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Piano Nazionale di Ripresa e Resilienza

INAF
Istituto Nazionale di Astrofisica

Luck [Mgastone]

Searching for four-leaf clovers in the Radio Transient Sky

FRB-Italy 2025
7-9 May Bologna

Matteo Trudu (INAF-OACa)

Patience [Gbabar]

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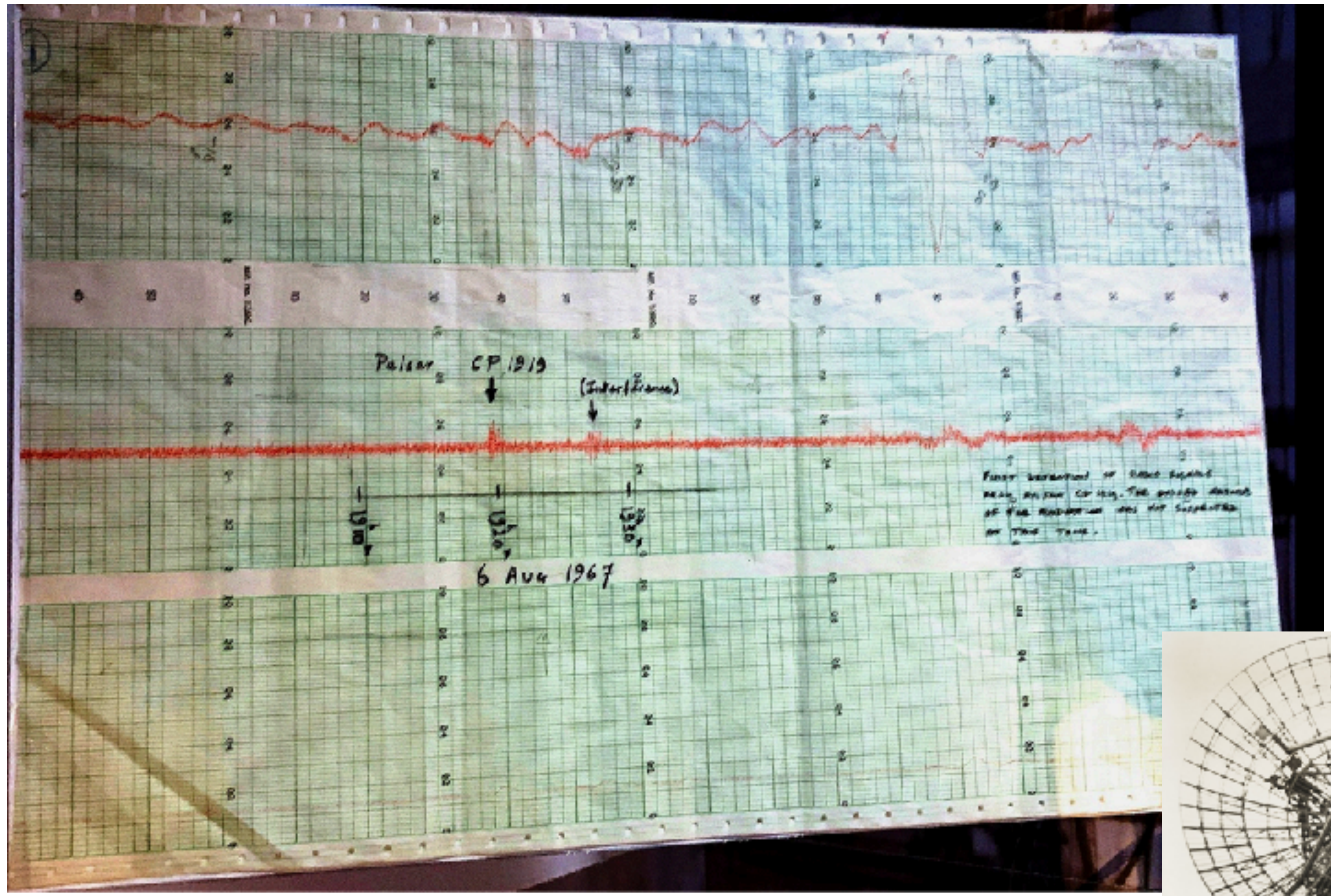
Let's go back in time...

- The first known pulsar, PSR B1919+21, was discovered by J. Bell (photo) by very patiently inspecting its single pulses in a pen chart recorder

- J. Bell with her eyes basically performed what now we usually call a matched filter search

- PSR B1919+21 was "just right": fairly small DM, not too short period, neither too long, very bright



J. Bell at the Mullard Radio Astronomy Observatory

Let's go back in time…

- A few year before Cooley and Tukey publish their seminal work on fast implementation of the discrete Fourier Transform (FFT)
- When large computing facilities became more accessible astronomers quickly realised that they could use FFT searches for pulsars
- Thanks to this Backer discovered the first milli-second pulsar
- Fourier-based searches became quickly the de-facto standard search algorithms for pulsars

An Algorithm for the Machine Calculation of Complex Fourier Series

By James W. Cooley and John W. Tukey

Letter | Published: 16 December 1982

A millisecond pulsar

D. C. Backer, Shrinivas R. Kulkarni, Carl Heiles, M. M. Davis & W. M. Goss

Nature **300**, 615–618 (1982) | Cite this article

3325 Accesses | **674** Citations | **50** Altmetric | Metrics

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Let's go back in time…

- Pulsar Giant Pulses (GPs) revamped the impetus to search for exotic sources again by performing a single pulse search (SPS) [Cordes&McLaughlin+03]
- The search is then done by convolving the recorded signal with a template function (matched filter)
- It did not take too much time to have very fruitful results: thanks to SPSs we discovered the so called rotating radio transients (RRATs)

THE ASTROPHYSICAL JOURNAL

FREE ARTICLE

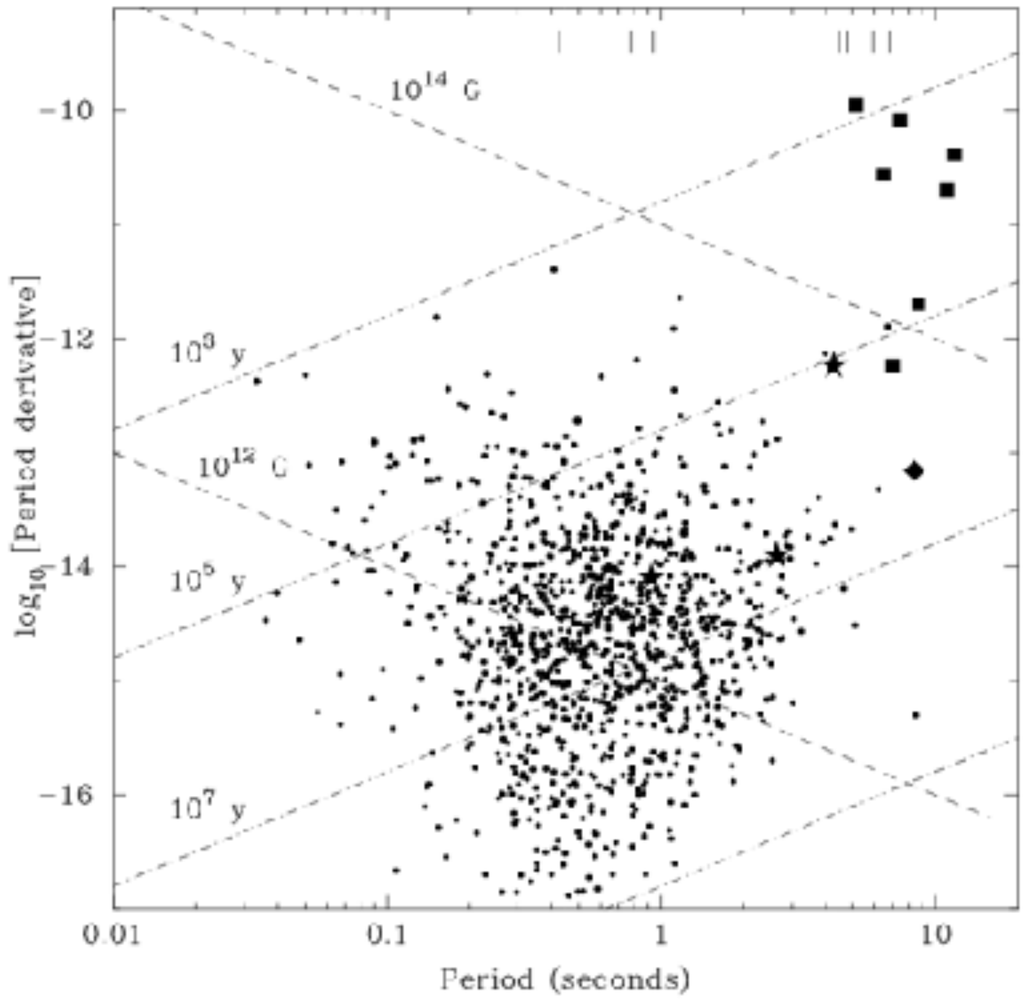
Searches for Fast Radio Transients

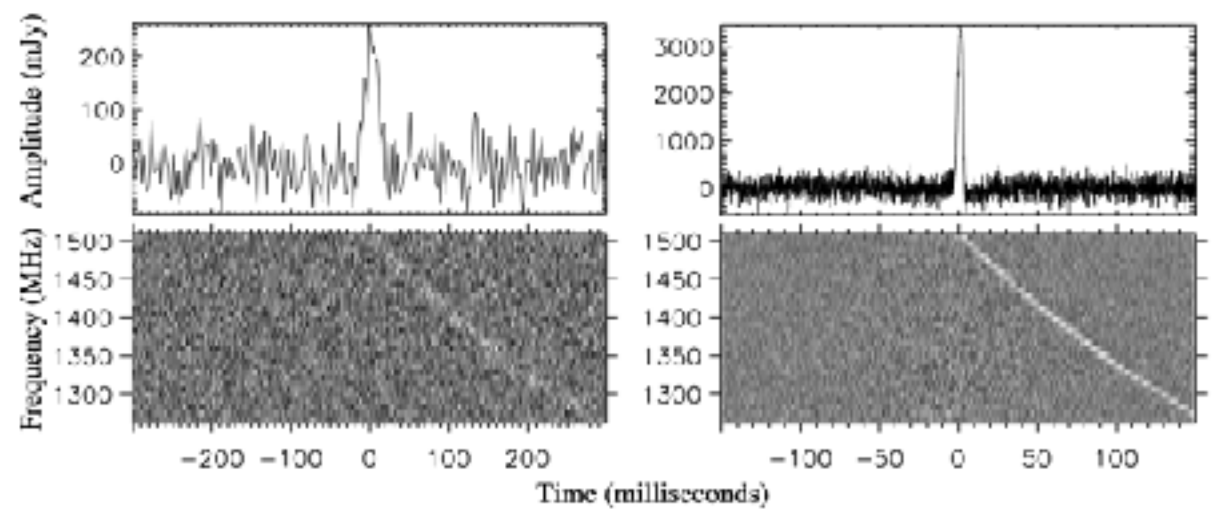
J. M. Cordes and M. A. McLaughlin

The Astrophysical Journal, Volume 596, Number 2

Citation J. M. Cordes and M. A. McLaughlin 2003 *ApJ* **596** 1142

DOI 10.1086/378231





nature

Letter | Published: 16 February 2006

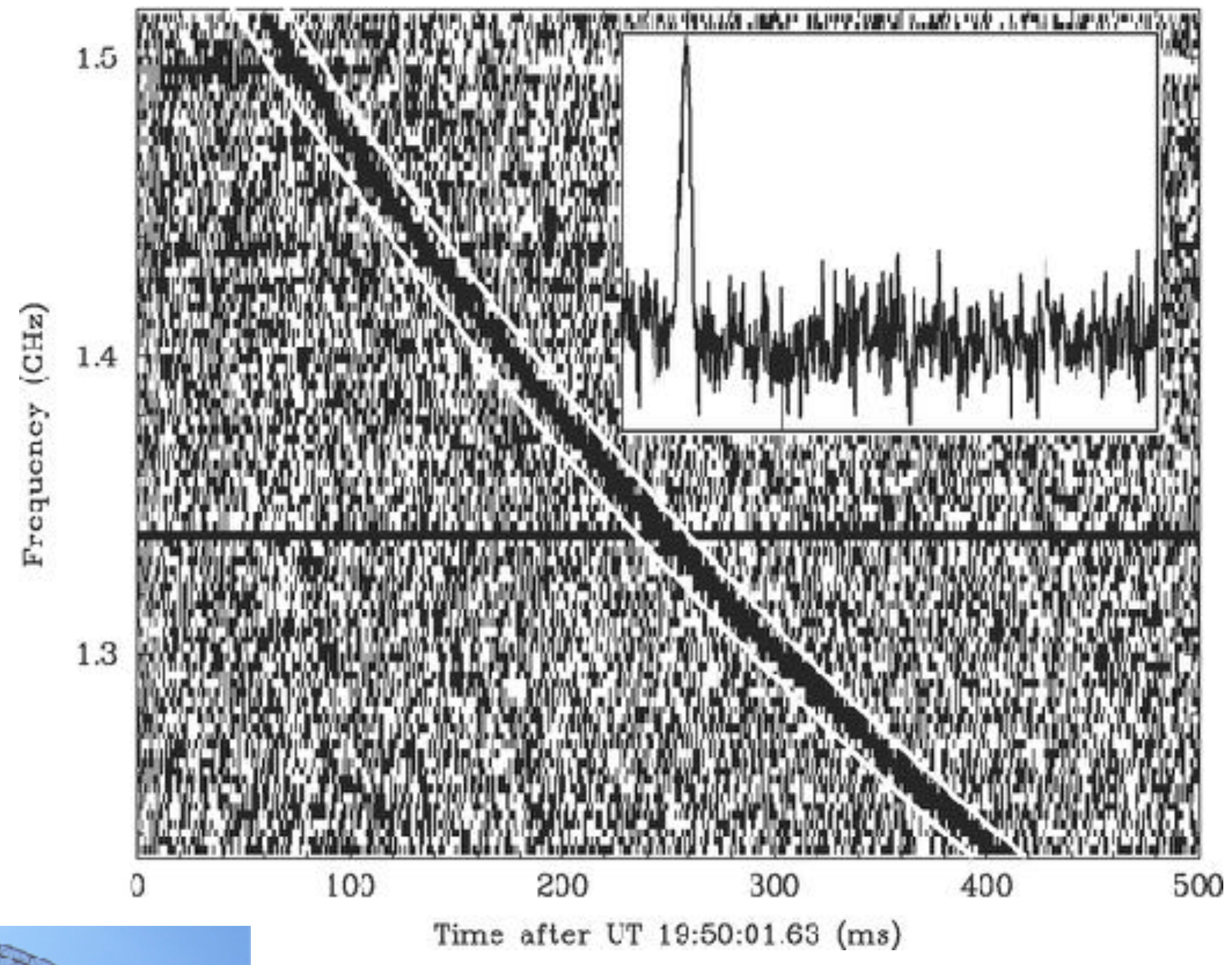
Transient radio bursts from rotating neutron stars

M. A. McLaughlin, A. G. Lyne, D. R. Lorimer, M. Kramer, A. J. Faulkner, R. N. Manchester, J. M. Cordes, F. Camilo, A. Possenti, I. H. Stairs, G. Hobbs, N. D'Amico, M. Burgay & J. T. O'Brien

Nature 439, 817–820 (2006)

We did discover FRBs… by searching something else!

- Desire to reprocess archival data to find RRATs
- Reprocessing of the Parkes (Australia) Small Magellanic Clouds Survey
- An unexpected single event: the Lorimer Burst (LB)



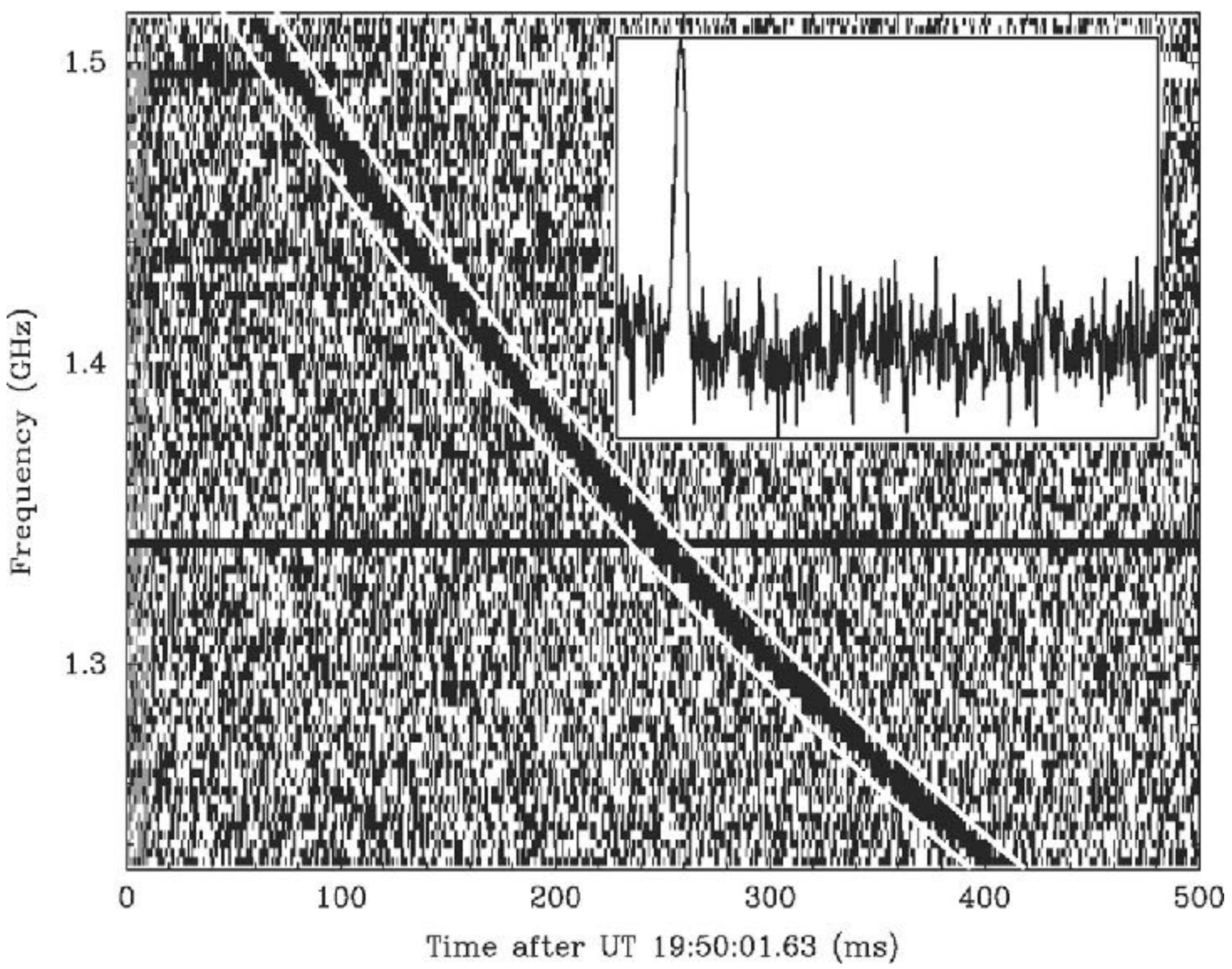
Lorimer+07 (Science)

What is an FRB ?

By studying the “anatomy" of the LB one can still pretty much define what is an FRB, or better saying what we think should be an FRB:

1. Very short duration, ms-long

2. Very energetic, about 10^{40} erg which translates into fluences of Jy ms - ish if they do come from outside our Galaxy or MJy ms if you see one from the MW



Lorimer+07 (Science)

What is an FRB ?

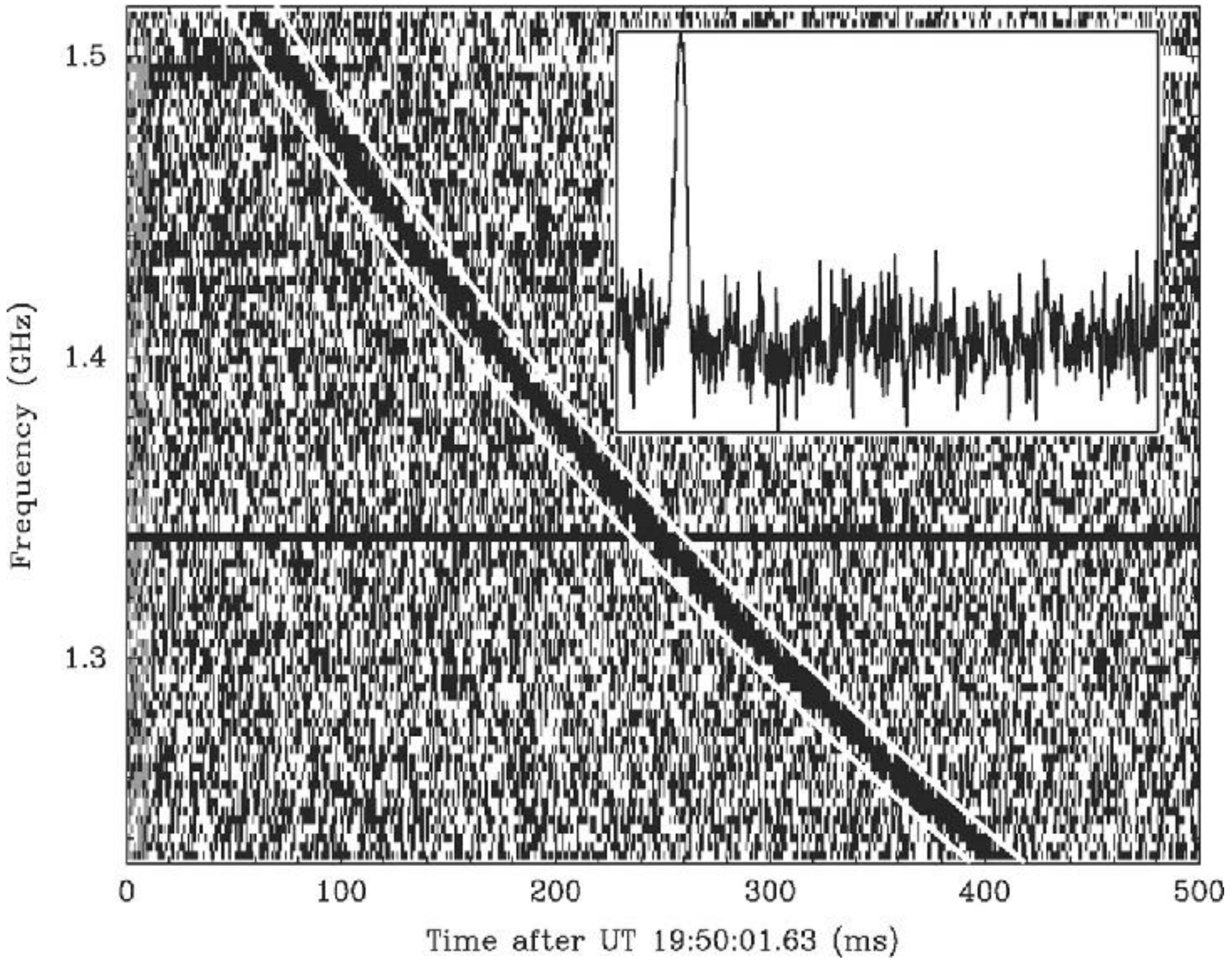
These super bright flashes experience the very same effects radio pulsar signals experience due to the interaction with the medium:

1. Dispersion

2. Scattering

3. Scintillation

4. Faraday rotation



Lorimer+07 (Science)

What is an FRB ?

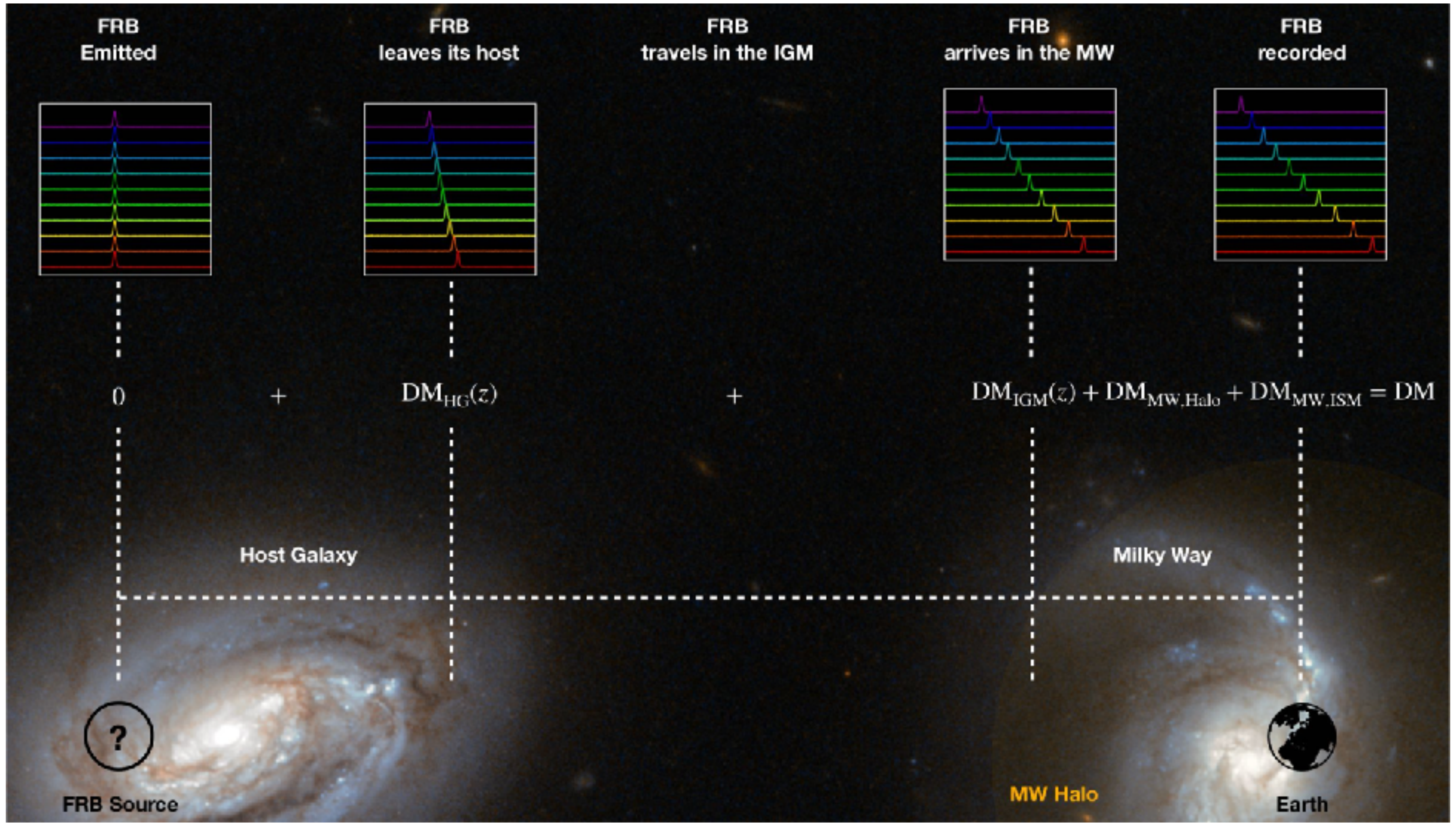
Dispersion

Each frequency component of the FRB signal is delayed and such delay depends on the frequency itself

$$\Delta t\left(\nu_a,\nu_b\right) \propto \mathrm{DM}\left(\nu_a^{-2}-\nu_b^{-2}\right)$$

and on the quantity of free electrons it interacts with via the dispersion measure (DM):

$$\mathrm{DM}=\int_{\mathrm{us}}^{\mathrm{source}} n_e(l)dl$$

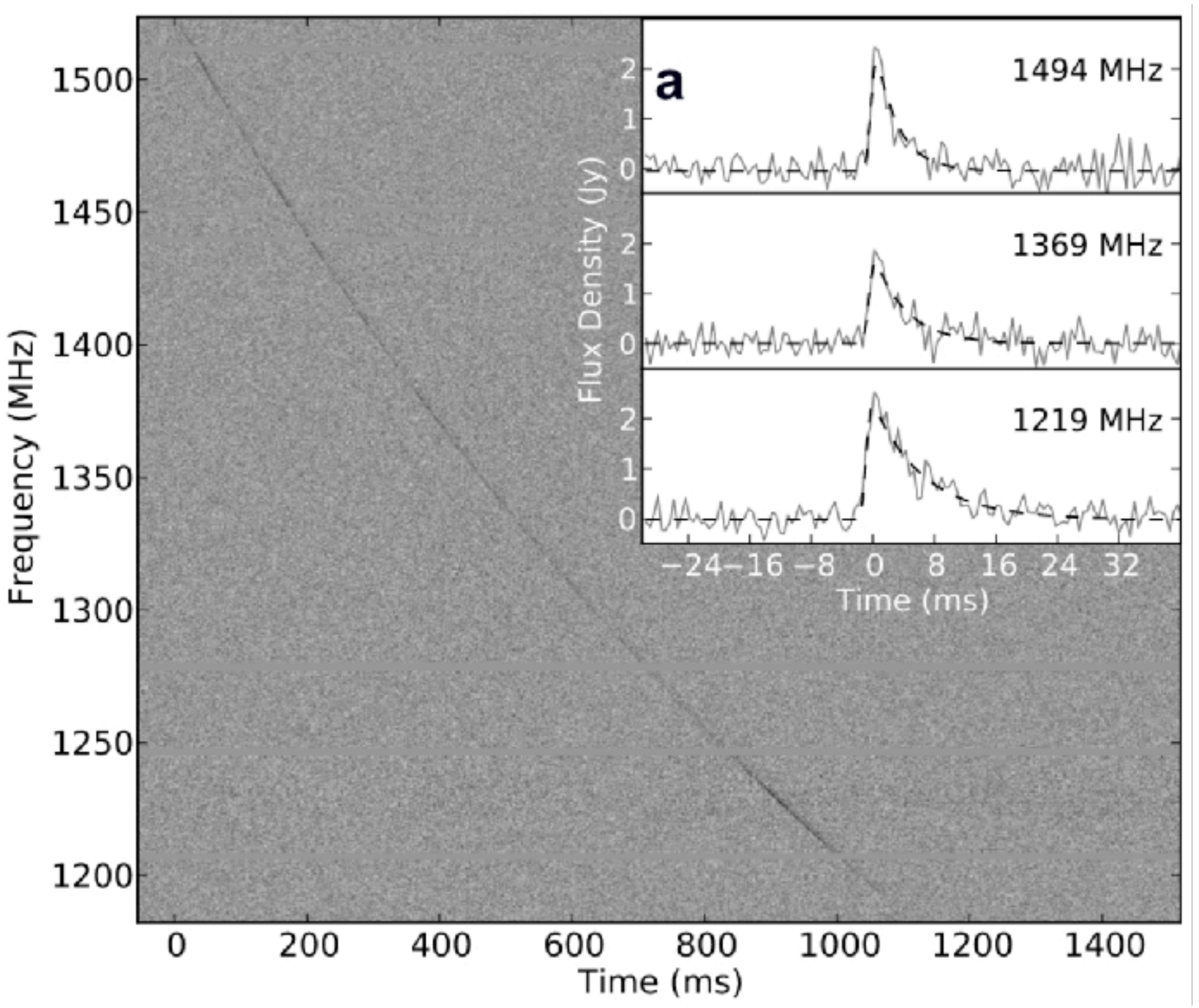


What is an FRB ?

Scattering

The inhomogeneities of the medium itself can cause multi-path propagation of the signal which turns into a frequency-dependent pulse broadening

$$I(t) \rightarrow I(t) \circledast \exp\left(-\frac{t}{\tau}\right) \qquad \tau \propto \nu^{-\rho} \quad \rho \sim 4$$



Thornton+14 (Science)

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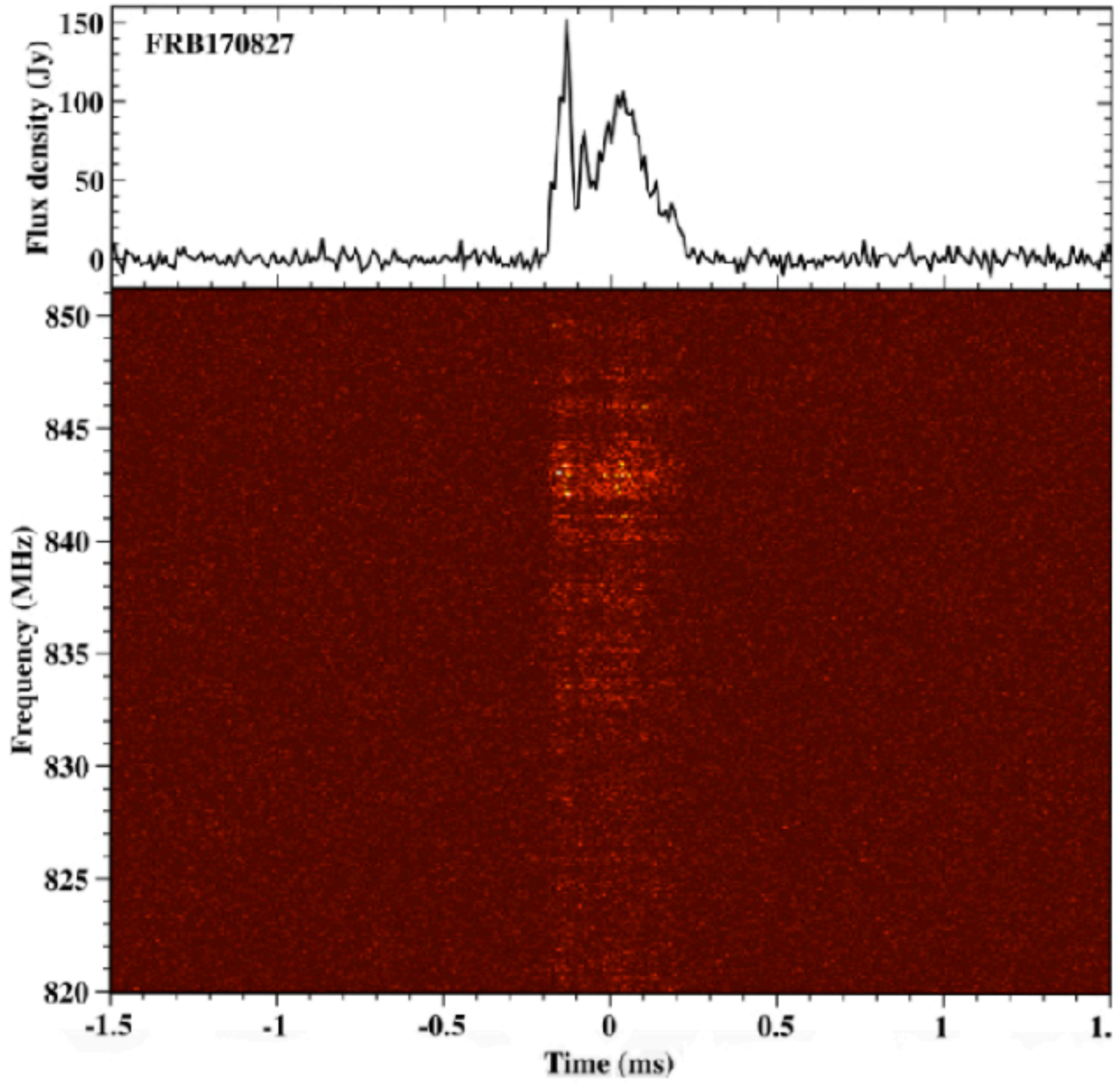
What is an FRB ?

Scintillation

The inhomogeneities of the medium causing the multi-path propagation makes also constructive/destructive sum of the signal wavefronts at the location of the observer's, creating an interference pattern



Farah+18 (MNRAS)

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What is an FRB ?

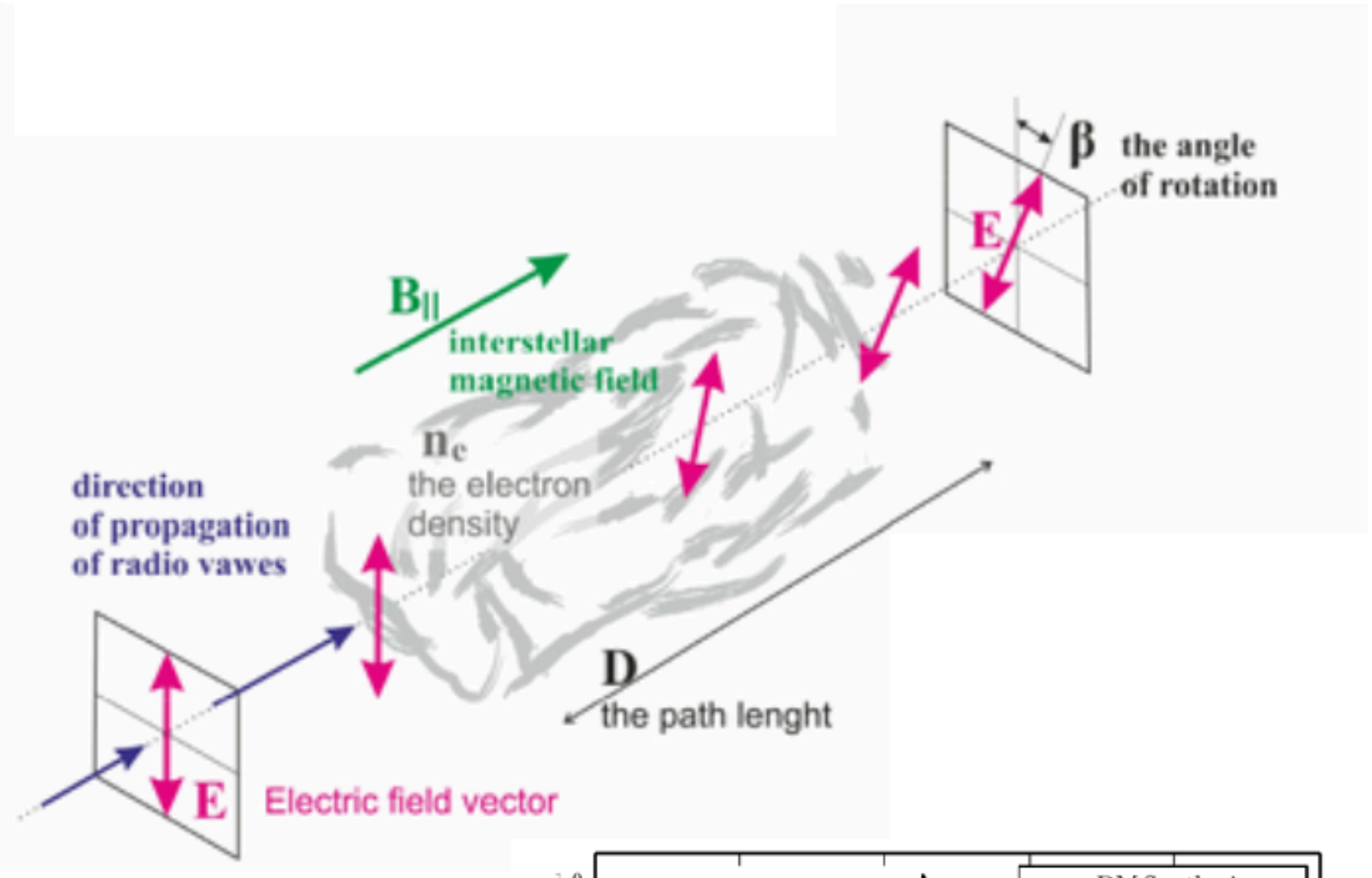
Faraday rotation

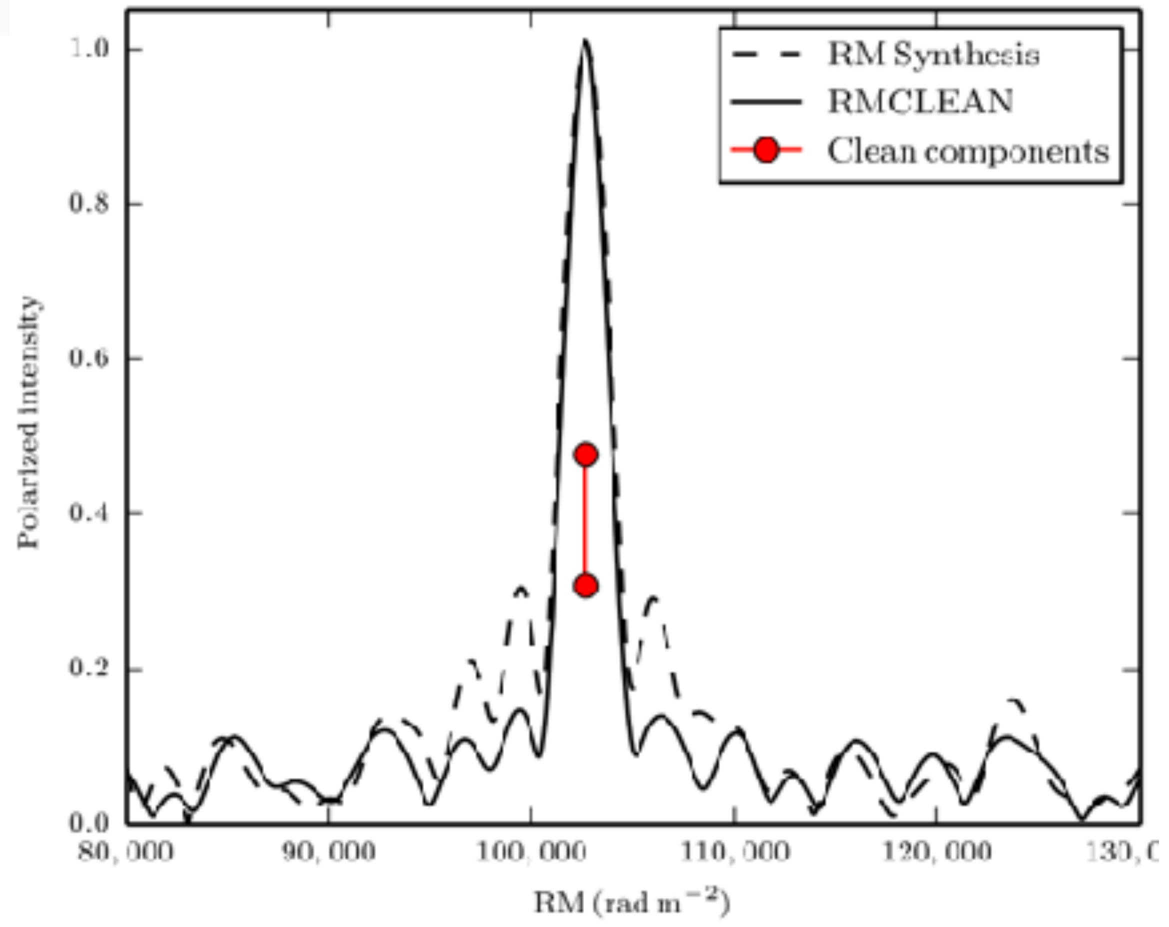
The magnetic field of the medium (its parallel component along the line of sight) can make rotate the plane of linear polarisation of an FRB signal, this rotation is frequency dependent

$$\Delta\Psi = \mathrm{RM}\frac{c^2}{\nu^2}$$

and it depends on the strength of the magnetic field via the rotation measure RM:

$$\mathrm{RM} \propto \int_{\mathrm{us}}^{\mathrm{source}} n_e(l) B_{||}(l) dl$$





FRB 20121102A, Michilli+18 (Nature)

What is an FRB ?

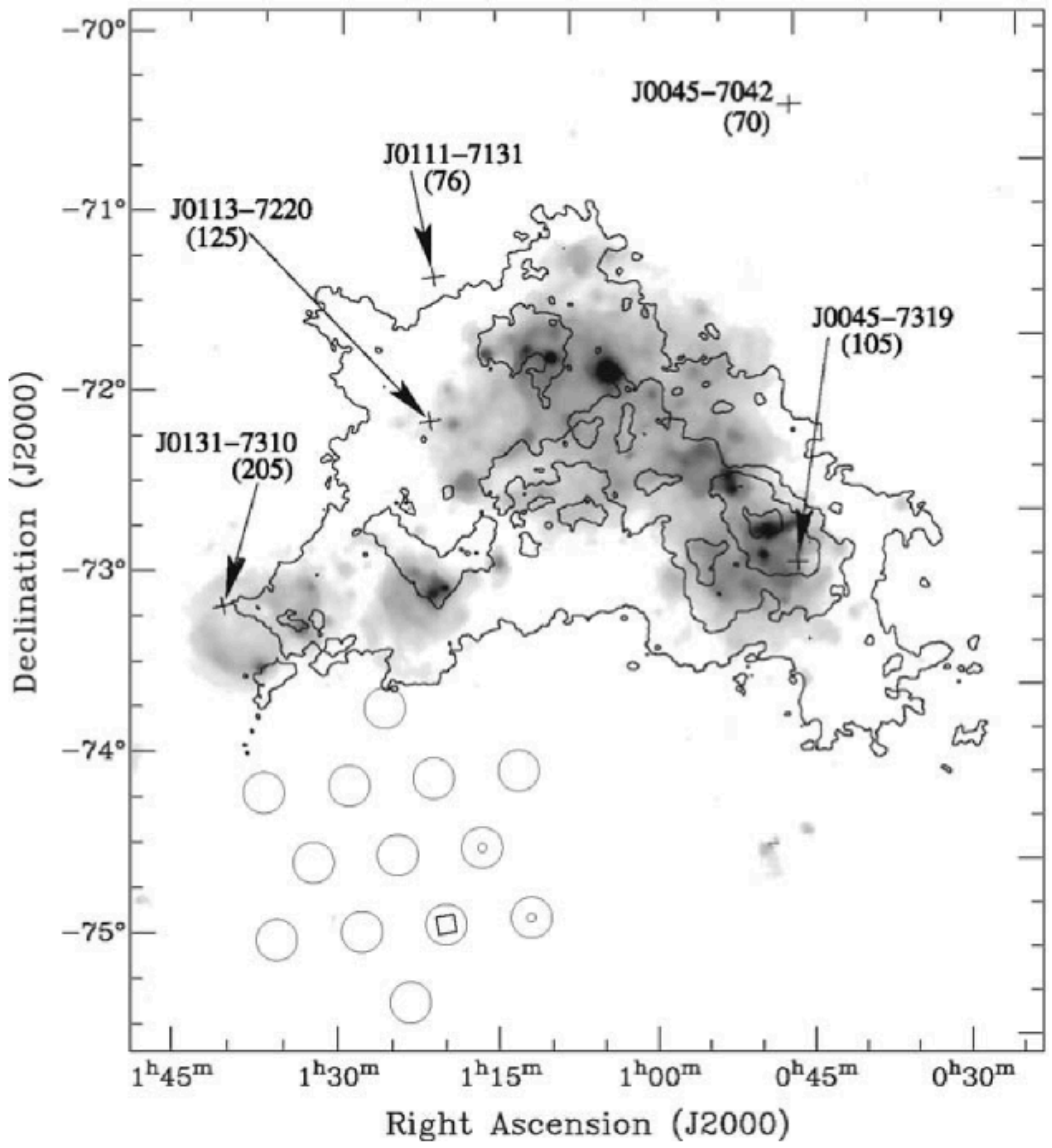
- Parkes Multi-Beam Receiver (PMB), 13 beams of 0.2 deg @ 1.4 GHz
- The LB fluence was 30 Jy ms
- The SMC Survey: A = 5 squared degrees T = 480 hours
- Let us do back-of-the-napkin math of the possible all sky rate:

$$\mathscr{R}\,(>30\ \mathrm{Jy\ ms}) = 1\ \mathrm{burst} \times \left(\frac{4\pi}{A}\right) \times \frac{1}{T} \sim 400\ \mathrm{burst\ sky^{-1}\ day^{-1}}$$

$$\mathscr{R}\,(>5\ \mathrm{Jy\ ms}) = \mathscr{R}\,(>30\ \mathrm{Jy\ ms}) \times \left(\frac{5}{30}\right)^{-3/2} \sim 6\times10^{3}\ \mathrm{burst\ sky^{-1}\ day^{-1}}$$

- For the scaling I just assumed that the log N - log S distribution follows what you would expect in a Euclidean Universe
- Despite being brutal math, this result is still pretty compatible with more recent measurements [CHIME/FRB+21, Niu+21, Jankowski+23]

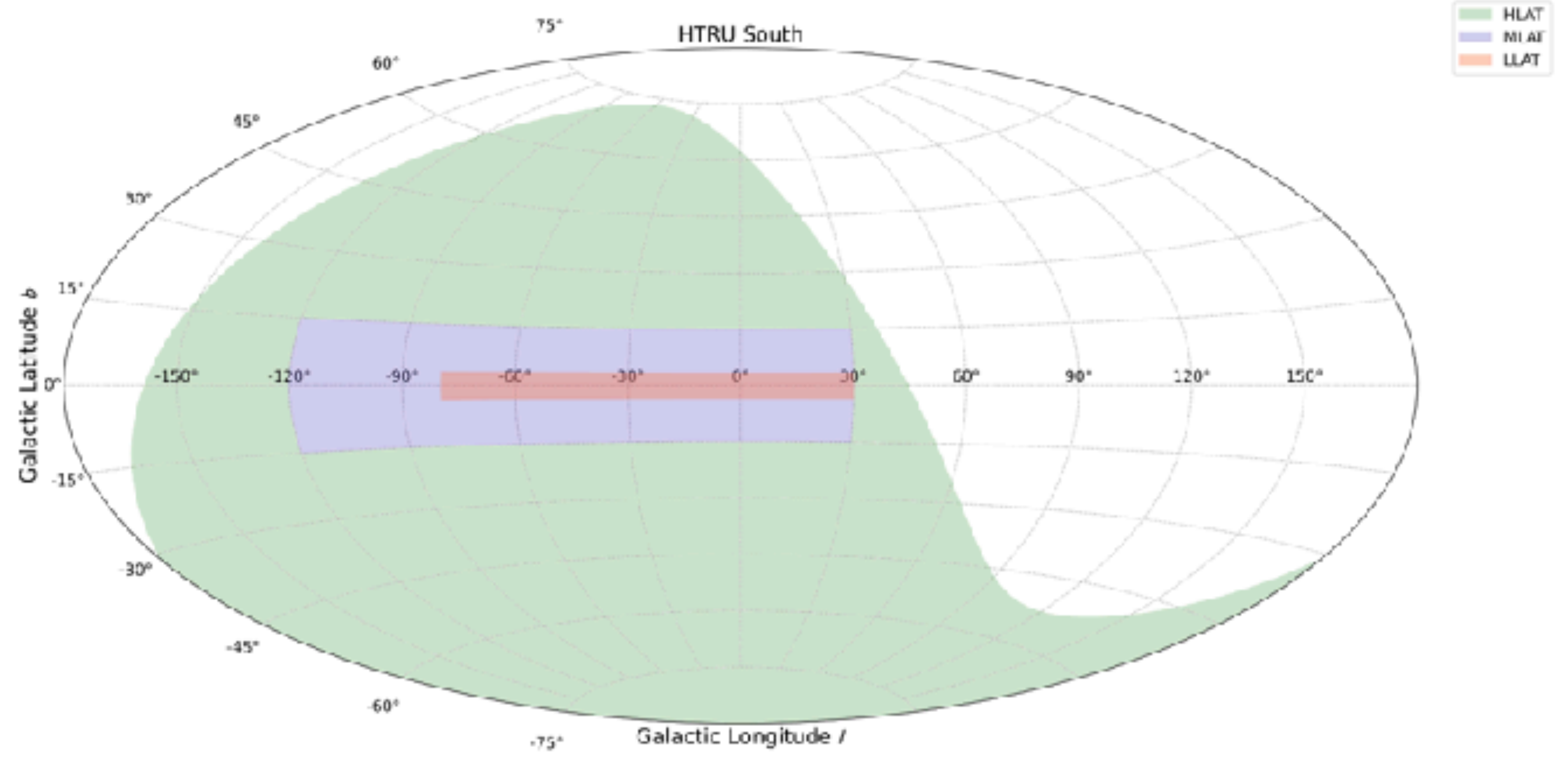
Lorimer+07 (Science)

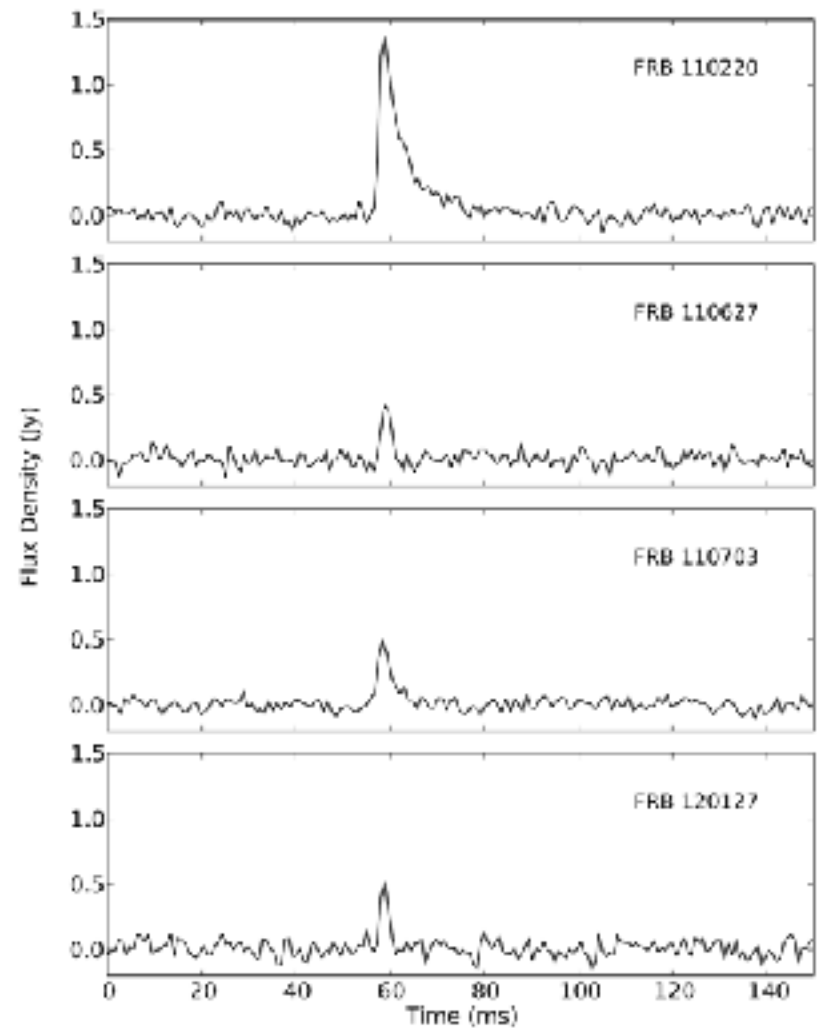


Parkes PMB, Staveley-Smith+97

Again back in time…

- One might think that, given this fairly high all-sky rate, it shouldn't be a big deal finding dozen of FRBs…
- 4π is very huge, you only inspect a tiny fraction of the Sky… If one scale the all-sky rate to the FoV of the PMB one gets way less then 1 event per day…
- Confirming that the LB belongs to a new class of object will require a lot patience… and a bit of luck…
- The Parkes High Time Resolution Universe (HTRU) Survey took on its shoulder this responsibility: after 2600 hours of observation the first unambiguous FRB population emerged





Thornton+14 (Science)

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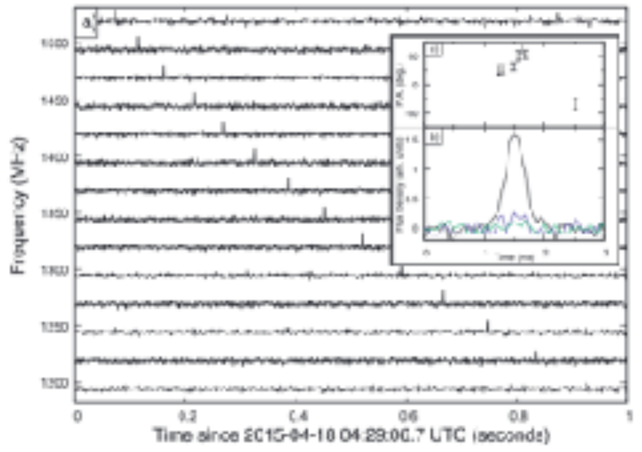
Again back in time…

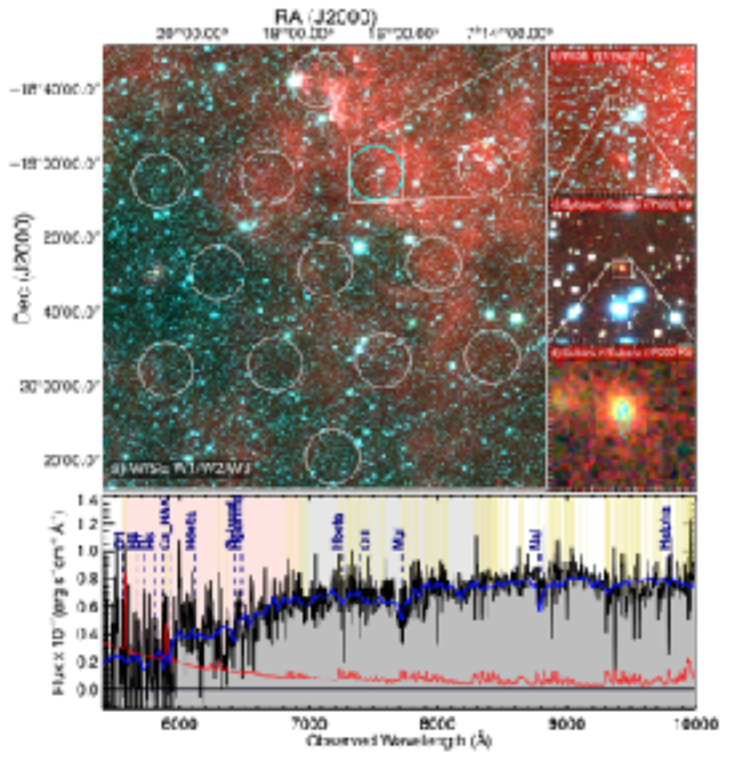
HTRU provided 3 very important lessons:

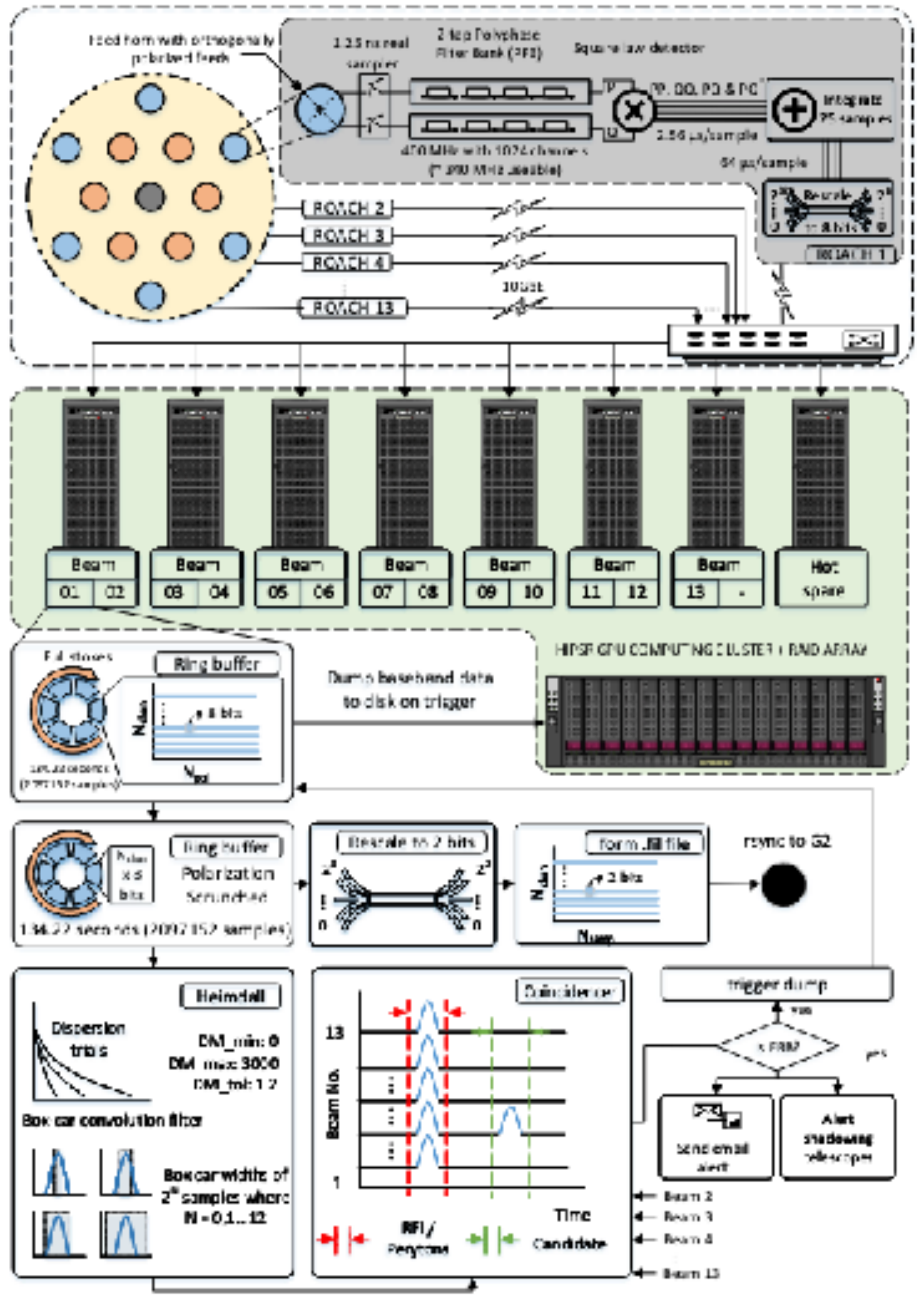
- In the long run it is really impossible to store all the data (HTRU was about a PB)… it is demanding having real-time capabilities…
- Finding FRBs is of course cool but it would be nice having a localisation…
- HTRU data were only Stokes I, polarisation is always nice to have…

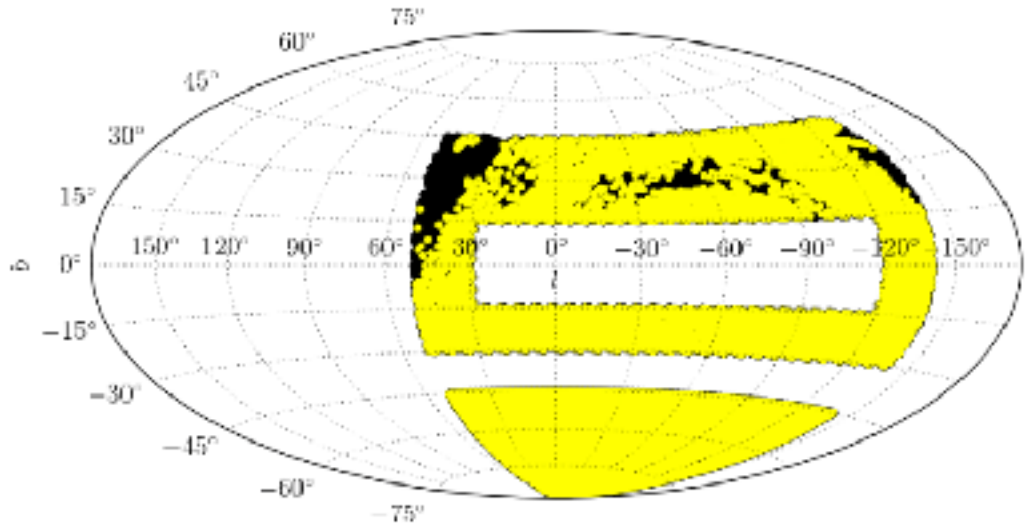
Parkes SUPERB survey tackled this! New FRBs discovered in real time (full Stokes) and 1 fairly good host galaxy association

Keane+16 (Nature)









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Wishlist for an FRB Machine

The pipeline

- Real-time capabilities
- Should form multiple beams within the FoV
- Be capable to deal with radio frequency interference (RFI)
- Needs to deal with the various propagation effects (dispersion and friends) to recover S/N
- Needs to have some degrees of freedom in the parameter space which explore (e.g. pulse width)
- If possible should provide the burst's raw data for maximum flexibility

Wishlist for an FRB Machine
The telescope

- A good instantaneous sensitivity
- A large FoV
- A good localising power

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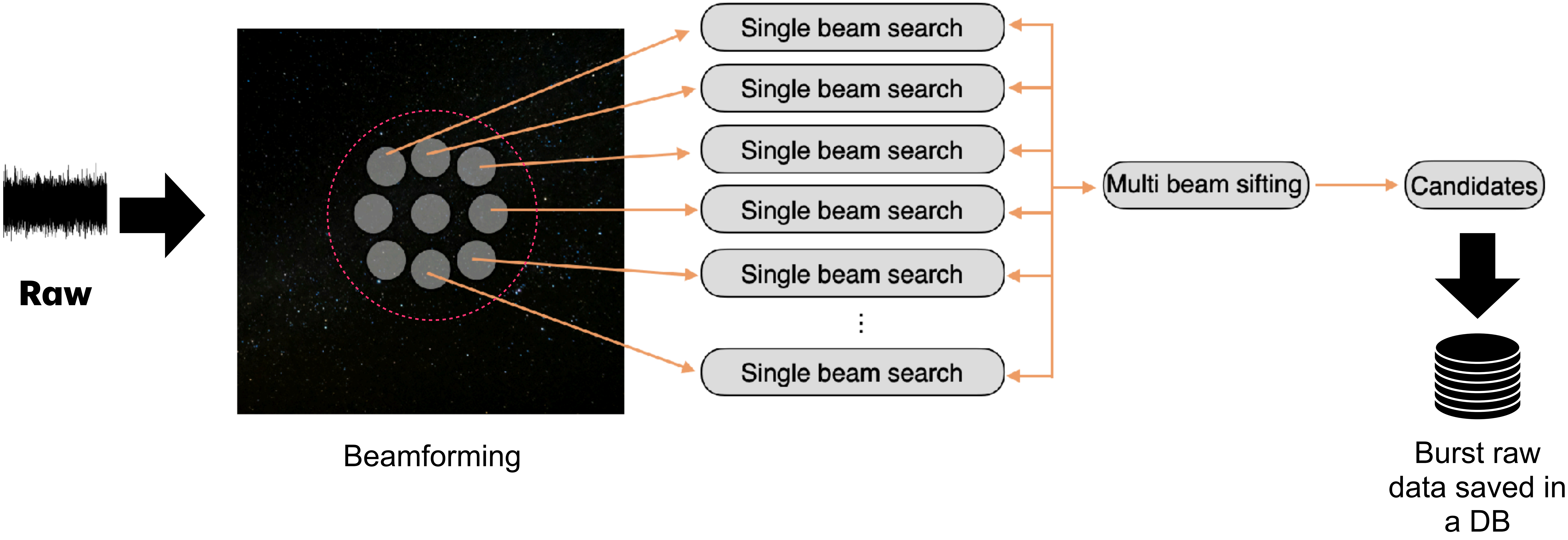
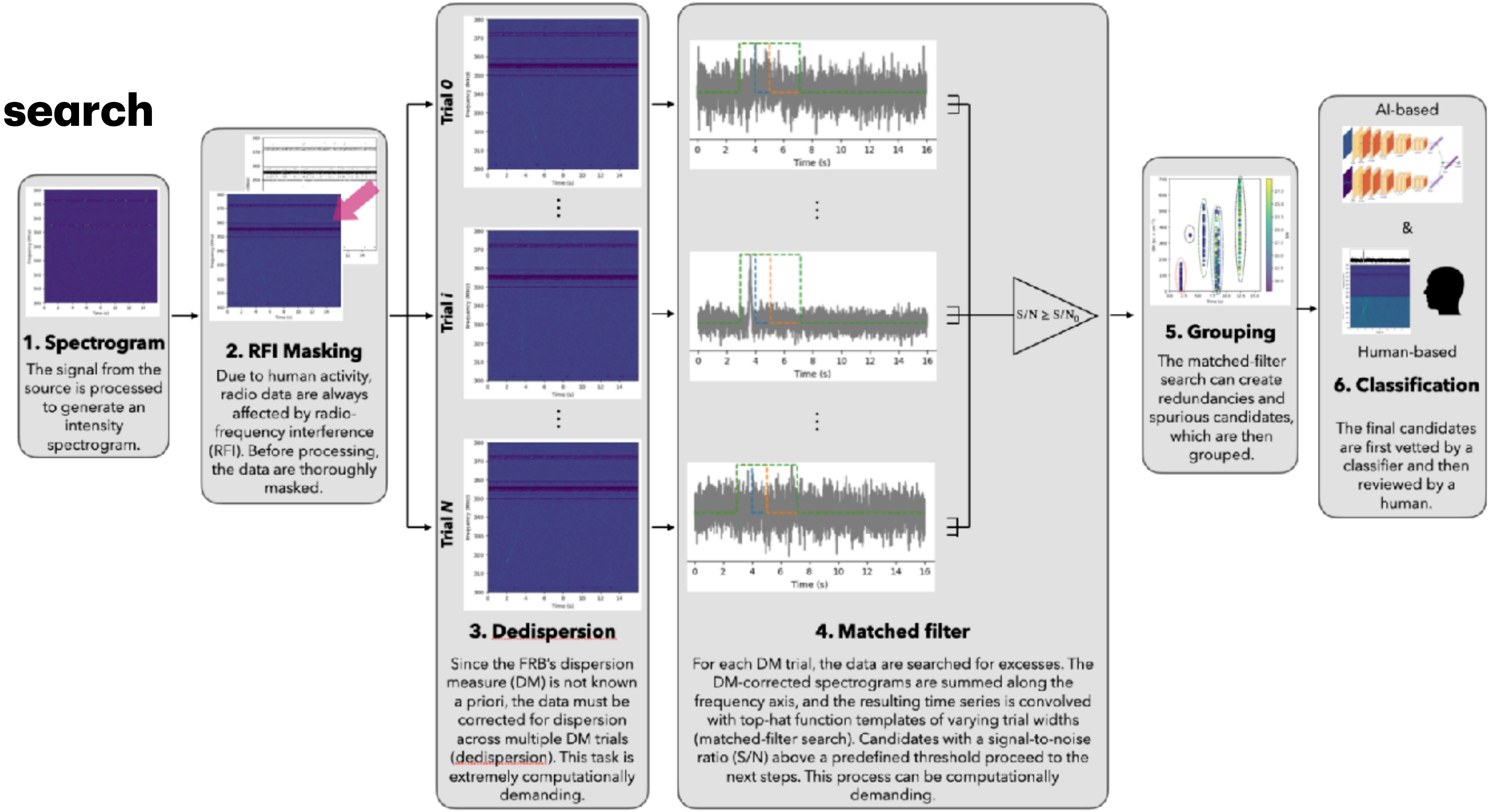
How do our pipelines work?



How do our pipelines work?

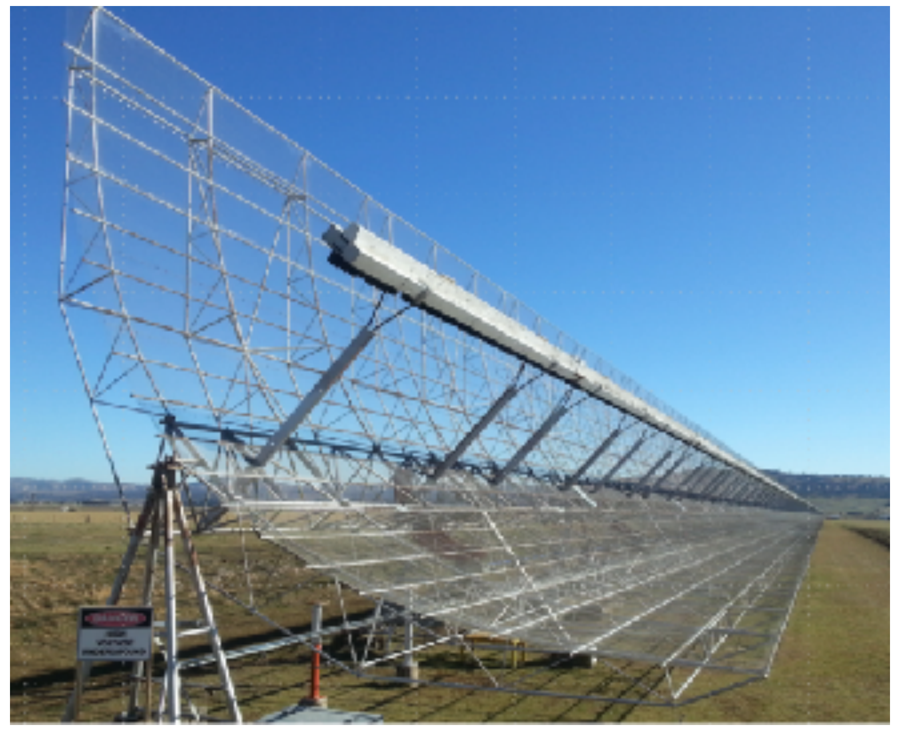
Single beam search



What are the major telescopes (almost) blindly searching for FRBs ?


CHIME (Canada)
2018 - Today


Northern Cross (Italy)
2020 - Today


UTMOST (Australia)
2017 - 2022


ASKAP (Australia)
2017 - Today


Apertif (Netherlands)
2019 - 2023


MeerKAT (South Africa)
2019 - Today


FAST (China)
2019 - Today


VLA (USA)
2020 - Today

Commensally

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These telescopes made wonderful discoveries (some of them already discussed in many talks here)

Now the question is:

How can we improve our searches?

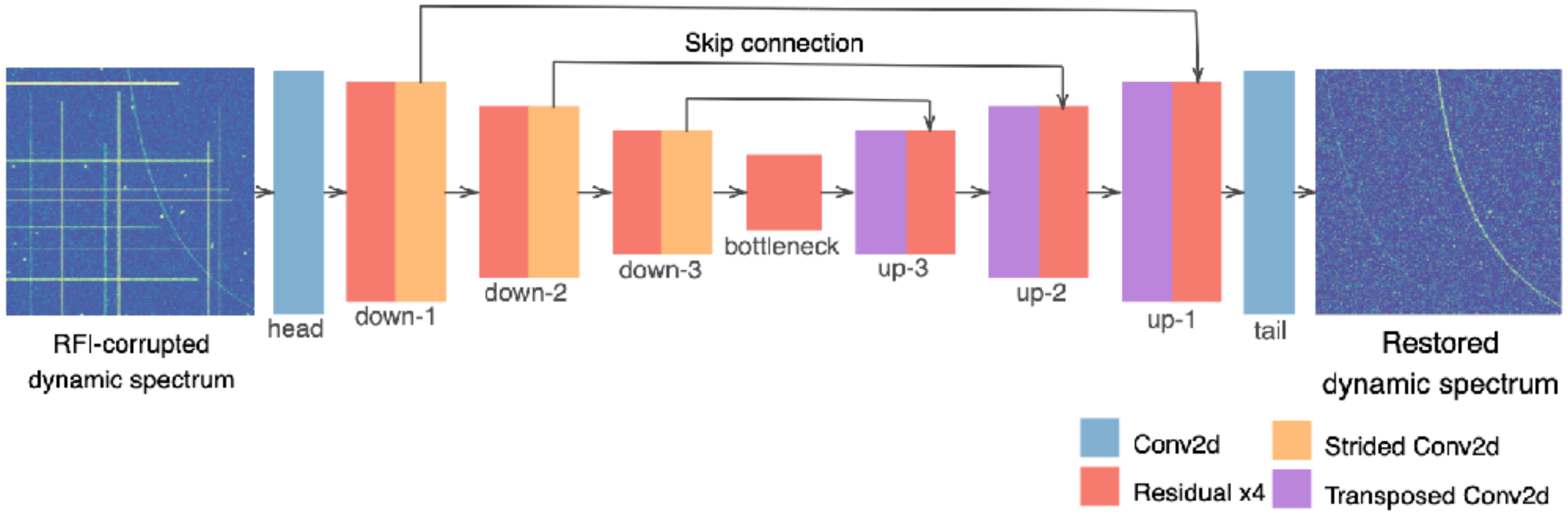
Improving our pipelines…(thanks to AI?)

RFI are becoming a major problem… placing our telescopes in the middle of nowhere is becoming insufficient…from a political standpoint our little community can do little… we'll have to get by… hence improving our mitigation strategies…

A&A 676, A75 (2023)

Unintended electromagnetic radiation from Starlink satellites detected with LOFAR between 110 and 188 MHz

F. Di Vruno[1,2,★], B. Winkel[3,2,★], C. G. Bassa[4,★], G. I. G. Józsa[3,2,5,★], M. A. Brentjens[4], A. Jessner[3] and S. Garrington[6,★]



Zhang+24 (A&C)

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Improving our pipelines...(thanks to AI?)

The FRB search is very expensive (in time)... to be in a real-time regime one must deploy top tier HPC facilities (hence very expensive in money)... it is essential to optimise our searches

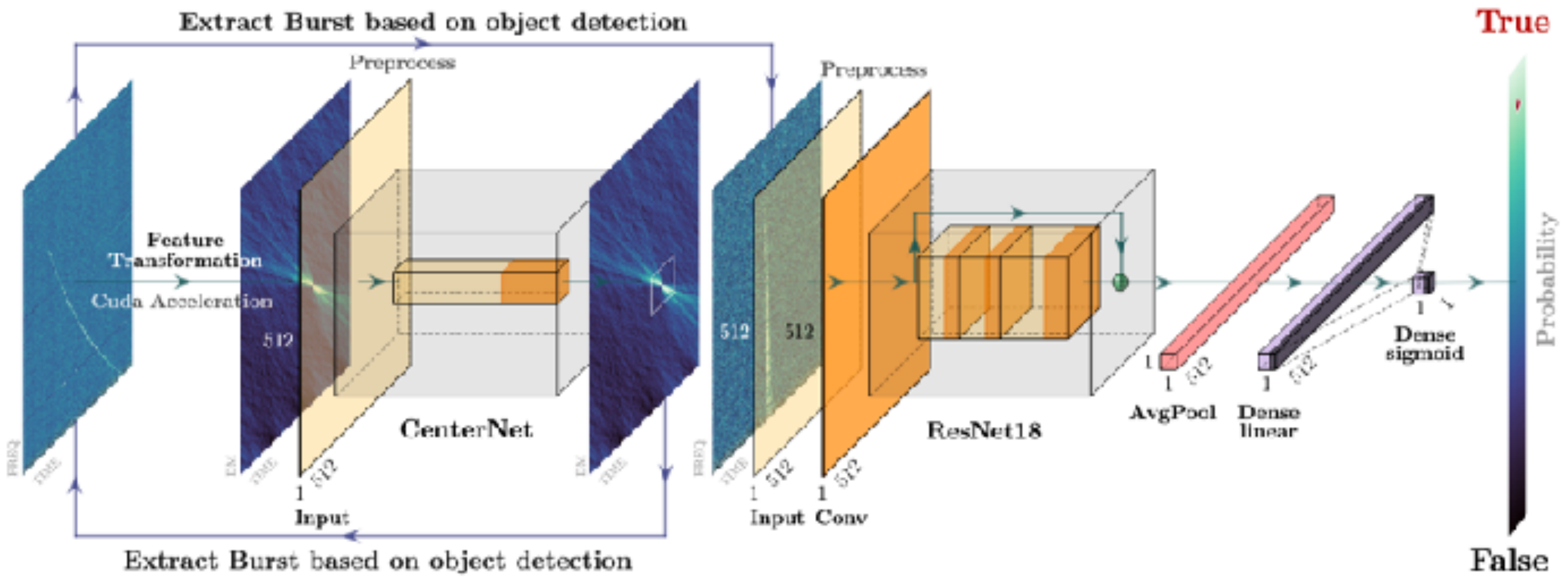
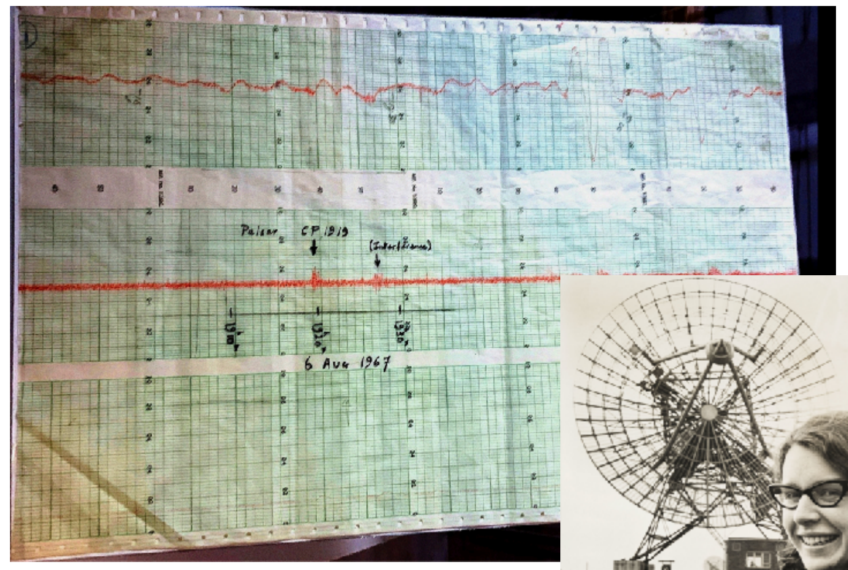
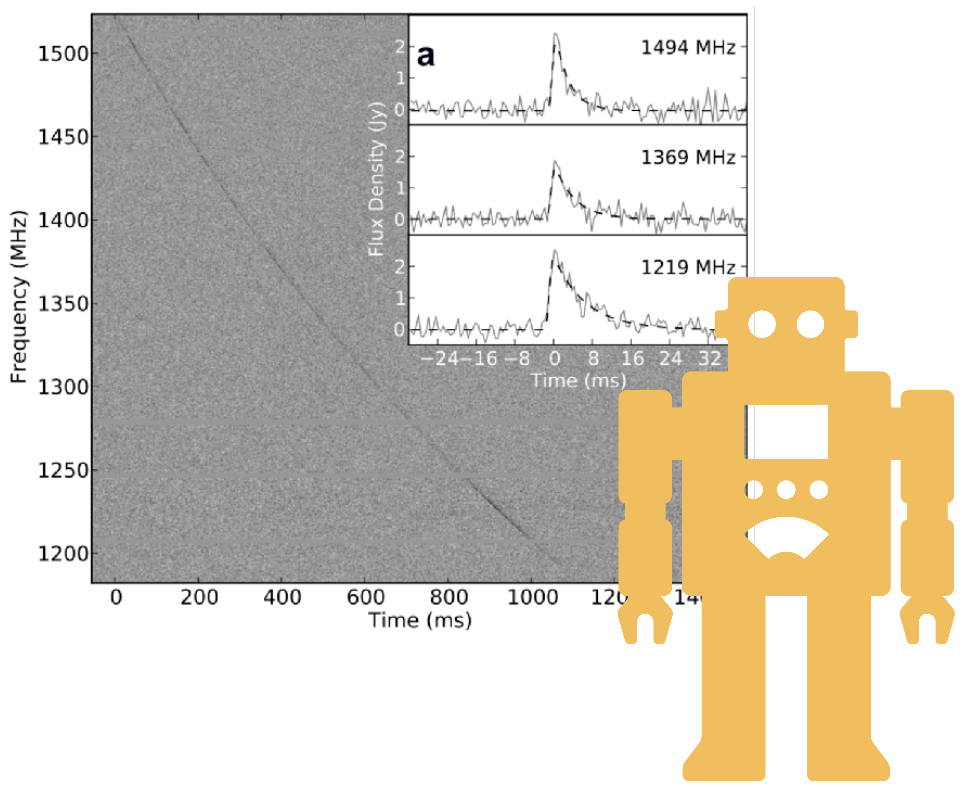


Figure 2. The workflow of DRAFTS.

Zhang+24 (ApJ)

The dedispersion stage is the most time consuming... maybe AI-powered non dedispersed searches?





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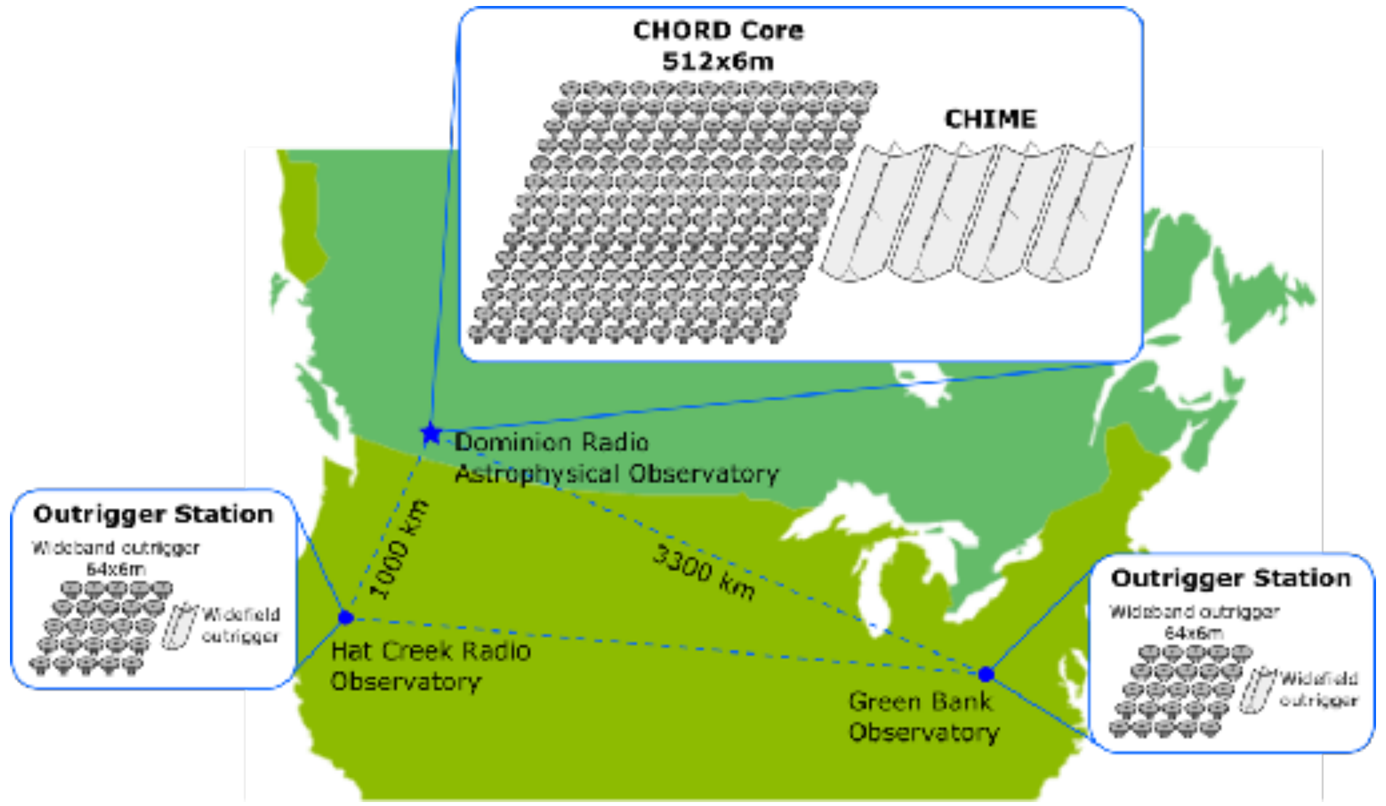
More powerful telescopes… (for the FRB-Italy community)

(See Gianni's talk)

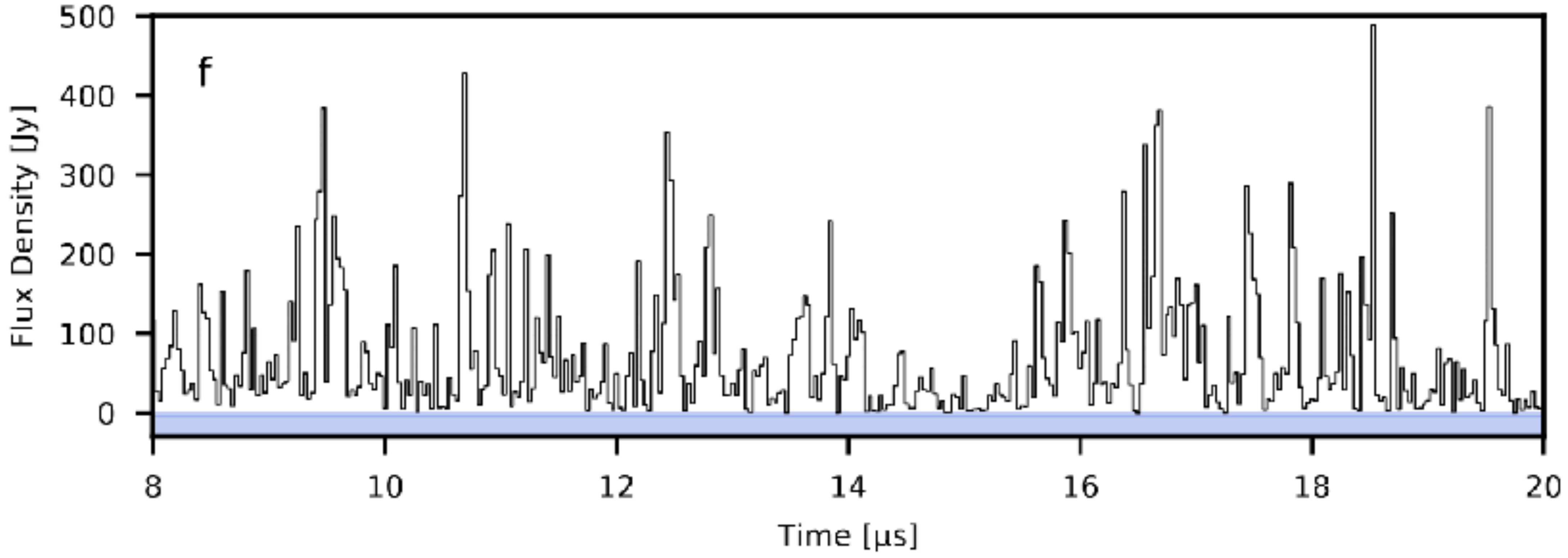


(See Andrea's talk)

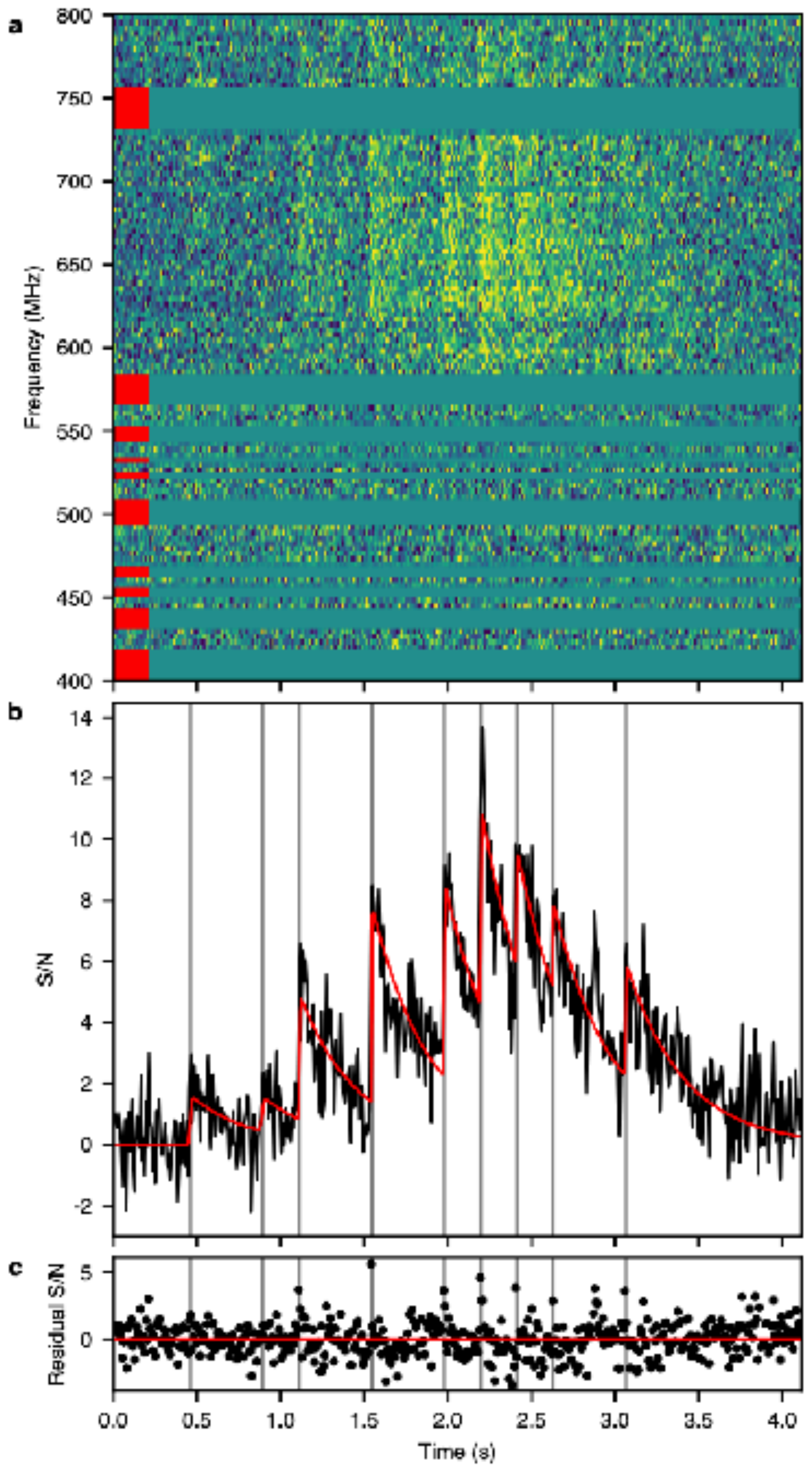
SKAO

Pushing the parameter search space…

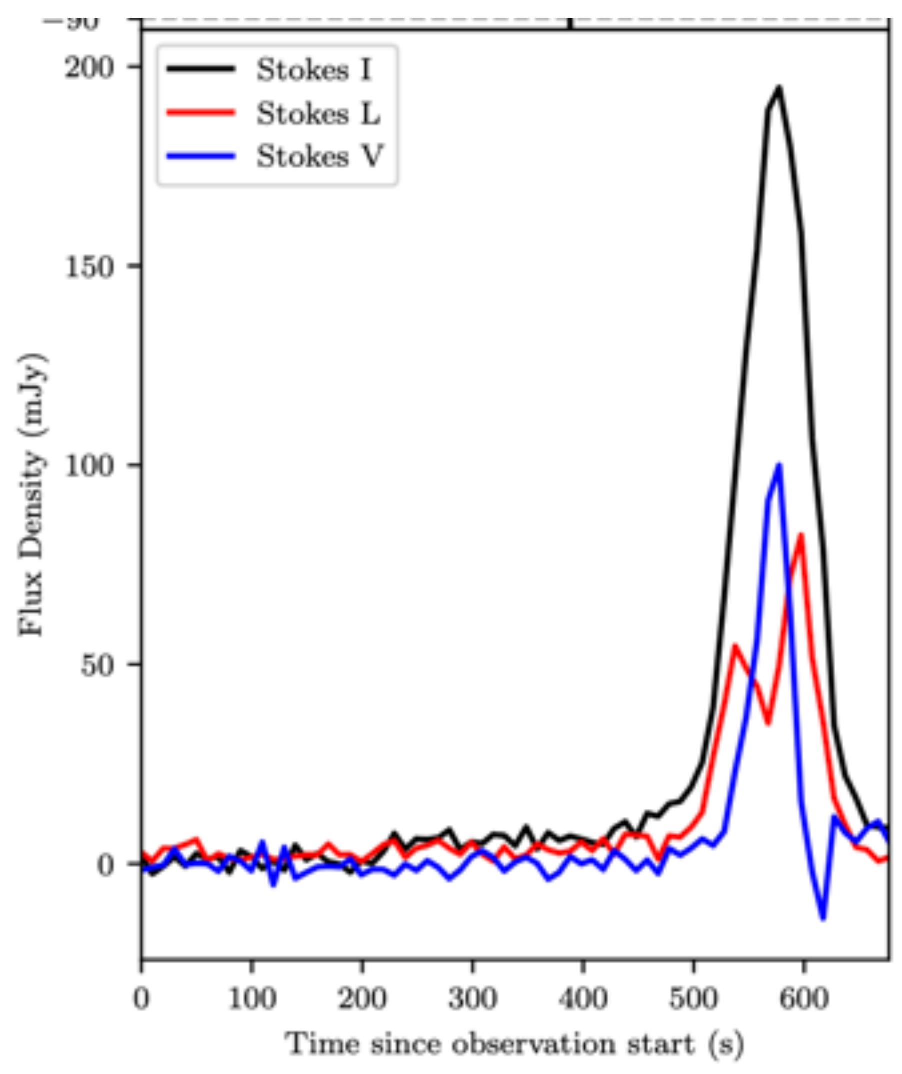
In time…



Nimmo+21 (NatAs)



CHIME/FRB+22 (Nature)

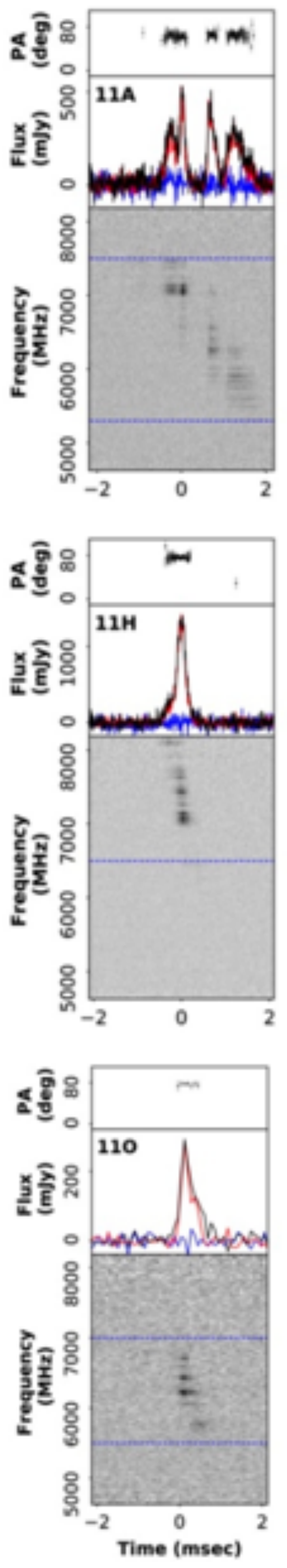


Dobie+24 (MNRAS)
This is a Galactic transient!

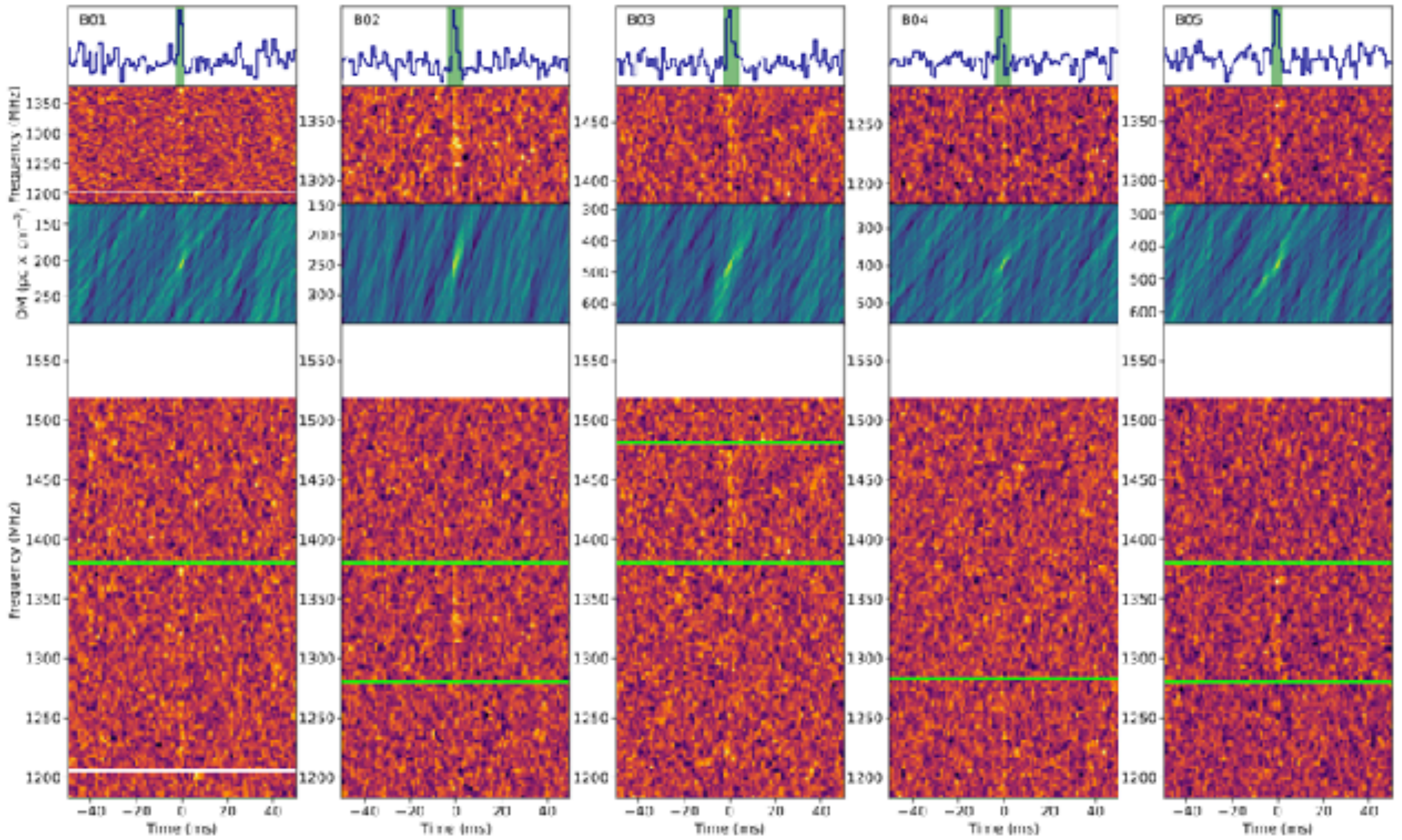
Pushing the parameter search space…

In frequency…

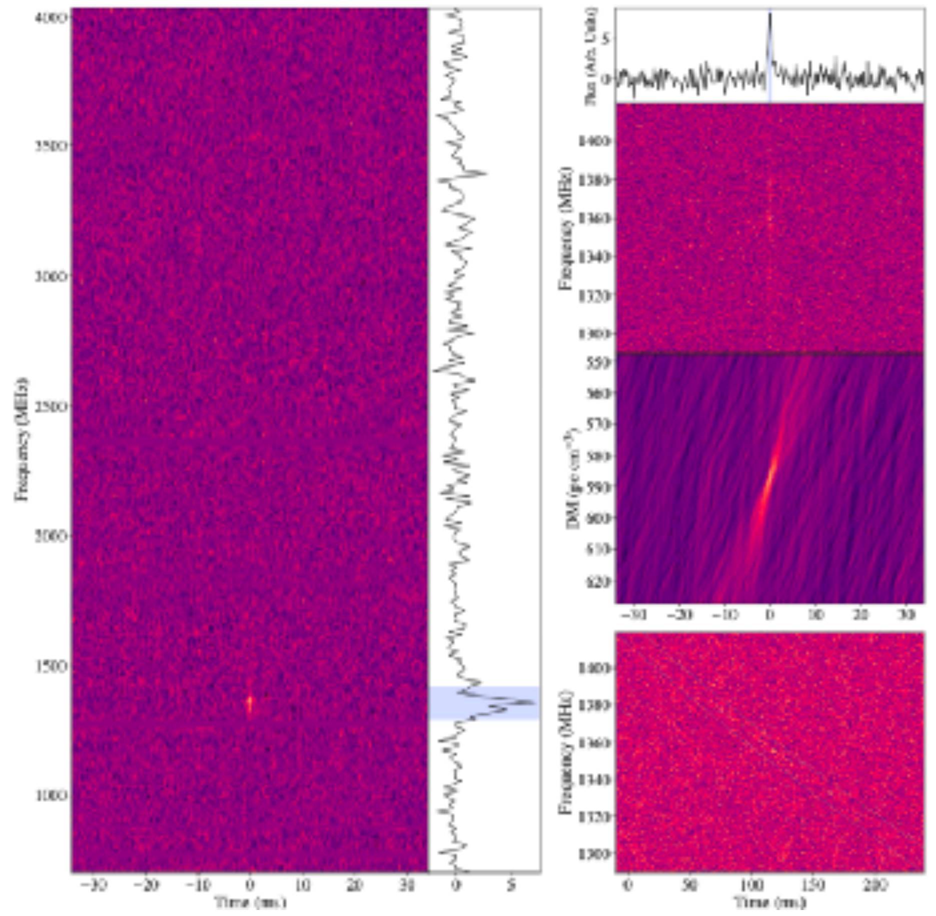
+ multi-frequency (see Maura's & Luca's reviews)



Gajjar+18 (ApJ)



Trudu+24 (A&A)



Kumar+21 (MNRAS)

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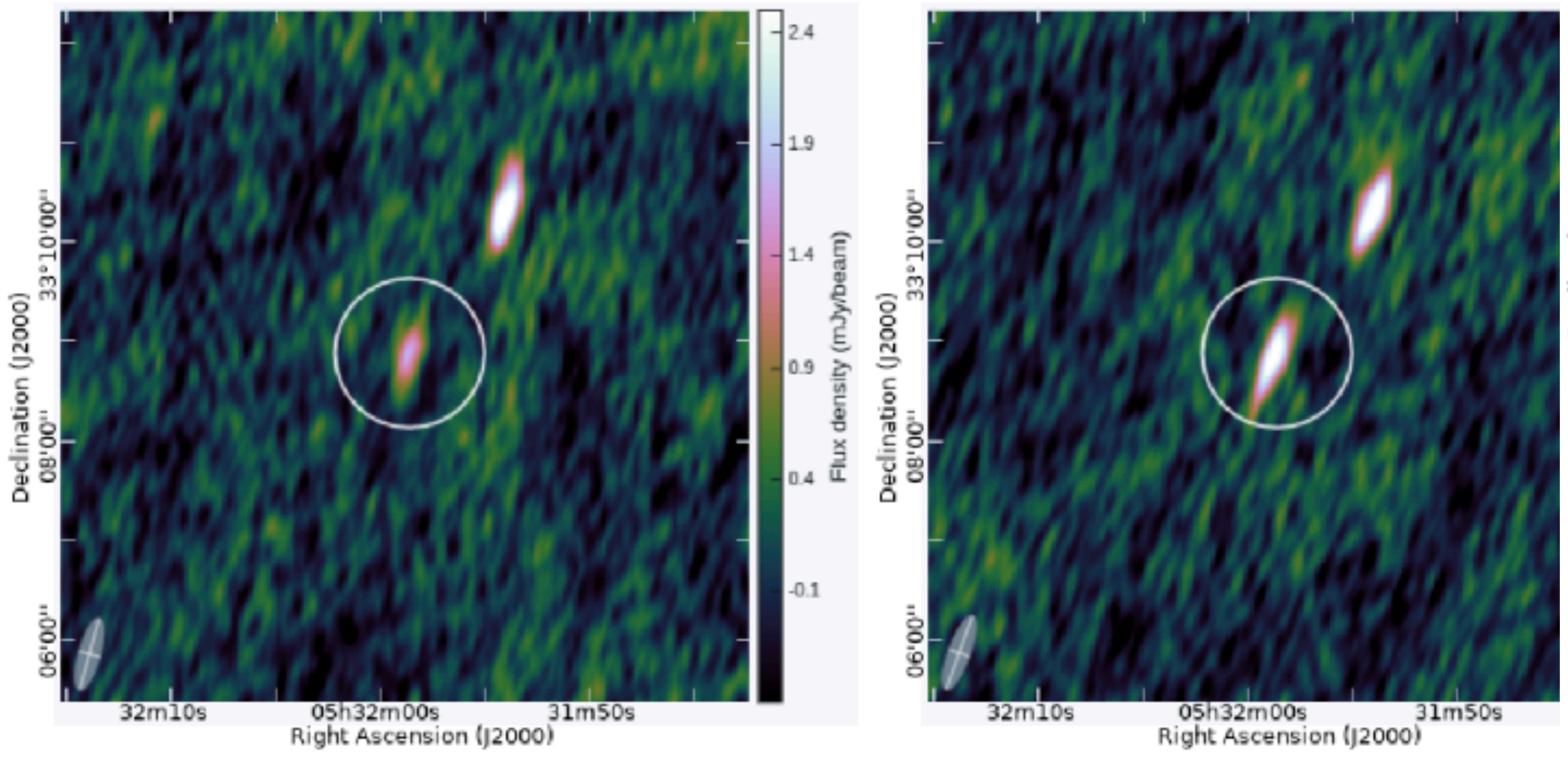
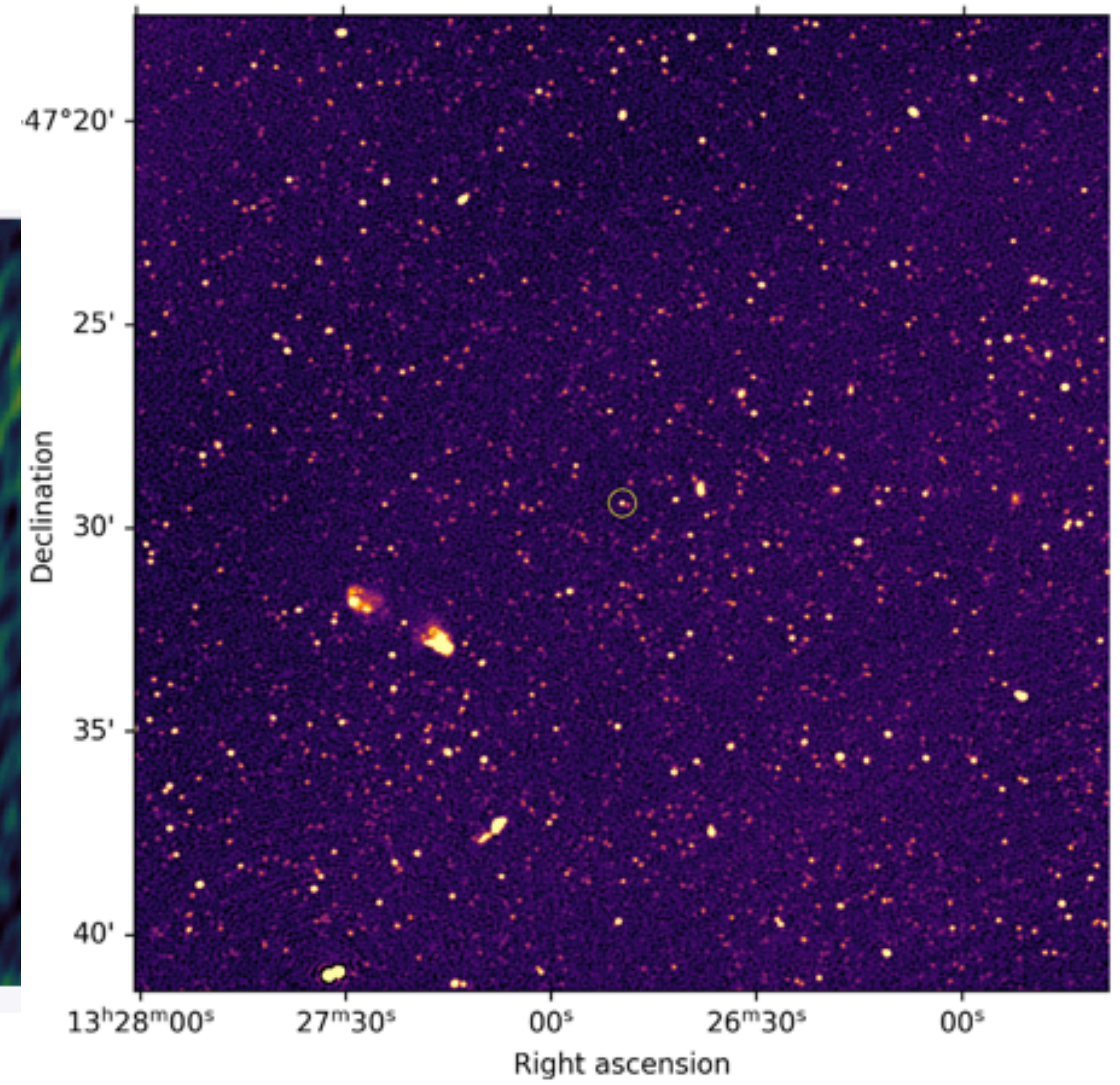
Pushing the parameter search space...

In space...

(see also Gabriele's review on PRSs)



(e) Burst 08 (f) Burst 11



FRB 20121102A, Andrianjafy+22 (MNRAS)

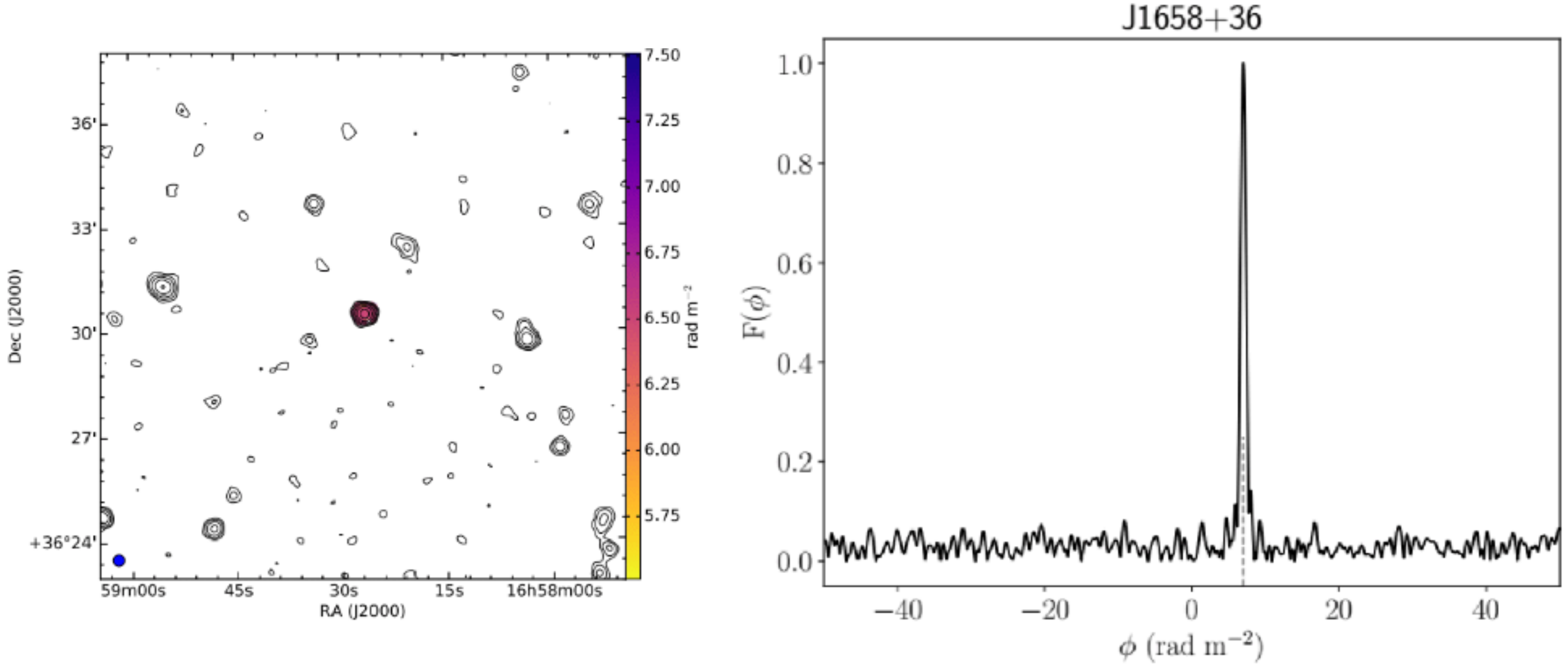
Smirnov+24 (MNRAS)

This is a millisecond pulsar!

Pushing the parameter search space…

Beyond the Stokes I…

- FRBs as pulsars are polarised sources
- Stokes Q,U,V could be searched for
- More resilience against RFI



Sobey+22 (A&A)

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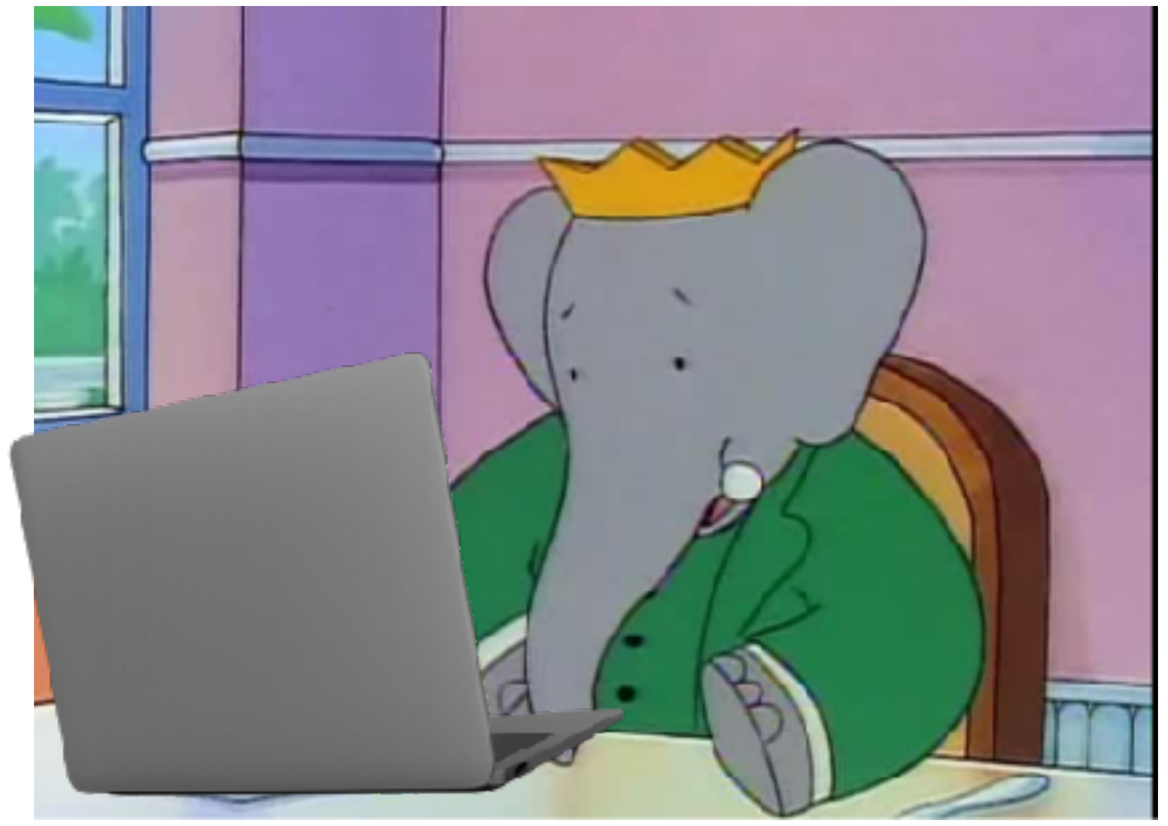
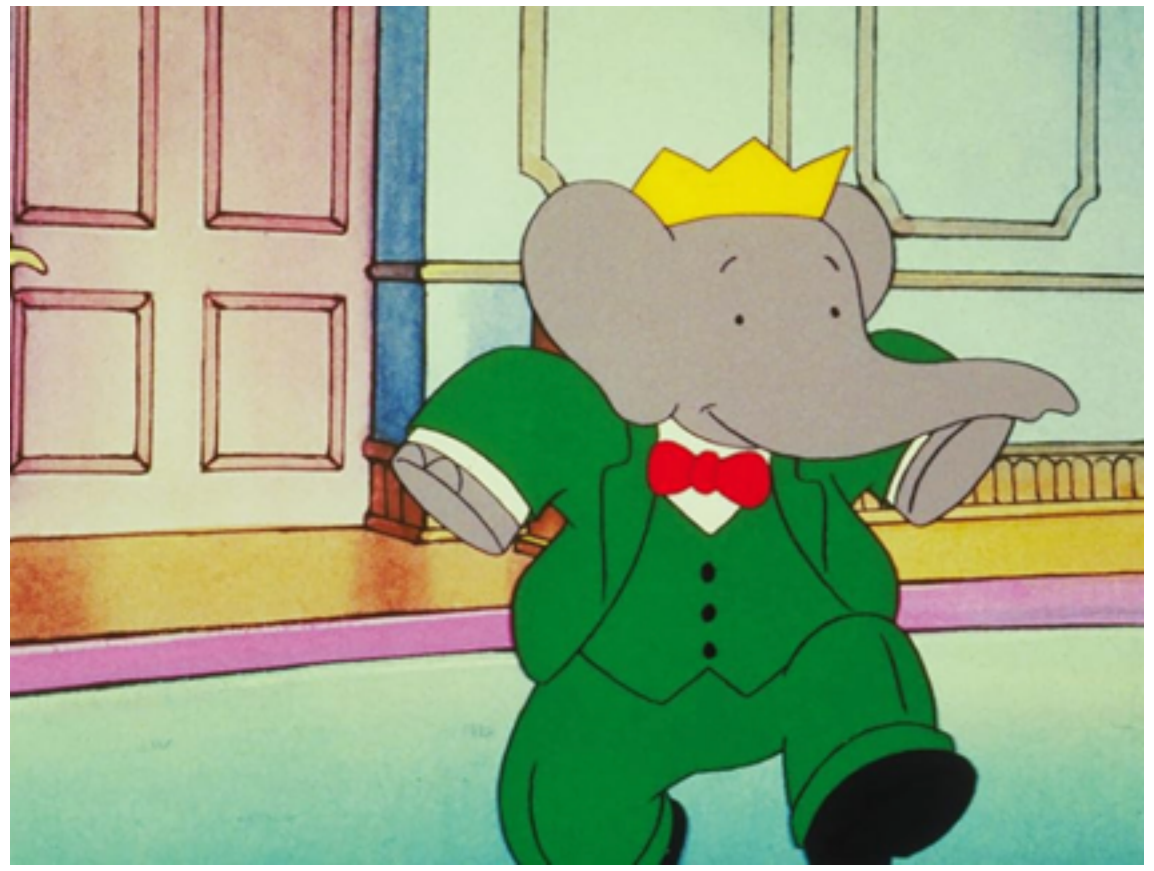
Final Thoughts

- As in many other cases in astronomy, the discovery of FRBs was a highly serendipitous process. Luck played a fundamental role, but it was patience and perseverance that allowed us to confirm their astrophysical origin
- That same perseverance led to the development of sophisticated search strategies and telescopes, which now enable the detection of several new FRBs each day
- Efforts are ongoing, and with the next generation of radio telescopes, we expect to increase this number by at least an order of magnitude
- However, significant challenges lie ahead: growing radio-frequency interference (RFI), the need to process massive data volumes in real time, and managing the increasing number of daily discoveries
- There remains a vast, unexplored parameter space — large, uncharted territories waiting to be discovered



Babar spent days processing his carefully designed observations, only to find nothing... lots of frustration!



But in one another single observation of 30 mins he detected a storm of 350 bursts! All his efforts payed!

Thank you!

Gastone is enjoying the FRB he found in a badly sampled 10-minute filterbank... so lucky!

However, without a proper strategy, Gastone never discovered again an FRB...