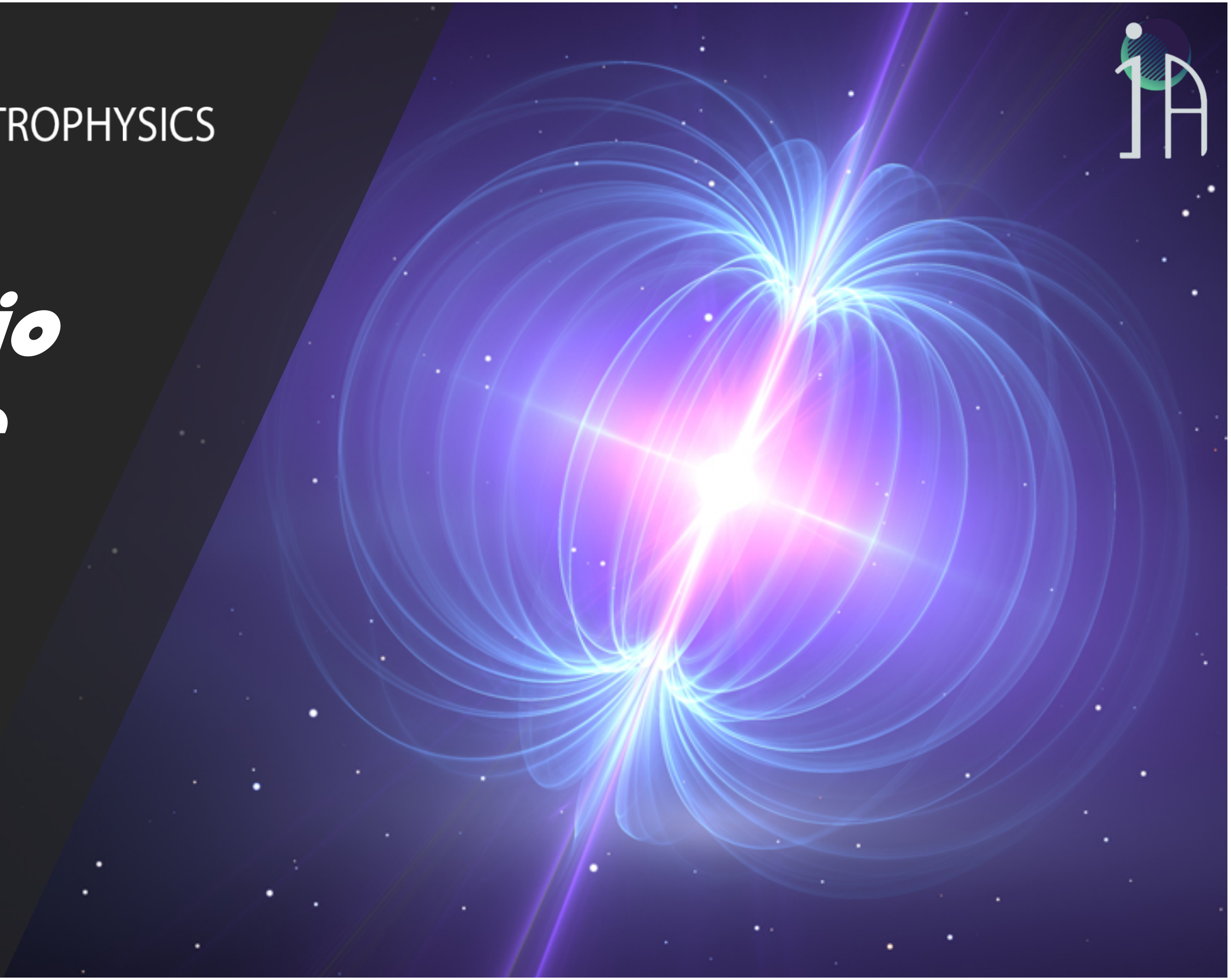
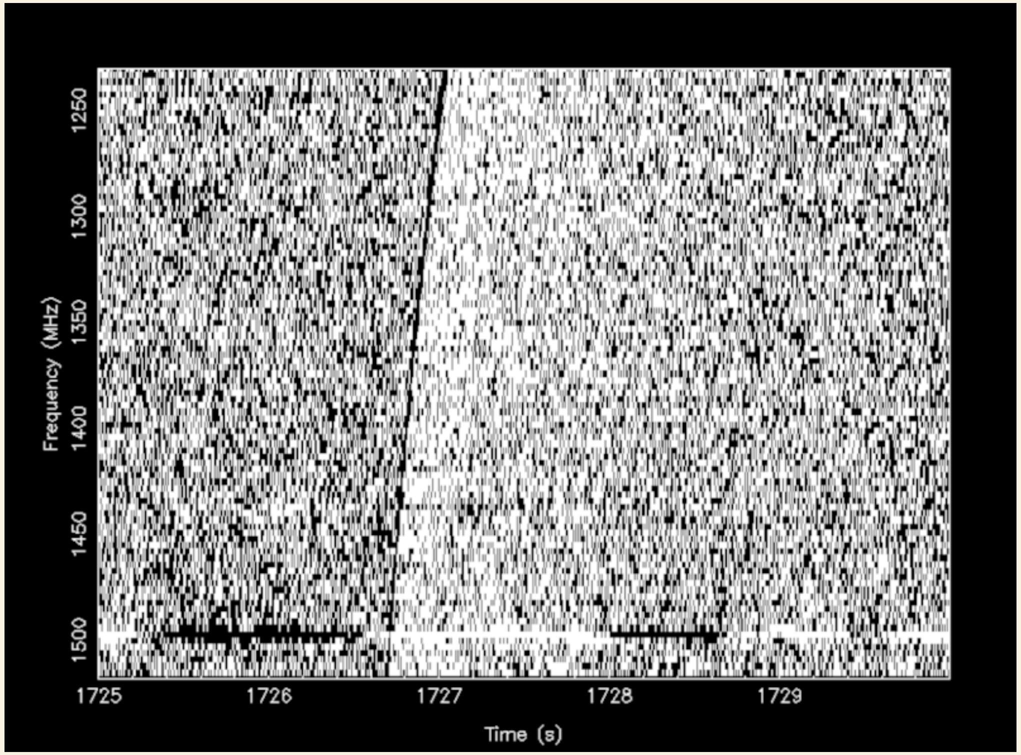
FORTH
INSTITUTE OF ASTROPHYSICS

A Fast Radio Burst in the Milky Way



Alexandros Tsouros, Journal Club
20/11/2020

Fast Radio Bursts (FRBs)



Lorimer et al. (2006)

The name of FRBs is quite apt:

Transient radio pulses ranging from a fraction of a millisecond to a few milliseconds, caused by some high-energy astrophysical process not yet understood.

Interestingly, there are more theories explaining their production than there are FRB events observed

All FRB observed events have had extragalactic origin.

FRB Phenomenology

Their source is a compact object: either a BH or NS:

$$w \sim 10^{-3} s \rightarrow l \sim cw \sim 10^{2}\ km$$

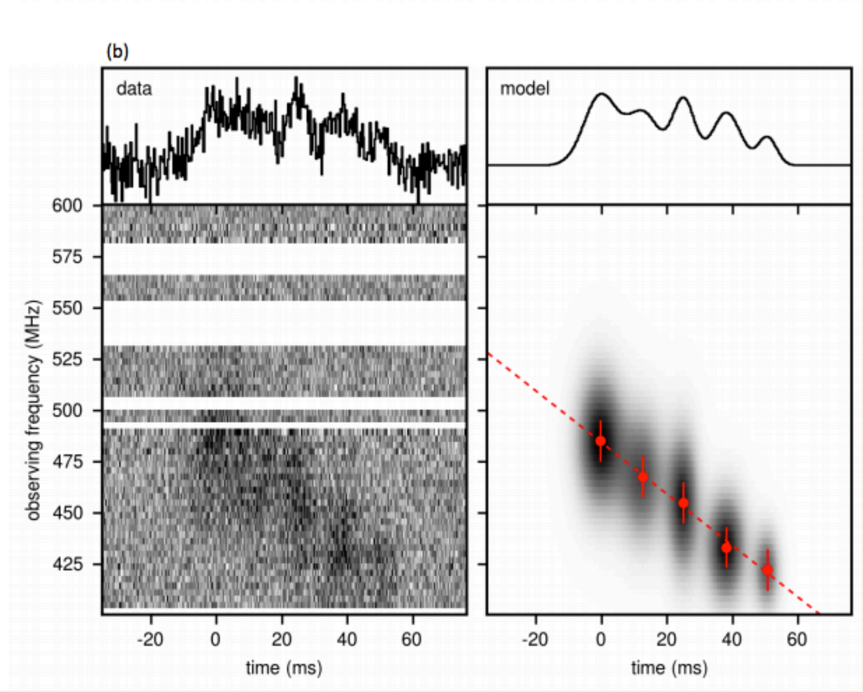
So their engine is a compact object

Some (mostly repeating sources) show a frequency down-drifting (see Figure)

Extragalactic in origin : $DM \sim 300 - 400\ ^{pc}/_{cm^3}$

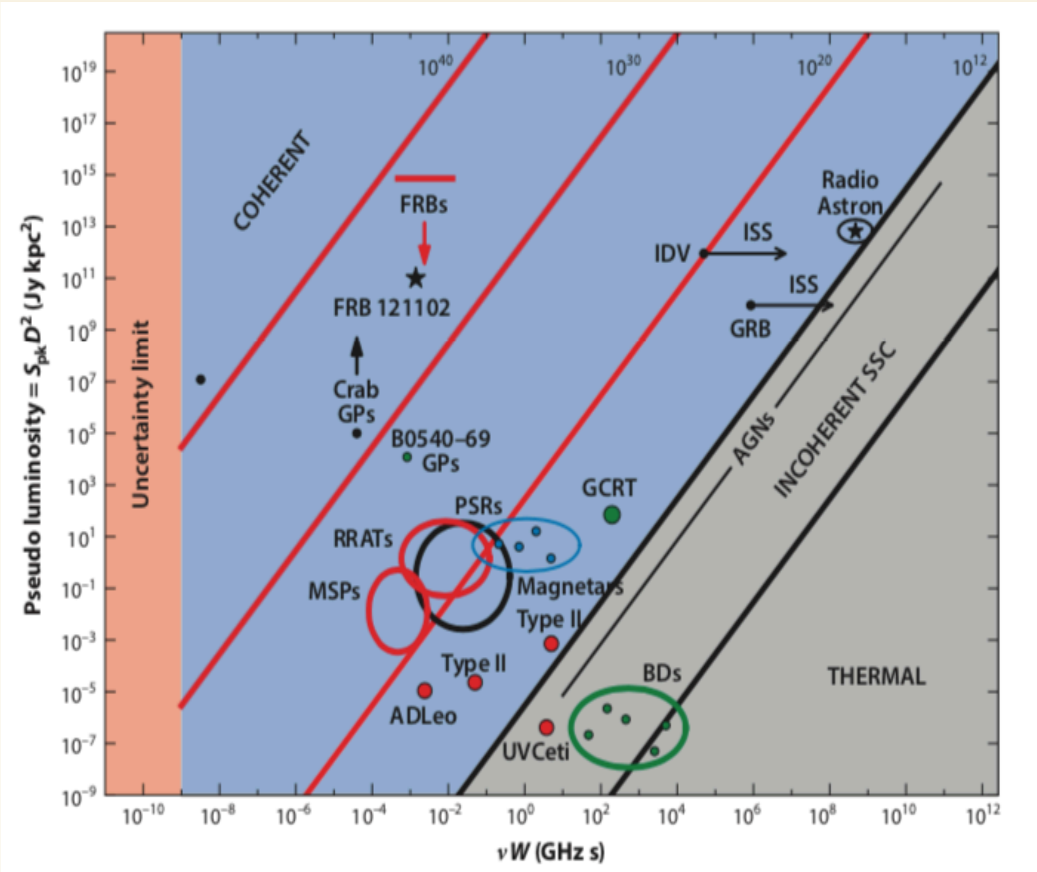
(much larger than values allowed by Galactic sources (??))

There is no definite answer about whether the bursts are periodic or not



CHIME/FRB collaboration (2019)

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



Cordes & Chatterjee (2019)

FRB Energetics

Sub-arcsecond localizations have been achieved allowing to identify host galaxies and hence the respective redshifts

(redshifts consistent with measured DM within standard framework of cosmology)

Hence, we can calculate isotropic energies: $10^{35} - 10^{43}$ erg

(very high compared to radio pulsars – very low compared to GRBs) – ***Note: These numbers do not include beaming! – should be reduced by a beaming factor***

Brightness Temperature: $T_b \sim 10^{36} K \rightarrow$ emission is *coherent:* radiation by rel. electrons is enhanced significantly compared to incoherent electron radiation (collective power $\propto N^2$ instead of $\propto N$, where *N* is number particles emitting with distinct phase relationship)

Radiation Mechanisms

Two main classes:

a) Invoke magnetosphere of a compact object (NS & BH)

– pulsar-like models

b) Relativistic shocks far outside the magnetosphere

-GRB-like

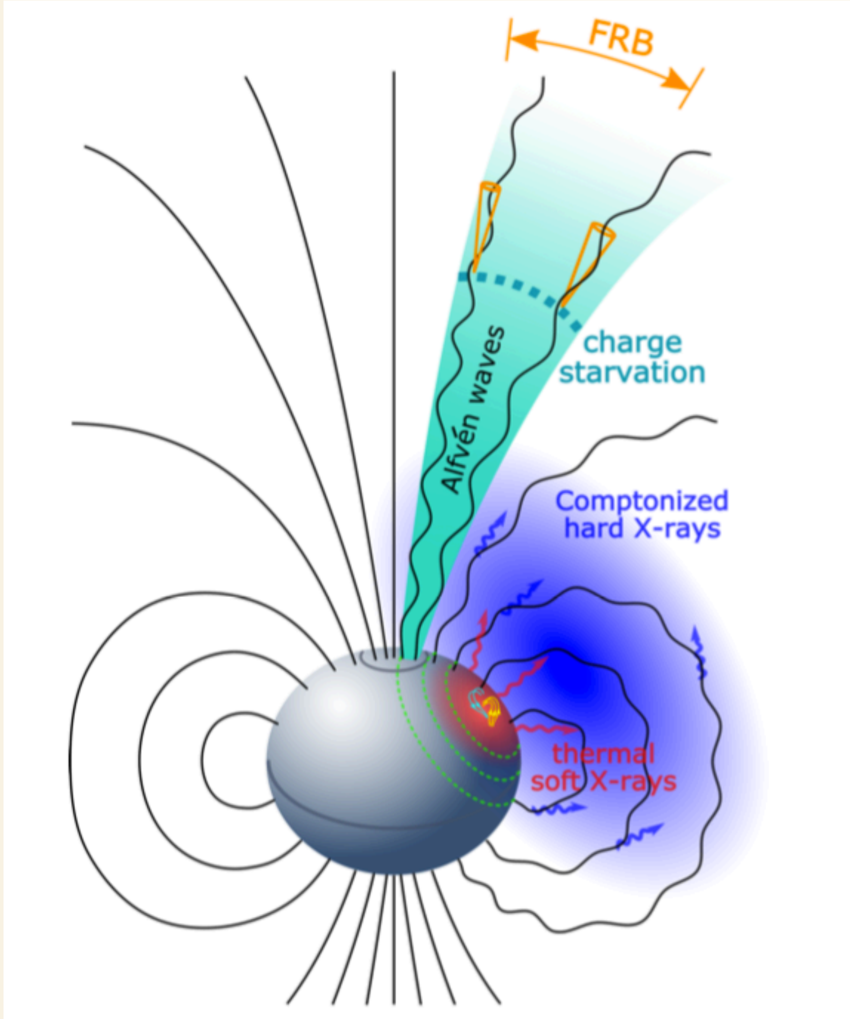
Pulsar-like models

There are models of both kinds. I will present a characteristic model for each type:

Here, there is sudden magnetic energy transfer onto the NS surface, which is heated up (red region).

This heated region produces energetic photons that can pair-produce, and the $e^{-}e^{+}$ pairs get trapped by the magnetosphere.

The X-rays are inverse Compton scattered by the pairs to higher energies.



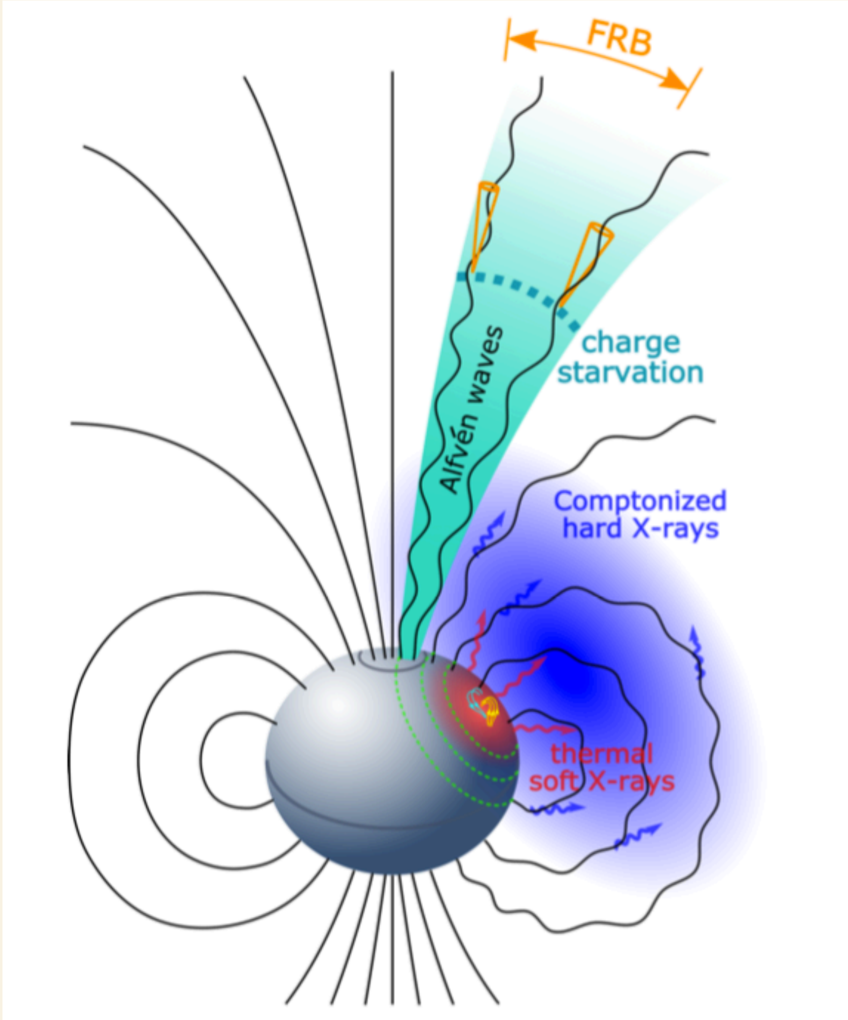
Lu et al (2020)

Pulsar-like models

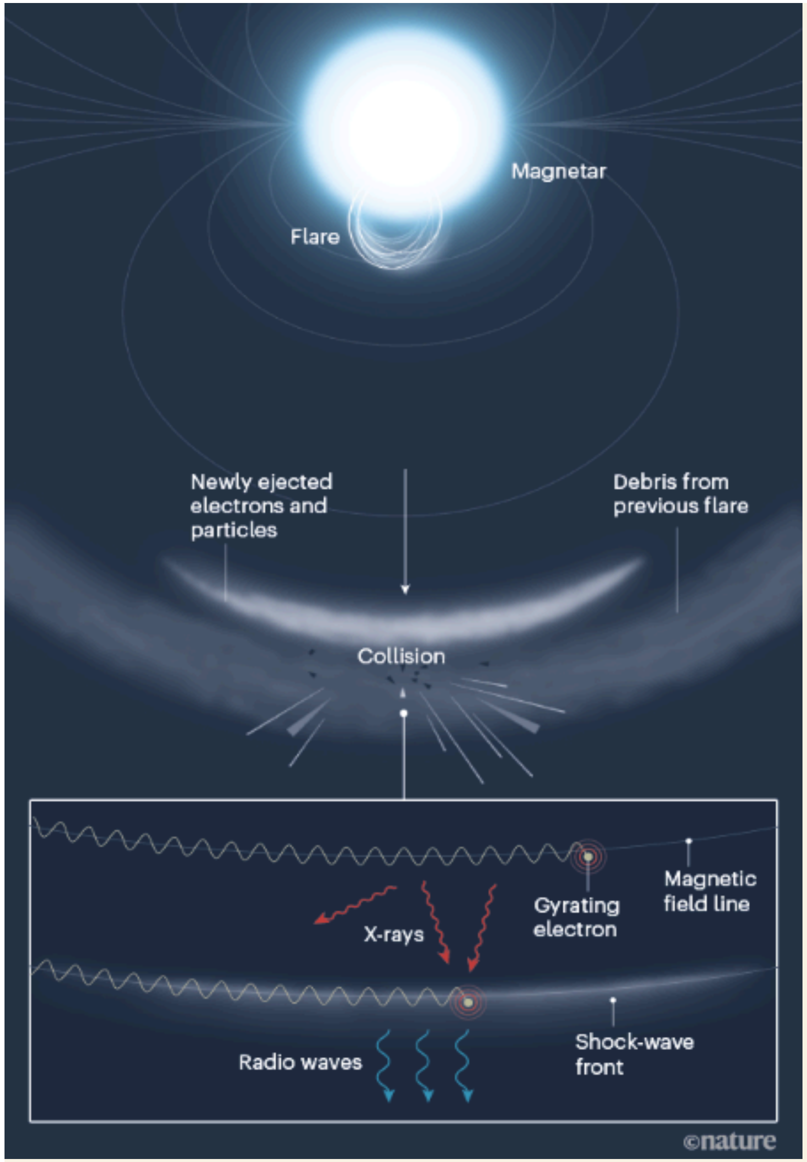
The disturbance spreads across the NS surface, and launches Alfvén waves along the MF lines.

Near the magnetic poles, the wave can travel far away, where density is substantially lower than close to the NS: not enough to sustain plasma current

<u>Charge starvation</u>: Displacement current develops in order to compensate for lost plasma current. Whatever charge is left is accelerated rapidly, and *coherently* emits curvature radiation.



Lu et al (2020)



Weltman & Walters (2020)

GRB-like model

Flare of electrons and charged particles is produced

Collision with previous flare (not to scale!)

Outward-moving shock front which produces strong magnetic fields

Electrons gyrate along MF, emitting synchrotron radiation.

The shockwave also heats the electrons, which causes them to emit in the X-rays.

From the typical temporal width of the pulses, we can again see that the engine must be a compact object.

Comparison between models

Beaming factor: Pulsar-like models invoke magnetic field lines to define radiation beam, and so there's a natural collimation. This favours a small beaming factor. Shocks from GRB-like models would have larger beaming factors, and thus the FRBs would have even higher energies still.

Efficiency: Pulsar-like models have high efficiency in producing radio emission (numerics), while GRB-like models are inefficient. Radio-to-X(γ) ratio agrees with observations, and radio pulses can be emitted without requiring a long waiting period. This is not true for GRB-like models (they require a long waiting time between bursts).

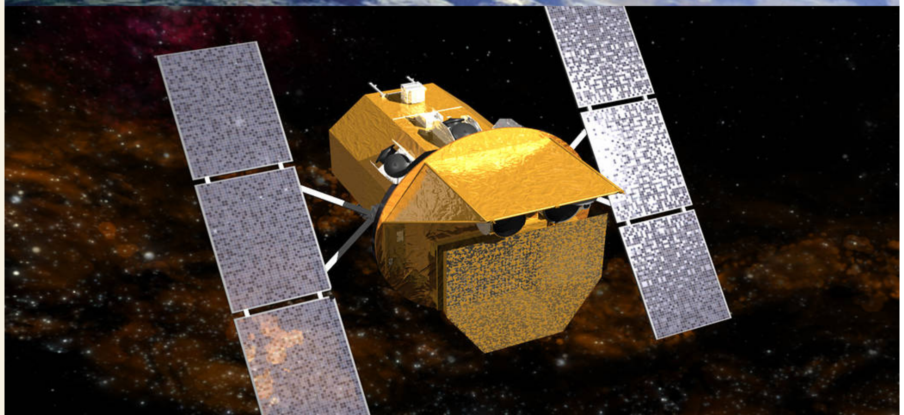
Polarization: Pulsar like models predict highly polarized radiation, and some GRB-like models predict the same, but cannot naturally account for rapid shifts of polarization angle.

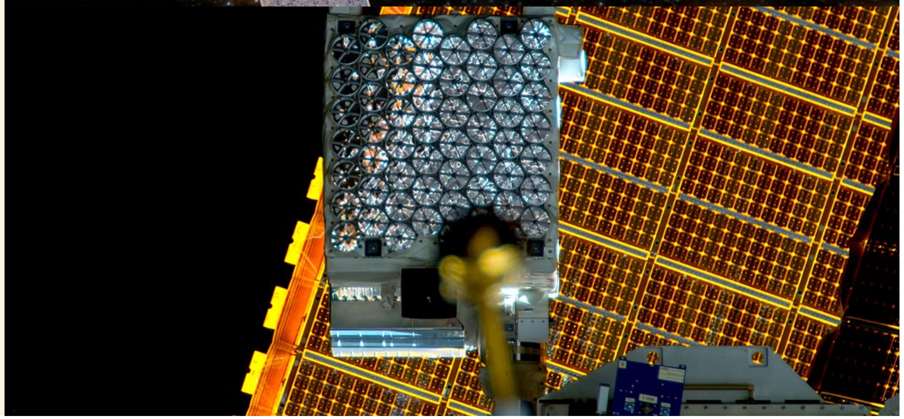
Timeline of events

27/04/2020: Forest of X-ray bursts from magnetar SGR1935+2154 was detected by Swift, and monitored by Fermi & NICER (pictured)

28/04/2020: 13hrs after the storm had subsided, another X-ray burst was captured by three different missions (Integral, Huiyan, & Konus)

This second event is of particular importance, since an FRB was also observed at the same time as the 2nd X-ray burst, by two radio instruments coming from the same location as SGR1935+2154!





CHIME/FRB

Four fixed reflecting cylinders, each 20m x 100m

256 equispaced antennae sensitive to 400-800 MHz

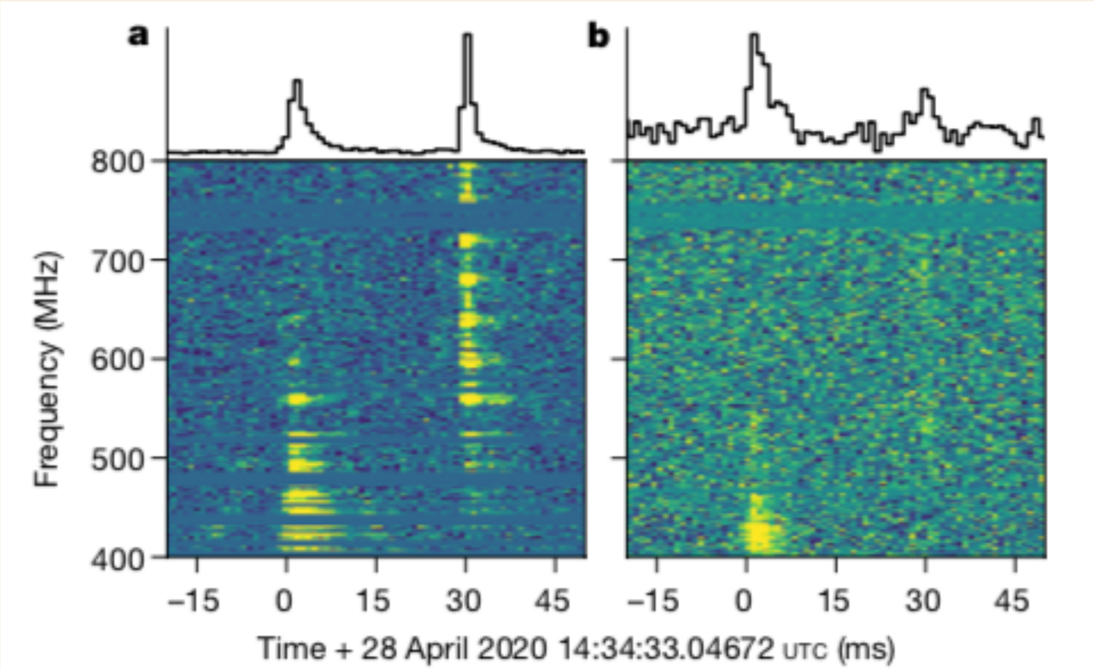
FOV of primary beam main lobe : $3^o \times 120^o$

Digitized and amplified antenna signals are sent to correlator → 1024 independent sky beams spanning the CHIME FOV

At the same time as the second X-ray activity of SGR1935+2154, the instrument detected a dispersed radio burst on 93/1024 beams

Directly after the detection, a 10-m radio disk (in Ontario) was signaled to save its buffered data – CHIME/FRB is in British Columbia

CHIME Detection



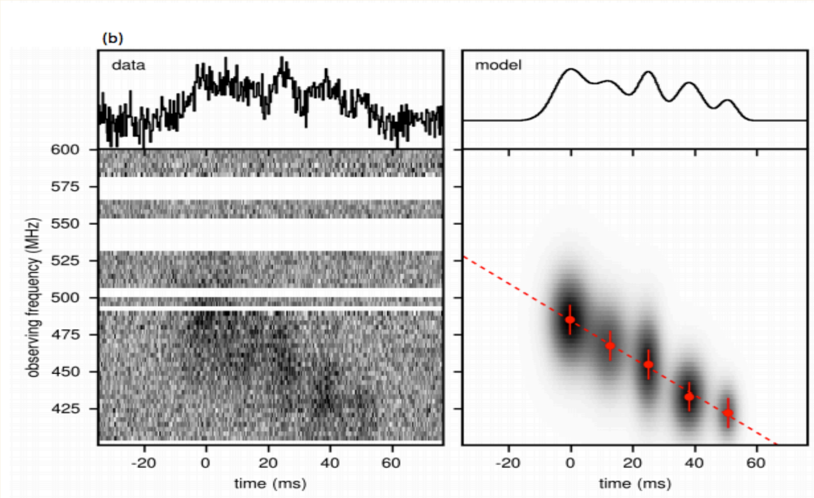
CHIME/FRB collaboration (2020)

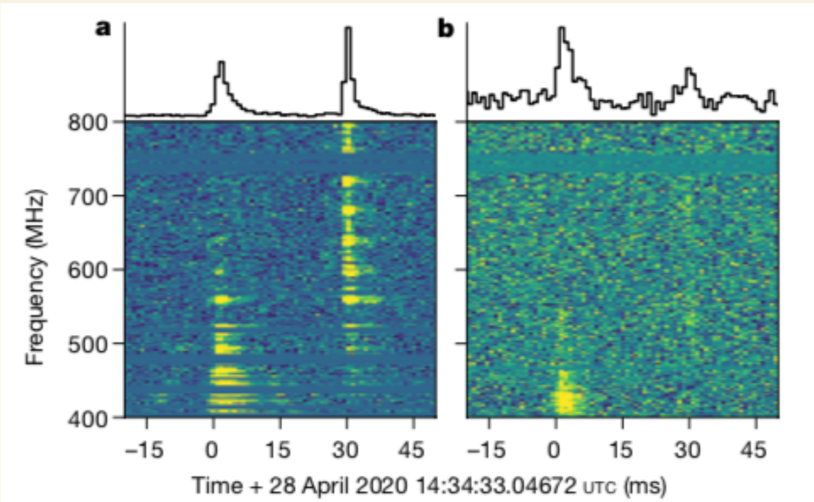
Total intensity normalized dynamic spectra and band-averaged time-series in CHIME (a) and Algonquin Radio Observatory (b)

Frequency channels due to radio interference are replaced with the median value of the off-burst region

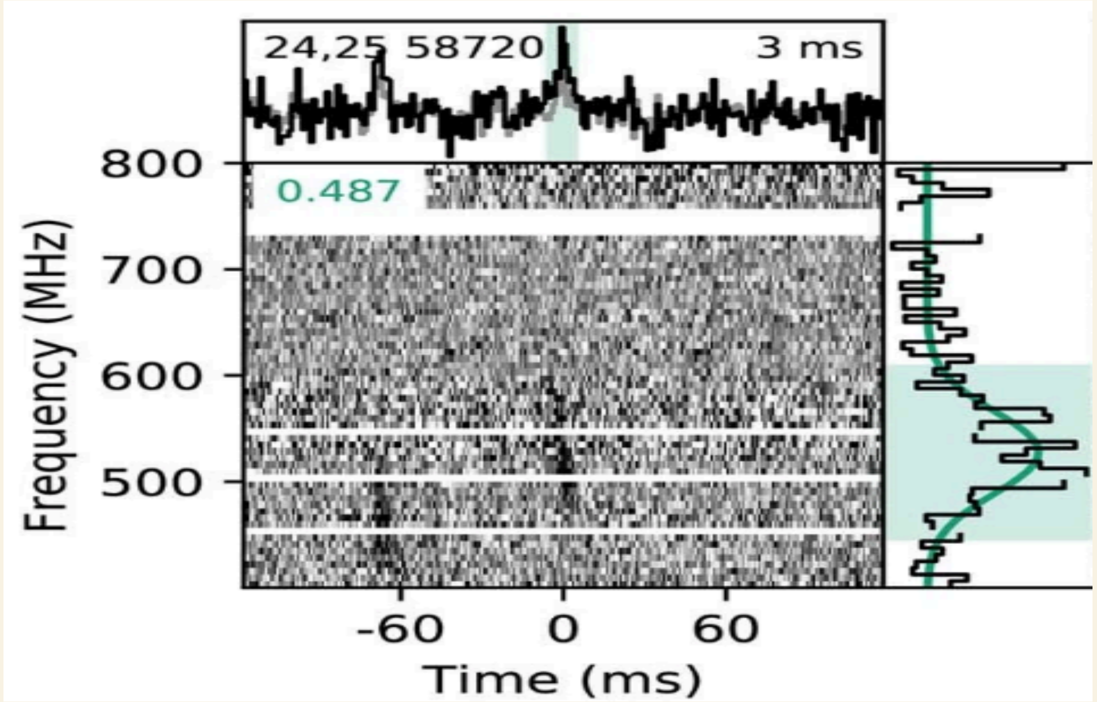
'Comb-like' spectral structure is due to the detection in a beam sidelobe as well as dispersed spectral leakage of instrumental origin

(That's how they mention it, they don't make it very clear what that means. In fact, the STARE2 paper does a better job at that)





CHIME/FRB collaboration (2020)



Note that upward frequency drifts have been observed in FRBs; FRB180196 shows two components that drift upwards and separated by 60ms

CHIME Detection

Average fluence taken in the 400-800 MHz range

$$< fluence >= \frac{(energy)}{(area)\cdot(frequency)} = (480 + 220)\ kJy\ ms = 700^{+700}_{-350}\ \ kJy\ ms$$

As already mentioned, there was a high-energy activity as well:

$$\frac{radio\ fluence}{\gamma - ray\ fluence} = 4^{+4}_{-2}\times10^{-6}$$

- 10^5 times above upper limit based on non-detection or radio emission during a giant flare of another magnetar (SGR1806-20)
- 10^2 times below the lower limit placed on the fluence ratio from non-detection of high energy activity from an FRB (FRB121102)

Four γ-ray bursts were detected (4-5 November 2019) from SGR1935 without a radio counterpart (at least <1.2 kJy and <3 kJy) while the source was at a similar place in CHIME's FOV

→HE/Radio 9 and 6 times smaller than observed above.

Radio counterparts to high-energy bursts are either not always emitted <u>or</u> extended to substantially lower ratios

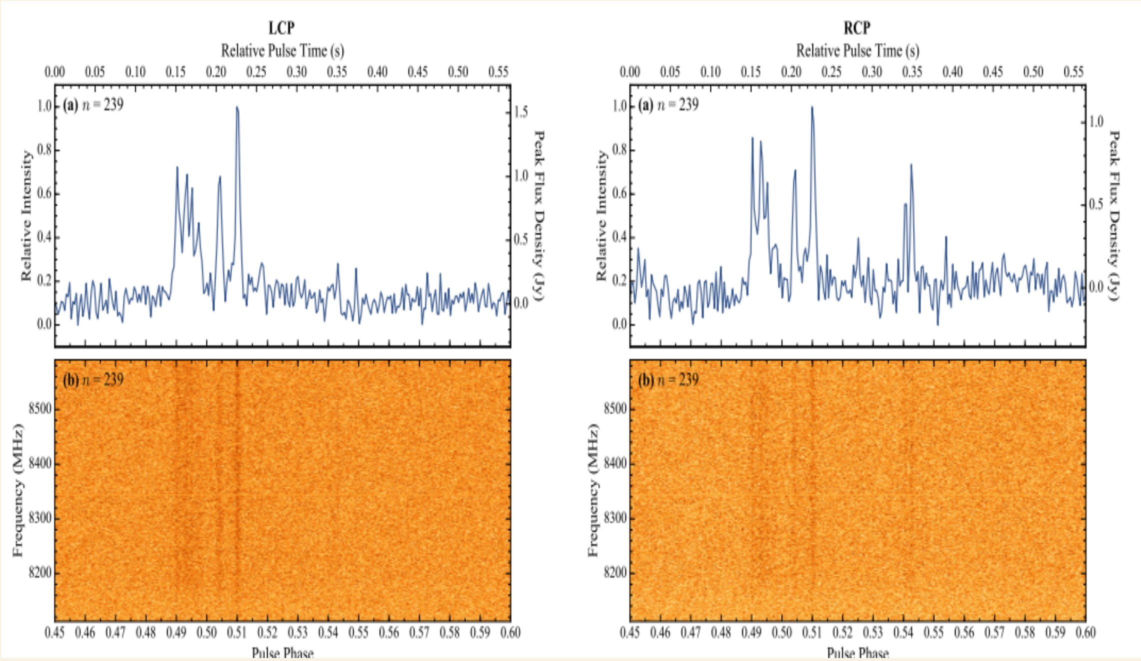
Magnetar/Pulsar Radio Emission

Five other Galactic magnetars have been observed to emit radio pulsations (ms width)

These are substantially dimmer (Figure in next slide)

Same holds for Crab Pulsar

Thus, this signal clearly implies that magnetars can emit far brighter signals than previously expected



Pearlman et al. (2018)

Comparison to extragalactic FRBs

STARE2 observed a pulse of fluence $1.5 \pm 0.3\ MJy\ ms$, measured at $\nu = 1.4\ GHz$.

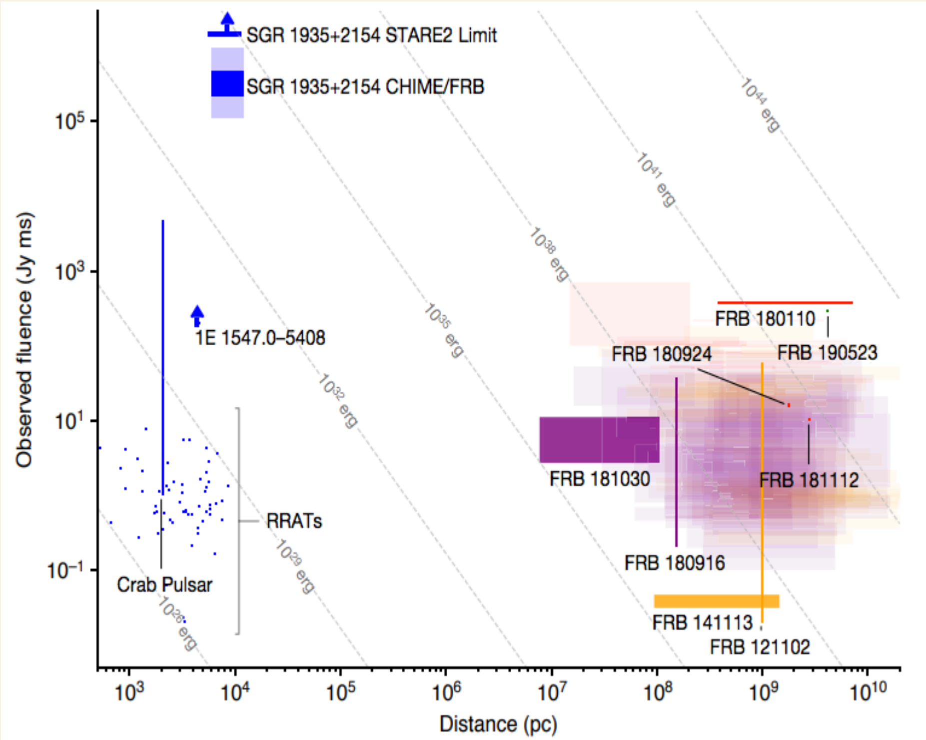
The timing of this pulse is consistent with CHIME's second component.

SGR1935's burst energy is comparable to that of known extragalactic FRBs, if *we assume that these are at their nearest possible distance*

This detection bridges the luminosity gap between galactic and extragalactic sources

Note however that FRBs at cosmological distances can be far more energetic.

From the current data, it is unclear whether the most energetic FRBs can be generated by conventional magnetars



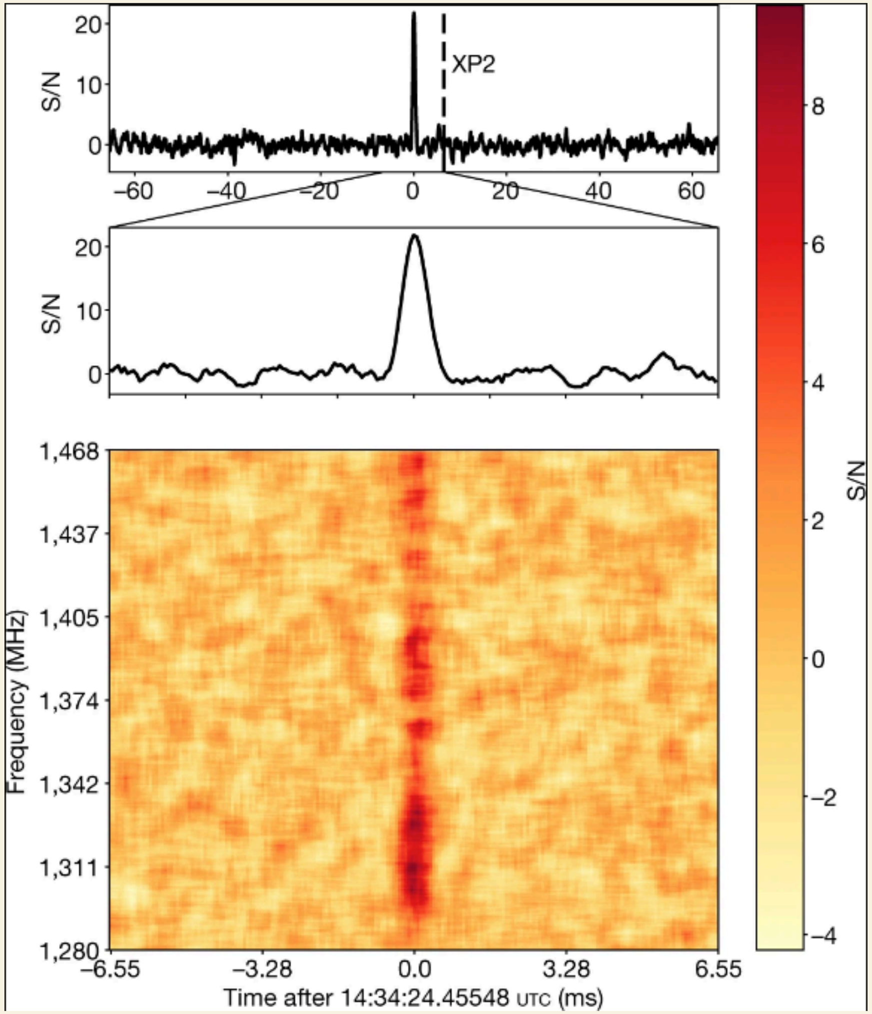
CHIME/FRB collaboration (2020)

STARE2

STARE2 is comprised of three 1281-1468 MHz detectors spread the southwestern US

Timescale resolution: 65.536 μs

Frequency resolution: 122.07 kHz



Bochenek et al. (2020)

STARE2 Detection

All three detectors were triggered by an event on 28/04/2020 at roughly the same time as CHIME

(Figure: S/N only from one detector)

S/N ratio : 21, 20, 15

DM = 332.702(8) $pc\ cm^{-3}$

FWHM temporal width 0.61(9) ms

$$fluence = 1.5(3){\times}10^{6} Jy\ ms$$

Roughly 1000 times higher than CHIME!

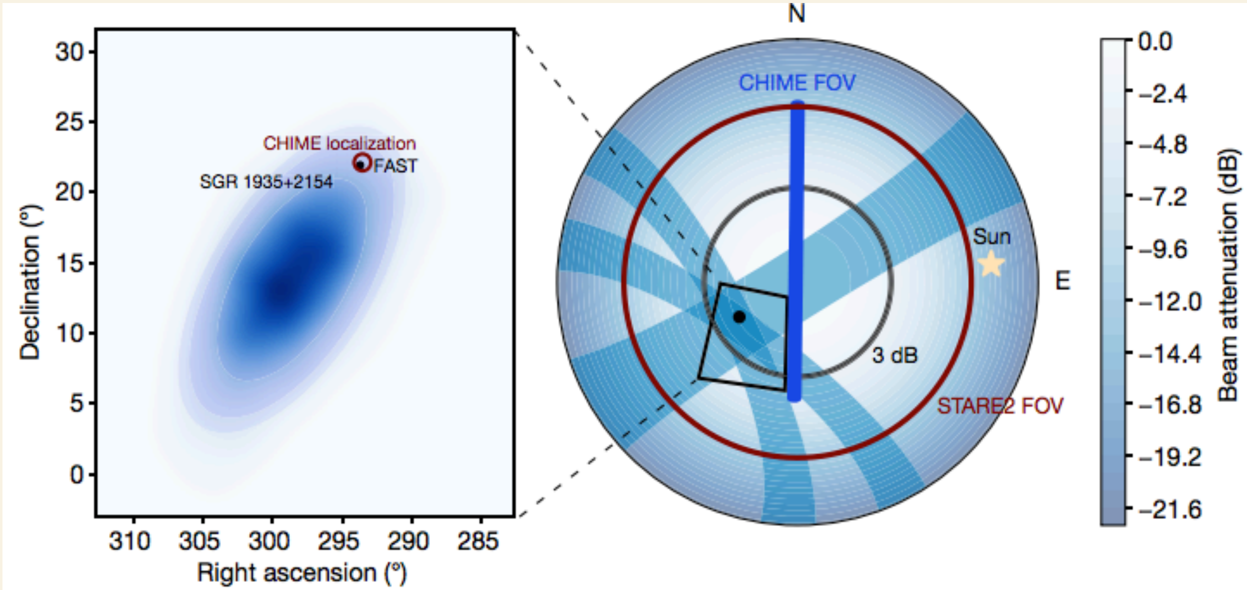
No other radio bursts detected in a window of approx. 131 ms.

Localization

Figure: Right, altitude and azimuth view of sky at the time of STARE2 trigger

The Sun is a usual source of STARE2 triggers, but at the time of the FRB it was outside the FOV

FAST localization is on the known location of SGR1935 (black dot)



Bochenek et al. (2020)

Phase Space of Radio Transients

Vertical extent of star corresponds to uncertainty in spectral luminosity (isotropic-equivalent) due to uncertainty in magnetar's position

GRP: Giant Radio Pulse

Accretors: Accreting BSs in Milky Way

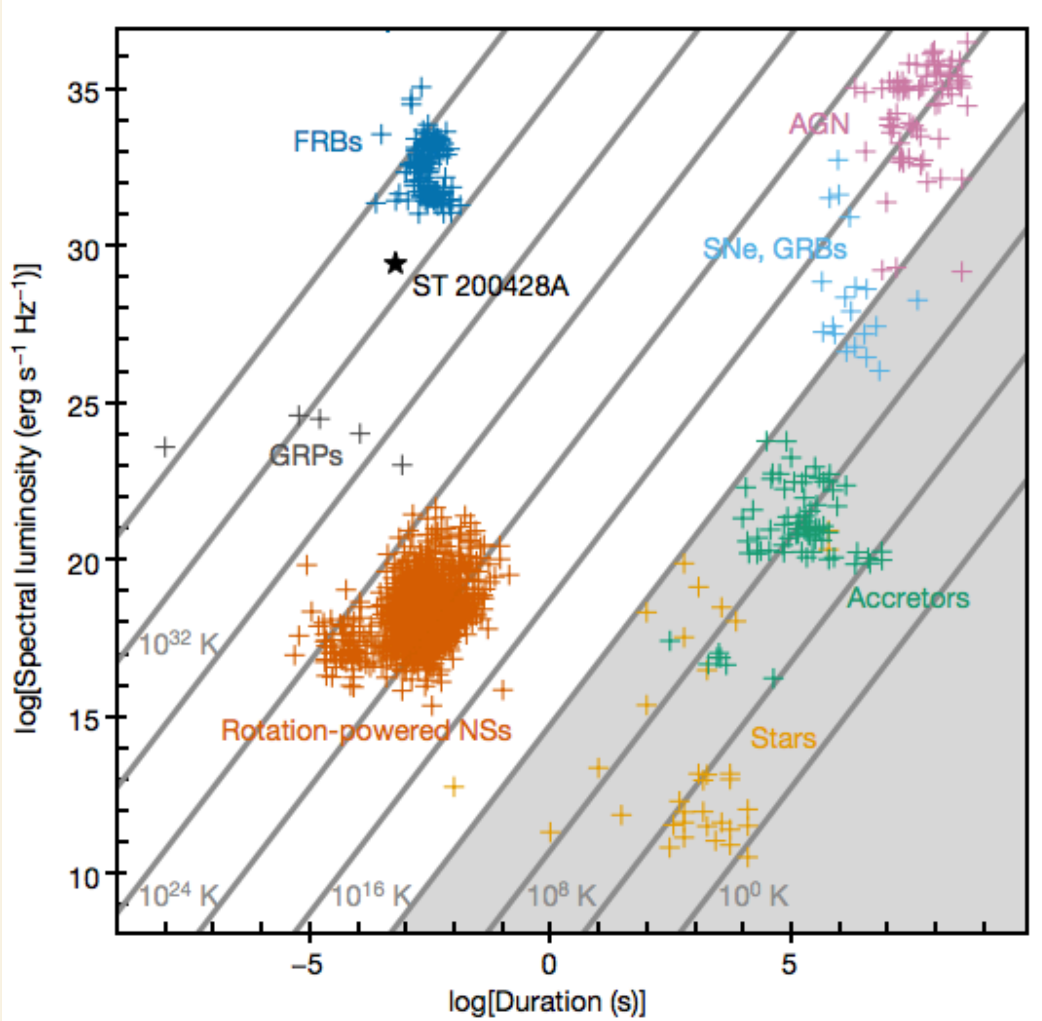
Sne, GRBs: Supernovae, Gamma-Ray Burst

All radio pulses plotted are detections in 1-2 GHz range

Lines of constant brightness temperature at frequency of $\nu = 1.4\ GHz$.

Shaded area (<$10^{12}\ K$): Incoherent emitters

Spectral luminosity of event derived by dividing the burst spectral energy by duration



Bochenek et al (2020)

Discussion & Conclusion

Magnetars are viable FRB engines, at least for some FRBs

Question: Why haven't such events been observed from any of the other known Galactic magnetars? Perhaps it's because bursts of this brightness are often flagged as radio-frequency interference

Similar high-energy events have been observed in the past from the same source, the accompaniment by radio bursts is not necessary.

The timing between high-energy and radio is not fully consistent with Pulsar-like models (within magnetospheres): if X-ray burst is emitted through standard mechanisms, the FRB emission is expected to be produced before the X-ray burst (unless outflow is highly relativistic)

Energetics are consistent with some GRB-like models that invoke flares – in particular, ratio of high-energy release over radio is consistent with these observations

Downward frequency drifts are seen in both sets of models