FAST RADIO BURSTS

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INTRODUCTION to FRBs

- What are Fast Radio Bursts?
  - Bright pulses of emission at radio frequency.
  - Duration of milliseconds or less.
  - Ranging from 400 MHz to 8GHz.
  - Origins are known to be extragalactic due to large dispersive delays.
  - They can be unique or repeating.

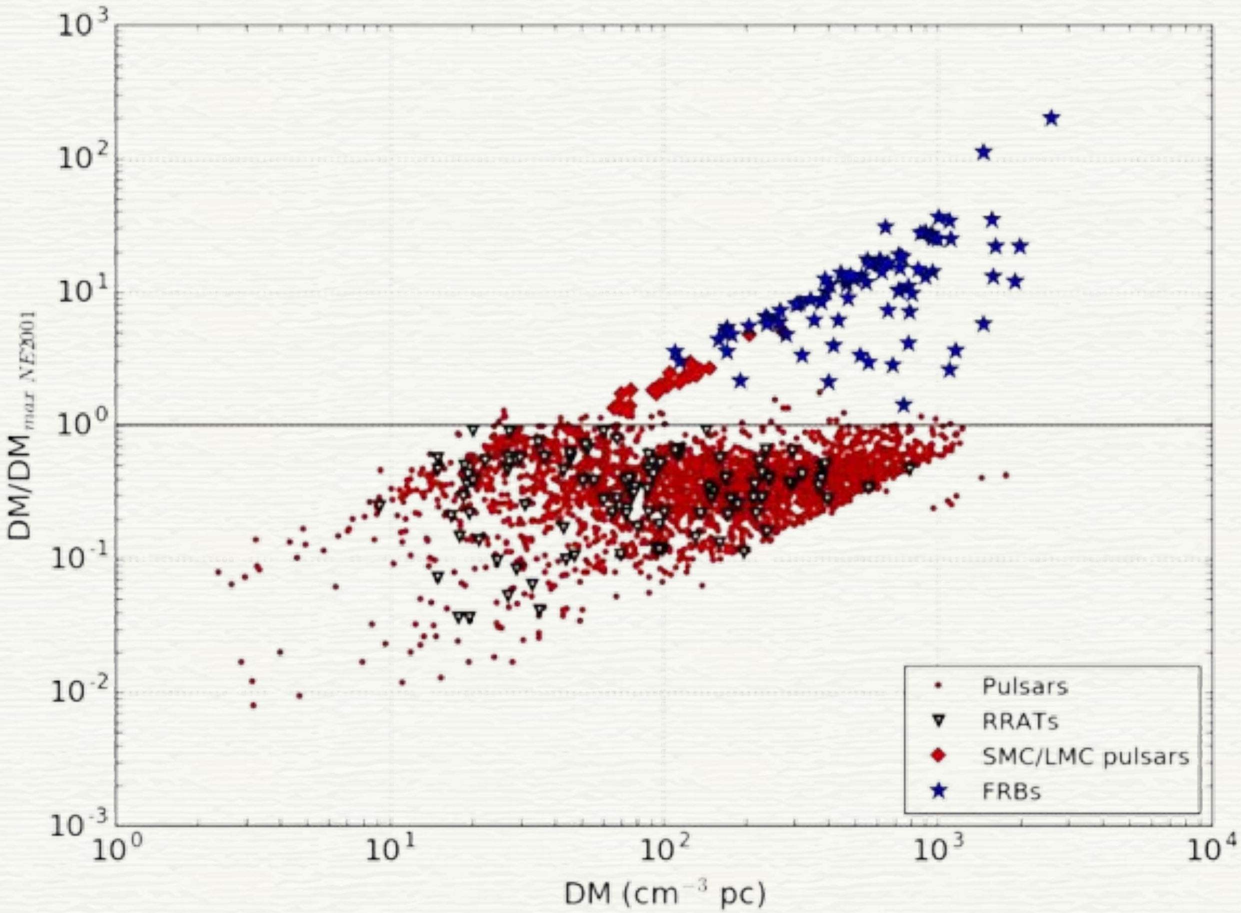
DISPERSION MEASURE

- It’s characterized by its **Dispersion Measure** (DM).
  - Time delay between the arrival of the radio signal's high and low frequencies, which is changed by the total number of free electrons between the observer and source
  - It tells us how much a radio signal is delayed as it travels through ionized gas, it also helps us determine the source distance.

DISPERSION MEASURE

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

cm^{-3} pc



DM for different sources. DM/DM_max > 1 characterize extragalactic sources Spitler et al. (2014)

OCCURRENCE and DETECTION RATE

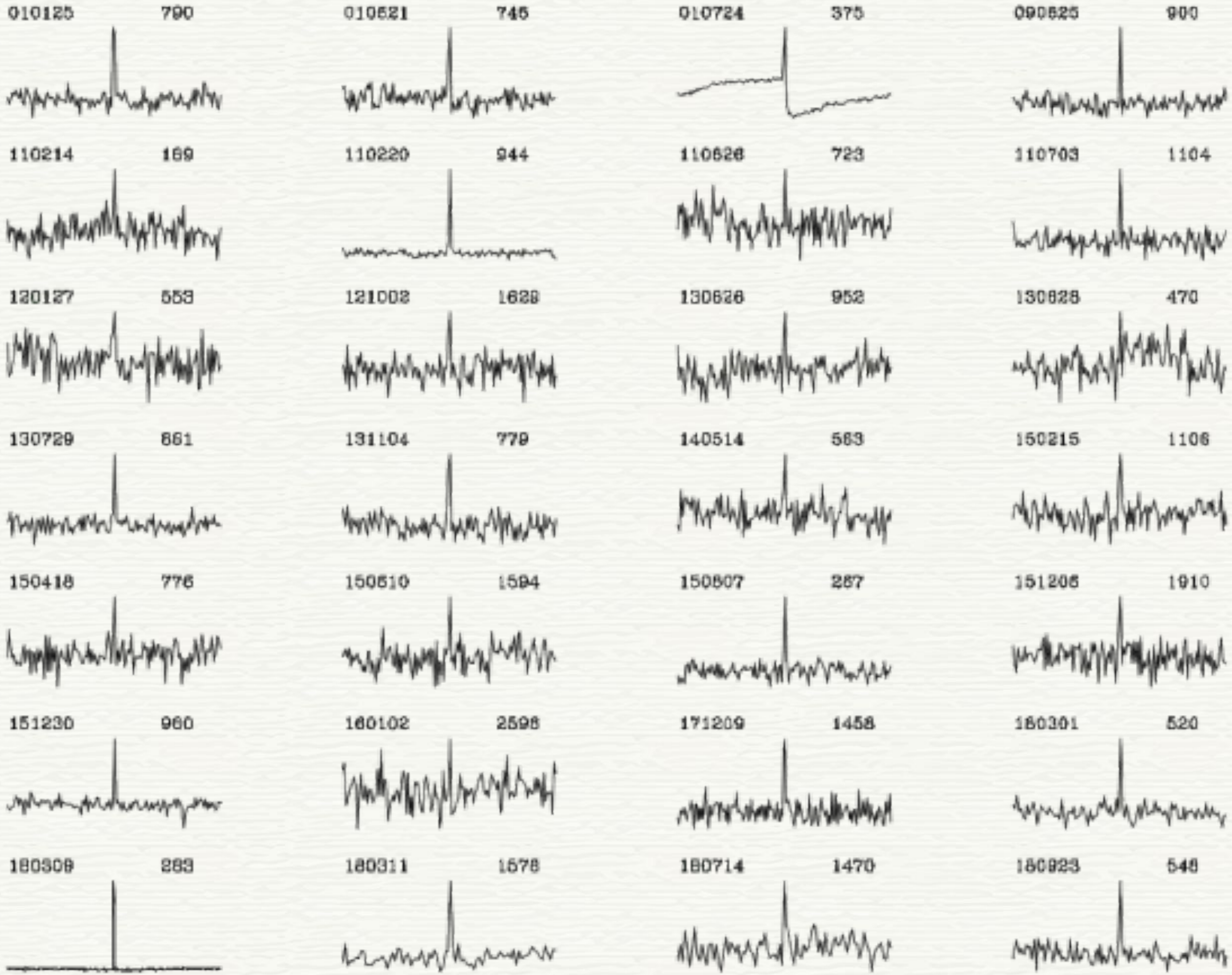
- Known population of 60 independent sources. (2019)

- Even for a cosmological distribution their sources must be relatively common and abundant.

WHY ARE THEY IMPORTANT?

- Mysterious Origins
- Probes of the Intergalactic Medium
- High Energy and Extreme Physics
- Rapid Technological Development
- Among others …

Parkes Telescope (Australia)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010621 745
010724 375
090625 900
110214 169
110220 944
110626 723
110703 1104
120127 553
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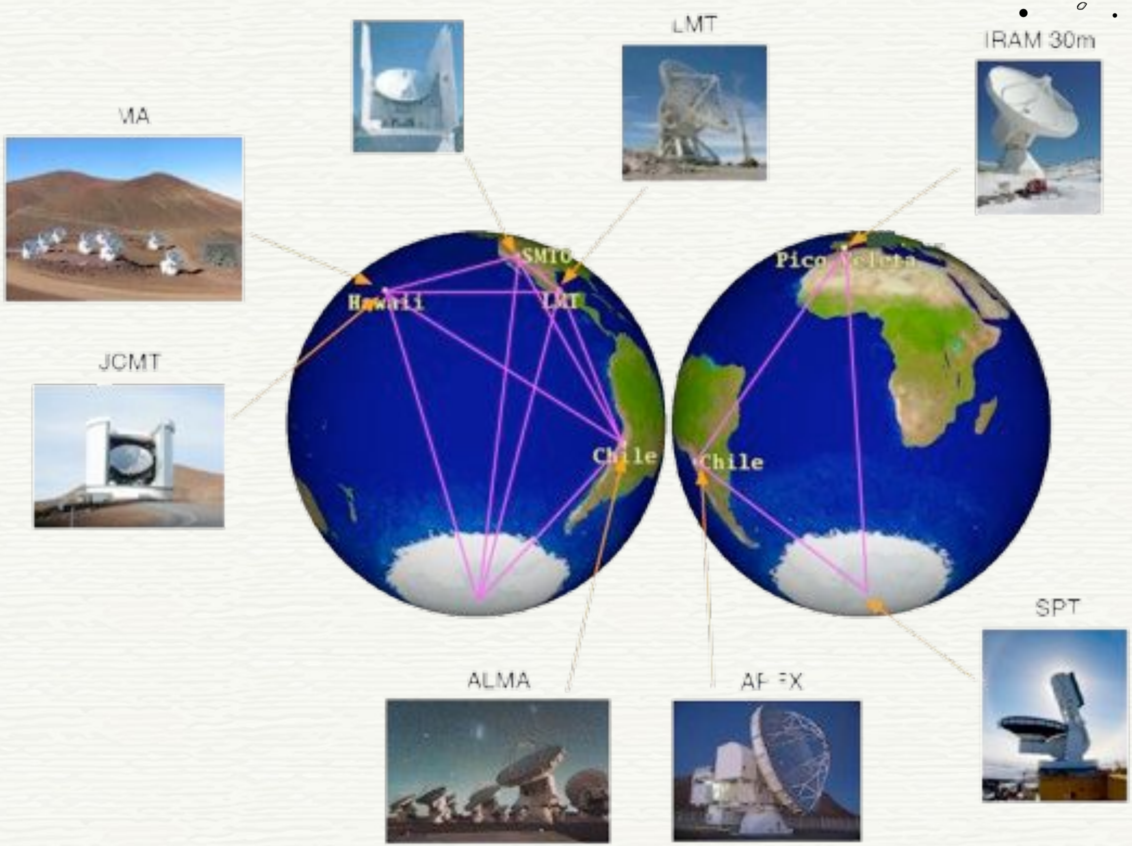
130626 952
130628 470
130729 861
131104 779
140514 563
150215 1106
150418 776
150610 1594
150807 267
151206 1910
151230 960
160102 2596
171209 1458
180301 520
180309 263
180311 1578
180714 1470
180923 548

Green Bank Telescope (US)

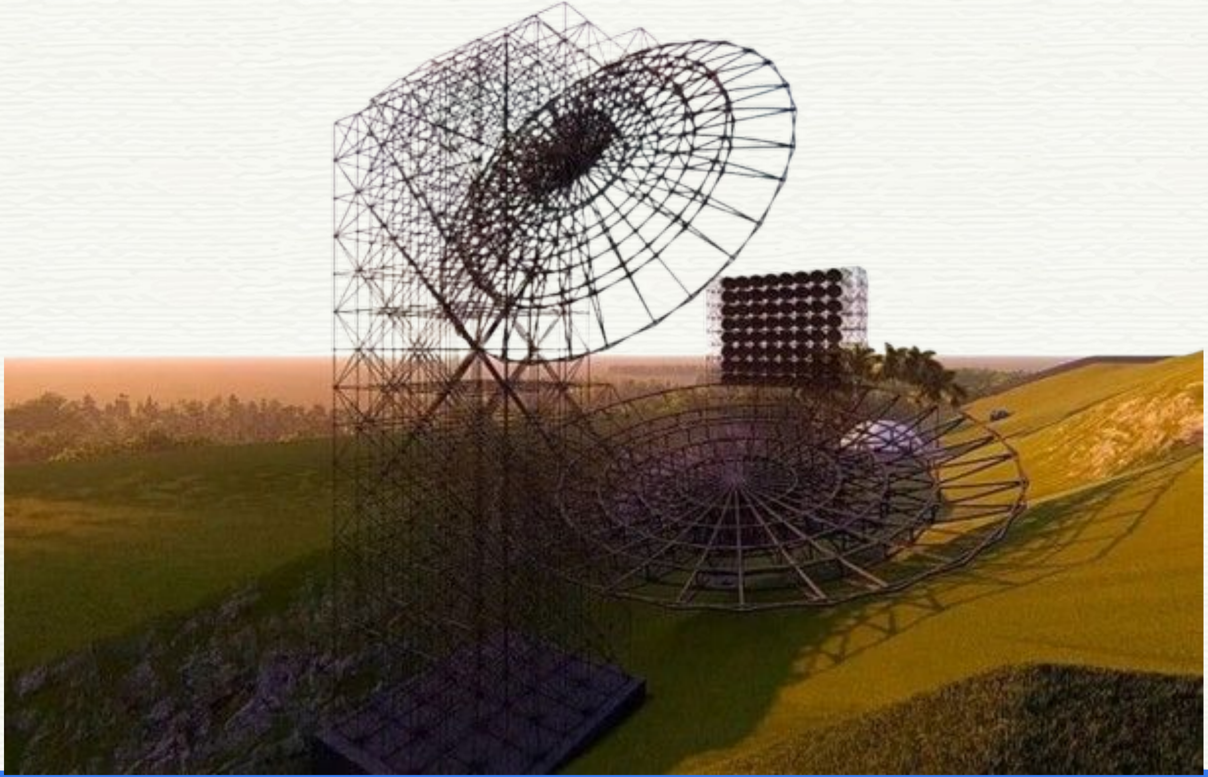
Canadian Hydrogen Intensity Mapping Experiment (CHIME)

Very-Long-Baseline Interferometry (VLBI)



Baryon Acoustic Oscillations from Integrated Neutral Gas Observations (BINGO)

First Light Forecast: February 2025



PROPERTIES of FRBs

TIME DELAY

- The observed Dispersion Measure (DM) is the time delay due to the propagation of the signal through ionized plasma, where lower-frequency waves travel slower than higher-frequency ones.

$$\Delta t = 4.15\,\mathrm{ms}\left(\frac{1}{f_{\mathrm{lower}}^2} - \frac{1}{f_{\mathrm{higher}}^2}\right) \times \frac{\mathrm{DM}}{1000}$$

DISPERSION MEASURE

- The observed DM of an FRB provides a clue about its distance because the DM is roughly proportional to the distance the signal has traveled through ionized material.
    - The DM can be broken down into contributions from different regions along the line of sight:

$$\mathrm{DM} = \mathrm{DM}_{\mathrm{MW}} + \mathrm{DM}_{\mathrm{IGM}} + \frac{\mathrm{DM}_{\mathrm{host}}}{1+z}$$

DISTANCE

- A rough estimate of the distance (Luminosity)to an FRB is given by the empirical relation (valid for z < 1)

$$d_L < \frac{\mathrm{DM}}{1000}\,\mathrm{Gpc}$$

- There is also a relationship between d_L and the Flux

$$d_L \propto \frac{\langle \mathrm{DM}_{\mathrm{IGM}} \rangle}{\left(\frac{S_{\mathrm{peak}}}{L}\right)}$$

LUMINOSITY

- Luminosity is the total amount of energy emitted by a source per unit time. For FRBs, the luminosity helps estimate the total energy output of these bursts and how bright they are.

$$L = \frac{4\pi d_L^2 S_\nu \Delta\nu}{1+z}$$

- Understanding luminosity is critical for figuring out what kinds of physical processes can generate such intense energy bursts.

FLUENCE

- Refers to the total energy received by the radio telescope from the burst, integrated over the duration of the burst. It is often measured in jansky milliseconds (Jy*ms).

$$F = S_{\text{peak}} W_{\text{eq}} = \int_{pulse} S\,(t) dt$$

$1\,Jy\ =\ 10^{-26} W m^{-2} Hz^{-1}$

WIDTH

- FRB pulses are characterized by their width (the duration of the burst) and peak flux density (how bright the burst is in a given frequency band).
  - The observed width of the pulse W is the result of various factors

$$W = \sqrt{W_{\mathrm{int}}^2 + t_{\mathrm{sample}}^2 + \Delta t_{\mathrm{DM}}^2 + \tau_s^2}$$

TEMPERATURE

- When we have non-thermal emission mechanism, one can define the temperature of an FRB source as the Thermodynamic Temperature of a black body of equivalent luminosity as:

$$T_B \approx 10^{36} \left(\frac{S_{\rm peak}}{\rm Jy}\right)\left(\frac{\nu}{\rm GHz}\right)^{-2}\left(\frac{W}{\rm ms}\right)^{-2}\left(\frac{d_L}{\rm Gpc}\right)^{2} {\rm K}$$

FRBs' INTERVALS

$DM : (100 - 1000)\, cm^{-3}pc$

$z : 0.1 - 1$

$F : (0.1 - 100)\, Jy$

$T : (10^{35} - 10^{37})\, K$

$d_L : (1 - 6)\, Gpc$

$L : (10^{40} - 10^{43})\, ergs/s$

PROPAGATION EFFECTS

The signal from an FRB can be modified as it travels across cosmic distances can be modified by some effects (which are very dependent on the frequency). Understanding these effects is important for interpreting its observed properties.

The main effects are: dispersion, scattering, scintillation, Faraday rotation and plasma lensing.

DISPERSION MEASURE

Variable	Type	DM contribution (cm^{-3} pc)
DM_{Iono}	Earth ionosphere	$\sim 10^{-5}$
DM_{IPM}	Interplanetary medium of Solar System	$\sim 10^{-3}$
DM_{ISM}	Galactic interstellar medium	$\sim 10^{0} - 10^{3}$
DM_{IGM}	Intergalactic medium	$\sim 10^{2} - 10^{3}$
DM_{Host}	Host galaxy interstellar medium	$\sim 10^{0} - 10^{3}$
DM_{Local}	Local FRB environment	$\sim 10^{0} - 10^{3}$

SCINTILLATION

- Given their implied small emitting regions and large distances FRBs should be perfect point sources, and thus scintillate.

- Scintillation is caused by delays imparted on the signal which cause destructive or constructive interference when these waves come back together.

$$\Delta\nu_{sci} \propto \nu^4$$

SCATTERING

- Scattering occurs when radio waves encounter inhomogeneities in the electron density of the medium, causing the signal to scatter and broaden.

- The pulse broadening due to scattering is related to the turbulence in the medium and is typically expressed as:

$$\tau \propto \nu^{-4}$$

FARADAY ROTATION

Occurs when polarized radio waves pass through a magnetized plasma. The plane of polarization rotates as the signal travels through the magnetic field. The amount of rotation is proportional to the strength of the magnetic field and the electron density along the line of sight. The rotation measure (RM) quantifies the amount of this effect and is given by:

$$RM = -0.81 \int_0^d B(l)_{||} n_e dl$$

This effect helps measure the strength and structure of the magnetic fields in the regions through which the FRB signal travels.

PLASMA LENSING

Plasma Lensing is similar to gravitational lensing but occurs when the signal passes through regions of plasma with varying electron densities, which act like a lens. This effect can magnify or demagnify the FRB signal and change its observed brightness.

OBSERVATIONAL TECHNIQUES

SEARCHING for FRBs

- Radio telescopes typically consist of an aperture that brings electromagnetic signals from the sky to a focus so that they can be measured as a function of time using feeds (transforms radio waves into electrical signal).

- The antenna and feed response is typically measured over a range of radio frequencies, i.e., a bandwidth, which is amplified and discretely sampled by a number of frequency channels.

AMPLIFICATION and SAMPLING

After the signals are captured by the feeds, they are amplified and divided into frequency channels. The voltage stream is sampled at a finite time resolution, which is essential for identifying short-duration pulses like those of FRBs.

DATA CUBE

The output from the telescope is stored in a data cube, where intensities are recorded across both time and frequency.

RADIO FREQUENCY INTERFERENCE (RFI)

- Unwanted signals from human-made sources, such as radio, cell-phones, satellite communications and so on.

- We have to identify and remove RFI to ensure that only astrophysical signals are analyzed.
  - This can be done before the observation by masking time samples and frequency channels.

  - One can also try to subtracted RFI from the data cube (after observation) by looking for peaks in the DM = 0 cm^{-3} pc.

DEDISPERSION

- It is the process of correcting the time delay across different frequencies to align the signal, compensating for the effects of DM.

- By removing this delay, we can reconstruct the original burst as it would appear if there were no plasma between the source and the observer, allowing for clearer detection of the FRB.

TIME SERIES

- After the signal has been dedispersed, a time series is extracted from the data. This involves converting the signal into a one-dimensional time series that represents the intensity of the radio waves as a function of time.

- It can now be analyzed for FRBs

MATCHED FILTERING

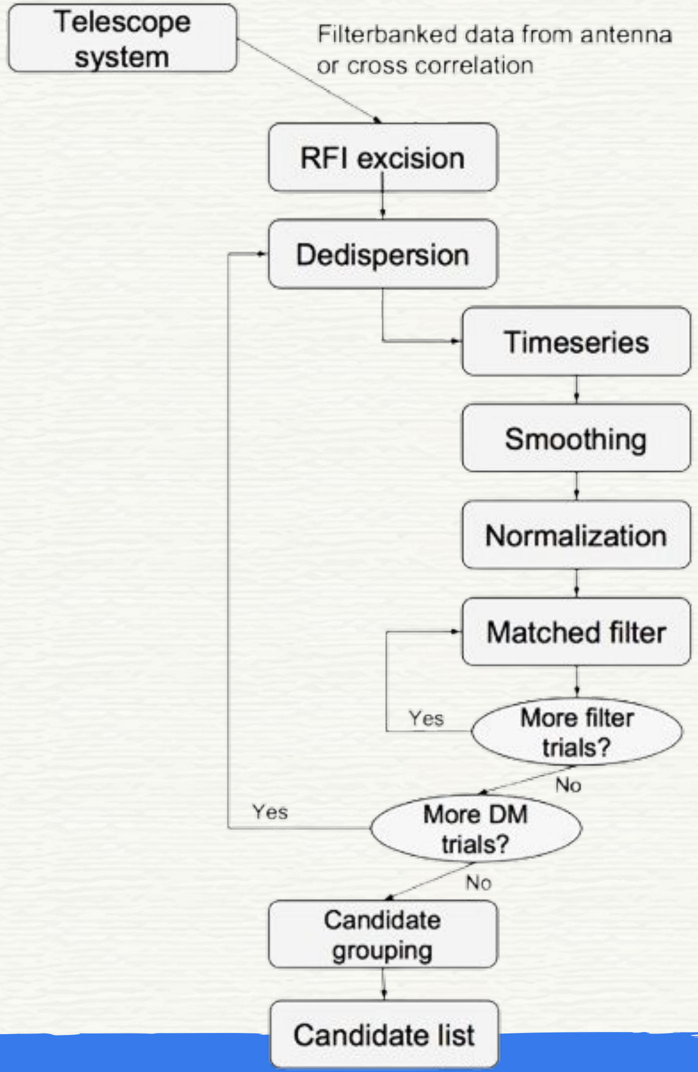
- Technique used to enhance the detection of signals with a known shape. In the case of FRBs, the expected signal is a brief pulse of radiation, so matched filtering uses a template of this pulse to search the time series for similar patterns.

- This method helps to maximize the signal-to-noise ratio (SNR), making it easier to detect weak FRBs in noisy data.

CANDIDATE GROUPING

- Once possible FRB signals are identified, the next step is to group them into **candidates**. These candidates are grouped based on their arrival times, dispersion measures, and other properties.

- This step reduces the number of false positives and ensures that only genuine candidates are further analyzed.



Telescope system
Filterbanked data from antenna or cross correlation
RFI excision
Dedispersion
Timeseries
Smoothing
Normalization
Matched filter
Yes
More filter trials?
No
Yes
More DM trials?
No
Candidate grouping
Candidate list

FRB DISCOVERY

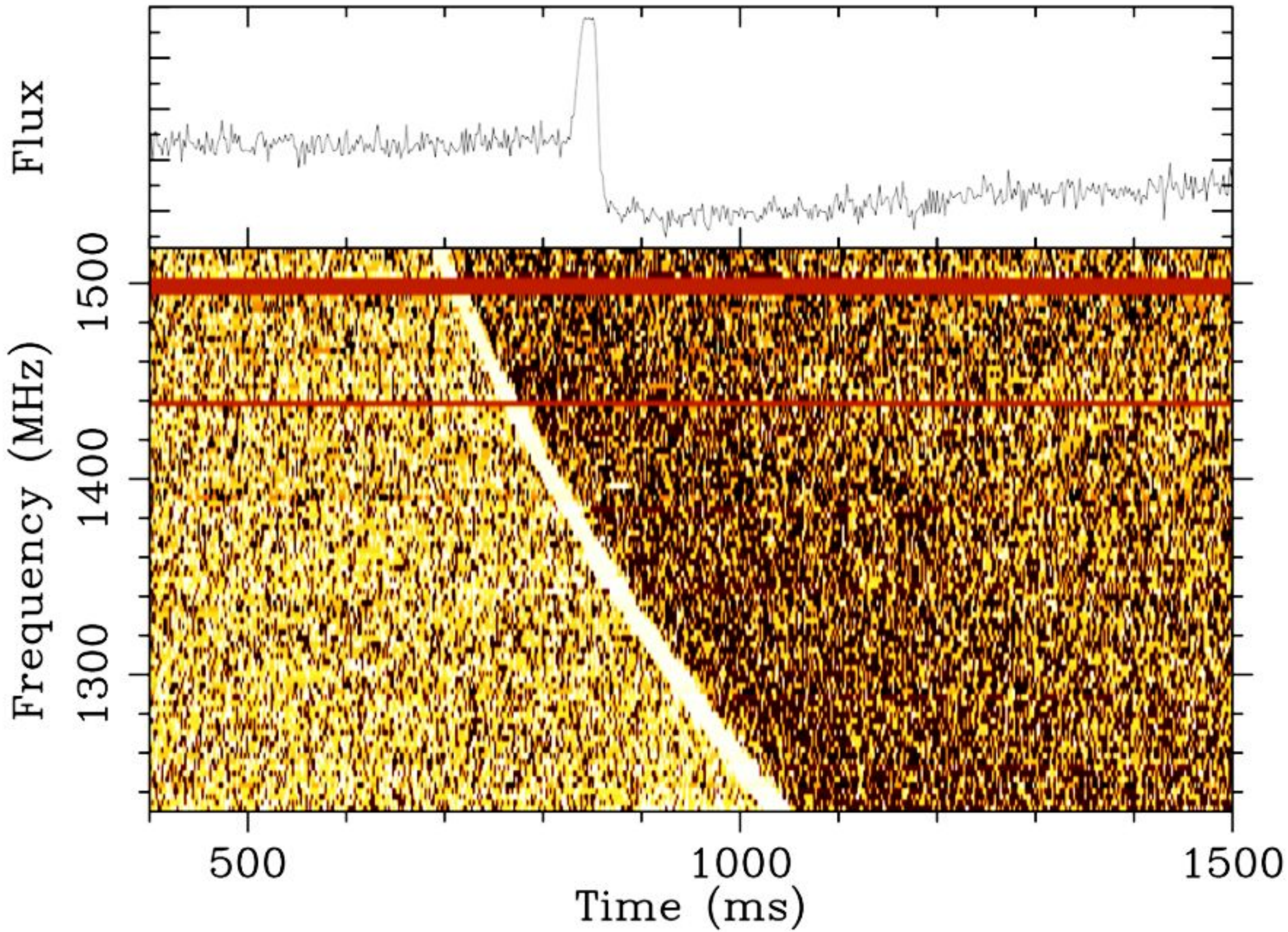
THE LORIMER BURST (2007)

- Discovered when searching for Pulsar in archived data.

- Large DM (375 cm^{-3} pc) suggesting it originated outside MW.
  - Milky Way
    - Galactic Plane: ~200   cm^{-3} pc
    - Off Galactic Plane: ~35 cm^{-3} pc

- Extremely energetic

- Some researchers want it to be excluded from statistical analyses of the FRB population



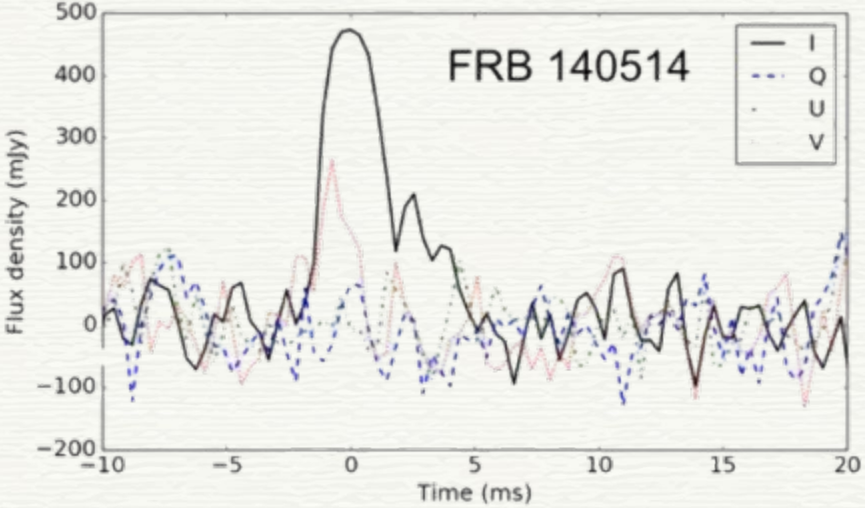
Lorimer et al. 2007

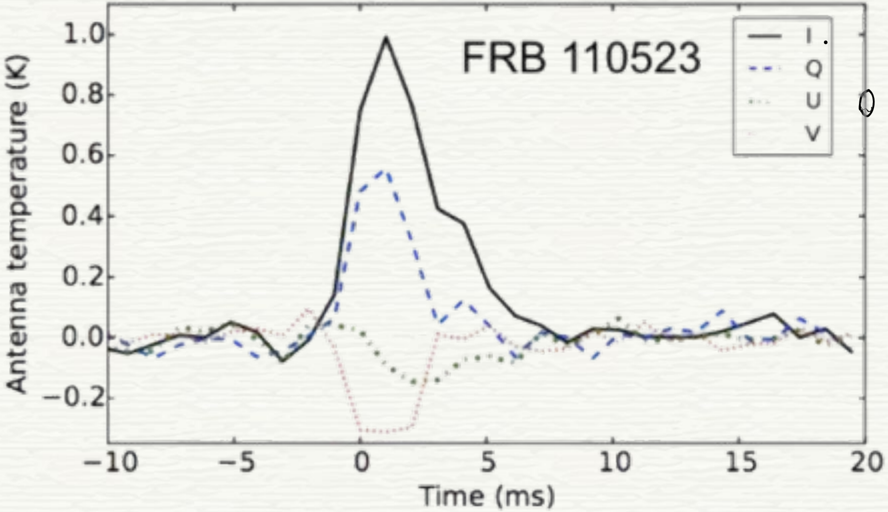
POPULATION PROPERTIES

POLARIZATION

- Only 9 out 60 FRB have polarimetric data available
    - Linear, Circular and both.
- Some appear to be completely unpolarized.
- It doesn’t necessarily reflect the physical origins

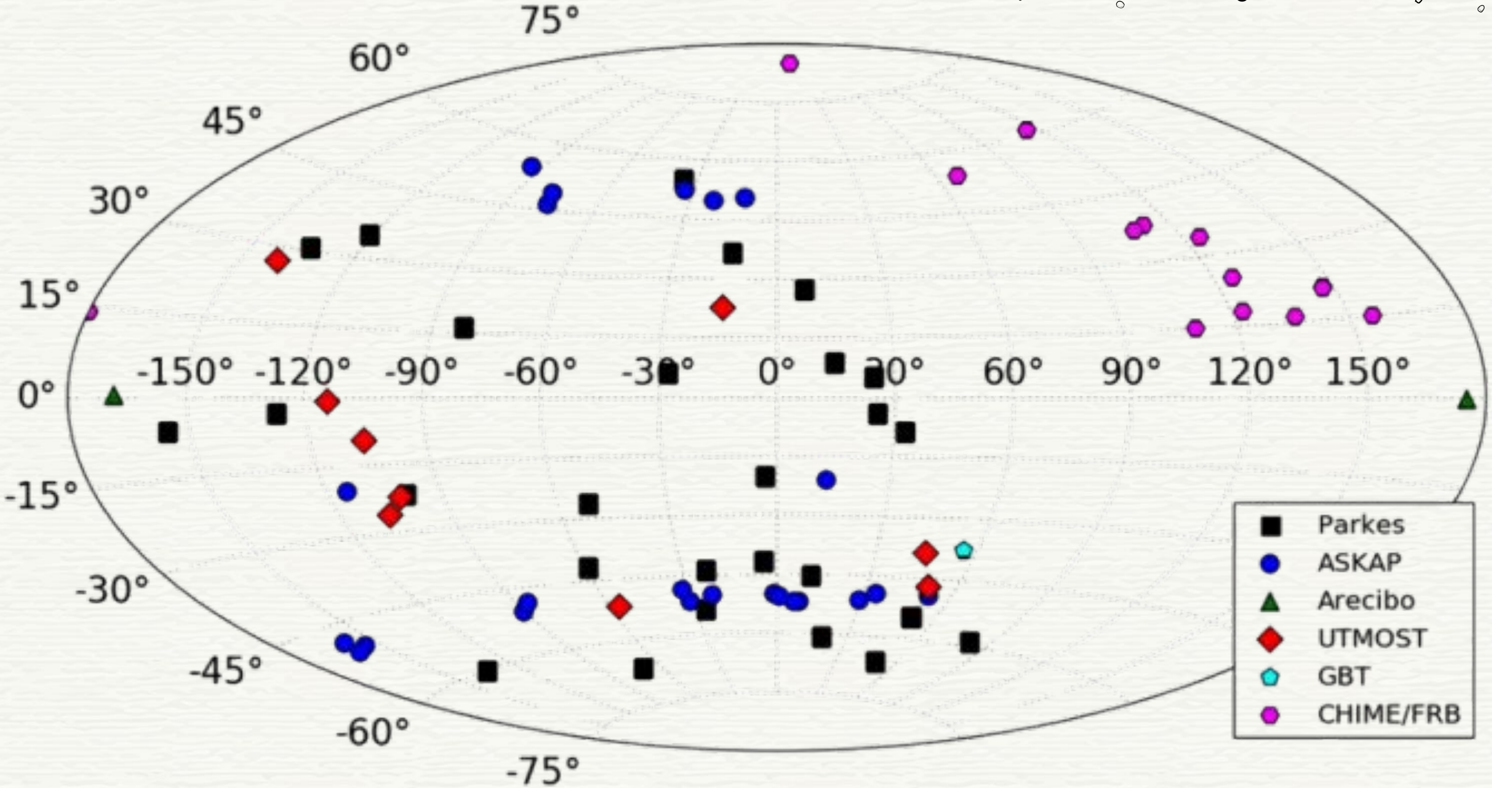
POLARIZATION





Petroff et al. 2015a

SKY DISTRIUTION

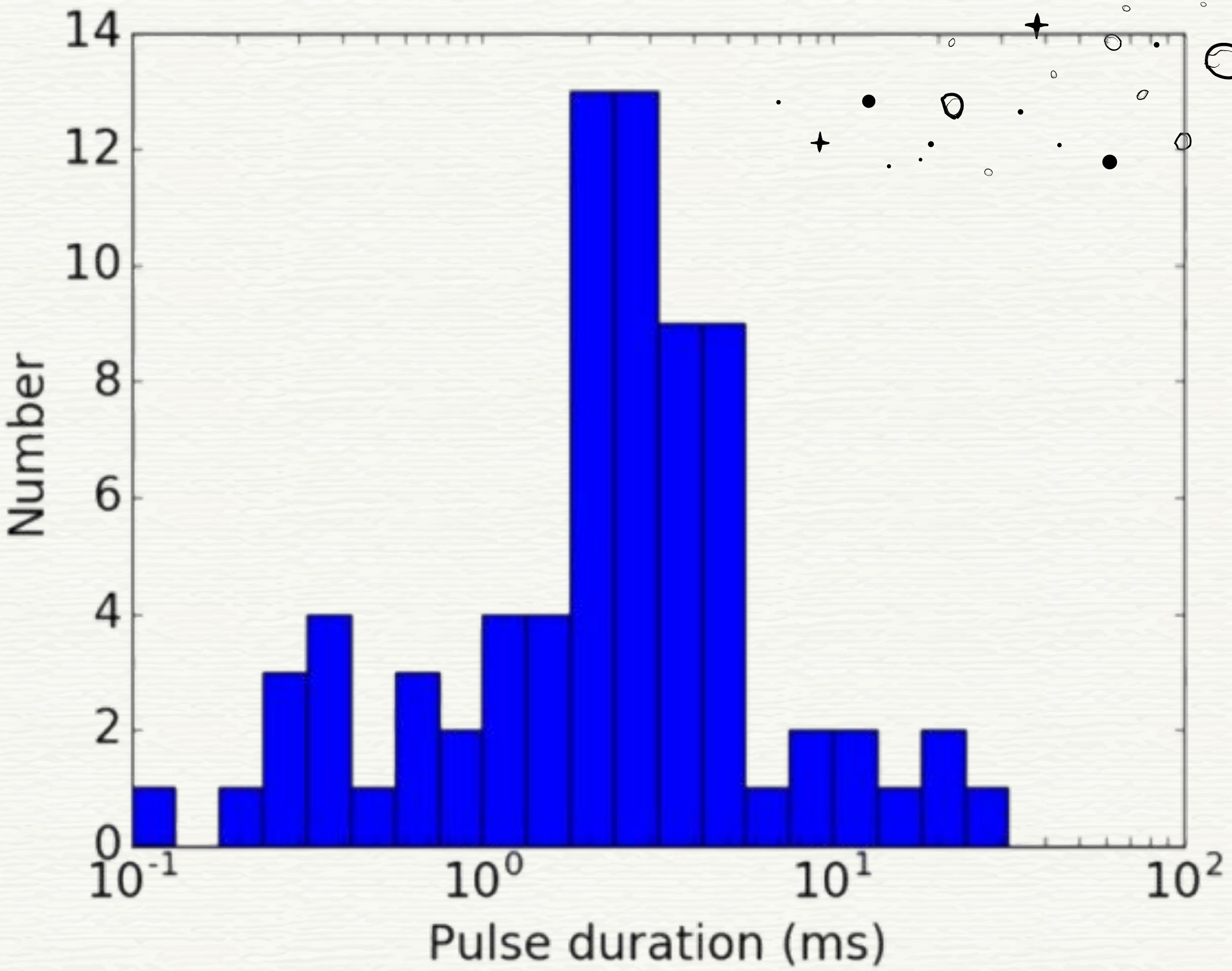


PULSE WIDTH

- The width of an FRB can be heavily affected by scattering, which broadens the pulse and reduces the peak flux density

- The shorter pulse width probes a minimum physical scale and might give insights into the nature of the source.

- The larger pulse width tell us more about the propagation effects

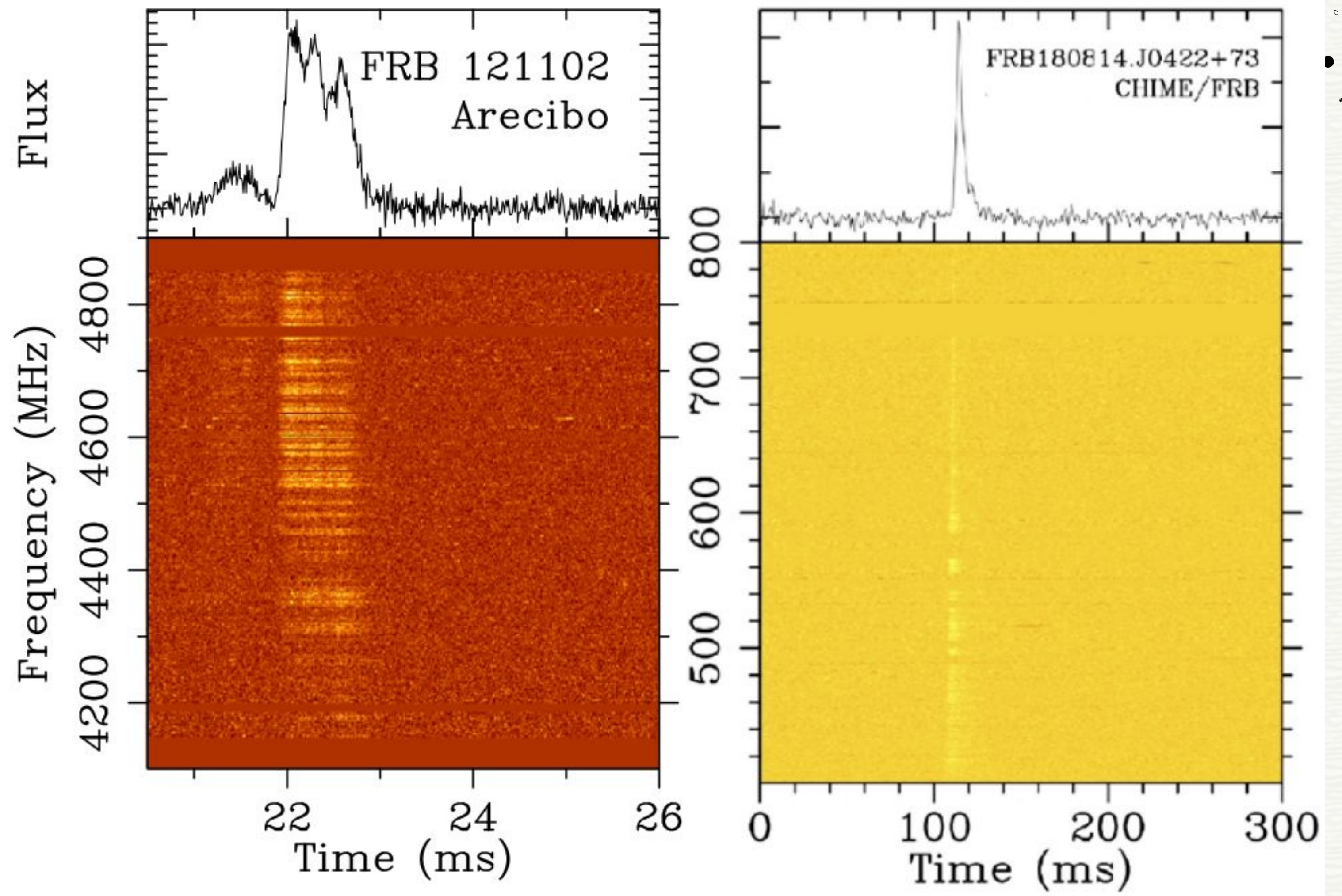


Number
14
12
10
8
6
4
2
0
10^{-1}
10^{0}
10^{1}
10^{2}
Pulse duration (ms)

REPEATING and NON-REPEATING

- Repeating: These sources emit multiple bursts, often over long periods. Only 2 sources so far, an example is FRB 121102.
  - Sometimes 10 bursts/hour
  - It varies enormously in width (from ~30μs to ~ 10ms)

- Non-repeating: These appear as one-off events, and the underlying physical mechanisms might be different from those of repeating FRBs.

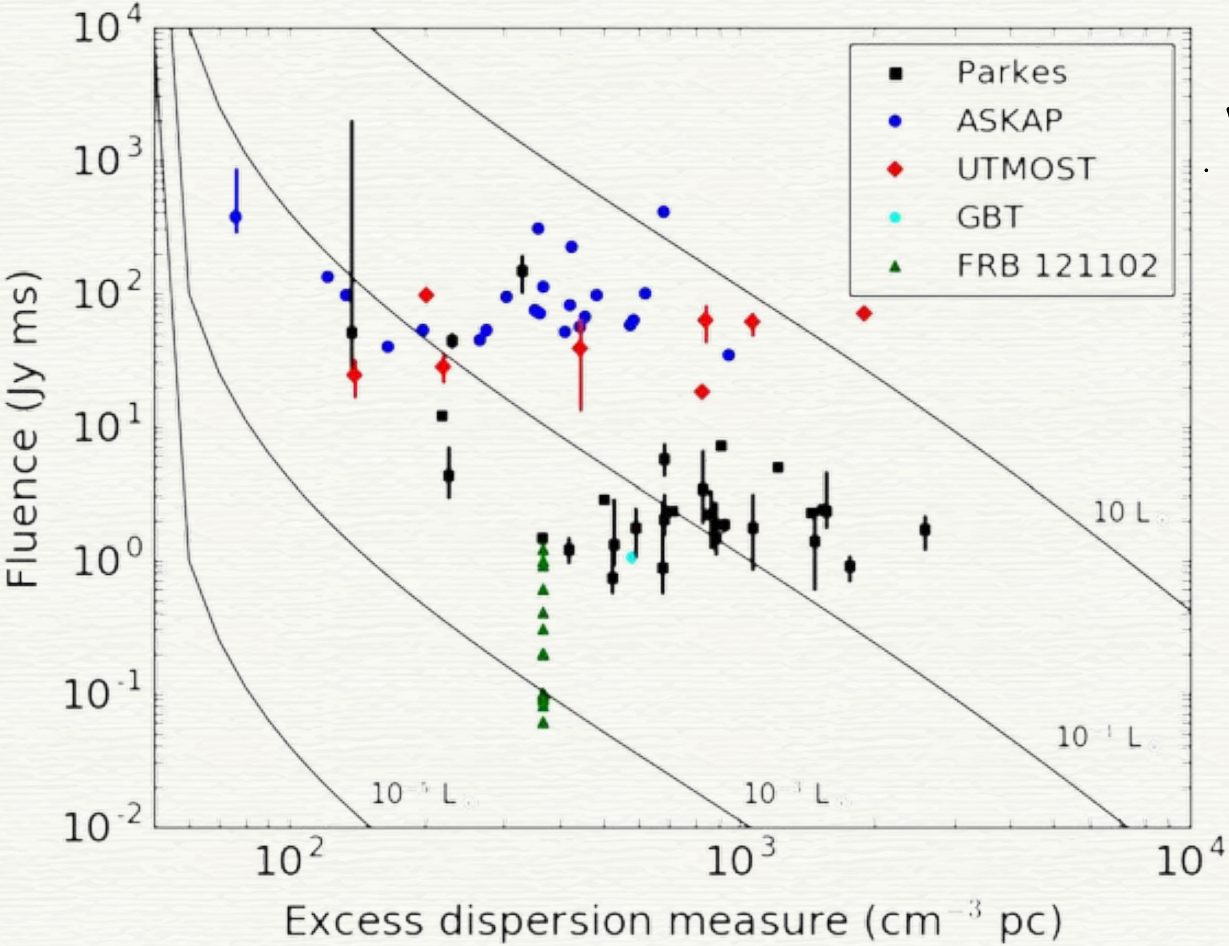


FRB 121102
Arecibo
Flux
Frequency (MHz)
4200
4400
4600
4800
22
24
26
Time (ms)
FRB180814.J0422+73
CHIME/FRB
500
600
700
800
0
100
200
300
Time (ms)

POPULATION DISTRIBUTION

FLUENCE-DISPERSION

- The relationship between fluence and DM can reveal how FRBs might be distributed in space, as one would expect the fluence to decrease with increasing DM.



Parkes
ASKAP
UTMOST
GBT
FRB 121102
Fluence (Jy ms)
Excess dispersion measure (cm⁻³ pc)
10 L

LUMINOSITY FUNCTION

Schechter luminosity function, which is an empirical model used to describe the number of objects per unit volume as a function of their luminosity especially when the population includes both bright and faint sources. It provides a way to describe how frequently we expect to observe FRBs of different luminosities.

$$\phi\,(Log\,L) = \left(\frac{L}{L_\star}\right)^{\beta+1} \exp\left(-\frac{L}{L_\star}\right)$$

INTRINSIC PULSE WIDTHS

The observed pulse width (duration) can provide clues about their emission mechanisms and the environments they come from. Being able to distinguish between intrinsic pulse widths and those broadened by interstellar medium effects like scattering is crucial for unraveling the physics of the FRB sources.

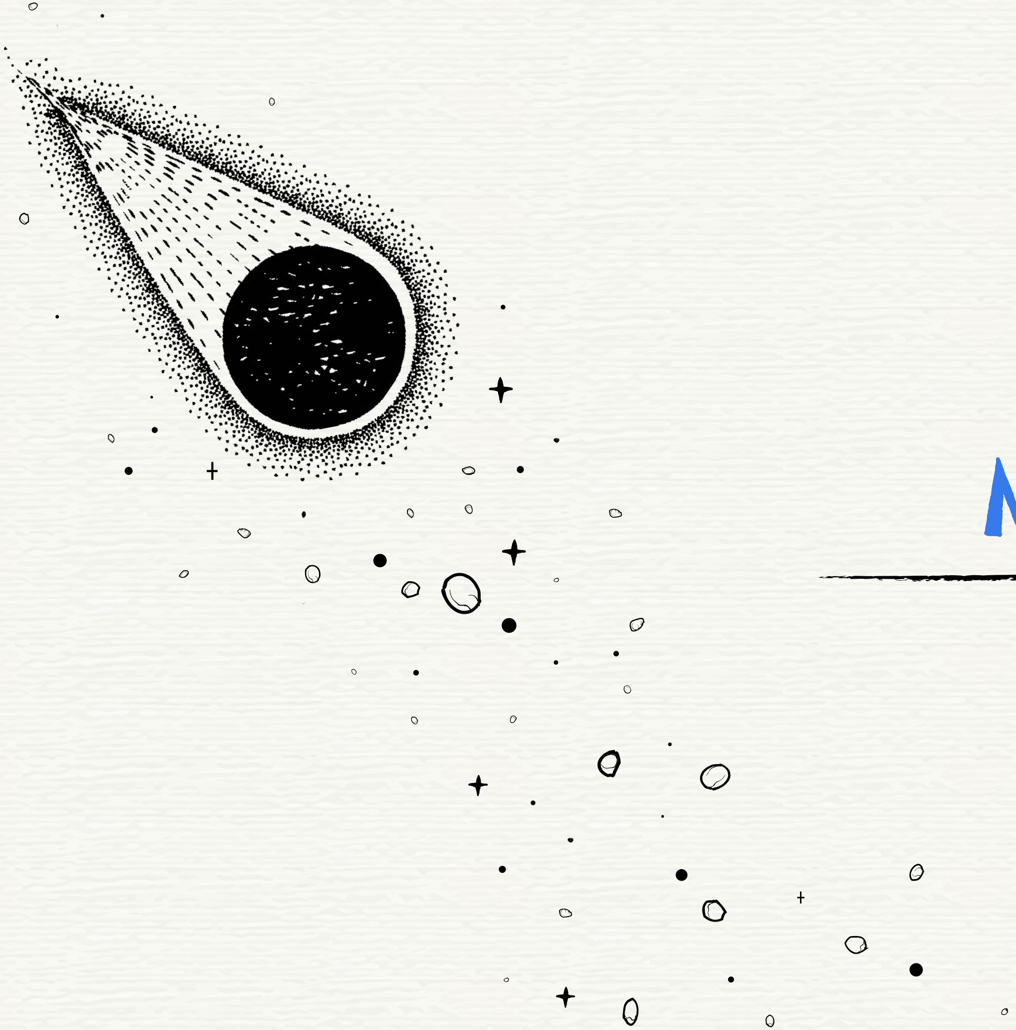
INTRINSIC SPECTRA

- Variations in the spectra among different FRBs could point to different physical conditions or emission mechanisms.

- A simple power-law model is commonly used to describe FRB spectra, where the flux density depends on the frequency.

    - Scattering in the intergalactic medium can artificially flatten the spectral index, making it appear less steep than it actually is.

    - Free-free absorption in dense environments could suppress signals at lower frequencies, thus affecting the perceived spectra.



EMISSION MECHANISMS

The very energetic and and their short intrinsic durations require a coherent emission process from a compact region.

a process where electromagnetic radiation is emitted with a fixed phase relationship among the emitting particles, leading to constructive interference that amplifies the signal

MAGNETARS

- Neutron stars with exceptionally strong magnetic fields (up to 10^{15} Gauss). These extreme magnetic fields can lead to catastrophic events, such as starquakes, releasing enormous amounts of energy.

- In this model, FRBs are believed to originate from curvature radiation (a process where charged particles (electrons) move along curved magnetic field lines and emit radiation). This process is highly efficient in generating coherent radio emission.

PULSARS

- Rotating neutron stars that emit regular pulses of radiation. In rare cases, some pulsars emit giant pulses, which are much more intense than their usual pulses.

SYNCHROTRON MASER EMISSION FROM SHOCKED PLASMA

- It occurs when charged particles (electrons) spiral in strong magnetic fields, emitting coherent radiation. This process is enhanced when the particles move in phase, generating intense, narrowband radio signals.

- Shocked Plasma: When a high-velocity shock wave propagates through a plasma, it can accelerate charged particles to relativistic speeds in the presence of a magnetic field, these particles can emit synchrotron radiation.

COMPACT OBJECT MERGERS

- FRBs could be generated during the merger of compact objects, such as neutron stars or black holes.

- During the merger process, intense gravitational forces and magnetic fields are involved. These extreme conditions can produce relativistic jets, in which particles are accelerated to near the speed of light. The interaction of these particles with magnetic fields can lead to coherent emission in the form of FRBs.

PROGENITOR MODELS

1

NEUTRON STARS

- Isolating
- Interacting
- Colliding

2

BLACK HOLES

3

WHITE DWARFS

4

EXOTIC PROGENITORS

- Cosmic String
- Primordial Black Holes

5 YEARS LATER …

FRB IS NOW A HOT TOPIC

NUMBER

- ~ 2000 FRBs.
- ~ 60 Repeating.

TELESCOPES

- VLBI.
- CHIME.

LOCATION

- Dwarf Galaxies.
- Massive Spiral Galaxies.
- Star-forming regions.

MAGNETARS

- SGR 1935+2154 emitted a signal of FRB in 2020.

PERIODICITY

- External factors.
- Up to 16 days period.

PROBING IGM

- They are now used to study the diffuse gas between galaxies.

Mischief Managed

Fred&George Weasley

Thank you very much