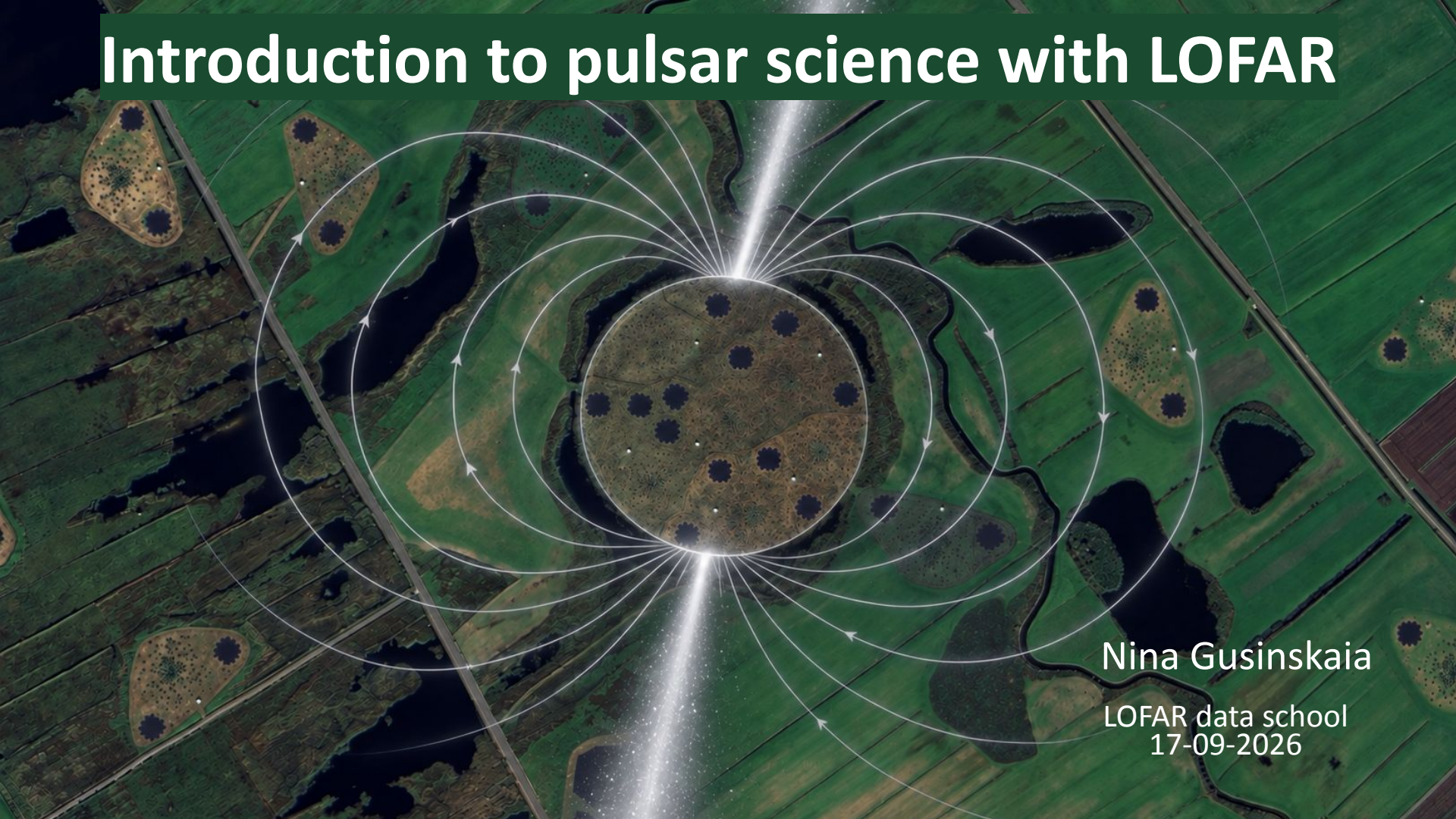
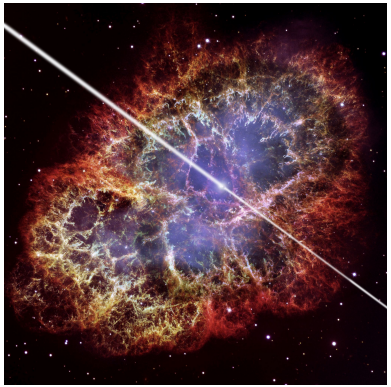
Introduction to pulsar science with LOFAR

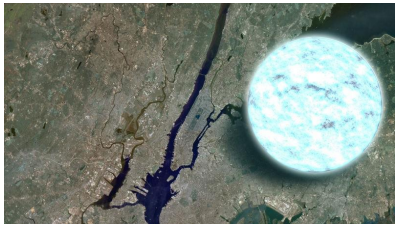


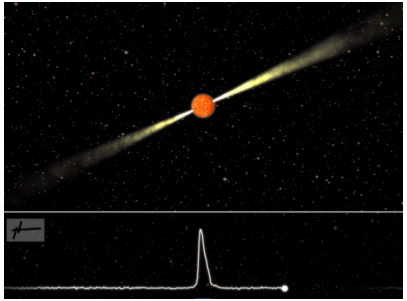
Nina Gusinskaia

LOFAR data school
17-09-2026

Neutron stars!





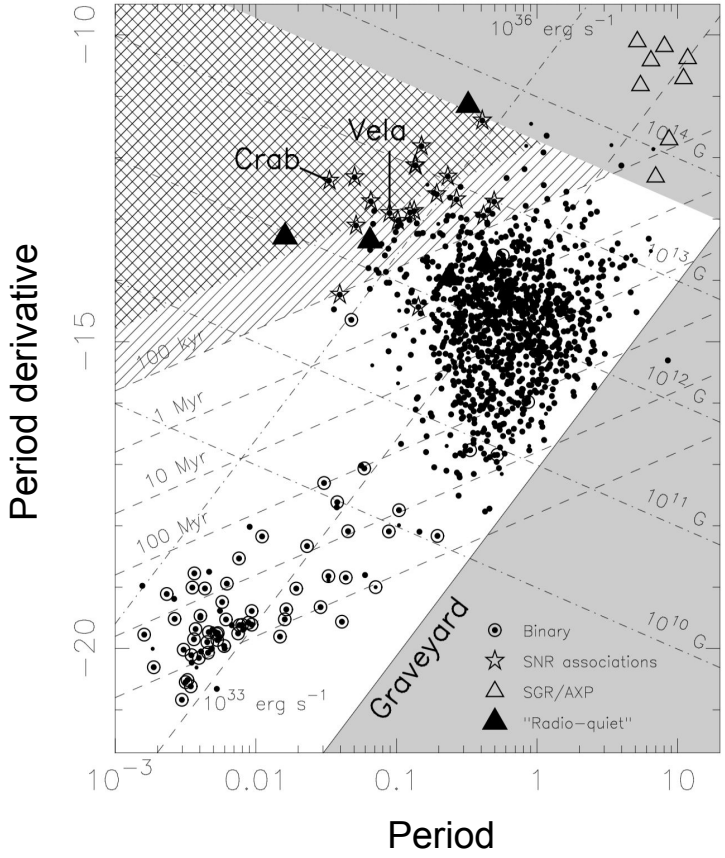


MASS
~1.4 MSun

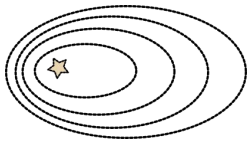
RADIUS
~10 km

DENSITY
~10^15 g/cm3

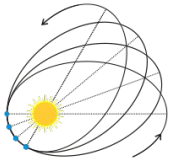
Extreme density
Extreme gravity
Extreme magnetic field



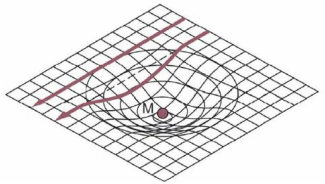
Fundamental physics applications of pulsars



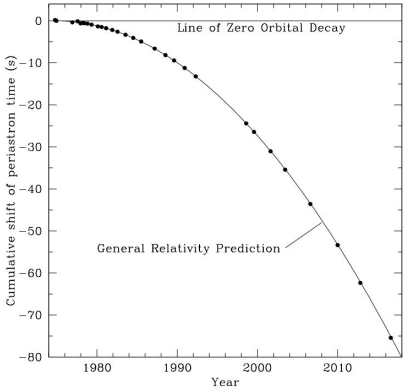
Orbital period decay in double neutron star PSR B1913+16 (Hulse-Taylor pulsar)



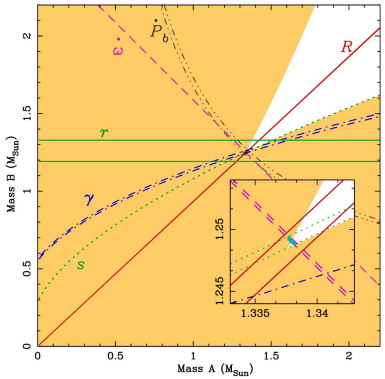
Multiple relativistic parameters intersect according to GR in double pulsar PSR J0737-3039



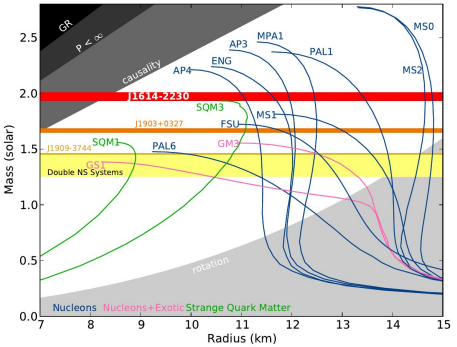
Measured mass of the PSR J1614-2230 put constraints on the EOS of neutron star



Weisberg & Huang 2016, ApJ, 829, 55



Kramer et al. 2006, Science, 314, 1318

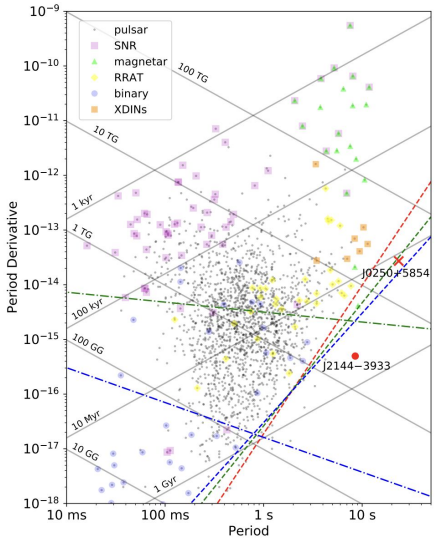


Demorest et al. 2010, Nature, 467, 1081

Fundamental physics applications of pulsars with LOFAR

PSR J0250+5854: 23.5 s pulsar (second slowest)

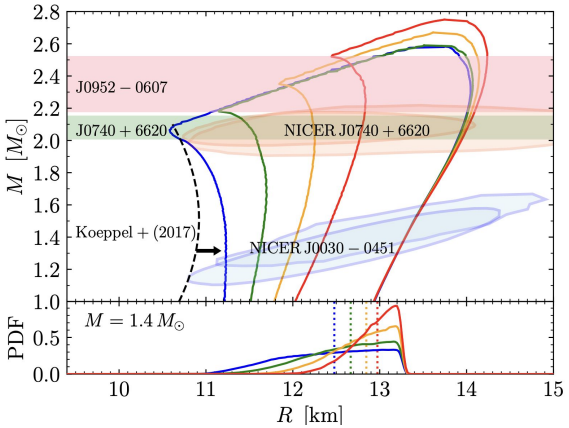
Discovered by LOFAR survey



Tan et al. 2018ApJ...866...54T

PSR J0952-0607: The Fastest and Heaviest Known Galactic Neutron Star

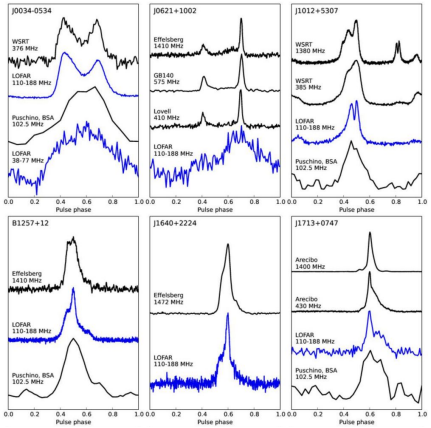
Discovered by LOFAR targeted search



Bassa et al. 2017ApJ...846L..20B
Romani et al., 2022ApJ...934L..17R
Ecker & Rezzolla, 2023MNRAS.519.2615E

Characterization of low-frequency emission of Millisecond Pulsars

with LOFAR census’



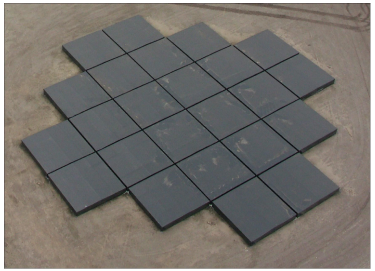
Kondratiev et al. 2016A&A...585A.128K
Tan et al. 2020MNRAS.492.5878T

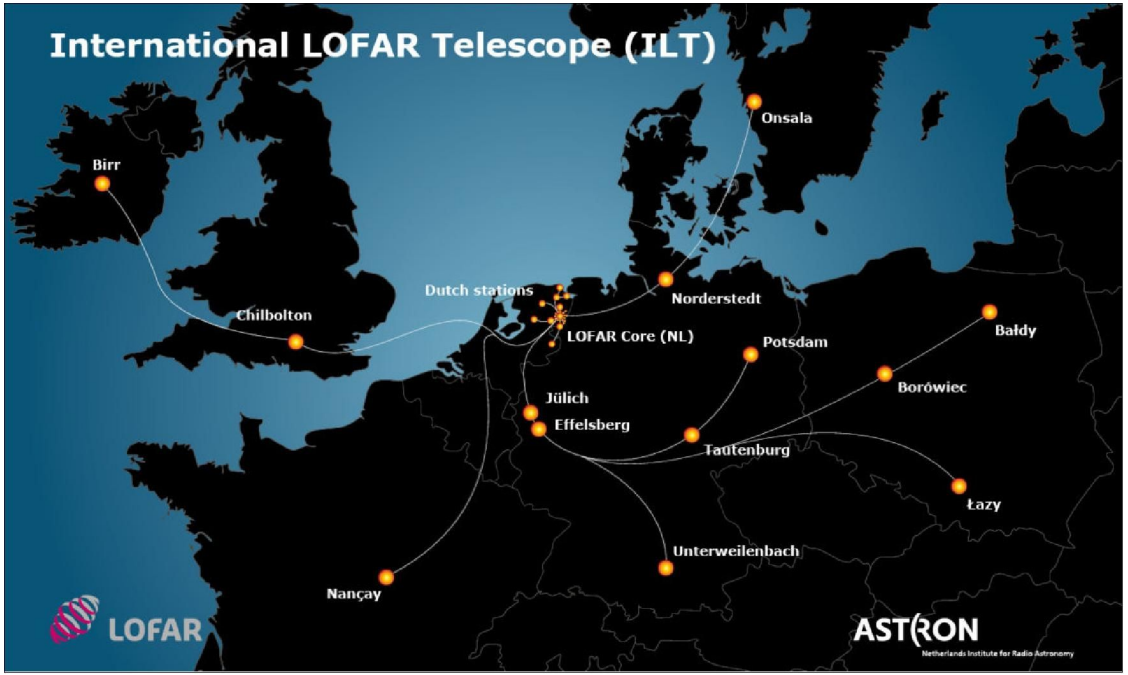
Observing pulsars with LOFAR

LBA: 30-80 MHz



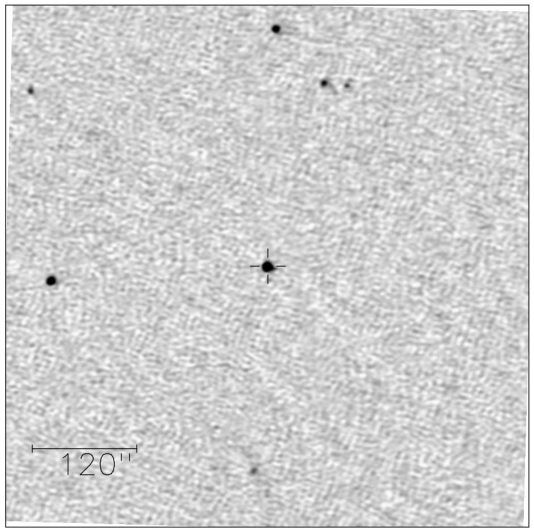
HBA: 110-190 MHz





Observing pulsars with LOFAR

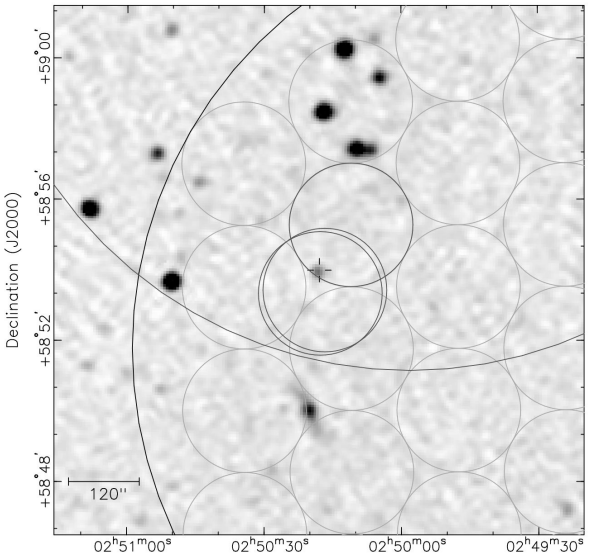
Imaging

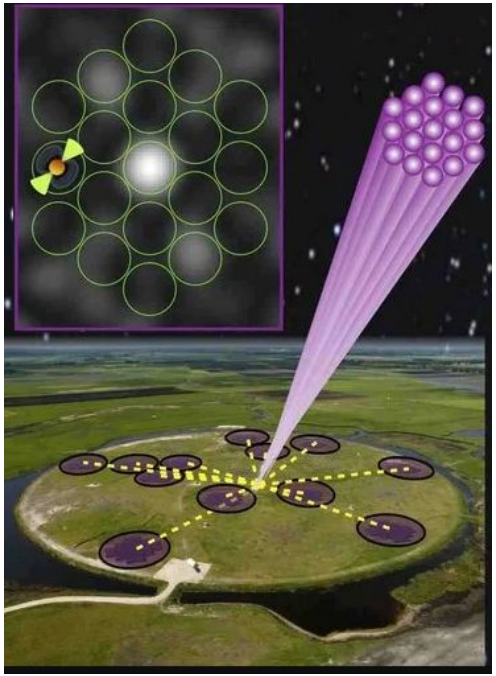


Tan et al. 2018ApJ...866...54T

Observing pulsars with LOFAR

~~Imaging~~ beamforming

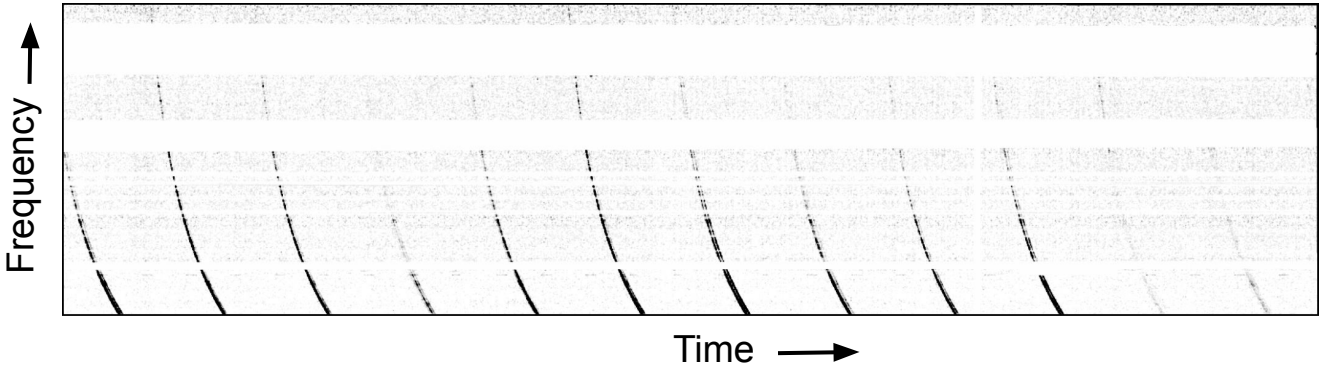


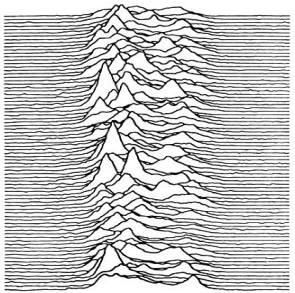


Tan et al. 2018ApJ...866...54T

P = 0.714519699726 s

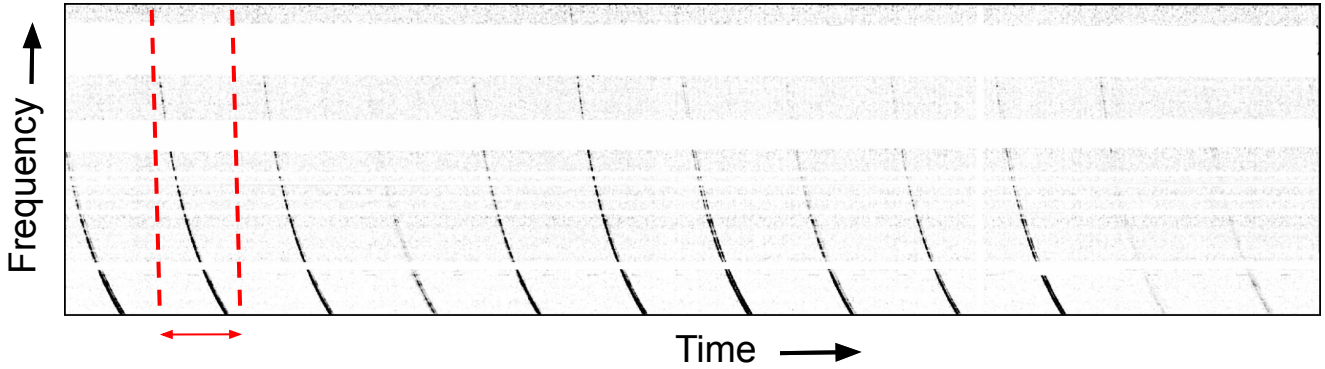
Raw pulsar signal

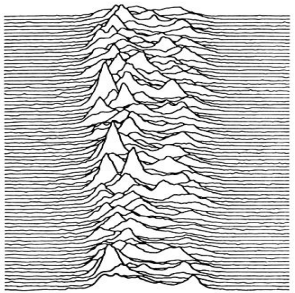




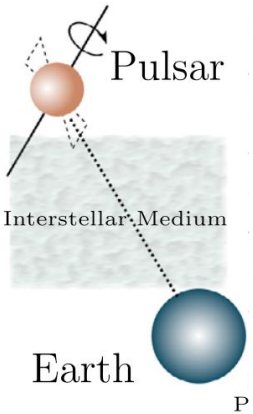
P = 0.714519699726 s

Dispersion



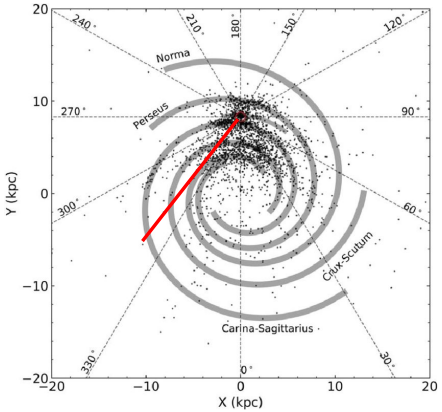


Dispersion

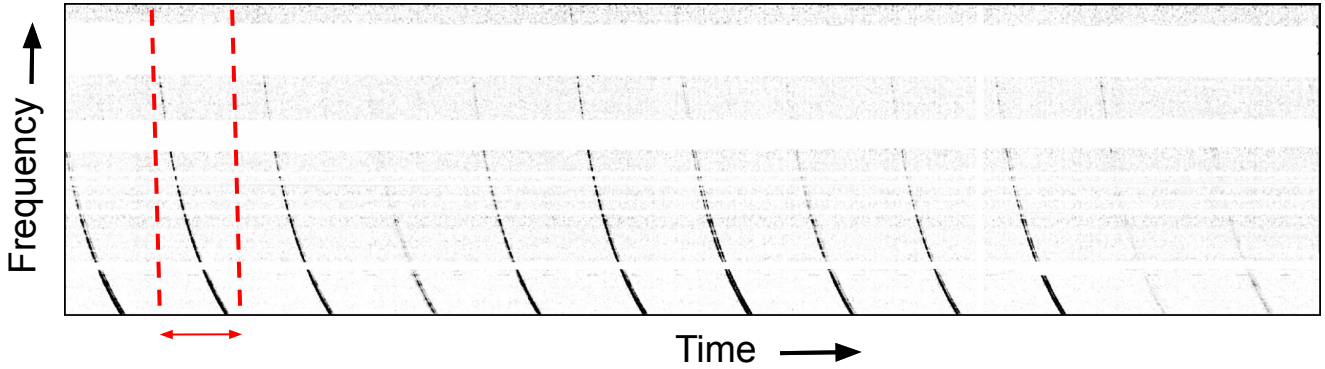


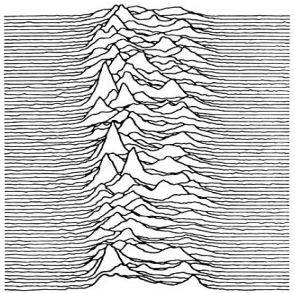
$$\mathrm{DM} = \int_0^d n_e \, dl$$

$$\Delta t \simeq 4.15 \times 10^6 \text{ ms } \times (f_1^{-2} - f_2^{-2}) \times \mathrm{DM}$$

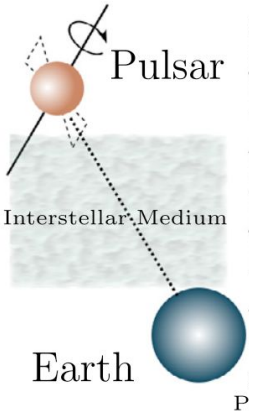


Dispersion



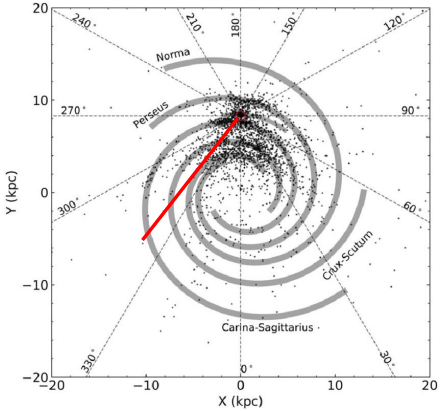


Dispersion



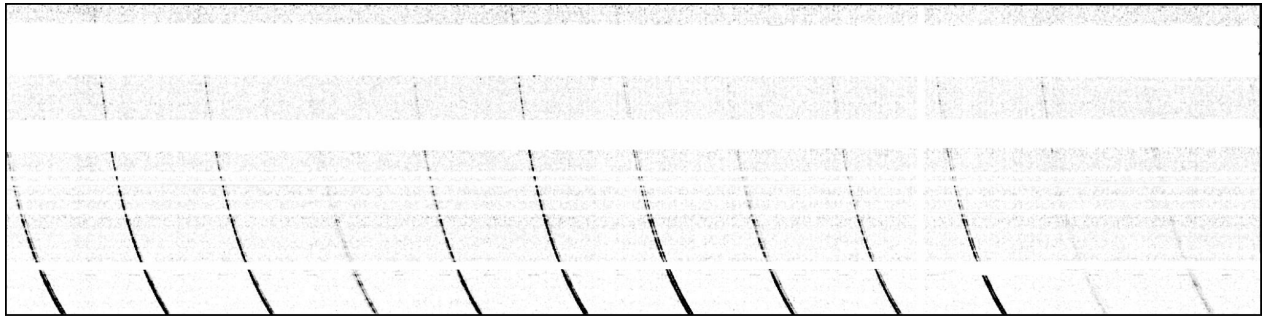
$$\mathrm{DM} = \int_0^d n_e \, dl$$

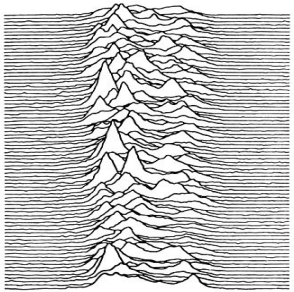
$$\Delta t \simeq 4.15 \times 10^6 \text{ ms } \times (f_1^{-2} - f_2^{-2}) \times \mathrm{DM}$$





Scattering





Scattering

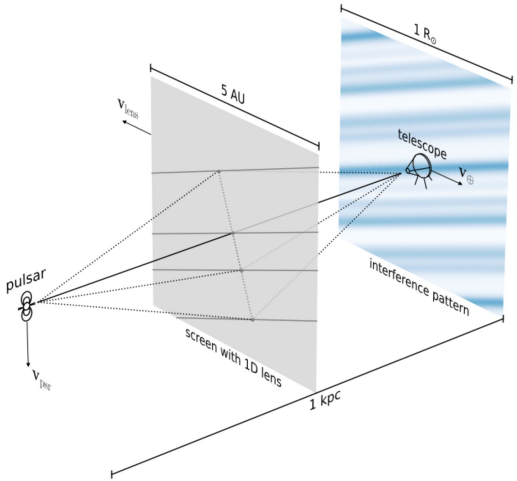
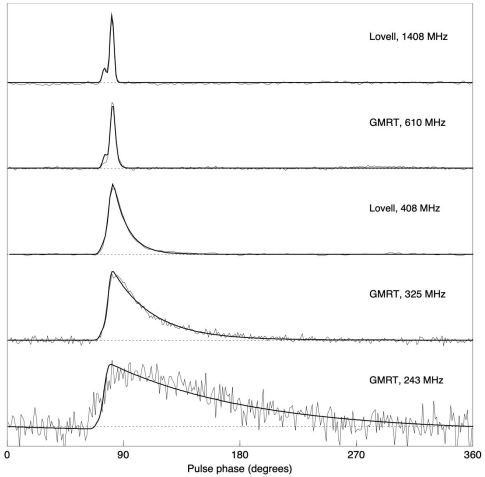
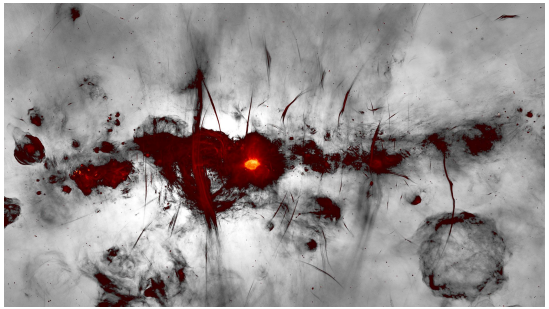


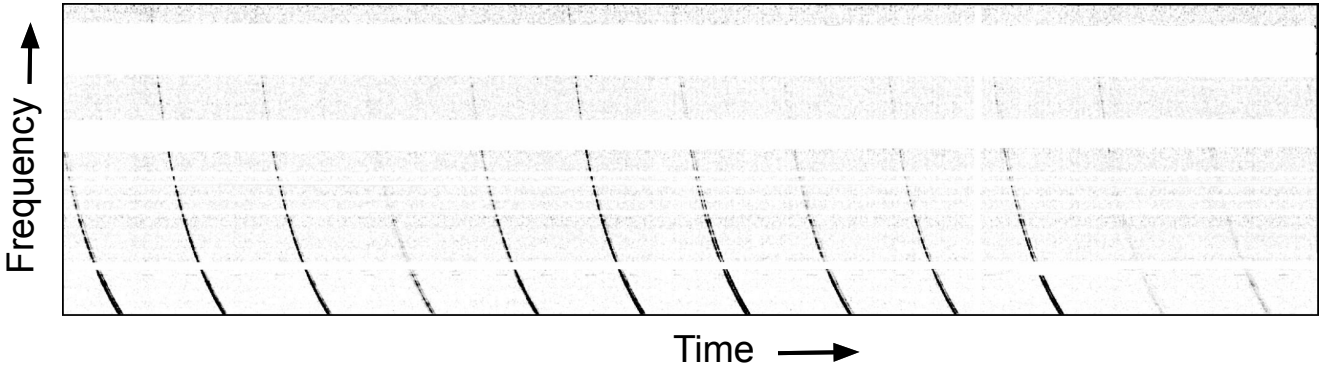
Illustration from “screens” package: https://screens.readthedocs.io/

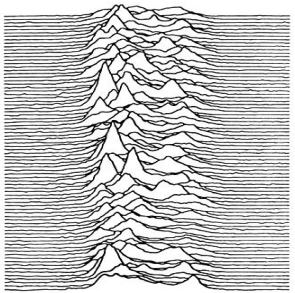




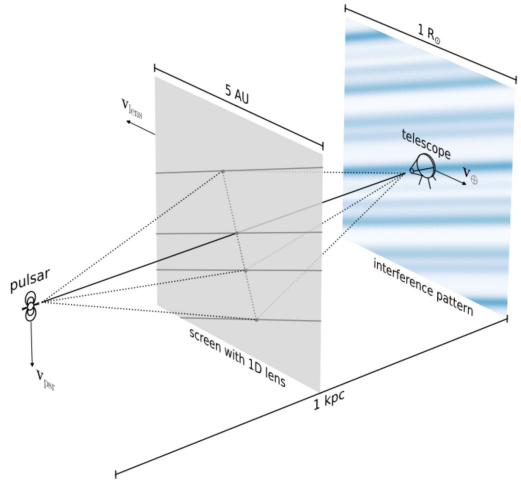
MeerKAT GC image. Credit: I. Heywood, SARAO

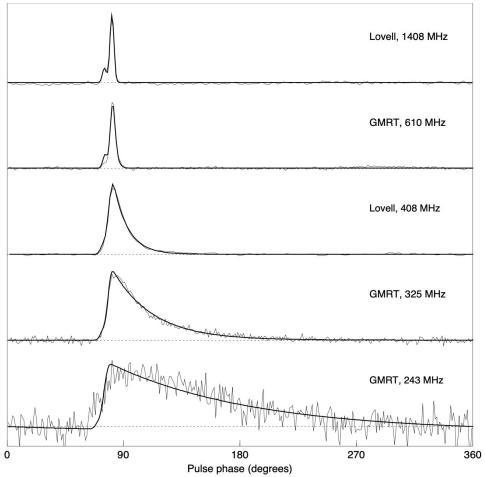
Scattering

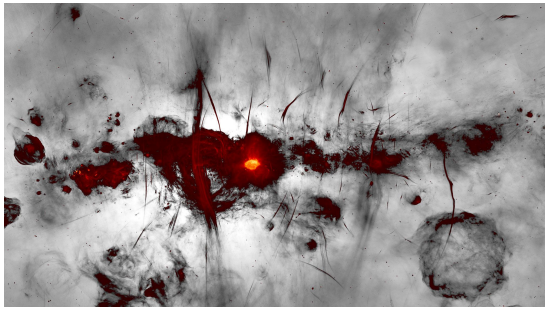




Scattering





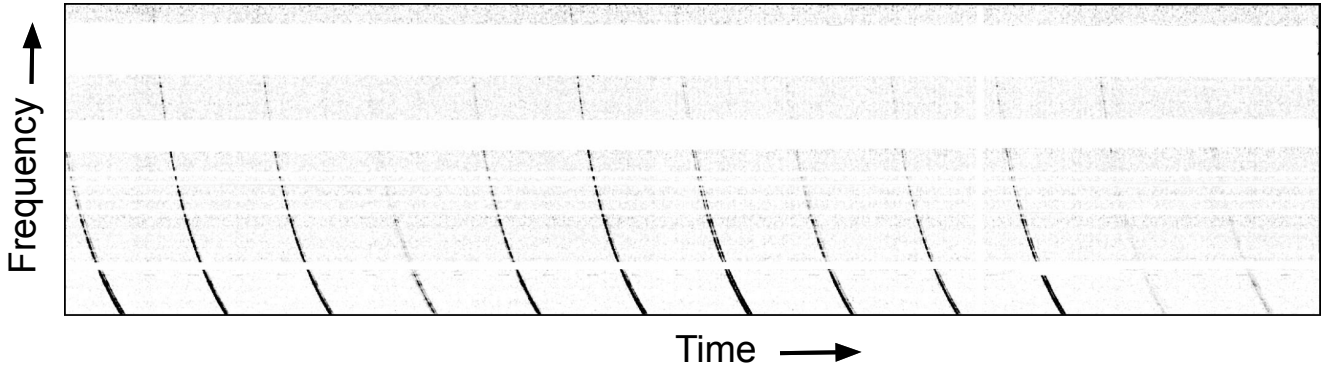


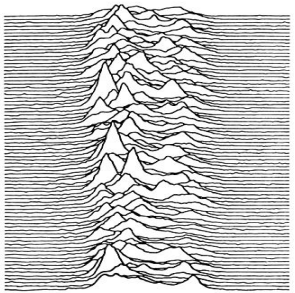
MeerKAT GC image. Credit: I. Heywood, SARAO



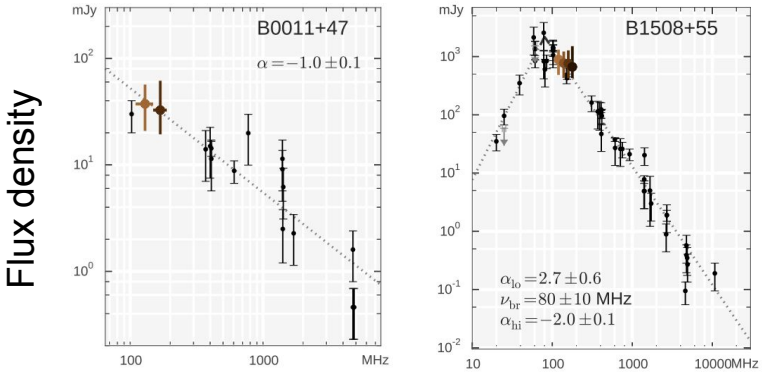
Illustration from “screens” package: https://screens.readthedocs.io/

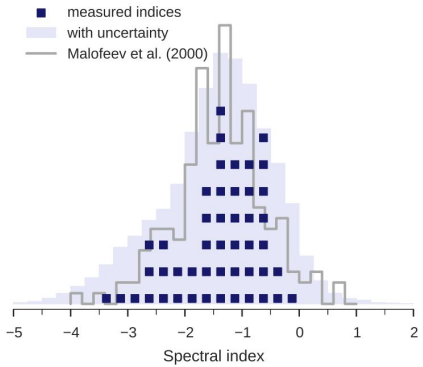
Steep spectrum





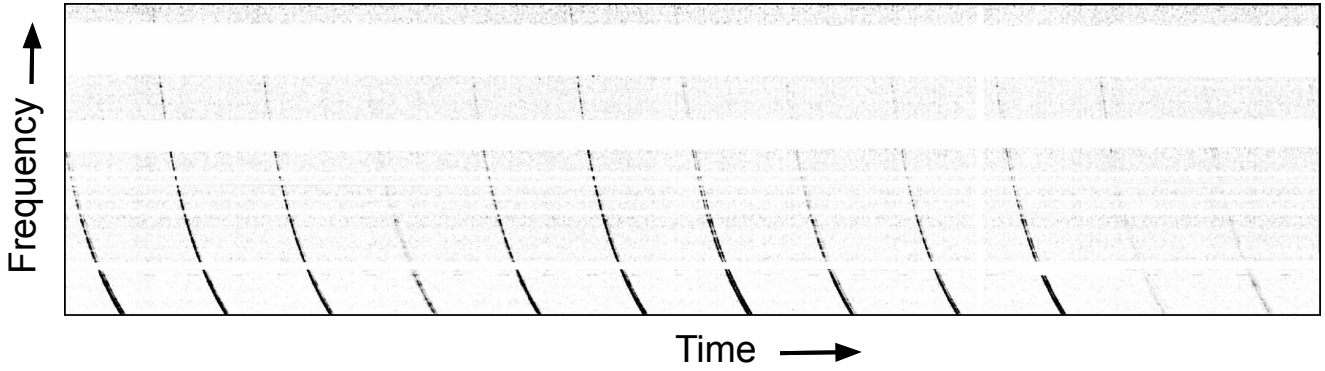
Steep spectrum

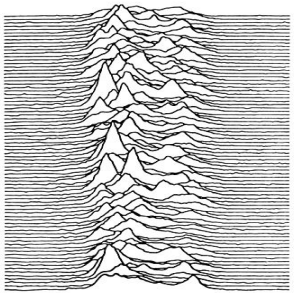




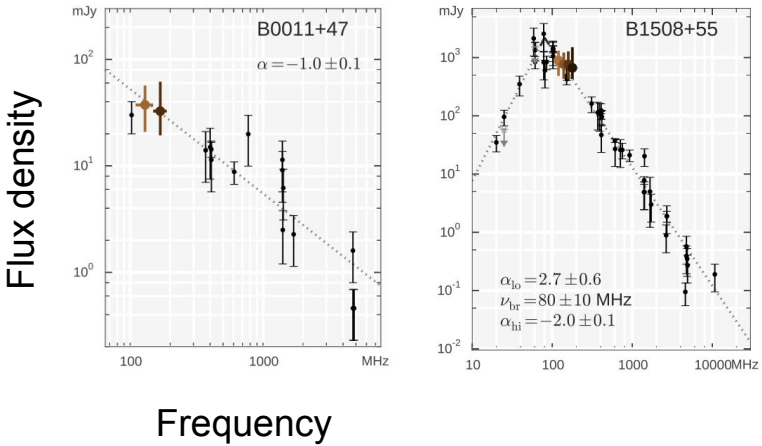
Bilous et al. 2016A&A...591A.134B

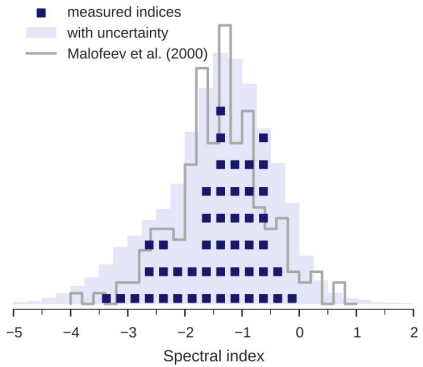
Steep spectrum





Steep spectrum





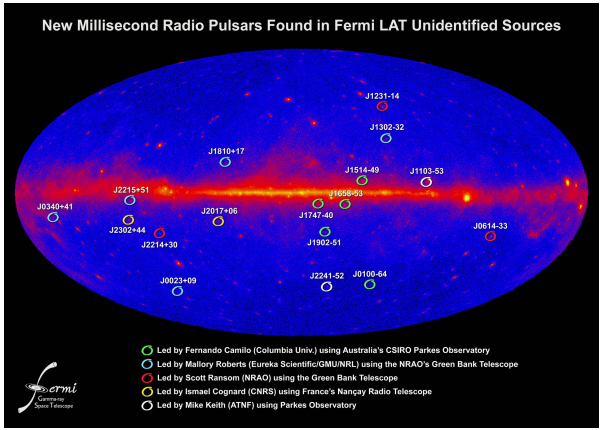


Bilous et al. 2016A&A...591A.134B

LOFAR Pulsar Surveys

Targeted

Survey targeting unassociated Fermi-Large Area Telescope γ-ray sources

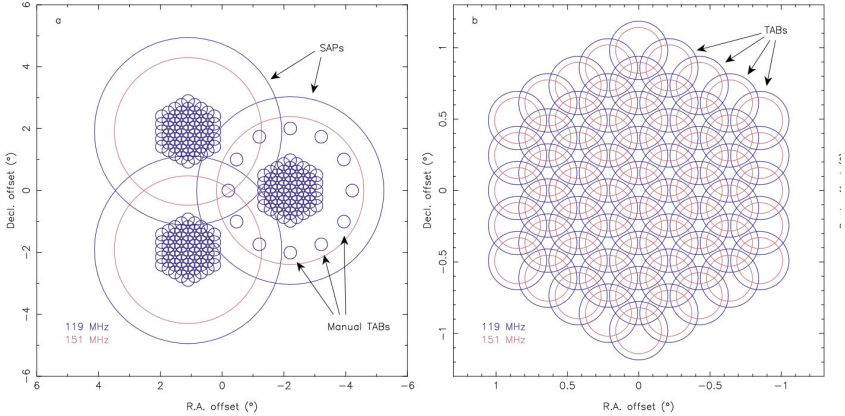


Bassa et al. 2017ApJ...846L..20B

Blind

LOTAAS:

The LOFAR Tied-Array All-Sky Survey

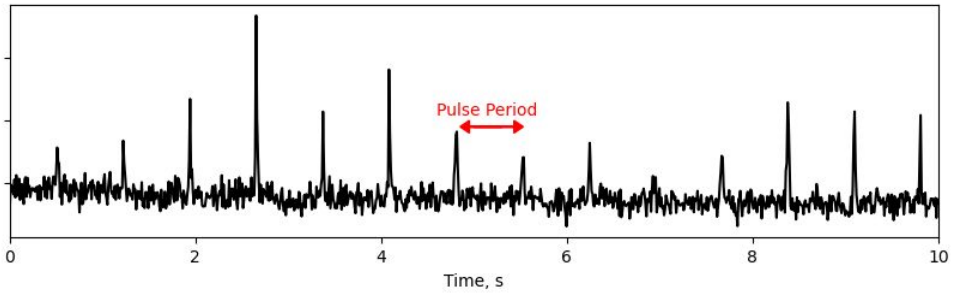


Sanidas et al. 2019A&A...626A.104S

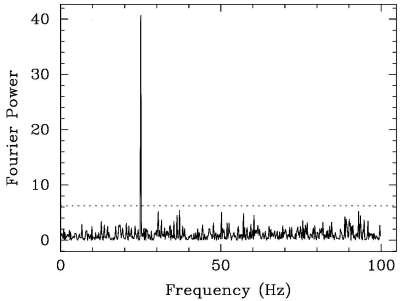
LOTSS:

LOFAR Two-metre Sky Survey

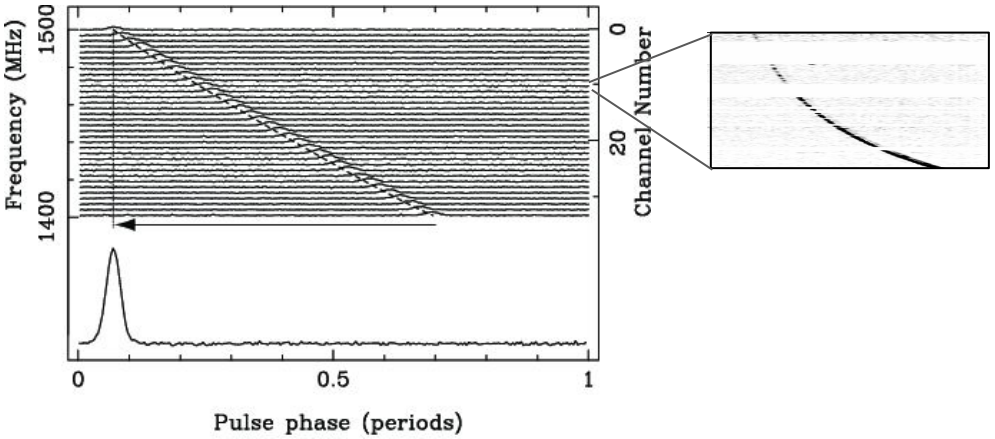
Pulsar searching and its challenges



FFT

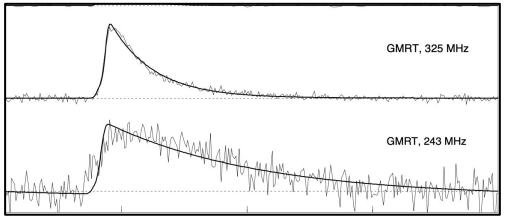


De-dispersion

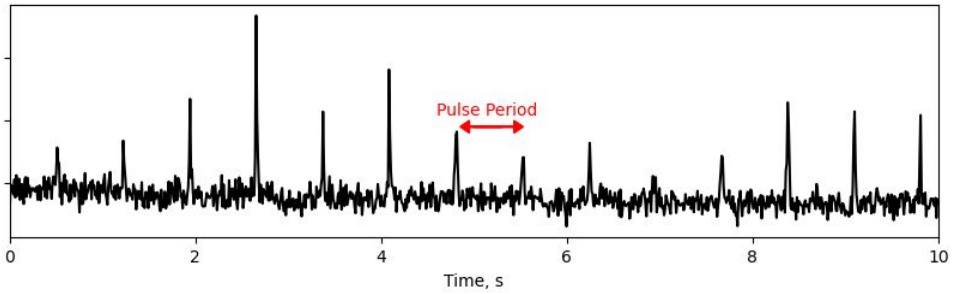


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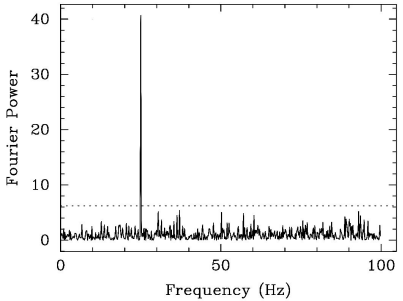
Scattering :(



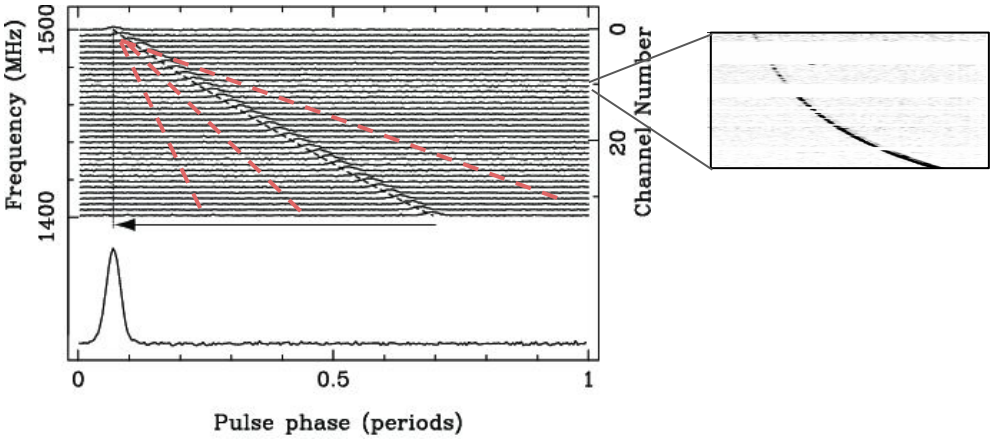
Pulsar searching and its challenges



FFT

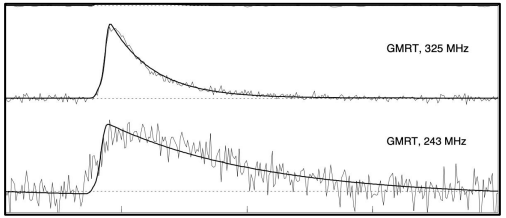


De-dispersion (trials)

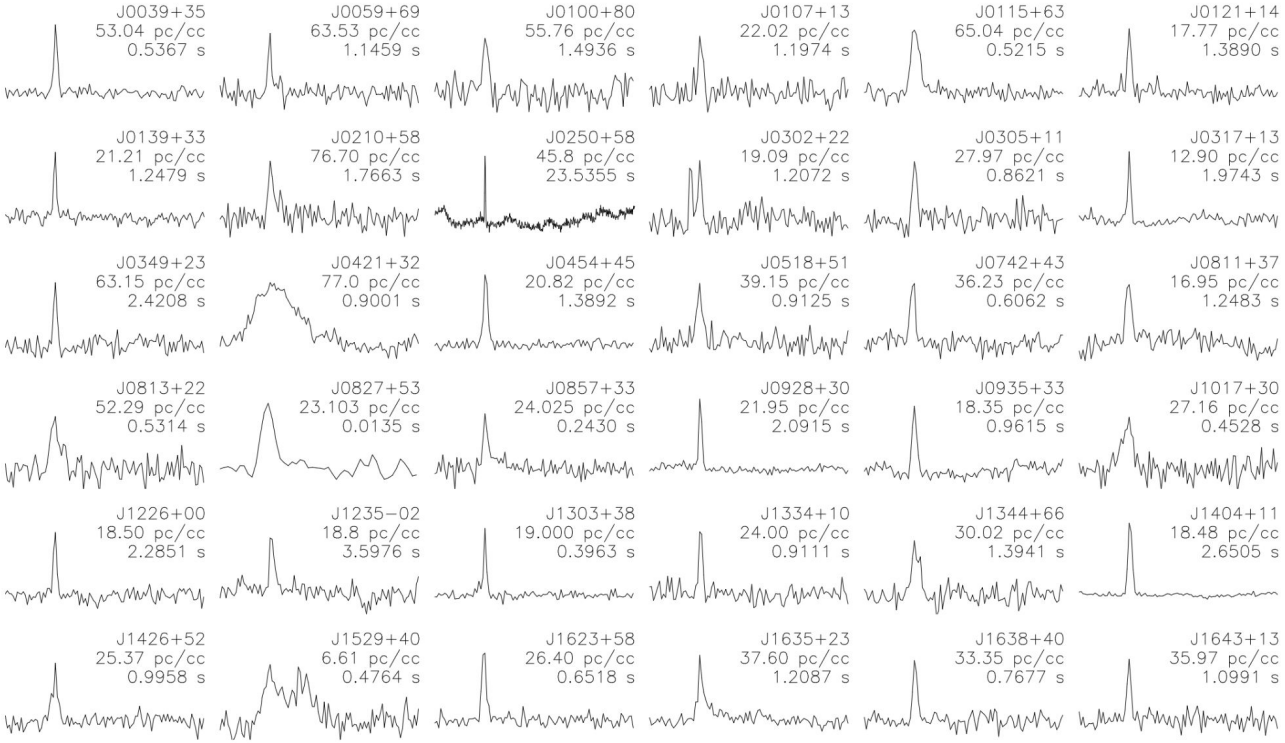


+

Scattering :(



LOFAR discovers >76 new pulsars

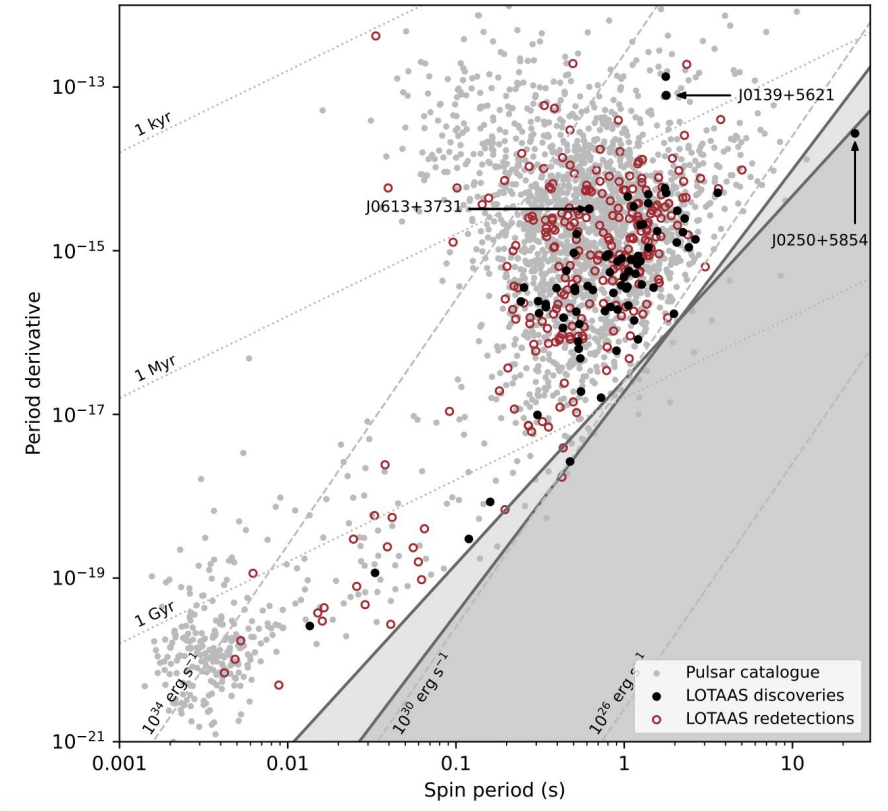


PSR J0952-0607: 1.414 ms
Second Fastest

PSR J0250+5854: 23.5 s
Second Slowest

Sanidas et al. 2019A&A...626A.104S

LOFAR discovers >76 new pulsars



PSR J0952-0607: 1.414 ms
Second Fastest

PSR J0250+5854: 23.5 s
Second Slowest

Van der Wateren et al. 2023A&A...669A.160V

PSR J0250+5854 is so slow it defies the pulsar death line

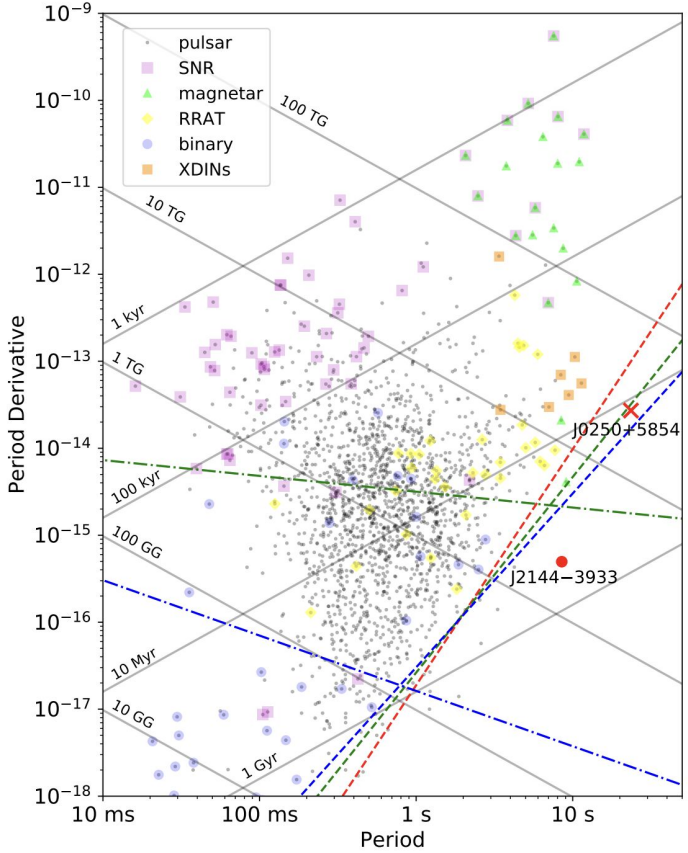
P = 23.5 s

Rotating magnetized neutron stars lose energy

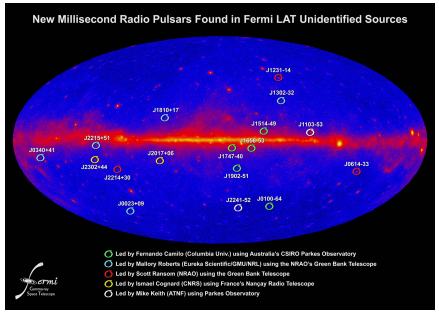
$$P, \dot{P} \quad \Longrightarrow \quad \dot{E} = 4\pi^2 I \frac{\dot{P}}{P^3}$$

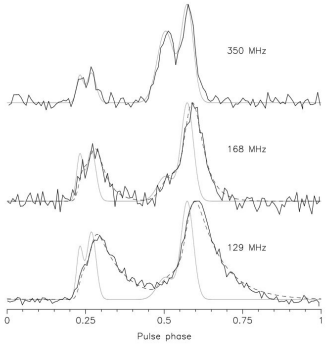
PSR J0250+5854 shouldn't have enough energy to emit radio pulses, but it does

Tan et al. 2018ApJ...866...54T



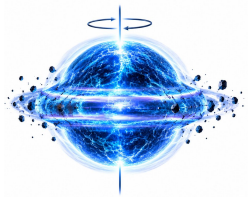
PSR J0952−0607 is so fast and heavy it pushes NS physics





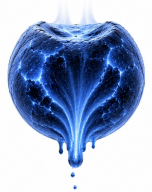
F0 = 707 Hz

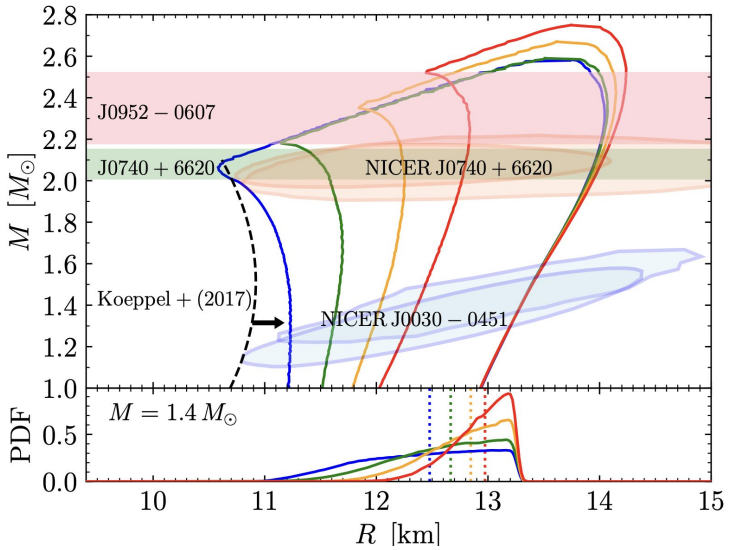
Extreme rotation constraints neutron-star structure and possible angular-momentum-loss mechanisms



$M_{NS} = 2.35 \pm 0.17 M_{\odot}$

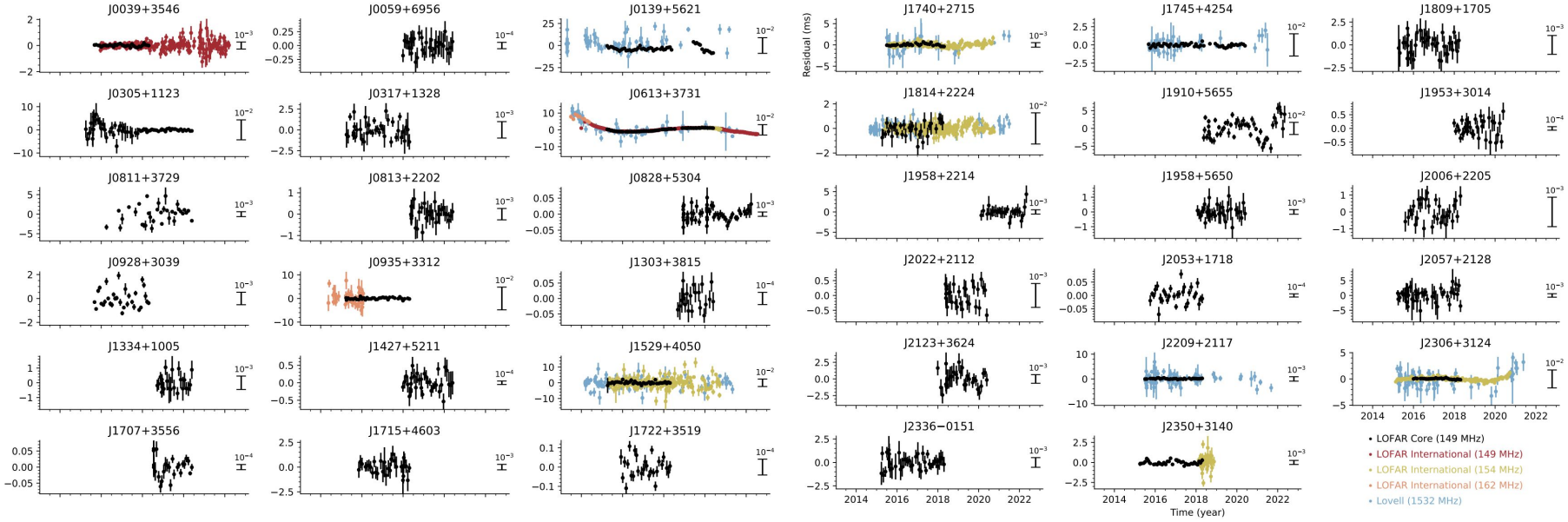
challenges EOS models that cannot support such a massive neutron star.





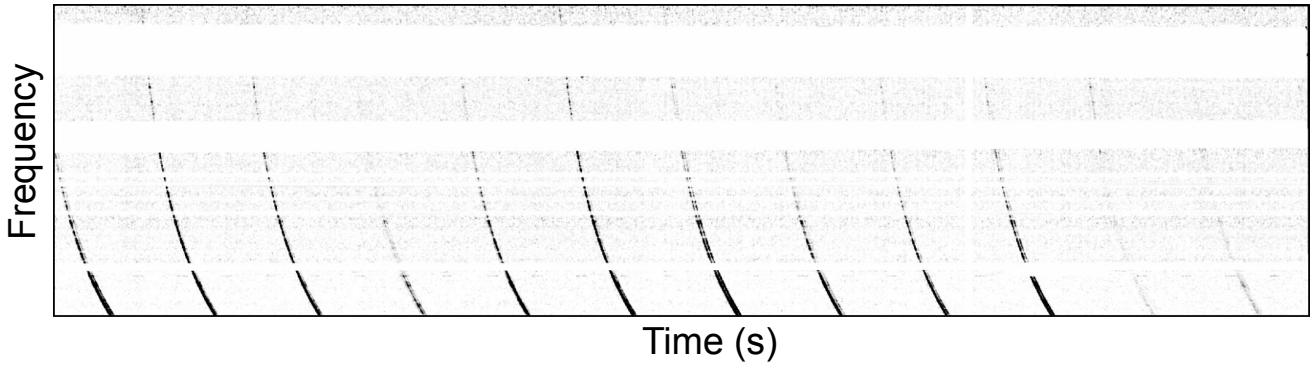
Bassa et al. 2017ApJ...846L..20B
Romani et al., 2022ApJ...934L..17R
Ecker & Rezzolla, 2023MNRAS.519.2615E

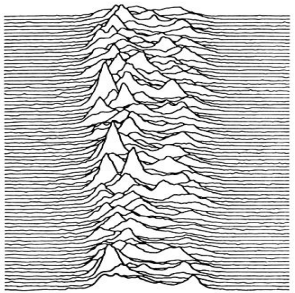
Pulsar Timing with LOFAR

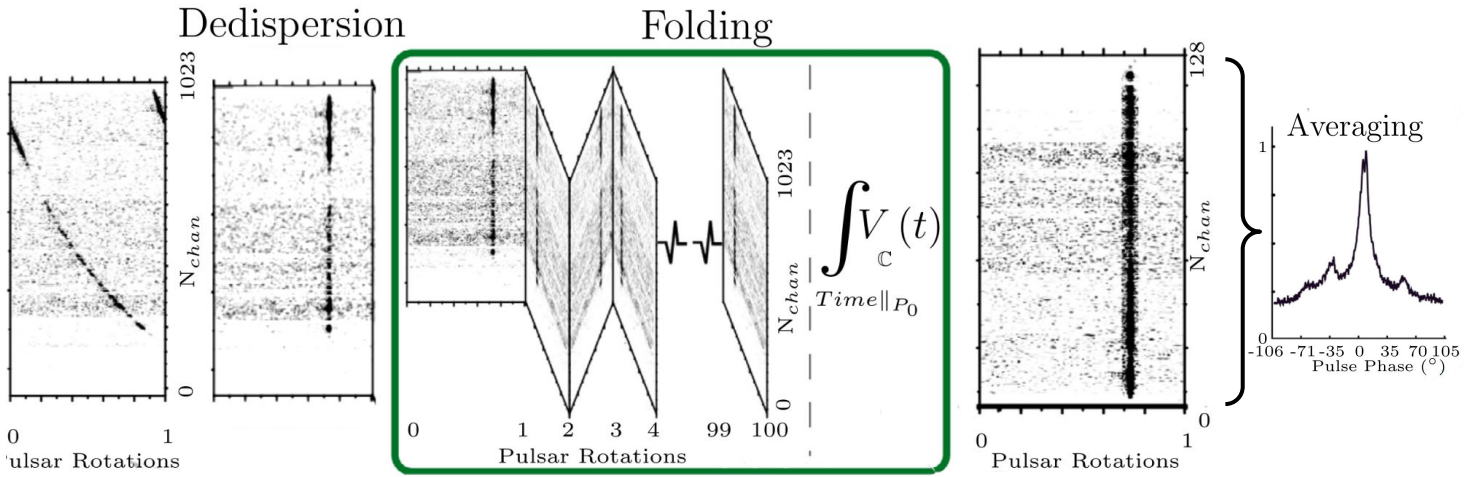


Van der Wateren et al. 2023A&A...669A.160V

Folding pulsar data

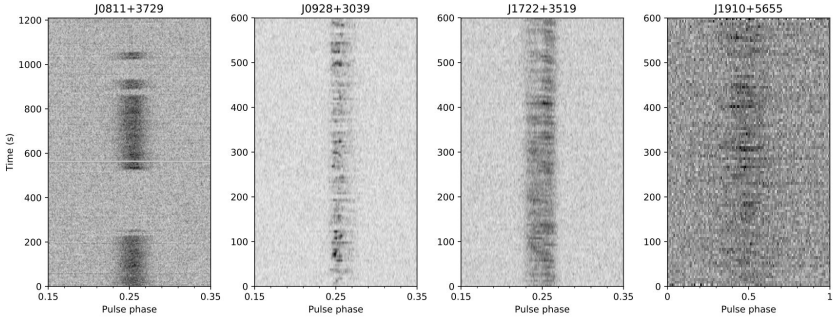


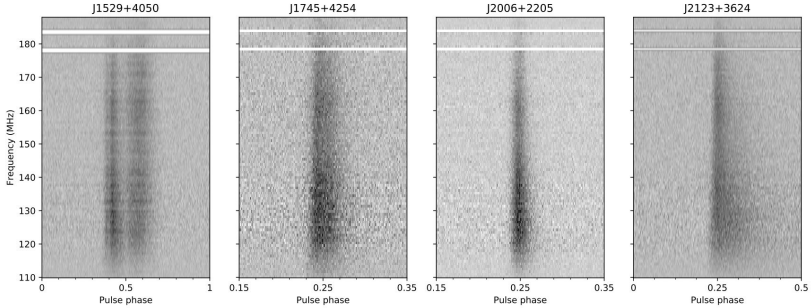




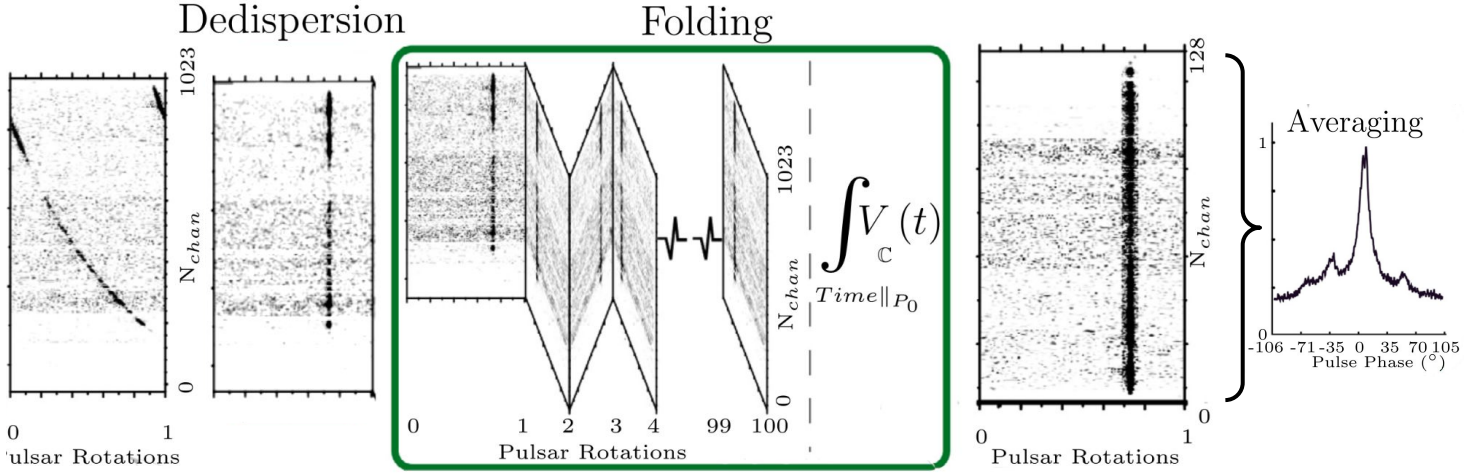
Verbiest & Shaifullah, 2018CQGra..35m3001V

Folding pulsar data





Van der Wateren et al. 2023A&A...669A.160V



Verbiest & Shaifullah, 2018CQGra..35m3001V

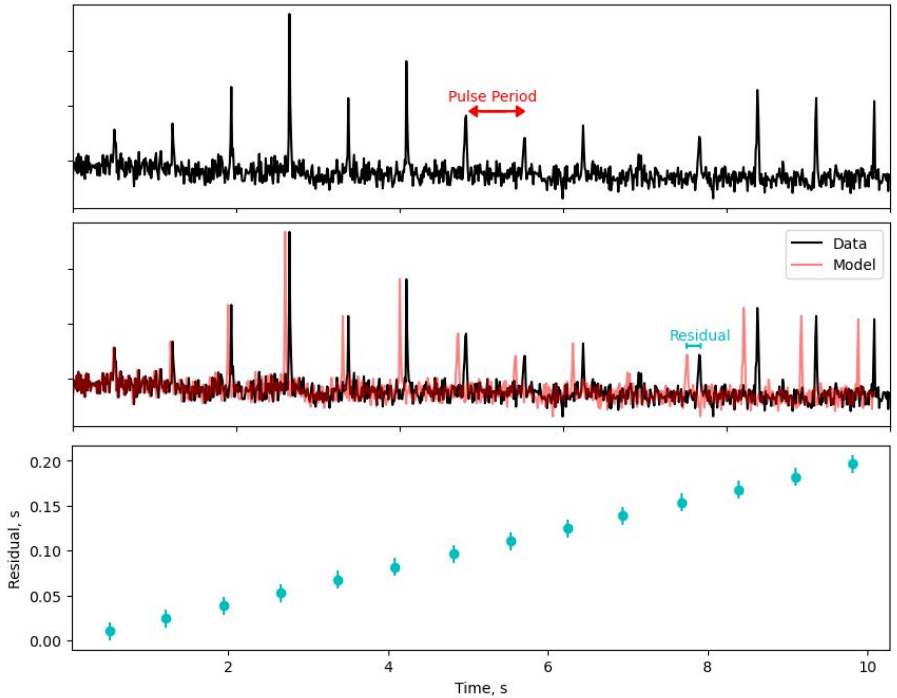
Pulsar Timing

Pulsar parameters

P_0

instr.

$$\Delta t = \Delta_{\mathrm{C}} + \Delta_{\mathrm{A}}$$



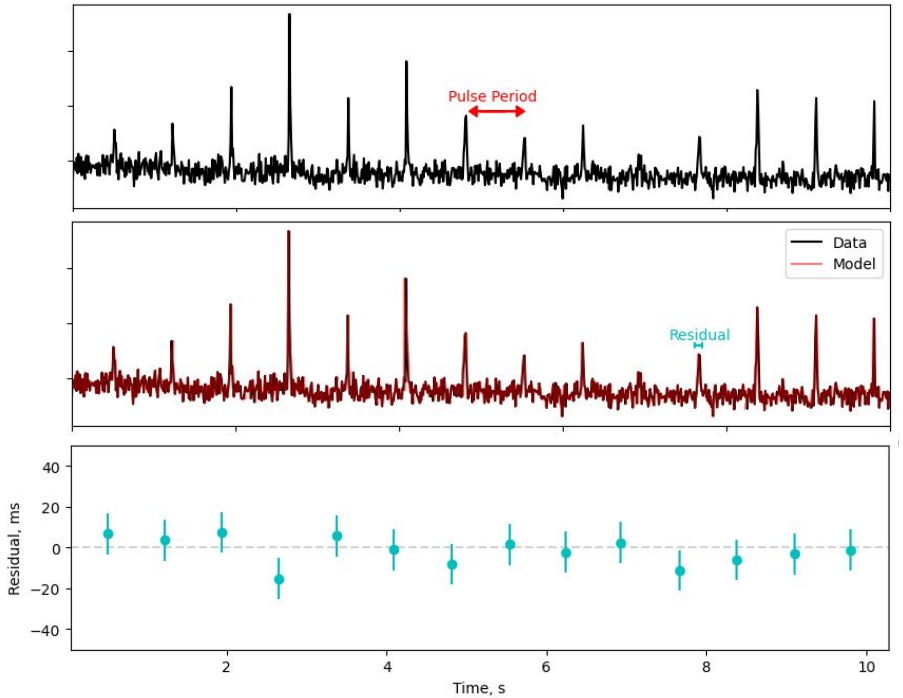
Pulsar Timing

Pulsar parameters

$$\mathrm{P}_0$$

instr.

$$\Delta t = \Delta_{\mathrm{C}} + \Delta_{\mathrm{A}}$$

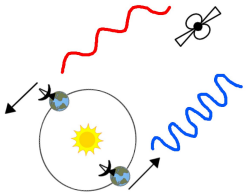


Pulsar Timing

Pulsar parameters

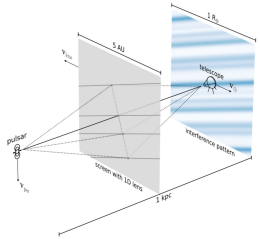
P_0

α, δ



$\dot{\mathrm{P}}_0$

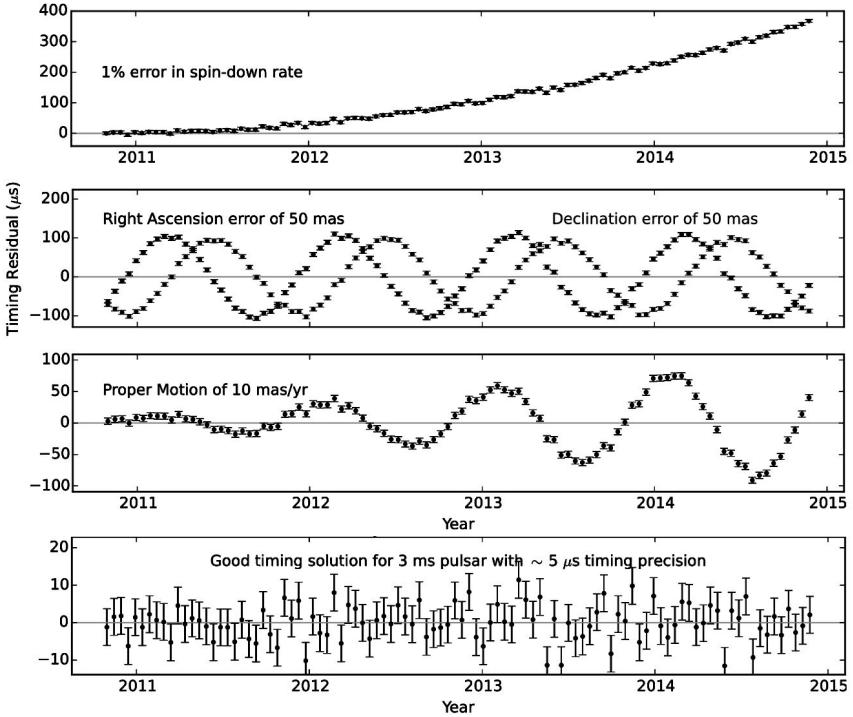
μ_α, μ_δ



DM

instr. solar system ISM

$$\Delta t = \Delta_{\mathrm{C}} + \Delta_{\mathrm{A}} + \Delta_{\mathrm{E}_\odot} + \Delta_{\mathrm{R}_\odot} + \Delta_{\mathrm{S}_\odot} - D/f^2$$



Pulsar Timing

Pulsar parameters

P_0

α, δ

$\dot{\mathrm{P}}_0$

μ_α, μ_δ

DM

+

Pulsar orbital parameters

P_b

e

x

T_0

ω

T_{asc}

η

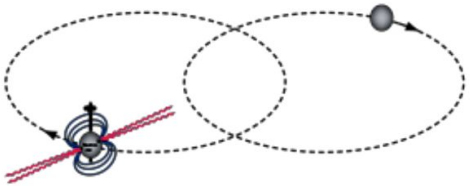
κ

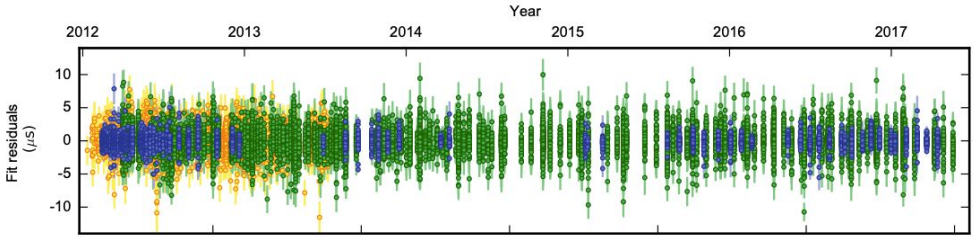
Ω

i

instr. solar system ISM pulsar orbit

$$\Delta t = \Delta_{\mathrm{C}} + \Delta_{\mathrm{A}} + \Delta_{\mathrm{E}_\odot} + \Delta_{\mathrm{R}_\odot} + \Delta_{\mathrm{S}_\odot} - D/f^2 + \Delta_{\mathrm{VP}} + \Delta_{\mathrm{B}}$$





Pulsar Timing

Pulsar parameters

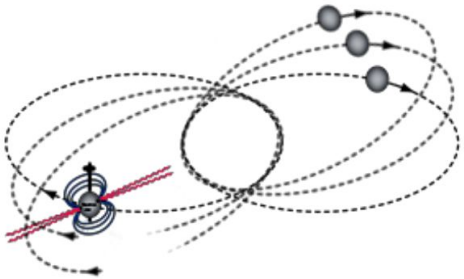
Pulsar orbital parameters

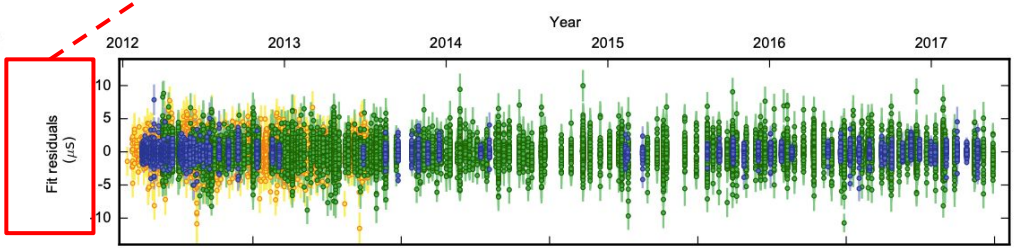
$$\mathrm{P}_0 \quad \alpha, \delta \quad \dot{\mathrm{P}}_0 \quad \mu_\alpha, \mu_\delta \quad \mathrm{DM} + \begin{matrix} P_b \\ e \\ x \\ T_0 \\ \omega \\ T_{\mathrm{asc}} \\ \eta \\ \kappa \\ \Omega \\ i \end{matrix} + \begin{matrix} \dot{\omega} \\ \dot{P}_b \\ \dot{e} \\ \dot{x} \\ \gamma \\ \dot{\eta} \\ \dot{\kappa} \end{matrix}$$

instr. solar system ISM pulsar orbit

$$\Delta t = \Delta_{\mathrm{C}} + \Delta_{\mathrm{A}} + \Delta_{\mathrm{E}_\odot} + \Delta_{\mathrm{R}_\odot} + \Delta_{\mathrm{S}_\odot} - D/f^2 + \Delta_{\mathrm{VP}} + \Delta_{\mathrm{B}}$$

km





Pulsar Timing

Pulsar parameters

Pulsar orbital parameters

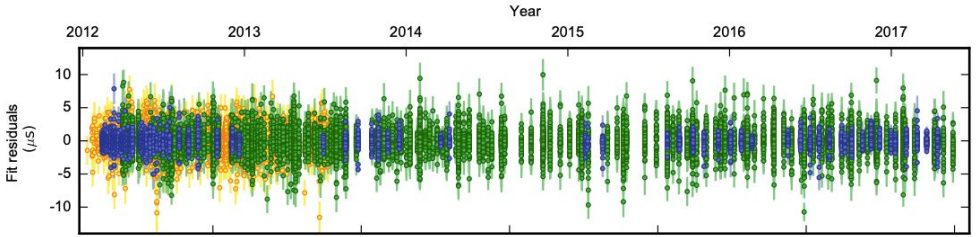
$$\mathrm{P}_0 \quad \alpha, \delta \quad \dot{\mathrm{P}}_0 \quad \mu_\alpha, \mu_\delta \quad \mathrm{DM} \quad + \quad P_b \; e \; x \; T_0 \; \omega \; T_{\mathrm{asc}} \; \eta \; \kappa \; \Omega \; i \quad + \quad \dot{\omega} \; \dot{P}_b \; \dot{e} \; \dot{x} \; \gamma \; \dot{\eta} \; \dot{\kappa}$$

instr. solar system ISM pulsar orbit

$$\Delta t = \Delta_{\mathrm{C}} + \Delta_{\mathrm{A}} + \Delta_{\mathrm{E}_\odot} + \Delta_{\mathrm{R}_\odot} + \Delta_{\mathrm{S}_\odot} - D/f^2 + \Delta_{\mathrm{VP}} + \Delta_{\mathrm{B}}$$

Pulsar ephemeris

PSRJ	J1915+1606	
RAJ	19:15:27.99942	3.000e-05
DECJ	+16:06:27.3868	5.000e-04
DM	168.770	1.000e-02
PEPOCH	52984.0	
F0	16.940537785677	3.000e-12
F1	-2.47330E-15	1.000e-19
PMRA	-0.72	1.100e-01
PMDEC	-0.03	1.400e-01
POSEPOCH	52984.0	
BINARY	DDH	
PB	0.322997448918	3.000e-12
ECC	0.6171340	4.000e-07
A1	2.341782	3.000e-06
T0	52144.90097849	3.000e-08
OM	292.54450	8.000e-05



Pulsar Timing

Pulsar parameters

Pulsar orbital parameters

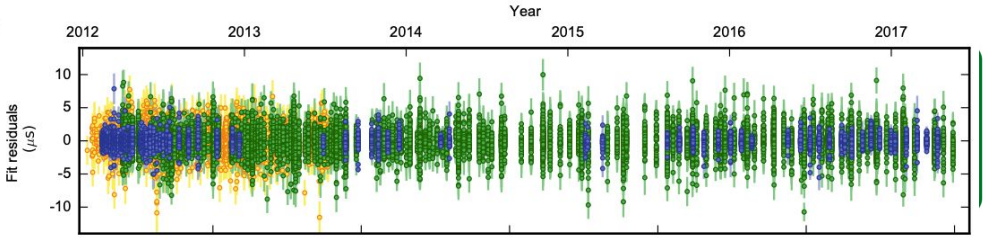
$$\mathrm{P}_0 \quad \alpha, \delta \quad \dot{\mathrm{P}}_0 \quad \mu_\alpha, \mu_\delta \quad \mathrm{DM} \quad + \quad P_b \; e \; x \; T_0 \; \omega \; T_{\mathrm{asc}} \; \eta \; \kappa \; \Omega \; i \quad + \quad \dot{\omega} \; \dot{P}_b \; \dot{e} \; \dot{x} \; \gamma \; \dot{\eta} \; \dot{\kappa}$$

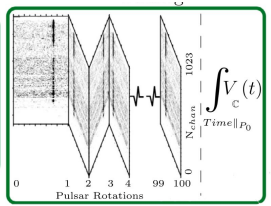
instr. solar system ISM pulsar orbit

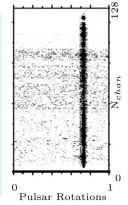
$$\Delta t = \Delta_{\mathrm{C}} + \Delta_{\mathrm{A}} + \Delta_{\mathrm{E}_\odot} + \Delta_{\mathrm{R}_\odot} + \Delta_{\mathrm{S}_\odot} - D/f^2 + \Delta_{\mathrm{VP}} + \Delta_{\mathrm{B}}$$

Pulsar ephemeris

PSRJ	J1915+1606	
RAJ	19:15:27.99942	3.000e-05
DECJ	+16:06:27.3868	5.000e-04
DM	168.770	1.000e-02
PEPOCH	52984.0	
F0	16.940537785677	3.000e-12
F1	-2.47330E-15	1.000e-19
PMRA	-0.72	1.100e-01
PMDEC	-0.03	1.400e-01
POSEPOCH	52984.0	
BINARY	DDH	
PB	0.322997448918	3.000e-12
ECC	0.6171340	4.000e-07
A1	2.341782	3.000e-06
T0	52144.90097849	3.000e-08
OM	292.54450	8.000e-05

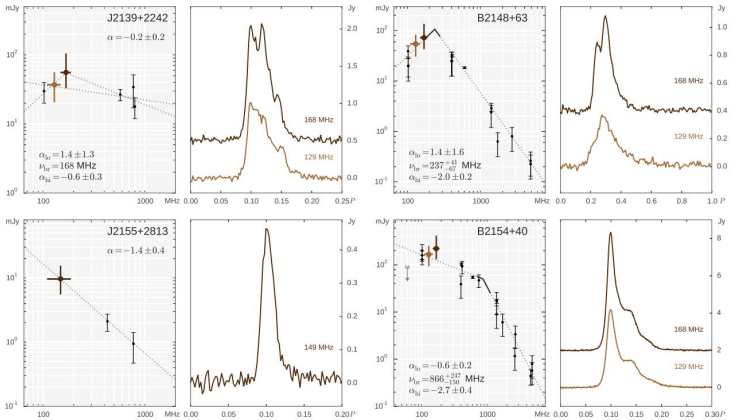




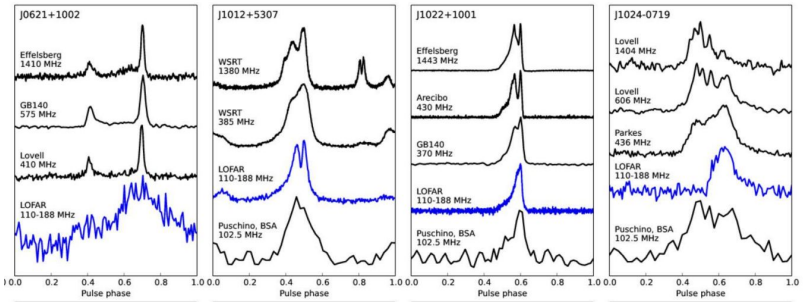


LOFAR Pulsar Census

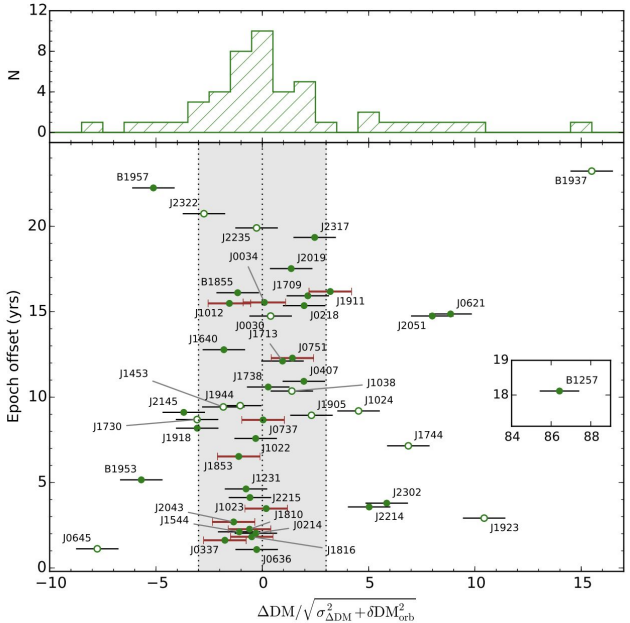
Pulsar spectra are more complex than simple power laws



MSP radio beams barely change width with frequency



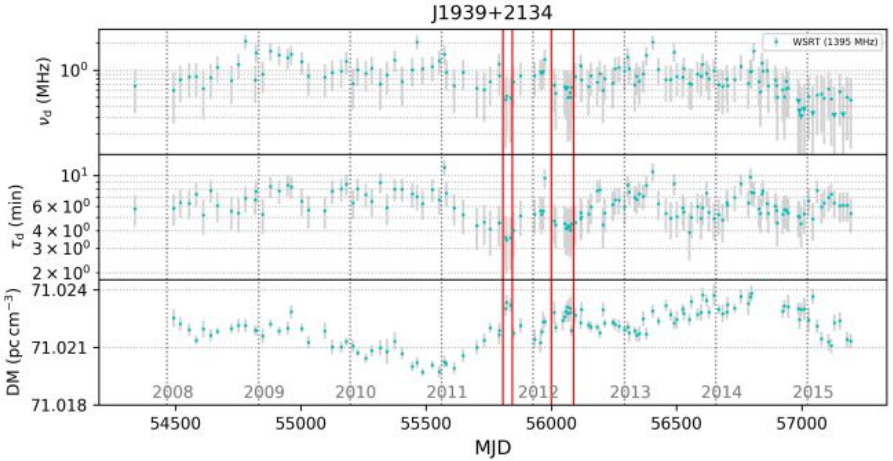
LOFAR dramatically improves dispersion-measure precision



Kondratiev et al. 2016A&A...585A.128K

Bilous et al. 2016A&A...591A.134B

LOFAR DM variability measurements



Long-term scintillation studies of EPTA pulsars; Liu et al. 2022.

LOFAR dramatically improves dispersion-measure precision

