FAST RADIO BURSTS

Searching for needles in a very large haystack

Shami Chatterjee

GR21, July 2016

Outline and Summary

- FRBs: Millisecond radio pulses with high pulse dispersion measures.
  - Almost certainly astrophysical in nature.
  - Very probably from outside our Galaxy.

- So far, most FRBs have been detected at Parkes.
  (Lorimer et al. 2007, Keane et al. 2012, Thornton et al. 2013,
  Burke-Spolaor & Bannister 2014, Ravi et al. 2015, Petroff et al. 2015, Champion et al. 2016, …)

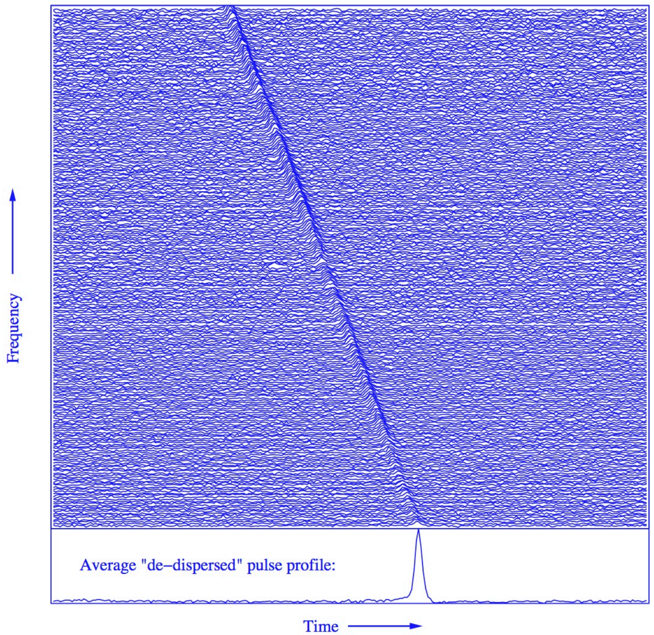
- FRBs also detected at Arecibo (Spitler et al. 2014)
  and Green Bank (Masui et al. 2015).

- At least one FRB source repeats. Not cataclysmic (Spitler et al. 2016).

- What are FRBs? Terrestrial, Galactic, Extragalactic?
  - Implied rates > 10,000 over sky per day.
  - Multiple populations are not yet required:
    extreme value statistics at work.
  - Source distance? Redshifts? Energetics? Connection to GWs?
    "Location, location, location."

Interstellar / Intergalactic Plasma Propagation Effects

Dispersion Delays



$$t_{\mathrm{DM}}(\nu) = \frac{4.15 \times \mathrm{DM\ \ ms}}{\nu^2_{\mathrm{GHz}}}$$

$$DM = \int_0^D ds\, n_e(s)$$

Deterministic, removable with coherent de-dispersion.

Multipath Broadening (Scattering)

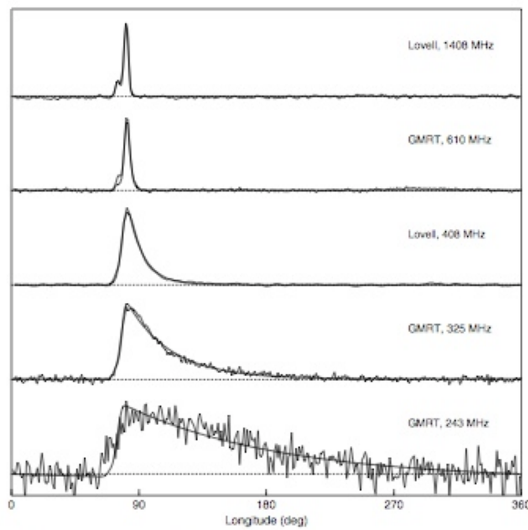
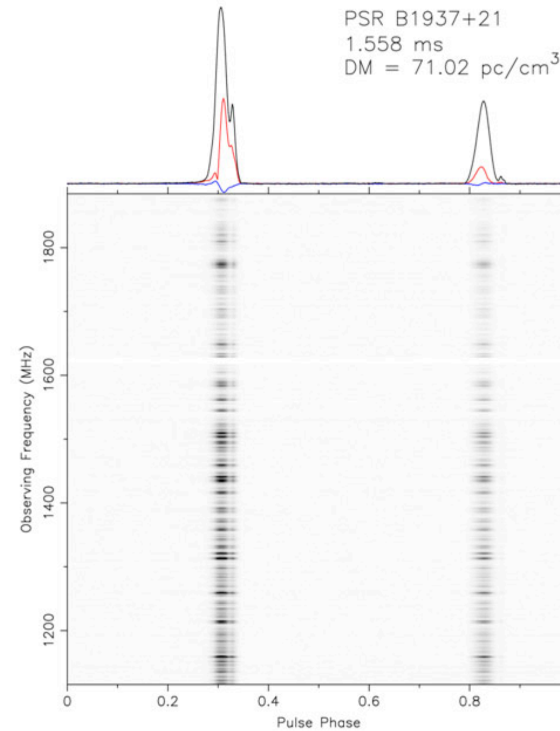


Fig. 1. Integrated pulse profiles and best-fit model profiles for PSR B1831−03 at different frequencies. The profiles at 243, 325 and 610 MHz were observed with the GMRT, whereas the 408 and 1408 MHz profiles were taken from the EPN database (Lovell observations). The alignment of the profiles for different frequencies was done with respect to the peak of the main pulse.

$$t_{\mathrm{scatt}} = \frac{D\theta_d^2}{2c}$$

Stochastic, not easily removable.

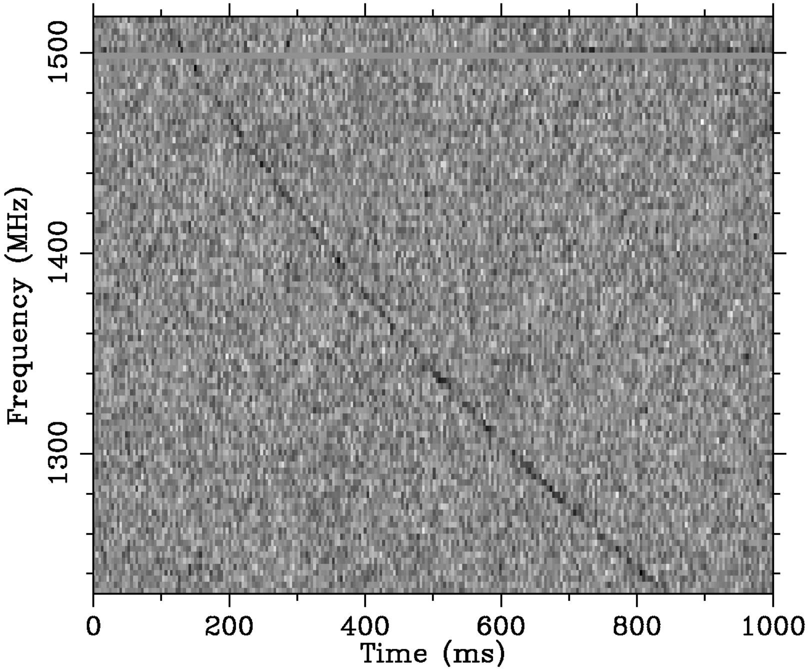
Diffractive Scintillation



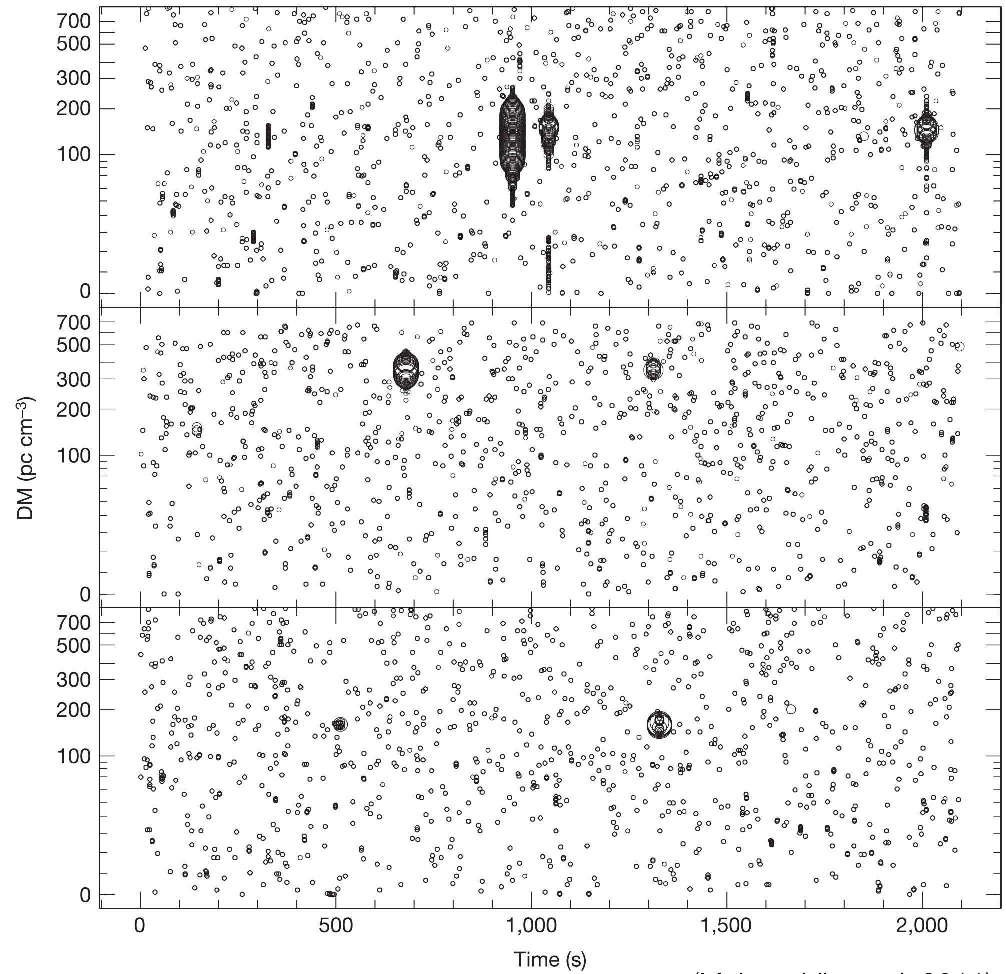
$$\Delta\nu_{\mathrm{scatt}} \approx \frac{1}{2\pi t_{\mathrm{scatt}}}$$

100% modulations of flux density.

Single Pulses, Pulse Dispersion, and Galactic Models



(Burke-Spolaor & Bannister 2014)



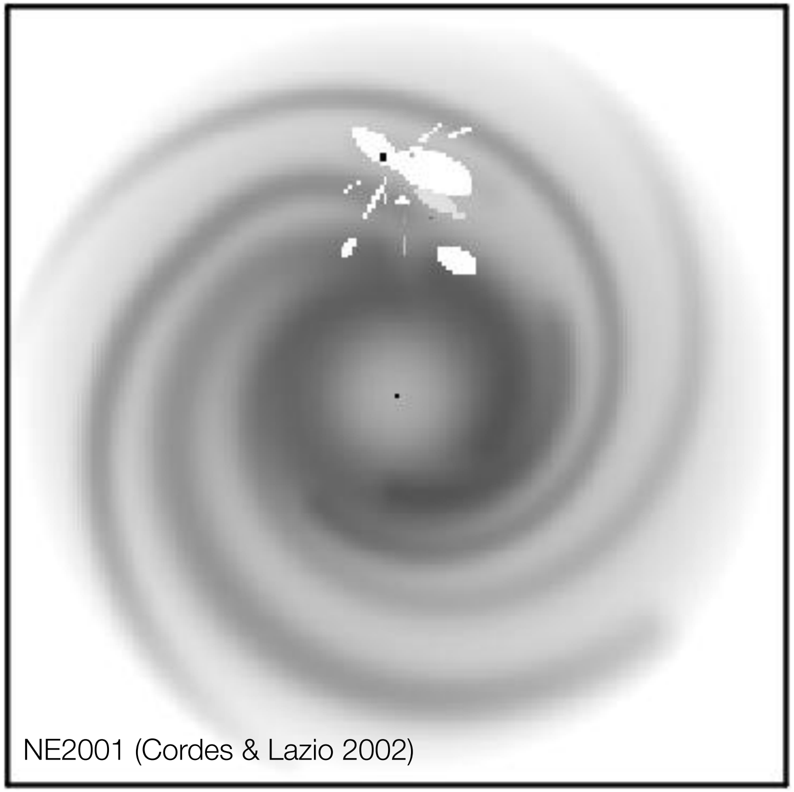
(McLaughlin et al. 2011)

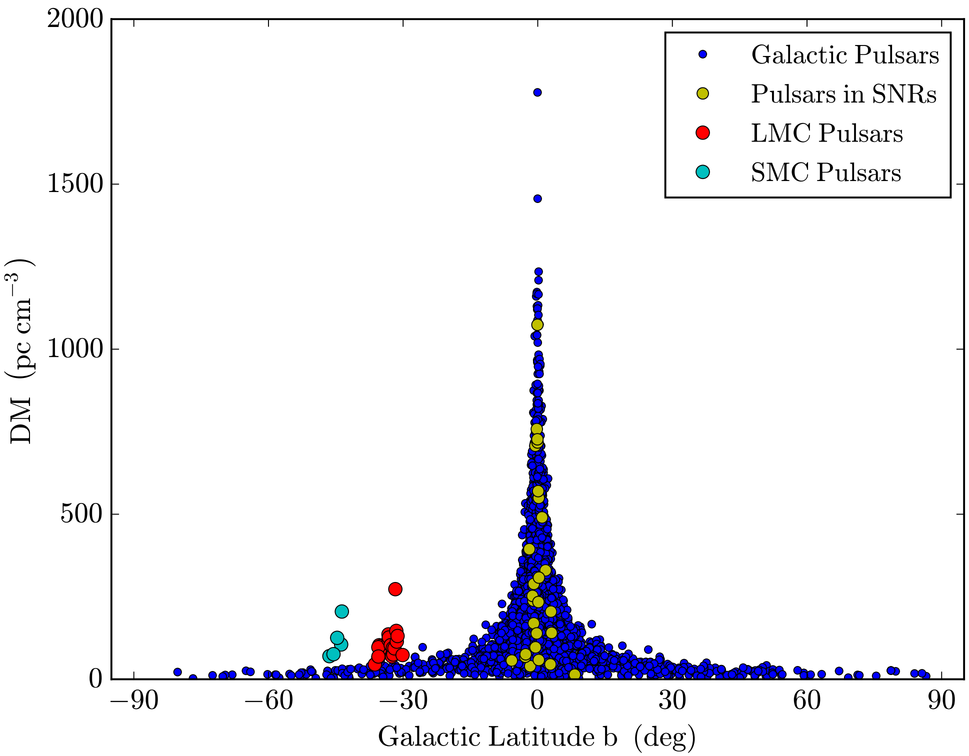
Single pulses sweep through time-frequency plane.

➔ Search space in time – DM.

➔ Observed DM → estimate distance.

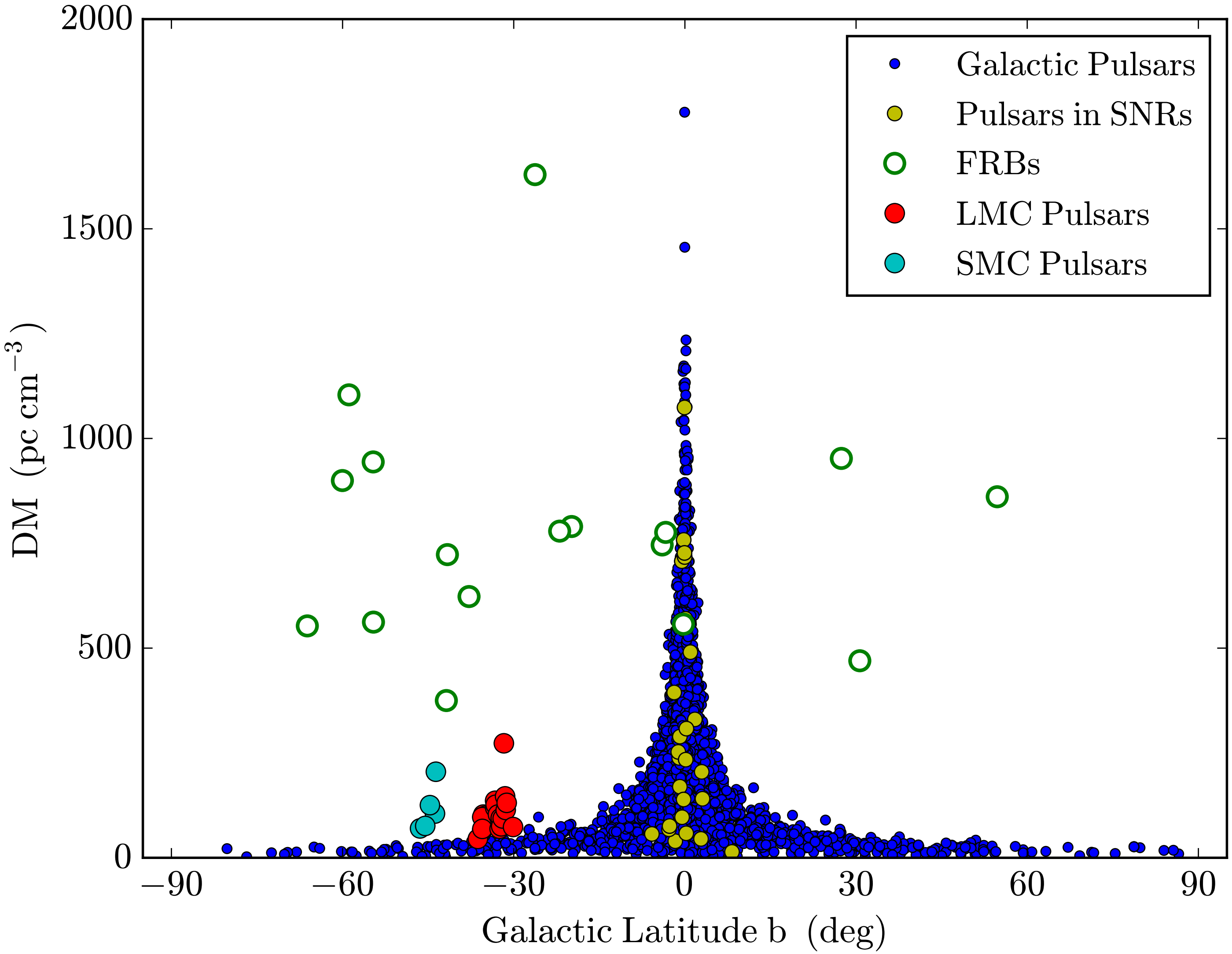
Single Pulses, Pulse Dispersion, and Galactic Models





Ensemble of detected pulsar DMs
+ independent distances + a variety of other constraints
➔ Models for the Galactic electron density distribution (e.g., NE2001).
➔ Distance estimates (or limits) for other dispersed pulses.

FRBs : Excess Pulse Dispersion



DM observed

$= \mathrm{DM}_{\text{Milky Way}}$

$+ \mathrm{DM}_{\text{IGM}}$

$+ \mathrm{DM}_{\text{Host Galaxy}}$

Some FRB examples

FRB 010724, the Lorimer burst

A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. Lorimer,[1,2]* M. Bailes,[3] M. A. McLaughlin,[1,2] D. J. Narkevic,[1] F. Crawford[4]

Pulsar surveys offer a rare opportunity to monitor the radio sky for impulsive burst-like events with millisecond durations. We analyzed archival survey data and found a 30-jansky dispersed burst, less than 5 milliseconds in duration, located 3° from the Small Magellanic Cloud. The burst properties argue against a physical association with our Galaxy or the Small Magellanic Cloud. Current models for the free electron content in the universe imply that the burst is less than 1 gigaparsec distant. No further bursts were seen in 90 hours of additional observations, which implies that it was a singular event such as a supernova or coalescence of relativistic objects. Hundreds of similar events could occur every day and, if detected, could serve as cosmological probes.

SCIENCE VOL 318 2 NOVEMBER 2007

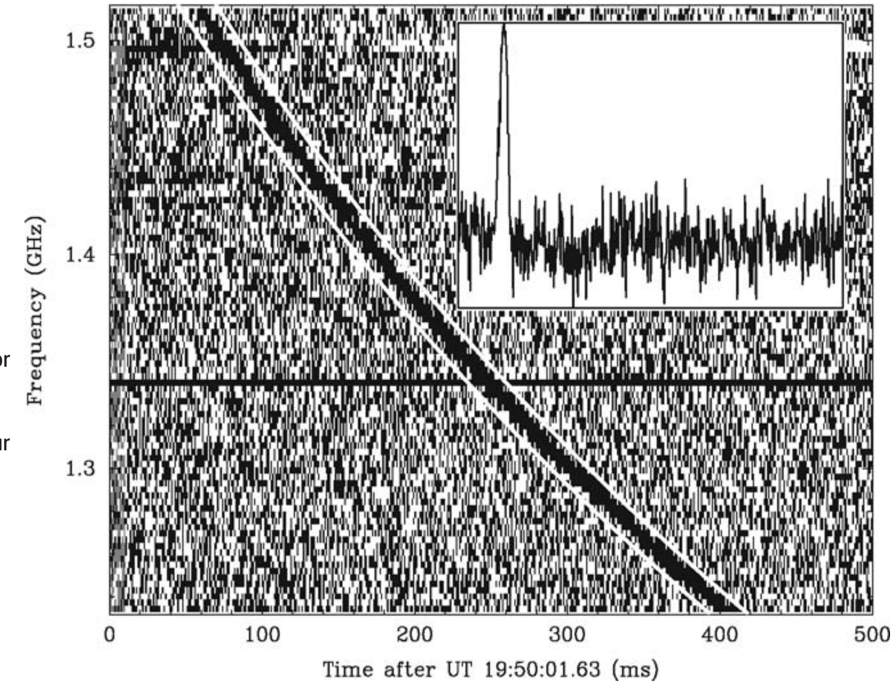


Fig. 2. Frequency evolution and integrated pulse shape of the radio burst. The survey data, collected on 24 August 2001, are shown here as a two-dimensional "waterfall plot" of intensity as a function of radio frequency versus time. The dispersion is clearly seen as a quadratic sweep across the frequency band, with broadening toward lower frequencies. From a measurement of the pulse delay across the receiver band, we used standard pulsar timing techniques and determined the DM to be 375 ± 1 cm^{-3} pc. The two white lines separated by 15 ms that bound the pulse show the expected behavior for the cold-plasma dispersion law assuming a DM of 375 cm^{-3} pc. The horizontal line at ~1.34 GHz is an artifact in the data caused by a malfunctioning frequency channel. This plot is for one of the offset beams in which the digitizers were not saturated. By splitting the data into four frequency subbands, we have measured both the half-power pulse width and flux density spectrum over the observing bandwidth. Accounting for pulse broadening due to known instrumental effects, we determine a frequency scaling relationship for the observed width $W = 4.6$ ms $(f/1.4\ \mathrm{GHz})^{-4.8 \pm 0.4}$, where f is the observing frequency. A power-law fit to the mean flux densities obtained in each subband yields a spectral index of −4 ± 1. The inset shows the total-power signal after a dispersive delay correction assuming a DM of 375 cm^{-3} pc and a reference frequency of 1.5165 GHz. The time axis on the inner figure also spans the range 0 to 500 ms.

- A single dispersed pulse.
- Width < 5ms.
- Brighter than 30 Jy (?)
- Follows f^{-2} dispersion law.
- DM = 375 pc cm^{-3} => 500 Mpc?
- Localized to one part of sky (strongest in 1 beam, of 13 on sky).

Several bright extragalactic FRBs

A Population of Fast Radio Bursts at Cosmological Distances

D. Thornton,[1,2]* B. Stappers,[1] M. Bailes,[3,4] B. Barsdell,[3,4] S. Bates,[5] N. D. R. Bhat,[3,4,6] M. Burgay,[7] S. Burke-Spolaor,[8] D. J. Champion,[9] P. Coster,[2,3] N. D'Amico,[10,7] A. Jameson,[3,4] S. Johnston,[2] M. Keith,[2] M. Kramer,[9,1] L. Levin,[5] S. Milia,[7] C. Ng,[9] A. Possenti,[7] W. van Straten[3,4]

Searches for transient astrophysical sources often reveal unexpected classes of objects that are useful physical laboratories. In a recent survey for pulsars and fast transients, we have uncovered four millisecond-duration radio transients all more than 40° from the Galactic plane. The bursts' properties indicate that they are of celestial rather than terrestrial origin. Host galaxy and intergalactic medium models suggest that they have cosmological redshifts of 0.5 to 1 and distances of up to 3 gigaparsecs. No temporally coincident x- or gamma-ray signature was identified in association with the bursts. Characterization of the source population and identification of host galaxies offers an opportunity to determine the baryonic content of the universe.

SCIENCE VOL 341 5 JULY 2013

- DMs = 553-1103 pc cm^{-3}.
- Seen in single Parkes beams.
- FRB 110220:
  $\delta t \sim f^{-\alpha}$; $\alpha = 2.003 \pm 0.006$.
- Fluence ~0.6-8 Jy-ms.
- Detectable scattering.
- No re-detections.

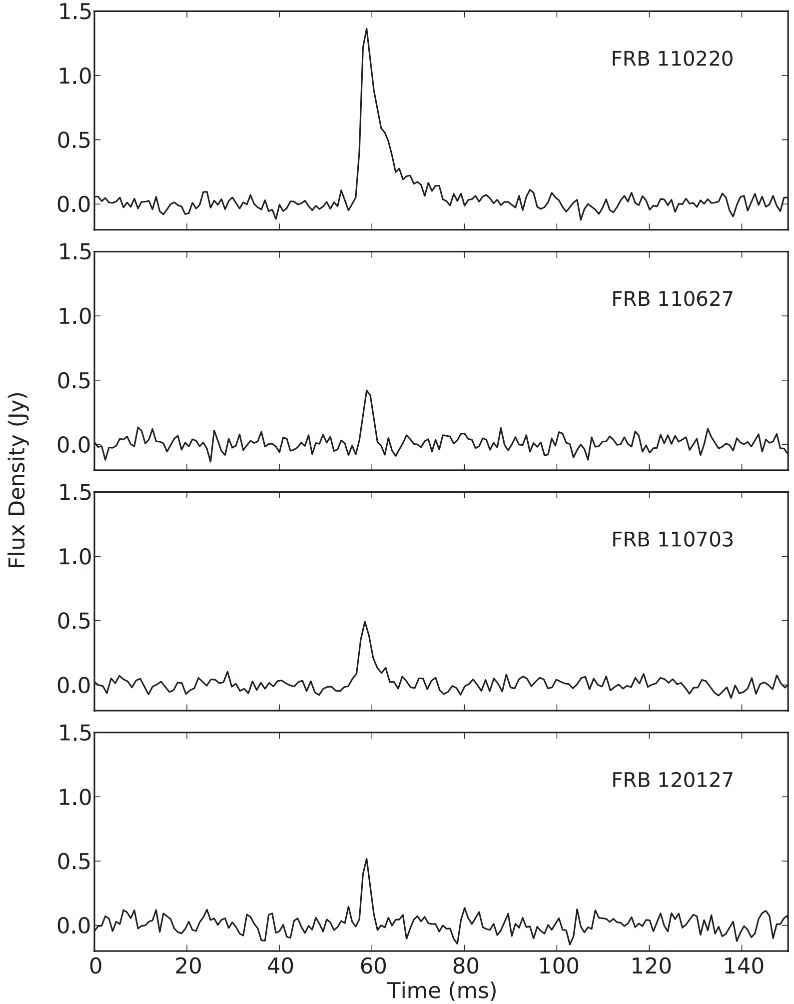
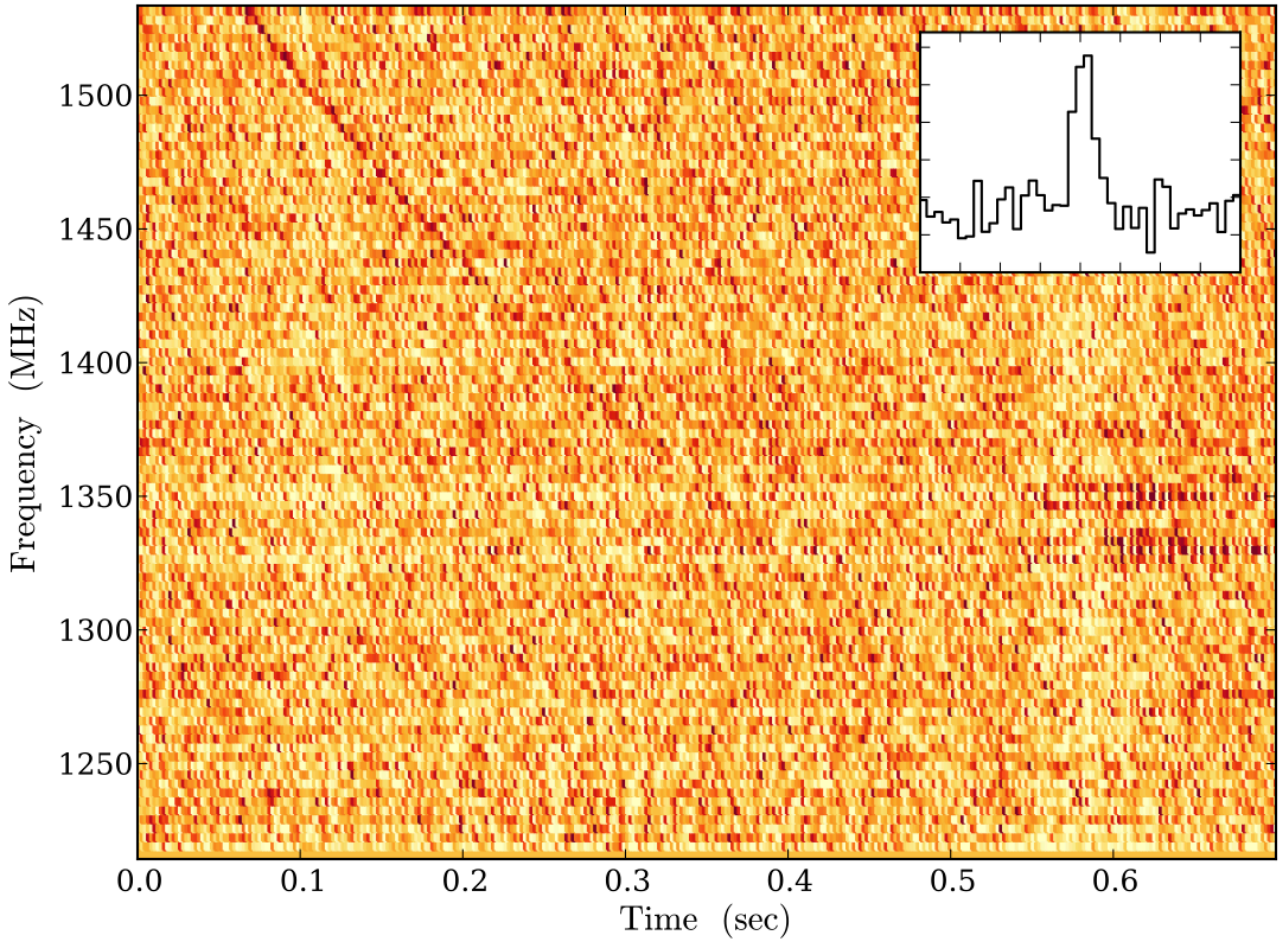


Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 ms, respectively).

FRB 121102 : Arecibo detection of an FRB



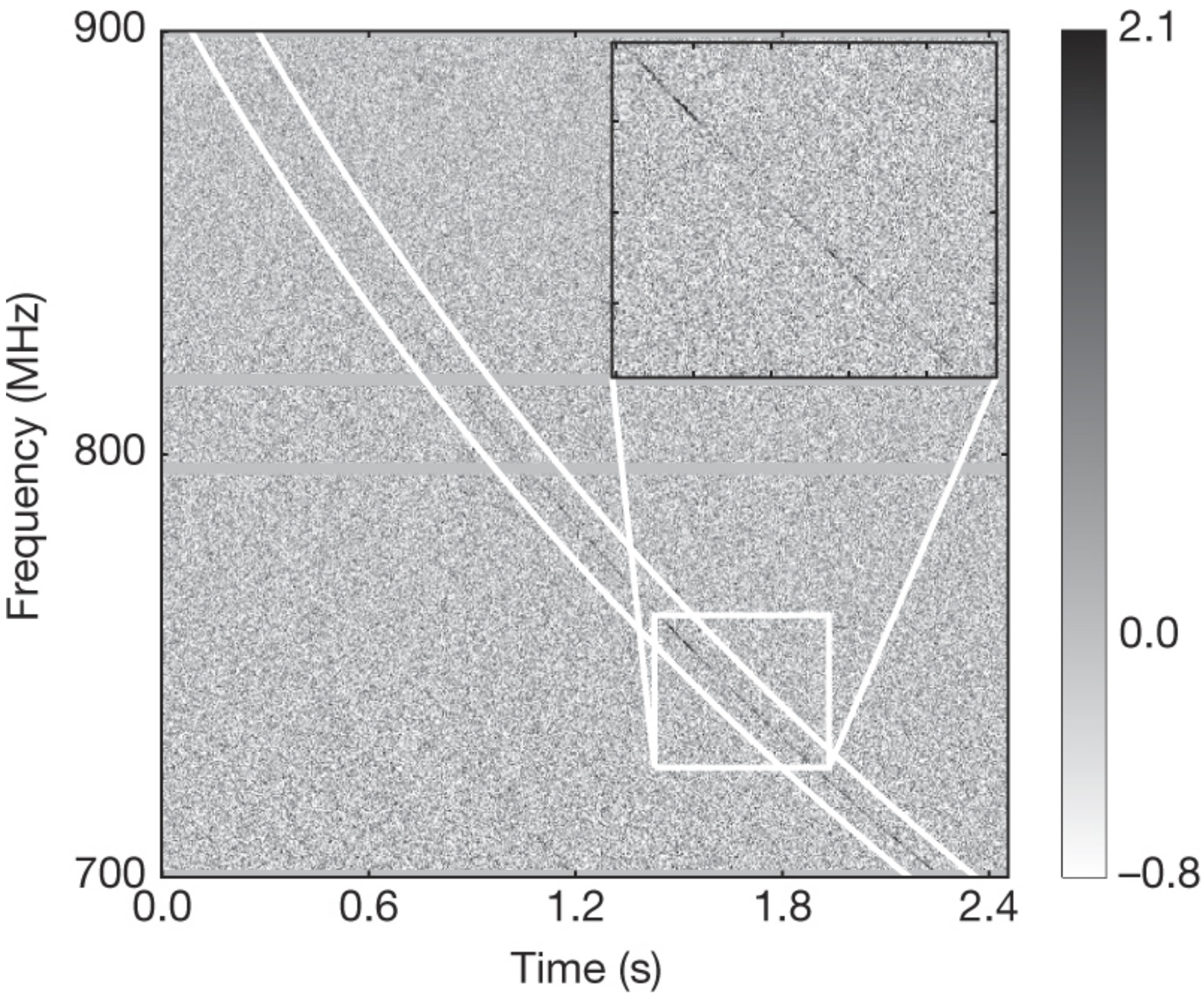
FRB 121102
(Spitler et al. 2014)

- l=175°, b=–0.2°.
- DM = 557 pc cm^{-3} (3x NE2001).
- Width= 3.0±0.5 ms.

- Single PALFA beam.
- No re-detection in multiple deep obs.

- Fainter at lower f: Telescope sidelobe? Or intrinsic?

FRB 110523 : A burst detected at GBT



FRB 110523 (Masui et al. 2015, from archival data).

- DM = 623 pc cm^{-3}. (Galactic max is 45.)
- 700-800 MHz; GBT. Note: beam was slewing during detection.
- Full polarization – can detect Faraday rotation. B >0.38 μG.
- Detection of scattering and scintillation, suggestive of host galaxy within z~0.5.

Masui et al., 2015, Nature
"Dense magnetized plasma associated with an FRB"

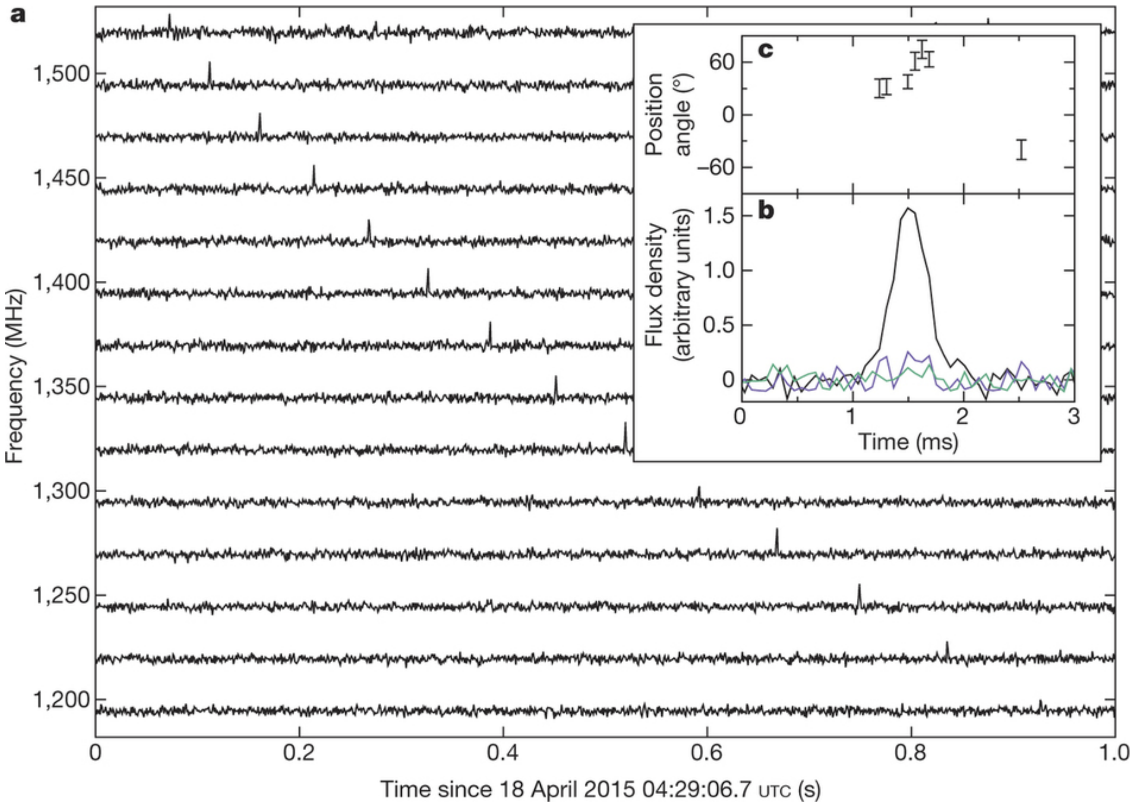
A host galaxy for an FRB?

FRB 150418 : a host galaxy

The host galaxy of a fast radio burst

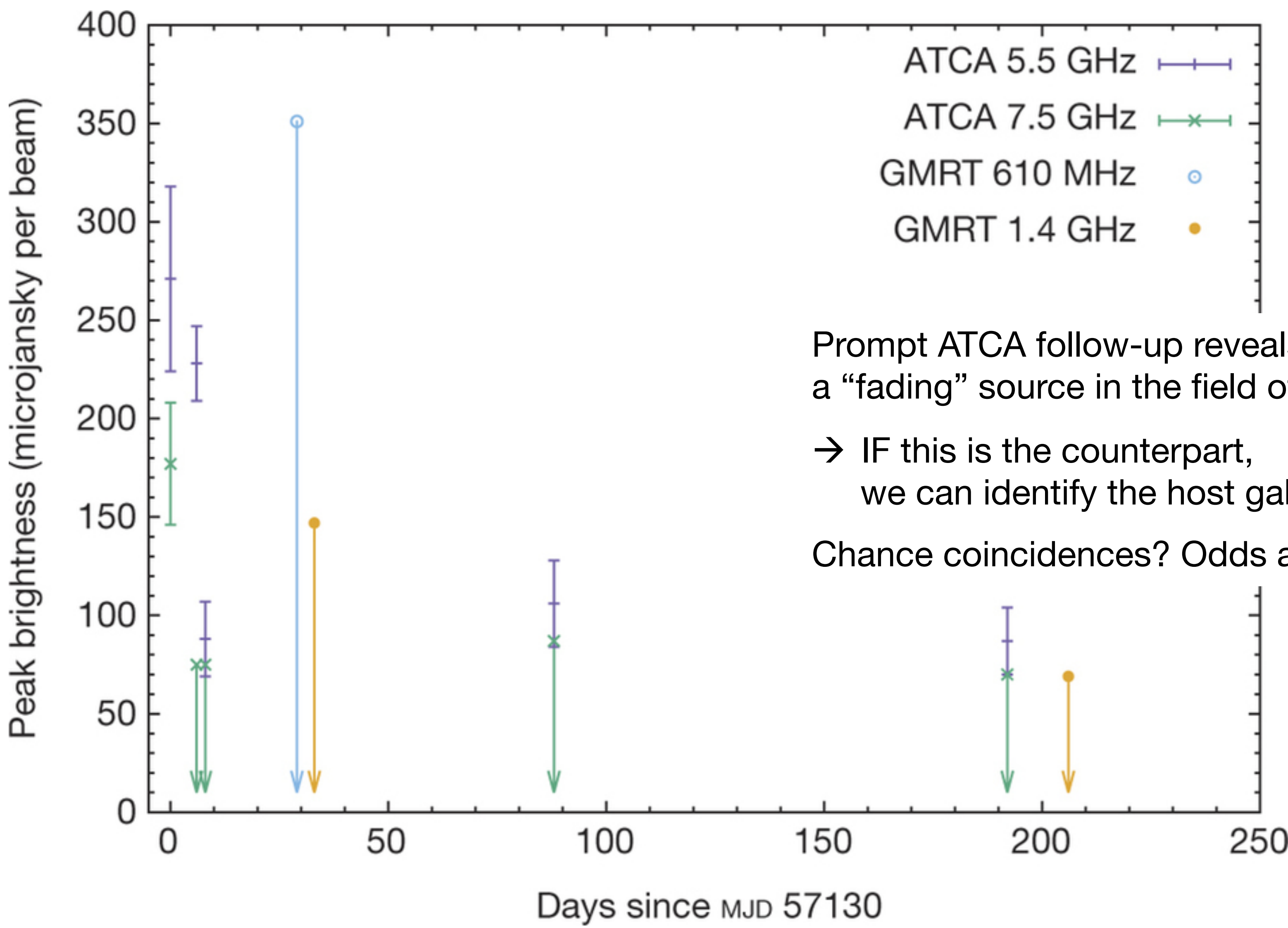
E. F. Keane, S. Johnston, S. Bhandari, et al., 2016, Nature.

… We report the discovery of a fast radio burst and the identification of a fading radio transient lasting ~6 days after the event, which we use to identify the host galaxy; we measure the galaxy's redshift to be z = 0.492 ± 0.008 … The ~6-day radio transient is largely consistent with the radio afterglow of a short γ-ray burst … suggesting that there are at least two classes of bursts.



- l=232.7°, b=–3.2°
- DM = 776.2 pc cm^{-3}, 4.1x NE2001.

FRB 150418 : rapid ATCA follow-up

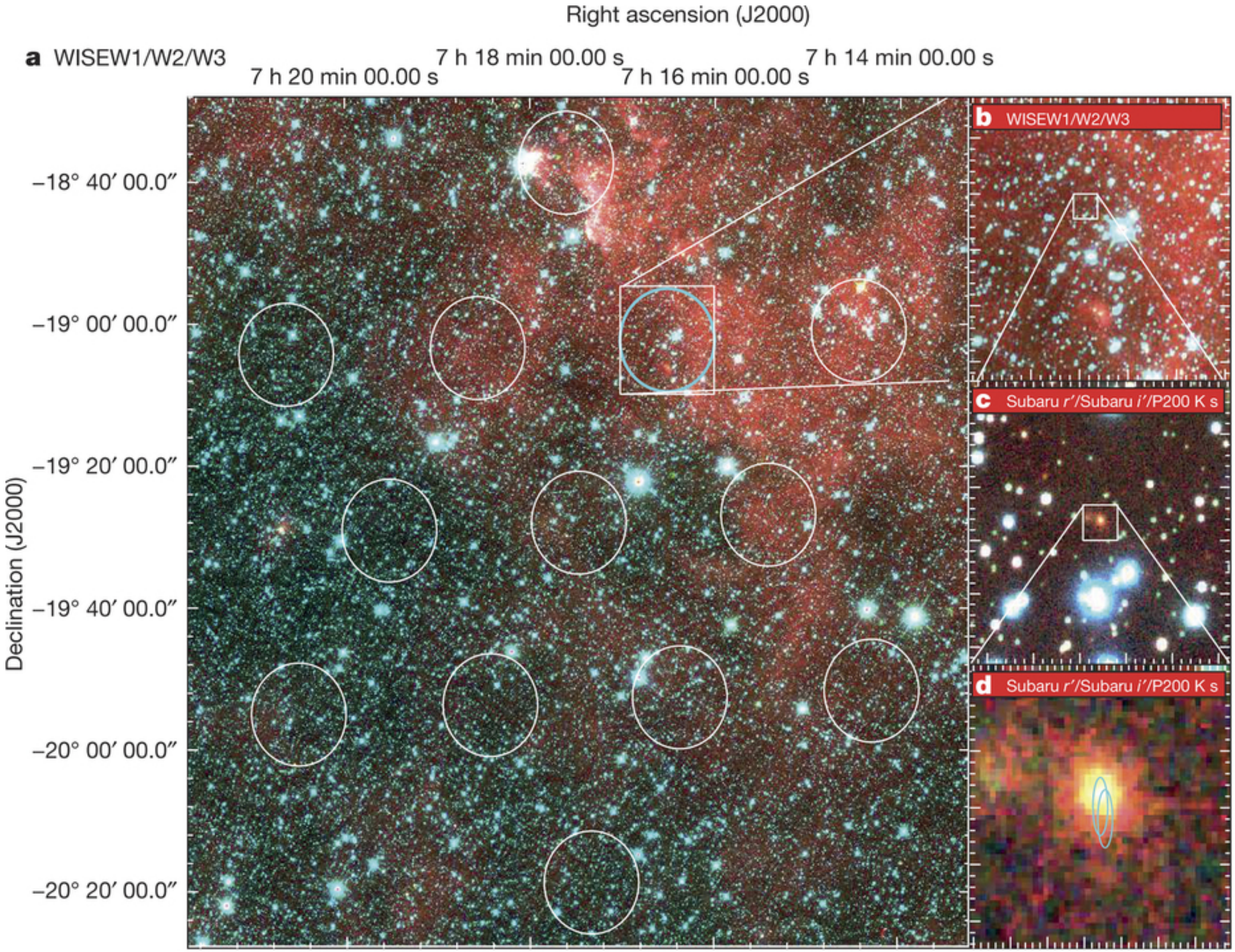


Prompt ATCA follow-up reveals a “fading” source in the field of view.

→ IF this is the counterpart, we can identify the host galaxy.

Chance coincidences? Odds are high.

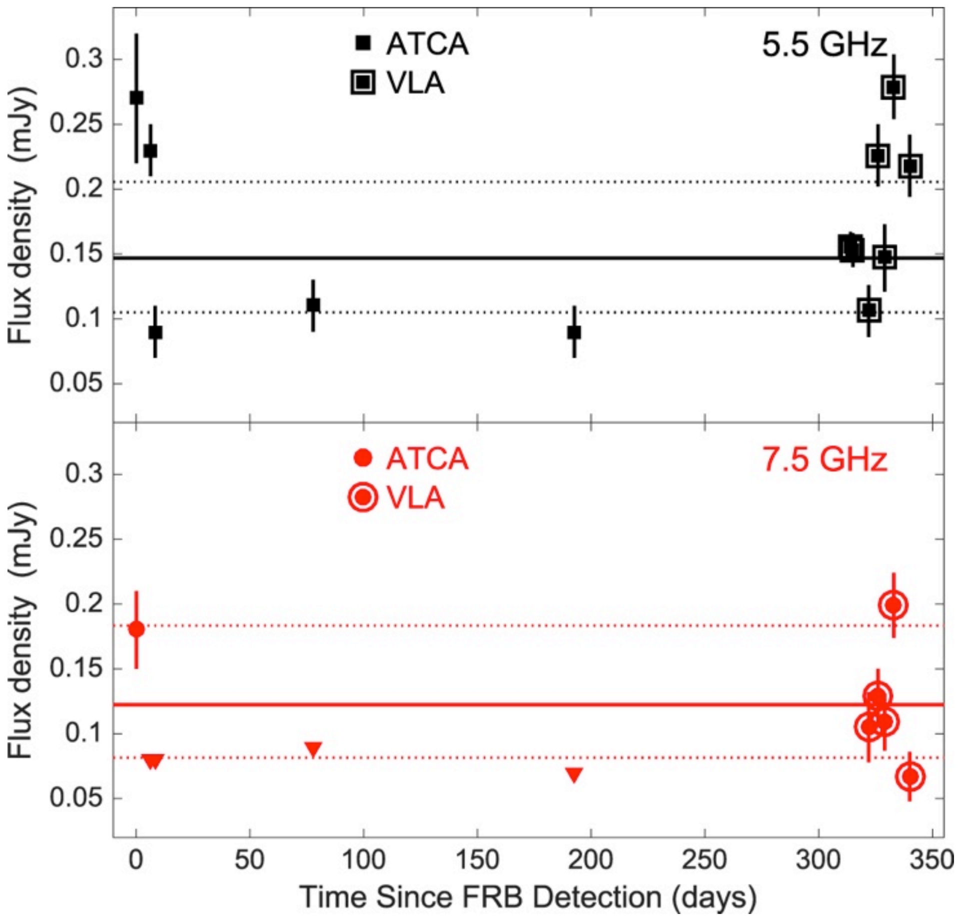
FRB 150418 : Subaru imaging



Cosmological Origin? Not so fast

- Vedantham et al., arXiv:1603.04421,
  "On associating Fast Radio Bursts with afterglows"
  → Too many afterglows expected.

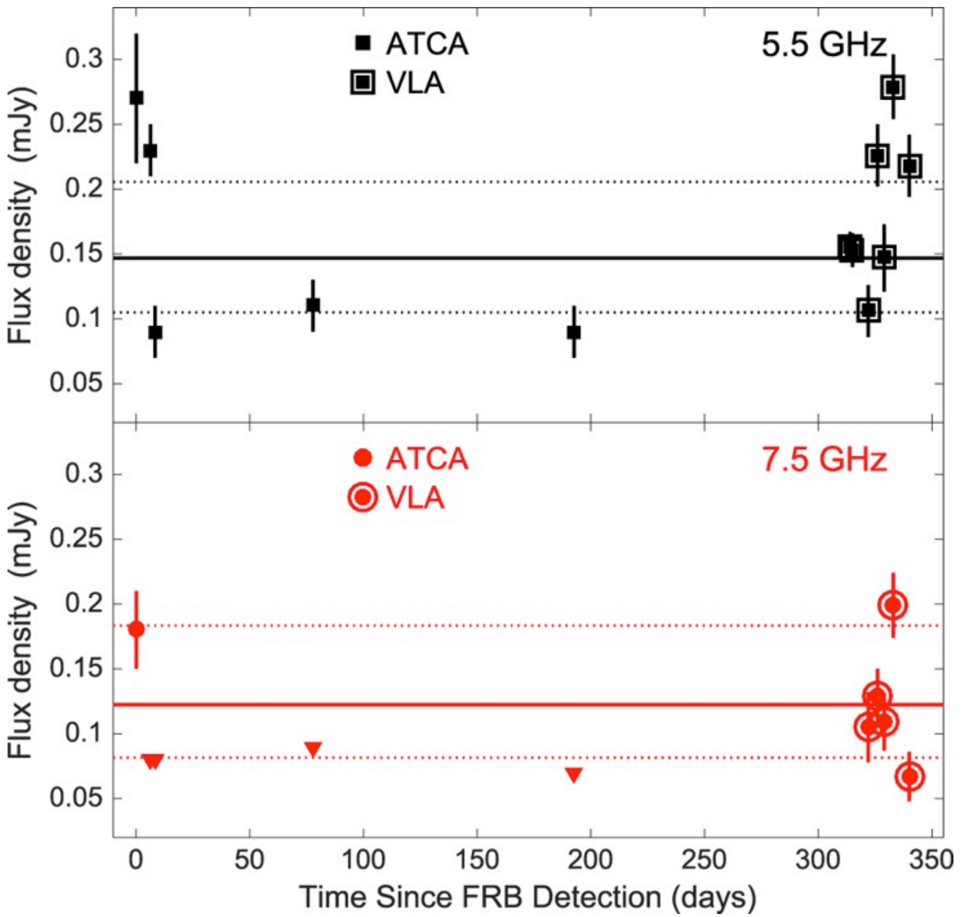
- Williams & Berger, ApJL 2016,
  "No Precise Localization for FRB 150418:
  Claimed Radio Transient Is AGN Variability"



Is it really an "afterglow"?

- Vedantham et al., arXiv:1603.04421,
  "On associating Fast Radio Bursts with afterglows"
  → Too many afterglows expected.

- Williams & Berger, ApJL 2016,
  "No Precise Localization for FRB 150418: Claimed Radio Transient Is AGN Variability"



Can this association be saved?

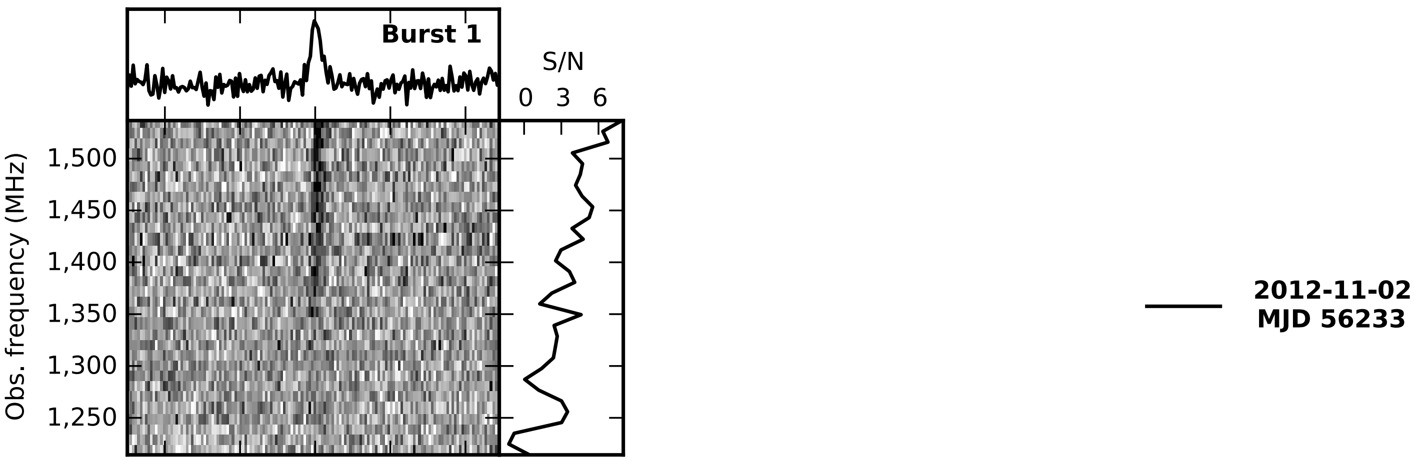
If the source really was a transient embedded in a radio galaxy, not an AGN, and was really associated with the FRB, and FRBs are really multiple populations,

then
the host association could still be valid.

But it is a stretch.

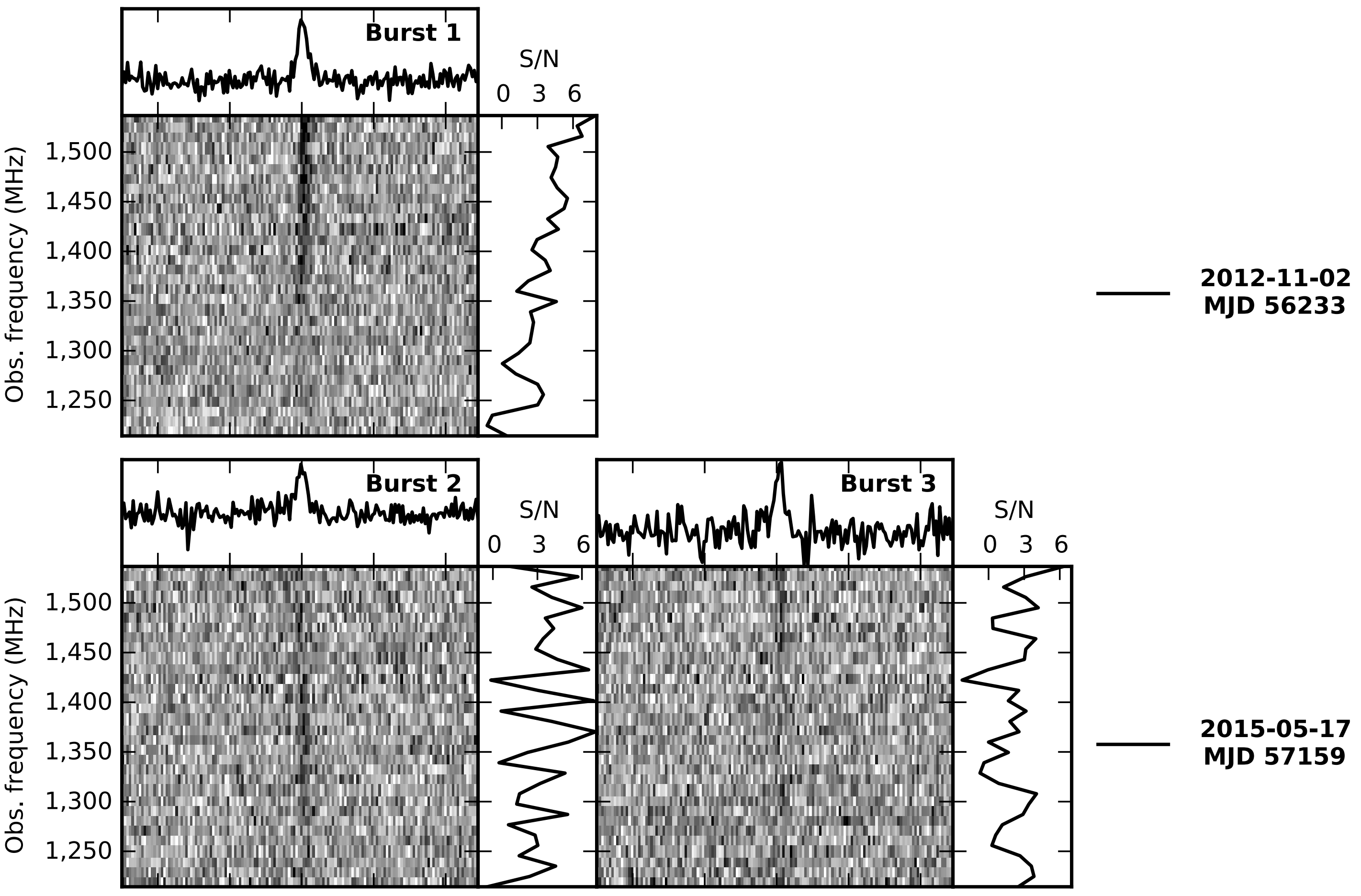
A repeating FRB

Remember FRB 121102?

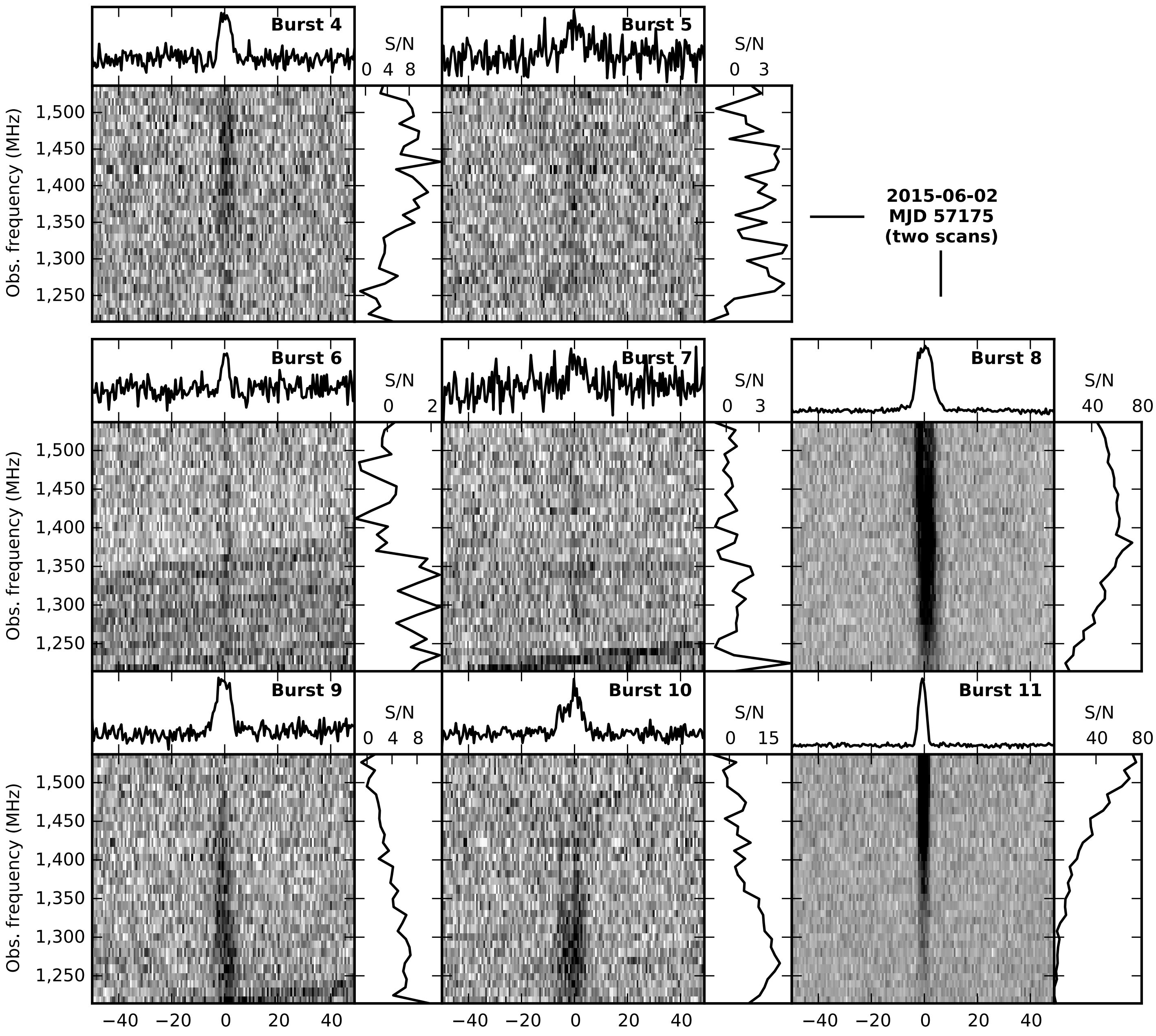


Re-observed with Arecibo in 2012: Nothing there.
Re-observed with Arecibo in 2013: Nothing there.
Re-observed with Arecibo in 2015: “A minor point of interest…”

Remember FRB 121102?



FRB 121102 is a repeating source



FRB J0531+3308

A Repeating Fast Radio Burst

L. G. Spitler, P. Scholz, J. W. T. Hessels, et al., 2016, Nature.

… Here we report the detection of ten additional bursts from the direction of FRB 121102, using the 305-m Arecibo telescope. These new bursts have DMs and sky positions consistent with the original burst… This unambiguously identifies FRB 121102 as repeating and demonstrates that its source survives the energetic events that cause the bursts.

- Consistent with original DM = 557.4±2 pc cm^{-3}, 3x NE2001.
- No obvious periodicity, but huge gaps – can't phase connect (yet). Pulse intervals of 23 sec to 572 sec on one day.
- Highly variable spectra from burst to burst. Must be mostly intrinsic. No apparent scattering.

FRB J0531+3308

A Repeating Fast Radio Burst

L. G. Spitler, P. Scholz, J. W. T. Hessels, et al., 2016, Nature.

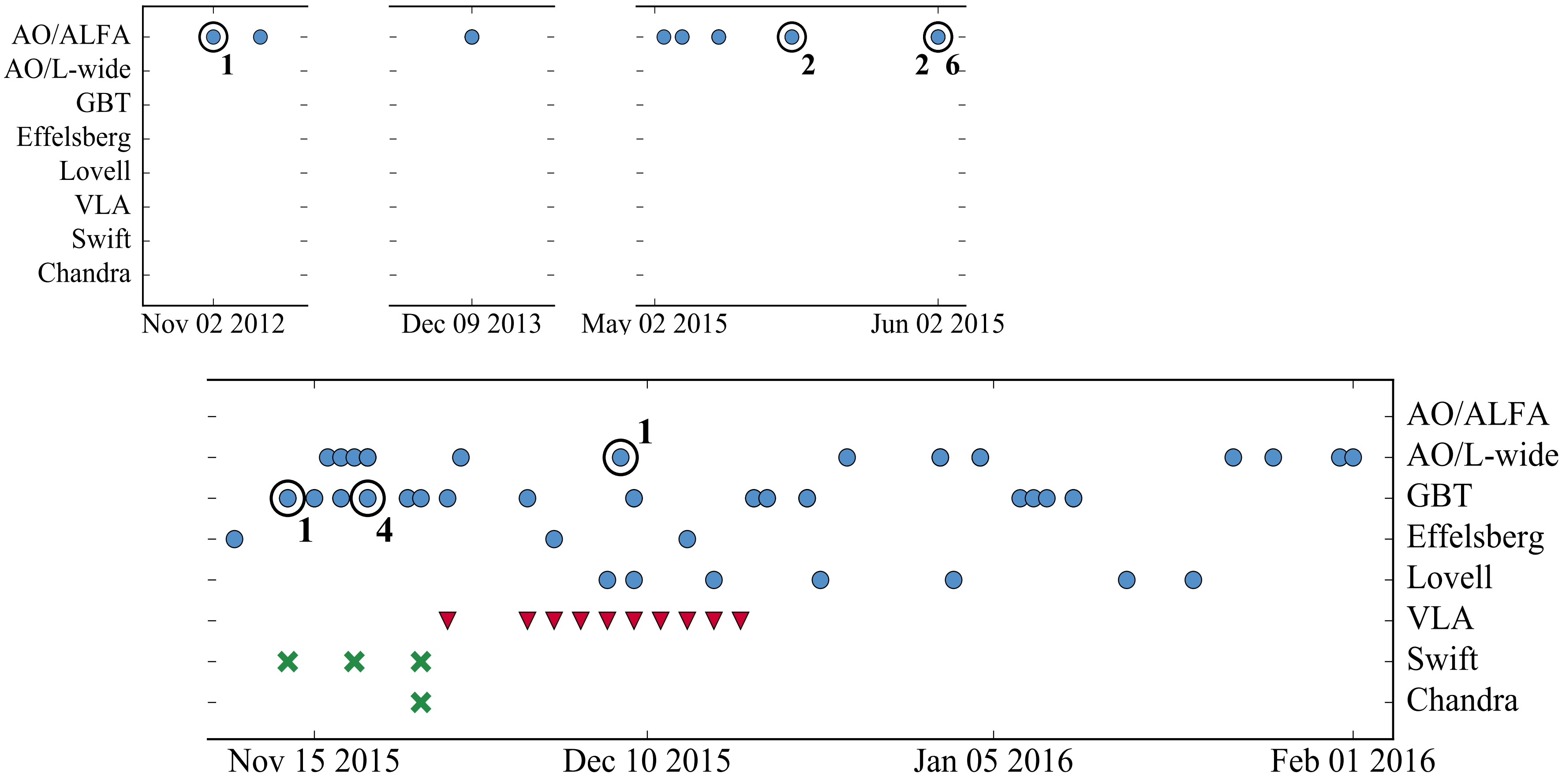
… Here we report the detection of ten additional bursts from the direction of FRB 121102, using the 305-m Arecibo telescope. These new bursts have DMs and sky positions consistent with the original burst… This unambiguously identifies FRB 121102 as repeating and demonstrates that its source survives the energetic events that cause the bursts.

- Consistent with original DM = 557.4±2 pc cm^{-3}, 3x NE2001.
- No obvious periodicity, but huge gaps – can't phase connect (yet). Pulse intervals of 23 sec to 572 sec on one day.
- Highly variable spectra from burst to burst. Must be mostly intrinsic. No apparent scattering.

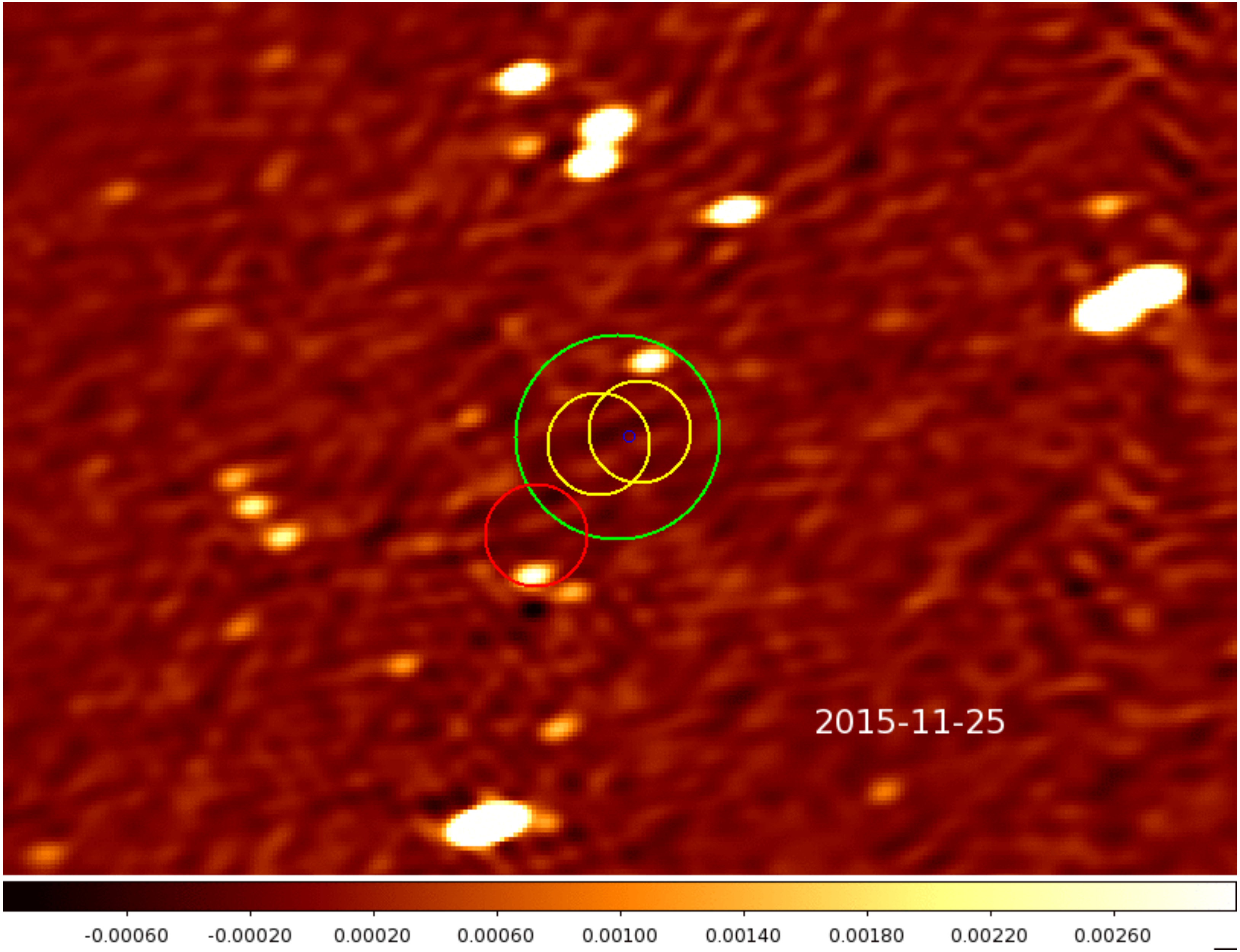
Is FRB 121102 representative of all FRBs?
Or might there be multiple astrophysical classes of FRBs?

Ongoing multi-wavelength follow-up

- Radio: Arecibo, Green Bank, Effelsberg.
- Radio interferometry: VLA, GMRT, EVN.
- X-rays: Swift, Chandra; gamma rays: Fermi.
- Optical: Keck, Gemini. Archival coverage in O/IR: GLIMPSE, 2MASS, IPHAS…

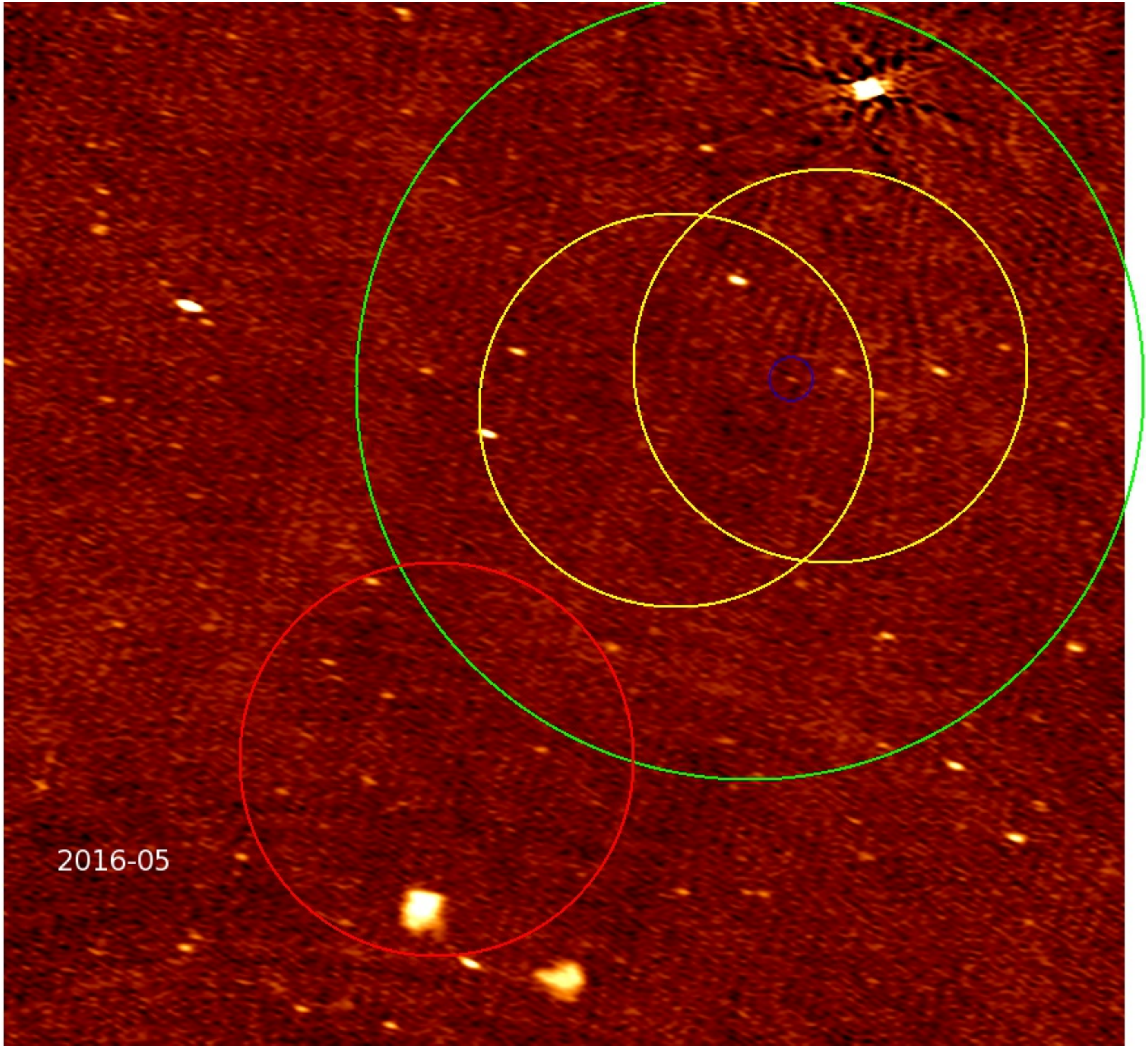


VLA imaging

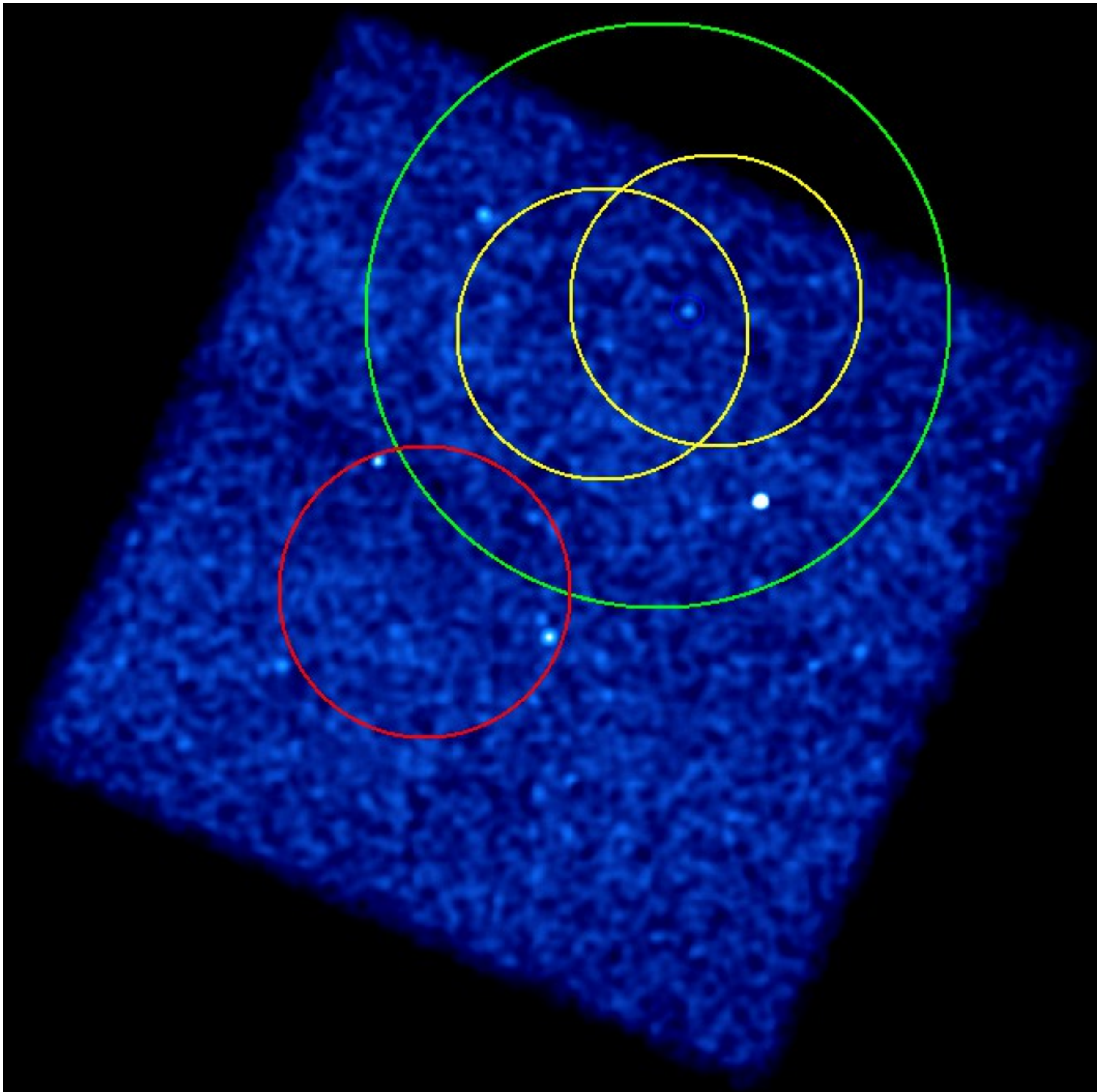


2015-11-25
-0.00060
-0.00020
0.00020
0.00060
0.00100
0.00140
0.00180
0.00220
0.00260

VLA imaging : higher resolution

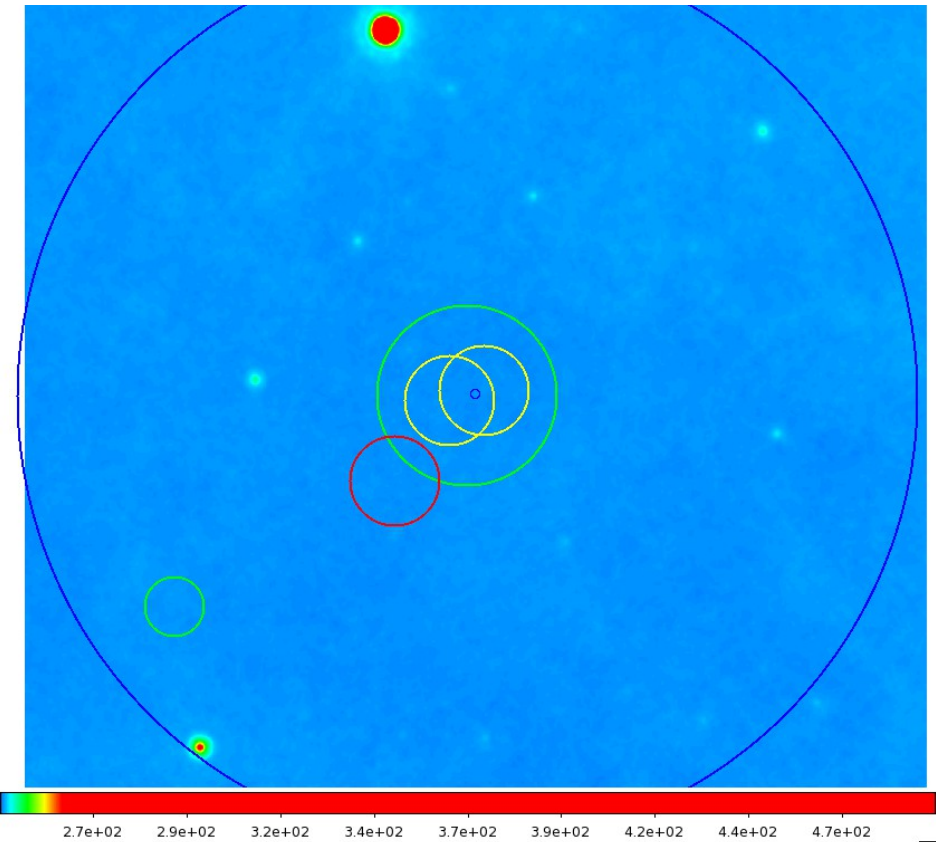


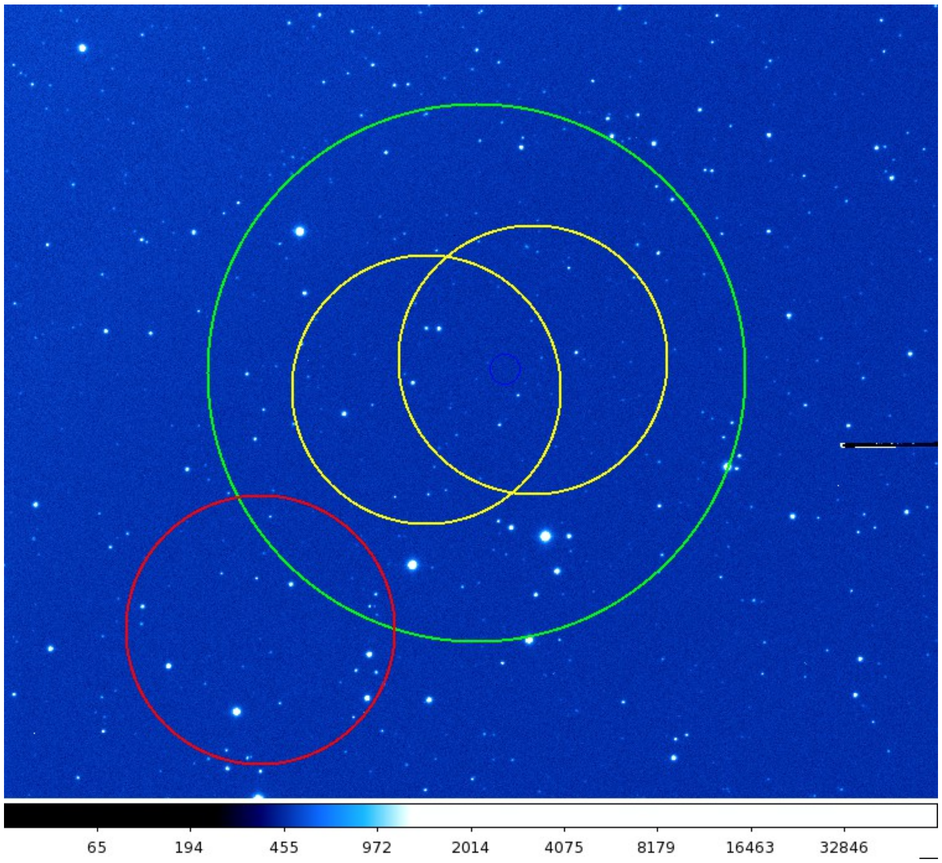
Chandra X-ray observations



Several X-ray sources, including a suggestive one, but no smoking gun.

Infrared and optical observations





WISE 22μm (far-IR):
no PNe or HII regions, down to sizes
produced by single O or B stars.

IPHAS Hα (optical):
"… it's full of stars!"
Recall, *b*=-0.2°, in Gal plane.

Radio + IR + optical: Very strong limit on Galactic source of dispersion.

What are FRBs?

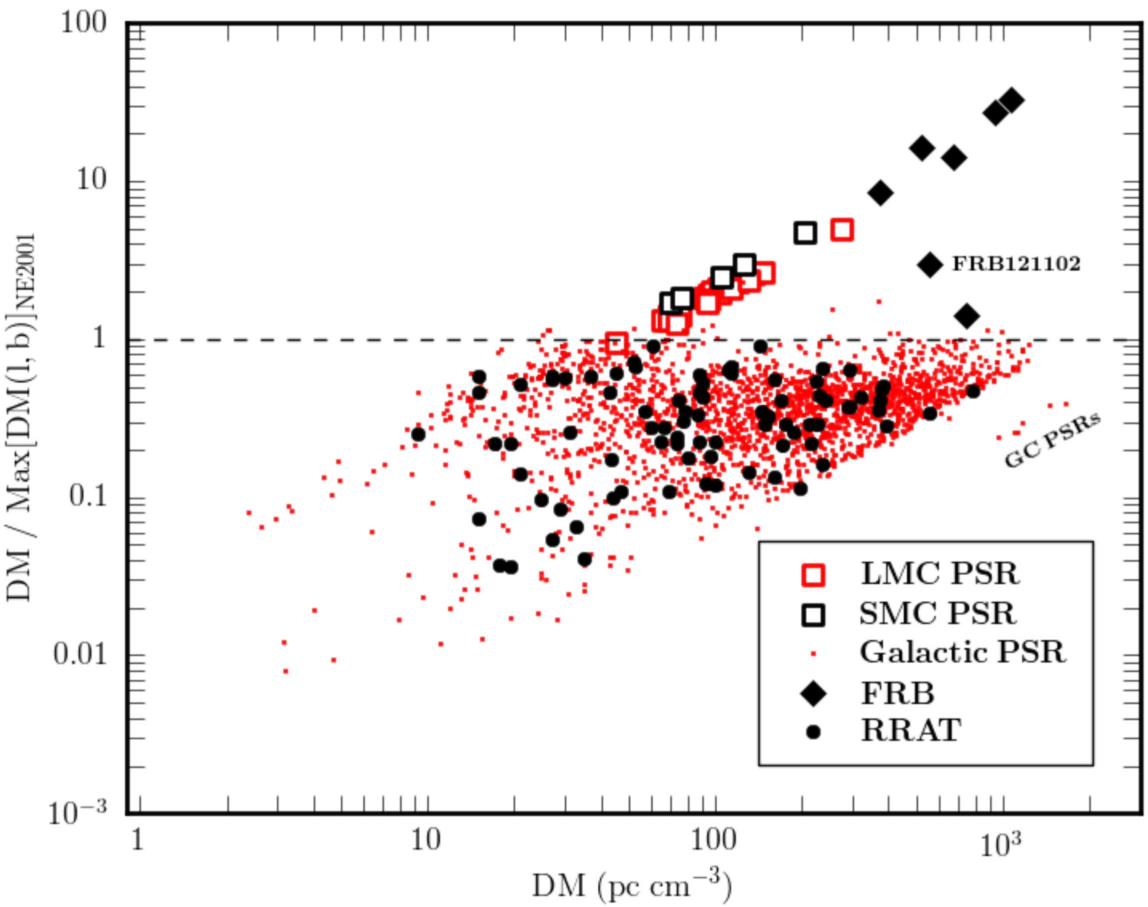
One population or several?

What are FRBs?

- Terrestrial sources?
  Observed pulse dispersion, scattering, seen at multiple sites → No.

What are FRBs?

- **Terrestrial sources?**
  Observed pulse dispersion, scattering, seen at multiple sites → No.
- **Galactic sources – Neutron stars (RRATs)?**
  No contributors to line of sight pulse dispersion in deep searches.



FRBs exceed max NE2001 model contribution by factors of 1.2 to 33.

DM observed
= DM $_{\text{Milky Way}}$
+ DM $_{\text{IGM}}$
+ DM $_{\text{Host Galaxy}}$

Host galaxy significant if
- In galactic center?
- Edge-on spiral?
  (Unlikely for all?)

What are FRBs?

- Terrestrial sources?
  Observed pulse dispersion, scattering, seen at multiple sites → No.
- Galactic sources – Neutron stars (RRATs)?
  No contributors to line of sight pulse dispersion in deep searches.
- Galactic sources – Flares from magnetically active stars?
  (e.g., Loeb et al. 2013, Maoz et al. 2015)
  Lower limits on size of dispersing region from e.g., FRB 110523:
  $T_{delay} \sim \nu^{-1.998(3)}$ ➔ $n_e < 1.3\times10^7$ cm^{-3} ➔ at least 10 AU.

What are FRBs?

- ~~Terrestrial sources~~.
- Galactic sources – ~~RRATs~~, ~~Flares from magnetically active stars~~.
- Extragalactic sources – local or cosmological?
  - Soft Gamma Repeater giant flares (Popov & Postnov 2007).
  - Merging WD (Kashiyama et al. 2013).
  - Merging NS (Hansen & Lyutikov 2001).
  - Collapsing supra-massive NS (Falcke & Rezzolla 2013).
  - Evaporating primordial black holes (Rees 1977).
  - Superconducting cosmic strings (Cai et al. 2012).
  - Bright, rare, Crab-like giant pulses from extragalactic pulsars (Cordes & Wasserman 2016).
  - Pulsar planets – Alfven wings (Mottez & Zarka 2014).
  - … ?
  - ETI radar. (Why not?)

Do we require multiple populations?

- One repeating FRB source (Arecibo, FRB121102).
- ~20 FRBs at Parkes, GBT, with deep limits on lack of repetition.

→ Two different populations?

→ Extreme value statistics:
Luminosity function, distance distribution,
Interstellar scintillation modulation distribution (+refraction, lensing).

→ Rare scintillation maxima, or rare intrinsic amplitudes, or both?

→ Multiple populations are <u>not yet *required*</u>.

We can account for observed FRB population so far with:
- Sporadic, repeating extragalactic bursts.
- Scattering in host galaxies.
- Scintillation / scattering in the Milky Way.
- Either a large population with extreme scintillation, or a smaller population with a ‘heavy tail’ amplitude distribution.

(Cordes et al.; Chatterjee et al., in prep)

Where things stand

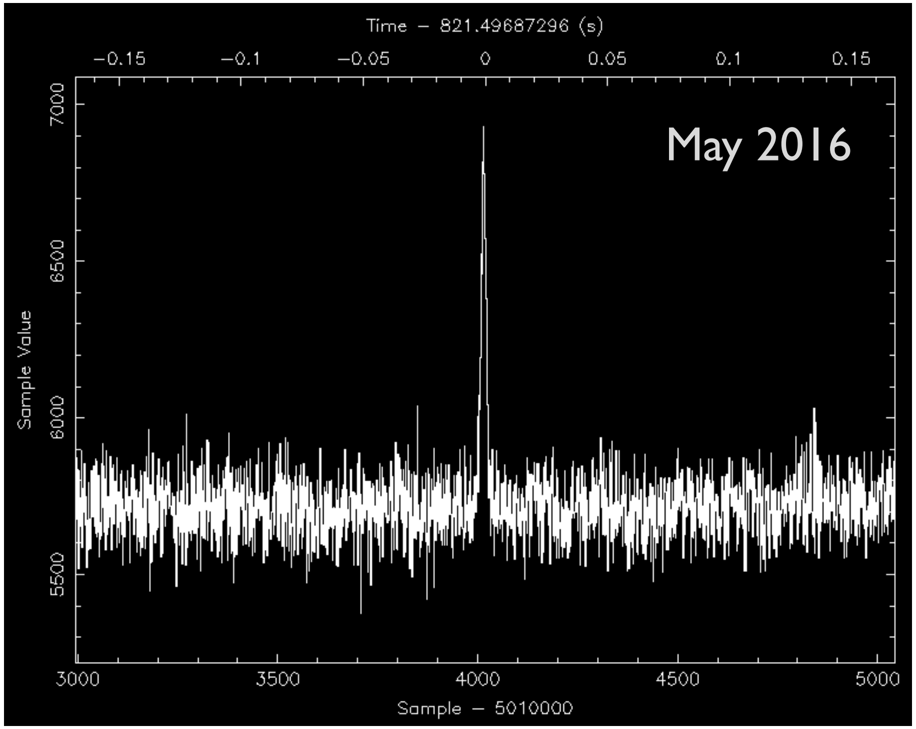
- Localization of an FRB is the key to progress:
  Host galaxy, counterpart, or lack thereof will be informative.

- FRB 121102 offers us a way to get at least one of them!

- Using Arecibo + VLA (+ GBT + Effelsberg + LOFAR + AMI + LWA)
  in a coordinated campaign of simultaneous observations.

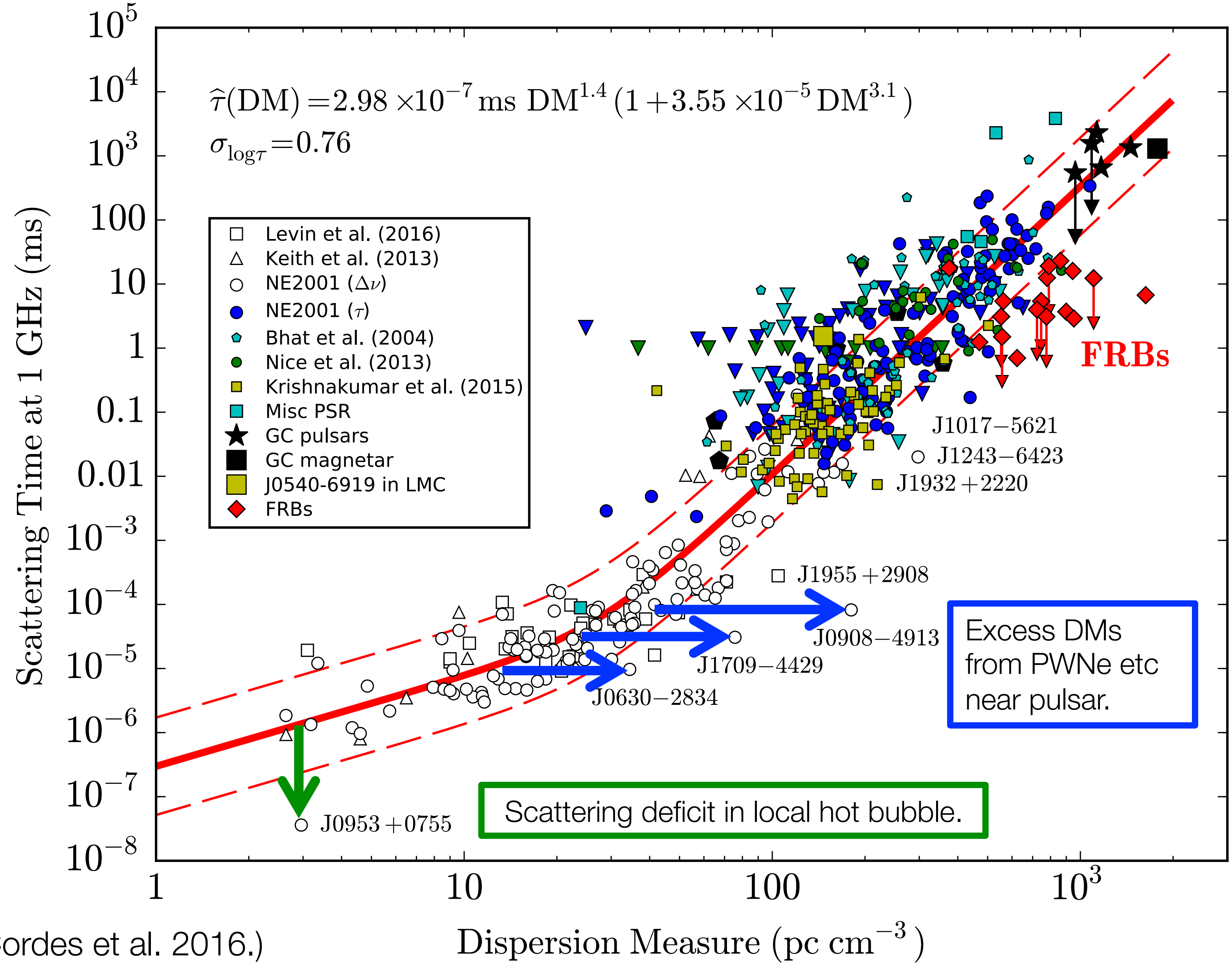
→ Arecibo tells us when to look.
→ VLA can tell us where it is.

→ Ongoing work.
(Massive data volumes.)



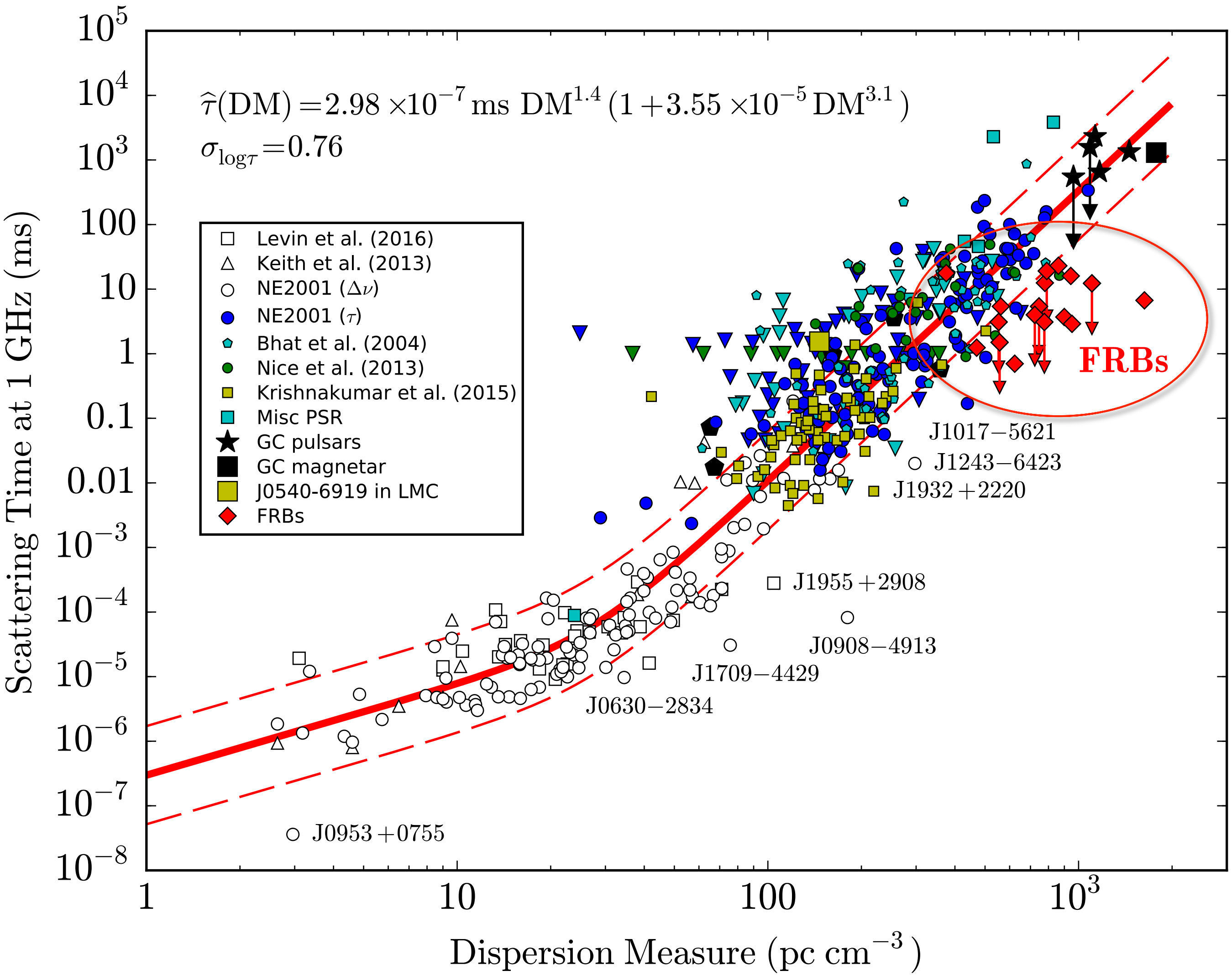
Thank You!

Pulse Broadening of FRBs



(Cordes et al. 2016.)

Pulse Broadening of FRBs



FRBs are "under-scattered" for their large DMs.

Either:

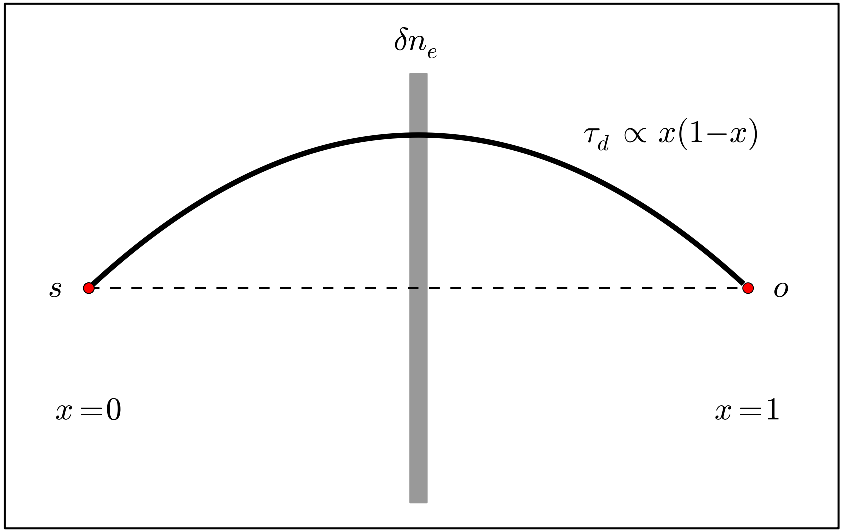
The dispersing electrons are much less turbulent than in the Milky Way.

Or:

Only a small part of the path length contributes to dispersion and scattering (e.g., sources embedded in galaxies).

(Cordes et al. 2016.)

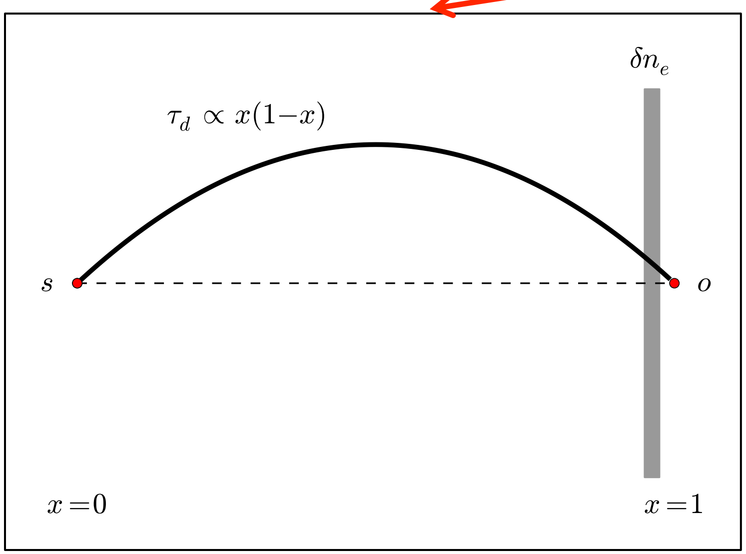
Pulse Broadening : it's just geometry

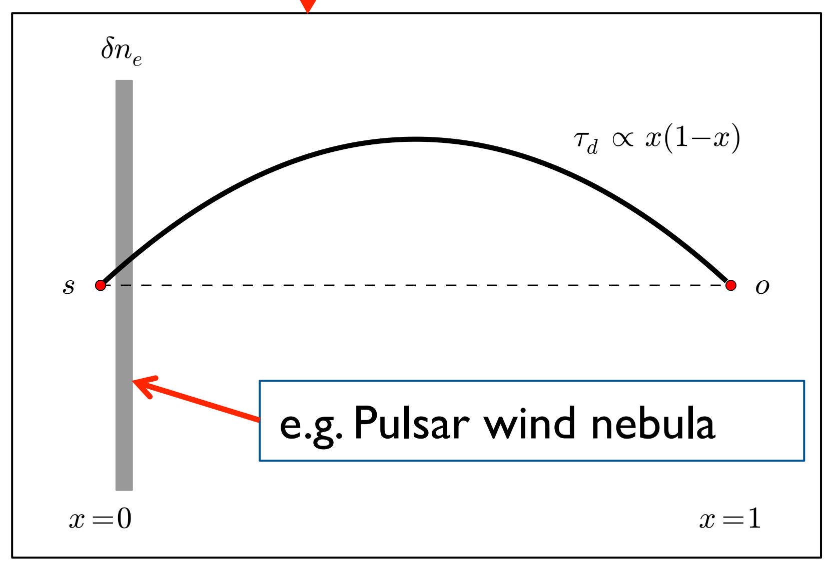


Biggest bang for scattering buck for midway screen

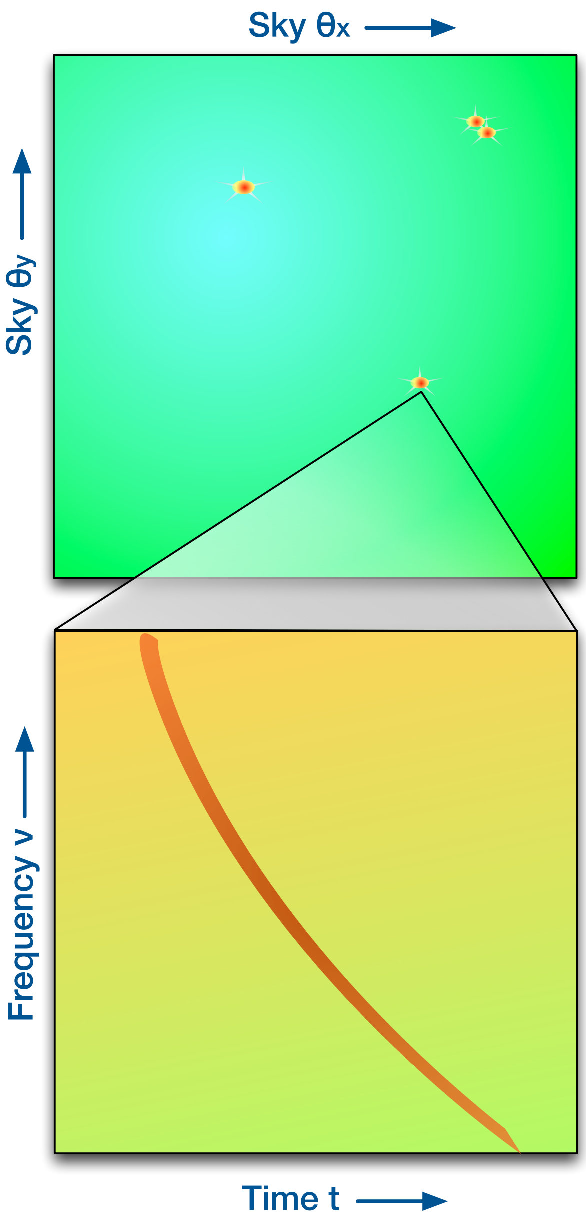
$$\tau_\mathrm{d} \propto x(1-x)$$

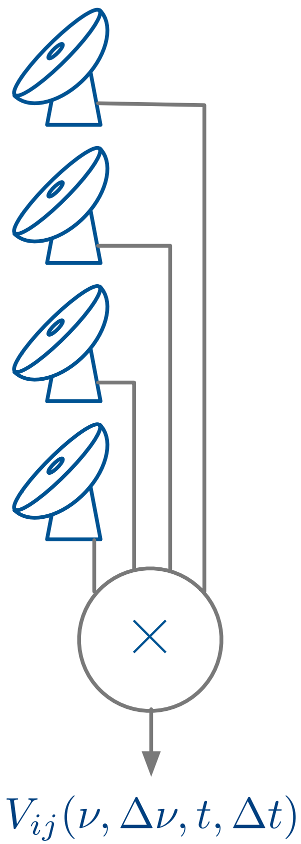
Scattering deleveraged





Localizing FRB121102 with the VLA





- Blind searches for FRBs at the VLA have come up empty so far (e.g., Law et al. 2015).

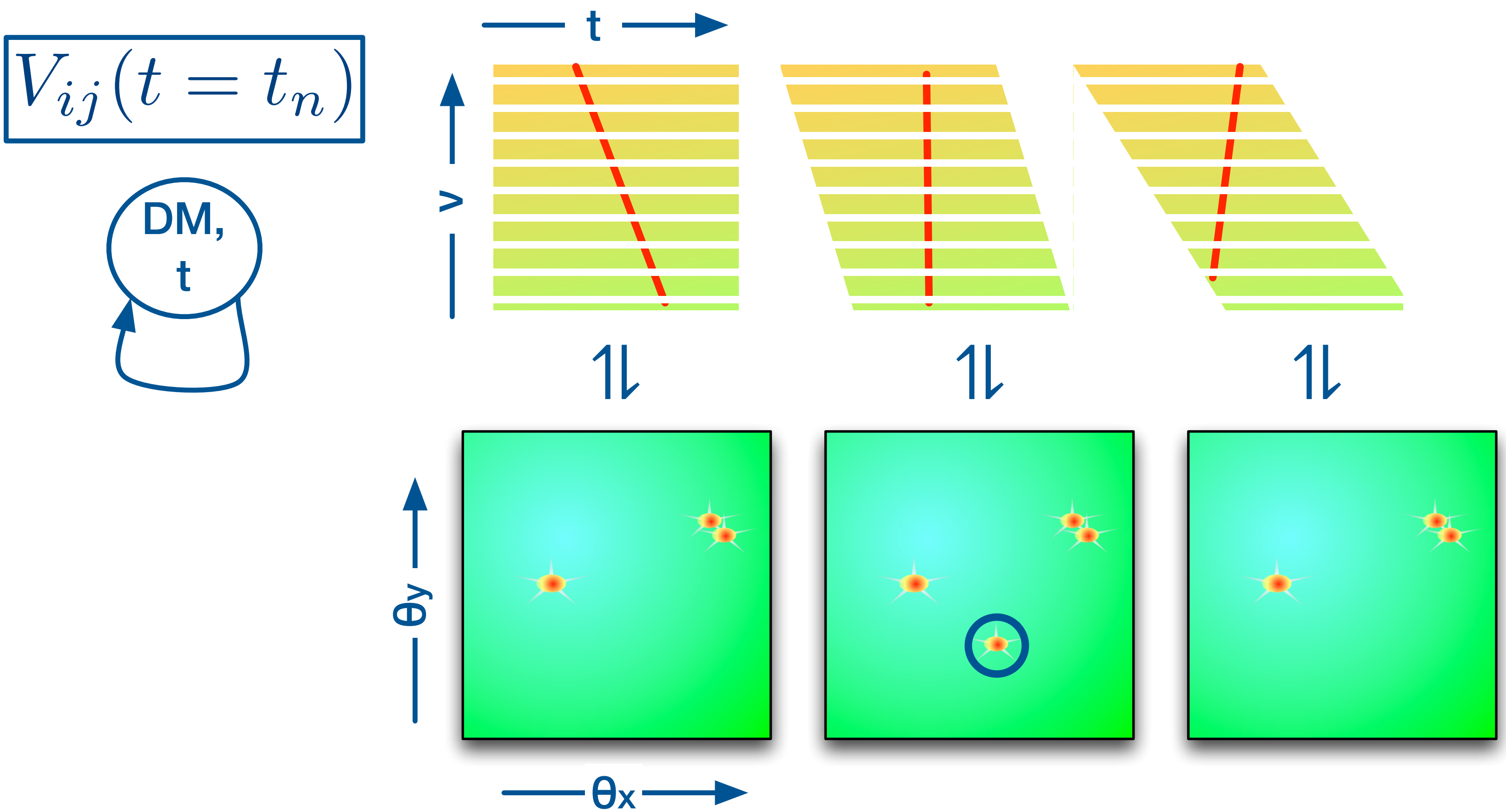
  But this one repeats…

- VLA fast dump observations: 1TB/hr upper limit on data rate → trade off between total BW, channel BW, and sample time.

- Now operating at 2-4 GHz, using two complementary search methods:
  1. Millisecond imaging search.
  2. Beam-forming pulse search.

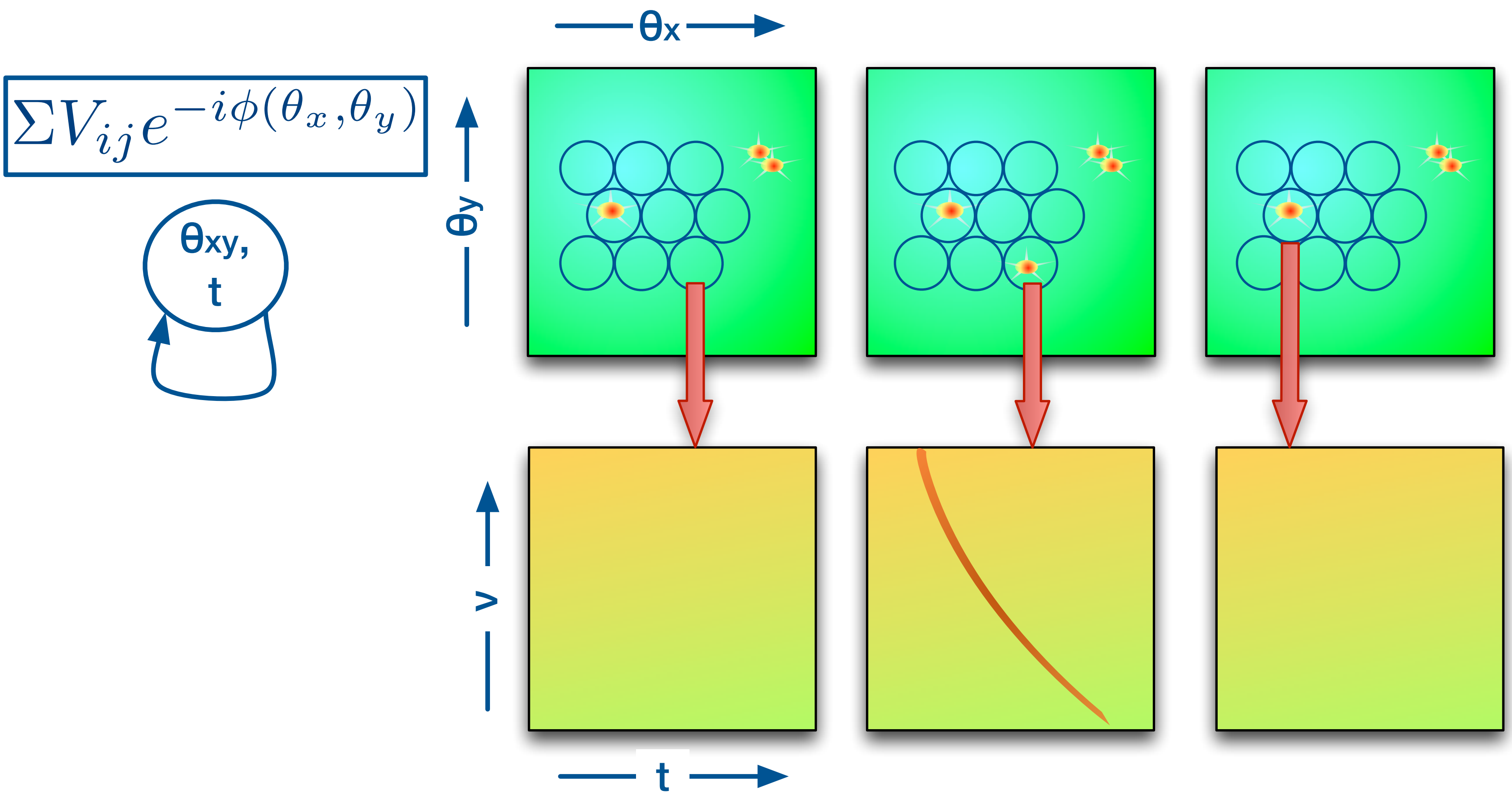
Millisecond Imaging Search

- De-disperse visibilities, make images for each sample time.
- Search for transient source in image domain.



Beam-formed Single-pulse Search

- Tile region with phased up beams.
- Search for pulse in time domain (t, DM).

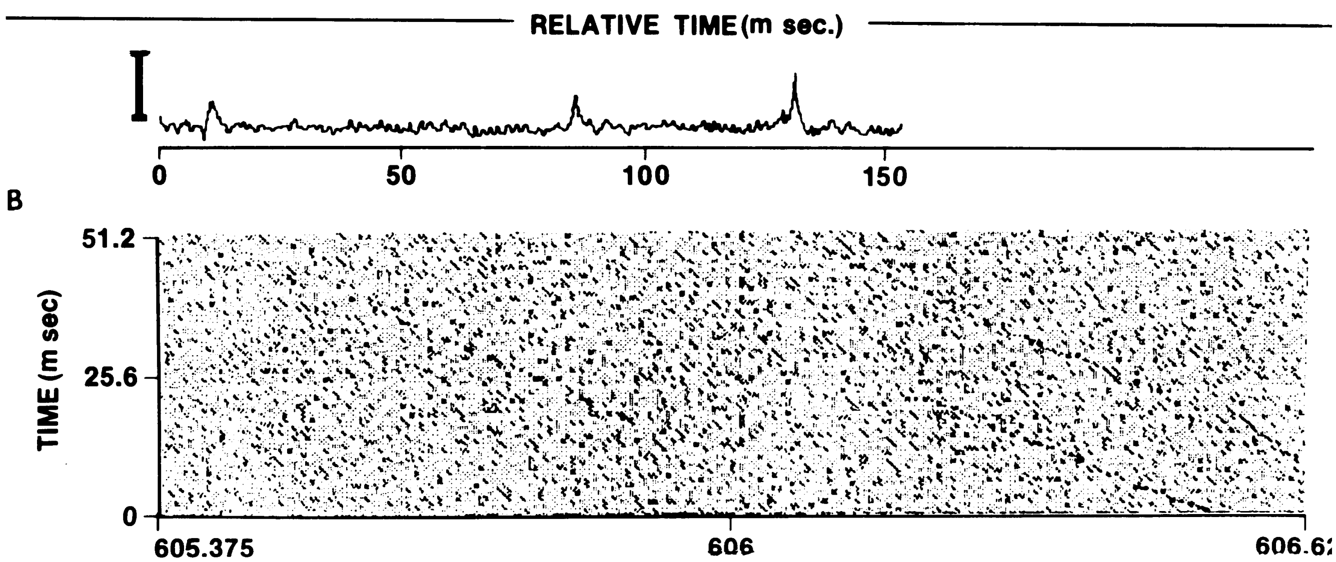


DISCOVERY OF MILLISECOND RADIO BURSTS FROM M87

I. R. LINSCOTT AND J. W. ERKES[1]
Dudley Observatory, Schenectady, New York
Received 1979 August 10; accepted 1979 December 19

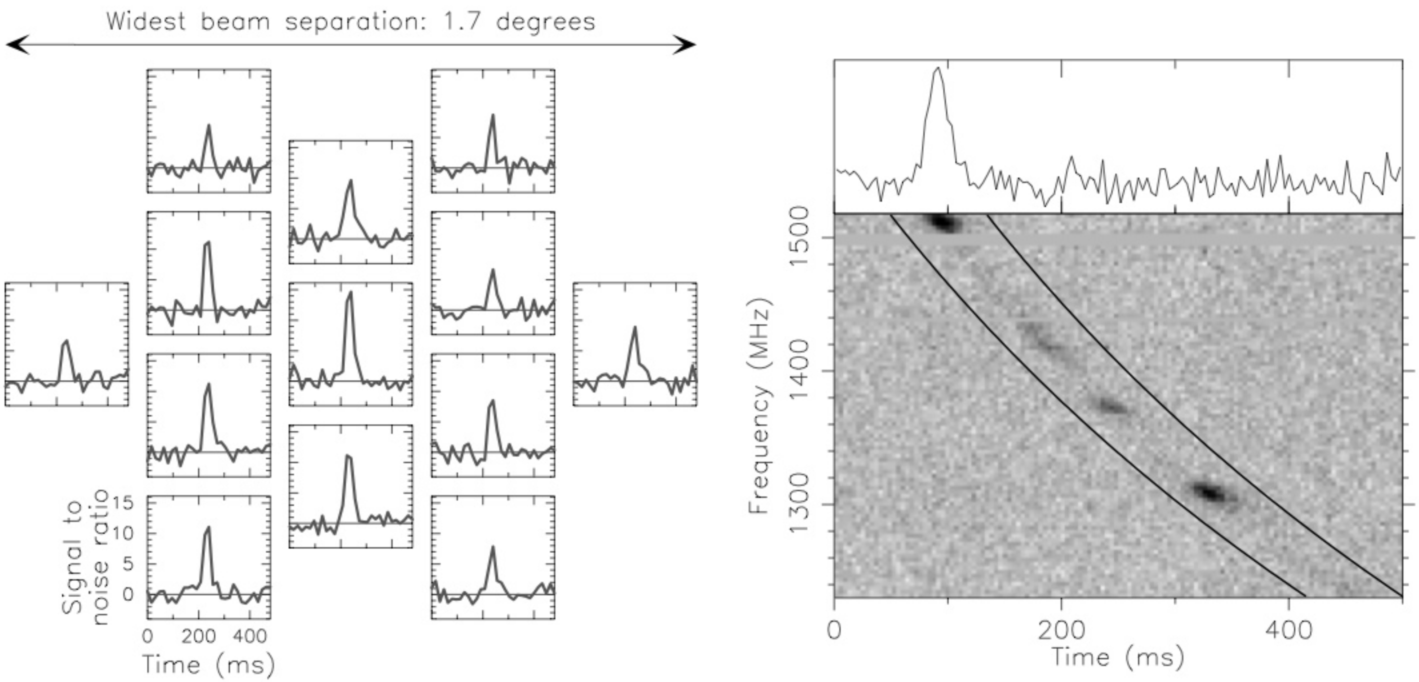
ABSTRACT

Highly dispersed radio pulses have been detected from M87 at radio frequencies of 430, 606, and 1420 MHz. The pulse sweep rates scale with the third power of the observing frequency as expected from the cold plasma law. The sweep rates correspond to dispersion measures in the range 1–5 $\times$ 10^3 parsec cm^{-3}. The pulses frequently appear grouped together separated within the group by approximately 50 ms. Peak power levels of 100 Jy and temporal widths of a few ms for individual pulses are found, and the group repetition rate is of the order of 1 s^{-1}.
Subject headings: galaxies: individual — radio sources: galaxies



THE ASTROPHYSICAL JOURNAL, 236:L109–L113, 1980 March 15

The infamous "Perytons"



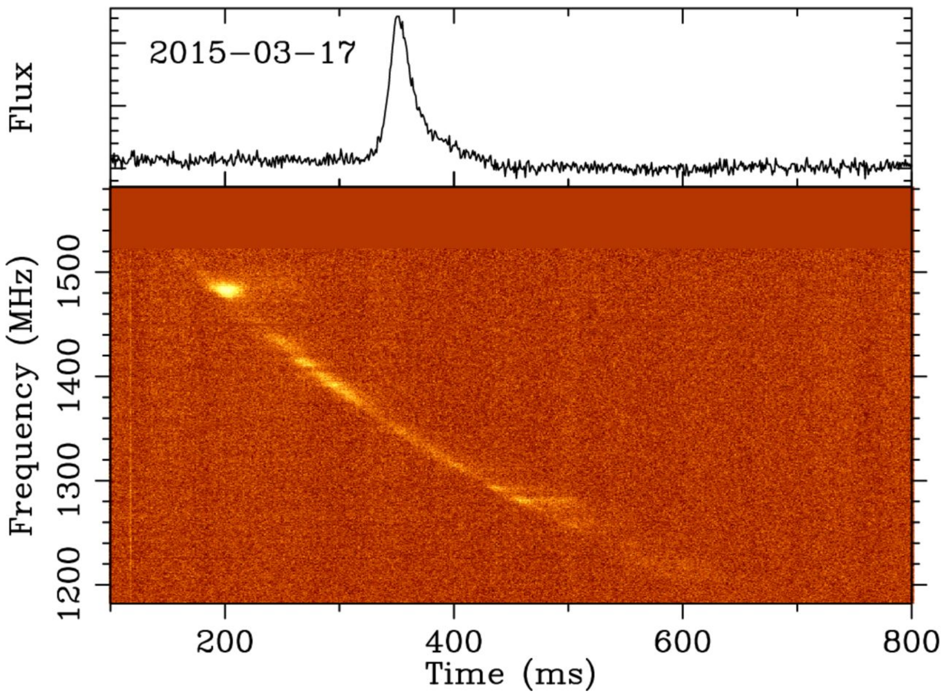
- Burke-Spolaor et al. 2010: 16 pulses in 1998-2003.
- DM=300-400 pc cm^{-3}, similar to Lorimer.
- Detected in all beams, not localized on sky → over 5° off-axis.
- Frequency sweep is not exactly f^{-2}.
- Non-random distribution in time (all mid-morning, mid-winter).

- Clearly NOT astrophysical. "Perytons".
- Traced to radio emission escaping from microwave ovens during the magnetron shut-down phase (Petroff et al. 2015). Not applicable to other FRBs.

The infamous "Perytons"

Petroff et al. 2015:

- Radio emission escaping from microwave ovens during the magnetron shut-down phase neatly explains all of the observed properties of the peryton signals.
- Microwave ovens on site could not have caused, e.g., FRB 010724.



"The decisive test occurred on 2015 March 17 … Instead of waiting for the microwave oven cycle to finish the microwave oven was stopped by opening the door. This test produced three bright perytons from the staff kitchen microwave oven all at the exact times of opening the microwave oven door with DMs of 410.3, 410.3 and 399.6 pc cm^{-3}."

FRB 150418 : What are the odds?

Argument has two prongs:

(1) Fading radio transient in field of FRB.
➔ Detected 2.5 hours after FRB at 5.5 / 7.5 GHz.
➔ Coincidence?
Scaling from ATCA survey at same λ, < 6% (9%).
Extrapolating from VLA survey at 20 cm, < 0.1% (0.2%).

(2) The host galaxy redshift $z = 0.492 \pm 0.008$.
Pulse DM = 776.2(5) cm^{-3} pc (4.1x Milky Way value).
➔ Implied $\Omega_{IGM} = 4.9 \pm 1.3\%$, in agreement WMAP, and including all the so-called ‘missing baryons’.

Parkes 1.4 GHz beam FWHM is ~14 arcmin.
➔ On-sky area is ~ 0.18 square degrees.
For comparison, SDSS has ~5×10^8 objects (stars, galaxies, etc.) in 14,555 sq deg.
➔ Expect over 2500 galaxies in 0.18 sq deg.

FRB 150418 : What are the odds?

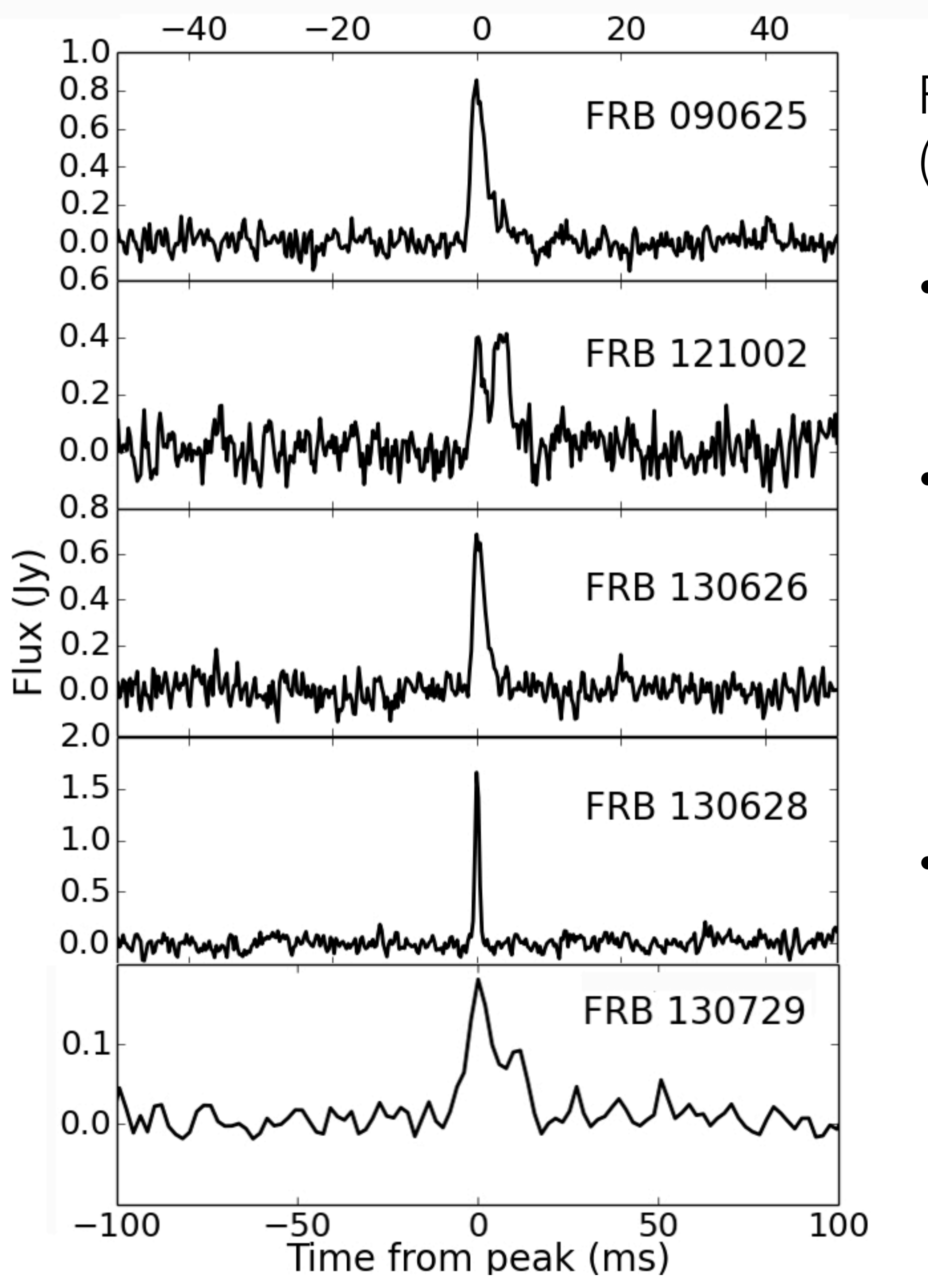
Argument (2) is weak:

➔ All the DM excess is ascribed to the IGM, none to the host galaxy.
➔ Many other galaxies in that cluster would have similar z.

➔ It really hinges on the “transient” being the “afterglow”.

> … By comparing to a recent survey with the Very Large Array in the 2–4 GHz band, we expect a 95% (99%) confidence upper limit of <0.001 (<0.002) such transients to occur in the ATCA observations of the FRB field, or equivalently an upper limit chance coincidence probability of <0.1% (<0.2%). We find that the detection of a fading transient source is therefore sufficiently rare that we conclude that it is the afterglow from the FRB event.

A two-component burst



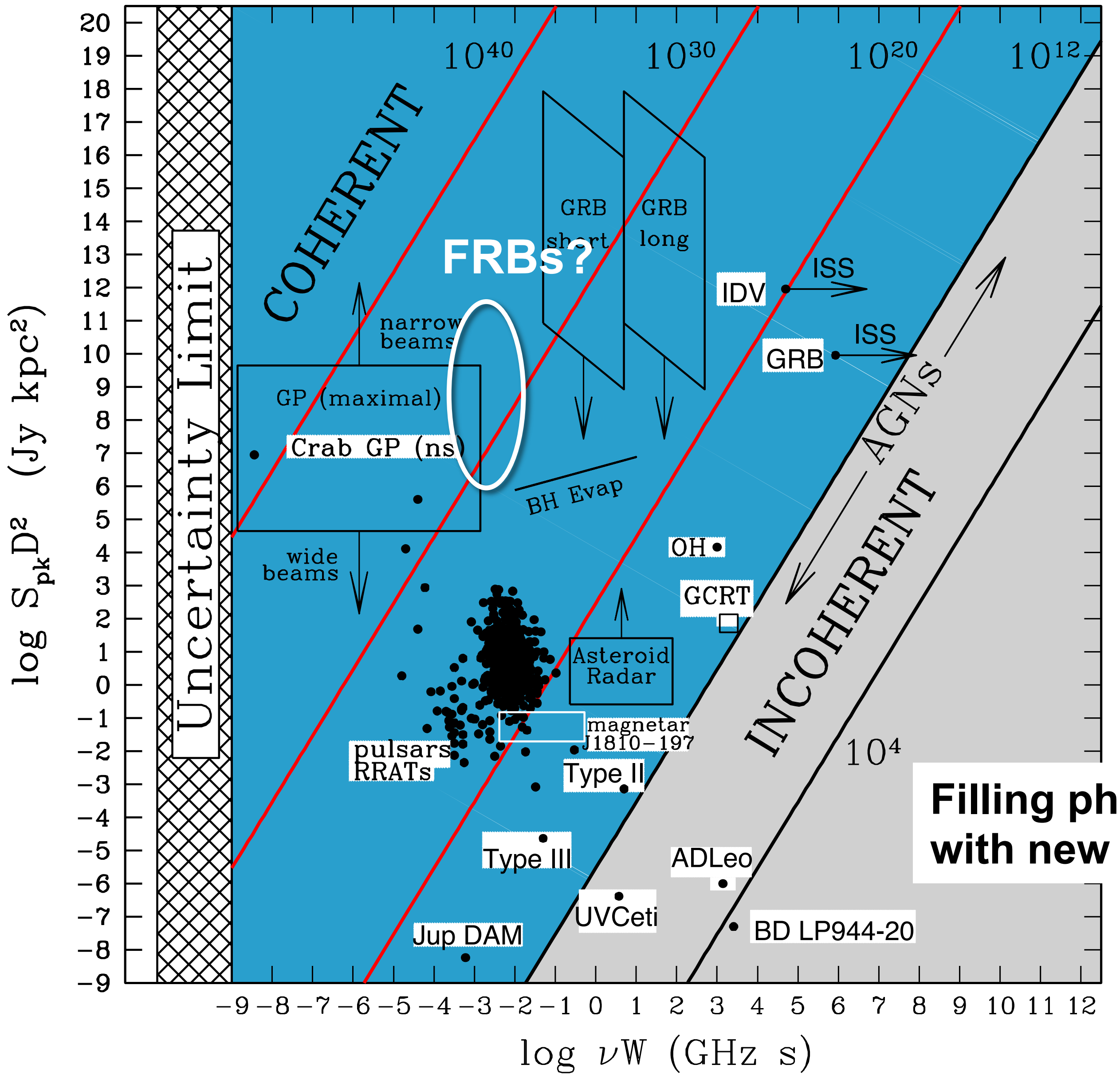
Five new bursts from HTRU – Parkes (Champion et al. 2016)

- All consistent with unresolved pulse + scattering

- FRB 121002:
  * Two components, separated by 2.4(4) ms.
  * Very high DM =1629 pc cm^{-3}.
  ➔ Non-cataclysmic origin?

- Inferred all-sky FRB rate = 6(+4-3) x 10^3 per day (for 0.128–262 ms timescales and 0.13 to 5.9 Jy-ms fluence).

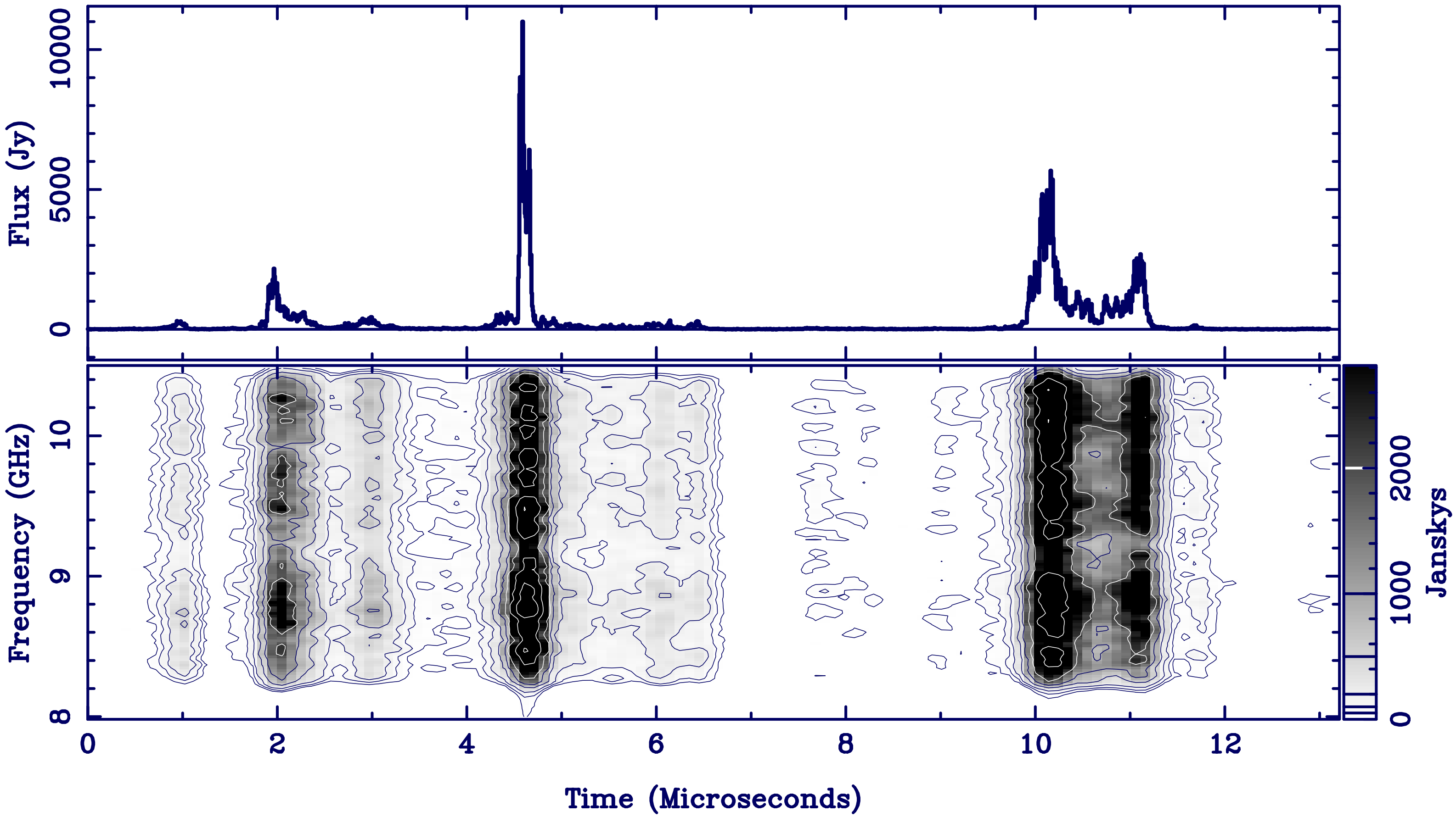
Radio Transient Phase Space



Filling phase space with new discoveries.

Crab giant pulses

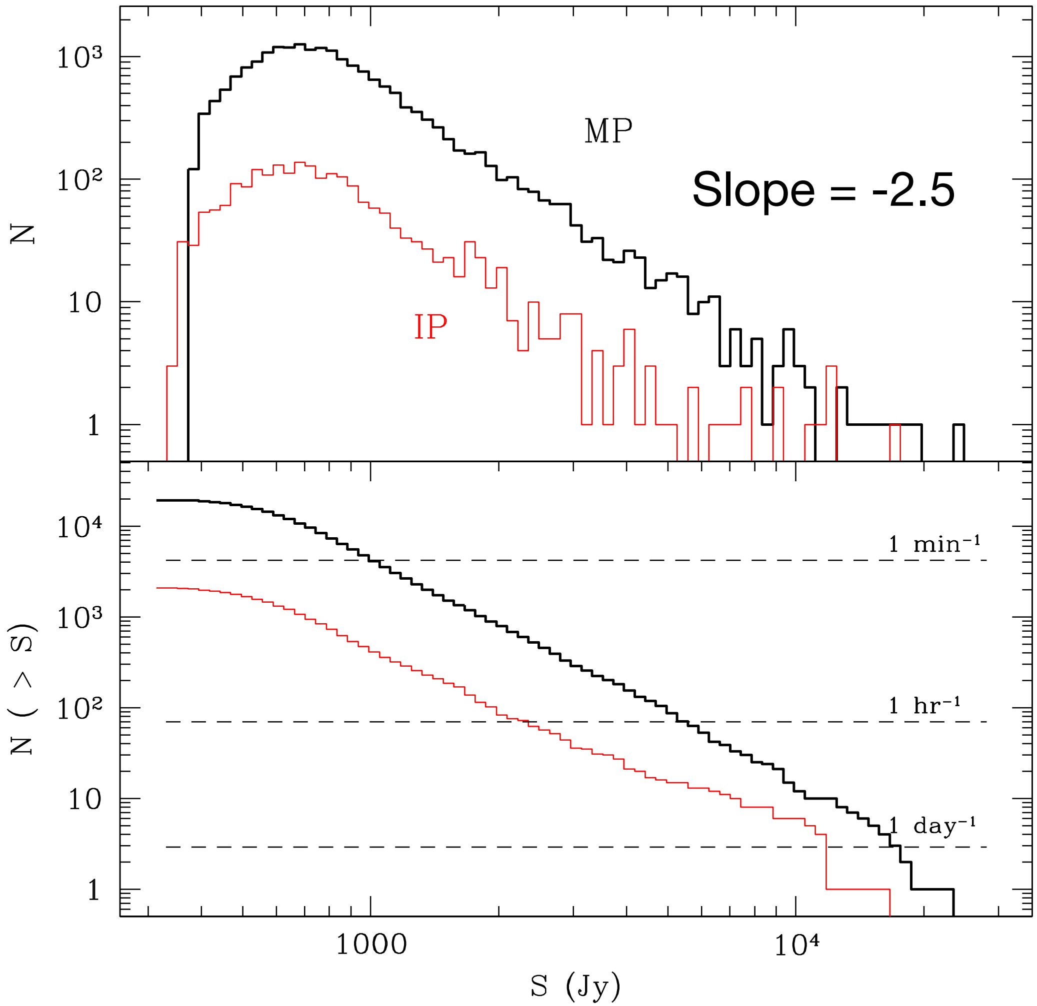
Crab pulsar: giant pulses on nanosecond timescales; MJy amplitudes; frequency structure. (Hankins et al. 2003, Eilek & Hankins 2007, etc.)



FRB problem: millisecond pulses, so need to scale up pulse fluence by 5-6 orders of magnitude.

Extrapolation of Crab GPs

91 hr of GP statistics at 0.8 GHz (Lundgren et al. 1995)



Period-averaged Flux Density at 800 MHz

- Slope of cumulative distribution of period-averaged S: $N(>S) \sim S^{-2.5}$
- Other studies at 0.43 GHz: 1 pulse in 1 hr with peak flux density $S_{pk} \sim$ 150 kJy at 0.43 GHz
- Correct for scattering broadening: $S_{pk} \sim$ 3 MJy in 1 hr
- $S_{pk} \sim$ 3 MJy $T_{hr}^{2/5}$(2 kpc/D)^2

→ 0.1 GJy in 1 yr

- Detectable to 20 Mpc at 1 Jy

→ 2 GJy in 1000 yr

- Detectable to 85 Mpc at 1 Jy