FRBs & Neutrinos
Modélisations multi-messagers

Quelques questions :

- Quels sont les modèles existants prédisant des émissions multi-messagers (neutrinos, gamma, ondes gravitationnelles, rayons cosmiques) liées à des FRBs ?
- Quand sont-elles émises vs le FRB ?
- Pour quels types ou populations de sources ?
- Quels modèles existent ou sont à bâtir ?

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Atelier FRB et Neutrinos **Nov 27 - 28 2023, IAP**

FRBs & Neutrinos: brief literature scan

HE neutrinos from magnetars (or others)

- Ex. ***High-energy neutrinos from magnetars***, Zhang B., Dai Z. G., Mészáros P., Waxman E., Harding A. K., 2003, https://arxiv.org/pdf/astro-ph/0210382.pdf
- Ex. ***Probing the birth of fast rotating magnetars through high-energy neutrinos***, Murase K., Mészáros P., Zhang B., 2009, https://arxiv.org/pdf/0904.2509.pdf
- Other examples **or other sources** here: https://www.lupm.in2p3.fr/users/guepin

HE neutrino production coincident with FRBs

Only a couple of recent papers

- Ex. ***Neutrino Counterparts of Fast Radio Bursts***, Brian D. Metzger, Ke Fang, and Ben Margalit, 2020, https://arxiv.org/pdf/2008.12318.pdf
- Ex. ***Neutrino emission from FRB-emitting magnetars***, Yuanhong Qu and Bing Zhang, 2022, https://arxiv.org/pdf/2111.04121.pdf

Other sources that could produce FRBs

- ***High-Energy Neutrinos from Gamma-Ray-Faint Accretion-Powered Hypernebulae***, Navin Sridhar, Brian D. Metzger and Ke Fang, 2022, https://arxiv.org/pdf/2212.11236.pdf

Production of HE neutrinos: mechanisms

$E \gtrsim 10^{12}\,\mathrm{eV}$

Production of charged pions, kaons, etc.

Interaction of cosmic rays

- hadronic and photohadronic processes: Xp, $X\gamma$ $(X = p, n, N)$
  - photohadronic process:
    - threshold $E'_p \simeq 10^{17}\,\mathrm{eV}\,(1\,\mathrm{eV}/\epsilon')$
    - neutrino energy $E'_\nu \simeq 0.05 E'_p$

Interaction of gamma rays

- $\gamma\gamma \to \mu^+\mu^-$ but expected to be subdominant w.r.t. $X\gamma$

Decay charged pions, kaons, charm hadrons → **production of HE neutrinos**

ex. $\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$

$$\downarrow$$

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

ex. $K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$

$K^\pm \to \pi^0 + e^\pm + \nu_e(\bar{\nu}_e)$

$K^\pm \to \pi^\pm + \pi^0$

Production of HE neutrinos: mechanisms

$E \gtrsim 10^{12}\,\mathrm{eV}$

Production of charged pions, kaons, etc.

Interaction of cosmic rays

- hadronic and photohadronic processes: Xp, $X\gamma$ $(X = p, n, N)$
  - photohadronic process:
    - threshold: at $\epsilon = 10\,\mathrm{keV}$, $E_p \gtrsim$ few 10 TeV
    - neutrino energy: $E_\nu \gtrsim$ TeV

} **Magnetars (cf. 2111.04121)**
Cosmic-ray acceleration?

Interaction of gamma rays

- $\gamma\gamma \to \mu^+\mu^-$ but expected to be subdominant w.r.t. $X\gamma$

Decay charged pions, kaons, charm hadrons → **production of HE neutrinos**

ex. $\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$
$\downarrow$
$e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$

ex. $K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$
$K^\pm \to \pi^0 + e^\pm + \nu_e(\bar{\nu}_e)$
$K^\pm \to \pi^\pm + \pi^0$

Production of HE neutrinos: properties I

$E \gtrsim 10^{12}\,\mathrm{eV}$

One/two zone models

Primed quantities: comoving frame, radiation region.

Properties observed signal

- variability timescale t_{var}
- bolometric luminosity L_{bol}
- spectral properties: ex. power-law with high-energy cutoff, broken power-law, black-body

+ frame change if external radiation field

↓

Properties radiation region

- typical comoving size $R' \simeq \delta\, c\, t_{\mathrm{var}}$ → or estimate typical distance from central object
- mean magnetic field $B' \simeq \left[2\,\eta_B\, L_{\mathrm{bol}} / \left(\delta^6\, c^3\, t_{\mathrm{var}}^2\right)\right]^{1/2}$ → or estimate from magnetar magnetic field
- bulk Lorentz factor Γ, viewing angle θ, Doppler factor $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$

+ transport properties if two-zone model

Production of HE neutrinos: properties II

$E \gtrsim 10^{12}\,\mathrm{eV}$

Processes

- acceleration $t'_{\rm acc} \simeq \eta_{\rm acc}^{-1} E' / (cZeB')$
- adiabatic $t'_{\rm dyn} \simeq \delta\, t_{\rm var}$
- synchrotron $t'_{\rm syn} \propto 1/(E'\, B'^2)$ + curvature radiation $t'_{\rm cur} = 3m_p^4 c^7 \rho^2 / 2e^2 E_p^3$
- photopion production $t'^{-1}_{N\gamma} = \dfrac{c}{2\gamma'^2} \displaystyle\int_0^\infty \frac{\mathrm{d}\epsilon'}{\epsilon'^2} \frac{\mathrm{d}n'_\gamma}{\mathrm{d}\epsilon'}(\epsilon') \int_0^{2\gamma'\epsilon'} \mathrm{d}\bar{\epsilon}\, \bar{\epsilon}\, \sigma_{N\gamma}(\bar{\epsilon})$

Energetics and spectrum

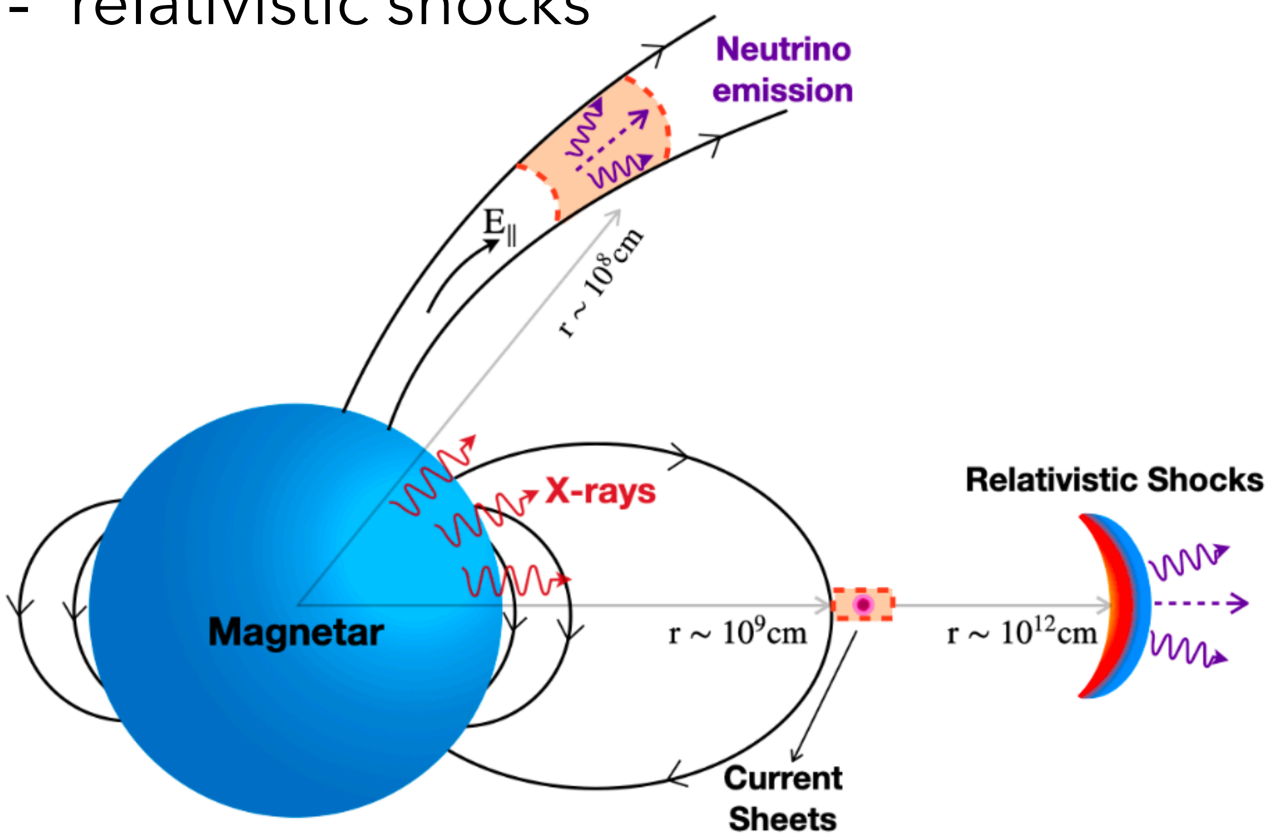
- total radiated energy U_γ and energy channeled into protons $U_p = \eta_p U_\gamma$
- energy channeled into HE neutrinos $U_\nu \simeq \eta_{\rm ch}\, f_{p\gamma}\, U_p$
    - $\eta_{\rm ch}$ depends on production channel
    - $f_{p\gamma} = \min(1,\, t'_{\rm dyn}/t'_{p\gamma})$ efficiency of photopion production
- proton spectrum, ex. power law with spectral index α_p & high energy cut-off $E_{p,\rm max}$
- photon spectrum, ex. broken power law (ex. radiation of accelerated leptons) with spectral indexes a, b and break energy $\epsilon_{\rm b}$
- $f_{p\gamma}$, secondary losses (suppression factor) and acceleration

Production of HE neutrinos: CR acceleration

From 2111.04121

Possible acceleration sites
- inner magnetosphere
- current sheet region
- relativistic shocks

Possible acceleration mechanisms
- parallel electric field
- magnetic reconnection
- Fermi acceleration



Production of HE neutrinos: CR acceleration

From 2111.04121 **Parameters? ex. estimate bulk Lorentz factor?**

Inner magnetosphere: parallel electric field $E_{\|}$

- balance between electric field acceleration and curvature radiation
- charged bunch of positrons (sign for protons!)
- 1 GHz radio waves -> estimate electric field
- net charge density, cross section, longitudinal size -> number of emitting charges
- electric potential -> maximum proton energy

Current sheet region: first order Fermi

- acceleration timescale from gyration radius
- cooling timescales, dynamic timescale: variability timescale of FRB
- competition between tacc and tdyn -> maximum proton energy
- possible additional $E_{\|}$ acceleration in inner magnetosphere not accounted for

Relativistic shocks

- propagation of Alfven waves, relativistic pancake-shape ejecta, collision with wind
- shock radius, magnetic field -> tacc versus tdyn -> maximum proton energy

More detailed estimates of shock properties from 2008.12318

Production of HE neutrinos: CR acceleration

From 2111.04121

Order of magnitude estimates

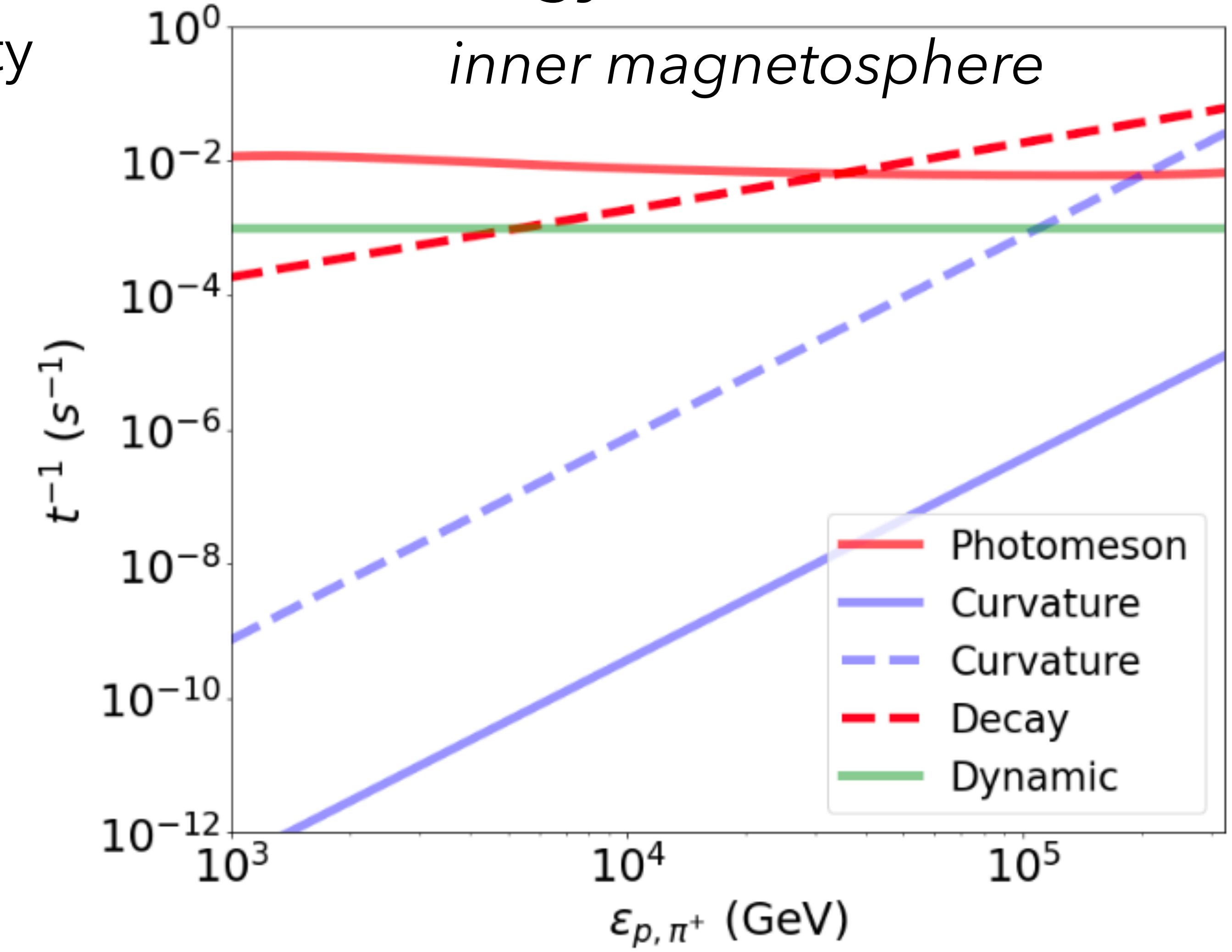
- X-ray flux -> luminosity -> energy density
- proton emission power
- neutrino emission power
- total isotropic energy of the flare
- total number of protons
- total neutrino luminosity
- total neutrino energy
- **neutrino energy fluence**

$$\epsilon_\nu^2 \phi_\nu = \frac{E_\nu}{4\pi D^2}$$

@10kpc

$$\simeq \begin{cases} (3.35 \times 10^{-6}\ \mathrm{erg\ cm^{-2}}\ \text{, or } 2.1 \times 10^{-3}\ \mathrm{GeV\ cm^{-2}}) \\ \quad \times\, \epsilon_{\rm acc} r_8^{-2} \gamma_{p,3}^2 L_{\rm X,40} E_{\rm flare,41} f_{g,0}^2 D_{\rm 10kpc}^{-2} \\ (6.96 \times 10^{-10}\ \mathrm{erg\ cm^{-2}}\text{, or } 4.3 \times 10^{-7}\ \mathrm{GeV\ cm^{-2}}) \\ \quad \times\, \epsilon_{\rm acc} P^{-2} \gamma_{p,3}^2 L_{\rm X,40} E_{\rm flare,41} f_{g,0}^2 D_{\rm 10kpc}^{-2} \\ (2.94 \times 10^{-13}\ \mathrm{erg\ cm^{-2}},\ \text{ or } 1.8 \times 10^{-10}\ \mathrm{GeV\ cm^{-2}}) \\ \quad \times\, \epsilon_{\rm acc} \Delta t_{-3}^{-2} \Gamma_2^{-4} \gamma_{p,3}^2 L_{\rm X,40} E_{\rm flare,41} f_{g,0}^2 D_{\rm 10kpc}^{-2}. \end{cases}$$

Energy-loss timescales



Production of HE neutrinos: CR acceleration

From 2111.04121

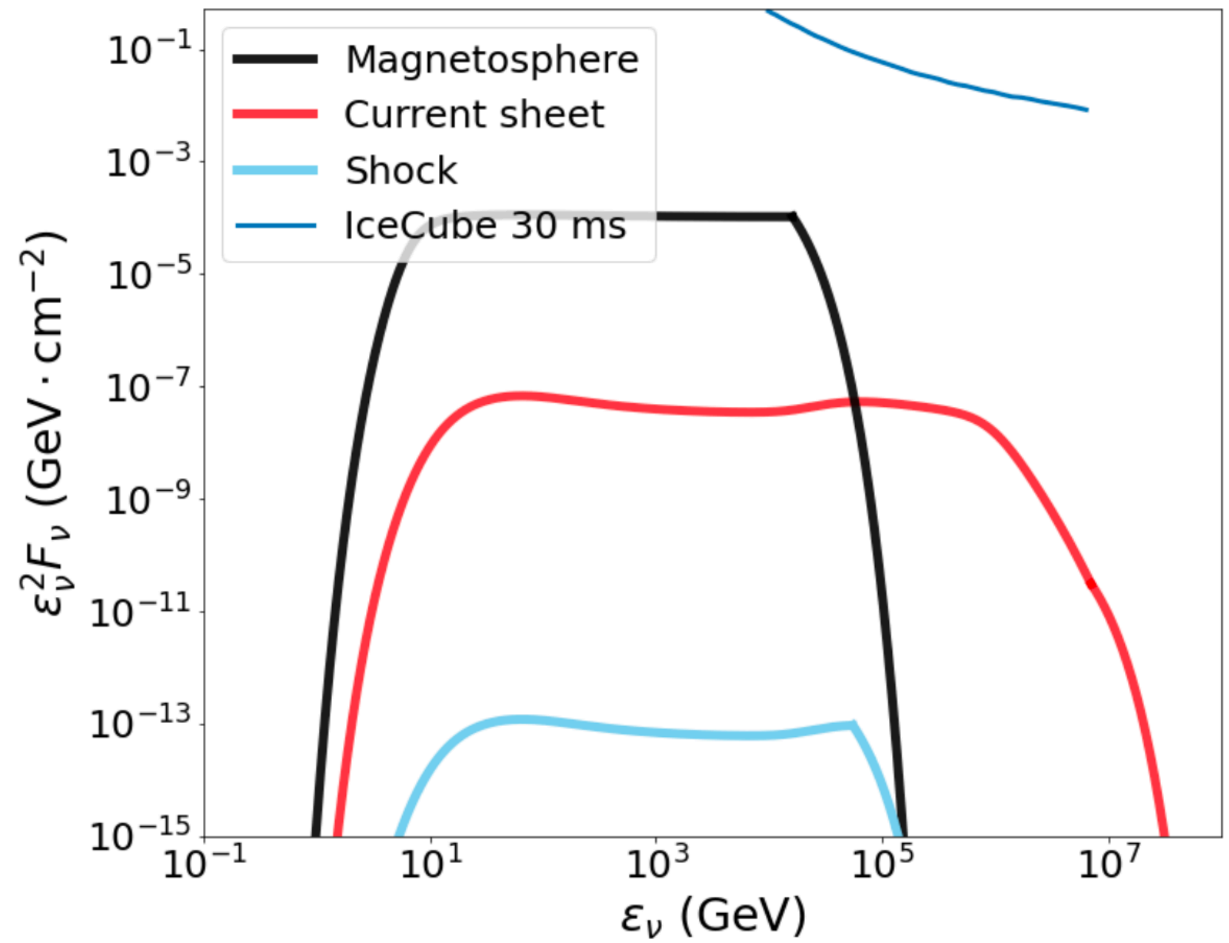
Spectra estimates

- cooling timescales
- suppression factors for protons
- for pions
- case of FRB 200428

Could be clarified

- energy losses of muons?
- acceleration and dynamical timescales
- particle propagation?
- …

Neutrino spectra



Galactic FRB detectable by IceCube?

Only if the burst is: 3 orders of magnitude more energetic and 2 orders of magnitude closer than FRB 200428

Production of HE neutrinos: CR acceleration

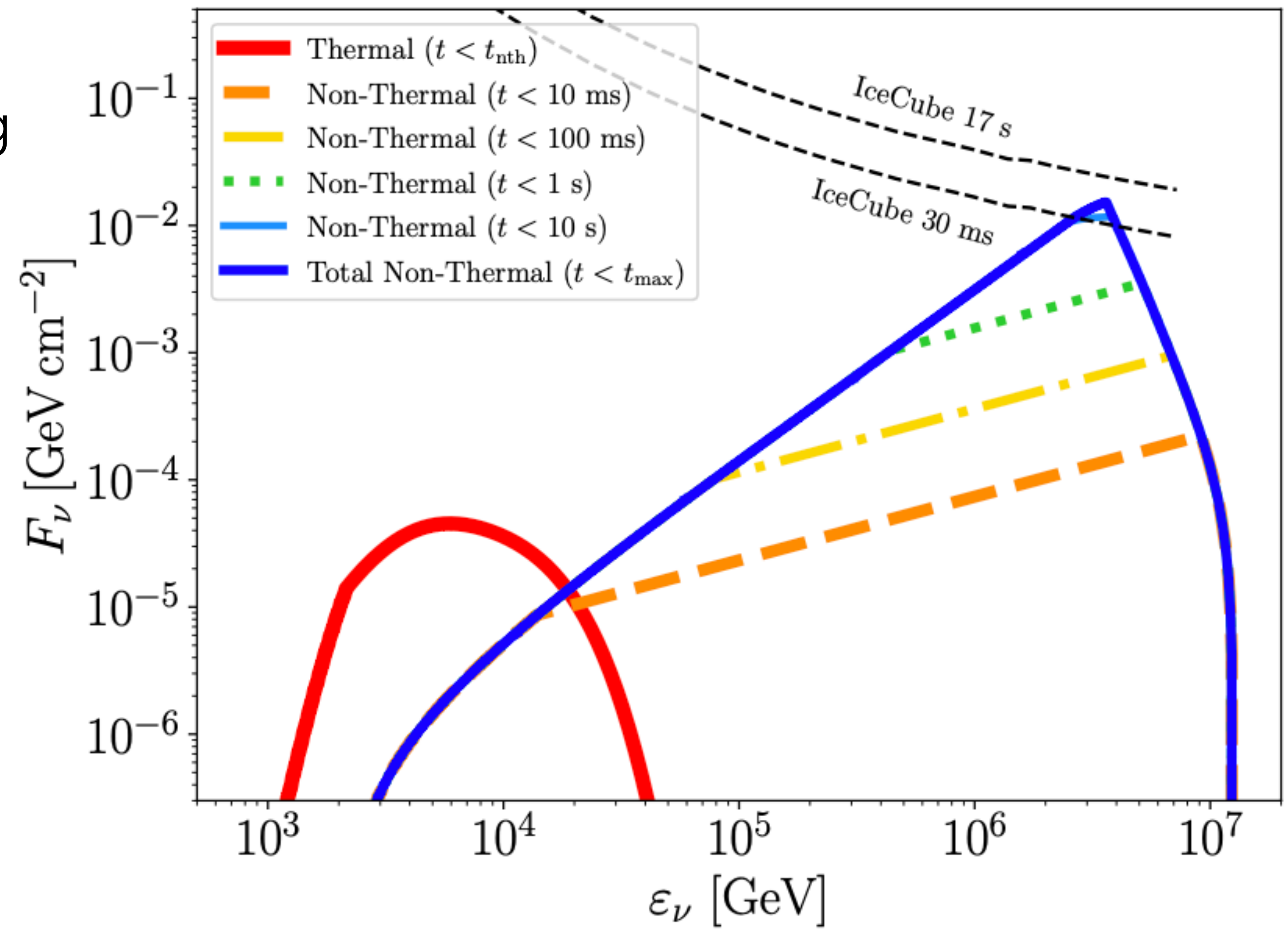
From 2008.12318

Spectra estimates

- burst of ~ TeV−PeV neutrinos
- total energy Ev ≈ 10^35 – 10^44 erg
- timescale tmax ~ 0.1 – 1000 s
- following the radio burst

- prospects at higher energies?
- requires further proton acceleration

Neutrino spectra



Conclusions / perspectives

General comments

- HE neutrinos from magnetars (and others!): various models in literature (BNS mergers)
- HE neutrino production coincident with FRBs: only a couple of recent papers
  - Focus photohadronic interactions
  - Detection prospects for HE neutrino associated with FRBs are low
  - Same for UHE gamma rays (attenuation)
  - More multi-wavelengths observations would be beneficial (parameters) -> when?

HE neutrino emission timescales: require specific model
But now: many uncertainties (many source types)

Some ideas from 2111.04121
Inner magnetosphere and current sheet models could be more detailed: acceleration mechanisms, dynamical timescale estimates, include trajectories of protons, detailed X-ray emission modeling etc.

Other ideas
General models, start from your favorite FRB production model
Better understanding / modeling of interaction backgrounds