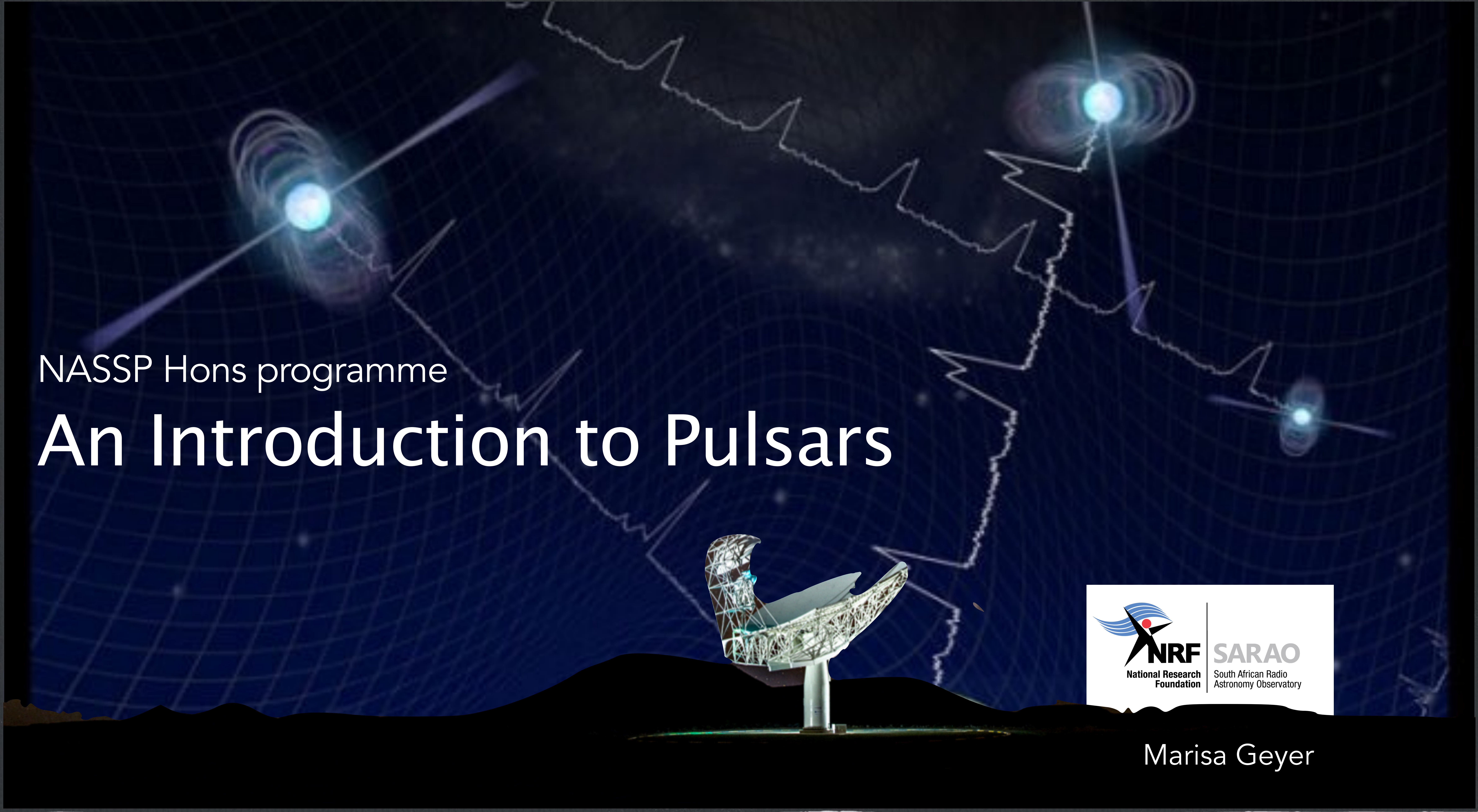
NASSP Hons programme

An Introduction to Pulsars



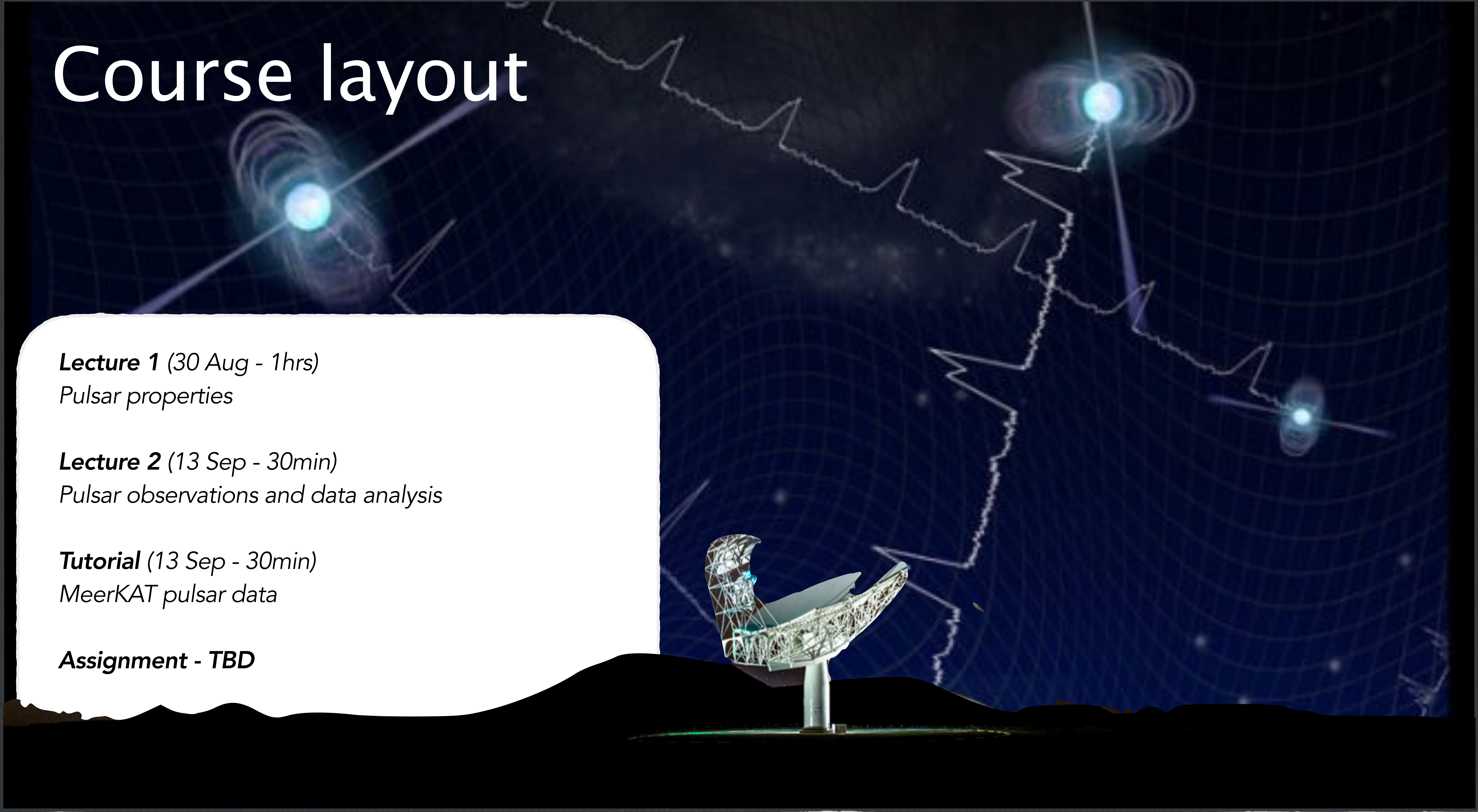
National Research Foundation

SARAO

South African Radio Astronomy Observatory

Marisa Geyer

Course layout



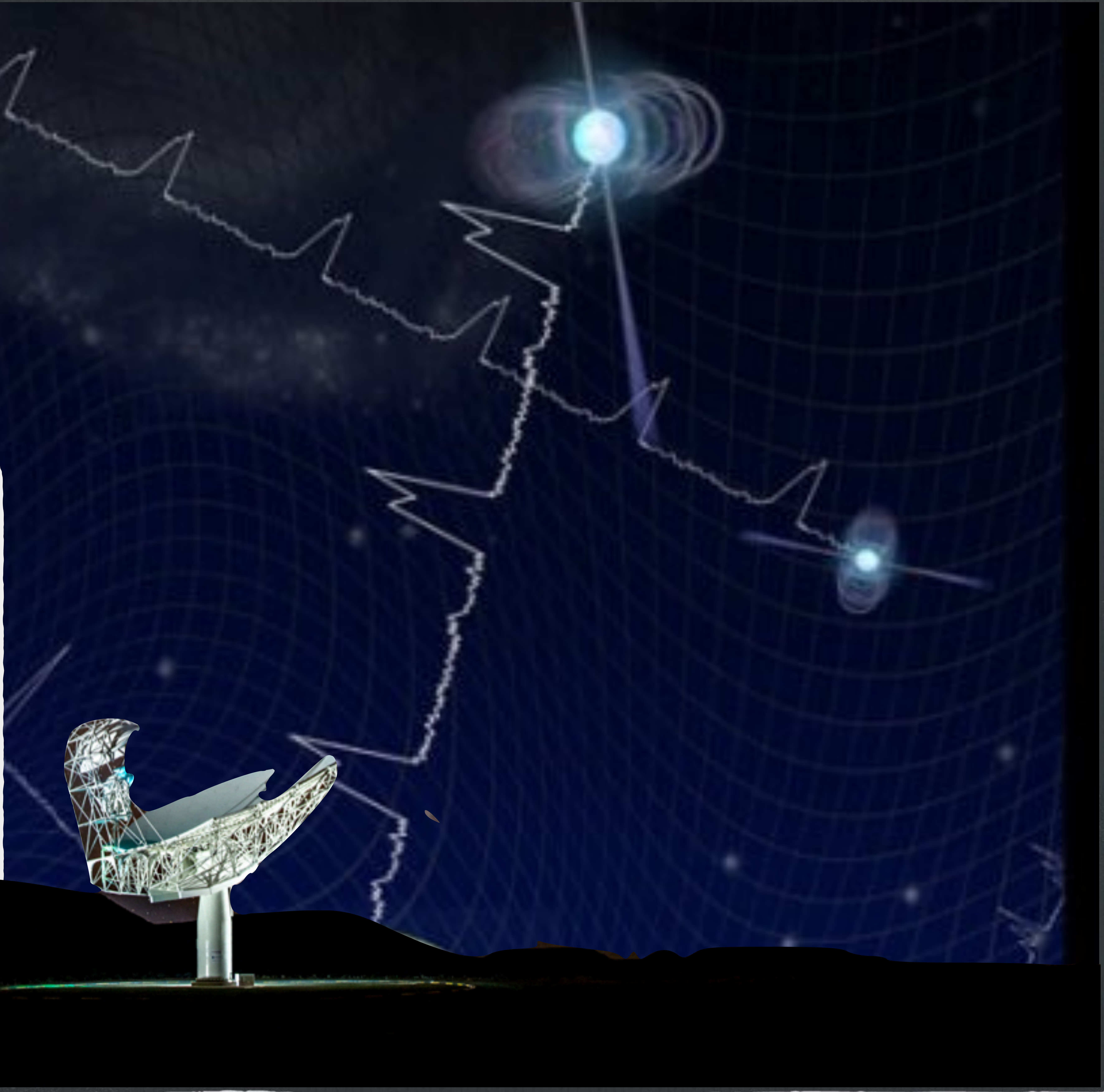
Lecture 1 *(30 Aug - 1hrs)*
Pulsar properties

Lecture 2 *(13 Sep - 30min)*
Pulsar observations and data analysis

Tutorial *(13 Sep - 30min)*
MeerKAT pulsar data

Assignment - TBD

Course material



Much of what is discussed here comes from

1) NRAO 'Essential Radio Astronomy' course at:
https://science.nrao.edu/opportunities/courses/era

2) Handbook of Pulsar Astronomy by Lorimer and Kramer

3) Additional/similar material can be found on
- SARAO Web YouTube channel
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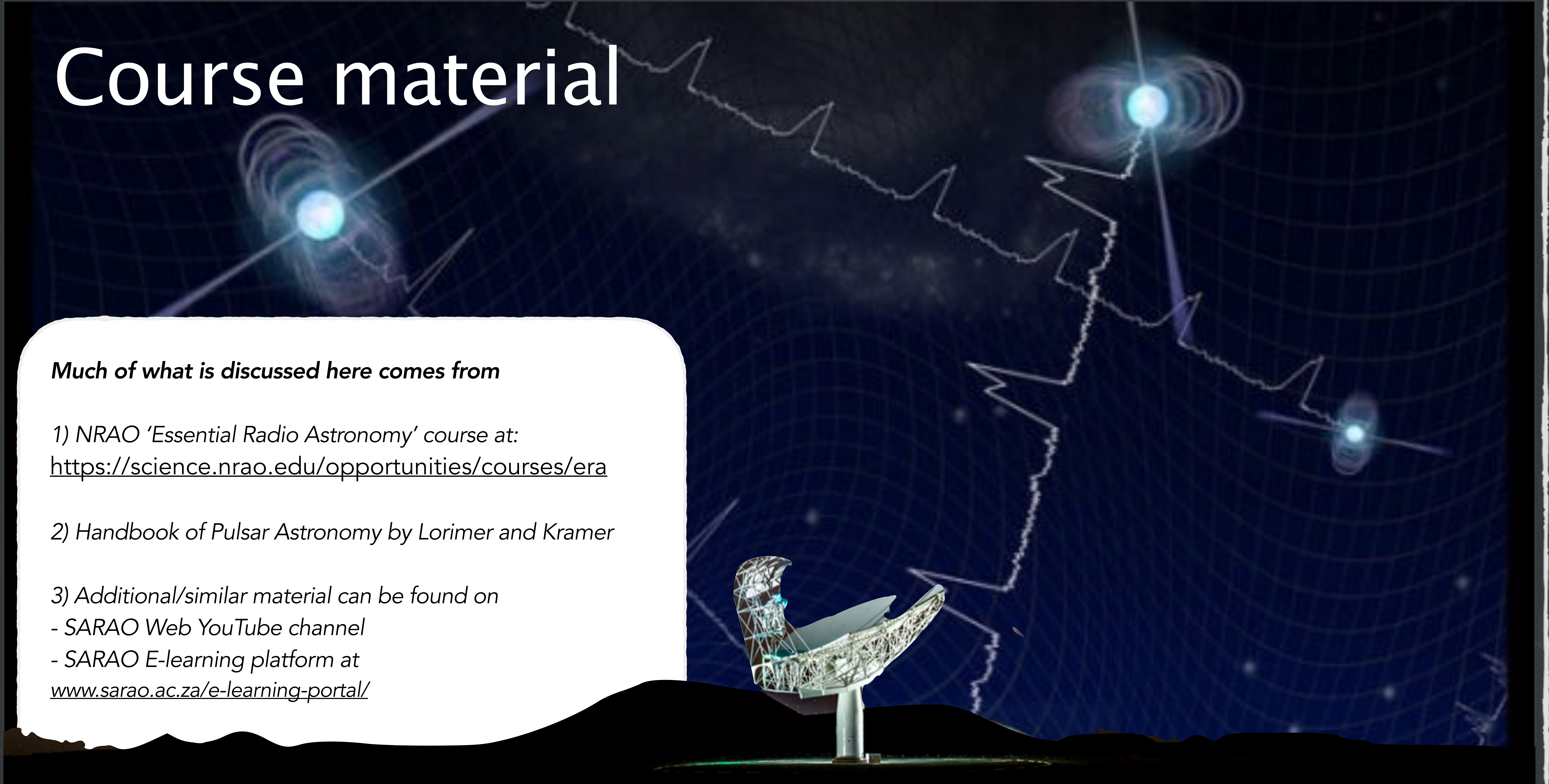

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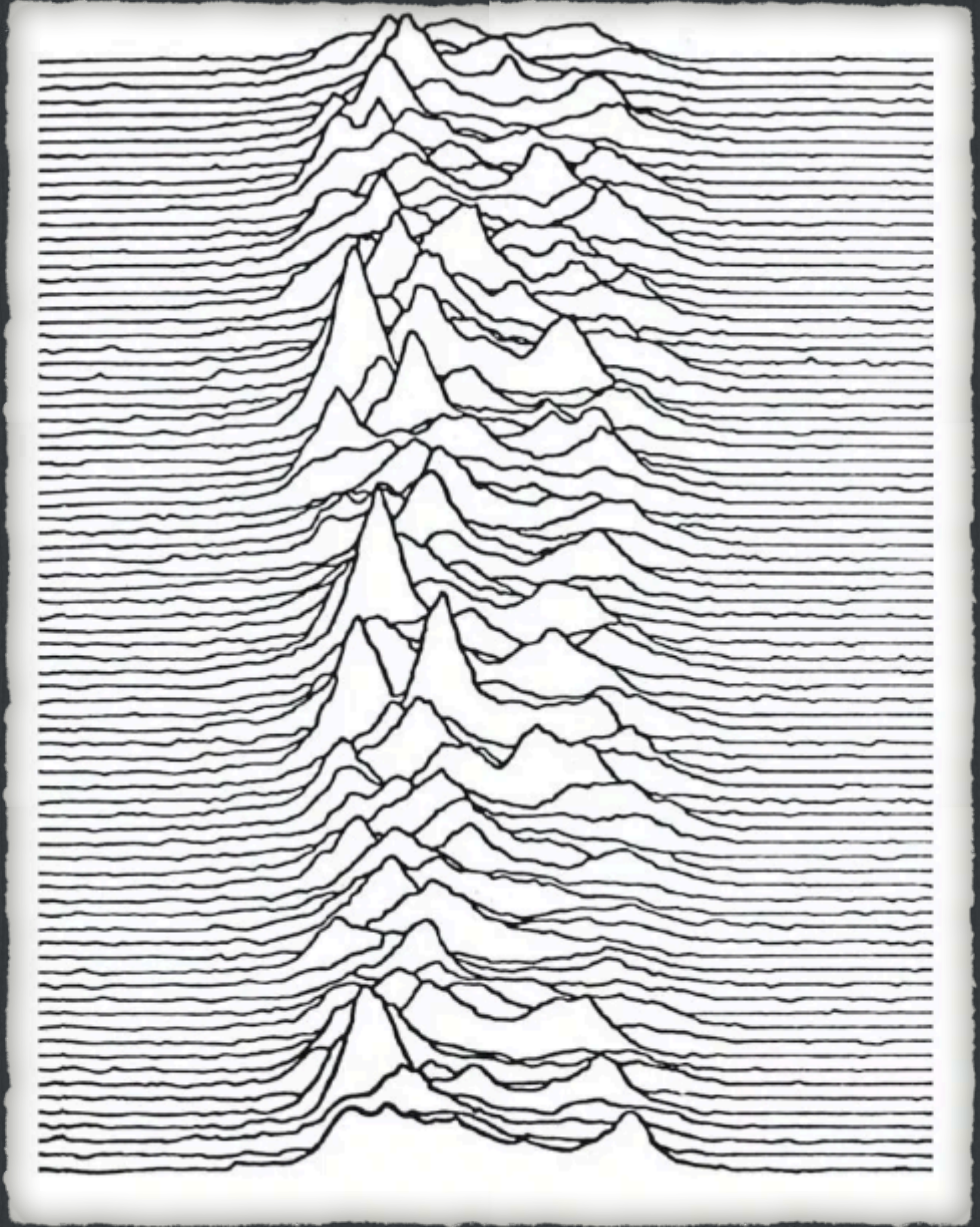
If you find typos or mistakes please get in touch!



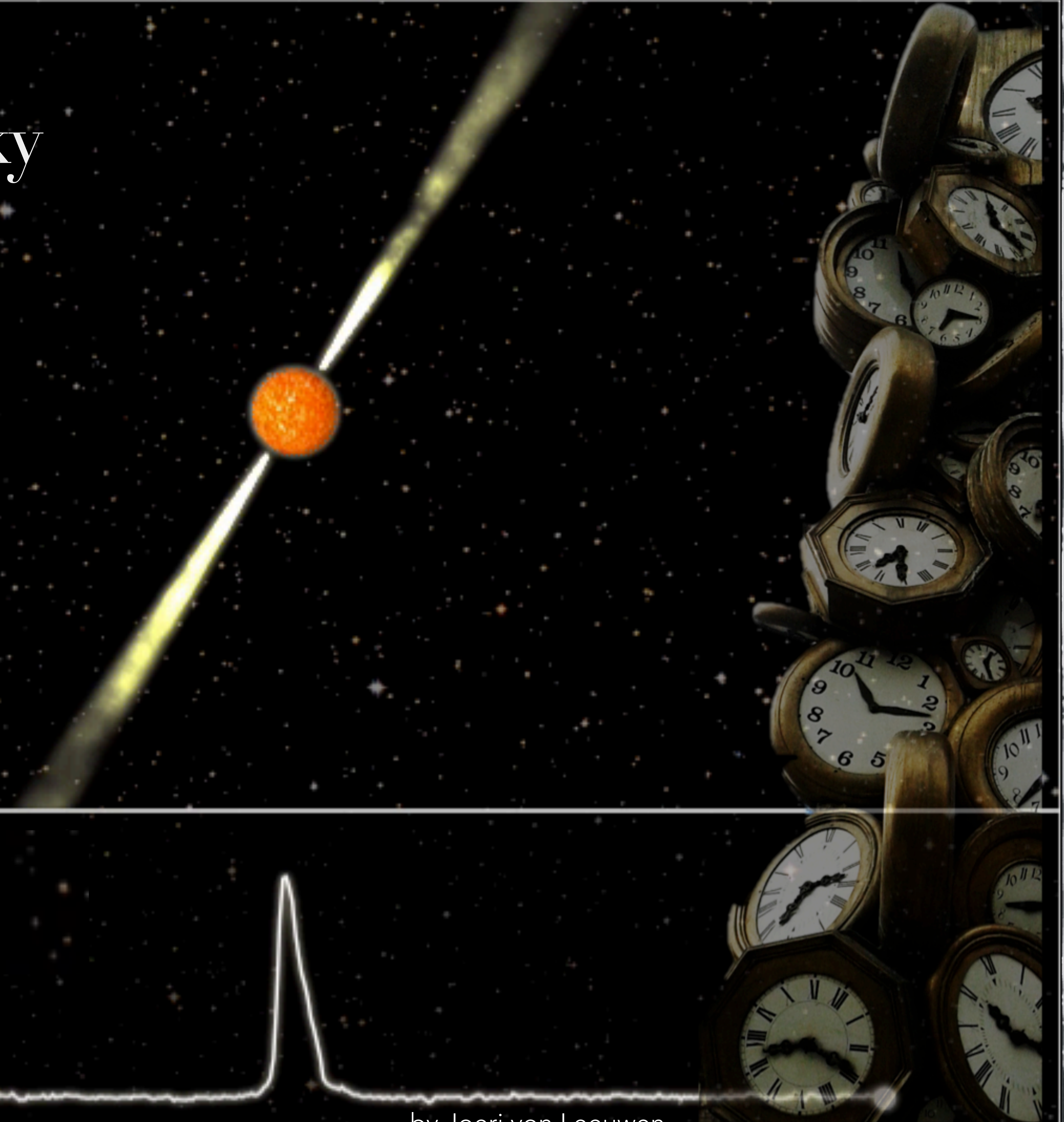
Lecture 2 : Pulsar observations and Data Analysis

The topics we will cover

- Revisit the simple lighthouse model
- Creating a stable pulse profile through folding
- Pulsars are broad band emitters
- Contamination by RFI
- Propagation of pulsar signals through the Interstellar Medium
    - The ISM refractive index
    - Dispersion delay by the ISM — and how we correct for it
    - Faraday rotation by the ISM
- Pulsar Sensitivity — Which pulsars can we detect using radio telescopes
    - Telescope parameters
    - The modified radiometer equation
- Introduction to pulsar timing

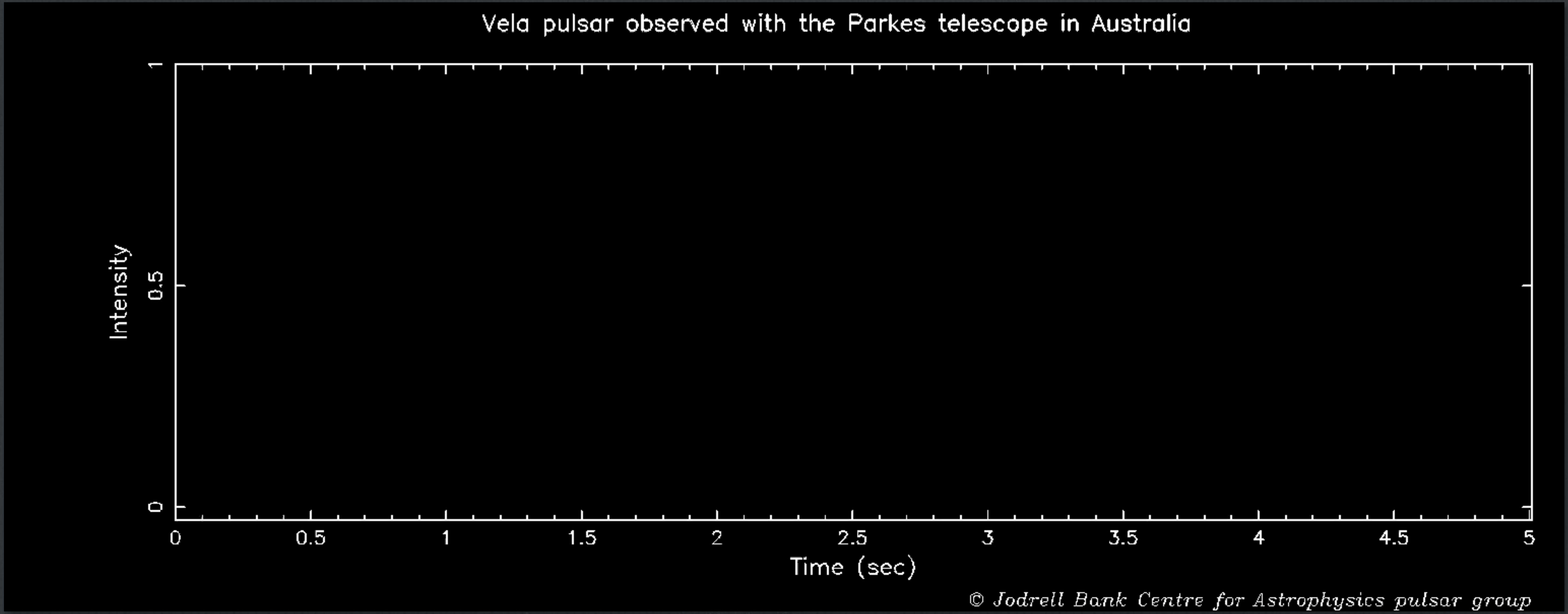
Pulsars: beamed beacons of the sky

- 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 and analyse a signal from a pulsar using a radio telescope such as MeerKAT



by Joeri von Leeuwen

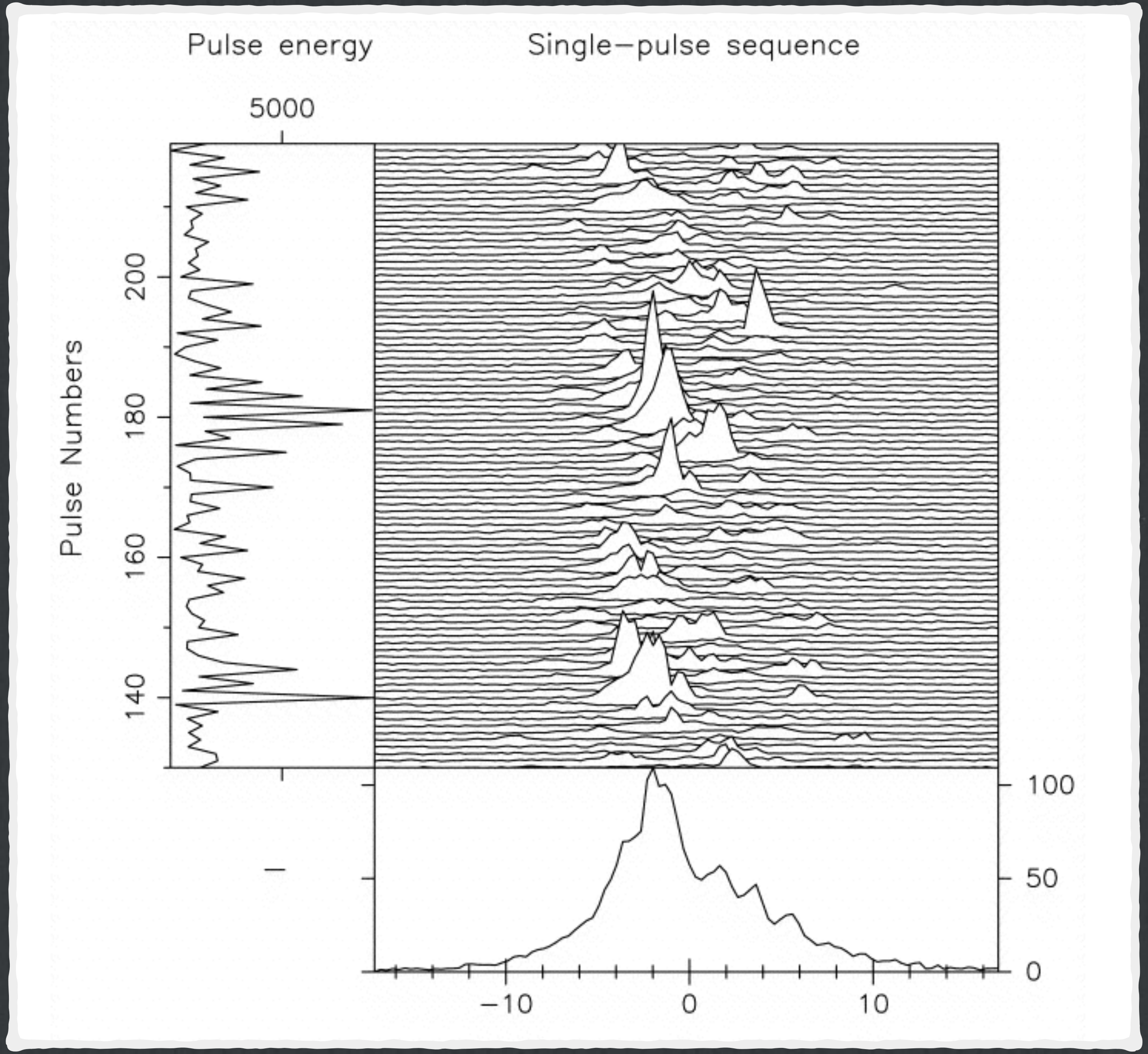
The bright Vela pulsar: PSR J0835-4510
Bright pulsar & close (300 pc): we can see single pulses



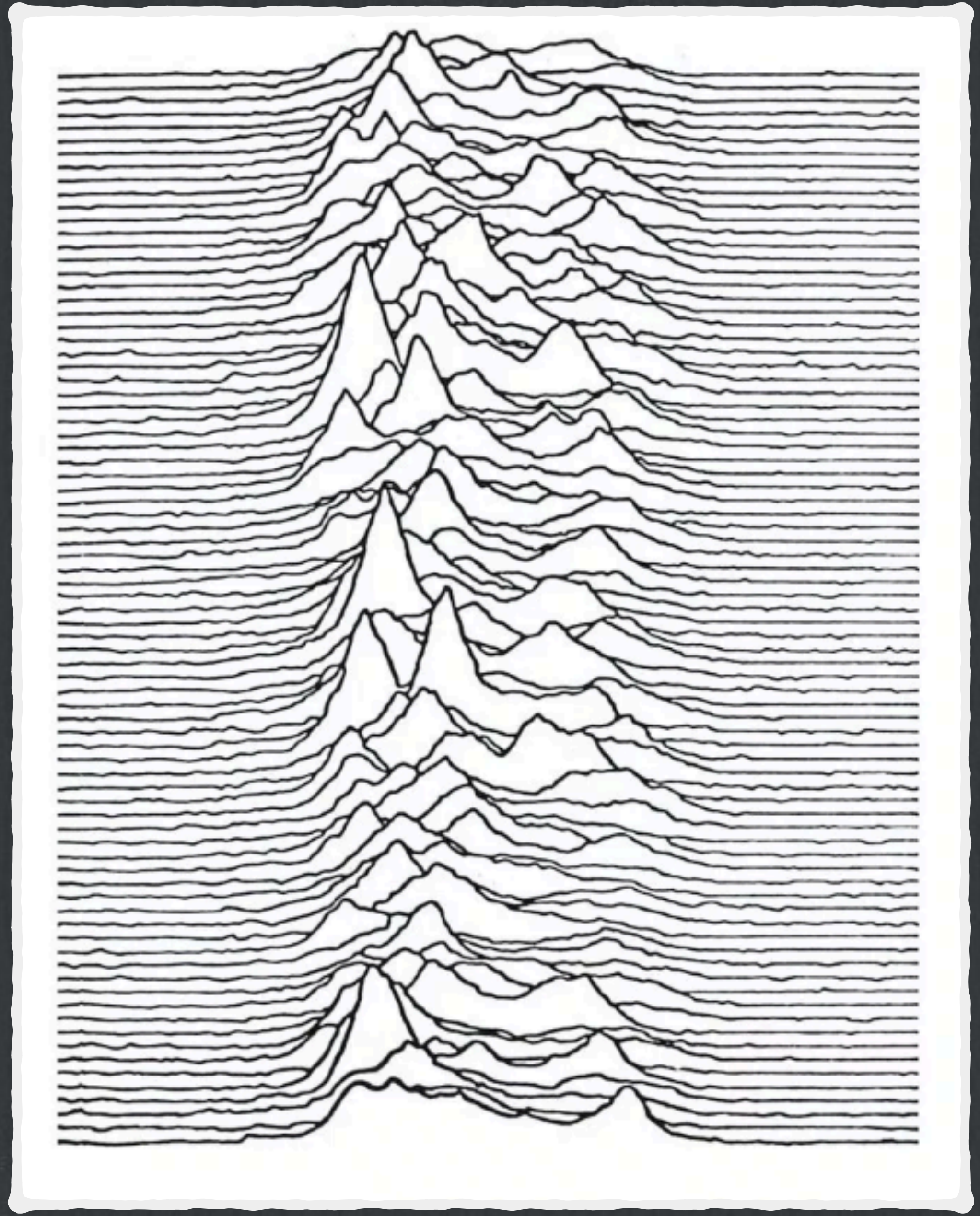
Folding pulsar signals to a stable pulse shape

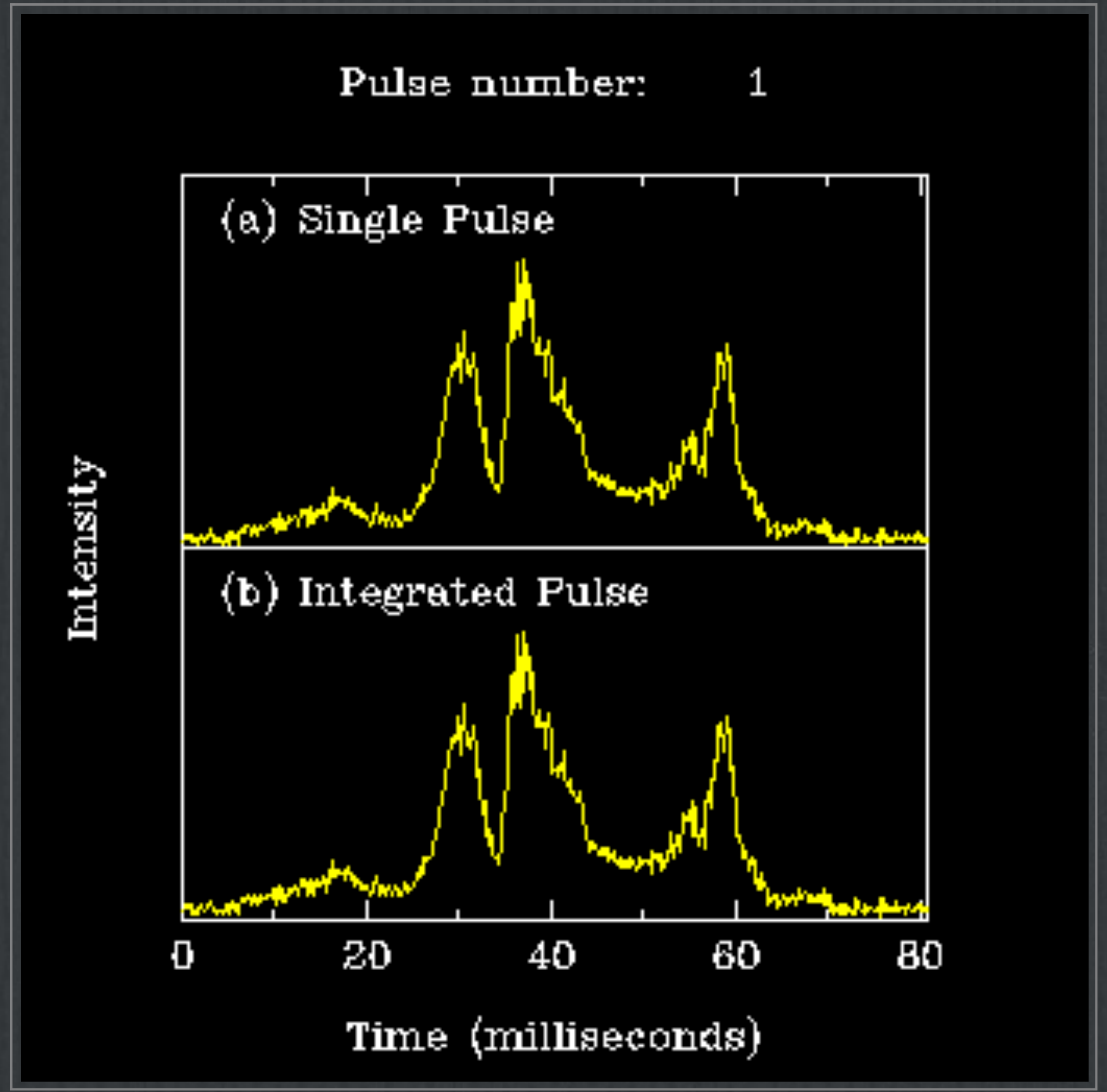
Many pulsars are too weak to easily detect single pulses

- Moreover single pulses mostly appear varied in shape
- However, when we average together ~ 1000 pulses a higher S/N stable pulse shape is formed
- By knowing the pulsar observing parameters we can add single pulses together to form detectable average pulses
- This process of adding pulsar data to form a stable pulse shape is called ‘folding’



PSR B0943+10





CP 1919 - the original pulsar

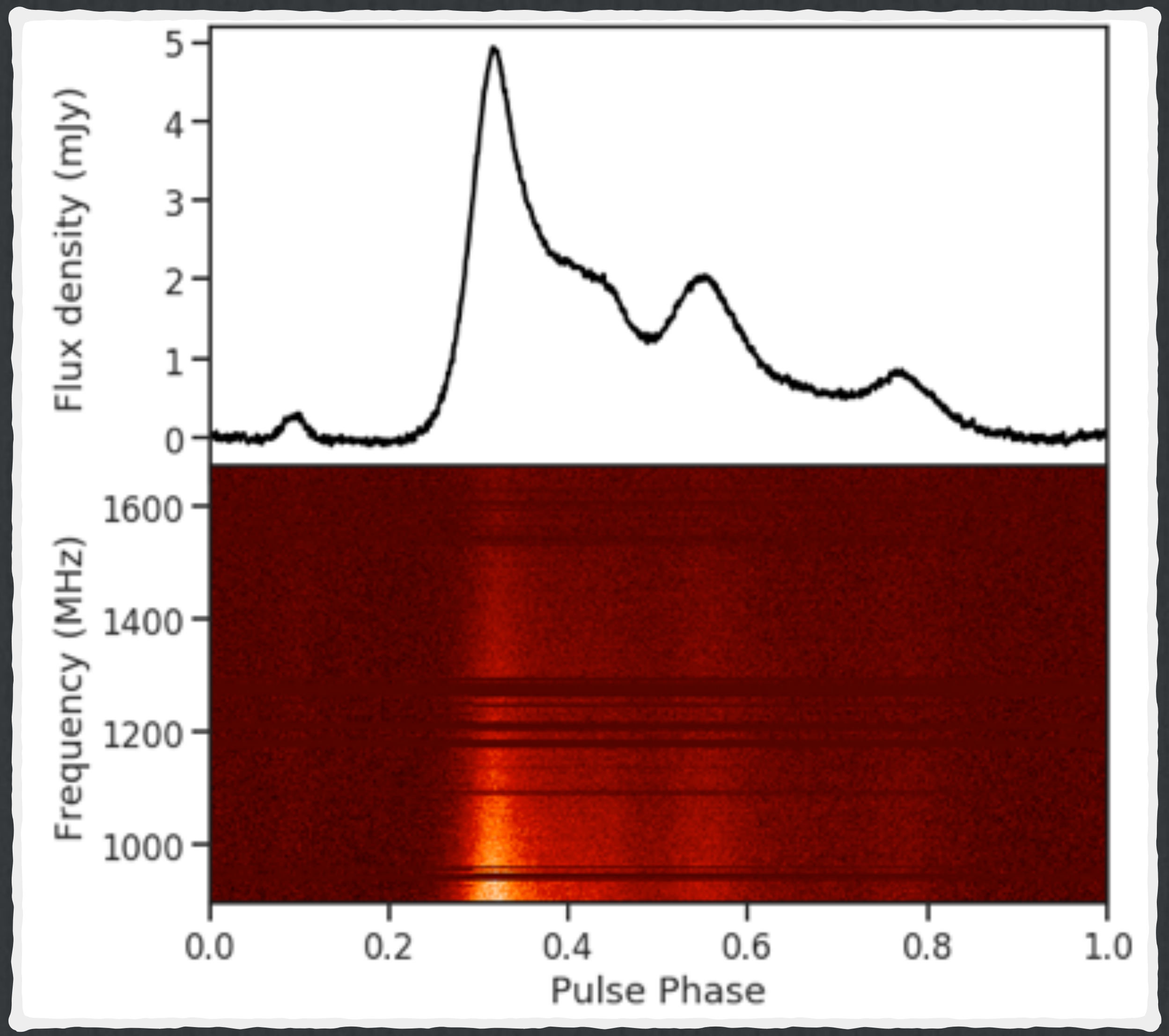
Pulsars are broadband radio emitters

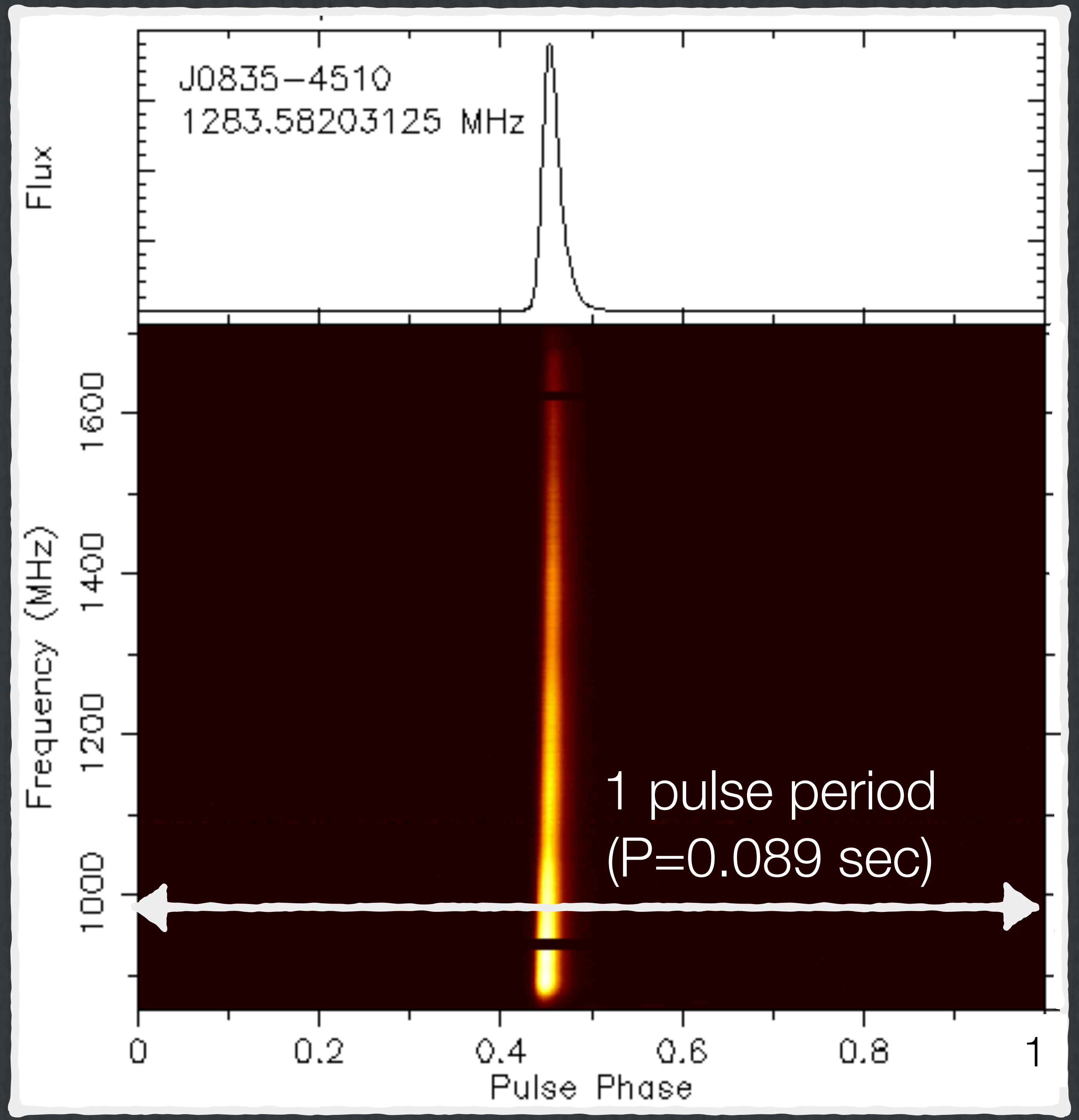
- They have been observed in the radio all the way from 30 MHz - 230 GHz!
- They are intrinsically brighter at lower frequencies
- Which means they are steep spectrum sources:

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

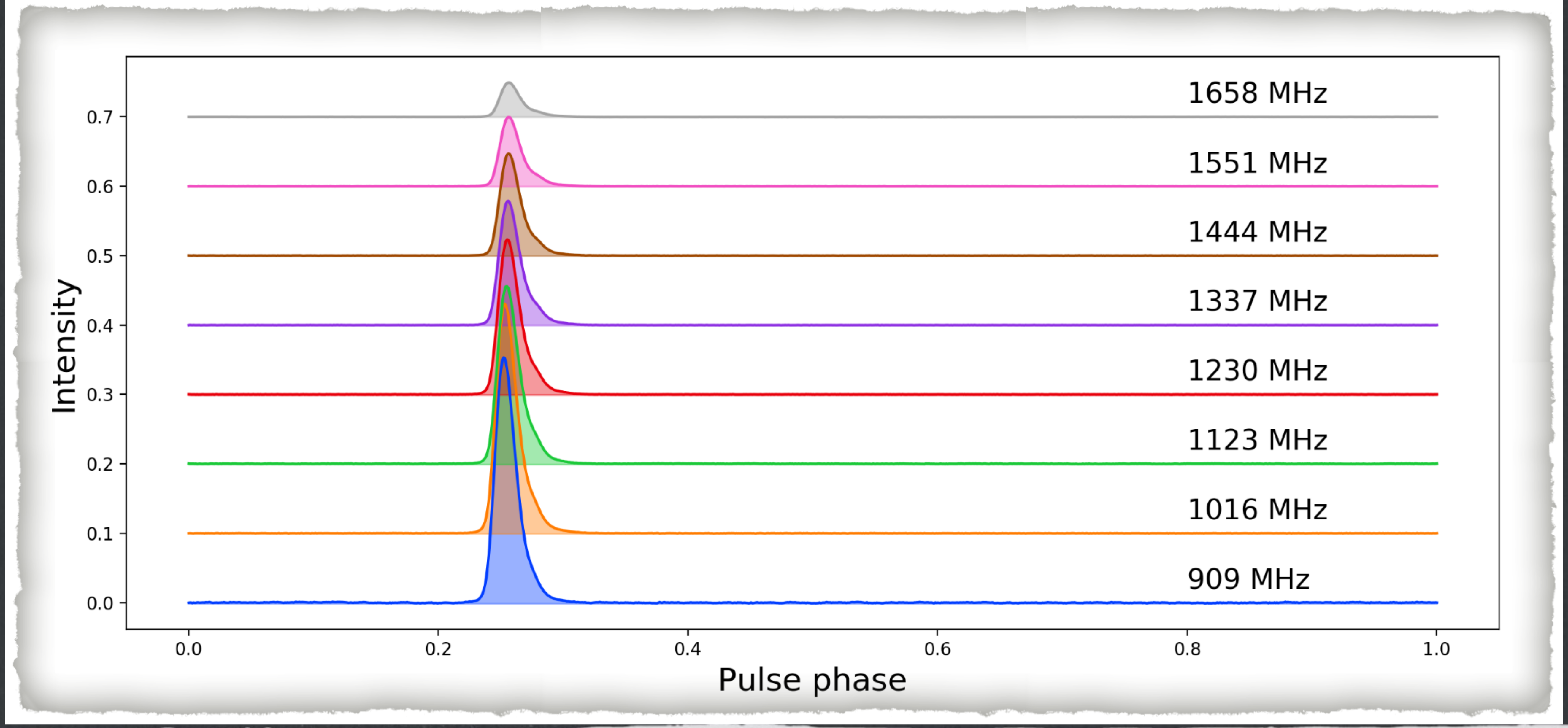
where S_ν is flux (Jy) at a frequency ν and typical values for α ~ 1.4 to 1.8

PSR J0955-6150 across the MeerKAT L-band





The Vela pulsar (J0835-4510) at MeerKAT L-band



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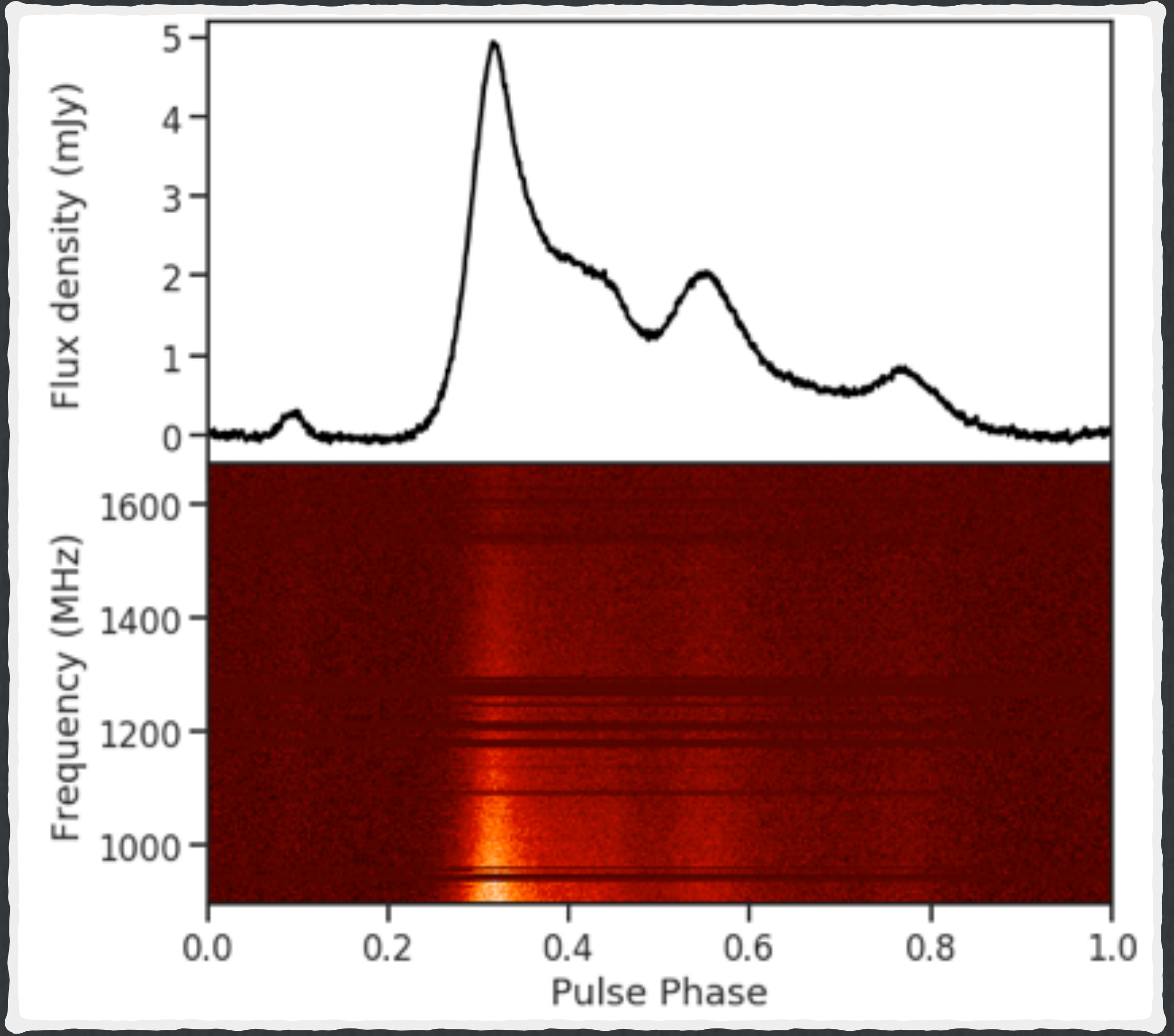

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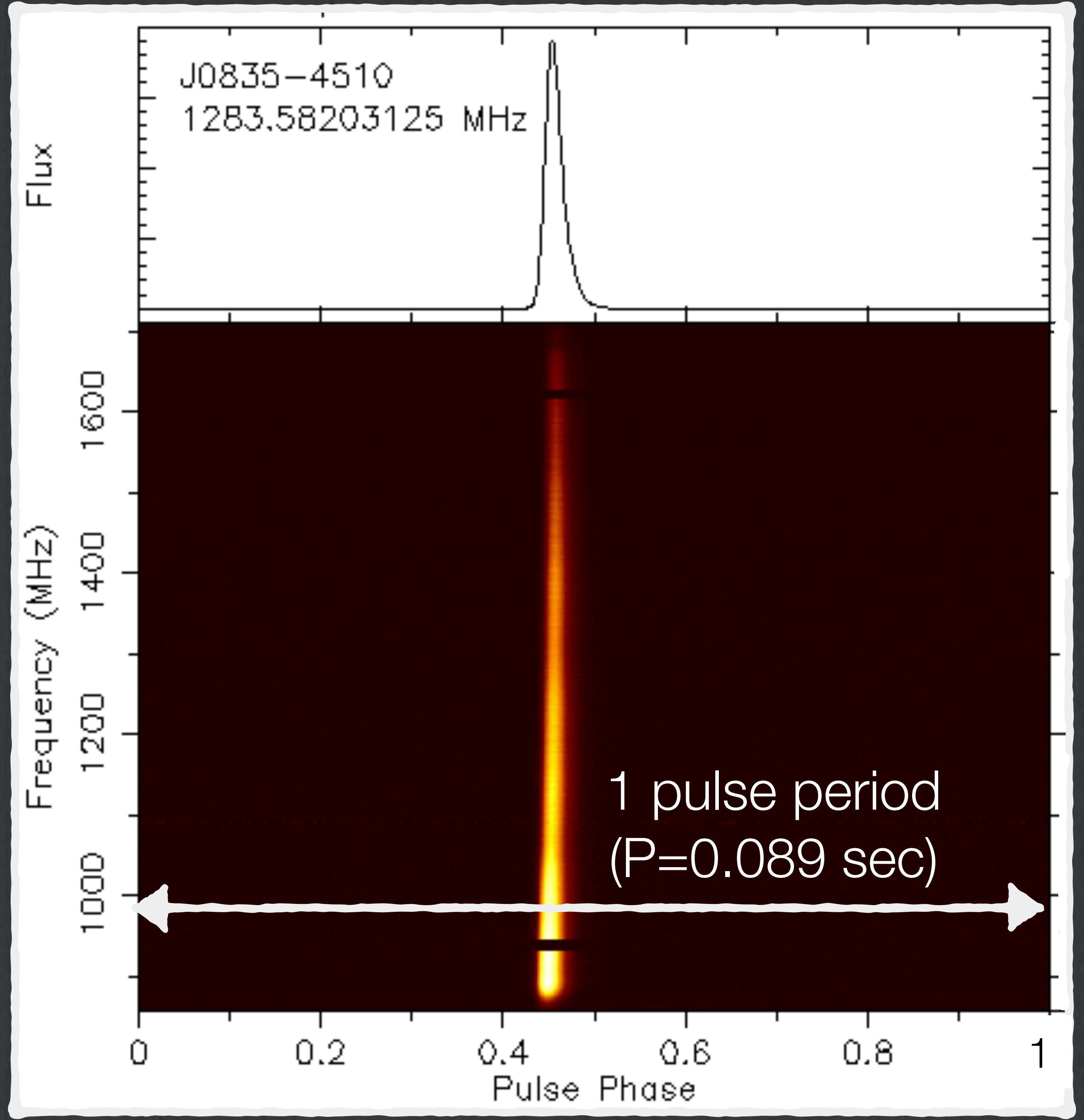


The observing frequency trade-off

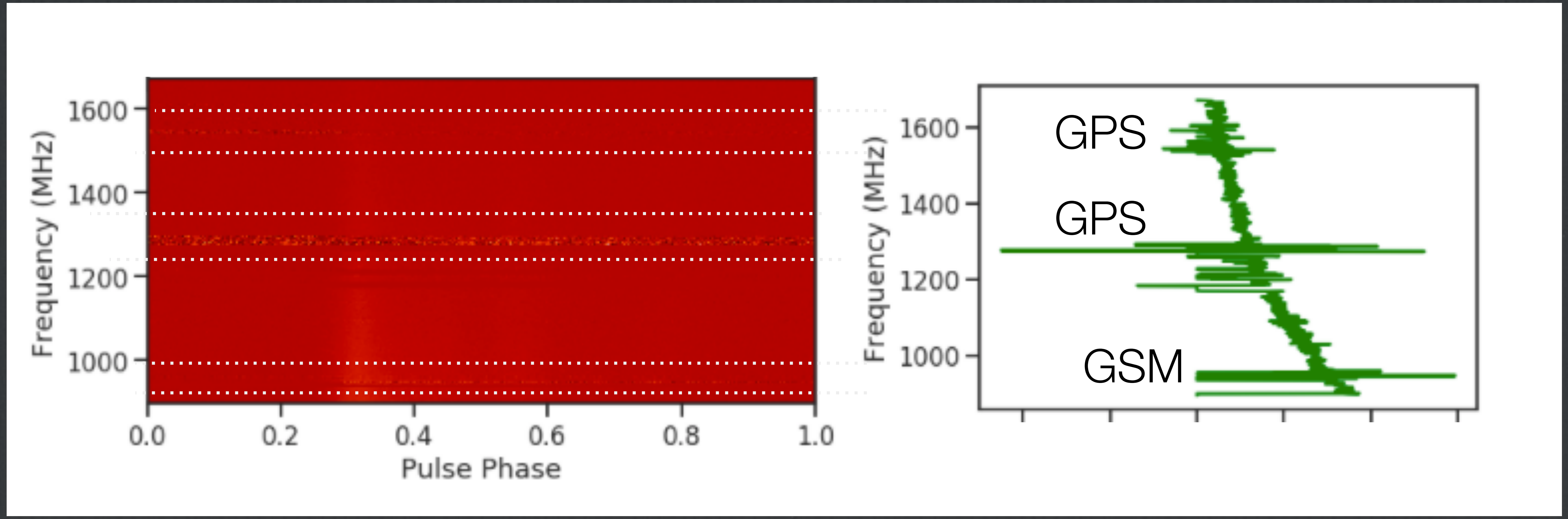
- Even though pulsars are brighter at lower frequencies, we'll see that lower frequency signals are more effected by the Interstellar Medium (ISM)

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

Contamination by Radio Frequency Interference

- Terrestrial telecommunication devices emit in narrow frequency bands

- Often these are well-defined and known to us



- At MeerKAT L-band frequencies (856 MHz - 1712 MHz) these are often dominated by GSM (mobile) and GPS
- Removing contaminated frequency channels is key before going ahead with data analysis
- However beyond narrowband interference, you may also need to scan for temporal RFI

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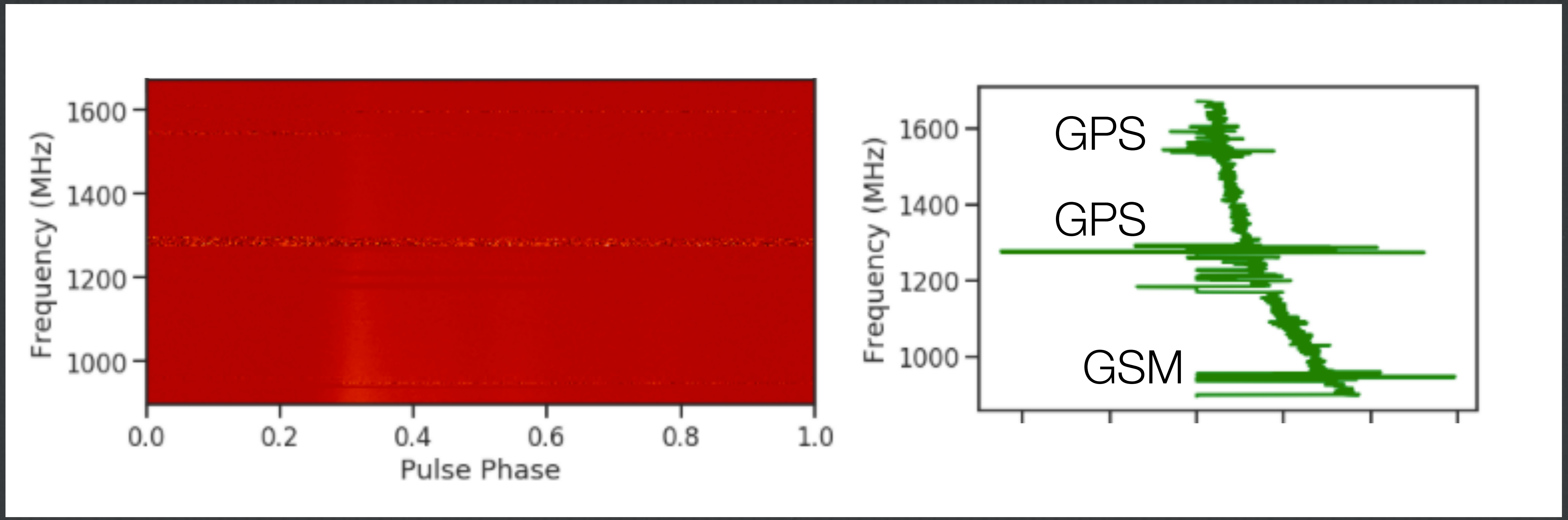
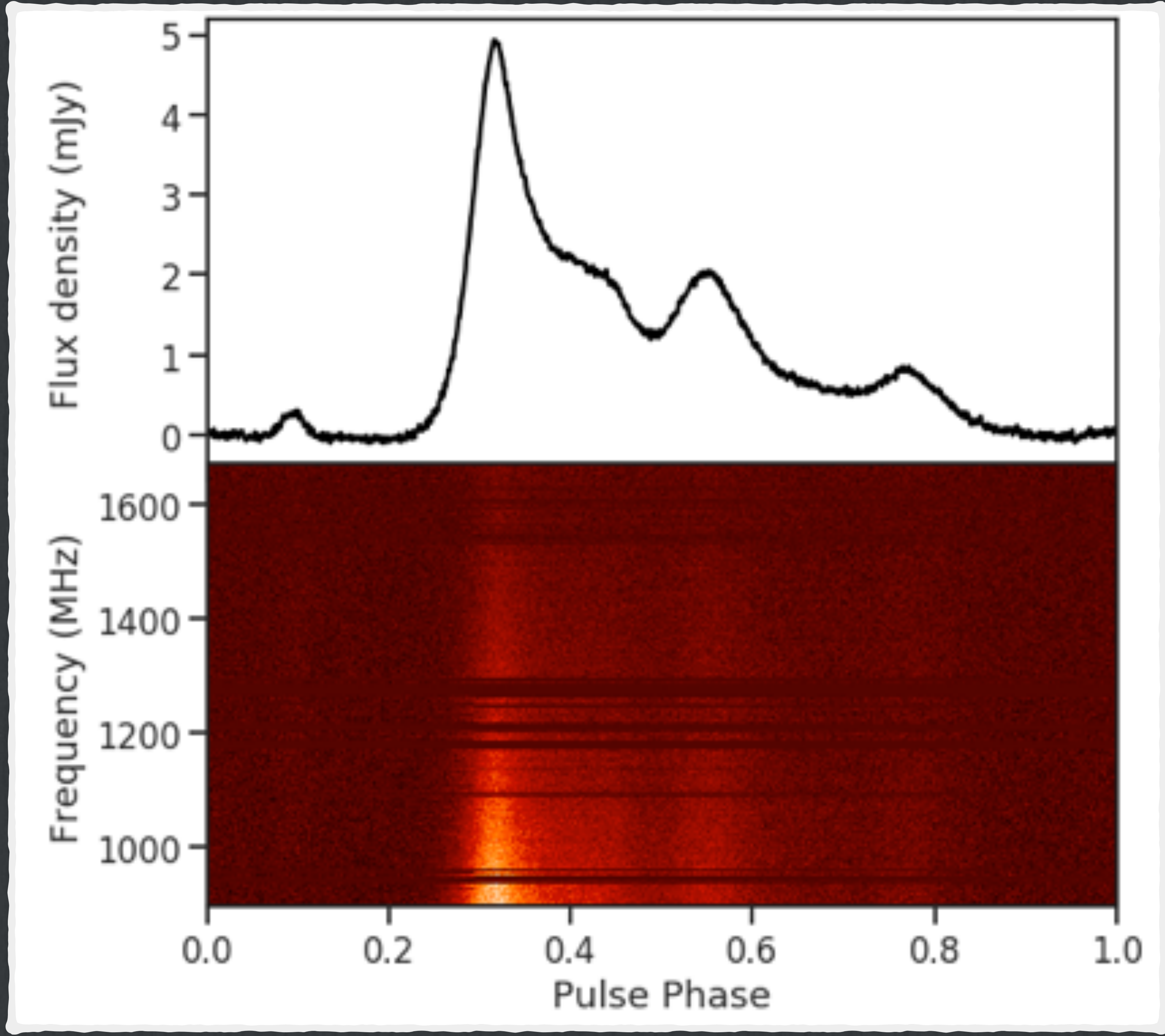
Once removed the pulse is brightly revealed!

PSR J0955-6150 across the MeerKAT L-band





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Propagation through the Interstellar Medium

- Here we investigate the effect of the Interstellar Medium in the propagation of radio signals - in general; and then consider the effects on pulsar signals in particular

- 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)

(credit: ESO/Digitized Sky Survey 2)

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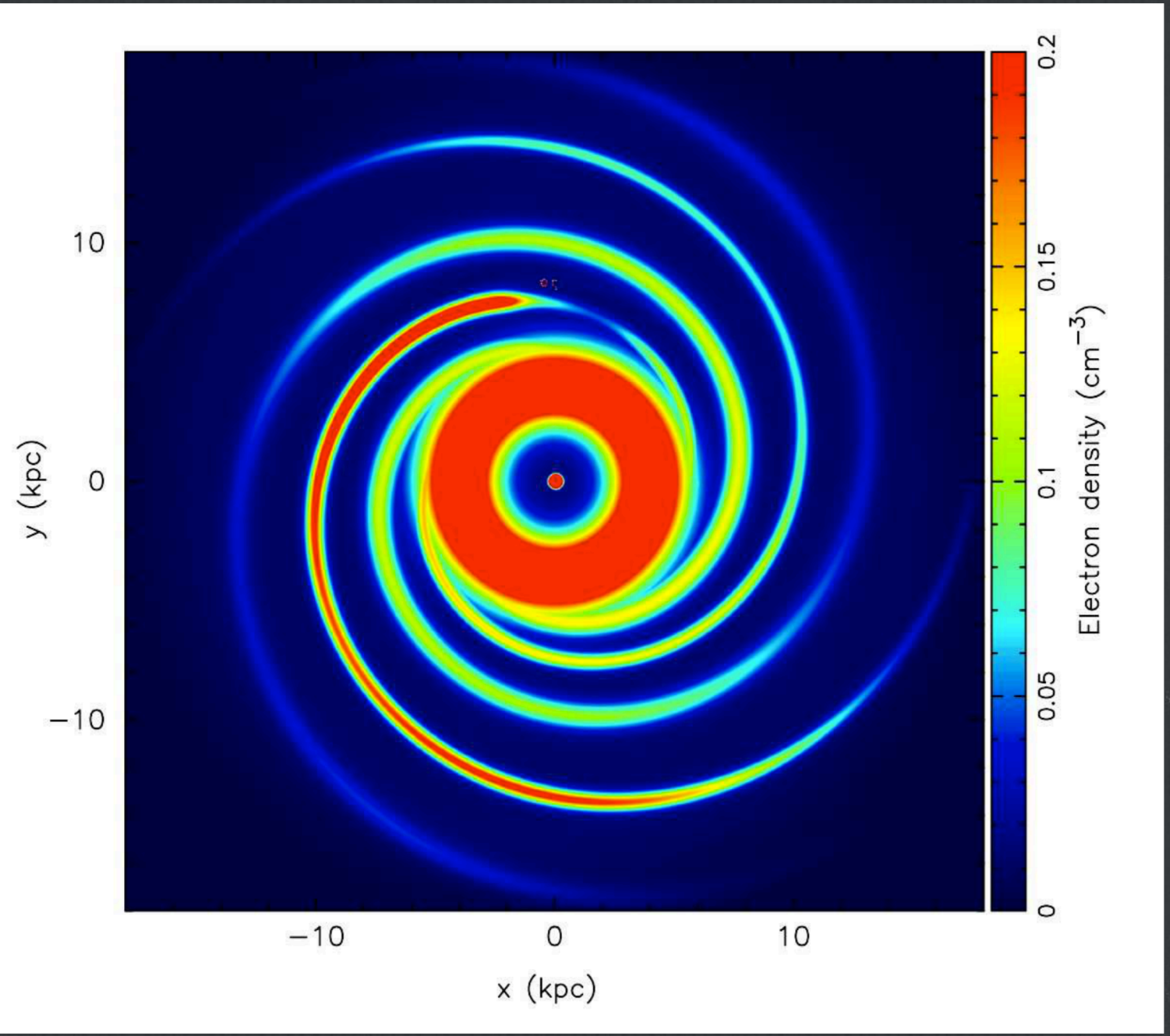
- gas (containing atoms, molecules, ions and free electrons)
- dust (tiny solid particles)

- This ionised ISM (containing free electrons) can be modelled as a cold** plasma of ~ 8000 K
- characterised by its line of sight electron densities

** note that cold means it is colder than the 'hot' or 'fully ionised' part of the ISM. In other words it is partially ionised.



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

The ISM Cold Plasma refractive index

- In Optics the refractive index (*n*) of a medium is given by Snell's Law:

$$n = c/v_m$$

- with c the speed of light, and
  v_m the altered speed of the waves in the particular medium

- In ISM physics we define the (inverse) refractive index (μ) in terms of

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

- ν is the frequency of the radio emission propagating through the ISM
- ν_p is the resonant ISM plasma frequency as a function of free electron density (n_e)

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

electron mass, $m_e = 9.109 \times 10^{-31}$ kg

electron charge, $e = 1.6022 \times 10^{-19}$ C

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

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SI conversions
1 cm^{-3} = 1x10^{-6} m^{-3}
1Hz = 1000kHz

typical average n_e densities in the galaxy ~ 0.03 cm^{-3}

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typical ~ 1.5 kHz

Radio wave propagation through ISM

- Radio waves in the ISM propagate with group velocity v_g

-The ISM refractive index (μ) can be written as the ratio of group velocity and speed of light (c)

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

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

waves don't propagate

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

waves propagate with velocity

$$v_g = c\mu < c$$

typical ~ 1.5 kHz

radio observations ~ 10 MHz - 100 GHz

Radio wave propagation through ISM

- Radio waves in the ISM propagate with group velocity v_g

- Since $\nu_p \ll \nu$ for 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
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Question: when observing a pulsar - will all its emission arrive at the telescope simultaneously?

Dispersive Delay by the ISM

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

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

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

$$t = \int_0^d \frac{dl}{v_g} - \frac{d}{c}$$

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

Astrophysical object at distance d, Observer at 0

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

Plugging in astronomical units

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

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

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Strong frequency dependence

Delay between radio frequencies by the ISM

Delay at 1 GHz (compared to speed of light)

$\nu = 1000$

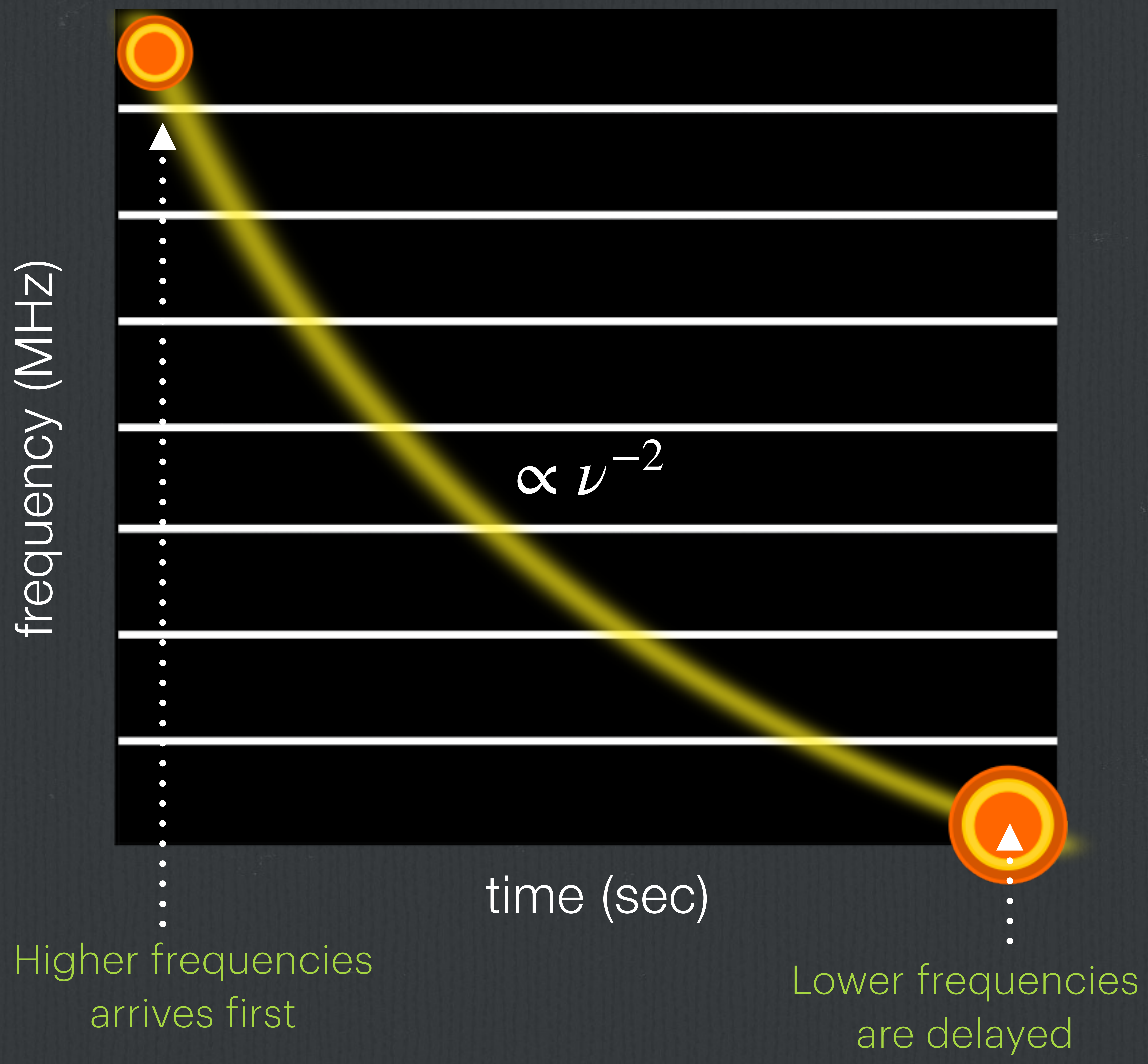
$$t = 4.149 \times 10^3 \mathrm{sec} \left(\frac{\nu}{\mathrm{MHz}}\right)^{-2} \left(\frac{\mathrm{DM}}{\mathrm{pc\ cm^{-3}}}\right)$$

$$t = 4.149\ \mathrm{ms} \left(\frac{\mathrm{DM}}{\mathrm{pc\ cm^{-3}}}\right)$$

With DM typically 100 - 1000 pc cm-3,
the delay at 1 GHz is 100 ms to 1 sec

Delay between two frequencies

$$\Delta t = 4.15 \times 10^3 \mathrm{sec} \times \mathrm{DM} \times \left[\frac{1}{\nu_{\mathrm{low}}^2} - \frac{1}{\nu_{\mathrm{high}}^2}\right]$$



Pulsar signals are dispersed by the ISM

Radio waves pass through the interstellar medium (ISM) as they travel towards us

The electron densities in the partially ionised component of the ISM, acts as a frequency dependent dispersive plasma

This plasma will **slightly delay** a radio signal: at 1 GHz and at few 100 pc (~1000 light years), the delay is typically < 1 sec

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2. Moreover since pulsars are **broadband** — the ISM will *stretch out the pulsar signal,* such that

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2. Moreover since pulsars are **broadband** — the ISM will *stretch out the pulsar signal,* such that

We observe the higher frequency components of the pulsar signal first, and the lower frequencies later

The time difference between two frequencies, $\nu_{\rm high}$ and $\nu_{\rm low}$, is given by $\Delta t = 4.15 \times 10^3 \times {\rm DM} \times \left[\frac{1}{\nu_{\rm low}^2} - \frac{1}{\nu_{\rm high}^2}\right]$

where the "dispersion measure" (DM) is the integrated electron column density, between the observer and the pulsar (in pc cm^{-3}):

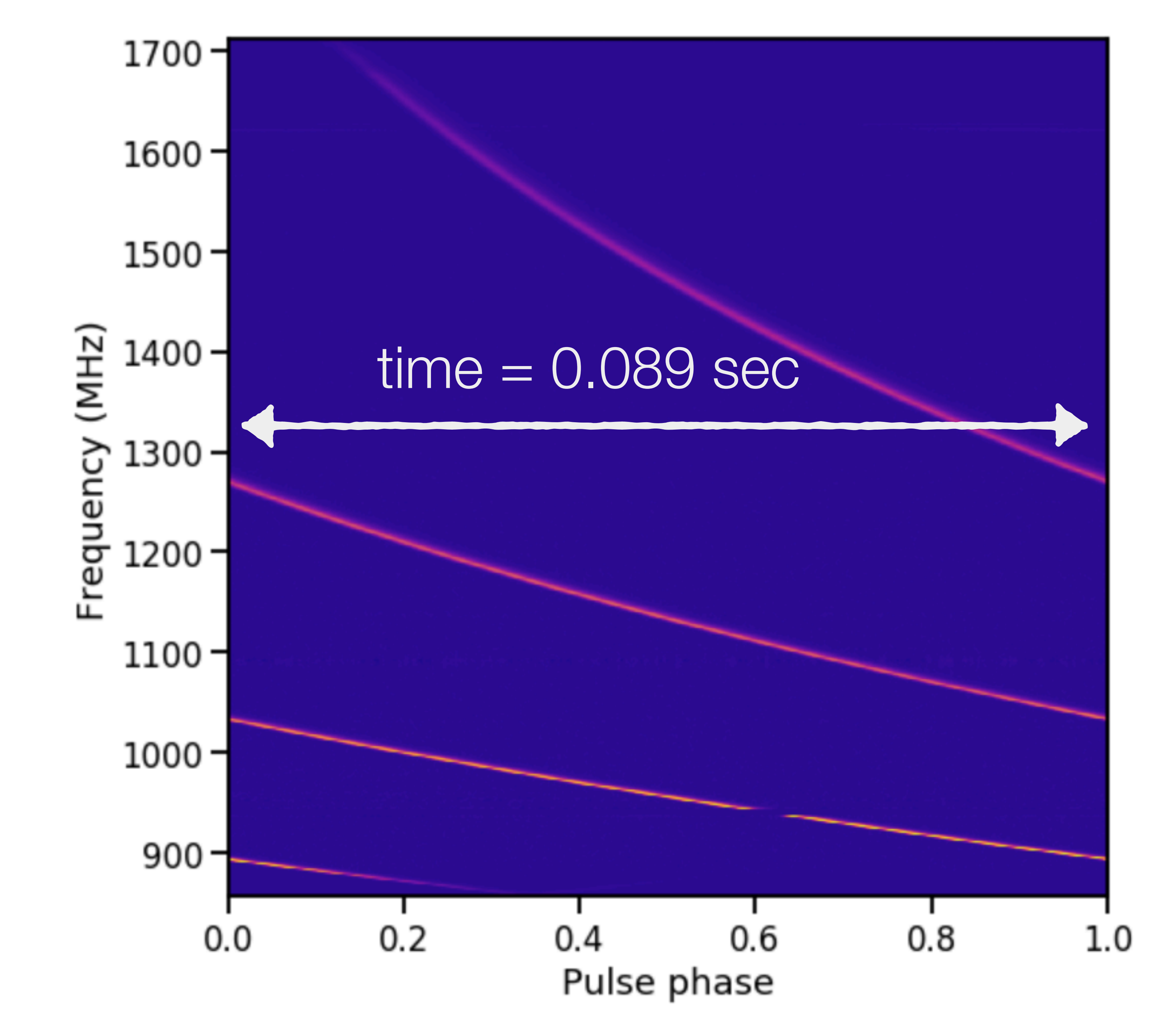
$${\rm DM} = \int_{\rm obs}^{\rm pulsar} {\rm n_e\, dl}$$

and therefore also a proxy for distance

$$\Delta t = 4.15 \times 10^3 \times \mathrm{DM} \times \left[\frac{1}{\nu_{\mathrm{low}}^2} - \frac{1}{\nu_{\mathrm{high}}^2}\right]$$

Pulsar signals are dispersed by the ISM

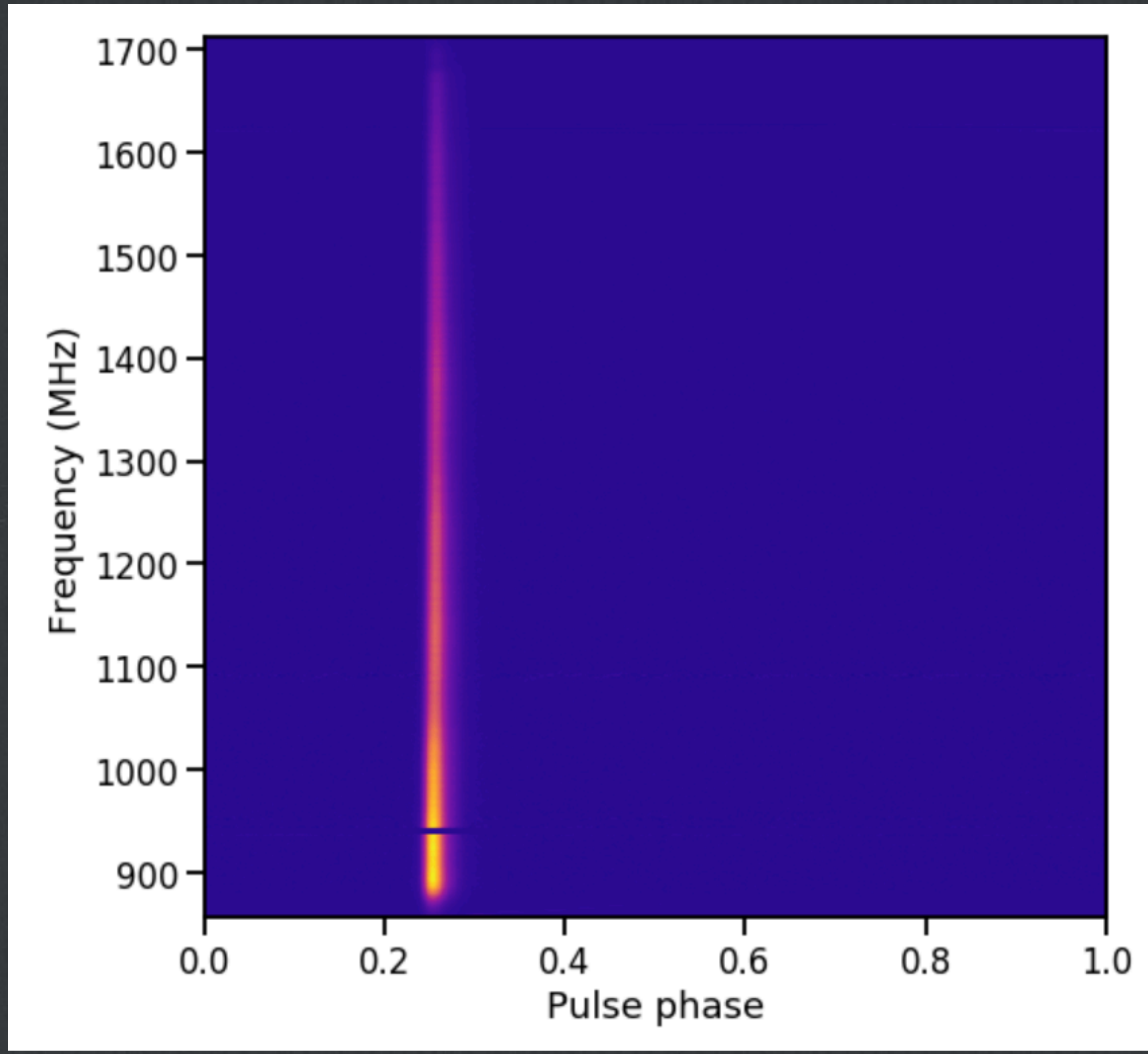
The Vela pulsar (J0835-4510) at MeerKAT L-band



The Vela signal has been folded on its pulse period of 89 ms

However, the dispersive delay between the highest frequency and the lowest is larger than the pulse period

Vela after dispersion correction



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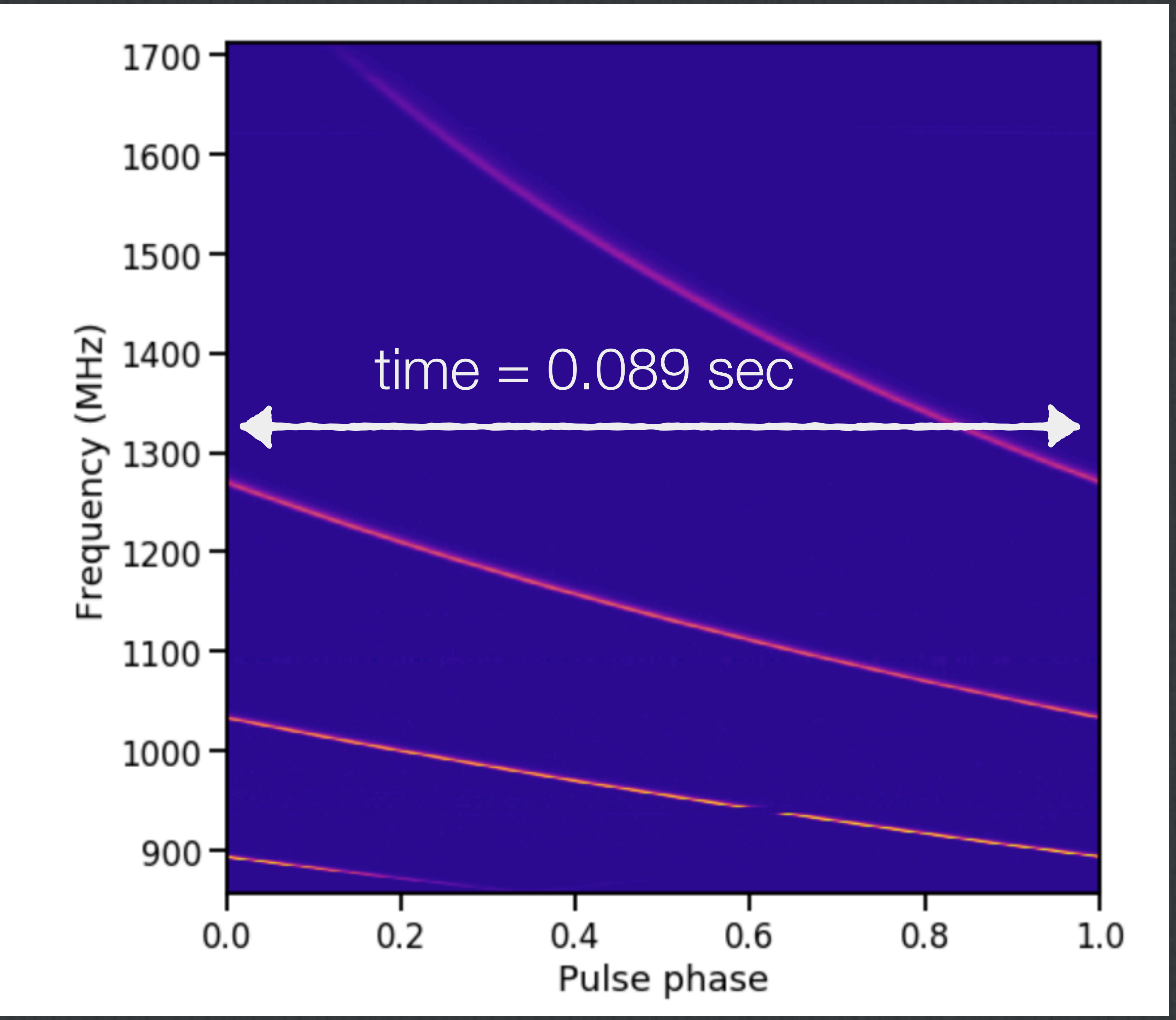

- The "dispersion measure" (DM) is the integrated column density of electrons between the observer and the pulsar
- Most well-known pulsars have good established estimates of their associated DM values
- Since the DM represents an integrated value along a long line of sight, it does not typically vary much from observation to observation
- However changes in pulsar DMs are observed, especially if the ISM environment towards a given pulsar is variable
- DM values can be obtained by conducting a ν^{-2} fit across the delayed folded pulsar signature in the observing band.
- Or more accurately through pulsar timing analysis

$$\Delta t = 4.15 \times 10^3 \times \mathrm{DM} \times \left[\frac{1}{\nu_{\mathrm{low}}^2} - \frac{1}{\nu_{\mathrm{high}}^2}\right]$$

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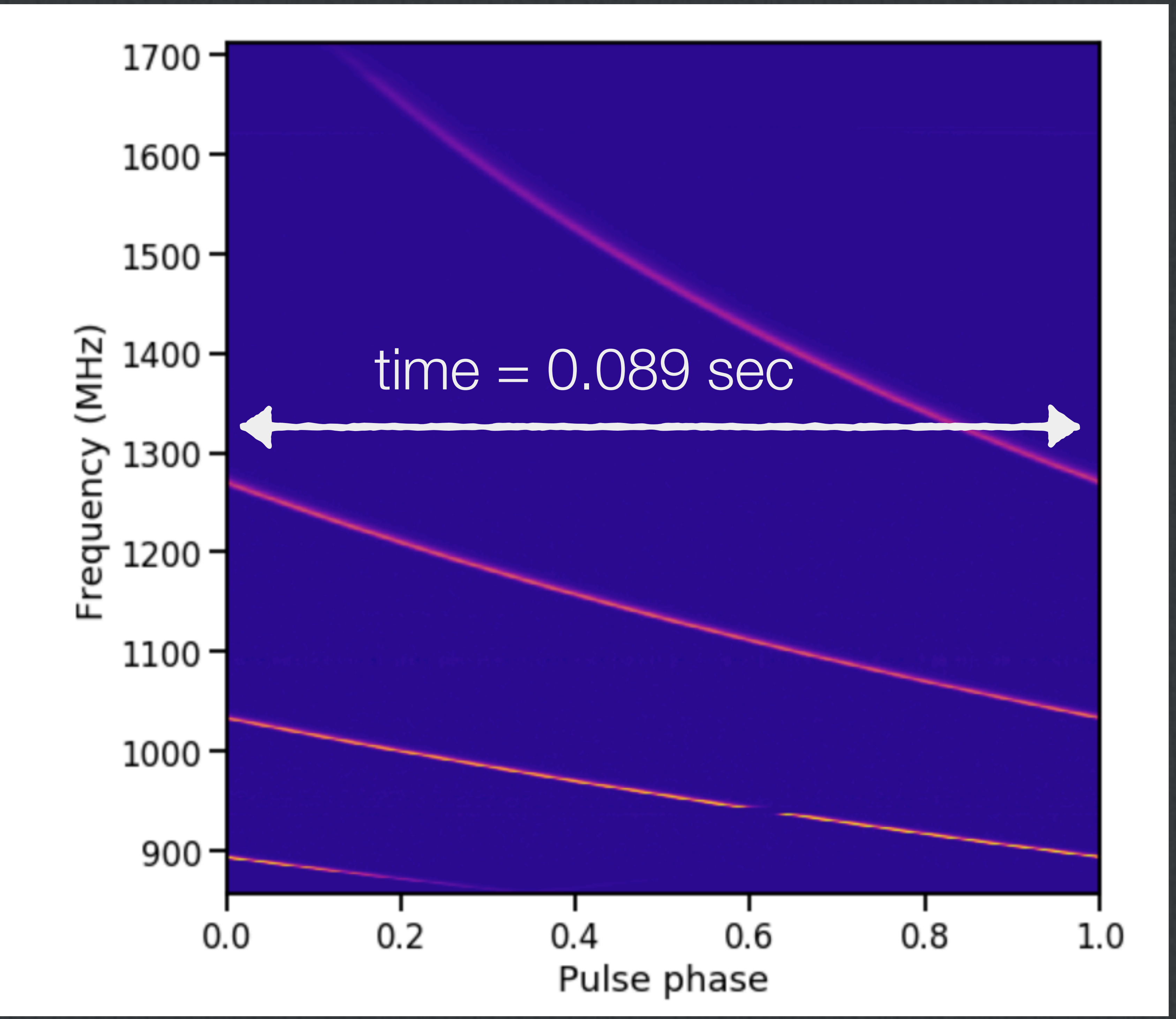
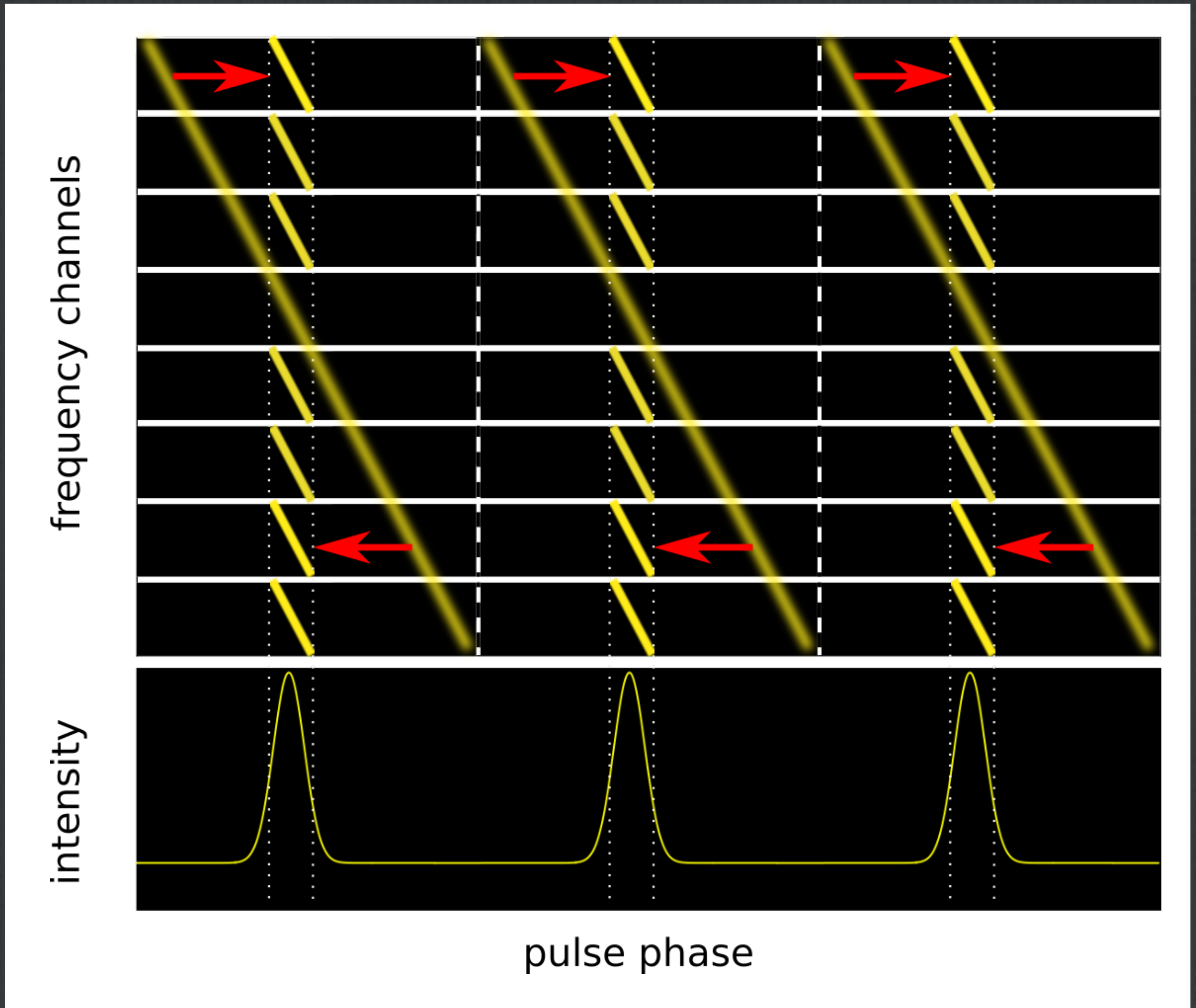


- Question: Can you estimate Vela's DM from this figure (roughly)?

Correcting dispersion

Incoherent de-dispersion

- Per frequency channel shift



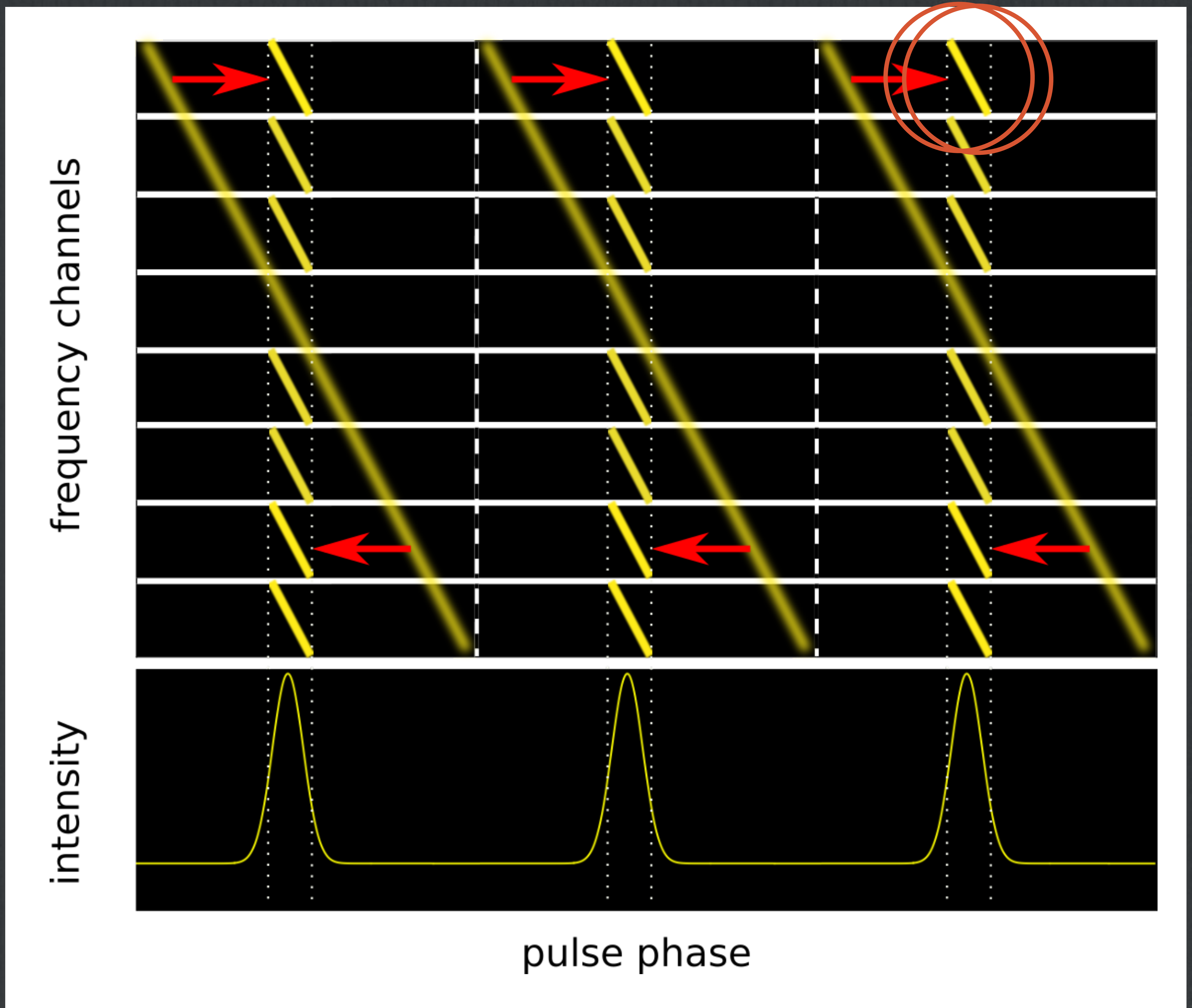
- The effect of dispersion can be removed by splitting the bandwidth up into a number of channels.
- In each channel we shift the time series by the calculated delay relative to the central frequency
- Correcting for dispersion in this way is called "dedispersion"
- In particular this method here is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

Correcting dispersion

Incoherent de-dispersion

- Per frequency channel shift

Residual smear within the frequency channel



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- In particular this method here is called "incoherent dedispersion"
- The signal within each frequency channel however remains uncorrected. This is called 'dispersion smear'.

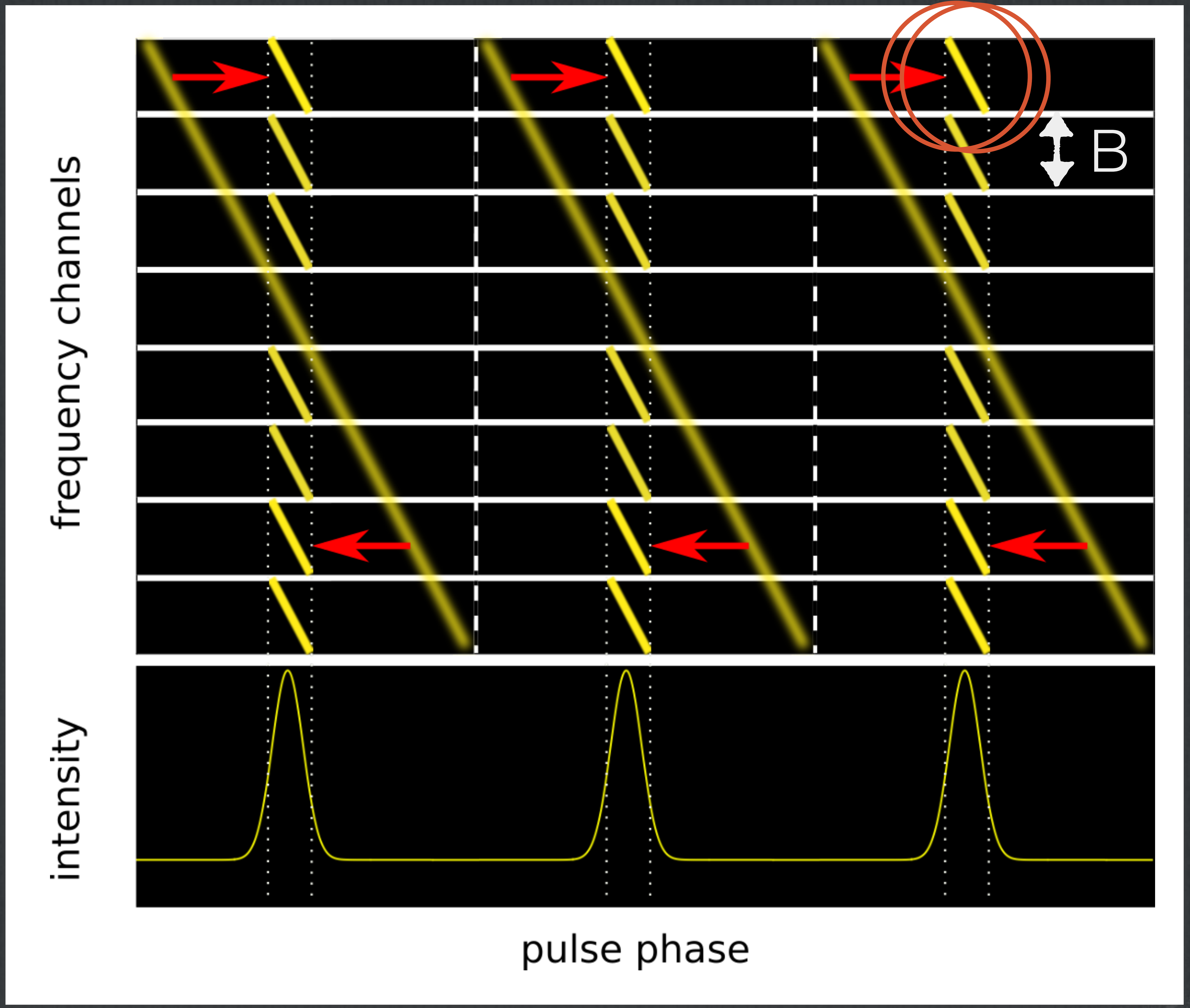
Question: how can we reduce the dispersion smear?

Correcting dispersion

Incoherent de-dispersion

- Per frequency channel shift

Residual smear within the frequency channel



Computing dispersion smear

If the channel bandwidth (B) is small compared to the observing frequency,

B << ν

then the smearing across the channel is given by

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

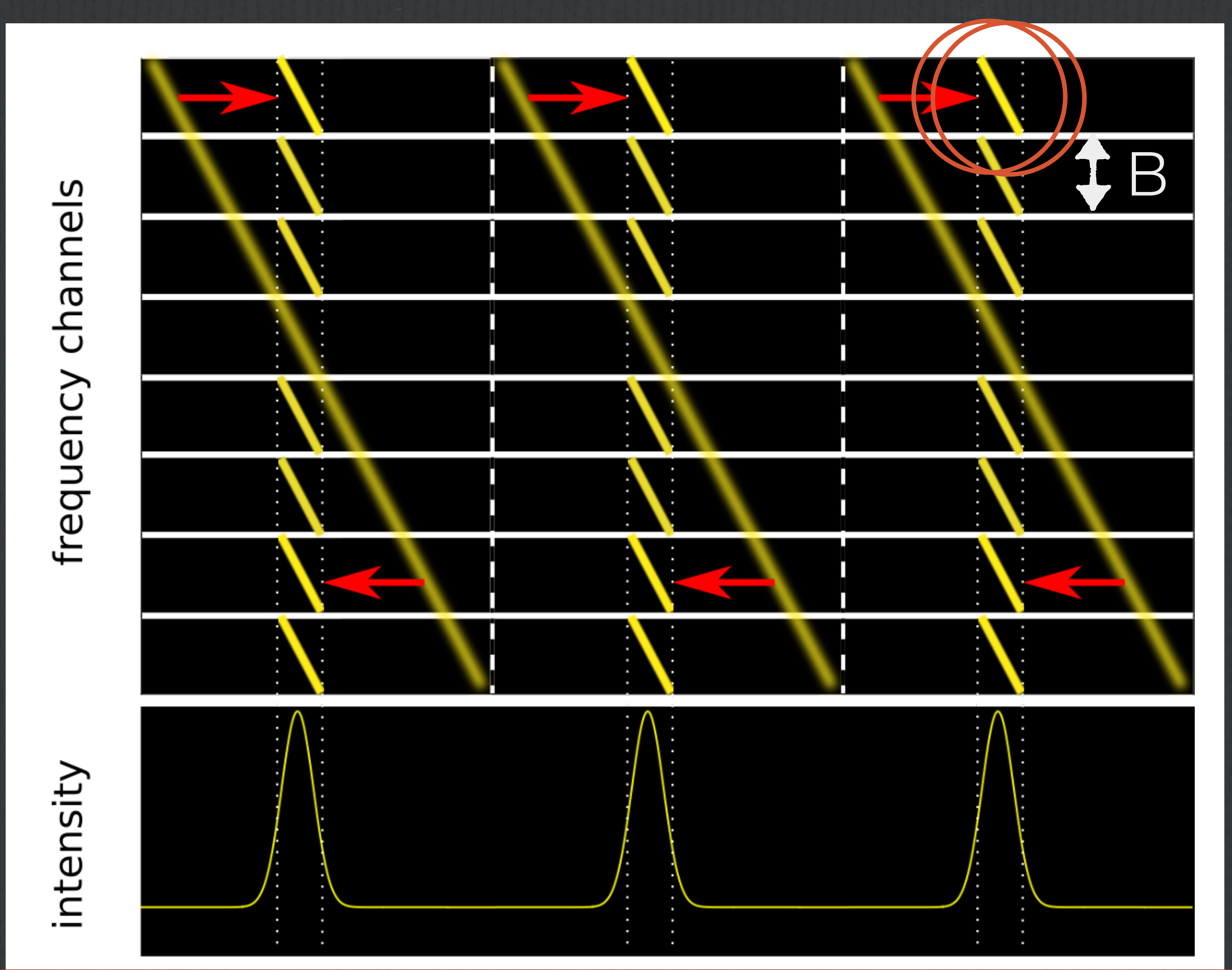
With incoherent dedispersion there is residual smearing across each channel.

Correcting dispersion

Incoherent de-dispersion

- Per frequency channel shift

Residual smear within the frequency channel



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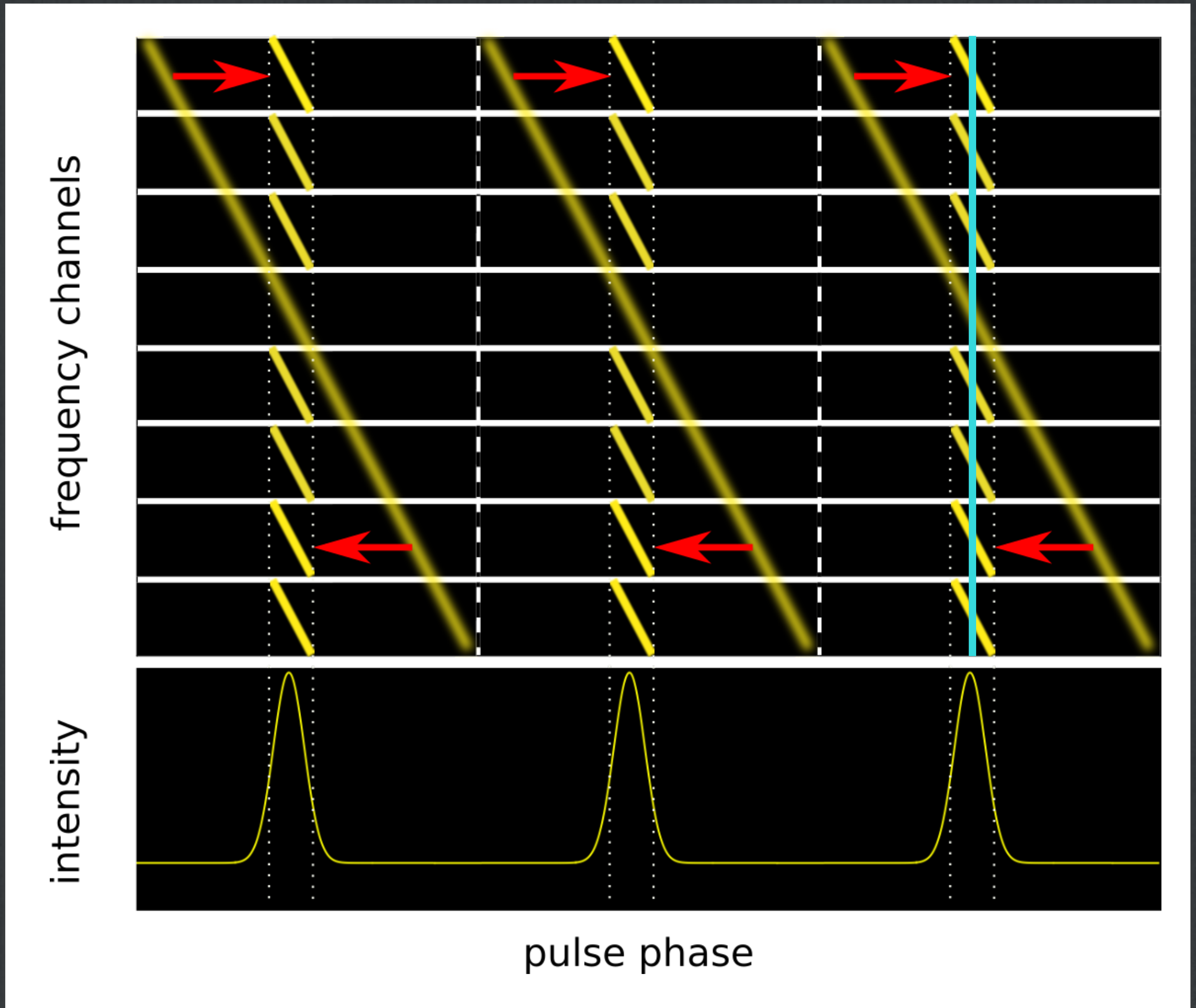
With incoherent dedispersion there is residual smearing across each channel.

Next-up: We can also fully remove the dispersion smear through a technique called coherent dedispersion

Correcting dispersion by applying phase changes

Coherent de-dispersion

ISM effect fully removed



- The ISM dispersive delay that we computed,
  imparts a frequency dependent phase change on the radio waves

- In the Fourier domain this is a phase change to the each component of the electric field of the signal

intrinsic E-field

$$E_m = E_i e^{ik\phi}$$

measured E-field

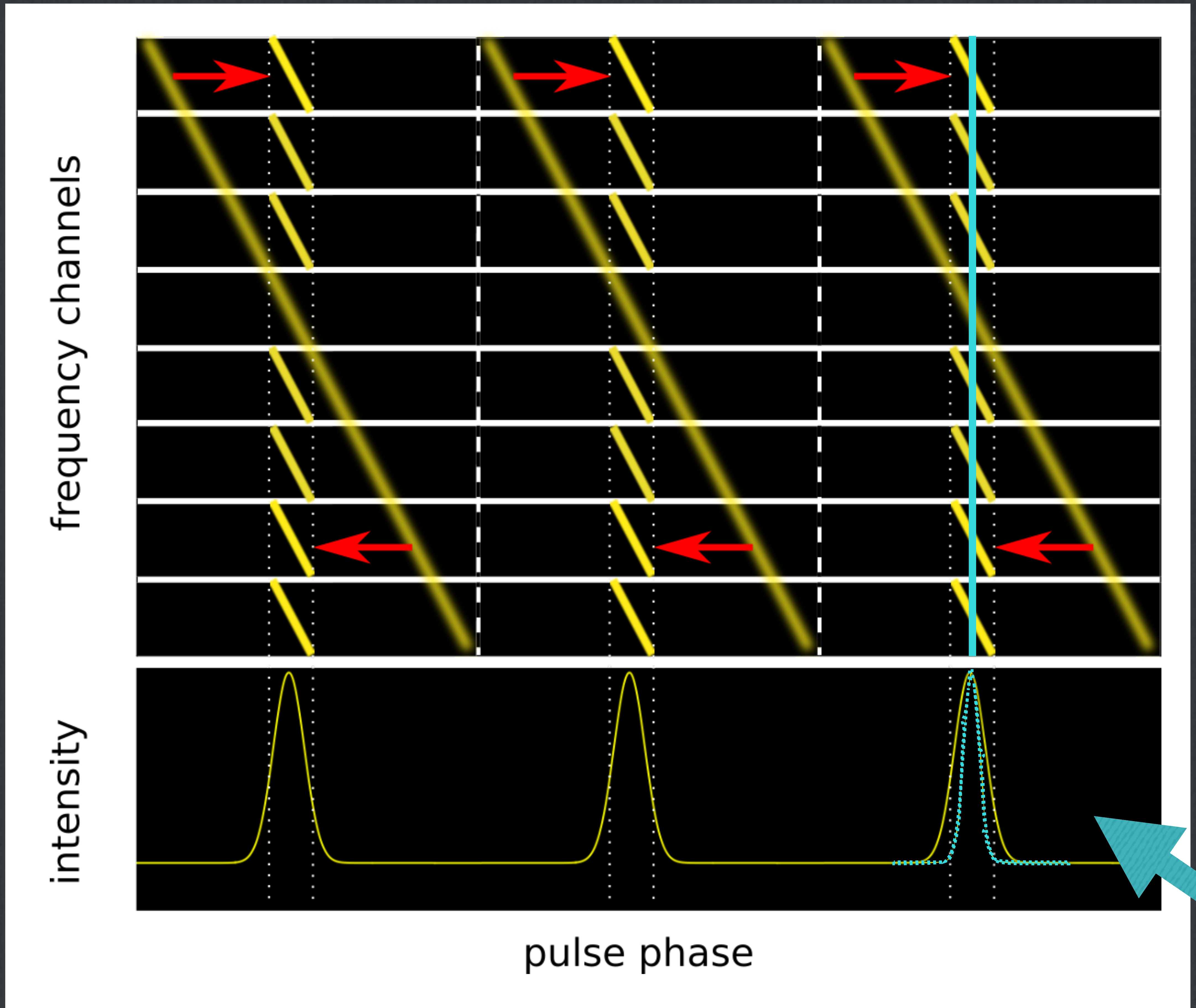
k: wavenumber
ϕ: phase change

- The dispersion can be removed by multiplying induced E_m with an inverse phase correcting function, $e^{-ik\phi}$ for each polarisation in the beamformer
- Correction to the raw complex voltages (before computing the pulsar intensities)

Correcting dispersion by applying phase changes

Coherent de-dispersion

ISM effect fully removed



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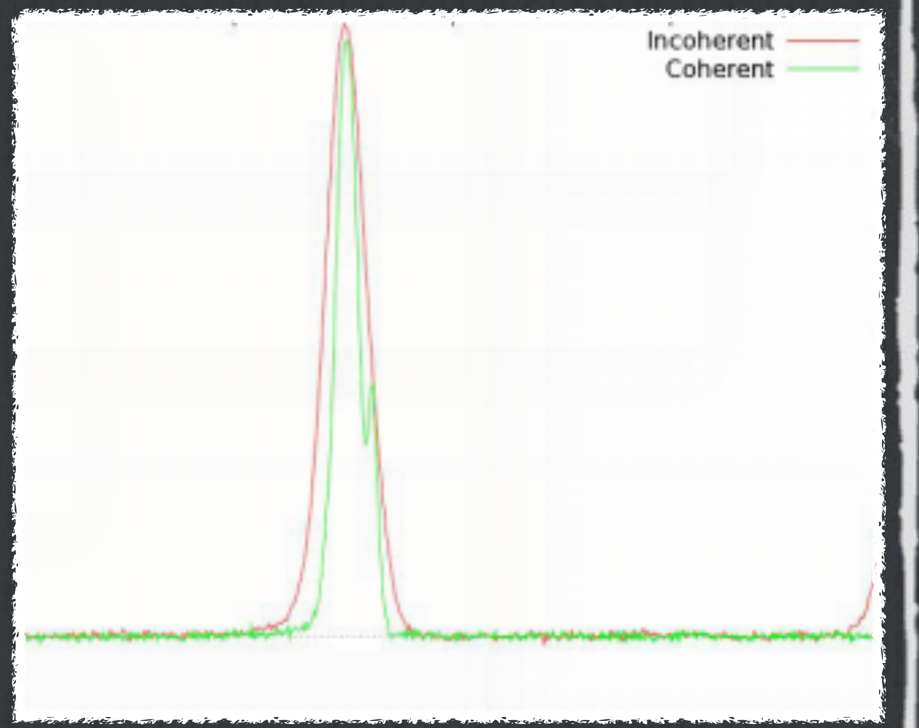
Comparison between the incoherent and coherently dedispersed pulse profile of PSR B1937+21
(picture credit: Paul Demorest)

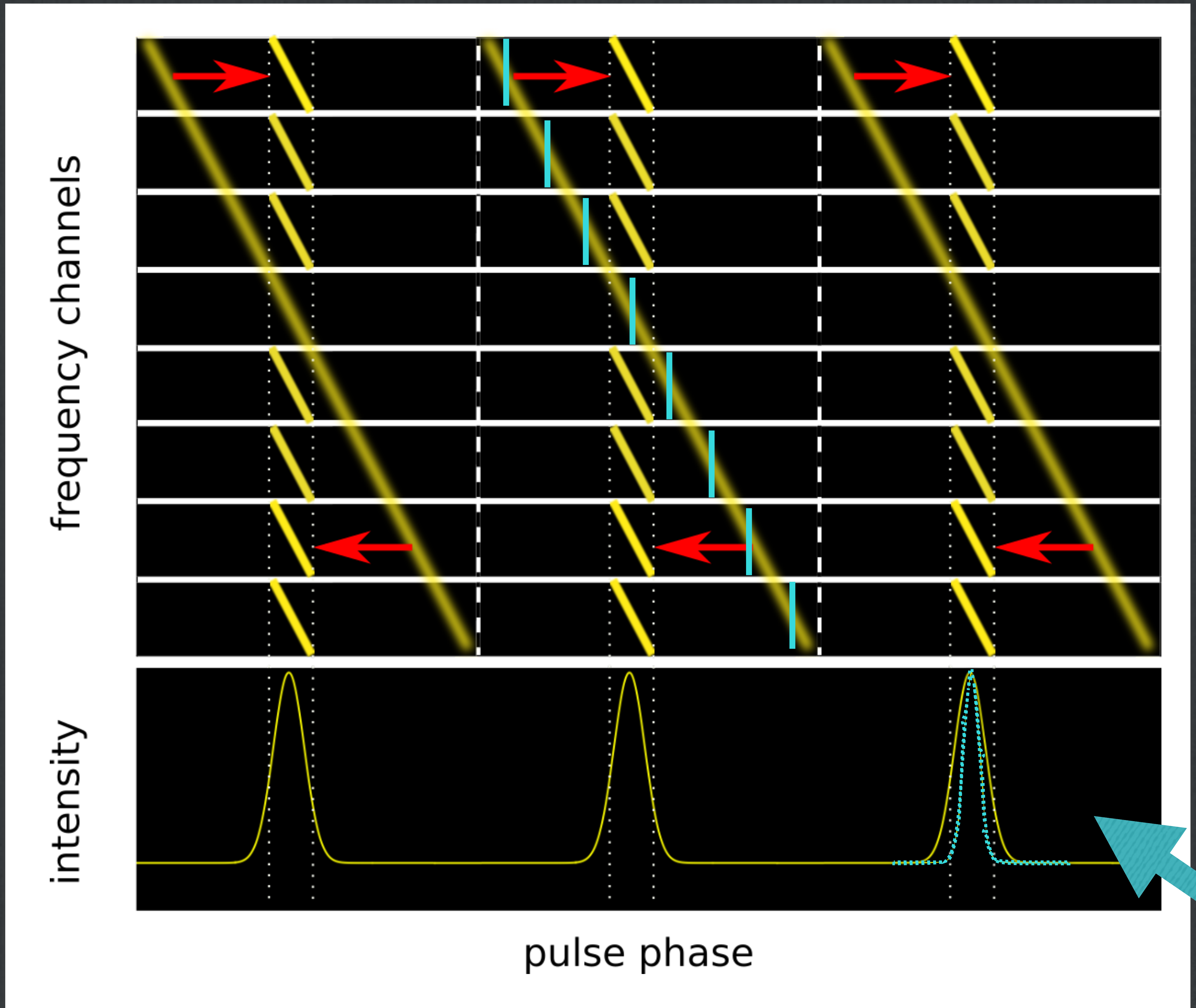


Improved sharpness and features of the detected pulse

Correcting dispersion by applying phase changes

Coherent de-dispersion

ISM effect fully removed



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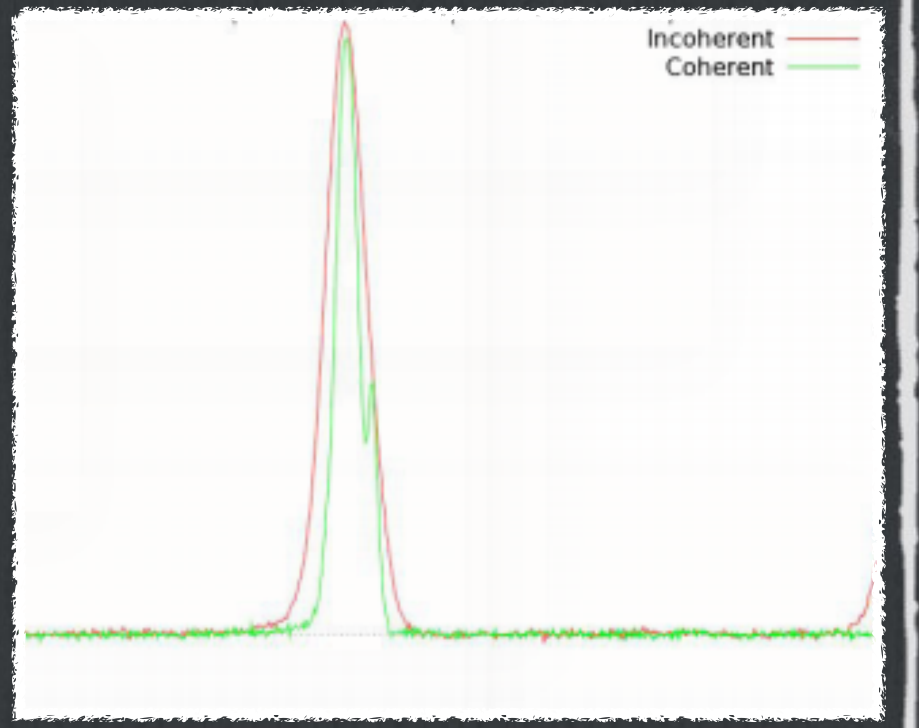


Improved sharpness and features of the detected pulse

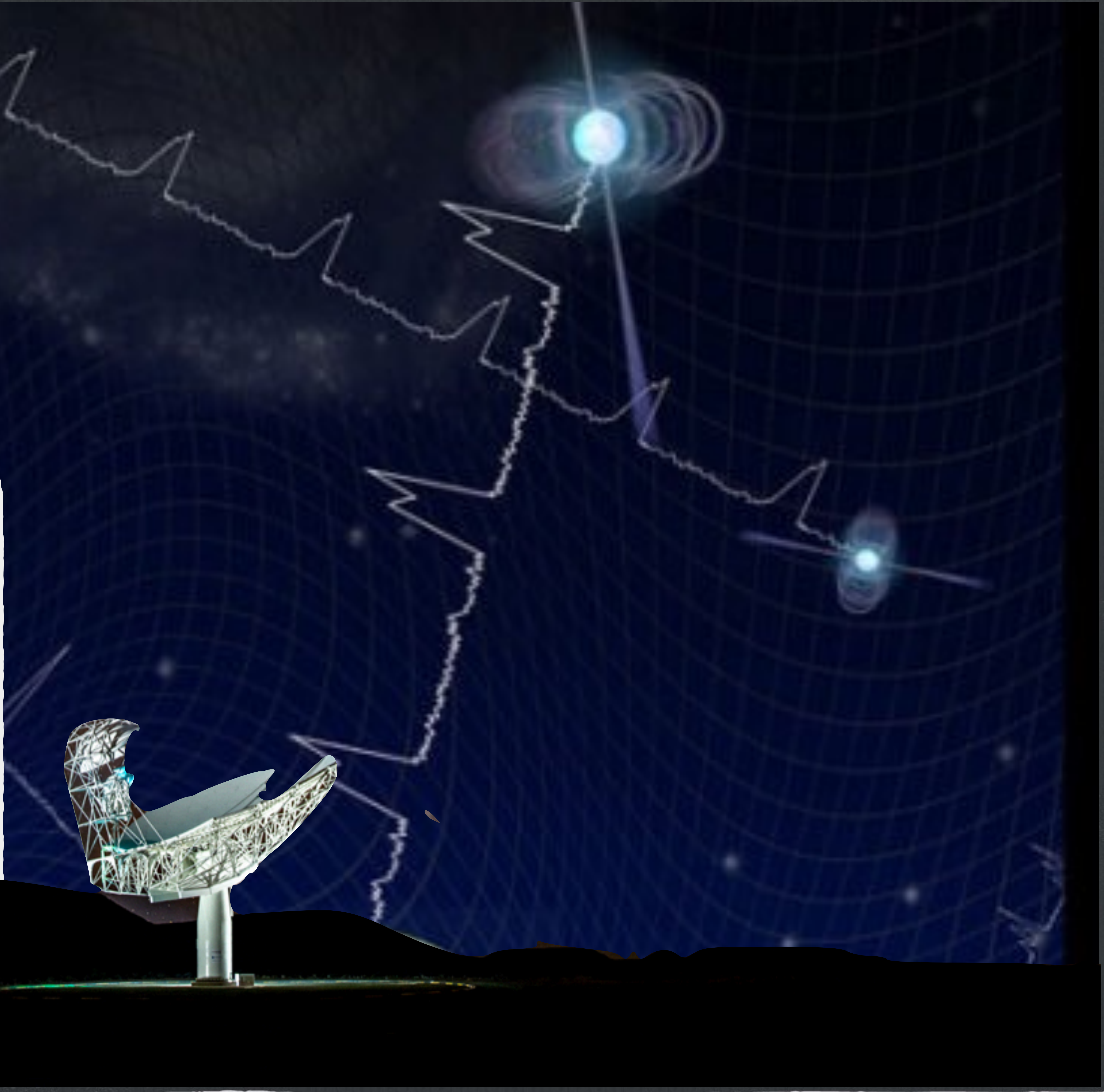
Course layout

End of Lecture 2,
next up
Tutorial on pulsar data analysis

Lecture 1 *(30 Aug - 1hrs)*
Pulsar properties

Lecture 2 *(13 Sep - 30min)*
Pulsar observations and data analysis

Tutorial *(13 Sep - 30min)*
MeerKAT pulsar data




Pulsar timing

Pulsars as Spacetime tools

Atomic clocks in the night sky!

- We couldn't have asked for better spacetime tools than atomic clocks in the night sky!

- These clocks have allowed us to carefully test theories of gravity, have lead to the first exoplanets discovery and have allowed indirect measurement of gravitational wave emission

- Timing pulsars with such precision relies on creating a stable average pulse profile

- The fast spinning MSPs pulsars, whose high angular momentum makes them rotationally stable, are better timers than most of the normal/isolated pulsars

- Bright, fast MSPs with narrow pulse profiles make the best timers.

How do we time pulsars?

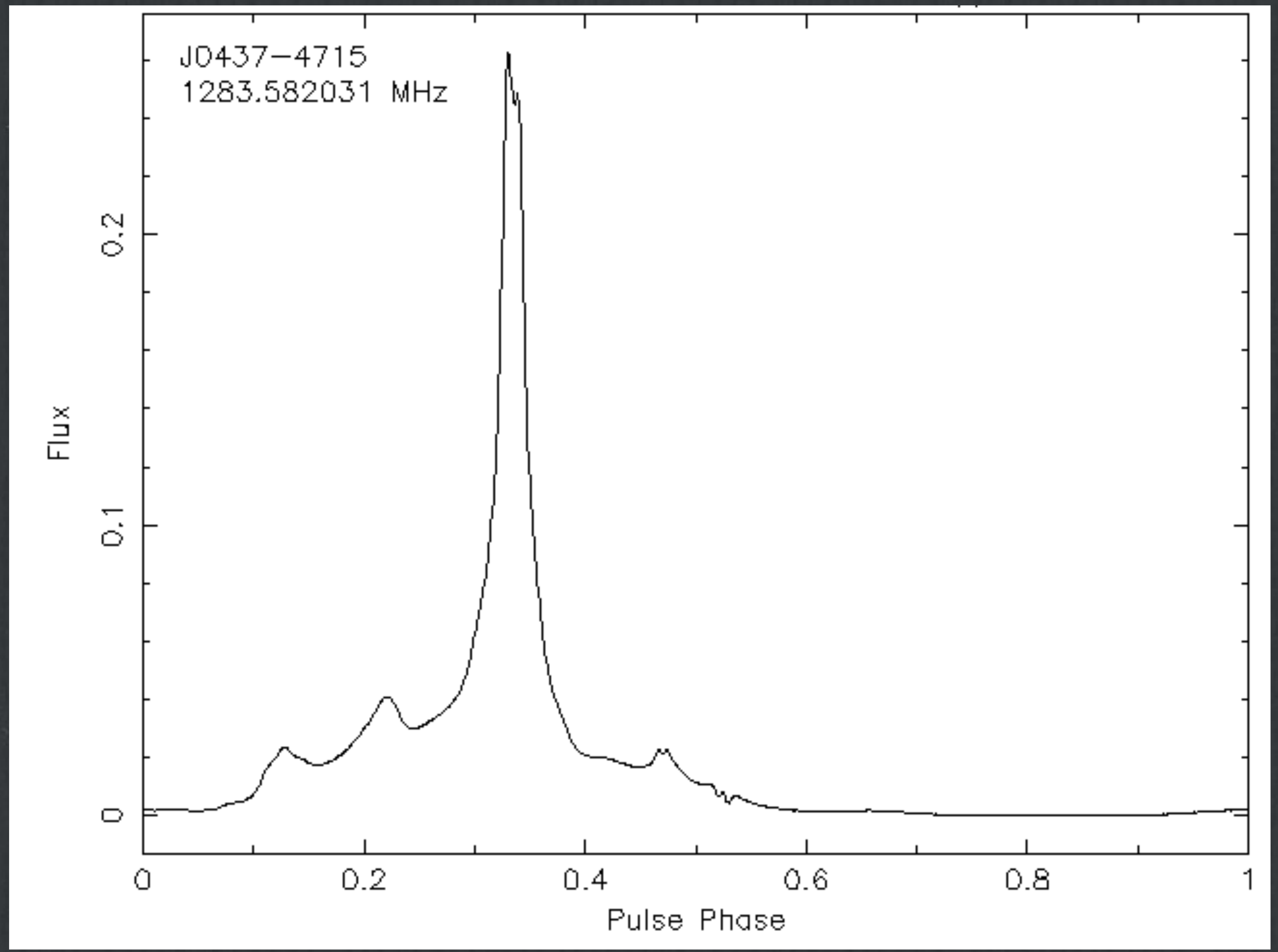
— The main idea in pulsar timing is that you can account for every single pulse the pulsar emits …

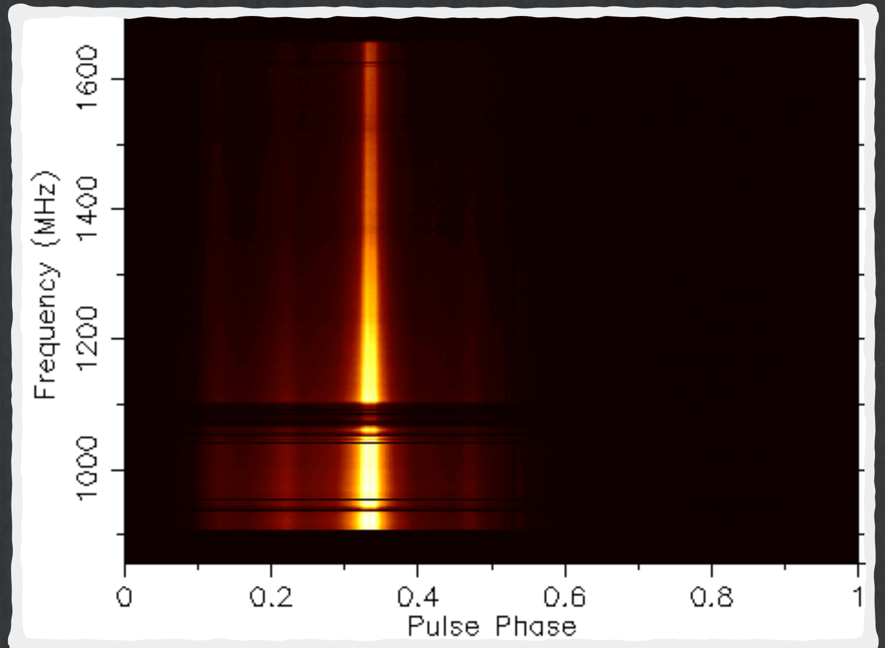
… over long timescales (months to years)

— We create a model to predict when a next pulse should arrive

— And then compare the model prediction to the outcome of an observation

Ave profile of PSR J0437-4715

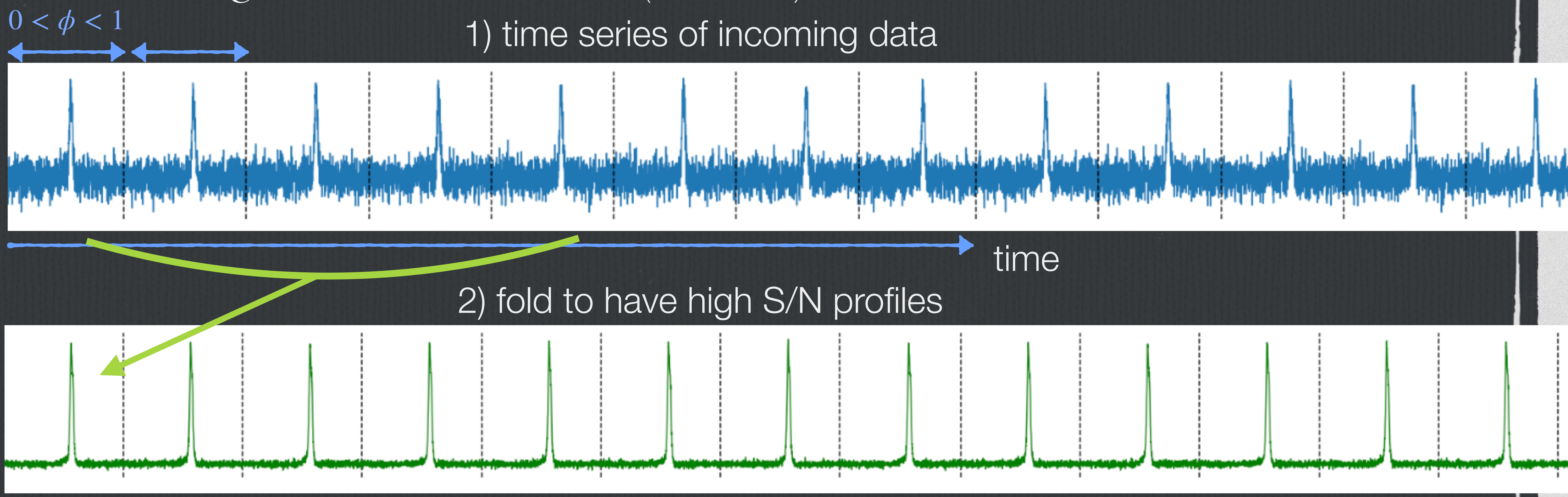




Pulse period: 5.757451956923**6**5 ms

Only changes every 500 years *Changes every 30 min*

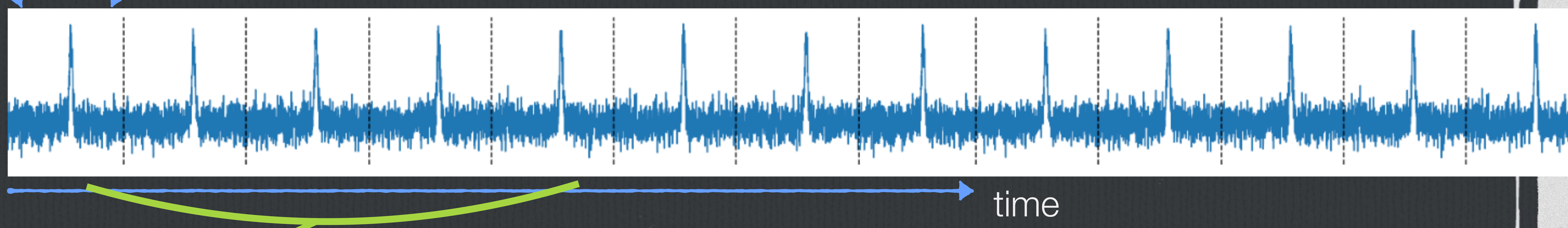
Measuring time of arrivals (TOAs)



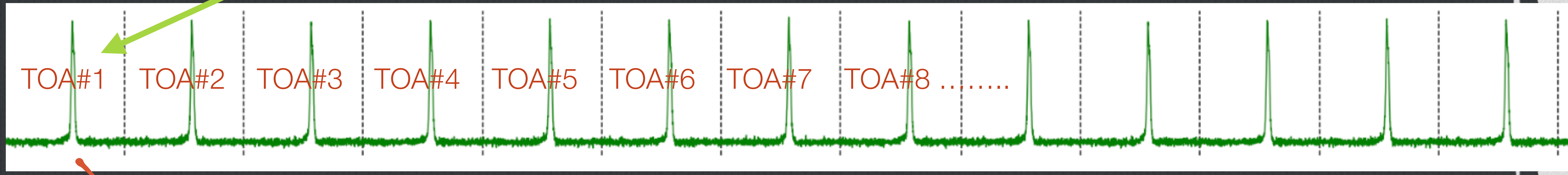
Measuring time of arrivals (TOAs)

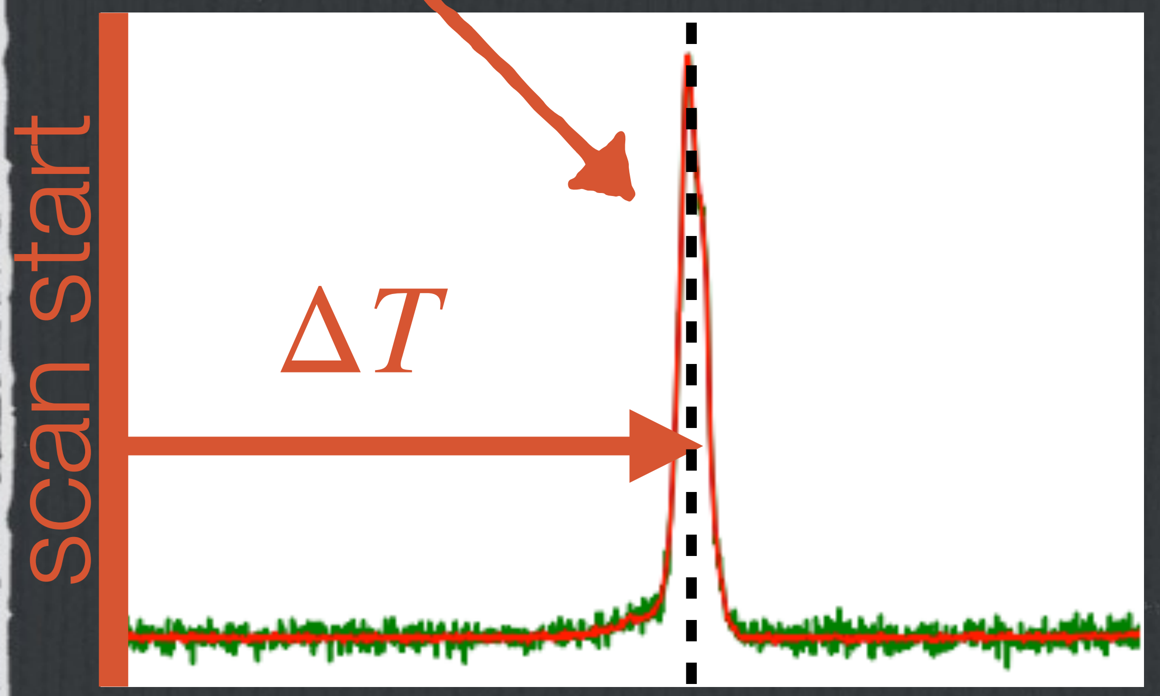
$0 < \phi < 1$

1) time series of incoming data



2) fold to have high S/N profiles





3) label time of arrivals, relative to some start

e.g. TOA = scan start + ΔT

$$\sigma_{TOA} \approx \frac{W}{S/N}$$

TOAs

Filename	Observing frequency (MHz)	TOAs in MJD	Uncertainty in microseconds
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1283.623987	59455.535312653712396	32.205
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1285.106042	59455.535405532875398	37.825
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1285.603461	59455.535498435145281	39.110
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1284.996531	59455.535591342179161	26.540
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1283.484842	59455.535684274162896	33.147
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1284.016055	59455.535777161586780	26.496
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1284.039502	59455.535870069026532	33.517
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1283.266703	59455.535962990234922	43.585
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1283.937490	59455.536055876273991	55.084
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1283.535826	59455.536148784470899	35.741
J1056-6258_2021-08-29-12:50:40_zap.F.ar	1283.571604	59455.536236796910319	37.701

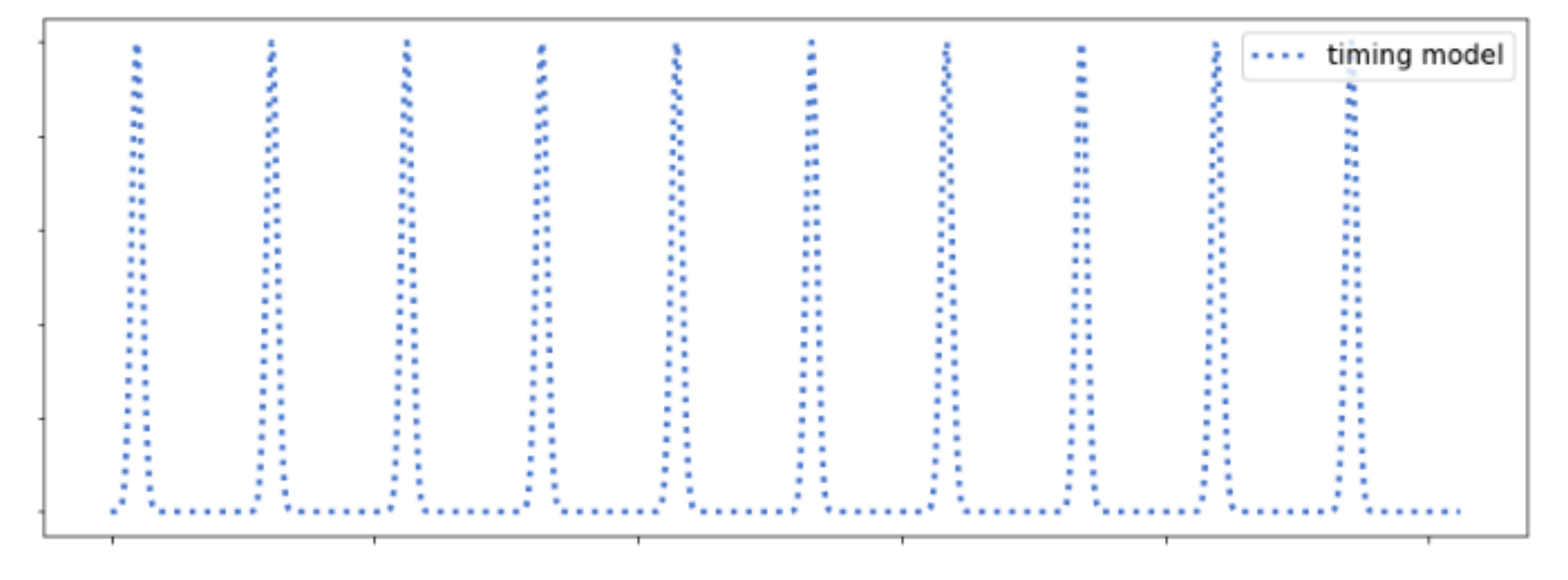
Next we want to compare our measured time of arrivals; to predicted values from timing models.

But to do so we need an inertial frame at which to compare the arrival values.

Our observatory time of arrival (TOA) measurements are therefore transferred to the Solar System Barycentre (SSB) reference frame.

In other words during comparisons to models we change these TOAs as if the pulse signals arrived to the SSB.
(This requires details Solar System models as well as observatory clock correction files.)

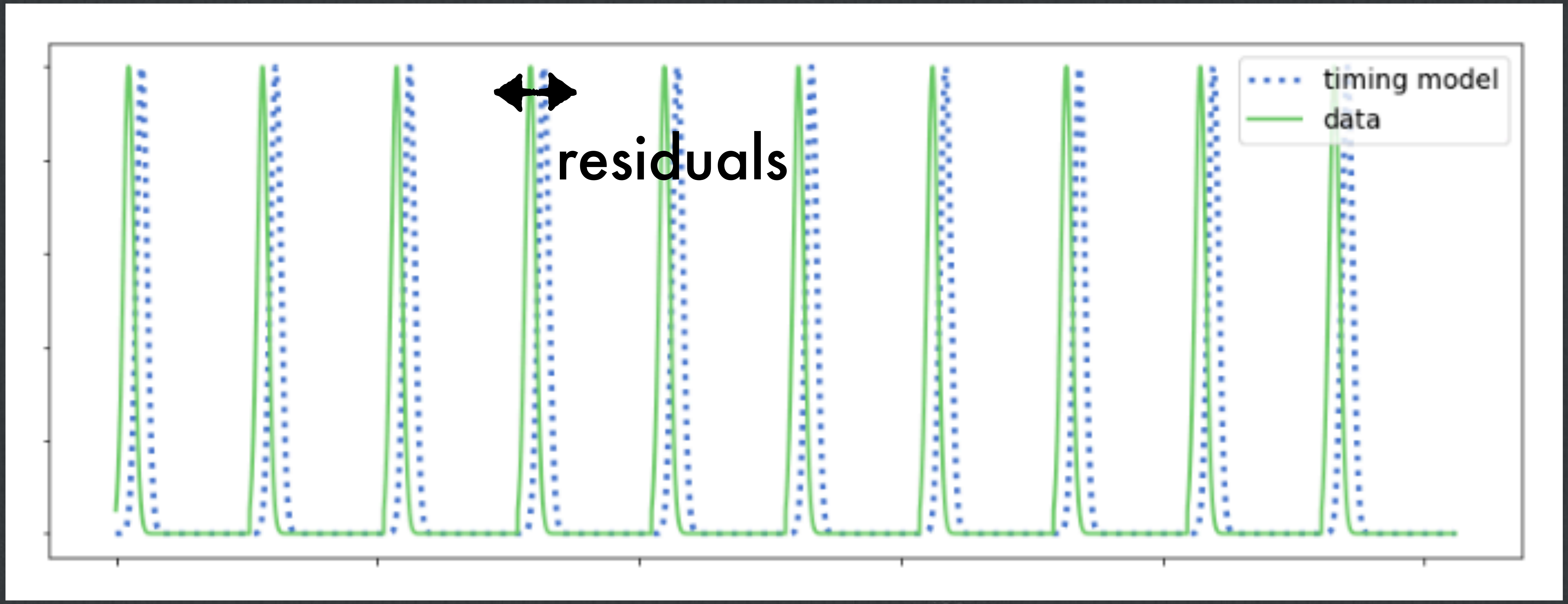
Comparing TOAs with model predictions



- Your timing model predicts when to expect pulses from the pulsar to arrive at the SSB.

Comparing TOAs with model predictions

Measure difference between model and data



residual = model - data

For good modelling residuals are typically measured in units of microseconds!

- Your timing model predicts when to expect pulses from the pulsar to arrive at the SSB.
- Now you check that against the measured TOAs.

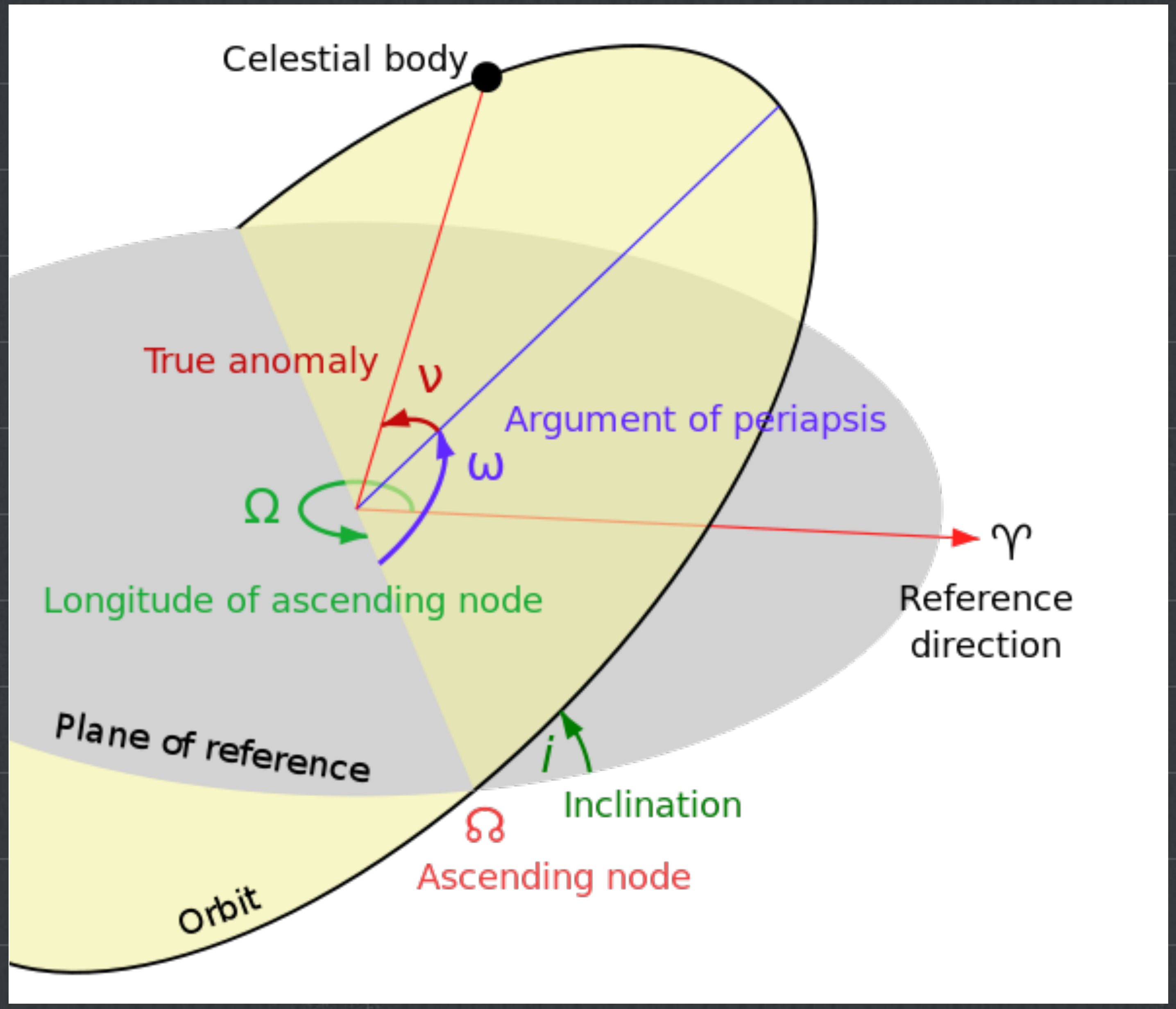
- The residuals are the differences between when the model predicts the pulse to arrive, and the measured TOAs

A good model will have residuals that resemble white noise

Bad timing model residuals will have unmodelled trends in them

Timing model for PSR J0437-4715 in a binary

PSRJ	J0437-4715		Description
RAJ	04:37:15.8961737	0.000000592223288330 97	Position RA, DEC in J2000
DECJ	-47:15:09.11071	0.00000626551891151144	
F0	173.687945812184279 73	4.6845149140224002772e-13	Pulse frequency (Hz, 1/P)
F1	-1.7283605122731730757e-15	4.1071593643911663336e-21	Pulse frequency derivative
DM	2.6449834563206059848	0.00008653635874335857	Dispersion measure (~ distance)
PMDEC	-71.475434041312093429	0.0019542994916079688 0	Proper motion (pulsars move fast!)
			Keplerian
PB			Orbital perdiod (days)
ECC			Eccentricity
ASINI			Projected semi-mayor axis
OM			Long. periastron
T0			Epoch of periastron
			Post-Keplerian
PBDOT			Orbital period decay
OMDOT			Periastron advance (deg/yr)
GAMMA			Einstein delay
R,S			Shaprio rate and shape
M2			Mass of companion



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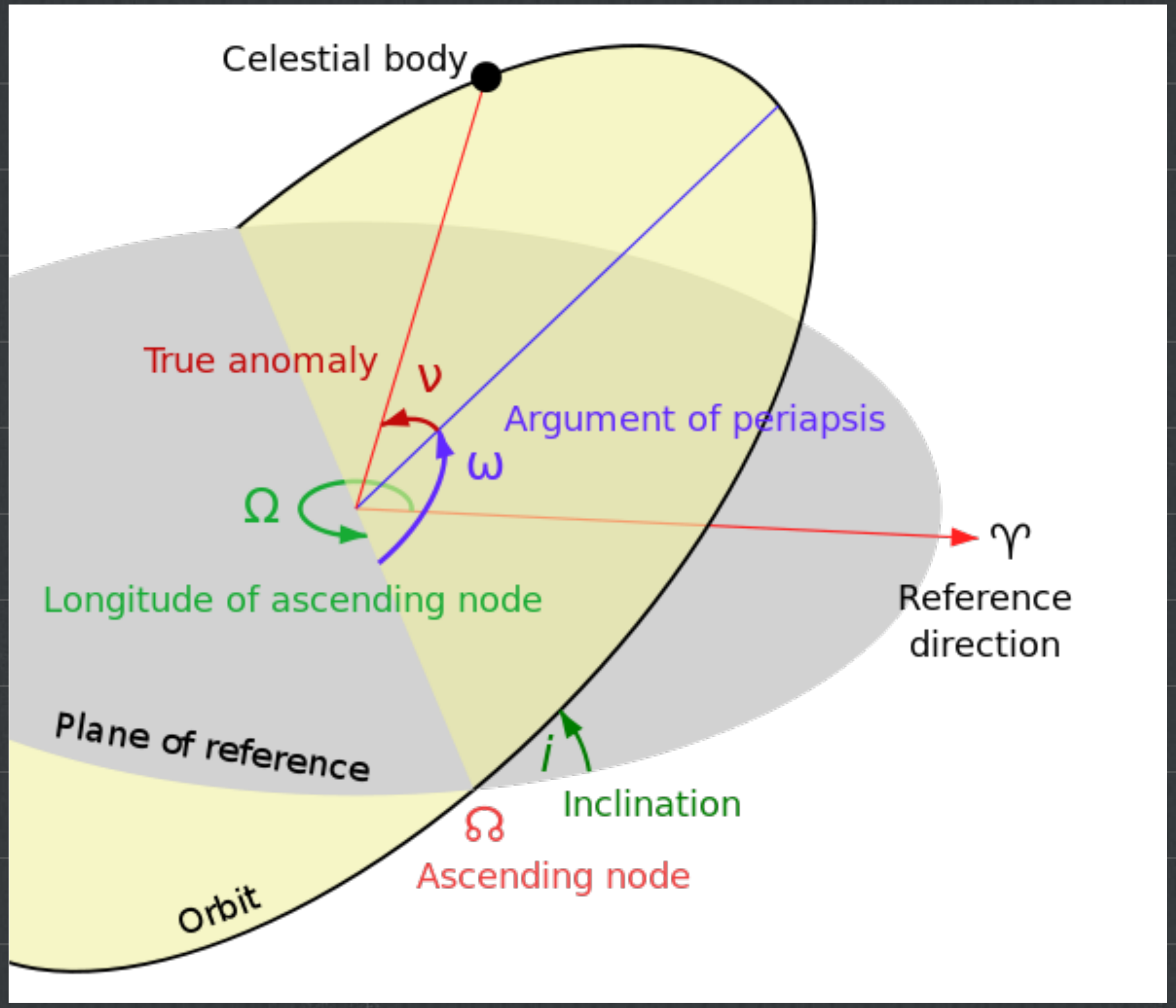
DM	2.6449834563206059848	0.00008653635874335857	Dispersion measure (~ distance)
PMDEC	-71.475434041312093429	0.00195429949160796880	Proper motion (pulsars move fast!)



		Description
PB	Keplerian	Orbital period (days)
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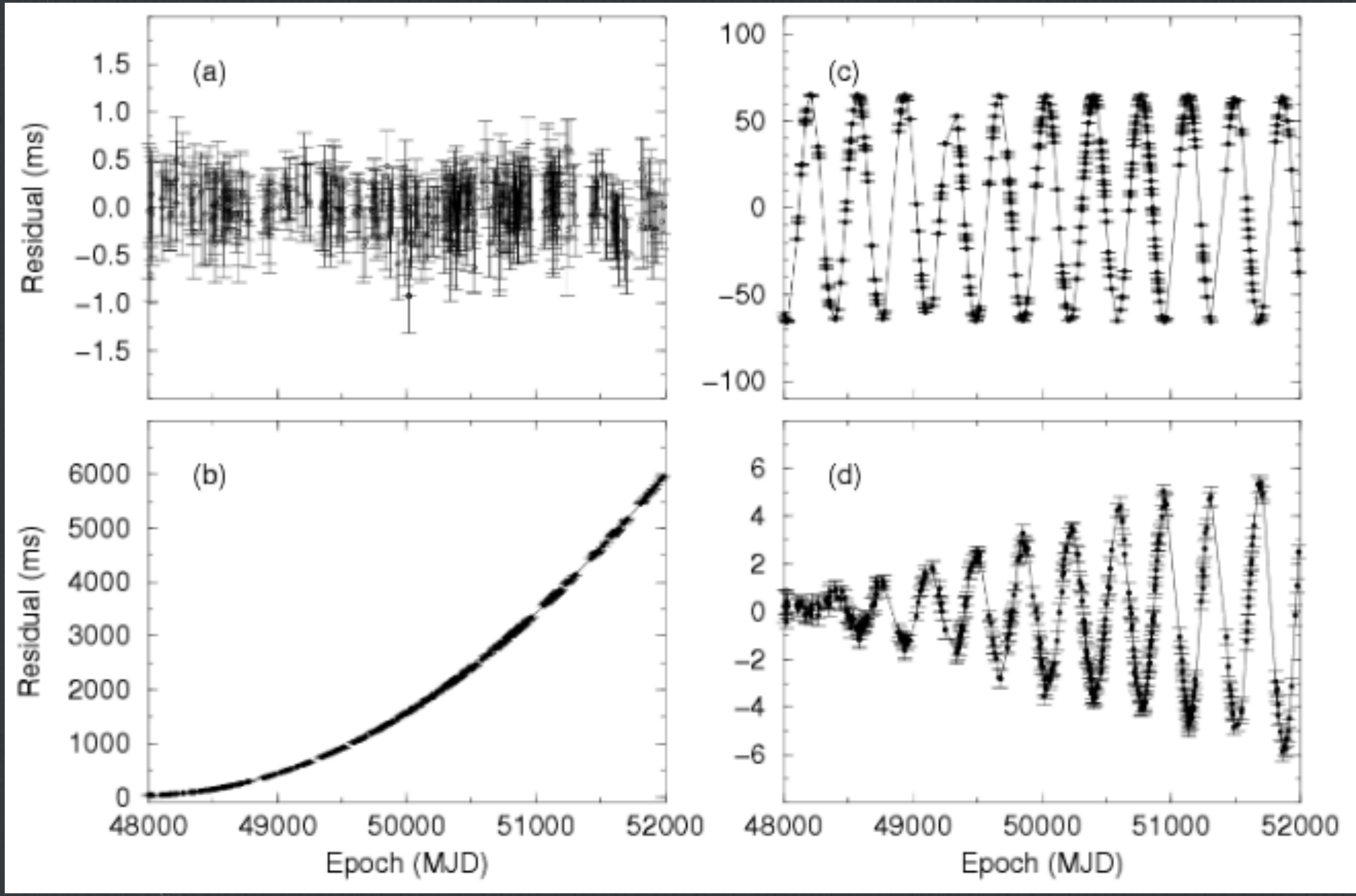
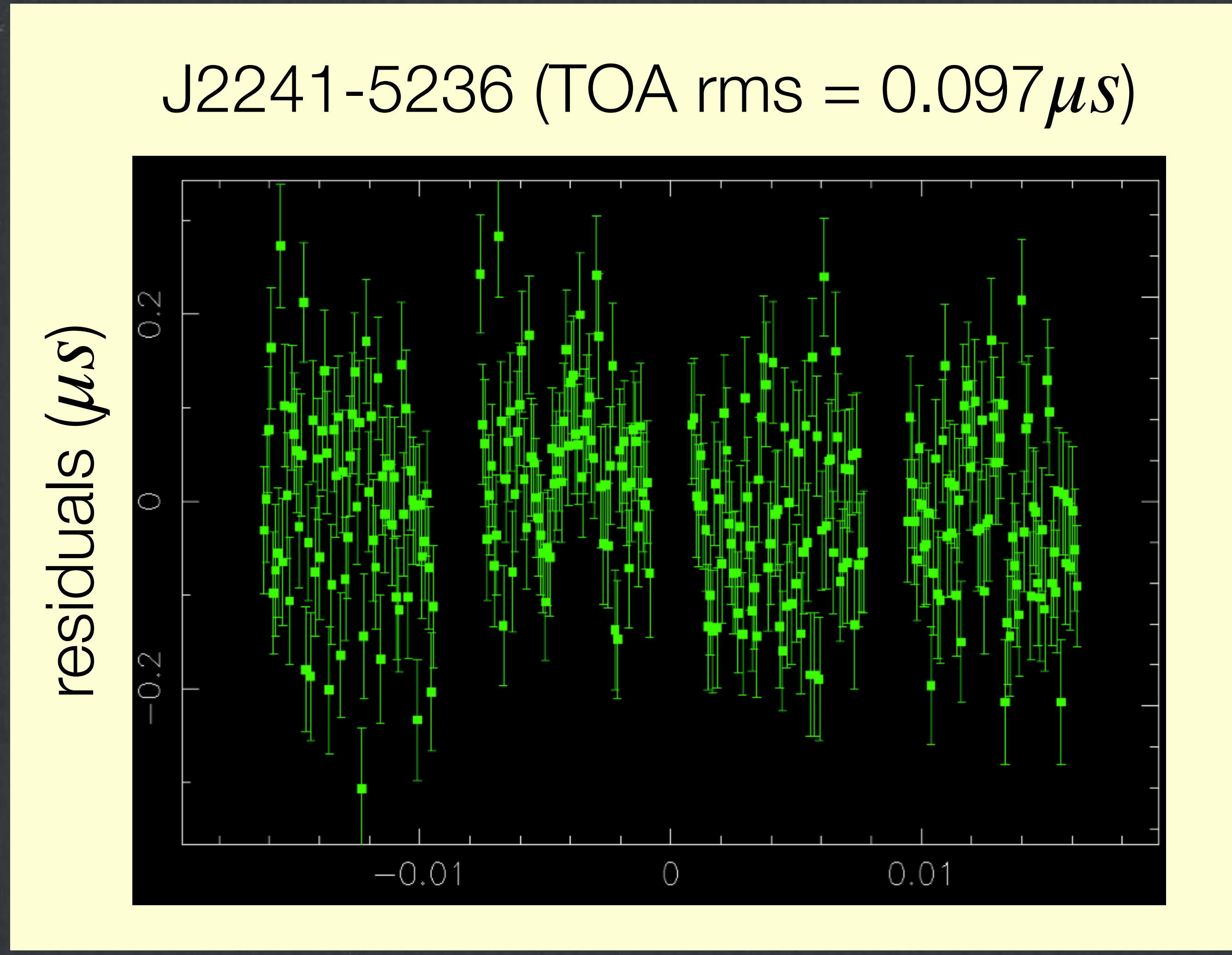
Tests of GR

Guess the problem!

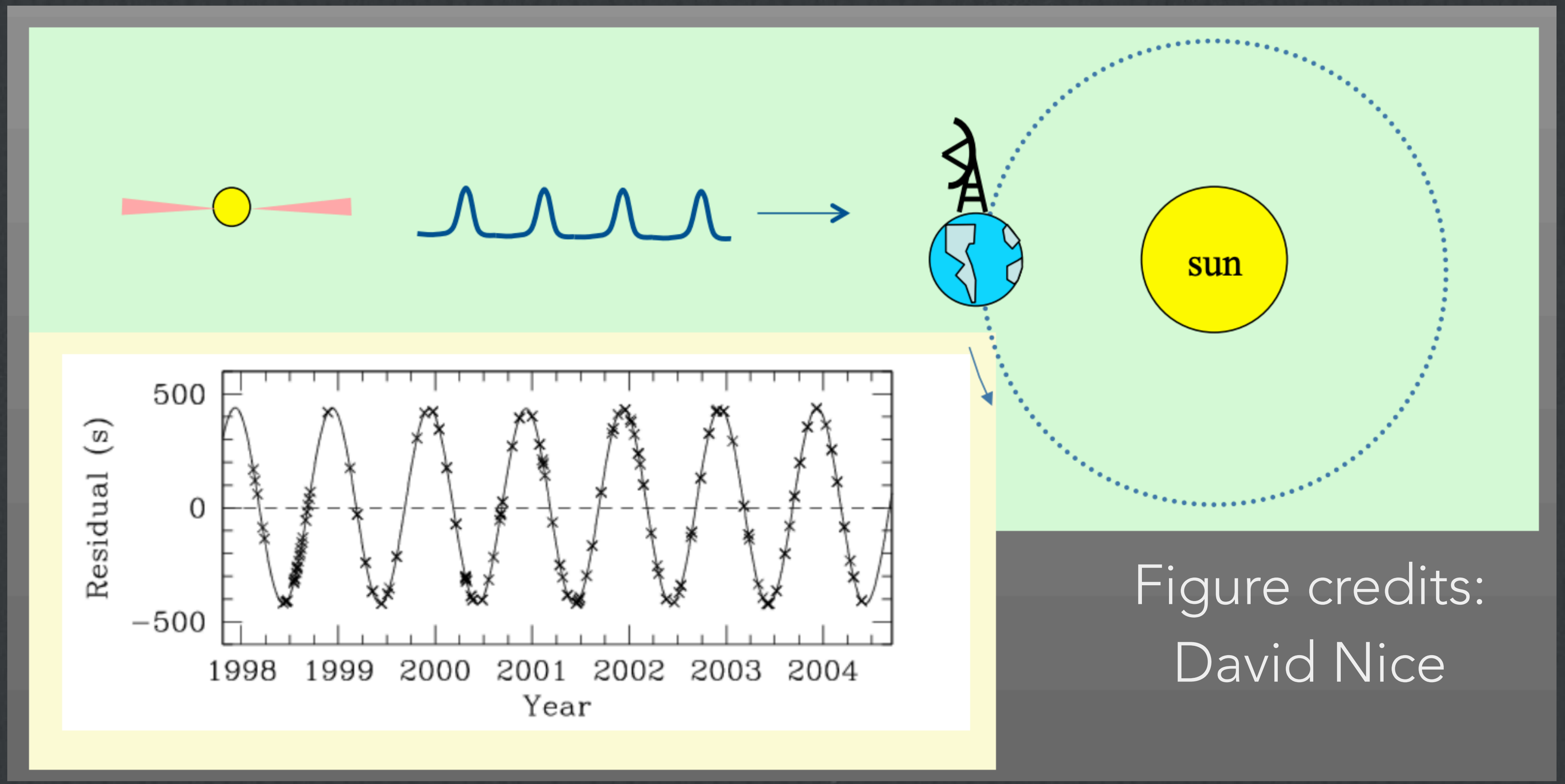


1. Wrong pulsar position
2. Good timing model
3. Period derivative (slow down rate) is wrong
4. Proper motion not modelled
5. Mass of companion is wrong

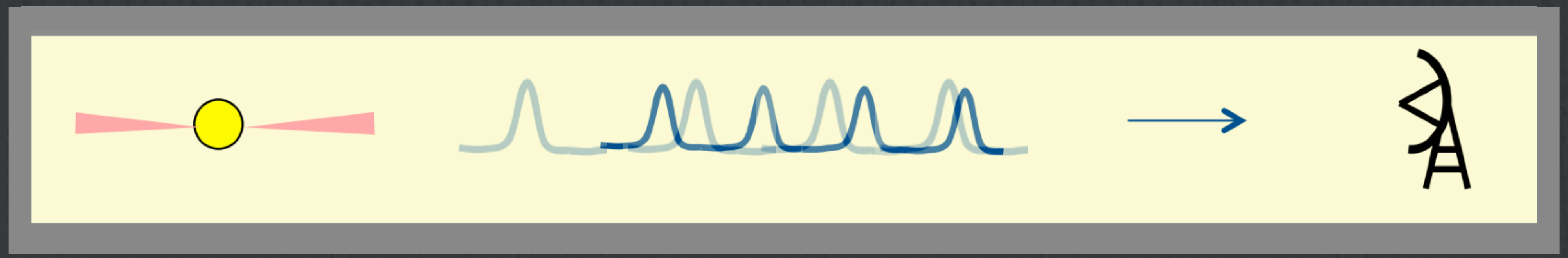
Guess the problem! - Answers

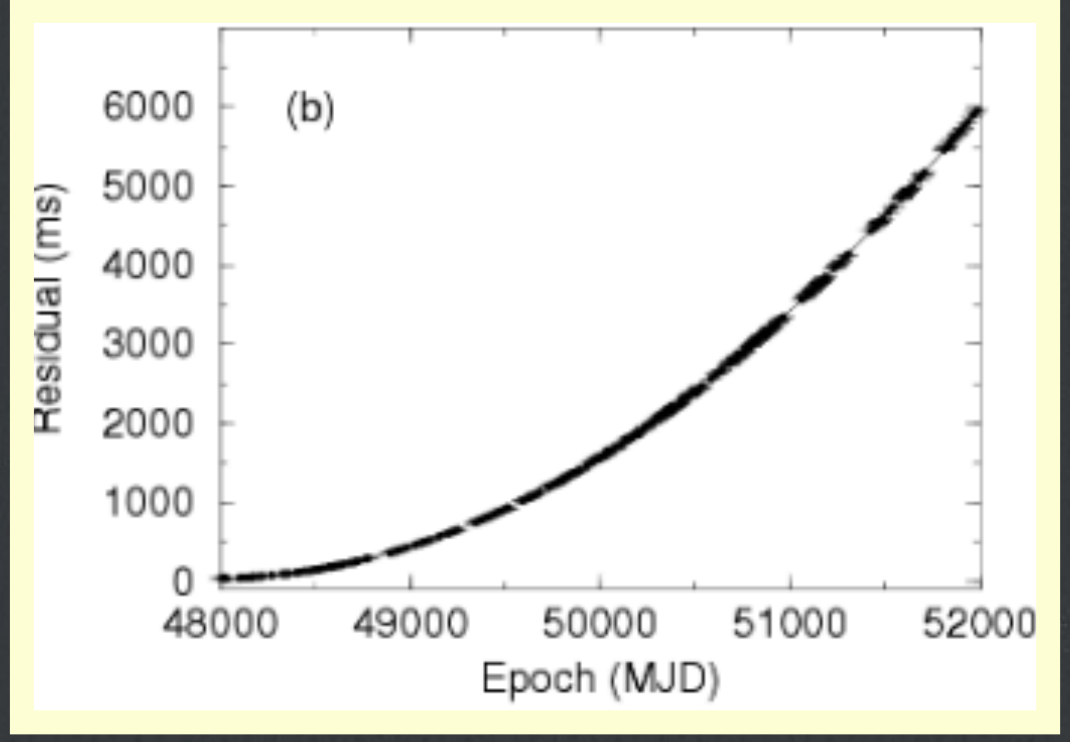


(a) Good timing model!



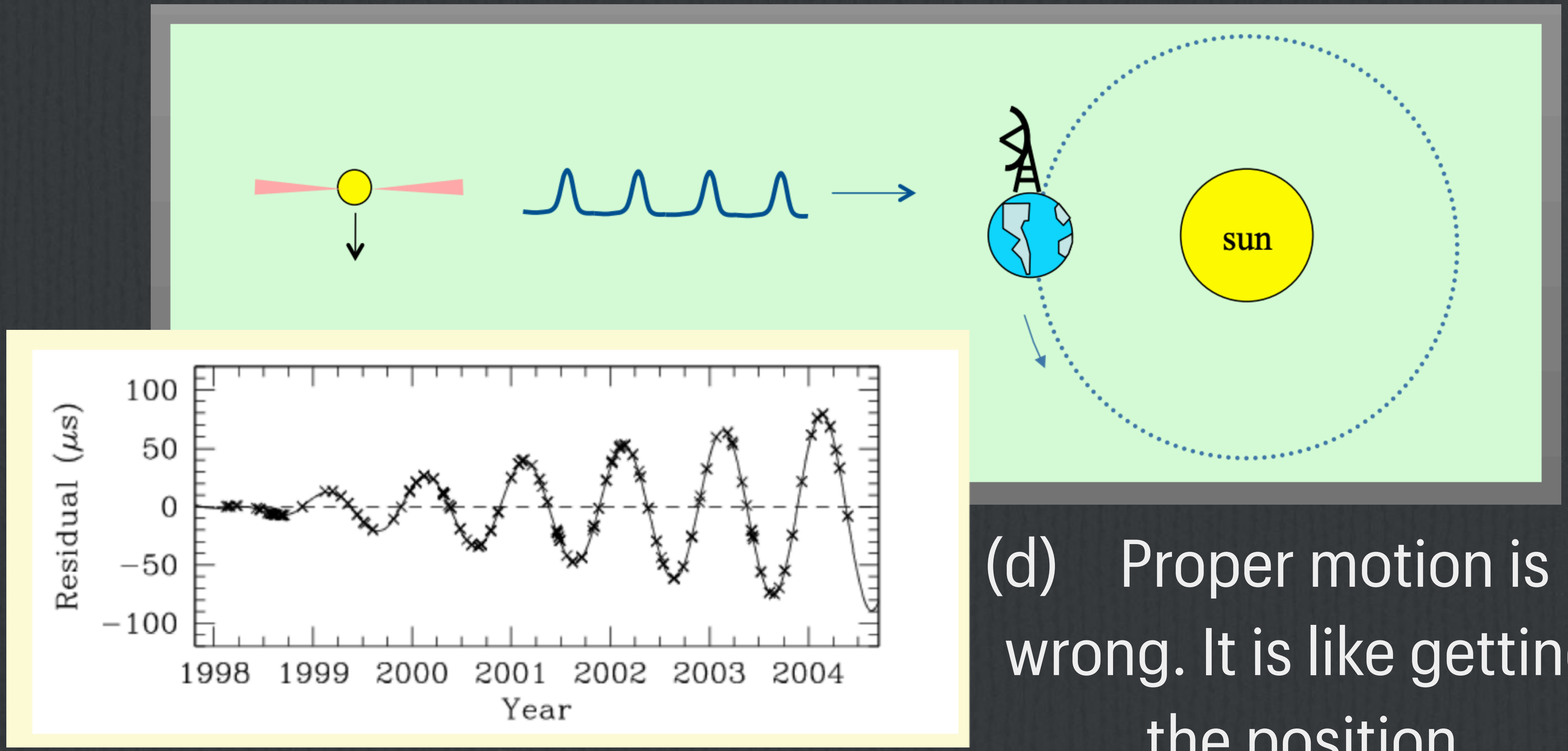
(c) Wrong pulsar position. Delay in residuals due to travel time across Earth's orbit. Size of the delay depends on pulsar position!





(b) Period derivative is wrong!

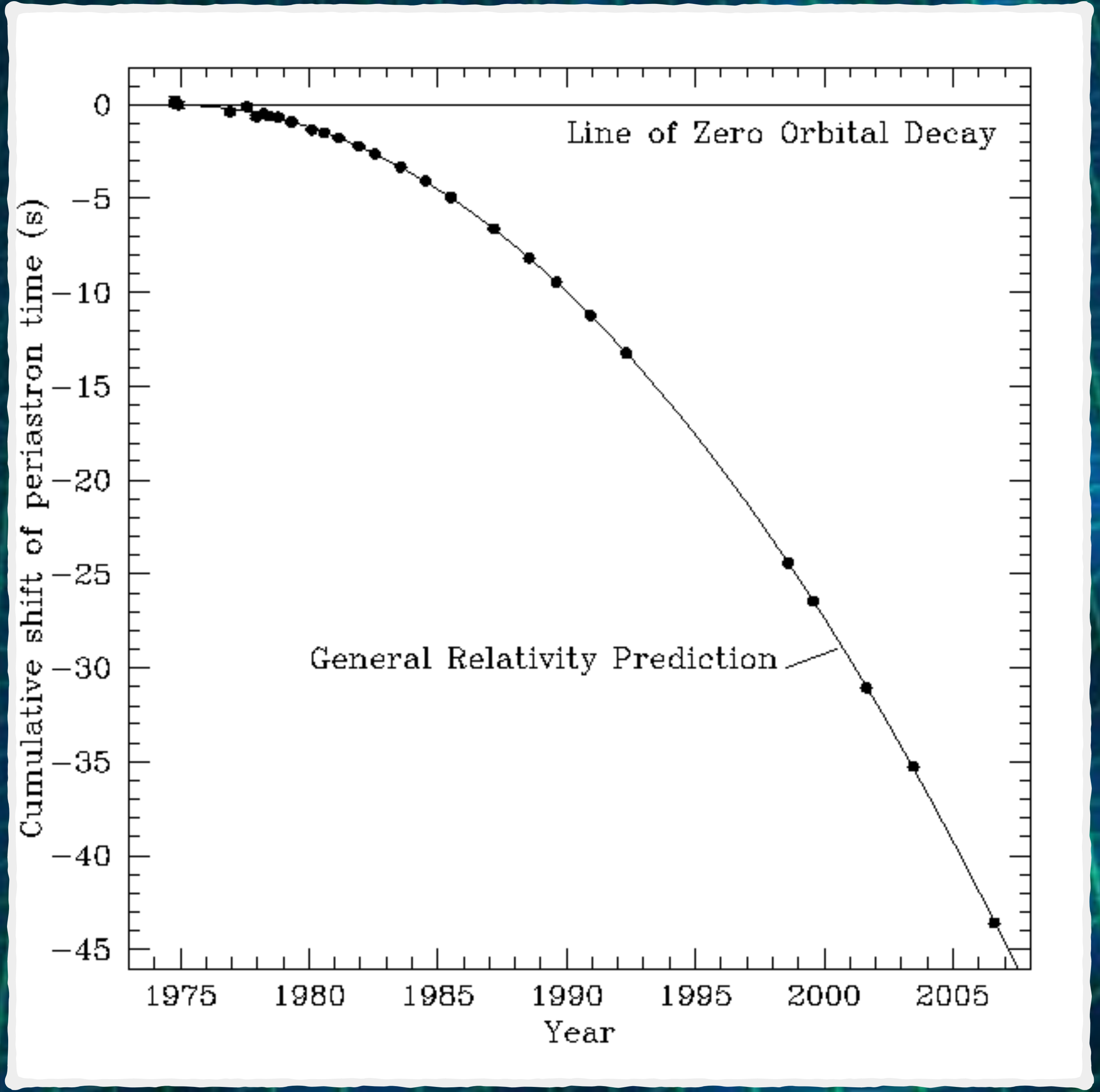
Pulses are delayed $\propto t^2$



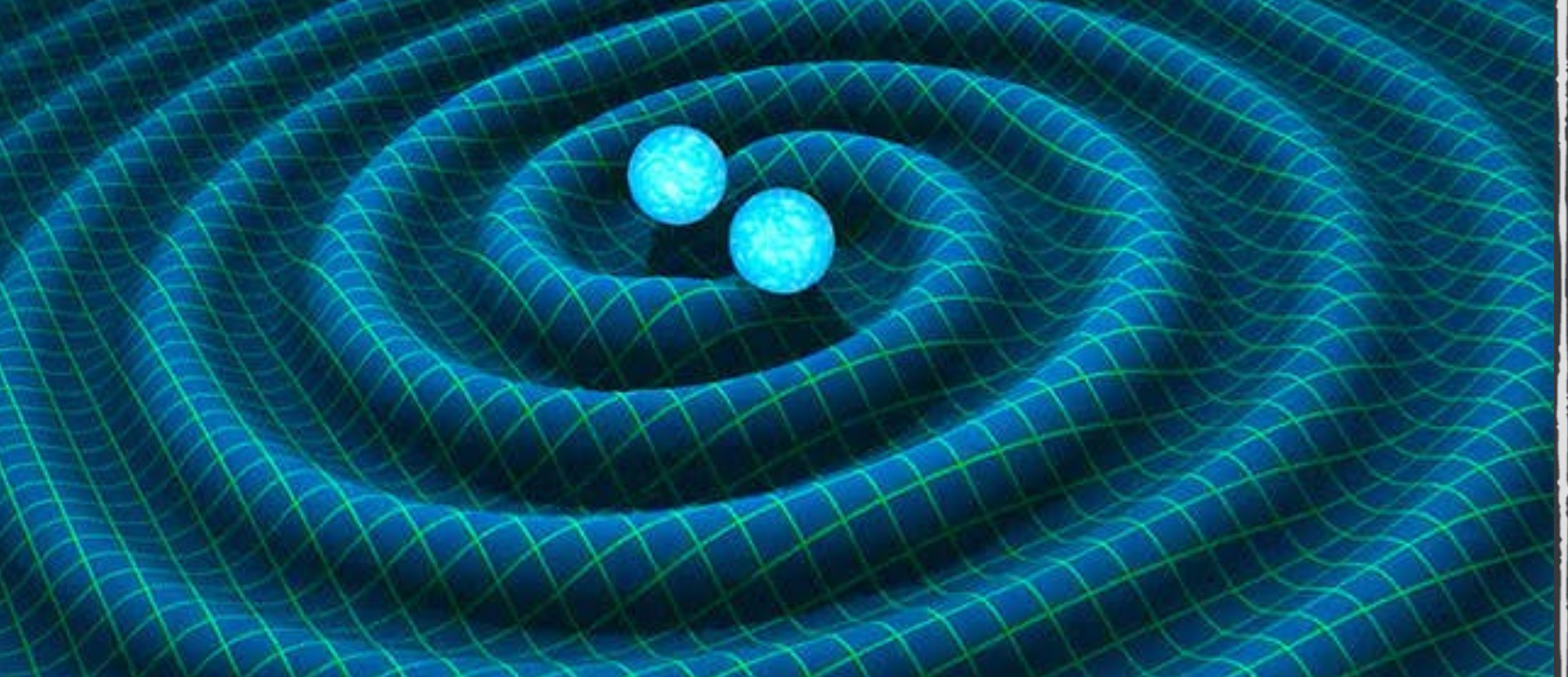
(d) Proper motion is wrong. It is like getting the position increasingly wrong!

Spacetime tests: Orbital decay due to GW emission

- First binary pulsar, discovered by Russell Hulse and Joseph Taylor in 1974
- Relativistic binary of NS and pulsar in orbit
- Pulsar: 59 ms pulse period
- Orbit: **7.75 hr** orbit
- Orbital precession: dω/dt = 4.2°/yr



Hulse-Taylor PSR B1913+16



- Orbital decay due to GW emission
- NSs are getting closer
- Semimajor axis decrease 3.5 m/yr
- Inspiral in 300 million yrs

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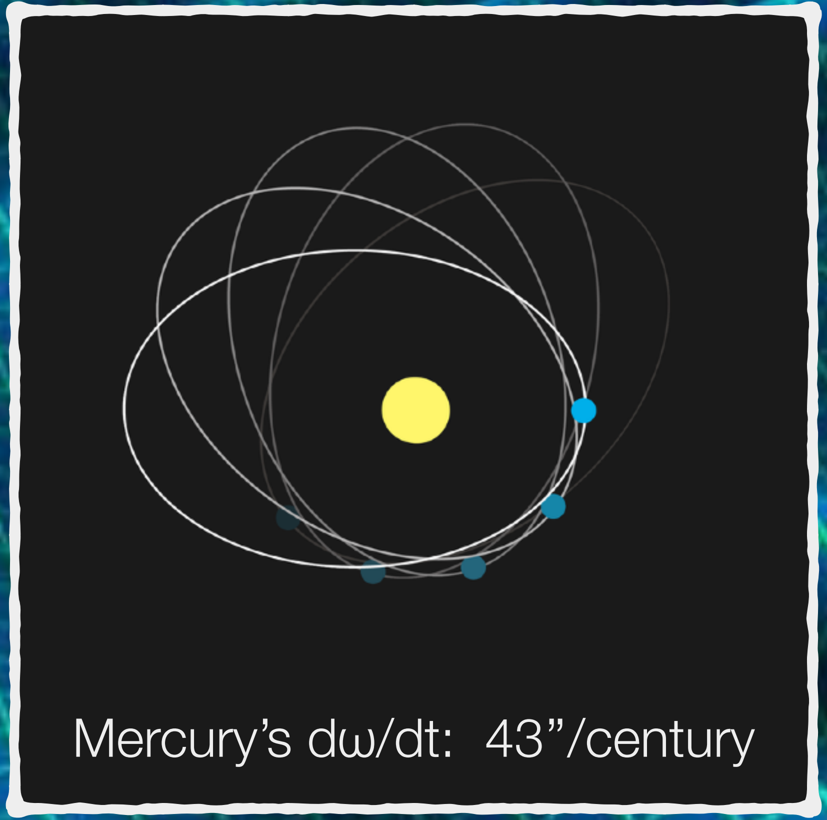

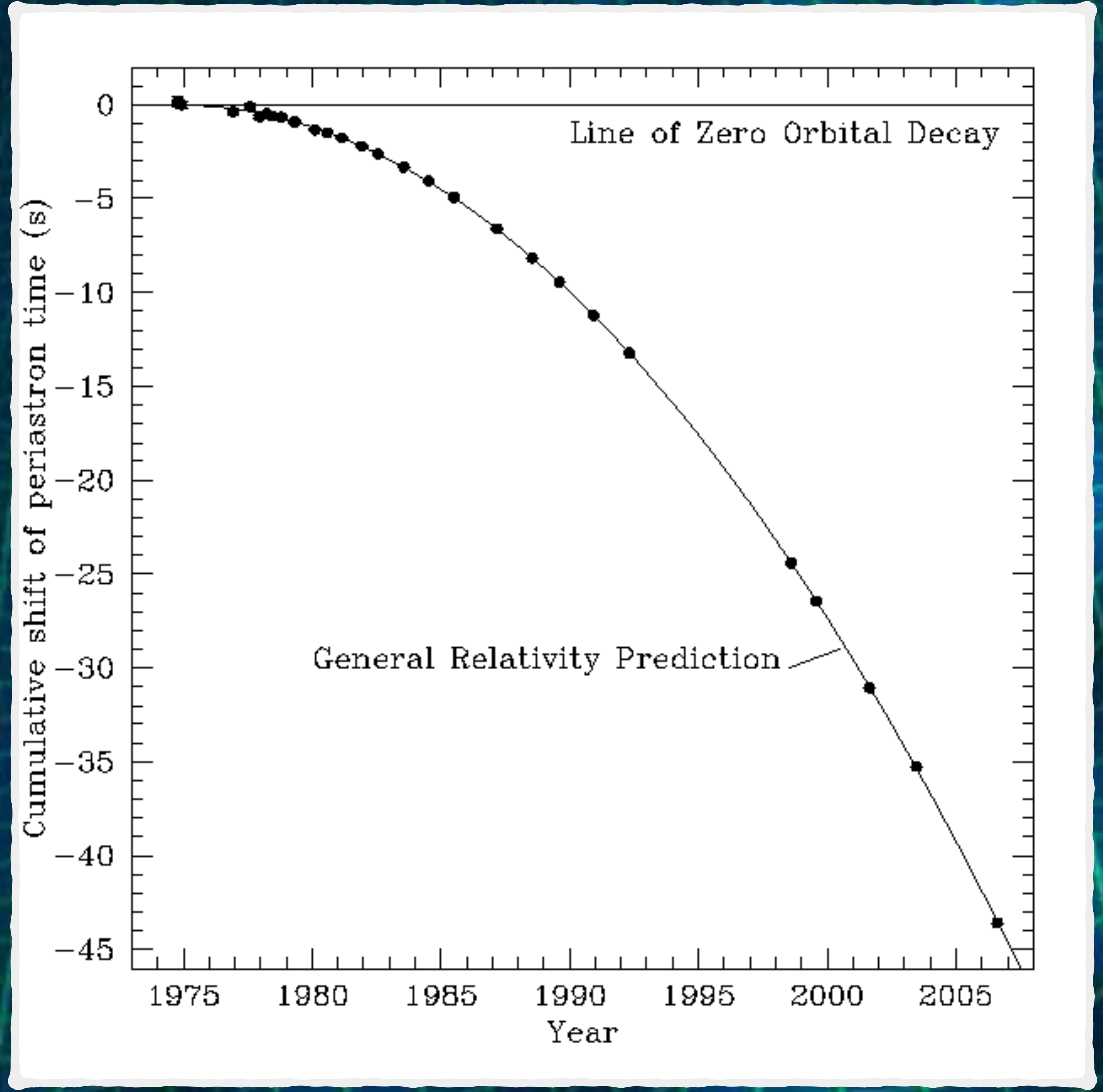

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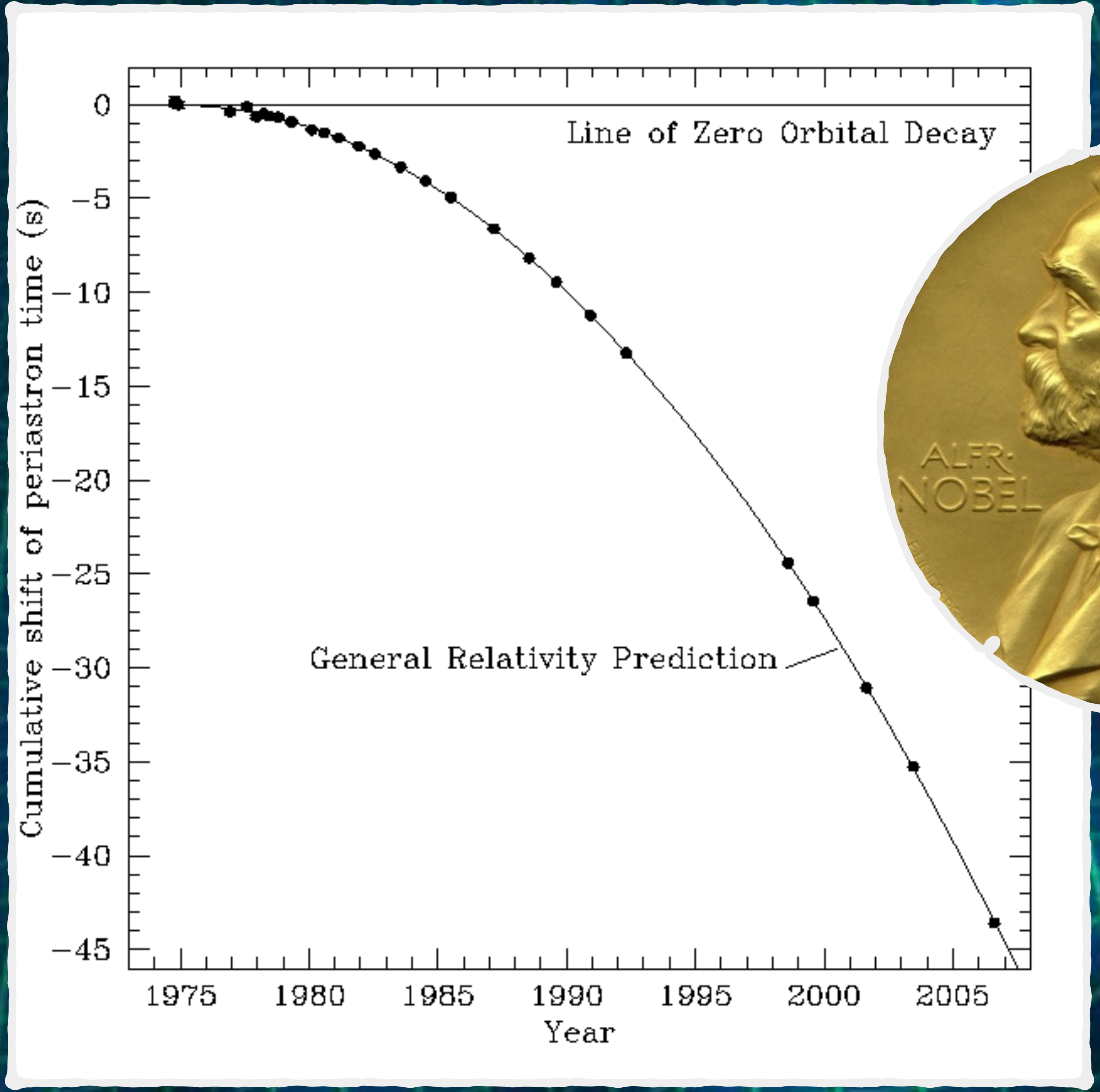

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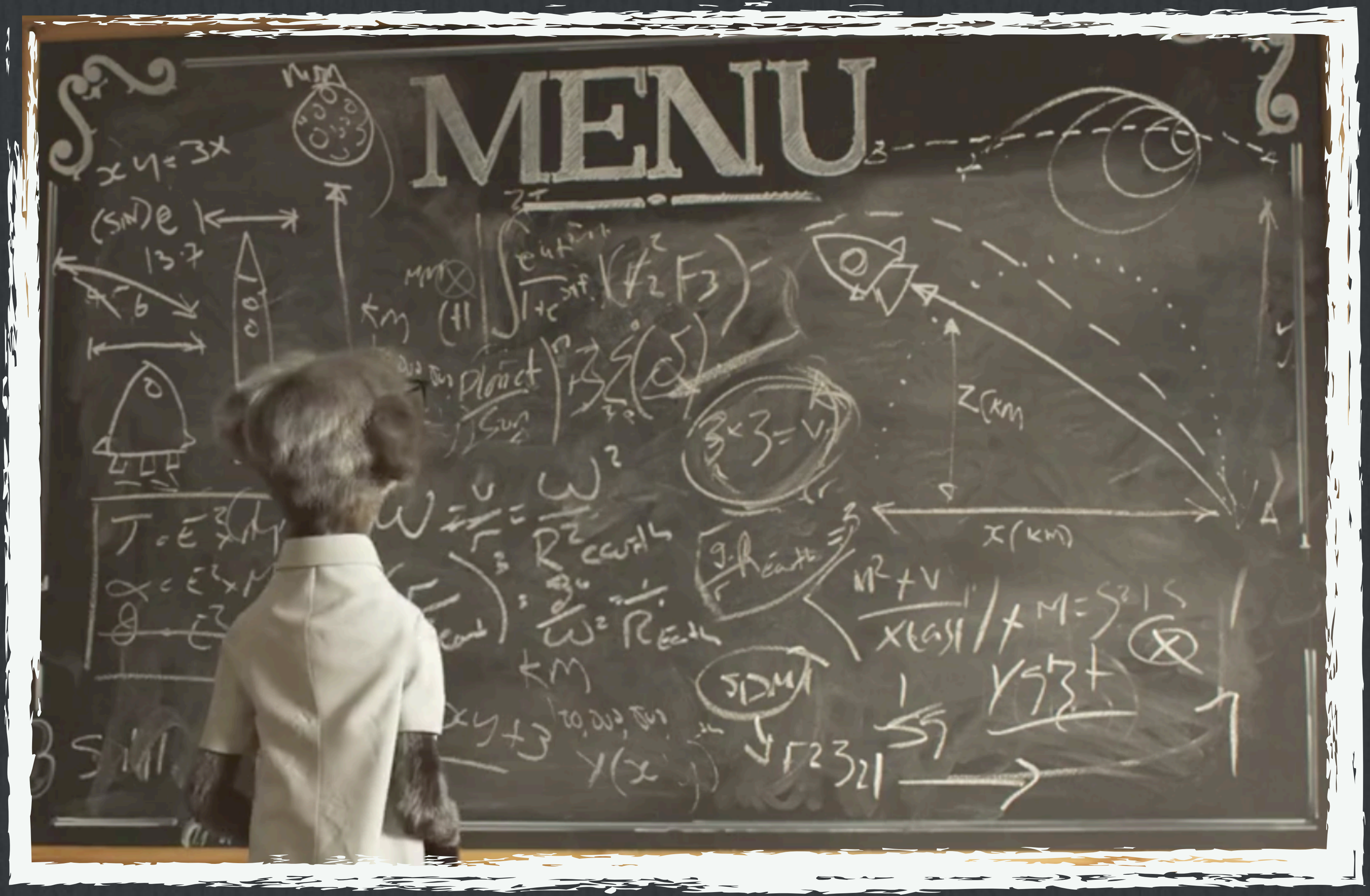
Energy loss calculated by GR and energy loss measured lie to within 0.3%



These days an even more extreme system than the Hulse-Taylor binary has been discovered, and is used for ever-stringent tests of Einstein's Theory of General Relativity.

... But more on that in the tutorial!