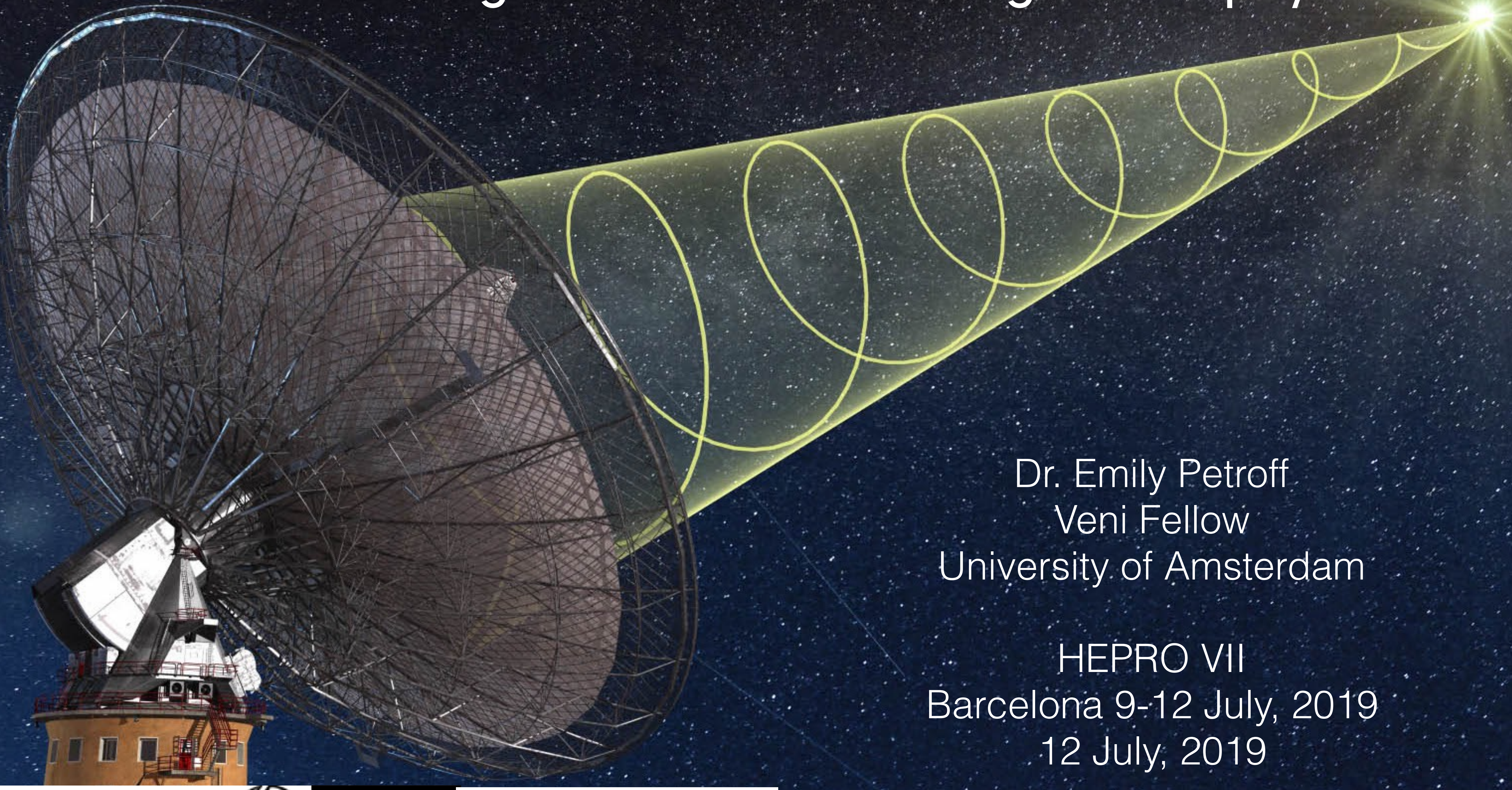
Fast Radio Bursts

multi-wavelength and multi-messenger astrophysics



Dr. Emily Petroff
Veni Fellow
University of Amsterdam

HEPRO VII
Barcelona 9-12 July, 2019
12 July, 2019

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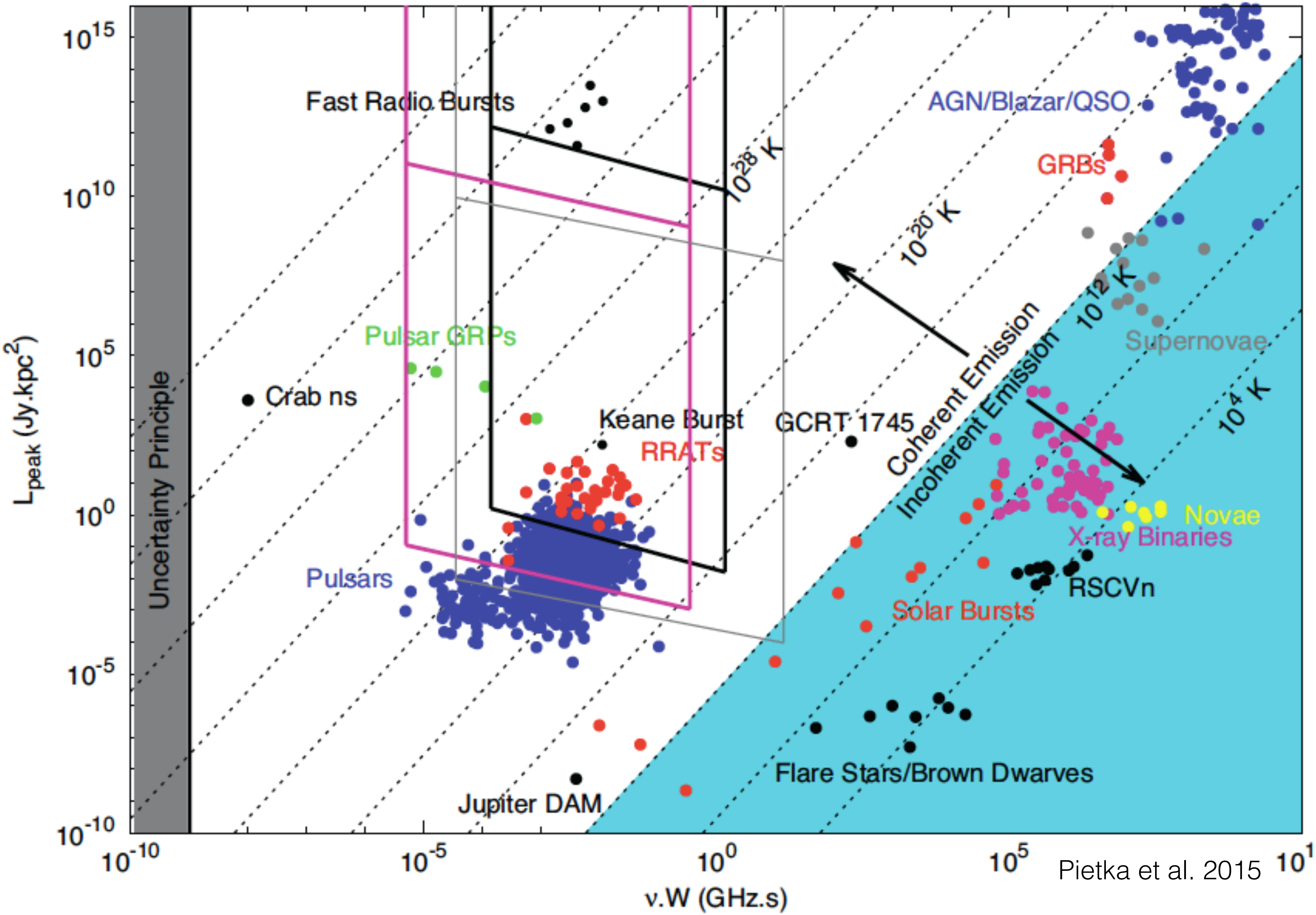
www.ebpetroff.com



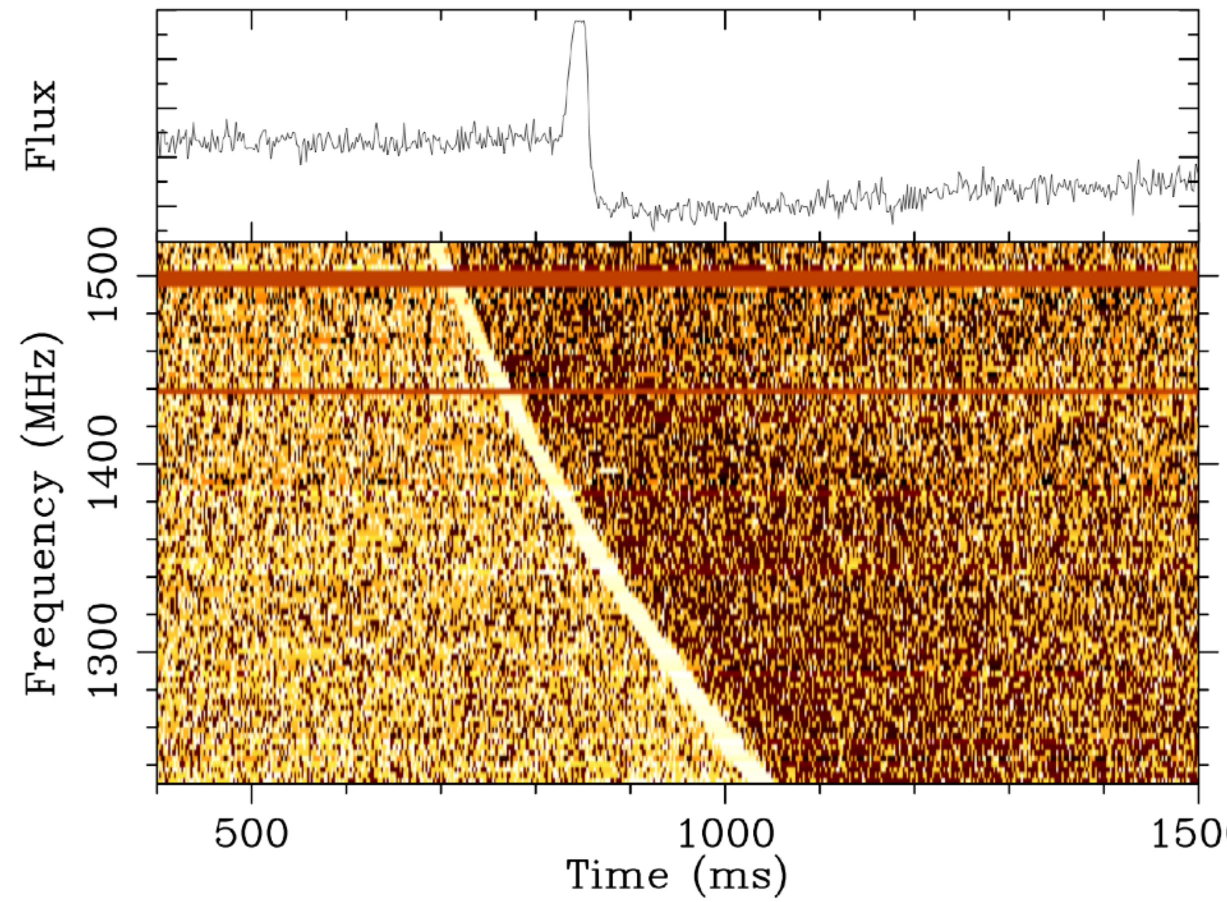
Pietka et al. 2015

Fast radio bursts (FRBs)

- Bright, short radio pulses
- High dispersion measure (DM)

$$DM = \int_0^d n_e \, ds$$

- DM(FRB) ~ 10 x DM(MW)
- Some or all DM from the IGM

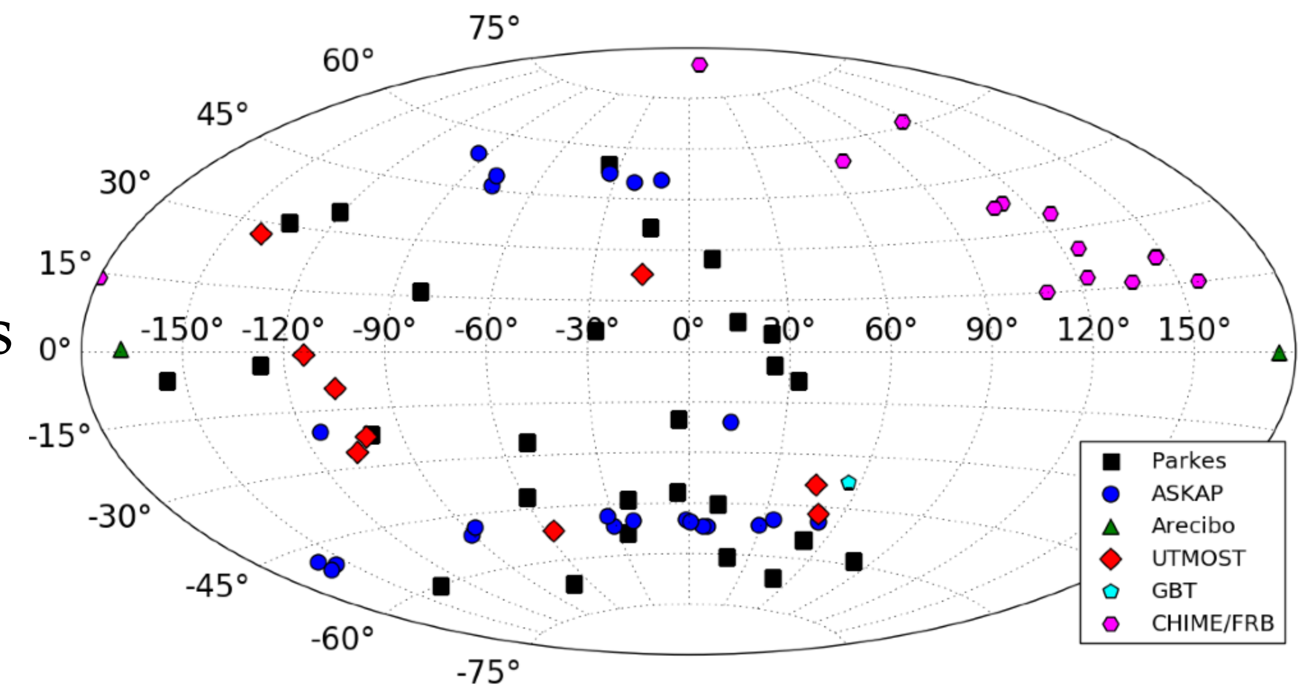


Lorimer et al. 2007

- Hugely energetic, relatively common new transients (R_{FRB} ~ 5,000 sky^{-1} day^{-1})

Fast radio bursts (FRBs)

- 80+ published FRBs on www.frbcat.org
- Discovered by 6+ telescopes, 10+ observed
- Interferometric and single dish detections
- 5+ polarization profiles
- 4+ precise localizations + host galaxies
- 2 published repeating FRBs



Petroff, Hessels & Lorimer (2019)

https://arxiv.org/abs/1904.07947

What could FRBs be?

- Neutron stars collapsing to black holes, ejecting “magnetic hair” (Falcke & Rezzolla ‘14; Zhang ’14)
- Merger of charged black holes (Zhang ‘16; Liu et al. ’16; Liebling & Panenzuela ‘16)
- Magnetospheric activity during neutron star mergers (Totani ‘13)
- Unipolar inductor in neutron star mergers (Hansen & Lyutikov ‘01; Piro ‘12; Wang et al. ‘16)
- White dwarf mergers (Kashiyama et al. ‘13)
- Pulses from young neutron stars (Cordes & Wasserman ’15; Connor et al. ‘15; Lyutikov et al. ’16; Popov & Pshirkov ’16; Kashiyama & Murase ‘17)
- (Young) Magnetars (Popov et al. ’07; Kulkarni et al. ‘14; Lyubarsky ‘14; Katz ’15; Pen & Connor ’ 15; Lu & Kumar ‘16; Metger et al. ’ 17; Beloborodov ‘17; Margarlit & Metzger ‘18)
- Schwinger instability in young magnetars (Lieu ‘17)
- Sparks from cosmic strings (Vachaspati ‘08; Yu et al. ‘14)
- Evaporating primordial black holes (Rees ’77; Keane et al. ‘12)
- White holes (Barrau et al. ’14)
- Flaring stars (Loeb et al. ‘13; Maoz et al. ‘15)
- Axion stars (Tkachev ‘15; Iwazaki ‘15)
- Asteroids/comets falling onto neutron stars (Geng & Huang ’ 15; Dai et al. ‘16)
- Quark novae (Chand et al. ‘15)
- Dark matter-induced collapse of neutron stars (Fuller & Ott ‘15)
- Higgs portals to pulsar collapse (Bramante & Elahi ’15)
- Planets interacting with a pulsar wind (Mottez & Zarka ’15)
- Black hole superradiance (Conlon & Herdeiro ‘17)
- Extragalactic light sails (Lingam & Loeb ‘17)
- Neutron star-white dwarf binaries (Gu et al. ’16)
- Clumpy jets from accreting black holes (Yi et al. ’19)
- Black hole interacting with an AGN (Das Gupta & Saini ‘17; Waxman ‘17)
- Wandering AGN beam (Katz ’17)
- Black hole laser powered by axion superradiant instabilities(Rosa & Kephart ‘18)
- Starquakes and lightning of pulsars (Wang et al. ’18; Song et al. 2017)

Slide credit: Tony Piro

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www.frbtheorycat.org

Slide credit: Tony Piro

What we measure

- We only measure a handful of properties

- Dispersion measure

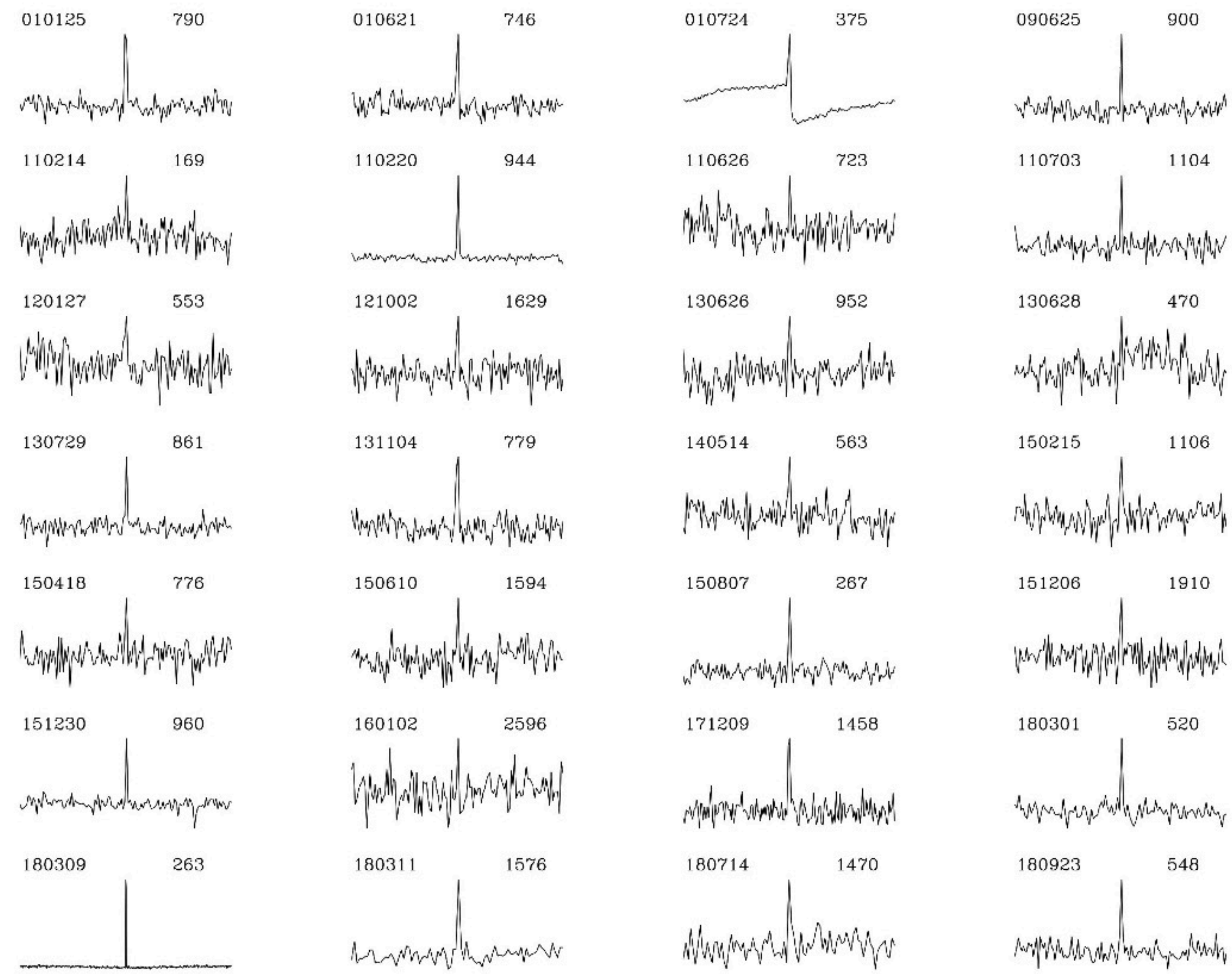
$$\mathrm{DM} = \int_0^d n_e \, \mathrm{d}l.$$

- Pulse width

$$W = \sqrt{W_{\mathrm{int}}^2 + t_{\mathrm{samp}}^2 + \Delta t_{\mathrm{DM}}^2 + \Delta t_{\mathrm{DMerr}}^2 + \tau_{\mathrm{s}}^2},$$

- Fluence

$$\mathcal{F} = S_{\mathrm{peak}} W_{\mathrm{eq}} = \int_{\mathrm{pulse}} S(t) \, \mathrm{d}t.$$



- Derive properties like Energy (iso), Luminosity

$$E_{\mathrm{FRB}} = F_{\mathrm{obs}} \, \mathrm{BW} \, D_L^2 \times 10^{-29} \, (1+z) \, \mathrm{J}$$

$$L = \frac{4\pi d_L^2 S_\nu \Delta\nu}{(1+z)}.$$

Petroff, Hessels & Lorimer (2019)

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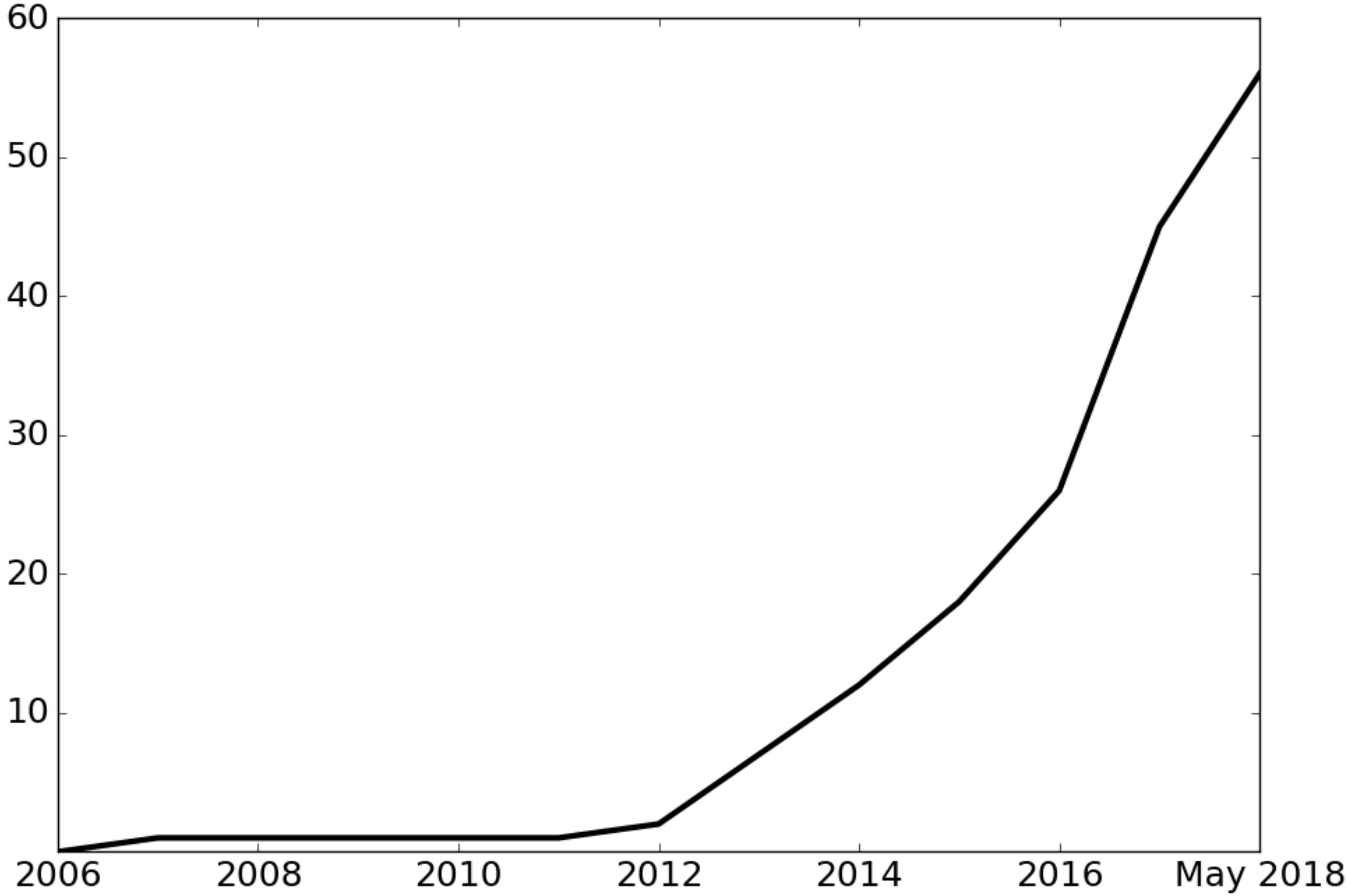
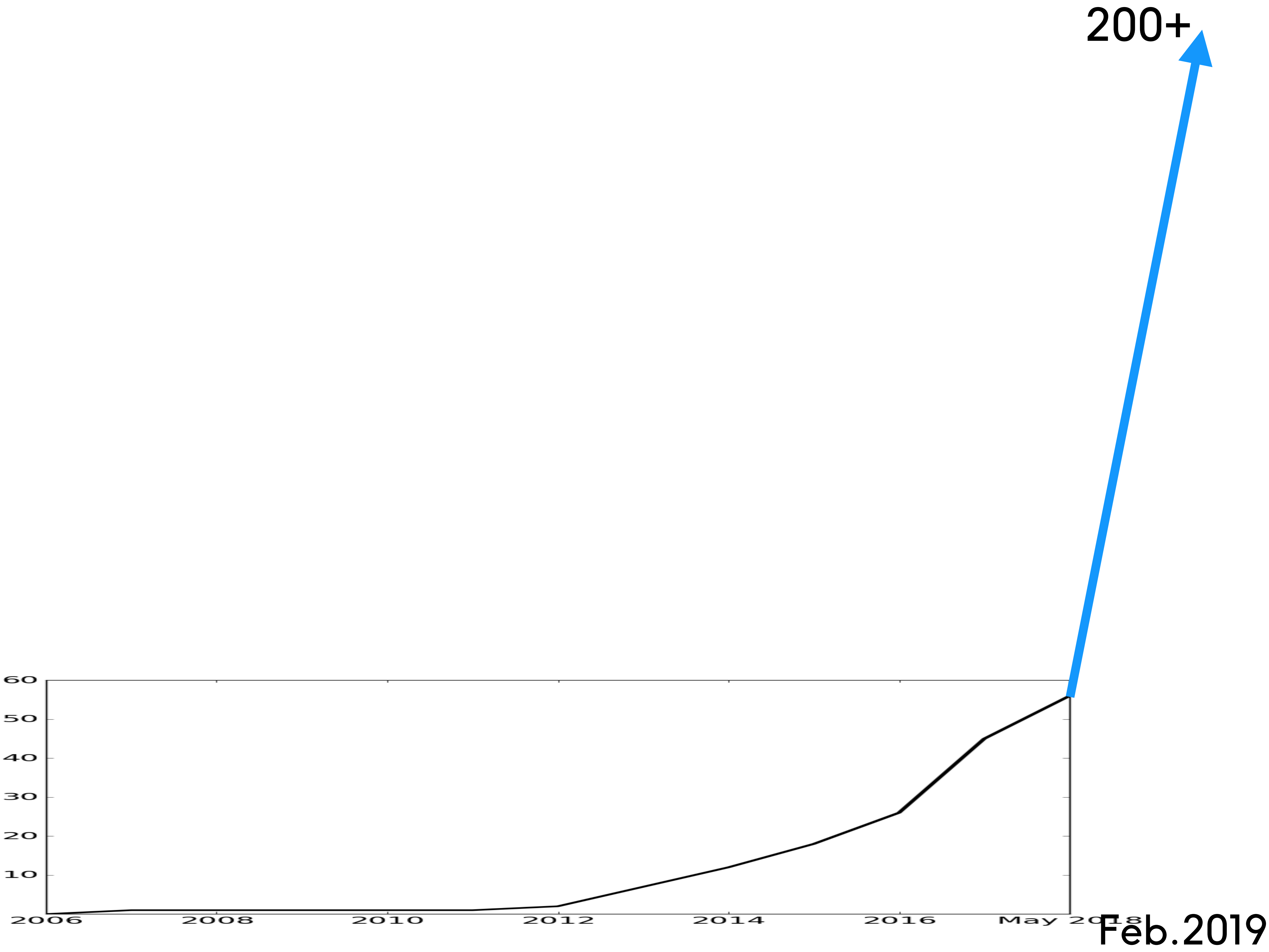

60
50
40
30
20
10
2006
2008
2010
2012
2014
2016
May 2018


200+
60
50
40
30
20
10
2006
2008
2010
2012
2014
2016
May 2018
Feb.2019

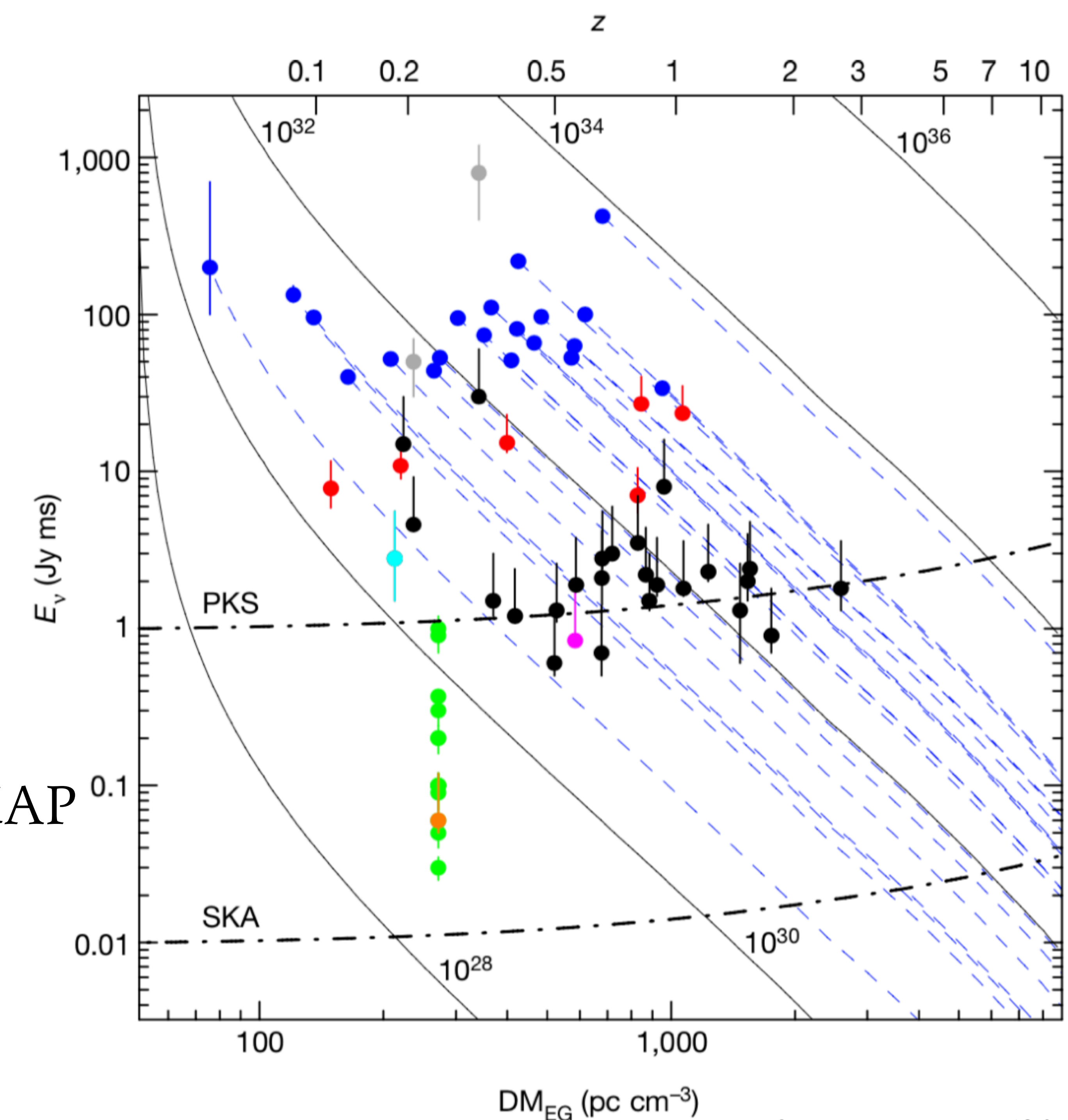
The FRB population

- Possible DM — brightness relation
  - Lower DM FRBs are brighter
- α = Slope of Log N — Log F

$$N(> F_\nu) \propto {F_\nu}^{\alpha},$$

- Shannon et al. (2018) — Parkes + ASKAP

$$\alpha = -2.1^{+0.6}_{-0.5} \text{ (67\% confidence)}$$



Shannon et al. (2018)

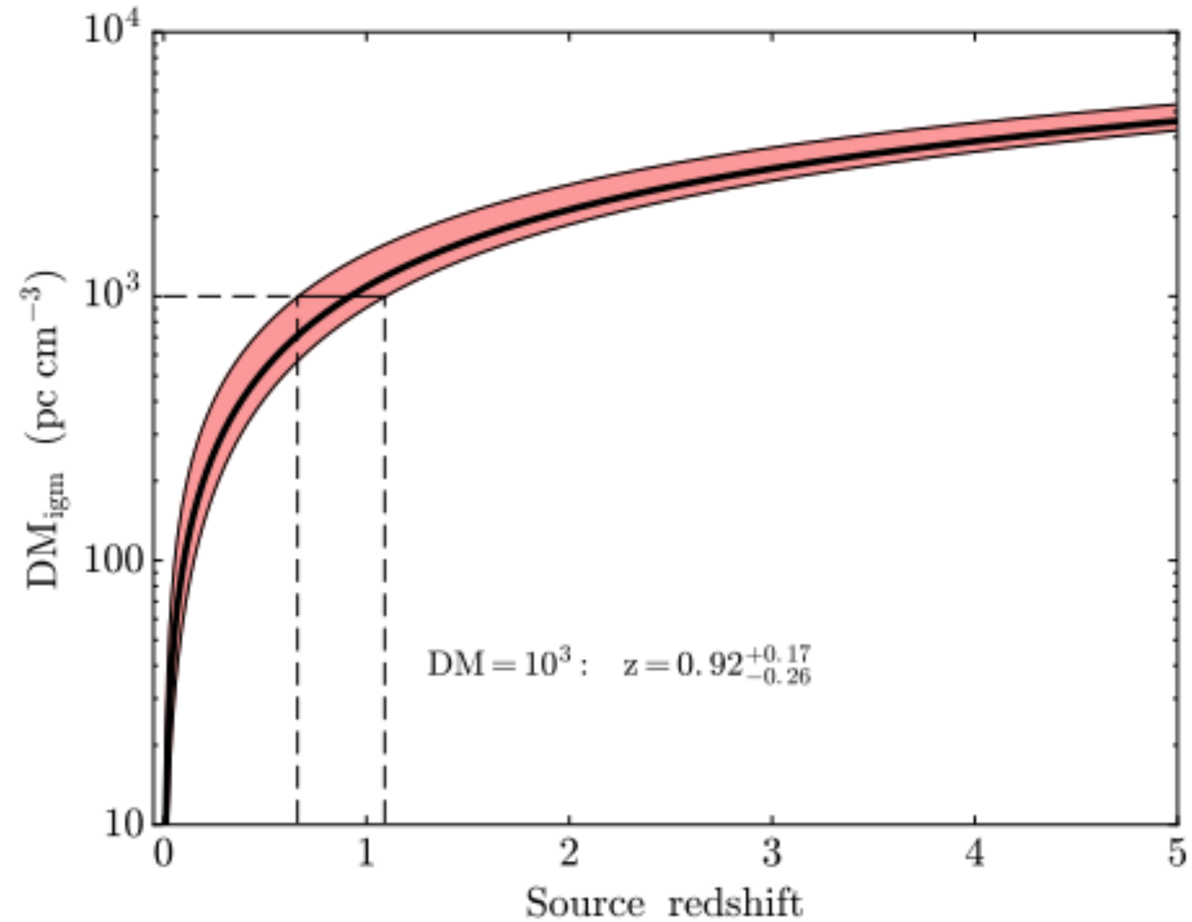
Converting between DM and distance

- Particle density
  - ISM ~ 0.5 particles cm^{-3}
  - IGM ~ 10^{-7} particles cm^{-3}
- DM as a function of redshift

$$\overline{\mathrm{DM}}_{\mathrm{IGM}}(z_s) = \frac{cn_{e_0}}{H_0}\int_0^{z_s} dz\,\frac{(1+z)}{E(z)}\,\frac{\mu_e}{\mu_{e_0}}.$$

$$E(z) = \sqrt{\Omega_m(1+z)^3 + 1 - \Omega_m}.$$

$$\mathrm{DM_f} = \mathrm{cn_{e_0}/H_0} = 977\ \mathrm{pc\ cm^{-3}}\,(\Omega_{\mathrm{IGM}}/\Omega_b)(\mu_e/\mu_{e_0}).$$



Cordes & Chatterjee (2019)

- Need more FRBs to determine how correct this is!!

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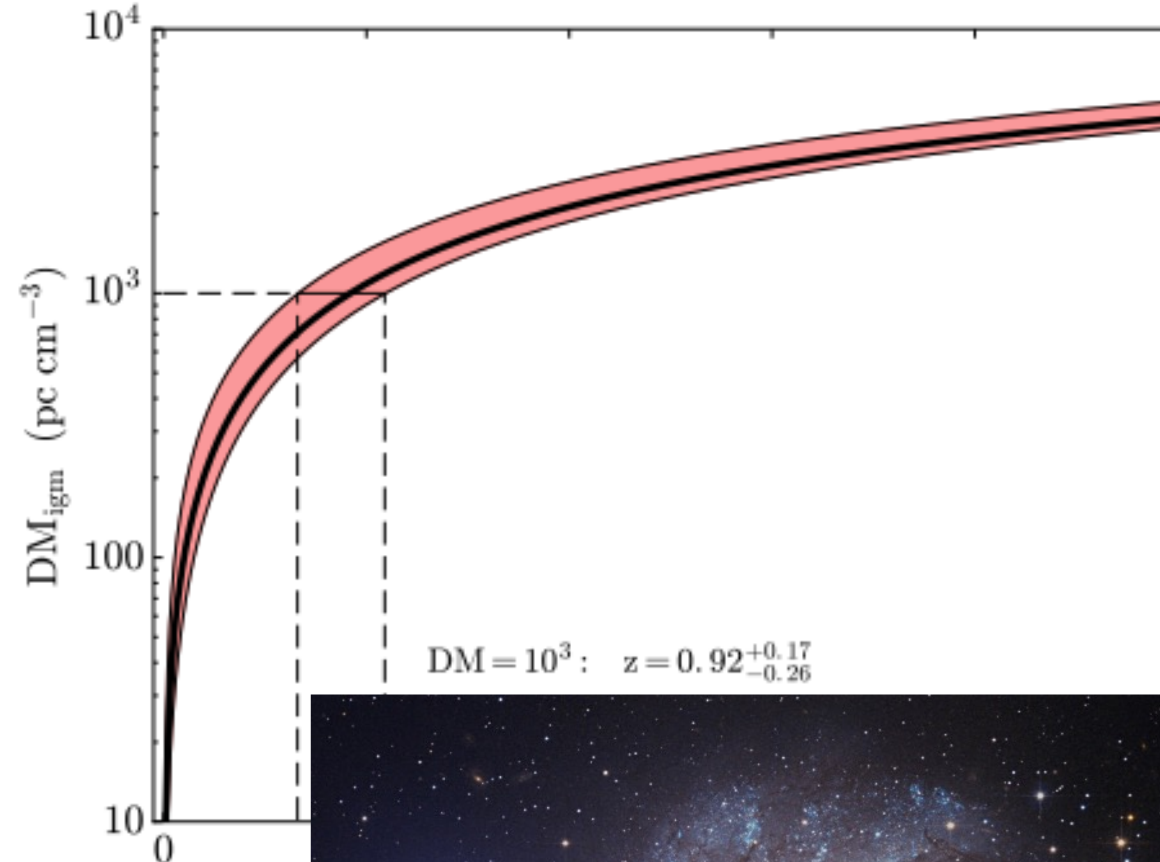

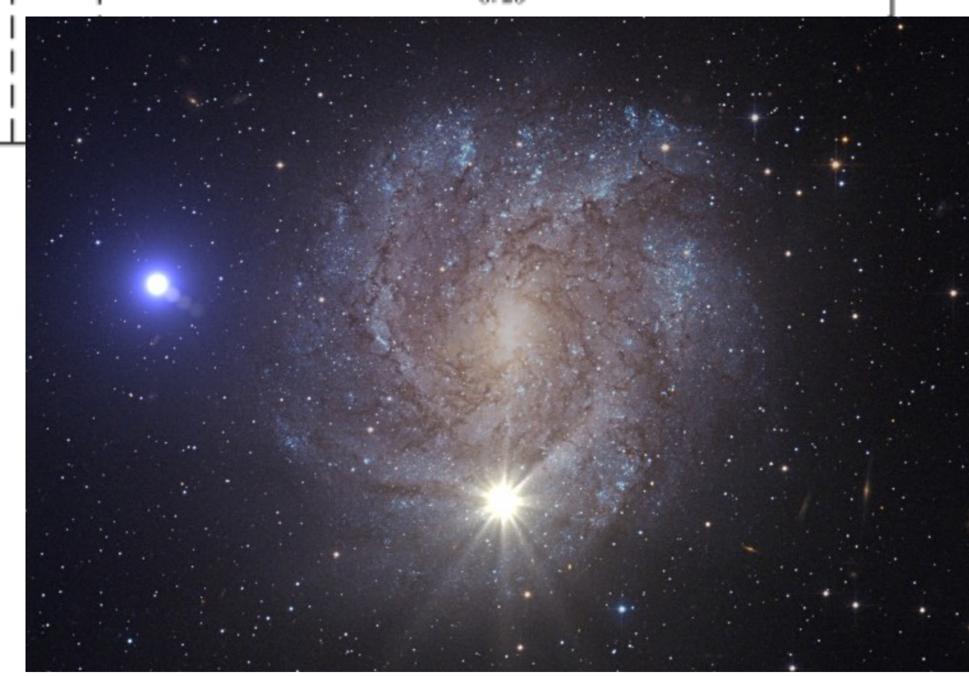

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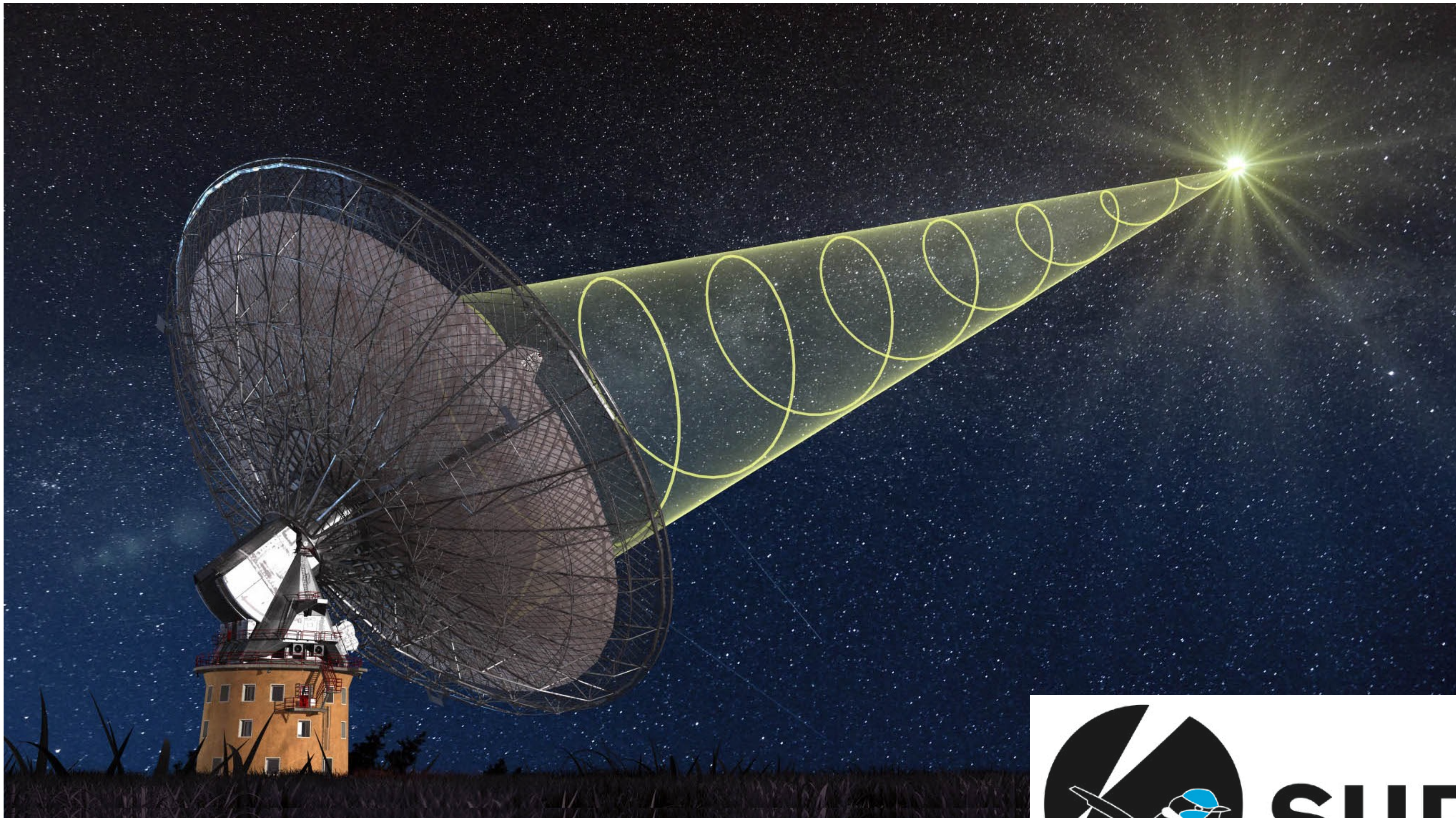
Real-time detection and multi-wavelength follow-up



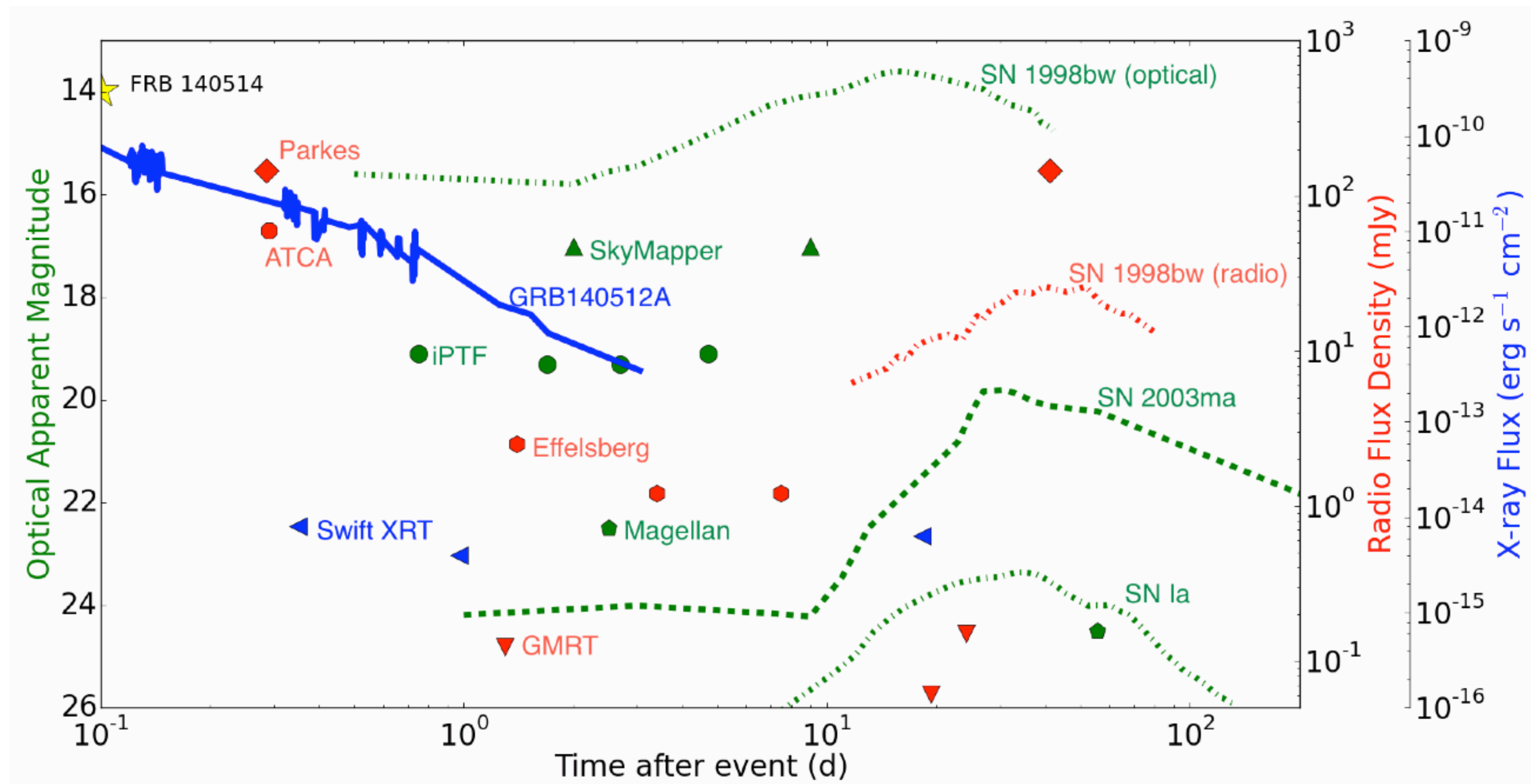
SUPERB
Survey for Pulsars and Extragalactic Radio Bursts

Emily Petroff | HEPROVII, Barcelona | 12 July, 2019

Real-time detection and multi-wavelength follow-up

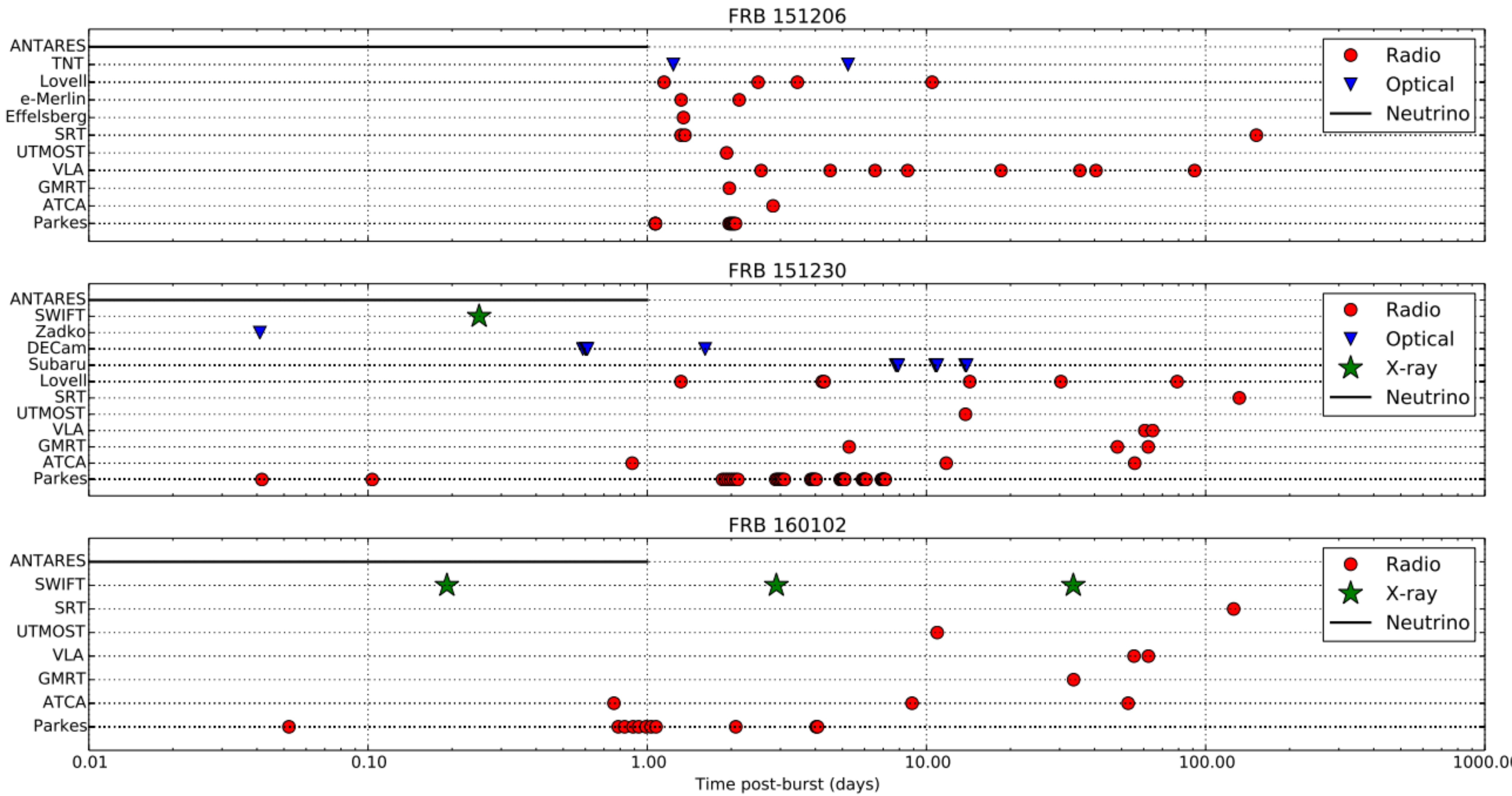
Telescope	Date Start time UTC	T+	Limits
Parkes	Feb 15 20:41:42	1 s	145 mJy at 1.4 GHz
ANTARES	Feb 15 20:41:42	1 s	1.4×10^{-2} erg cm^{-2} (E^{-2}) 0.5 erg cm^{-2} (E^{-1})
ATCA	Feb 16 01:22:26	4.6 h	280 μJy at 5.5 GHz 300 μJy at 7.5 GHz
GMRT	Feb 16 06:36:00	8.9 h	100 μJy at 610 MHz
DECam	Feb 16 09:01:36	12.3 h	$i = 24.3$, $r = 24.8$, VR = 25.1
Swift	Feb 16 15:30:23	18.8 h	1.7e−13 erg cm^{-2} s^{-1}
ATCA	Feb 16 20:41:44	24 h	208 μJy at 5.5 GHz 200 μJy at 7.5 GHz
ANTARES	Feb 16 20:41:42	1.0 d	1.4×10^{-2} erg cm^{-2} (E^{-2}) 0.5 erg.cm^{-2} (E^{-1})
TNT	Feb 16 21:59:00	1.0 d	R = 21.3
GMRT	Feb 17 05:08:00	1.3 d	100 μJy at 610 MHz
Magellan	Feb 17 08:53:05	1.5 d	$J = 18.6$
Parkes	Feb 17 20:26:47	1.9 d	145 mJy at 1.4 GHz
Chandra	Feb 18 03:56:00	2.3 d	1e−14 erg cm^{-2} s^{-1}
Swift	Feb 18 04:44:58	2.3 d	2.4e−13 erg cm^{-2} s^{-1}
Magellan	Feb 18 08:59:44	2.5 d	$J = 19.1$
Parkes	Feb 18 20:04:25	2.9 d	145 mJy at 1.4 GHz
Swift	Feb 19 01:27:59	3.2 d	9.7e−13 erg cm^{-2} s^{-1}
ATCA	Feb 19 17:13:44	3.8 d	192 μJy at 5.5 GHz 228 μJy at 7.5 GHz
GMRT	Feb 20 05:51:00	4.3 h	100 μJy at 610 MHz
Swift	Feb 20 12:36:58	4.6 d	2.1e−13 erg cm^{-2} s^{-1}
Swift	Feb 21 18:53:59	5.9 d	6.8e−13 erg cm^{-2} s^{-1}
H.E.S.S.	Feb 22 02:53:00	6.3 d	see text
Parkes	Feb 23 19:41:53	7.9 d	145 mJy at 1.4 GHz
H.E.S.S.	Feb 25 02:49:00	9.3 d	see text
DECam	Feb 28 08:13:46	12.5 d	$i = 24.3$, $r = 24.8$, VR = 25.1
DECam	Mar 1 08:59:45	13.5 d	$i = 24.3$, $r = 24.8$, VR = 25.1
VLA	Mar 1 13:59:46	13.7 d	7.92 μJy at 10.1 GHz
VLA	Mar 6 14:26:00	18.7 d	7.83 μJy at 10.1 GHz

Petroff et al. 2017



Petroff et al. 2015

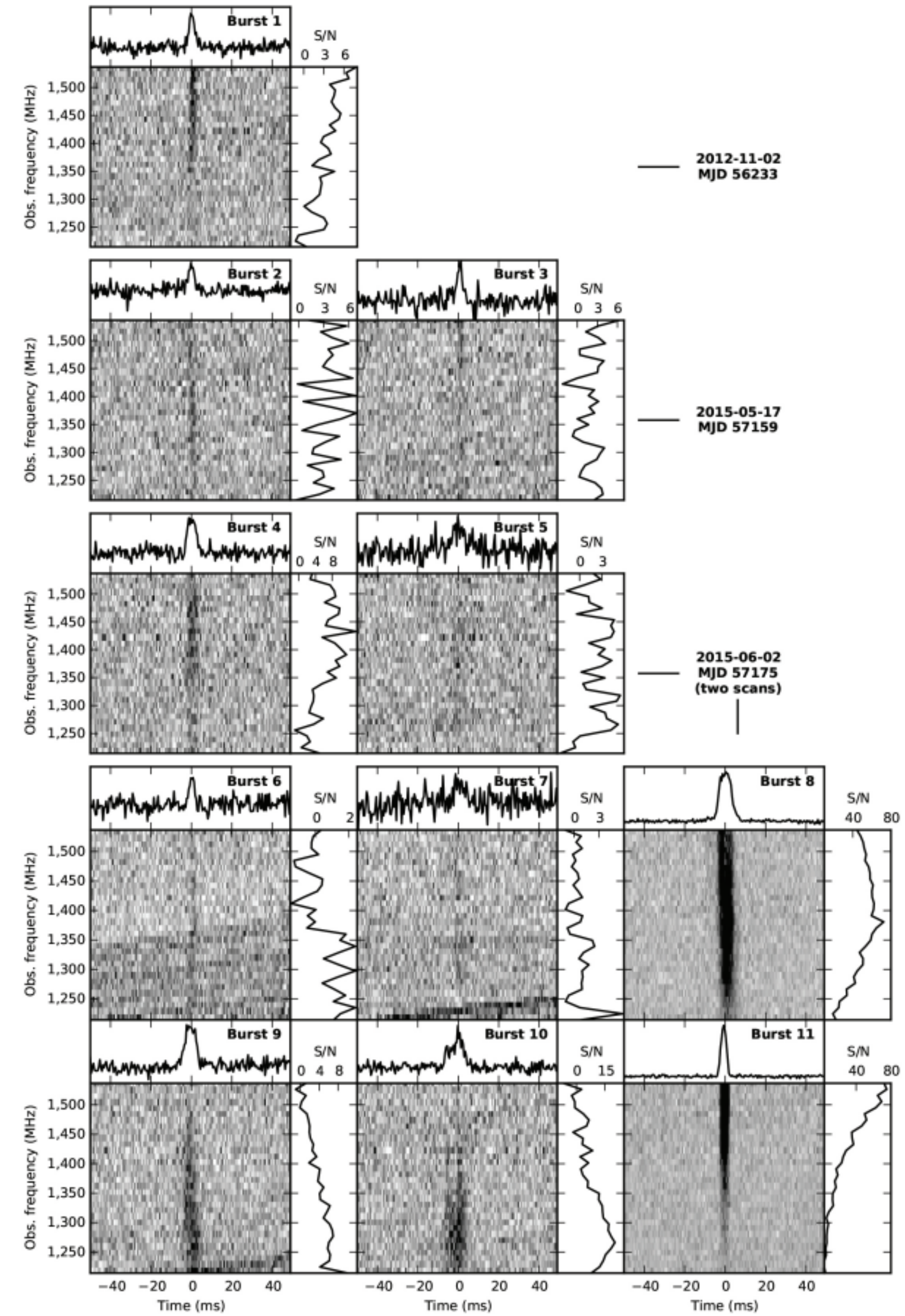
Additional follow-up



Bhandari et al. 2018

Repeating FRBs

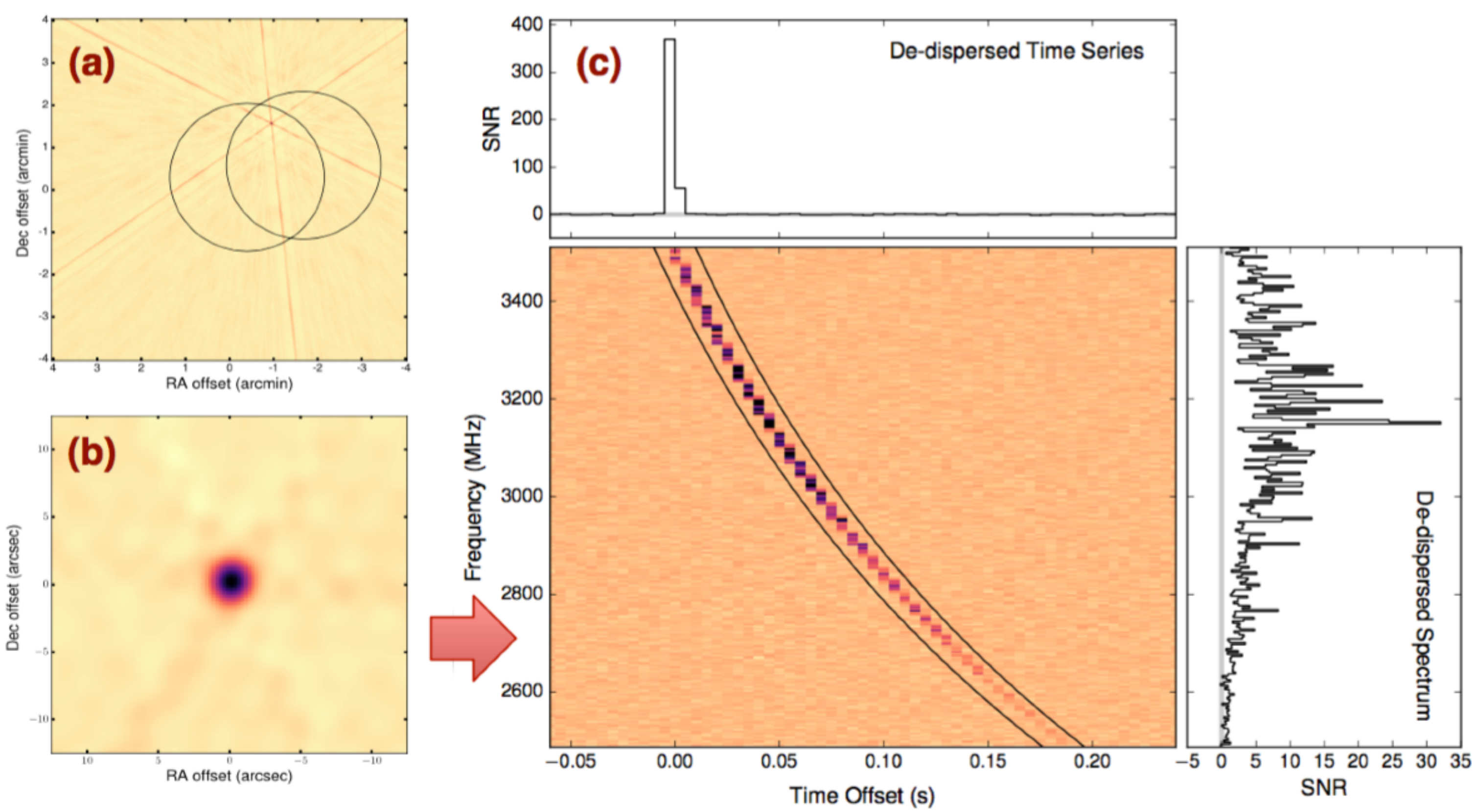
- An FRB that repeats!
  FRB 121102
- Found and followed-up with Arecibo
- > 200 pulses found
- Highly clustered in time
- No underlying periodicity



Spitler et al. 2016

Repeating FRBs

- Localized through repeating pulses with the VLA
- Localized to a dwarf galaxy
  - z = 0.19 (~1 Gpc away)
- Co-located with a persistent radio source



Chatterjee et al. 2017

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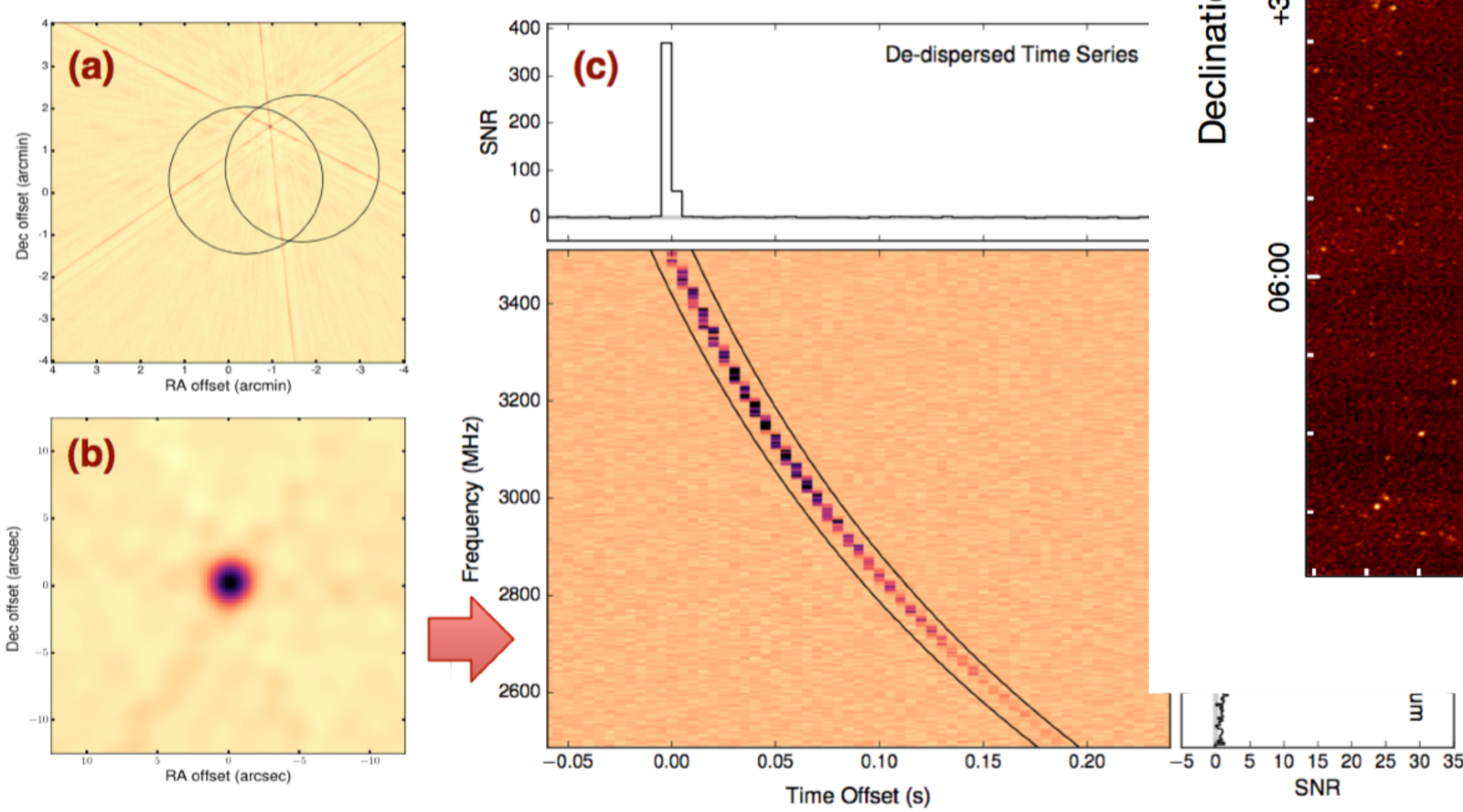

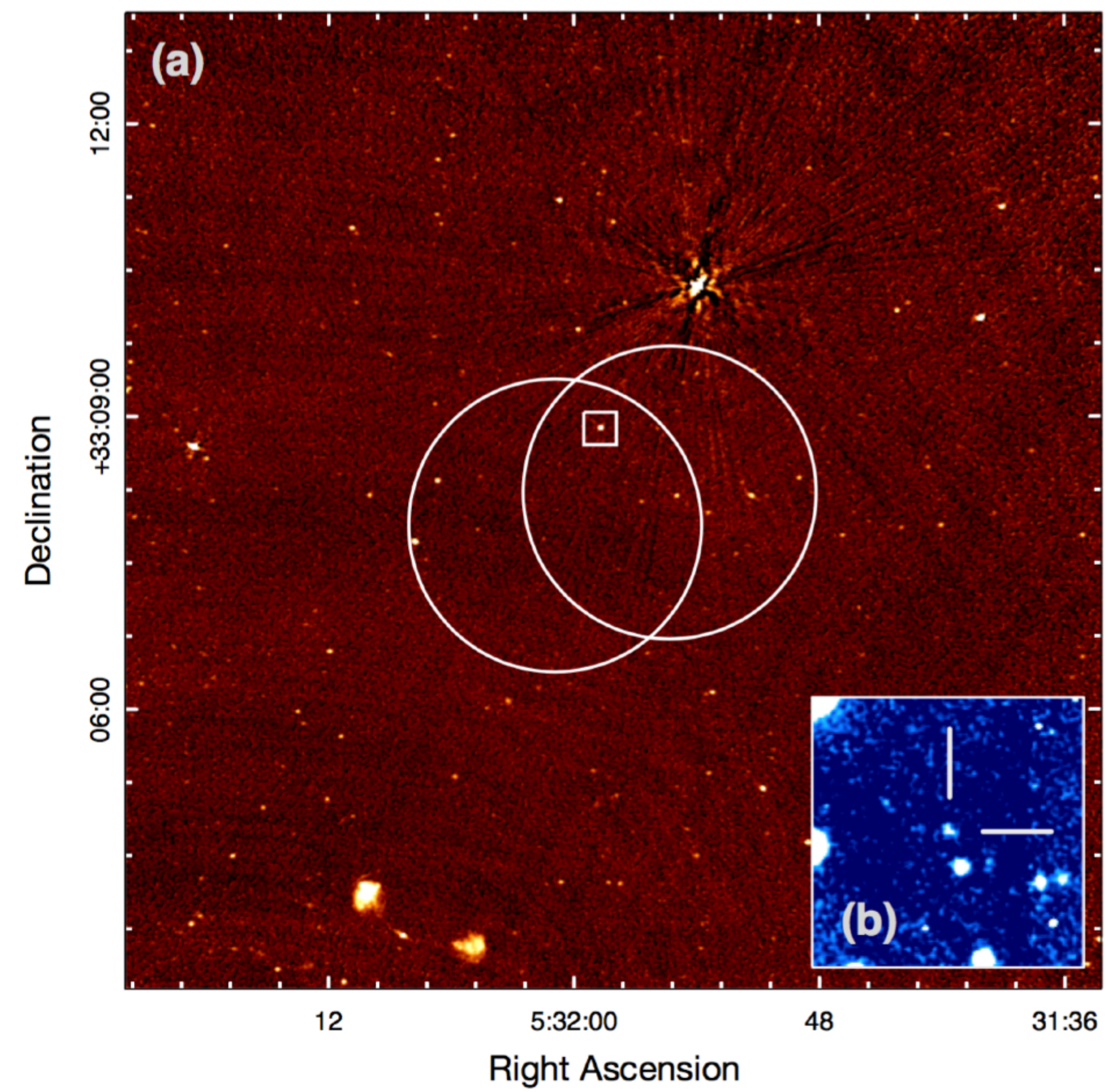

Tendulkar et al. 2017
Chatterjee et al. 2017

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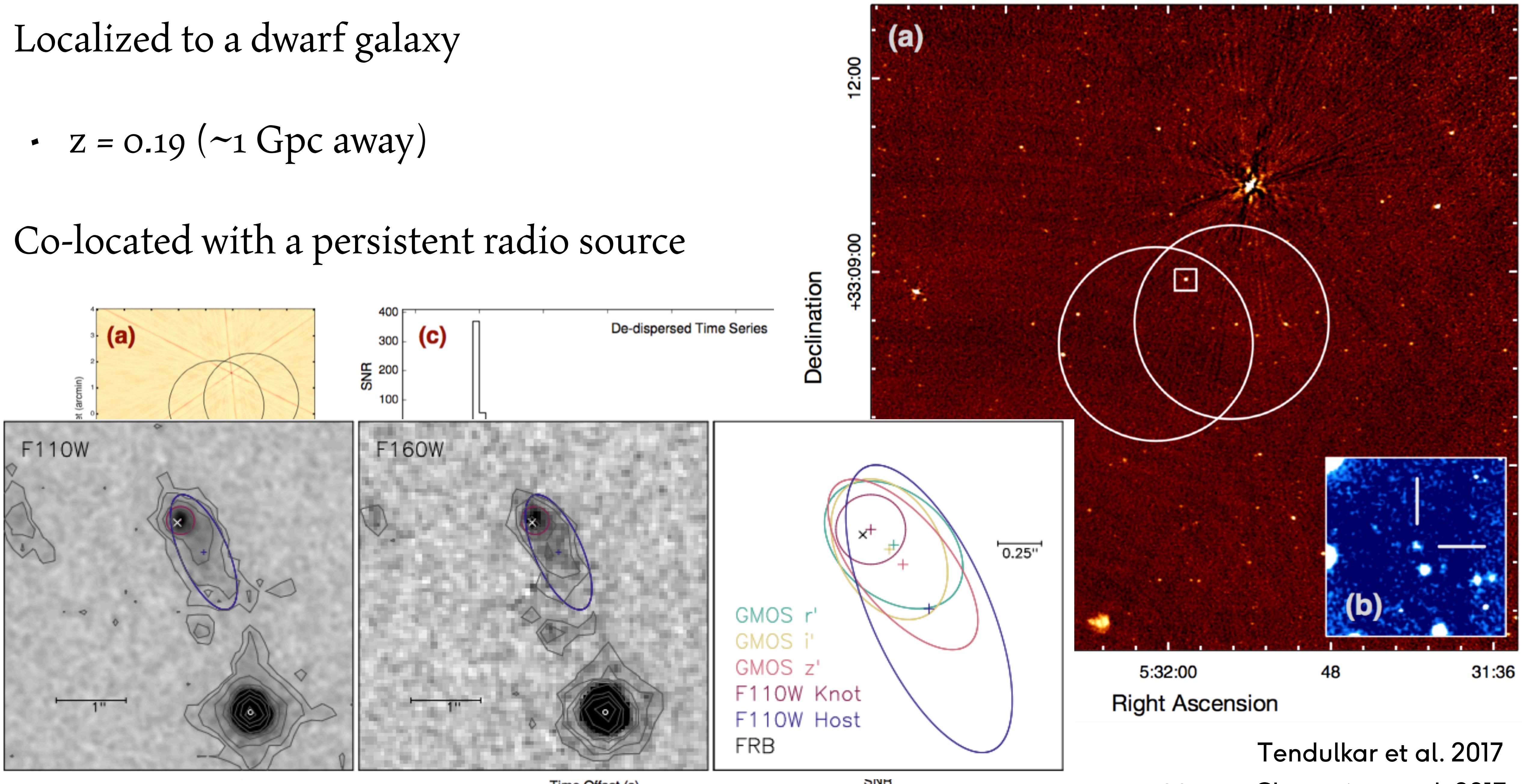
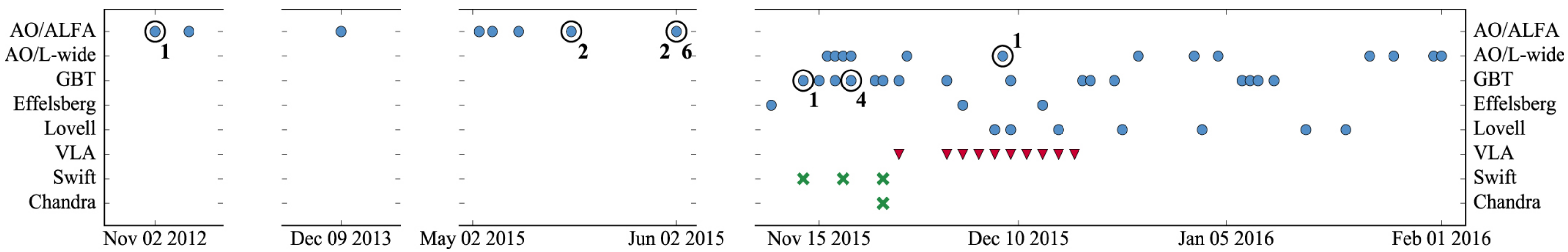


Tendulkar et al. 2017

Bassa et al. 2017

Chatterjee et al. 2017

Repeating FRBs

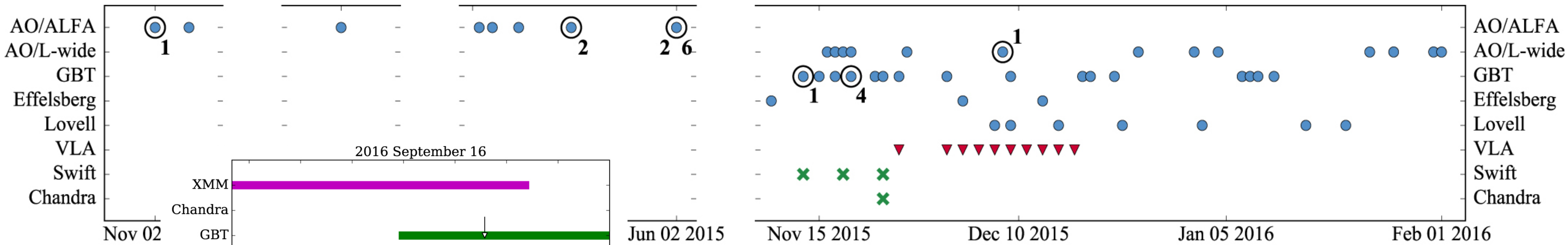


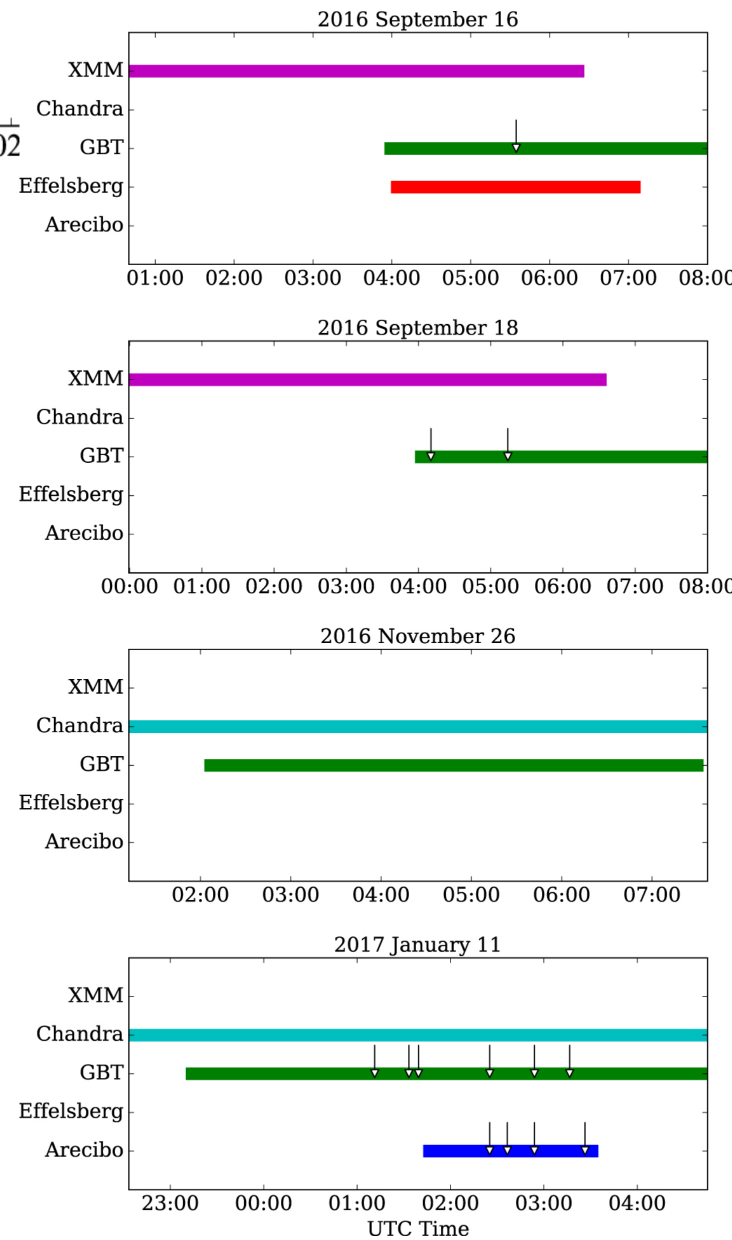
Scholz et al. 2016

Scholz et al. 2017

- Early search for variable emission around time of bursts
- Later: commensal observing
- No X-ray, gamma-ray emission observed
- Emission at radio also frequency-dependent

Repeating FRBs





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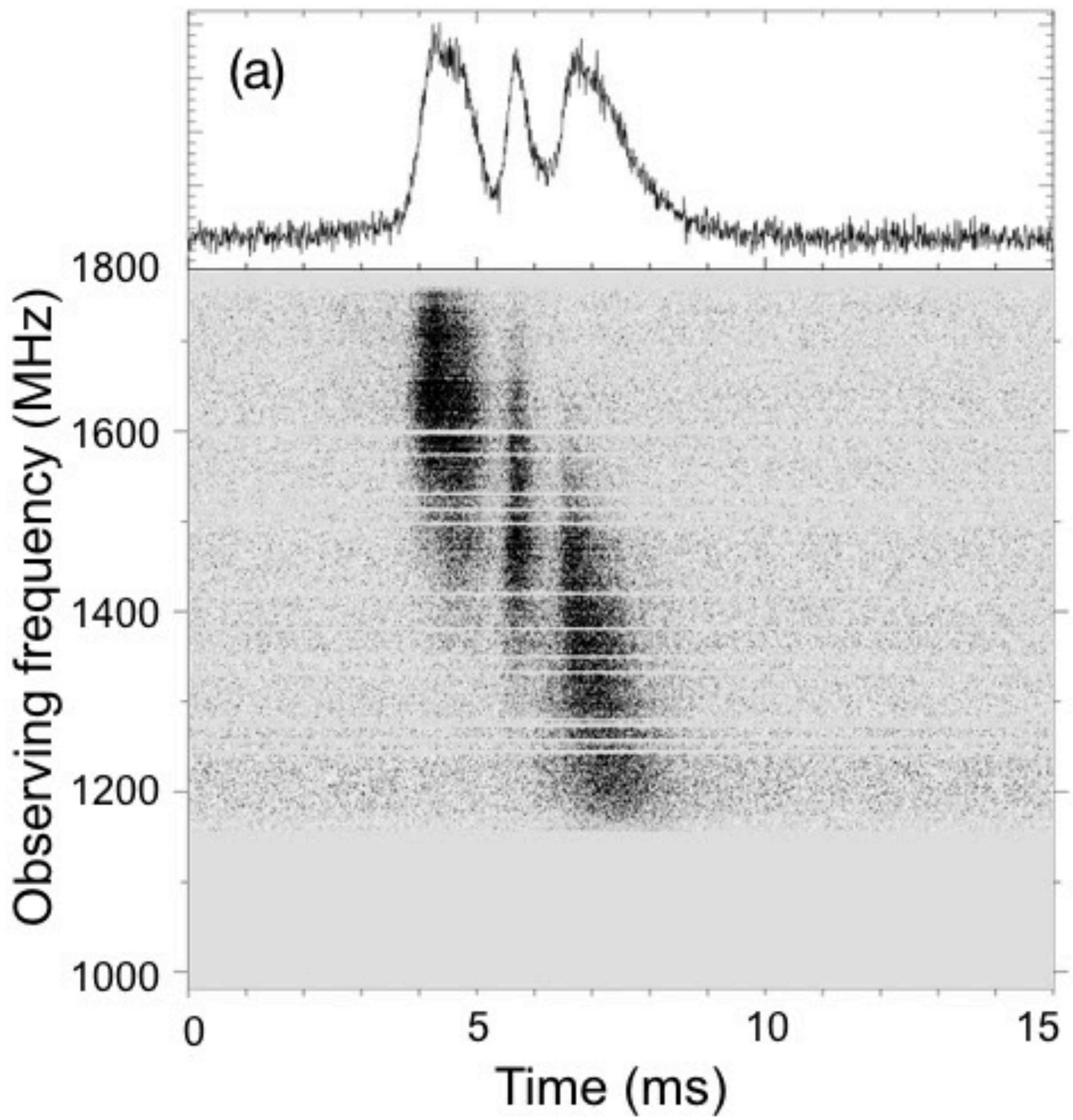
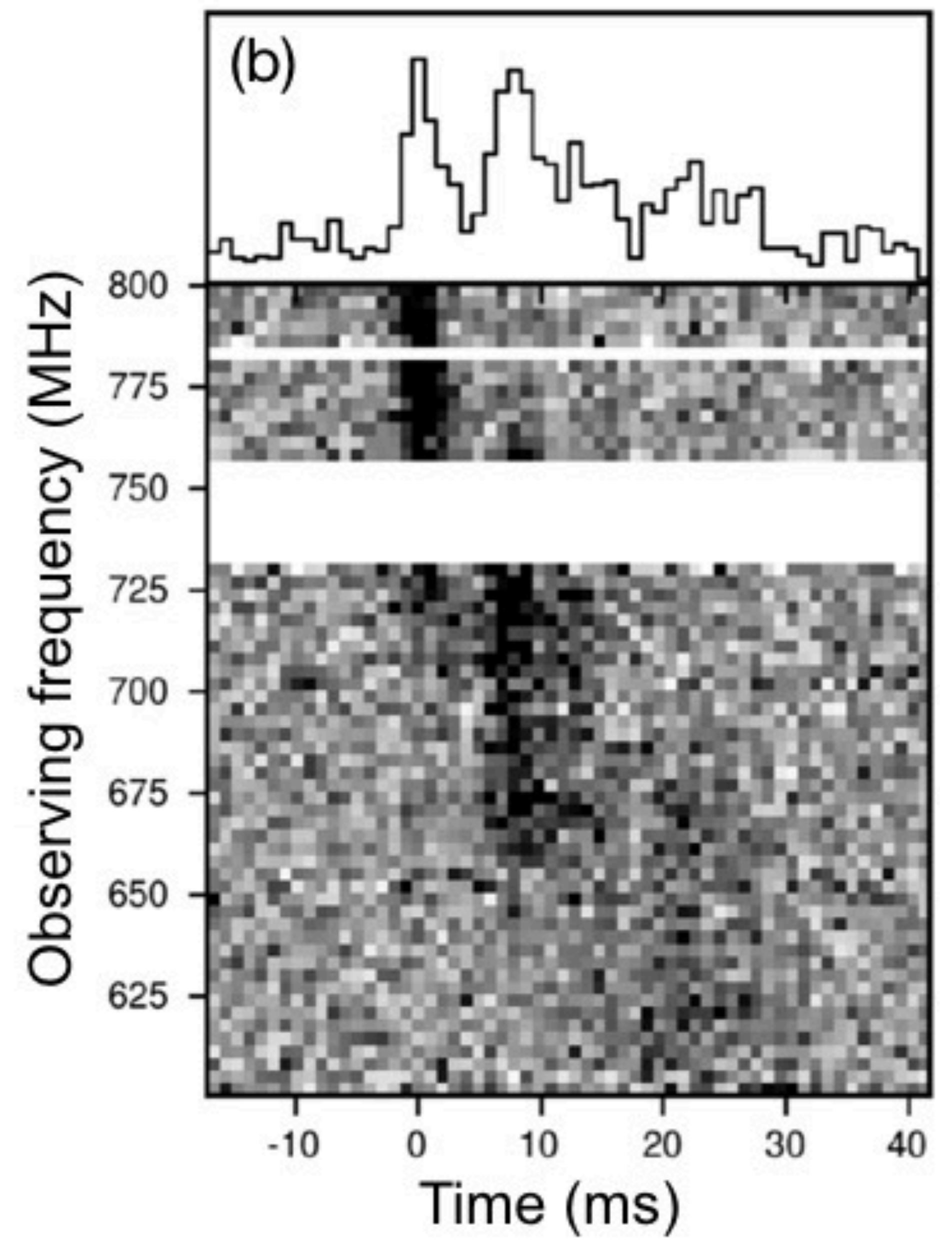
Frequency structure

“R1” - Arecibo

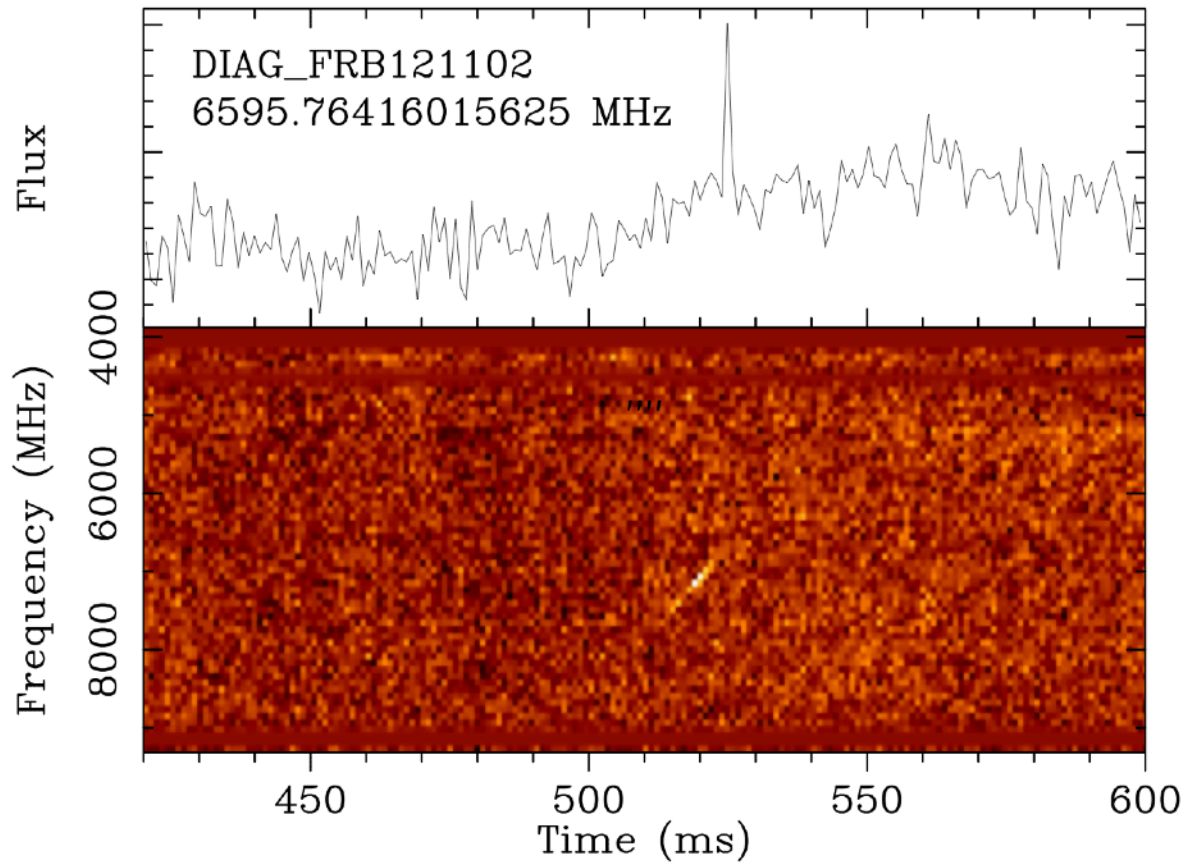


“R2” - CHIME

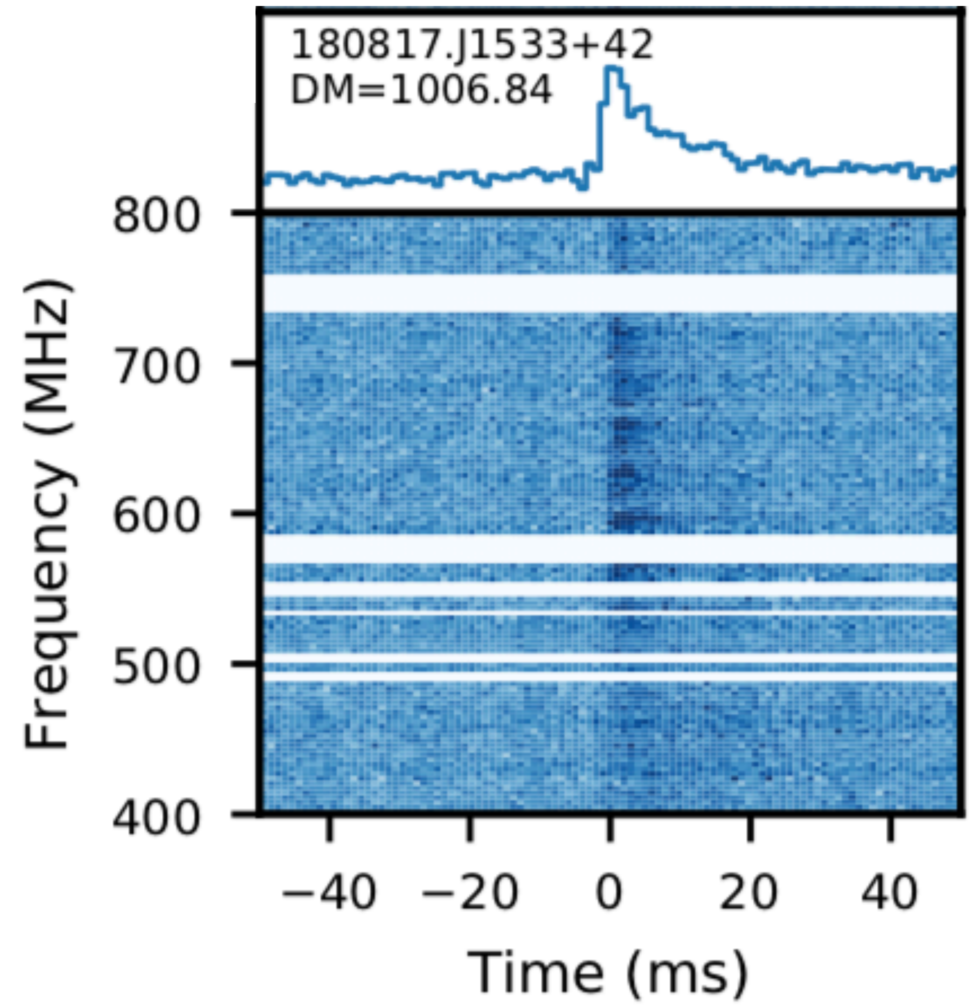


Petroff, Hessels & Lorimer (2019)

Lowest and highest frequencies



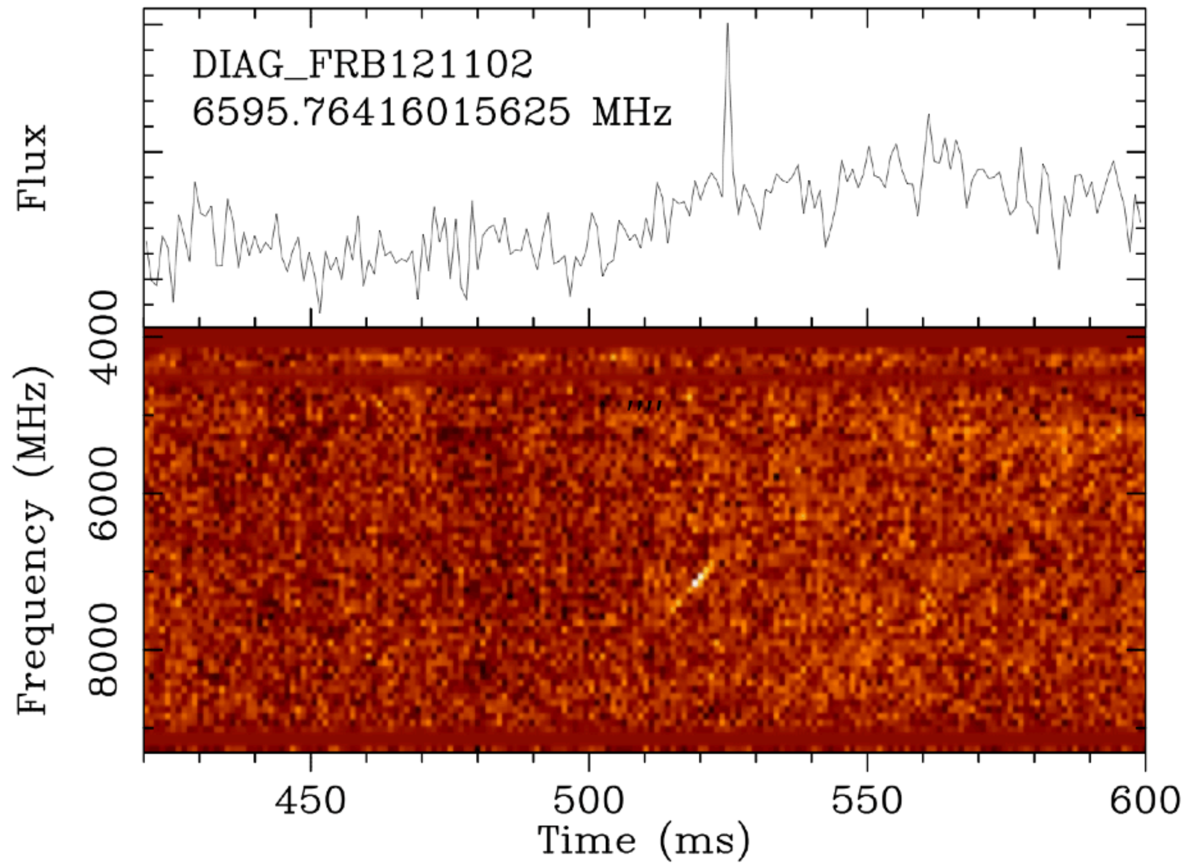
Gaijar et al. ATel 10675



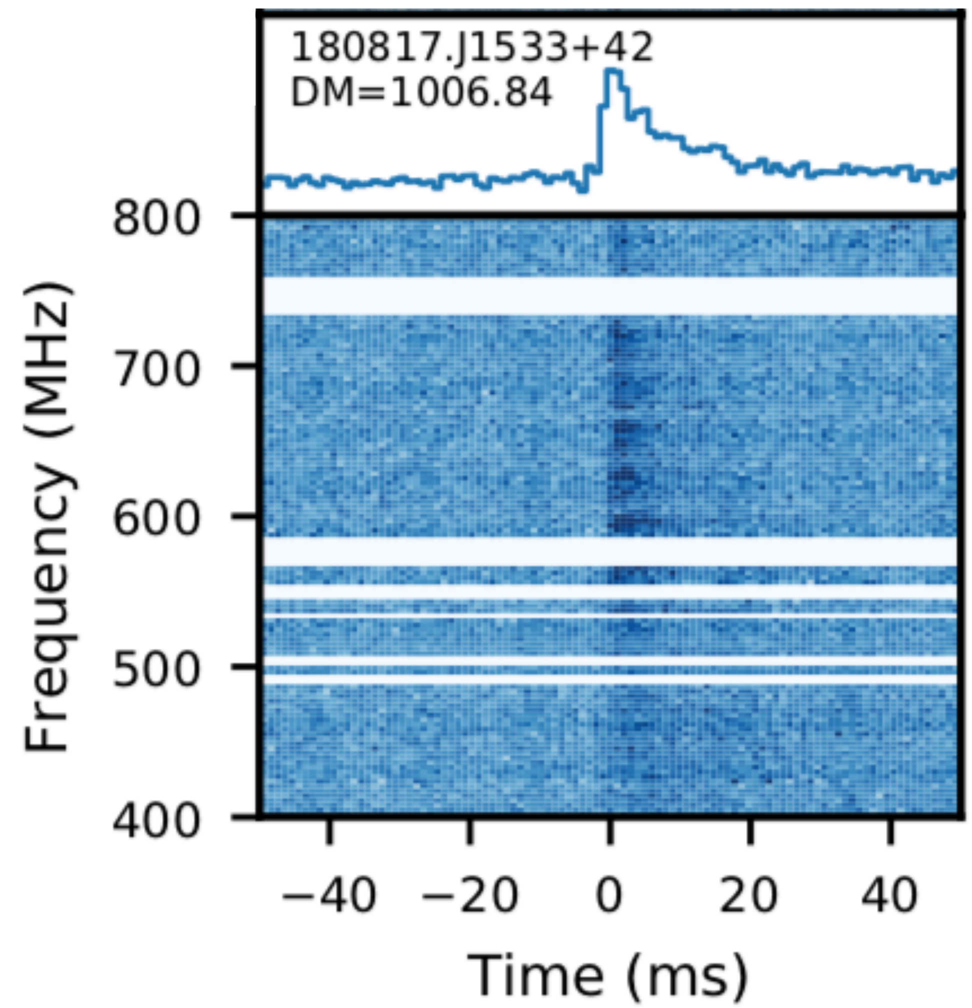
CHIME/FRB Collaboration 2019

Possible detection at ~111 MHz

Lowest and highest frequencies



Gaijar et al. ATel 10675



CHIME/FRB Collaboration 2019

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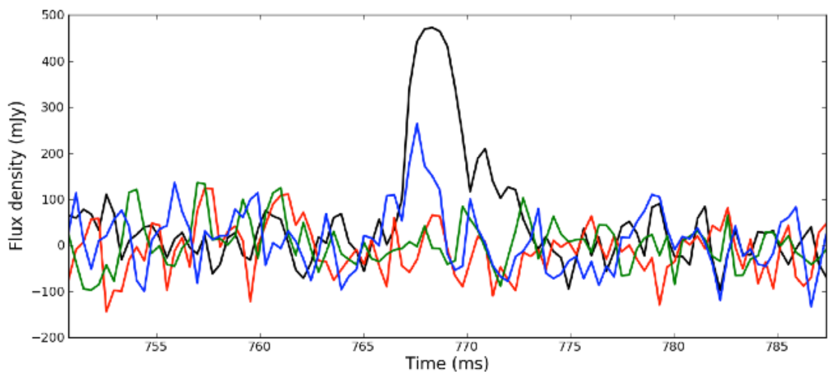
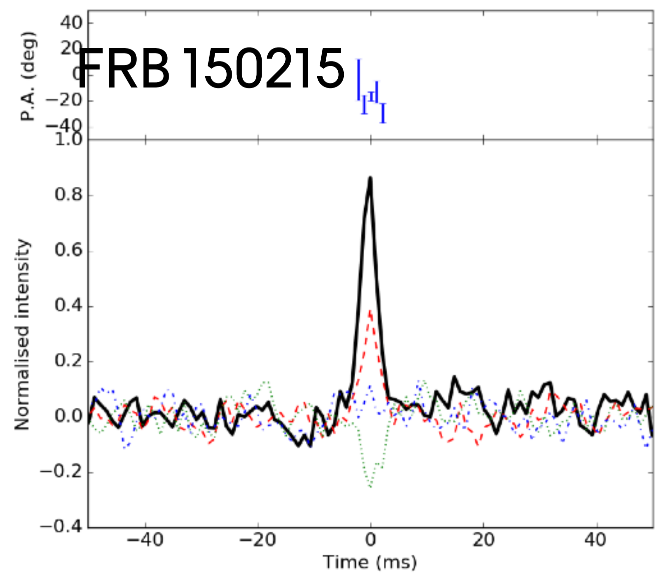
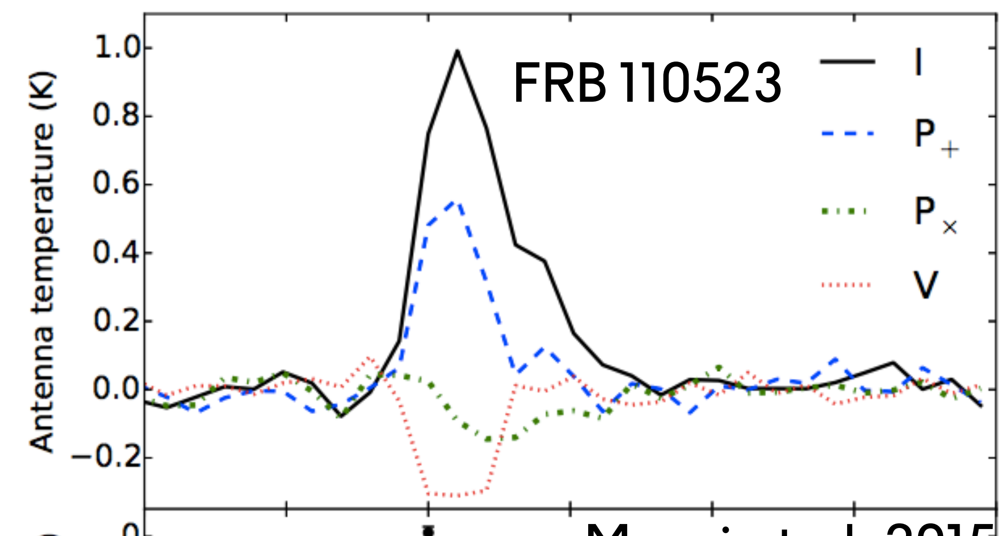
FRB polarization



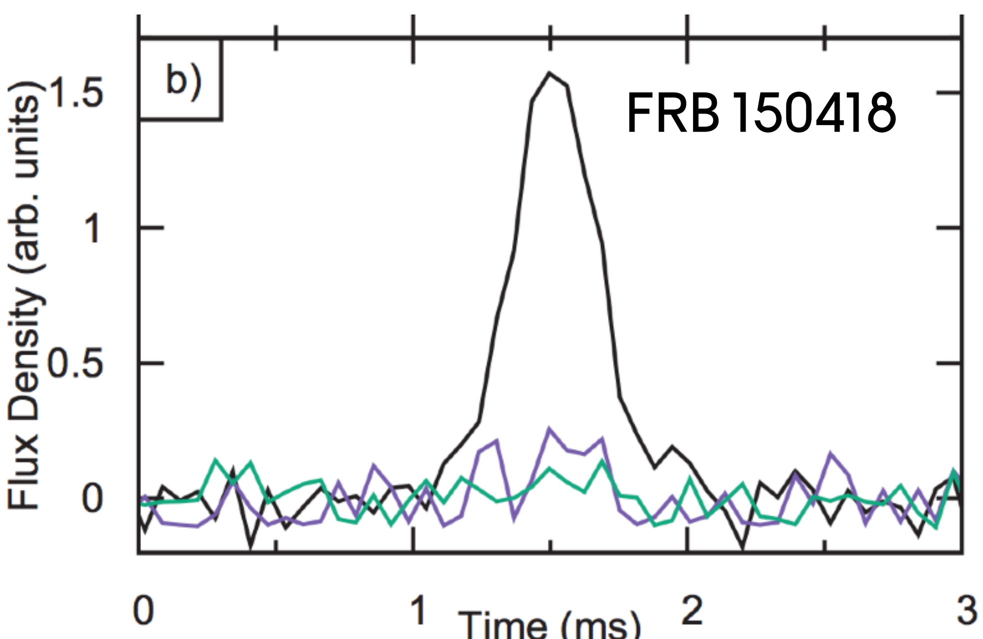
Petroff et al. 2015a



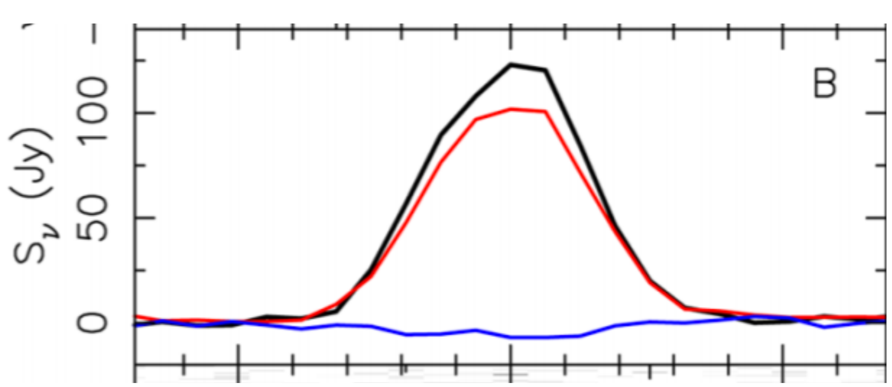
Petroff et al. 2017



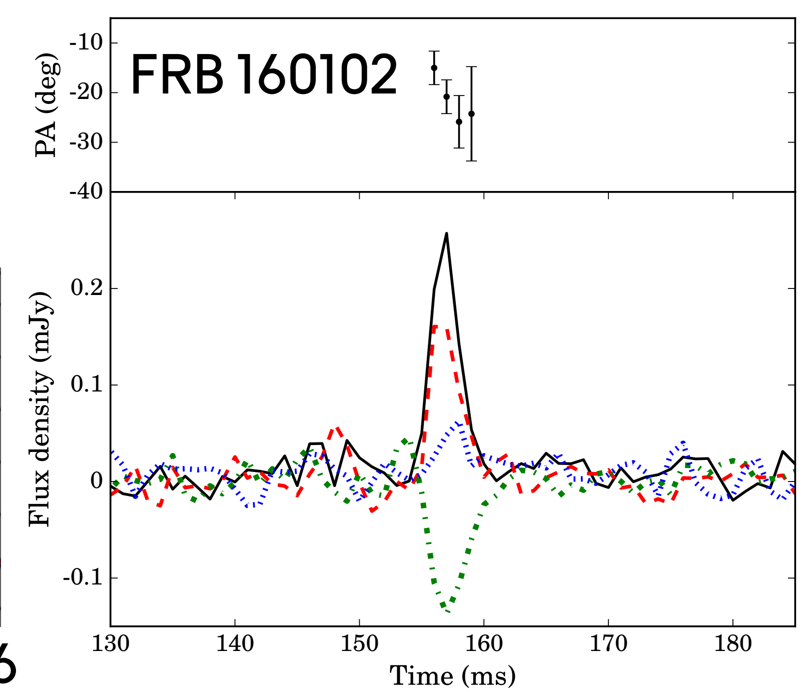
Masui et al. 2015



Keane et al. 2016

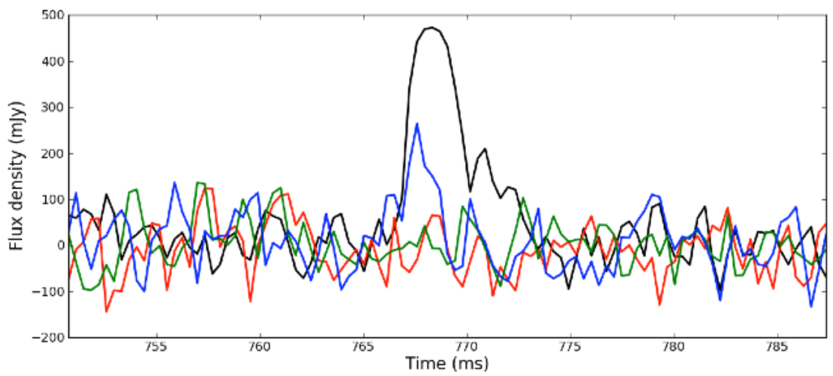


Ravi et al. 2016

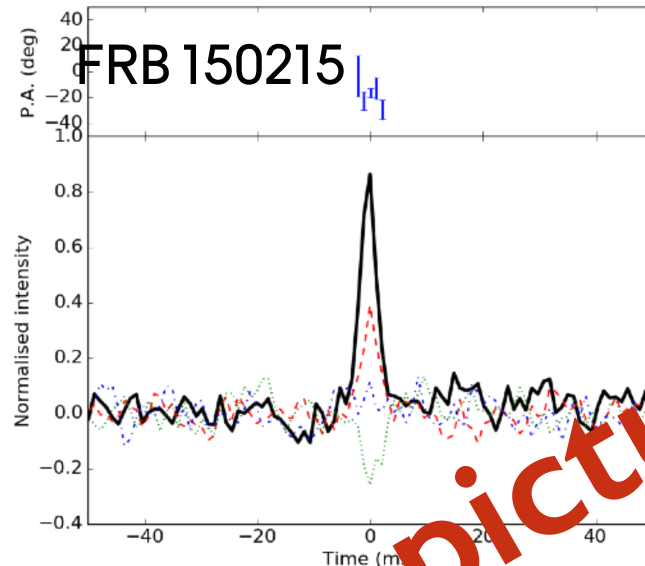


Caleb et al. 2018

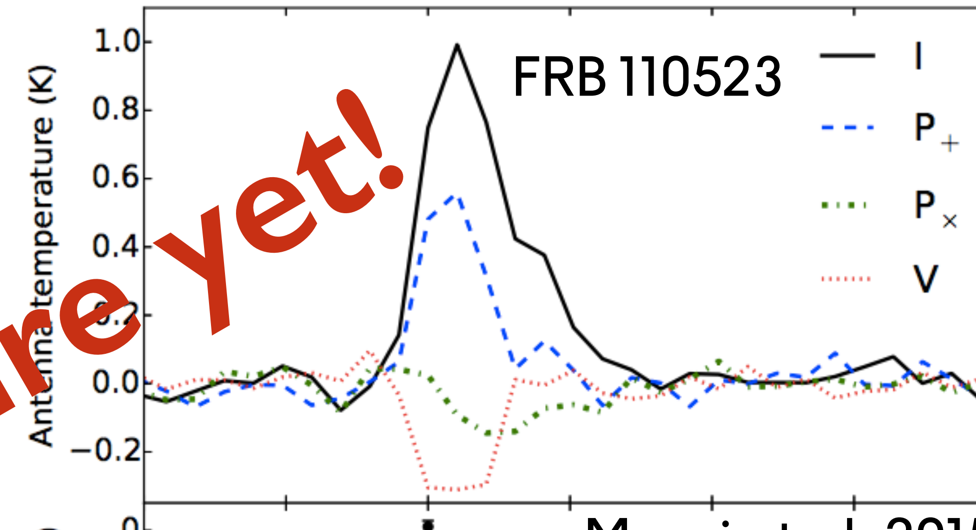
FRB polarization



Petroff et al. 2015a

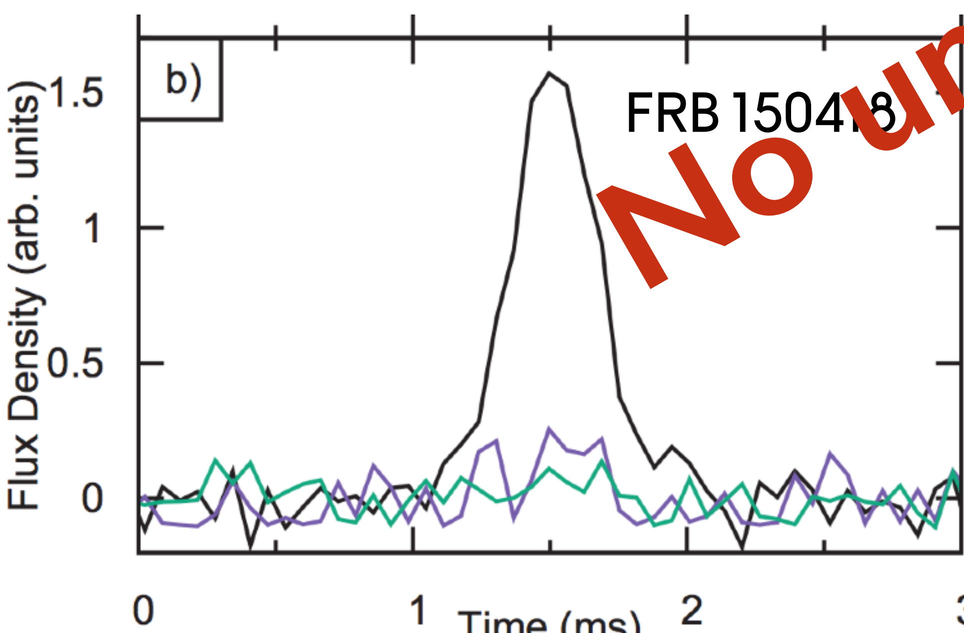


Petroff et al. 2017

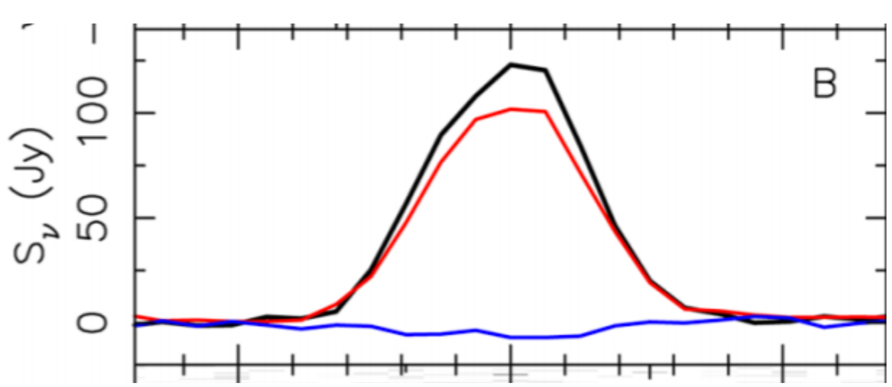


Masui et al. 2015

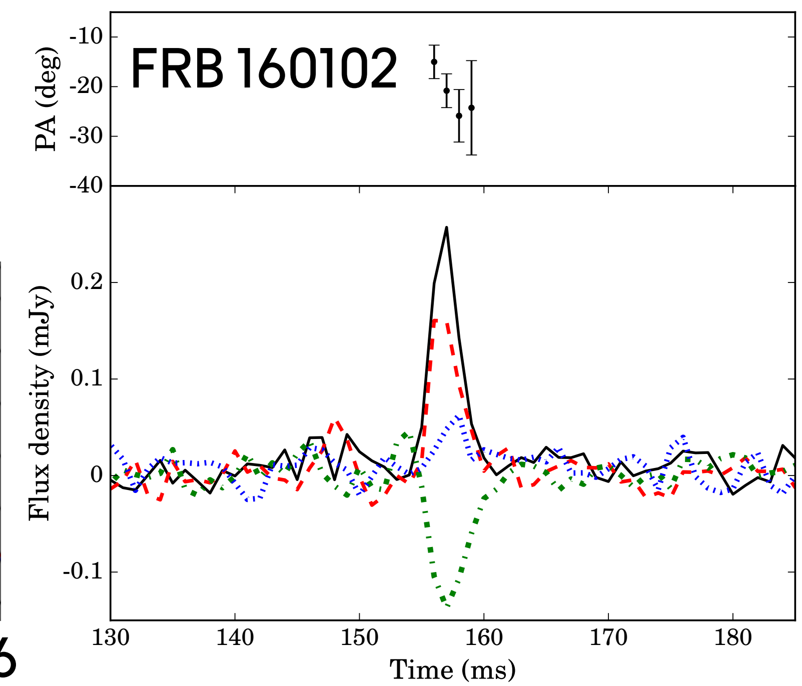
No unifying picture yet!



Keane et al. 2016



Ravi et al. 2016



Caleb et al. 2018

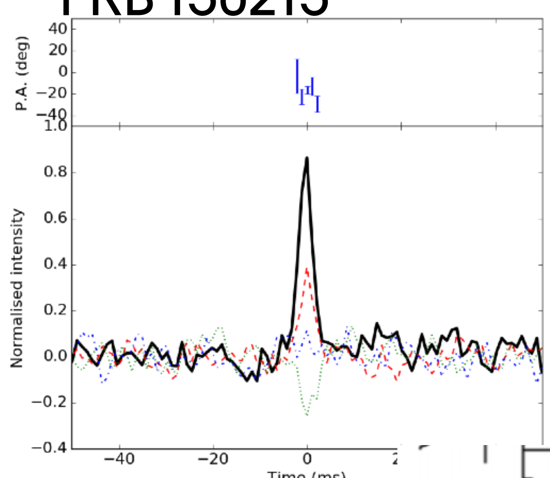
Rotation measure and magnetic

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^d n_e B_{\parallel} d\ell$$

FRB 150215	1.5±10 rad m^{-2}
FRB 150807	12±0.7 rad m^{-2}

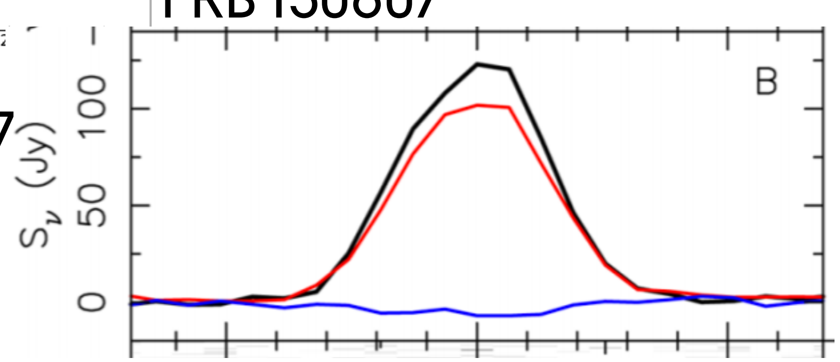
FRB 110523	-186.1±1.4 rad m^{-2}
FRB 160102	-220.6±6.4 rad m^{-2}

FRB 150215



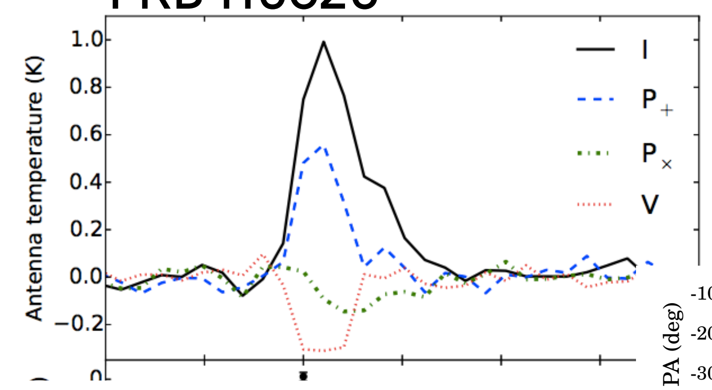
Petroff et al. 2017

FRB 150807



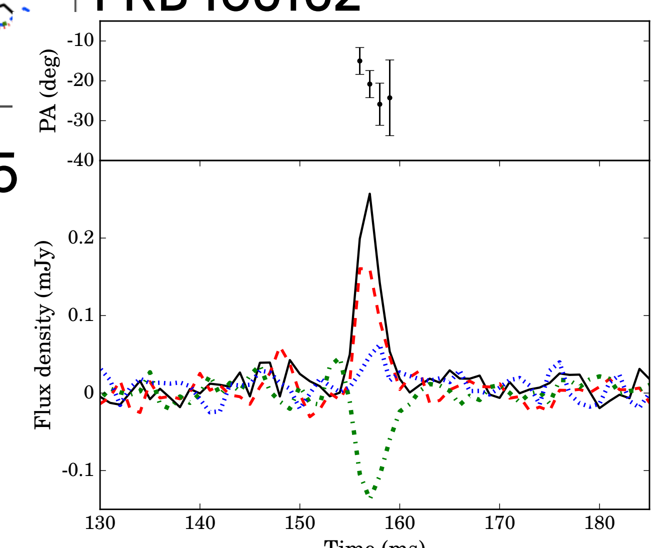
Ravi et al. 2016

FRB 110523



Masui et al. 2015

FRB 160102



Caleb et al. 2018

RM and local magnetic field

- FRBs 150215, 150807
    - High fractional linear polarization
    - Low RM consistent with estimates of Galactic foreground
    - No ordered magnetic field in addition to Galactic contribution

- FRBs 110523, 160102
    - High fractional linear polarization
    - RM much higher than estimated foreground
    - Ordered magnetic field local to progenitor or in host galaxy

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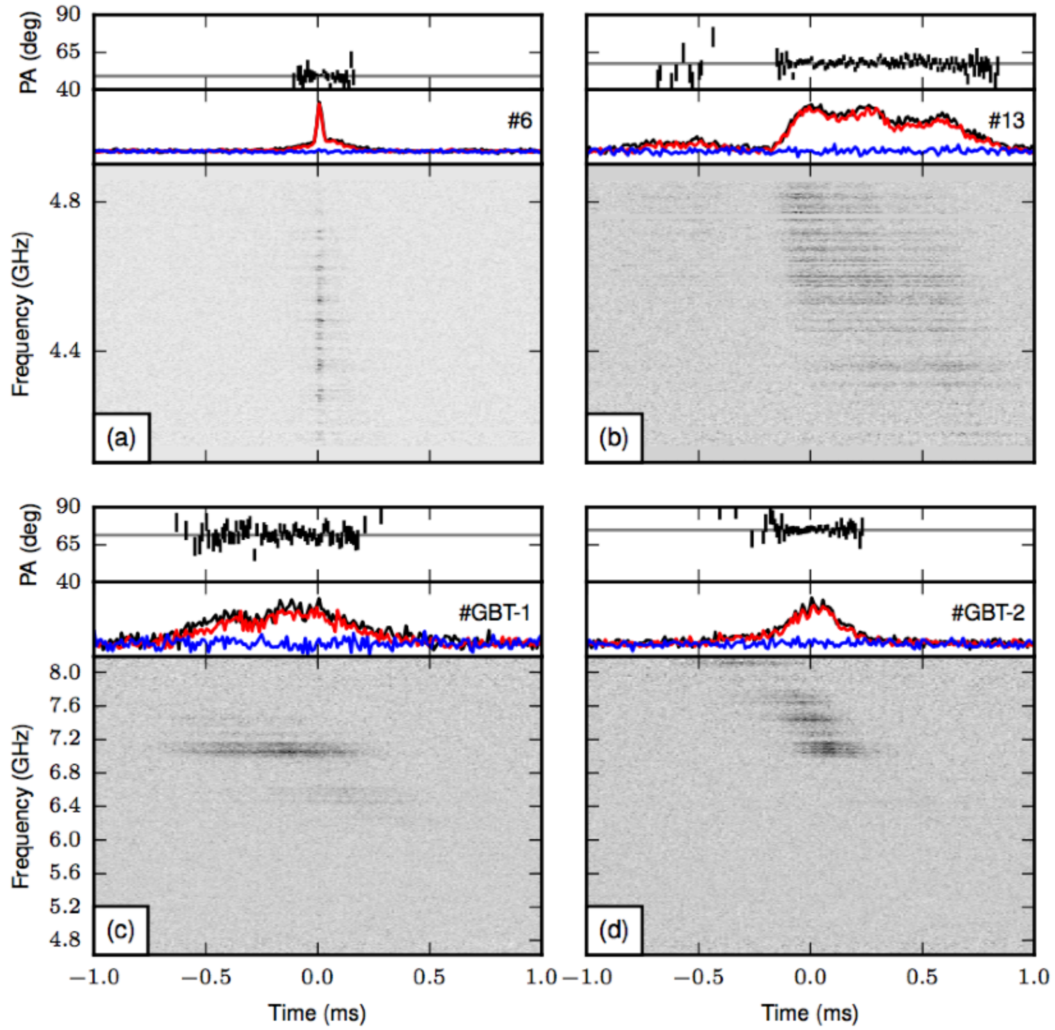
    - RM much higher than estimated foreground
    - Ordered magnetic field local to progenitor or in host galaxy

RM may give greatest insights into local environment!

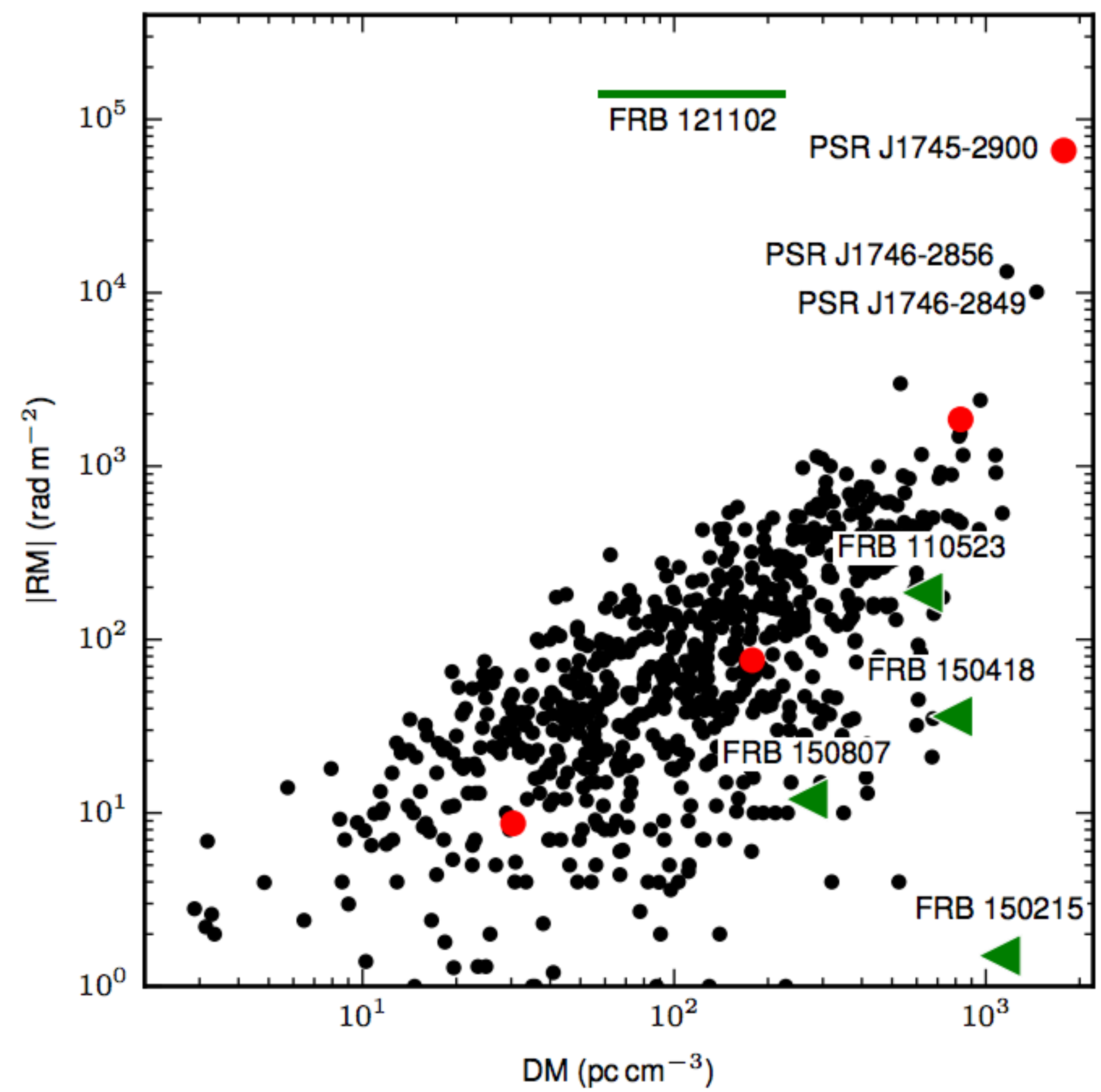
FRB 121102 rotation measure



100% linearly polarized

RM = 1.0 x 10^5 rad m^{-2}!!!

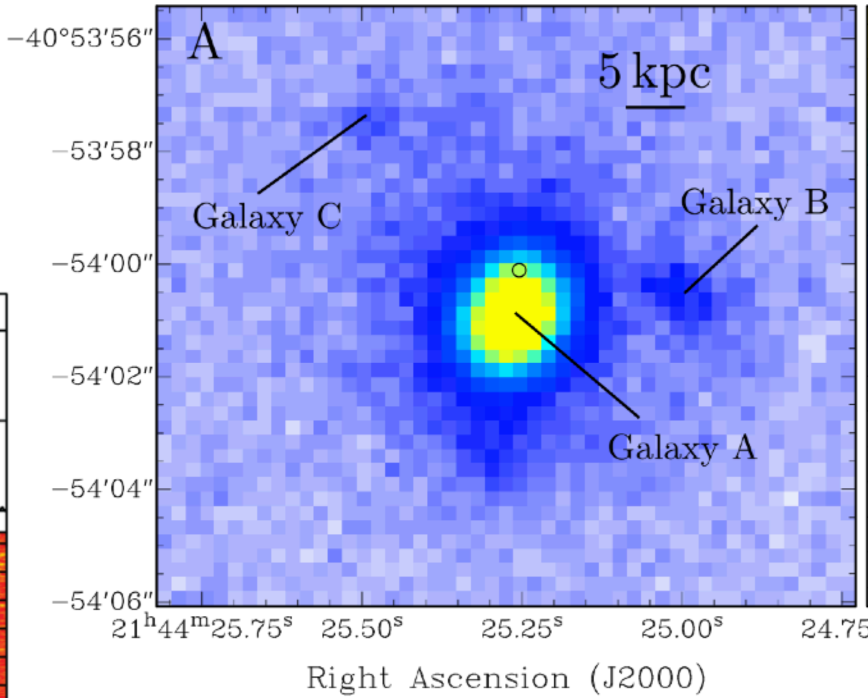
$$B_{||}^{\mathrm{FRB}} = (0.6\text{–}2.4) \times f_{\mathrm{DM}}\,\mathrm{mG}$$

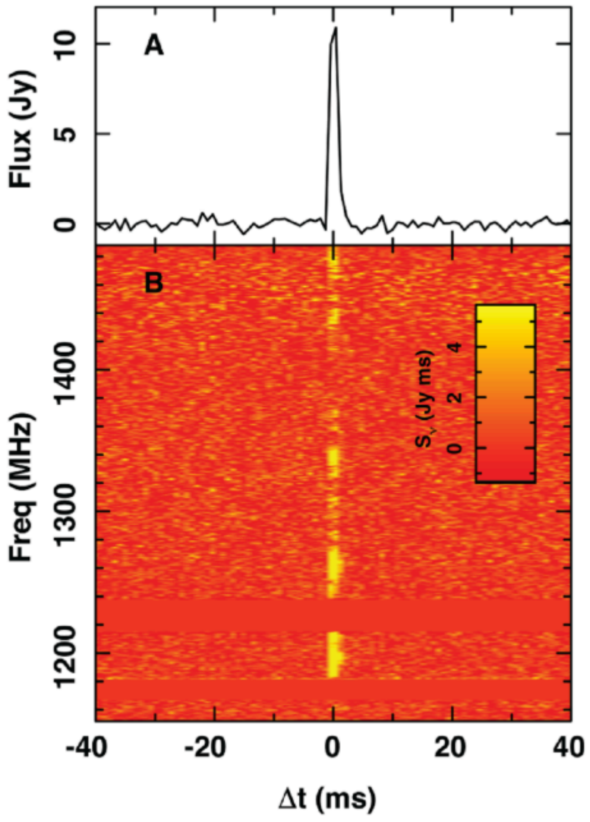


Michilli et al. 2018

Contrast: ASKAP FRB 180924

- Observed single pulse
- Localized to host galaxy from discovery pulse
- $z = 0.3214$, 10^{10} M_{sun} elliptical
- RM = 14 rad m^{-2}
- No radio, X-ray, gamma-ray source
- LIGO not in observing mode

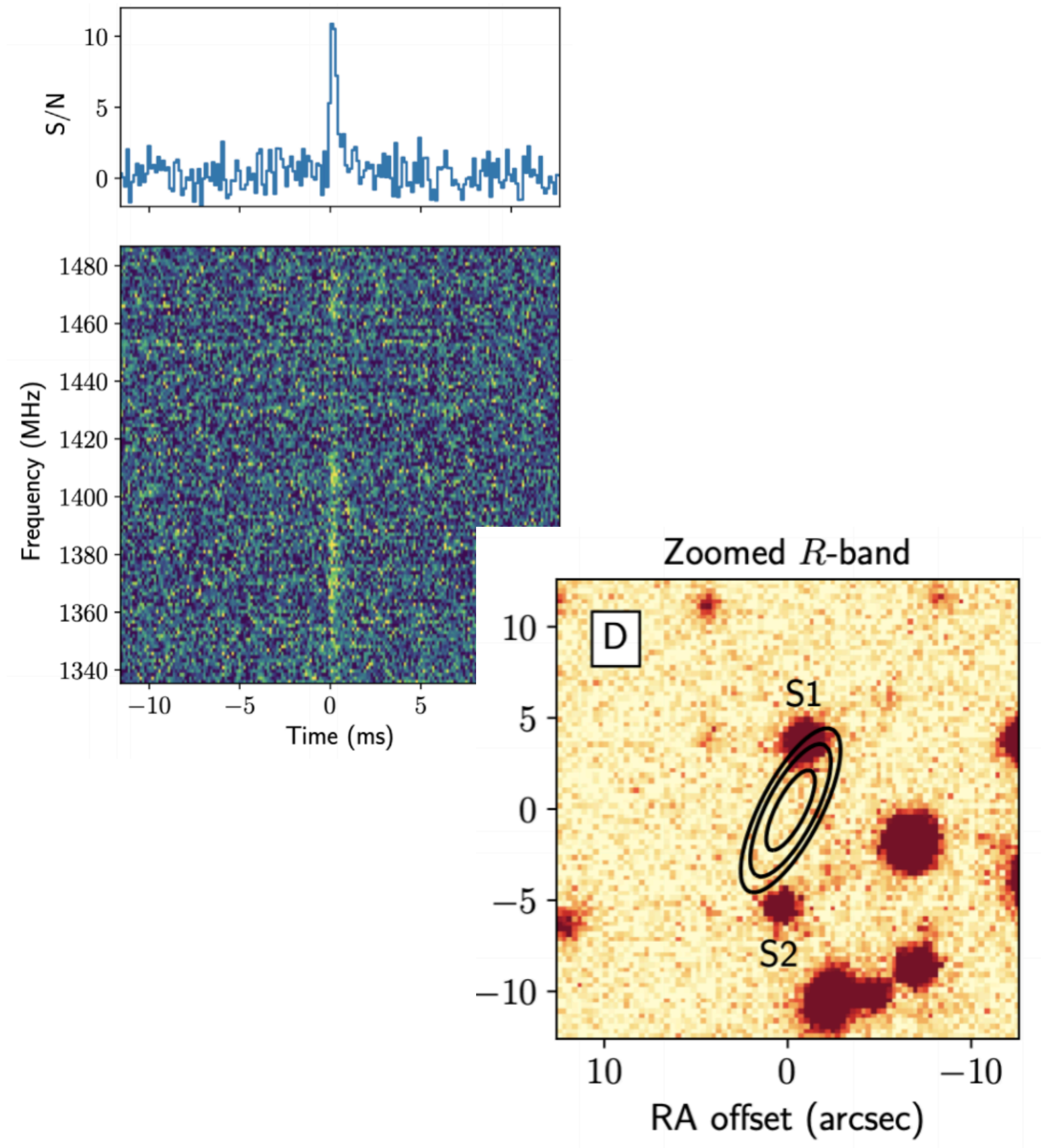




Bannister et al. 2019

And: DSA-10 FRB 190523

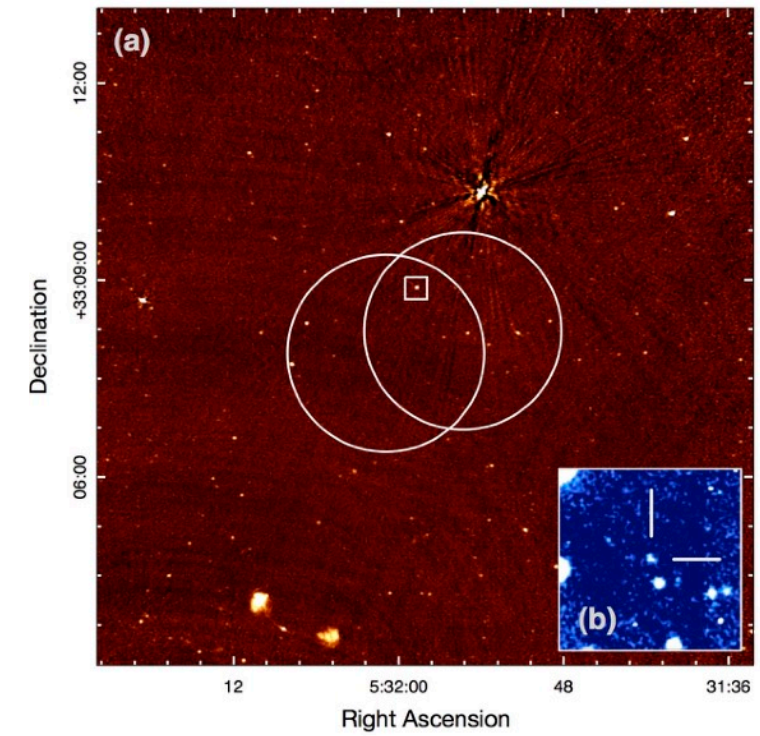
- Observed single pulse
- Localized to host galaxy from discovery pulse
- z = 0.66, 10^{11} M_{sun} elliptical
- No search for multi-wavelength emission
- LIGO O3 ongoing, nothing yet reported

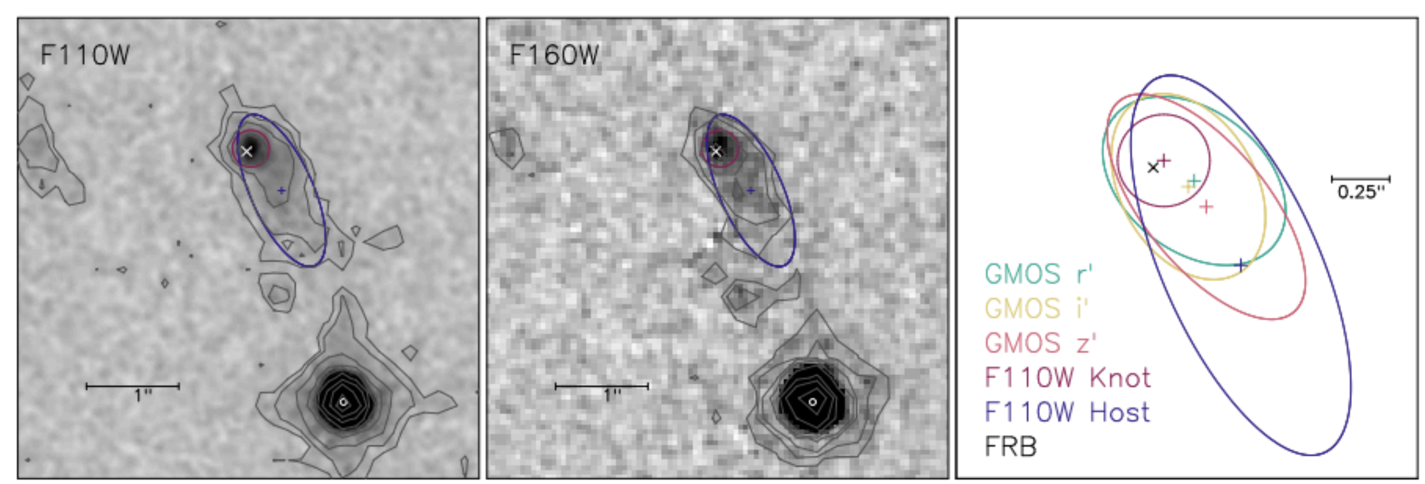


Ravi et al. 2019

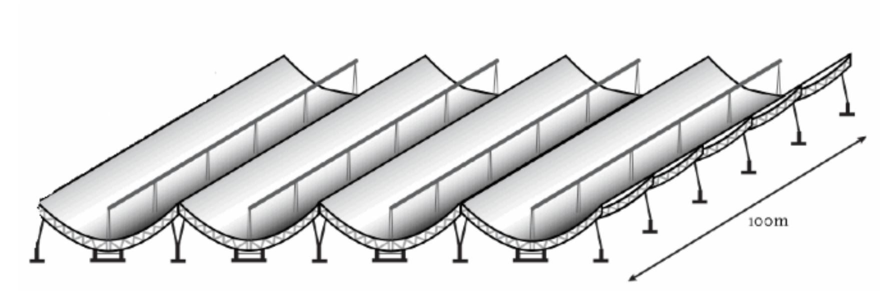
Future searches for associated emission

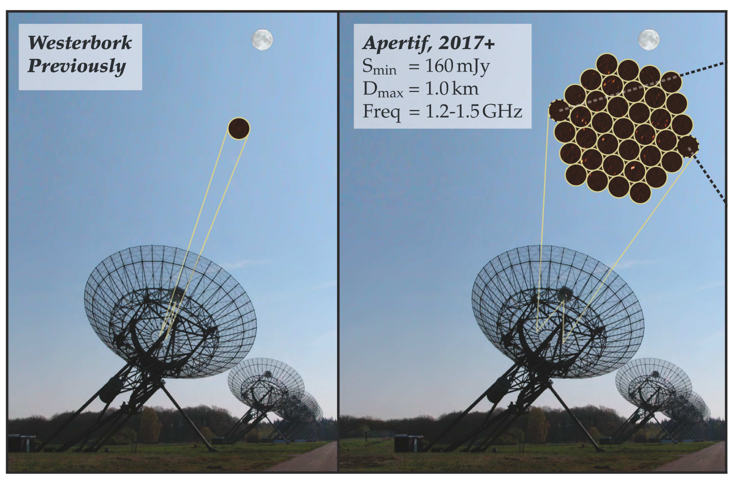
- Focusing on the nearest/lowest DM FRBs
- Detailed study of location in host + host properties
- Multi-wavelength study of progenitor environment
    - Getting a handle on DM_{local}
- Quantifying the MW + Halo DM contribution



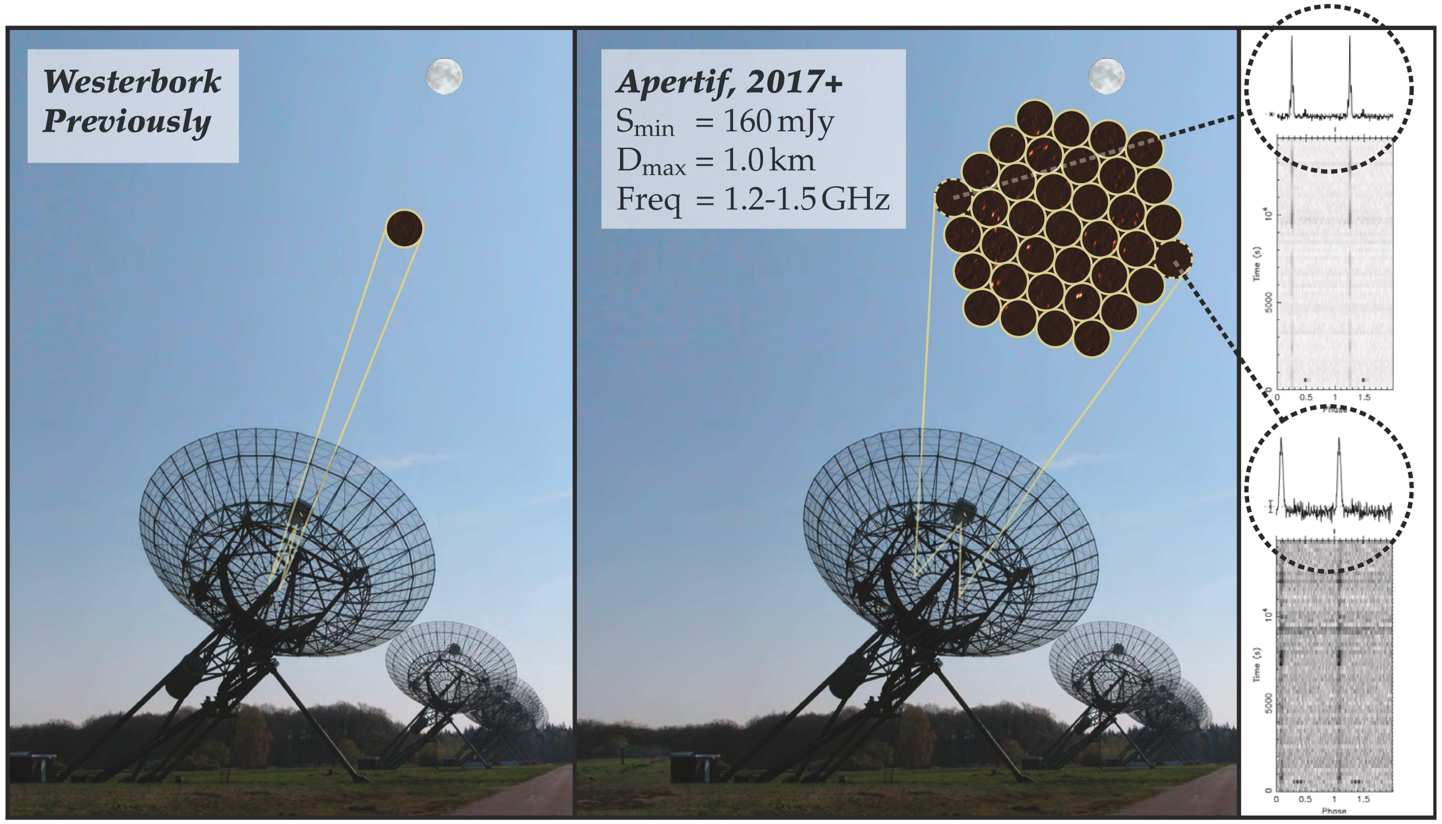


Future searches for associated emission





Searches with Apertif



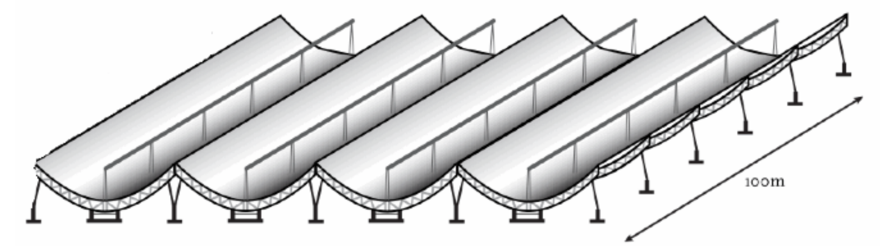
1.4 GHz

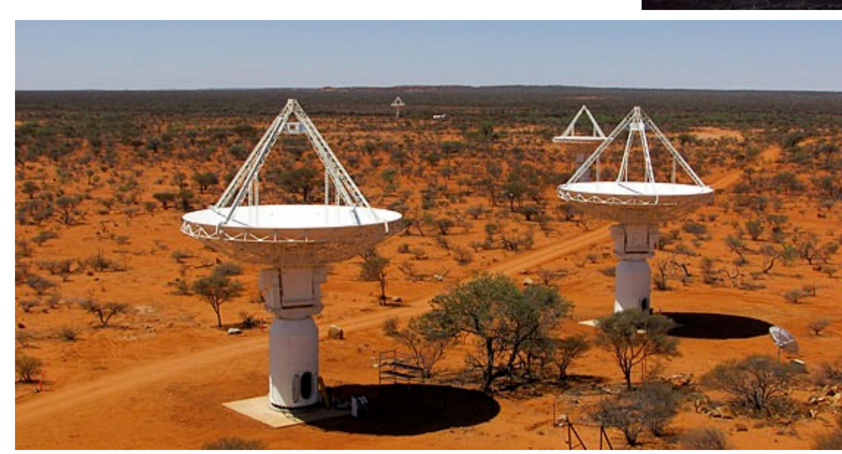
150 MHz

1-5 FRBs per month

Next few years

- More FRBs (and more localized) means more opportunities to search for associated emission
- Promising avenues:
    - Nearest sources, repeaters, precise localizations
- X-ray, gamma-ray, VHE
- But also lower radio frequencies, multimessenger



Further future

- Large population of events to cross-check with other facilities (LSST, LIGO/VIRGO, SVOM, CTA)
- More detailed data with SKA
- Complete multi-wavelength/multi-messenger picture

FRB Catalogue

@FRBCatalogue

This catalogue contains up to date information for the published population of Fast Radio Bursts (FRBs). This site is maintained by the FRBCAT team and is updated as new sources are published or refined numbers become available. Sources can now be added to the FRBCAT automatically via the VOEvent Network, details of this process are given in Petroff et al., 2017. FRBs confirmed via publication, or received with a high importance score over the VOEvent Network, are given 'Verified' status and are shown on the default homepage; to see all events (including unverified candidates received via the VOEvent Network) toggle the "Show all/Show verified" button below.

Information for each burst is divided into two categories: intrinsic properties measured using the available data, and derived parameters produced using a model. Cosmological values are obtained using the Cosmology Calculator (Wright, 2006). The intrinsic parameters should be taken as lower limits, as the position within the telescope beam may be uncertain. Where multiple fits or measurements of a burst have been made each one is provided as a separate sub-entry for the FRB.

You may use the data presented in this catalogue for publications; however, we ask that you cite the paper (Petroff et al., 2016) and provide the url (http://www.frbcat.org). Any issues relating to the use of the catalogue should be addressed to FRBCAT team (primary contact: Emily Petroff).

Visible columns | Show verified | Export to CSV | Search | Clear

	FRB	UTC	Telescope	RAJ	DECJ	GL	GB	DM	Width	SNR
+	FRB170922	2017/09/22 11:22:23.400	UTMOST	21:29:50.61	-07:59:40.49	45.1	-38.7	1111	26	22
+	FRB170827	2017/08/27 16:20:18.000	UTMOST	00:49:18.66	-65:33:02.3	303.2	-51.7	176.4±0	0.4	90
+	FRB170107	2017/01/07 20:05:45.139	ASKAP	11:23:10	-05:01	266	51.4	609.5±0.5	2.6	16
+	FRB160608	2016/06/08 03:53:01.088	UTMOST	07:36:42	-40:47:52	254.11	-9.54	682±7	9	12
+	FRB160410	2016/04/10 08:33:39.680	UTMOST	08:41:25	06:05:05	220.36	27.19	278±3	4	13

www.frbcat.org

Petroff et al. 2016

Concluding remarks

What did you learn?

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- Repeaters and precisely localized sources offer the best opportunities to constrain emission
- New telescopes coming online will give us answers on a relatively short timescale
- Watch this space!

ANTON PANNEKOEK INSTITUTE

Thank You!

ebpetroff@gmail.com