Lecture 10

Time-domain radio astronomy (from baseband to discovery) 19/02/2024

Lecturer: **Dr Charles Walker** (crhw3)

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Syllabus Overview

- Introduction to Big Data Radio Astronomy and Key Science Projects
    - Lecture 1: SKA Key Science Projects
    - Lecture 2: Brief history of radio astronomy and the SKA telescope
    - Lecture 3: The modern "large-N" radio interferometers
- Instrument simulations and design tools
    - Lecture 4: Intro into numerical methods for electromagnetic modelling
    - Lectures 5 and 6: Mutual coupling in antenna arrays
- Science Data Processing
    - Lecture 7: Calibration of radio observations
    - Lecture 8: Imaging techniques
    - Lecture 9: Advanced imaging techniques
    - Lecture 10: Time-domain radio astronomy
- Computing infrastructure
    - Lecture 11: Federation and scaling approaches for exascale data
    - Lecture 12: Data centre challenges and opportunities
- Advanced ML and Bayesian methods for data analysis and science extraction
    - Lecture 13: Nested sampling and MCMC
    - Lecture 14: Applications of Bayesian analysis
    - Lecture 15: Signal emulation for astrophysics and cosmology
    - Lecture 16: Simulation-based inference in astrophysics and cosmology

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Background to the SKA:
- History of radio astronomy
- Radio interferometry
- Why we're building the SKA

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Instrumentation:

- Simulating, designing instruments and experiments

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Imaging:

- Calibrating, imaging sources using interferometric data

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Time-domain radio astronomy:
Q) Has anybody not been here for the last three lectures?

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Time-domain Radio Astronomy

Time-domain techniques are different to those you've learned so far...

Why?

- The sources that we want to observe **are transient**
- Their signals undergo **interesting effects** we want to study

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Lecture 10 Overview

Introduction to...

Transient Radio Sources

1: The time-variable radio sky
2: Fast Radio Transients

Propagation effects, and why we care

3: Dispersion, Scattering, Scintillation, Faraday Rotation

Time-domain astronomy techniques

4: A time-domain signal chain
5: Time-domain astronomy in the SKA era

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Part 1: The time-variable radio sky

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Part 1: The time-variable radio sky

1.1: A brief introduction
1.2: Types of radio transients
1.3: Recent advances in time-domain astronomy

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1.1: A brief introduction

By now you must know...

- You can image **all sorts of things** with radio telescopes...

Key Science Objectives for the SKA

- Probing the cosmic dawn
- Challenging Einstein
- Cosmology and Dark Energy
- Exploring galaxy evolution
- Our home galaxy
- Seeking the origins of life
- Studying our nearest star
- Understanding cosmic magnetism
- The bursting sky

Remember this from early lectures?

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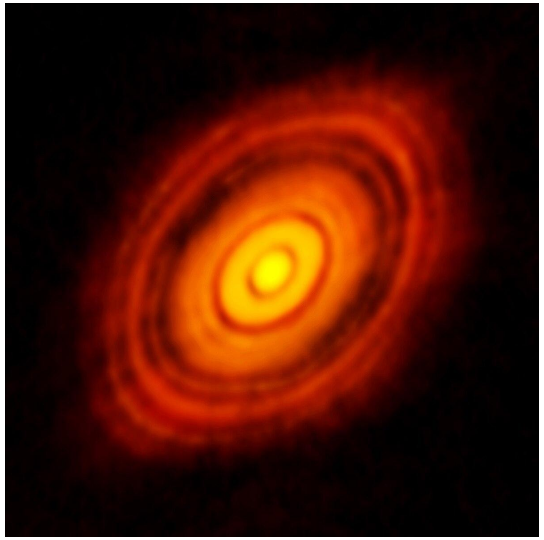
Protoplanetary discs



Credit: Ralph Bennett – ALMA (ESO/NAOJ/NRAO) [Attribution 4.0 International](#) [2]

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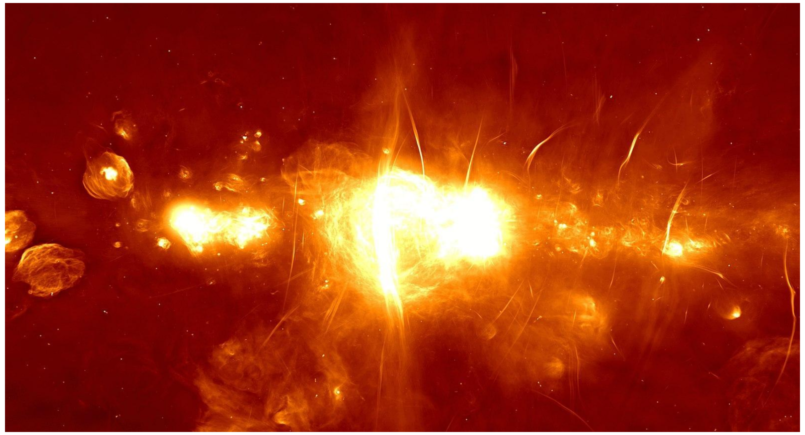
Our Milky Way



Credit: MeerKAT Public release photo [1]

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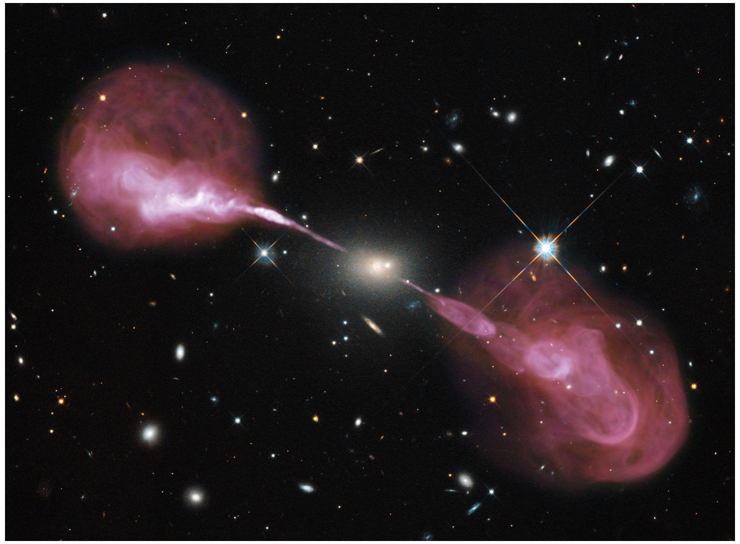
Radio galaxies



Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA) [Attribution 3.0 Unported](#) [3]

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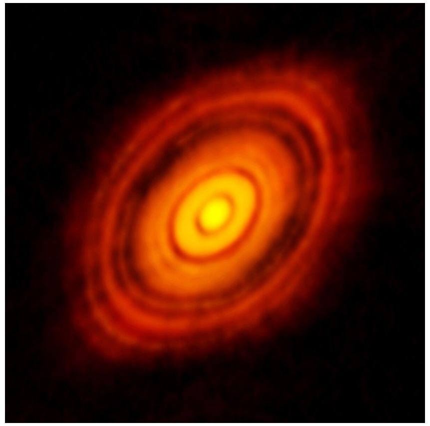
1.1: A brief introduction

Imaging is great for these sources...

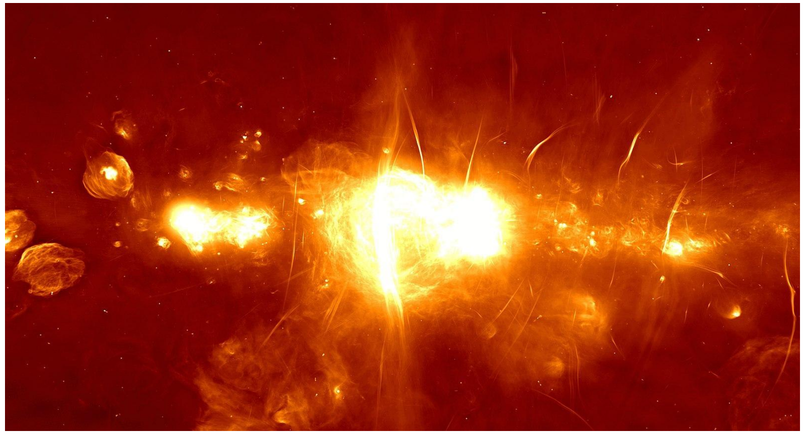
- Because they generally **remain static**
- The longer you look, the better your S/N...
  - and the better your images!

Protoplanetary discs



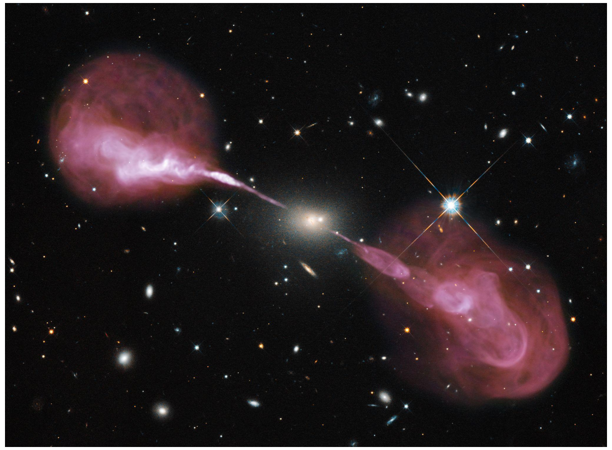
Credit: Ralph Bennett – ALMA (ESO/NAOJ/NRAO) Attribution 4.0 International [2]

Our Milky Way



Credit: MeerKAT Public release photo [1]

Radio galaxies



Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA) Attribution 3.0 Unported [3]

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1.1: A brief introduction

But not everything in the radio sky is static!

- In fact, many sources are **highly variable**...

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1.1: A brief introduction

One* of the SKA's KSOs is linked to variable sources...

Key Science Objectives for the SKA

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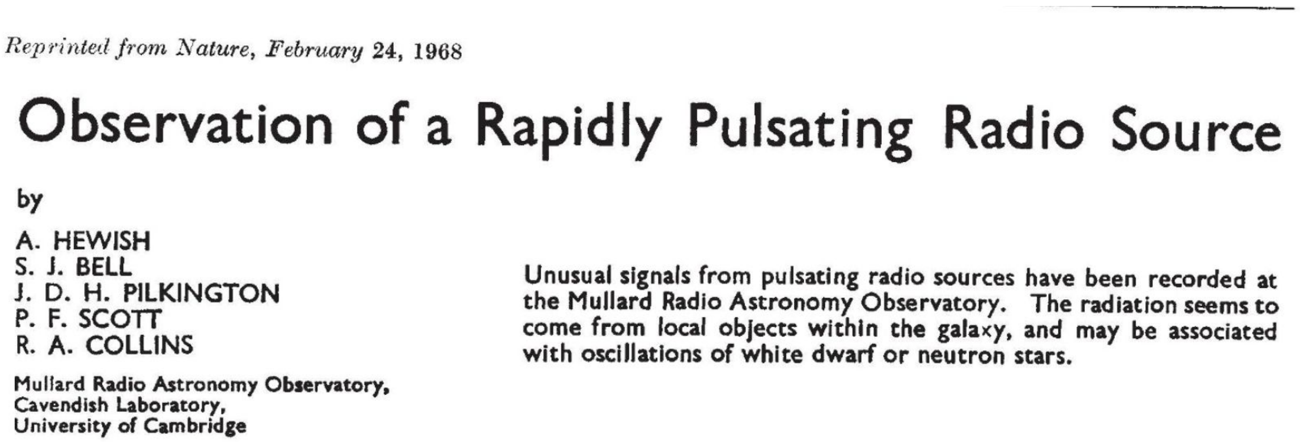
*at least

1.1: A brief introduction

Perhaps the most famous variable source: Pulsars

- B1919+21 (Hewish, Bell et al., 1968) [4]
  - Discovered at Mullard Observatory, **in Cambridge**!



Reprinted from Nature, February 24, 1968

Observation of a Rapidly Pulsating Radio Source

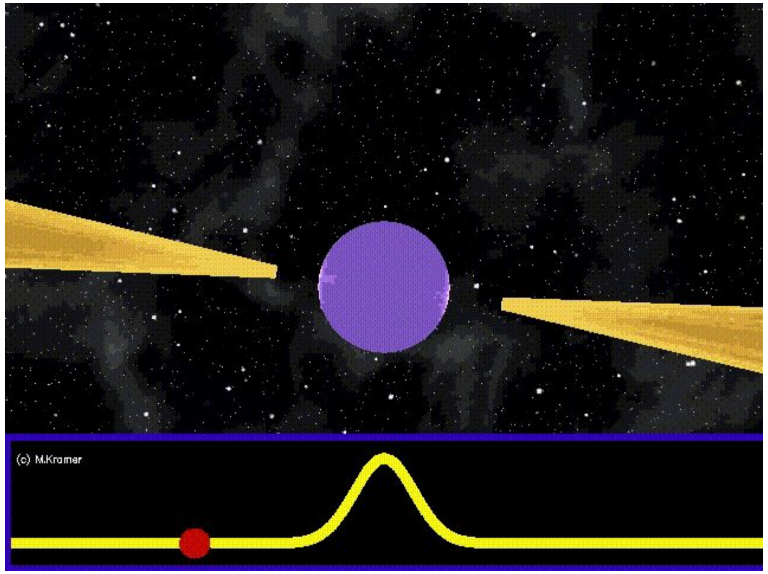
by

A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

Credit: Hewish, Bell et al. (1968) [4]

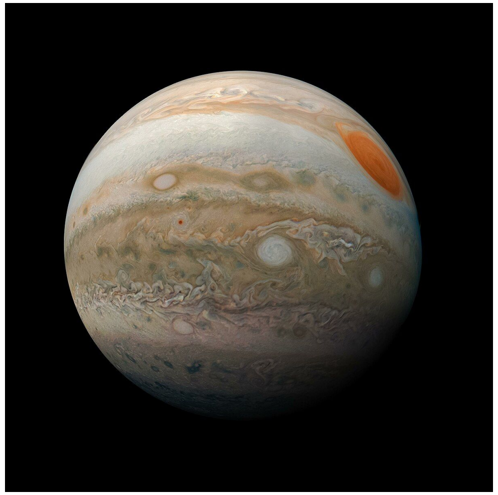


Credit: Michael Kramer Attribution-Share Alike 3.0 Unported [5]

1.1: A brief introduction

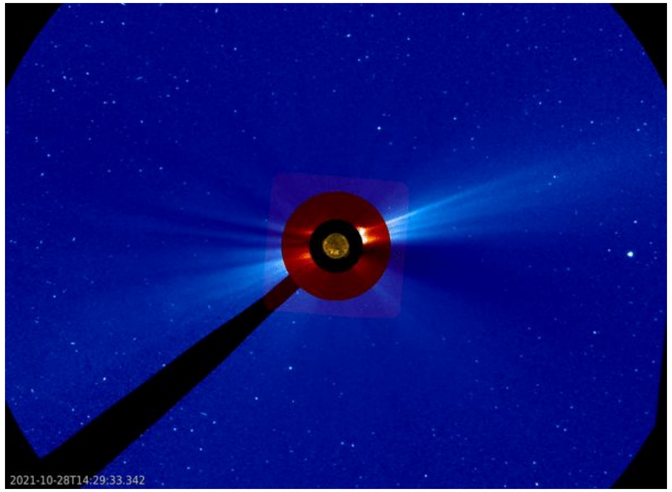
But many other sources can emit time-variable radio emission...

Giant planets [6]



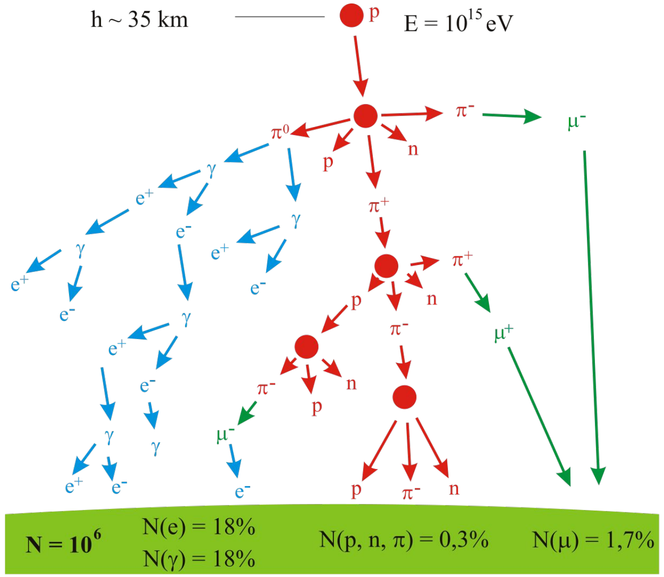
Credit: NASA/JPL-Caltech/SwRI/MSSS/Kevin M. Gill [7]

Solar emission during CMEs [8,9]



Credit: SOHO (ESA & NASA), [CC BY-SA IGO 3.0] [10]

Cosmic ray - atmospheric interaction [11]



Credit: Mpfiz [Attribution 3.0 Unported] [12]

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1.2: Types of Transient

So transient emission itself is highly variable!

- **Emission timescales** vary...
  - From years, to minutes, to subsecond [13,14,15]
- Some emission is **one-off**...
  - e.g. cataclysmic sources
- Other emission **repeats**...
  - e.g. pulsars
- Often classed as **slow, and fast transients**
  - detected in imaging data or time-series data respectively
    - See e.g. the VAST and CRAFT [16,17]

TABLE 1
CLASSES OF RADIO TRANSIENTS[a]

Object	Timescale
SNe, GRBs, TDEs	tens of minutes–years
AGN	tens of minutes–years
gravitational wave event	tens of minutes?–years?
fast radio burst?	sub-second
gravitational wave event?	sub-second?
circumstellar, interstellar masers	??
neutron stars	sub-second
sub-stellar objects	sub-second–hours
synchrotron flares, late-type stars, novae, colliding stellar winds	minutes–hours
"Hyman bursters"	minutes
affects pulsars, compact extragalactic sources	minutes–days (pulsars), hours–years (AGN)

Credit: Lazio et al. (2014) [13]

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1.2: Types of Transient

We've been detecting some radio transients for decades...

- Solar radio emission was detected during WW2 and kept secret for years (Hey, 1946) [8]
- Pulsars were discovered **over 50 years ago** [4]

Solar Radiations in the 4–6 Metre Radio Wave-Length Band

THE solar radiation spectrum does not normally extend into the 5-metre wave-length region with sufficient intensity to be detectable on radio receiving equipments in commercial or Service use. It is now possible to disclose that, on one occasion during the War, Army equipments observed solar radiations of the order of 10^5 times the power expected from the sun, assuming that the sun behaves as a perfect black-body radiator at a temperature of 6,000° K.

This abnormally high intensity of solar radiation occurred on February 27 and 28, 1942, when Army

Credit: Hey et al. (1946) [8]

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Credit: Hewish, Bell et al. (1968) [4]

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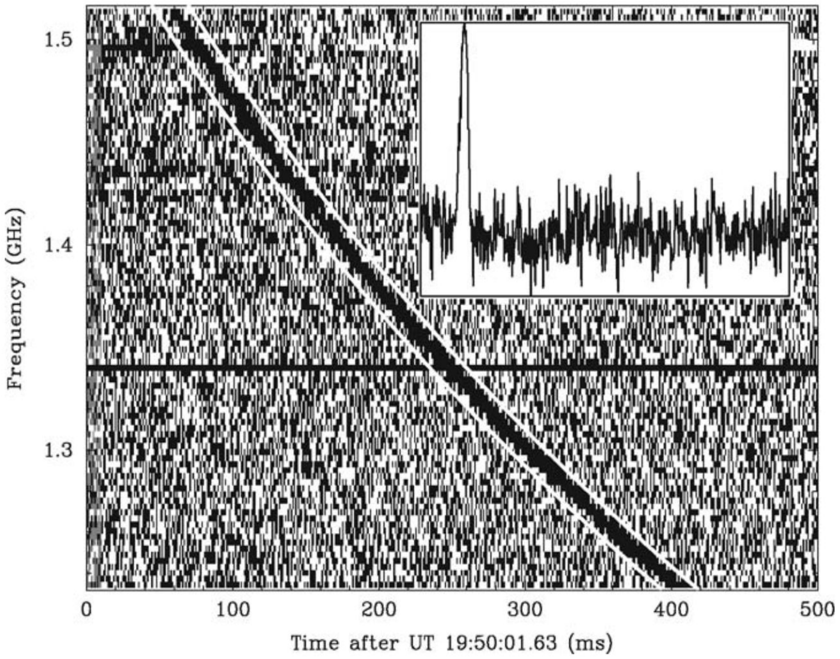
1.2: Types of Transient

But some transients are (relatively) new...

- **First FRB** discovered in 2007 (Lorimer et al, 2007) [18]



A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. Lorimer,[1,2*] M. Bailes,[3] M. A. McLaughlin,[1,2] D. J. Narkevic,[1] F. Crawford[4]

Pulsar surveys offer a rare opportunity to monitor the radio sky for impulsive burst-like events with millisecond durations. We analyzed archival survey data and found a 30-jansky dispersed burst, less than 5 milliseconds in duration, located 3° from the Small Magellanic Cloud. The burst properties argue against a physical association with our Galaxy or the Small Magellanic Cloud. Current models for the free electron content in the universe imply that the burst is less than 1 gigaparsec distant. No further bursts were seen in 90 hours of additional observations, which implies that it was a singular event such as a supernova or coalescence of relativistic objects. Hundreds of similar events could occur every day and, if detected, could serve as cosmological probes.

Credit: Lorimer et al. (2007) [18]

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1.3: Advances in time-domain astronomy

The question is: what changed?

- Historically, **instrumental limitations** were a bottleneck to transient research:
  - Detecting **short bursts**:
    - requires high time-resolution observations
  - **Rare events**:
    - require long, wide-field surveys with great sensitivity
  - **Localisation**:
    - requires good angular resolution

To achieve this we needed:

- Fast computing
- Lots of memory
- Sensitive, long baseline interferometers

1.3: Advances in time-domain astronomy

Technological advances have accelerated progress

- Computing advances
  - **GPUs, optimised algorithms**
    - for speed
  - Increased **storage capacity**
    - for more, higher fidelity data

- Instrumental advances
  - FoV improvements
    - Multi-beam receivers [19]
    - Phased-array feeds [20,21]

Figure 1: The first Mk. II ASKAP PAF installed on antenna 29 at the MRO.

Credit: Chippendale et al. (2015) [20]

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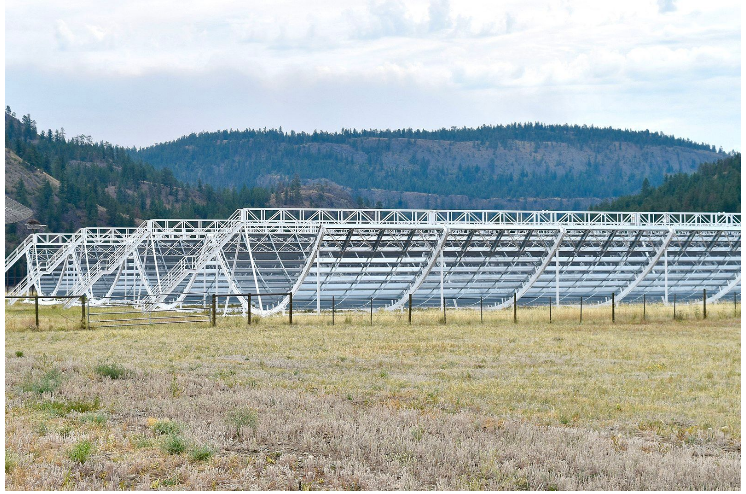
1.3: Advances in time-domain astronomy

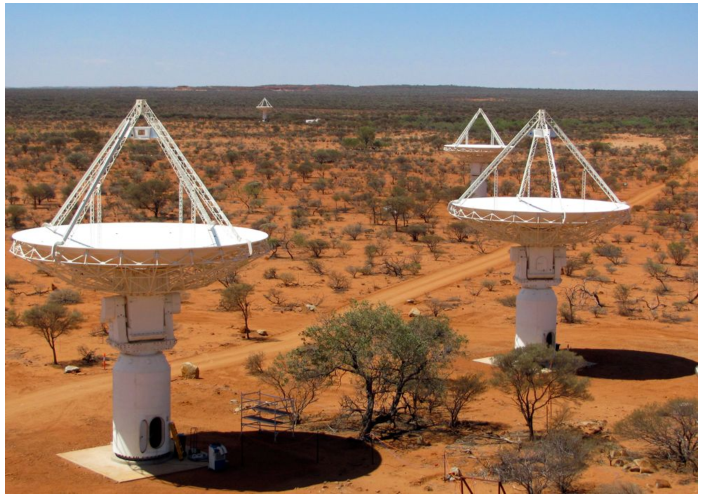
This has already led to developing powerful new instruments...

CHIME (Canada)



Credit: Z22 [Creative Commons Attribution-Share Alike 4.0 International] [22]

ASKAP (Australia)



Credit: [Ant Schinckel, CSIRO], [Creative Commons Attribution-Share Alike 3.0 Unported] [23]

MeerKAT (South Africa)

Credit: Square Kilometre Array Organisation (SKAO) / South African Radio Astronomy Observatory (SARAO) Creative Commons Attribution 3.0 Unported *[24]*

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1.3: Advances in time-domain astronomy

And these are pathfinders and precursors for the SKA!

Credit: Square Kilometre Array Organisation (SKAO) / South African Radio Astronomy Observatory (SARAO) [Creative Commons](#) [Attribution-Share Alike 3.0 Unported](#) [25]

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Part 2: Fast Radio Transients

Part 2: Fast Radio Transients

This course is about data-driven astronomy, so we'll focus on the most data-intensive transients...

2.1: Fast Transients (timeseries data)
2.2: Neutron stars and pulsars
2.3: Fast Radio Bursts

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2.1: Fast Transients

Why focus on pulsar and FRB signals?

- Studying them is **technically challenging**...
  - and highly relevant to this course
    - More on that in parts 4 and 5

- They are **scientifically interesting**...
  - Associated with **compact objects**
    - Probes of condensed matter, strong gravitational fields
  - They are **affected by the diverse environments** they traverse
    - Probes of cosmological parameters and large-scale structure of the Universe

- Their **signals and effects** are critical to how we process their data
  - so we need a bit of background...

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2.2: Neutron stars and pulsars

Pulsars have a long and storied history...

1968: First pulsar detected

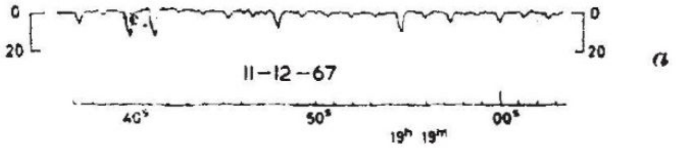

Fig. 1. *a*, A record of the pulsating radio source in strong signal conditions (receiver time constant 0·1 s). Full scale deflexion corresponds to 20×10^{-26} W m^{-2} Hz^{-1}. *b*, Upper trace: records obtained with additional paths (240 m and 450 m) in one side of the interferometer. Lower trace: normal interferometer records. (The pulses are small for $l = 240$ m because they occurred near a null in the interference pattern; this modifies the phase but not the amplitude of the oscillatory response on the upper trace.) *c*, Simulated pulses obtained using a signal generator. *d*, Simultaneous reception of pulses using identical receivers tuned to different frequencies. Pulses at the lower frequency are delayed by about 0·2 s.

Credit: Hewish, Bell et al. (1968) [4]

1934: Neutron stars proposed

5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. Baade
F. Zwicky

Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

Credit: Baade & Zwicky (1934) [26]

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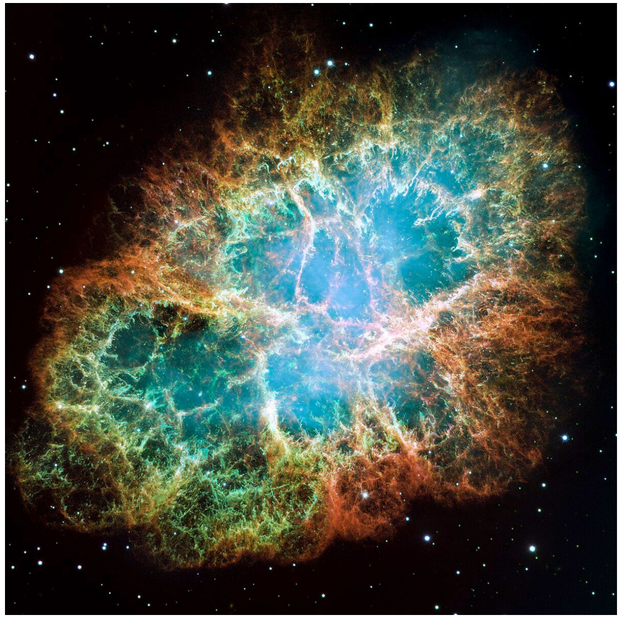
2.2: Neutron stars and pulsars

Want to go back further?

1969: The Crab Nebula was co-located with the Crab Pulsar [29]



The Crab Nebula, Credit: NASA, ESA, J. Hester and A. Loll (Arizona State University) [28]

1054 AD: Crab supernova observed

ANCIENT RECORDS AND THE CRAB NEBULA SUPERNOVA

By Kenneth Brecher
Department of Astronomy, Boston University
and
Robert A. Fesen, Stephen P. Maran and John C. Brandt
Goddard Space Flight Center

Established and suspected records of the guest star of A.D. 1054 and their relationship to the Crab Nebula supernova event are discussed. The well-known Suzhou (Soochow) star map appears to depict the guest star and to show it in the correct orientation with respect to ζ Tauri (*i.e.* northwest), a circumstance that has been generally overlooked in the West. Thus, there seems little reason to doubt the standard interpretation, that the guest star was in fact the progenitor of the Crab Nebula. A European account, proposed as a possible

Credit: Brecher et al. (1983) [27]

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2.2: Neutron stars and pulsars

A pulsar is a type of neutron star

- Classic quote: "*A pulsar is a highly magnetised, rapidly rotating neutron star...*"

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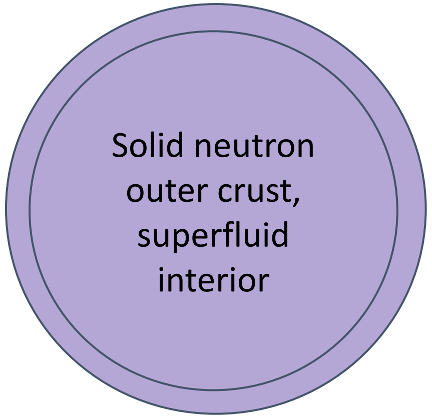
2.2: Neutron stars and pulsars

We can do better than that...

- More detailed pulsar model:
  - See **The Handbook of pulsar astronomy** [30] for more



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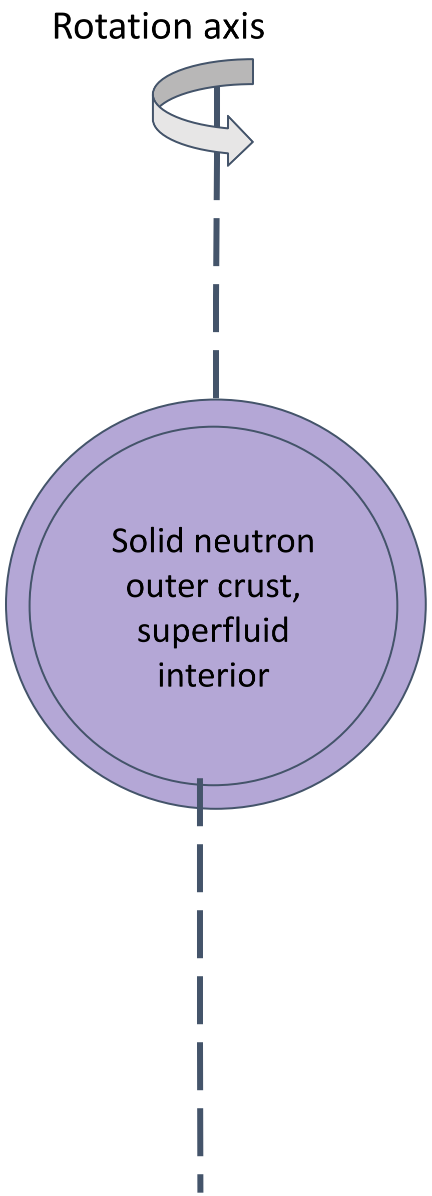

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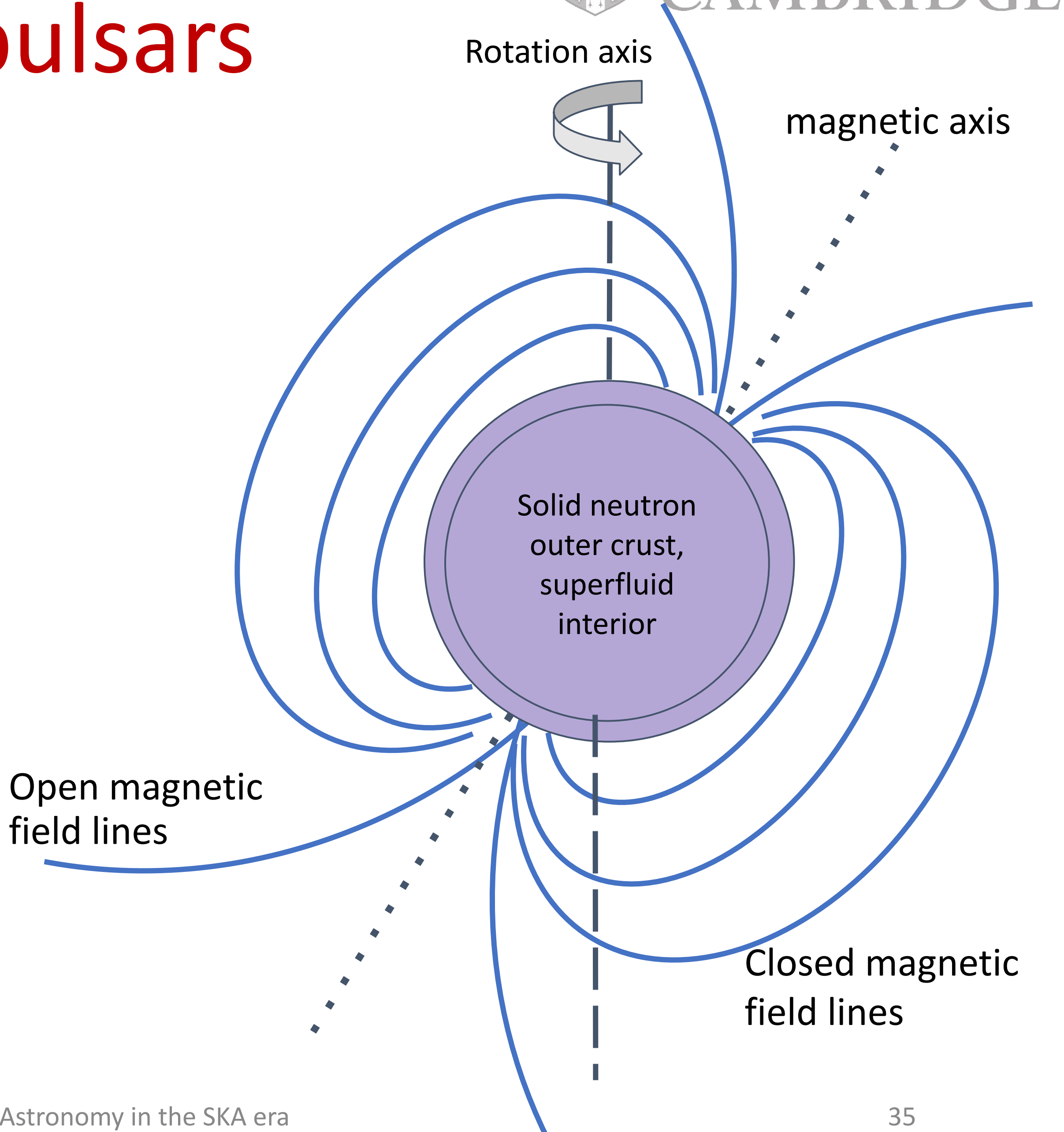

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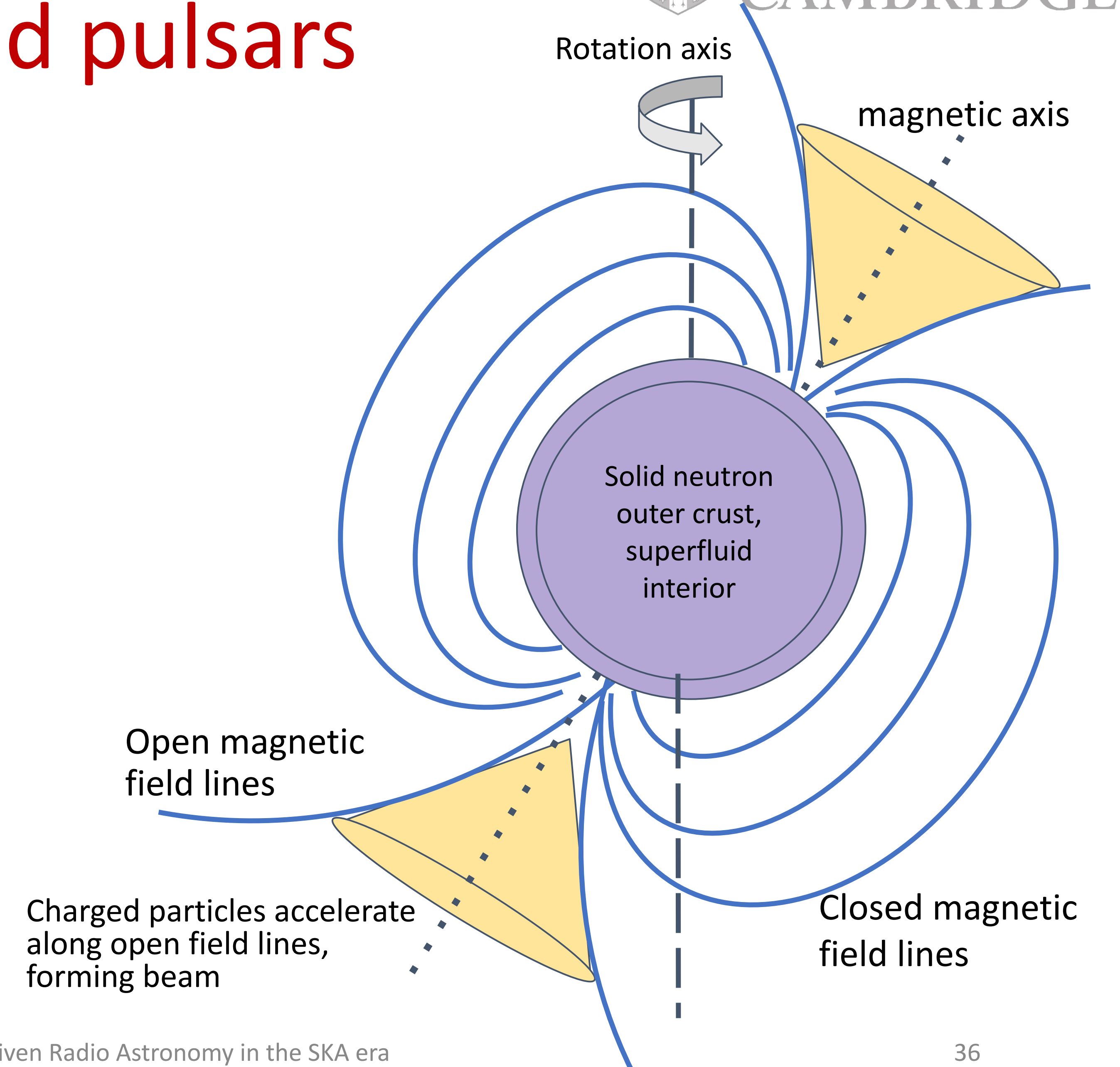

2.2: Neutron stars and pulsars

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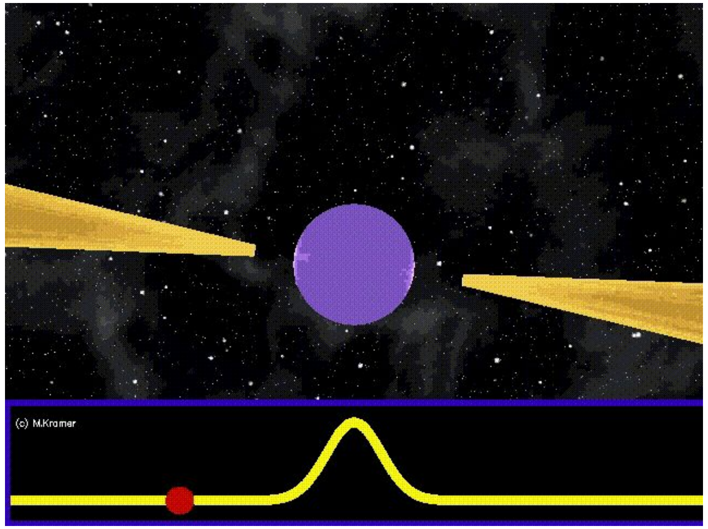
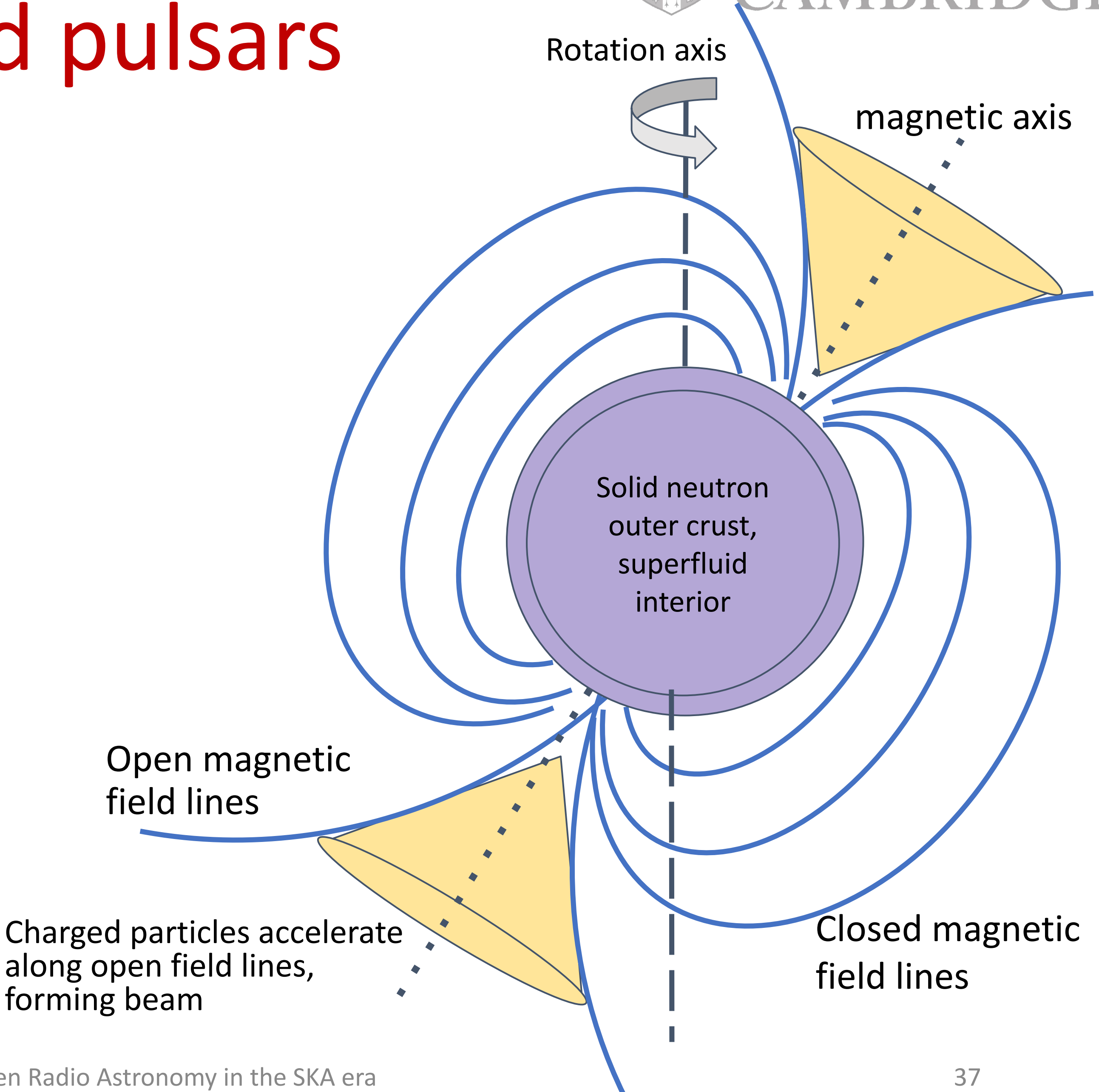
  - See **The Handbook of pulsar astronomy** [30] for more

Beam sweeps observer's line of sight once per rotation



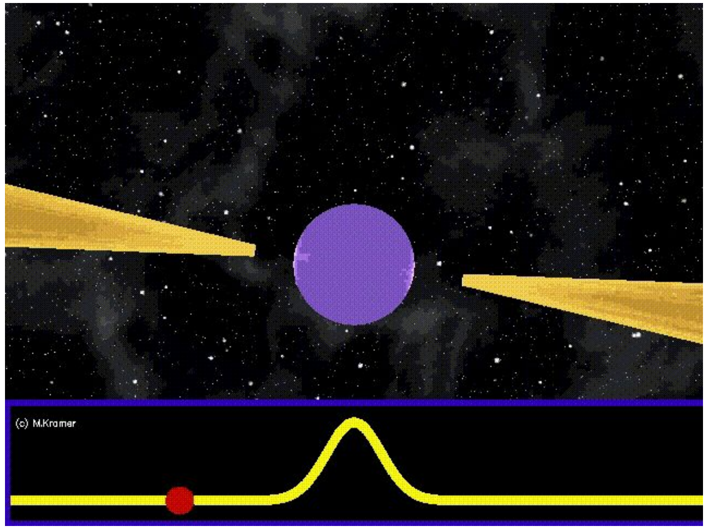
Credit: Michael Kramer Attribution-Share Alike 3.0 Unported [5]



2.2: Neutron stars and pulsars

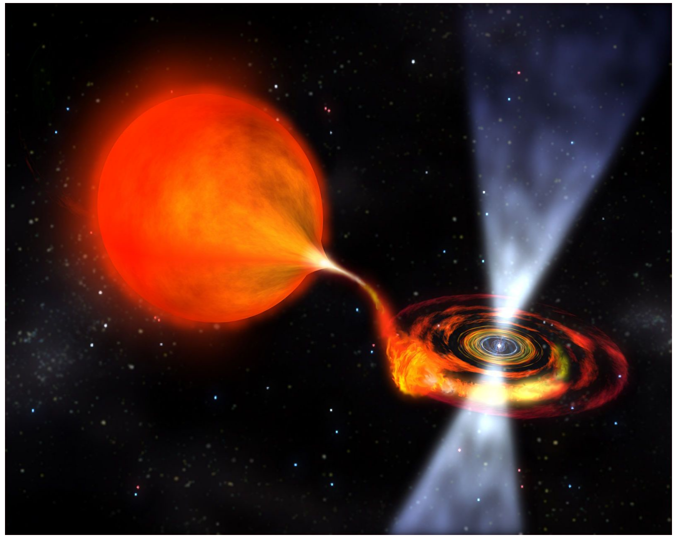
There are even multiple types of pulsar!

'Regular' pulsars: ~second rotations



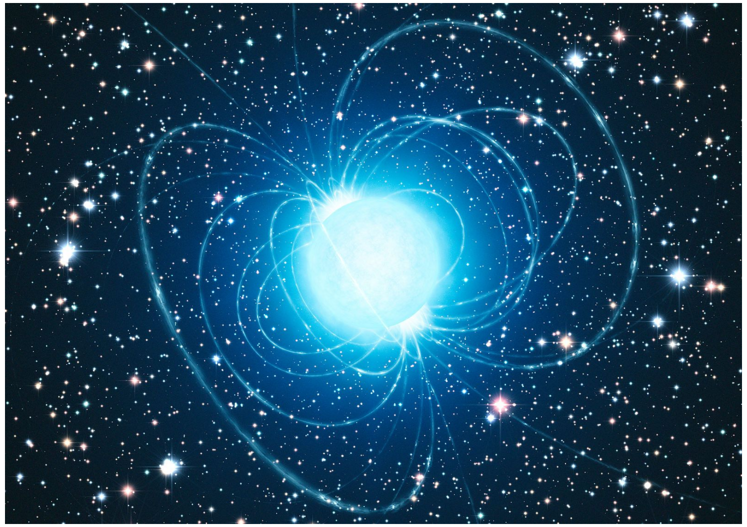
Credit: Michael Kramer Attribution-Share Alike 3.0 Unported [5]

Millisecond pulsars: sped up via accretion [31]



Credit: Dana Berry/NASA Goddard Space Flight Center [32]

Magnetars: extremely strong magnetic fields, X-ray bursts [33]



Credit: ESO/L. Calçada Creative Commons Attribution 4.0 International License [34]

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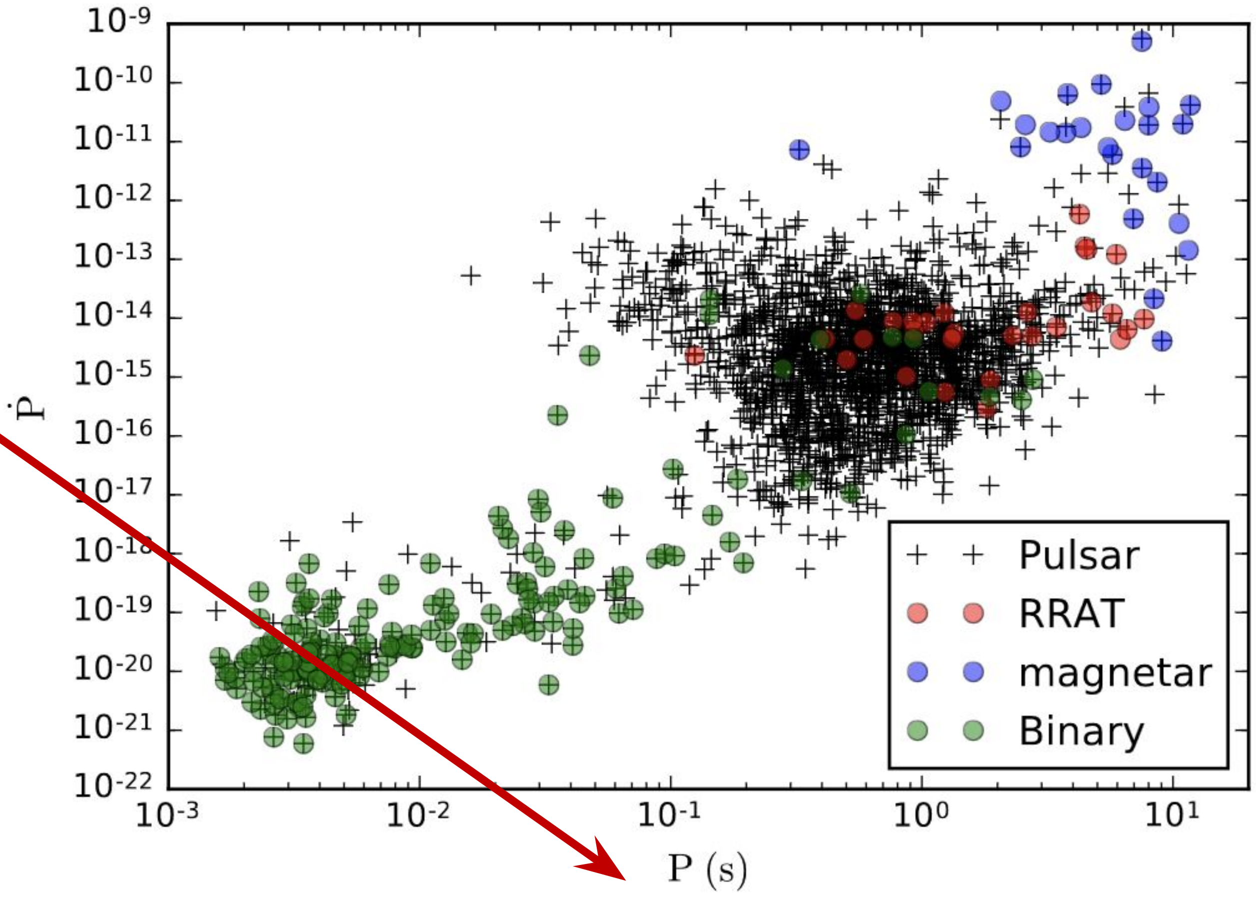
2.2: Neutron stars and pulsars

The "p - pdot diagram" shows the huge range of pulsar periods...

P: spin period of the pulsar



Pdot: period derivative

Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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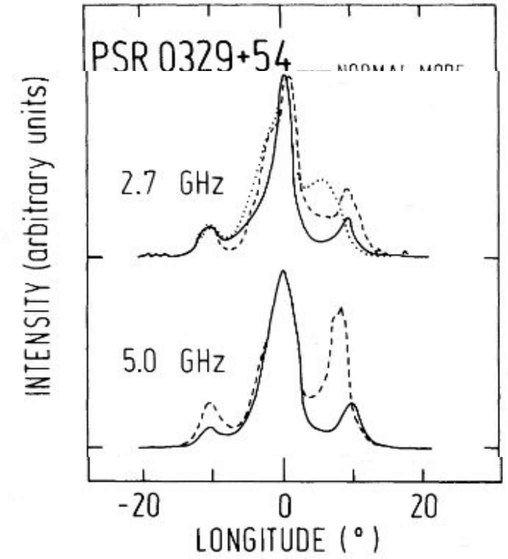
2.2: Neutron stars and pulsars

Question: Why do we care about pulsars?

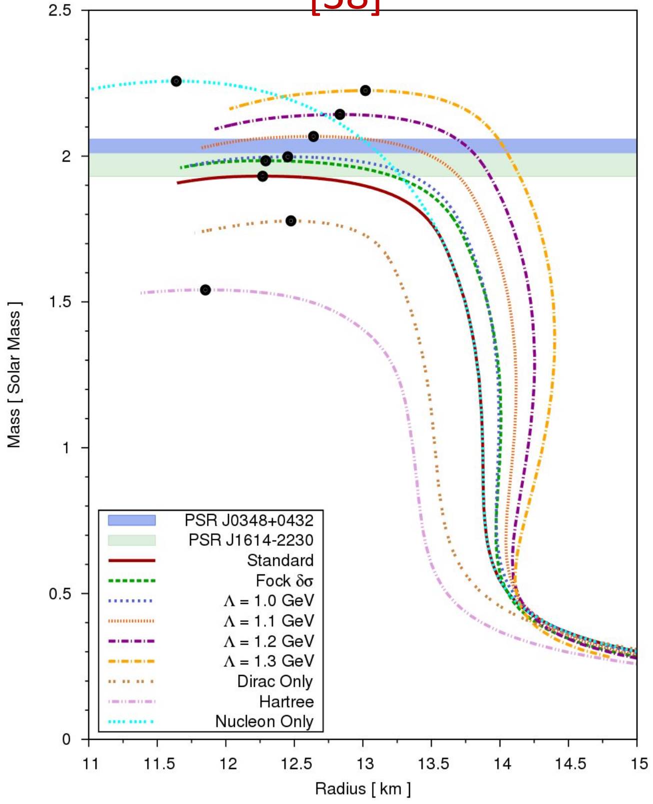
- Reason 1: We want to **learn about the objects** themselves...

Emission mechanisms:
Why do some exhibit mode switching, nulling? [36,37]



Credit: Bartel et al. (1982) [36]

Use as dense matter laboratories:
Could NS equation of state probe how matter behaves at extreme densities? [38]



*Credit: A. W. Thomas, D. L. Whittenbury, J. D. Carroll, K. Tsushima, and J. R. Stone, (2013). "Equation of State of Dense Matter and Consequences for Neutron Stars". EPJ Web of Conferences **63**: 03004. DOI:10.1051/epjconf/20136303004. ISSN 2100-014X. Figure 2, Creative Commons Attribution 2.5 Generic [37]*

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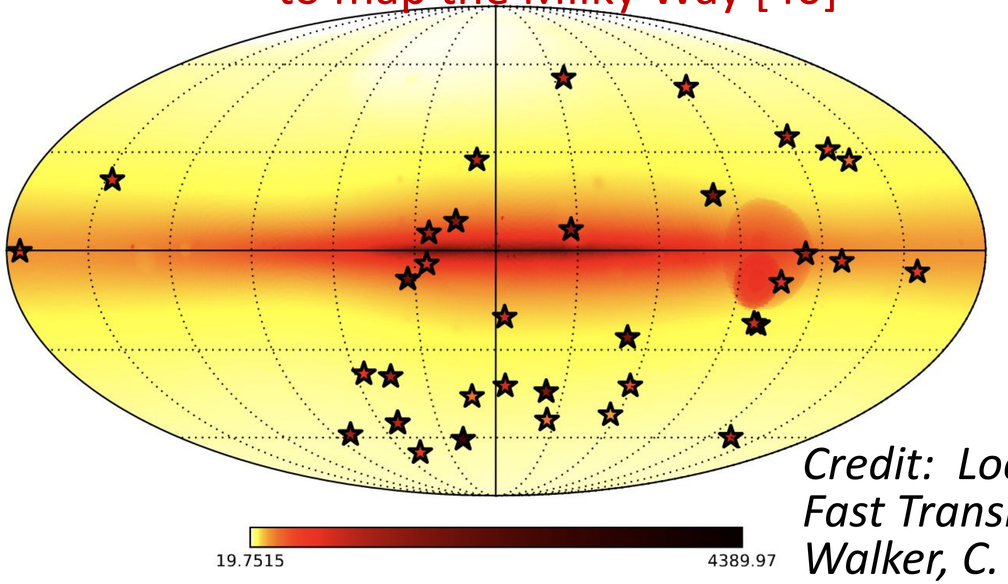
2.2: Neutron stars and pulsars

Why do we care about pulsars?

- Reason 2: We can use them as **astrophysical tools**...

Use pulsar dispersion measures to map the Milky Way [40]



Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

Use binary orbital decay to test general relativity and gravitational wave theory [41-44]

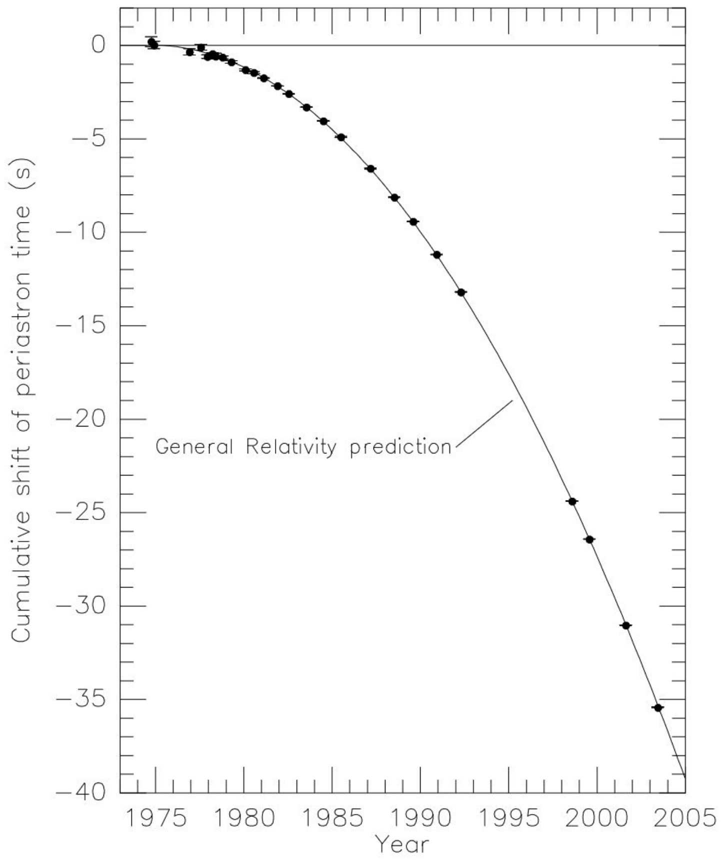


Figure 1. Orbital decay of PSR B1913+16. The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch for a system emitting gravitational radiation, according to general relativity.

Credit: Weisberg & Taylor (2005) [41]

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2.3: Fast radio bursts (FRBs)

Introduction to FRBs...

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2.3: Fast radio bursts (FRBs)

FRBs have a much more recent history...

2007: The 'Lorimer Burst' discovered [18]

A Bright Millisecond Radio Burst of Extragalactic Origin

D. R. Lorimer,[1,2*] M. Bailes,[3] M. A. McLaughlin,[1,2] D. J. Narkevic,[1] F. Crawford[4]

Pulsar surveys offer a rare opportunity to monitor the radio sky for impulsive burst-like events with millisecond durations. We analyzed archival survey data and found a 30-jansky dispersed burst, less than 5 milliseconds in duration, located 3° from the Small Magellanic Cloud. The burst properties argue against a physical association with our Galaxy or the Small Magellanic Cloud. Current models for the free electron content in the universe imply that the burst is less than 1 gigaparsec distant. No further bursts were seen in 90 hours of additional observations, which implies that it was a singular event such as a supernova or coalescence of relativistic objects. Hundreds of similar events could occur every day and, if detected, could serve as cosmological probes.

Credit: Lorimer et al. (2007) [18]

2012: The 'Keane Burst' discovered [45]

On the origin of a highly dispersed coherent radio burst

E. F. Keane,[1★] B. W. Stappers,[2] M. Kramer[1,2] and A. G. Lyne[2]

[1] *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*
[2] *School of Physics & Astronomy, Jodrell Bank Centre for Astrophysics, University of Manchester, Manchester M13 9PL*

Credit: Keane et al. (2012) [45]

2013: Four more bursts detected [46]

A Population of Fast Radio Bursts at Cosmological Distances

D. Thornton,[1,2*] B. Stappers,[1] M. Bailes,[3,4] B. Barsdell,[3,4] S. Bates,[5] N. D. R. Bhat,[3,4,6] M. Burgay,[7] S. Burke-Spolaor,[8] D. J. Champion,[9] P. Coster,[2,3] N. D'Amico,[10,7] A. Jameson,[3,4] S. Johnston,[2] M. Keith,[2] M. Kramer,[9,1] L. Levin,[5] S. Milia,[7] C. Ng,[9] A. Possenti,[7] W. van Straten[3,4]

Searches for transient astrophysical sources often reveal unexpected classes of objects that are useful physical laboratories. In a recent survey for pulsars and fast transients, we have uncovered four millisecond-duration radio transients all more than 40° from the Galactic plane. The bursts' properties indicate that they are of celestial rather than terrestrial origin. Host galaxy and intergalactic medium models suggest that they have cosmological redshifts of 0.5 to 1 and distances of up to 3 gigaparsecs. No temporally coincident x- or gamma-ray signature was identified in association with the bursts. Characterization of the source population and identification of host galaxies offers an opportunity to determine the baryonic content of the universe.

Credit: Thornton et al. (2013) [46]

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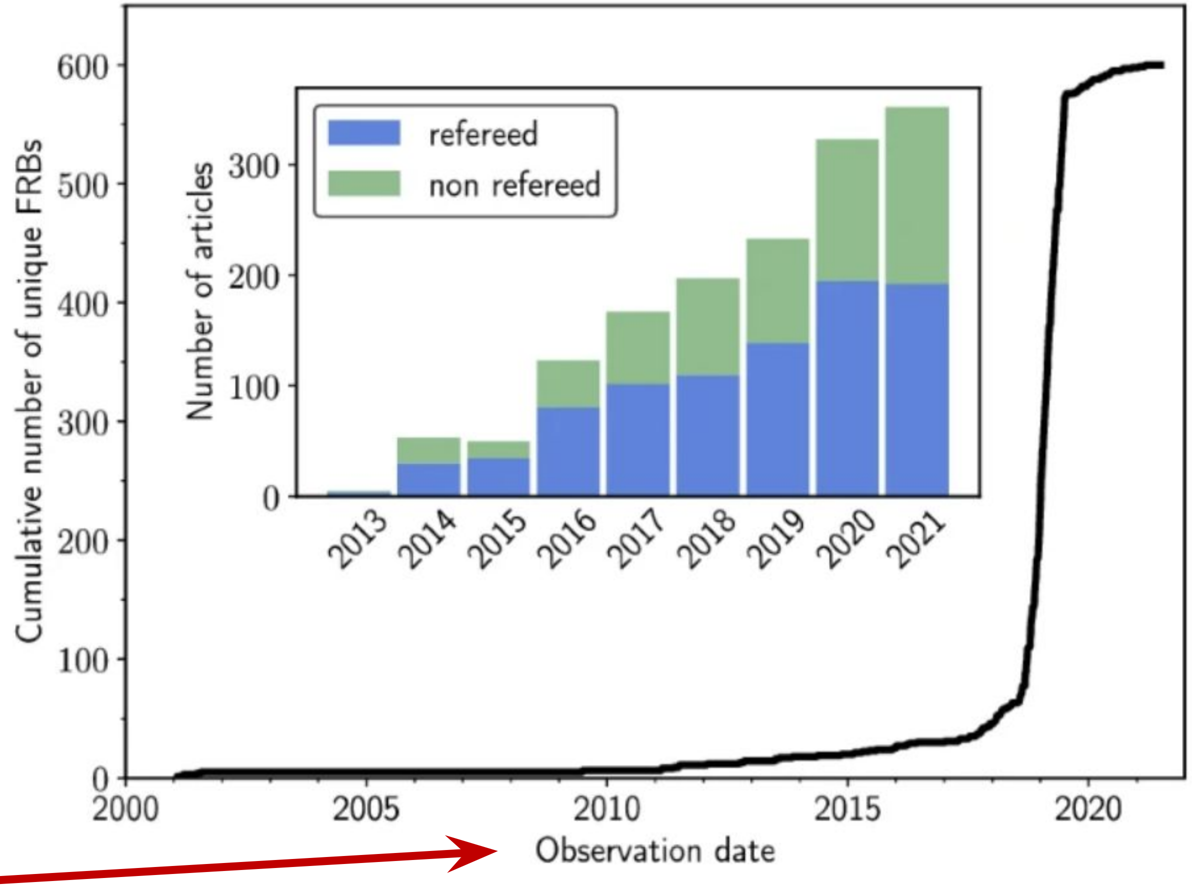
2.3: Fast radio bursts (FRBs)

Since 2013 we have detected many bursts!

Number of FRBs



Time

Credit: Petroff et al. (2022) [47]

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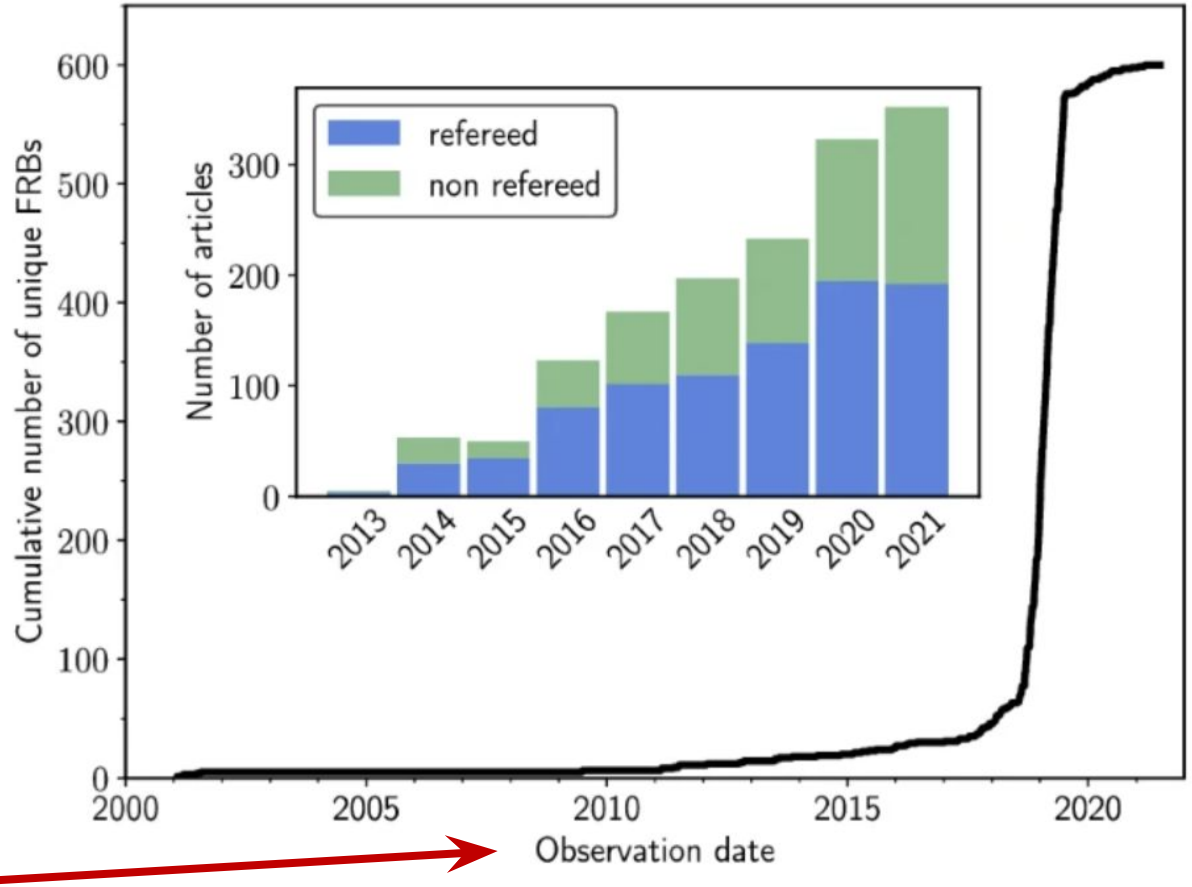
2.3: Fast radio bursts (FRBs)

Since 2013 we have detected many bursts!

Number of FRBs



The reason?

- Advances in **data-driven astronomy**!

Time

Credit: Petroff et al. (2022) [47]

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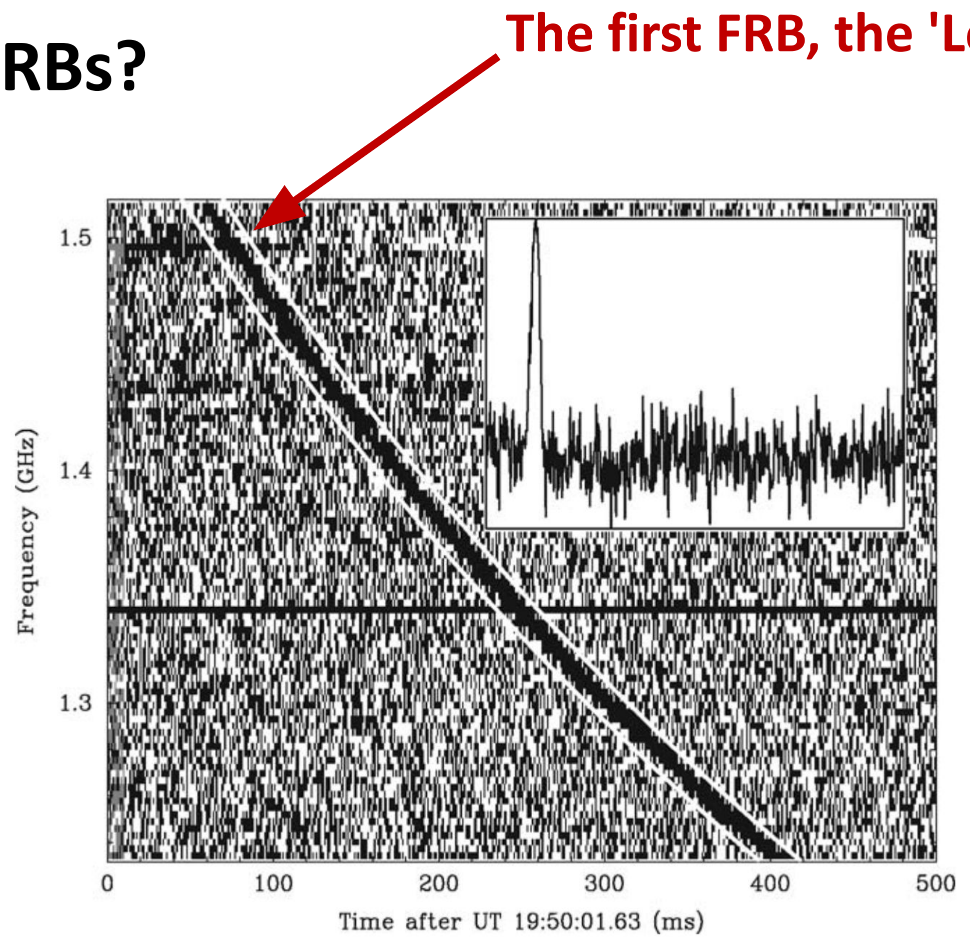
2.3: Fast radio bursts (FRBs)

What are the properties of FRBs?



Credit: Lorimer et al. (2007) [18]

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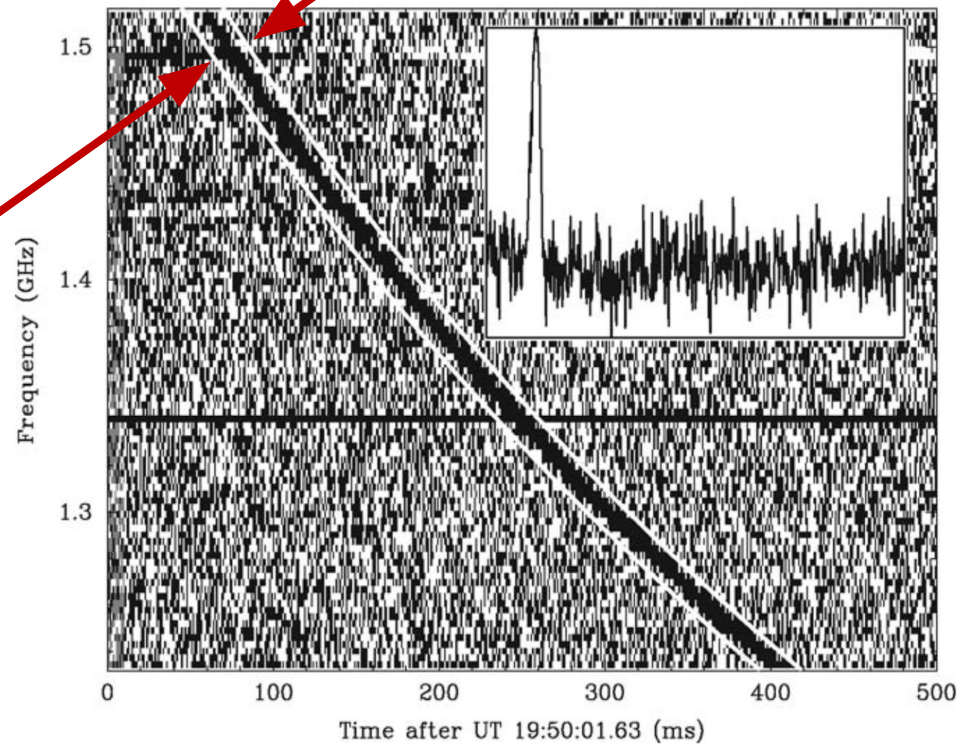
2.3: Fast radio bursts (FRBs)

What are the properties of FRBs?

Short
(millisecond durations)



Credit: Lorimer et al. (2007) [18]

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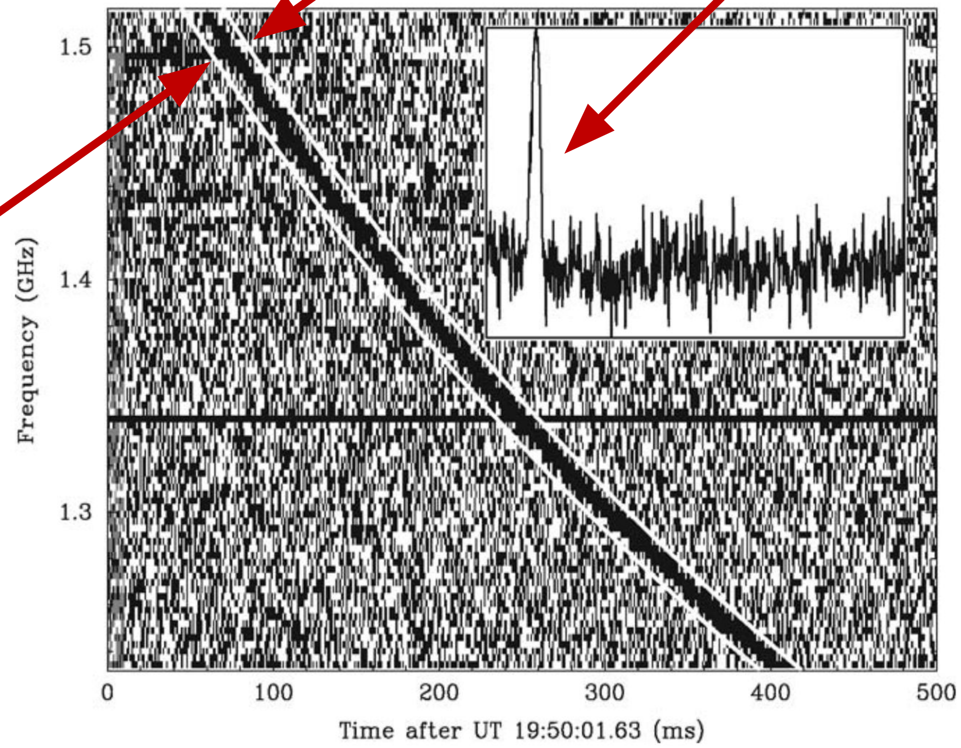
2.3: Fast radio bursts (FRBs)

What are the properties of FRBs?

Bright
(stand out above noise)

Short
(millisecond durations)



Credit: Lorimer et al. (2007) [18]

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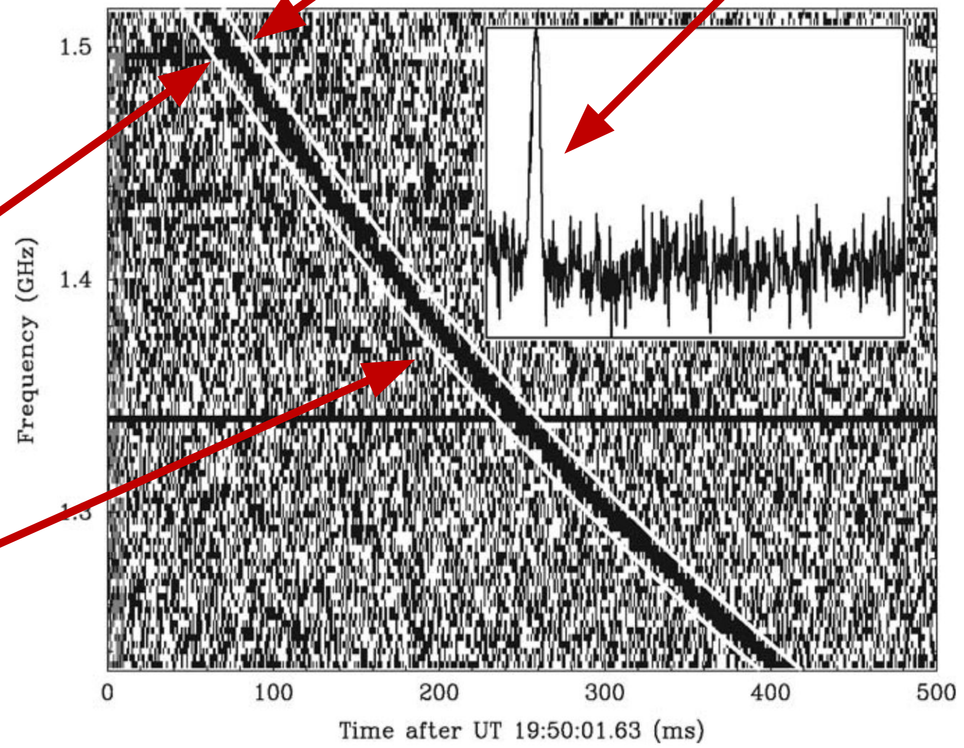
2.3: Fast radio bursts (FRBs)

What are the properties of FRBs?

Bright
(stand out above noise)

Short
(millisecond durations)

Highly dispersed
(higher frequency emission arrives first)



Credit: Lorimer et al. (2007) [18]

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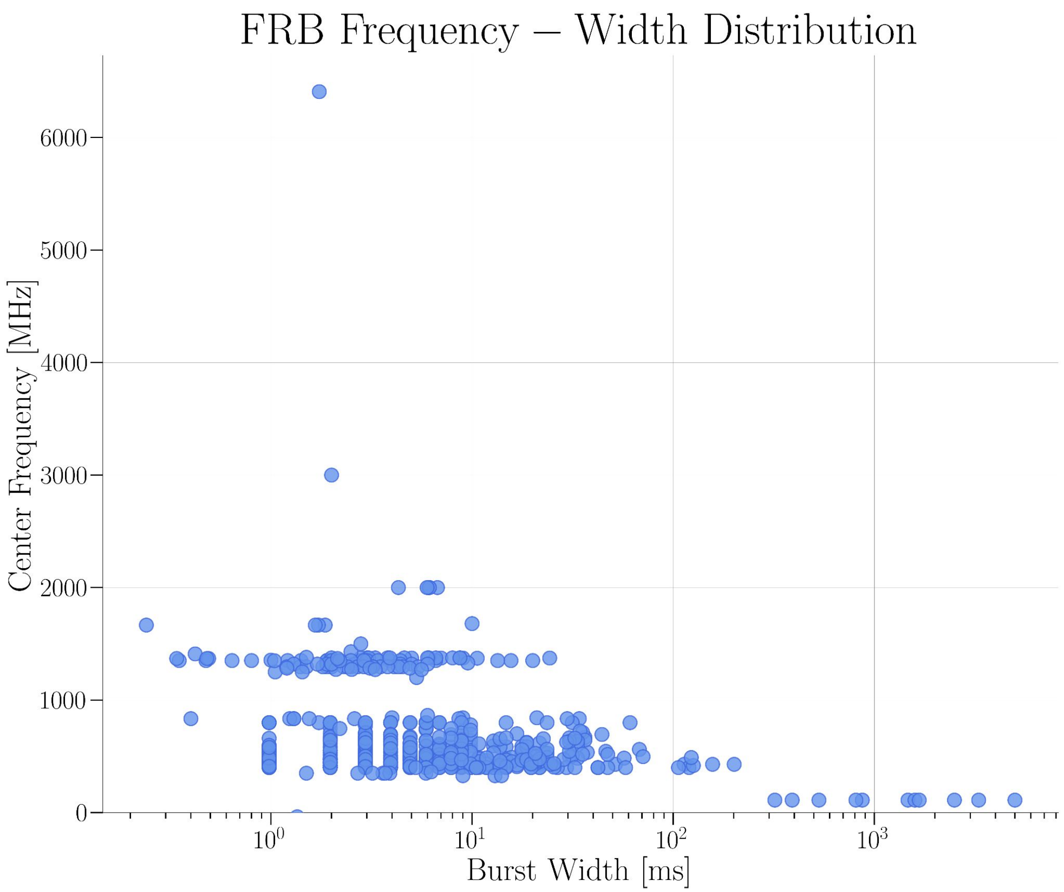
2.3: Fast radio bursts (FRBs)

FRBs are highly diverse sources...

- They have **variable frequencies**

Detected from 100MHz - 8GHz



Credit: Spanakis-Misirlis et al., 2021 [48]

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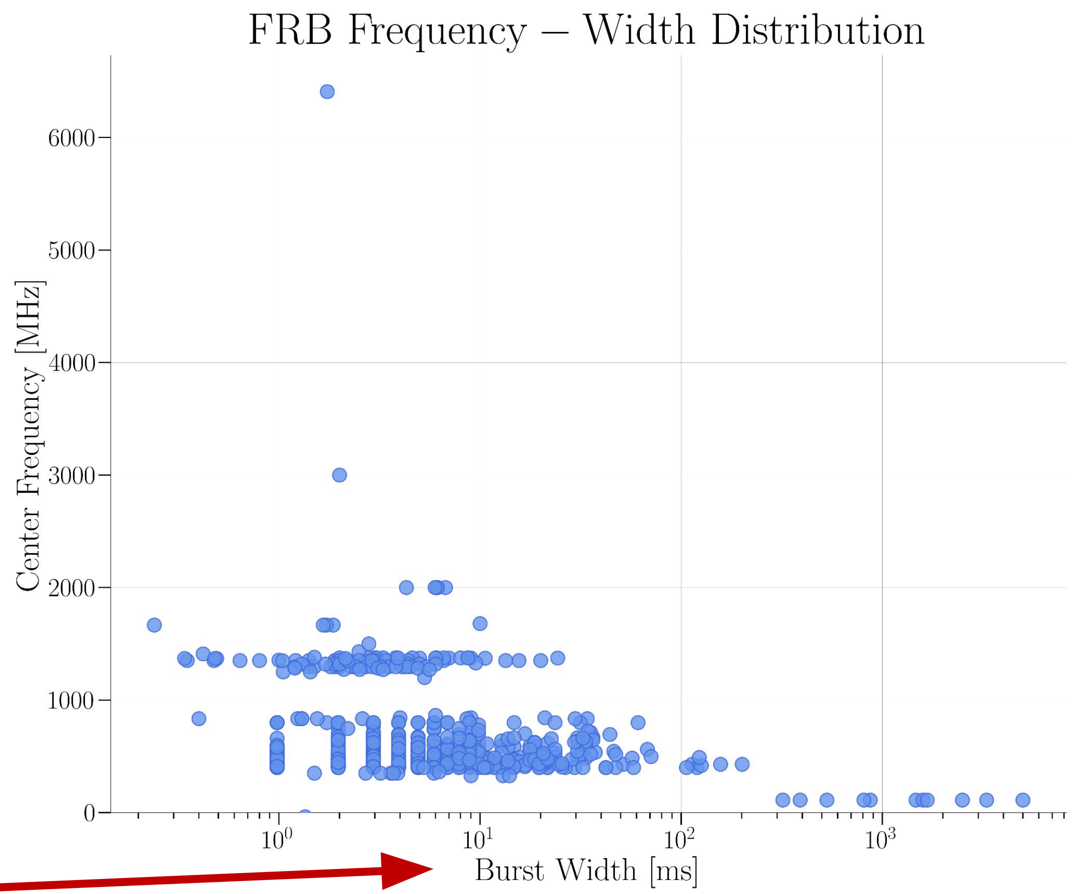
2.3: Fast radio bursts (FRBs)

FRBs are highly diverse sources...

- They have **variable frequencies**
  - And **variable widths**

Detected from 100MHz - 8GHz

widths from milliseconds - microseconds



Credit: Spanakis-Misirlis et al., 2021 [48]

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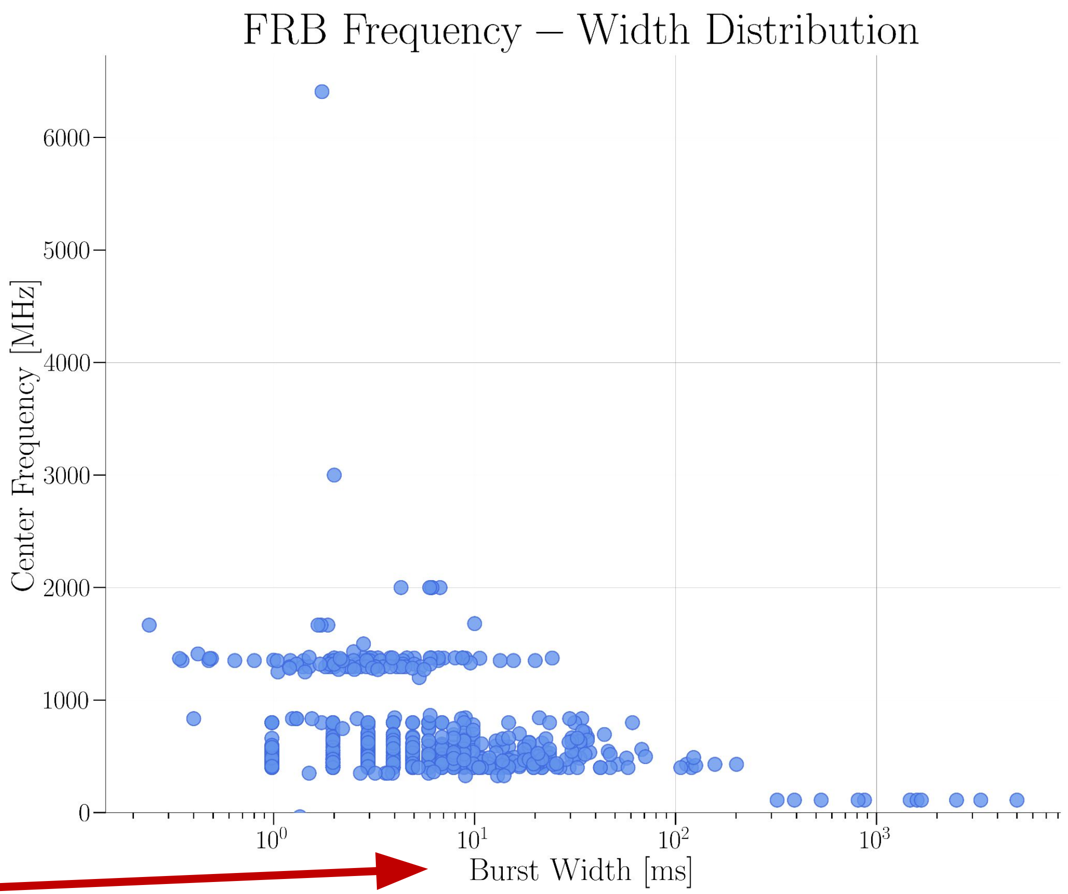
2.3: Fast radio bursts (FRBs)

FRBs are highly diverse sources...

- They have **variable frequencies**
  - And **variable widths**
- Making them **challenging to detect**
  - (see Part 4)

Detected from 100MHz - 8GHz

widths from milliseconds - microseconds



Credit: Spanakis-Misirlis et al., 2021 [48]

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2.3: Fast radio bursts (FRBs)

So why do we care about FRBs?

- Reason 1: We want to **learn about the sources** themselves...
    - What causes them? There are **many theories**... [49]

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2.3: Fast radio bursts (FRBs)

So why do we care about FRBs?

- Reason 1: We want to **learn about the sources** themselves...
  - What causes them? There are **many theories**... [49]
    - Some are quite exotic...

Quark nova model for fast radio bursts

Zachary Shand, Amir Ouyed, Nico Koning and Rachid Ouyed

Department of Physics and Astronomy, University of Calgary, 2500 Ur
Canada; *rouyed@ucalgary.ca*

Credit: Shand et al. (2016) [50]

PHYSICAL REVIEW D **90**, 127503 (2014)

Fast radio bursts and white hole signals

Aurélien Barrau,[1] Carlo Rovelli,[2] and Francesca Vidotto[2,3]

Credit: Barrau et al. (2014) [49]

Fast Radio Bursts from Extragalactic Light Sails

Manasvi Lingam[1,2] and Abraham Loeb[2]
ngineering and Applied Sciences, Harvard University, 29 Oxford Street, Cambridge, MA 02138, USA; ma
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
ived 2017 January 2; revised 2017 February 26; accepted 2017 February 26; published 2017 March 8

Abstract

Credit: Lingam & Loeb (2016) [51]

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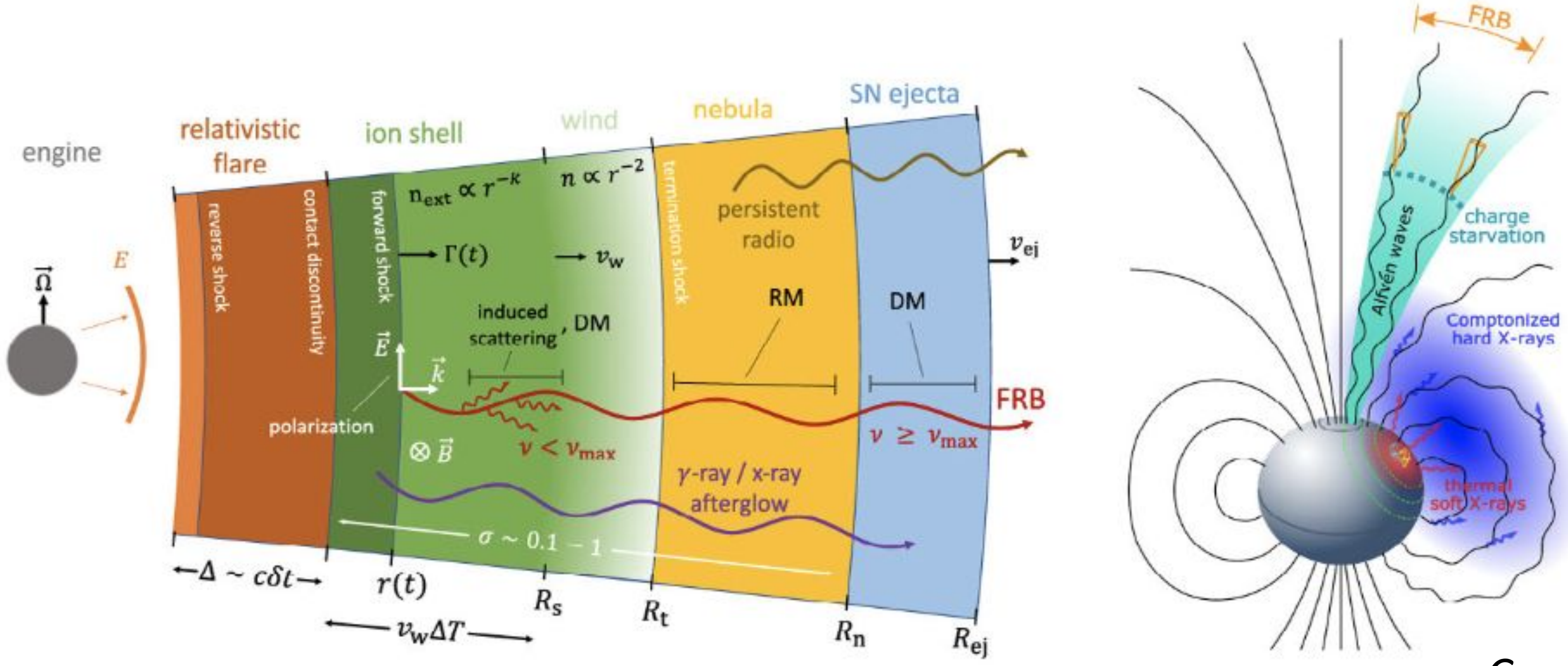
2.3: Fast radio bursts (FRBs)

So why do we care about FRBs?

(Note: we're settling on mostly **neutron star origins** these days)



a Shock models **b** Magnetospheric models

Credit: Petroff et al. (2022) [47]

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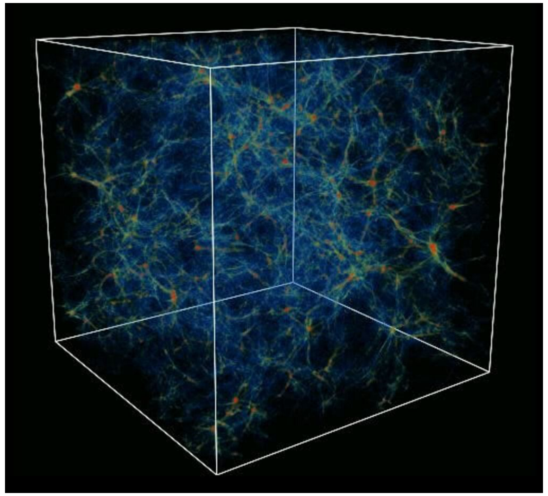
2.3: Fast radio bursts (FRBs)

So why do we care about FRBs?

- Reason 2: We can use them as **astrophysical tools** (just like pulsars!)

Use FRB to probe ionised matter in the Cosmic Web [52]



Credit: International Gemini Observatory/NOIRLab/NSF/AURA/G. L. Bryan/M. L. Norman
Creative Commons Attribution 4.0 International [54]

Use **many** FRBs to measure cosmological parameters (e.g. Hubble Constant, Baryon density) [52,53]

$$\mathrm{DM}_{\cos}(z) = c\int_0^{z_s} \frac{n_e(z)\mathrm{d}z}{(1+z)^2 H(z)},$$

$$n_e = \frac{3\Omega_b H_0^2}{8\pi G m_p}(1+z)^3 f_d(z) f_e(z),$$

Credit: Walker et al. (2023) [55]

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2: Conclusion

Much of the science relies on understanding propagation effects

- So on to part 3...

Part 3: Propagation effects

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Part 3: Propagation effects

Radio transients undergo effects which allow us study the Universe

- Therefore in this section we'll cover:

3.1: Dispersion
3.2: Scattering
3.3: Scintillation

Because measuring them requires **different data processing** to that you've been learning...

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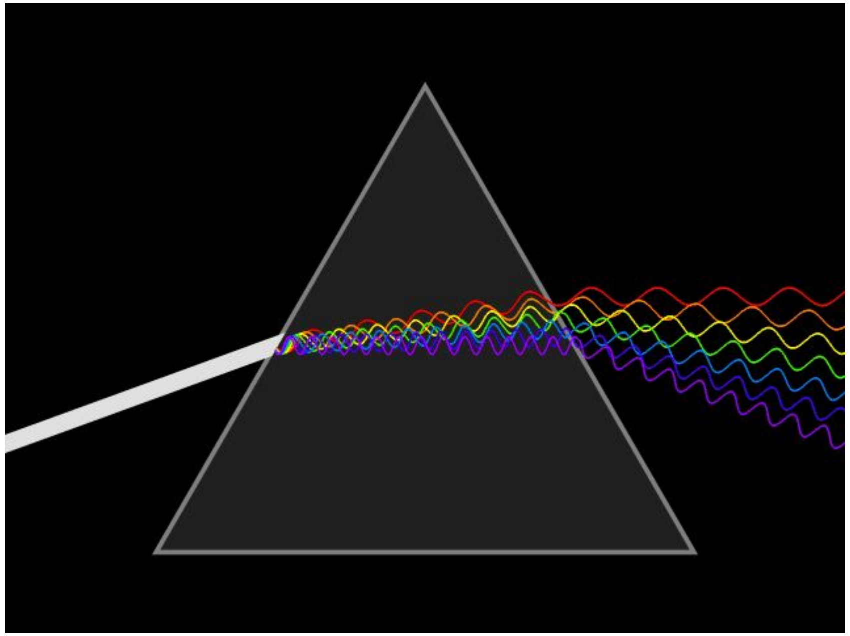
3.1: Dispersion

Radio waves are affected by the ionised matter they traverse...

- Specifically, they undergo a **frequency-dependent index of refraction** during propagation through an ionised medium
  - Just like **white light through a prism**

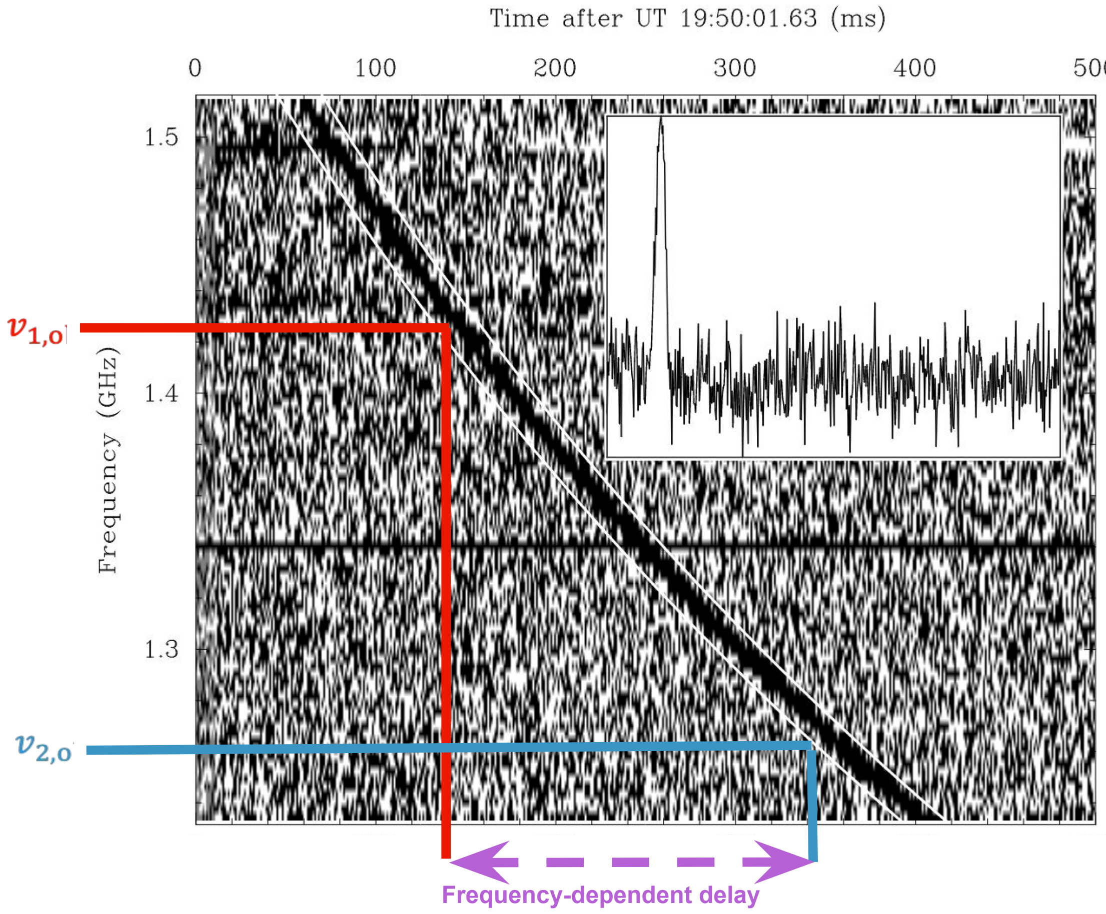


Credit: Lucas Vieira [56]

3.1: Dispersion

We observe a frequency-dependent delay in arrival time…

- **Higher-frequency** radiation arrives at observer before **lower-frequency** radiation



$\Delta t_{obs} \propto \mathrm{DM}_{obs} \times ({\nu_{1,obs}}^{-2} - {\nu_{2,obs}}^{-2})$

Credit: Lorimer et al. (2007) [18]

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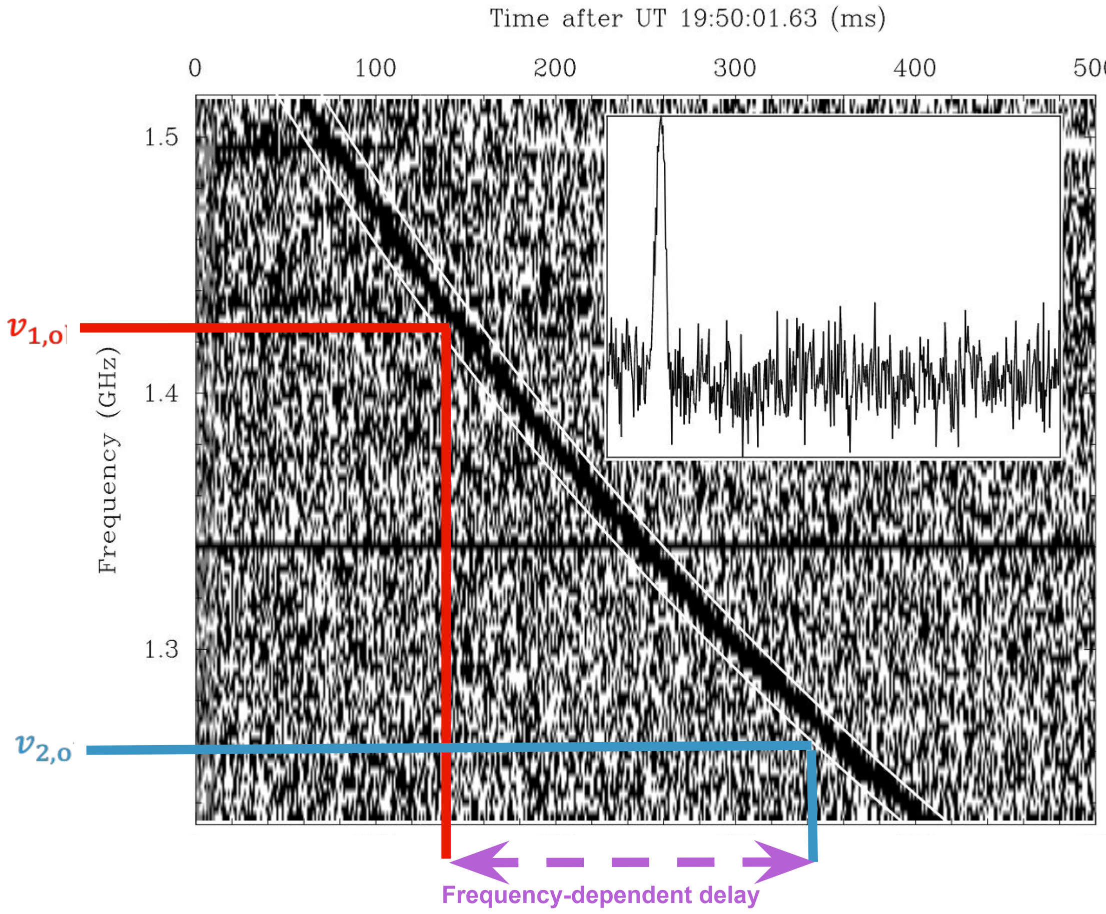
3.1: Dispersion

We observe a frequency-dependent delay in arrival time...

- **Higher-frequency** radiation arrives at observer before **lower-frequency** radiation
  - The delay is quantified by the **Dispersion Measure** (DM)



$$\Delta t_{obs} \propto \mathrm{DM}_{obs} \times (\nu_{1,obs}{}^{-2} - \nu_{2,obs}{}^{-2})$$

Credit: Lorimer et al. (2007) [18]

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3.1: Dispersion

DM is directly proportional to the integrated electron density along the line of sight to a souce...

- And thus to **every electron** the signal travels through!

$$\mathrm{DM}_{\mathrm{obs}} = \int_0^z \frac{\mathrm{n_e}}{(1+\mathrm{z})}\,\mathrm{dl}$$

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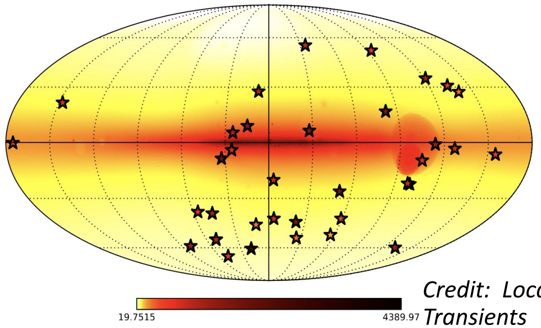
3.1: Dispersion

By isolating DM components, you can probe ionised matter...

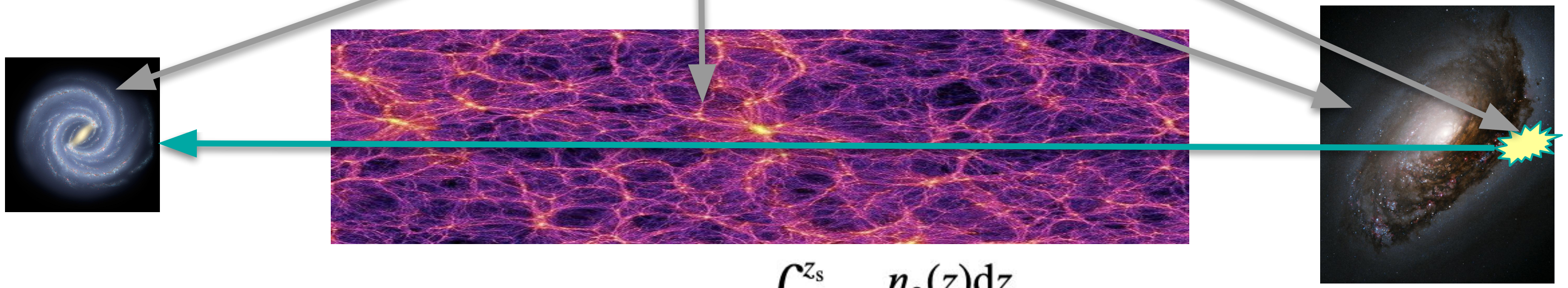
Mapping Milky Way n_e with pulsar DMs [40]



Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

Isolate the cosmological DM of FRBs, weigh the Universe's baryon content (Ωb) [52]

$$\mathrm{DM_{obs}} = \mathrm{DM_{MW}} + \mathrm{DM_{cosmic}} + \mathrm{DM_{host}} + \mathrm{DM_{local}}$$



$$\mathrm{DM_{cos}}(z) = c\int_0^{z_s} \frac{n_e(z)\mathrm{d}z}{(1+z)^2 H(z)},$$

$$n_e = \frac{3\Omega_b H_0^2}{8\pi G m_p}(1+z)^3 f_d(z) f_e(z),$$

Credit: Volker Springel / Max Planck Institute For Astrophysics, Attribution-Share Alike 4.0 International [57], NASA/JPL-Caltech/ESO/R. Hurt [58], NASA and The Hubble Heritage Team (AURA/STScI) [59], Walker et al. (2023) [55],

3.2: Scattering

While dispersion probes the amount of matter traversed...

- ... **Scattering** probes **how that matter is distributed**

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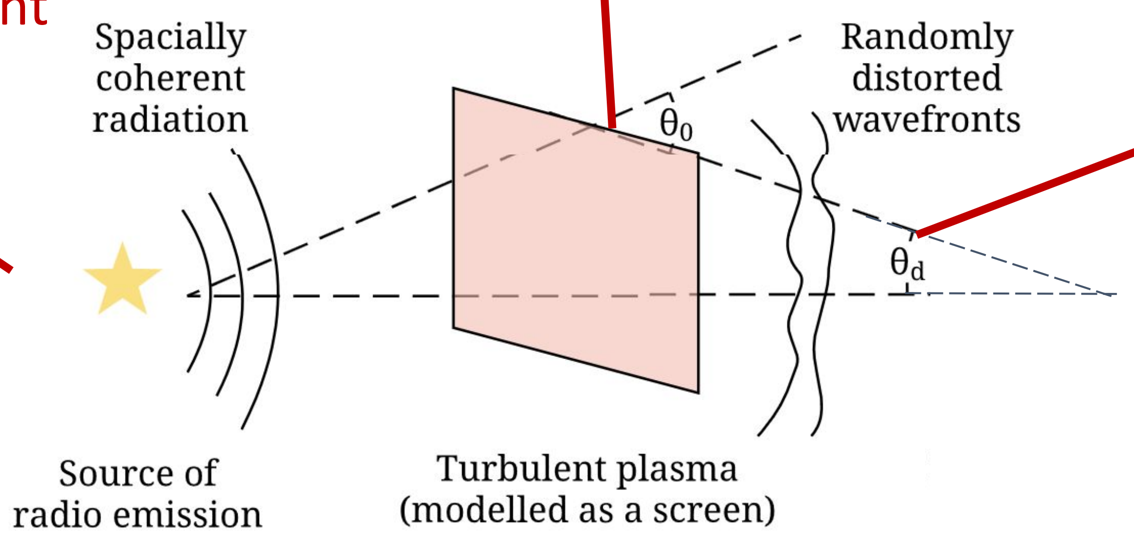
3.2: Scattering

Cause of scattering: inhomogeneous material along the line of sight...

2) Place 'scattering screen' of ionised media along the sightline...

1) Take a transient source

3) This causes multi-path propagation of signal

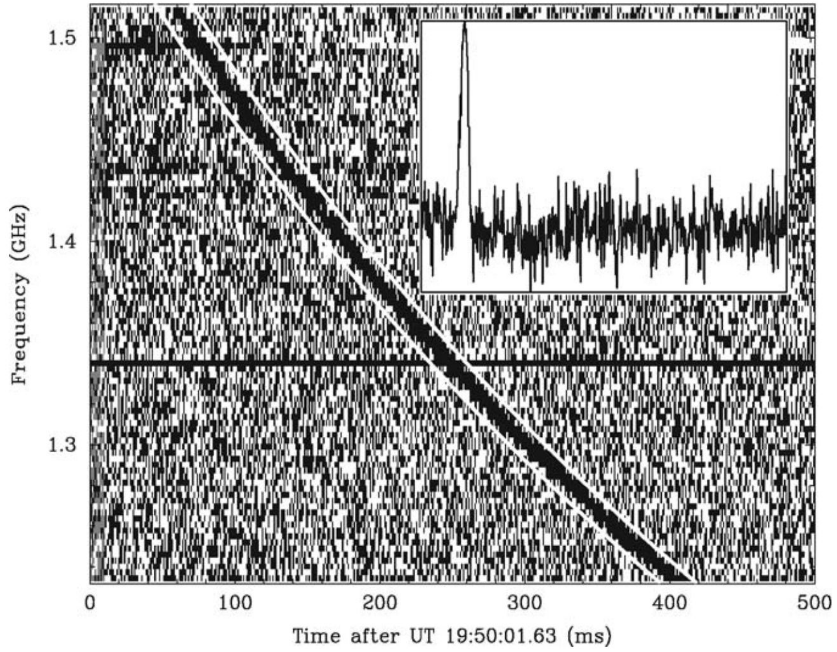


Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35], Lorimer & Kramer [30]

3.2: Scattering

Multi-path propagation affects pulse shape...

Example 1: FRB with no measurable scattering



Credit: Lorimer et al. (2007) [18]

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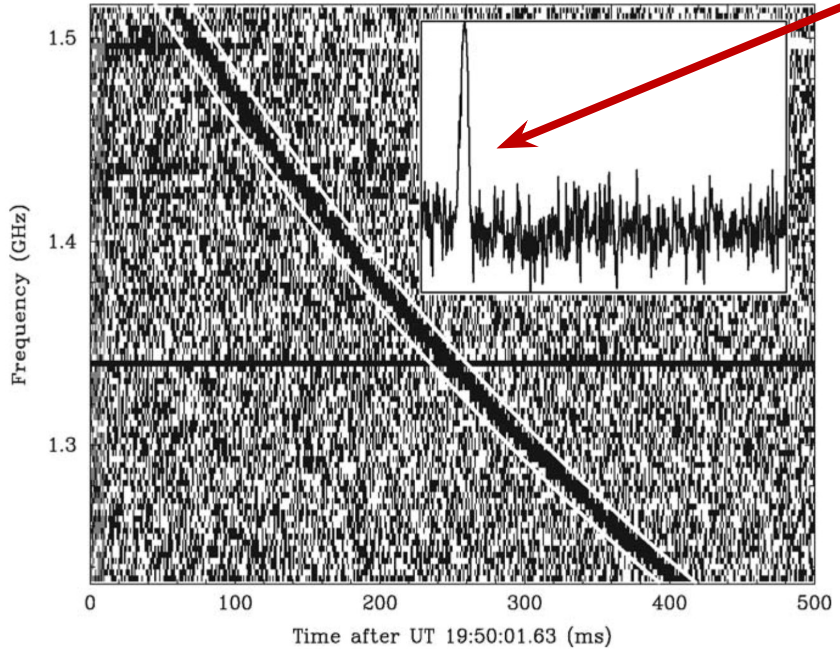
3.2: Scattering

Multi-path propagation affects pulse shape...

Sharp peak in timeseries data

Example 1: FRB with no measurable scattering



Credit: Lorimer et al. (2007) [18]

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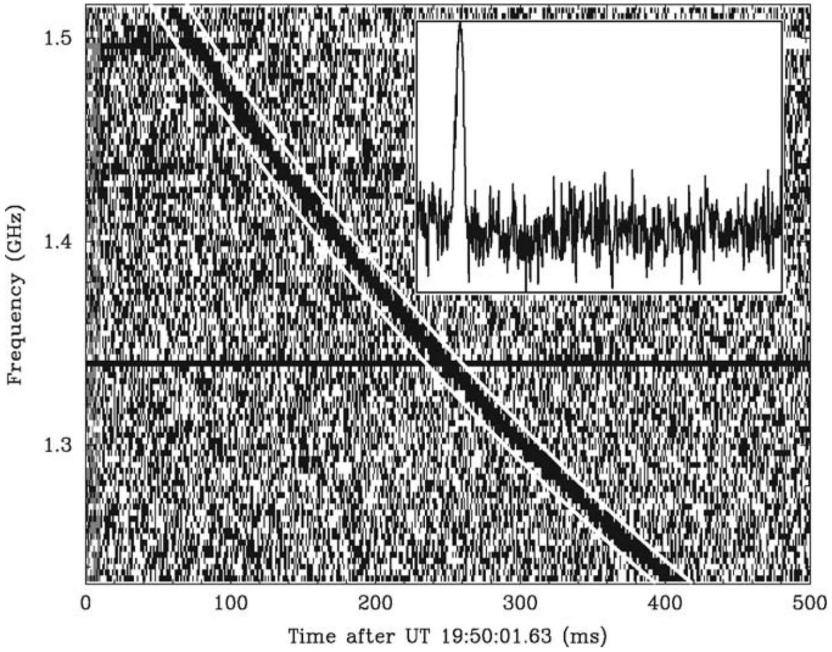
3.2: Scattering

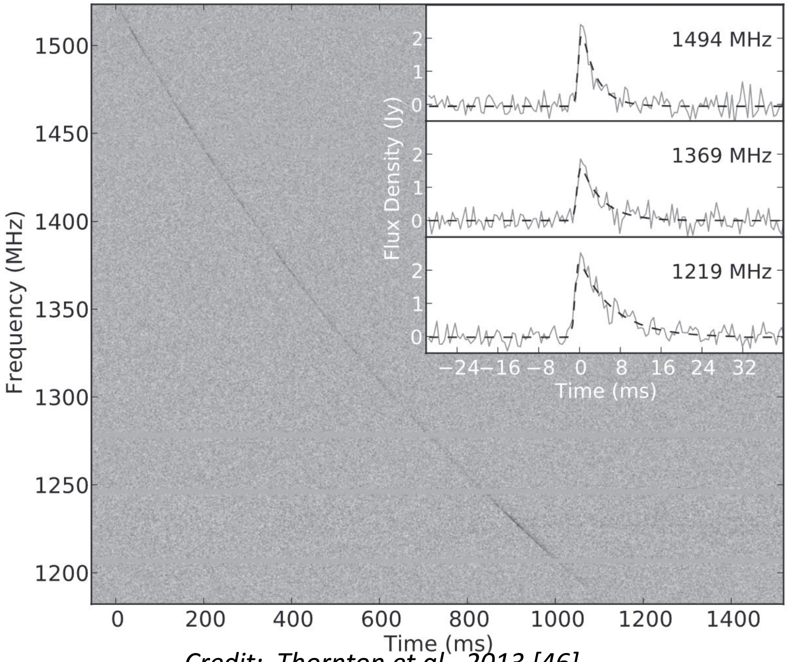
Multi-path propagation affects pulse shape...

Example 1: FRB with no measurable scattering



Credit: Lorimer et al. (2007) [18]

Example 2: FRB with scattering



Credit: Thornton et al., 2013 [46]

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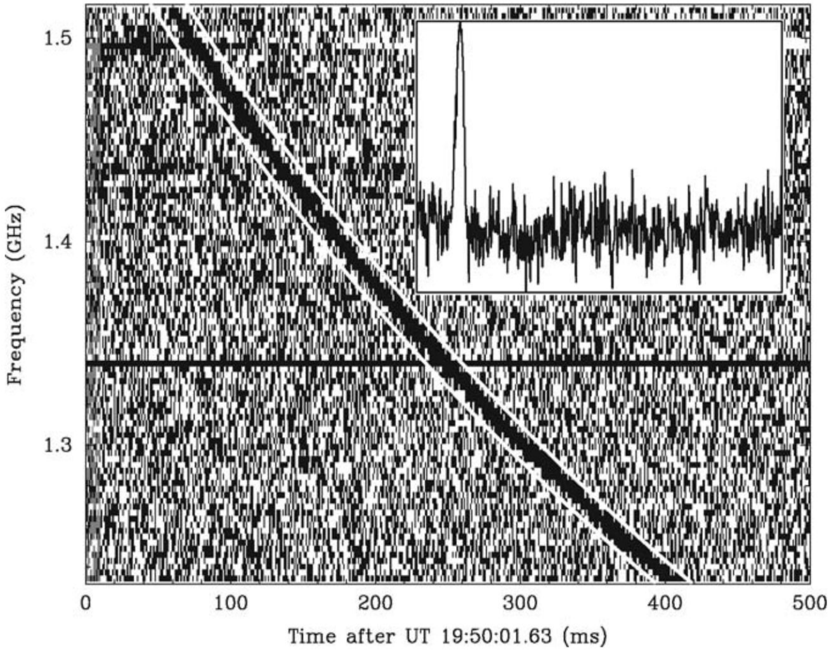
3.2: Scattering

Multi-path propagation affects pulse shape...

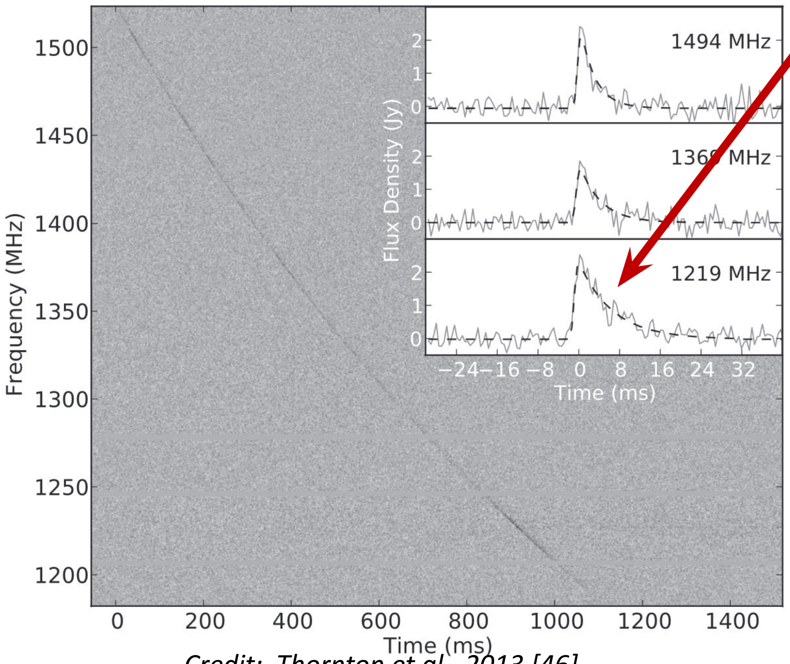
Example 1: FRB with no measurable scattering



Credit: Lorimer et al. (2007) [18]

Example 2: FRB with scattering

Exponentially decaying 'scattering tail'



Credit: Thornton et al., 2013 [46]

3.2: Scattering

Scattering analysis can probe both environments and progenitors of sources...

- Masui et al (2015) used scattering to infer a likely **neutron star progenitor** in a supernova remnant for FRB 110523! [60]

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3.3: Scintillation

Scintillation of transients is analogous to stars twinkling due to atmospheric turbulence... [60.5]

- Here, **turbulent ISM/IGM** causes constructive/destructive interference...

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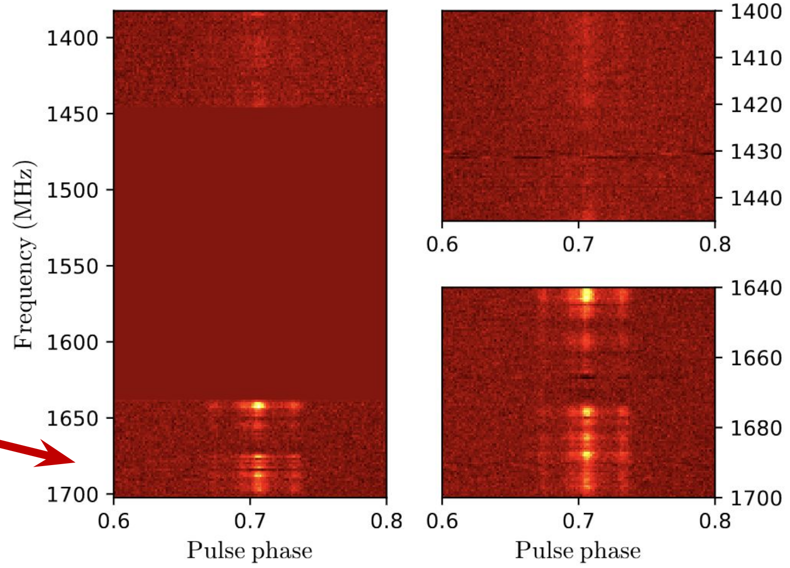
3.3: Scintillation

Scintillation of transients is analogous to stars twinkling due to atmospheric turbulence... [60.5]

- Here, **turbulent ISM/IGM** causes constructive/destructive interference...

RESULT: Intensity fluctuations in signal as a function of frequency and time



Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35], Lorimer & Kramer [30

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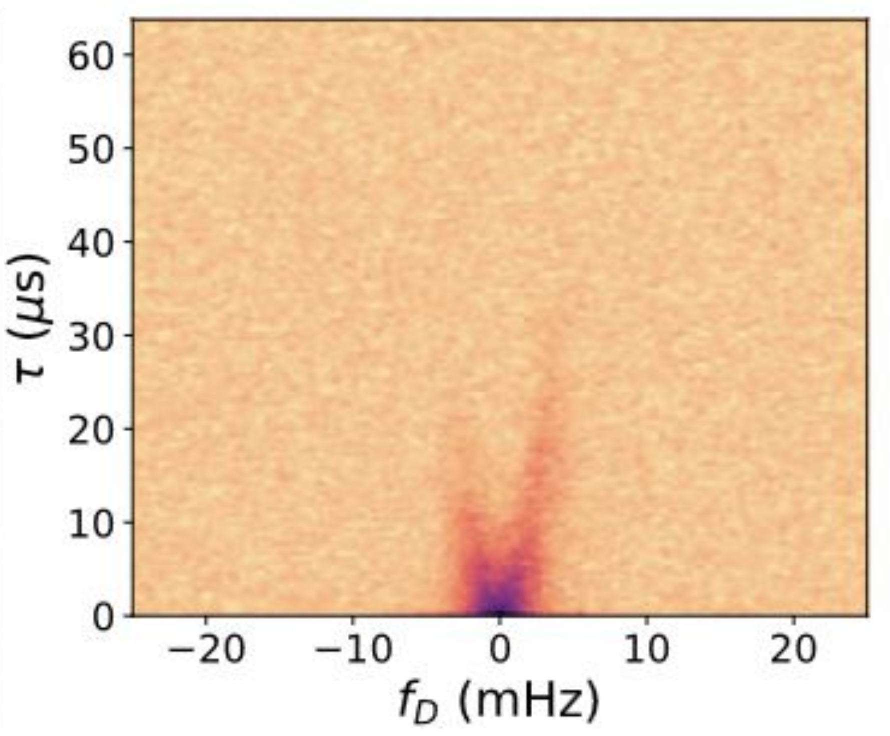
3.3: Scintillation

Scintillation can also probe environments...

- Mall et al. (2022) create a **secondary spectrum** for PSR J1643-1224
  - Infer scintillation comes from a **HII region** ionised by a known O-type star! [61]



Credit: Mall et al. (2022) [61]

3: Conclusion

There are other propagation effects as well...

- But now get onto the **data processing**

Part 4: A time-domain signal chain

Notice that many of the plots I've showed present radio data in a very different way...

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Part 4: A time-domain signal chain

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- Not looking at images!

Credit: Ralph Bennett – ALMA (ESO/NAOJ/NRAO) [Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) [2]

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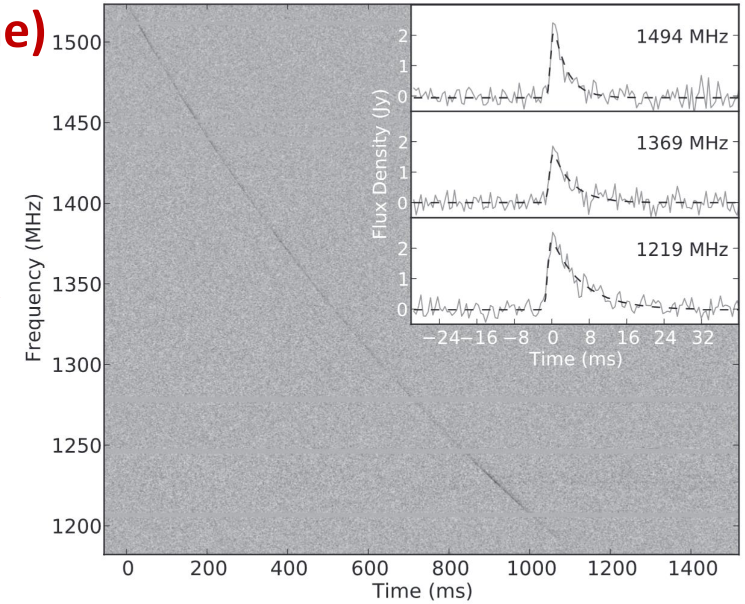
Dynamic spectra (frequency vs time)



Credit: Thornton et al., 2013 [46]

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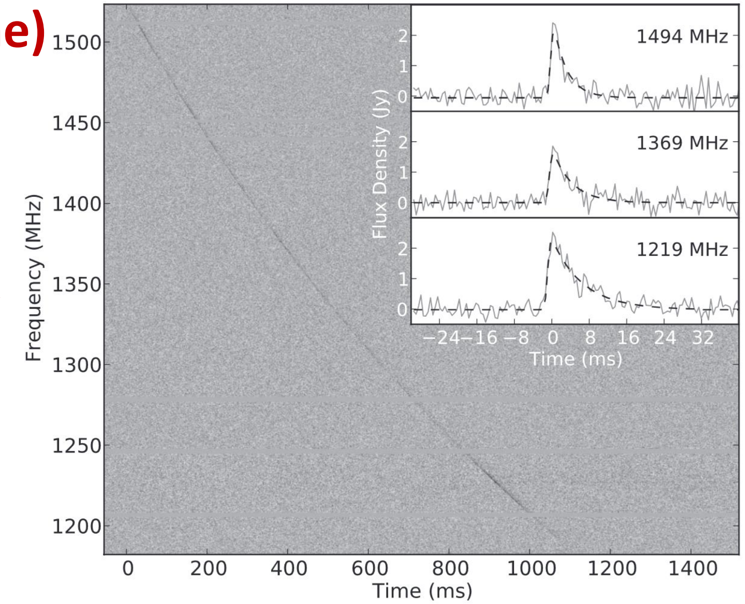

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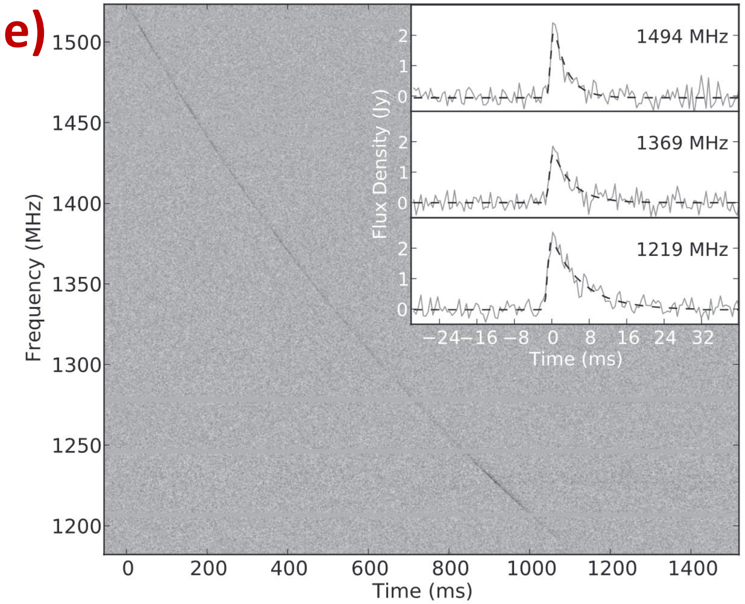
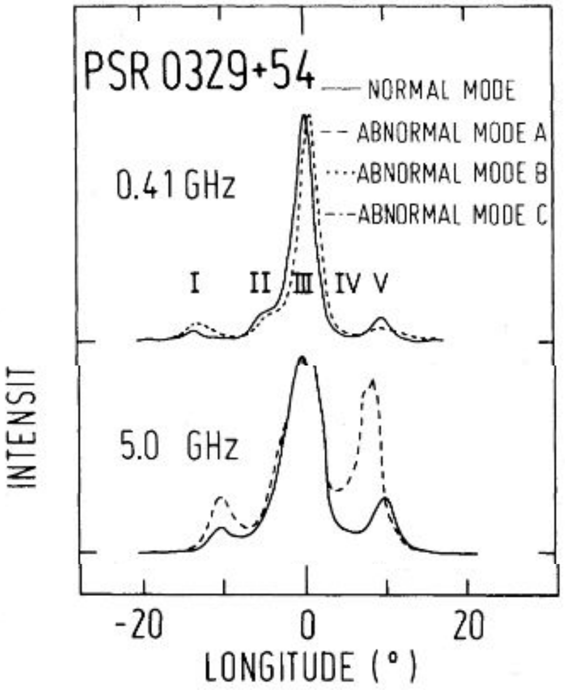


Credit: Thornton et al., 2013 [46]

Pulse profiles (intensity vs pulse phase)



Credit: Bartel et al. (1982) [36]

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Part 4: A time-domain signal chain

To get these plots requires different data processing...

- Which can be **data intensive**!

4.1: Data capture
(from telescope to data processor)
4.2: Data processing
(channelisation, rfi mitigation, combination)
4.3: Candidate analysis
(dedispersion, single-pulse searching, candidate sorting, pulsar analysis)

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Note: Module Alerts!

Note these symbols referring to the major modules for your course

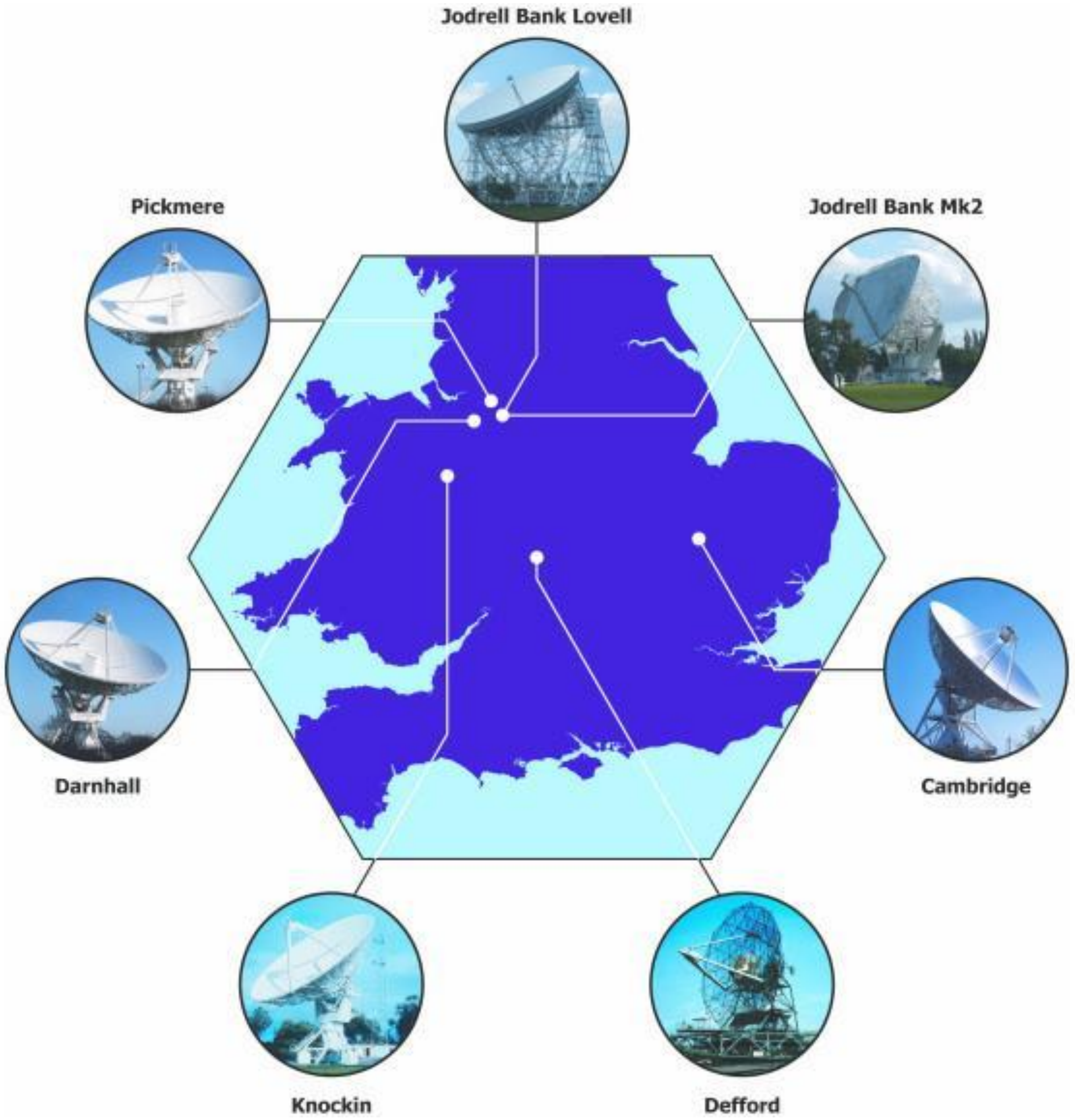
- I'll include them on slides where I think they might be relevant
  - Exercise your own judgement!

S1	Principles of data science	S2	Statistics for data science
M1	Applied data science	M2	Application of machine learning
C1	Research computing	C2	Advanced research computing

4.1: Data capture

Our example signal chain: the e-MERLIN interferometer

- UK-based array consisting of **6-7 dishes**
  - But data analysis is **applicable to other telescopes** too.



Credit: Alastair Gunn, Creative Commons Attribution 3.0 Unported [62]

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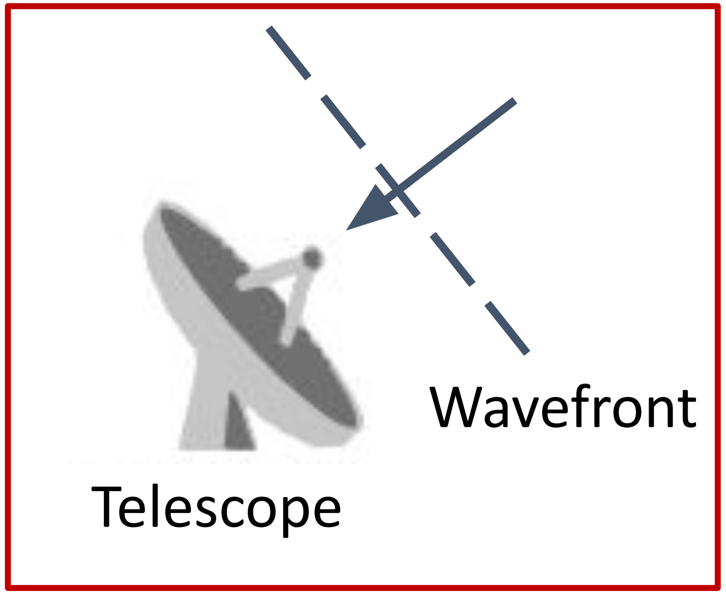
4.1: Data capture

Step 1: Getting data from dish to correlator [63]

1) Radio wave hits receiver



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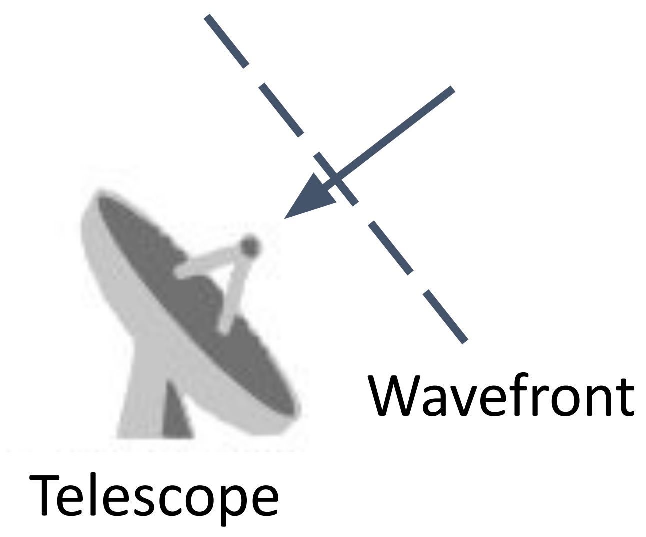

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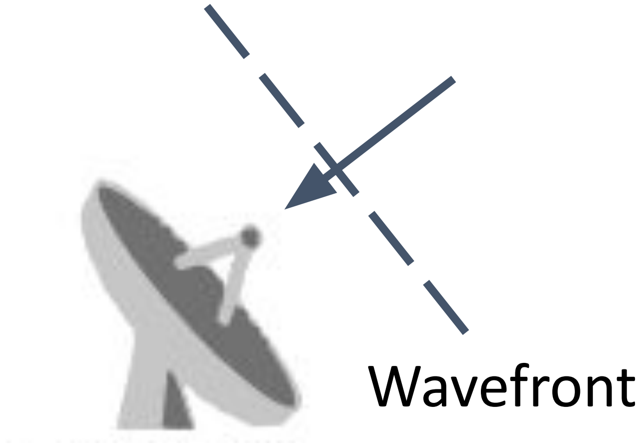
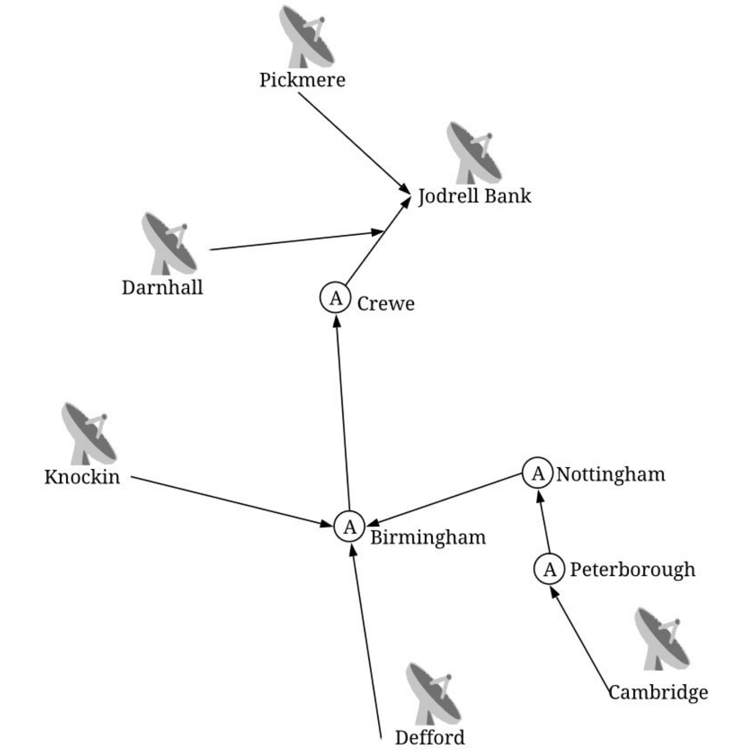


2) voltage data sampled by analogue-to-digital converter

3) data sent via fiber-optic cables to correlator



Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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In the correlator...

- Lots of **imaging-related processing** happens
  - But for transient analysis, **not all is necessary**

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Important things to note:

- Data is **split into sub-bands** in the correlator
- And **downsampled** to a lower bit-rate (e.g. for storage reasons)

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4.1: Data capture

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Important things to note:

- Data is **split into sub-bands** in the correlator
- And **downsampled** to a lower bit-rate (e.g. for storage reasons)

For e-MERLIN we end up with:

- **8 x 64MHz** sub-bands
- **2-bit** voltage data
  - This is the data we will be working with!

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4.1: Data capture

Step 2: Getting data from correlator to data processor...

- For e-MERLIN, the 2-bit voltage data is **streamed to a dedicated data processor**
  - via ethernet packets
  - over fiber-optic cables

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Let's do a quick calculation...

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4.1: Data capture

Question: How data-intensive is e-MERLIN?

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- Data comes in **64MHz sub-bands**...
  - To accurately sample a signal, you must **sample at the Nyquist Frequency** (twice the bandwidth) [64]:
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  - **One telescope produces 64MB/s data per sub-band**

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- The total e-MERLIN observing band is **8 x 64 = 512MHz**...
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- e-MERLIN uses up to **7 telescopes**...
  - 7*512 MB/s = ***~3.6 GB/s***

So the full array produces ~3.6 GB/s of data!

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So the full array produces ~3.6 GB/s of data!

Note 1: Already for e-MERLIN this isn't practical...

We're hardware-constrained to 12 streams (768 MB/s) across all telescopes and sub-bands.

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4.1: Data capture

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So the full array produces ~3.6 GB/s of data!

Note 2: data isn't the only thing we stream!

We also need metadata, containing all telescope/observing information necessary to describe the data products

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4.1: Data capture

Back to the data processor...

- For e-MERLIN, the 2-bit voltage data is **streamed to a dedicated data processor**
  - via ethernet packets
    - Data rate: 4000 UDP packets x 2 pols x 8032
      - **~=64 MB per second per sub-band per dish**
    - Data format: VDIF files

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    - Data format: VDIF files

This is your data in its most raw form

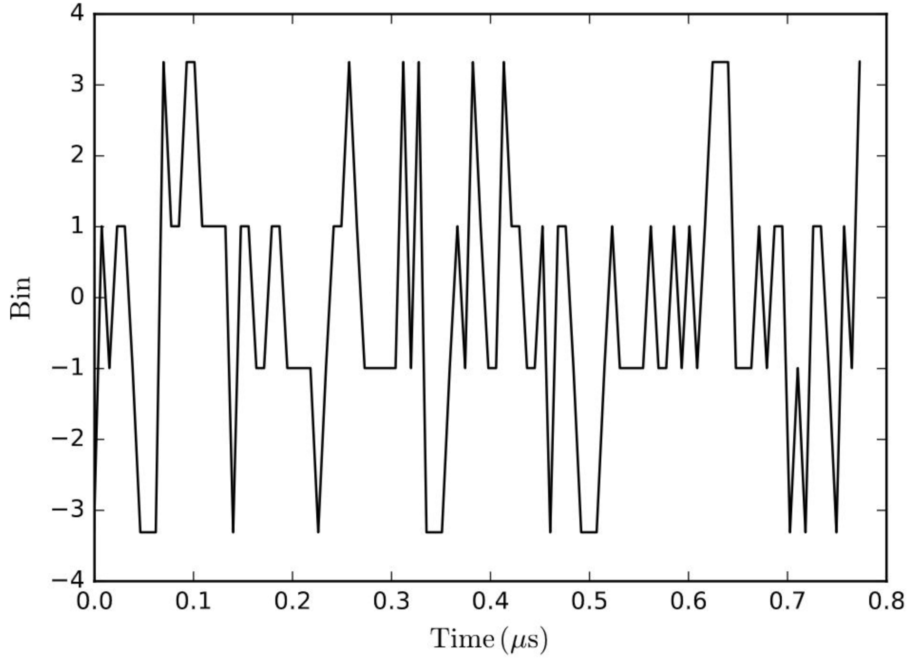

Figure 4.5: Time into an observation plotted against bin number, showing a sample of the 2-bit digitised signal aquired by LOFT-e from e-MERLIN's Cambridge Telescope during L-band observation of PSR B1933+16. Data is sampled at 128 MHz.

Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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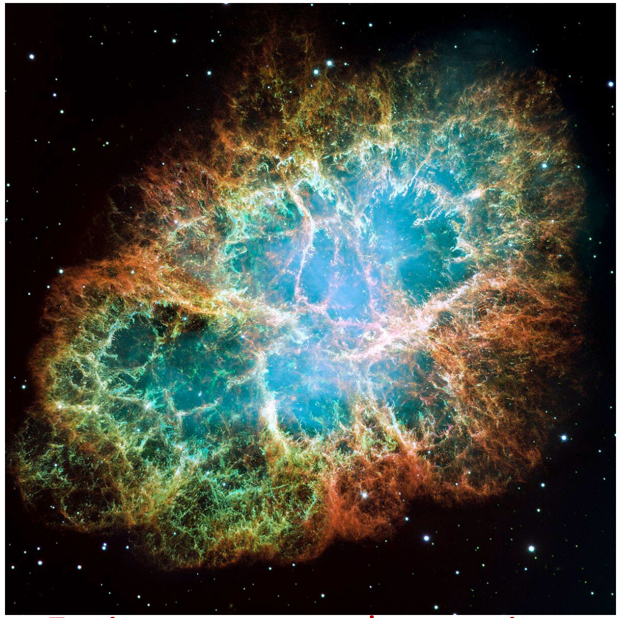
4.2: Data processing

Before we process, a question: how do you cope with 3.6 GB/s data?

Want to study a known source?



Easier to target observations, store less data & process it offline

Credit: NASA, ESA, J. Hester and A. Loll (Arizona State University) [28], JohannesBuchner, Attribution-Share Alike 4.0 International [65]

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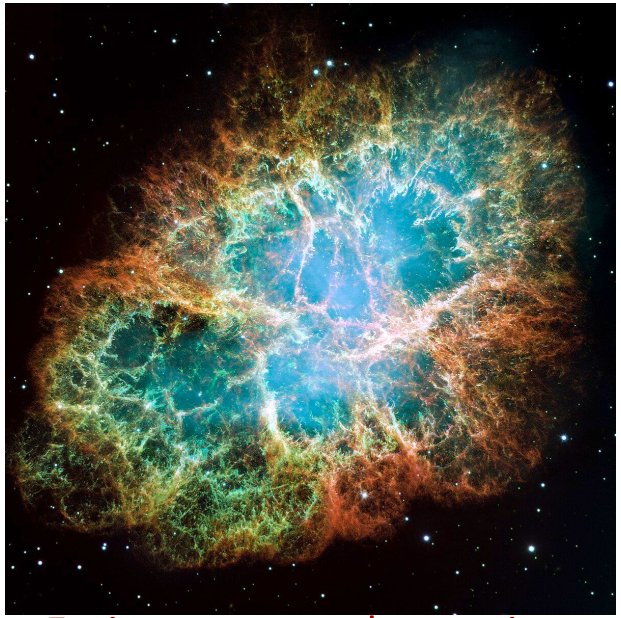

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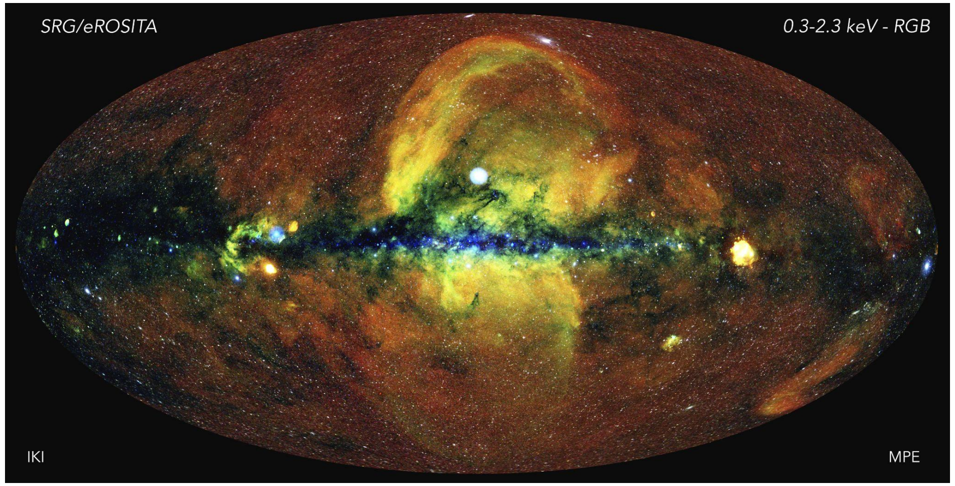

Harder to store and process hundreds of hours of observations

Credit: [NASA](), [ESA](), J. Hester and A. Loll (Arizona State University) [28], [JohannesBuchner](), [Attribution-Share Alike 4.0 International]() [65]

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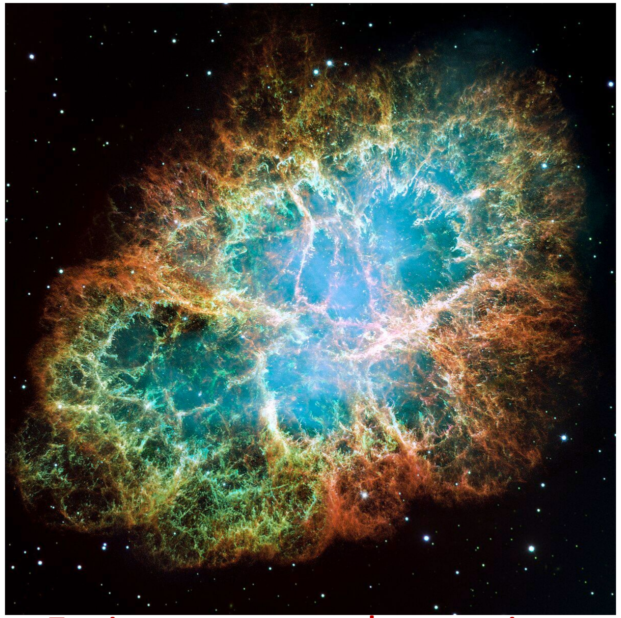

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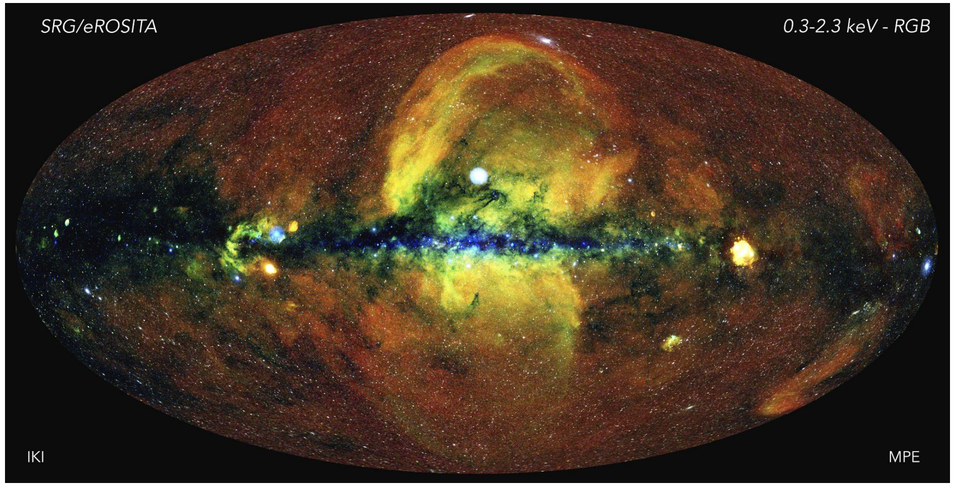

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High-Time Resolution Universe Pulsar Survey [66]

- High lat: 435 TB
- Mid lat: 190 TB
- Low lat: 250 TB

Credit: NASA, ESA, J. Hester and A. Loll (Arizona State University) [28], JohannesBuchner, Attribution-Share Alike 4.0 International [65]

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4.2: Data processing

Answer: We're increasingly turning to high-speed computing solutions...

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4.2: Data processing

Answer: We're increasingly turning to high-speed computing solutions...

- The SUPERB survey [67] kept a portion of the data (e.g. 2 minutes) **in a ring buffer**
- Efficient algorithms **processed in real-time**
- Only **promising candidates were stored**
  - Better for storage
  - Also allows fast follow-up (more on this later)

backend for further processing. It is here that the observing systems of HTRU-S and SUPERB diverge. Where previously data arriving in HIPSR would have been bit-compressed and the Stokes I component written to disc and thence to magnetic tape, for the SUPERB survey the data are instead pushed into a 120-s ring buffer. This ring buffer serves two purposes; it provides input to a real-time transient search and it enables full-Stokes data to be recorded upon receipt of a trigger. Following the transient search, the Stokes I component of the data is bit-compressed to 2 bits per sample and is written

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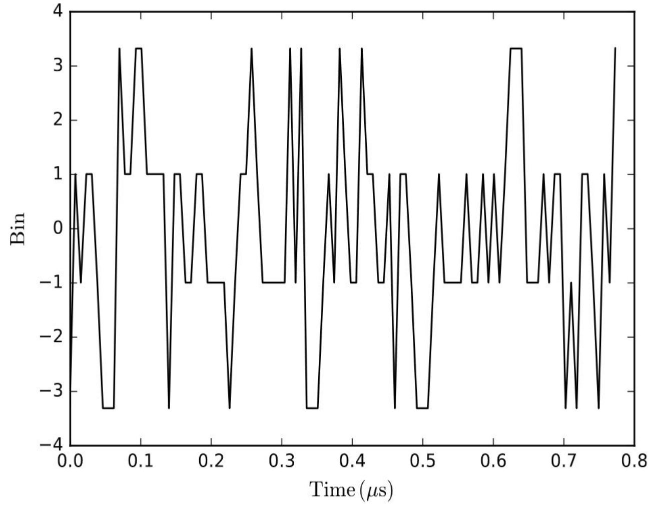
4.2: Data processing

So how do we process data? First, channelise it...

1) Take your timeseries



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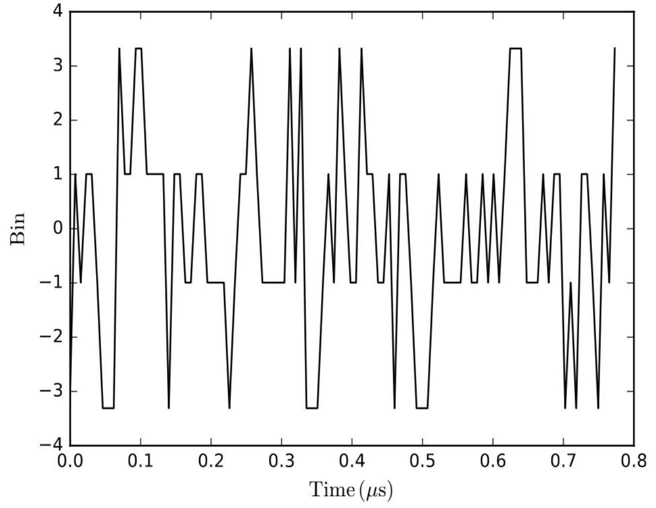

2) Accumulate N timesamples, apply discrete fourier transform

$$F_k = \sum_{n=0}^{N-1} t_n \exp(-2\pi i n k/N),$$

$$\nu_k = k/(N t_{\mathrm{samp}}),$$

Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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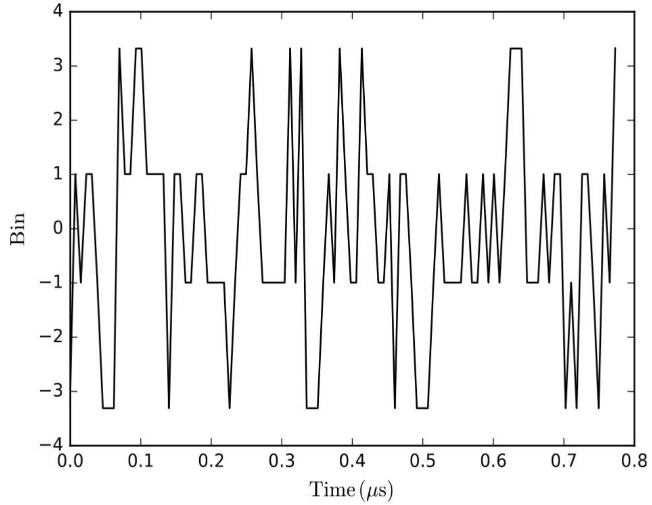

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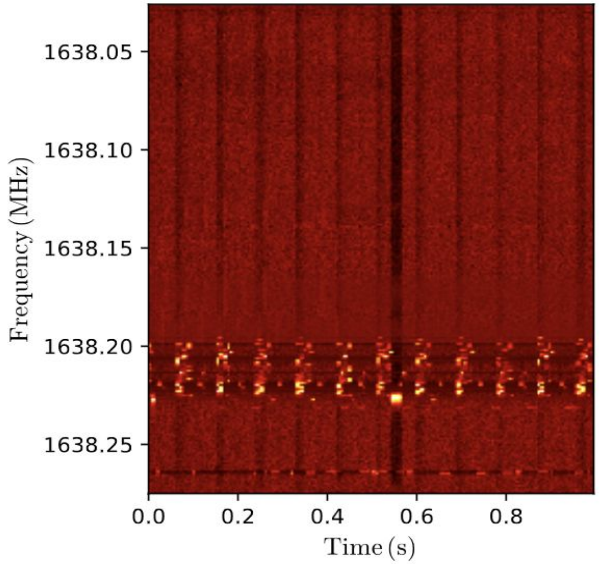
3) Result: 2-D dynamic spectrum



Credit: Localising Fast Transients
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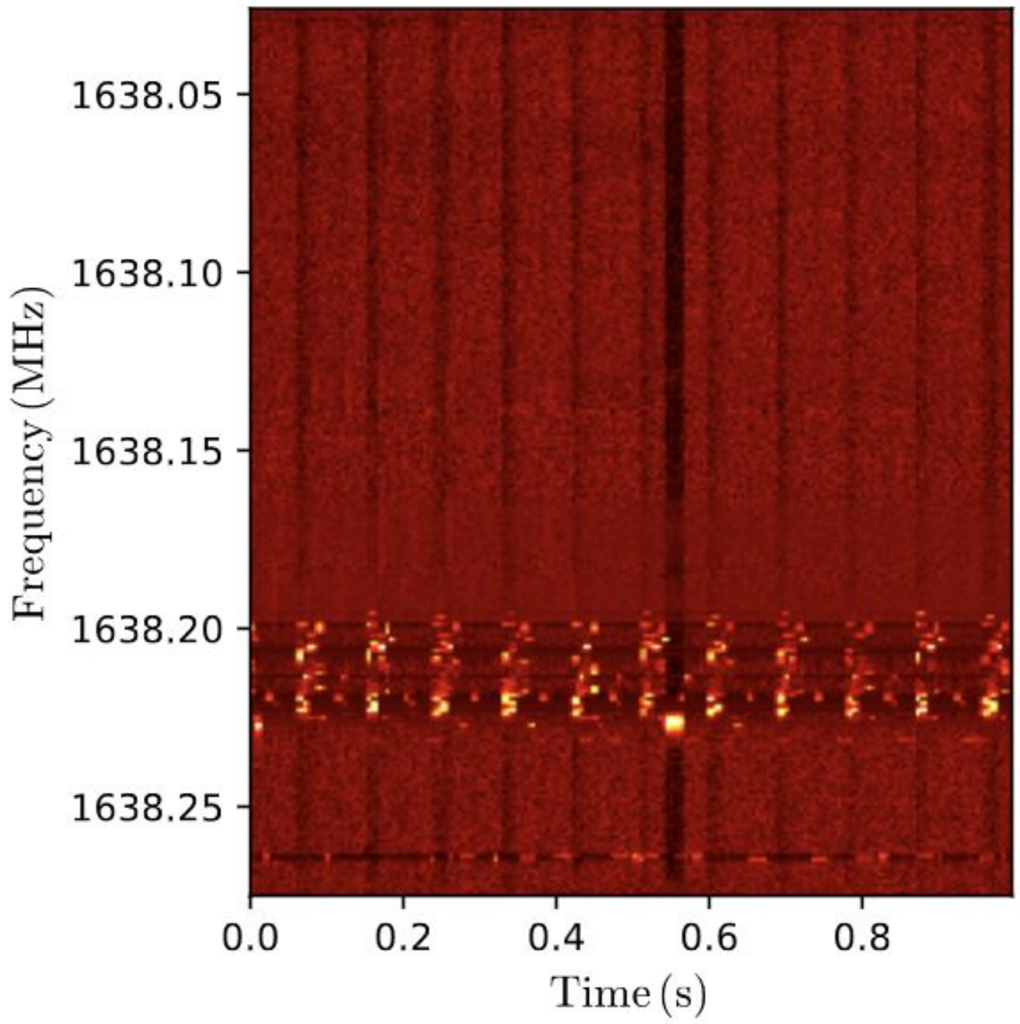
4.2: Data processing

Channelising allows for variable temporal and spectral resolution...

- Width of frequency channels, time samples **depend on the number of samples** you accumulate for your fourier transform



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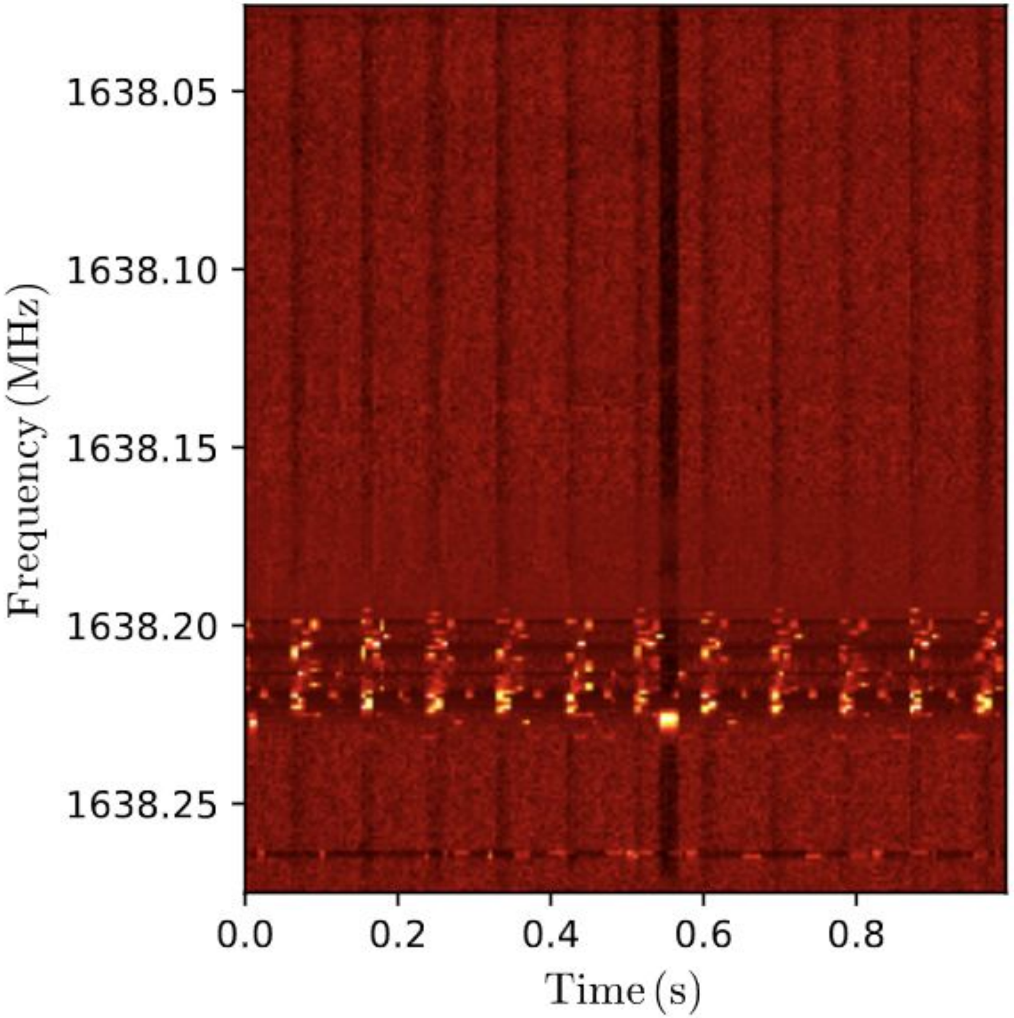
4.2: Data processing

Channelising allows for variable temporal and spectral resolution...

- Width of frequency channels, time samples **depend on the number of samples** you accumulate for your fourier transform

Choice of resolution is a tradeoff...

- Finer temporal resolution = worse spectral resolution
  - Better for **narrow bursts**
- Finer spectral resolution = worse temporal resolution
  - Better for **propagation effect studies**



Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

C2

4.2: Data processing

The choice of Fourier Transform algorithm is important...

...because we **have to do lots** of them!

- Generally use **efficient** Fast Fourier Transform (FFT) algorithms
  - e.g. N x *log2(*N*)* operations per transform (Lorimer & Kramer, 2012)

C2

4.2: Data processing

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- Generally use **efficient** Fast Fourier Transform (FFT) algorithms
    - e.g. N x *log2(*N*)* operations per transform (Lorimer & Kramer, 2012)
- **Parallelising** the process is useful...
    - E.g. across telescopes, sub-bands, or data chunks
        - By using **GPU programming**
        - Or **multiple computing nodes**

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4.2: Data processing

Important Note: DFTs operate on uniformly-spaced data!

- Fine in theory: telescope data is uniformly-spaced...
  - ...in practice **you may drop packets**!

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4.2: Data processing

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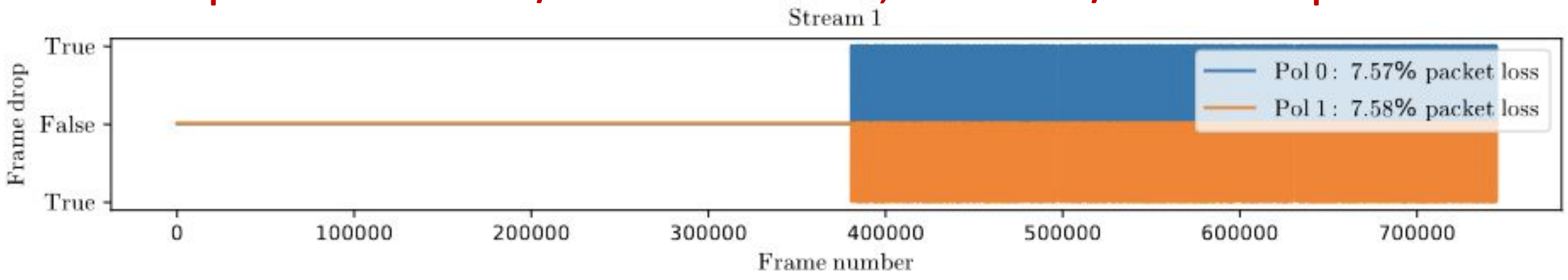
Example 1: 256 MB/s data stream, 238 MB/s write speed...



unacceptable data loss!

Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

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4.2: Data processing

Important Note: DFTs operate on uniformly-spaced data!

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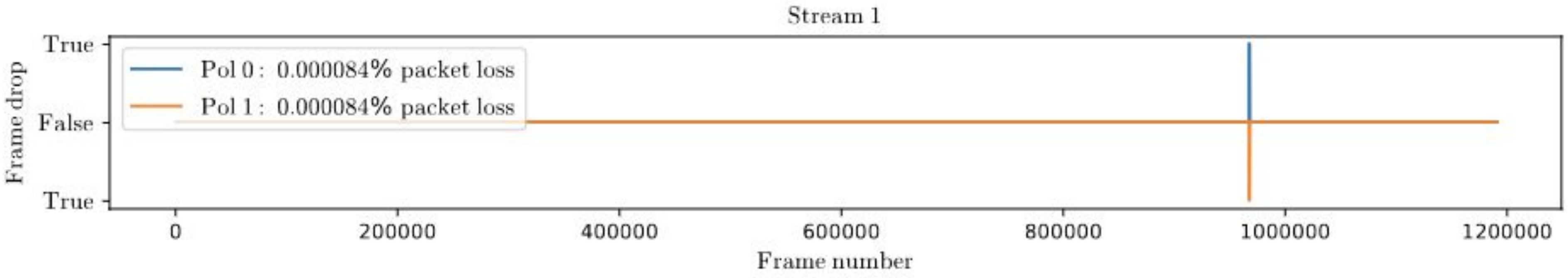
Example 2: 256 MB/s data stream, 383 MB/s write speed...



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C2

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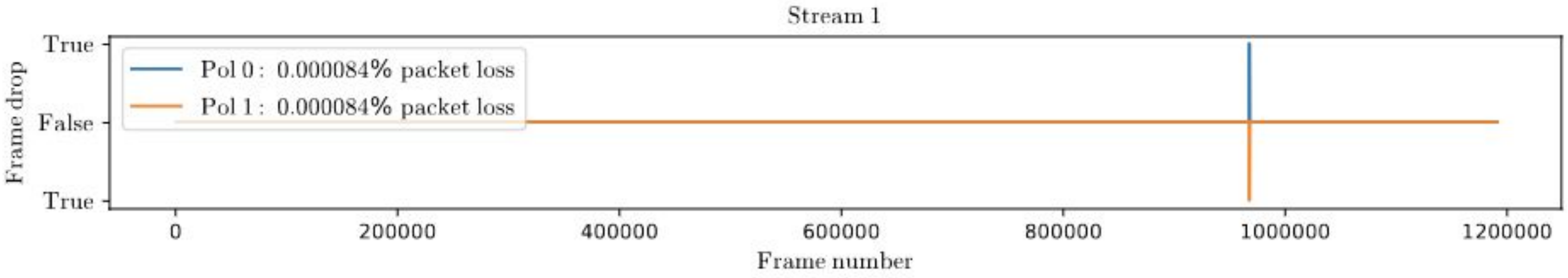

acceptable packet loss (fill in data in real-time with fast data capture code (probably compiled))

Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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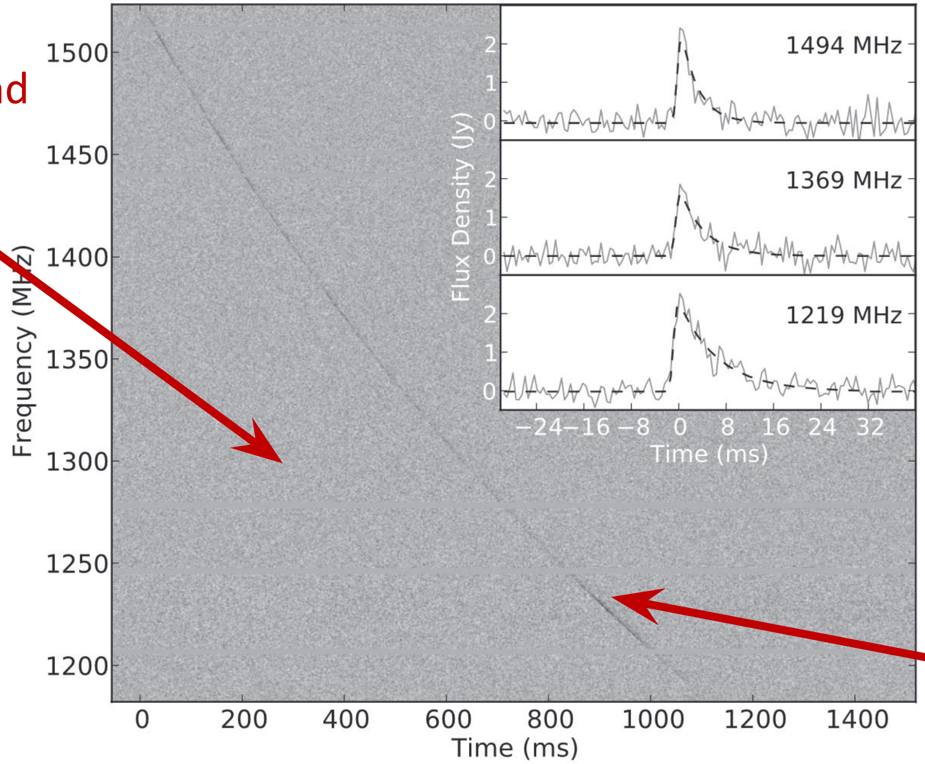
4.2: Data processing

Once you've channelised, you hopefully have a nice, clean dataset...

Random background fluctuations



Clearly visible burst

Credit: Thornton et al., 2013 [46]

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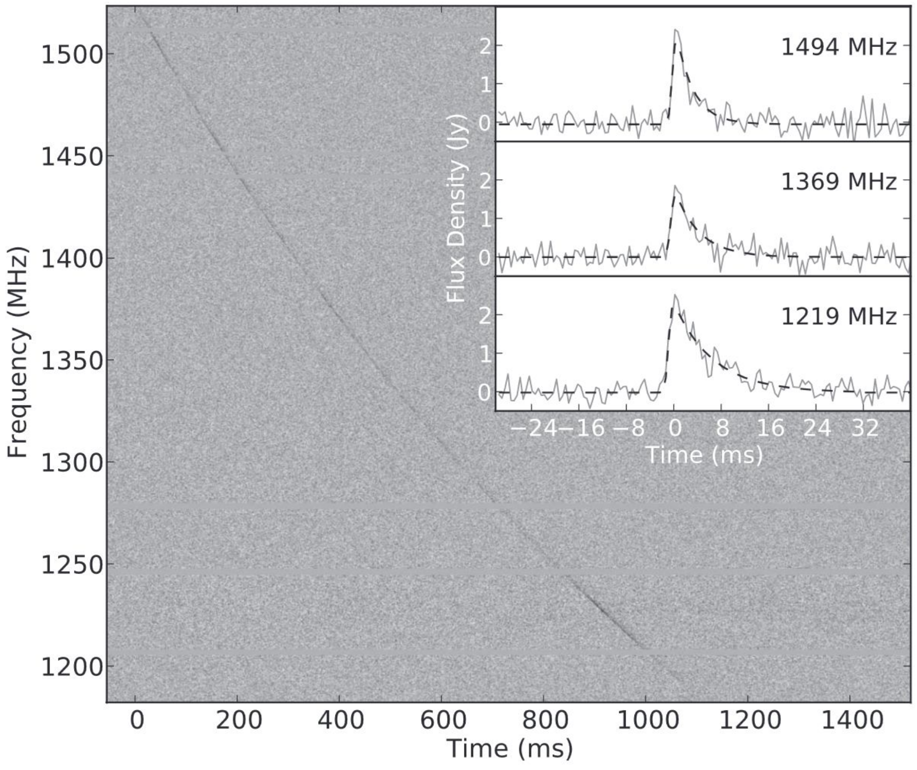
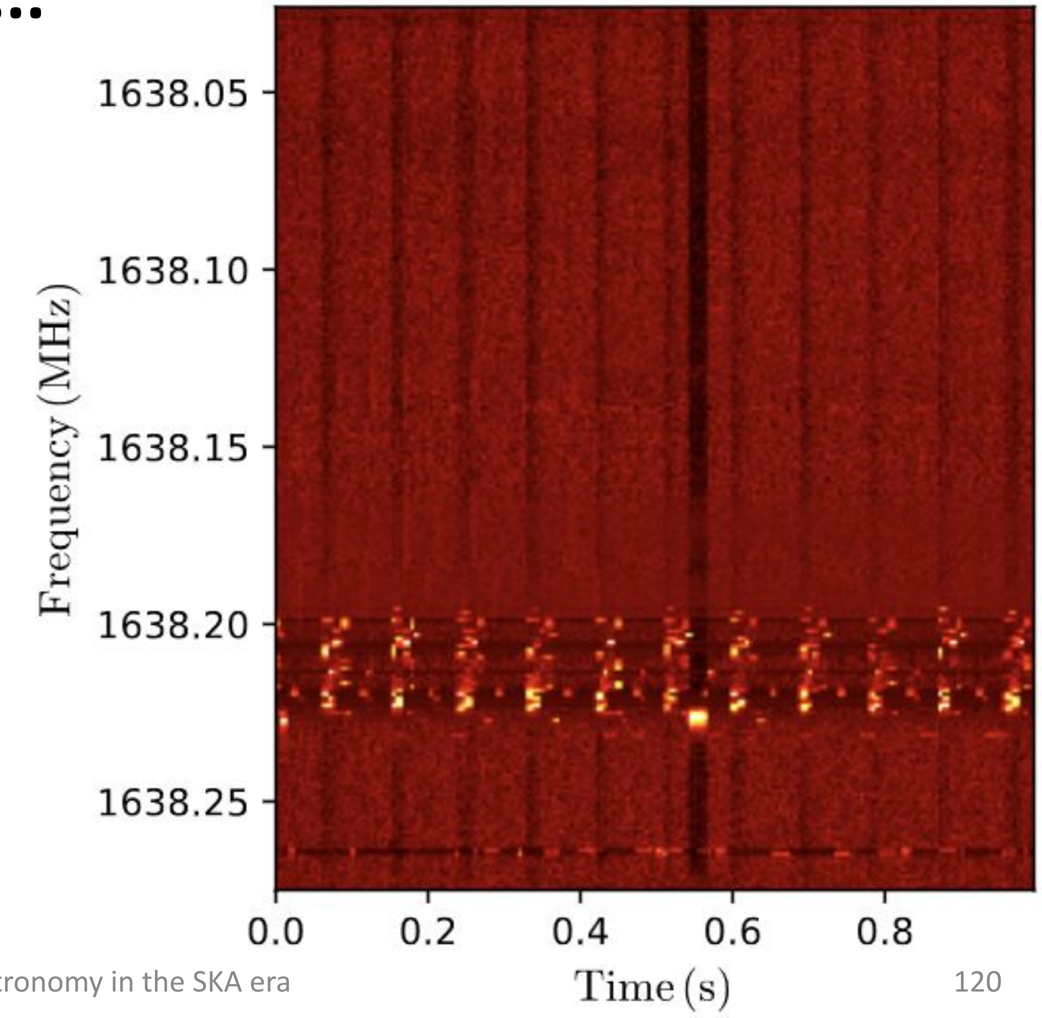
4.2: Data processing

This e-MERLIN data is not nearly as nice...



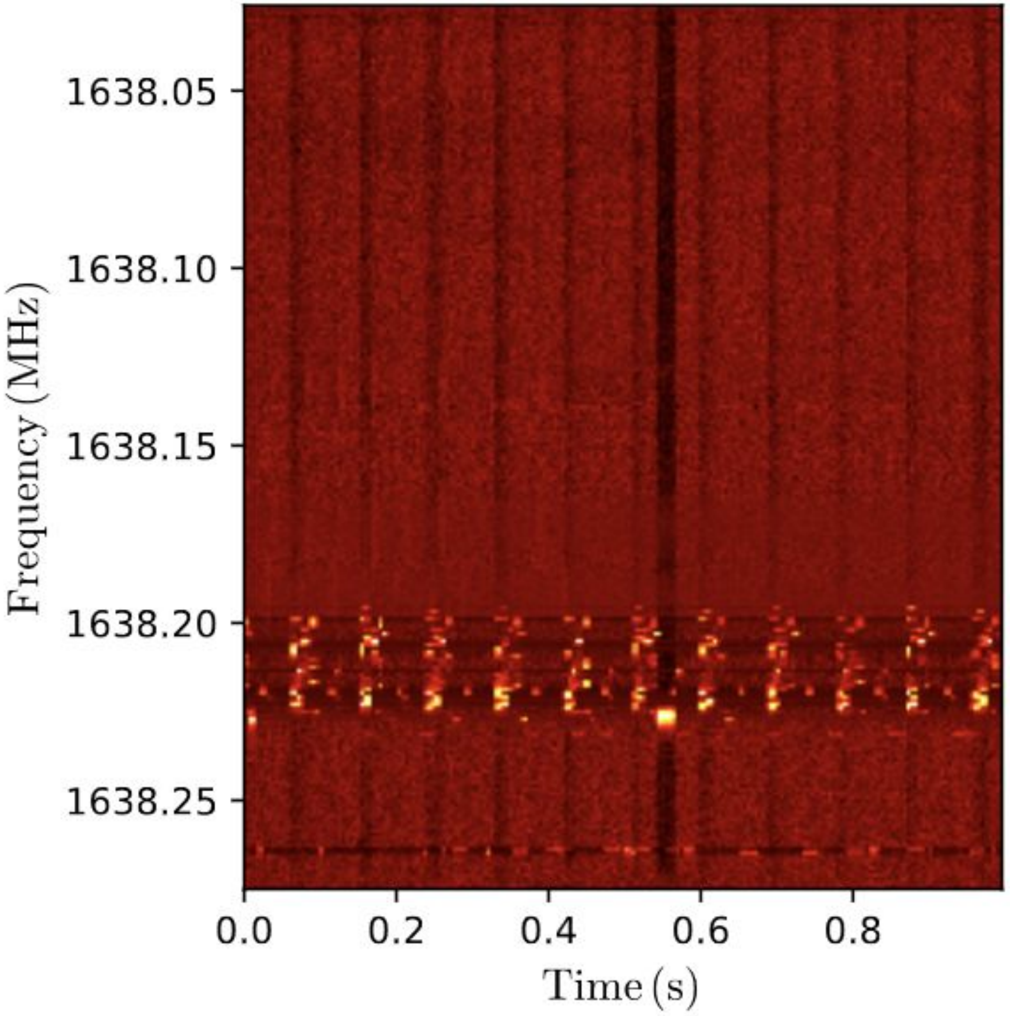
Credit: Thornton et al., 2013 [46]



Credit: Localising Fast Transients

4.2: Data processing

You're seeing radio frequency interference (RFI)



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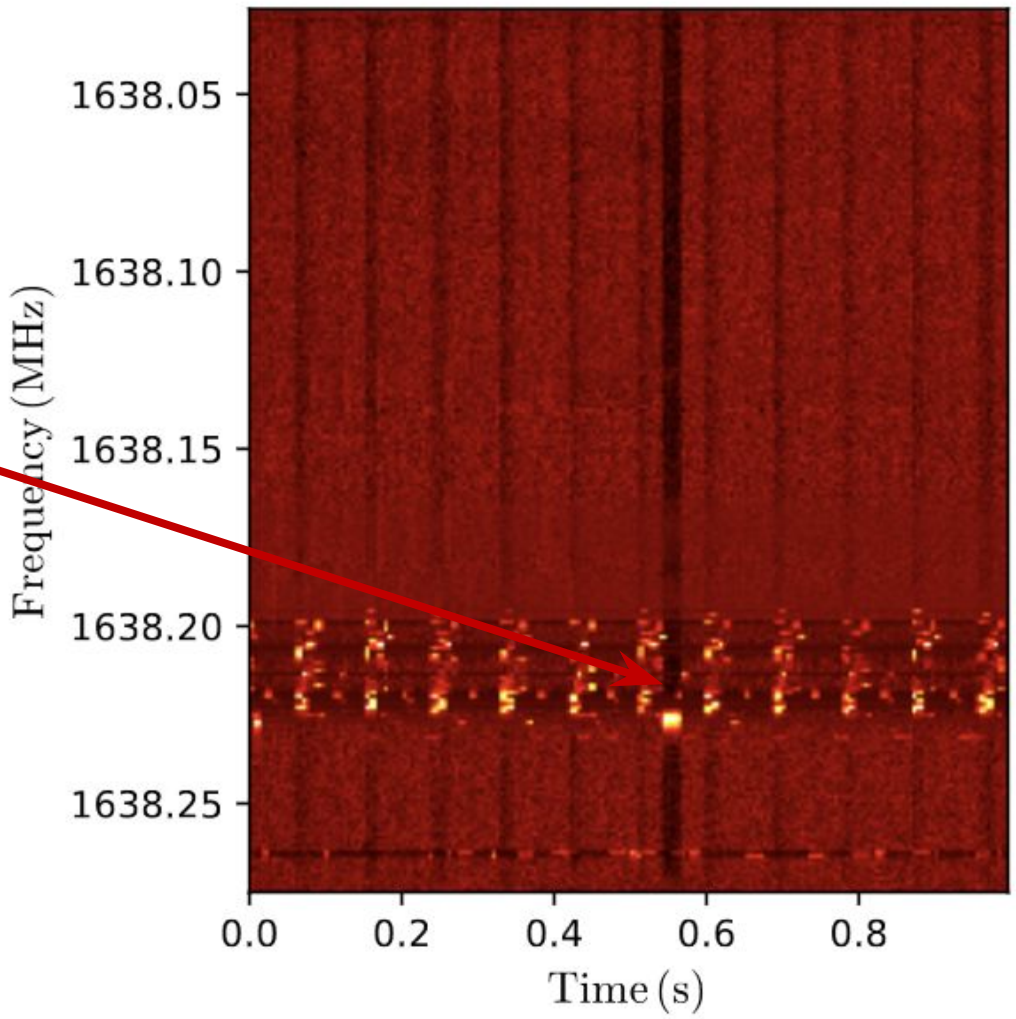
4.2: Data processing

You're seeing radio frequency interference (RFI)

Oversaturated timesamples



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4.2: Data processing

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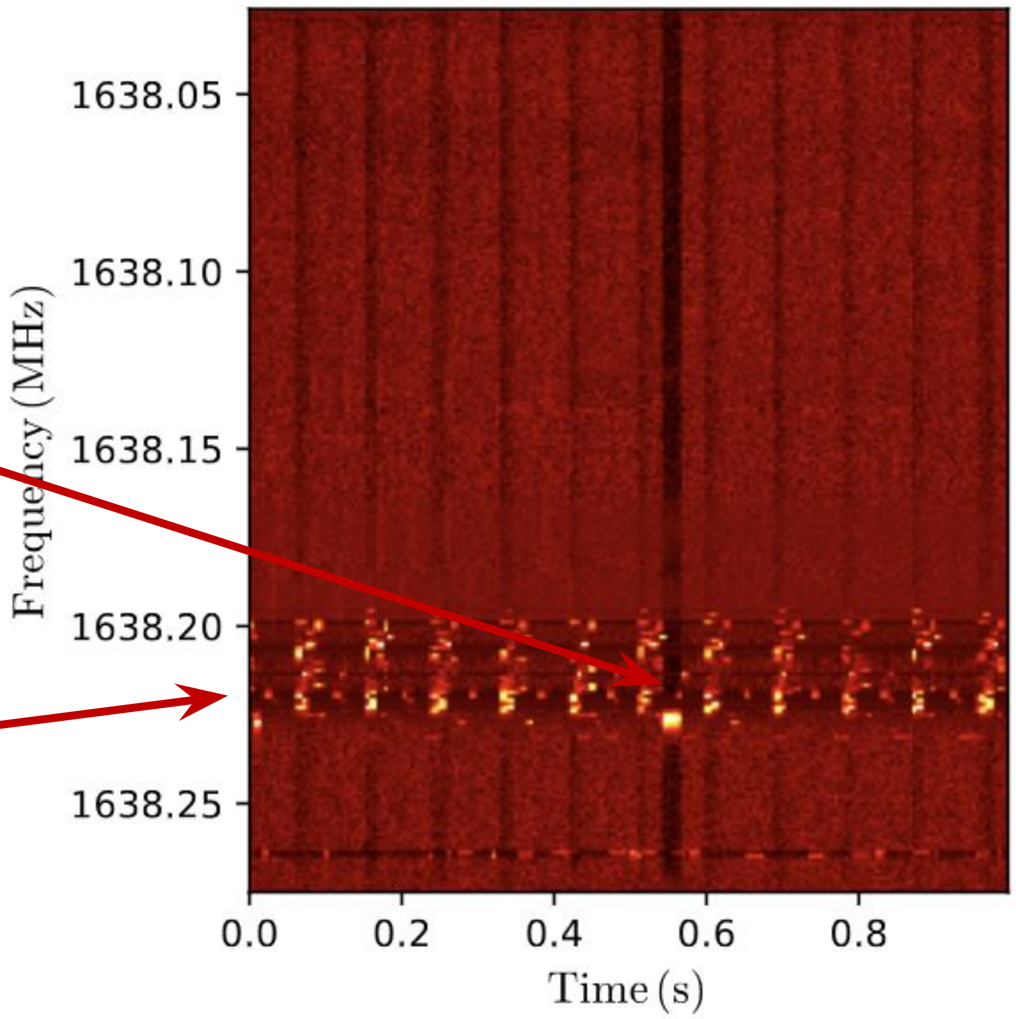
Oversaturated timesamples

Contaminated frequency channels



Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

S1

4.2: Data processing

This RFI is a serious problem!

- Fundamental tenet of radio astronomy: **The radiometer equation** [68,69]

$$S_{\rm min} = \beta \frac{(S/N_{\rm min})\,{\rm SEFD}}{\sqrt{n_{\rm p}\tau\Delta\nu}}.$$

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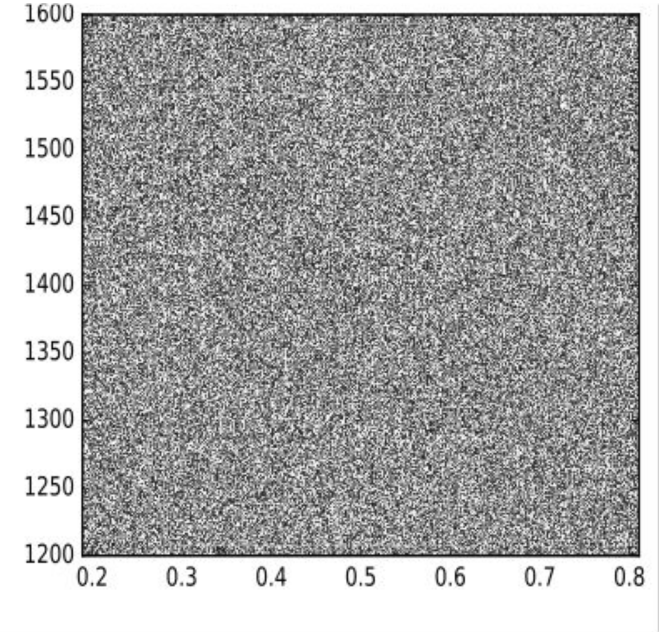
S1

4.2: Data processing

This RFI is a serious problem!

- Fundamental tenet of radio astronomy: **The radiometer equation** [68,69]
  - Assumes that many astronomical radio sources in sky result in a background of **Gaussian random noise**

$$S_{\min} = \beta \frac{(S/N_{\min})\mathrm{SEFD}}{\sqrt{n_p \tau \Delta\nu}}.$$



Credit: [68,69]; Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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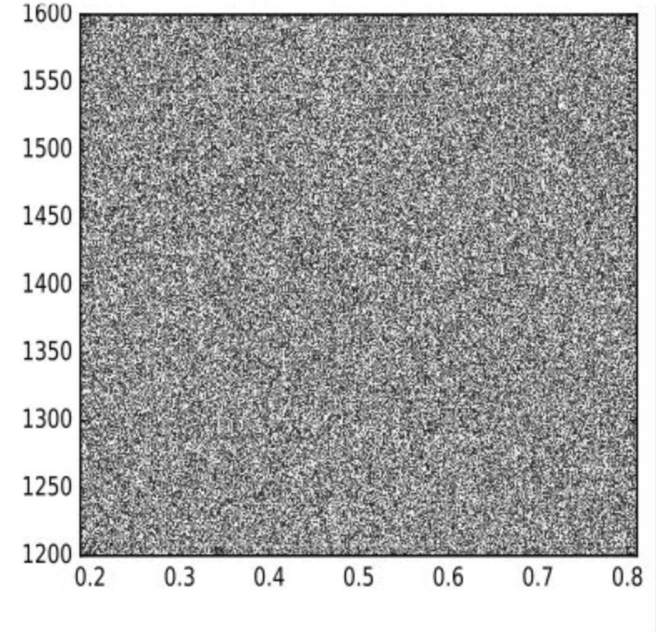
S1

4.2: Data processing

This RFI is a serious problem!

- Fundamental tenet of radio astronomy: **The radiometer equation** [68,69]
  - Assumes that many astronomical radio sources in sky result in a background of **Gaussian random noise**
    - Transient signals **stand out against this noise**

$$S_{\min} = \beta \frac{(S/N_{\min})\mathrm{SEFD}}{\sqrt{n_p \tau \Delta\nu}}.$$



Credit: [68,69]; Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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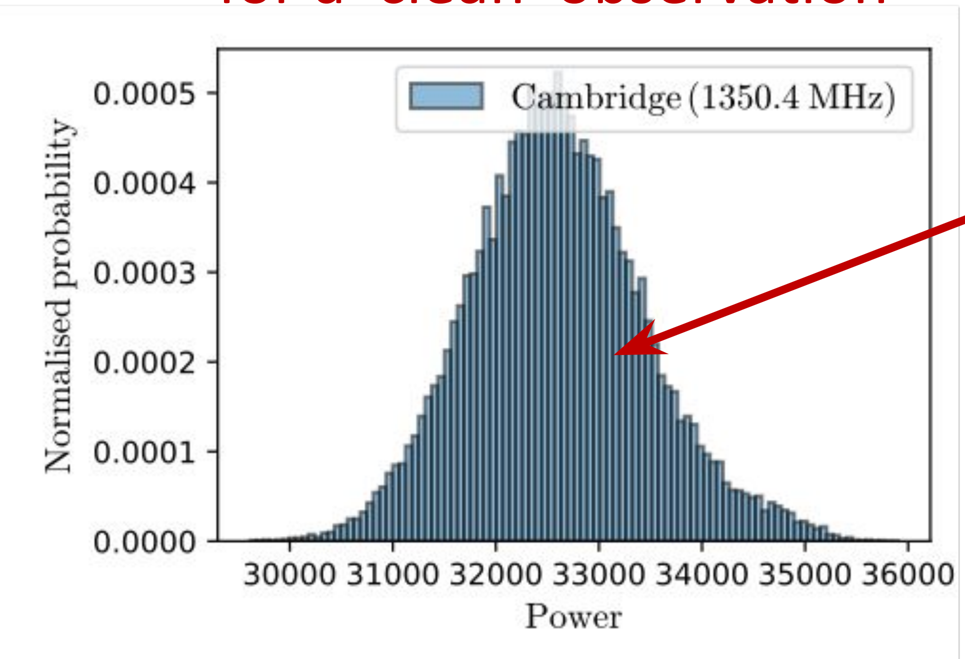
S1

4.2: Data processing

Here's a histogram of some good data...

Example 1: data distribution for a 'clean' observation



Gaussian distribution

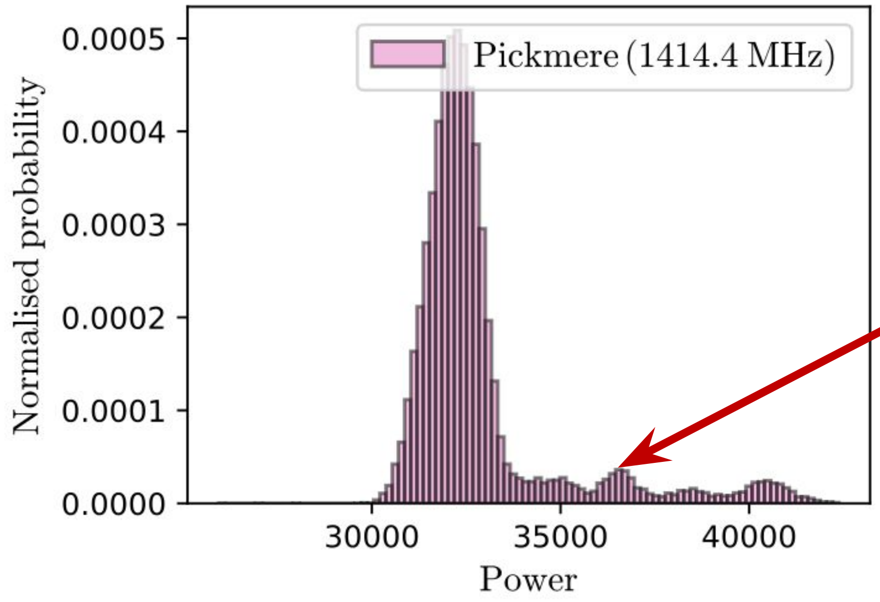
Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

S1

4.2: Data processing

And here's a histogram of some bad data...

Example 2: data distribution for a contaminated observation



Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

Completely non-Gaussian distribution

S1

4.2: Data processing

Unfortunately, this non-Gaussian data is mostly RFI...

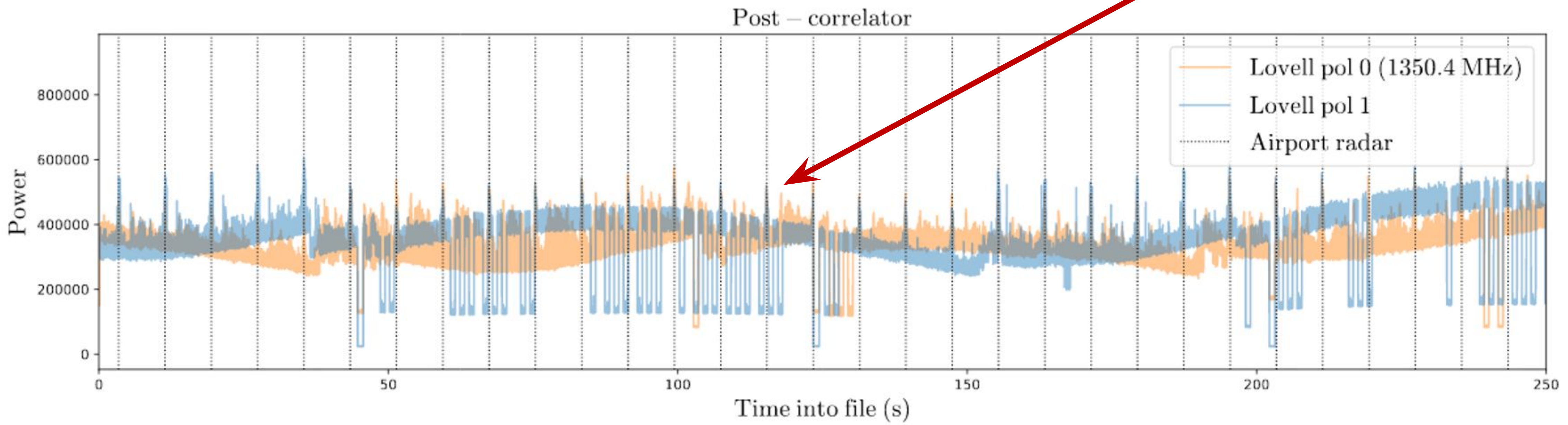
- It comes from **modern technology**
  - E.g. mobile phones, microwave ovens, etc...
  - Can **contaminate, hide, or even mimic** real transients

S1

4.2: Data processing

RFI can even mimic transients!

Example 1: Regular 8-s pulses...



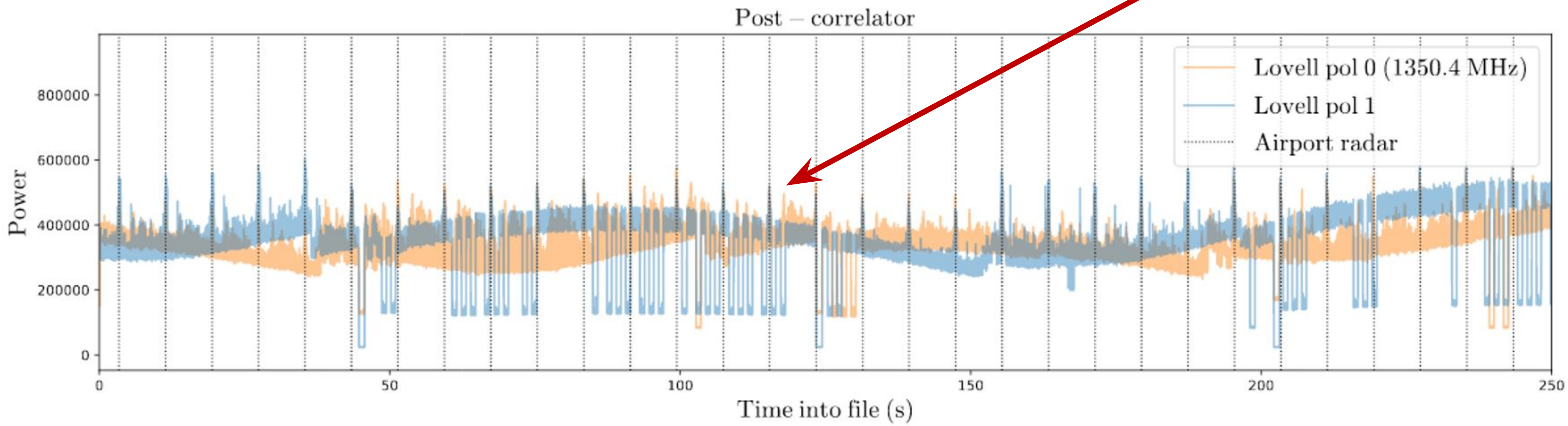
Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

S1

4.2: Data processing

RFI can even mimic transients!

Example 1: Regular 8-s pulses... from airport radar!



Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

S1

4.2: Data processing

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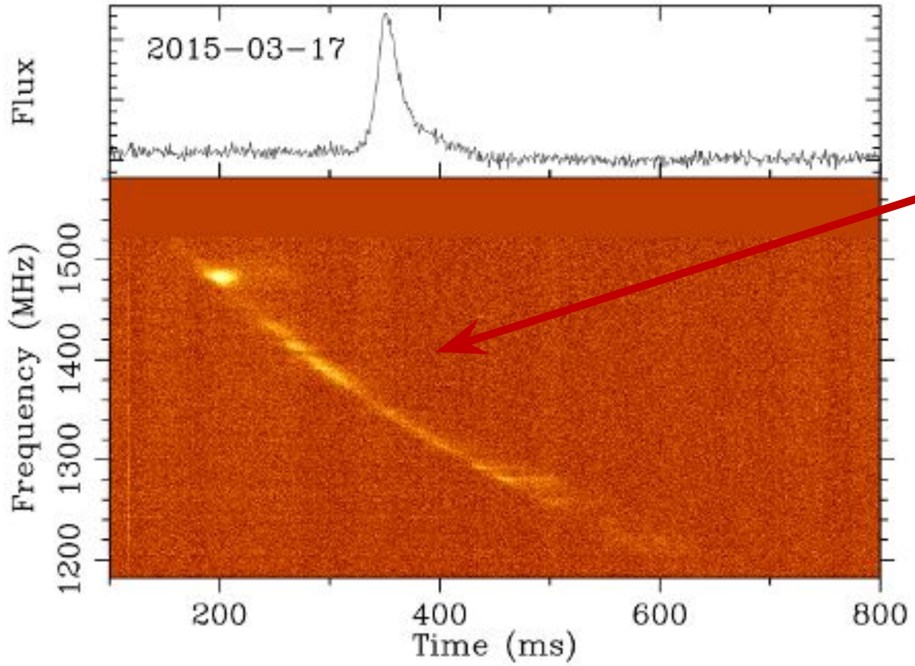

Figure 5. One of the bright perytons generated during the test on 17 March with DM = 410.3 cm^{-3} pc. RFI monitor data at the time of this peryton is shown in Figure 3.

Credit: Petroff et al. (2015) [71]

Example 2:
***Almost*-DM-like sweep...**

S1

4.2: Data processing

RFI can even mimic transients!

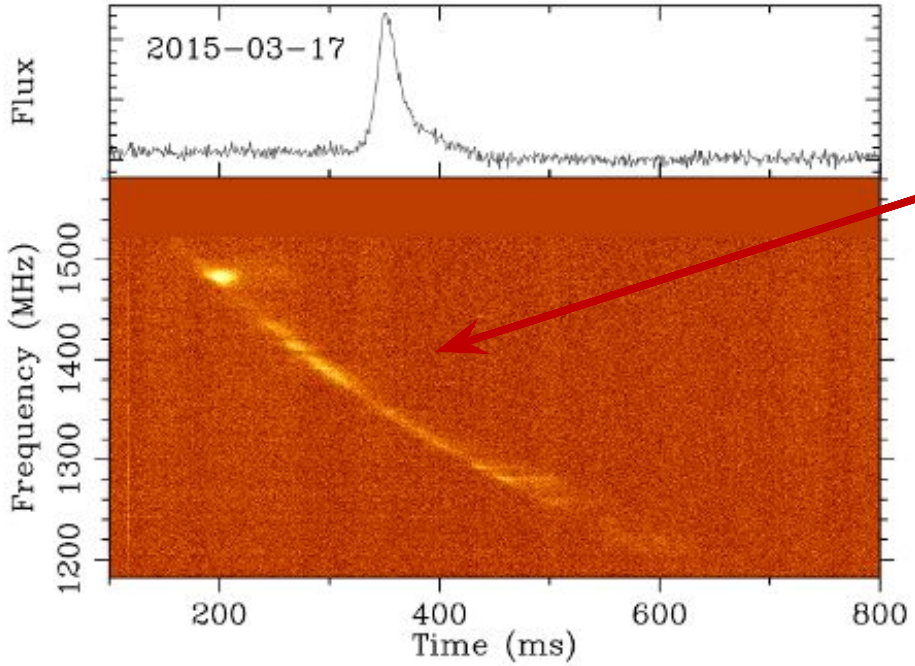

Figure 5. One of the bright perytons generated during the test on 17 March with DM = 410.3 cm^{-3} pc. RFI monitor data at the time of this peryton is shown in Figure 3. *Credit: Petroff et al. (2015) [71]*

Example 2:
***Almost*-DM-like sweep...**
a peryton from a
microwave oven! [70,71]

4.2: Data processing

Why is RFI such a big problem?

- Ultimately, when searching for transients in RFI-contaminated data...
  - **you're left with a mess.**

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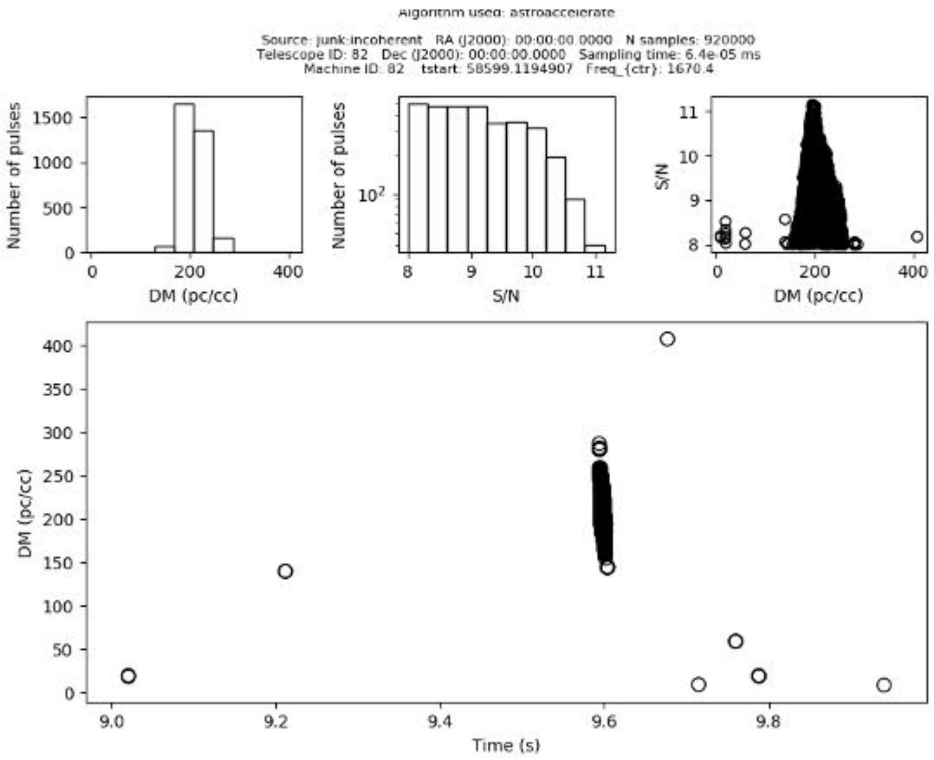
Example 1: A single-pulse search algorithm's output for 'clean' data



4.2: Data processing

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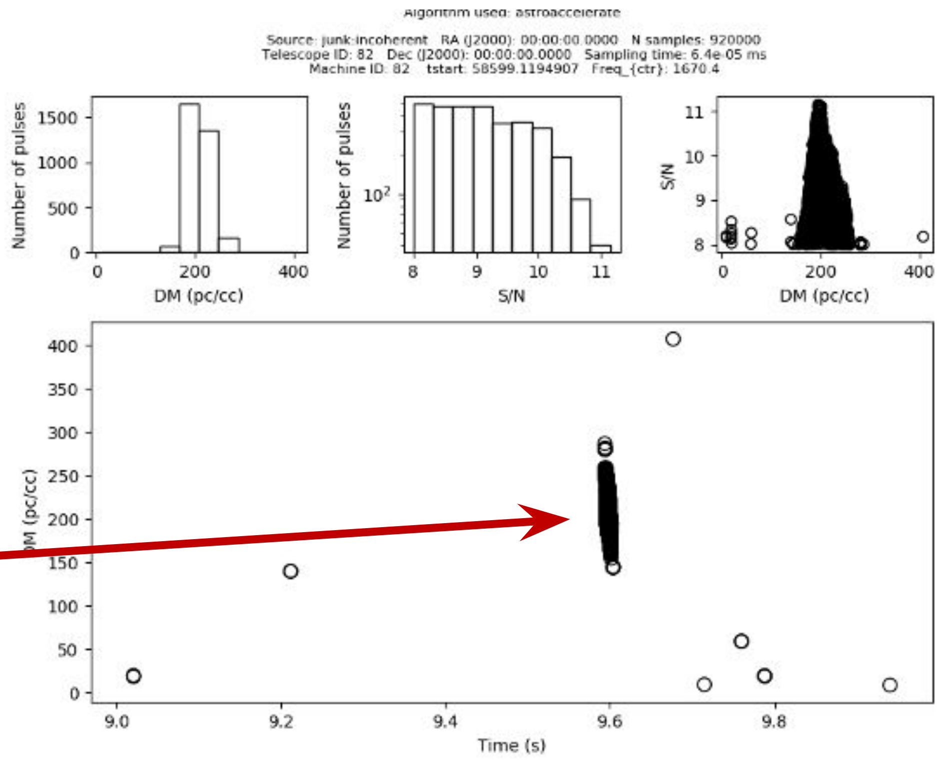

Single pulse detected (DM=200, time=9.6s)

4.2: Data processing

Example 2: A single-pulse search algorithm's output for contaminated data

Why is RFI such a big problem?

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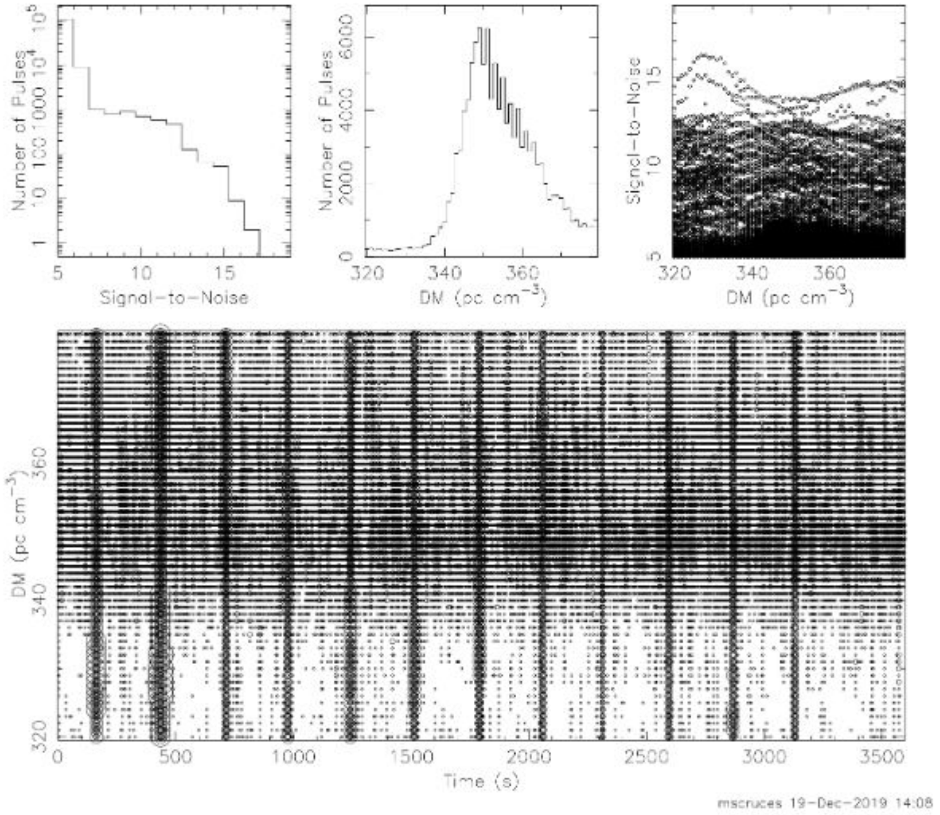

No chance!

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4.2: Data processing

RFI mitigation is a crucial stage of data processing...

- Ideally, **treat the cause**, e.g.:
  - Turn off your mobile phone
  - Put microwave oven in a Faraday cage
    - (and don't open it until it's finished!) [71]
  - Build your telescope somewhere remote...

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4.2: Data processing

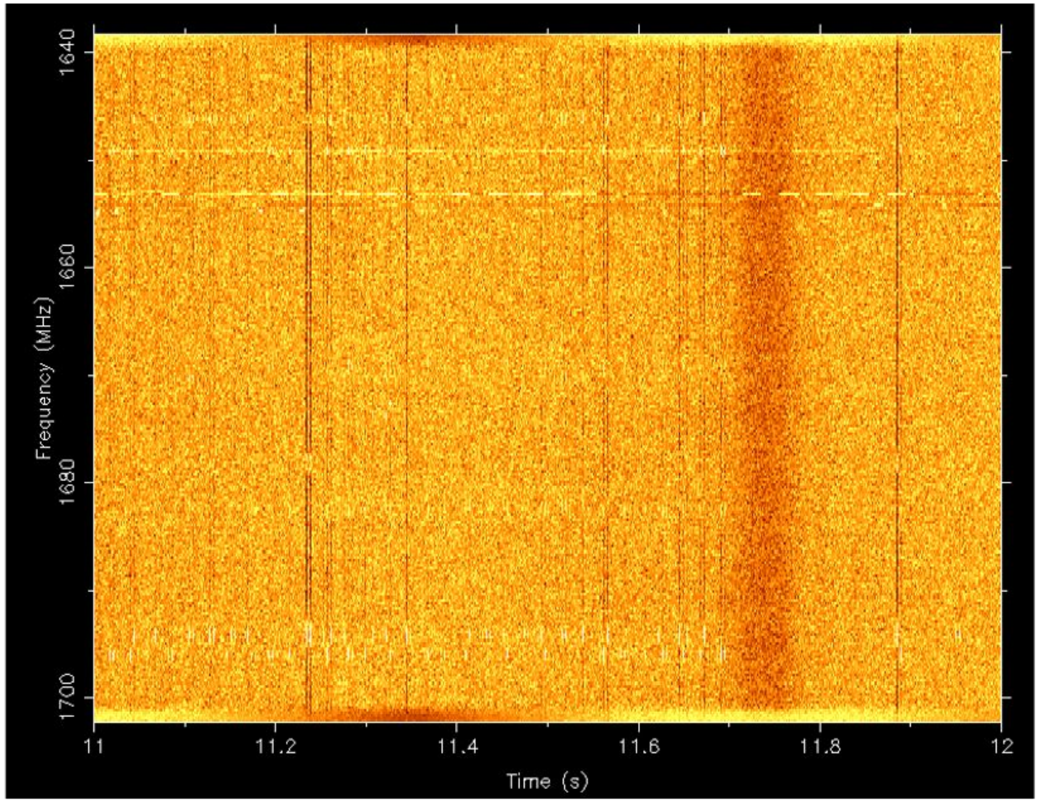
RFI mitigation is a crucial stage of data processing...

- Sometimes you must **treat the symptoms**...
  - e.g. **suppress**, **discard**, or **replace** bad data with something better

S1

4.2: Data processing

There are multiple types of RFI mitigation



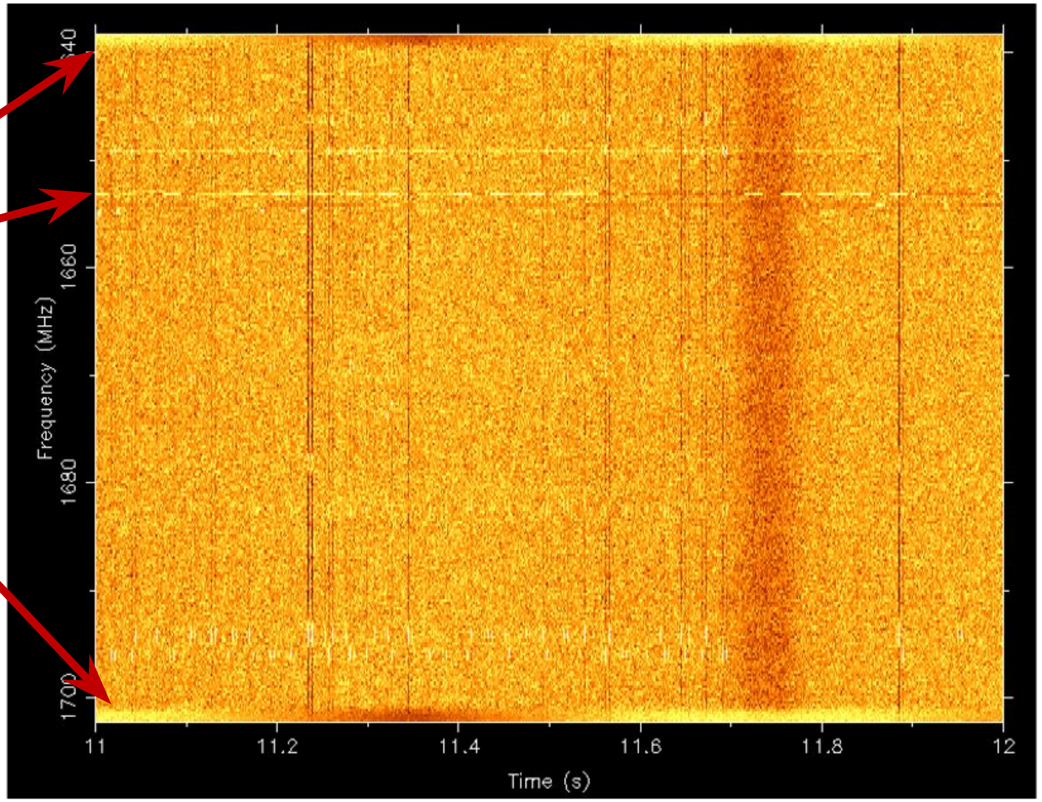
S1

4.2: Data processing

There are multiple types of RFI mitigation

Technique 1: Masking

1) Find contaminated frequency channels
2) Replace bad data (e.g. with random noise)



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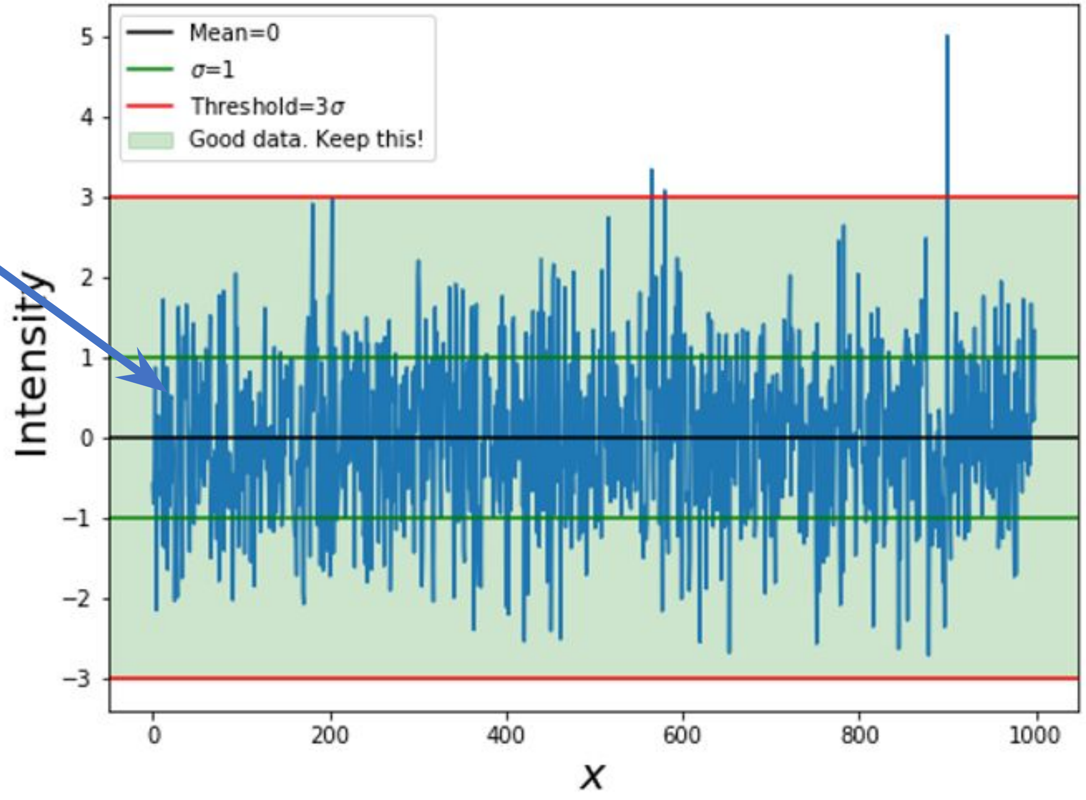
S1

4.2: Data processing

There are multiple types of RFI mitigation

Technique 2: Statistical thresholding

1) Collapse data into a timeseries



S1

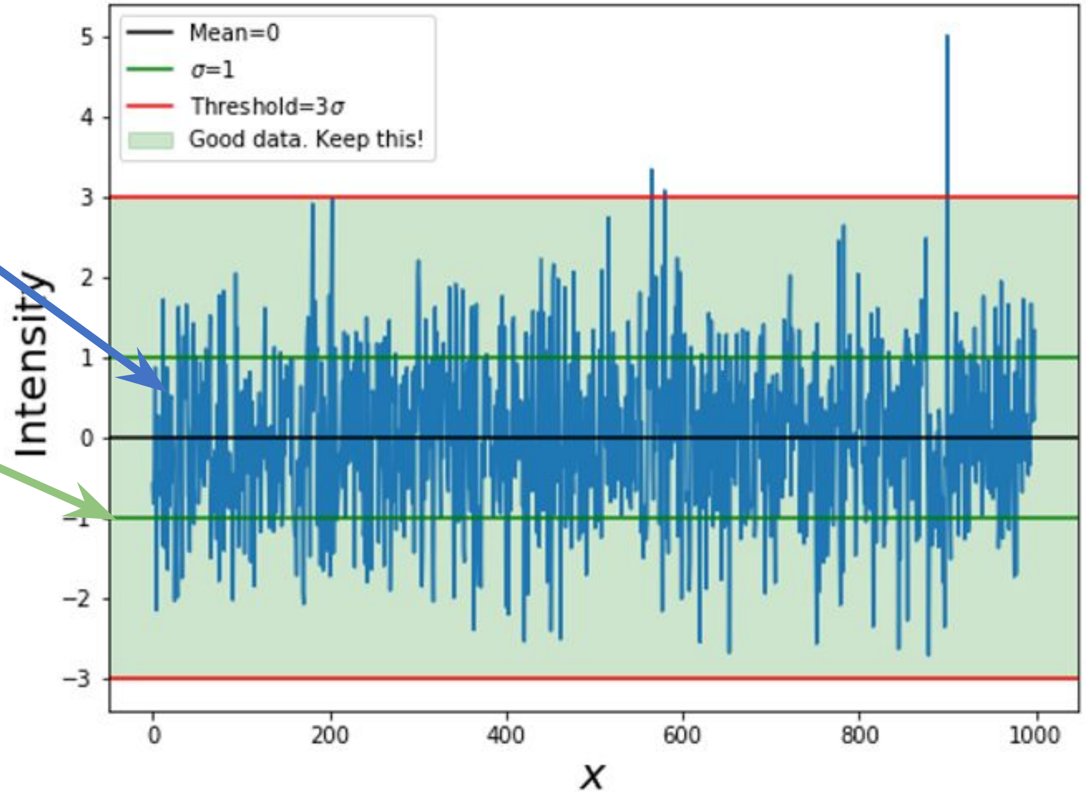
4.2: Data processing

There are multiple types of RFI mitigation

Technique 2: Statistical thresholding

1) Collapse data into a timeseries

2) Calculate a metric for your data (e.g. standard deviation, MAD [72])



S1

4.2: Data processing

There are multiple types of RFI mitigation

Technique 2: Statistical thresholding

1) Collapse data into a timeseries

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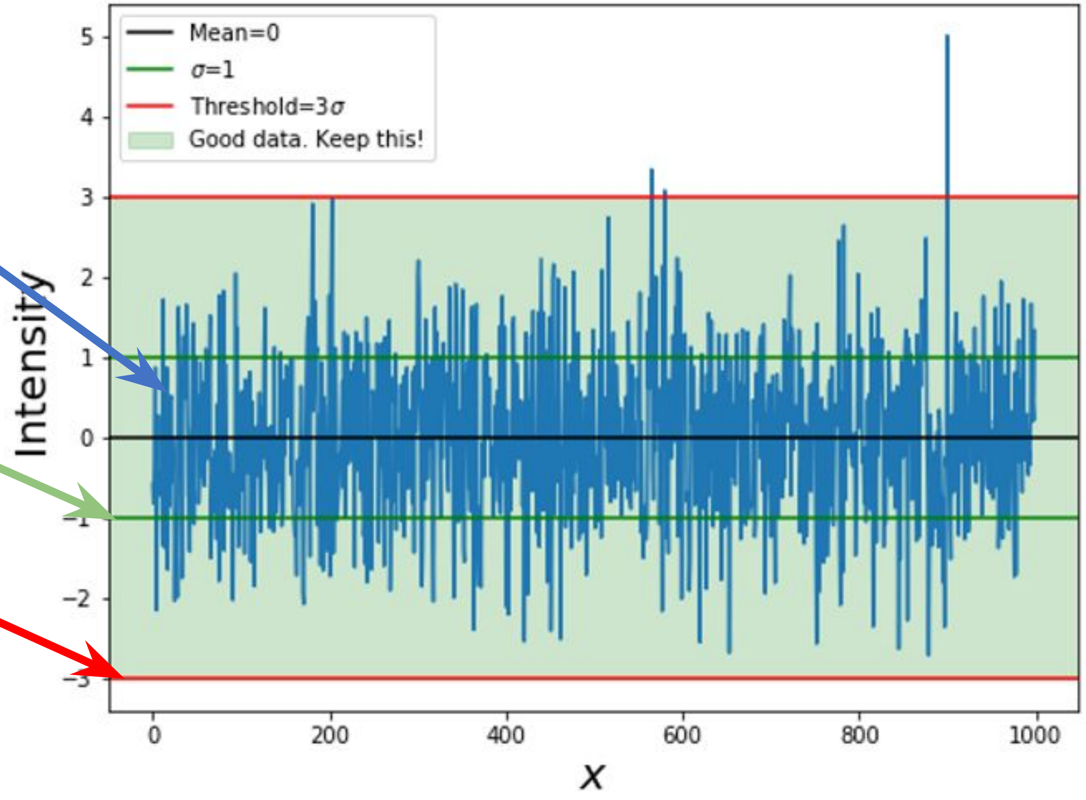


S1

4.2: Data processing

There are multiple types of RFI mitigation

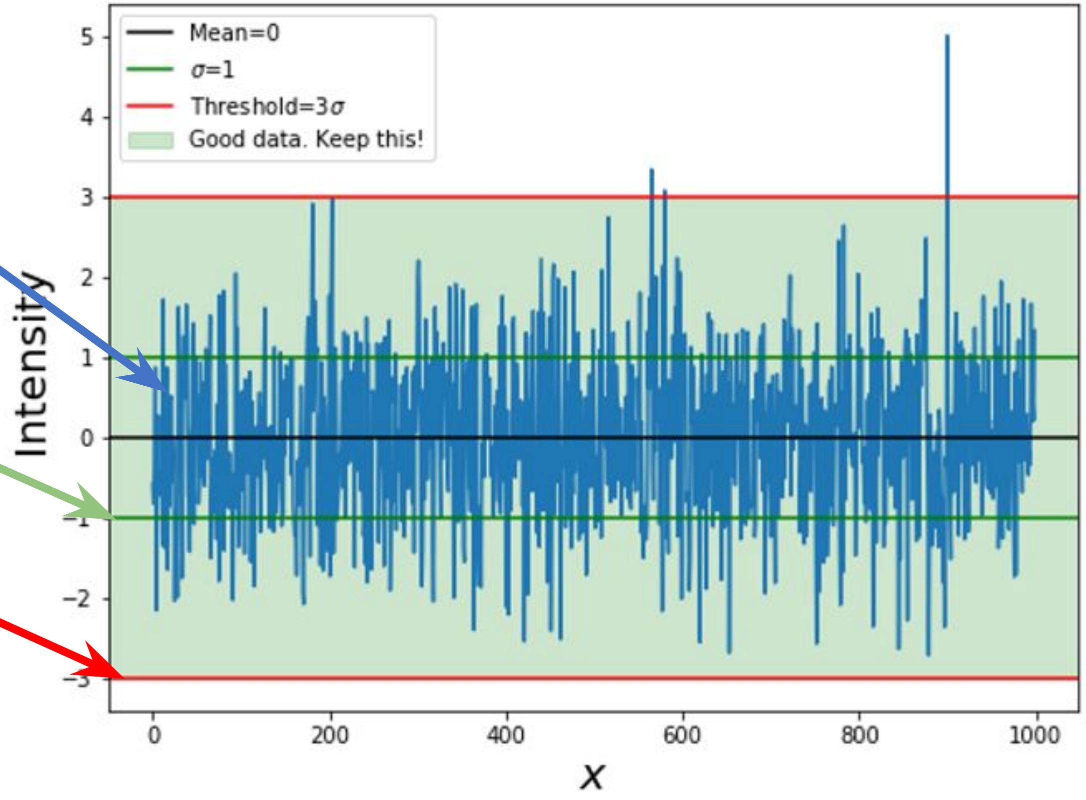
Technique 2: Statistical thresholding

1) Collapse data into a timeseries

2) Calculate a metric for your data (e.g. standard deviation, MAD [72])

3) Define a threshold, above/below which, data is assumed to be RFI

4) Replace bad timesamples!



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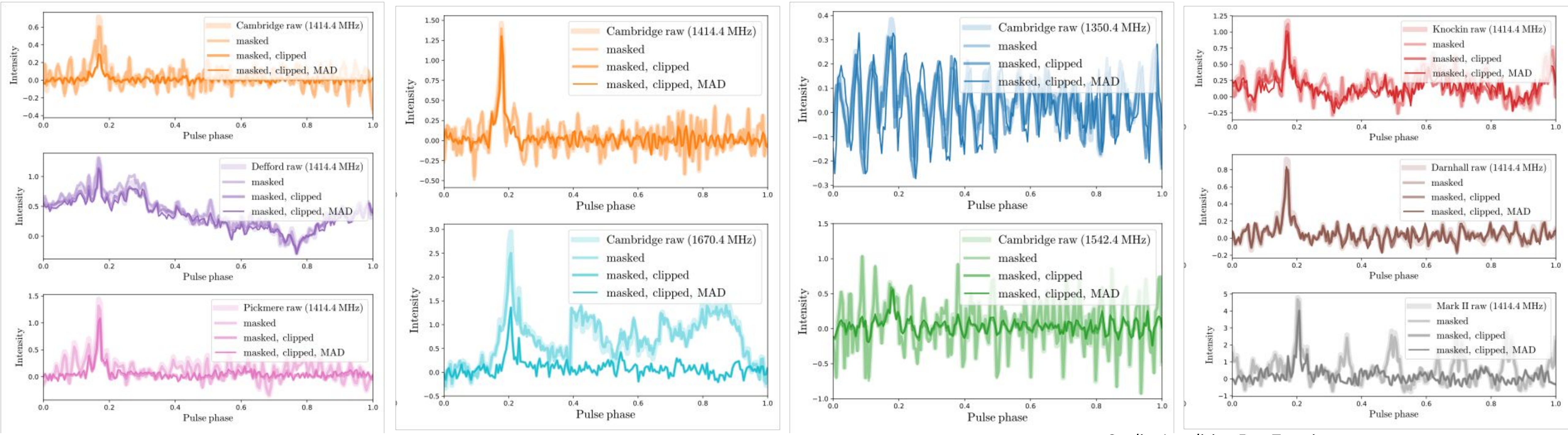
4.2: Data processing

A rogues gallery of RFI mitigation effectiveness on pulsar observations...



Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

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4.2: Data processing

Finally, remember that your data is split across multiple telescopes and sub-bands...

- But your sensitivity to signals increases as a function of both **bandwidth**, **Δv**, and **number of telescopes, N** [69,73-75]

Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

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S1

4.2: Data processing

Finally, remember that your data is split across multiple telescopes and sub-bands...

- But your sensitivity to signals increases as a function of both **bandwidth, $\Delta\nu$**, and **number of telescopes, N** [69,73-75]

Radiometer equation (single dish)

$$S_{\rm min} = \beta \frac{(S/N_{\rm min})\mathrm{SEFD}}{\sqrt{n_p \tau \Delta\nu}}.$$

Radiometer equation (multi-dish, incoherent)

$$S_{\rm min,arr} = \beta \frac{(\mathrm{SNR}_{\rm min})\mathrm{SEFD_i}}{\sqrt{\mathrm{N}}\sqrt{n_p \tau \Delta\nu}}.$$

Radiometer equation (multi-dish, coherent)

$$S_{\rm min,arr} = \beta \frac{(\mathrm{SNR}_{\rm min})\mathrm{SEFD_i}}{\mathrm{N}\sqrt{n_p \tau \Delta\nu}}.$$

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Walker, C. (Author). 1 Aug 2019 [35]

S1

4.2: Data processing

Finally, remember that your data is split across multiple telescopes and sub-bands...

- But your sensitivity to signals increases as a function of both **bandwidth**, **Δv**, and **number of telescopes, N** [69,73-75]

Therefore you should combine your data again to measure faint signals

- (and do more advanced analysis)

C1

4.2: Data processing

Data combination could be challenging!

- For large datasets, what if you have had to **distribute your data** over multiple data centers?
  - This is something the **SKA will have to do**...
    - More in lectures 11, 12

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4.2: Data processing

And another challenge...

- Doing all that processing in **real-time** is hard...
- And it has its pros and cons

What are the pros of real-time processing?

C1 C2

4.2: Data processing

And another challenge...

- Doing all that processing in **real-time** is hard...
- And it has its pros and cons

What are the pros of real-time processing?

- **Save space** by only storing good candidates
- Can send out detection alerts for **prompt, coordinated multi-wavelength follow-up** [76]
  - Do FRBs burst at other wavelengths? In neutrinos or Gravitational Waves? [67,80]
  - **Progenitor implications**!

C1 C2

4.2: Data processing

And another challenge...

- Doing all that processing in **real-time** is hard...
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But what are the pros of keeping all data?

C1 C2

4.2: Data processing

And another challenge...

- Doing all that processing in **real-time** is hard...
- And it has its pros and cons

But what are the pros of keeping all data?

- The **"unknown unknowns"**
  - You aren't **locking yourself out** of future discoveries based on current processing techniques, thresholds
    - Example: the Keane burst was discovered in 2012... in survey data from 2001! [45,77]

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4.3: Candidate analysis

Work doesn't stop after you've cleaned up your data...

- You must still **search for fast transient candidates**!

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4.3: Candidate analysis

Work doesn't stop after you've cleaned up your data...

- You must still **search for fast transient candidates**!

This is also data-intensive...

- You must search over **many variables**:
  - e.g. DM, pulse width, periodicity, acceleration...
- Resulting in a **large parameter space**...

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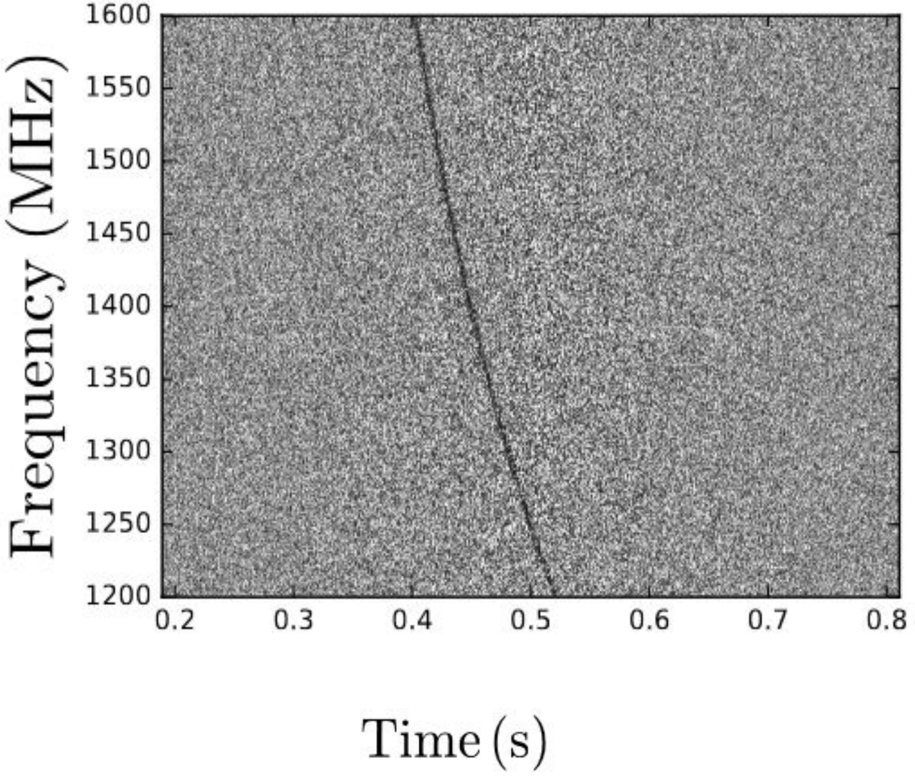
4.3: Candidate analysis

Let's start with dedispersion...

4.3: Candidate analysis

Let's start with dedispersion...

- As previously discussed, dispersion is great for **studying baryons** in the Universe...



$$\mathrm{DM_{obs}} = \mathrm{DM_{MW}} + \mathrm{DM_{cosmic}} + \mathrm{DM_{host}} + \mathrm{DM_{local}}$$

Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

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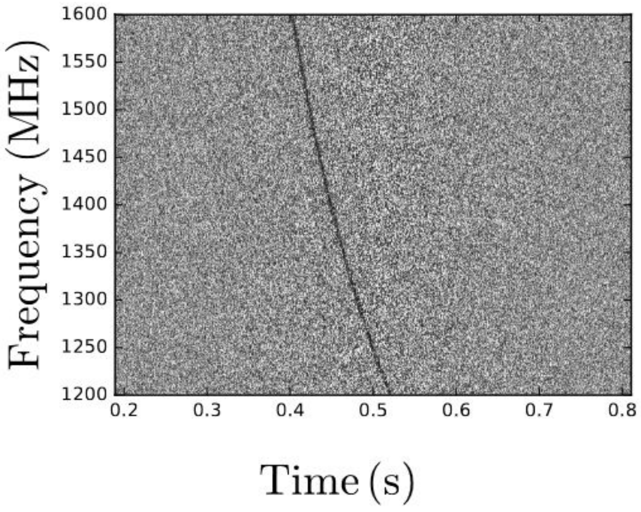
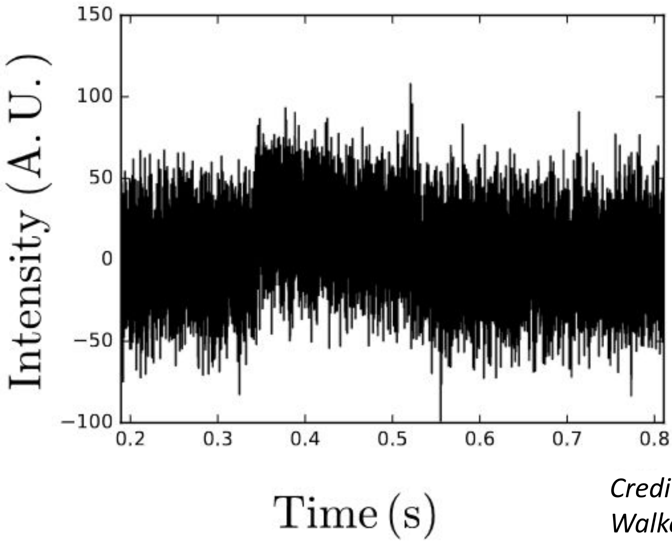
4.3: Candidate analysis

Let's start with dedispersion...

- But dispersion also **smears out a burst's power** in timeseries data



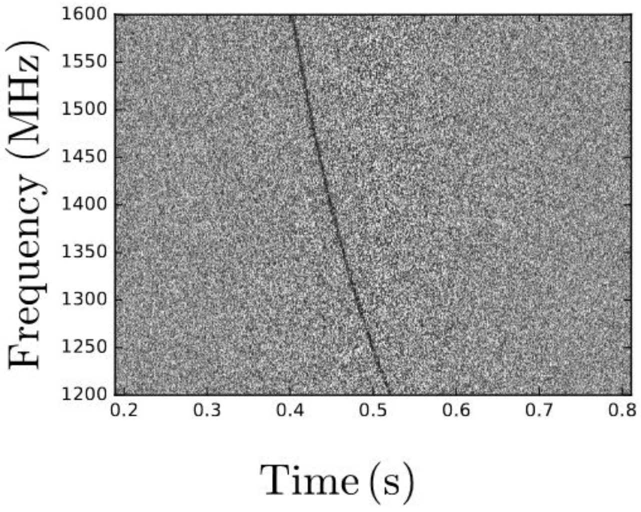


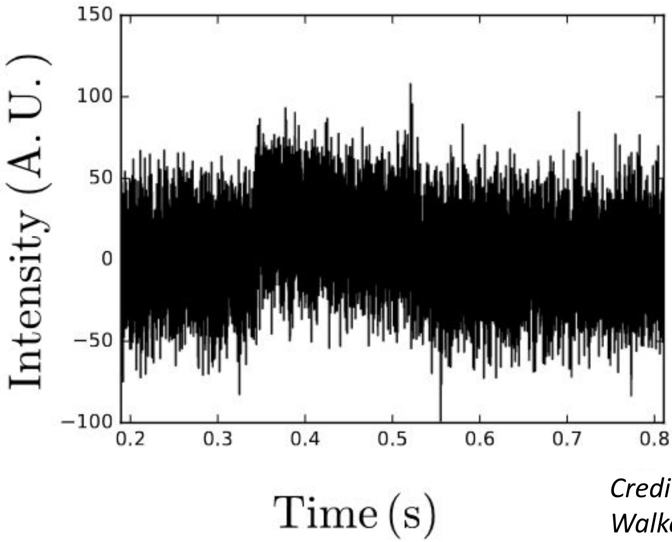
Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

4.3: Candidate analysis

Let's start with dedispersion...

- But dispersion also **smears out a burst's power** in timeseries data
  - Leaving it more difficult to detect
    - Sometimes **below detection thresholds**!



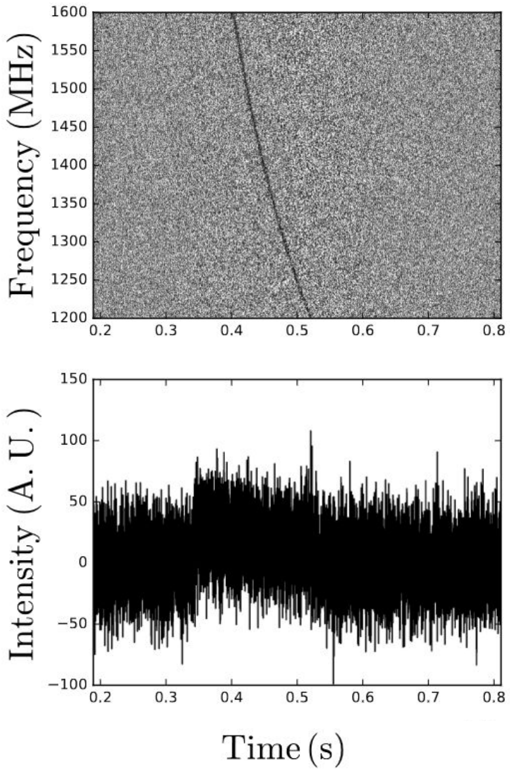


Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

4.3: Candidate analysis

You can undo this effect using dedispersion...

1) **Take dispersed pulse**



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4.3: Candidate analysis

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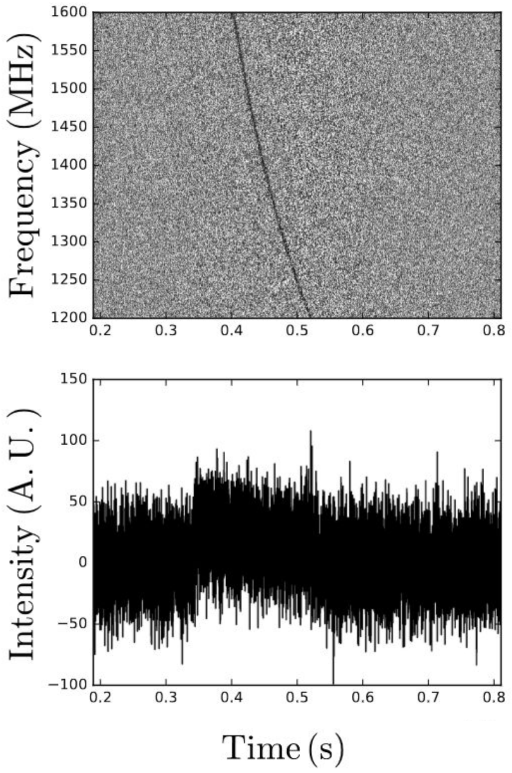


2) Apply time shifts to each frequency channel...

$$\Delta t = \frac{1}{2.41 \times 10^{-16}} \times (\nu_1^{-2} - \nu_2^{-2}) \times \mathrm{DM},$$

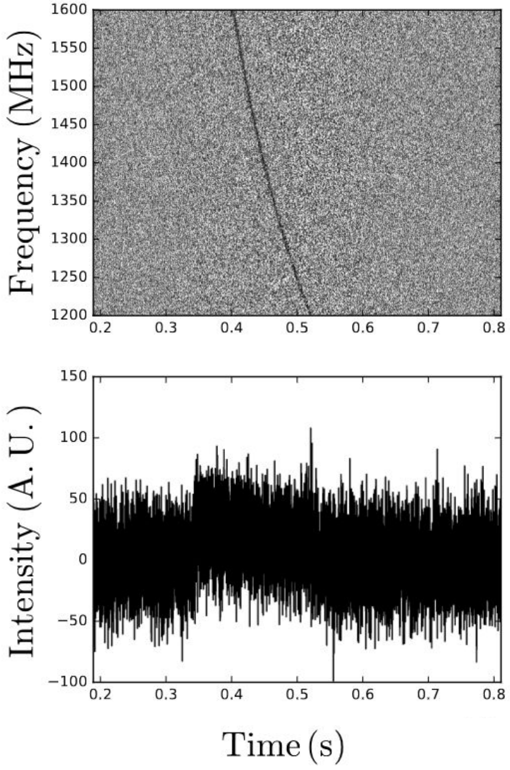
The dispersion measure, DM

Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

4.3: Candidate analysis

You can undo this effect using dedispersion...

1) Take dispersed pulse



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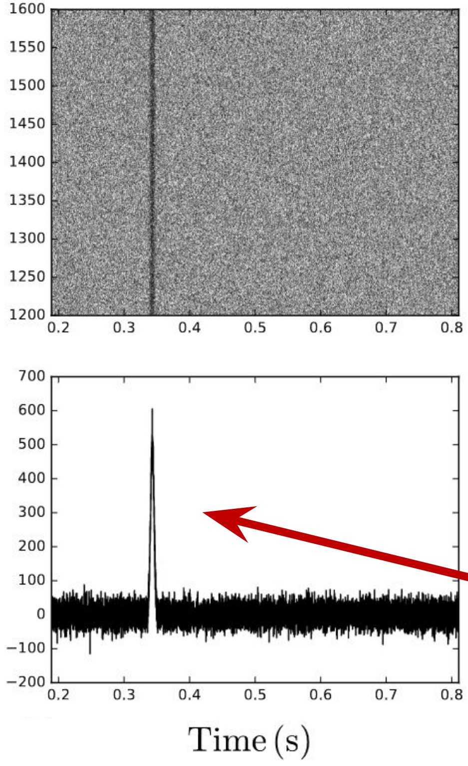
$$\Delta t = \frac{1}{2.41 \times 10^{-16}} \times (\nu_1^{-2} - \nu_2^{-2}) \times \mathrm{DM},$$

The dispersion measure, DM

3) Get de-dispersed pulse



easier to detect!

Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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4.3: Candidate analysis

To do this properly, you need to know your source's DM!

- Studying a **known source**?
  - **DM is known**.
- But what if you're searching for **new sources**?

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4.3: Candidate analysis

To do this properly, you need to know your source's DM!

- Studying a **known source**?
  - **DM is known**.
- But what if you're searching for **new sources**?
  - You must search over a **DM range**!

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4.3: Candidate analysis

The problem: Transients can have many dispersion measures...

4.3: Candidate analysis

Distance scale:
Nearest star: 1.3 pc [a]
Width of MW: 30 kpc [b]
Comoving dist. to z=2.1: 5400 Mpc [c]

The problem: Transients can have many dispersion measures...

- Nearby pulsar PSR J1744-3933:
    - D~100 pc, not much matter on sightline
    - **DM = 2 pc/cc** [78]

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4.3: Candidate analysis

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- Nearby pulsar PSR J1744-3933:
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  - Lots of matter along sightline
  - **DM = 1700 pc/cc** [79]

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4.3: Candidate analysis

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- Nearby pulsar PSR J1744-3933:
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  - **DM = 2 pc/cc** [78]
- Galactic center pulsar PSR J1447-2900:
  - Lots of matter along sightline
  - **DM = 1700 pc/cc** [79]
- High-redshift (z~2.1) FRB 160102:
  - **DM = 2600 pc/cc** [80]

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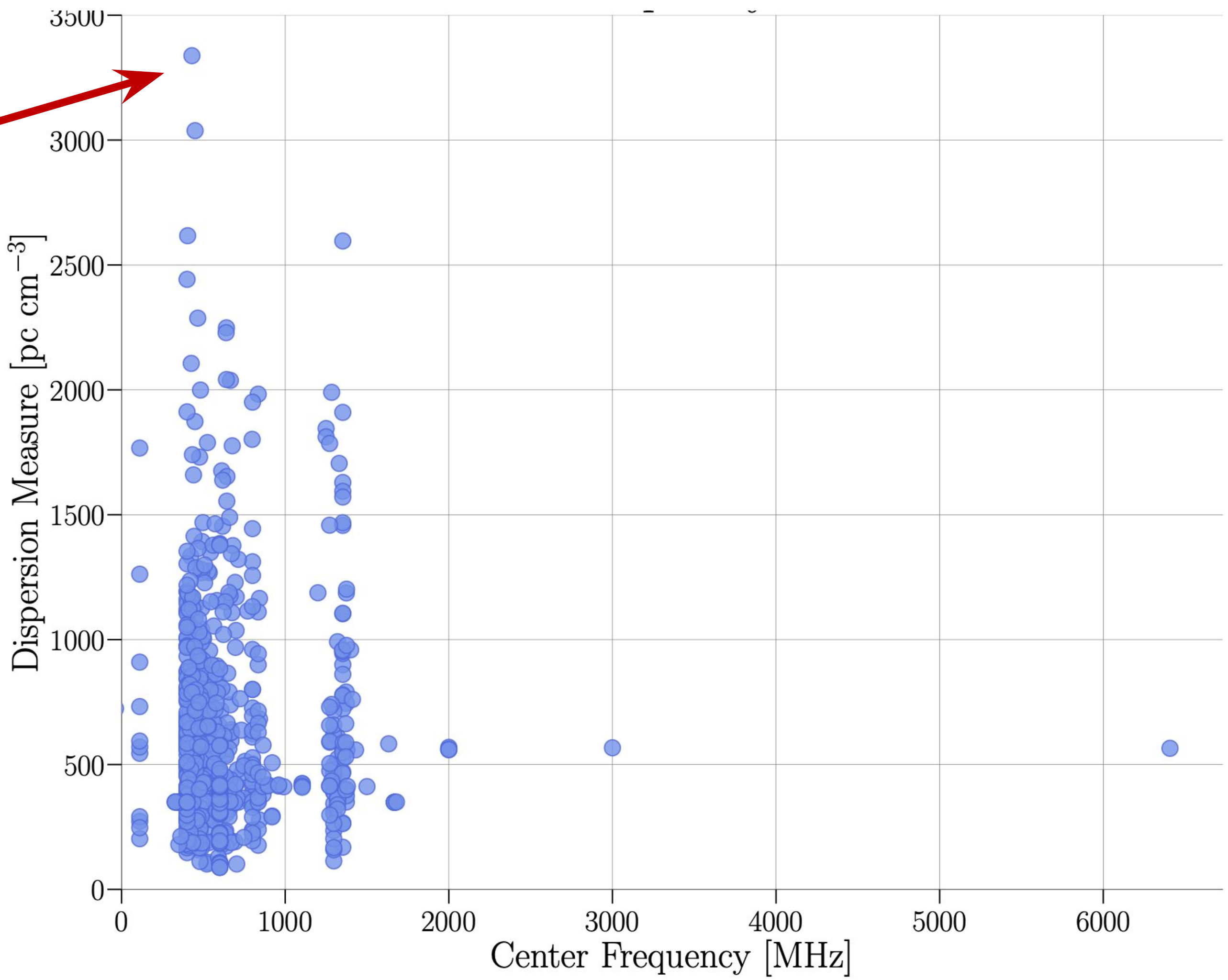
4.3: Candidate analysis

The DM distribution of detected FRBs goes up over 3000!

(and counting)



Credit: FRBSTATS, Spanakis-Misirlis et al. (2021) [48]

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4.3: Candidate analysis

So when searching, you must trial many DMs...

- But you **can't search every DM**, or you'd be wasting computing resources
  - **Optimising DM trials** is important
    - Must account for min, max DM searched, DM step sizes, etc...
    - See [30,81] for details on algorithms, computational costs

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4.3: Candidate analysis

DM is not the only thing to consider during searches...

- **Pulse width** is also important!
  - Because many single-pulse search algorithms use **matched filtering**...

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4.3: Candidate analysis

In matched filtering, timeseries is convolved with a boxcar kernel...

Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

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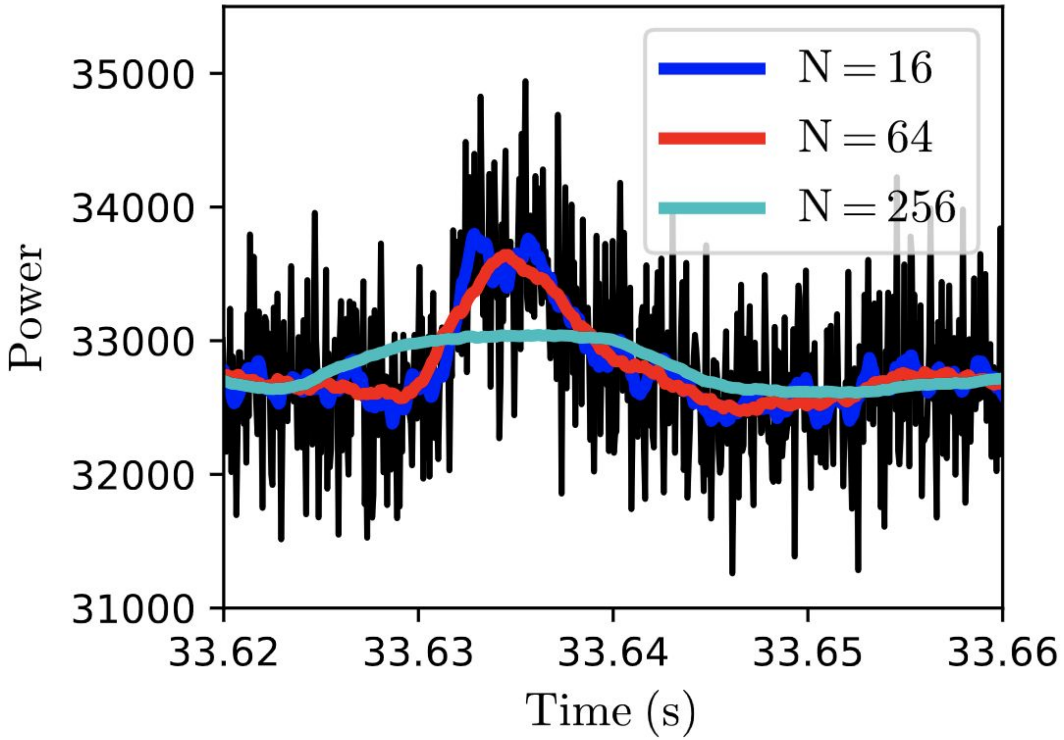
4.3: Candidate analysis

In matched filtering, timeseries is convolved with a boxcar kernel...

- Result: a **time-moving average** of data

Data convolved with multiple boxcars



Credit: Localising Fast Transients
Walker, C. (Author). 1 Aug 2019 [35]

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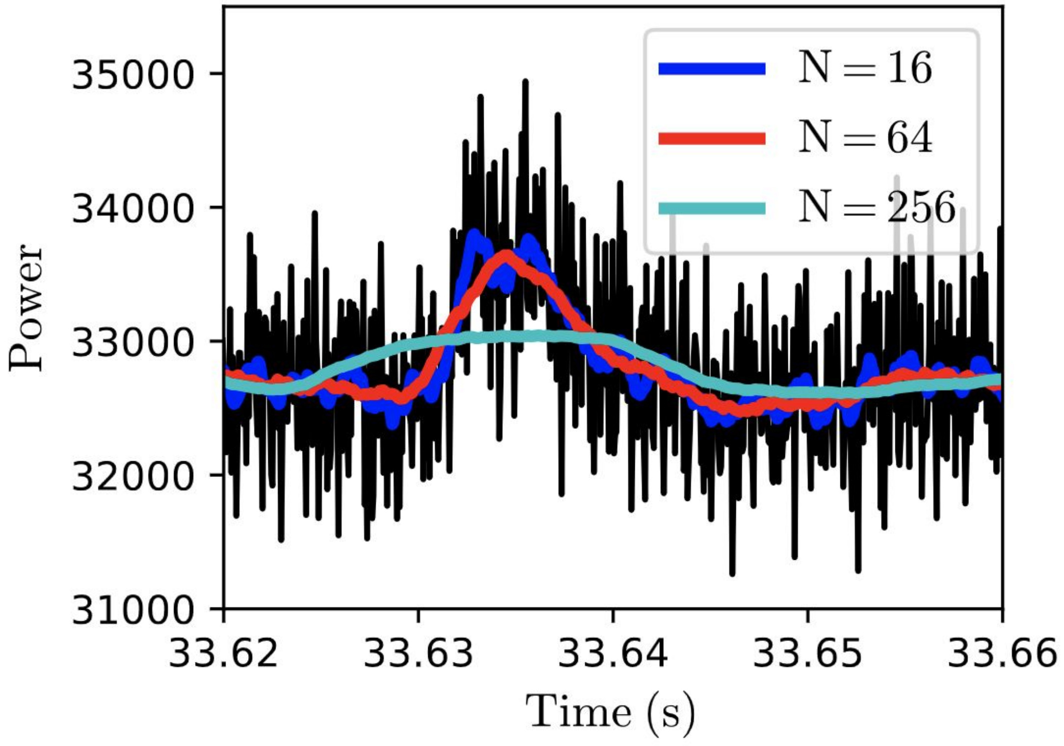
4.3: Candidate analysis

In matched filtering, timeseries is convolved with a boxcar kernel...

- Result: a **time-moving average** of data
  - S/N is maximised when the **boxcar is the same width** as the pulse
    - (b/c you average noise with noise, and signal with signal)

Data convolved with multiple boxcars



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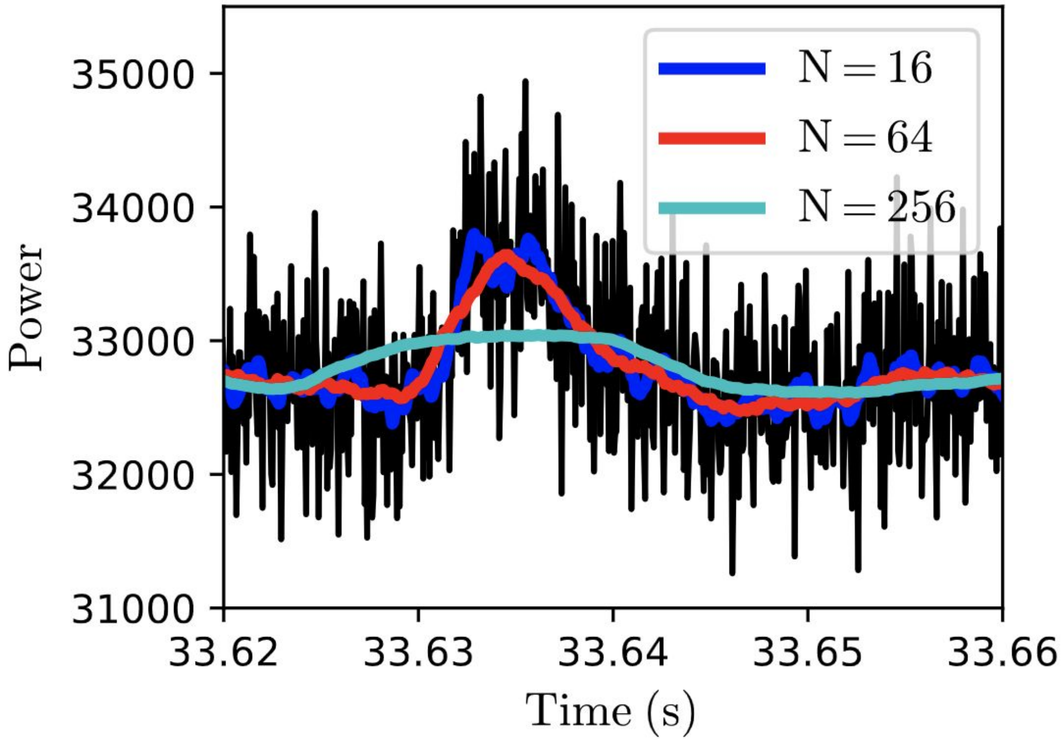
4.3: Candidate analysis

In matched filtering, timeseries is convolved with a boxcar kernel…

- Result: a **time-moving average** of data
  - S/N is maximised when the **boxcar is the same width** as the pulse
    - (b/c you average noise with noise, and signal with signal)
  - If your boxcar is **too small** or **too large** S/N is reduced
    - (b/c you mix noise into your signal)

Data convolved with multiple boxcars



Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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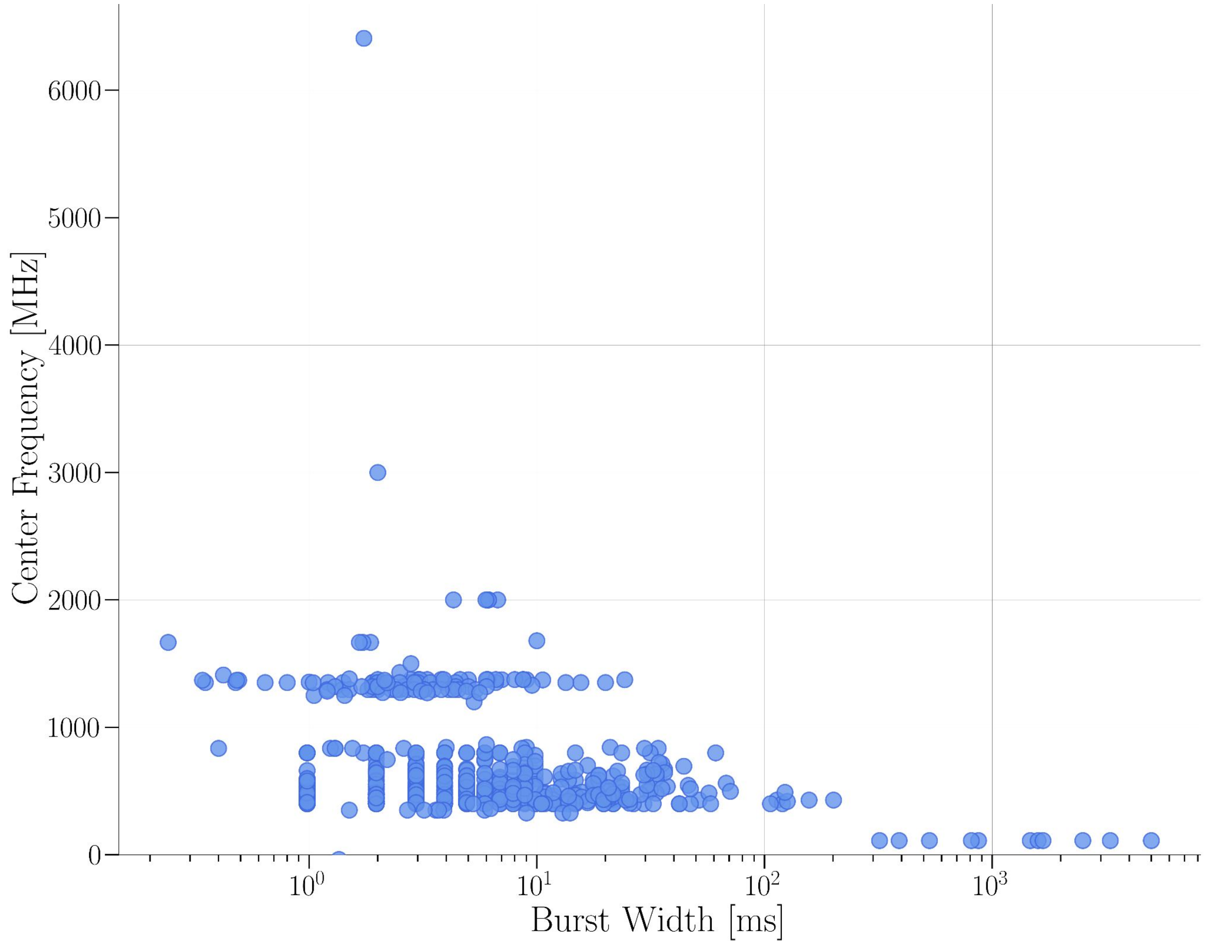
4.3: Candidate analysis

Just as with DMs, pulses can take many different shapes!

- Thus you must also **trial many widths**...
  - Parameter space to search is adding up!

The pulse-width distribution of detected FRBs



Credit: FRBSTATS, Spanakis-Misirlis et al. (2021) [48]

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4.3: Candidate analysis

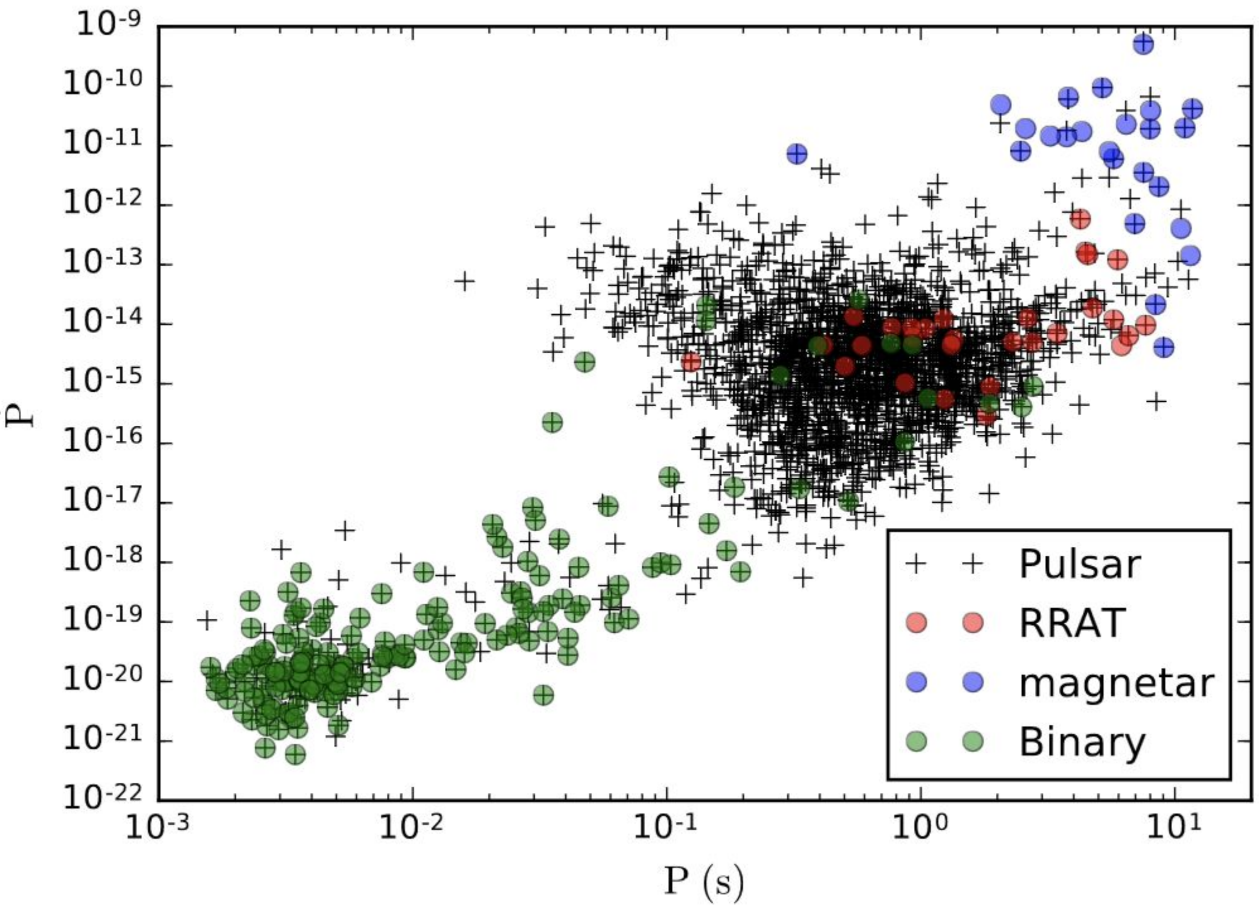
Similar story for repeating sources...

- Unlike FRBs & RRATs, **pulsars aren't usually bright enough** to be discovered in single pulses
  - Thus you must consider **pulse periods**...

4.3: Candidate analysis

Pulsars have many periods!

- As shown in **p-pdot** diagram



Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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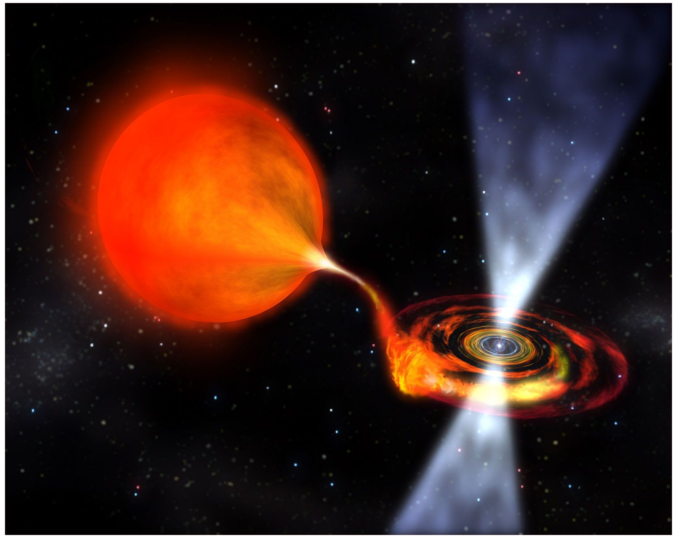
4.3: Candidate analysis

And if a pulsar is in a relativistic binary system...

- The **acceleration of the system** must be accounted for searching
  - Thus you must also **trial many accelerations** during a search
    - See, e.g. Ransom et al. (2002) [82]



Credit: Dana Berry/NASA Goddard Space Flight Center [32]

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4.3: Candidate analysis

There are many algorithms and software designed for pulsar and FRB searching...

- Software includes:
  - PRESTO [83], SEEK [84], DESTROY [85], Heimdall [86], transientx [87]...

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4.3: Candidate analysis

There are many algorithms and software designed for pulsar and FRB searching...

- Software includes:
  - PRESTO [83], SEEK [84], DESTROY [85], Heimdall [86], transientx [87]...

Increasingly, efficient GPU-based software is being developed...

- Software includes:
  - FDAS (acceleration) [88,89], AstroAccelerate (single pulse) [90]...
  - Which allow the previously mentioned **real-time processing** and **rapid follow up**

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4.3: Candidate analysis

There's another problem with searching a large parameter space... what is it?

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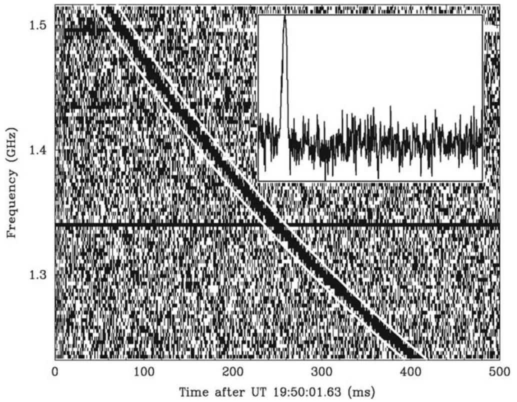
4.3: Candidate analysis

There's another problem with searching a large parameter space...

- You end up with **MANY candidates**!
- Some **real sources**
  - And some **redetections** at slightly different DMs, widths, periods, accelerations...



Credit: Lorimer et al. (2007) [18]

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There's another problem with searching a large parameter space...

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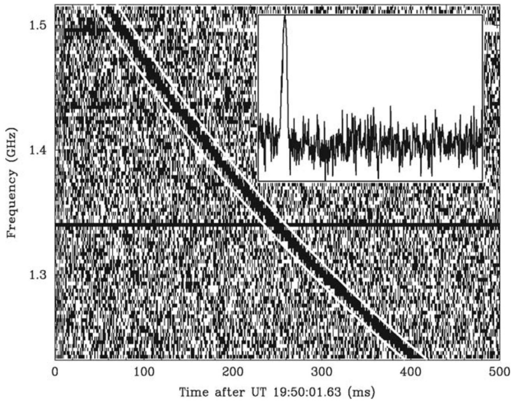
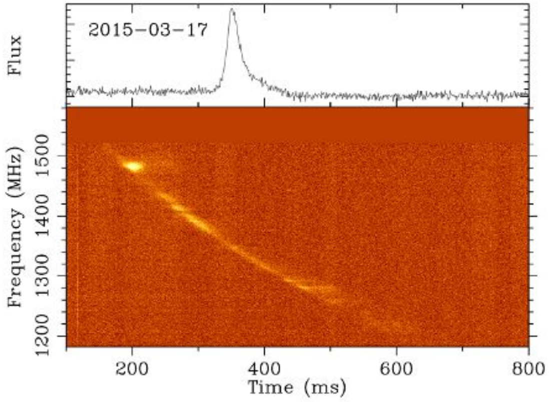


Credit: Lorimer et al. (2007) [18]



Credit: Petroff et al. (2015) [71]

4.3: Candidate analysis

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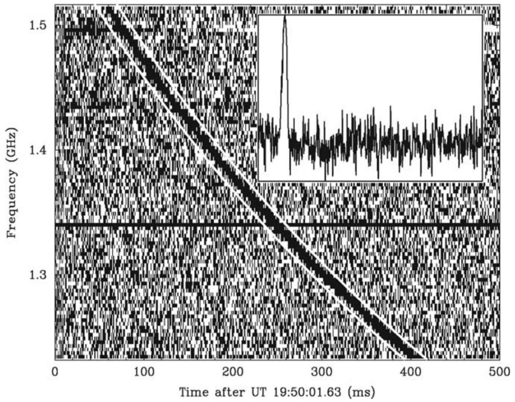

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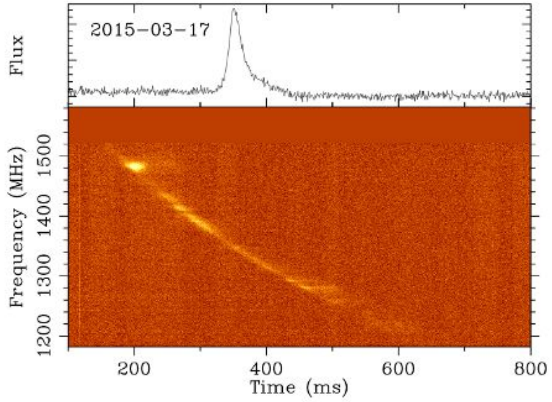

Credit: Petroff et al. (2015) [71]

All these must be sifted through!

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4.3: Candidate analysis

Historically, you'd have to sift by eye...

- This is **time-consuming** (& **impractical** for large modern datasets)
  - But **alternatives** are being developed...

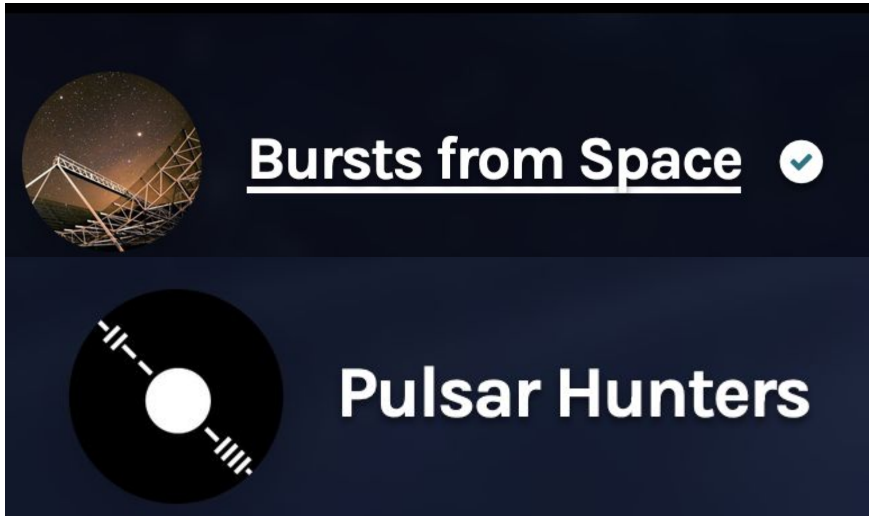
M1 M2

4.3: Candidate analysis

Historically, you'd have to sift by eye...

- This is **time-consuming** (& **impractical** for large modern datasets)
  - But **alternatives** are being developed...

Alternative 1: Citizen Science -- Many eyes on large datasets [91]



Alternative 2: Machine Learning to identify real signals [92,93]

FETCH: A deep-learning based classifier for fast transient classification

Devansh Agarwal[1,2★†] Kshitij Aggarwal,[1,2★†] Sarah Burke-Spolaor,[1,2] Duncan R. Lorimer[1,2] and Nathaniel Garver-Daniels[1,2]

[1]*Department of Physics and Astronomy, West Virginia University, P. O. Box 6315, Morgantown, WV 26506, USA*
[2]*Center for Gravitational Waves and Cosmology, West Virginia University, Chestnut Ridge Research Building, Morgantown, WV 26506, USA*

Credit: Agarwal et al. (2020) [93]

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Part 5: Time-domain in the SKA era

Now we've overviewed the fundamentals of time-domain radio astronomy...

- **Q: Where does the SKA fit in?**

5.1: Recap: time-domain observatory requirements

5.2: Summary: the SKA data challenge

5.3: Conclusion

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5.1: Time-domain requirements

In Part 1 we discussed some technical requirements for a time-domain observatory...

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- Fast transients are **rare**:
  - Detection requires great **sensitivity**
- We want to **localise them** to maximise science:
  - requires good **angular resolution**
- Their signals are **short**:
  - requires **high time-resolution** observations

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  - requires good **angular resolution**
- Their signals are **short**:
  - requires **high time-resolution** observations

We've picked up other requirements too...

- We want to study **fine temporal/spectral features**:
  - requires **fast sampling** (Nyquist frequency)
- We want to **follow-up events promptly**:
  - requires **real-time** processing and alerts
- We want to store data, but **not get overwhelmed**:
  - by large data volumes and candidate numbers

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5.1: Time-domain requirements

You can get good sensitivity from big dishes...

5.1: Time-domain requirements

You can get good sensitivity from big dishes...

- According to the radiometer equation...
  - Sensitivity depends on **collecting area**

$$S_{\mathrm{min}} = \beta \frac{(\mathrm{S/N_{min}})\boxed{\mathrm{SEFD}}}{\sqrt{n_{\mathrm{p}} \tau \Delta \nu}}.$$

$$\mathrm{SEFD} = \frac{T_{\mathrm{sys}}}{G} = \frac{2k_{\mathrm{B}} T_{\mathrm{sys}}}{\boxed{A_{\mathrm{e}}}},$$

Effective area

Credit: Lovell telescope: Mike Peel; Jodrell Bank Centre for Astrophysics, University of Manchester., Attribution-Share Alike 4.0 International [94]; Arecibo telescope: H. Schweiker/WIYN and NOAO/AURA/NSF, Creative Commons Attribution 4.0 International [95]; FAST: N509FZ, Attribution-Share Alike 4.0 International [96]; [68,69]; Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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5.1: Time-domain requirements

You can get good sensitivity from big dishes...

- According to the radiometer equation...
  - Sensitivity depends on **collecting area**
  - Which is why we've built **successively large dishes**...

$$S_{\min} = \beta \frac{(\mathrm{S/N_{min}})\boxed{\mathrm{SEFD}}}{\sqrt{n_p \tau \Delta \nu}}.$$

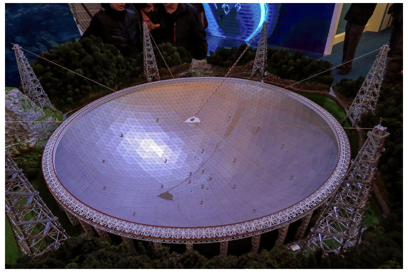
$$\mathrm{SEFD} = \frac{T_{\mathrm{sys}}}{G} = \frac{2k_B T_{\mathrm{sys}}}{\boxed{A_e}},$$

Effective area

Lovell telescope, UK (76m) (1957)

Arecibo telescope (RIP) (305m) (1963)

FAST telescope, China (500m) (2016)



Credit: Lovell telescope: Mike Peel; Jodrell Bank Centre for Astrophysics, University of Manchester., Attribution-Share Alike 4.0 International [94]; Arecibo telescope: H. Schweiker/WIYN and NOAO/AURA/NSF, Creative Commons Attribution 4.0 International [95]; FAST: N509FZ, Attribution-Share Alike 4.0 International [96]; [68,69]; Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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5.1: Time-domain requirements

But a big dish still only has one beam!

- It's **hard to localise** a source within one beam...

5.1: Time-domain requirements

But a big dish still only has one beam!

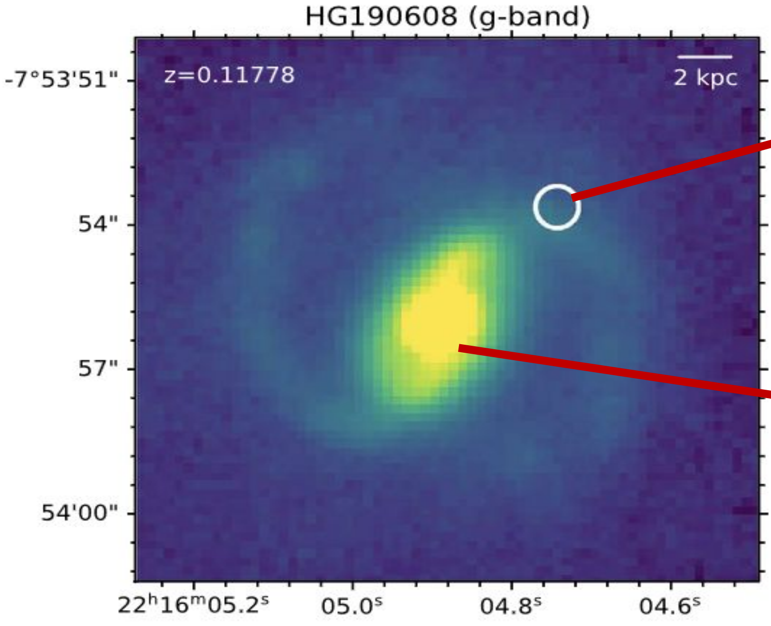
- It's **hard to localise** a source within one beam...
  - But localising **maximises scientific yield**!

S1 S2

5.1: Time-domain requirements

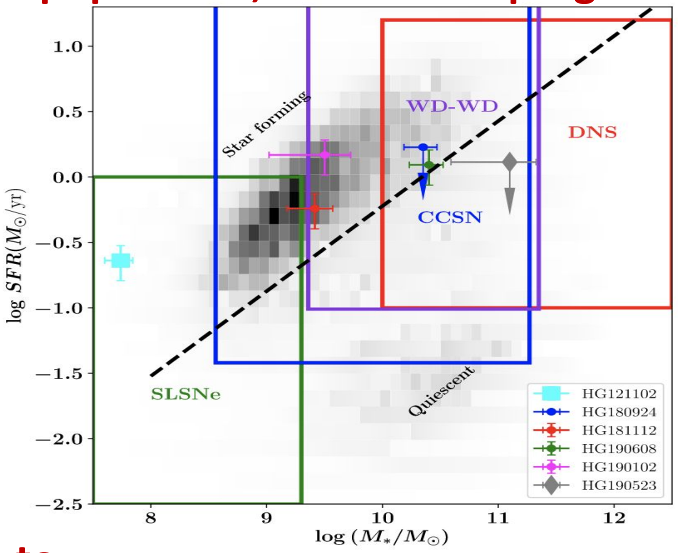
Benefits of localisation...

Example: If you can pin down many FRBs to host galaxies...



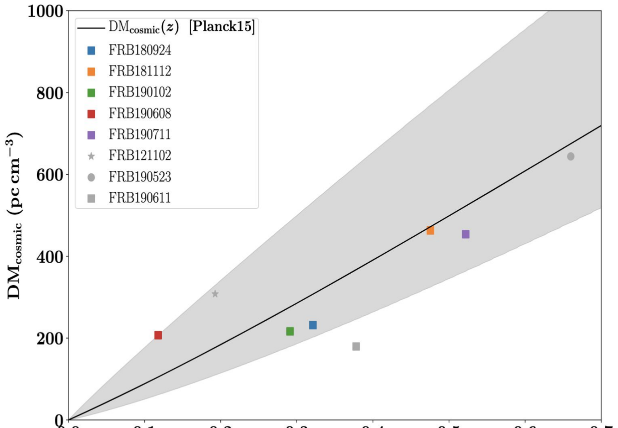
Credit: Bhandari et al. (2020) [97]

Use Case 1: Study host galaxy population, understand progenitors?



Credit: Bhandari et al. (2020) [97]

Use Case 2: Get redshifts, use to measure baryons and cosmological parameters



Credit: Macquart et al. (2020) [52]

5.1: Time-domain requirements

Localising requires beamforming/imaging...

- ...to **good angular resolutions**
  - many beams require many dishes, long baselines...

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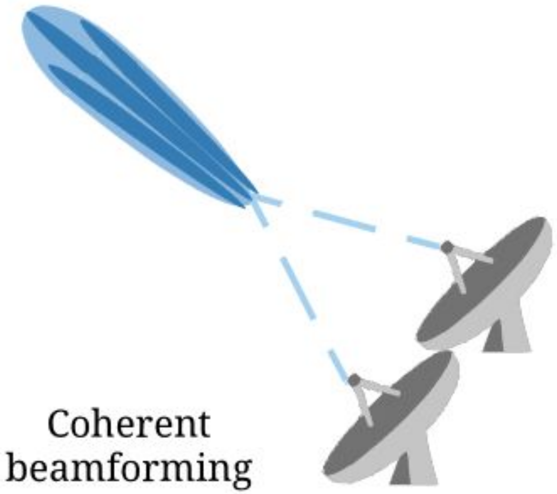
5.1: Time-domain requirements

Localising requires beamforming/imaging...

- ...to **good angular resolutions**
  - many beams require many dishes, long baselines...
- So previous lectures' techniques are **still important** to us after all!

Credit: Square Kilometre Array Organisation (SKAO) / South African Radio Astronomy Observatory (SARAO)

 [24]



Credit: Localising Fast Transients Walker, C. (Author). 1 Aug 2019 [35]

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5.1: Time-domain requirements

One more catch...

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5.1: Time-domain requirements

One more catch...

- Must perform transient searches **in each beam**
  - Making things even more data intensive!
- Especially if you want to do things in **real-time**

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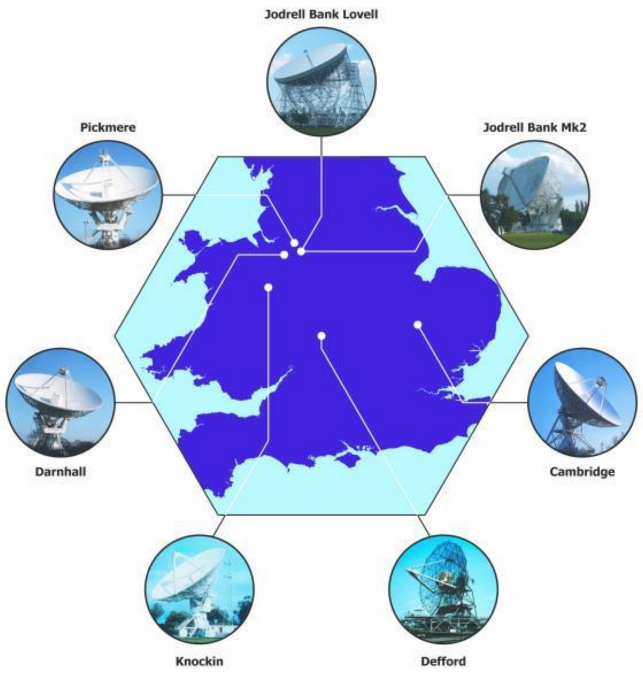
5.2: The SKA Data challenge...

Let's compare data rates for various telescopes...

- e-MERLIN: **~3.6 GB/s**



Credit: Alastair Gunn, Creative Commons Attribution 3.0 Unported [62]

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5.2: The SKA Data challenge...

Let's compare data rates for various telescopes...

- e-MERLIN: **~3.6 GB/s**
- CHIME/FRB: 1.5 PB/day = **17 GB/s** [98]

Credit: Z22 Creative Commons Attribution-Share Alike 4.0 International [22]

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5.2: The SKA Data challenge...

Let's compare data rates for various telescopes...

- e-MERLIN: **~3.6 GB/s**
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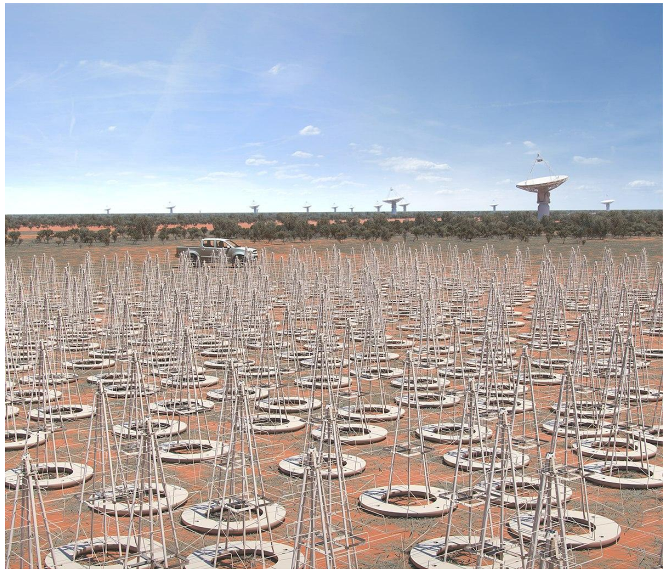
- SKA-LOW (PSS): 500 beams x 244 MB/s = **122 GB/s** [99]



Credit: SKA Organisation: Attribution 3.0 Unported [100]

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- SKA-LOW (PSS): 500 beams x 244 MB/s = **122 GB/s** [99]
- SKA-MID (PSS): 1500 beams x 244 MB/s = **366 GB/s** [99]

Credit: SKA Organisation: [Attribution 3.0 Unported] [101]

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5.2: The SKA Data challenge...

Much of the processing will be done in the SKA Central Signal Processor [102]...

- Pulsar searching alone predicted to be **>10 POps/s**! [99]

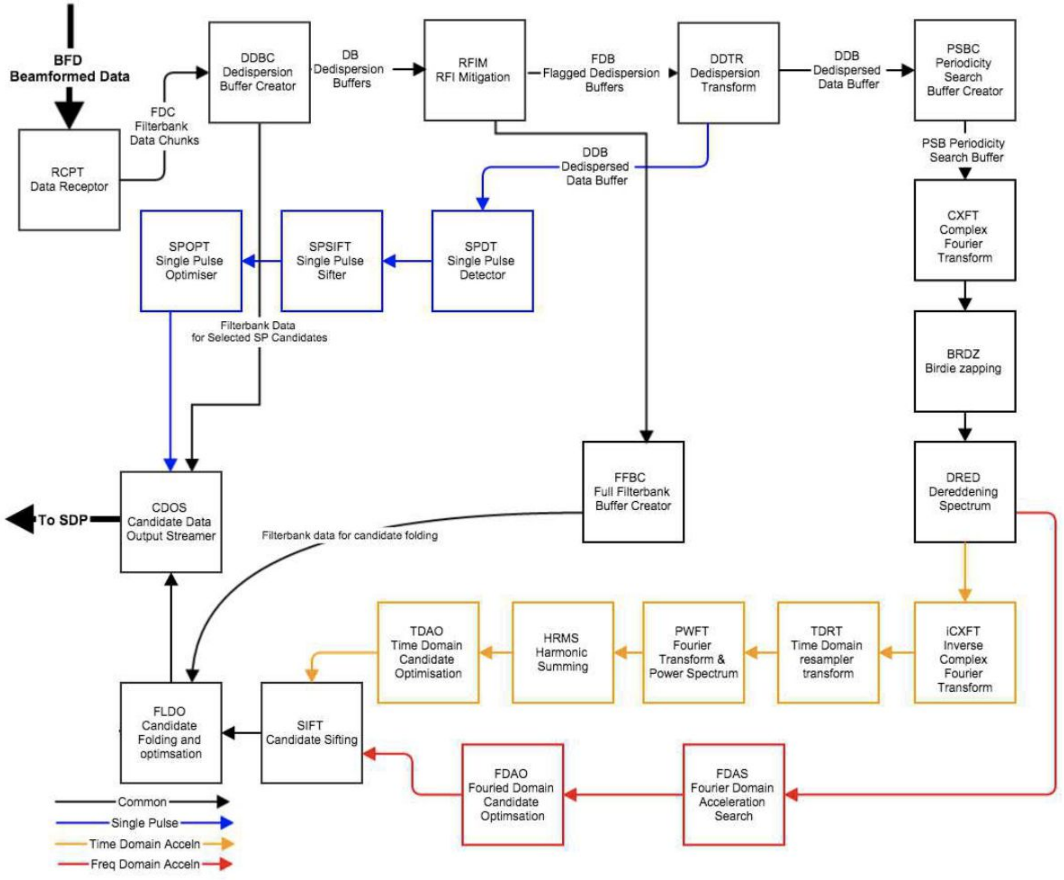

Figure 1. Schematic of the pulsar search processing work flow within CSP.

Credit: Levin et al. (2017) [102]

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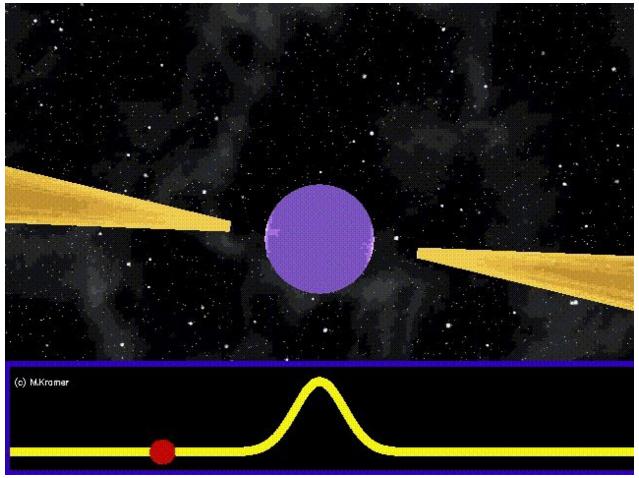
5.3: Conclusion: Big challenge, big rewards

Predicted number of pulsar discoveries...

- Currently funded SKA:
  - **9000 pulsar** discoveries (up from 3000) [102,103]
  - **1200 MSP** discoveries (up from 300) [102,103]



Credit: Michael Kramer
Attribution-Share Alike 3.0 Unported [5]

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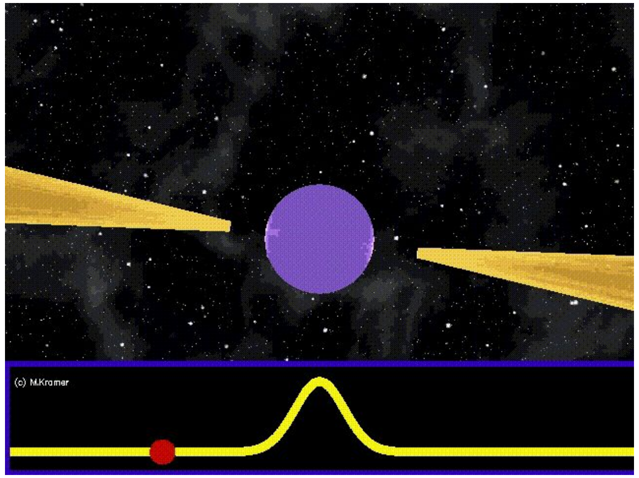

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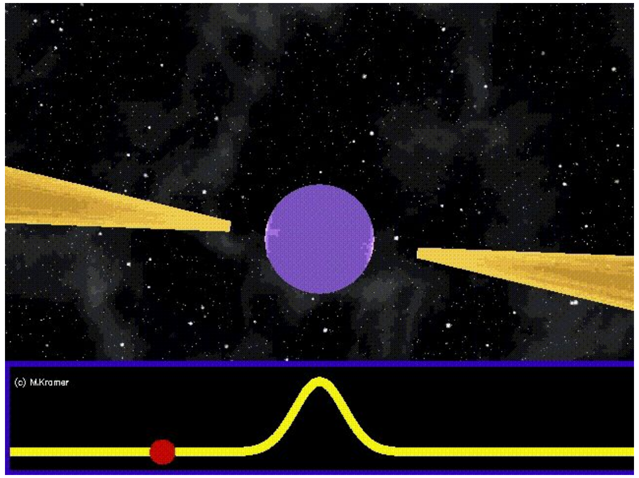
And potentially hundreds of FRBs per sky per day [104]!



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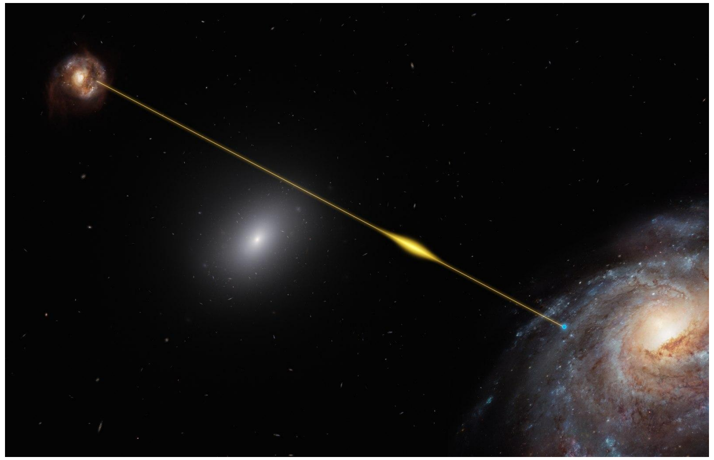

Credit: ESO/M. Kornmesser Attribution 4.0 International [105]

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Thanks for listening!

Questions?

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