On the origin of Fast Radio Bursts and sub-milliarcsecond localization

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Joint Institute for VLBI ERIC (JIVE)

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Introduction

Time-domain sources

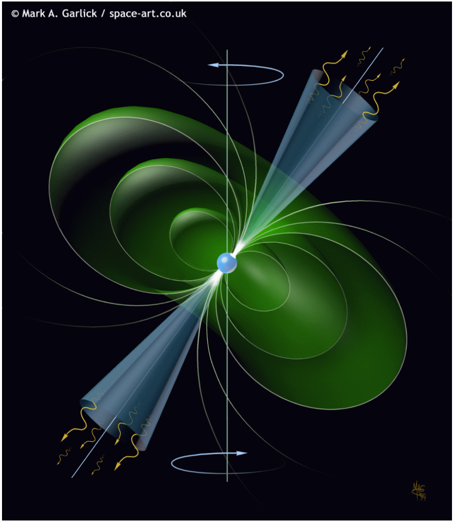
Sources with emission on timescales shorter than seconds (extremely compact: $\sim 1\,000$ km):

- Pulsars
- Magnetars bursts
- Rotating radio transients (RRATs)
- Fast Radio Bursts (FRBs)

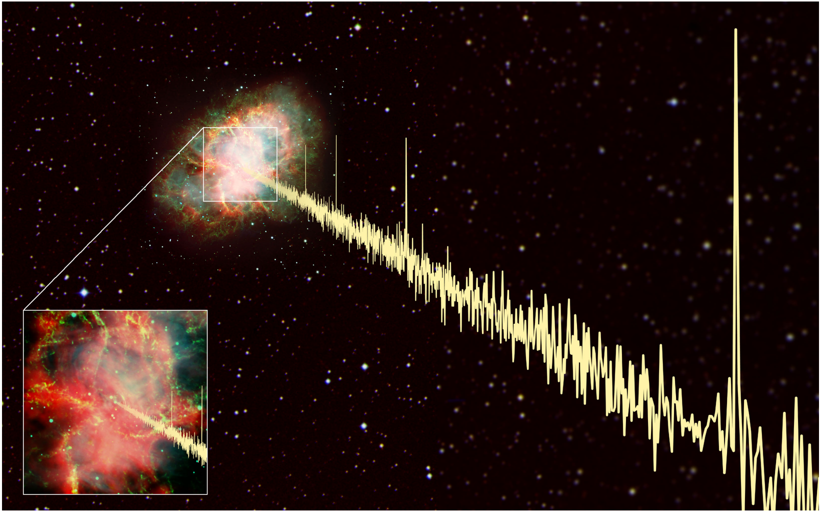
Neutron star compared with Tenerife

Pulsars

- A star of $\sim$ 10–30 $\mathrm{M}_\odot$ explodes as a supernova.
- A neutron star was born.
- Magnetized neutron stars rapidly rotating: pulsar
- Light is emitted through the magnetic poles.
- Can rotate several times per second.

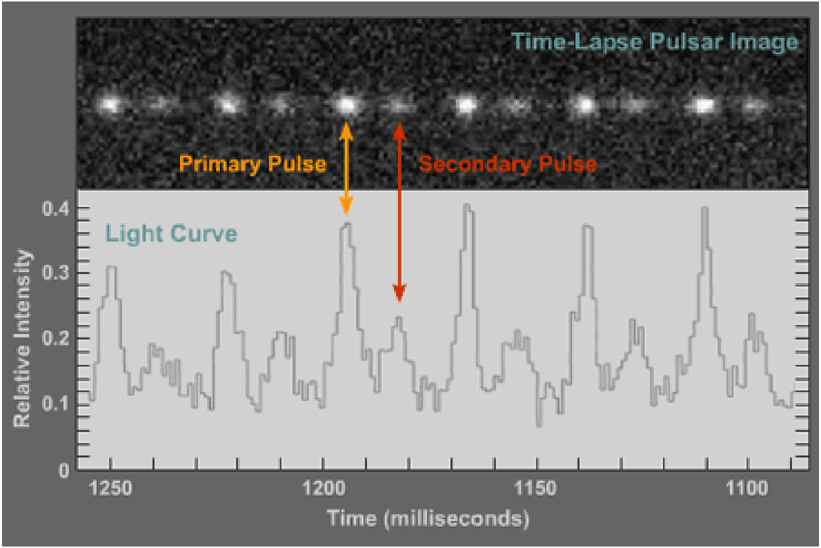


Pulsars



Crab pulsar: ∼6 000 ly away; ∼1 000 yr old; Period: 33 ms.

Pulsars



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Pulsars

Comparison of pulsar-timing together with their accurate proper motions can provide the best mapping on Galactic rotation, cosmological frames, and gravitational waves.

Single dish radio observations: poor astrometry ($\sim$arcmin)

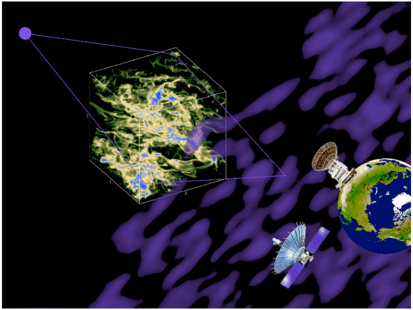
Astrometry of pulsars can be reach sub-milliarcsecond precision only with pulsar timing along several years.

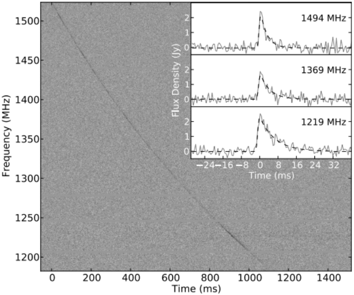
Dispersion Measure (DM)

- The interstellar material disperses the light.
- Broadening of the pulses.
- $t \propto \nu^{-2}$
- $DM \equiv$ integrated column density of free electrons between the emitter and the observer.

$$
\begin{aligned}
DM &= \int_0^D n_\mathrm{e} \mathrm{d}l \\
&\propto \frac{t_2 - t_1}{\nu_2^{-2} - \nu_1^{-2}}
\end{aligned}
$$

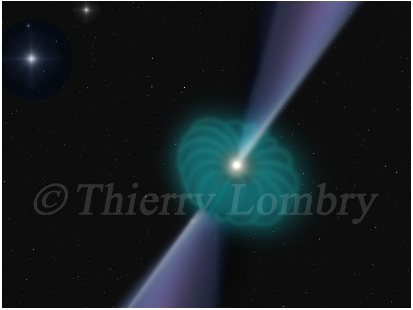
Indirect measurement of the distance or the column density.





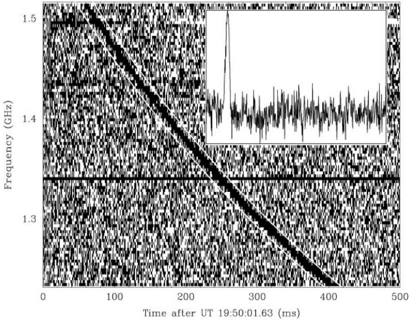
Rotating Radio Transients (RRATs)

- Pulsars where most of the pulses are missing.
  $\Rightarrow$ Easier detectable by single pulse searches.
- Interval between pulses: 4 min–3 hr.
- Periods of 0.4–7 s.
- The presence of a debris disk could originate the *missing* pulses.
- More difficult to localize with single dish observations
  Some of them only $\sim$arcmin

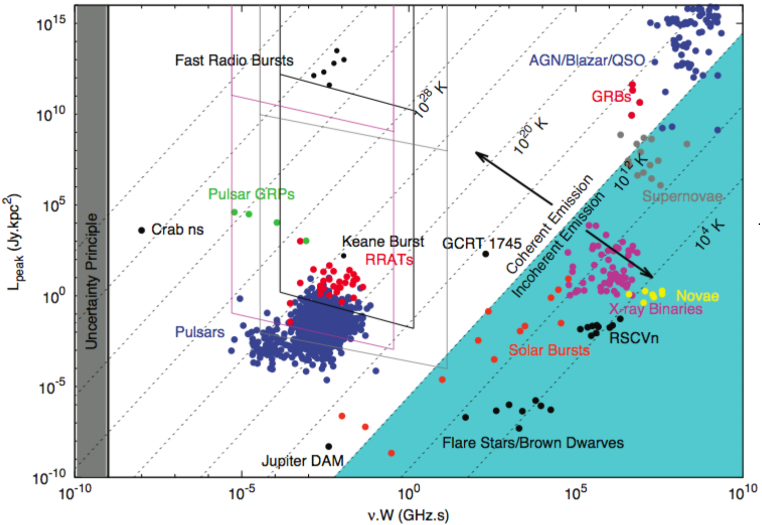


Fast Radio Bursts (FRBs)

- Transient sources exhibiting **a single** bright burst: ∼Jy in ∼ms
- Discovered by Lorimer et al. (2007)
- ∼20 discovered up to now
- The bursts resembles the ones observed in pulsars
- Not obvious associations
- Large DM ⇒ extragalactic
- Origin? extremely young pulsars, magnetars, AGNs?
  Galactic? Extragalactic?



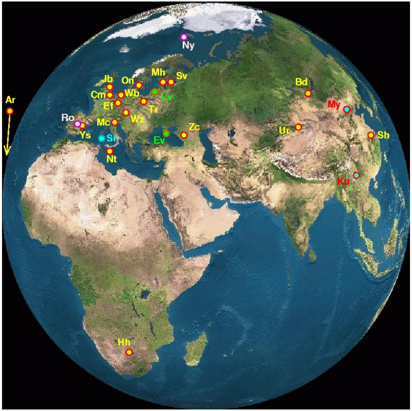
Time-domain sources



Credit: J. P. Macquart

Unveiling the nature of FRBs

- We need a good localization of the FRBs to unveil their nature
  Much better than several arcmin.
- Not possible with single-dish telescopes
  ⇒ interferometry!
- European VLBI Network (EVN): milliarcsecond resolution
- Two different approaches:
  - Image the single pulses (never done)
  - Detect the putative afterglow



FRB afterglows: FRB 150418

FRB 150418: The first announced association

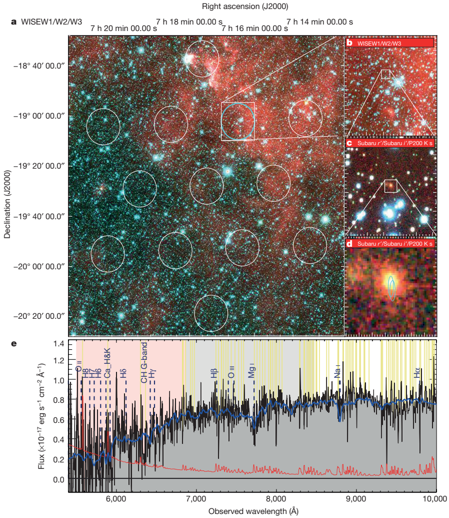
FRB detected by Parkes on 18/04/2015
Pulse width of 0.8 ± 0.3 ms
Linear polarization: $8.5 \pm 1.5\%$
Circular polarization: $\sim$ zero.
DM$= 776.25 \text{ cm}^{-3} \text{ pc}$
($\sim \times 4$ Galactic contribution)

Follow-up with ATCA after 2-hr.
- Two variable compact sources detected.

One previously known source.
- A 6-d transient with $\alpha \sim -1.37$

consistent with an early-type galaxy.
Spurious transient in the field: $< 0.1\%$

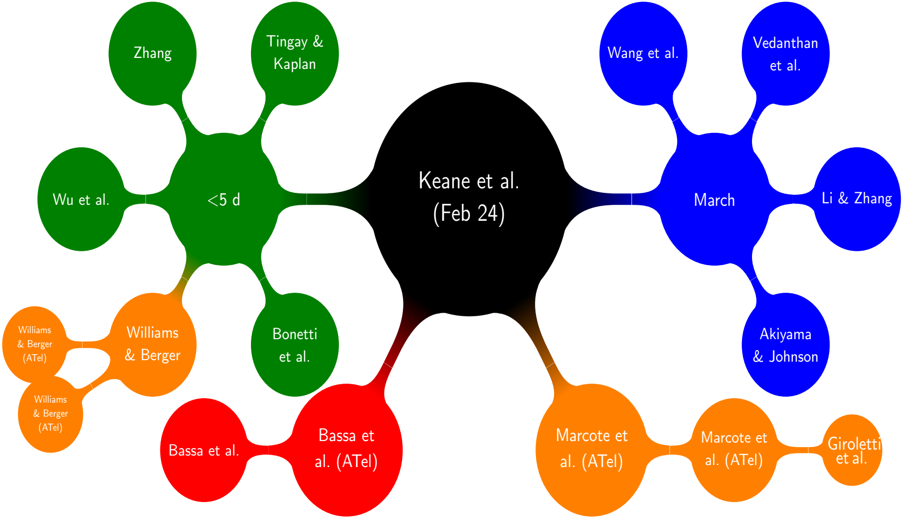
The optical counterpart corresponds to a galaxy at $z \sim 0.5$: **WISE J0716−1900**



Keane et al. (2016, Nature)

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

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



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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.

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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.

Marcote et al. (2016a,b);Giroletti et al. (2016): EVN obs. Keep listening!

EVN observations

We conducted four e-EVN observations from March to June 2016 on WISE J0716−19 at 5.0 GHz.

9 participating stations: Effelsberg, Jodrell Bank, Westerbork, Medicina, Noto, Onsala, Torun, Yebes, and Hartebeesthoek.

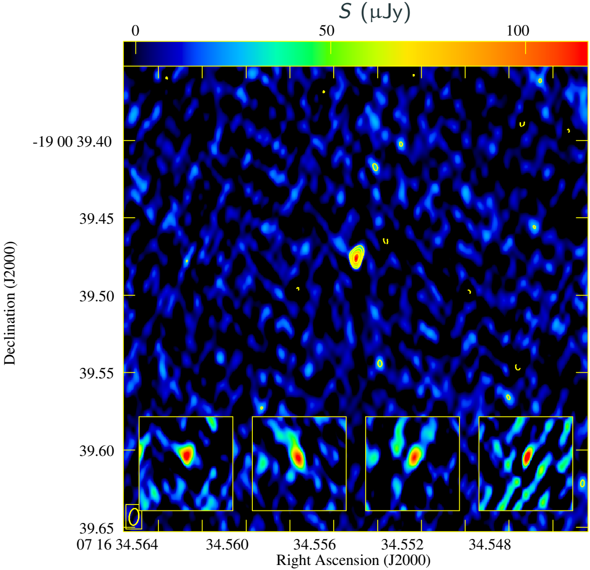
We also conducted simultaneous e-MERLIN observations at three epochs.

Epoch		EVN data				e-MERLIN data				
Date in 2016	MJD	HPBW (mas × mas, °)	I_{peak} (μJy beam^{-1})	I_{noise} (μJy beam^{-1})	$S_{5.0,JMFIT}$ (μJy)	HPBW (mas × mas, °)	I_{peak} (μJy beam^{-1})	I_{noise} (μJy beam^{-1})	$S_{5.0,JMFIT}$ (μJy)	$\Delta S_{5.0}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
March 16	57463.8	10.1 × 6.2, 3.9	123	18	125 ± 22	...	...	...	...	
May 10	57518.6	9.7 × 6.1, 8.7	113	14	137 ± 20	261 × 25, 12	169	55	176 ± 58	40 ± 60
May 31	57539.6	10.9 × 6.1, −7.5	107	16	117 ± 20	231 × 27, 11	145	48	158 ± 51	40 ± 55
June 2	57541.6	9.3 × 5.3, 1.3	133	20	125 ± 32	212 × 28, 10	254	52	272 ± 59	145 ± 70

EVN observations

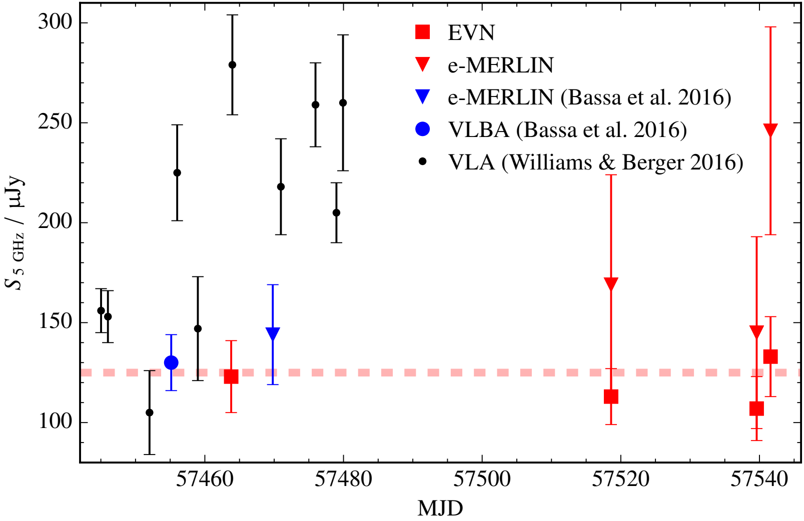
Peak brightness (μJy beam^{-1}):

$$I_{\mathrm{Mar16}} = 123 \pm 18$$
$$I_{\mathrm{May10}} = 113 \pm 14$$
$$I_{\mathrm{May31}} = 107 \pm 16$$
$$I_{\mathrm{Jun2}} = 133 \pm 20$$
$$I_{\mathrm{sum}} = 115 \pm 9$$



EVN observations

Light-curve more than 1 yr after the FRB.



Discussion and conclusions

- The VLBI observations show a compact $\sim$130-μJy source persistent on day-to-month timescales.
- Bolometric radio luminosity of 5.6×10^{39} erg s^{-1}.
- Brightness temperature of $\gtrsim 10^{8.5}$ K.
- But the VLA data indicate variability! on hour timescales?
- Missing VLA flux? no more compact sources in the field.
- The compact source seems to be compatible with a scintillating low-luminosity AGN.
- Origin of FRB 150418?

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

Direct single pulse imaging

Direct single pulse imaging

The unambiguous approach to localize a FRB: **image its single pulse**.

Problems:

- Requires to produce an image of only $\sim$ms with an interferometer.
- Really small sensitivity and (lack of) *uv* coverage.
- Strong artifacts (lobes) in the image.
- How to calibrate the data?
- Never done before with interferometers!

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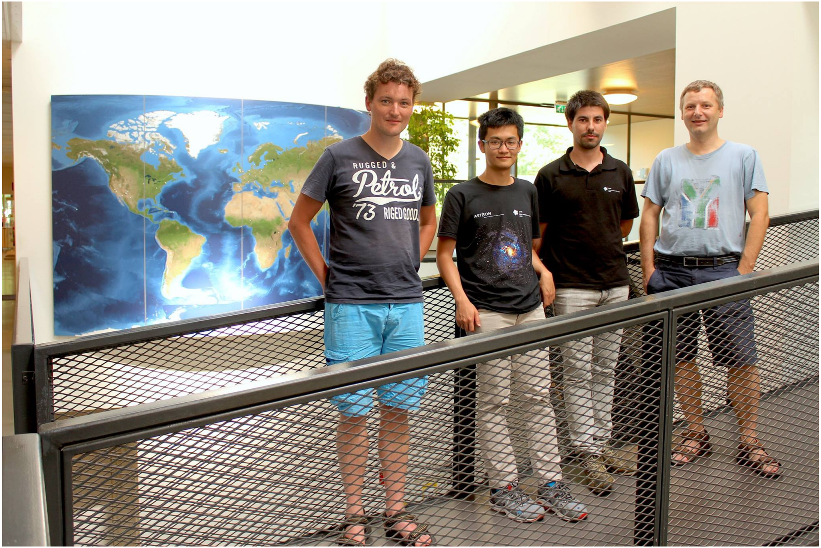
- How to calibrate the data?
- Never done before with interferometers!
- Project started last year in the EVN
- Boosted this summer in collaboration with Yuping Huang (ASTRON/JIVE summer student)

Direct single pulse imaging



Aard Keimpema, Yuping Huang, Benito Marcote, Zsolt Paragi

EVN single pulse imaging

We observed two different sources:

- A bright known pulsar: PSR B0525+21
- A RRAT: J1819−1458

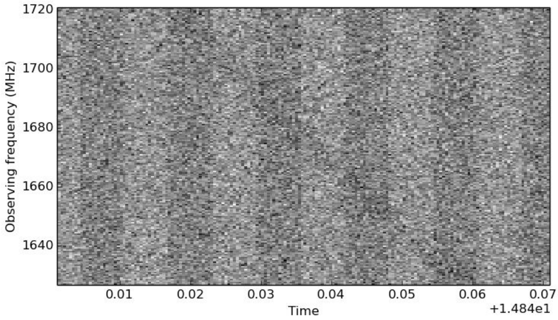
The single pulse imaging requires two different parts:

- Pulsar-timing data (as regular in pulsar obs.)
  BUT: no pulsar backend.
- Standard continuum data with 1–2 s integration time.

De-disperse the data & apply continuum calibrations to data with $<$ms integration time.

Challenges: no pulsar backend

Backend not Designed for Pulse Search



A chunk of our data showing signatures of the 80Hz calibration signal

Challenges: extrapolating calibration

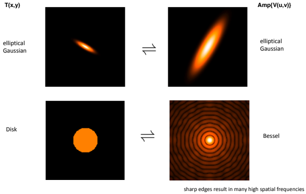
- We calibrate the dataset with 1–2 s integration time as usual in EVN observations
- Phase-referencing observations: calibrator + target + calibrator. . .
- We extrapolate solutions during minutes.
- The solutions work in normal 1–2 s solutions.
- Does they work at ms timescales?

. . . in principle they should!

Challenges: *uv*-coverage

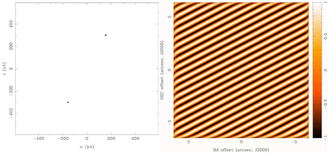
Interferometry is based on the signal combination of different antennas.

2D Fourier Transforms



PSF shape vs. N ants

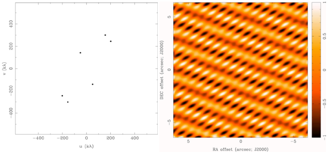
2 antennas



- to characterize a source, I need to sample as much as possible the uv plane.

PSF shape vs. N ants

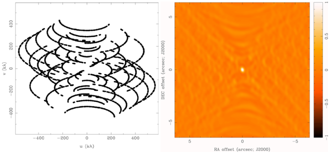
3 antennas



by increasing the number of antennas …

PSF shape vs. N ants

8 antennas x 240 samples



- ALMA has an *"instantaneous"* coverage uv plane…

Challenges: *uv*-coverage

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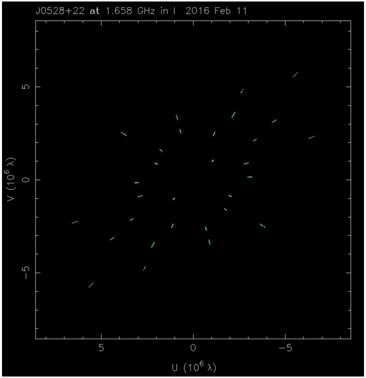
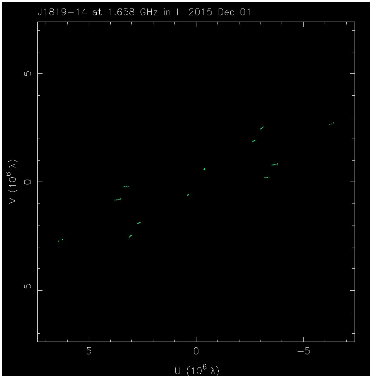
UV Coverage



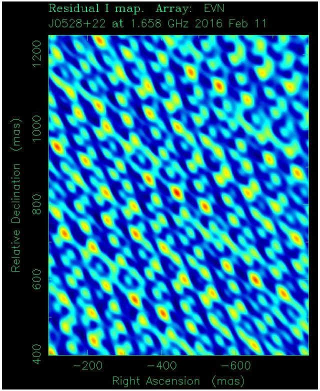
PSR B0525+21: Ef, Jb2 ,Mc ,O8 ,Tr ,Wb
750 mJy pulse, 15 baselines



RRAT J1819-1458: Ef,Jb2 , Mc, Wb
7 Jy pulse, 6 baselines

Challenges: *uv*-coverage

Dirty image: the good & the bad



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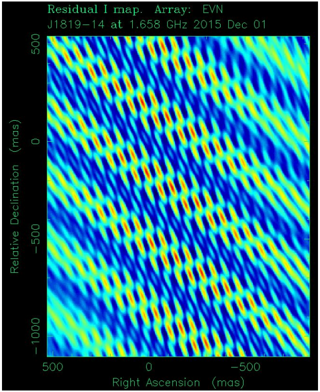

RRAT J1819-1458: Ef,Jb2 , Mc, Wb
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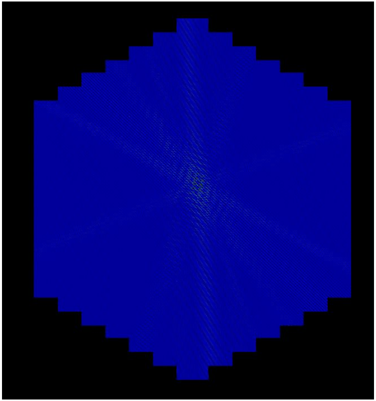
Wide-field Facet Imaging

Why?

- Sometimes we don't have good a priori position
- EVN as a non-coplanar array
- Easy parallelization for analysis



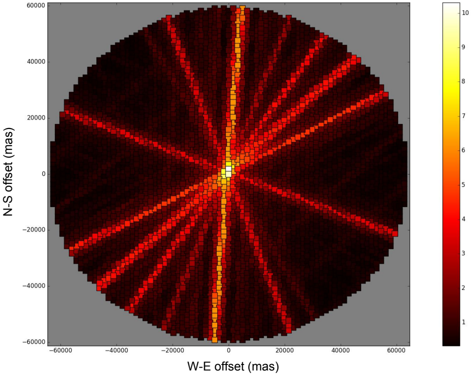
PSR B0525+21
10 arcsec radius
2-arcsec facets
0.5 mas resolution

Source Detection

- Combining all images is hard

instead we can

- Estimate noise from the entire map (parallelized)
- Plot peak SNR for each 2’’x2’’facet



PSR B0525+21 diagnostic
750mJy pulse
1-arcmin radius
2-arcsec facets

Delay Mapping

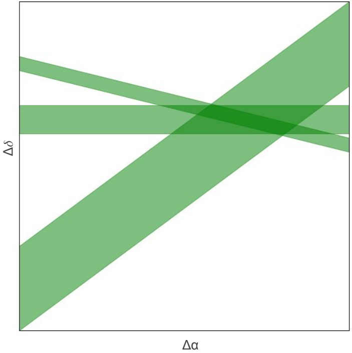
The residual delay from the phase center for each antenna with coordinate (u,v), to the first order, is given by

$$\tau = \frac{1}{c}(u\Delta\alpha + v\Delta\delta)$$

where Δα, $\Delta\delta$ are right ascension and declination offsets from the phase center.

Hence for each antenna, we have linear constraint on (Δα, $\Delta\delta$).

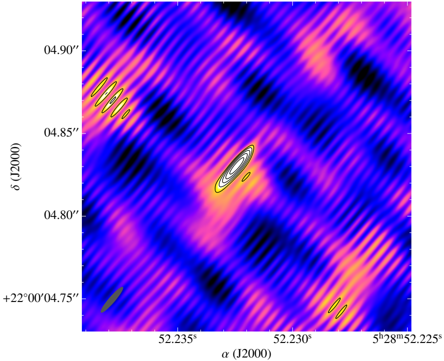
In our data, this method gives ~1 arcsec constraint on position



Schematic illustration of delay mapping in the (Δα, $\Delta\delta$) plane

Localizing single pulses: we did it!

- Pulsar PSR B0525+21.
- Images of single pulses.
- Position accuracy within the synthesized beam.
- Pulses with SNR > 6 within few mas.



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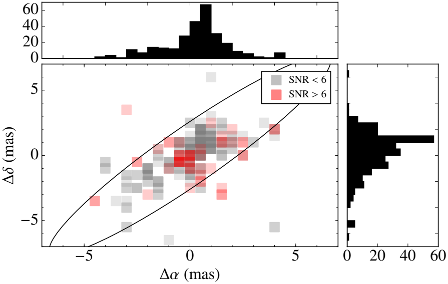


406 pulses imaged

50 with SNR $>$ 6.

Conclusions

The EVN can image single pulses of ∼mas reaching astrometric measurements of ∼arcsec (Huang et al. in prep.).

Completely new observing window with this instrument.

Interesting for several sources:

- **Pulsars:** imaging of pulsars, e.g. inter-pulse emission.
- **RRATs:** mas localization.
- **FRBs:** imaging and localization (*unambiguous* localization).

In the coming years we will provide an accurate astrometry of poorly localized RRATs, and hopefully FRBs.

Thank you

Challenges: localization

Position Measurements for RRAT J1819-1458

Need NW - SE Baselines

Phase instability

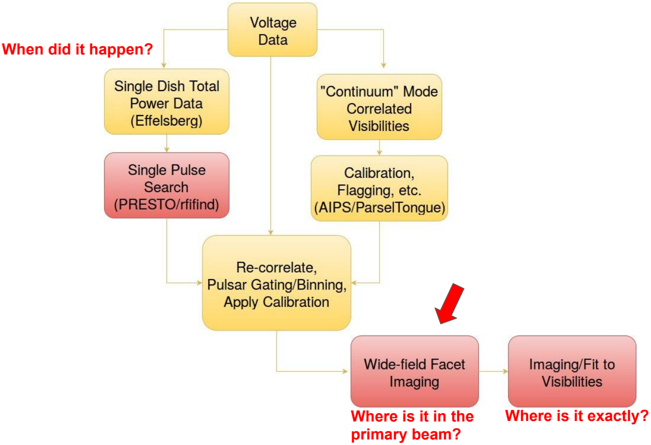
- Low elevation
- 3° separation from the calibrator
- Only 29° away from the sun
- Calibrator in the galactic plane

Discarding points around bad calibration solutions improves consistency (red-blue markers)

➡ **Simply concatenating all pulses might lead to spurious position (phase slope) measurement**

EVN imaging: steps to be done

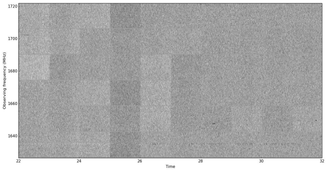
Next step



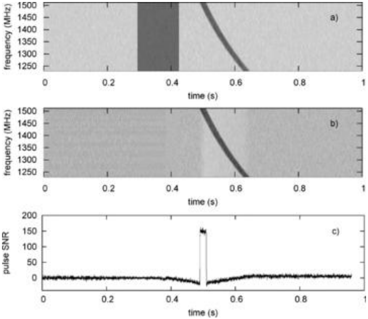
Challenges: pulsar backend

Single Pulse Search with the EVN Backend

- **Bandpass correction**
- **IF-dependent Zero-DM subtraction (modified from Eatough et al. 2009)**
- De-disperse Trials & Match Filtering (Cordes & McLaughlin 2003)



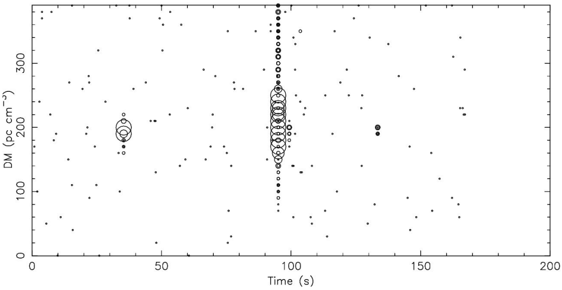
Dynamic spectrum of a chunk of our data



Simulated dispersed & undispersed signals (Eatough et al., 2009)

Challenges: pulsar backend

Pulse detection example output from our data



RRAT J1819-1458, size of circle proportional to SNR