Localizing a Fast Radio Burst for the first time

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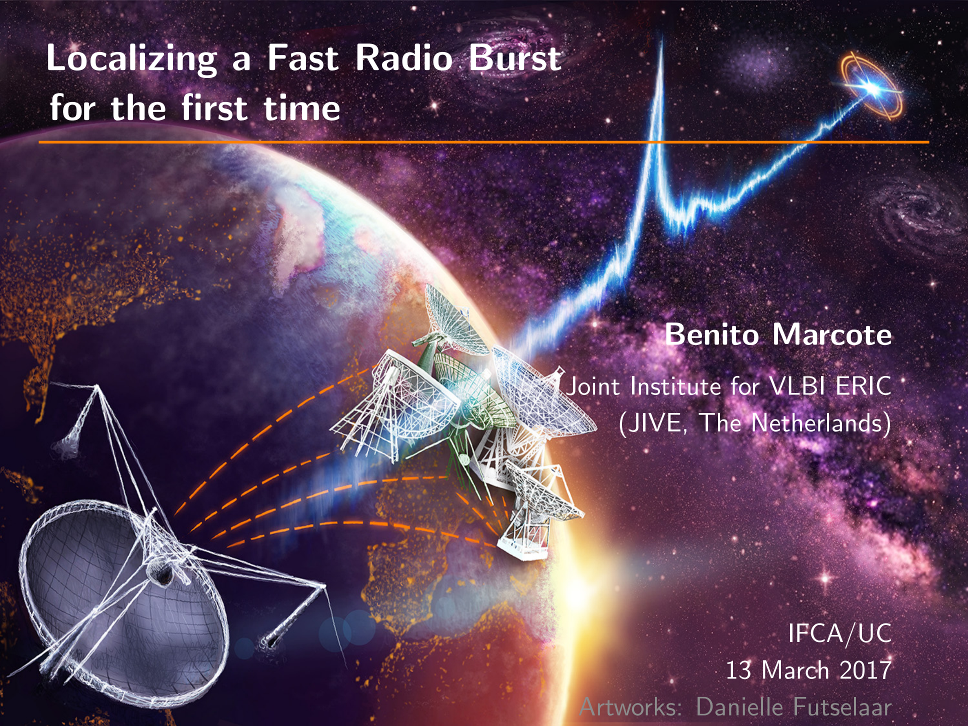
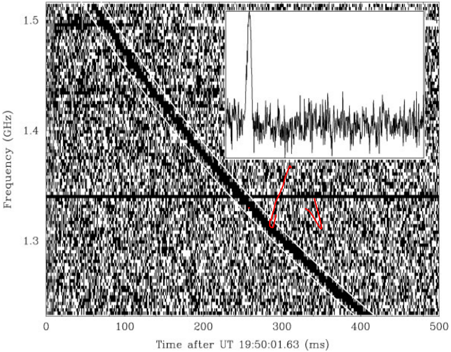
Artworks: Danielle Futselaar



Introduction

Introduction: What is a Fast Radio Burst?

- **Fast and strong radio flashes**
- Duration of a few milliseconds
- Detected at $\sim$ 1 GHz
- Bright: $\sim$ 0.1–1 Jy
- Discovered by Lorimer et al. (2007)
- Origin: completely unknown
- All possibilities are still open during these 10 yr



Lorimer et al. (2007)

The known Fast Radio Bursts

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

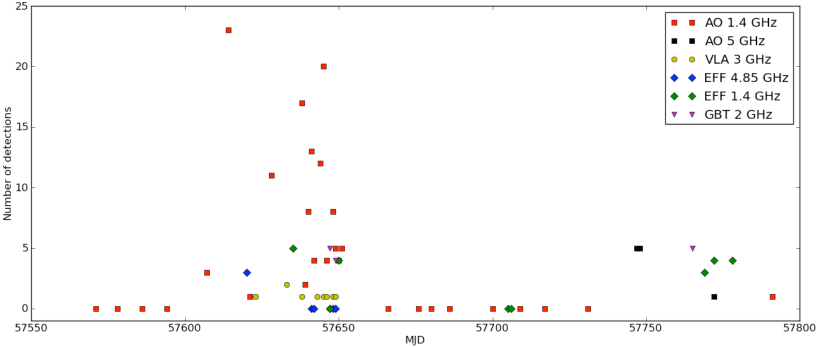
Petroff et al. (2016)

- 18 FRBs have been reported to date Petroff et al. (2016)
- Plus 6 detected in 2016/17
- No correlation with the Galactic plane
- Almost all of them detected by Parkes
- 1 by Green Bank
- 1 by Arecibo
- Rate: $\sim 10^4$ day^{-1} sky^{-1}

The repeating FRB 121102

- The only one observed by Arecibo (305-m diameter)
- The only one detected more than once: Spitler et al. (2014, 2016), Scholz et al. (2016)
- In the Galactic anticenter
- One of the closest ones?
- Is it like a strange pulsar? Two types of FRBs?

FRB 121102, optical emission



Credit: L. Spitler

The Dispersion Measure

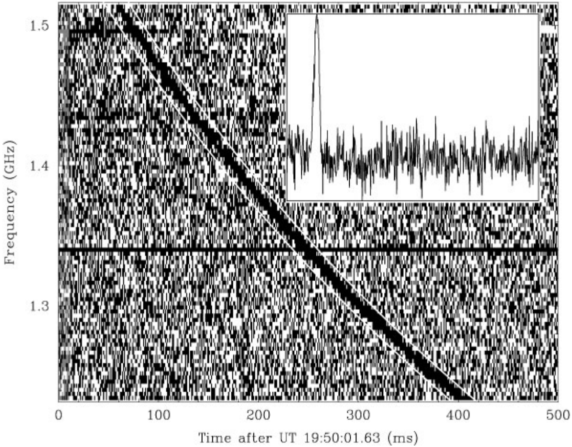
Light is dispersed by the material in the medium.

Dispersion Measure:

$$\mathrm{DM} = \int n_e \mathrm{d}l$$

All FRBs show unexpected large DMs.

Larger than the contribution of our Galaxy



Lorimer et al. (2007)

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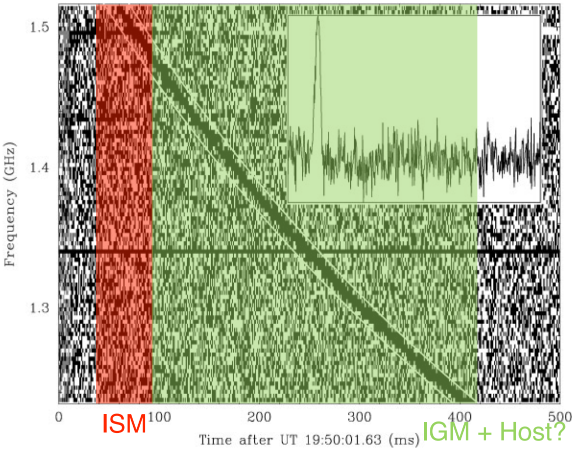
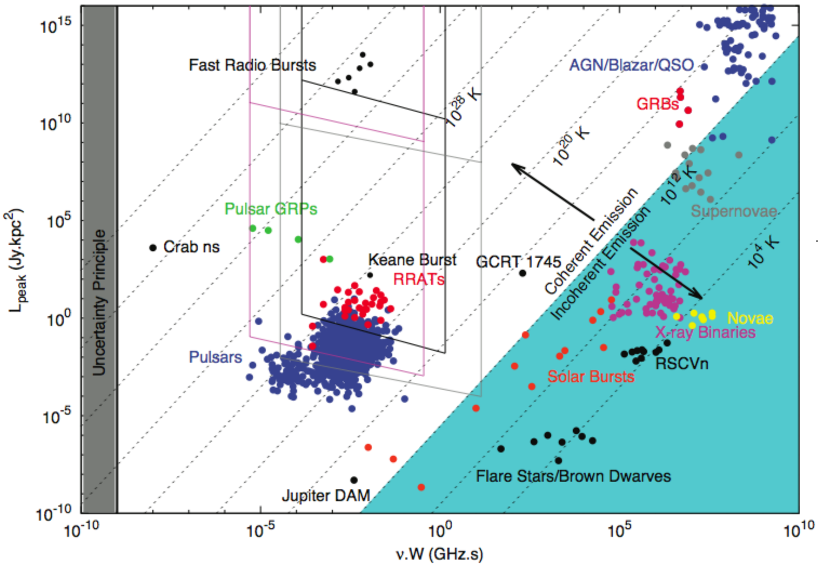


Lorimer et al. (2007)

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

The fundamental problem: poor localization

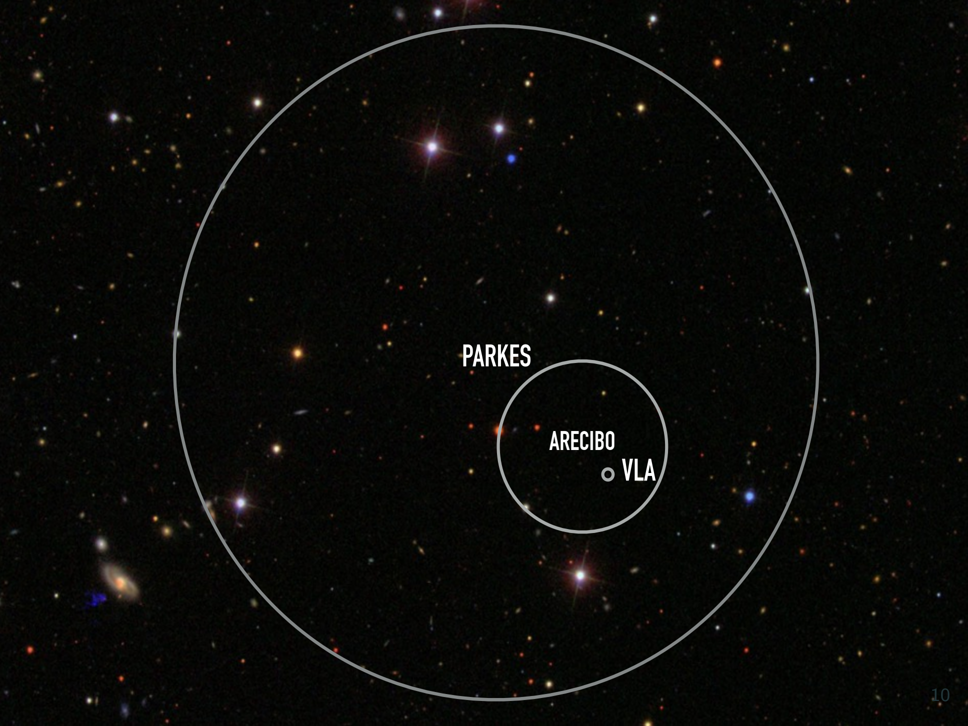
Discovered by single-dish ratio telescopes:

- 64-m Parkes
- 305-m Arecibo
- 100-m Green Bank

Resolution of $\sim$arcmin

More resolution required to identify counterparts:

Interferometric observations


PARKES
ARECIBO
VLA

Localizing Fast Radio Bursts

How can we localize Fast Radio Bursts?

Direct detection.

The only unambiguous approach.
High resolution $\Longrightarrow$ limited field of view
Requires imaging on ms scales
Extremely challenging (technically and operationally)

Looking for afterglows.

When a FRB occurs, look at the field with higher resolution telescopes.
If they are cataclysmic $\Longrightarrow$ should be an afterglow
Can produce spurious identifications

FRB 150418: The first announced association

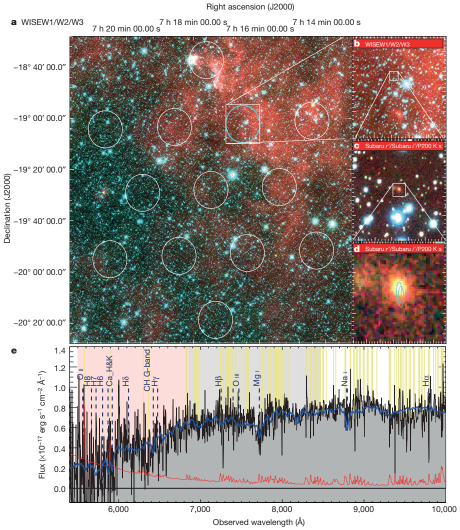
FRB detected by Parkes
on 18 Apr 2015

ATCA follow-up 2-hr later.

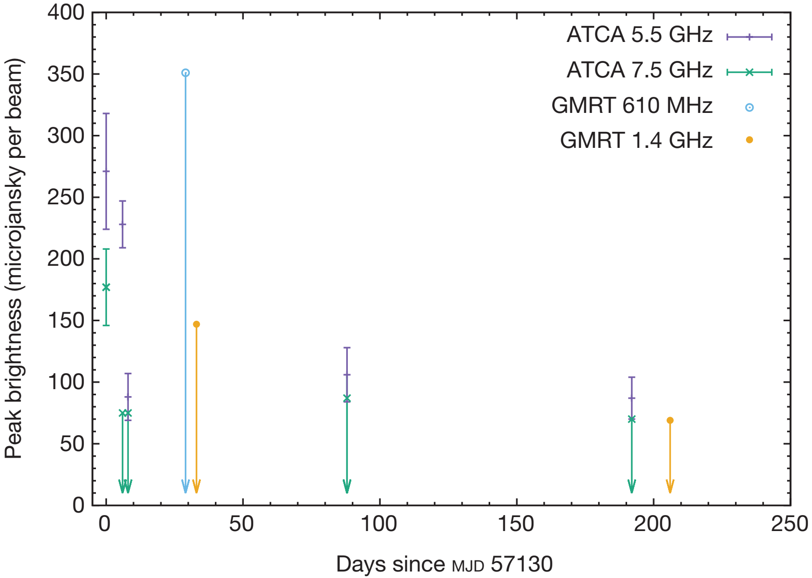
Two variable sources:
- A already known one
- 6-d non-thermal transient

Optical counterpart:
early-type galaxy at $z \sim 0.5$
WISE J0716−1900

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



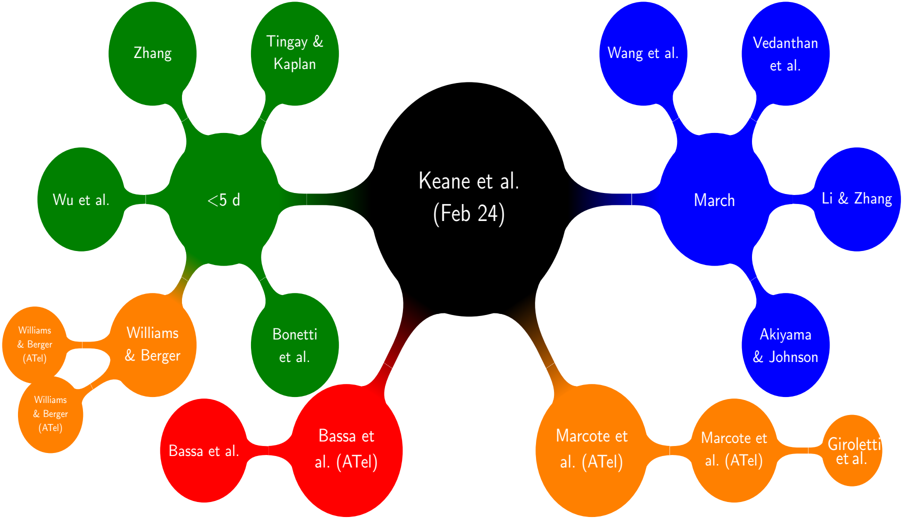
FRB 150418: The first announced association



Keane et al. (2016)

FRB 150418: Publications after Keane et al. (2016)

6 publications in arXiv in less than 7 days (∼15 within 2 months).



FRB 150418: Publications after Keane et al. (2016)

Zhang (2016): Afterglow $\Rightarrow \sim 10^{50}$ erg (like short duration GRB).
Mergers of BH-BH, NS-NS, or BH-NS (similar to GW 150914).

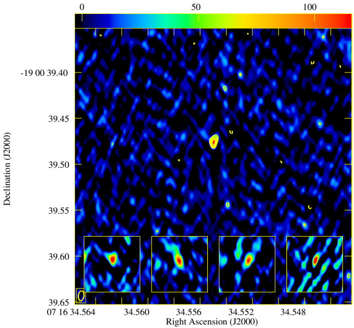
Williams & Berger (2016): WISE J0716−1900 exhibits a similar variability one year after the FRB in VLA data.
Scintillating steady AGN!
Probability of spurious transient not negligible.

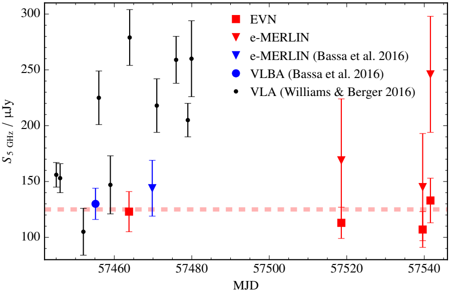
Vedanthan et al. (2016): ATCA and optical observations
Source consistent with an AGN.

Marcote et al. (2016a,b);Giroletti et al. (2016): EVN obs. Consistent with a scintillating low-luminosity AGN

Bassa et al. (2016a,b): e-MERLIN, VLBA, ATCA, and optical. Persistent radio source in the center of the optical galaxy: consistent with a weak radio AGN.

FRB 150418: The first announced association





Giroletti et al. (2016, A&A, 593, L16)

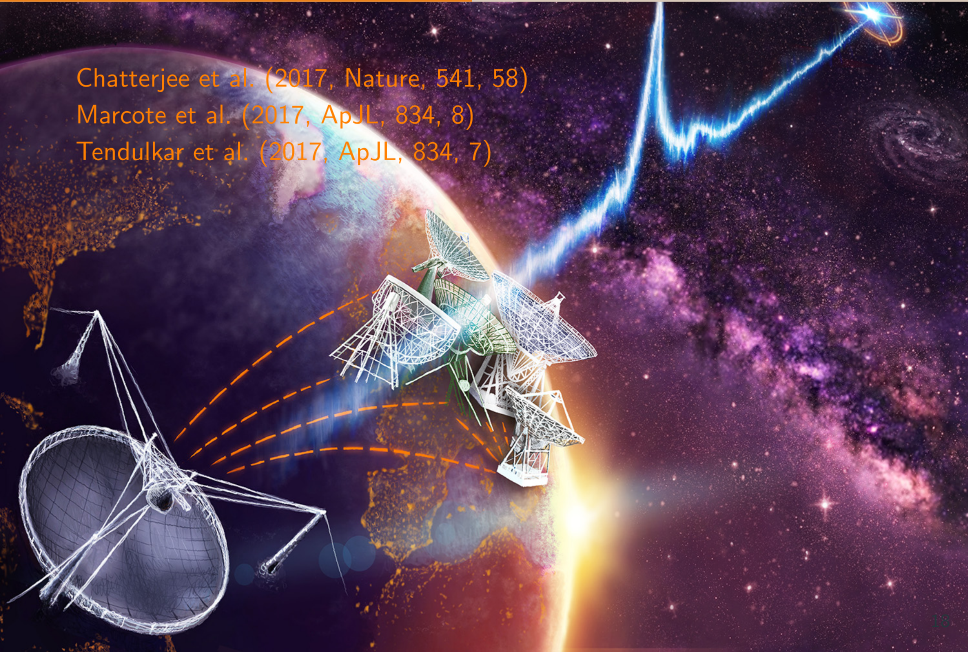
Localizing FRB 121102

FRB 121102: We have a repeater!

- The only FRB discovered by Arecibo (305-m)
  Position with an uncertainty of $\sim$ arcmin
- **It is the only known repeating FRB**
  (Spitler et al. 2014,2016; Scholz et al. 2016)
- DM $\sim 560\ \mathrm{pc\ cm^{-3}}$ ($\times$3 Galactic contribution)
- "standard" pulsar or same as other FRBs? Two types of FRBs?
- Why it is the only repeater? Maybe it is much simpler:
  one of the closest FRBs & Arecibo ($\times$10 more sensitive)

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 last crusade: the localization of FRB 121102

Karl G. 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

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

Real-time correlation + raw data buffering to search for pulses
(techniques developed just during the last years)

The last crusade: the localization of FRB 121102

Karl G. Very Large Array (VLA)

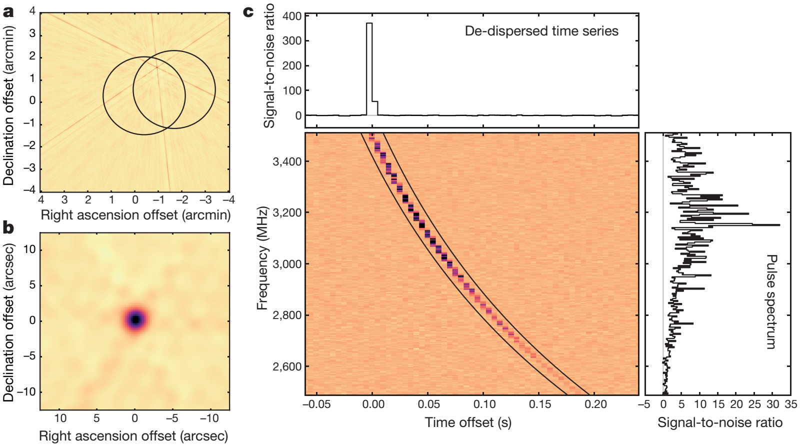
- 27 25-m dishes
- ∼100 km apart
- From Nov 2015 to Sep 2016
- 83 h at 1.6 and 3 GHz
- One burst on 23 Aug 2016
- 8 more in Sep 2016

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

Real-time correlation + raw data buffering to search for pulses (techniques developed just during the last years)

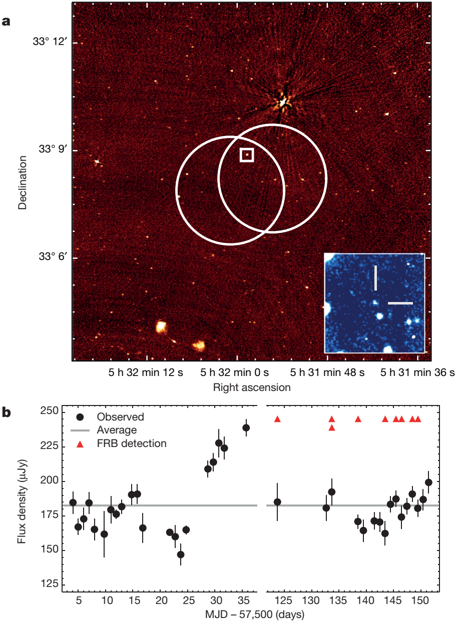
The VLA localization of FRB 121102



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

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

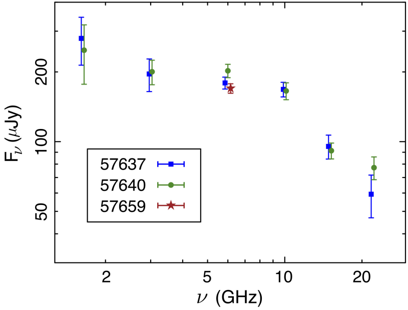
The VLA localization of FRB 121102



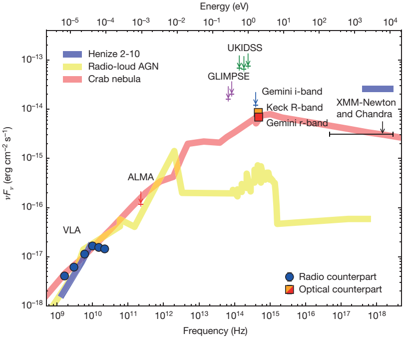
- Persistent radio counterpart
- Co-located within ~ 0.1 arcsec
- $\langle S_{3\ \mathrm{GHz}} \rangle \sim 180\ \mu\mathrm{Jy}$
- Variability $\sim 10\%$
- Variability uncorrelated with the bursts

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

The VLA localization of FRB 121102



Spectrum of FRB 121102

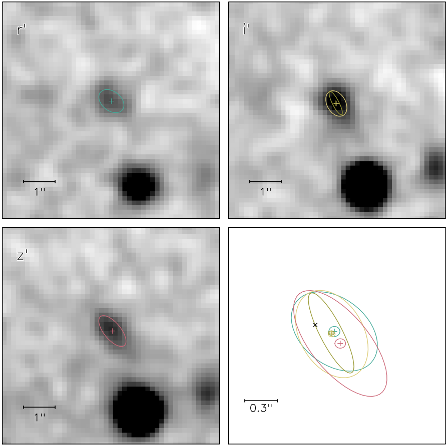


SED of FRB 121102

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

The optical counterpart

- Archival Keck data from 2014
- Gemini observation (Oct 2016)
- Extended 25-mag counterpart
- $z = 0.19273(8) \Longrightarrow$ 972 Mpc
  Extragalactic!
- Emission lines
  $\Rightarrow$ low-metallicity star-formation
- Dwarf galaxy!
  Diameter: $\lesssim$ 4 kpc
  Mass: 4–7$\times 10^7$ $\mathrm{M}_\odot$
  Star Formation: $\sim$ 0.4 $\mathrm{M}_\odot$ yr^{-1}



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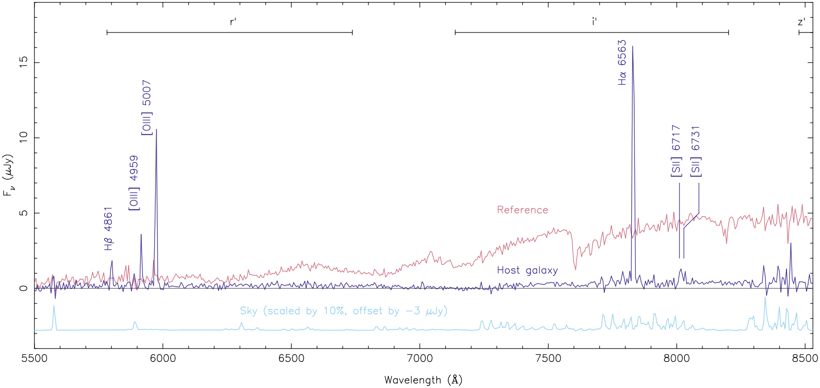
FRB 121102, optical emission



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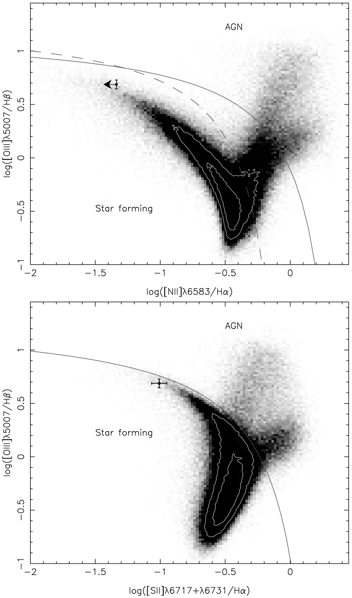


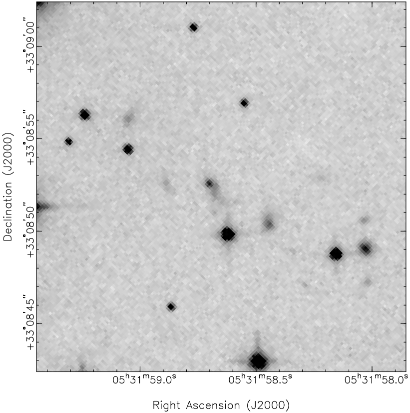
Emission lines dominated by SF

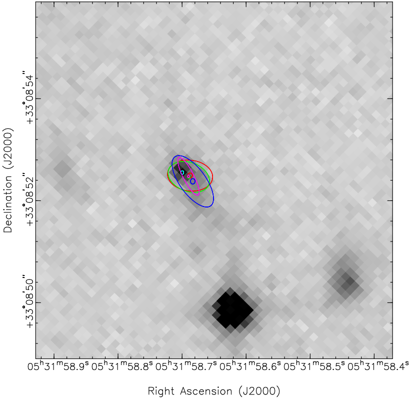
No emission detected at:

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

FRB 121102, optical emission

Preliminary *HST* data!





but. . . are the FRBs and the persistent counterparts physically related?

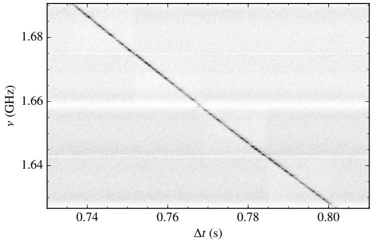
EUROPEAN vlbi NETWORK

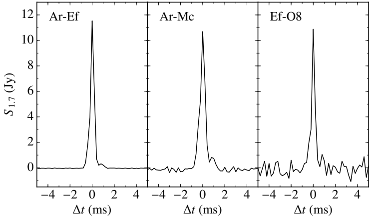
JOINT INSTITUTE FOR VLBI IN EUROPE

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





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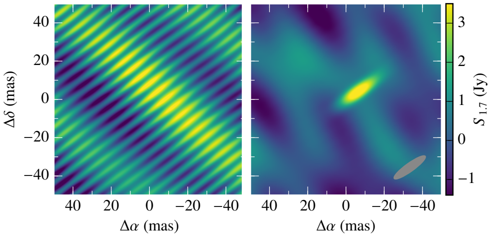
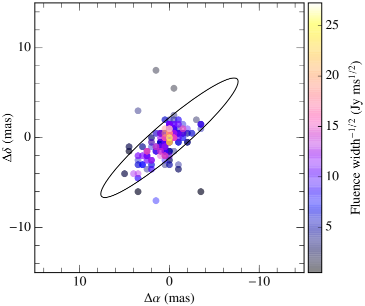
Localizing FRB 121102 on milliarcsecond scales



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 EVN imag

Contours: 1.7-GHz image

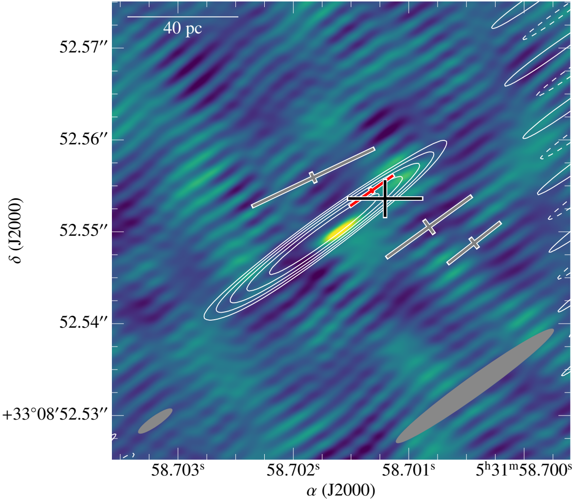
(Bursts observed at 1.7 GHz)

Red cross: brightest burst

Gray cross: other bursts

Black cross: average burst position. Weighted by $\xi = F \cdot w^{-1/2}$

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



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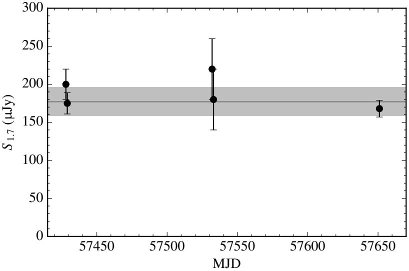

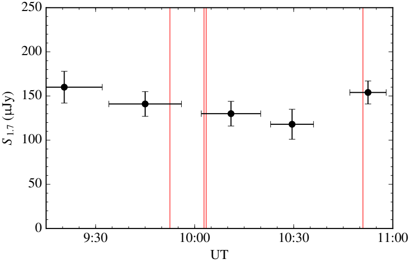

Marcote et al. (2017, ApJL, 834, 8)

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
- Luminosity $L_{5.0} \approx 7 \times 10^{38}\ \mathrm{erg\ s^{-1}}$
- Brightness temperature $T_{\mathrm{b}} \gtrsim 5 \times 10^{7}$ K
- X-ray upper-limit: $3 \times 10^{41}\ \mathrm{erg\ s^{-1}}$ (5σ)
  No X-ray bursts during radio ones (Scholz et al. in prep.)
- Ratio between X-ray and radio emission: $R_X > -2.4$

Possible origins for FRB 121102

- What it is not:
  - A standard pulsar / RRAT / flare star / . . .
  - Supernova remnant, as Cas A (at least 4 orders of magnitude fainter)
  - Compact star-forming regions, as Arp 220 (similar luminosity but would need a much larger region and SFR)
  - IMBH, X-ray binary, ultraluminous X-ray nebula, . . .

Possible origins for FRB 121102

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  - IMBH, X-ray binary, ultraluminous X-ray nebula, ...
- What it could be:
  - Young superluminous supernovae powered by the spin-down power of a neutron star or magnetar (e.g. Murase et al., Piro et al. 2016)
  - Bursts produced by a strong plasma turbulence excited by the jet of a massive black hole (Romero et al. 2016, Vieyro et al. submitted)
  - Neutron star interacting with the jet of a massive black hole (Pen & Connor 2015, Cordes & Wasserman 2016, Zhang 2017)
  - Synchrotron maser activity from an AGN? (Ghisellini 2017)
  - Possibly new suggestions coming!

Possible origins for FRB 121102

Based on SLSN + pulsar

- 10–100 yr old
- Bursts
- SF in dwarf galaxies
- Persistent source
- Luminosity
- Variability

Based on AGNs

- $\sim 10^5$–10^6 $M_\odot$
- Radio persistent source
- Radio luminosity
- AGN emission lines?
- offset AGN in dwarf galaxy?
- Burst production?

Possible origins for FRB 121102

Persistent source:

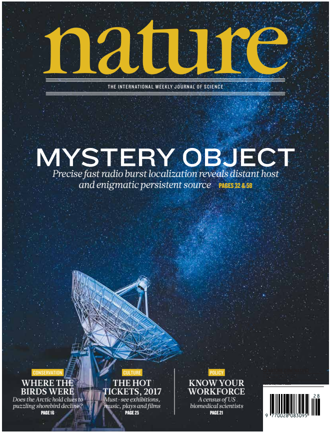
- $L_{\mathrm{5GHz}} \sim 7 \times 10^{38}$ erg s^{-1}
- $L_{\mathrm{1.6GHz}} \sim 3 \times 10^{38}$ erg s^{-1}
- $L_{\mathrm{4.5\mu m}} \lesssim 1.8 \times 10^{40}$ erg s^{-1}
- $L_{\mathrm{3.6\mu m}} \lesssim 2 \times 10^{40}$ erg s^{-1}
- $L_{\mathrm{0.5-10keV}} \lesssim 10^{40}$ erg s^{-1}

- $R_{\mathrm{X}} \gtrsim -2.4$
- $S_{\mathrm{3.6\mu m}} - S_{\mathrm{4.5\mu m}} = 0.24\ \mathrm{\mu Jy}$

Conclusions

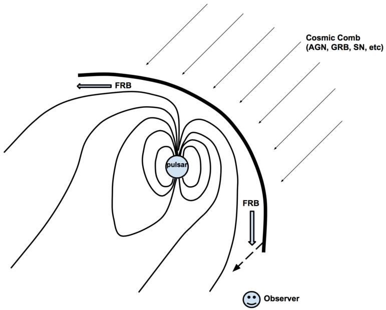
Conclusions

- FRB 121102 is extragalactic
- Common scenarios do no explain what we observe
- Are FRBs located in dwarf galaxies?
  Is FRB 121102 the exception?
- Localization of more FRBs is still needed
- Coming soon: many observations
  from radio to TeV. . .

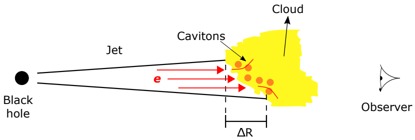


Thank you!

AGN models I



Zhang (2017)



Vieyro et al. (2017)