The localization of a repeating Fast Radio Burst

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ERIC

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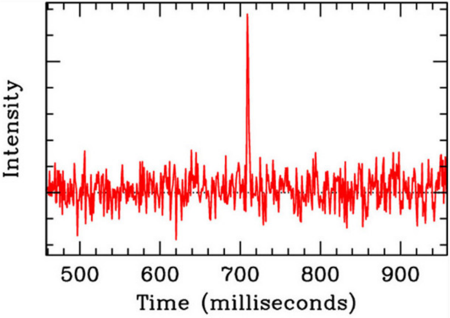
(Artwork: Danielle Futselaar)

Introduction

Introduction: What is a Fast Radio Burst?

- **Fast and strong radio flashes**
- Duration of a few milliseconds
- Bright: $\sim$ 0.1–1 Jy
- Detected at radio freq. ($\sim$1 GHz)
- Discovered by Lorimer et al. (2007)
- Origin: unknown



FRB 140514

Introduction: What is a Fast Radio Burst?

Event	Telescope	gl [deg]	gb [deg]
FRB010125	parkes	356.641	-20.020
FRB010621	parkes	25.433	-4.003
FRB010724	parkes	300.653	-41.805
FRB090625	parkes	226.443	-60.030
FRB110220	parkes	50.828	-54.766
FRB110523	GBT	56.119	-37.819
FRB110626	parkes	355.861	-41.752
FRB110703	parkes	80.997	-59.019
FRB120127	parkes	49.287	-66.203
FRB121002	parkes	308.219	-26.264
FRB121102	arecibo	174.950	-0.225
FRB130626	parkes	7.450	27.420
FRB130628	parkes	225.955	30.655
FRB130729	parkes	324.787	54.744
FRB131104	parkes	260.549	-21.925
FRB140514	parkes	50.841	-54.611
FRB150418	parkes	232.665	-3.234
FRB150807	parkes	336.709	-54.400
FRB160317	UTMOST	246.050	-0.990
FRB160410	UTMOST	220.360	27.190
FRB160608	UTMOST	254.110	-9.539

frbcat.org

- 30 FRBs have been reported to date
  Petroff et al. (2016)
- Poor localizations ($\sim$ arcmin)
  No associations
- Typical observing frequency: 1.4 GHz
- No correlation with the Galactic Plane
- Rate: $\sim 10^{3\text{–}4}$ sky^{-1} day^{-1}

The Dispersion Measure

Light is dispersed by the material in the medium.

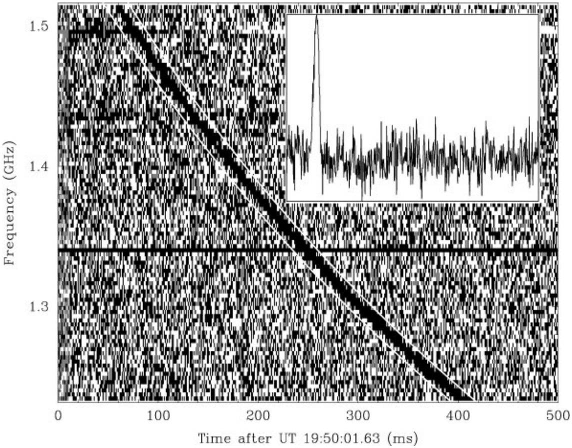
Dispersion Measure:

$$\mathrm{DM} = \int n_e \mathrm{d}\ell \quad \propto \nu^{-2}$$

All FRBs show unexpected large DMs.

Much larger than the contribution of our Galaxy

Estimated $z \sim 0.16$–1.3



Lorimer et al. (2007)

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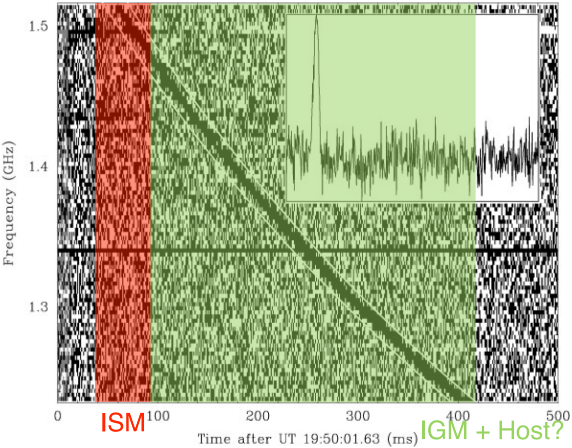
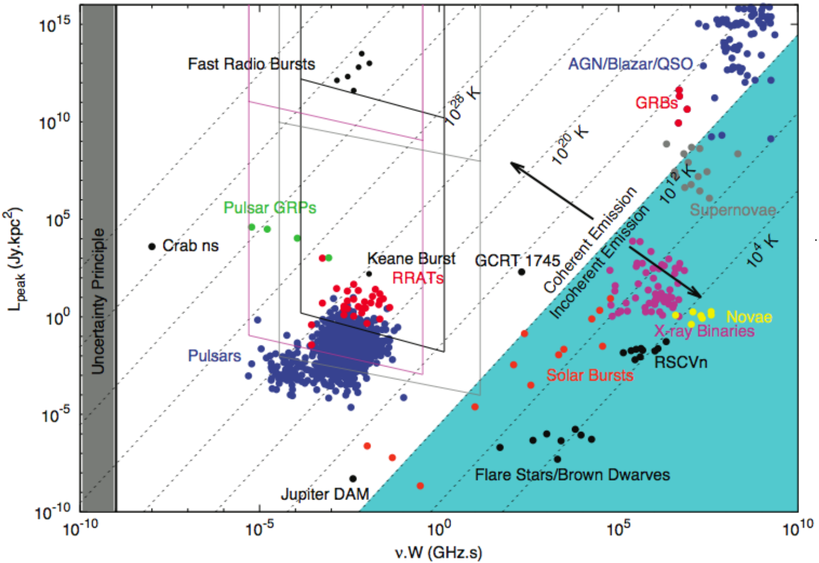


Lorimer et al. (2007)

What can FRBs be?



Credit: J. P. Macquart


Merging Black Holes
Supernovae
Magnetars
Evaporating Black Holes
Super-giant Pulses
The Unknown
extra-Galactic
Implied rate of 1000s per day, per sky... but what are they?
Gamma-ray Bursts
Micro-quasars
Flare stars
Galactic
SETI
Pernicious RFI
Atmospheric effects
"Blitzars"
Magnetars
Pulsars
We are here
Credit: Jason Hessels

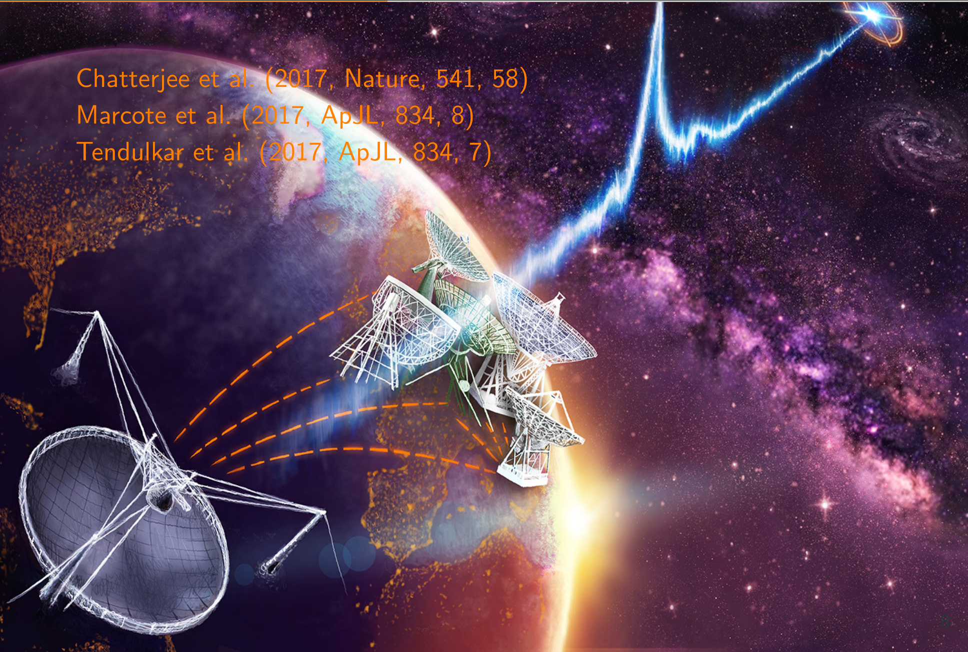
The only repeater, FRB 121102

The repeater FRB 121102

- The only one discovered by Arecibo (305-m diameter)
- The only repeater:
  Spitler et al. (2014, 2016),
  Scholz et al. (2016)
- In the Galactic anticenter
- No periodicities
  Active periods?
- One of the closest ones?
  DM $\sim$ 560 pc cm^{-3}
  ($\times$3 Galactic contribution)
- Two types of FRBs?

The First Precise Localization of a Fast Radio Burst

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



The precise localization of FRB 121102

Karl G. Jansky Very Large Array (VLA)

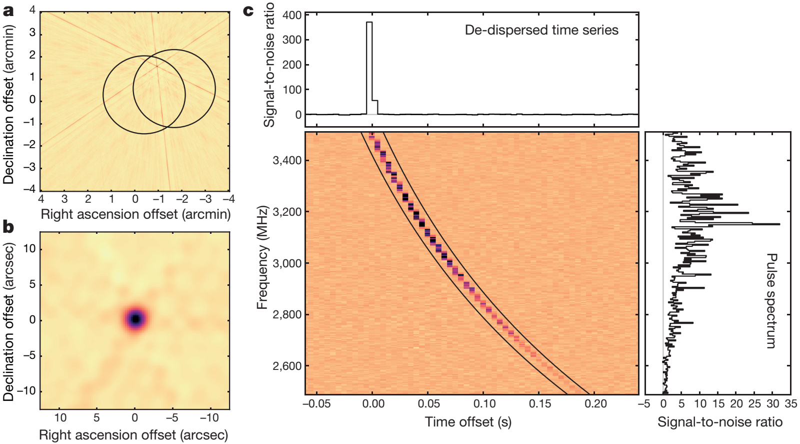
- 27 25-m dishes
- ∼100 km apart
- From Nov 2015 to Sep 2016
- 83 h at 1.6 and 3 GHz
- One burst on 23 Aug 2016
- 8 more in Sep 2016

Real-time correlation + raw data buffering to search for pulses

European VLBI Network (EVN)

- 6–10 stations (Europe, Asia, Africa)
- ∼10 000 km apart
- From Feb to Sep 2016
- 8 epochs at 1.6 and 5.0 GHz
- 4 bursts on 20 Sep 2016

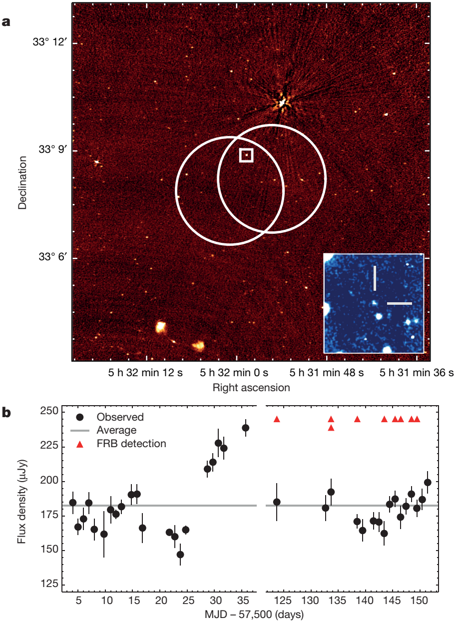
The VLA localization of FRB 121102



5-ms image (dispersion corrected) of one burst.

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

The VLA localization of FRB 121102



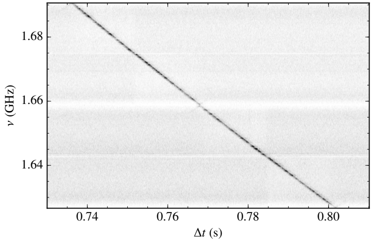
- Persistent radio and optical counterparts
- $z = 0.19273(8) \Longrightarrow 972$ Mpc
- Co-located within ~ 0.1 arcsec
- Variability $\sim 10\%$
- Variability uncorrelated with bursts
- $L_{\rm persistent} = 3 \times 10^{38}$ erg s^{-1}
- $L_{\rm bursts} \sim 10^{42}$ erg s^{-1}

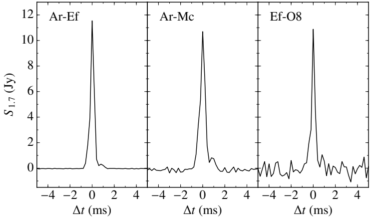
Chatterjee et al. (2017, Nature, 541, 58) but. . . are the bursts and the persistent counterpart physically related?

Localizing FRB 121102 on milliarcsecond scales

The EVN observations

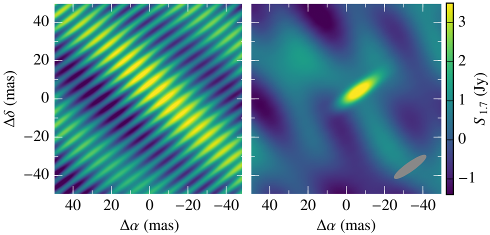
- 4 bursts on 20 Sep 2016
  - The brightest one: ∼4 Jy
  - The other three ∼ 0.2–0.5 Jy
- Arrival times obtained from Ar data
  - Bursts also detected in other EVN stations
  - Coherently de-dispersion
  - Correlation with higher time resolution around the pulses
  - Calibration from the continuum data
- Images of bursts and persistent source



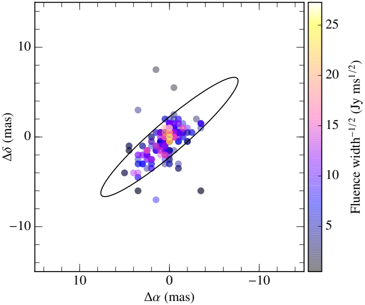


Marcote et al. (2017, ApJL, 834, 8)

Localizing FRB 121102 on milliarcsecond scales



Dirty and clean image from FRB 121102.



Astrometry limited by signal-to-noise ratio

Positions derived from 406 pulses from the pulsar B0525+21

Marcote et al. (2017, ApJL, 834, 8)

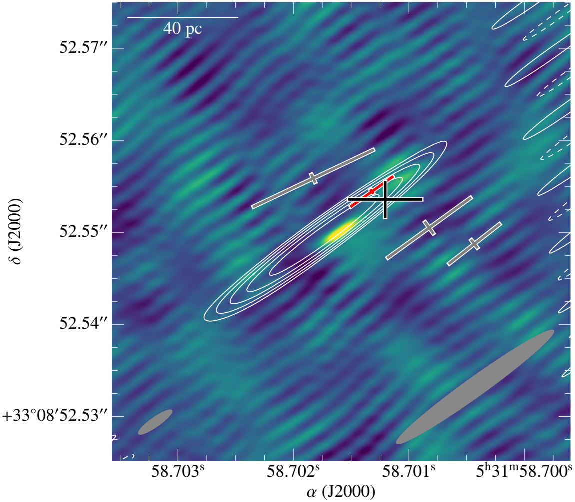
Localizing FRB 121102 on milliarcsecond scales

colorscale: 5-GHz image

Contours: 1.7-GHz image

(Bursts observed at 1.7 GHz)

+: brightest burst
+: other bursts
+: average position



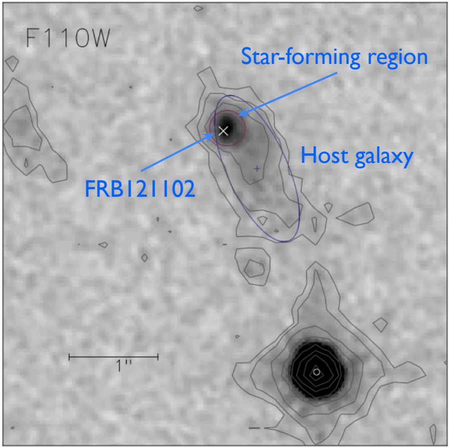
Marcote et al. (2017, ApJL, 834, 8)

Source size < 0.7 pc

Bursts coincident within 2σ:
< 40 pc at 95% C.L.

The optical counterpart

- Archival Keck data from 2014
- Gemini observation (Oct 2016)
- *HST* data in early 2017
- Extended 25-mag counterpart
- $z = 0.19273(8) \Longrightarrow 972$ Mpc
- **Dwarf galaxy**:
  Diameter: $\lesssim$ 5–7 kpc
  Mass: 10^8 $M_\odot$
  Star Formation: ~ 0.4 $M_\odot$ yr^{-1}
- **Low-metallicity star-forming region**:
  Diameter of ~ 1.3 kpc



Tendulkar et al. (2017, ApJL, 834, 7)
Bassa et al. (2017, ApJL, 843, 8)

Polarization and Faraday Rotation Measure

Observations at 5 GHz

Arecibo and Green Bank telescopes

Bursts $\sim 100\%$ linearly polarized

High Faraday rotation measure:
$\approx 1.4 \times 10^5$ rad m^{-2}

Michilli et al. (2018, Nature, 553, 182)

Discussion & Conclusions

Summary from FRB 121102

- FRB 121102 is associated with a compact source located in the star-forming region of a dwarf galaxy

- **Are FRBs located in dwarf galaxies?**
  Is FRB 121102 an exception?
  Are there more repeating FRBs?

- Localization of more FRBs is still needed, but this do not guarantee the unveiling of its nature

- Burst emission at other wavelengths?

- Still no clear scenario to explain FRB 121102...

Possible origins for FRB 121102

- **Young superluminous supernovae powered by the spin-down power of a neutron star or magnetar**
  (e.g. Murase et al., Piro et al. 2016)

- **Neutron star interacting with the jet of a massive black hole ($\sim 10^{5\text{–}6}$ M$_\odot$)**
  (Pen & Connor 2015, Cordes & Wasserman 2016, Zhang 2018)

- Bursts produced by a strong plasma turbulence excited by the jet of a massive black hole (Romero et al. 2016, Vieyro et al. 2017)

- Synchrotron maser activity? (Ghisellini 2017)

- ...

The future for Fast Radio Bursts

- **More precise localizations are required in this field**
- **Discoveries of new repeaters?**
- Several instruments with time dedicated to discover new FRBs: UTMOST, Apertif, CHIME, ASKAP,...
- Some of them will produce arcsecond localizations
- Detection of bursts on mas scales are required to pinpoint associated counterparts

Thank you!

RadioNet has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562.

Observations at other wavelengths

Bursts at other wavelengths:

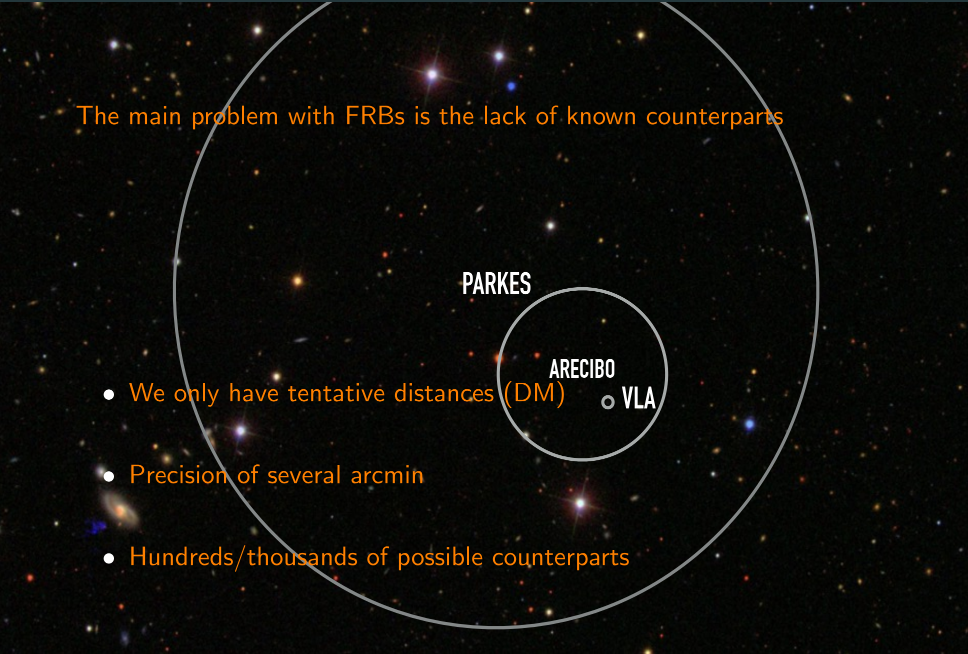
- Optical upper-limits on burst fluence of < 0.046 Jy ms (Hardy et al. 2017)
- Optical/TeV-radio observations with MAGIC: (MAGIC Coll. et al. 2018)
- X-ray observations: Scholz et al. (2017, ApJ, 846, 80)

Concerning the persistent counterpart:

- X-rays: $L < 3 \times 10^{41}$ erg s^{-1} Scholz et al. (2017, ApJ, 846, 80)
- GeV: No significant *Fermi*/LAT emission: $\lesssim 4 \times 10^{44}$ erg s^{-1}
- TeV: upper-limits from VERITAS and MAGIC (Bird et al. 2017, MAGIC Col. 2018) (Zhang & Zhang 2017)

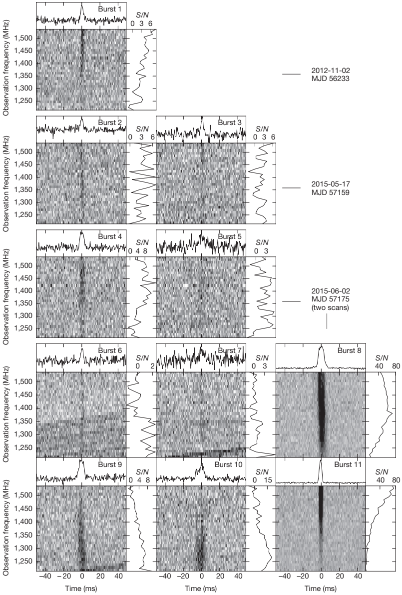
Next step: find counterparts (higher resolution)

The main problem with FRBs is the lack of known counterparts



- We only have tentative distances (DM)
- Precision of several arcmin
- Hundreds/thousands of possible counterparts

The repeater FRB 121102 (Spitler et al. 2016, Nature, 531, 202)



Next step: find counterparts

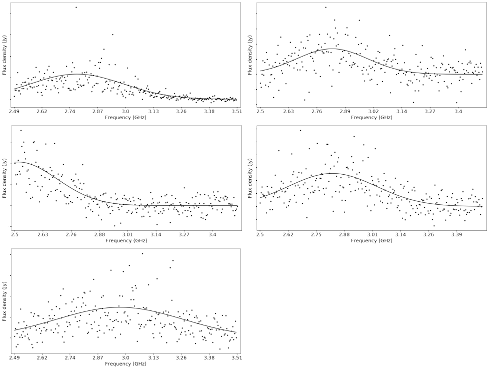
The main problem on FRBs is the lack of known counterparts

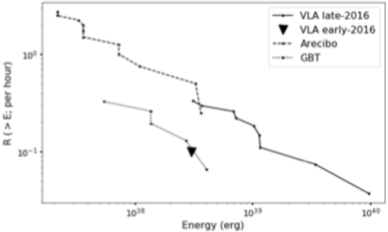
- We only have a tentative distance
- Precision of several arcmins
- Hundreds/thousands of possible counterparts

The repeater FRB 121102

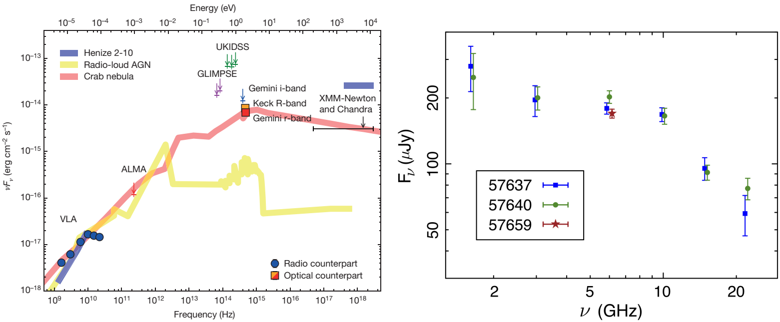
- The bursts seem to be localized in freq.
- Width of hundreds of MHz
- Rate vs E: power-law
- Different normalization depending on the “epoch”

Law et al. (2017, ApJ, 850, 76L)





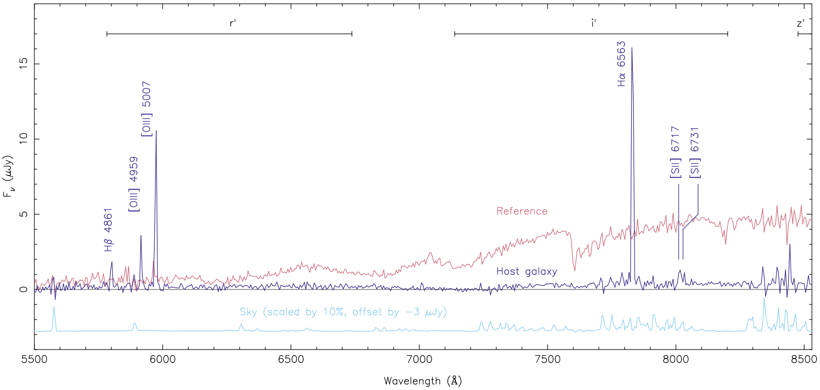
The VLA localization of FRB 121102



SED and radio spectrum of FRB 121102

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

The optical counterpart



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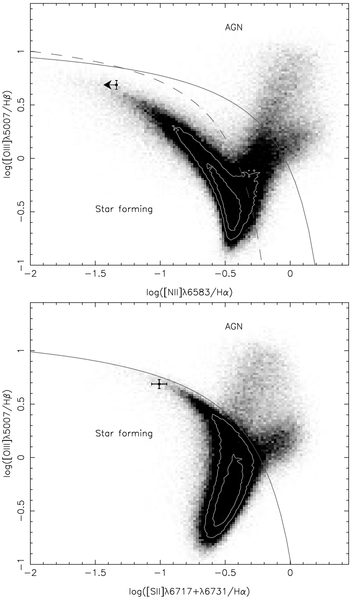


BPT diagrams

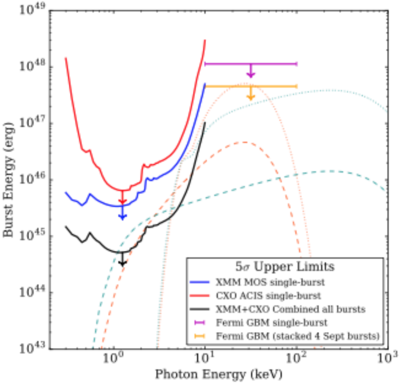
Emission lines dominated by Star Formation

No emission detected at:

- sub-mm (ALMA)
  rms of 17 μJy
- X-rays (*Chandra*, *XMM*)
  $< 5 \times 10^{41}$ erg s^{-1} (5σ)
- γ-rays (*Fermi*/LAT)

Simultaneous radio and X-ray observations

- 12 radio bursts observed
- No X-ray photons at those times
  $< 3 \times 10^{-11}$ erg cm^{-2}
  or $\sim 4 \times 10^{45}$ erg
- No X-ray bursts at all
  $< 5 \times 10^{-10}$ erg cm^{-2}
- No *Fermi*/GBT detections:
  $< 4 \times 10^{-9}$ erg cm^{-2}
- X-ray Persistent emission?
  $L < 3 \times 10^{41}$ erg s^{-1}



Scholz et al. (2017, ApJ, 846, 80)

The radio counterpart

- Bursts and persistent radio source coincident within 40 pc
- Compactness at 5 GHz $\Longrightarrow$ source $\lesssim 0.7$ pc
- No afterglows observed
- Extragalactic origin also supported by the EVN radio observations: Scintillation & scatter broadening
- Offset from the center of the host galaxy, within the star-forming region
- Brightness temperature $T_{\rm b} \gtrsim 5 \times 10^7$ K

Polarization and Faraday Rotation Measure

Observations at 5 GHz

Arecibo and Green Bank telescopes

Bursts $\sim$ 100% linearly polarized

High Faraday rotation measure:
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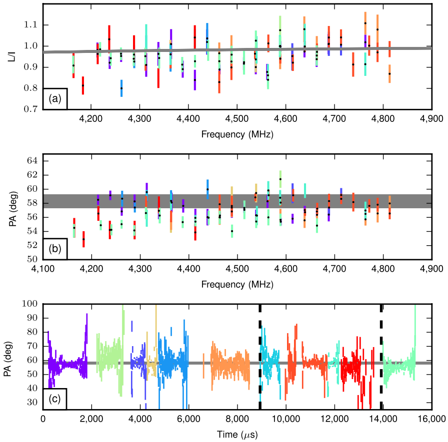
Michilli et al. (2018, Nature, 553, 182)



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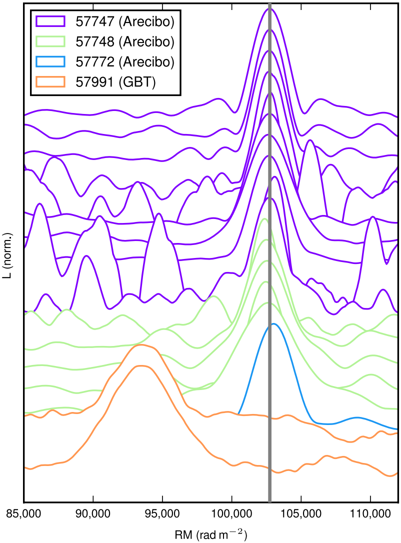
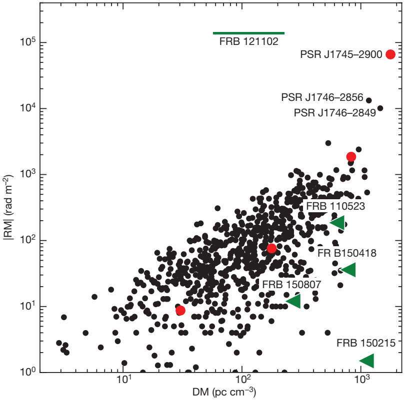


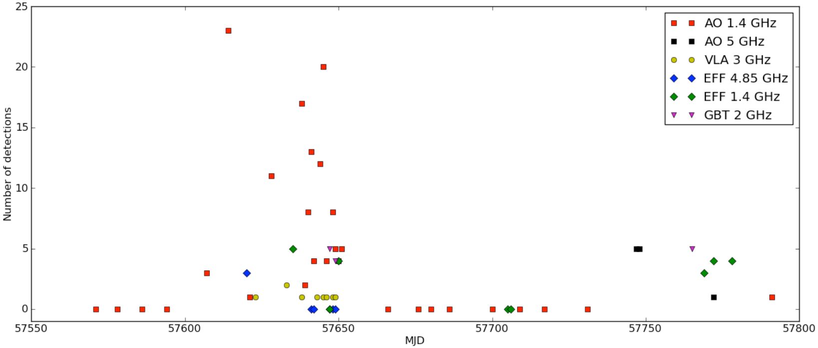


Michilli et al. (2018, Nature, 553, 182)

Possible origins for FRB 121102 (facts)

- The star-forming region in the dwarf galaxy resembles the hosts of long-duration gamma-ray bursts and hydrogen-poor superluminous supernovae
- The persistent source is more consistent with a low-luminosity massive black hole
- This high rotation measure has only been observed in pulsars/magnetars around Sgr A* (a 10^6-$M_\odot$ black hole)
- Structures observed in the bursts similar to other FRBs or the giant Crab flares

The repeating FRB 121102



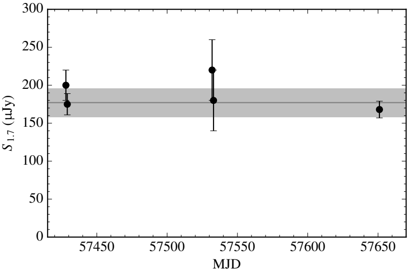
Credit: L. Spitler (preliminary data)

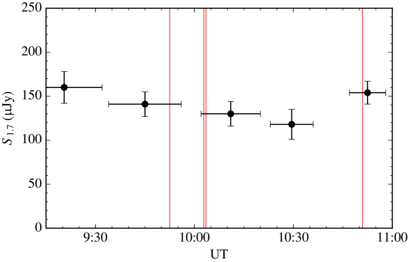
No periodicities are observed **at all**.

Bursts exhibit short bandwidths ($\sim$ 500 MHz)

Shortest separation between bursts: $\sim$ 34 and 37 ms

Localizing FRB 121102 on milliarcsecond scales





Marcote et al. (2017, ApJL, 834, 8)

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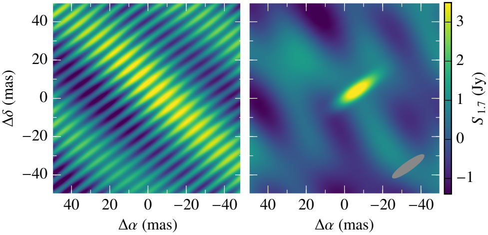
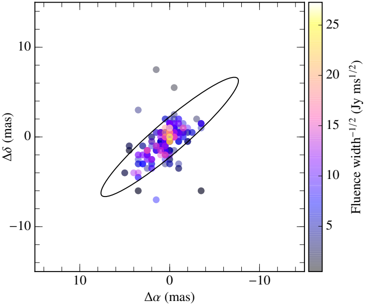


Dirty and clean image from FRB 121102.

Astrometry limited by signal-to-noise ratio



Positions derived from 406 pulses from the pulsar B0525+21

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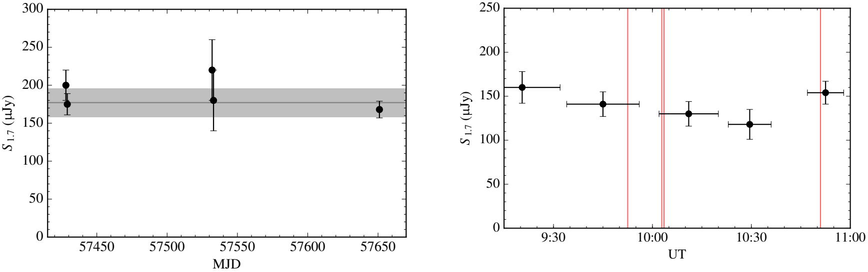
Localizing FRB 121102 on milliarcsecond scales



Marcote et al. (2017, ApJL, 834, 8)

Other possible repeaters?

FRB 110220 and FRB 140514 were detected within 9 arcmin and 3-yr apart.

- FRB 110220. DM $= 944.4$ pc cm^{-3} (Thornton et al. 2013)
- FRB 140514. DM $= 562.7$ pc cm^{-3} (Petroff et al. 2015)

Probability of chance coincidence: 1–32%

Possible explanations: DM dominated by SNR (young and expanding) (Piro & Burke-Spolaor 2017)

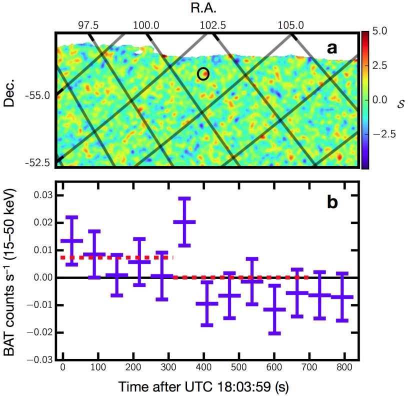
FRB 131104 also observed at X-rays ("gamma")?

Swift detected a 100-s transient coincident with FRB 131104 (DeLaunay et al. 2016)

- 15–200 keV
- $E \sim 5 \times 10^{51}$ erg

However,

- 3-σ detection
- Change coincidence subestimated (Shannon & Ravi 2017)
- Would point out to a much different (and close) distance (Gal & Zhang 2017)



FRB 150418: The first announced association

Keane et al. (2016, Nature, 530, 453)

Parkes detection
ATCA follow-up 2-hr later.

Association with a transient source
Early-type galaxy at $z \sim 0.5$

. . . or just an unassociated AGN?
Williams & Berger (2016)
Vedanthan et al. (2016)
Giroletti et al. (2016)
Bassa et al. (2016)