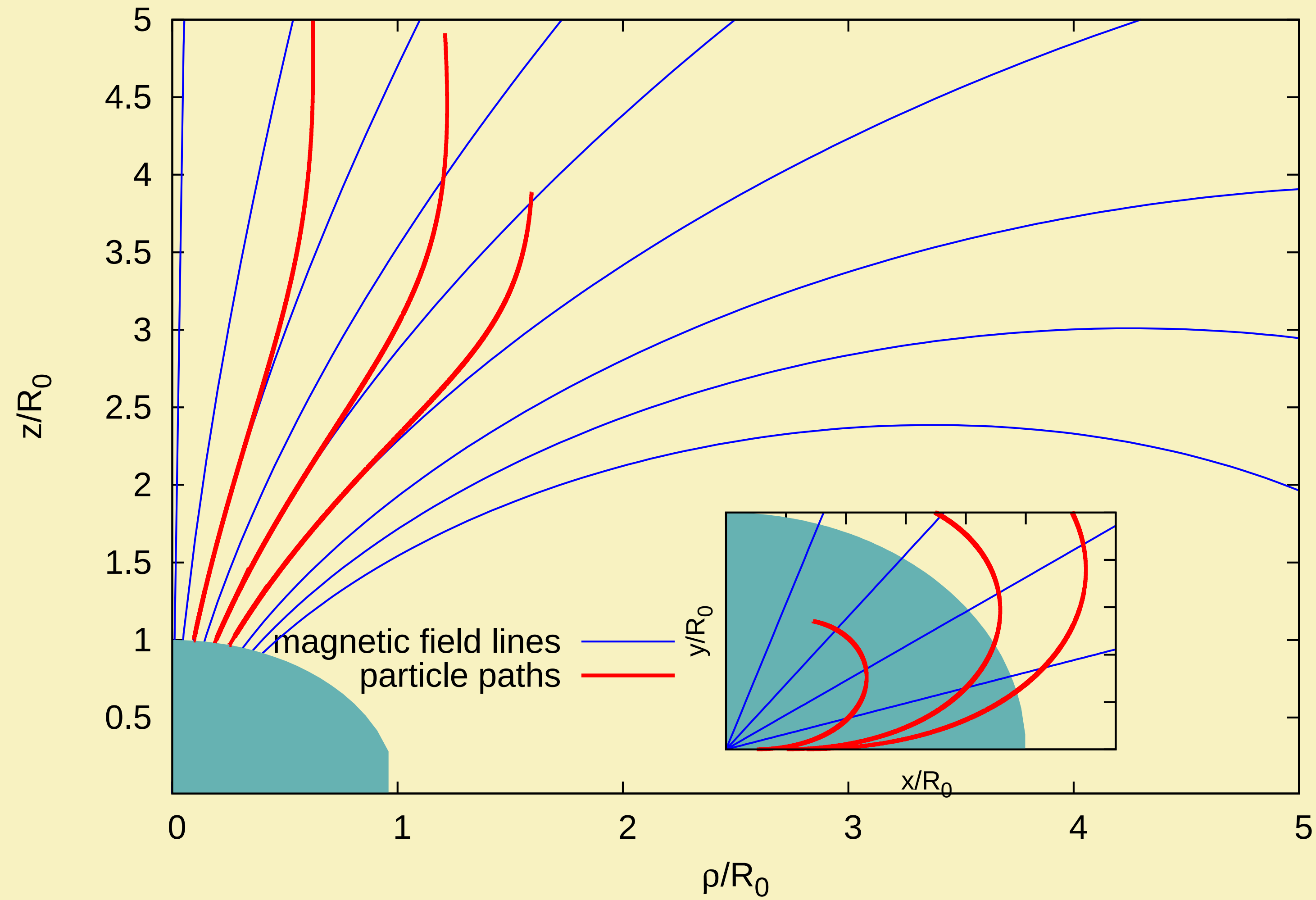
$$\mathcal{P}_{\pi^+} = g^2 m^2 \frac{(m/m_\pi)^2(2\sqrt{2}-m_\pi/m)}{\sqrt{24}\left[1+\sqrt{2}m/m_\pi\right]^4}\chi \exp\left[-\frac{\sqrt{3}}{\chi}\left(\frac{m_\pi}{m}\right)^2\right]$$

The path of the protons

The electric field depends on $R_0,\ M,\ B_0,\ P \equiv 2\pi/\Omega$.

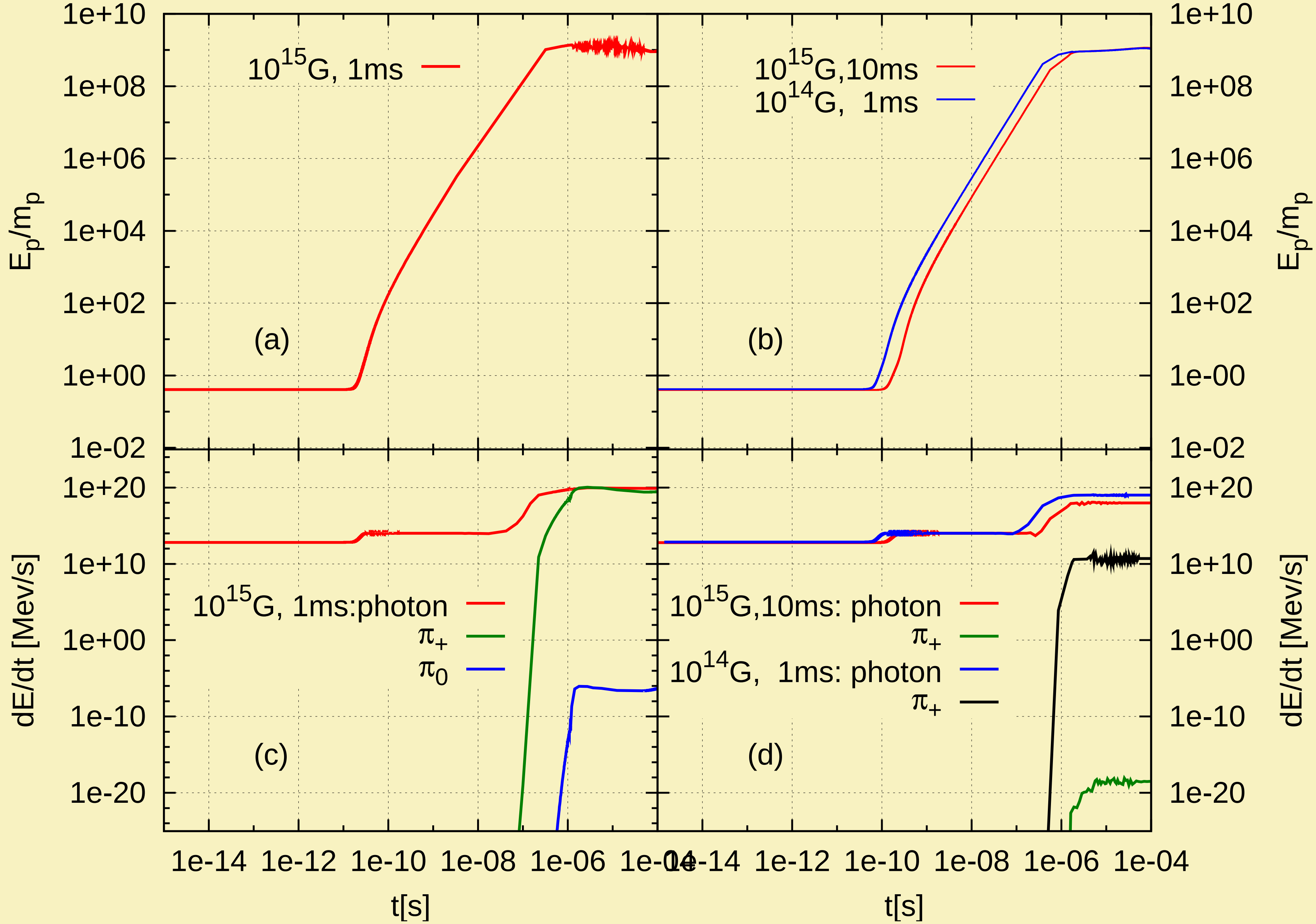
- $R_0 = 10$ km
- $M = 1.4\, M_\odot$

B_0[G]	P[ms]
10^{15}	1
10^{15}	10
10^{14}	1



The path of the proton for different initial angle (10^{15}G, 1ms)

The solution



The energy of the protons (a,b); The intensity of different radiations (c,d)

Ion acceleration

Ions mass: Am_p; charge: Ze.

- $m \to mA$ and $e \to Ze$ replacement in the Lorentz force

Assuming that the radiation intensity for the ions is the incoherent sums of individual nucleonic contribution:

- $\mathcal{P}_{\pi^0} \to A\mathcal{P}_{\pi^0}$ because both protons and neutrons can emit π^0 with the same probaility
- $\mathcal{P}_{\pi^+} \to A\mathcal{P}_{\pi^+}$ because the radiation of π^+ by protons and radiation of π^- by neutorns having the same probability
- $\mathcal{P}_{ph} \to Z\mathcal{P}_{ph}$

The solution provide that ions can reach the same order of energy as the protons. However, the transverse momentum transfer from individual nucleons to photons and pions ($k_\perp \approx 100$ MeV) larger than the average maximum energy of the nucleons 10 MeV

Detected neutrino flux

From magnetar models the outflow rate of protons:

$$\dot{N} \approx \frac{B_0 \Omega^2 R_0^3}{ec} = 1.4 \cdot 10^{33} \frac{B_{15} R_6^3}{P^2} \cdot \frac{1}{\mathrm{s}},$$

where $B_{15} = B_0/(10^{15}\mathrm{G})$ and $R_6 = R_0/(10\,\mathrm{km})$

In case of $B = 10^{15}$ G and $P = 1$ ms each proton decays into π^+, and each pions produce

$$\pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

two neutrino ν_μ, ν_e and one anti neutrino $\bar{\nu}_\mu$. And on the earth, the corresponding neutrino number is

$$\dot{N}_\nu = 7.3 \cdot 10^5 \frac{B_{15} R_6^3}{P^2 D_{10}^2} \frac{1}{\mathrm{year}}$$

in a 1 km^2 detector, where $D_{10} = D/(10$kpc$)$ is the distance of the magnetar.

Detected neutrino energy

Typical pion energy radiated by protons $E_\pi \approx E_p/4 \approx 0.25 \cdot 10^9$ GeV

Taking into account the energy loss of pions and muons in the magnetosphere, the energy of the produced neutrinos

$$\boxed{E_{\nu_\mu} \approx 33\,\text{TeV and } E_{\bar{\nu}_\mu,\nu_e} \approx 3.3\,\text{TeV}}$$

and using the effectivity of the ICECUBE detector

$$P_{\nu\to\mu} \approx 1.3 \cdot 10^{-6} E_\nu/\mathrm{TeV}$$

one can obtain the detected neutrino flux on earth:

$$\boxed{\dot{N}_\nu \approx \begin{cases} 6.3 \cdot 10^5 \frac{1}{year} & \text{for } \nu_\mu \\ 9.5 \cdot 10^4 \frac{1}{year} & \text{for } \nu_e,\ \bar{\nu}_\mu \end{cases}}$$

from a magnetar ($B = 10^{15}$ G; $P = 1$ ms) at 10 kparsec distance.

These values are too large comparing the experiments.

Conclusion

• The charged pion (and subsequent neutrino) radiation comparable with photon radiation only in magnetars which have $B \geq 10^{15}$ G and $P \leq 1$ ms

• But in this case the corresponding neutrino flux on the earth is too large comparing to the experiments.

These magnetars don't exist in our galaxy
or
their rotation axis doesn't point to the earth.

Publications:
T. Herpay, A. Patkós, *Jphys. G* (2007)
T. Herpay, S. Razzaque, A. Patkós, P. Mészáros, *JCAP* (2008)