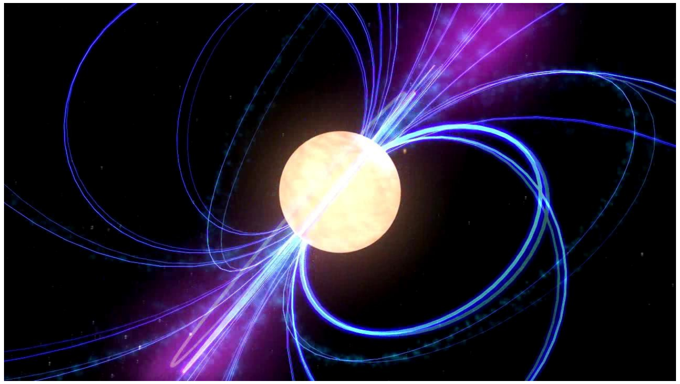
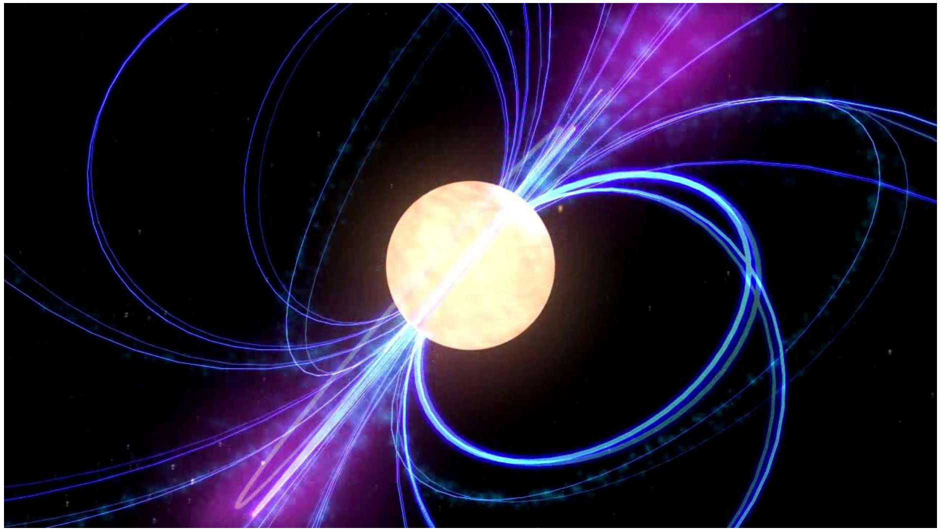


The French Pulsar timing experience

G.Theureau
CNRS-Orléans and Paris Observatory

What is a pulsar ?



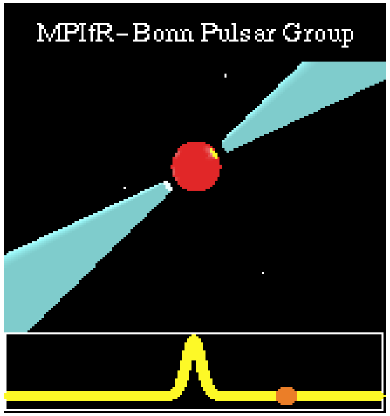
A rapidly rotating neutron star (up to 700 rot/s)

1-2 solar masses in a 12 km radius

dense matter like in atome nucleus 150 10^6 t/cm^3

Strong magnetic field : $10^{12} – 10^{13}$ Gauss
(Earth 0.5, Sun 10^3, lab $<10^6$)

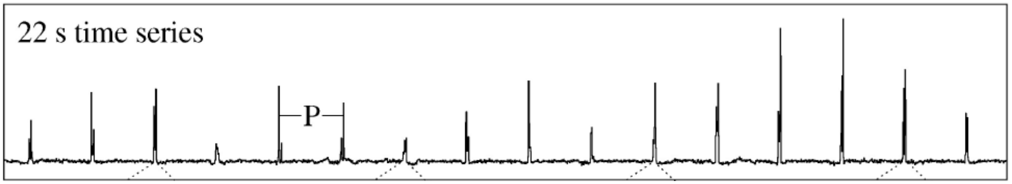
Pulsars : cosmic light houses



Particles accelerators, non-thermal radiation

Matter equation of state in extreme conditions

Natural and very stable clocks



Observed mainly in radio (2500 pulsars known)

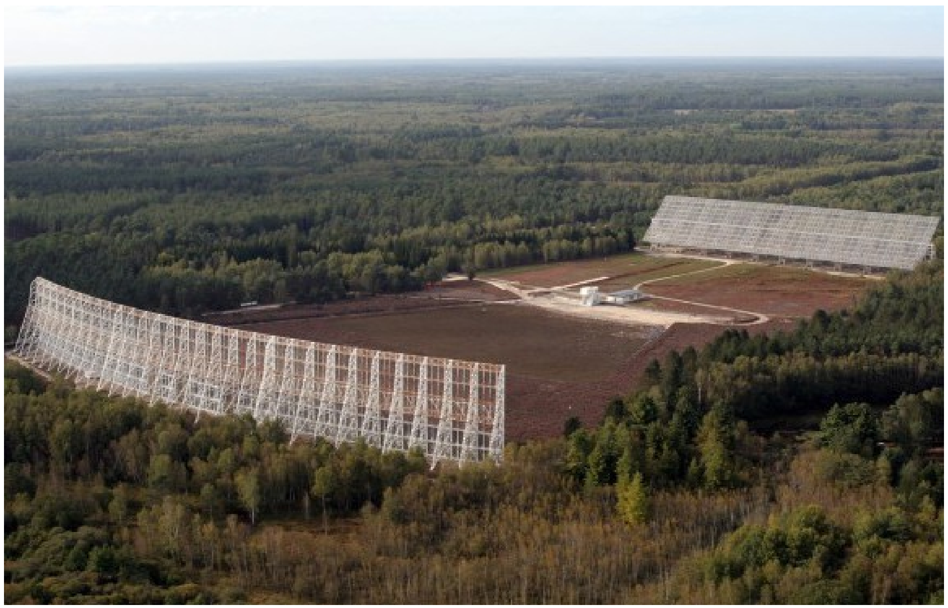
Also in X-rays and γ-rays (230 detected by Fermi)

Nançay Observatory : the French national radio facility

(Paris Observatory, INSU/CNRS & Université d'Orléans)

NRT: 1.1-3.5 GHz ; single dish ~100 m

60 % of telescope time devoted to pulsars



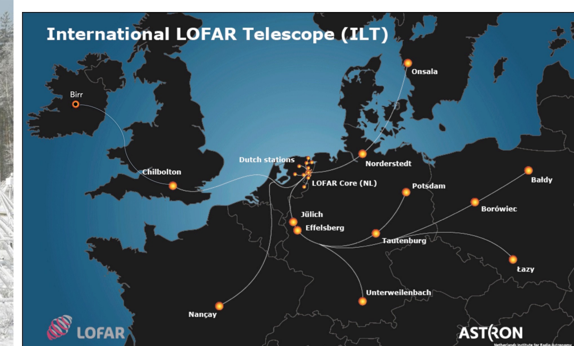
- **Multi-λ observations, emission mechanisms support to high energy**
- **new pulsars blind surveys**
- **Characterize interstellar medium**
- **Test of Gravity in pulsar binaries**
- **Detect low frequency gravitational waves**

LOFAR-FR606: 15-250 MHz, phased array ~100 m, 2x96 antennae, part of international LOFAR Telescope

50% of stand alone time

NenuFAR : 10-80 MHz, phased array ~500m, 1824 antennae ~ LOFAR core

first light instrumentation

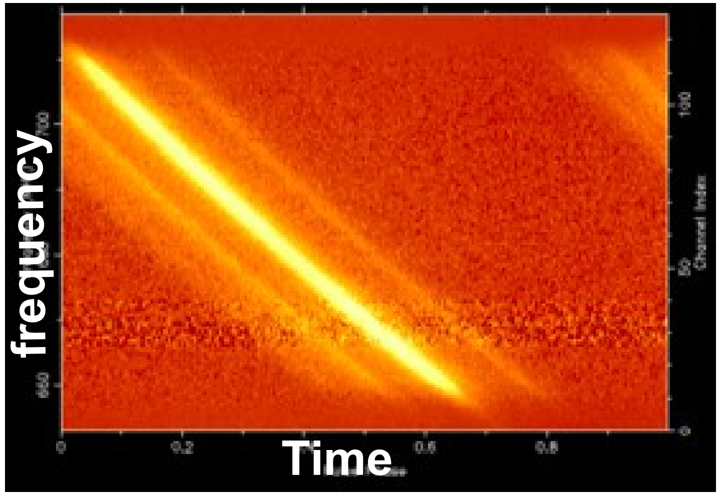


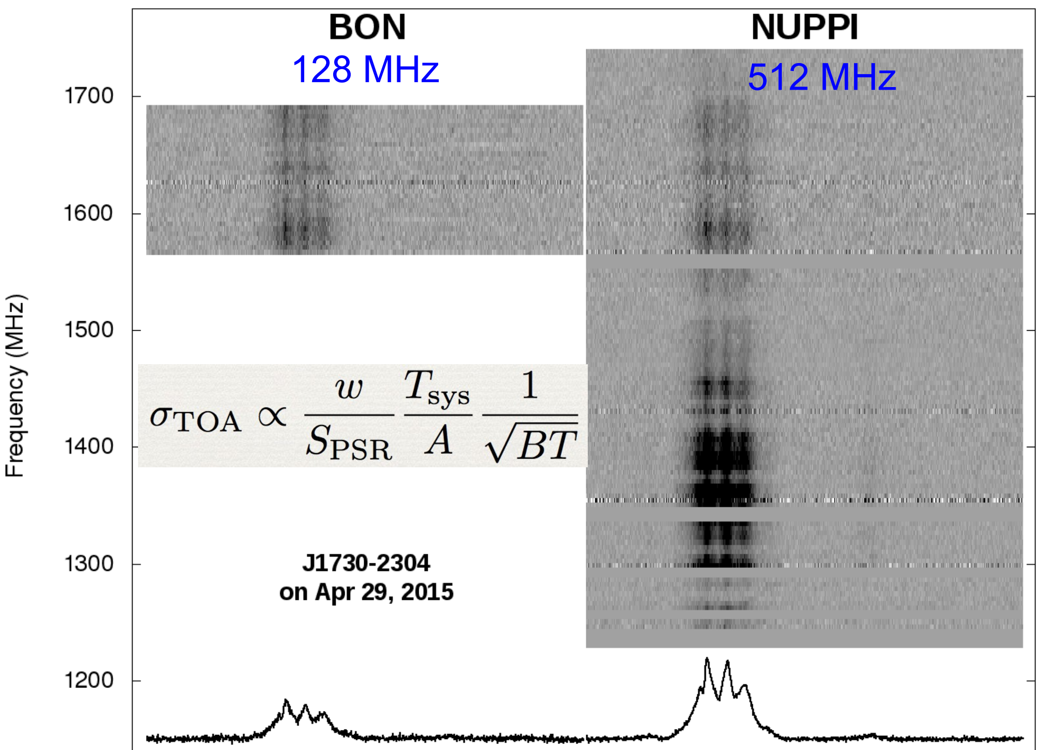
I.Cognard, G.Theureau et al
CNRS Orléans & Paris Observatory

SKA FRANCE SQUARE KILOMETRE ARRAY

The art of pulsar timing : coherent dedispersion

Due to the ionized interstellar medium, the arrival times of the pulses (TOA) are frequency dependent





1st generation (1988) :
analogical
swept local oscilator
5-10 MHz

2nd generation (2004) :
numerical
FPGA + 77 bi-athlon CPUs
64-128 MHz

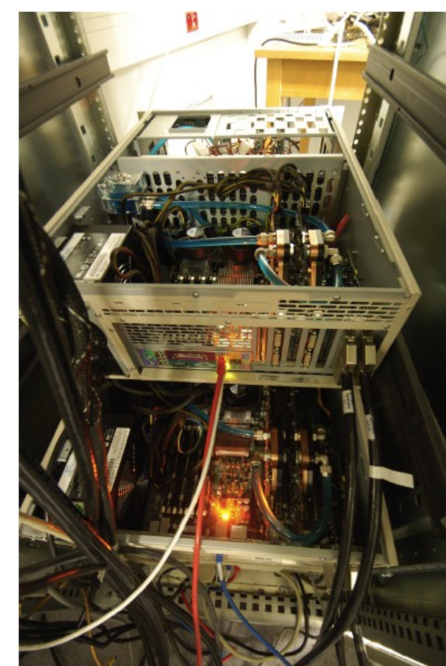
3rd generation (2008):
numerical
FPGA + CPUs + GPUs
128 MHz

→ 512 MHz (2011)

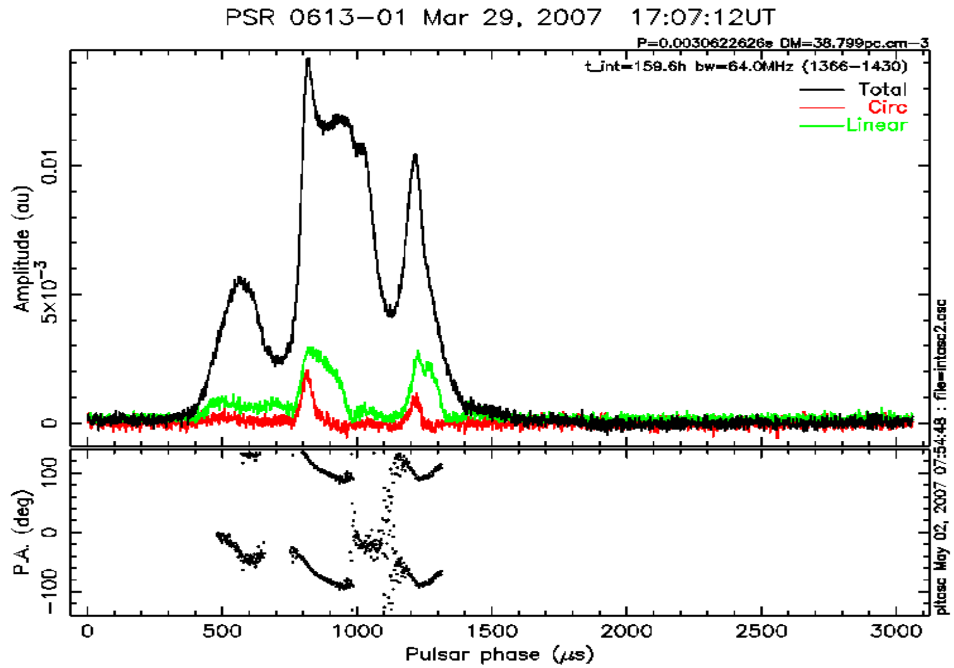
→ 2 GHz (2018)

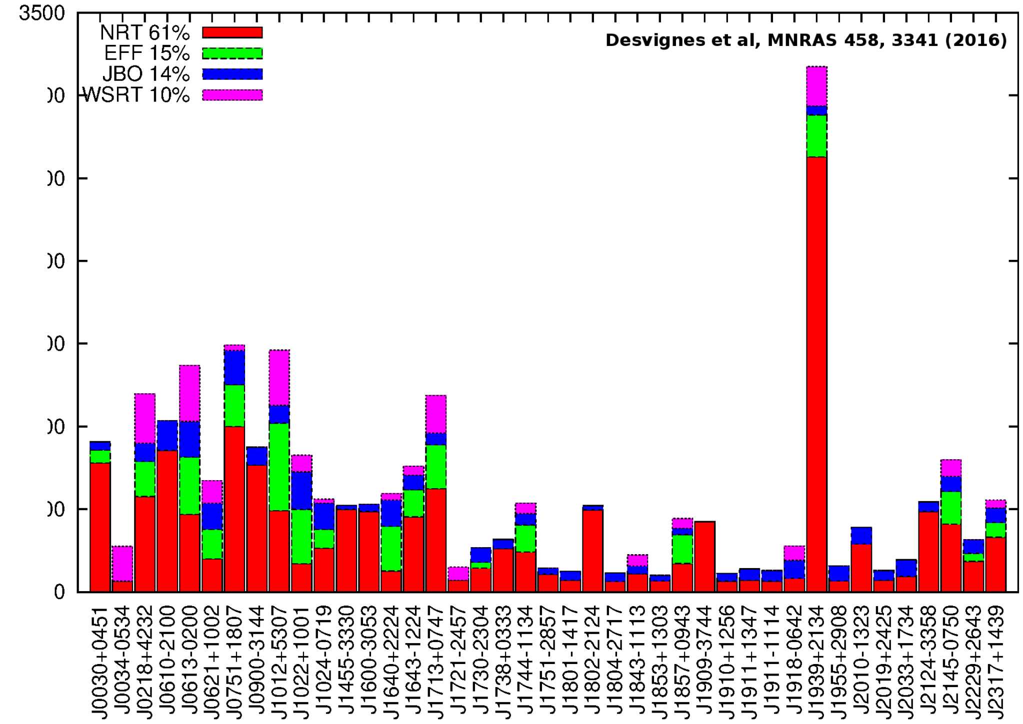
<u>At the state of the art</u>

(Cognard et al
CNRS Orléans)



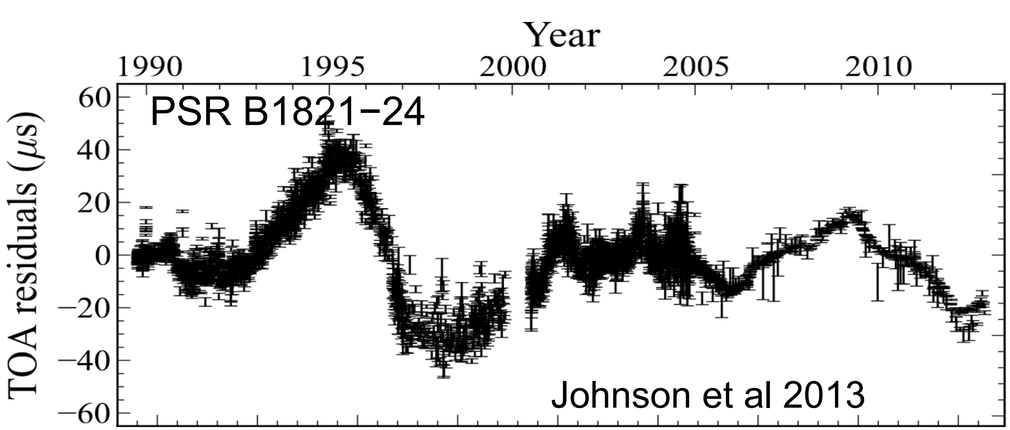
NRT Timing performances

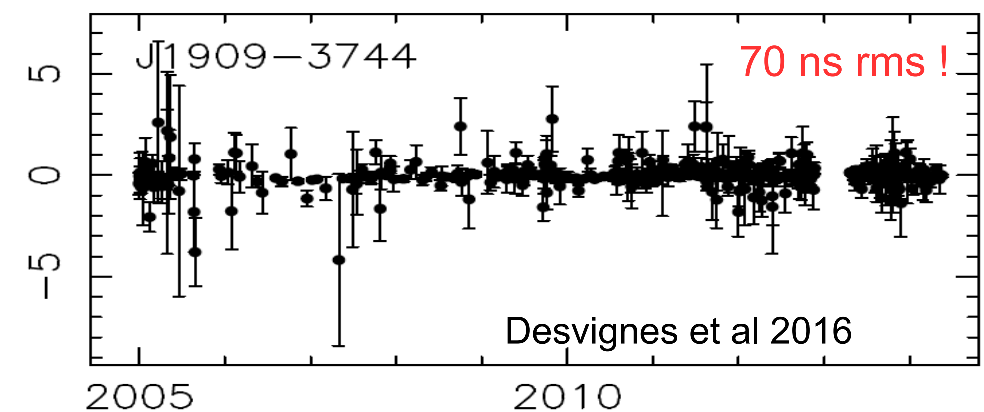




TOA residuals rms over 6 years with NUPPI 512 MHz :

N(rms < 500 ns) = 15
N(rms < 800 ns) = 30
N(rms < 1 μs) = 40





SKA FRANCE SQUARE KILOMETRE ARRAY

Multi-wavelength synergies

INTEGRAL (X-ray and γ-ray) : C.Gouiffes et al (CEA, Saclay)

Crab giant pulses, Fast Radio Burst repeater

XMM-Newton (X-rays) : N.Webb, D.Barret et al (IRAP, Toulouse)

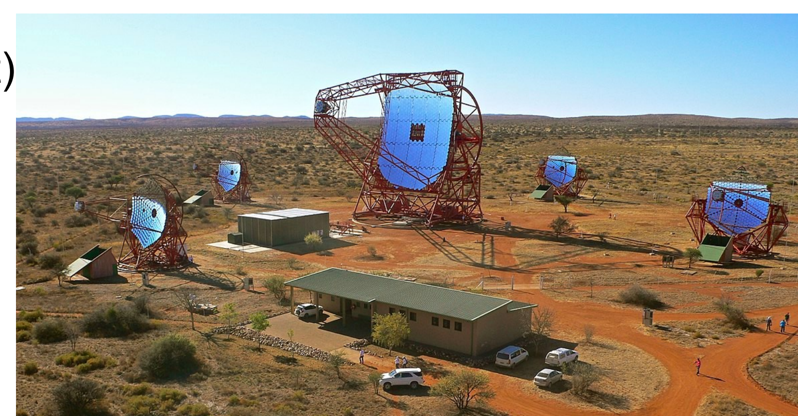
X-rays emission properties, mass and radius measurements (EoS),
+ joint LOFAR observation for mode changing studies

Fermi-LAT (γ-ray) : D.Smith, M.Lemoine-Goumard et al (CENBG, Bordeaux)
N.Webb et al (IRAP, Toulouse)

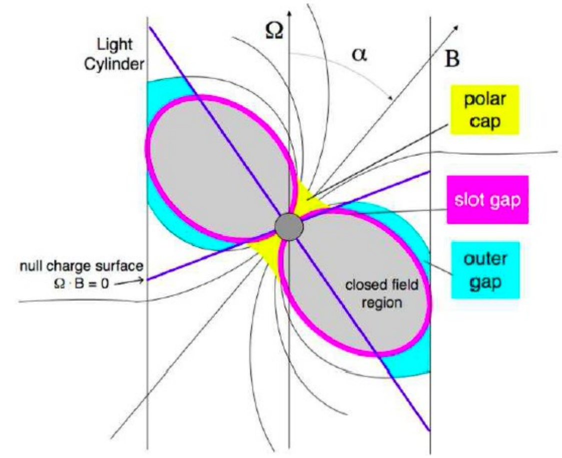
γ-ray pulsar population,
pulsar environment (Pulsar Wind Nebulae, Super Novae Remnants)

HESS/HESS-II (TeV γ-ray) : A.Djanati et al (APC, Paris-Diderot)
Y.Gallant et al (Univ Montpellier)

Characterize known pulsars at TeV energies
preparation for CTA

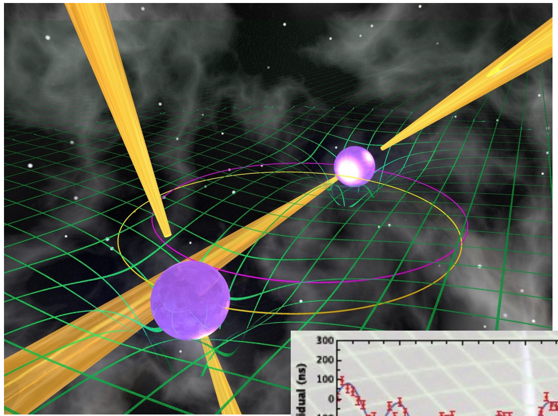


Pulsars & fundamental Physics



Emission mecanisms

Phenomenological models : I.Grenier et al, CEA, Saclay
Force free models : J.Pétri et al, Strasbourg Observatory
Vlasov models : F.Mottez et al, Paris Observatory
Particles in Cells models : B.Cerruti et al, IPAG, Grenoble

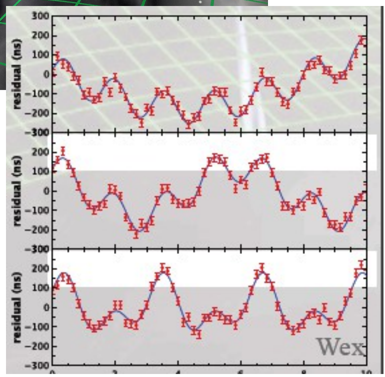


Gravitation theories

Post Newtonian approximation : L.Blanchet et al, IAP, Paris
Numerical models : A.LeTiec, Paris Observatory
Gravitational waves : A.Petiteau, S.Babak, APC, Paris-Diderot

Neutron stars equation of state (masses, radius and glitches)

J.Margueron et al, IPNL, Lyon
J.Novak, M.Oertel et al, Paris Observatory



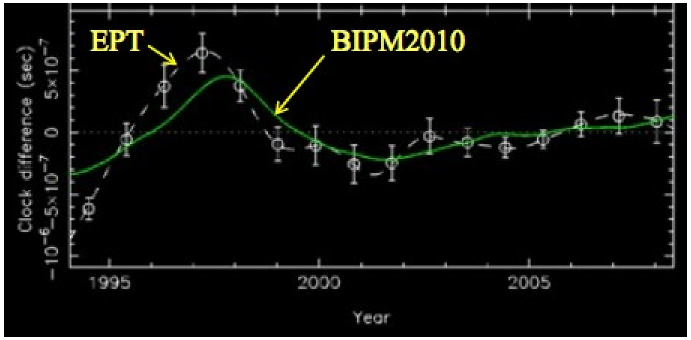
Pulsars & reference systems

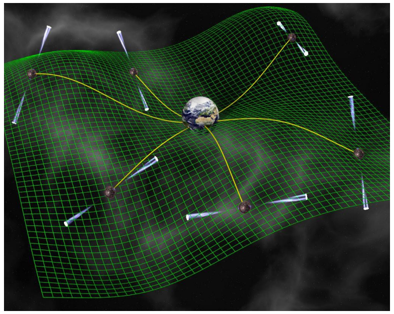
Planetary ephemerides vs ICRF

INPOP : A.Fienga et al, OCA, Nice
ICRF : J.Souchay et al, Paris Observatory

Reference time scale

clock comparisons techniques : F.Vernotte et al, Obs Besançon
Pulsar reference time scale : G.Petit, BIPM, Sèvres



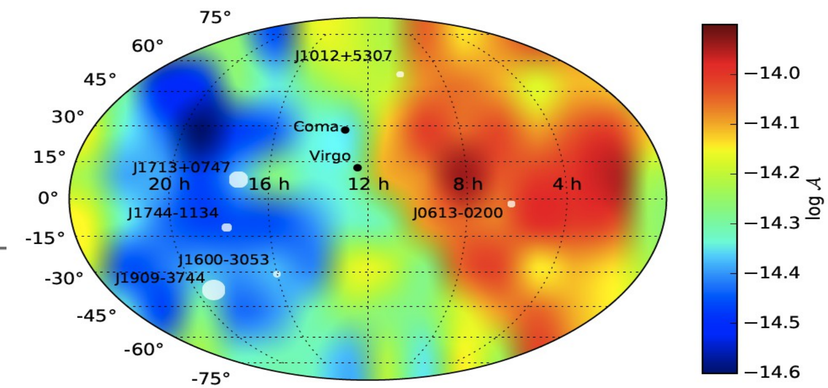


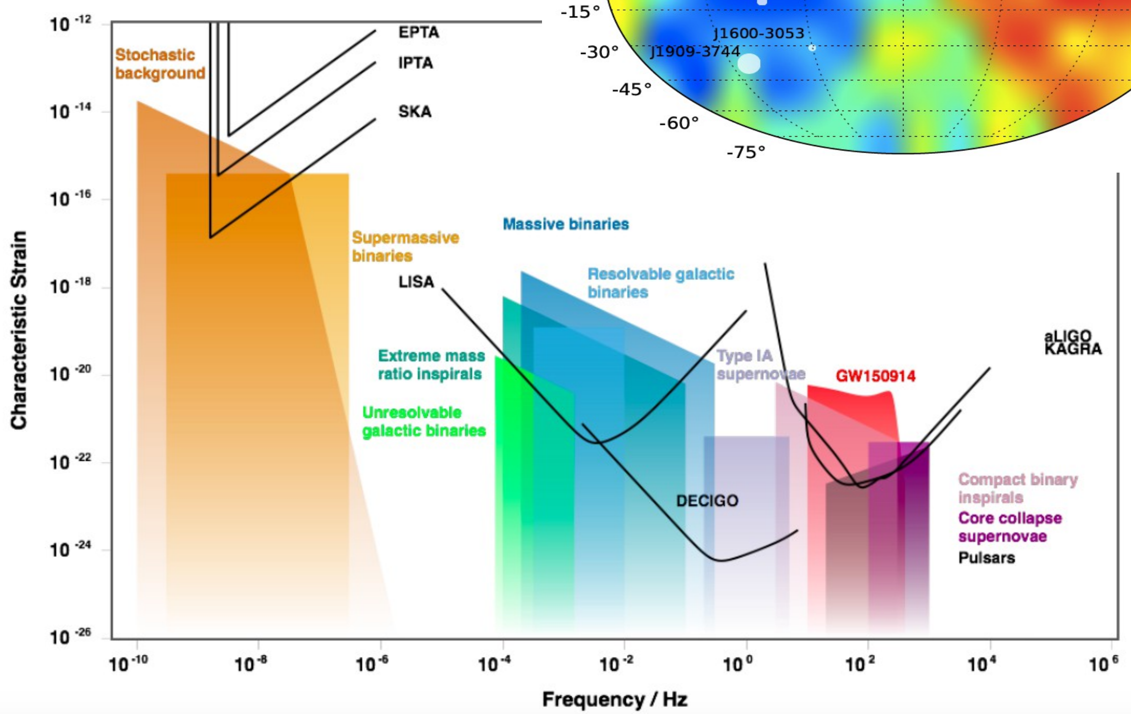
European Pulsar Timing Array

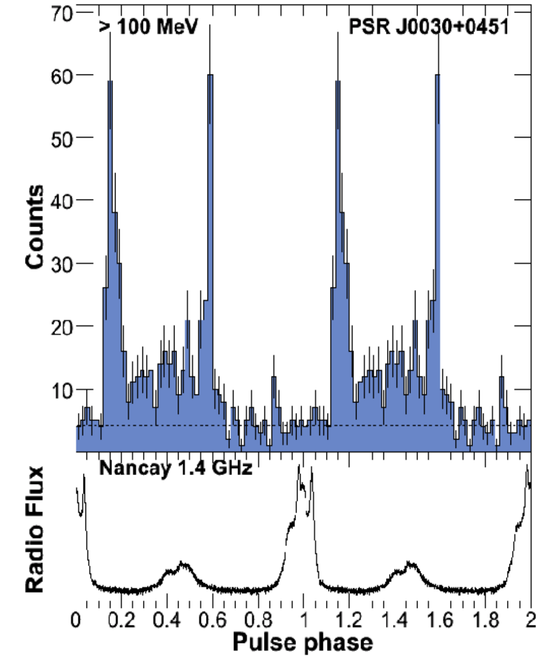
Nançay provides 61% of EPTA data

2015-2016 : first series of constraints on the super massive black hole binary population

Investigate the nHz-µHz gravitational wave regime

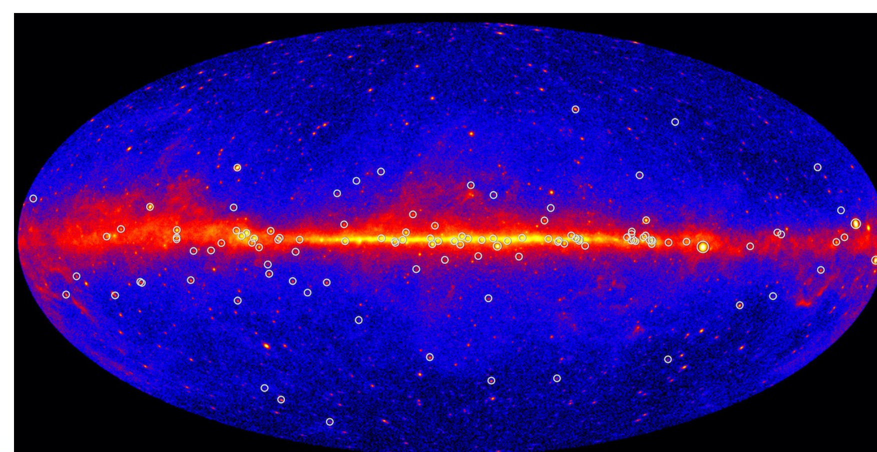






The Fermi Sky

The population of γ-ray millisecond pulsars unveiled thanks to radio-γ collaboration



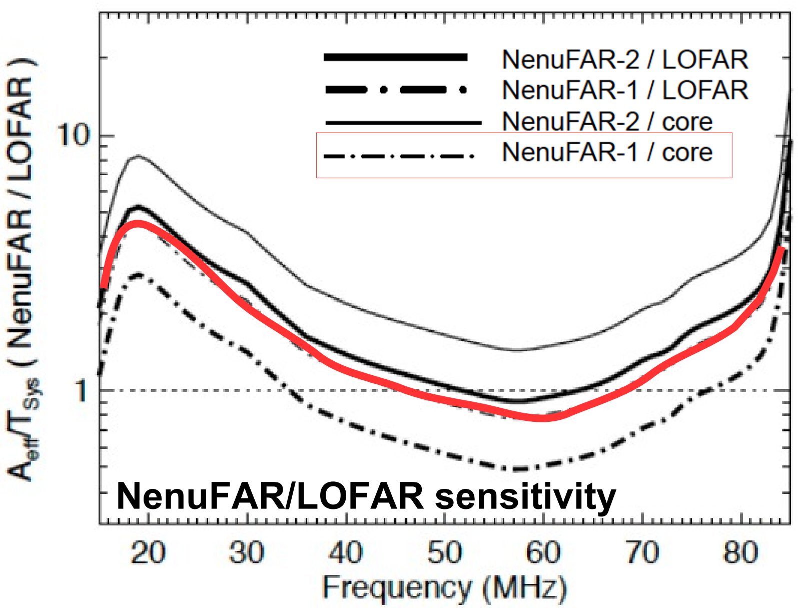
NenuFAR early science

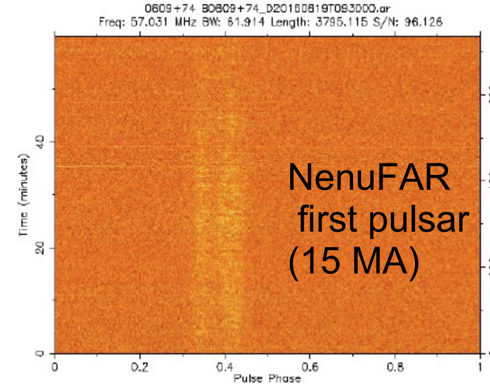
Multi-wavelength studies
(10-250 MHz + 1.0-3.5 GHz)
Magnetospheres : mecanism of emission, origin of particle acceleration

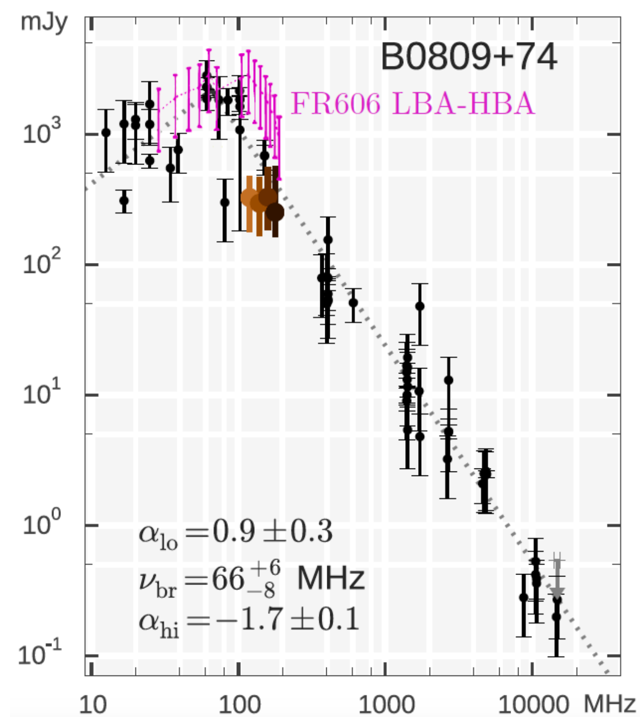
Population/surveys (efficiency !)

Studies of the interstellar medium

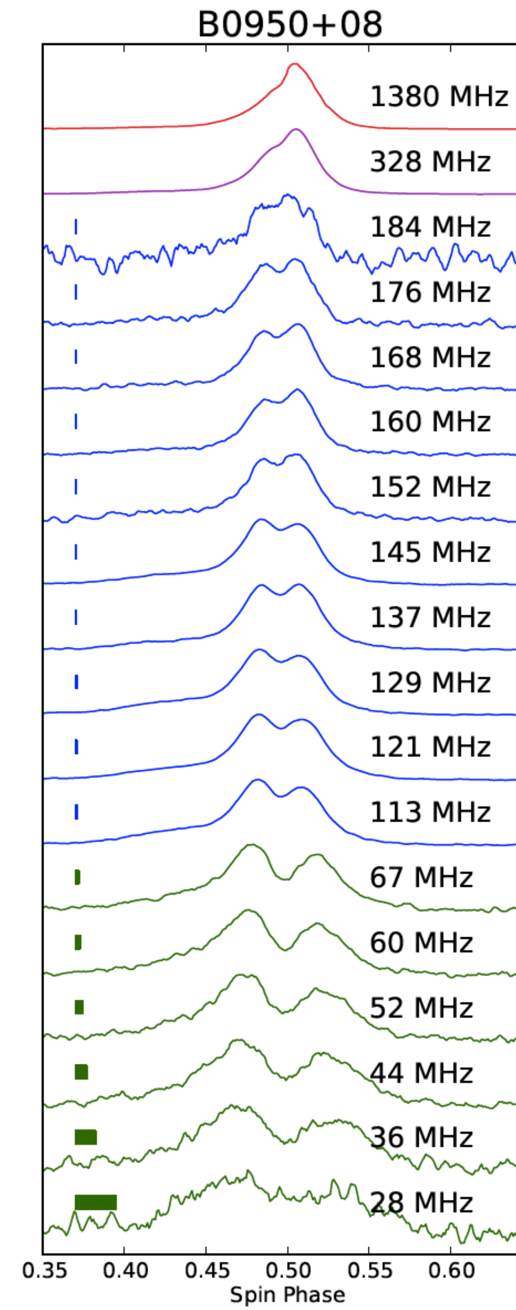
Pathfinder for SKA_low







Pulsar spectrum studies
turn-off characterization
(L.Bondonneau, Univ Orléans)



Pilia et al 2015 (pulsar WG)

International links

European Pulsar Timing Array (MoU) → International Pulsar Timing Array (MoU)
Member of the board
Provides 60% of TOAS
Participate in timing and GW analysis

Fermi PSC (MoU)
Coordinated observational campaigns
Provide ephemerides and pulsars radio pulse profiles
+ Preparation of CTA

MeerKAT
Member of MeerTime and Trapum consortia
Will participate to telescope commissioning and operation

SKA Science Working Group
Meetings, writing of the pulsar science case
(e.g. Cosmic census, Equation of State, Multi-messenger/multi-λ articles)

LIGO-Virgo (MoU)
Provide ephemeride for accurate apparent period monitoring
+ TOO observation on alert : SN/GRB afterglows, post-merging AGNs

NICER (X-rays telescope on ISS)
Provide ephemerides for navigation using pulsars (SEXTANT project)
Measure neutron star radius

Thank you