Pulsar Timing Array and Gravitational Waves detection

Ismaël Cognard
icognard@cnrs-orleans.fr

and Antoine Lassus, PhD, G.Theureau, Ast,
LPC2E, CNRS - Université d'Orléans, France
Nançay Radio Telescope

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

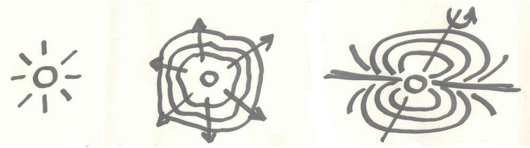
The Pulsar Timing Array (PTA)

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

Reference :

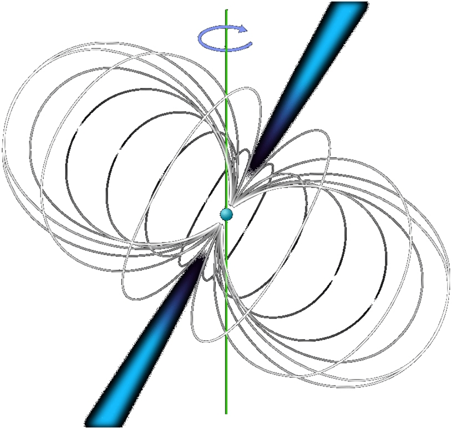
Handbook of Pulsar Astronomy, D.Lorimer and M.Kramer,
Cambridge University Press, 2005

Highly stable clocks

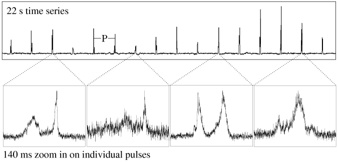


The neutron star : remains of a big star

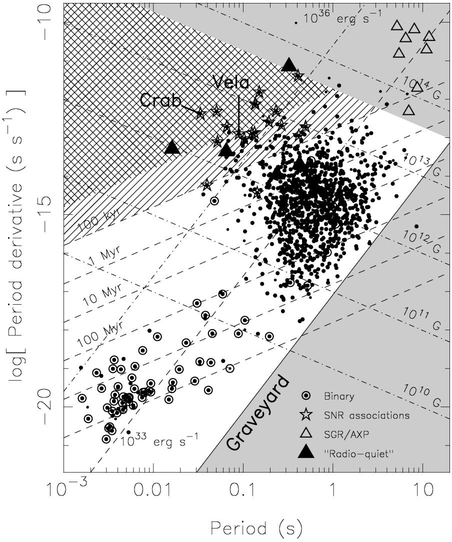
The pulsar : a magnetized neutron star



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 for fast recycled pulsars



A first very short life...

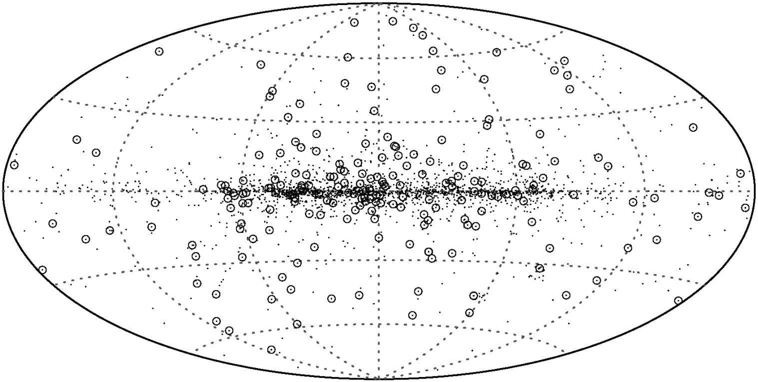
After a birth at ∼30ms,
the pulsar is rapidly slowing down
and stops emission after
few millions years.

... 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)

Galactic distribution



Distribution of radio pulsars (∼2200 known in 2013)

dots = slow pulsars found along the Galactic Plane,
open circles = millisecond pulsars with a more isotropic distribution

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 highly precise Times of Arrival (ToAs) measurements with uncertainties as low as $\sim$ 30ns.

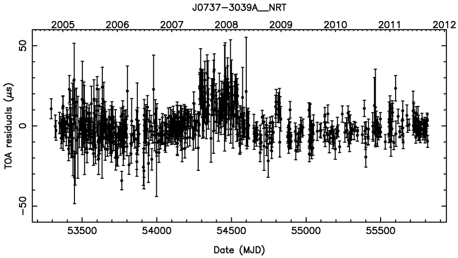
A large number of applications

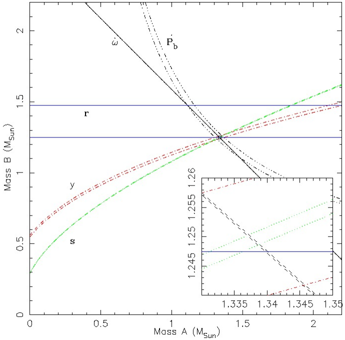
- search for a Gravitational Waves Background
- tests of the theories of gravitation
- propagation through and turbulence in the interstellar medium
- stellar evolution
- globular clusters and our Galaxy gravitational potential
- constrains on the solar system planetary ephemeris
- detection of extra-solar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

Tests of General Relativity

Double pulsar J0737-3039A

Up to 5 post-Keplerian parameters
'agreement with general relativity
within an uncertainty of 0.05%'
Kramer et al. Science 314, 97 (2006)

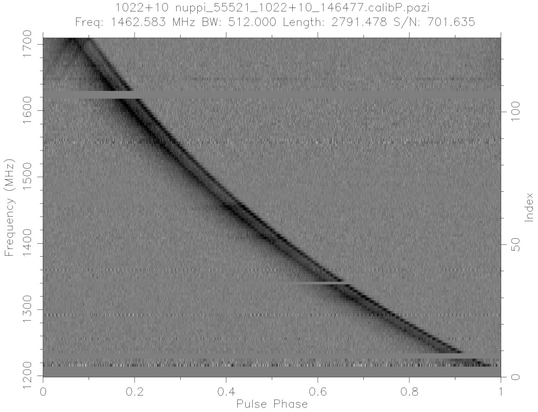




Mass-mass constrains diagram
obtained
from Nançay observations

A very specific instrumentation

Dispersion in the interstellar medium



PSR J1012+5304 data
folded for each channel between 1.2 and 1.7 GHz
P=5.25ms DM=9.0233 pc.cm^{-3}

a cold and ionized plasma

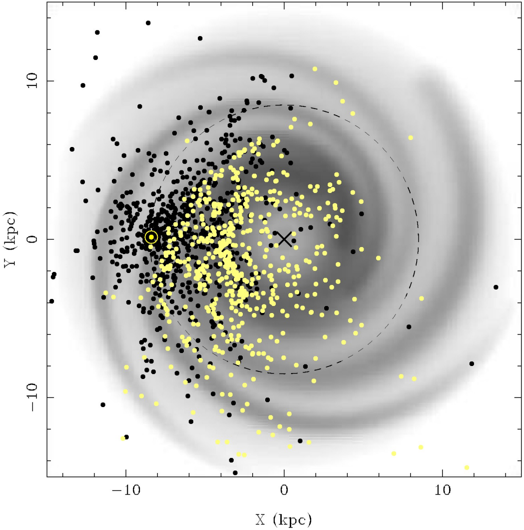
delay w.r.t. infinite frequency

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

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

$$DM = \int n_e dl$$

Electron density distribution



Observed pulsar distribution (lighter points are pulsars discovered at high frequency) and model for the electronic density distribution
Cordes & Lazio, 2002, astro-ph/0301598

Dedisperse to increase total bandwidth and SNR

we need to **integrate** in **time** and **frequency** to increase the SNR
dispersion has to **be removed** to integrate in frequency

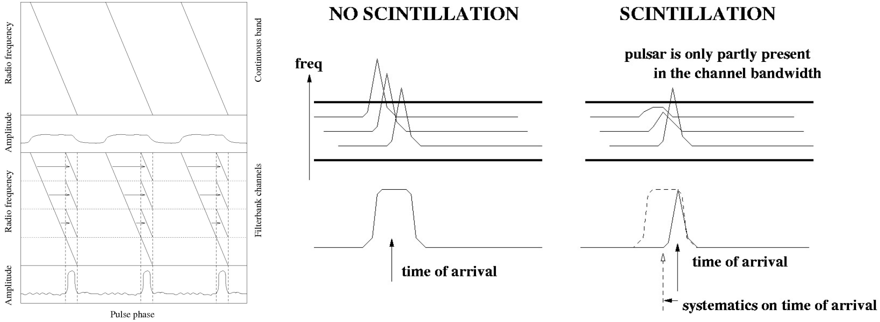
Incoherent dedispersion

the dispersion is removed after signal detection
(on the mean intensity averaged over a given time and bandwidth)
by variable temporal delays applied on each channel
$\rightarrow$ 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
$\rightarrow$ computer instrumentation

Incoherent dedispersion : systematic effects



A small dispersive effect still present within the channels
together with the scintillation due to the turbulence of the Interstellar Medium
produce an unpredictable systematic effect on the Times of Arrival

Coherent dedispersion

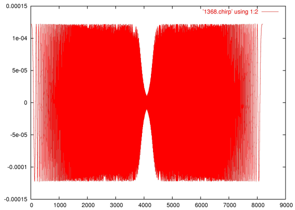
Playing with the phases

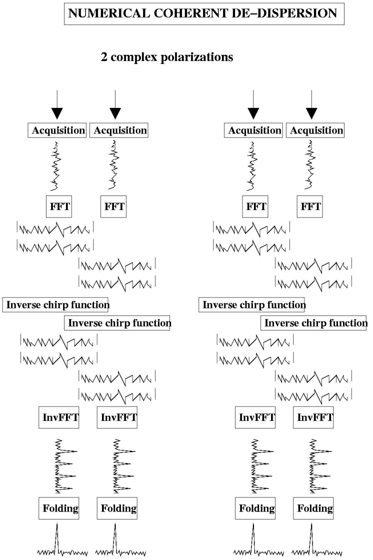
ISM dispersion acts as a phase filter only. The 'digital' coherent dedispersion applies an inverse transfer function in the complex Fourier domain :

FFT + inverse filter + FFT^{-1}

(with overlap management)

Need for a huge computing power!





A long history at the Nançay radiotelescope...

1986, 1988-2004

swept LO dedispersor - analogic coherent

1996-2004

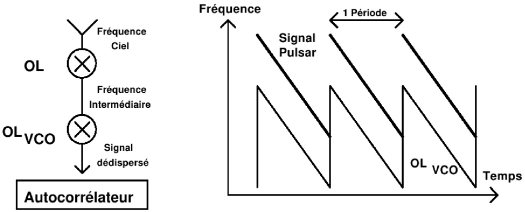
NBPP (Navy Berkeley Pulsar Processor) - incoherent

from 2000

BON instrumentation - digital coherent
hardware + super-computer
(Berkeley-Orléans-Nançay)

swept LO dedispersor
("pulsaroscope", 1988-2005)

1998-2004 : 'analogic' coherent dedispersion



The "pulsaroscope" : a swept LO dedispersor

One of the constant Local Oscillator (LO) of the heterodyne receiver of the telescope is replaced by a variable LO (based on a swept VCO) acting as the effect of the ISM and the result of the mixing is analyzed by a standard spectrometer (autocorrelator). Used to get ∼2000 high quality ToAs over ∼17 years on B1821-24 and B1937+21.

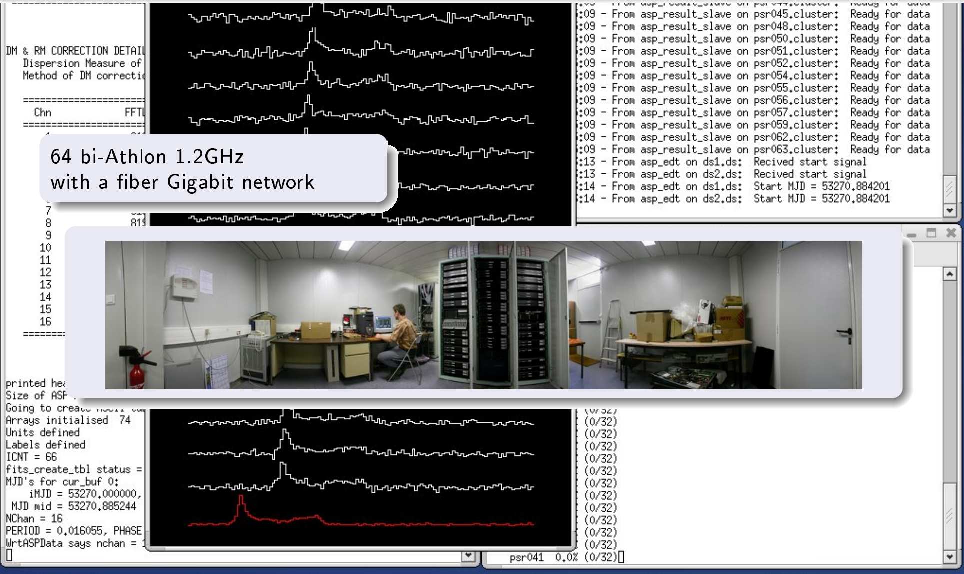
1996-2004 : incoherent dedispersion

The Navy Berkeley Pulsar Processor

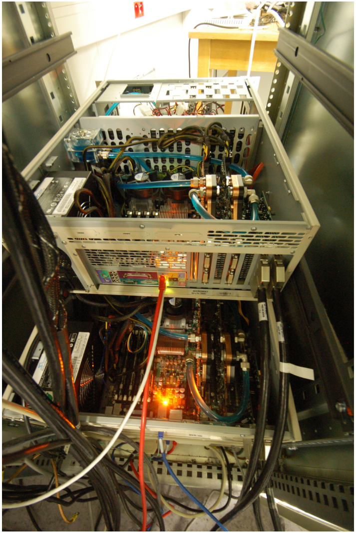
The Navy Berkeley Pulsar Processor (1996-2006)
had 96 chanels each 1.5MHz wide (total 144MHz)
Used to conduct the first large scale pulsar 'survey' at Nançay (and some timing).

2004-2008 : a super-computer for coherent dedispersion

64 bi-Athlon 1.2GHz
with a fiber Gigabit network



2008-now : GPUs based coherent dedispersion at Nançay



Diversion of GPUs

Using high performance graphical card (GPU), water-cooled to increase their lifetime,
2 PCs / 4 GPUs easily dedisperse bw 128MHz (512MB/s=4Gb/s) in real time

An ultimate precision

Timing uncertainty can be as good as 30ns for a few pulsars.

Nvidia CUDA and C code

Using NVidia GPUs, the CUDA libraries and C code to wrap
(Common Unified Development Architecture)

```
// -- Allocate and transfer of chirp function --
cudaMalloc((void**)&chirp_device, mem_chirp);
cudaMemcpy(chirp_device, chirp, mem_chirp, cudaMemcpyHostToDevice);

// -- CUFFT plan --
CUFFT_SAFE_CALL(cufftPlan1d(&plan,obs_params.fft_len,CUFFT_C2C,2*NFFTinSend));

// -- Transfer data --
cudaMemcpyAsync(tbuf_device, tbuf_host, mem_tbuf, cudaMemcpyHostToDevice,0);
CUDA_SAFE_CALL(cudaThreadSynchronize());

// -- Forward FFT --
CUFFT_SAFE_CALL(cufftExecC2C(plan,fftbuf_device,fftbuf_device,CUFFT_FORWARD));

// -- Chirp filter multiply --
vec_mult_complex<<<nb_mult,512>>>
    ( (float2 *)&fftbuf_device[i*obs_params.fft_len],
    (float2 *)&chirp_device[obs_params.fft_len*freq_chan],
    obs_params.fft_len, 2*NFFTinSend );

// -- Inverse FFT --
CUFFT_SAFE_CALL(cufftExecC2C(plan,fftbuf_device,fftbuf_device,CUFFT_INVERSE));

// -- Detect and Stokes --
detect_4pol<<<32,64>>>((float2 *)fftbuf_device,
    (float2 *)fftbuf_mid, obs_params.fft_len*NFFTinSend);
```

More bandwidth (2011-)

BON512/NUPPI

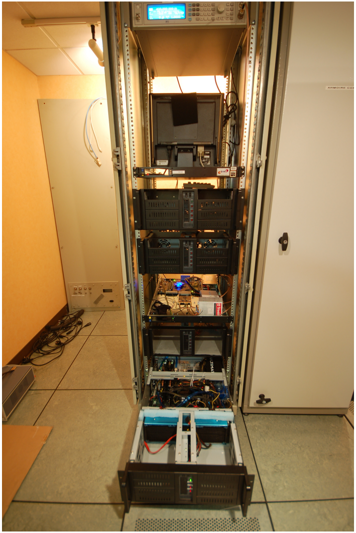
With more computing power (8 GPUs GTX285),
a new acquisition board and
a new pre-processing board (ROACH, CASPER),
it is possible to do real-time
dedispersion over a 512MHz total bandwidth
(16Gb/s)

Improvements

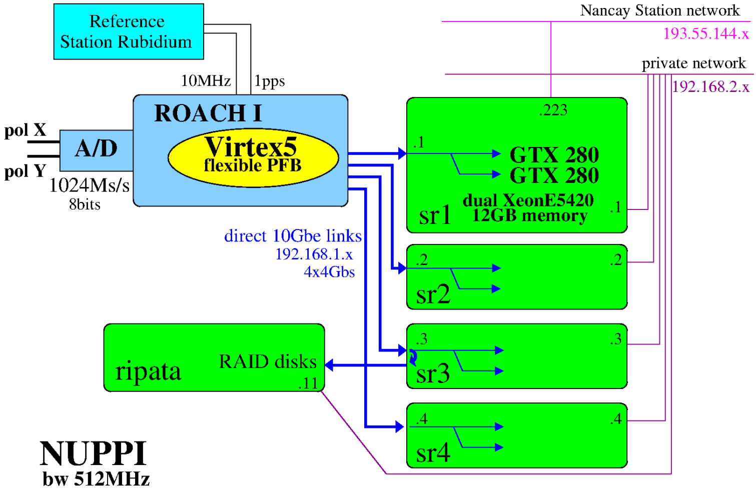
4x bandwidth

- better SNR $\rightarrow$ better ToAs
- larger bandwidth $\rightarrow$ more 'scintels'

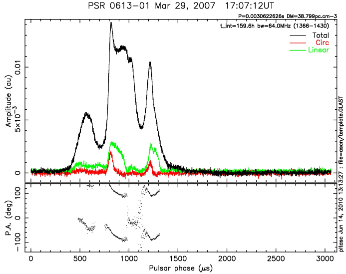
scintel = patch in the frequency-time space
where the pulsar is brighter due to scintillation



Schematic

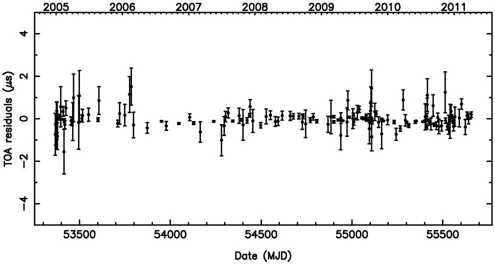

Reference
Station Rubidium
10MHz
1pps
ROACH I
Virtex5
flexible PFB
pol X
pol Y
A/D
1024Ms/s
8bits
direct 10Gbe links
192.168.1.x
4x4Gbs
Nancay Station network
193.55.144.x
private network
192.168.2.x
.223
.1
GTX 280
GTX 280
dual XeonE5420
12GB memory
sr1
.1
.2
sr2
.2
.3
sr3
.3
.4
sr4
.4
ripata
RAID disks
.11
NUPPI
bw 512MHz

Differents kind of data outputs



Full characterization of the emission

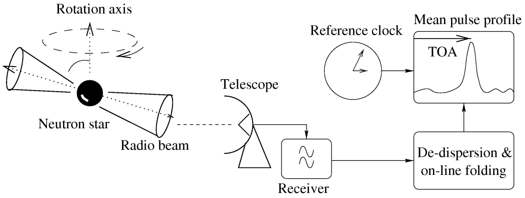
→ Polarization of the radio waves
→ geometry of the system (orientation)



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 ∼110ns

Pulsar Timing



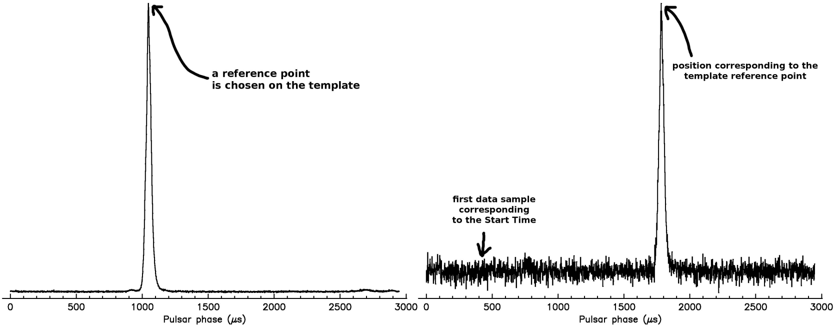
Measuring a time of arrival

a large radiotelescope
a good clock,
and a special **instrumentation**
to remove the ISM dispersion

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...

Cross-correlation with a 'template'

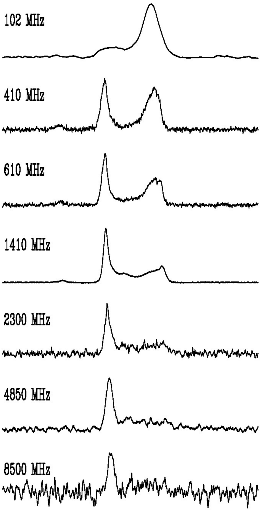


A 'template' is built as :

- 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,
it can be delicate to define
an easy and accurate reference point.

Some Times of Arrival

Times of Arrival of the pulsar J1909-3744

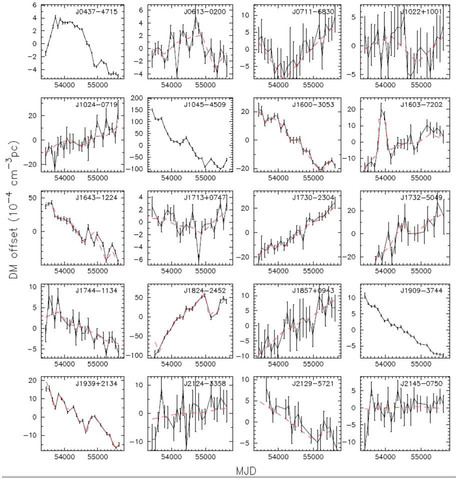
Observatory Code	'1'	Pulsar Name	Freq [MHz]	TOA [MJD]	Uncert [μs]
f	1	1909-37	1598.000	55545.5374539557567	0.31
f	1	1909-37	1598.000	55549.5256599575306	0.10
f	1	1909-37	1598.000	55557.5209261657210	0.14
f	1	1909-37	1598.000	55559.5185882118428	0.21
f	1	1909-37	1598.000	55566.4836692244367	0.46
f	1	1909-37	1598.000	55578.4462618139097	0.07
f	1	1909-37	1598.000	55591.4109261640786	0.42
f	1	1909-37	1598.000	55600.3941206354503	2.07
f	1	1909-37	1598.000	55603.3758798788730	0.24
f	1	1909-37	1598.000	55633.3038775564485	0.18
f	1	1909-37	1598.000	55642.2707872896909	0.24
f	1	1909-37	1598.000	55650.2537734017033	0.04
f	1	1909-37	1598.000	55657.2350118358209	0.12

Dispersion Measure variations ?

a ionized turbulent medium

the ionized component of the ISM produces **DM variations**, usually easy to measure using different frequencies of observations

but scattering produces **multi-propagation** and a cigar shape probed volume which is highly dependent on the radio frequency
→ difficult to measure relevant DM variations



Dispersion Measure variations
(Keith et al., astro-ph/1211.5887)

Result of the adjustment done by the 'tempo2' code

Results for PSR J1909-3744

RMS pre-fit residual = 0.107 (us), RMS post-fit residual = 0.107 (us)
Fit Chisq = 284 Chisqr/nfree = 283.99/128 = 2.21871   pre/post = 0.999928
Number of points in fit = 146

PARAMETER	Pre-fit	Post-fit	Uncertainty	Difference	Fit
RAJ (hms)	19:09:47.4366067	19:09:47.4366067	1.3342e-06	-4.9e-08	
DECJ (dms)	-37:44:14.37997	-37:44:14.37997	4.3898e-05	1.7615e-06	
F0 (s^-1)	339.315687409498	339.315687409498	2.2937e-13	0	Y
F1 (s^-2)	-1.61484383413344e-15	-1.61484387186145e-15	2.6034e-21	-3.7728e-23	Y
PEPOCH (MJD)	53631	53631	0	0	N
DM (cm^-3 pc)	10.3925080785892	10.3925080785892	0	0	N
PMRA (mas/yr)	-9.50030757366594	-9.50027597516677	0.0040831	3.1598e-05	Y
PMDEC (mas/yr)	-35.785071494643	-35.7852499621001	0.011502	-0.00017847	Y
PX (mas)	0.923565193641923	0.92389357235835	0.024929	0.00032838	Y
SINI	0.997320486861691	0.99733682277151	0.00029013	1.6336e-05	Y
PB (d)	1.53344947463577	1.5334494746355	1.6353e-11	-2.72e-13	Y
A1 (lt-s)	1.89799100955783	1.89799101245577	6.7335e-08	2.8979e-09	Y
PBDOT	4.5717646386028e-13	4.57418671721292e-13	1.4806e-14	2.4221e-16	Y
XDOT	-8.38976507676744e-16	-8.38811914145483e-16	3.0151e-16	1.6459e-19	Y
TASC (MJD)	53630.7232148727	53630.7232148728	5.6285e-09	5.0932e-11	Y
EPS1	1.94072230516237e-09	3.00946422522297e-09	2.6514e-08	1.0687e-09	Y
EPS2	-1.01236889720615e-07	-1.01096208732956e-07	1.2766e-08	1.4068e-10	Y
M2	0.215142138110059	0.214935843207888	0.0035106	-0.00020629	Y
TZRMJD	54497.4278023997	54497.4278023997	0	0	N
TZRFRQ (MHz)	1398	1398	0	0	N
TZRSITE	f				

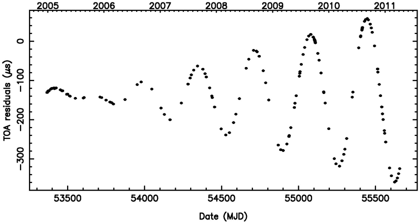
Derived parameters:

P0 (s)	= 0.00294710806810757	1.9922e-18
P1	= 1.40256391911332e-20	2.2612e-26
tau_c (Myr)	= 3331.5	
bs (G)	= 2.0574e+08	

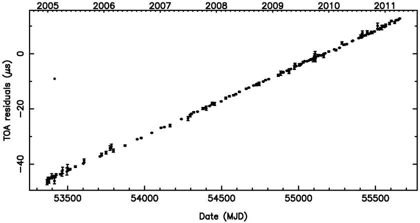
Binary model: T2
Mass function = 0.003121952127 +- 0.000000000014 solar masses
Minimum, median and maximum companion mass: 0.1954 < 0.2288 < 0.5030 solar masses
Pulsar Mass (Shapiro Delay): 1.56135 (+/- 0.0400087) Msun.

only one such code...

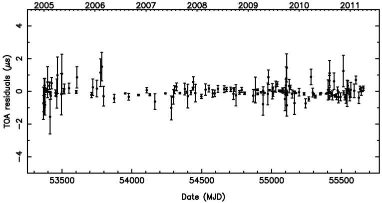
Times of Arrival residuals



before adjustment for the proper motion,

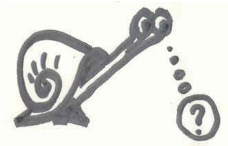


for the rotational frequency,



after the adjustement of all the parameters

The Pulsar Timing Array (PTA)

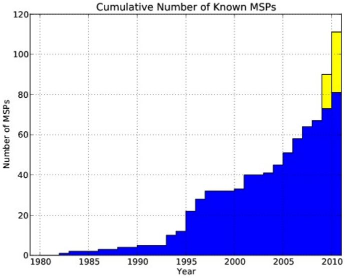


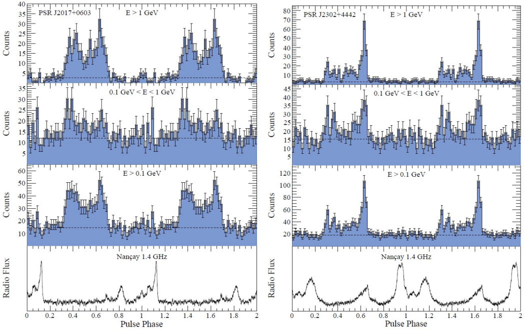
Carefully looking at the Times of Arrival residuals

FERMI catalog of unidentified sources

More than 40 new MSPs

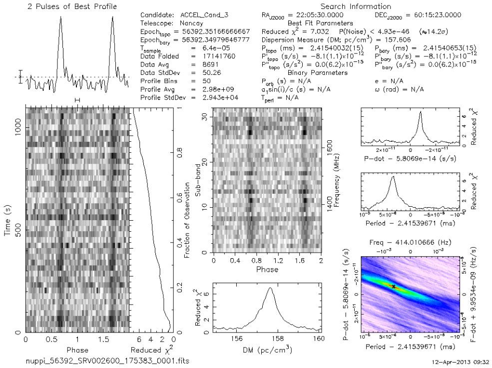
some of them will be used as quasi-perfect clocks





The first two MSPs J2017+0603 and J2302+4442 seen by FERMI (3 energy bands) and Nançay
Cognard, et al., ApJ 732, 47 (2011)

Several on-going pulsar search programs



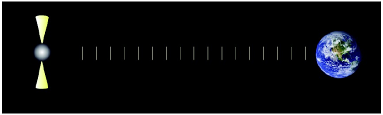
the SPAN512 Nançay survey

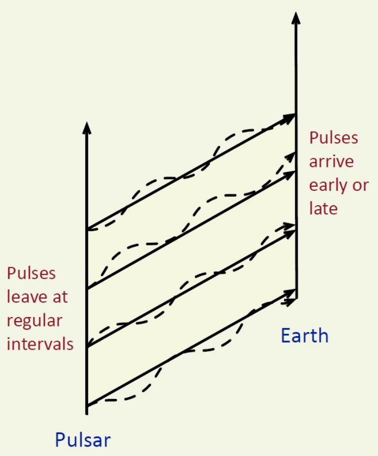
a new interesting MSP discovered 3 weeks ago : J2205+6015
thanks to the CC-IN2P3 for the processing power !

Search for a Gravitational Waves Background

Effect of a gravitational wave on the propagation of 'pulsar' signals

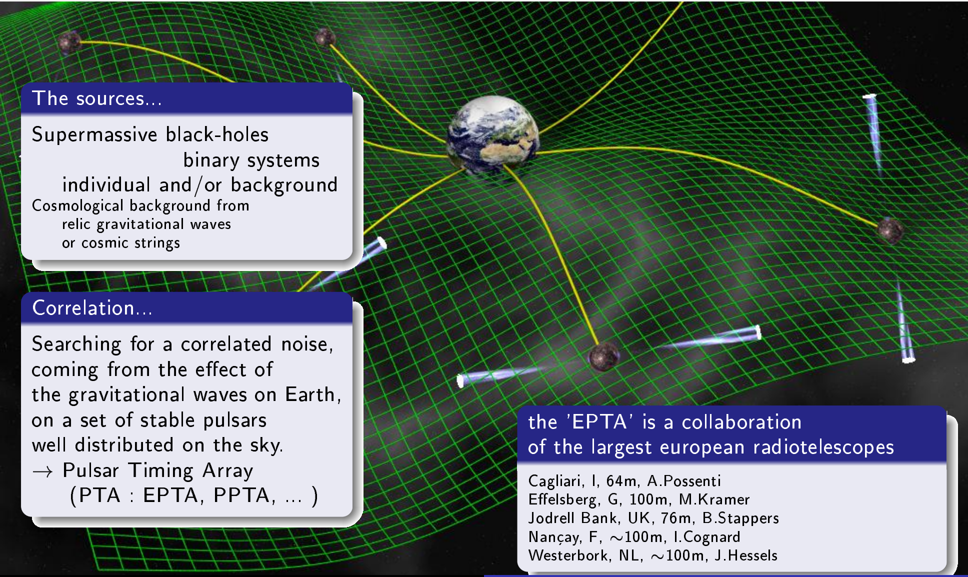
Consecutive wavefronts travel along different 'parallel' null-geodesics from pulsar to Earth producing variable propagation times.





S.Finn, IPTA meeting, Leiden 2010

Detection of a Gravitational Waves Background



The sources...

Supermassive black-holes
binary systems
individual and/or background
Cosmological background from
relic gravitational waves
or cosmic strings

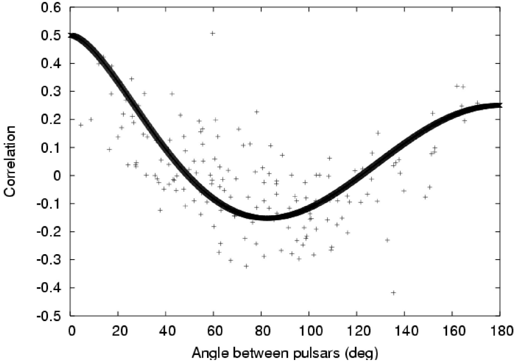
Correlation...

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

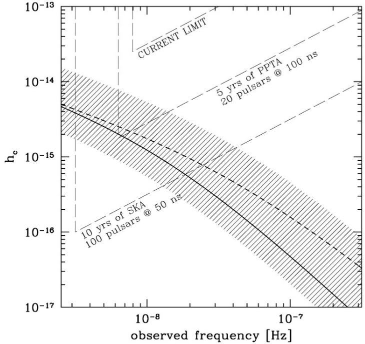
Cagliari, I, 64m, A.Possenti
Effelsberg, G, 100m, M.Kramer
Jodrell Bank, UK, 76m, B.Stappers
Nançay, F, ∼100m, I.Cognard
Westerbork, NL, ∼100m, J.Hessels

Expected correlation

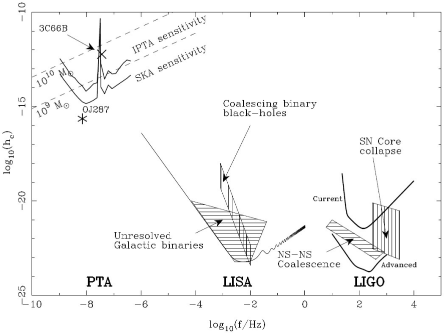


Expected correlation in the timing residuals of pairs of pulsars
as a function of angular separation for an isotropic GW background
Hellings and Downs, ApJ 265, L39 (1983)

Expected background and complementarity of the detectors



Theorical expected background
(Sesana & Vecchio, CQG 27, 084016, 2010)
with the Parkes GWB limit
(Jenet *et al*, ApJ 653, 1571, 2006)
and what is expected from future Parkes and SKA



Very-low frequency sensibility
complementary to VIRGO-LIGA and LISA

Nançay is a major contributor to the PTA

The Pulsar Timing Array (PTA) program ~2000hr/yr

Title : **Timing of an array of millisecond pulsars (MSPs)**
and detection of multi-wavelength gravitational waves
Around 30 highly stables millisecond precisely timed once a week
to search for the signature of gravitational waves (GW) background
A.Lassus PhD work (2010-2013)

High precision timing

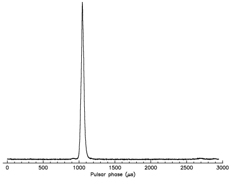
over ~30 stable pulsars
regularly timed at Nançay :
10 are better than 1μs,
5 better than 500ns...

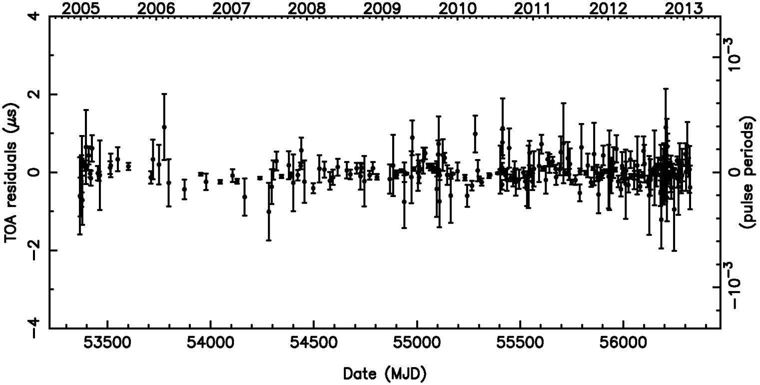
and part of the LEAP

Large European Array for Pulsars :
ERC funds to build
a 'virtual' 200m radiotelescope
by coherent addition of the voltages
recorded at the five telescopes

The ultra-stable pulsar PSR J1909-3744 at Nançay

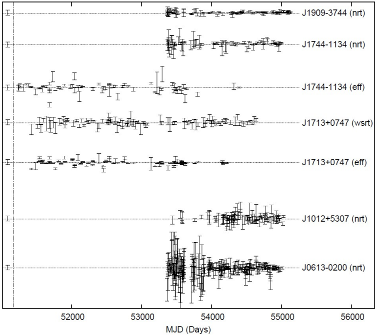
For the pulsar J1909-3744
(P=2.95ms, DM=10.39pc.cm^{-3}, P_b=1.53d)
the ToAs residuals
are characterized by an rms ∼110ns



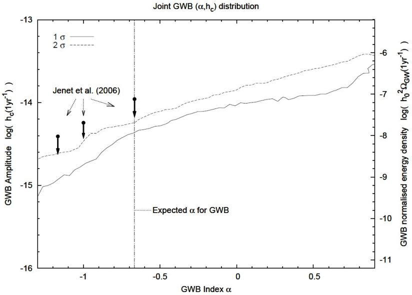


an european Bayesian limit

From EPTA high precision pulsar timing data (4NRT+2EFF+1WSRT)
R.van Haasteren (Leiden) determined with a Bayesian algorithm an upper limit, $A=6\times10^{-15}$, which is 2 times better than the Parkes one (Jenet et al, 2006)
vanHaasteren, MNRAS 434, 3117 (2011)

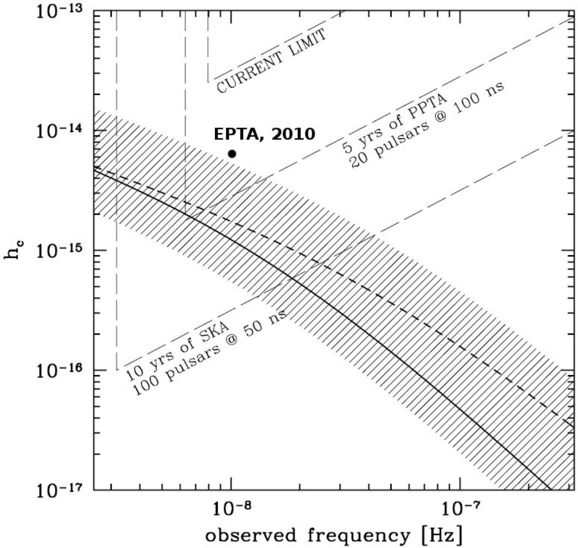


MSPs ToAs residuals

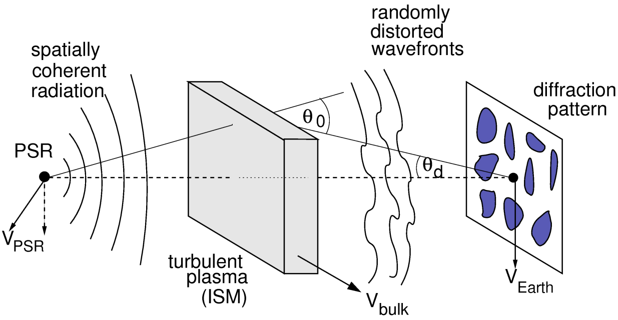


Joint GWB distribution
Characteristic strain $h_c(f) = A(f/yr^{-1})^{\alpha}$
Limit on amplitude $A=6\times10^{-15}$ (2-sigma, $\alpha=2/3$)

So close to the Sesana & Vecchio prediction...



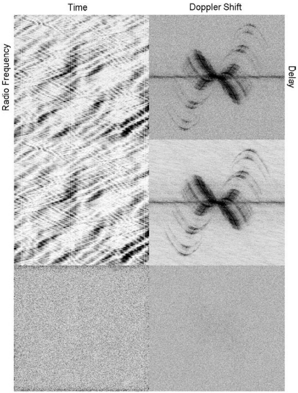
Difficulties exist... propagation through a turbulent medium



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

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

Interstellar holography

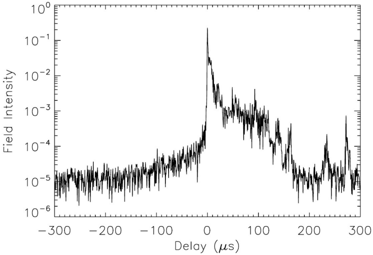


PSR B0834+06, Arecibo, 321MHz
Dynamical and secondary spectra :
data, model and residuals

Impulse response

a high SNR dynamic spectra,
the calcul of the 'secondary spectrum',
and the adjustment of thousands of coefficients describing the electric field provide the impulse response of the medium

Here, multi-propagation delays up to 100 μs are observed
and the pulse has a mean delay $\sim$15μs...
Walker et al., MNRAS 388, 1214 (2008)



Conclusion

Timing of ultra-stable pulsars
is a promizing way to search for a 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.

With a large collecting area and with an excellent instrumentation,
the Nançay radiotelescope is deeply involved in the European Pulsar Timing Array
and then within the International PTA : EPTA + Parkes PTA + US NanoGrav