Investigating the FRB-magnetar connection in nearby galaxies with the Northern Cross Radio Telescope

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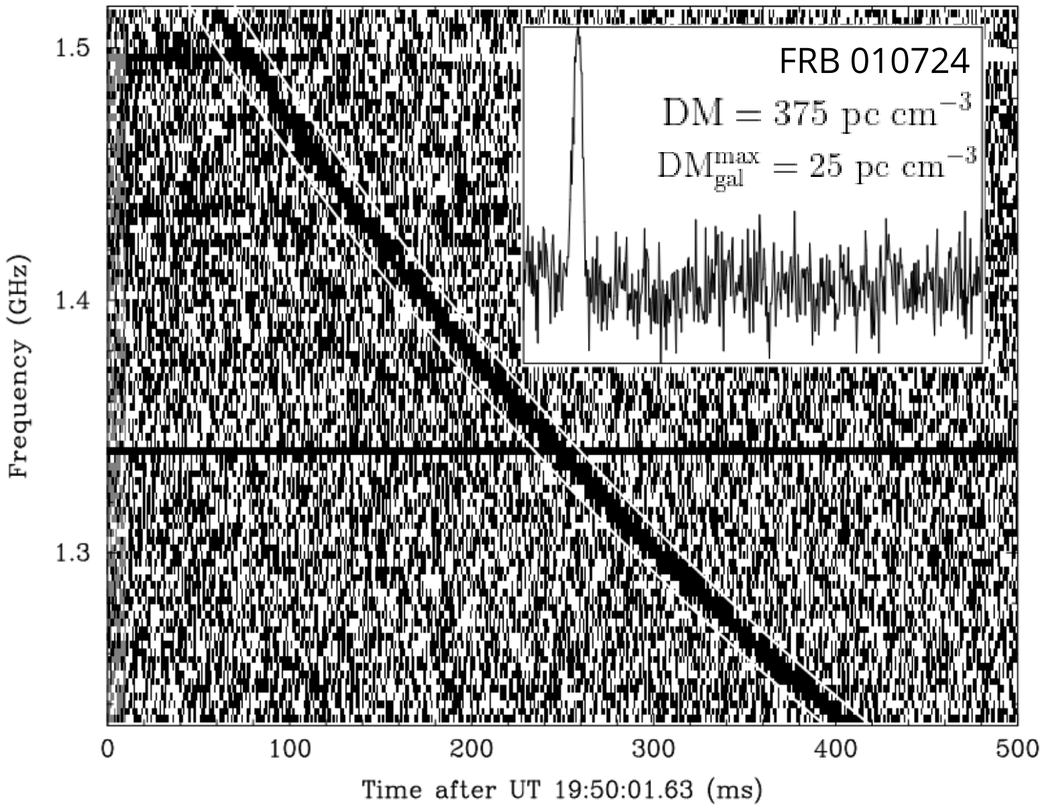
The Transient Universe 2023, Cargese (Fr)

What are Fast Radio Bursts?

Lorimer+07



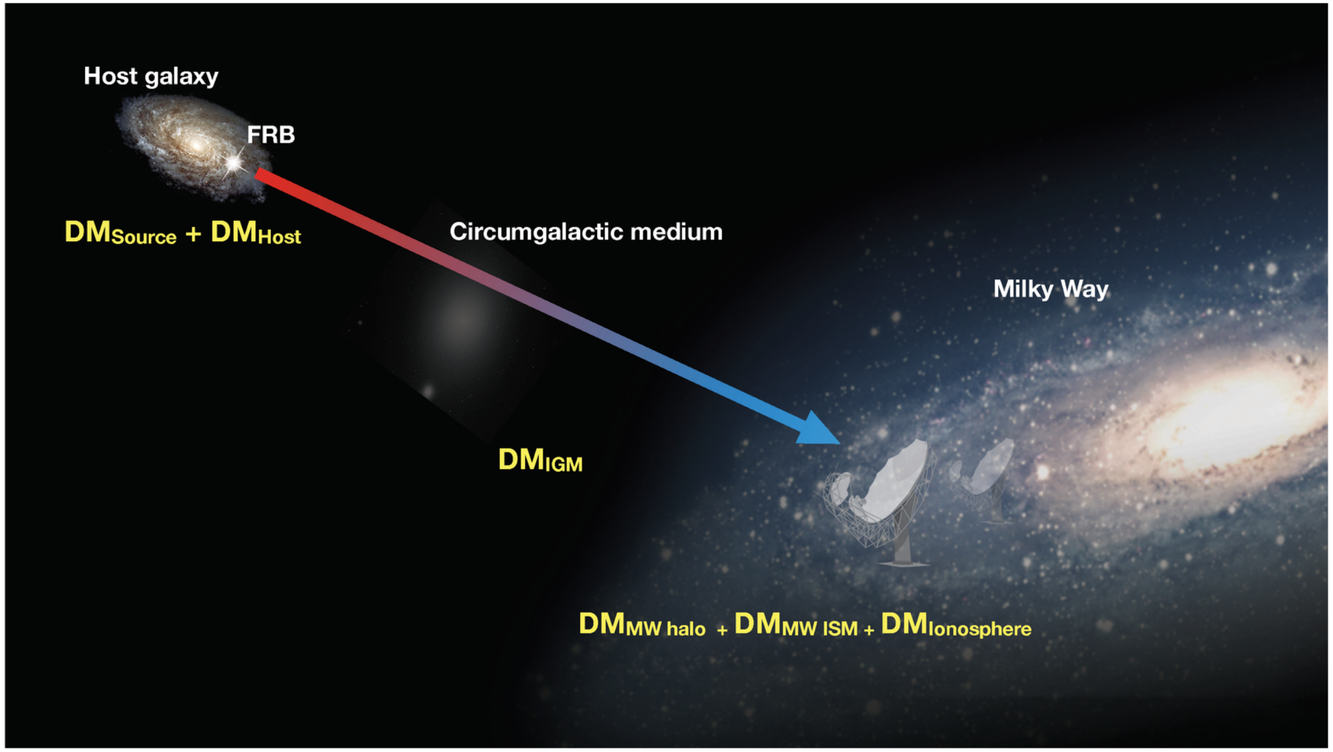
Delay between first and last freq. channel

source distance

$$\Delta t \equiv \mathcal{D} \times \frac{\mathrm{DM}}{f^2}, \qquad \mathrm{DM} = \int_0^d n_\mathrm{e}\, \mathrm{d}l$$

Dispersion measure

numerical density of free (ionised) electrons

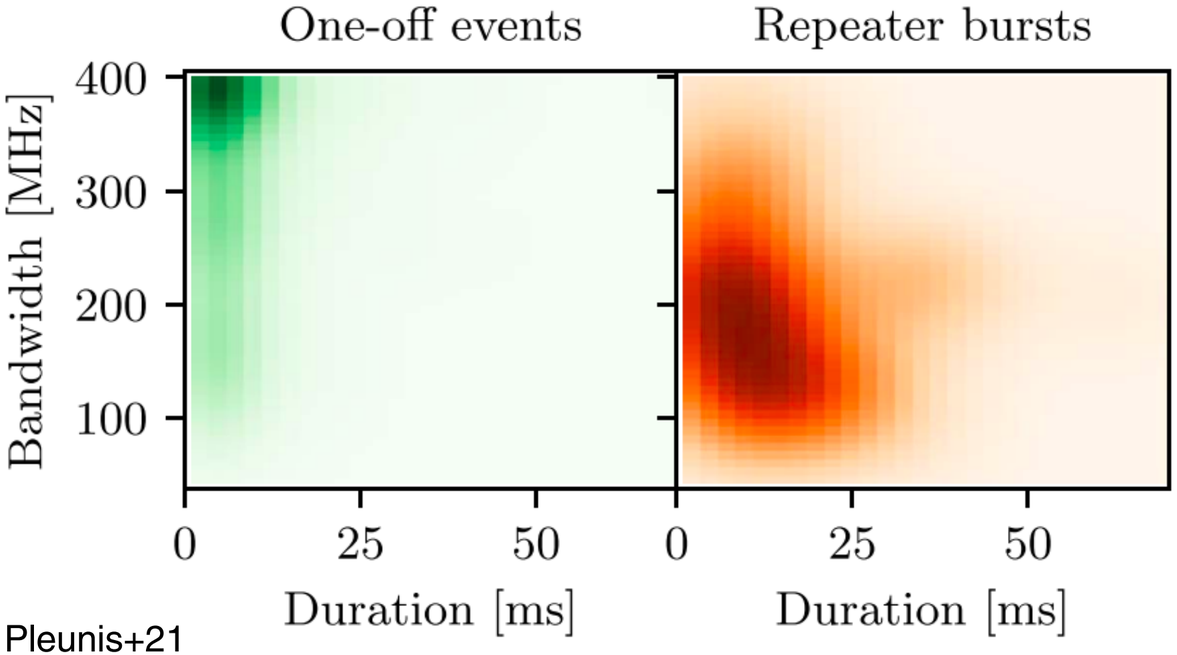


One-off vs. Repeating

Nowadays: nearly 650 FRB sources known (mostly from CHIME), of which ~ 50 are repeaters -> for some of them a **catastrophic** origin is ruled out.

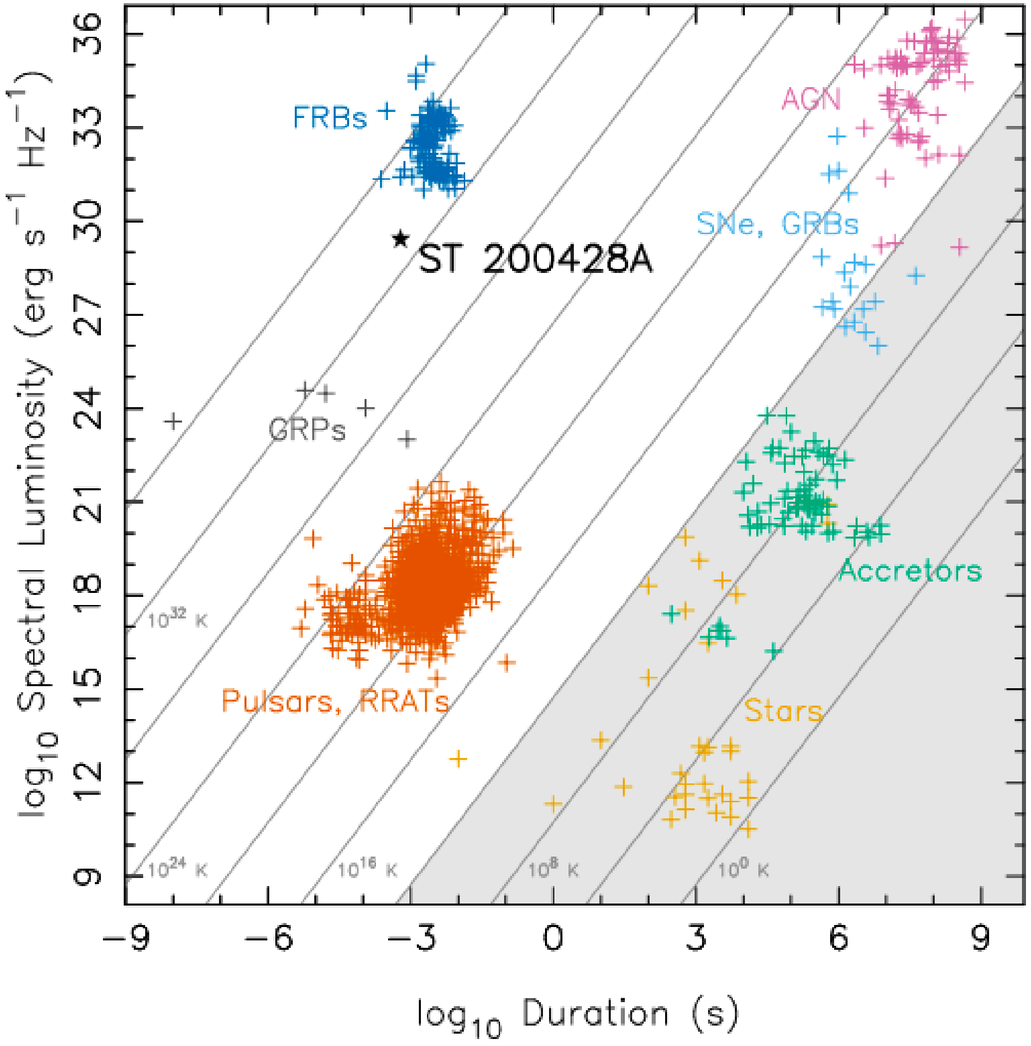
..Are all FRBs repeating sources?

..Are one-off the and repeaters originated from the same progenitors?



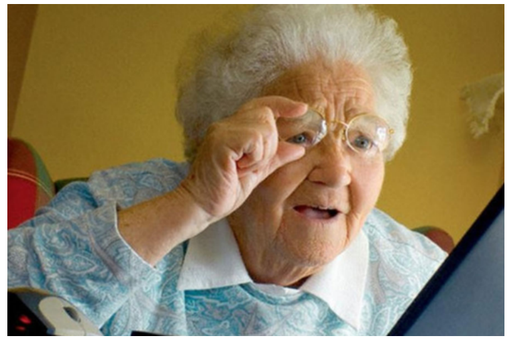
Pleunis+21

Bochenek+20



ok but.. what is generating FRBs?

- **Magnetar's outbursts / flares** (e.g. Lyubarsky+02)
- **Giant pulses from young NS** (e.g. *Cordes & Wasserman 15*)
- NS collapsing to BHs, ejecting "magnetic hair" (*Falcke & Rezzolla+14*)
- Merger of charged BHs (*Zhang+16, Liu+16*)
- **White dwarf mergers** (*Kashiyama+13*)
- Sparks from cosmic strings (*Vachaspati+08, Yu+14*)
- White holes (*Barrau+14*)
- Axion stars (*Tkachev15, Iwazak15*)
- Asteroids/comets falling onto a NS (*Geng & Huang15*)
- Quark novae (*Chand+15*)
- Dark matter-induced collapse of a NS (*Fuller & Ott 15*)
- BH superirradiance (*Conlon & Herdeiro 17*)
- Extraterrestrial light sails (*Lingam & Loeb 17*)
- .. many others



A living Theory Catalogue for FRBs (Platts+18)

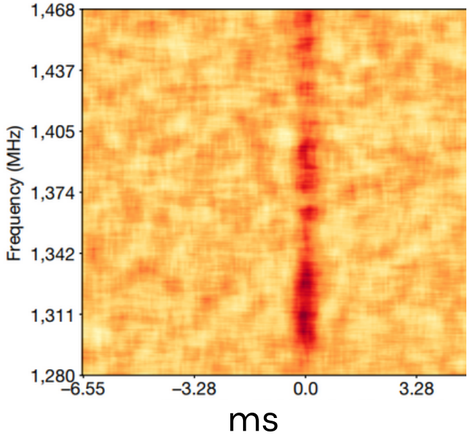
https://frbtheorycat.org/

Name	Category	Progenitor	Type	Energy Mechanism	Emission Mechanism	LF Radio Counterpart	HF Radio Counterpart	Microwave Counterpart	THz Counterpart	OIR Counterpart	X-ray Counterpart	Gamma-ray Counterpart	GW Counterpart	Neutrino Counterpart	References	Comments
NS-WD Accretion	Accretion	NS-WD	Repeat	Mag. reconnection	Curv.	Yes	--	--	--	--	--	Yes, but unlikely detectable	--	--	URL	None
AGN-KBH	AGN	AGN-KBH Interaction	Repeat	Maser	Synch.	Yes	--	--	--	Supernova	--	Yes	Yes	Yes	URL	Neutrinos from preceding SN and from collapse to BH.
AGN-SS	AGN	AGN-Strange Star Interaction	Repeat	Electron oscillation	--	Yes	--	--	--	Thermal	--	Yes	Yes	Yes	URL	Neutrinos from preceding SN and from collapse to BH. GW from collapse and persistent GWs from SS.
Jet-Cavition	AGN	Jet-Cavition Interaction	Both	Electron scattering	Bremsst.	Yes	Yes	--	--	--	--	Possible GRB	Yes	--	URL + URL	Persistent scintillating radio emission.
Wandering Beam	AGN	Wandering Beam	Repeat	--	Synch.	Yes	--	--	--	--	Yes	--	--	--	URL	None
NS to BH (DM-Induced)	Collapse	NS to BH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	Yes	--	URL	None
NS to KNBH	Collapse	NS to KNBH	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	Possible afterglow	Possible GRB	Yes	--	URL + URL + URL	Possible X-ray afterglow and a short/long GRB created in NS birth prior to the FRB.
NS to Quark Star	Collapse	NS to Quark Star	Single	β-decay	Synch.	Yes	--	--	--	--	Yes	Yes	Yes	--	URL	The burst is predicted to be several seconds, explainable if the de-dispersion process that cracks t
SS Crust	Collapse	Strange Star Crust	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	--	--	Yes	--	URL	None
Axion Cloud and BH	Collision / Interaction	Superradiant Axion Cloud and BH	Repeat	Laser	Synch.	Yes	--	--	--	--	--	--	Yes	--	URL	Observational counterparts could be associated with electron-positron annihilation and/or positroniu
Axion Minicluster and NS	Collision / Interaction	Axion Minicluster and NS	Single	Maser	Synch.	Yes	--	--	--	--	--	--	--	--	URL	None
Axion Quark Nugget and NS	Collision / Interaction	Axion Quark Nugget and NS	Repeat	Mag. reconnection	Curv.	Yes	Possible	Possible	--	--	--	--	--	--	URL	None
Axion Star and BH	Collision / Interaction	Axion Star and BH	Repeat	Electron oscillation	--	Yes	--	--	--	--	--	--	--	--	URL	None
Axion Star and NS	Collision / Interaction	Axion Star and NS	Single	Electron oscillation	Coherent dipole radiations	Yes	--	--	--	--	--	--	--	--	URL + URL + URL + URL + URL	None
NS and Primordial BH	Collision / Interaction	NS and Primordial BH	Both	Mag. reconnection	--	Yes	--	--	--	--	--	--	Yes	--	URL	None
Small Body and Pulsar	Collision / Interaction	Small Body and Pulsar	Single	Maser	Synch.	Yes	--	--	--	--	--	--	--	--	URL	None
NS and Asteroid Belt	Collision/ Interaction	NS and Asteroid Belt	Repeat	Electron stripping	Curv.	Yes	--	--	--	--	--	Yes	--	--	URL + URL	None
NS and Asteroids/Comets	Collision/ Interaction	NS and Asteroids/ Comets	Single	Mag. reconnection	Curv.	Yes	--	--	--	--	Yes (probably too faint to detect)	Yes (probably too faint to detect)	--	--	URL	None
Pulsar-BH Interaction	Interaction	Pulsar-BH	Single	--	--	Yes	?	--	--	--	--	--	Yes	--	URL	
Annihilating Mini BHs	Instable	Annihilating Mini BHs	Single	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	URL	None
Stellar Corona	Instable	Stellar Corona	Both	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	URL + URL	None
KNBH-BH (Inspiral)	Merger	KNBH-BH	Single	Mag. flux change	Curv.	Yes	Afterglow	--	--	--	Yes	sGRB if jet aligned	Yes	--	URL	Unlikely to account for full FRB population.
KNBH-BH (Magneto. Collapse)	Merger	KNBH-BH	Single	Mag. reconnection	Curv.	Yes	Afterglow	--	--	--	--	Afterglow	Yes	--	URL	Can only account for a sub-population of FRBs.
NS-BH Merger	Merger	NS-BH	Single	BH battery	--	--	--	--	--	--	Yes	Yes	Yes	--	URL	None
NS-NS Merger (Mag. Braking)	Merger	NS-NS	Single	Mag. braking	--	Yes	Yes	--	--	Kilonova	Afterglow	sGRB if jet aligned	Yes	--	URL	
NS-NS Merger (Mag. Flux Change)	Merger	NS-NS	Both	Mag. flux change	--	Yes	Yes	--	--	Kilonova	Afterglow	sGRB if jet aligned	Yes	--	URL	In dense stellar clusters
NS-NS Merger (Mag. Reconnection)	Merger	NS-NS	Both	Mag. reconnection	Curv.	Yes (excl. self absorption)	Yes	?	?	Kilonova	Afterglow	sGRB if jet aligned	Yes	--	URL	None
NS-WD Merger	Merger	NS-WD	Single	Mag. reconnection	Curv.	Yes	Yes	--	--	--	--	--	--	--	URL	
WD-BH Merger	Merger	WD-BH	Single	Maser	Synch.	--	--	--	--	--	Yes (transient accretion disk)	--	--	--	URL	None
WD-WD Merger	Merger	WD-WD	Single	Mag. reconnection	Curv.	Yes	--	--	--	Supernova	Afterglow	--	--	--	URL	--
Young Magnetars	Merger/Collapse	Magnetars Born in BNS Mergers and WD Col	Repeat	Maser	Synch.	Yes	Afterglow	--	--	Possible SN	Afterglow	sGRB	Yes	--	URL	Same mechanisms as flares, but magnetars born in mergers or collapse as opposed to in to SLSNe or LGRBs
Alien Light Sails	Other	Alien Light Sails	Repeat	Artificial transmitter	--	Yes	--	--	--	--	--	--	--	--	URL	Highly speculative.
DSR in Galaxies	Other	Dicke's Superradiance in Galaxies	Both	Dicke's Superradiance	Spectral line	Yes	Yes	--	--	--	--	--	--	--	URL + URL	--
Magnetars with Low Magnetospheric Twist	Other	Magnetars with Low Magnetospheric Twist	Repeat	Mag. reconnection	Pulsar-like	Yes	---	Maybe	Maybe	Maybe	Maybe	Unlikely detectable	---	---	URL + URL	Unlikely to form in Galactic magnetars.
Neutral Cosmic Strings	Other	Neutral Cosmic Strings	Single	Cusp decay	--	Yes	--	--	--	--	--	--	--	--	URL	None
NS Combing	Other	NS Combing	Both	Various	Mag. reconnection	Yes	--	--	--	--	--	--	--	--	URL + URL	The model can apply to a variety of events, and thus counterparts will depend on the scenario.
Pulsar Lightning	Other	Pulsar Lightning	Repeat	Electrostatic	Curv.	Yes	--	--	--	--	--	--	--	--	URL	None
RDM Stars	Other	RDM Star	Both	Stimulated emission	Synch.	---	---	---	---	---	---	---	---	---	URL + URL	Repeaters are possible if multiple asteroids collide with the star
Starquakes	Other	Starquakes	Repeat	Mag. reconnection	Curv.	Yes	--	--	--	Possible	Possible	Yes if pulsar jet aligned	Yes, but unlikely detectable	--	URL + URL	None
Superconducting Cosmic Strings	Other	Superconducting Cosmic Strings	Single	Cusp decay	--	Yes	--	--	--	--	--	GRB if jet aligned	Yes	Yes	URL + URL + URL	High energy cosmic rays are also expected.
Tiny EM Explosions	Other	Tiny EM Explosions	Both	Thin shell interactions	Curv.	Yes	Yes	--	--	--	--	Unlikely observable	--	--	URL + URL	None
Variable Stars	Other	Variable Stars	Repeat	Undulator	Synch.	Yes	--	--	--	--	--	--	--	--	URL	None
Wandering Pulsar	Other	Wandering Pulsar Beams	Repeat	--	--	Yes	--	--	--	--	--	--	--	--	URL	Any counterparts will be associated with the pulsar, but are not specified.
White Holes	Other	White Holes	Single	--	--	Yes	--	--	--	Yes	--	Yes	--	--	URL + URL	None
Decelerating Blast Waves	Shock Interaction	Magnetar	Repeat	Thin shell	Synch. Maser	Yes (excl. self absorption)	Yes	--	--	Possible, Prompt	Prompt	Prompt	No	No	URL	None
NS-SN Interaction	Shock Interaction	NS-SN Interaction	Single	Mag. reconnection	--	Yes	--	--	--	Supernova	--	possible GRB (low flux)	--	--	URL	
MWN Shock (Clustered Flares)	SNR (Magnetars)	MWN Shock (Clustered Flares)	Repeat	Maser	Synch.	Yes	Afterglow	--	--	Possible bright optical	Yes but ~100 years later	Low energy gamma-rays, sGRB if jet aligned	Yes	--	URL	FRB 121102 may by unlikely in this scenario.
MWN Shock (Single Flare)	SNR (Magnetars)	MWD Shock (Single Flare)	Single	Maser	Synch.	Yes	Afterglow	--	--	Maybe	--	Low energy gamma-rays, sGRB if jet aligned	Yes	--	URL + URL + URL	None
Giant Pulses	SNR (Pulsars)	Giant Pulses	Repeat	--	Synch. / Curv.	Yes	--	--	--	--	--	--	--	--	URL + URL + URL	Rapid flux decay expected to be observed within a few years.
Pulsar Schwinger Pairs	SNR (Pulsars)	Pulsar Schwinger Pairs	Single	Schwinger	Curv.	Yes	--	--	--	--	--	--	--	--	URL	None
Pulsar Wind Bubble	SNR (Pulsars)	Pulsar Wind Bubble (NS and MWD)	Single	--	Synch.	Yes	--	--	--	--	Yes	--	--	--	URL	None

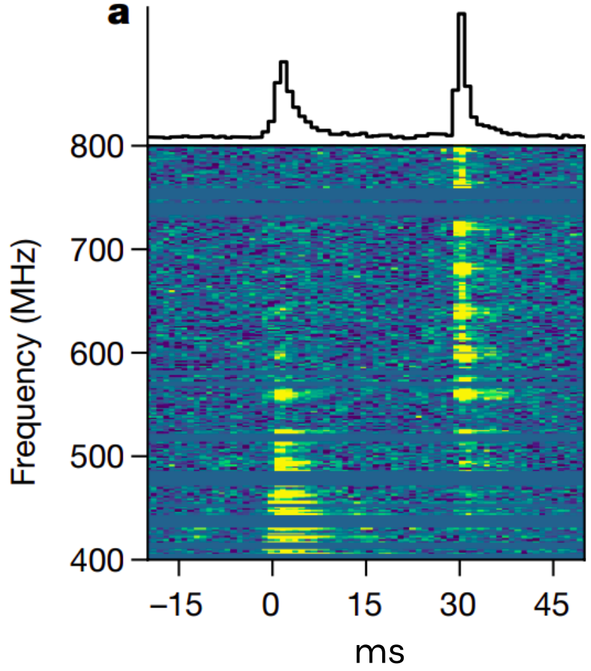
Magnetars can emit FRBs!

Radio

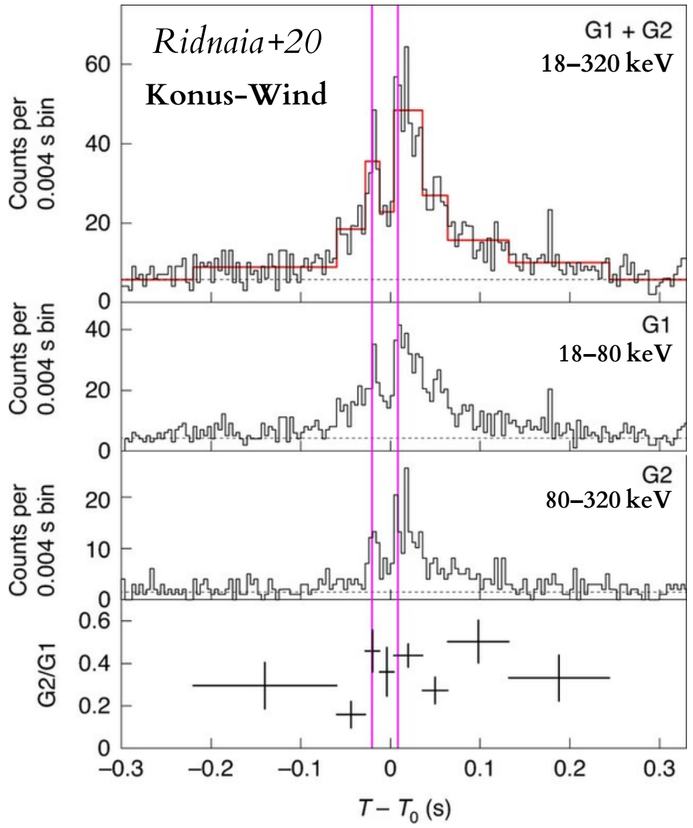
STARE2
(Bochenek+20)



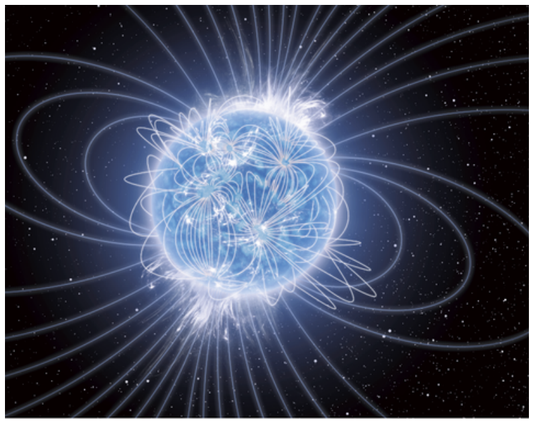
CHIME/FRB
(CHIME/FRB+20)



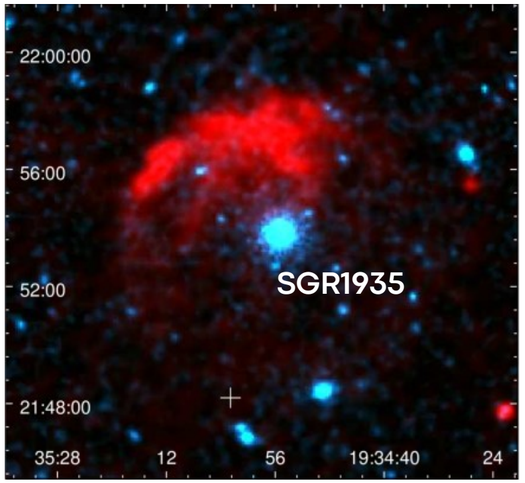
(first!) X-ray counterpart



SGR 1935+2154



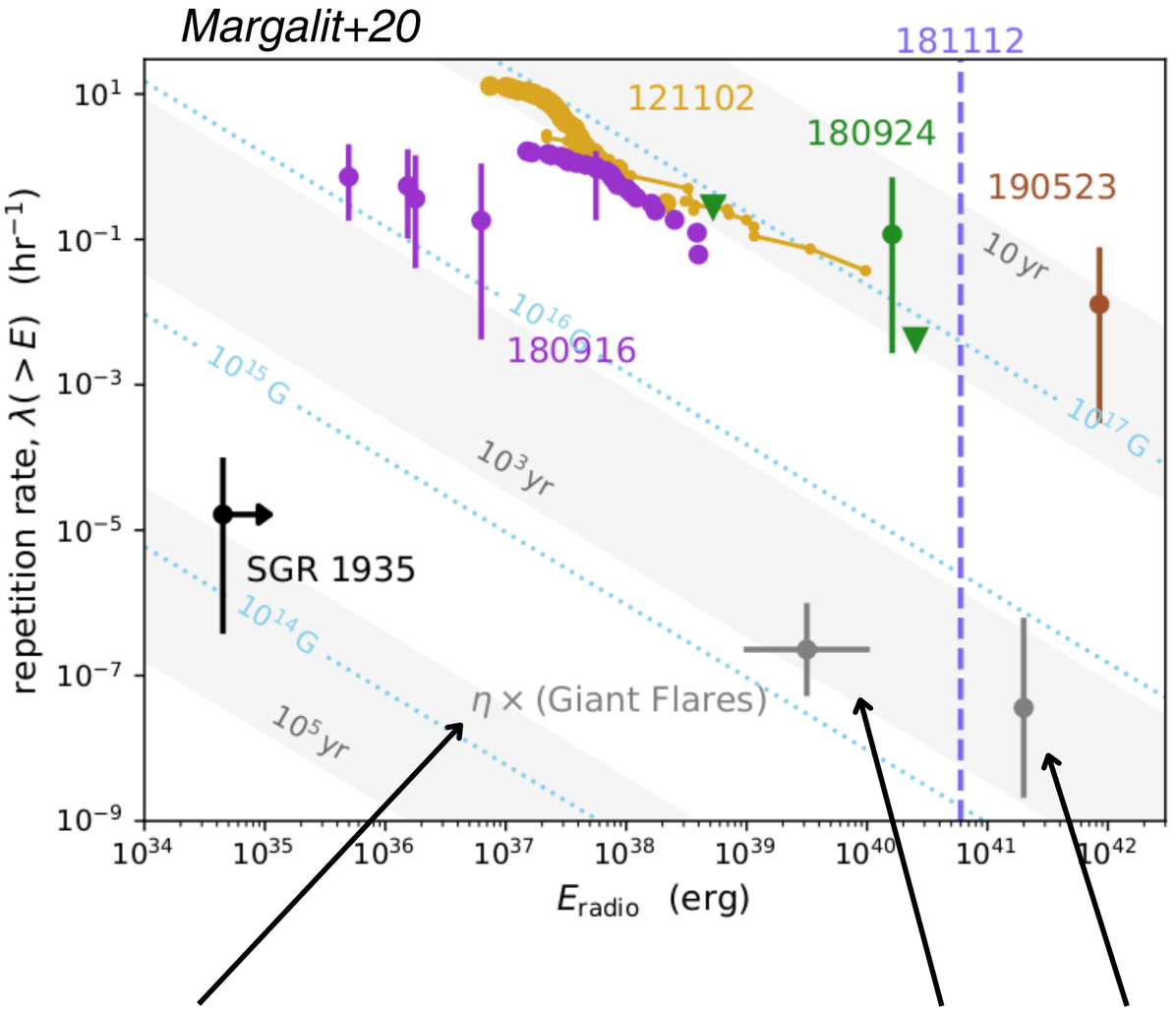
+ INTEGRAL (*Mereghetti+20*)
+ AGILE (*Tavani+20*)
+ XHMT (Zhang+20)



The FRB–magnetar connection

However, a single population of SGR1935-like magnetars, i.e. from CCSNe, cannot explain the **repetition rate** of cosmological FRBs.

One can recover the observed (high) repetition rate by considering an additional magnetar population with stronger B field, **more active**, but born at a rate at least 2 orders of magnitude **lower** than SGR-like ones



SGR1935 radio efficiency

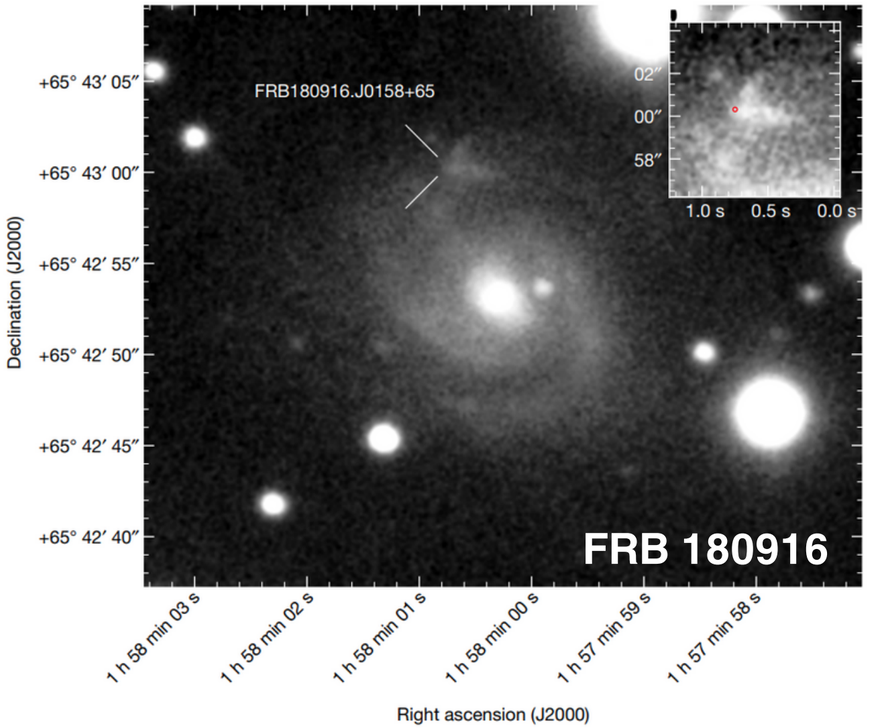
SGR1935-like magnetars can power even the most powerful FRB

FRB host galaxies

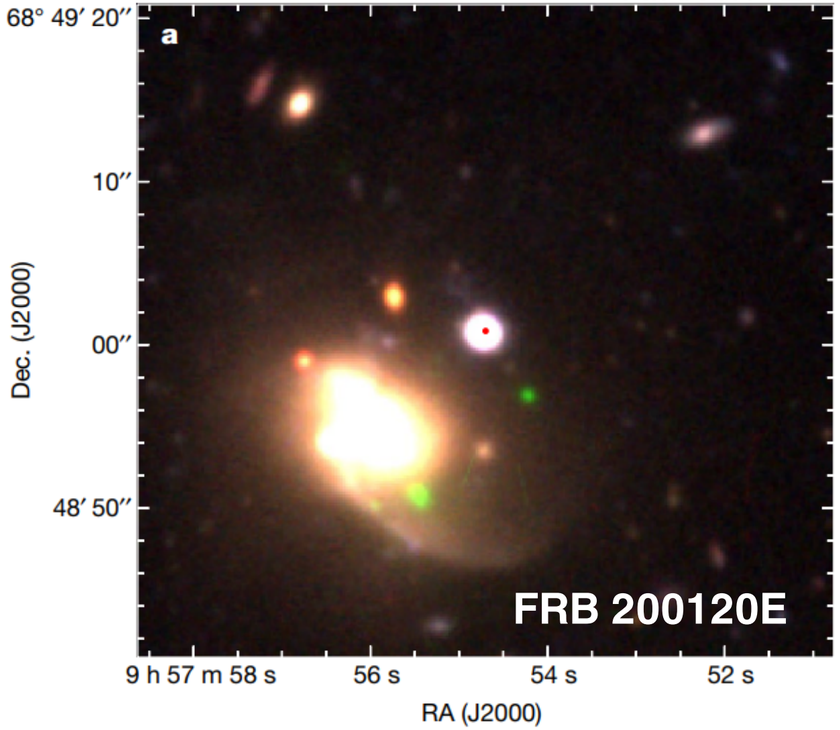
- Nearly **30 sources** have been associated to different types of host galaxies. The majority are spirals (generally with moderate SFR), but some of them are older and/or quiescient in star formation.

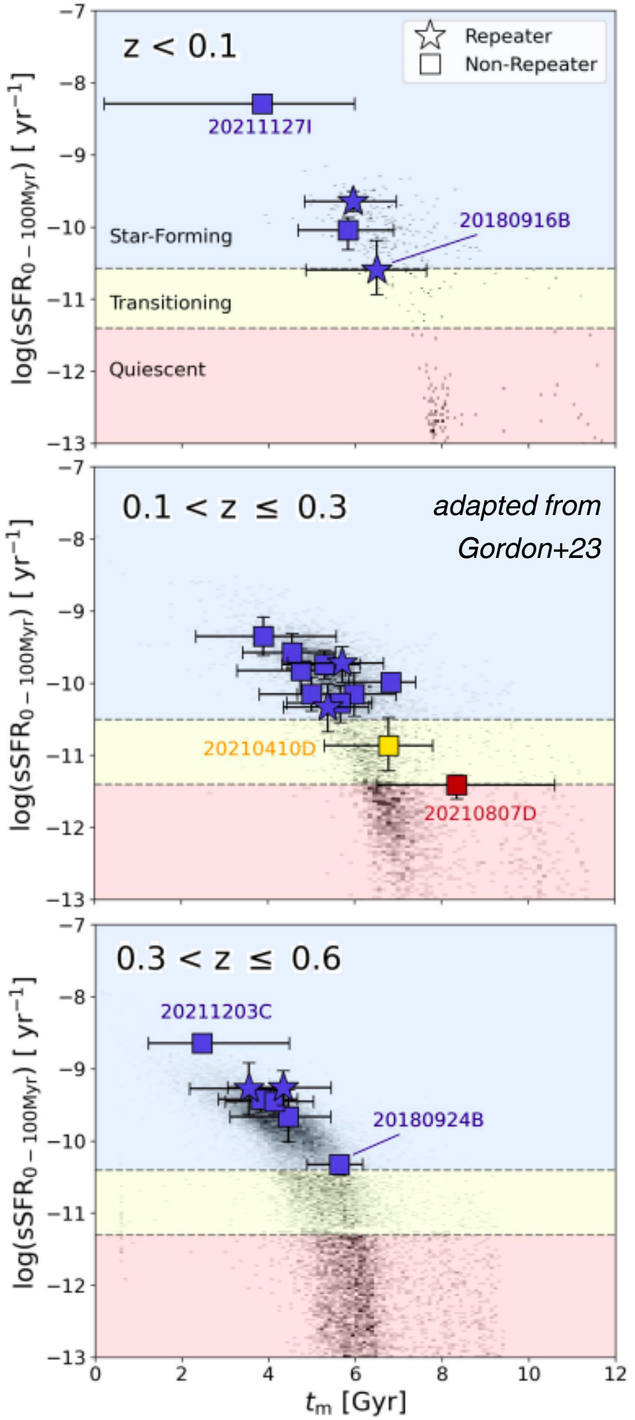
- Notably: FRB 20200120E pin-pointed to a **globular cluster** in M81 (nearby galaxy, 3.8 Mpc)

Marcote+20



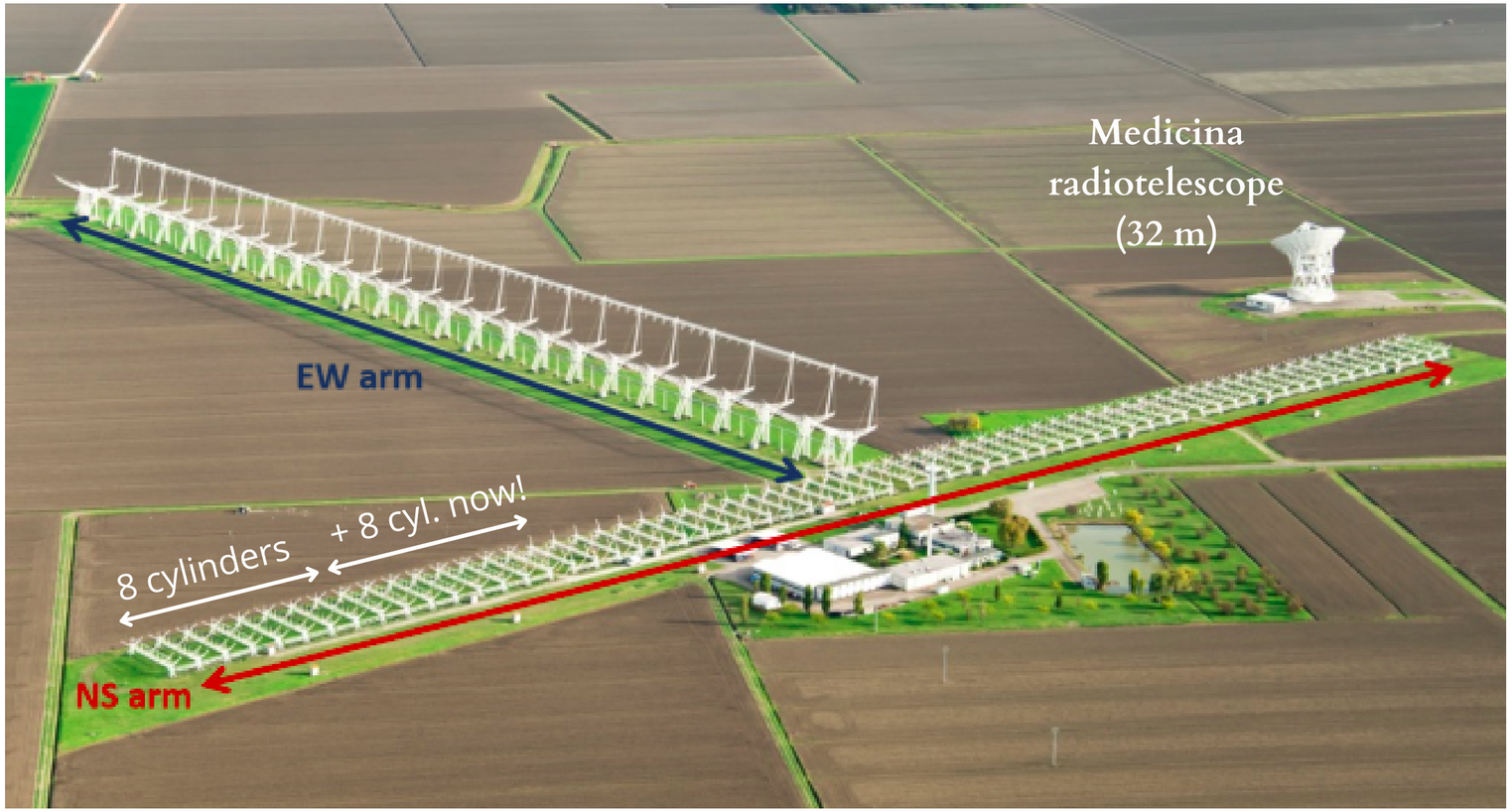
Kirsten+21



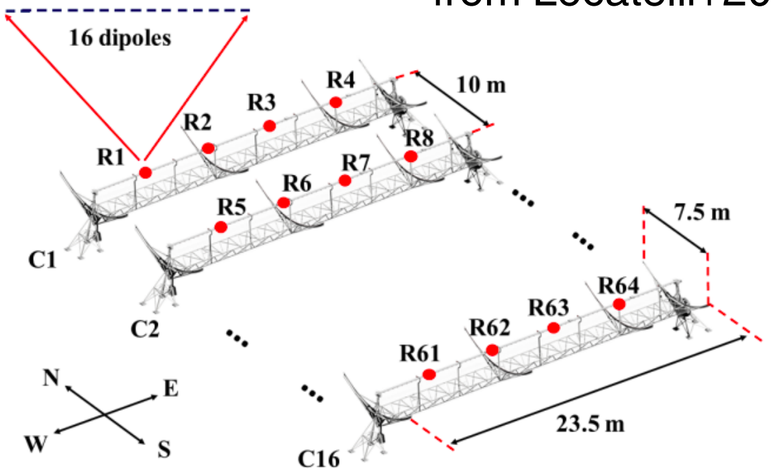


The Northern Cross Radio Telescope

Northern Cross
FRB Project



from Locatelli+20



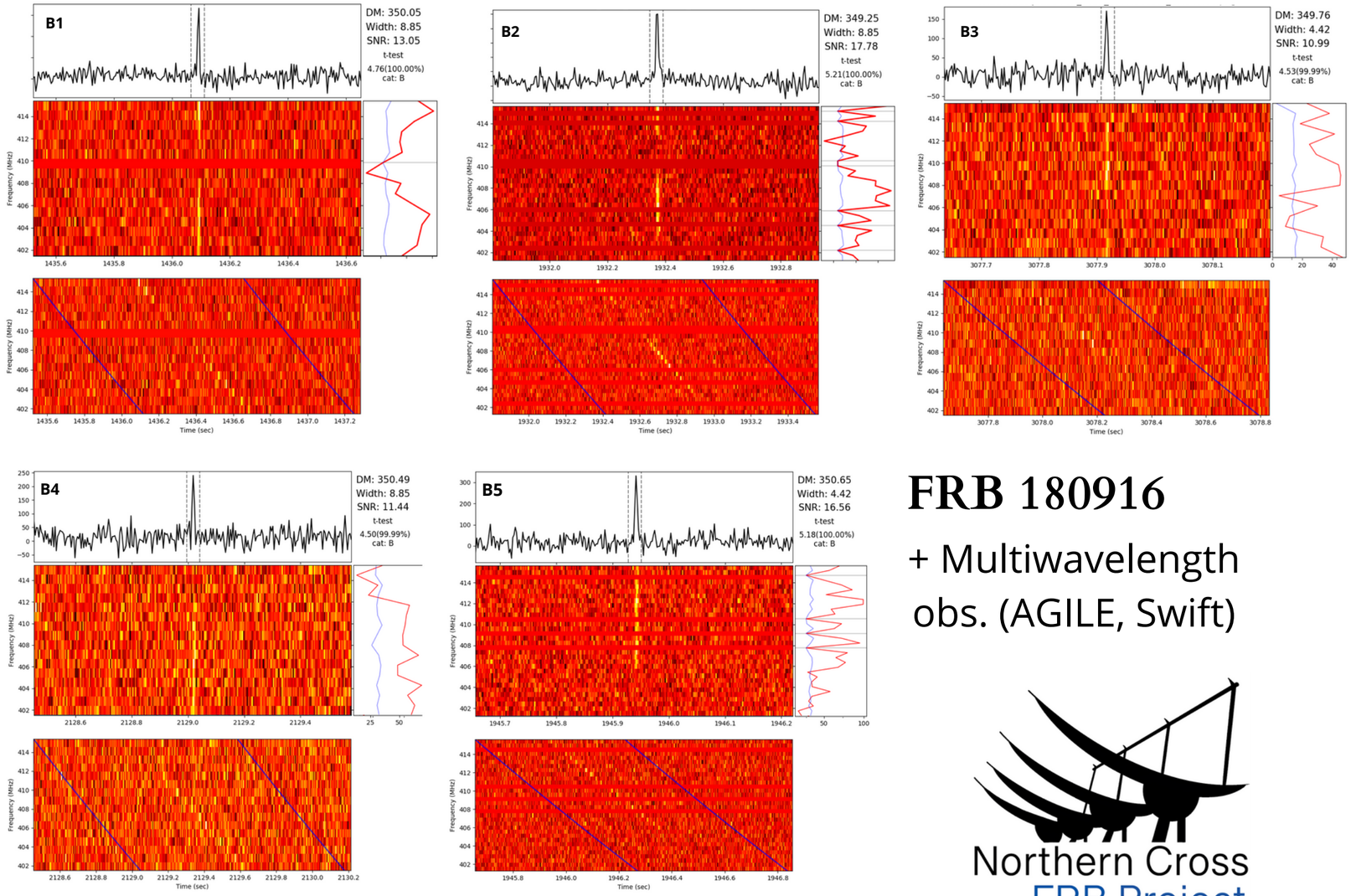
The focal line of 16 cylinders has been modified in order to group the signals of 64 dipoles together, providing 4 analogue signals per cylinder

The signal from different cylinders is then **combined** together to form a **steering electronic beam** in the sky

$$\nu_0 = 408 \text{ MHz}$$
$$\text{BW} = 16 \text{ MHz}$$
$$\Delta\nu_{\text{ch}} \simeq 14.5 \text{ kHz}$$
$$\text{t}_{\text{samp}} = 138 \ \mu\text{s}$$

Monitoring the most active repeaters

from Trudu, ...**Pelliciari**, 2022, MNRAS, 513, 1858



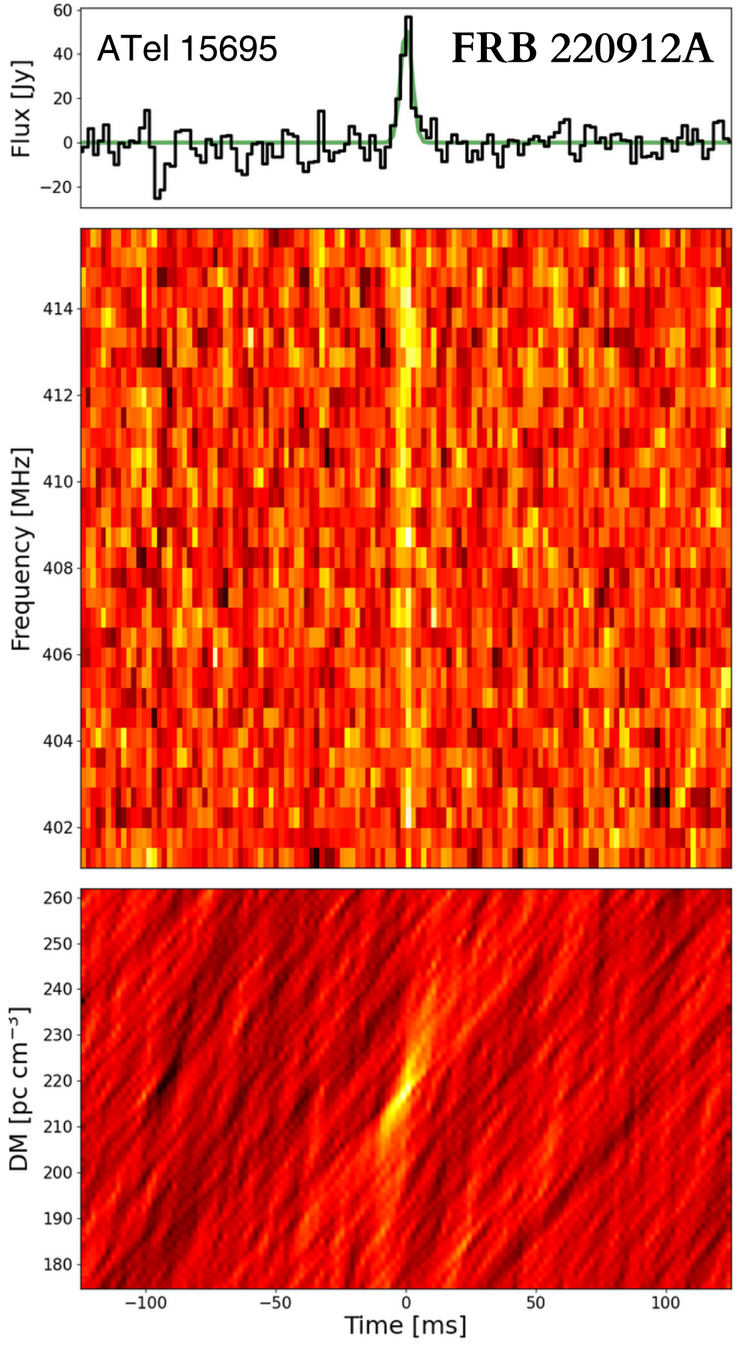
adapted from Pelliciari et al. 2023

(accepted for A&A publication)

FRB 180916

+ Multiwavelength obs. (AGILE, Swift)

Northern Cross FRB Project



Searching for FRBs in a sample of nearby galaxies

Started from December 26th 2021, observing 7 nearby galaxies located within D < 12 Mpc and star forming

	R.A. (J2000)	Dec (J2000)	D [Mpc]	SFR [$M_\odot$ yr^{-1}]	DM_{ISM} [pc cm^{-3}]	T [hr]
M31	$00^h42^m44.3^s$	+41°16′07.5″	0.79 ± 0.03 [1]	0.35 [8]	142	51
IC342	$03^h46^m48.5^s$	+68°05′46.0″	3.3 ± 0.3 [2]	2.8 [9]	178	102
M82	$09^h55^m52.4^s$	+69°40′46.9″	3.53 ± 0.04 [3]	13 [10]	41.2	184
M101	$14^h03^m12.6^s$	+54°20′55.5″	6.4 ± 0.5 [4]	2.9 [11]	30.9	96
NGC6946	$20^h34^m52.3^s$	+60°09′13.2″	7.7 ± 0.3 [5]	4.3 [11]	145.8	115
M106	$12^h18^m57.6^s$	+47°18′13.4″	7.8 ± 0.6 [6]	2.8 [11]	25.8	84
M66	$11^h20^m15.0^s$	+12°59′28.6″	11.1 ± 0.4 [7]	2.7 [11]	31.1	63

} ~ 692 hr

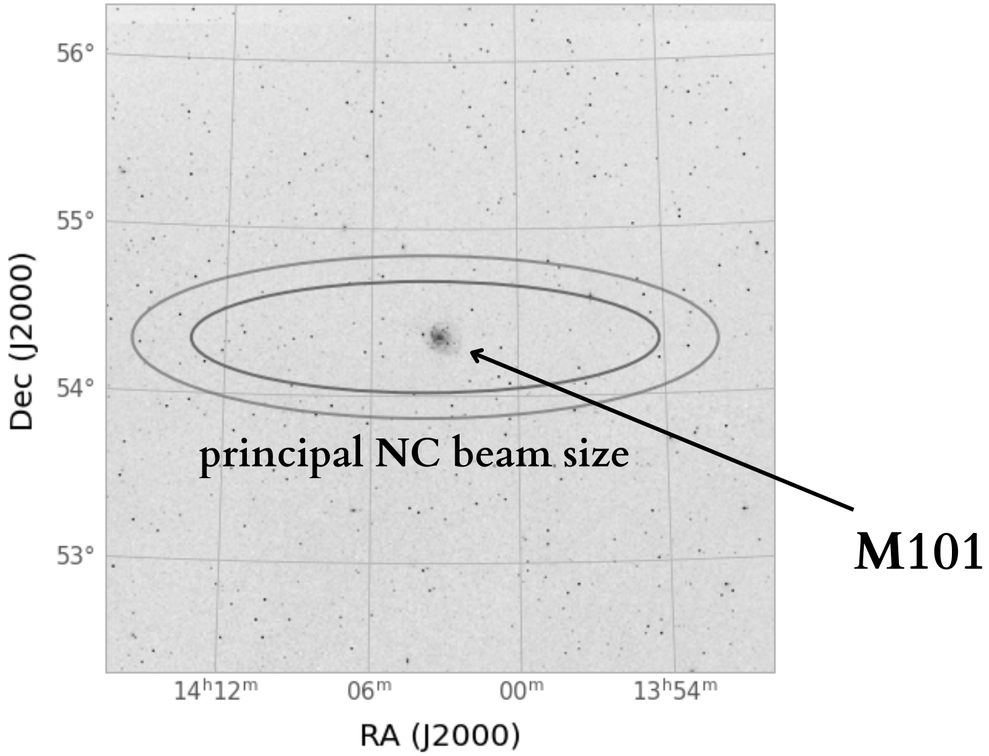
from Pelliciari et al. 2023 (accepted for A&A publication)

FRB searching strategy:

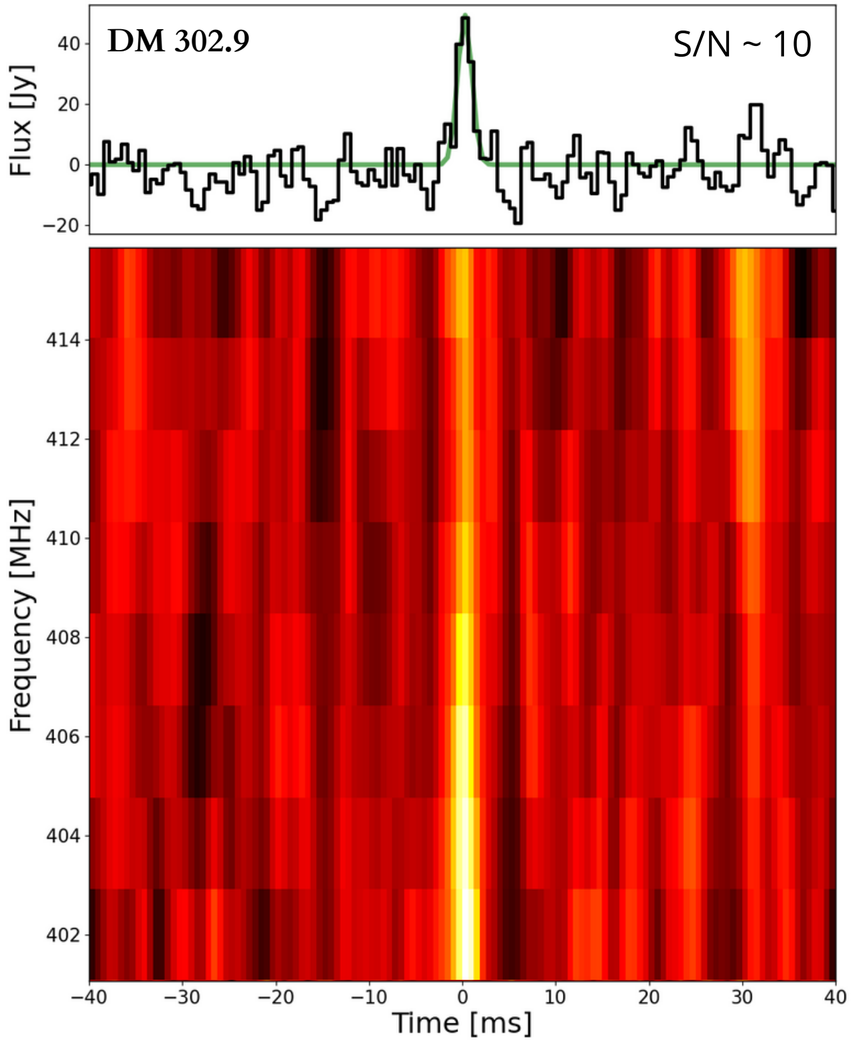
- 0 < DM < 1000 pc cc
- t < 35 ms

A one-off FRB in the direction of M101

- **Detection date**: 2022-03-20 02:08:49.34 (UT)
- **Duration**: ~ 1.8 ms
- **Fluence**: ~ 60 Jy ms
- **Dispersion measure** (DM): 302.9 pc cm-3
- **Implied DM host**: 220 pc cm-3
- **Maximum lum. distance**: 870 Mpc



FRB 20220320



Pelliciari et al. 2023 (accepted for A&A publication)

Upper limit on the magnetar burst rate

Modulating for a *power-law* energy function and scaling for the **SFR**, the total burst rate from the galaxies of our sample can be written as:

<u>for a single galaxy:</u>

$$\mathcal{R}(\lambda_{\rm mag}, \gamma; > E_{{\rm min},i,j}) = N_{\rm mag} \frac{\rm SFR_i}{\rm SFR_{MW}} \times \times \int_{E_{{\rm min},i,j}}^{E_{\rm max}} K_0 \left(\frac{E}{E_0}\right)^{\gamma} \Theta[E - E_0]\, dE$$

SGR energy

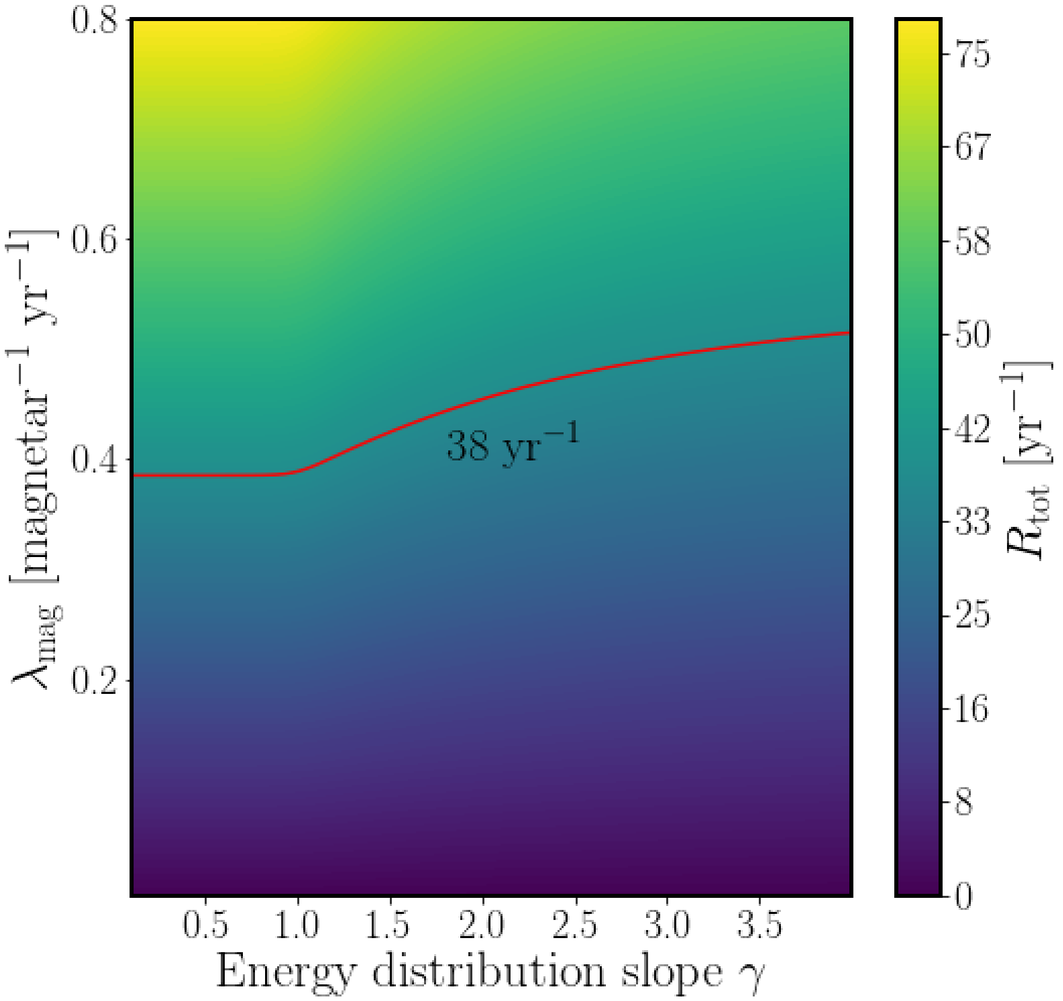
then:

$$\mathcal{R}_{\rm tot}(\lambda_{\rm mag}, \gamma) = \frac{\sum_i^N \sum_j^{N_b} \mathcal{R}(\lambda_{\rm mag}, \gamma; > E_{{\rm min},i,j})\, T_{i,j}}{\sum_i^N \sum_j^{N_b} T_{i,j}}$$

$$E_{\rm max} = \eta E_{\rm mag} = 3 \times 10^{49} \eta \left(\frac{B}{10^{16}\ {\rm G}}\right)^2 \ {\rm erg}$$

$N_{\rm mag} = 29$ (e.g. Kaspi+17)

$K_0 \propto \lambda_{\rm mag}$



Marginalising over γ we get:

$$\lambda_{\rm mag} < 0.45\ {\rm magnetar}^{-1}\ {\rm yr}^{-1}$$

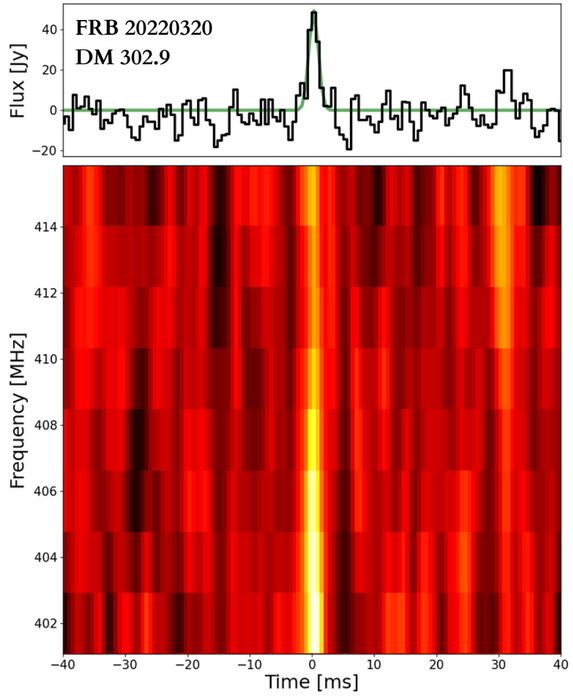
Conclusions

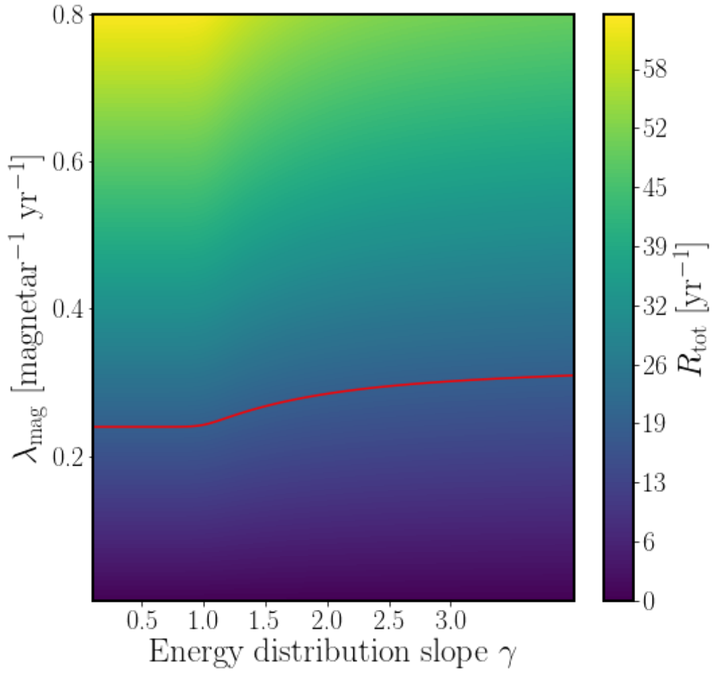
- FRBs are a *real mistery* in astrophysics. A Galactic magnetar emitted a FRB-like signal but show a too-low repetition rate, inconsistent with active repeaters.

- Northern Cross observed 7 nearby galaxies for a total of ~ 700 hrs, obtaining ***no detections****, apart from* **FRB 20220320,** a one-off burst *likely* coming from **beyond** M101

- We reported stringent upper limits on the **magnetar burst rate**, which halves the literature range --> SGR1935-like FRBs *seems to be rarer* than expected

- Considering a multi-magnetar population model, **rare** (& active) magnetars should be more prominent than considered earlier in order to compensate the small burst rate from SGR-like magnetars





Conclusions

- FRBs are a *real mistery* in astrophysics. A Galactic magnetar emitted a FRB-like signal but show a too-low repetition rate, inconsistent with active repeaters.

- Northern Cross observed 7 nearby galaxies for a total of ~ 700 hrs, obtaining ***no detections****, apart from* **FRB 20220320,** a one-off burst *likely* coming from **beyond** M101

- We reported stringent upper limits on the **magnetar burst rate**, which halves the literature range --> SGR1935-like FRBs *seems to be rarer* than expected

- Considering a multi-magnetar population model, **rare** (& active) magnetars should be more prominent than considered earlier in order to compensate the small burst rate from SGR-like magnetars