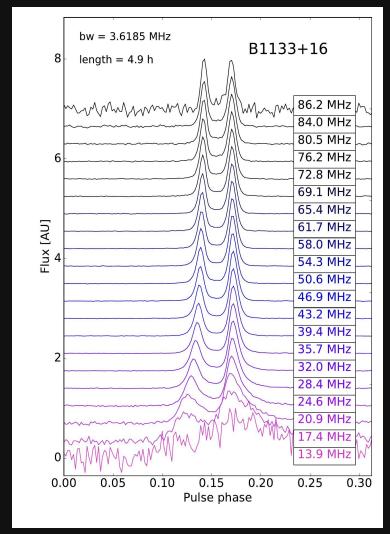
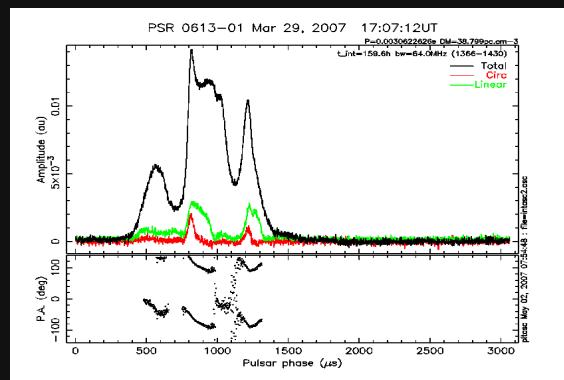
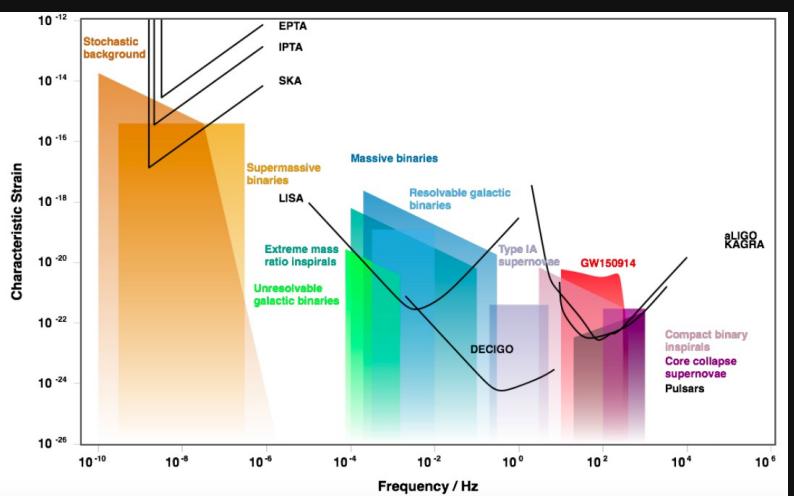




# An overview of pulsar observations with french radio telescopes

Gilles Theureau

I.Cognard, L.Guillemot, J.M.Griessmeier (Orléans)  
and collaborators

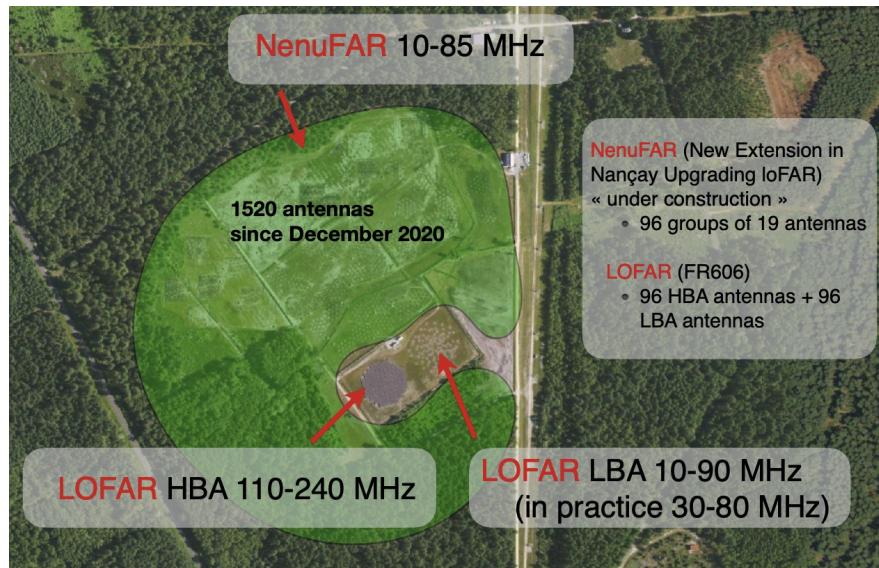


# National facilities

NRT  
LOFAR  
NenuFAR

(Nançay radio observatory)

frequency coverage  
10 MHz – 3.5 GHz



# The International Pulsar Timing Array

Effelsberg



Jodrell



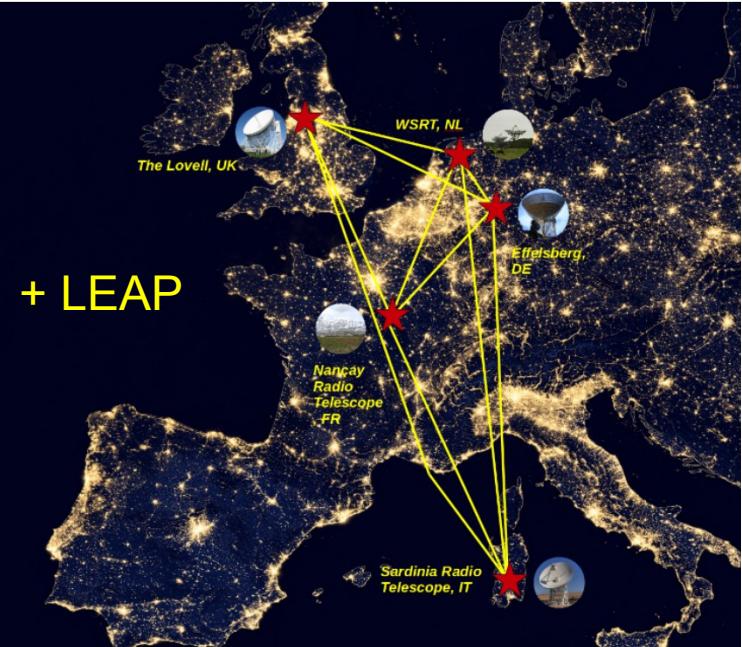
Westerbork



NRT



SRT



Green Bank



CHIME



VLA



Arecibo



NANOGrav



MeerKAT

EPTA  
(5 radio telescopes)



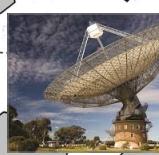
InPTA



GMRT



FAST



Parkes

PPTA

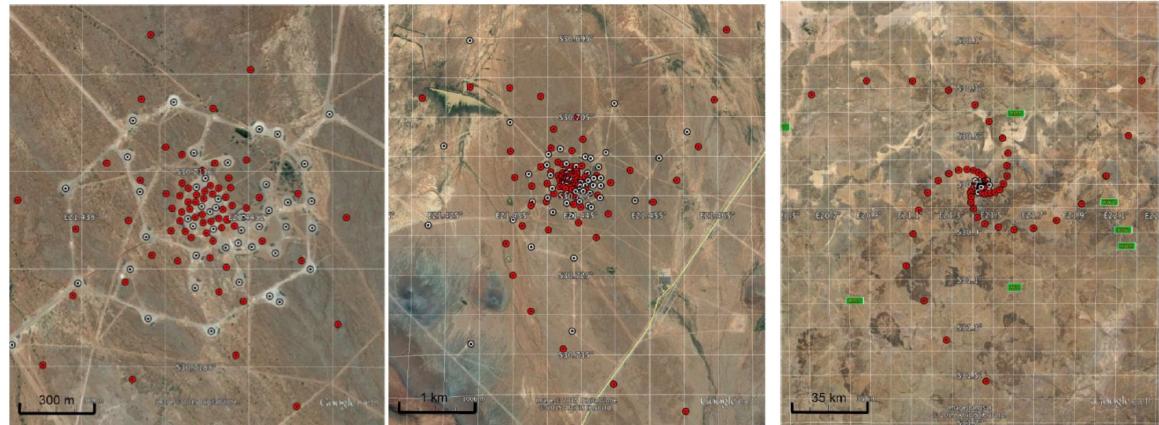
# SKA construction phase: 2021-2029

Pulsar Science Working Group

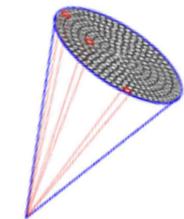
Key Science goal « challenging Einstein »

Last SKA Science meeting 15-19 March 2021

Pulsar Slack channel : 69 participants  
(6 french)

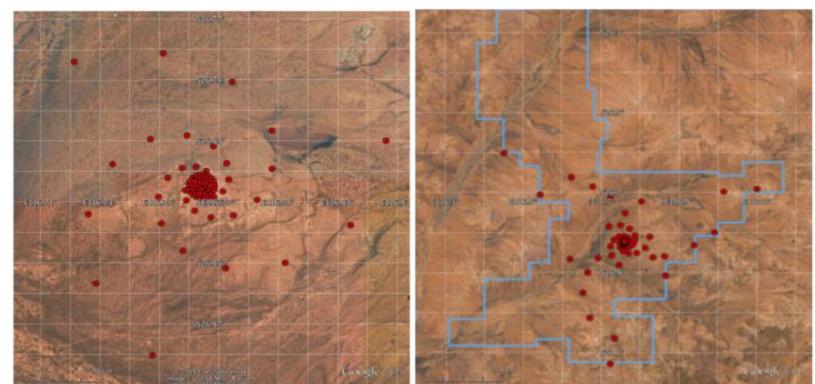
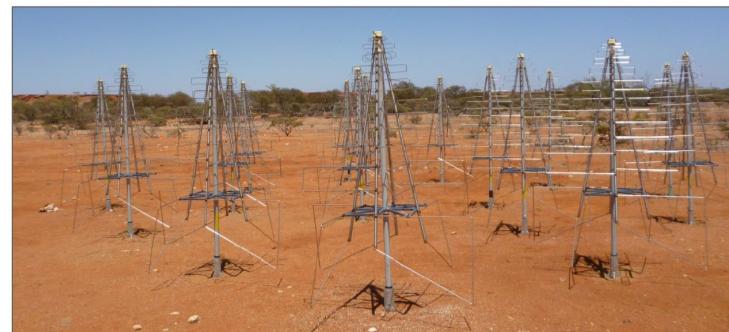


**SKA1\_MID:** **South Africa** and surrounding countries  
200 dishes (single feed) including MeerKAT, 1500 beams  
0.35-1.05 GHz / 0.95-1.76 GHz / 4.6-13.8 GHz  
+ 36 ASKAP dishes (focal plane arrays) in Australia



Sensitivity x 10  
Multibeamforming  
Multi-frequencies  
Sub-arraying  
VLBI & imaging

**SKA1\_LOW:** **West Australia**  
131,000 aperture array antennas , 500 beams  
grouped in 512 stations  
50-350 MHz



## Observational projects :

Binary pulsars vs **Gravity theory** (post-keplerian parameters) and **EoS** (neutron star masses)

Pulsar timing arrays (PTA) and **low frequency gravitational waves**

Pulsar **population** and surveys

**Support to high energy pulsar observations + Virgo-LIGO**

Multi-wavelengths observations, polarimetry and **emission processes**

**ISM/heliosphere studies** through dispersion & scintillation

### Telescope time per year

LOFAR FR-606 : ~1600 hrs

LOFAR core : ~200-500 hrs

NenuFAR : ~800 hrs

NRT : ~4300 hrs

MeerKAT : ~500 hrs

## Networking and fundings :

**ANR PTA France**      LPC2E + APC +USN (9 people)

**ANR MORPHER**      Obs.Strasbourg + APC+IRAP+LPC2E+Obs.Bordeaux (11 people)

**Ateliers PNHE**      MODE (50 people) → link with SNR, PWN, EoS, high energy emission, models  
Entretiens (15 people) → pulsars : theory and observations

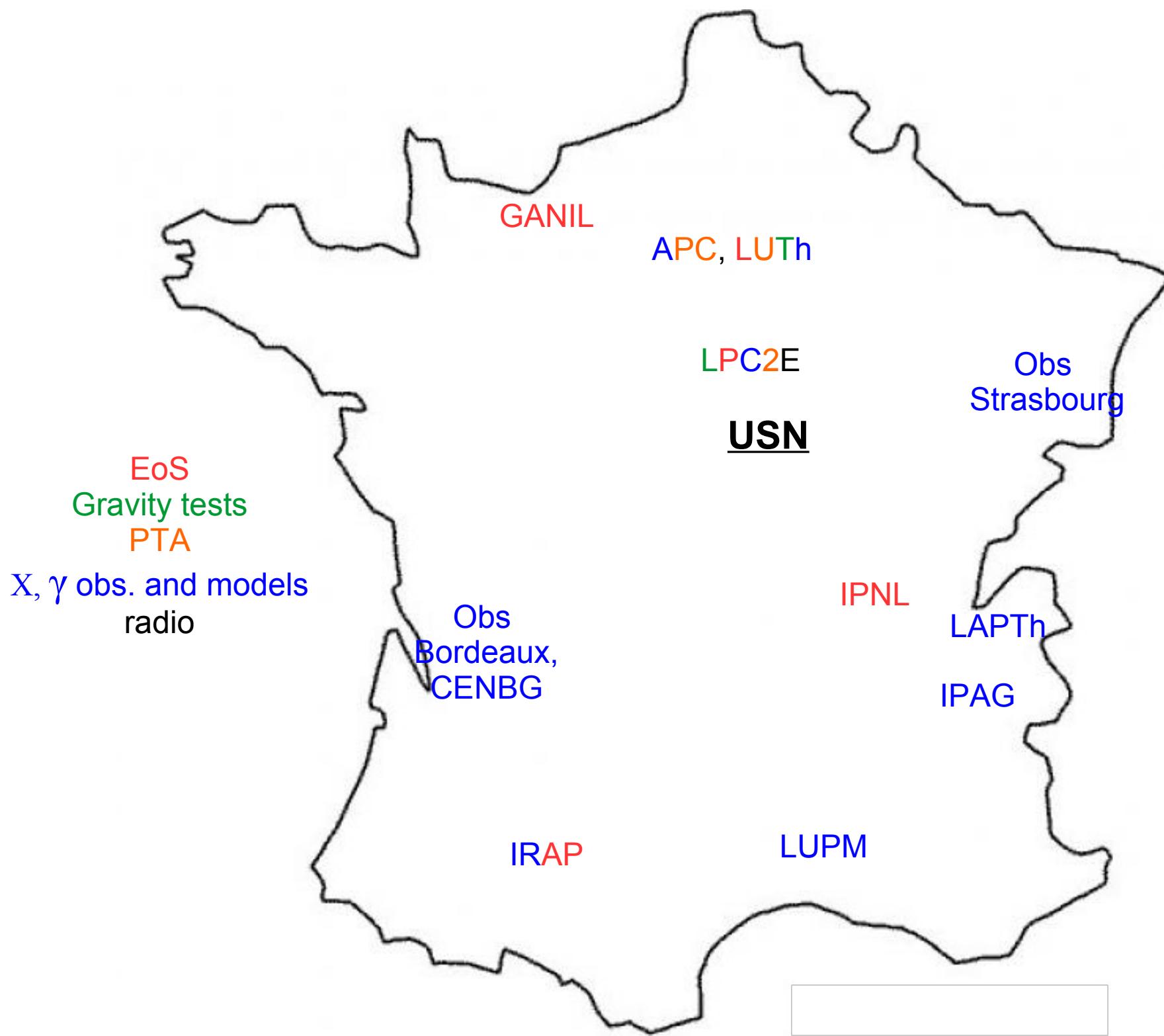
**PNCG+PNHE**      PTA-France (9 people, LPC2E, APC, USN)

**PNHE**      « Sondes Multi-longueurs d'onde de l'Excès de Fermi : du domaine Radio aux rayons X »  
(7 people, LAPTh, IPAG, LPC2E)

**AS SKA-LOFAR**      NenuFAR developments, SKA preparation

**PNGRAM**      tests GR and Reference Syst. (7 people, LPC2E, LUTH, USN, FemtoST)

**Paris Observatory**      Actions fédératrices RT21, HESS/CTA, GPhys/PhyFOG



# The NenuFAR pulsar Key project

25 participants (mainly european)

DM variations, scintillation and ISM studies

Polarisation

Single pulse emission

Spectral energy distribution and turn-over

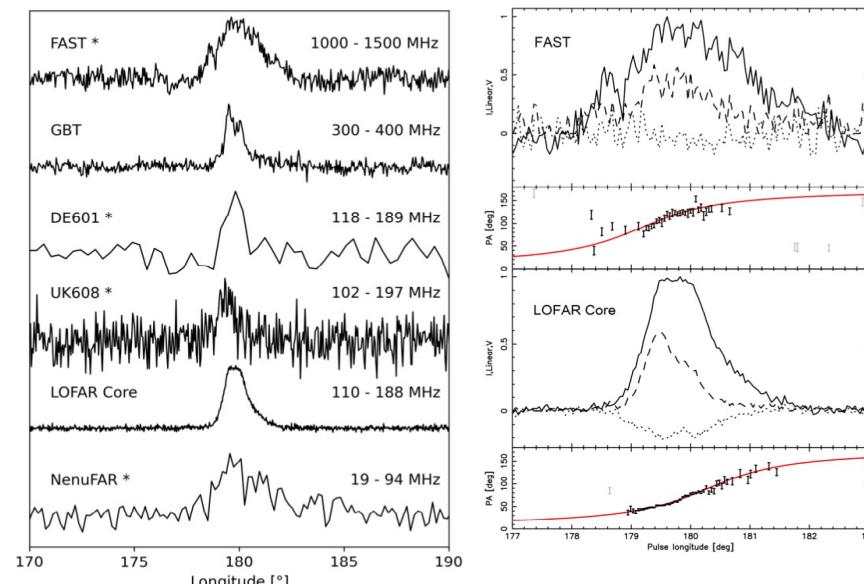
Low frequency population census

## Some recent results (a few examples)

### The « slowest pulsar » J0250+5854

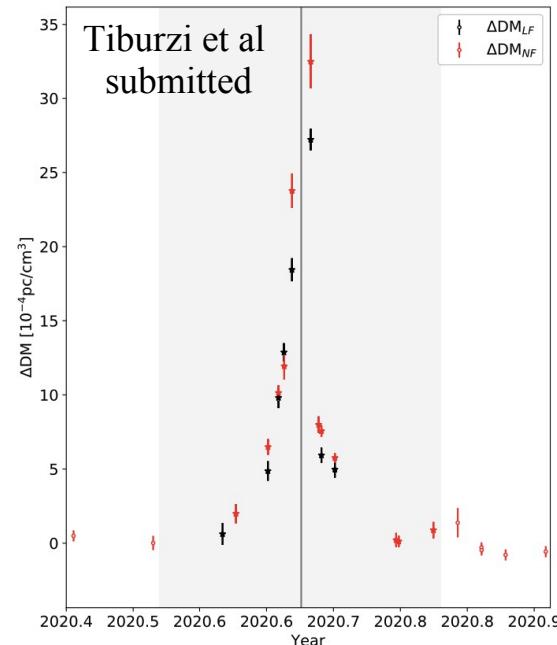
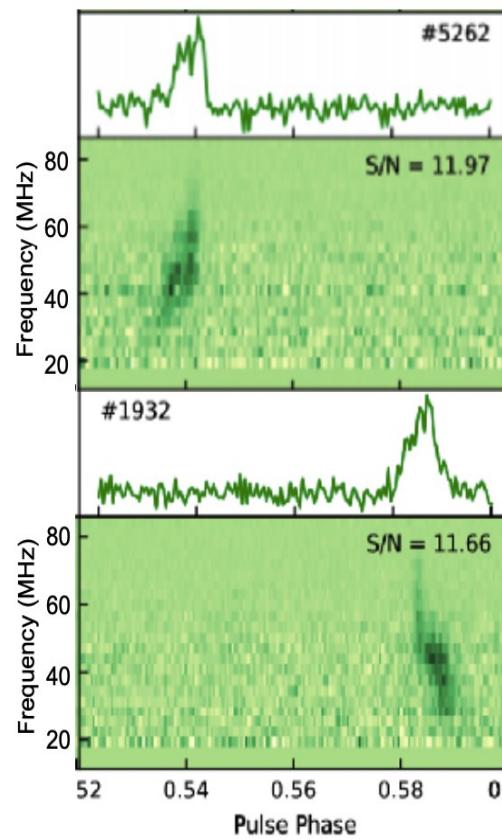
(multi telescopes observations)

Agar et al (2021)



**Single pulse studies**  
Kondratiev et al in prep

**B1237+25**



### Solar conjunction of PSR J1022+1001

simultaneous observing campaign using HBA/LOFAR core ( $> 110$  to  $> 190$  MHz) and NenuFAR ( $> 10$  to  $> 90$  MHz),

test whether the observed  $\Delta \text{DM}$  can be caused by SW-induced scattering

# The NenuFAR pulsar Key project

25 participants (mainly european)

DM variations, scintillation and ISM studies

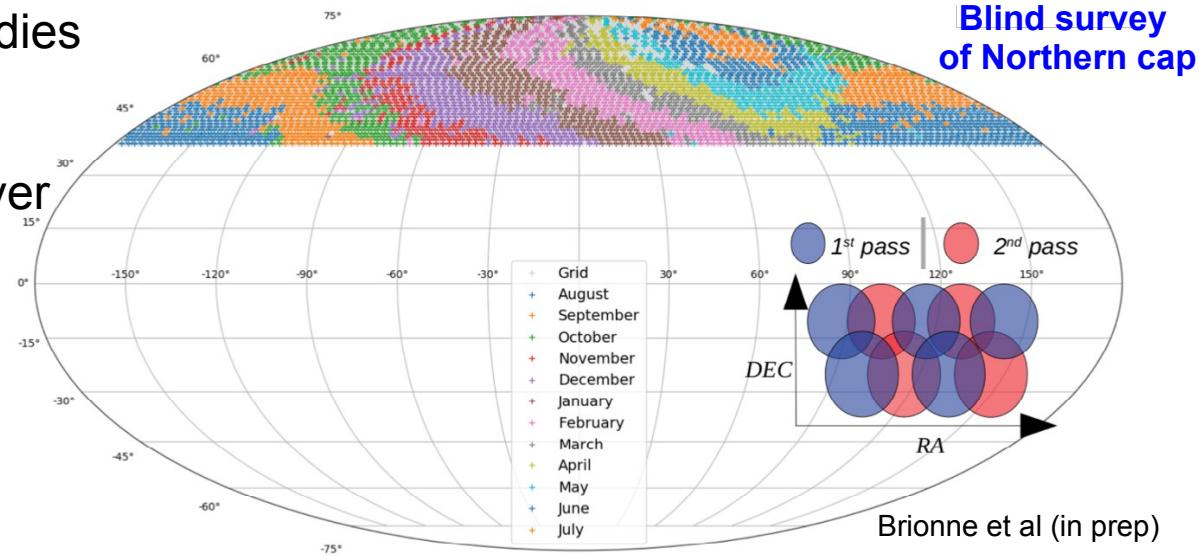
Polarisation

Single pulse emission

Spectral energy distribution and turn-over

Low frequency population census

surveys

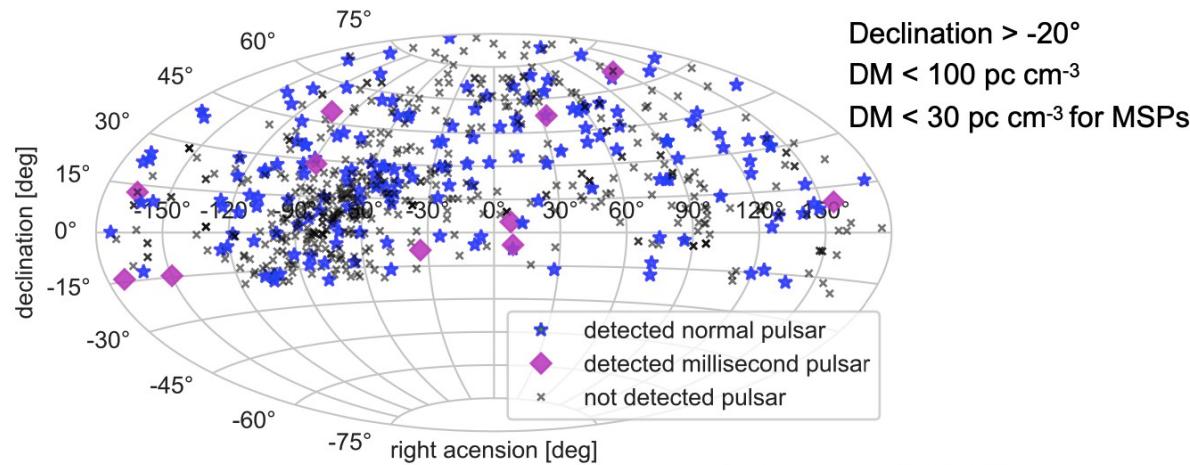


Blind survey  
of Northern cap

Brionne et al (in prep)

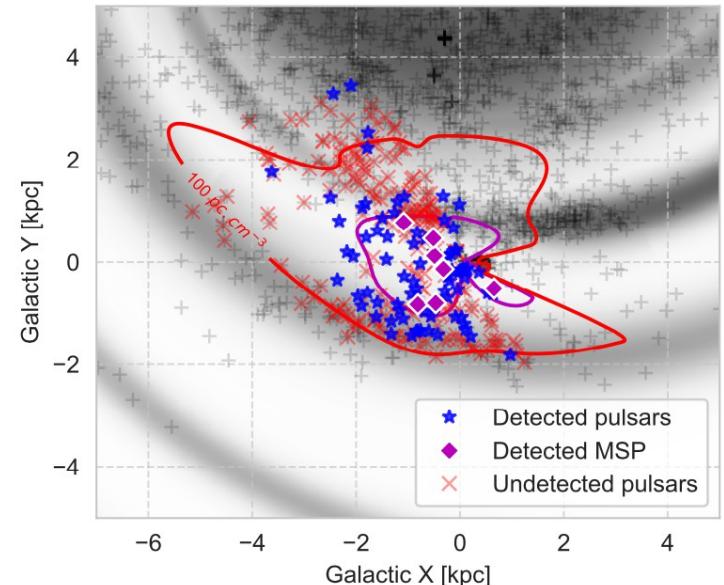
## Some recent results (a few examples)

### Known pulsar census



Bondonneau et al. (in prep)

→ ~100 new detections below 100 MHz



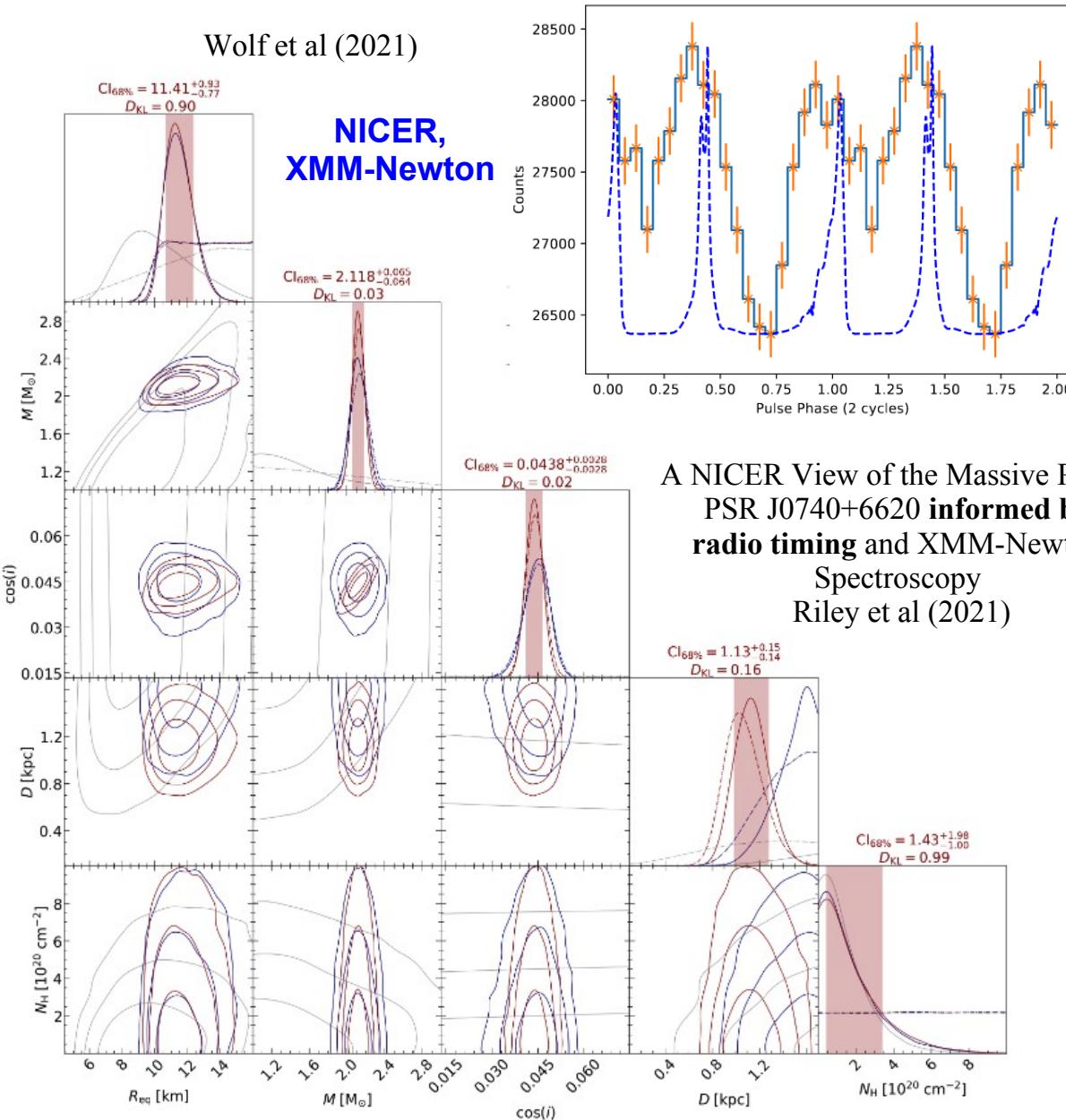
# Radio support to high energy X and gamma observations, Equation of State + constraints on emission mechanisms

Fermi-LAT, NICER,  
INTEGRAL, XMM-Newton,  
HESS, MAGIC

PSR J0740+6620 in the  
energy range 0.30–1.25 keV,  
folded with NRT radio ephemeris at 1.4 GHz

Wolf et al (2021)

NICER,  
XMM-Newton



A NICER View of the Massive Pulsar  
PSR J0740+6620 informed by  
radio timing and XMM-Newton  
Spectroscopy  
Riley et al (2021)

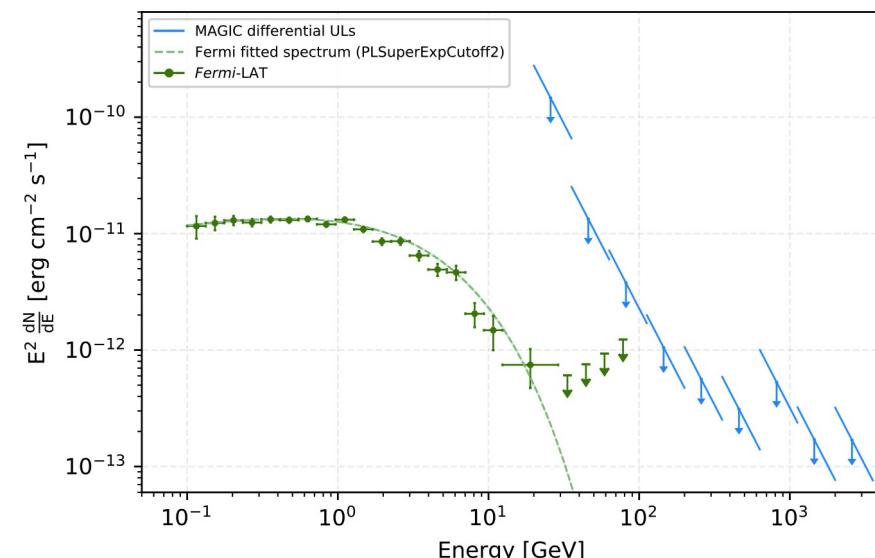
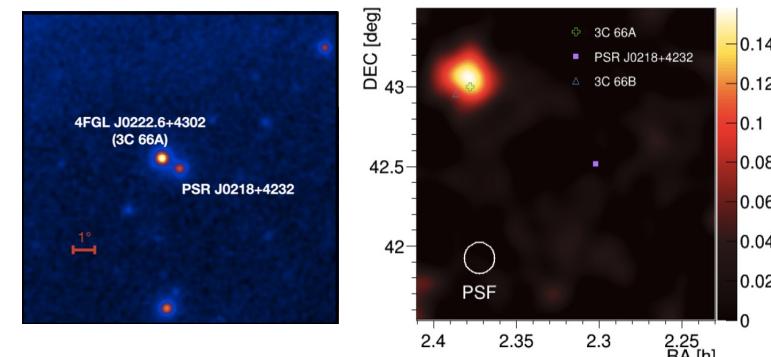
Search for VHE emission  
from PSR J0218+4232

folded with NRT radio ephemeris at 1.4 GHz

Acciari et al (2021)

Fermi-LAT

MAGIC



# Testing Gravity in binary pulsars

Measure Shapiro,  $\dot{\omega}$ ,  $\dot{P}_b$ ,  $\dot{X}$ , geodetic precession

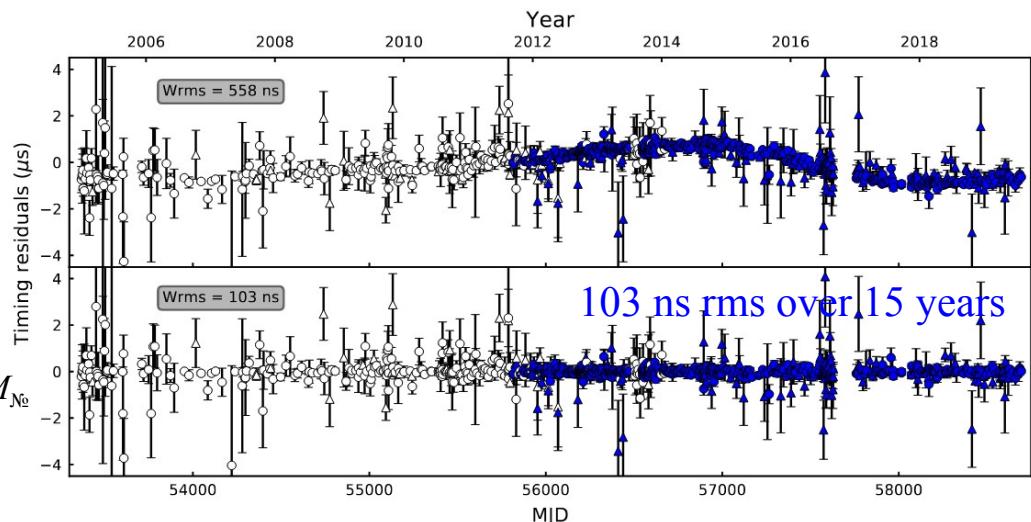
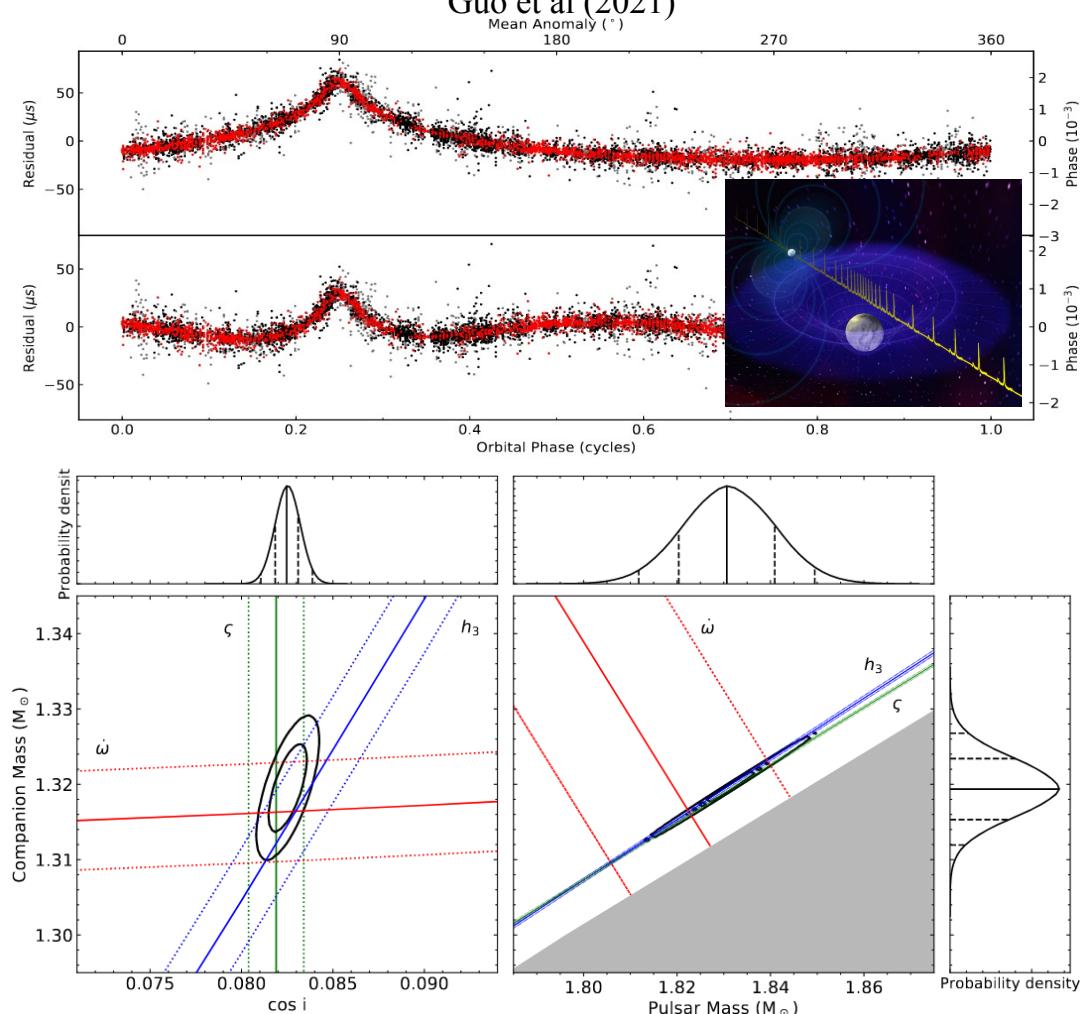
Put constraints on  $\dot{G}$ ,  $\hat{\alpha}$ ,  $\dot{P}_b$  dipolar radiation...

## PSR J2222-0137

The most massive double degenerate known in the Galaxy :  $3.150(14) M_{\odot}$

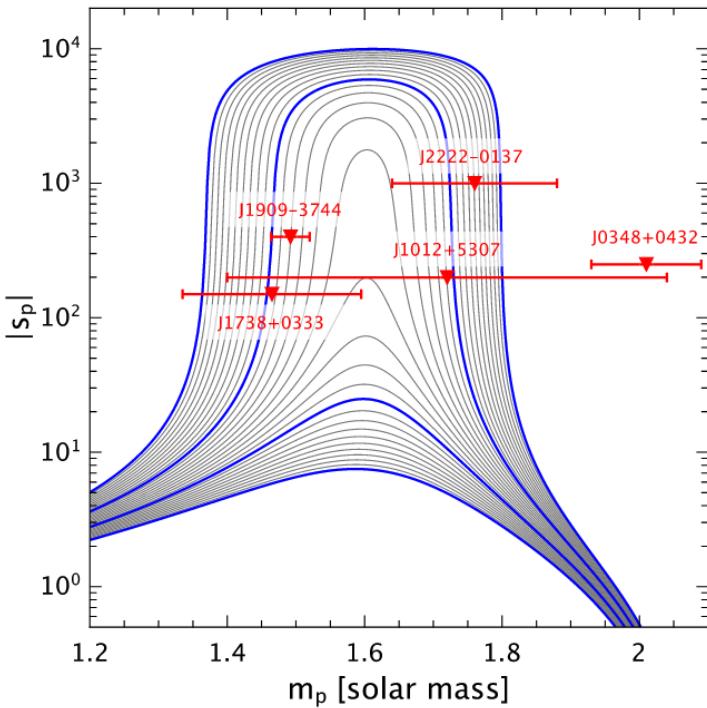
A new  $> 1\%$  test of general relativity (GR) from the agreement of the Shapiro delay parameters and the rate of advance of periastron.

Guo et al (2021)



NRT

monitoring  
of 20  
relativistic  
binaries



High-precision timing analysis and an astrophysical study of the binary millisecond pulsar, **PSR J1909-3744**

Upper limits on spontaneous scalarization within Damour–Esposito–Farèse (DEF) gravity from dipolar radiation

Liu et al (2020)

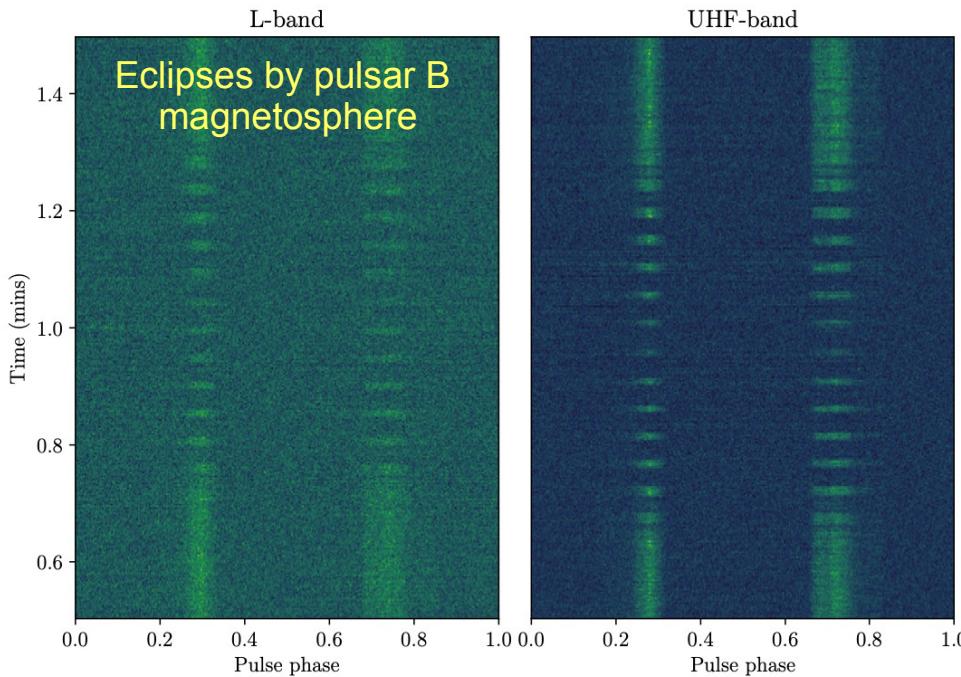
# Testing Gravity in binary pulsars

Measure Shapiro,  $\dot{\omega}$ ,  $\dot{P}_b$ ,  $\dot{X}$ , geodetic precession

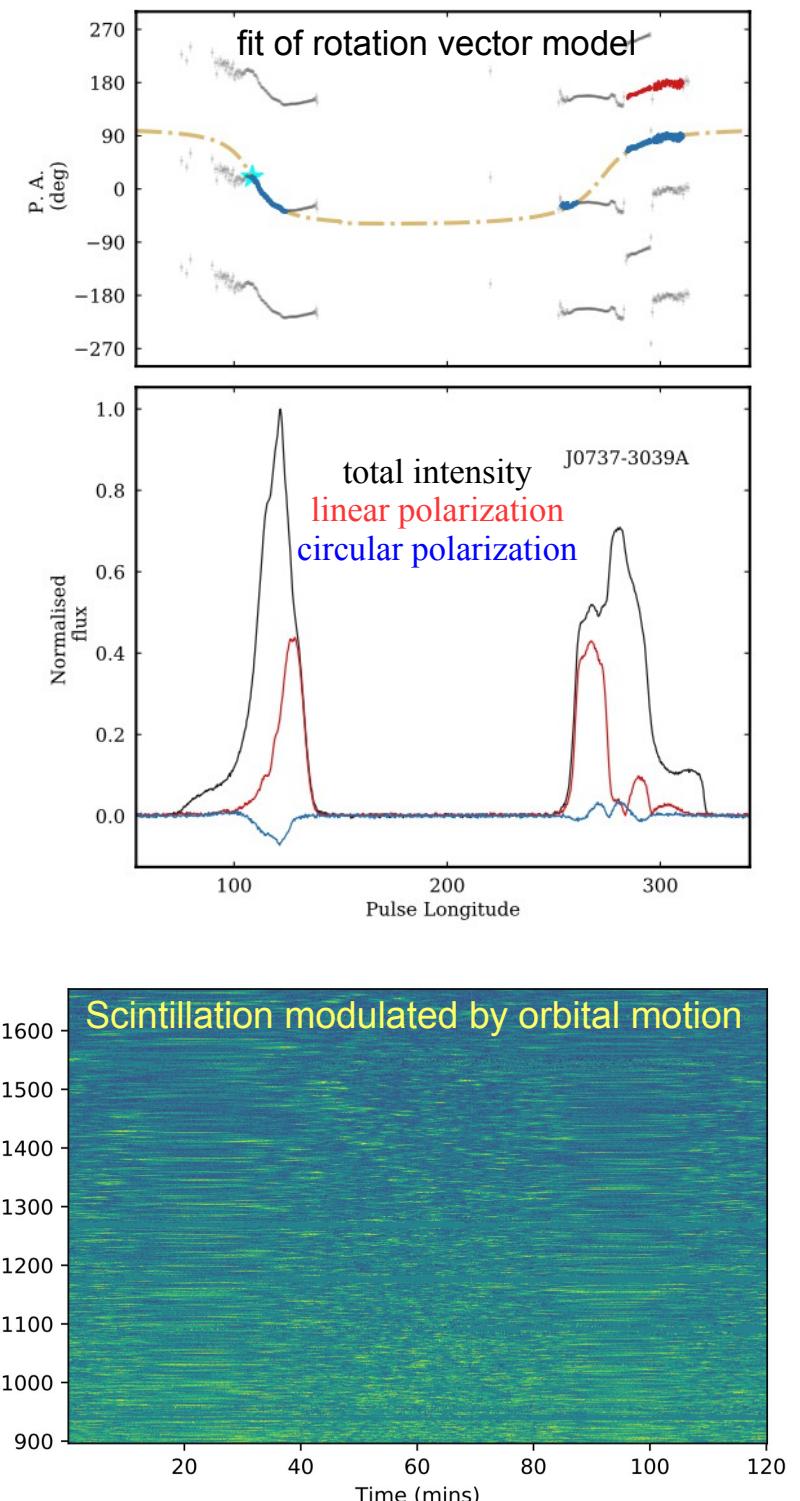
Put constraints on  $\dot{G}$ ,  $\dot{\alpha}$ ,  $\dot{P}_b$  dipolar radiation...

## MeerKAT

**25 pulsars as an initial high priority list of targets,**  
some with coordinated long term timing with the NRT



**The double pulsar 0737-3039 as an example**  
Kramer et al (2021)

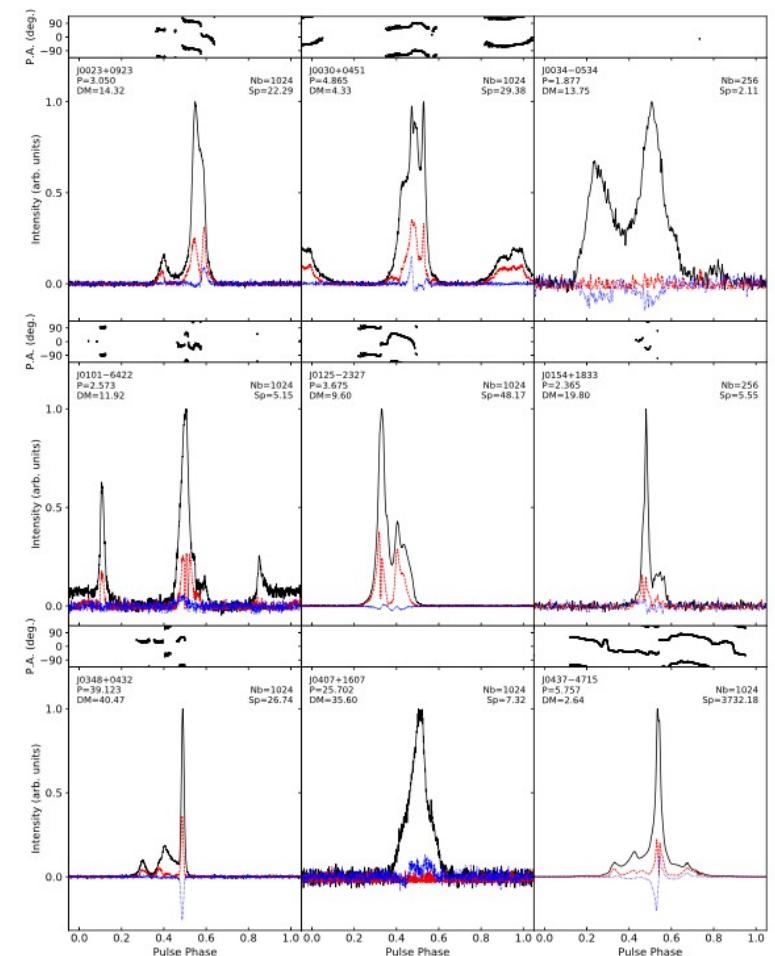
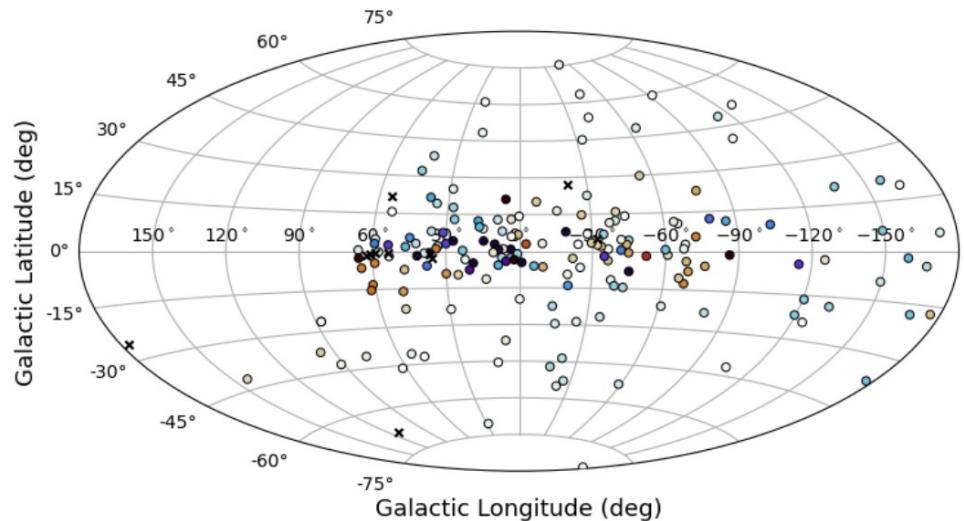
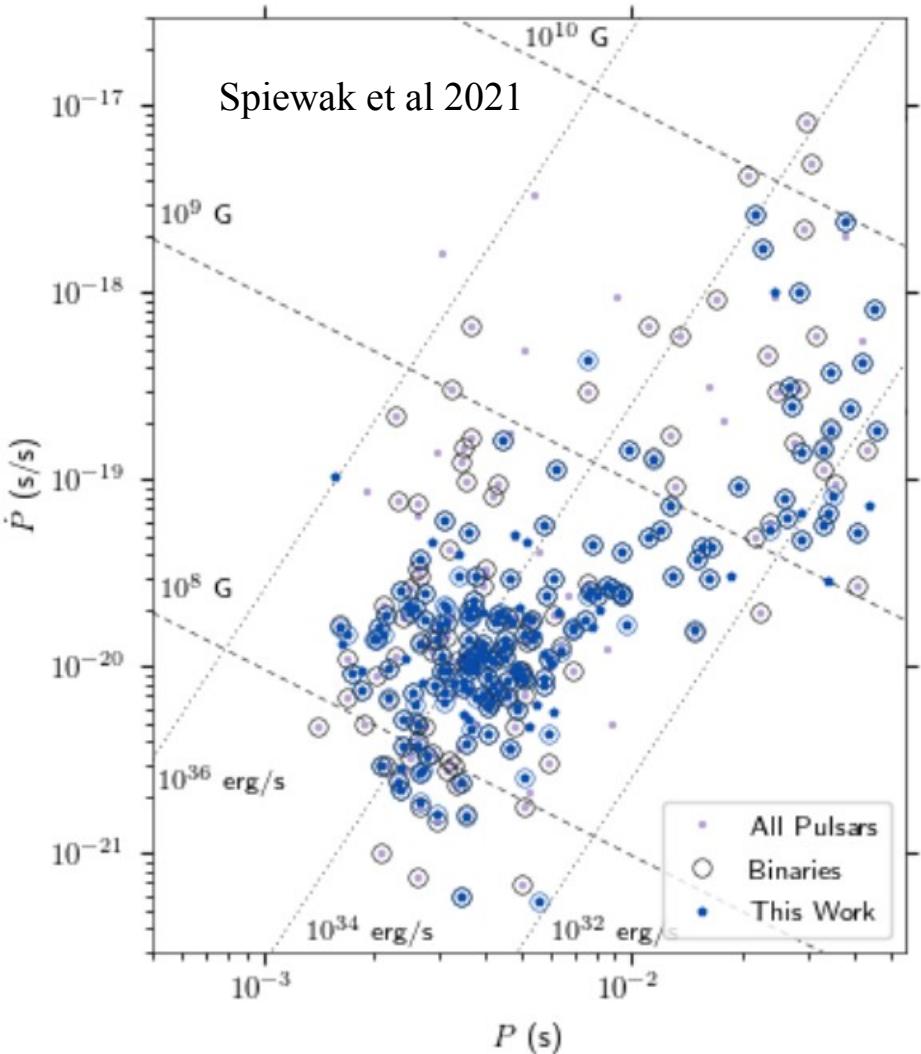


# Millisecond pulsars and PTA program

Since 2018 : 4000 observations of 189 millisecond pulsars

→ 80 MSPs with timing rms < 1  $\mu$ s

## MeerKAT



Spiewak et al 2021

## Pulsar Timing Arrays : principles

pulsar times series sensitive  
to local space time perturbations → gravitational waves  
detector

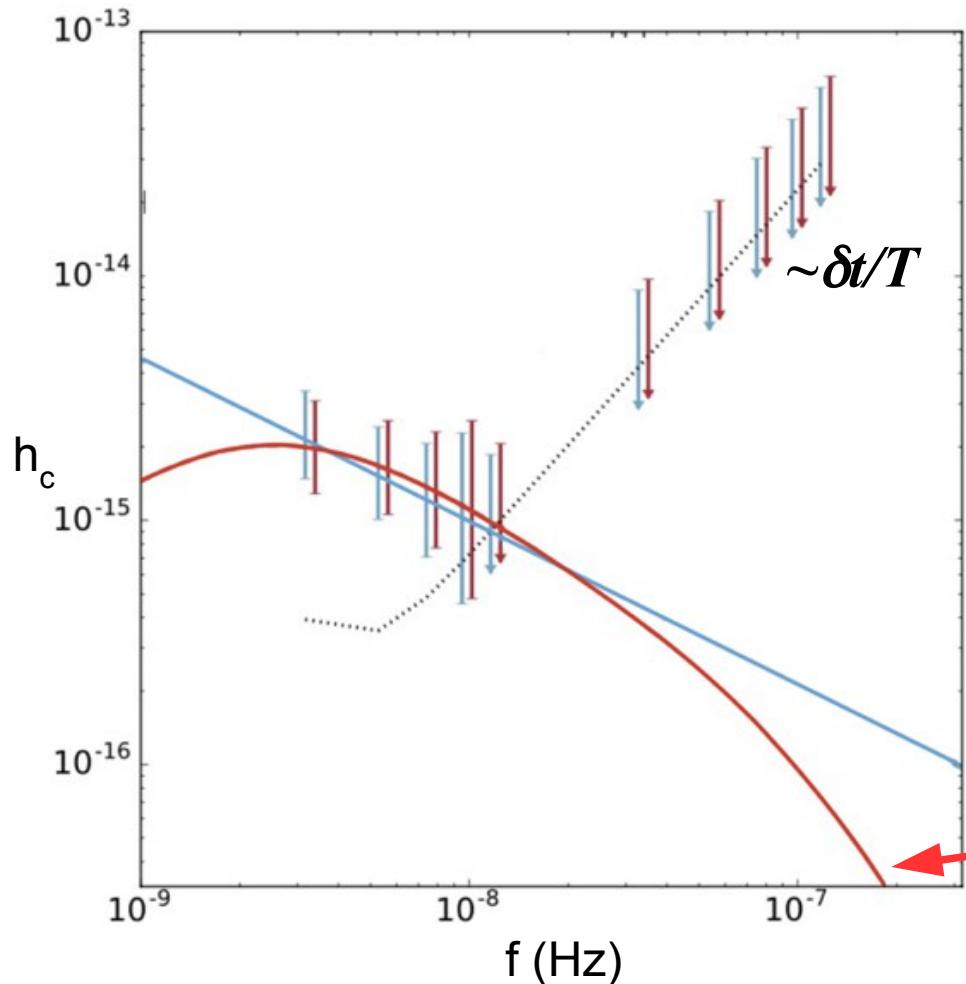
With timing uncertainties  $\delta t$  ( $\sim 100$  ns) and observation time spans  $T$  ( $\sim 25$  years)  
→ PTA are sensitive to *amplitudes*  $\sim \delta t/T$  and to *frequencies*  $f \sim 1/T$

$$\text{Sensitivity} \sim 100 \cdot 10^{-9} / 25 \times 3 \cdot 10^7$$

$$\rightarrow A \sim 1.3 \cdot 10^{-16}$$

Frequency domain (25 years - 1 week)

$$\rightarrow 10^{-9} - 10^{-6} \text{ Hz}$$



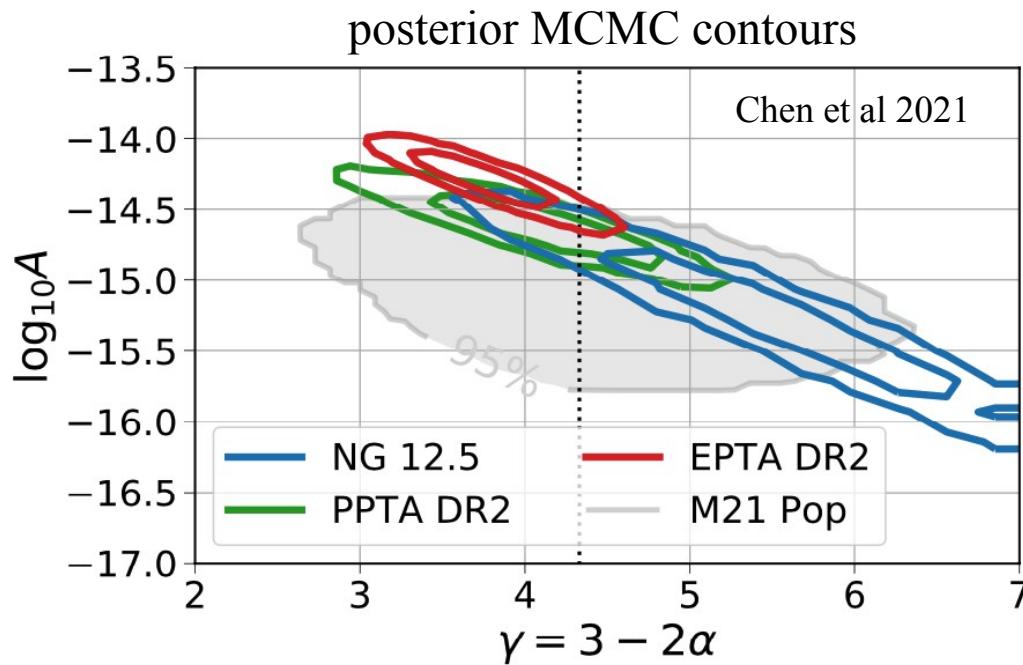
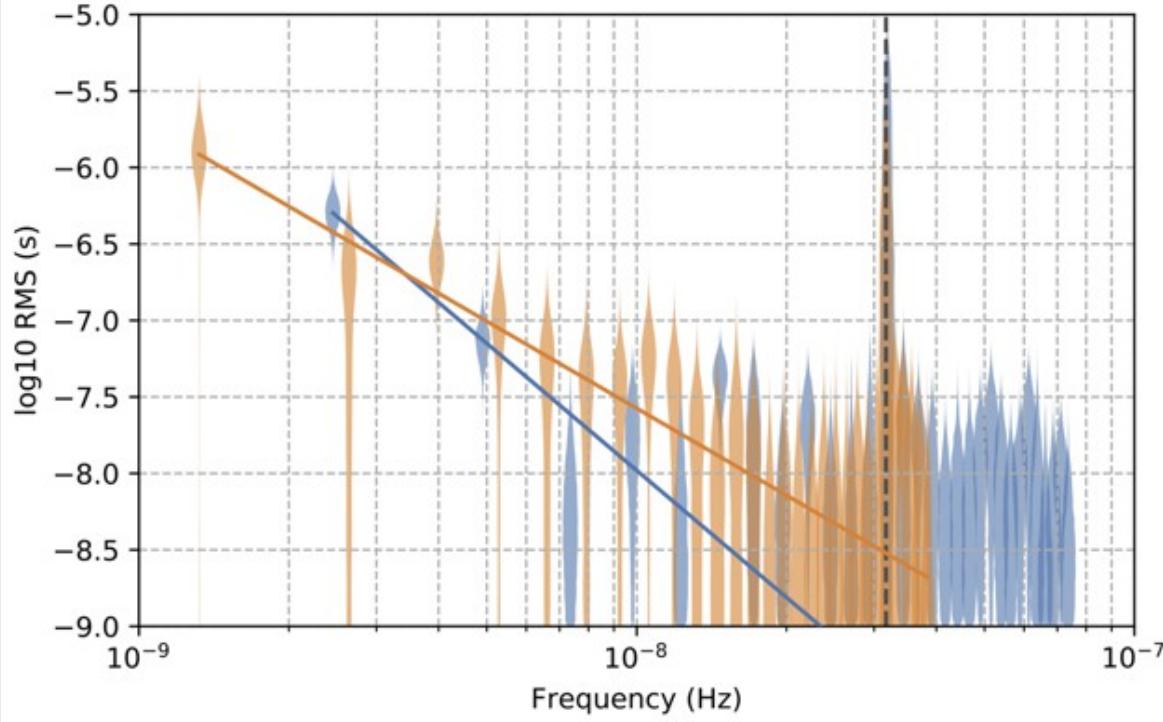
$$h_c(f) = A \left( \frac{f}{\text{yr}^{-1}} \right)^{-2/3}$$

Expected spectrum for a population  
of super massive black hole binaries  
(cf Marta Volonteri talk on Tuesday)

purely circular orbits, isolated pairs

including eccentricity, stellar hardening, ...

# Pulsar Timing Arrays looking for a stochastic background

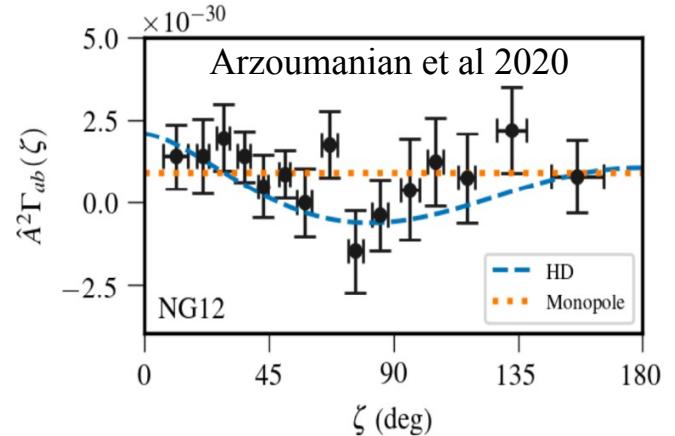
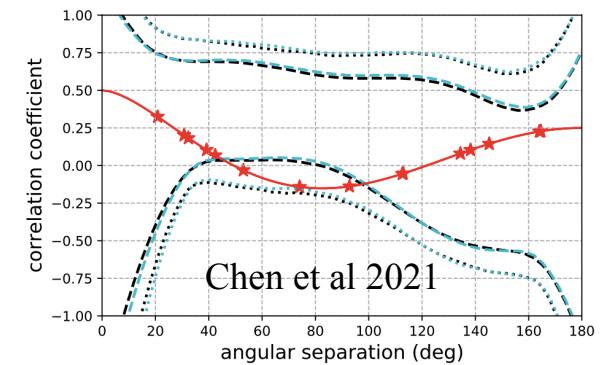


## A first detection ?

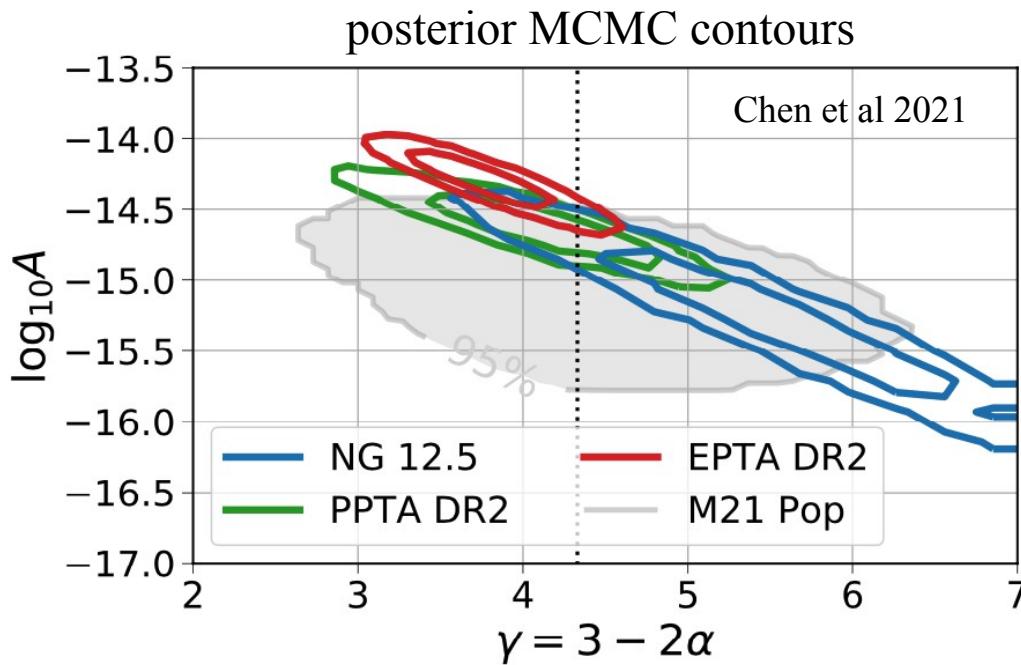
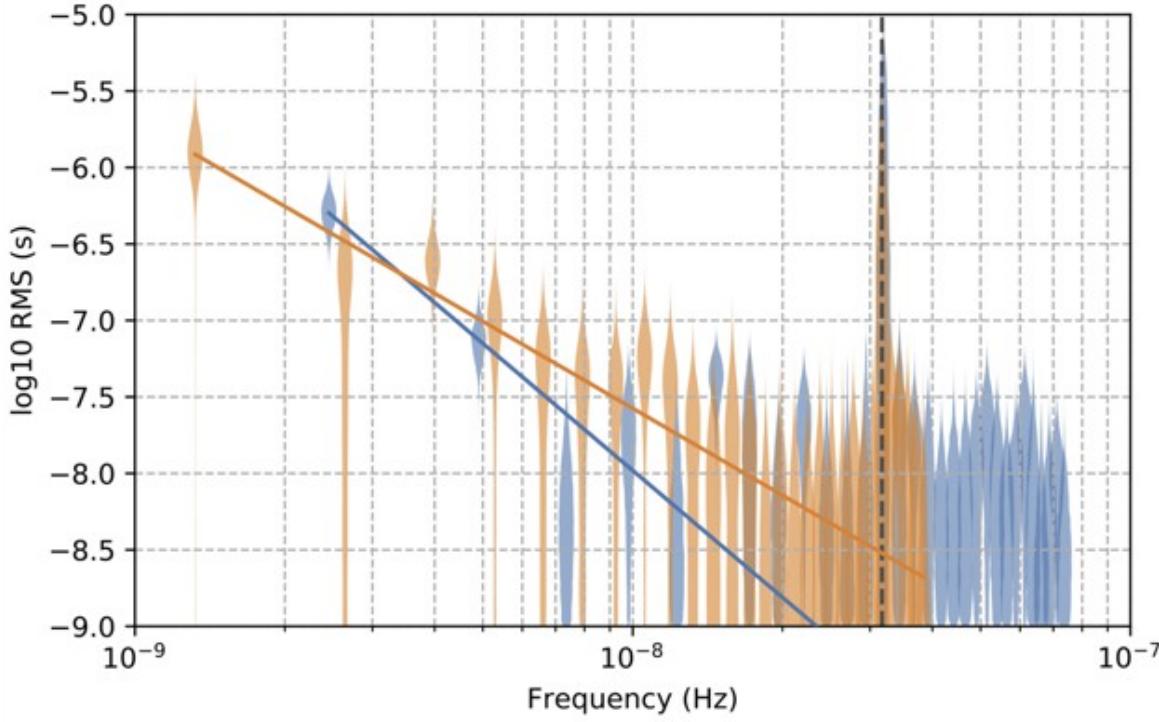
EPTA result :  
6 « best » pulsars, 14-25 years  
(Chen et al 2021)

NANOGrav result :  
47 pulsars, 12.5 years  
(Arzoumanian et al 2020)

Hellings & Downs  
spatial correlation



# Pulsar Timing Arrays looking for a stochastic background

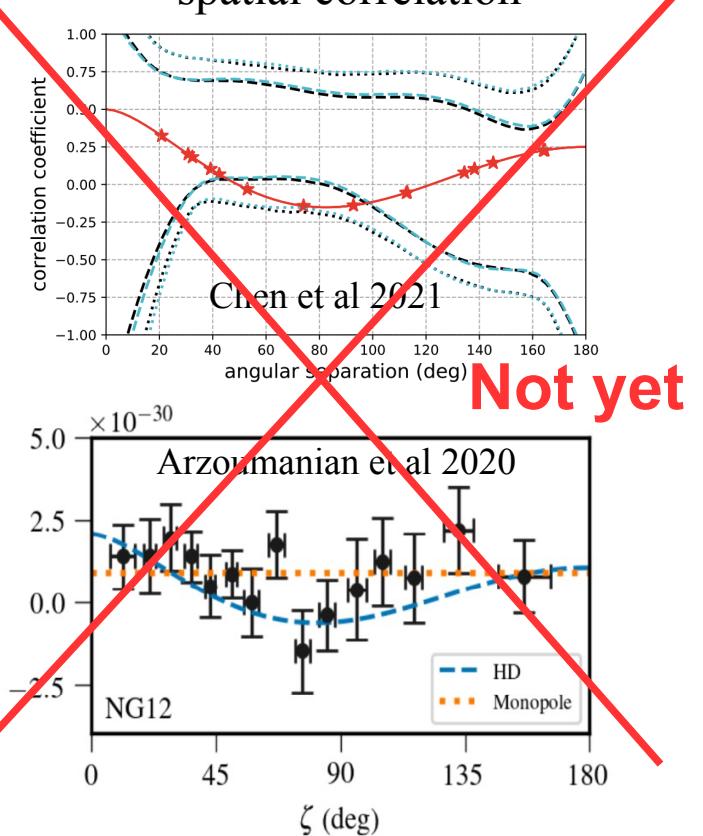


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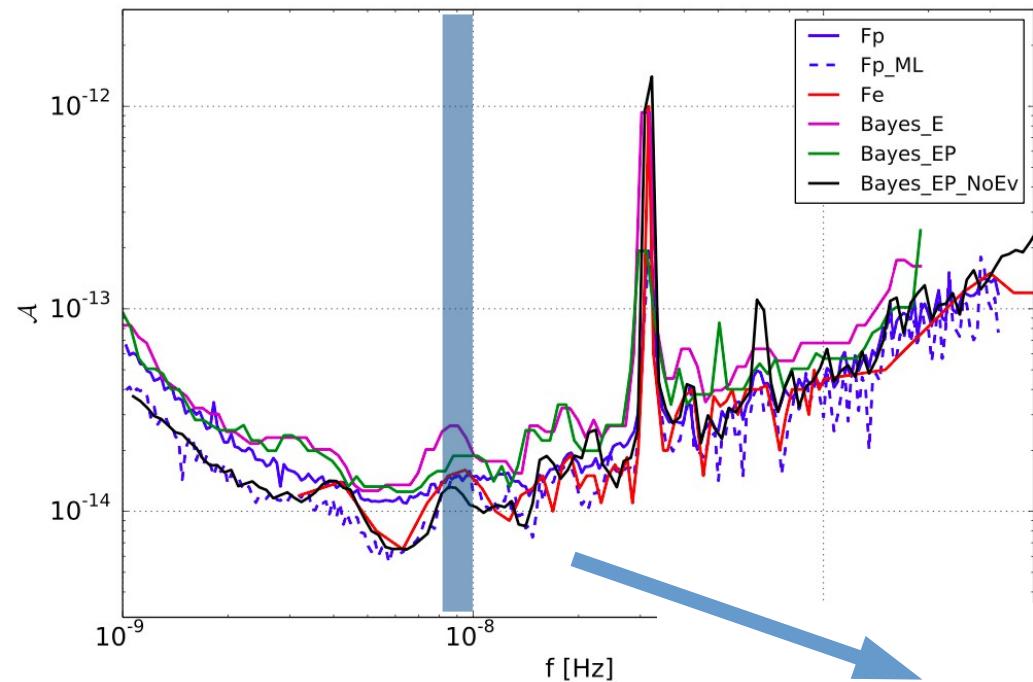
NANOGrav result :  
47 pulsars, 12.5 years  
(Arzoumanian et al 2020)

Hellings & Downs  
spatial correlation



# Pulsar Timing Arrays

single source (continuous wave) search and sensitivity maps



EPTA-DR1 42 pulsars

Babak et al 2015

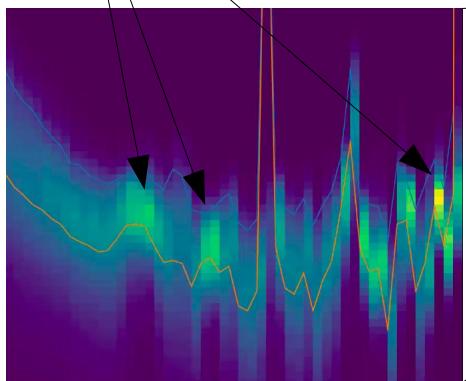
EPTA DR2 – 26 « best » pulsars (2021)

Proxy : EPTA DR1 + recent NRT data



$f = 10 \text{ nHz}$

$(\alpha, \delta)$  GW spectrum



preliminary

Courtesy of Mikel Falxa (PhD – APC)

