Physical Mechanisms of FRBs: Clues from Data and Progress in Theory

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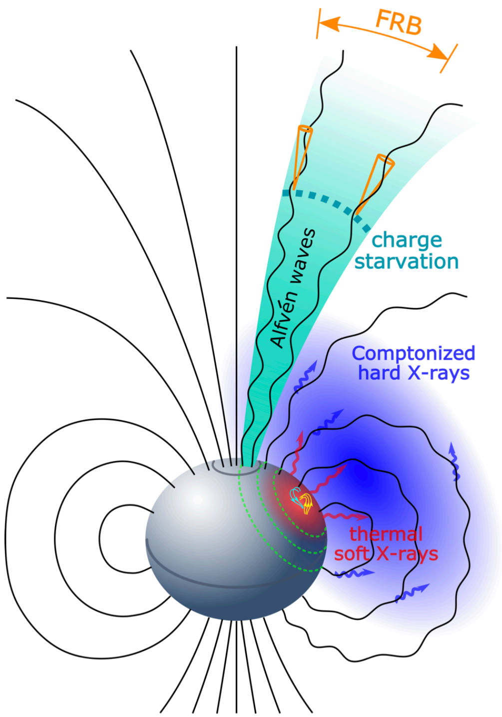
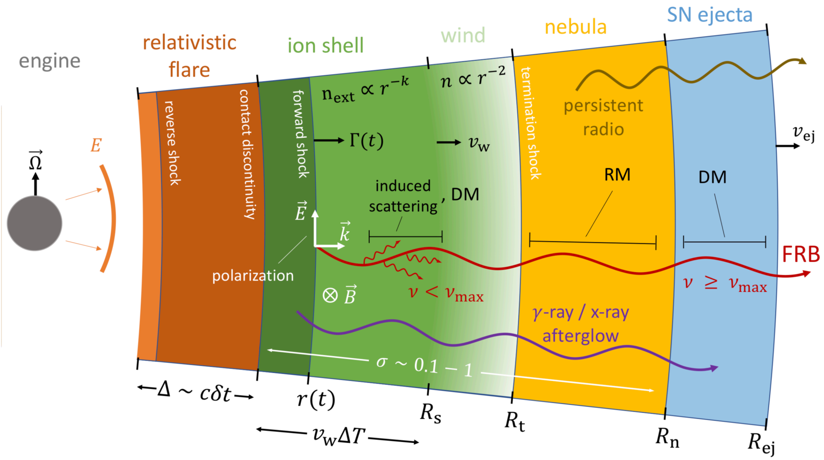
Open Questions:
What? Where? & How?



Lu et al. 2020

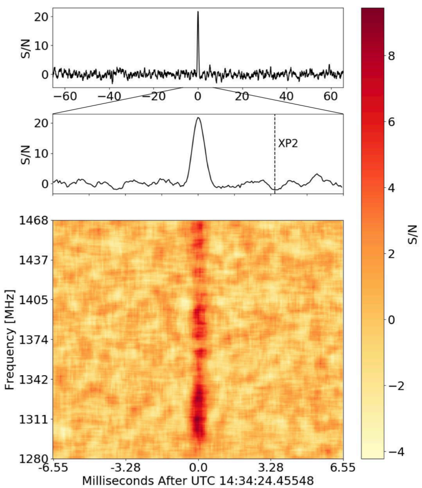


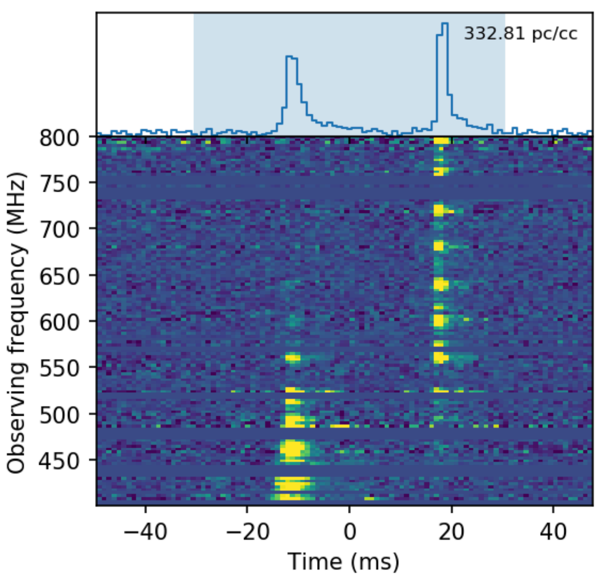
Metzger et al. 2019

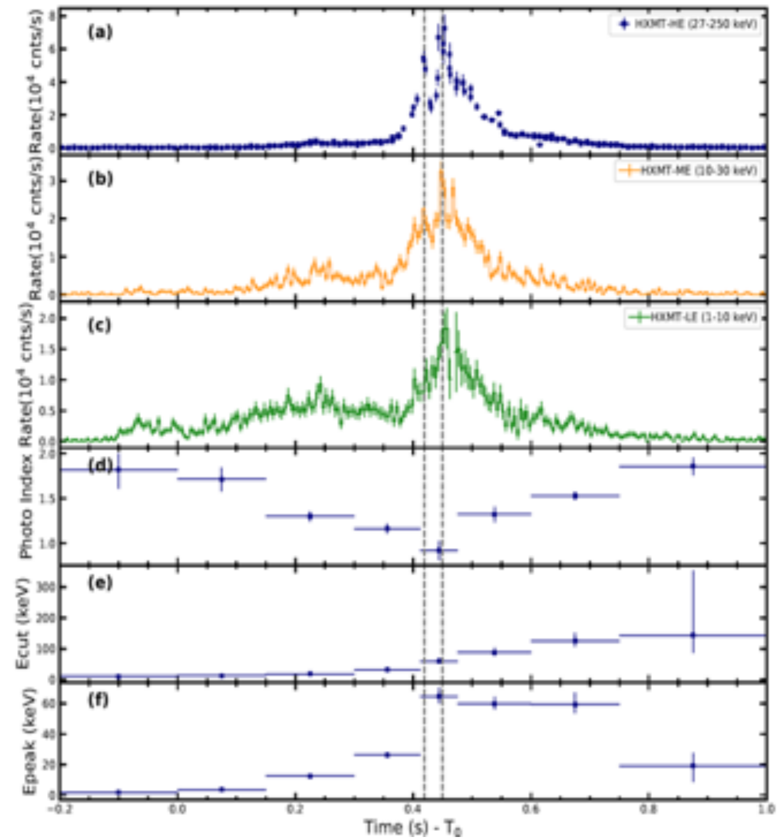
What?

FRB 200428-SGR J1935+2154 Association

CHIME/FRB Collaboration 2020; Bochenek et al. 2020; Li+ 20; Mereghetti+ 20; Ridnaia+ 20; Tavani+ 20



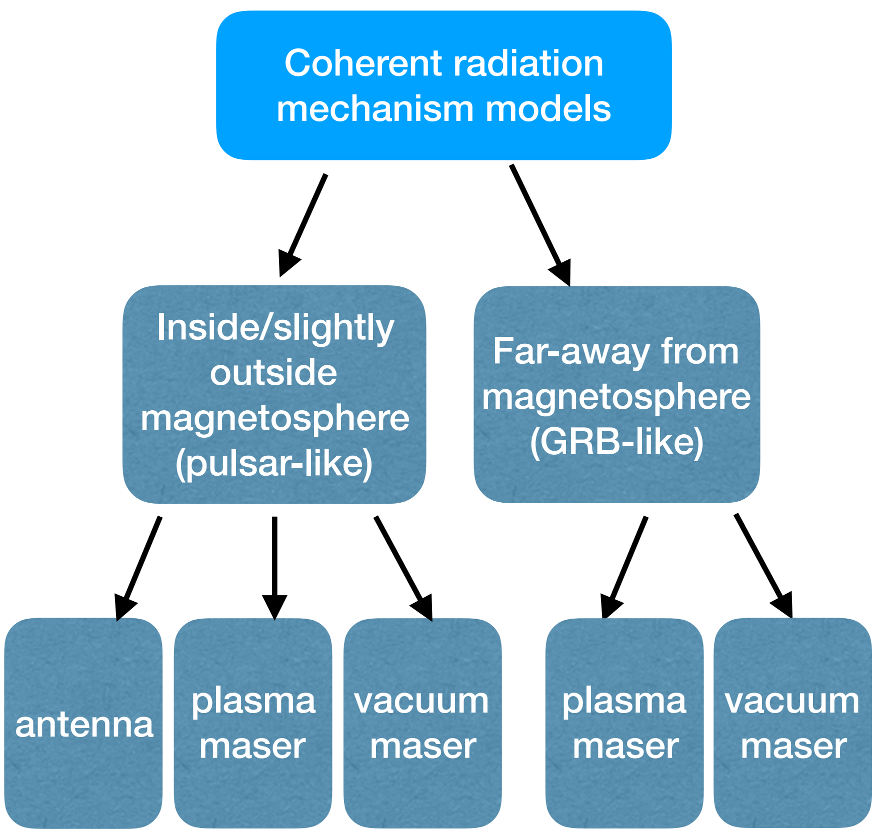


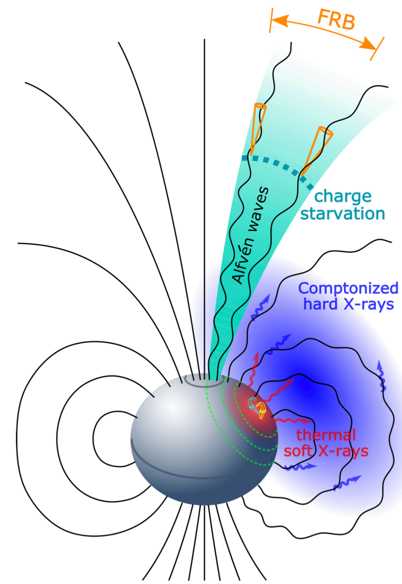


Radio bursts coincide with X-ray burst peaks: Magnetars can produce at least some FRBs!

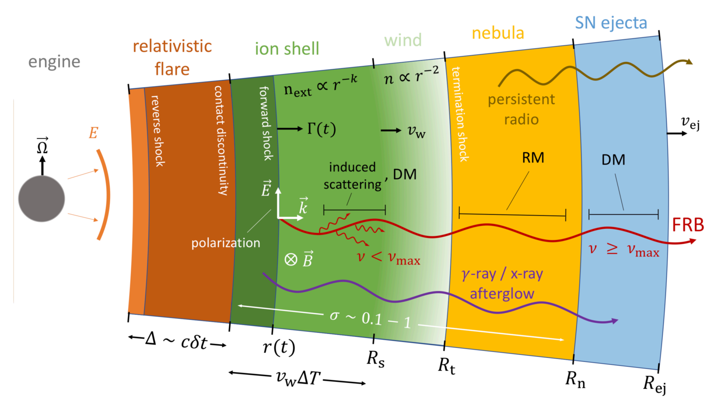
Where?

Coherent Radiation Mechanisms





Pulsar-like: from Lu et al. 2020

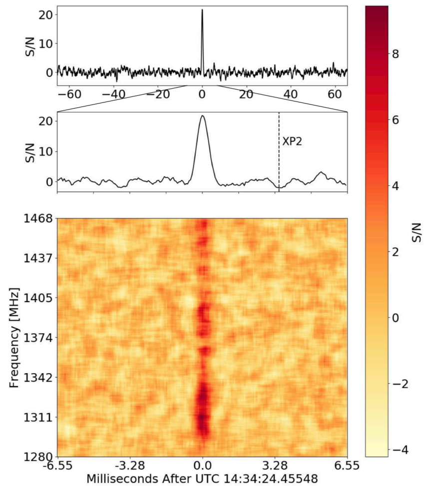


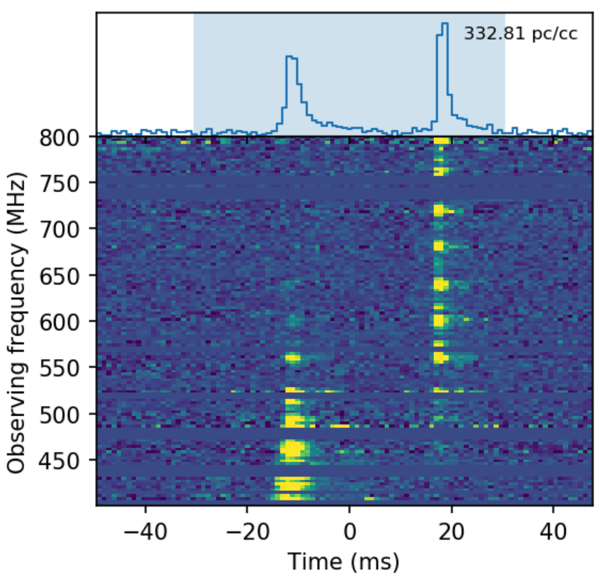
GRB-like: from Metzger et al. 2019

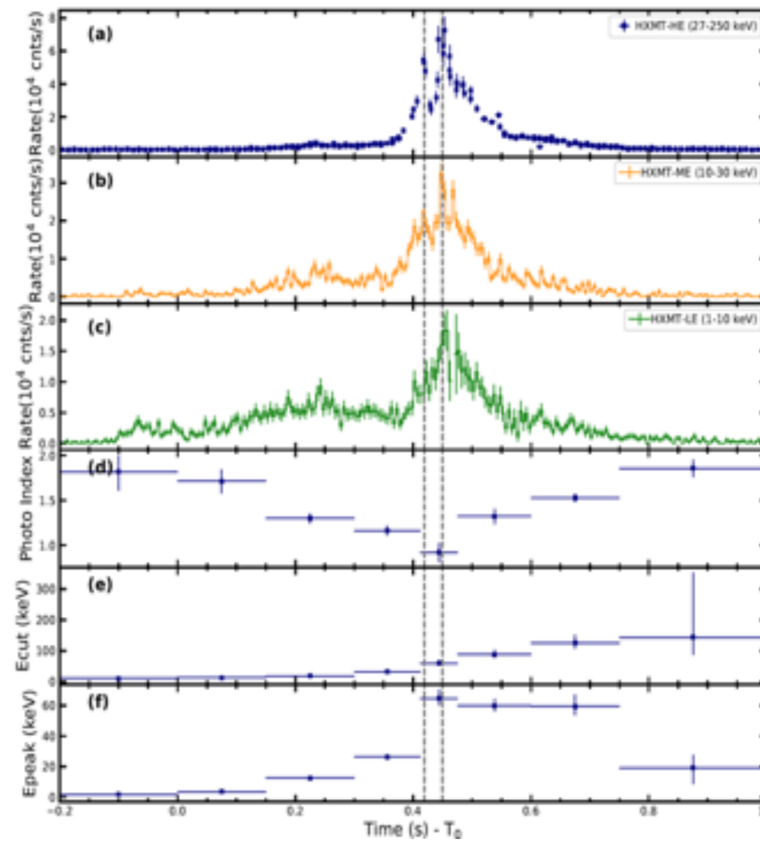
	Pulsar-like models	GRB-like models
Beaming angle	• Likely narrow	• Likely wide
Radio efficiency	• Relatively high	• Relatively low
High energy counterparts	• Moderately bright X-ray / gamma-ray emission	• Bright X-ray / gamma-ray / optical emission
Polarization properties	• High (up to 100%) linear polarization degree • Non-varying (straight field lines, slow rotation) or diverse swings of polarization angles (inner magnetosphere)	• No polarization (low-B version) • High (up to 100%) linear polarization degree & constant polarization angle (high-B version)

FRB 200428-SGR J1935+2154 Association

CHIME/FRB Collaboration 2020; Bochenek et al. 2020; Li+ 20; Mereghetti+ 20; Ridnaia+ 20; Tavani+ 20

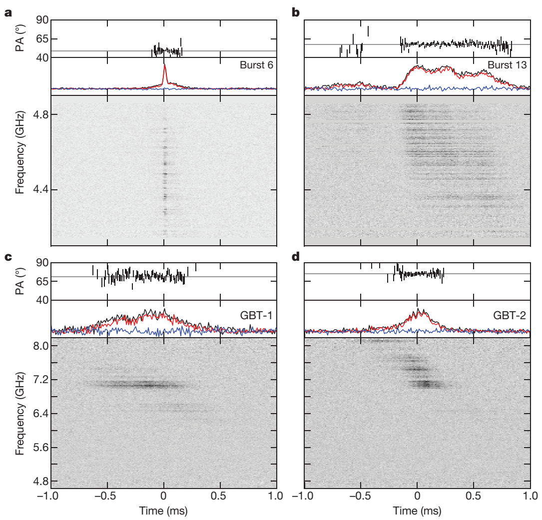




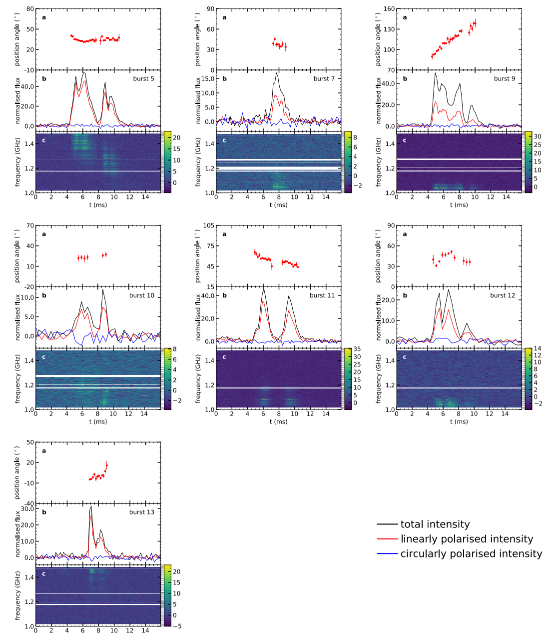


Radio bursts coincide with X-ray burst peaks:
X-ray burst from magnetosphere

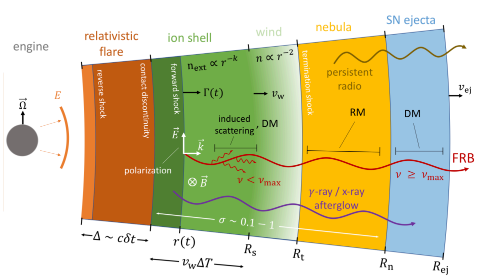
Polarization properties as a clue: Polarization angle swings

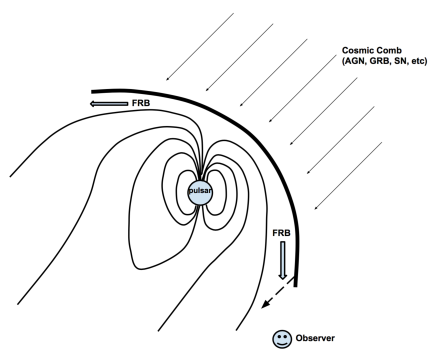


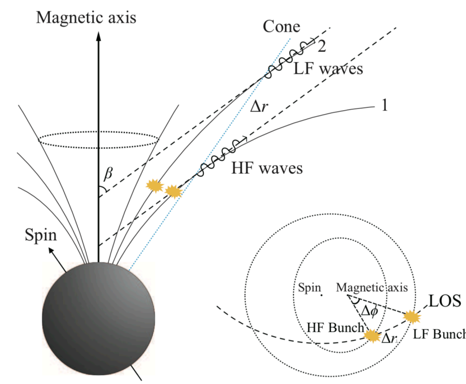
FRB 121102
Michilli et al. 2017



FRB 180301 (FAST)
Luo et al. 2020

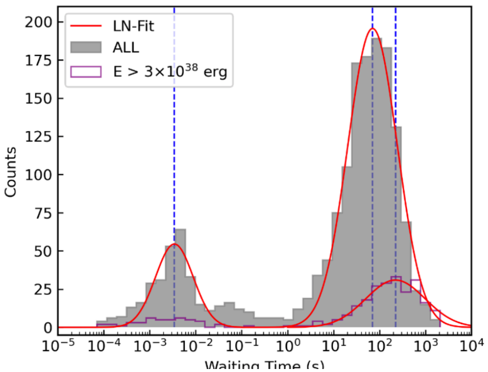


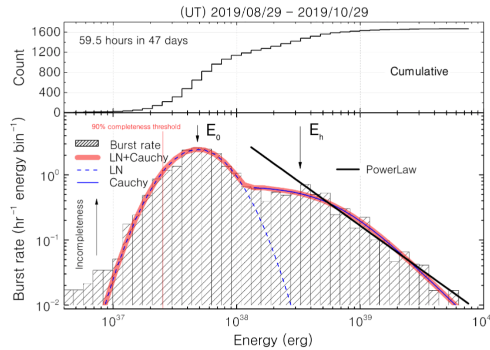


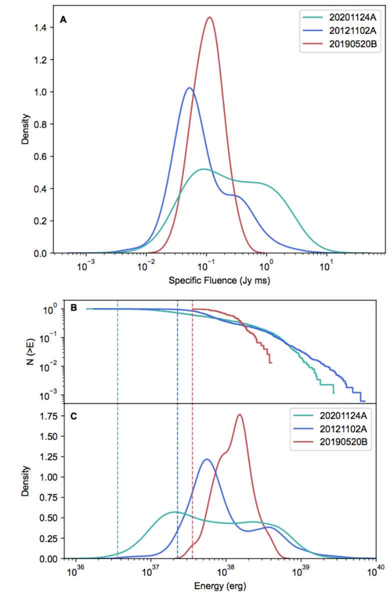


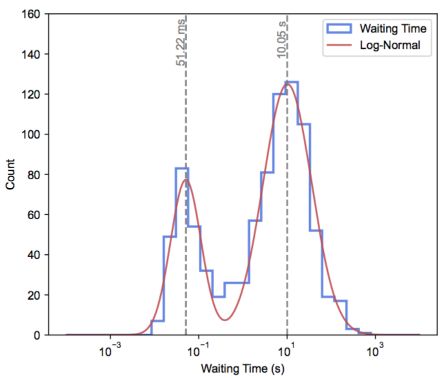
FRB 121102 & FRB 20201124A

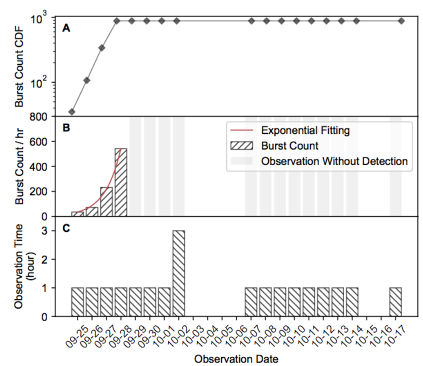
D. Li et al. 2021, Nature; H. Xu et al. 2022, Nature;
Y. K. Zhang et al. 2022, RAA











Challenges to synchrotron maser shock (GRB-like) models:

* Very high repetition rate (>500/hr for FRB 20201124A on Sep. 28, 2021)
* Short waiting time (<50 ms)
* Total energy exceeds 10% of (dipolar) magnetic energy (FRB 121102 in ~1.5 month and FRB 201124A in 4 days) if not beamed or efficient

(FRB 20121102 in 47 days)

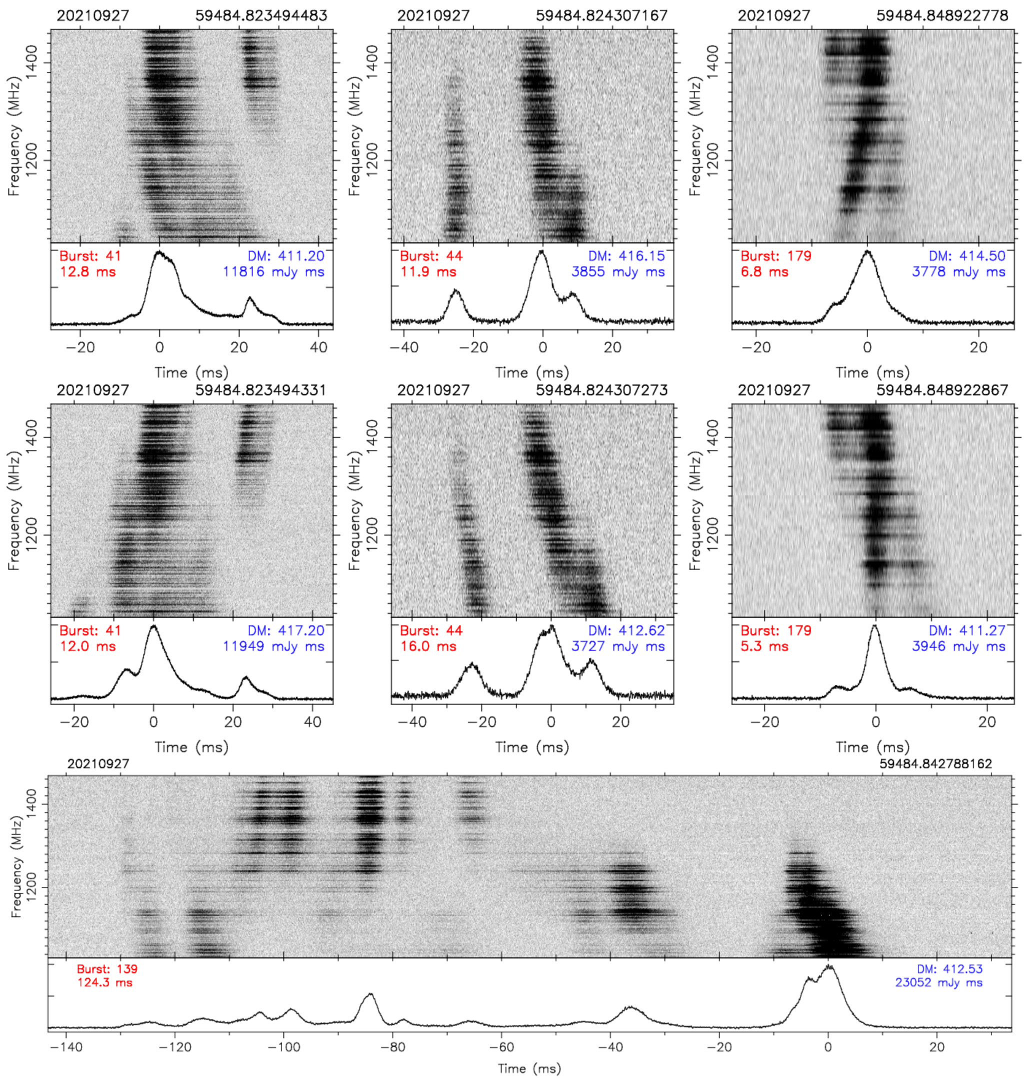
$$E_{\rm bursts} = (6.4\times10^{45}\ {\rm erg})\left(\frac{E_{\rm radio}}{3.4\times10^{41}\ {\rm erg}}\right)\left(\frac{F_b}{0.1}\right)\left(\frac{\eta}{10^{-4}}\right)^{-1}\left(\frac{\zeta}{0.053}\right)^{-1}$$

$(3.85\times10^{45}\ {\rm erg})$ (FRB 20201124A in 4 days)

$$E_{\rm mag} \simeq (1.7\times10^{47}\ {\rm erg}) B_{*,15}^2 R_6^3$$

FRB 20201124A

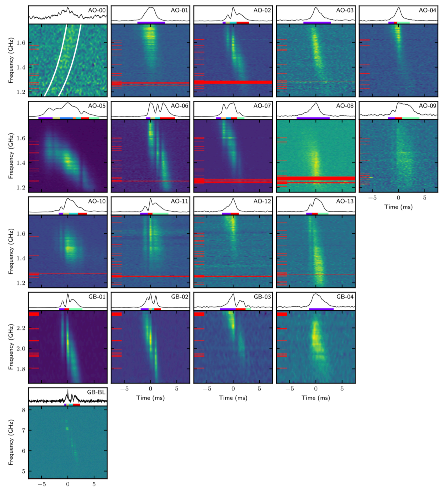
D. J Zhou et al. 2022, RAA

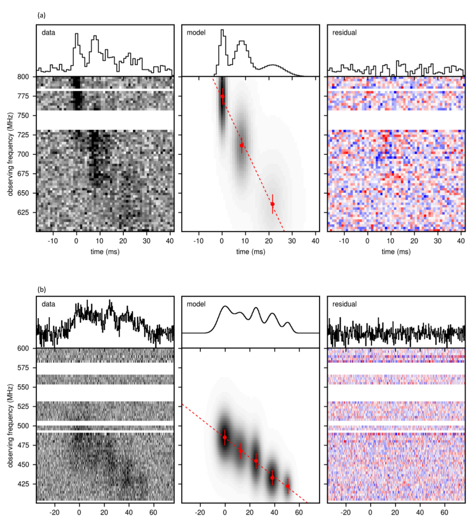


Burst clusters:

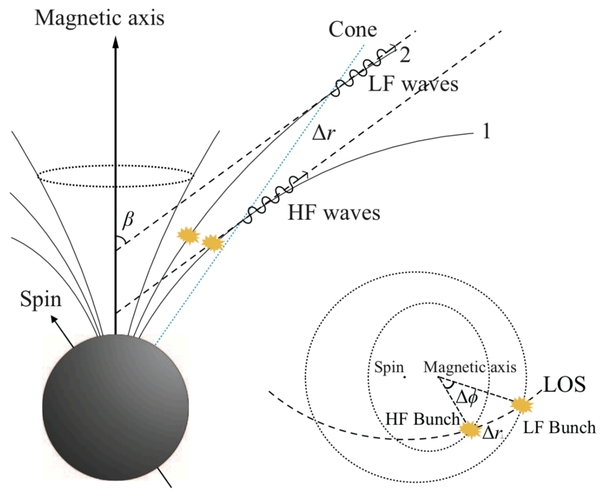
11 bursts in <0.2 s

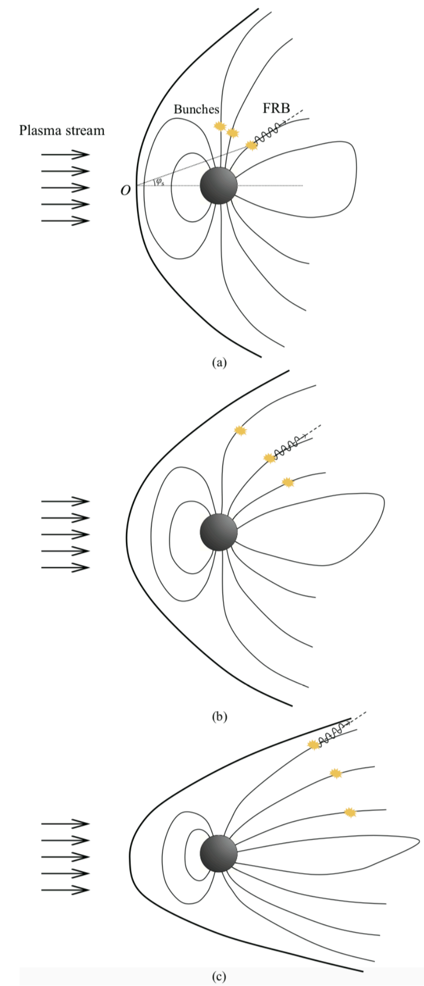
Time-frequency down-drifting





Hessels et al; CHIME/FRB Collaboration





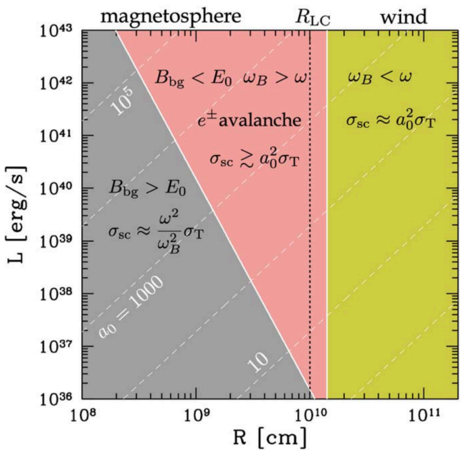
- Radius-to-frequency mapping
- Difficult to “re-calibrate” in the shock models

Wang et al., 2019, ApJL, 876, L15

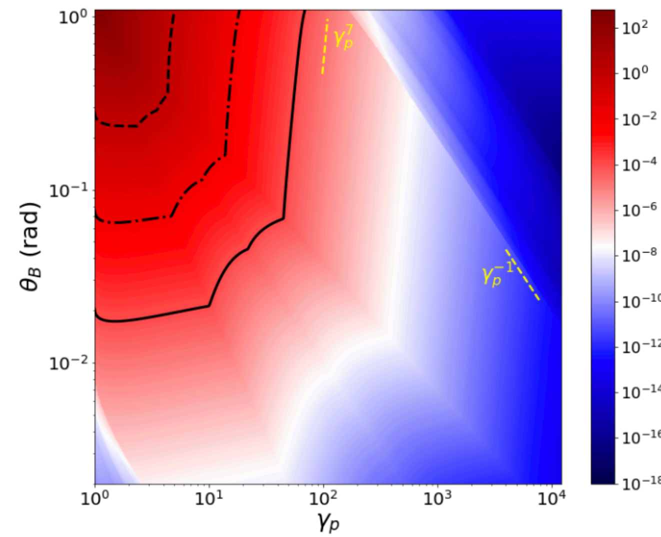
Magnetar magnetospheric emission of FRBs

- Supports:
  - FRB 200428 - XRB association, peak alignment
  - Pulsar-like behavior: PA swing
  - Short waiting time, burst clusters
  - High burst rates, large energy budget requires narrow beaming and efficient radio emission
- Issues:
  - Lack of periodicity? (multipolar B, BHs?)
  - Opacity due to scattering, cannot escape? (no problem in open field line region with outflows)

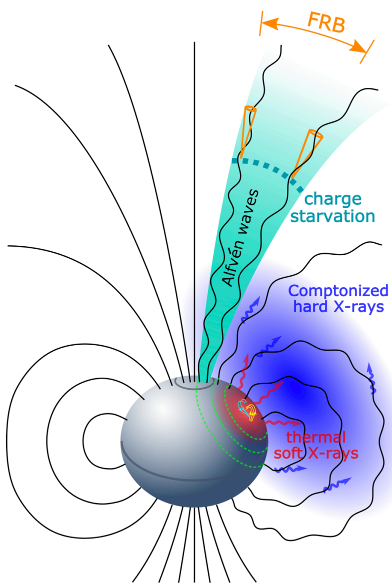
FRB propagation in magnetar magnetospheres



Beloborodov, 2021, ApJL, 922, L7



Qu, Kumar & Zhang 2022, MNRAS, 515, 2020

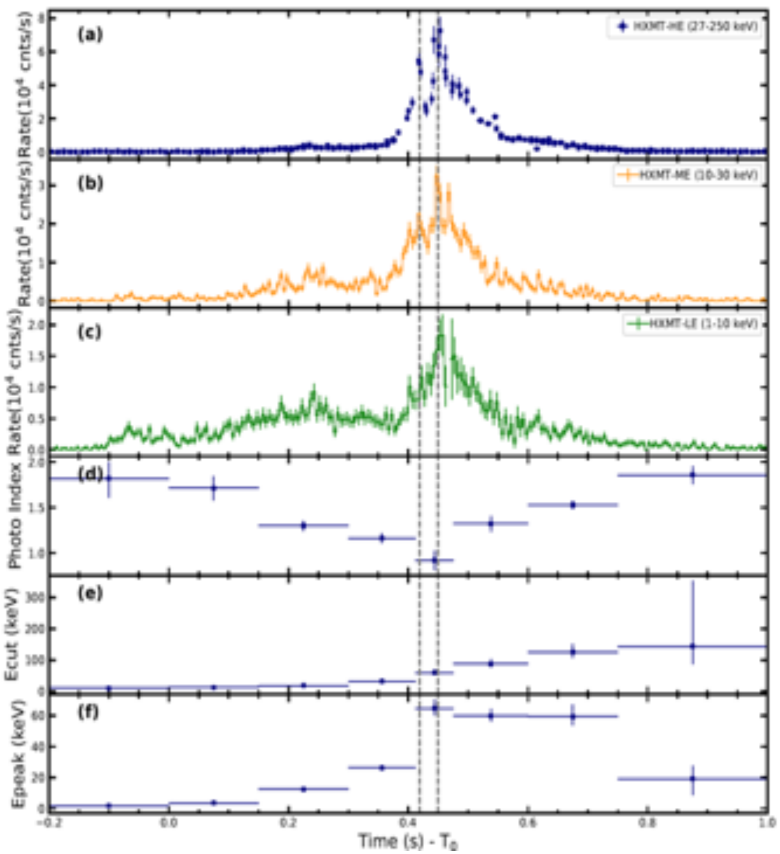


Lu, Kumar & Zhang 2020, MNRAS, 498, 1397

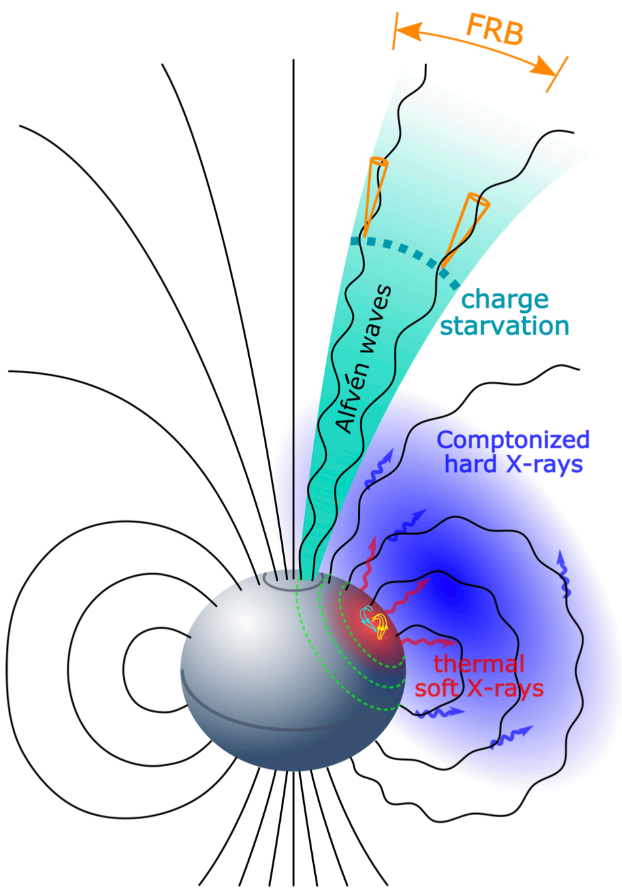
1. Plasma are moving with high Lorentz factor (especially in open field line regions)
2. Angle between k, B is small

How?

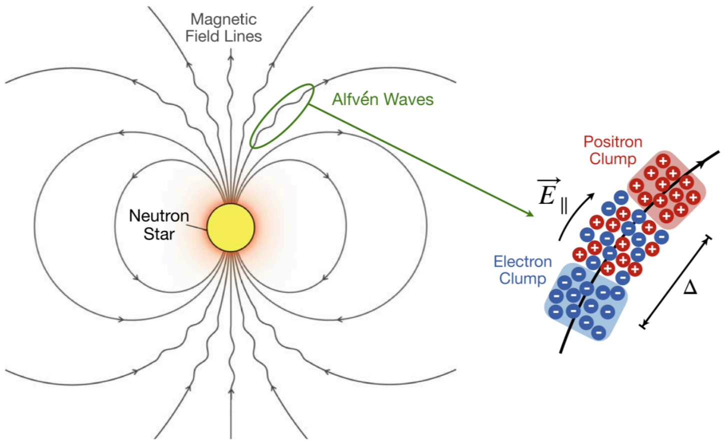
How are FRBs generated in a magnetar magnetosphere?



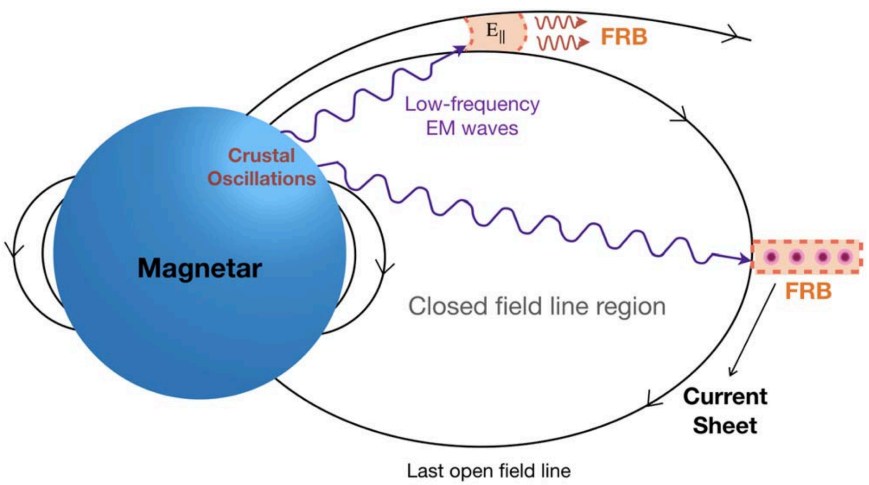
FRBs from magnetar magnetospheres



Lu, Kumar & Zhang 2020, MNRAS, 498, 1397



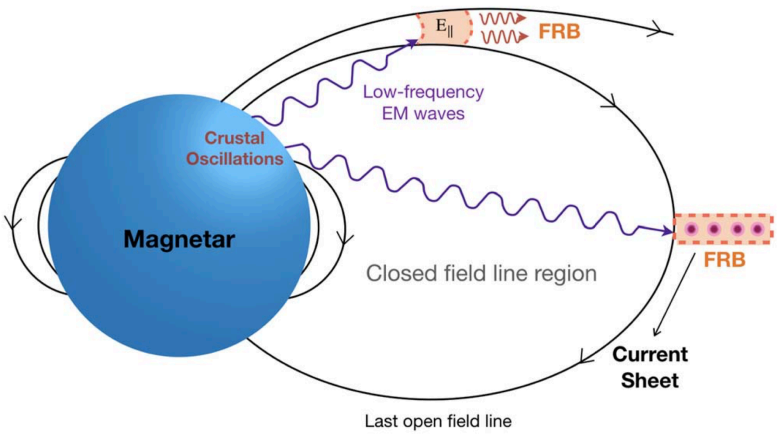
Yang et al., 2020, ApJL, 901, L13

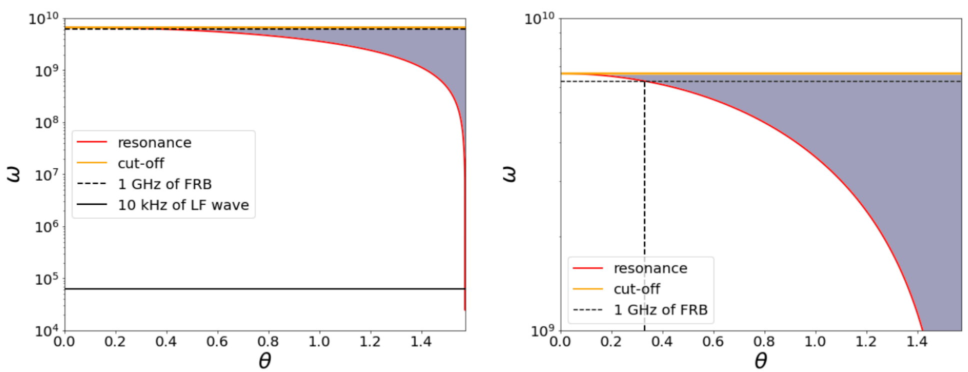


Zhang, 2022, ApJ, 925, 53

Inverse Compton scattering

Zhang, 2022, ApJ, 925, 53; Qu, Zhang & Kumar 2022, MNRAS





$$\sigma(1) = \sigma_{\rm T}\left\{\frac{\sin^2\theta_i}{\gamma^2(1-\beta\cos\theta_i)} + \frac{(\cos\theta_i - \beta_i)^2}{2(1-\beta\cos\theta_i)} \times \left[\frac{\omega'^2}{(\omega'+\omega_{\rm B})^2} + \frac{\omega'^2}{(\omega'-\omega_{\rm B})^2}\right]\right\},$$

$$\sigma(2) = \frac{\sigma_{\rm T}}{2}\left[\frac{\omega'^2}{(\omega'+\omega_{\rm B})^2} + \frac{\omega'^2}{(\omega'-\omega_{\rm B})^2}\right].$$

$$P_e^{\rm ICS} \simeq \frac{4}{3}\gamma^2\sigma(1)cU_{\rm ph} \simeq (2.1\times10^{-7}\ {\rm erg\ s^{-1}})f(\theta_i)(\delta B_{0,6})^2\hat{r}_2^{-2},$$

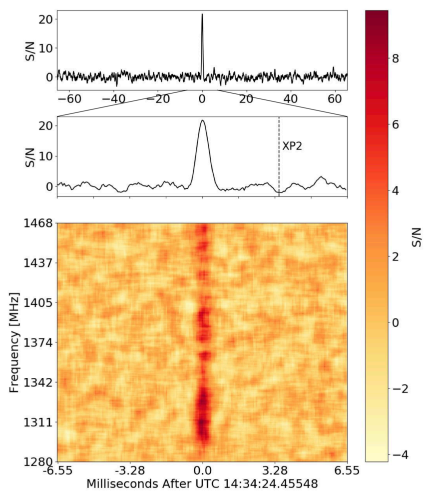
$$P_e^{\rm CR} = \gamma^4\frac{2e^2c}{3\rho^2} \simeq (4.6\times10^{-15}\ {\rm erg\ s^{-1}})\gamma_{2.5}^4\rho_8^{-2},$$

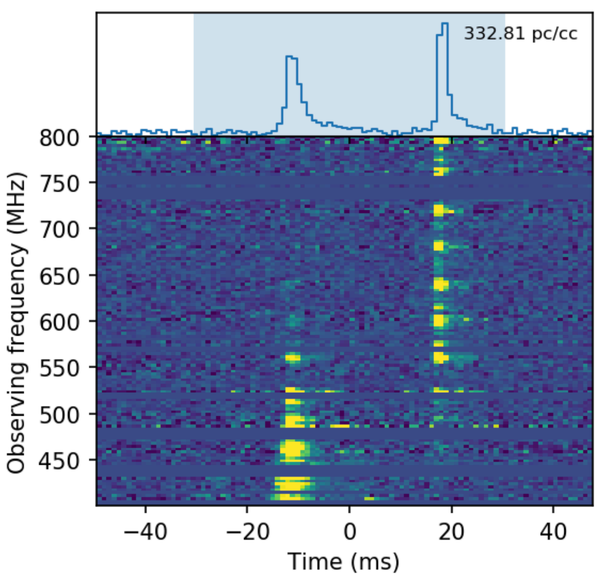
- Physical picture:
  - Crustal cracking -> charge oscillations -> low-frequency EM waves
  - low-frequency EM waves (both X and O modes) are essentially transparent
  - Charge-starving region, relativistic electrons up-scatter low-frequency waves
- Features:
  - ICS is much more efficient than curvature radiation
  - Less degree of coherence needed
  - narrow spectrum
  - linear polarization
  - radius-to-frequency mapping

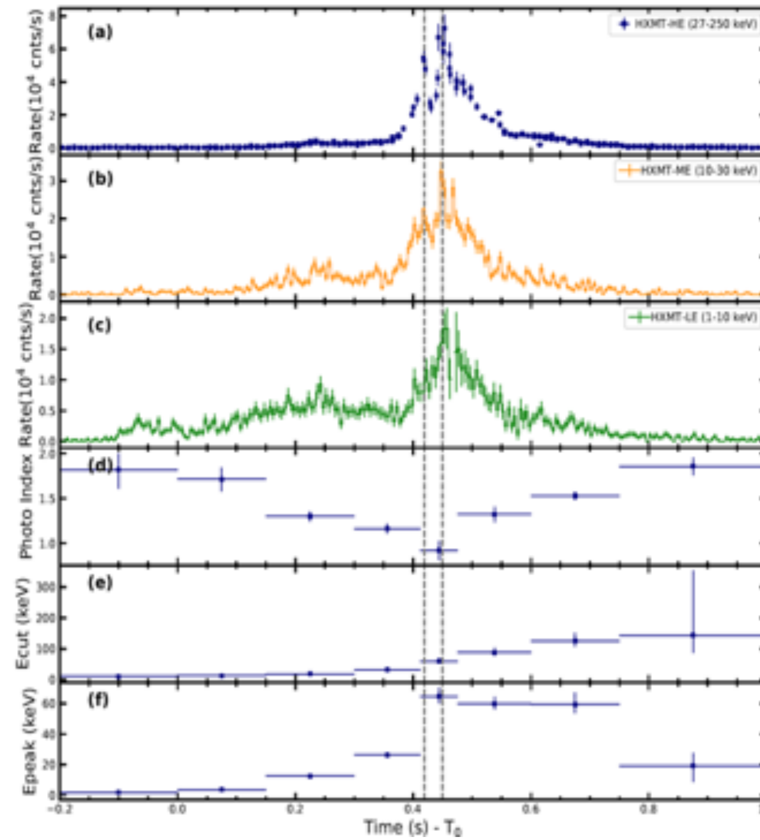
What else?

FRB 200428-SGR J1935+2154 Association

CHIME/FRB Collaboration 2020; Bochenek et al. 2020; Li+ 20; Mereghetti+ 20; Ridnaia+ 20; Tavani+ 20

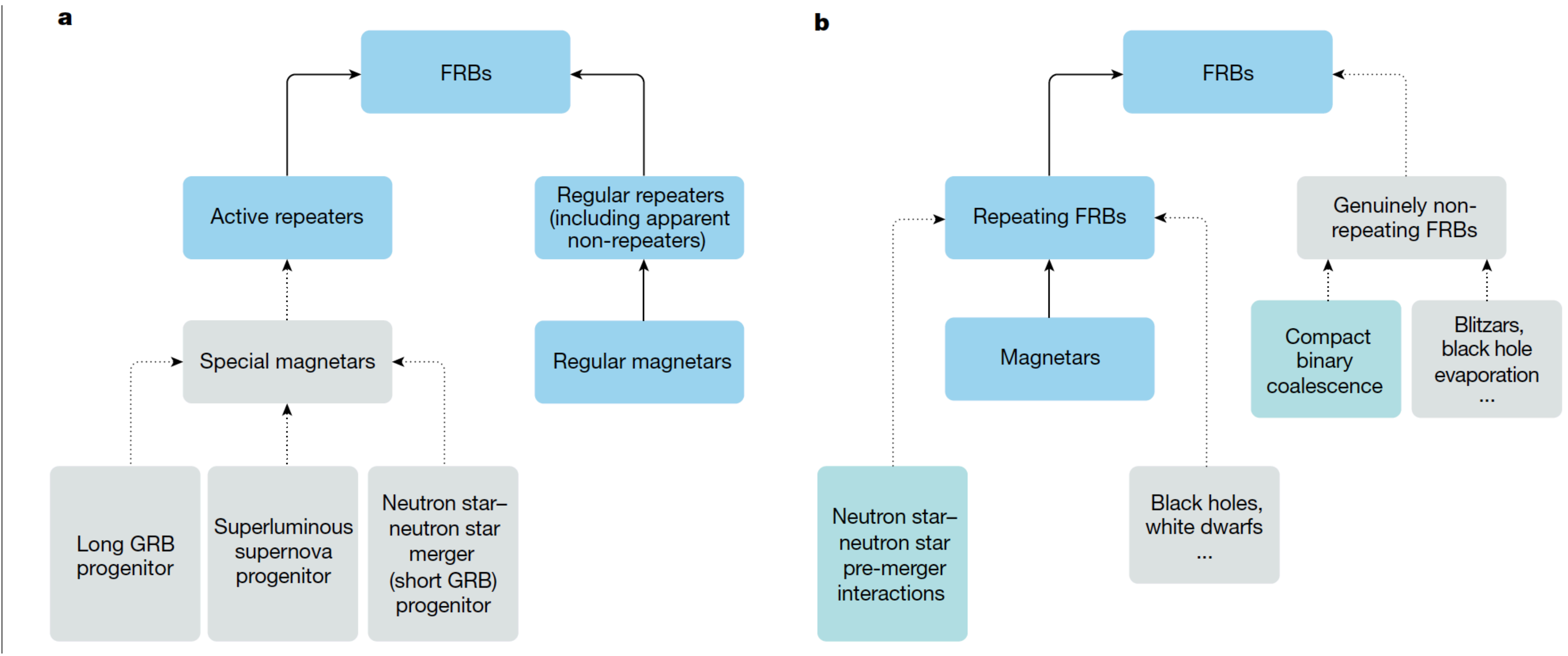






Radio bursts coincide with X-ray burst peaks:
Magnetars can produce at least some FRBs!

Two extreme versions of source models



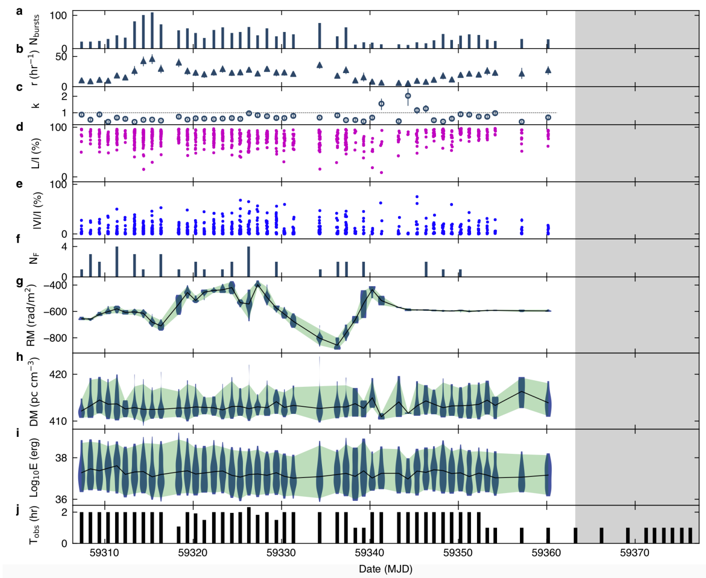
BZ, 2020, Nature, 587, 45

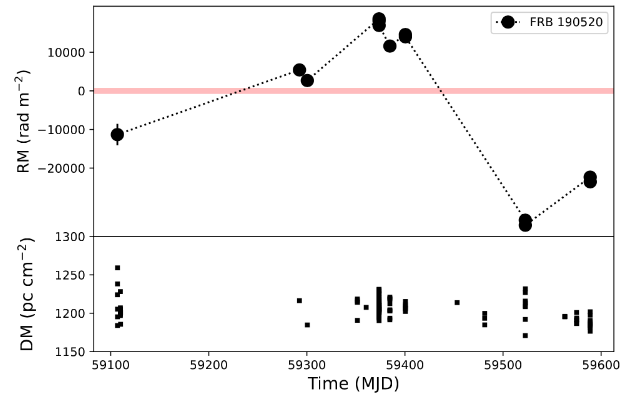
Challenges to the "Magnetars make them all" hypothesis

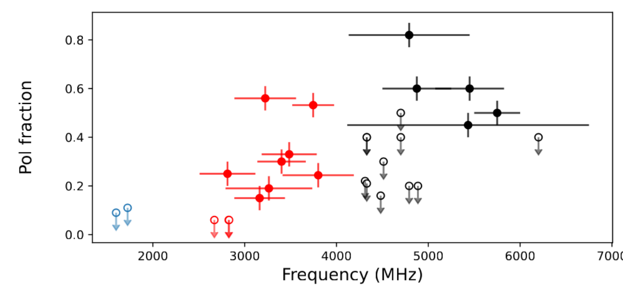
- Active repeater data show complicated, dynamically evolving, magnetized environments
- One repeater was found in a globular cluster, where no significant star formation is expected
- Many host galaxies and the FRB locations in the galaxies are not actively star forming
- CHIME FRBs seem not to globally track the star formation history of the universe

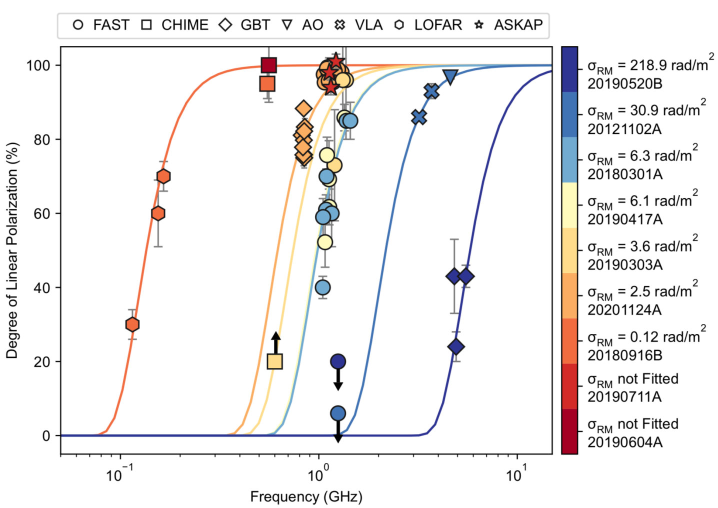
Complicated environments

Y. Feng et al. 2022; Science; H. Xu et al. 2022, Nature; Anna-Thomas et al. 2022; Dai et al. 2022





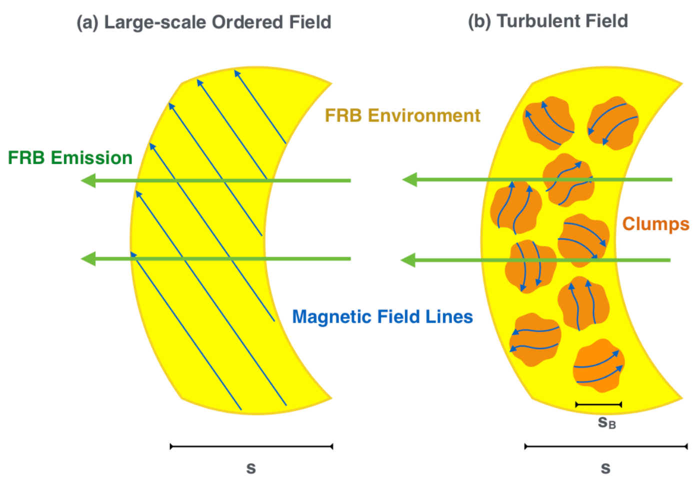


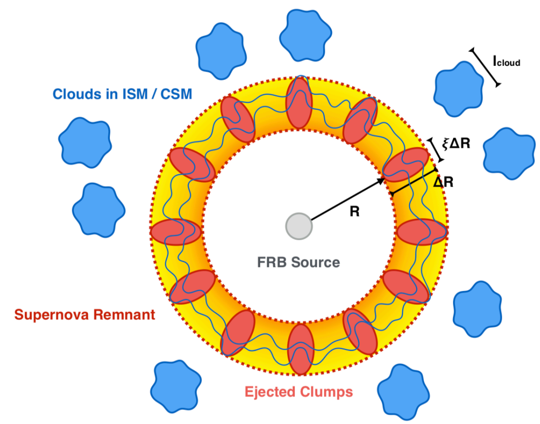


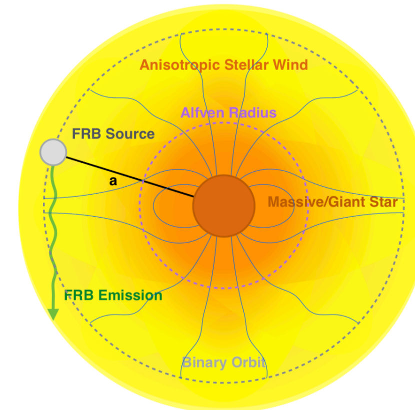
Dynamically evolving, magnetized environment

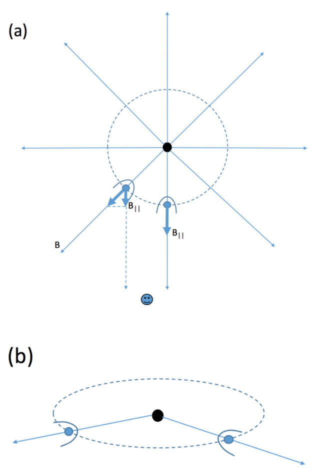
Physical scenarios for RM variations

Yang, Xu & Zhang, 2022, arXiv:2208.08712

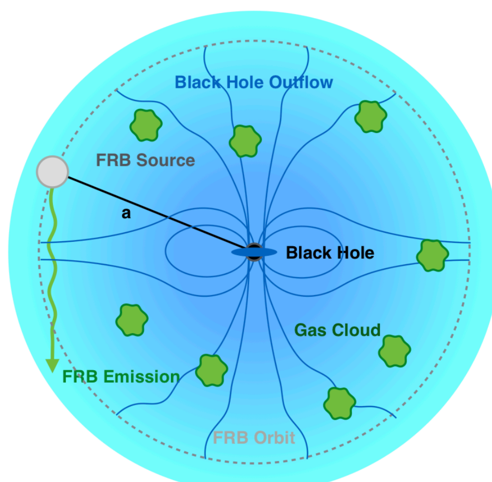






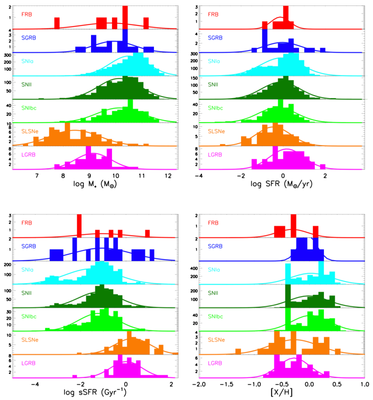


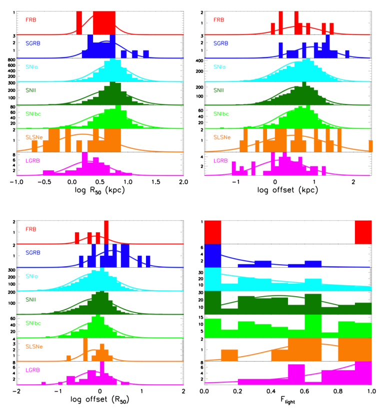
Zhang, 2018, ApJL

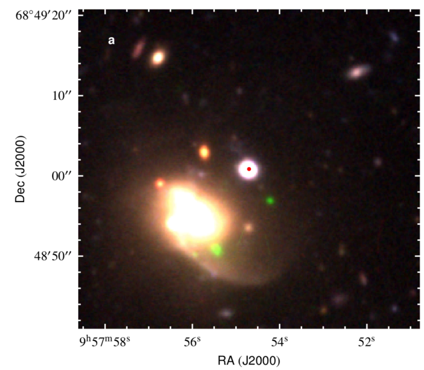


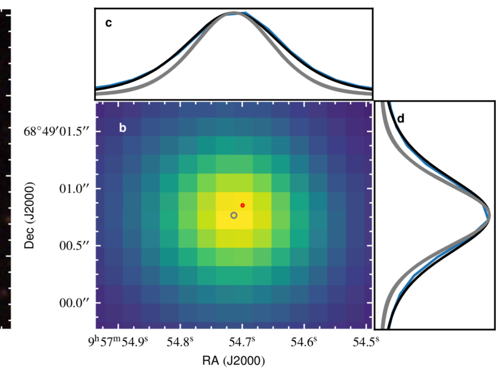
- Monotonic evolution (SN remnants) disfavored
- Binary companion?
- Multi-path?

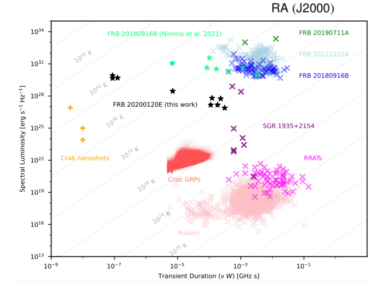
FRB host galaxies & locations

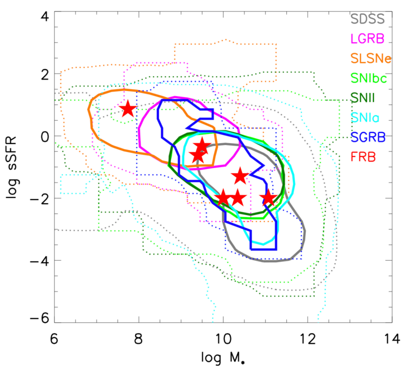












Host galaxy properties & FRB locations consistent with old population:

Li & Zhang, 2020, ApJL, 924, L14

FRB 20200120E; M81 globular cluster
Kirsten et al. 2022; Nimmo et al. 2022

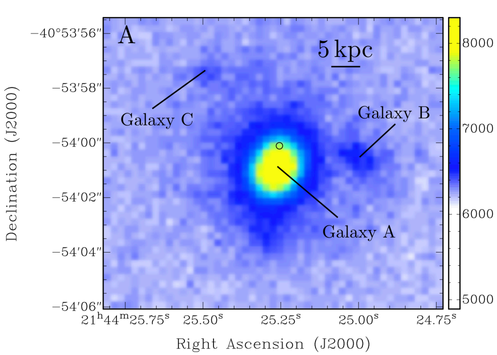
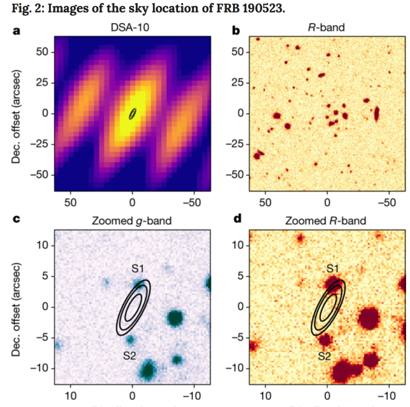
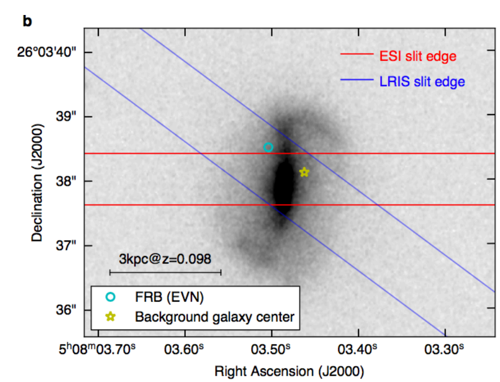


Fig. 2: Images of the sky location of FRB 190523.



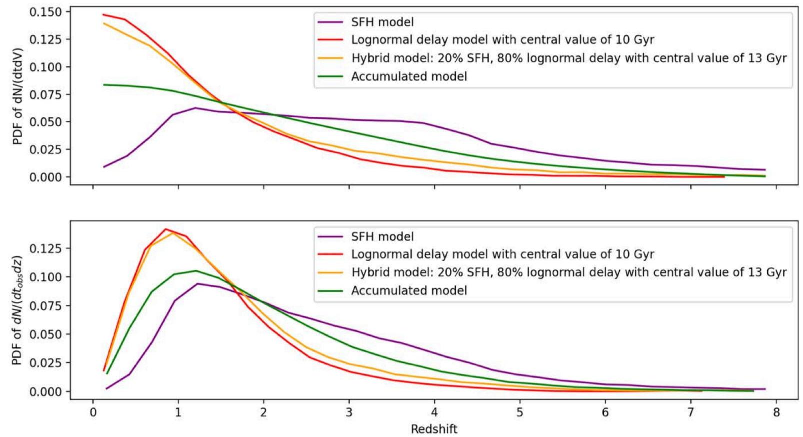


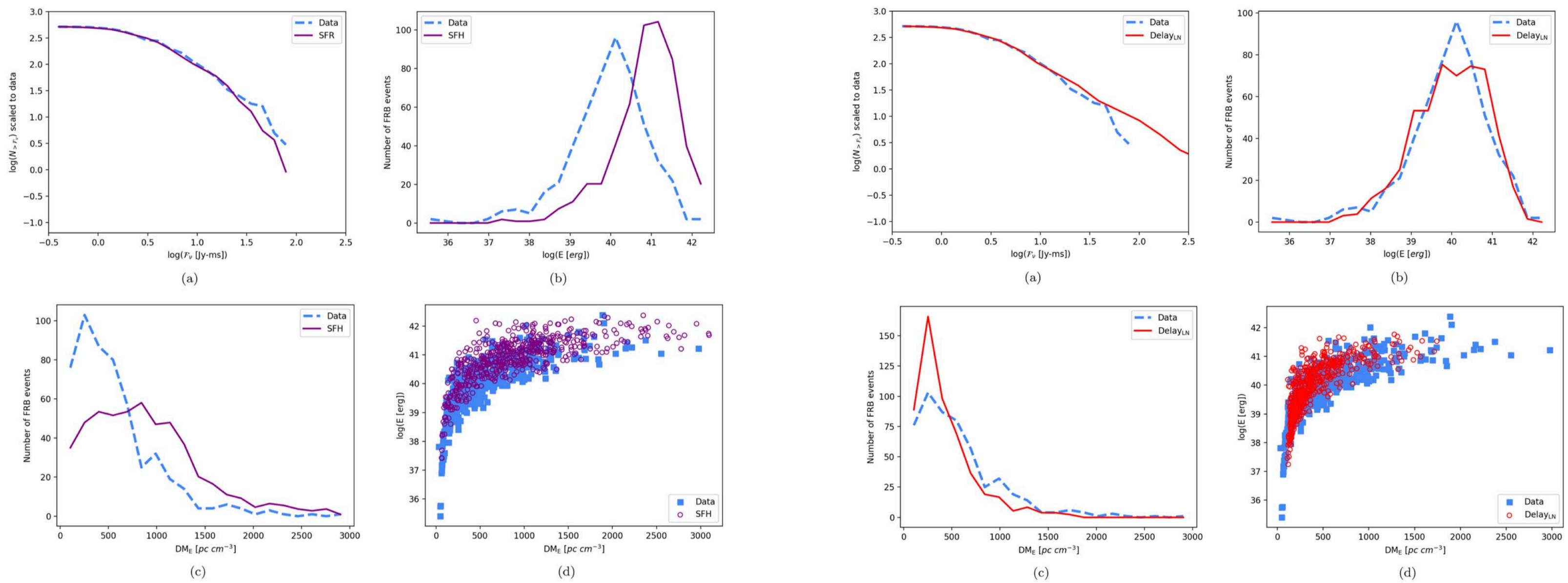
Bannister et al. 2019

Ravi et al. 2019

FRB 20201124A, Xu et al. 2022

CHIME FRBs do not track star formation

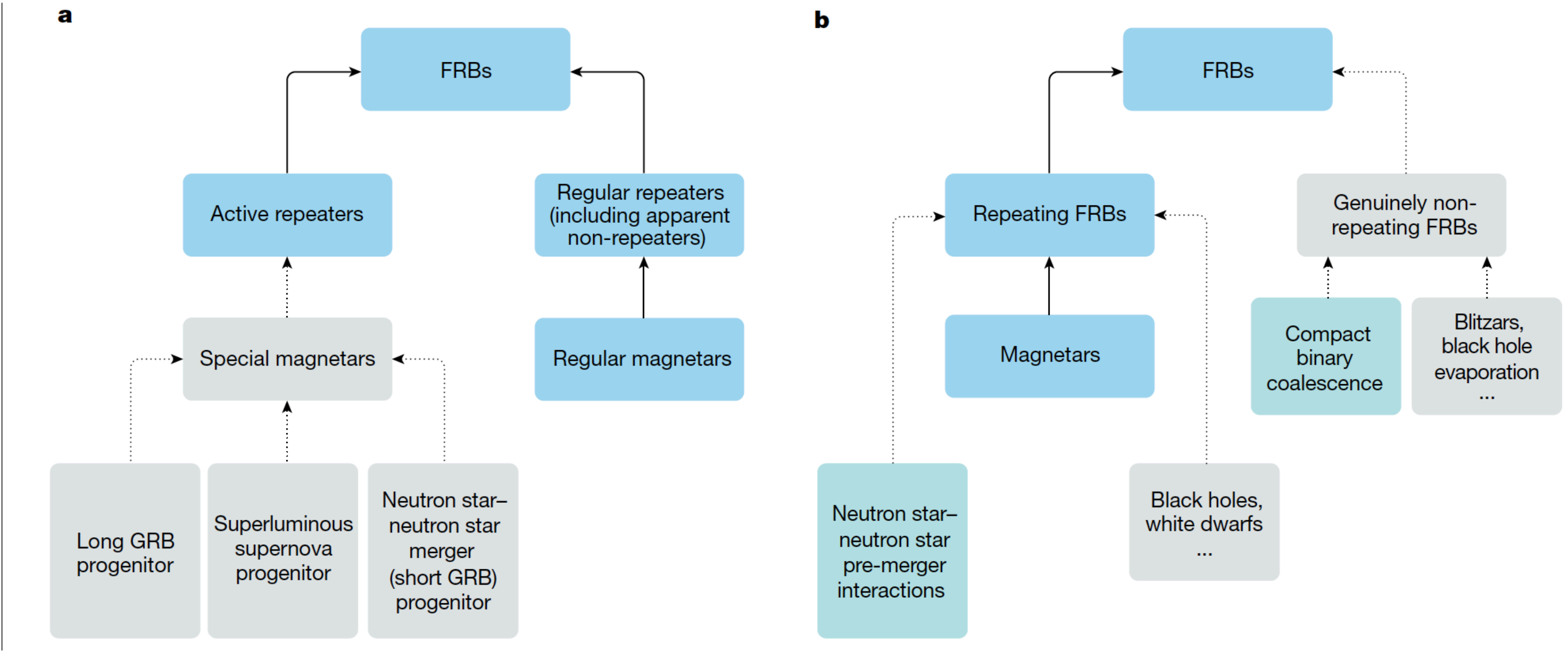




R. C. Zhang & B. Zhang, 2022, ApJL, 924, L14

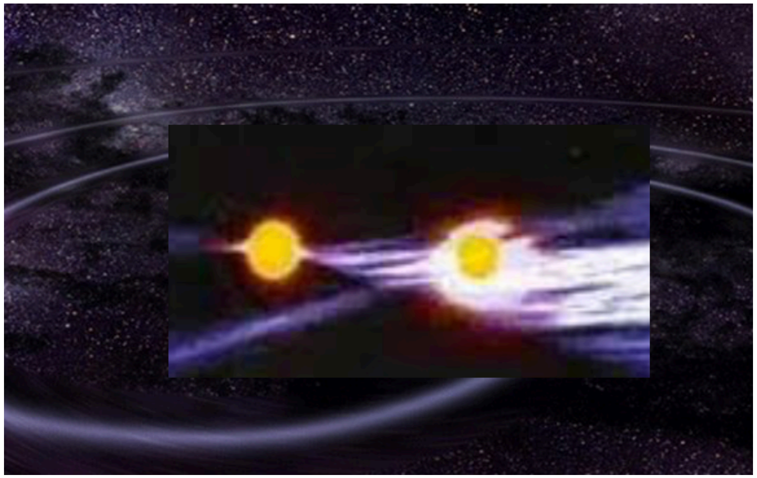
see also Qiang et al. 2021; Hashimoto et al. 2022

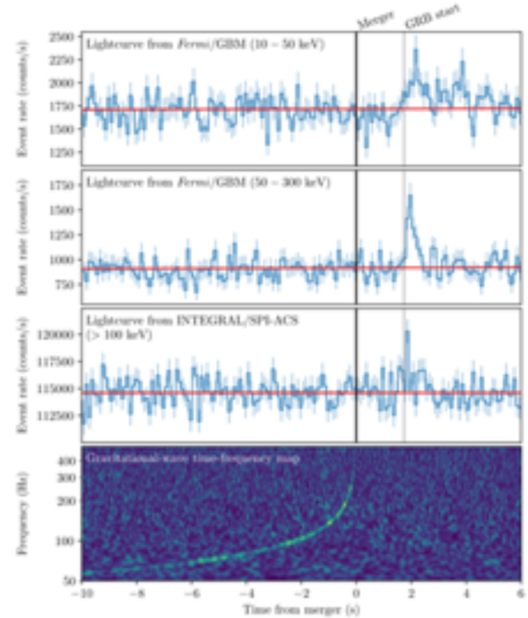
Two extreme versions of source models

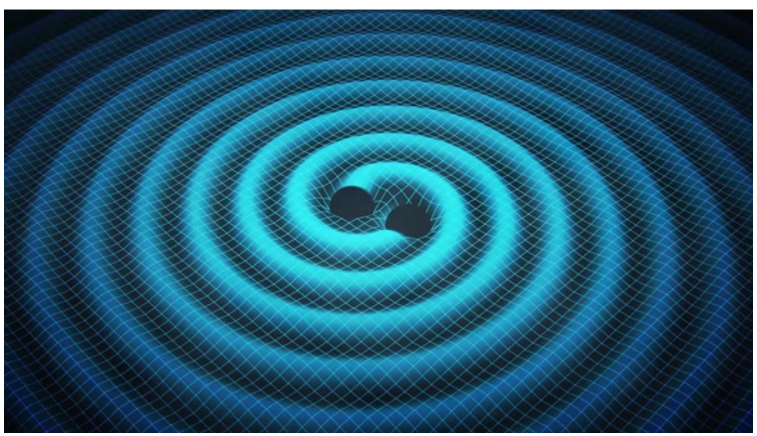


BZ, 2020, Nature, 587, 45

Other scenarios
(with gravitational wave associations)

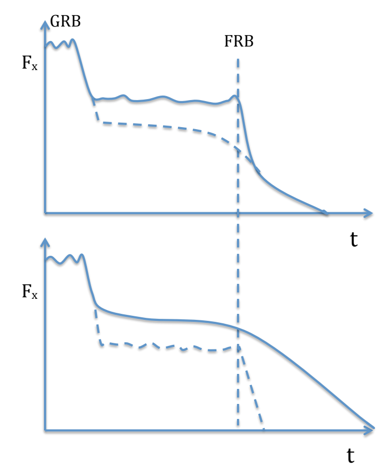






NS-NS mergers
NS-BH mergers
BH-BH mergers

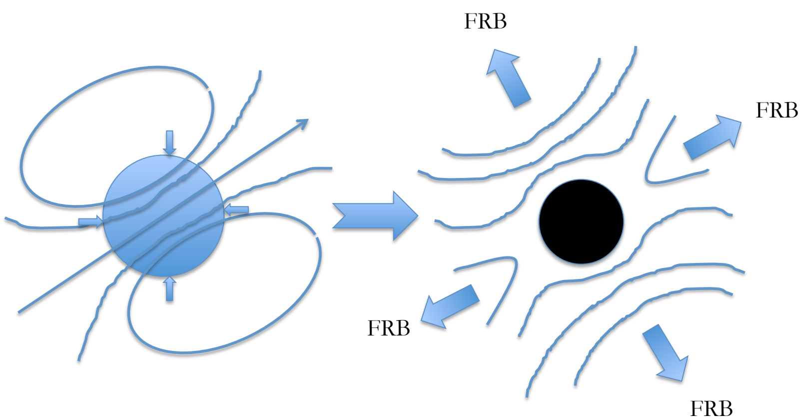
before, during, after

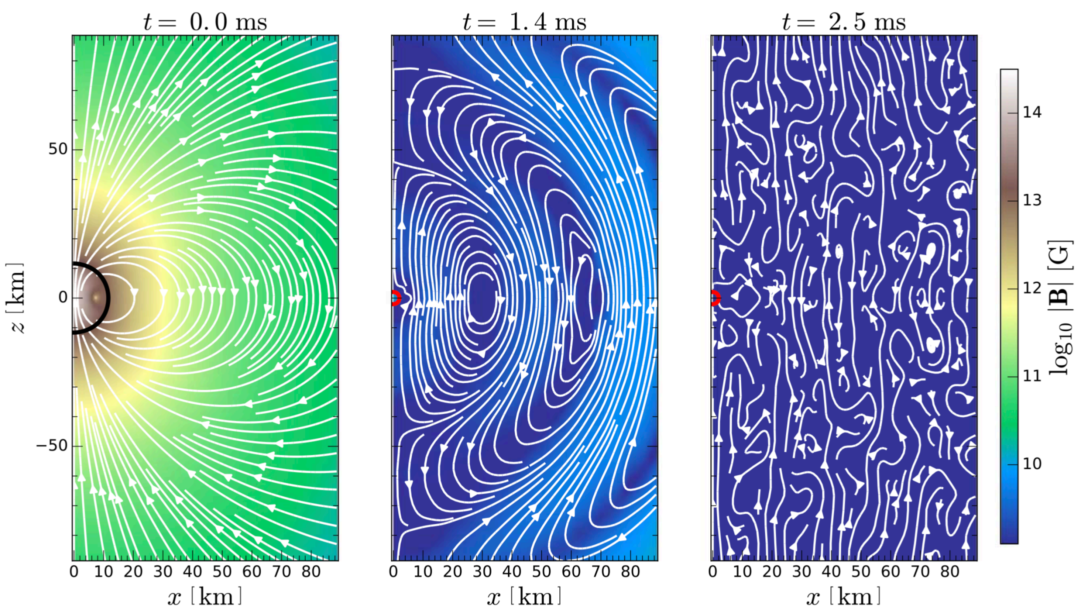


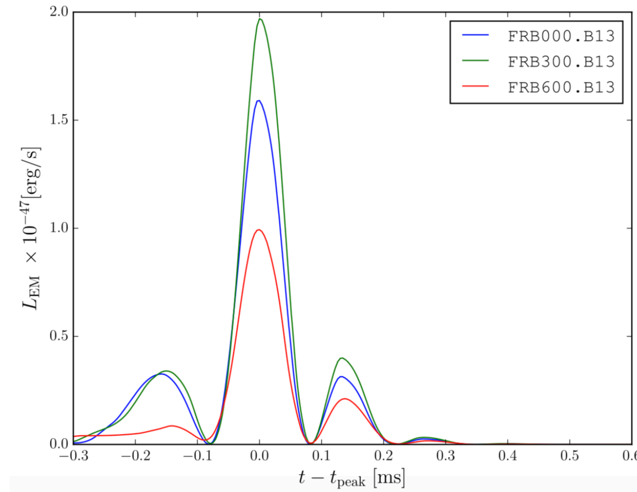
Zhang, 2014, ApJ, 780, L21

Blitzars

Falcke & Rezzolla (2014); Most et al. (2018)







Collapse of a supramassive neutron star (SMNS) leads to ejection of magnetosphere and the launch of a brief Poynting-flux burst

— an FRB?

Blitzar following a short GRB and BNS merger?

THE ASTROPHYSICAL JOURNAL LETTERS, 780:L21 (4pp), 2014 January 10 doi:10.1088/2041-8205/780/2/L21

A POSSIBLE CONNECTION BETWEEN FAST RADIO BURSTS AND GAMMA-RAY BURSTS

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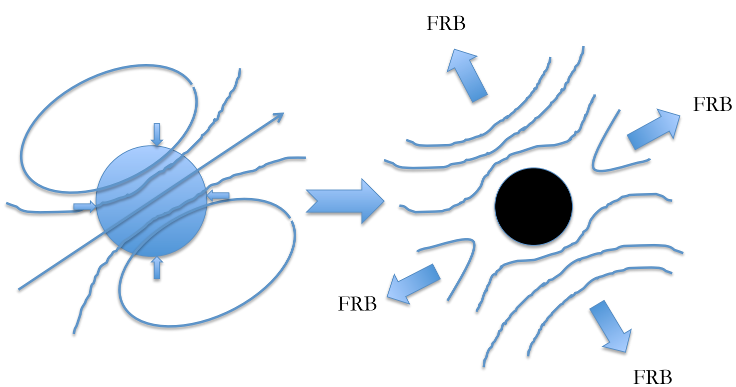
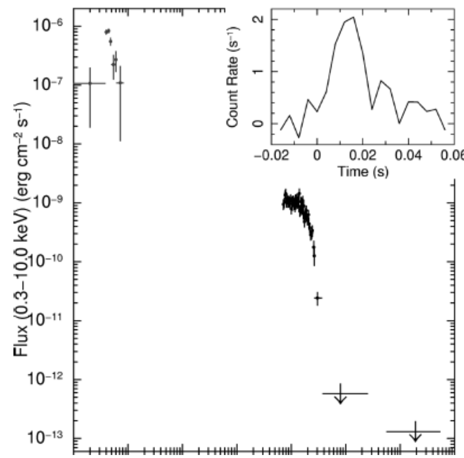
ABSTRACT

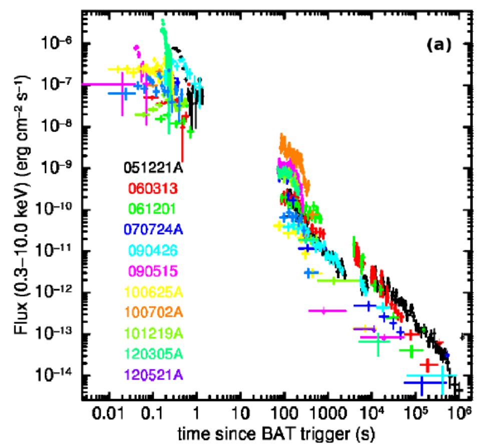
The physical nature of fast radio bursts (FRBs), a new type of cosmological transient discovered recently, is not known. It has been suggested that FRBs can be produced when a spinning supra-massive neutron star loses centrifugal support and collapses to a black hole. Here, we suggest that such implosions can happen in supra-massive neutron stars shortly (hundreds to thousands of seconds) after their births, and an observational signature of such implosions may have been observed in the X-ray afterglows of some long and short gamma-ray bursts (GRBs). Within this picture, a small fraction of FRBs would be physically connected to GRBs. We discuss possible multi-wavelength electromagnetic signals and gravitational wave signals that might be associated with FRBs, and propose an observational campaign to unveil the physical nature of FRBs. In particular, we strongly encourage a rapid radio follow-up observation of GRBs starting from 100 s after a GRB trigger.

Key words: gamma-ray burst: general – stars: black holes – stars: neutron

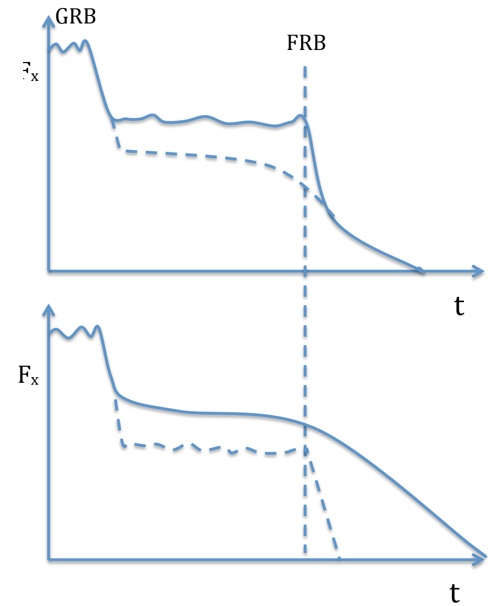
Online-only material: color figure







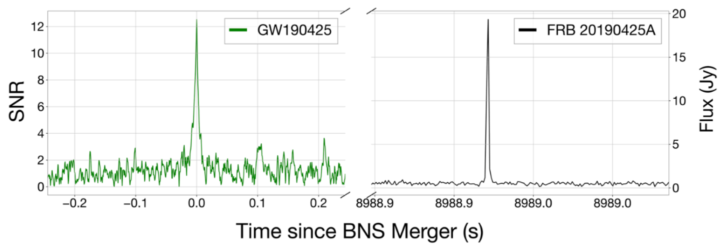
Rawlinson et al. 2010, 2013

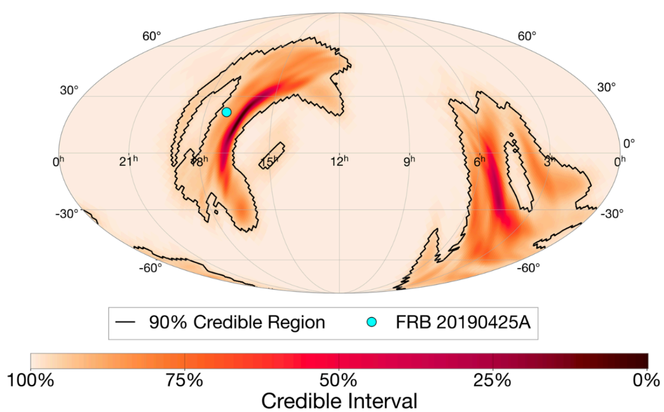


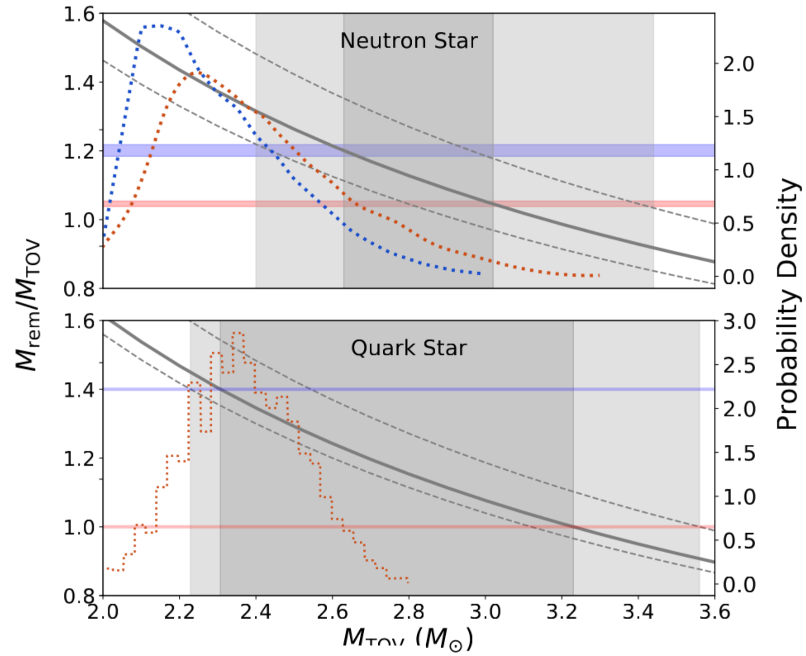
Zhang, 2014, ApJ, 780, L21

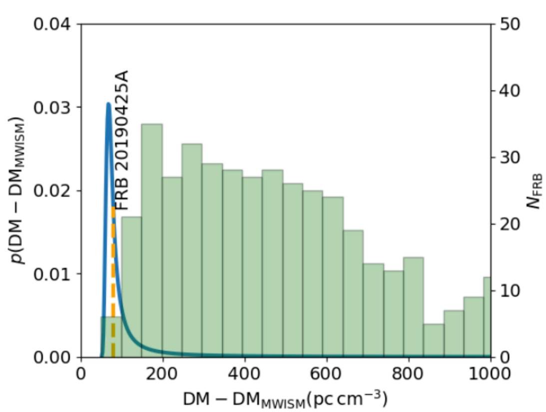
GW190425 & FRB 20190425A: an association?

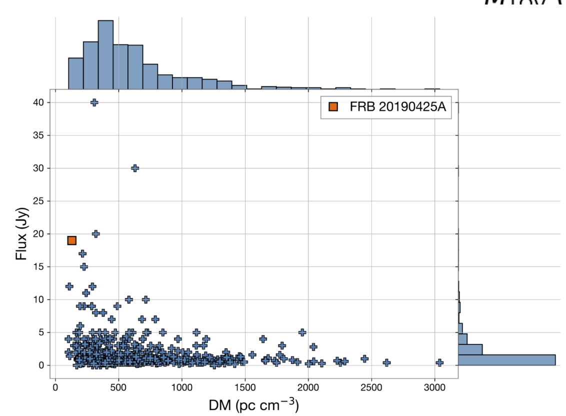
Moroianu et al. (2022), under review, **confidential please**











Random chance: 1.9×10^{-4}

Summary

- What?
  - Magnetars
  - Something else for repeaters? Older population? Binaries?
  - Genuinely non-repeating FRBs? GW association for some?
- Where?
  - Location: magnetospheres vs. shocks
- How?
  - Curvature radiation, ICS, something else?
- Prospects
  - Observations:
    - Galactic FRBs hold the key to identify sources
    - Multi-messenger observations/data analyses hold the key to identify/eliminate models
  - Theory:
    - Debate on coherent mechanism will continue (cf. pulsar field)
    - Magnetars vs. other systems (BHs, CBCs, blitzars …)