Modèles FRBs : une revue partiale et partielle.

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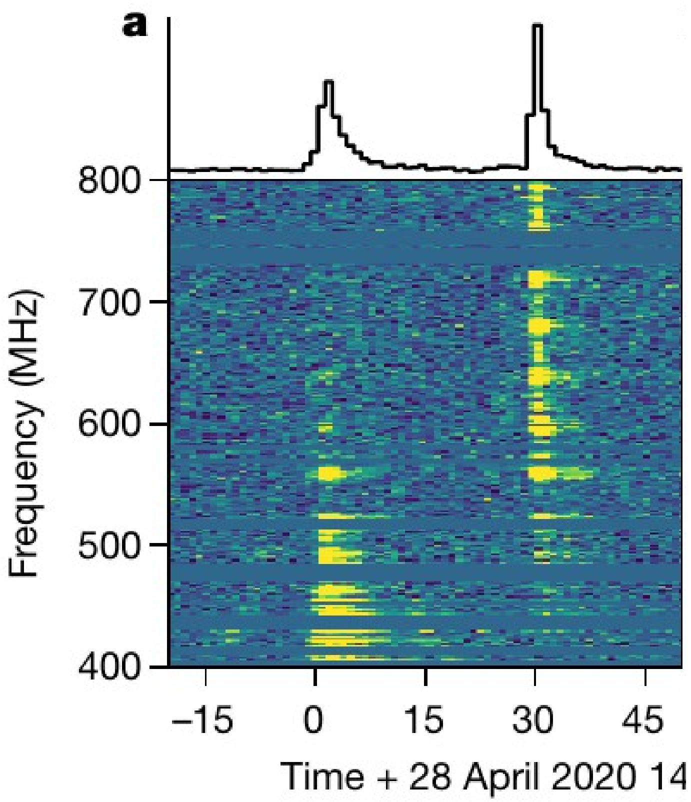
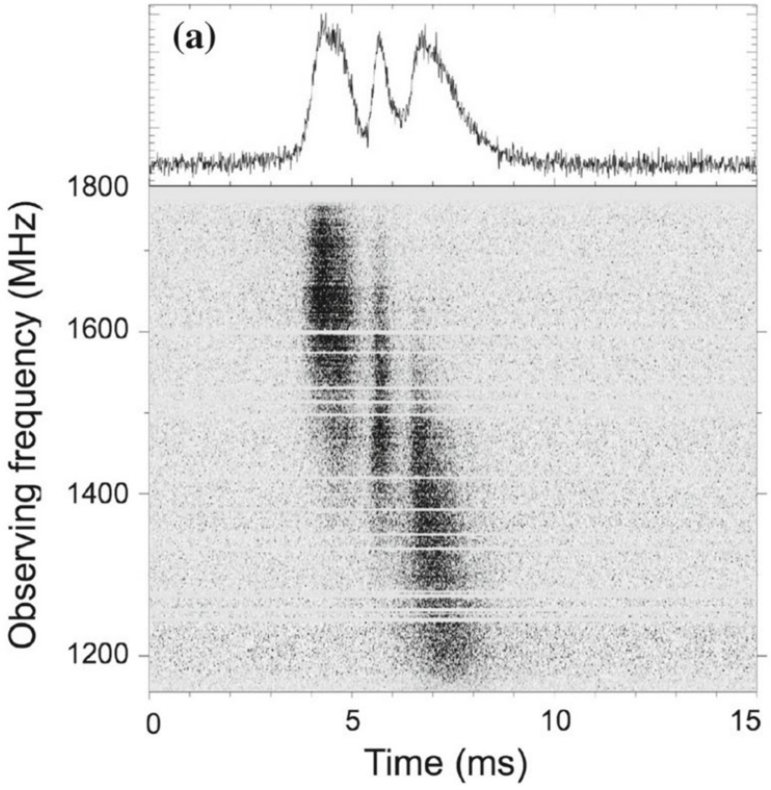
Fast radio bursts

One-off : broad-band and shorter



FRB200428, (Chime/FRB 2020b)

Repeaters : narrow-band, longer, downward-drifting sub-bursts

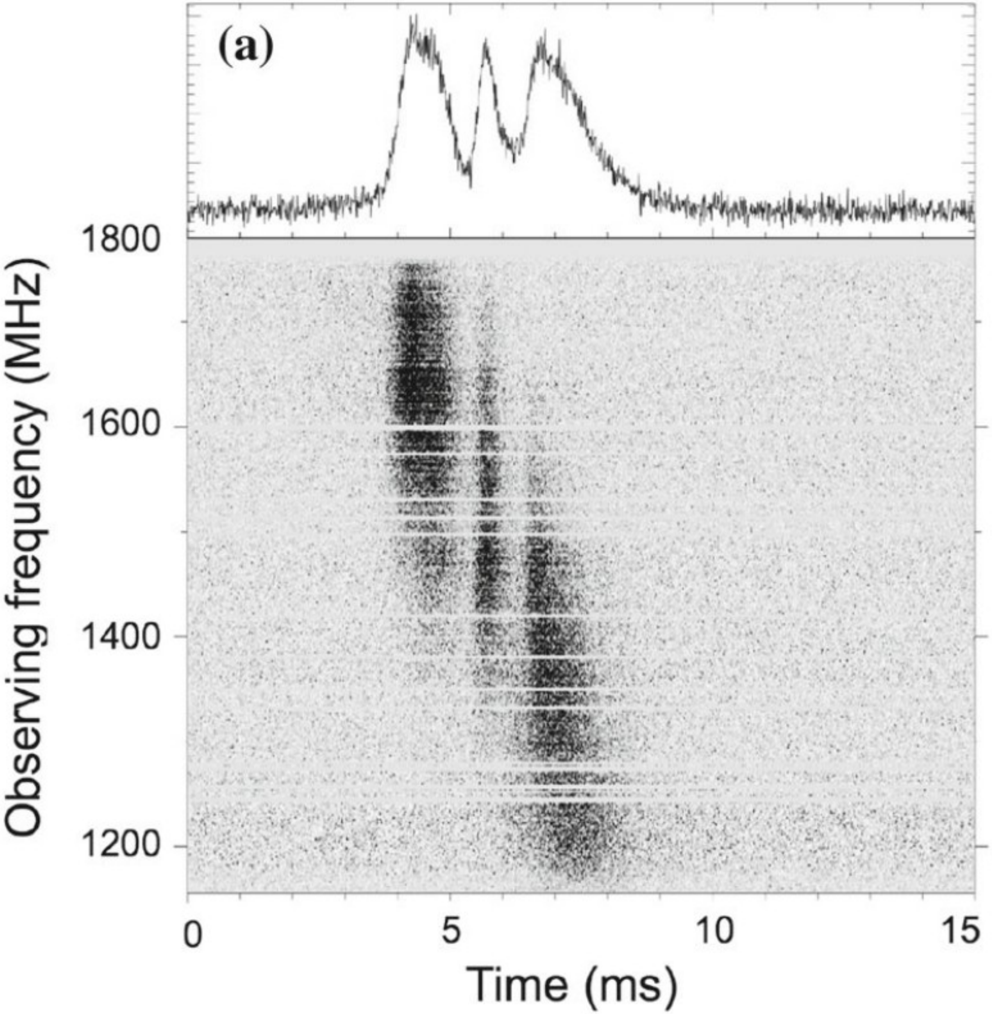


FRB121102, Hessels+18

Fast radio bursts

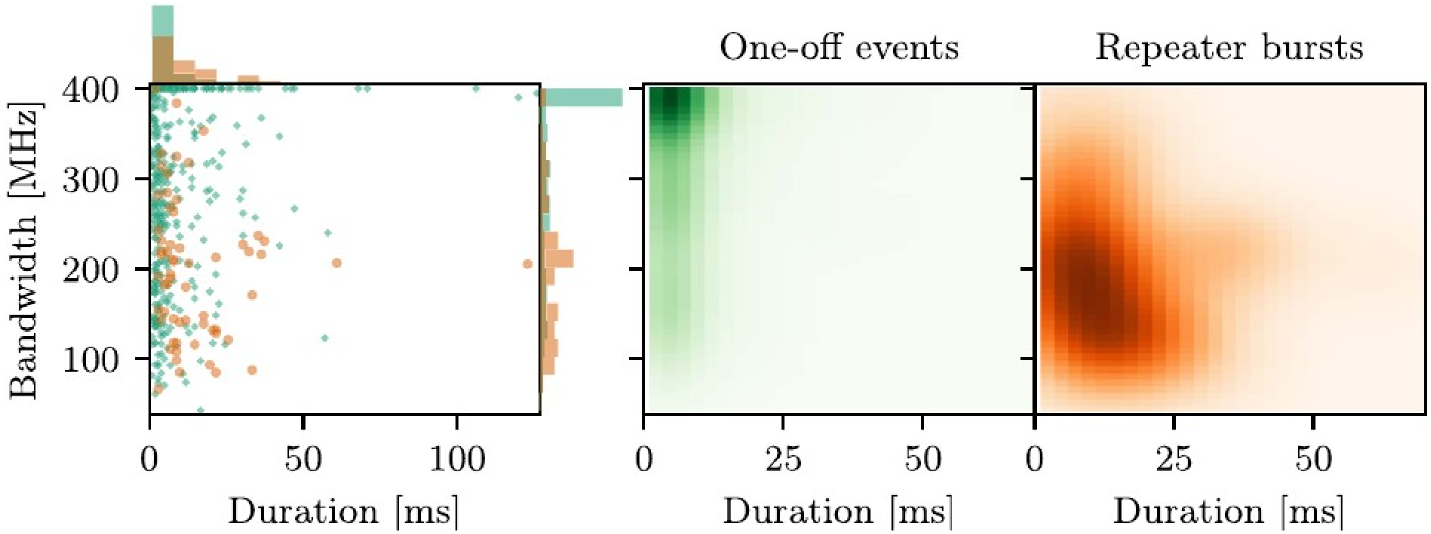
FRB121102, Hesseels18

- Extragalactic DM/distance
- Intense : >> 10^{23} erg/Hz/s, brightness temperature >> 10^{30} K
- Fast : a few ms with ~10µs substructures
- Bandwidth : narrow (repeaters) / wide (one-off)
- Repeaters : Downward drifting subpulses
- Repeaters : clustered, but clusters are Poisson distributed (Cruzes+20)
- Polarisation :
  - ➔ Mostly or totally linear
  - ➔ No clear trend on Faraday rotation (across sources)
  - ➔ Moderate or no swing



State of the art (more or less)

- Statistical distributions: occurrence times, bandwidth/duration correlations...
- Physical constraints on observables are broadly averaged quantities: flux, duration, bandwidth, frequency drift..
- Burst morphology fitted with empirical functions (e.g. Gaussian).



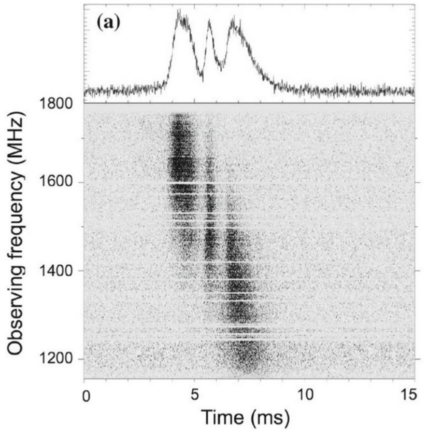
Pleunis+ 2021

Some observational constraints

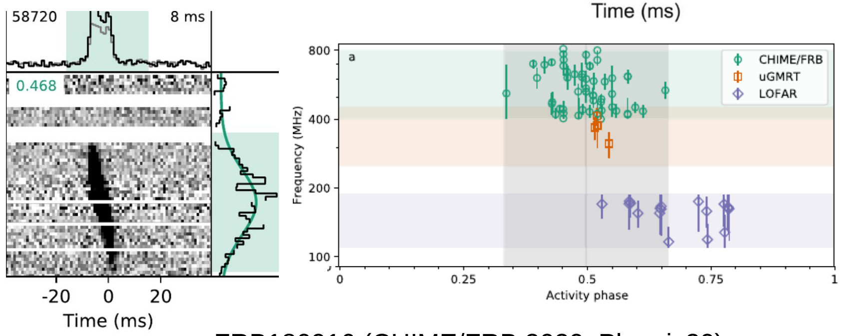
Celebrities

- **FRB121102** : the <u>loud</u> one
  - ➔ Up to 30 bursts/hour
  - ➔ 1 Gpc
  - ➔ Very high RM (10^5 rad/m^2)
  - ➔ Persistent radio counterpart
  - ➔ periodic with period 160 days

FRB121102, (Hessels18)

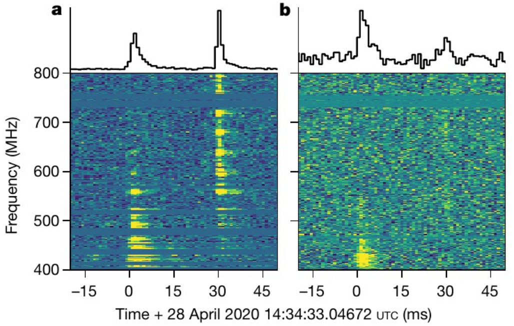


- **FRB180916.J0158+65** : the <u>periodic</u> one
  - ➔ 16 days periodicity with 5 day activity window
  - ➔ Star-forming region



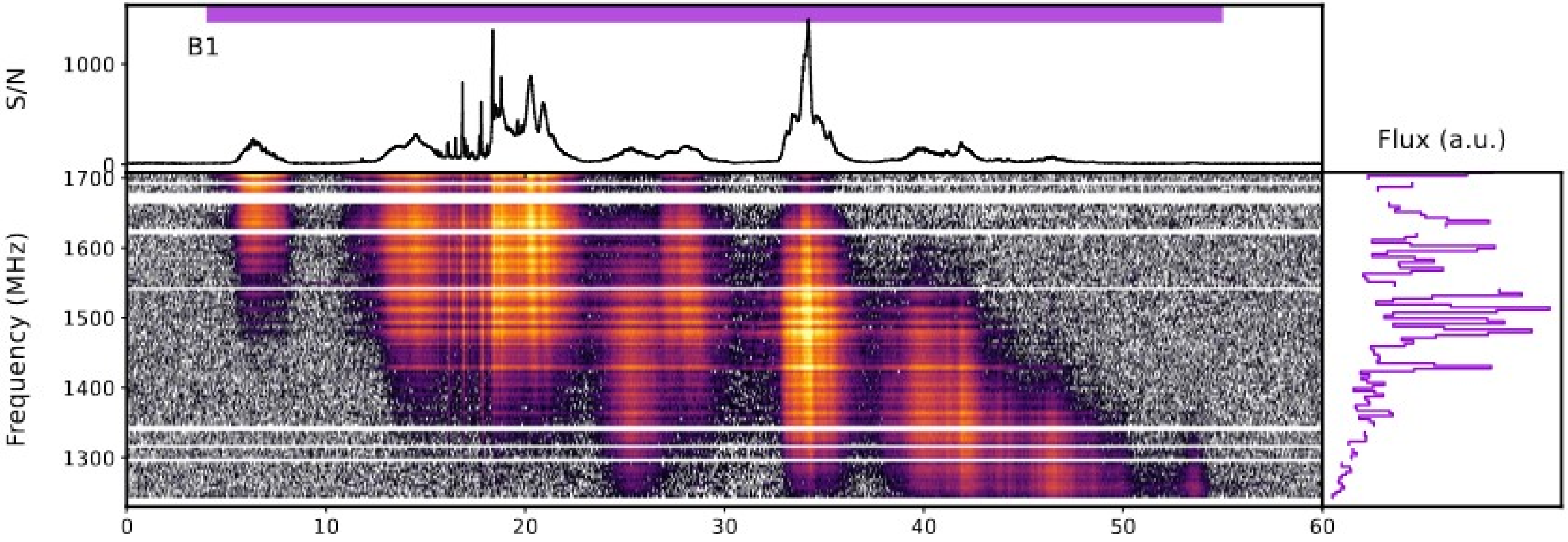
FRB180916 (CHIME/FRB 2020, Pleunis20)

- **FRB200824.SGR1935+2154** : the <u>Galactic</u> one
  - ➔ Low luminosity
  - ➔ (but 10^3 brighter than other magnetars)
  - ➔ X-ray counterpart (Magnetar flare)



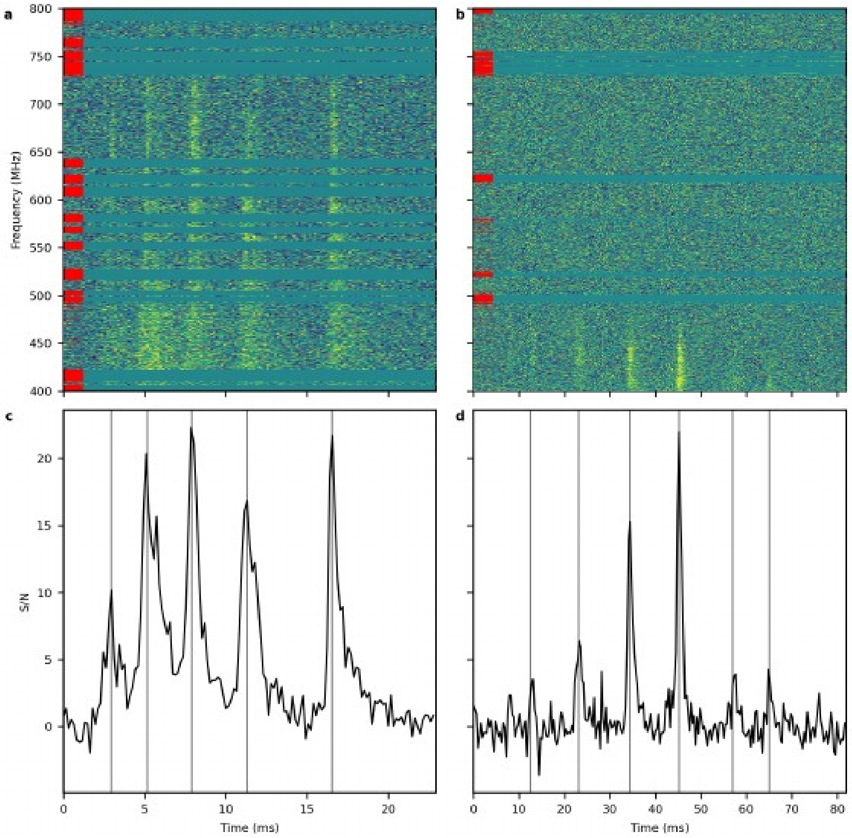
FRB200428, (Chime/FRB 2020b)

High burst density event

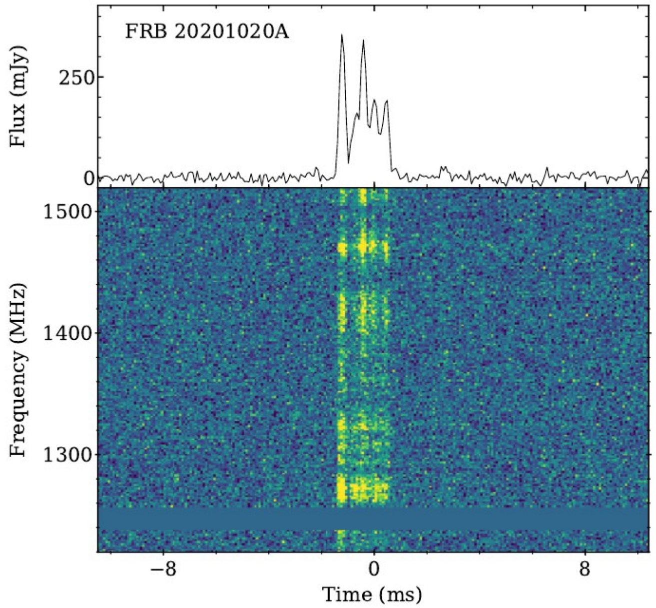


“Dense Forests of Microshots in Bursts from FRB 20220912A”, Hewitt+2023

Sub-second periodicity



FRB 20191221A: 9 bursts with period ~216 ms @6.5sigma, (CHIME/FRB Collaboration, Nature 607, 2022)



FRB20201020A: 5 bursts with period 0.4ms@2.2sigma (Pastor-Marazuela+ 2023)

Models

Overview of the model maze

- Asteroids + Neutron star (NS)
- White dwarf – Neutron star (NS)
- Giant pulses (Young pulsars)
- Magnetar
  - ➔ Shock wave
  - ➔ Magnetospheric
- Pulsar – O/B star close binary (or combed NS)
- Flare stars
- Catastrophic events (mergers...)
- Plasma lensing
- Blitzars
- Cavitons (AGNs)
- (Even more) exotic :
  - ➔ Quark novae
  - ➔ Axion stars
  - ➔ Light sails (aliens)
  - ➔ ...

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- **Asteroids + Neutron star (NS)**
- **White dwarf – Neutron star (NS)**
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- ~~Catastrophic events (mergers...)~~
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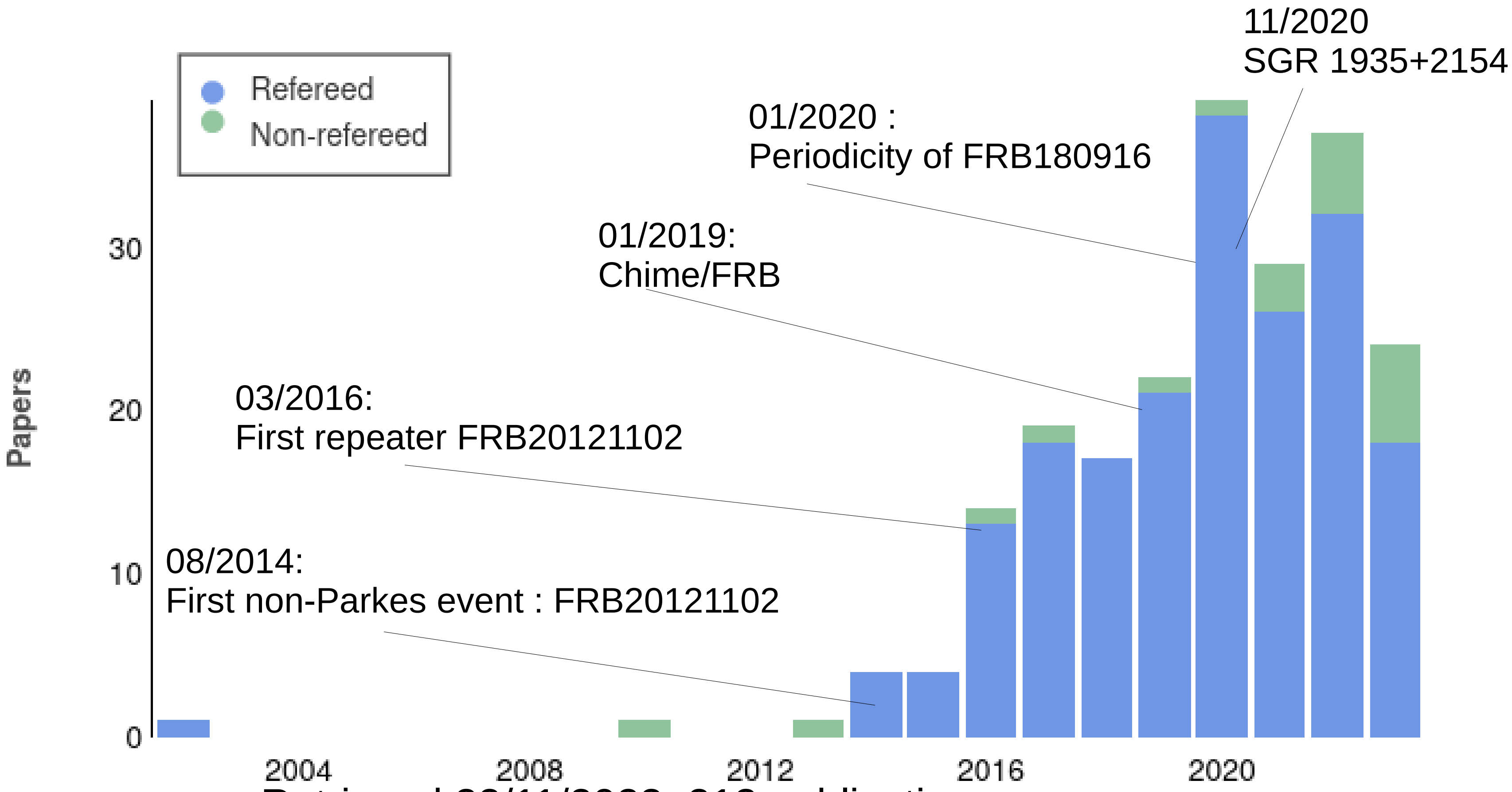
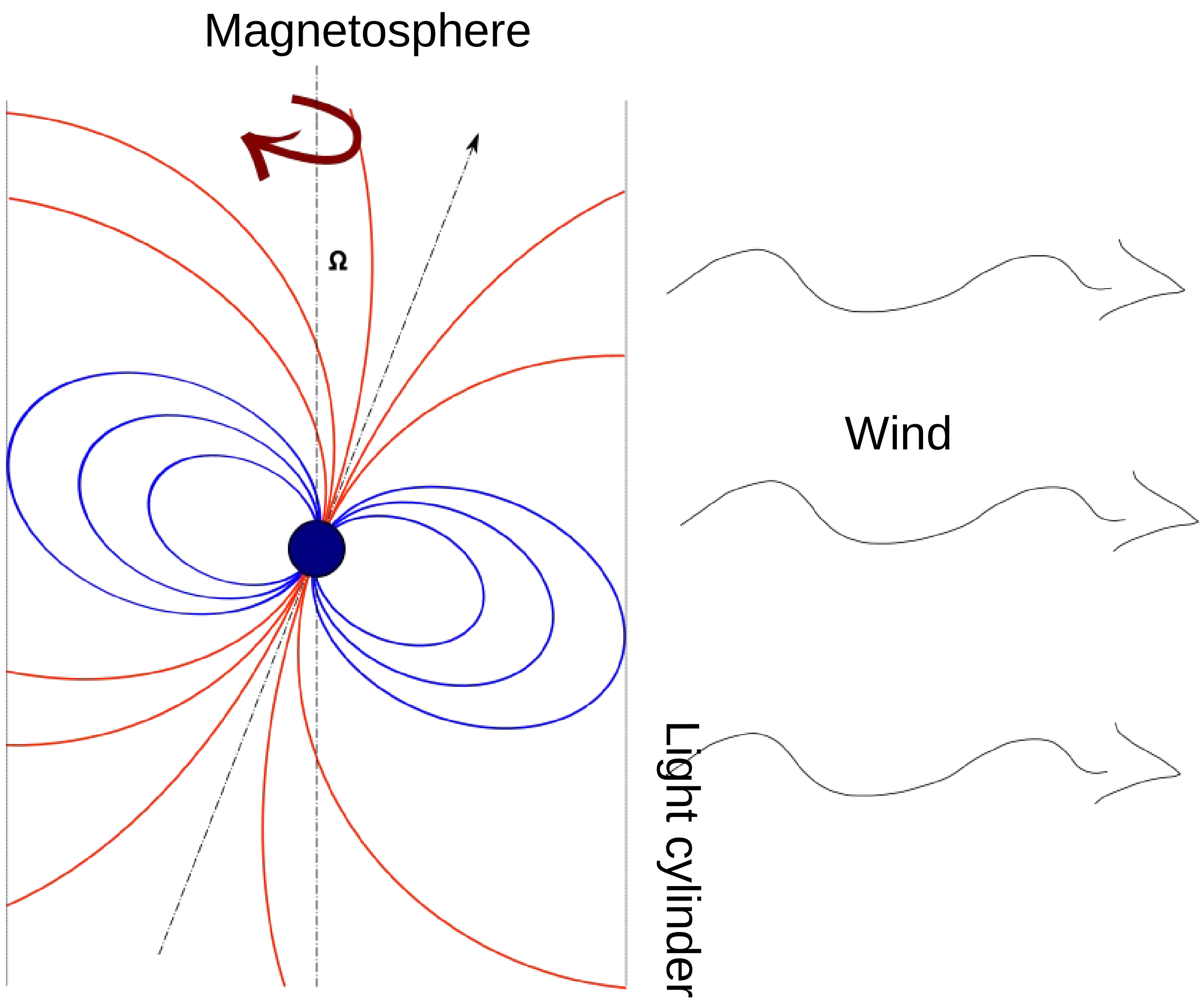
Bibliography on FRB models



Retrieved 22/11/2023, 213 publications,

https://ui.adsabs.harvard.edu/public-libraries/0wJ4Jgh8RtuboZNzlkONMg

Neutron star magnetosphere/wind



In magnetars:

- “*Twisted magnetosphere*” : Strong toroidal magnetic field
- Magnetic field : $10^{12} – 10^{16}$ G
- *Star quakes* (responsible for magnetar flares)
- Magnetically-powered emission (vs rotation-powered for pulsars)
- Rotation period ~ few seconds for “normal” magnetars

Energetics: basic definitions

Inspired by Metzger+2017

- FRB luminosity:

Beaming factor (radio)

$$L_{\rm FRB} = \frac{f_b}{f_r} L_{\rm iso\ radio} \sim 10^{42} {\rm erg/s}$$

Radio fraction

Isotropic equivalent radio luminosity

- FRB energy :

$$E_{\rm FRB} \sim L_{\rm FRB} \Delta t \sim 10^{39} {\rm erg\ with\ } \Delta t \sim 1{\rm ms}$$

Energetics : spin-down power (pulsar-like)

Inspired by Metzger+2017

- Magnetar with P = 1ms at birth has spin-down timescale :

$$t_{\rm sd} \simeq 5 \left(\frac{B}{10^{14}{\rm G}}\right)^{-2} \left(\frac{P}{1{\rm ms}}\right)^{2} {\rm days} \rightarrow {\rm P} \sim 27{\rm ms\ after\ 10yr}$$

- Spin-down luminosity after 10 years:

$$L_{\rm sd} \underset{t>>t_{\rm sd}}{\simeq} 8 \times 10^{40} \left(\frac{B}{10^{14}{\rm G}}\right)^{-2} \left(\frac{t}{10{\rm yr}}\right)^{-2} {\rm erg/s}$$

- Condition for spin-down powering of FRBs:

$$L_{\rm sd} > L_{\rm FRB} \Rightarrow t \lesssim 3 \frac{f_r}{f_b} \left(\frac{L_{\rm FRB}}{10^{42}{\rm erg/s}}\right)^{-1/2} B_{14}^{-1} {\rm yr}$$

Energetics: magnetic reservoir (magnetar-like)

Inspired by Metzger+2017

- Magnetic energy stored in the crust:

$$E_B \simeq 10^{49} \left(\frac{B_{\rm int}}{10^{16}{\rm G}} \right)^2 {\rm erg}$$

- Maximum number of bursts:

$$N_{\rm FRB} < \frac{E_B}{E_{\rm FRB}} \simeq 3 \times 10^2 f_b^{-1} \left(\frac{f_r}{10^{-8}} \right) \left(\frac{B_{\rm int}}{10^{16}{\rm G}} \right)^2 \left(\frac{E_{\rm FRB}}{10^{39}{\rm erg}} \right)^{-1}$$

(Metzger+2017 assuming emission mechanism of Lyubarsky 2014)

- Remark : interest of a localised and ultra-relativistic source for $f_b \ll 1$

Emission mechanisms

- Curvature radiation by bunches (e.g. Cooper and Wijers 2021, Kumar+17)
- Inverse Compton scattering by bunches (Zhang21)
- Reconnection of fast magnetosonic waves in magnetar magnetospheres (Lyubarsky 2020, Mahlmann+22)
- Maser in relativistic shocks (Khangulyan+22, Sironi21, Lyutikov21 (argues against))
- Free Electron Laser (Lyutikov20) : wiggler-type emission with wiggler provided by Alfven waves.
- "Pulsar mechanism"…

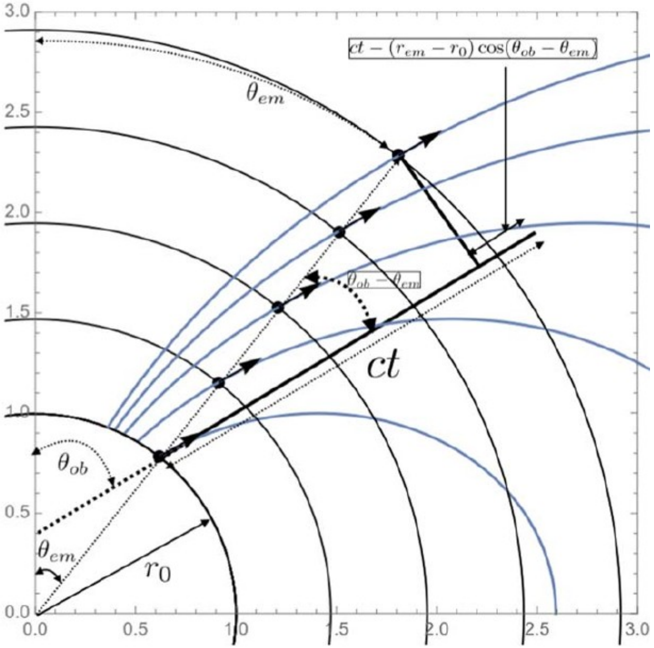
Radius-to-frequency mapping

- **Idea** : emission frequency $\omega \propto 1/r^{\alpha}$

  where r = distance from central engine

  ➔ Emitting plasma is propagating outwards

  ➔ Emission is relativistically beamed



Lyutikov20

- **Emission mechanisms:**
  - ➔ Synchrotron Maser : $\omega_{\rm peak} \propto B$
  - ➔ Curvature radiation : $\omega_c \propto 1/r_c$
  - ➔ Plasma frequencies : $\propto B^{\beta}$

- **Interesting result :**
  - ➔ If NS magnetosphere rotating slow / burst duration then *linear frequency drift*

FRBs created by interaction of an object with a pulsar/magnetar

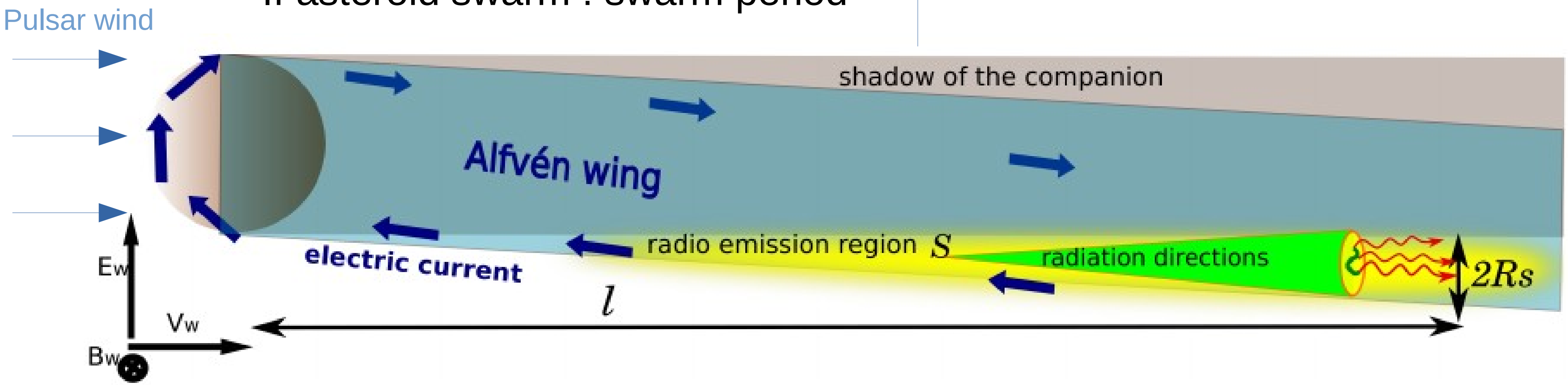
Asteroid orbiting around NS

- **Source :** Plasma wake (Alfven wings) in NS wind
  - ➔ Very high collimation / low energy
  - ➔ Randomness: due to orbital dynamics and turbulence
  - ➔ Period
    - If asteroid belt : None
    - If asteroid swarm : swarm period

- **Emission mechanism:**
  - ➔ Unspecified plasma instability

References :

Mottez14, Mottez20, Decoene20, Voisin21



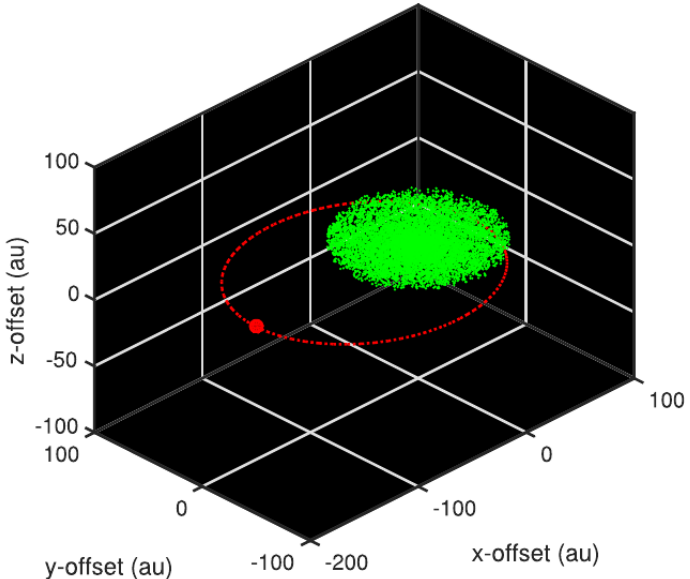
Mottez20

Asteroid orbiting around NS

Energetics	NS wind + Very high collimation
Duration	Orbital transit + Wind turbulence
Population	?
Frequency range	?
Bandwidth	Clumpiness (wind turbulence)
Downward drifting subpulses	Radius-to-frequency mapping + Clumpiness (wind turbulence)
Polarisation	? (linear if set by magnetic field)
Polarisation swing	? (flat if set by magnetic field)
Faraday rotation	Extrinsic
Counterpart	?

Asteroid colliding with NS

- **Source :** Collision of an asteroid with an old pulsar
  - ➔ Asteroid torn apart by tidal field
  - ➔ Moving pieces create unipolar inductor electric field
  - ➔ Electrons are accelerated and radiate



Smallwood19

- **Emission mechanism:**
  - ➔ Coherent curvature radiation accelerated

References :

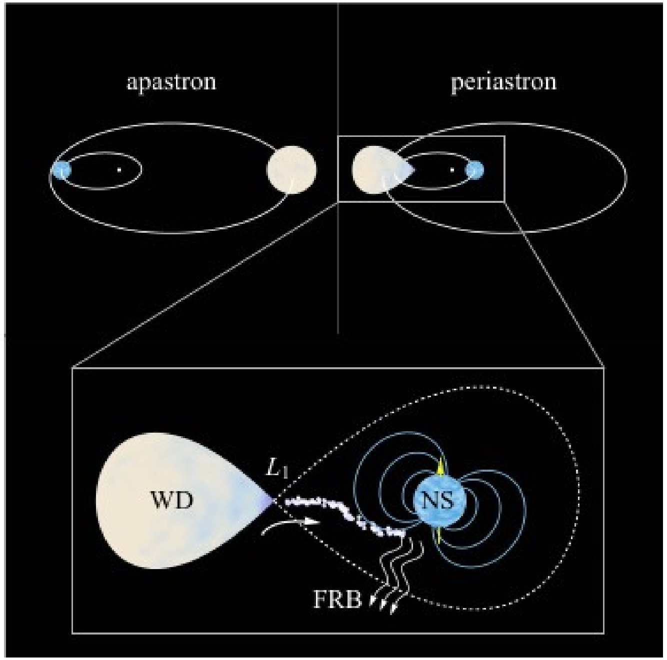
Geng15, Dai16, Bagchi17, Smallwood19, Liu20, Dai20, Dai&Zhong20

Asteroid colliding around NS

Energetics	Asteroids gravitational energy
Duration	Impact duration ~ size of the train of asteroid pieces
Population	? Needs extremely dense asteroid population (/ solar system)
Frequency range	Asteroid size
Bandwidth	?
Downward drifting subpulses	Radius-to-frequency mapping and electron bunching
Polarisation	Curvature radiation
Polarisation swing	Depends on magnetic geometry, expected mild
Faraday rotation	?
Counterpart	? But NS-asteroid were proposed for GRBs in the past

White-dwarf-pulsar binary

- **Source :** A white dwarf is periodically accreted at periastron. The stream of matter falling en waves that trigger reconnection



Gu20

- **Emission mechanism:**
  - ➔ Bunched curvature radiation

- Issue:
  - ➔ High viscosity needed to get the material down to the star in t < Porb

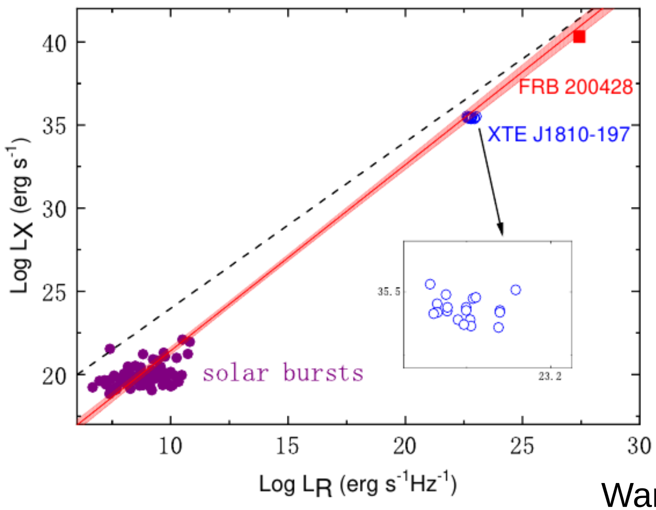
- **References :**
  Gu16, Gu20

FRBs created from the magnetar/pulsar itself

Magnetar: hints and analogies

Repeating FRB ~ Magnetar high-energy bursts ~ Type III Solar flares
(Popov10) (Lyutikov02)

- Radio/x-ray fluence ~ 10^{-4}
  - ➔ for type III flares and FRB200428 (e.g. Lu20)
- Similar frequency / energy distributions
  (e.g. Wadiasingh19, Wang21)
- Sufficient Source population (e.g. Popov10, Metzger17)

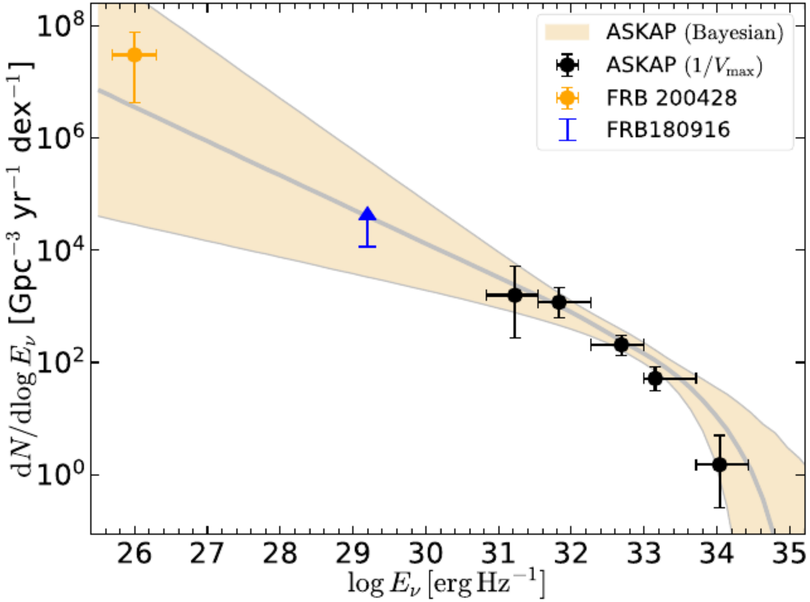


Wang21

- Energetics :
  - ➔ Rotation power unlikely sufficient even with ms-magnetar (e.g. Metzger17)
  - ➔ Magnetic power OK even with “normal” magnetar if high radio/xray efficiency (10^{-2})
- Expected supernova remnant:
  - ➔ FRB121102 permanent radio source, DM/RM variations (e.g. Hessels19, Marcote17)
  - ➔ But does not work with e.g. FRB180916 (could be other supernova channel) (Marcote20)

Magnetar Magnetosphere

- **Source :** Young Magnetar magnetosphere
  - ➔ FRB200428/SGR1935+2154 is the tail of the extragalactic FRB spectrum
  - ➔ Radio bursts are caused by star quakes, as is the HE counterpart



Lu20

- **Emission mechanism:**
  - ➔ Bunched curvature radiation
  - ➔ "Pulsar mechanism"
  - ➔ Fast magnetosonic wave packets
  - ➔ ...
- **Predictions :**
  - ➔ If very young magnetar (a few decades) activity should decay within a few decades (e.g. Metzger17)

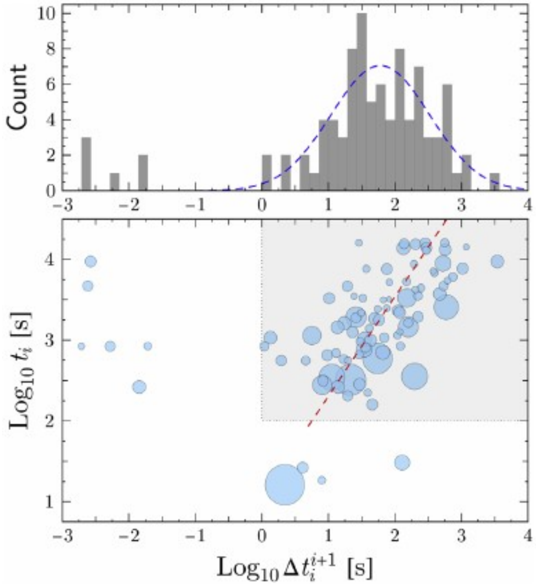
- **References :** Kumar17, Ghisellini18, Katz18, Yang18, Lu19, Wang19, Lyubarsky20, Lyutikov20, Lu20…

Magnetar magnetosphere

Energetics	Magnetic energy in magnetar magnetosphere
Duration	~ms given by light-crossing time in magnetosphere
Population	Strong repeaters : Young magnetars (Expected in star-forming regions) Galactic/weaker :“Normal” magnetars (Lu20)
Frequency range	?
Bandwidth	Narrow-band expected in “solar flare” model (Lyutikov02)
Downward drifting subpulses	Possibly radius-to-frequency mapping (Lyutikov20a)
Polarisation	Usually imposed by local magnetic field (linear)
Polarisation swing	Possible depending on location
DM / Faraday rotation	Extrinsic
Counterpart	X-ray burst, 10^2 to 10^5 more energetic

Low-twist Magnetar

- **Source :** A rather old magnetar (~10 000 years) having lost its toroidal field i.e. “low-twist”
  - ➔ The twist produces a large charge density in the magnetosphere
  - ➔ Starquakes produce waves that are creating an electric field
  - ➔ If twist too low, then not enough charges to screen the field



Wadiasingh20

- **Emission mechanism:**
  - ➔ Pulsar-like mechanism but possibly along *closed magnetic field lines*

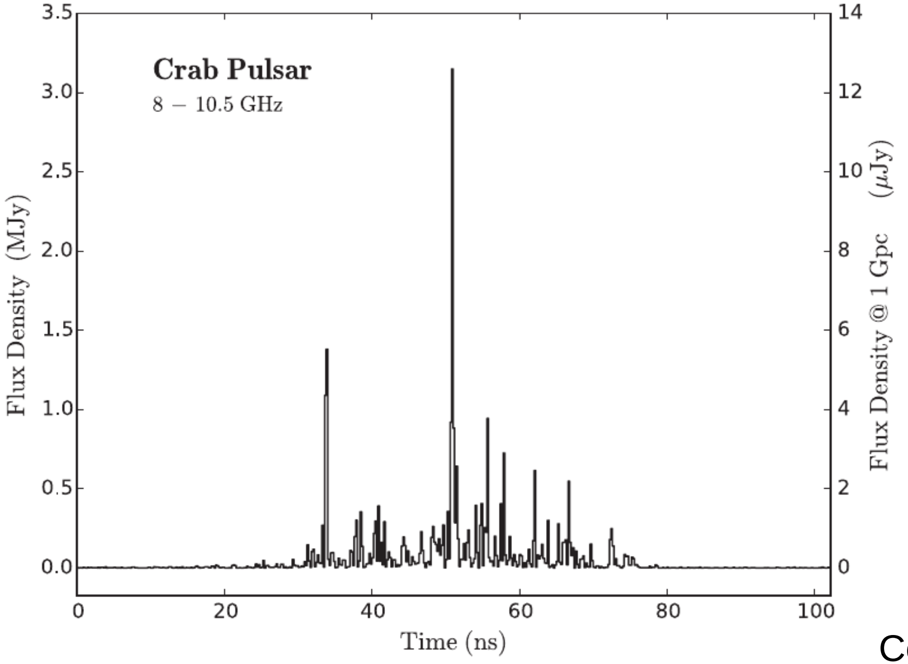
- **Prediction :**
  - ➔ Possible (isotropic) energy cutoff below 10^{37} erg

    (at odds with SGR1935)

- **References :**
  Wadiasingh19, Wadiasingh20a, Wadiasingh20b, Beniamini20

Supergiant pulses

- **Source :** Young pulsar/magnetar producing giant pulses and nanoshots akin to the Crab's
  - ➔ Based on extrapolation from Crab observation
  - ➔ Beaming could be more or less favorable (e.g. the Crab's twin has giant pulses 10 times smaller)



Cordes16

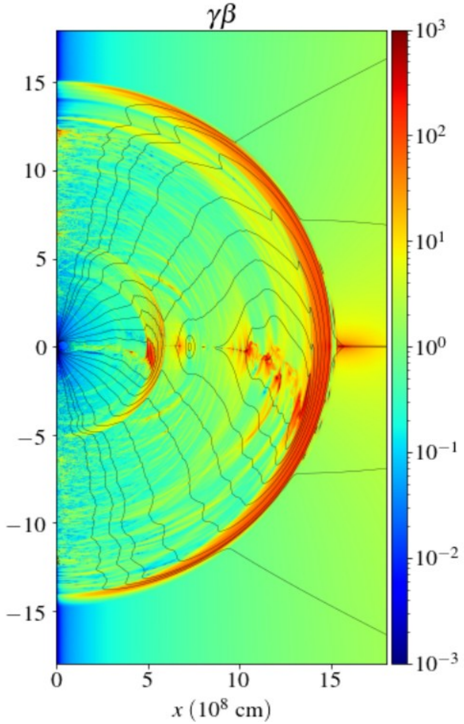
- **Emission mechanism:**
  - ➔ Unclear

- **Problems :**
  - ➔ Rotation power may be insufficient (Metzger17, Lyutikov17) for 1Gpc distance

- **References :** Cordes16, Connor16, Lyutikov16, Lyutikov17, Lyu21

Magnetar Blast Waves

- **Source :** Strong shock between relativistic plasmoid from reconnection and surrounding material
  - ➔ Star quakes produce Alfven waves that trigger reconnection



Yuan20

- **Emission mechanism:**
  - ➔ Synchrotron Maser

- **Prediction :**
  - ➔ Optical flash
  - ➔ Wide frequency range

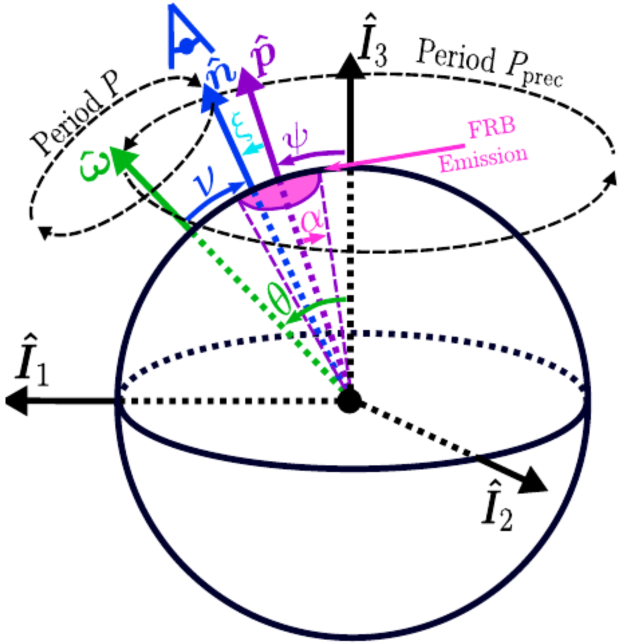
- **References :**
  Popov13, Lyubarsky14, Beloborodov17, Metzger17, Plotnikov19, **Metzger19**, Babul20, **Beloborodov20**, Wu20, Xiao20, **Yuan20**, Margalit20, Yu21

Magnetar Blast Waves

Energetics	Magnetic energy in magnetar magnetosphere
Duration	< 1 ms for GHz (Related to Doppler-compressed propag time)
Population	Strong repeaters : Young magnetars (Expected in star-forming regions) Galactic/weaker :“Normal” magnetars (Lu20)
Frequency range	Wide (>>1Ghz)
Bandwidth	? Unclear
Downward drifting subpulses	(Sort-of) radius to frequency mapping (frequency ~ local magnetic field)
Polarisation	Quasi-linear (according to maser simulations)
Polarisation swing	?
DM / Faraday rotation	Extrinsic (*potential small variations?*)
Counterpart	X-ray and optical burst, 10^6 more energetic

Freely Precessing Magnetar

- **Source :** A young (decades) precessing magnetar
  - ➔ Strong magnetic field strains the star creating a quadrupole moment
  - ➔ If initial kick (e.g. due to magnetospheric braking) then precession with period ~ 10 – 1000 days



Zanazzi20

- **Problem:**
  - ➔ Superfluidity suppresses precession (never observed on known neutron stars)
- **Solution :**
  - ➔ Interior temperature > T_c = 10^9K. Possible for young magnetars
- **Predictions :**
  - ➔ Rapid period increase (a few years)

References :
Zanazzi20, Levin20, Li21

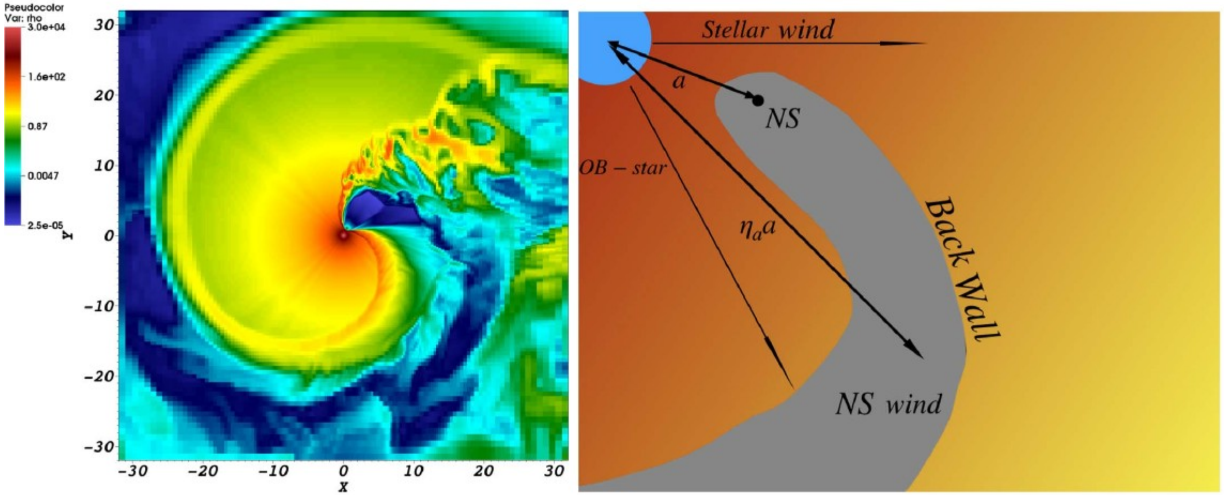
Magnetar orbiting O/B star / Combed NS

- **Source :** Enshrouded magnetar
  - ➔ O/B star wind enshroud the magnetar and prevents radio emission from exiting due to free-free absorption
  - ➔ The tail of the magnetar wind leaves open a radio corridor for a fraction of the orbit

- **Emission mechanism:**
  - ➔ Plasma laser (Lyutikov20)
  - ➔ Any other Magnetar/pulsar mechanism ?

- **Predictions :**
  - ➔ Small DM variations
  - ➔ Increase of the activity window with frequency
  - ➔ No periodicity < 10 days (O/B stars)

    < 0.1 days (NS companion) (Ioka20)

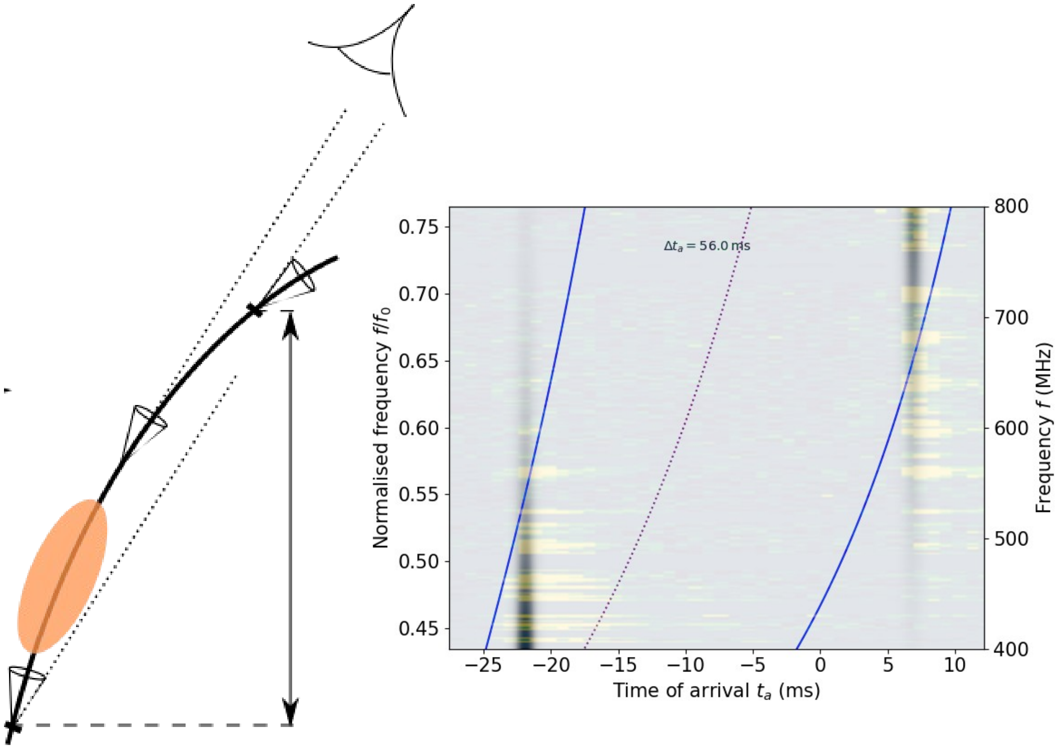


Lyutikov20

References :
Lyutikov20, Ioka20, Pleunis21

Geometric magnetospheric models

- **Source :** propagation of relativistic material in the magnetosphere



Voisin 2023

- **Emission mechanism:**
  - ➔ Depends on authors, but the details of the emission mechanism do not really affect the results.

- **Prediction :**
  - ➔ Dependent on model: explanations for repearter/non-repeater morphologies, low-frequency lag etc..

- **References :**
  Zhang 21, Connery+22, Liu+23, Voisin+23

Some conclusions

- A lot of work still needed to falsify models, either by observation, or by making finer predictions.
- Some of the important things that I did not discuss :
  - ➔ propagation (RM, DM, lensing…),
  - ➔ models not based on neutron stars,
  - ➔ polarisation hardly touched,
  - ➔ high energy counterparts...
  - ➔ Population studies..
- All papers cited can be found in the public library at https://ui.adsabs.harvard.edu/public-libraries/0wJ4Jgh8RtuboZNzlkONMg (link also on my personal webpage luth.obspm.fr/~luthier/gvoisin/mywork)
- FRB Theory Catalogue (Platts+ 2018) : frbtheorycat.org
- FRB Community Newsletter : https://forms.gle/fFE8uQWfavWA48s5A

Some existing reviews

- Fast Radio Bursts, Akshaya+ 2017,   DOI:10.1007/s12036-017-9478-1
- Fast Radio Bursts, Popov+ 2018, arXiv:1806.03628
- **Fast Radio Bursts, Petroff+ 2019, arXiv:1904.07947**
  - Complete, especially on observations (at that time).
- **A living theory catalogue for fast radio bursts, Platts+ 2019, arXiv:1810.05836**
- **Fast Radio Bursts: An Extragalactic Enigma, Cordes+ 2019, arXiv:1906.05878**
  - Complete review, especially on (intergalactic) radio propagation
- **The physical mechanism of fast radio bursts, Zhang B.+ 2020, arXiv:2011.03500**
  - Concise and synthetic review that advocates the two-population magnetar scenario with magnetospheric emission
- The physics of fast radio bursts, Xiao+ 2021, arXiv:2101.04907
- **Emission mechanisms of fast radio bursts, Lyubarsky 2021, DOI:10.3390/universe7030056**
  - Blast waves and Masers, reconnection, propagation…

Quelques questions

- Quelle est la localisation des FRBs par rapport à la phase rotationnelle de l’étoile ?
- A quelle distance de l’étoile: magnétosphère ou vent ?
- Y a-t-il plusieurs modèles/mécanismes simultanément à l’oeuvre ?
- Quelle relations avec les contreparties ?