

FAST RADIO BURSTS (FRB) & CHIME

UNIT DESCRIPTION

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1) Overview and Introduction:

What are Fast Radio Bursts?

Radio waves from space are a form of **electromagnetic radiation**, just like visible light, but with longer wavelengths and lower energy. These waves are produced by a wide variety of **natural cosmic processes** and can be detected by radio telescopes on Earth.

Fast Radio Bursts (FRBs) are short-lived, incredibly powerful bursts of these **radio waves** that last for just a few milliseconds (thousandths of a second).

Discovery History & Major Milestones:

FRBs are one of the most intriguing astronomical discoveries of the 21st century. Let's talk about the discoveries of FRBs in brief:

1) 2001: The **first FRB** was detected in the year of 2001, in **Parkes Radio Telescope of Australia**, but was not identified at that moment. Later, in 2007, **Duncan Lorimer** and student **David Narkevic** discovered this pulse while reviewing archival data. This event is now known as '**Lorimer Burst**'. Lorimer and his colleagues published this discovery in the famous science journal, "SCIENCE" which sparked global interest.

2) 2012: The **first repeating FRB** was detected by **Arecibo Observatory** in 2012. Before this event, Scientists thought that Supernovas are the reason of this bursts as they emit a lot of energy in a very short time. But repeated radio bursts changed the entire scenario. Supernovas or neutron star mergers are one-time, catastrophic, cosmic events, so they immediately destroy or permanently alter the original object, therefore they can't generate such repeated radio wave bursts. As multiple bursts were detected from the same source, scientists concluded that:

- The source survived the burst.
- The mechanism was a high-energetic but non-catastrophic process (i.e. not destructive)

3) 2016: The **Australian Square Kilometre Array Pathfinder (ASKAP)** detected FRBs in **real-time** (i.e. processed immediately as it happened, rather than being found later in stored data.).

There are a lot of advantages of Real-Time detection method:

- If an FRB is detected in real-time, **other telescopes** (radio, optical, X-ray, etc.) can be alerted instantly.
- Astronomers can observe **afterglows** and other related activities.
- Real-Time detection makes it easier to find the **exact location** of the burst and also gives clues about the **physical process** that caused the burst.

4)2018: The **Canadian Hydrogen Intensity Mapping Experiment (CHIME)** started detecting FRBs in large numbers. Within weeks, CHIME found dozens of new FRBs, including several repeaters.

5)2019: FRB 180916.J0158+65 was found to repeat every **about 16.35 days**. It was the first evidence that some FRBs follow periodic patterns, hinting at possible connections to **binary star systems** or **magnetars** (Magnetars are the remnants of massive stars that have undergone a supernova and have ultra-strong magnetic fields).

6)2020: First FRB was detected in our **Milky Way**, that was associated with a **magnetar (SGR 1935+2154)**. It confirmed magnetars as a possible source for at least some FRBs.

7)2022-2024: CHIME, **Five-hundred-meter Aperture Spherical Telescope (FAST)** (China), and other observatories have detected thousands of FRBs, including numerous repeaters and complex patterns.

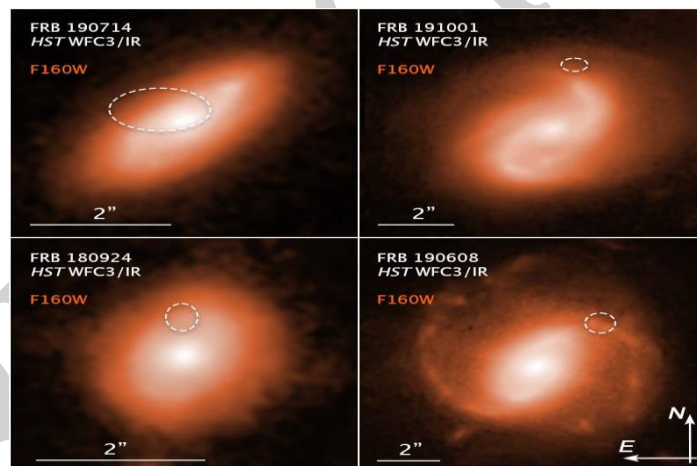


Fig-1: Hubble Space Telescope (HST) images of five distant galaxies, which are the host galaxies for specific FRBs

Importance of FRB studies in modern astrophysics:

FRBs have one of the fascinating phenomena of the universe. We must study their nature and activities very carefully in order to know the mysteries of our universe. Here are some facts that explain their importance in modern astrophysics and cosmology:

A) Understanding extreme physics: Studying FRBs helps us understand **super-dense matter**, **ultra-strong magnetic fields**, and relativistic effects under extreme conditions. They help us to test theories of **plasma physics** and **high-energy astrophysics**.

B) Probing the Intergalactic Medium: As FRBs travel through space, their signals are dispersed and altered by electrons in intergalactic space. This allows scientists to **measure matter between galaxies**, including **ionized gas and cosmic filaments**, which are otherwise hard to detect.

C) Measuring Cosmic Distances and Expansion: FRBs originate from faraway galaxies, they help us in estimating **cosmological distances**. When combined with redshift data, FRBs can help study the **rate of expansion of the universe** and possibly probe **dark energy**.

D) Testing Fundamental Laws of Physics: By studying the FRBs, we can check whether the speed of light is the same at every point of universe or not. Also we can test the fundamental nature of gravity for objects across billions of light years.

2) Nature and Characteristics of FRBs: Now we are going to discuss the nature and characteristics of fast radio bursts (FRB).

Duration, frequency range, intensity, and dispersion measure (DM):

A) Duration: FRBs are **extremely short** lived. Their typical duration is 1-10 milliseconds ($1 \text{ ms} = 10^{-3} \text{ s}$). Some bursts even have substructure on microsecond timescale ($1 \text{ microsecond} = 10^{-6} \text{ s}$)

B) Frequency: FRBs have been detected in a frequency range of **400 MHz- 8 GHz mostly**. For example, CHIME operates in 400-800 MHz range. On the other hand, PARKES and FAST detect bursts in a range of 1-1.5 GHz.

C) Intensity: Intensity of FRBs vary depending on their **nature** and **distance** from earth. For nearby FRBs, peak flux density can be 30 Jy or more than that. Distant bursts may appear weaker but remain detectable due to extremely high intrinsic energy.

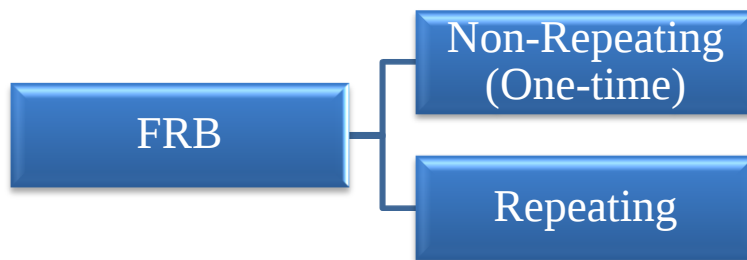
Jy (Jansky) is a unit of **flux density (brightness)** used in radio astronomy. $1 \text{ Jy} = 10^{-26} \text{ W/m}^2 \text{ Hz}$ [A radio signal from distant galaxies contain several electromagnetic waves of different wavelengths which belong to radio spectrum. So, we get a bandwidth for the signals. “Flux density of a radio burst = 1Jy” means “the telescope receives 10^{-26} J energy per unit surface area, for unit bandwidth, in 1 second”.]

D) Dispersion Measure (DM): DM quantifies the total number of **free electrons** between the source and us . The formula of DM is given by:

$$DM = \int_0^d n_e(l) dl$$

Where, $n_e(l)$ is the number of electrons per unit volume at a distance l from the source, and dl = differential length element along the path. By multiplying n_e and dl , we get electron density on a very thin surface at distance l from the source. Then, by integrating it from 0 to d , we get the total number of electrons.

Classification of FRBs: There are mainly two types of FRBs which have been observed till date. They are:



A) One time FRB: These are **non-repeating FRBs** (also called a *singular* or *non-recurrent* FRB). These are radio bursts detected **only once** from a specific sky location. **No further bursts** are observed even after extensive follow-up monitoring with sensitive telescopes. Such events are interpreted as **catastrophic** — meaning the source is **destroyed or permanently altered** during the burst, so it cannot emit radiation again.

- **Duration:** These bursts are observed only for a few milliseconds (1-5 ms)
- **Frequency:** Typically 400 MHz - 2 GHz.
- **Fluency:** One time bursts are often brighter than repeating bursts.
- **DM:** DM is very high which indicates very large cosmological distances.
- **Polarization:** Highly polarised, which suggests strong magnetic field is present near the source.

Example: FRB 010724 (Lorimer Burst) (Discovered in 2007 in Parkes telescope archival data), FRB 180924 (Detected by ASKAP (Australia) in 2018), FRB 190523 (Localized to a galaxy 7.9 billion light-years away).

B) Repeating FRB: Repeating FRBs are such sources that emit **multiple radio bursts** from the **same sky location**, detected at **different times** — ranging from minutes to months or even years apart. As multiple bursts come from the same exact location, it is obvious that the source of the burst doesn't get destroyed or altered. The progenitor in this case **survives each burst**, meaning the energy source can **recharge and burst again**.

- **Duration:** Repeating FRBs last for a few milliseconds (like one time bursts).
- **Frequency:** Frequency range is 400 MHz – 8 GHz.
- **Fluency:** Generally **lower energy** per burst compared to one-time FRBs.
- **DM:** DM is almost same near the burst that confirms the presence of same source.
- **Polarization:** Often very high, indicating the presence of very strong magnetic fields near the source.

Theories about the origin of FRBs:

Scientists still don't know the exact cause of FRBs, but there are **leading hypotheses** based on energy scale, repetition behaviour, and host galaxy observations.

A) Magnetars: The magnetar model is the most popular model used to describe the origin of FRBs.

Magnetars are **young neutron stars** with a very **strong magnetic field** ($\sim 10^{15}$ Gauss). They can produce powerful flares as well as magnetic reconnection events. Thus they can produce impulsive electromagnetic bursts in a very short time which can be detected as FRB in radio telescopes.

Evidence:

- The first direct link between a magnetar and a FRB was FRB 200428. It was thought to be originated from a magnetar in our galaxy (SGR 1935+2154).
- Observed timescales of FRBs (millisec) match neutron star process.
- Magnetars explain **both one-time and non-repeating** FRBs as magnetars can have a single, impulsive electromagnetic burst as well as multiple flare events.



Fig-2: Magnetar

B)Neutron star merger: Merger of neutral stars is another widely accepted theory.

Two neutron stars rotate in two different elliptical orbits, keeping the centre of mass at the common focus of the orbits. Gradually the stars spiral toward each other due to **gravitational wave emission**. Each neutron star has a powerful **magnetosphere** (region filled with plasma and magnetic fields). As they spiral in, these magnetospheres start interacting and reconnecting. Due to these magnetic reconnections, an induced current is generated which accelerates both electrons and positrons of magnetospheres to **relativistic speeds**. As a result, the charged particles create electromagnetic wave pulses.

Neutron star merger can produce **only one-time FRBs** as after the merger, no second event happens. Hence, no further bursts can be detected.

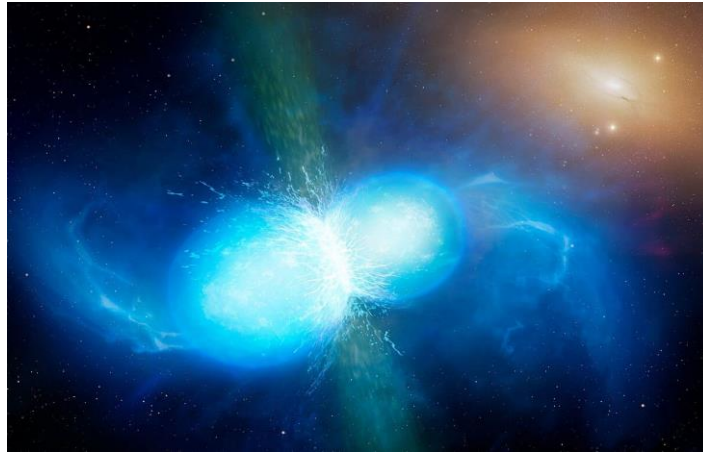


Fig-3: Neutron Star Merger

C)Neutron star- Black Hole merger: This theory is recently also becoming very popular among astrophysicists across the globe.

We know in a binary system, two stars orbit in two different elliptical orbits. In some special cases, one of these stars explodes as a supernova and leaves behind a neutron star. On the other hand, the other star collapses into a black hole due to complete consumption all of its fuel and absence of such a force that can counteract its own gravitational pull. In this way, a normal binary star system transforms into a NS-BH system.

In this system, the neutron star continuously rotates along its orbit. According to general relativity, any accelerating mass in strong gravity emits gravitational waves that carry away its **energy** and **angular momentum**. Thus, the neutron star continuously loses its energy and the orbit shrinks. Then its orbital speed starts decreasing and after a sufficient amount of time, the neutron star spirals into the black hole. Just before being swallowed, the NS's magnetic field lines sweep through the black hole's **accretion plasma** (thin, glowing disk near the black hole, made of hot gas, dust , plasma). The motion induces intense **currents** and **electromagnetic induction**, producing a brief but powerful **radio pulse** — the FRB. This model can produce **only one-time FRBs** as neutron star is completely destroyed. Some possible precursor signals may be detected before the gravitational waves or gamma-ray bursts.

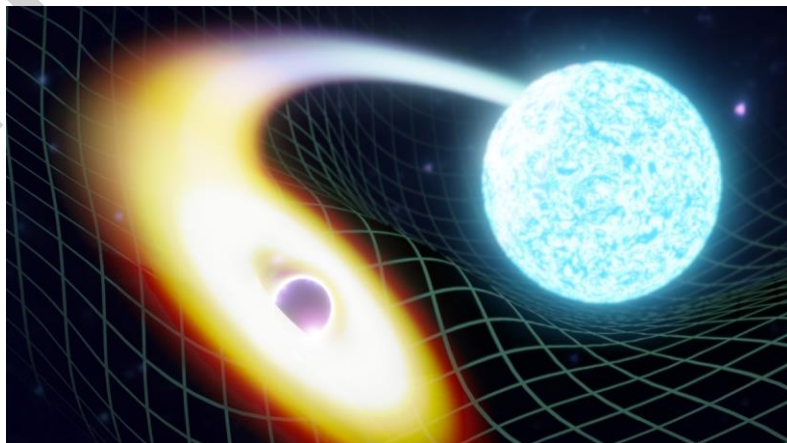


Fig-4: NS-BH merger

3)Detection and Observation Techniques:

How FRBs are detected and recorded?

FRBs are detected using **radio telescopes** — large antennas or arrays that capture radio waves from the sky. Let's go through how an FRB is actually **captured and identified**.

- The telescope receives **radio waves** from the sky as electric signals (voltages) in its antennas or dishes.
- The analog radio signal is converted into a **digital data stream** — a sequence of numbers representing signal strength vs. time and frequency.
- A **digital backend computer** (often using GPUs or FPGAs) analyzes the incoming data in real-time. It searches for **short, bright pulses** in the data — these could be FRBs.
- Computers apply a mathematical correction called **de-dispersion**, which aligns all frequencies to reconstruct the **original sharp pulse**.
- If a **millisecond pulse** remains strong even after de-dispersion, it is flagged as a **candidate FRB**.
- Once confirmed, the burst data — including **intensity vs. time and frequency** — is stored. The exact **arrival time, sky coordinates, intensity, frequency range, and dispersion measure (DM)** are noted. Other telescopes may be alerted to observe afterglows.

Role of radio telescopes and signal processing:

We'll look first at the **role of radio telescopes**, then at the **signal processing** that converts those faint cosmic radio waves into usable scientific data.

A) Radio Telescopes: A radio telescope is essentially a **giant antenna system** that receives **radio-frequency (RF)** electromagnetic waves from space.

- Collects as much radio energy as possible.
- Covers wide frequency ranges,
- Continuously monitors large areas of the sky.
- Pinpoints the source's direction.

B) Signal Processing: Once the telescope receives the radio signal, **the real work begins** — transforming noisy voltages into scientifically meaningful data. Signal processing is what allows scientists to **detect, analyze, and confirm** an FRB event.

- As the raw signal is very weak, low noise amplifiers boost that signal which is easier to analyse.
- The analog voltage signal is converted into a digital stream using **Analog-to-Digital Converters (ADCs)**.
- The data is split into many narrow frequency channels using a **Fast Fourier Transform (FFT)**.

- The signal is mathematically corrected so that the signal can be recognizable as a FRB.

Challenges in identifying genuine FRBs from background noise:

Since Fast Radio Bursts are incredibly faint and brief, scientists have to face a lot of key challenges in identifying genuine FRBs . Let's discuss about them in details:

A) Galactic and Cosmic Background Noise: The **Milky Way** itself emits strong **synchrotron radiation** in radio frequencies. The **cosmic microwave background (CMB)** and **extragalactic radio sources** also contribute low-level noise. As a result, a high noise floor is created, making FRBs harder to detect.

B) Short duration and random occurrence: FRBs last for only a few milliseconds and can appear at any moment. Also, most of them are one-time bursts so they don't repeat at all. So, if the radio telescope is not looking at the right location of the sky at the exact moment, FRBs can be missed!

C) Dispersing and scattering: FRBs traveling through plasma (in galaxies and intergalactic space) are **dispersed** and **scattered**. If the **de-dispersion correction** is not perfect, the burst can appear faint or smeared — making it harder to identify.

D) Instrumental defects: Imperfect calibration, reflections within the telescope, or software glitches can mimic short pulses. Also dead pixels or bad channels can introduce spurious signals.

E) Data Volume: Telescopes like CHIME or ASKAP produce **petabytes of data** daily. It's impossible to store all data permanently. Real-time algorithms must **detect FRBs instantly**, otherwise the data are overwritten.

4) CHIME (Canadian Hydrogen Intensity Mapping Experiment):

Detailed description of CHIME telescope and its design:

Here is a detailed, component-by-component breakdown of CHIME's design:

A) Reflector system: CHIME has 4 parabolic, half-cylindrical reflectors side by side. Each of them is 20 m wide, 100 m long and oriented in North-South direction. These are made of **metal mesh panels** (galvanized steel wire mesh) and reflect radio waves of **400–800 MHz** but allows rain, snow, and wind to pass through , reducing weather impact.

B) Feed System (Antenna Array): At the focal line of each cylinder are antennas that collect the focused radio waves and convert them into electrical signals.

Each cylinder has **256 dual-polarization feeds**, so there are total 1024 antennas. Each feed can receive two orthogonal polarizations (X & Y), so total 2048 independent signal channels are there. Aluminum plates shaped like four curved petals (“clove-leaf”) mounted on a printed circuit board to make these feeds. Mounted on a **metal support boom** running along the focus line.

C) Analog Electronics (Front-End System): Before digital conversion, signals undergo analog processing.

Low Noise Amplifier is mounted directly behind the antenna. It amplifies the very weak cosmic radio signals ($\sim 10^{-20}$ W) with minimal added noise. There is a band pass filter that removes unwanted frequencies. Some coaxial cables, known as Transmission Lines, carry the amplified signal to the main electronic system.

D) Digital Backend (Signal Processing System): This is CHIME's **brain** — a highly advanced supercomputing system that processes terabits of data per second.

Field-Programmable Gate Arrays (FPGAs) are there to split the entire 400-800 MHz band into narrow frequency channels (typically 1024-2048 sub-channels). Data are then processed by **Graphics Processing Units (GPUs)** and signals coming from all antennas are mathematically combined. Finally, real time software searches for short, dispersed pulses and processed FRB alert are sent to other telescopes.

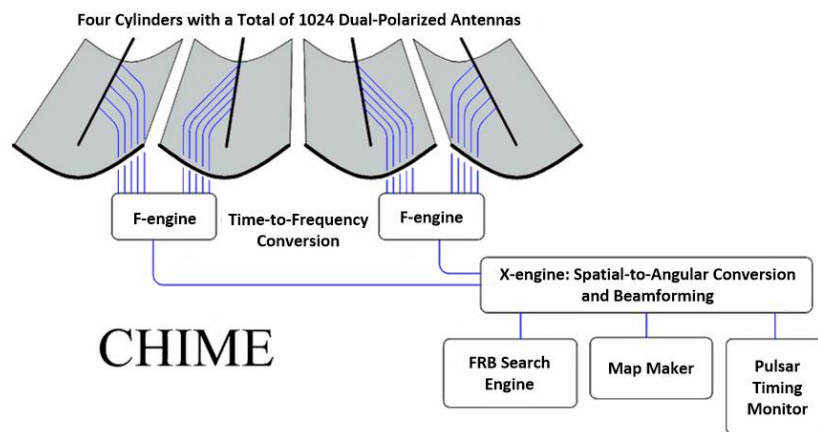


Fig-5: Structural design of CHIME

Location, structure, and technological features:

A) Location: CHIME is located at Dominion Radio Astrophysical Observatory (DRAO), near Penticton, **British Columbia, Canada** (Latitude $\sim 49^\circ$ N, Longitude $\sim 119^\circ$ W and almost 545 meters above sea level). This location was chosen because minimal human-made radio noise is there, also the **climate is stable** and there is a open valley, which are ideal for large fixed radio arrays.

B) Structure: CHIME has a unique structure that makes it technologically advanced. It has 4 parabolic reflectors that act like mirrors for radio waves. These reflectors are oriented in North-South direction. Every reflector has a parabolic curve in East-West direction and is flat in North-South direction.

Each of them has **256 dual-polarized** "cloverleaf" antennas per cylinder (total 1024 feeds, 2048 channels). The path of signal receiving and processing is:

Radio waves $\rightarrow$ metal reflectors $\rightarrow$ feeds $\rightarrow$ amplifiers $\rightarrow$ digitizers $\rightarrow$ GPUs for processing and FRB detection.

C) How CHIME detects FRBs and processes data: Here's a clear, step-by-step explanation of how CHIME detects and processes Fast Radio Bursts (FRBs):

- The **four large cylindrical reflectors** of CHIME focus incoming radio waves.
- The waves are collected by 1024 dual-polarized antennas placed along the focal lines.
- The weak cosmic signals are first **amplified** using **Low-Noise Amplifiers (LNAs)** to preserve faint details.
- Then they are **converted from analog to digital** signals by **digitizers** (Analog-to-Digital Converters).
- Supercomputers **combine signals from all antennas** to form **hundreds of simultaneous “beams”** across the sky. This allows CHIME to **monitor the entire visible sky** continuously as the Earth rotates.
- The digitized signals go into a **real-time GPU-based pipeline**, where the system corrects for **frequency-dependent delays** caused by interstellar electrons.
- If the signal shows a broadband pulse, dispersion signature and non-repeating pattern (or repeating with same DM) then it is flagged as a candidate FRB.
- The event is then **recorded and verified** by scientists. Other observatories may follow up for **afterglow or repeating behavior**.

D) Role in global astrophysics research: From the description of CHIME's advanced technological features, it is obvious that it has a major impact on the ongoing astrophysics research at global level. Let us talk about some of its roles in current space projects:

- It is used to study the expansion of the universe using hydrogen line emissions.
- It helps us to measure electron density of the universe, magnetic fields in galaxies and intergalactic spaces and distribution of matter, including dark baryons.
- It continuously monitors a huge portion of the northern sky, by using advanced technologies like **Real-time data analysis pipelines** and **Machine learning algorithms** for signal classification. Such technologies have influenced global telescope design.
- CHIME has become a global hub of astrophysics research. Thus, it contributes in training programme of new astrophysicists, open data access and transparency as well as global scientific cooperations.

5) Major Discoveries and Results:

Key FRBs detected by CHIME:

A) FRB 180814.J0422+73 (2018): It was discovered in **August 2018**. It was a **repeating** FRB (second known after FRB 121102). It proved that repeating FRBs are not unique to a single source. It also helped confirm the existence of multiple classes of FRB progenitors and allowed long-term monitoring to study repetition rates and emission patterns.

B) FRB 180916.J0158+65 (2019): This FRB was discovered in the year of 2019. Scientists found it to originate from a spiral galaxy about **500 million light-years away** (one of the closest known FRBs). This was the first FRB to show **regular periodic activity cycle** — a **16.35-day repeating pattern**. Researchers also suggested possible links to **binary systems**.

C) FRB 200428 (2020): After discovering it in April, 2020, scientists found that it had its origins in a **Galactic magnetar (SGR 1935+2154)** — **within the Milky Way**. This was the first-ever FRB to be

observed from our own galaxy. The discovery provided **direct evidence** that at least some FRBs are produced by **magnetars**.

D) FRB 20200120E: It was detected in 2021 and its source was found in M81 galaxy (a nearby galaxy almost 12 million light-years away). This was the the **closest extragalactic FRB** ever detected. Origin was traced to a **globular cluster**, suggesting **old stellar populations** can also host FRB sources.

E) FRB 20191221A: After being discovered in 2019, it was reported three years later, in 2022. The burst lasted about **3 seconds**, much longer than typical millisecond bursts. It contained **regular sub-pulses every 0.2 seconds**, resembling a **pulsar or magnetar spin**, suggesting FRBs might originate from **highly magnetized neutron stars** with periodic emission.

Implications of CHIME results on cosmology and intergalactic medium studies:

A) “Missing Baryon Problem”: About half of the normal (baryonic) matter predicted by previous cosmological models was not found in stars or galaxies. FRBs act as cosmic probes because their **dispersion measure (DM)** directly traces **free electrons** between galaxies. By analyzing CHIME’s large dataset of FRBs with known distances, researchers suggest that the **missing baryons** indeed reside in the **warm-hot intergalactic medium (WHIM)**.

B) Cosmological Distance Indicators: DM of a FRB is directly proportional to the distance between the source and the observer. **This allows FRBs to serve as** independent cosmological probes. By using this property of FRB, CHIME helps us to estimate cosmic expansion rate (H_0) and **trace** evolution of ionized matter density **over time**.

C) Studying the Intergalactic Medium (IGM): By observing the **scattering and polarization** of FRB, **magnetic fields** in the IGM, **turbulence** and density fluctuations in the plasma, IGM’s impacts on radio wave propagation, variations in plasma density across the cosmos etc. are studied.

6)Scientific importance and future prospects:

How FRB research can help understand the universe’s structure and evolution?

- FRBs come from cosmological distances, which means each burst gives snapshots of the same universe, just at different epochs. Comparing DMs and redshifts from different FRBs allows astronomers to study how ionization and density evolved over time.
- FRBs are heavily affected by magnetic fields along their path. Measuring this effect helps scientists map the large-scale magnetic field structure of galaxies and intergalactic spaces.

Future research missions, instruments and open questions:

FRBs are one of the most discussed topics of modern astrophysics. Here are some of future research missions about FRBs:

- Additional CHIME stations being built in the US and Canada will allow precise localization of FRB. We will be able to detect the host galaxy as well as know about the environment of the FRB more accurately.
- **SKA (Square Kilometer Array)** is being constructed in South Africa and Australia that will have more sensitivity and sky coverage.
- **DSA-2000 (Deep Synoptic Array)** of US will localize thousands of FRBs precisely every year.
- **Space-based FRB detector** has been theoretically proposed. Researchers are claiming that it will be able to avoid Earth's radio interference and have the power of low-frequency FRB detection also.

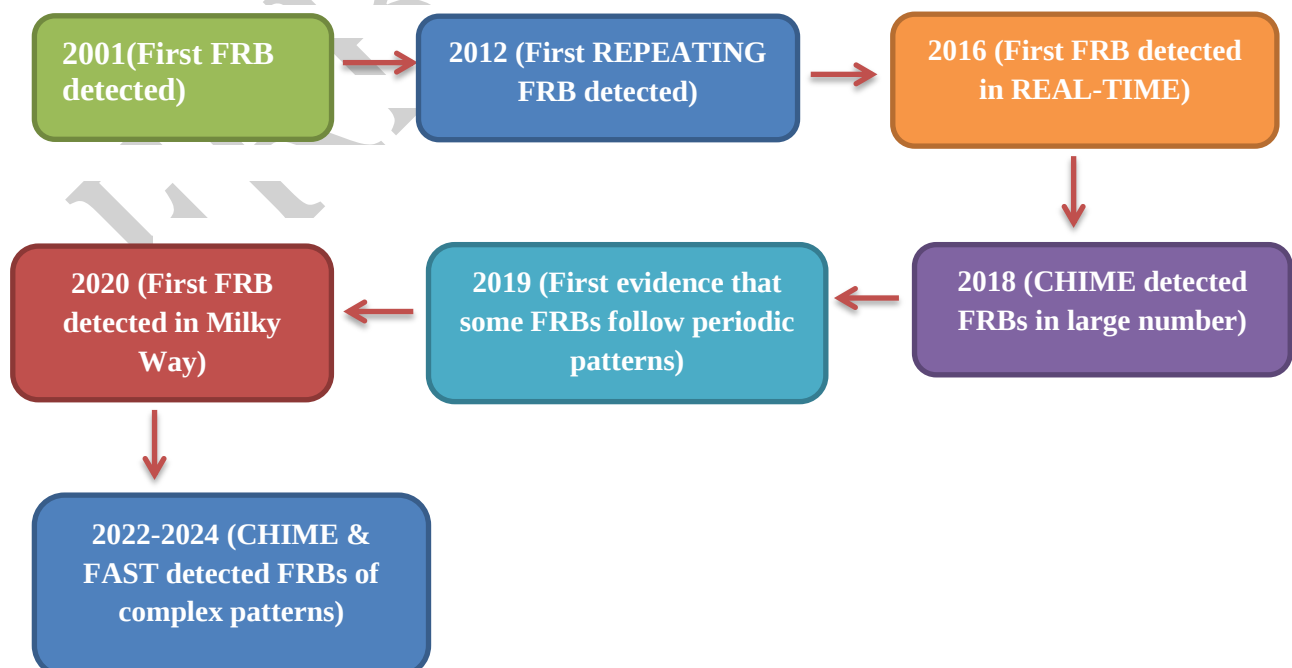
There are still some open questions in FRB research:

- The origin of FRBs is still not confirmed. Although FRB 200428 was found to be originated from a magnetar, that doesn't prove that all bursts are created by magnetars. So what is the source of all other FRBs? Does multiple mechanism (NS-NS merger, NS-BH merger, Supernova etc.) exist?
- We have seen that one-time FRBs doesn't show further bursts. But is it true? Are they really turn-off events, or do they show further bursts on a very very long timescale? In simple words, we still can't say anything about the probability of further bursts accurately.
- We don't know whether the why some FRBs are repeating and others are not. Also scientists are trying to know about the physical differences of the origins of one-time and repeating FRBs.

7) Conclusion:

Summary of findings:

Before coming to the conclusion, let's recap all the discoveries of FRBs till date:



Conclusion:

After such a long discussion, it is needless to say that FRBs are the current “hot topic” of modern astrophysics! FRBs travel across the entire cosmos and give us all the information they have.

By observing and studying FRBs, we can understand the environment (distribution of various chemical components, temperature, magnetic field) in distant galaxies. So from here, we can indirectly find out whether there is a habitable region (i.e. probability of extra-terrestrial life) or not. Also, when FRB comes very close to a black hole, the gravitational pull of the BH bends the wave and magnifies its amplitude (also known as gravitational lensing). By studying these patterns, we can map the **mass and structure** of the intervening BH.

Well, our universe has many more mystical characteristics. The universe is made of 4.9 % baryonic (normal) matter, 26.8% dark matter and 68.3% dark energy. Among these, we have fairly well understood the normal matter only, whereas dark matter and dark energy are still unsolved mysteries for us. We know they exist, but don't know what they actually are.

So basically, we know only ~5% of this vast universe. In this scenario, FRBs may represent a truly path breaking phenomenon. If we study them thoroughly, probably we will be able to solve those mysteries in near future. Maybe what is known as radio wave bursts today, might become the ultimate solution to every question regarding our universe tomorrow.

WHO KNOWS?