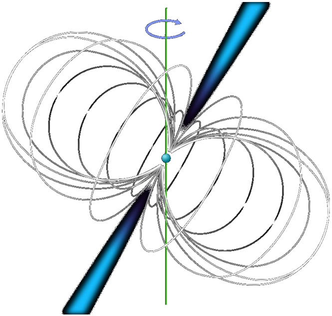
High precision timing of millisecond pulsars for the detection of Gravitational Waves

Ismaël Cognard, G.Theureau, L.Guillemot

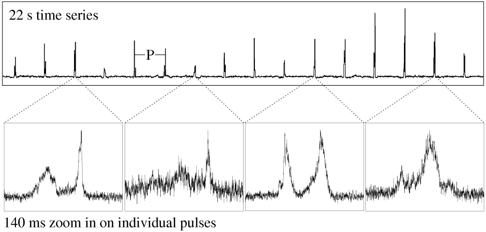
LPC2E, CNRS - Université d'Orléans, France
Station de radioastronomie de Nançay

+ A.Petiteau, S.Babak (APC) + EPTA / IPTA

The pulsar : a magnetized neutron star

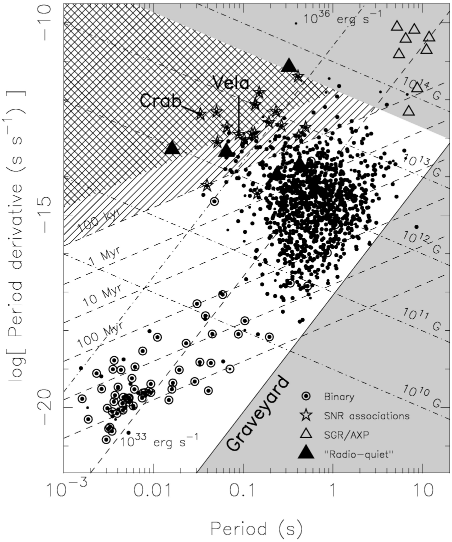


As a lighthouse, two beams of radio waves,
emitted along the magnetic axis,
sweep the sky as the star rotates,
producing reception of periodic pulses on Earth.



The individual pulses are highly variable,
but integrated over thousands of rotation,
the pulse shape is very stable !

An outstanding stability



A first very short life...

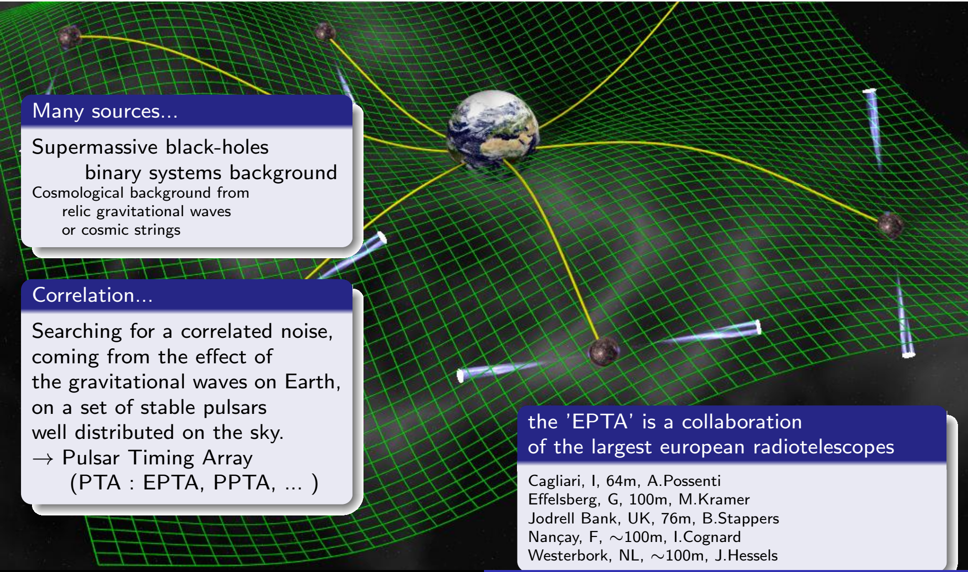
After a birth at ∼30ms,
the pulsar is rapidly slowing down
and stops emission after
few millions years.

... 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)

Detection of a Gravitational Waves Background



Many sources...

Supermassive black-holes
binary systems background

Cosmological background from
relic gravitational waves
or cosmic strings

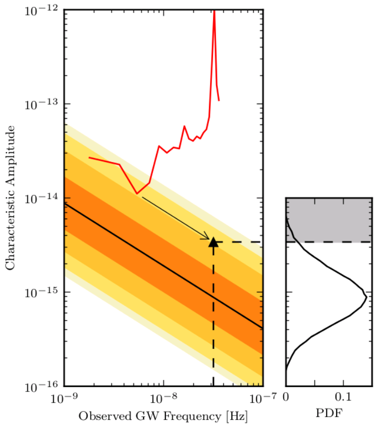
Correlation...

Searching for a correlated noise,
coming from the effect of
the gravitational waves on Earth,
on a set of stable pulsars
well distributed on the sky.
→ Pulsar Timing Array
(PTA : EPTA, PPTA, ...)

the 'EPTA' is a collaboration of the largest european radiotelescopes

Cagliari, I, 64m, A.Possenti
Effelsberg, G, 100m, M.Kramer
Jodrell Bank, UK, 76m, B.Stappers
Nançay, F, ∼100m, I.Cognard
Westerbork, NL, ∼100m, J.Hessels

An european limit

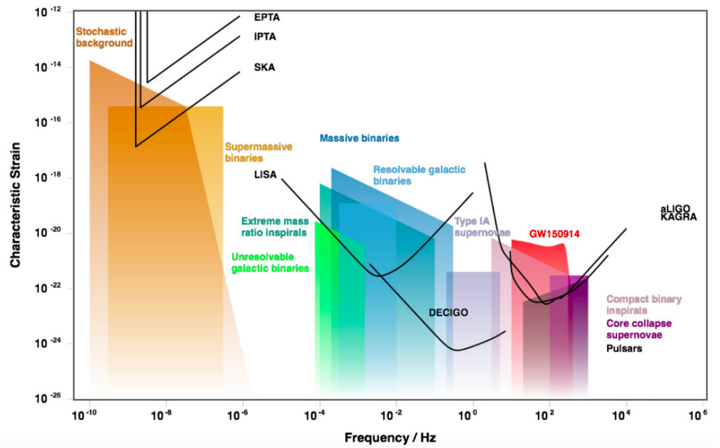


Over six pulsars observed ~18 years from the 2015 EPTA data release, a Bayesian analysis fits simulaneously for intrinsic pulsar noise and common correlated signals.
This analysis sets an upper limit on the dimensionless strain amplitude A of the background at 3.0×10^{-15} (Lentati et al., MNRAS 453, 2576, 2015)

red curve : EPTA limit
color areas : Sesana (2013) expectations and extrapolation at f=1yr^{-1}

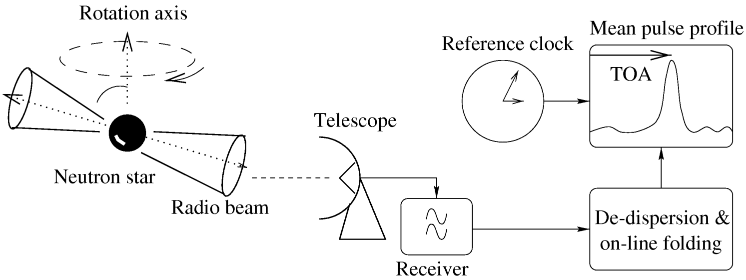
with timing uncertainty δt ($\sim$ 100ns), observing time T ($\sim$ 20 years), daily cadence
amplitude sensitivity δt / T at frequency $\sim$ T ($\sim$ few 10^{-15} at 10^{-7}-10^{-9}Hz)

Complementarity



The expected performance of current and future detectors
in terms of strain and frequency
(Scientific Background on the Nobel Prize in Physics 2017, The Royal Suedish Academy of Science)

A pulsar timing experiment

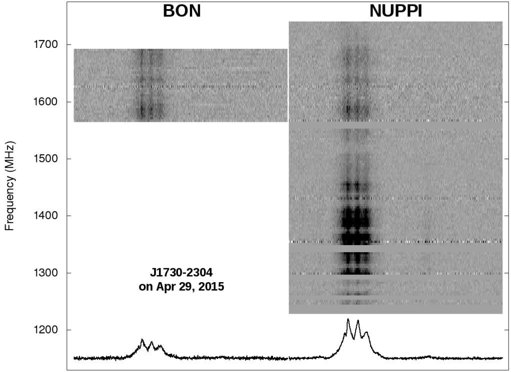


In a pulsar timing experiment :
- a pulsar is observed a few times a month (typically) with a dedicated instrument
- pulses are 'dedispersed' and added to form a mean pulse profile
- data receive a time stamp, and the mean profiles are compared to a 'template' profile to extract a 'Time of Arrival' ToA

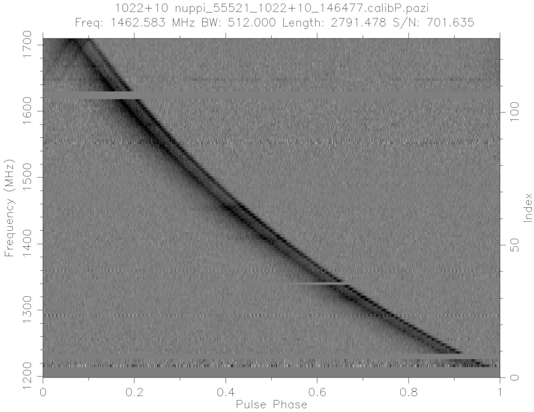
How scale ToA measurement uncertainty ?

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

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).



Dispersion in the interstellar medium



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

a cold and ionized plasma
delay w.r.t. infinite frequency

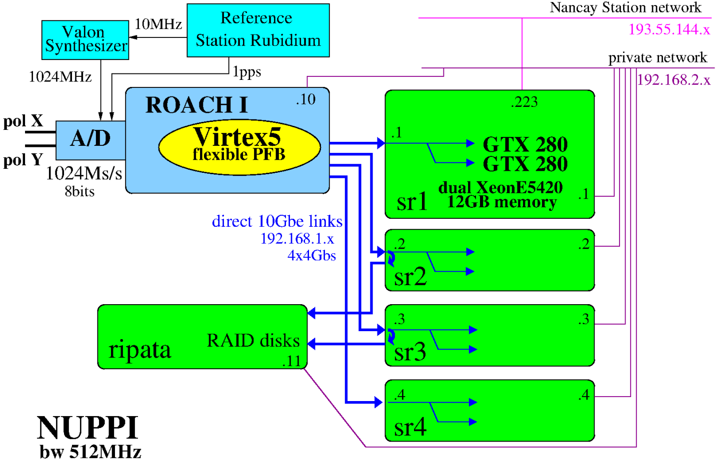
$$t = \int_0^d \frac{dl}{v_g} - \frac{d}{c} \equiv k \frac{DM}{f^2}$$

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

$$DM = \int n_e dl$$

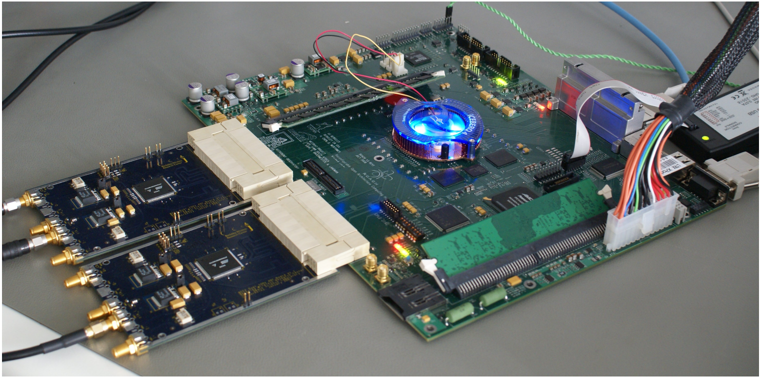
Schematic of a pulsar instrumentation

the **Nançay** Ultimate Pulsar Processing Instrument (NUPPI)



ROACH + 2 A/D boards

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



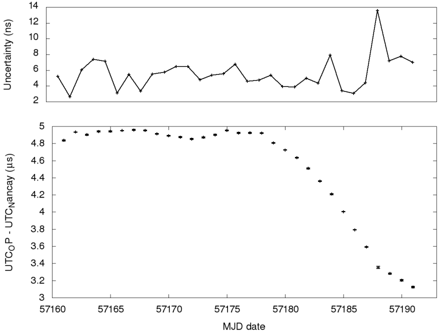
- a clock at 1024MHz
- a 1pps signal
- 2 polarizations sampled at 1024Ms/s, 8bits

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

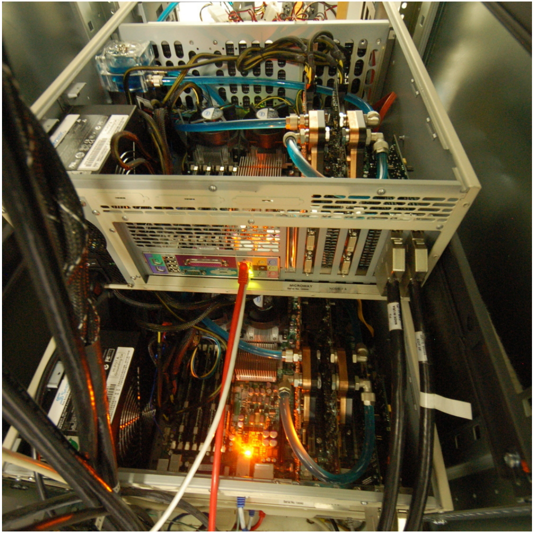
Link from UTC_Nançay to UTC_OP : 1pps monitoring

the link is at ∼5ns, twice a day

GTR50 receiver from Dicom Inc.



GPUs as powerful real-time processors



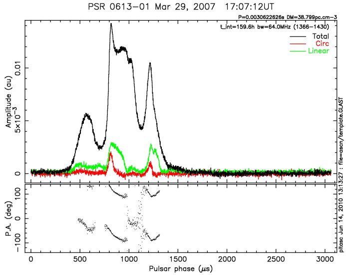
Diversion of GPUs

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

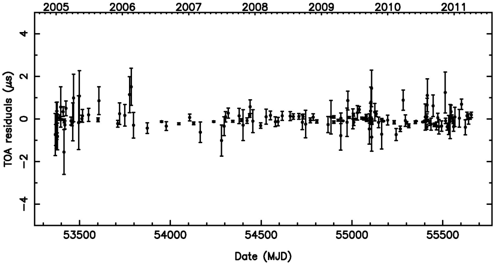
Timing uncertainty can be as good as ∼10ns for a few pulsars.

Differents kind of data outputs



Full characterization of the emission

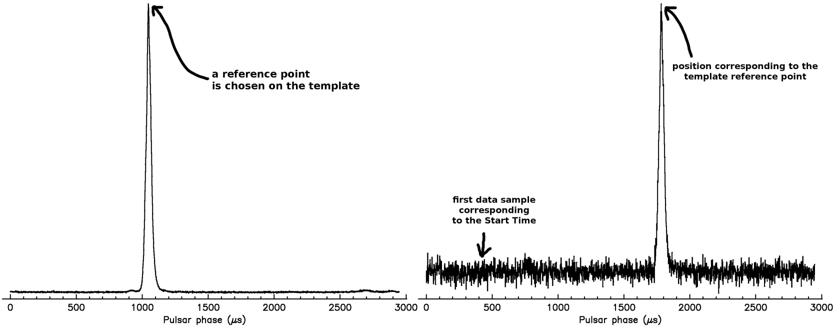
→ Polarization of the radio waves
→ geometry of the system (orientation)



The Times of Arrival (ToAs)

Times of Arrival residuals on pulsar J1909-3744 (P=2.95ms, P_b=1.53d) are caracterized by an rms of ∼90ns over 15yrs

A ToA : cross-correlation with a 'template'

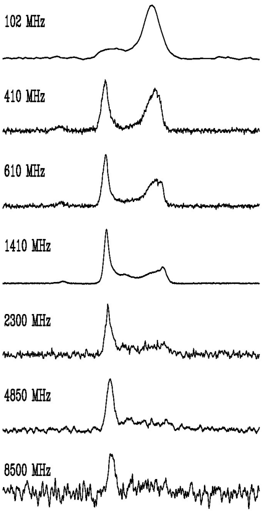


A 'template' is built as :

- a smoothed version of a given observation, or
- the addition of a set of functions (a synthetic template), or
- the coherent integration of a large number of observations

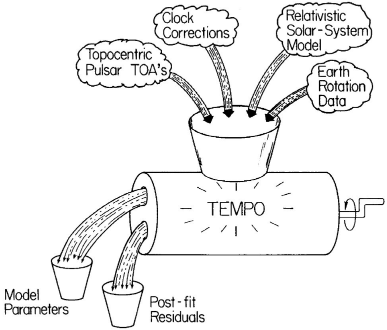
A cross-correlation of the template with each of the daily observations provides a shift converted in a Time of Arrival

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

Pulsar Timing

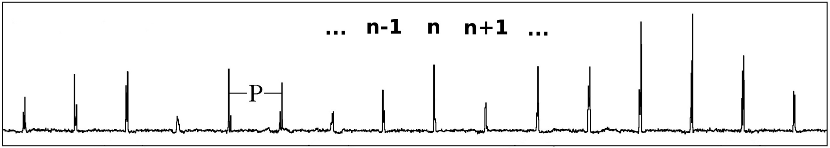


Analysis of a collection of measured times of arrival (ToAs)

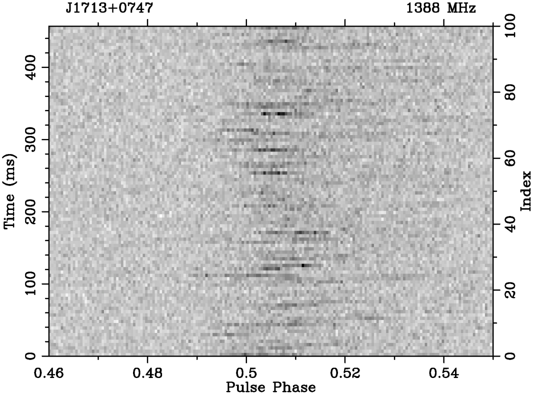
→ Having a set of parameters (period, position, etc...),
→ computing 'calculated times of arrival',
→ fitting the parameters by minimization of the differences (called residuals) between 'measured ToAs' and 'calculated ToAs'
→ looking at the residuals to find unmodeled effects...

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 20 years, for a 2ms period pulsar,
this is keeping track of $\sim 3 \times 10^{11}$ rotations exactly !

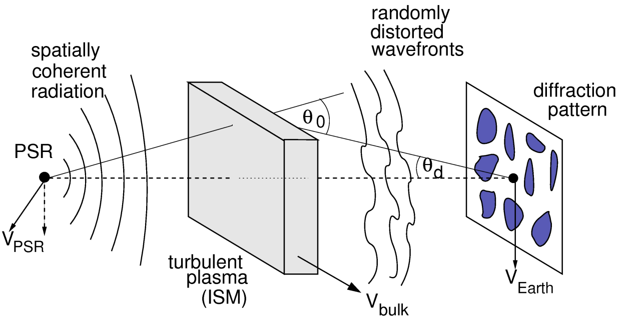


Difficulties exist... pulse jitter



individual pulses are highly variable in shape (seen in this J1713+0747 obs, P =4.5ms)
→ need to integrate long enough and characterize the induced systematics

Difficulties exist... propagation through a turbulent medium



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

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

Conclusion

Timing of ultra-stable pulsars is
a promizing way to search for a low frequency Gravitational Waves Background...

Millisecond pulsars can be seen as ultra-stable clocks
Recent instrumentations can time MSPs with a very high precision
International collaboration sharing data and building Pulsar Timing Array
are putting stronger and stronger upper limits on a GWB.