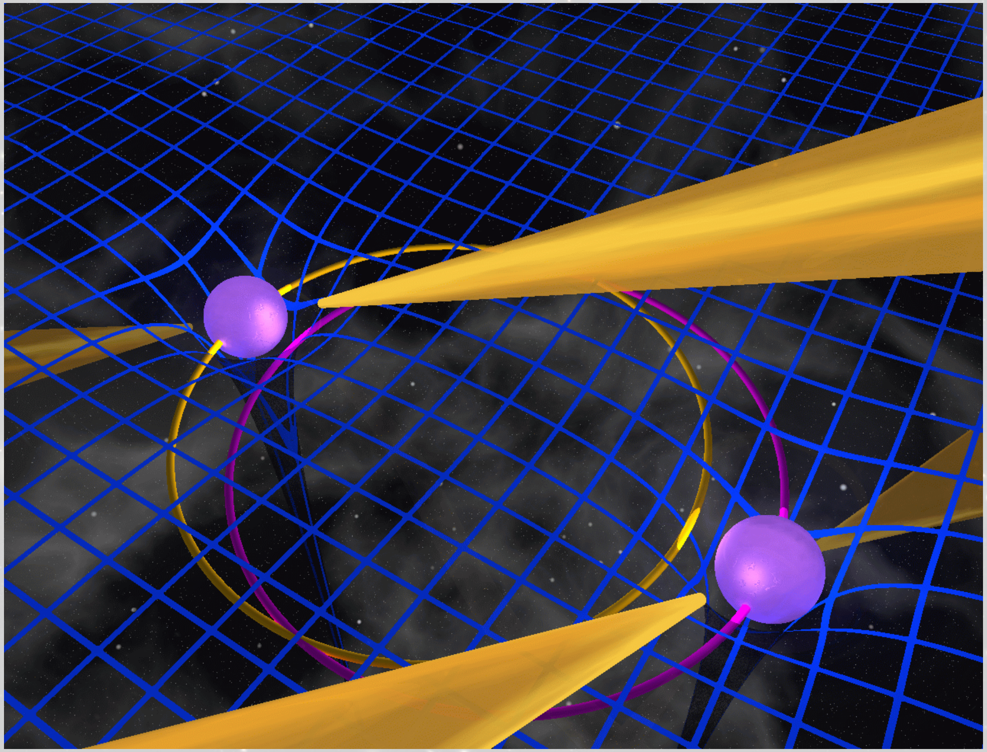
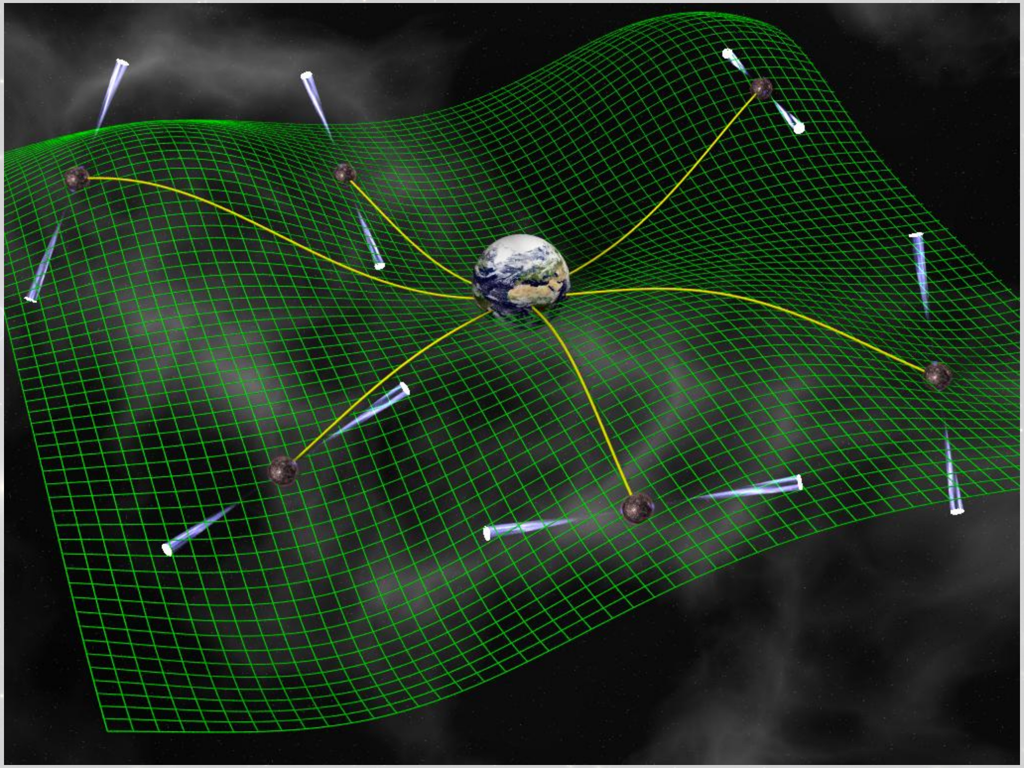
Pulsar Timing Arrays & GR tests





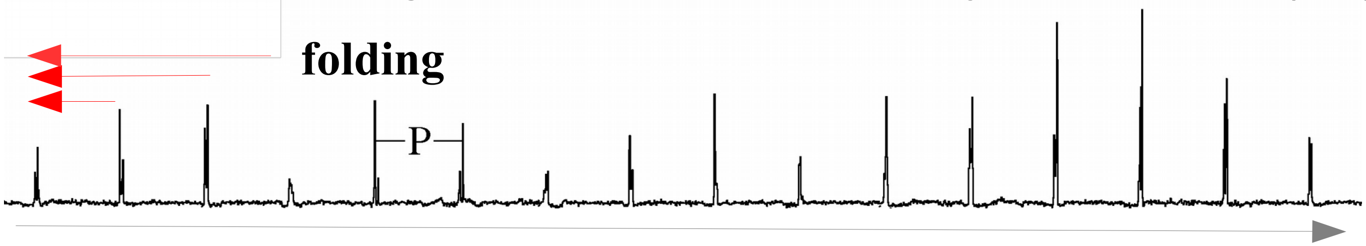
Journée PhyFOG – 21 mai 2019

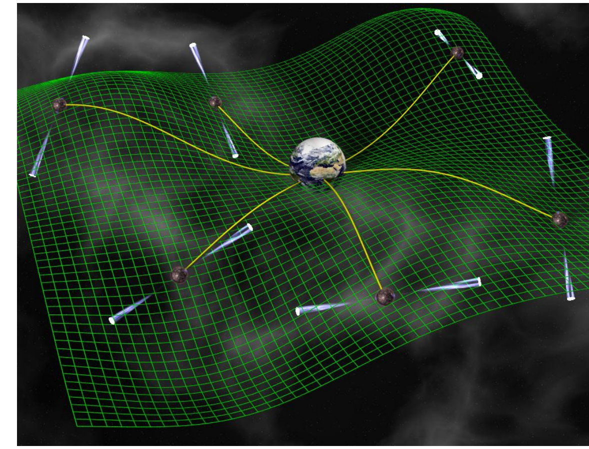
Gilles Theureau (LUTh/USN/LPC2E) & **A.Petiteau** (APC)

S.Babak (APC), **I.Cognard** (LPC2E/USN), **L.Guillemot** (LPC2E/USN)
Post-doc – **S.Chen** (LPC2E/USN), **G.Voisin** (LUTh, Univ. Manchester)
PhD – **A.Berthereau** (LPC2E/USN), **A.Chalumeau** (APC/USN/LPC2E), **Mikel Falxa** (APC)

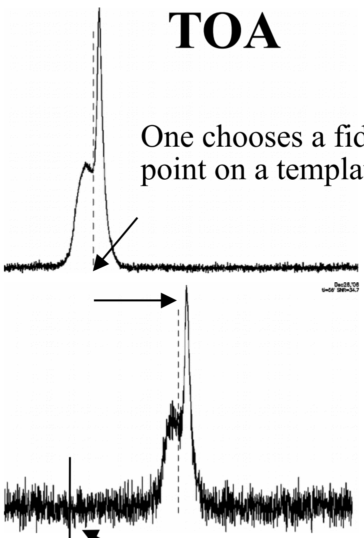
PTAs : principle and state-of-the-art

- **rapidely rotating (few ms) and stable (few 100 ns) neutron stars**
- **radio pulses: counting each rotation and measure precisely the time of arrivals (TOA)**





TOA



One chooses a fiducial point on a template profile

Position of the first sample of data, corresponding to the start of the observation

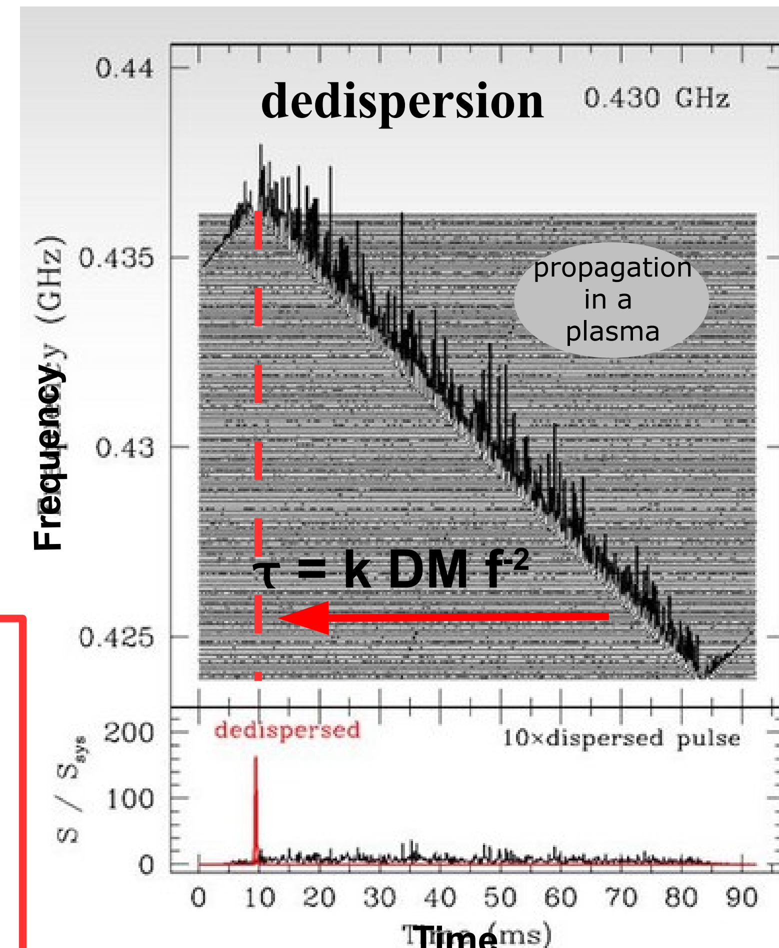
Sensitivity and precision

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

Choose the right pulsar

Have a good receiver and a big radio telescope

integrate on a wide band



The passing of a gravitational wave perturbs the metrics and produce fluctuations in the time of arrivals of the pulses

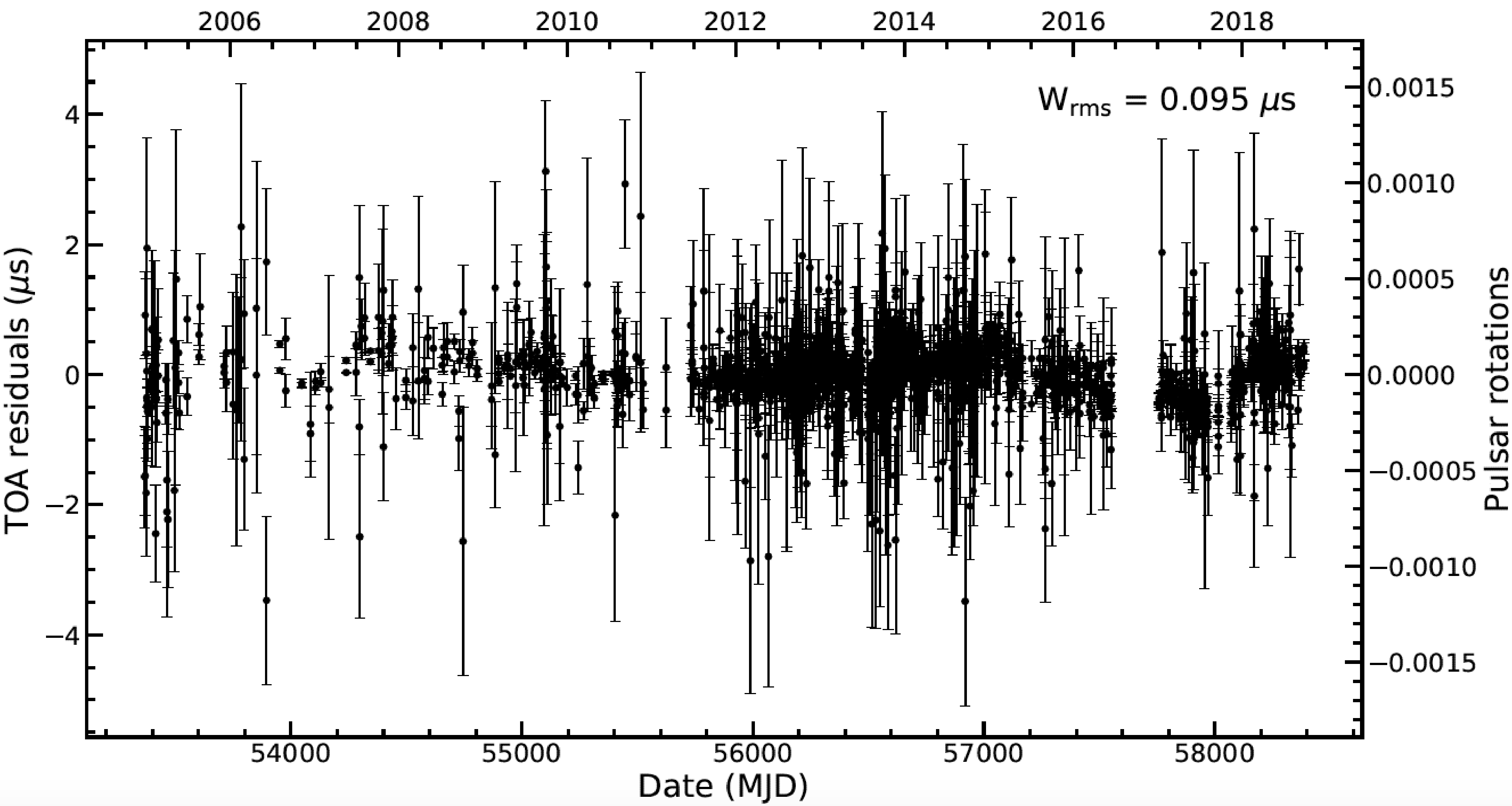
with an uncertainty dt (~100 ns) and a time span T (~20 years)

→ one is actually sensitive to amplitude ~ dt/T (10^{-16})

→ and to frequencies of the order of f ~ 1/T (10^{-9} – 10^{-7} Hz)

PTAs : principle and state-of-the-art

Time of arrival residuals for pulsar PSR J1909-3744



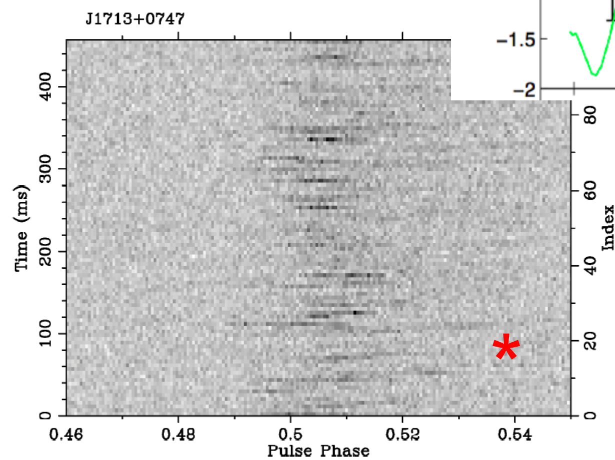
PTAs : questions

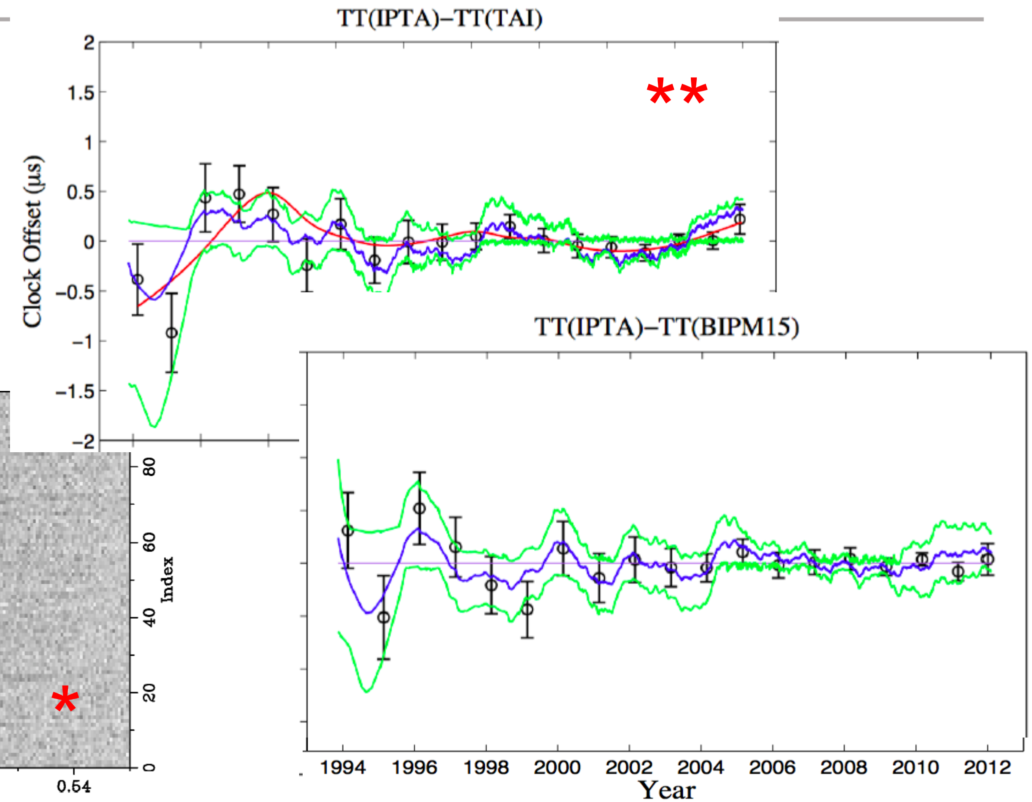
White noises (uncorrelated noise)

Instrumental
→ radiometer noise, calibration in polarisation
Multi-telescope measurements, LEAP

Astrophysical
→ 'pulse jitter' *

Scintillation
→ cyclic spectroscopy
2D template matching





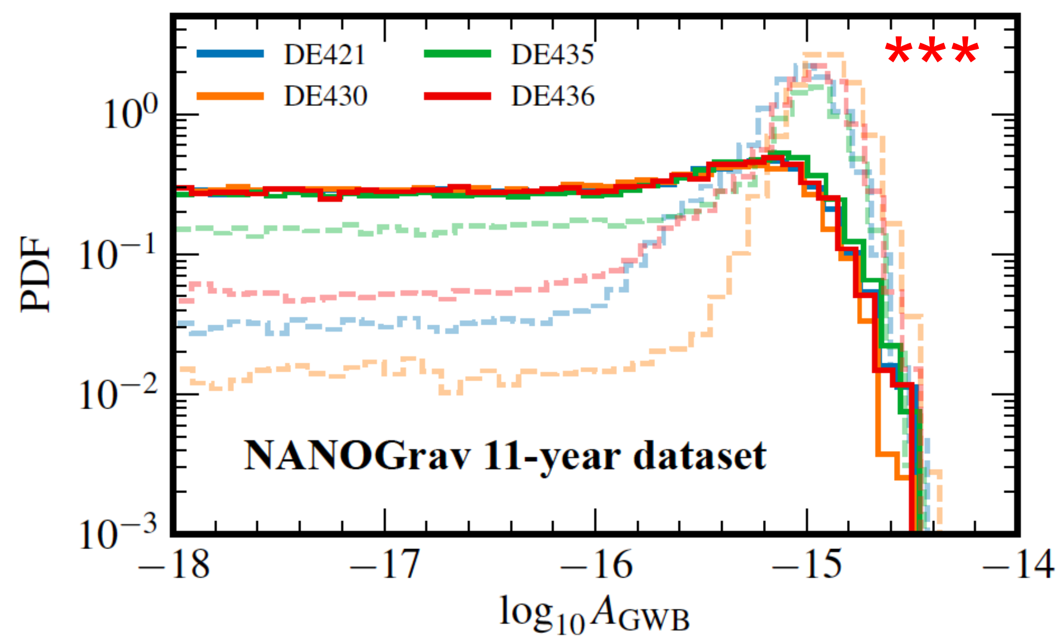
Red noise (correlated noise)

Dispersion measure variations
→ multi-frequency measurements

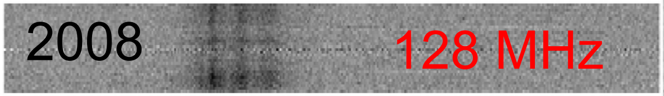
Rotation noise
→ perturbation of small bodies ?
Variations in Edot ? Series of micro-glitches ?

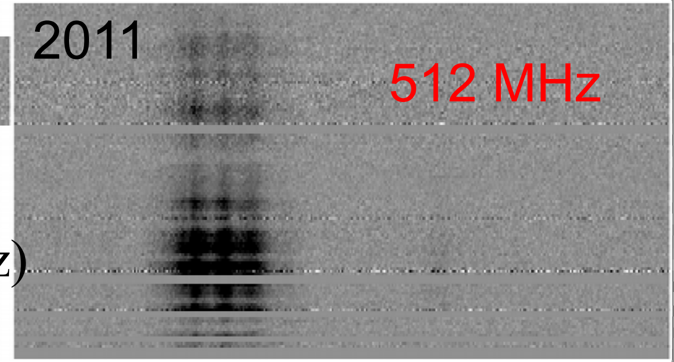
Clock variations **
→ link with TAI, TT-BIPM

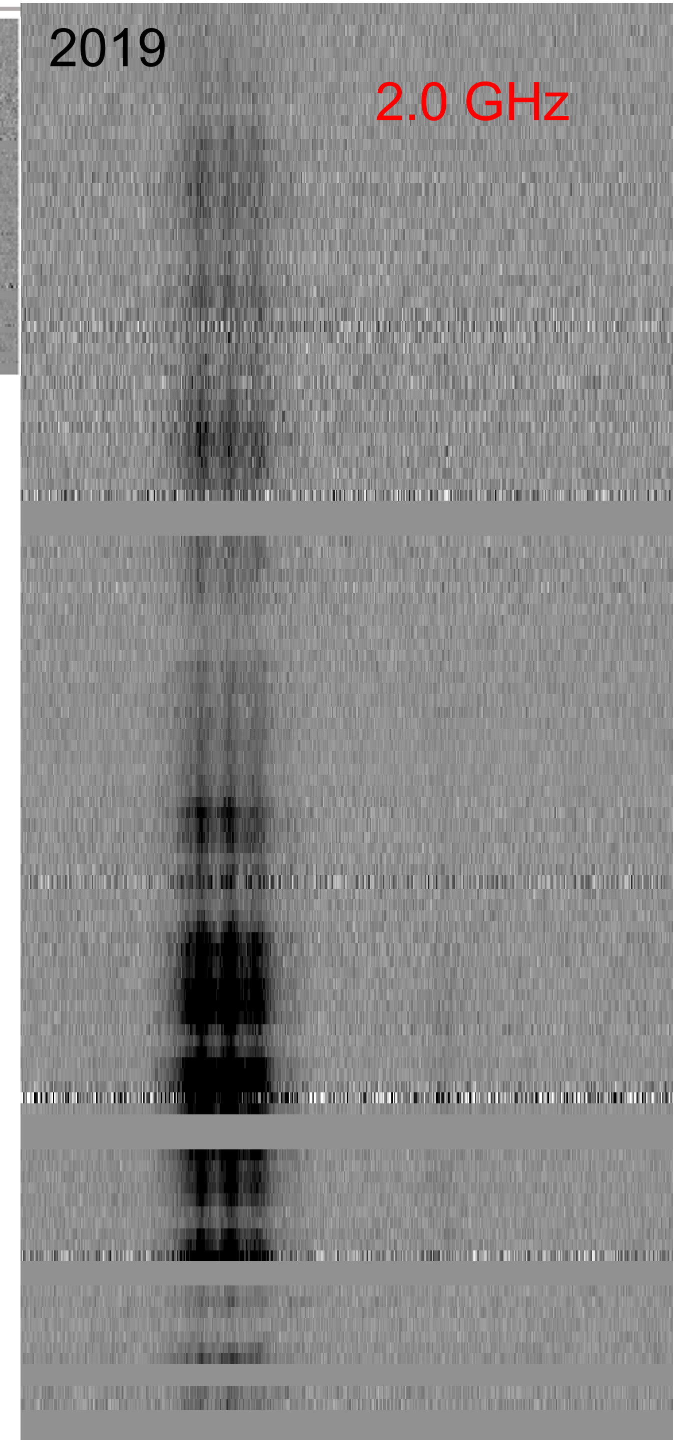
Solar system ephemerides ***
→ link with INPOP, JPL



PTAs : planning

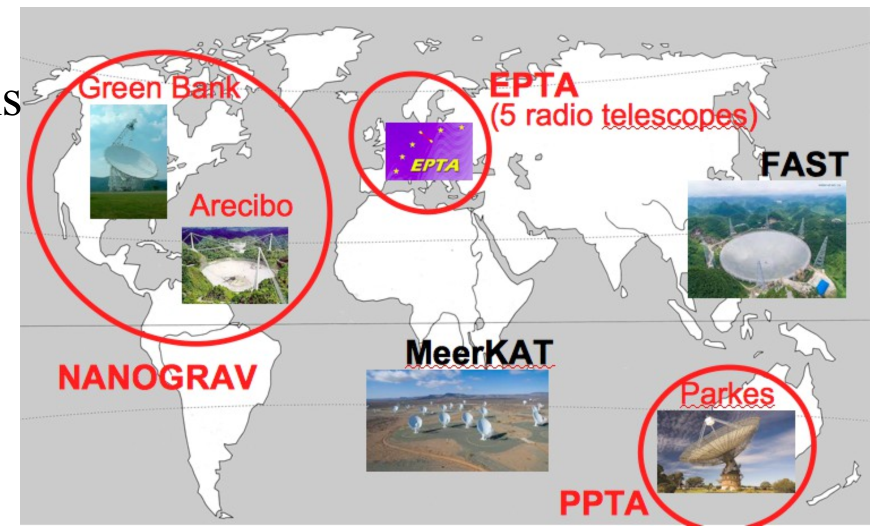




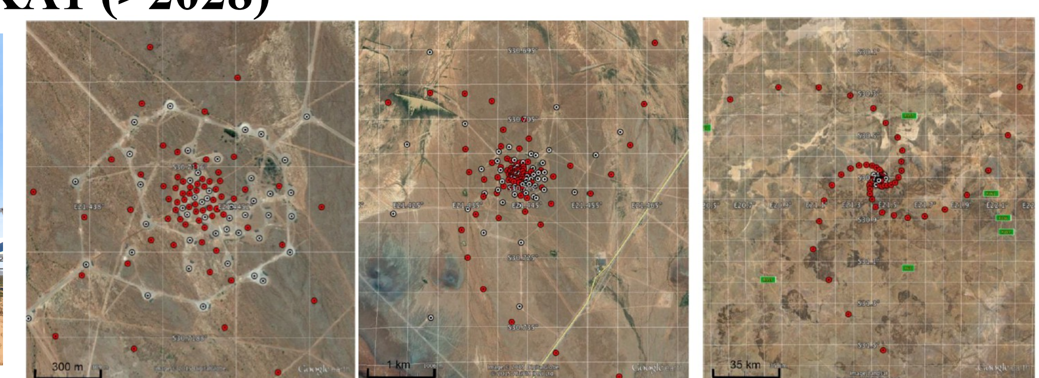


NRT instrumentation:
Enlarge the band width (1.5-3.5 GHz)

IPTA :
share observations and methods (> 2016)

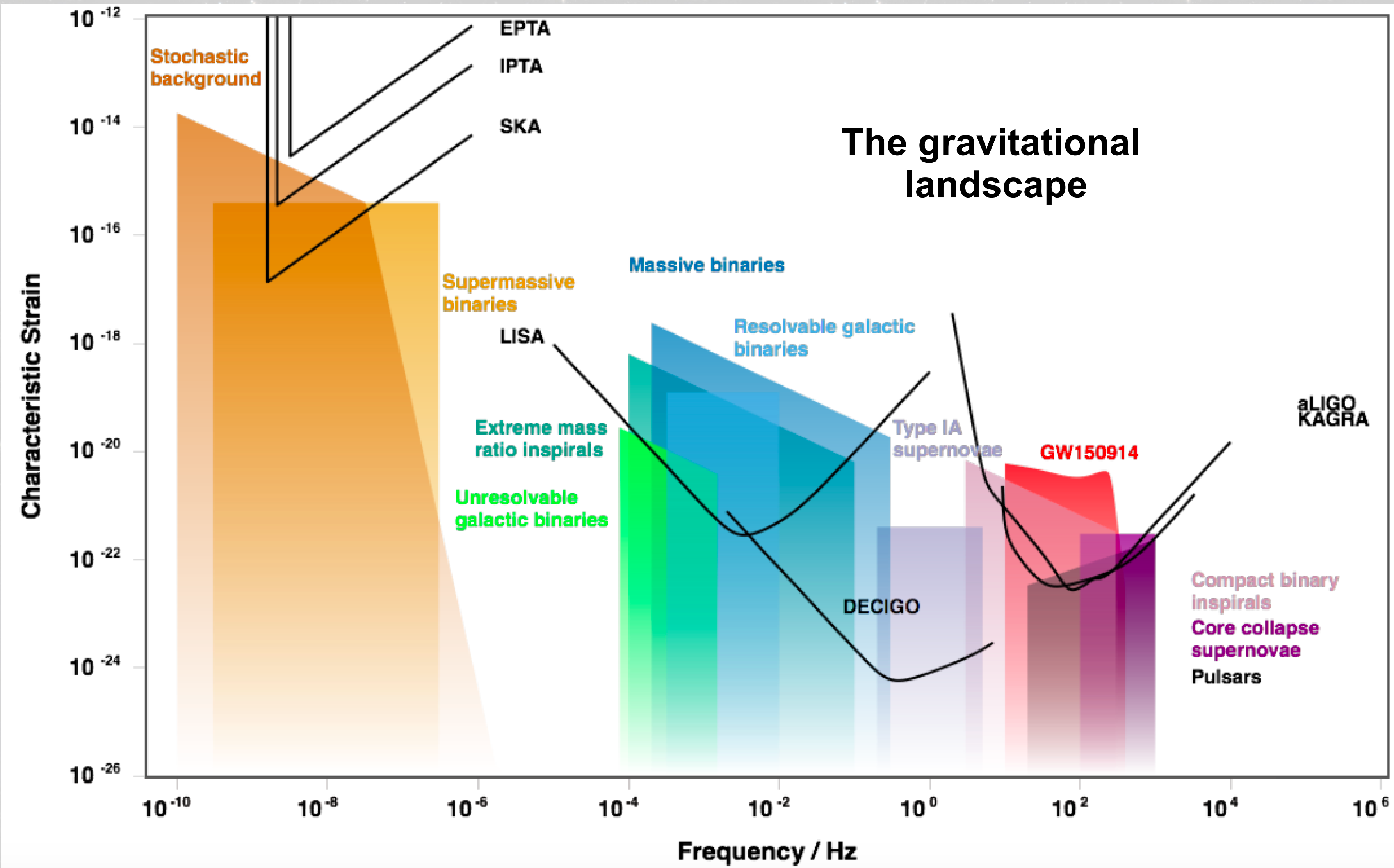


Participation in MeerKAT (2019-2023)
perpective of SKA1 (>2028)

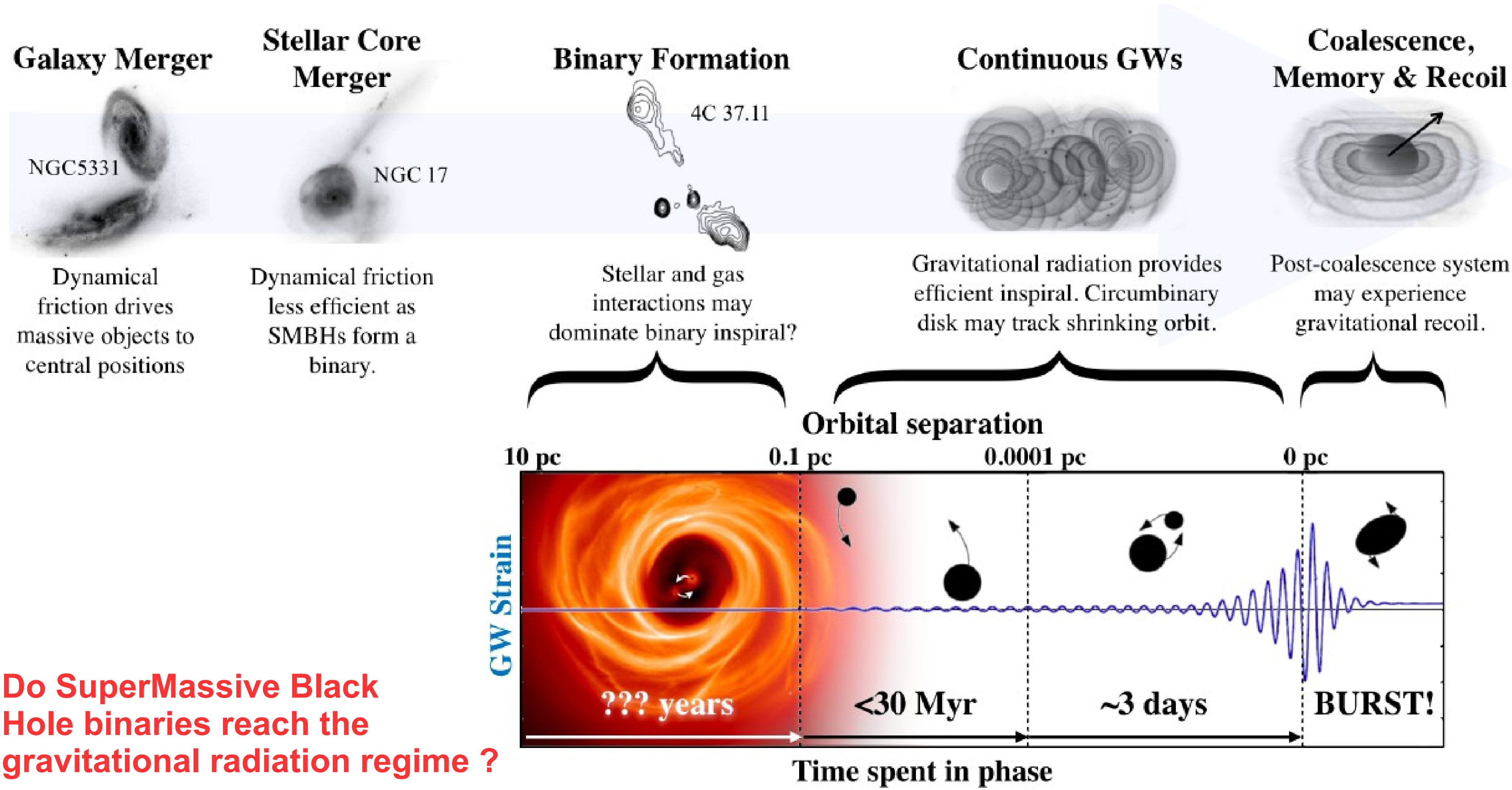


PTAs : the gravitational wave background : *nHz-μHz domain*

- Super massive black hole binaries (SMBHB)
- Cosmic string loops
- Relics of inflation



The life cycle of supermassive binary black holes



Do SuperMassive Black Hole binaries reach the gravitational radiation regime ?

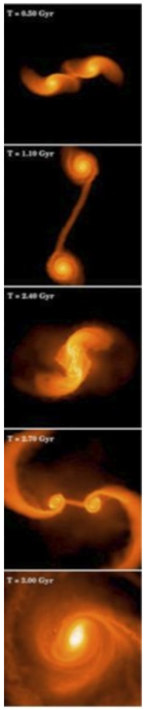
Do we have a chance to get a detection with the PTA technique in a reasonable time ?

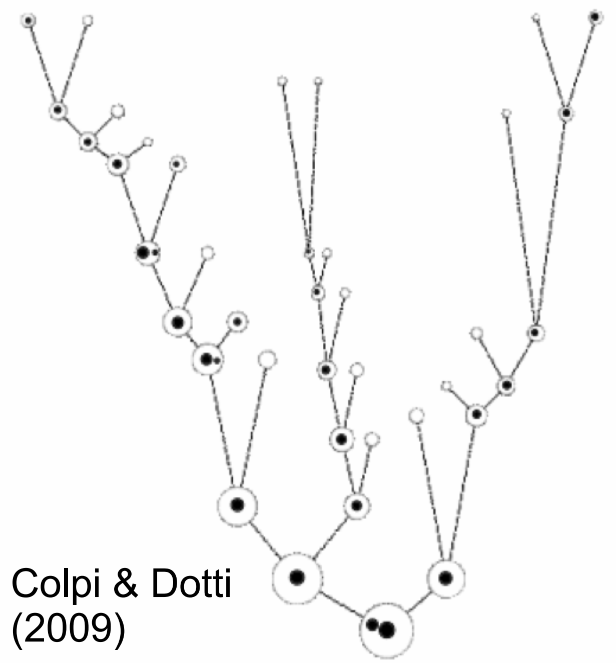
How can we characterize the detected signal ?

monochromatic PTA regime

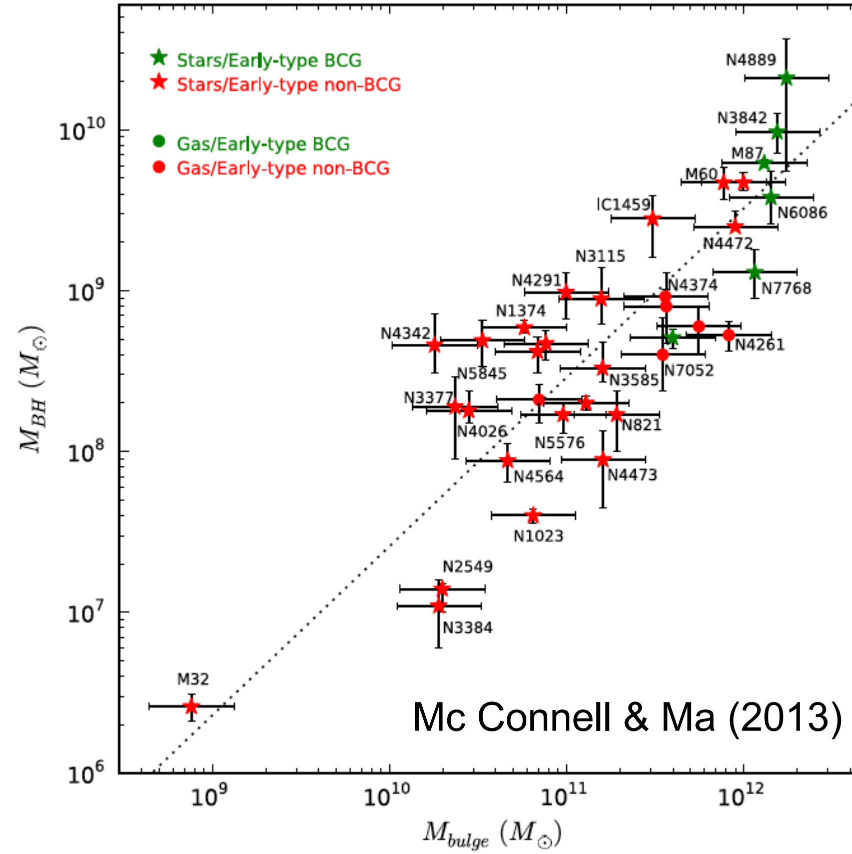
Burke-Spolaor 2018

Populations synthesis ingredients





Colpi & Dotti (2009)



Mc Connell & Ma (2013)

Merger trees from cosmological N-body simulations

Bulge to BH mass ratio from galaxies dynamical studies

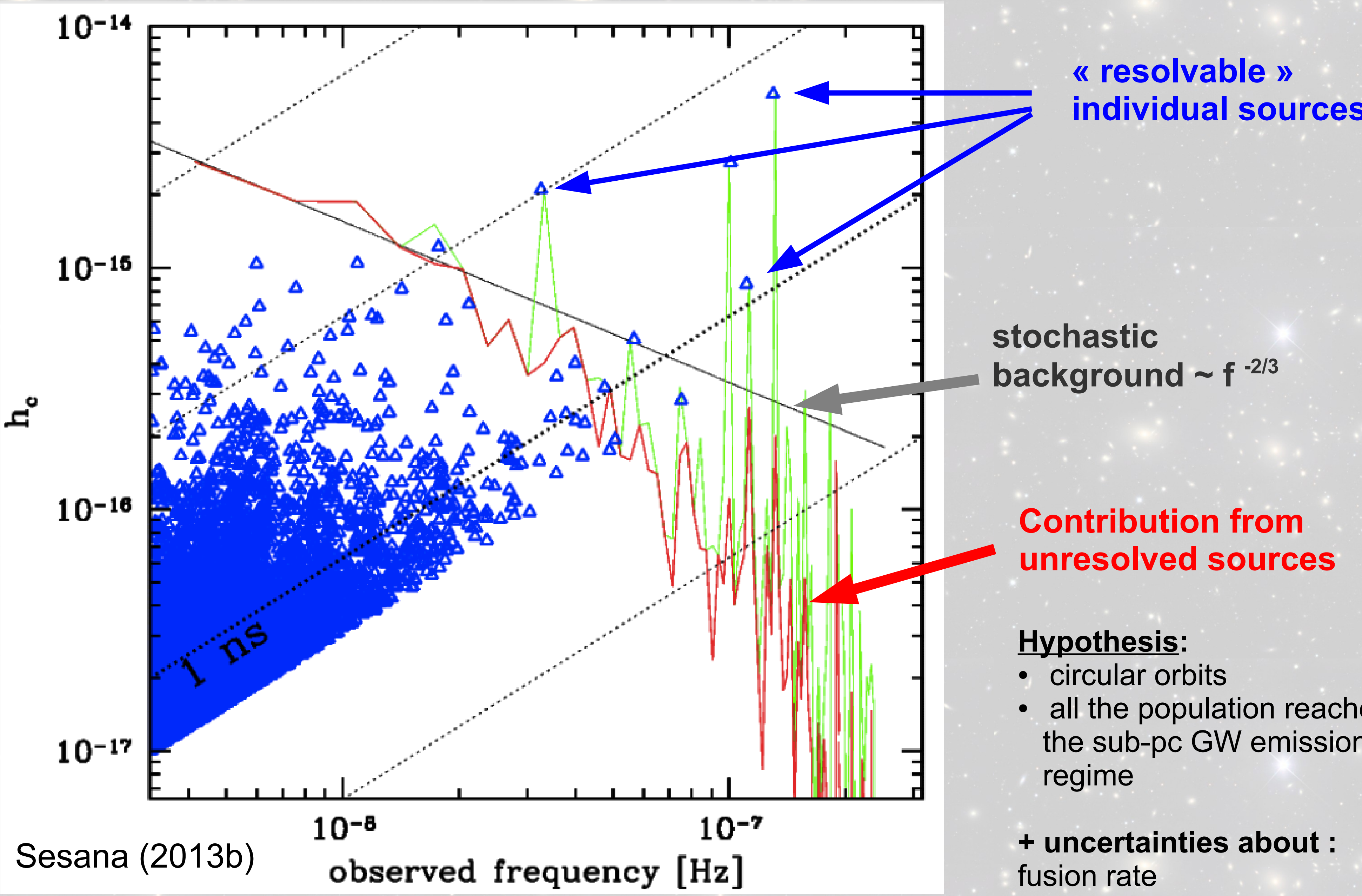
Add dynamical friction with stars and gas to migrate the BHs towards the center

Three body interaction with stars from the loss cone region (when binary orbital velocity > stars)

Find mechanisms to solve the last parsec problem

- massive BH triplets (Bonetti et al 2018),
- triaxial potential/density of the nuclei refilling the loss-cone (Vasiliev et al 2015),
- circumbinary accretion disk (Tang et al 2017)
- accretion of clumpy cold gas (Goicovic et al 2018),
- a large population of stalled binaries at low frequencies (Dvorkin&Barausse 2017)

Population of SMBBH: contribution from background & individual sources



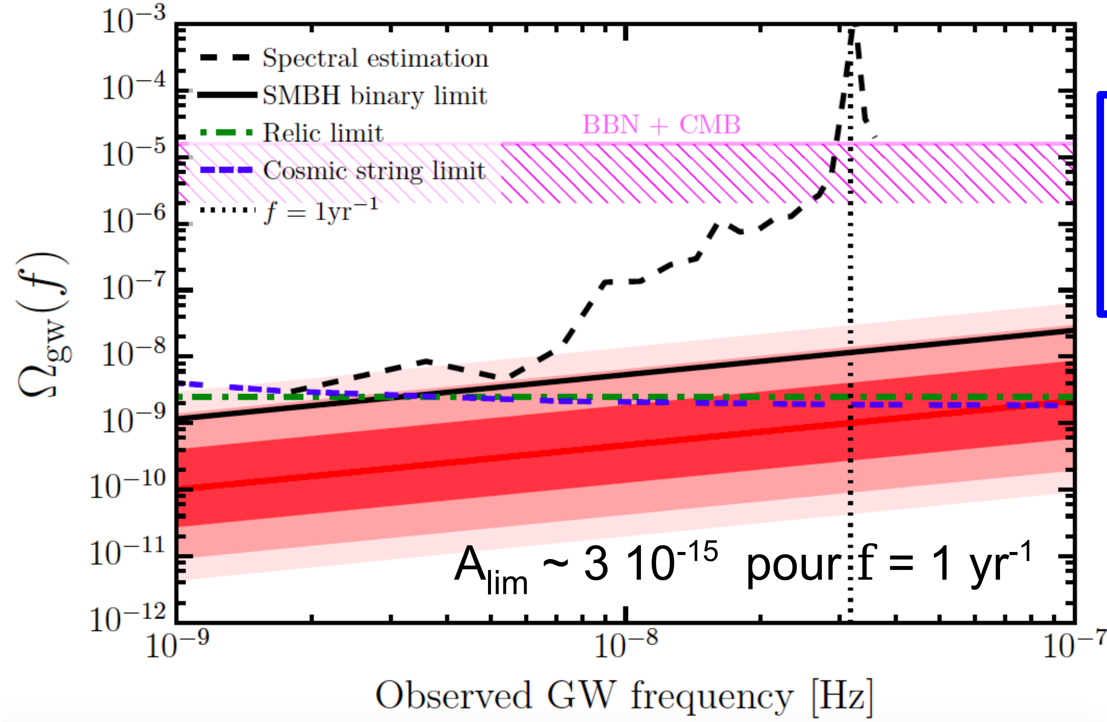
Hypothesis:

- circular orbits
- all the population reaches the sub-pc GW emission regime

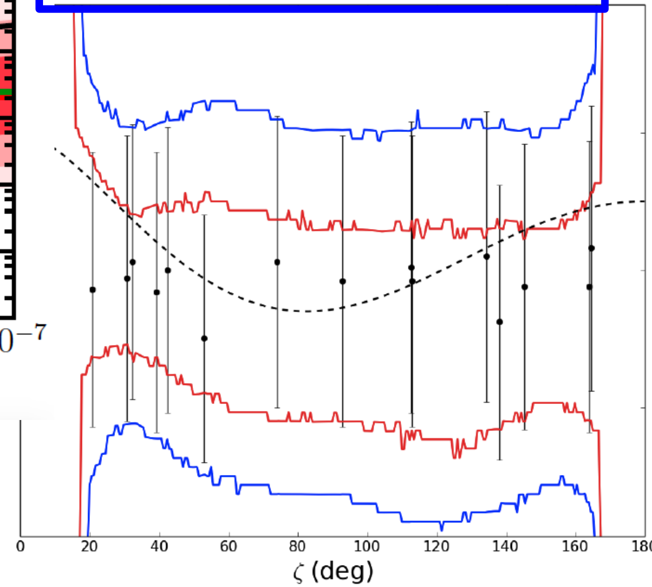
+ uncertainties about :

fusion rate
BH – host galaxy mass relation
time to coalescence

First European results in 2015-2016

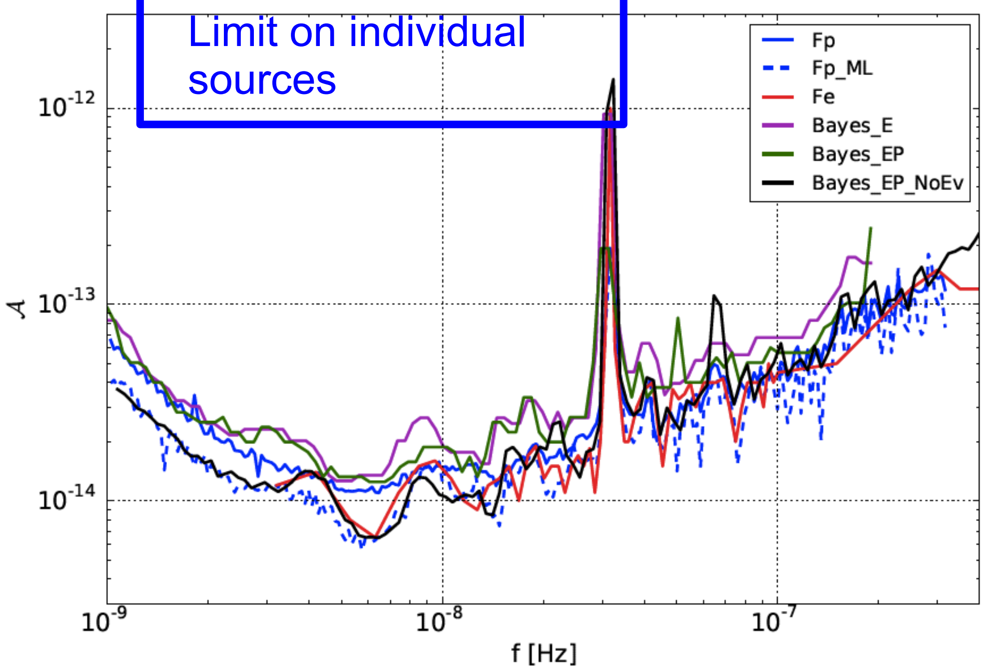


EPTA – 6 « best » pulsars
Lentati et al 2015
Limit on the isotropic stochastic background

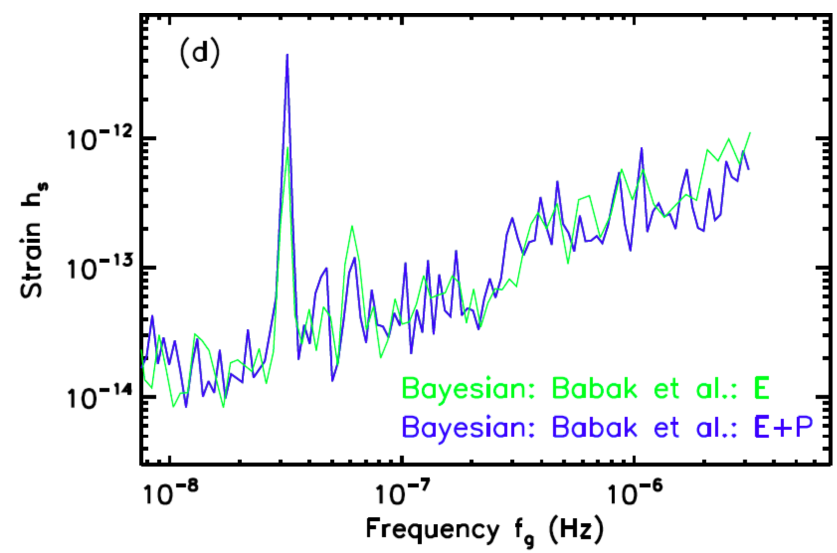


« Hellings&Downs » correlation curve
→ no detection

EPTA – 42 pulsars
Babak et al 2016
Limit on individual sources



EPTA – « high cadence single pulsar»
Perera et al 2018 Limit in μHz regime



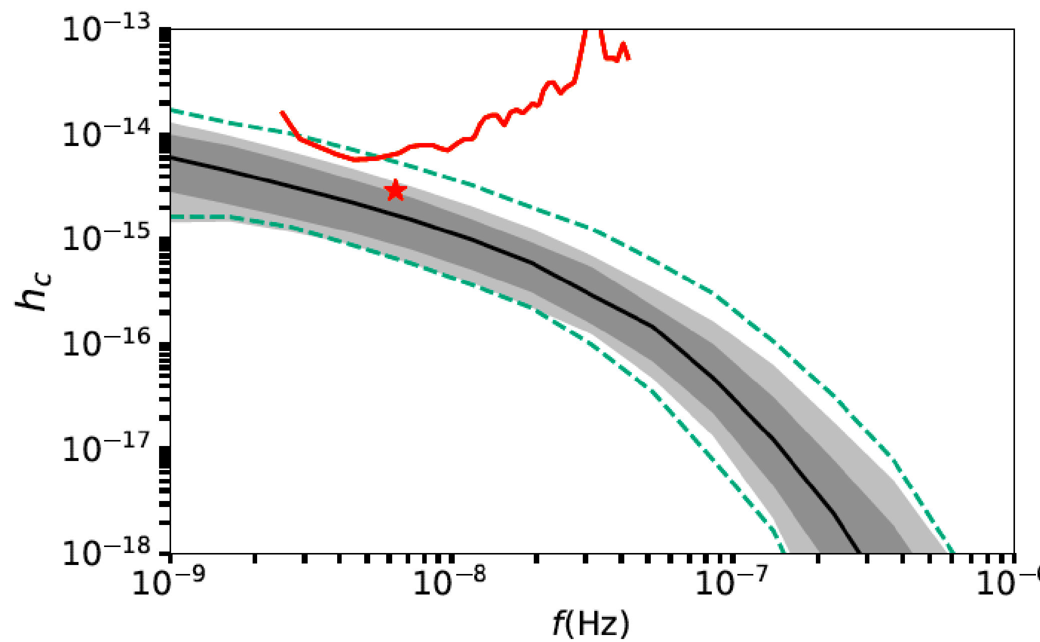
Tests of Astrophysical models

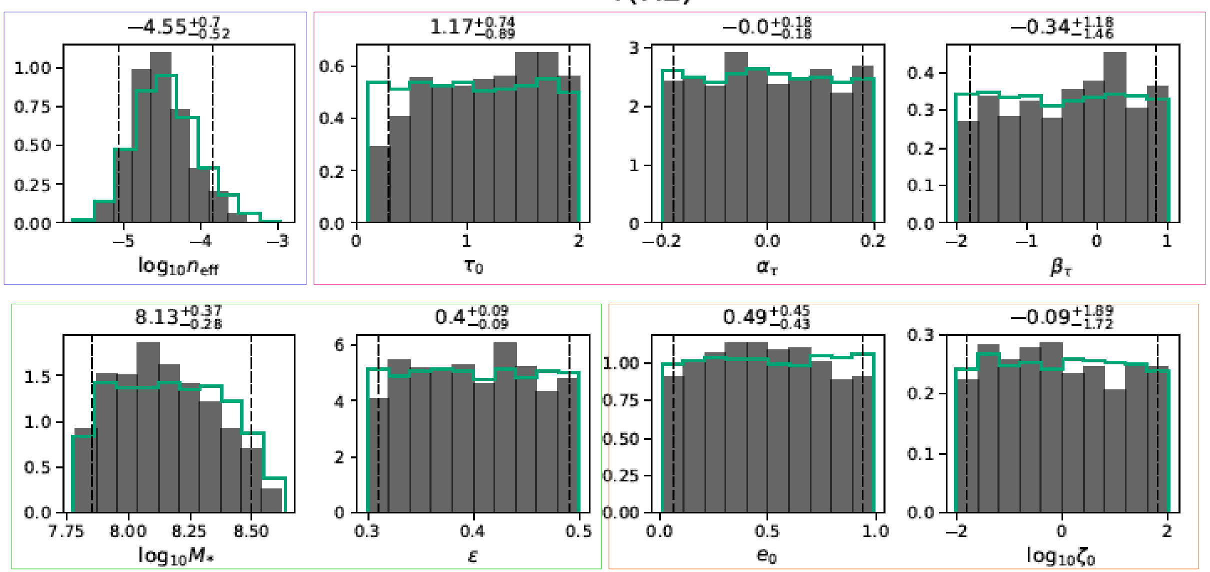
Chen et al 2018
EPTA – population synthesis

parameter	description	standard	extended
	Galaxy stellar mass function		
Φ_0	GSMF norm	-2.8 ± 0.3	-2.8 ± 0.3
Φ_I	GSMF norm redshift evolution	-0.25 ± 0.22	-0.25 ± 0.22
$\log_{10}M_0$	GSMF scaling mass	11.25 ± 0.2	11.25 ± 0.2
α_0	GSMF mass slope	-1.25 ± 0.17	-1.25 ± 0.17
α_I	GSMF mass slope redshift evolution	0 ± 0.15	0 ± 0.15
	Pair fraction		
f_0	pair fraction norm	[0.02,0.03]	[0.01,0.05]
α_f	pair fraction mass slope	[-0.2,0.2]	[-0.5,0.5]
β_f	pair fraction redshift slope	[0.6,1]	[0,2]
γ_f	pair fraction mass ratio slope	[-0.2,0.2]	[-0.2,0.2]
	Merger timescale		
τ_0	merger time norm	[0.1,2]	[0.1,10]
α_τ	merger time mass slope	[-0.2,0.2]	[-0.5,0.5]
β_τ	merger time redshift slope	[-2,1]	[-3,1]
γ_τ	merger time mass ratio slope	[-0.2,0.2]	[-0.2,0.2]
	M_{bulge} - M_{BH} relation		
$\log_{10}M_*$	$M_{bulge}-M_{BH}$ relation norm	8.17 ± 0.33	8.17 ± 0.33
α_*	$M_{bulge}-M_{BH}$ relation slope	1 ± 0.1	1 ± 0.1
ϵ	$M_{bulge}-M_{BH}$ relation scatter	[0.3,0.5]	[0.2,0.5]
	Eccentricity and stellar density		
e_0	binary eccentricity	[0.01,0.99]	[0.01,0.99]
$\log_{10}\zeta_0$	stellar density factor	[-2,2]	[-2,2]

~2015 limit

$$A(f=\mathrm{yr}^{-1})=1\times10^{-15}$$





Tests of Astrophysical models

Chen et al 2O18
EPTA – population synthesis

~2025 limit ?

parameter	description	standard	extended
Φ_0	GSMF norm	-2.8 ± 0.3	-2.8 ± 0.3
Φ_I	GSMF norm redshift evolution	-0.25 ± 0.22	-0.25 ± 0.22
$\log_{10} M_0$	GSMF scaling mass	11.25 ± 0.2	11.25 ± 0.2
α_0	GSMF mass slope	-1.25 ± 0.17	-1.25 ± 0.17
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f_0	pair fraction norm	[0.02,0.03]	[0.01,0.05]
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β_f	pair fraction redshift slope	[0.6,1]	[0,2]
γ_f	pair fraction mass ratio slope	[-0.2,0.2]	[-0.2,0.2]
τ_0	merger time norm	[0.1,2]	[0.1,10]
α_τ	merger time mass slope	[-0.2,0.2]	[-0.5,0.5]
β_τ	merger time redshift slope	[-2,1]	[-3,1]
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$\log_{10} M_*$	$M_{bulge} - M_{BH}$ relation norm	8.17 ± 0.33	8.17 ± 0.33
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e_0	binary eccentricity	[0.01,0.99]	[0.01,0.99]
$\log_{10} \zeta_0$	stellar density factor	[-2,2]	[-2,2]

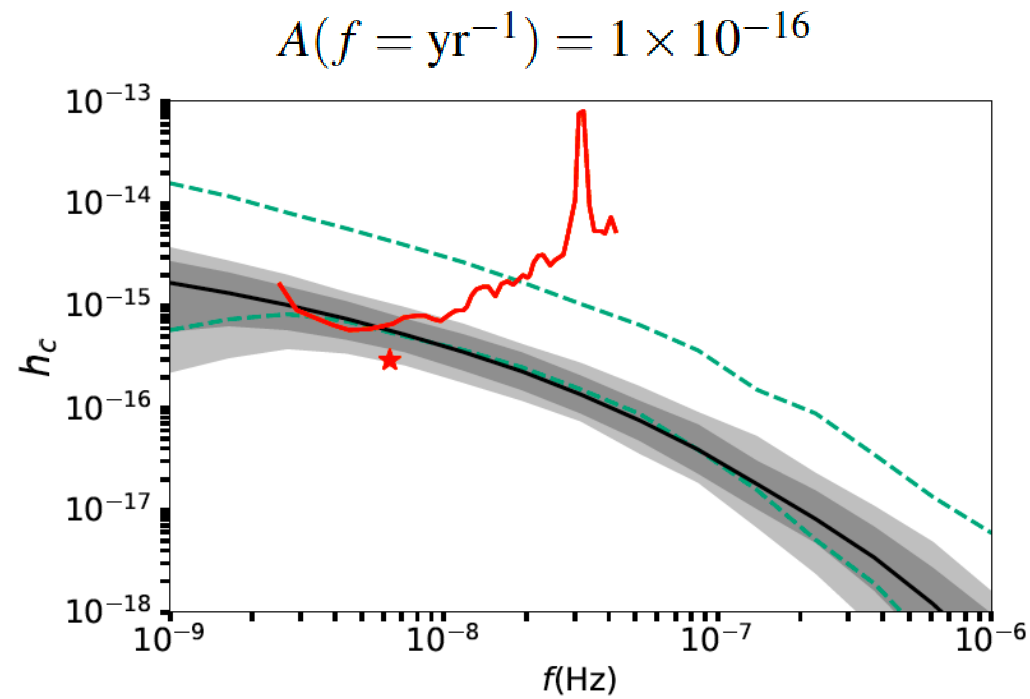
Galaxy stellar mass function

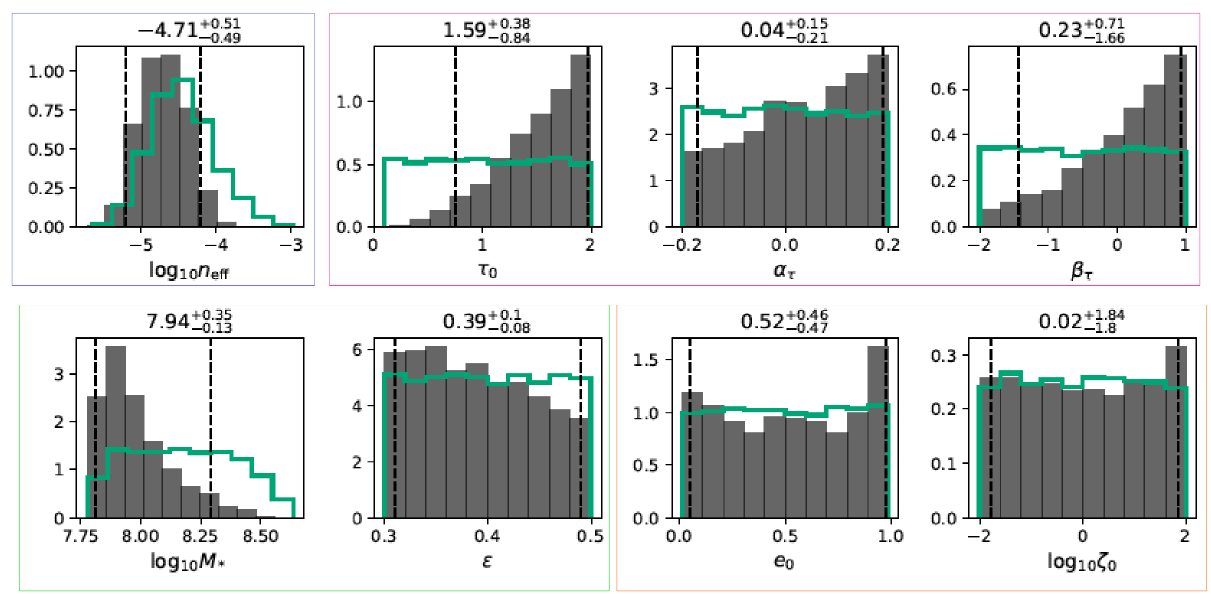
Pair fraction

Merger timescale

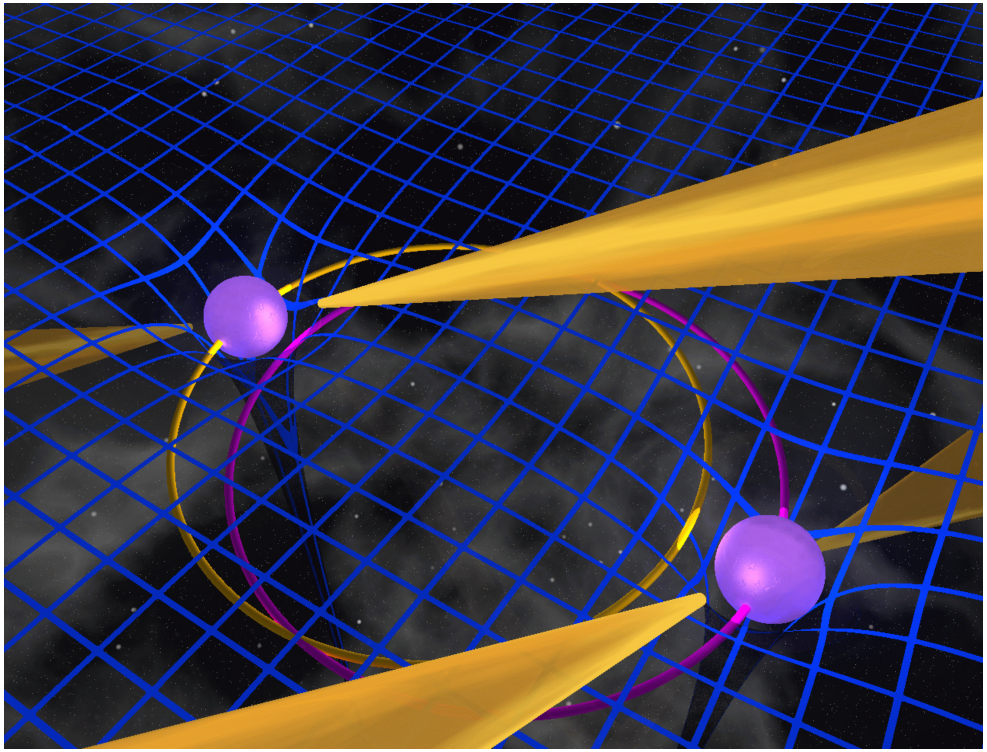
M_{bulge} -M_{BH} relation

Eccentricity and stellar density





GR tests, constraints on Equation of State (EoS)



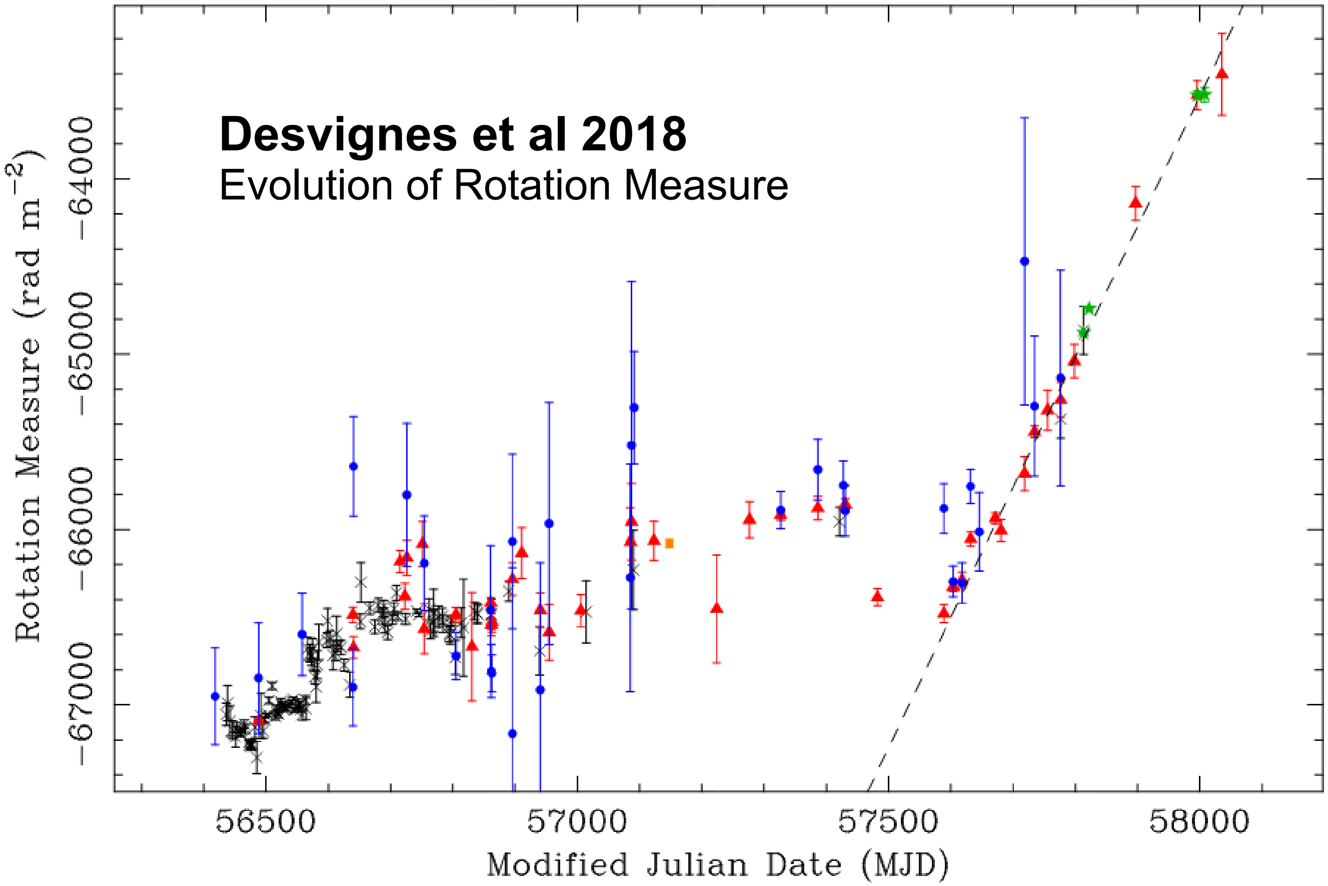
Recent results :
PSRJ1713+0747 (Zhu et al 2018)
« Tests of gravitational symmetries with pulsar binary J1713+0747 »

PSR J1745−2900 (Desvignes et al 2018)
« Large Magneto-ionic Variations toward the Galactic Center Magnetar, PSR J1745-2900 »

On-going projects

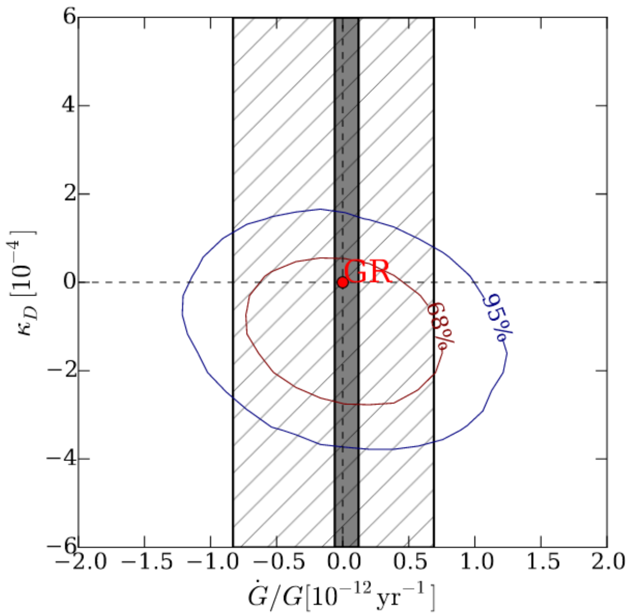
Binary/multiple systems
Double pulsar (Kramer et al)
Tripple system PSRJ0337+1715 and SEP (Voisin, Freire et al)
PSRJ0751+1807 (Nice et al) – masses, EoS
PSRJ1012+5307(Liu, Madhuri et al) – GR tests
PSRJ1518+4904 (Janssen et al) – masses
PSRJ1600-3053 (McKee, Desvignes et al) – x_dot, masses
PSRJ1756-2251 (Ferdman et al) – gamma, omega_dot, Pb_dot, ecc
PSRJ2045+3633 (32 ms/32d, omega_dot, masses) & PSRJ2053+4650 (Freire, McKee et al)

LIGO/Virgo (Abbott et al)
Search for signals at twice the rotational frequency of 200 known pulsars (provide .par)

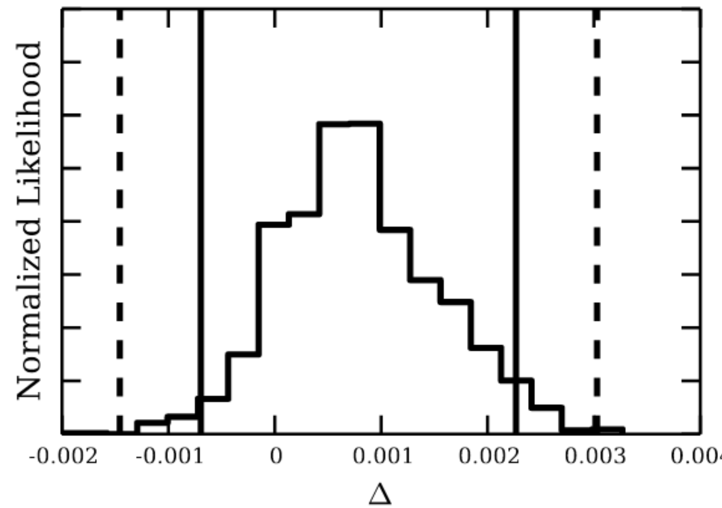


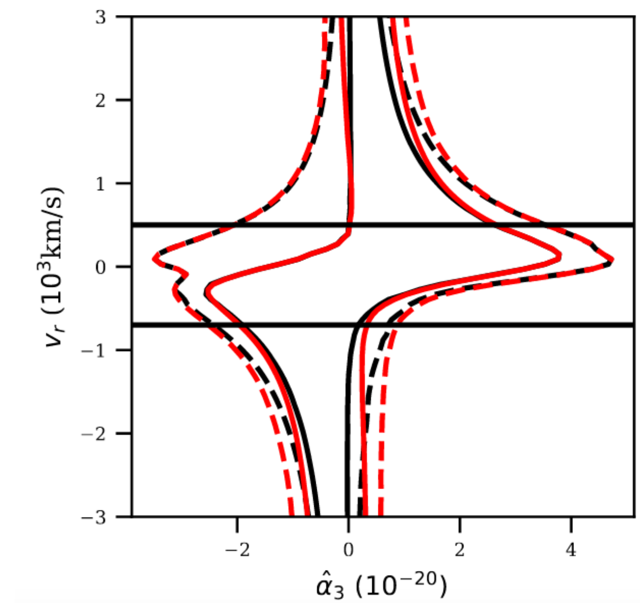
Analysis of J1745-2900

Use the polarized emission of PSR J1745−2900 to study **the intensity of the magnetic field in Galactic Center**, close to Sagittarius A* (0.1 pc)



Zhu et al 2018



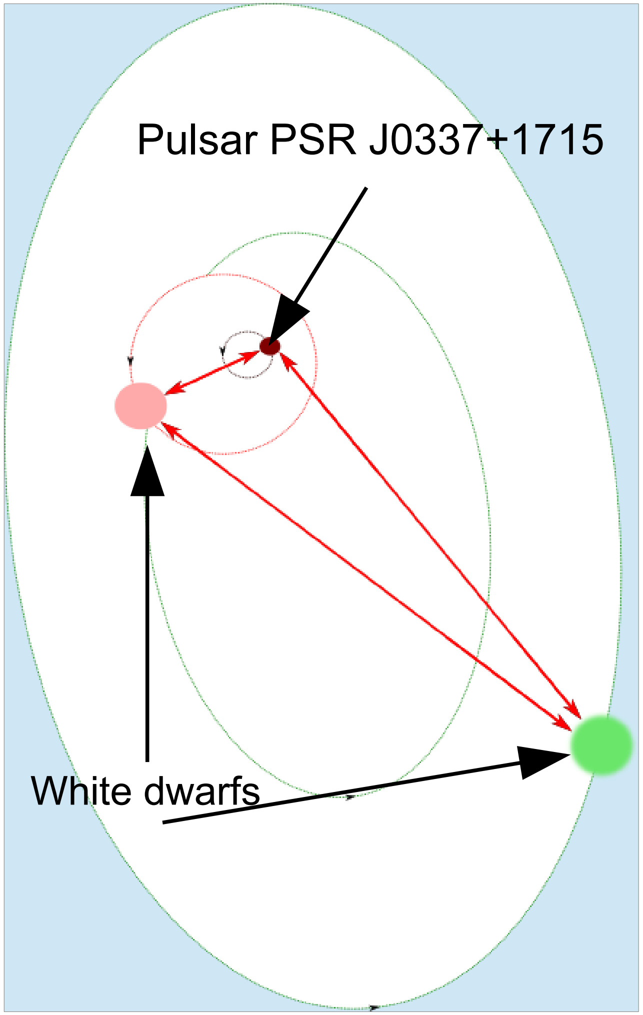


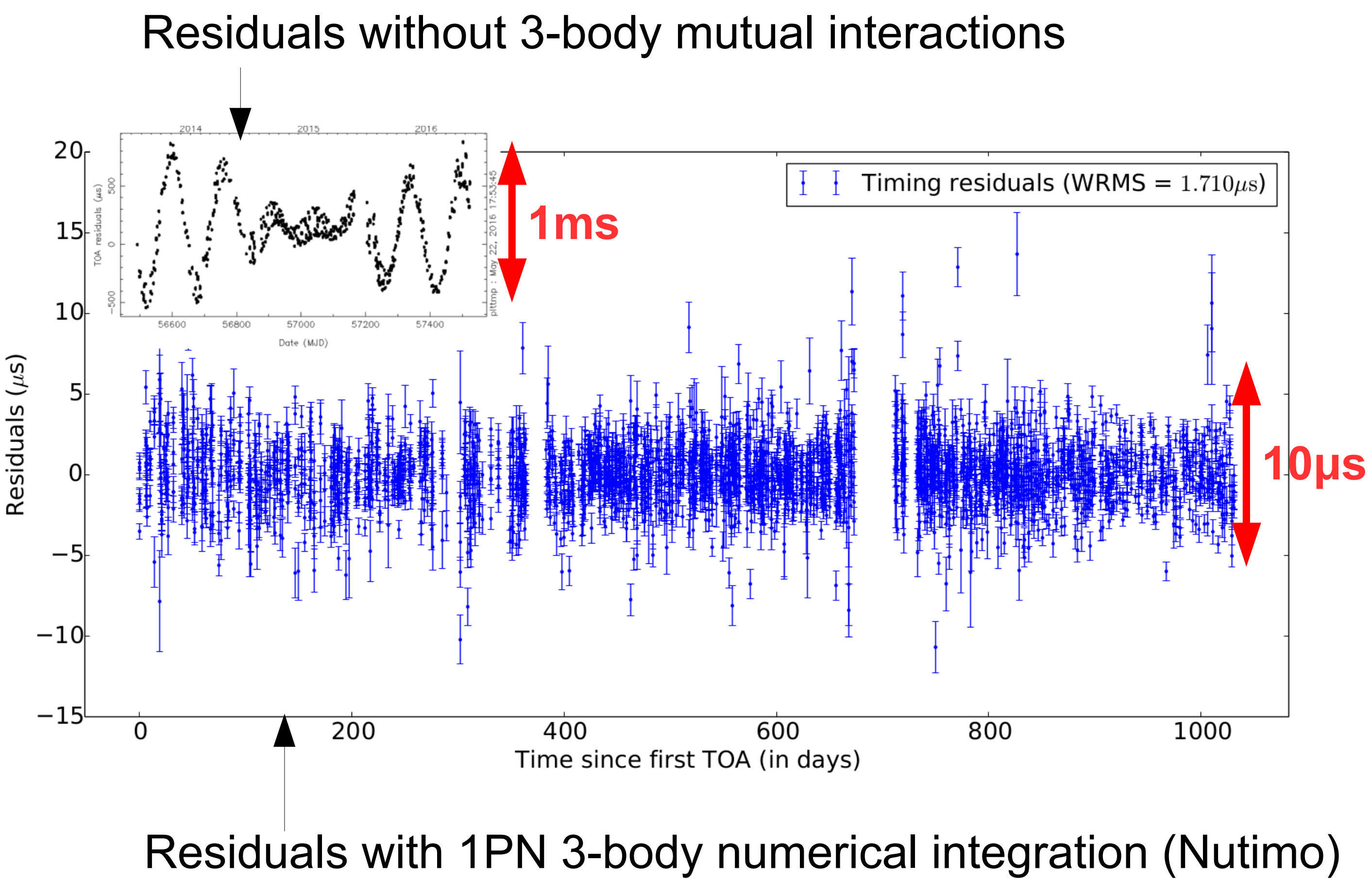
Analysis of PSRJ1713+0747

3 tests of **equivalence principle in strong field regime (SEP)** by observing of rate of fluctuation of orbital period and eccentricity of the system:

- stability of gravitation constant G,
- test of universality of free-fall: limit on the parameter UFF $|\hat{\Delta}|$
- constrain of post-newtonian parameter α_3 (gravitational Lorentz invariance)

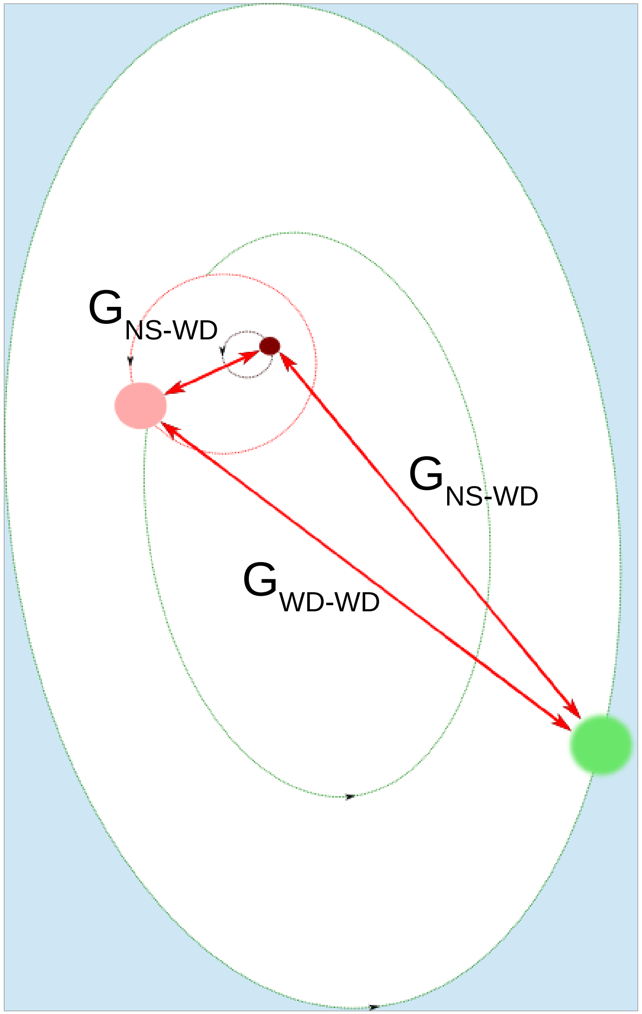
<u>THE</u> triple system J0337+1715





→ **<u>Very accurate timing data from Nançay</u>**

How to test the strong equivalence principle ?



- Similar to the **Laser-Moon** experiment:

→ Earth and Moon fall in the potential of the Sun

- J0337+1715 system :

→ Pulsar and Inner WD fall in the potential of the outer WD

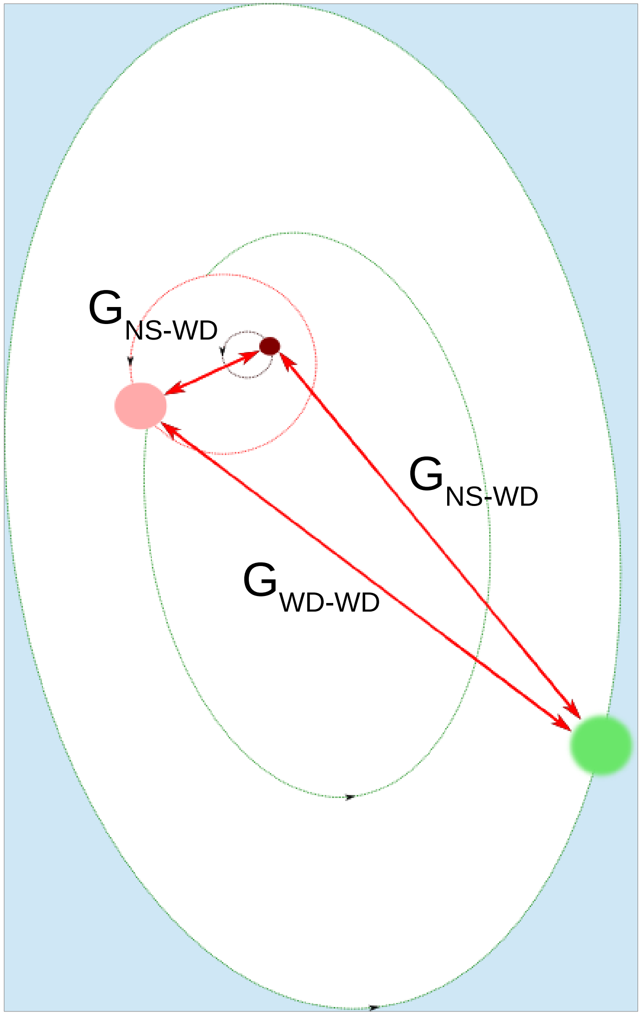
- Difference with Laser- Moon :

→ **Neutron star (NS) strongly gravitating !**
Regime unreachable in the Solar system.

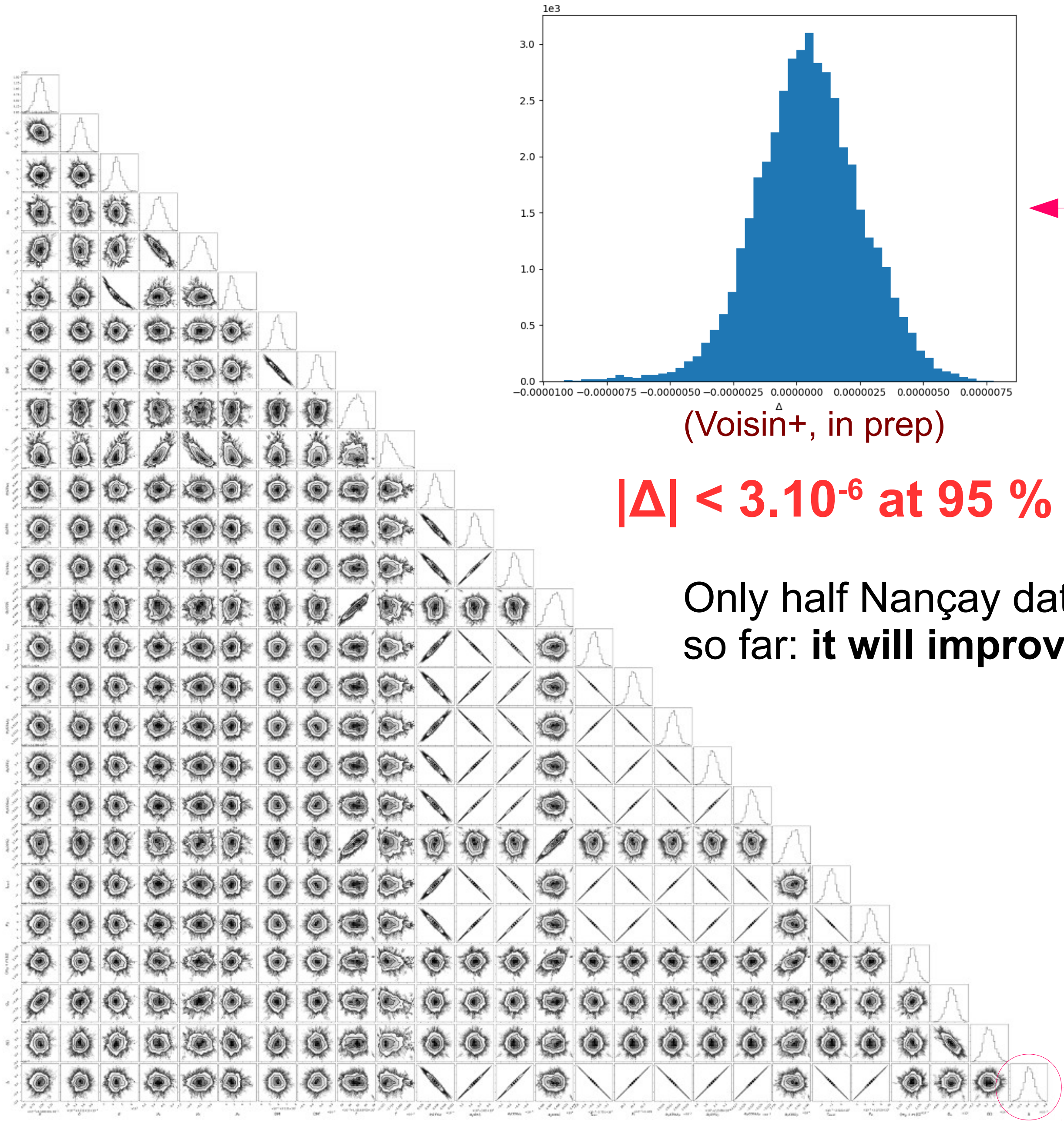
- At Newtonian order, **SEP violation means**:
  Gravitational constants $G_{NS\text{-}WD} \neq G_{WD\text{-}WD}$

→ **<u>We fit for Δ</u>: $G_{NS\text{-}WD} = (1 + \Delta)\, G_{WD\text{-}WD}$**

Preliminary results



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



(Voisin+, in prep)

Covariance plot, 26-parameter MCMC.

$|\Delta| < 3.10^{-6}$ at 95 %

Only half Nançay data used so far: **it will improve !**

Conclusion

- PTAFrance team (APC, LPC2E, LUTh, Nancay Station) embedded in European PTA and International PTA + starting collaboration with MeerKAT:
  - Observations of more than 50 pulsars (between few and 20 years)
  - Search for:
    - Background:
    - Continuous sources: individual SMBHb
  - No detection => constrain on astrophysical models

- More use of the pulsars timing:
    - Test of GR: tests of strong equivalence principle
      - J1713+0747
      - J0037+1715: triple system
      - J1906+0746
      - ...
    - Measures of magnetic field: J1745-2900

- Continuous progresses both on observations and sciences