Hints for very low frequency Gravitational Waves using a Pulsar Timing Array

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Plan

Highly stables clocks

to be convinced that, despite being far away in the Galaxy,
millisecond pulsars are ideal tools for high-precision measurements

A very specific instrumentation

to be convinced that, despite the very disturbing interstellar medium,
our instrumentations are doing the best we can do

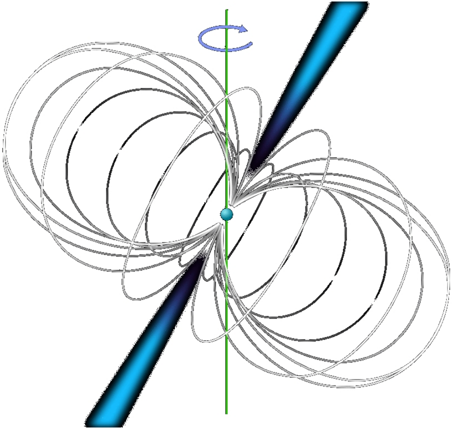
Search for very low frequency Gravitational Waves

to be convinced that, despite being extremely difficult to find,
a Gravitational Waves signal may be close to be detected

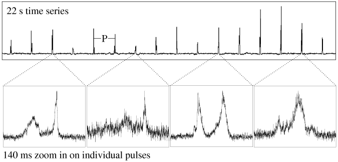
References :

Handbook of Pulsar Astronomy, D.Lorimer and M.Kramer,
Cambridge University Press, 2005

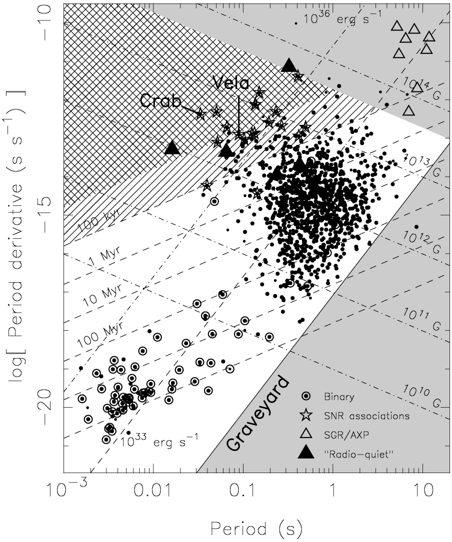
The pulsar : a magnetized neutron star



As a lighthouse,
two beams of radio waves,
emitted along
the magnetic axis,
sweep the sky
as the star rotates,
producing reception of
periodic pulses on Earth.



An outstanding stability



At first, a very short life...

After a birth at ∼30ms,
the pulsar is rapidly slowing down
and stops radio emission after
a few millions years.

... but then... eternity !

Those still present in a binary system
speed-up by angular momentum transfer,
and produce radio waves again,
those are
the recycled millisecond pulsars
with an outstanding rotational stability !

Alpar et al., Nature *300*, **728** (1982)

Many applications

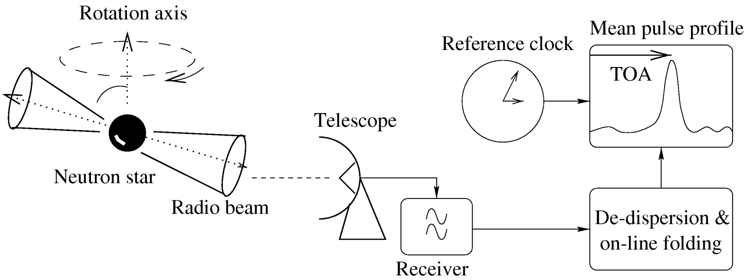
Exceptional stability and timing precision

Together with the exceptional rotational stability of the fastest pulsars, state of the art coherent dedispersion instrumentations provide high precision Times of Arrival (ToAs) measurements with uncertainties as low as $\sim$10ns.

A large number of applications

- search for a Gravitational Waves signature
- tests of the theories of gravitation (GR and others)
- propagation through and turbulence in the interstellar medium
- stellar evolution
- globular clusters and our Galaxy gravitational potential
- constrains on the solar system planetary ephemeris
- detection of extra-solar planets
- emission processes of pulsars
- long term stability of terrestrial time scales
- link between celestial reference frames (equatorial and ecliptic)

A pulsar timing experiment

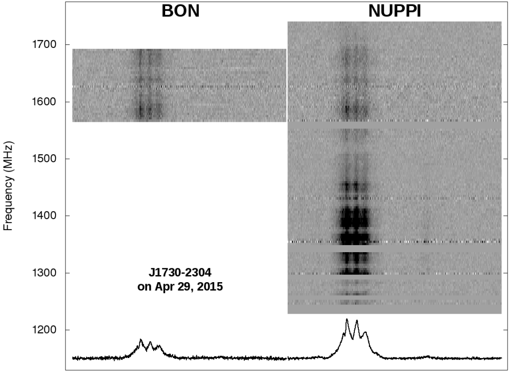


In a pulsar timing experiment :
- a pulsar is observed a few times a month (typically) with a dedicated instrument
- pulses are 'dedispersed' and folded to form an integrated pulse profile
- data receive a time stamp, and the daily profiles are compared to a 'template' profile to extract a 'Time of Arrival' ToA

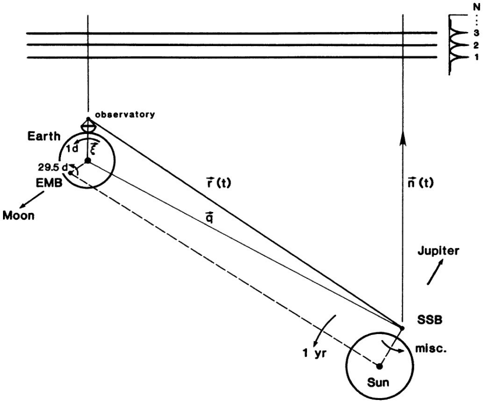
How scale ToA measurement uncertainty ?

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

Need bright pulsars (S_{PSR}) with narrow pulses (w), observed with large telescopes (A) sensitive receivers (T_{sys}), over large bandwidths (B) and long integration times (T).

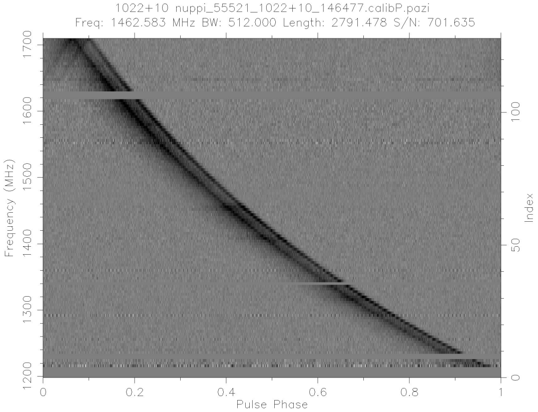


Time integration : relative motions



The radio telescope and the pulsar are constantly moving...
the very short **apparent period** is **not constant !**
→ to be able to place all the impulsions on top of the first one
we have to build a special instrumentation

Frequency integration : dispersion in the ISM



PSR J1012+5304 data
folded for each 4-MHz channel (1.2→1.7 GHz)
P=5.25ms DM=9.0233 pc.cm^{-3}

the Interstellar Medium (ISM) is
a cold and ionized plasma
delay w.r.t. infinite frequency

$$t = \int_0^d \frac{dl}{v_g} - \frac{d}{c} \equiv k \frac{DM}{f^2}$$

with $k = \frac{e^2}{2\pi m_e c}$
and DM the 'dispersion measure'
integrated electronic content
along the line of sight

$$DM = \int n_e dl$$

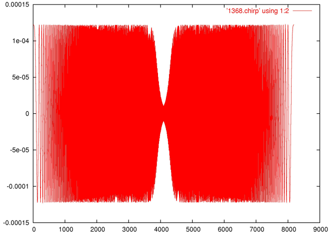
Coherent dedispersion

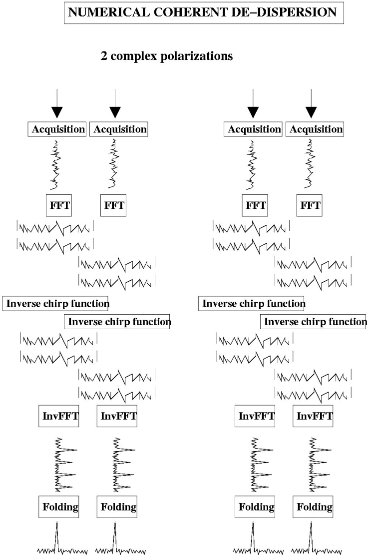
ISM dispersion acts as a phase filter only.
On the **recorded voltages** induced by the incoming electromagnetic radiation, the 'digital' coherent dedispersion applies an inverse transfer function in the complex Fourier domain :

$$\text{FFT} + \text{inverse filter} + \text{FFT}^{-1}$$

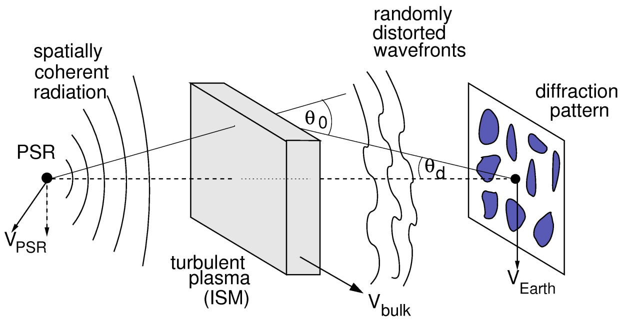
(with overlap management)

For large bandwidth and **real-time** processing instrumentations, we need a **huge computing power !**





Note : the ISM is a turbulent medium...

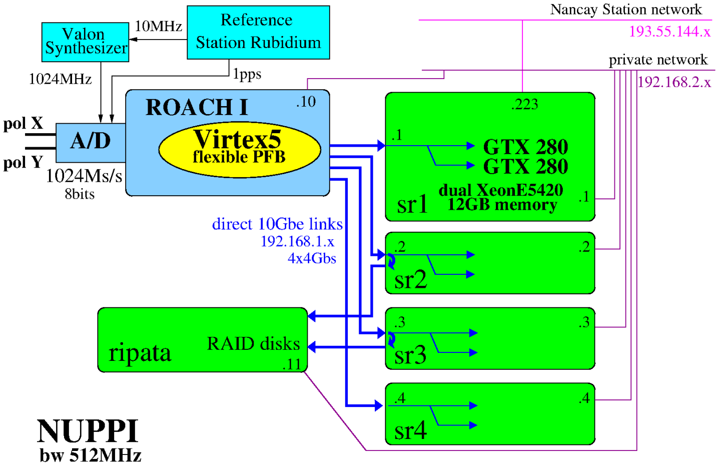


in addition to the more or less constant net dispersive effect,
there is variable multi-propagation

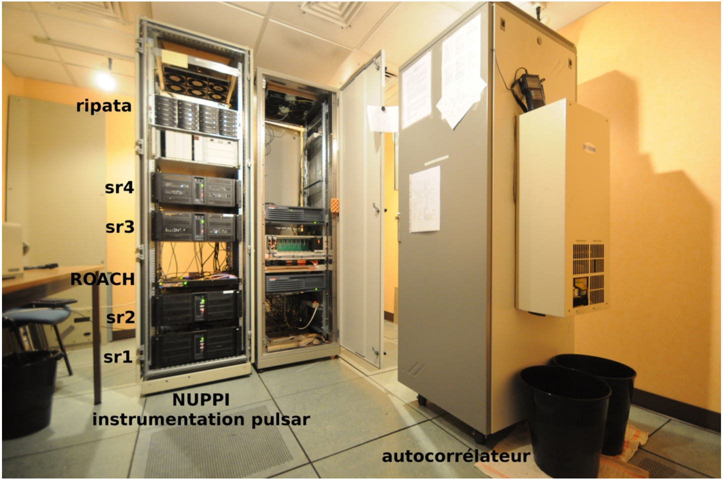
- the probed volume (cigar shape) highly depends on frequency
- signal is affected by scintillation (in time and frequency)
- the received signal is a mixture of differentially delayed pulses

Schematic of NUPPI instrumentation

the **Nançay** Ultimate Pulsar Processing Instrument

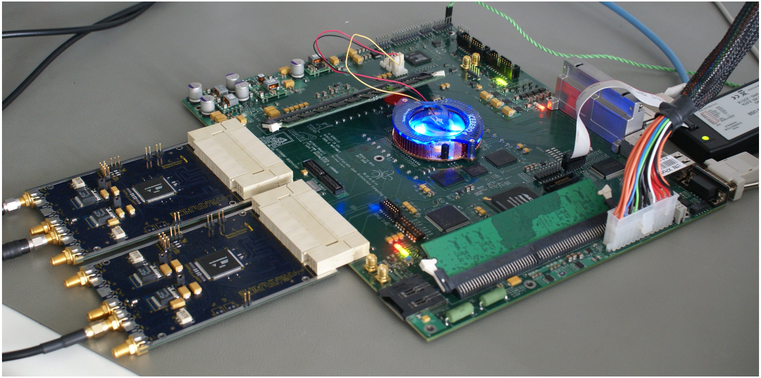


A picture of NUPPI



ROACH + 2 A/D boards

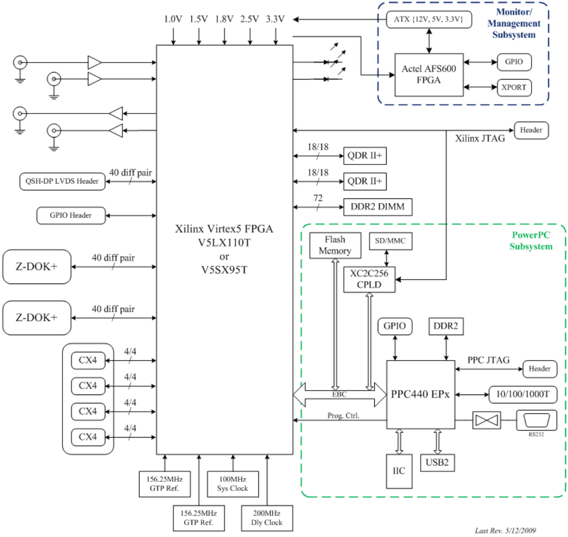
a ROACH board (CASPER, Berkeley + Xilinx Virtex 5) and 2 A/D conversion boards



- a clock at 1024MHz
- 2 polarizations sampled at 1024Ms/s, 8bits
- a 1pps signal

+ FPGA design (PFB=PolyphaseFilterBank)
to transform 1 data stream 512MHz bw to 128 data streams 4MHz bw each

ROACH architecture



FPGA :
- a Virtex 5 FPGA

Interfaces :
- 2x Z-DOK+ 40 diff pair connectors
- 4x CX4 10Gbps

Peripherals :
- 2x 2M x 18-bit QDRII+ SRAMs
- 1x DDR2 DRAM DIMM

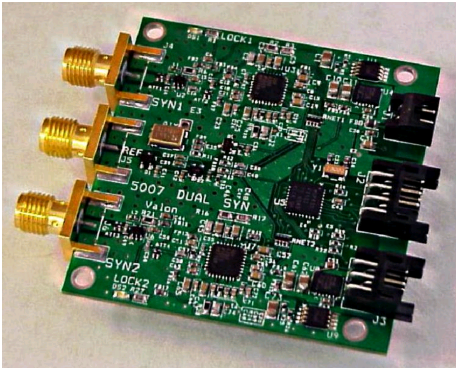
CPU :
- 1x AMCC PowerPC 440EPx

PULSAR TIMING :

the PFB is running continuously, and the **1pps** signal is used to **reset** the **block counter** which is used to actually start further processing

A good A/D clock

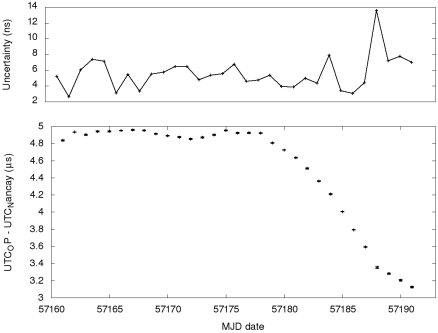
The A/D 1024MHz clock is built by a Valon 5007 device
and locked on the **Rubidium reference clock** of the Observatory



Link from UTC_Nançay to UTC_OP : 1pps monitoring

GTR50 receiver from Dicom Inc.

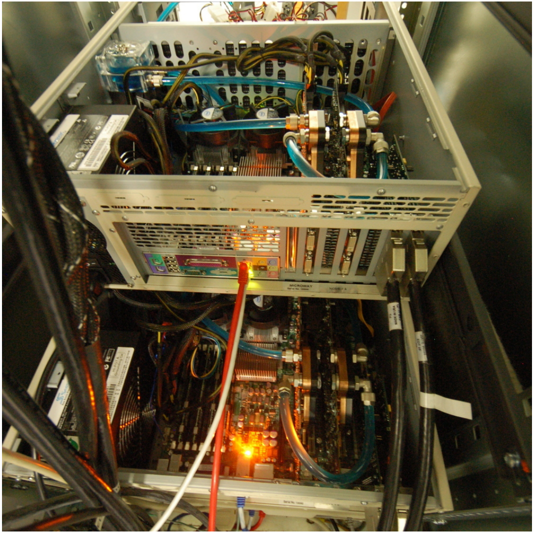
the link is at ∼5ns, twice a day



Ionospheric TEC variations could be a limit

REFIMEVE link is long-awaited !

GPUs as powerful real-time processors



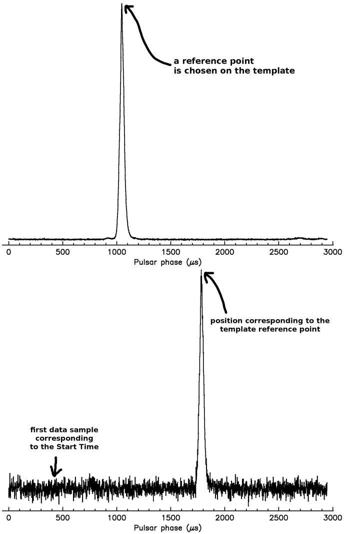
Diversion of GPUs

Using high performance graphical card (GPU), and water-cooled system to increase their lifetime, 4 PCs / 8 GPUs can easily dedisperse bw 512MHz (4GB/s=16Gb/s) in real time

An ultimate precision

Timing uncertainty can be as good as ∼10ns for a few pulsars.

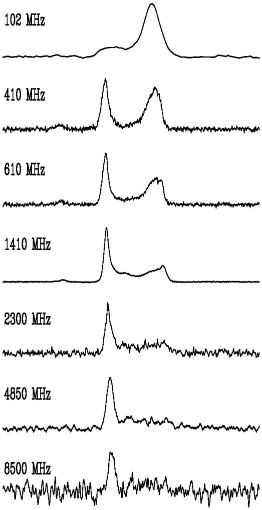
A ToA : cross-correlation with a 'template'



A 'template' is built as :
- a smoothed version of a given observation, or
- the addition of a set of unctions (synthetic template), or
- the coherent integration of a large number of observations

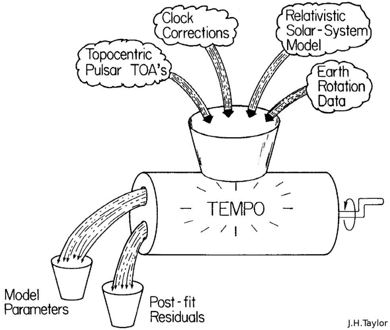
A cross-correlation of the template with each of the daily observations provides a shift converted in a Time of Arrival

A reference point ?



As the profile can change substantially
with frequency (here MSP J2145-0747),
it can be delicate to define
an easy and accurate **common reference point**
all over the frequency range
... needed to track dispersion delay variations...

Pulsar Timing

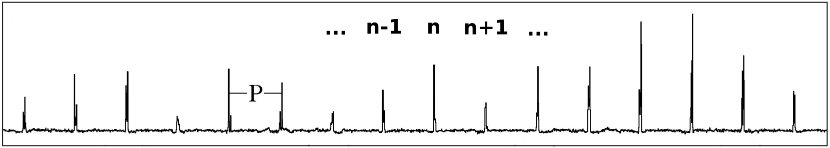


Analysis of a collection of measured times of arrival (ToAs)

→ Having a set of parameters (period, position, etc...),
→ computing 'calculated times of arrival',
→ fitting the parameters by minimization of the differences (called residuals) between 'measured ToAs' and 'calculated ToAs'
→ looking at the residuals to find unmodeled effects...

Keeping track of the rotational phase...

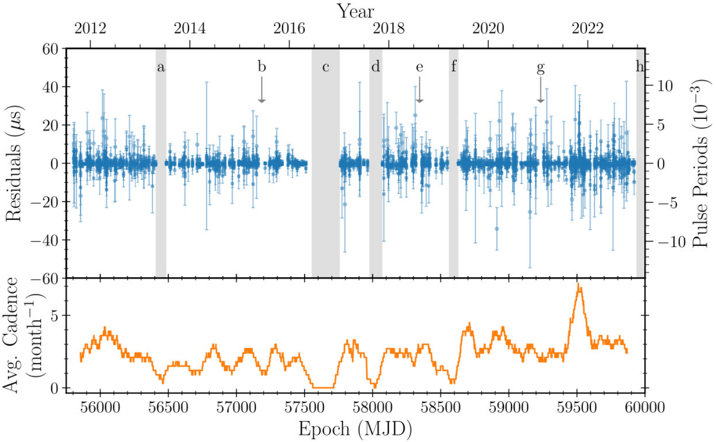
A key aspect of the timing analysis
is the **exact count** of the received radio pulses.
Each measured Time of Arrival got a rotation index number
and if the parameters are well known, NOT a single rotation of the pulsar is missed !
Over 10 years, for a 2ms period pulsar,
this is keeping track of $\sim 1.5 \times 10^{11}$ rotations exactly !



Nançay observations

From late 2011, the NUPPI instrumentation
$\sim$ 50000 observations on $\sim$ 150 MSPs...

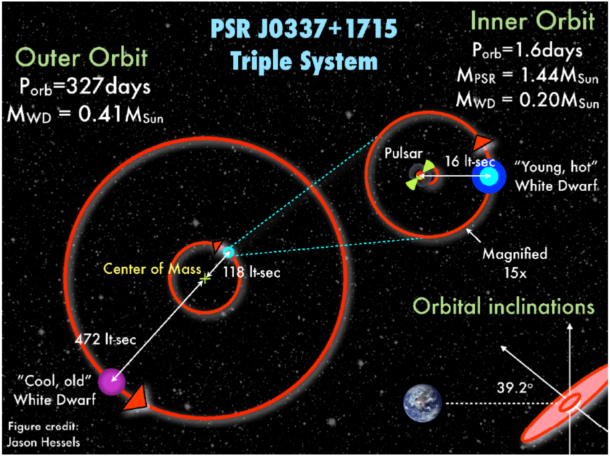
The $\sim$ 571 ones conducted on pulsar J1744-1134 :



Testing theories of gravity

Strong Equivalence Principle test using a triple system pulsar

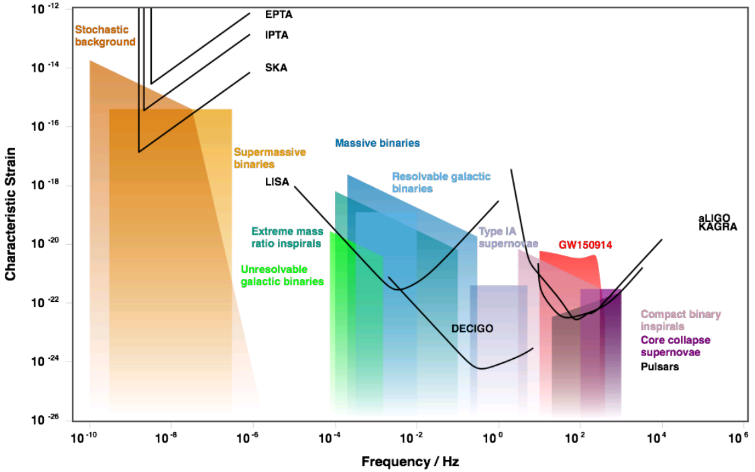
see presentation by G.Voisin (LUTh, Obs Paris)



Search for very low frequency Gravitational Waves

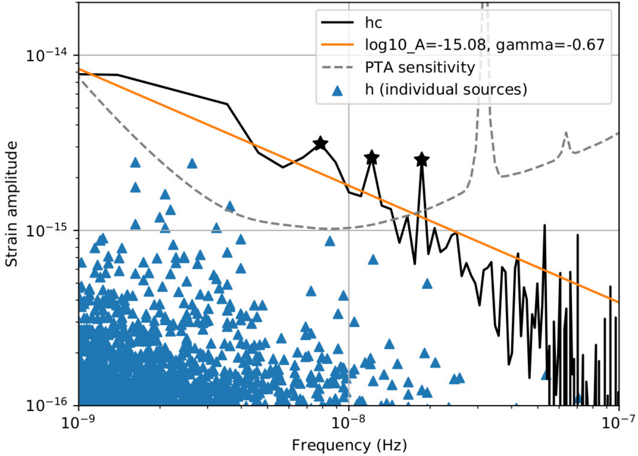
A set of highly stable pulsars well distributed on the sky is a galactic size detector

The Gravitational Waves detectors



Expectations for Low Frequency GWs

A population of Super-Massive Black Holes Binaries



(M.Falxa, PhD thesis 2022, Sesana 2013)

Data analysis

Fit a timing model to predict ToAs and get the timing residuals

Build a noise model : white noise, red noise and dispersion variation noise

Conduct a Bayesian analysis, using a likelyhood

$$p(\boldsymbol{\delta t}|\boldsymbol{\eta}) = \frac{\exp\left(-\frac{1}{2}\boldsymbol{\delta t}^T C^{-1}\boldsymbol{\delta t}\right)}{\sqrt{\det(2\pi C)}}$$

we want parameters η maximizing the likelyhood
to match the observed δt

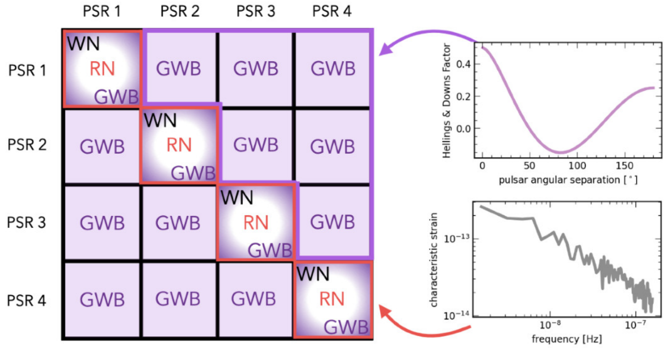
The covariance matrix C is made of

- diagonal autocorrelated terms (intrinsic noise properties of pulsars)
- cross correlated terms for common correlated signals (the GW one !)

Data analysis

White noises (WN) : instrumental (telescope gain), astro (pulse jitter)
Red noises (RN) : modeled as power law $S = Af^{-\gamma}$

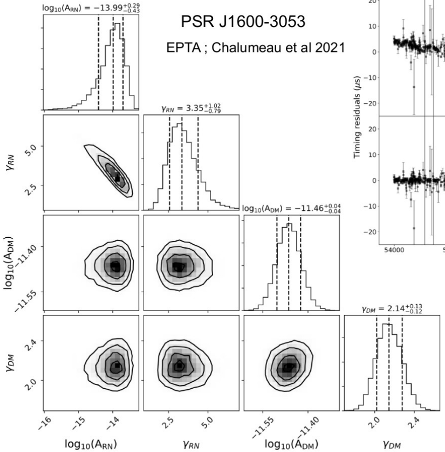
- Dispersion variations, Scattering variations,
- Intrinsic pulsar noise rotations
- Gravitational waves (individual sources, stochastic background, ...)

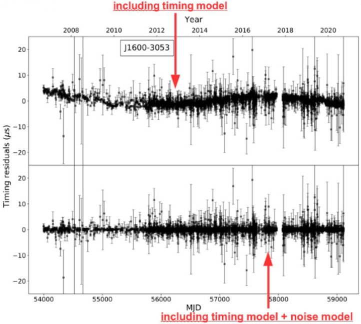


Taylor et al 2022

Individual pulsar noise models

A noise model is defined for each pulsar





- **Spin noise**
- **DM chromatic noise**
- Scaterring noise
- Band noise
- System noise

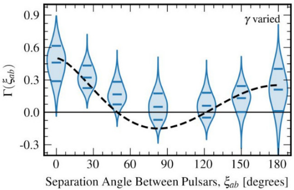
\+

Nb of freq bins
to characterise each

June 29th, 2023 press releases

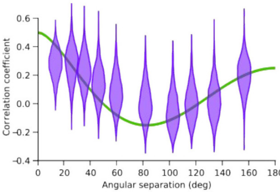
All the continental collaborations find
first evidence for very low frequency gravitational waves,
especially on the spatial correlation (quadrupole GW)

NANOGrav, 2023
15 years, 70 PSRs
4σ



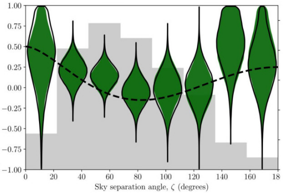
arXiv: 2306.16213

EPTA+InPTA, 2023
10.3 years, 25 PSRs,
3.5σ



arXiv: 2306.16214

PPTA, 2023
18 years, 32 PSRs
2σ

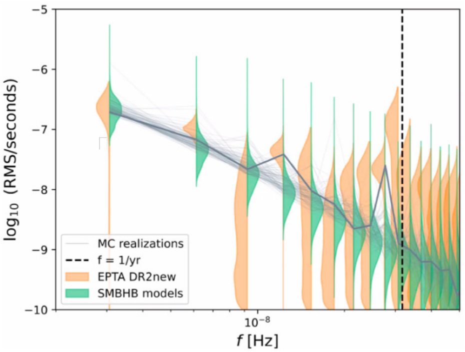


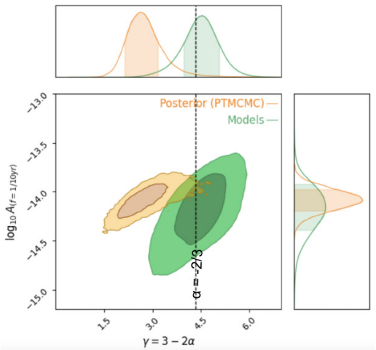
arXiv: 2306.16215

$\rightarrow$ 18 papers in one shot !

The PTA signal vs SMBHB population models

The EPTA result is consistent with a signal coming from SMBHB having a background or an individual source is not yet clear enough...

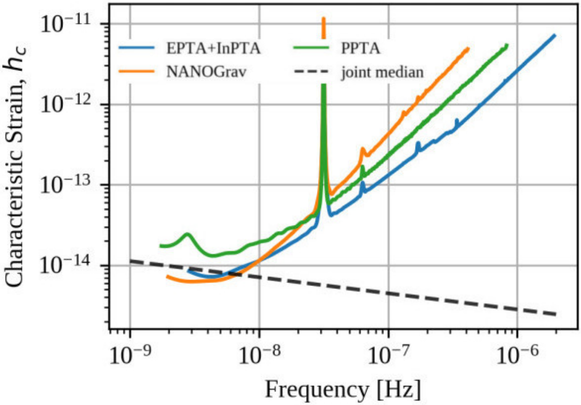




Antoniadis et al, 2023 (EPTA paper V)

Comparison of June 2023 results

sensitivity curves and 'joint detection'

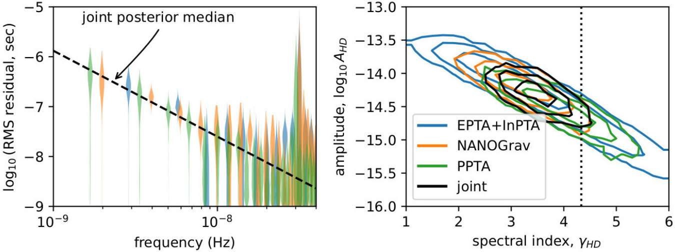


Backer et al, "Comparing recent PTA results ...", arXiv : 2309.00693

The coming year

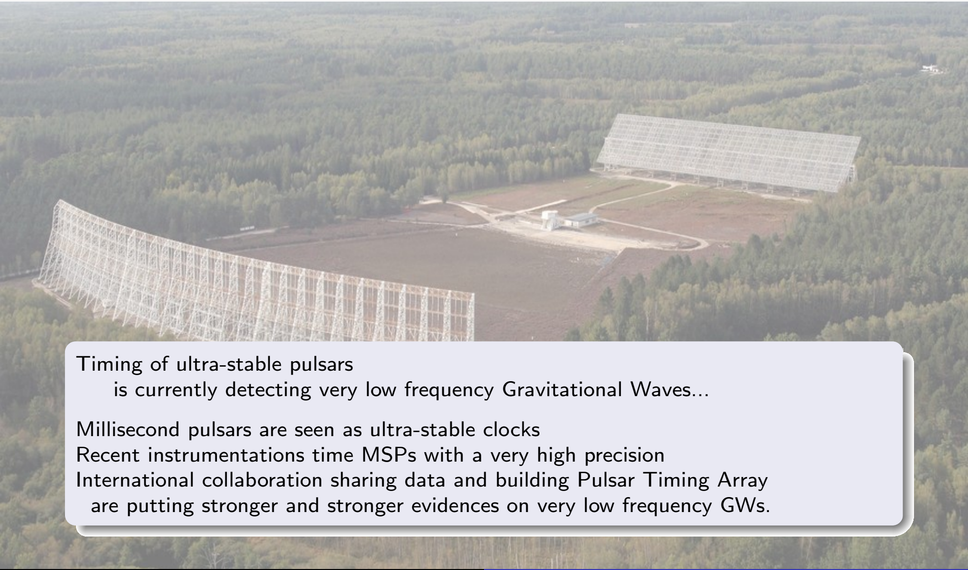
The ToAs provided by the different continental collaborations will be analysed all together...

A quick 'superposition' of the June 2023 results is promizing :



Backer et al, "Comparing recent PTA results ...", arXiv : 2309.00693

Conclusion



Timing of ultra-stable pulsars
is currently detecting very low frequency Gravitational Waves...

Millisecond pulsars are seen as ultra-stable clocks
Recent instrumentations time MSPs with a very high precision
International collaboration sharing data and building Pulsar Timing Array
are putting stronger and stronger evidences on very low frequency GWs.