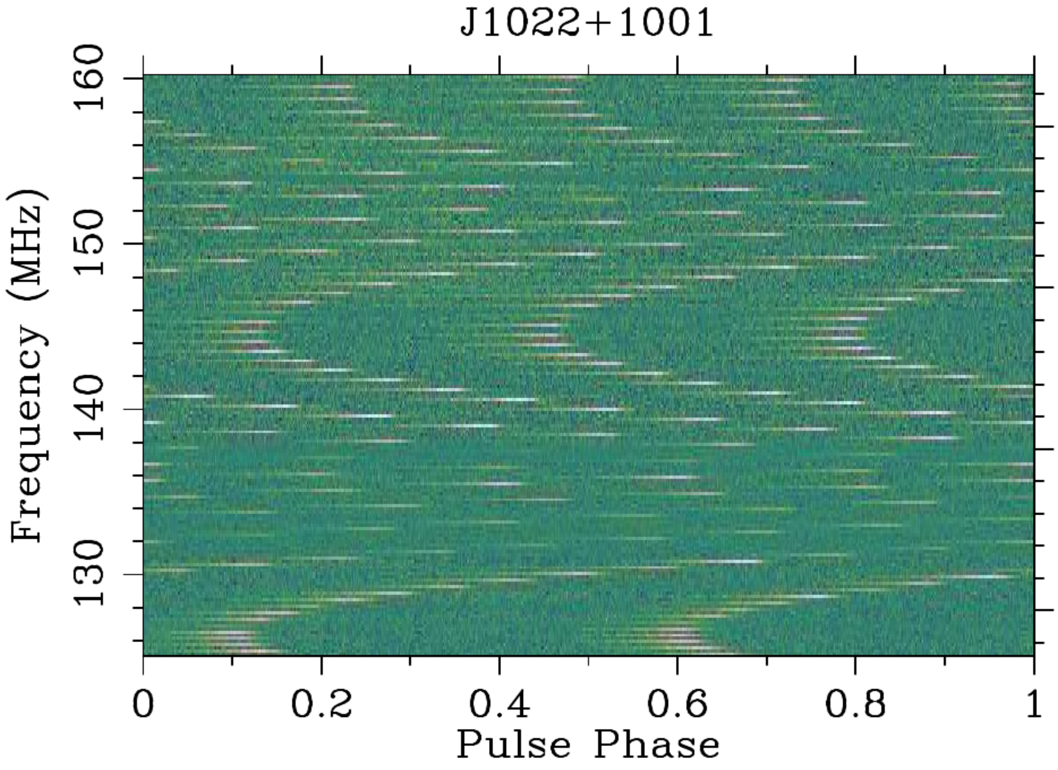
International School on Space Science

Frontend research at low radio frequency Radio astronomy: Science and technical challenges

Pulsars at low radio frequencies



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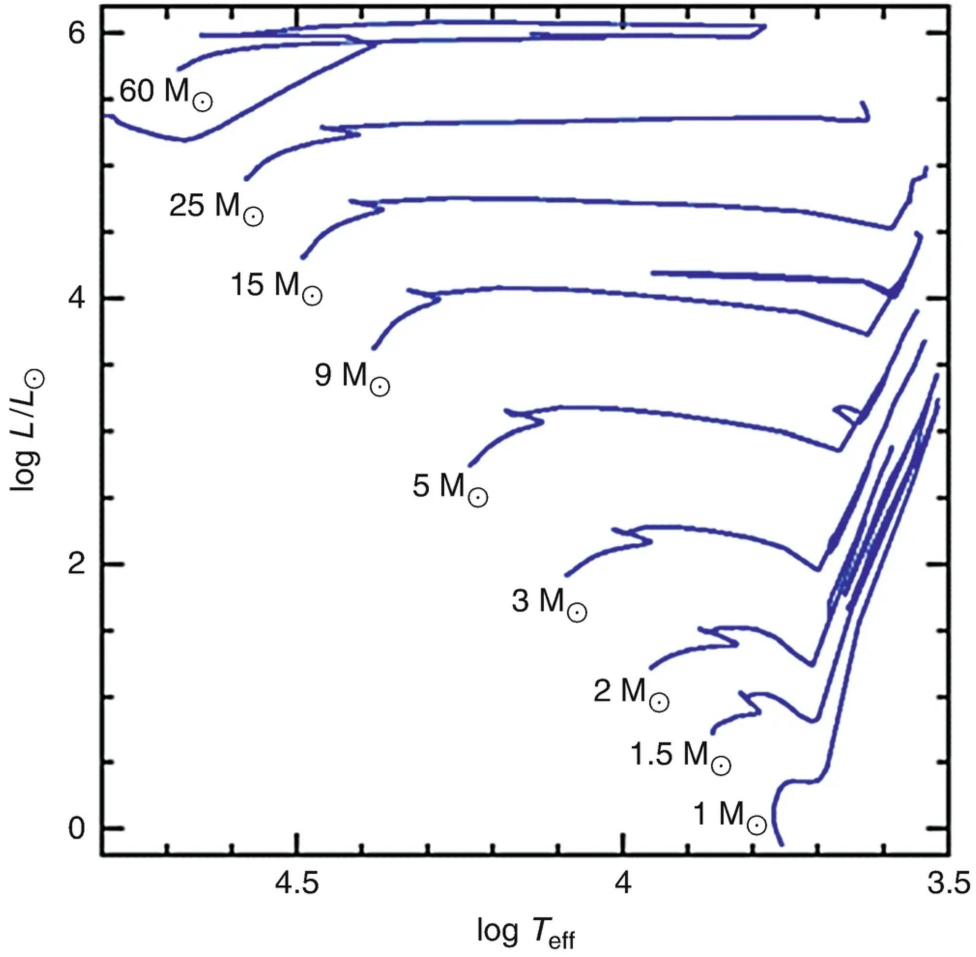
OAC
Osservatorio Astronomico di Cagliari

Contents

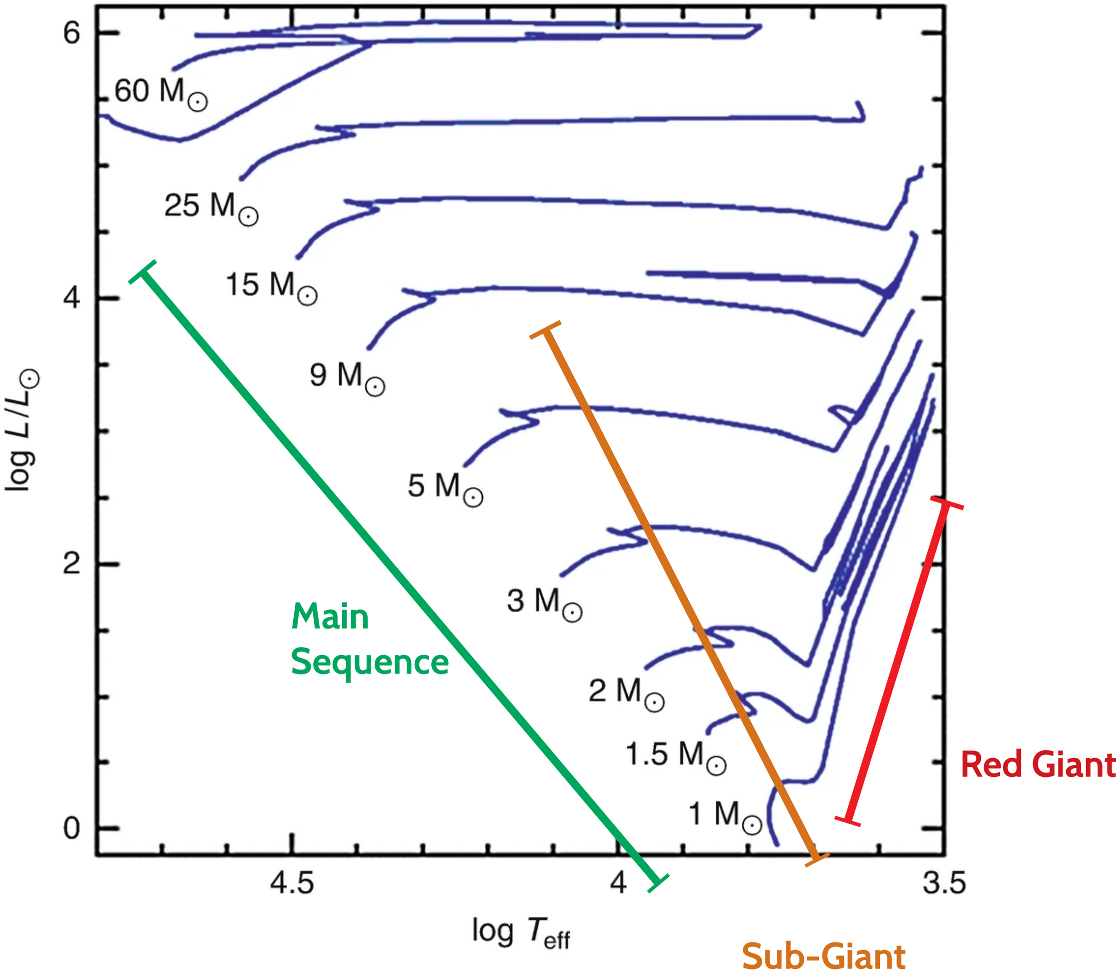
- Pulsars in a nutshell
- Radio frequencies – how low can we go?
- Pulsar monitoring campaigns with LOFAR
- Propagation effects and applications
- Emission mechanisms

A mass-depending evolution



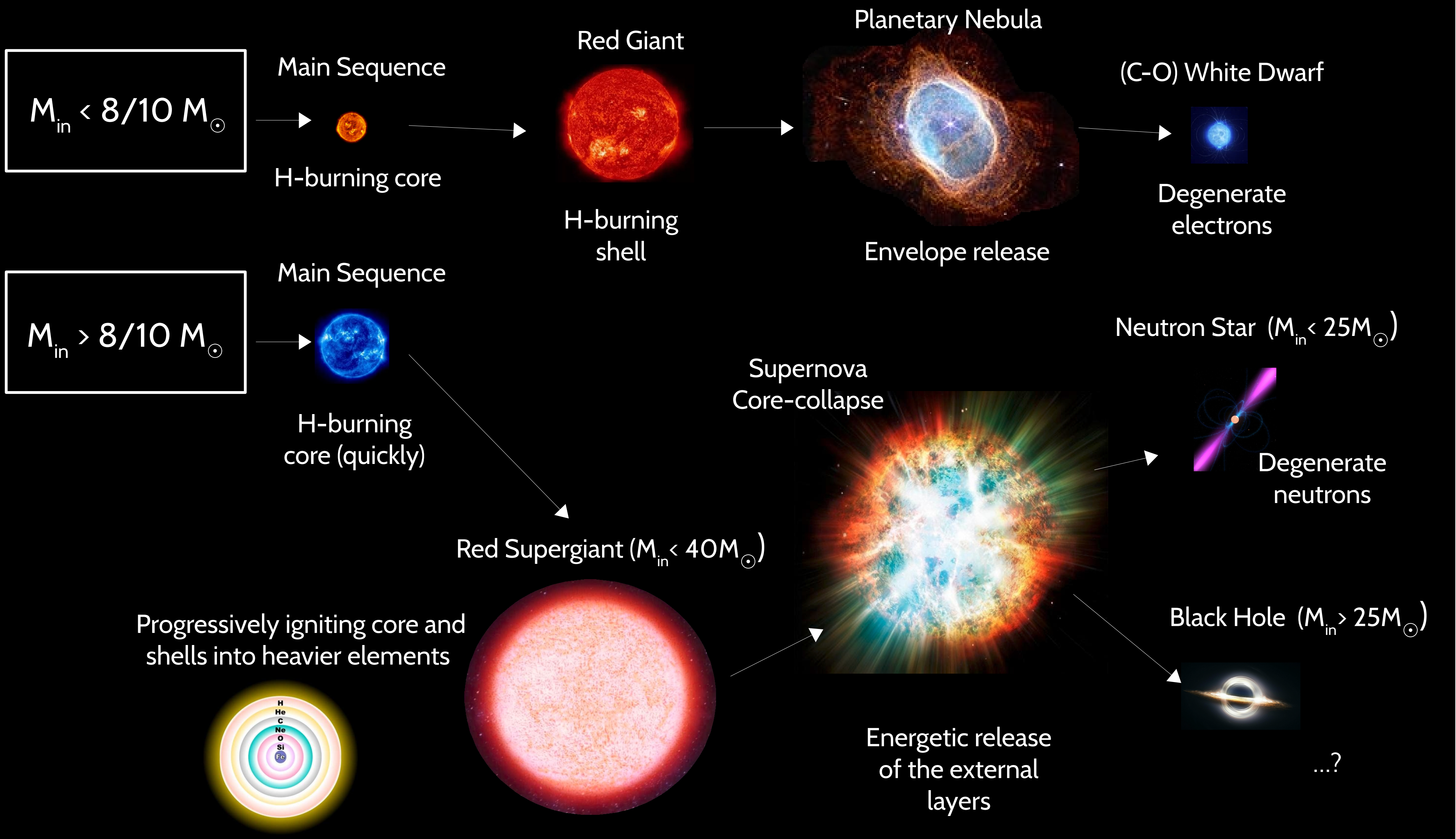
Eggenberg 2020

A mass-depending evolution



Eggenberg 2020

A mass-depending evolution



$M_{in} < 8/10\ M_\odot$

Main Sequence

H-burning core

Red Giant

H-burning shell

Planetary Nebula

Envelope release

(C-O) White Dwarf

Degenerate electrons

$M_{in} > 8/10\ M_\odot$

Main Sequence

H-burning core (quickly)

Red Supergiant ($M_{in} < 40M_\odot$)

Progressively igniting core and shells into heavier elements

H

He

C

Ne

O

Si

Fe

Supernova Core-collapse

Energetic release of the external layers

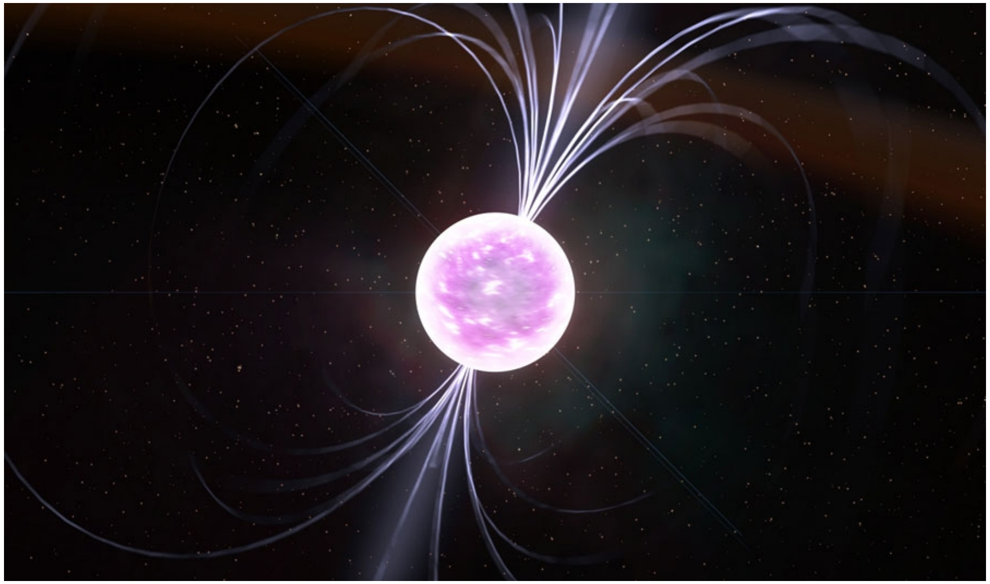
Neutron Star ($M_{in} < 25M_\odot$)

Degenerate neutrons

Black Hole ($M_{in} > 25M_\odot$)

...?

A neutron star is born



- Collapse is halted by degenerate neutrons (up to the limit of Oppenheimer-Volkoff)

- $\rho \sim 7\text{x}10^{14}$ g/cm^3

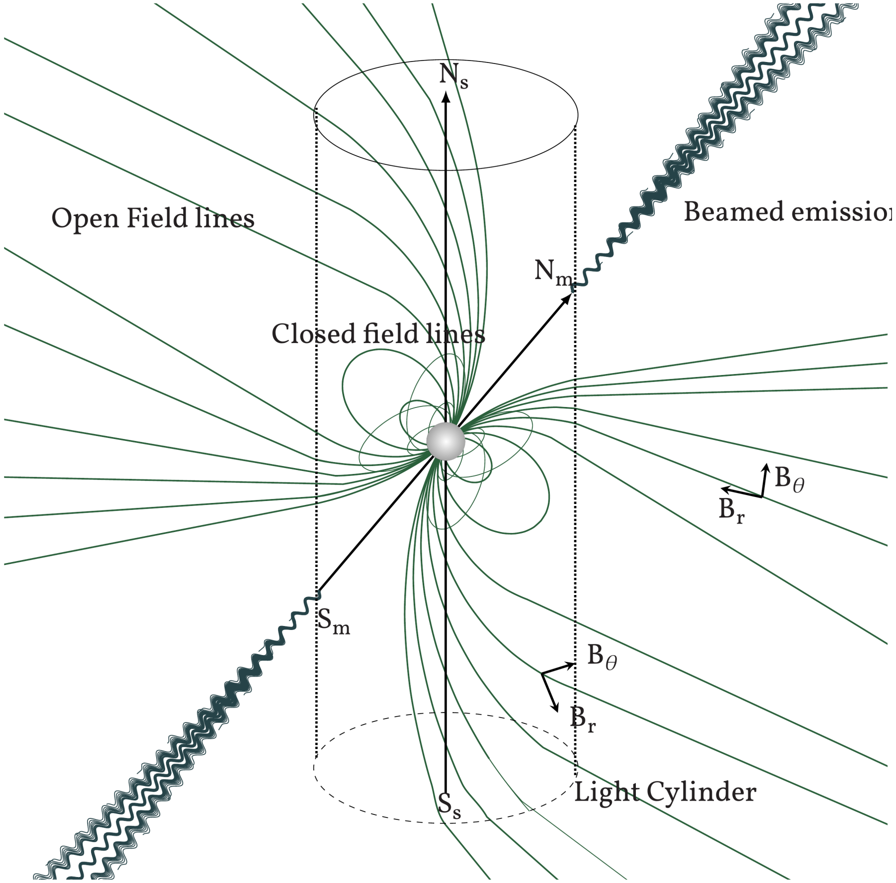
- $R_{NS} \sim 10$ km

- P_{NS} reaches <1s → Fast-spinning due to conservation of angular momentum

- B_{NS} reaches 10^{12} G → Highly-magnetised due to conservation of magnetic flux

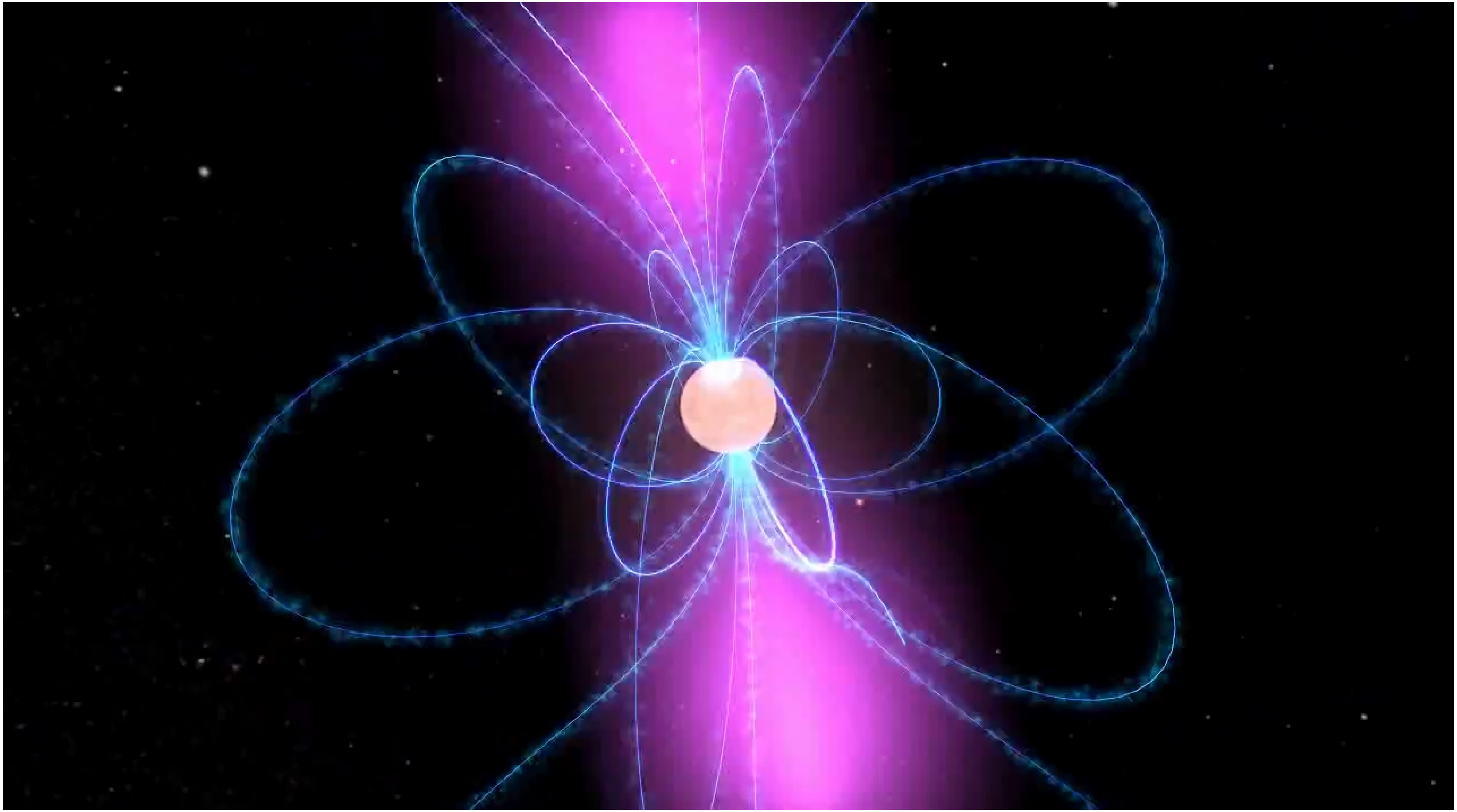
… and a pulsar is born

- **Pulsars** are **neutron stars**
- They produce **two beams of emission mainly visible at radio wavelengths**, radiating their rotational kinetic energy;
- The beams **co-rotate with the star**;
- They can be seen if the line-of-sight of an observer crosses one (or both) of the beams
- Due to the pulsar rotation, the signal appears periodic (“**Lighthouse Effect**”)

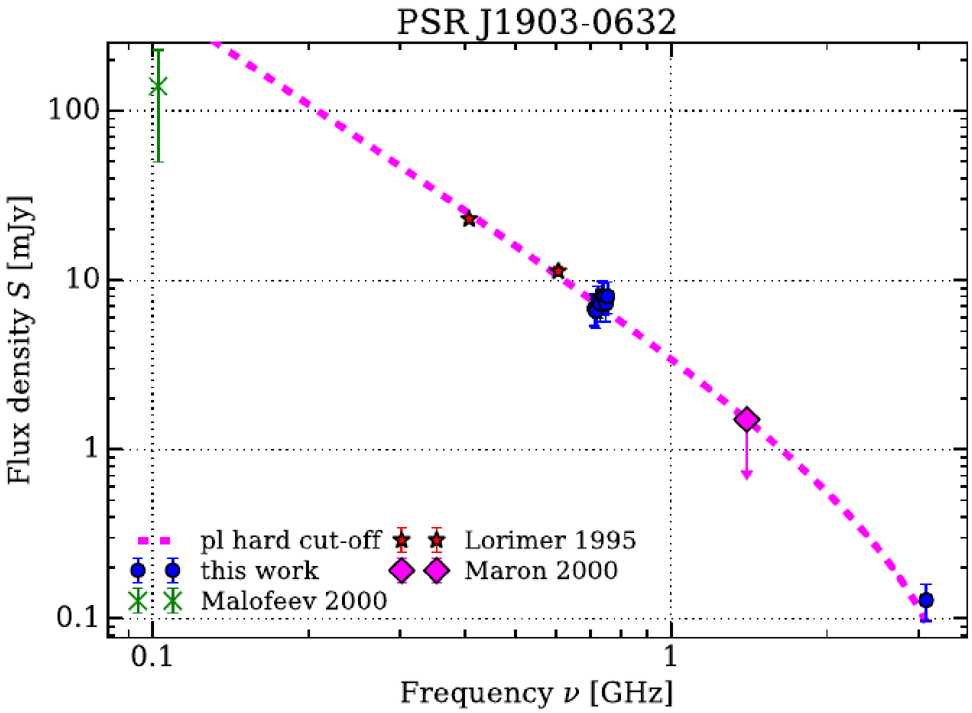


Shaifullah

Pulsars in a nutshell

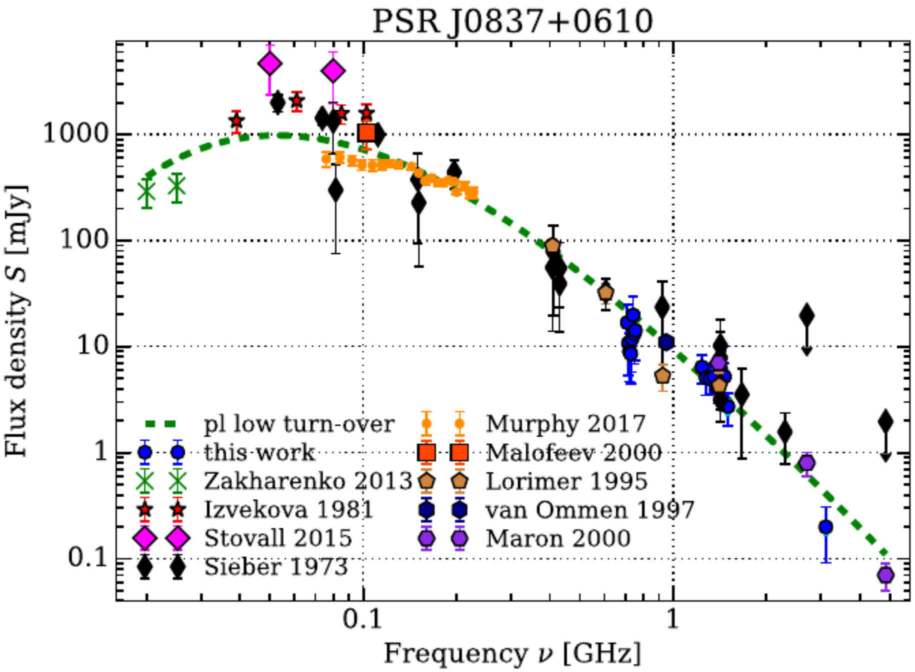


Flux density spectra

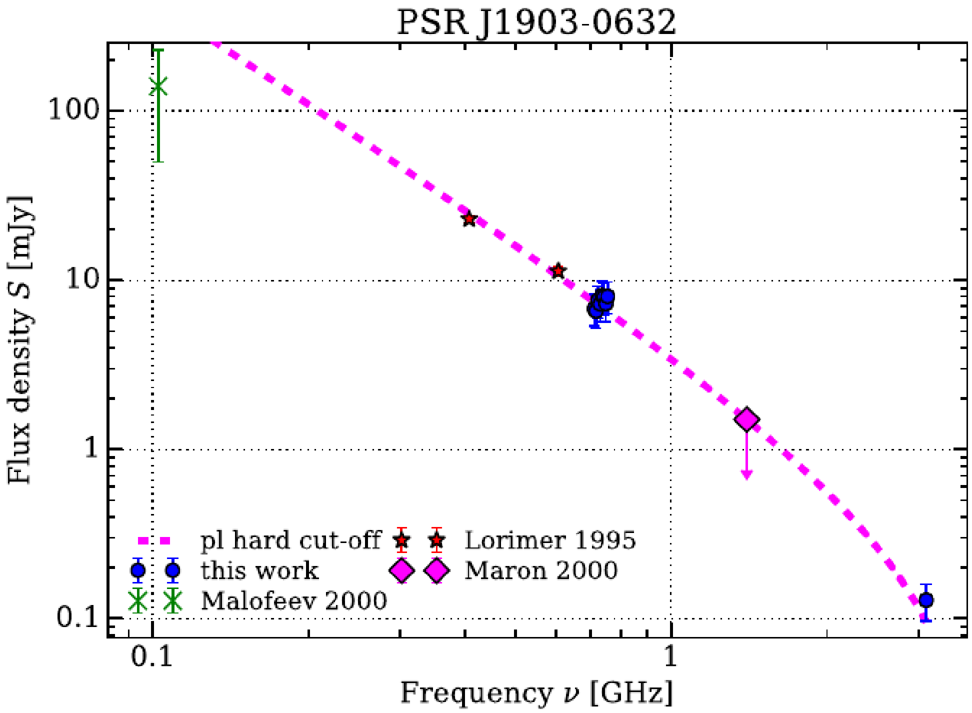


Jankowski+2018

A large number of pulsars have **power-law flux density spectra with negative spectral indexes (-1.60 +/- 0.03)**



How low is low in pulsar astronomy?

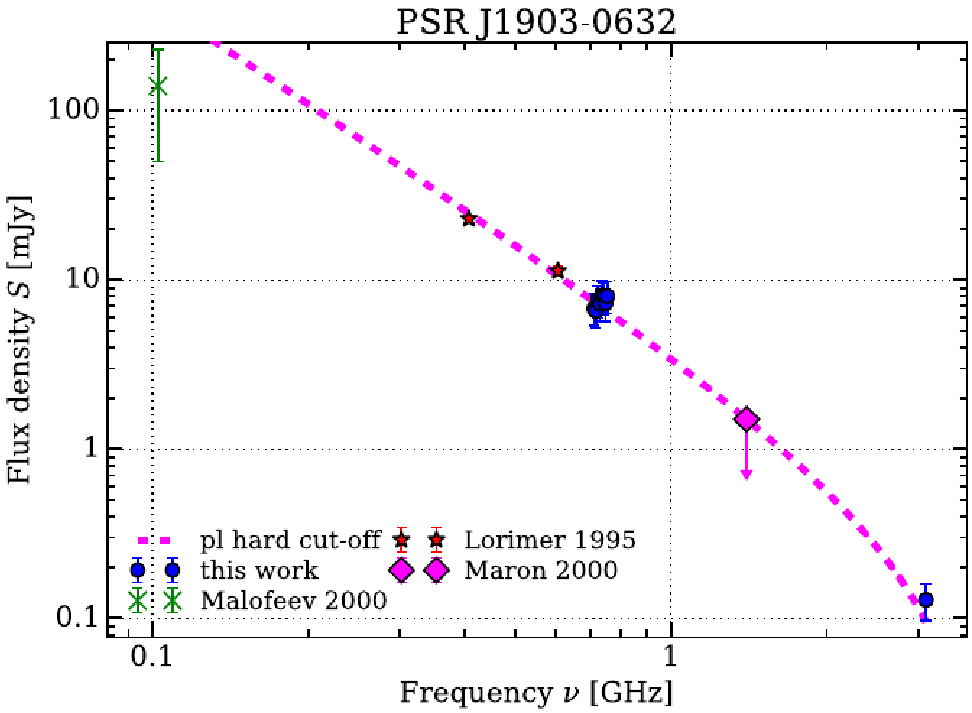


$$S \propto f^{\alpha}$$

$$\alpha \sim -1.6$$

... as low as the atmosphere doesn't bounce you back (~few tens of MHz)

How low is low in pulsar astronomy?



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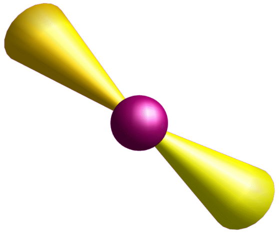
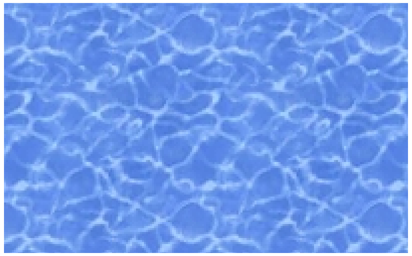


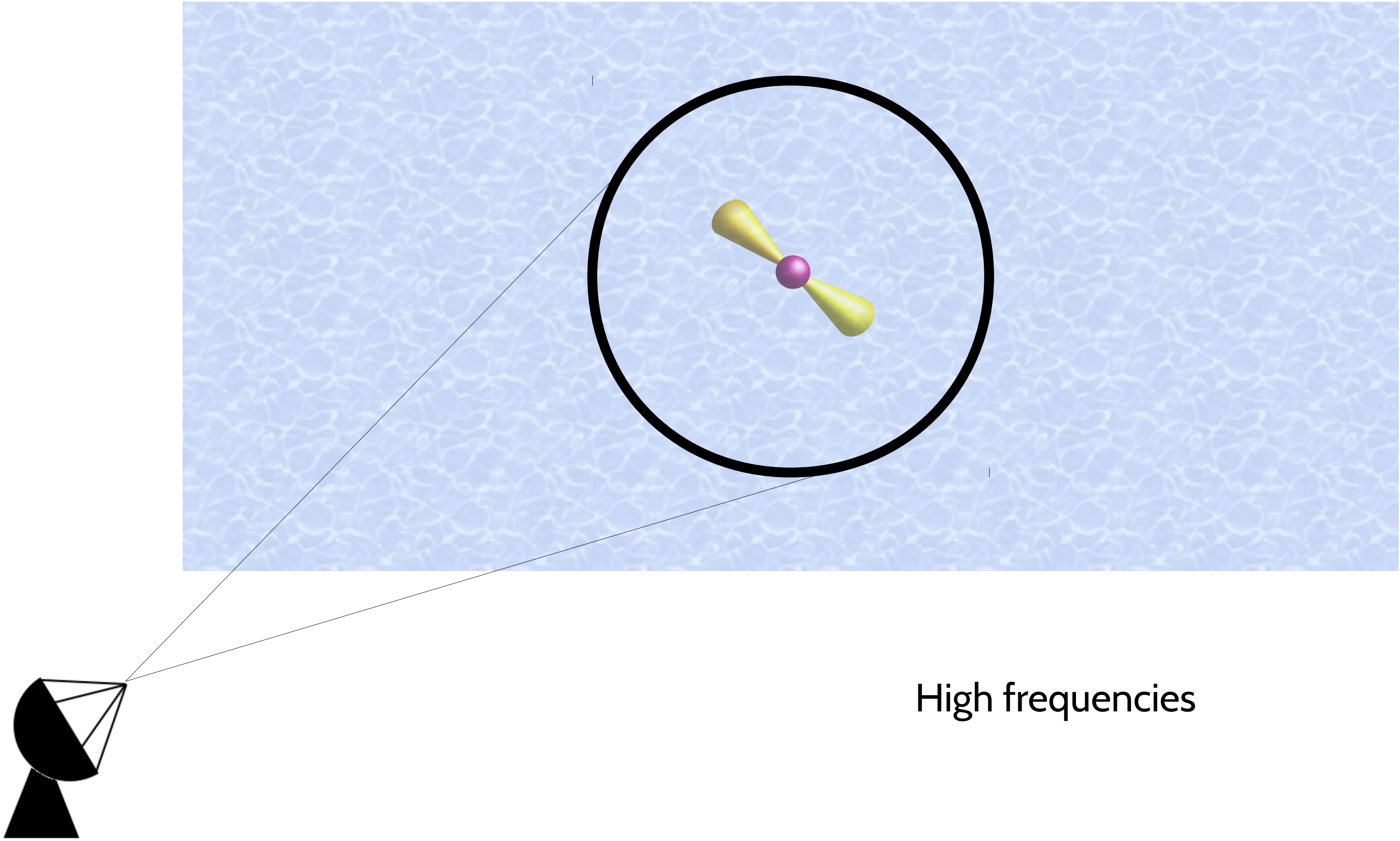


Galactic background

$$S \propto f^{\beta}$$

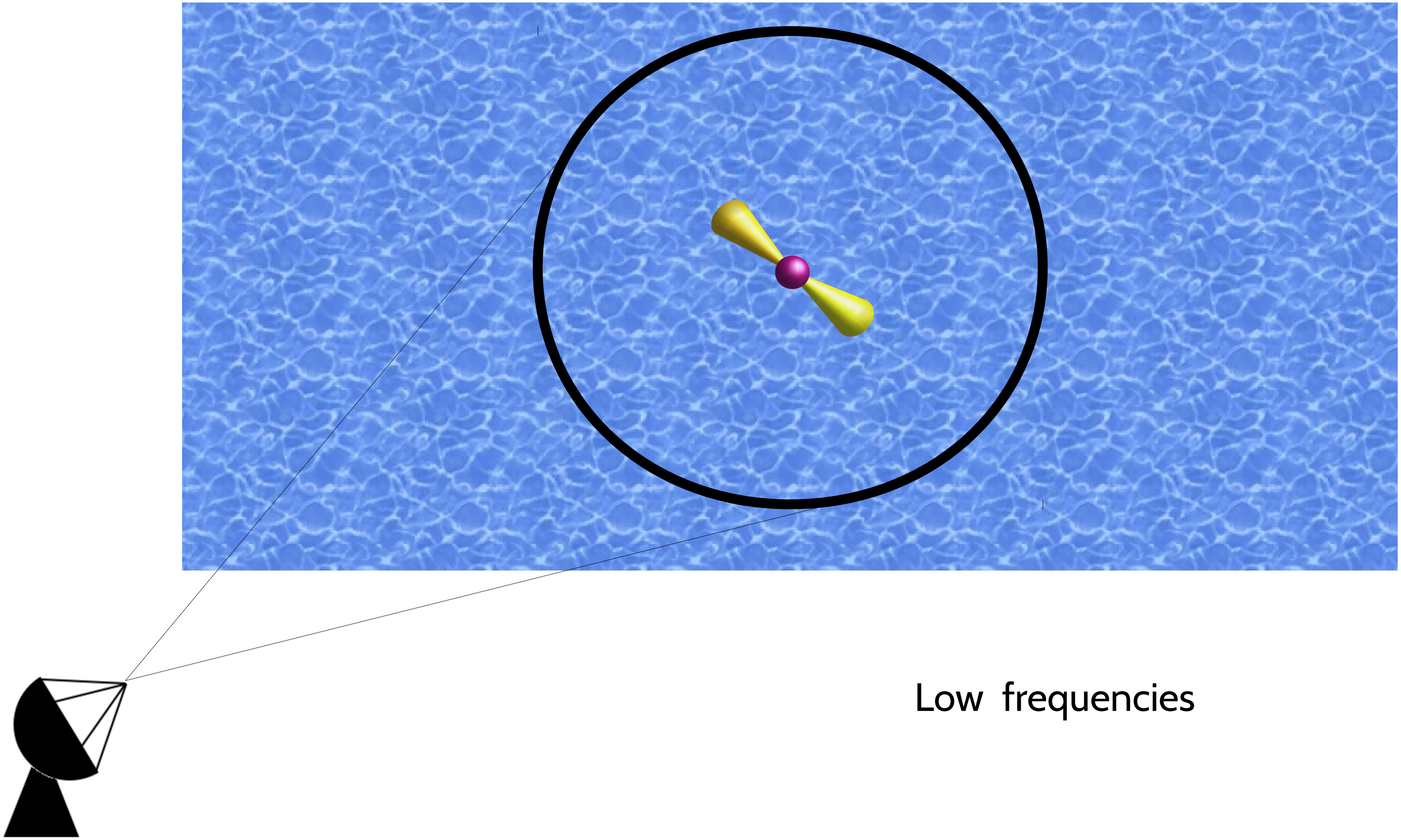
$$\beta \sim -2.56$$

How low is low in pulsar astronomy?



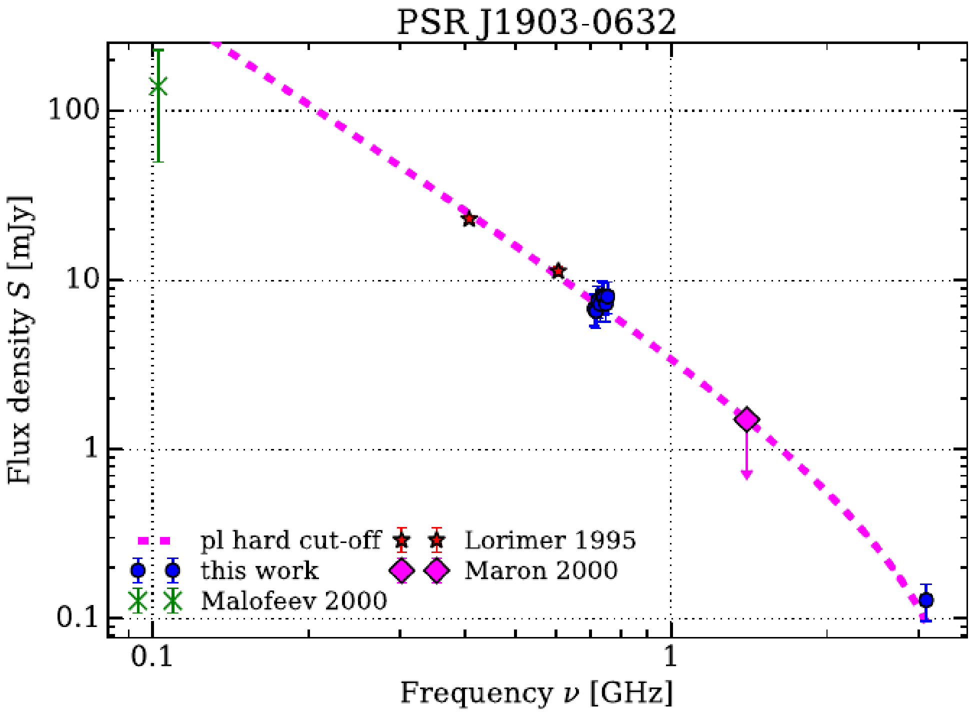
High frequencies

How low is low in pulsar astronomy?



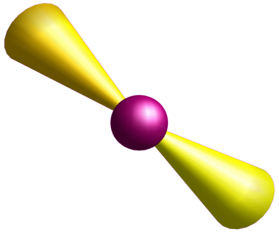
Low frequencies

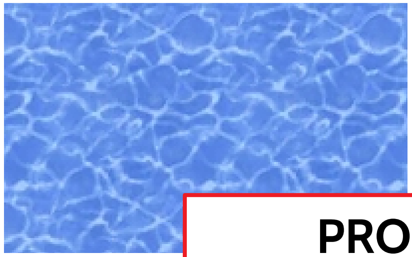
How low is low in pulsar astronomy?



$$S \propto f^{\alpha}$$

$$\alpha \sim -1.6$$





$$S \propto f^{\beta}$$

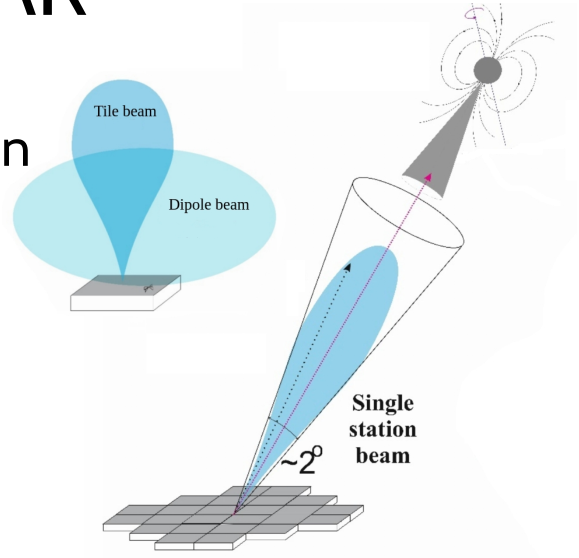
Gal

backg

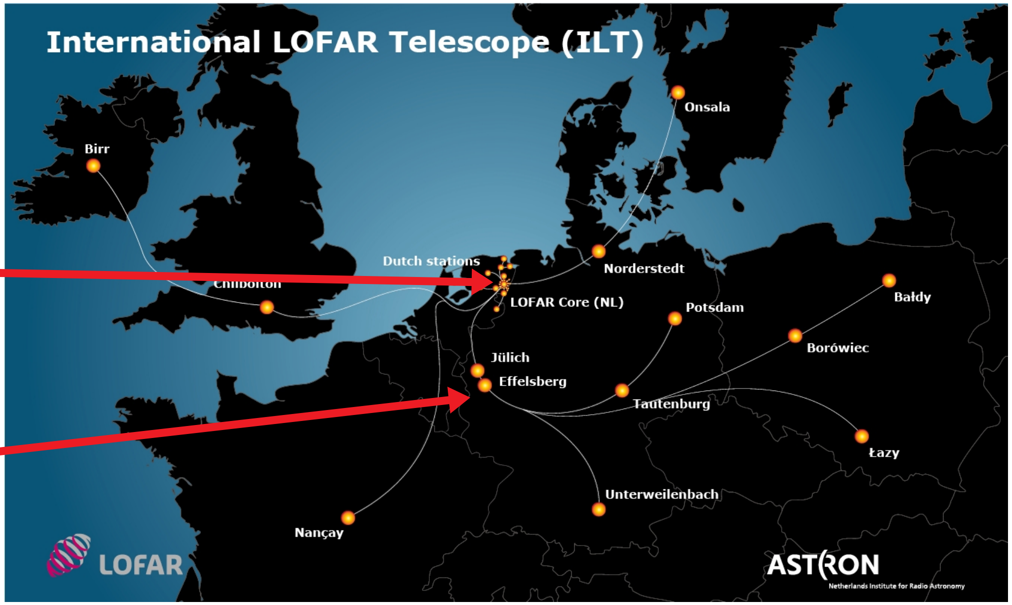
PROBLEM N. 1 IN LOW-FREQUENCY OBSERVATIONS

Observing pulsars with LOFAR

Błaszkiewicz+2020



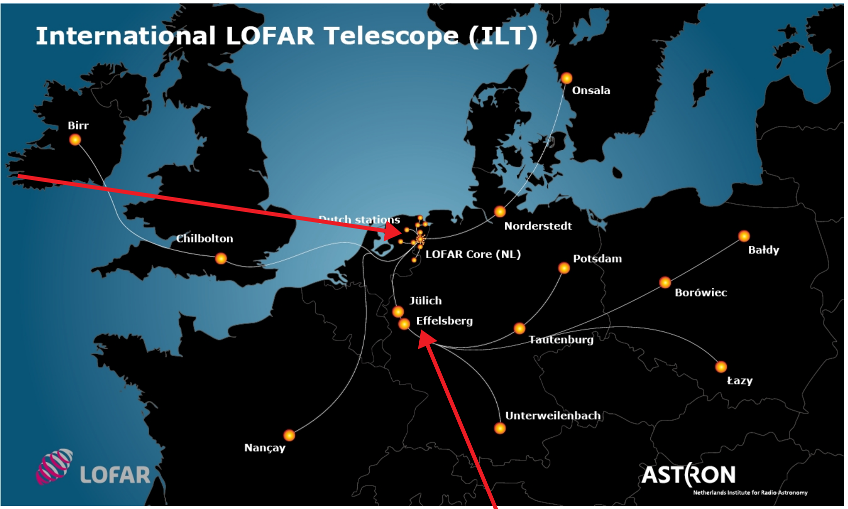
- Pulsars are point-like sources, and they are typically studied in **time-domain** → "no" imaging, "no" interferometry
- Beam-formed observations (tied-array or station beam)
- (Limited) HBA band only, 110-200 MHz
- NenuFAR covering <100 MHz
- Core and Single-stations campaigns



Observing pulsars with LOFAR

- Observations ongoing since 2013

- Core observations (P.I. Tiburzi):
  - Bi-monthly cadence
  - 52 pulsars



- International stations used as stand-alone telescopes (P.I. Griessmeier):
  - Weekly cadence
  - >100 pulsars
  - 6 German, 1 French, 1 Swedish stations
  - Part of data streamed to the Juelich Supercomputing Center (Germany)

- All data are then transferred to the University of Bielefeld, where they are preprocessed (i.e., RFI-cleaned and beam-calibrated) and made ready to use

What do low frequencies unveil?

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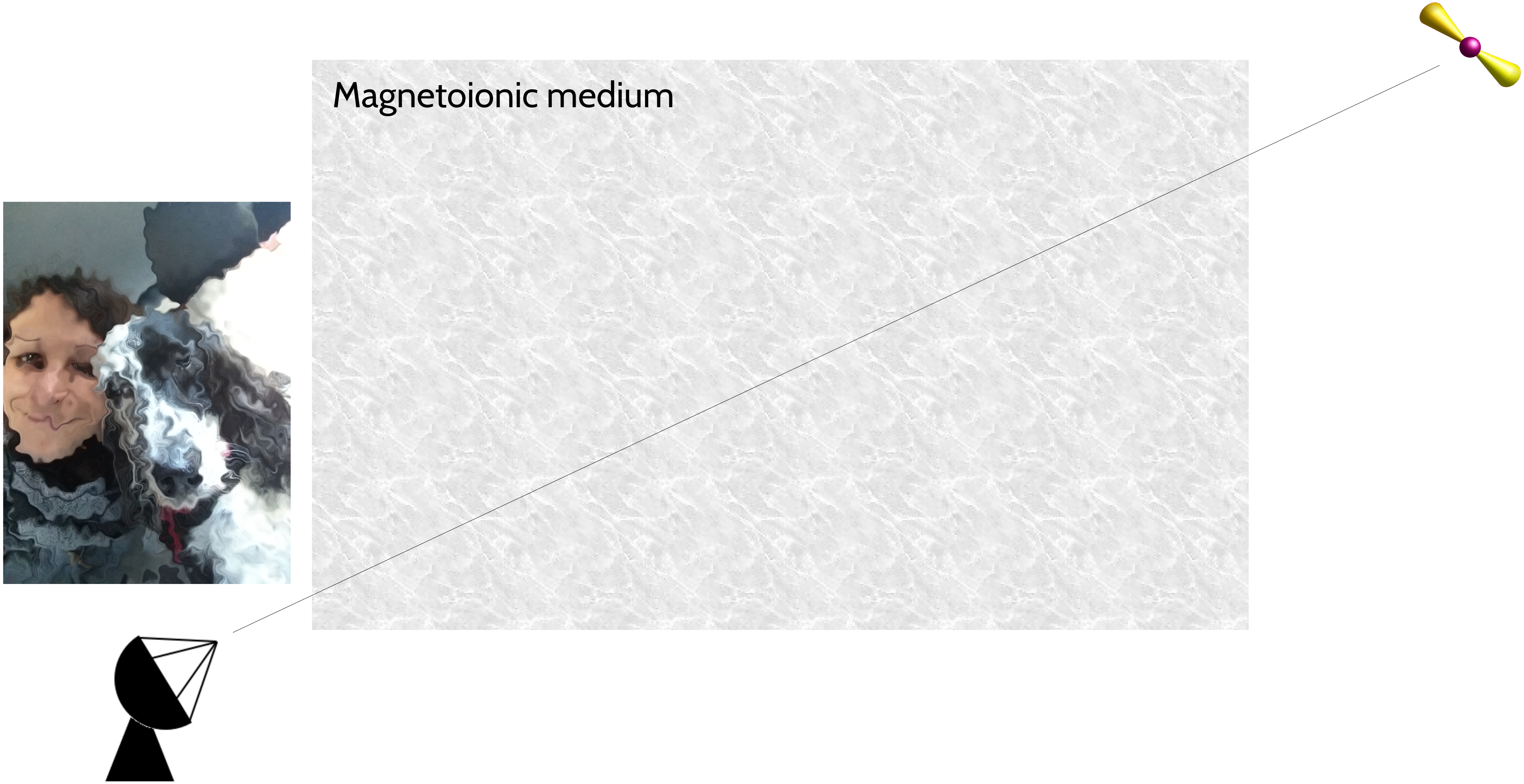
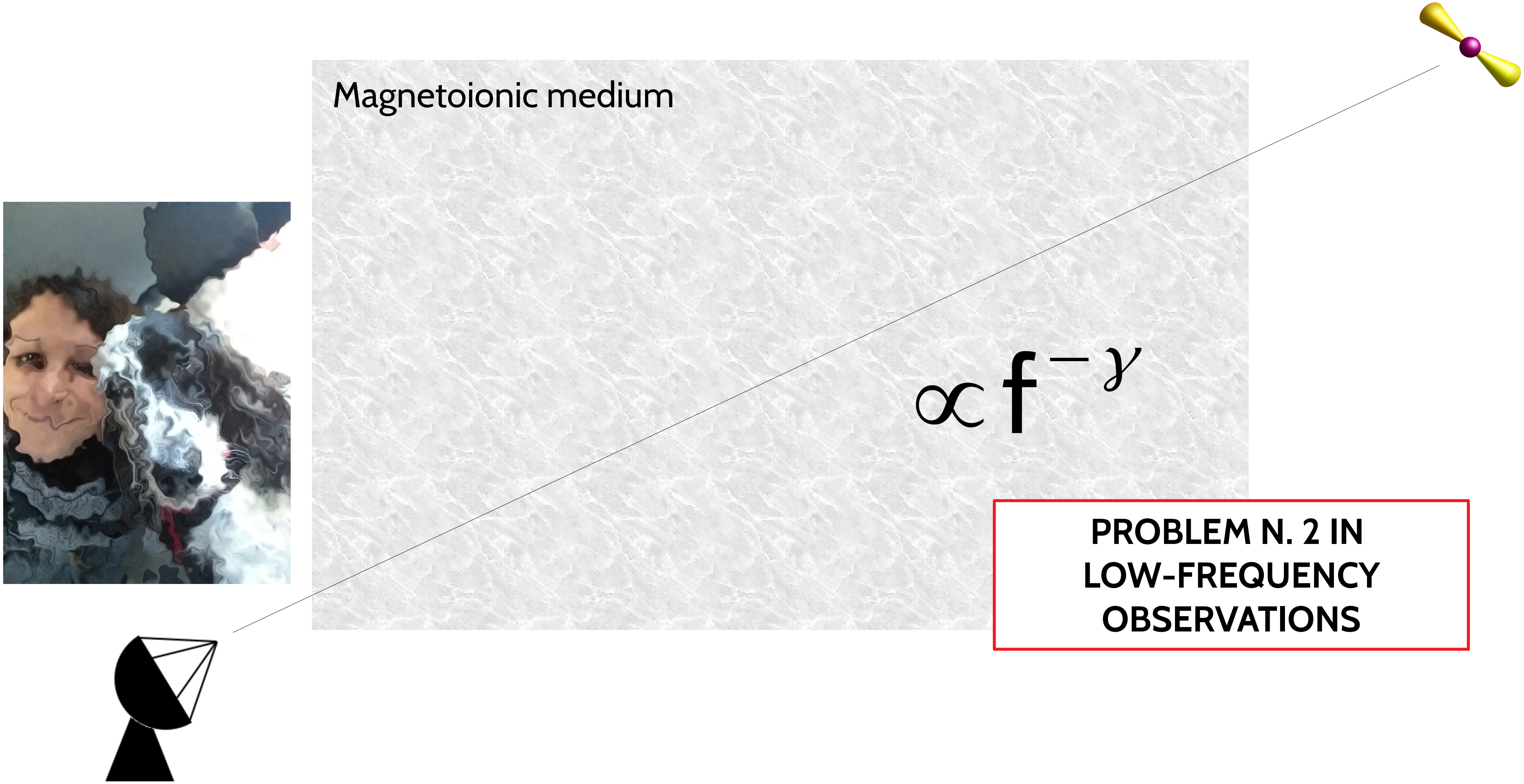


Magnetoionic medium

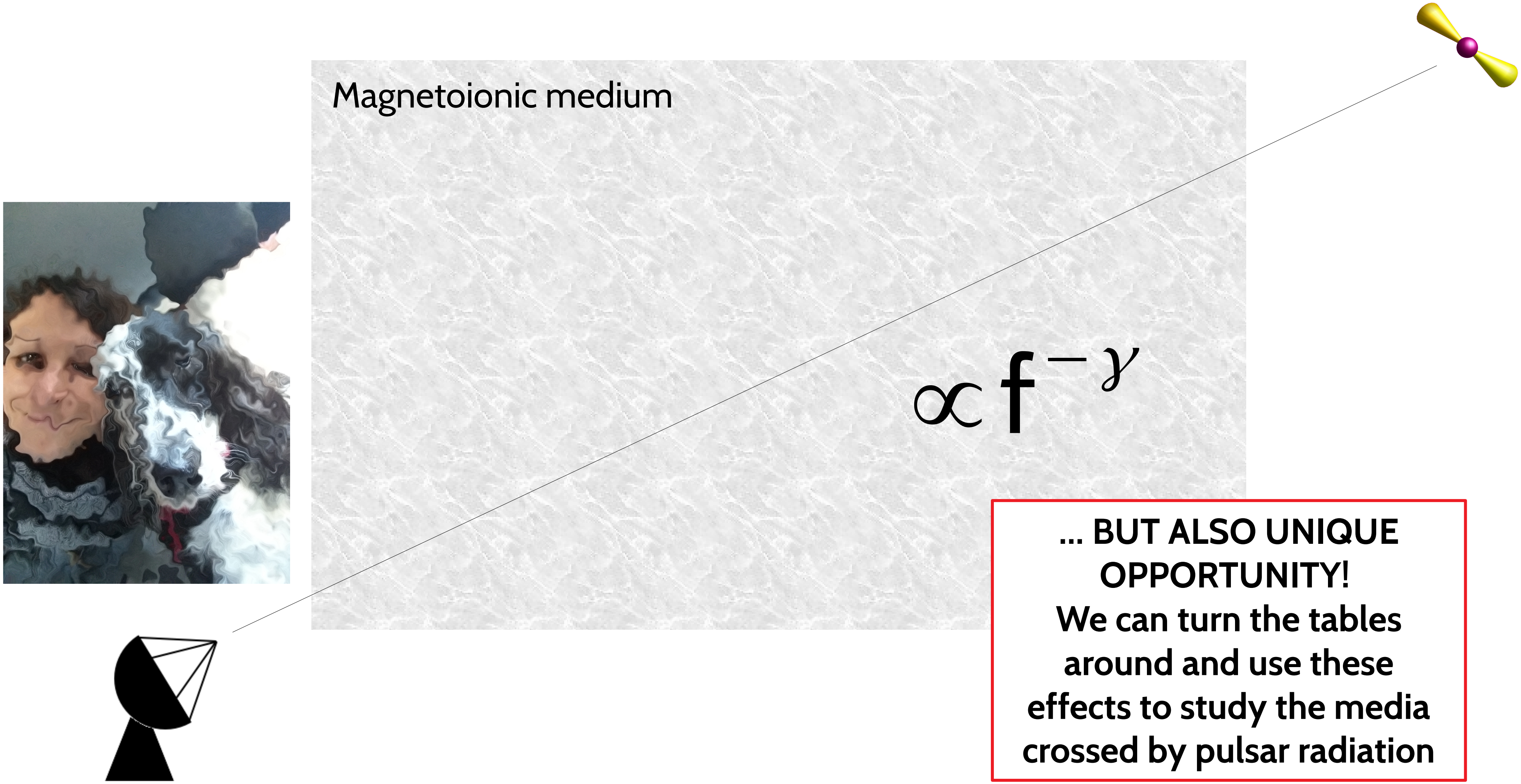
What do low frequencies unveil?



$\propto f^{-\gamma}$

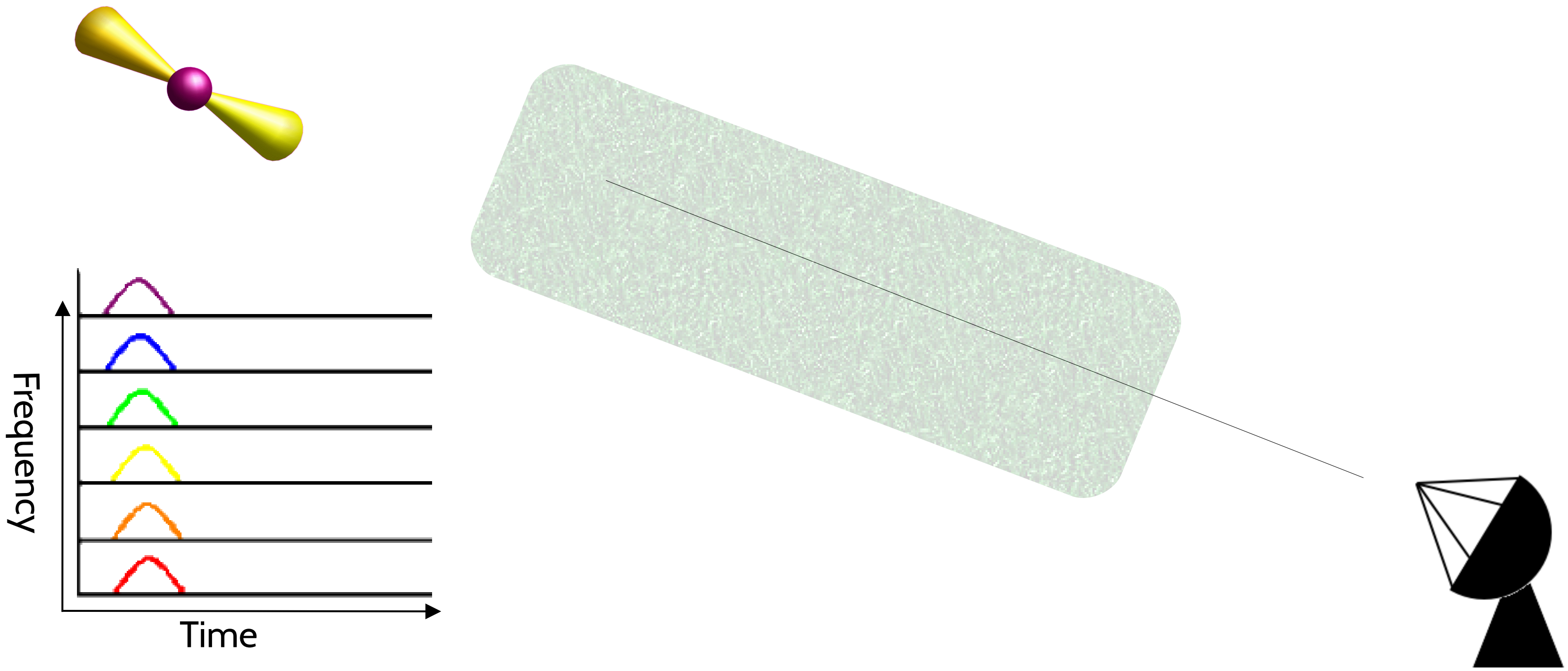
PROBLEM N. 2 IN LOW-FREQUENCY OBSERVATIONS

What do low frequencies unveil?

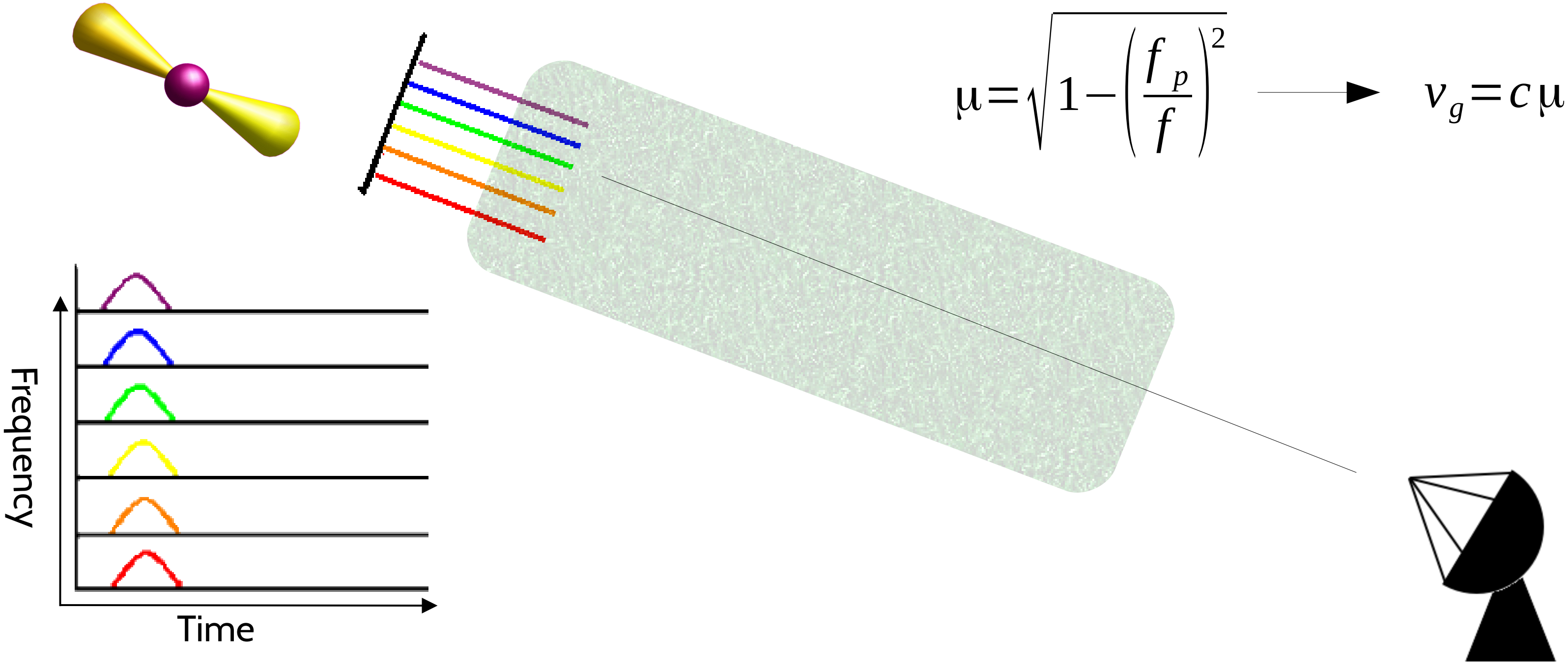


... BUT ALSO UNIQUE OPPORTUNITY!
We can turn the tables around and use these effects to study the media crossed by pulsar radiation

Dispersion

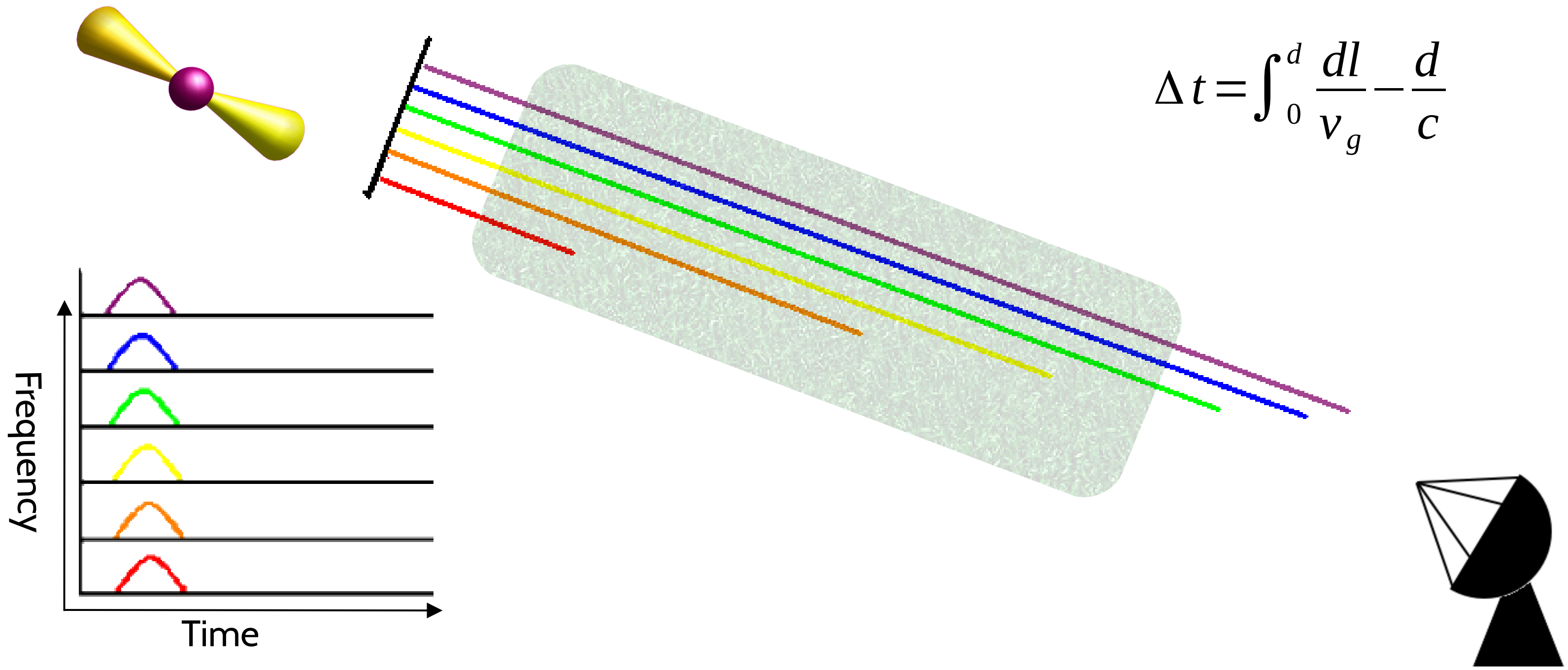


Dispersion



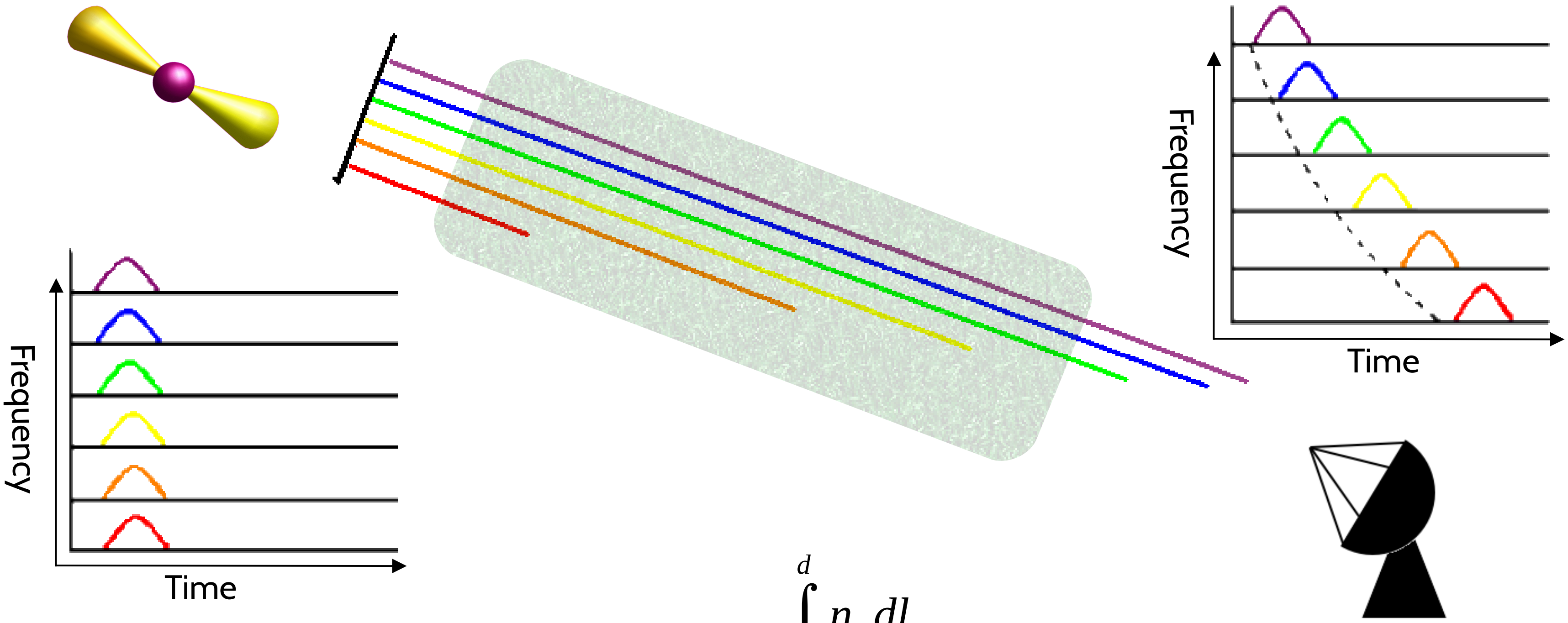
$$\mu = \sqrt{1-\left(\frac{f_p}{f}\right)^2} \longrightarrow v_g = c\mu$$

Dispersion



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

Dispersion

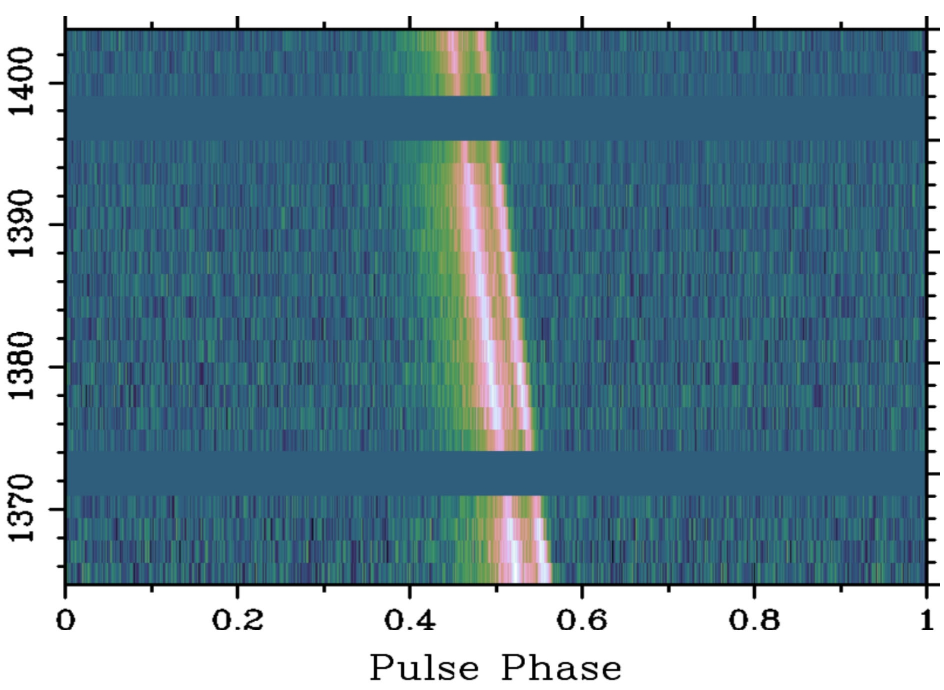


$$\Delta t = \frac{e^2}{2\pi m_e c}\,\frac{\int_0^d n_e\,dl}{f^2} \propto \frac{DM}{f^2}$$

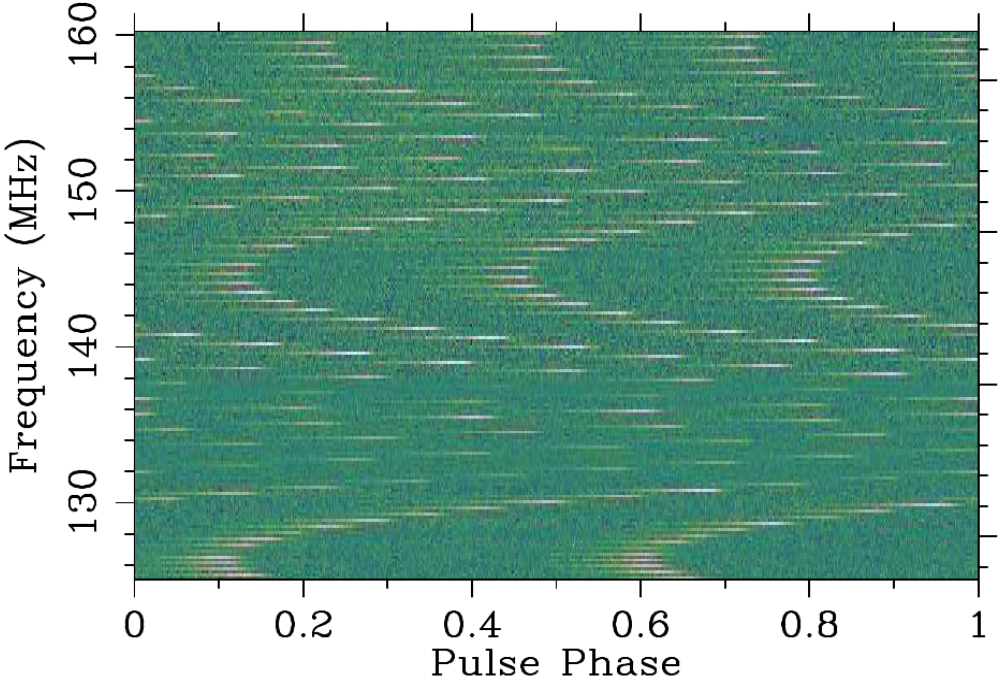
$$DM = \int_0^d n_e\,dl$$

Dispersion

J1022+1001

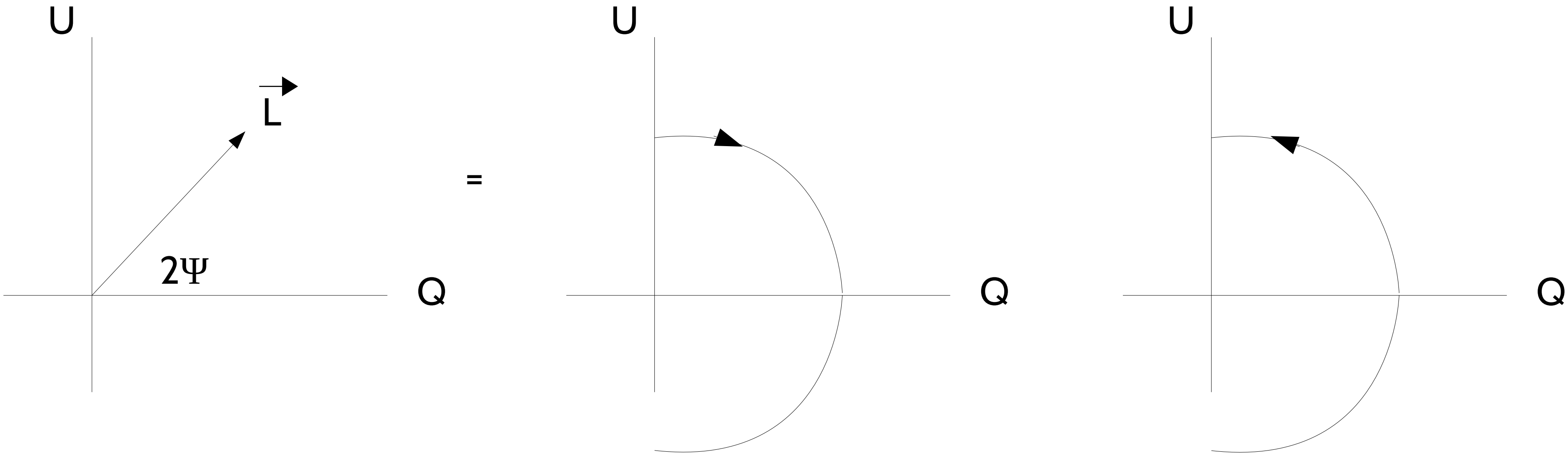


1385 MHz



142 MHz

Faraday Rotation

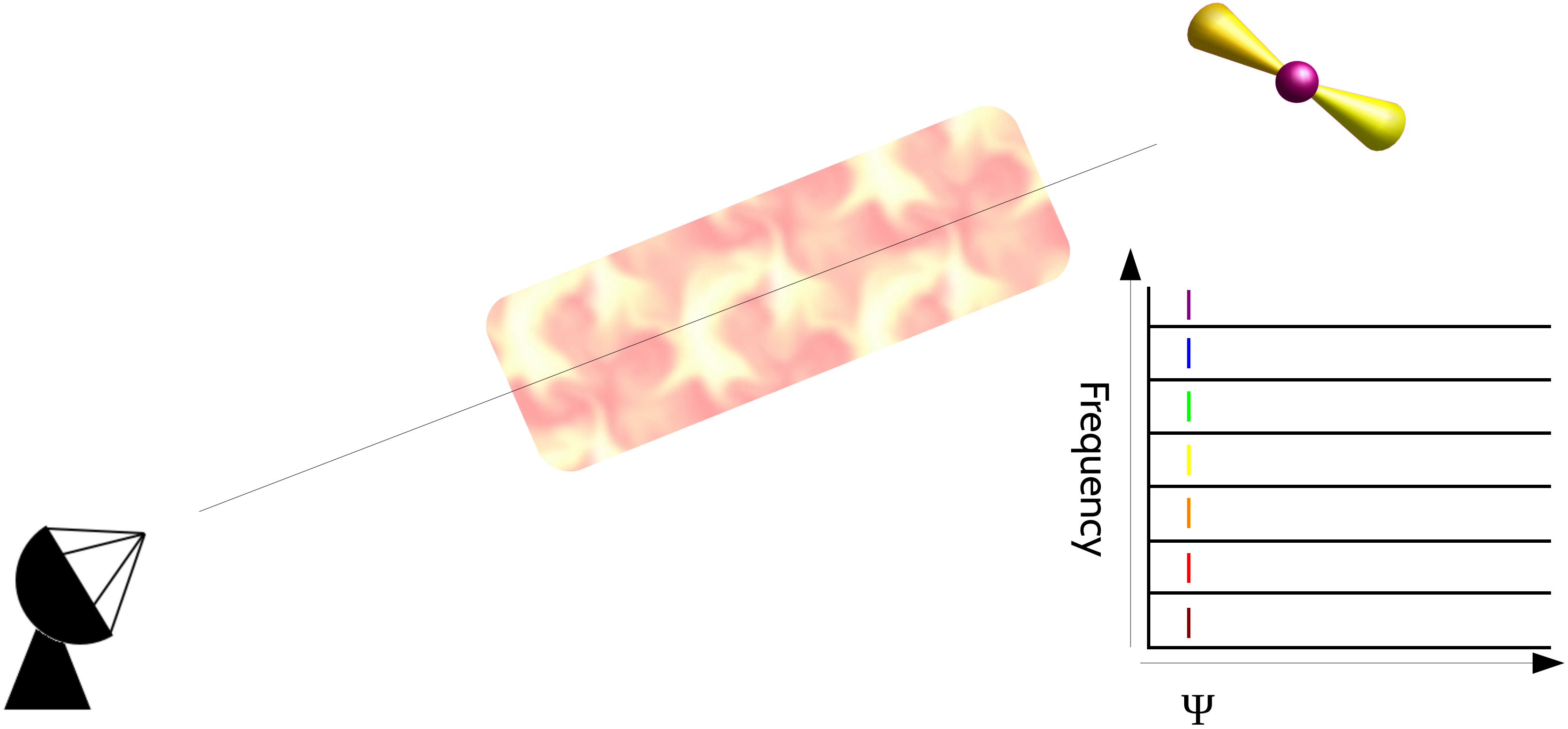


Linear

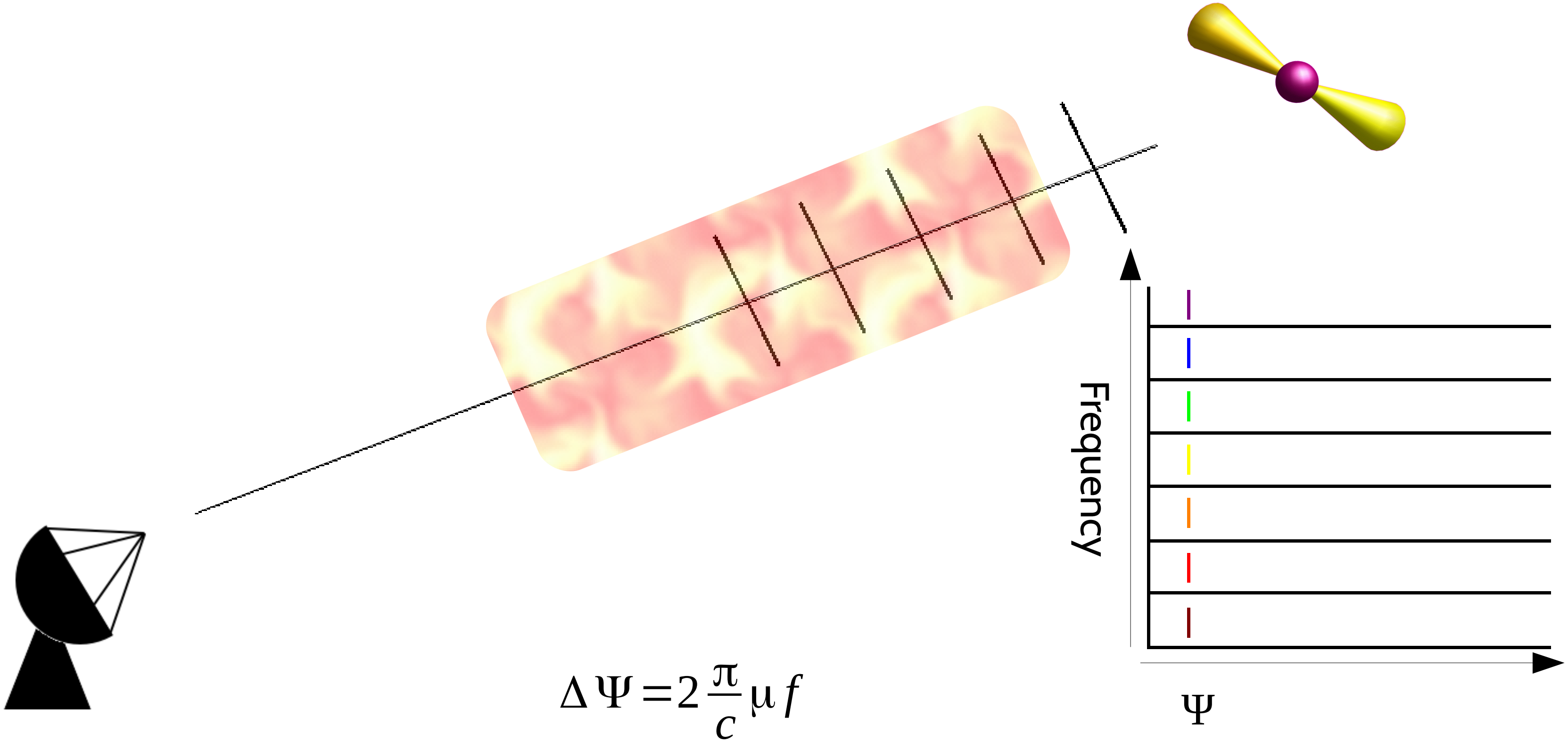
RCP

LCP

Faraday Rotation



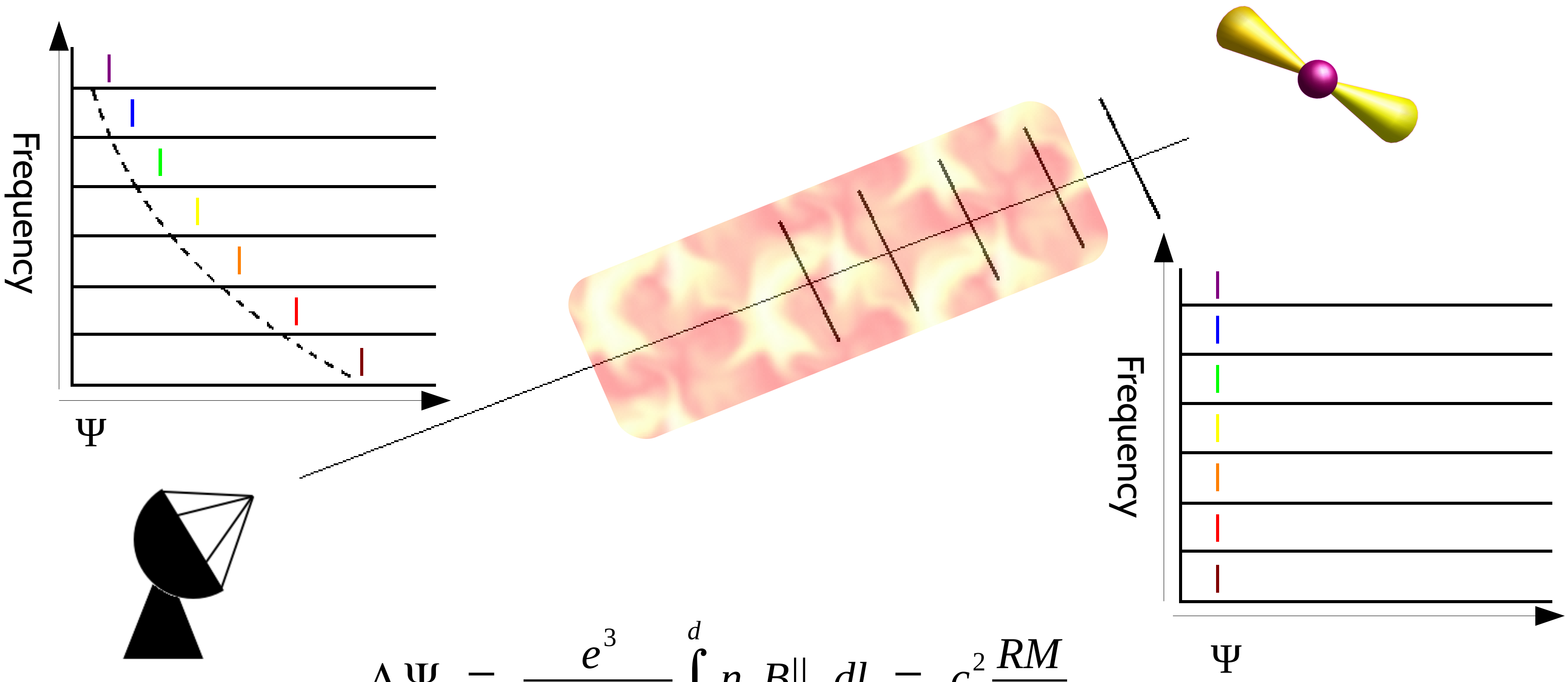
Faraday Rotation



$$\Delta\Psi = 2\frac{\pi}{c}\mu f$$

$$\mu = \sqrt{1-\left(\frac{f_p}{f}\right)^2 \mp f_p^2 \frac{f_B}{f^3}}$$

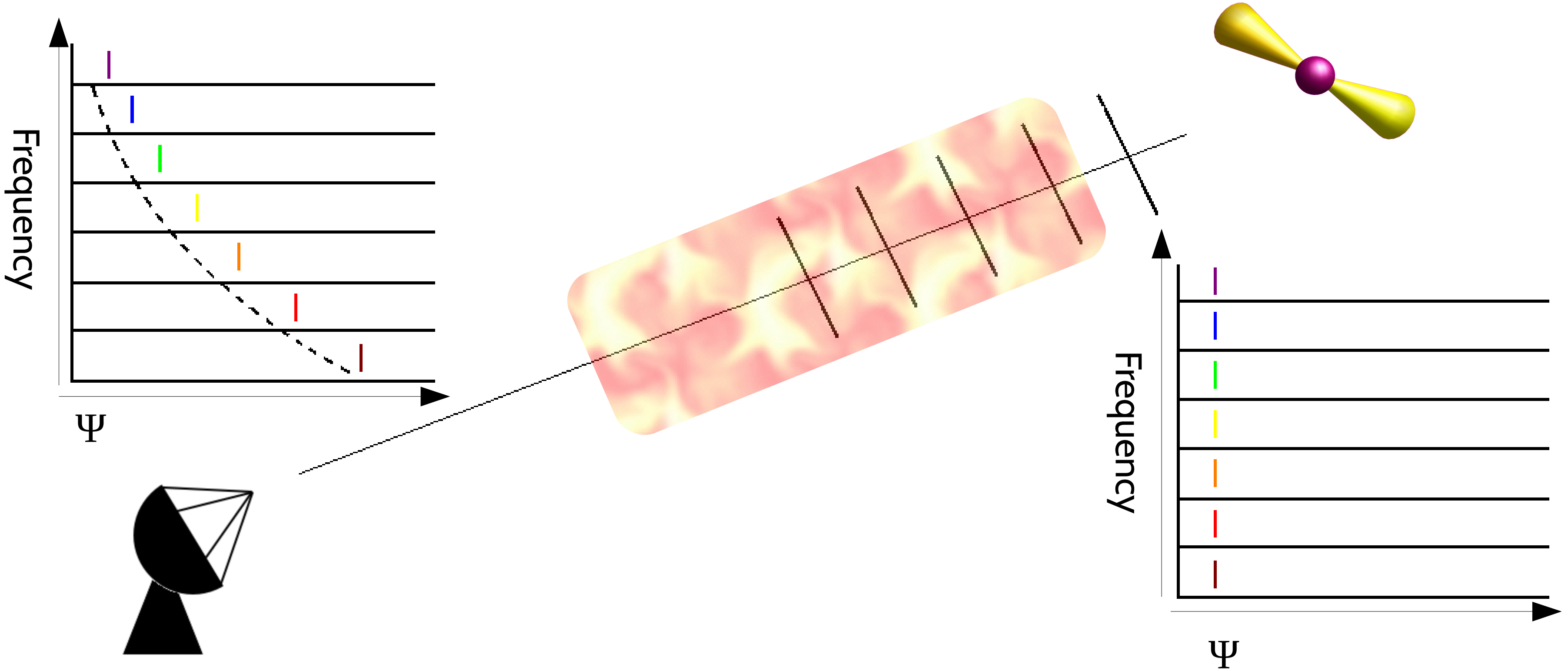
Faraday Rotation



$$\Delta\Psi \;=\; \frac{e^3}{2\pi m_e c^2}\int_0^d n_e B\| \; dl \;=\; c^2\frac{RM}{f^2}$$

$$RM = \frac{e^4}{2\pi m_e}\int_0^d B\| n_e dl$$

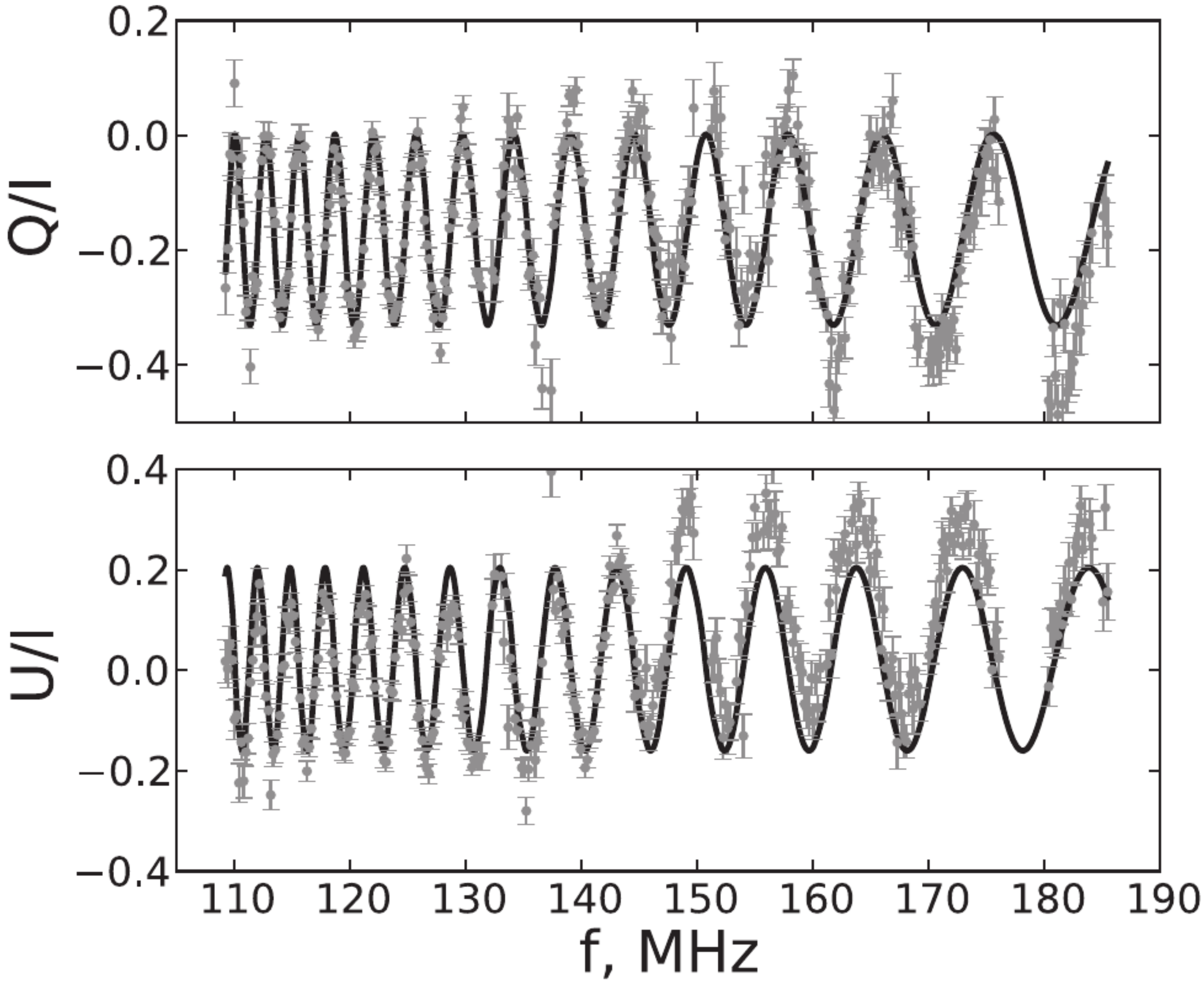
Faraday Rotation



$$Q \propto \cos\left(2\,RMc^2/f^2 + \psi_0\right)$$

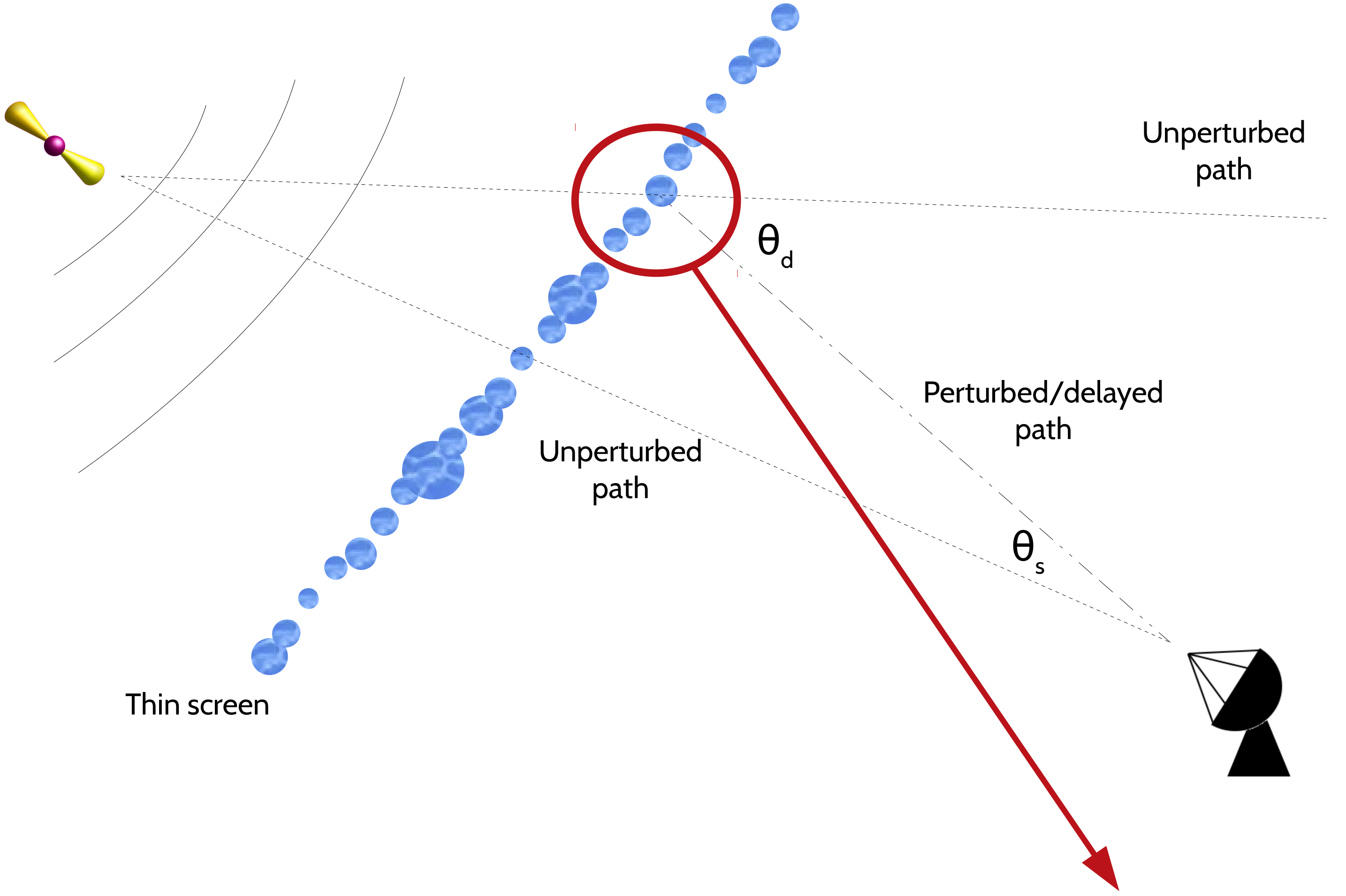
$$U \propto \sin\left(2\,RMc^2/f^2 + \psi_0\right)$$

Faraday Rotation



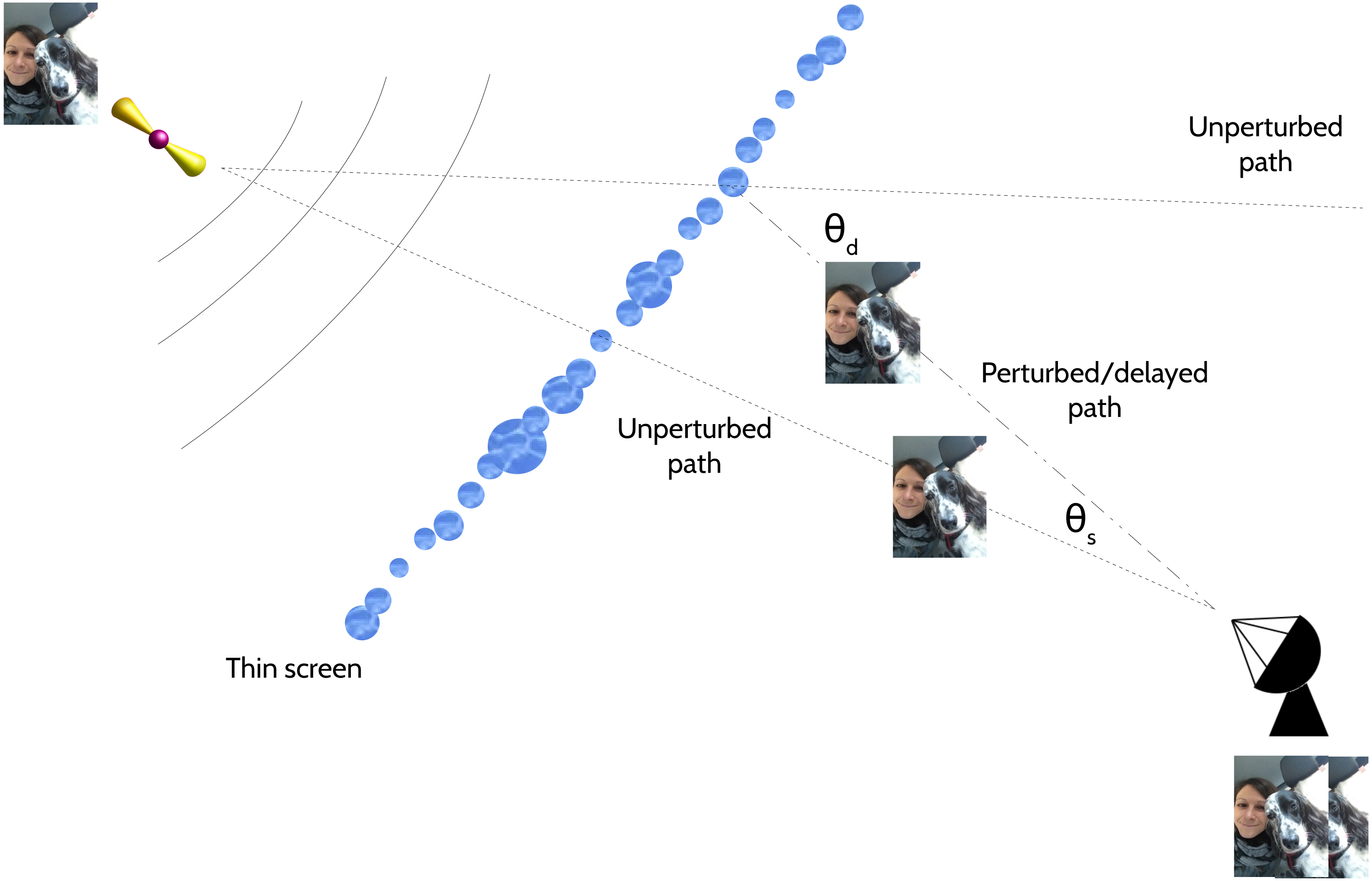
Credits: Porayko et al., 2019

Scattering



Change in the refractive index happening

Scattering



Unperturbed path

θ_d

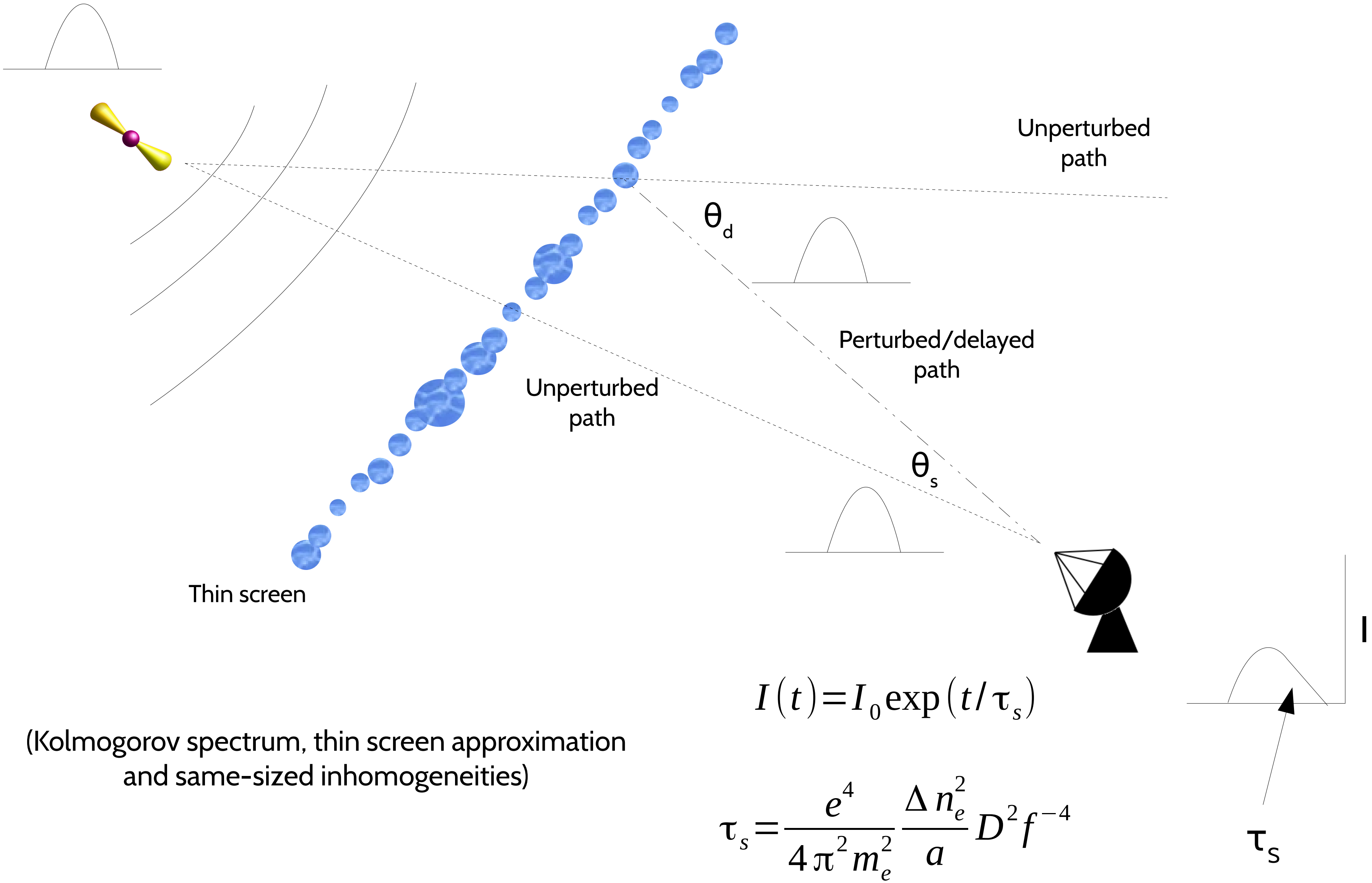
Perturbed/delayed path

Unperturbed path

θ_s

Thin screen

Scattering

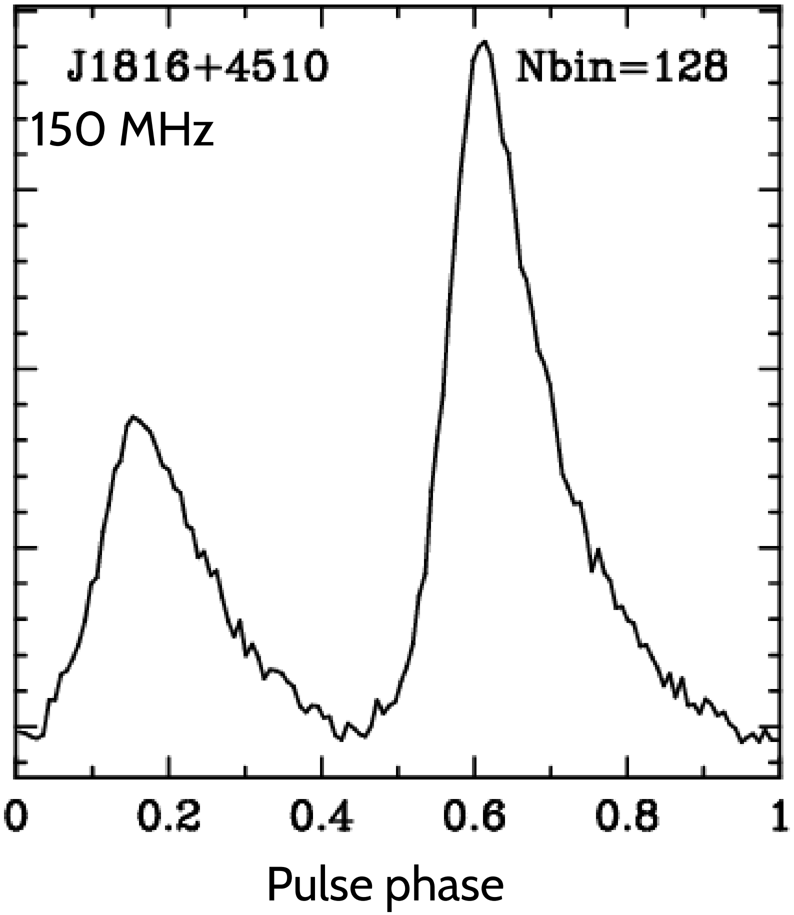


$$I(t) = I_0 \exp(t/\tau_s)$$

$$\tau_s = \frac{e^4}{4\pi^2 m_e^2} \frac{\Delta n_e^2}{a} D^2 f^{-4}$$

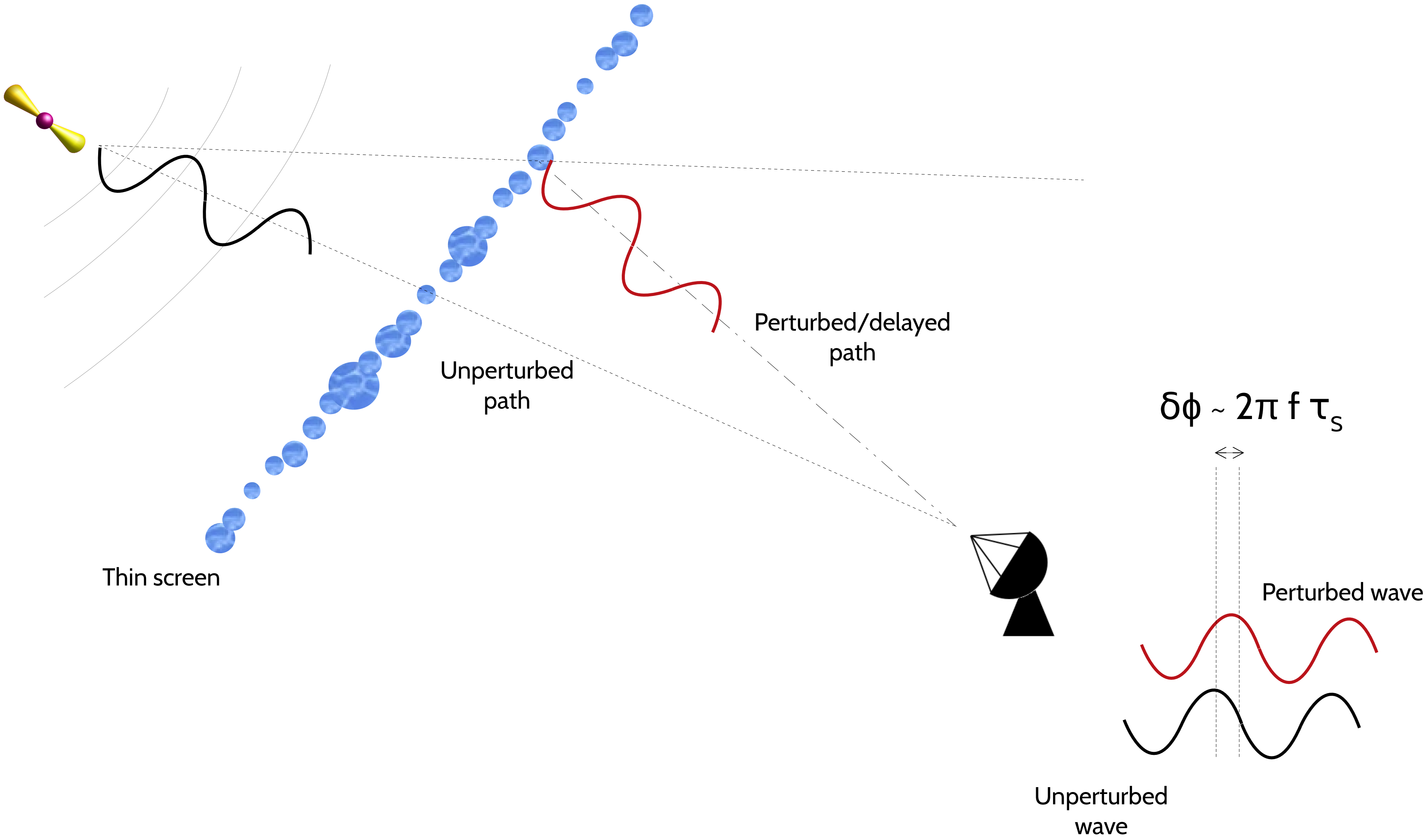
(Kolmogorov spectrum, thin screen approximation
and same-sized inhomogeneities)

Scattering



Credits: Kondratiev et al. 2016

Scintillation



Perturbed/delayed path

Unperturbed path

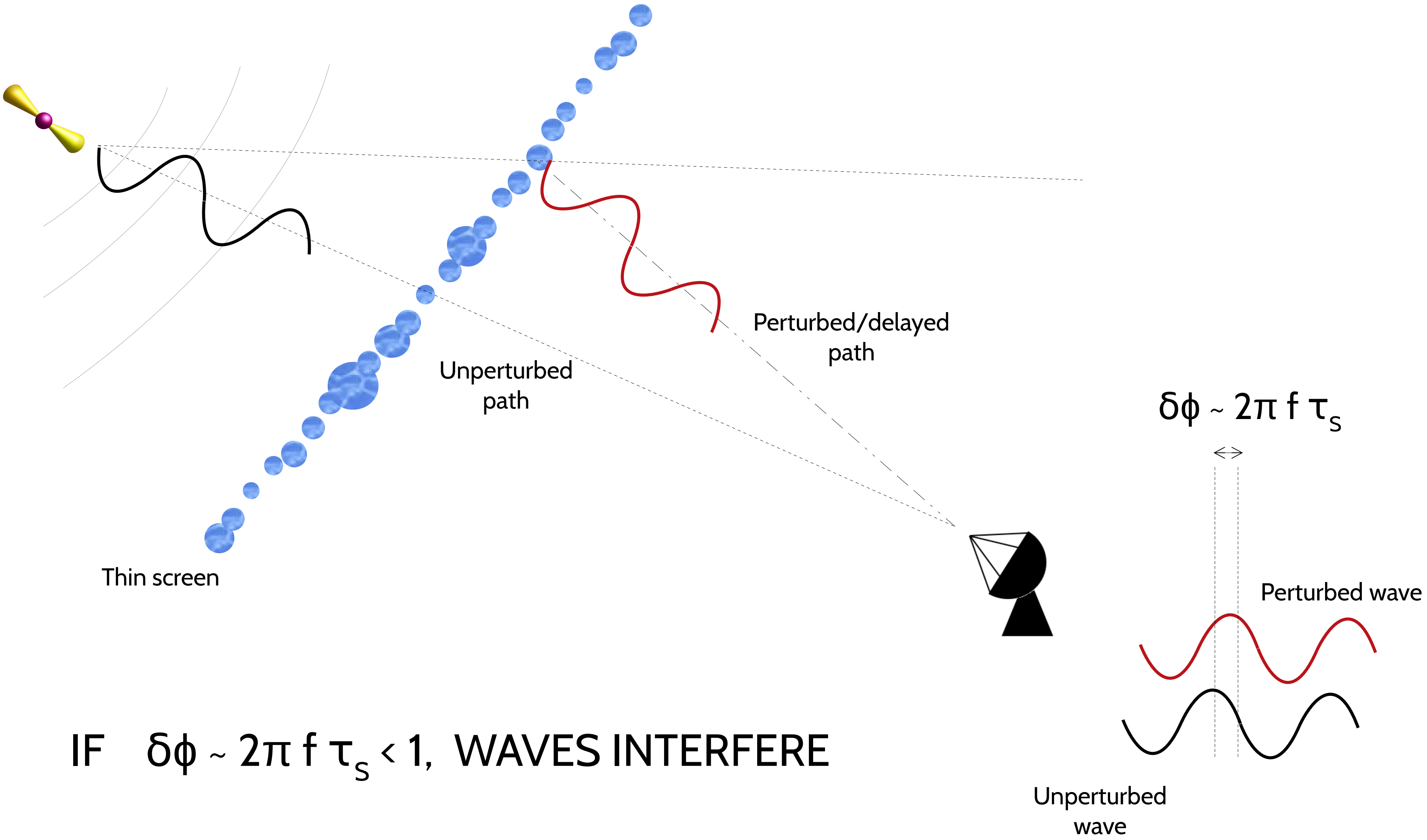
Thin screen

$$\delta\phi \sim 2\pi f \tau_s$$

Perturbed wave

Unperturbed wave

Scintillation



Perturbed/delayed path

Unperturbed path

Thin screen

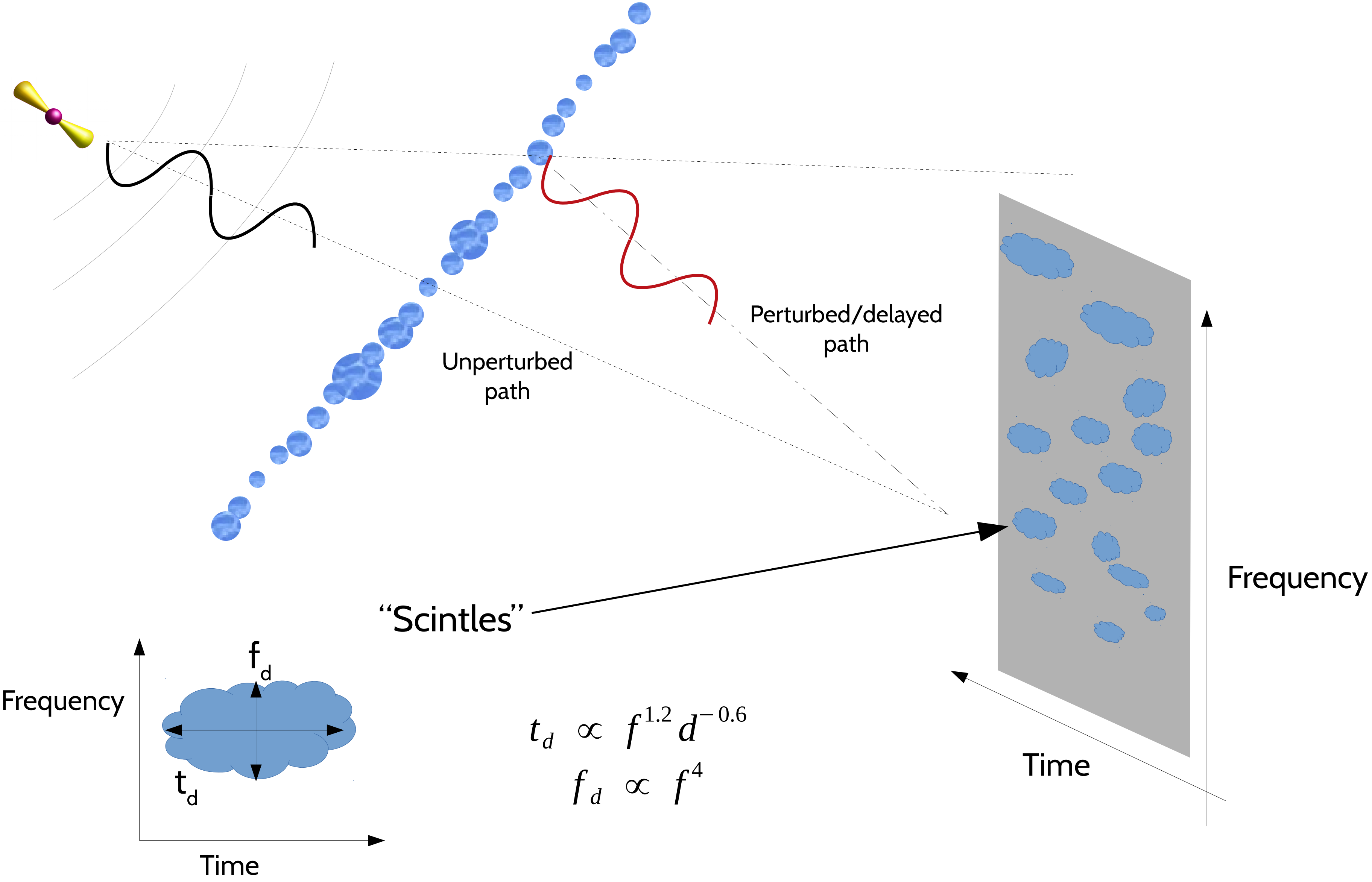
$\delta\phi \sim 2\pi f \tau_s$

Perturbed wave

Unperturbed wave

IF $\delta\phi \sim 2\pi f \tau_s < 1$, WAVES INTERFERE

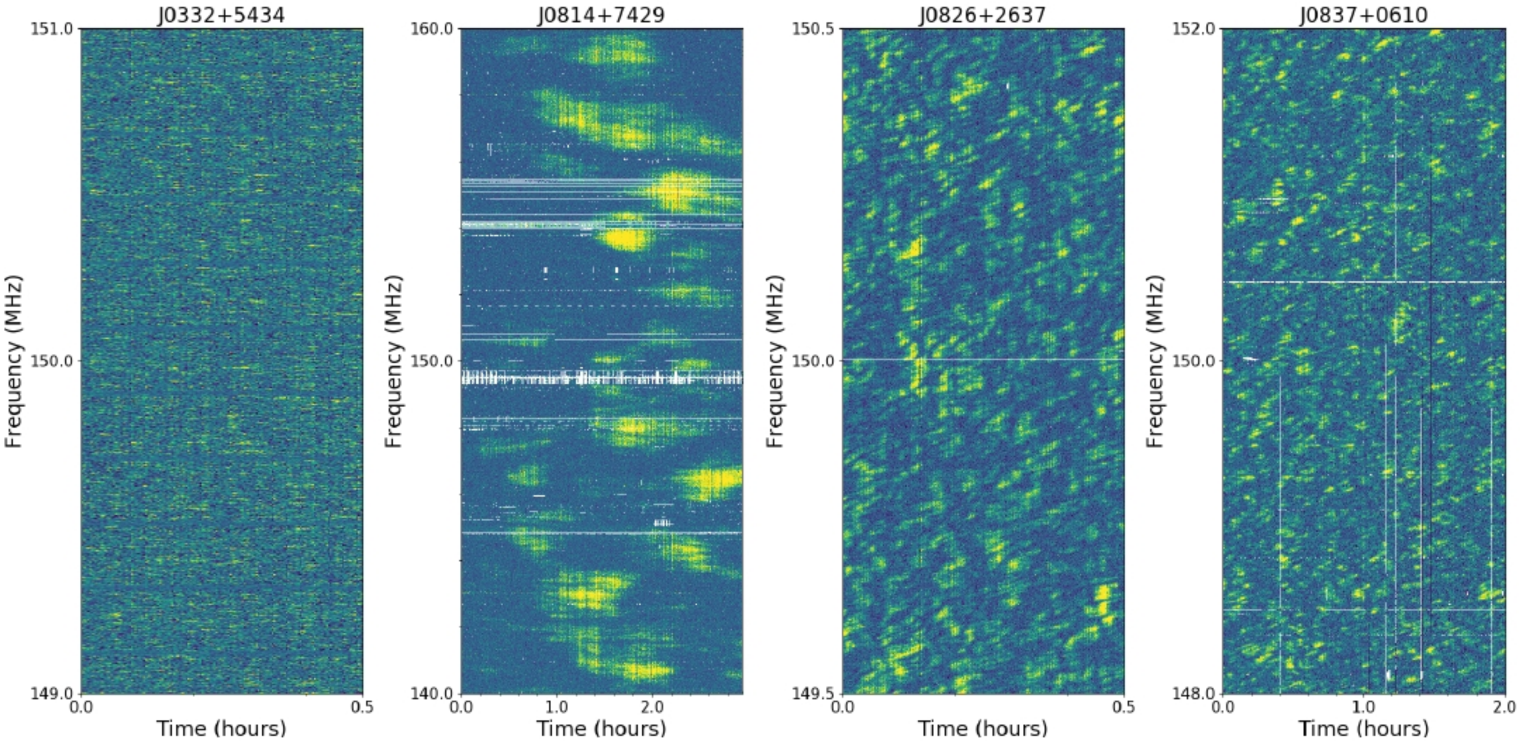
Scintillation

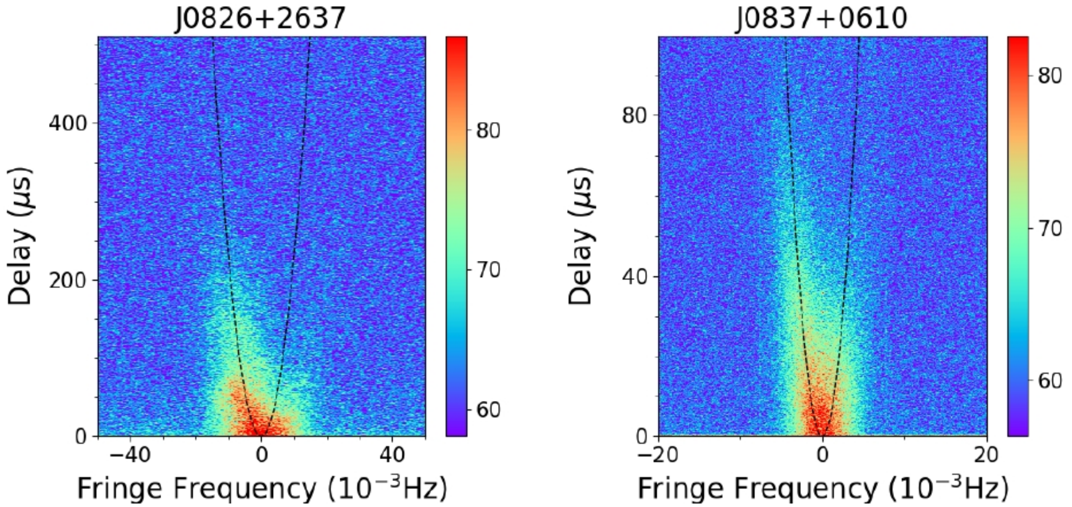


$$t_d \propto f^{1.2} d^{-0.6}$$

$$f_d \propto f^{4}$$

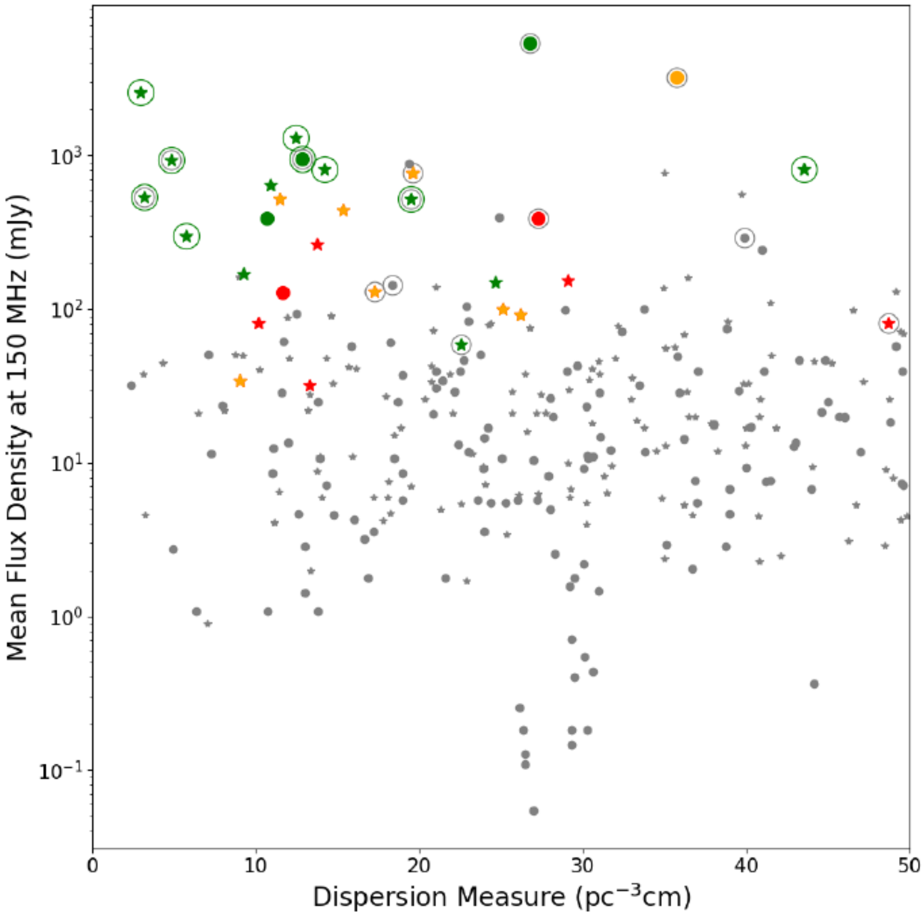
Scintillation





Wu+2022

Scintillation



- ★ Published flux at 150 MHz
- 🟩 Scintillation detected with LOFAR
- 🟥 Scintillation non detected with LOFAR
- 🟧 Scintillation detected but not resolved with LOFAR
- ○ Scintillation arcs detected in literature
- ○ Scintillation arcs detected with LOFAR

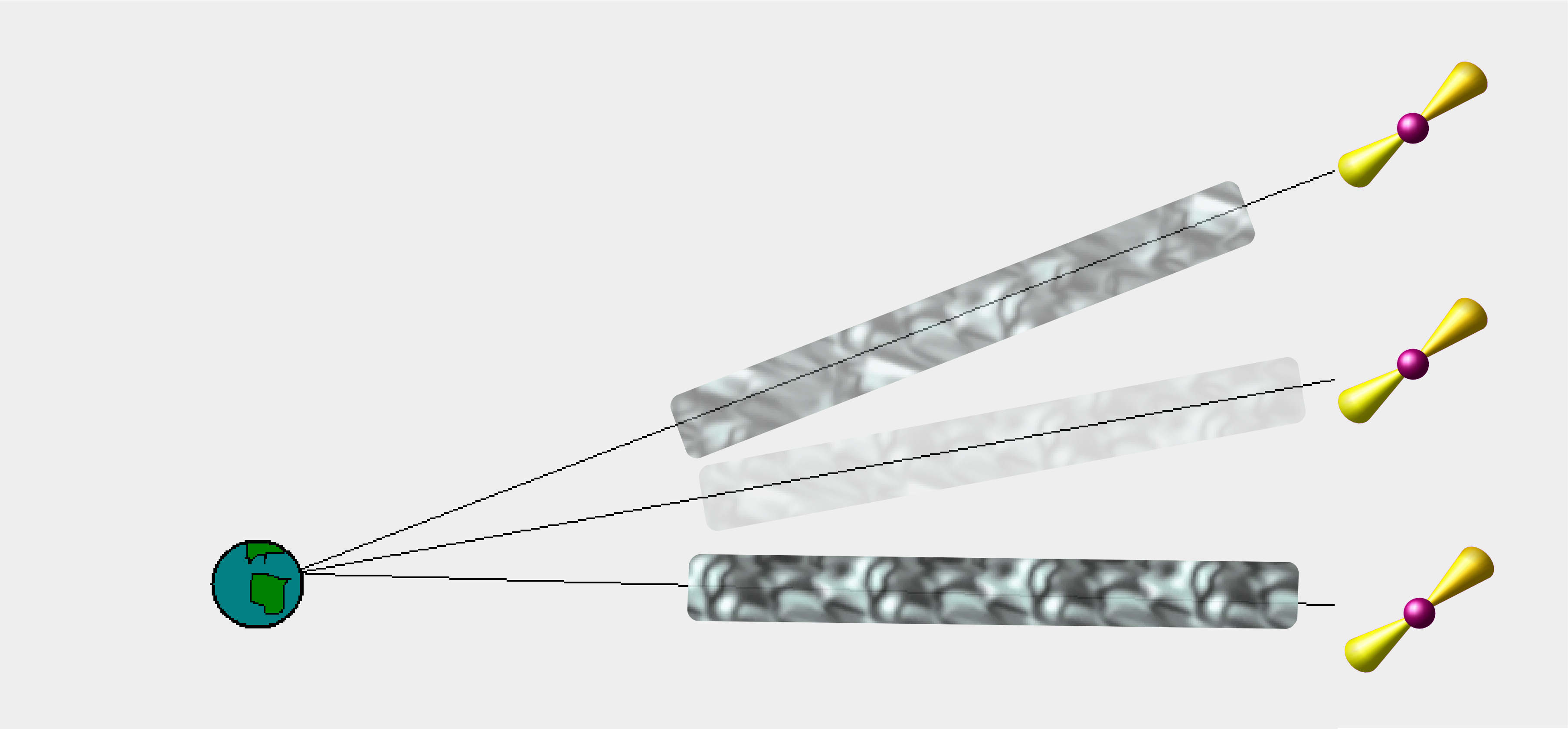
Wu+2022

DM and RM variations

DM and RM variations

$$\left.\begin{array}{l} DM = \int_0^d n_e \, dl \\ \\ RM \propto \int_0^d B\|n_e \, dl \end{array}\right\} \langle B\|\rangle \propto RM/DM$$

DM and RM variations

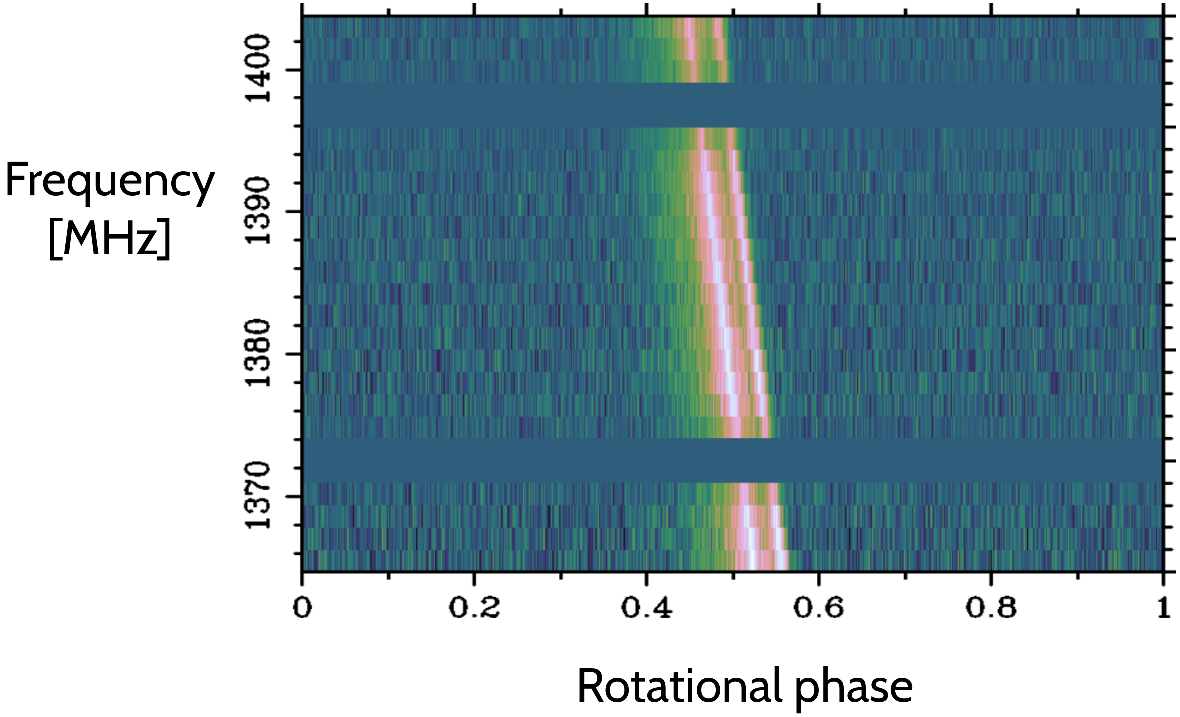


1) DM and RM values change in time

2) *ANY* magnetoionic medium can induce DM and RM (ISM, Solar wind, ionosphere)

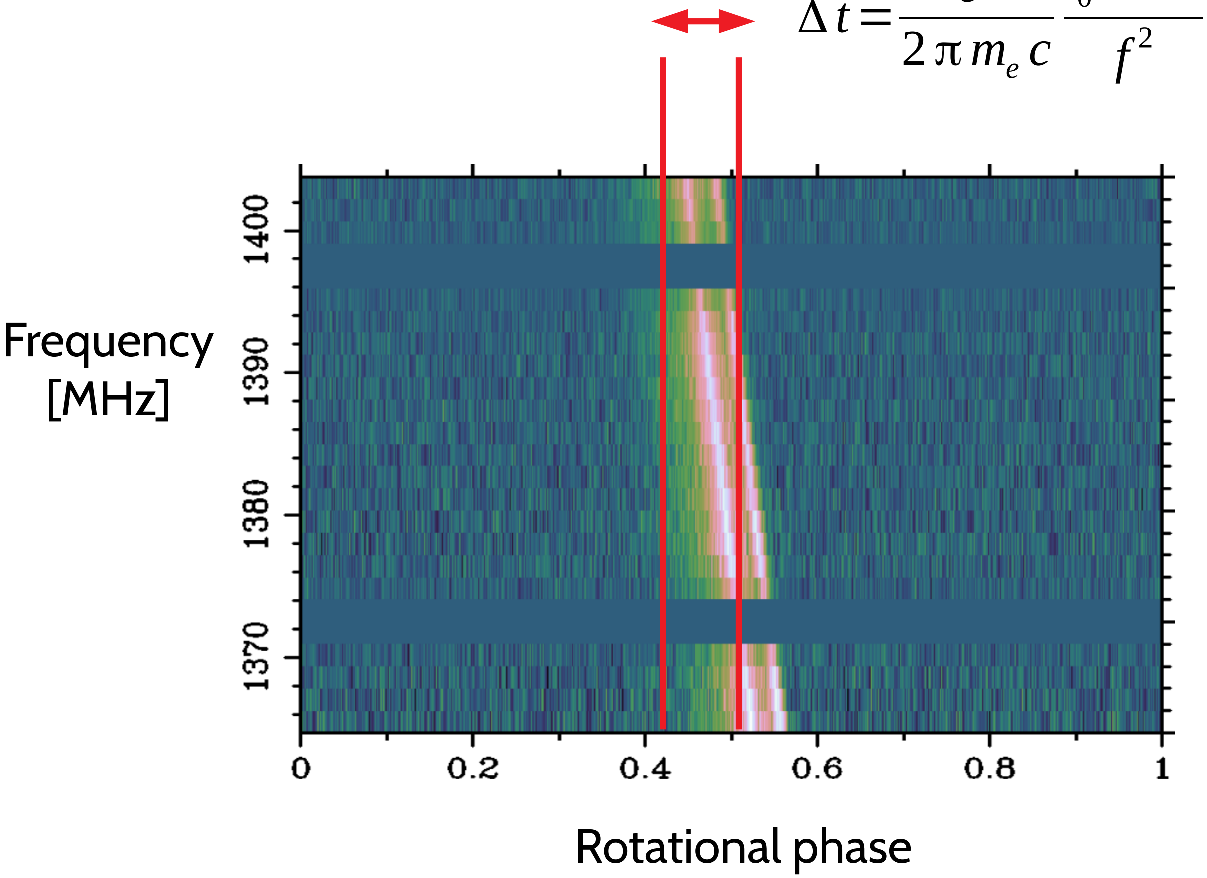
DM variations

DM variations



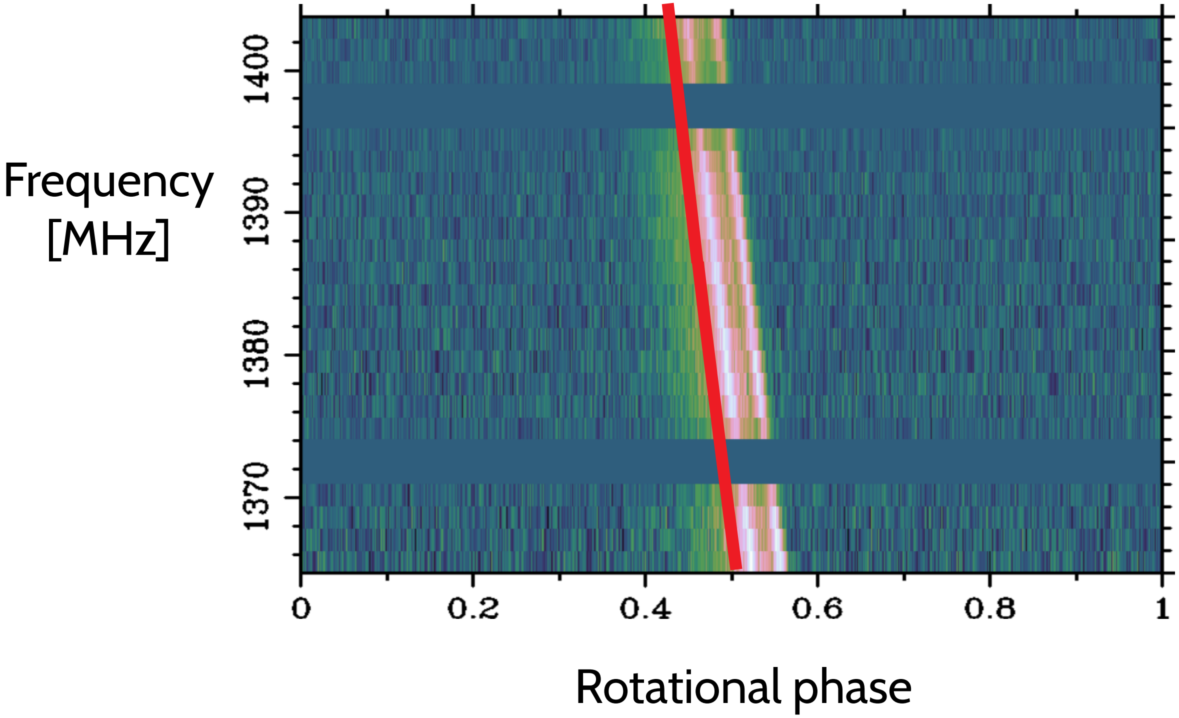
DM variations

$$\Delta t = \frac{e^2}{2\pi m_e c}\,\frac{\int_0^d n_e\,dl}{f^2} \propto \frac{DM}{f^2}$$



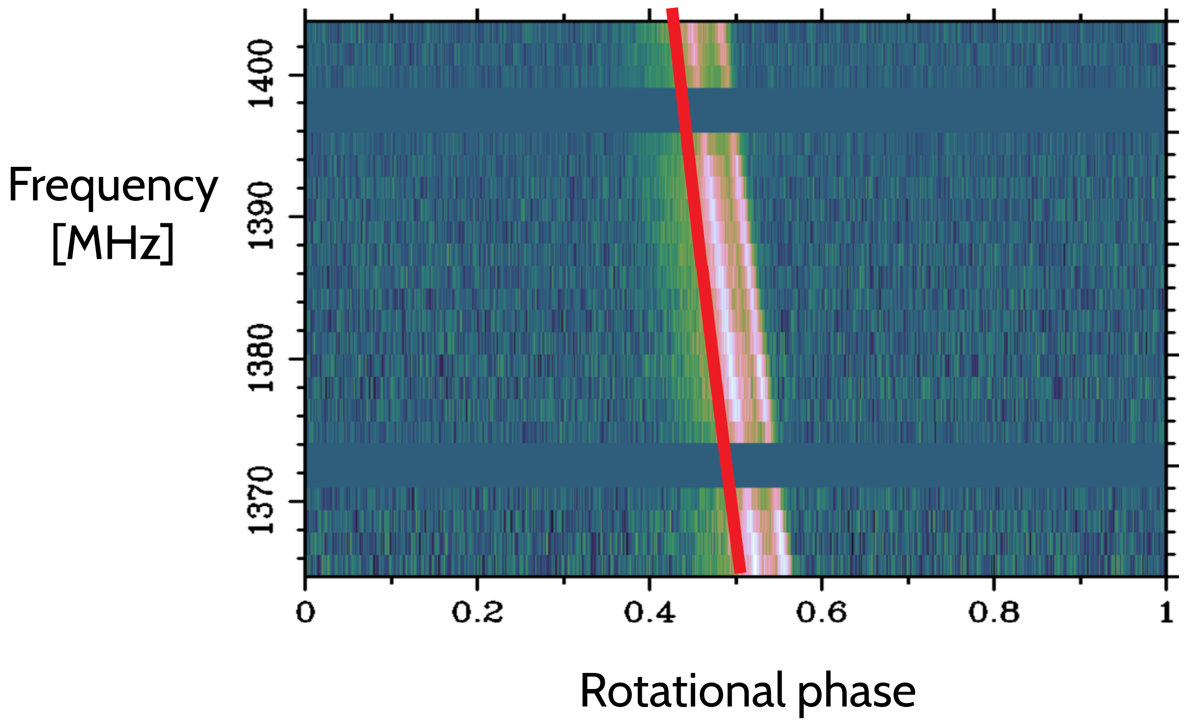
DM variations

$$\Delta t = const \frac{x}{f^2}$$

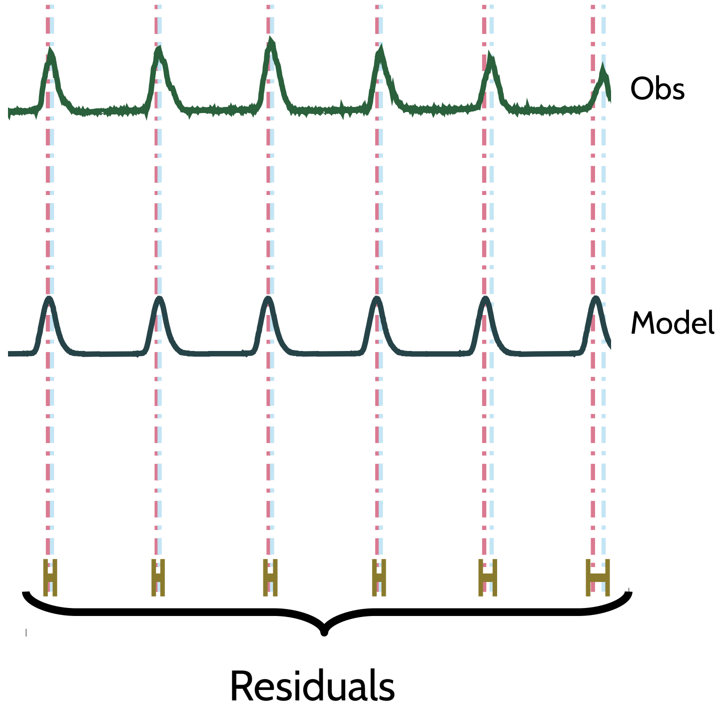


DM variations

$$\Delta t = const \frac{x}{f^2}$$

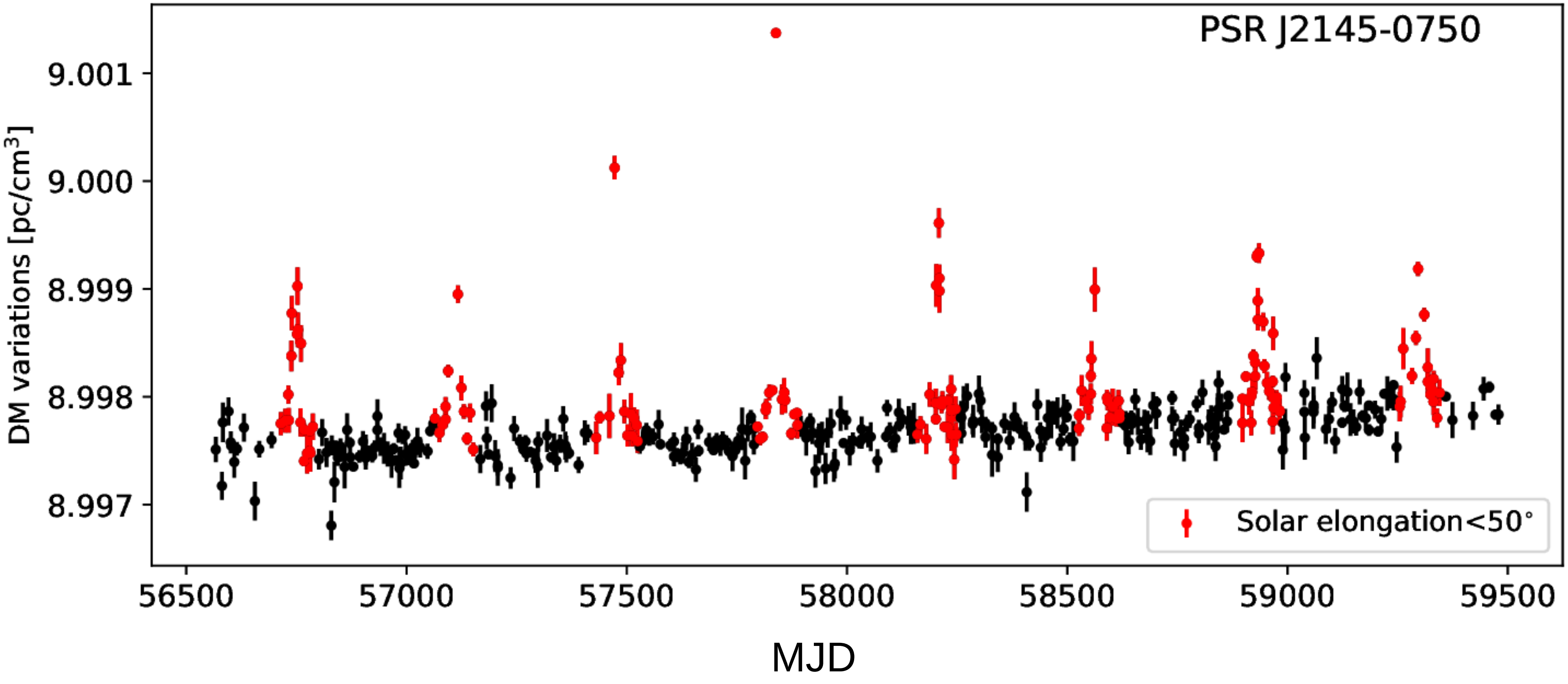


Pulsar timing technique

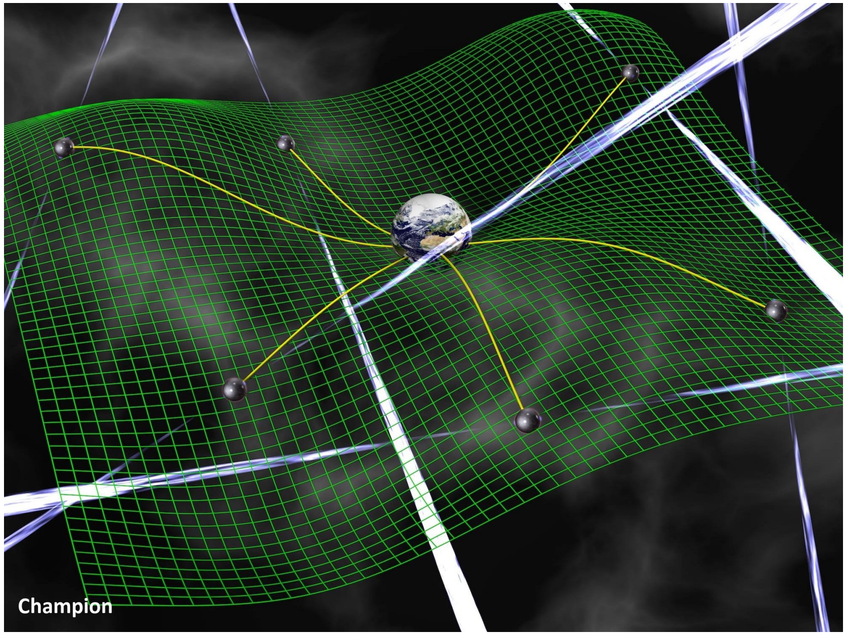


Credits: Shaifullah

DM variations



DM 'noise' and the search for gravitational waves



Pulsar Timing Array experiments search for low-frequency gravitational waves by monitoring unmodelled fluctuations in the arrival times of pulsar emission on Earth.

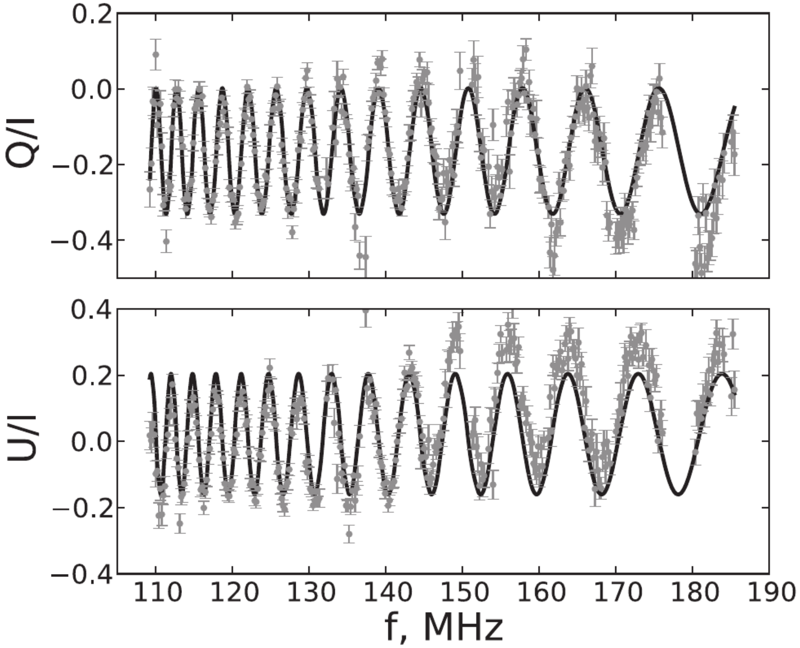
DM variations also induce analogous fluctuations, and they **become a source of 'noise' for GW searches**.

EPTA

In the **European PTA**, we are using LOFAR data to provide an exceptionally precise DM monitoring and neutralise dispersion noise

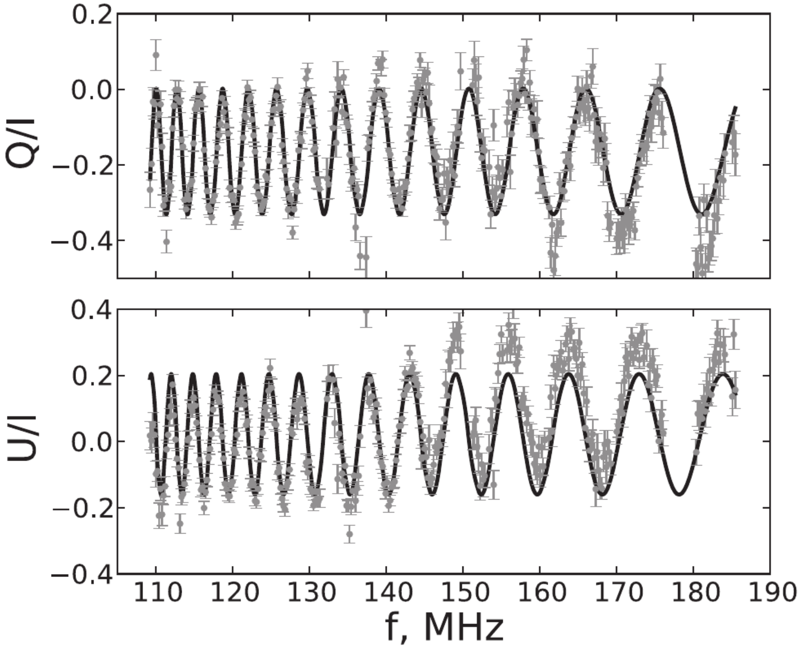
RM variations

RM variations



Credits: Porayko

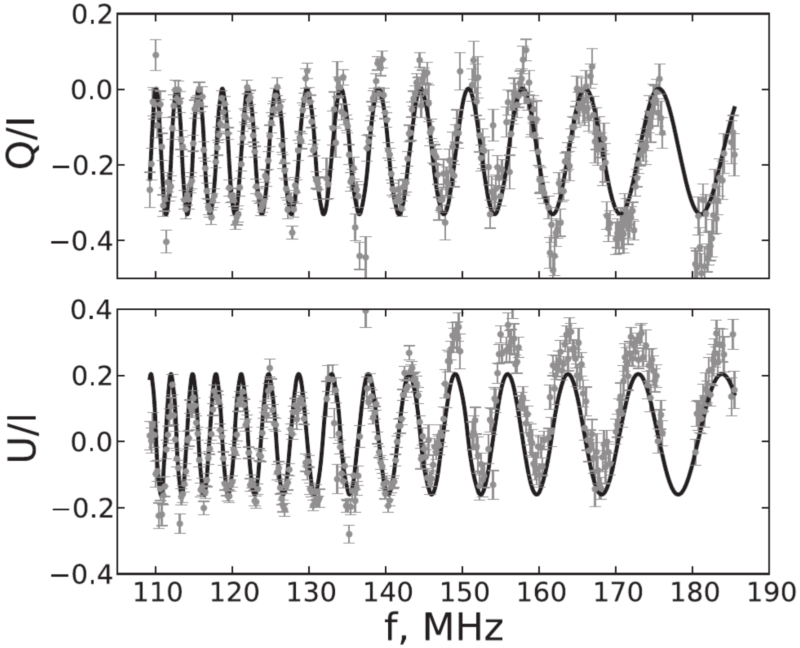
RM variations



$$\left.\begin{aligned} Q &\propto \cos\left(2\,RMc^2/f^2+\psi_0\right)\\ U &\propto \sin\left(2\,RMc^2/f^2+\psi_0\right)\end{aligned}\right\}\quad P = Q + iU$$

Credits: Porayko

RM variations



$$\left.\begin{array}{l} Q \propto \cos\left(2\,RMc^2/f^2+\psi_0\right) \\ U \propto \sin\left(2\,RMc^2/f^2+\psi_0\right) \end{array}\right\}$$ P = Q + iU

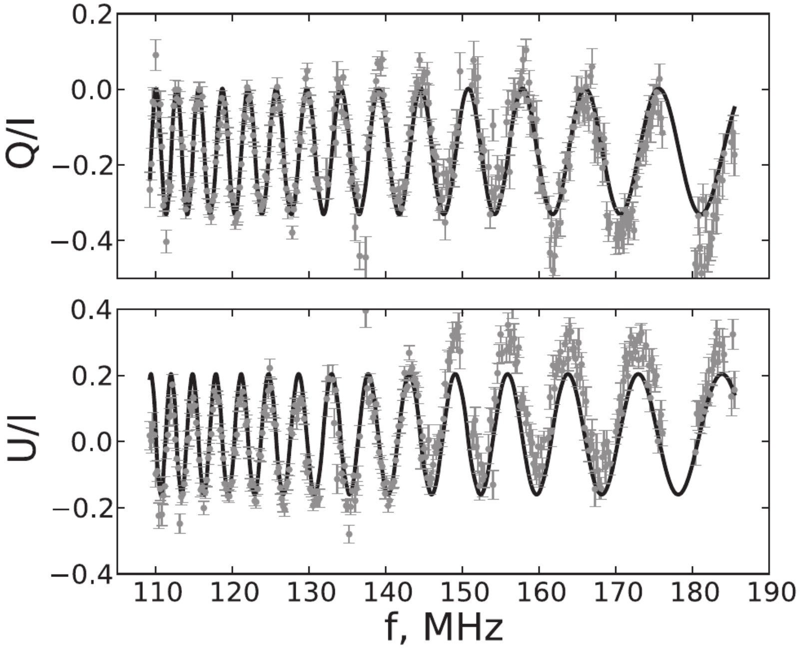
FT(cos(2πk$_0$x)) ∝ [δ(k + k$_0$) + δ(k − k$_0$)] 2 solutions

FT(sin(2πk$_0$x)) ∝ i[δ(k + k$_0$) - δ(k − k$_0$)] 2 solutions

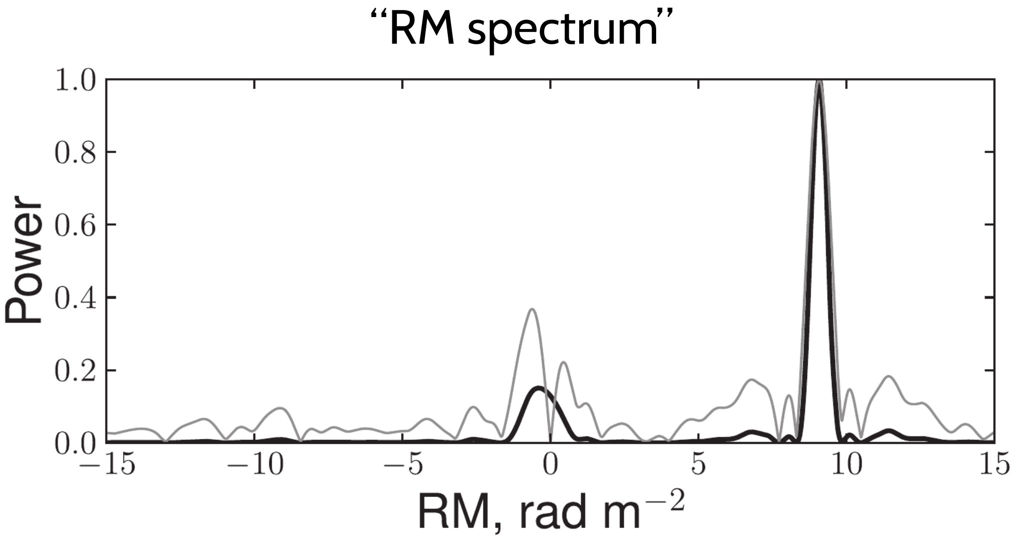
FT(cos(2πk$_0$x) + i sin(2πk$_0$x)) ∝ δ(k − k$_0$) 1 solution!

Credits: Porayko

RM variations

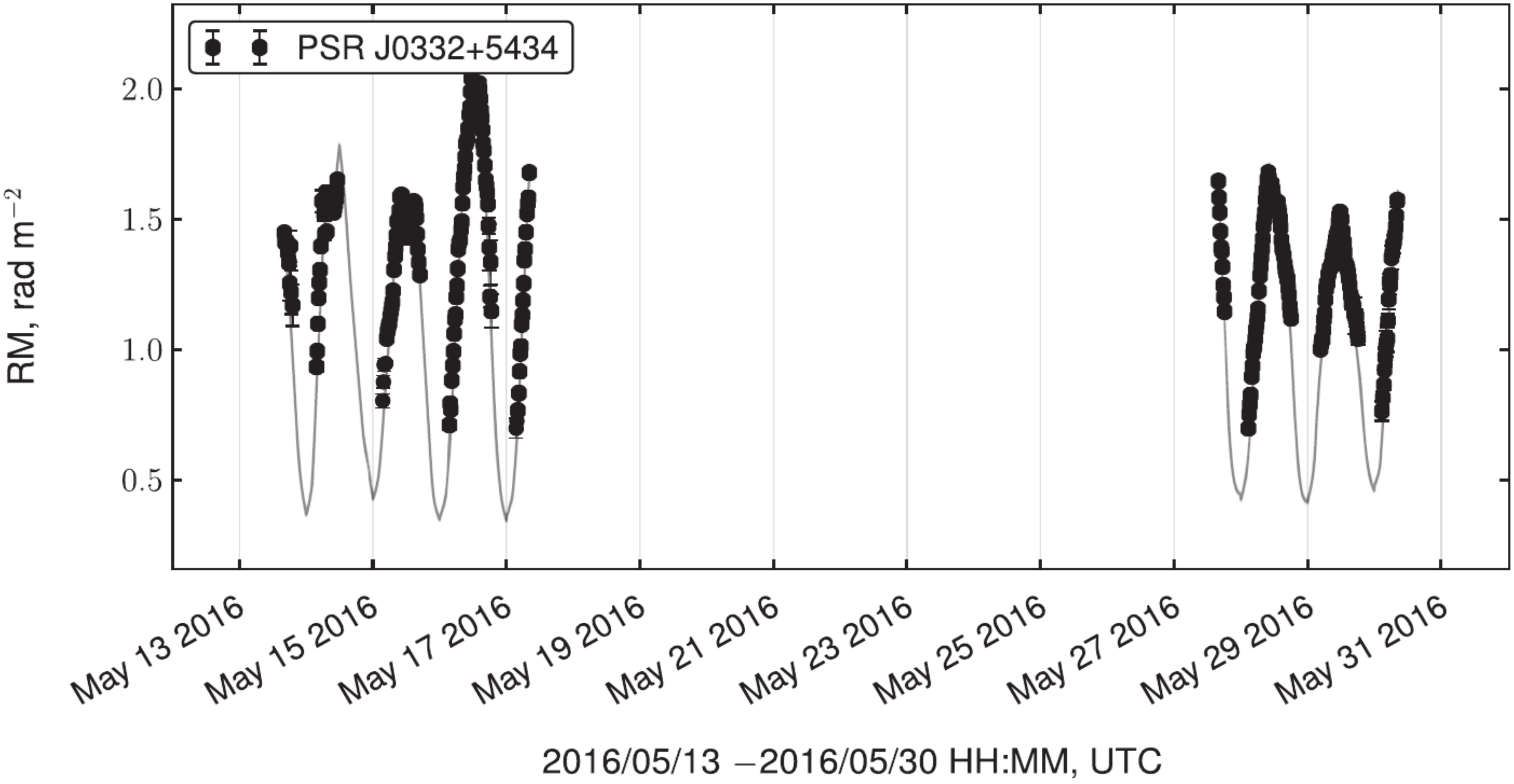


FT(P)


“RM spectrum”

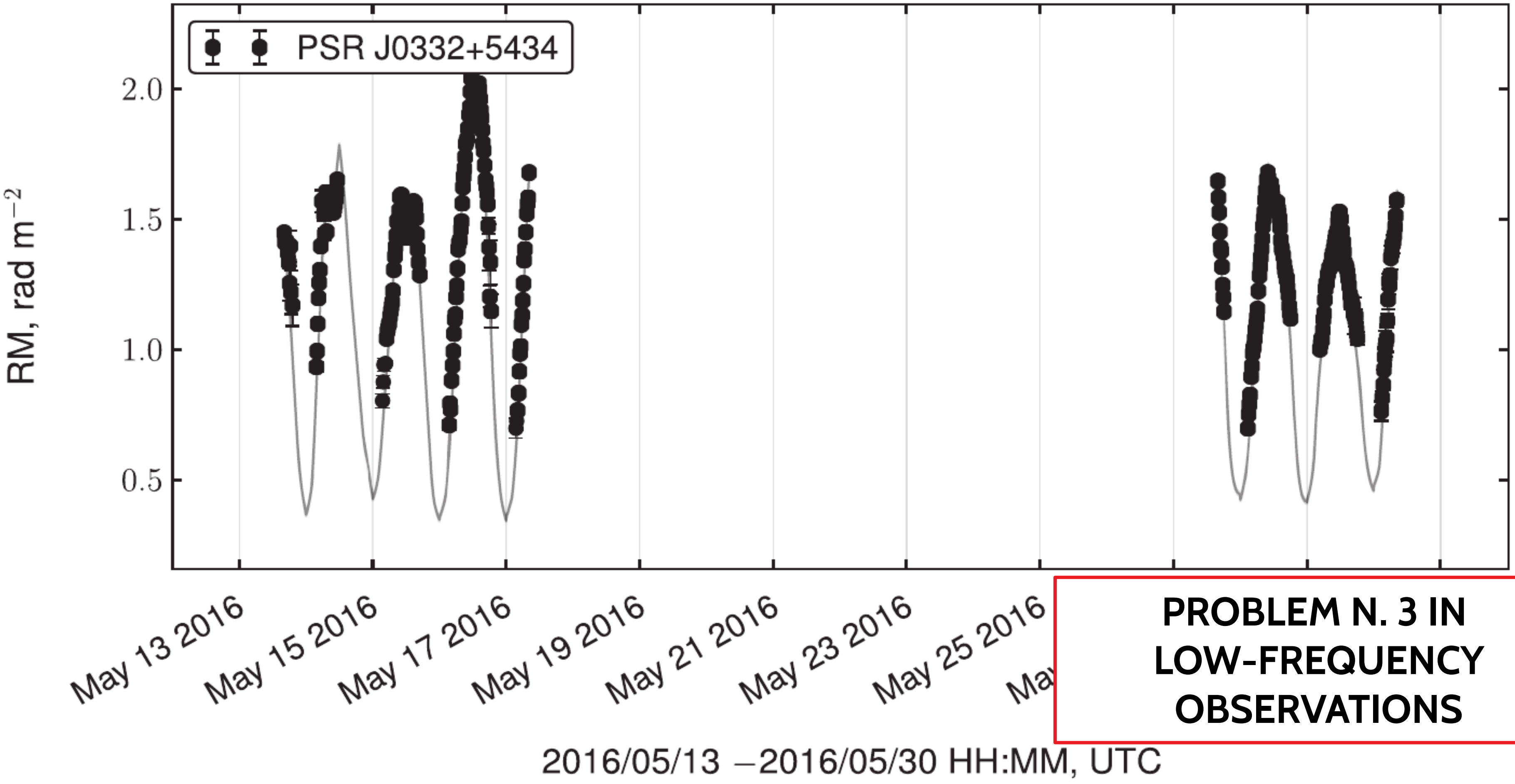
Credits: Porayko

RM variations



Credits: Porayko

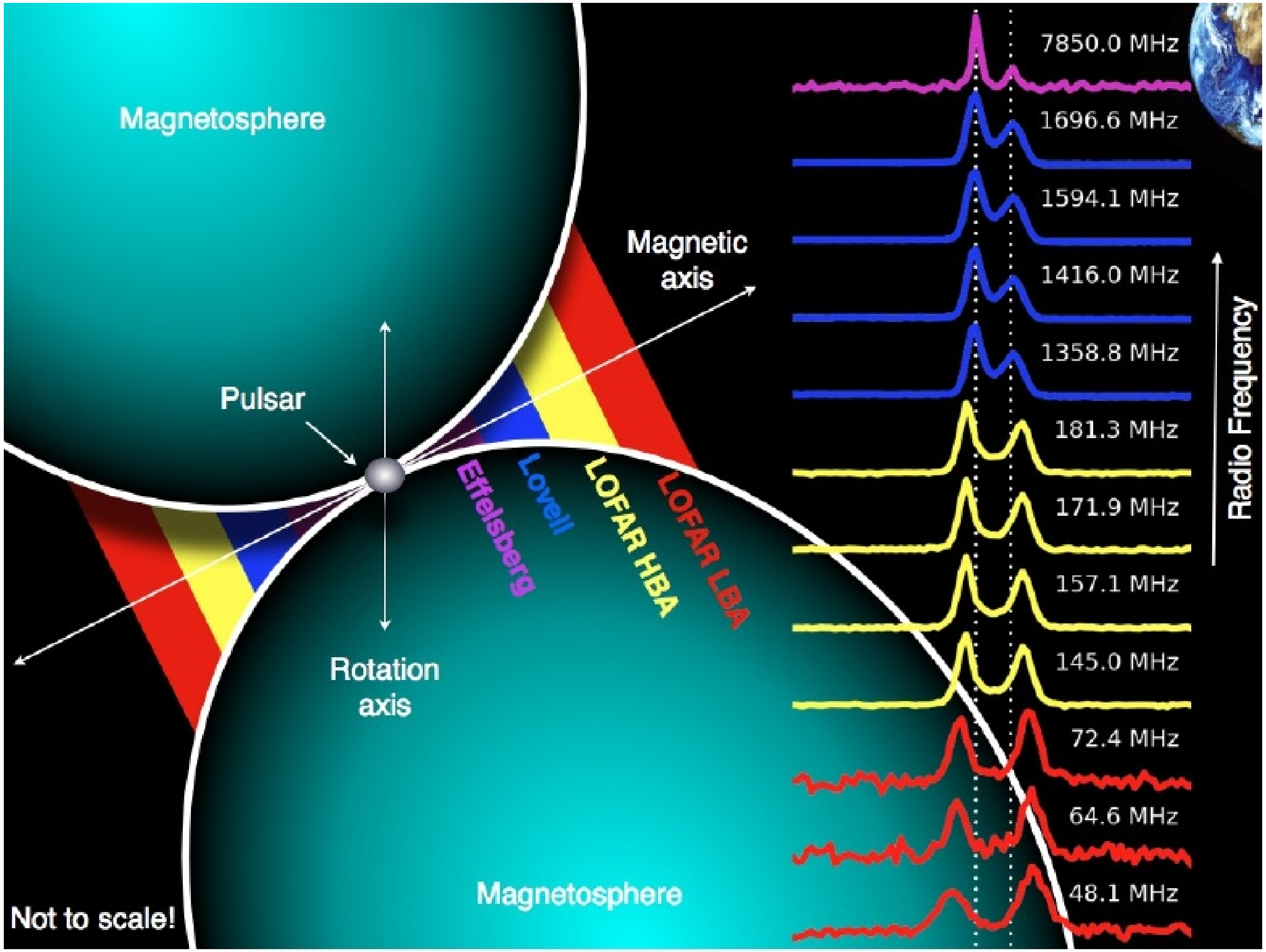
RM variations



PROBLEM N. 3 IN LOW-FREQUENCY OBSERVATIONS

Credits: Porayko

Radius-to-frequency mapping

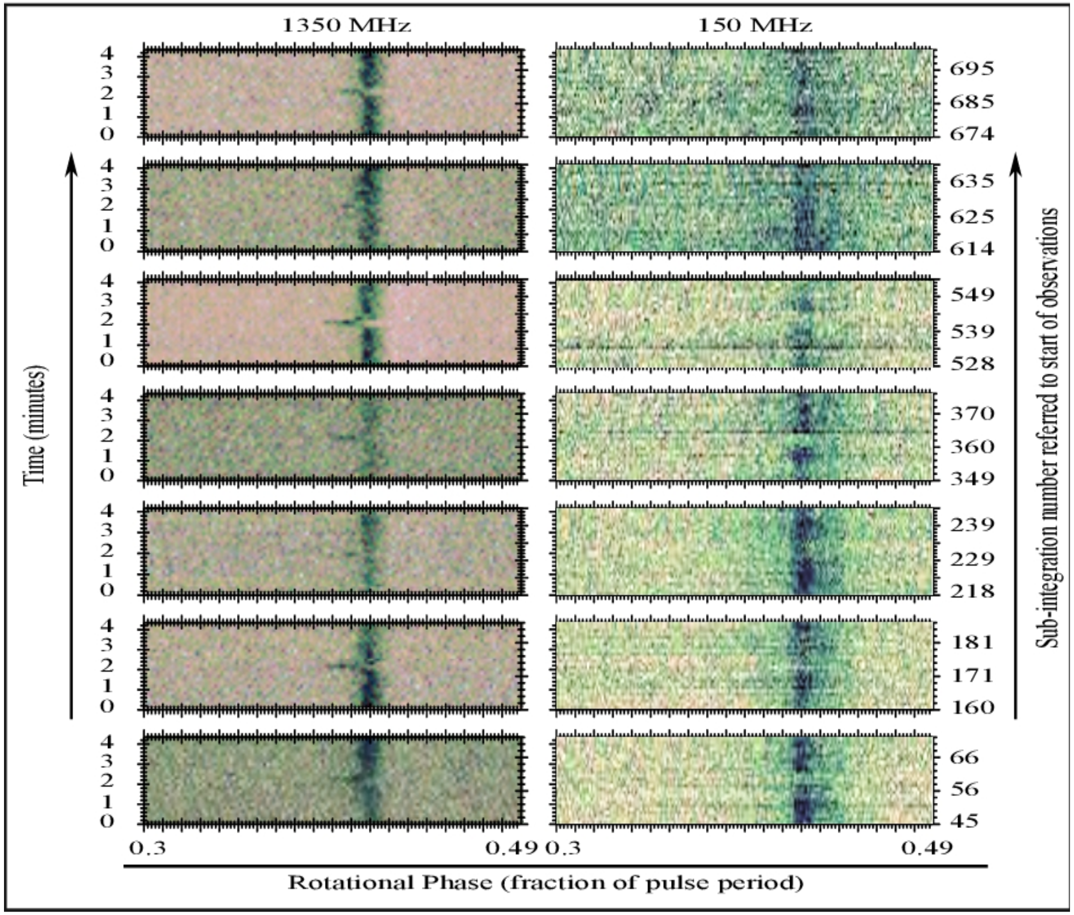


Credits: Hassall

“Swooshing pulsar” doesn’t swoosh for us

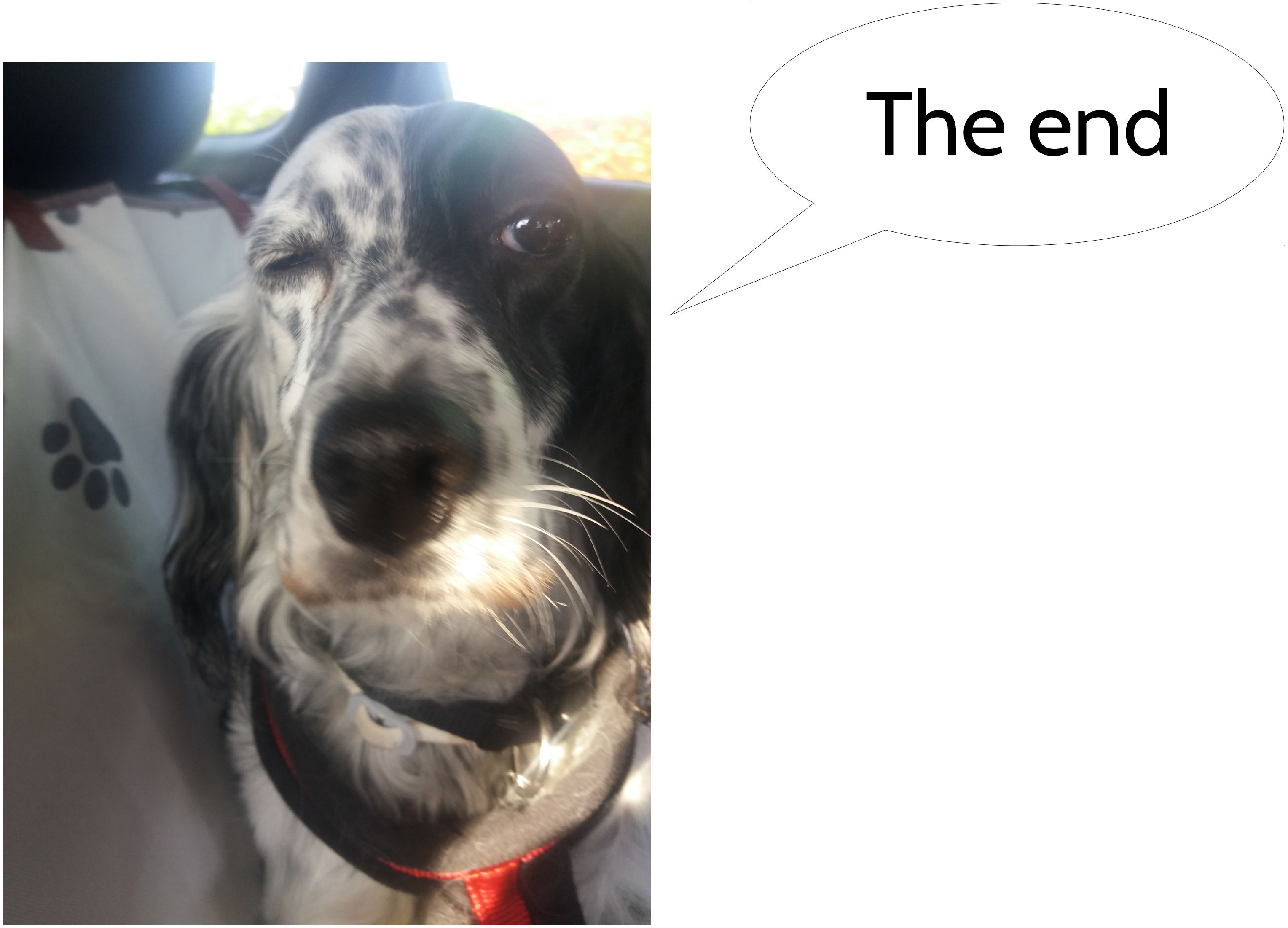
PSR J0922+0638

Effelsberg,
L-Band

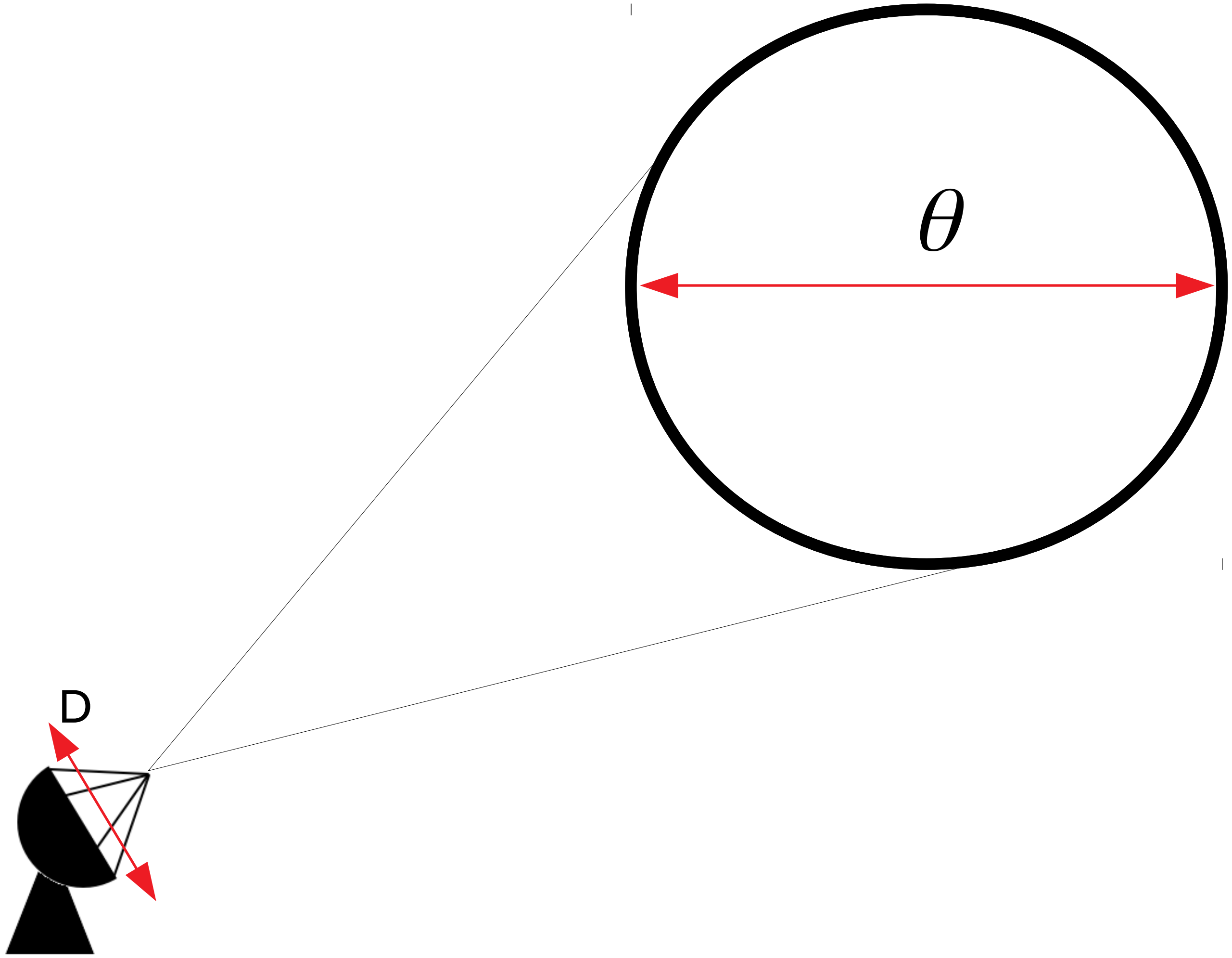


LOFAR

Shaifullah+2018

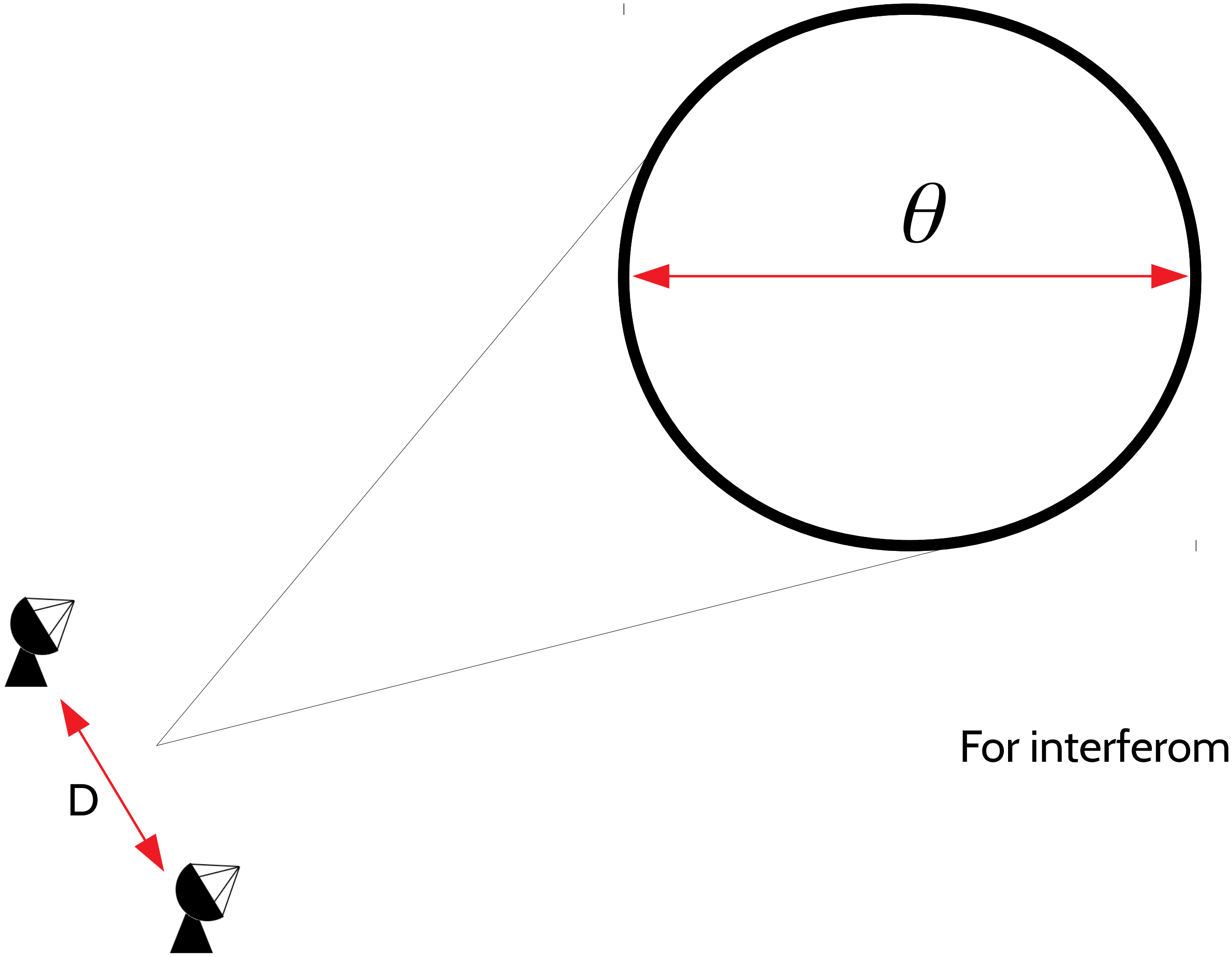

The end

Are low frequencies more optimal for pulsar astronomy?



$$\theta \propto 1/(fD)$$

Are low frequencies more optimal for pulsar astronomy?



$$\theta \propto 1/(fD)$$

For interferometers, D is the maximum baseline