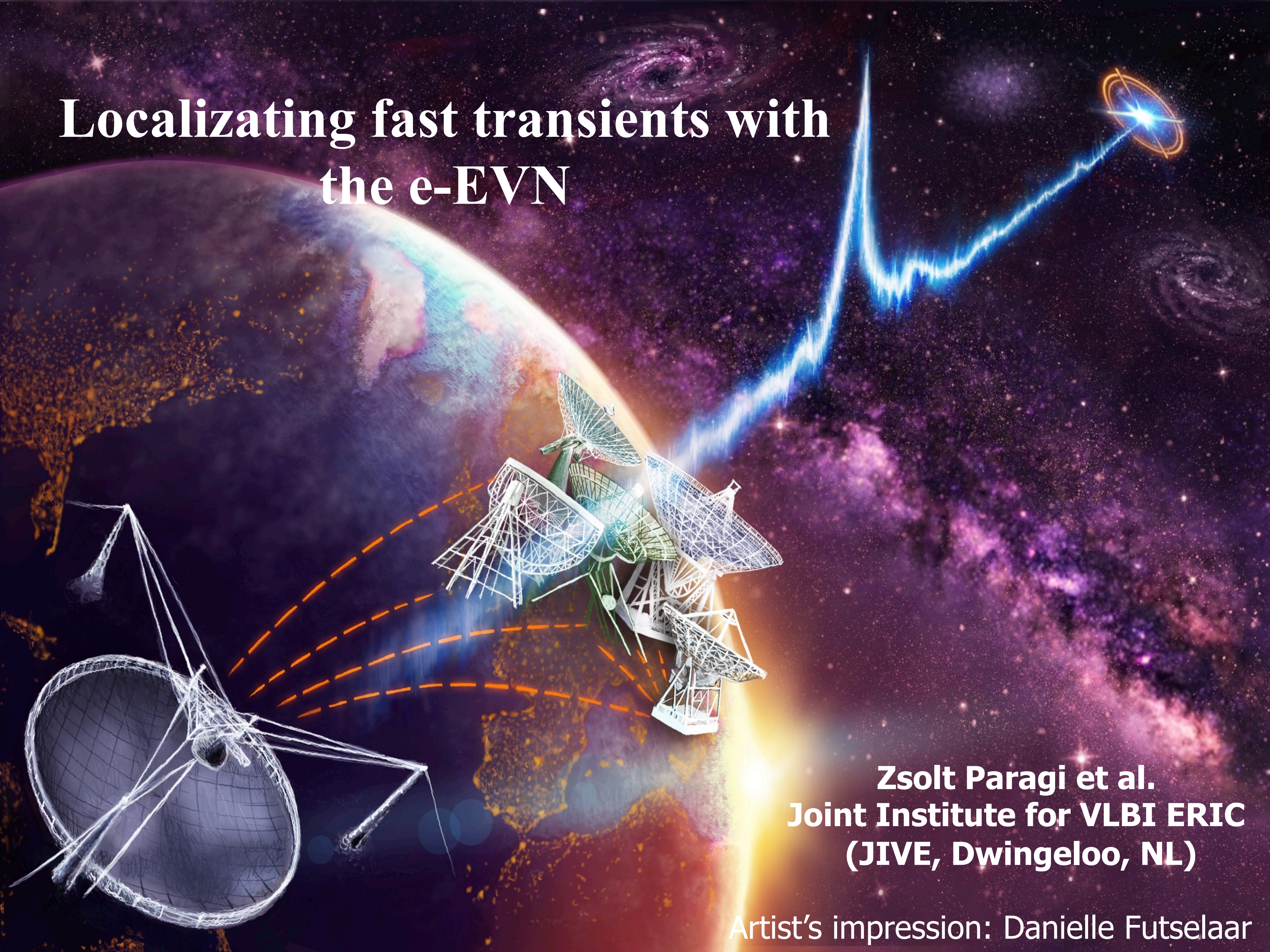
Localizating fast transients with the e-EVN

Zsolt Paragi et al.
Joint Institute for VLBI ERIC
(JIVE, Dwingeloo, NL)



Artist's impression: Danielle Futselaar

A historical fast transient search

- Evaporating primordial BH smaller than 10^{12} kg will produce short flashes in gamma rays

Hawking (1974), Nature, 248, 30

- Radio waves predicted from e^{-} and e^{+} interacting with magnetic fields; detectable at least out to 10 kpc

Rees (1977), Nature, 266, 333

- Radio limits on explosive primordial BH e.g. by the Dwingeloo Radio Telescope

O'Sullivan, Ekers, Shaver (1978), Nature, 590, 591

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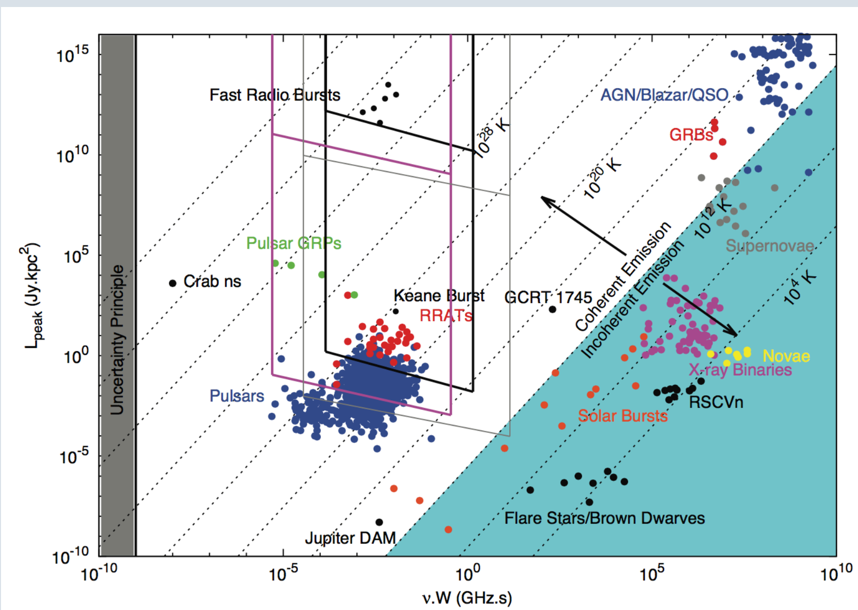
Wikipedia:

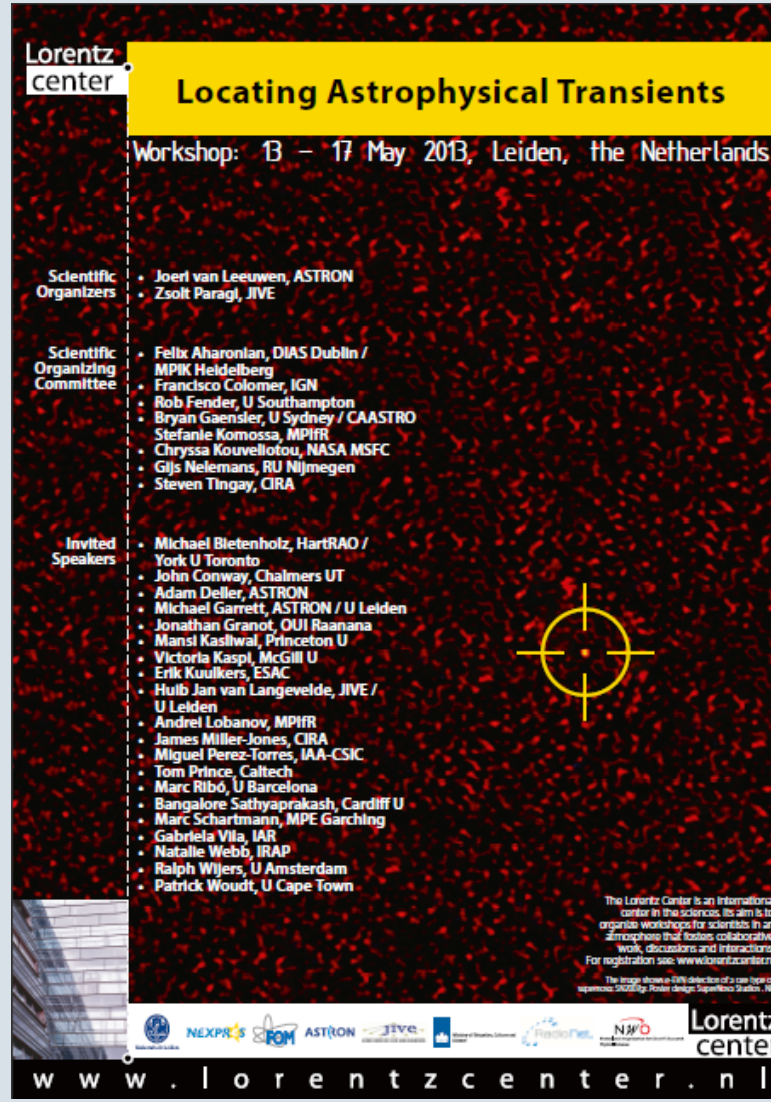
"**John O'Sullivan** is an Australian electrical engineer whose work in the application of Fourier transforms to radio astronomy[1] led to his invention with colleagues of a core technology that made wireless LAN fast and reliable…"

The European VLBI Network

Real-time e-VLBI and transients

- e-VLBI developments EXPReS/NEXPReS projects 2006-2013 made the e-EVN a flexible array for (synchrotron=‘slow’) transients
- LC Workshop on transient science in 2013 – Dan Thornton announced 4 new FRBs
- How the e-EVN can contribute to fast transients science?





Why FRBs are so important?

Dispersion measures well in excess of Galactic values.
Proposed explanations include:

- 'Blitzar': collapsing supramassive neutron stars

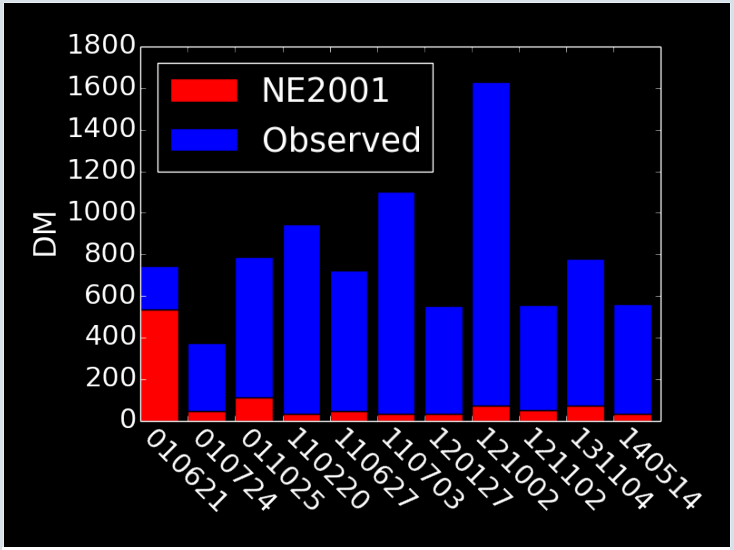
Falcke & Rezzola et. al. (2011), A&A, 562, A137

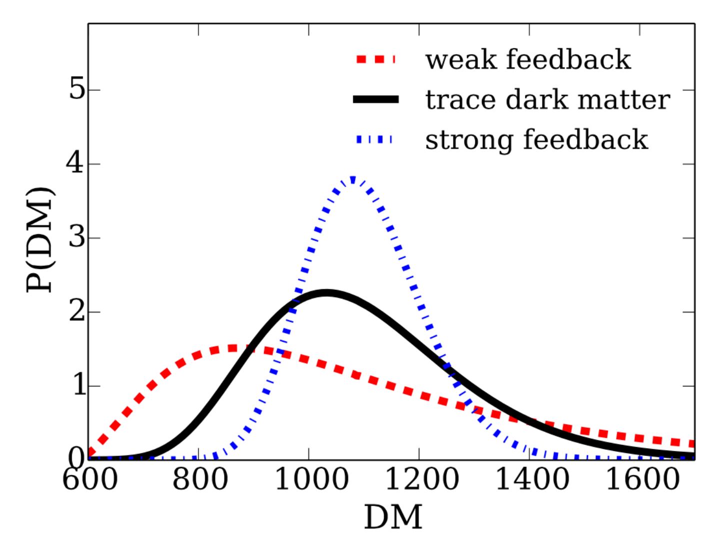
- Nearby flare stars; DM due to coronal plasma effects

Loeb, Shvartzvald, Maoz *(2014), MNRAS, 439, L46*
Maoz et al. (2015), MNRAS, 454, 2183

If extragalactic, they are important for cosmology:

- To weigh the missing barions *(McQuinn 2014)*
- To measure intergalactic magnetic field and determine dark energy equation of state *(Gao, Li & Zhang 2014; Zhou et al. 2014)*





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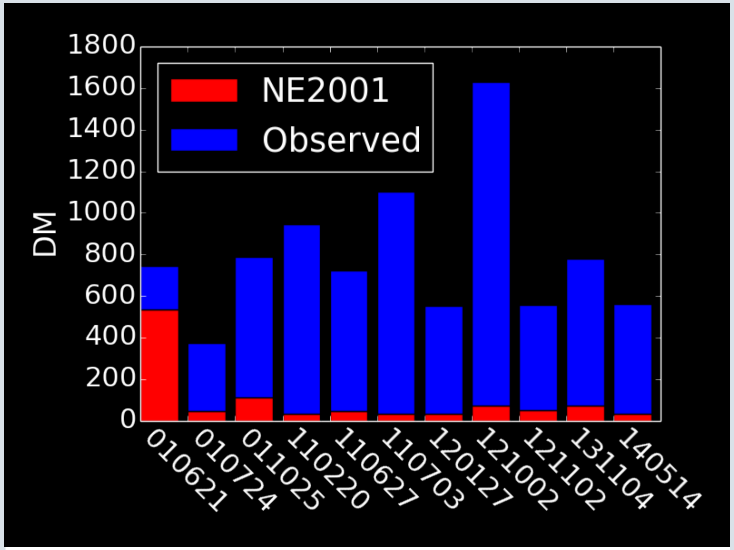
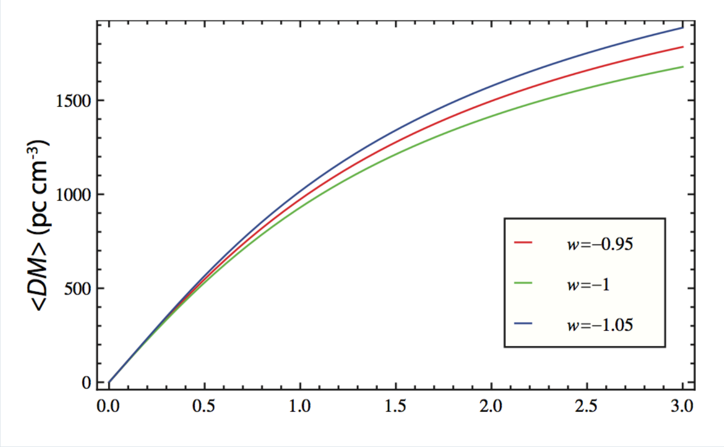
Localization needed to prove extragalactic origin!



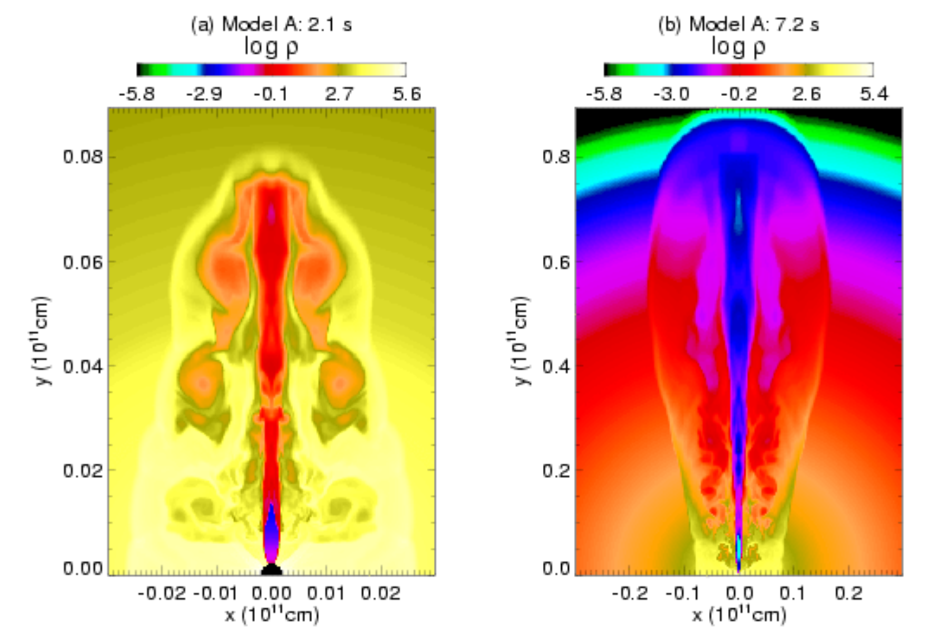


I. Localization of "afterglows"

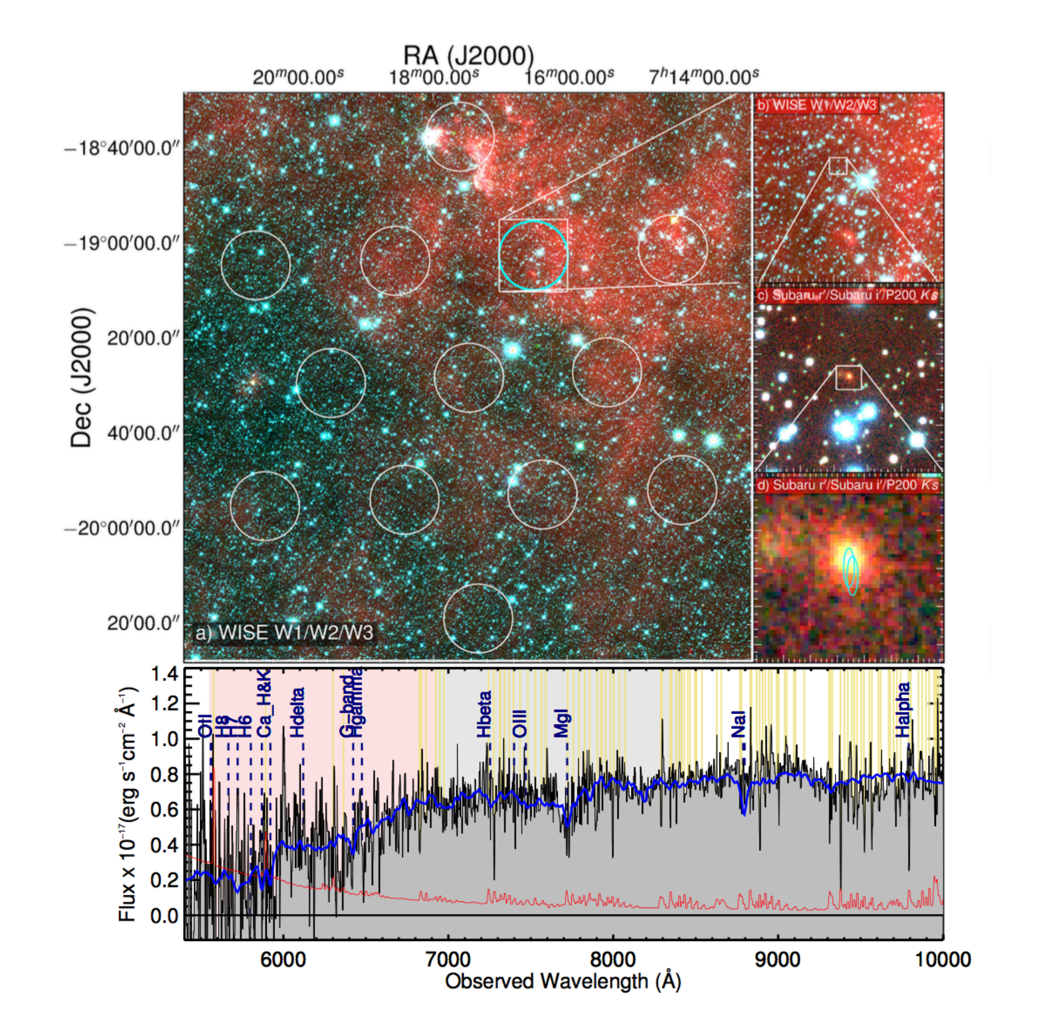
By analogy to GRBs:

explosive phenomena / engine-driven relativistic jets / shocks

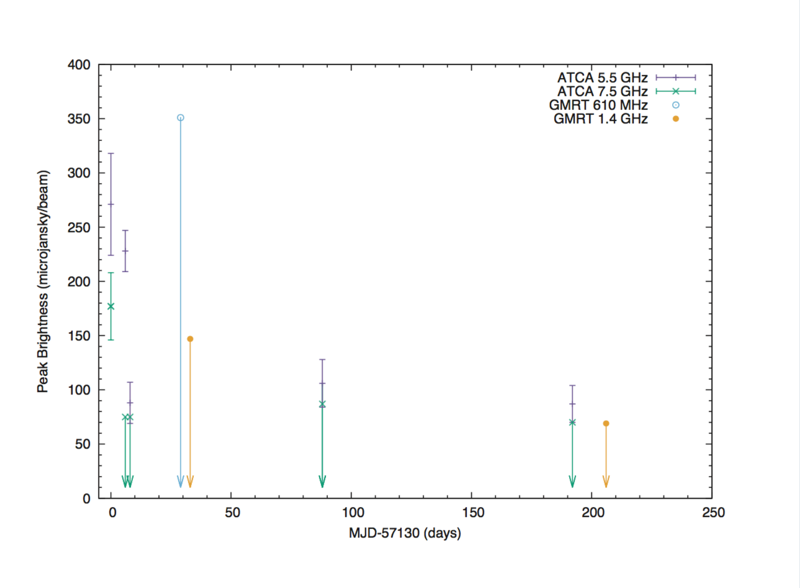
Woosley (1993)
MacFadyan & Woosley (1999)



FRB150418 – real-time detection



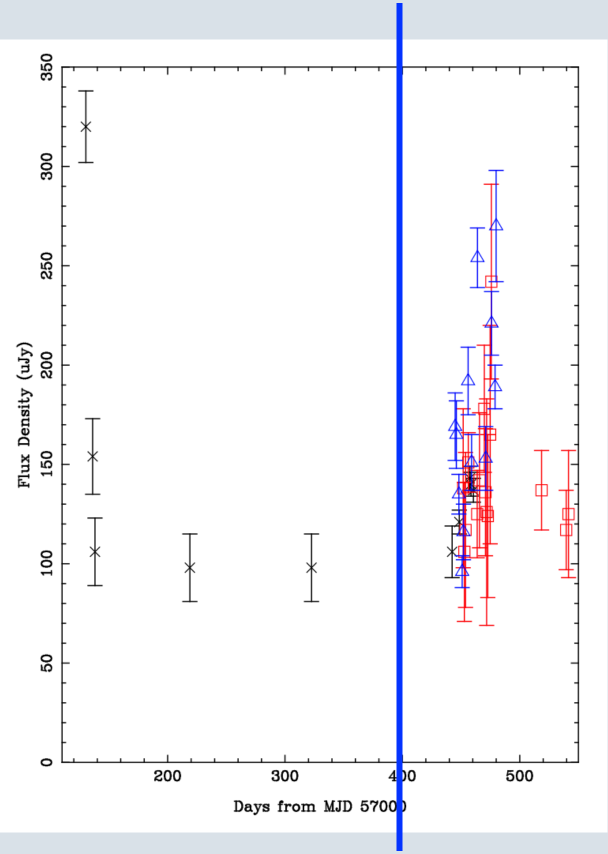
- **Parkes multi-beam receiver search**
- **ATCA fading radio source points to candidate host galaxy counterpart**

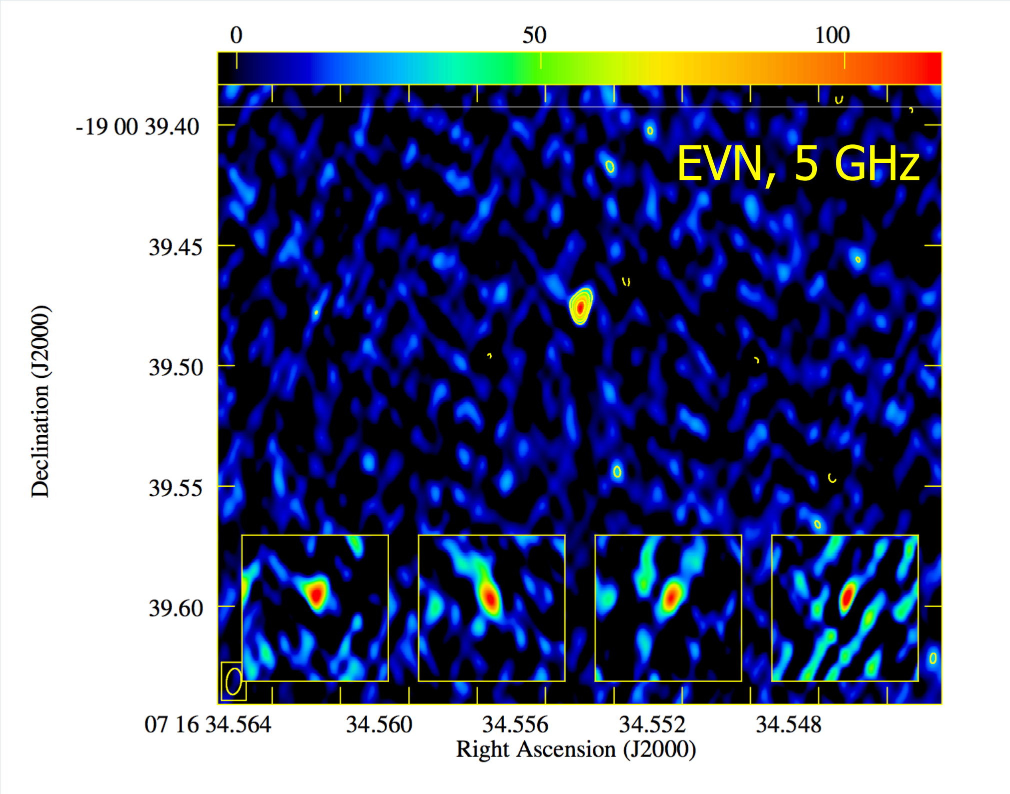


Keane et al. (2016)

FRB150418 – no counterpart

Further studies with the JVLA, VLBA and the EVN:



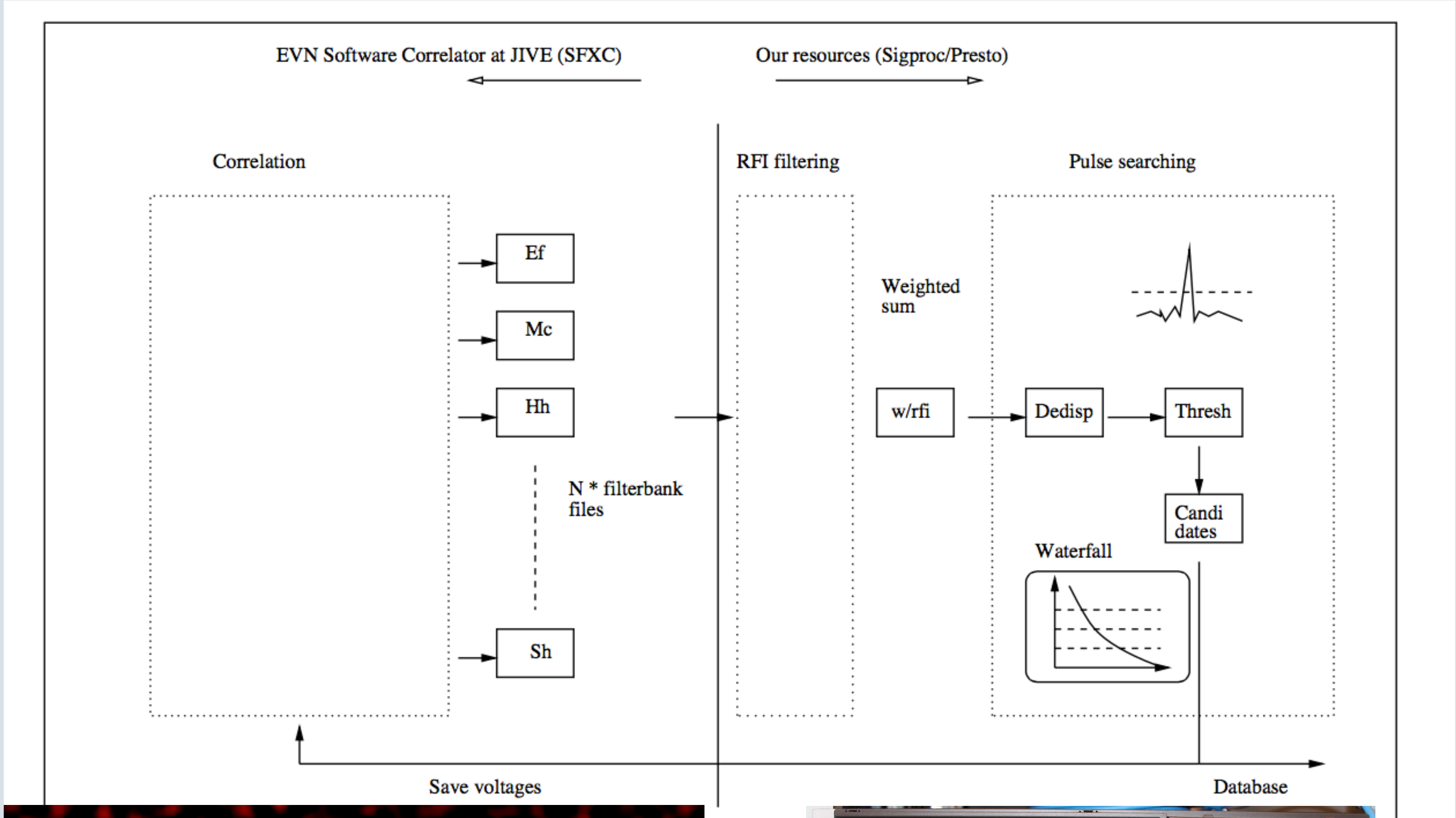


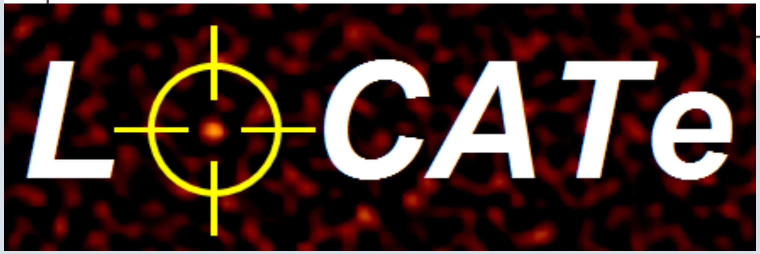
Johnston, Keane et al. (2017) …/… Giroletti et al. (2016) ➔ variable AGN most likely

II. Direct Localization

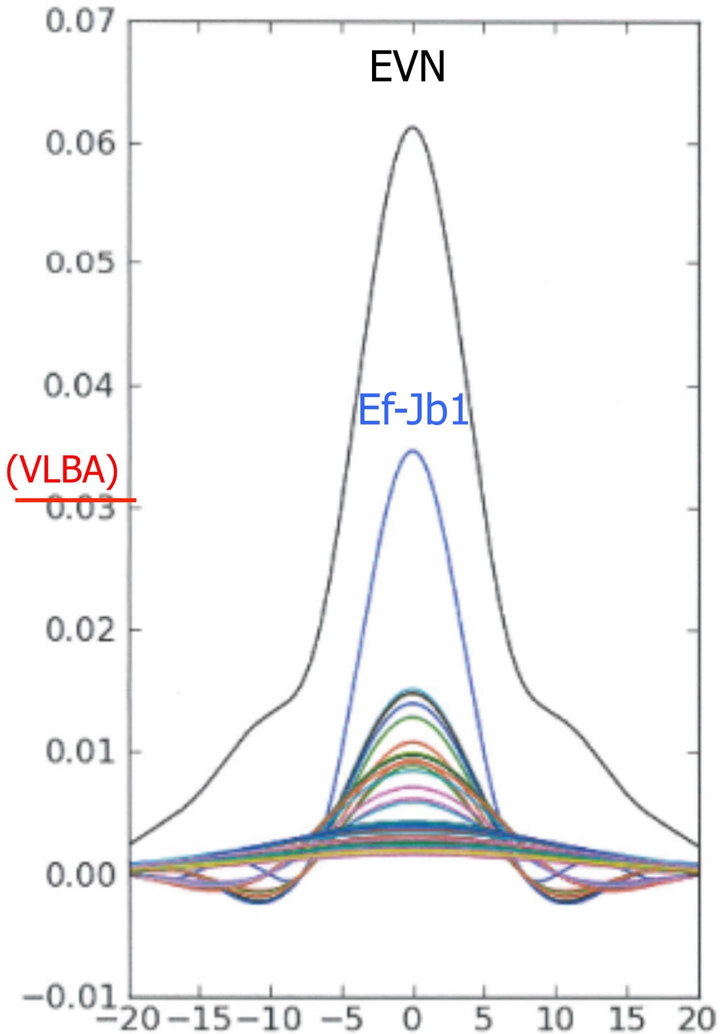
- **VFASTR project**
  (VLBA; latest: *Burke-Spolaor et al. 2016, ApJ 826, 223*)
- **LOCATe**
  (EVN; *Paragi 2016, arXiv 1612.00508*)

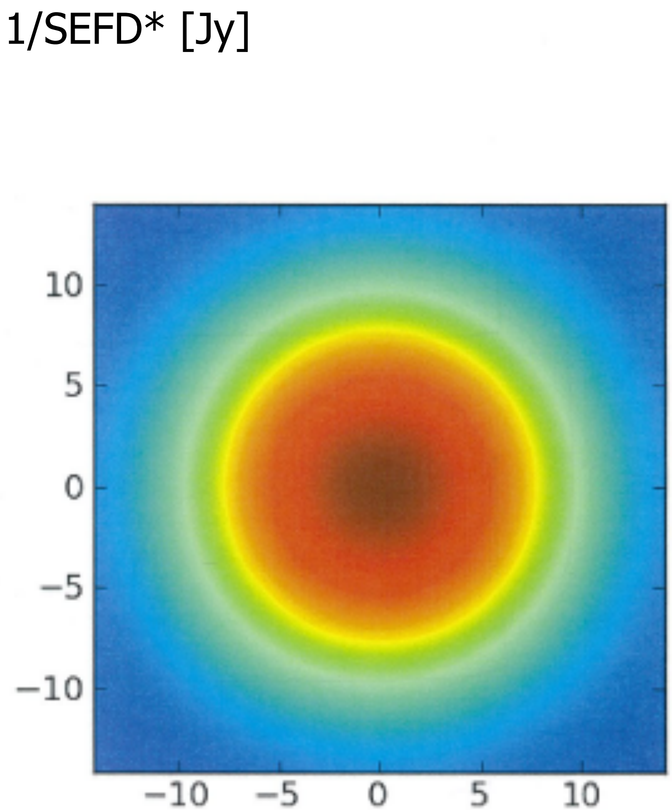
The idea of an EVN commensal project





Feasible with the EVN FoV?





Radius [arcmin]:

<5′ → ~0.1-0.3 Jy

5-10′ → ~0.3-1 Jy

>10′ → >1 Jy

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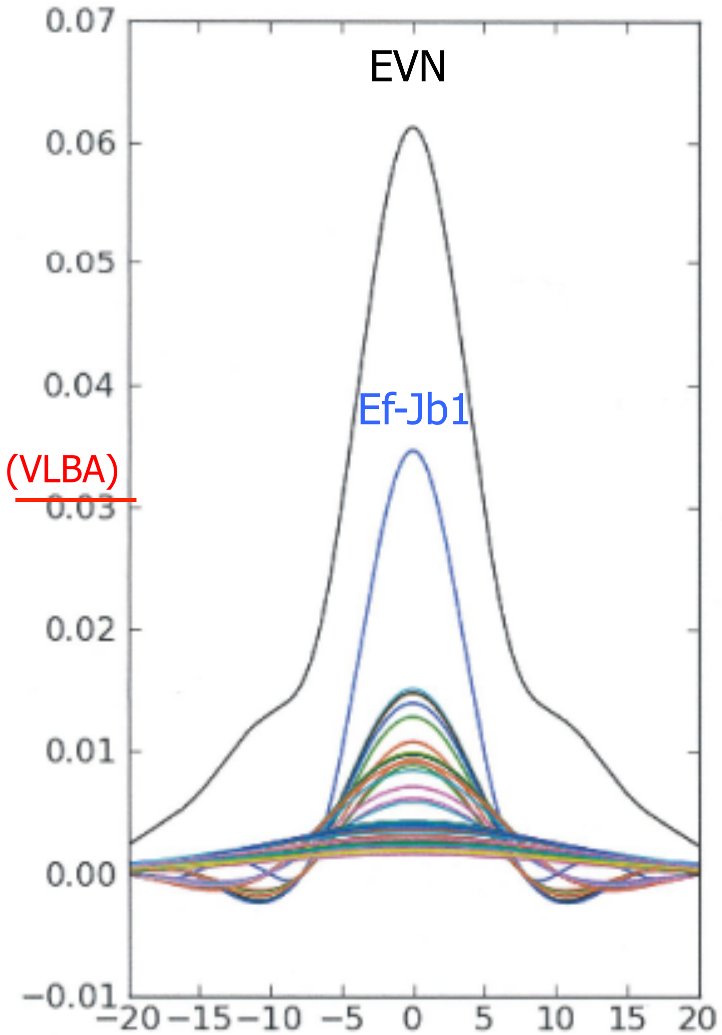

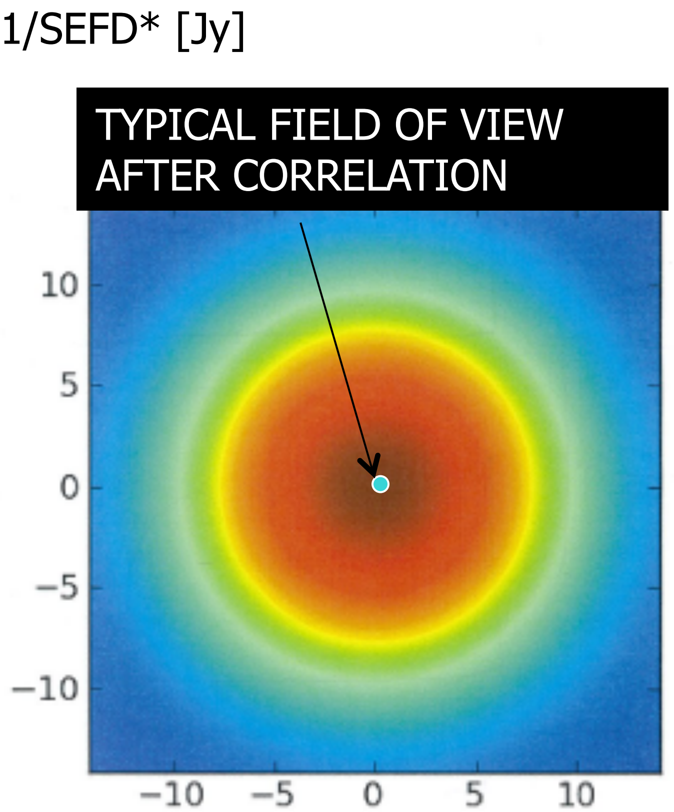

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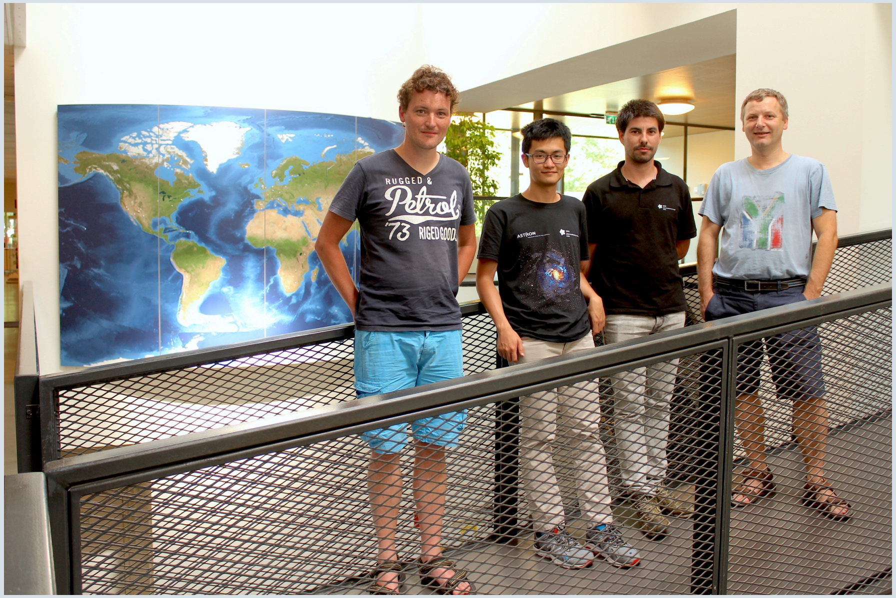
Feasibility studies (2015 & 2016 summer projects)

- Find pulsar and RRAT single pulses in Arecibo/Effelsberg autocorrelations (dedicated EVN observations, PI ZP), and then localize them in the image plane with VLBI resolution using ~standard VLBI techniques

2015 team (not complete): Sander ter Veen (Astron), Zhigang Wen (Urumqi Obs.), Anne Archibald (Astron), Aard Keimpema (JIVE) (myself taking the photo)



The 2016 “tiger team”: Aard Keimpema (JIVE), Yuping Huang (Carleton College), Benito Marcote (JIVE), and me.

It works … we are ready for the challenge!

Pulse search

1. De-dispersion (Loop over DM trails)
2. Matched filtering (Loop over boxcar filter widths)
3. Peak detection and clustering

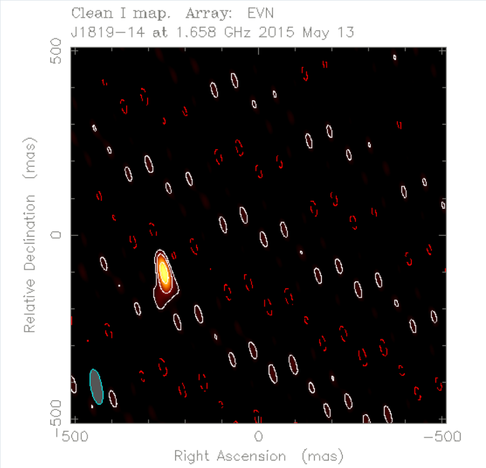
VLBI processing

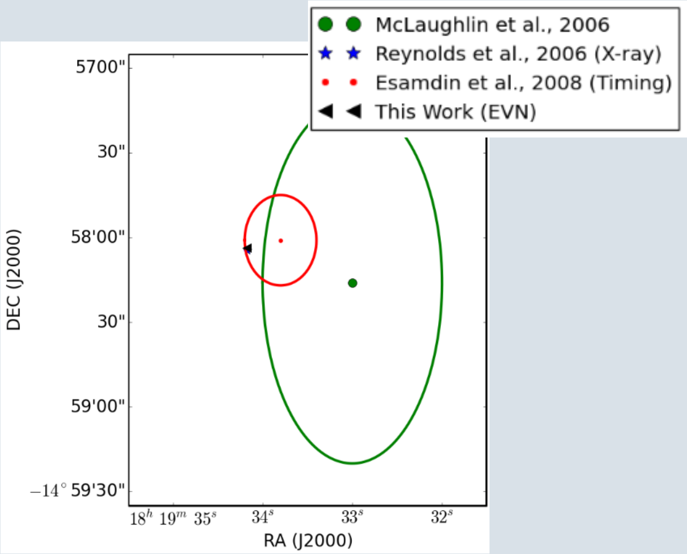
1. Calibrate the phase-referencing experiment (normal correlation)
2. De-disperse and re-correlate a few seconds of data around the burst time with high spectral and time resolution (~5ms)
3. Pass the calibration tables to pulse data
4. Guess initial position (delay mapping etc.)
5. Make an image around <u>a-priori position</u>

(note this mode of observation requires buffering/recording VLBI voltage data)

Initially, the astrometry errors were not understood well.

Single pulse e-EVN image of RRAT J1819-1458





Then comes the repeater FRB120211

First FRB that repeats, and shows similarity to RRATs/magnetars.

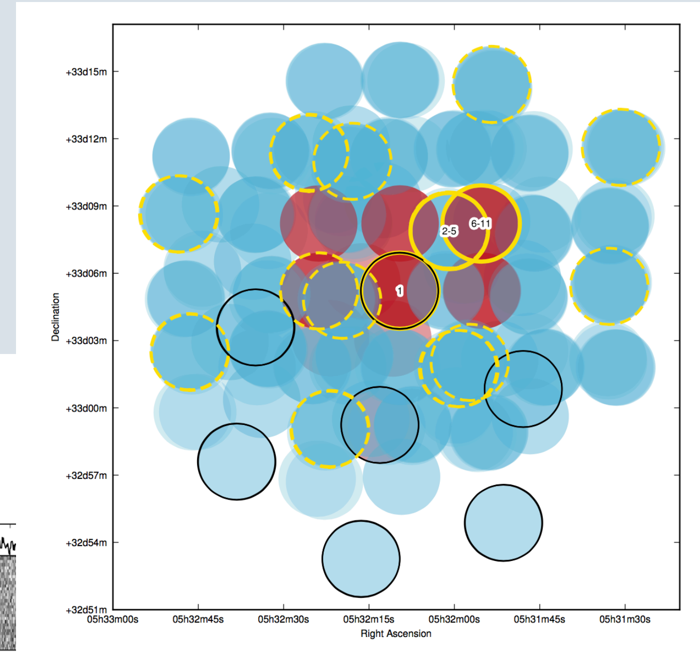
Spitler et al. (2016)

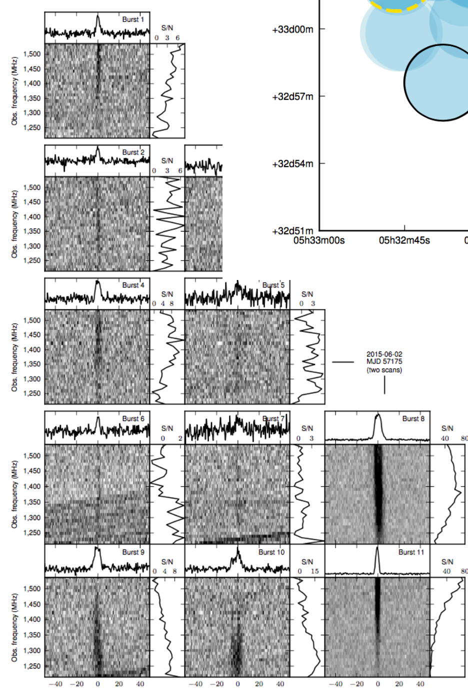
Five epoch e-EVN monitoring (including Arecibo; PIs Hessels/Paragi)

<u>We aim at direct detection of pulses in our Arecibo data and then do e-EVN localization</u>

1, 10, 11 February 2016
24, 25 May 2016

No activity in FRB120211

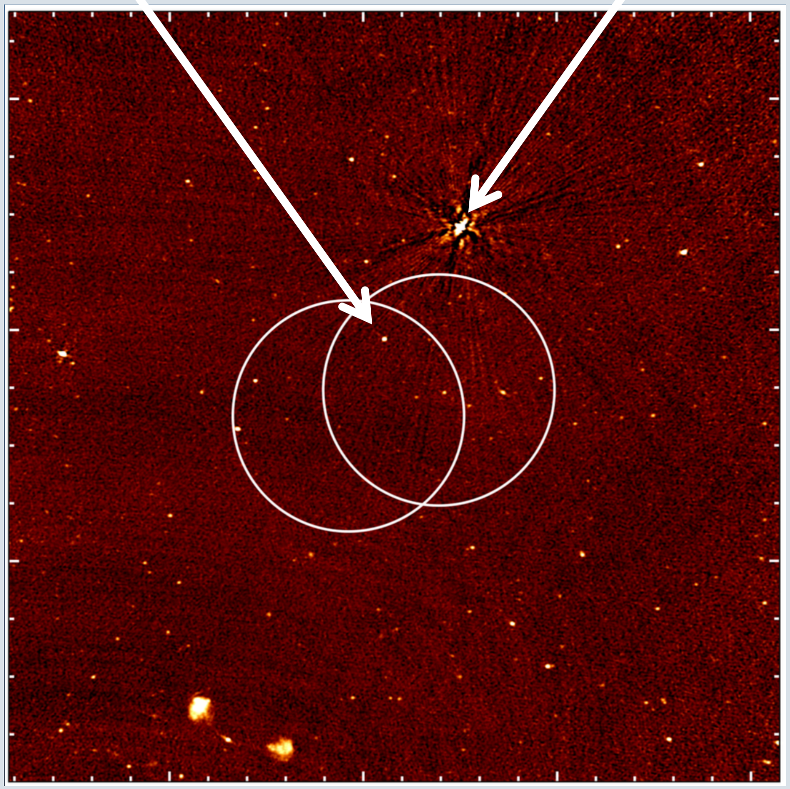




Following JVLA localization…

FRB121102
persistent source

in-beam cal.
for e-EVN data



Deep VLA image of the field
(Chatterjee et al. 2017)

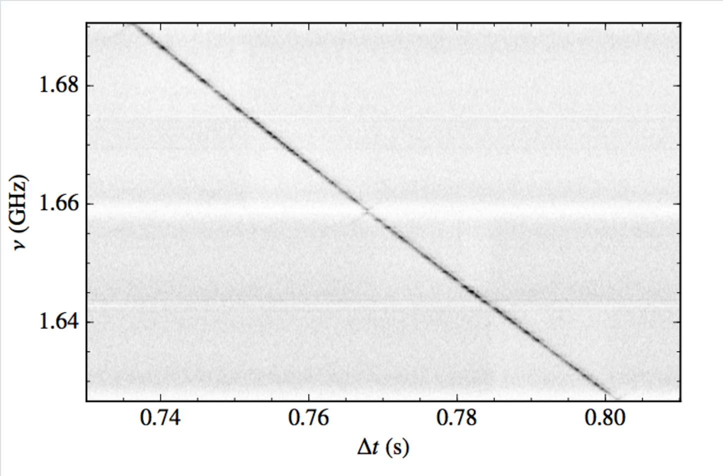
- ❑ Deep JVLA image shows a number of radio sources, one coincident with FRB121102 (hereafter “the persistent source”)
- ❑ Recorrelation of e-EVN data (real-time correlation +JIVE recording) at two different positions show the persistent source and a nearby (~)in-beam calibrator candidate are compact on mas scales
- ❑ Persistent source ~180 uJy @ 1.6 GHz, consistent with no variability in the e-EVN data
- ❑ Persistent and in-beam sources appear slightly resolved, possibly due to angular broadening
- ❑ AGN? – far too bright for a normal SNR

Bulk of the VLBI data reduction: Z. Paragi

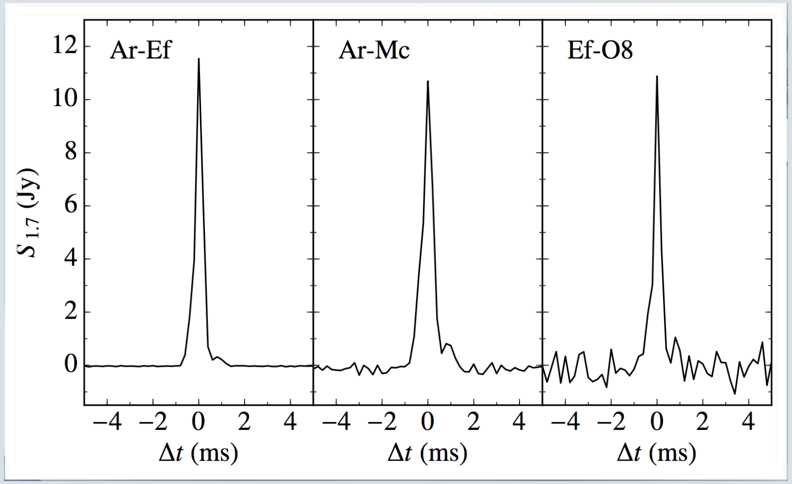
- ❑ Because of the observed renewed activity with the VLA and Arecibo in August 2016, we initiated new e-EVN+Ar and VLBA ToO observations… (L/C/X-bands)

First VLBI detection of FRB pulses!

Brightest burst dynamic spectrum (Arecibo)



Also seen in cross-correlation, for example:

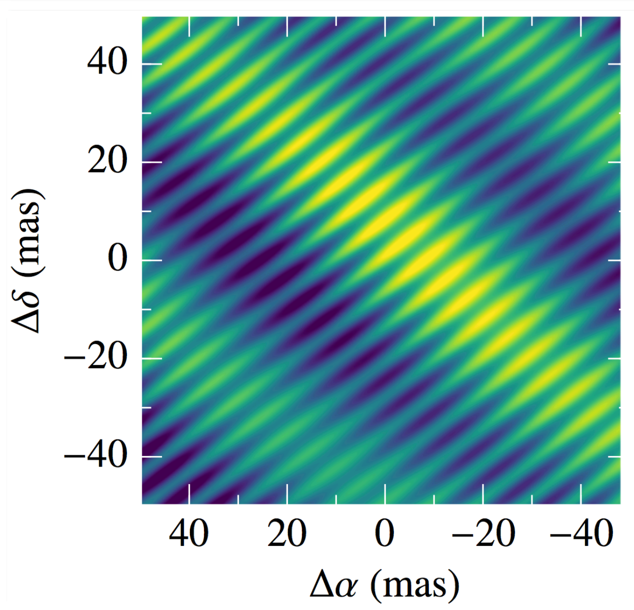


(coherently dedispersed)

- 20 Sep 2017, L-band: detected four bursts, brightest ~4 Jy, other three 0.2-0.5 Jy

Find bursts in Arecibo PUPPI data: J. Hessels
Dedispersion & recorrelation e-EVN: A. Keimpema
Bulk of the VLBI data reduction: B. Marcote

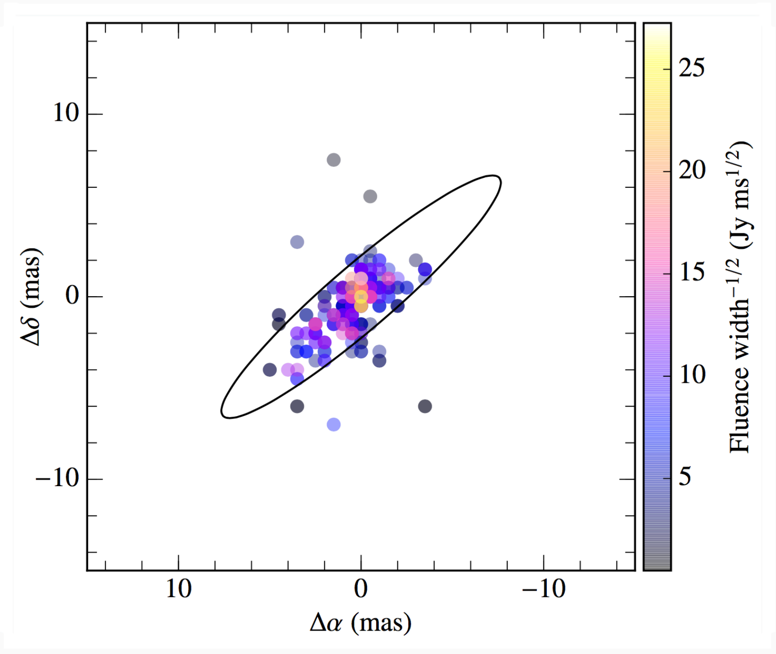
Dirty map: very strong sidelobes (sparse u-v coverage)



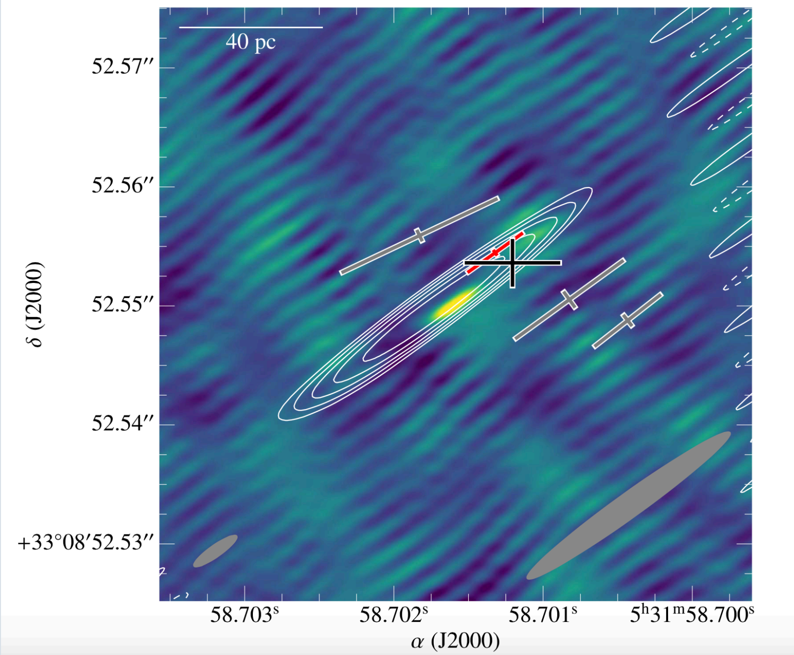
Marcote et al. (2017)

e-EVN localization

Test pulsar B0525+21
(Marcote et al. 2017)
ξ ~ 1–25 Jy $ms^{1/2}$



FRB121102
grey: weak pulses; red: bright pulse; black: weighted mean
ξ ~ 0.2–0.8; ξ ~ 5



Astrometry errors

- related to the detection statistics

$$\xi = Fw^{-1/2}$$

- i.e. fluence times pulse width [Jy $ms^{1/2}$]

Offset from persistent source is not significant

- they are coincident within 2σ (12 milliarcseconds)

Knowing the redshift:

- < 40 parsec, 95% confidence level

VLBI Source properties

Persistent source

5 GHz data: angular size <~0.2-0.4 mas
(linear size of about a parsec at z=0.19273(8))

1.7 GHz data: slightly resolved (few mas)

Luminosity: $L_{5.0} \approx 7 \times 10^{38}$ erg s^{-1}

Radio-loudness: log $R_X > -2.4$

Brightness temperature: $T_b > 5{\times}10^7$ K

Proper motion constrained to <few mas/yr [ongoing]

Bursts [or brightest burst]

Coincident with persistent source within 12 mas
(linear size of 40 pc)

1.7 GHz data: resolved (2±1 mas)
- consistent with angular broadening, also seen in the persistent source and the in-beam calibrator

Luminosity: $L_{5.0} \approx {\sim}6 \times 10^{42}$ erg s^{-1} [in 2ms]

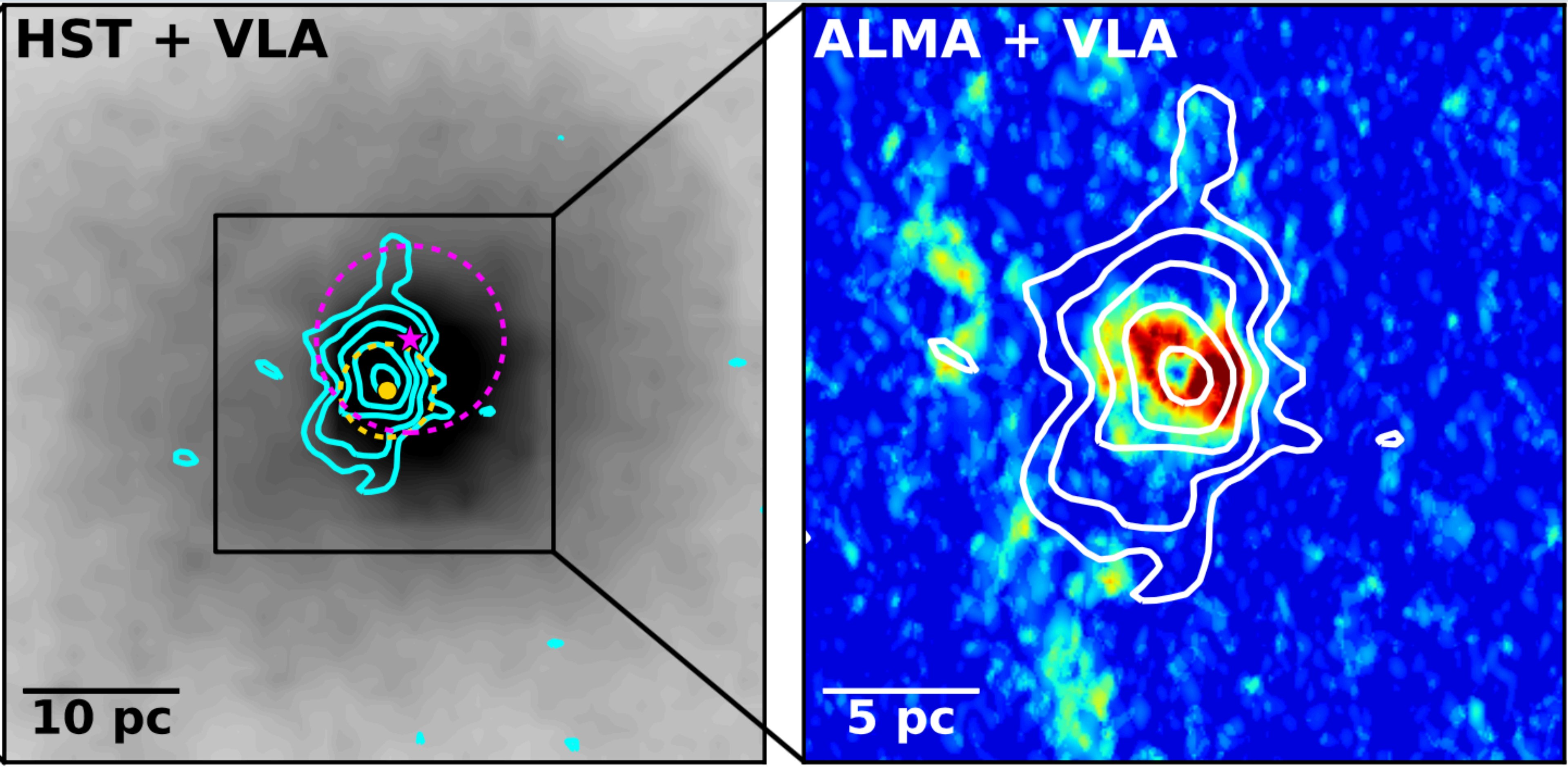
or Energy: $L_{5.0} \approx {\sim}10^{40}$ erg $(\Delta\Omega/4\pi)$

Marcote et al. (2017), ApJ, 834, L8

VLBI data are consistent with extragalactic origin; the persistent source (main suspects)

- **is not typical AGN (SMBH in dwarf glx unlikely; it is far too radio-bright for ~IMBH)**
- **is not typical SNR (orders of magnitude more powerful)**
- **cannot be nuclear starburst (glx would be booming in the IR, but it is not detected)**

AGN/SF in a dwarf galaxy: NGC 404

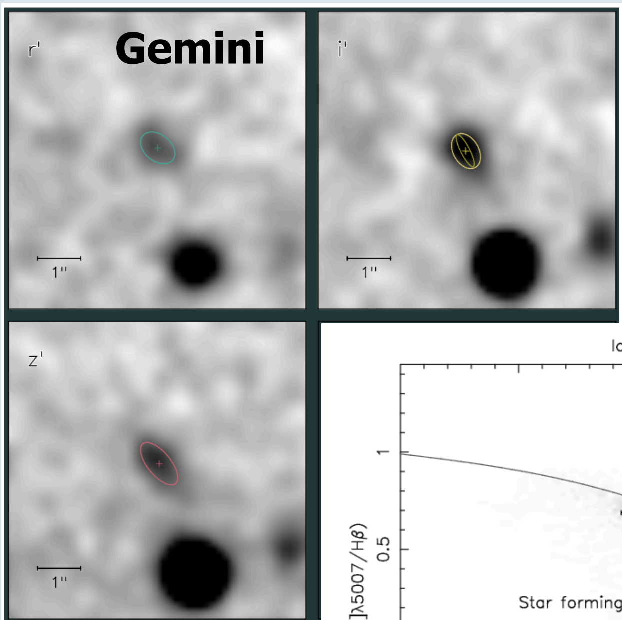


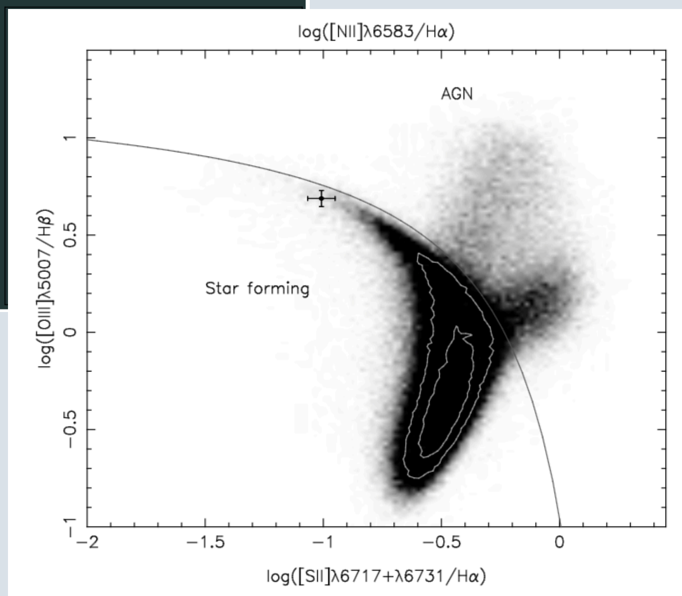
Nyland et al. submitted

Classic AGN/SF indicators do not (always) work in dwarfs/LLAGN

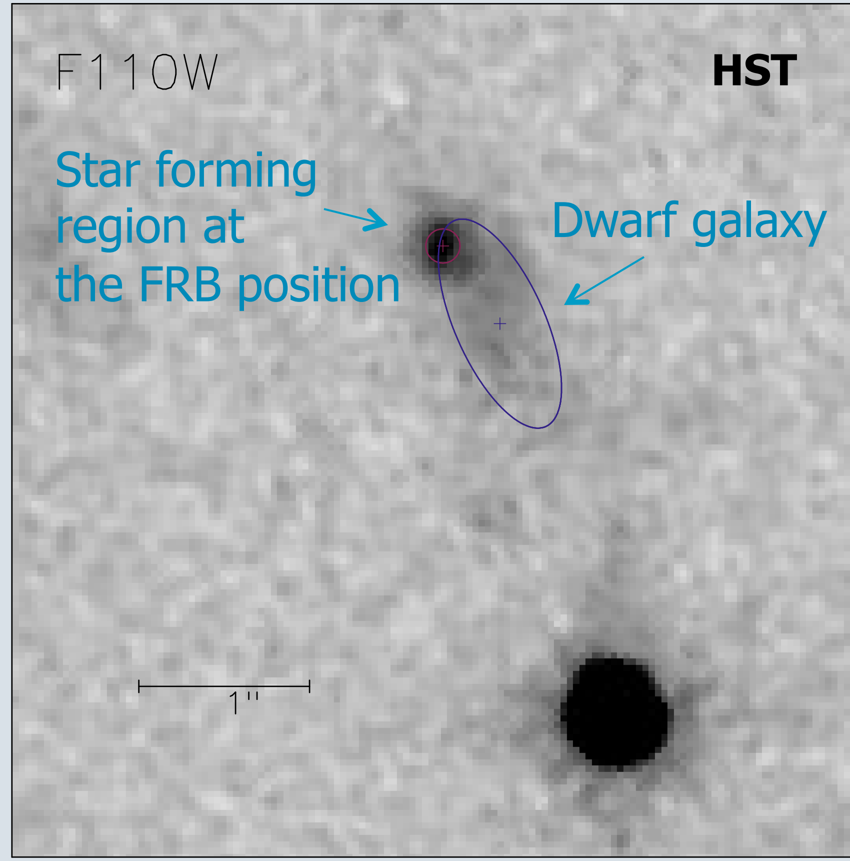
...and AGN/SF often go together in (post-)mergers

What about FRB121102 counterpart?





Tendulkar et al. 2017



Bassa et al. submitted

A young (superluminous) supernova remnant powered by a magnetar?
Host properties are consistent with SLSNe hosts, low-metallicity dwarfs.

Final remarks

- e-EVN fast transients work was also motivated by SETI
  - Lot lots of help from Andrew Siemion/Berkely
  - We learned to look at our data in new ways
  - Started a new adventure

- Are FRBs lightsails?
  - NO! Why are we hinting on this to the public than?
  - Is science indeed so boring?

Are we alone? – the most important question people want to get the answer for…

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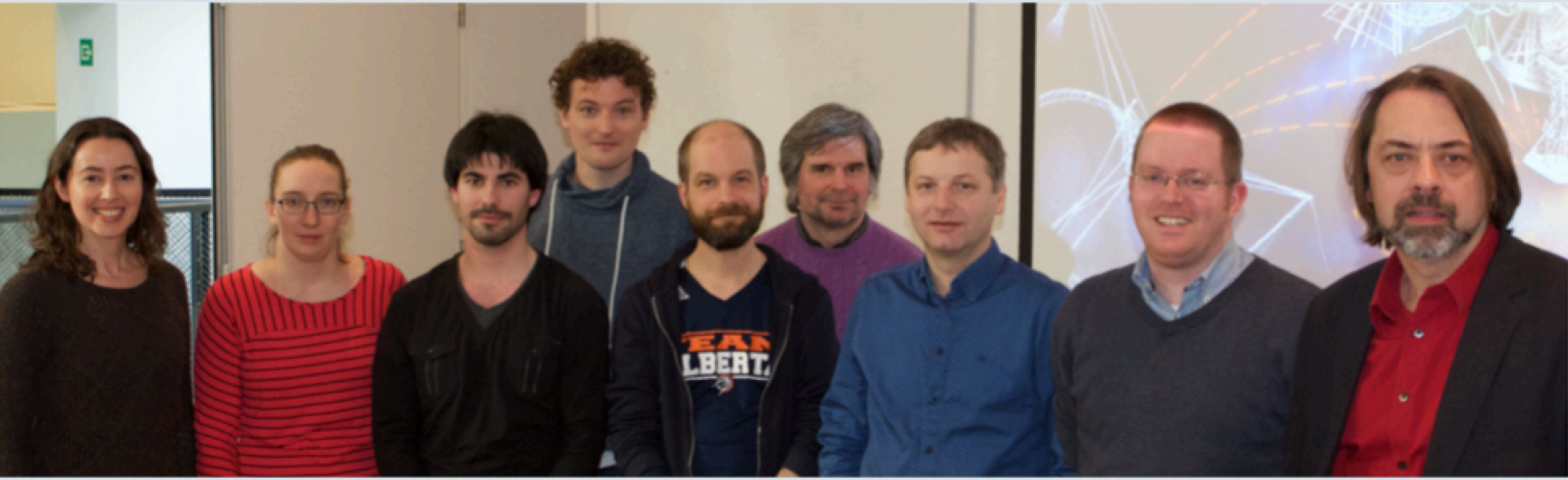
We want more – we also want to answer questions that have never been asked before!

This is how we should find our ways in the Labyrinth of the unexpected!

FRB121102 team: ASTRON/JIVE members

Left to right: Natasha Maddox (A); Betsey Adams (A); Benito Marcote (J); Aard Keimpema (J);



Jason Hessels (A); Bob Campbell (J); Zsolt Paragi (J); Cees Bassa (A); Huib van Langevelde (J)

Additional slides: ‘radplot’

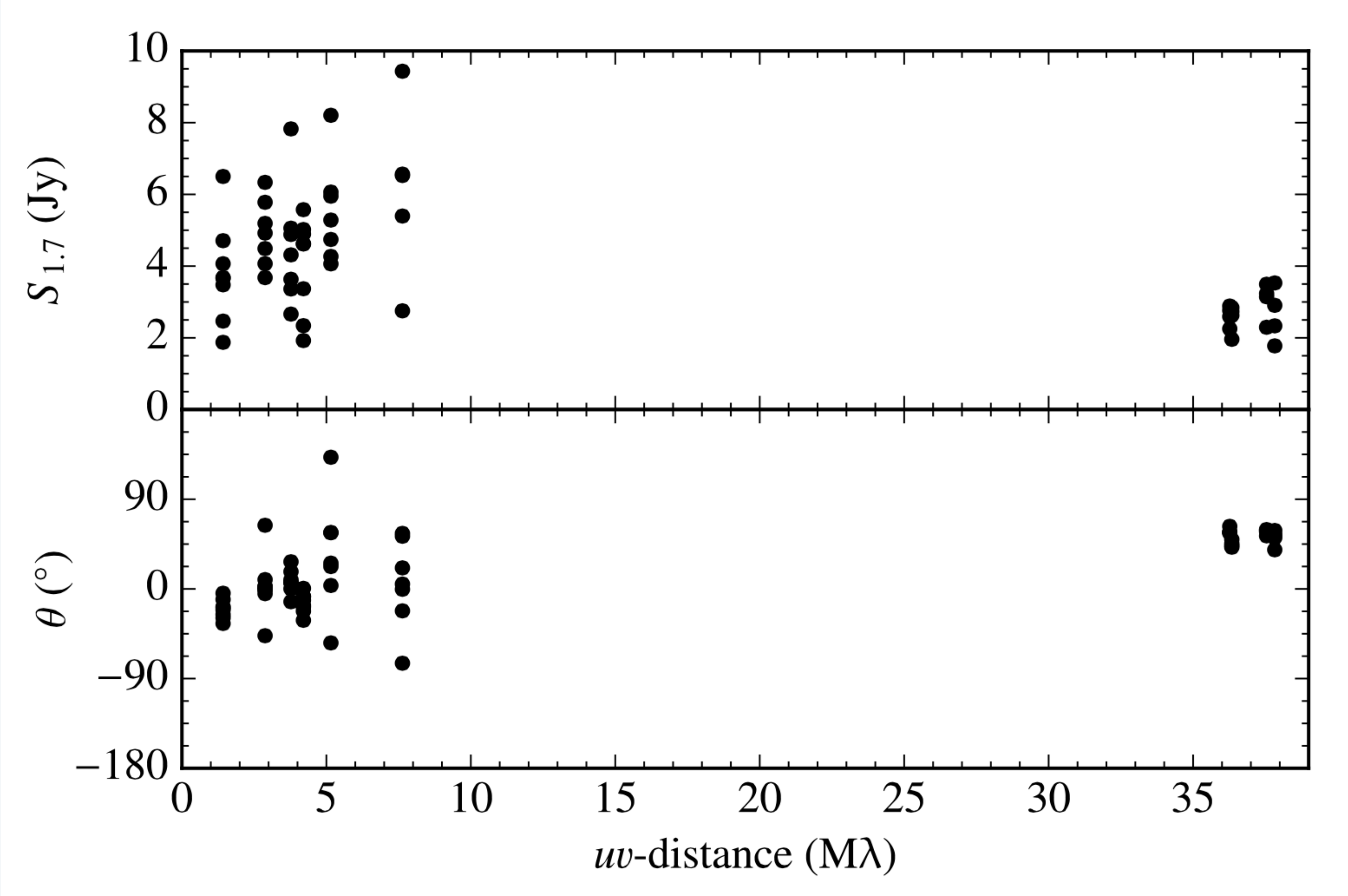
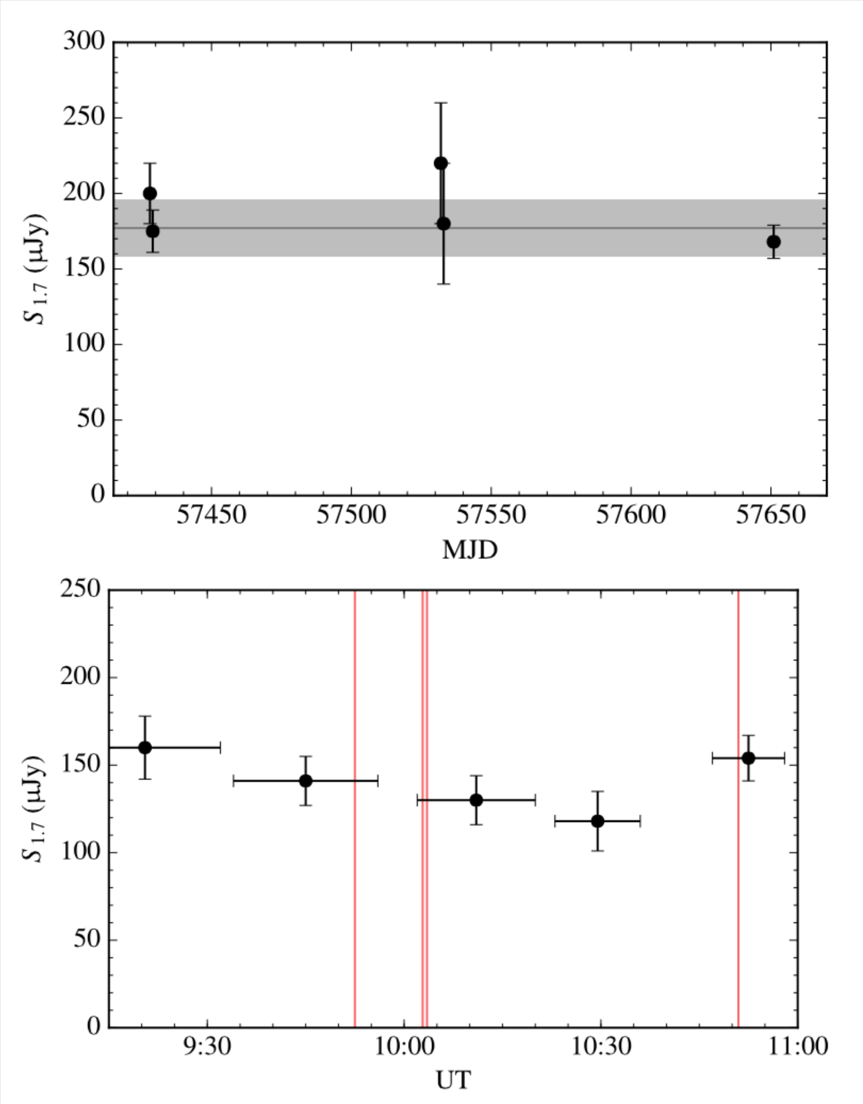


Table 1. Properties of the persistent radio source and detected FRB 121102 bursts from the Arecibo+EVN observations. All positions are referred to the 5-GHz detection of the persistent source (RP026C epoch): $\alpha_{\mathrm{J2000}} = 5^{\mathrm{h}}31^{\mathrm{m}}58.70159^{\mathrm{s}}$, $\delta_{\mathrm{J2000}} = 33°8'52.5501''$. The observations conducted on 2016 Feb 1 (RP024A) and 2016 Sep 19 (RP026A) did not produce useful data, and are not included here (see main text). The arrival times of the bursts are UTC topocentric at Arecibo at the top of the observing band (1690.49 MHz). All these bursts had gate widths of 2–3 ms, and the quoted flux densities are averages over these time windows. We note that the larger error on the flux density of Burst #2 is due to the fact that the image is dynamic-range limited because of the burst's brightness. The last row shows the average position obtained from the four bursts weighted by the detection statistic $\xi = F/\sqrt{w}$ (fluence divided by the square-root of the burst width).

Session	Epoch	ν	$\Delta\alpha$	$\Delta\delta$	S_ν	ξ
	(YYYY-MM-DD)	(GHz)	(mas)	(mas)	(μJy)	(Jy ms$^{1/2}$)
RP024B	2016-02-10	1.7	1.5 ± 2	-2 ± 3	200 ± 20	—
RP024C	2016-02-11	1.7	-4 ± 2	-5 ± 3	175 ± 14	—
RP024D	2016-05-24	1.7	1 ± 3	-5 ± 4	220 ± 40	—
RP024E	2016-05-25	1.7	1 ± 3	2 ± 4	180 ± 40	—
RP026B	2016-09-20	1.7	1.9 ± 1.8	-0.4 ± 2.3	168 ± 11	—
RP026C	2016-09-21	5.0	0.0 ± 0.6	0.0 ± 0.7	123 ± 14	—
	(YYYY-MM-DD hh:mm:ss.sss)				(Jy)	
Burst #1	2016-09-20 09:52:31.634	1.7	-14 ± 3	-1.4 ± 1.8	0.46 ± 0.02	~ 0.8
Burst #2	2016-09-20 10:02:44.716	1.7	-3.3 ± 2.5	4.3 ± 1.6	3.72 ± 0.12	~ 5
Burst #3	2016-09-20 10:03:29.590	1.7	-10 ± 5	0.8 ± 3	0.22 ± 0.03	~ 0.4
Burst #4	2016-09-20 10:50:57.695	1.7	3 ± 6	6 ± 4	0.17 ± 0.03	~ 0.2
Avg. burst pos.	2016-09-20	1.7	-5 ± 4	3.5 ± 2.2	—	—

EVN lightcurves (persistent source)



1.7 GHz e-EVN (Feb.-Sep. 2016)

20 Sep. 2016 run

Red vertical lines indicate the four bursts: no ‘afterglow’-like brightening seen