Origin of IceCube Detected Three PeV Neutrinos

APRIM – 2017

RAJAT K DEY
North Bengal University, Darjeeling, WB, India

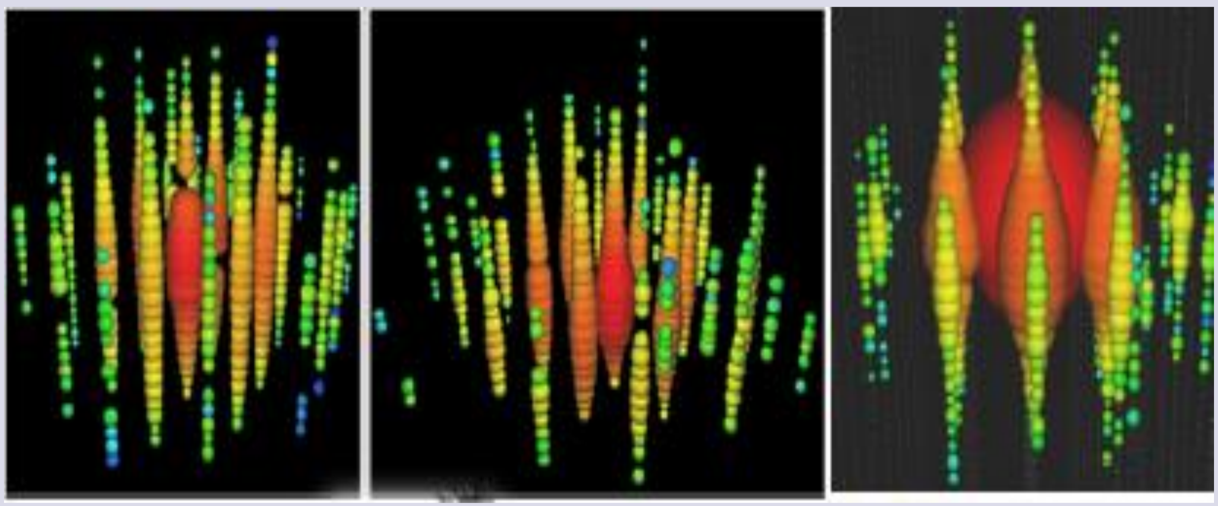
TAIPEI, July 6, 2017

Motivation

A window to fundamental physics at the highest energies from the discovery of 3 Astrophysical neutrinos at PeV scale by IceCube.

– M G Aartsen et al., PRL 111 021103 (2013)

Three Cascade events



"Bert" – 1.04 PeV
Aug 2011

"Ernie" – 1.14 PeV
Jan 2012

"Big Bird" – 2 PeV
Dec 2012

The highest energies in nature are believed to reside in dense astrophysical environments

What are the sources for these astrophysical neutrinos?

To explain their origins, about 22 Astrophysical models have been proposed so far including our work.

– Laha & Brodsky; arXiv:1607.08240

No correlation with any source class established so far……

Probable candidates

- **Galactic:** (full or partial contribution)
  - diffuse or unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [MA & Murase'13; Neronov, Semikoz & Tchernin'13;Neronov & Semikoz'14; Guo, Hu & Tian'14]
  - extended Galactic emission [Su, Slatjer & Finkbeiner'11; Crocker & Aharonian'11] [Lunardini & Razzaque'12;MA & Murase'13; Razzaque'13; Lunardini *et al.*'13] [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein *et al.*'13; Esmaili & Serpico '13; Bai, Lu & Salvado'13]
- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13] [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - active galactic nuclei (AGN) [Stecker'91,'13;Kalashev, Kusenko & Essey'13] [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14;Kalashev, Semikoz & Tkachev'14]
  - gamma-ray bursts (GRB) [Murase & Ioka'13]
  - starburst galaxies [Loeb & Waxman'06; He *et al.*'13;Yoast-Hull, Gallagher, Zweibel & Everett'13] [Murase, MA & Lacki'13; Anchordoqui *et al.*'14; Chang & Wang'14]
  - hypernovae in star-forming galaxies [Liu *et al.*'13]
  - galaxy clusters/groups [Murase, MA & Lacki'13;Zandanel *et al.*'14]
  - . . .

Slide from M. Ahlers, NeuTel 2015

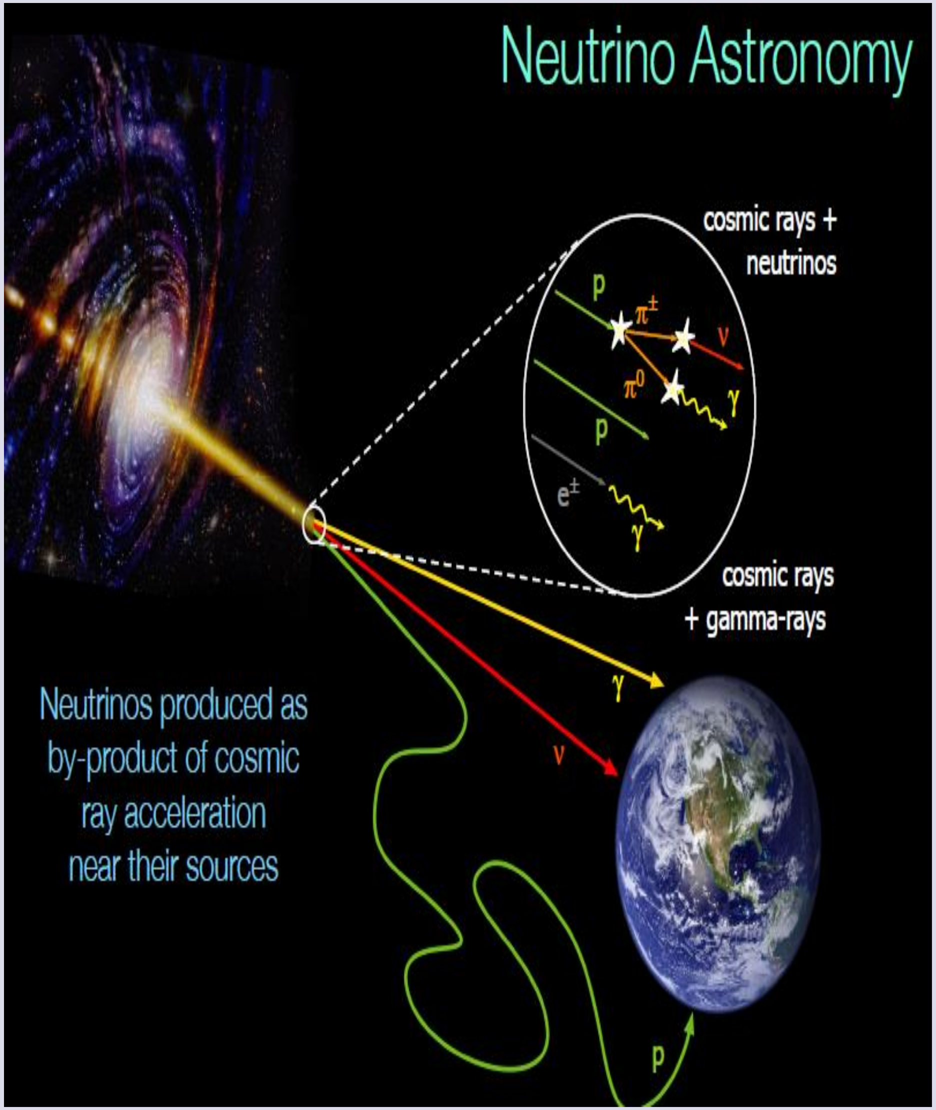
And

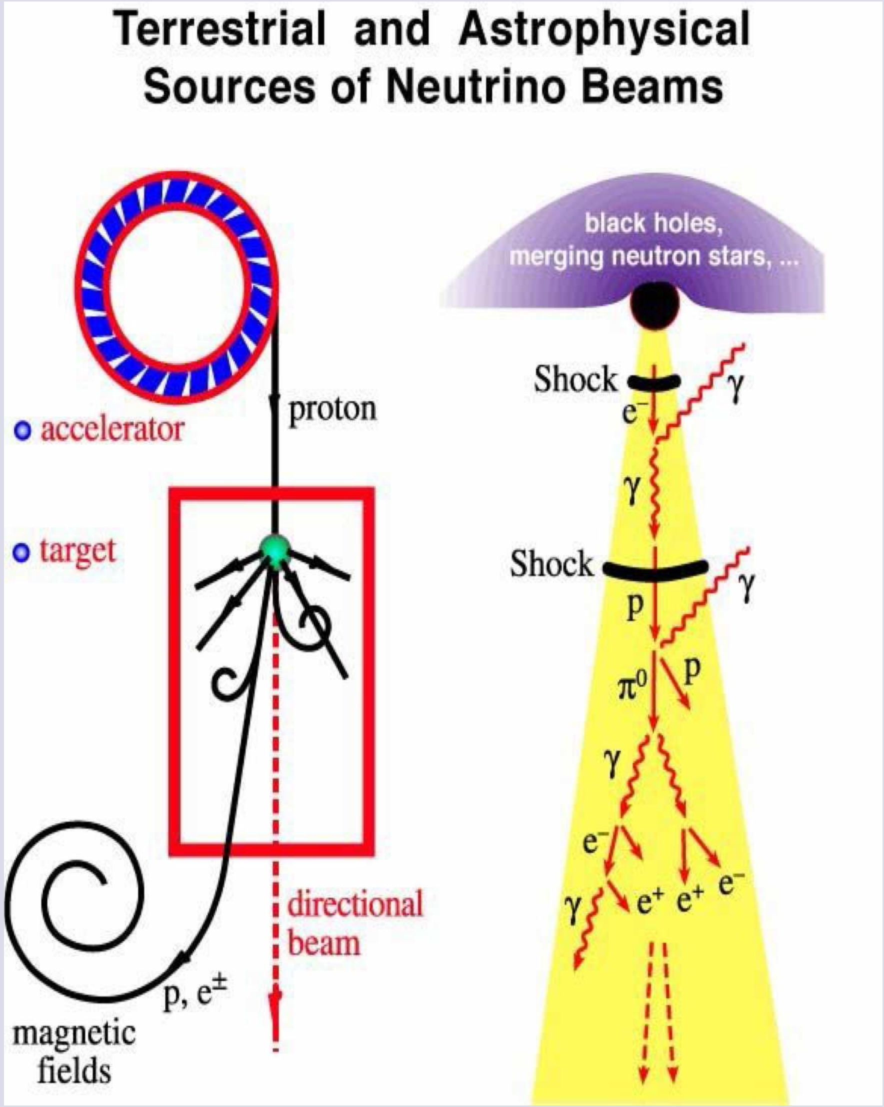
- **Laha & Brodsky; arXiv:1607.08240 and references therein**

Galactic origin

- The potential galactic candidate sources.
  - The remnants of supernova explosions - cannot reach normally ~ 10^{17} eV , if cosmic rays are protons.
  - Pulsars – may produce muon neutrinos up to few hundred TeV only.
  - Magnetars - Stand out as capable of generating PeV muon neutrinos.

Looking for the sources of cosmic rays





Detection of VHE neutrinos over gamma rays

- TeV gamma ray sources - GRB, AGN, Pulsars etc. – hadronic origin.
- Gamma rays are also produced -
  - Bremsstrahlung and Inverse Compton processes by electrons – leptonic origin.
- Gamma rays – leptonic or hadronic origins !!
- Neutrinos are produced in hadronic processes and form directional beam.
- Unambiguous identification of accelerators of high-energy hadronic cosmic rays.

Pulsars/Magnetars as TeV neutrinos and/gamma rays emitters

- Magnetars and Pulsars have been proposed as potential strong sources of TeV neutrinos.

  - Zhang et al ApJ 2003; Link and Burgio PRL 2005; MNRAS 2006, Bhadra & Dey; MNRAS 2009

- Protons/heavier ions are accelerated near the surface of the pulsar/magnetar by the polar caps to PeV energies.
- They interact with the thermal radiation field of pulsar - Δ resonance states are formed.
- TeV muon neutrinos and/or gamma rays are subsequently produced from the decay of Δ states.

Galactic Magnetars as PeV neutrino and gamma ray sources

Two conditions to be satisfied:

If -

1. Ions are accelerated near the Magnetar surface by the polar caps up to 30 PeV or above.
2. Target photons/radiative background of the star are to be converted from UV-C/X photons (0.2 – 0.4 keV) to UV-A/B (0.01 keV) photons.

$$\gamma \rightarrow \gamma + \gamma$$

$$\gamma_1 \rightarrow \gamma_1 + \gamma_2 \text{ ; magnetized vacuum}$$

$$\gamma_1 \rightarrow \gamma_2 + \gamma_2 \text{ ; magnetized plasma}$$

Then,

- **Accelerated ions of energies > 30 PeV interact with the modified radiative background of a magnetar resulting an occurrence of Δ resonance state provided their energies exceed the threshold energy for the process.**

- **PeV muon neutrinos & gamma rays are subsequently produced from the decay of Δ particles.**

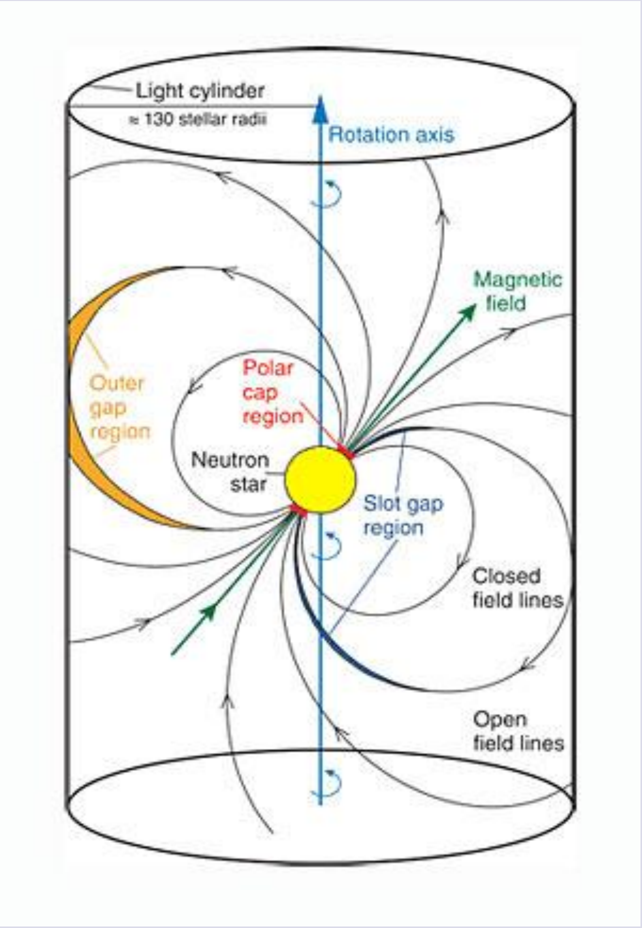
- **Constraint from PeV neutrino observation –**
  - **Some idea about the expected PeV gamma ray flux should be readily available from the neutrino observations.**

Models for acceleration of protons or ions by Magnetars

- The Polar gap model:
  - by Ruderman & Sutherland 1975.

➢ Acceleration of particles takes place in the open field line region above the magnetic pole of the neutron star.

➢ Particles are extracted from the polar cap and accelerated by large rotation-induced electric fields, forming the primary beam.



Contd..

- The region of acceleration in the polar-gap model is close to the magnetar surface.
- Two possibilities

$\Omega \cdot \mathbf{B} > 0$ electron may be accelerated

or, ✓ $\Omega \cdot \mathbf{B} < 0$ may lead acceleration of positive ions

- The maximum potential drop that may be induced across the magnetic field lines between the magnetic pole and the last field lines that opens to infinity

$$\Delta\varphi = B_s R_S{}^3 \Omega^2 / 2c^2 \sim 7 \times 10^{21}\ B_{15} P_{ms}{}^{-2}$$

$B_S = B_{15} \times 10^{15}$ G, P_{ms} is the magnetar period in millisecond.

Photomeson threshold

- The threshold condition for the production of Δ-resonance state between proton & modified radiative field interaction is

$$\varepsilon_p \varepsilon_\gamma (1-\cos\theta_{p\gamma}) \geq 0.3 \text{ GeV}^2$$

ε_p Proton energy, ε_γ photon energy

$\theta_{p\gamma}$ angle between proton and photon in the Lab frame.

- The energy of a modified radiative photon near the surface of the magnetar suffering photon splitting process in star's strong magnetic field is $\varepsilon_\gamma \sim 0.01$ keV.

- Then the threshold limit for ε_p would be ≥ 30 PeV.

Gamma ray and Neutrino production, and their fluxes.

- Gamma-rays and neutrinos are produced via Δ-resonance through the following channels

$$p + \gamma \to \Delta^{+} \to \begin{cases} p + \pi^{o} \to p + 2\gamma \\ n\pi^{+} \to n + e^{+} + \nu_{e} + \nu_{\mu} + \bar{\nu_{\mu}} \end{cases} .$$

- The charge-changing reaction takes place just one-third of the time,
- On the average four high-energy gamma-rays are produced for every three high-energy neutrinos.
- The gamma-ray/neutrino flux at the Earth from a magnetar of distance d is given by

$$\phi_{\upsilon_{\mu}/\gamma} = 2c\zeta\xi\eta f_{b} f_{s} f_{d}(1-f_{d}) n_{GJ}(R/d)^{2} P_{C}$$

The flux of muon neutrinos and gamma-rays

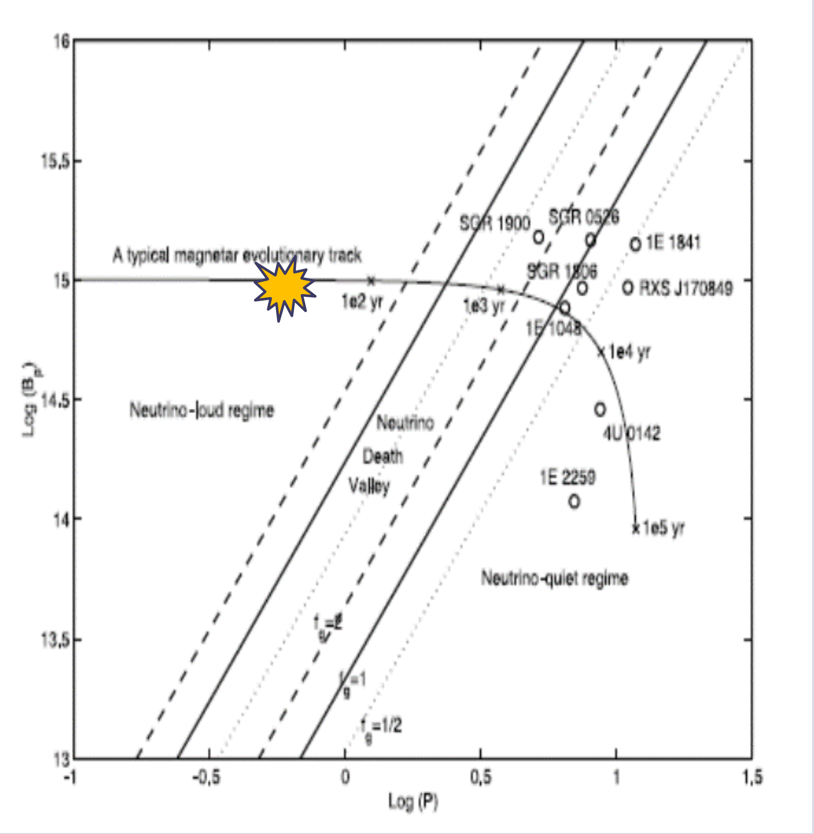
B Zhang et al., ApJ 595 (2003)

For a typical galactic magnetar:

d ~ 2 kpc, P ~ 350 ms, B_{15} ~ 1.5,
$T_{0.1}$ keV ~ 0.0255, and $f_{dc} \leq 0.10$
in both the cases when,

η_A is equal to (i) 1 and (ii) Ω R/(4c) .
We choose Z = 1 and f_d = ½, and
$f_s = 1$ here.

This type of magnetars (P = 200 – 500 ms) has not reported yet.



P-B diagram

Calculation for Energy, Flux and Event Rates

$$\epsilon_{\nu_\mu} \sim 50 \times T_{0.1\,\mathrm{keV}}^{-1}\,\mathrm{TeV} \sim 1.97\mathrm{PeV}.$$

$$\epsilon_\gamma \sim 100 \times T_{0.1\,\mathrm{keV}}^{-1}\,\mathrm{TeV} \sim 3.93\mathrm{PeV}.$$

1.02 – 3.2 PeV from IceCube (2017)

$E^2\phi_{\nu_\mu/\widetilde{\nu_\mu}} \sim 6.03 \times 10^{-10}$

$E^2\phi_\gamma \sim 48.34 \times 10^{-10}$

$GeV\ cm^{-2}s^{-1}$ for $\eta_A = 1$

$E^2\phi_{\nu_\mu/\widetilde{\nu_\mu}} \sim 0.0009 \times 10^{-10}$

$E^2\phi_\gamma \sim 0.007 \times 10^{-10}$

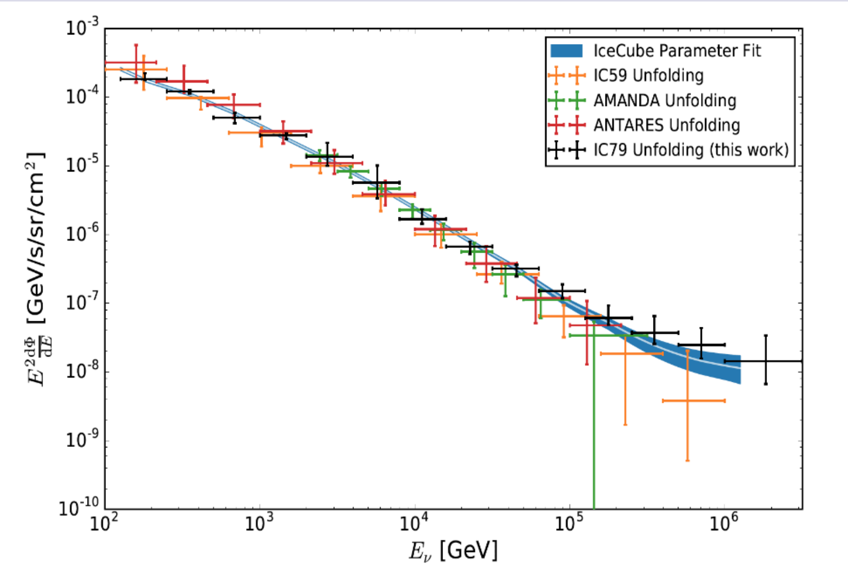
$GeV\ cm^{-2}s^{-1}$ for $\eta_A = \frac{\Omega R}{4c}$ P.C.

$E^2\phi_{\nu_\mu/\widetilde{\nu_\mu}} \sim 2.40 \times 10^{-9}$ | $GeV\ cm^{-2}s^{-1}$ from IceCube

$\frac{dN}{dAdt}(\nu_\mu \to \mu) \sim 2.5 \times 10^{-4}$ | $km^{-2}yr^{-1}$ expected event rates

Present/Future VHE Ground-based Experiments

- Model predicted PeV neutrino events and flux are much lower compared to IceCube limits with its current sensitivity.
- Next generation IceCube i.e. 'Gen2' – 10 km^3 & 75 km^2: Expected to cover these lower limits of flux of muon neutrinos.



IceCube Col. arXiv: 1705.07780

$E^2\phi_{\nu_\mu/\widetilde{\nu_\mu}} \sim 6.03 \times 10^{-10}$ case (i)

$E^2\phi_{\nu_\mu/\widetilde{\nu_\mu}} \sim 0.0009 \times 10^{-10}$ case (ii)

Concluding remarks

- If protons reach **10 - 100 PeV** energy scale in a magnetar then their interactions with **modified UV-A/B photon targets** may generate PeV neutrino events with energies between **1 - 4 PeV** as observed by the IceCube experiment.
- No possible indication of any statistically significant excess from the direction of any local magnetar **(therefore it is not found in IceCube's catalogue as a probable PeV neutrino point source to be observed in near future).**
- The present study takes into account the effect of **the photon splitting mechanisms that should modify the radiative background,** and provide an energetically favourable condition to produce the neutrino and gamma-ray fluxes at **PeV** energies.
- **Gen2 IceCube** detector and/or **upgraded HAWC Observatory** would provide opportunities to explore the possible origin of very high energy neutrinos and gamma-rays including from magnetars.

Based on

1. A Bhadra and R K Dey, ‘TeV neutrinos and gamma rays from pulsars’, MNRAS, 395, 1371 (2009).

2. R K Dey, S Ray and S Dam, ‘Searching for PeV neutrinos from photomeson interactions in magnetars’, EPL, 115, 69002 (2016).

~THANK YOU~