Technique et science de l'observation des pulsars à $\lambda \lesssim$ cm

Ismaël Cognard, icognard@cnrs-orleans.fr
+ G.Theureau, L.Guillemot, J.-M.Griessmeier, ...

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

Plan

Highly stables clocks

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

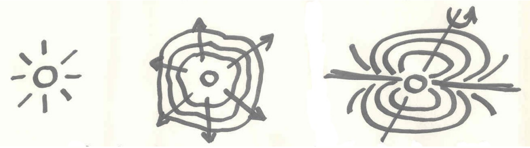
A very specific instrumentation

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

The Pulsar Timing Array (PTA)

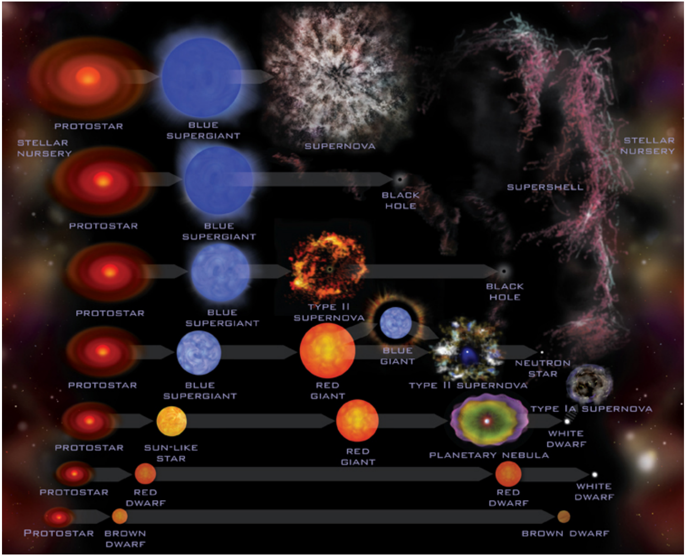
to be convinced that, despite being extremely difficult to find,
a Gravitational Waves background may be close to be detected

Highly stable clocks



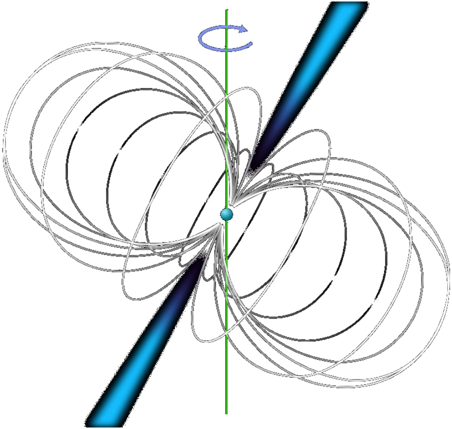
The neutron star : ashes of a big star

A supernovae and a neutron star

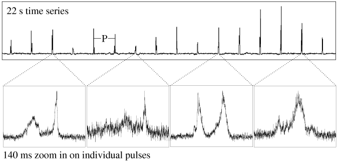


Explosions
of massive stars
($\sim$10-20$M_\odot$)
produce
neutron stars !

The pulsar : a magnetized neutron star

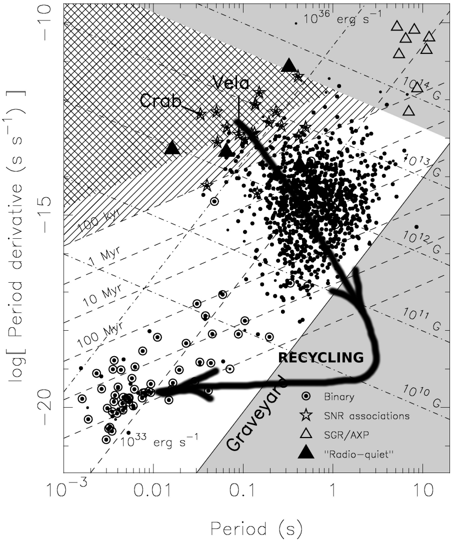


As a lighthouse,
two beams of radio waves,
emitted along
the magnetic axis,
sweep the sky
as the star rotates,
producing reception of
periodic pulses on Earth.



Radio emission detected from ∼10MHz up to ∼250GHz !

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)

Many applications

Exceptional stability and timing precision

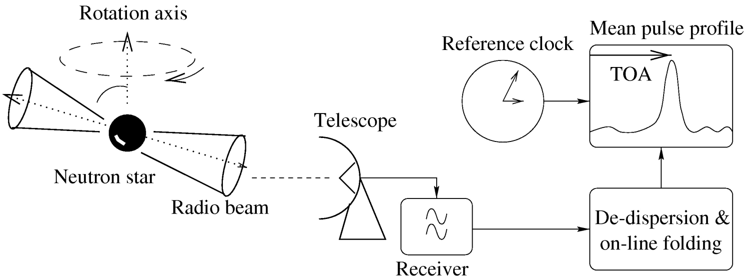
Together with the exceptional rotational stability of the fastest pulsars, state of the art coherent dedispersion instrumentations provide high precision Times of Arrival (ToAs) measurements with uncertainties as low as $\sim$10ns.

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 very specific instrumentation

A pulsar timing experiment

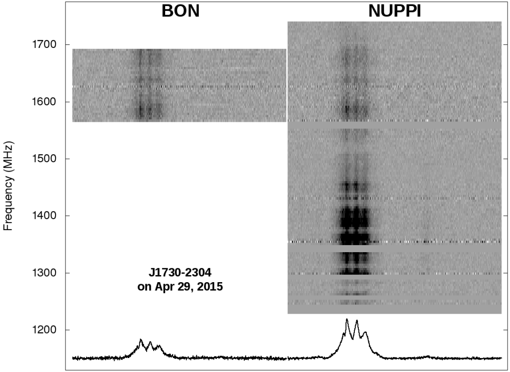


In a pulsar timing experiment :
- a pulsar is observed a few times a month (typically) with a dedicated instrument
- pulses are 'dedispersed' and added to form a mean pulse profile
- data receive a time stamp, and the mean profiles are compared to a 'template' profile to extract a '**Time of Arrival**'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

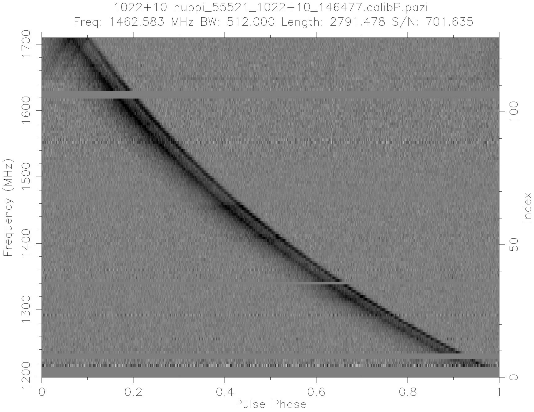
How scale ToA measurement uncertainty ?

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

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

$$DM = \int n_e dl$$

Dedisperse to increase total bandwidth and SNR

Incoherent dedispersion

the dispersion is removed after signal detection
(on the intensity=$|\text{voltage}|^2$ averaged over a given time and bandwidth)
by variable temporal delays applied on each channel
→ filterbank instrumentation

Coherent dedispersion

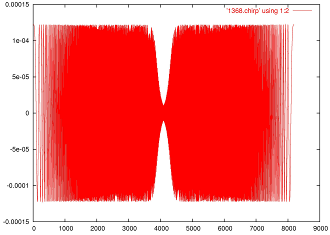
the dispersion is removed before detection
directly on the recorded voltages induced by the incoming electromagnetic radiation
by making a proper use of the phase of the signals
(requires sampling at the rate of the bandwidth)
→ computer instrumentation

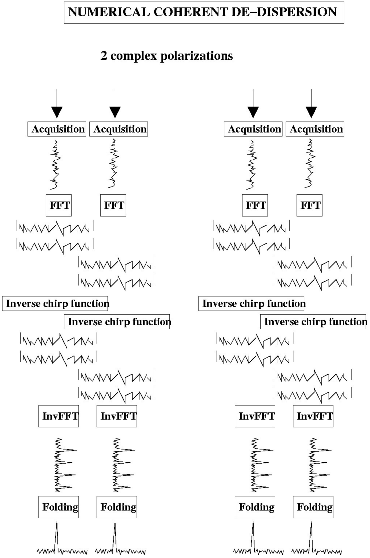
Coherent dedispersion

ISM dispersion acts as a phase filter only.
The 'digital' coherent dedispersion applies an inverse transfer function in the complex Fourier domain :

FFT + inverse filter + FFT^{-1}
(with overlap management)

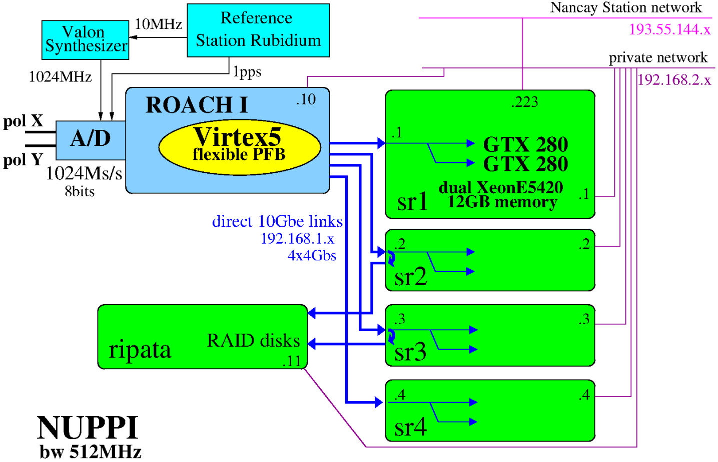
Need for a huge computing power !





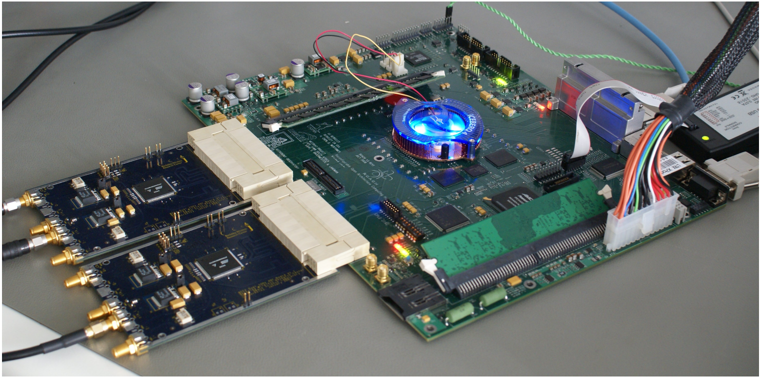
Schematic of NUPPI instrumentation

the **Nançay** Ultimate Pulsar Processing Instrument (**1-3GHz**)



ROACH + 2 A/D boards

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



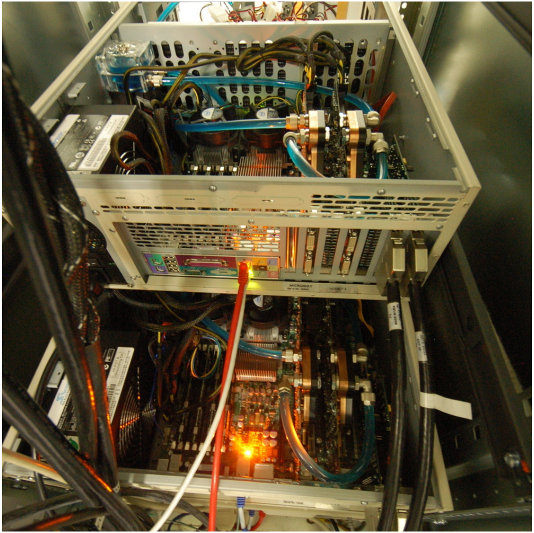
- a clock at 1024MHz

- 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

GPUs as powerful real-time processors



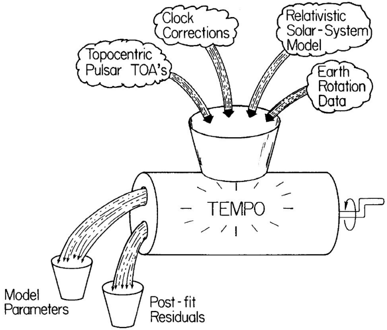
Diversion of GPUs

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 ∼5-10ns for a few pulsars.

Pulsar Timing

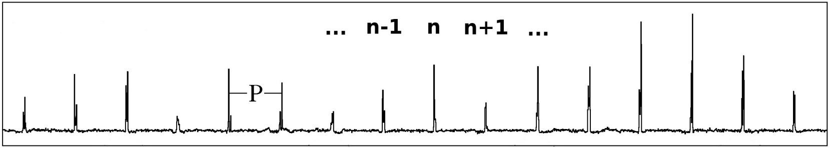


Analysis of a collection of measured times of arrival (ToAs)

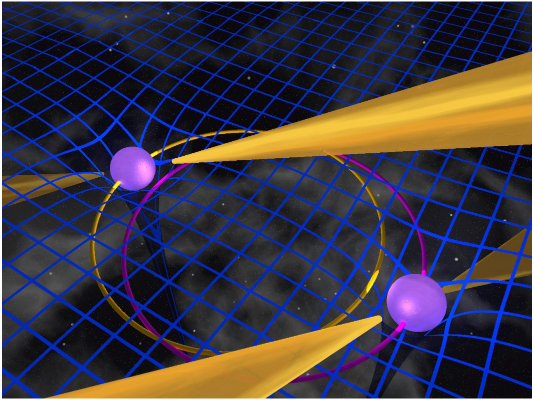
→ Having a set of parameters (period, position, etc...),
→ computing 'calculated times of arrival',
→ fitting the parameters by minimization of the differences (called residuals) between 'measured ToAs' and 'calculated ToAs'
→ looking at the residuals to find unmodeled effects...

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 !

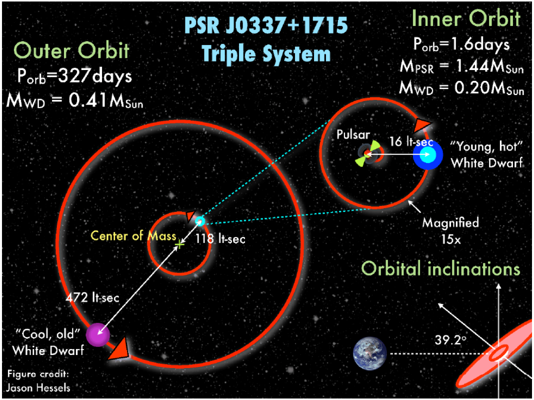


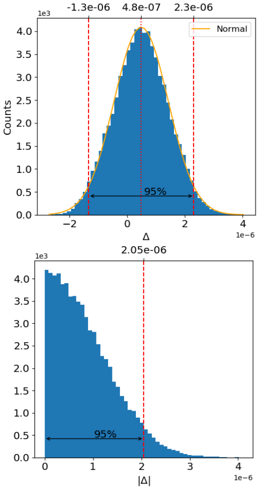
Testing theories of gravity



Compact binary systems are used to test theories of gravity

Strong Equivalence Principle with pulsar triple system





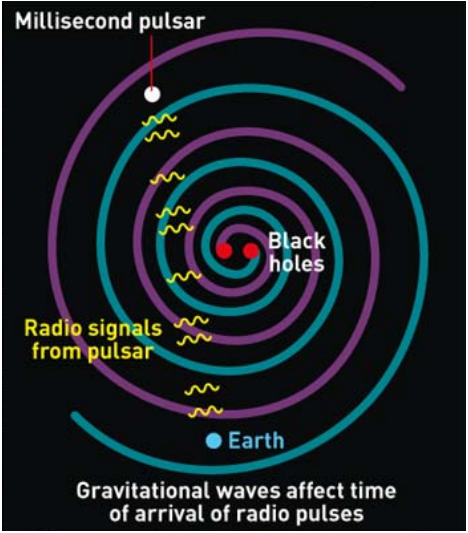
A test of the universality of free fall :
a body-dependent effective gravitational constant

$$G_{NS-WD} = (1 + \Delta) G_{WD-WD}$$

→ most precise Einstein theory confirmation
for large self-gravitational energy objects

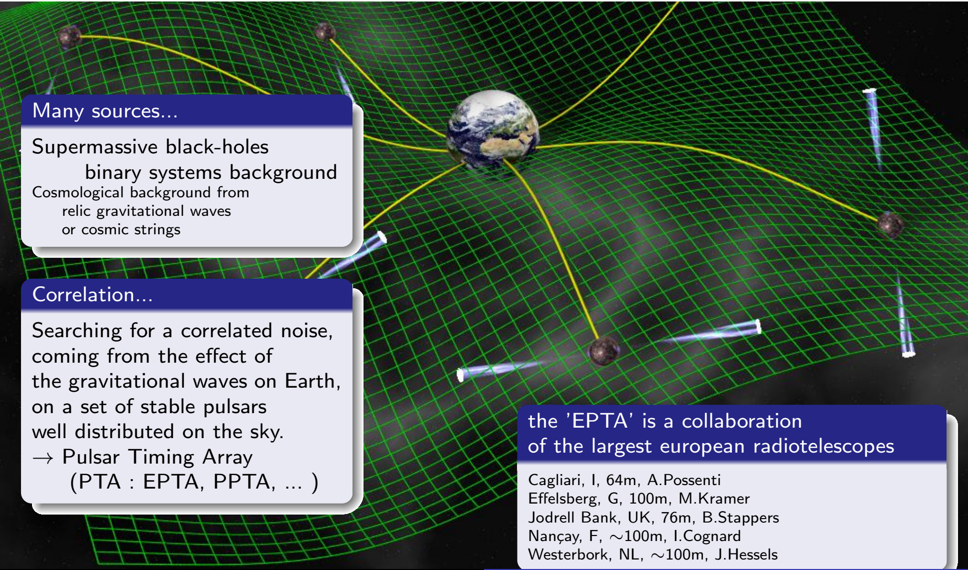
Voisin et al., A&A 638, A24

Search for Gravitational Waves



Search for the signature of Gravitational Waves (space-time perturbations) emitted by super-massive binary black holes

Detection of a Gravitational Waves Background



Many sources...

Supermassive black-holes
binary systems background

Cosmological background from
relic gravitational waves
or cosmic strings

Correlation...

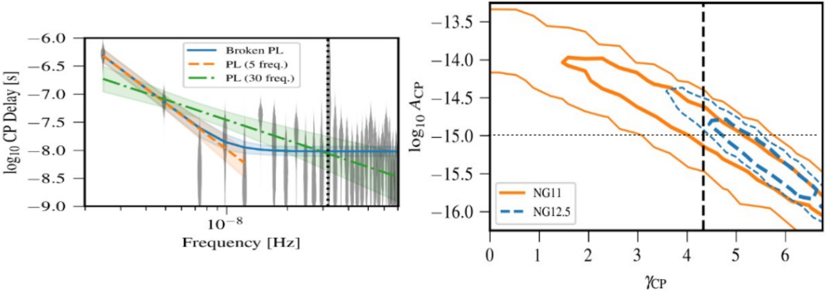
Searching for a correlated noise,
coming from the effect of
the gravitational waves on Earth,
on a set of stable pulsars
well distributed on the sky.
→ Pulsar Timing Array
(PTA : EPTA, PPTA, ...)

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

Nearly detected...

the North American collaboration NanoGRAV just published
evidence for a common red noise (Arzoumanian et al., ApJ 305, 34, 2021)



The same signal is also seen in the longest EPTA data !
A paper (Chen et al.) is expected next month... stay tuned.

Conclusion

Highly-precise timing of ultra-stable pulsars around $\sim$1GHz
is a way to detect for a very low frequency Gravitational Waves...

Pulsars can also be observed at higher frequencies (but fainter)
as well as at much lower frequencies...
around 10-100MHz with the new NenuFAR instrument at Nançay !