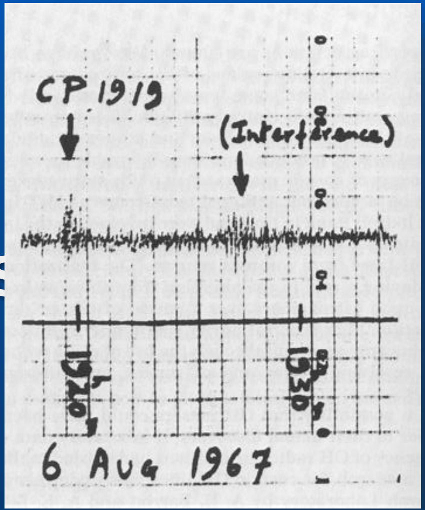
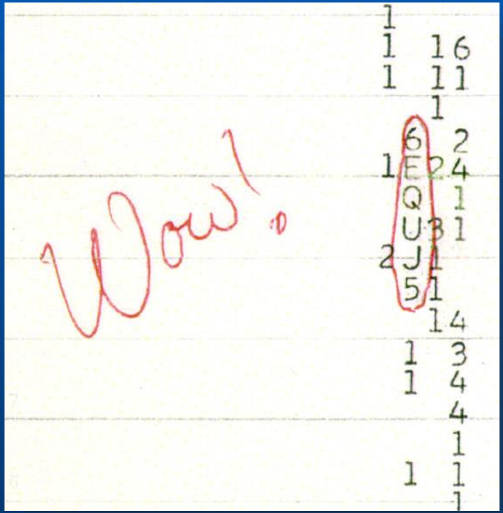
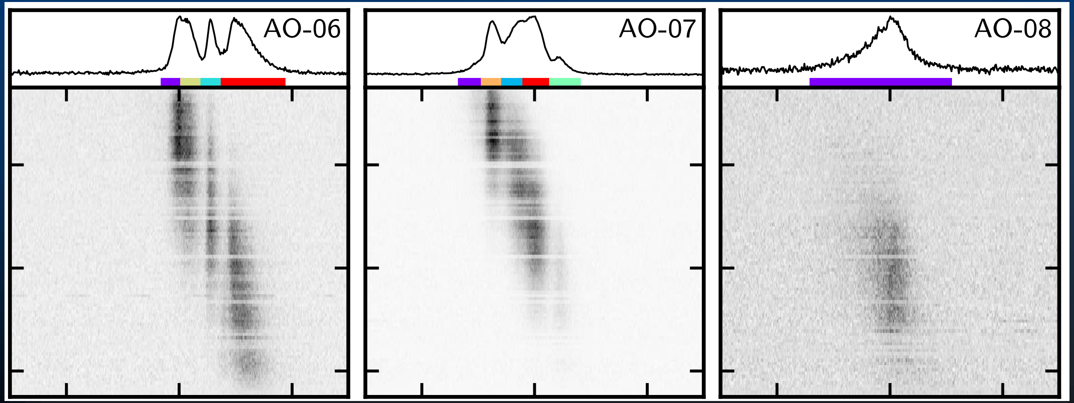
Fast Radio Bursts, Known Unknowns, Unknown Unknowns







Shami Chatterjee

Cornell University

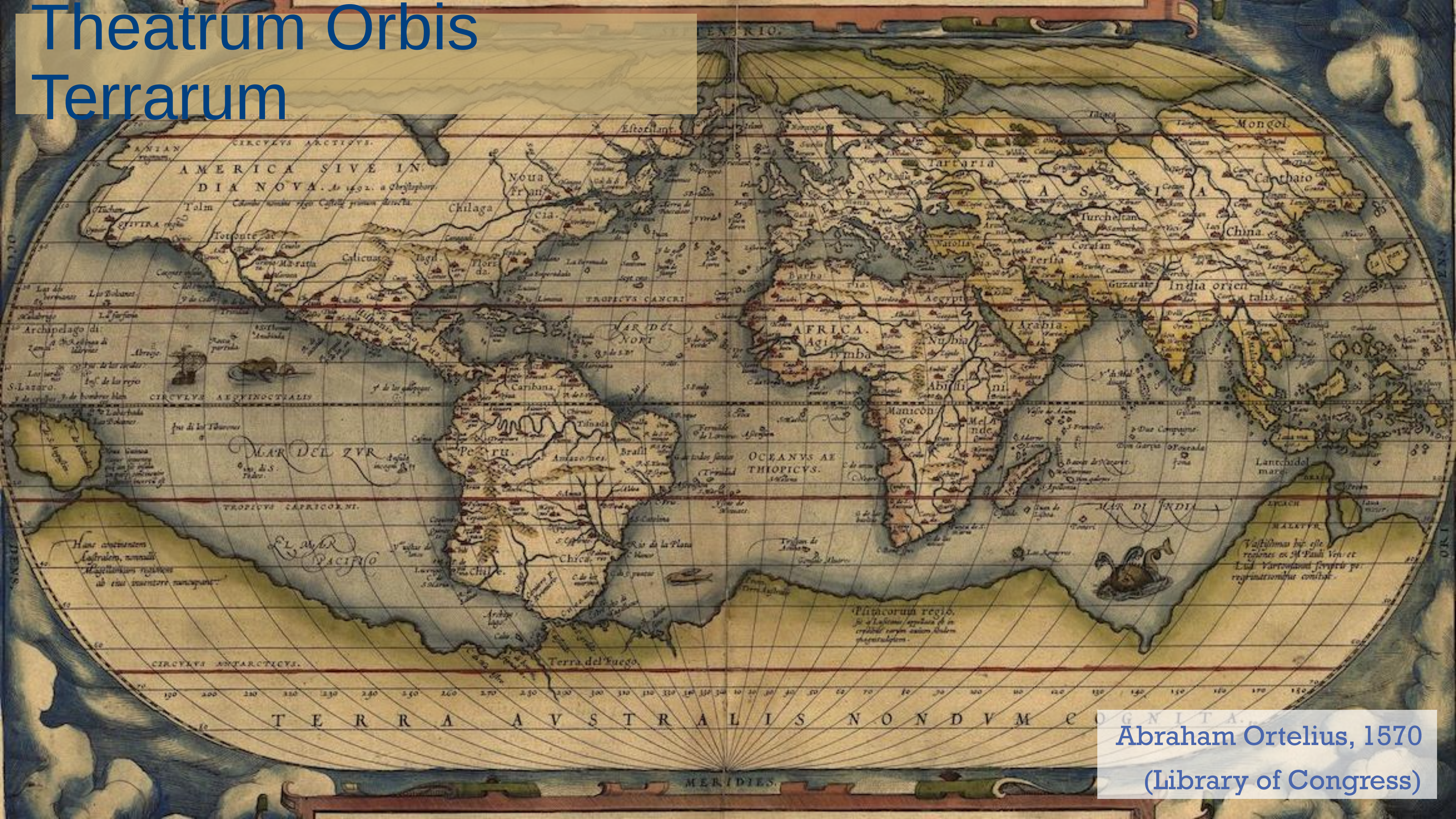
NASA TDAMM Workshop
August 2022

The accidental poetry of Donald Rumsfeld

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

– Sec. Def. D. H. Rumsfeld
12 Feb 2002, Department of Defense news briefing

Theatrum Orbis Terrarum



Abraham Ortelius, 1570

(Library of Congress)

Theatrum Orbis Terrarum

Here be dragons?

If monsters exist, they must lurk in the unexplored regions of phase space.

Abraham Ortelius, 1570

(Library of Congress)

The phase space for (radio) transients

Rayleigh-Jeans approximation:
Source with brightness temperature T_B

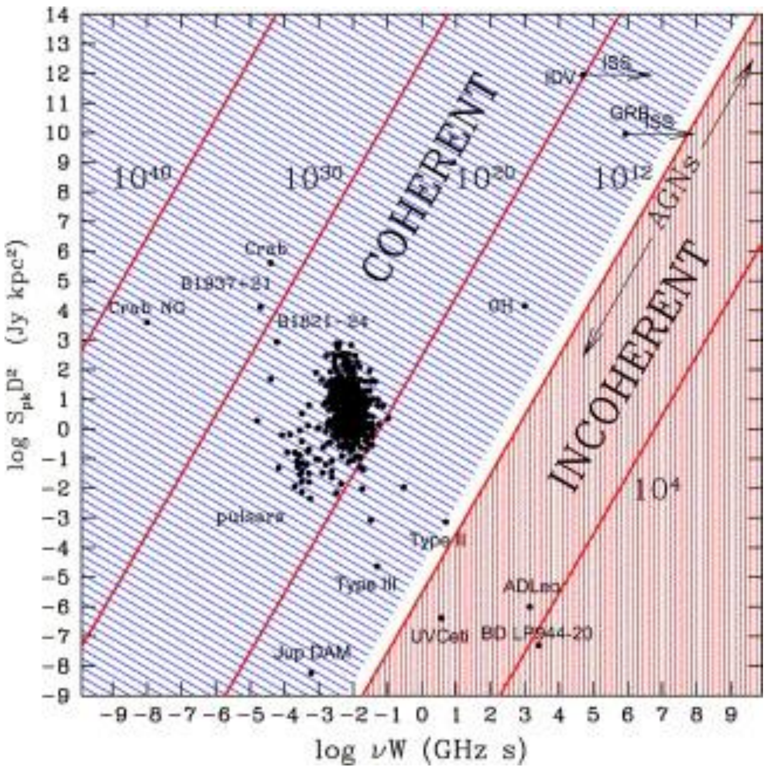
→ Intrinsic luminosity SD^2
→ Observed at frequency v
→ Intrinsic variations on timescale W:

$$W^2 = \frac{1}{2\pi k_B} \frac{SD^2}{T_B} \frac{1}{\nu^2}$$

i.e.,

$$W^2 \nu^2 \propto S_{pk} D^2$$

→ Related through the brightness temp.



Cordes, Lazio, McLaughlin (2004)
The Dynamic Radio Sky

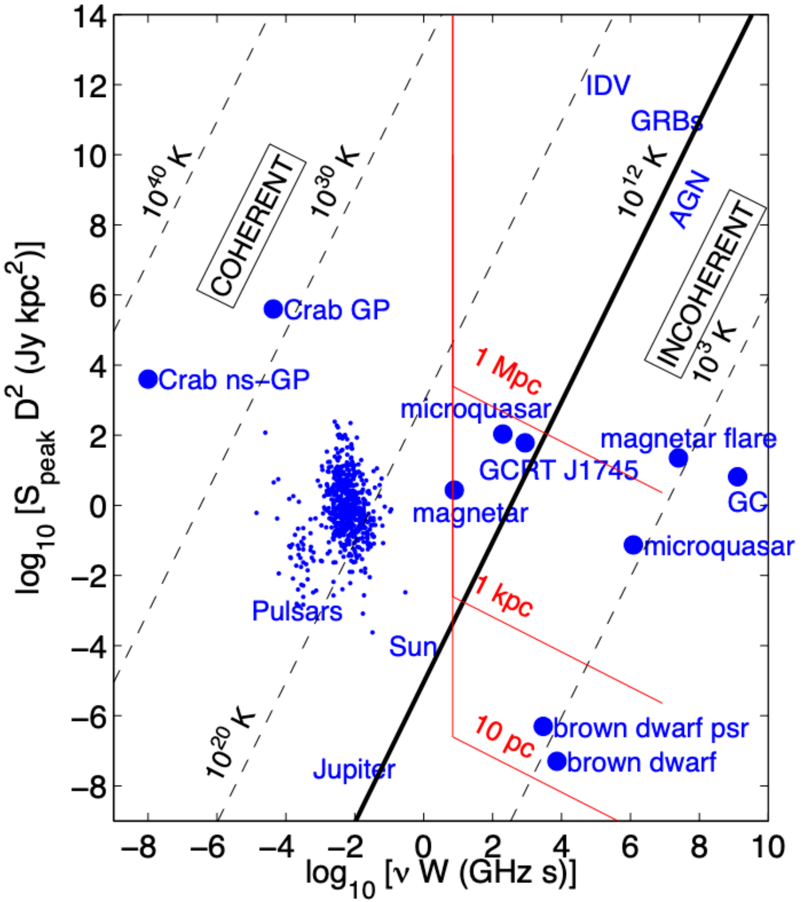
The phase space for (radio) transients

A guide for discovery:

Nature may have ways to fill empty parts.

Advances in technology and improvements in our observational capabilities help fill in the map.

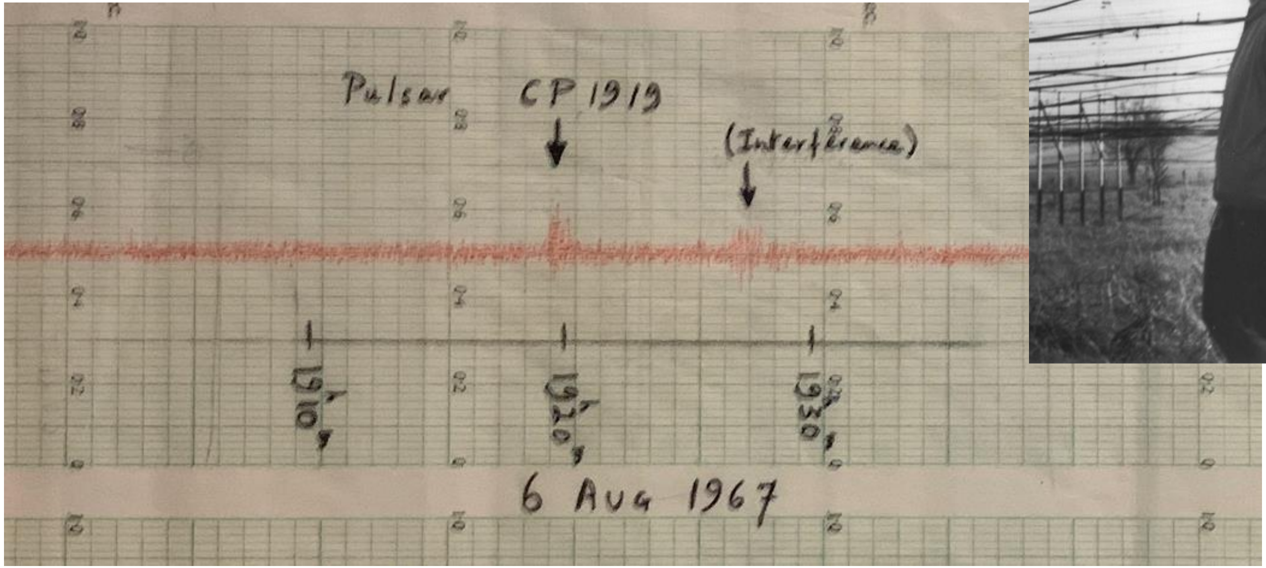
- → Sensitivity
- → Time resolution
- → Spectral coverage, sky coverage
- → Cadence and span of observations
- → And more.



Little Green Men

Prototypical example: the discovery of pulsars with higher time resolution + sensitivity.

Hewish, Bell et al. (1968)



The pulsar zoo

The $P - \dot{P}$ plane is still being filled in with new classes of objects:

→ Young objects in SNRs.

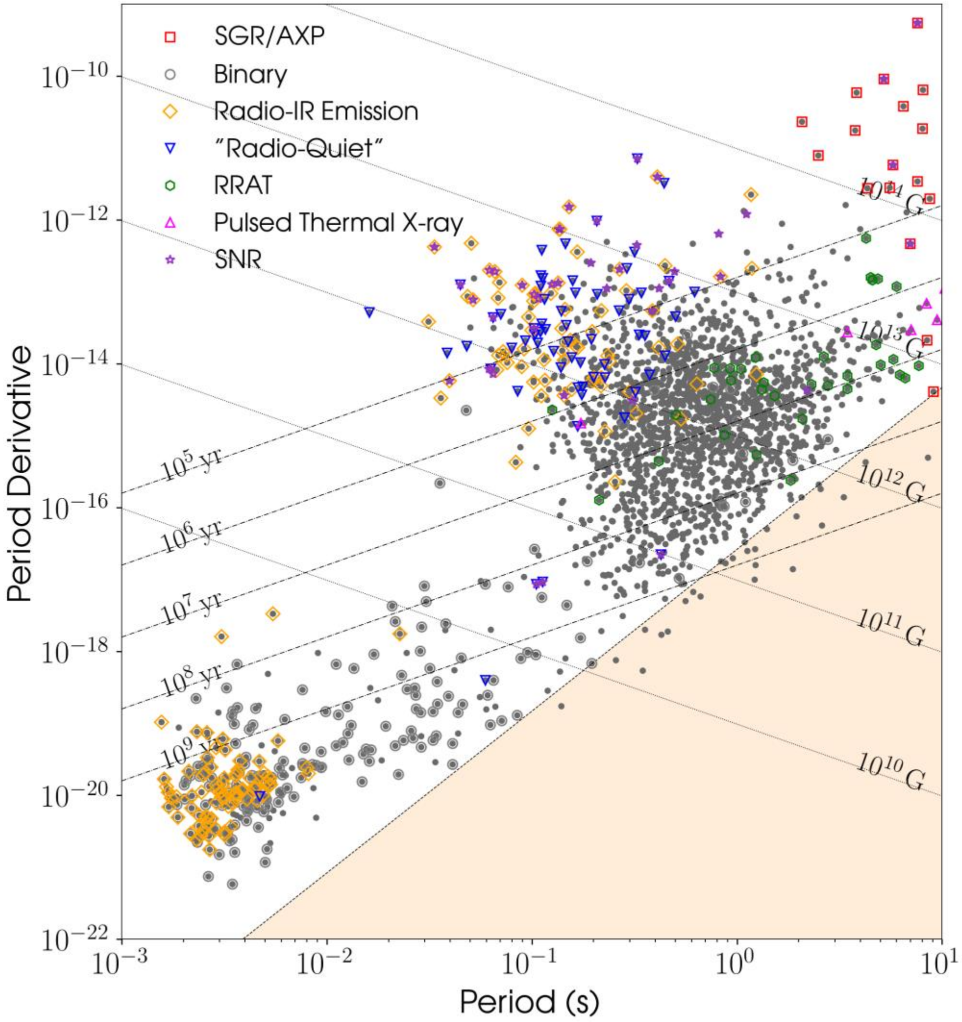
→ Millisecond (recycled) pulsars.

→ Rotating Radio Transients.

→ Magnetars (SGRs, AXPs).

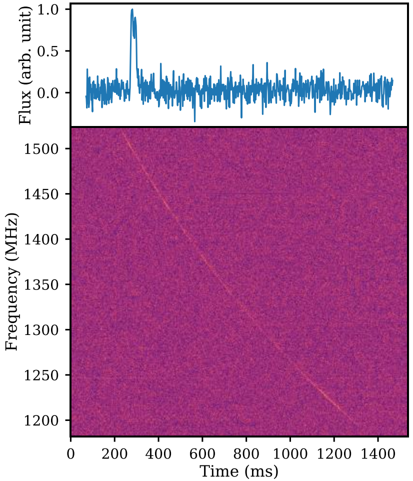
→ X-ray dim isolated NS (XDINS).

→ Transitional MSPs.



Ionized Medium Propagation Effects

Dispersion Delays

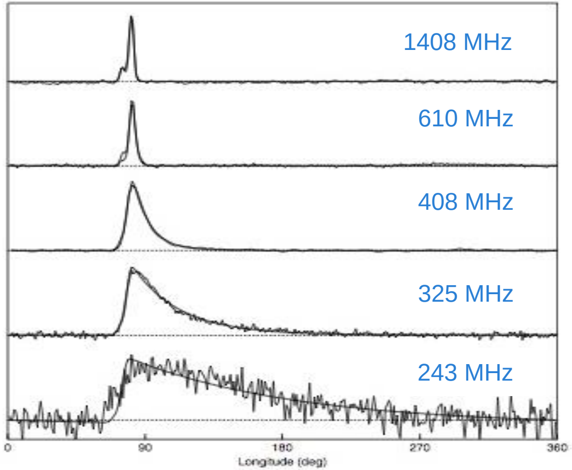


$$t_{\mathrm{DM}}(\nu) = \frac{4.15\times\mathrm{DM}\ \ \mathrm{ms}}{\nu_{\mathrm{GHz}}^2}$$

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

Deterministic, removable with coherent de-dispersion.

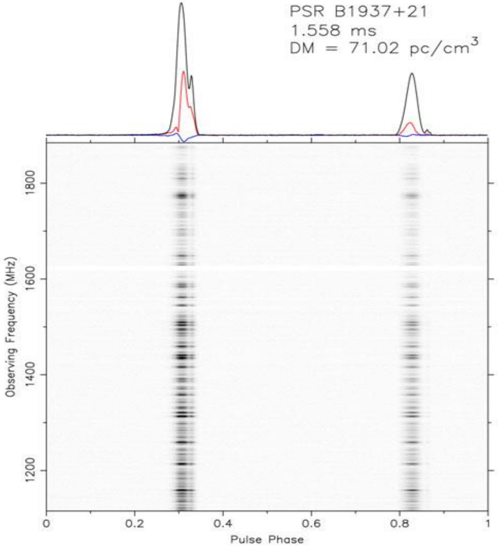
Multipath Broadening (Scattering)



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

Stochastic,
not easily removable.

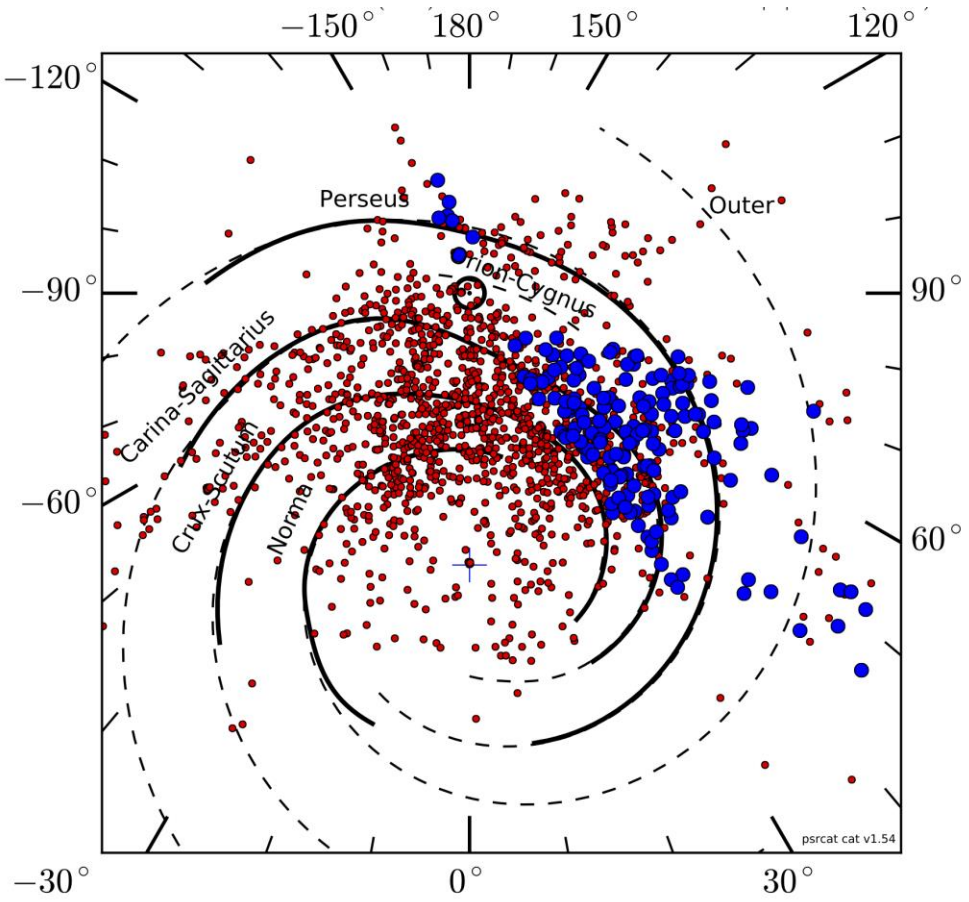
Diffractive Scintillation



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

100% modulations
of flux density.

Mapping the Galaxy with Dispersion Measure

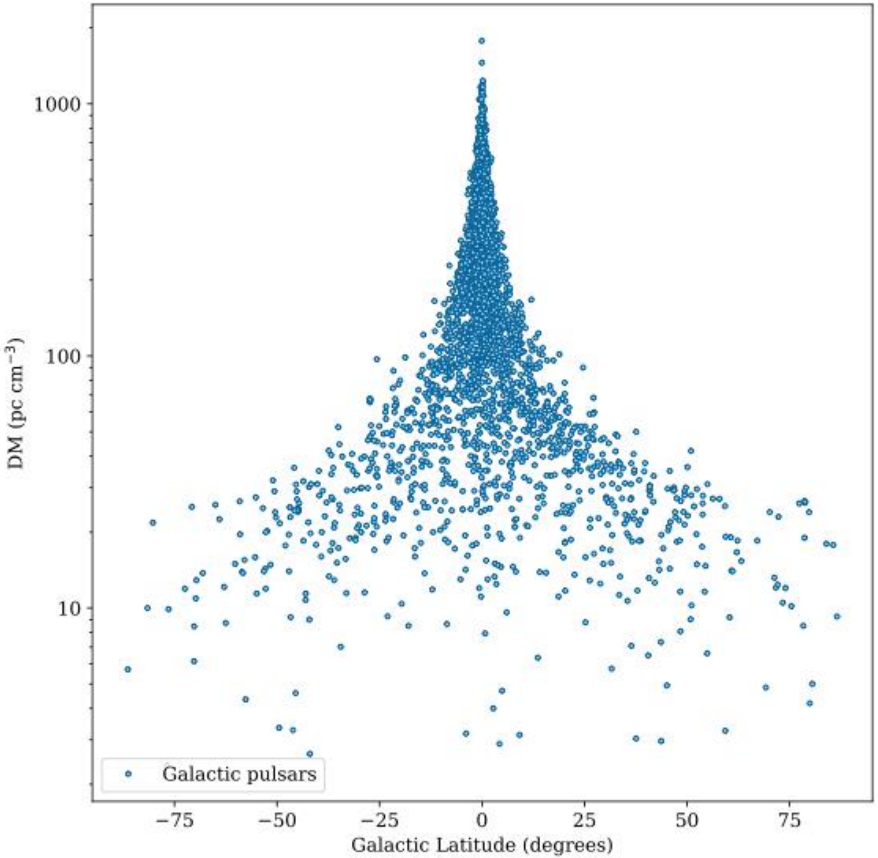


Pulsars:
Rapidly rotating *neutron stars*.

→ Galactic population.

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

Mapping the Galaxy with Dispersion Measure



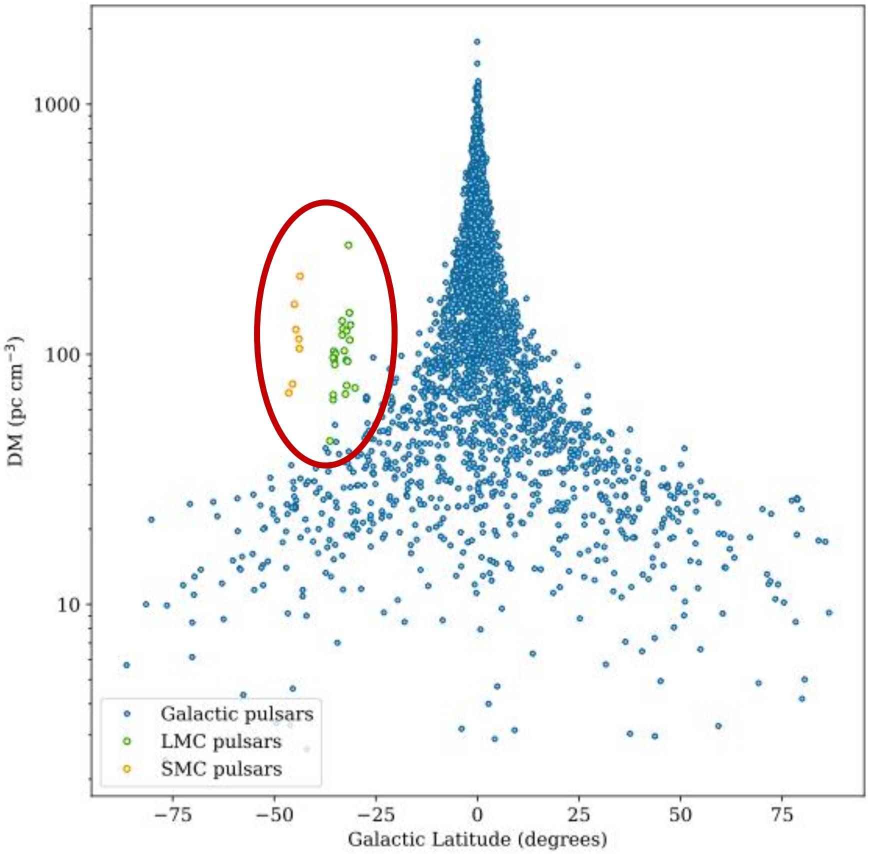
Pulsars:
Rapidly rotating *neutron stars*.

→ Galactic population.

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

→ Electron density is highest in the Galactic plane; rolls off with latitude.

Mapping the Galaxy with Dispersion Measure



Pulsars:
Rapidly rotating *neutron stars*.

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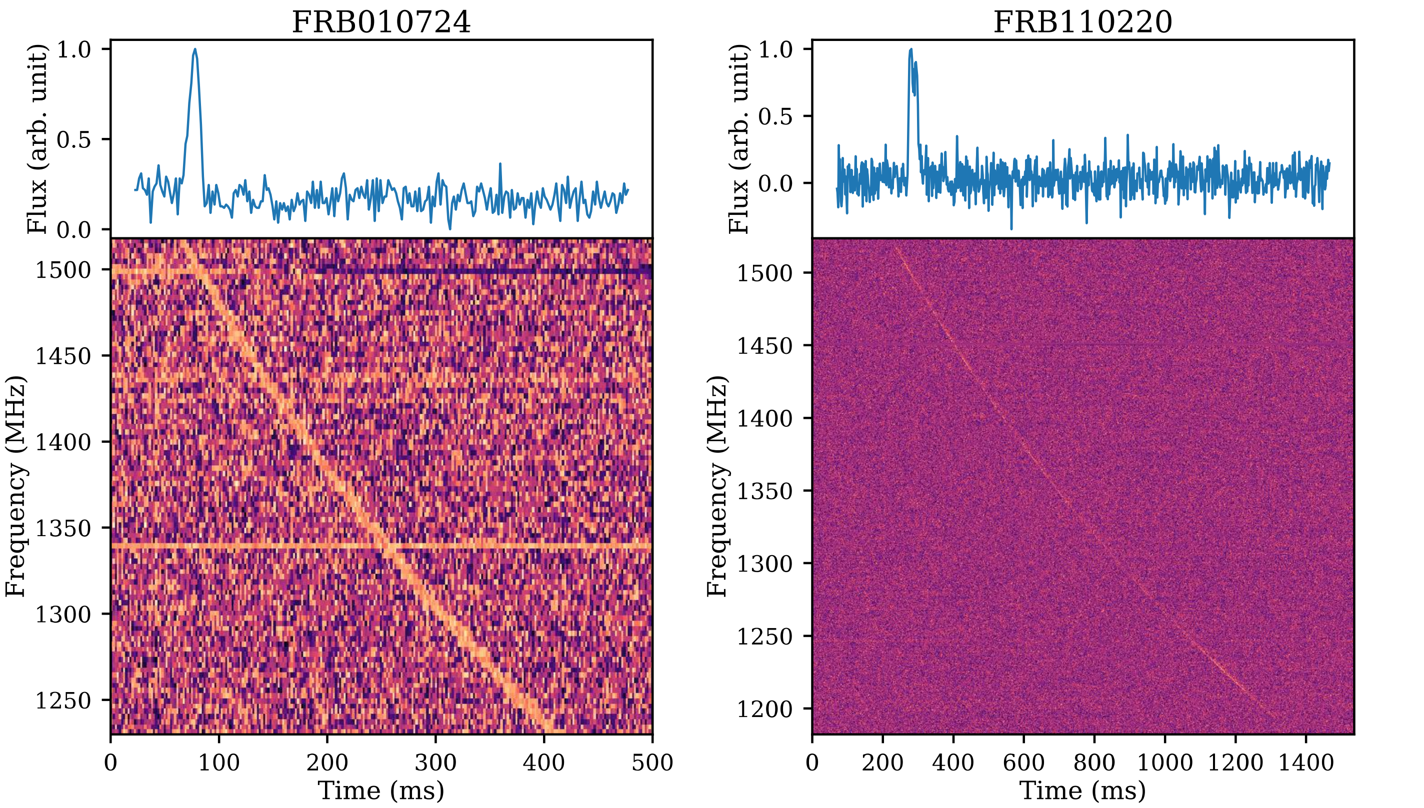
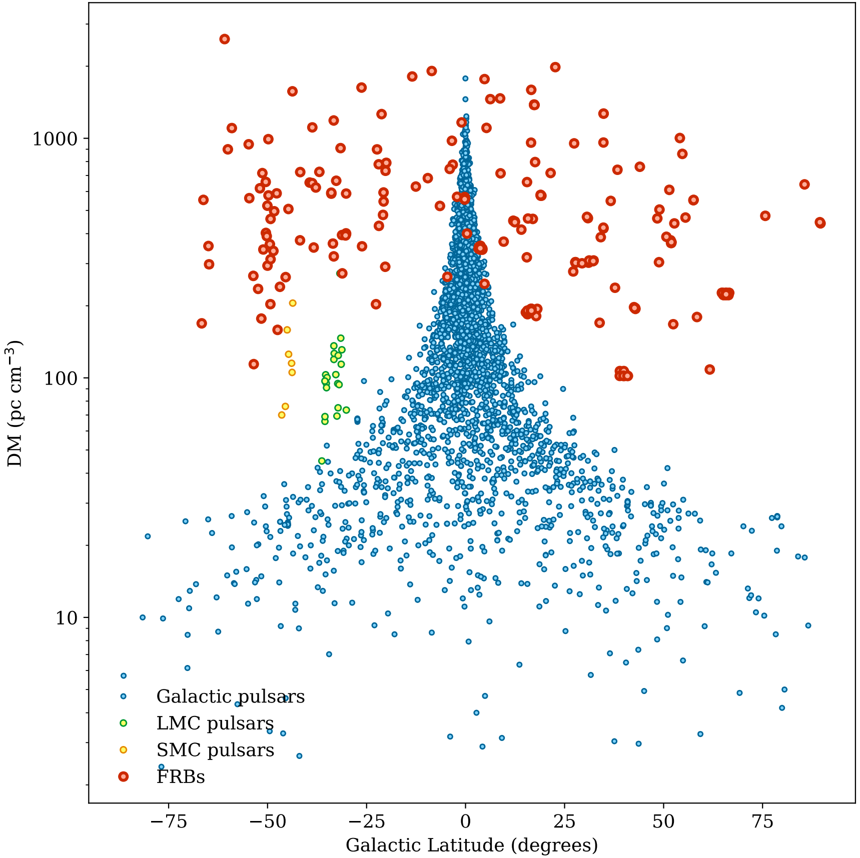
Fast Radio Bursts



FRBs: an extragalactic population



Bright millisecond single pulses.

Very high dispersion measures

→ Milky Way
+ Intergalactic Medium (IGM)
+ Host Galaxy.

Detected in small fields of view

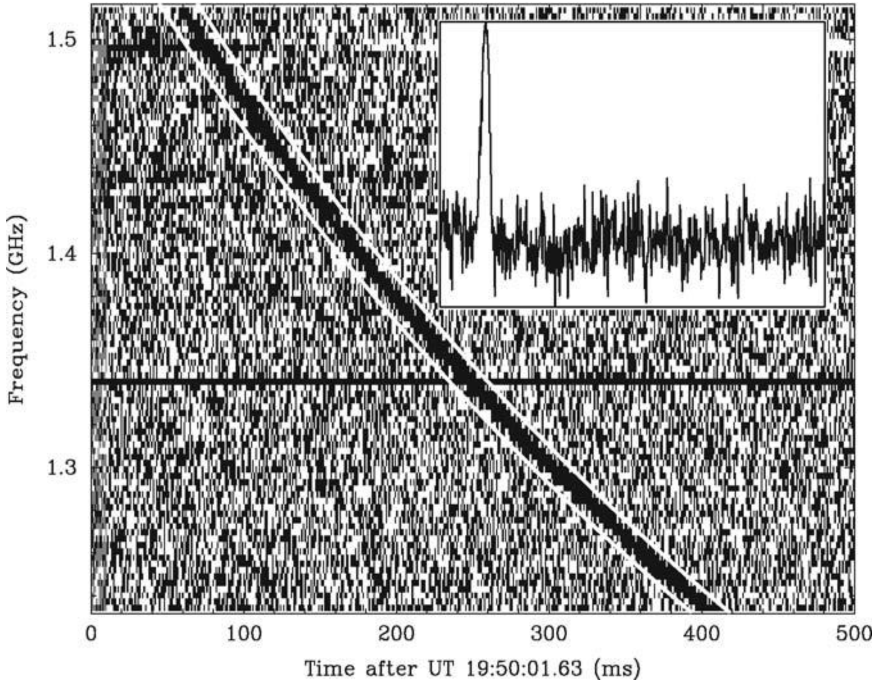
→ Very high inferred all-sky rate,
5-10,000 / sky / day.

Uncertain distances

→ Uncertain energetics; unknown engine.

Figure: Chatterjee (2021), Cordes & Chatterjee (2019)

FRB 010724, the one that started it all



FRB 010724, the "Lorimer burst":

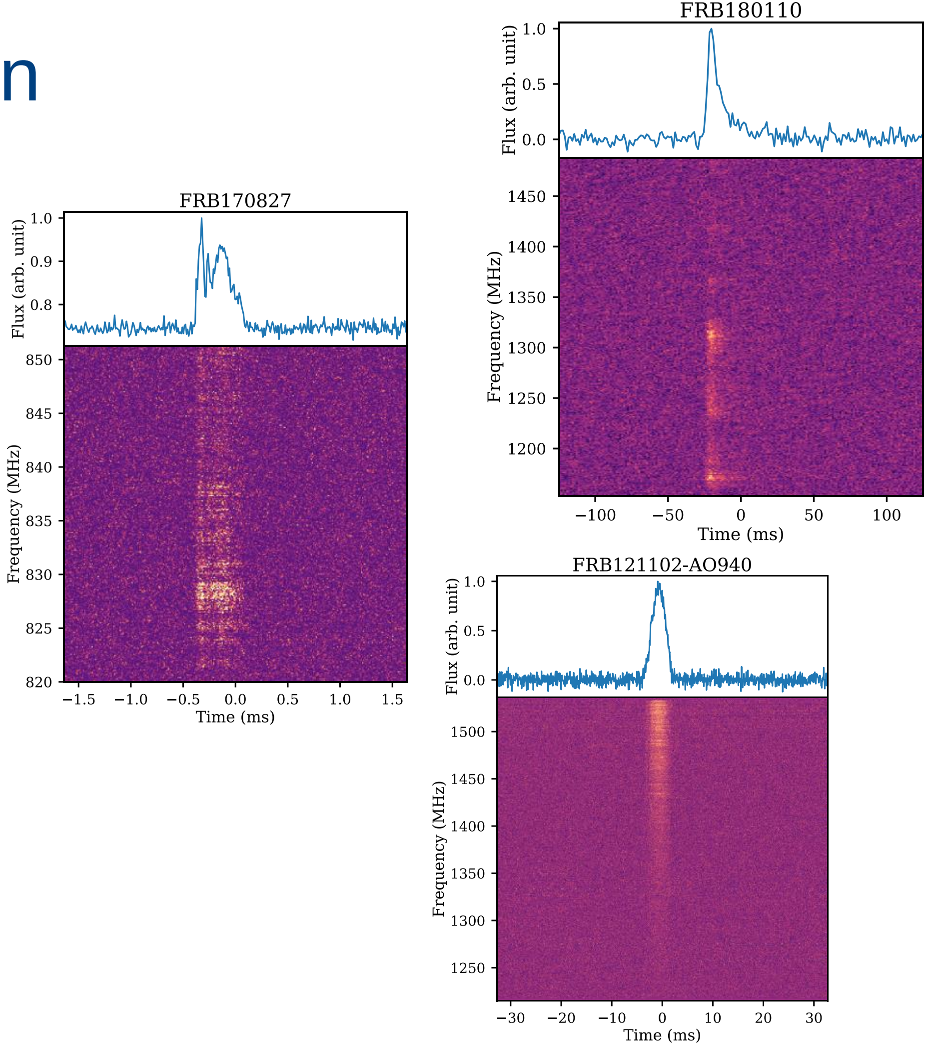
- Archival survey data from Parkes.
- A single dispersed pulse.
- Width < 5 ms.
- Brighter than 30 Jy (?)
- Follows ν^{-2} dispersion law.
- DM = 375 pc cm^{-3} → 500 Mpc?

→ Extragalactic.

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

The known FRB population

- 623 sources published so far.
- Inferred all-sky rate is large, ~5-10,000 / sky / day.
- Dispersion measure excess: 100 – 3000+ pc cm^{-3}.
- Currently incomplete in every FRB parameter (fluence, DM, width, rate, repetition, polarization…)



Figures: Chatterjee (2021), Cordes & Chatterjee (2019)

The known FRB population

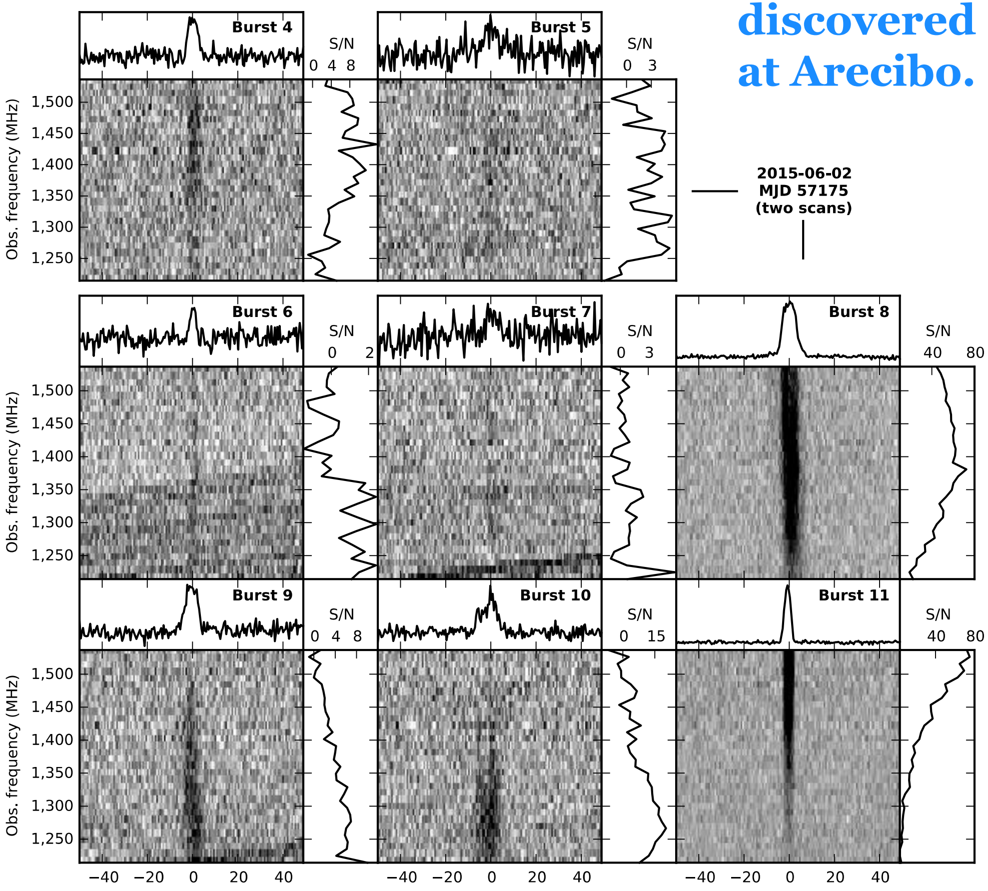
- Some FRB sources repeat!

→ Currently 24 of 623 published.

→ Can't have cataclysmic central engines for these sources.

→ Can be followed up and localized with smaller FoV instruments.

FRB 121102, discovered at Arecibo.

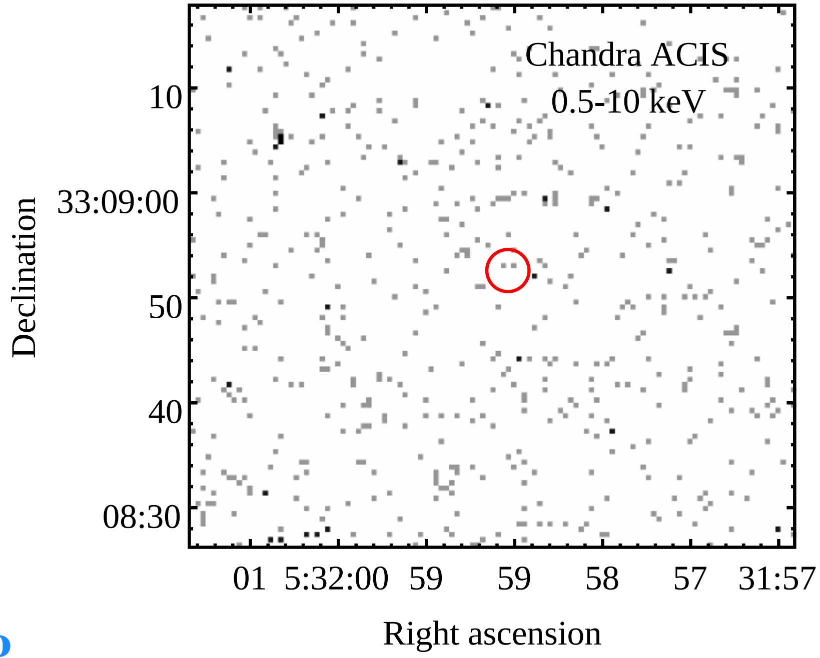


Spitler et al. 2016, Nature, A repeating fast radio burst

FRB121102: Simultaneous Radio + X-ray observations

- Observations with Chandra, XMM, GBT, Arecibo, Effelsberg.
- 12 bursts detected at Arecibo and GBT.
- **No** X-ray counts at burst times.
  X-ray photons consistent with background.

(However, e.g., giant magnetar flares are hard to rule out at z=0.2, even with stacked limits.)



Scholz et al. 2017,
Simultaneous X-Ray, Gamma-Ray, and Radio Observations of the Repeating Fast Radio Burst FRB 121102

FRB 121102 is a prolific emitter

FAST observations:
59.5 hr over 47 days.

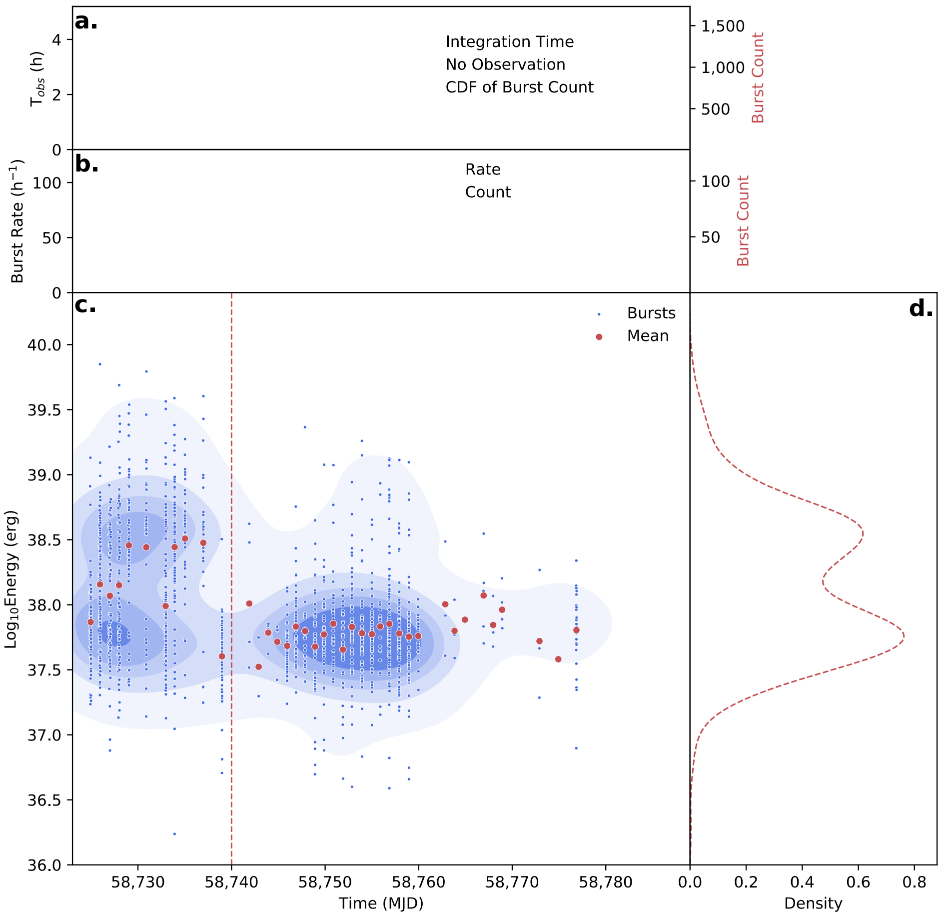
→ 1652 bursts detected!

→ No apparent periodicity.

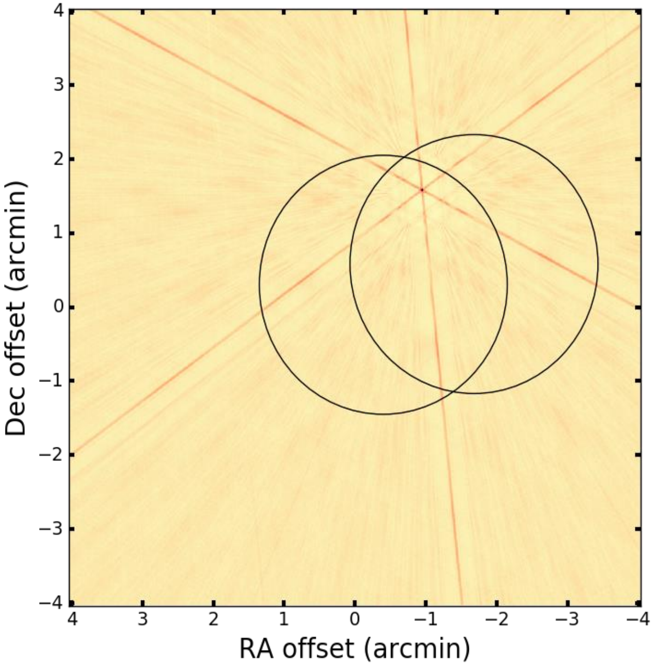
→ Bimodal energy distribution?

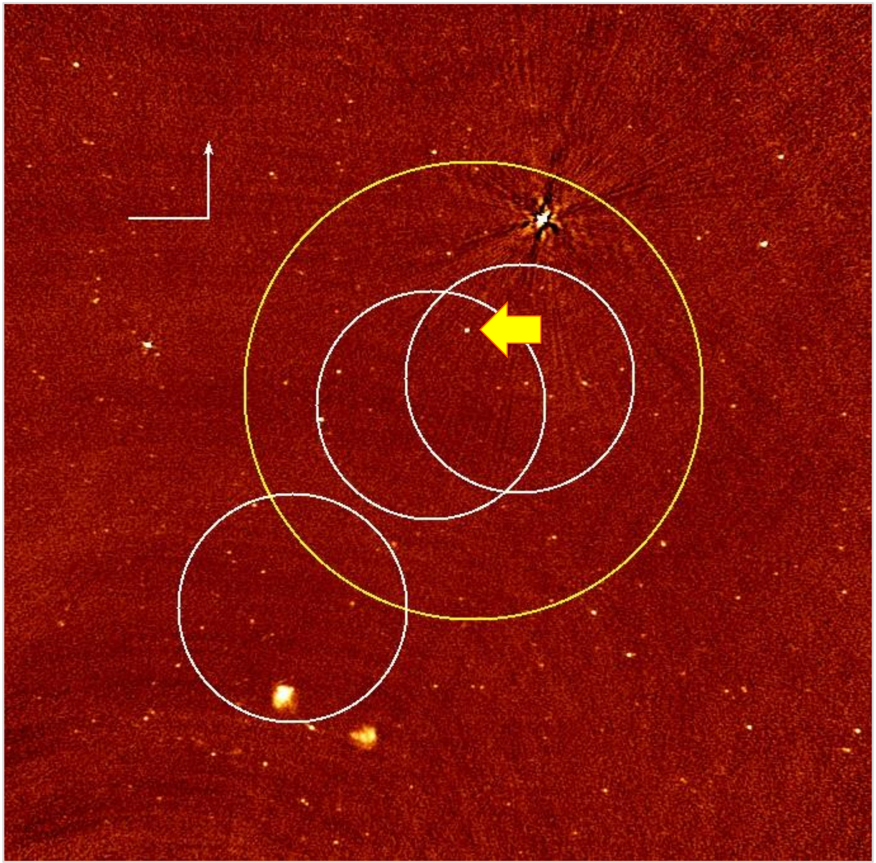
➔ Disfavors models with large energy requirements or complex triggering mechanisms.

Li et al. 2021, Nature
A bimodal burst energy distribution of a repeating fast radio burst source



Localizing FRBs



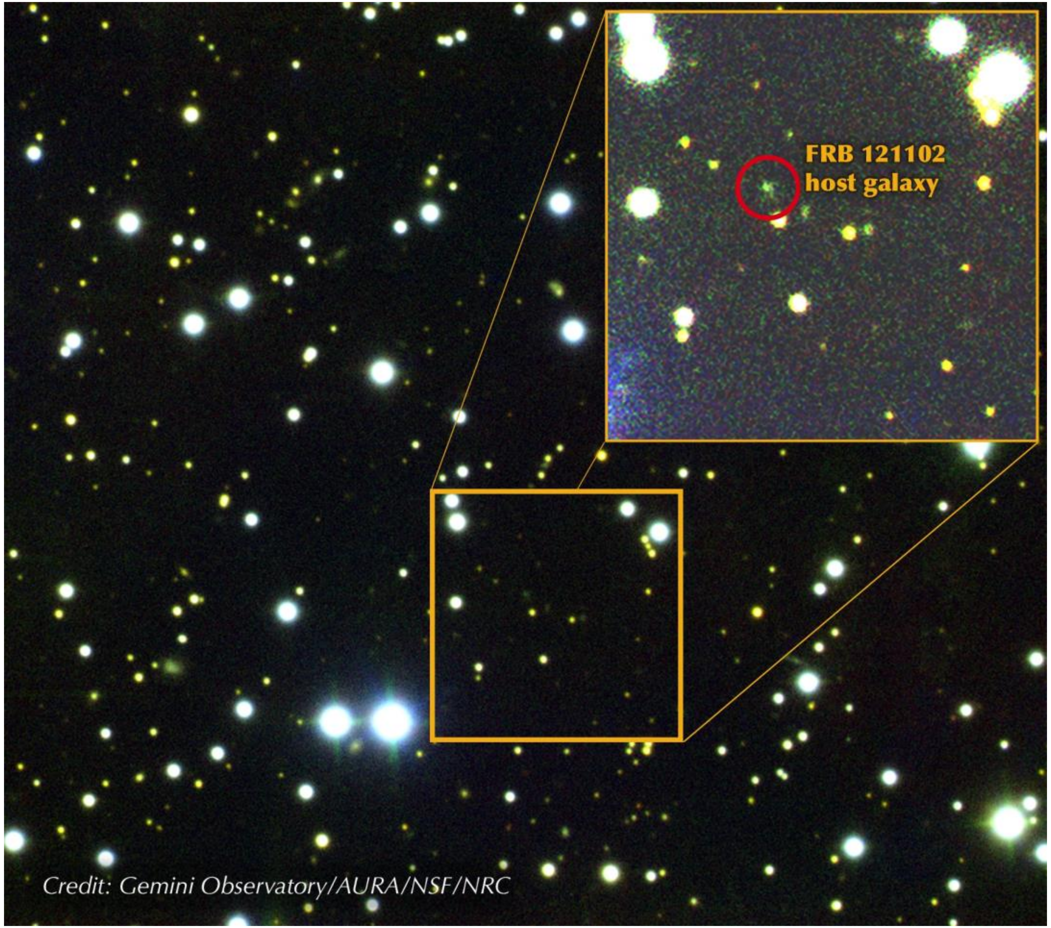


FRB 121102, localized at the VLA.

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

FRB host galaxies

- FRB 121102 host galaxy is a star-forming dwarf, z=0.193, about 1 Gpc away.

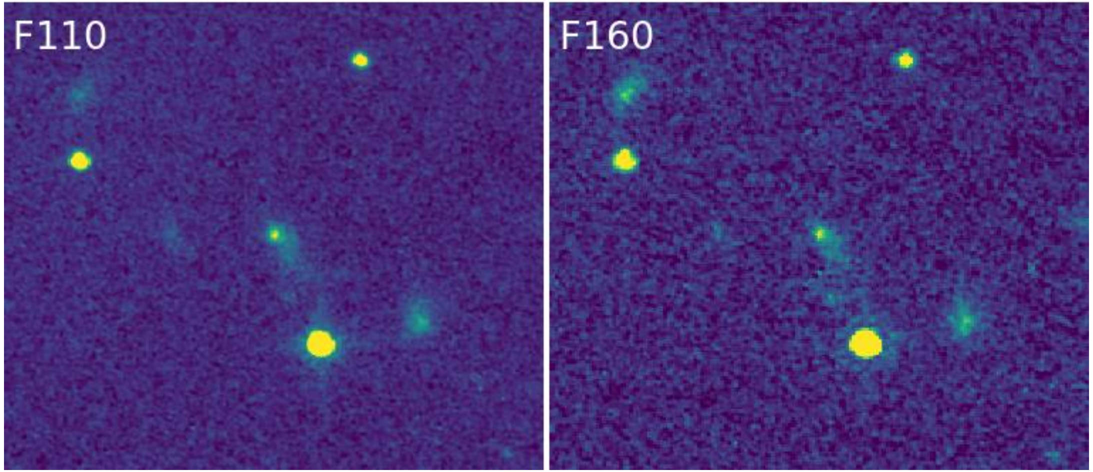


Chatterjee et al. 2017, Tendulkar et al. 2017

FRB host galaxies

- FRB 121102 host galaxy is a star-forming dwarf, z=0.193, about 1 Gpc away.

➔ Is the high specific star formation suggestive of a link to massive stars and/or SLSNe, LGRBs?

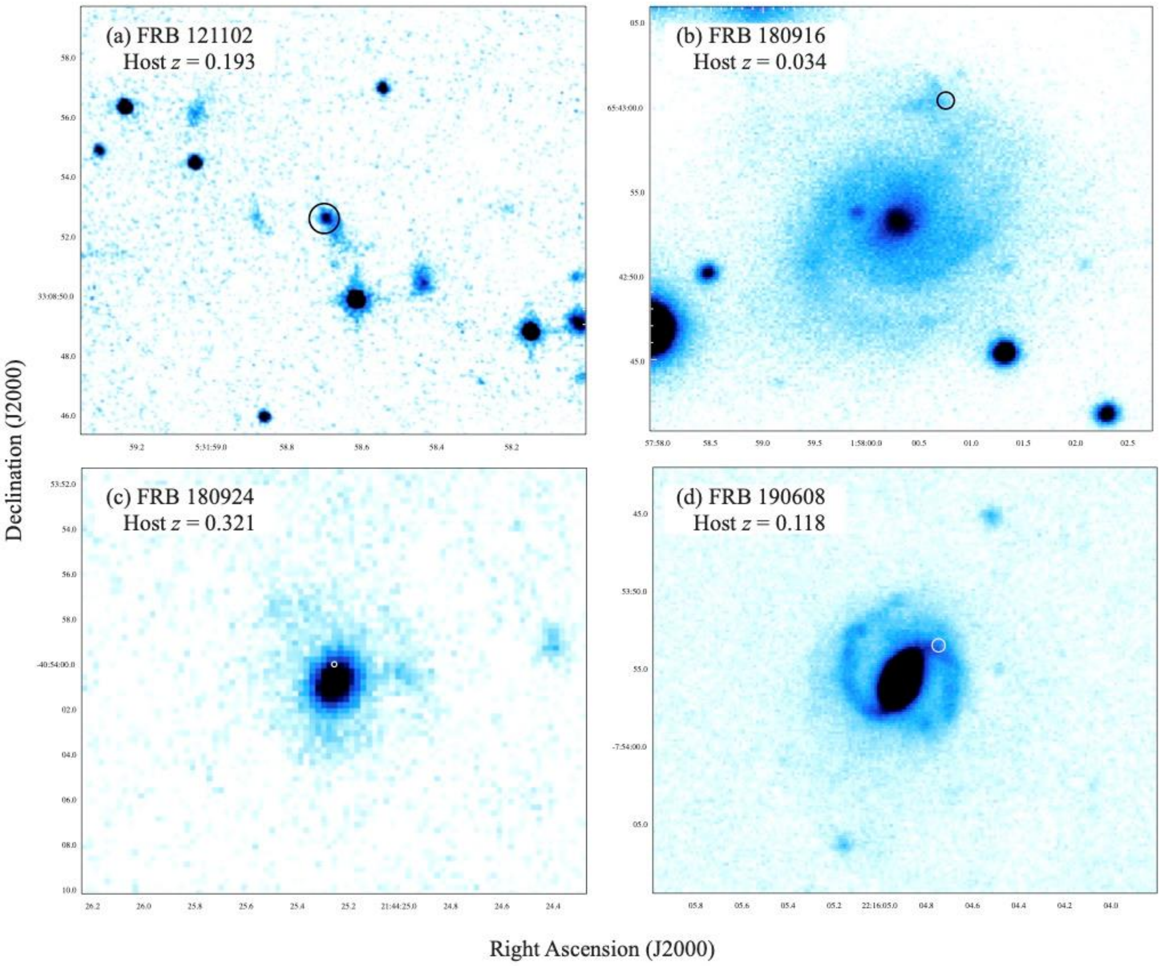


Bassa et al. 2017

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

FRB host galaxies

- FRB 121102 host galaxy is a star-forming dwarf, z=0.193, about 1 Gpc away.
- Other host galaxies show a diversity of types (old ellipticals, young spirals), and a diversity of locations within galaxies.

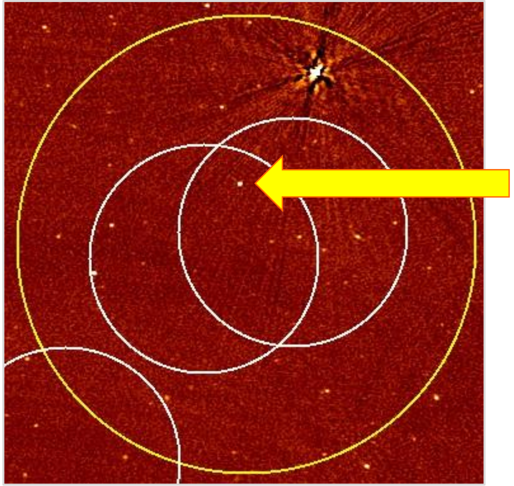


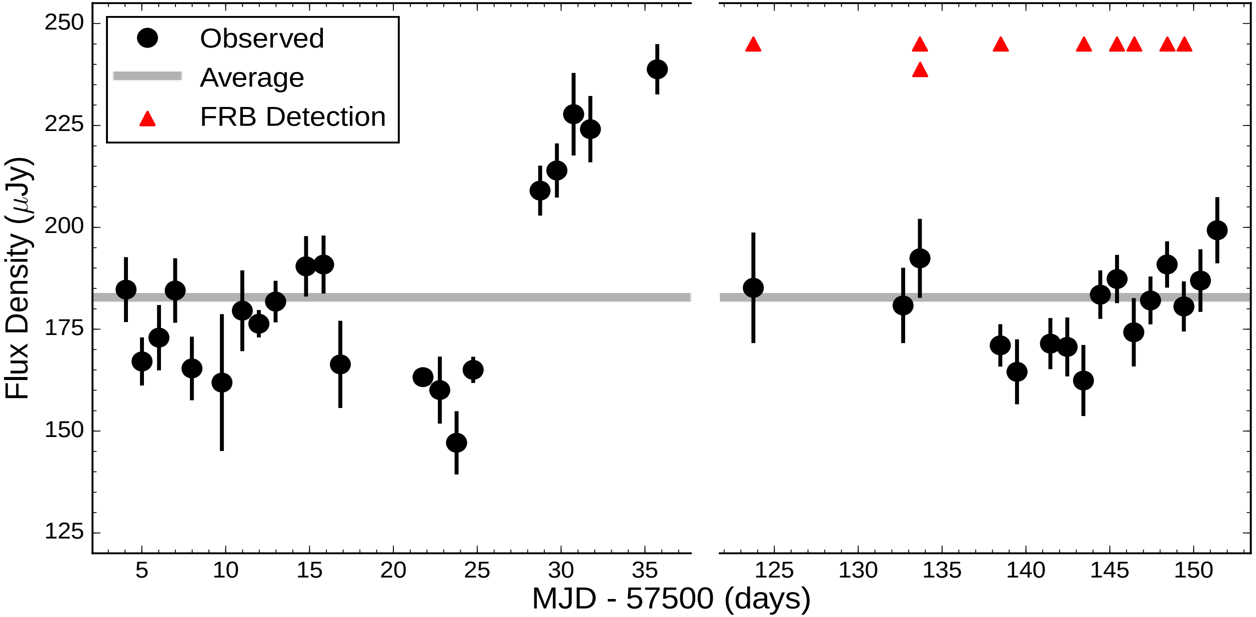
Persistent radio sources associated with FRBs

- FRB 121102 is associated with a persistent radio source.

→ Similar to a low-luminosity AGN?

→ Or possibly an extreme young supernova remnant / pulsar wind nebula.

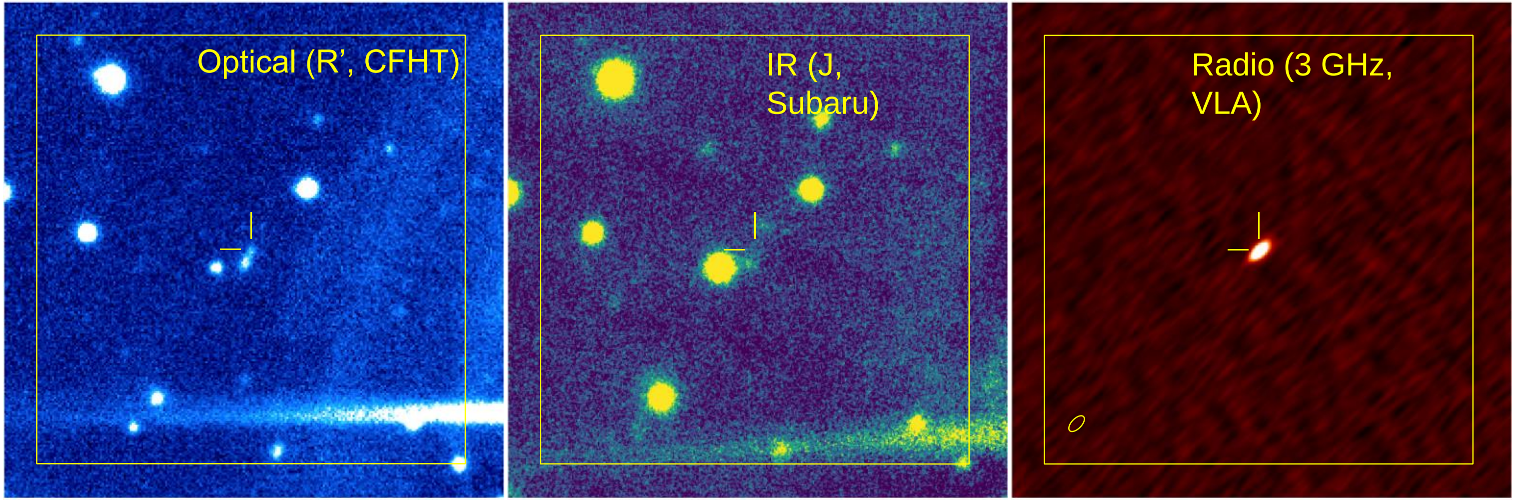




Chatterjee et al. 2017

Persistent radio sources associated with FRBs

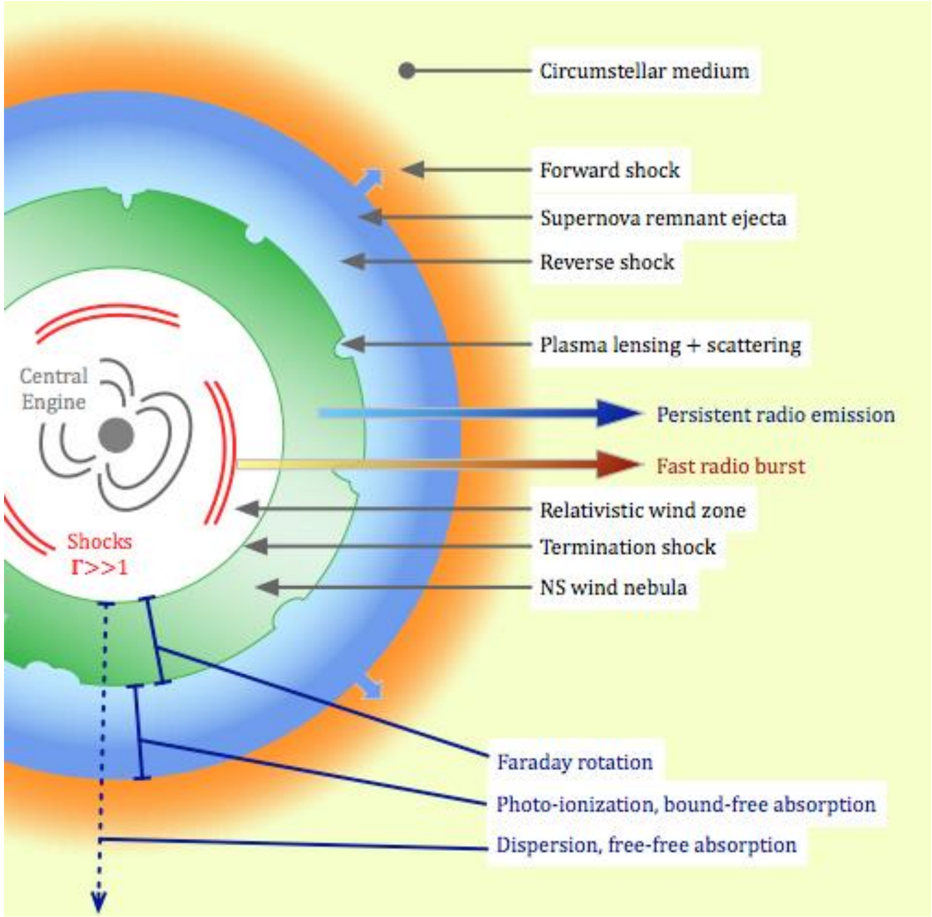
- FRB 121102 is associated with a persistent radio source.
- So is FRB 20190520B – another active repeating source in a dwarf galaxy.



Niu et al. 2022, Nature,
A repeating FRB in a dense environment with a compact persistent radio source

Concordance model for FRB + PRS

Figure: Cordes & Chatterjee (2019)



A magnetar in an extreme nebula

→ Association with star formation.
→ Persistent radio source.
→ Extreme rotation measure.
→ Randomness of burst times.

Margalit & Metzger 2018,
A concordance picture of FRB 121102 as a flaring magnetar embedded in a magnetized ion-electron wind nebula

A Galactic FRB!

Galactic magnetar SGR 1935+21:

Emitted an extremely bright radio burst on 28 April 2020

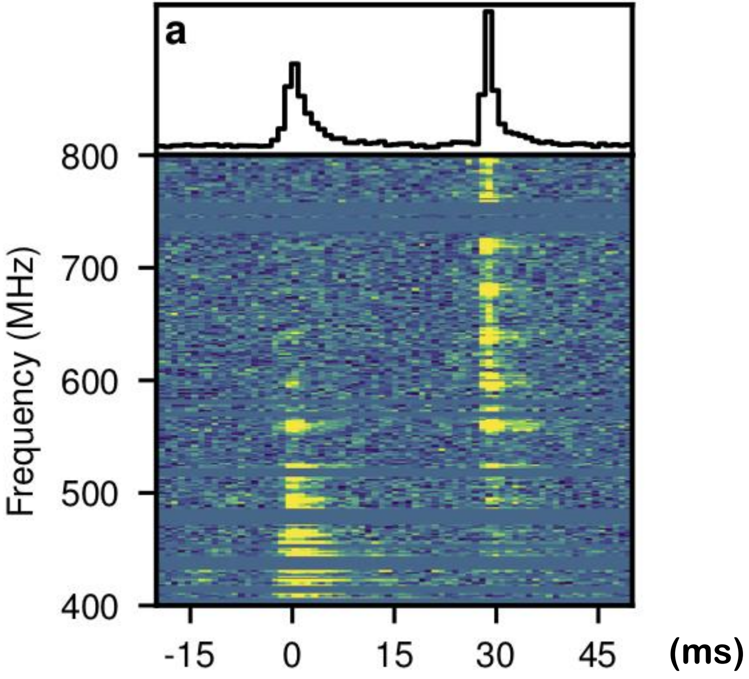
→ 700 kJy-ms at CHIME

→ 1.5 MJy-ms at STARE-2

→ Bright, hard X-ray burst, in a forest of other bursts (e.g., with AGILE).

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

The environments of FRBs

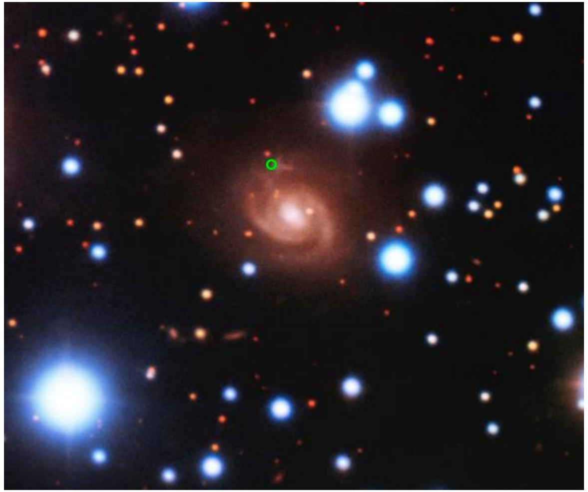
- FRB 121102 is associated with a persistent radio source.
- So is FRB 190520B – another active repeating source in a dwarf galaxy.
- But other, much closer localized FRBs are not associated with PRS.

Repeating FRB 20180916B ("R3")

→ Discovered by CHIME.

→ Localized by EVN to a spiral galaxy at only 149 Mpc.

→ No persistent radio source.



CHIME/FRB collab 2019, Nature
Marcote et al. 2020, Nature

The environments of FRBs

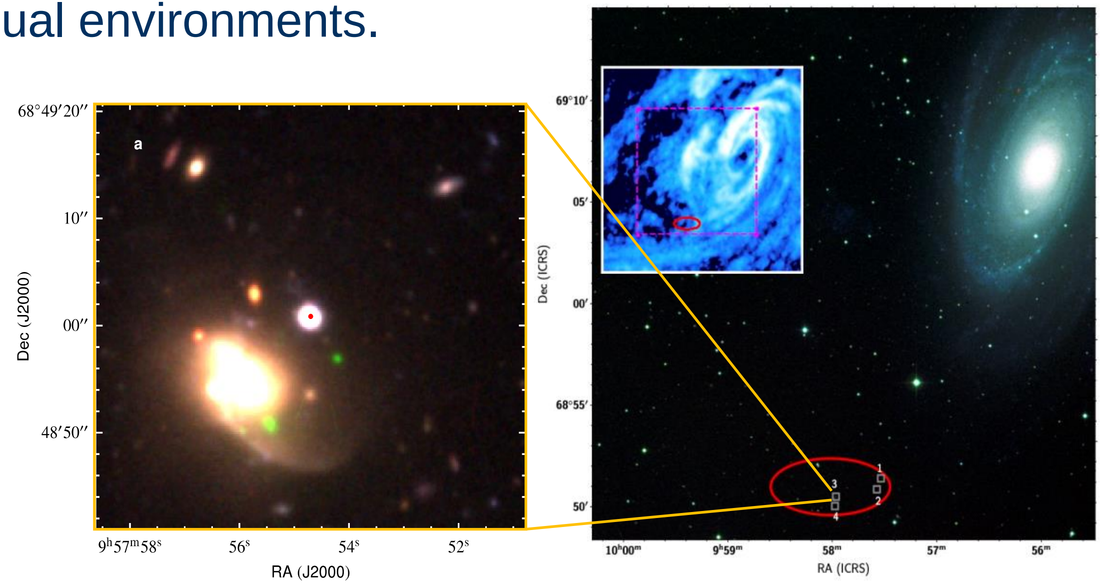
- FRB 121102 is associated with a persistent radio source.
- So is FRB 190520B – another active repeating source in a dwarf galaxy.
- But other, much closer localized FRBs are not associated with PRS.
- In fact, some are in rather unusual environments.

Repeating FRB 20200120E:

→ Associated with a globular cluster on outskirts of M81.

→ Unlikely to be a young magnetar from a core collapse SN.

→ Possible AIC or merger product?



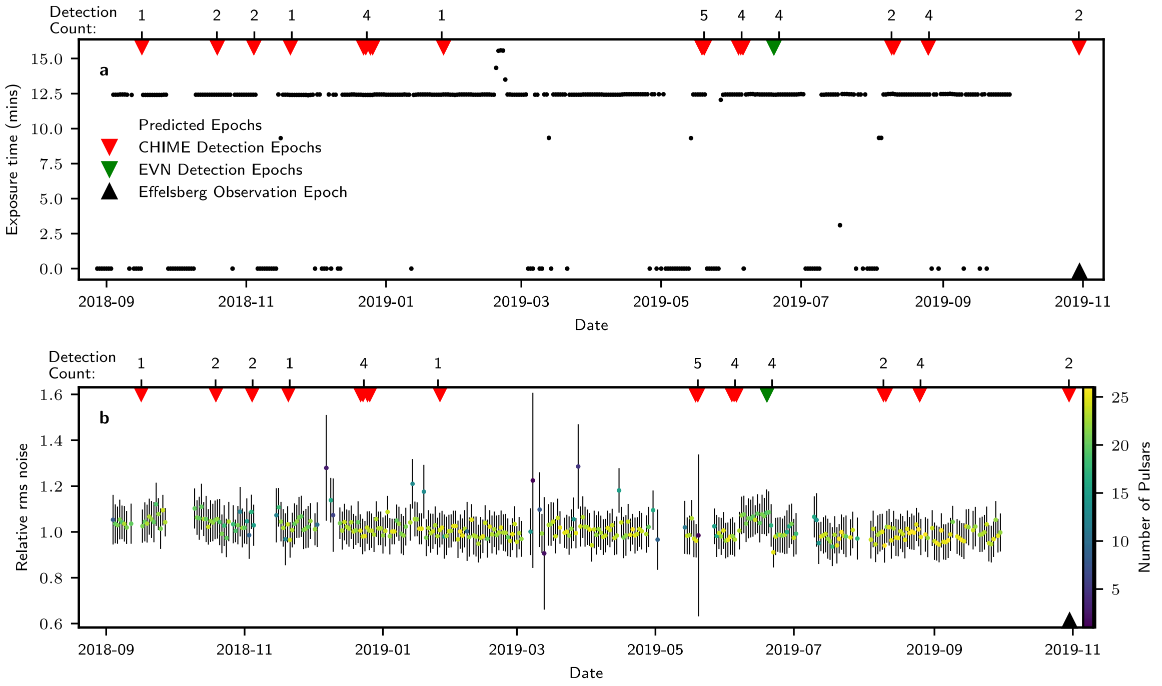
Bhardwaj et al. 2021, ApJL
Kirsten et al. 2022, Nature

Periodic emission windows for FRBs

FRB 20180916B is detected only during periodic windows,

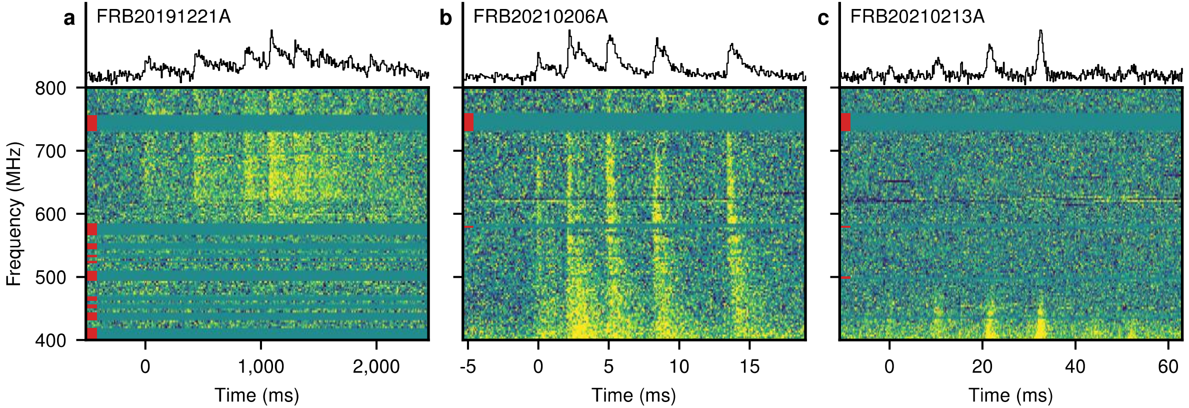
~5 days every 16.35 days.

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



CHIME/FRB collab 2020, Nature
Periodic activity from a fast radio burst source

Periodicity in FRB emission



CHIME/FRB collaboration 2022, Nature, Sub-second periodicity in a fast radio burst

Detections with CHIME:

→ FRB 20191221A
216.8(1) ms; 6.5σ.

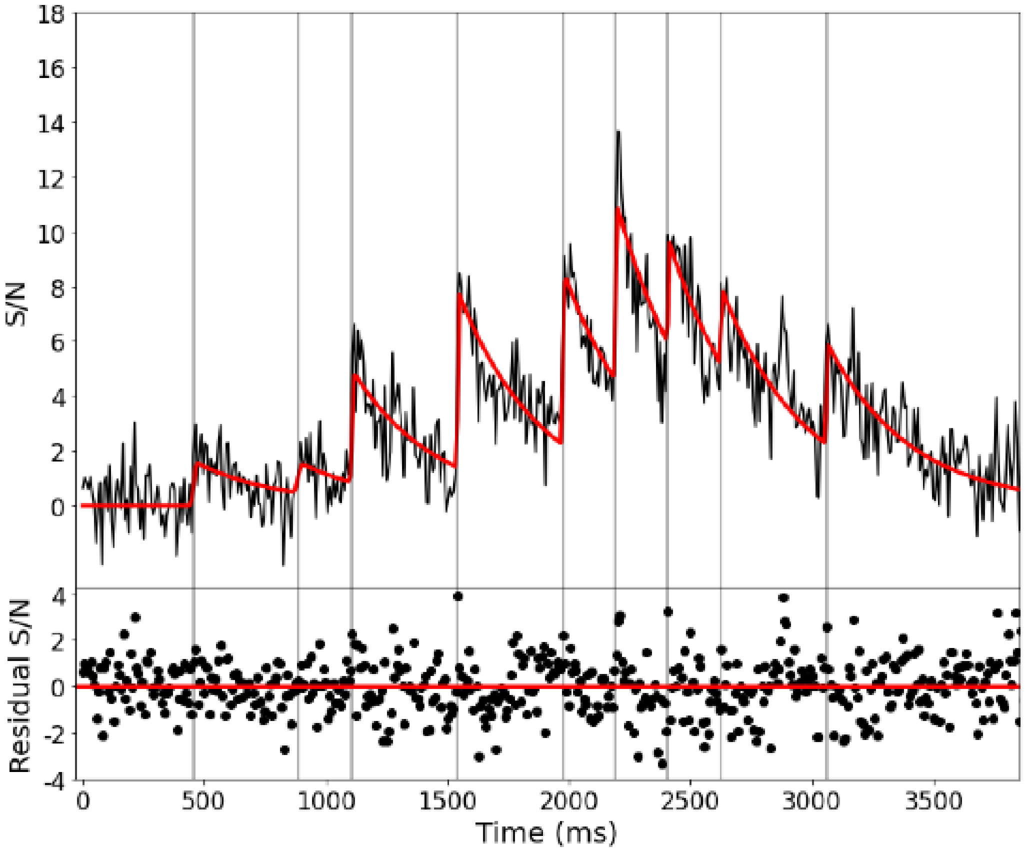
→ P(False alarm) < 10^{-10}.

And also, suggestive:

→ FRB 20210206A
2.8(1) ms; 1.3σ.

→ FRB 20210213A
10.7(1) ms; 2.4σ.

Periodicity in FRB emission



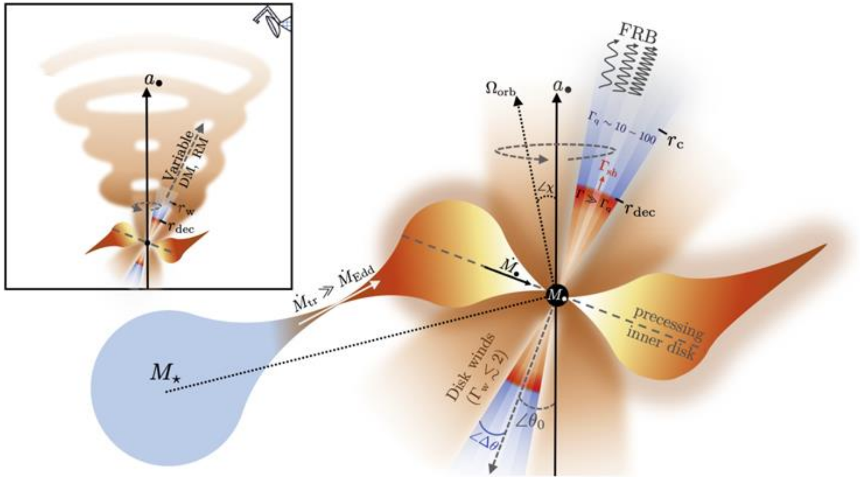
FRB 20191221A:
216.8(1) ms; 6.5σ.
→ FAP is < 10^{-10}.

→ Strong evidence for rotating NS origin, in magnetosphere rather than in nebula.

CHIME/FRB collaboration 2022, Nature, Sub-second periodicity in a fast radio burst

Other models for FRB emission

- → There are many (many!) suggested models for FRB emission.
  See, e.g., FRBtheorycat.org: lists over 50 different models
- → Range from the exotic to … the somewhat less exotic.
- → Multiwavelength observations might discriminate between them.
- → Radio photons are "cheap" - multiple classes are possible, even likely.



← **Sridhar et al. 2021,**
Periodic Fast Radio Bursts from Luminous X-ray Binaries

Fundamental physics with FRBs

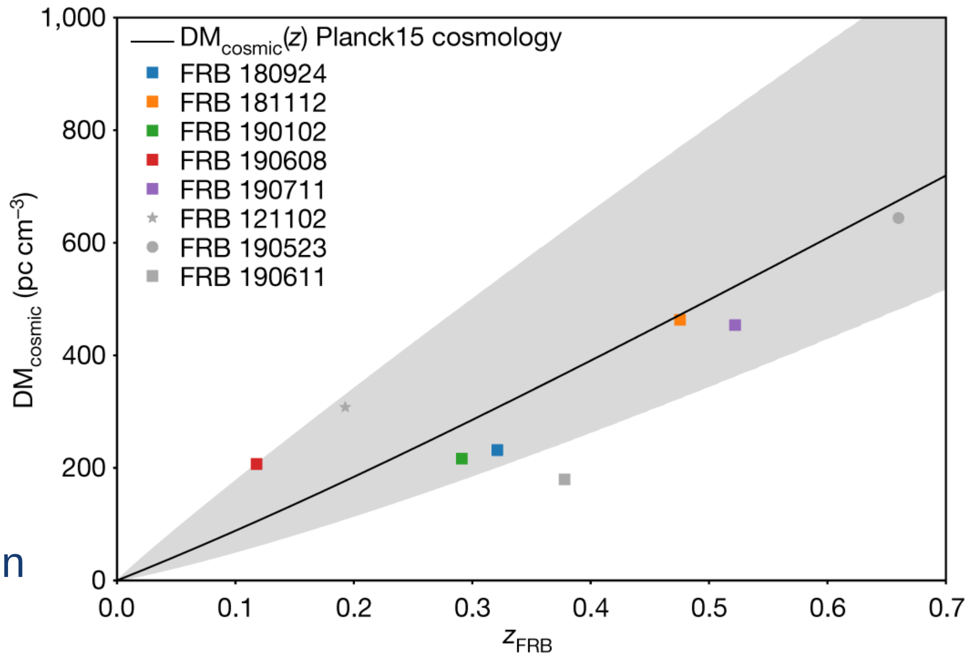
➔ What is the central engine?

➔ FRBs as probes:

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

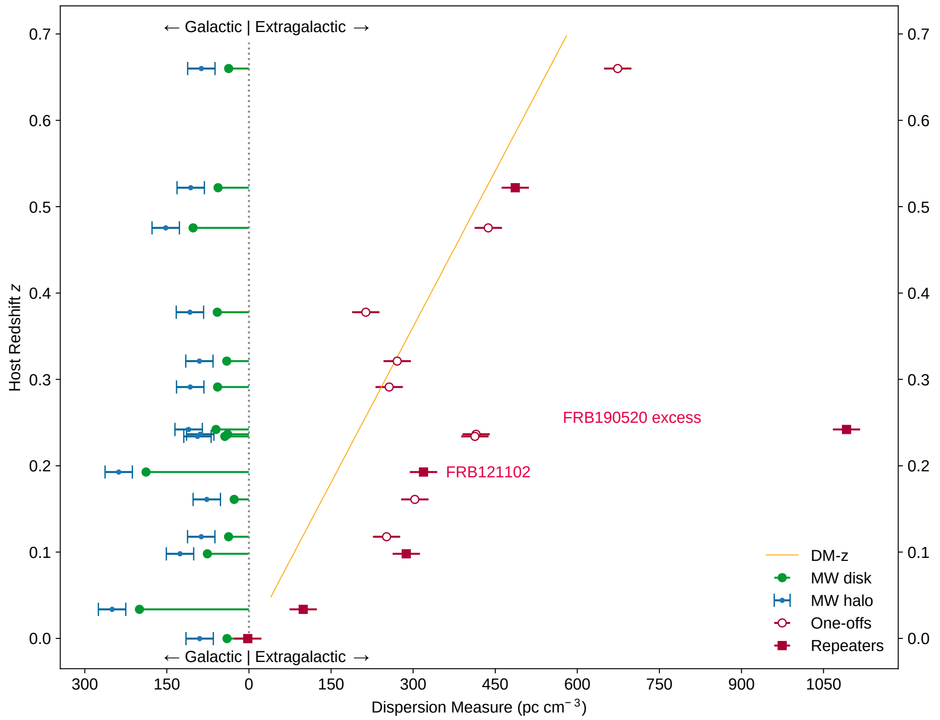
e.g., direct estimate [*] of the cosmic baryon density, consistent w/CMB, BBN:

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



Macquart et al. 2020, Nature
A census of baryons in the Universe from localized fast radio bursts

Probing the intergalactic medium



DM excess for FRB 190520B

→ Contribution from complex environment in the host galaxy.

→ Cosmology with FRBs will require host galaxy IDs and redshifts. Can't assume an "average" host contribution.

Niu et al. 2022, Nature
A repeating FRB in a dense environment with a compact persistent radio source

Frontiers in understanding FRBs

→ Localization, host identification, redshifts, distances.

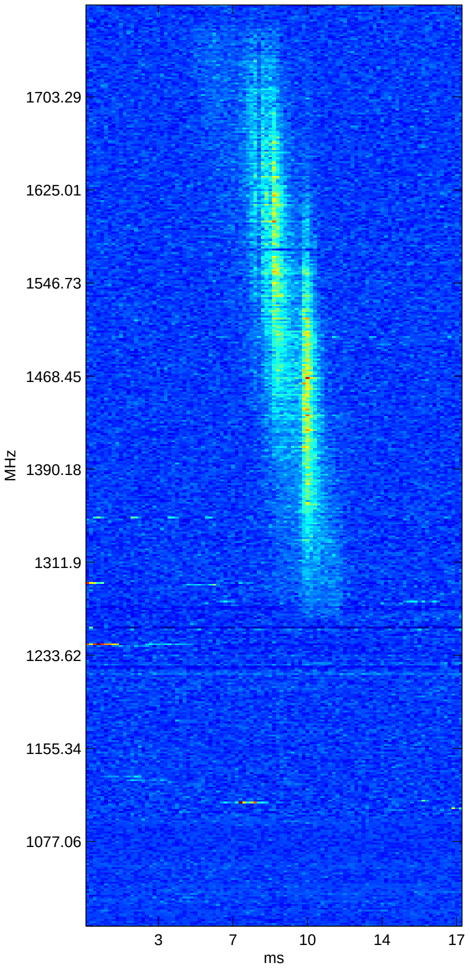
→ Local environments: variability in scattering and rotation measures of repeating FRBs.

→ High time resolution observations.

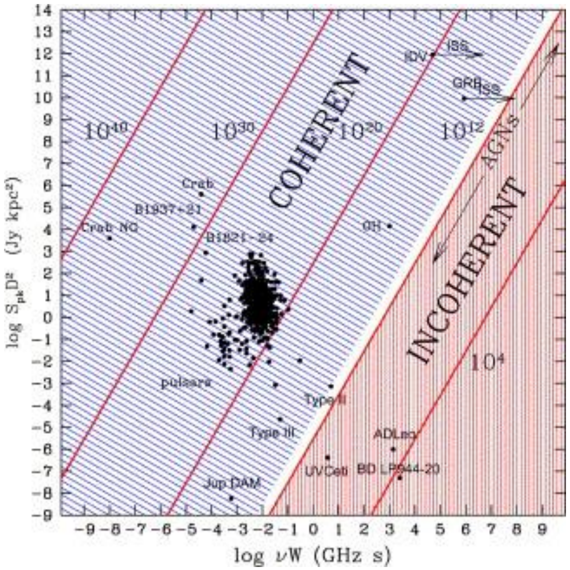
→ Multiwavelength and multi-messenger counterparts, especially for FRBs in our local neighborhood.

➔ Central engine(s) of FRBs.

➔ FRBs as probes of hidden baryons – halos, intercluster medium, intergalactic medium.

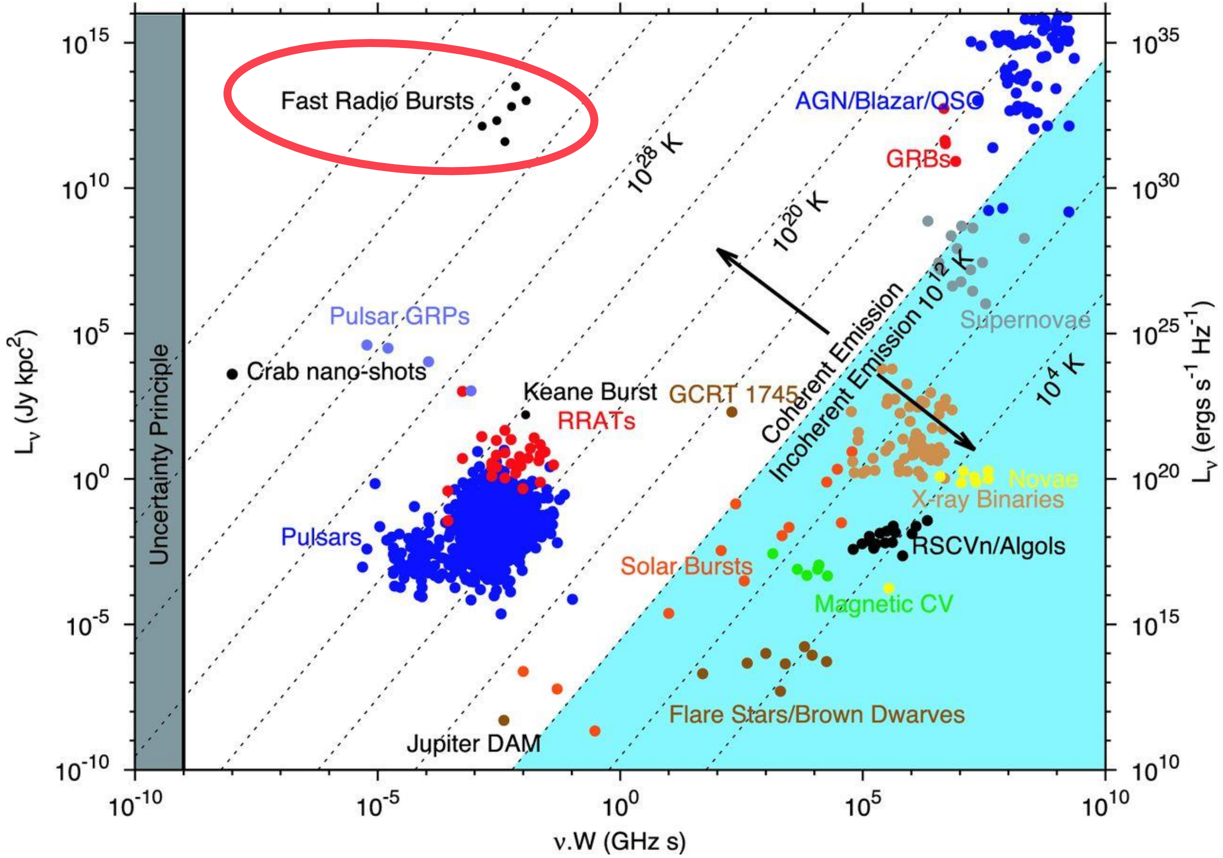


The phase space for (radio) transients



Cordes, Lazio, McLaughlin (2004)

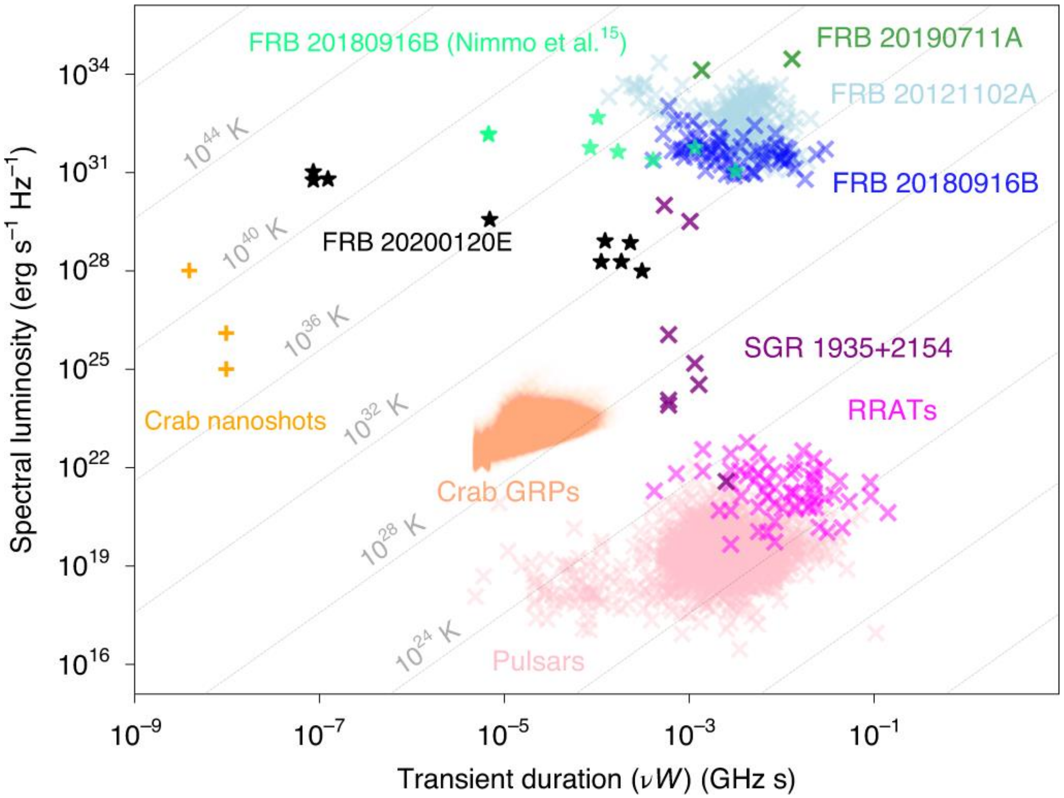
Pietka, Fender, Keane (2014) →



The phase space for (radio) transients

→ "Local" FRBs fill in the gap between Crab giant pulses and other FRBs.

→ Ultra-fast radio transients probably exist at nanosecond to microsecond timescales.



Nimmo et al. (2022)
"Burst timescales and luminosities as links between young pulsars and fast radio bursts"

“Unknown unknowns”

The pattern is consistent across wavelength.

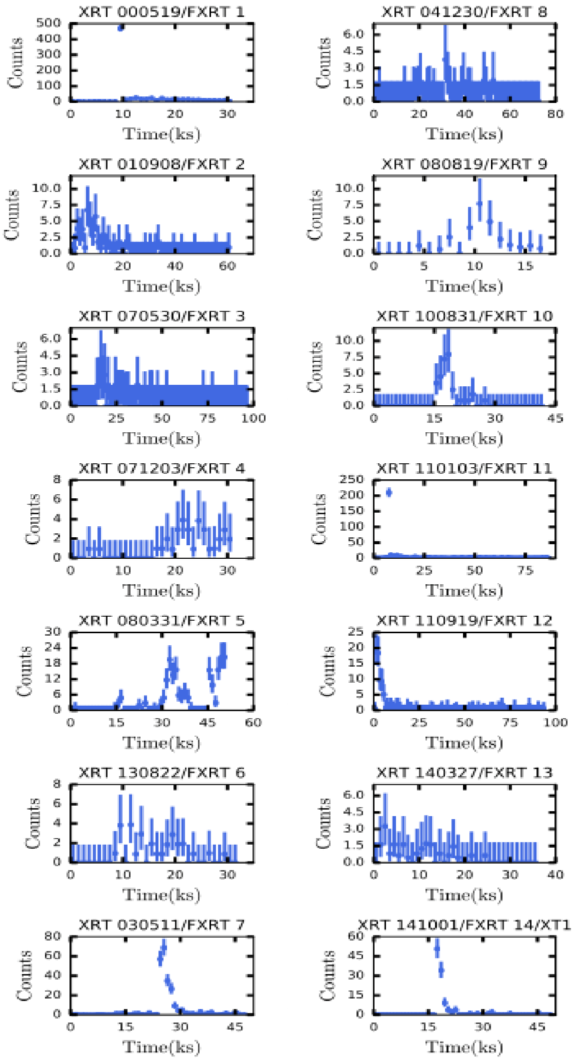
→ Fast Blue Optical Transients

→ Supergiant Fast X-ray Transients

→ Extragalactic Fast X-ray Transients

➔ The time domain is (still) a discovery frontier.

Quirola-Vásquez et al. 2022 → Extragalactic Fast X-ray Transient candidates discovered by Chandra (2000-2014)



“Unknown unknowns”

The time domain is a discovery frontier.

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.

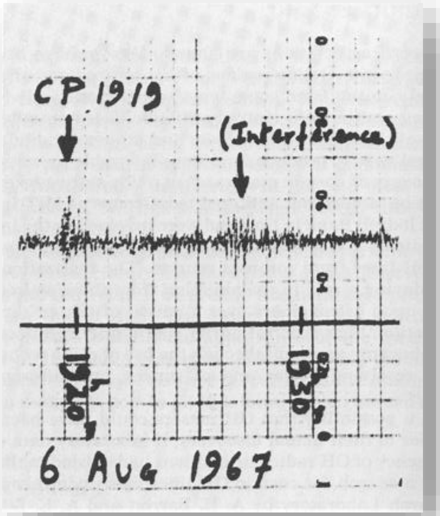
→ High angular resolution.
Unique counterparts require ~1” localization.

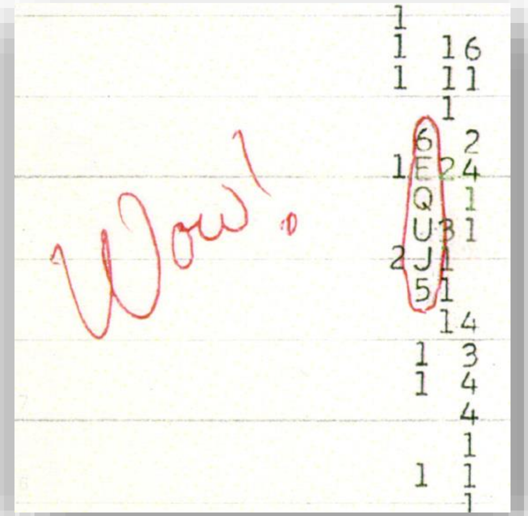
→ Massive storage, high throughput computation. ➔Archives important.
(But: embarrassingly parallel problems.)

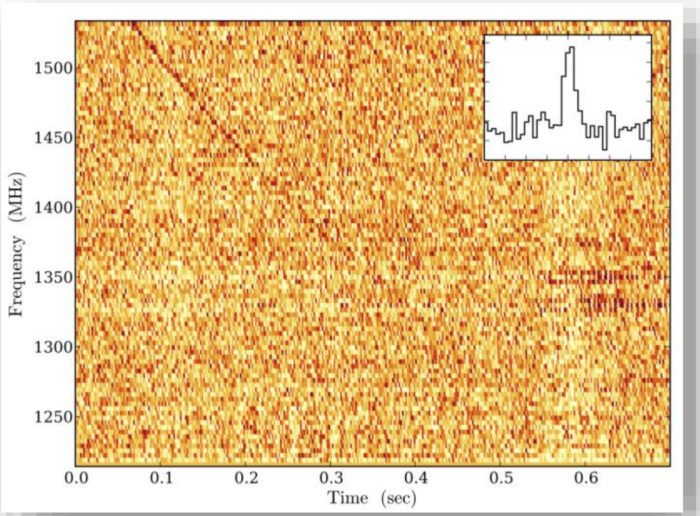
"Unknown unknowns": Leave room for discovery

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

→ The most important future discoveries are likely to be surprises.









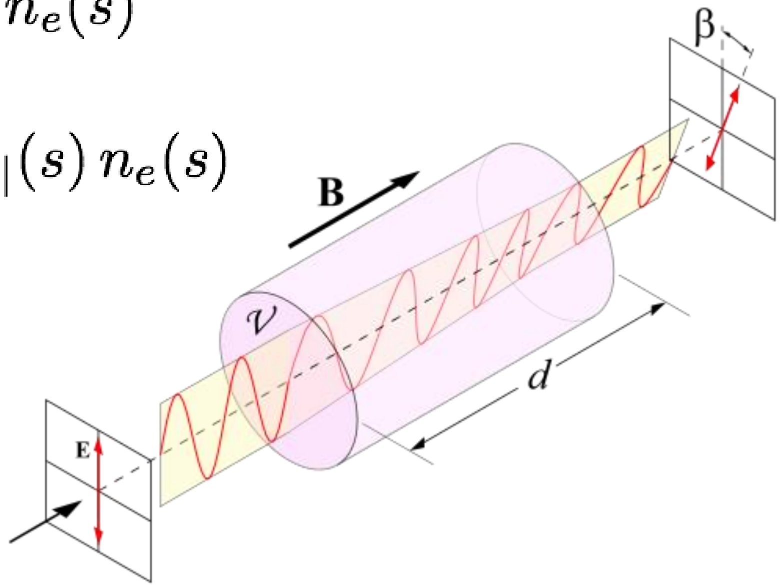

Interstellar / Intergalactic Propagation Effects

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

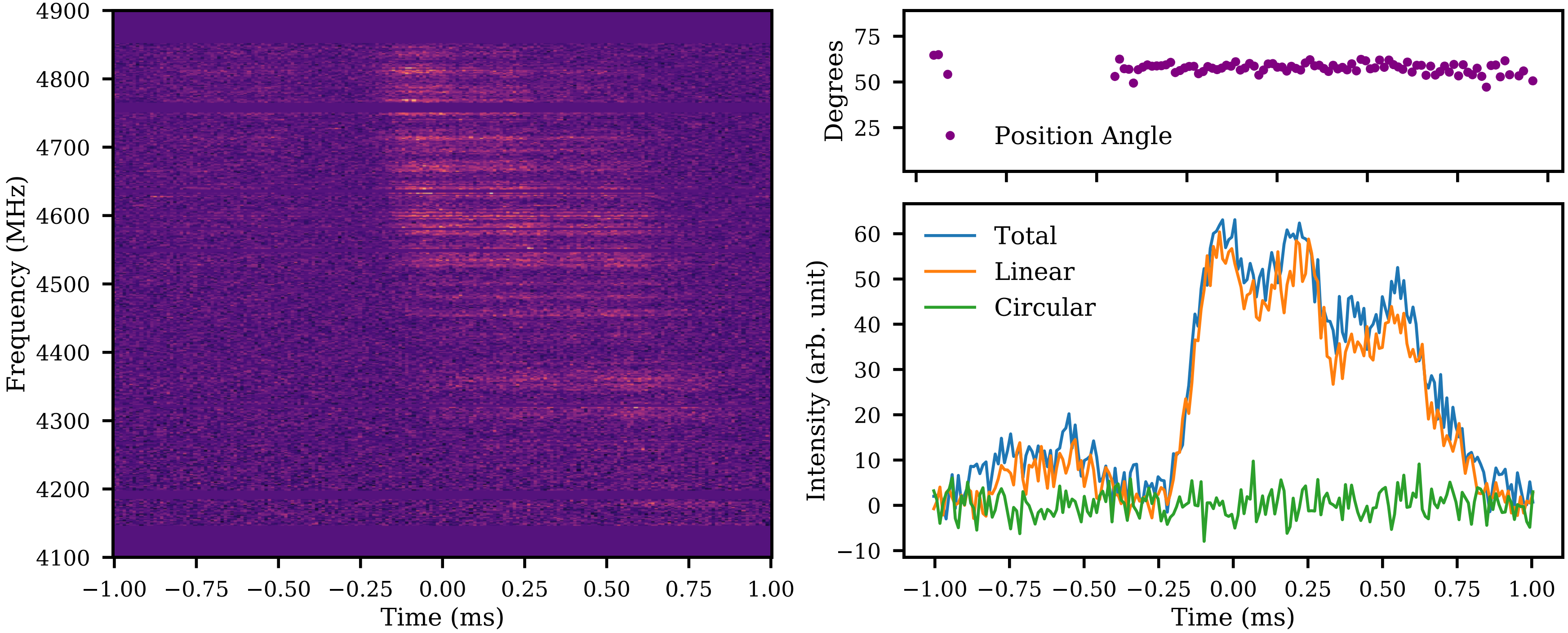
Pulse dispersion measure: $DM = \int_0^D ds\, n_e(s)$

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

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



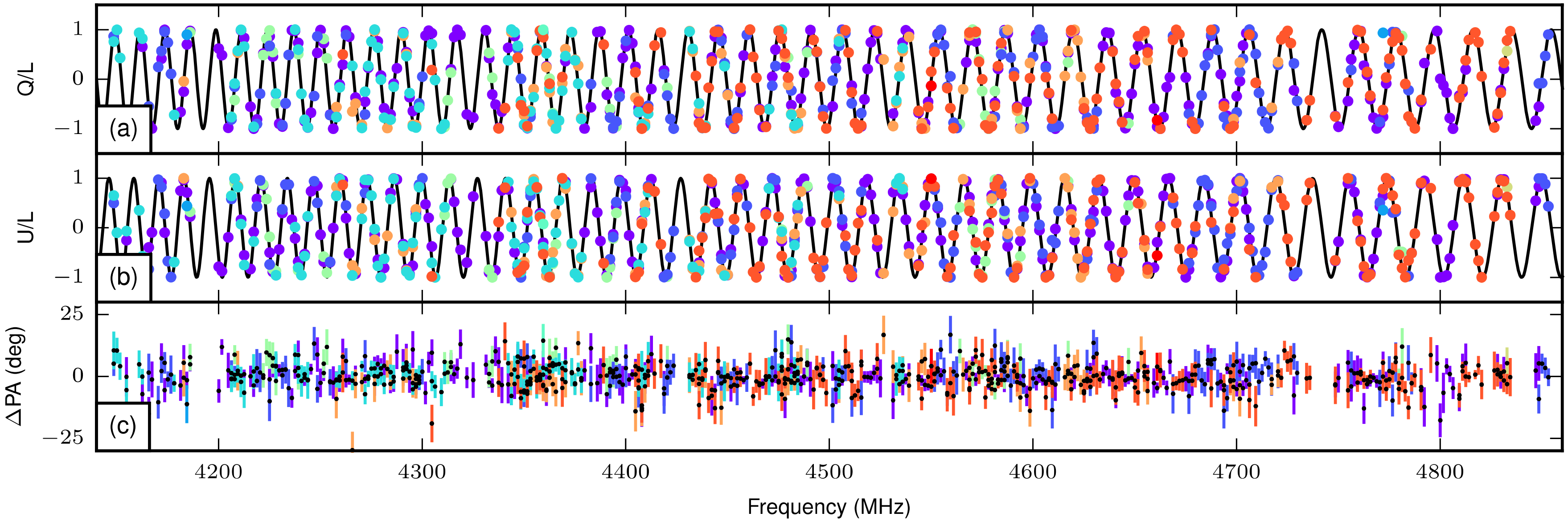
FRB 121102: Detection of polarization



Michilli et al. 2018, Nature

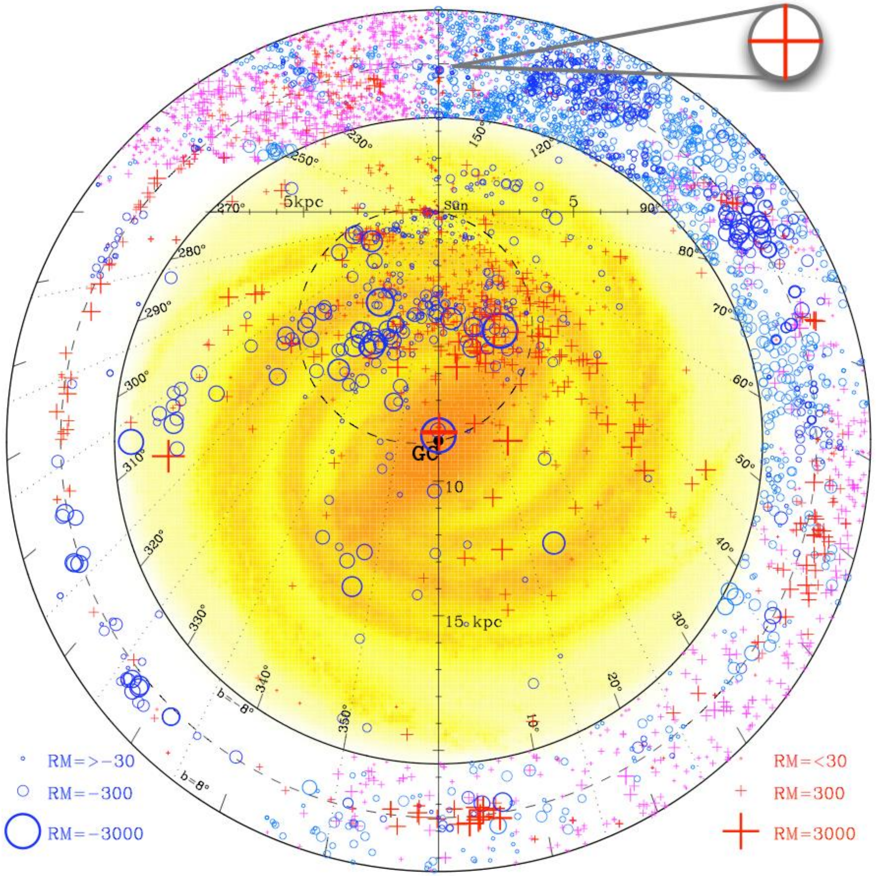
FRB 121102: Detection of polarization

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



Michilli et al. 2018, Nature

FRB 121102: Detection of polarization



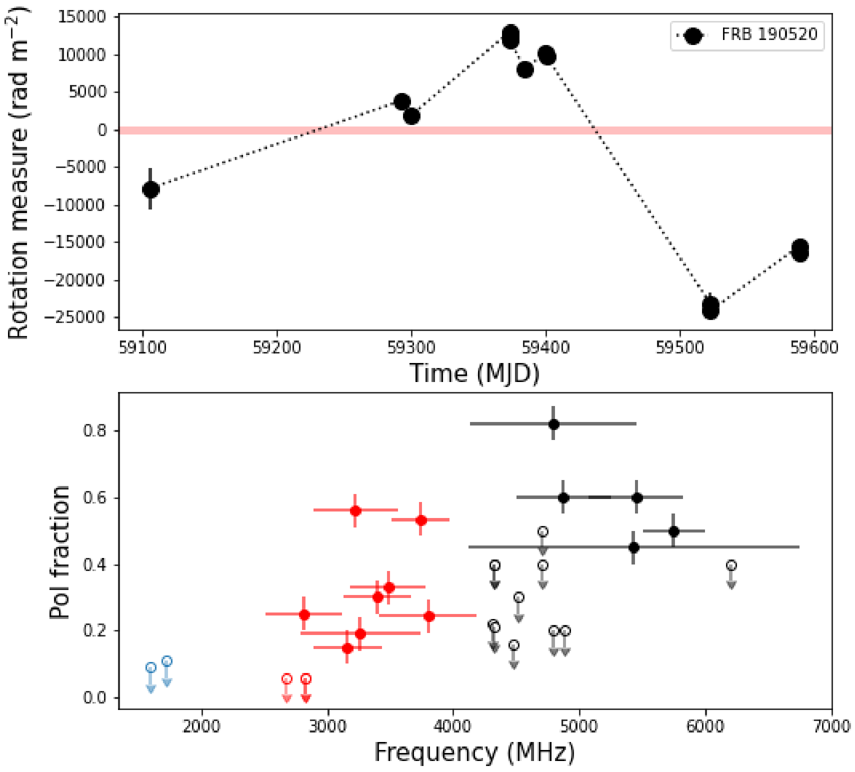
RM map: Han et al. 2017

Six bright bursts at Arecibo

- 100% linear polarization.
- RM_{src} $= RM_{obs}(1+z)^2$ $= 1.46 \times 10^5$ rad m^{-2}.
- Time variable.
- Comparable RM only seen at the center of our Galaxy.
- Arises in compact region, must be associated with FRB. B > ~mG, compared to μG for our ISM.

Michilli et al. 2018, Nature

FRB 190520B: Rapidly variable polarization



Bright bursts at GBT, Parkes

- RM appears to vary rapidly,
- Even changes sign!

➔ Field reversals.

- Source associated with a stellar wind or NS/BH accretion disk?
- Or a more complex medium.

Anna-Thomas et al. 2022, in prep.

Understanding Fast Radio Bursts

- Do all FRBs repeat?
- Or are multiple source classes really required?
- What is (are) the central engine(s)?
- Magnetars: magnetospheric bursts, or nebular?

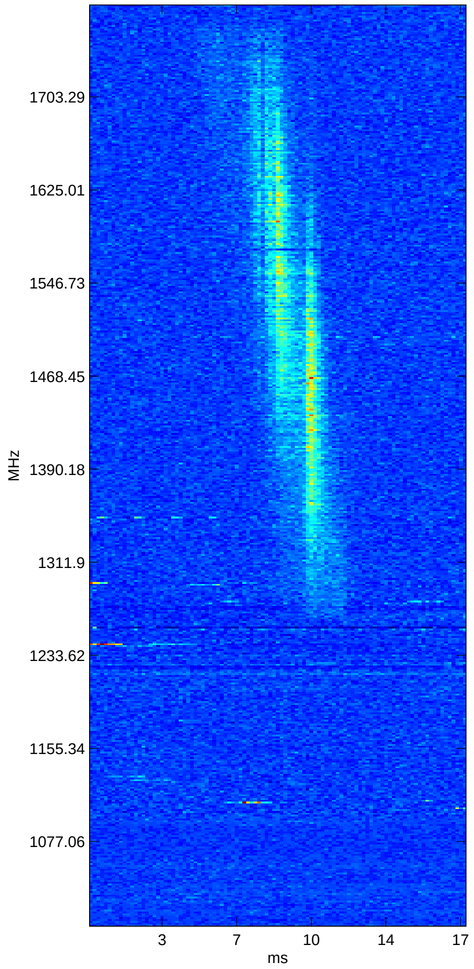
An emerging possibility: an evolving population.

→ Youngest objects are most active, repeating; PRS.

→ As they age, they become harder to detect.

Using FRBs as probes:

→ Requires detection and localization of FRBs.

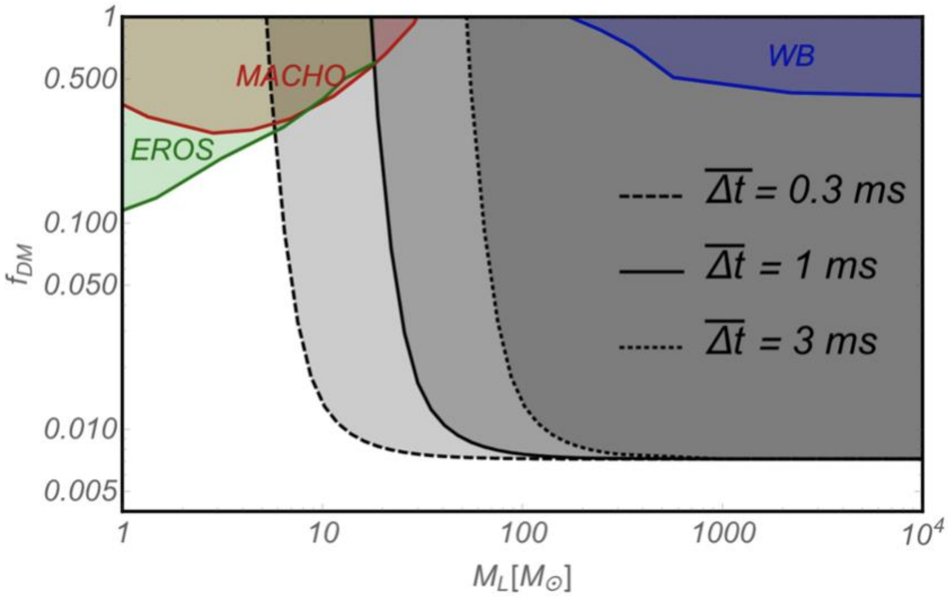


Using FRBs as probes

Astro 2020 WP:
arXiv: 1903.06535

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

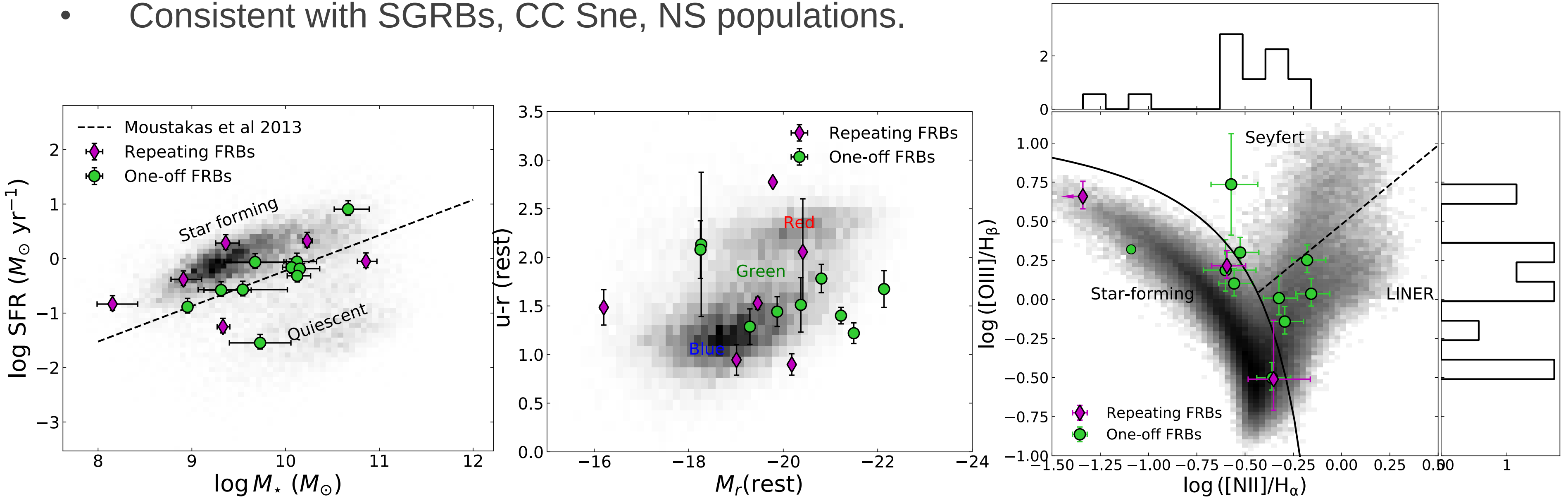
Ravi et al. (including Battaglia, Chatterjee, Cordes).



← Non-detection of micro- or nano-lensing in 10^4 FRBs produces deep constraints on the fraction of dark matter in primordial black holes.

FRB host galaxies are a mixed bag

- No strong physical distinctions between the two apparent source populations (repeating vs one-off).
- Consistent with SGRBs, CC Sne, NS populations.



Bhandari et al., arXiv:2108.01282
Characterizing the FRB host galaxy population

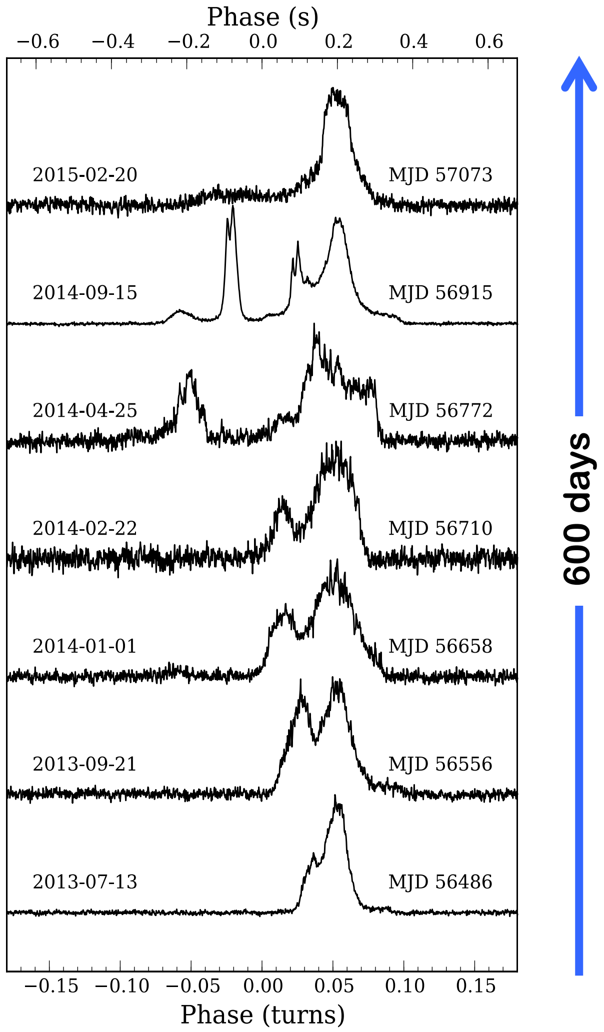
The Galactic Center magneta

Magnetar J1745–2900:

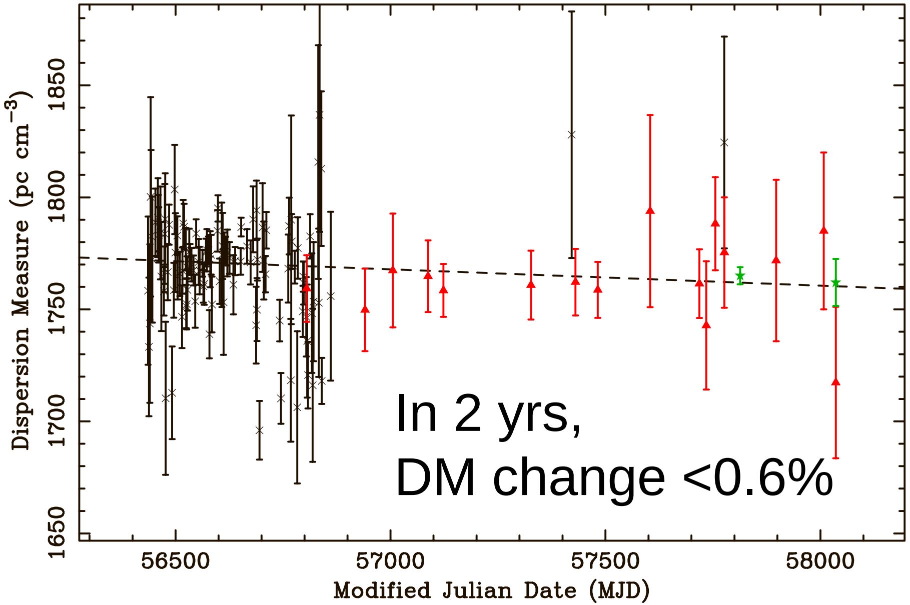
- 2.4’’ from Sgr A*.
- 0.1 pc at 8.5 kpc.

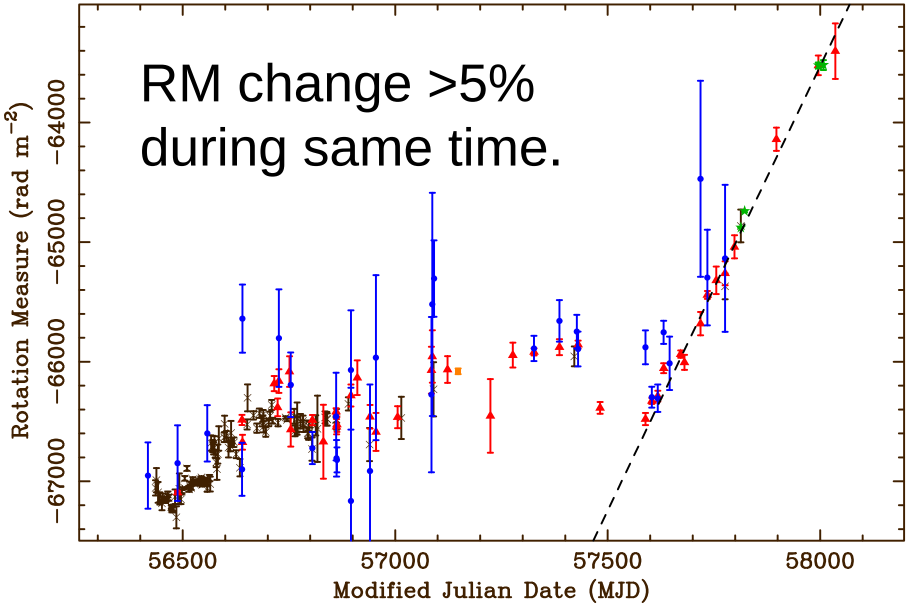
- Radio pulse profile:
  rapid evolution,
  unlike any regular pulsar.

(Wharton et al. 2019.)



The GC magnetar: DM and RM





➔ Significant change in projected B field.

Desvignes et al., 2018

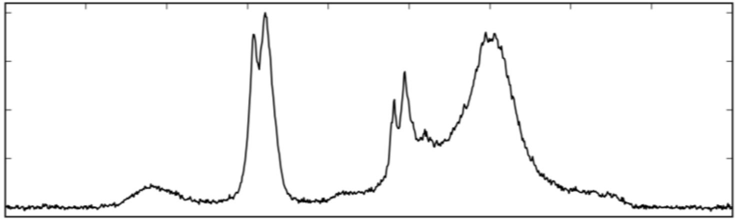
Large magnetic field variations towards the GC magnetar

Single pulses

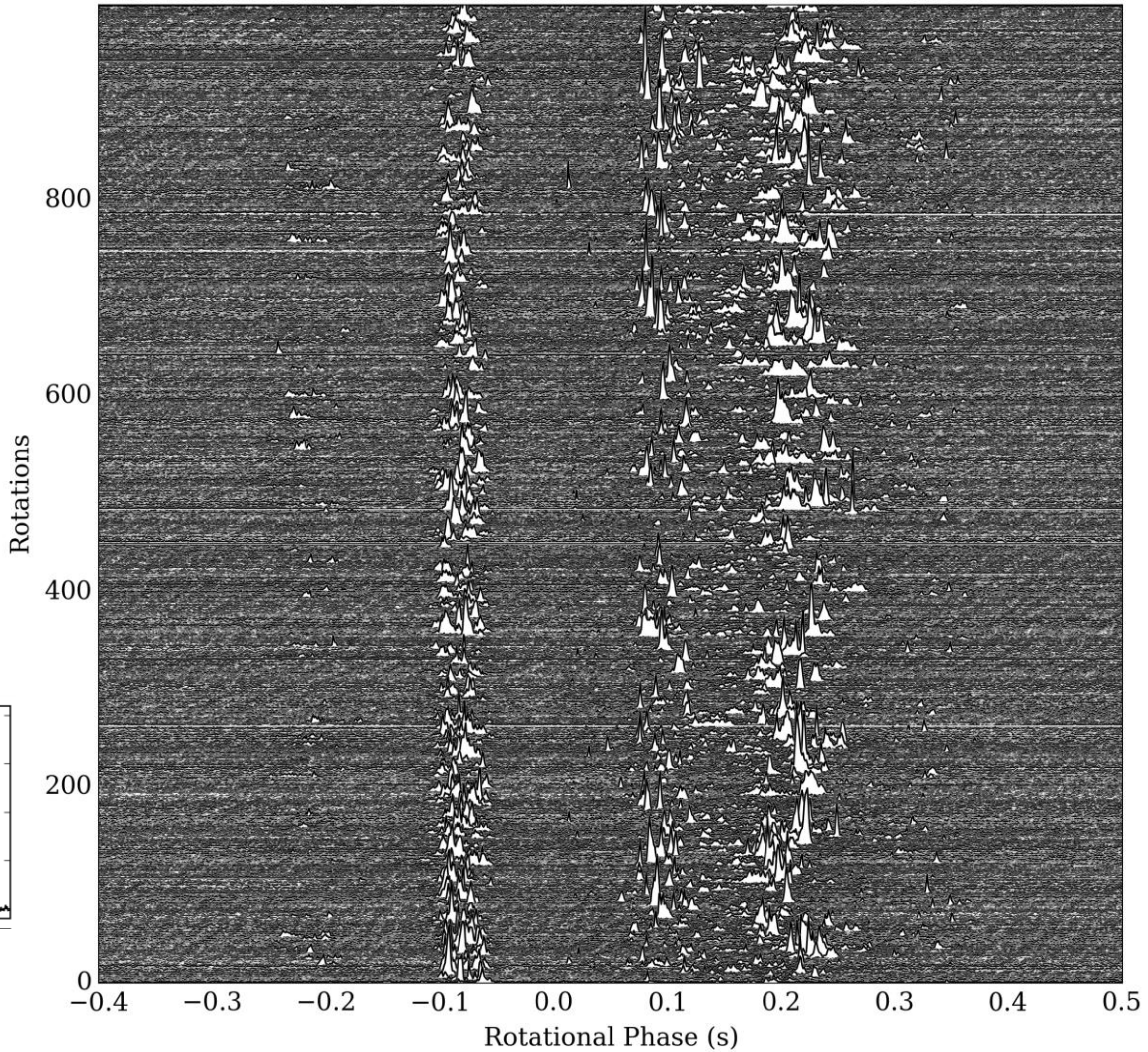
Magnetar J1745–2900:

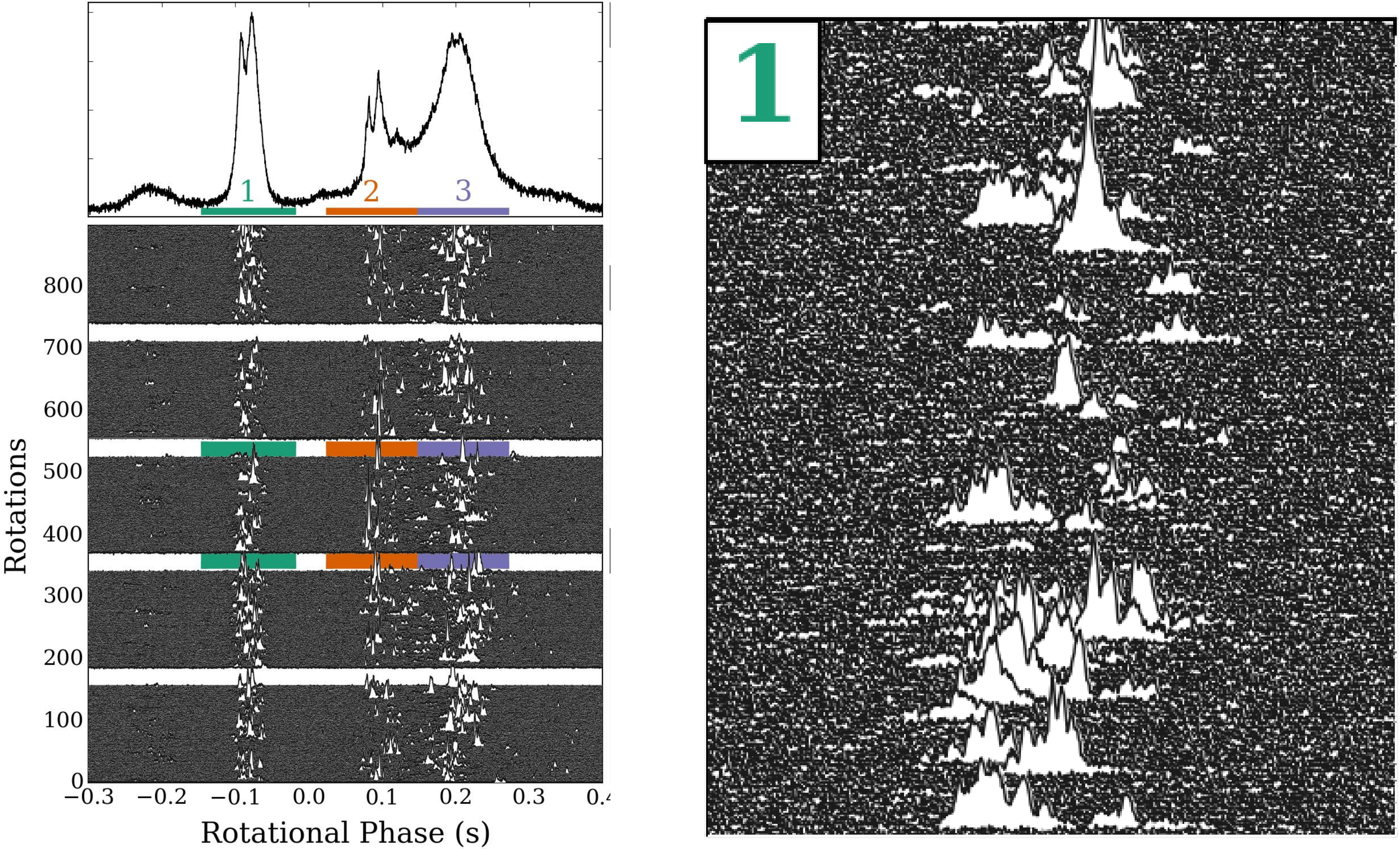
- Incredible variability in single pulses.

(Wharton et al. 2019)



(Average profile for reference)




1
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Rotations
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Rotational Phase (s)
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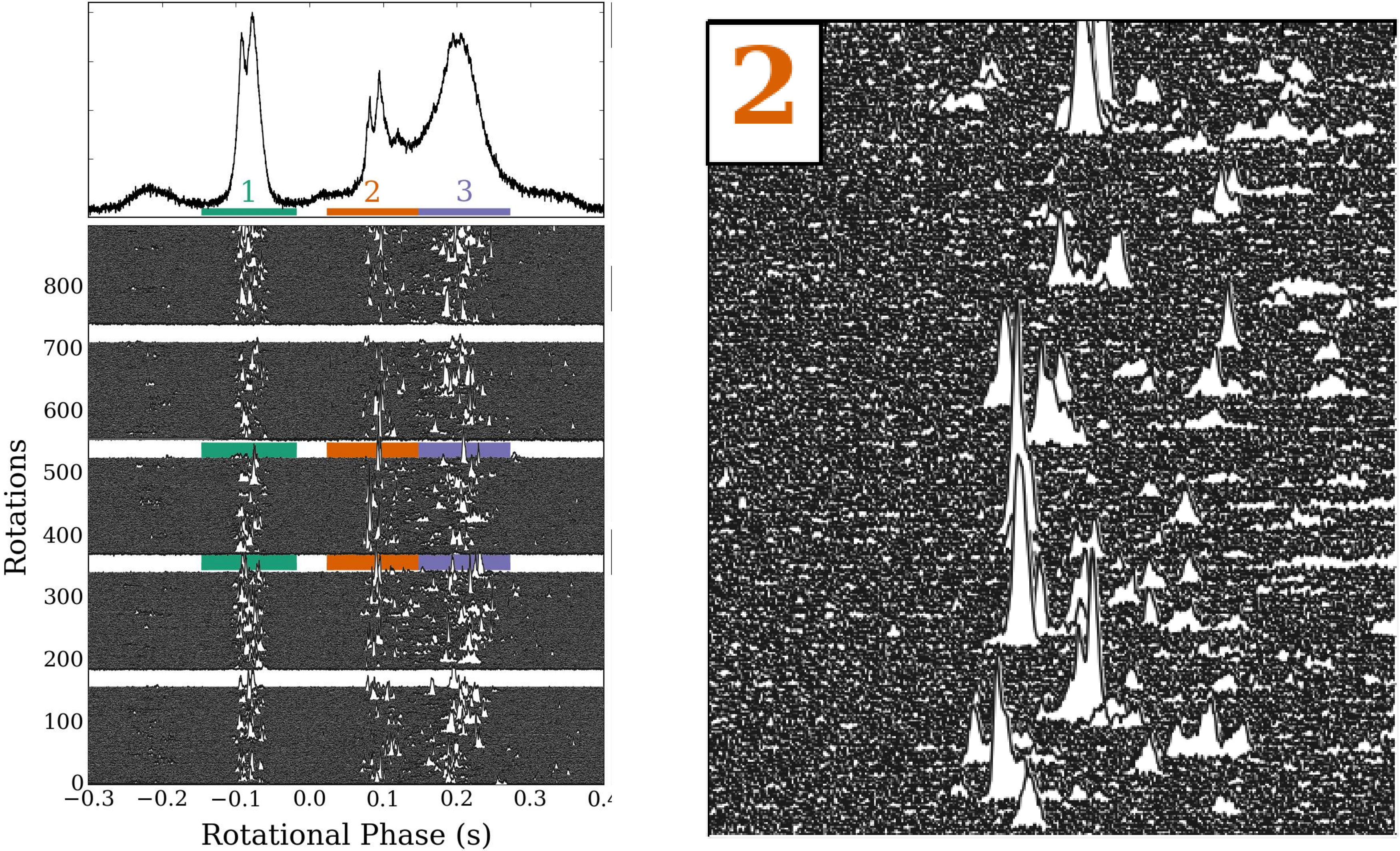

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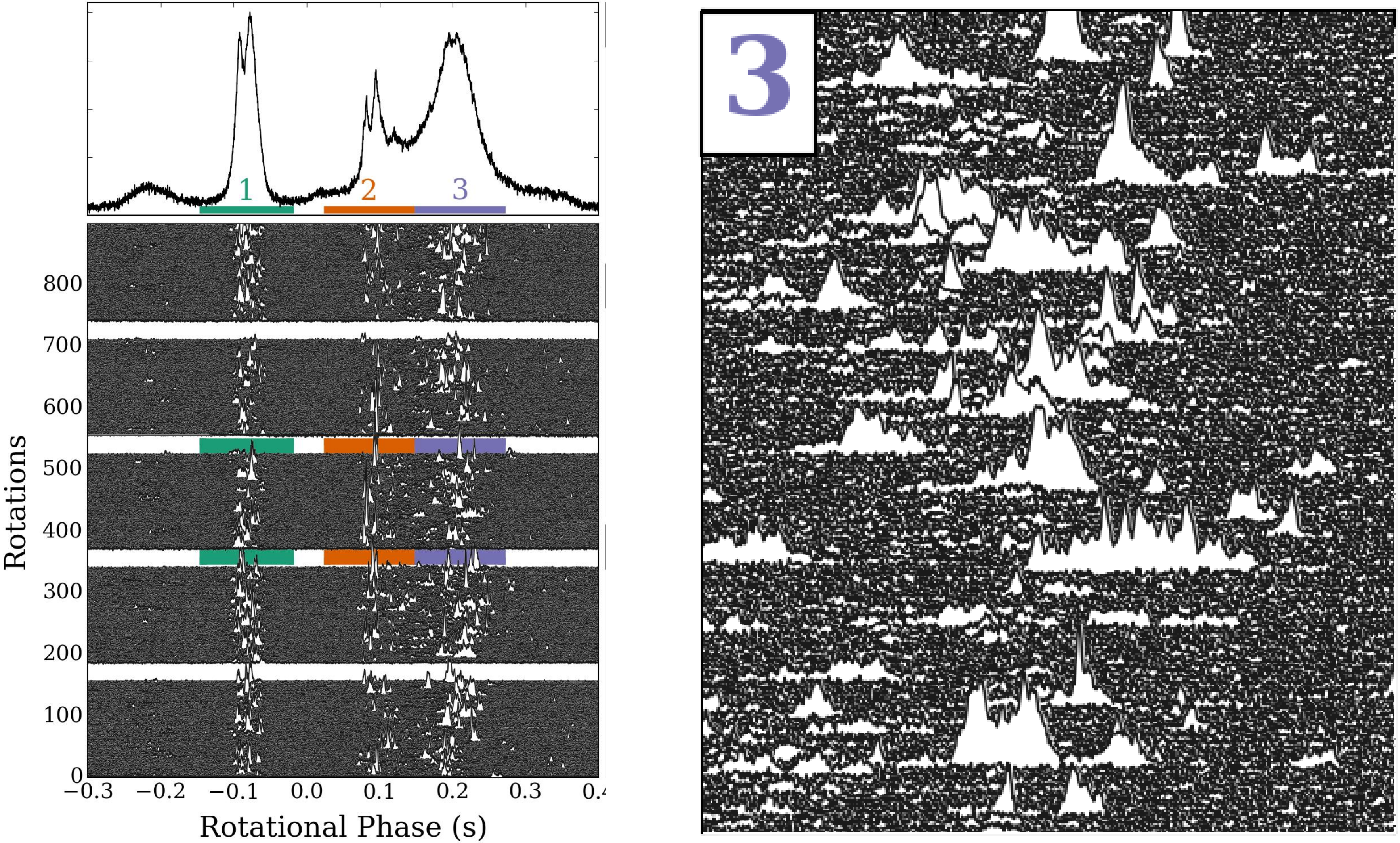
Rotations
−0.3 −0.2 −0.1 0.0 0.1 0.2 0.3 0.4
Rotational Phase (s)
2



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Rotations
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−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
Rotational Phase (s)
3