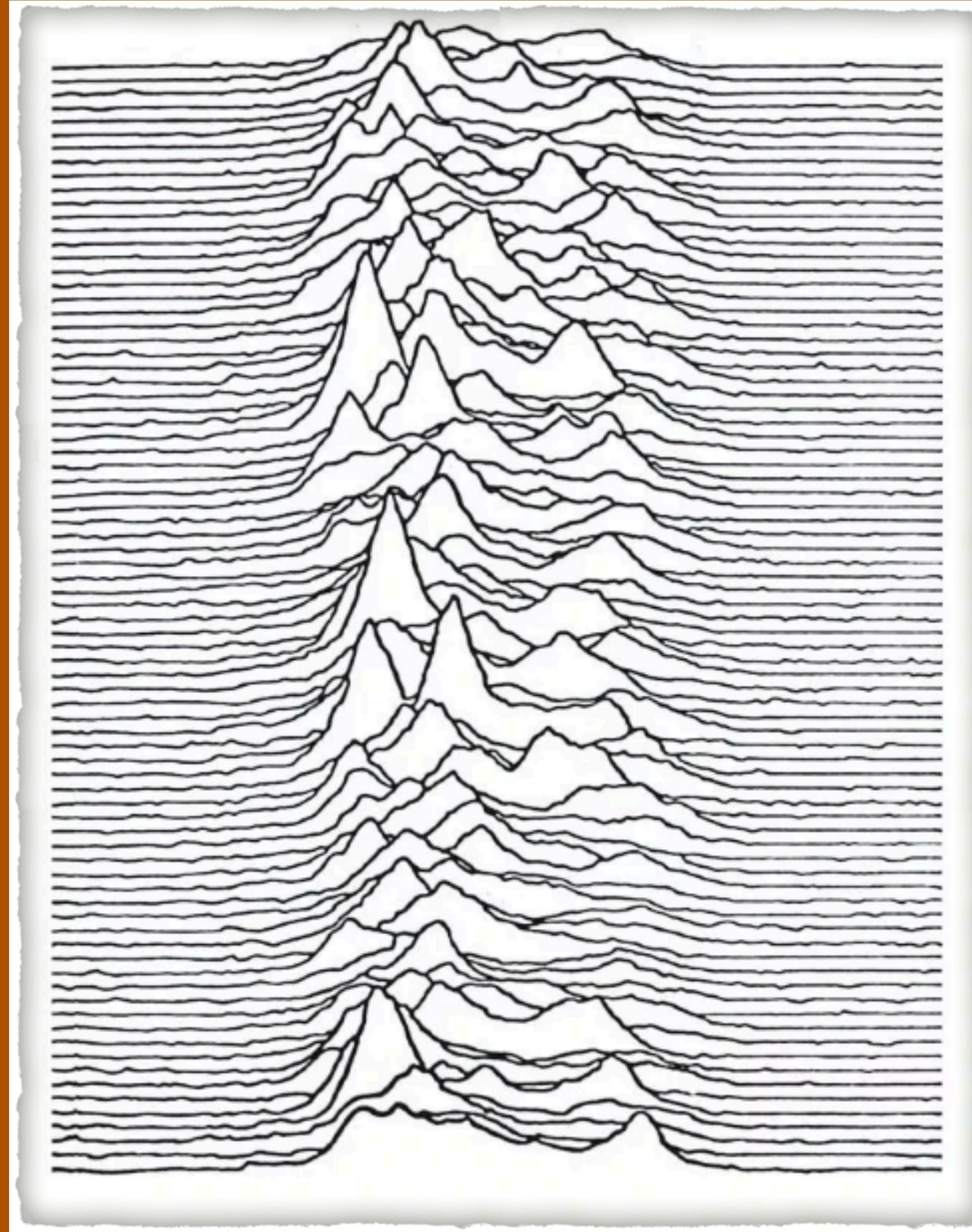


NASSP Pulsar lectures



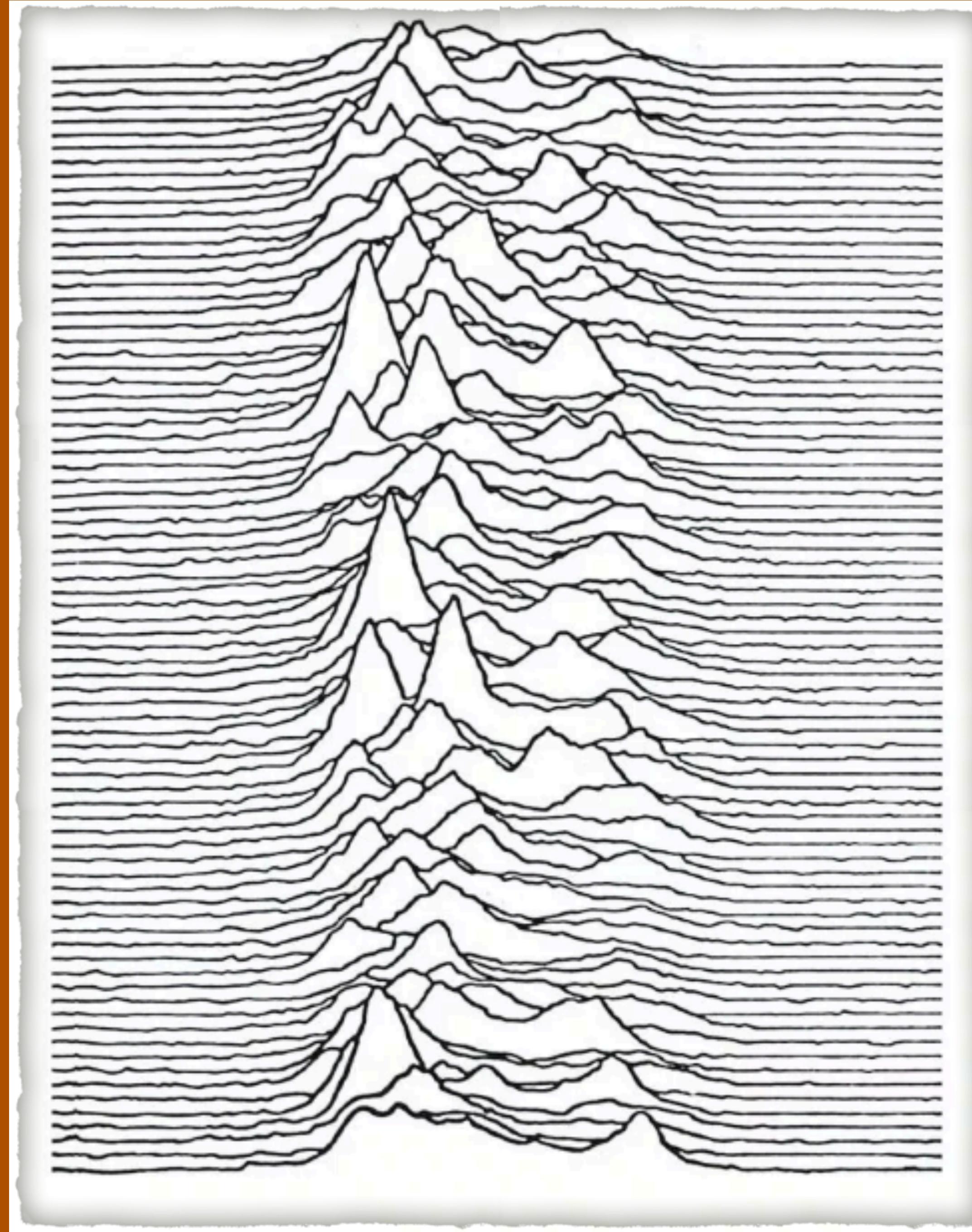
Course layout:

Lecture 1: Radio pulsar observations

Lecture 2: Pulsar properties

Marisa Geyer, SARAO

NASSP Pulsar lectures

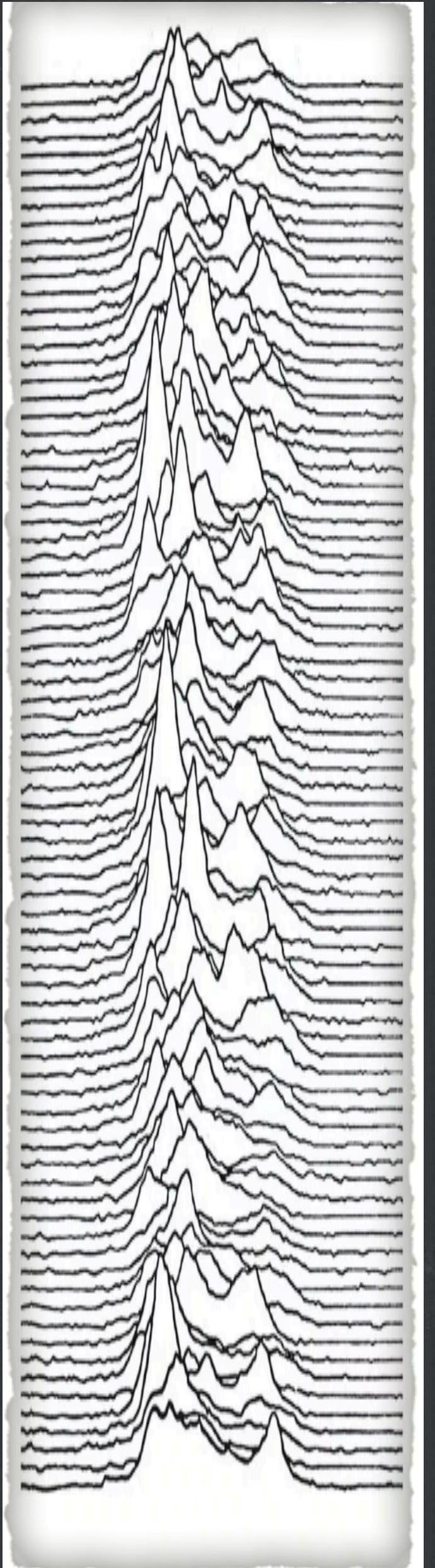


Course layout:

*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

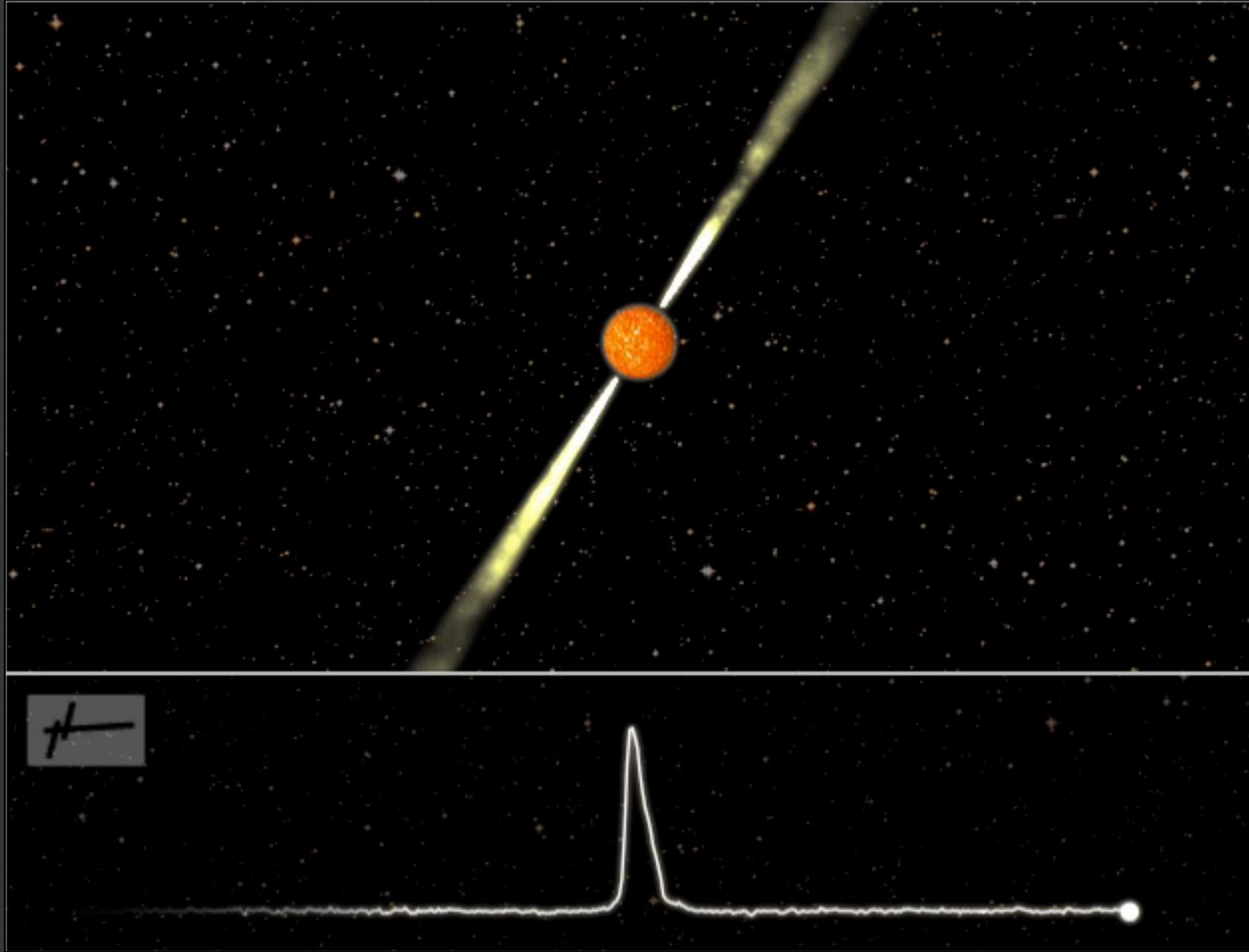
The simple lighthouse picture



- 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**

The simple lighthouse picture

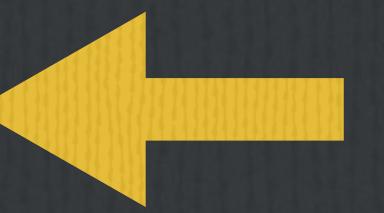
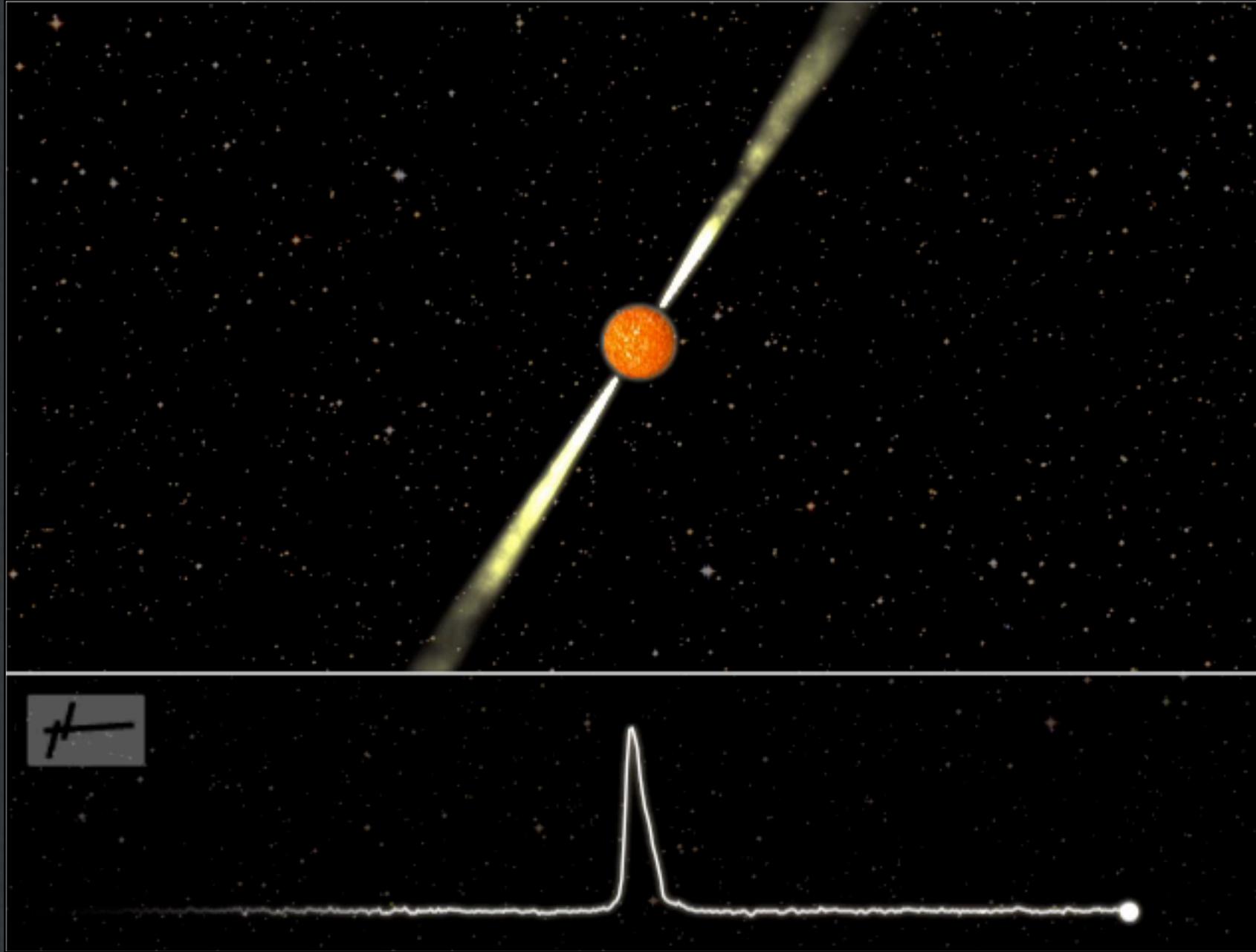
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Credit: Joeri van Leeuwen, <https://www.astron.nl/pulsars/animations/>

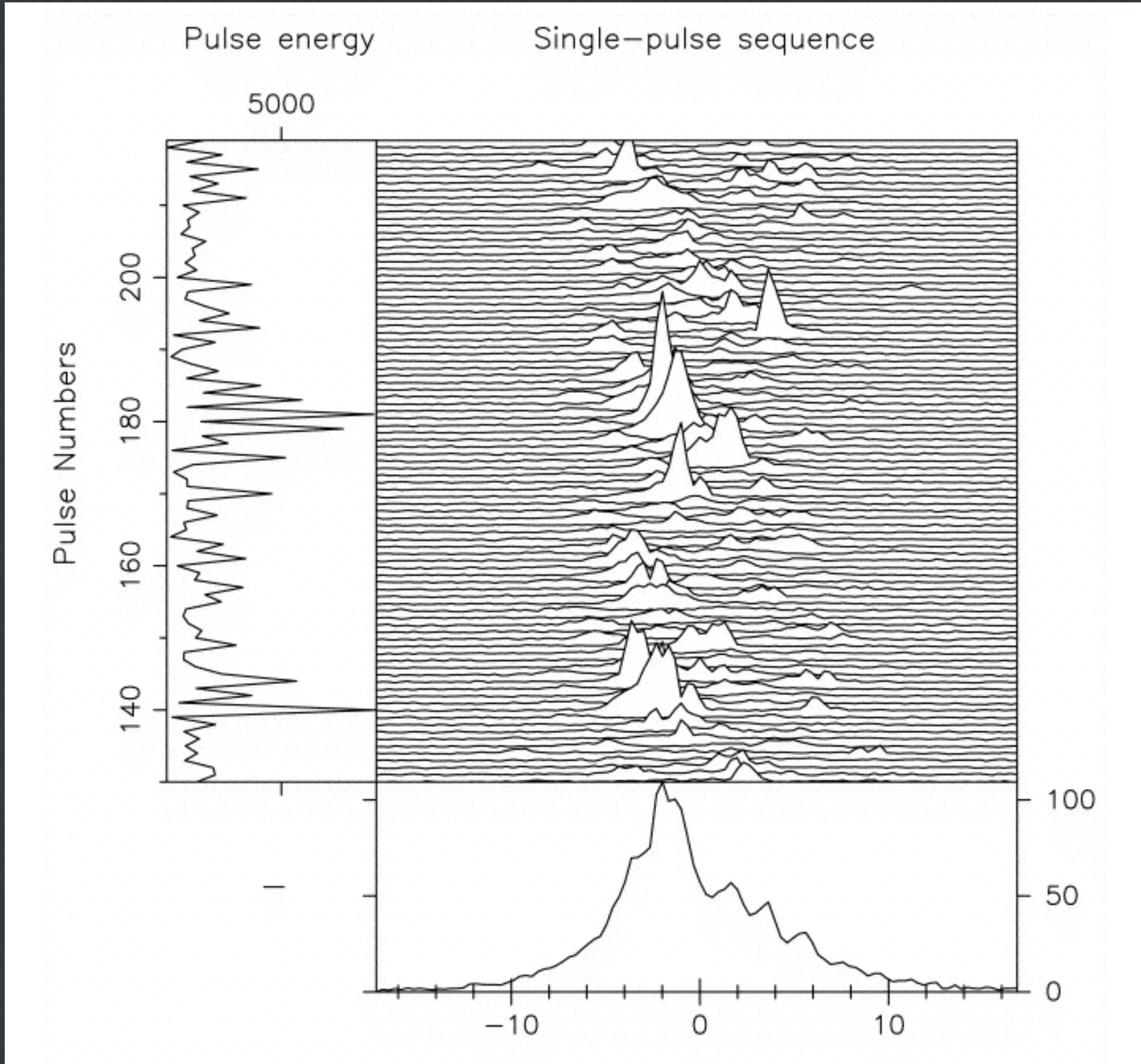
Adding single pulses to form a stable pulse

- 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



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PSR B0943+10

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:

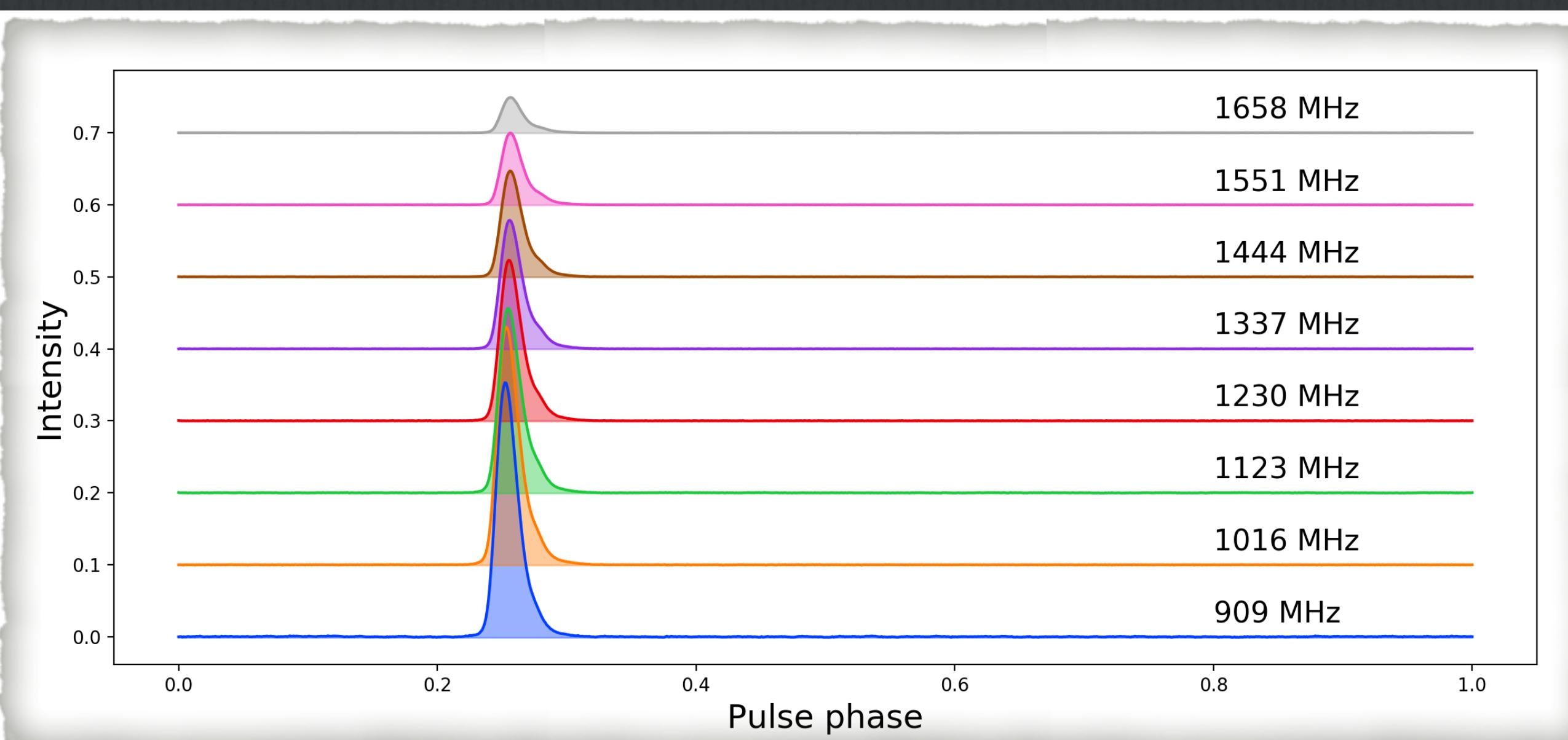
$$S_\nu \propto \nu^{-\alpha}$$

- where S_ν is flux (Jy) at a frequency ν and typical values for $\alpha \sim 1.4$

- 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)

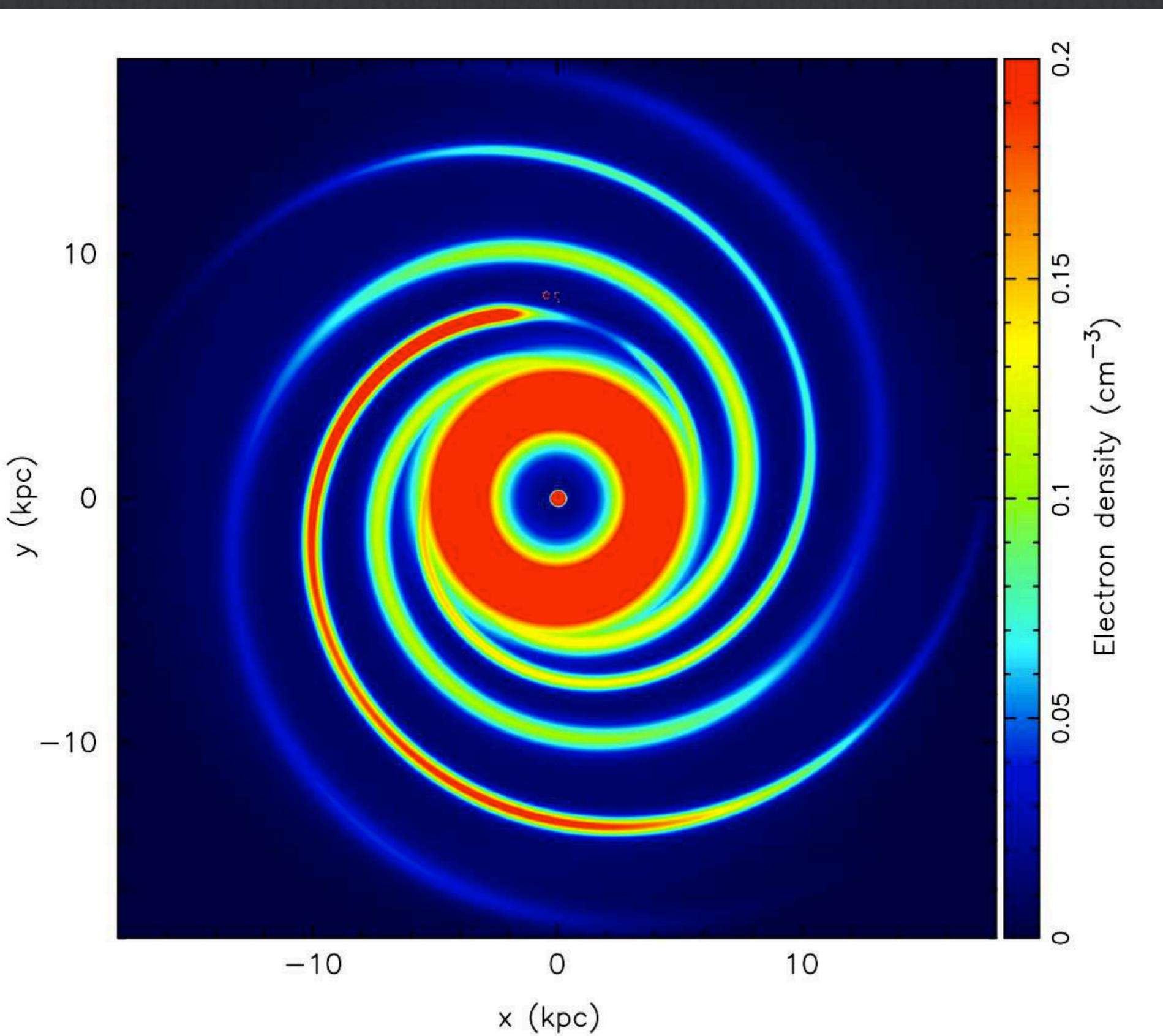
Interstellar Medium Effects

- 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)

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

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

SI conversions:

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

The ISM refractive index

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

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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 $n_e \sim 0.03 \text{ cm}^{-3}$
- What is ν_p for $n_e = 0.03 \text{ cm}^{-3}$?

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

$$v_g = c\mu < c$$

The wave group velocity

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- From definition of refractive index

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

typical ~ 1.5 kHz

$\nu_p > \nu$ then $\mu \rightarrow$ imaginary
waves don't propagate

$\nu_p < \nu$ then $\mu < 1$
waves propagate with velocity

$$v_g = c\mu < c$$

typical ~ 10 MHz - 100 GHz

The wave group velocity

- Radio waves in the ISM propagate with group velocity v_g
- Since $\nu_p \ll \nu$ 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?

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first 2 terms
of Taylor expansion

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

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

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

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

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

$$\frac{1}{v_g} \approx \frac{1}{c} \left(1 + \frac{\nu_p^2}{2\nu^2}\right)$$
$$\nu_p = \left(\frac{e^2 n_e}{\pi m_e}\right)^{1/2}$$

Dispersive Delay

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

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

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Plugging in astronomical units

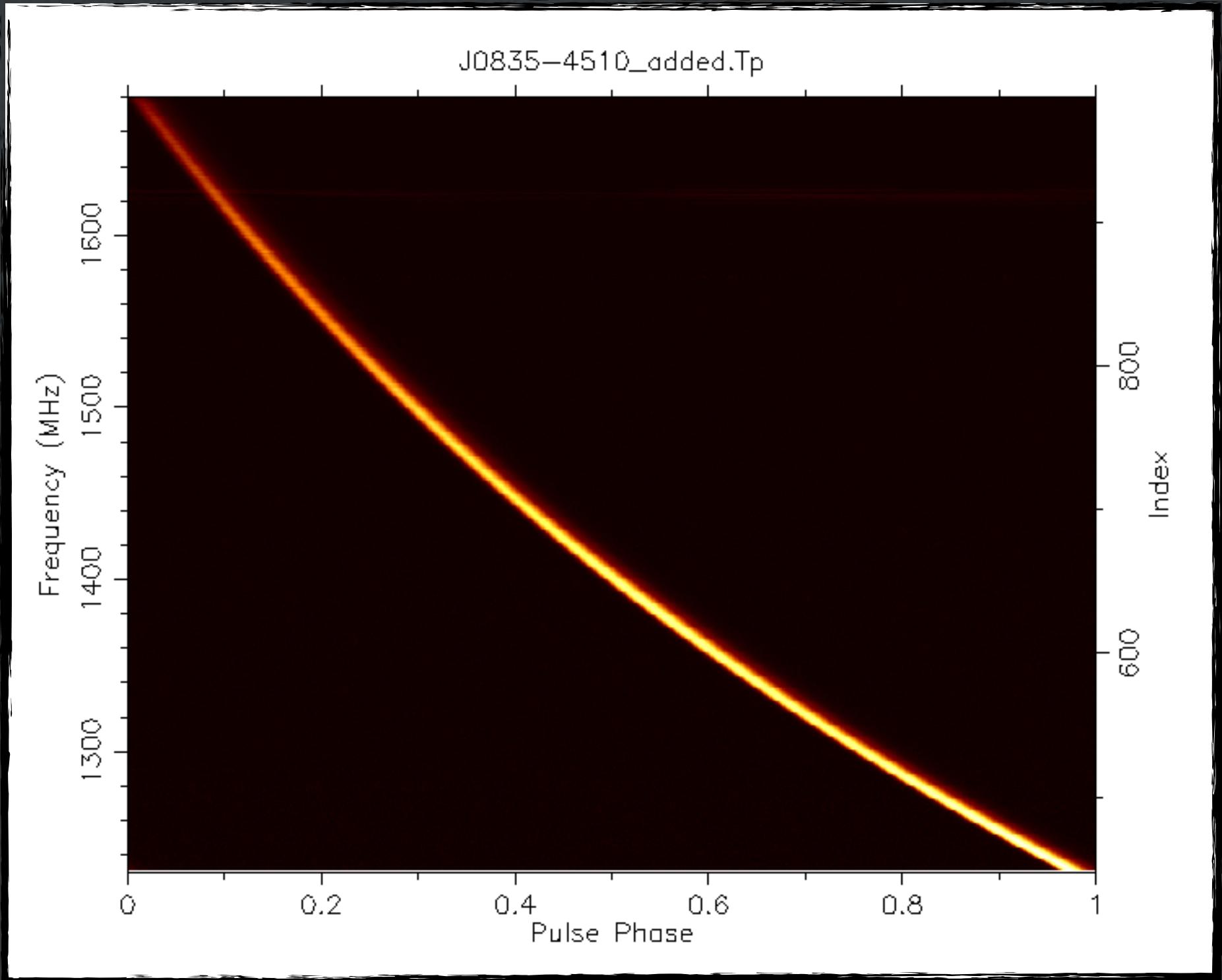
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Dispersion measure,
unit: pc cm⁻³

Dispersive Delay

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Plugging in astronomical units

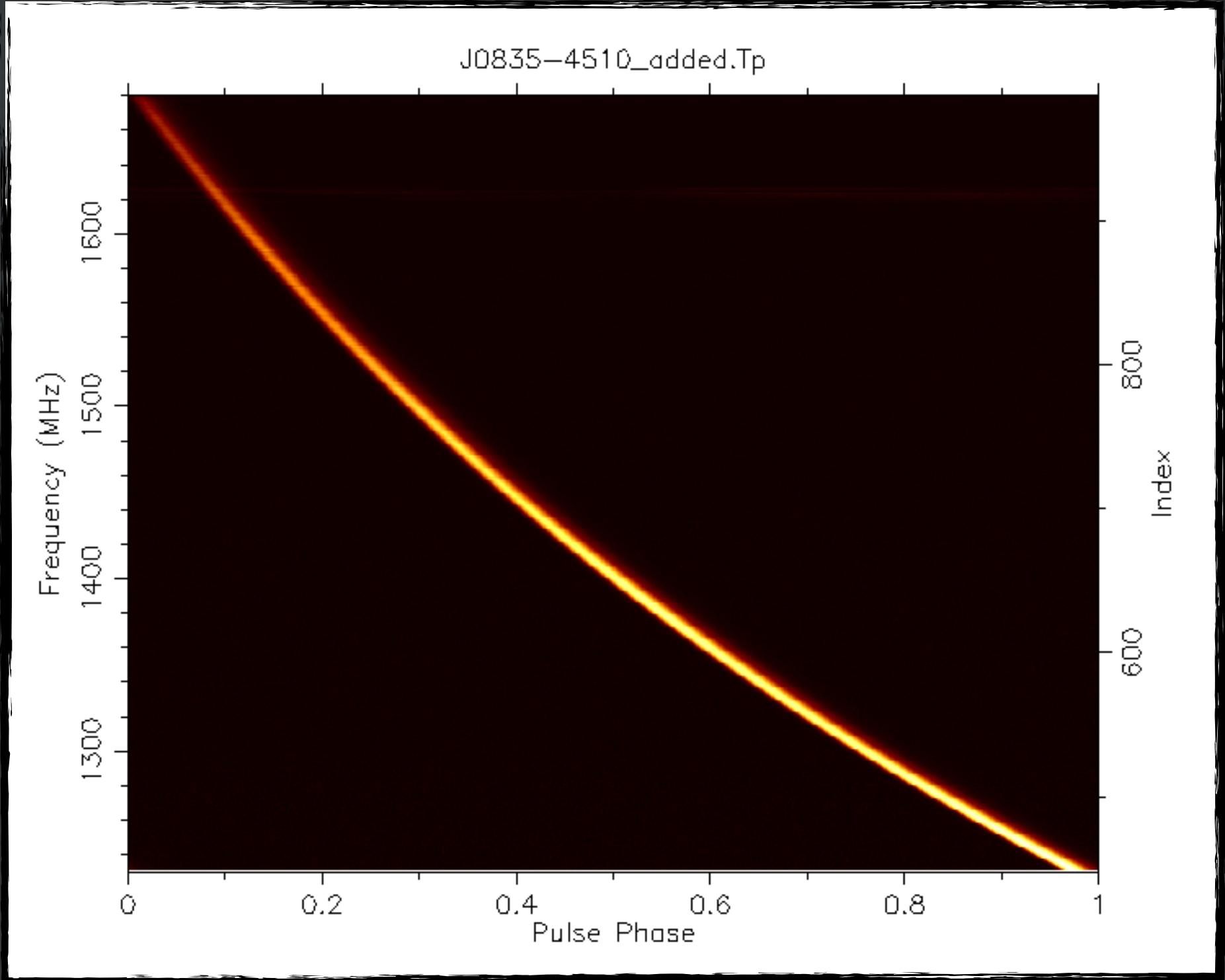
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Strong frequency dependence

**Dispersion measure,
unit: pc cm⁻³**

Dispersive delay between high and low frequencies

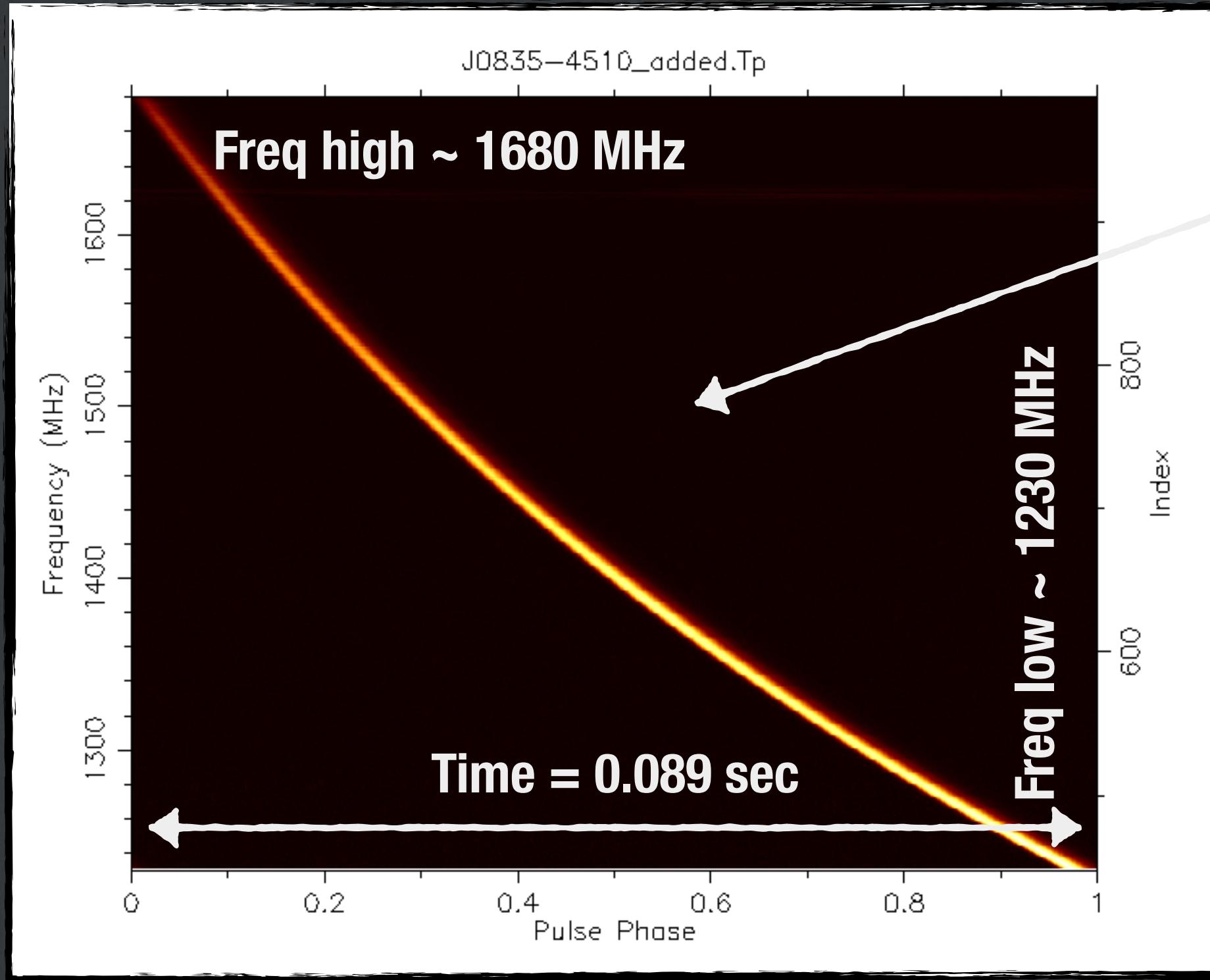
$$t_l - t_h = 4.15 \times 10^3 \times \text{DM} \times \left[\frac{1}{\nu_1^2} - \frac{1}{\nu_h^2} \right]$$



- 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.

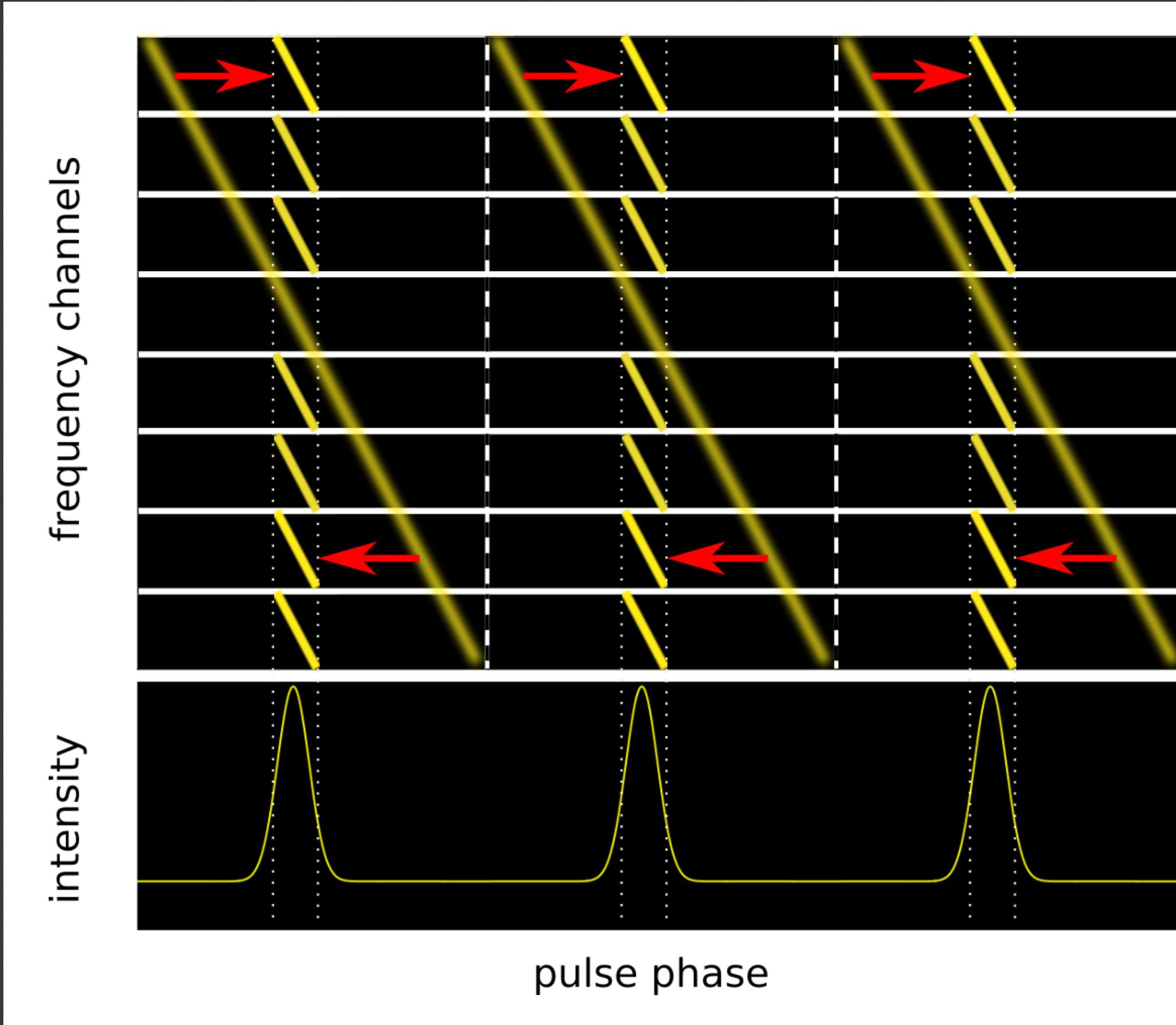
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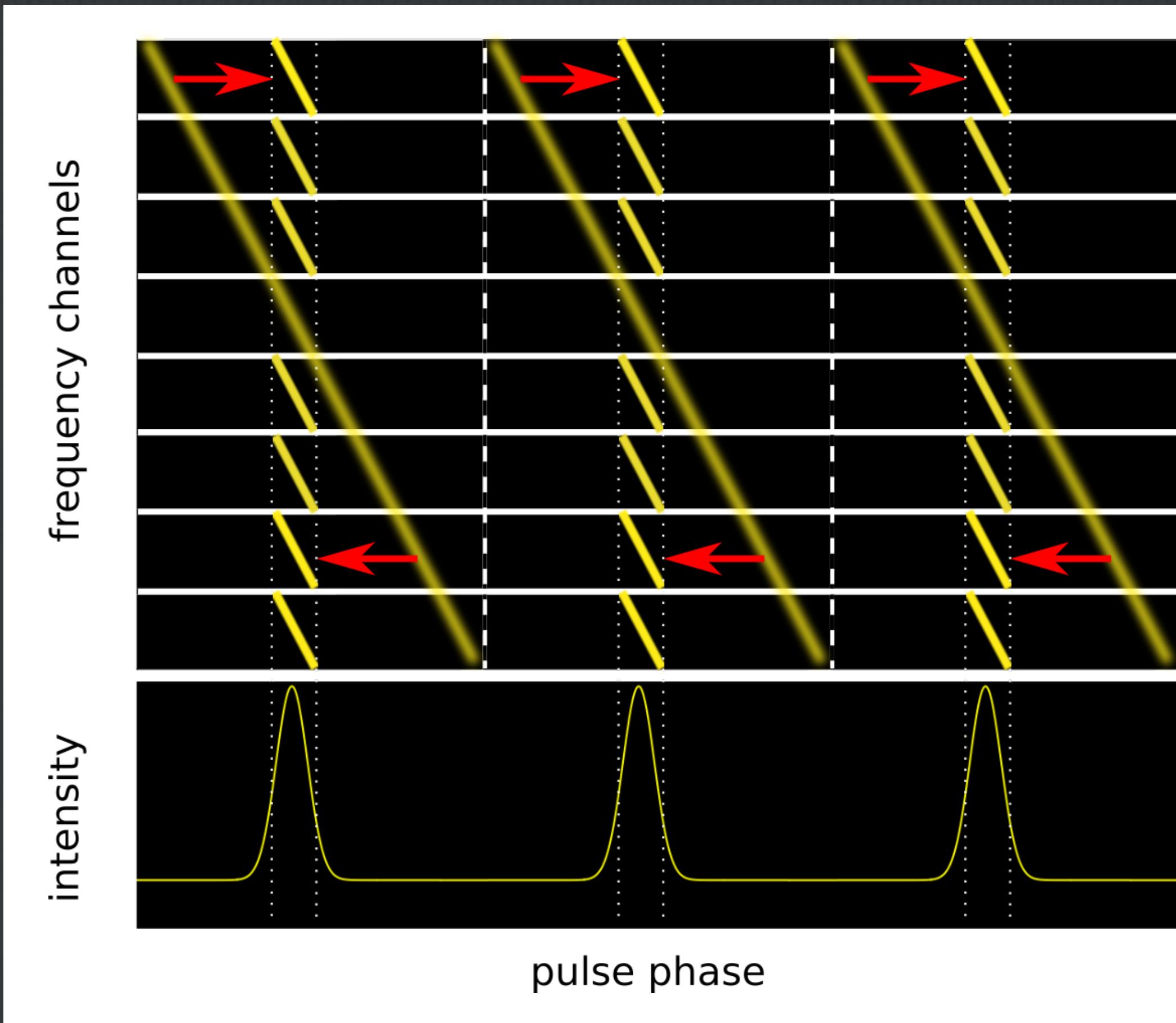
- Can you estimate Vela's DM from this figure?
- How could you improve on the estimate?
- In today's tutorial you will estimate the DM value of PSR J0738-4042 using a MeerKAT observation with a bandwidth of 856 MHz

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”

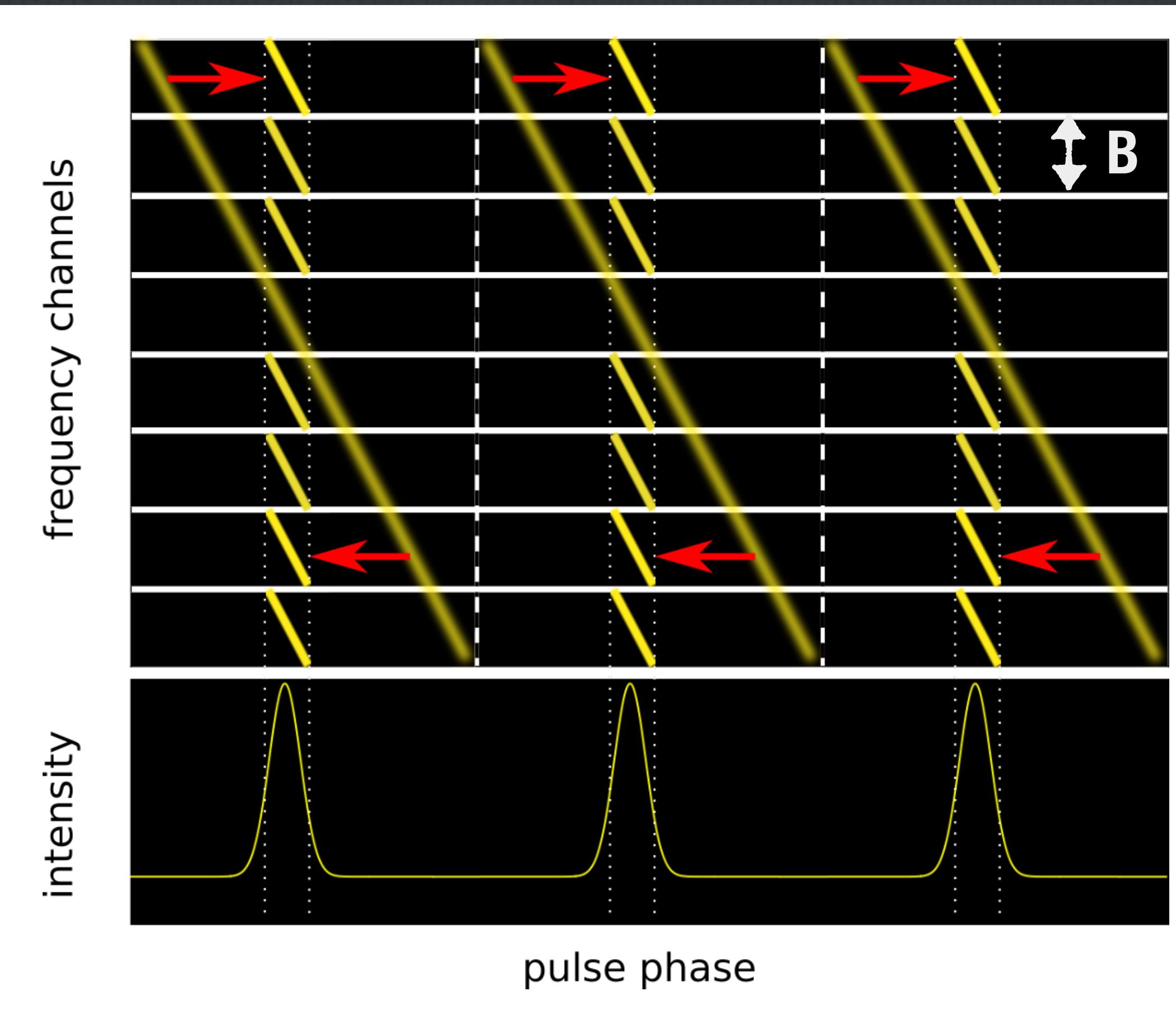
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What happens if we have more frequency channels across the band?

Incoherent dedispersion



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

$$B \ll v$$

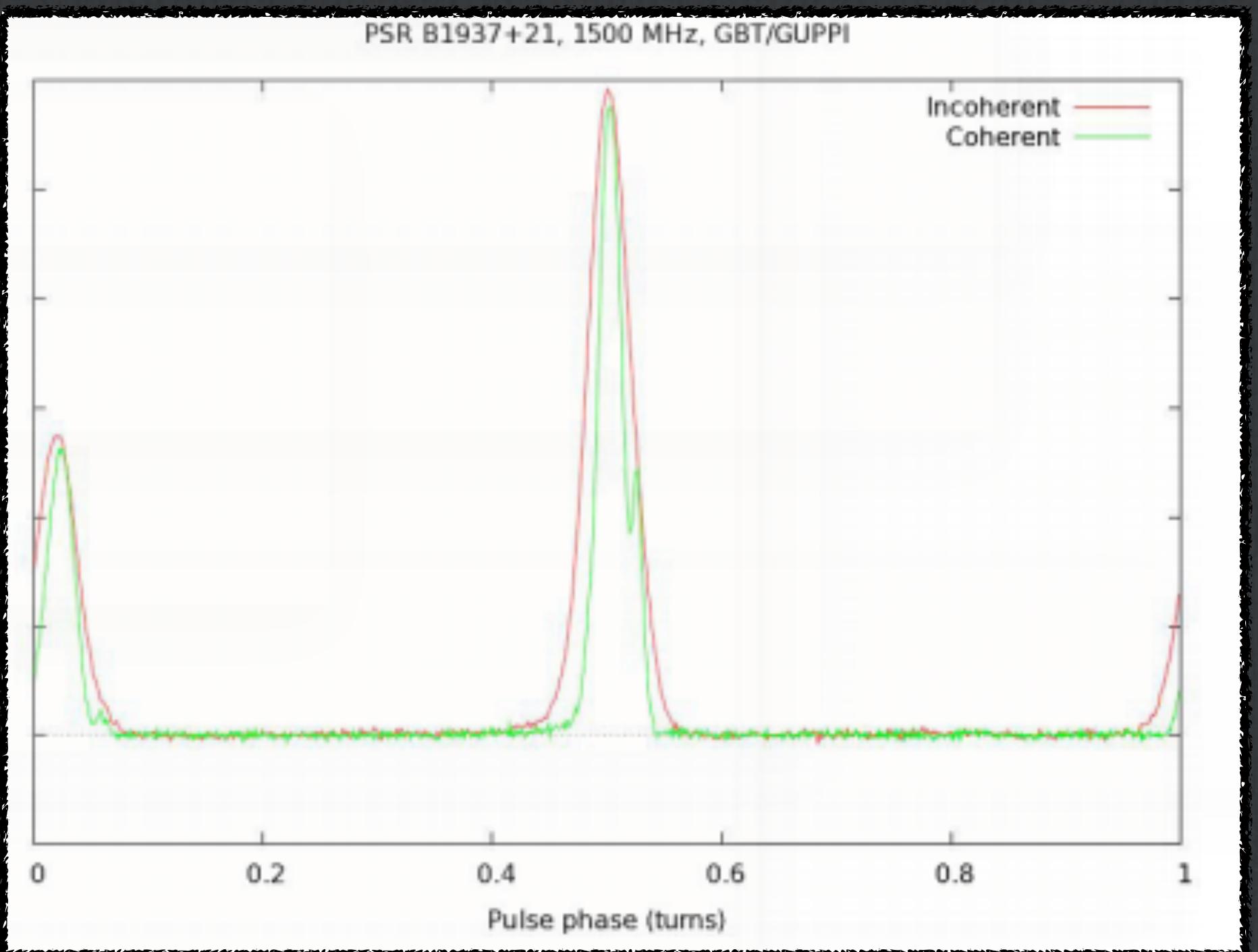
then the smearing across the channel is given by

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

With incoherent dedispersion there is residual smearing across each channel.

Coherent dedispersion

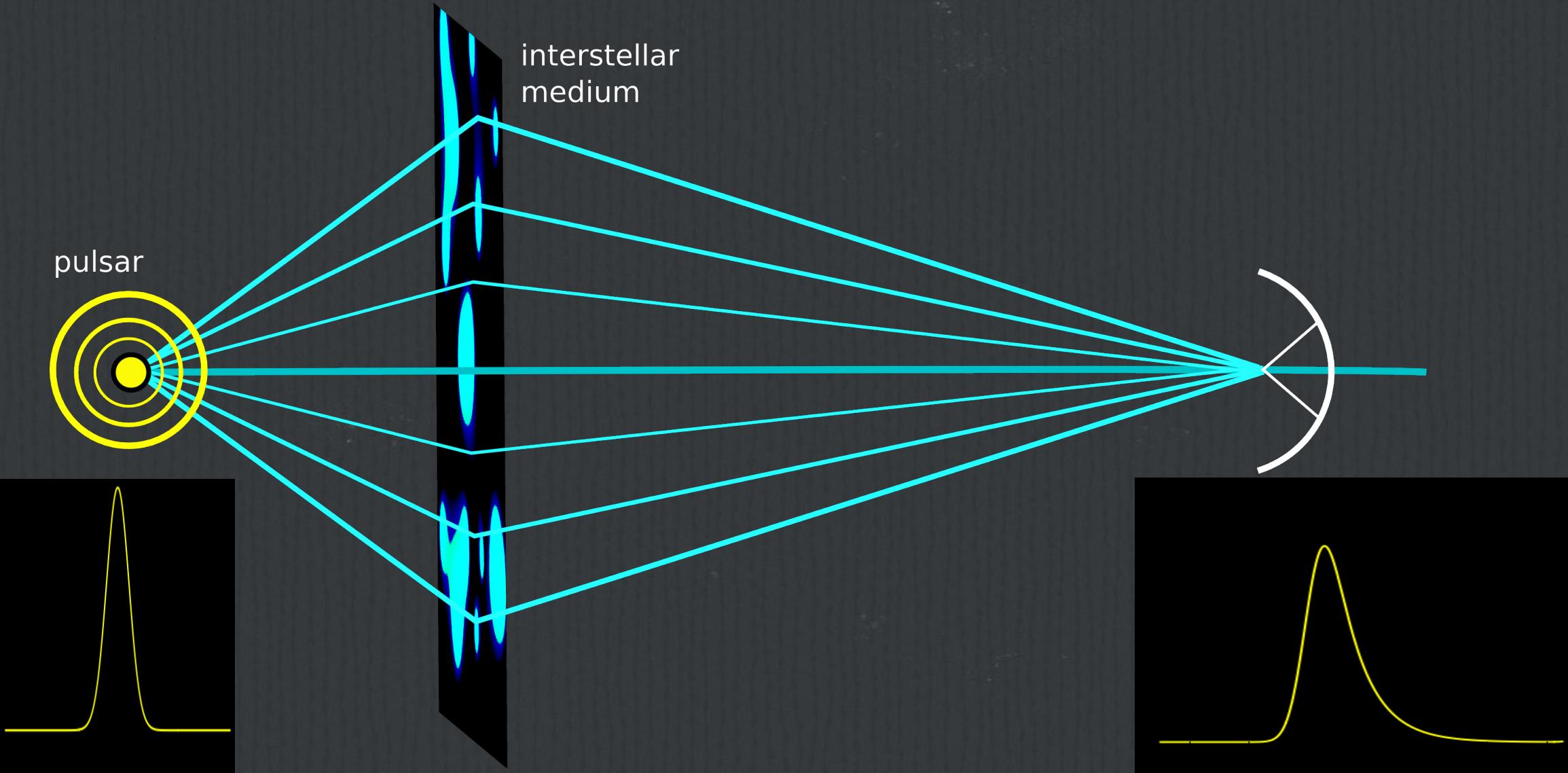
- Per channel residual smearing can be eliminated by using a more sophisticated dedispersion technique known as ‘coherent dedispersion’
- This technique involves applying the ISM correction before computing the pulsar intensity values (power values) at a given frequency channel
- Using a model of the 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

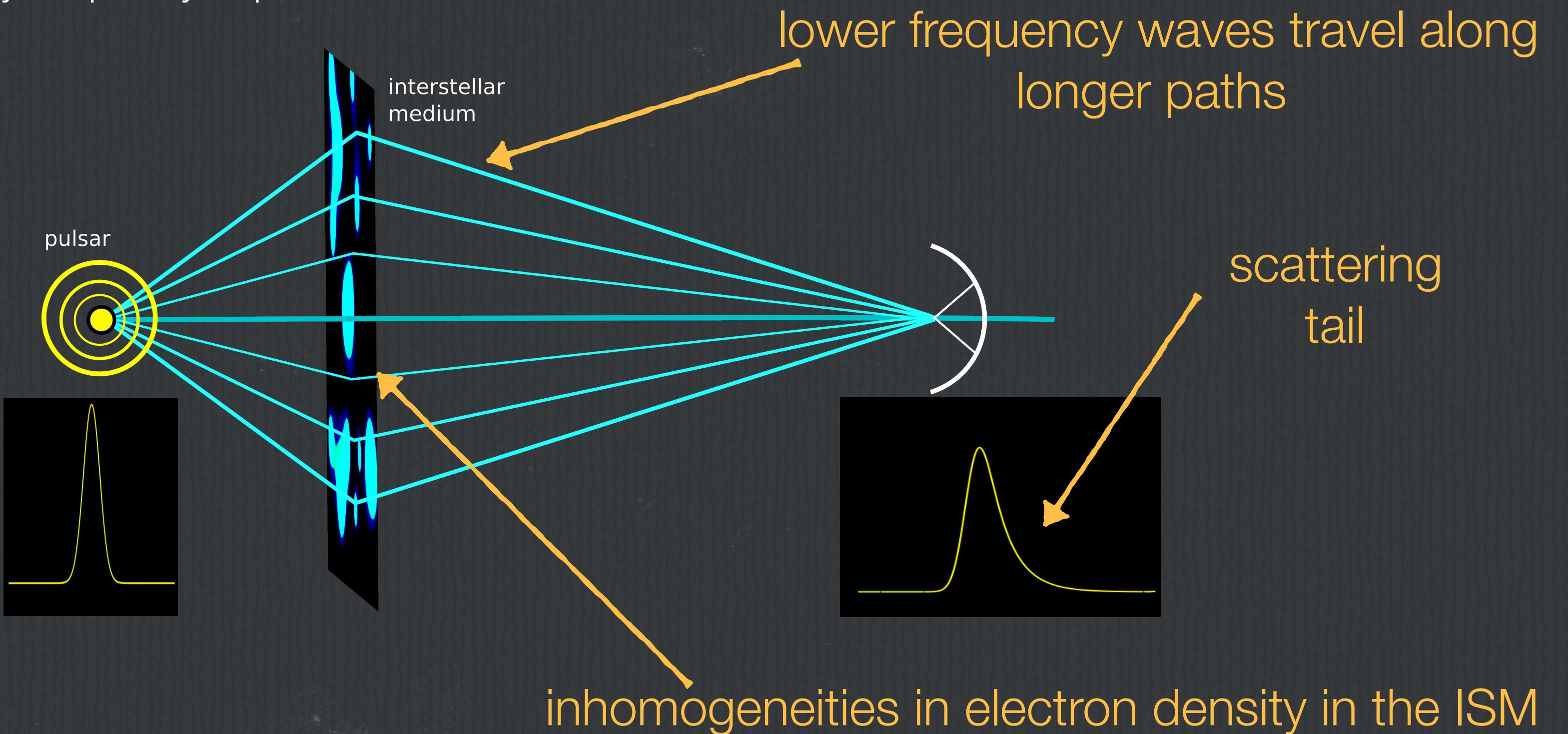
- The ionised ISM not only slows down the group velocity of radio waves depending on its frequency (dispersive delay)
- It can also ‘scatter’ radio waves leading to radio waves travelling along multiple paths.
- This effect is known as “interstellar or pulsar scattering” and it too has a strong frequency 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:

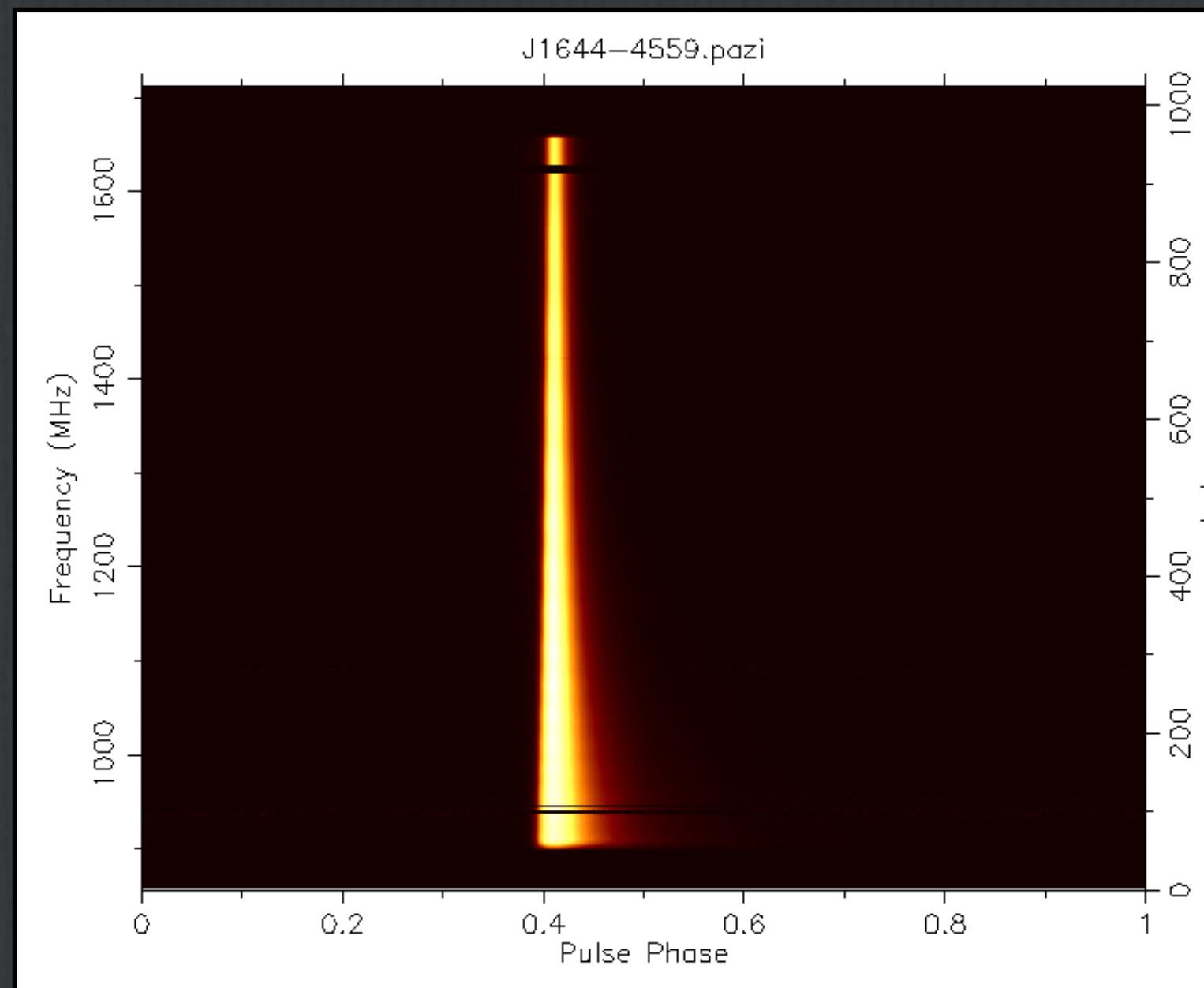
$$\tau \propto \nu^{-4}$$



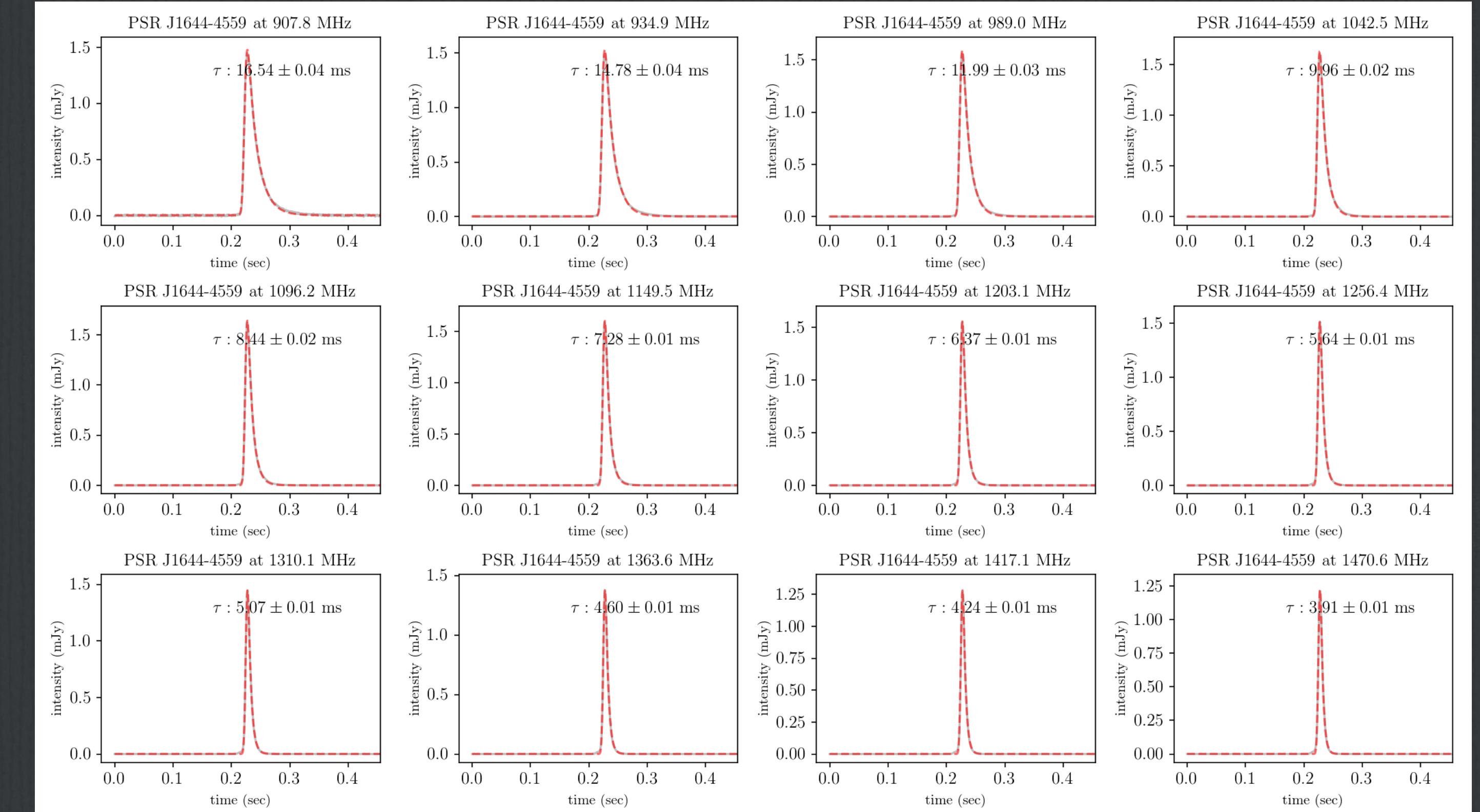
Examples of Pulsar Scattering

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

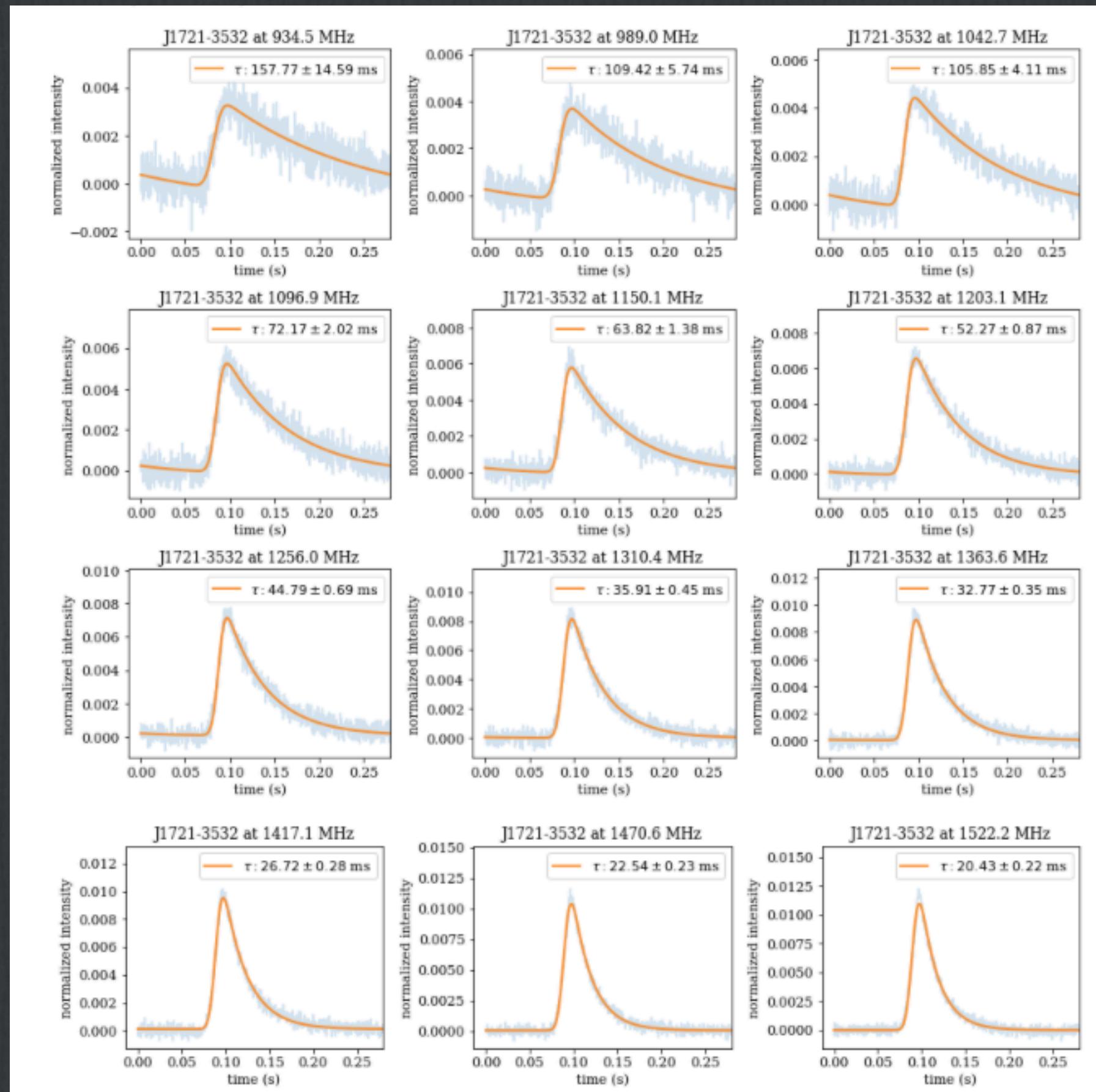
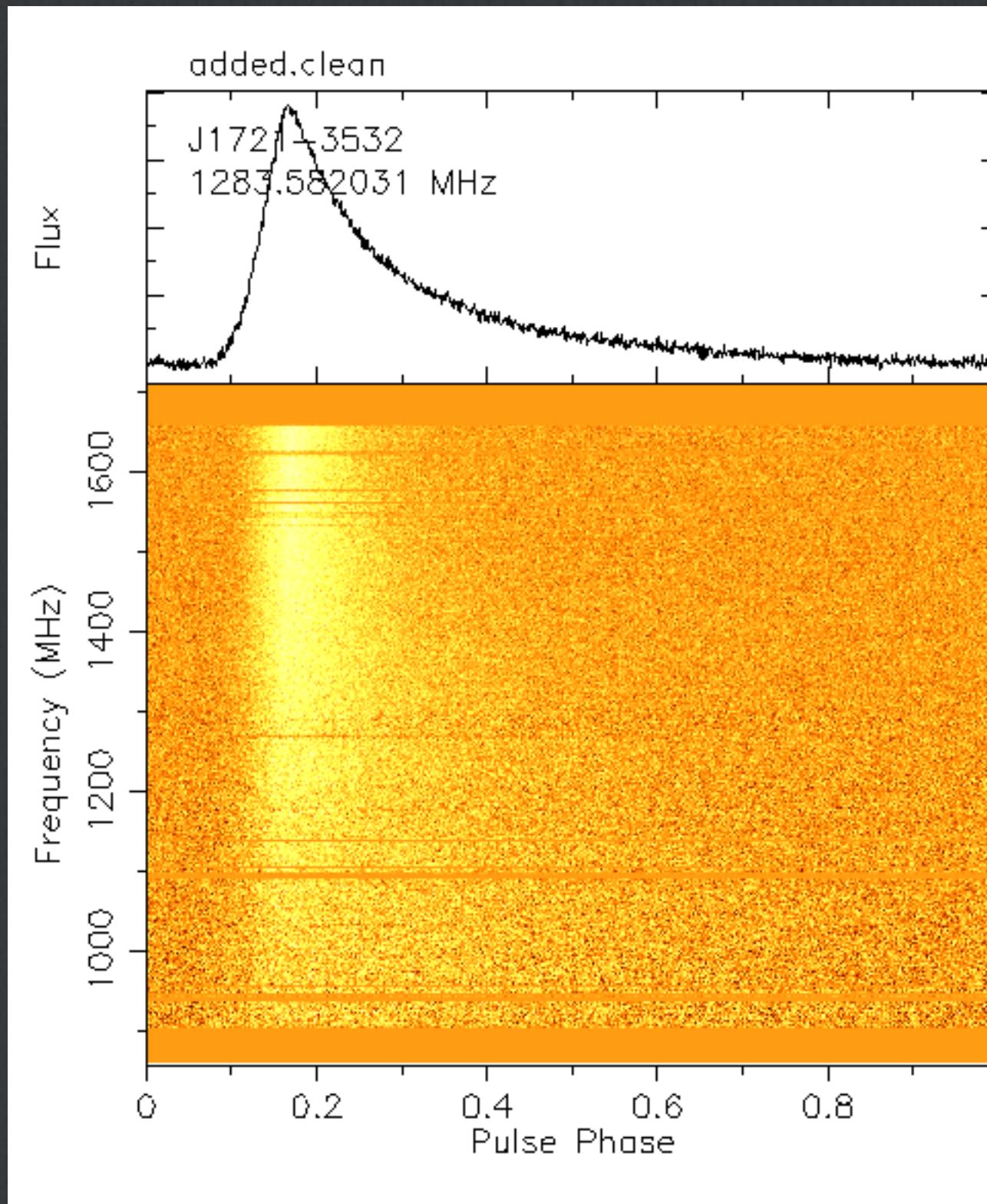


PSR J1644-4559

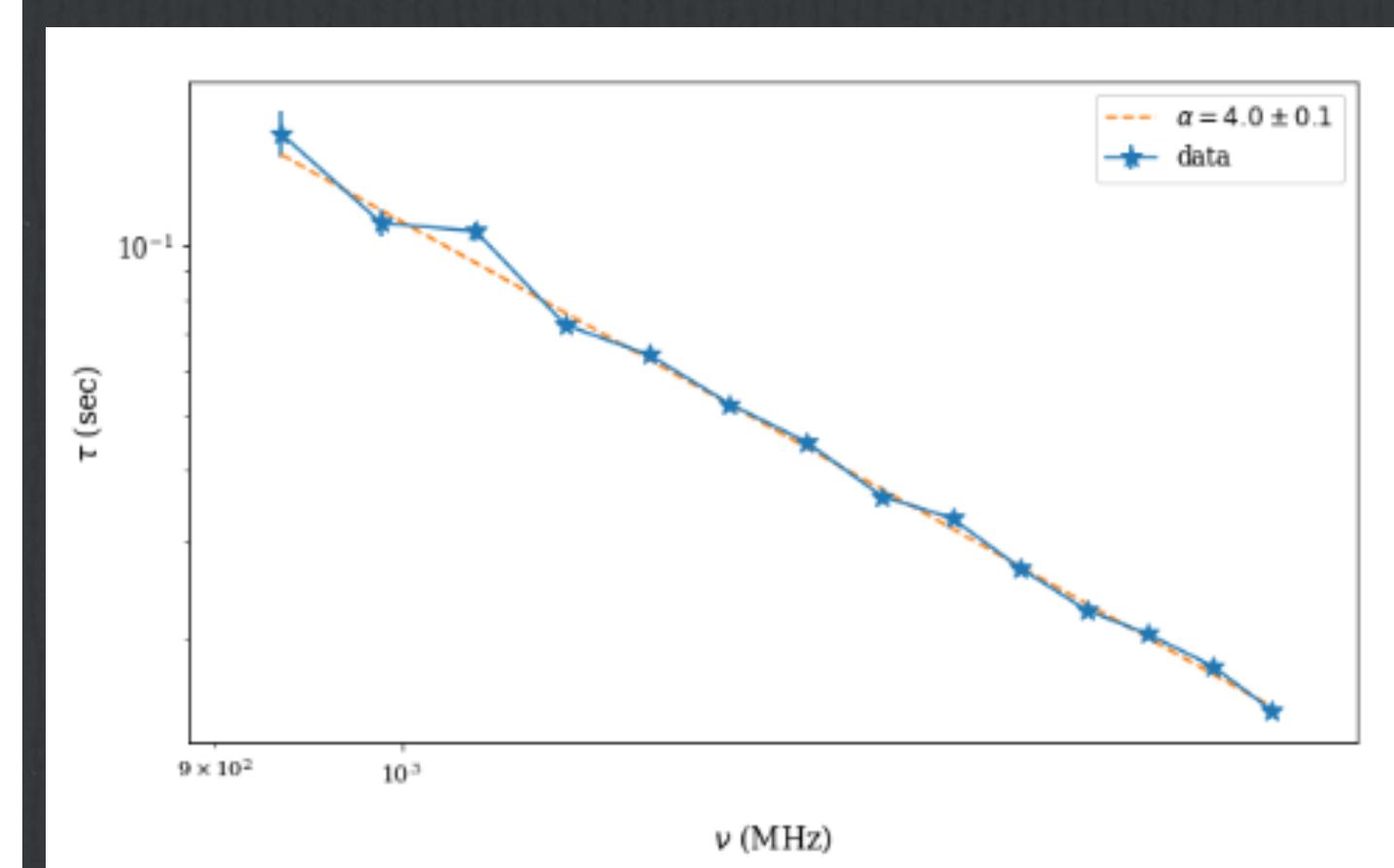


Examples of Pulsar Scattering

PSR J1721-3532



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



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

Area of radio dish

Number of dishes

Bandwidth (MHz)

Observing time (sec)

System temperature (K)

Antenna Gain
(K/Jy)



Effect

Bigger area = higher sensitivity

More dishes = higher sensitivity

More bandwidth = higher sensitivity

Long observing = higher sensitivity

Lower system temp = higher sensitivity

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,

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

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

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

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,

$$G = \frac{\eta A}{2761} \quad [\text{K/Jy}]$$

- The MeerKAT gain per dish:

Effective diameter: 13.97 m

Efficiency: 0.76

$$G_{\text{MeerKAT dish}} = \dots$$



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:

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

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 polarizations
B	Bandwidth
t	Observing time (sec)
(S/N) _{min}	Detection threshold signal-to-noise
G	Antenna Gain (K/Jy)

The End of Lecture 1



