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The Physics of Fast Radio Bursts

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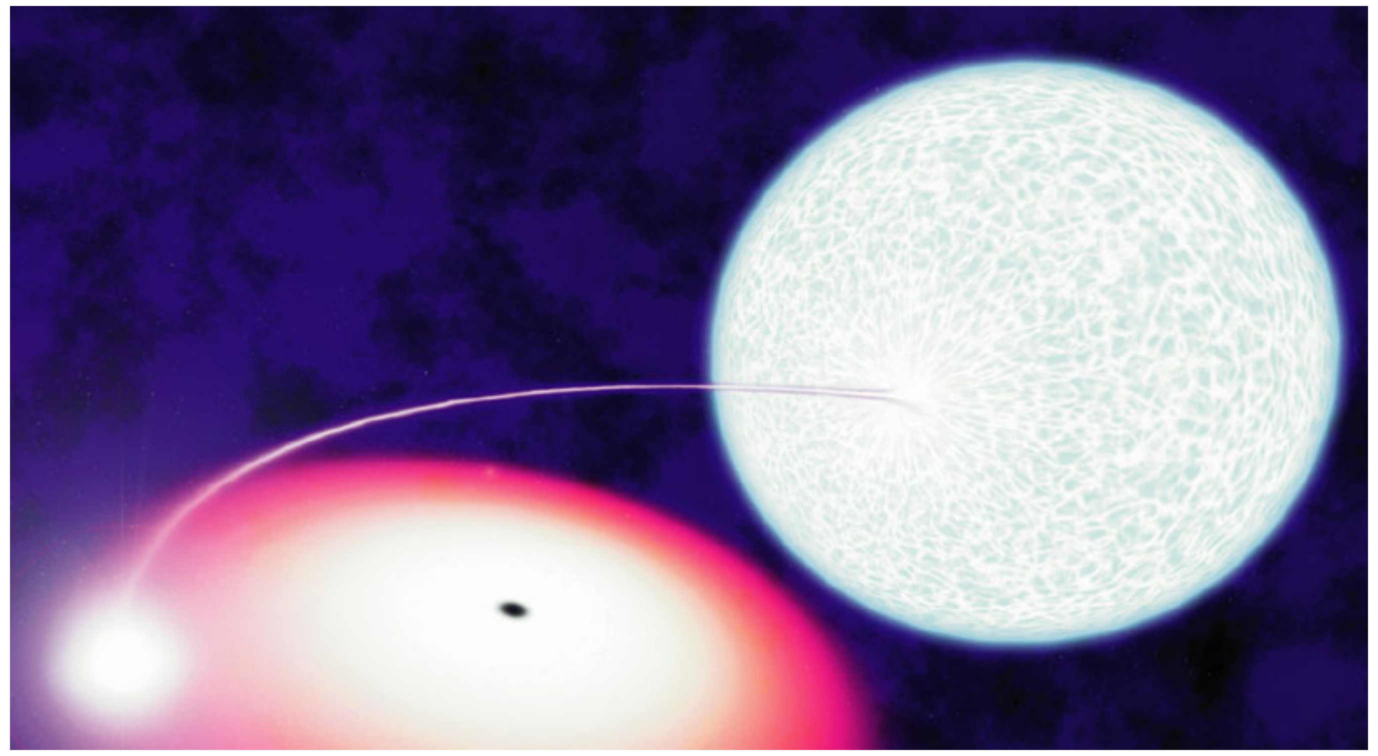
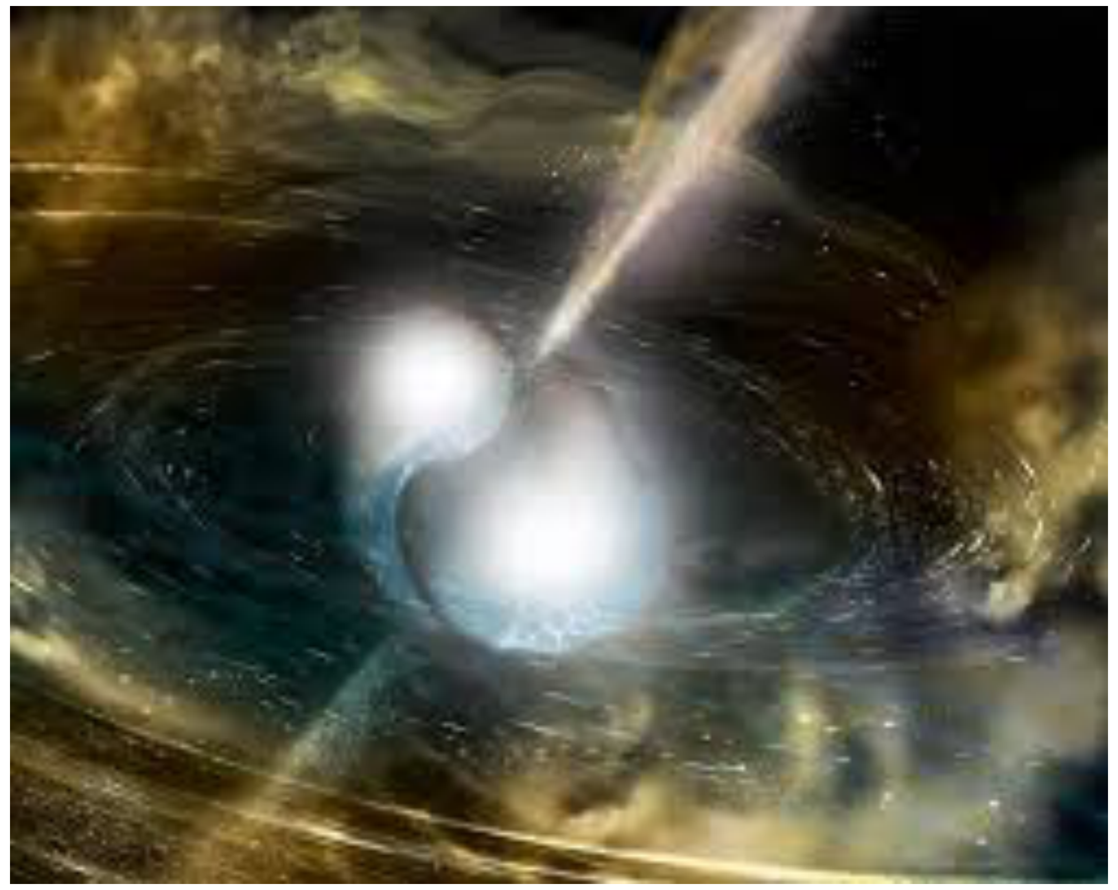
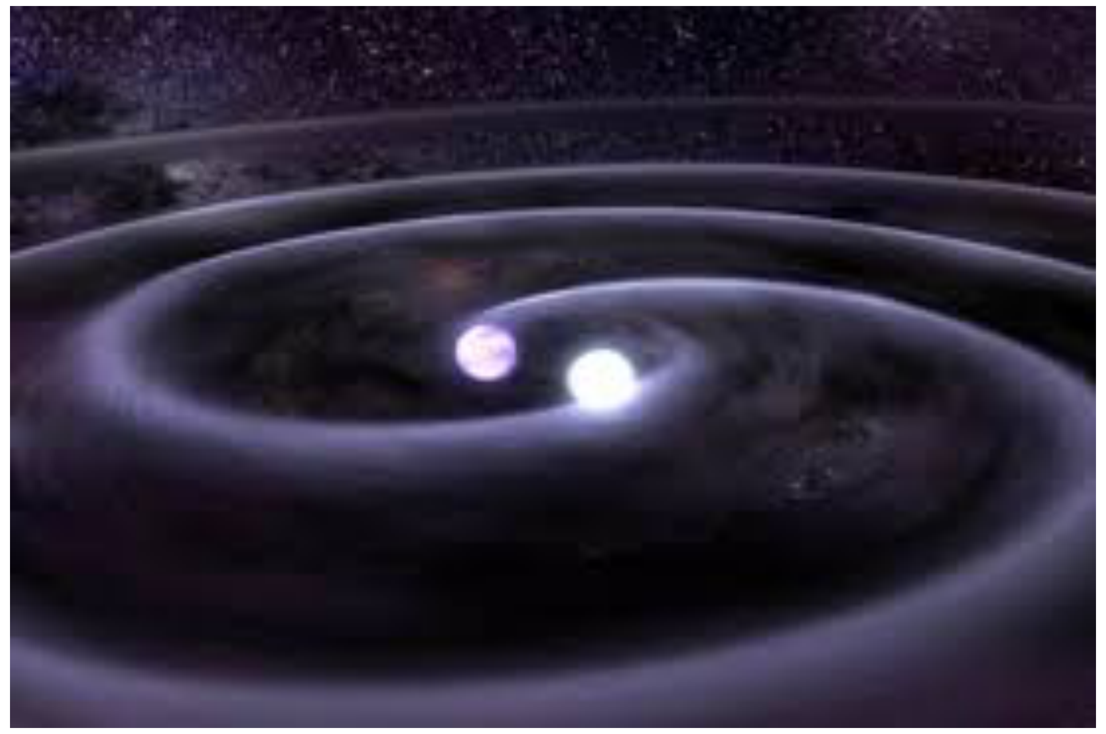
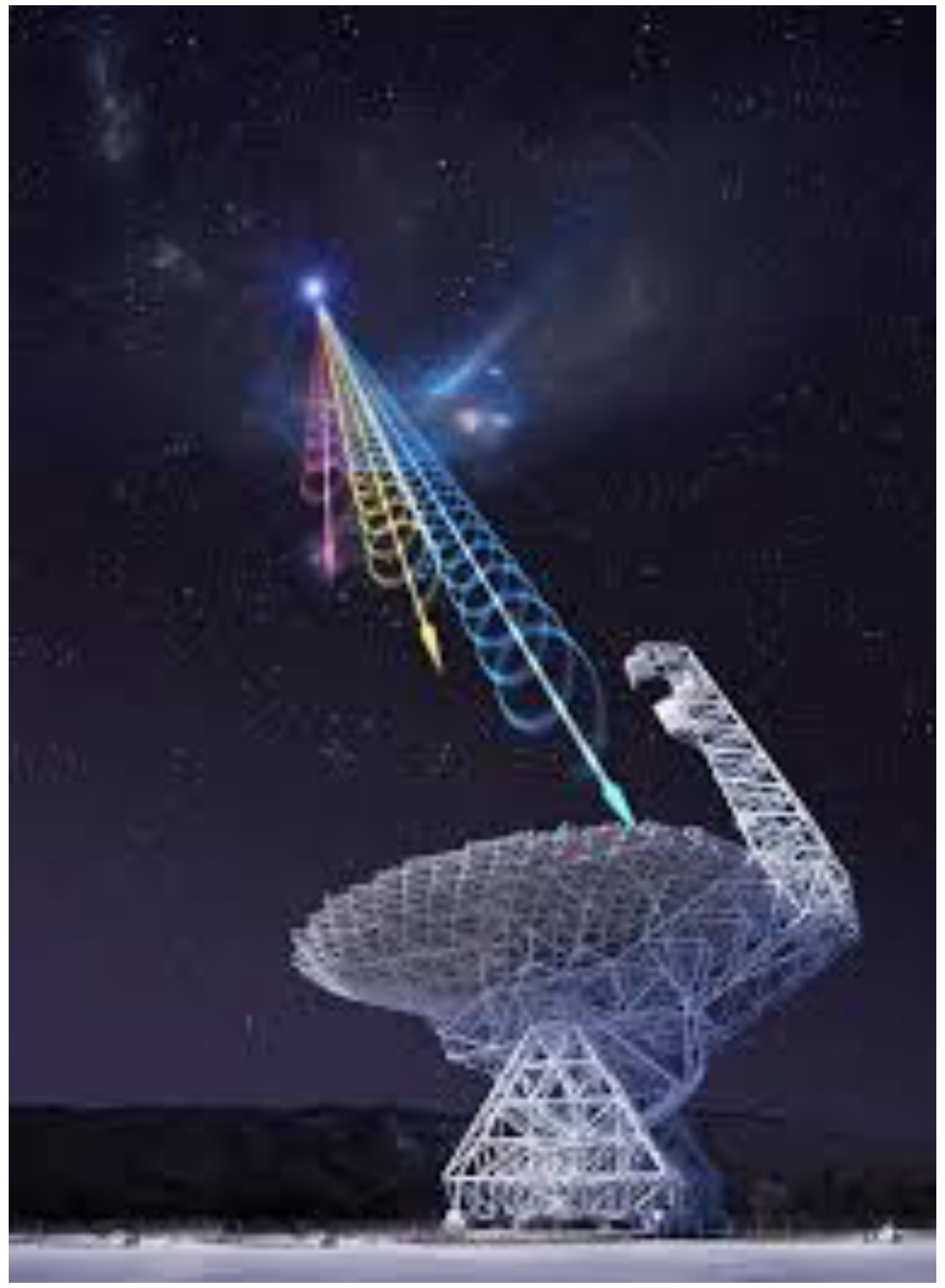
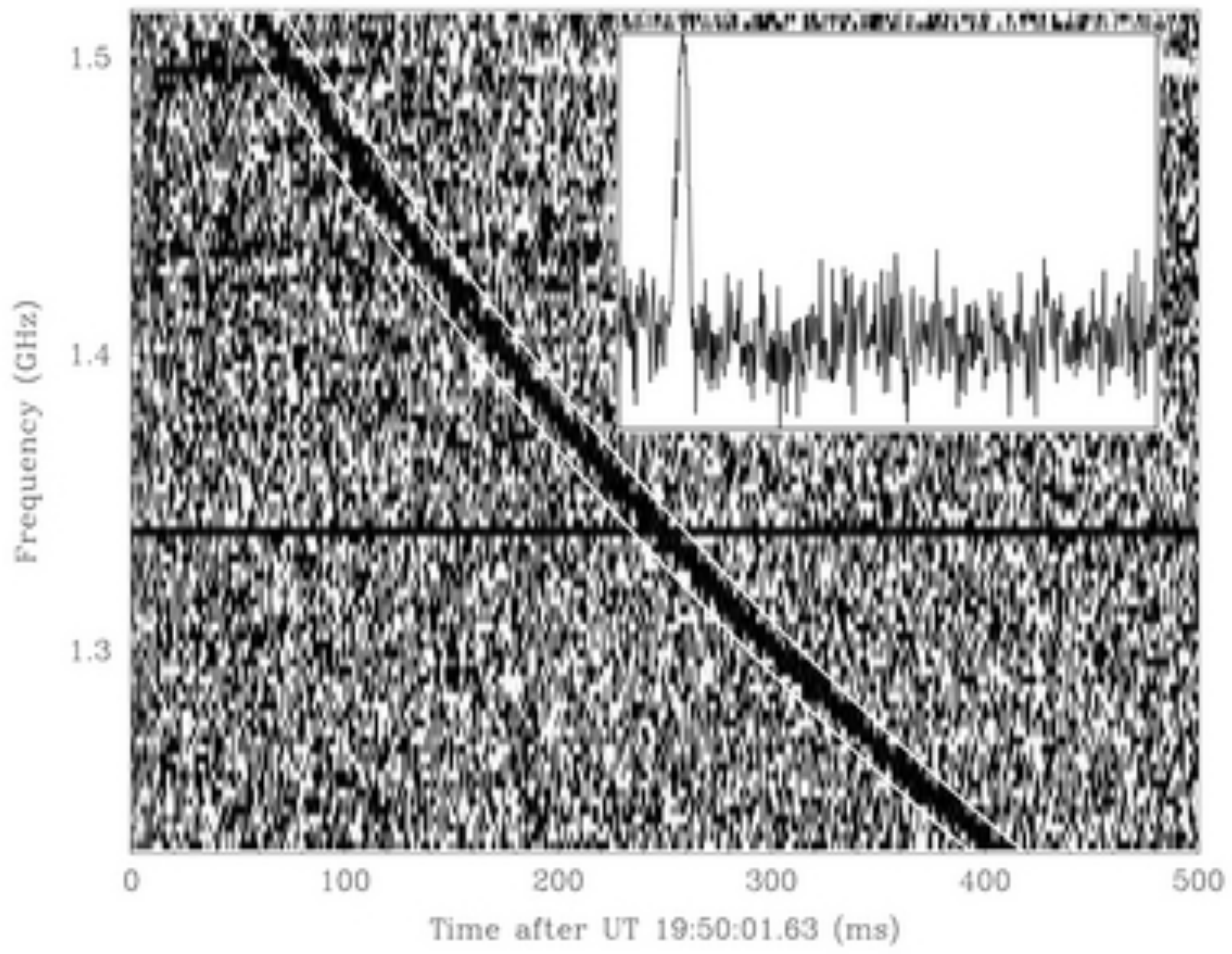


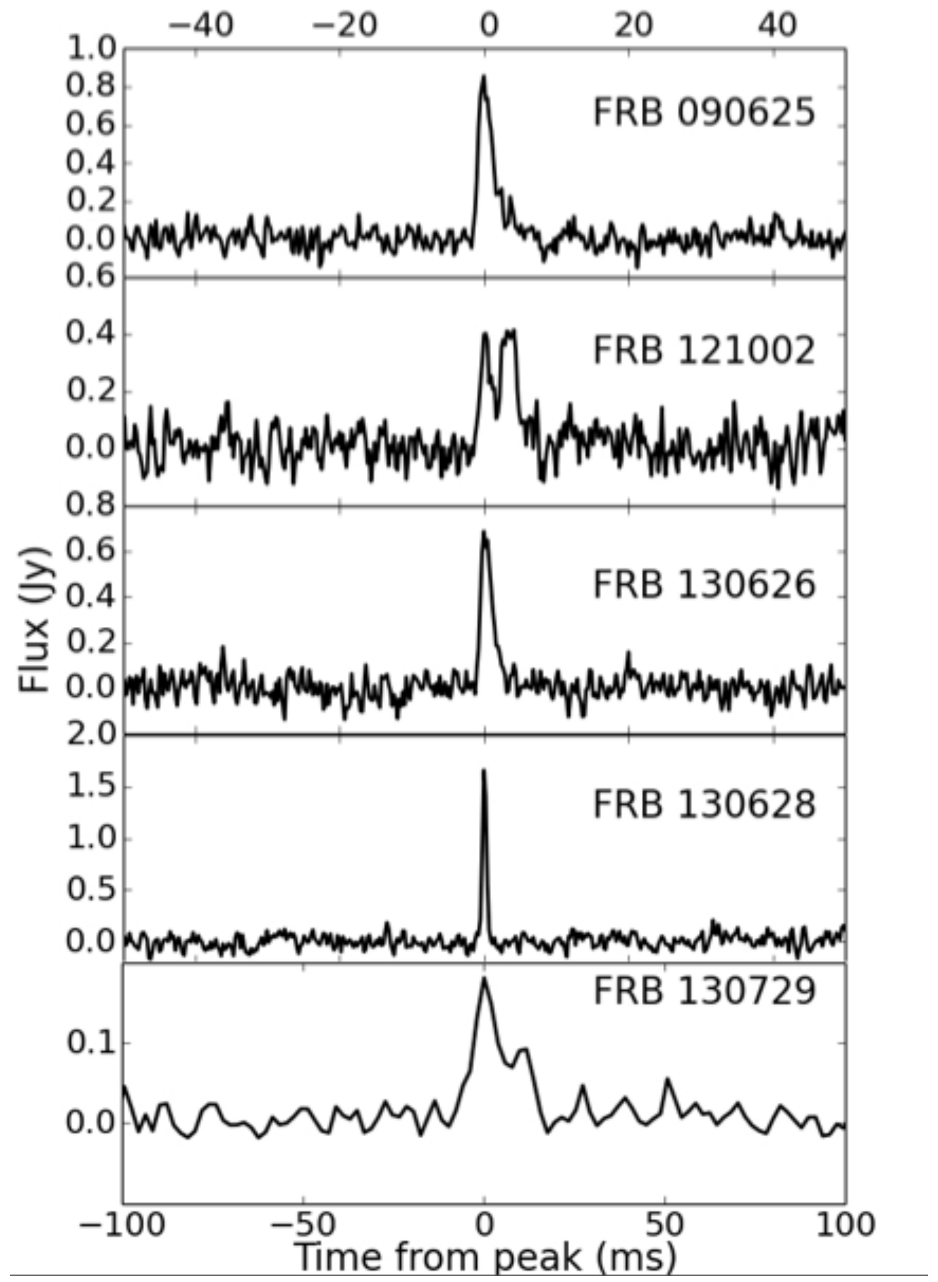


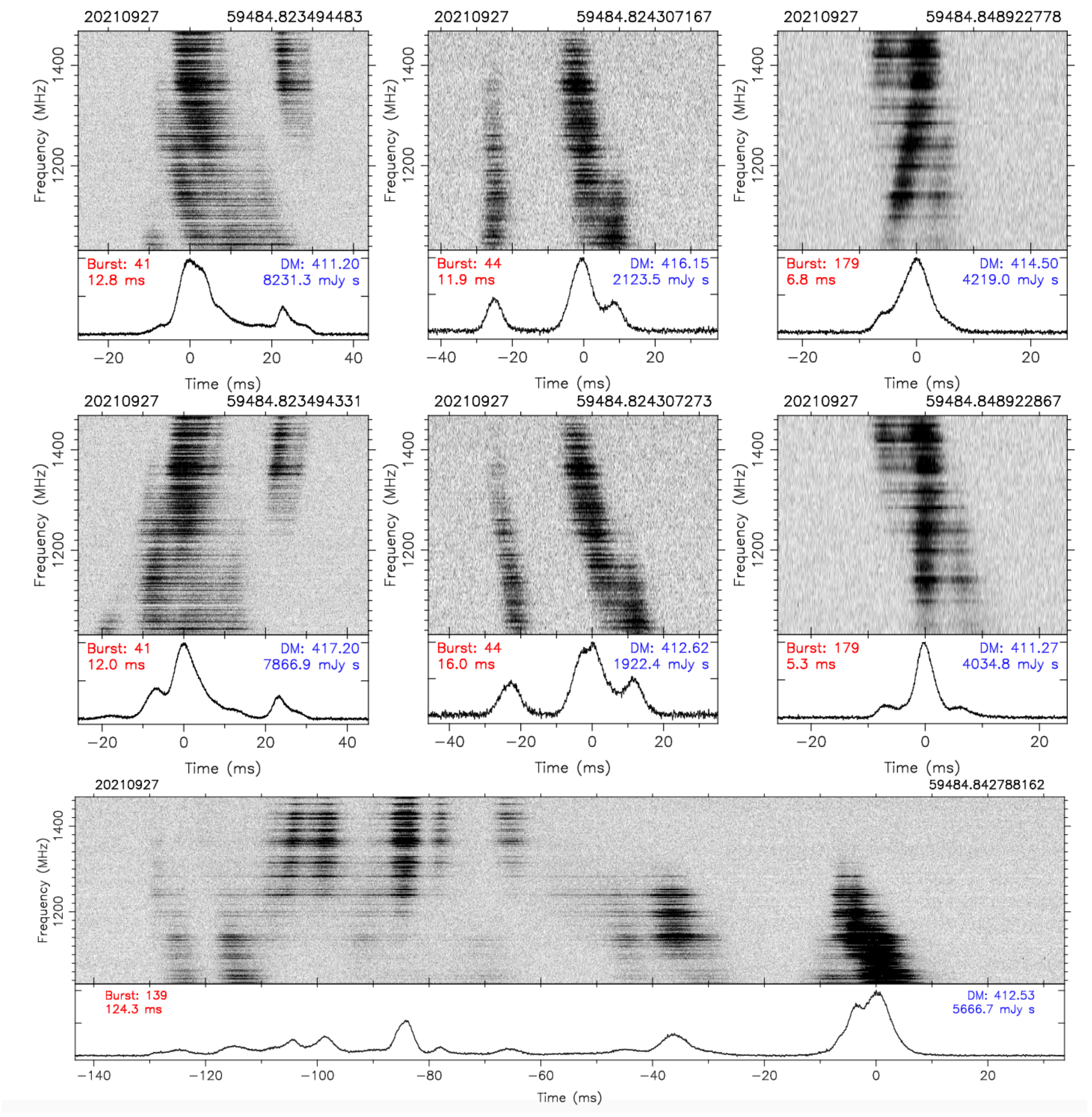
A dynamic universe



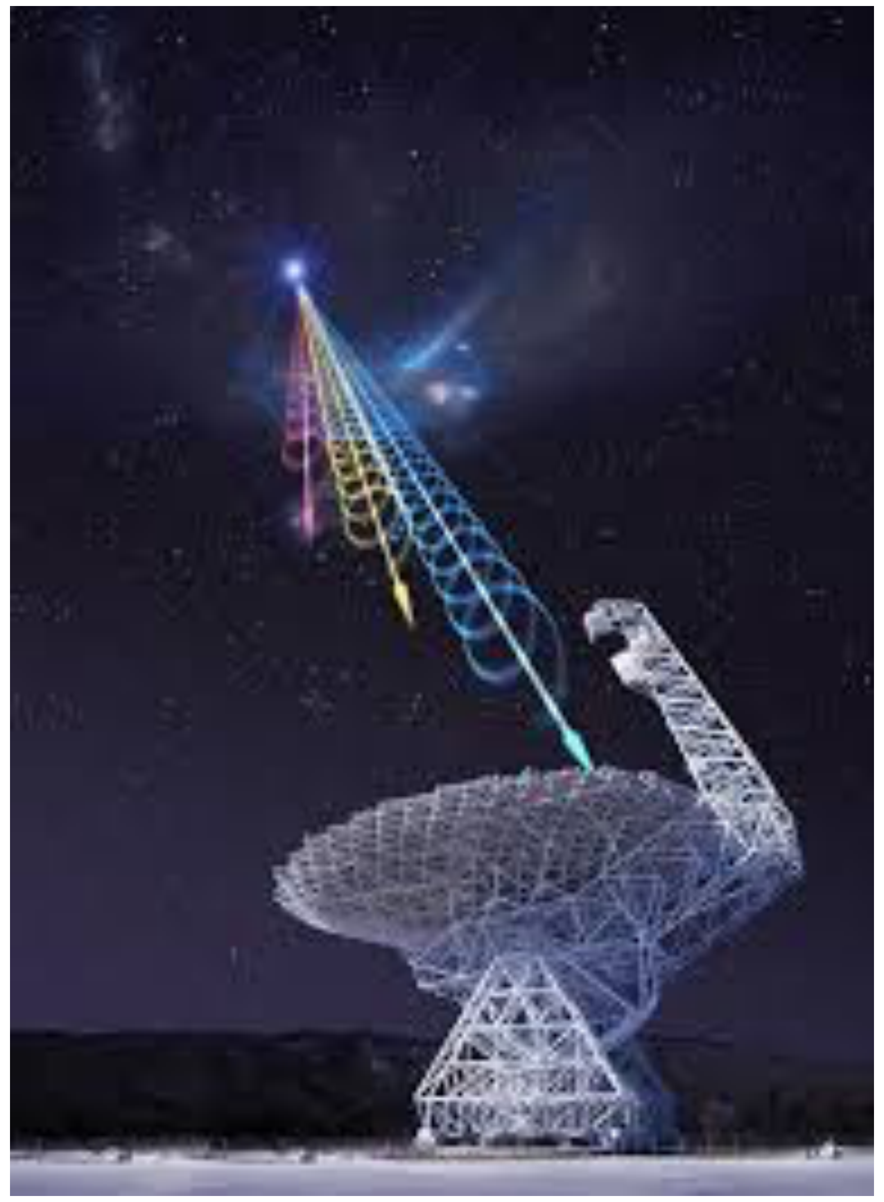



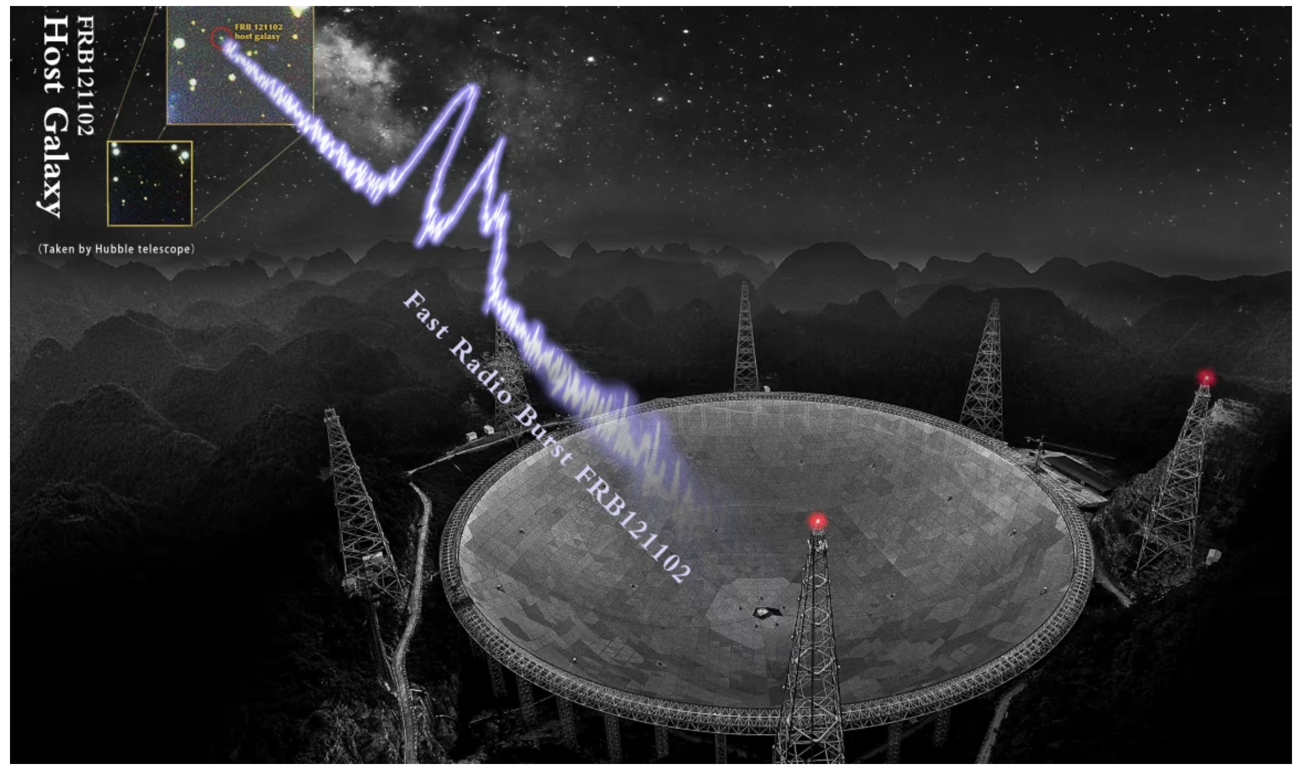






Fast Radio Bursts





The Physics of Fast Radio Bursts

Review

The physical mechanisms of fast radio bursts

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Bing Zhang[1]✉

Fast radio bursts are mysterious millisecond-duration transients prevalent in the radio sky. Rapid accumulation of data in recent years has facilitated an understanding of the underlying physical mechanisms of these events. Knowledge gained from the neighbouring fields of gamma-ray bursts and radio pulsars has also offered insights. Here I review developments in this fast-moving field. Two generic categories of radiation model invoking either magnetospheres of compact objects (neutron stars or black holes) or relativistic shocks launched from such objects have been much debated. The recent detection of a Galactic fast radio burst in association with a soft gamma-ray repeater suggests that magnetar engines can produce at least some, and probably all, fast radio bursts. Other engines that could produce fast radio bursts are not required, but are also not impossible.

ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

Multiwavelength and Multimessenger Counterparts of Fast Radio Bursts

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REVIEWS OF MODERN PHYSICS, VOLUME 95, JULY–SEPTEMBER 2023

The physics of fast radio bursts

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Fast radio bursts (FRBs), millisecond-duration bursts prevailing in the radio sky, are the latest large puzzle in the Universe and have been a subject of intense observational and theoretical investigations in recent years. The rapid accumulation of observational data has painted the following sketch about the physical origin of FRBs: They predominantly originate from cosmological distances, so their sources produce the most extreme coherent radio emission in the Universe; at least some, probably most, FRBs are repeating sources that do not invoke cataclysmic events; and at least some FRBs are produced by magnetars, neutron stars with the strongest magnetic fields in the Universe. Many open questions regarding the physical origin(s) and mechanism(s) of FRBs remain. This review addresses the phenomenology and possible underlying physics of FRBs. Topics include a summary of the observational data, basic plasma physics, general constraints on FRB models from the data, radiation mechanisms, source and environment models, and propagation effects, as well as FRBs as cosmological probes. Current pressing problems and future prospects are also discussed.

Annu. Rev. Nucl. Part. Sci. 2024. 74:89–112

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https://doi.org/10.1146/annurev-nucl-102020-124444

Keywords

fast radio bursts, neutrinos, gravitational waves, multimessenger astrophysics

Abstract

Fast radio bursts (FRBs) are brief, highly dispersed bursts detected in the radio band that originate from cosmological distances. The only such event detected in the Milky Way Galaxy, FRB 20200428D—which was associated with an X-ray burst emitted by a magnetar named SGR J1935+2154—revealed the first case of a multiwavelength counterpart of an FRB. Counterparts in other wavelengths accompanying or following FRBs, as well as the bright emission associated with the progenitor of the FRB engine, have been proposed in various FRB models, but no robust detection has been made so far. In general, FRBs as we know them are not favored multimessenger emitters. Nonetheless, possible neutrino and gravitational wave emission signals associated with FRBs or FRB-like events have been discussed in the literature. Here I review these suggested multiwavelength and multimessenger counterparts of FRBs or FRB-like events and the observational progress in searching for these signals. Topics include multiwavelength (X-rays, γ-rays, optical) emission and neutrino emission from FRBs within the framework of the magnetar source models and possible FRB-like events associated with gravitational waves.

host galaxy …

polarization …

SGR connection

Detective's job: A lot of fun!

Respect data
Remove theoretical prejudice

Special acknowledgment

FAST FRB Key Science Project

> 100 members from >20 institutions
>25 papers published/accepted (8 NS), >10 papers being reviewed or in preparation

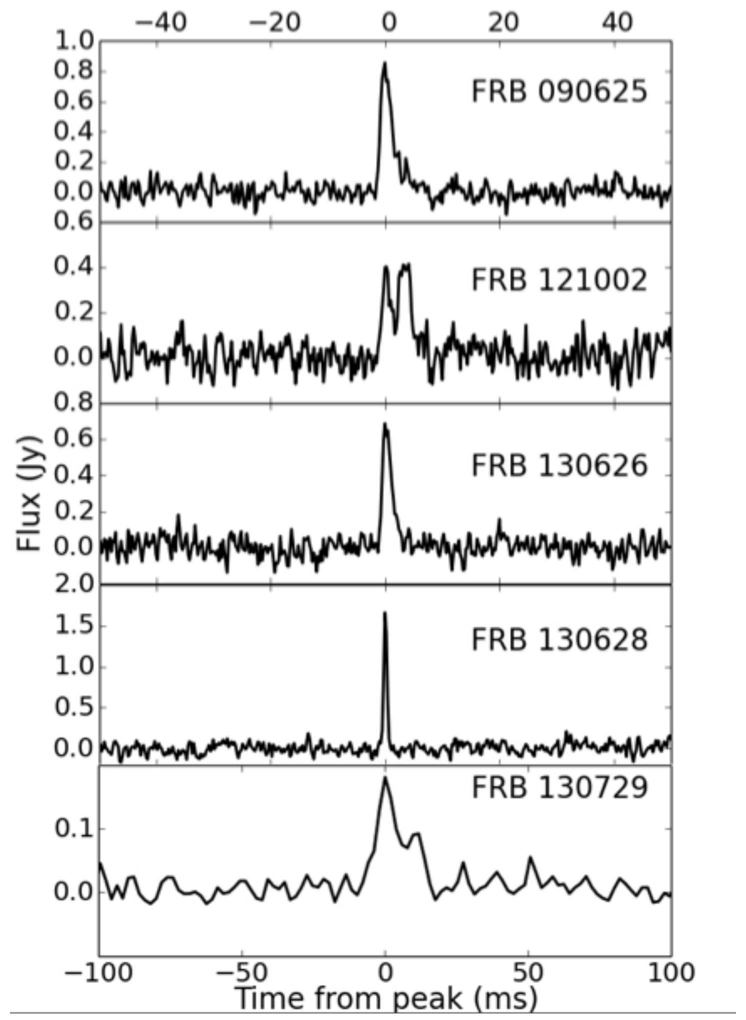
Also: **CRAFTS**, **GPPS**, and many PI programs

Observations

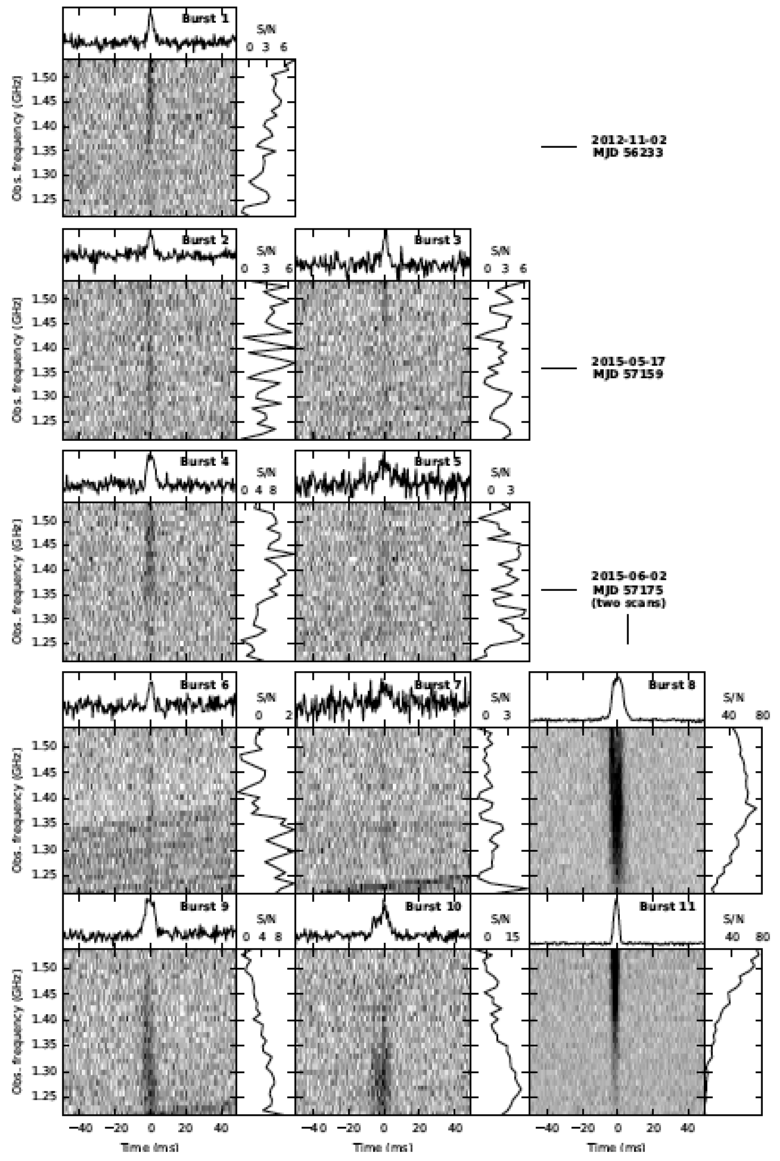
Finger prints, foot prints & smoking guns

FRB observational properties: Temporal

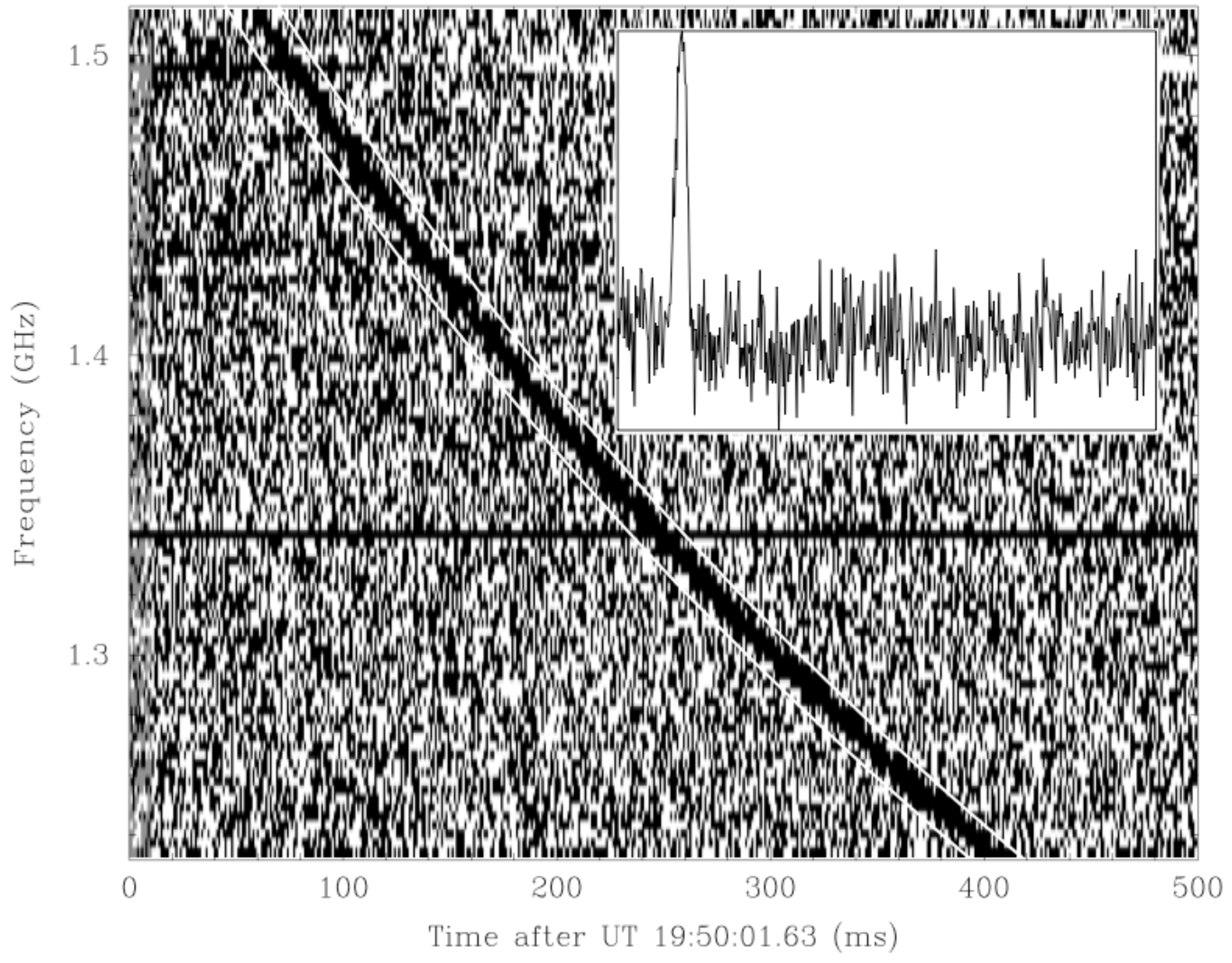
- Short duration: milli-seconds
- Internal structure & scattering tail
- Repetition:
  - Repeaters vs. apparent non-repeaters
  - Maybe all bursts repeat?
  - Possible observational dichotomy between repeaters and one-off FRBs



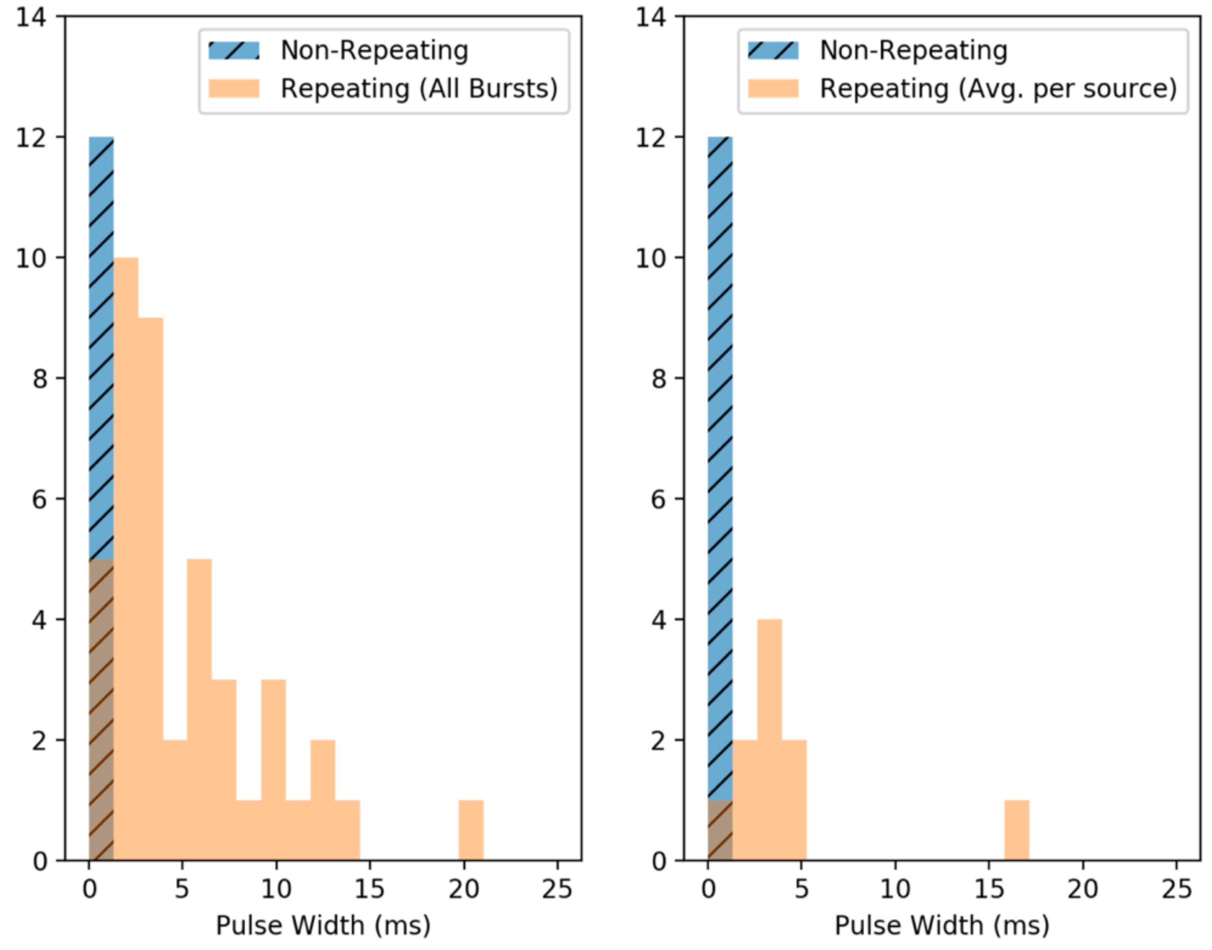
Champion et al. 2016



Spitler et al. 2016



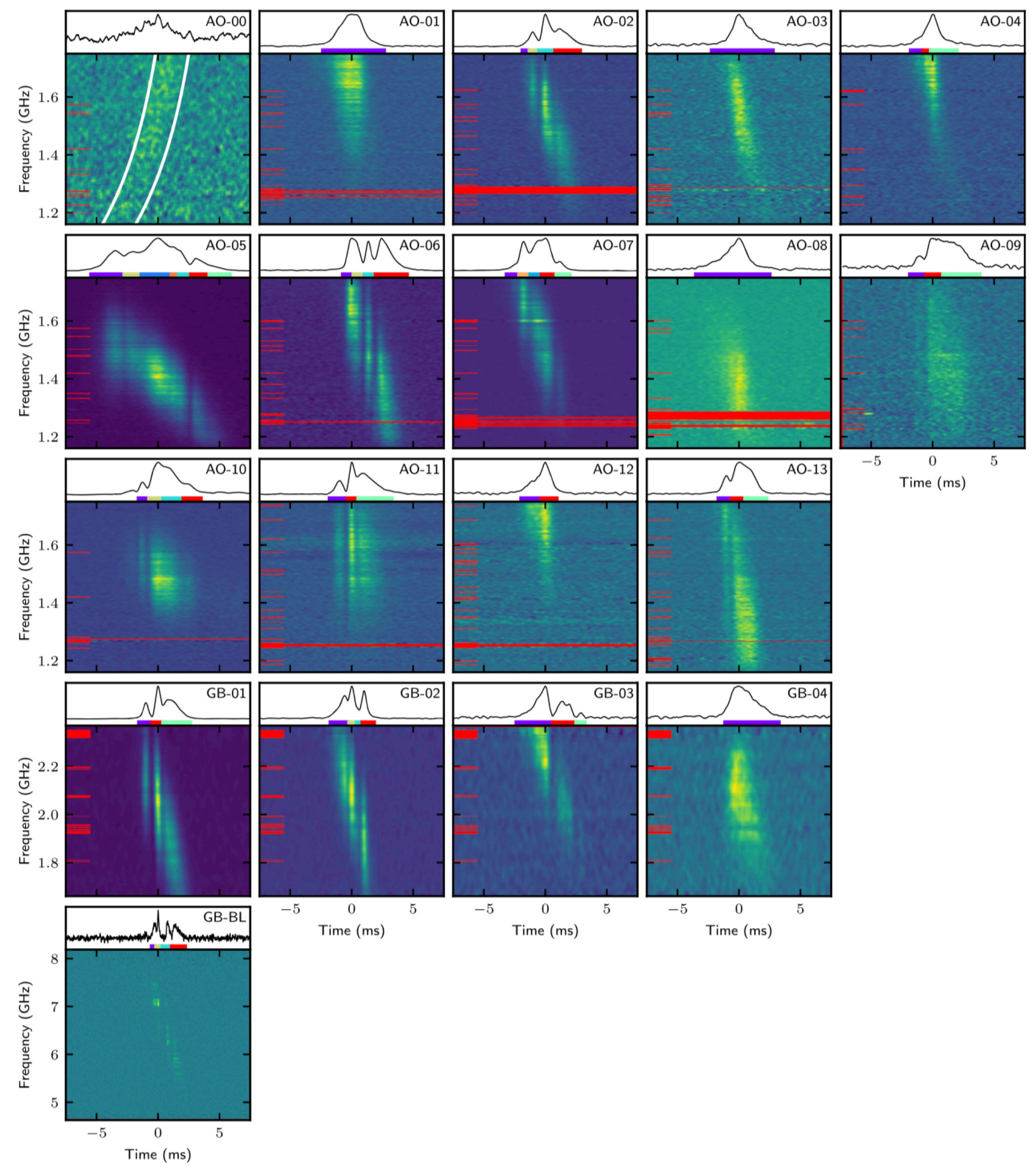
Lorimer et al. 2007



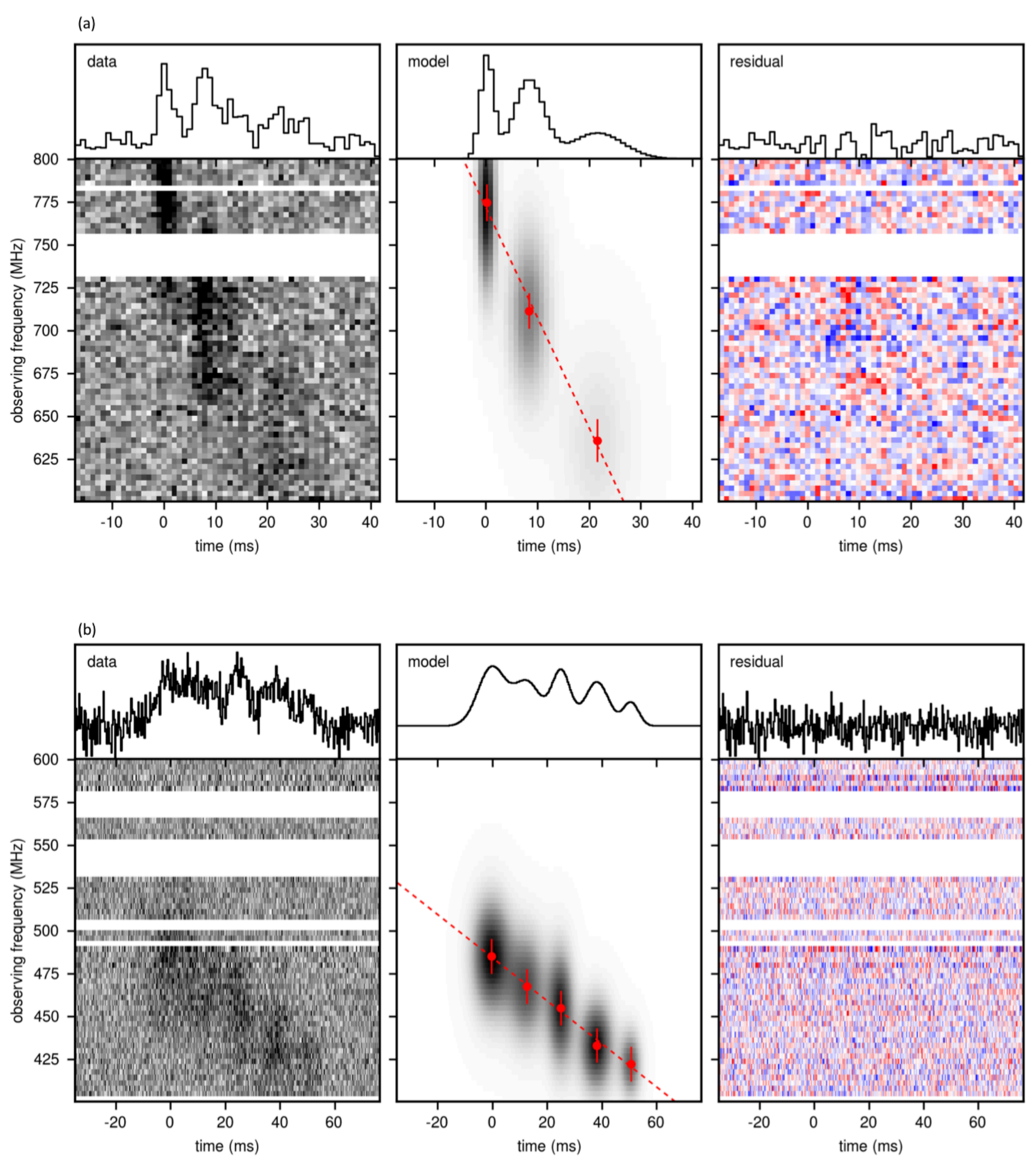
CHIME/FRB Collaboration, 2019

FRB observational properties: Spectral

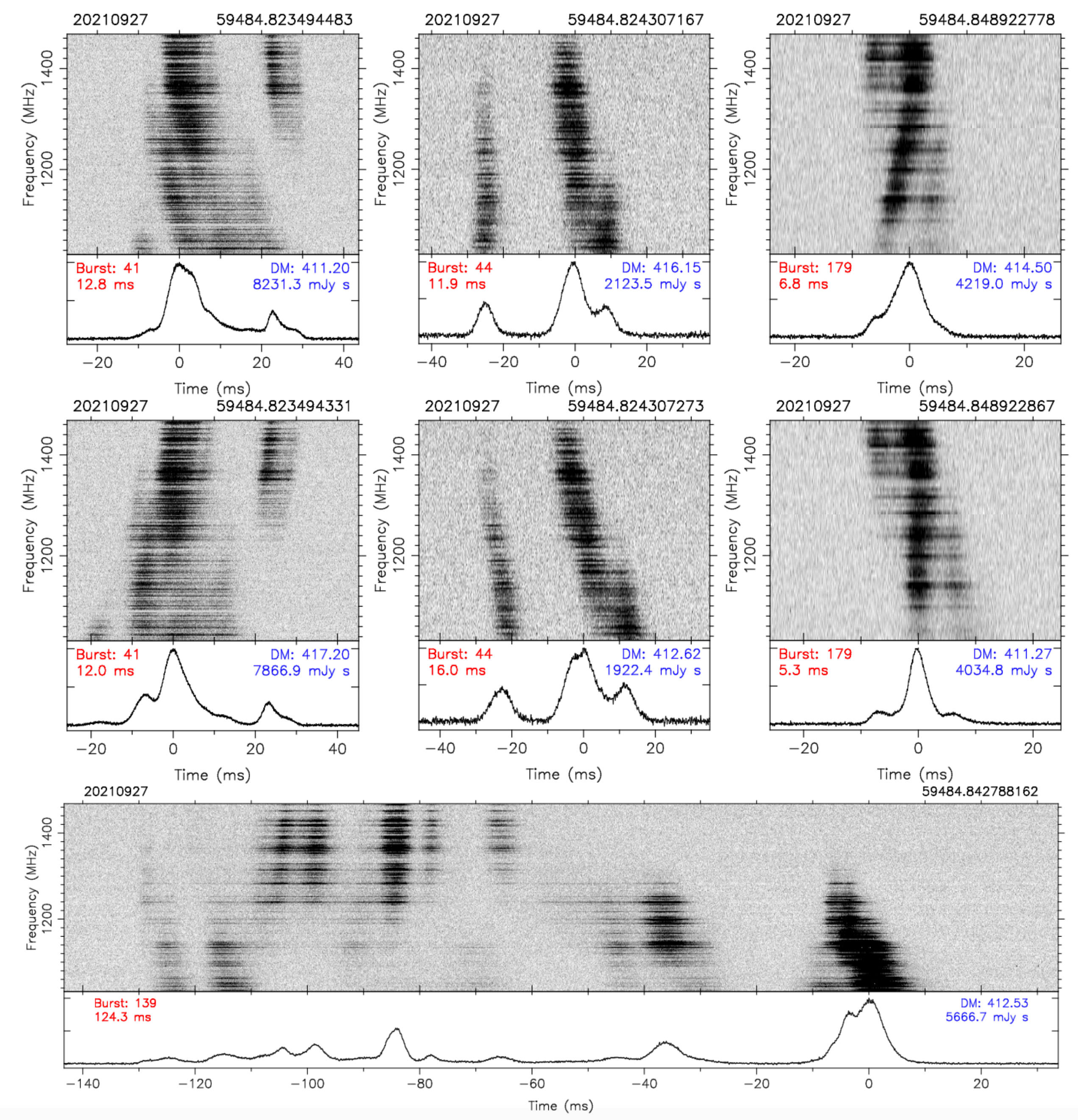
- Frequency (110 MHz to 8 GHz)
- Spectral shape: power law or Gaussian-like narrow spectrum (repeaters)
- Frequency down drifting (sad trombone)



rFRB 121102
Hessels et al. 2019



rFRB 180814.J0422+73
CHIME/FRB collaboration 2019



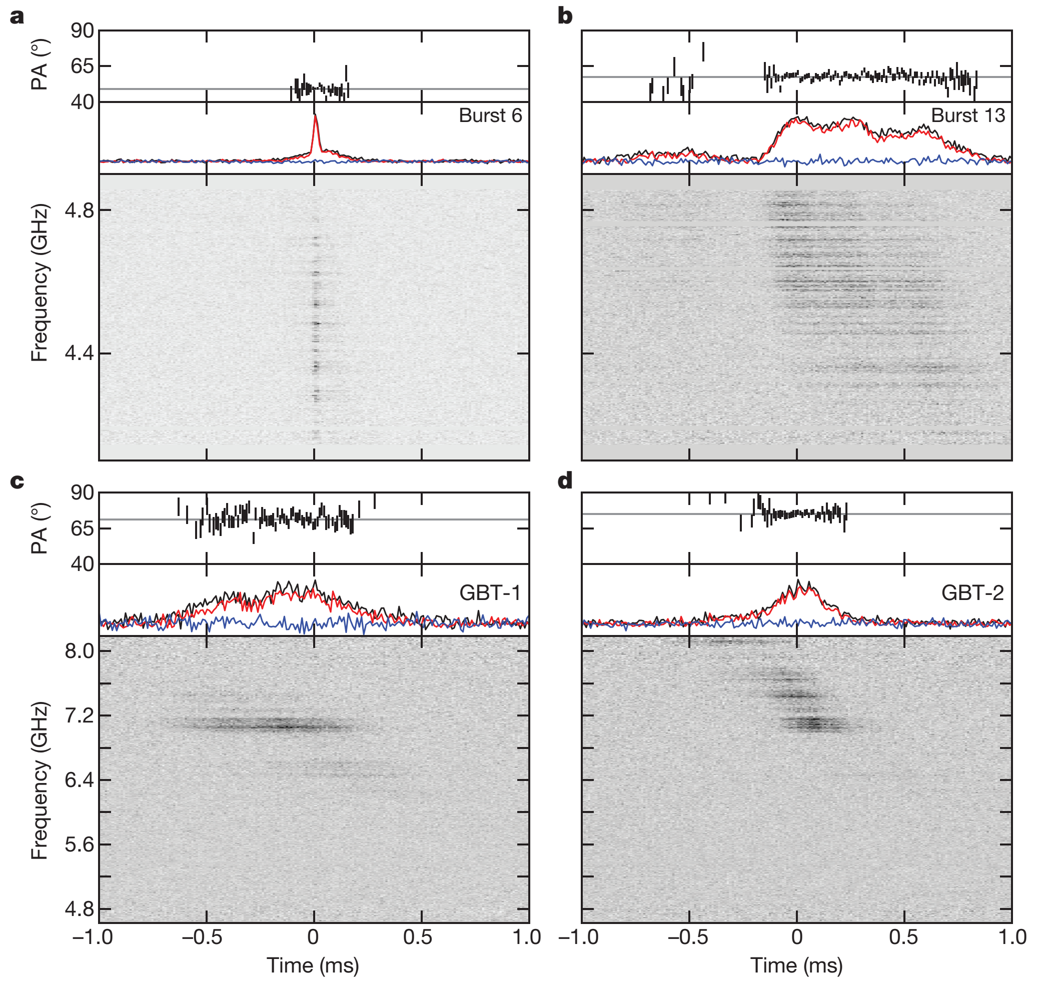
rFRB 20201124A
Zhou et al. 2022
(FAST FRB KSP)

FRB observational properties: Polarization

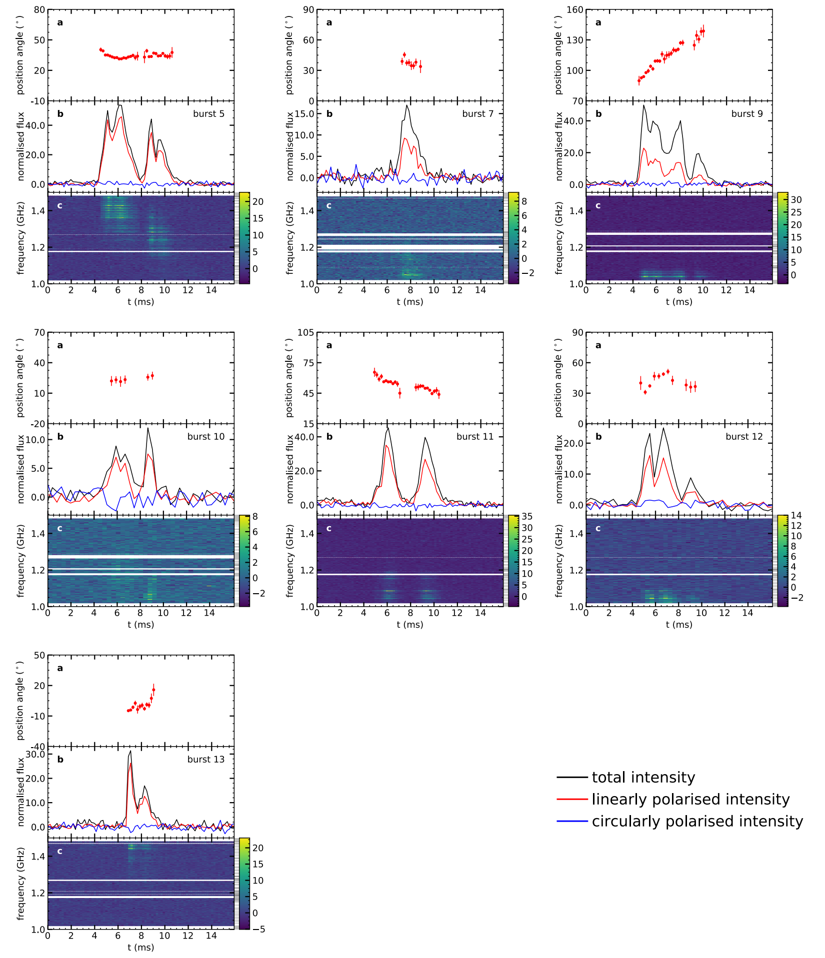
- ~100% linear polarization for most bursts
- High circular polarization (up to 90%) in some bursts
- Constant PA in each burst in some sources (rFRB 20121102); varying PA in each burst in some other sources (rFRB 20180301A)
- Large rotation measure (RM) for some FRBs. Regular or low RM for some others. Secular & short-term variations

$$\Delta\theta = \frac{2\pi e^3}{m^2 c^2 \omega^2} \int_0^d n B_{\|} \, ds.$$

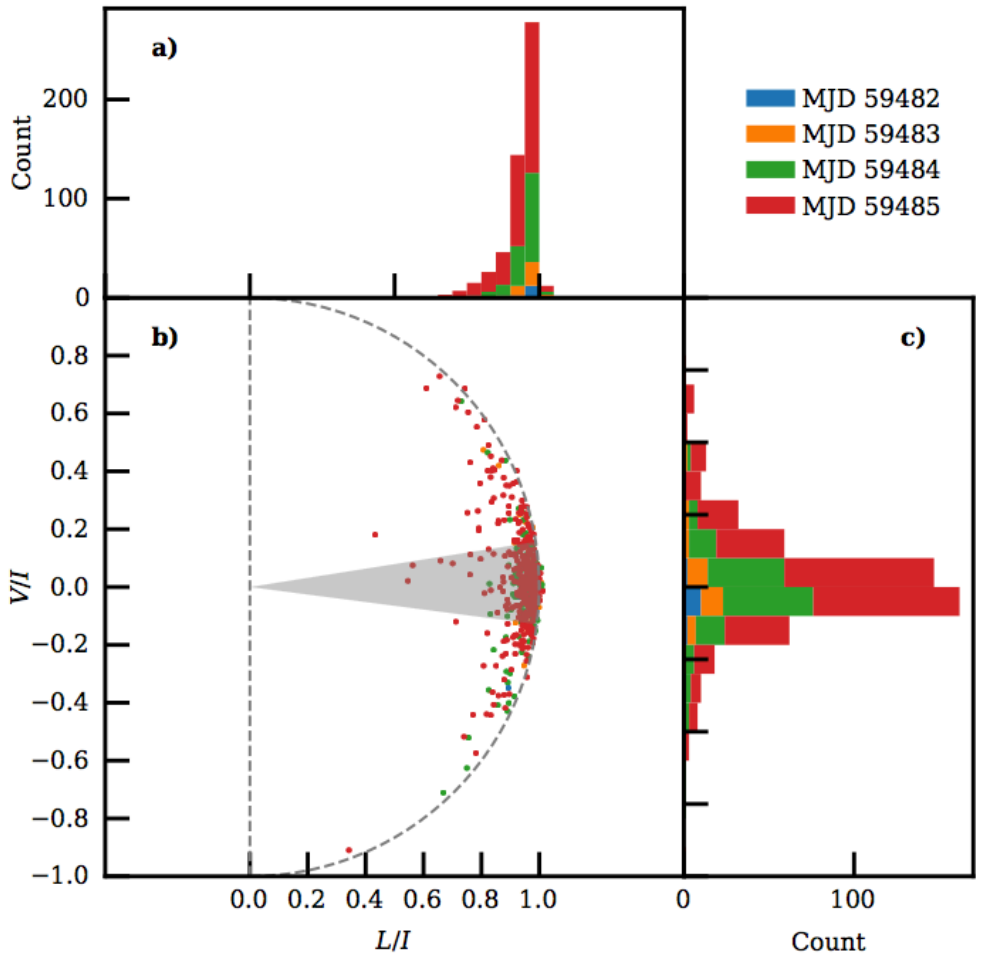
$$\mathrm{RM} = \int_0^d n B_{\|} \, ds$$



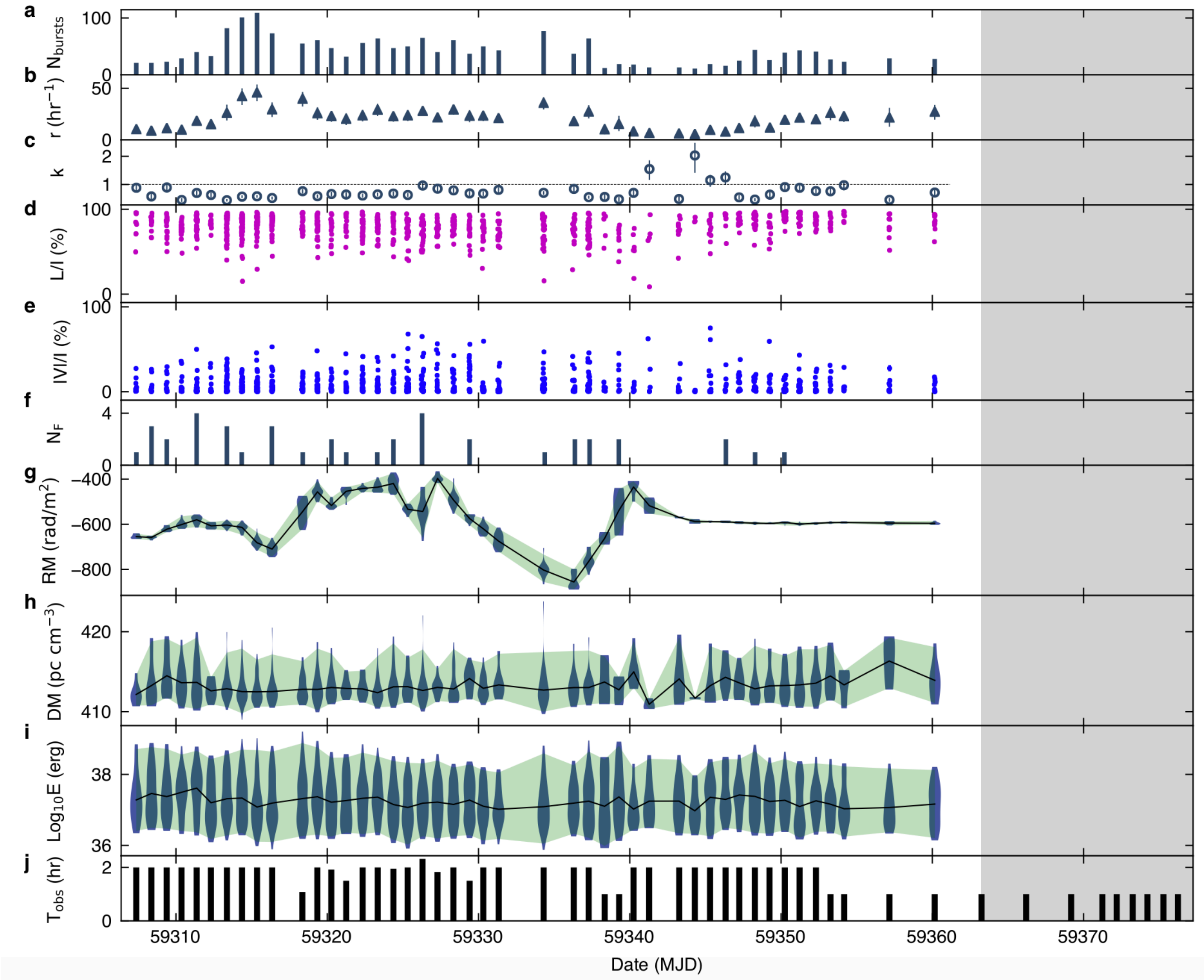
Michilli et al. 2017, Nature



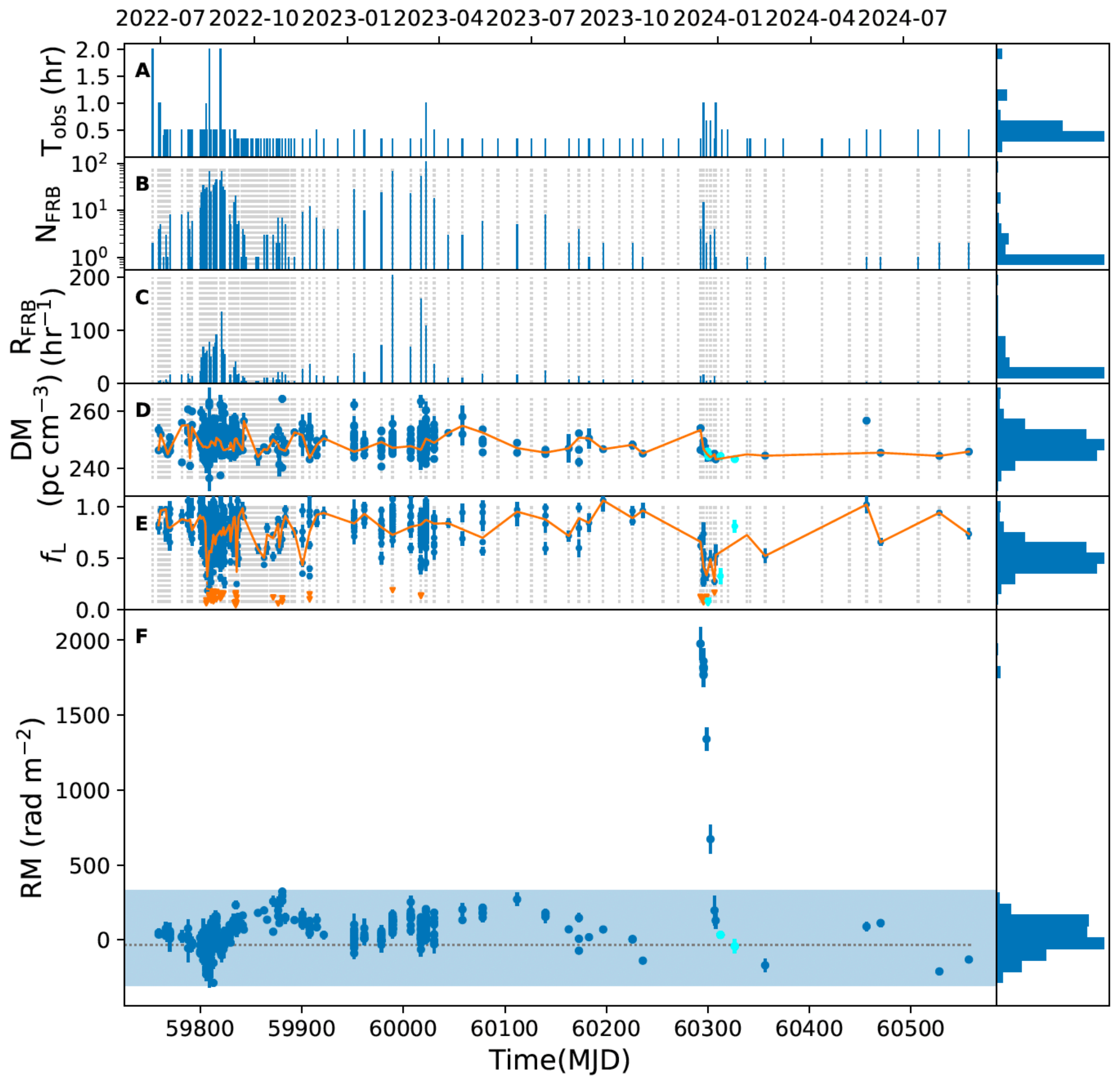
Luo et al. 2020, Nature



Jiang et al. 2022, RAA



Xu et al. 2022, Nature



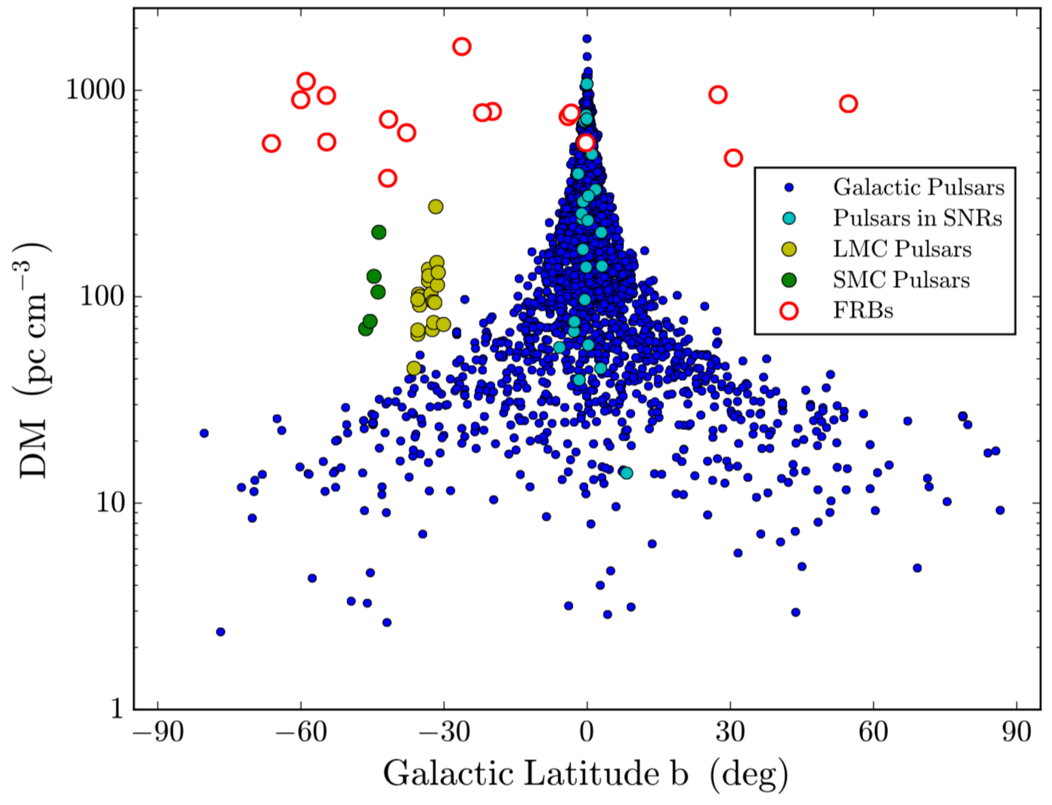
Li, Y. et al. 2026, Science

FRB observational properties: DM and z

- Excess dispersion measure (DM)

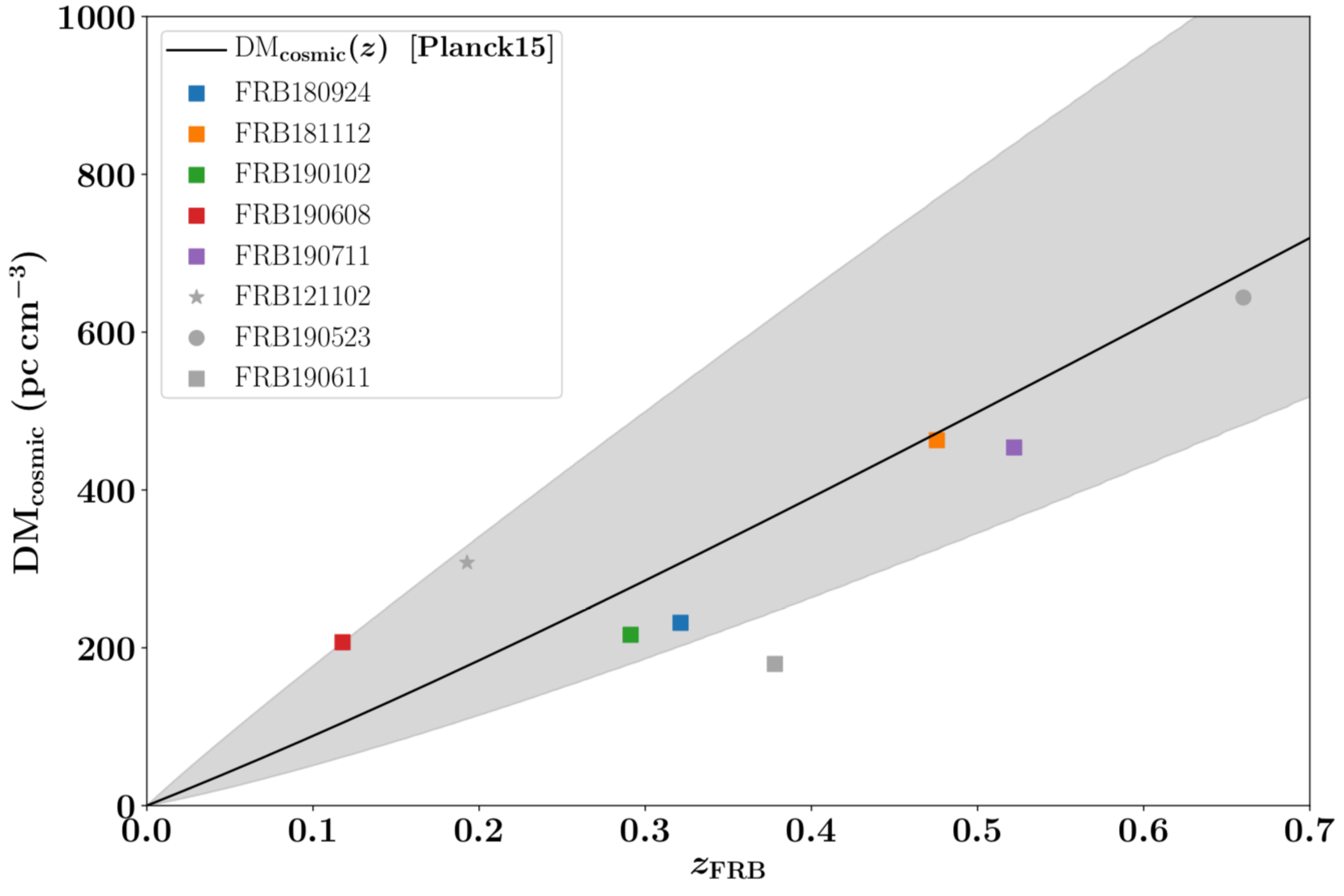
$$\mathrm{DM} = \int_0^{D_z} \frac{n_e(l)}{1+z(l)}\,dl,$$

- Redshift:
  - From DM: z << 1 to z > 3;
  - Measured: 0.1-0.7

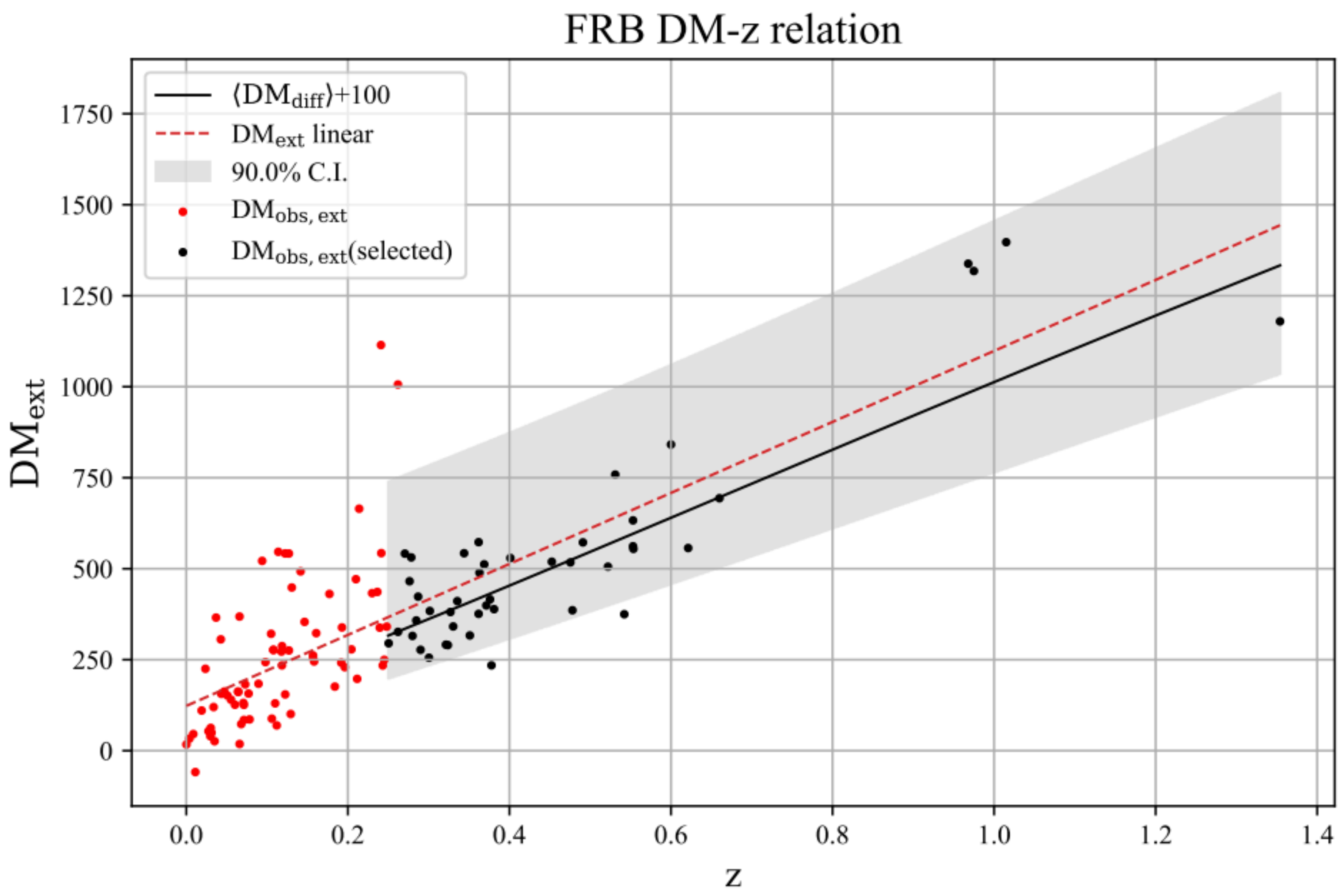


Cordes +, 2016, ApJ

FRBs are natural probes to study the universe and fundamental physics



Macquart et al. 2020, Nature, 581, 391



Zhuge et al. 2025

FRB observational properties: luminosity, energy, brightness temperature

- Luminosity and energetics

$$L_{\mathrm{p,iso}} \simeq 4\pi D_{\mathrm{L}}^2 \mathcal{S}_{\nu,p} \cdot \begin{cases} \Delta\nu, & \text{narrow spectrum}, \\ \nu_c, & \text{broad spectrum}, \end{cases}$$
$$= (4\pi \cdot 10^{42}\ \mathrm{erg\ s^{-1}}) \left(\frac{D_{\mathrm{L}}}{10^{28}\ \mathrm{cm}}\right)^2 \frac{\mathcal{S}_{\nu,p}}{\mathrm{Jy}} \frac{(\Delta\nu \text{ or } \nu_c)}{\mathrm{GHz}}, \quad (16)$$

$$E_{\mathrm{iso}} \simeq \frac{4\pi D_{\mathrm{L}}^2}{1+z} \mathcal{F}_\nu \cdot \begin{cases} \Delta\nu, & \text{narrow spectrum}, \\ \nu_c, & \text{broad spectrum}, \end{cases}$$
$$= \frac{4\pi \cdot 10^{39}\ \mathrm{erg}}{1+z} \left(\frac{D_{\mathrm{L}}}{10^{28}\ \mathrm{cm}}\right)^2 \frac{\mathcal{F}_\nu}{\mathrm{Jy \cdot ms}} \frac{(\Delta\nu \text{ or } \nu_c)}{\mathrm{GHz}}, \quad (17)$$

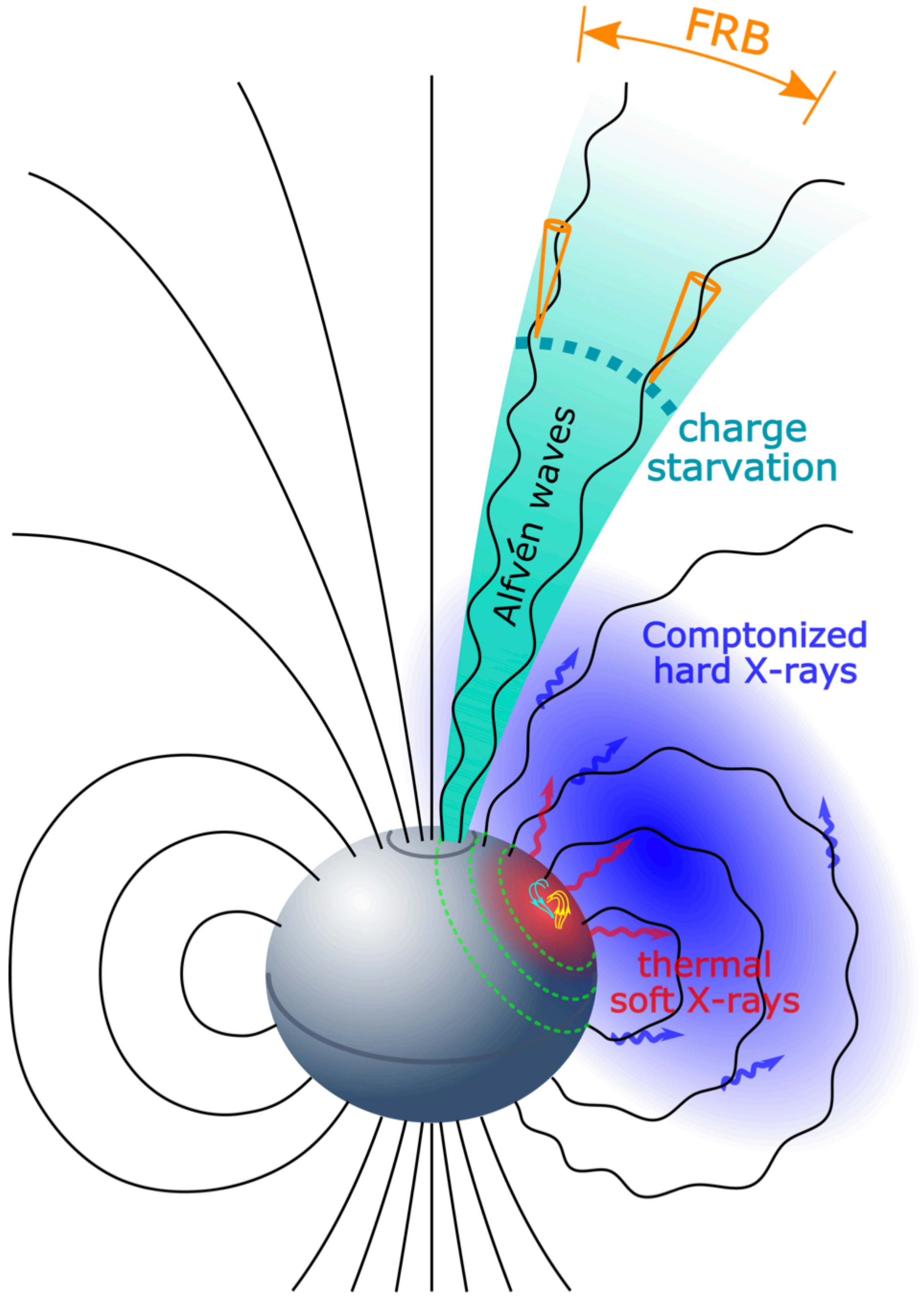
  - Isotropic peak luminosity: $10^{38} - 10^{46}$ erg/s
  - Isotropic energy: $10^{35} - 10^{43}$ erg
  - These numbers are smaller by a factor of $f_b \equiv \Delta\Omega/4\pi$ if FRBs are beamed; the total number of bursts may increase by the same factor (if isotropic).

- Brightness temperature (imaginary temperature if radiation is from a blackbody)

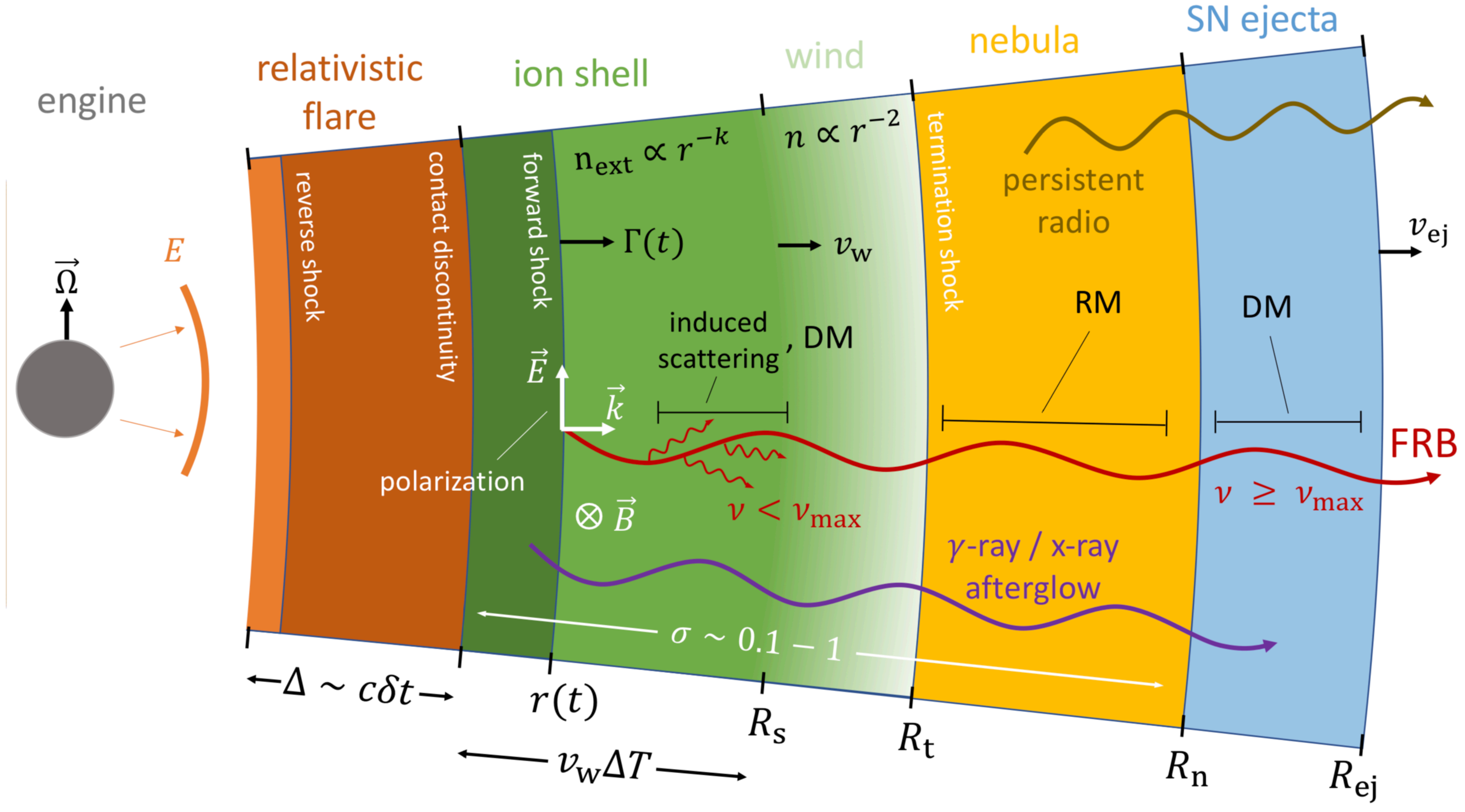
$$T_b \simeq \frac{\mathcal{S}_{\nu,p} D_{\mathrm{A}}^2 (1+z)^3}{2\pi k_B (\nu \Delta t)^2} = (1.2 \times 10^{36}\ \mathrm{K})(1+z)^3$$
$$\times \left(\frac{D_{\mathrm{A}}}{10^{28}\ \mathrm{cm}}\right)^2 \frac{\mathcal{S}_{\nu,p}}{\mathrm{Jy}} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2} \left(\frac{\Delta t}{\mathrm{ms}}\right)^{-2},$$

Radiation mechanism must be Coherent!

The Physics of FRBs: What? Where? & How?

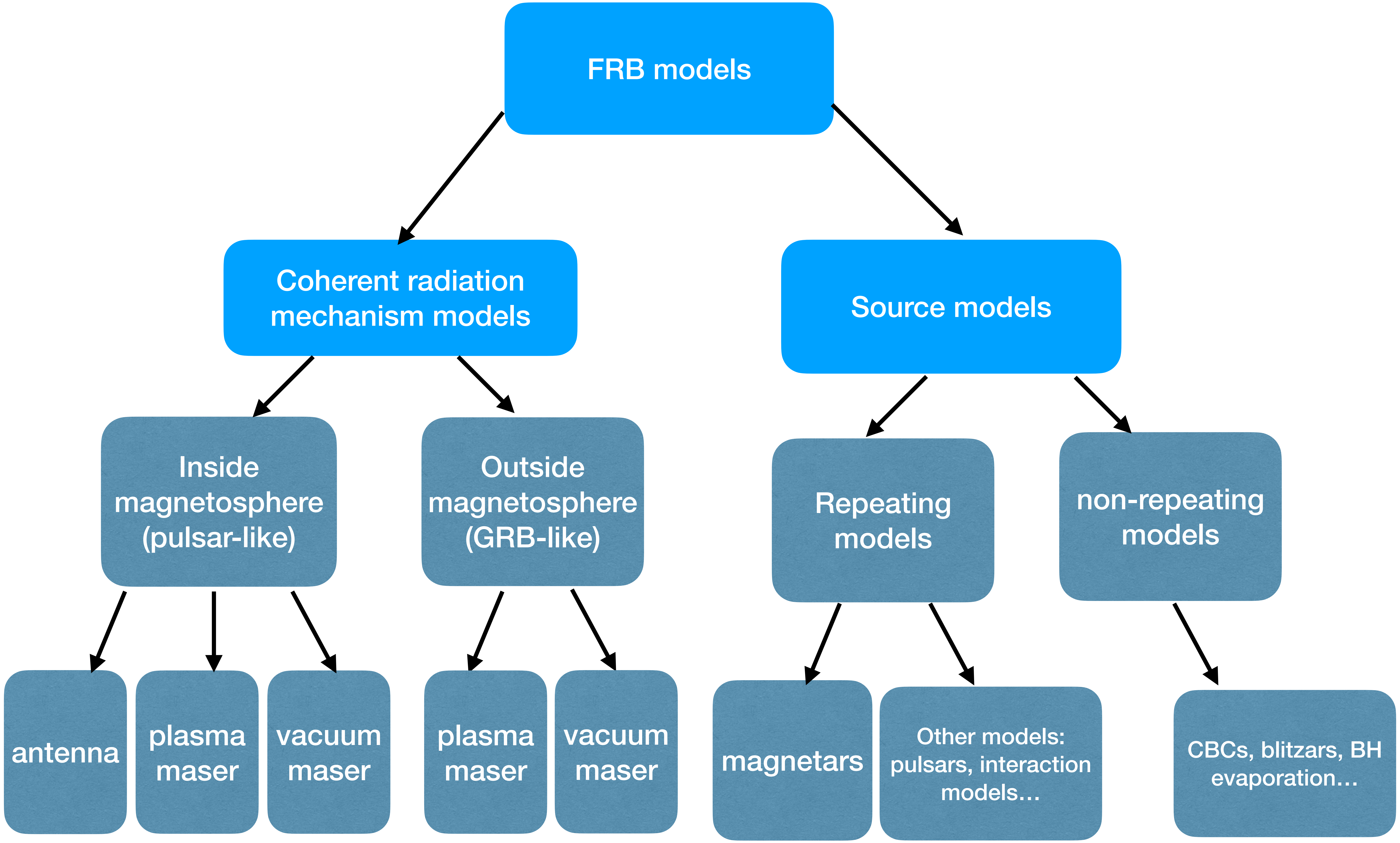


Lu et al. 2020

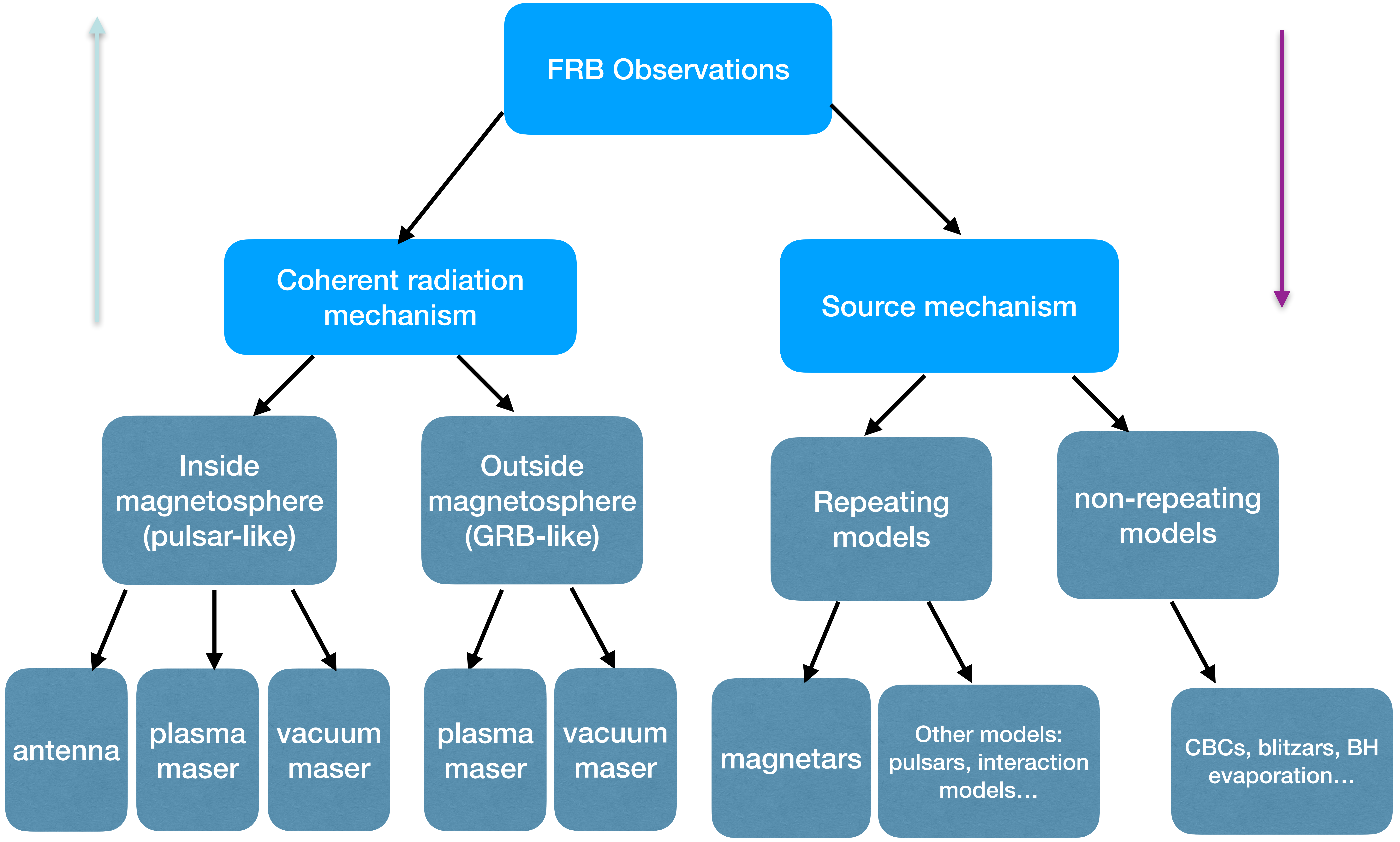


Metzger et al. 2019

Components of FRB Models



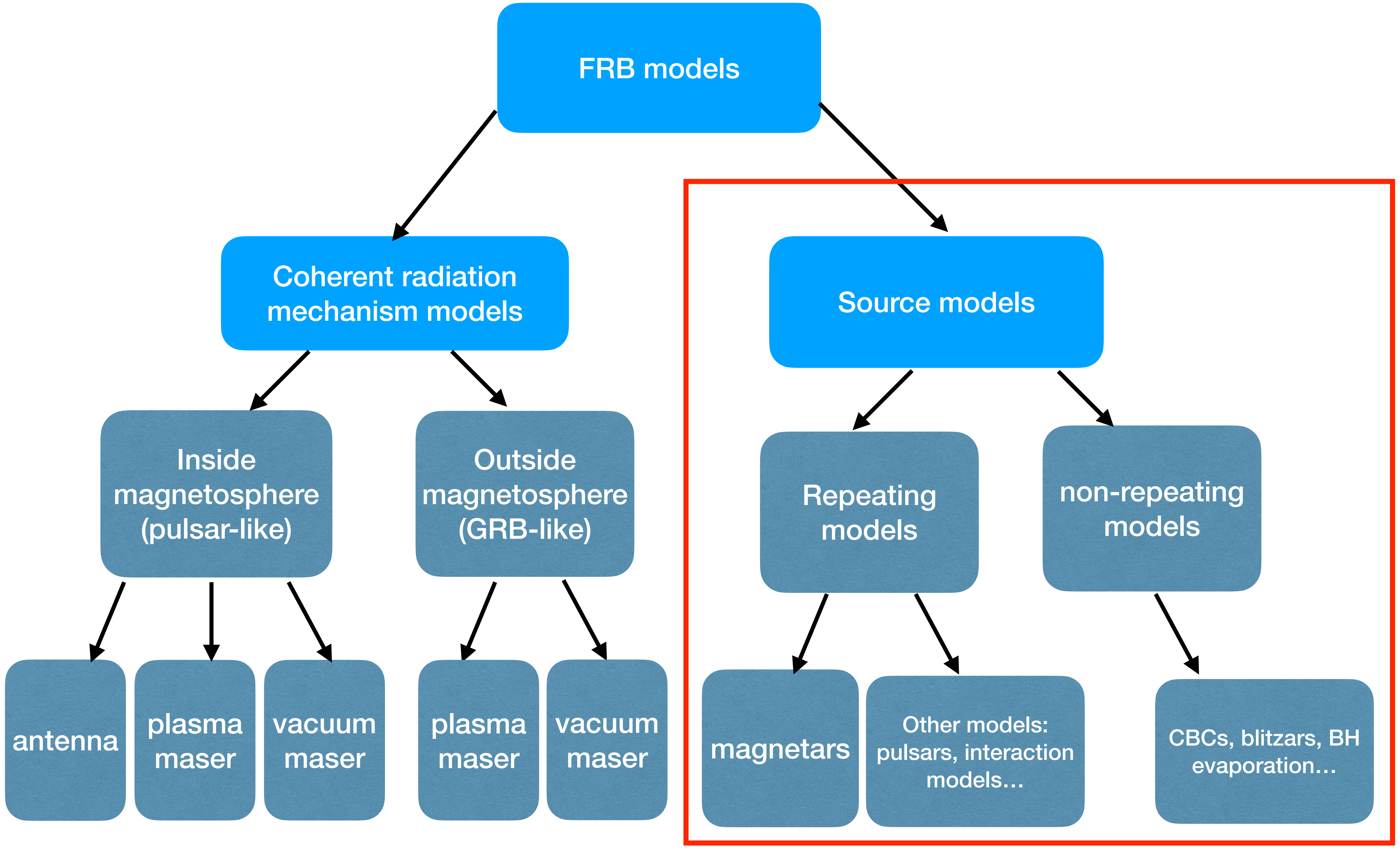
Bottom-up vs. Top-down



What?

Sources & Source progenitors

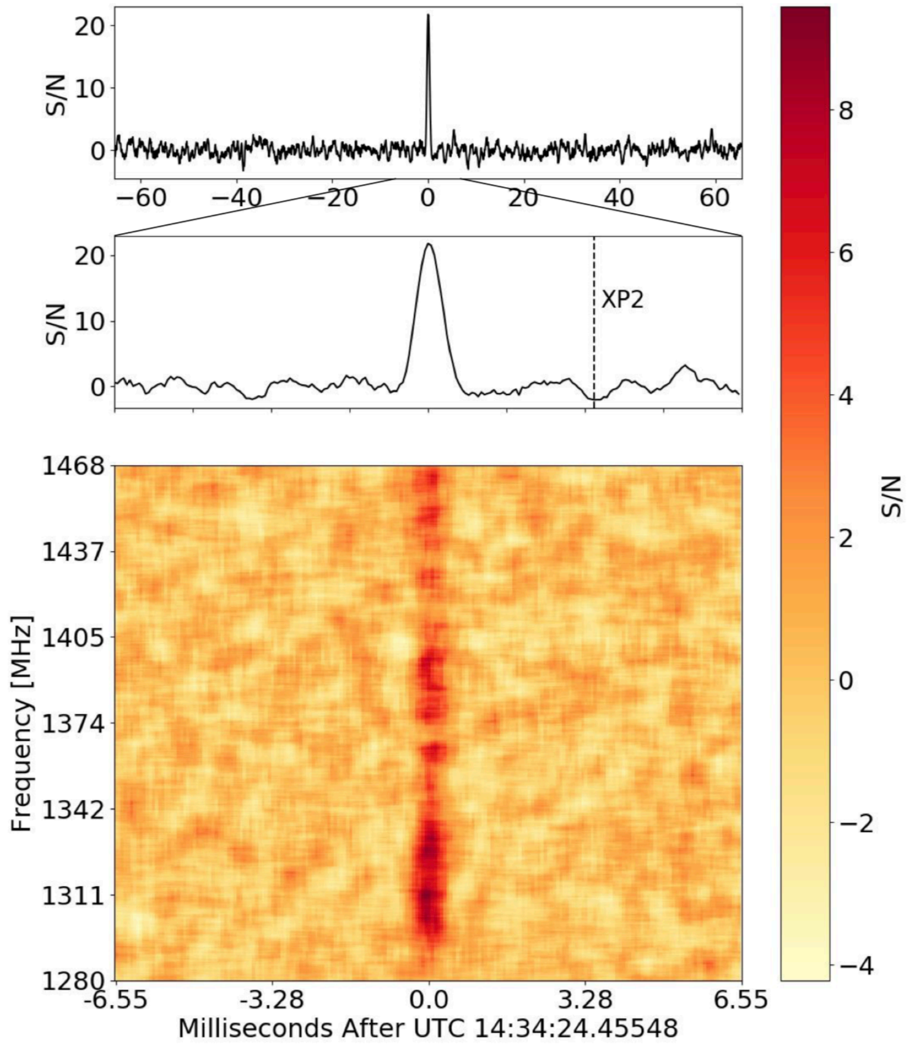
Components of FRB Models

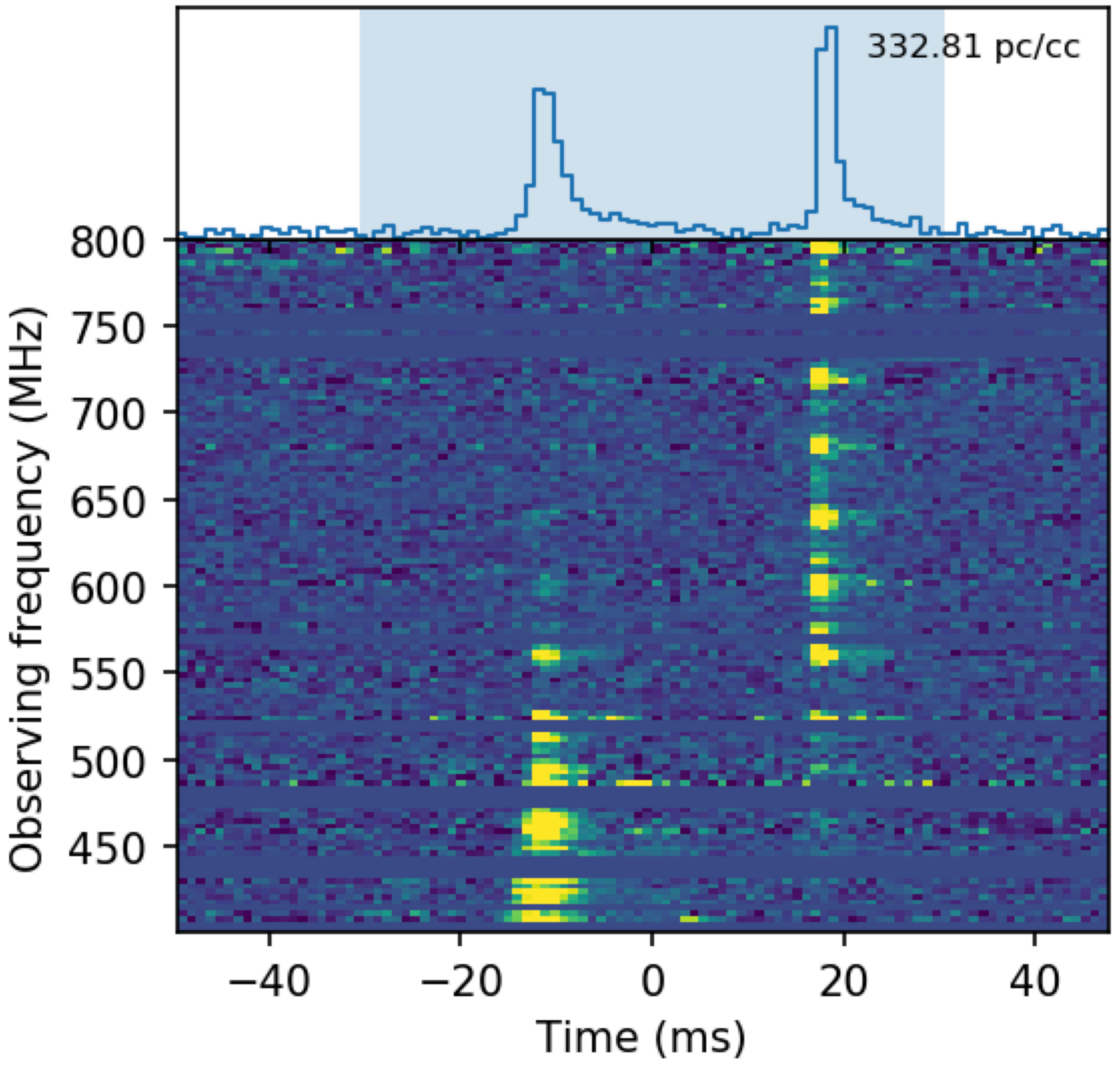


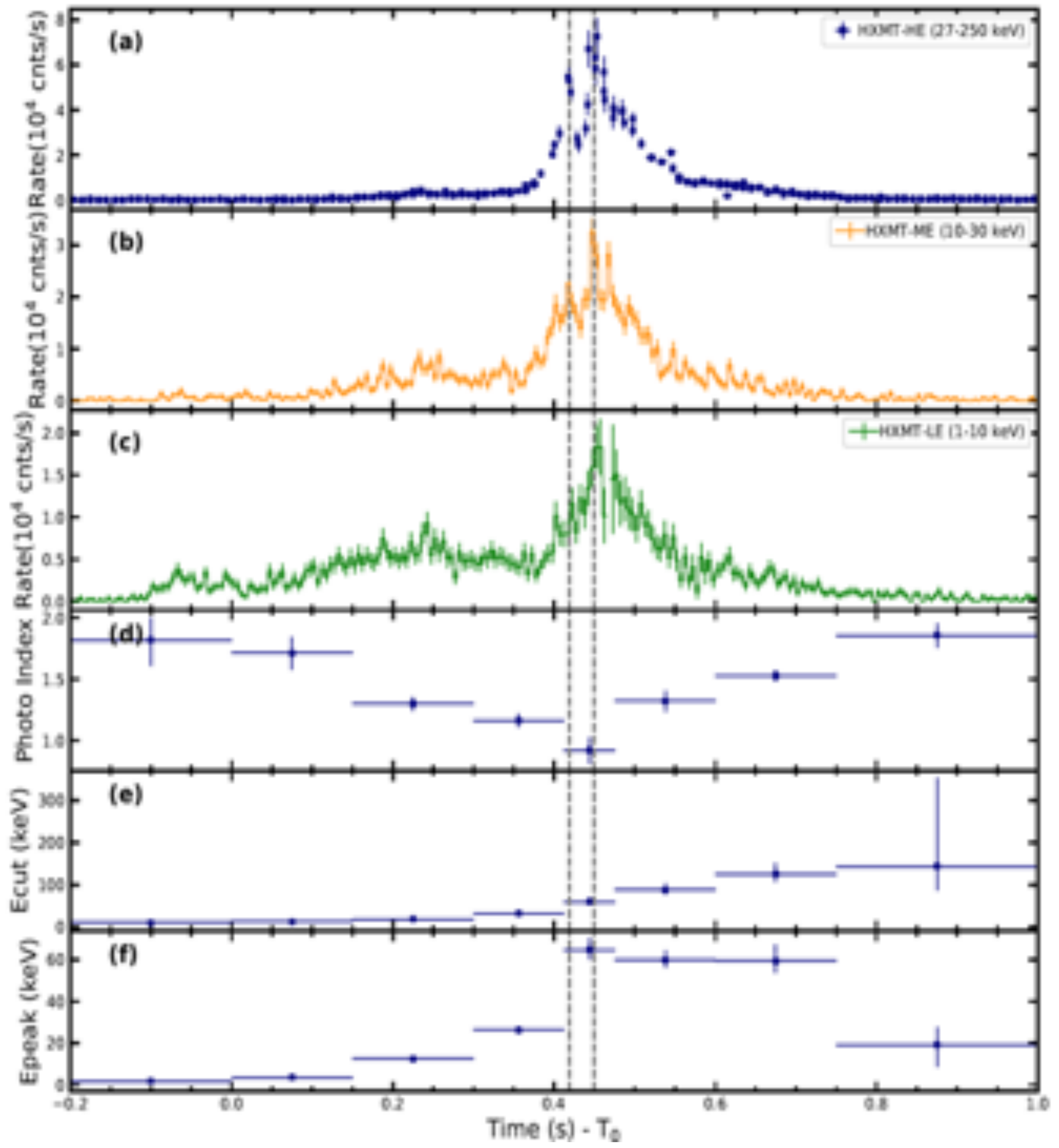
What? Magnetars

Magnetars are the most magnetized neutron stars, with surface magnetic field of the order of 10^{15} G

- **Major breakthrough in 2020:** FRB 20200428D came from Galactic magnetar SGR J1935+2154!







CHIME/FRB Collaboration 2020;
Bochenek et al. 2020;
Lin et al. 2020;
Li et al. 2021;
Mereghetti et al. 2020;
Ridnaia et al. 2021;
Tavani et al. 2021

What?

- All magnetars?
- Active repeaters: magnetars in binaries with aligned geometry (or a small fraction: isolated magnetars with aligned geometry)
- Inactive repeaters: magnetars in isolated systems or in binaries with misaligned geometry

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AAS NOVA Research highlights from the journals of the American Astronomical Society

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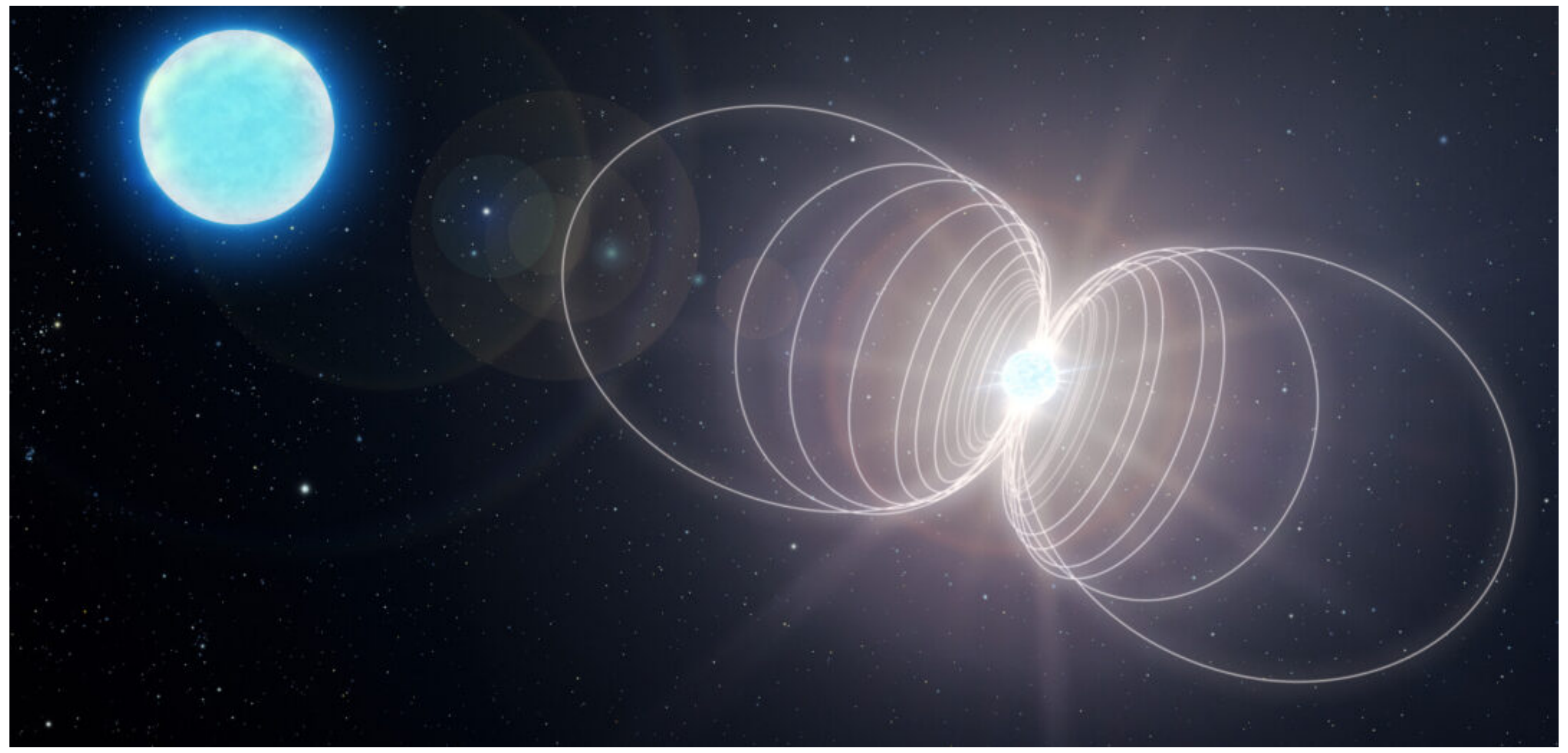
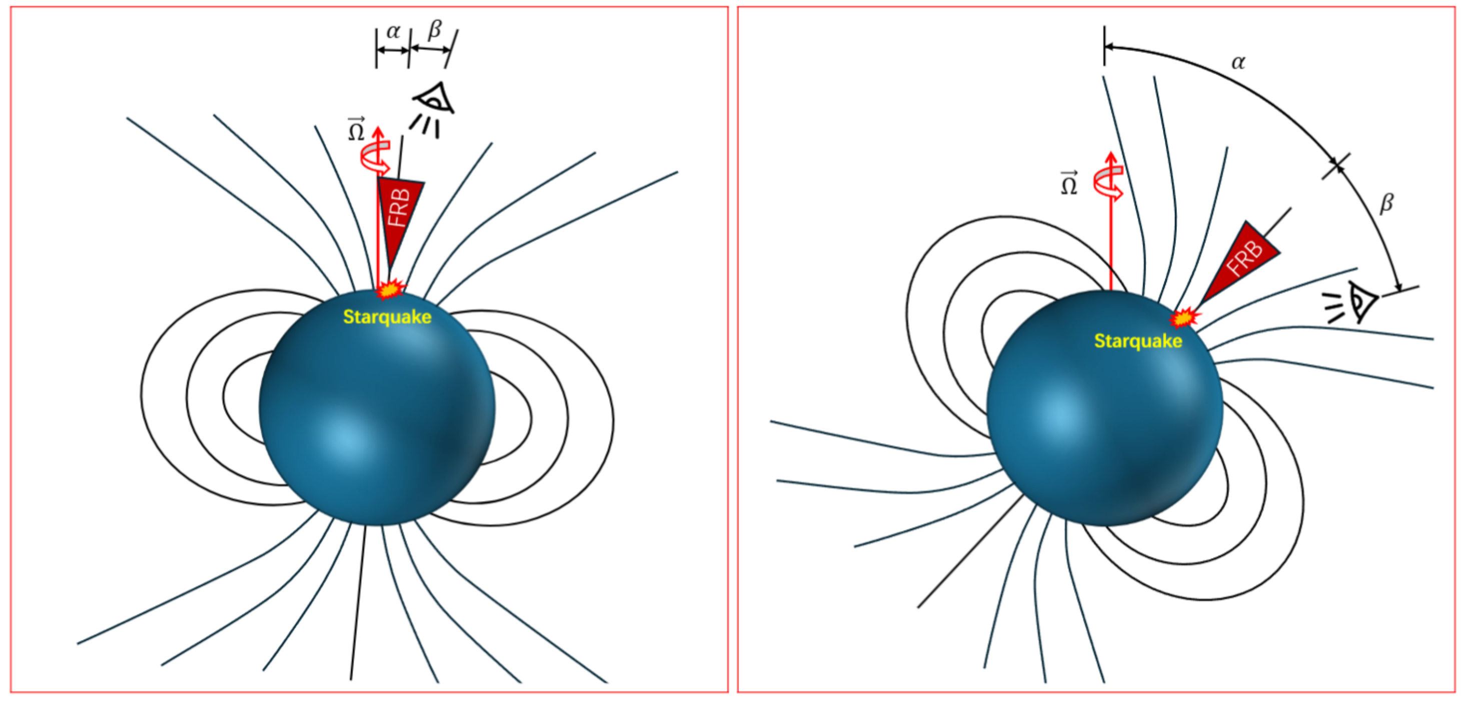
A Unified Explanation for Fast Radio Bursts

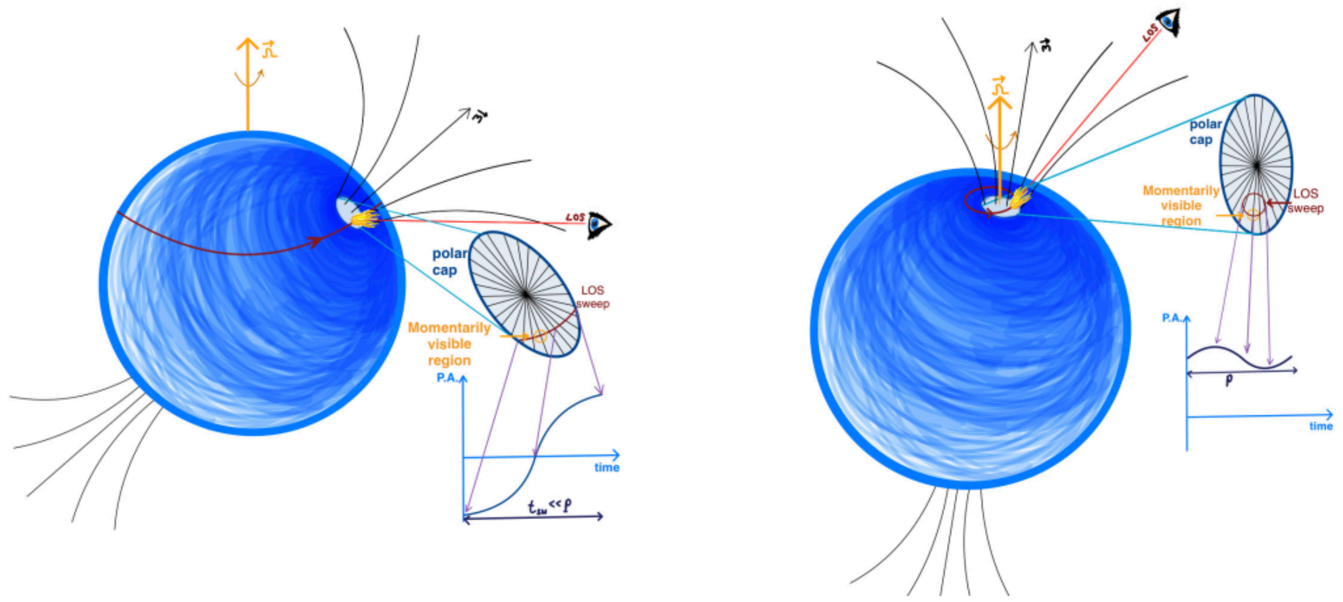




(a) Repeaters (b) Non-repeaters

Figure 12. A cartoon sketch demonstrating the possible difference between repeaters and non-repeaters in the model presented in this paper. Repeaters shown on the left have low α and β, therefore more events can be observed, but the spin period is hidden. Non-repeaters shown on the right have high α and β, and very few events can be observed due to high viewing angles.

J.-W. Luo et al. (2025)



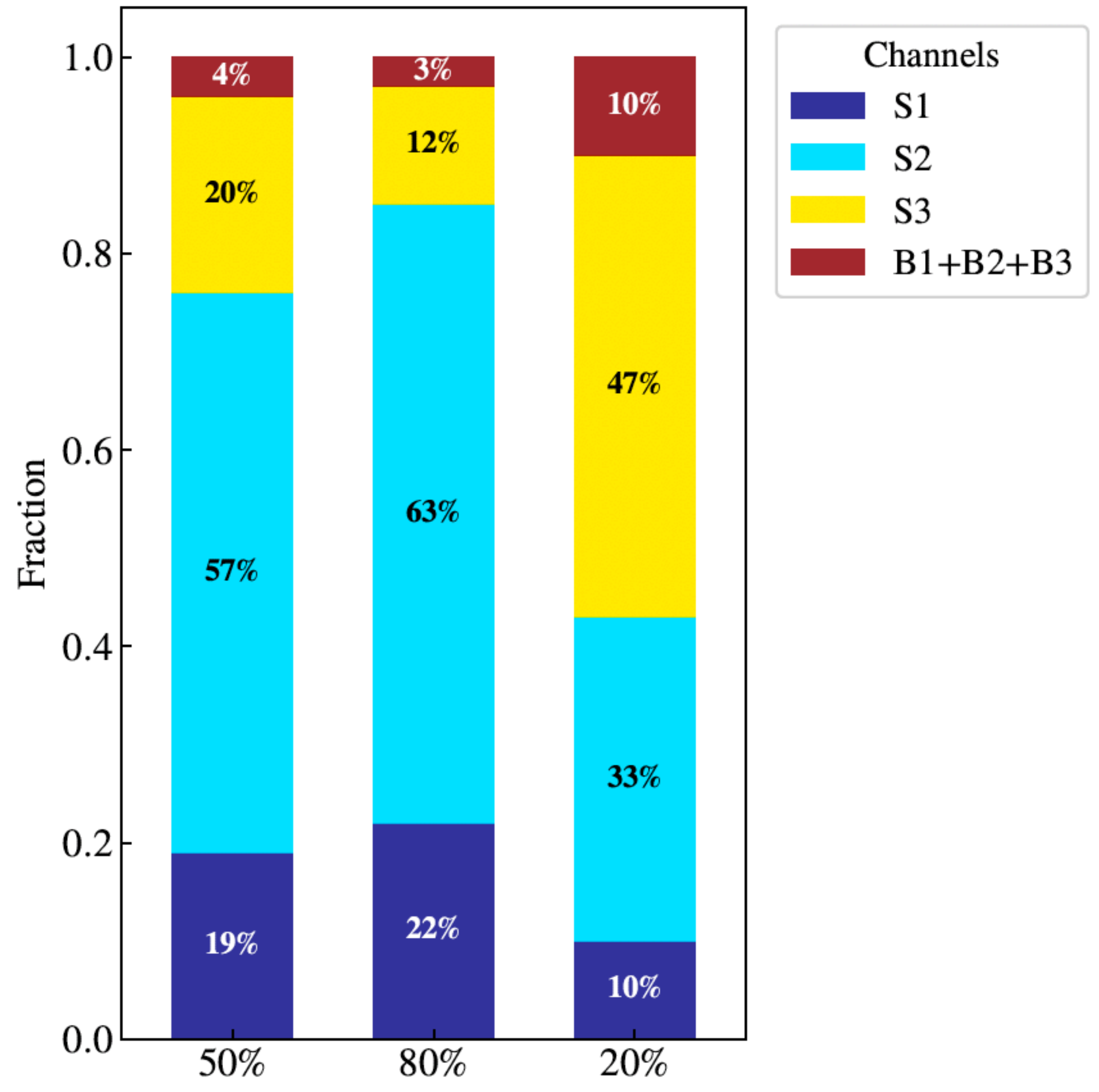
Beniamini & Kumar (2025)

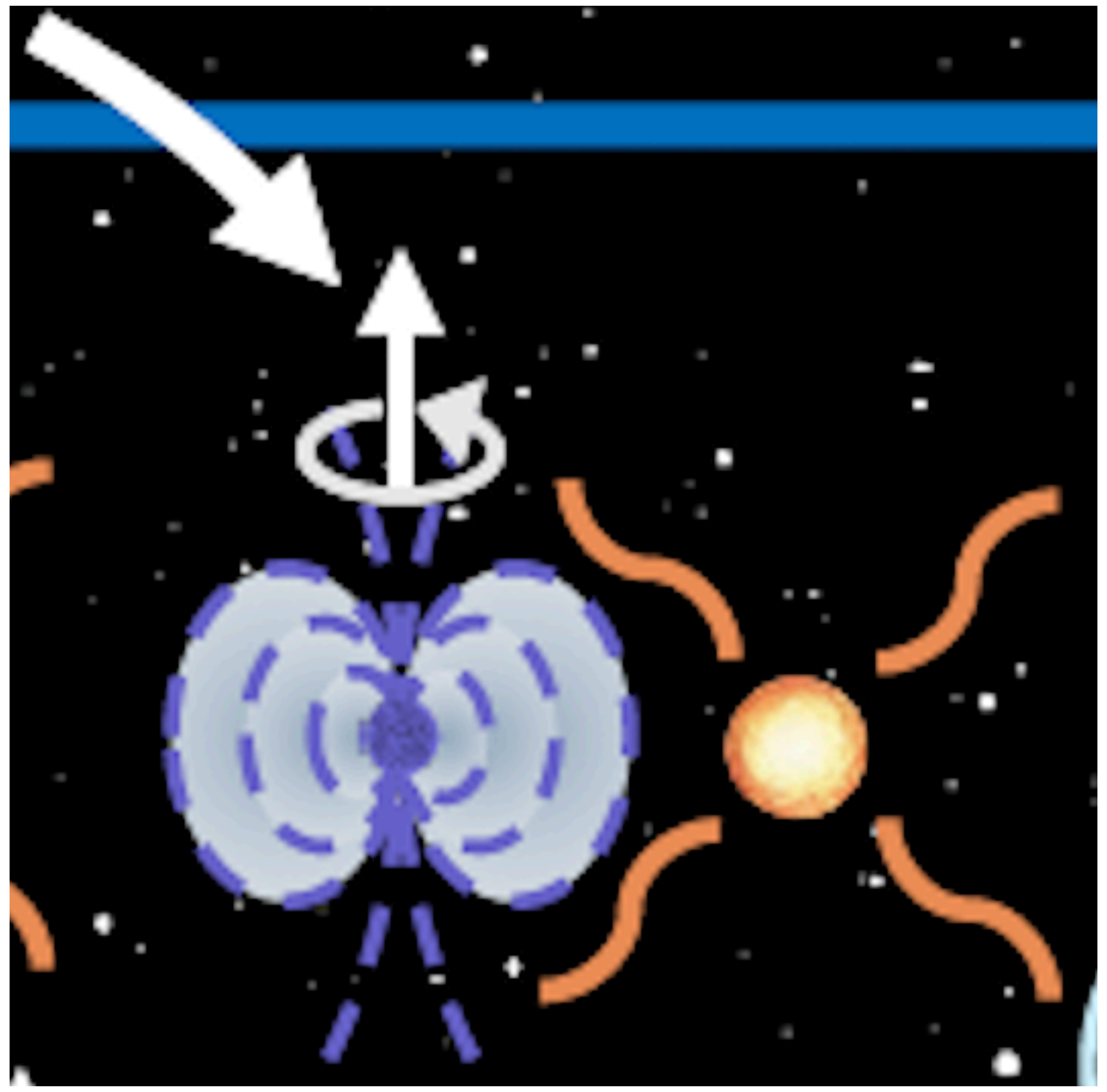
For binary models, see also earlier papers: Ioka & Zhang (2020); Wang et al. (2022); Yang et al. (2023) ….

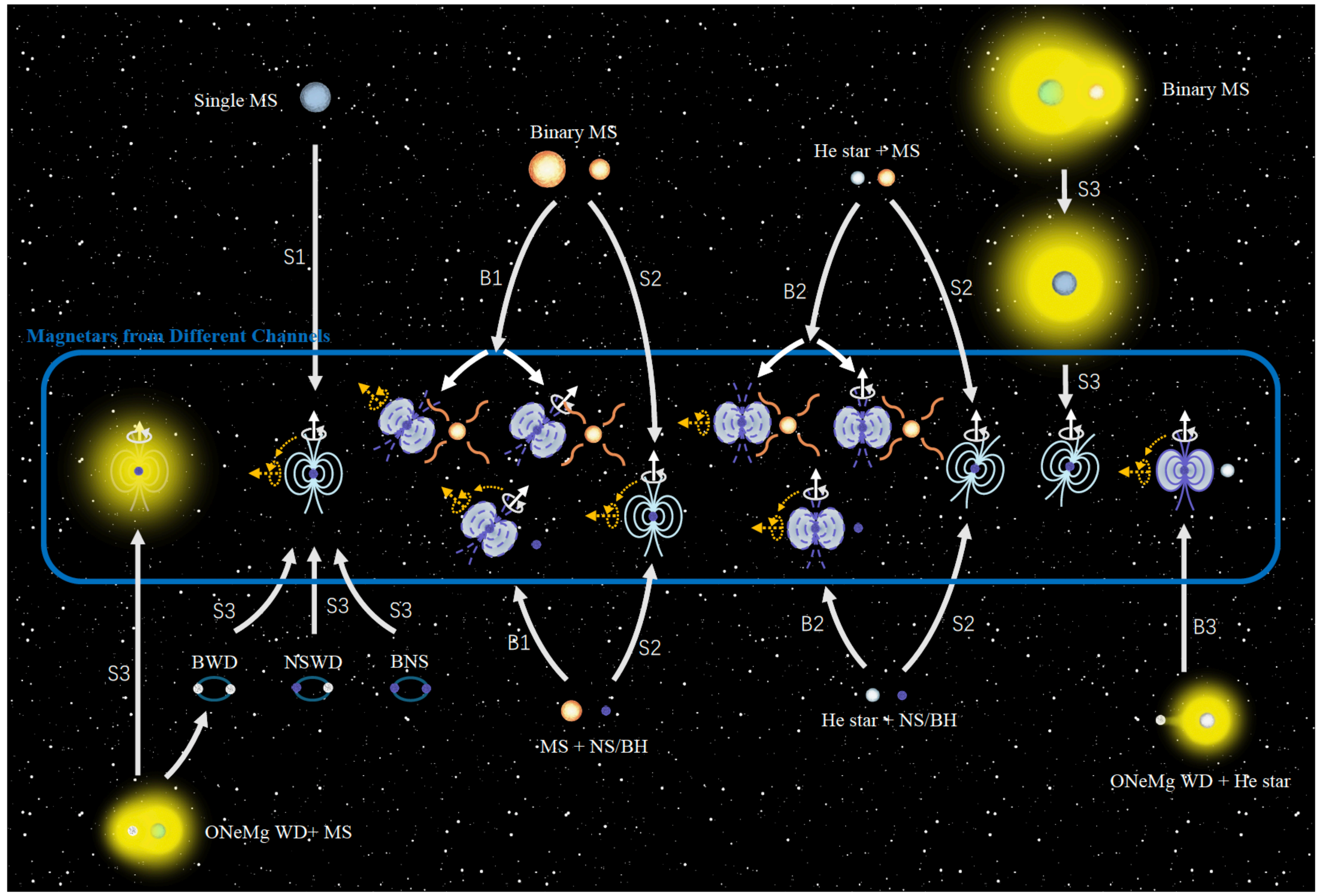
Formation channels of magnetars: Single vs. binary systems

- Most in single systems, most are born with aligned geometry, but later undergo spin-flip

- Multiple channels can form magnetars in binary systems; some are born and can maintain the aligned geometry







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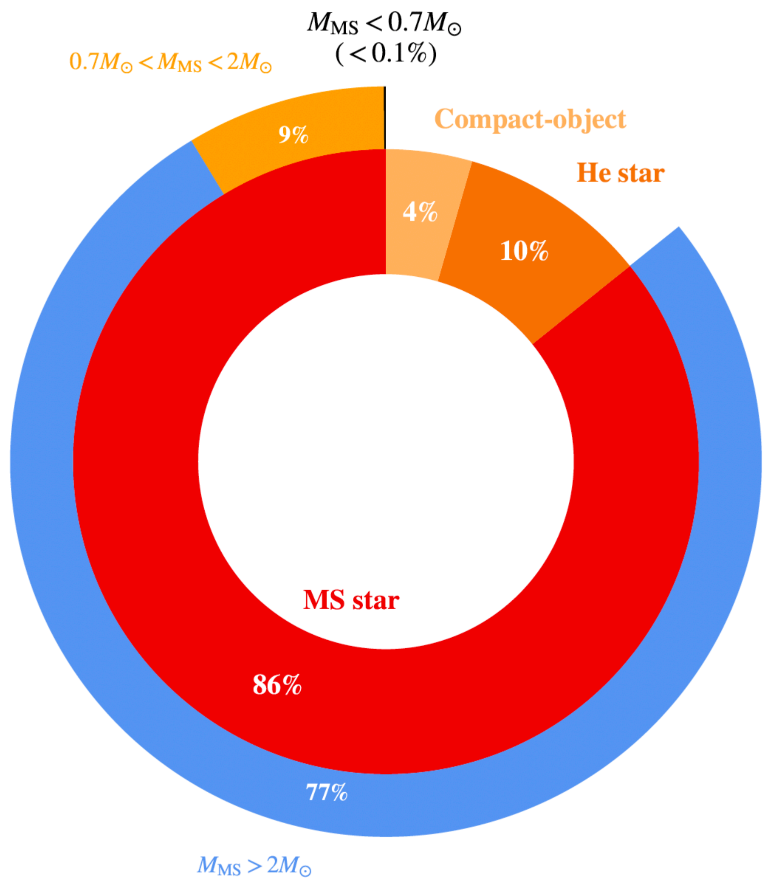
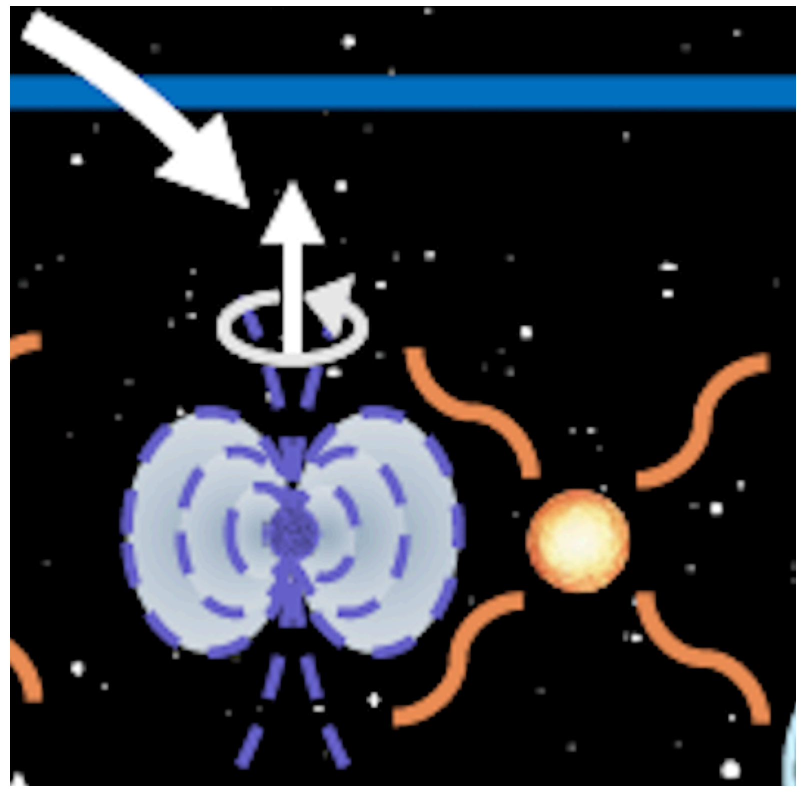
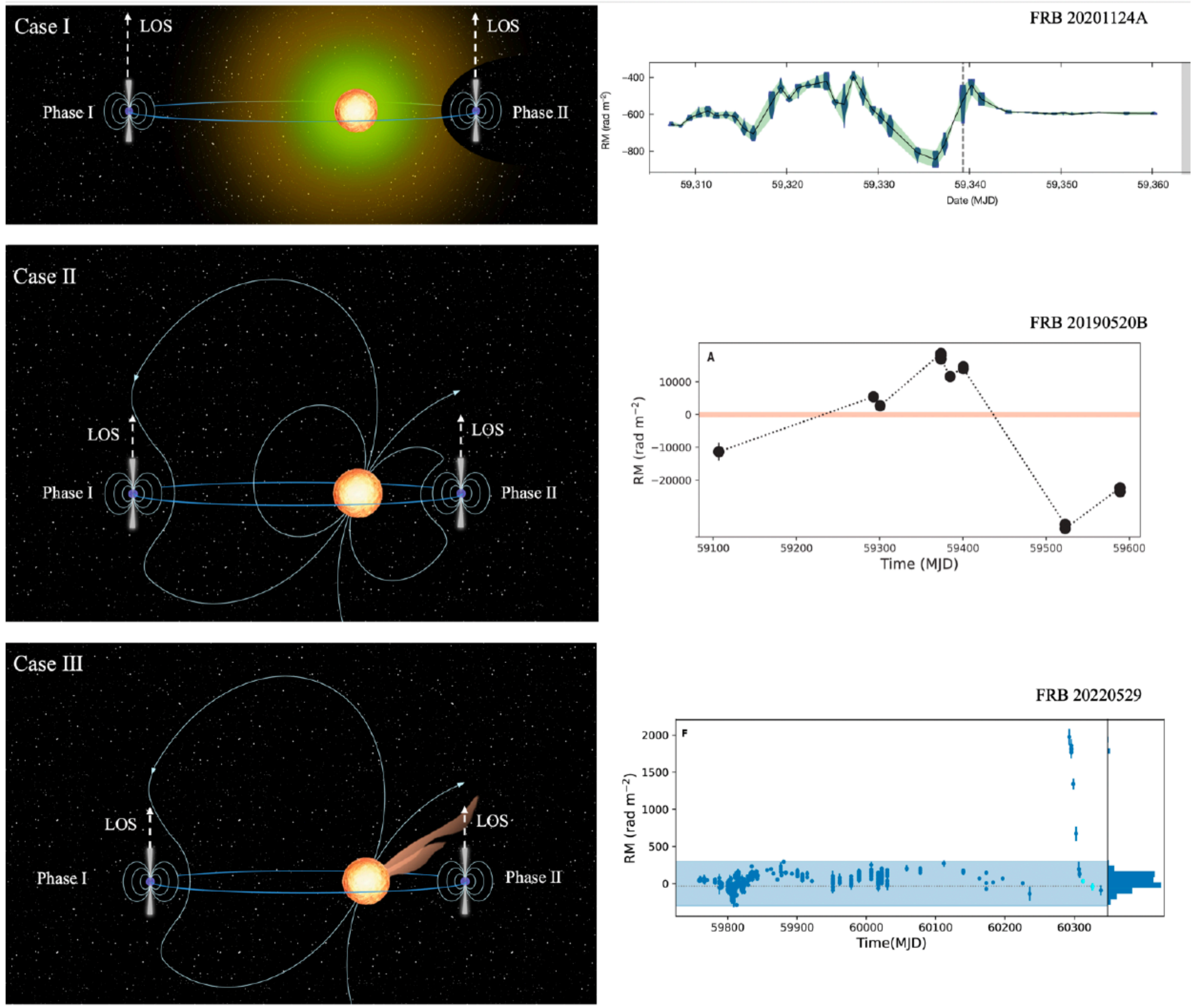
R.-C. Hu & B. Zhang (2025)

The role of the companion
& diverse RM evolution behaviors

- Most have a massive star companion
- The companion wind helps to maintain spin/ magnetic axis alignment and prefers a triple-alignment geometry
- The companion wind may also help to increase the FRB trigger rates







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Where & How?

Radiation mechanisms

Components of FRB Models

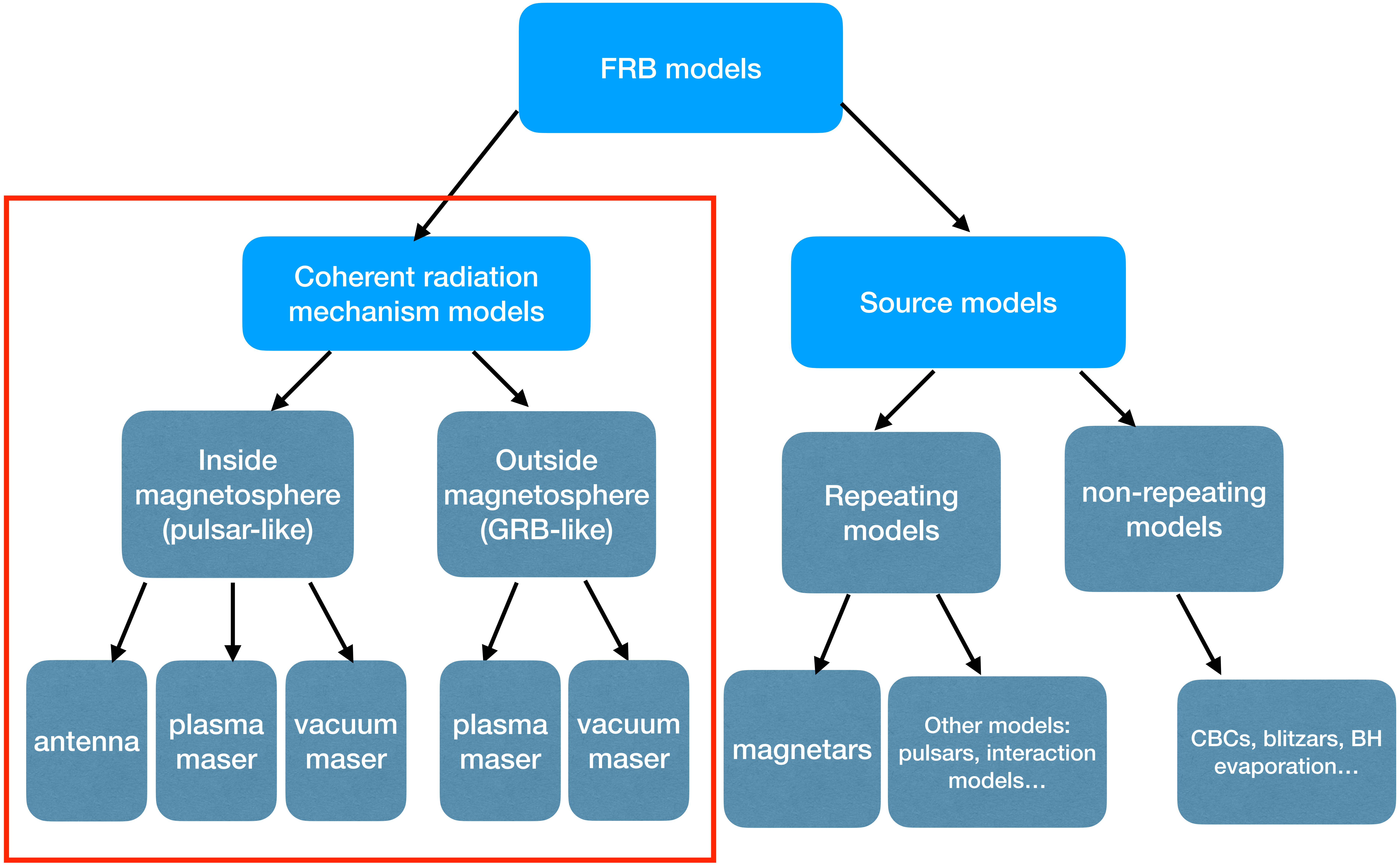


TABLE II. Astrophysical radiation mechanisms.

Mechanisms	Particles	Photons	Examples
Blackbody	Thermal equilibrium	Thermal equilibrium	CMB, stars
Thermal	Thermal equilibrium	May or may not be in thermal equilibrium	Disks, intracluster medium
Incoherent nonthermal	Nonthermal	Subject to self-absorption limit	SNRs, GRBs, blazars
Coherent nonthermal	Nonthermal	Not subject to self-absorption limit	Radio pulsars, FRBs

Brightness temperature:

$$T_b(\nu_0) = \frac{S_\nu D_A^2 (1+z)^3}{2\pi k_B (\nu \Delta t)^2} = \frac{S_\nu D_L^2}{2\pi k_B (\nu \Delta t)^2 (1+z)}$$
$$\simeq (1.2 \times 10^{36}\ \mathrm{K}) \frac{S_\nu}{\mathrm{Jy}} \left(\frac{\nu}{\mathrm{GHz}}\right)^{-2} \left(\frac{\Delta t}{\mathrm{ms}}\right)^{-2}$$
$$\times \begin{cases} (1+z)^3 \left(\frac{D_A}{10^{28}\ \mathrm{cm}}\right)^2, \\ \frac{1}{1+z} \left(\frac{D_L}{10^{28}\ \mathrm{cm}}\right)^2. \end{cases}$$

Condition for coherent emission:

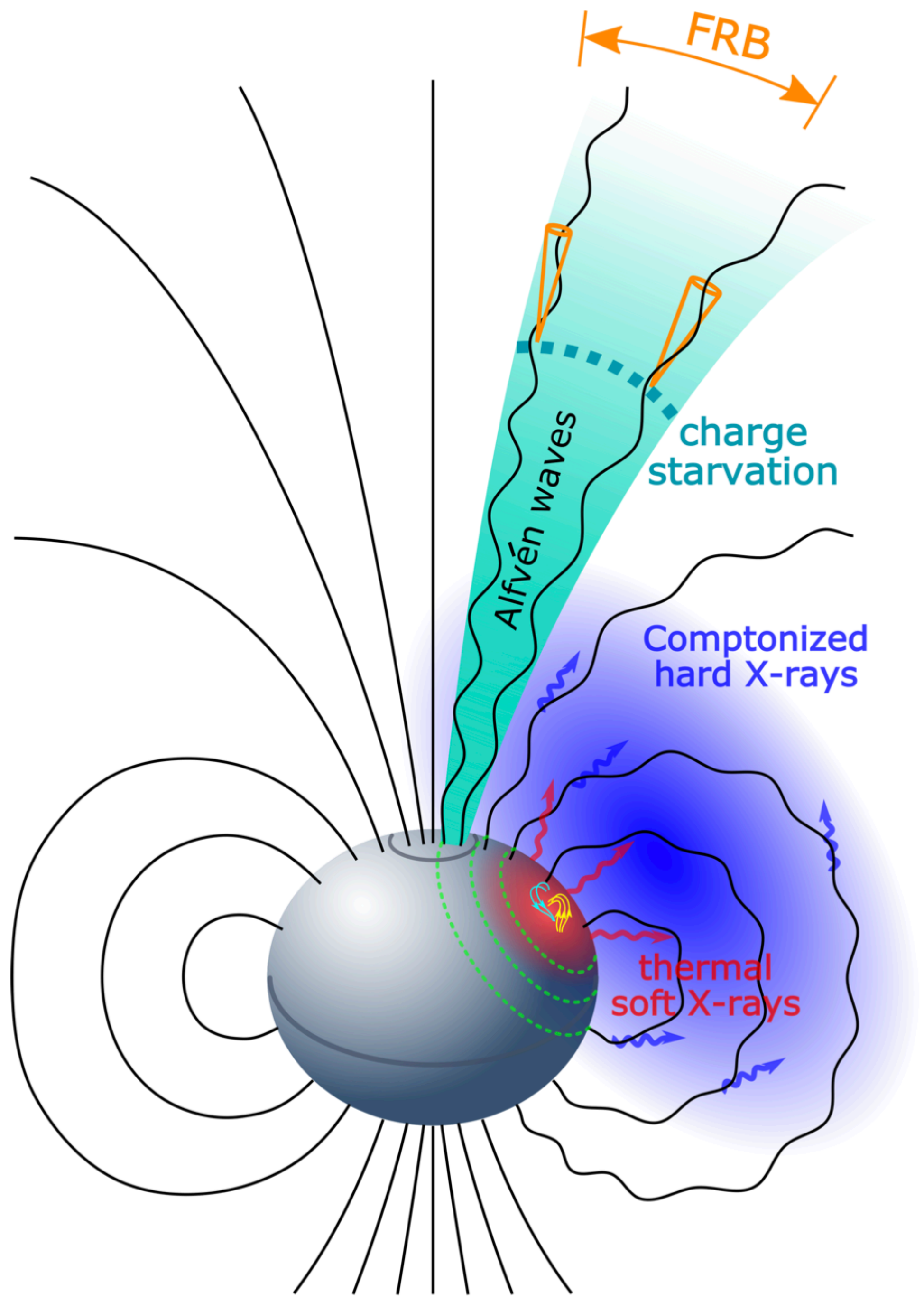
$$T_b \geq \mathcal{D}\gamma_e m_e c^2/k \simeq (5.9 \times 10^{13}\ \mathrm{K})\Gamma_2 \gamma_{e,2}.$$

General coherent mechnanisms:

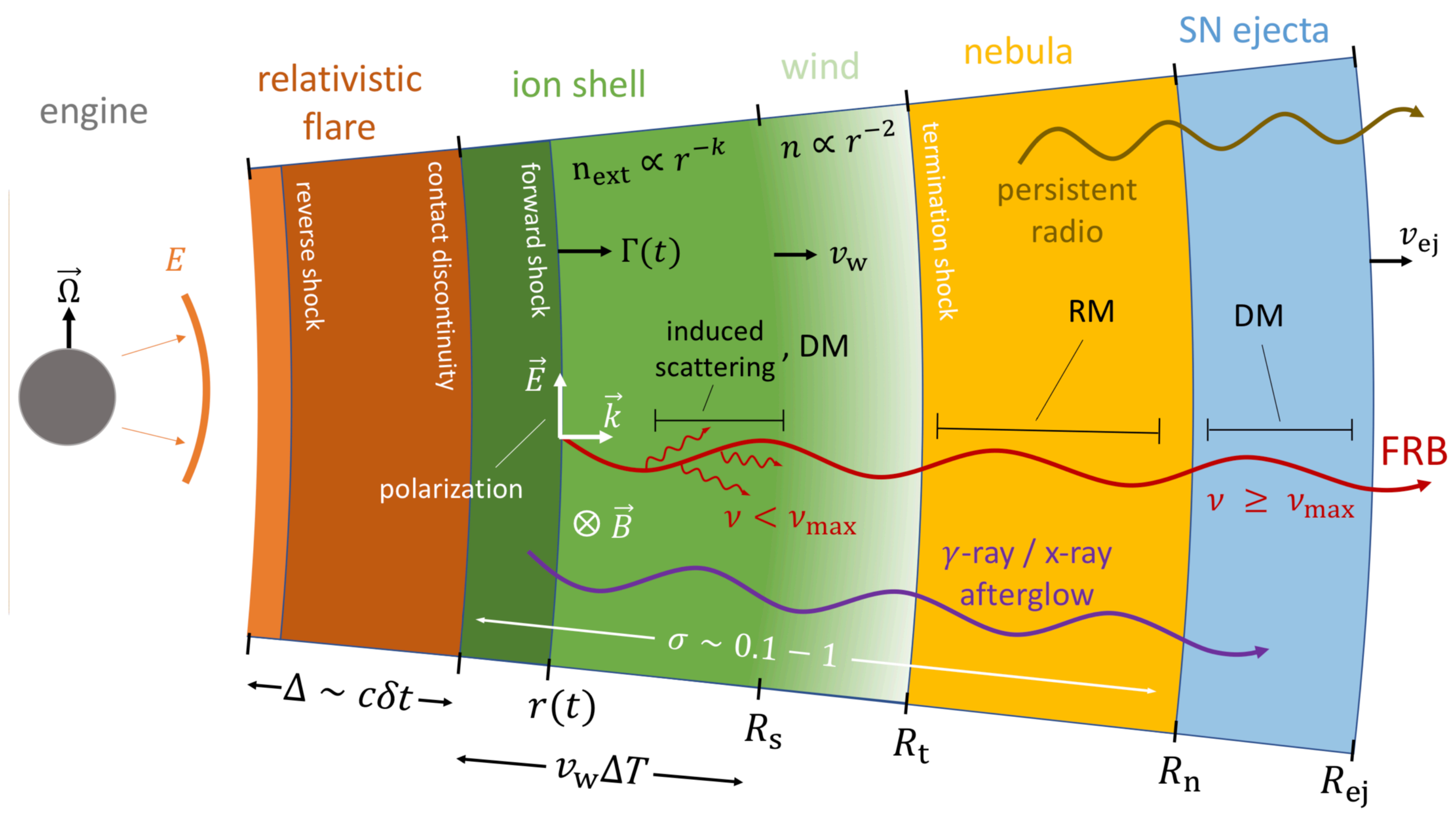
- Antenna mechanism (bunches)
- Plasma instabilities (plasma masers)
- Vacuum masers

Where?

For magnetars: inside or far awar from magnetosphere?



Lu, Kumar & Zhang (2020)



Metzger, Margalit & Sironi (2019)

Magnetospheric origin of FRB emission

- Observational supports:
  - FRB 200428 - XRB association, peak alignment
  - Pulsar-like behavior: PA swing (rotation vector model), orthogonal jump, circular polarization
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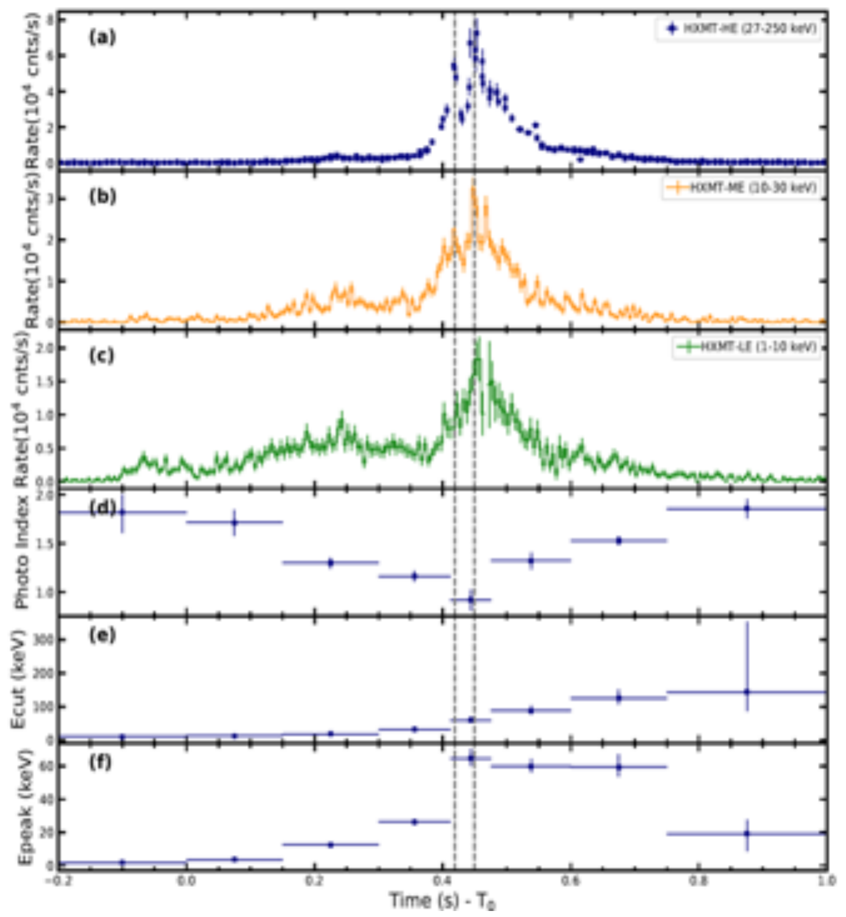
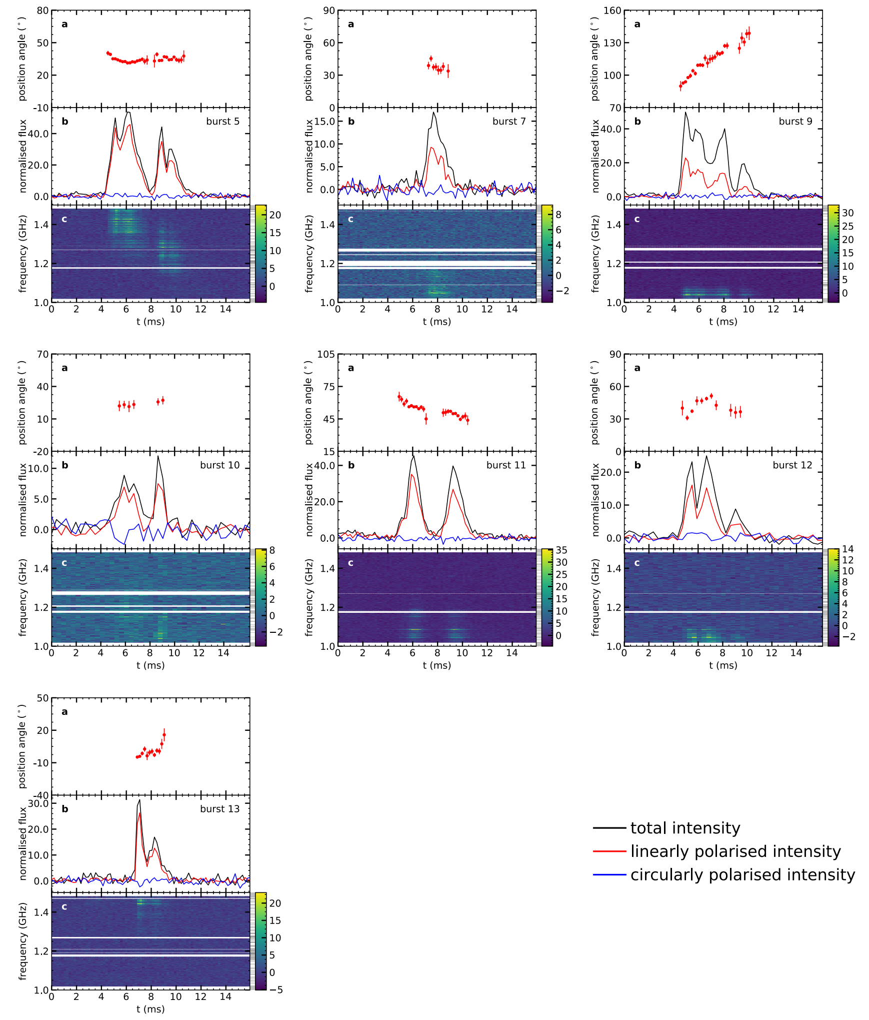
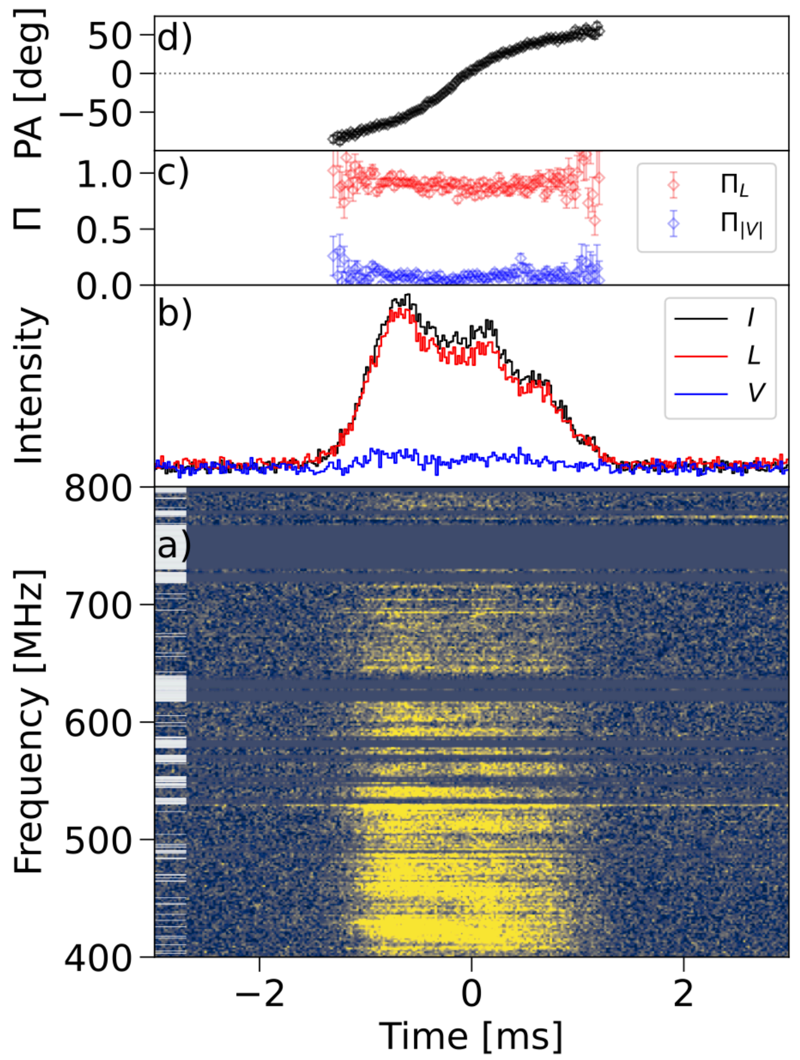


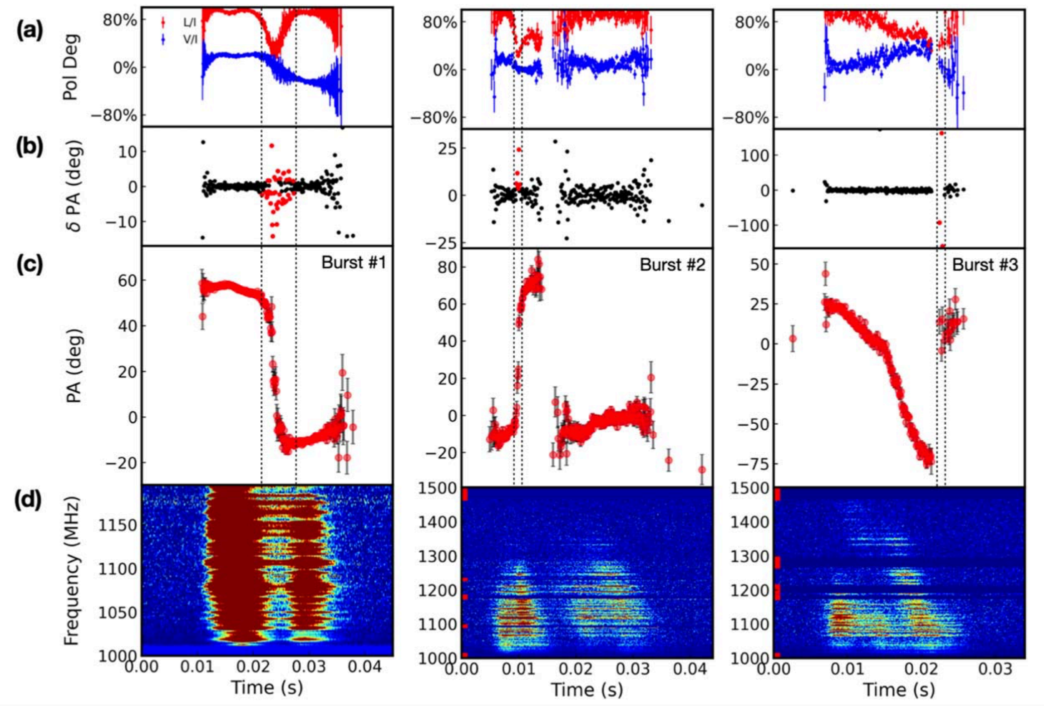
Li, C. K. et al. 2021



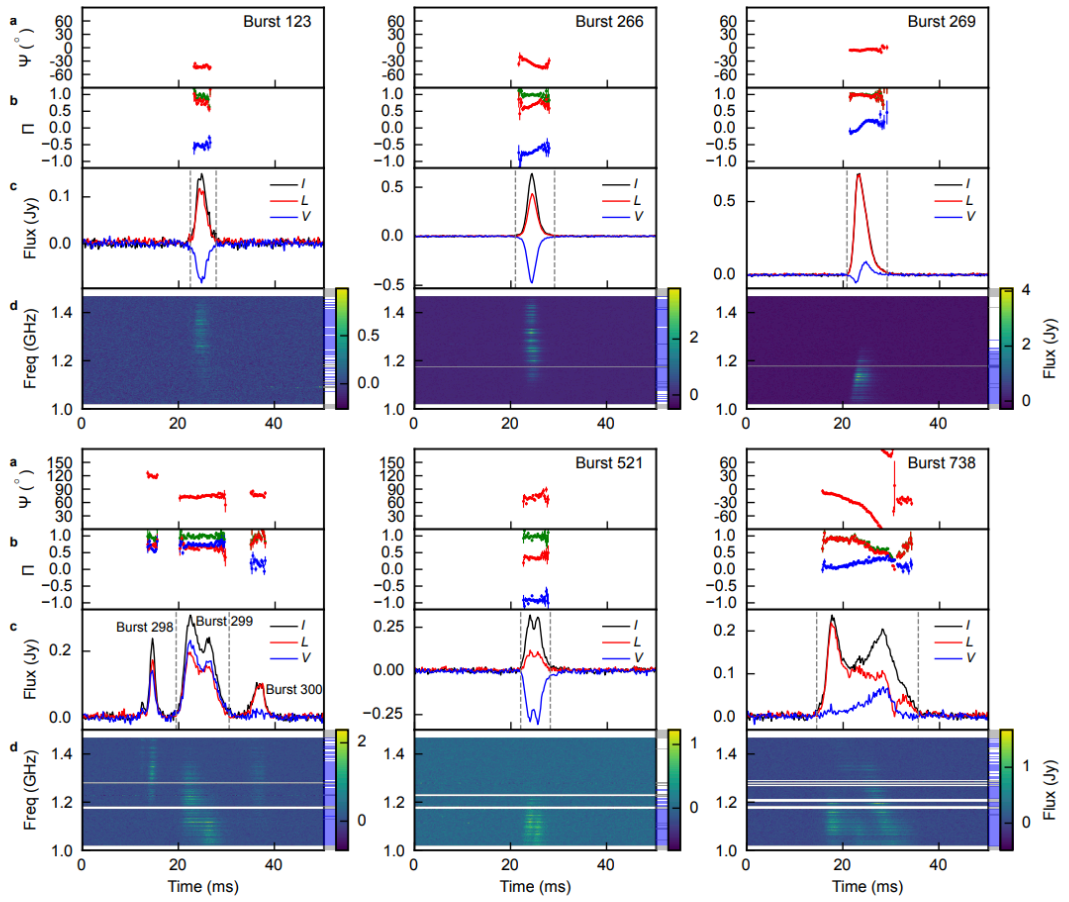
Luo et al. 2020



Mckinven et al. 2024



Niu et al. 2024



Jiang et al. 2024

Magnetospheric origin of FRB emission

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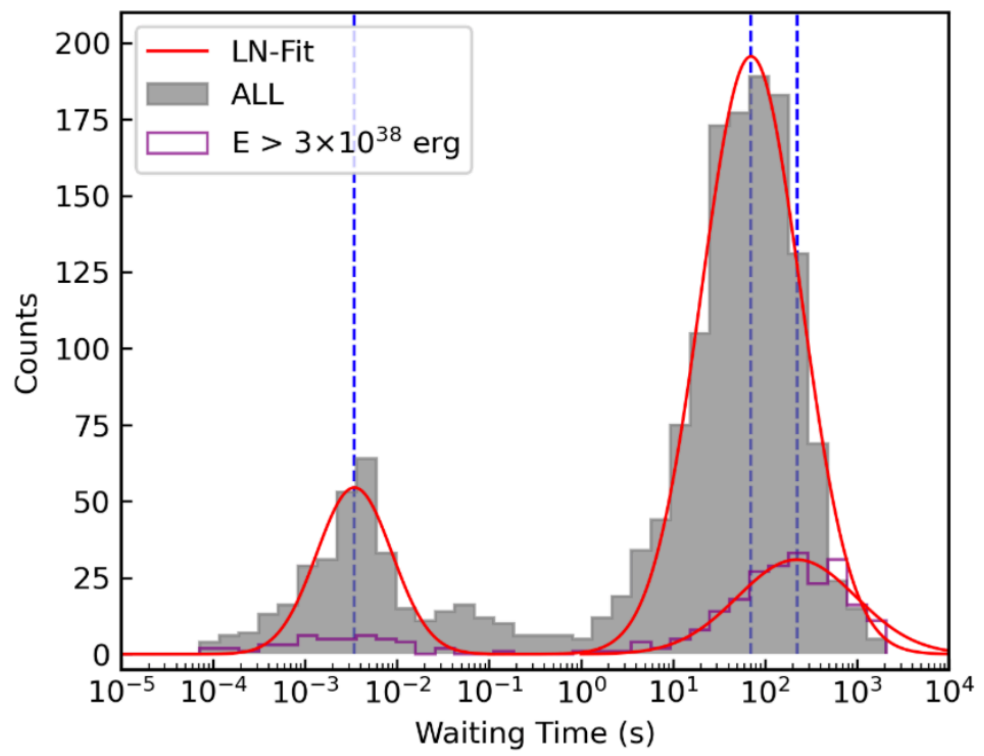
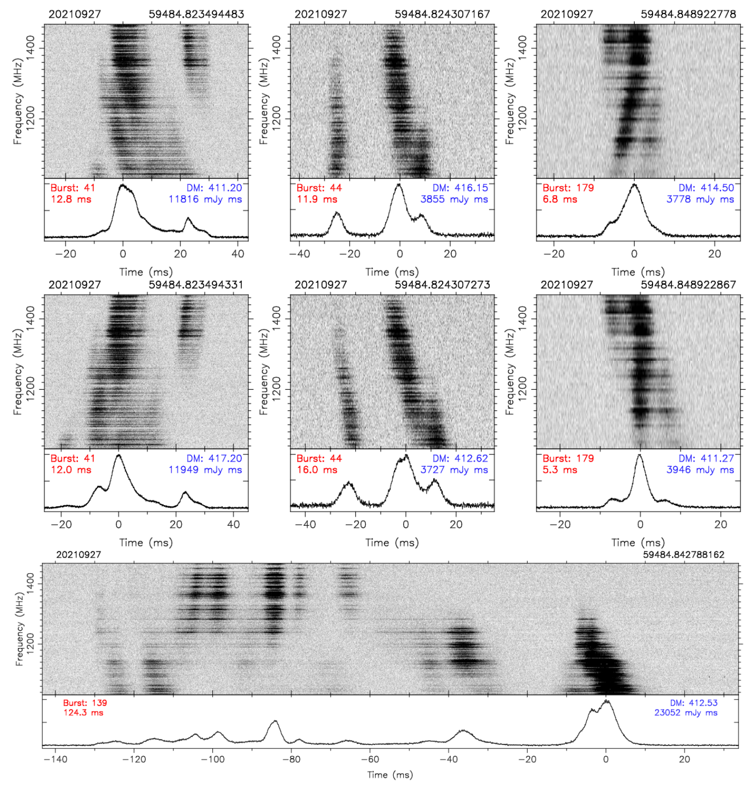


Li, D. et al. 2021



Zhou et al. 2022

(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)

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

Li, D. et al. 2021; Xu, H. et al. 2022; Zhang, Y. K. et al. 2022
Zhang, J. S. et al. 2025, submitted

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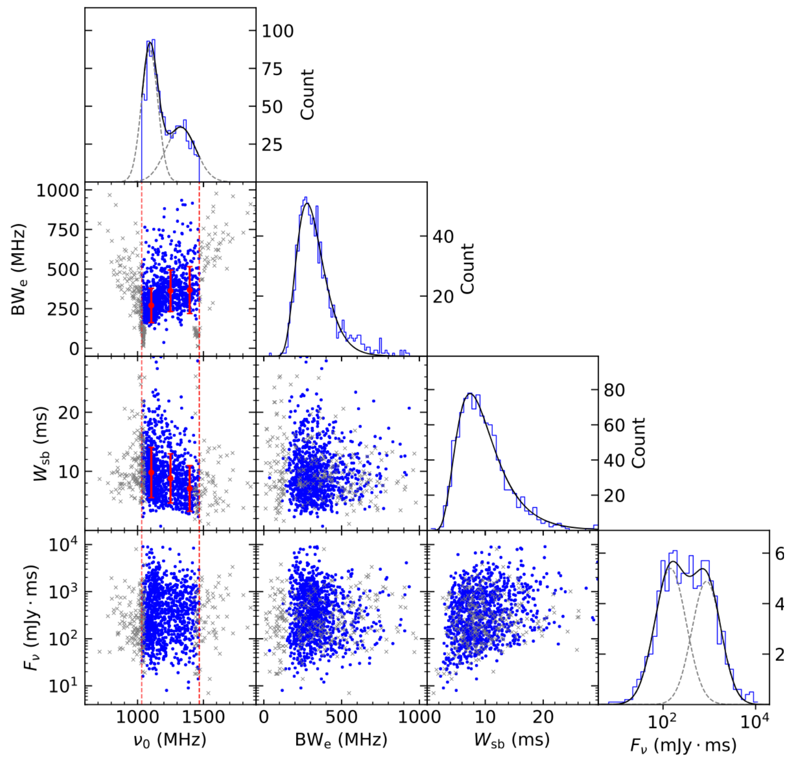
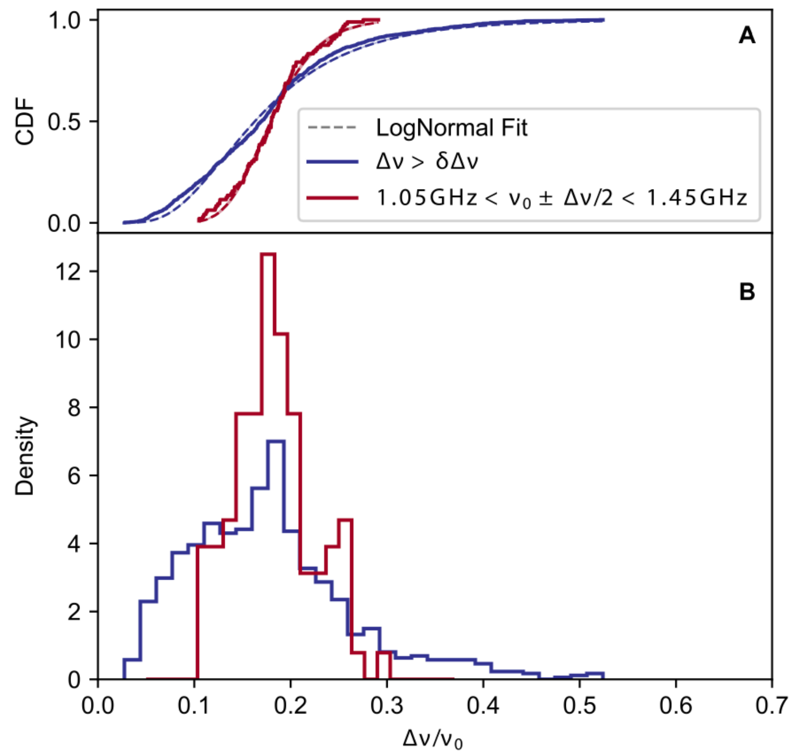
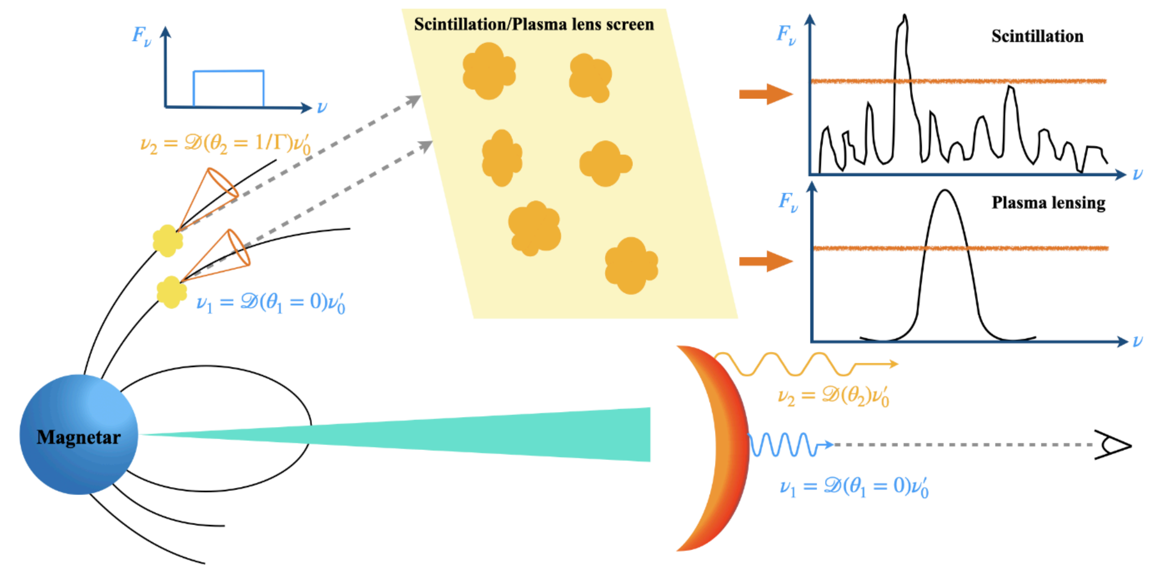


Zhou et al. 2022

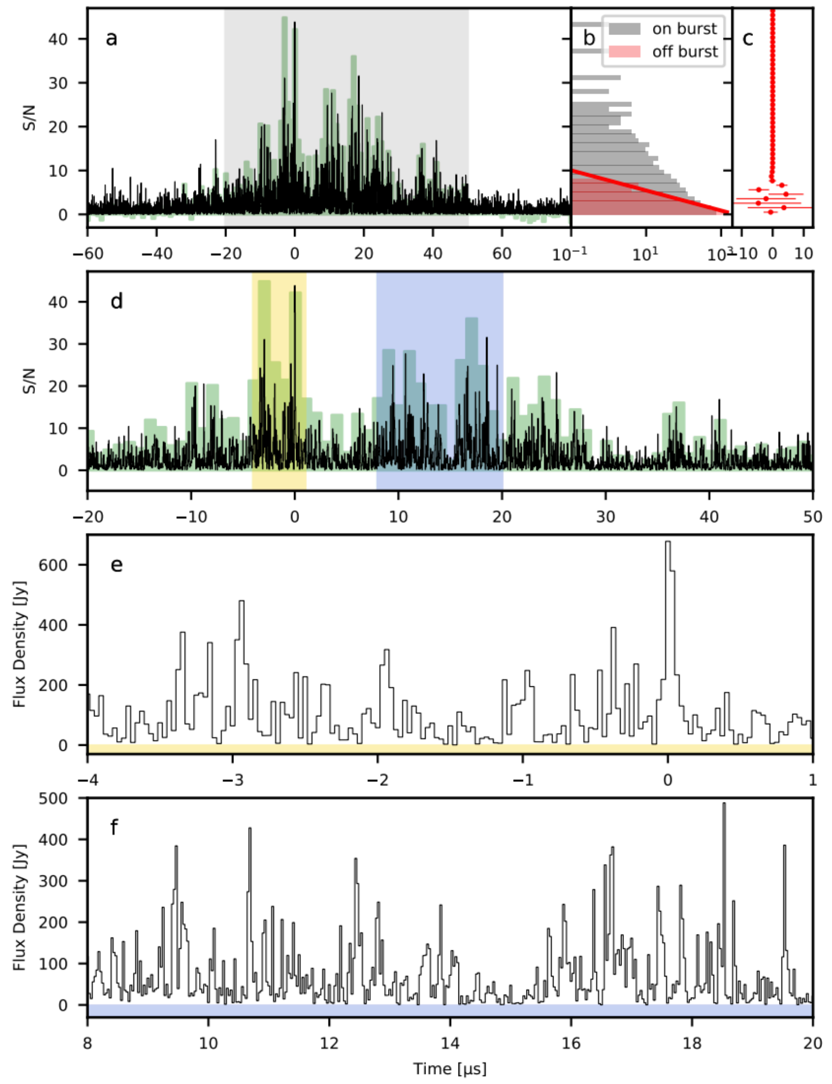


Zhang, Y. K. et al. 2022

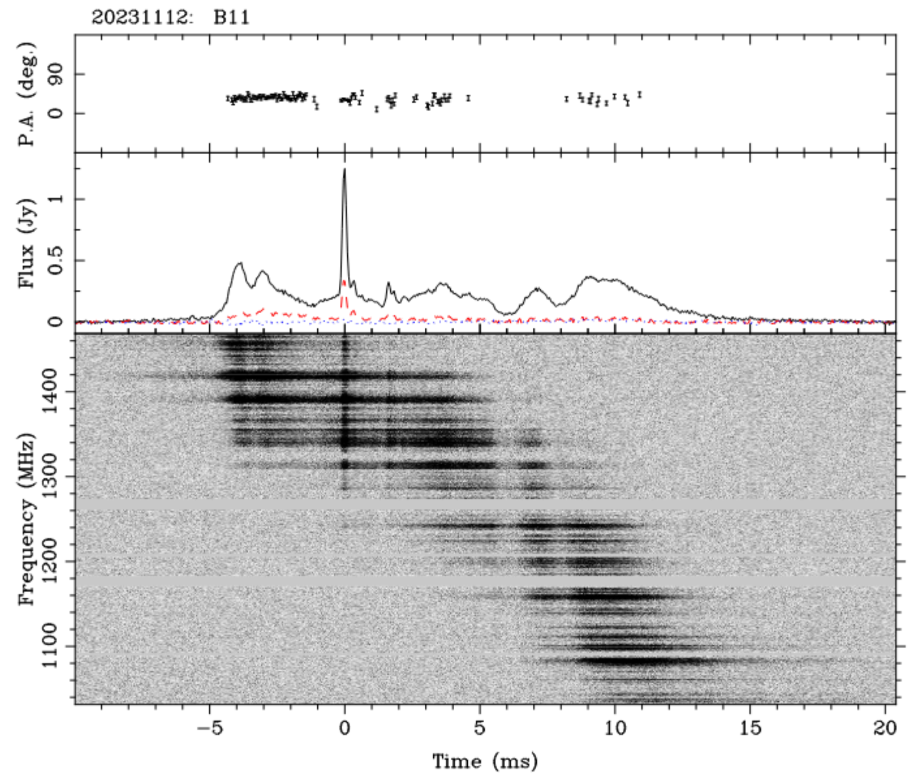


$$\frac{\Delta\nu}{\nu_0} = 2 - \frac{2}{\sqrt{2}} \simeq 0.58.$$

Kumar, Qu & Zhang 2024



Nimmo et al. 2021
Lu, Beniamini & Kumar 2022



Zhou et al. 2024

$$\Delta t/T \ll 1$$

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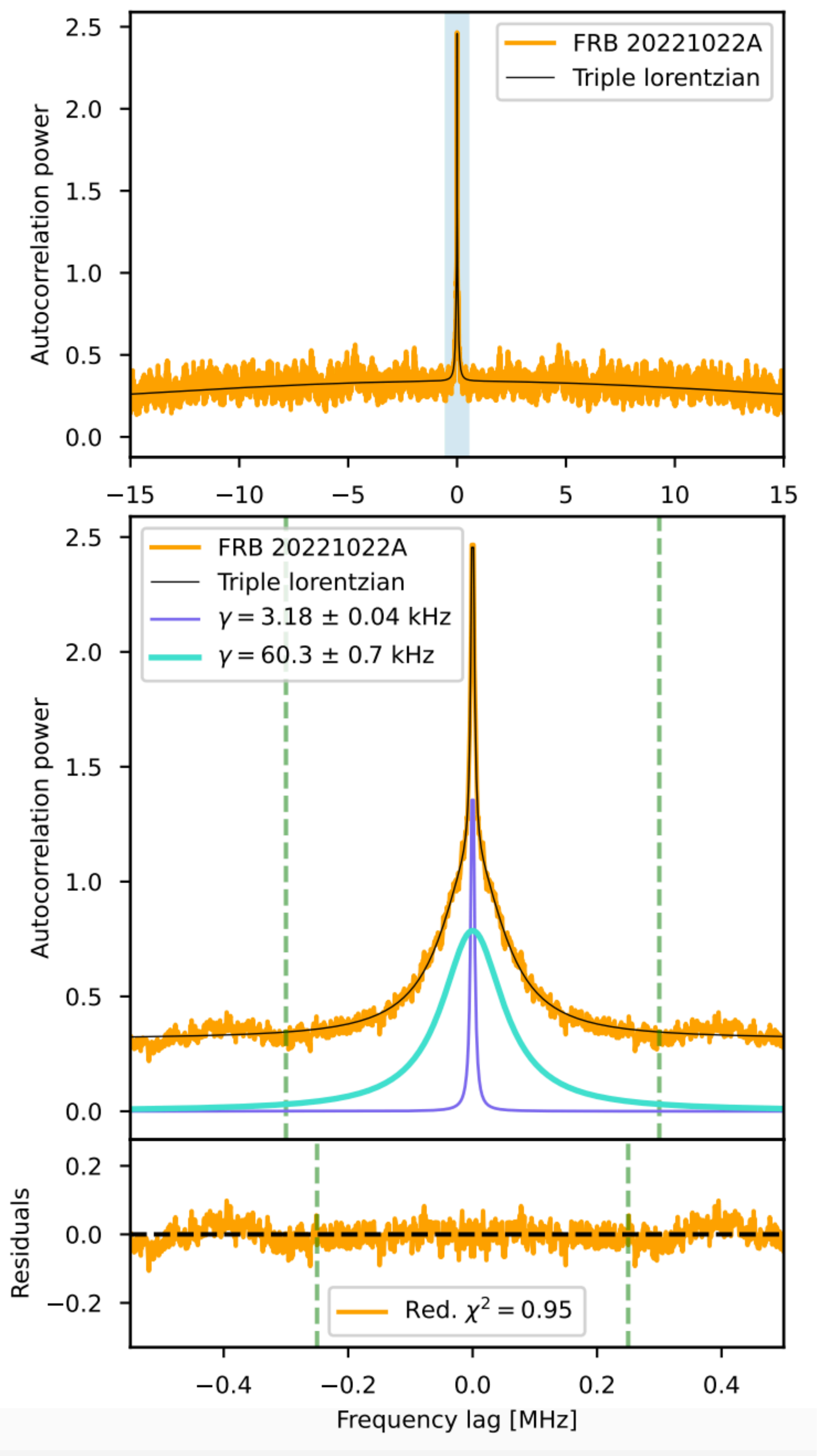

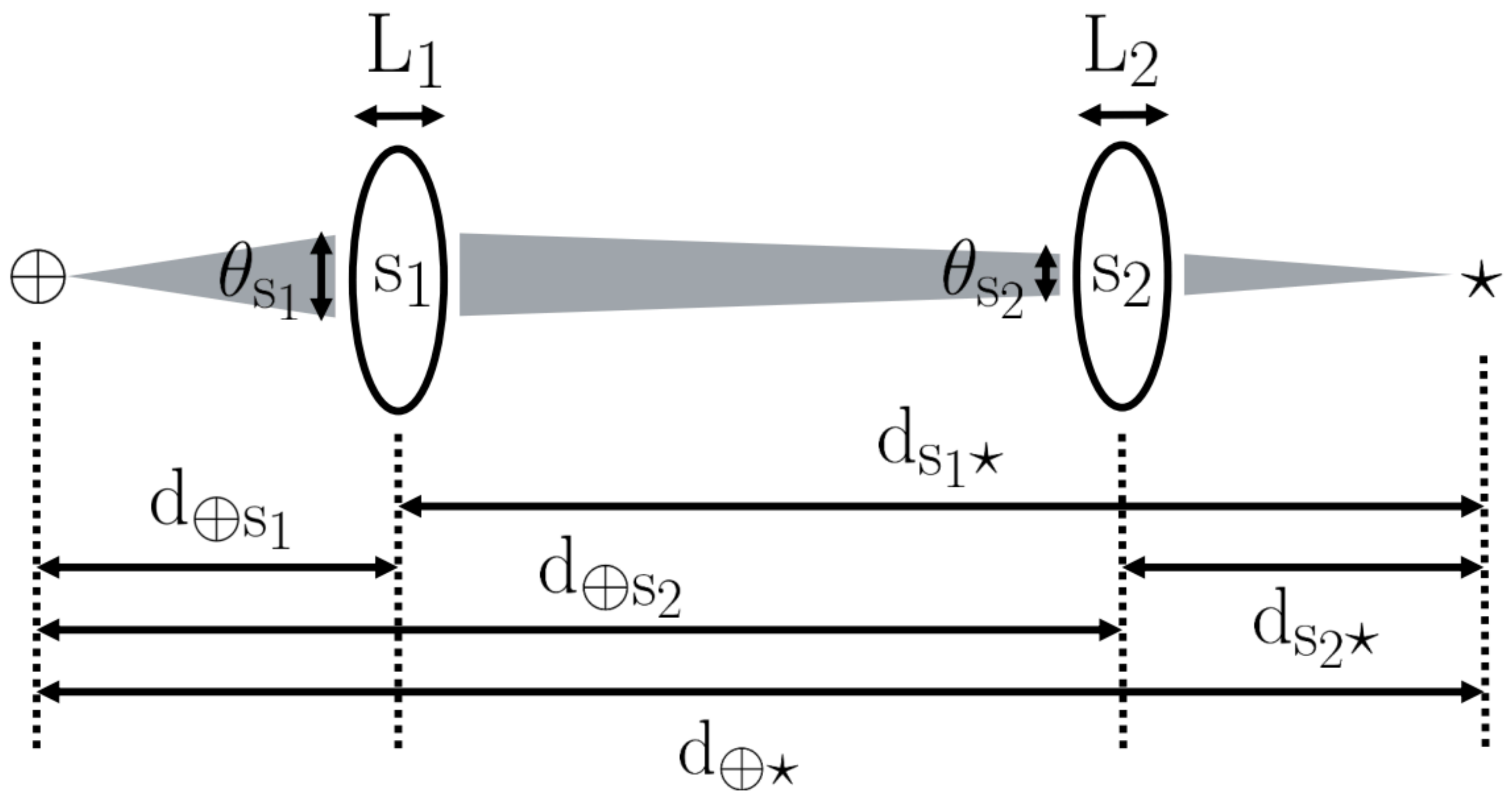

Nimmo et al. 2024
Kumar, Beniamini, Gupta 2024

Magnetospheric origin of FRB emission

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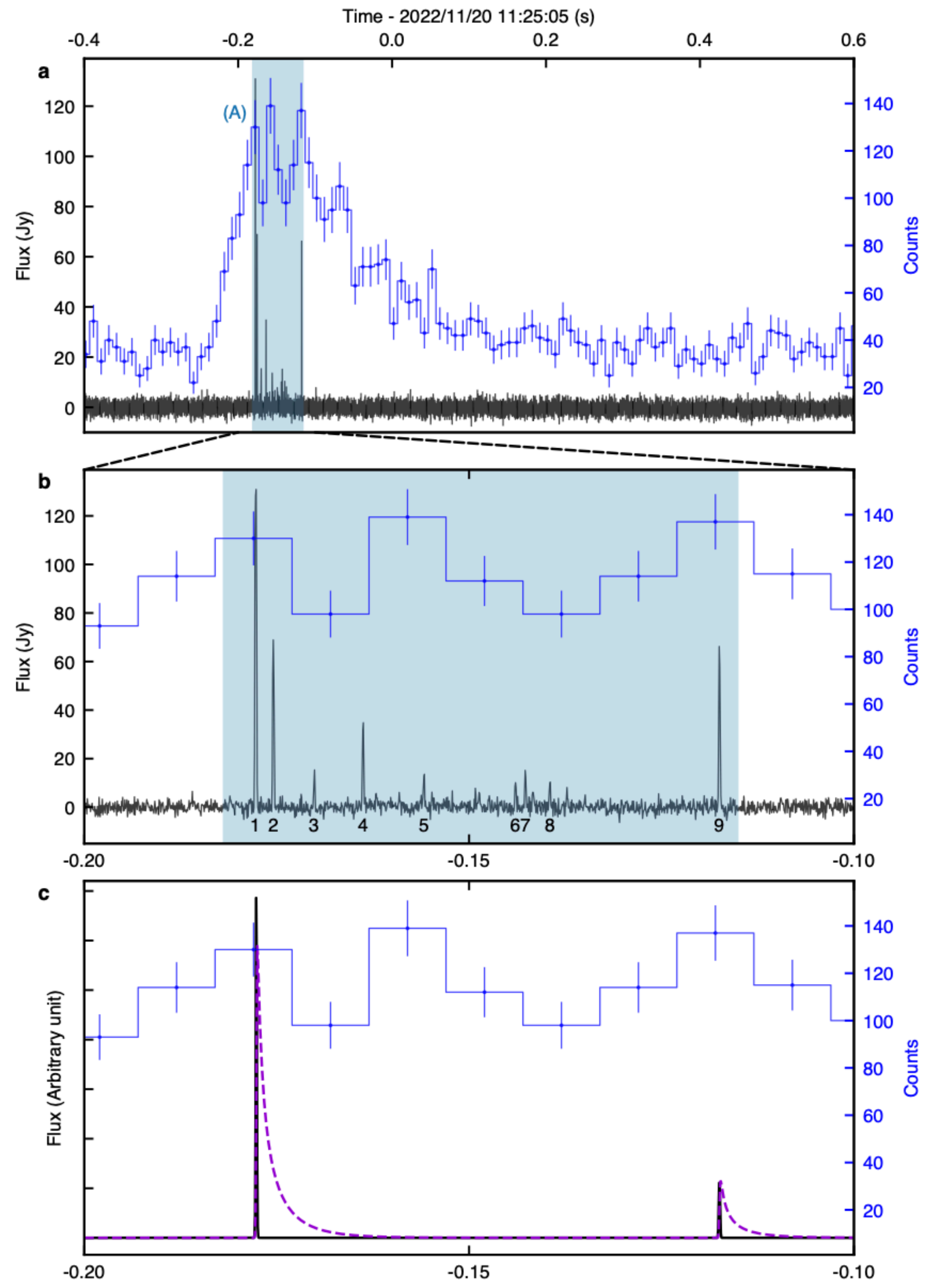
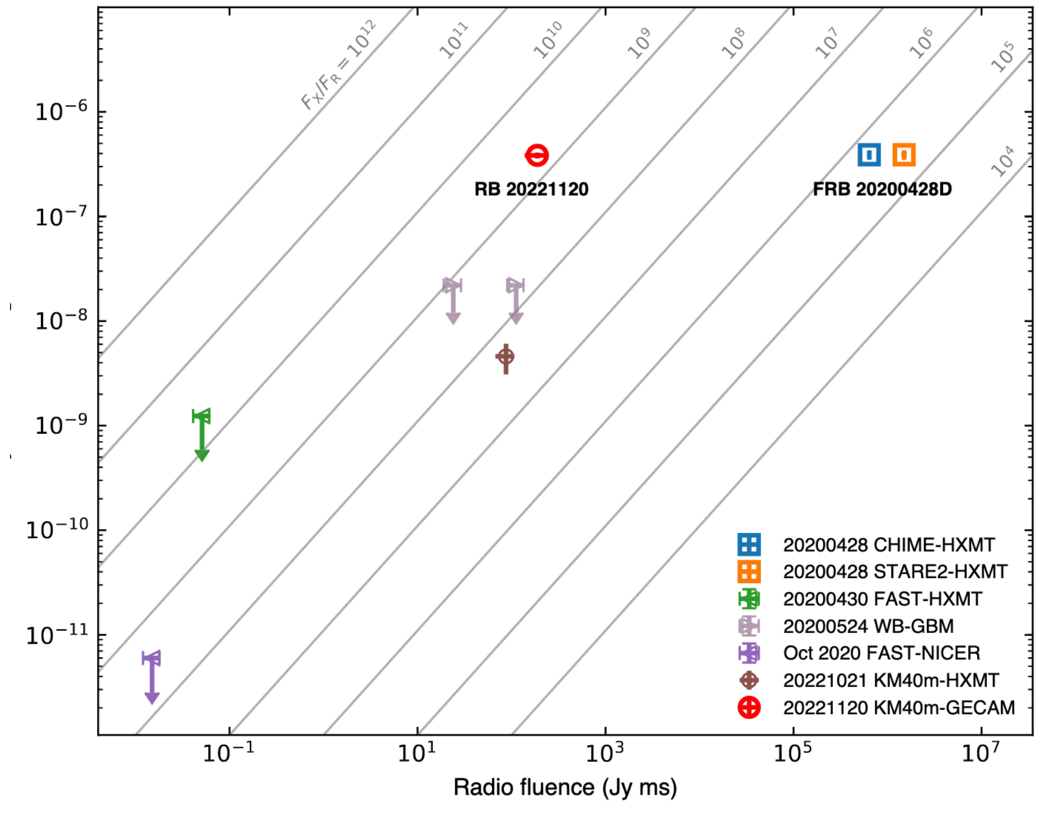
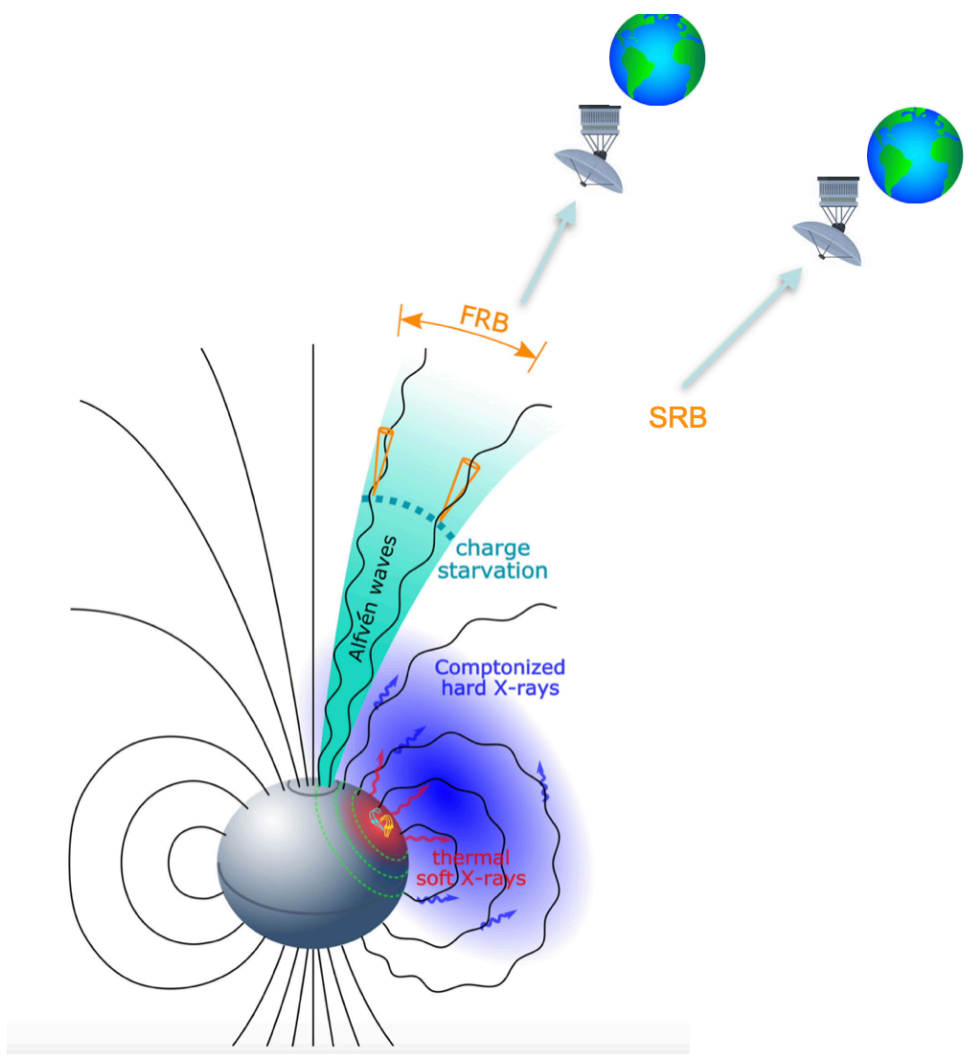


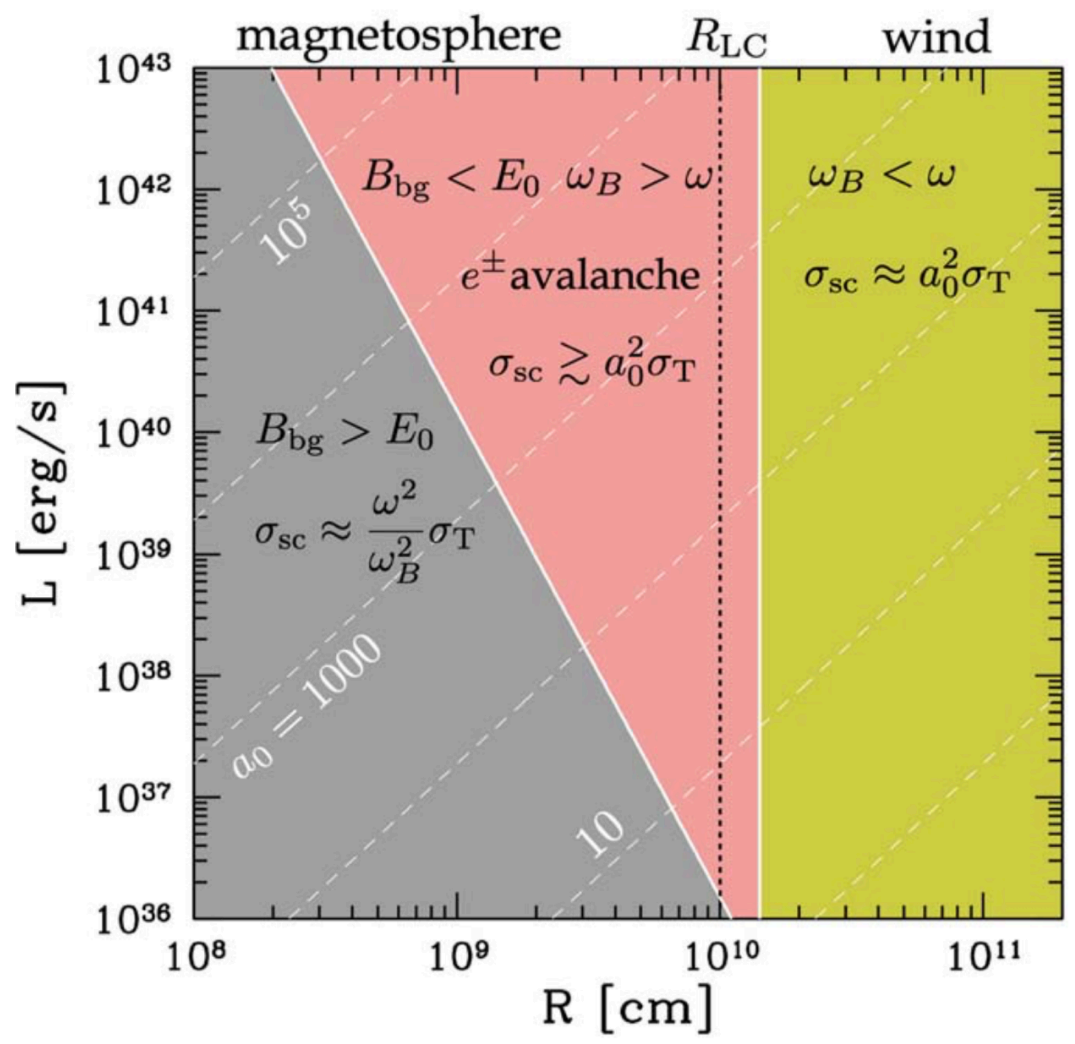
X. B. Li et al. (2024)



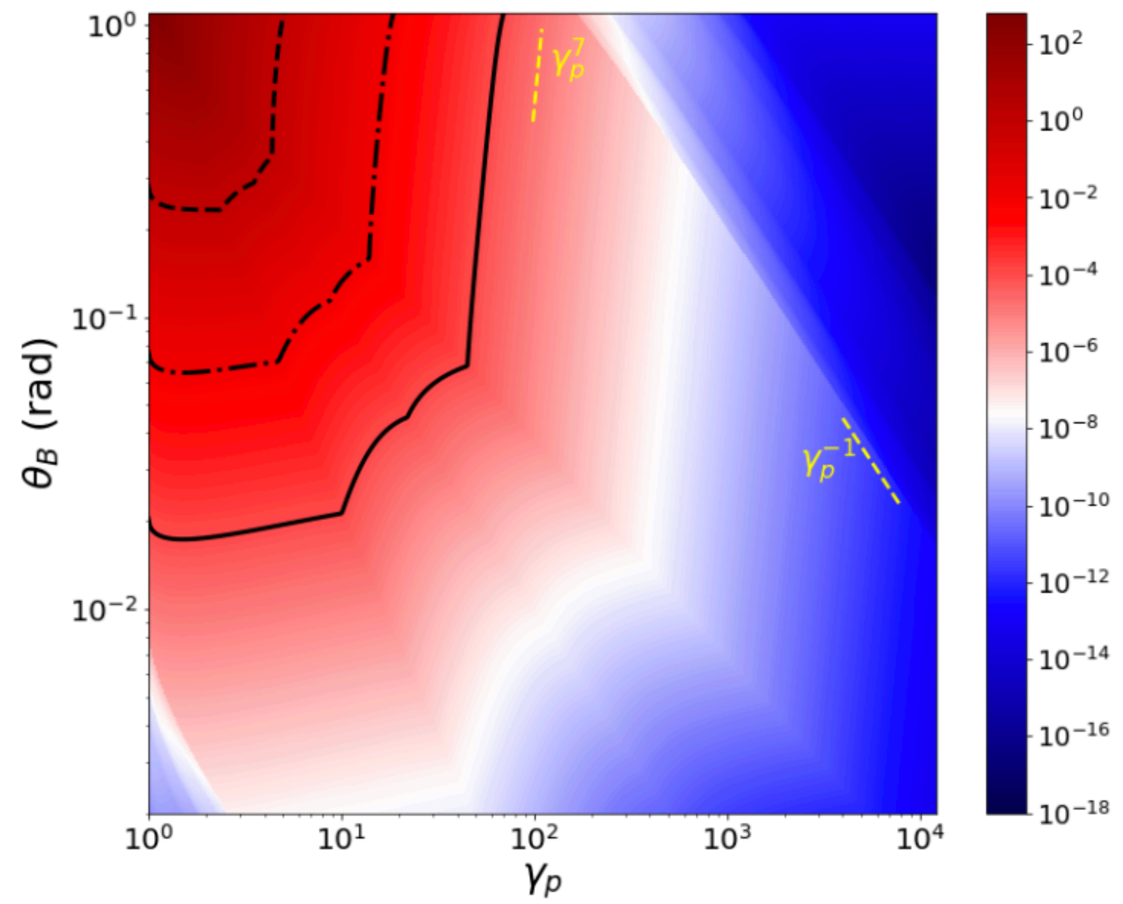


Zhang (2021)

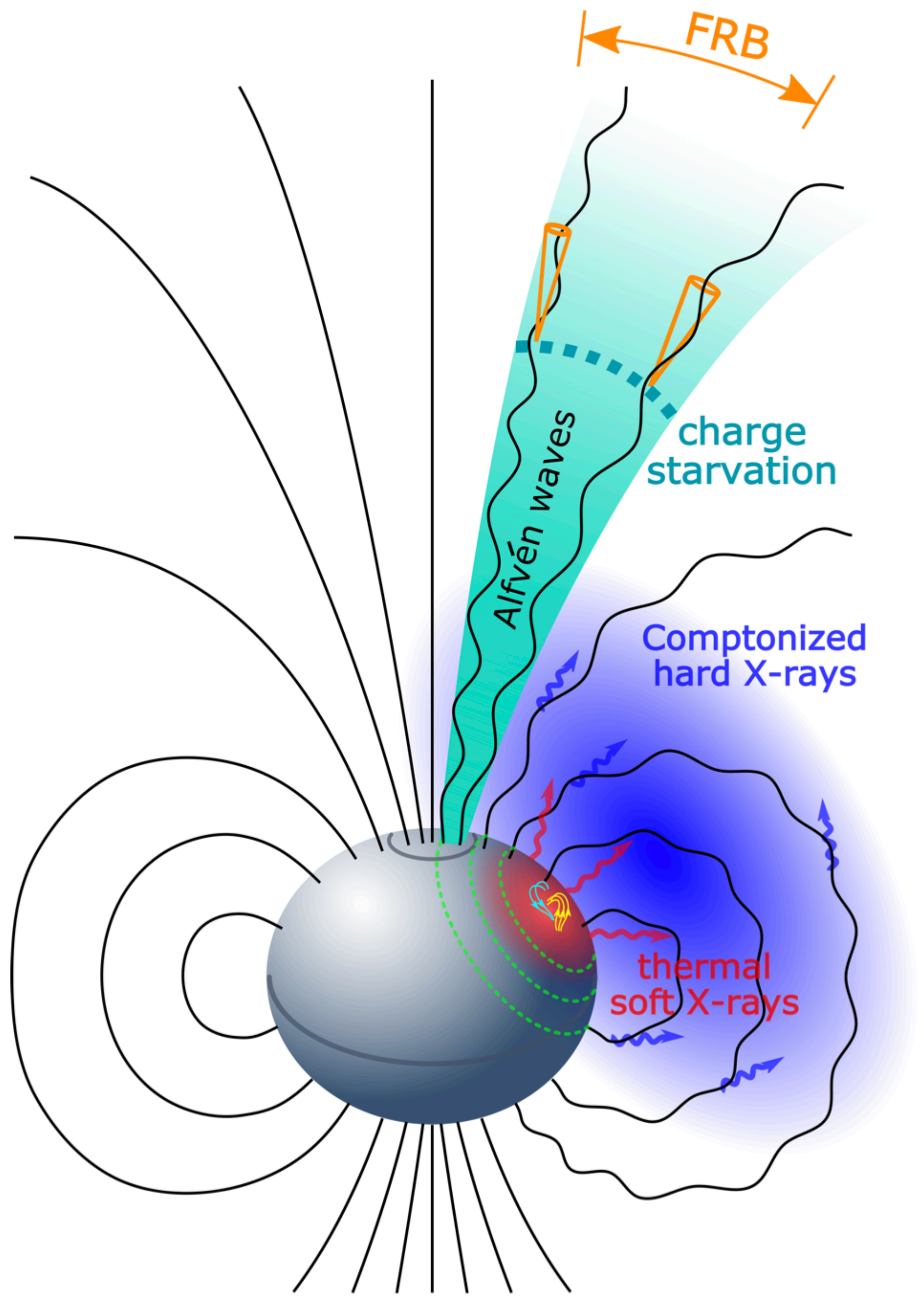
Theoretical difficulties?

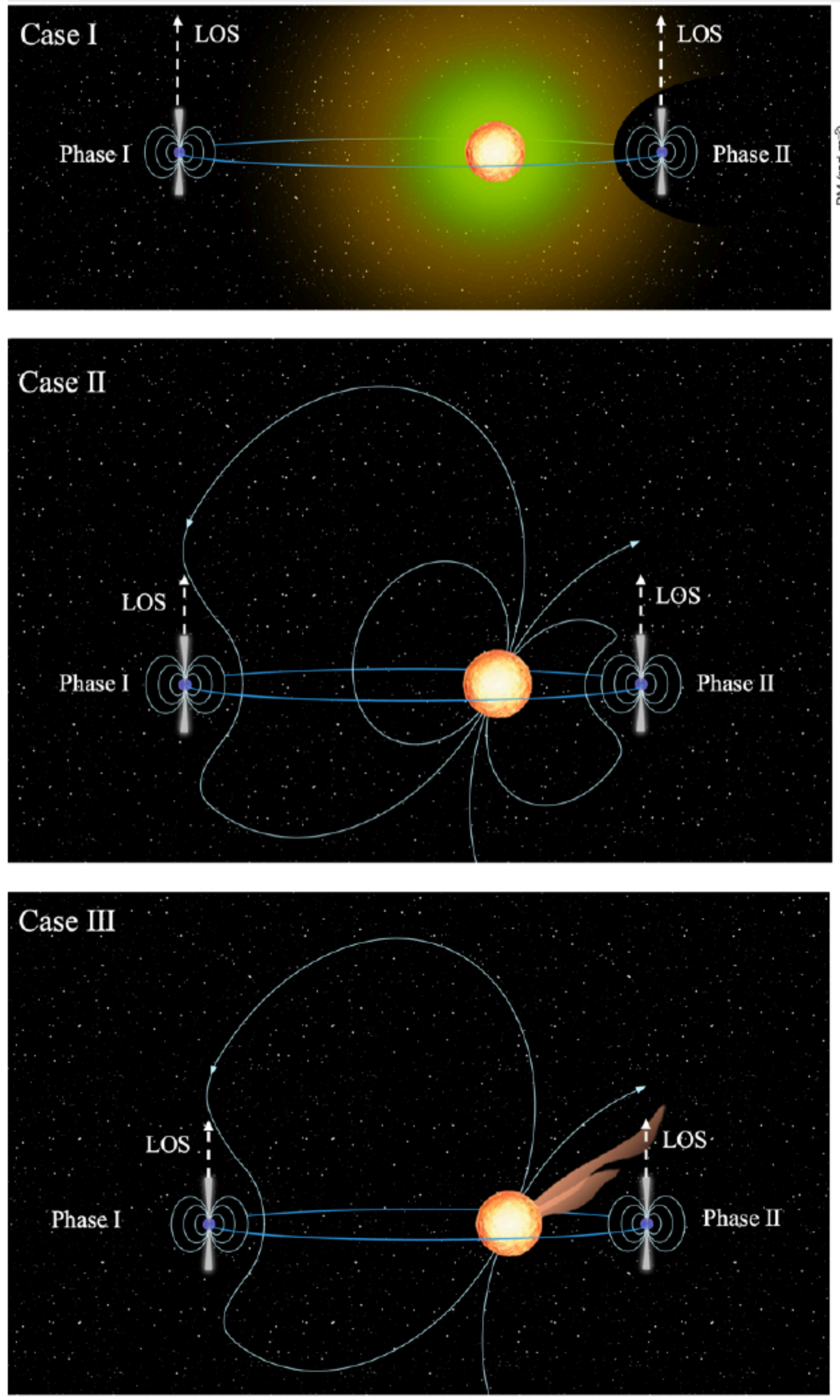


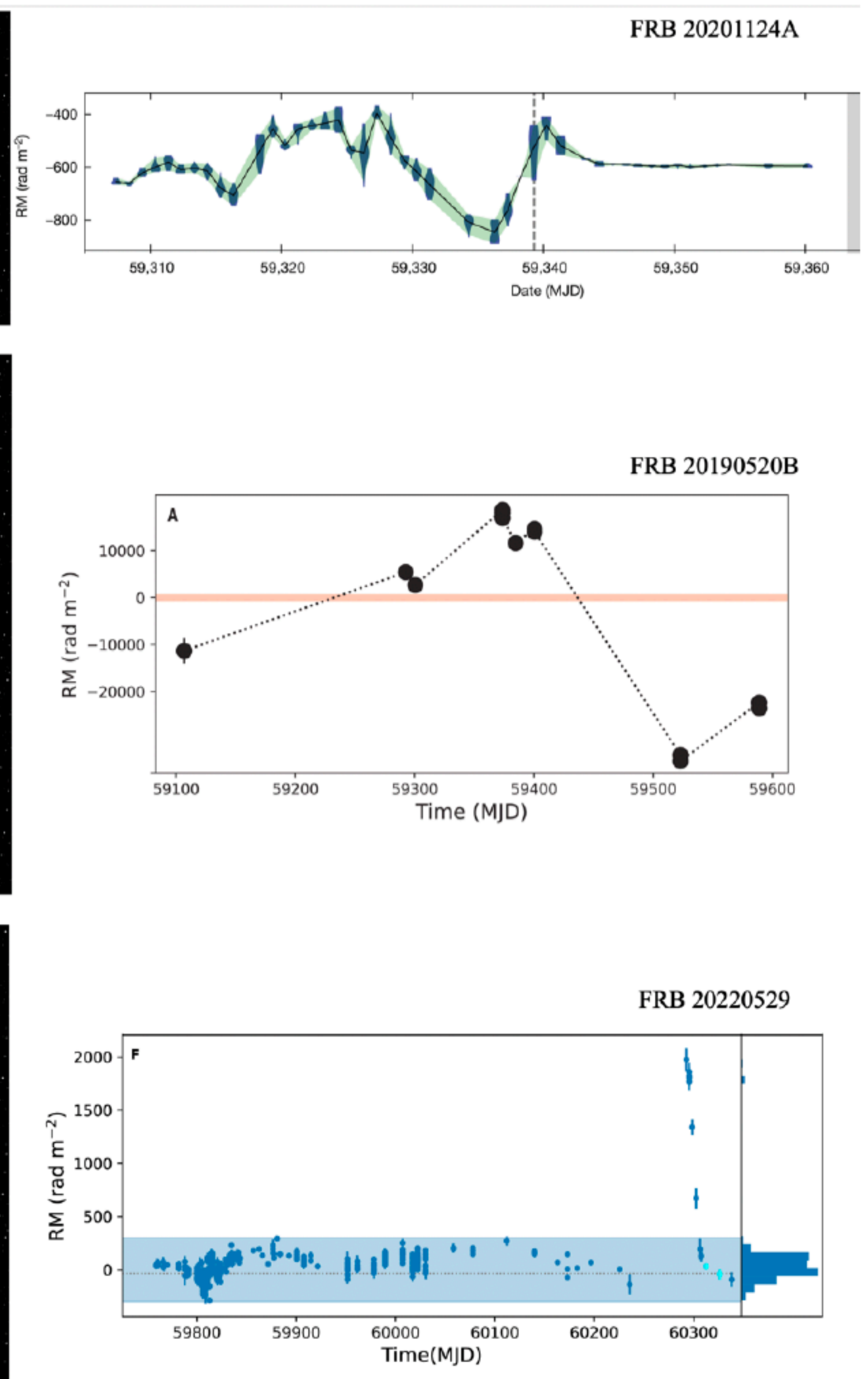
Beloborodov (2021)
Sobacchi et al. (2024)



Qu, Kumar & Zhang (2022)





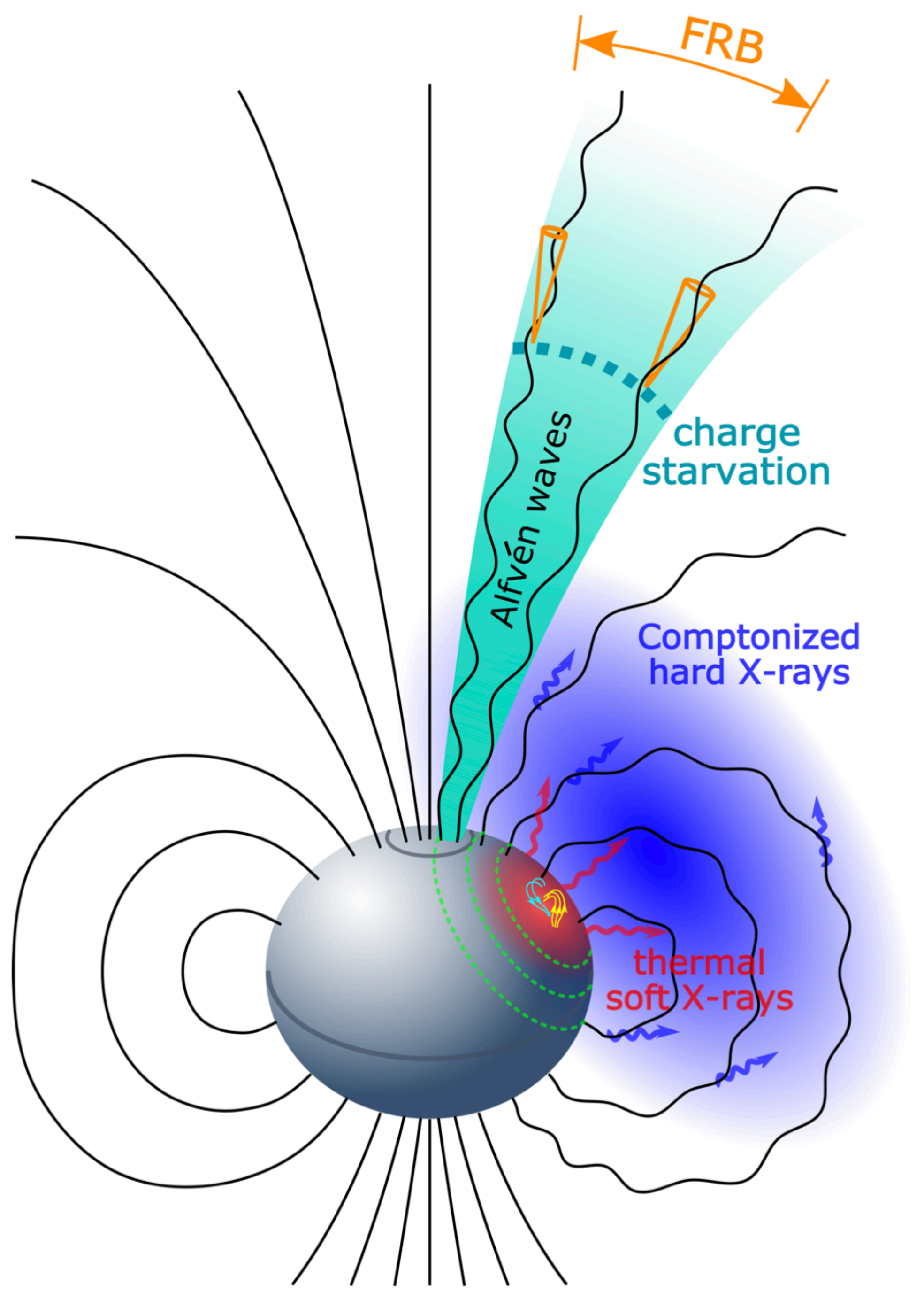


Zhang & Hu (2025)

FRB waves can propagate within a magnetar magnetosphere if it originates from an open field line region where the plasma moves relativistically outward, especially under the nearly aligned geometry

Where?

- Overwhelming observational evidence suggests that FRB bursts (at least those emitted by active repeaters) originate from magnetospheres!

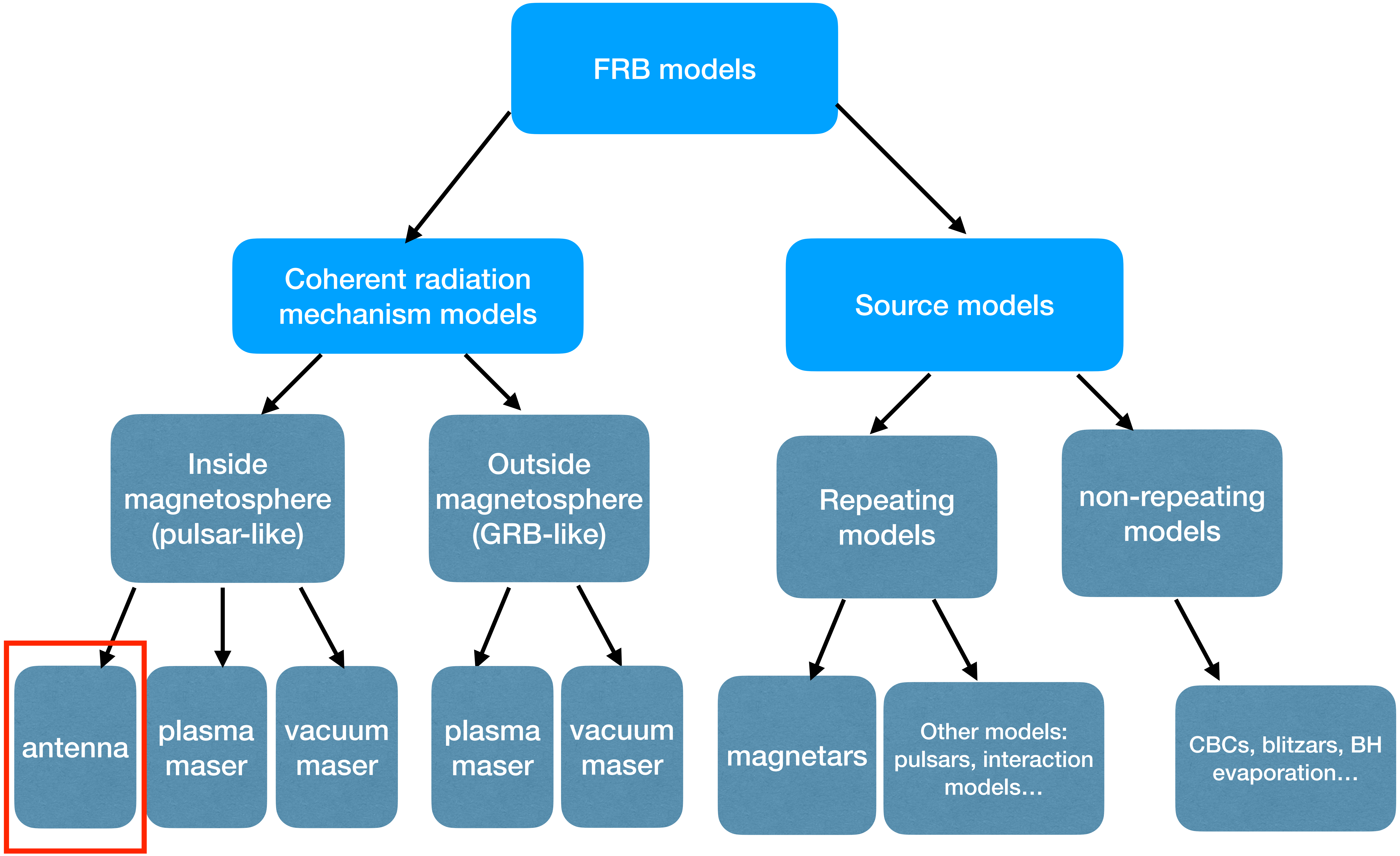


Lu, Kumar & Zhang (2020)

How?

Radiation mechanisms

Components of FRB Models

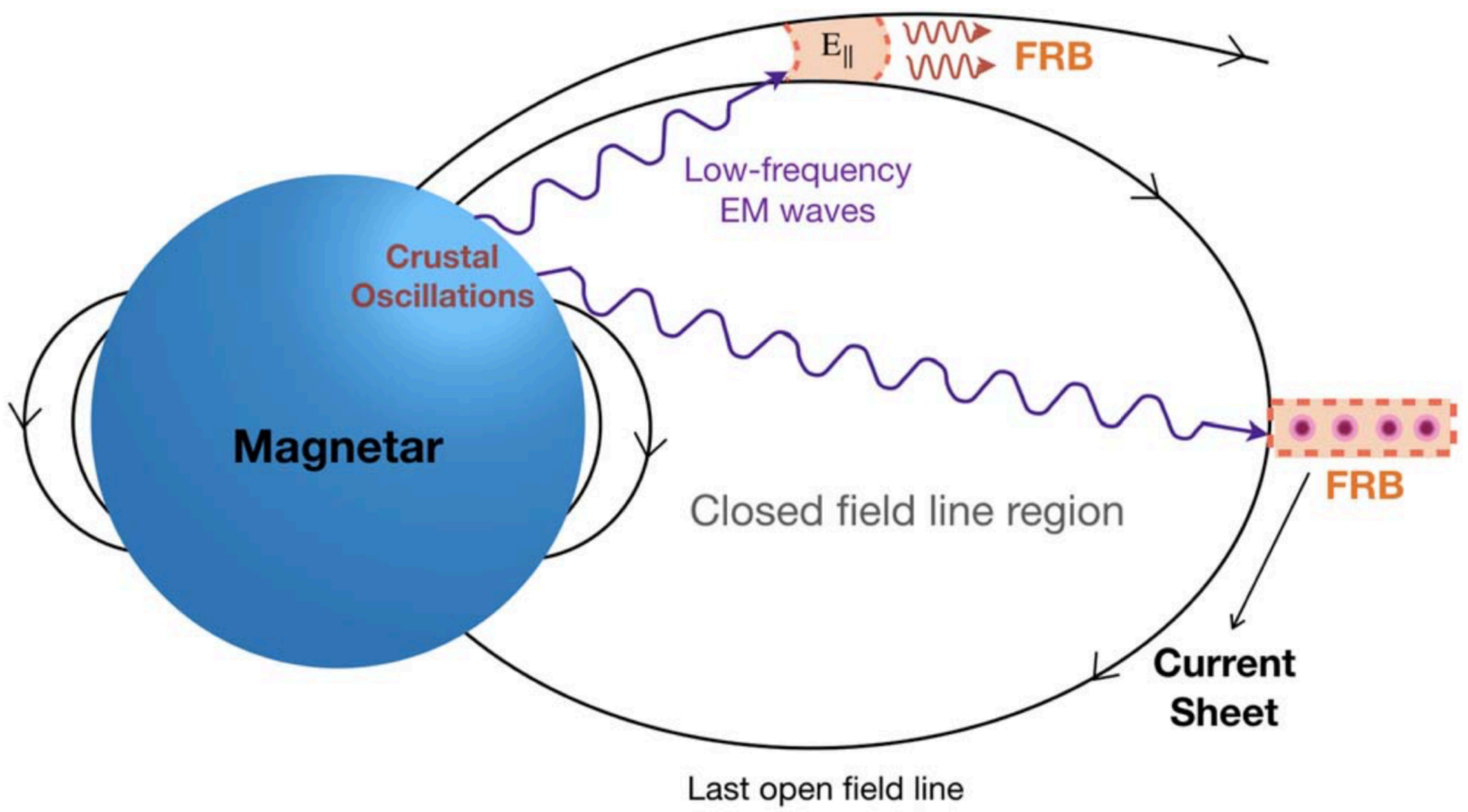


Personal favorate model: Inverse Compton scattering

Zhang, 2022, ApJ, 925, 53
Qu & Zhang 2023, MNRAS; 2023, 522, 2448
Qu & Zhang, 2024, ApJ, 972, 124

Bridging kHz seismic waves and GHz radio waves

Narrow spectra Linear & circular polarization



High emission power for individual particles, less coherence demanded

Bunching by low-frequency waves?

Conclusions

- **What:**
    - Active repeaters are likely powered by magnetars in binary systems with aligned geometry
    - Inactive repeaters are likely isolated magnetars or magnetars in binaries with mis-aligned geometry
    - There could be other possibilities, including those associated with gravitational waves
- **Where:**
    - Magnetospheric origin at least for most active repeater bursts
- **How:**
    - Still uncertain, but possibilities are narrowed down; inverse Compton scattering?
    - Top-down approaches (from observations) should be more fruitful than bottom-up approaches
- FRBs are valuable probes for the universe, and fundamental physics