Multi-wavelength follow-ups for FRBs

SUPERB

The case of SUPERB FRBs

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FRB Conference, Aspen, 2017

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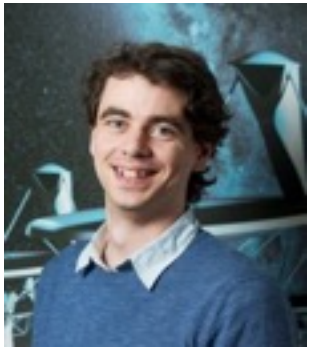
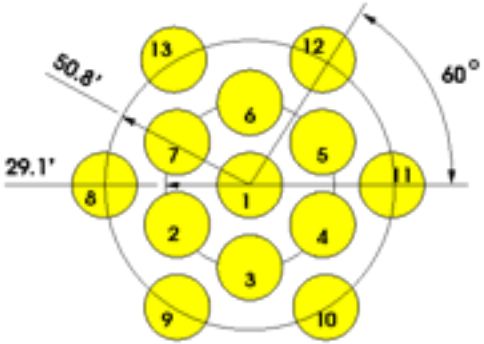
Outline

- Efforts for FRB searching in real-time
  - Introduction to SUPERB and survey specifications
  - SUPERB data processing pipelines
  - New FRB detections
- Multi-wavelength follow-ups
- Why multi-wavelength follow-up is important?
  - The rise and fall of J071634.59-190039.2
  - FRB 131104: Gamma ray association and the unusual variable radio source
- Current strategies and Discussion

SURVEY FOR PULSARS AND EXTRA-GALACTIC RADIO BURSTS

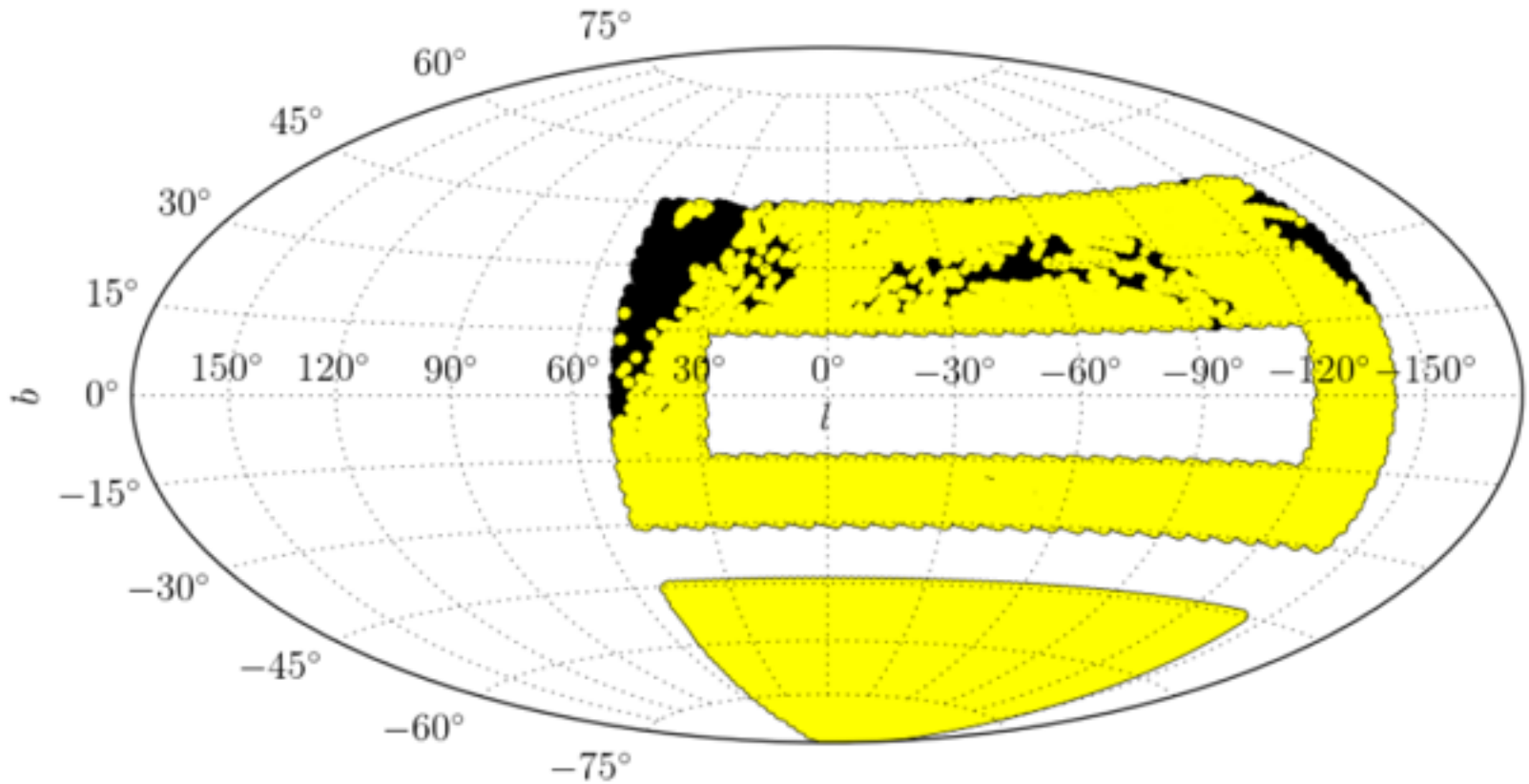


- Finding FRBs in real time
- Effecting multi-wavelength follow-ups
- Understanding nature and origin of FRBs



SUPERB
Survey for Pulsars and Extragalactic Radio Bursts

Specifications



SUPERB data processing pipelines

- Transient and periodicity searches.
- There are two data pipelines
  - Fast pipeline: Real-time processing
  - Thorough pipeline: Offline processing

Parameter	F pipeline	T pipeline
DM range (pc cm^{-3})	0–5000	0–9988
DM trials, N_{DM}	1749	1986
Width trials	$(1-2^{10}) \times t_{\mathrm{samp,\,DM}}$	$(1-2^{12}) \times t_{\mathrm{samp,\,DM}}$
RFI excision methods	Bad channels	Bad channels eigenvector excision

Keane et al. 2017 (in prep)

Real time processing
Single pulse search

- Data acquisition and RFI flagging
- HEIMDALL – Box car convolution algorithm
- Coincidence filtering

$$\mathrm{S/N} \geq 10$$
$$N_{\mathrm{beams}} \leq 4$$
$$N_{\mathrm{events}}(t_{\mathrm{obs}} - 2\,\mathrm{s} \rightarrow t_{\mathrm{obs}} + 2\,\mathrm{s}) \leq 5$$

→ Pulsar candidates from single pulse search

↓

$$\mathrm{DM} \geq 1.5 \times \mathrm{DM}_{\mathrm{Galaxy}}$$
$$\mathrm{W} \leq 16.384 \quad \mathrm{ms}$$

← FRB candidates

Keane et al. 2017 (in prep)

From: BPSR FRB Detector [Andrew.Jameson@atnf.csiro.au]
Sent: Saturday, 18 April 2015 2:29 PM
To: Andrew Jameson
Subject: New Detection: FRB150418

UTC START	2015-04-18-04:21:15
Source	G233.2-03.3_s
PID	P892
NE2001 DM	189.1684

FRB Detections

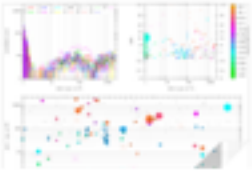
SNR	Time	DM	Length	Beam	Known Source(s)
29.5571	471.66	774.723	1.024	04	

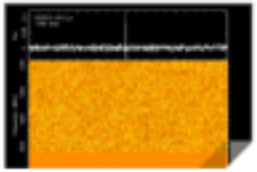
Beams Positions & Known Sources

Beam	RA	DEC	Gl	Gb
01	07:17:28.3	-19:28:08.7	233.16997547	-3.2600178939
02	07:16:22.4	-19:52:44.6	233.41381672	-3.6792507386
03	07:15:25.0	-19:26:58.0	232.92805616	-3.6803552890
04	07:16:30.9	-19:02:24.4	232.68442586	-3.2610104572
05	07:18:33.9	-19:03:31.4	232.92633778	-2.8407264687
06	07:19:31.6	-19:29:13.3	233.41169448	-2.839618867
07	07:18:25.0	-19:53:51.0	233.65552280	-3.2587968426
08	07:17:19.0	-20:18:51.5	233.90496614	-3.6809846212
09	07:14:17.4	-19:51:42.4	233.17191166	-4.1058511689
10	07:14:26.6	-19:01:00.3	232.43691718	-3.6843297815
11	07:17:36.5	-18:37:25.0	232.43560046	-2.8385186410
12	07:20:38.3	-19:04:22.7	233.1680439	-2.4141821187
13	07:20:30.0	-19:55:05.8	233.9024127	-2.835175025

Plots

2 Attachments





Multi-wavelength synergies

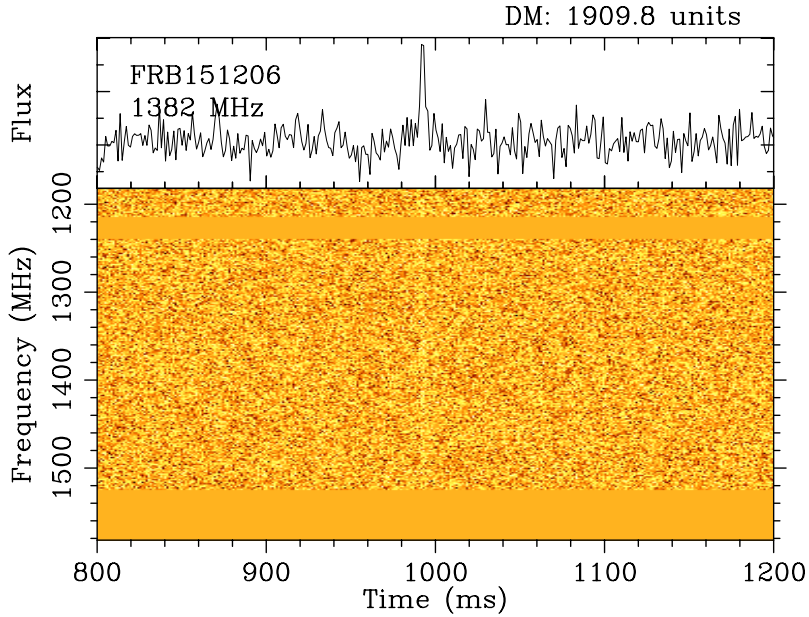
Radio Telescope | HESS | Optical Telescope | ANTARES

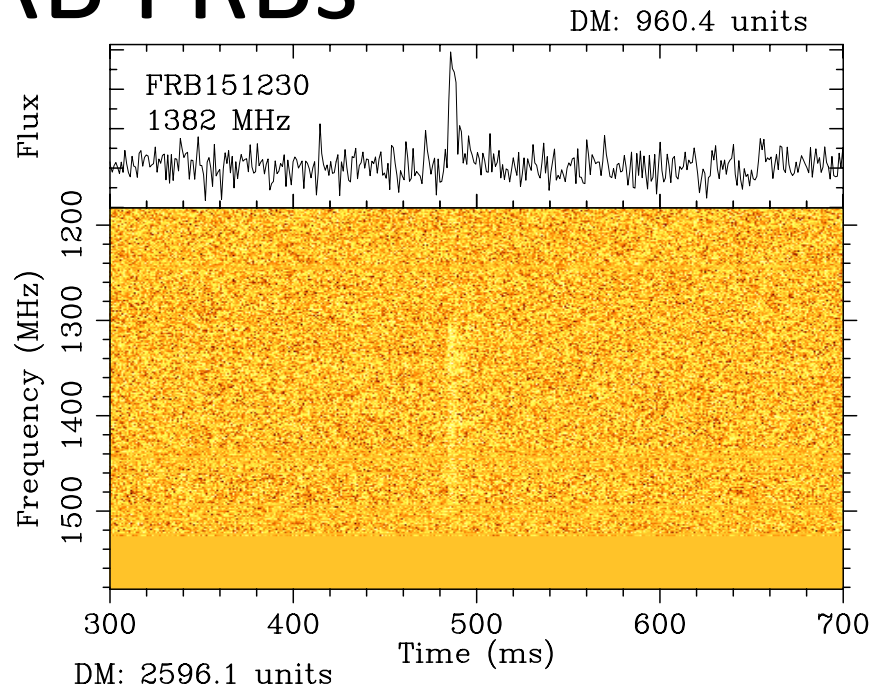
Christmas and New Year FRBs

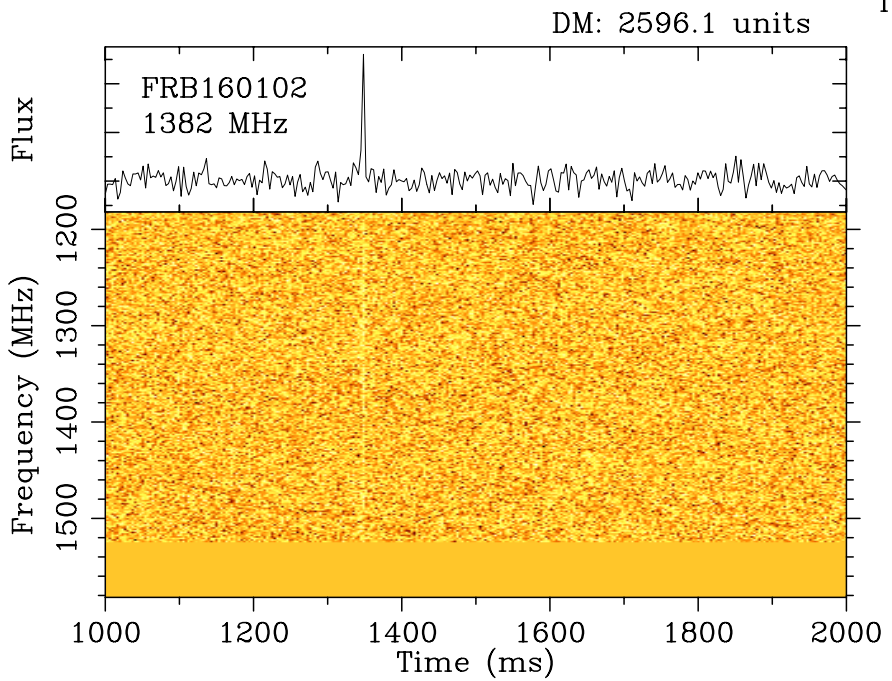
#fireworks in the radio sky

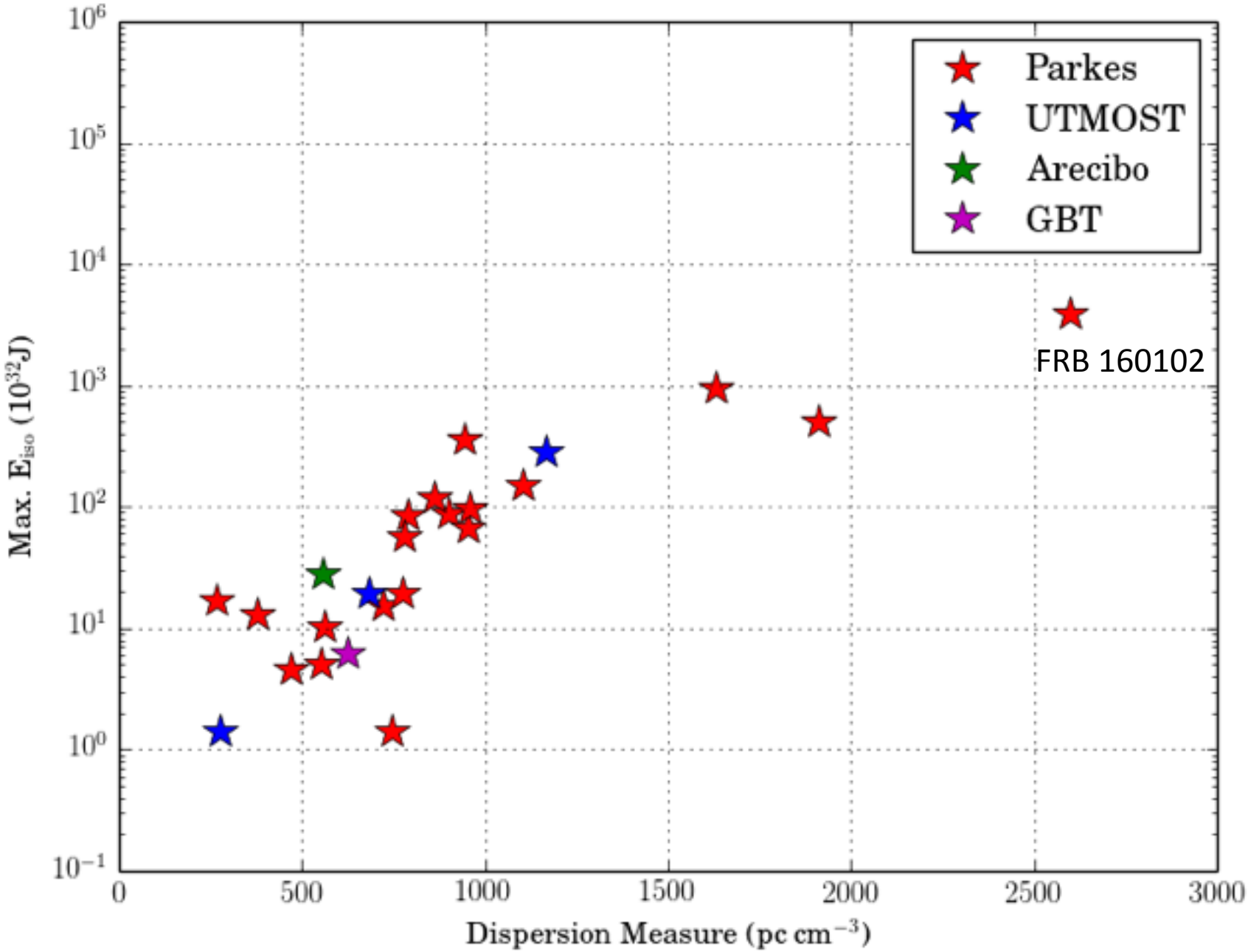
Bhandari et al. 2017 (in prep)

SUPERB FRBs

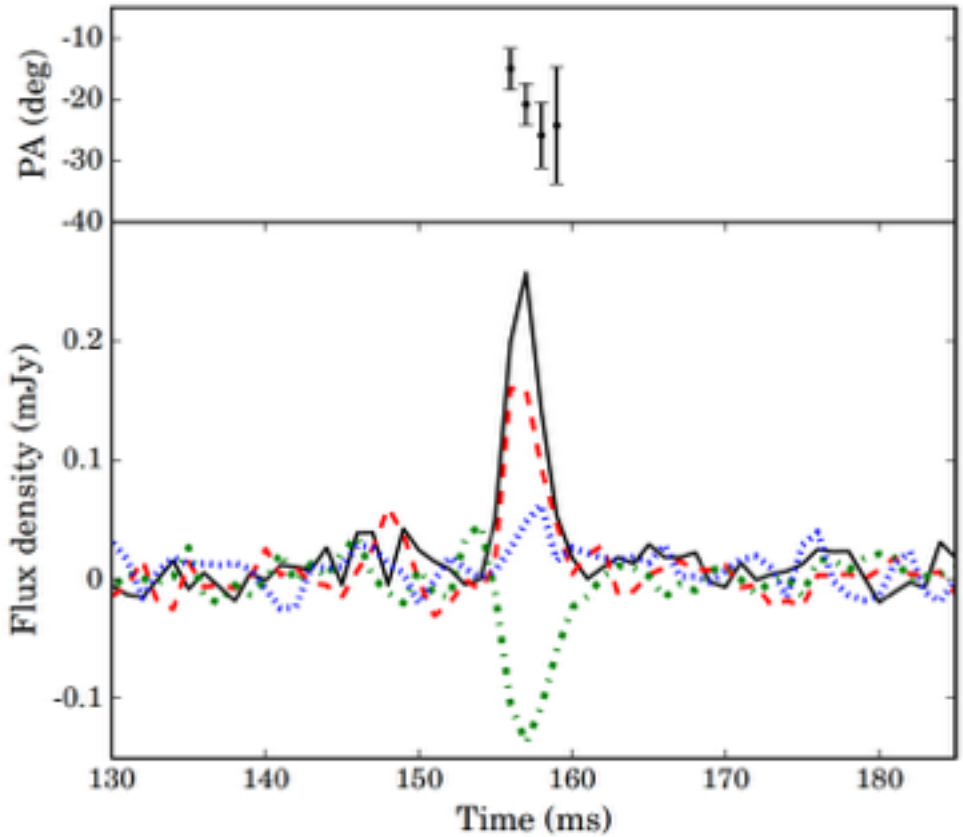

DM: 1909.8 units
FRB151206
1382 MHz
Flux
Frequency (MHz)
1200
1300
1400
1500
800
900
1000
1100
1200
Time (ms)


DM: 960.4 units
FRB151230
1382 MHz
Flux
Frequency (MHz)
1200
1300
1400
1500
300
400
500
600
700
Time (ms)


DM: 2596.1 units
FRB160102
1382 MHz
Flux
Frequency (MHz)
1200
1300
1400
1500
1000
1200
1400
1600
1800
2000
Time (ms)


Parkes
UTMOST
Arecibo
GBT
FRB 160102
Max. E_{iso} (10^{32}J)
Dispersion Measure (pc cm^{-3})
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
500
1000
1500
2000
2500
3000

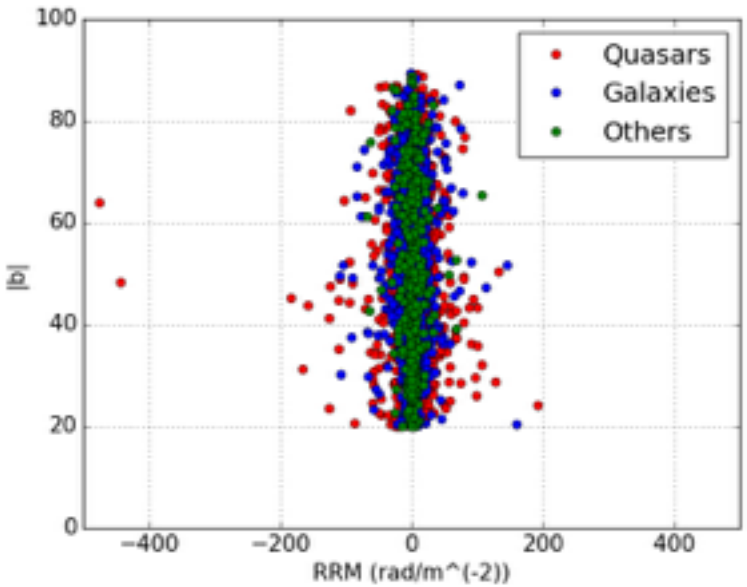
Polarisation for FRB 160102

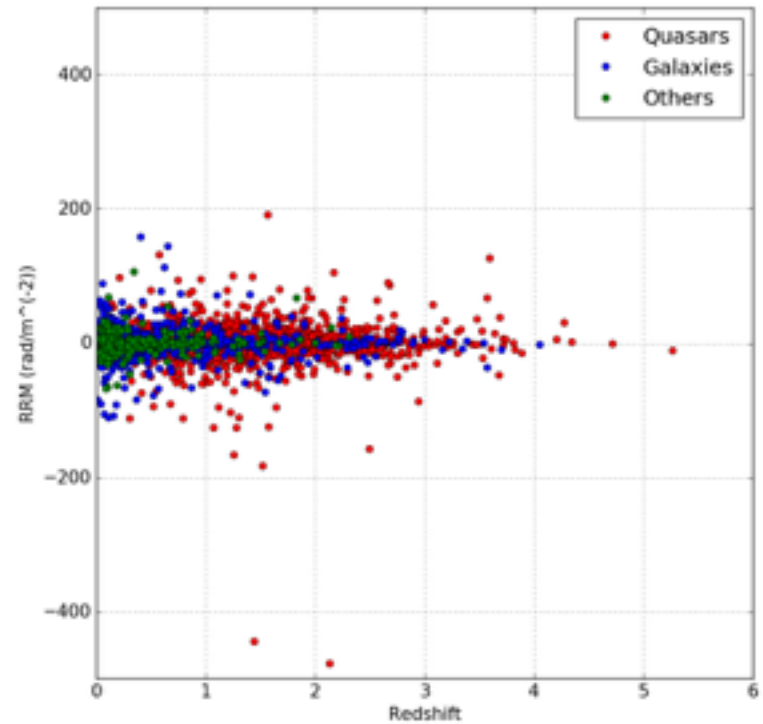


FRB 160102 – 100% polarised
RM = -220.6 +/- 6.4 rad m^{-2}

Caleb & Bhandari et al. 2017 (in prep)

How many high RM continuum extragalactic radio sources are there in the Universe ?

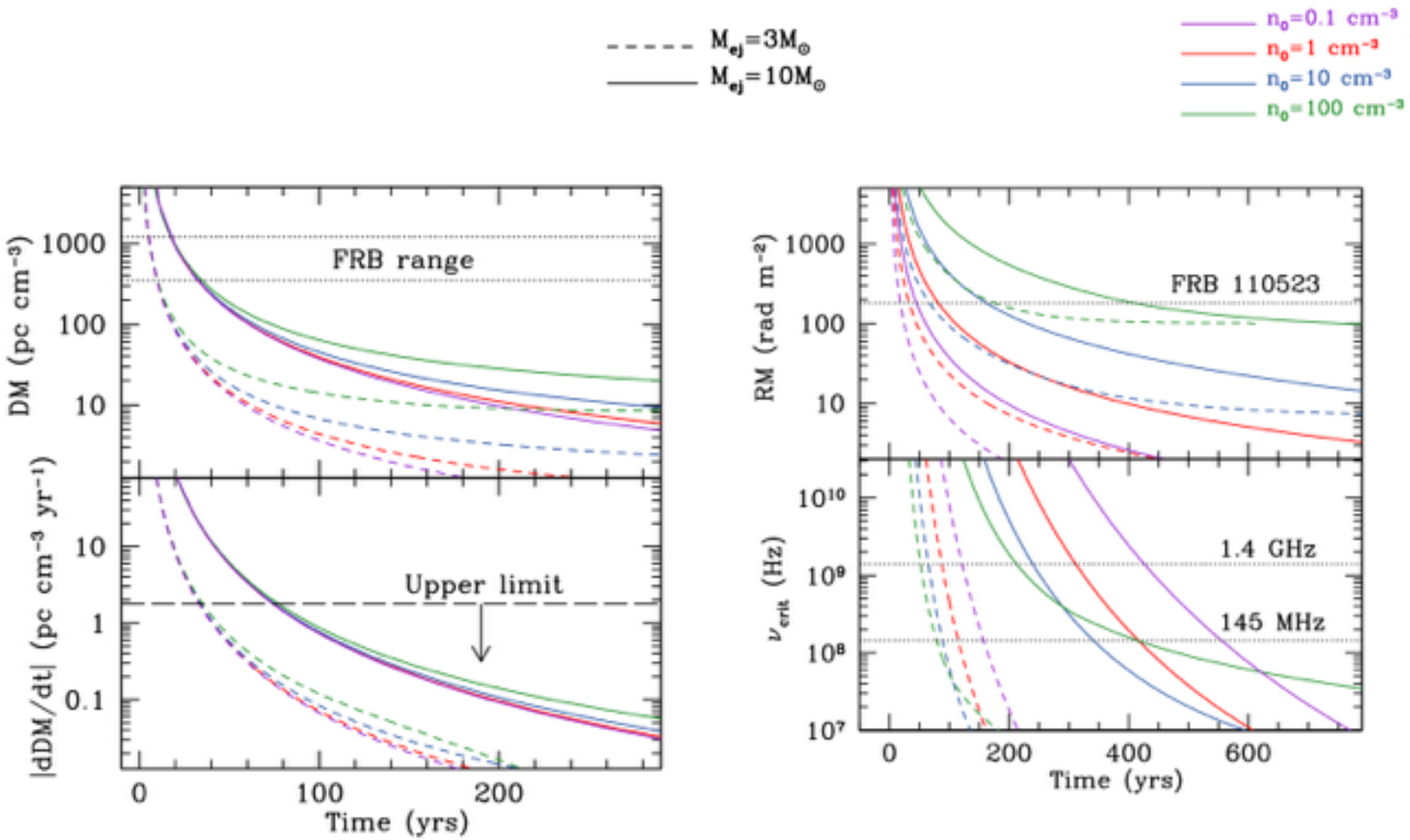




NOT MANY!

Adapted from Hammond et al. 2013

Young and expanding SNRs?



PIRO (2016)

Possible progenitors

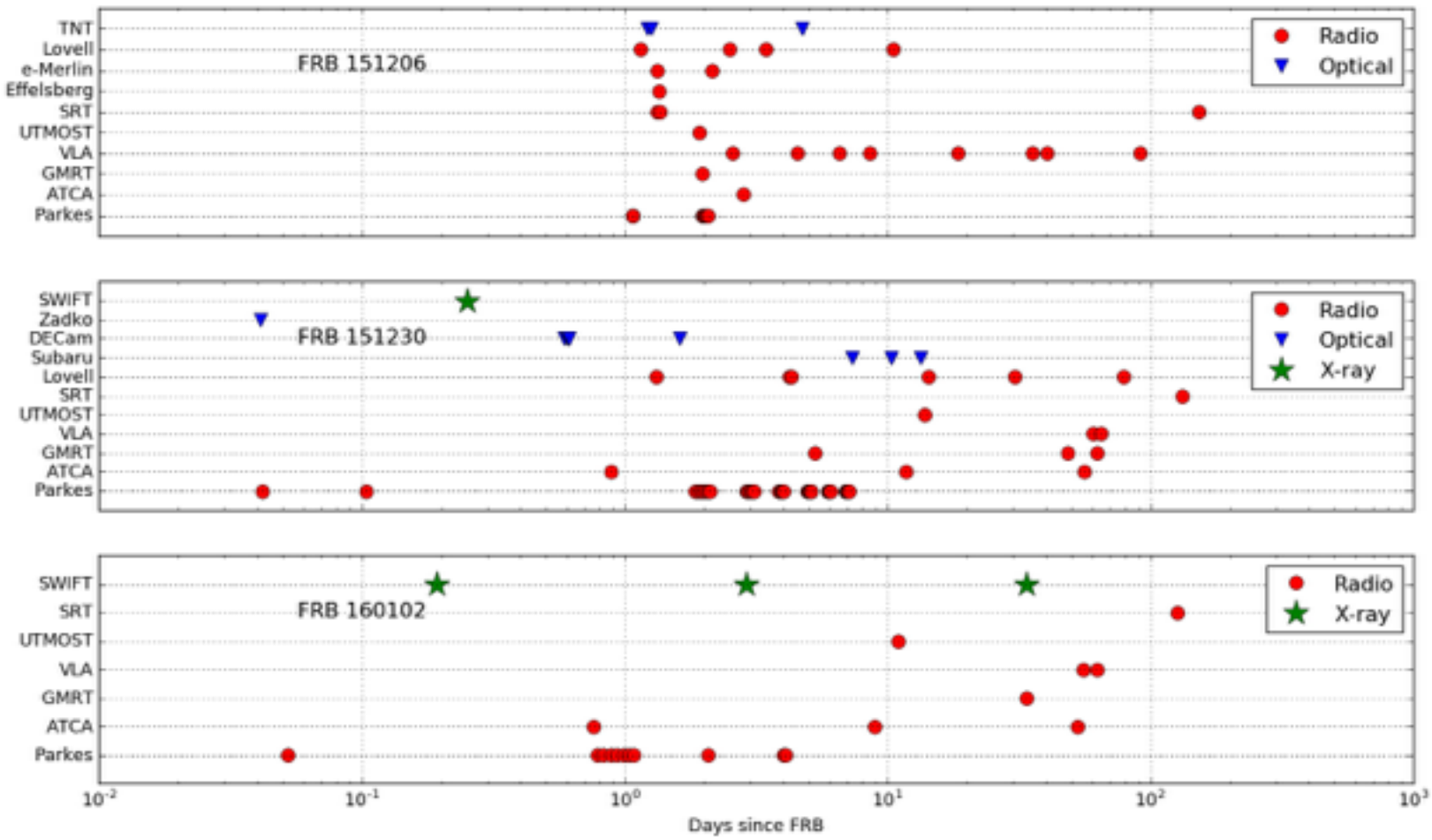
- Young and expanding SNRs (Piro 2016)
- Young SNR pulsars (Connor et al. 2015)
- Supergiant pulses from extragalactic neutron stars (Cordes et al. 2015)
- Magnetars (Popov et al. 2013)

Connor et al 2015.

Location	Model	Galactic scintillation	Faraday rotation	$\frac{d\ln N_{FRB}}{d\ln S_\nu}$	Counterpart	DM range (pc cm^{-3})	Pol angle swing
Cosmological ($\gtrsim 1h^{-1}$Gpc)	Blitzars	×	$\lesssim 7$ rad m^{-2}	?	gravitational waves	300-2500	×
	Merging COs	×	$\lesssim 7$ rad m^{-2}	?	type Ia SNe, X-ray, γ-ray	300-2500	×
	Primordial BHs	×	$\lesssim 7$ rad m^{-2}	?	~TeV	300-2500	×
	Magnetar flare	×	$\lesssim 7$ rad m^{-2}	?	~ms TeV burst	300-2500	✓
Extragalactic, local ($\lesssim 200h^{-1}$Mpc)	Edge-on disk	✓	50-500 rad m^{-2}	-3/2	?	10-2000	?
	Nuclear magnetar	✓	10^{3-5} rad m^{-2}	-3/2	none	10-3000	✓
	SNR pulsar	✓	20-10^3 rad m^{-2}	-3/2	archival CC SNe or nearby galaxy	10^2-10^4	✓
Galactic ($\lesssim 100$ kpc)	flaring MS stars	✓	RM_{gal}	-3/2	main sequence star	$\gtrsim 300$	×
Terrestrial ($\lesssim 10^5$ km)	RFI	×	$\lesssim RM_{ion}$	$\begin{cases} -1/2 \; if \; 2D \\ -3/2 \; if \; 3D \end{cases}$	none	?	×


Multi-wavelength follow-up campaign
Image credit: NASA.

Follow-up campaign

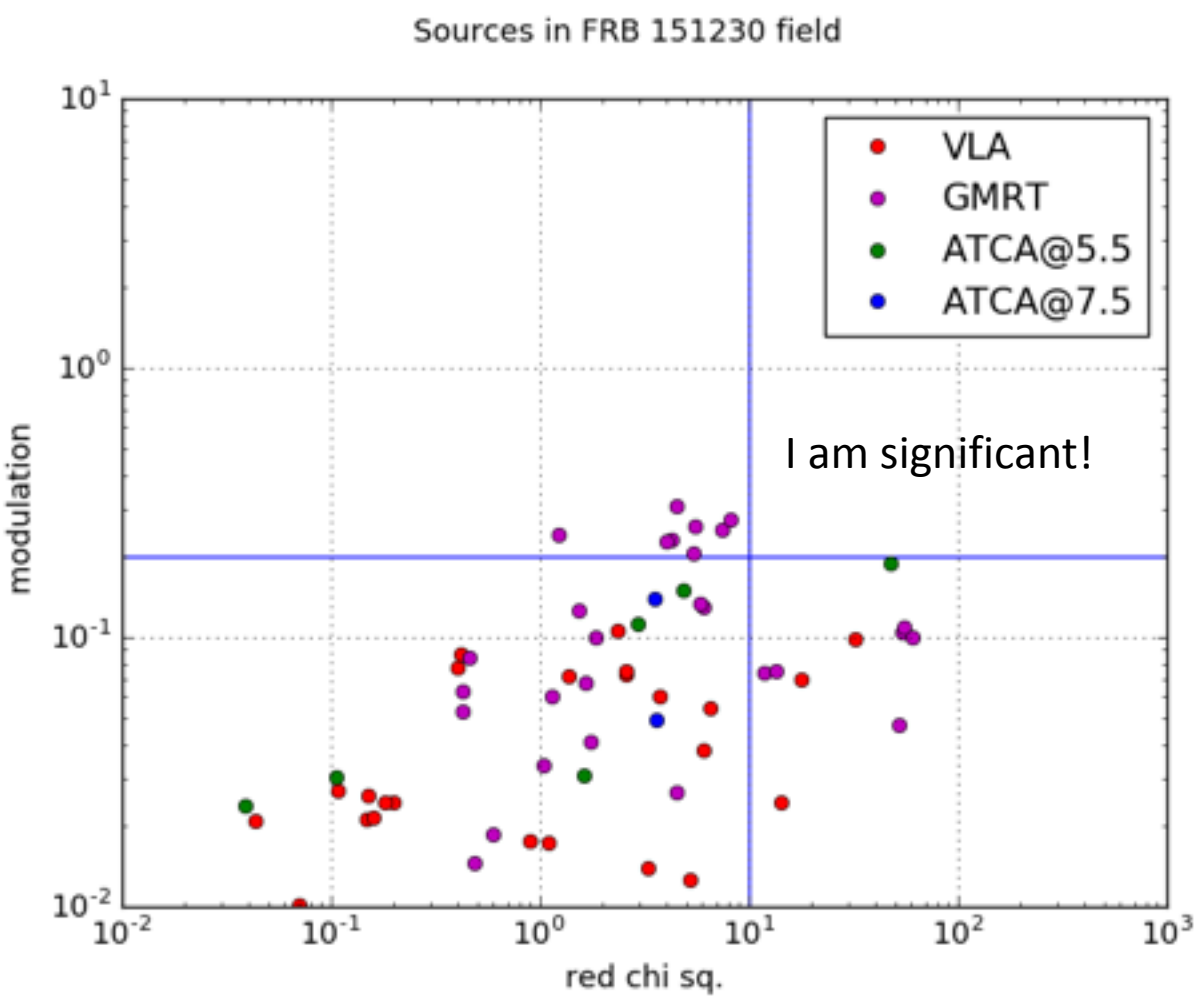


Any hints in radio follow-ups? Observations

- ATCA
  - 42 pointing mosaics encompassing Parkes 15’ FWHM
  - C band 2 IFs – center freqs : 5.5 GHz and 7.5 GHz
  - Best RMS ~ 40 uJy/beam
- GMRT
  - L band – center freq : 1.4 GHz
  - Best RMS ~ 30 uJy/beam
- VLA
  - 7 pointing mosaics encompassing Parkes 15’ FWHM
  - C band – center freq : 5.9 GHz
  - Best RMS ~ 10 uJy/beam

Image credit: NRAO.

Any hints in radio images ?
Results: FRB 151230



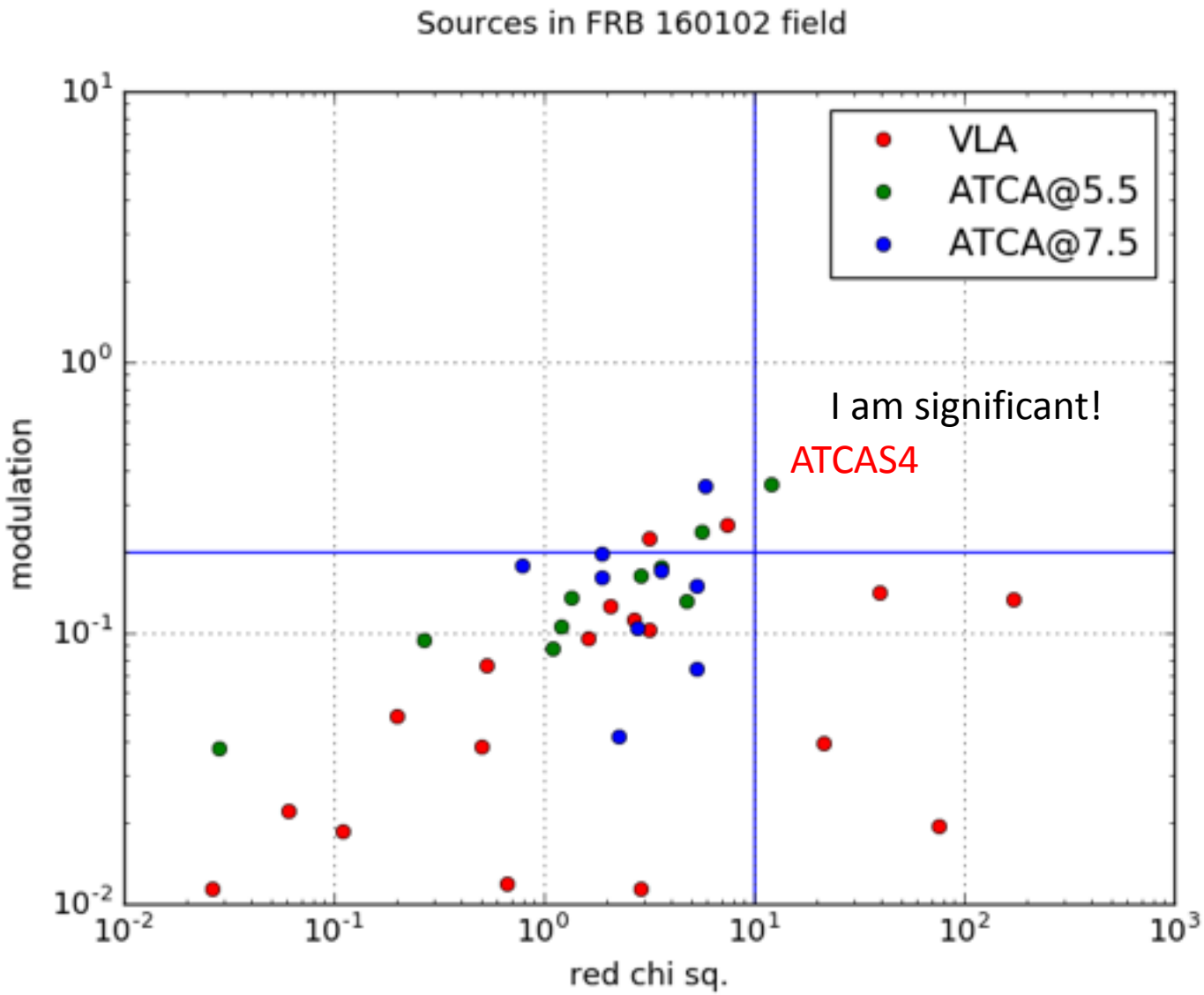
$$\chi^2 = \sum_{i=1}^{n} \frac{(S_i - \bar{S}_{\mathrm{wt}})^2}{\sigma_{i^2}}$$

$$\eta = \frac{\chi^2}{\mathrm{n} - 1}$$

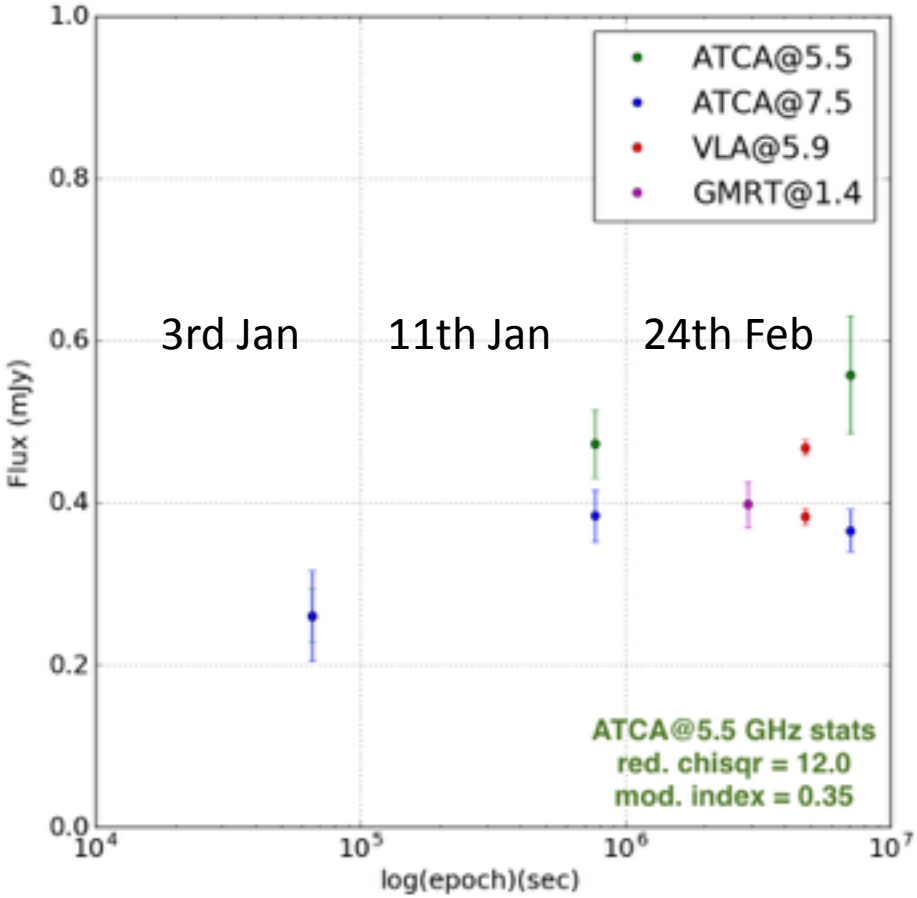
$$m = \frac{1}{\bar{S}} \sqrt{\frac{\sum_{i=1}^{n} (S_i - \bar{S})^2}{n - 1}}$$

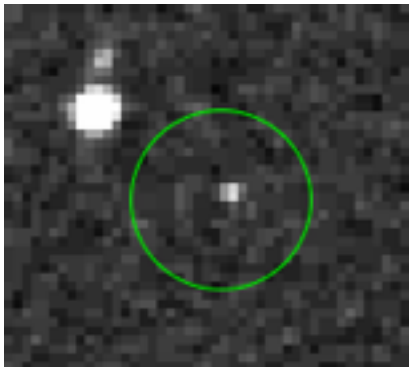
Variability and transient criteria from Rowlinson et al 2016

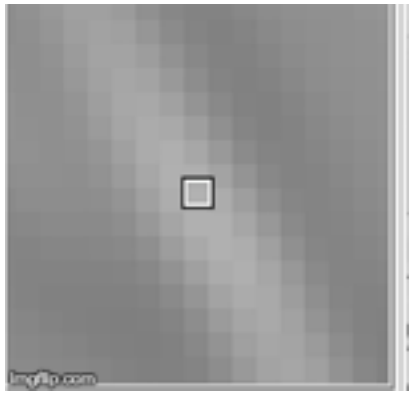
Any hints in radio images ?
Results: FRB 160102



ATCAS4 details







- This source is identified to be a quasar in the HMQ catalog (Flesch E. 2015).
- It is also identified in GALEX and has a DSS (optical) counterpart.

Did FRBs repeat?

Optical follow-ups

- Thai National Telescope (TNT) – FRB 151206
  - FOV = 8’X8’
  - r’ band 5 sigma detection limit ~ 22.0
  - 5 variable sources – maximum delta mag ~ + 0.5
  - Stellar variability.
- Subaru – FRB 151230
  - g, r and i band, 5 sigma detection limits ~ 25
  - 2 AGNs in field
  - No optical transients

Optical follow-up conti..

- DECam – FRB 151230
  - FOV ~ 3 deg^2
  - u, g, r and i band; i band 5 sigma detection limits ~ 22.5
  - 4 asteroids and 1 unidentified transient.
- Zadko – FRB 151230 shadowing!
  - FOV ~ 23’X23’
  - Limiting r band magnitude ~ 19.8
  - Asteroids
  - No convincing variables/transients!

Optical follow-up results

- Variability attributed to stellar variability, AGN variability or presence of asteroids.
- No optical afterglows with limiting magnitude I mag ~ 25.0 and R mag ~ 22.0
- Cadence under investigation: minutes, days to week.

Credit: Gemini Observatory/AURA

X-ray follow-up

- Triggered for FRB 151230 and FRB 160102.
- FRB 151230
  - No sources detected above 3 sigma
  - limiting flux ~ 1.9E-13 erg/cm^2/s
- FRB 160102
  - No sources detected above 3 sigma
  - limiting flux ~ 1.4E-13 erg/cm^2/s

SUMMARY I

SUPERB FRBs

- SUPERB - three new FRB discoveries.
- FRB 160102 is ~100% polarised.
- No significant transients in radio, optical or x-ray in any of the three FRB fields.
- ATCAS4 is a significantly variable source detected in the FRB 160102 field.
- None of the FRBs have repeated yet in 92 (21+52+19) hours of follow-up!

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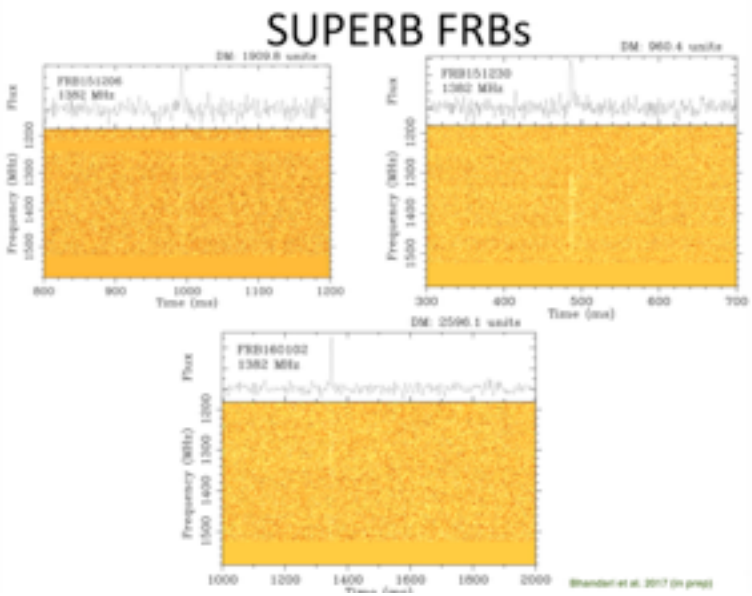
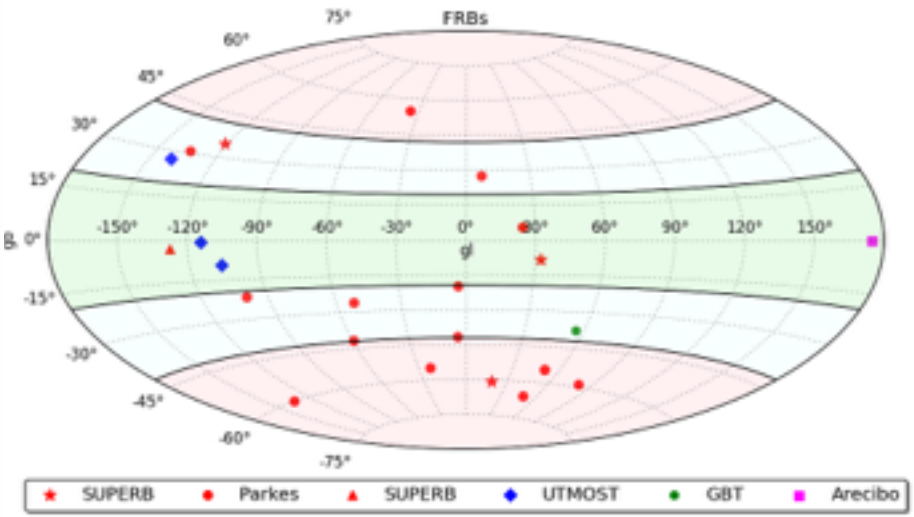
Why multi-wavelength follow-ups?

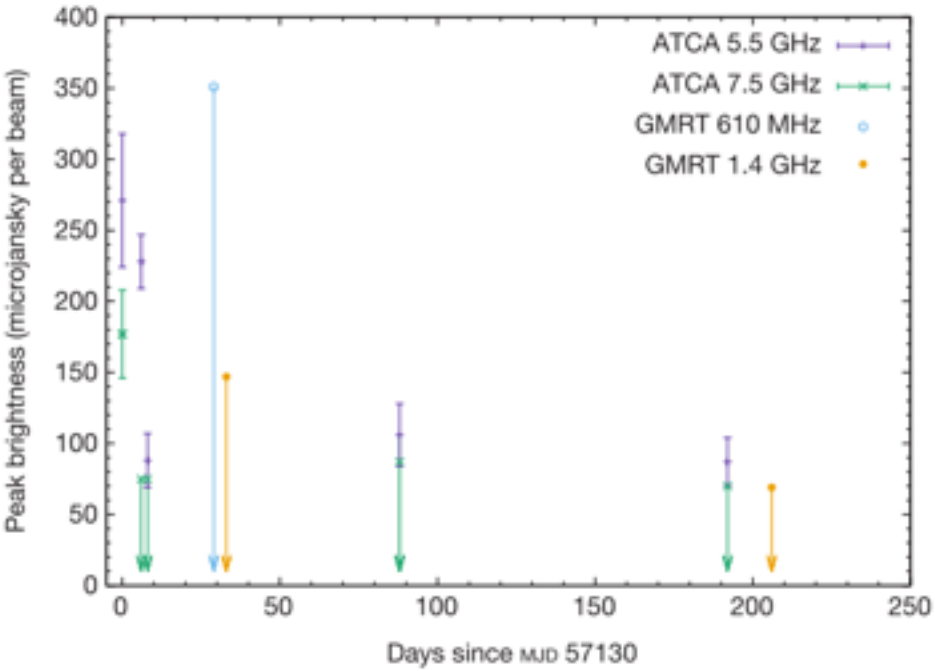
FRB detections!



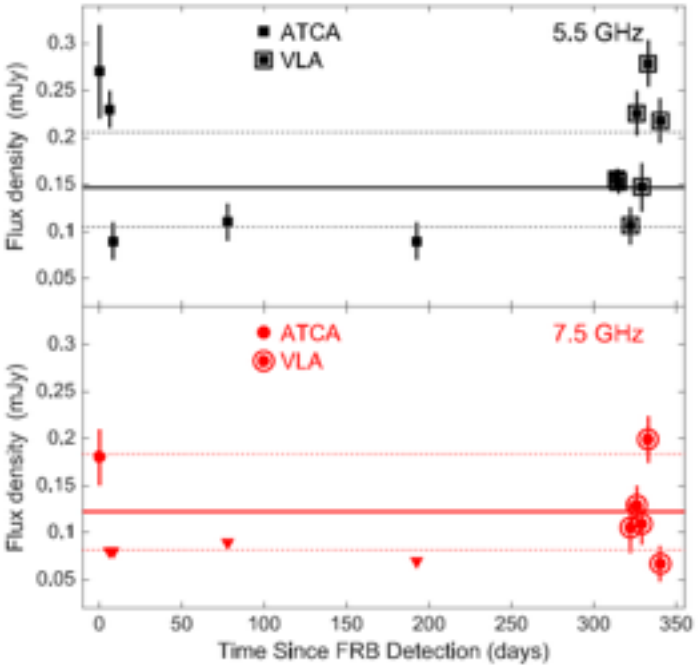


The phase of real-time detections and multi-wavelength follow-ups

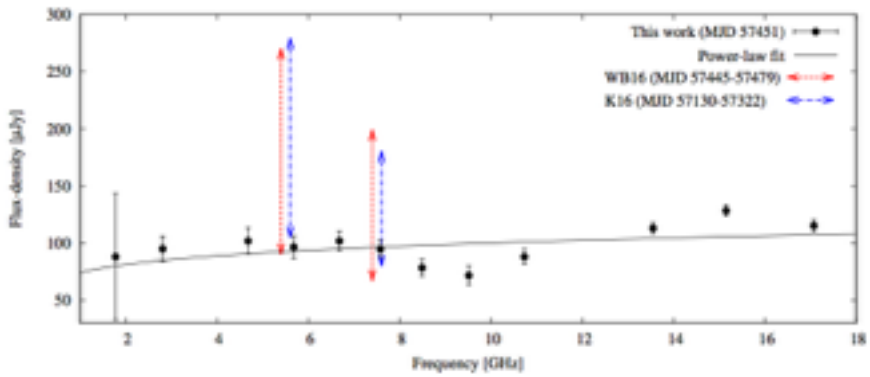
The rise and fall of J071634.59-190039.2



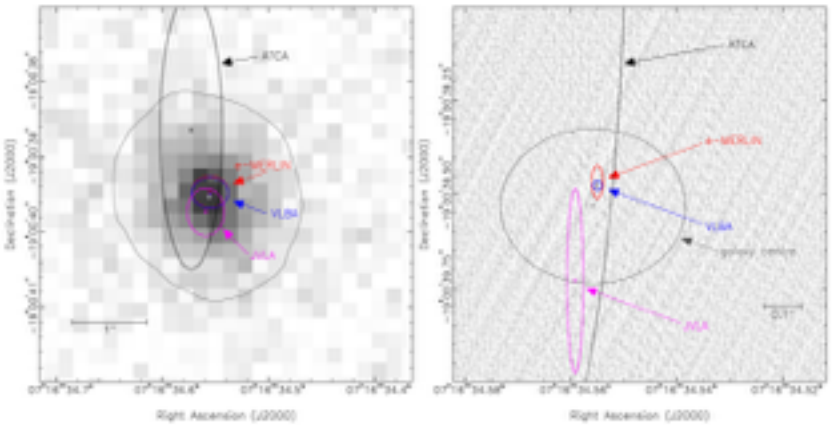
Keane et al. 2016



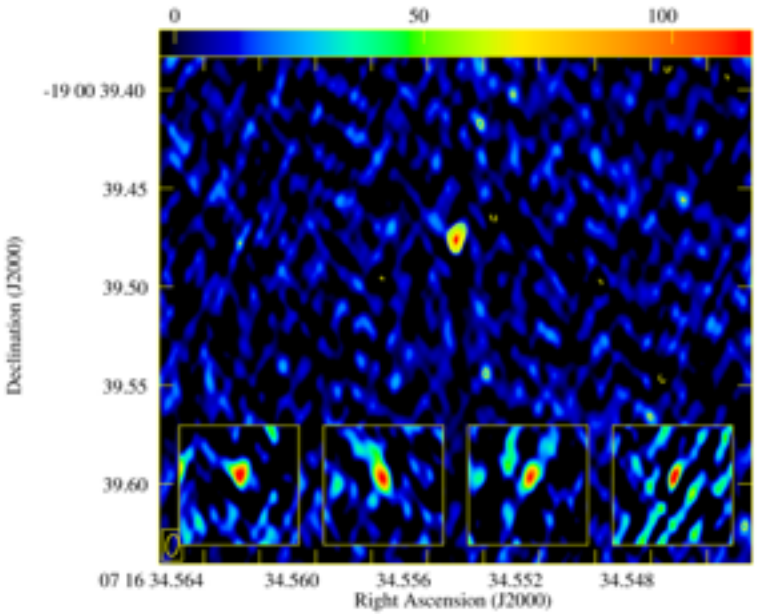
Williams & Berger 2016



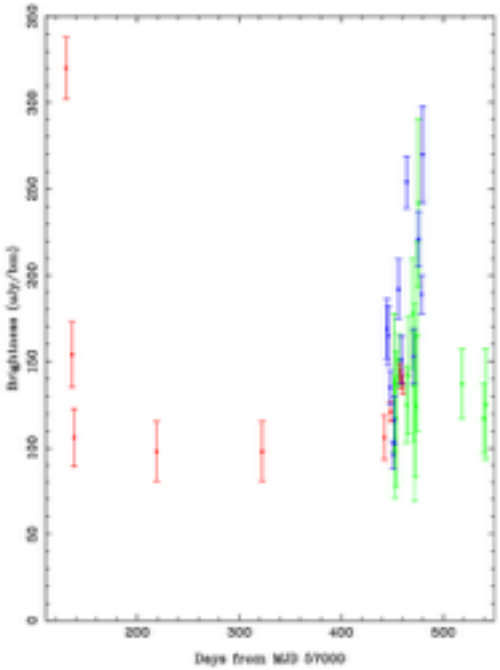
Vedantham et al 2016



Bassa et al 2016



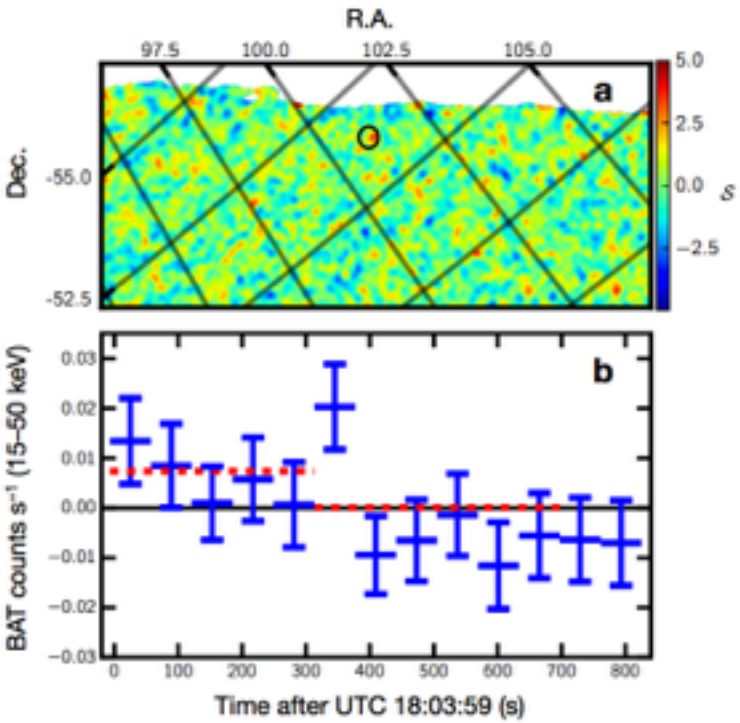
Giroletti et al 2016



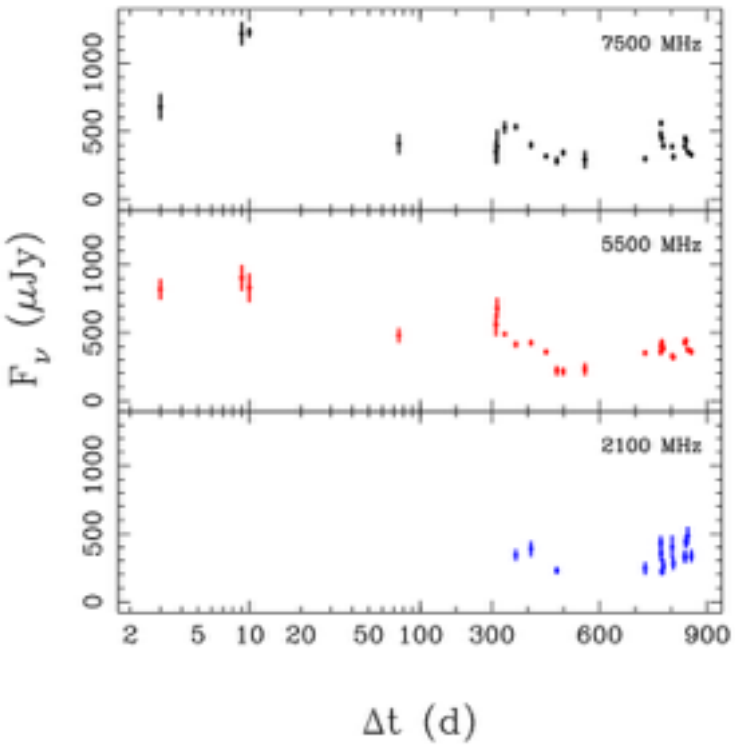
Johnston et al 2016

FRB 131104

Gamma ray association and unusual radio variable

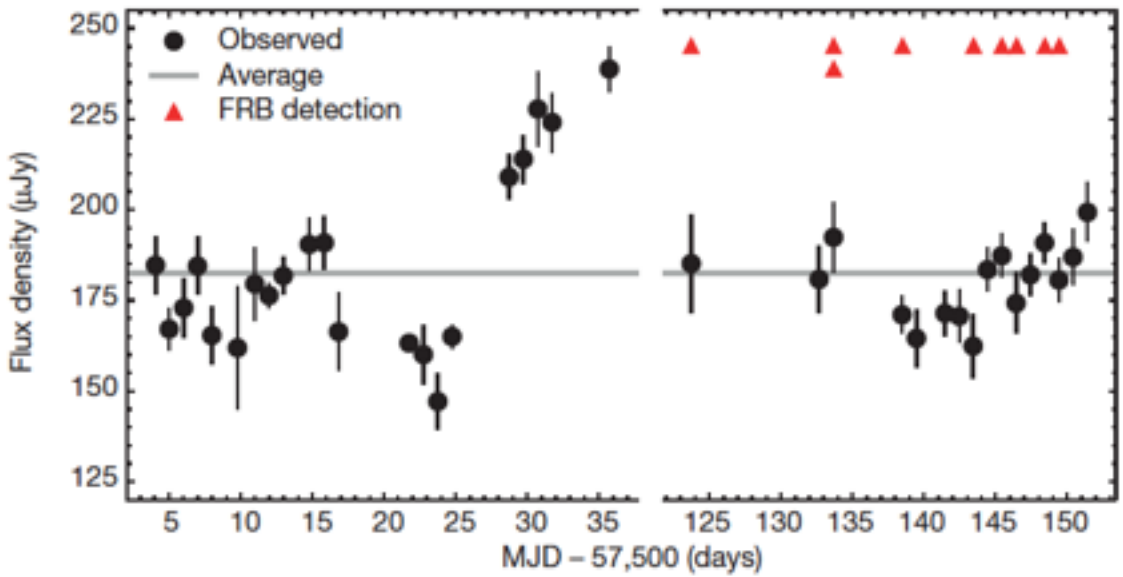


DeLaunay et al 2016



A Coincident AGN flare
(Shannon et al. 2016)

FRB121102
The Repeater!



FRB 121102 – Direct FRB localisation co-located with radio source. (Chatterjee et al 2017)

Why multi-wavelength follow-ups?

To identify host galaxies and progenitors of FRBs thus probing cosmology!

Current strategy

Triggering telescopes to observe FRB field as soon as possible after the detection.

ADVANTAGES

- Highly effective collaboration in place
- Shadowing observations
- Exploring unknowns
- Learning from non-detections

DISADVANTAGES

- Manual Triggering
- Use of large telescope time
- Blind searches

What is the optimal strategy ?

Deeper, Wider, Faster

(as of July 2016, now 80+ members, 28 institutions)

PI: *Jeff Cooke* [1]

Radio: *Emily Petroff* [2], *Chris Flynn* [1], *Manisha Caleb* [1,3], *Shivani Bhandari* [1], *Evan Keane* [4], *Stuart Ryder* [5], *Wael Farah* [1], *Fabian Jankowski* [1], *Vivek Venkatraman Krishnan* [1], *Themiya Nanayakkara* [1], *Aditya Parthasarathy* [1], *Sarah Burke-Spolaor* [6], *Casey Law* [6]

Optical: *Tyler Pritchard* [1], *Tim Abbott* [7], *Chris Curtin* [1], *Stephanie Bernard* [8], *Chuck Horst* [9], *Mansi Kasliwal* [10], *David Coward* [11], *the SkyMapper team, the Zadko team, and the Gemini-South and SALT support astronomers*

UV/x-ray/gamma-ray: *Tyler Pritchard* [1], *Igor Andreoni* [1], *Amy Lien* [12], *Neil Gehrels* [13]

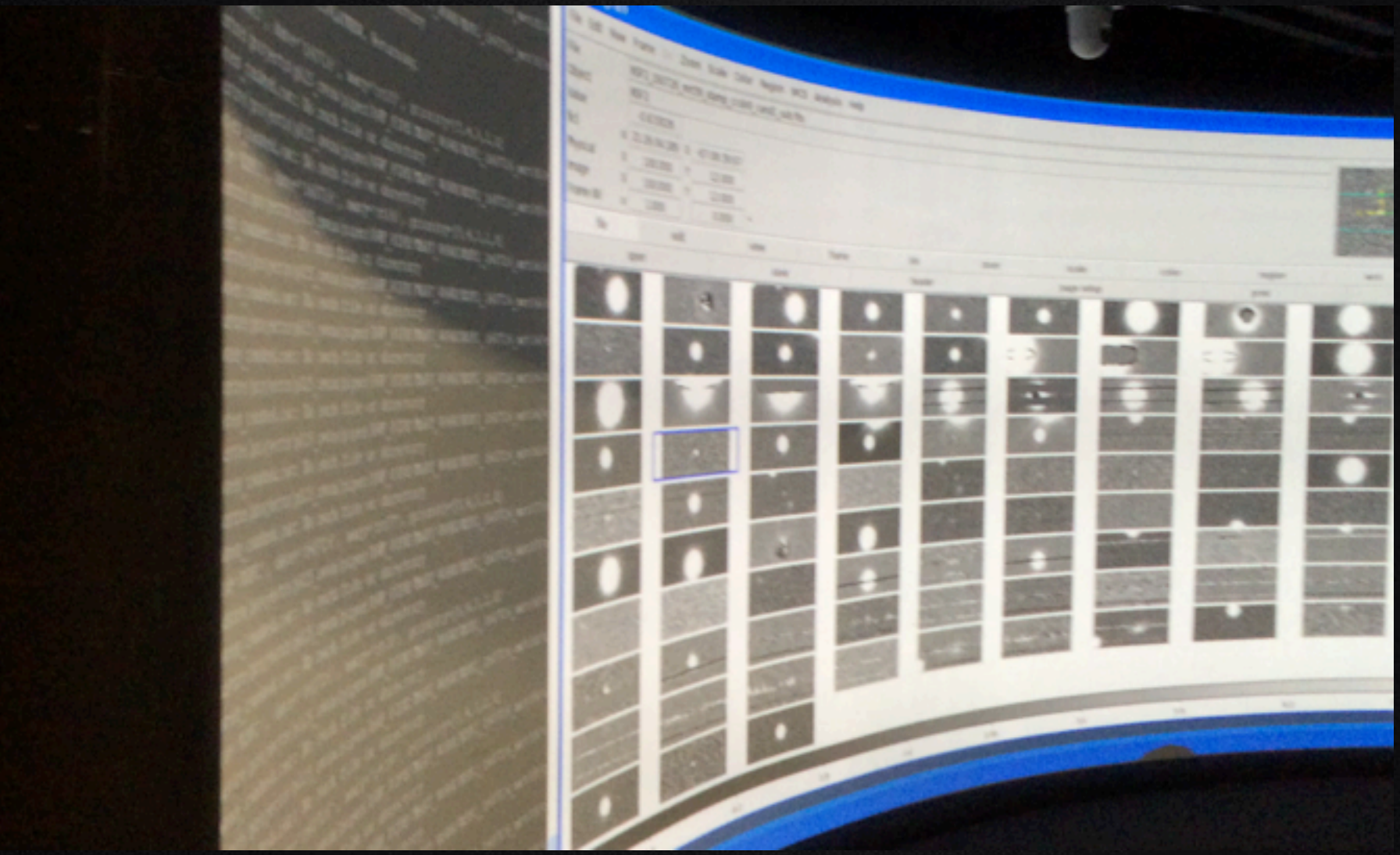
Real-time processing: *Igor Andreoni* [1], *Tyler Pritchard* [1], *Armin Rest* [12,14], *Alex Codoreanu* [1], *Phil Cowperthwaite* [14], *Chuck Horst*

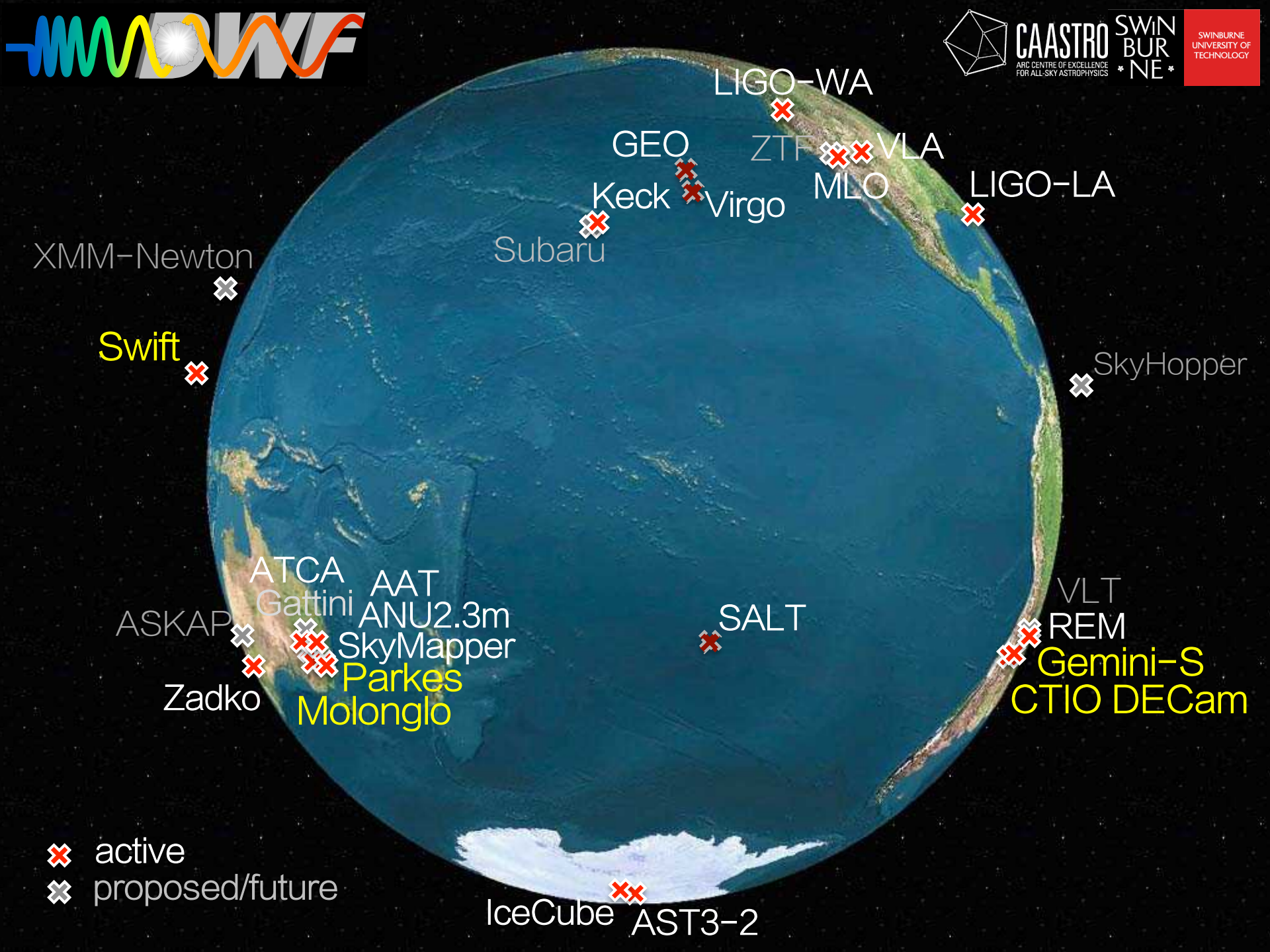
Data Science: *Dany Vohl* [1], *Colin Jacobs*[1], *Vincent Morello* [15]

Visualization: *Bernard Meade* [8], *Chris Fluke* [1], *Dany Vohl* [1], *Sarah Hegarty* [1]

Real-time data Inspection and Analysis: *Uros Mestric* [1], *Chuck Horst* [9], *Garry Foran* [1], *Stephanie Bernard* [8], *Rebecca Allen* [1], *Michael Murphy* [1], *Katie Mack* [8], *Srdan Kotus* [1] *Albany Asher* [1], *Bernard Meade* [8], *Shivani Bhandari* [1], *Chris Curtin* [1], *Wael Farah* [1], *Sarah Hegarty* [1], *Eric Howell* [11], *Colin Jacobs* [1], *Fabian Jankowski* [1], *Regina Jorgenson* [16], *Vivek Venkatraman Krishnan* [1] *Aditya Parthasarathy* [1], *Tristan Reynolds* [8], *Geoff Bryan* [1], *Frederic Robert* [1], *Themiya Nanayakkara* [1], *Fanual Rumokoy* [8], *Luciana Sinpetru* [17], *Cameron van der Veldon* [8], *Ibnul Hussaini* [8], *Pamela Bain, Dany Vohl* [1], *SAO students* [1]

[1]Swinburne [2]ASTRON/NIRA [3]ANU [4]University of Manchester/SKAO [5]AAO [6]NRAO [7]CTIO/NOAO
[8]University of Melbourne [9]San Diego State University [10]Caltech [11]UWA [12]STScI [13]NASA/GSFC
[14]Harvard University [15]University of Bonn [16] Maria Mitchell Observatory [17] University of Edinburgh




LIGO-WA
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Gattini
ANU2.3m
ASKAP
SkyMapper
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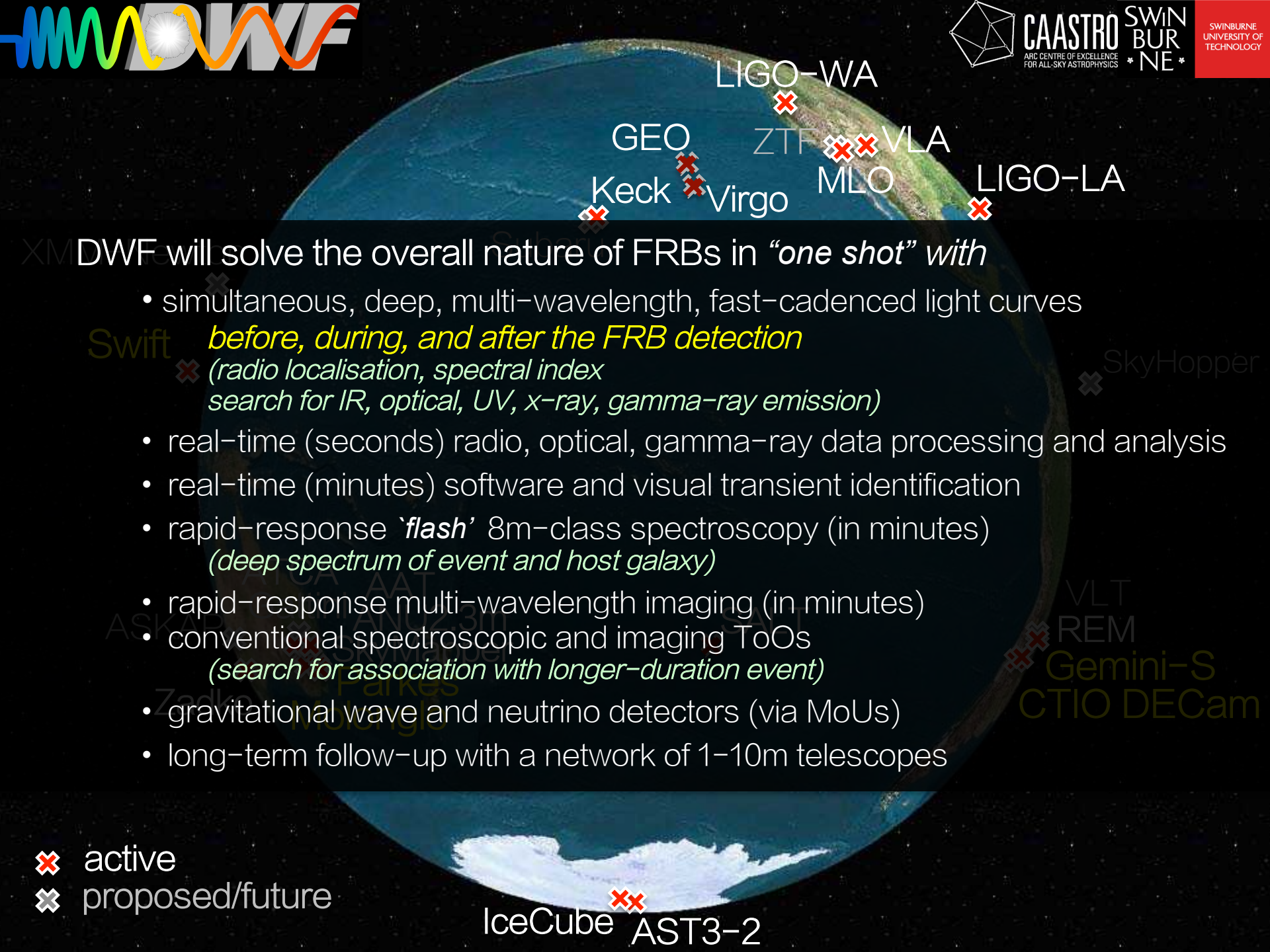
SALT
VLT
REM
Gemini-S
CTIO DECam
IceCube
AST3-2
active
proposed/future

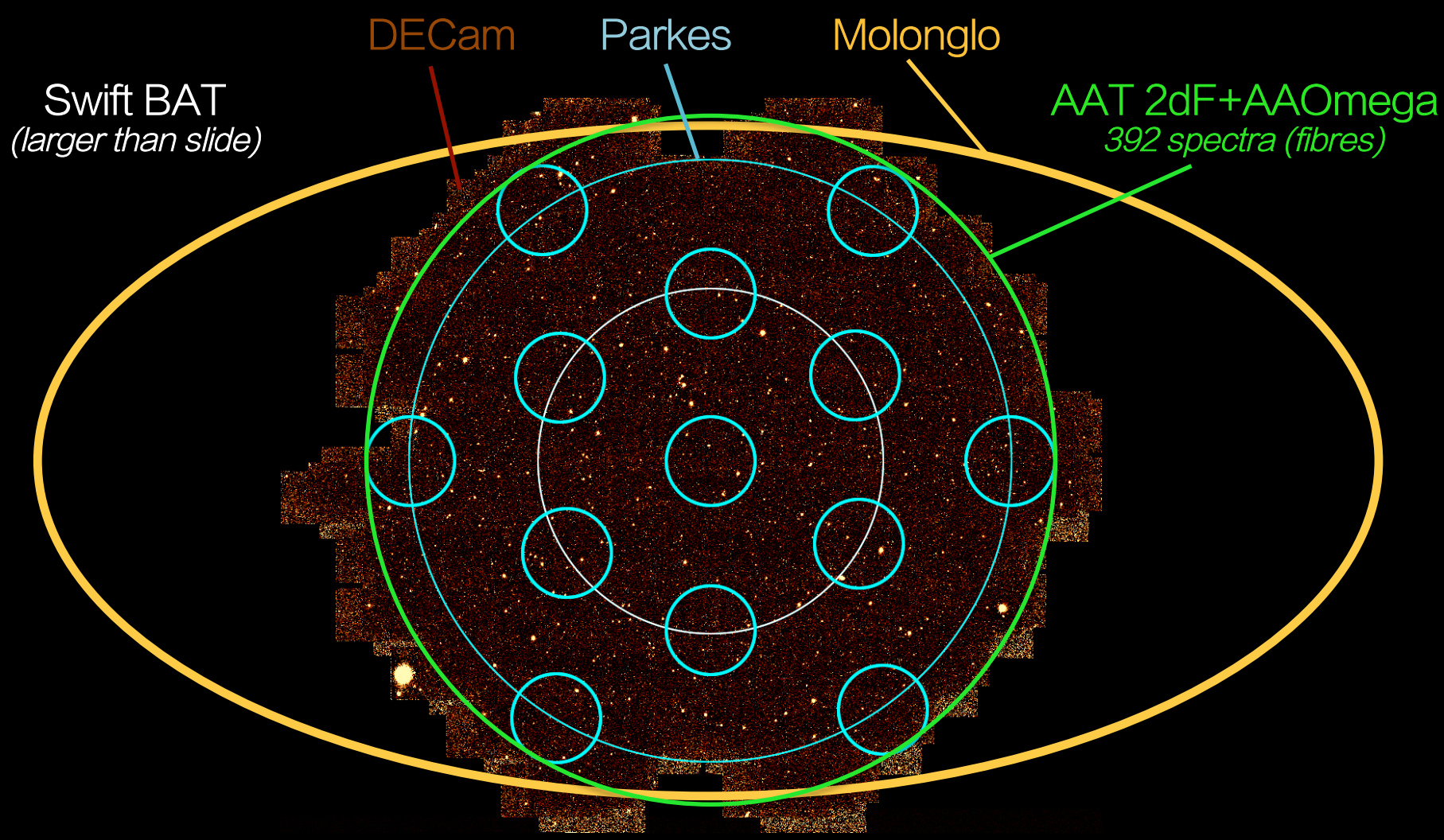


DWF will solve the overall nature of FRBs in *"one shot" with*

- simultaneous, deep, multi-wavelength, fast-cadenced light curves
  before, during, and after the FRB detection
  (radio localisation, spectral index
  search for IR, optical, UV, x-ray, gamma-ray emission)
- real-time (seconds) radio, optical, gamma-ray data processing and analysis
- real-time (minutes) software and visual transient identification
- rapid-response ***'flash'*** 8m-class spectroscopy (in minutes)
  (deep spectrum of event and host galaxy)
- rapid-response multi-wavelength imaging (in minutes)
- conventional spectroscopic and imaging ToOs
  (search for association with longer-duration event)
- gravitational wave and neutrino detectors (via MoUs)
- long-term follow-up with a network of 1-10m telescopes

active
proposed/future

Fields of view



Collect simultaneous data *(continuous 20s integrations)*, transfer it, process, calibrate and analyse it, and identify candidates *every ~1 minute*

Discussions

- What do we learn from current follow-ups?
  - No optical/radio/x-ray afterglows?
  - FRBs related to extremely variable AGNs?
  - FRBs originating in Dwarf galaxies?
  - Do all FRBs repeat?
  - Variability analysis vs direct imaging.
- What is the optimal follow-up strategies?
  - Telescopes on the field as soon as possible after FRB detection?
  - Follow-up approach with reduced localisation error upon detection?
  - Extensive follow-up only upon a FRB host detection?
  - Targeted selection in FRB fields
  - Telescopes on the field before a detection? (Deeper Wider Faster)