Fast Radio Burst Sources and Neutrinos in the Multi-Messenger Context

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Cosmic Rays and Neutrinos in the Multi-Messenger Context

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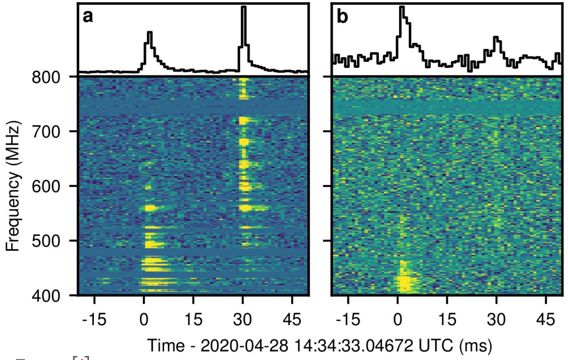
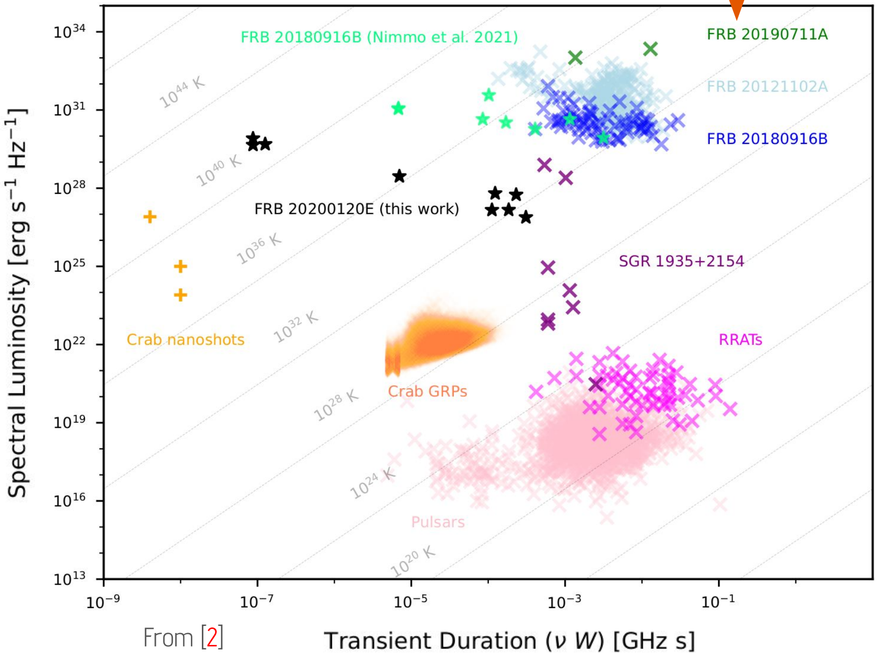
Disclaimer: Slides are really dense (you can find them online), follow the sign that indicates the key information of the slide

Fast Radio Bursts context



From [1]

- Most energetic radio signal ever detected: E_{iso} ~10^{35}–10^{43} erg
- Extremely short (~ms), with μs sub-structures
- Most coherent emissions in the Universe ⇒ Non-thermal mechanism



From [2]

Which population of sources can produce such features?

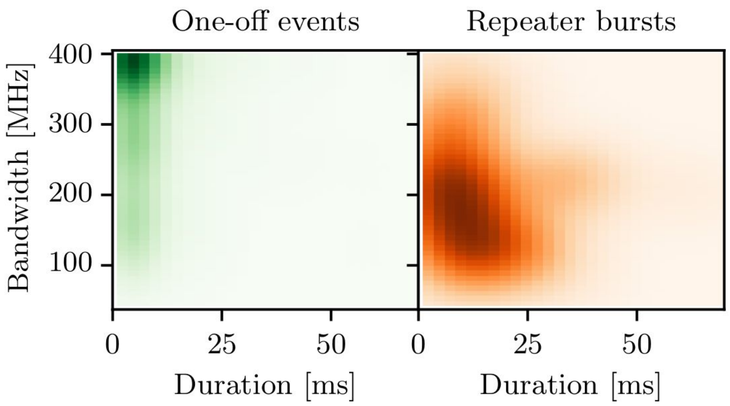
Total number of detected FRBs from the online catalogue Blinkverse

816	67	749	48
Total FRBs (source)	(8.21%) Repeaters	(91.79%) Non-repeaters	(5.88%) FRB Hosts

Fast Radio Bursts context

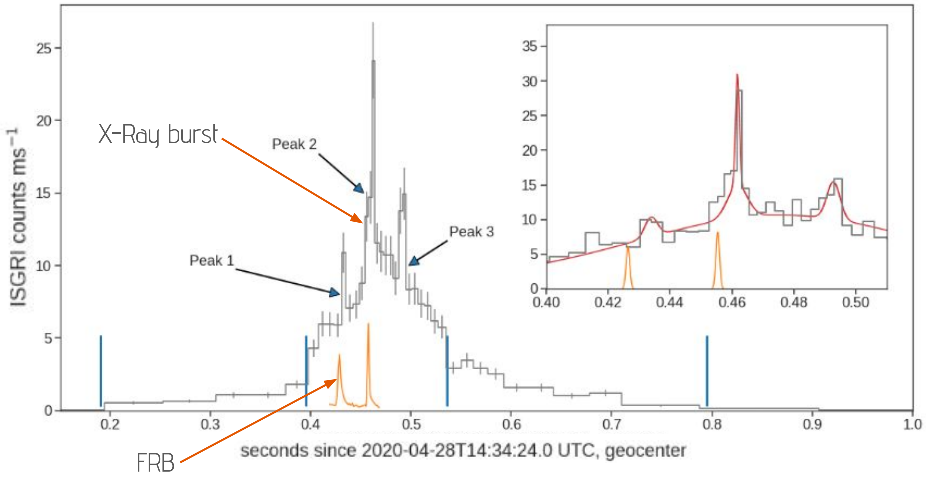
- 2016: Discovery of first repeating source [3]
- Repeater bursts are random, often clustered together
- **Repeaters** seem statistically different from the **One-off** FRBs

Smoothed distributions of FRB per category in duration and bandwidth (from [4])



- April 28, 2022: Hard X-Ray Burst (HXRB) detected in coincidence with galactic FRB coming from **magnetar SGR 1953+2154** [5]

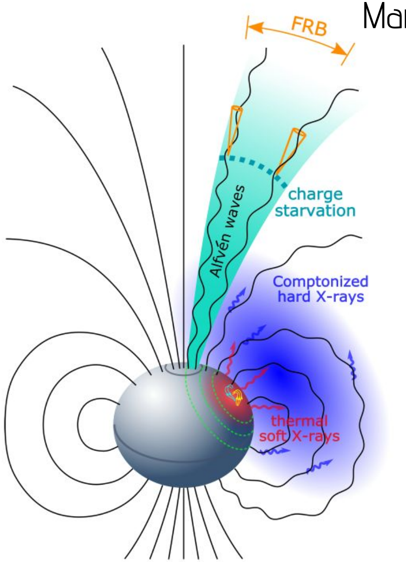
Lightcurve of the HXRB measured by INTEGRAL (from [5])



Hypothesis of the magnetar source strongly favored!

Fast Radio Burst Models

Many models emerged to explain FRB emissions [6,7]. They mostly fall into two categories:



Magnetospheric model (from 8])

Magnetospheric models

Magnetically powered

Mechanisms

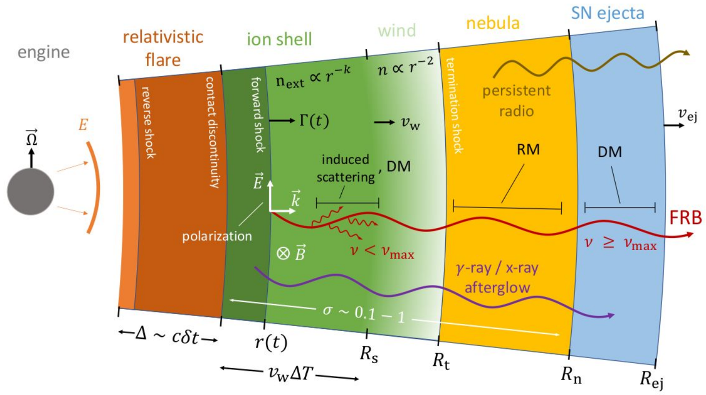
Curvature radiation of bunches
Mag. Field Lines Reconnection
"Pulsar mechanism"
Inverse Compton Scattering
…

Sources

Magnetars
Neutron Star mergers
Neutron star with companion
(asteroid, White Dwarf)
…

Shock/ejecta models

Powered by quakes or wind



Shock model (from [9])

Mechanisms

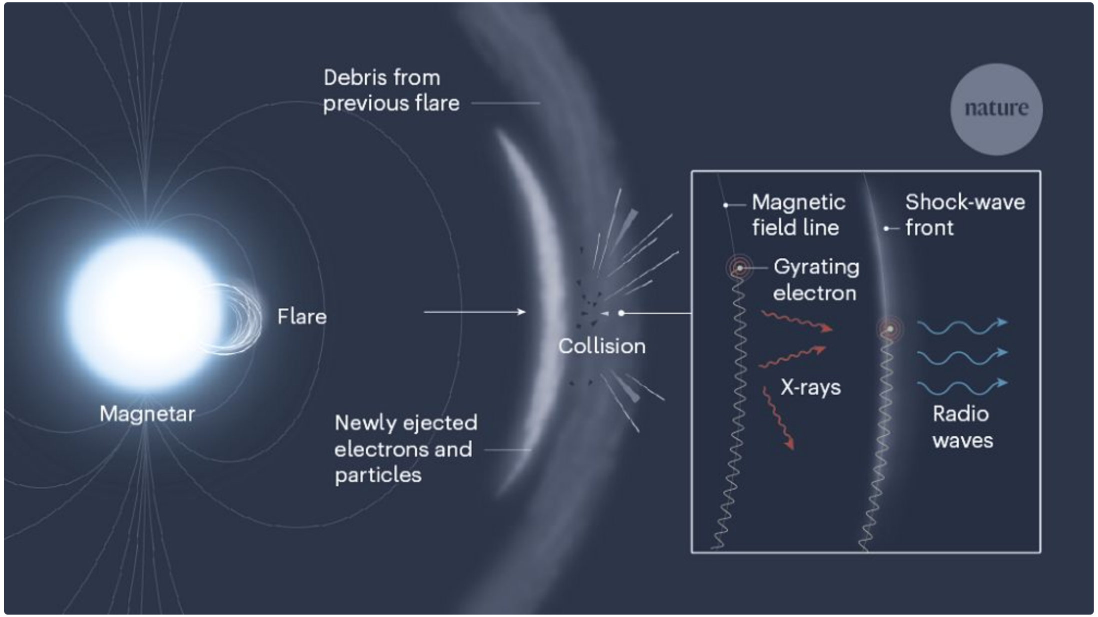
Maser
Mag. Field Line Reconnection
Plasma Laser
…

Sources

Magnetars
Black Holes
BH - NS merger
NS - WD merger
Axion stars / Quark stars / …

- Both Shock & Magnetosphere models involve **dense**, **highly magnetized media** ⇒ High Energy counterparts

- High Energy Neutrino counterpart?
  - Can escape dense media
  - Missing piece of the FRB puzzle?



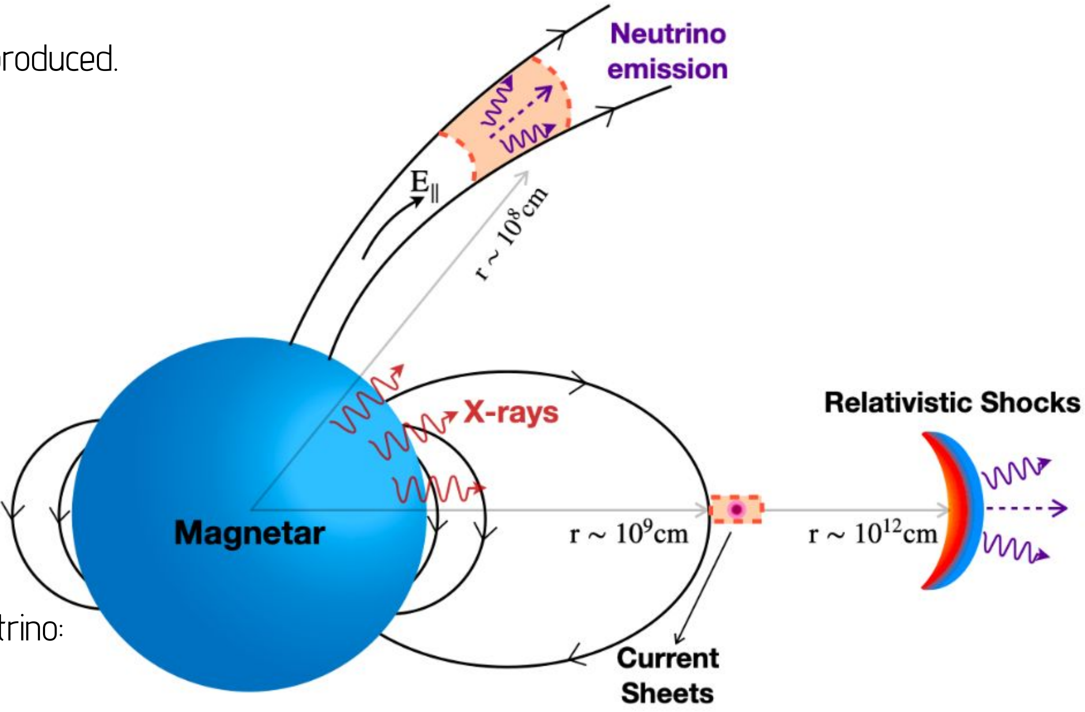
FRB mechanism from a magnetar (from [10])

❖ Some models [11-13] postulate the emission of neutrinos from magnetars (without assuming any FRB emission model):

- HE Neutrinos need a hadronic component to be produced. With pion production, $E_\nu \approx 0.05\, E_p$

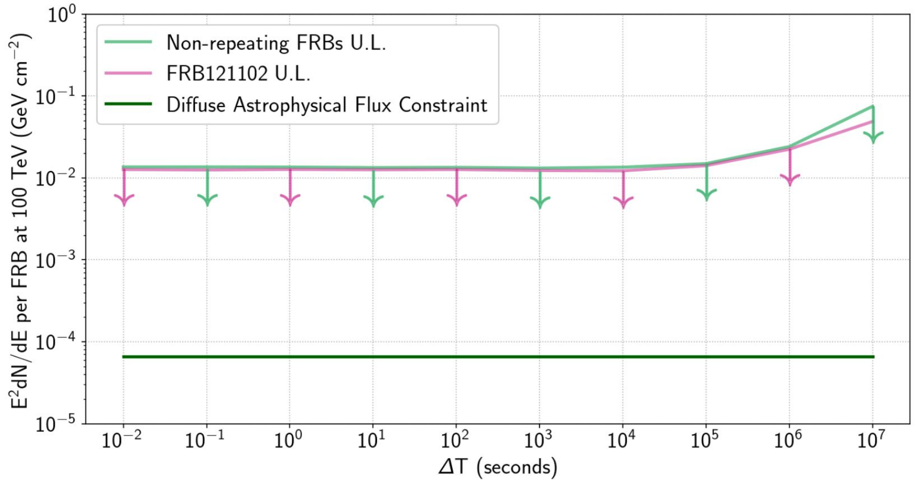
- 3 emission sites (and associated mechanism) [14]

- Problem of the time delay between FRB and neutrino:
  - ➢ Are they from the **same mechanism**?
  - ➢ Emitted **simultaneously**?



Emission sites for a possible neutrino production in magnetars. The magnetosphere, the current sheets and relativistics socks region are studied. From [13]

- FRB-Neutrino search in experiments: Looking for spatial and temporal coincident neutrino candidates
  - ANTARES: 12 One-Off FRBs studied [15] ⇒ Flux Upper Limit ~1 GeV.cm^{-2} @ 100 TeV
    - ➢ New bursts since, Larger detector
  - IceCube: 4, 13, and 28 FRBs studied [16-18] ⇒ Flux Upper Limit ~10^{-2} GeV.cm^{-2} @ 100 TeV
    - ➢ New bursts since, Different sky coverage
- Let's try with KM3NeT!



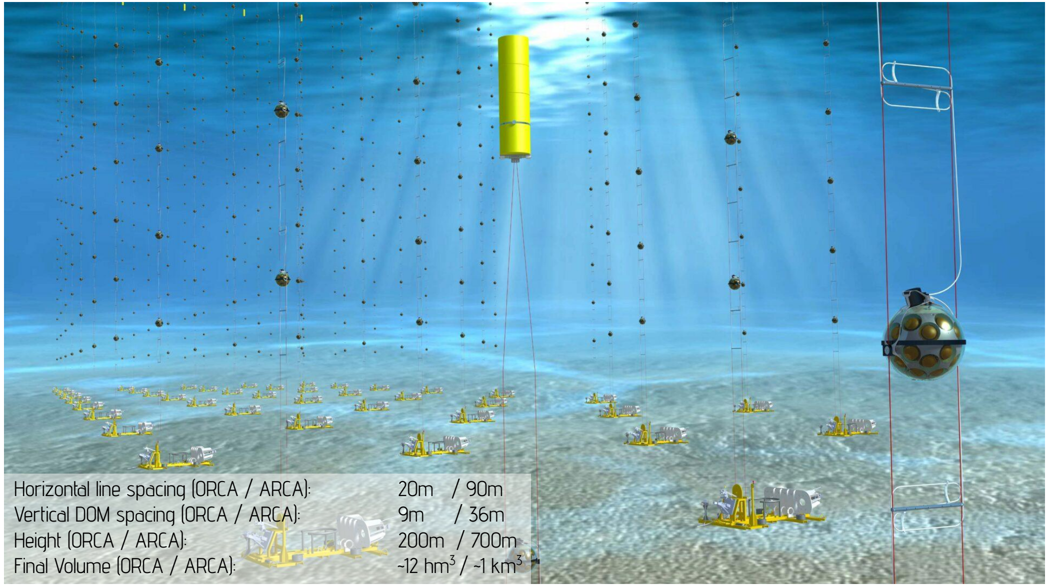
Upper limits on a neutrino flux coming from FRB sources (from [18])

Neutrino candidates in KM3NeT data

❖ KM3NeT is a neutrino telescope in the Mediterranean Sea (see Aart's presentation tomorrow!)

➢ Detects atmospheric and cosmic neutrinos with the Cherenkov light from their interactions products

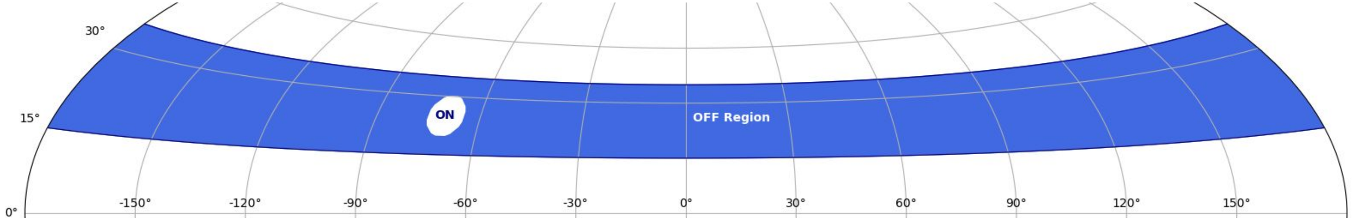
➢ KM3NeT/ARCA aims an angular resolution of ~ 0.1° at 1 TeV, most sensitive in the 100 GeV – 1 PeV range [19]



➢ KM3NeT/ORCA and KM3NeT/ARCA under construction, finished in the 2030's

- Analysis Strategy: **Spatial** and **Temporal correlation**
  - **Time Window of 1000 seconds centered around the FRB time**
  - On/Off search: **OFF** region to estimate with large statistics the background in the **ON** region.

    The ON region size is determined with the detector's angular resolution
  - **250 FRBs** studied with different configurations of **ORCA** & **ARCA**, from 2020 to 2024



- Results: Come see my poster!

References

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Backup

Fast Radio Burst Models

Many models emerged to explain FRB emission [6]. They mostly fall into two categories: **Shock/ejecta** models and **Magnetospheric** models

- (Supermassive) Black Holes
- Blitzars
- Stellar flares
- Exotic objects: strange quark stars, Primordial Black Holes, superconducting cosmic strings, White Holes
- Alien technology (light sails)
- Binary Mergers with NS/WD/BH

❖ The models involving a Neutron star or a magnetar are studied in depth:

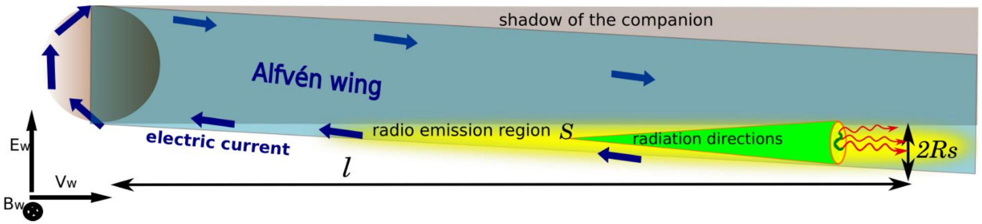
- Magnetar with companion: White dwarf, Asteroid colliding or orbiting
- **Magnetars alone**

❖ Magnetars: young neutron stars with intense magnetic fields [7]:

- **Twisted magnetospheres** with **B** $\gtrsim 10^{14}$ G creating flares
- Magnetically-powered emissions
- Rotation periods ~s

Impression of a strange quark star emitting a FRB, by the AI leonardo.ai

Fast Radio Bursts mechanisms



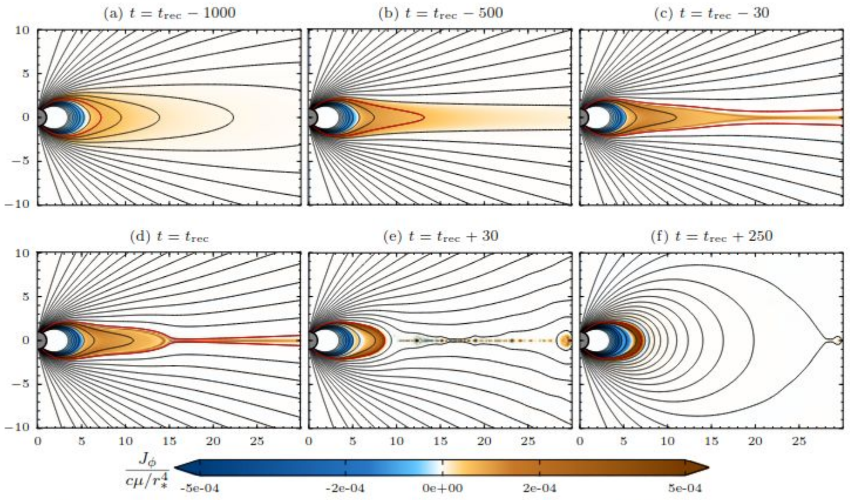
- ❖ Reconnection of magnetic field lines
- ❖ Maser in distant relativistic shocks
- ❖ Curvature radiation by bunches of leptons
- ❖ Collimated Alfvén Wave trail (*Wing*) creates coherent ra
- ❖ Inverse Compton Scattering by bunches
- ❖ Free Electron Laser

All of these mechanisms involve highly magnetized and relativistic plasma: it matches really well a **magnetar progenitor** [8]

- ❖ Magnetars: young neutron stars with intense magnetic fields [7]:
  - **Twisted magnetospheres** with **B** $\gtrsim 10^{14}$ G creating flares
  - Magnetically-powered emissions

Rotation periods ~s

The rate of magnetic flares is compatible with the expected FRB rate



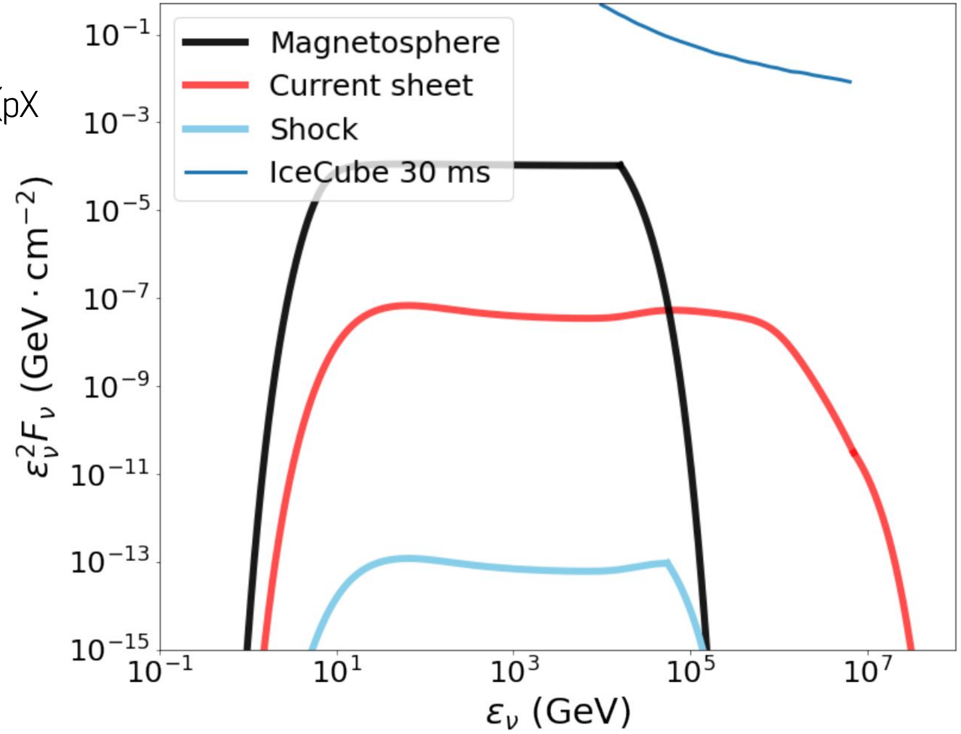
Description of the current sheet formation and magnetic reconnection. The black lines are the field lines, and the color show the toroidal current density. Reconnection begins at t_{rec}, figure (d). From [9]

- Some models postulate the emission of neutrinos from magnetars (without assuming any FRB emission model):

- HE Neutrinos need a hadronic component to be produced (pX or pγ, where X = p,n,N). With pion production, $E_\nu \simeq 0.05\ E_p$
  - Photopion processes: $p + \gamma \rightarrow \pi^\pm + n$ or $\pi^0 + p$
  - Hadronic processes: $p + X \rightarrow \pi^\pm + Y$
  - Gamma-ray interactions (subdominant): $\gamma + \gamma \rightarrow \mu^+ + \mu^-$
    - Then $\pi^\pm \rightarrow \mu^\pm + \nu_\mu\ (\overline{\nu_\mu})$
    - And $\mu^\pm \rightarrow e^\pm + \nu_e\ (\overline{\nu_e}) + \overline{\nu_\mu}\ (\nu_\mu)$

- 3 emission sites (and associated mechanisms):
  - Magnetosphere (‖ **E** field acc.)
  - Current sheets (Fermi First Order acc.)
  - Relativistics shocks (Alfvén waves)

- Consider the time delay between FRB and neutrino:
  - Are they from the same mechanism?
  - Are they emitted simultaneously?



Expected flux from the magnetar SGR 1935+2154, with the neutrino energy derived from the X-ray energy (E_γ=100 keV). For this model, $E_{iso}=10^{41}$ erg, B=2.2 × 10^{14} G and D_L =10 kpc. From [14]