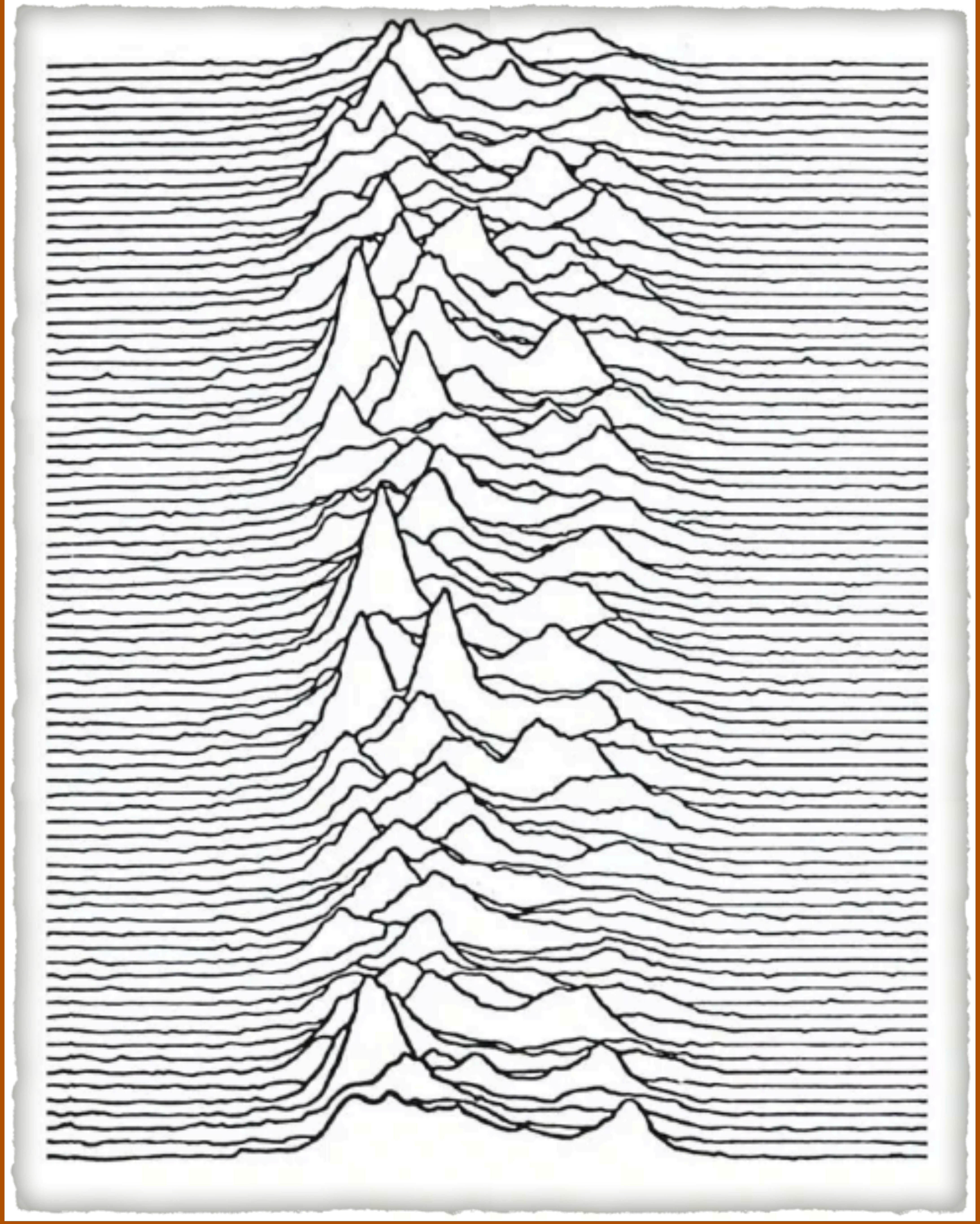
NASSP Pulsar lectures



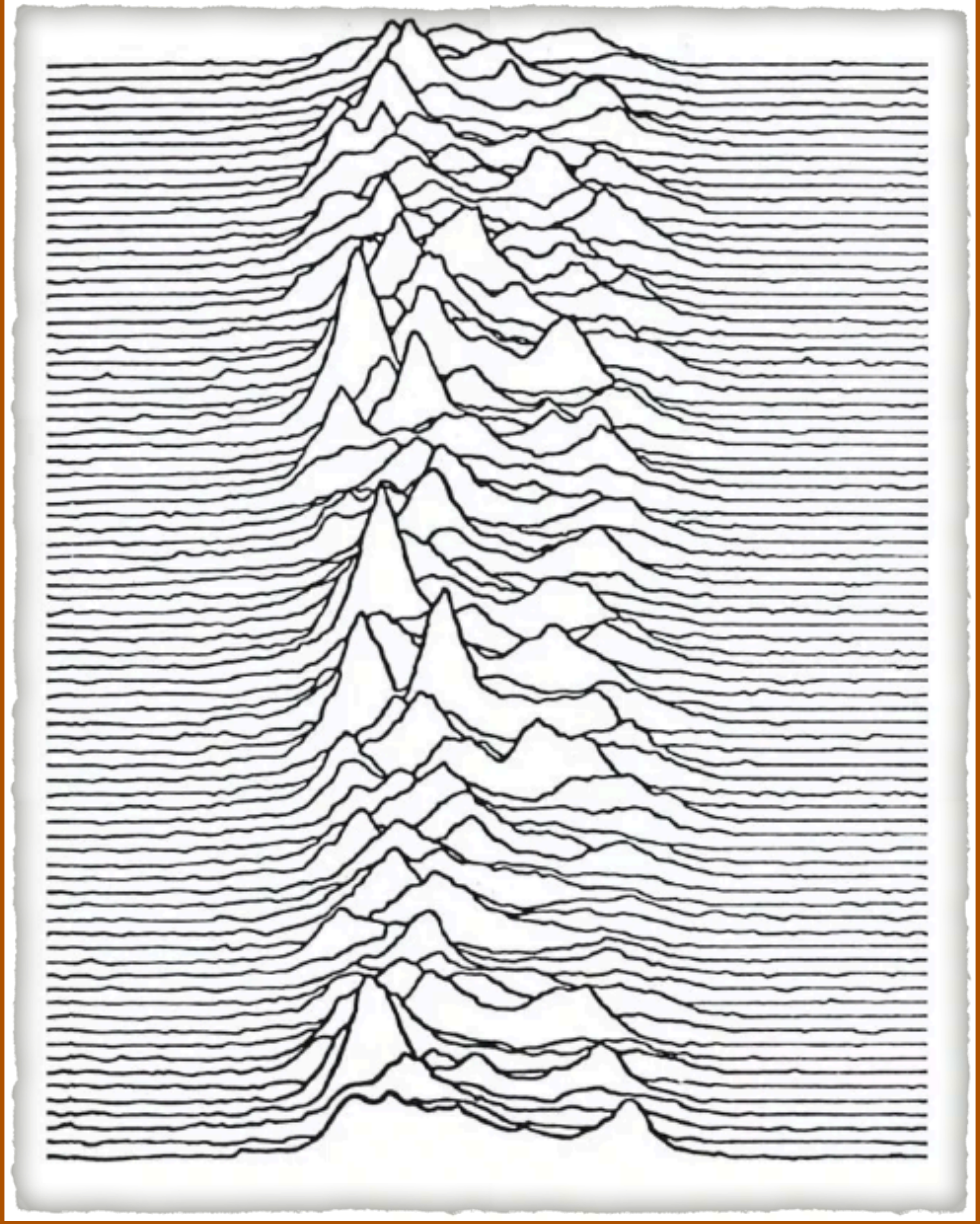
Course layout:

Lecture 1: Radio pulsar observations

Lecture 2: Pulsar properties

Marisa Geyer, SARAO

NASSP Pulsar lectures



Course layout:

Lecture 1: Radio pulsar observations

Lecture 2: Pulsar properties

Marisa Geyer, SARAO

Lecture 1 : Radio pulsar observations

- The simple lighthouse model
- Creating the stable pulse profile
- Pulsars are broad band emitters
- Propagation of pulsar signals through the Interstellar Medium
    - The ISM refractive index
    - Dispersion delay by the ISM — and how do we correct for it
    - Pulsar scattering by the ISM— and how do we model it
- Pulsar Sensitivity — how can we detect pulsars using radio telescopes
    - Telescope parameters
    - The modified radiometer equation

The simple lighthouse picture

- As a simple picture we can think of pulsars as the (radio) lighthouses of the night sky
- Using a sensitive telescope, we aim to pick up its signal every time the beam crosses our line of sight
- In this lecture we will see what it takes to detect a signal from a pulsar using a radio telescope such as MeerKAT
- **In the next lecture we'll take a step back, and look at what pulsars are and how they form**

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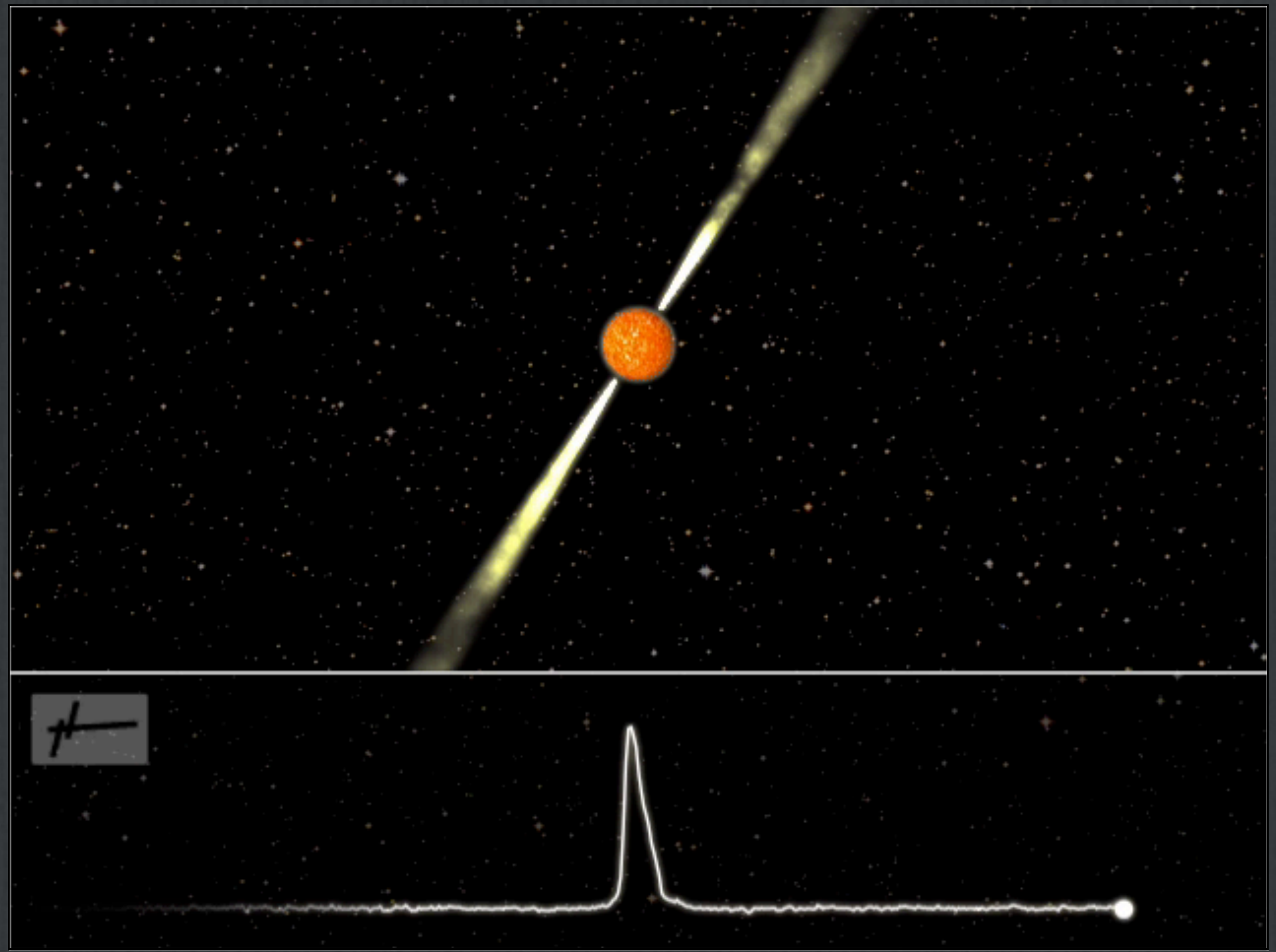


Credit: Joeri van Leeuwen, https://www.astron.nl/pulsars/animations/

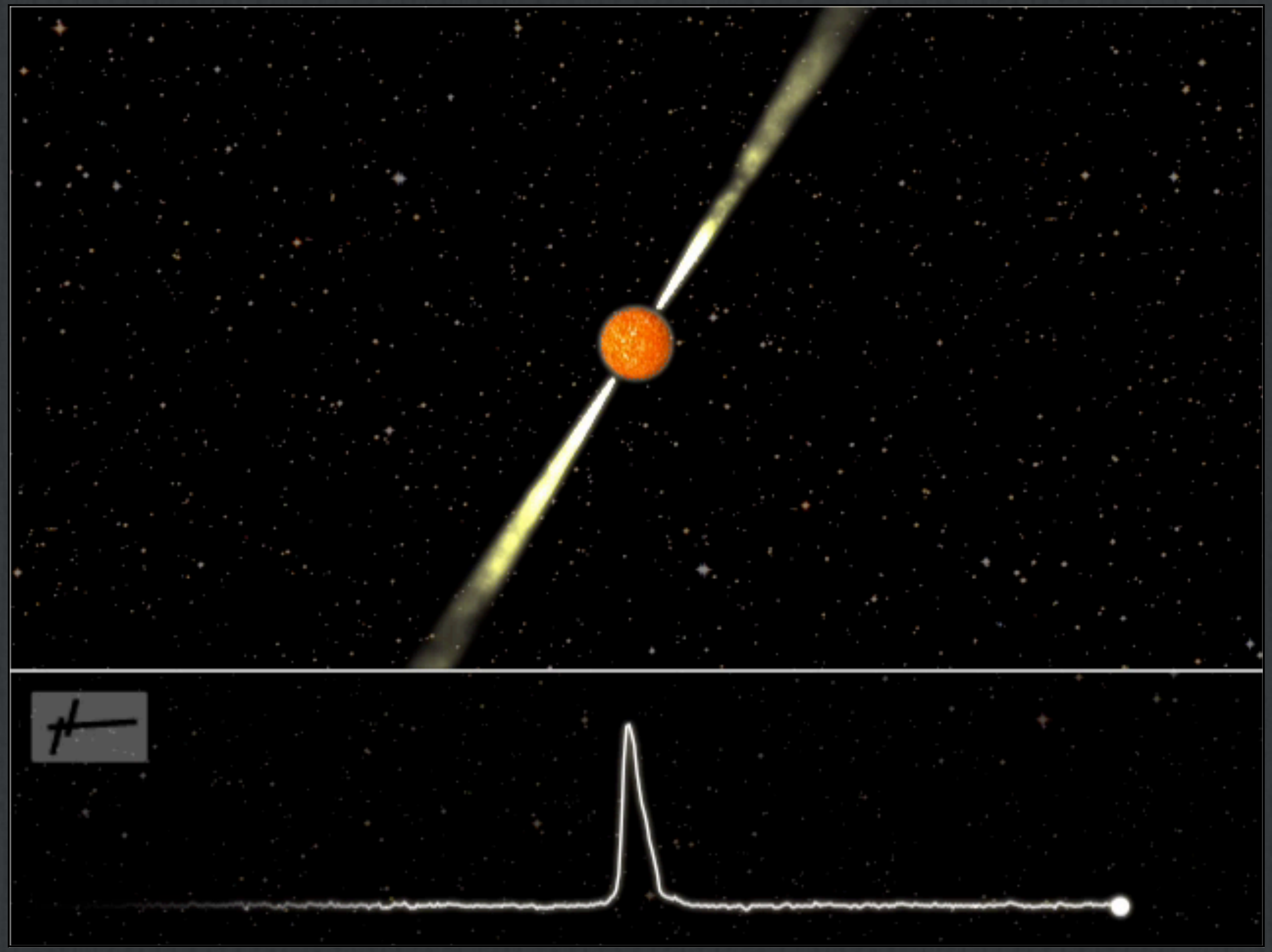
Adding single pulses to form a stable pulse

- Single pulses are very faint and variable

- Only for some very bright pulsars can we detect single pulses using sensitive radio telescopes

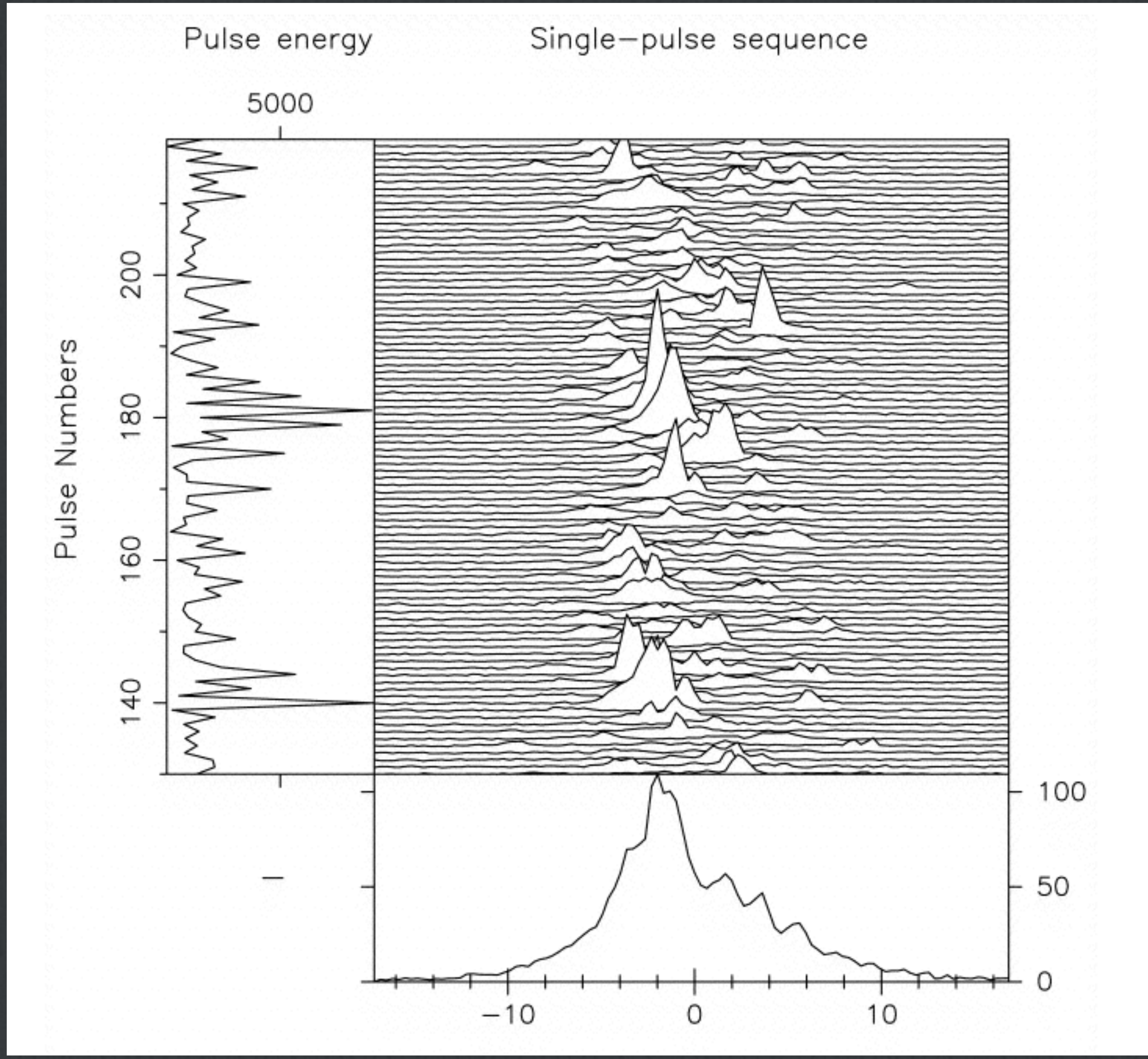
- Single pulses appear very varied, but averaging ~ 1000 pulses gives a stable pulse shape called the “average pulse profile”

- By knowing the pulsar observing parameters (including location, pulse period) we can add single pulses together to form detectable average pulses



Only see individual pulses in a small number of bright pulsars using sensitive telescopes

Adding single pulses to form a stable pulse



PSR B0943+10

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Pulsars are broad band

- Broad band emitters: they have been observed in the radio all the way from 30 MHz - 230 GHz!

- They are intrinsically brighter at lower frequencies. In other words they are steep spectrum sources:

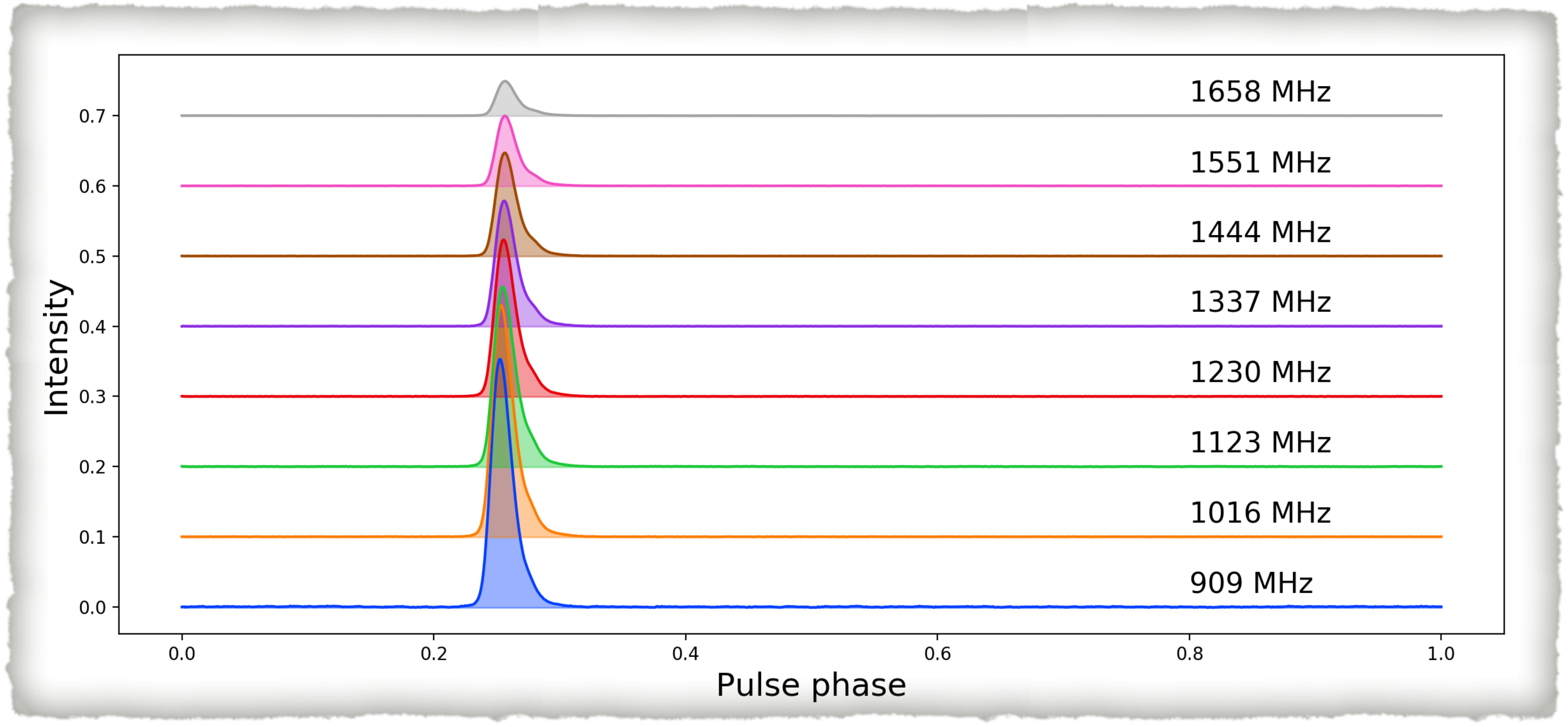
$$S_\nu \propto \nu^{-\alpha}$$

- where S_ν is flux (Jy) at a frequency ν and typical values for α ~ 1.4

- Even though pulsars are brighter at lower frequencies, we'll see that lower frequency signals are more effected by the Interstellar Medium (ISM)

- Finding the ideal observing frequency is therefore a trade-off between intrinsic brightness and ISM effects

The Vela pulsar (J0835-4510) across the MeerKAT band



Interstellar Medium Effects

- All stars and objects in the Galaxy are embedded in a diffuse medium, called the 'Interstellar Medium'

- The ISM has many different components, including

    - gas (containing atoms, molecules, ions and free electrons)

    - dust (tiny solid particles)

Various Types of Interstellar Matter:

- Reddish nebulae - light emitted by hydrogen atoms.
- The darkest areas - clouds of dust
- The bluish glows - light reflected from hot stars embedded in large cool clouds of dust and gas.

(credit: ESO/Digitized Sky Survey 2)

Interstellar Medium Effects

- All stars and objects in the Galaxy are embedded in a diffuse medium, called the ‘Interstellar Medium’

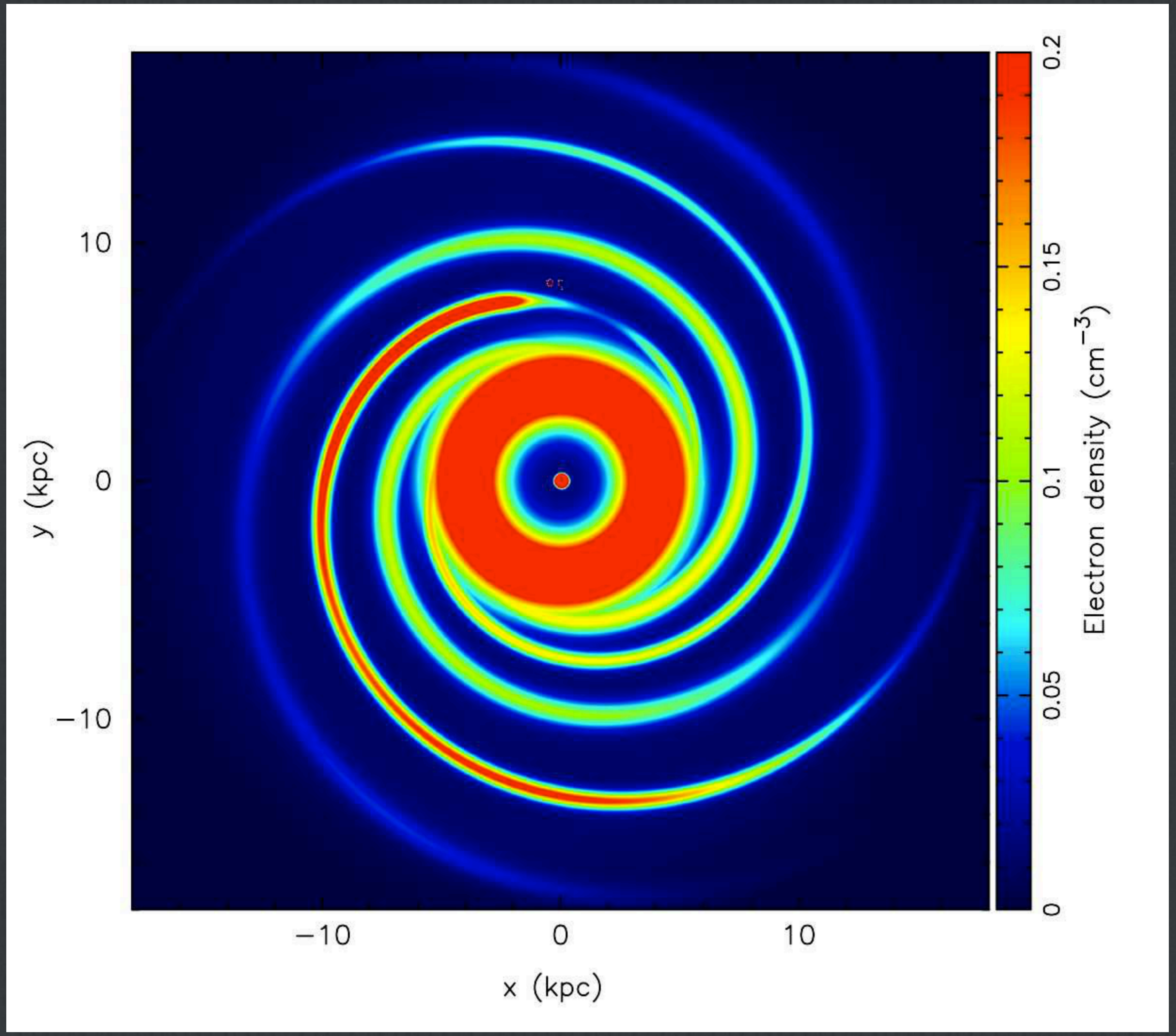
- The ISM has many different components, including

- gas (containing atoms, molecules, ions and free electrons)
- dust (tiny solid particles)

-**The ionised component of the ISM has a frequency dependent impact on pulsar signals that we can model**

- This ionised ISM (containing free electrons) can be modelled as a cold (“partially ionised”) plasma of ~ 8000 K

(note that cold means it is colder than the ‘hot’ or ‘fully ionised’ part of the ISM)



Yao et al. 2017: Electron density model in the galactic plane

The ISM refractive index

- μ ISM refractive index i.t.o its plasma frequency, and the propagating radio wave frequency

$$\mu = \sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2}$$

- ν is the frequency of the pulsar radio emission propagating through the ISM

- ν_p is the resonant ISM plasma frequency as a function of free electron density (n_e)

$$\nu_p = \left(\frac{e^2 n_e}{\pi m_e}\right)^{1/2} \approx 8.97 \left(\frac{n_e}{\mathrm{cm}^{-3}}\right)^{1/2} \mathrm{kHz}$$

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electron mass, $m_e = 9.109 \times 10^{-31}$ kg
electron charge, $e = 1.6022 \times 10^{-19}$ C

SI conversions:
1 $\text{cm}^{-3} = 1 \times 10^{-6}\ \text{m}^{-3}$
1Hz = 1000kHz

The ISM refractive index

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- ν is the frequency of the pulsar radio emission propagating through the ISM
- ν_p is the resonant ISM plasma frequency as a function of free electron density (n_e)
- Typical average n_e densities in the galaxy are $n_e \sim 0.03\ \mathrm{cm}^{-3}$
- What is ν_p for $n_e = 0.03\ \mathrm{cm}^{-3}$?

The wave group velocity

- Radio waves of frequency ν propagate with group velocity v_g in the ISM

- From definition of refractive index

$$\mu = \frac{v_g}{c} = \sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2}$$

$\nu_p > \nu$ then $\mu \rightarrow$ imaginary

waves don't propagate

$\nu_p < \nu$ then $\mu < 1$

waves propagate with velocity

$$v_g = c\mu < c$$

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$$v_g = c\mu < c$$

typical ~ 1.5 kHz

typical ~ 10 MHz - 100 GHz

The wave group velocity

- Radio waves in the ISM propagate with group velocity v_g

- Since $\nu_p << \nu$ for most radio observations we can compute v_g using a Taylor expansion

$$v_g = c\,\mu = c\,\sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2} \approx c\left(1 - \frac{\nu_p^2}{2\nu^2}\right)$$

first 2 terms
of Taylor expansion

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Question: how will the wave velocity change with radio wave frequency?

The wave group velocity

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Question: how will the wave velocity change with radio wave frequency?

Question: when observing a pulsar - will all its emission arrive at the telescope simultaneously?

Dispersive Delay

$$\frac{1}{\mathrm{v_g}} \approx \frac{1}{c}\left(1+\frac{\nu_p^2}{2\nu^2}\right)$$

$$\nu_p = \left(\frac{e^2 n_e}{\pi m_e}\right)^{1/2}$$

Radio emission of frequency ν is delayed by the ISM by t sec:

$$t = \int_0^d \frac{dl}{v_g} - \frac{d}{c} \qquad = \frac{1}{c}\int_0^d \left(1+\frac{\nu_p^2}{2\nu^2}\right) dl - \frac{d}{c} = \left(\frac{e^2}{2\pi m_e c}\right)\nu^{-2}\int_0^d n_e \, dl$$

Pulsar at distance d,
Observer at 0

Time to travel from pulsar
to observer
at the speed of light (no delay)

Plugging in astronomical units

$$t = 4.149 \times 10^3 \mathrm{sec} \left(\frac{\nu}{\mathrm{MHz}}\right)^{-2}\left(\frac{\int_0^{\mathrm{d}} \mathrm{n_e\, dl}}{\mathrm{pc\ cm^{-3}}}\right)$$

Dispersive Delay

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$$= 4.149 \times 10^3 \mathrm{sec}\ \left(\frac{\nu}{\mathrm{MHz}}\right)^{-2} \left(\frac{\mathrm{DM}}{\mathrm{pc\ cm^{-3}}}\right)$$

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Dispersion measure, unit: pc cm^{-3}

Dispersive Delay

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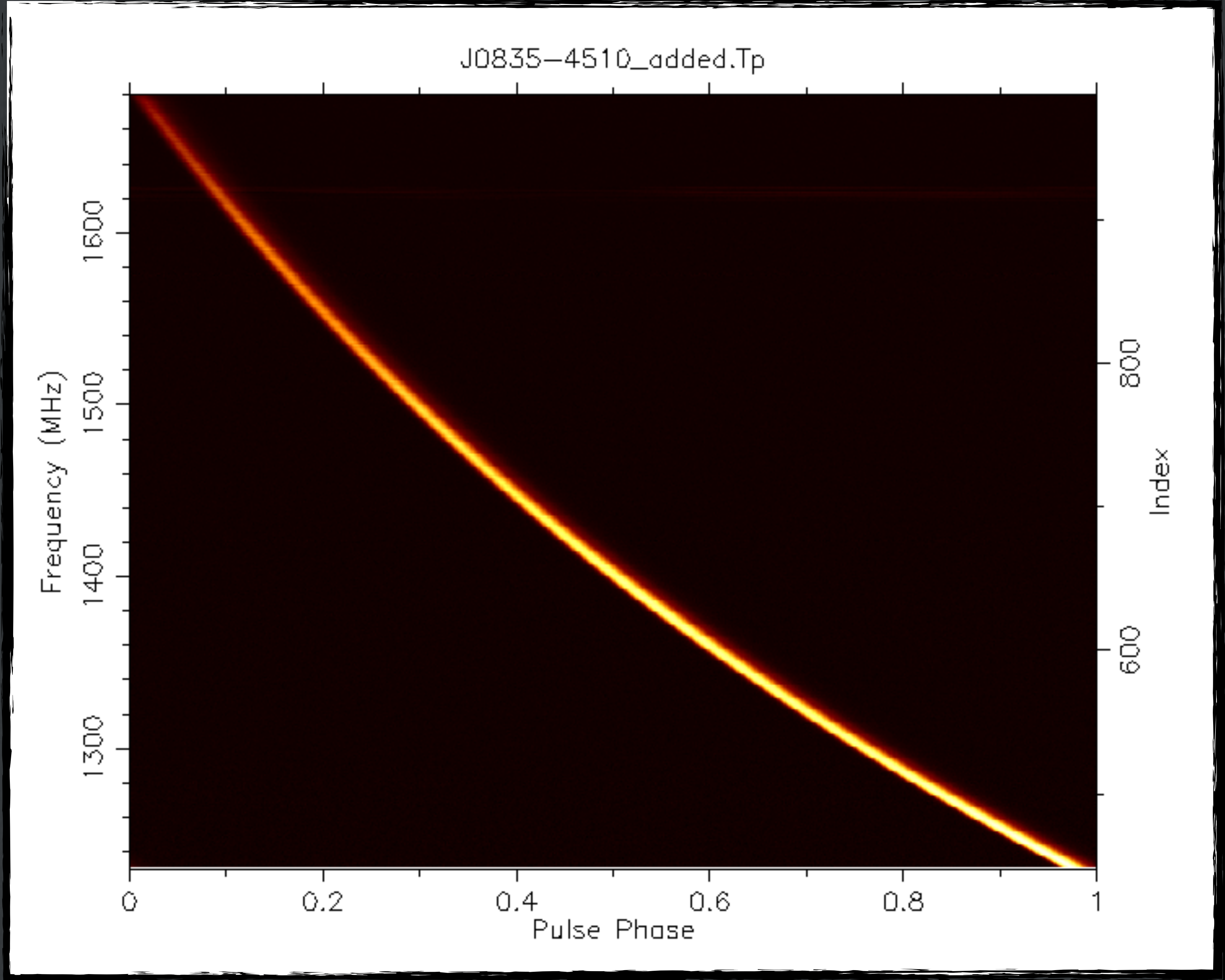

Plugging in astronomical units

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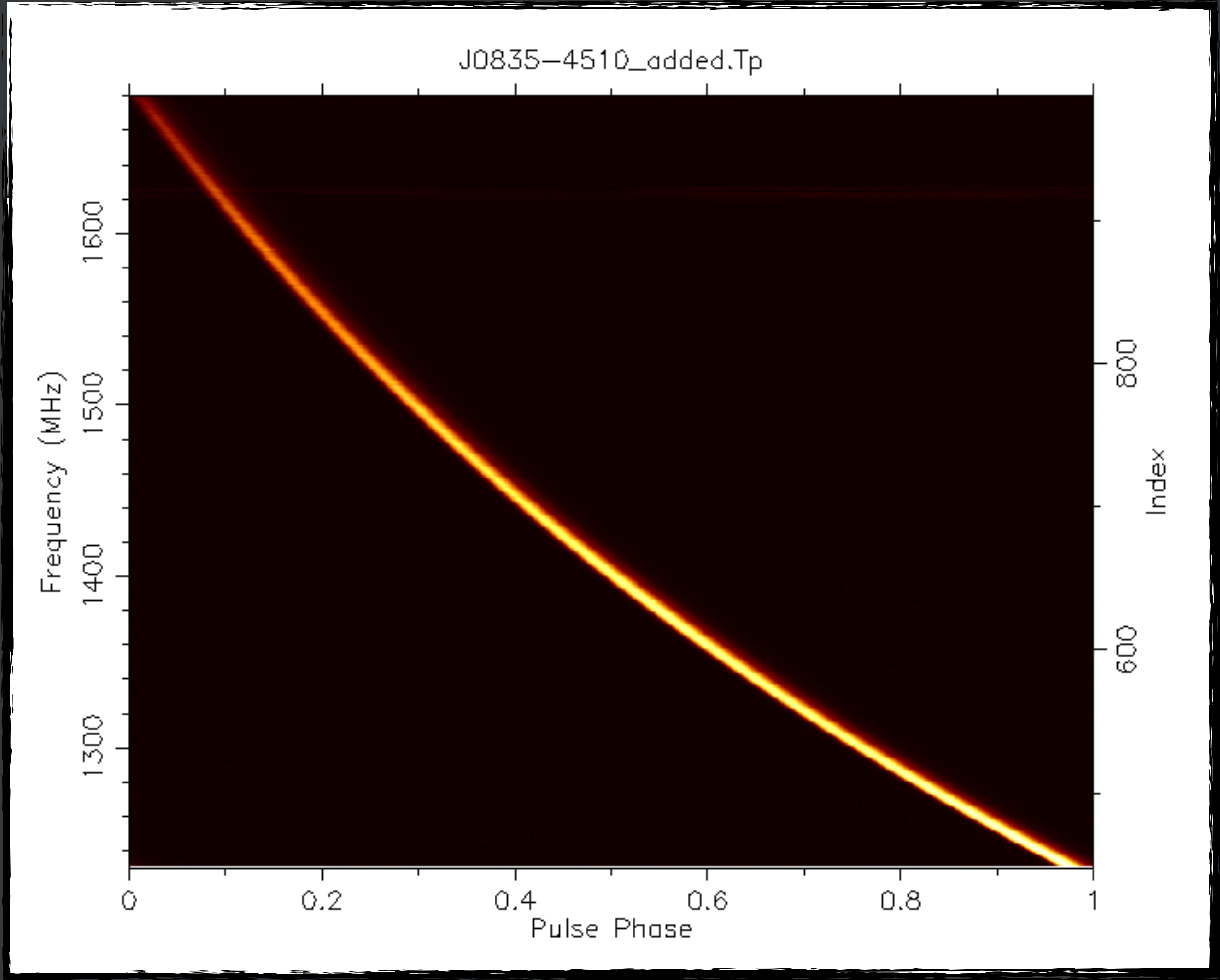
Strong frequency dependence

Dispersion measure, unit: pc cm^{-3}

Dispersive delay between high and low frequencies

$$t_l - t_h = 4.15 \times 10^3 \times \mathrm{DM} \times \left[\frac{1}{\nu_\mathrm{l}^2} - \frac{1}{\nu_\mathrm{h}^2}\right]$$



- The "dispersion measure" (DM) is the integrated column density of electrons between the observer and the pulsar
- Most well-known pulsars have good established estimates of their associated DM values
- The DM value can have a dependence on time/observing epoch, especially if the ISM environment towards a given pulsar is variable
- However, since the DM represents an integrated value along a long line of sight, it does not vary much (to a first approximation) from observation to observation
- DM values can be obtained/refined by conducting a ν^{-2} fit across the delayed folded pulsar signature in the observing band.

Dispersive delay between high and low frequencies

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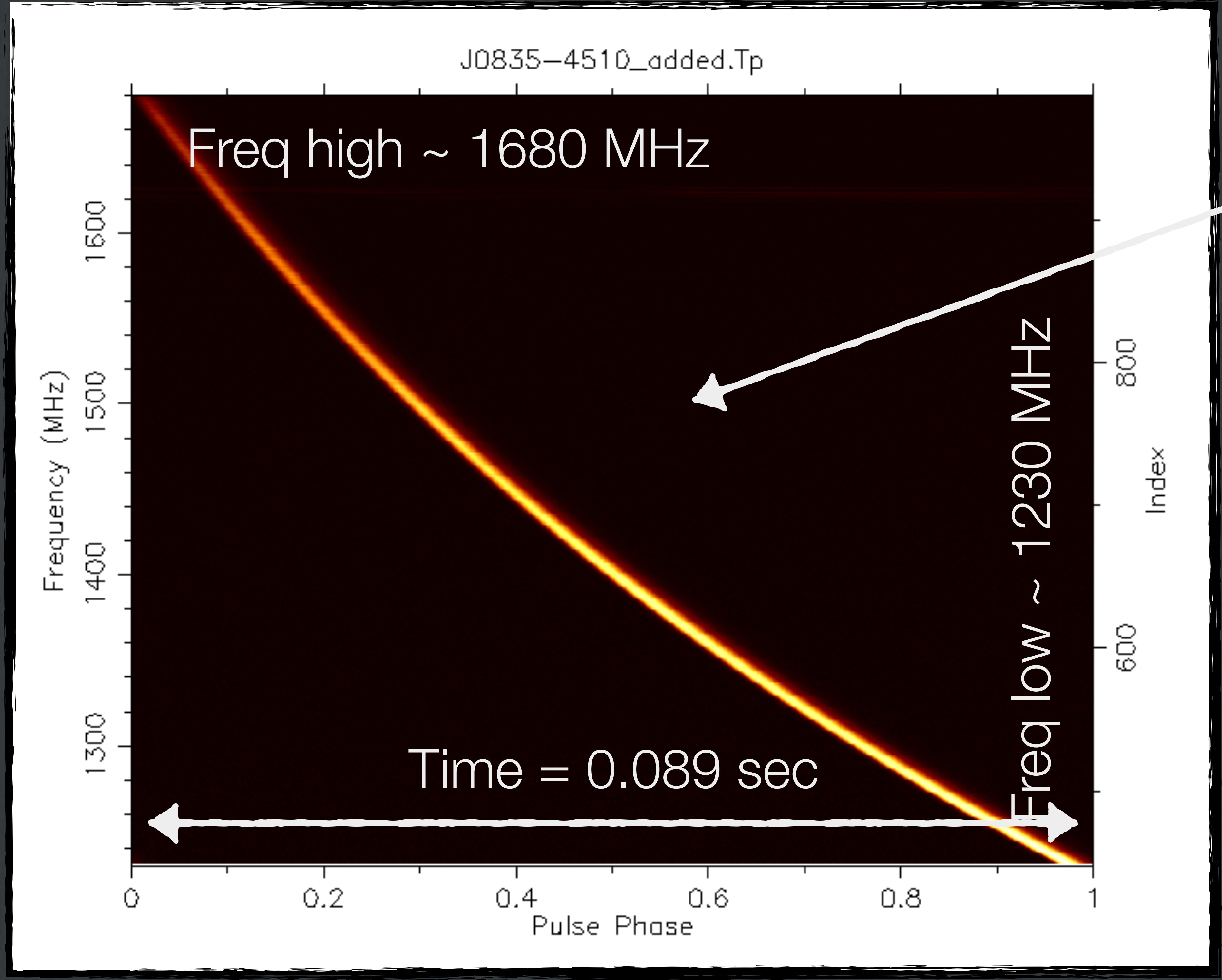
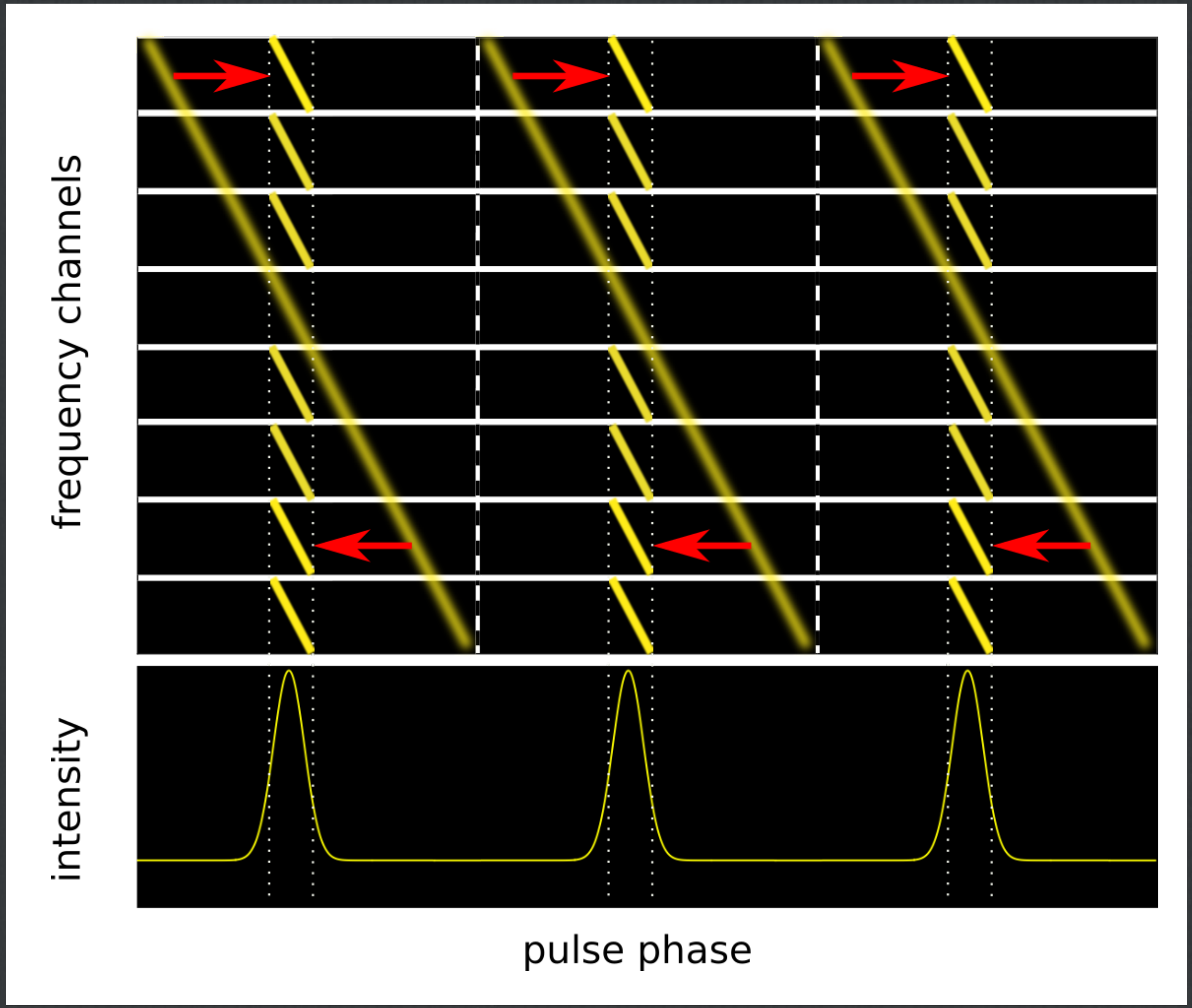


- Can you estimate Vela's DM from this figure?
- How could you improve on the estimate?

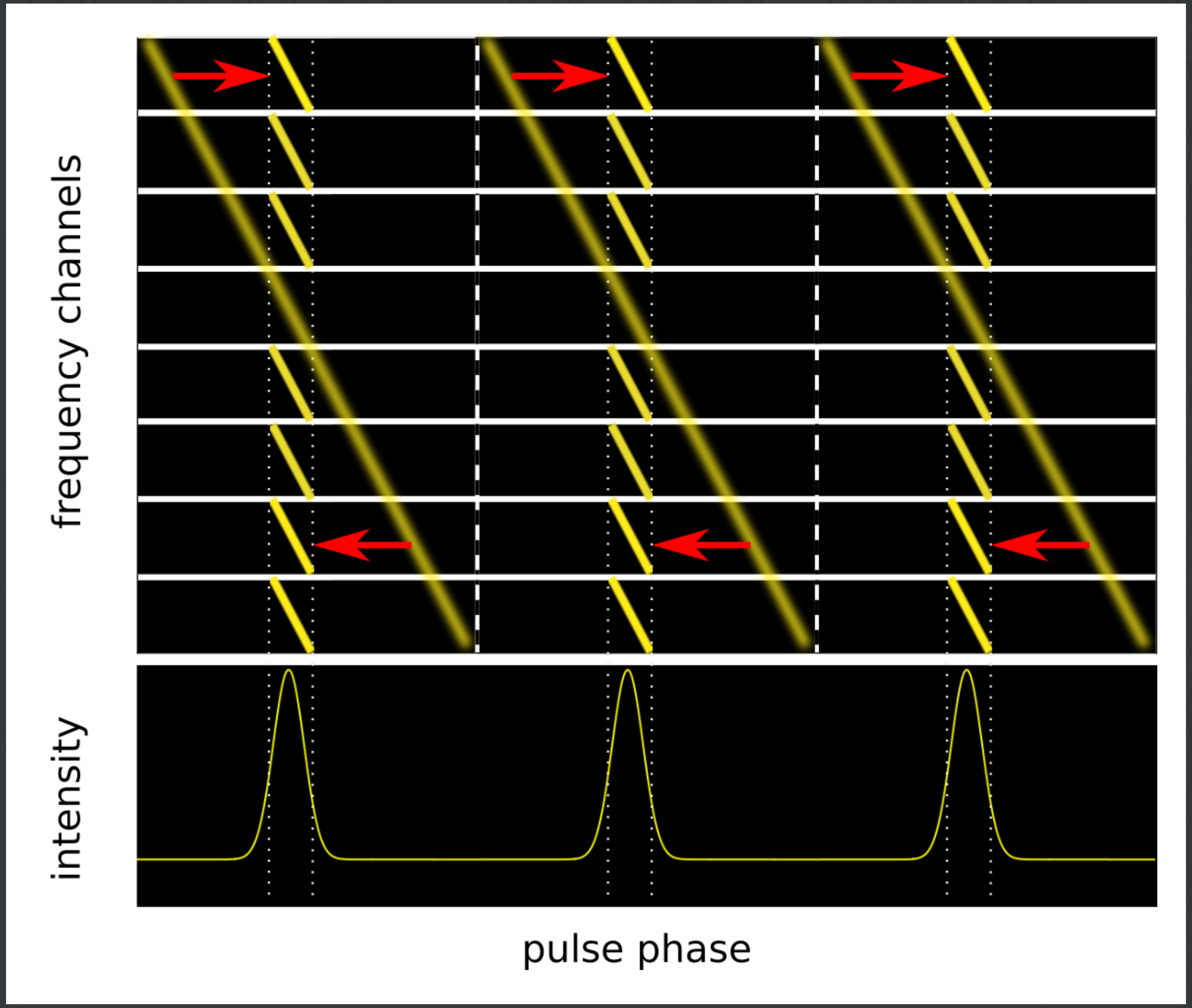
- In today's tutorial you will estimate the DM value of PSR J0738-4042 using a MeerKAT observation with a bandwidth of 856 MHz

Incoherent dedispersion



- The effect of dispersion can be removed by splitting the bandwidth up into a number of channels.
- In each channel we shift the time series by the calculated delay relative to the central frequency
- Correcting for dispersion in this way is called “dedispersion”
- In particular this method here is called “incoherent dedispersion”

Incoherent dedispersion



- The effect of dispersion can be removed by splitting the bandwidth up into a number of channels.
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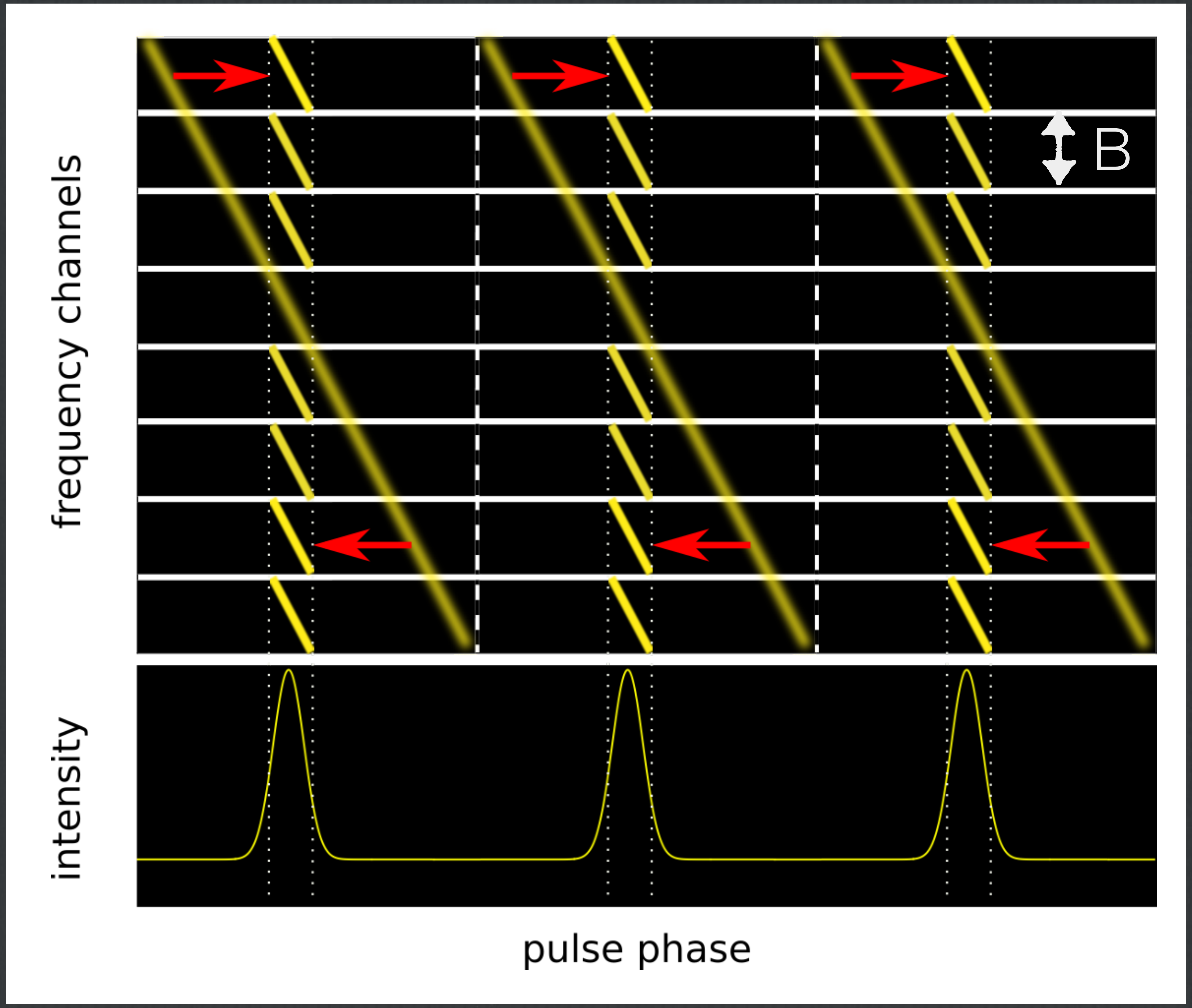
What happens if we have more frequency channels across the band?

Incoherent dedispersion



If the channel bandwidth is small compared to the observing frequency,

B << ν

then the smearing across the channel is given by

$$\boxed{\left(\frac{\Delta t}{\mathrm{sec}}\right)} = 8.3\times 10^{3}\left(\frac{\nu}{\mathrm{MHz}}\right)^{-3}\left(\frac{B}{\mathrm{MHz}}\right)\left(\frac{DM}{\mathrm{pc\ cm^{-3}}}\right)$$

With incoherent dedispersion there is residual smearing across each channel.

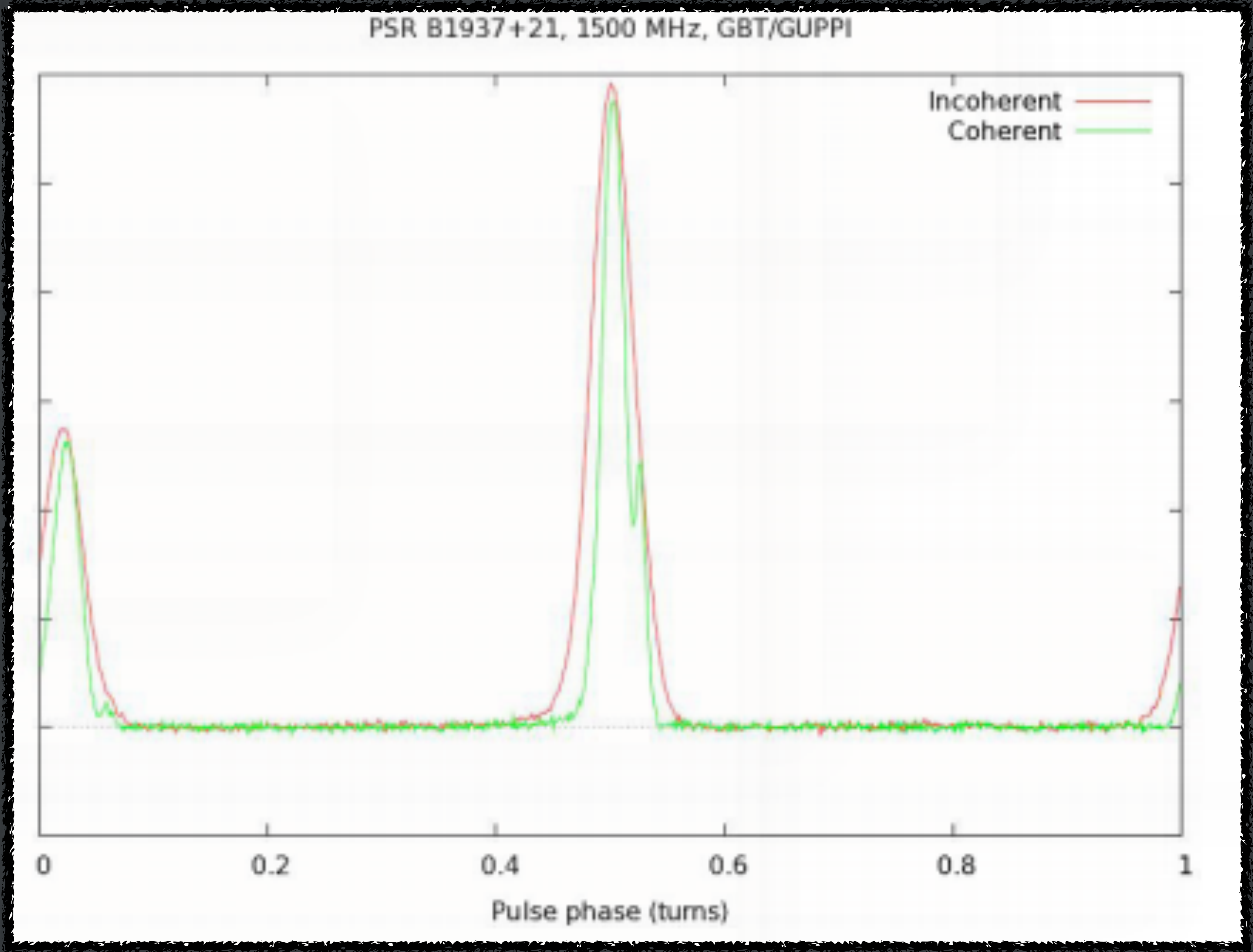
Coherent dedispersion

- Per channel residual smearing can be eliminated by using a more sophisticated dedispersion technique known as ‘coherent dedispersion’

- This technique involves applying the ISM correction before computing the pulsar intensity values (power values) at a given frequency channel

- Using a model of the ISM transfer function (in other words the ISM response), the corrective delays are applied directly to the **original measured phases** of the electric field associated with the radio waves

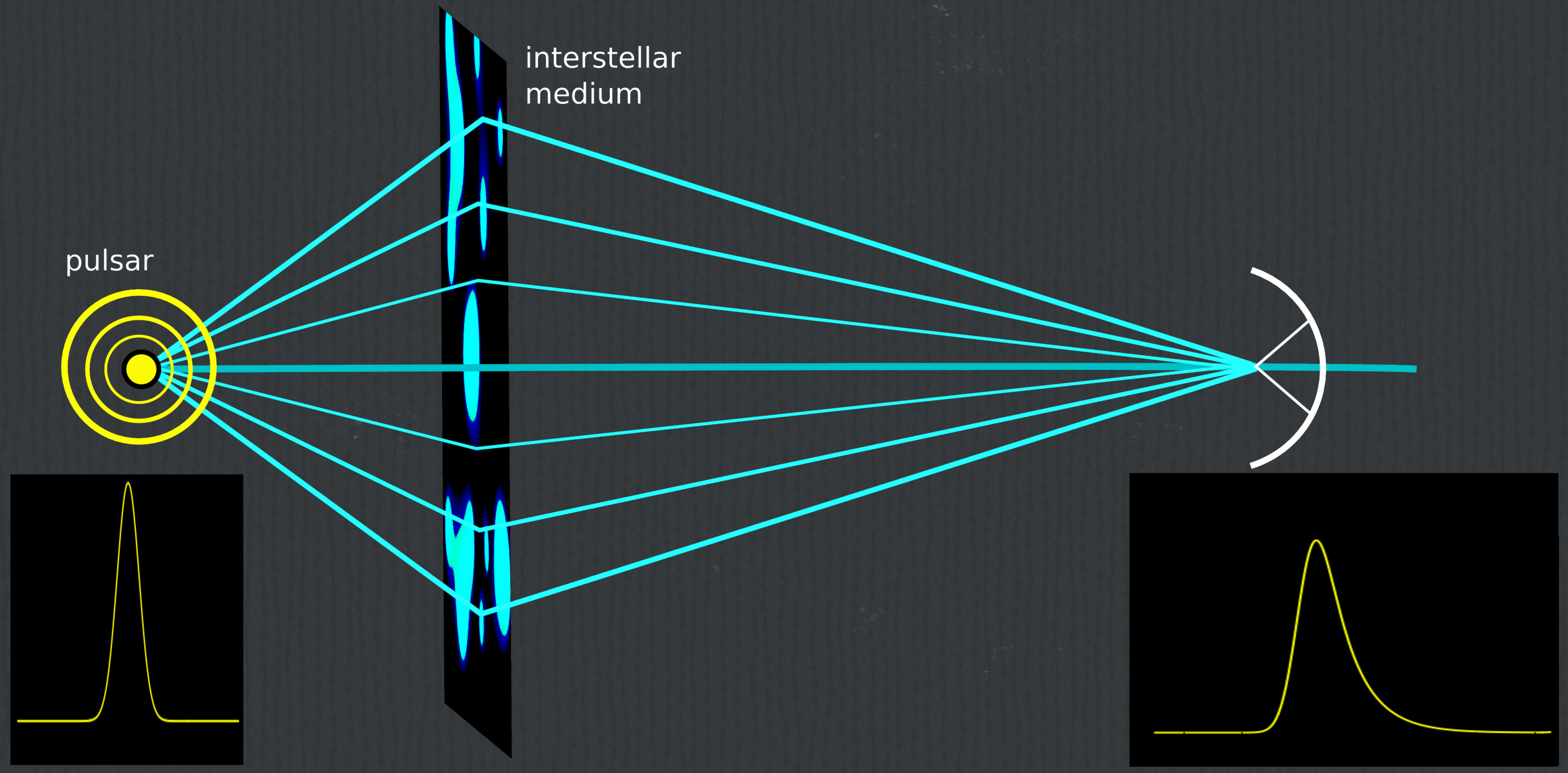
- Coherent dedispersion is a computationally expensive process, but it does remove residual channel smearing completely



Comparison between the incoherent and coherently dedispersed pulse profile of PSR B1937+21 (picture credit: Paul Demorest)

Pulsar Scattering

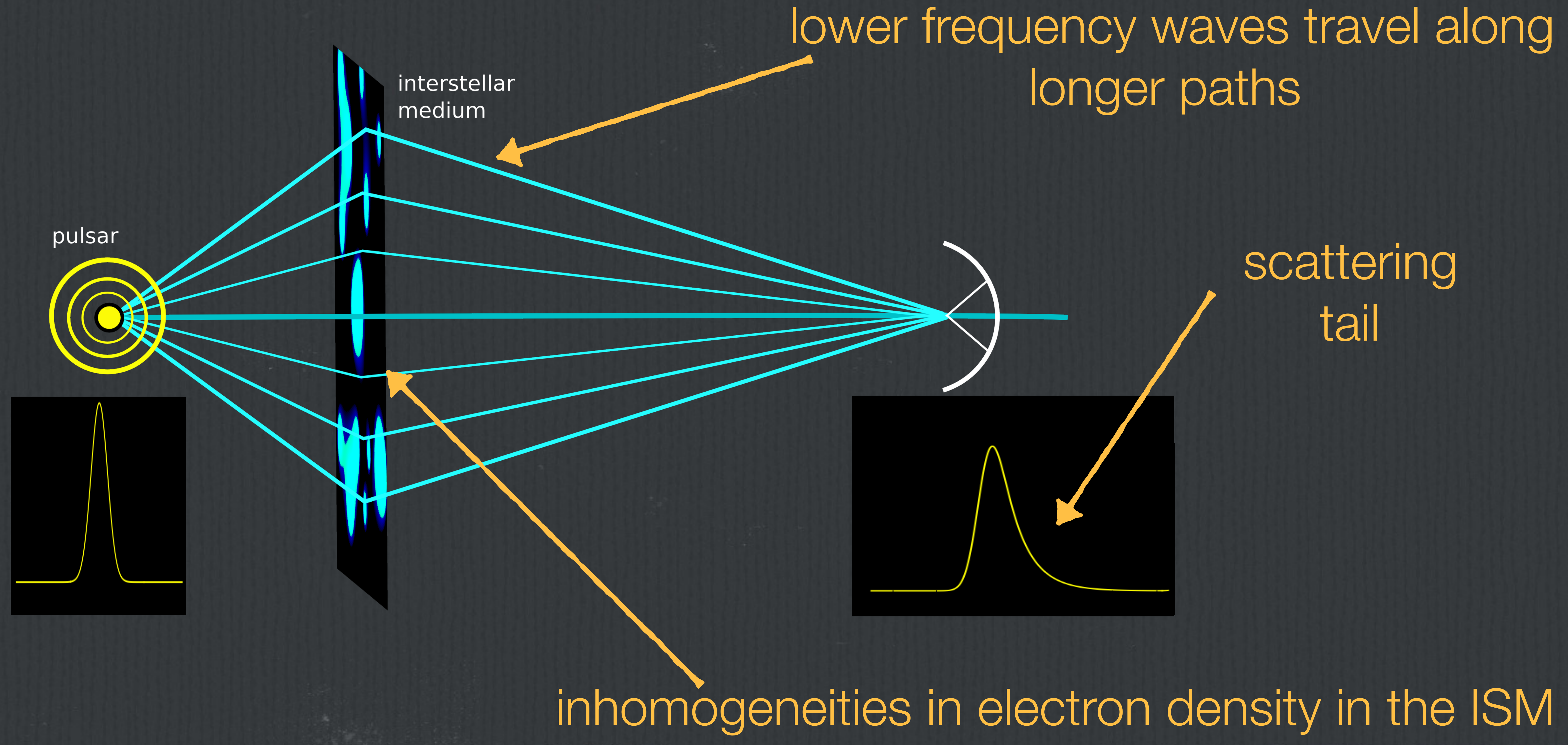
- The ionised ISM not only slows down the group velocity of radio waves depending on its frequency (dispersive delay)
- It can also ‘scatter’ radio waves leading to radio waves travelling along multiple paths.
- This effect is known as “interstellar or pulsar scattering” and it too has a strong frequency dependence
- In the case of dispersive delays the pulse delay depended on the **average electron density along the line of sight**
- **In the case of pulsar scattering the degree to which radio waves are scattered depend on electron density gradients — that is steep changes in electron densities as can be expected of a turbulent ISM medium**



Modelling Pulsar Scattering

- Average pulsar profiles that have been scattered by the ISM show ‘scattering tails’
- The ISM scatters lower frequency waves through larger angles, leading to longer delays
- In most cases scattering tails are well modelled with an exponential decay function: $e^{-t/\tau}$
- where τ is the “scattering timescale”
- This scattering time scale is strongly frequency dependent:

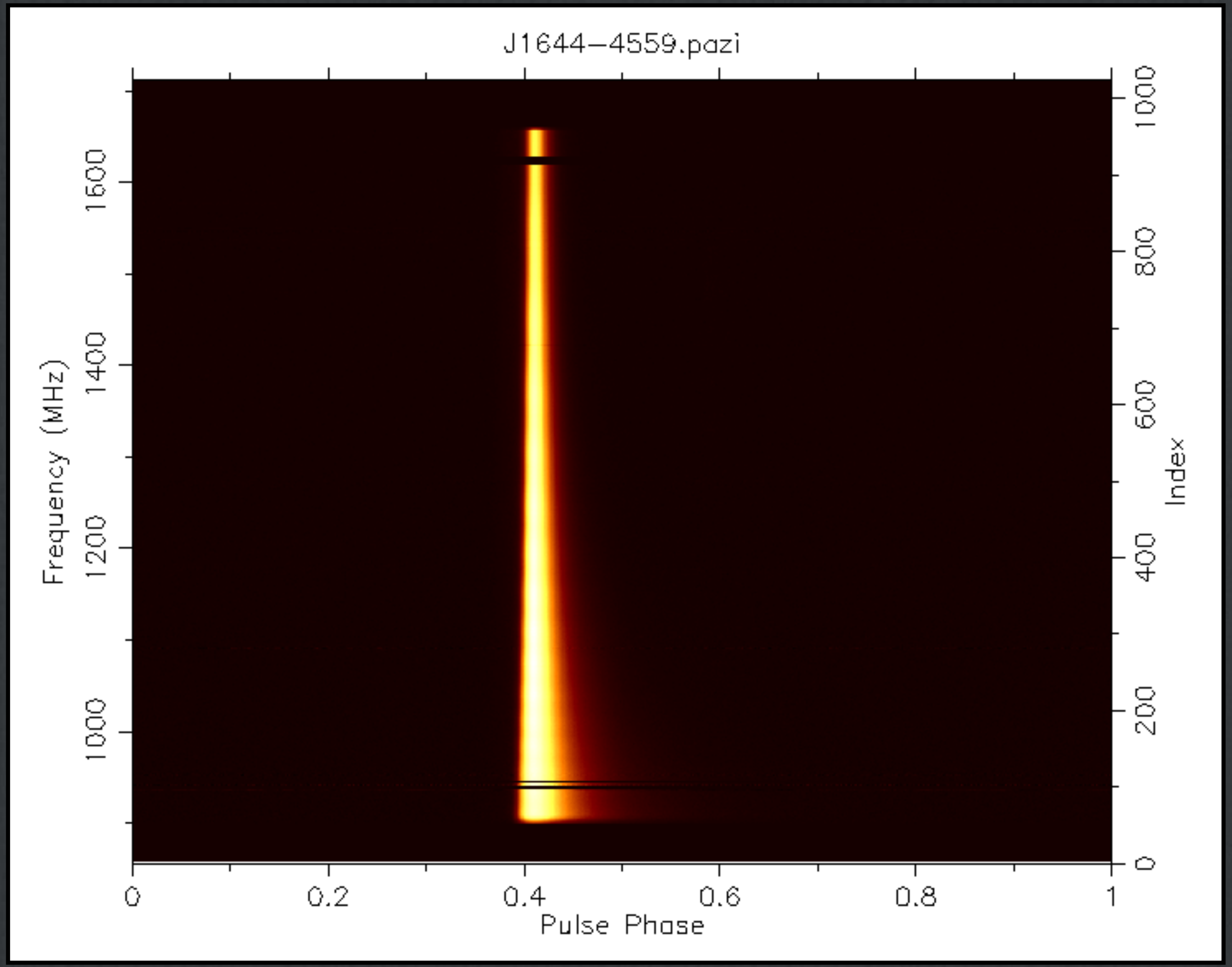
$$\tau \propto \nu^{-4}$$



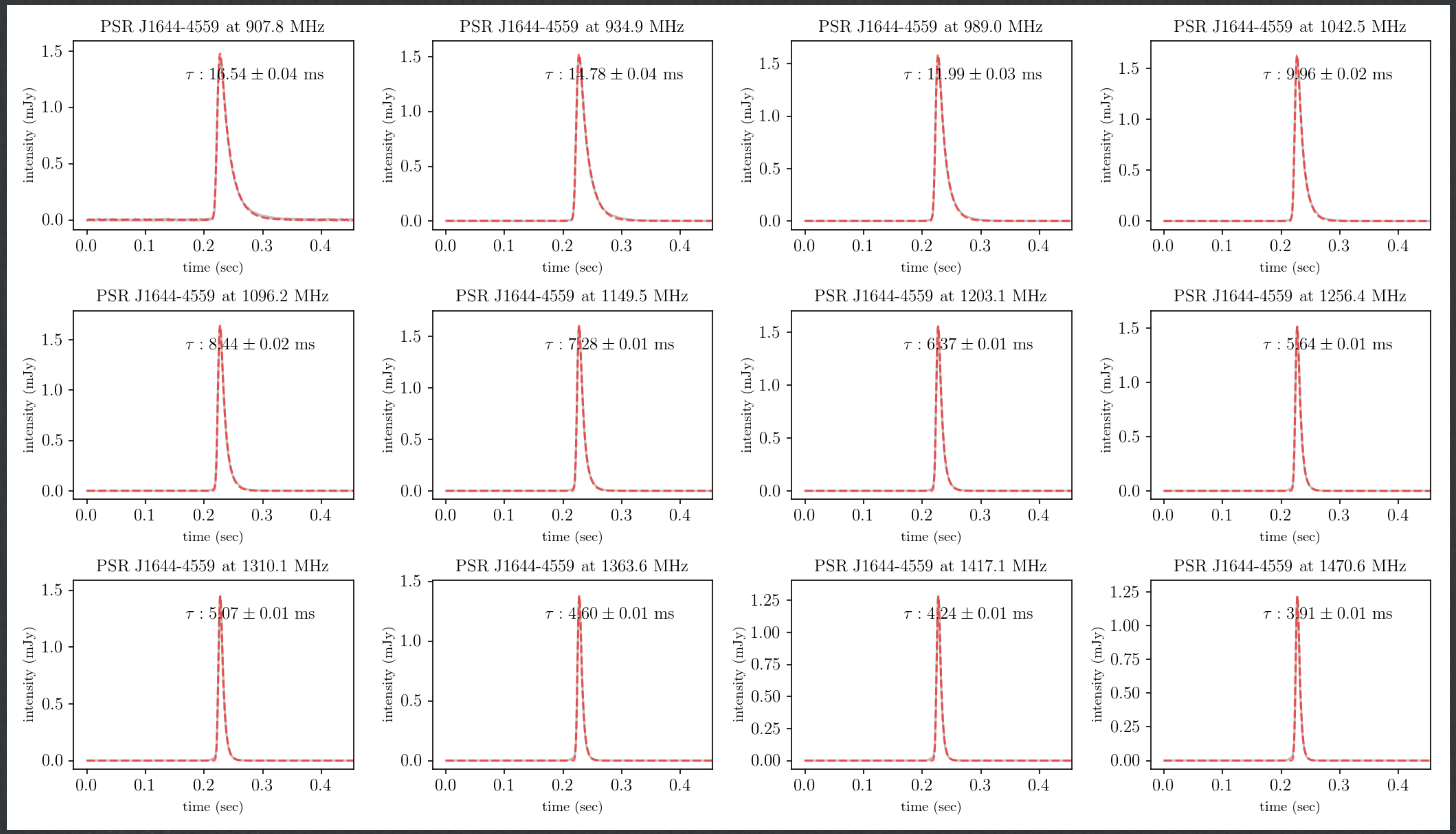
Examples of Pulsar Scattering

Studying pulsar scattering allow us to:

1) study the characteristics of the ISM along a given line of sight in more detail
2) By modelling scattering well, we can “fix” the pulse profile, and reconstruct it to its shape before it was distorted by the ISM

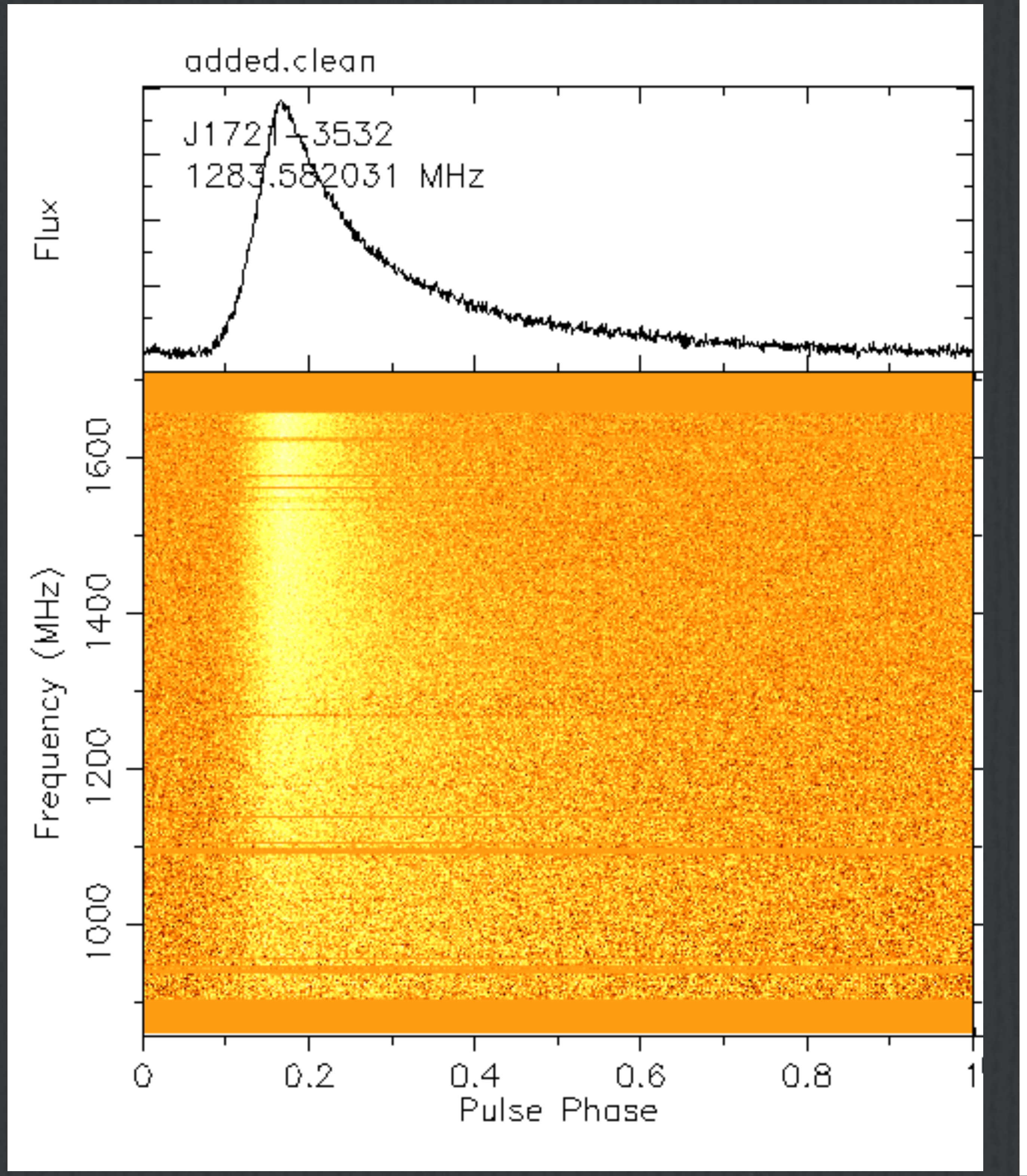


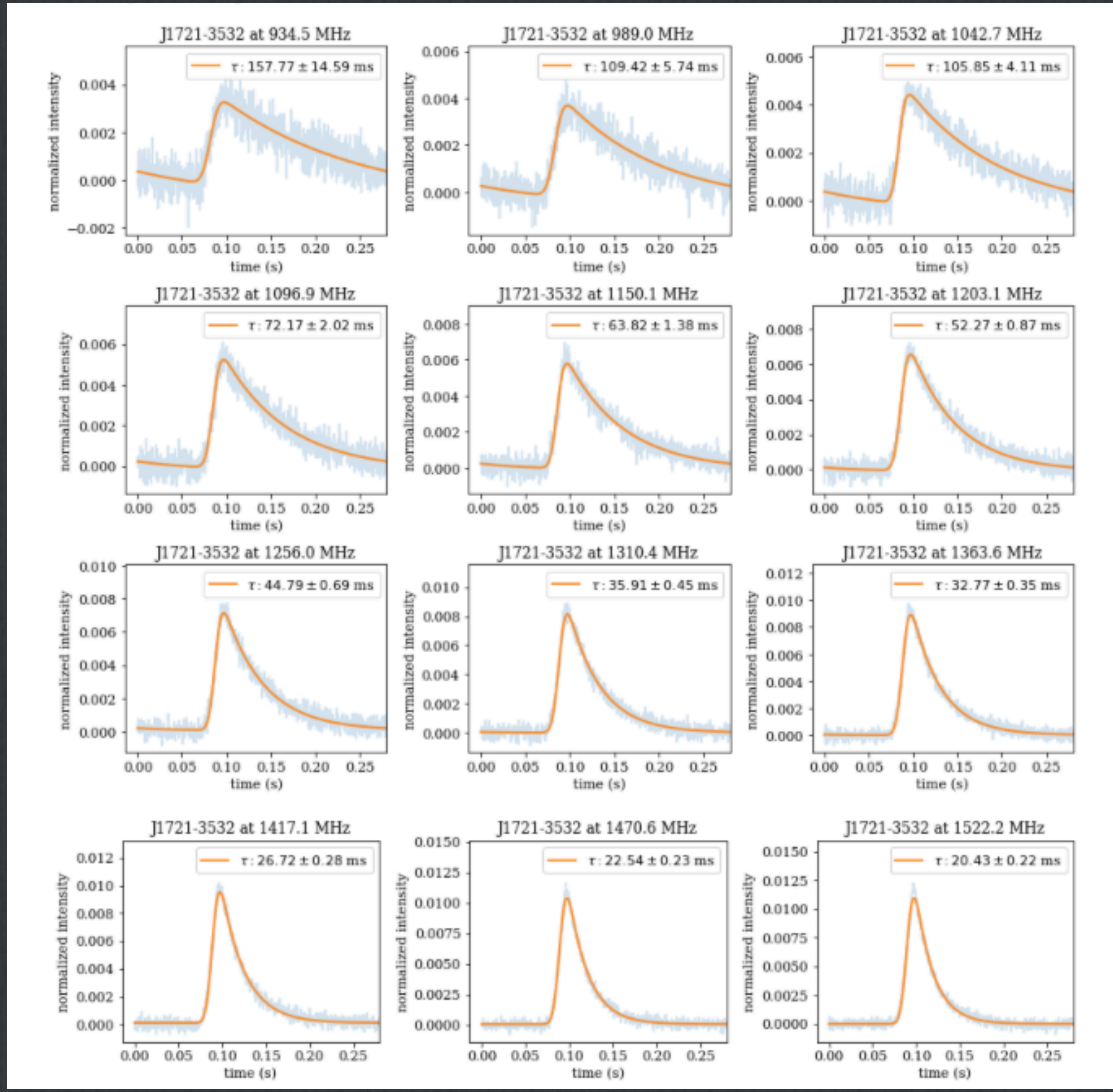
PSR J1644-4559



Examples of Pulsar Scattering

PSR J1721-3532





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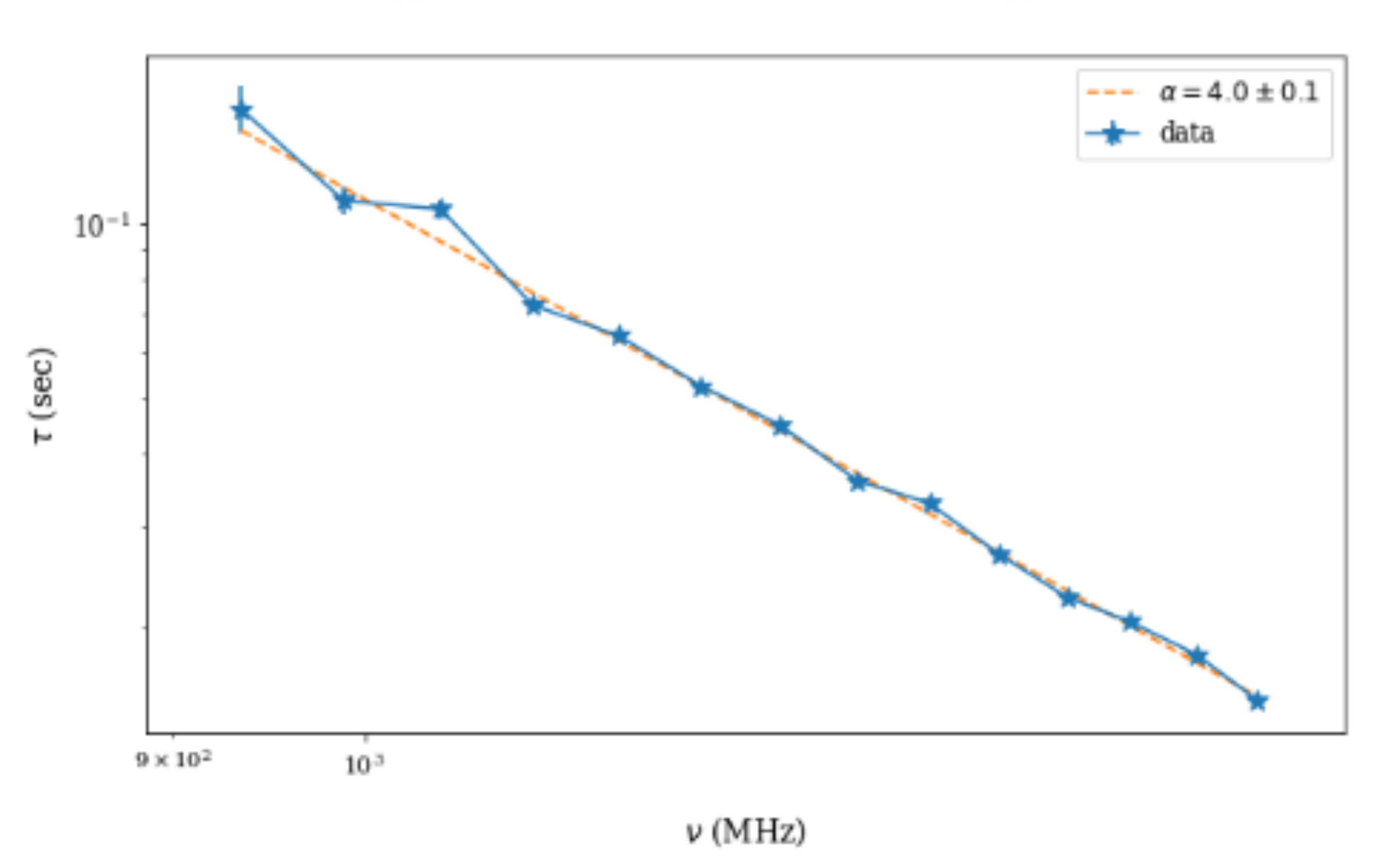

Pulsar Sensitivity

How many pulsars can we observe with a certain telescope?

Telescope parameter
Area of radio dish
Number of dishes
Bandwidth (MHz)
Observing time (sec)
System temperature (K)
Antenna Gain (K/Jy)

Telescope Parameters

How many pulsars can we observe with a certain telescope?

Telescope parameter	Effect
Area of radio dish	Bigger area = higher sensitivity
Number of dishes	More dishes = higher sensitivity
Bandwidth (MHz)	More bandwidth = higher sensitivity
Observing time (sec)	Long observing = higher sensitivity
System temperature (K)	Lower system temp = higher sensitivity
Antenna Gain (K/Jy)	Higher antenna gain = higher sensitivity

Telescope Parameters

How many pulsars can we observe with a certain telescope?

Telescope parameter
Area of radio dish
Number of dishes
Bandwidth (MHz)
Observing time (sec)
System temperature (K)
Antenna Gain (K/Jy)

Antenna Gain (K/Jy)

- Describes the conversion between temperature and flux (K/Jy)
- This involves the so-called “efficiency of the dish” a measured dish performance metric, $\eta < 1$:
- Antenna Gain (G) per dish is expressed as,

$$G = \frac{\eta A}{2k} \rightarrow \frac{\eta A}{2761}$$

$$[\mathrm{m^2 K/J}] \rightarrow [\mathrm{K/Jy}]$$

With A the area of the dish, k Boltzmann’s constant (k = 1.38 × 10^{-23} J/ K) and η the efficiency of the dish. In the above we have changed units to Jansky, through 1 Jy = 10^{26} J m^{-2}

What is the gain of each MeerKAT dish?

Antenna Gain (K/Jy)

- Describes the conversion between temperature and flux (K/Jy):
- Antenna Gain (G) per dish is,

$$G = \frac{\eta A}{2761} \qquad [\mathrm{K/Jy}]$$

- The MeerKAT gain per dish:

Effective diameter: 13.97 m

Efficiency: 0.76

$$G_{\mathrm{MeerKAT\,dish}} = \ldots$$

Modified Radiometer Equation

Combining the telescope parameters and pulsar properties

The min detectable flux S_{min} for pulsar, where:

$$S_{min} = \frac{(S/N)_{min}\ T_{sys}}{G\,N_{ant}\sqrt{n_p\ t\ B}}\sqrt{\frac{W}{P-W}}$$

P	Pulsar period (sec)
W	Width of pulsar (sec)
N_{ant}	Number of antennas
n_p	Number of polarizatons
B	Bandwidth
t	Observing time (sec)
$(S/N)_{min}$	Detection threshold signal-to-noise
G	Antenna Gain (K/Jy)

Modified Radiometer Equation

Combining the telescope parameters and pulsar properties

The min detectable flux S_{min} for pulsar, where:

$$S_{min} = \frac{\boxed{(S/N)_{min}}\, T_{sys}}{G\, N_{ant} \sqrt{n_p\, t\, B}} \sqrt{\frac{W}{P - W}}$$

This is a choice - what do you call a detection?

P	Pulsar period (sec)
W	Width of pulsar (sec)
N_{ant}	Number of antennas
n_p	Number of polarizatons
B	Bandwidth
t	Observing time (sec)
$(S/N)_{min}$	Detection threshold signal-to-noise
G	Antenna Gain (K/Jy)

Modified Radiometer Equation

Checking the units of S_{min}

sec/sec
=> dimensionless

$$S_{min} = \frac{(S/N)_{min}\ T_{sys}}{G\,N_{ant}\sqrt{n_p\ t\ B}}\boxed{\sqrt{\frac{W}{P-W}}}$$

n_p and N_{ant} are
dimensionless integers

S/N is dimensionless

Removing the dimensionless parameters,
the unit will be set by:

$$[S_{min}] \rightarrow \frac{T_{sys}}{G\sqrt{t\,B}} \rightarrow \frac{K}{\mathrm{K\,Jy^{-1}}\sqrt{\mathrm{sec\,Hz}}}$$

Modified Radiometer Equation

The units for S_{min} can be:

- Jy if B (bandwidth) is in Hz
- mJy if B (bandwidth) is in MHz

$$[S_{min}] \rightarrow \frac{T_{sys}}{G\sqrt{t\,B}} \rightarrow \frac{\cancel{K}}{\cancel{\mathrm{K}}\,\mathrm{Jy}^{-1}\sqrt{\cancel{\mathrm{sec\,Hz}}}} \rightarrow \mathrm{Jy}$$

$$[S_{min}] \rightarrow \frac{T_{sys}}{G\sqrt{t\,B}} \rightarrow \frac{\cancel{K}}{\cancel{\mathrm{K}}\,\mathrm{Jy}^{-1}\sqrt{\cancel{\mathrm{sec}}\,\underbrace{\mathrm{MHz}}_{10^6\cancel{\mathrm{Hz}}}}} \rightarrow 10^{-3}\mathrm{Jy} = \mathrm{mJy}$$

The End of Lecture 1