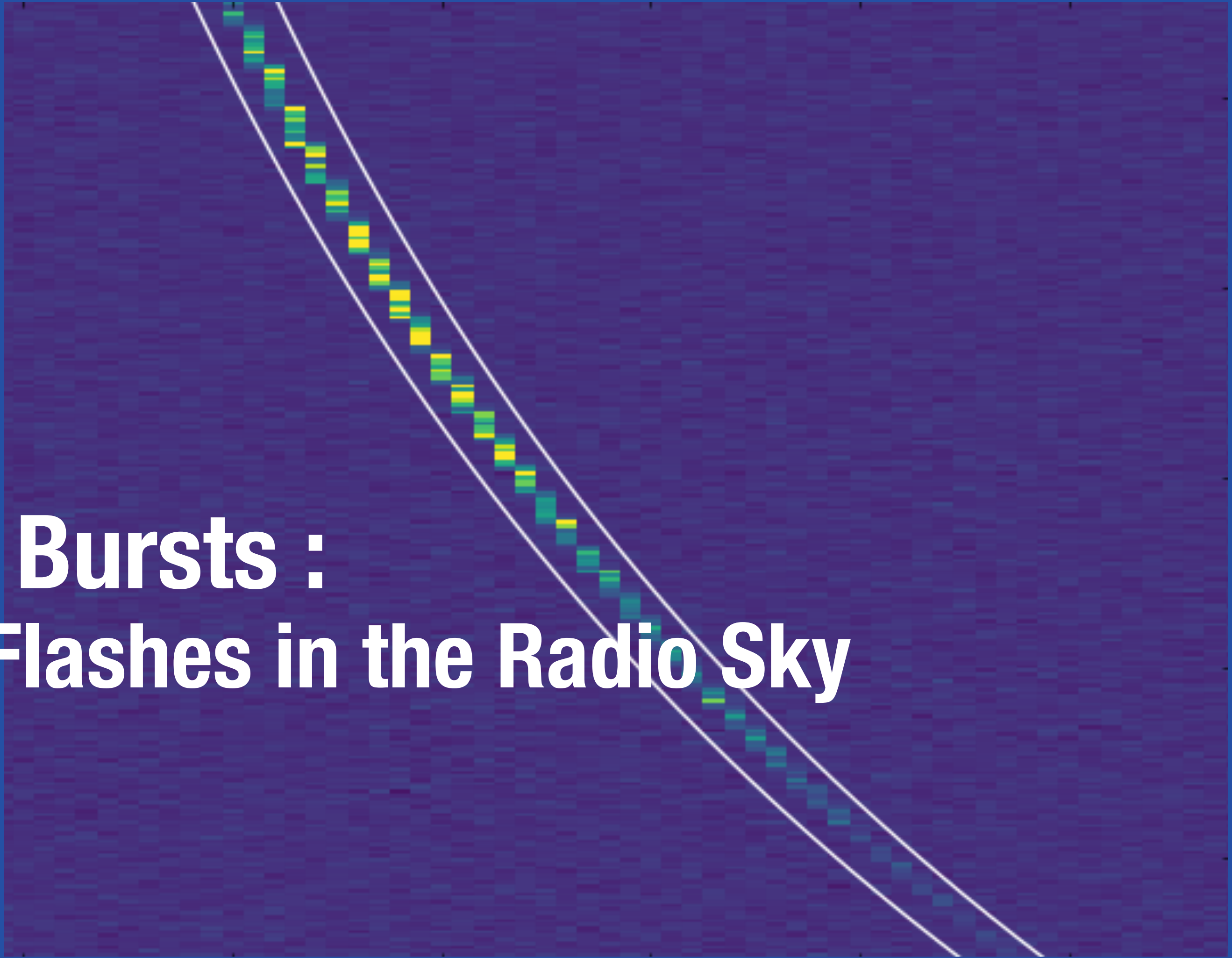
Shami Chatterjee
Cornell University

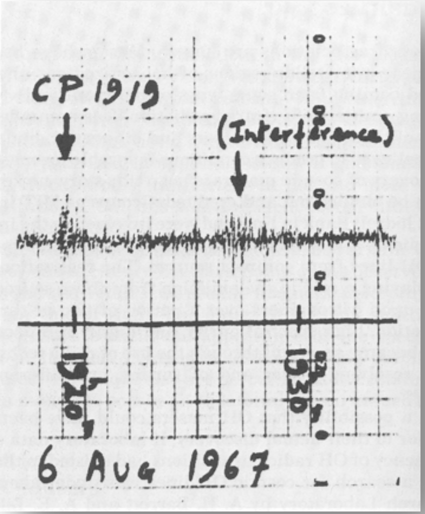
Fast Radio Bursts : Mysterious Flashes in the Radio Sky

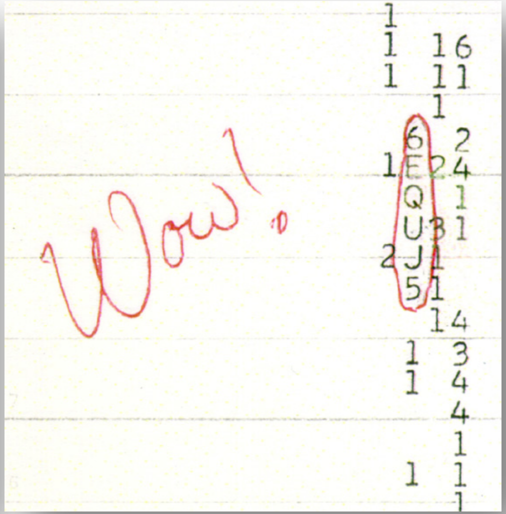


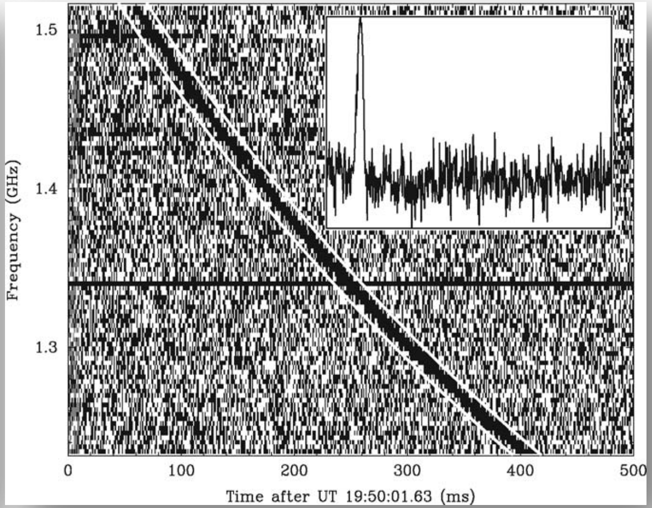
August 2020

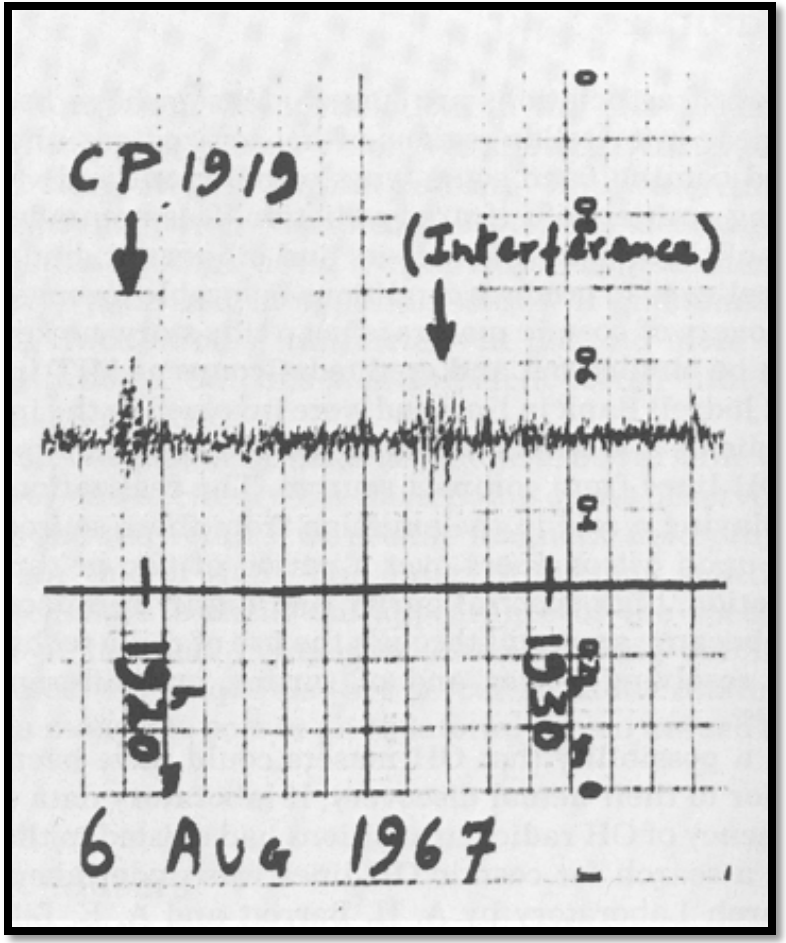
Fast Radio Transients

- Discovery space in the time domain radio sky.
- Data-intensive and computation-intensive science.

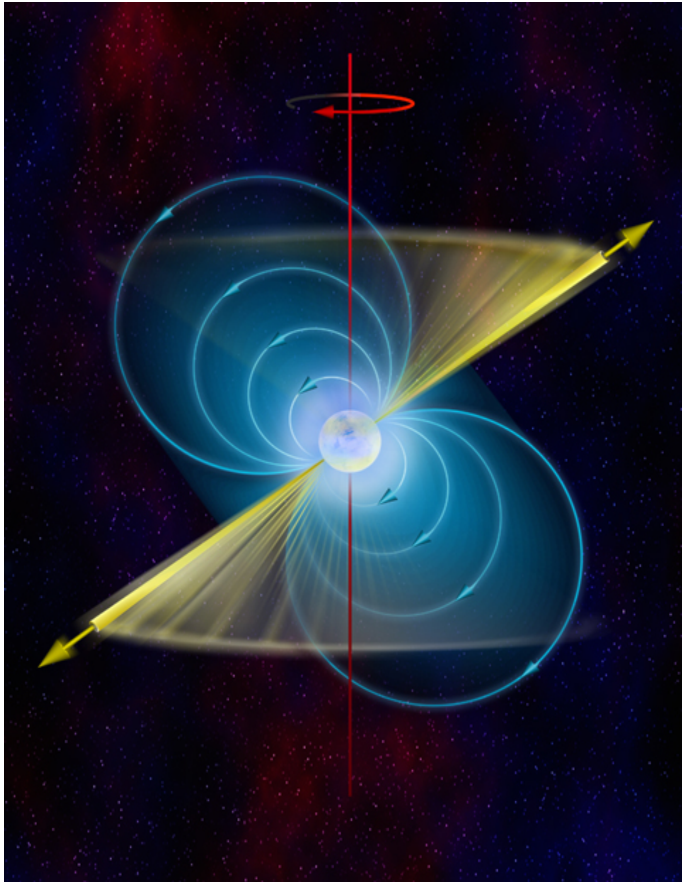






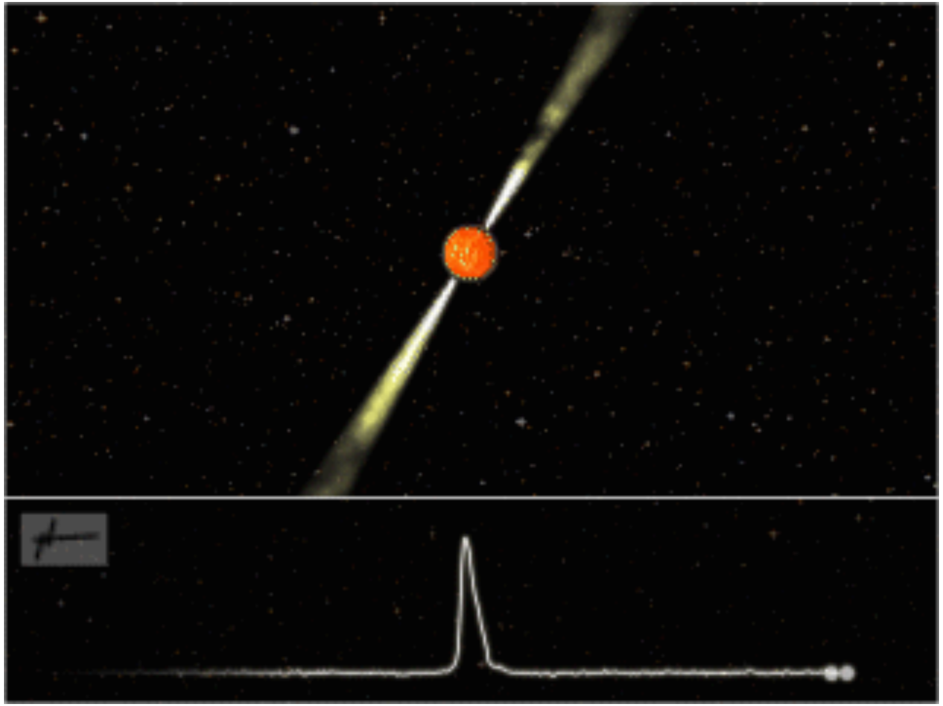

CP 1919
(Interference)
1920
1930
6 Aug 1967

What is a pulsar?

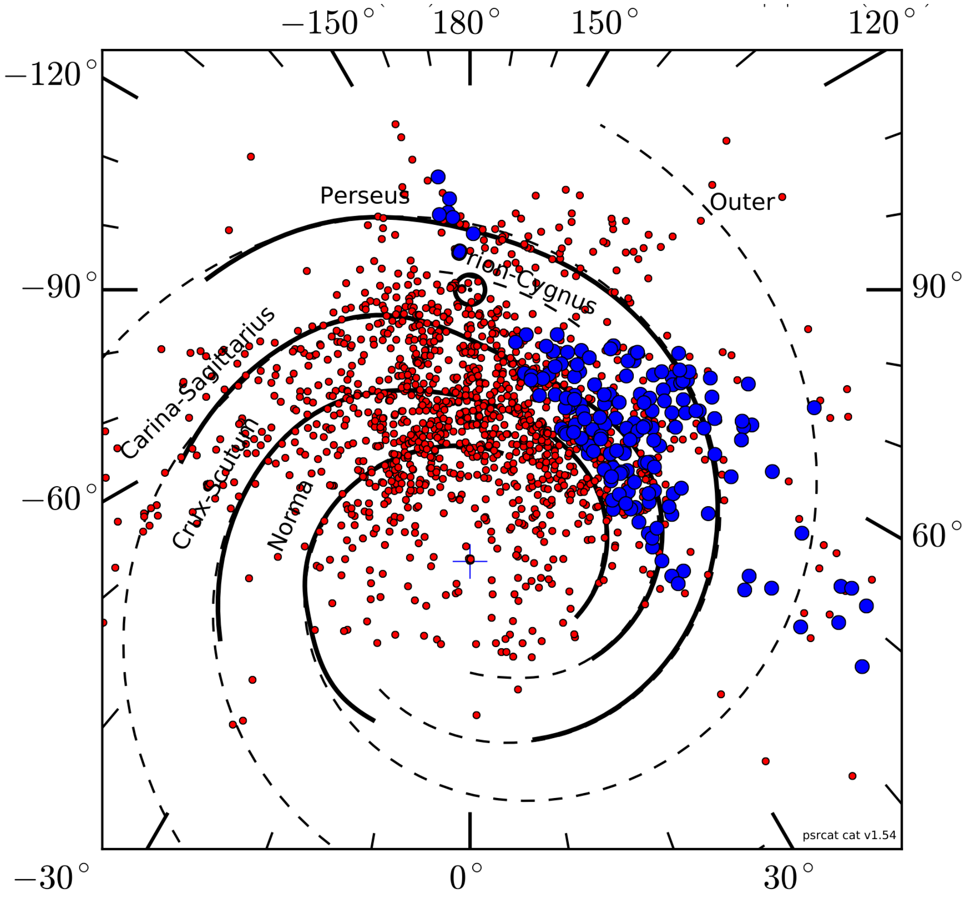


Rapidly rotating *neutron stars*.

→ Left behind by the death of massive stars via supernova core collapse.



What is a pulsar?



Rapidly rotating *neutron stars.*

→ Left behind by the death of massive stars via supernova core collapse.

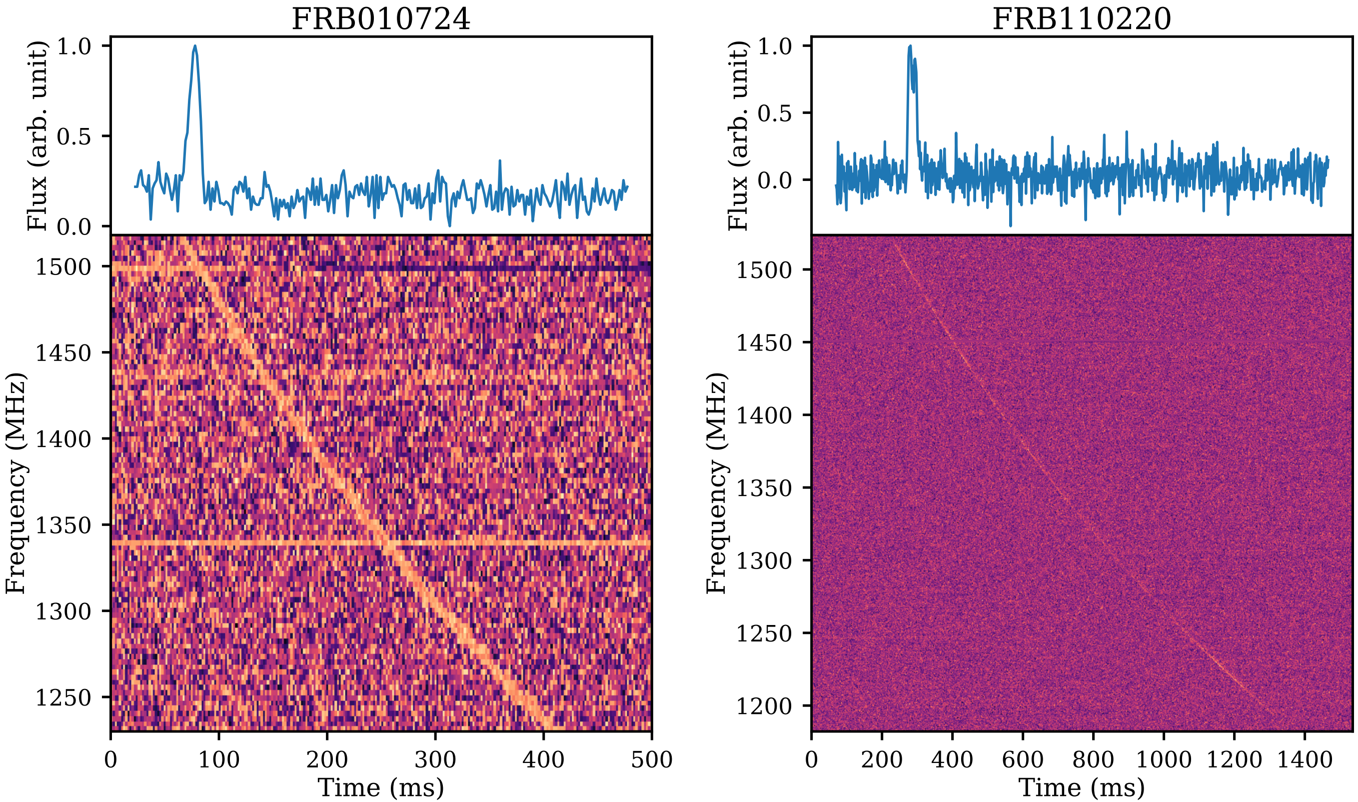
→ Typically *periodic* sources, but some sources detected as single pulses.

→ Galactic population.

- → Arecibo PALFA discoveries
- → Other known pulsars

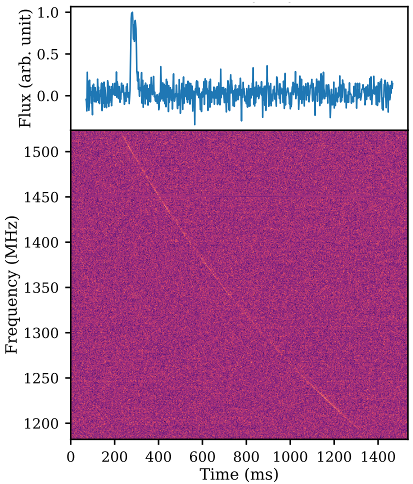
Fast Radio Bursts: An Overview

Fast Radio Bursts



Interstellar / Intergalactic Propagation Effects

Dispersion Delays

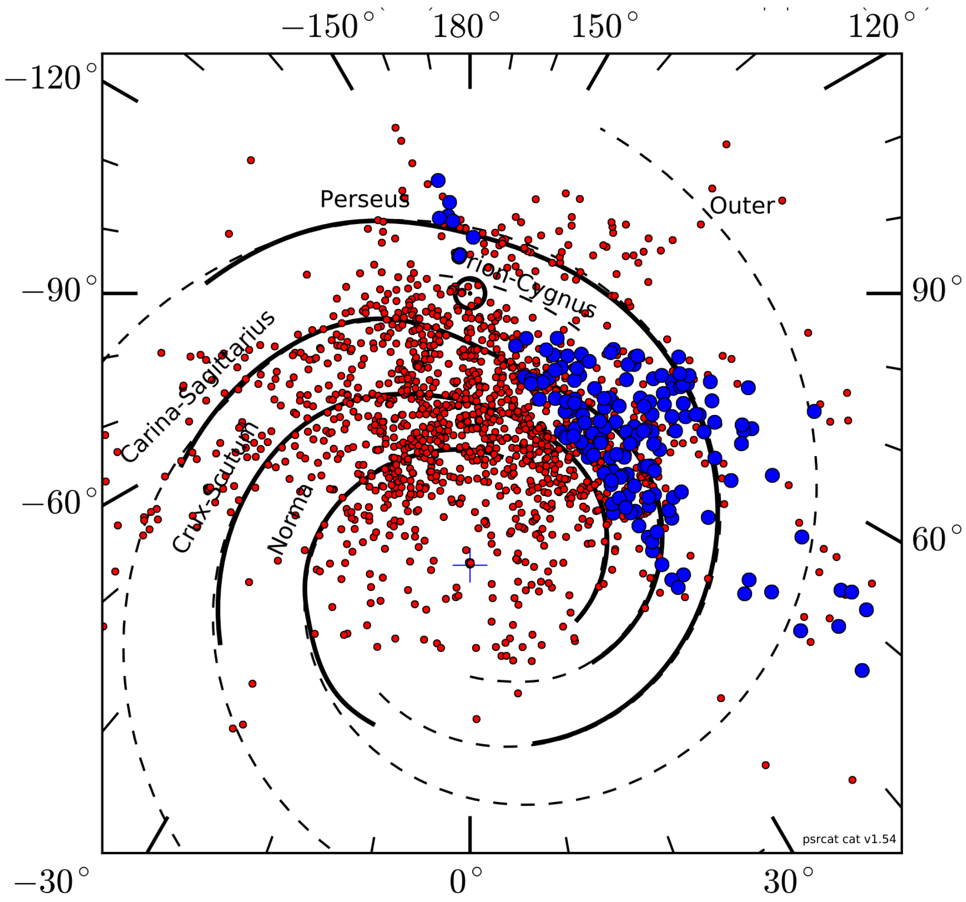


$$t_{\mathrm{DM}}(\nu) = \frac{4.15\times\mathrm{DM}\ \ \mathrm{ms}}{\nu_{\mathrm{GHz}}^2}$$

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

Deterministic, removable with coherent de-dispersion.

Pulsars in our Galaxy



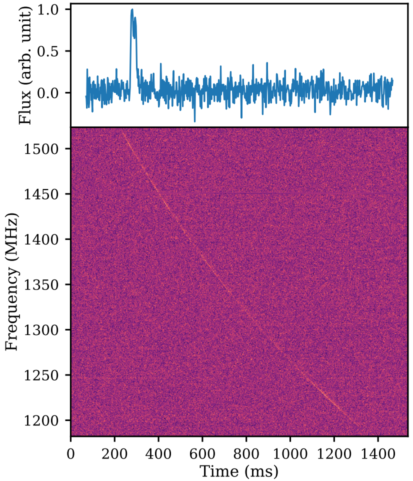
Rapidly rotating *neutron stars*.

→ Galactic population.

→ Can use pulsar DMs to model the Galactic electron density distribution.

Interstellar / Intergalactic Propagation Effects

Dispersion Delays

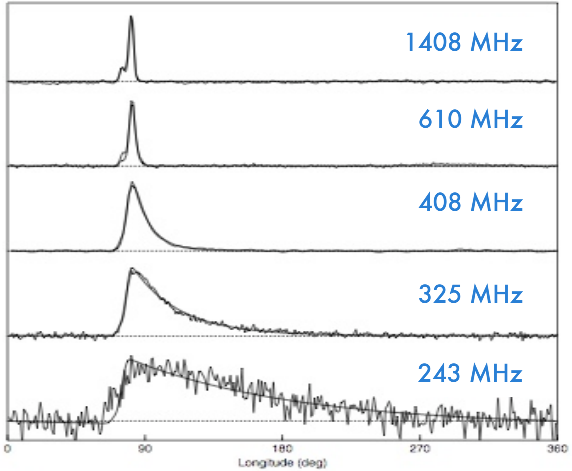


$$t_{\rm DM}(\nu) = \frac{4.15\times{\rm DM\ \ ms}}{\nu^2_{\rm GHz}}$$

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

Deterministic, removable with coherent de-dispersion.

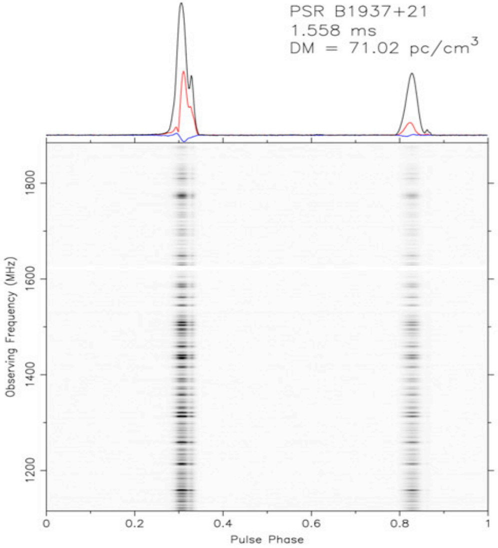
Multipath Broadening (Scattering)



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

Stochastic,
not easily removable.

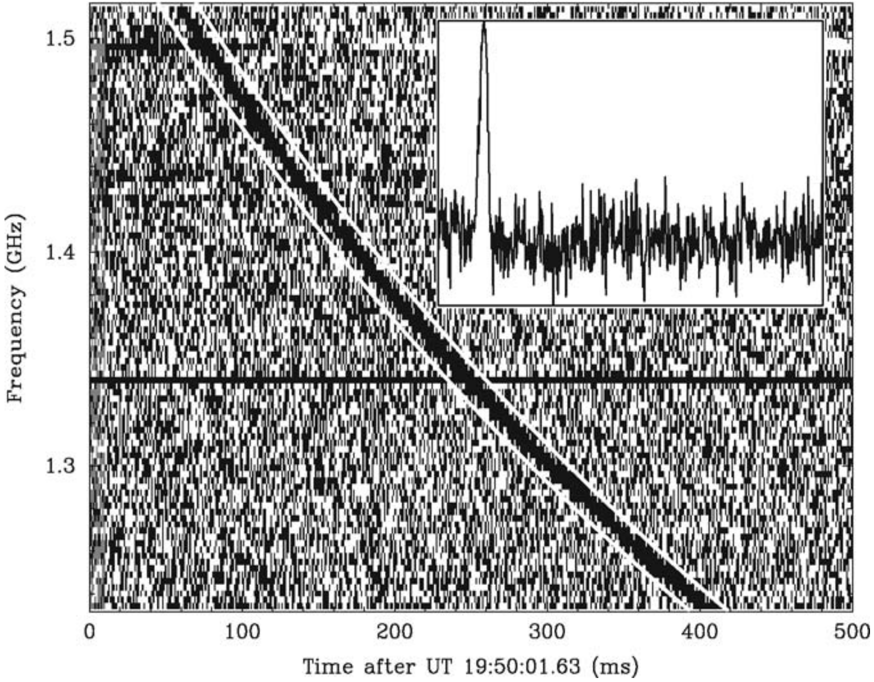
Diffractive Scintillation



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

100% modulations
of flux density.

Fast Radio Bursts



FRB 010724, the “Lorimer burst”:

- Archival survey data from Parkes.
- A single dispersed pulse.
- Width < 5ms.
- Brighter than 30 Jy (?)
- Follows f^{-2} dispersion law.
- DM = 375 pc cm-3 → 500 Mpc?

→ Extragalactic.

Lorimer et al. 2007, Science,
A Bright Millisecond Burst of Extragalactic Origin

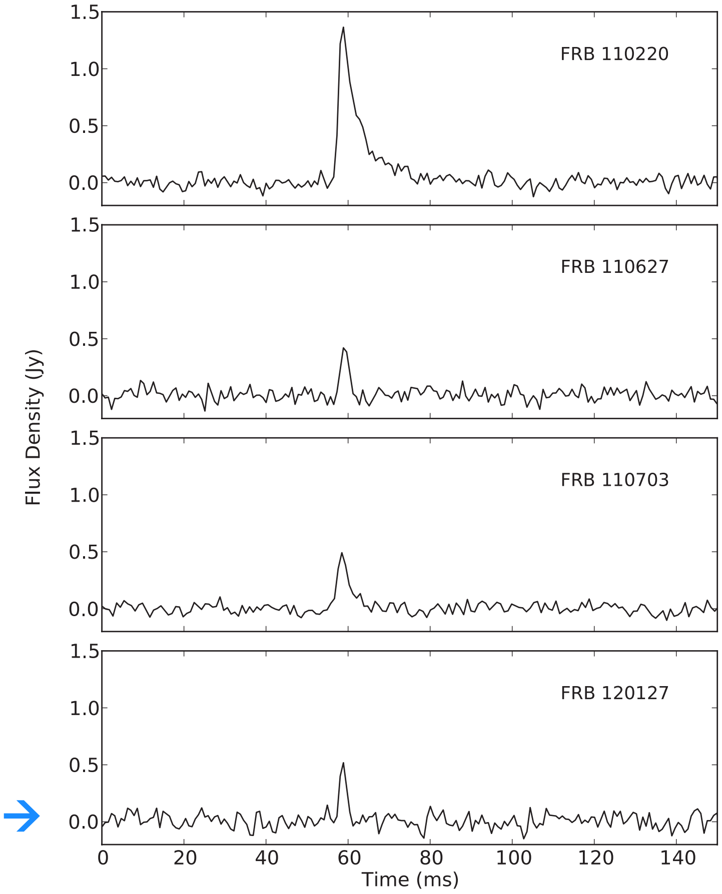
The known FRB population

- ~130 sources known so far.

  Detected at Parkes, Arecibo, Green Bank, UTMOST, ASKAP, CHIME.

- Inferred all-sky rate is large,
  ~5000 / sky / day
  (dependent on detection threshold).

Thornton et al. (2013) →

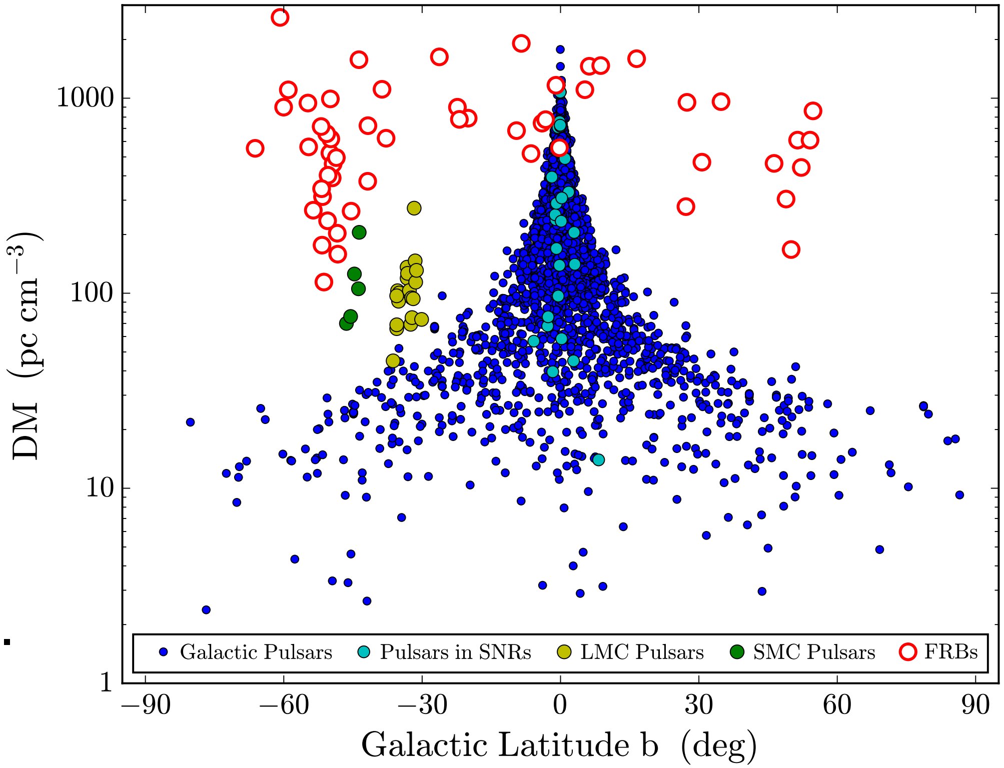


The known FRB population

- ~130 sources known so far.
- Inferred all-sky rate is large, ~5000 / sky / day.
- Dispersion measures: 100 – 3000+ pc cm^{-3}.

➔ Extragalactic;

DM = Milky Way + IGM + Host.

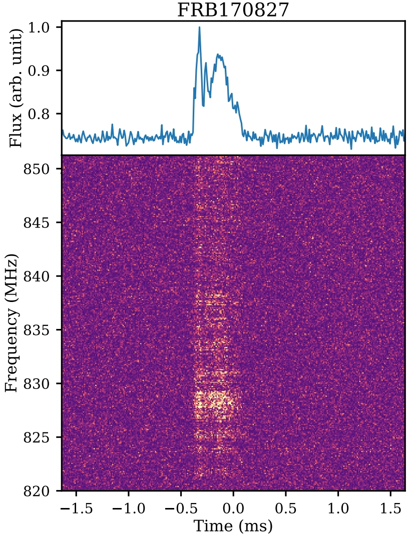


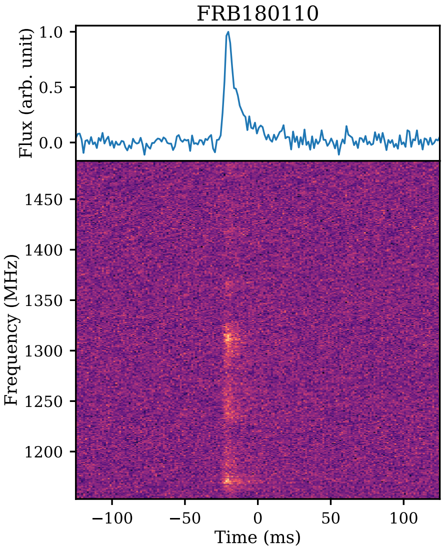
Models for FRBs

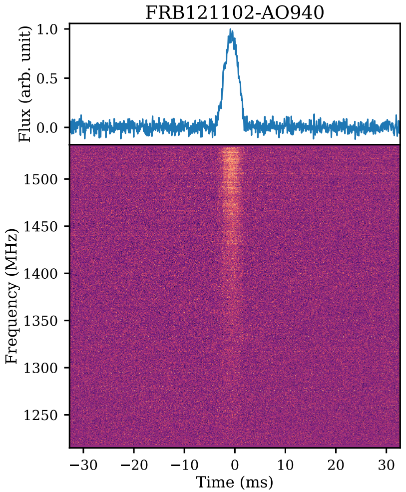
- Terrestrial / solar system sources? (Ruled out by lower limit on parallax.)
- Galactic sources with intrinsic pulse dispersion?
  - Flares from nearby magnetically active stars. (Ruled out.)
- Extragalactic sources – local or cosmological?
  - Soft Gamma Repeater giant flares (Popov & Postnov 2007).
  - Merging white dwarfs (Kashiyama et al. 2013).
  - Merging neutron stars (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).
  - … etc. etc. etc.

The known FRB population

- ~130 sources known so far.
- Inferred all-sky rate is large, ~5000 / sky / day.
- Dispersion measures: 100 – 3000+ pc cm^{-3}.
- Currently incomplete in every FRB parameter (fluence, DM, width, rate, repetition, polarization…)



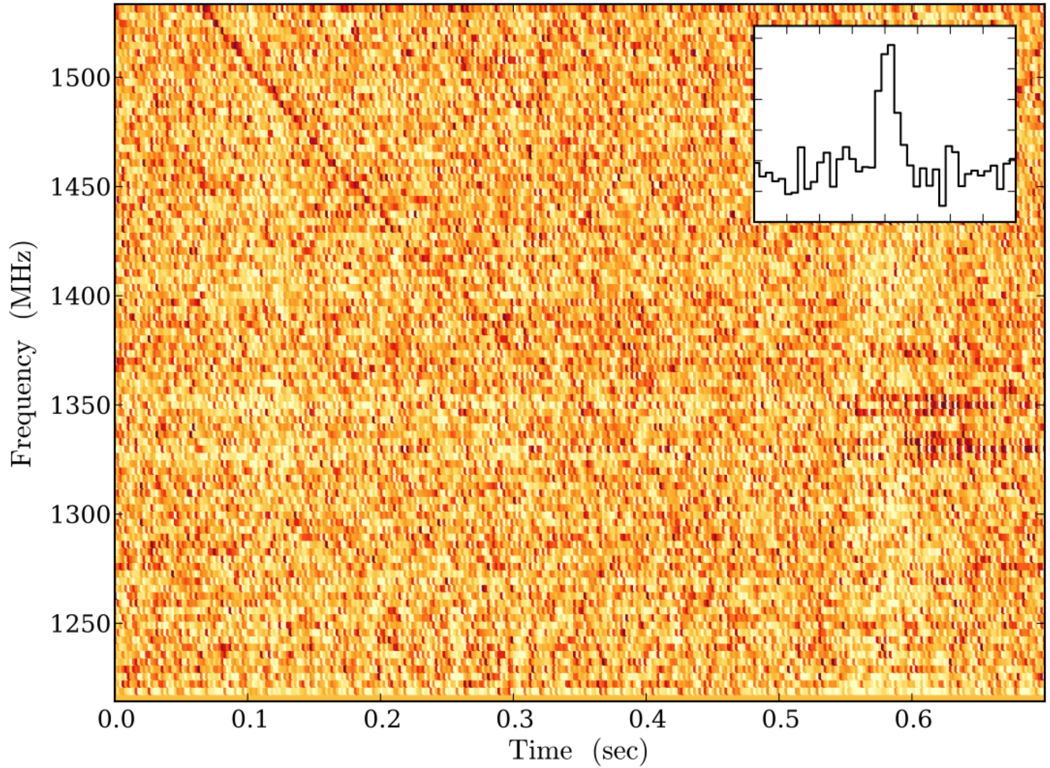




A very special Fast Radio Burst

FRB 121102: Arecibo detection

- Discovered at Arecibo.
- l,b = 175°, –0.2°.
- DM = 557 pc cm^{-3}.
  (DM_{NE2001} = 188 pc cm^{-3}.)
- Width = 3.0±0.5 ms.
- No re-detection in multiple deep follow-ups…



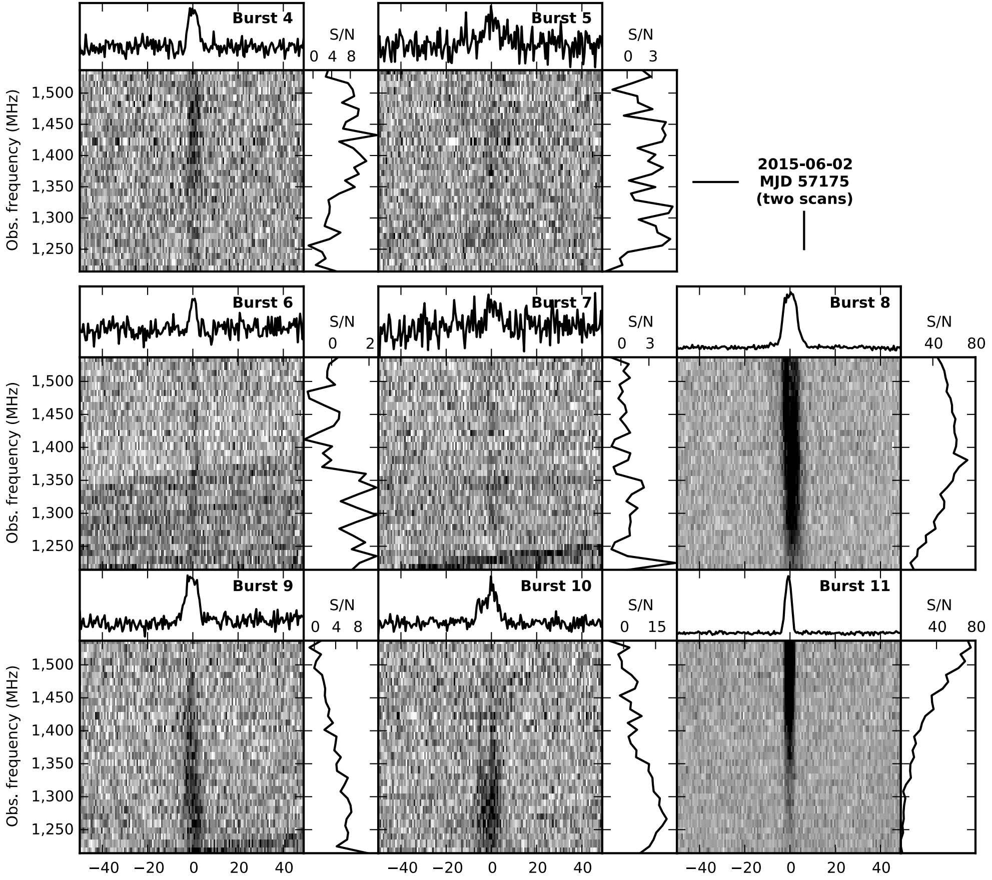
Spitler et al. 2014,
Fast Radio Burst discovered in the Arecibo Pulsar ALFA Survey

"A minor point of interest"

- Discovered at Arecibo.
- l,b = 175°, –0.2°.
- DM = 557 pc cm^{-3}.

- FRB 121102 is a *repeating source*.

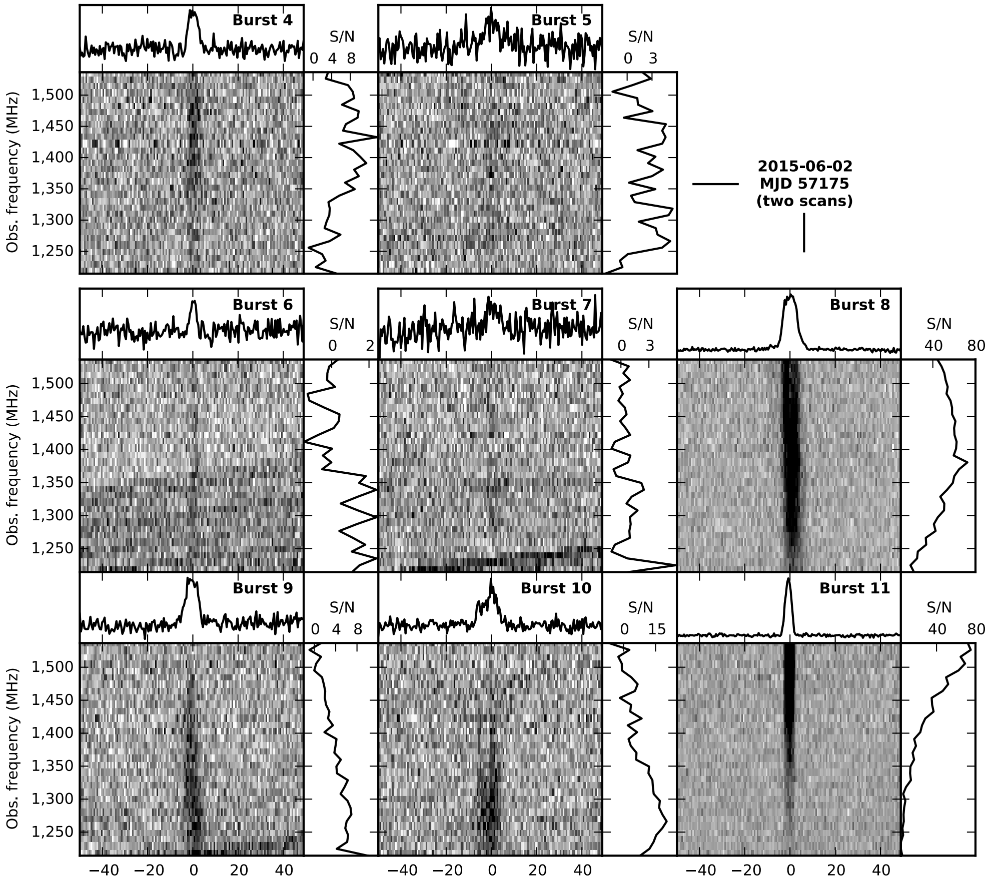
Spitler et al. 2016, Nature,
A repeating fast radio burst



FRB 121102 is a repeating source

→ Rules out cataclysmic or explosive models, at least for this one source.

→ A better-than-random location to go fishing.

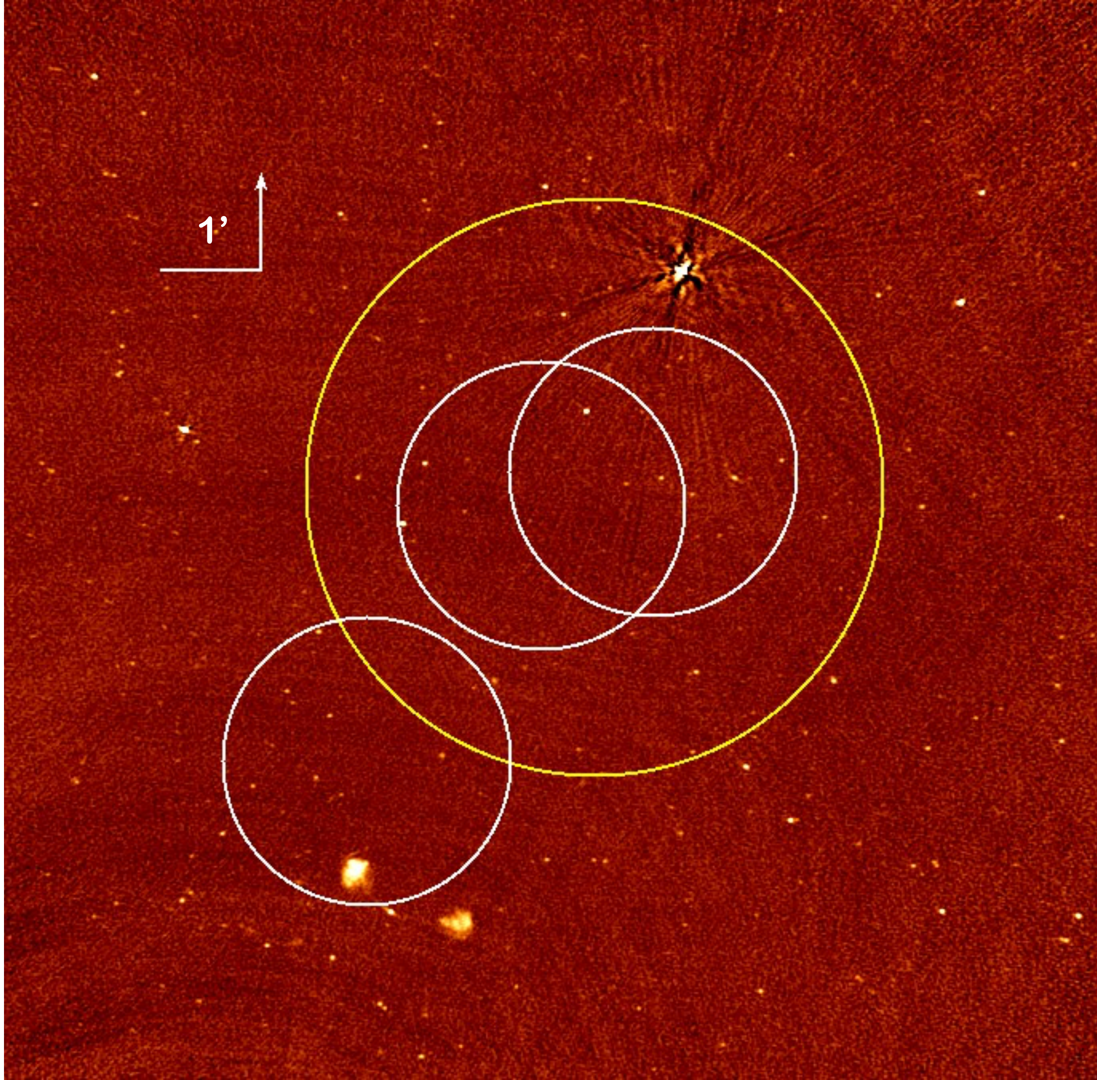


Spitler et al. 2016, Nature, A repeating fast radio burst

So where is it?

Arecibo detection beams cover dozens of sources in higher resolution VLA observations.

➔ Original detection (Spitler et al. 2014) was apparently in a sidelobe.



VLA localization

Fast sampled visibility data (u, v, t, f) for ~83 hours of observing.

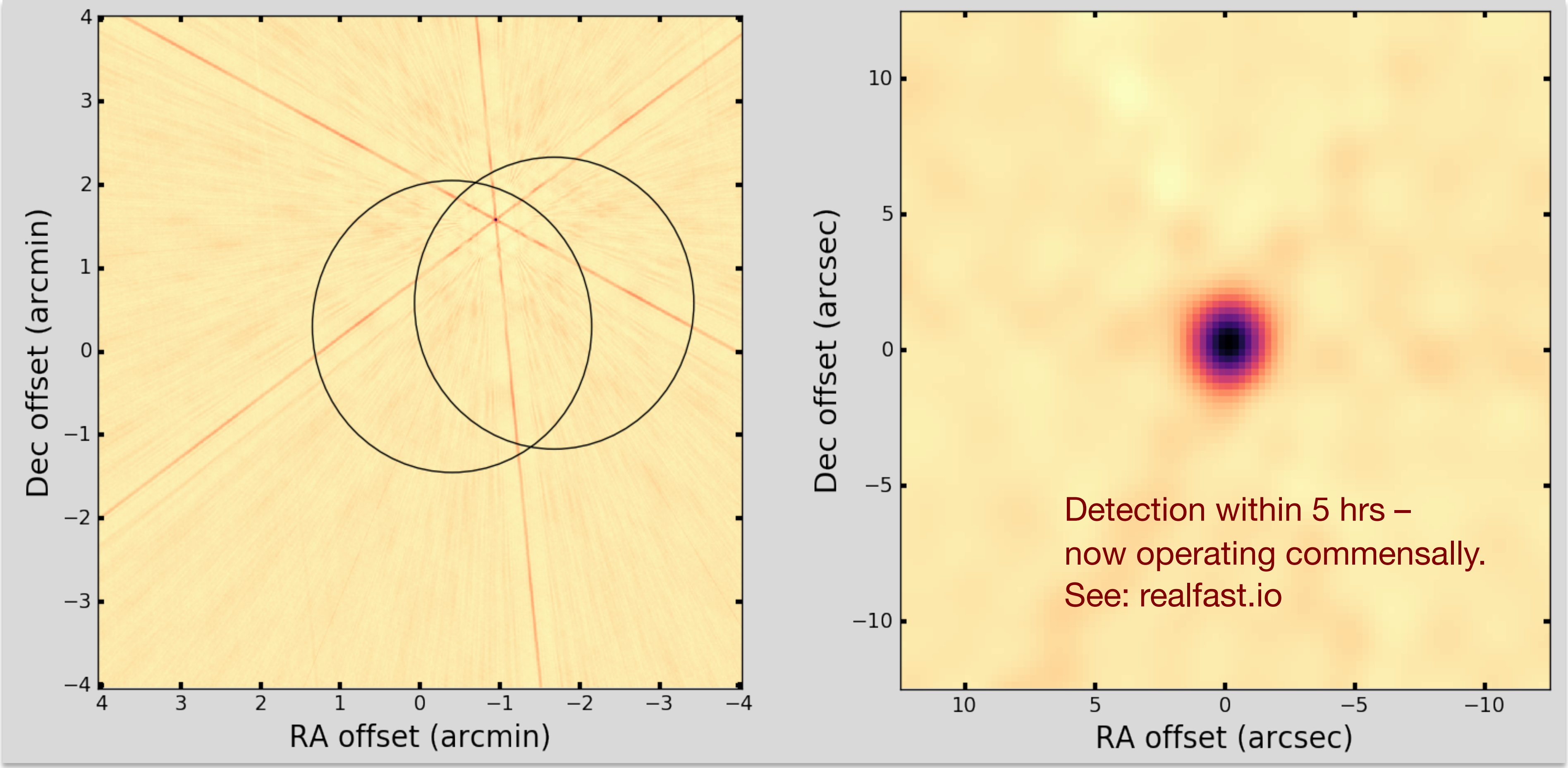
Millisecond Imaging:

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

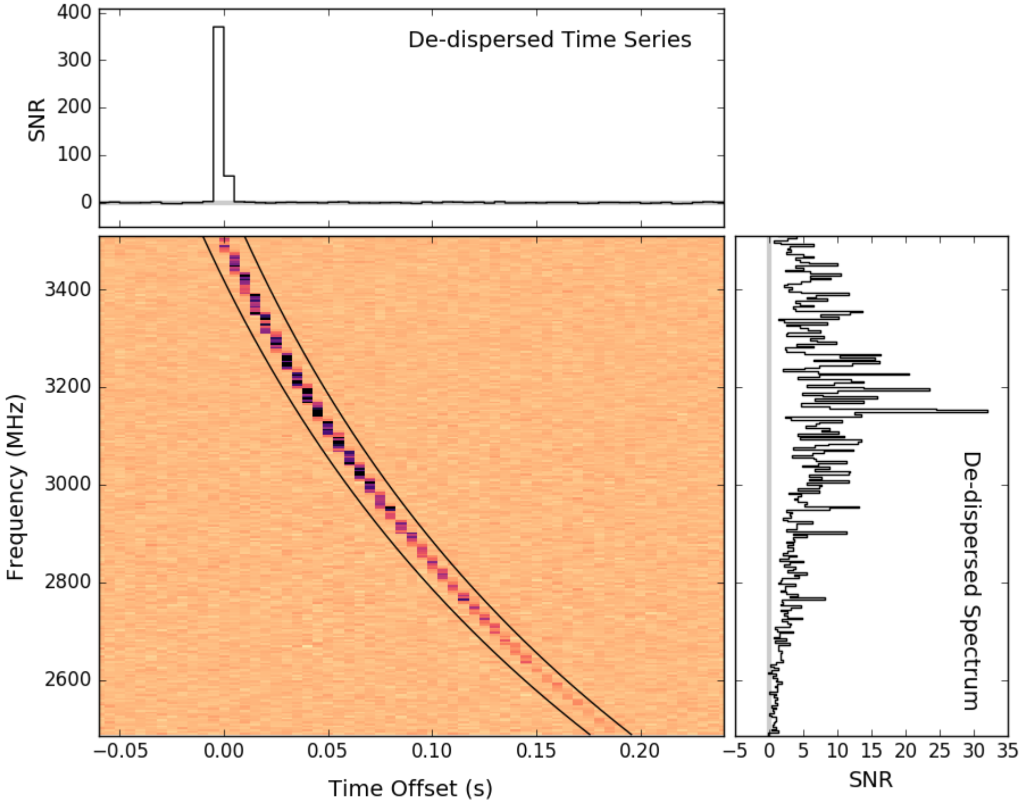
Beam-formed Single-pulse Search:

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

VLA localization: success!



VLA beam-forming: pulse sweep



Pulse S/N ratio peaks at the image peak pixel.

Lines indicate ν^{-2} sweep.

(Work by former graduate student Robert Wharton.)

Chatterjee et al. 2017, Nature, A direct localization of a fast radio burst and its host


nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
MYSTERY OBJECT
Precise localization of fast radio burst reveals distant host and enigmatic persistent source
PAGES 32 & 58
POLICY
KNOW YOUR WORKFORCE
A census of US biomedical scientists
PAGE 21
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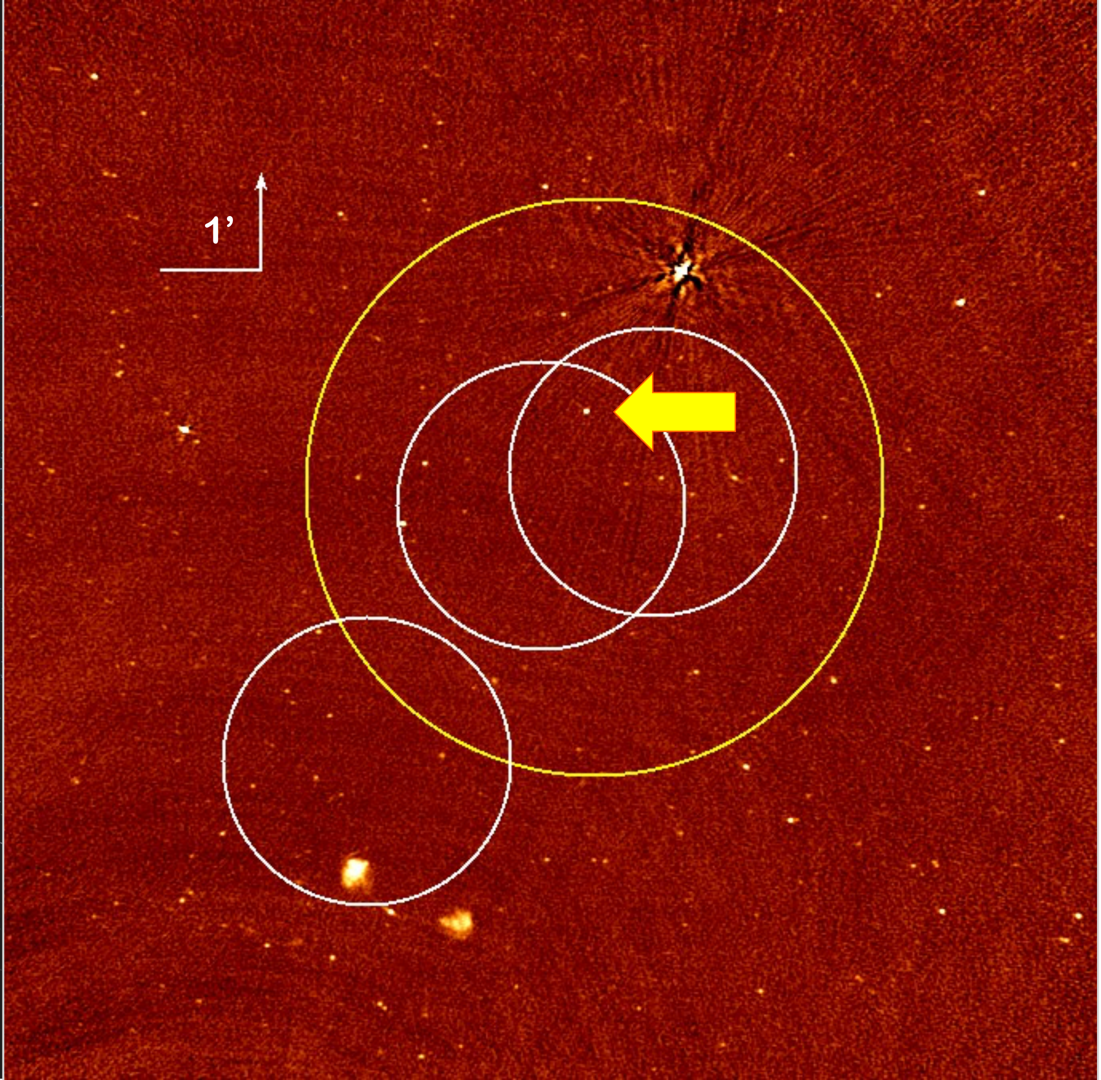
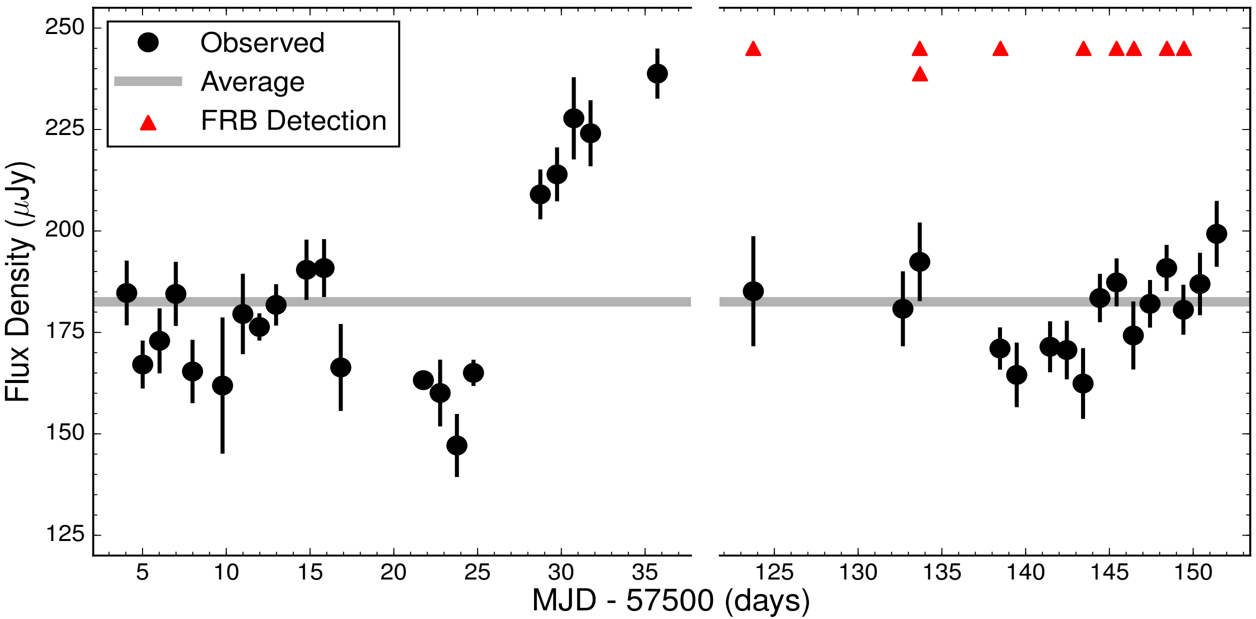

1’

A counterpart and a host galaxy

Radio counterpart: Persistent radio source



- Bursts are sporadic.
- Persistent, variable, 180 μJy radio counterpart.
- Non-thermal.
- AGN? PWN? SNR?

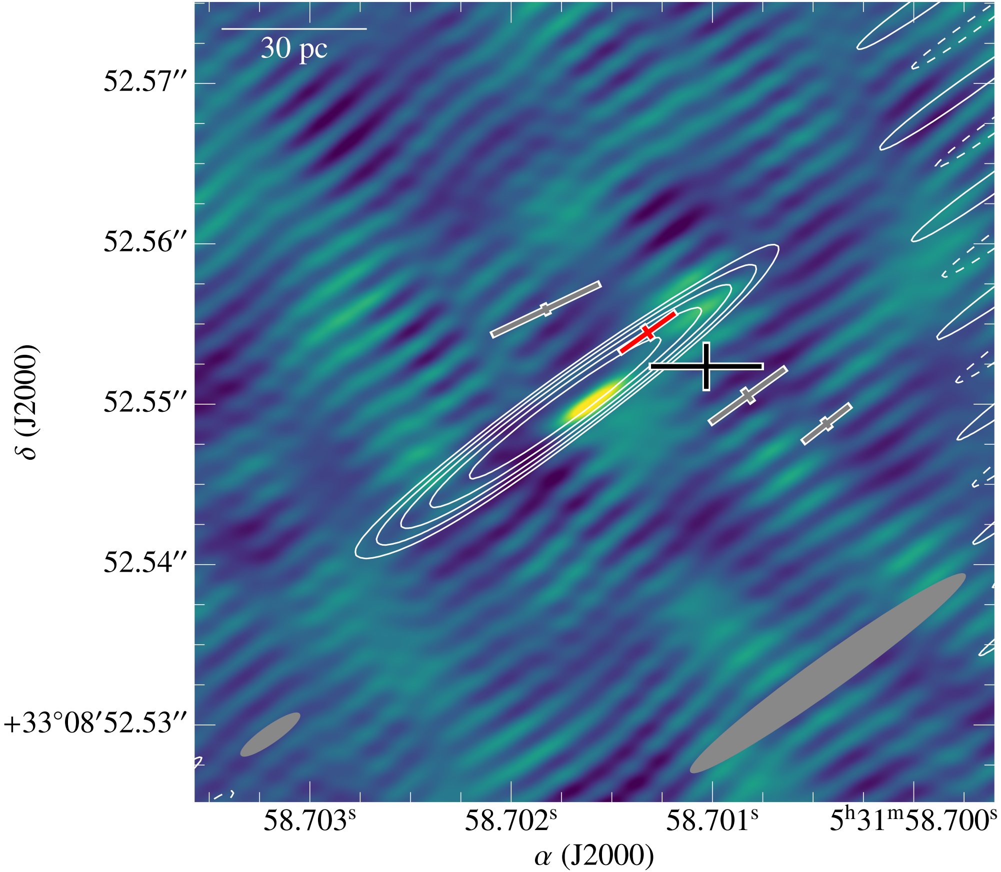
Chatterjee et al. (2017)

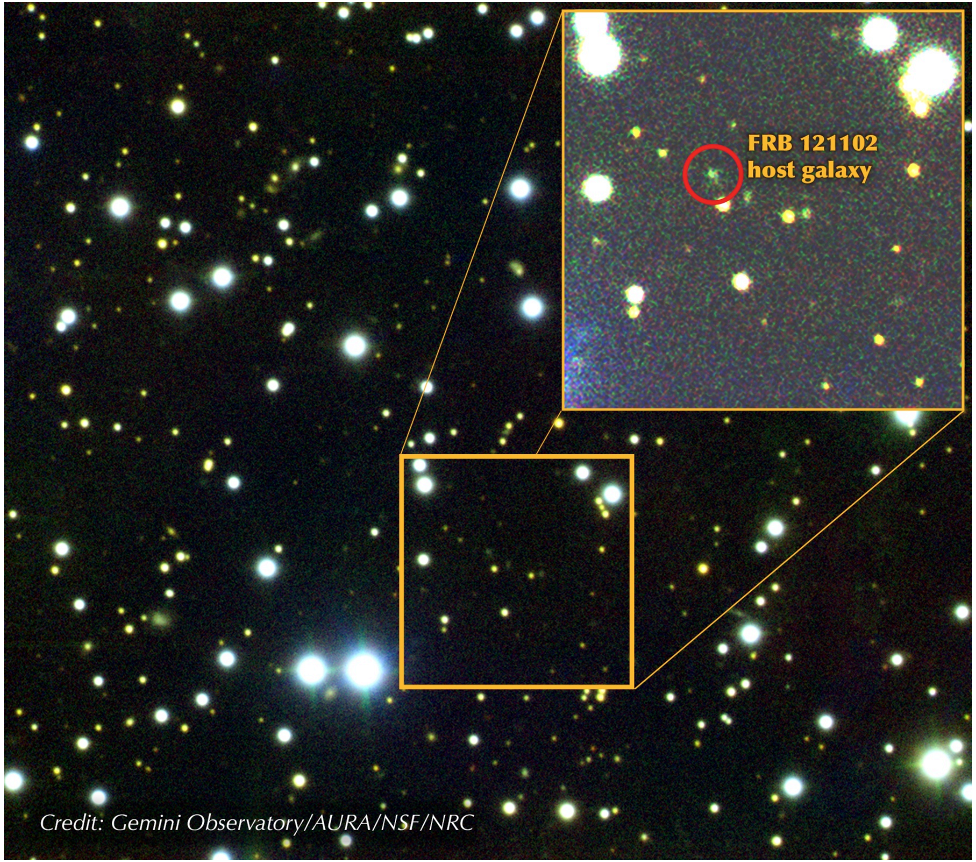
Bursts and persistent source coincide

VLBI with Arecibo + EVN:

→ Bursts and persistent radio source coincide to better than 12 mas (40 pc).

Marcote et al. (2017)



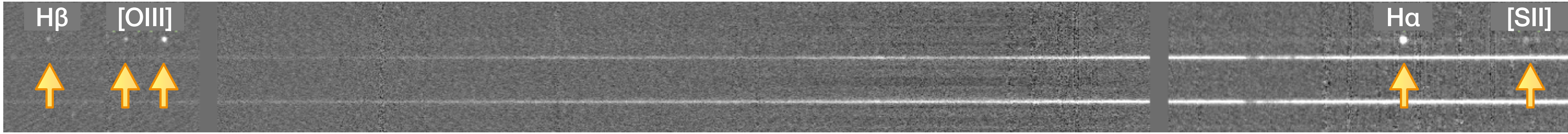


Optical host galaxy

Deep imaging with Gemini:
25th magnitude counterpart.

→ Dwarf galaxy.
→ Emission dominated by spectral lines.
→ z = 0.193;
host is ~1 Gpc away.

← **Tendulkar et al. (2017)**



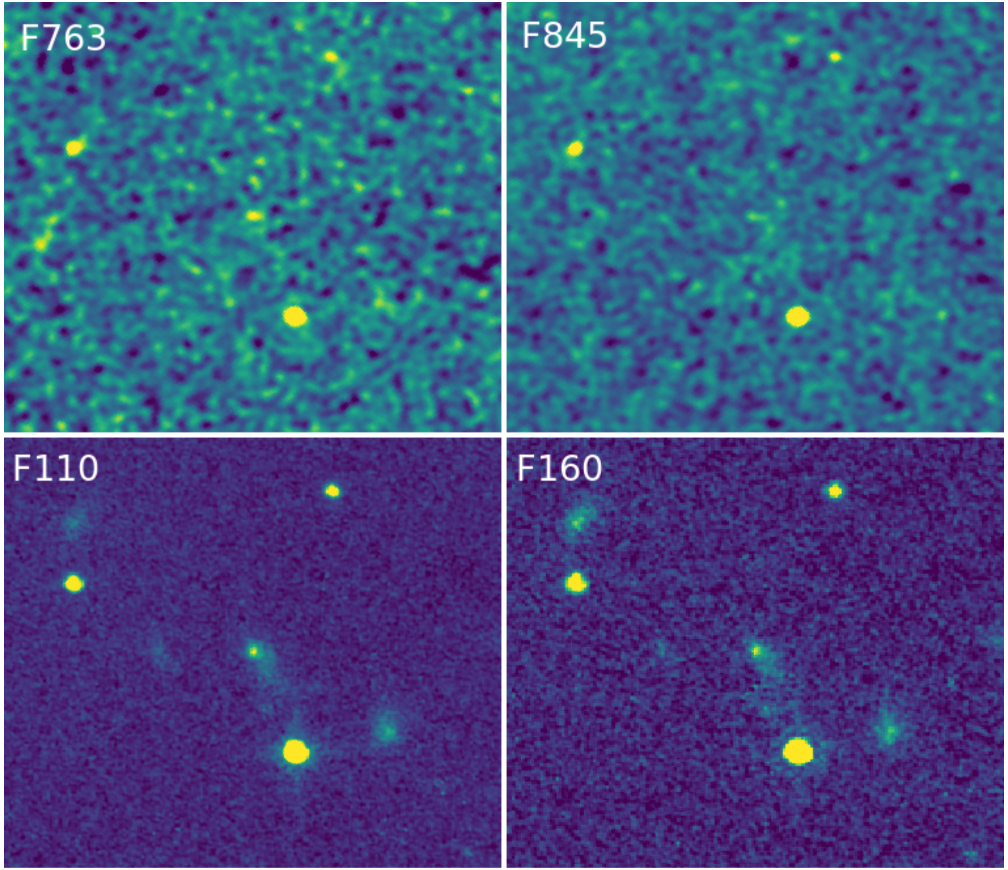
Host galaxy morphology and environment

- Dwarf galaxy emission is dominated by single bright knot – star formation?
- Coincident with FRB and persistent counterpart.

➔ Suggestive of connection to superluminous supernovae and long gamma ray bursts.

➔ Magnetar models.

Bassa et al. (2017) →



What produces these bursts?

$E_{burst} \approx 10^{38}$ erg $(\delta\Omega/4\pi)$ D^2_{Gpc} (A/0.1Jy-ms) $\Delta\nu_{GHz}$

Repeating source, precise localization.

➔ Can observe over a broad range of frequencies.
Simultaneous coverage at radio and, e.g.,
X-ray, gamma-ray, optical bands.

➔ No counterparts to the radio bursts (yet).
(But these observations are sensitivity-starved
for millisecond bursts.)

Polarization, Rotation Measure, and Dispersion Measure

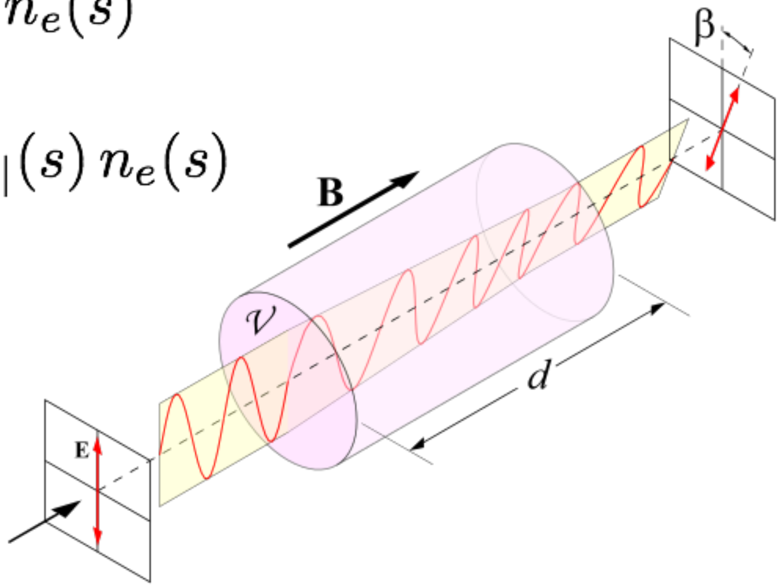
Interstellar / Intergalactic Propagation Effects

The Faraday effect causes a rotation of the plane of polarization of the propagating wave as a function of wavelength (λ).

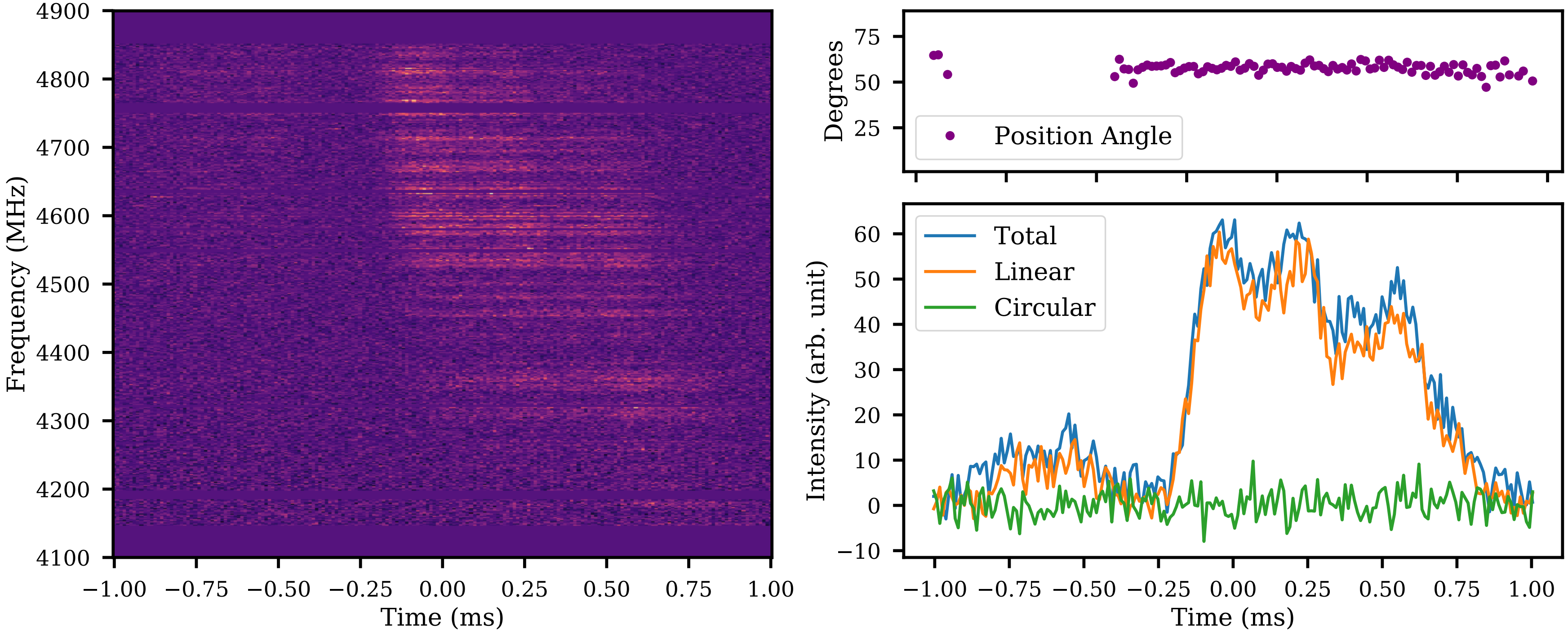
Pulse dispersion measure: $DM = \int_0^D ds\, n_e(s)$

Pulse rotation measure: $RM \propto \int_0^D ds\, B_{||}(s)\, n_e(s)$

Faraday Rotation: $\beta = \mathrm{RM}\, \lambda^2$



FRB 121102: Detection of polarization

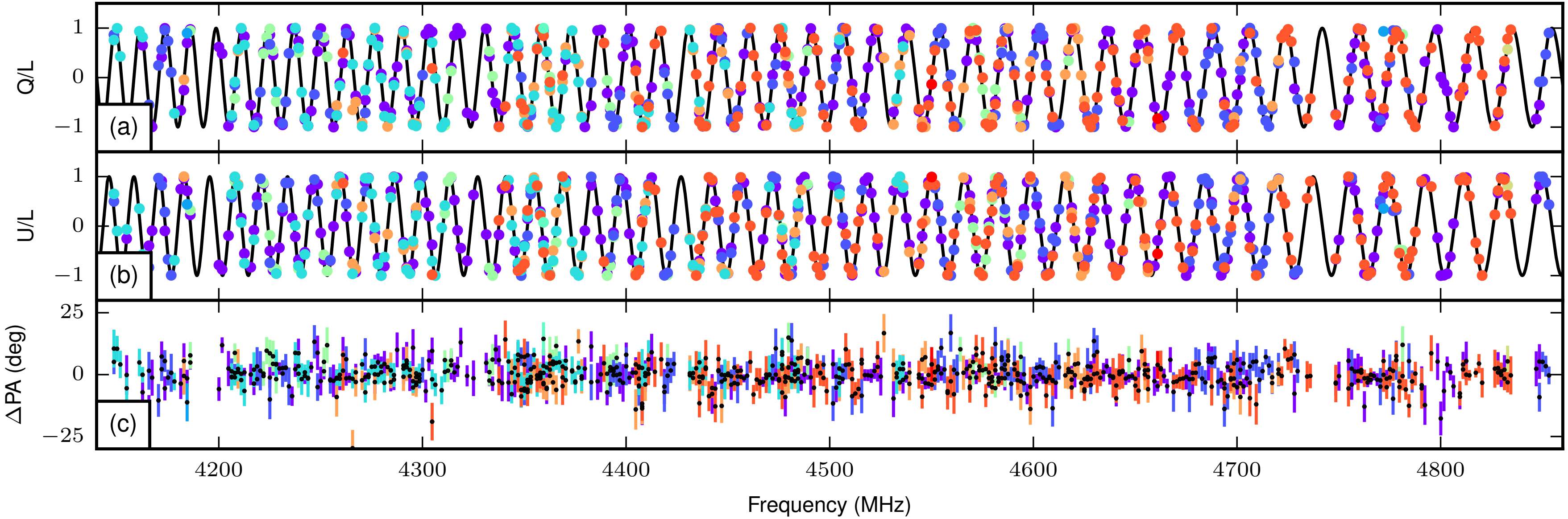


Michilli et al. 2018, Nature,

An extreme magneto-ionic environment associated with fast radio burst source FRB 121102

FRB 121102: Detection of polarization

Six bright bursts at Arecibo, Dec 2016: 100% linear polarization.



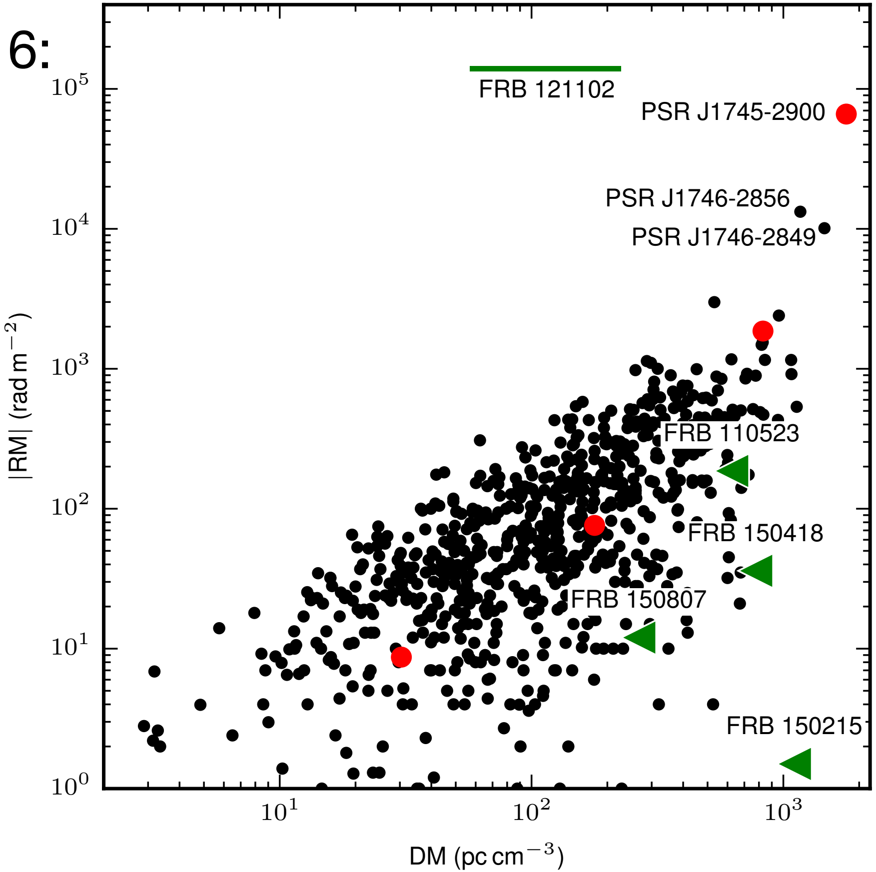
Michilli et al. 2018, Nature,
An extreme magneto-ionic environment associated with fast radio burst source FRB 121102

FRB 121102: Detection of polarization

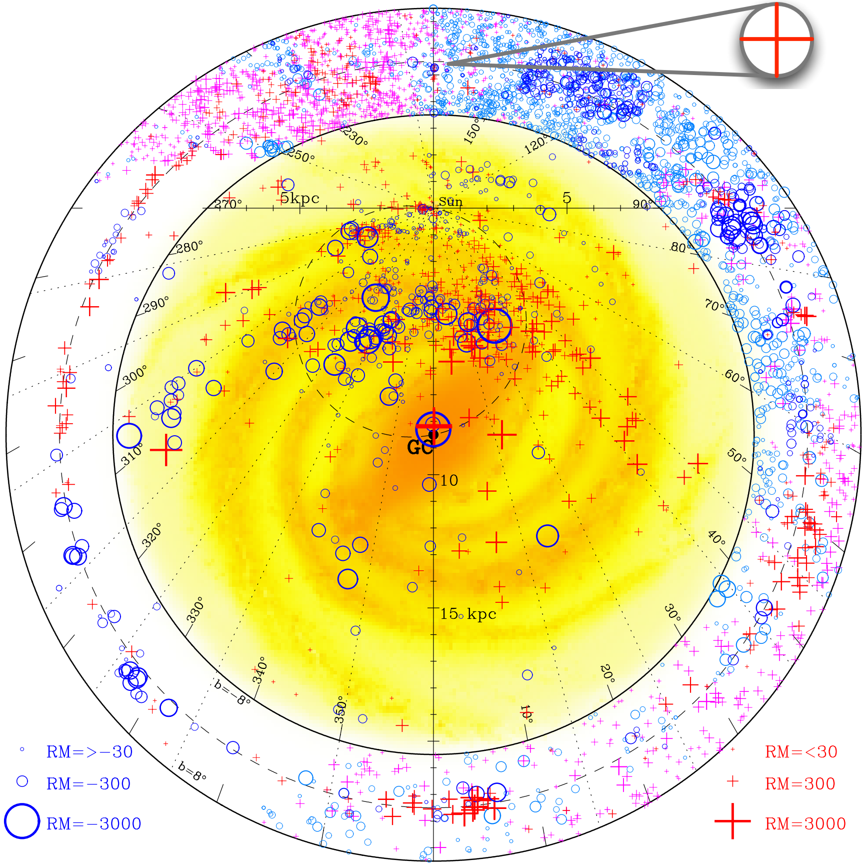
Six bright bursts at Arecibo, Dec 2016:

- 100% linear polarization.
- RM_{src}
  $= RM_{obs}(1+z)^2$
  $= 1.46 \times 10^5$ rad m^{-2}.

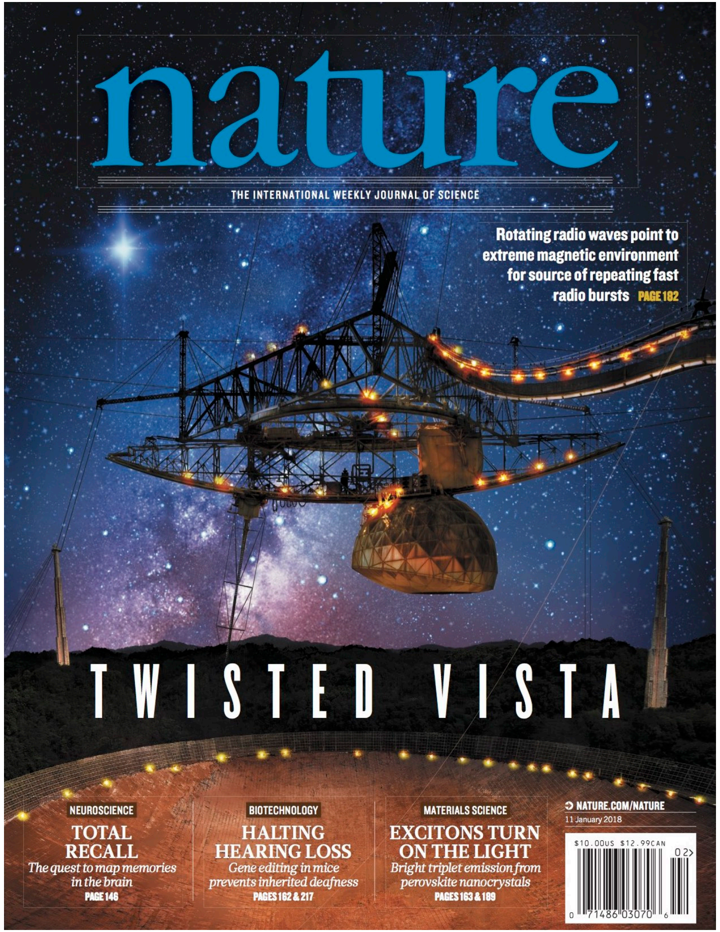
Michilli et al. 2018, Nature,
An extreme magneto-ionic environment



FRB 121102: An extreme magneto-ionic environment



RM map: Han et al. 2017



FRB 121102: An extreme magneto-ionic environment

- High RM measured at Arecibo.
- High RM confirmed at GBT, but with 10% change in 6 months.
- No corresponding change in DM, <0.5%.

➔ Arises in compact region, must be associated with FRB source. B > ~mG, compared to μG for our ISM.

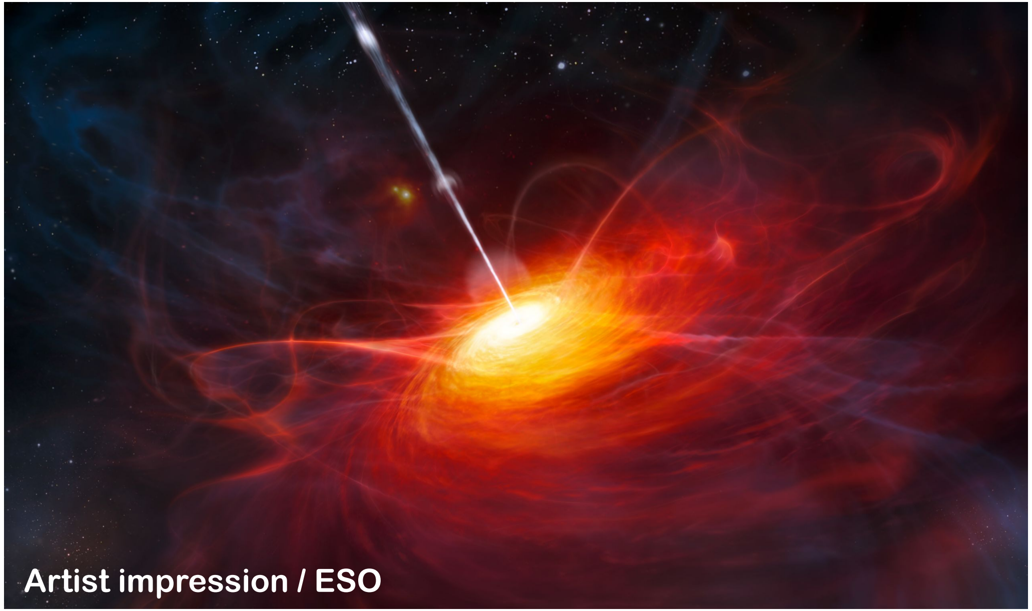
→ UC HII region? No.

→ Massive BH environment? Fits.

→ Extreme SNR/PWN? Maybe.

FRB 121102: An extreme magneto-ionic environment

→ AGN? Magnetar in a BH environment?
Persistent radio src, RM, ΔRM, etc.

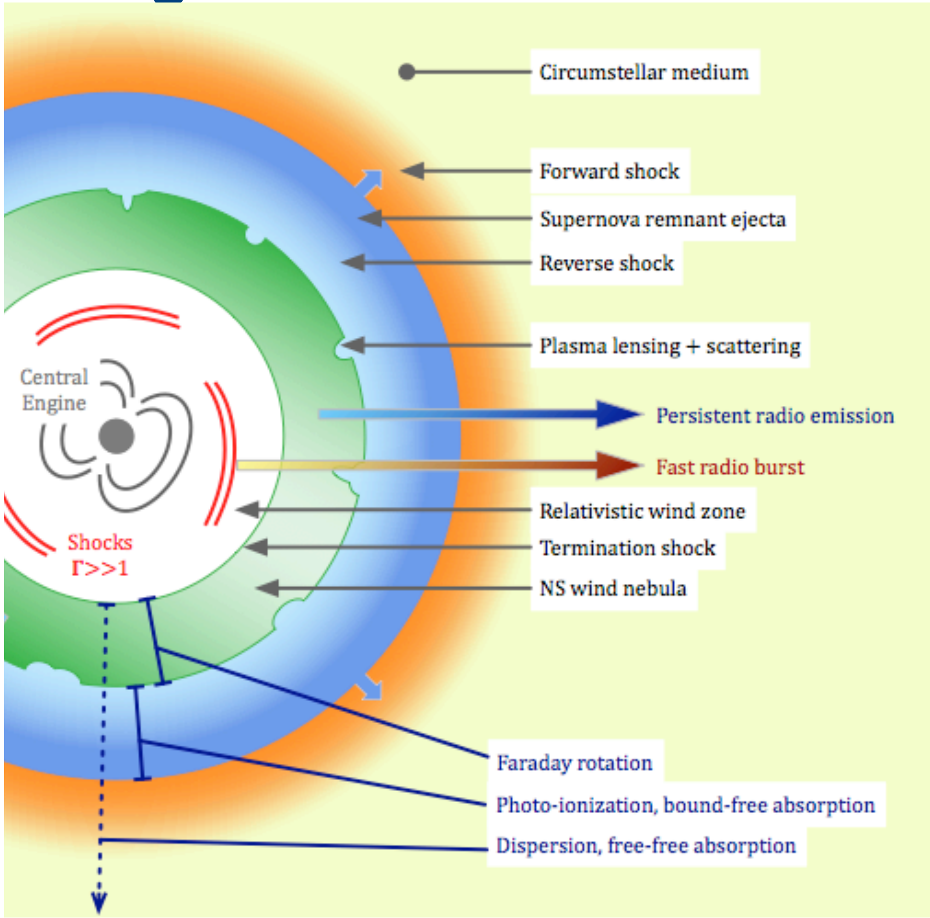


FRB 121102: An extreme magneto-ionic environment

→ AGN? Magnetar in a BH environment? Persistent radio src, RM, ΔRM, etc.

→ Magnetar in extreme SNR/PWN? Maybe.

(Margalit et al. 2018)



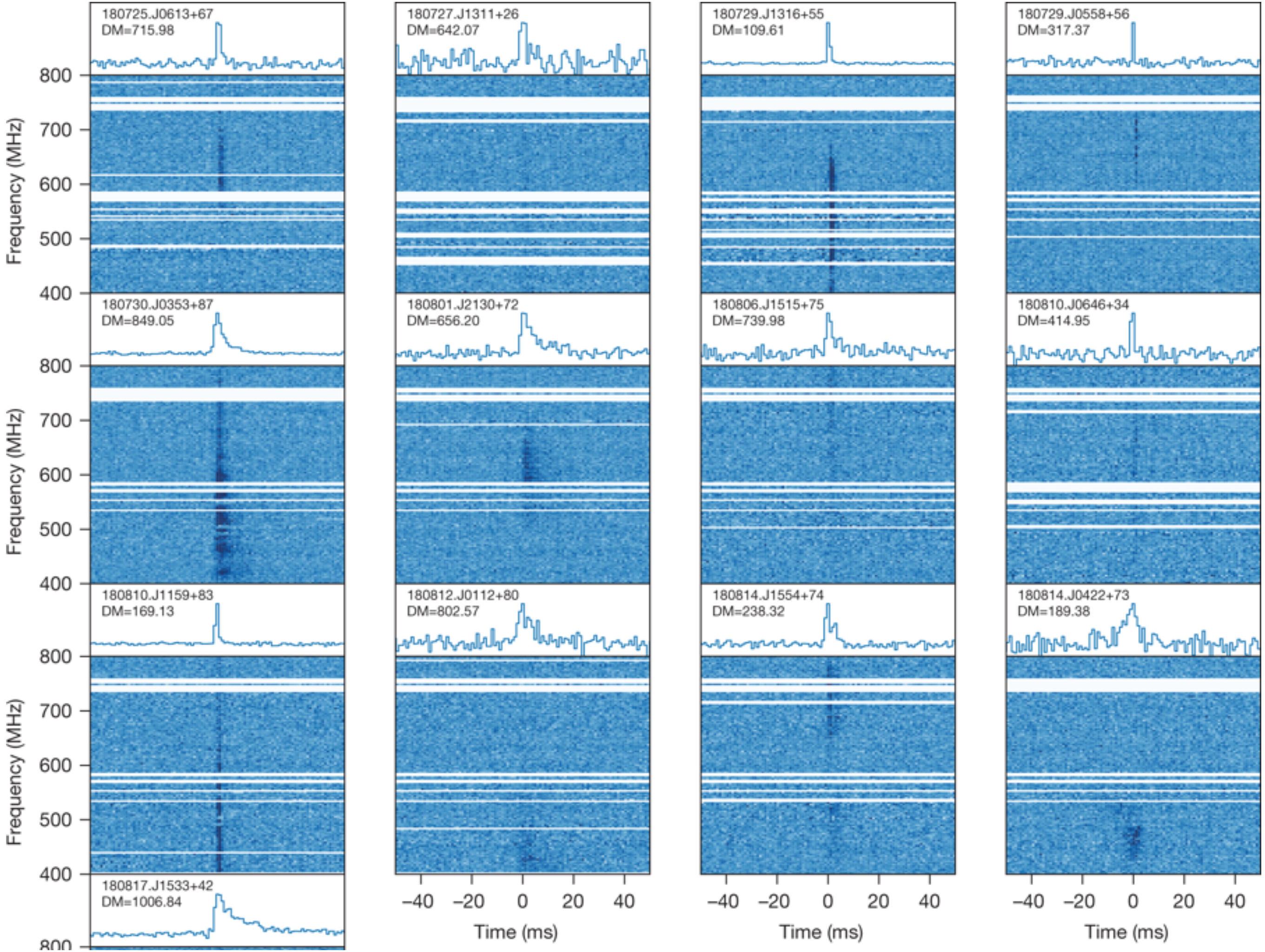
New frontiers in FRB observations

New discoveries from CHIME

→ 80m x 100m, operating at 400-800 MHz.

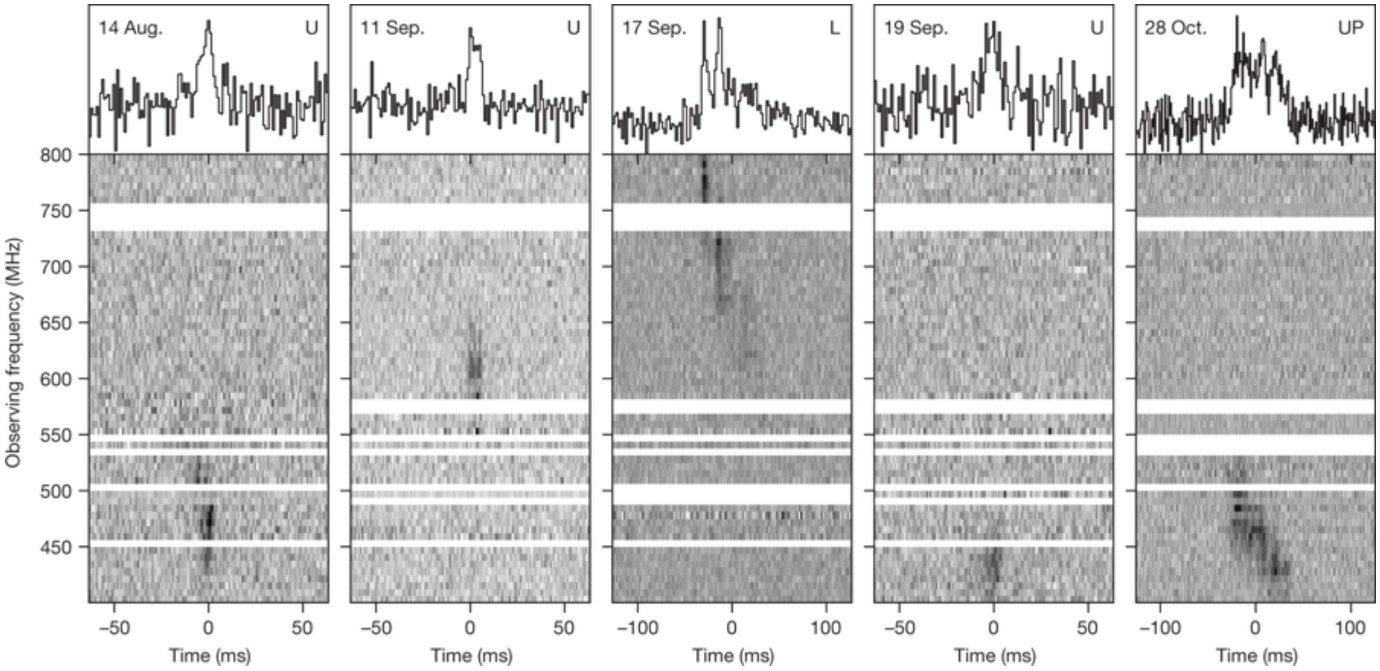
→ Many FRB detections even with pessimistic assumptions.

→ Baseband data can allow post-detection beam-forming.
0.3° x 0.2° beams; localization to ~10s of arcsec for bright bursts.



13 new FRBs in pre-commissioning observations.

(CHIME/FRB collaboration, Nature, 2019a)



One of 13
is a new
repeating FRB!

Similar drift
in frequency
for burst
components.

(CHIME/FRB collaboration, Nature, 2019b)

New discoveries from CHIME

CHIME has now discovered *hundreds* of FRBs.

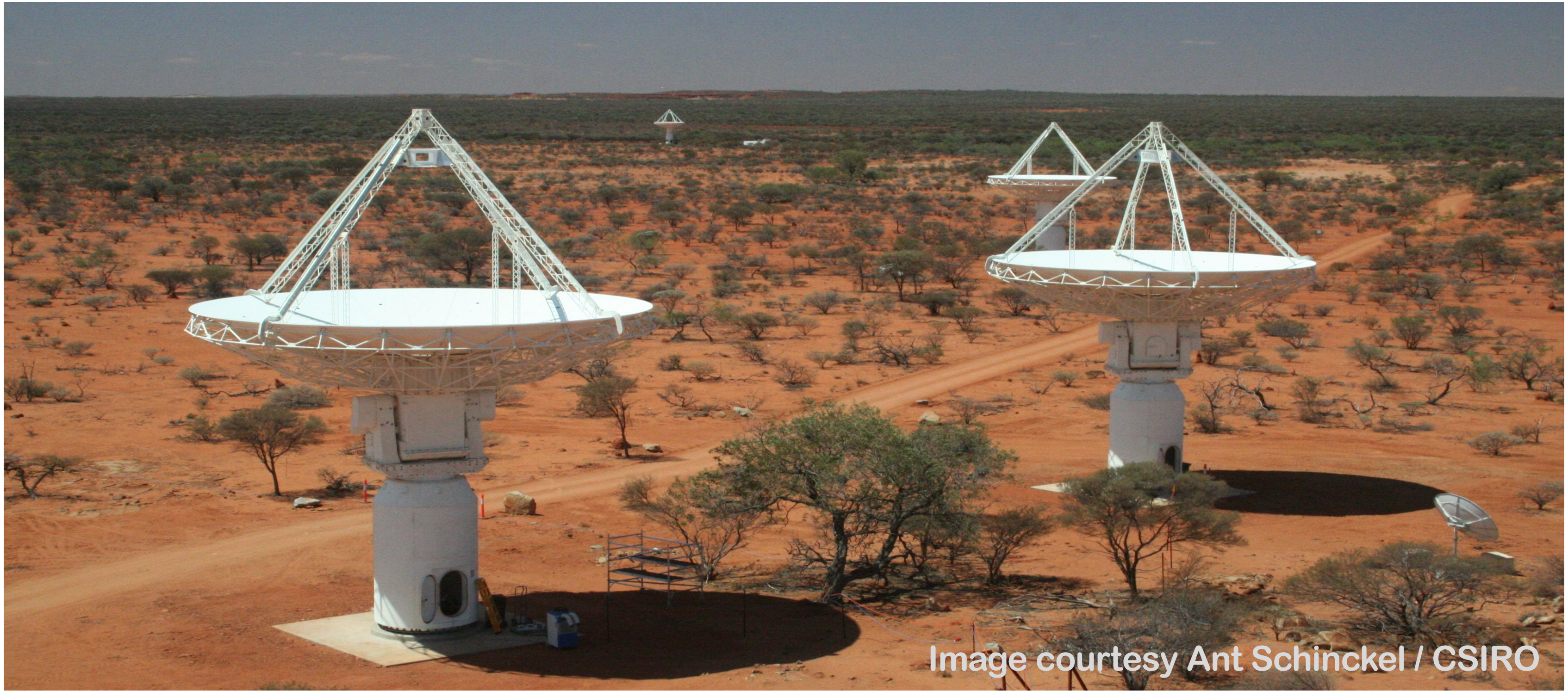
→ Many new repeating FRBs!

→ Single reported re-detection of FRB 121102.

(CHIME/FRB collaboration, 2019)

New discoveries from ASKAP

- → ASKAP has detected FRBs in Fly's-Eye mode.
- → Full array has now been commissioned for fast-dump interferometry.



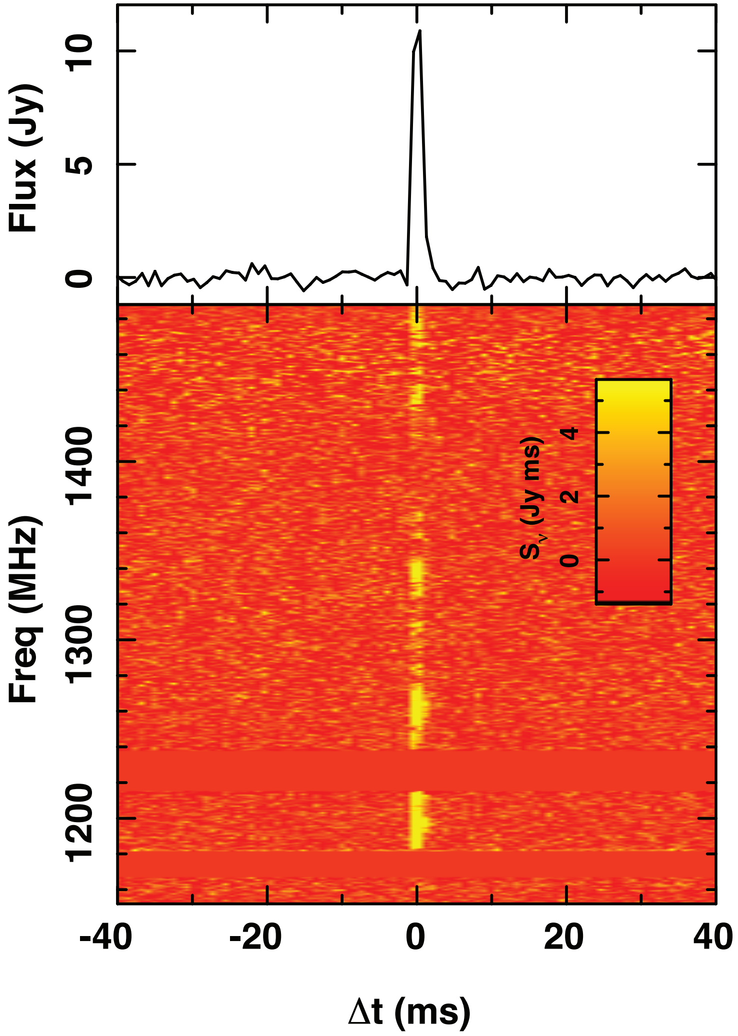
Localizing FRBs with ASKAP

→ Detect FRBs in incoherent sum.
e.g., FRB 180924:
DM = 361 pc cm^{-3} (MW+halo ~ 100).
RM = 14 rad m^{-2}, low.

→ Dump voltages, correlate.

→ Localize FRB on image plane.

Bannister et al. 2019, Science →



A host galaxy for a one-off FRB detection

Luminous host galaxy:

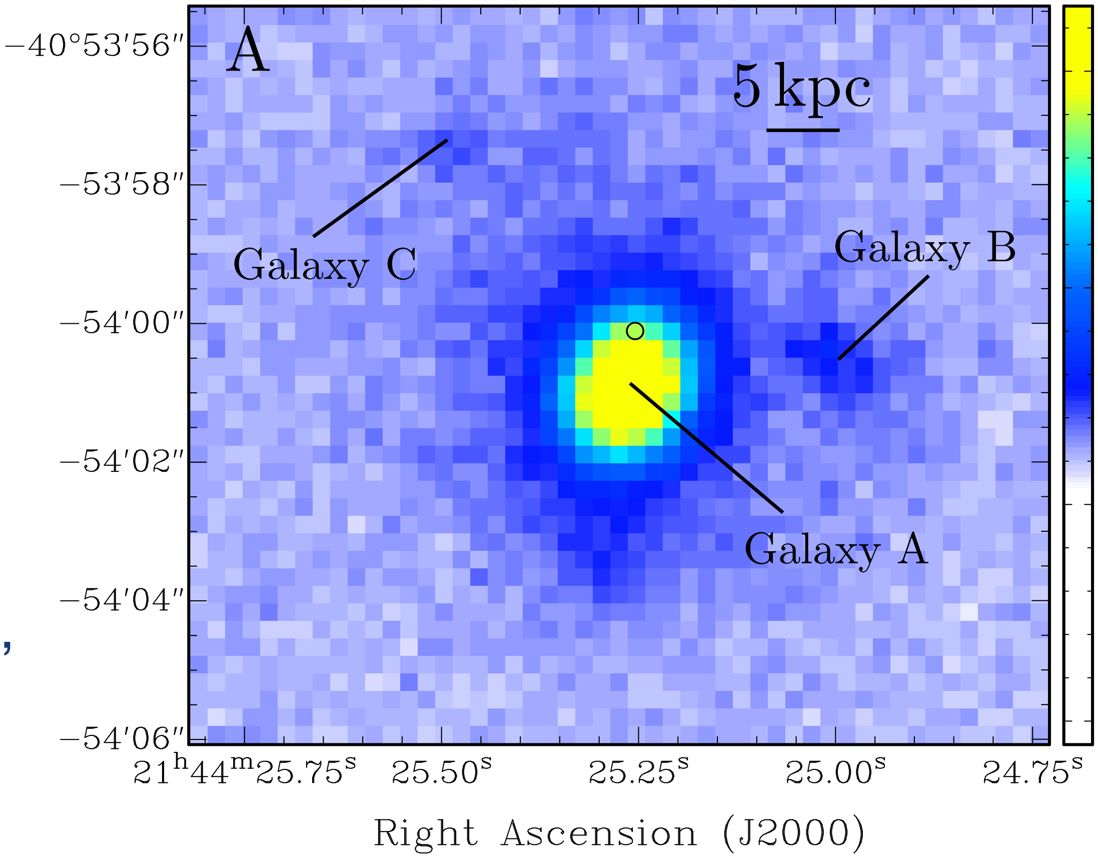
→ z=0.321 (1.7 Gpc),

→ Massive lenticular or early-type spiral.

→ Stellar mass ~ 2 x 10^{10} $M_\odot$

→ SFR < 2 $M_\odot$ yr^{-1}.

FRB 180924 offset by ~19 kpc, not in star forming region.



Bannister et al. 2019, Science

Localizing FRBs with ASKAP

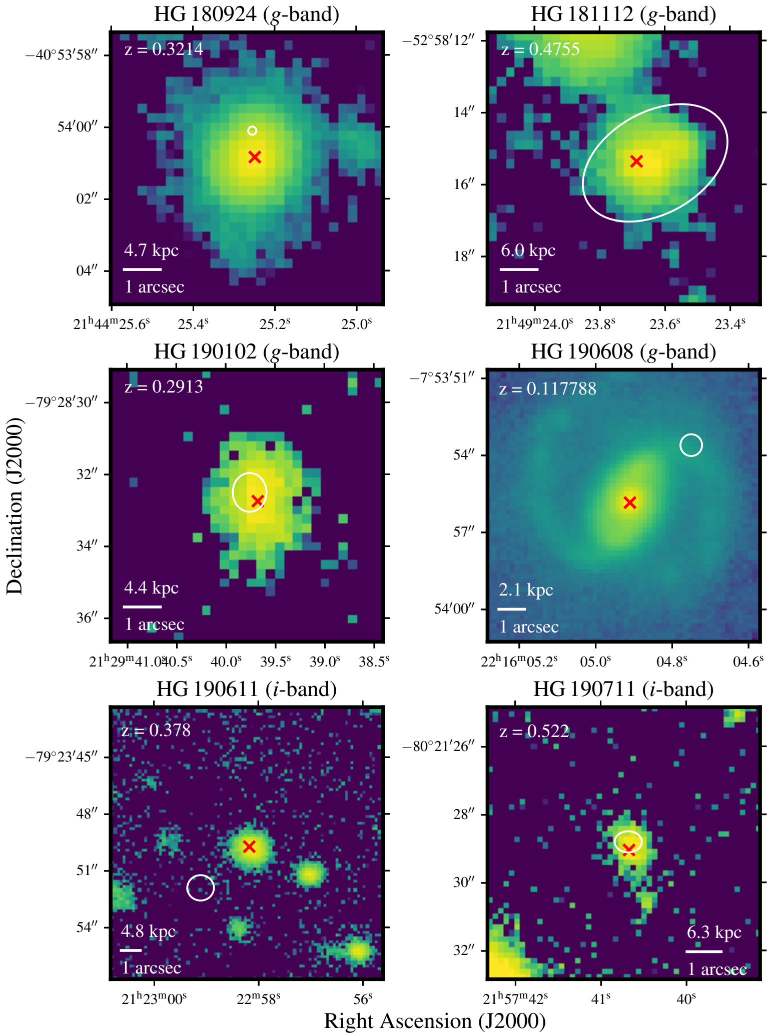
→ Detect FRBs in incoherent sum.

→ Dump voltages, correlate.

→ Localize FRB on image plane.

= This process has now been successful for a bunch of FRBs!

Macquart et al. 2020, Nature→

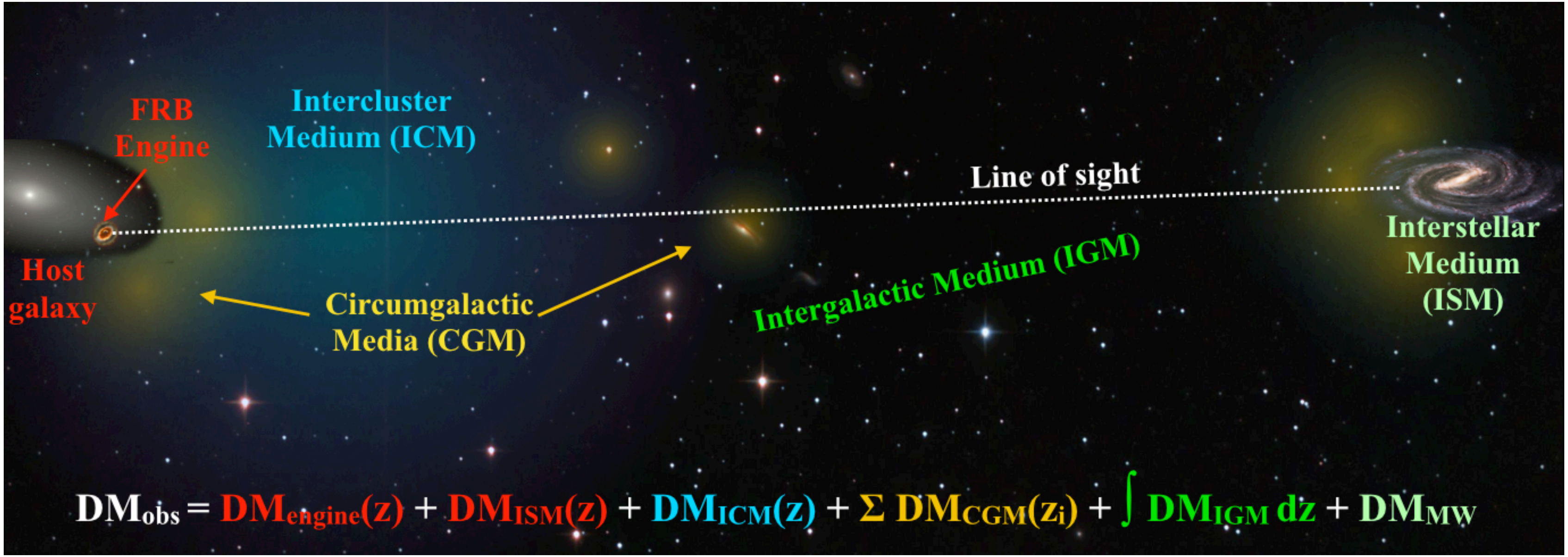


Using FRBs as probes

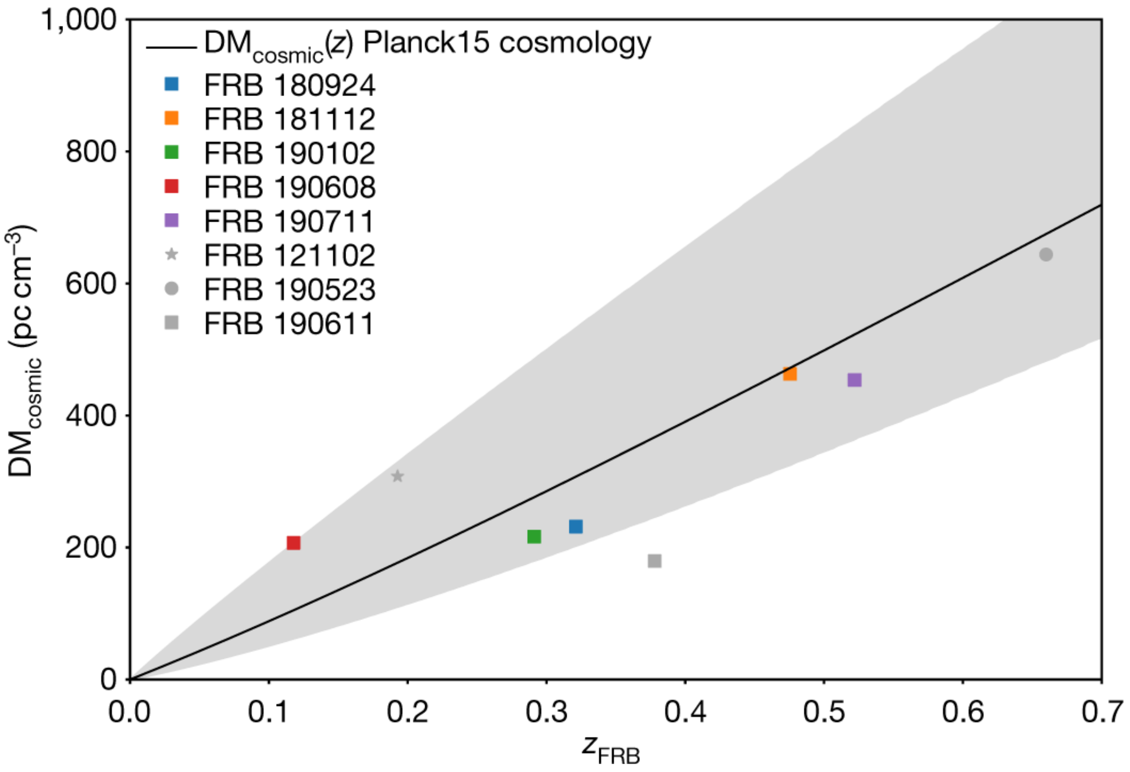
Astro 2020 WP:
arXiv: 1903.06535

Astro 2020 white paper:
"Fast Radio Burst Tomography of the Unseen Universe"

Ravi et al. (including Battaglia, Chatterjee, Cordes).



Probing the Intergalactic Medium



FRB dispersion measure after subtracting Milky Way and (estimated, fixed) host galaxy contributions, versus host redshift.

➔ Direct estimate of the Cosmic baryon density, consistent w/CMB, BBN:

$$\Omega_b = 0.05 \pm 0.02\ h_{70}^{-1}$$

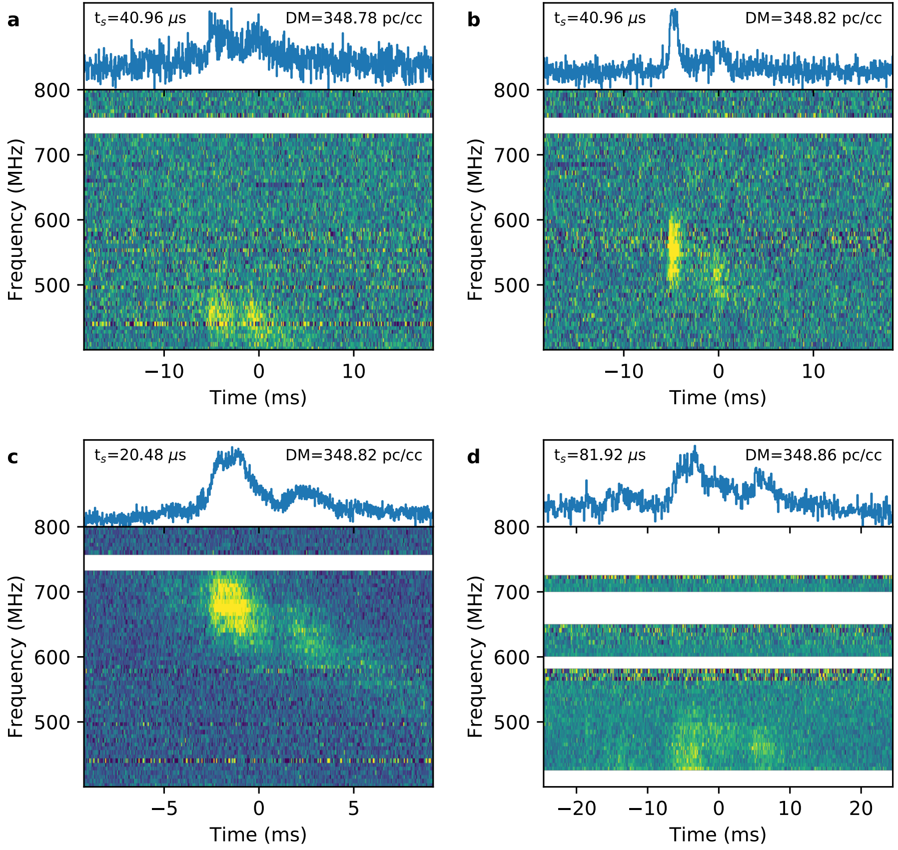
Macquart et al. 2020, Nature

Clues to the central engine of FRBs

Periodic emission windows for FRBs?

CHIME:

Repeating FRB 180916 (“R3”)



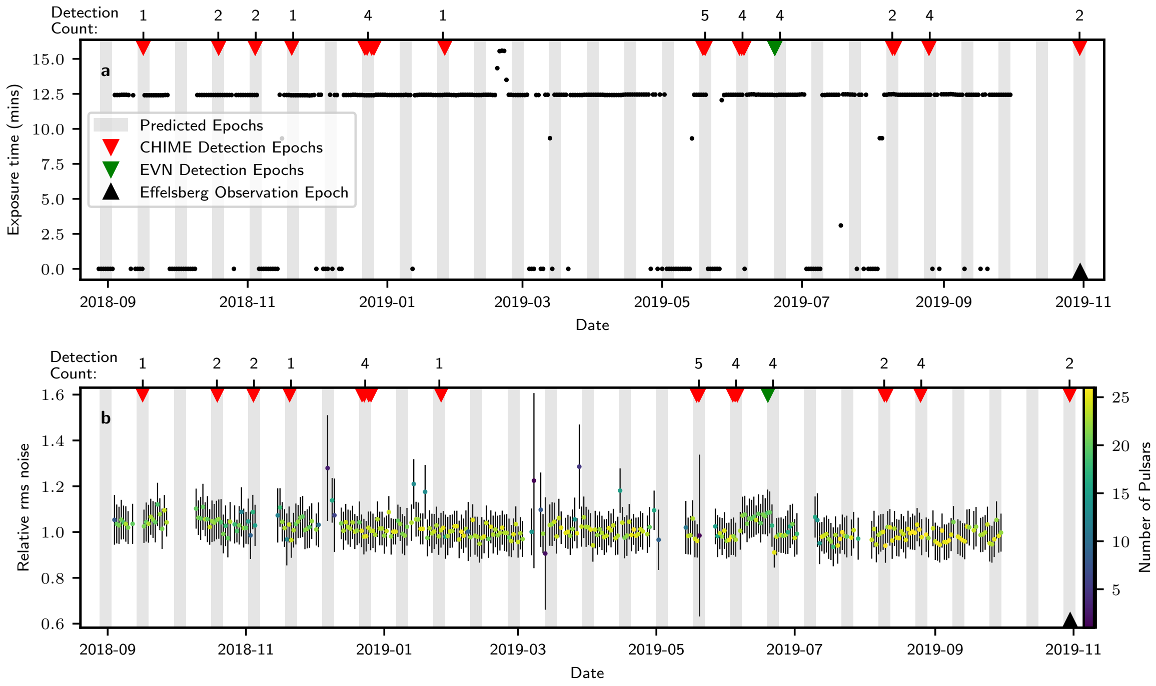
CHIME collab 2020, Nature

Periodic emission windows for FRBs?

CHIME:

R3 is detected only during periodic windows, ~5 days every 16.35 days.

→ Suggests an orbit?
→ Or precession?
Associated with the central engine.



CHIME collab 2020, Nature

A Galactic FRB?

Galactic magnetar SGR 1935+21:

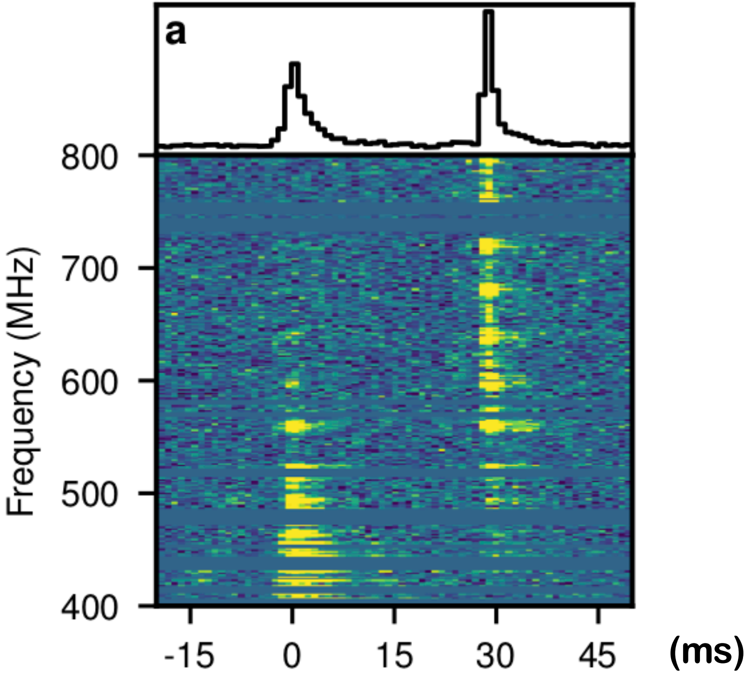
Emitted an extremely bright radio burst on 28 April 2020

→ 700 kJy-ms at CHIME

→ 1.5 MJy-ms at STARE-2

Such a burst from a nearby galaxy would be considered an extragalactic FRB.

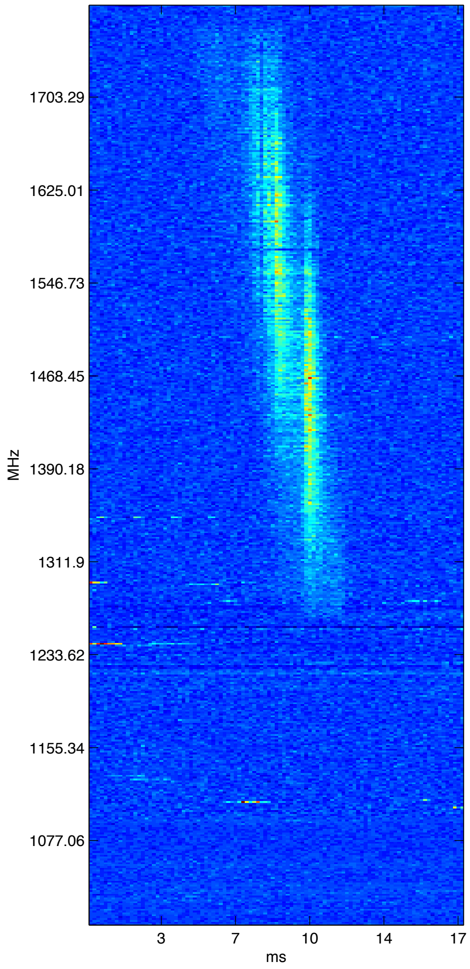
➔ At least *some* FRBs are produced by magnetar bursts.



CHIME collab 2020, Nature and Bochenek et al. 2020, Nature (submitted)

FRBs: Some things we know

- Fast radio bursts are extragalactic.
- At least some repeat:
  not an explosive, cataclysmic mechanism.
- A variety of host galaxy environments so far.



FRBs: Some things we know

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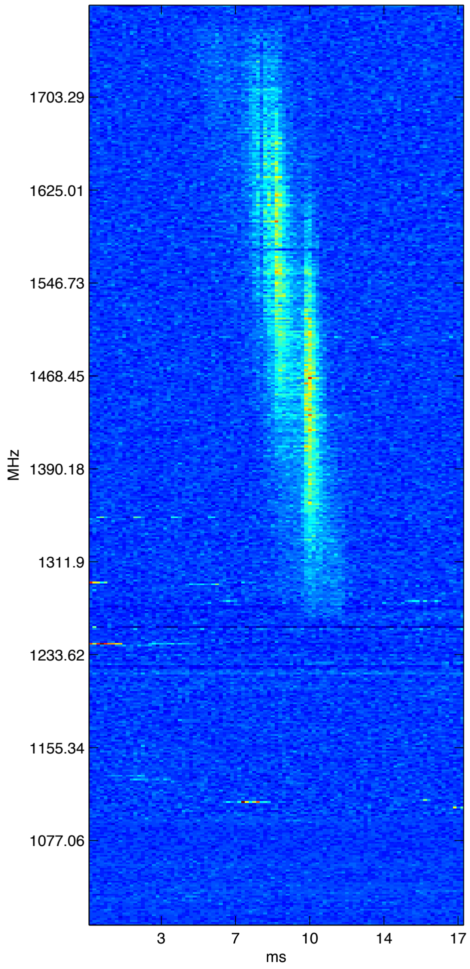
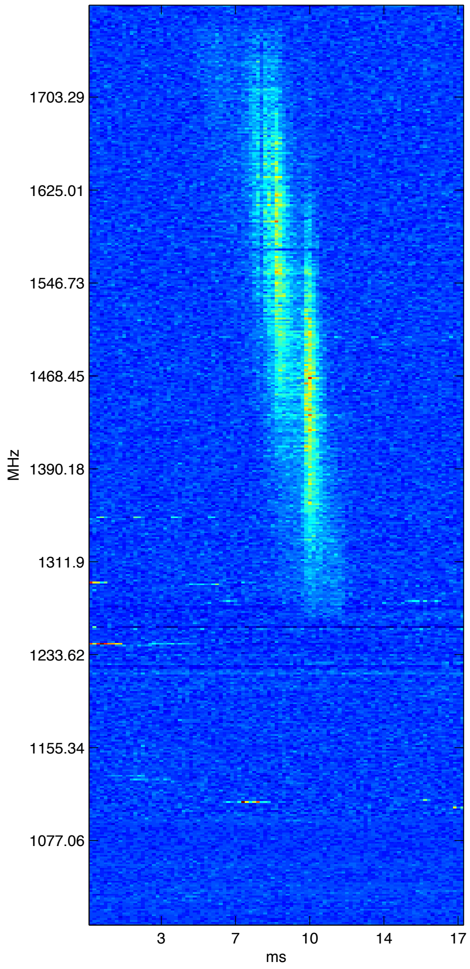
FRB 121102 and other repeating FRBs:

- No simultaneous X-ray, gamma ray, optical emission.
- Emission is not continuous over a broad band:
  Plasma lensing may play a significant role.
- Extreme magneto-ionic environment.
- Periodic emission windows?

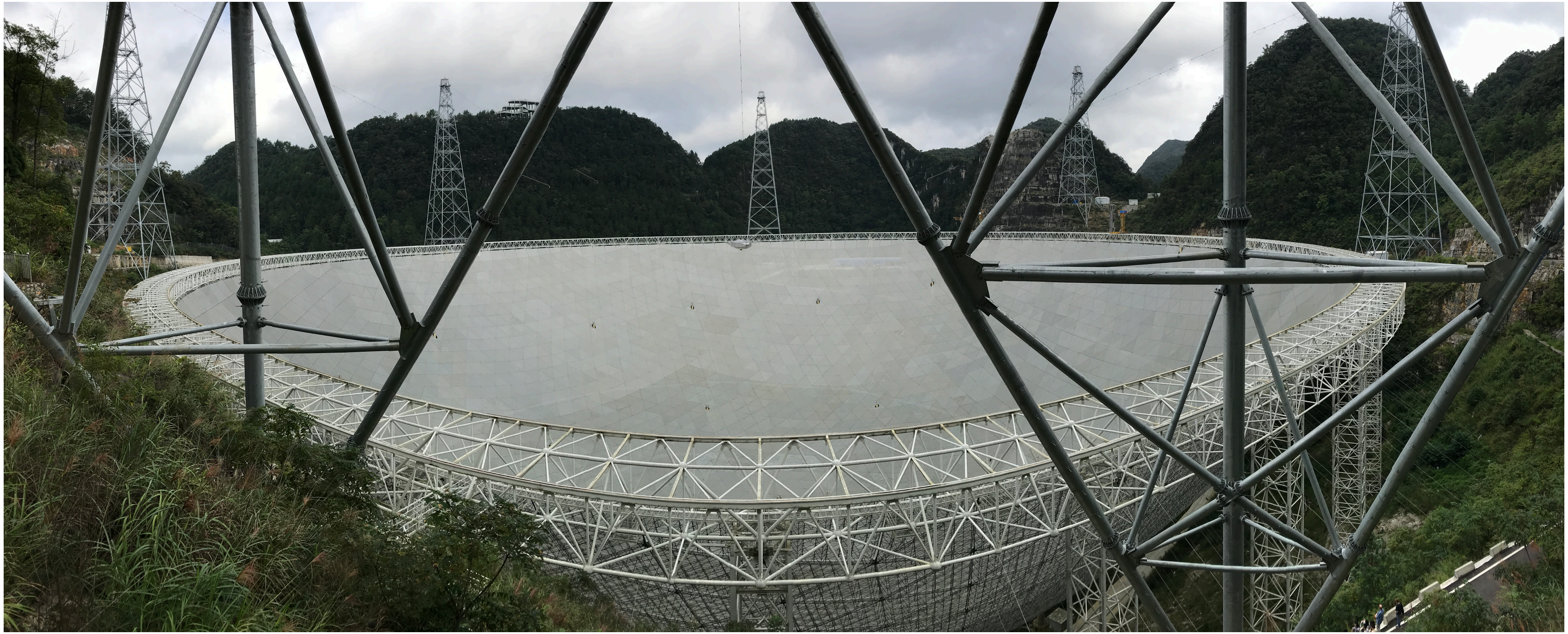


FRBs: What's next

- Do all FRBs repeat?
- Or are multiple source classes really required?
- What is (are) the central engine(s)?



New discoveries at a rapid clip!



Five Hundred Meter Spherical Aperture Telescope (FAST)

FRBs: What's next

- Do all FRBs repeat?
- Or are multiple source classes really required?
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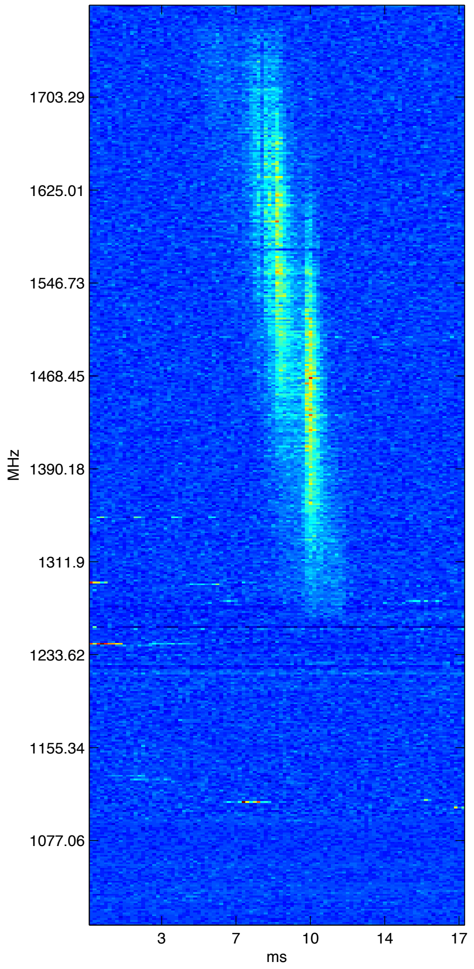
Using FRBs as probes:

- Dispersion: IGM electron density.
  Census of baryons in the local universe.
- Polarization: RM and magnetic fields in the IGM.
- Scattering: IGM turbulence.

→ Best use requires detection *and localization* of FRBs.



Fast Radio Bursts: An Extragalactic Enigma

James M. Cordes[1] and Shami Chatterjee[1]

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Keywords

transients, radio surveys, fast radio bursts, neutron stars, extragalactic sources

Abstract

We summarize our understanding of millisecond radio events from an extragalactic population of sources. FRBs occur at an extraordinary

FRB Newsletter Issue 01 -- September 2019

Total FRB count: 97
Repeaters: 10

From the editors:

Welcome to the FRB community newsletter. Our goal is to select and summarize recent results relevant to FRB researchers, both observational and theoretical, as well as to provide a curated selection of other relevant scientific news items, conferences, and more. We will aim to be:

- timely and topical,
- brief,
- and archival,

such that the newsletter provides a monthly snapshot summary of the state of the field for the duration of this project.

We welcome your feedback, opinions, suggestions for items to post, news tips, etc.
- Emily Petroff and Shami Chatterjee, editors.

General news

- *Editors' note.* This issue includes items from the first nine months of 2019. We anticipate future issues will be much shorter.
- *The FRBCAT VOEvent Broker is live.* Interested parties can now subscribe to the FRBCAT Comet broker to receive VOEvents. Those interested in sending VOEvents via the FRBCAT broker or receiving broadcasted events should follow the instructions at the FRB_VOEvent github page.

Papers of interest

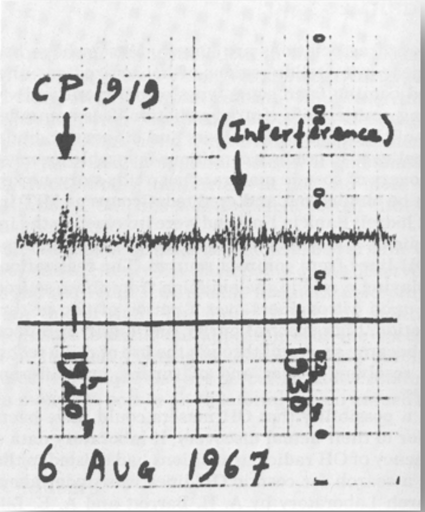
Cordes & Chatterjee, Annual Review, 2019.

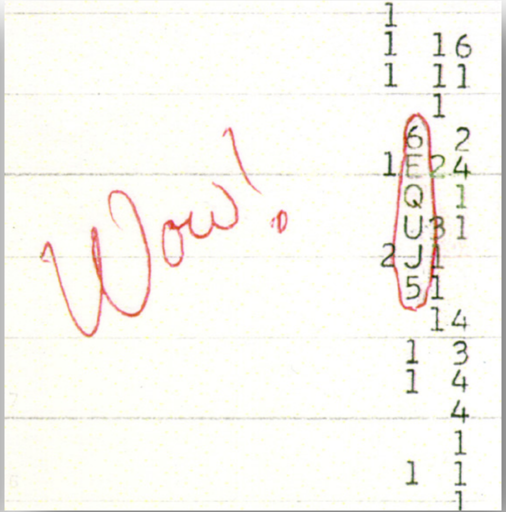
FRB Community Newsletter, eds Petroff & Chatterjee.

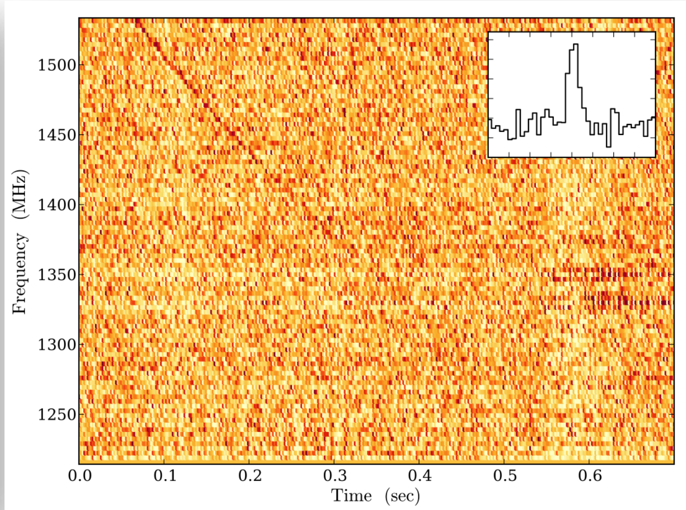
Realizing the Potential of Fast Radio Transients

Key requirements are instrumental flexibility
and breadth of coverage of phase space.

→ Very likely that the most important future discoveries will be surprises.







Realizing the Potential of Fast Radio Transients

Time domain science of all stripes: consistent requirements.

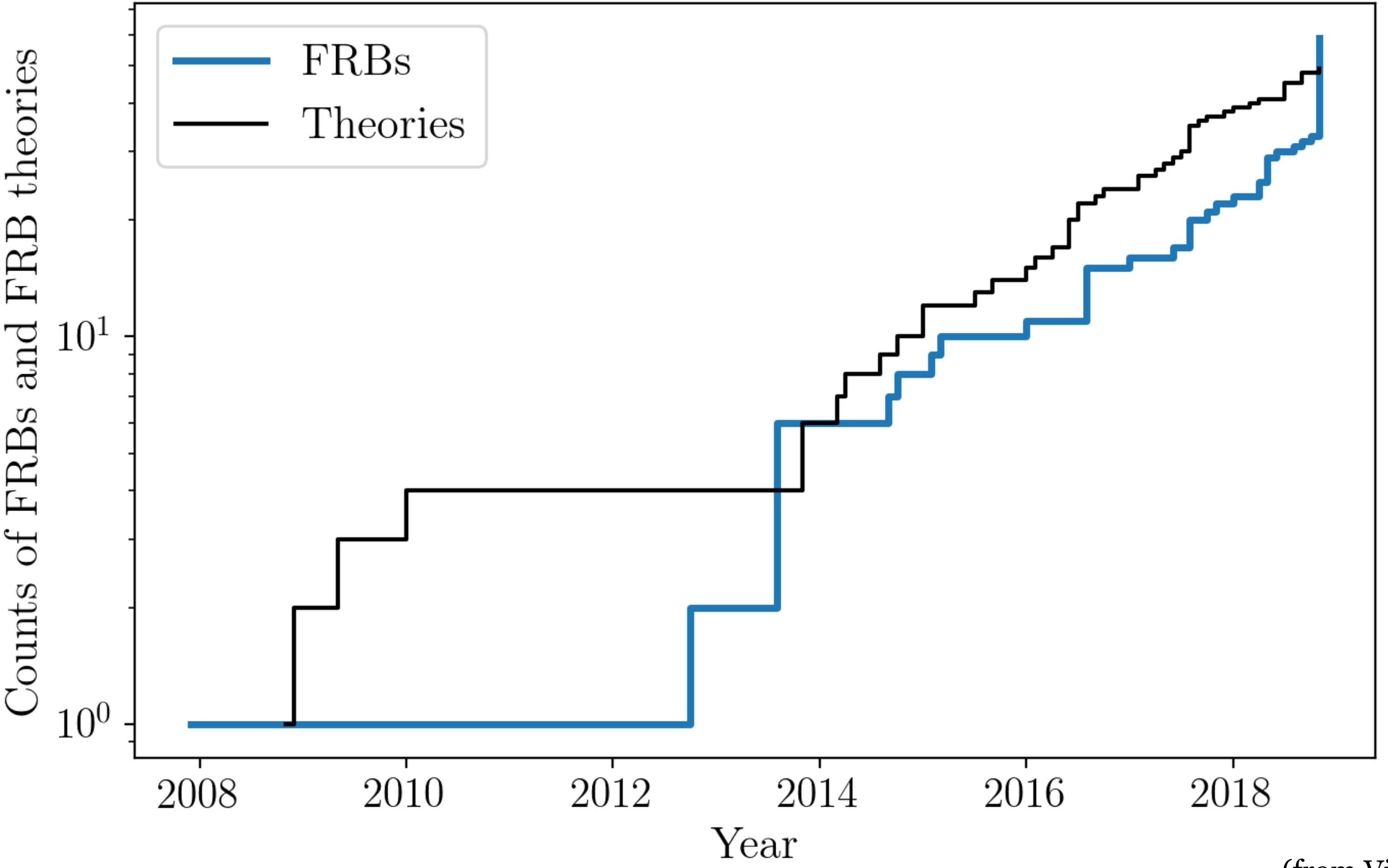
→ Large fields of view and high sensitivity. (Not just survey speed.)

→ High resolution in time and frequency. ➔ High data rates.

→ Broad range of timescales to cover. ➔ Large data volumes.

→ High angular resolution. Unique counterparts require ~1” localization.

→ Massive storage, high throughput computation.
(But: embarrassingly parallel problems.)



(from Vikram Ravi)