RADIO 2024

Erlangen Center for Astroparticle Physics

How scintillation reshapes small-scale ISM models

Tim Sprenger

14.11.2024

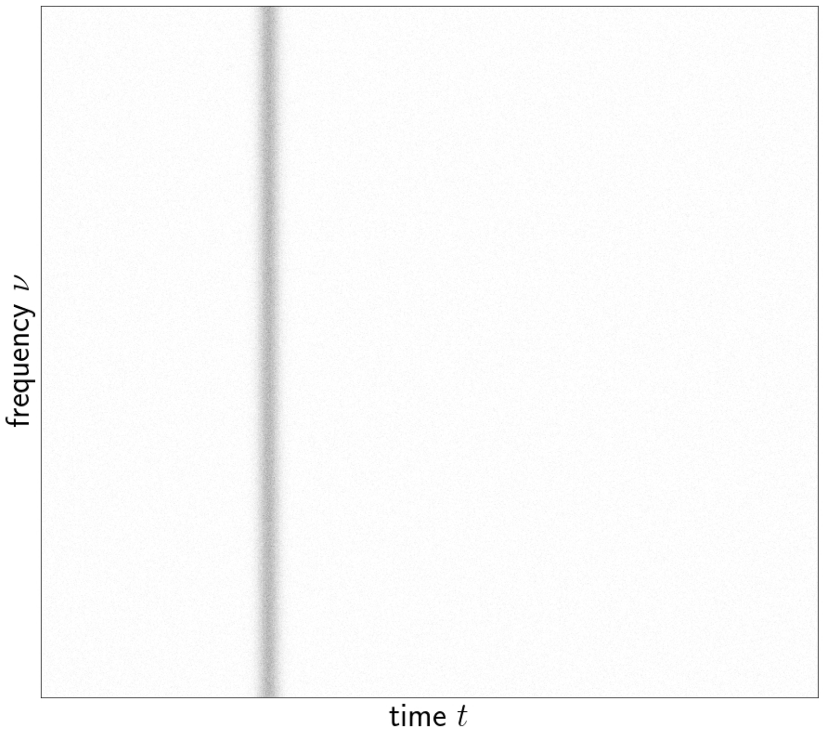
Max-Planck-Institut für Radioastronomie

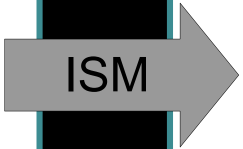
Michael Kramer

Olaf Wucknitz
Robert Main
Sachin Pradeep

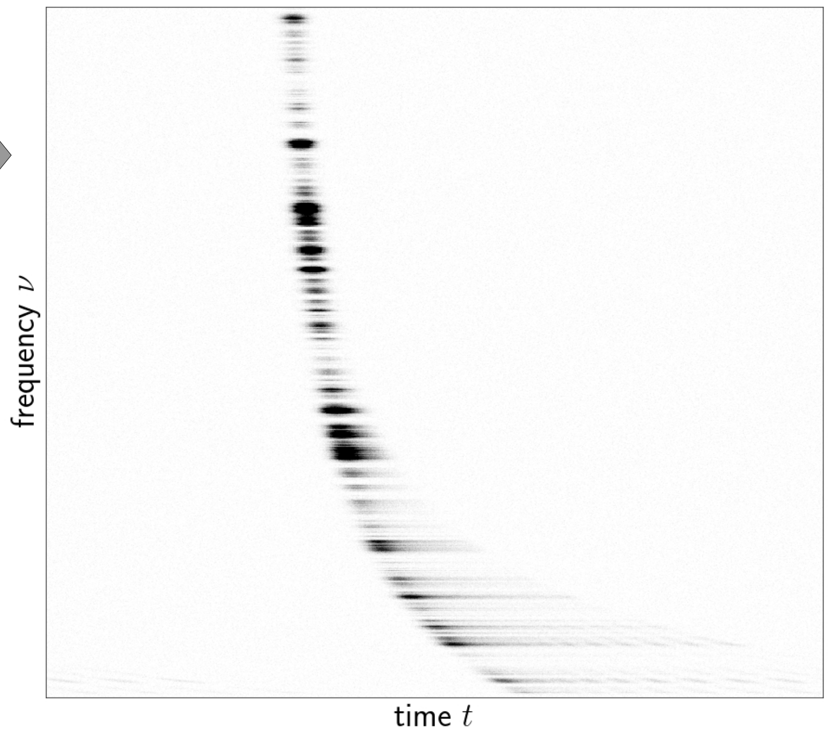
What is scintillation?

Vacuum



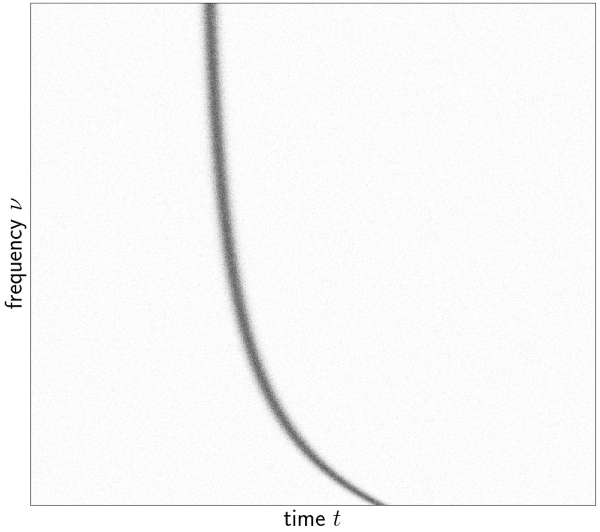


Interstellar Medium

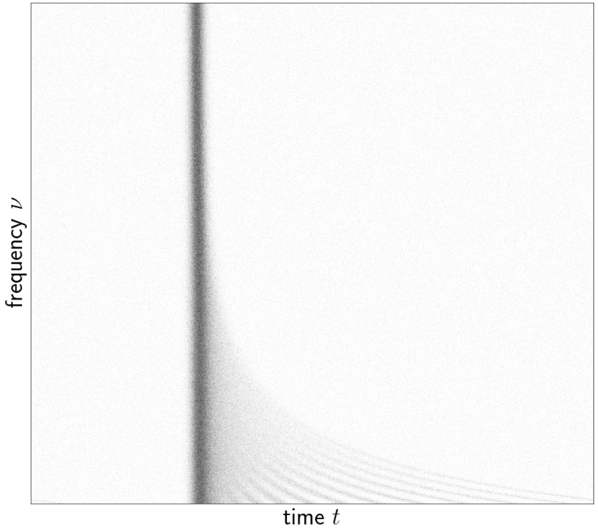


Interstellar Medium (ISM) Effects

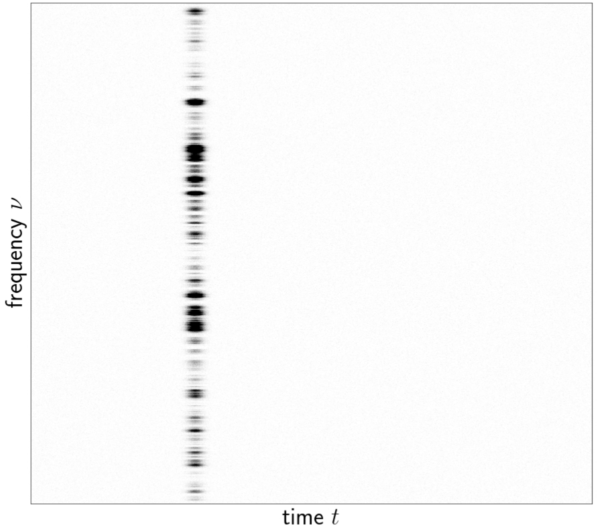
Dispersion



Scattering



Scintillation

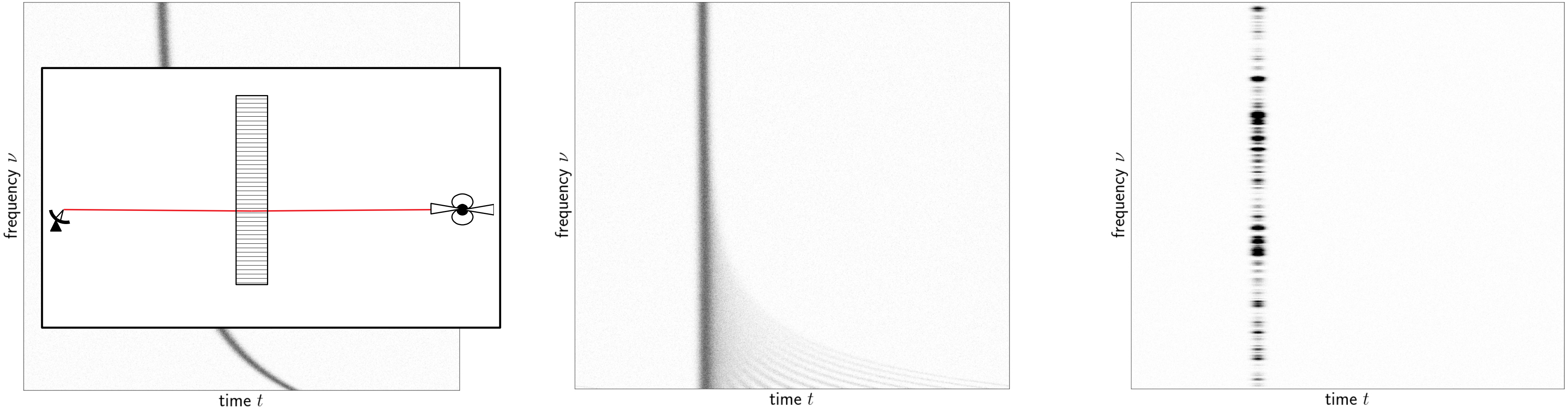


Interstellar Medium (ISM) Effects

Dispersion

Scattering

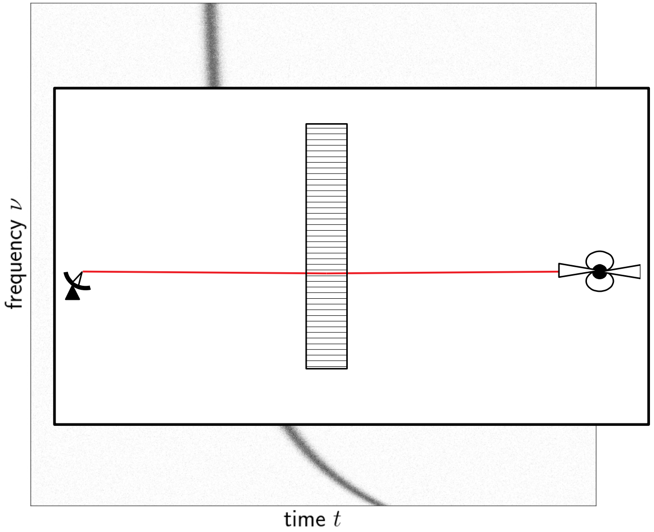
Scintillation



Column density
of electrons

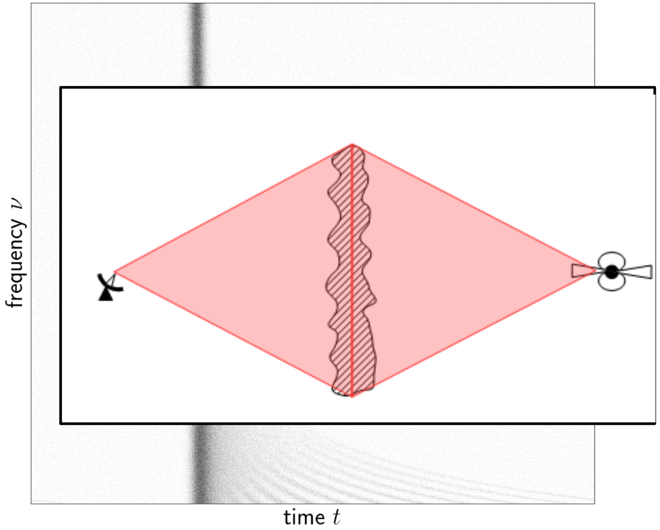
Interstellar Medium (ISM) Effects

Dispersion



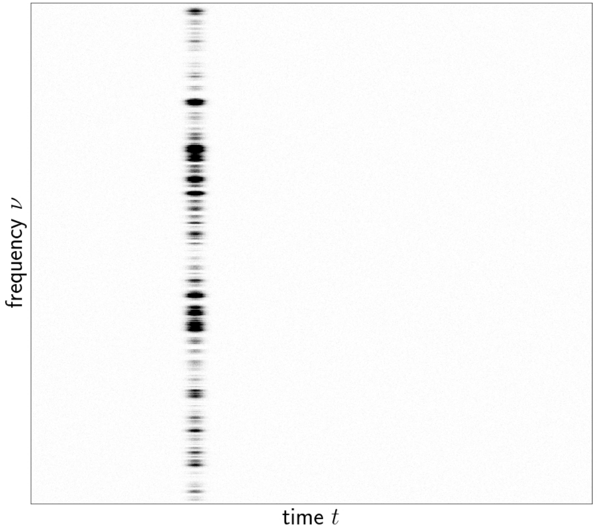
Column density
of electrons

Scattering



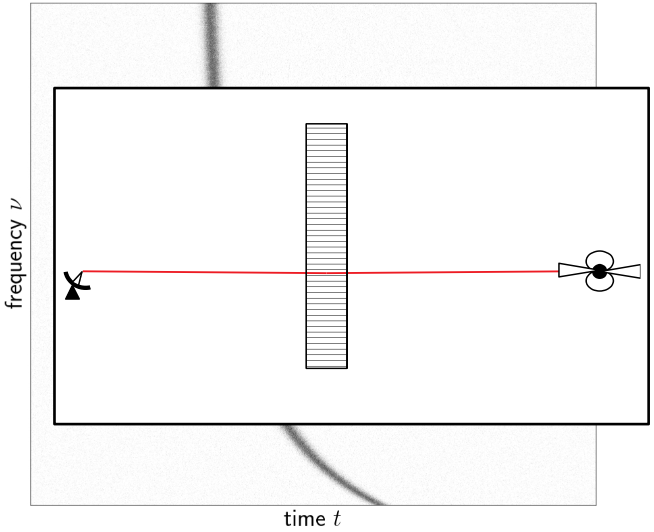
Multiple paths:
Different travel times

Scintillation



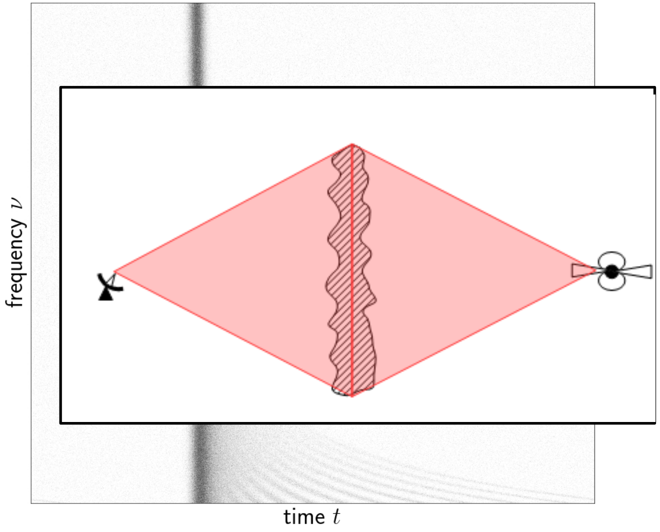
Interstellar Medium (ISM) Effects

Dispersion



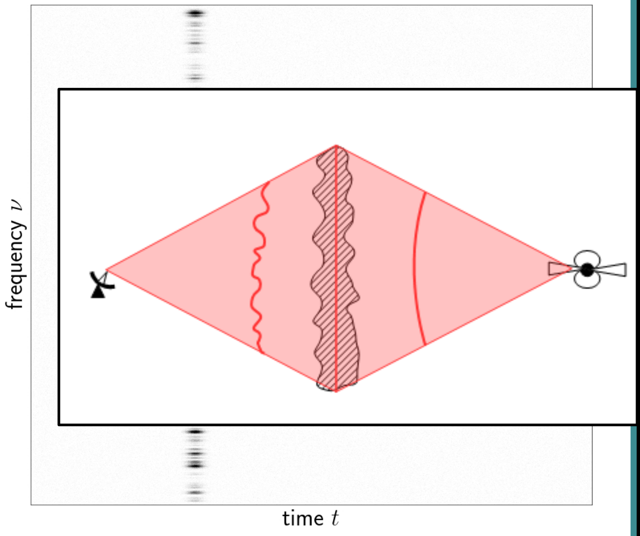
Column density
of electrons

Scattering



Multiple paths:
Different travel times

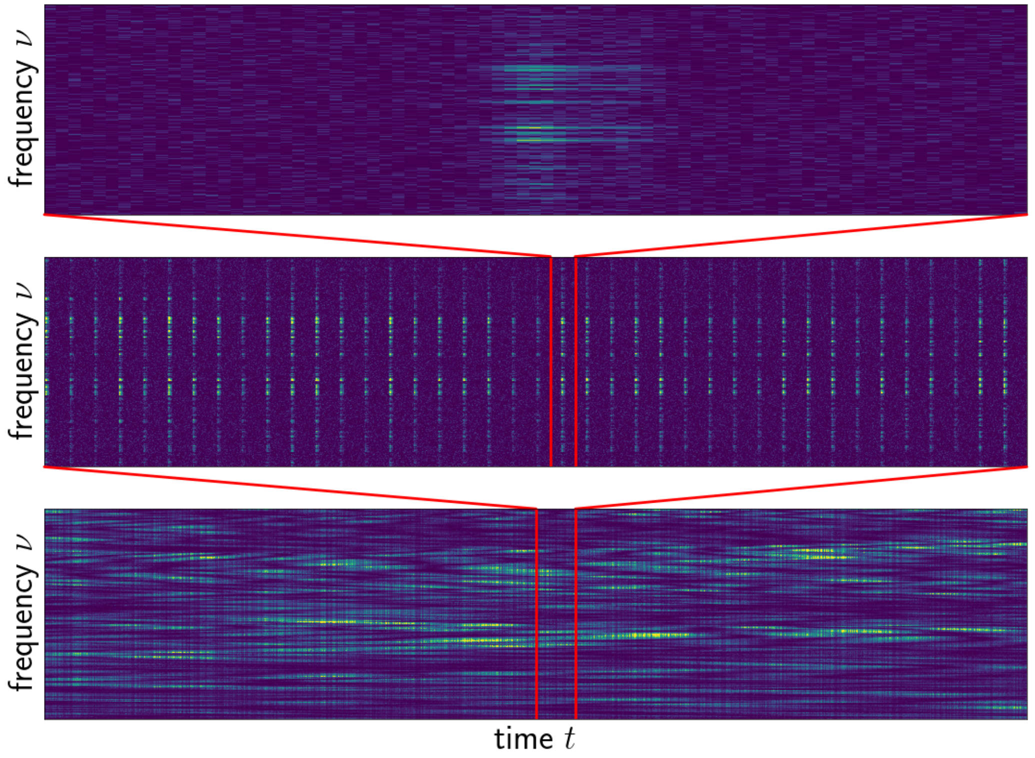
Scintillation



Multiple paths:
Interference

Dynamic spectrum

Creation of a dynamic spectrum



Discovery of pulsar scintillation

1967/68: Discovery of pulsars

using the

Interplanetary Scintillation Array

1968: Interpretation of scintillation as a propagation effect.

Amplitude Variations in Pulsed Radio Sources

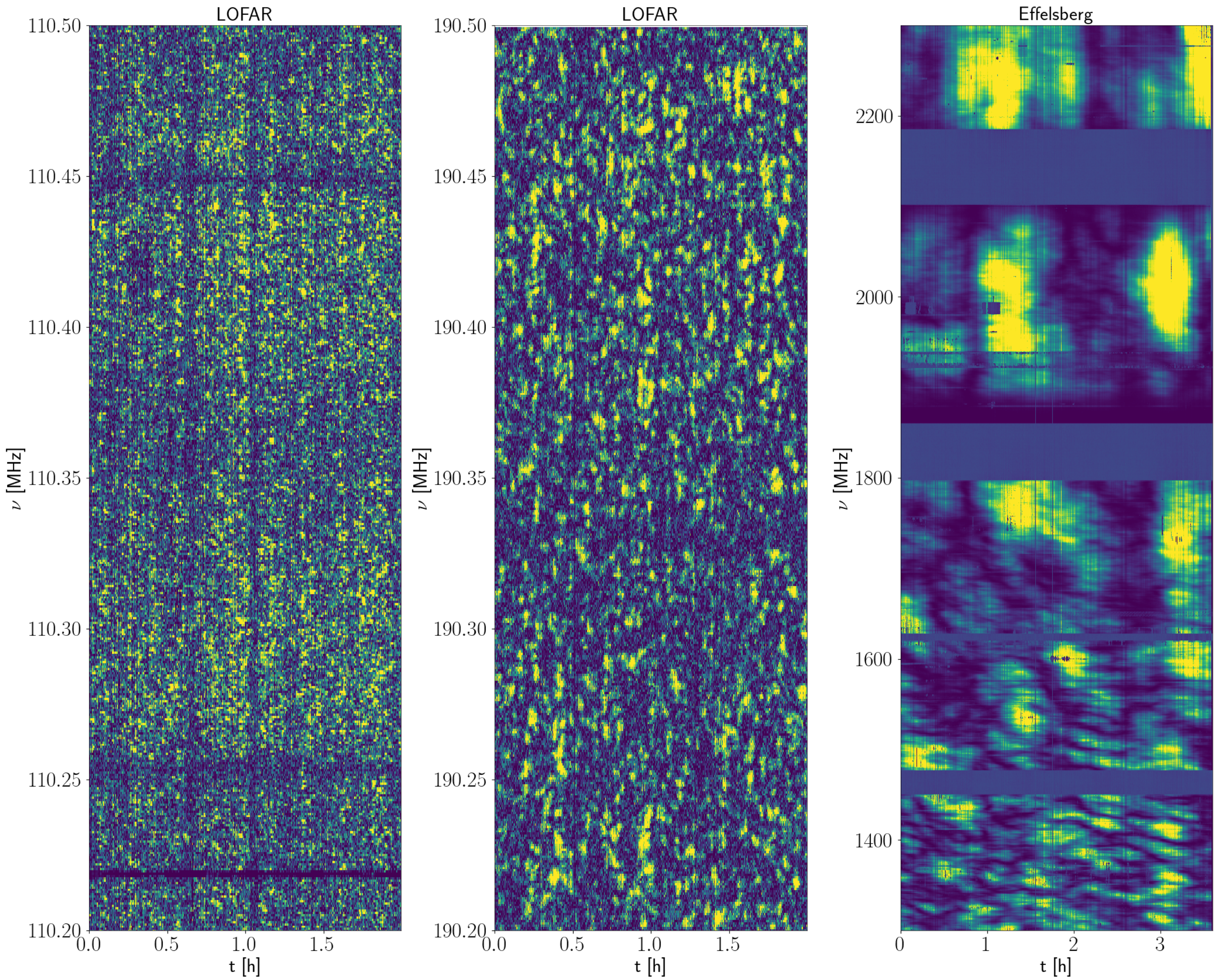
by

P. A. G. SCHEUER

Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Refraction by irregularities in the interstellar medium may cause the long period fluctuations in the amplitudes of radio signals from the pulsed sources.

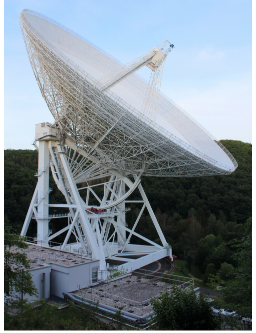
Scintles



Size of scintles grows with frequency.

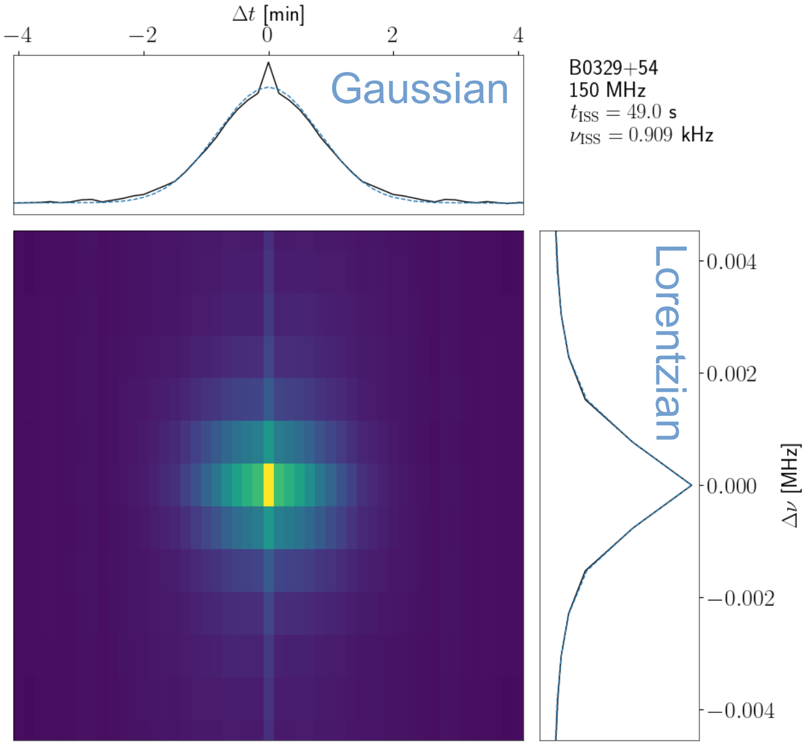
Stays characteristic for each pulsar for some time.

PSR B0329+54 observed at Effelsberg & LOFAR

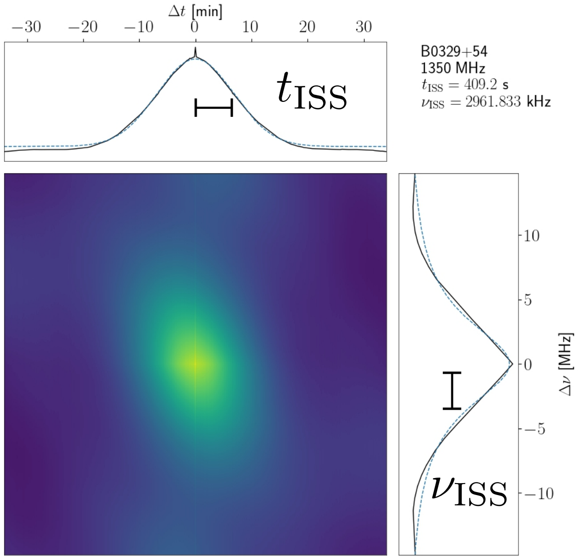


Autocorrelation Function (ACF)

150 MHz



1450 MHz



Scaling:

$\propto \nu^{\alpha}$

$\alpha \approx 4$

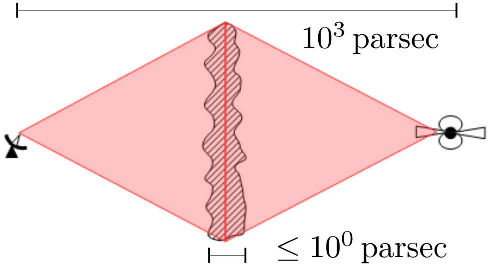
Scintillation time scale $t_{\rm ISS}$

Scintillation bandwidth $\nu_{\rm ISS}$

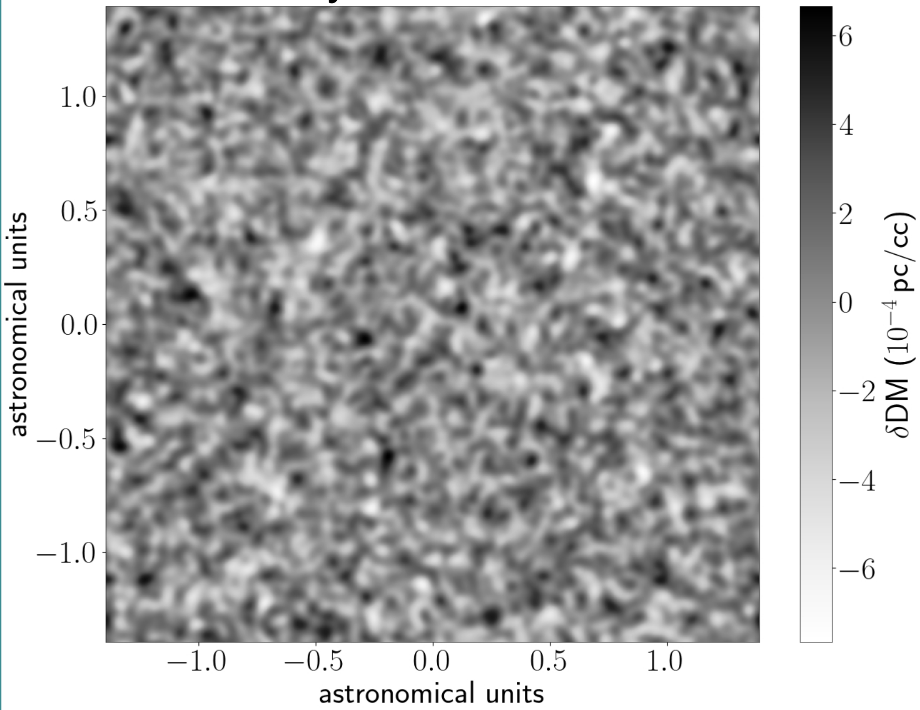
Kolmogorov turbulence

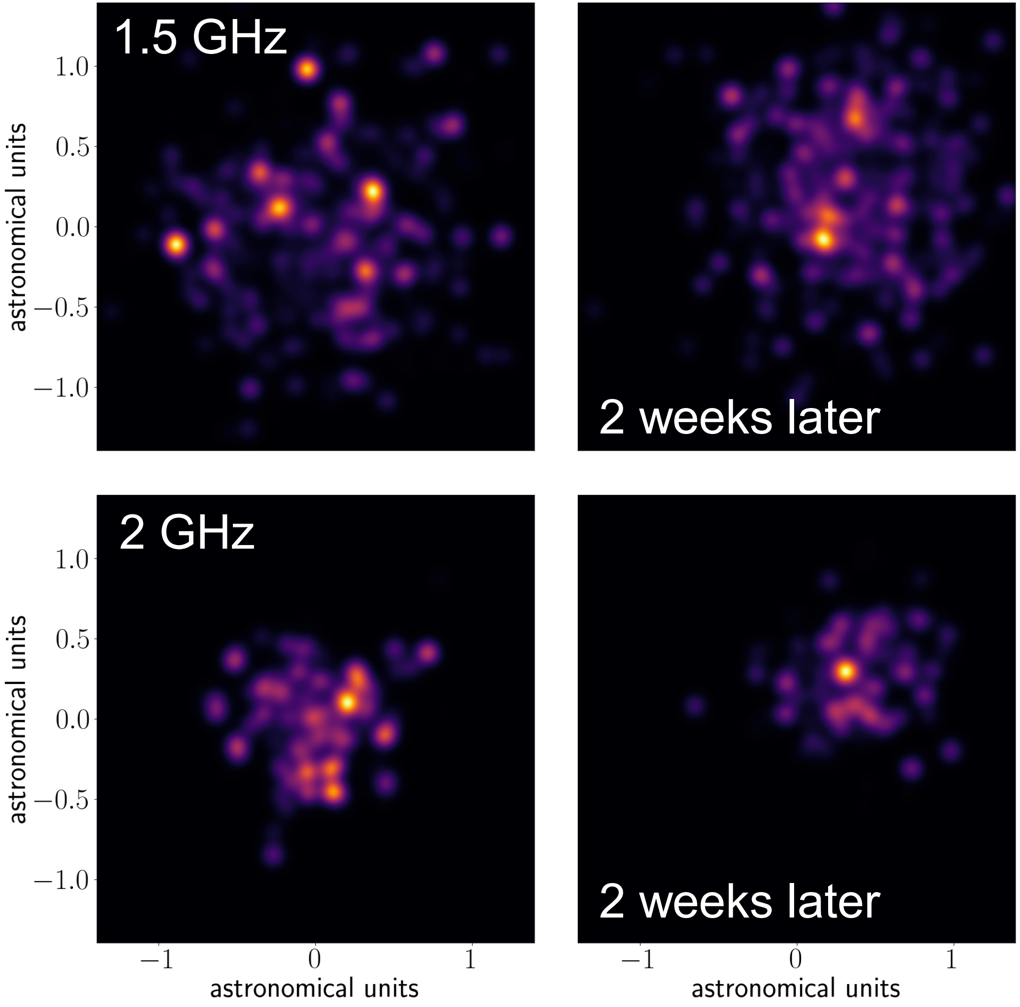
$\alpha = 4.4$

"Thin" screen:



Plasma density:

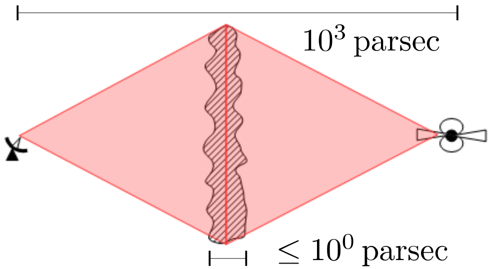




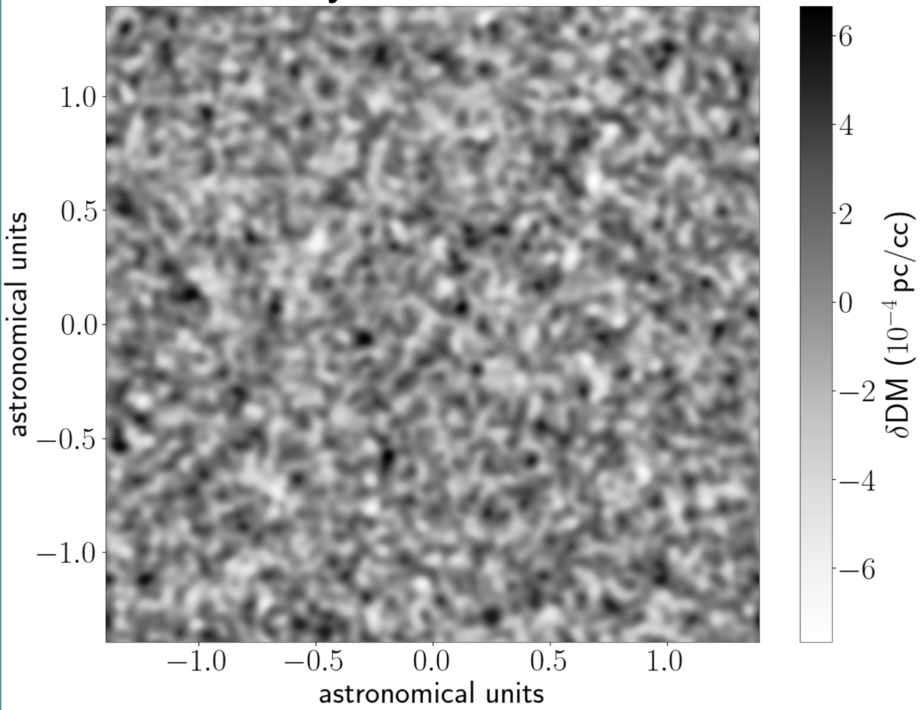
Kolmogorov turbulence

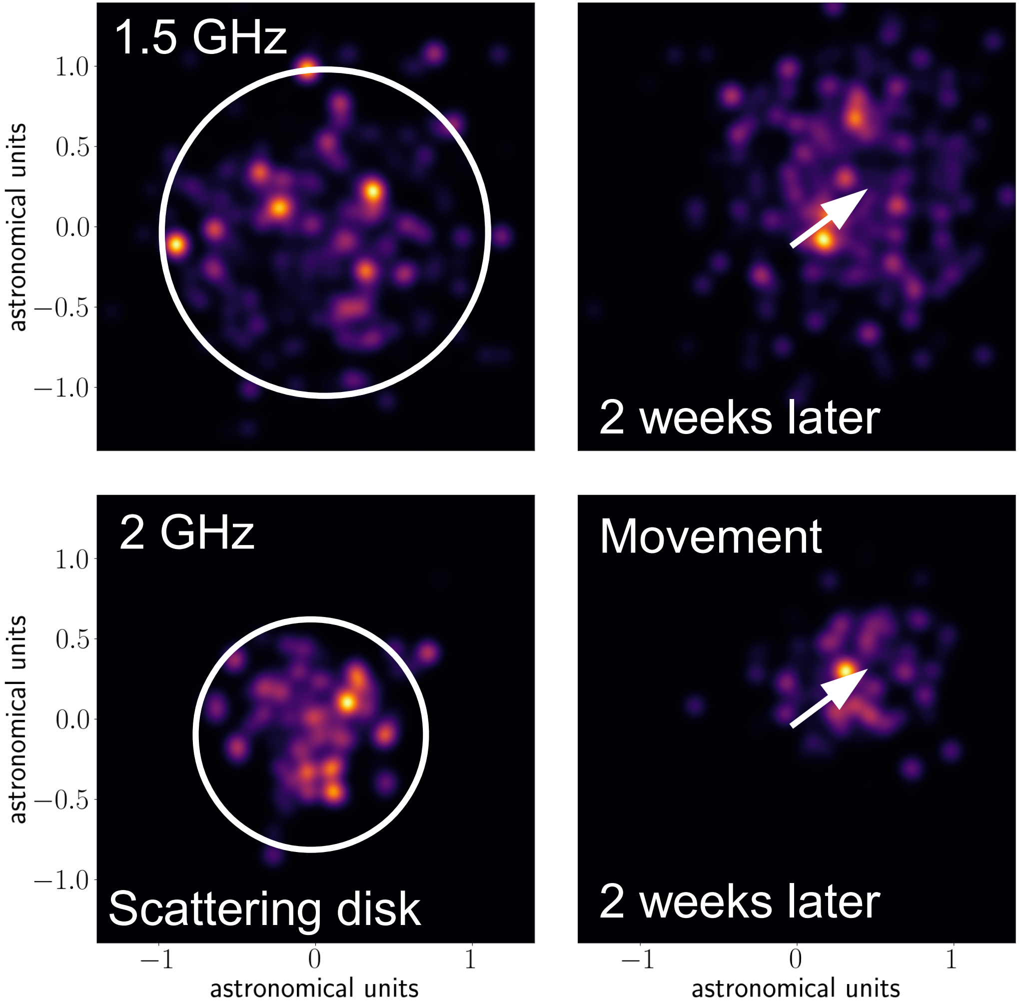
$\alpha = 4.4$

"Thin" screen:



Plasma density:

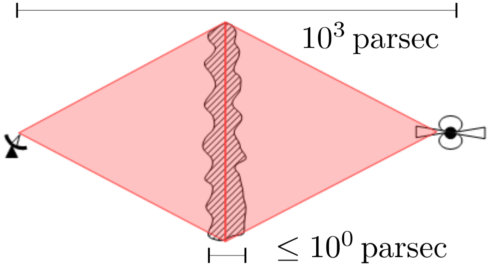




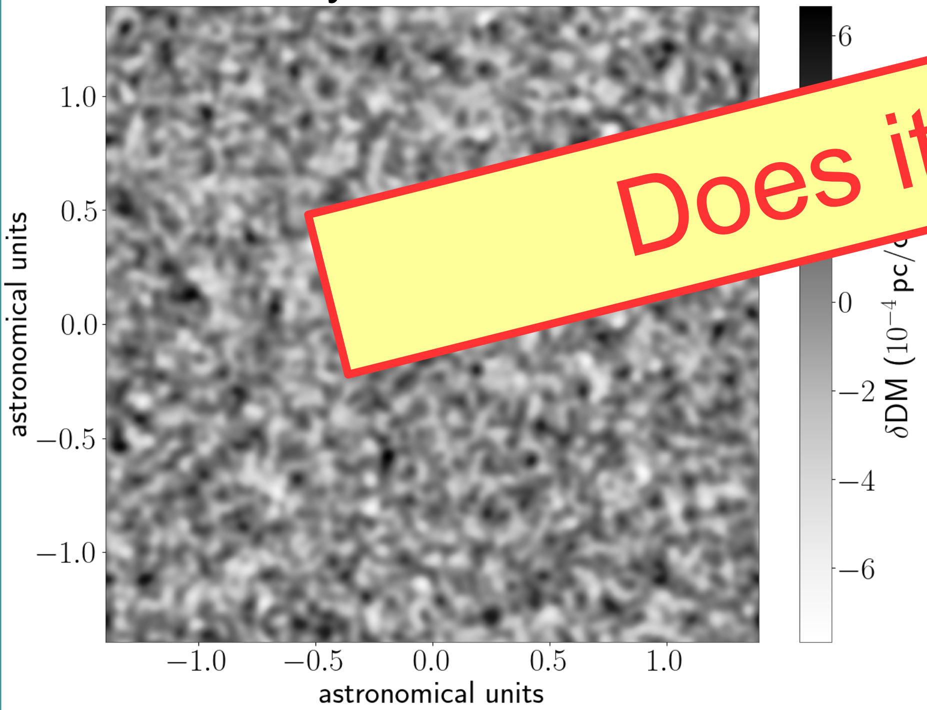
Kolmogorov turbulence

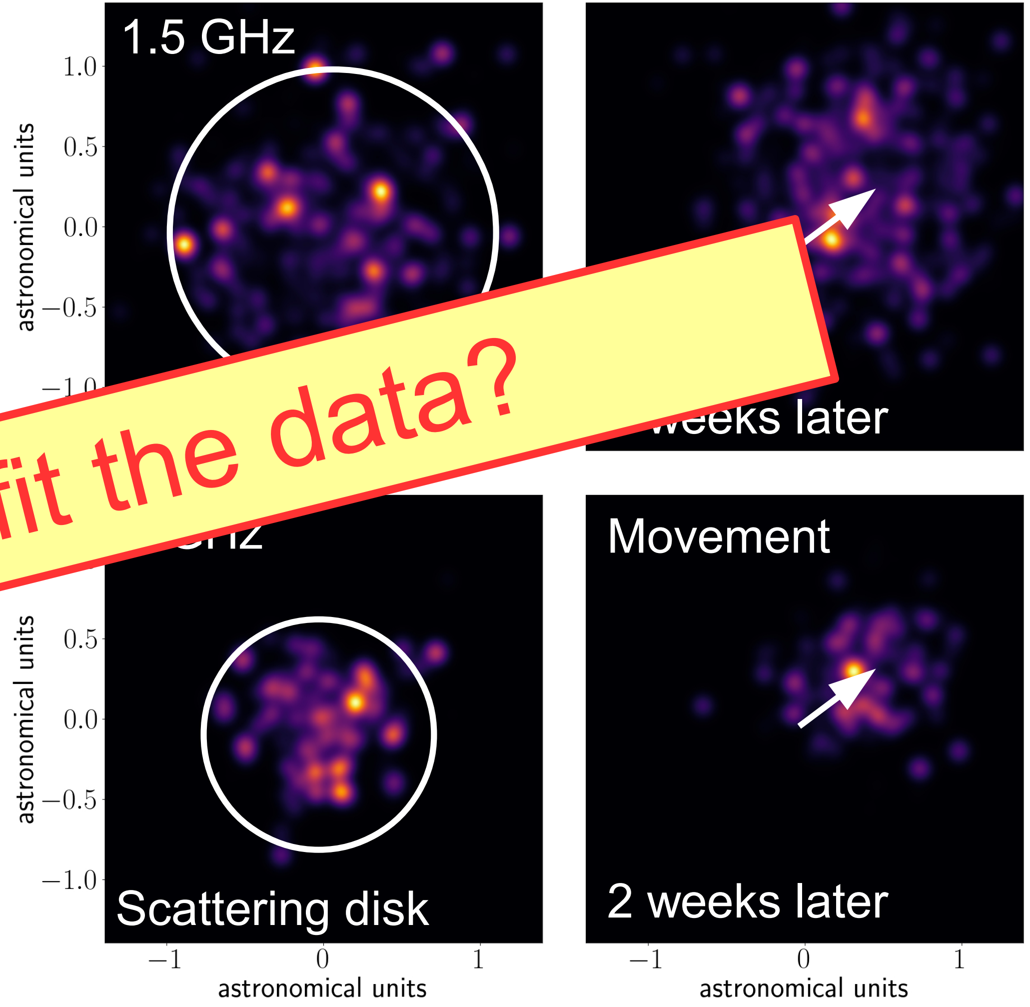
$\alpha = 4.4$

"Thin" screen:



Plasma density:





Does it fit the data?

Observational evidence

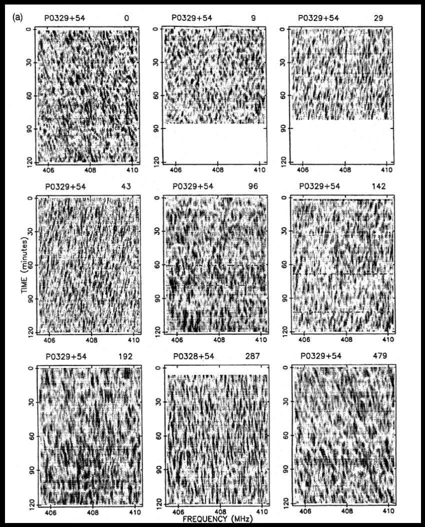
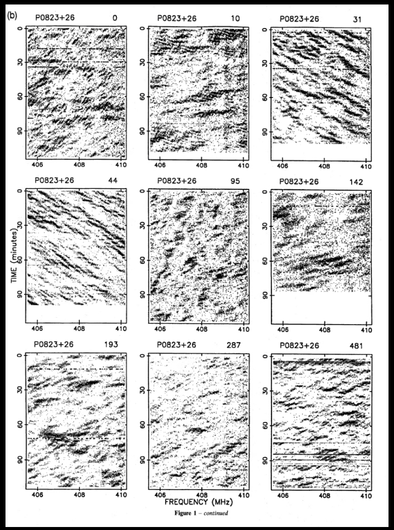
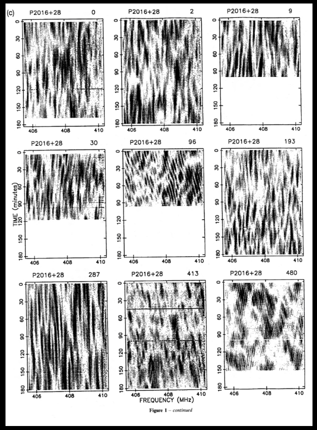
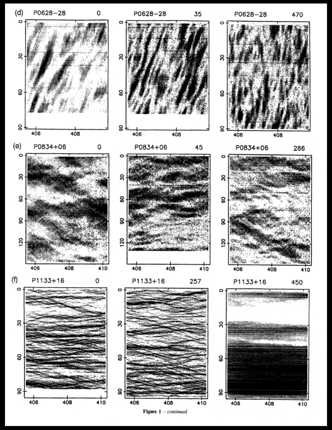
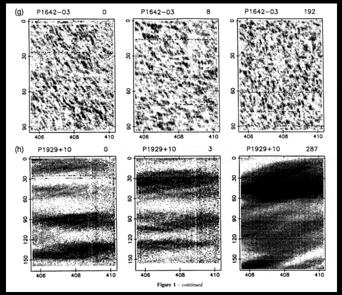
Situation around the year 2000:

30 years of data found lower average scaling index than Kolmogorov turbulence.

Mounting examples of refraction events: tilted and periodic scintles.

Still, an adapted version of the turbulence power spectrum was thought to solve these problems.

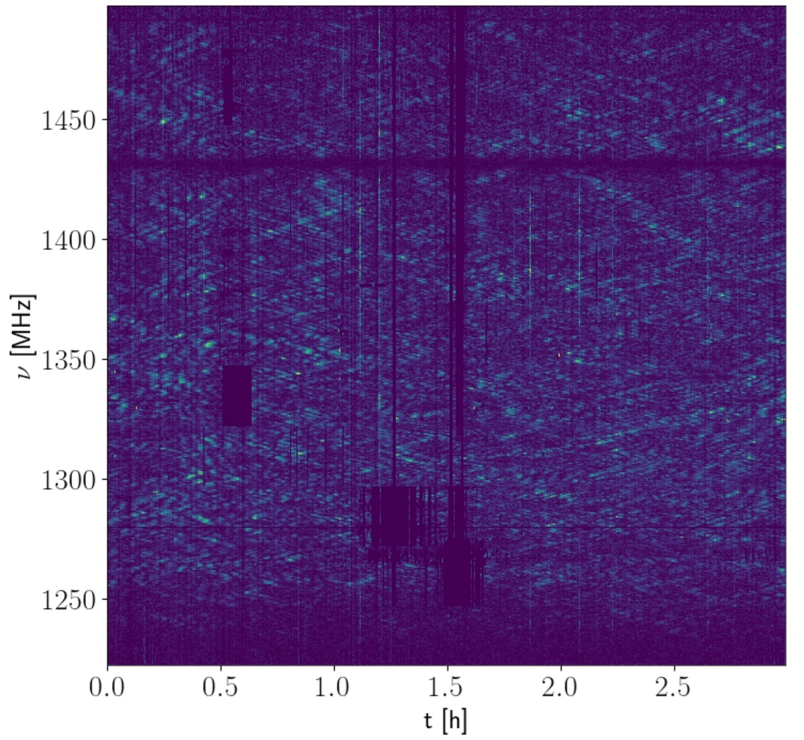
Pulsar Astronomy: 2000 and Beyond, Bonn

Gupta et al. 1994

The disruptive discovery of scintillation arcs

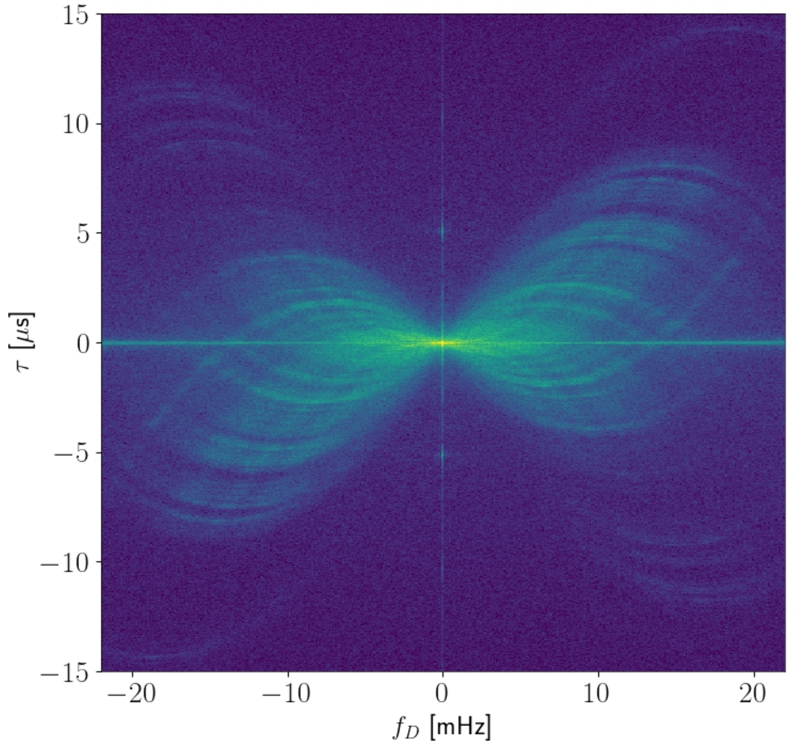
Dynamic spectrum



Fourier transform

First noted to be present in many pulsars by Stinebring et al. 2001.

Secondary spectrum



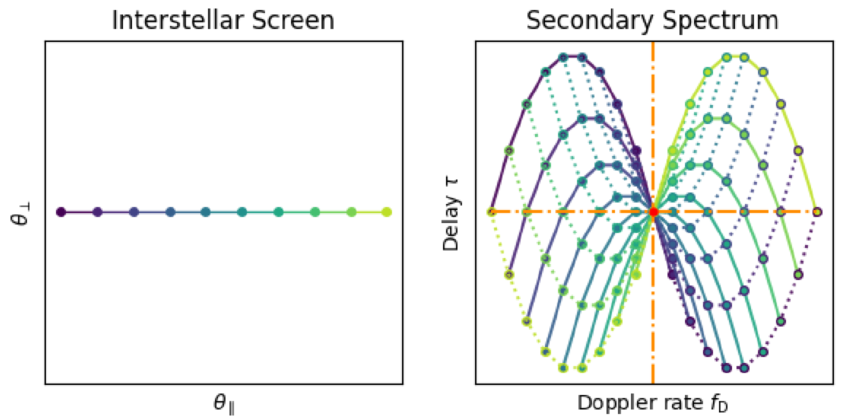
PSR B1508+55, Effelsberg

Sprenger et al. 2022

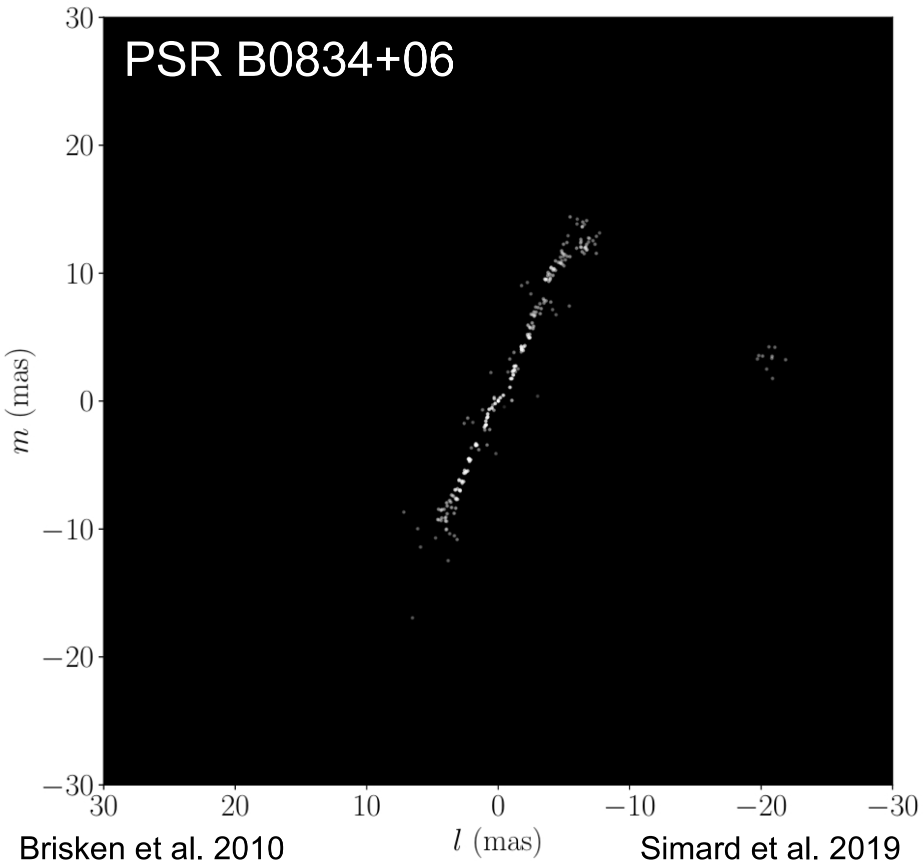
Lines of images

Secondary spectra often show sharp parabolic arcs or even collections of arclets.

Similar to interferometric imaging, the scattered pulsar can be reconstructed.



Sprenger et al. 2021



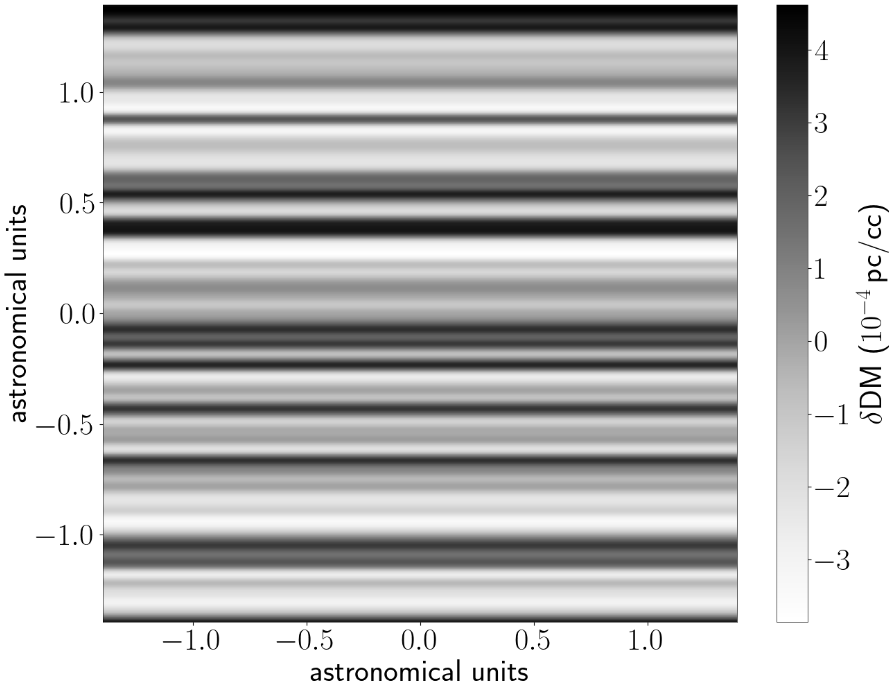
Brisken et al. 2010

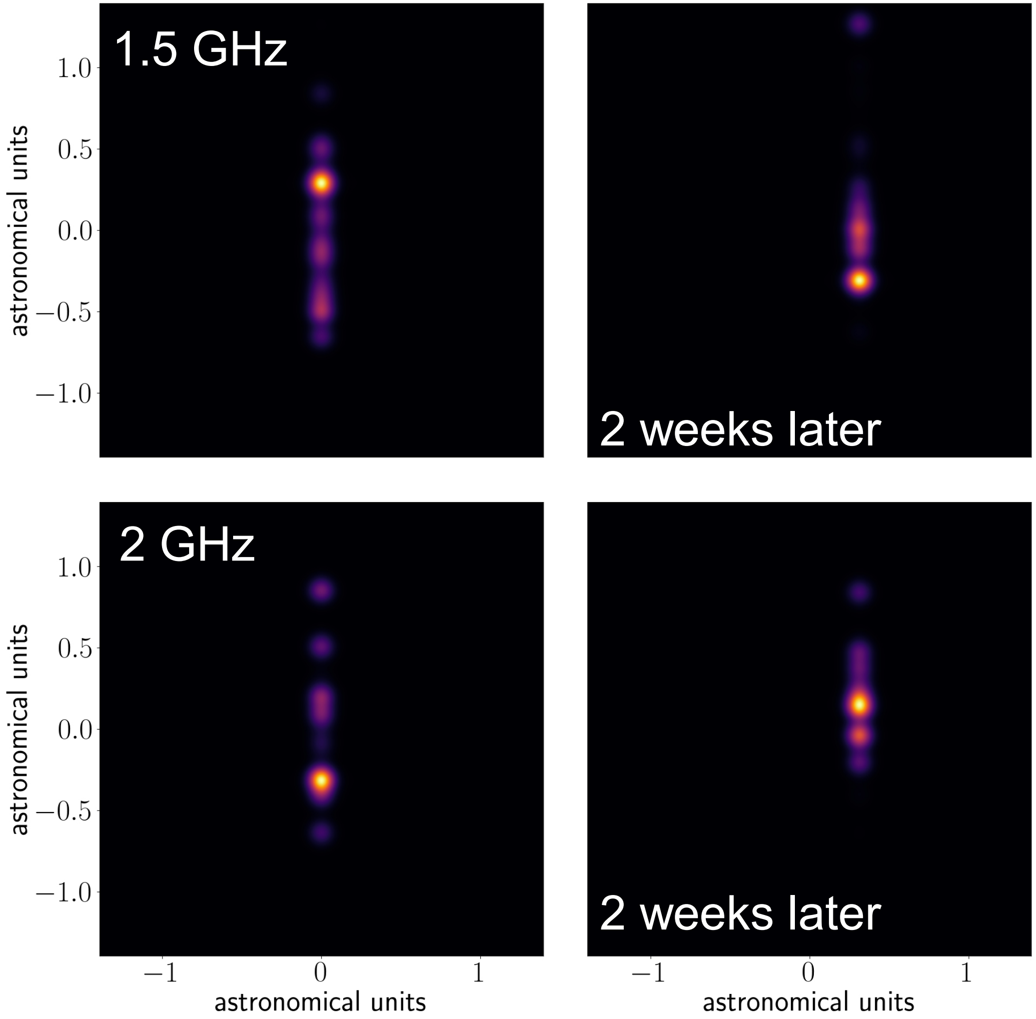
Simard et al. 2019

Anisotropic turbulence

A straight line of images requires an anisotropic screen.

Turbulence exists on different scales in two directions.

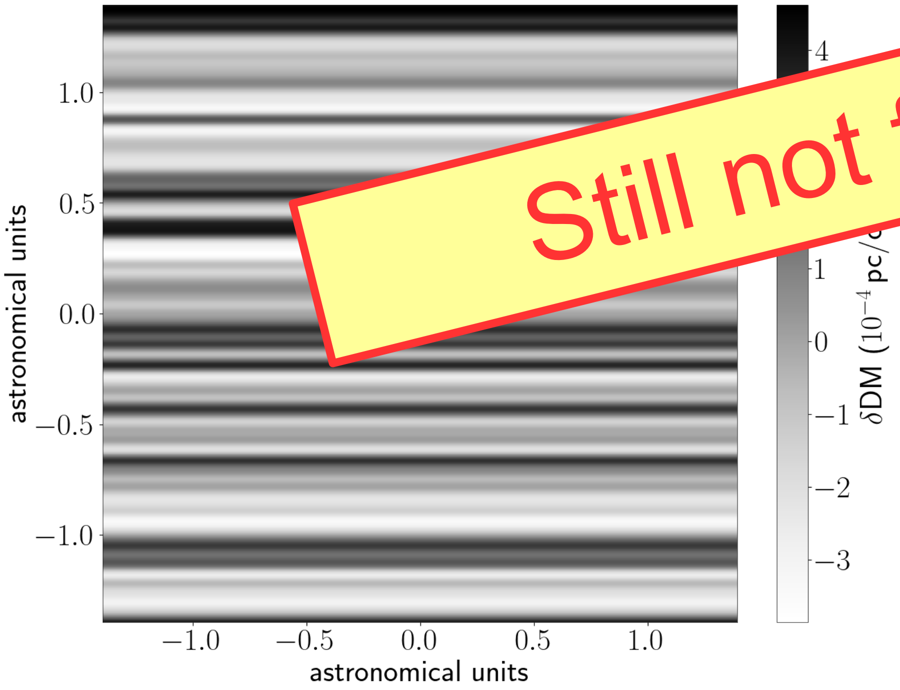


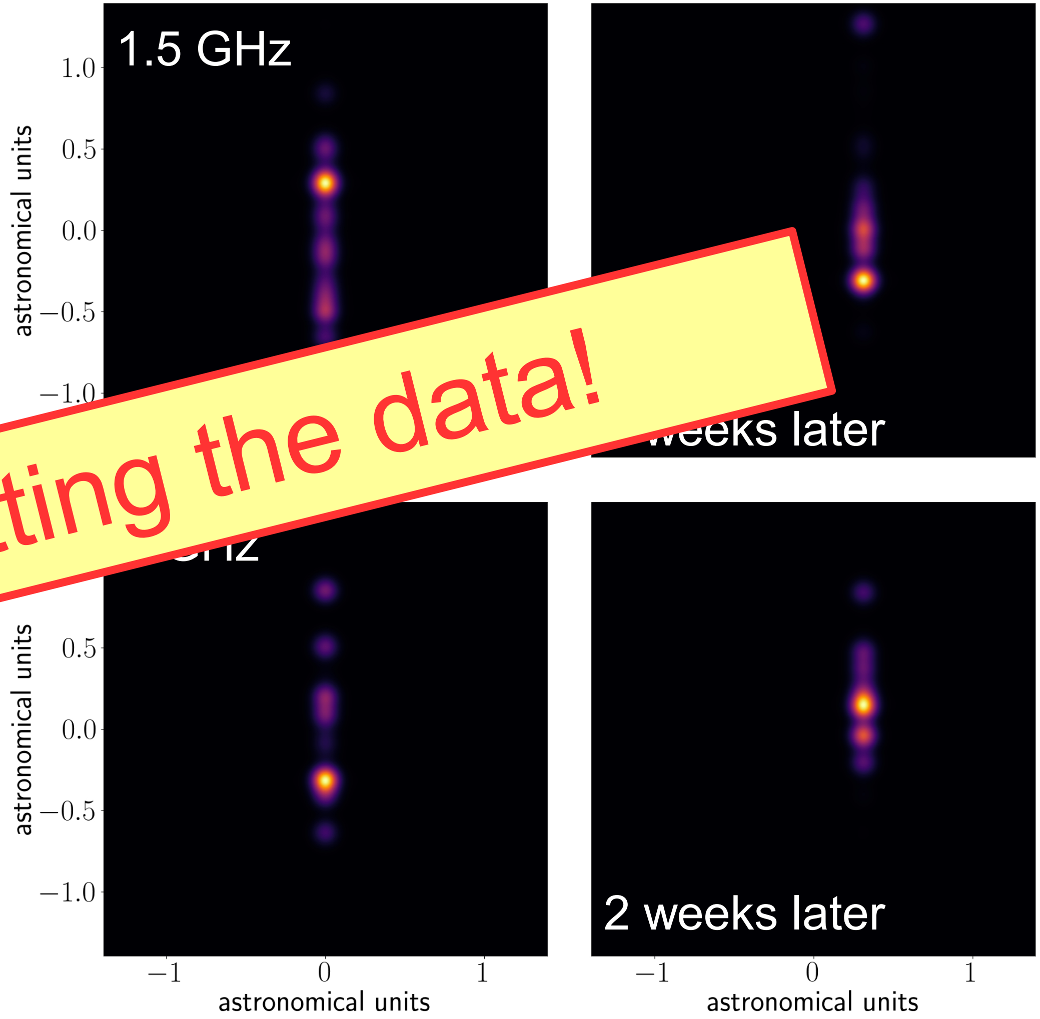


Anisotropic turbulence

A straight line of images requires an anisotropic screen.

Turbulence exists on different scales in two directions.



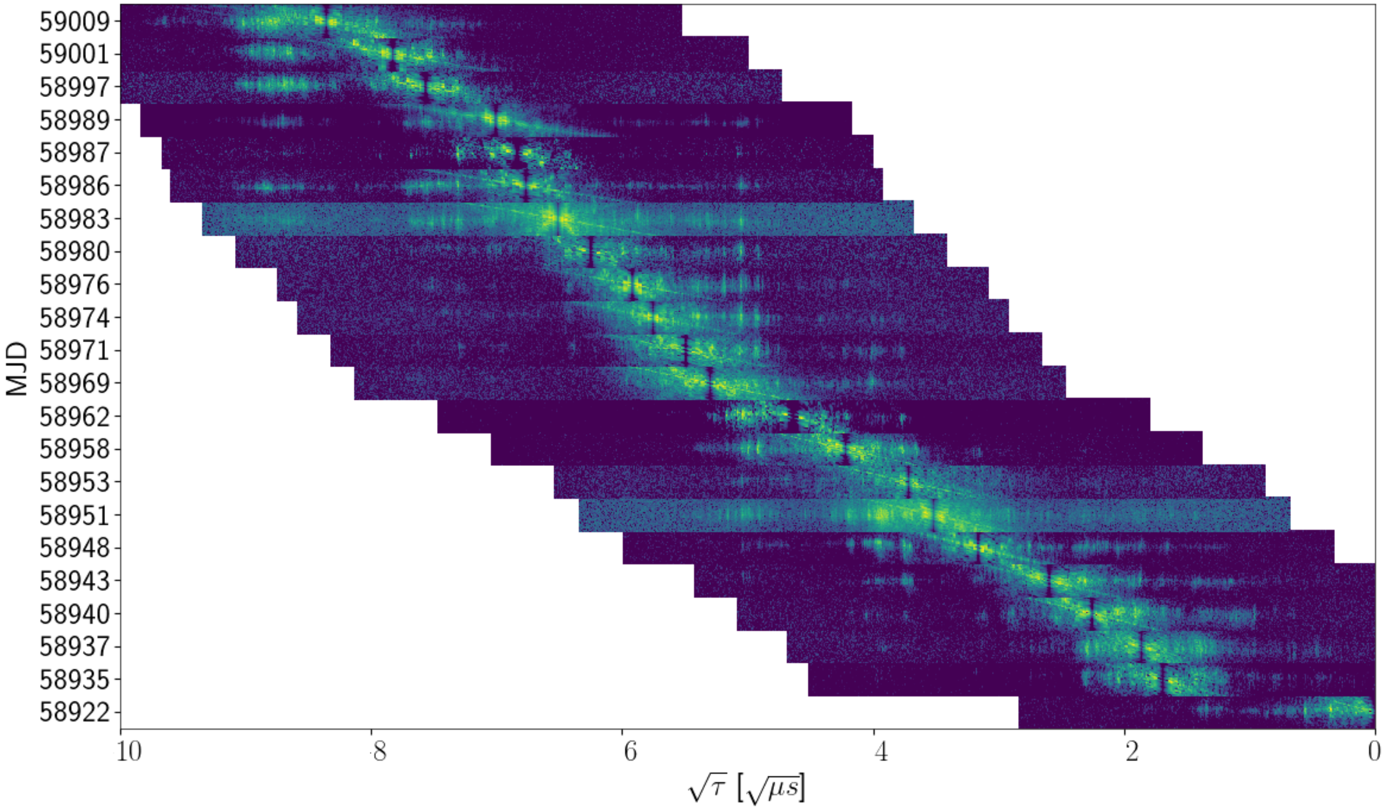


Still not fitting the data!

$\sqrt{\tau} \propto \theta$

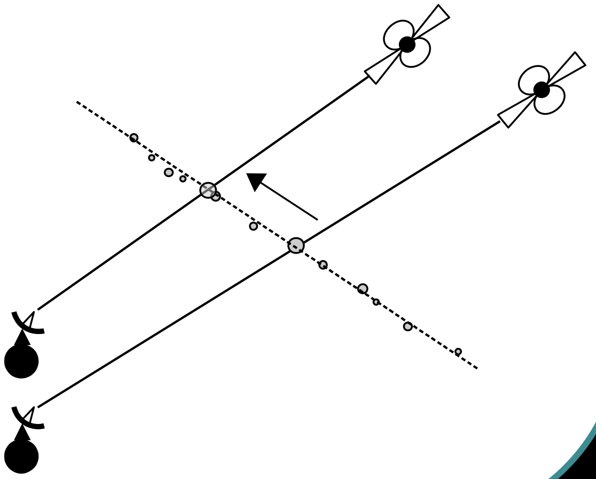
Feature Alignment

B1508+55



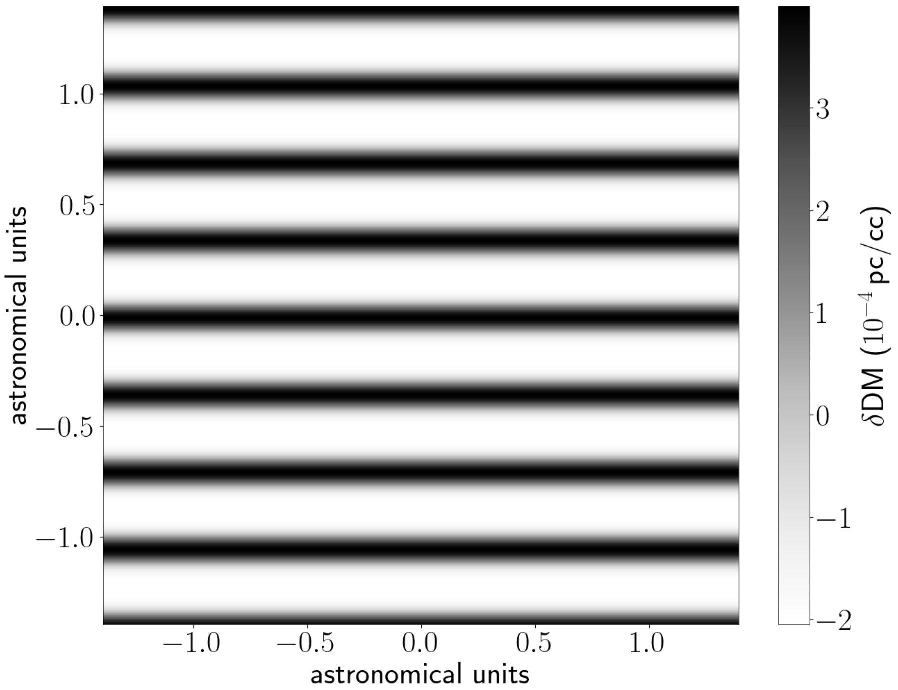
“Images” stay stable while the line of sight moves along.

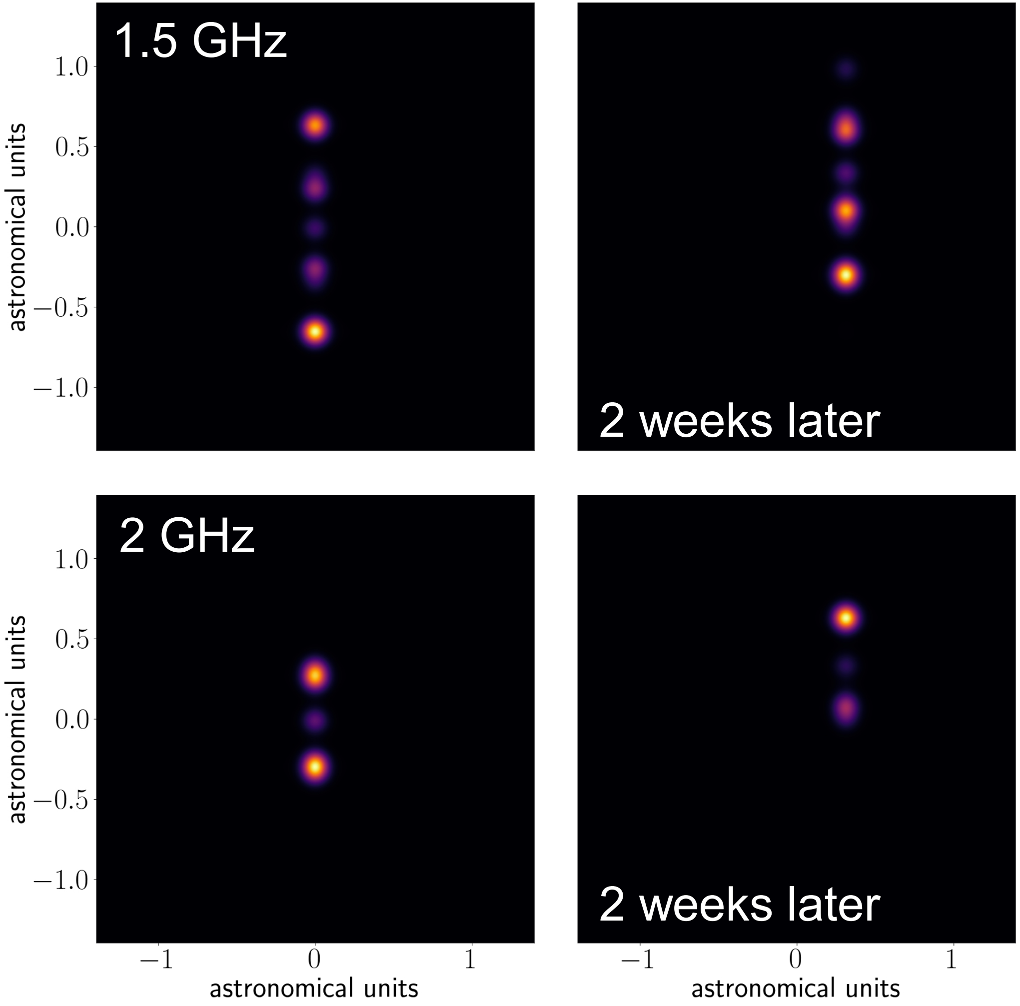
→ Sprenger et al. 2022



Projected filaments

Images can only form along certain filaments.
Leads to a scaling of $\nu_{\mathrm{ISS}} \propto \nu^4$

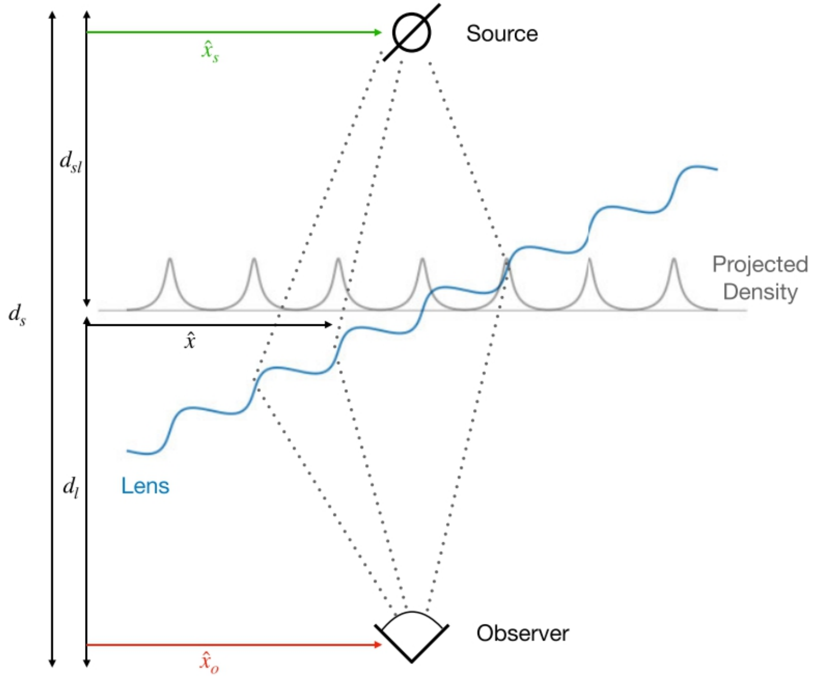




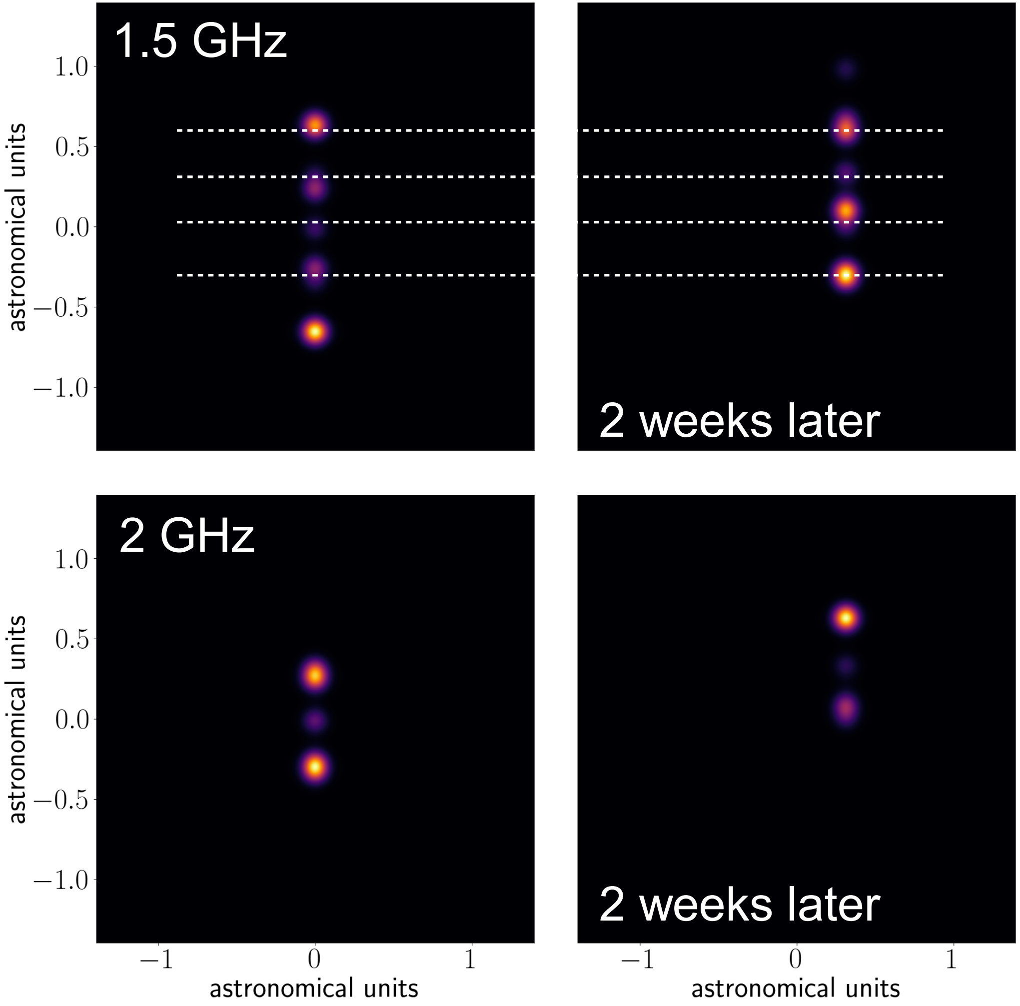
Projected filaments

Projected noodles or sheets.
Likely supported by magnetic fields.

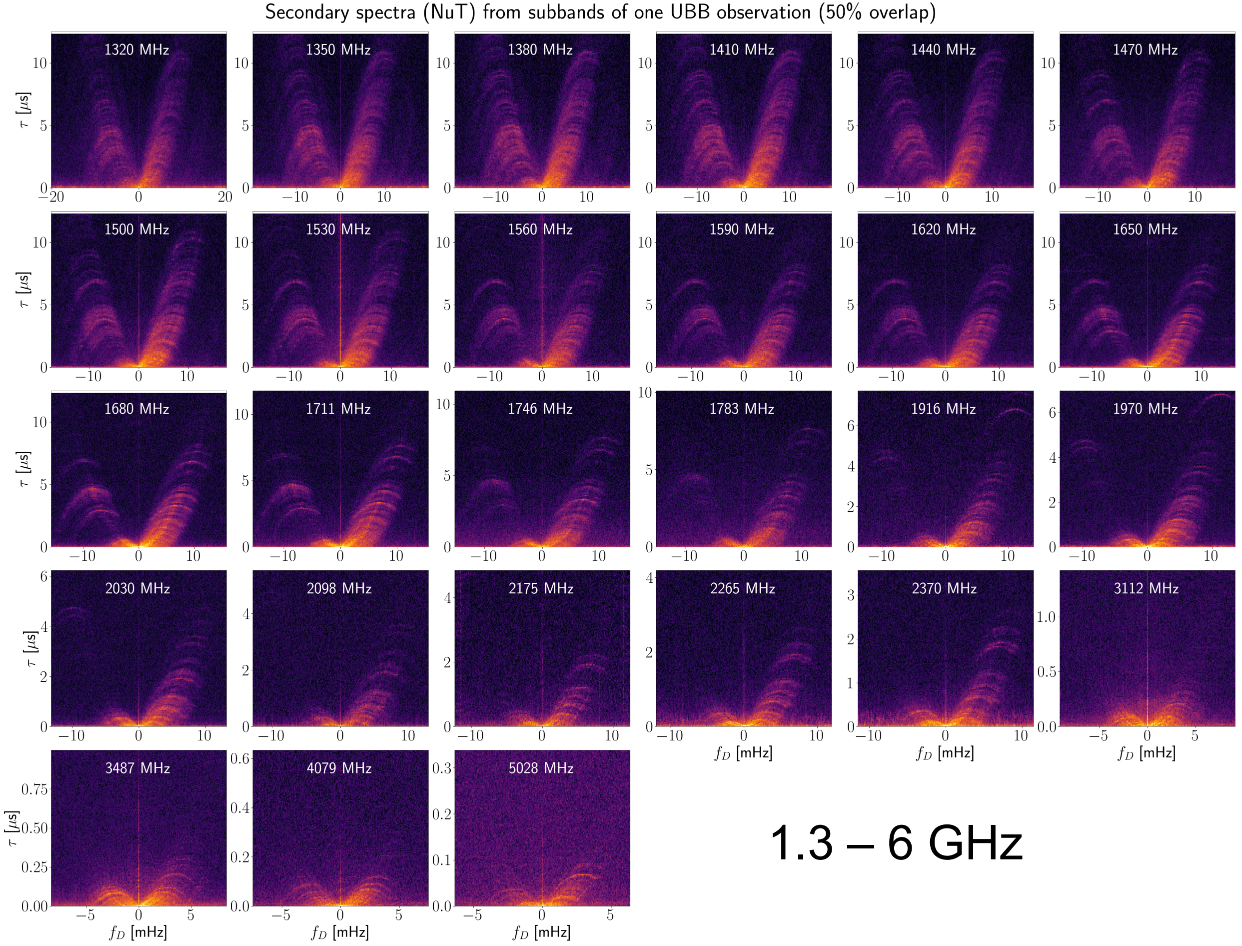
e.g. waves on reconnection current sheets:



Jow et al. 2024, Pen & Levin 2014

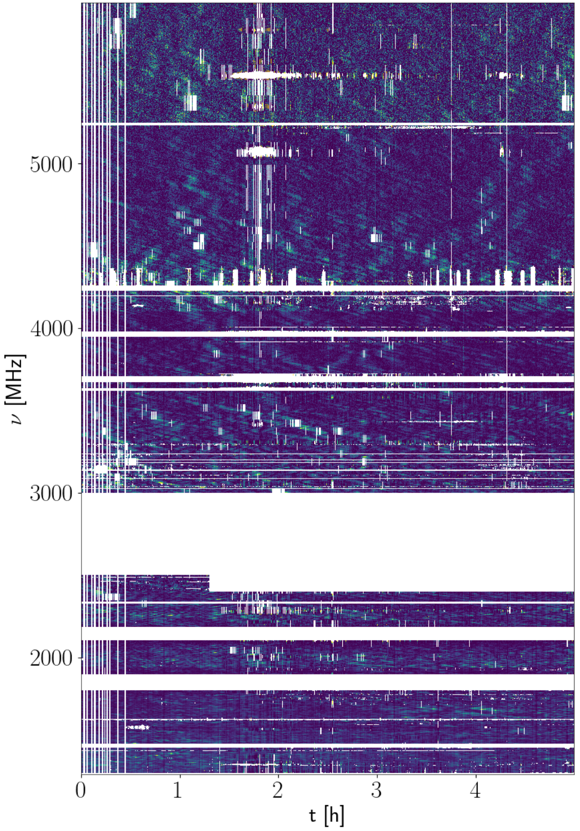


Effelsberg Ultra Broad Band (UBB) receiver



1.3 – 6 GHz

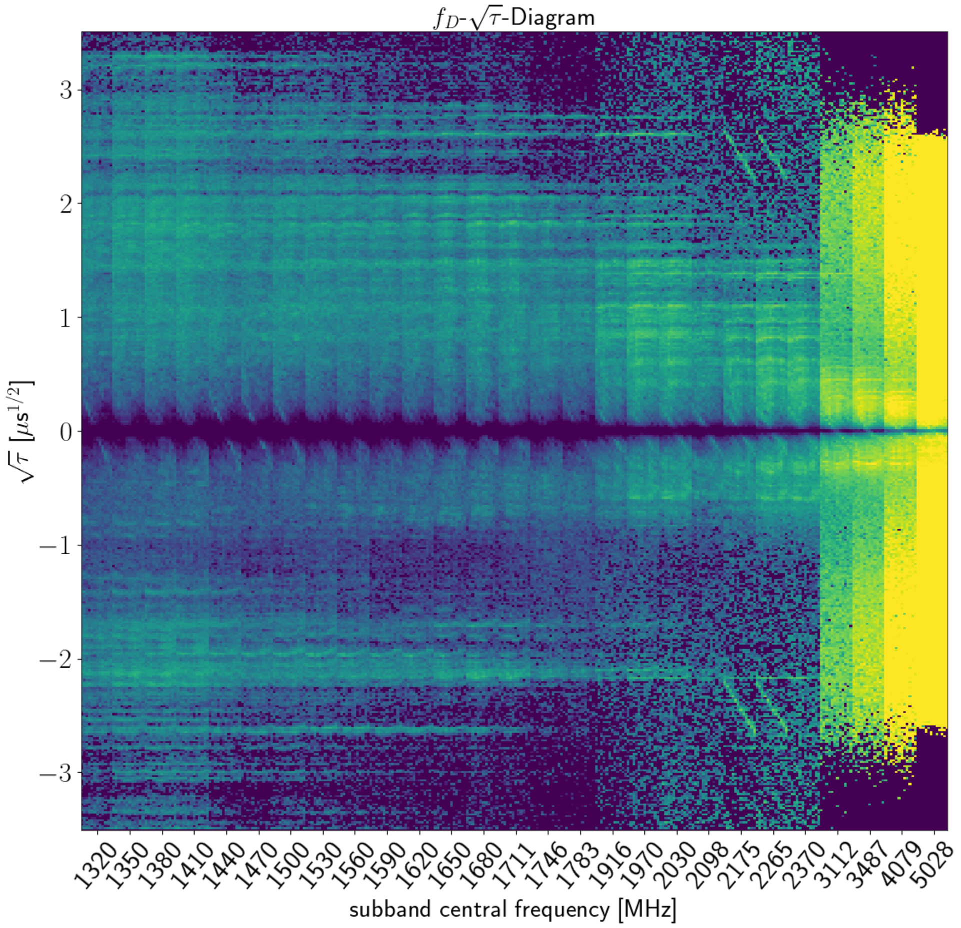
PSR B1508+55



$\sqrt{\tau} \propto \theta$

Frequency evolution

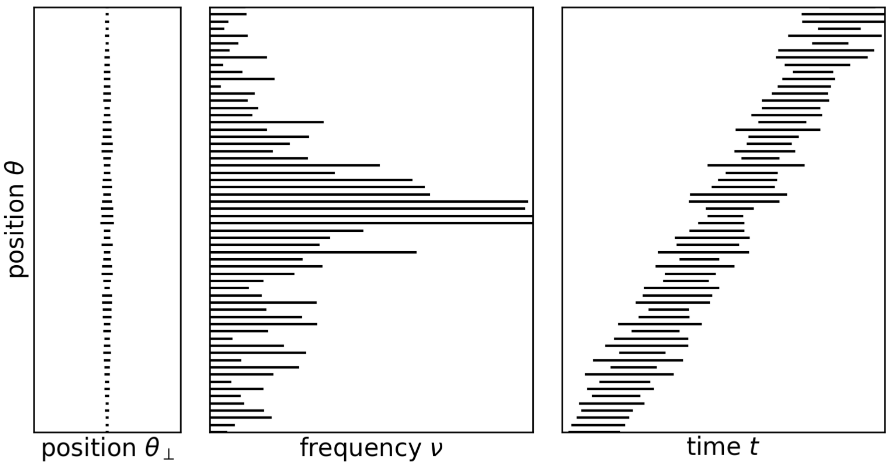
B1508+55



Images remain in position

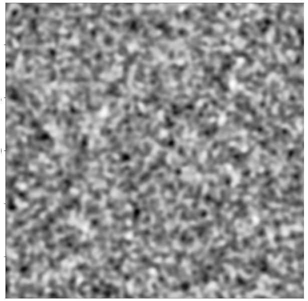
Some images persist over a factor of 2 in frequency!

"Nail in the coffin of turbulence models"
All three properties of filaments now observed:

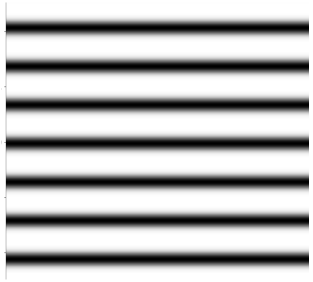


Conclusion

Random turbulence



Ordered filaments

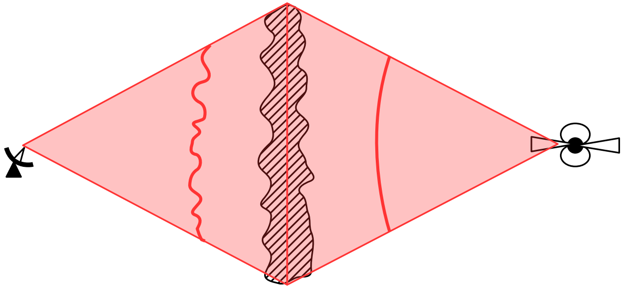


Turbulence stopped being the standard model of scintillation.

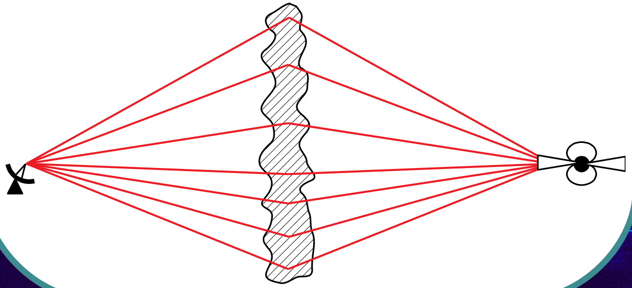
Small scale filaments seem to be aligned with large scale filaments (Stock et al. 2024).

Not all secondary spectra are this clear. Ongoing debate if caused by multiple screens of filaments or turbulence.

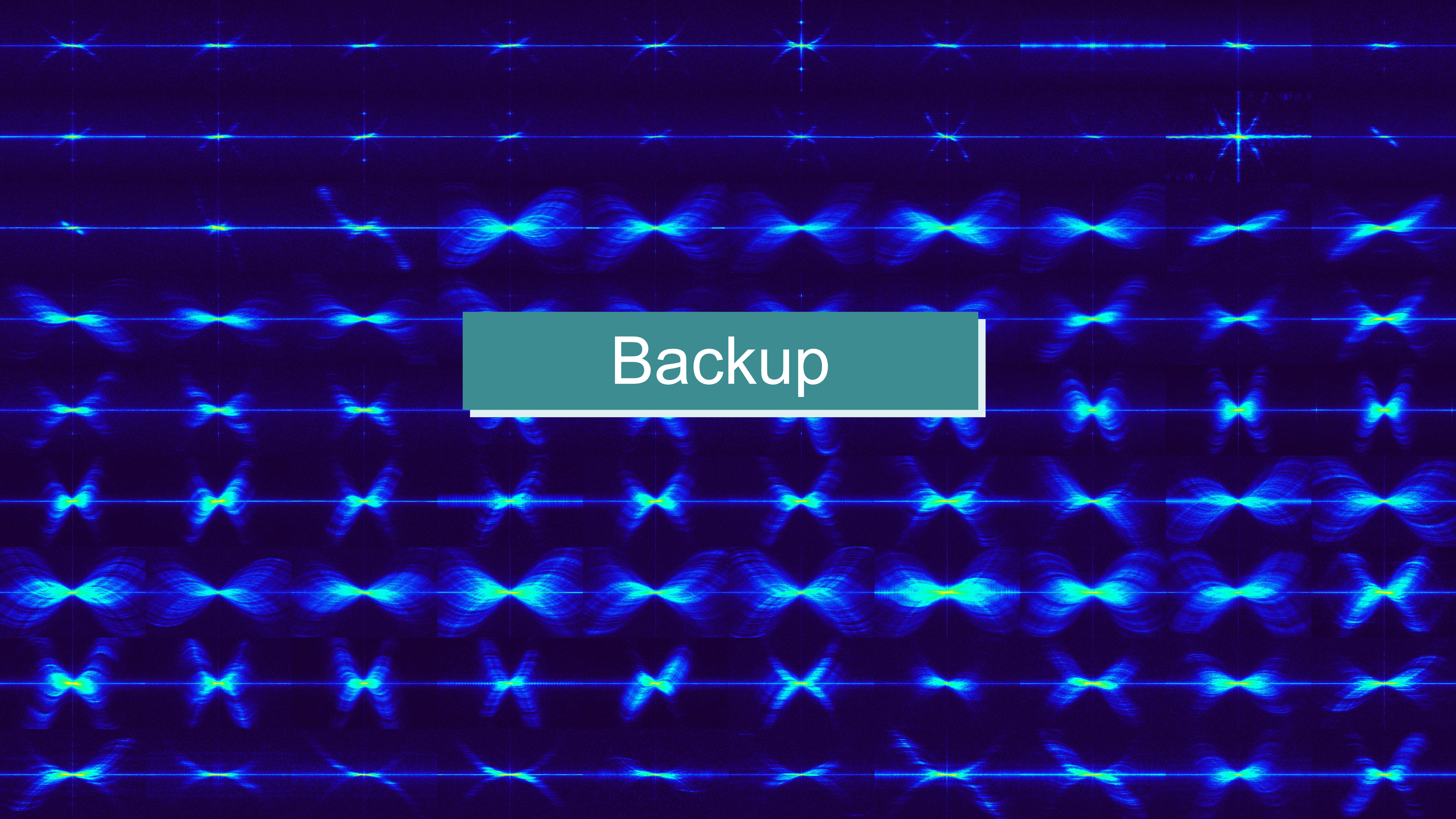
Diffraction



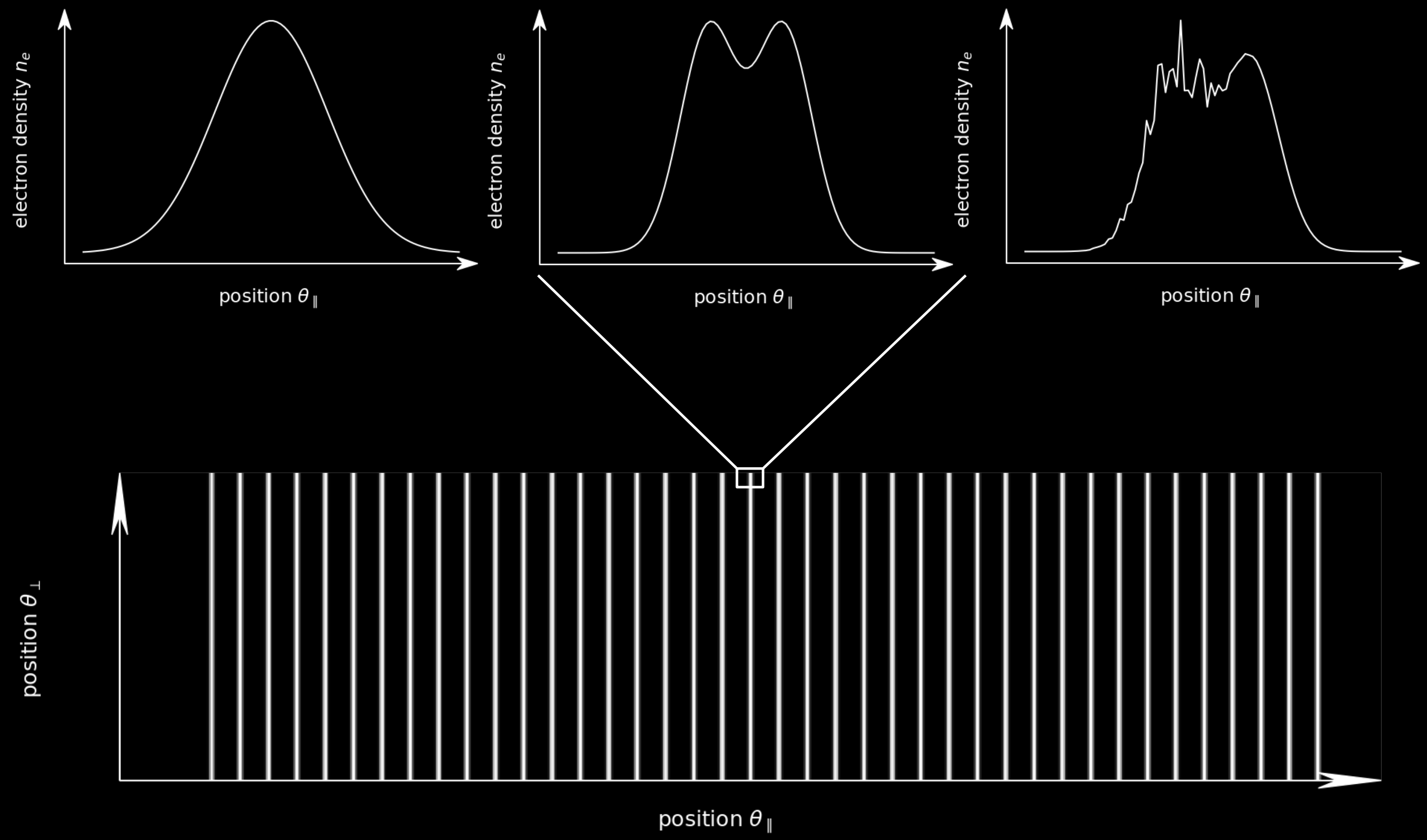
Refraction



Backup



Interpretation



Internal structure

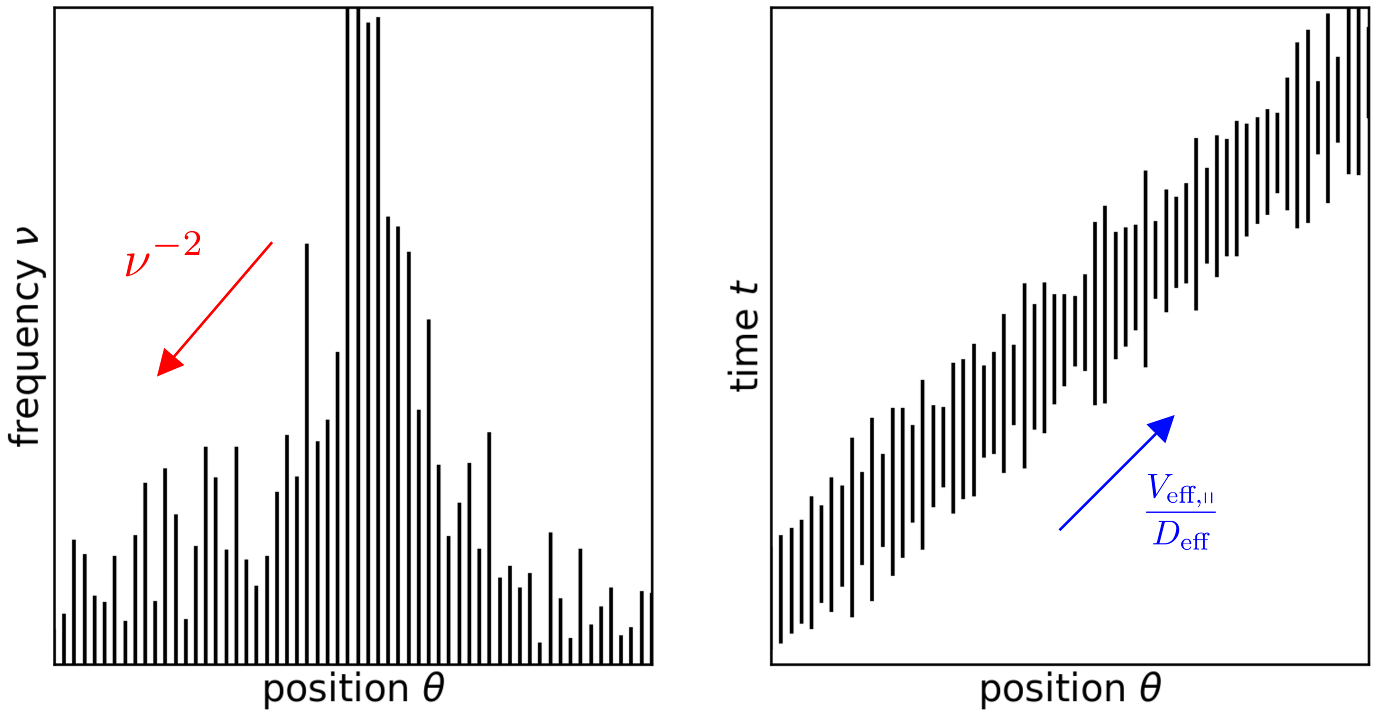
Needs to have a highest gradient that is similar for all filaments:

$$\vec{\theta}_{\max} = \nu^{-2}\,(\vec{\nabla} n_e)_{\max}$$

No strong amplifications observed, thus need to suppress caustics.

Substructure may also come from additional screens.

Interpretation



More than points of stationary phase

Wave phase:

$$\Phi = -c_e \frac{n_e(\vec{\theta})}{\nu} + \nu D_{\text{eff}} \left(\vec{\theta} - \frac{\vec{V}_{\text{eff}}}{D_{\text{eff}}} t \right)^2$$

Stationary condition:

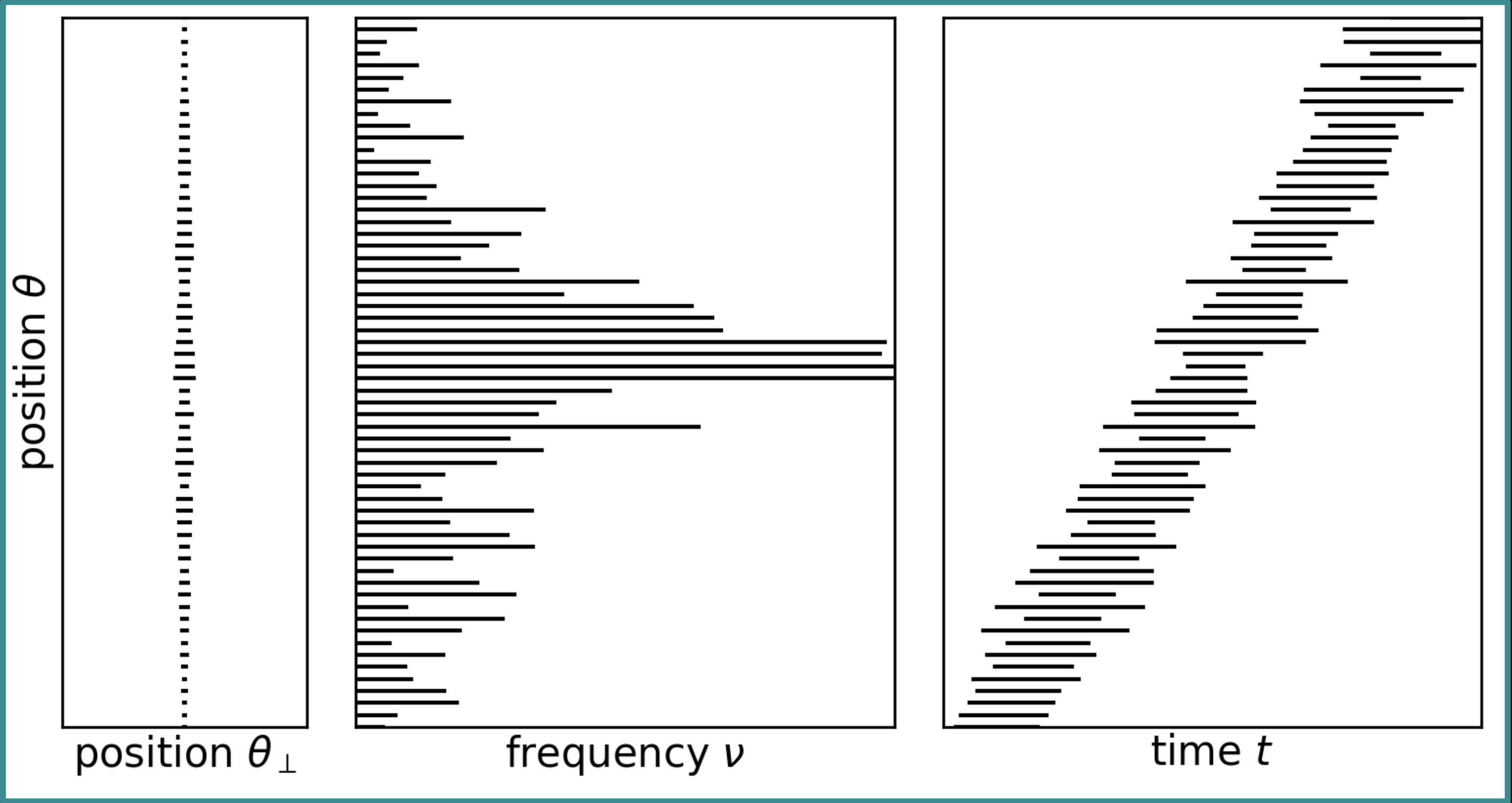
$$\vec{\theta} - \frac{\vec{V}_{\text{eff}}}{D_{\text{eff}}} t = c_e \frac{\nu^{-2}}{2 D_{\text{eff}}} \vec{\nabla} n_e(\vec{\theta})$$

At most one solution!

$$\vec{\theta}(t, \nu)$$

Data is broadly consistent with image points being frozen in place for all times and frequencies!

Interpretation

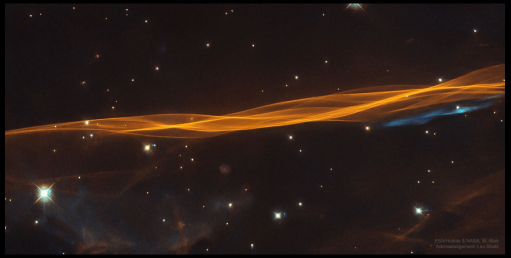


Filaments

One-dimensional.

Most of the plasma density is flat.

Concentrated regions of many solutions of stationary phase.

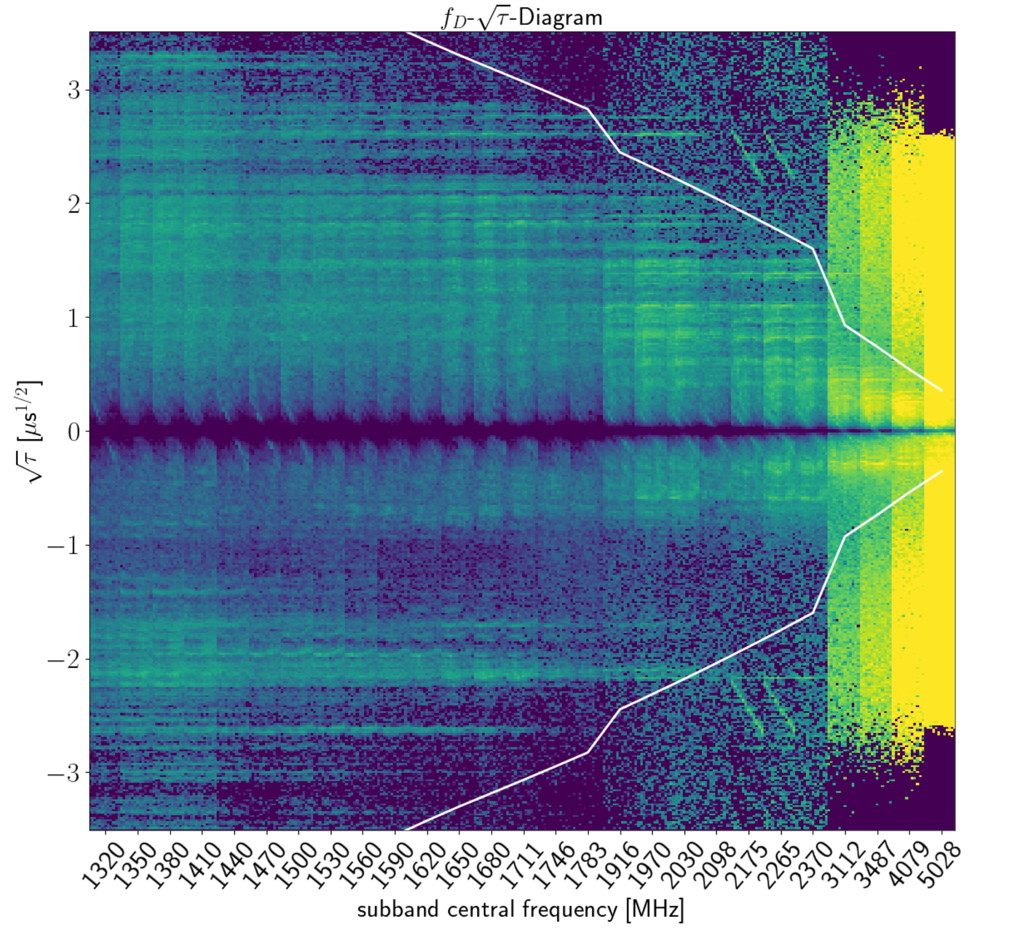


ESA/Hubble & NASA, W. Blair

$\sqrt{\tau} \propto \theta$

Effelsberg UBB receiver

B1508+55

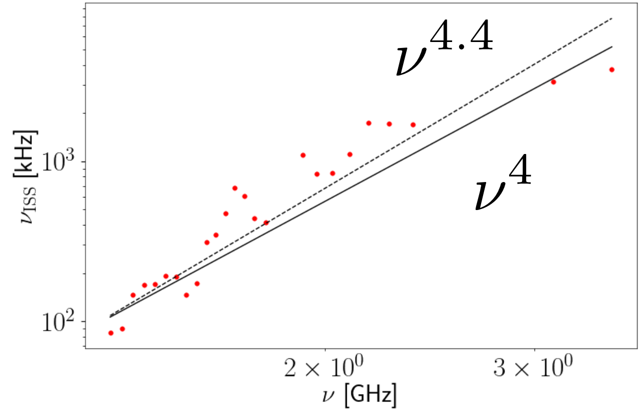


ν^{-2}

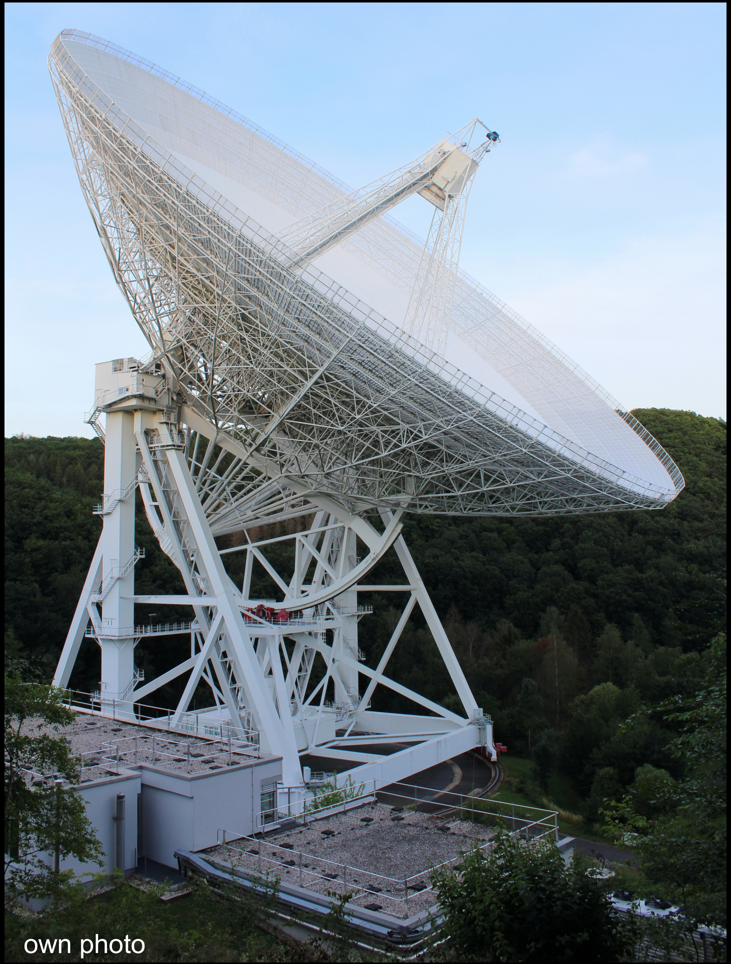
B1508+55

Images are at stable positions but disappear following power law.

Nearly continuous band crucial to match images.
Power variations and tiny positional shifts not excluded.



Effelsberg 100m telescope and the UBB



own photo

Located in the Eifel. Operated by the Max Planck Institute for Radio Astronomy (MPIfR).

New Ultra Broad Band (UBB) receiver installed. Comissioning finished end of 2023.

1.3-6 GHz (1.3-2.6 + 3-6)

Pilot observations in 2024 taking filterbank data.

UBB receiver

Figure 1: Picture of the UBB Rx in the laboratory. The feed points downwards and is automatically pulled up into the Rx box for storage. In the centre left is the highly integrated EDD front-end unit, which provides control, monitoring, RF conditioning and digitization.

From the Effelsberg Newsletter, 15, 1, 2024

LOFAR

100-200 MHz
Multi-station baseband
1-2 observations each during 2023

Observed pulsars

PSR B0329+54

First half of this talk.

PSR B0834+06

Too few scintles.
No detection above 2 GHz.

PSR B1508+55

Second half of this talk.

PSR B1919+21

Too few scintles.