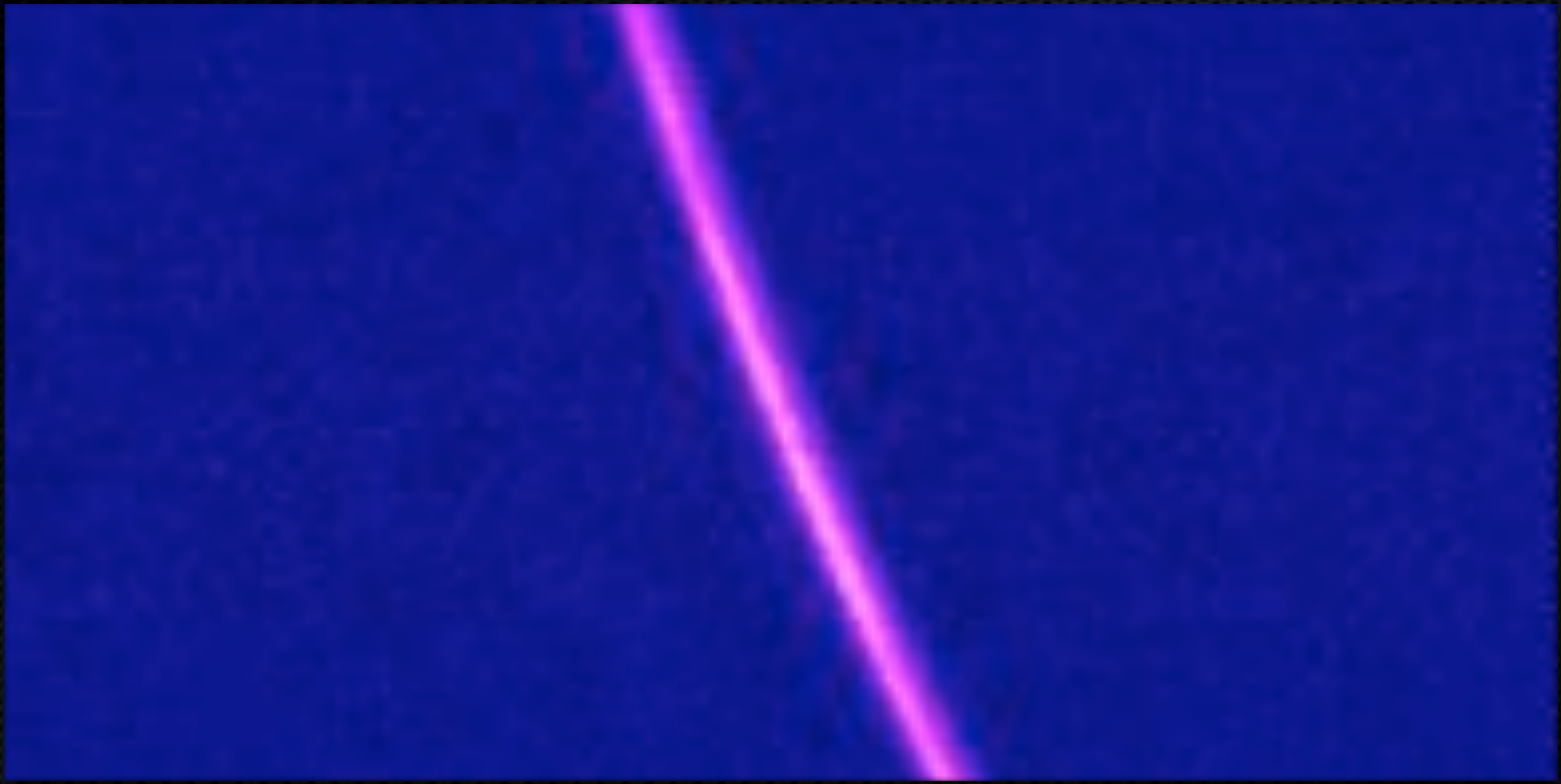


High Time Resolution Observing

Michael Keith

Parkes Radio Astronomy School 2009

Overview

- In this talk we are considering observing signals with pulses lasting less than a few seconds.
- Generally, this applies to pulsars, however there may be other sources of periodic or aperiodic pulses and much of this talk does not consider the source of the pulses
- For this talk, pulsars can just be considered to be a source of pulsing radio emission...

Overview

- Effects of the interstellar medium
  - Cold plasma dispersion
  - Scattering and Scintillation
- Searching for short time-scale signals
  - Single pulses
  - Periodicity Searches
- Pulsar timing

Not going to worry about...

- Observation strategy: if $t<1s$, size is less than 3e5 km. At any astronomical distance, that's a point source! Therefore we just point at our target and observe.
- Flux calibration is relatively simple as pulse duration much less than gain fluctuation times, so it's easy to subtract a baseline.
- Polarisation calibration has already been dealt with in other talks.

Effects of the interstellar medium

Interstellar Dispersion

The ISM is a cold, ionised plasma. We know that electromagnetic waves experience a frequency dependant refractive index as they pass through such a medium.

Plasma Frequency

Electron density

$$\mu = \sqrt{1 - \frac{\nu_p^2}{\nu^2}} \qquad \nu_p = \sqrt{\frac{e^2 n_e}{\pi m_e}}$$

For the ISM $n_e \sim 0.03\ \mathrm{cm}^3$ Therefore $\nu_p \sim 1.5$ kHz

Since $\mu < 1$, the group velocity of the wave (μc) will be less than c. This means that any signal will suffer a *frequency dependant delay* as it travels through the ISM. As we will see, this delay is of the order of milliseconds → seconds and therefore is an important effect when observing with time resolution less than a few seconds.

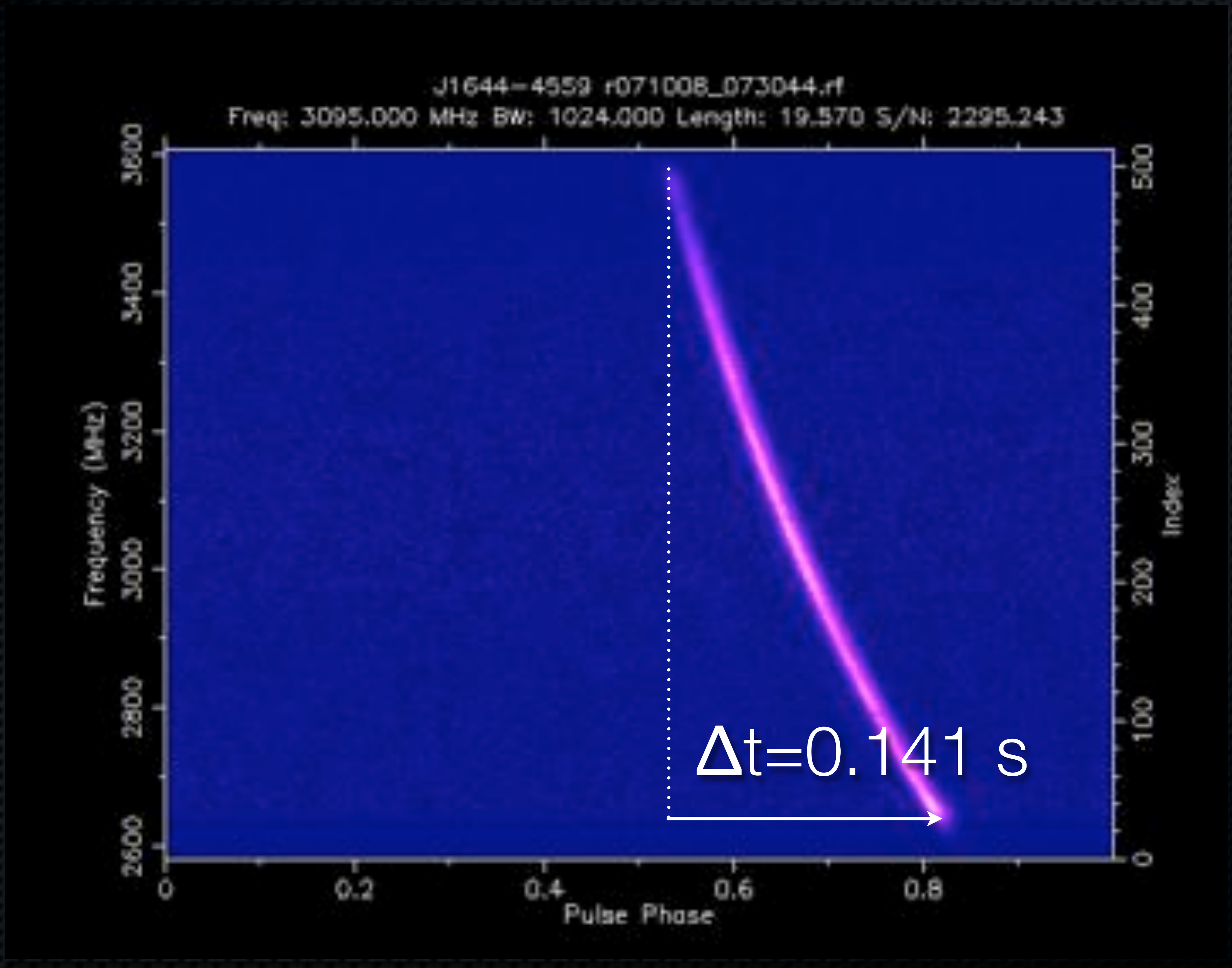
Interstellar Dispersion

A wave of frequency ν will be delayed with respect to a wave at 'infinite frequency' by

$$t = \int_0^d \frac{1}{\mu c} \mathrm{d}l = \frac{1}{c} \int_0^d \left(1 + \frac{\nu_p^2}{2\nu^2}\right) \mathrm{d}l = \frac{e^2}{2\pi m_e c} \frac{\int_0^d n_e \mathrm{d}l}{\nu^2}$$

$$t = k_{\mathrm{DM}} \frac{\mathrm{DM}}{\nu^2}$$

Where DM is the "dispersion measure" a quantity measured in $\mathrm{cm}^{-3}\,\mathrm{pc}$ and $k_{\mathrm{DM}} = 4.148808\mathrm{x}10^3\ \mathrm{MHz}^2\,\mathrm{pc}^{-1}\,\mathrm{cm}^3\,\mathrm{s}$


J1644−4559 r071008_073044.rf
Freq: 3095.000 MHz BW: 1024.000 Length: 19.570 S/N: 2295.243
Frequency (MHz)
Pulse Phase
Index
Δt=0.141 s

P = 0.455 s

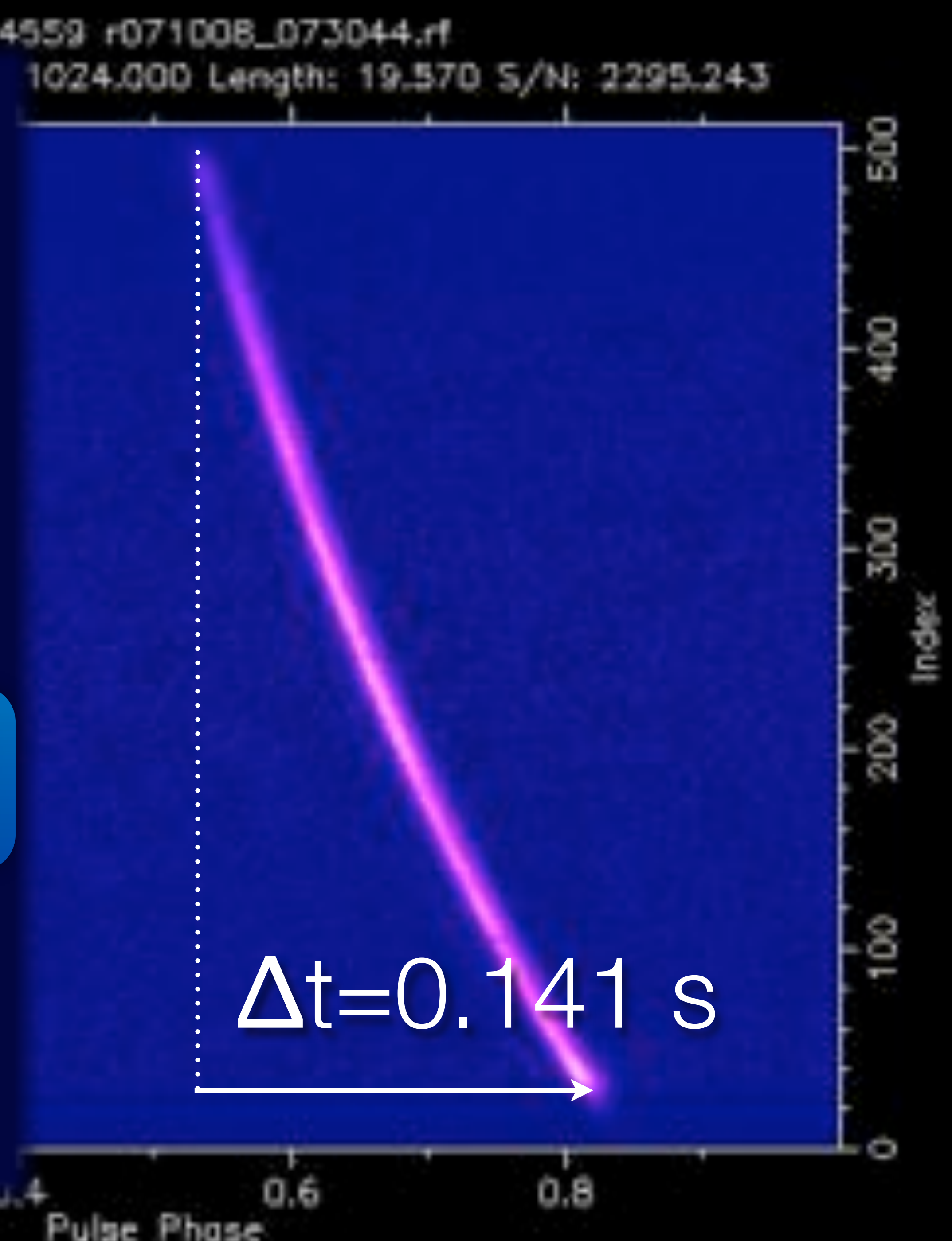
Δt = 0.141 s

νlo = 2600 MHz

νhi = 3600 MHz

$$\Delta t = k_{DM}(\nu_{lo}^{-2} - \nu_{hi}^{-2})DM$$

DM = 480 cm-3 pc

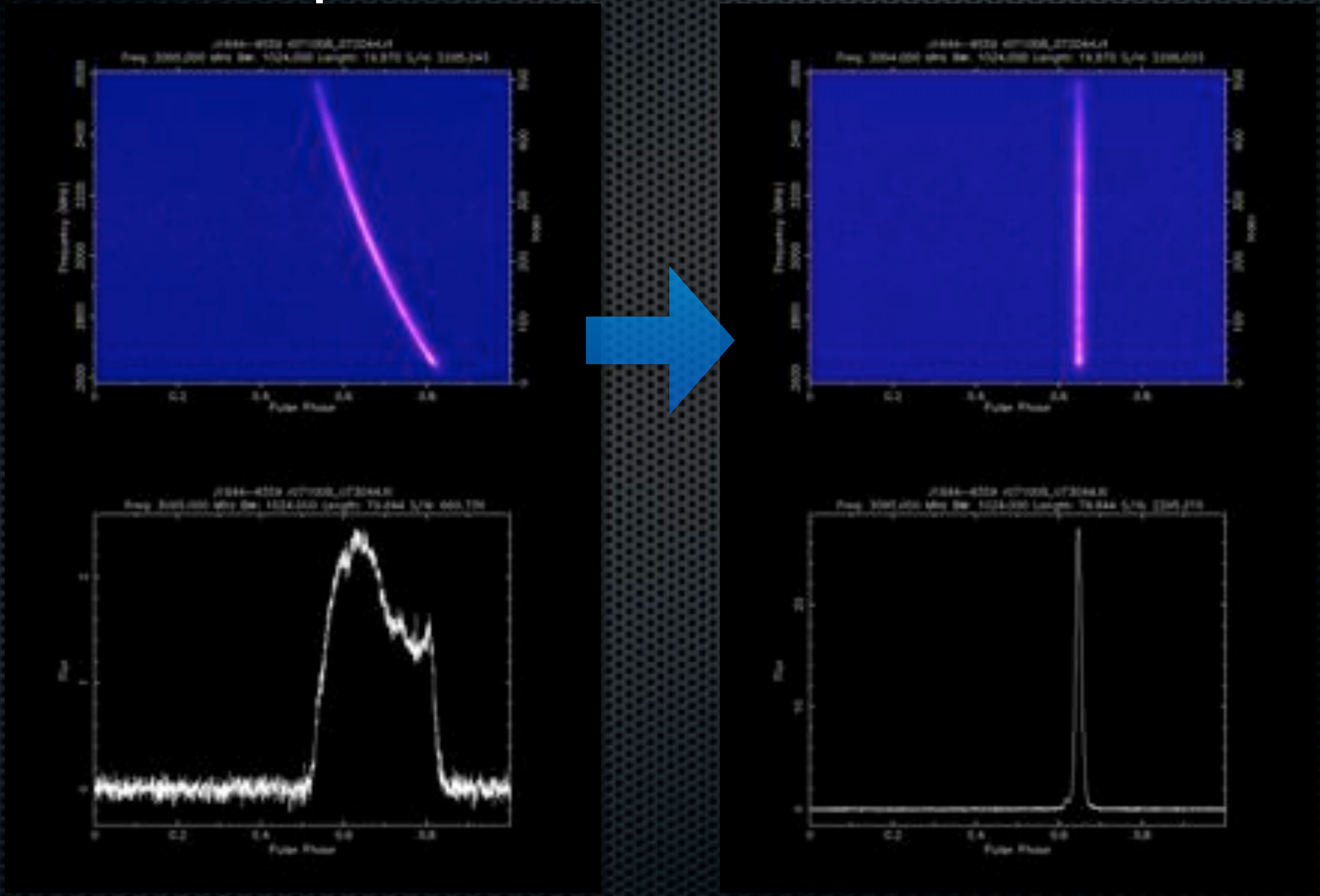


De-Dispersion

Interstellar dispersion is generally a useful effect as it helps to distinguish terrestrial signals (RFI) from extra-terrestrial signals (pulsars). If the dispersion measure is known, the effect can be removed from the data by "de-dispersion".

A simple method for de-dispersion is to chop the observing band into many small channels, then adding an appropriate delay to each channel before re-combining. The amount of pulse broadening is then dependant on the width of each channel and the DM to the source.

De-Dispersion



Coherent De-dispersion

Using finite width channels will always introduce some dispersion smearing of the signal.

The dispersion effect can be perfectly removed by the process of coherent de-dispersion. Since Dispersion can be thought of as a linear filter on the transmitted waveform, computing and applying the inverse filter to the observed voltages will completely remove the effect of dispersion.

Typically, this process is computationally expensive and require powerful backend hardware. See talk by W. v. Straten.

The turbulent ISM

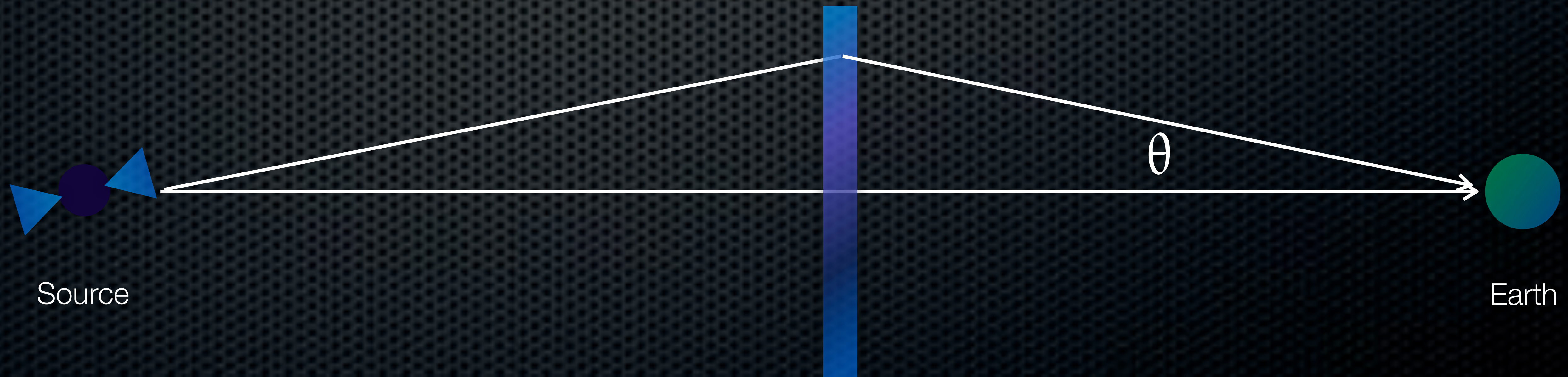
The interstellar medium is not a homogeneous plasma. By considering a turbulent ISM we can begin to understand the effects of **scattering** and **scintillation**.

Although the turbulent ISM extends all the way from the source to the observer, we can more easily model the observed behaviour by assuming the inhomogenious material lies in a thin screen, half way between source and observer.

Scattering Basics

The scattering screen allows for multiple light paths to reach the observer. This has the effect making a point source appear to be surrounded by diffuse disk with a characteristic angular radius θ_d. If our screen has perturbations in the electron density of magnitude Δn_e of typical physical size *a*, then

$$\theta_d \approx \frac{e^2}{2\pi m_e} \frac{\Delta n_e}{\sqrt{a}} \frac{\sqrt{d}}{\nu^2} \qquad I(\theta)d\theta \propto \exp(-\theta^2/\theta_d^2)2\pi\theta d\theta$$



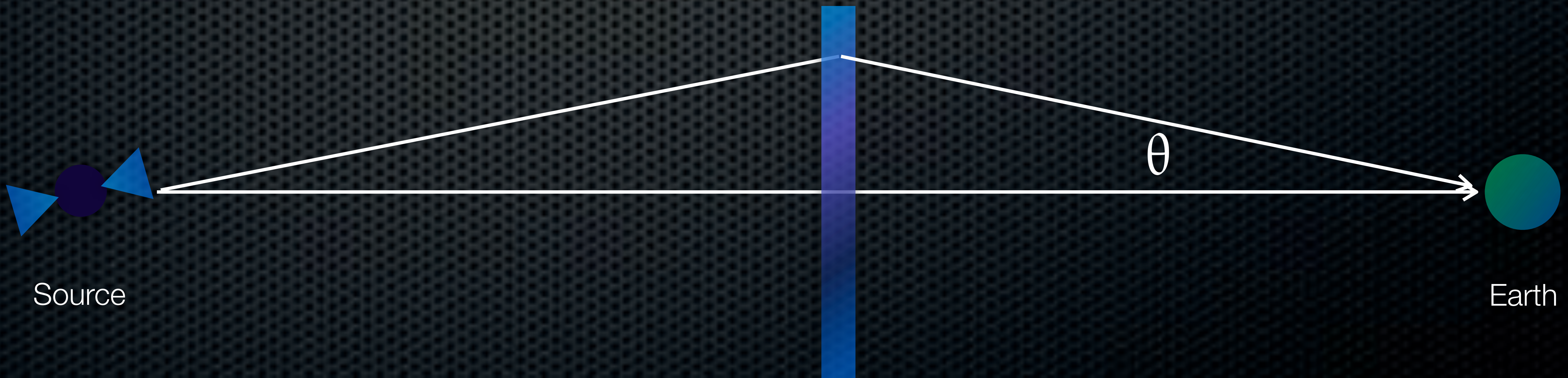
Scattering Basics

Rays that travel at an angle θ arrive slightly later than those that travel un-deflected. The delay can be derived by simple geometry:

$$\Delta t(\theta) = \frac{\theta^2 d}{c}$$

And since we have the angular intensity distribution, we can show that the intensity varies with time as:

$$I(t) \propto \exp(-c\Delta t/(\theta_d^2 d))$$



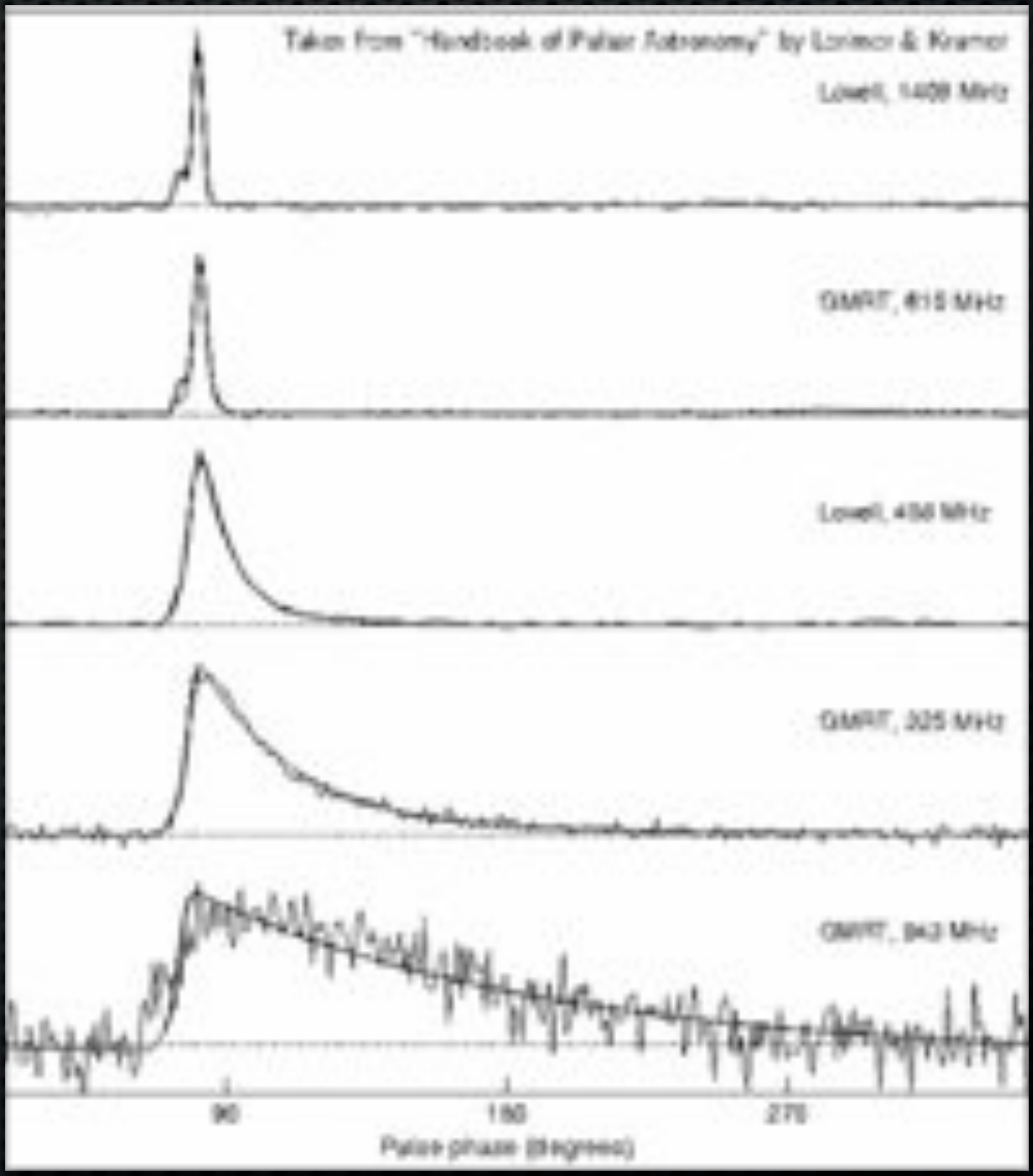
Scattering Basics

Therefore a narrow pulse emitted from the source, the observed intensity goes as:

$$I(t) \propto e^{-\Delta t/\tau_s}$$

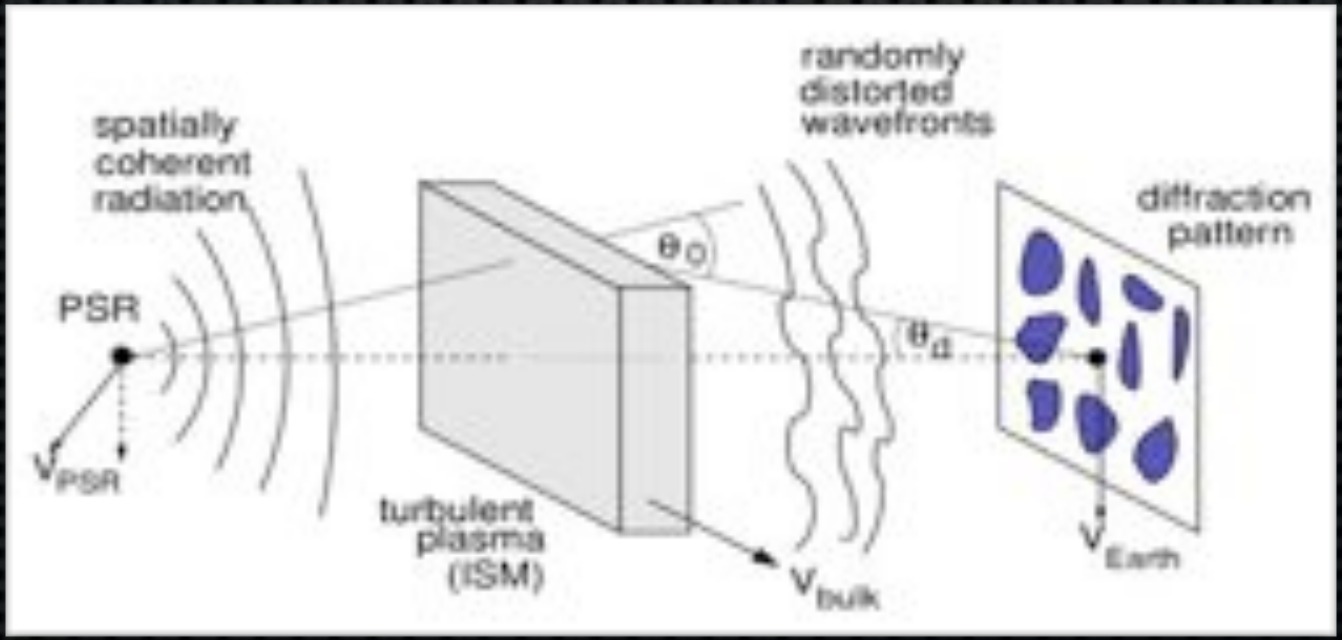
The "scattering time-scale" τ_s is dependant on the distance to the source, and on the observing frequency:

$$\tau_s \propto d^2 \nu^{-4}$$



Scintillation Basics

As the wave travels through the ISM the delays cause relative phase shifts between the different paths. Interference between waves traveling along different paths causes an interference pattern in the plane of the observer.



This pattern of enhanced and reduced intensity moves over the observer due to the relative motion of the source, scattering screen and observer. We observe fluctuations in brightness with a characteristic timescale dependant on this velocity.

Scintillation Basics

If a wave is delayed by the scattering time τ_s, the phase of the wave changes by $2\pi\nu\tau_s$.

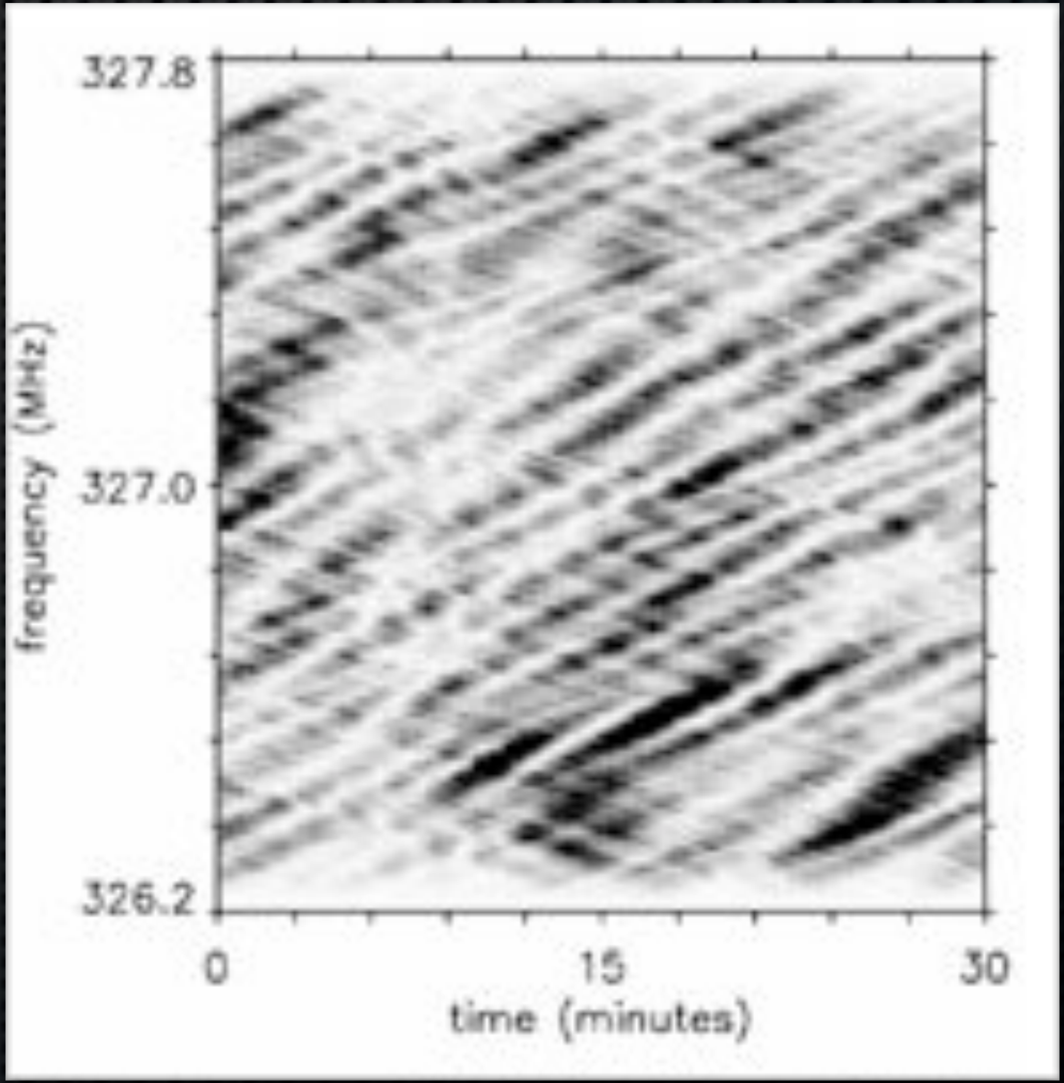
Interference can only occur if the phase of the interfering waves do not differ by ~1 radian. Since the phase depends on ν, any enhancements or detriments in intensity will be seen only within a "scintillation bandwidth" $\Delta\nu$

$$\begin{aligned} 2\pi\Delta\nu\tau_s &\sim 1 \\ \Delta\nu &\propto 1/\tau_s \\ \therefore \Delta\nu &\propto \nu^4 \end{aligned}$$

Scintillation Basics

A dynamic spectrum shows pulsed flux as a function of time and frequency. We can use this to measure Δt and $\Delta \nu$.

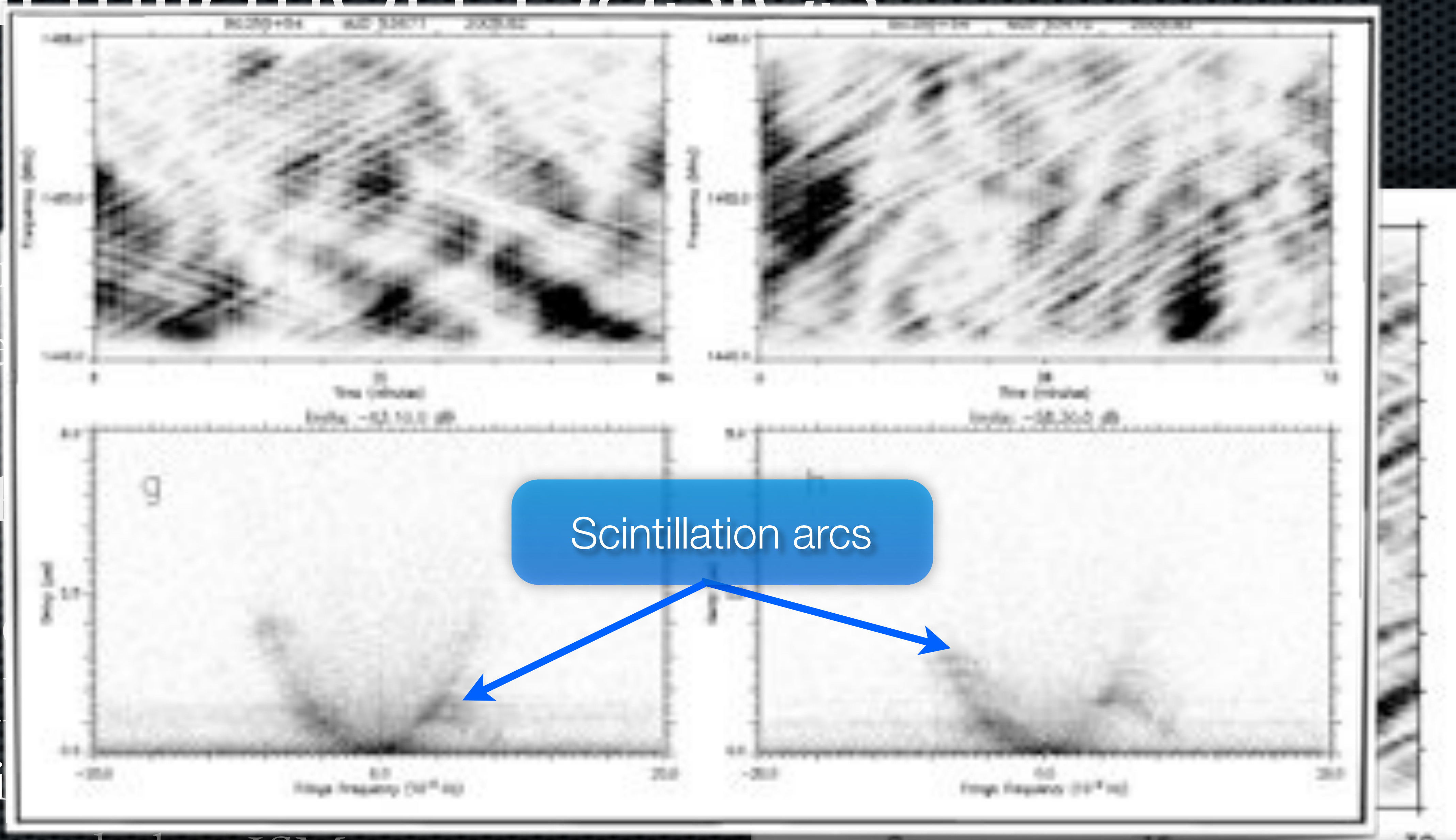
These parameters, and more detailed spectral analysis can give insight into the properties of the turbulent ISM.



Scintillation Basics

A dy
pulse
time
use t

Thes
detai
give i
of the turbulent ISM.



In a thin screen model, the curvature of the arcs is a function of the location of the screen between the source and observer...

ISM Summary

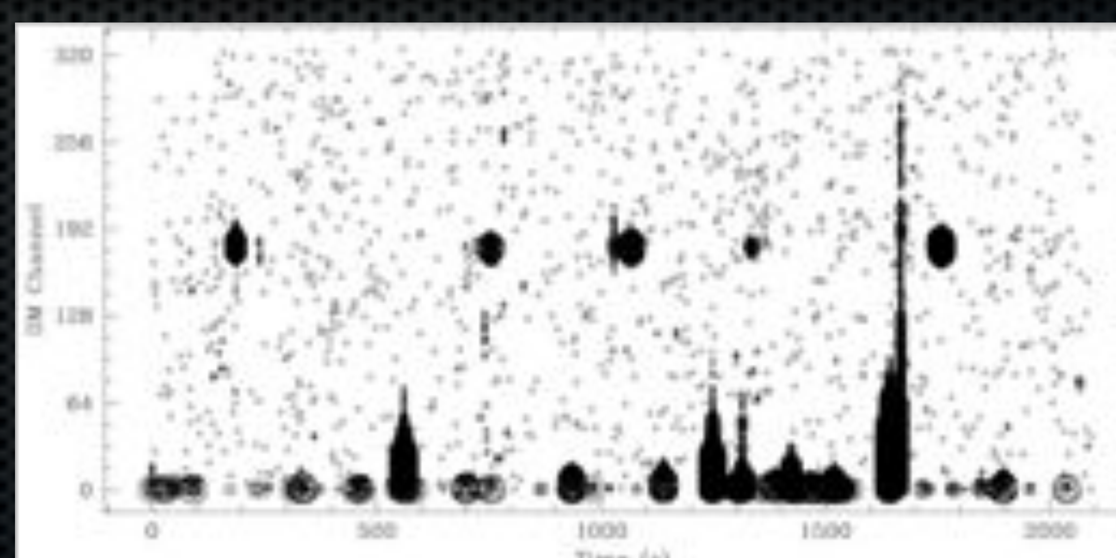
- Short time duration events are affected by the ISM in different ways to continuous signals
- Dispersion is the most significant effect, but can be removed.
- Scattering plays a significant role at low frequencies, and/or when measuring pulse arrival times to high precision
- Scintillation gives us a way to measure the scale sizes of inhomogenities in the ISM.

Searching for unknown sources

Searching for Dispersed Pulses

When searching for pulsed emission it can be difficult to distinguish extra-terrestrial signals from RFI. Since we are looking for broad-band *dispersed* emission, it is useful to transform the recorded data from many time-series at different observing frequencies to many time-series de-dispersed at different DMs.

In the figure we can see RFI at DM=0 and a pulsar at DM=190



Searching for Dispersed Pulses

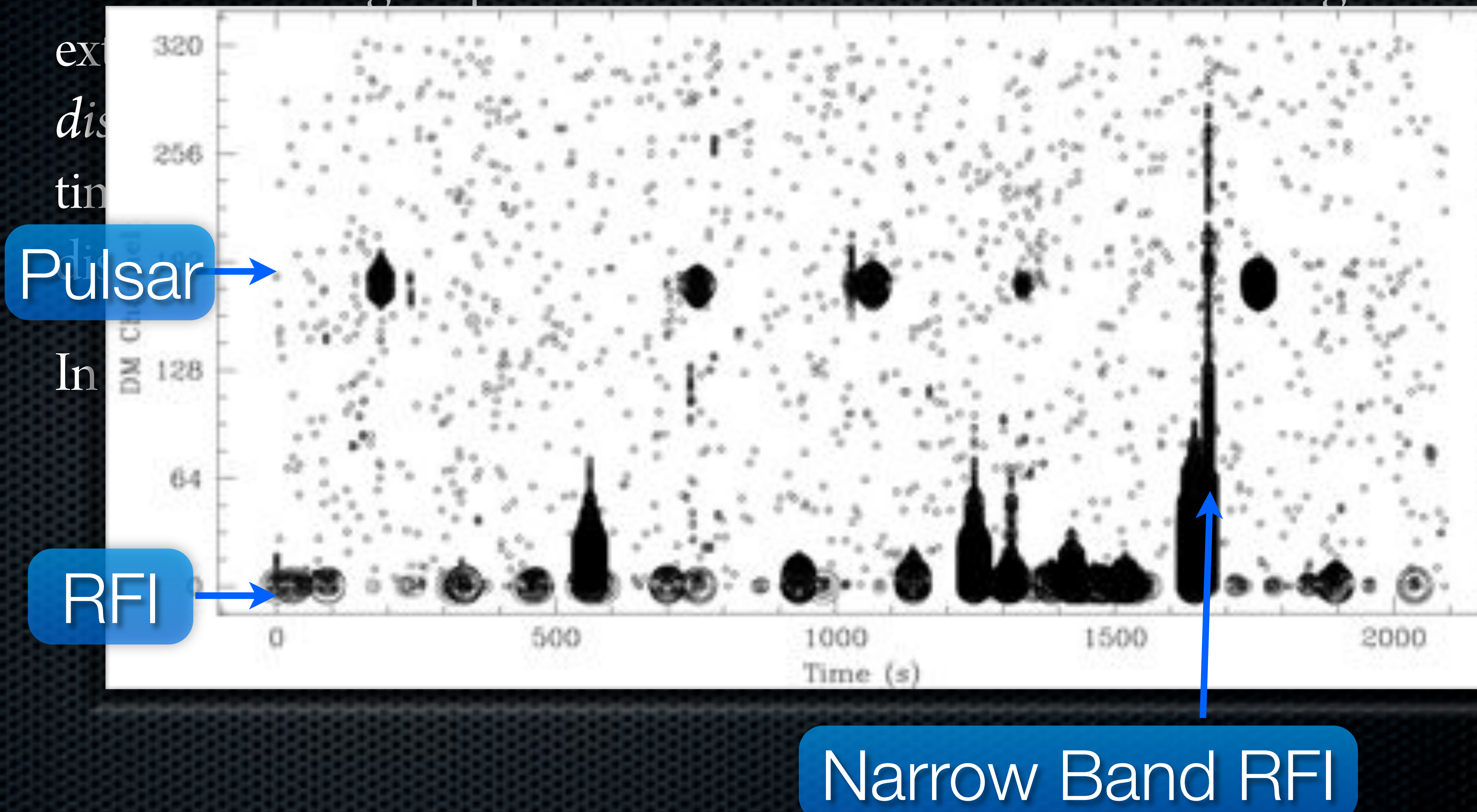
When searching for pulsed emission it can be difficult to distinguish

ex

dis ny

tin

In



Searching in "Dispersion Space"

In order to recover the maximum signal-to-noise ratio of a dispersed signal, we want to search enough DM trials such that the effective time resolution in the de-dispersed time-series is the same as the effective time resolution of the individual channels.

Data sampling interval

DM Smearing in a channel

$$\Delta t < \sqrt{\Delta t_s^2 + \Delta t_{ch}^2}$$

Sky freq of first and second channels

$$\Delta \mathrm{DM} = \frac{\sqrt{\Delta t_s^2 + k_{\mathrm{DM}}^2 (\nu_0^{-2} - \nu_1^{-2})^2 \mathrm{DM}^2}}{k_{\mathrm{DM}} (\nu_0^{-2} - \nu_N^{-2})}$$

Sky freq of first and last channels

Searching in "Dispersion Space"

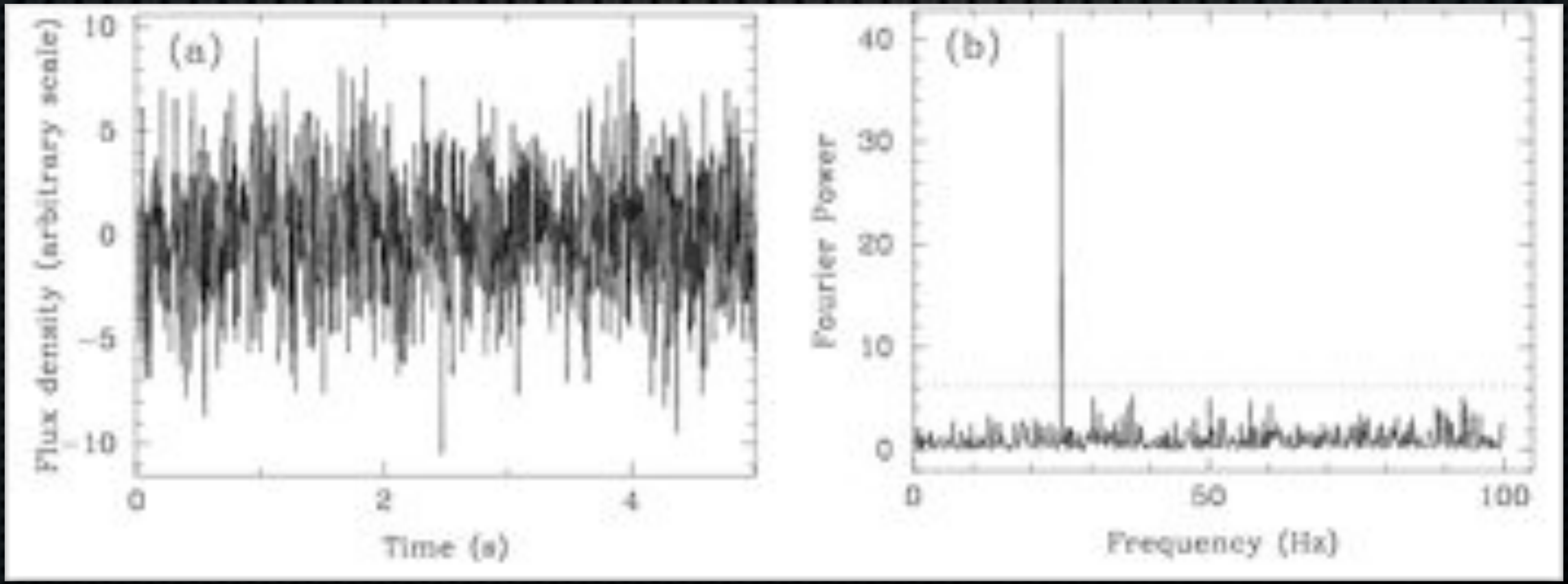
This turns often turns out to be a large number of trial DMs.

To search data taken with 1024 channels over a 400 MHz band at 1.4 GHz to a DM of 2000 cm^{-3} pc requires the computation (and searching) of around 1500 time-series. Production of these time-series for a few minutes worth of data may take several hours on a modern supercomputer node.

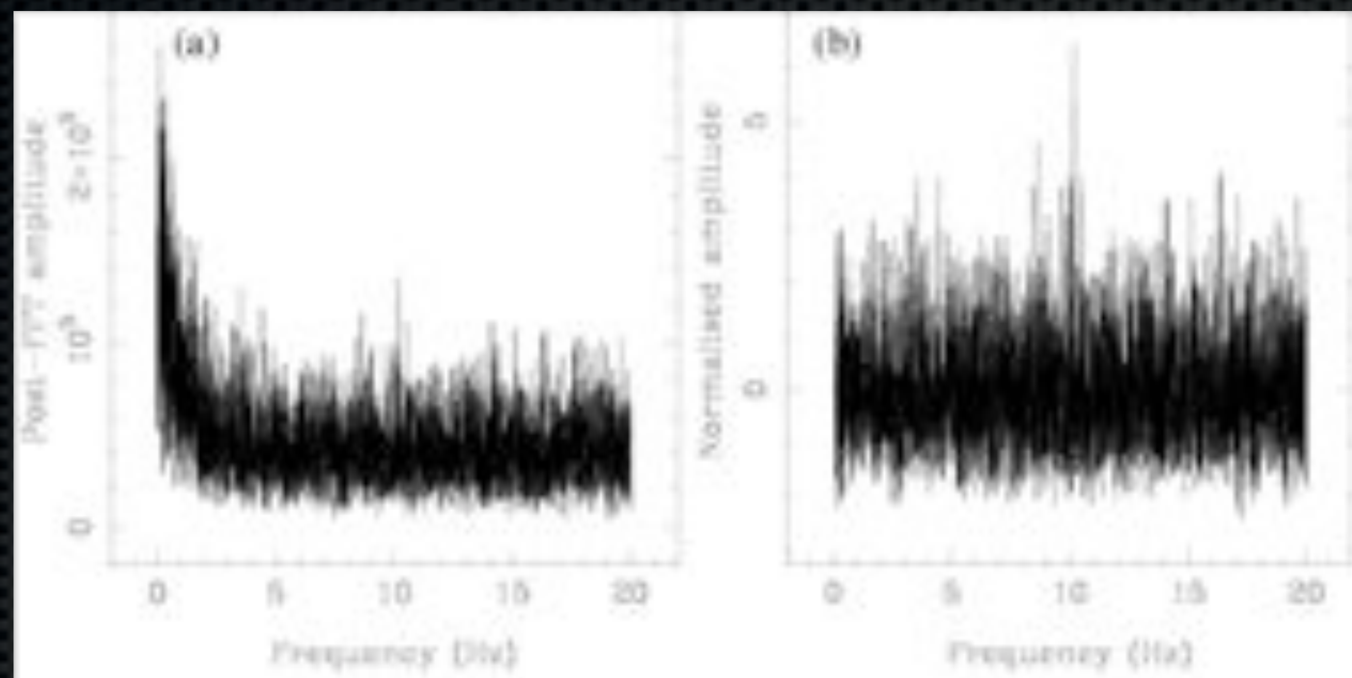
This takes a considerable amount of computing resource. Pulsar searches are often dominated by the time taken to de-disperse the data.

Detecting periodic signals

Even after we have correctly de-dispersed the data, *the individual pulses of most pulsars are too weak to detect.* Therefore we can only discover these signals by periodicity analysis. Since we have regularly sampled, continuous data, we do this using the **Fourier transform**.



Spectral Whitening



Real data tend to be dominated by "red noise", which *must* be removed in order to detect signals < ~10 Hz (i.e. most pulsars).

Typical approaches subtract a running mean (or median) and divide by a running RMS to whiten and normalise the data.

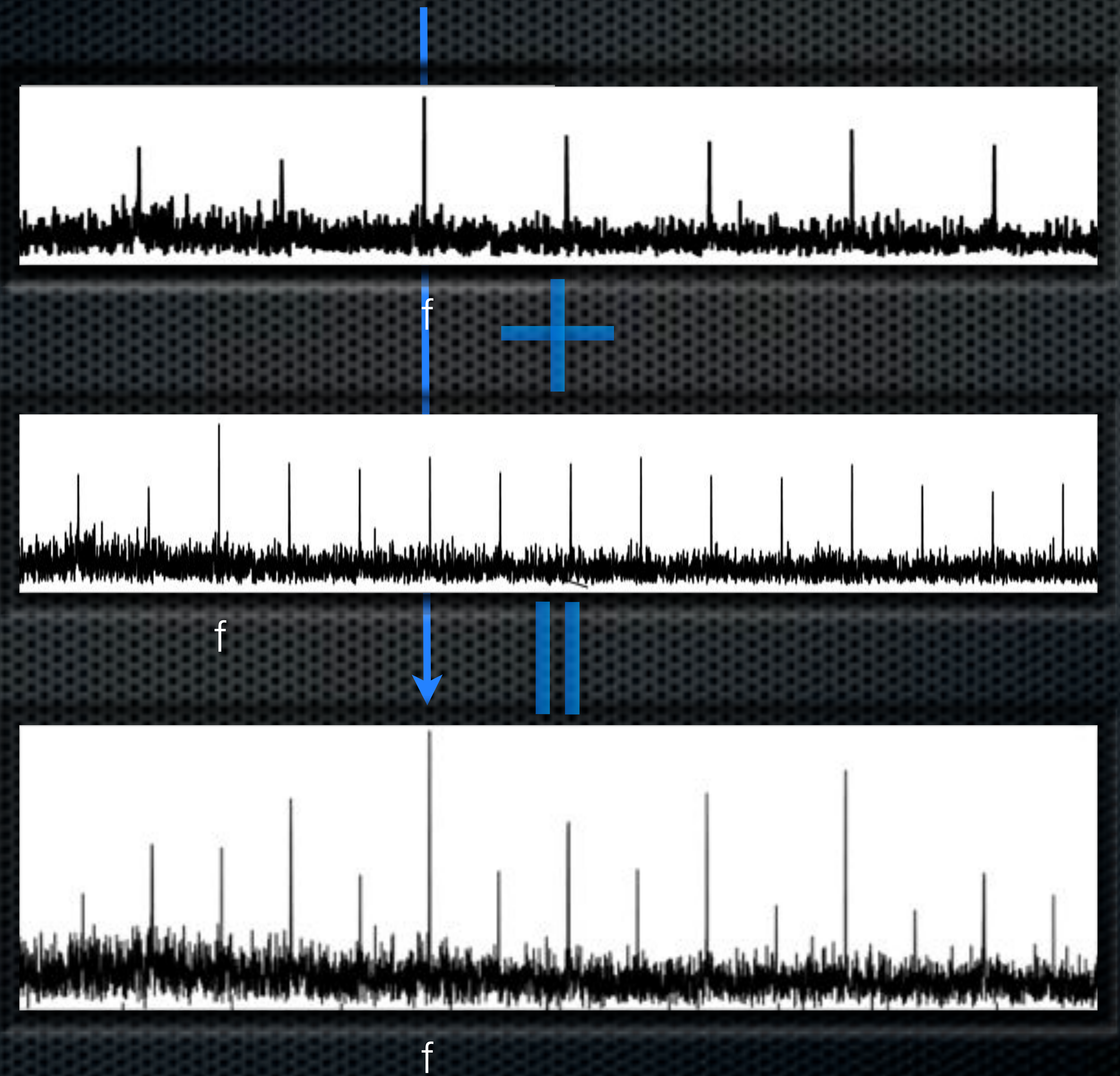
The whitening process is often complicated by RFI which can easily throw off the normalisation algorithm. The most common cause for failure to detect long period signals is incorrect red-noise compensation.

Harmonic Summing

Signals from pulsars tend to have a fairly narrow duty cycle. This means that their spectral power gets distributed into many harmonics and so sensitivity is lost compared to an equivilent sinusoidal signal.

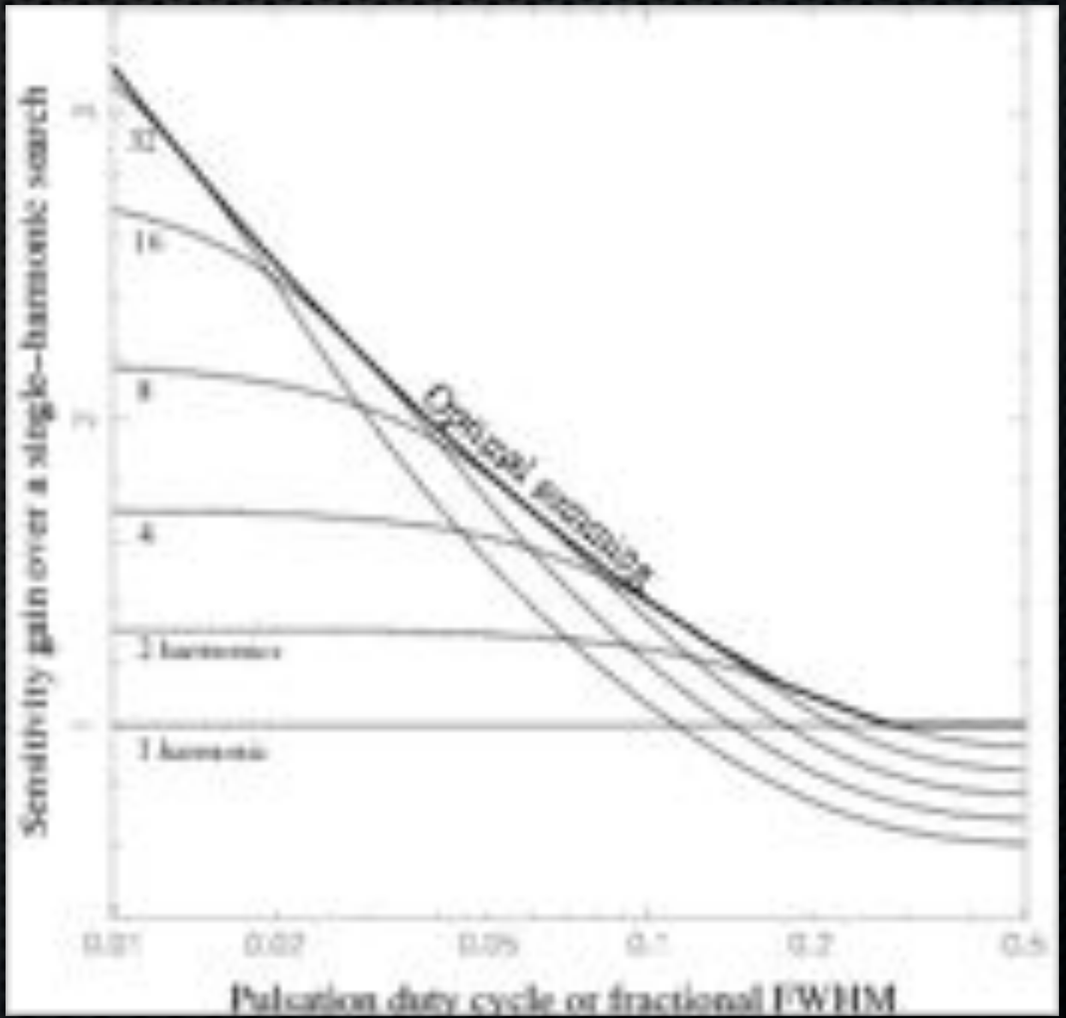
We can recover this power by incoherent "harmonic summing". Here we take the amplitude spectrum, stretch it by a factor of 2 and add it to the original amplitudes. The fundamental and 1st harmonic are added together and so produce a more significant spike.

Harmonic Summing



Harmonic Summing

- We can repeat the process many times, summing more and more harmonics
- Higher harmonic folds increase sensitivity to narrower pulses
- e.g. the “16th” harmonic fold has sums harmonics 1-16.



Candidate selection

After searching for peaks in each harmonic fold and for each dispersion measure, we are left with a huge number of signals.

Many of these signals are detected at the same frequency in many different dispersion measure trials and many signals are harmonics of each other.

Therefore we combine related signals into a single candidate, generating of the order of 100 candidates for a typical observation. (remember that a typical survey will have many thousands of observations)

Of these, only a tiny fraction will be real astronomical signals... we must use clever algorithms and human effort to decide which signals to follow up.

Searching summary

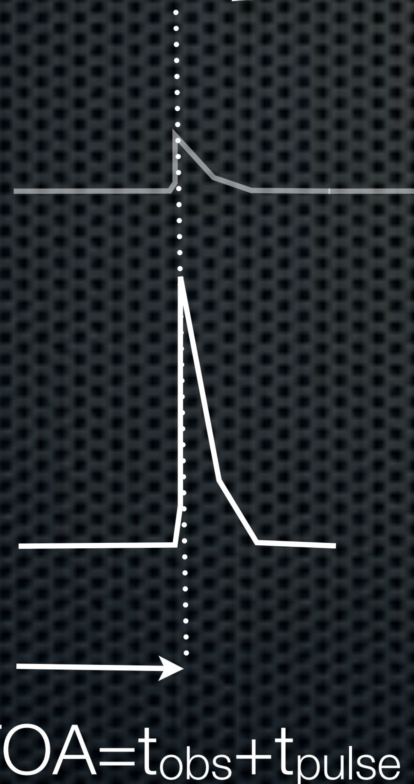
- In order to detect short duration signals we must de-disperse to a large number of trial dispersion measures
- These time-series can be searched for bright individual pulses, or we can use Fourier techniques to find periodic sources (e.g. most pulsars)
- There is a large amount of computational effort to perform the search
- The number of candidates returned by the search is vast, therefore we must use artificial and human intelligence to sift the candidates for interesting signals.

Precision timing of pulsars

Measuring the arrival time of a pulse

Before we can do any timing of pulsars we must be able to accurately measure the time-of-arrival (TOA) of an observed pulse.

This begins with high quality observations of enough consecutive pulses of the pulsar that we can "fold" the detected pulses on top of each other to produce a pulse profile with a suitably high signal-to-noise ratio.



a TOA is the time that **a** pulse arrives at the telescope

How to measure t_{pulse}?

Although each pulse from a pulsar is different, each pulsar has a characteristic mean profile which is often very stable.

Therefore we create a template profile for each pulsar, which is then convolved with the observed profile. The TOA is taken as the time at which this convolution peaks.

Templates can be high signal-to-noise ratio observed profiles, or analytic templates composed of Gaussian (or similar) components.

The time is then related to a high precision clock at the telescope, which then must be corrected to a standard time frame.

Barycentric correction

Since the Earth, and therefore the telescope moves with time, our measured TOAs are dominated by the path length differences between the pulsar and the Earth.

To a high degree, the solar centre barycentre is an inertial frame, therefore we convert the observed TOAs to the time the pulse would have arrived at the barycentre.

$$t_{SSB} = t_{obs} + t_{corr} + k_{DM} DM \nu^{-2} + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

Measured time

Clock correction

DM Correction

Roemer Delay

Shapiro Delay

Einstein Delay

Barycentric correction

Since the Earth, and therefore the telescope moves with time, our measured TOAs are dominated by the path length differences between the pulsar and the Earth.

To a high degree, the solar centre barycentre is an inertial frame, therefore we convert the observed TOAs to the time the pulse would have arrived at the barycentre.

$$t_{SSB} = t_{obs} + t_{corr} + k_{DM} DM \nu^{-2} + \Delta_{R\odot} + \Delta_{S\odot} + \Delta_{E\odot}$$

More terms are added if the pulsar is in a binary system...

Pulsar timing

To compute the pulsar period, we can count the number of pulses in a given time frame and divide...

But to get an accurate position, we would have to observe the pulsar continuously so that we never missed a pulse.

To get the best precision, we would want to do this over many years.

Therefore we have to be more clever

Pulsar timing

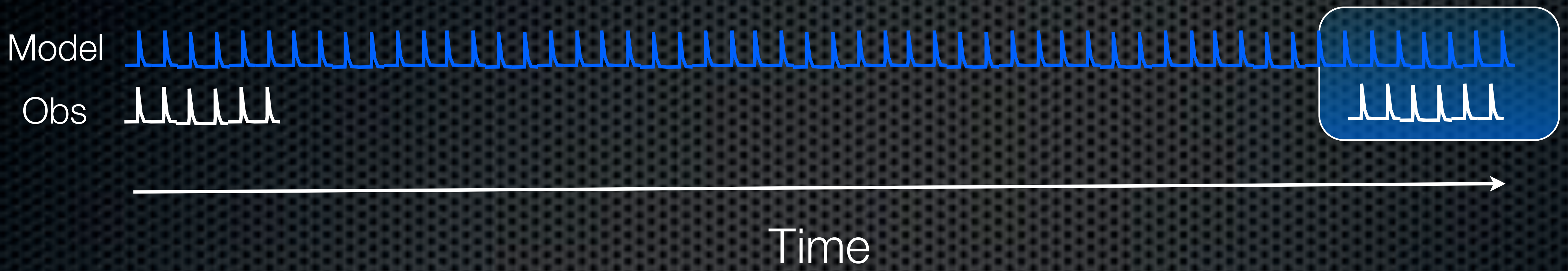
To compute the pulsar period, we can count the number of pulses in a given time frame and divide...

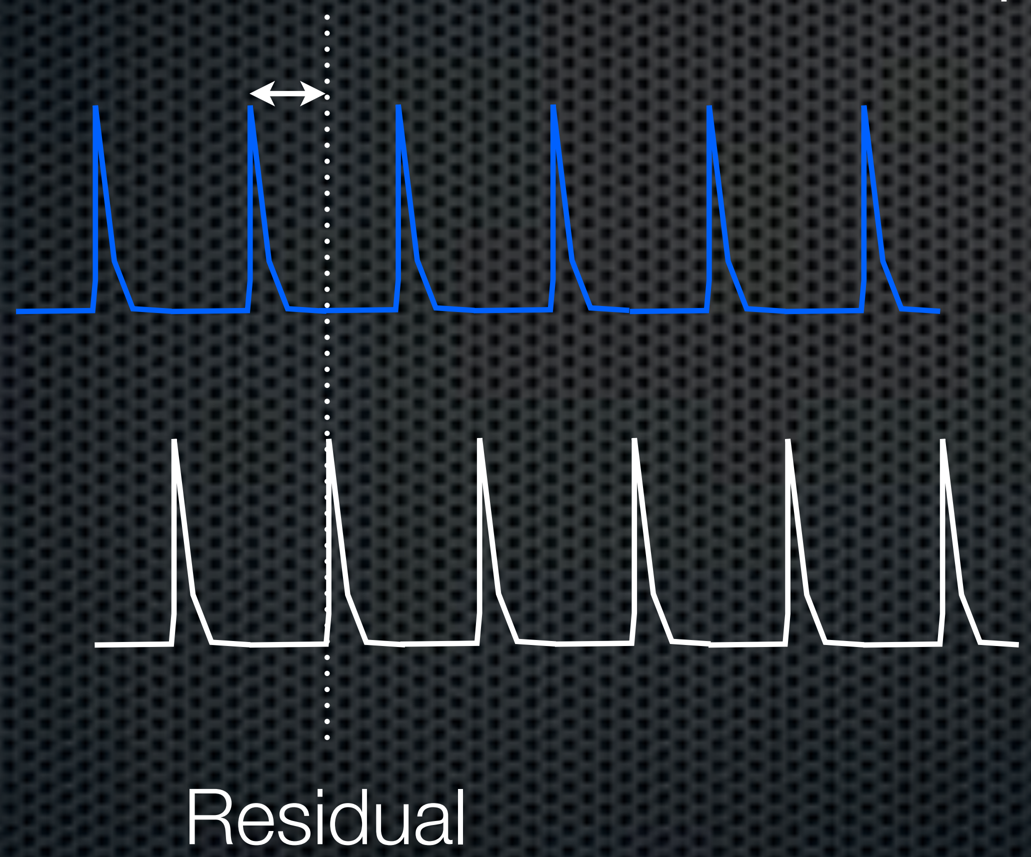
But to get an accurate position, we would have to observe the pulsar continuously so that we never missed a pulse.

To get the best precision, we would want to do this over many years.

Therefore we have to be more clever

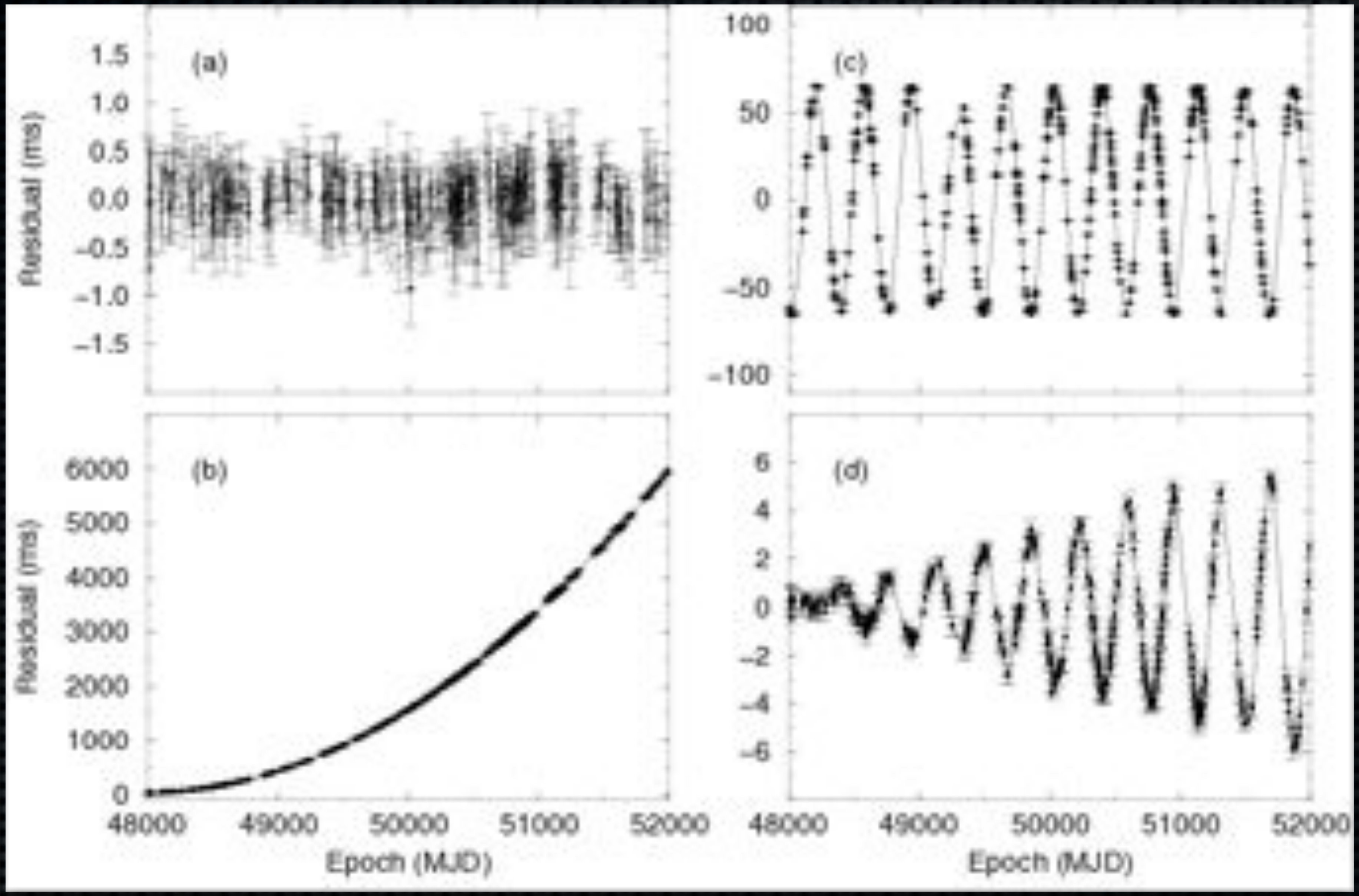
Pulsar timing & residuals





An error in the period of the source causes the residual to increase linearly with time

$$R = t_{obs} - t_{Model}$$



Pulsar residuals

a) Best fit of all parameters; b) Without fitting for frequency derivative

c) An error in the pulsar position; d) Without fitting for proper motion

Very high precision timing

Some pulsars are inherently very precise clocks.

We can use these as “test mass/clocks” in gravitational experiments to test theories of gravity (e.g. in binary systems) and as “arms” of a giant gravity wave detector.

Some of the requirements to perform the accurate measurements required for these tests are:

- High signal-to-noise ratio observations.
- Pulsars with low scattering and well modelled dispersion measure.
- Well characterised antenna, signal-chain and backend
- Pulsars with low intrinsic variability.

Timing Summary

- Modelling of the arrival times allows us to determine the source period, period derivative, sky position, proper motion, binary parameters, etc...
- Pulsar timing can measure parameters of astronomical objects to extraordinary precision.

Thanks & Further Reading

Most of the figures in this presentation come from "Handbook of Pulsar Astronomy" **Lorimer & Kramer** (Cambridge University Press).