What Are Fast Radio Bursts (FRBs)

A Research Paper for
PHYS 0255 – Introduction to Astrophysics

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Date of Submission: April 18, 2025

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04/18/2025

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I Introduction

I.1 Definition of Fast Radio Bursts (FRBs)

Fast Radio Bursts (FRBs) are exactly what their name suggests: brief but intense bursts of radio waves. These fleeting signals last only a few milliseconds and are typically detected coming from deep space, as we will explore and justify later. What makes them particularly intriguing is their immense energy, despite their short duration.

To better understand FRBs, it is important to first clarify what radio waves are. Radio waves are a type of electromagnetic radiation with long wavelengths and low frequencies compared to visible light. Typically, we consider/encounter radio waves that have frequencies ranging from 3 kHz to 300 GHz and wavelengths spanning from 1 millimeter to 100 kilometers. They are widely used in communication technologies such as radio and television broadcasting, radar, and wireless networks.

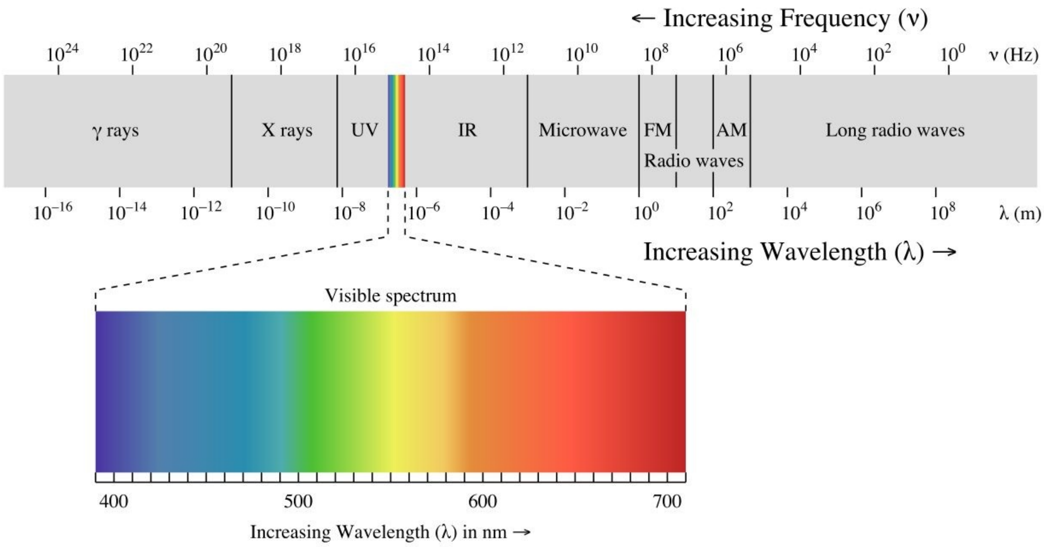

Fig. 1. Electromagnetic spectrum. Show the position of radio waves relative to other types of radiation. [1]

I.2 Discovery and Historical Background

The first confirmed detection of an FRB, known as the Lorimer burst (named after the scientist who discovered it), was made in 2007 [2]. Back in 2007, Duncan Lorimer and his student David Narkevic were looking through archival pulsar survey data (from Summer 2001) from the Parkes Observatory. Since then, advances in radio astronomy, such as improved telescopes and more sensitive detection methods, have drastically increased the rate of FRB discoveries. These developments will be explored further later.

Initially, scientists were skeptical about the ”cosmic” nature of Fast Radio Bursts due to their rarity and the limited data available at the time. However, modern observations have significantly changed this perspective. Today, it is estimated that approximately 1,000 FRBs occur daily across the entire sky (assuming we could observe 100% of the sky at all times), indicating that these events may be far more common than initially thought.

II Analysis of the Lorimer Burst

Let’s take a closer look at the first-ever detected FRB, the Lorimer burst. Specifically, we can examine its Waterfall Plot, a two-dimensional representation of intensity (as a function of frequency) over time (**Fig. 2**). One of the most striking features of this burst is the ”swiping” pattern, illustrating the fact that higher frequencies arrive before lower ones. This distinctive characteristic has become a key signature of FRBs, and we will explore its significance in more detail later. One can additionally identify the amount of noise, namely the grain on the grayscale, received by the radio telescope (due to interference/spurious signals).

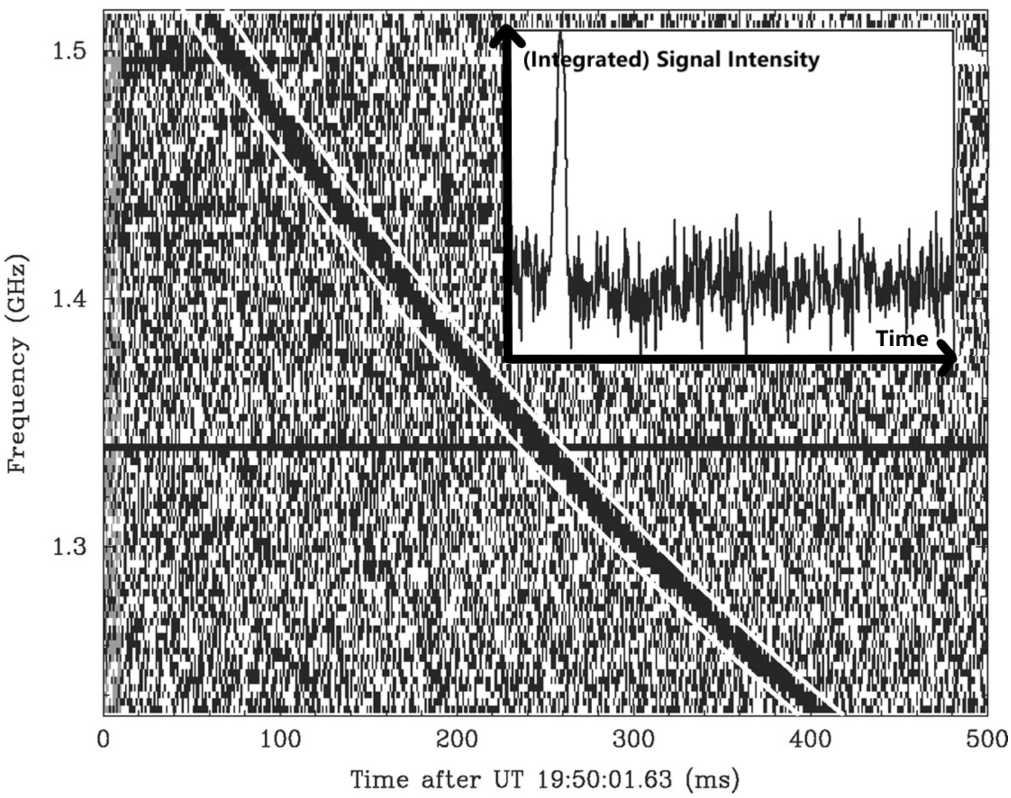

Fig. 2. The Lorimer burst - Intensity per frequency as a function of time (Waterfall Plot) & Integrated pulse shape of the radio burst (Signal Intensity vs. time) [2]

Also, note the presence of a horizontal line around 1.35 GHz (**Fig. 2**), which is characteristic of a signal of human origin. Why do we attribute this to human activity? Because this signal appears at a very precise, narrow frequency, in contrast to the dispersed signals typical of natural astrophysical phenomena like FRBs.

Human-made radio signals, such as those from satellites, radar systems, and communication networks, are typically transmitted at fixed, well-defined frequencies, which is exactly what we see here. One could argue that an external source from deep space could also emit at a specific frequency. However, this argument fails immediately: there is no observed dispersion. Theoretically, different frequency components of the signal should not arrive simultaneously, as seen with FRBs, whose signals are dispersed during their journey from deep space to Earth.

Why does this matter, or rather, why do I mention it? Because dispersion tells us far more than just "this source is very far away." As we will develop shortly, it provides strong insight into how far this FRB source is from us.

Additionally, when you combine all frequencies from the FRB, you get an incredibly sharp peak (**Fig. 2**), which shows just how energetic these events are. To put it into perspective, the energy released by a typical FRB in just one millisecond is roughly equivalent to the amount of energy the Sun emits over the course of three days. [3] This comparison really emphasize the immense power of these bursts, especially for such a brief duration.

III How far are they from us?

III.1 Light Dispersion and Dispersion Measure

As mentioned before, light dispersion is the key to estimate the distance between us and the source of this FRB. Light dispersion corresponds to the phenomenon where electromagnetic waves (radio waves here, but the phenomenon is more general) travel through a medium (which, in this case, is space) and interact with free electrons, causing a delay that depends on the frequency of the waves. In other words, different frequencies travel at different speed depending on the medium (refractive index). Unlike an ideal vacuum, space contains dust, gas, cosmic objects, and most importantly, free electrons, which are the primary cause of the dispersion of radio waves (or EM waves in general). This aspect is clearly visible on the Lorimer Waterfall Plot (**Fig. 2**), as discussed in the previous section.

In fact, this experimental dispersion (from the collected radio data) can be directly computed/measured using the observed time delay and the following formula (See Eq. 21 from [4]):

$$D(\nu_1, \nu_2) \equiv \frac{t(\nu_1) - t(\nu_2)}{\nu_1^{-2} - \nu_2^{-2}} \tag{1}$$

Note that this quantity D is often called the dispersion measure. However, it should be clarified that while astronomers commonly treat $D(\nu_1, \nu_2)$ as the dispersion measure, this is not entirely accurate. Historically, this distinction has even led to miscalculations and errors in various estimations especially in astronomical estimates where the transition/conversion between the CGS (centimetre-gram-second) unit system and the ”Système International d'Unités” (SI) arises frequently. *D* is still closely related to the dispersion measure *DM* but is not strictly equal to it. Nevertheless, *D* can be considered a proxy for *DM* as they are directly proportional (See Eq. 22 from [4]):

$$D(\nu_1, \nu_2) = K \times DM \tag{2}$$

where *K* is a constant derived from statistical mechanics, specifically from the study of the electron plasma frequency:

$$K^{-1} \equiv \frac{1}{8\pi^2} \frac{e^2}{\varepsilon_0 m_e c} \times \text{parsec (pc)} \tag{3}$$

Substituting the values of the known constants, we obtain (here given in the CGS Unit System):

$$K \approx 241.0331787\ GHz^{-2}\ cm^{-3}\ pc^{-1} \tag{4}$$

Thus, we can immediately get *DM* for future use to determine how far an emitting source is from us:

$$DM = \frac{t(\nu_1) - t(\nu_2)}{K(\nu_1^{-2} - \nu_2^{-2})} \tag{5}$$

We now have a way to determine *DM* using our previous Waterfall plot (i.e. using the raw data from the radio telescope) to get the time delay between the reception of given frequencies ν_1 & ν_2 (numerator of the equation). Note how DM only depends on 2 frequencies and the value of the (reception) time delay between them. *K* encapsulates the connection to the free electrons which dictate how it affects the dispersion (again, remember that DM quantifies the dispersion which is due to free electrons in the case of radio waves: it is *K* that mathematically makes the link between them).

III.2 Relation to Distance

Now that we can experimentally determine the dispersion measure (*DM*), we could estimate the distance to an FRB source by using a ”dispersion map” of our galaxy. This type of map actually exists (fortunately!) and are called a Galaxy Dispersion Contour Plots. They visually shows the amount of dispersion we would observe for a source located along different lines of sight throughout the galaxy (**Fig. 3**). It illustrates how the interstellar medium, including our free electrons, affects the propagation of radio waves (or EM waves in general) in various regions. By comparing the previously measured *DM* (experimental) with the values on the map, we can estimate the FRB's distance and potentially determine its location at the time the signal was emitted.

Note that these maps (**Fig. 3**) are created by modeling the distribution of free electrons in the interstellar medium using data from surveys of the galaxy's electron density. This free electron mapping can, for example, be done using pulsars as beacons, since they emit highly regular radio pulses (that is actually what Lorimer's student was doing when he discovered the first ever discovered FRB). By determining the distance to a pulsar—often through parallax measurements or associations with known astronomical objects (standard candles), we can then measure the dispersion measure (DM) from the observed time delay between radio frequencies (as detailled before). This DM tells us the total number of free electrons along the line of sight between us and the pulsar. With both the DM and the distance known, we can calculate the average electron density along that path.

In addition, hydrogen mapping, particularly of ionized hydrogen (H II regions), provides valuable insights into the distribution of free electrons. Since ionized hydrogen consists of free protons and electrons, regions with strong Hα emission (a key indicator of ionization) often correspond to areas with higher free electron density. By combining pulsar data with observations of ionized gas, it is possible to build detailed models of the Galactic electron density distribution. There is much to say about this, but we won't delve into the details of this process as it's not the focus of our study.

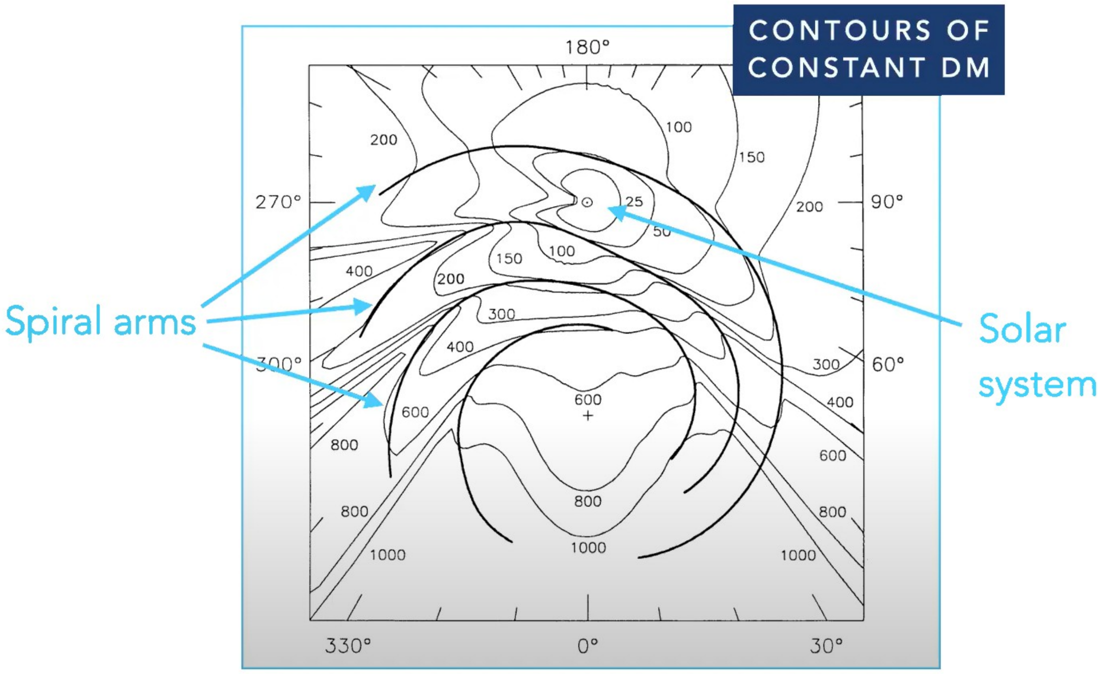

Fig. 3. 2D Milky Way Galaxy Dispersion Contour Plot (DM in $pc.cm^{-3}$) - Shows the expected amount of dispersion for a source located at a given point in this specific plane. [5]

Also, it is important to indicate that we now have enough data to map the entire galaxy in 3D and not only in specific 2D planes (in a way, a 2D Dispersion plot is now outdated).

The dispersion measure DM is in fact rigorously defined as the integral of the electron density n_e along the line of sight:

$$DM = \int_{\text{path}} n_e \, dl \tag{6}$$

where n_e is the electron density. This quantity quantifies the total number of free electrons encountered by a radio wave as it travels through the interstellar medium. It can be estimated using survey data, as well as results and estimations from statistical physics as mentioned earlier.

Thus, by computing this integral along the line of sight (path followed by the radio signal/burst) using known n_e, we can get the associated DM and compare it to the experimental DM measured thanks to the time delay so that we can get an estimate of how far away the source is or was.

III.3 The Lorimer Burst Source

In our own galaxy, the Milky Way, the amount of free electrons is finite, which imposes a maximum possible dispersion measure for sources originating within it. By analyzing the Galaxy Dispersion Contour Plot (the 3D one ideally), we can determine whether an observed dispersion measure exceeds this galactic maximum, indicating that the FRB must have originated from a much greater distance, well beyond our galaxy.

Today, we know or at least estimate this galactic maximum (Milky Way) to be about $DM_{max} \approx 25 \pm 0.1 \ pc/cm^3$ (from the NE2001.I. model - the most recent at the time) in the direction where the Lorimer FRB was detected. However, if we measure the experimental DM, meaning the one determined using the time delay between the reception of different frequencies, we eventually get a value of about $DM_{Lorimer} \approx 375 \pm 1 \ pc/cm^3$.

This indicates that the source is particularly far from us and is definitely not in our galaxy. In fact, today estimations account for different contributions to the total DM:

- $DM_{MilkyWay} = 25 pc/cm^3$ - the previously mentioned galactic maximum in the direction of the FRB source;
- DM_{IGM} – which corresponds to the intergalactic medium contribution to the dispersion. It is not directly measurable, but is estimated using cosmological models and statistical physics, based on the redshift z of the source. Because the IGM contains very dilute, ionized gas, primarily hydrogen and helium, its effect accumulates over cosmological distances. The estimation assumes a nearly fully ionized IGM after reionization and incorporates parameters such as the baryon density, Hubble constant, and matter-energy content of the universe.
- DM_{Host} - the contribution from the host galaxy;
- DM_{Source} - as the source could potentially contributes to the Dispertion Measure too (if for example the source is or is in a gas cloud that contains free electrons).

Thus, today's estimates of all these contributions to DM suggest a distance not only greater than the edge of our galaxy, but significantly greater than those associated with the local supercluster (very far away indeed, see **Fig. 4** to get a sense of how big the scale we are using here is: we work on the scale of the observable universe!). Accounting for all listed DM, the estimate of the distance to the source is about 3.42 ± 0.05 $Gly \approx 1.049 \pm 0.015$ Gpc [2]. This also implies that the energy released by the source was enormous (very 'bright'), as it remains very easily detectable on Earth despite the vast distance between us and the source.

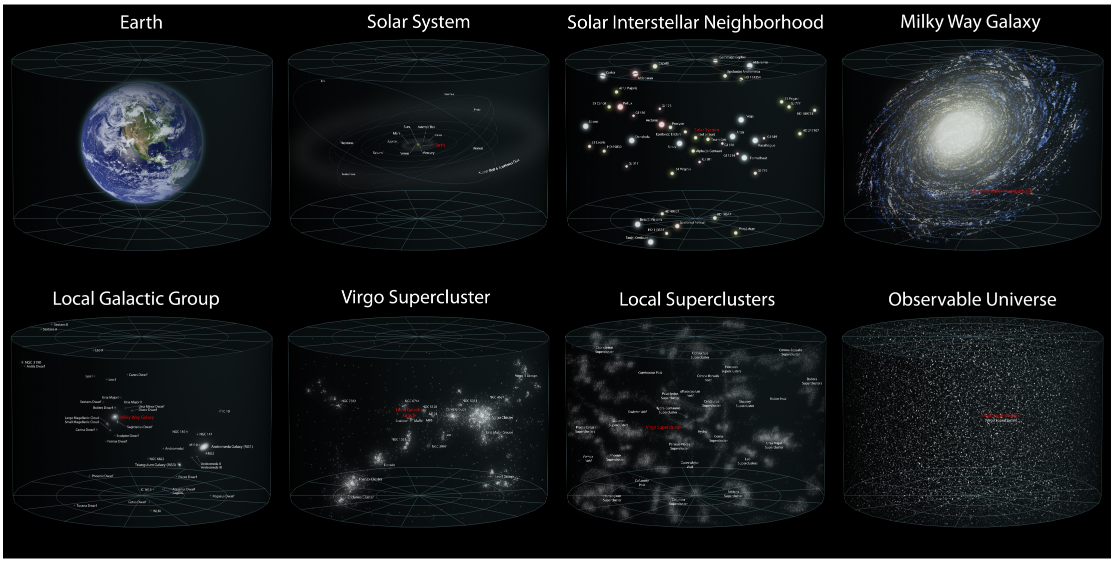

Fig. 4. Scales in Astronomy - Gives a sense of how far the Lorimer FRB is as we work in the last scale : Observable Universe one.

To conclude this section and transition to the next one, we now have a rough estimate of the distance to the source, but can we pinpoint its exact location? Which cluster, or even better, which galaxy does it belong to? Identifying this would not only provide more precision on its position and allow us to potentially identify a source, but could also allow us to refine our DM_{Host} and DM_{Source} estimates (and so to map the free electron distribution in the universe).

IV Exact Location of an FRB Source

IV.1 Sky Localization Problem

One of the biggest challenges in studying fast radio bursts is determining their exact location in the sky. Unlike optical telescopes (for example), which can pinpoint celestial objects with high precision, radio telescopes generally have poor angular resolution. This means they are not precise enough to identify a specific host cluster or galaxy for an FRB, as it is located too far away from us. As a result, hundreds, thousands, or even millions of galaxies could fall within the relatively large uncertainty range of its (angular) position. In short, this makes it difficult to localize FRBs, given their extra-galactic distances (at least for an average FRB like the previously mentioned Lorimer burst/FRB).

As an example, a single-dish radio telescope like the 64-meter PARKES, which was used by Lorimer, struggles with precise localization. Its angular resolution at 1.4 GHz (the typical frequency for detecting FRBs, like the Lorimer Burst) is around 16 arcminutes [6]. Even the 305-meter Arecibo, which played a crucial role in FRB detection (as discussed in the next subsection), had superior sensitivity but still lacked the resolution needed to pinpoint the exact position of each FRB. Arecibo's angular resolution at 1.4 GHz was about 3 arcminutes, which is far from sufficient to identify a host galaxy considering how far away these sources are, as discussed in the previous section (**Fig. 5** shows the angular resolution of both telescopes).

Note that the angular resolution of a radio telescope can be approximated using the formula from our textbook (Eq. 6.7, [7]):

$$\theta_{min} \approx 1.22\frac{\lambda}{D} \tag{7}$$

where λ is the observing wavelength, D is the telescope's diameter and θ_{min} is the angular resolution (minimum "angular distance" measureable) in radians.

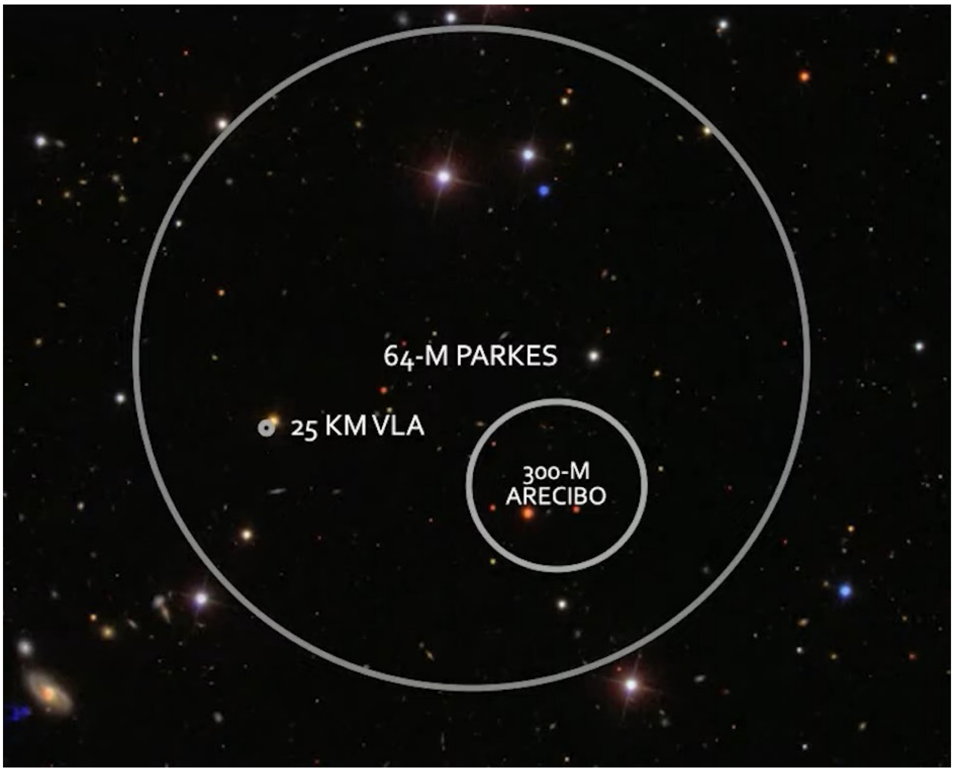

Fig. 5. Angular Resolution of 3 Telescopes, including the VLA Radio Interferometer - Helps us to visualize that literally millions of galaxies could be in these uncertainty regions - Also note how the radio interferometer is way more precise

For 1.4 GHz observations (meaning with $\lambda \approx 21$ cm), this gives the previously stated angular resolutions for both PARKES and Arecibo. For PARKES, the formula would actually yield a value of 14 arcminutes, which is still consistent with the 16 arcminutes quoted in the paper considering approximations.

Using the small angle formula : $Size = \theta \times D$, we can compute the minimum linear size that both PARKES and Arecibo can distinguish. We get 13.9 $Mly \approx 4.27$ Mpc for PARKES and 2.99 $Mly \approx 0.917$ Mpc for Arecibo. Most galaxies are about a few hundred of kpc (that is even already big for a galaxy, most are actually smaller than that), so generally smaller than these values. Therefore, they are indistinguishable by either of these telescopes.

A potential solution to this localization problem is radio interferometry, where multiple telescopes work together to improve resolution. Arrays like the 25-km Very Large Array (VLA) can achieve much greater precision by combining signals from multiple antennas. However, these interferometers can only observe a small portion of the sky at a time, making it difficult to detect FRBs, as they were believed to appear unpredictably.

IV.2 Repeating and Non-Repeating FRBs

So far, we have only discussed one specific FRB: the Lorimer burst. However, since its discovery in 2007, many more FRBs have been detected, as we will emphasize later. Before diving deeper, it is important to introduce a key distinction that will be essential moving forward: we now classify FRBs into two distinct types.

Initially, scientists believed that all FRBs were one-time events, meaning they emitted a single, brief burst and were never detected again. However, later observations revealed that some FRBs repeat, meaning they produce multiple bursts over time! This led to the classification of FRBs into two categories : repeating and non-repeating FRBs.

The first repeating FRB was discovered by Paul Scholz in 2016 using the 300-meter Arecibo telescope. He identified a source that emitted a radio burst multiple times (emits once and repeats later on). [8]

Fig. 6 shows the different Waterfall Plots corresponding to different bursts, each captured/received at a different time. Note, for example, that the first burst was received in 2012 and the second one in 2015.

This repeatability provides a crucial advantage: since their approximated locations are known thanks to radio telescopes, we can now use radio interferometers to determine a way more precise location (as we already know where to look!). Obviously, this approach applies only to repeating FRBs, limiting our ability to generalize findings to non-repeating bursts.

Also note that it raised new questions about FRBs like do they all repeat, but on different timescales (so that we have been unable to see all of them repeat)? Additionally, ”repeating” does not mean periodic here, at least for most FRBs (as we will see, we have been able to identify only one FRB with periodic activity among all repeating FRBs).

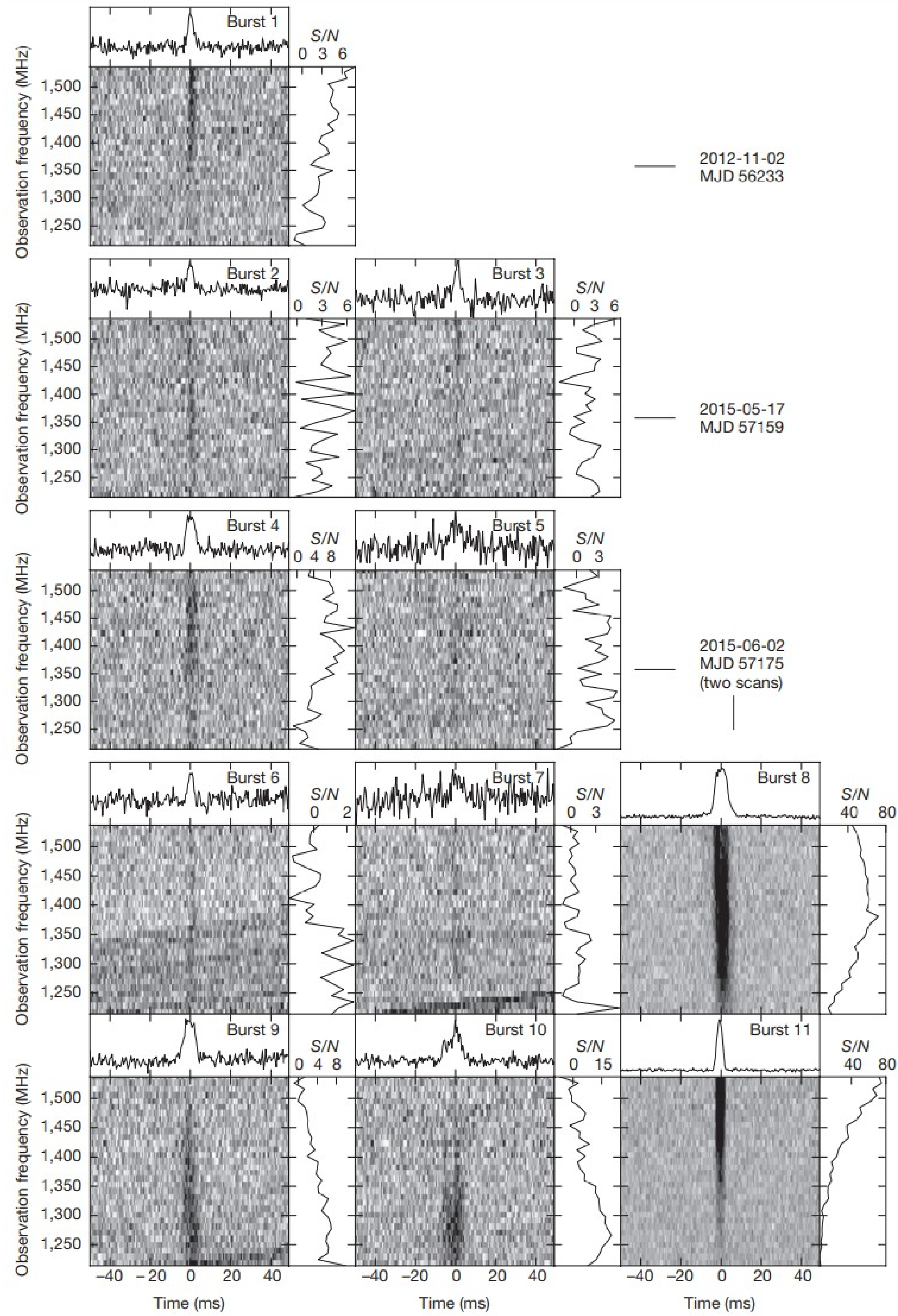

Fig. 6. FRB 121102 burst morphologies and spectra (Waterfall Plots) - Bursts from 2012 and 2015 as indicated [8]

IV.3 An Example: The Breakthrough of 2016

The very first ever discovered repeating FRB was thus the first candidate for a radio interferometry observation. The goal being to identify a precise location for the FRB source, allowing us to determine a host galaxy.

This major step forward came in 2017 with the Jansky Very Large Array (VLA) in New Mexico. Initially, a six-hour observation detected nothing, but on a second attempt, astronomers successfully captured an FRB from the same source (See **Fig. 7**). Again, remember that we know where to look, but not necessarily when to look as ”repeating” does not mean ”periodic” as mentioned before.

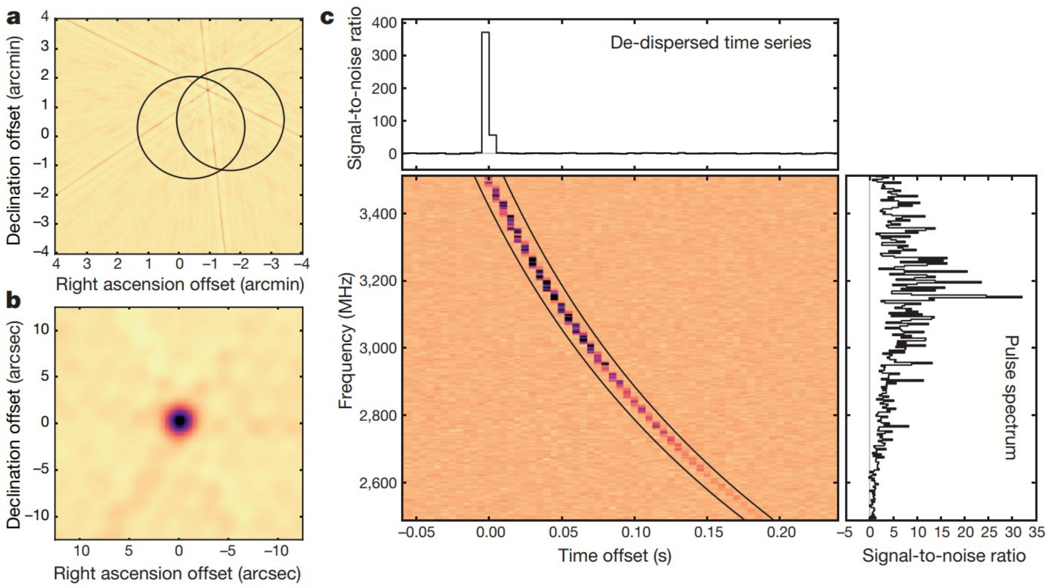

Fig. 7. VLA detection of FRB 121102 - Sky Location Dec/R.A plots (**a** and **b** - different scales) and the WaterFall Plot with the decomposed pulse/signal intensity plot (**c**) [9]

Note the usual FRB shape due to dispersion on the Waterfall Plot. Also, **a** and **b** gives us the location in the sky from which the signal is coming, i.e. the location in the sky of the FRB source (with high precision thanks to radio interferometry). The intersection of the 3 lines on **a** is the location of the source (dot on **b**) and the circles on **a** correspond to the uncertainty regions (so that the final uncertainty is their overlap only).

In addition to the coherent location, this data led to an identical measure of dispersion confirming that it was indeed the same source and not another source very close in the sky to the original one. Since then, this source has been detected hundreds of times using various telescopes, reinforcing the fact that it is an astrophysical phenomenon and not a local interference.

By combining radio observations from nine VLA bursts with optical data from the 8-meter Gemini Telescope in Hawaii, astronomers pinpointed the host galaxy of the FRB (See **Fig. 8**). Surprisingly, it was located in a dwarf galaxy — an unexpected finding, as dwarf galaxies are not typically associated with high rates of energetic events. This discovery also confirmed that the source was extremely distant (about 972 $Mpc = 3.17\ Gly$), consistent with previous estimates.

This ability to trace FRBs back to their host galaxies was literally a "game-changer" as you would have understood by now, but it does rely on the repeatability (so that we know where to point our telescope/radio interferometer).

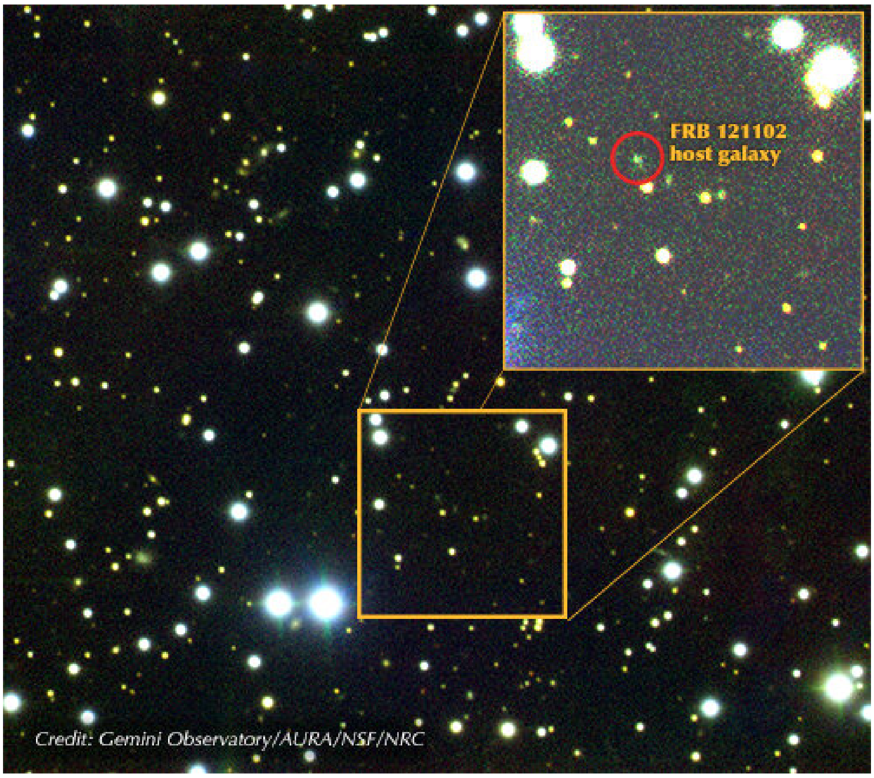

Fig. 8. The location of the host galaxy of FRB 121102. Image via Gemini Observatory/AURA/NSF/NRC/Phys.org

V Possible Origins of FRBs

V.1 Initial Hypotheses

From the previous sections, it is clear that Fast Radio Bursts must be particularly energetic. The discovery of these mysterious signals sparked a vast range of hypotheses regarding their origin. In fact, at one point, scientists had more proposed explanations for the potential sources of FRBs than the number of actual FRBs that had been observed! These hypotheses ranged from conventional astrophysical phenomena to more exotic and speculative ideas.

For example, some of the early suggestions included:

- **Magnetars**: A type of highly magnetized neutron star (a very strong hypothesis as we will see).

- **Merging neutron stars**: A violent event where two neutron stars collide.
- **Black hole interactions**: Such as those involving black hole evaporation.
- **Supernova remnants**: The remains of massive stars that have exploded.
- **Exotic theories**: Some even considered the possibility that FRBs might be related to extraterrestrial technologies, such as alien communication systems.

V.2 One Hypothesis (Best?): Magnetars

As research progressed, it became clear that not all of these hypotheses could account for the observed behavior of FRBs. Specifically, for the repeating type of FRBs, it was determined that the origin could not be from a supernova explosion or the collision of neutron stars, as both of these events are one-time occurrences. Therefore, any hypothesis involving punctual or one-time events could be discarded. This significantly narrowed the list of potential sources.

The leading model for explaining the origin of repeating FRBs is **magnetars**, although it is important to note that not all FRBs are believed to be caused by magnetars. So, what exactly is a magnetar?

A magnetar is an ultra-highly magnetized neutron star, often formed when a massive star undergoes a supernova explosion. It gets its extreme magnetization primarily from a fast-spinning star generating a powerful dynamo effect shortly after the supernova explosion. These objects possess an enormous energy reservoir due to their strong magnetic fields. [10] In fact, only about 24 magnetars have been confirmed in the Milky Way galaxy, making them relatively rare.

Magnetars have very unstable magnetic fields, and these fields can lead to massive explosions. However, these explosions have primarily been observed in X-rays and gamma rays, not in radio waves. This has led researchers to propose that the intense magnetic activity associated with magnetars might be responsible for generating the powerful bursts of energy that we observe as FRBs. But again, until very recently, no direct radio emission had been observed from magnetars.

V.3 Major Breakthrough - Identification of the First FRB Source (2020)

A significant breakthrough in the study of Fast Radio Bursts occurred in 2020 when the first galactic FRB was identified as originating from a magnetar. [10] This discovery marked the first time that a magnetar was observed emitting in the radio frequency range, which had been a major unknown until then. It was also the first time in history that an FRB source was identified and it is still the only one ever identified so far!

This finding opened up new possibilities for the origin of FRBs, suggesting that at least some of these bursts might indeed be generated by magnetars.

The main question that remains now is thus: could all FRBs be the result of very powerful magnetars? And what about non-repeating FRBs? In fact, these questions are still unanswered like many other questions about this phenomenon.

VI Improvements and Current Research

VI.1 State of Research Before 2019

Before 2019, the field of Fast Radio Bursts had made significant progress, though many questions remained open. By this time, astronomers had identified 12 host galaxies of FRBs (as shown on **Fig. 9**), though not all of them were dwarf galaxies as initially expected because of the first host galaxy identification (FRB 121102, as previously discussed). We can actually see that one of them is in a (2 arms) spiral galaxy (**Fig. 9**).

A major discovery was the identification of at least one repeating FRB, raising the question of whether other FRBs might repeat on a different timescale or not. The discovery of an FRB in a tiny/dwarf galaxy left scientists wondering about its origins and why it occurred in such a galaxy. In short, there were far more questions than answers at this stage.

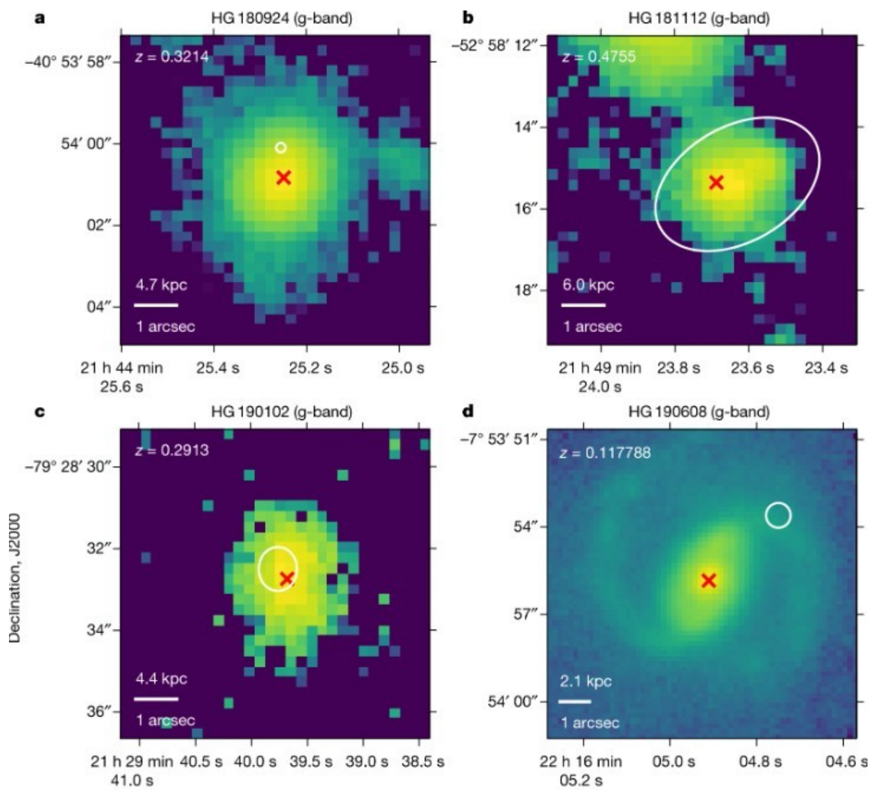

Fig. 9. Sky Locations of FRBs relative to their host galaxies (both axis give the coordinates in the sky) - Optical images of the host galaxies of six FRBs localized by ASKAP (an Australian Radio Interferometer) - The red cross corresponds to the galactic center and the white ellipse to the uncertainty region for the FRB source location [11]

VI.2 CHIME: Canadian Hydrogen Intensity Mapping Experiment (Post-2019)

Fig. 10. Photo of the CHIME Telescope (from CHIME's official website - https://chime-experiment.ca)

In the post-2019 era, the Canadian Hydrogen Intensity Mapping Experiment (CHIME) played a substantial role in advancing the study of FRBs. CHIME's unusual design made it highly efficient in detecting FRBs as it can cover a large section of the sky and analyze a lot of data quickly. It allowed us to identify 18 new FRBs repeaters, providing further insights into the differences between repeating and non-repeating FRBs. Indeed, to start identifying patterns and make deductions we need more data (up to the point from which we can potentially invoke and use statistical methods).

A major discovery from CHIME was the identification of an FRB with periodic activity occurring every 16 days. This event marked the second FRB to be localized, and in this case, it was located in a spiral galaxy [13]. This finding raised new questions regarding the nature of FRBs and suggested that periodicity might be a characteristic of certain repeating FRBs (not understood at this point).

Additionally, as mentioned in the last section, CHIME made a groundbreaking discovery with the identification of the first galactic FRB which revealed to be a magnetar. As said before, this raised further speculation about whether all FRBs could potentially be powerful magnetars or not?

VII Conclusion

Fast Radio Bursts have gone from complete mysteries to one of the most exciting areas in modern astrophysics in just a few years (not even 2 decades!). With instruments like CHIME, we have now identified over 500 sources (by 2020, see **Fig. 11** and **Fig. 12**), but many questions still remain.

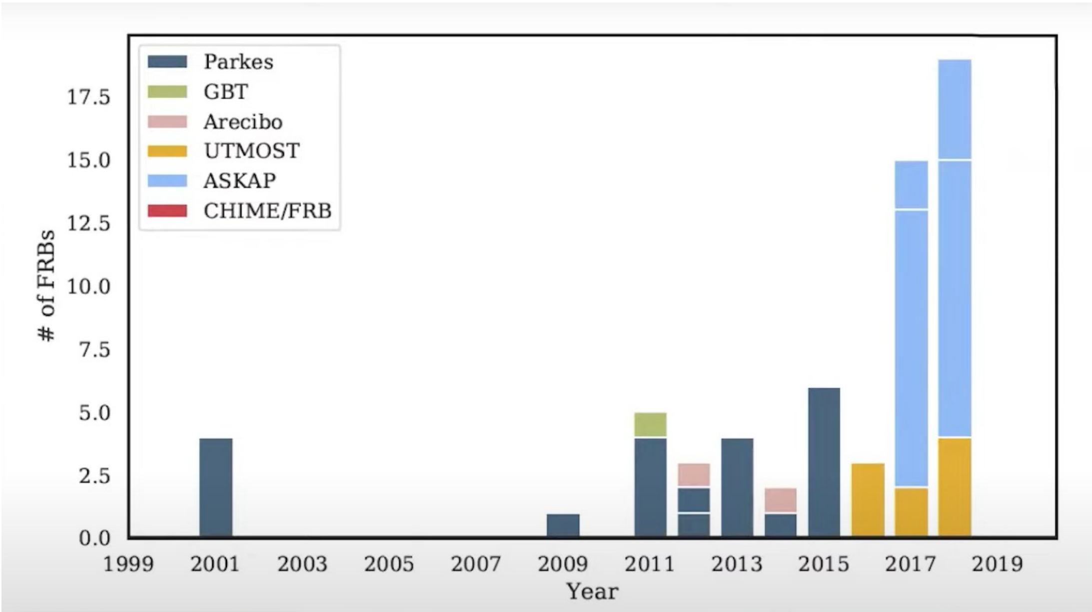

Fig. 11. Number of FRBs discovered before mid-2018 vs. year, by Professor Victoria Kaspi.

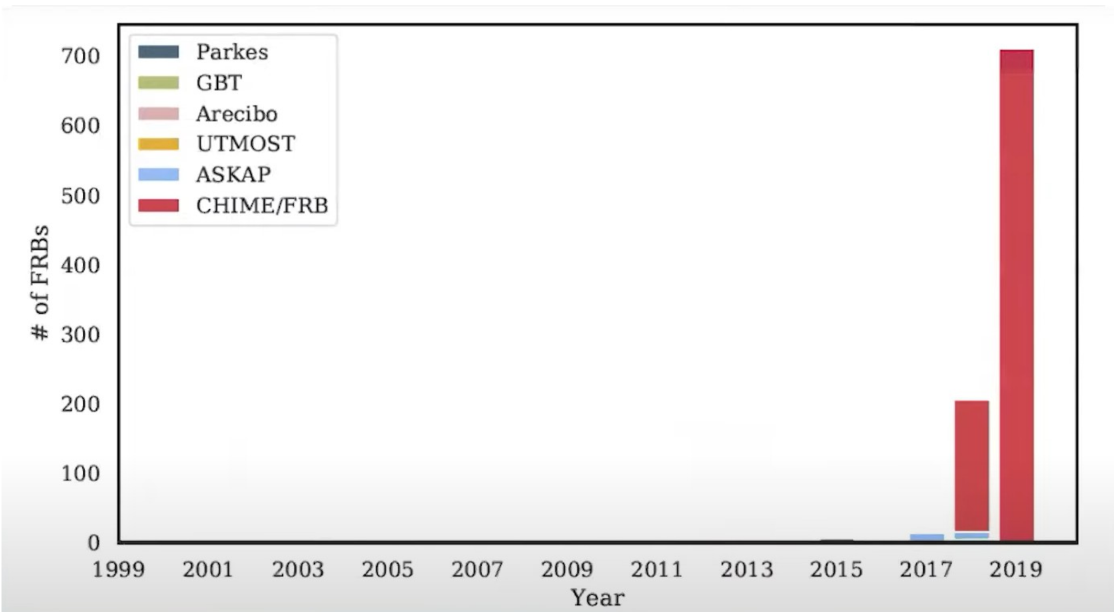

Fig. 12. Number of FRBs discovered including mid-2018 and 2019 vs. year, by Professor Victoria Kaspi (we literally no longer see the data from some of the previous years)

The next steps are clear: we need to pinpoint the location of as many FRBs as possible using powerful radio interferometers. Knowing where they come from is key to understanding what they are. It would also allow us to start identifying patterns and use statistical physics/methods.

To boost our capabilities, scientists are also working on building smaller, CHIME-like telescopes around the world. More telescopes mean better sky coverage and thus more discoveries —and hopefully, more answers. For example, we need to identify and understand the formation mechanisms of FRBs, but also answer the questions about if there are multiple ”types” of FRBs.

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