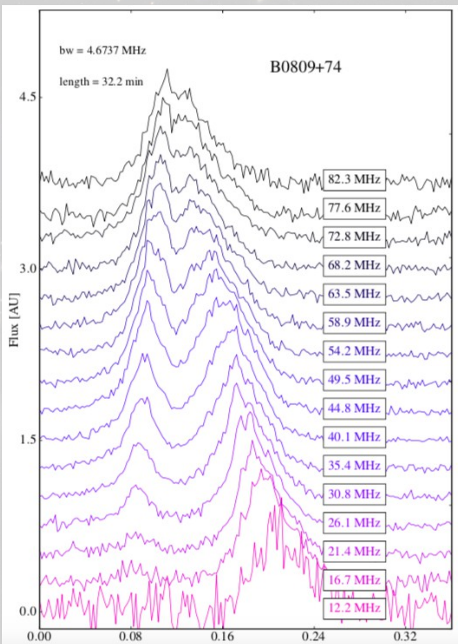
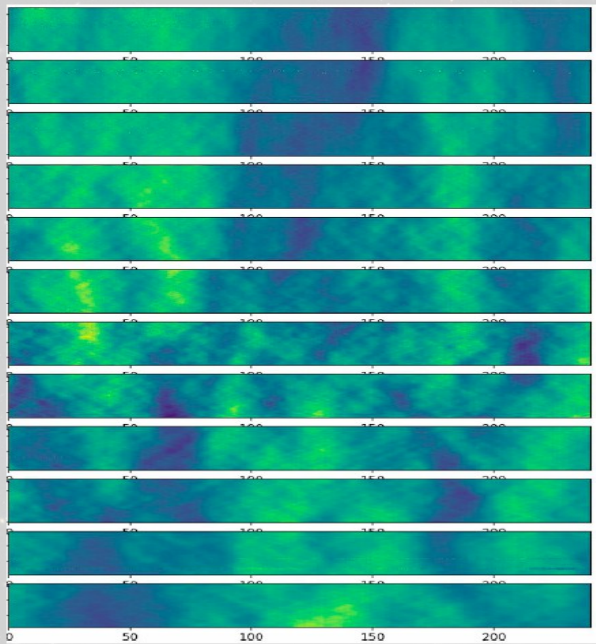
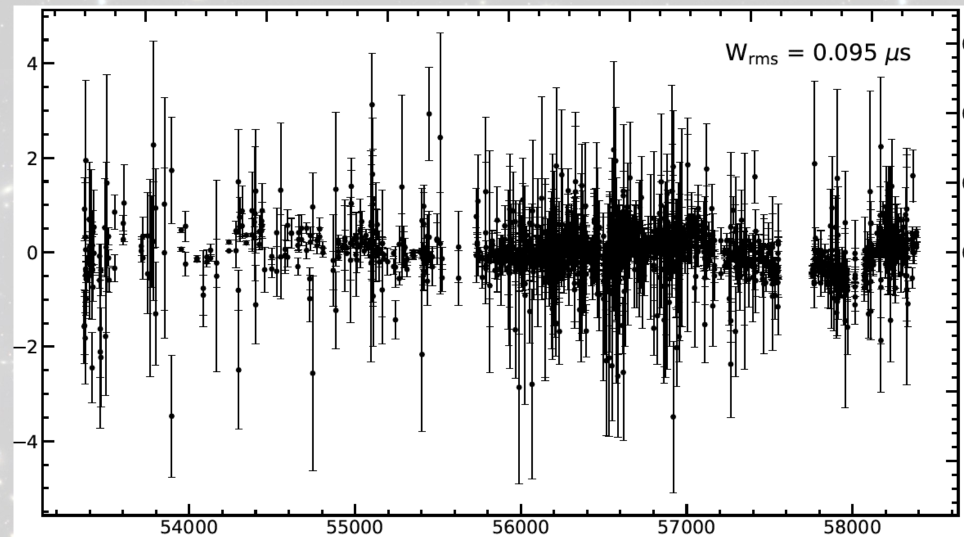
Pulsars : a brief overview of last results from NenuFAR, MeerKAT and IPTA





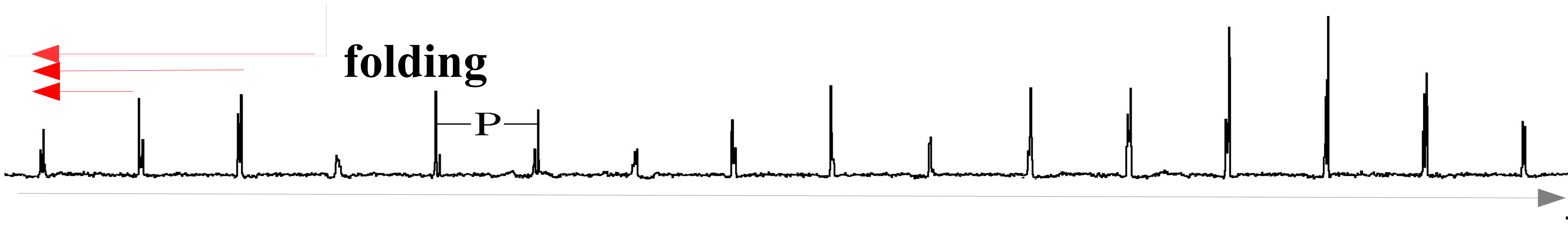


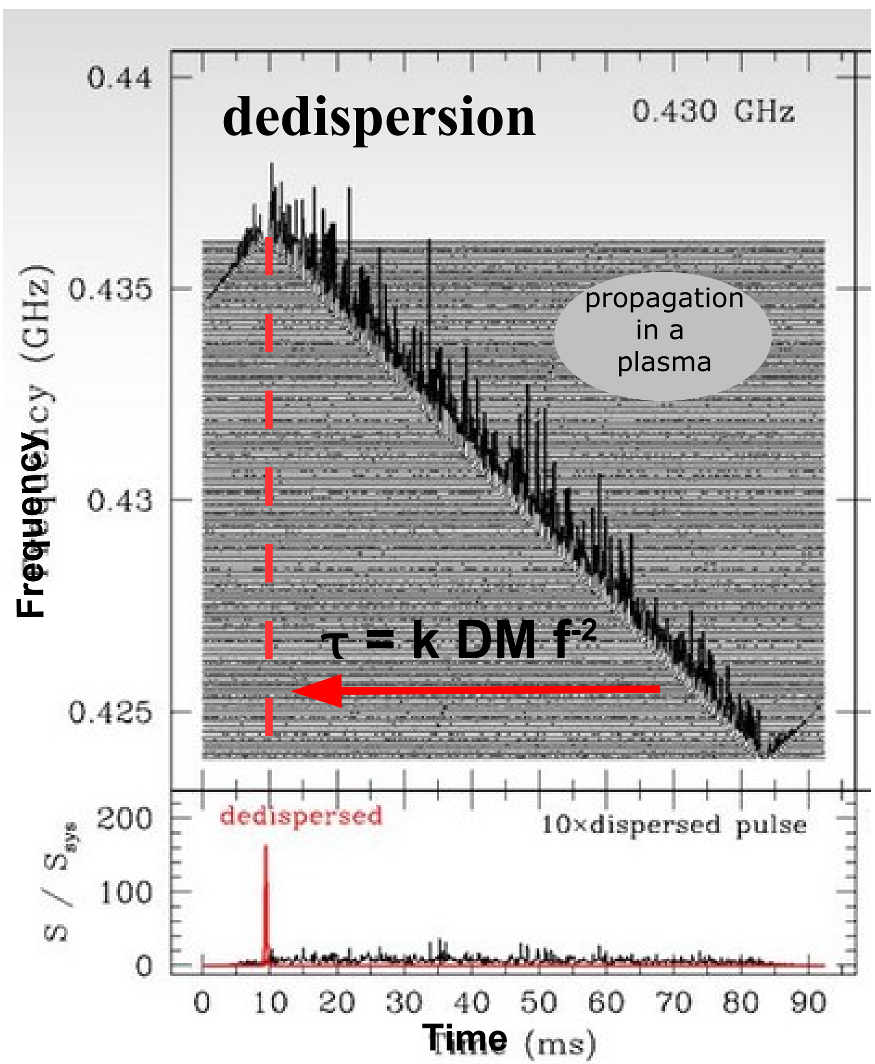
SKA-LOFAR, November 2019

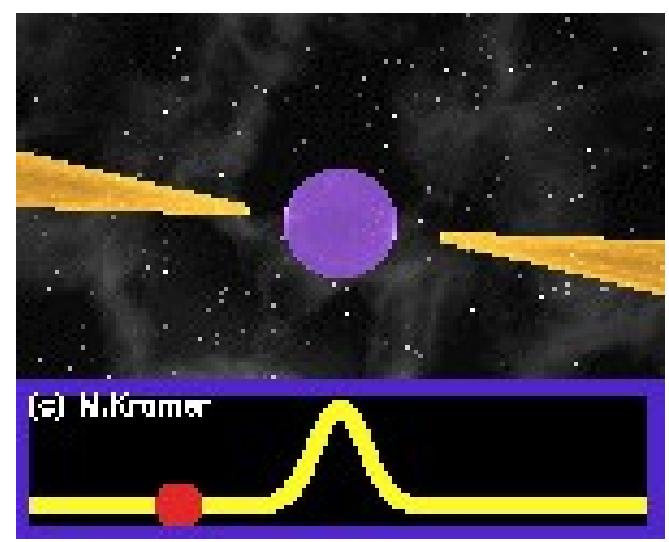
G.Theureau (LUTh/USN/LPC2E)

A.Petiteau, S.Babak (APC), **I.Cognard, L.Guillemot, J.M.Griessmeier** (LPC2E/USN),
Post-doc – **S.Chen, L.Bondonneau** (LPC2E/USN), **G.Voisin** (LUTh, Univ. Manchester)
PhD – **A.Berthereau, Mark Brionne** (LPC2E/USN), **A.Chalumeau**, **Mikel Falxa** (APC)

Timing pulsars







Characterize and model the radiation beam

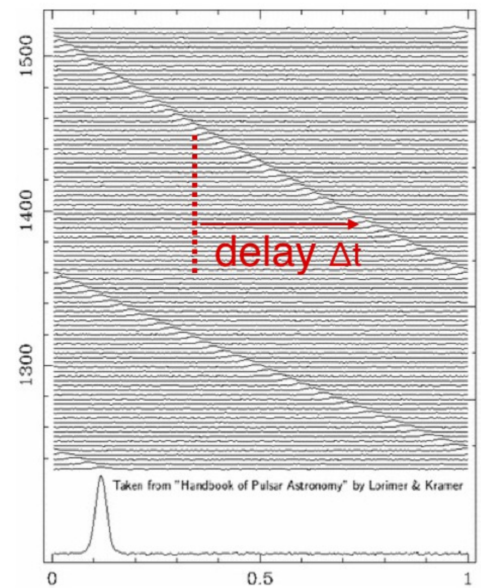
Time precisely the pulsar rotation and use it as a clock → GR tests, GW

NenuFAR

UnDysPuTeD backend

LUPPI coherent dedispersion code

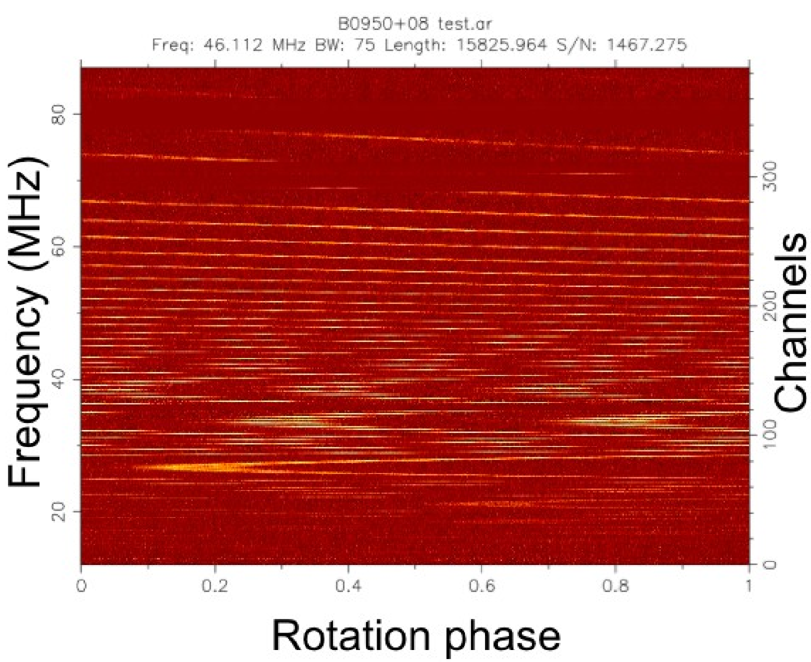
(Louis Bondonneau PhD thesis)

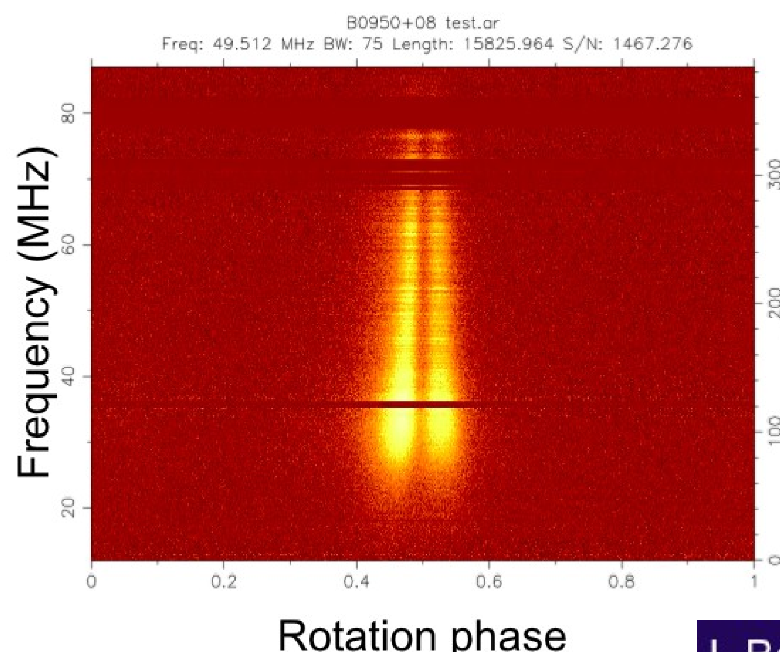


$\Delta t \propto f^{-2}$

1400 MHz	x1
60 MHz	x500
10 MHz	x20000

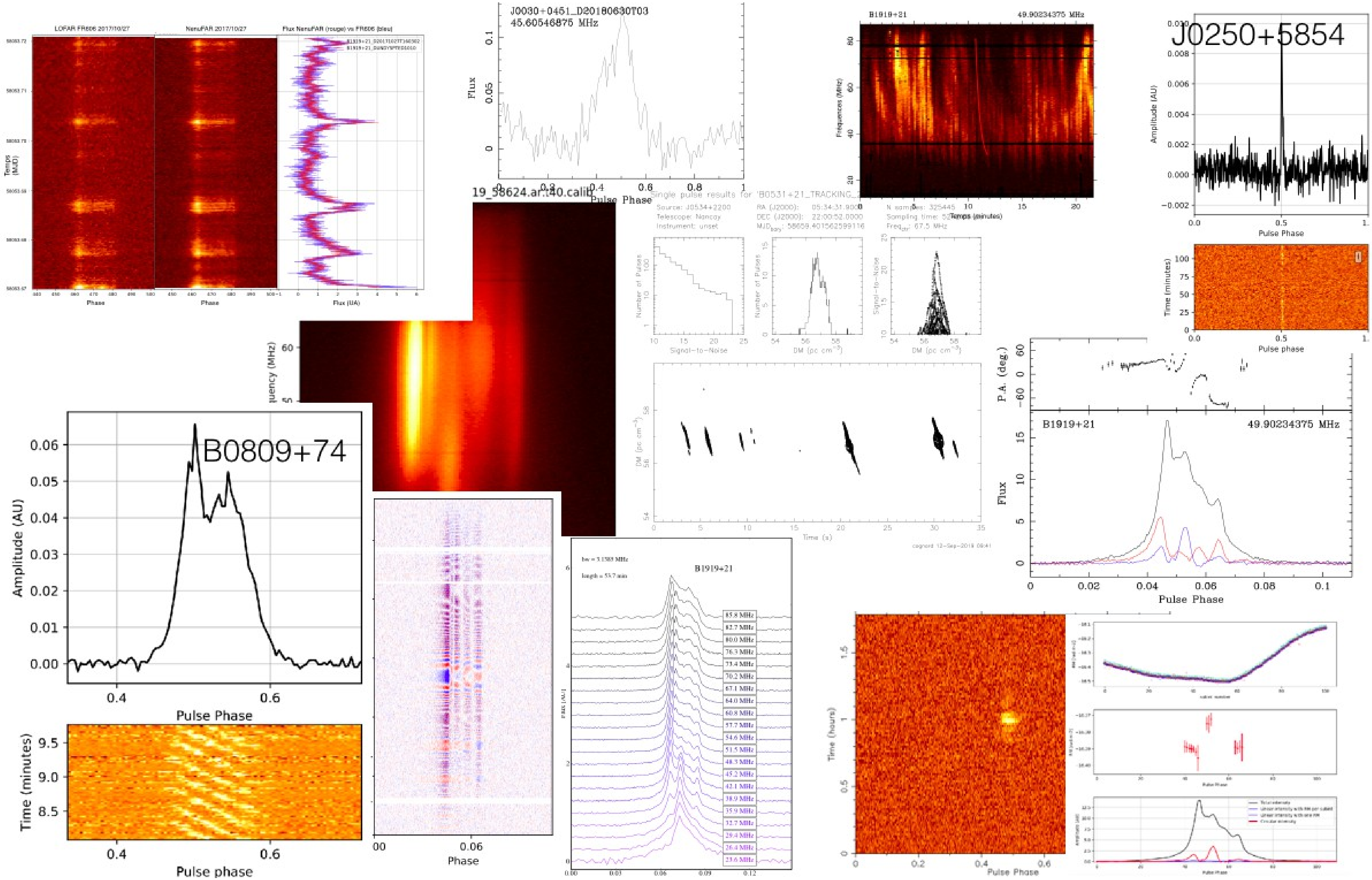
Dispersed pulsar — Pulsar backend → De-dispersed pulsar





L.Bondonneau (LPC2E)

NenuFAR commissioning data : exploring observing modes

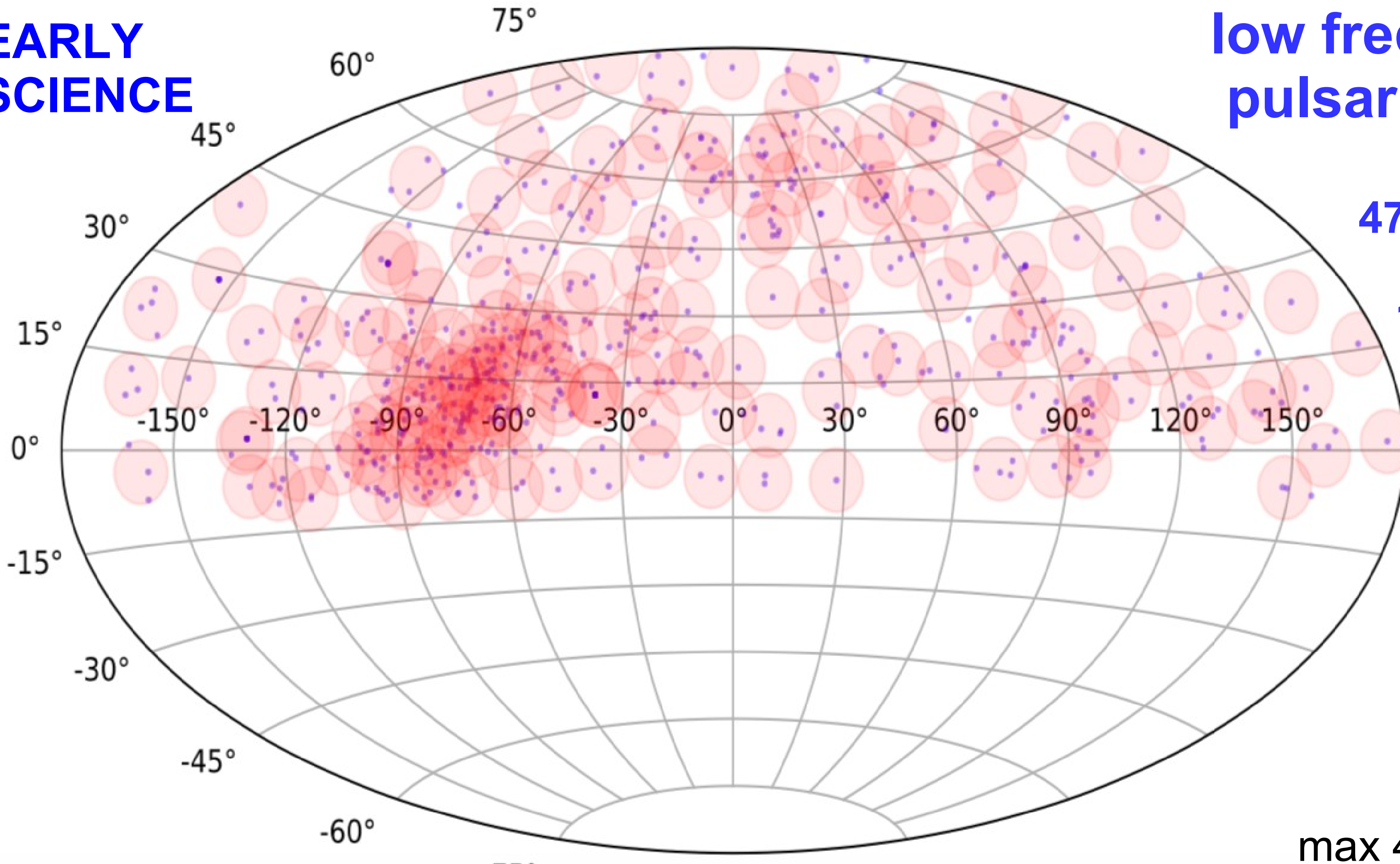


L.Bondonneau (LPC2E)

EARLY SCIENCE

low frequency pulsar census

47.5-85 MHz or 10-85 MHz

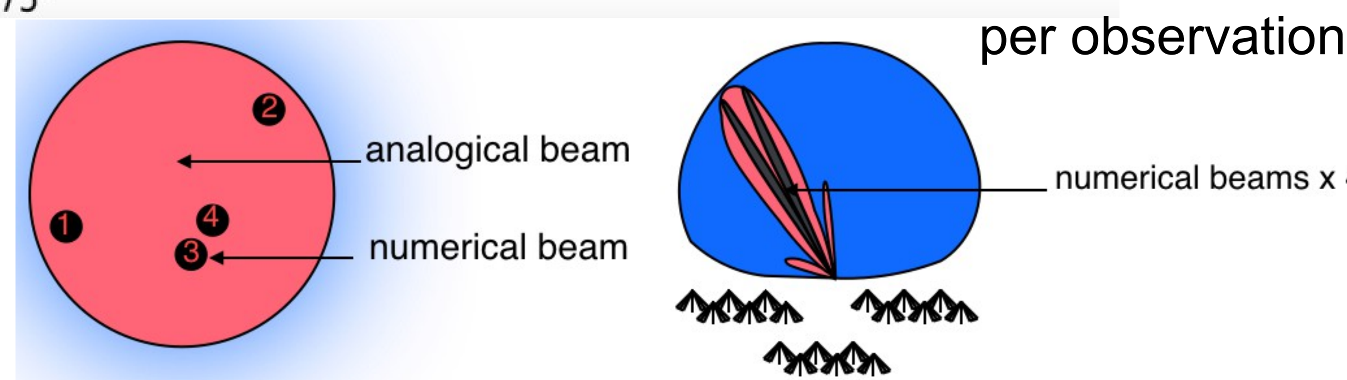


DM < 100 pc/cm-3
DEC > -10°

513 known sources

244 pointings

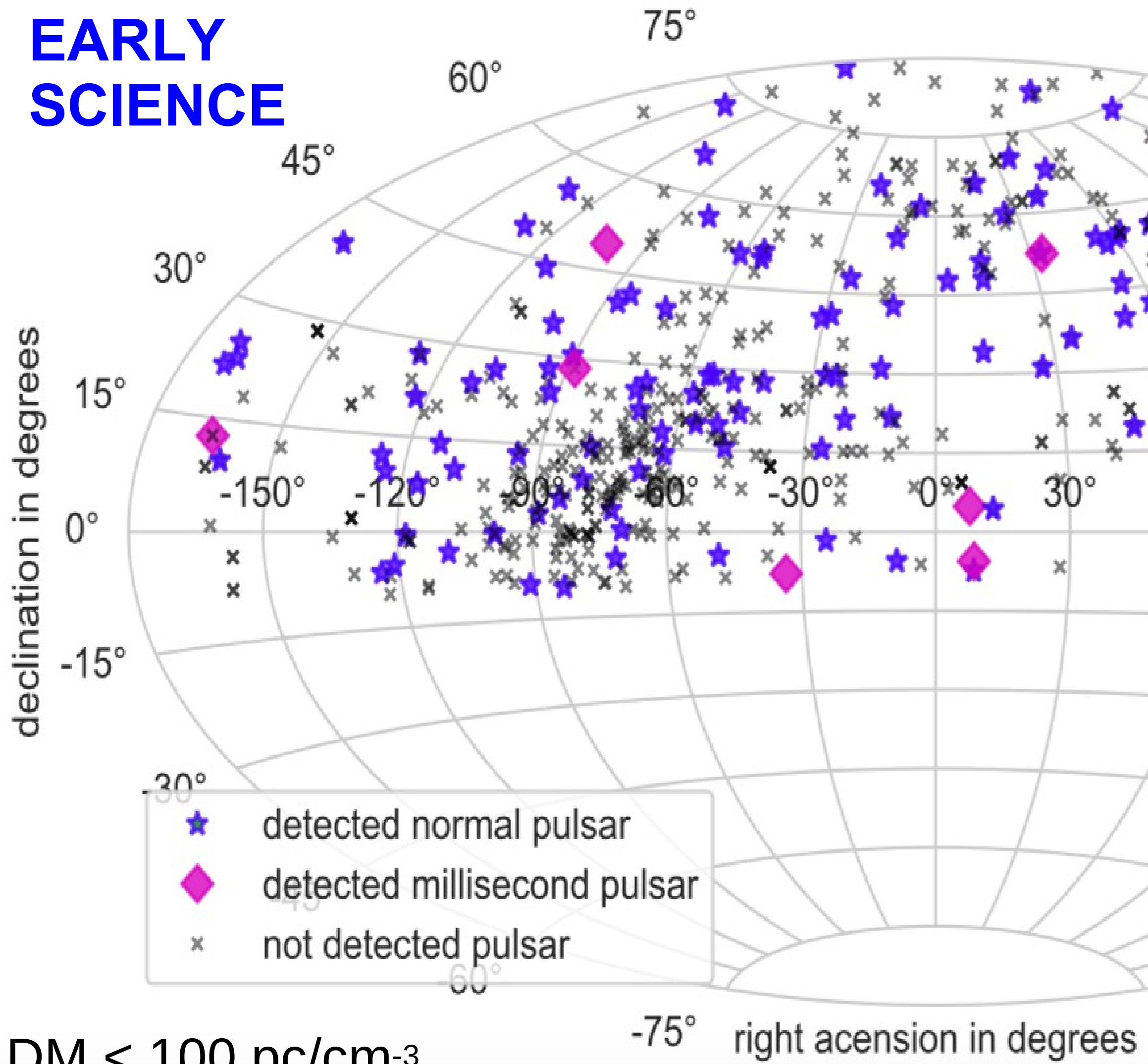
max 4 PSRs per observation

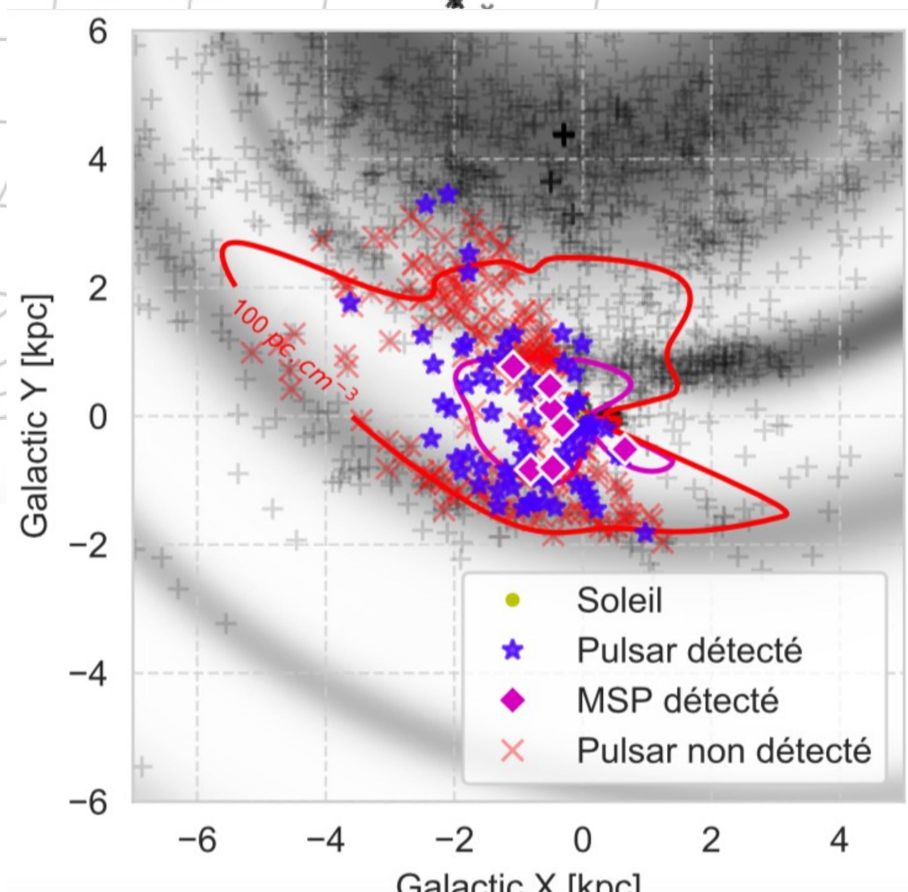


L.Bondonneau (LPC2E)

EARLY SCIENCE

135 detections (27%),
66 new below 100 MHz





DM < 100 pc/cm^{-3}
DEC > -10°

513 sources

244 pointings (max 4 PSRs per observation)

Being extended : -20° < DEC < -10° + LOTASS new PSRs

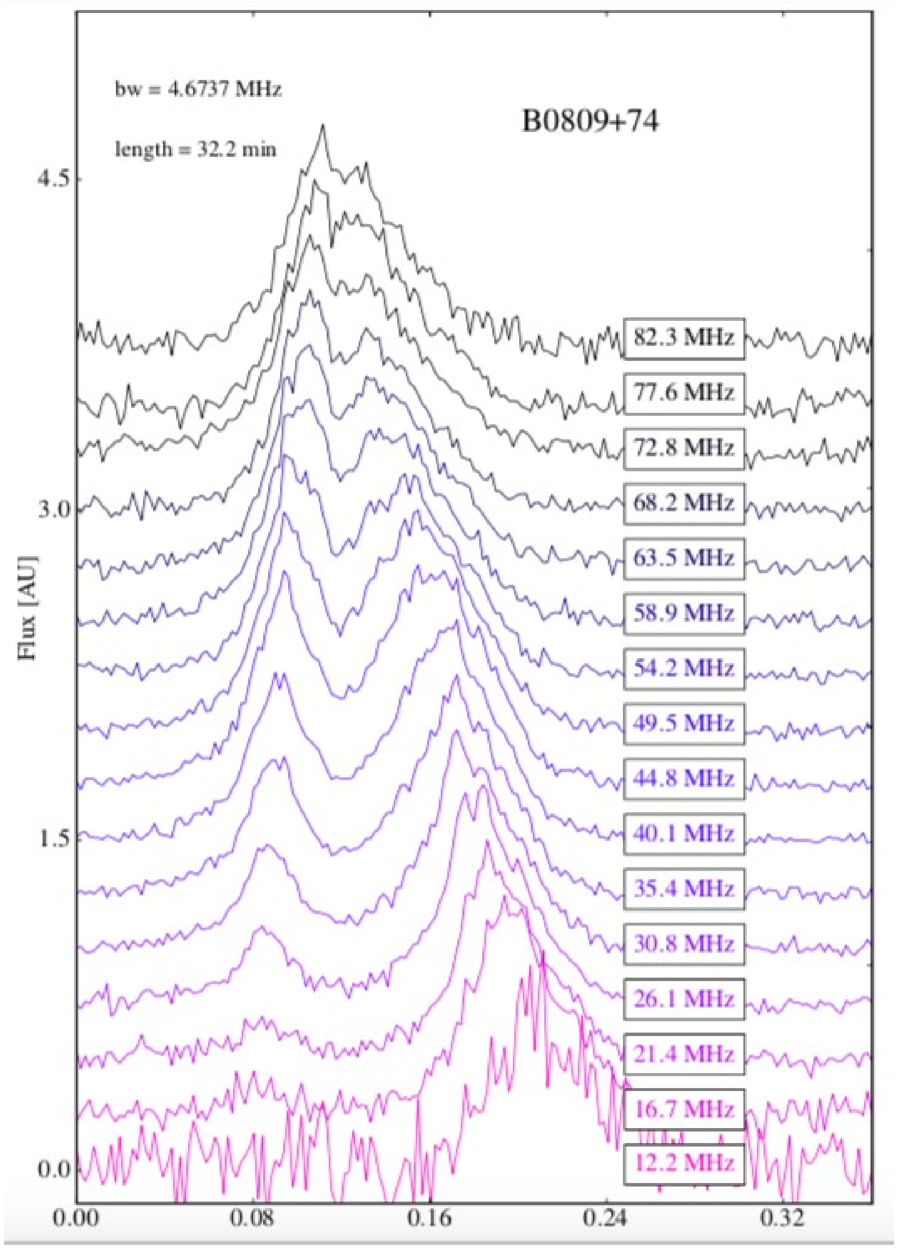
L.Bondonneau (LPC2E)

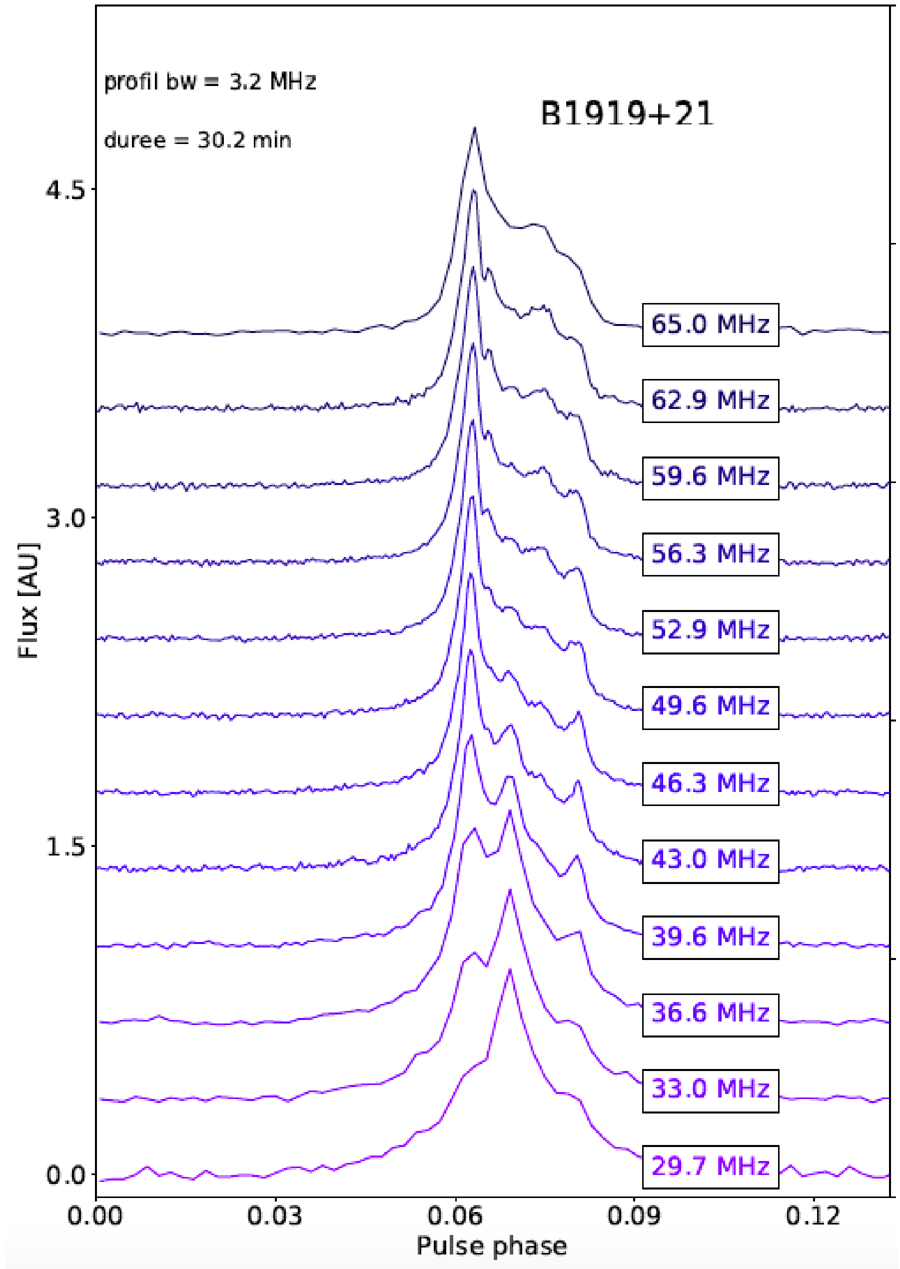
135 detections (27%), 66 new below 100 MHz

Being extended : -20° < DEC < -10° + LOTASS new PSRs

L.Bondonneau (LPC2E)

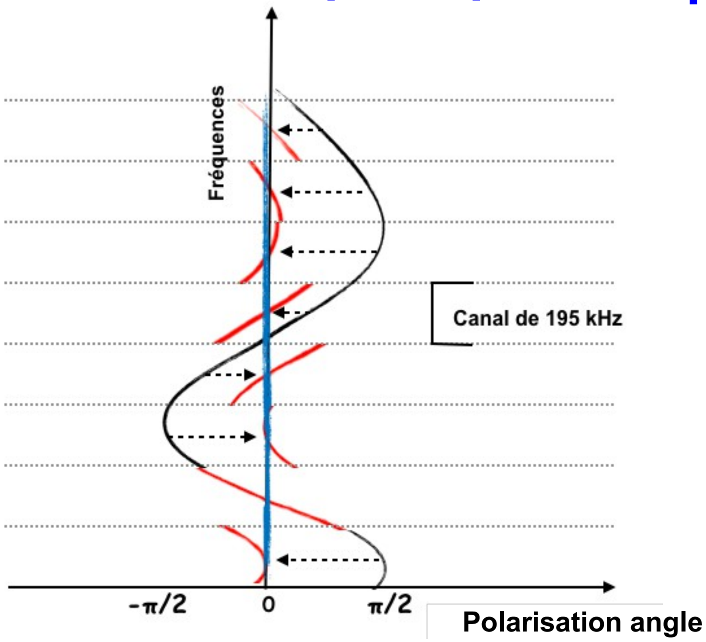
Use the high NenuFAR sensitivity to explore pulsar's upper magnetosphere



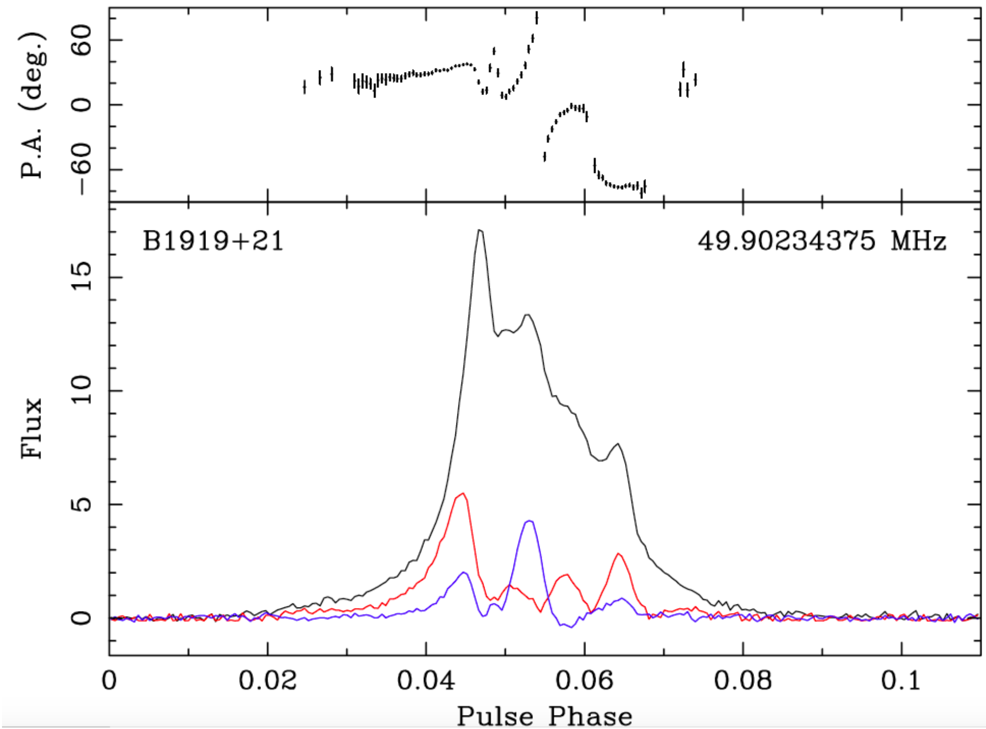


L.Bondonneau (LPC2E)

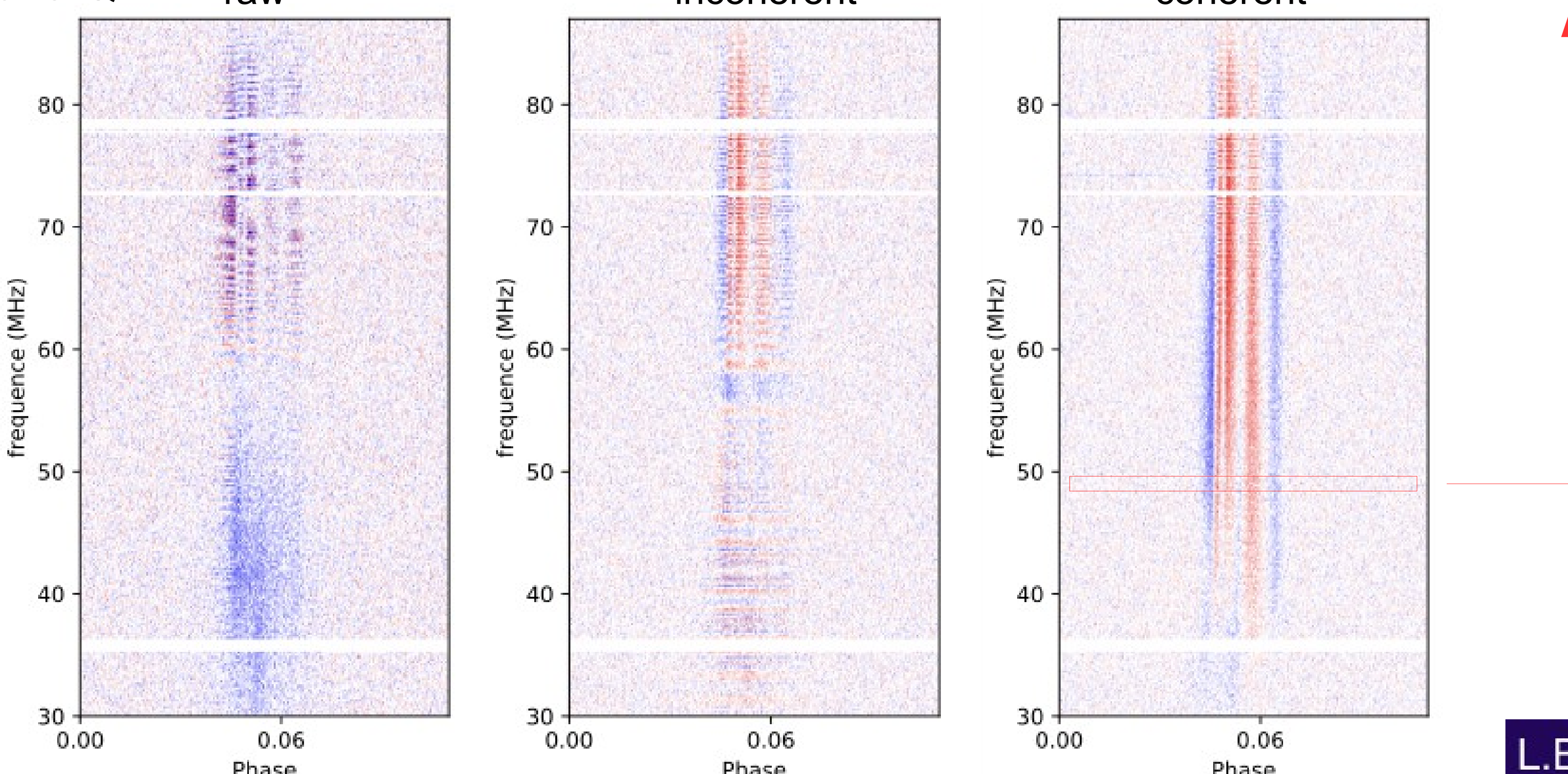
Explore pulsar's polarisation



Coherent « defaraday »



Stoke Q



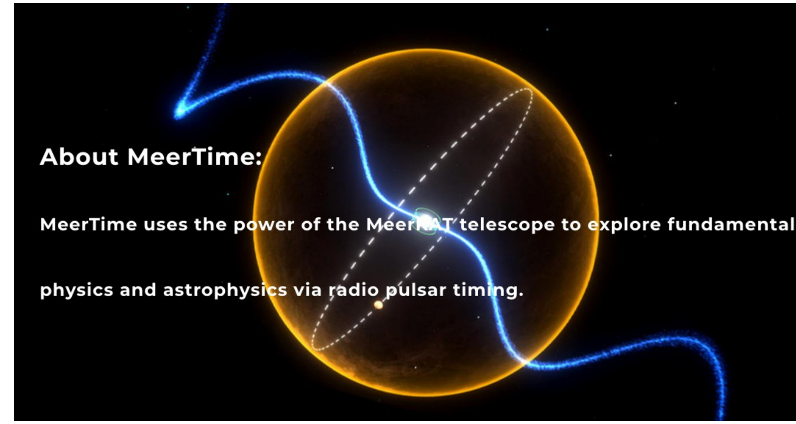
L.Bondonneau (LPC2E)

NenuFAR pulsar Key Project : ~2200 hrs of observing time

P.I.s: Jean-Mathias Griessmeier, Gilles Theureau (LPC2E & USN)
Hanna Bilous (Univ Amsterdam), **Louis Bondonneau** (LPC2E), **Ismaël Cognard** (LPC2E), **Julien Donner** (Univ. Bielefeld), **Lucas Guillemot** (LPC2E), **Gemma Janssen** (ASTRON), **Vlad Kondratiev** (ASTRON), **Michael Kramer** (MPIfR), **M.A. Krishnakumar** (Univ. Bielefeld), **James McKee** (MPIfR), **Robert Main** (MPIfR), **Aris Noutsos** (MPIfR), **Maura Pilia** (INAF-Cagliari Obs), **Andrea Possenti** (INAF-Cagliari Obs), **Maciej Serylak** (Cape Town Univ.), **Golam Shaiffulah** (ASTRON), **Caterina Tiburzi** (ASTRON), **Oleg Ulyanov** (Kharkov), **Joris Verbiest** (Univ. Bielefeld), **Olaf Wucknitz** (MPIfR), **Vyacheslav Zakharenko** (Kharkov), **Serge Yerin** (Kharkov)

Projects	Telescope time (hours) / 2.5 years	Science case
High DM census 100-200 pc.cm^{-3}	90	Local population
Blind survey	960	
41 PSR monitoring	720	Mean spectra, DM/RM variations, scintillation
Eclipsing binaries	41	Characterize eclipses and local environment
Polarized emission	30	Emission mecanisms in pulsar magnetospheres, Pulsar beam models, multi-propagation in ISM
Single pulse	44	
Drifting sub-pulse	20	
ISM/GP	78	
Heliosphere	250	DM variations, heliosphere e- mapping

MeerTime (http://www.meertime.org/)



7xParkes sensitivity

2-3 better than current 100m radio telescopes

Science WGs :

1000 pulsars array (LB, JMG)

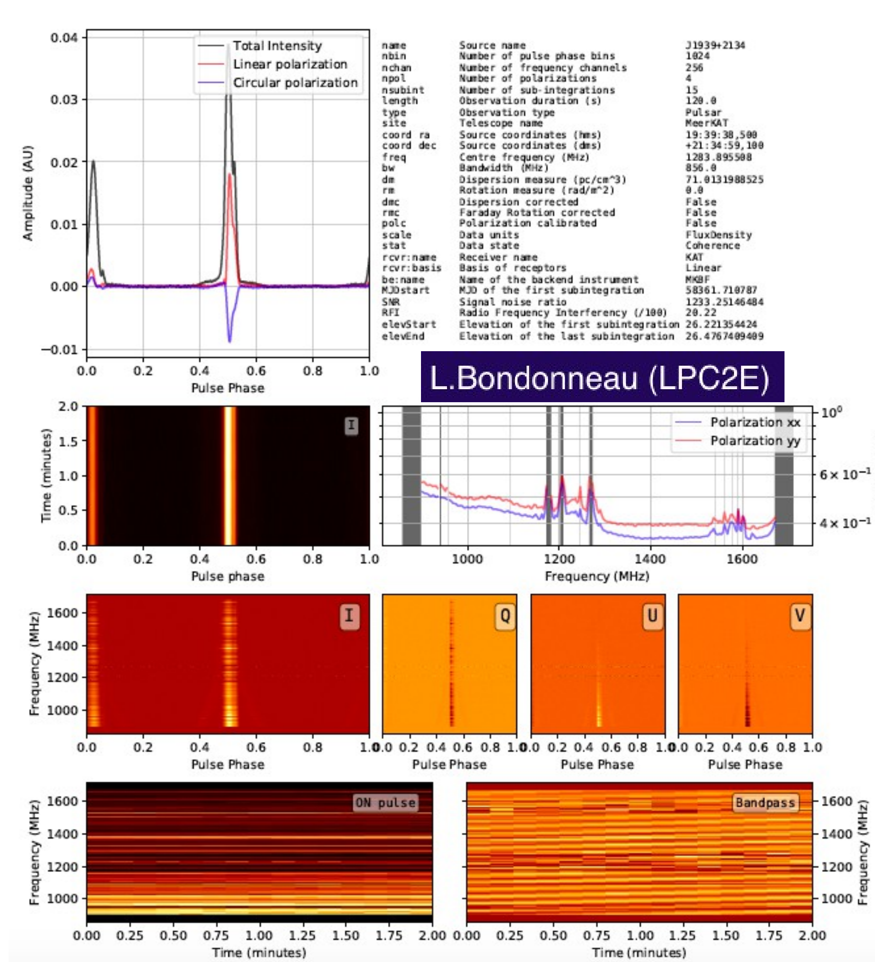
Globular clusters

Relativistic binaries (IC, GT, LG, AB)

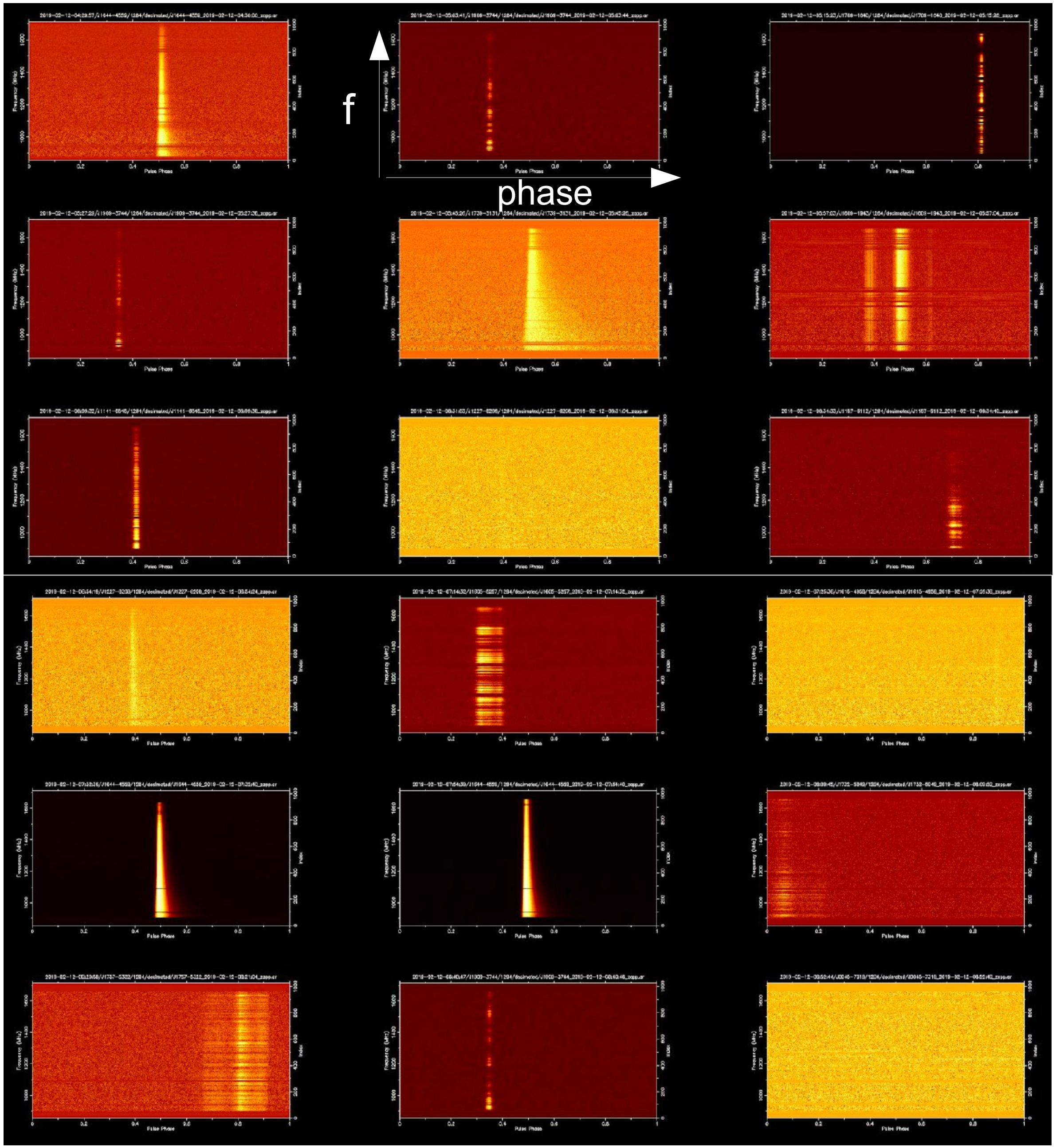
MSPs/PTA (IC, GT, LG, AC)

Cool things:

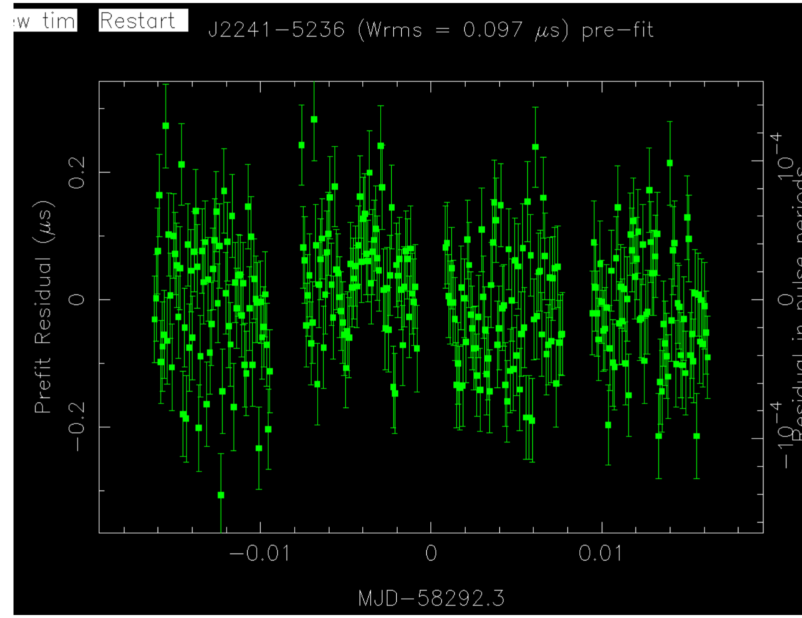
- J0540-6919 giant pulses and FRB-like nature ?
- Double pulsar Eclipses.
- Jitter limits on MSPs
- NGC6440 Shapiro campaign.
- J0955-6150 mass measurements
- 8 scintillation arcs from J0437!!!
- Tons of GC pulsar detections.
- J1909-3744 timing over 6 months.
- 3 ns jitter from J2241-5236
- forthcoming TPA and million-pulse array.
- 20,000 giant pulses from B1820-30A.



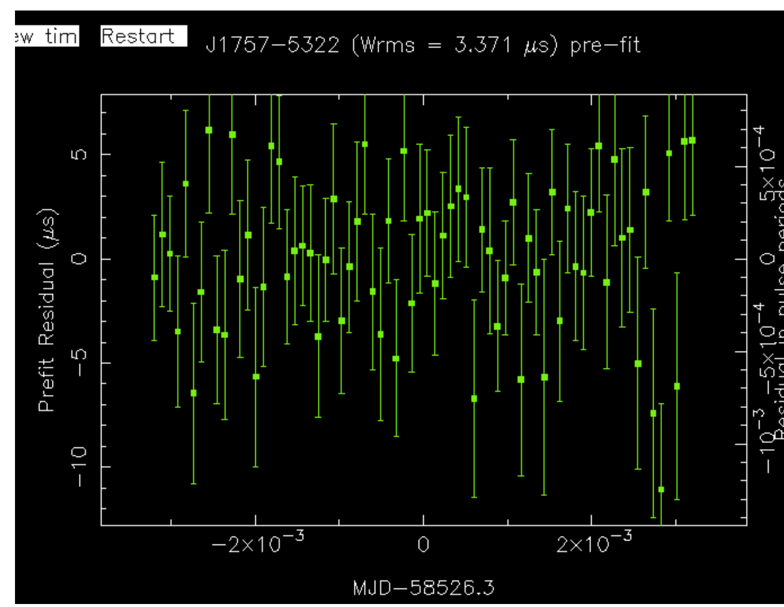
First run 12 Feb 2019 UT 5-9



First 18 MSPs



PSR J2241-5236 / pulse jitter < 5 ns



PSR J1757-5322

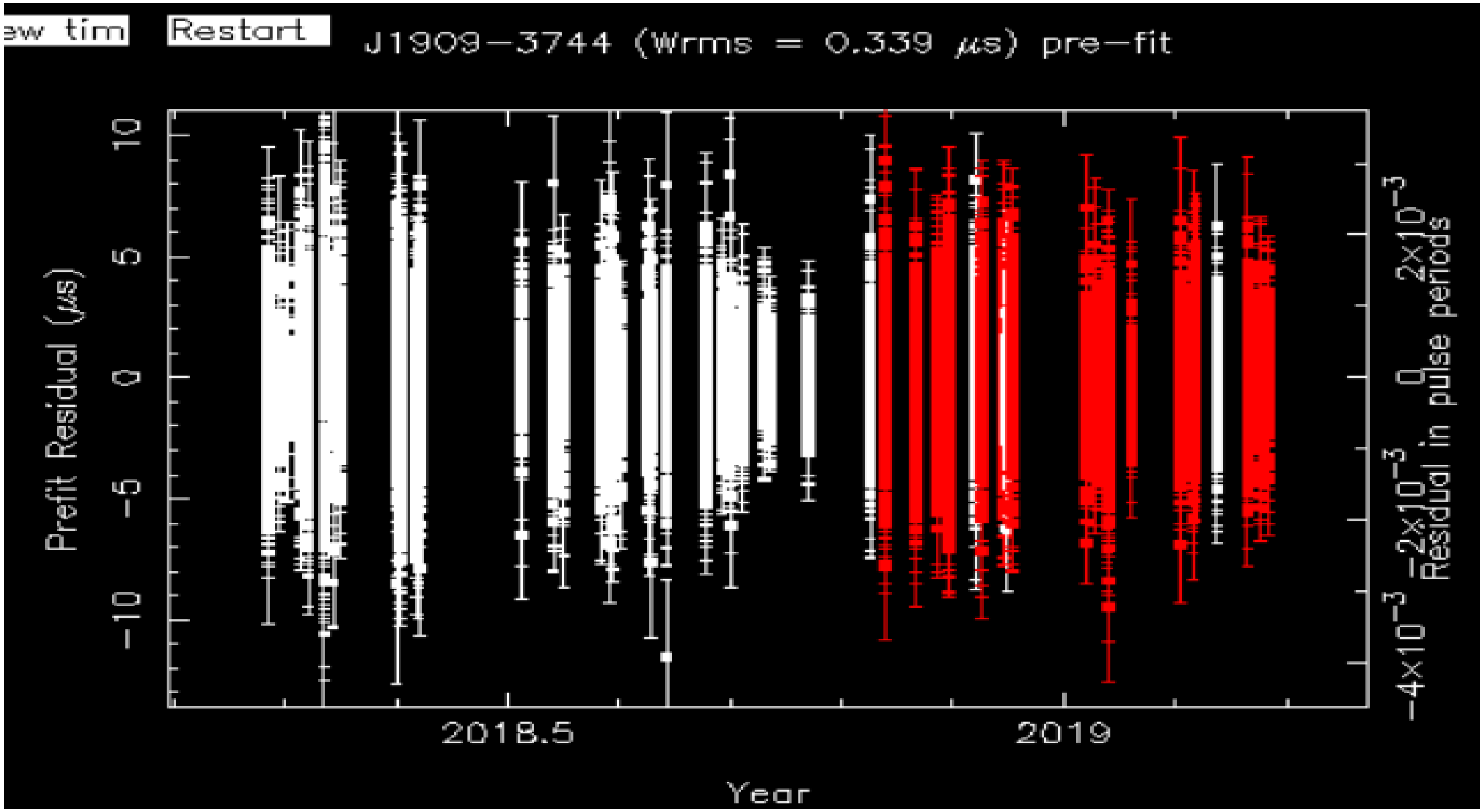
3 μs rms in 8 sec → 160 ns in 1 hr

Pulsar Timing Array

300-400 hrs/yr for MSP monitoring
(jitter studies)

all MSP below dec 0° → 82 MSPs currently
typically 256 sec integ
use sub-arraying

10 psrs weekly @ 100 ns (150 hrs/yr)
52 psrs monthly @ 1 μs (170 hrs/yr)
> 62 pulsars can be observed to (at least) 1 μs in a total of 9 hours integration time.
Could reasonably have 40 epochs per year

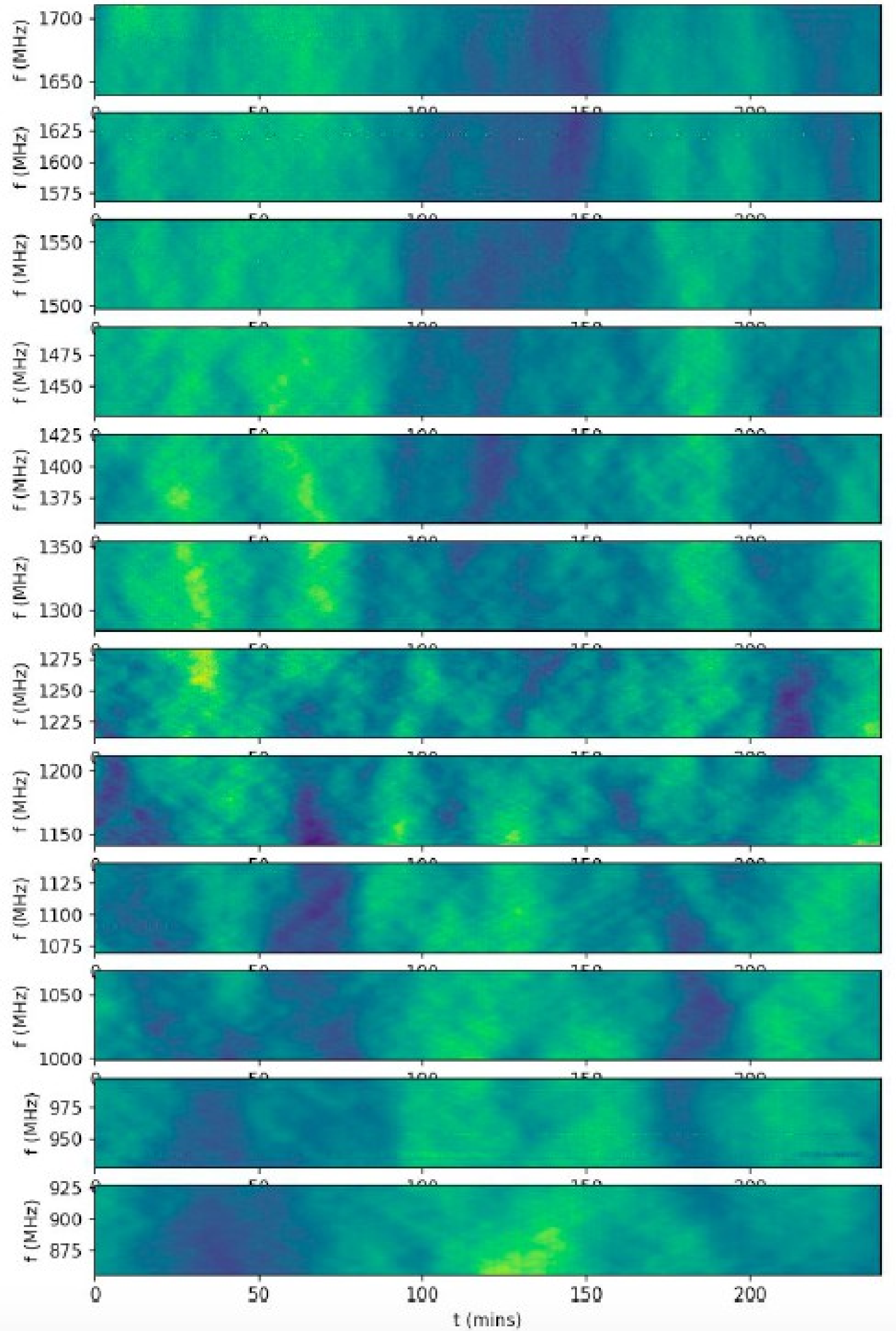


PSR J1909-3744
64s subintegrations,
over 32 sub-bands

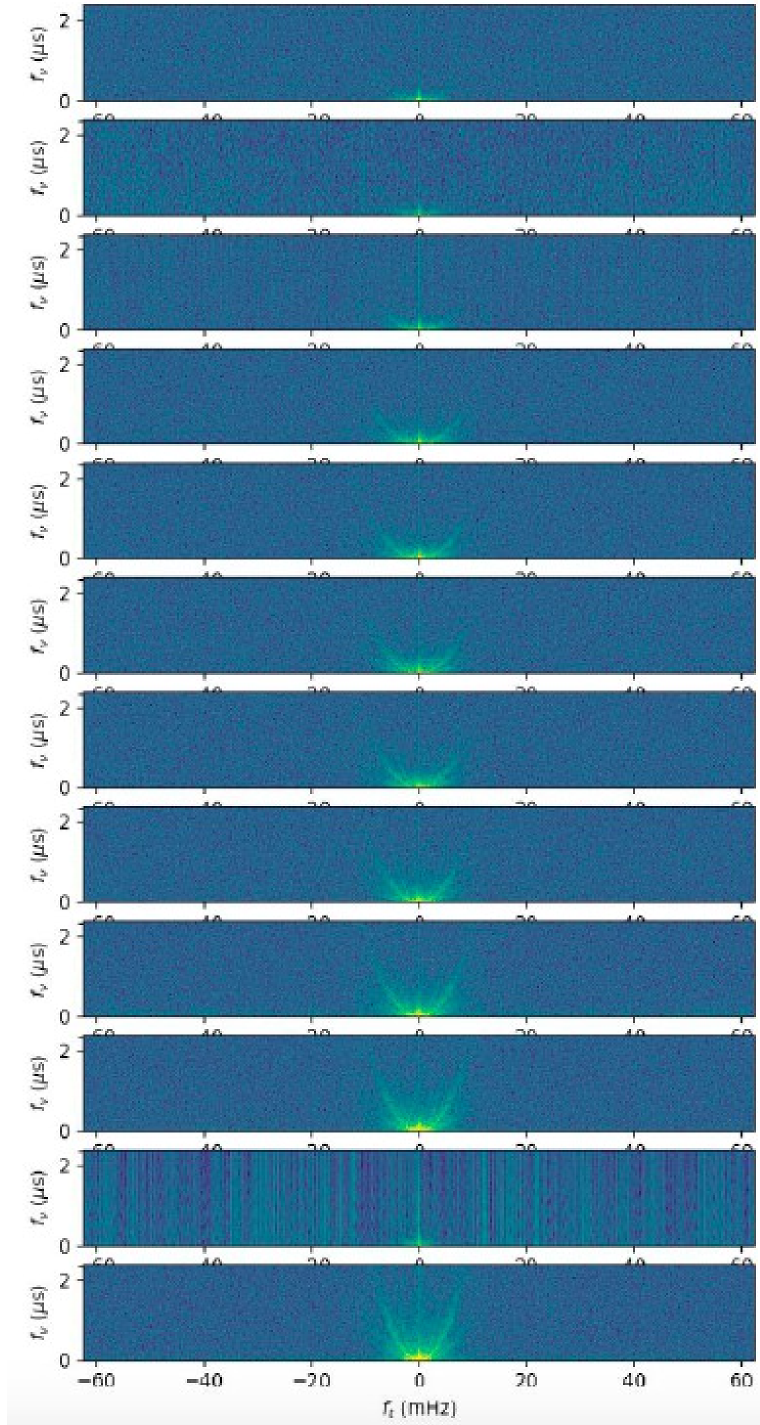
PSR0437-4715

Scintillation studies

Flux-normalised dynamic spectrum
from 4 hours observation broken into 12 subbands



Secondary spectra of dynamic spectrum subbands



Cf Walker et al. (2004) and Cordes et al. (2006)

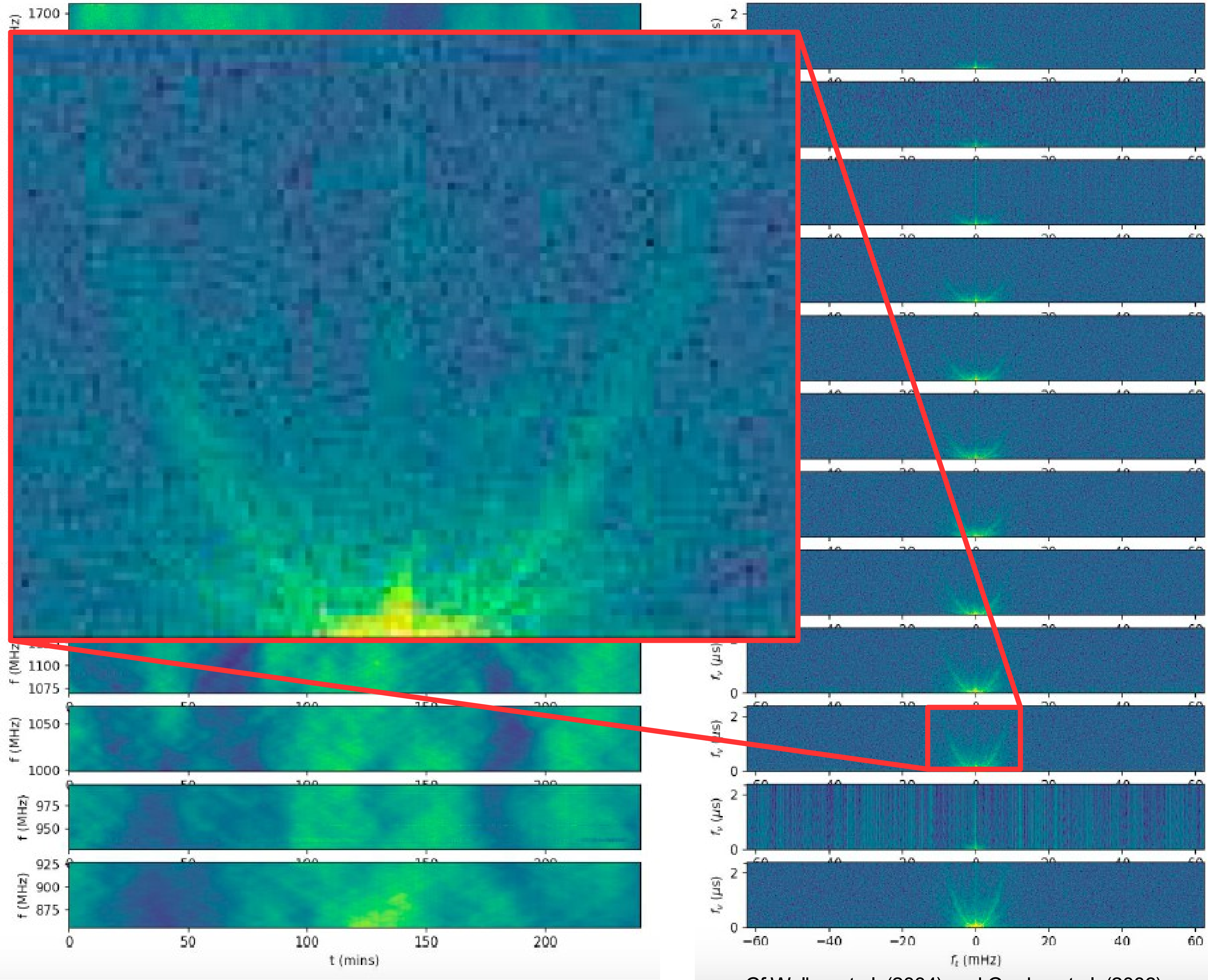
PSR0437-4715

Scintillation studies

Up to 8 scintillation arcs !

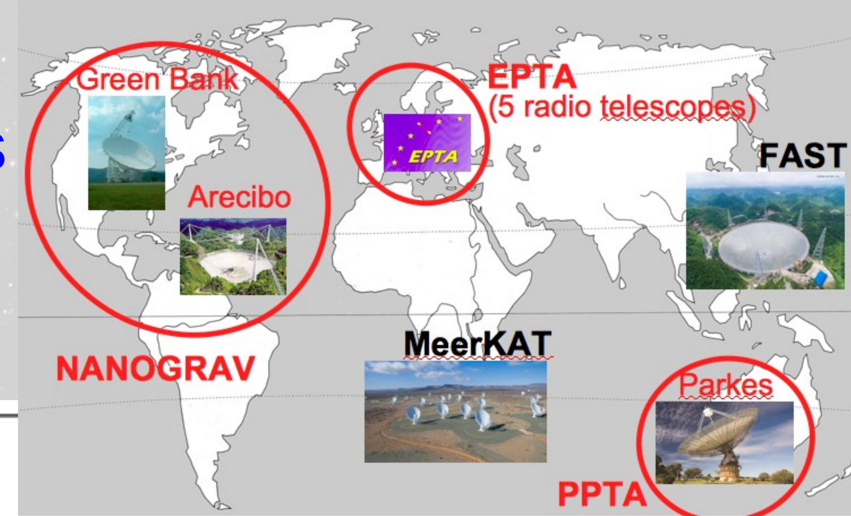
Flux-normalised dynamic spectrum from 4 hours observation broken into 12 subbands

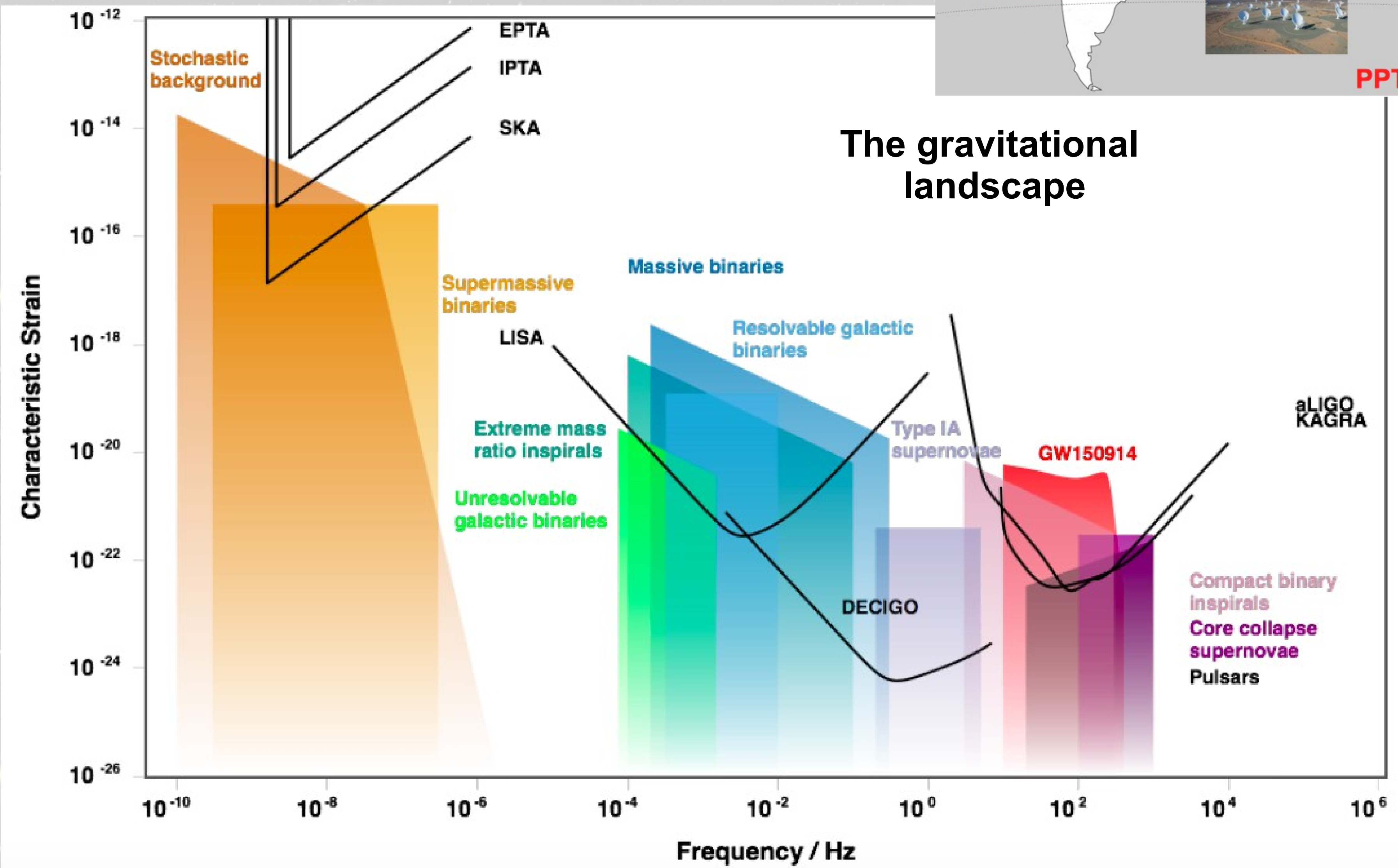
Secondary spectra of dynamic spectrum subbands



Cf Walker et al. (2004) and Cordes et al. (2006)

IPTA use pulsar timing to detect nHz-μHz gravitational waves





IPTA

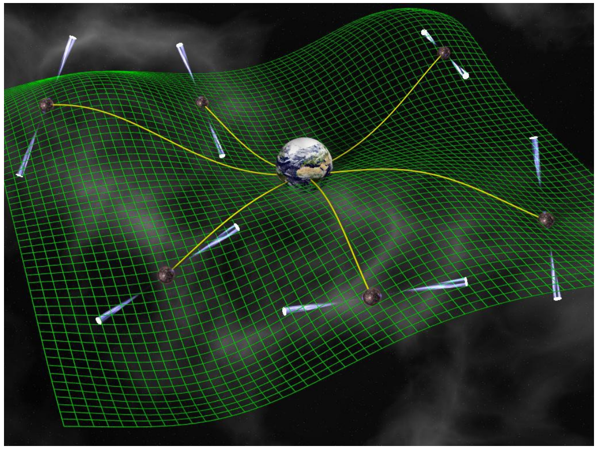
use pulsar timing to detect nHz gravitational waves

The passing of a gravitational wave perturbs the metrics and produce fluctuations in the time of arrivals of the pulses

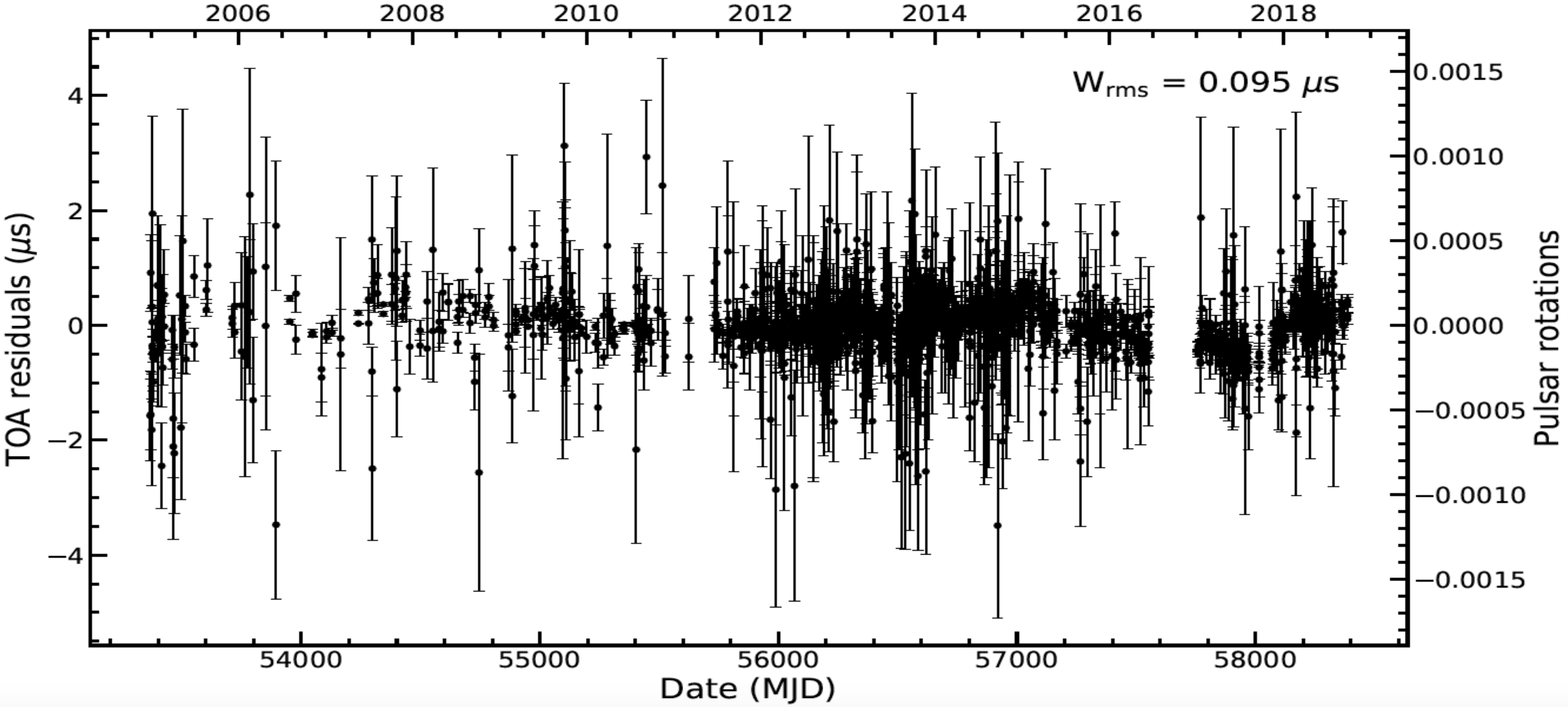
with an uncertainty dt (~100 ns) and a time span T (~20 years)

→ one is actually sensitive to amplitude ~ dt/T (10^{-16})

→ and to frequencies of the order of ~ 1/T (10^{-9} – 10^{-7} Hz)



Time of arrival residuals for pulsar PSR J1909-3744 @ NRT



IPTA

use pulsar timing to detect
nHz gravitational waves

Sensitivity and timing precision

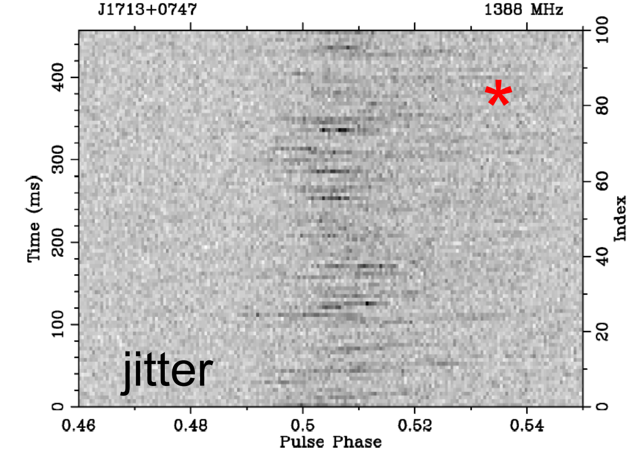
$$\sigma_{\mathrm{TOA}} \propto \frac{w}{S_{\mathrm{PSR}}} \frac{T_{\mathrm{sys}}}{A} \frac{1}{\sqrt{BT}}$$

Choose the right pulsar

Have a good receiver
and a big radio telescope

integrate
on a wide band

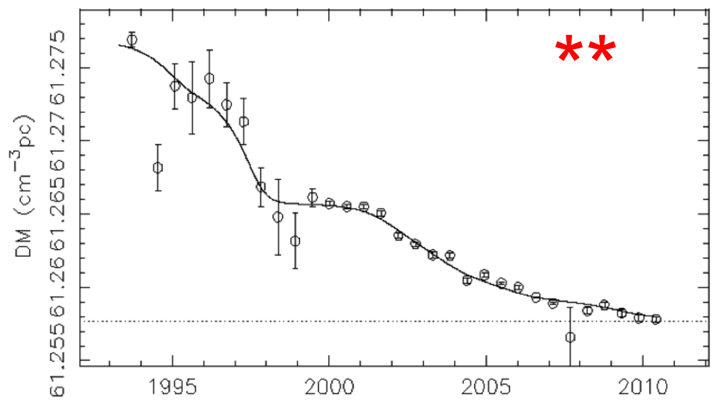
IPTA use pulsar timing to detect nHz gravitational waves



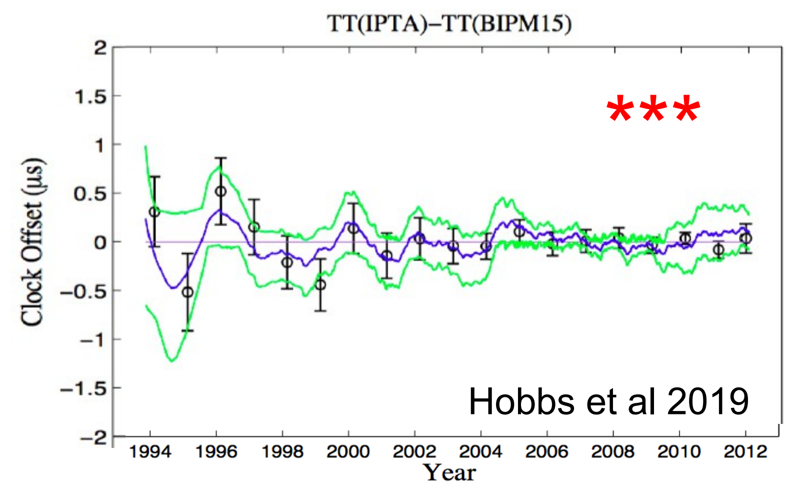
White noises (uncorrelated noise)

Instrumental
→ radiometer noise, calibration in polarisation
Multi-telescope measurements, LEAP

Astrophysical *
→ 'pulse jitter'



Scintillation
→ cyclic spectroscopy
2D template matching



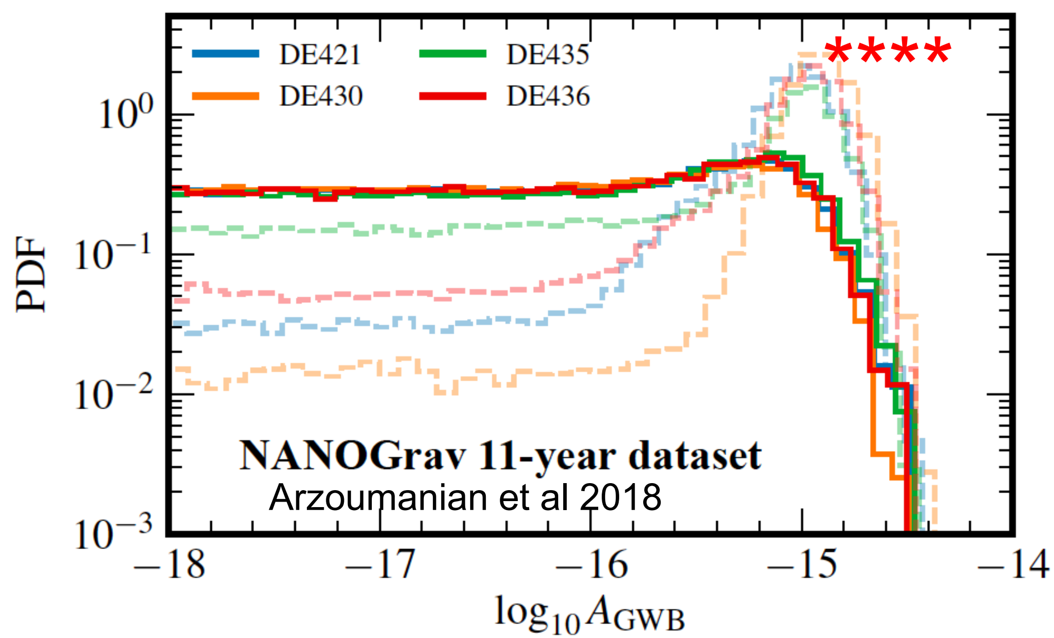
Red noise (correlated noise)

Dispersion measure variations **
→ multi-frequency measurements

Rotation noise
→ perturbation of small bodies ?
variations in Edot ? series of micro-glitches ?

Clock variations
→ link with TAI, TT-BIPM ***

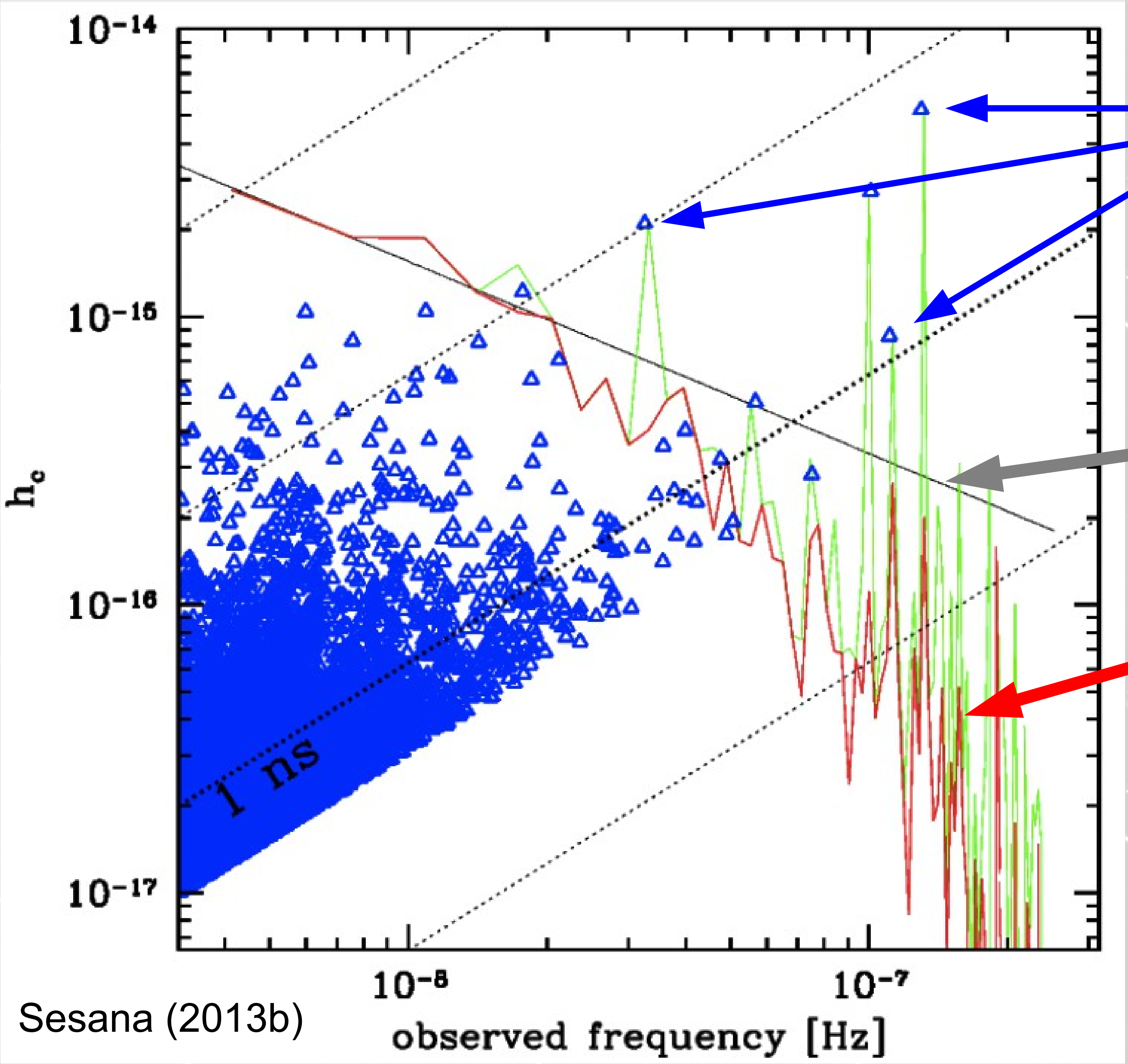
Solar system ephemerides ****
→ link with INPOP, JPL



Gravitational wave signal

→ background, continuous single source, events

Population of SMBBH : contribution from background & individual sources



Sesana (2013b)

« resolvable » individual sources

stochastic background ~ f $^{-2/3}$

Contribution from unresolved sources

Hypothesis :

- circular orbits
- all the population reaches the sub-pc GW emission regime

+ uncertainties about :

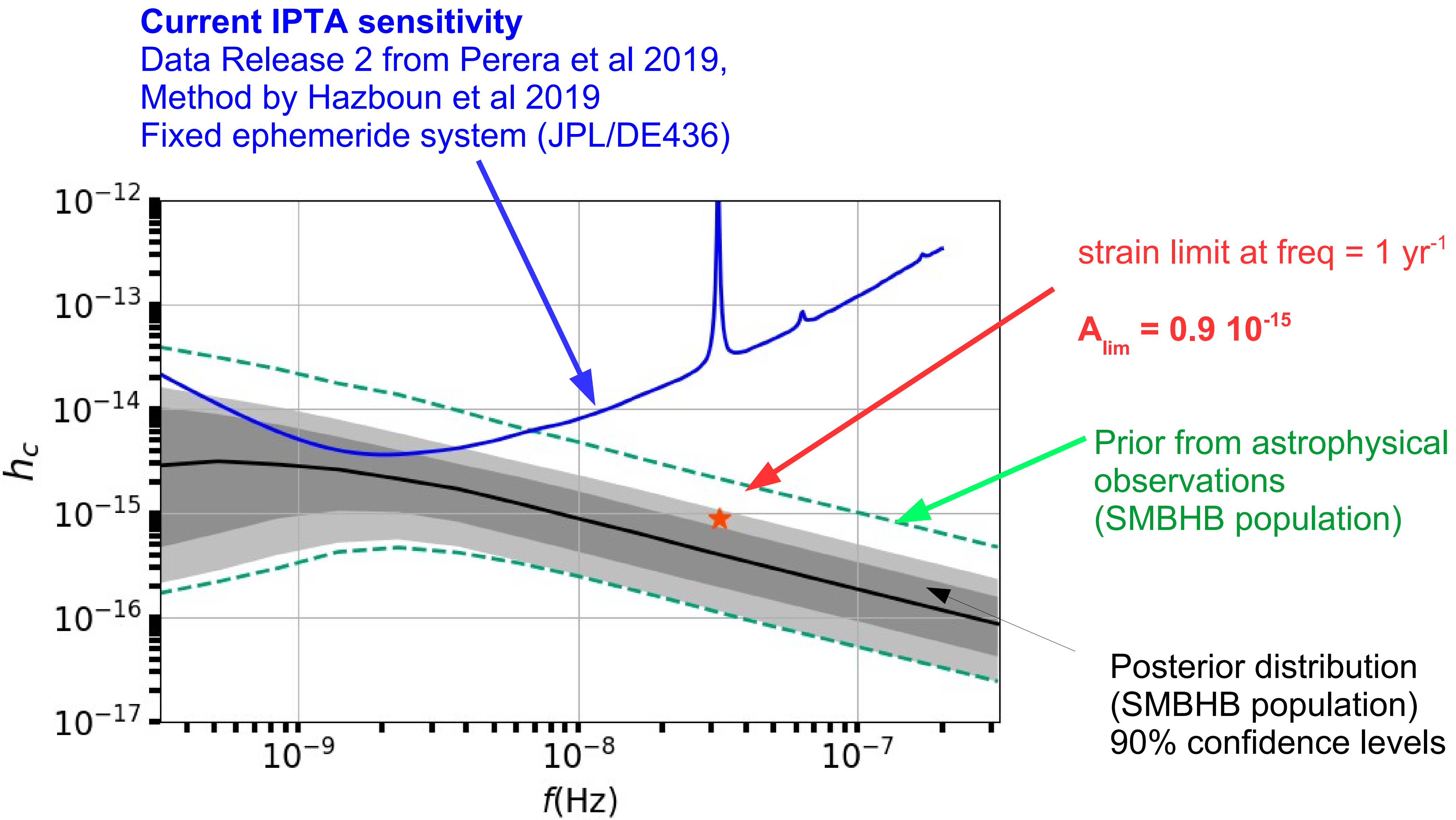
fusion rate

BH – host galaxy mass relation

time to coalescence

PTA upper limits are starting to probe astrophysical parameter space :

- galaxy merger rate,
- black-hole/galaxy mass ratio



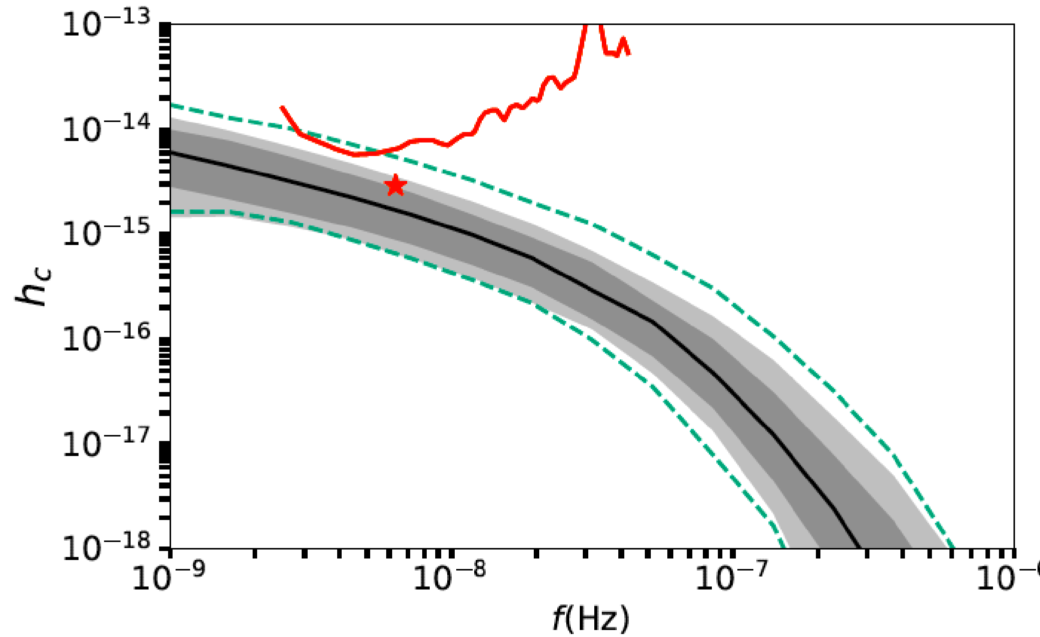
Tests of Astrophysical models

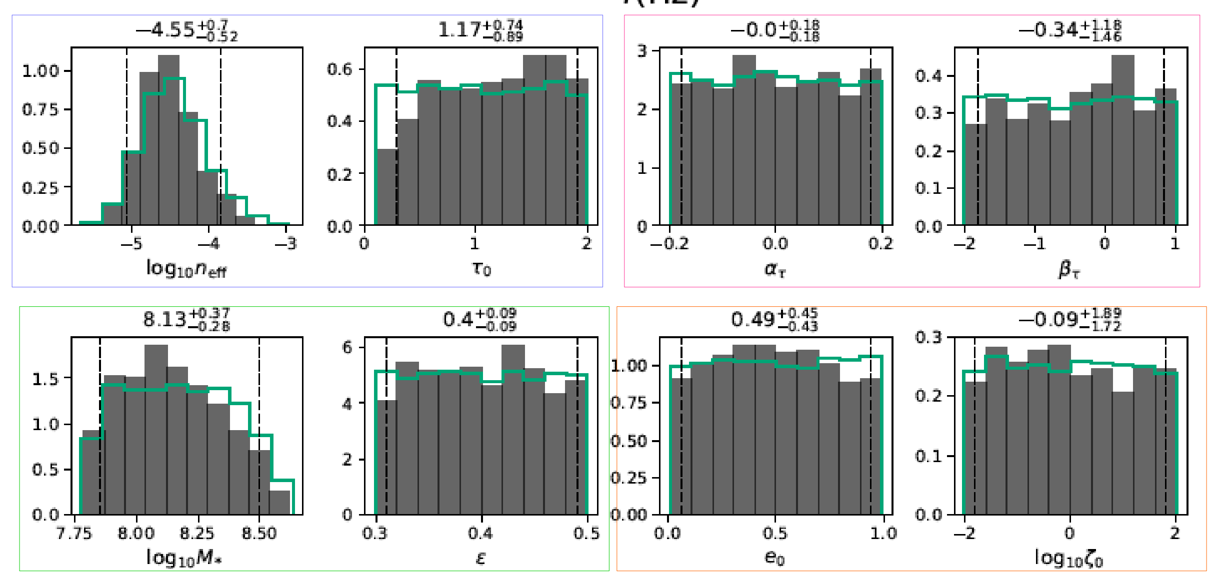
Chen et al 2019
EPTA – population synthesis

parameter	description	standard	extended
Φ_0	GSMF norm	-2.8 ± 0.3	-2.8 ± 0.3
Φ_I	GSMF norm redshift evolution	-0.25 ± 0.22	-0.25 ± 0.22
	Galaxy stellar mass function		
$\log_{10}M_0$	GSMF scaling mass	11.25 ± 0.2	11.25 ± 0.2
α_0	GSMF mass slope	-1.25 ± 0.17	-1.25 ± 0.17
α_I	GSMF mass slope redshift evolution	0 ± 0.15	0 ± 0.15
f_0	pair fraction norm	[0.02,0.03]	[0.01,0.05]
α_f	pair fraction mass slope	[-0.2,0.2]	[-0.5,0.5]
	Pair fraction		
β_f	pair fraction redshift slope	[0.6,1]	[0,2]
γ_f	pair fraction mass ratio slope	[-0.2,0.2]	[-0.2,0.2]
τ_0	merger time norm	[0.1,2]	[0.1,10]
α_τ	merger time mass slope	[-0.2,0.2]	[-0.5,0.5]
	Merger timescale		
β_τ	merger time redshift slope	[-2,1]	[-3,1]
γ_τ	merger time mass ratio slope	[-0.2,0.2]	[-0.2,0.2]
$\log_{10}M_*$	$M_{\rm bulge}-M_{\rm BH}$ relation norm	8.17 ± 0.33	8.17 ± 0.33
α_*	$M_{\rm bulge}-M_{\rm BH}$ relation slope	1 ± 0.1	1 ± 0.1
	M_{bulge} -M_{BH} relation		
ϵ	$M_{\rm bulge}-M_{\rm BH}$ relation scatter	[0.3,0.5]	[0.2,0.5]
e_0	binary eccentricity	[0.01,0.99]	[0.01,0.99]
	Eccentricity and stellar density		
$\log_{10}\zeta_0$	stellar density factor	[-2,2]	[-2,2]

~2015 limit

$$A(f=\mathrm{yr}^{-1}) = 1\times10^{-15}$$





Tests of Astrophysical models

Chen et al 2019
EPTA – population synthesis

~2025 limit ?

parameter	description	standard	extended
Φ_0	GSMF norm	-2.8 ± 0.3	-2.8 ± 0.3
Φ_I	GSMF norm redshift evolution	-0.25 ± 0.22	-0.25 ± 0.22
$\log_{10}M_0$	GSMF scaling mass	11.25 ± 0.2	11.25 ± 0.2
α_0	GSMF mass slope	-1.25 ± 0.17	-1.25 ± 0.17
α_I	GSMF mass slope redshift evolution	0 ± 0.15	0 ± 0.15
f_0	pair fraction norm	[0.02,0.03]	[0.01,0.05]
α_f	pair fraction mass slope	[-0.2,0.2]	[-0.5,0.5]
β_f	pair fraction redshift slope	[0.6,1]	[0,2]
γ_f	pair fraction mass ratio slope	[-0.2,0.2]	[-0.2,0.2]
τ_0	merger time norm	[0.1,2]	[0.1,10]
α_τ	merger time mass slope	[-0.2,0.2]	[-0.5,0.5]
β_τ	merger time redshift slope	[-2,1]	[-3,1]
γ_τ	merger time mass ratio slope	[-0.2,0.2]	[-0.2,0.2]
$\log_{10}M_*$	$M_{\rm bulge}-M_{\rm BH}$ relation norm	8.17 ± 0.33	8.17 ± 0.33
α_*	$M_{\rm bulge}-M_{\rm BH}$ relation slope	1 ± 0.1	1 ± 0.1
ϵ	$M_{\rm bulge}-M_{\rm BH}$ relation scatter	[0.3,0.5]	[0.2,0.5]
e_0	binary eccentricity	[0.01,0.99]	[0.01,0.99]
$\log_{10}\zeta_0$	stellar density factor	[-2,2]	[-2,2]

Galaxy stellar mass function

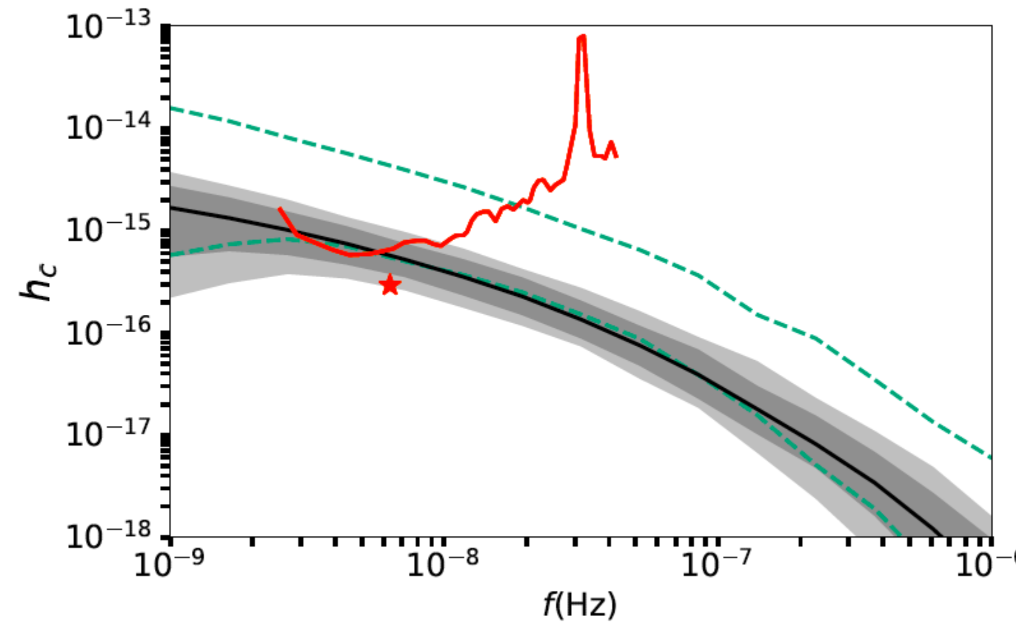
Pair fraction

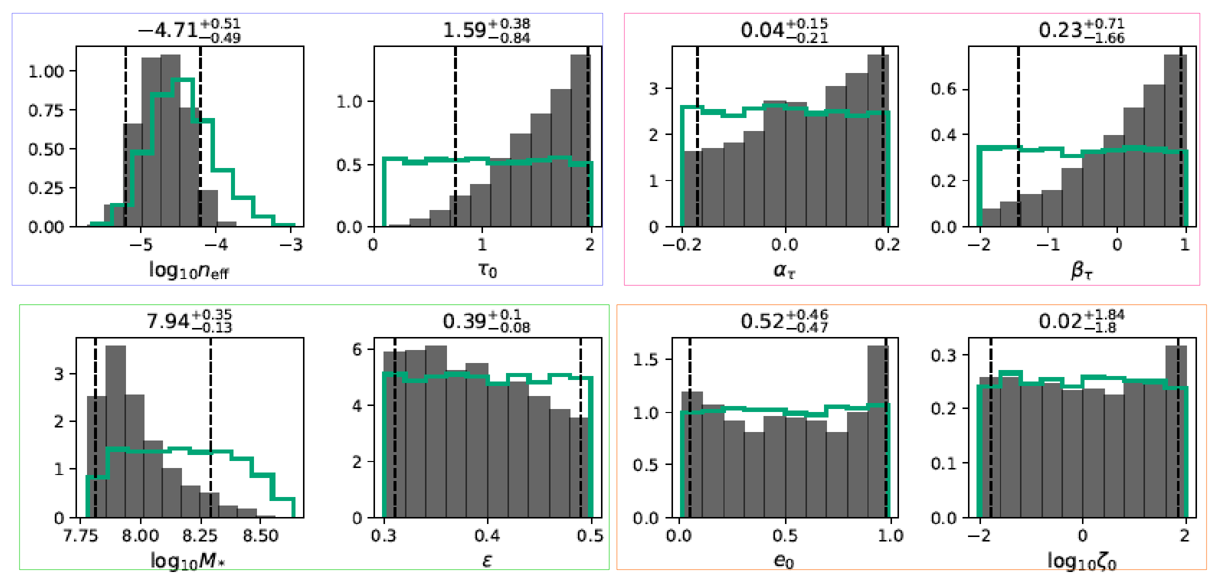
Merger timescale

M_{bulge} - M_{BH} relation

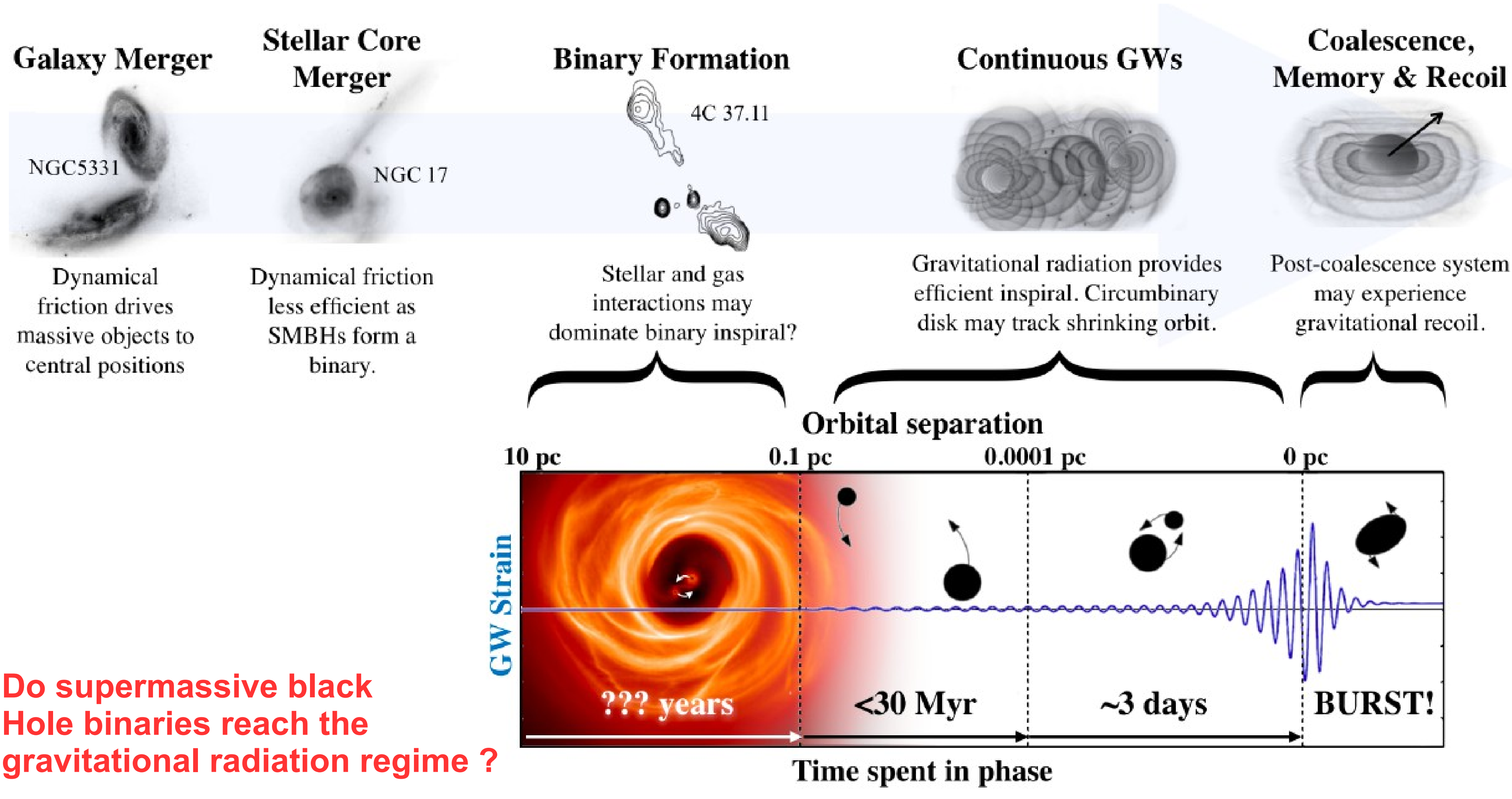
Eccentricity and stellar density

$$A(f=\mathrm{yr}^{-1}) = 1\times10^{-16}$$





The life cycle of supermassive binary black holes



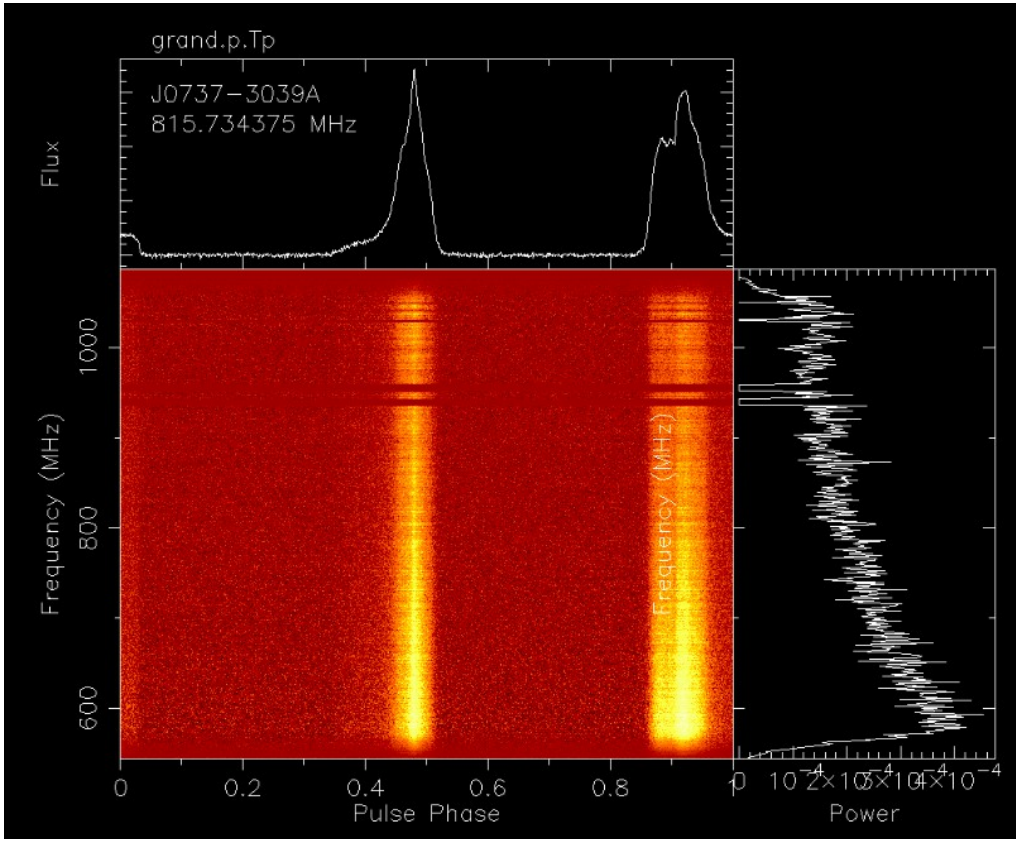
Do supermassive black Hole binaries reach the gravitational radiation regime ?

Do we have a chance to get a detection with the PTA technique in a reasonable time ?

How can we characterize the detected signal ?

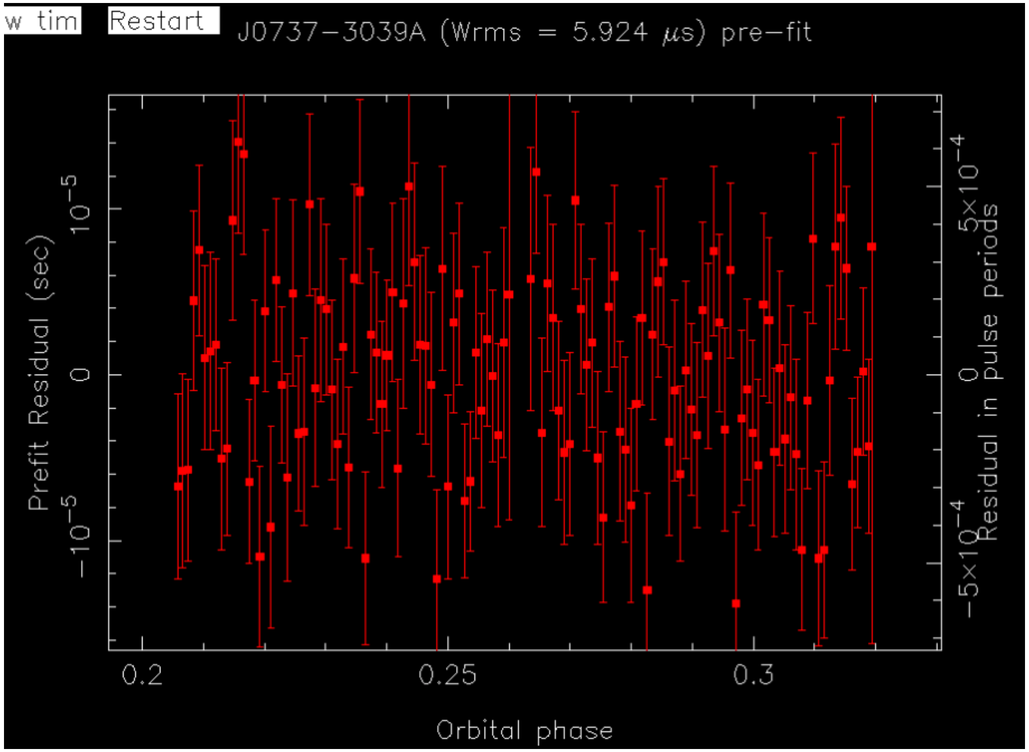
monochromatic PTA regime

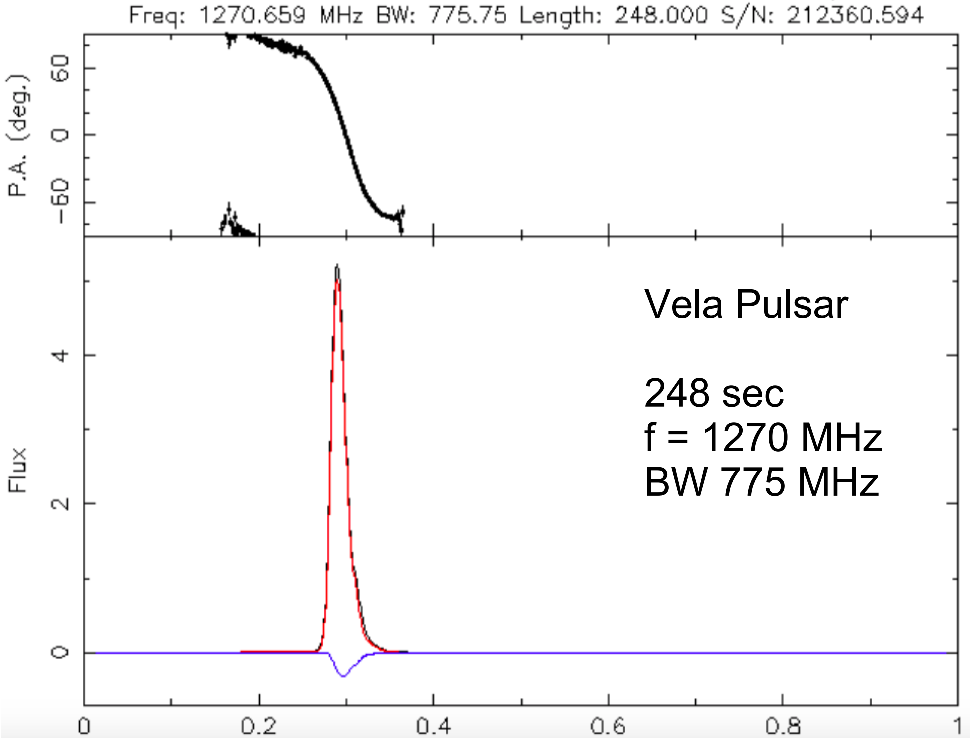
Burke-Spolaor 2018

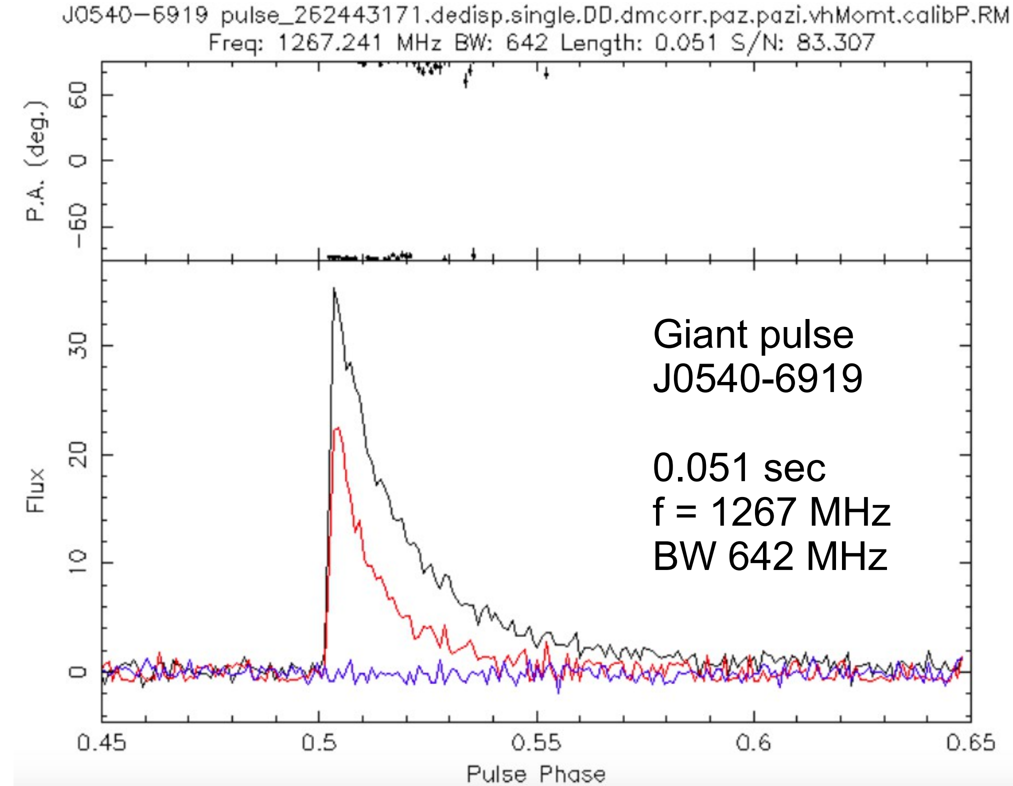


double pulsar PSRJ0737-3039A
UHF band – S/N =865 in 16 min

6 μs rms residuals in 8 second dumps,
twice better than GBT







PSRJ1909-3744 single pulses