Fast Radio Bursts and magnetars

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on behalf of the PRECISE and AstroFlash projects

JIVE
Joint Institute for VLBI
ERIC

ASTROFLASH

4 October 2023

20 MAGIC Years Conference

(Artwork credit: Danielle Futselaar)

Introduction to Fast Radio Bursts

- What is a Fast Radio Burst?
- In a galaxy far far away…
- Why do we care about FRBs?

FRBs at high resolution

- Understanding the local environments
- Multiple formation channels?

MAGIC & AstroFlash

- Multiwavelength observations
- Optical & VHE MAGIC searches

Summary and conclusions

What is a Fast Radio Burst (FRB)?

Fast Duration of $\sim$ 1 μs–10 ms

Radio Observed at GHz frequencies

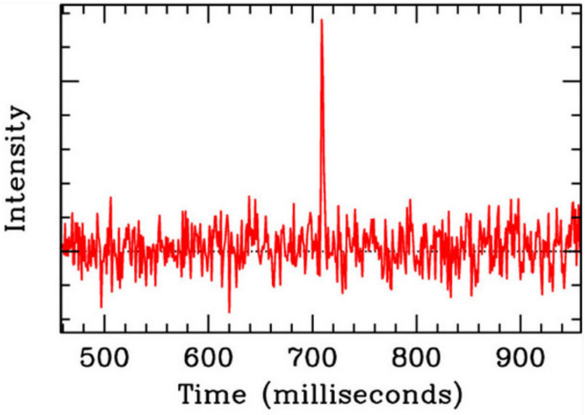
Burst Bright $\sim$ 0.1–100 Jy

Discovered by Lorimer et al. (2007)

Hundreds/thousands of them reported (*frbcat.org*; Petroff et al. 2022)

Only a small fraction exhibit multiple bursts (so-called **“repeaters”**)

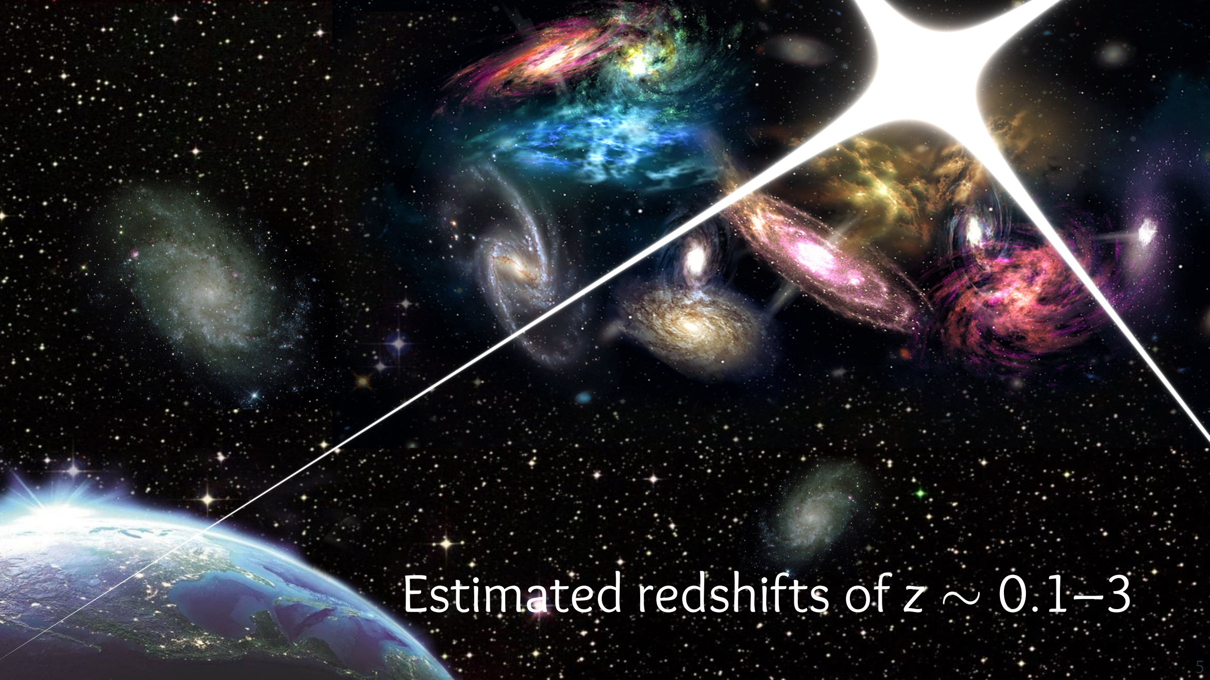
Origin: unclear



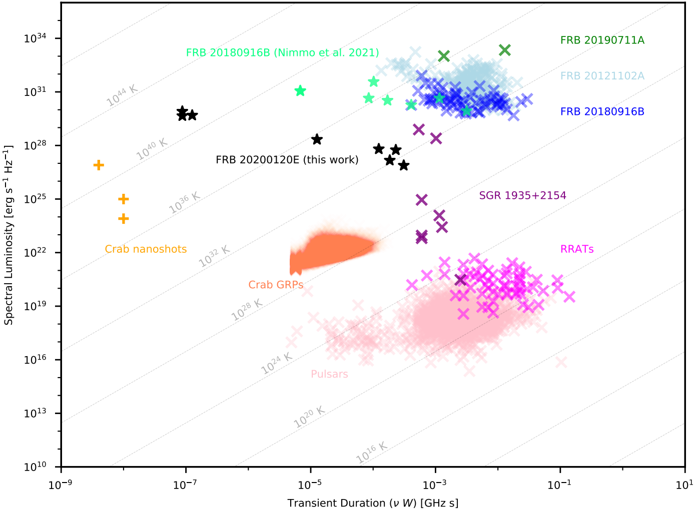
FRB 140514

$$\sim 10^{3-4}\ \text{FRBs sky}^{-1}\ \text{day}^{-1}$$

$$> 10^{5}\ \text{FRBs Gpc}^{-3}\ \text{yr}^{-1}$$


Estimated redshifts of $z \sim 0.1$–3

FRBs: very luminous sources



(Nimmo et al. 2022, Nature Astronomy, 6, 393)

Why are FRBs important?

- FRBs look like single pulses from pulsars but $\sim$ **10^{10} brighter**.
- Possible emission from radio to gamma-rays?
- Trace properties of the intergalactic medium and Galactic Halos (Prochska & Zheng 2019).
- Can probe the reionization history of H and He in the Universe.
- Constraints on fundamental physics (equivalence principle, photon mass,...).
- Constrain the baryon content of the Universe (Macquart et al. 2020), ...

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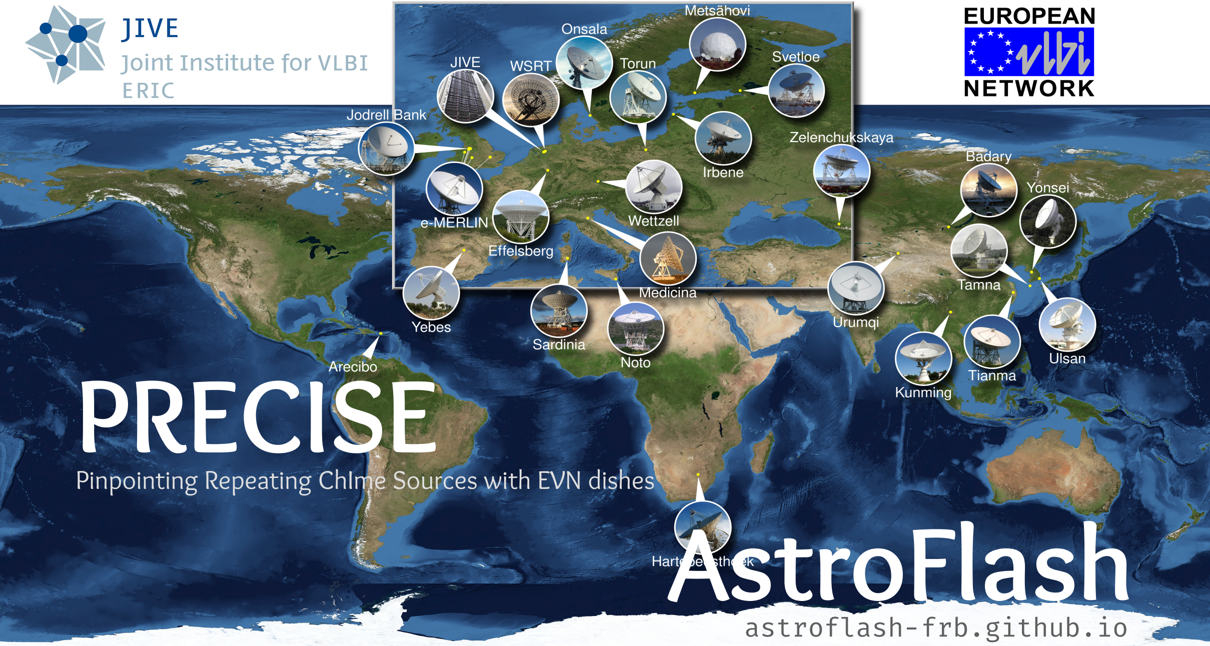
EUROPEAN vlbi NETWORK



PRECISE

Pinpointing Repeating ChIme Sources with EVN dishes

AstroFlash

astroflash-frb.github.io

Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

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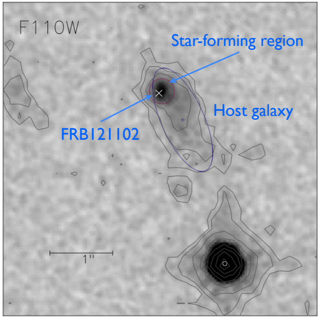
`astroflash-frb.github.io`

Localizing FRBs to milliarcsecond precision

FRB 20121102A

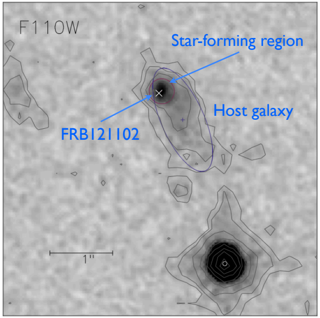


Chatterjee et al. (2017, Nat, 541, 58)
Marcote et al. (2017, ApJL, 834, 8)
Tendulkar et al. (2017, ApJL, 834, 7)
Bassa et al. (2017, ApJL, 843, 8)

Star-forming dwarf galaxy

Localizing FRBs to milliarcsecond precision

FRB 20121102A



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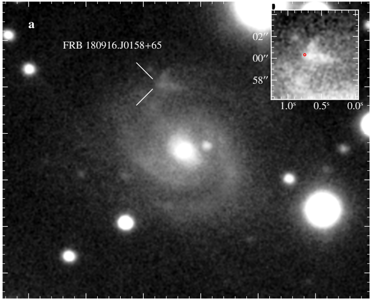
FRB 20180916B



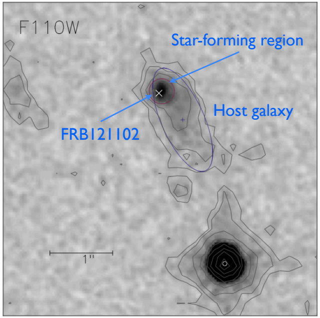
Marcote et al. (2020, Nature, 577, 190)

Star-forming dwarf galaxy

Star-forming spiral galaxy

Localizing FRBs to milliarcsecond precision

FRB 20121102A



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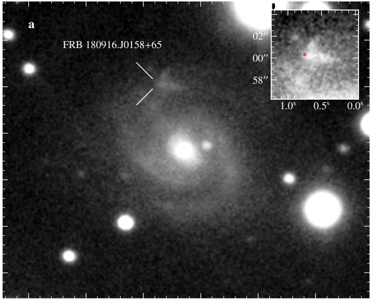
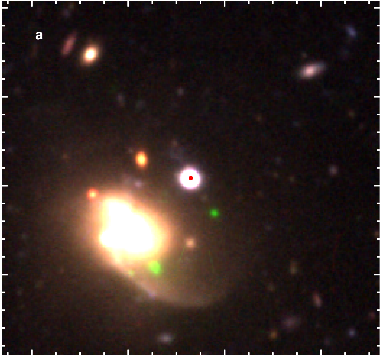
FRB 20180916B



Marcote et al. (2020, Nature, 577, 190)

FRB 20200120E



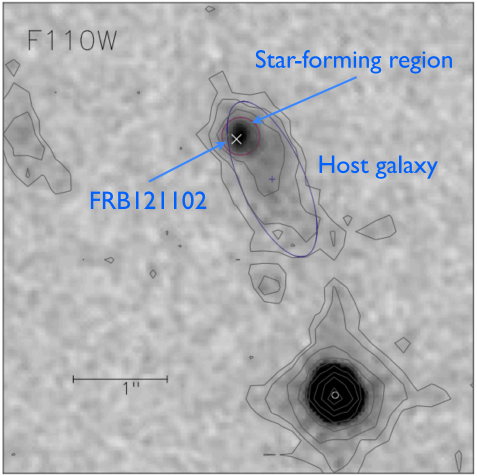
Kirsten, Marcote et al. (2022, Nat, 602, 585)
Nimmo et al. (2022, Nat Astr, 6, 393)

Star-forming dwarf galaxy

Star-forming spiral galaxy

Globular cluster!

The First Precise Localization of a Fast Radio Burst: FRB 20121102A



Tendulkar et al. (2017, ApJL, 834, 7)
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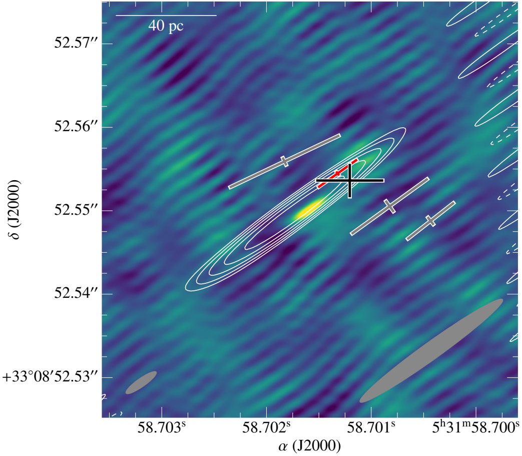

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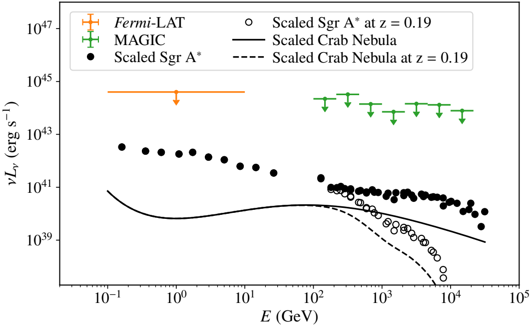
Simultaneous radio, optical and TeV observations

Bursts at other wavelengths:

- Optical upper-limits on burst fluence of < 0.046 Jy ms (Hardy et al. 2017)
- Optical/TeV-radio observations with MAGIC (MAGIC Coll. et al. 2018)

Concerning the persistent counterpart:

- TeV: upper-limits from VERITAS & MAGIC (Bird et al. 2017, MAGIC Col. 2018)



(MAGIC Collaboration et al. 2018, MNRAS, 481, 2479)

The Second Localized Repeating FRB: 20180916B

(CHIME/FRB et al. 2019, ApJL, 885, L24)

Four bursts on 19 June 2019 localized to $\sim$ 2 mas

Marcote et al. (2020, Nature , 577, 190)

At the edge of a star-forming region

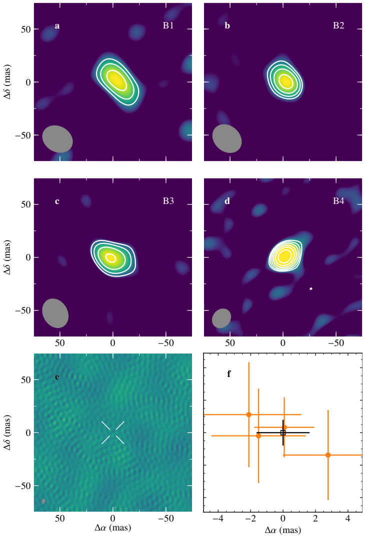
Tendulkar et al. (ApJL 2021, 908, L12)

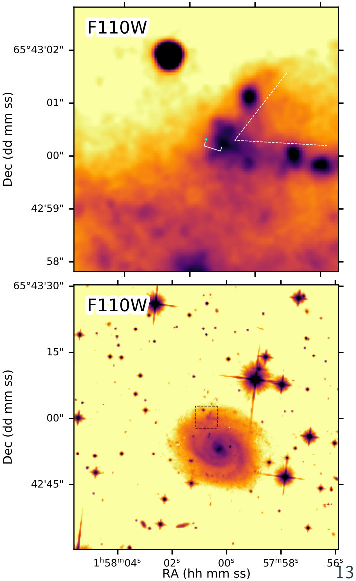
The bursts appear in a $\sim$ 4-d window with a period of 16.35 ± 0.15 days

(CHIME/FRB et al. 2020, Nature, 582, 351)

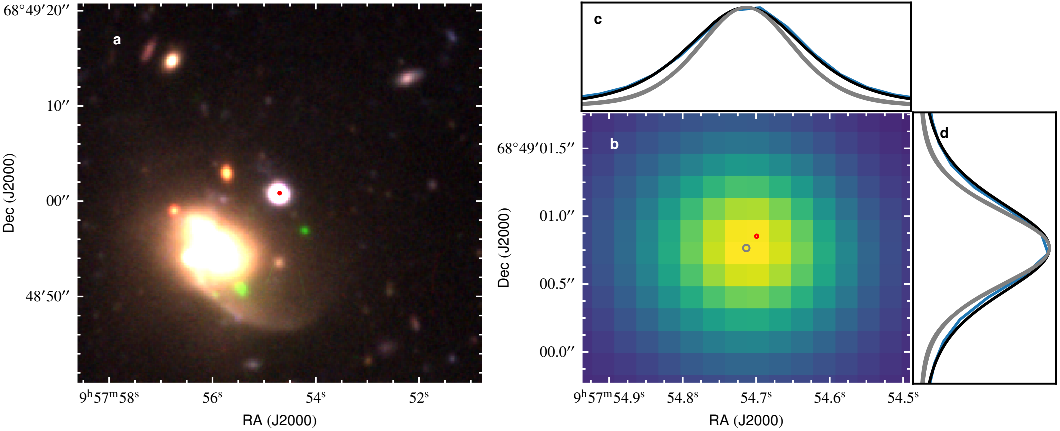
Shortest components of 3–4 μs

Nimmo et al. (2021, Nat Astr, 5, 594)





FRB 20200120E — in a globular cluster in M81!



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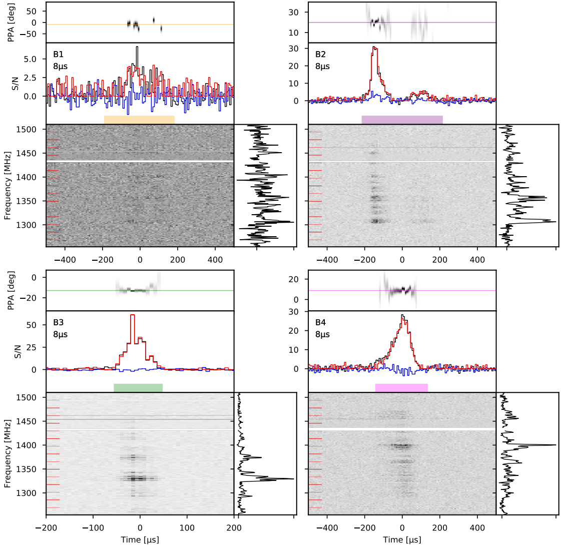
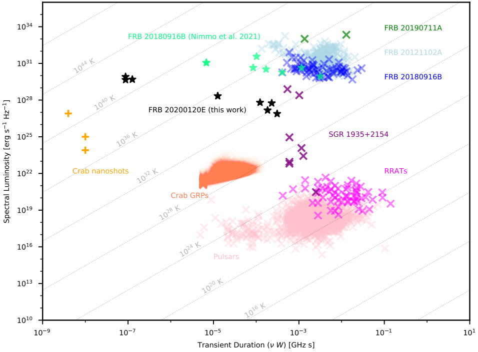




Sub-components as narrow as 60 ns

(Nimmo et al. 2022, Nature Astronomy, 6, 393)

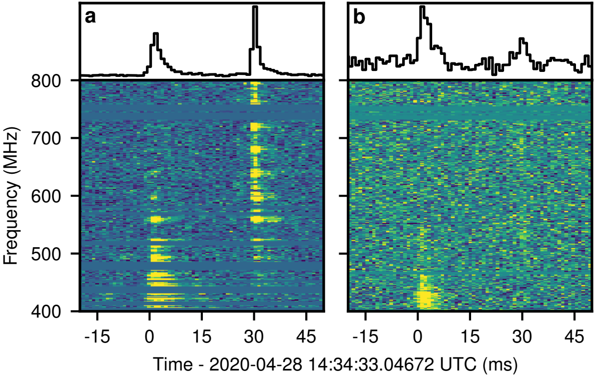
SGR 1935+2154

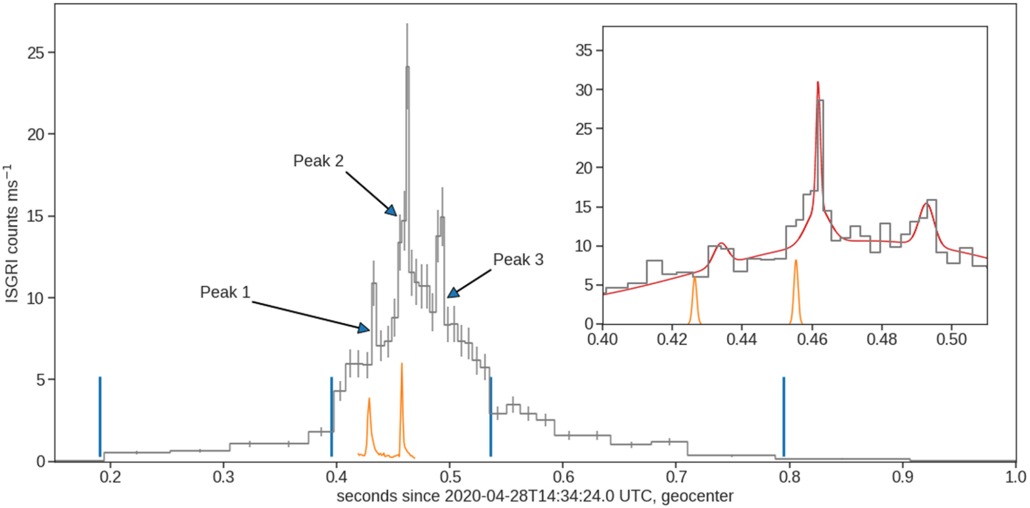
A Galactic magnetar

Known soft γ-ray repeater

On 28 April 2020...

- Bright radio bursts: $\sim$ 1 kJy ms
  (CHIME/FRB Collaboration 2020)
- STARE2 FRB detection: $\sim$ 1.5 MJy ms
  (Bochenek et al. 2020)
- Simultaneous X-ray burst
  (Mereghetti et al. 2020)





Magnetospheric or non-magnetospheric emission? (Mereghetti et al. 2020)

Optical and very-high-energy MAGIC searches

Current MAGIC/radio observations of

- SGR 1935+2154 (plus X-rays; 2020–2023)
  Alicia Lopez-Oramas et al.
- Nearby and active FRBs (2017–2023)
  Tarek Hassan, Irene Jiménez-Martínez et al.
- FRB candidates? γ-ray binary LS I +61 303
  T.H., A.L.-O., +Daniella Hadasch

$$10^{-7}$$

$\gtrsim$ 2 500 *hours observed…*

… $\lesssim$ 1 *second of FRB signals!*

Take home messages

- **Fast Radio Bursts** are still intriguing sources with many unknowns.
- Combines both time-domain & continuum observations.
- Implications from pulsar to extragalactic.
- Our goal is to get tens of precise localizations.
- MAGIC & European radio telescopes in perfect combination for multiwavelength searches.
- Optical constraints with the central pixel specially meaningful for nearby (or Galactic) FRBs.


Thank you!
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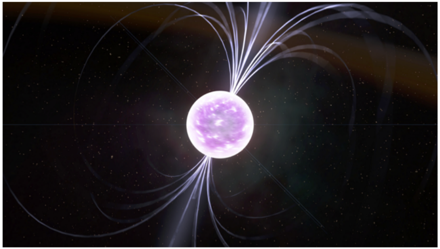
Possible origins of FRB 20121102A



Pulsar/magnetar powering up a young superluminous supernovae?
(e.g. Margalit et al. 2018, Metzger & Margalit et al. 2019)

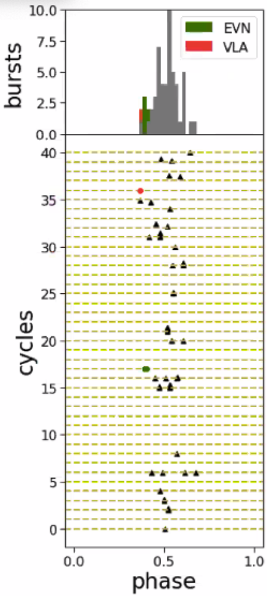
Young pulsar/magnetar interacting with a massive black hole?
(e.g. Pen & Connor 2015, Cordes & Wasserman 2016, Zhang 2018)

Neutron star/high-mass star X/γ-ray binaries?
(e.g. Barkov & Popov 2022)

After that a periodic pattern was discovered in FRB 20180916B:

Binary system? Precession? Spin?

Note the similar evidences in FRB 20121102A, with a periodicity of $\sim$ 150 days (Rajwade et al. 2020)



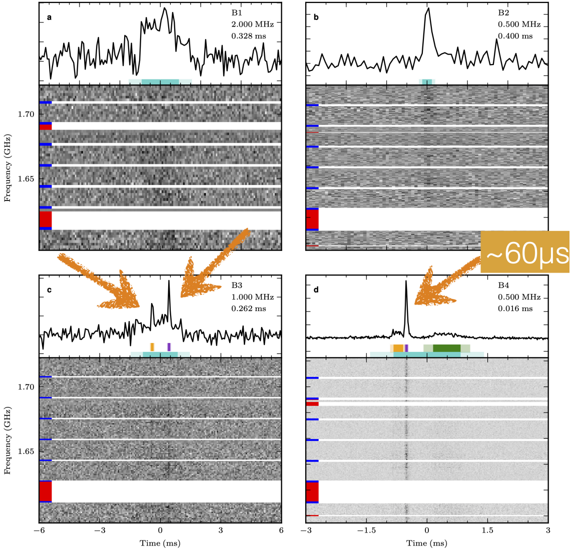
EVN baseband data

Highly linearly polarized ($\gtrsim$ 80%)
No circularly polarized ($\lesssim$ 15%)

Constant polarization Position Angle
but with a few deg. variations

Magnetospheric origin?

Marcote et al. (2020, Nature, 577, 190)



The Astrophysical Journal Letters, 898:L29 (10pp), 2020 August 1 Mereghetti et al.

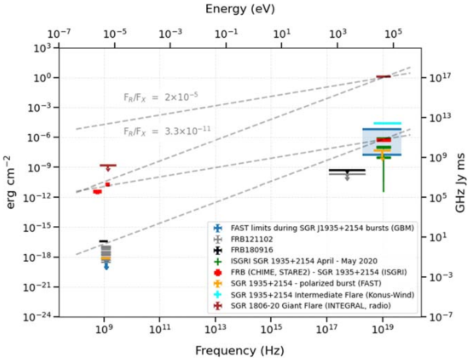


Figure 7. Comparison of the spectral energy distribution of burst-G from SGR 1935+2154 (red) with the upper limits for other magnetars and FRBs obtained from simultaneous radio and X-ray observations (Hurley et al. 2005; Kozlova et al. 2016; Tendulkar et al. 2016; Scholz et al. 2017, 2020; Bochenek et al. 2020; Lin et al. 2020b; Pilia et al. 2020; The CHIME/FRB Collaboration et al. 2020b).

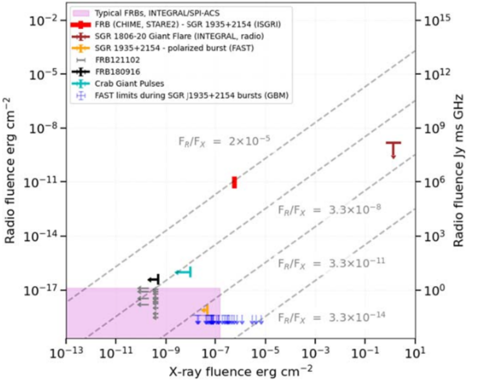
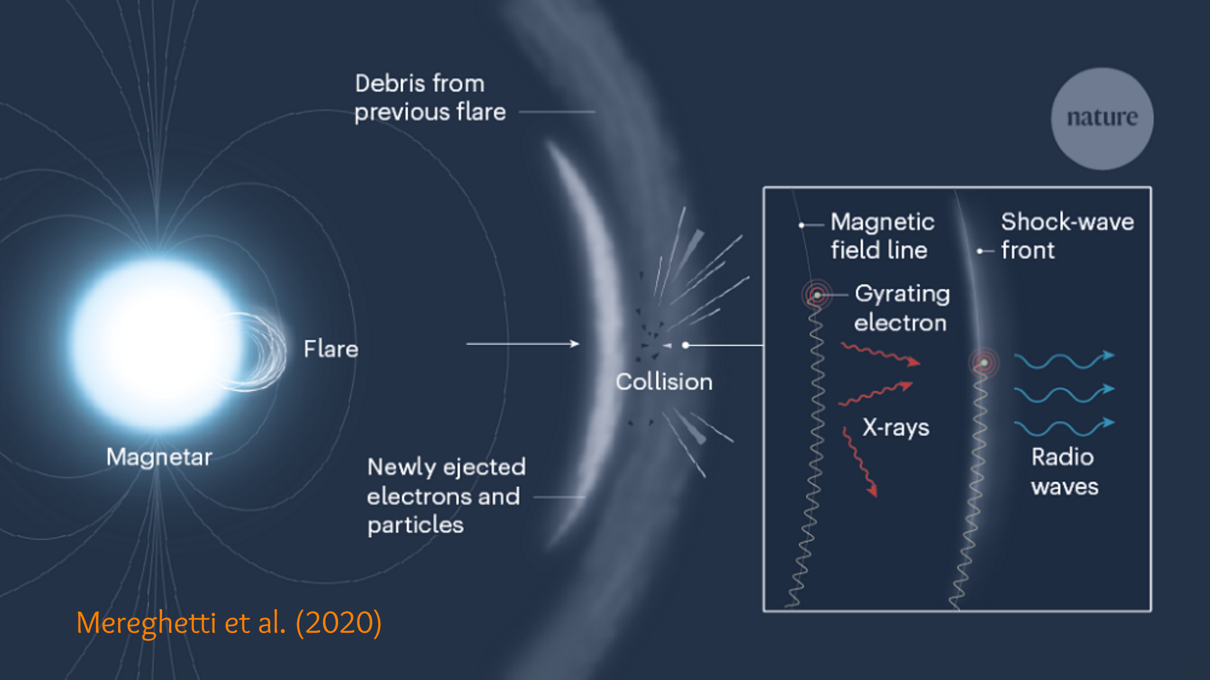


Figure 8. Radio vs. X-ray (starting from 0.5 keV) fluences for FRBs and magnetar bursts. The range of FRB fluences corresponds to a variety of detections reported in the past years (references in Figure 7 and Karuppusamy et al. 2010). The purple region indicates a robust upper limit on the hard X-ray fluence of FRBs as derived with a high-duty-cycle detector, such as the INTEGRAL SPI/ACS (Savchenko et al. 2017).

Mereghetti et al. 2020

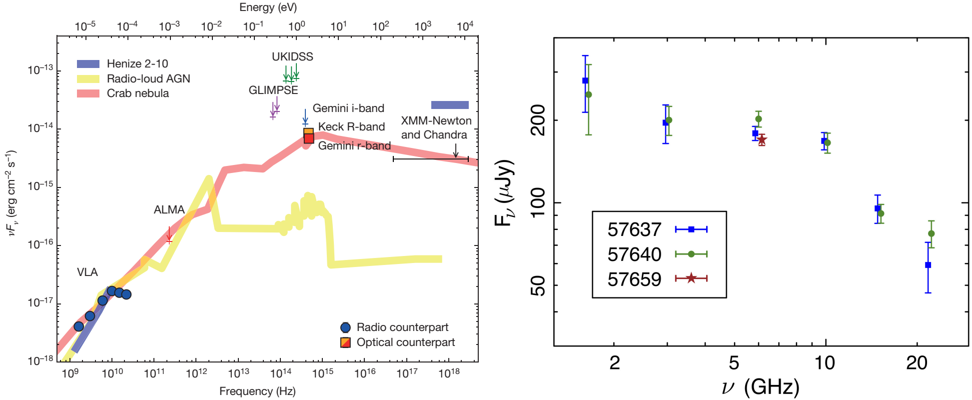


Mereghetti et al. (2020)

Predictions at high energies

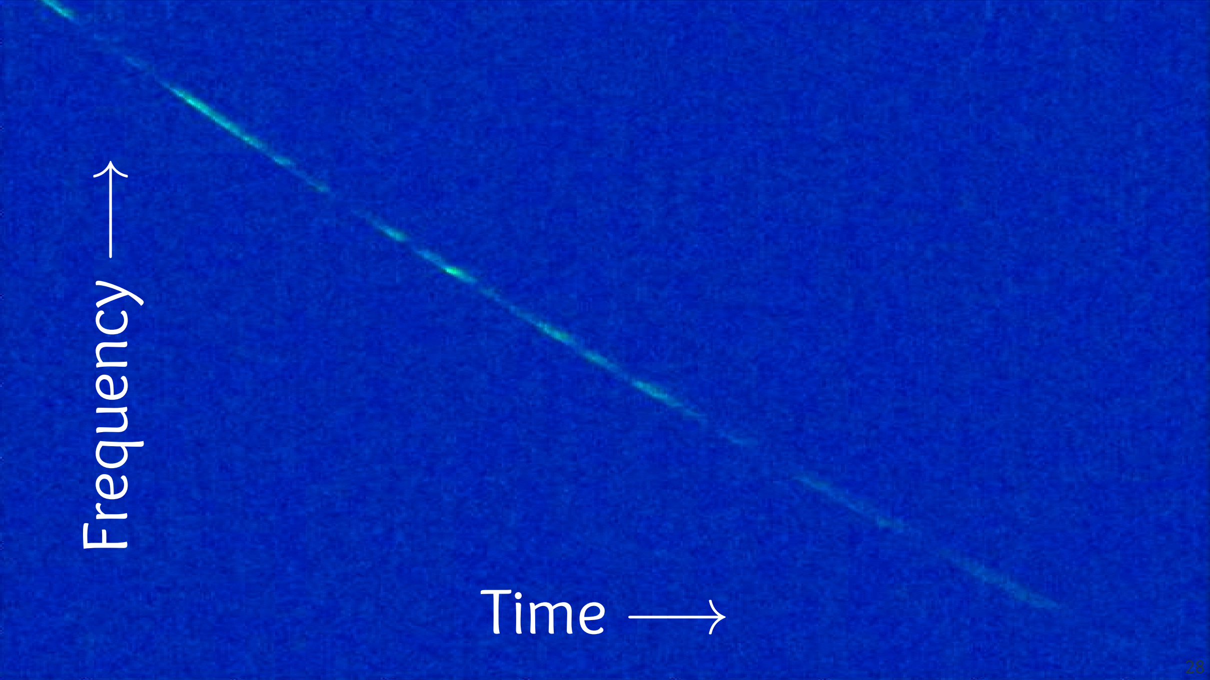
- **In a magnetar scenario...**
  Quasi-simultaneous X-ray to MeV gamma-ray bursts
  X-ray/radio $\sim 10^4$ (Lyutikov 2002)
  $\sim 10^{42-43}$ erg s^{-1} above 1–10 keV for 0.1–1 s
  $\sim 10^{45-46}$ erg s^{-1} above MeV–GeV for 0.1–10 ms (Metzger et al. 2019)
- **Ultrarelativistic outflows interacting with the nebula...**
  TeV flashes, TeV/radio $\sim 10^{5-6}$ (Lyubarsky 2014, Murase et al. 2016)
- **Synchrotron maser emission...**
  TeV bursts "could" happen if external shock strong enough (Lyubarsky 2014)
- ***B* reconnections near the magnetar surface...**
  Bursts up to optical wavelengths: independent ones, lower rate (Kumar et al. 2017)
- **Coherent curvature emission...**
  Only radio bursts (Ghisellini & Locatelli 2017)

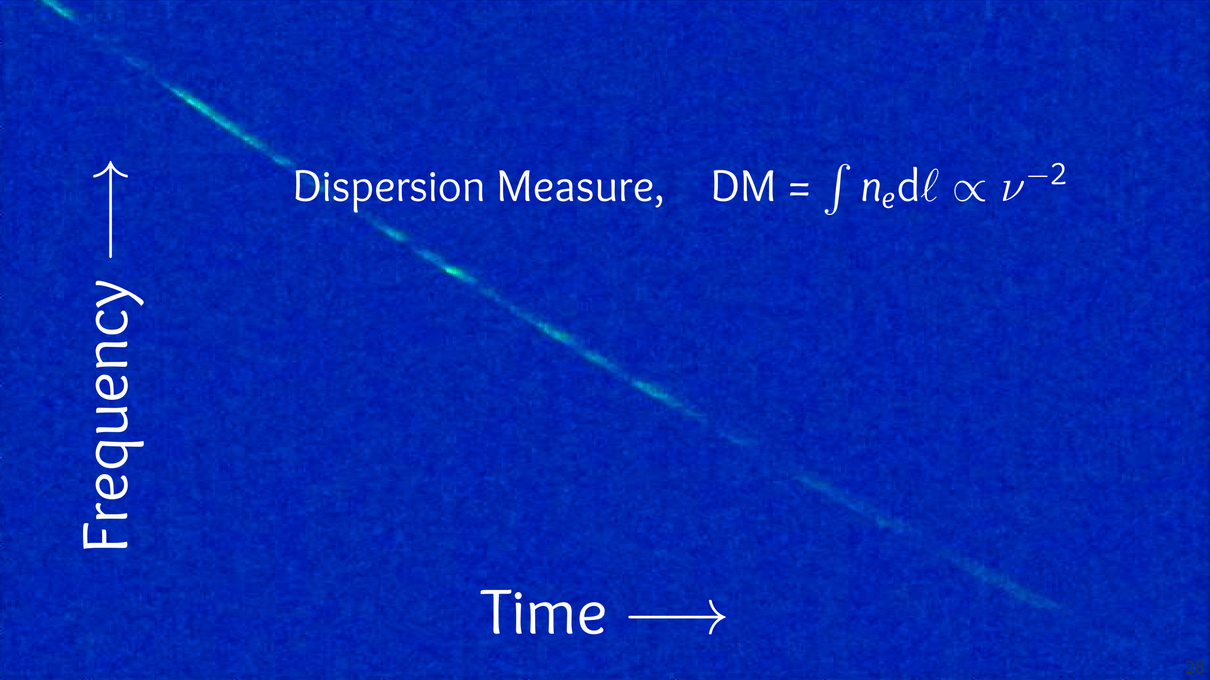
The VLA localization of FRB 121102



SED and radio spectrum of FRB 121102

(Chatterjee et al. 2017, Nature, 541, 58)


Frequency →
Time →


Dispersion Measure, DM = $\int n_e \mathrm{d}\ell \propto \nu^{-2}$
Frequency ⟶
Time ⟶