Localizing a Fast Radio Burst for the first time

Benito Marcote

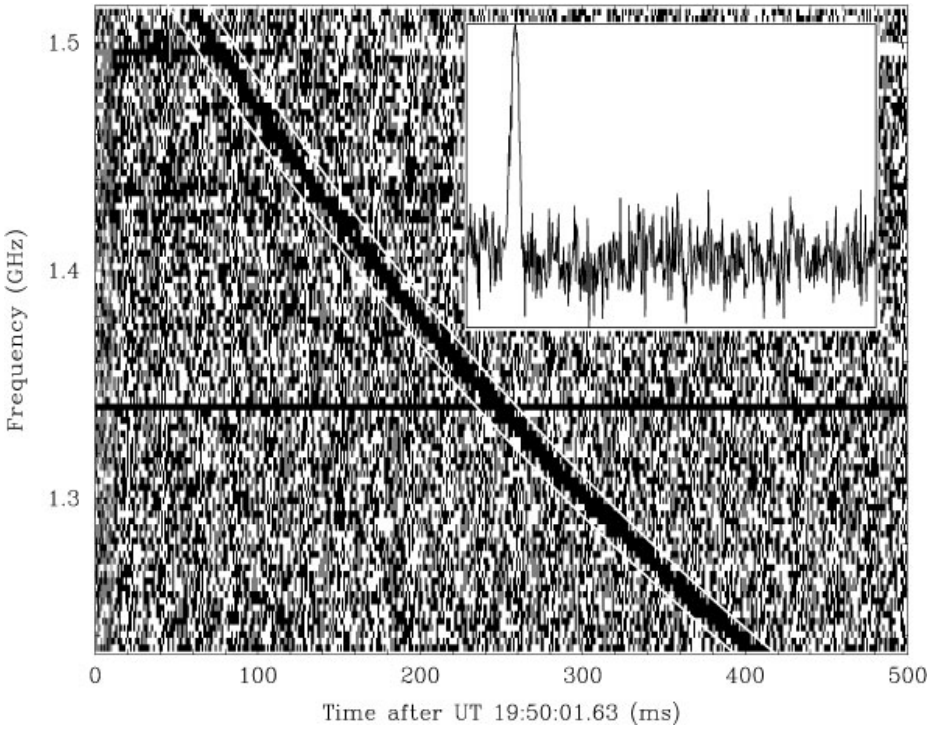
Joint Institute for VLBI ERIC
(JIVE, The Netherlands)

ICC Winter Meeting
6 February 2017

Artworks: Danielle Futselaar

Introduction: What is a Fast Radio Burst?

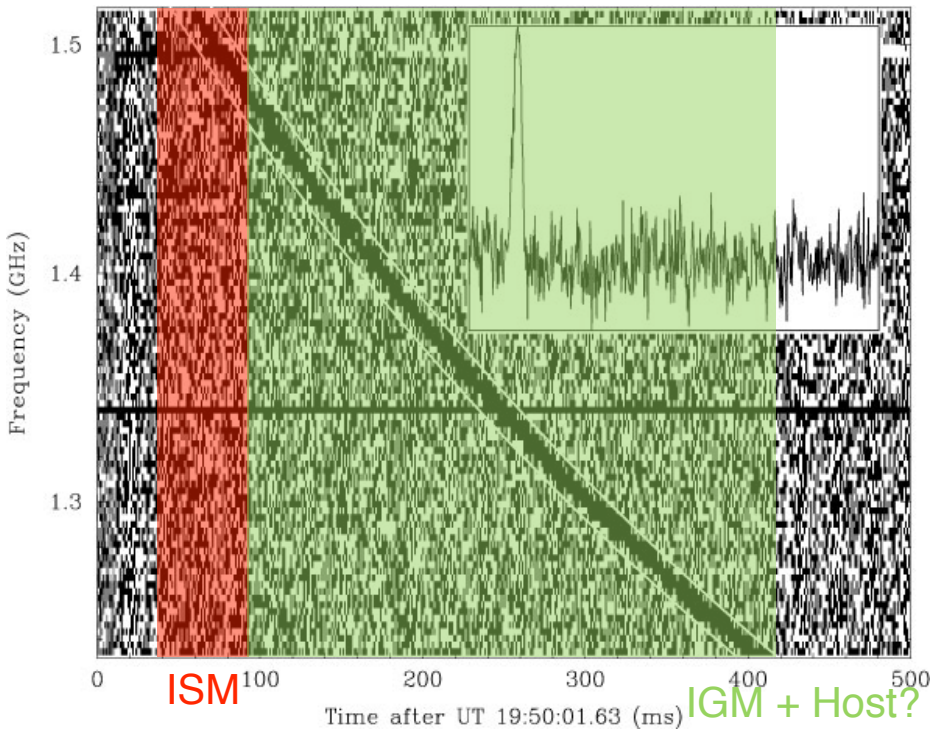
- **Fast and strong radio flashes**
- Duration of a few milliseconds
- Bright: $\sim$0.1–1 Jy
- Discovered by Lorimer et al. (2007)
- 18 known to date
- Origin: completely unknown
- All possibilities were still open during these 10 yr
- Dispersion mesure (DM) consistent with extragalactic origin



Lorimer et al. (2007)

Introduction: What is a Fast Radio Burst?

- **Fast and strong radio flashes**
- Duration of a few milliseconds
- Bright: $\sim$0.1–1 Jy
- Discovered by Lorimer et al. (2007)
- 18 known to date
- Origin: completely unknown
- All possibilities were still open during these 10 yr
- Dispersion mesure (DM) consistent with extragalactic origin



Lorimer et al. (2007)

Introduction: Possible origins of Fast Radio Bursts

From the Earth?

- Perytons?
  Microwaves, aircrafts, ...
- Excluded several years ago

From our Galaxy?

- Pulsars
- Flaring stars
- ...
- Cannot explain DM
- Highly repeatable
- Ultra dense clouds?

Extragalactic?

- Cataclysmic events
- gamma-ray bursts
- AGN-related
- ...
- Extremely intense!
- Rates don't match GRBs

The Big Problem: we only know their positions with ∼arcmin precision

We do need a precise localization to search for counterparts!

Introduction: How do we observe a Fast Radio Burst?

- All of them (18) discovered by single-dish radio telescopes:

  16 by the 64-m Parkes
  1 by the 305-m Arecibo
  1 by the 100-m Green Bank

- Poor resolution ($\sim$arcmin)

  Many sources consistent with that position!

- A precise localization is needed to determine the nature of FRBs: Interferometric observations

Parkes Telescope (Australia)

Introduction: 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.

After a FRB occurs, search the field with higher resolution telescopes.

If they are cataclysmic $\Longrightarrow$ should be an afterglow

Keane et al. (2016) $\rightsquigarrow$ unclear!

Williams & Berger; Giroletti et al.; Bassa et al.; Vedanthan et al. (2016)

FRB 121102: We have a repeater!

- The only FRB discovered by Arecibo (305-m)
- **It is the only known repeating FRB**
  (Spitler et al. 2014,2016; Scholz et al. 2016)
- Located towards the Galactic anticenter
- DM ~ 560 $\mathrm{pc\ cm^{-3}}$ ($\times 3$ Galactic contribution)
- Probably one of the closest ones?
- "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 last crusade: the localization of FRB 121102

From the bursts detected by Arecibo: position $\sim$ arcmin

The Very Large Array (VLA)

- 27 25-m dishes
- $\sim$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

The European VLBI Network (EVN)

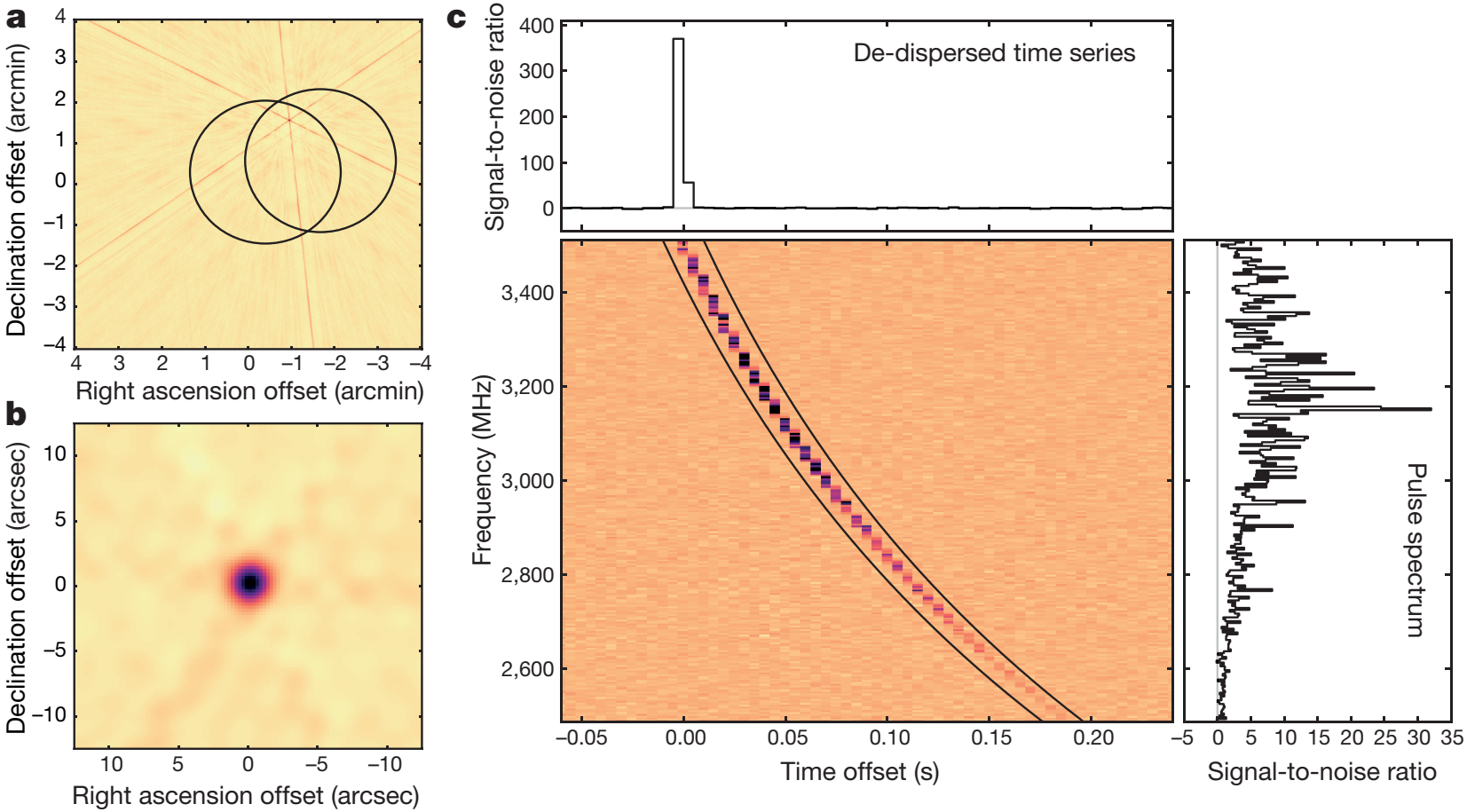
- 6–10 stations (EU, Asia, Africa)
- $\sim$10 000 km apart
- From Feb to Sep 2016
- 8 epochs at 1.6 and 5.0 GHz
- Bursts on 20 Sep 2016

Arecibo joined the observations in all cases

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

(techniques developed just during the last years)

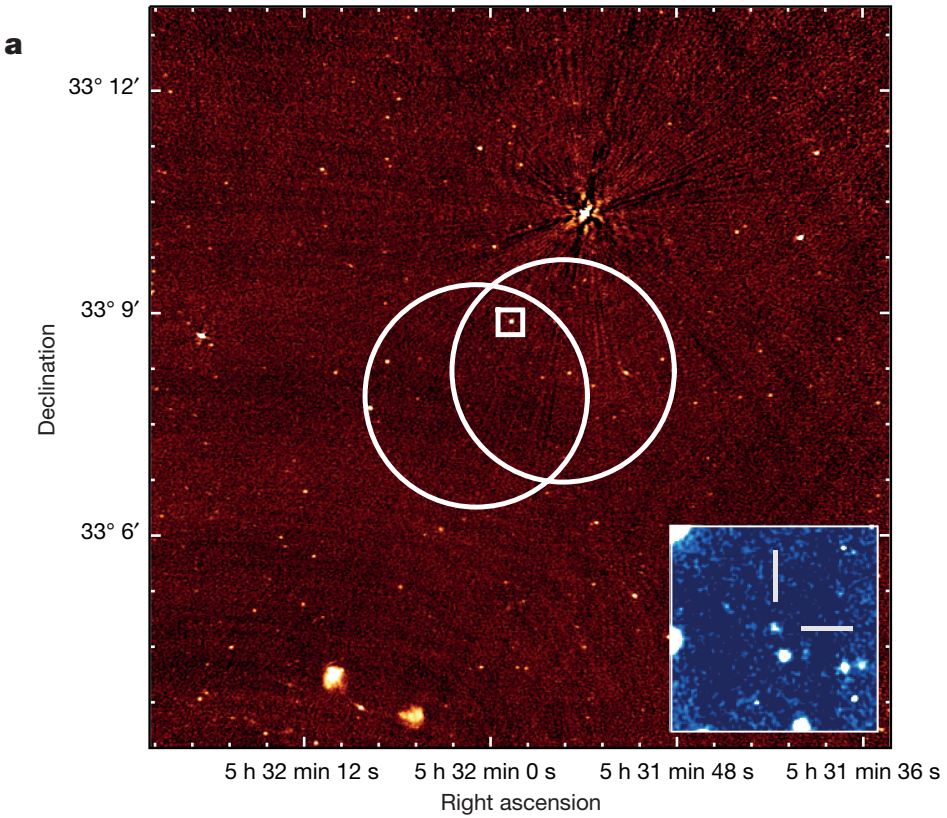
The first localization of FRB 121102

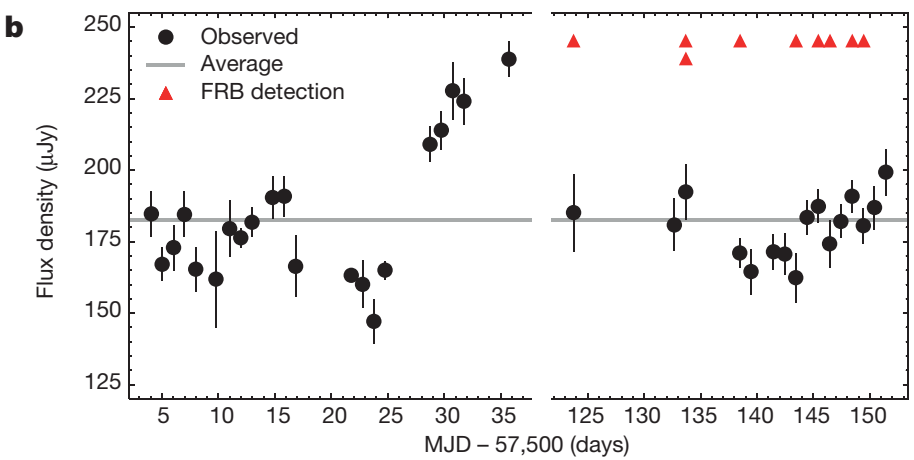


5-ms image (dispersion corrected) of one burst.

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

The first localization of FRB 121102



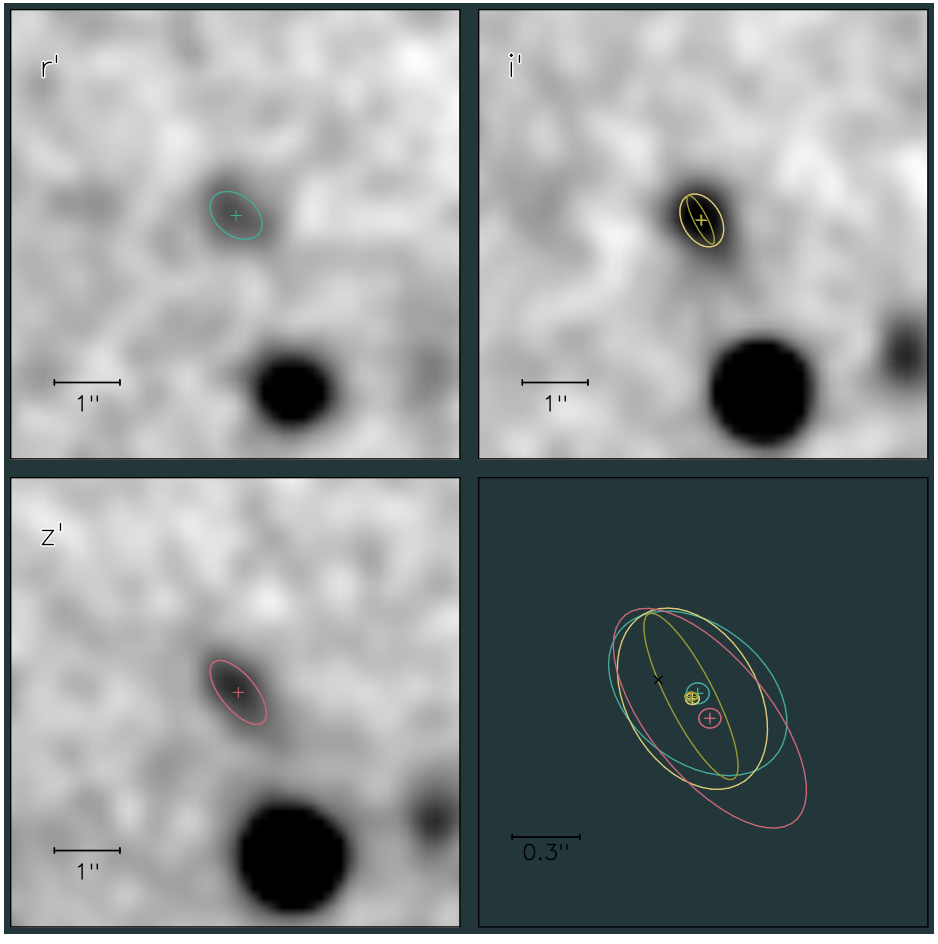


- Persistent radio counterpart
- Co-located within ~ 0.1 arcsec
- $\langle S_{3\ \mathrm{GHz}} \rangle \sim 180\ \mu\mathrm{Jy}$
- Variability $\sim 10\%$
- Variability uncorrelated with the bursts

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

The optical counterpart

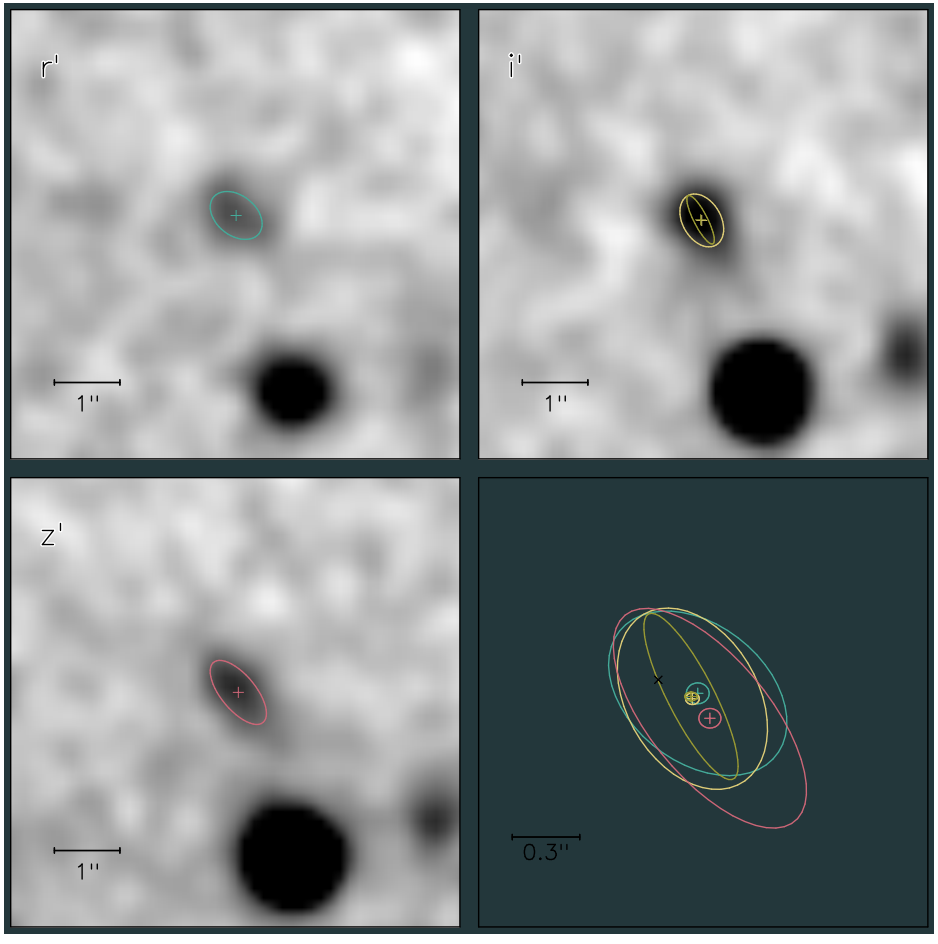
- Archival Keck data from 2014
- Gemini observation (Oct 2016)
- Extended 25-mag counterpart
- $z = 0.19273(8) \Longrightarrow 972$ Mpc
  Extragalactic!
- Emission lines
  $\Rightarrow$ low-metallicity star-formation
- Dwarf galaxy!
  Diameter: $\lesssim 4$ kpc
  Mass: 4–7$\times 10^7$ $\mathrm{M}_\odot$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



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

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: ~ 0.4 $\mathrm{M}_\odot$ yr^{-1}



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

But. . . are both physically linked?

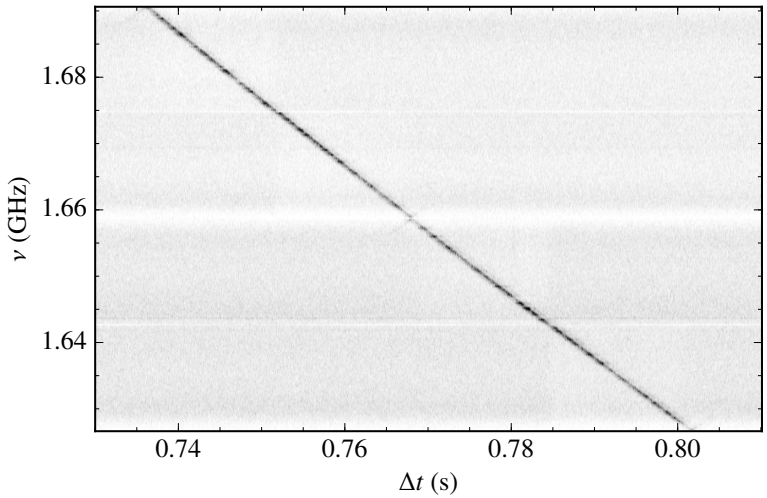
Localizing FRB 121102 on milliarcsecond scales

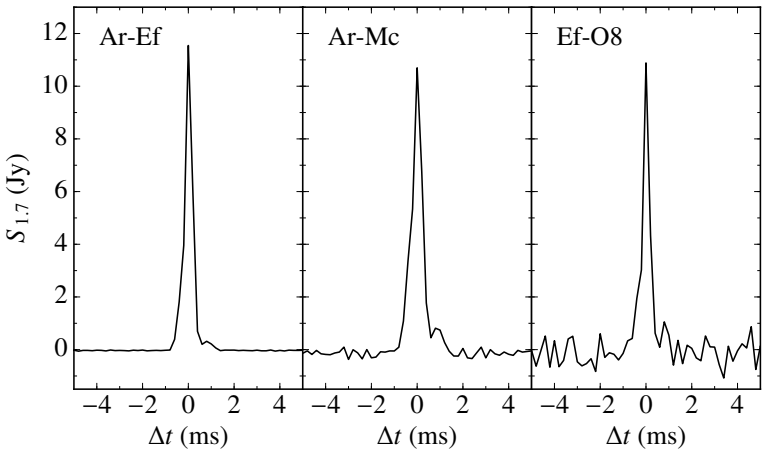
The EVN observations

- 4 bursts on 20 Sep 2016
  - The brightest one: $\sim$4 Jy
  - The other three $\sim$ 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

colorscale: 5-GHz EVN imag

Contours: 1.7-GHz image

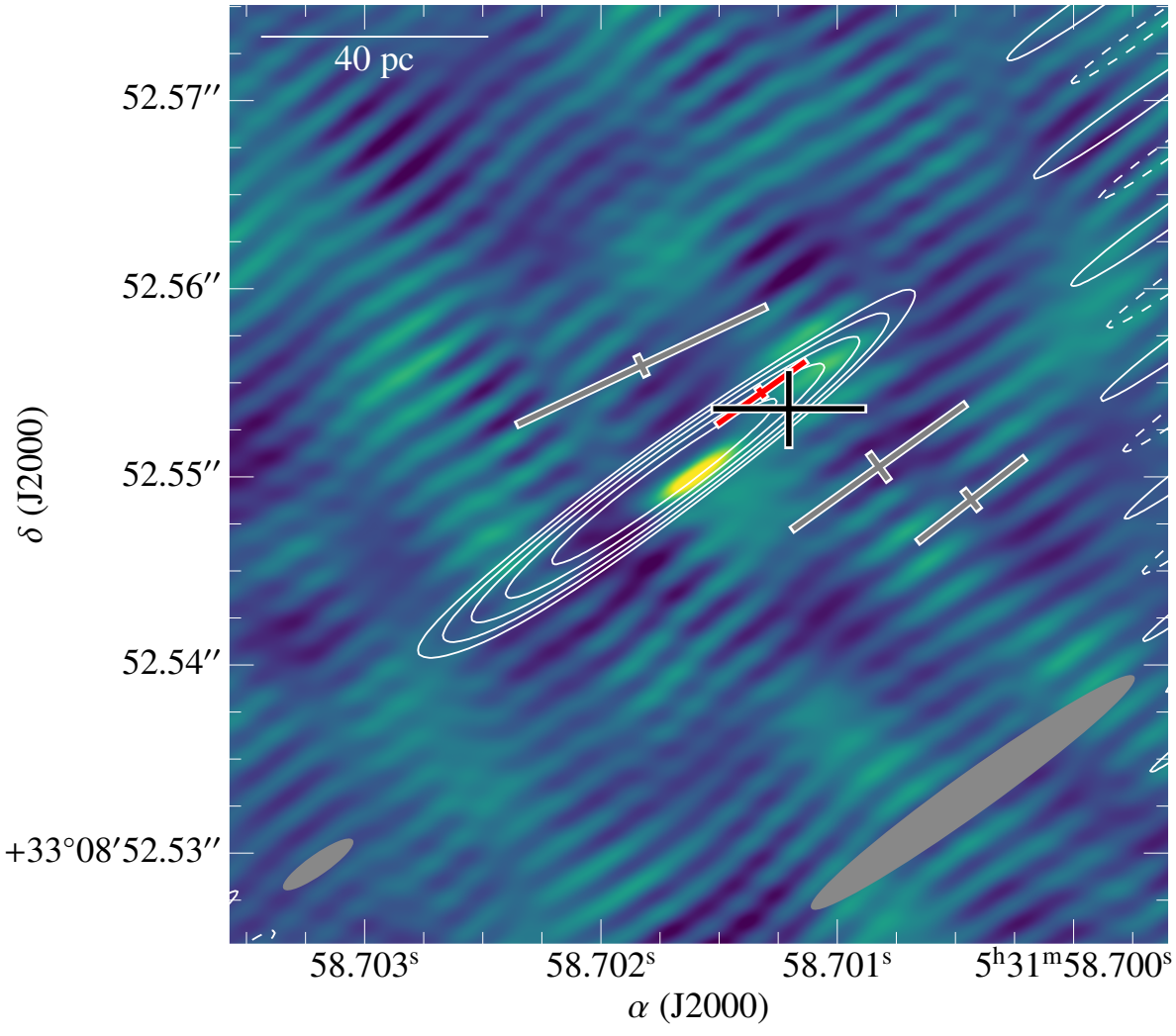
(Bursts observed at 1.7 GHz)

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.



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
- 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
- No submillimeter or IR emission
- X-ray upper-limit: $5 \times 10^{41}\ \mathrm{erg\ s^{-1}}$ (5σ)
- Ratio between X-ray and radio emission: $R_X > -2.4$

Possible origins of FRB 121102

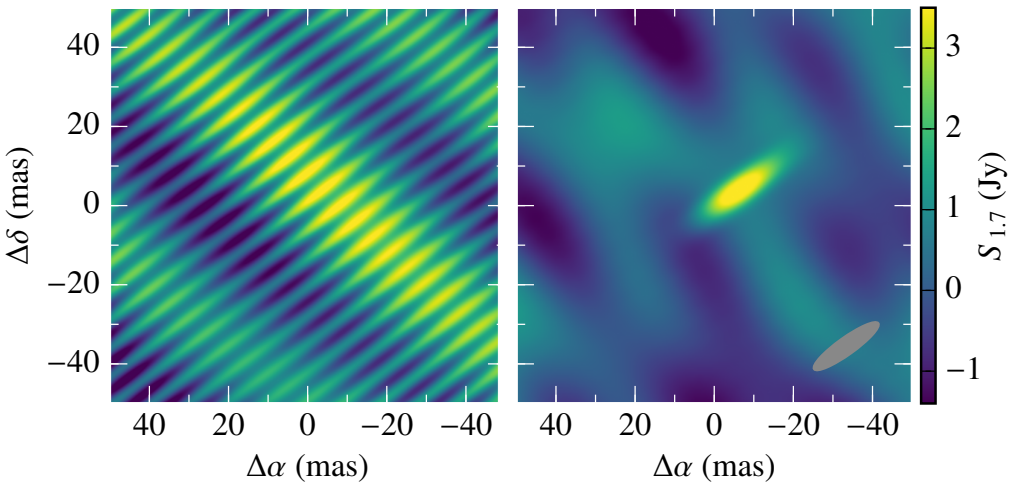
- What it is not:
  - A standard pulsar / RRAT / flare star / ...
  - Supernova remnant, as Cas A (at least 4 orders of magnitude fainter)
  - Compact star-forming regions, as Arp 220 (similar luminosity but would need a much larger region and SFR)
  - IMBH, X-ray binary, ultraluminous X-ray nebula, ...
- 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 (Vieyro et al. submitted)
  - Neutron star interacting with the jet of a massive black hole
  - Synchrotron maser activity from an AGN? (Ghisellini 2017)
  - Possibly new suggestions coming!

Conclusions

- FRB 121102 is extragalactic
- Also the other FRBs?
- Common scenarios do no explain what we observed
- 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...

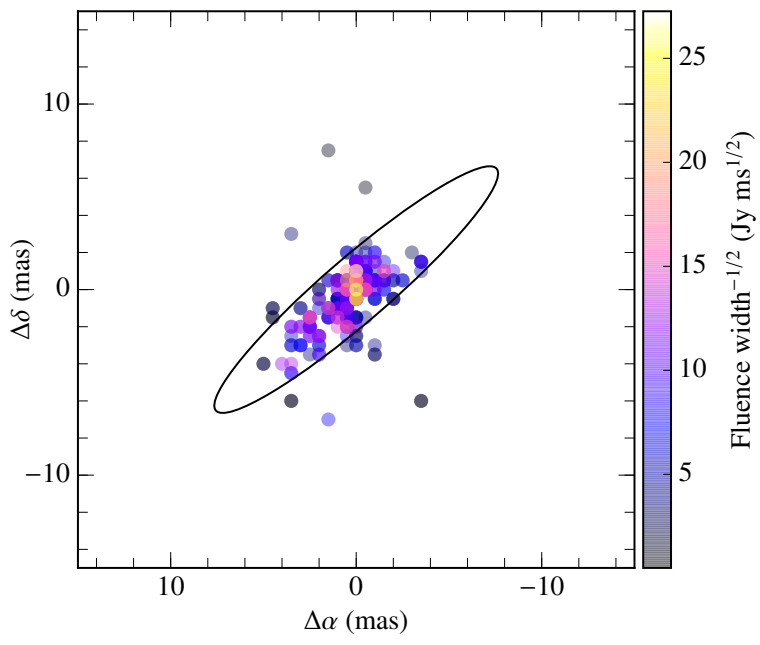
Thank you!

Localizing FRB 121102 on milliarcsecond scales



Dirty and clean image from FRB 121102.

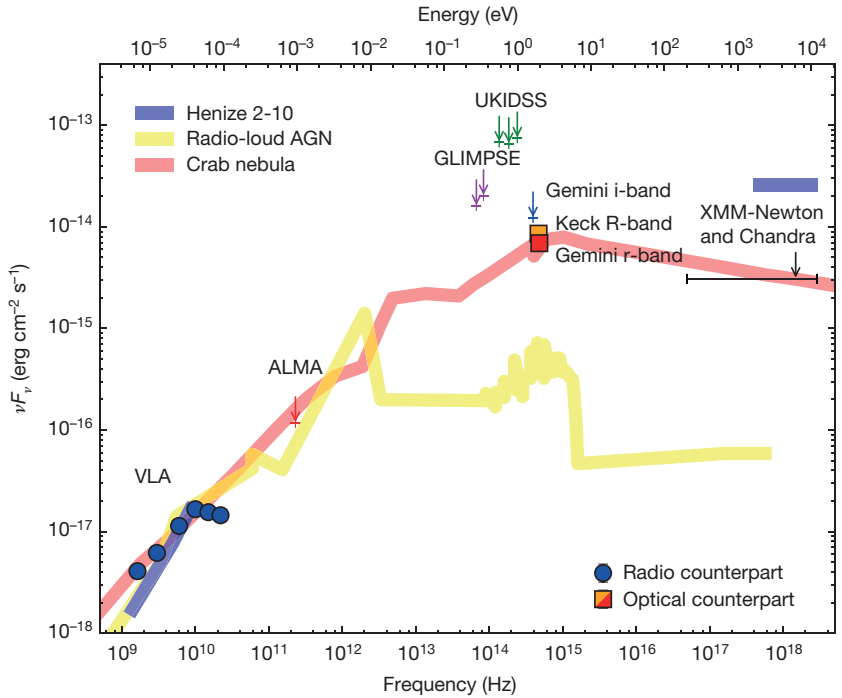
Astrometry limited by signal-to-noise ratio

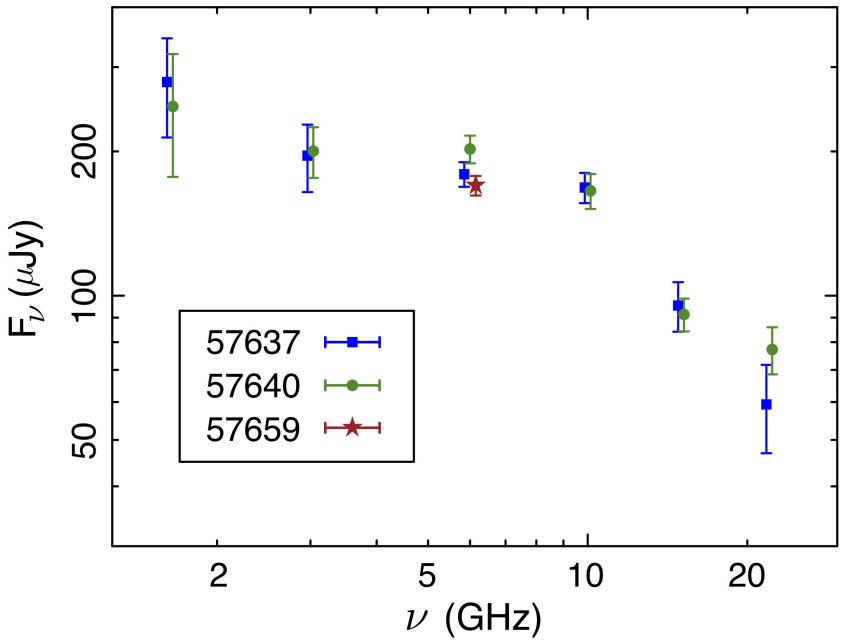


Positions derived from 406 pulses from the pulsar B0525+21

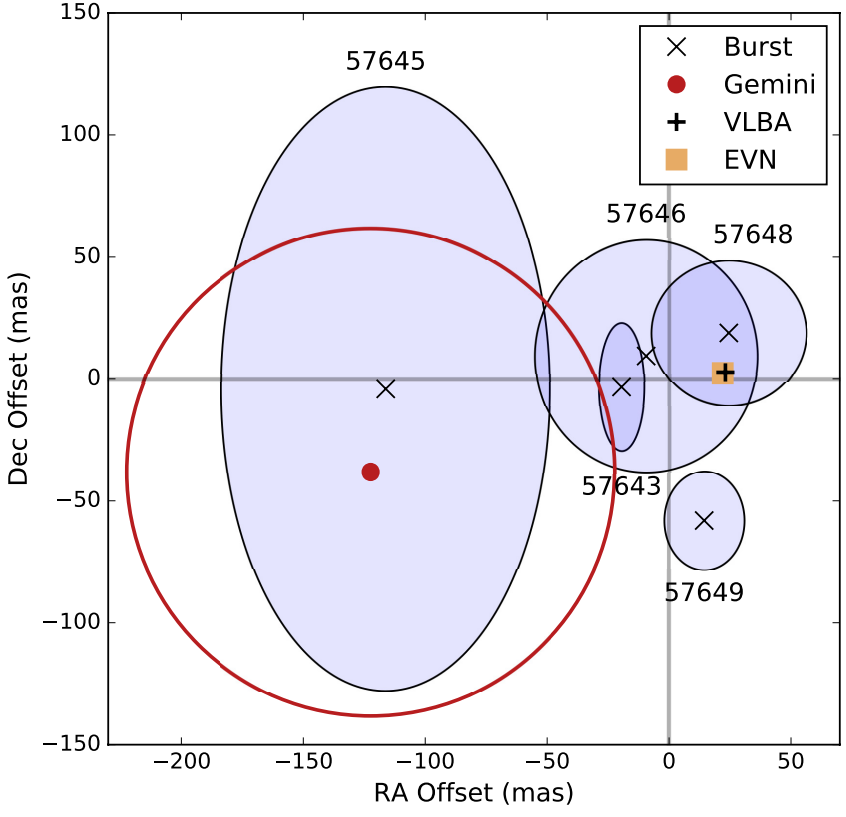
Marcote et al. (2017, ApJL, 834, 8)

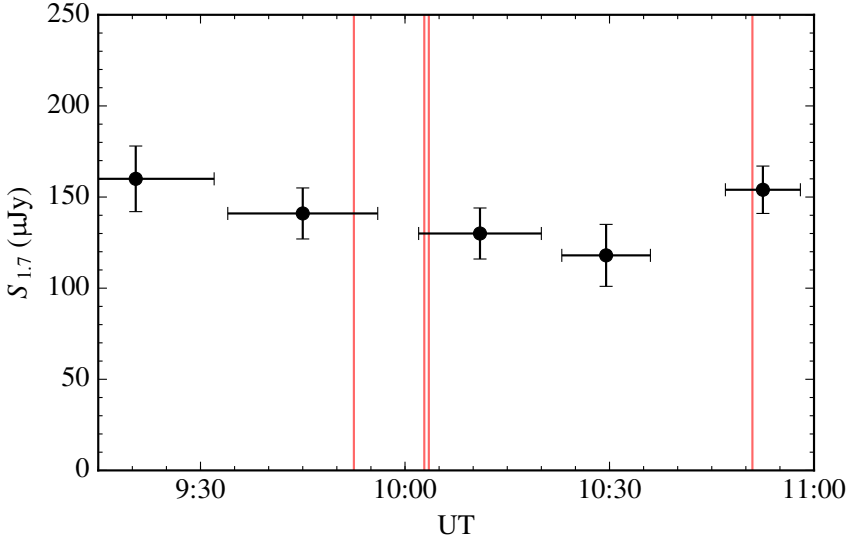
FRB 121102


Energy (eV)
Henize 2-10
Radio-loud AGN
Crab nebula
UKIDSS
GLIMPSE
Gemini i-band
Keck R-band
Gemini r-band
XMM-Newton
and Chandra
ALMA
VLA
Radio counterpart
Optical counterpart
Frequency (Hz)


57637
57640
57659
F_ν (μJy)
ν (GHz)

FRB 121102, optical emission





FRB 121102, optical emission