Impact of planetary ephemerides on gravitational wave searches with Pulsar Timing Arrays

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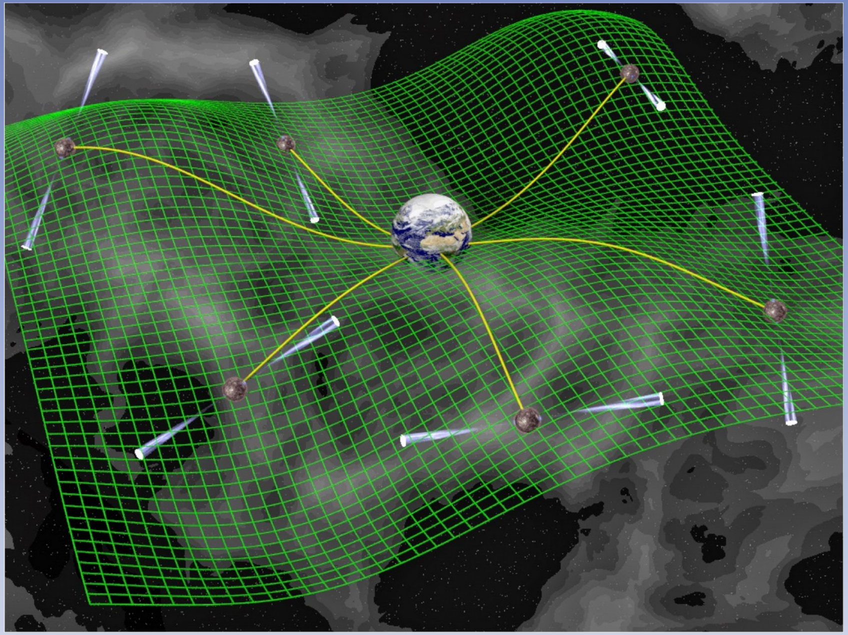
Collaborations with A. Fienga (Géoazur), M. Vallisneri (JPL/Caltech)

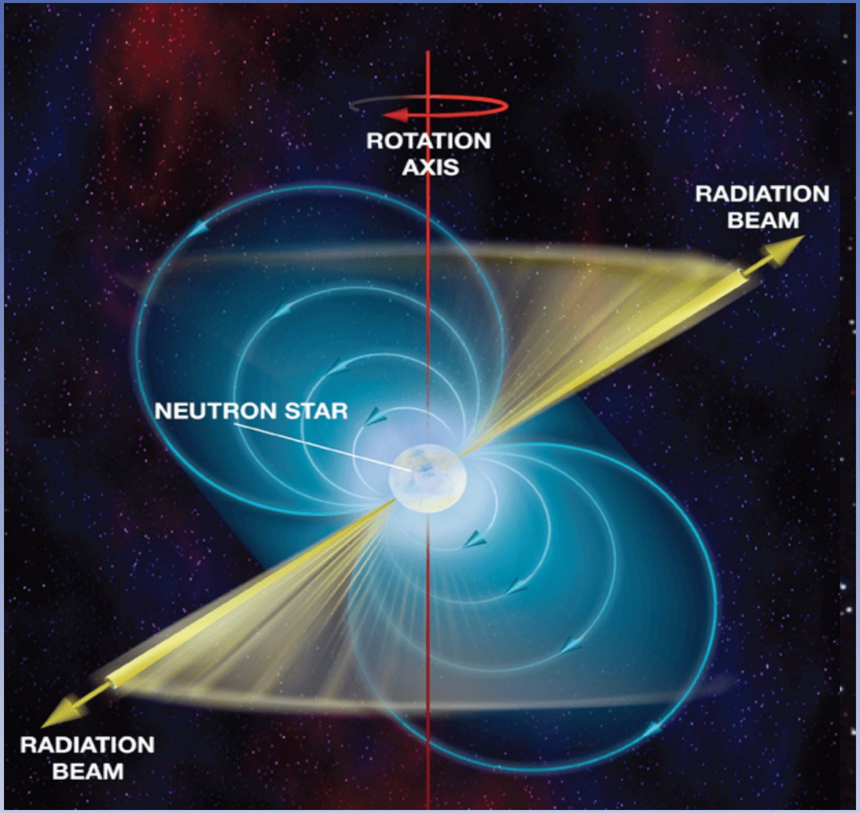


YERAC Dublin, 27/08/2019

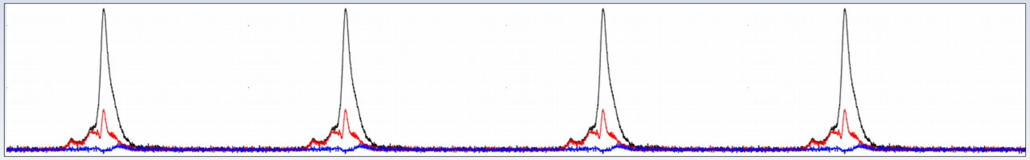
Pulsars

Fast spinning, highly magnetized compact objects

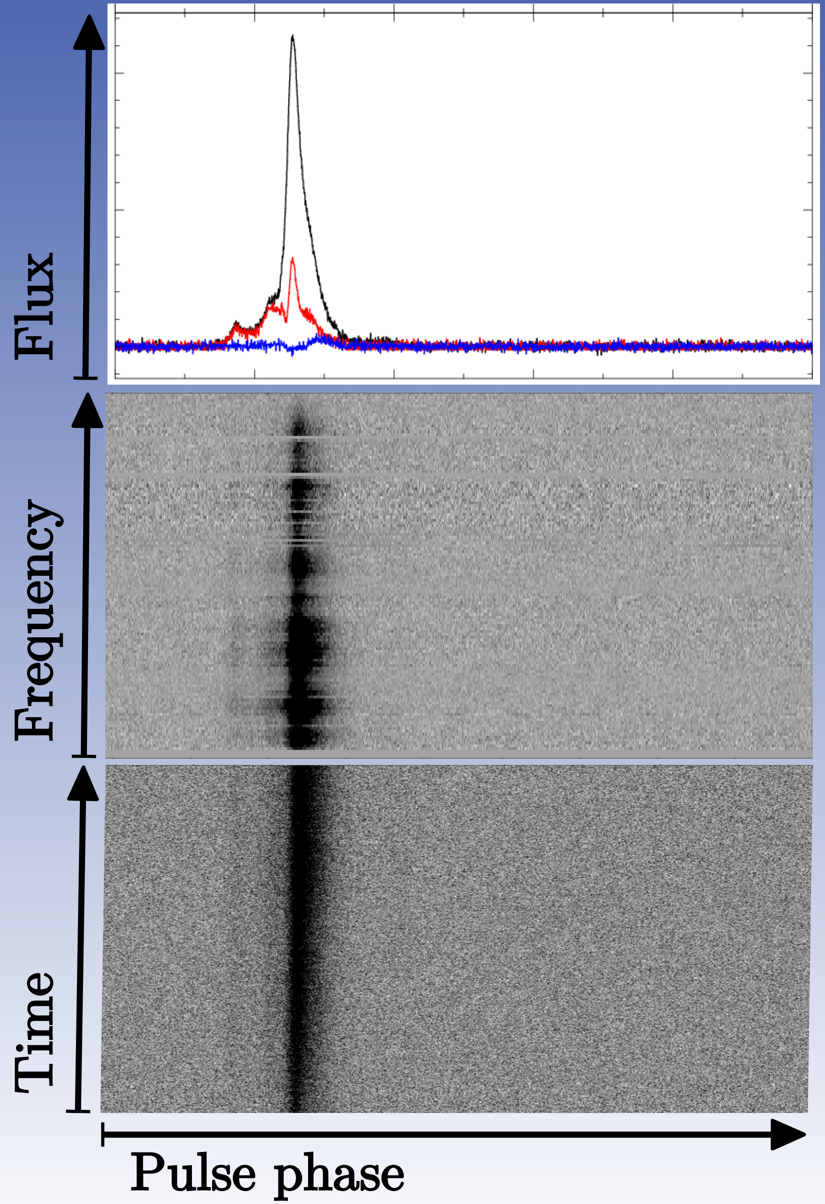
Credit : B. Saxton.



Emitting a pulsated signal



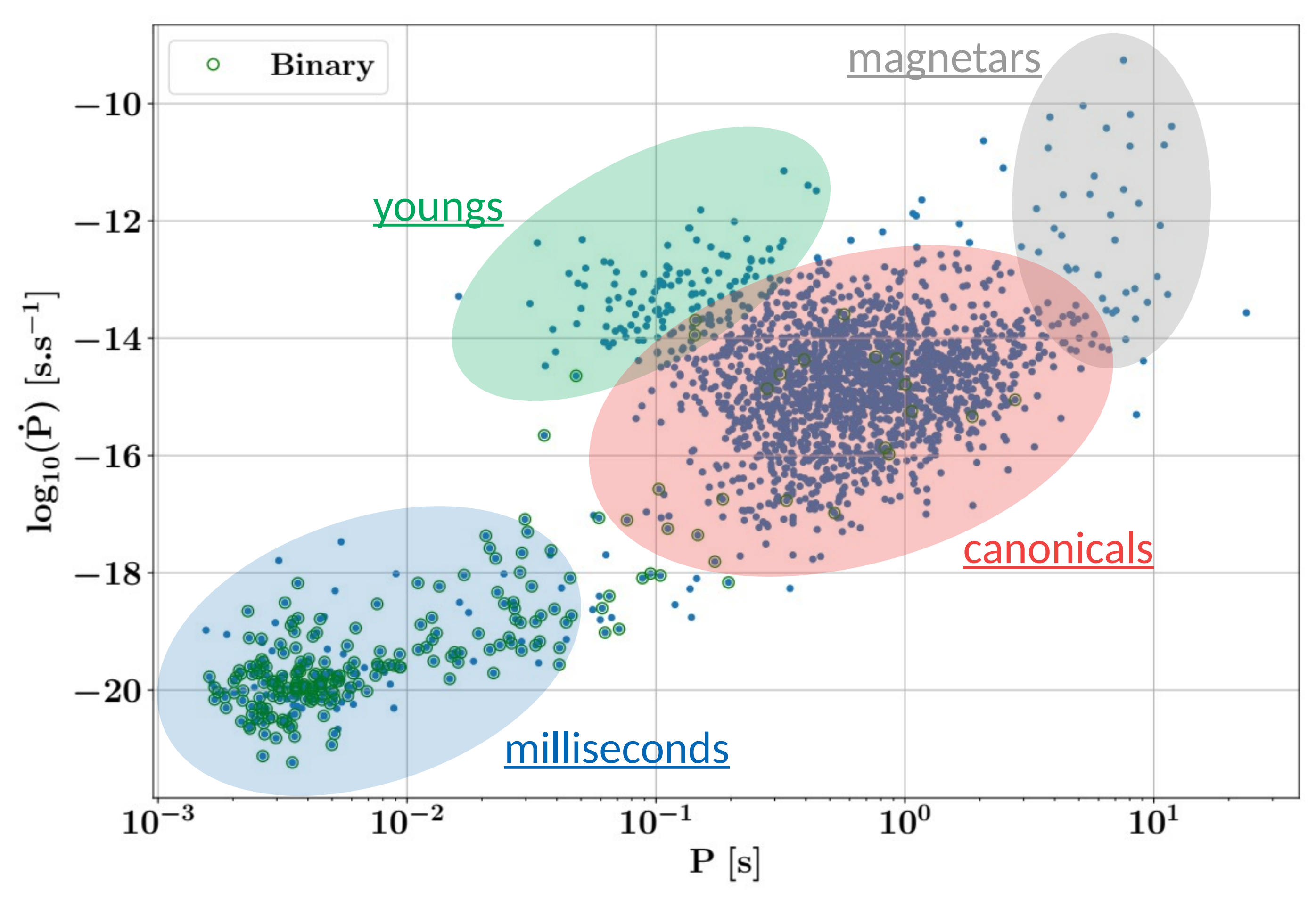
Mostly observed in radio freq.



Pulsars

A full zoology !

- Canonical pulsars
- Millisecond pulsars
- Magnetars
- Young pulsars
- X-ray pulsar
- Gamma-ray pulsar
- Spiders
- .....



Pulsars

A full zoology !

- Canonical pulsars
- **Millisecond pulsars**
- Magnetars
- Young pulsars
- X-ray pulsar
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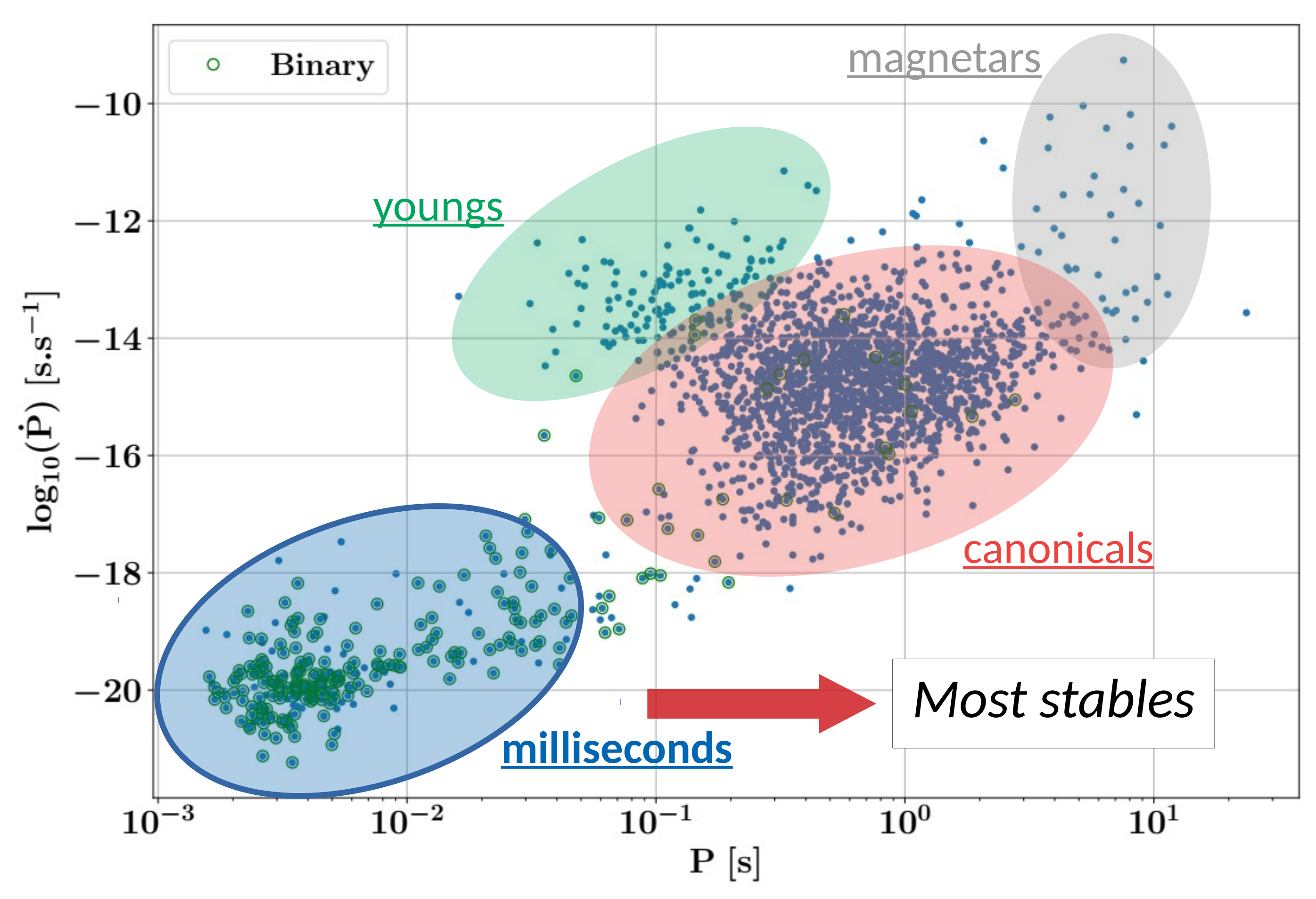
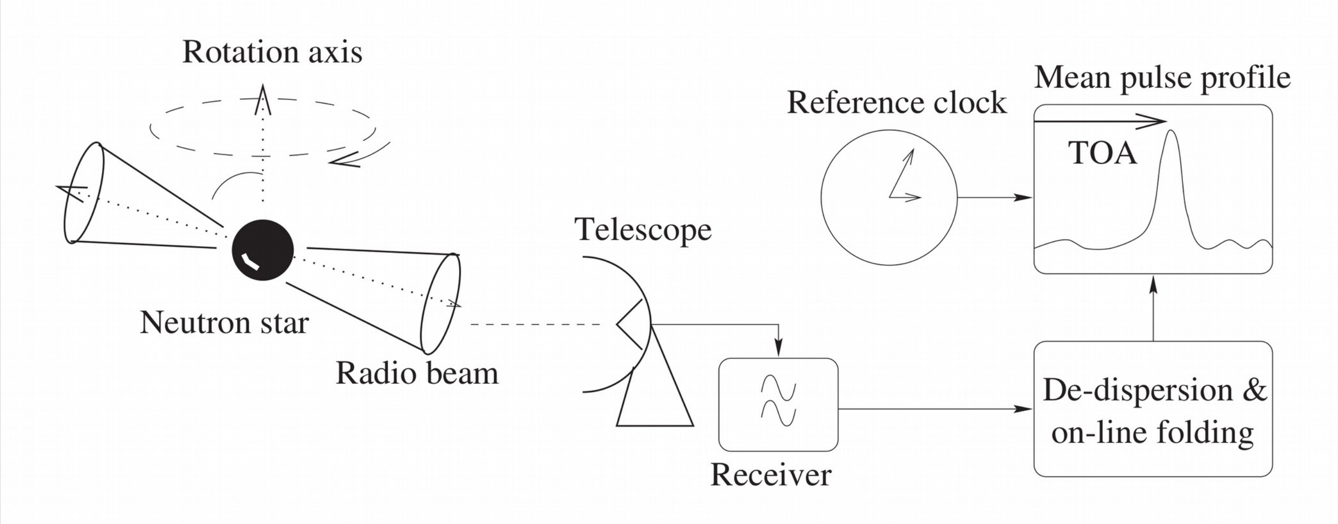
- …..

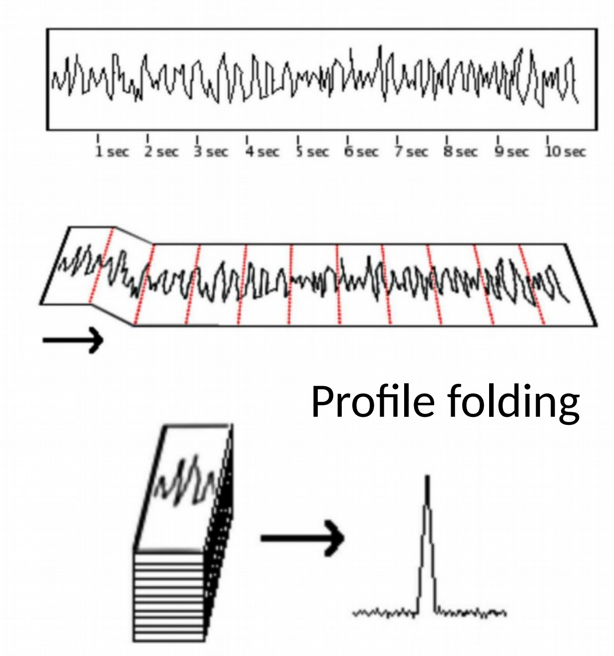


Pulsar timing

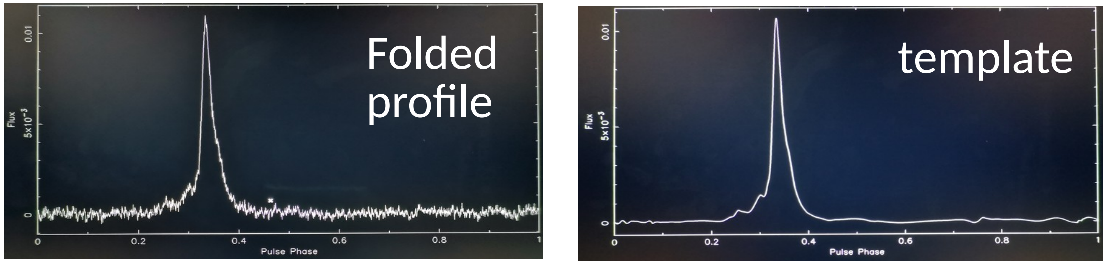
Determinate times of arrival (TOAs)



cf. Lorimer & Kramer 2005



cf. McKee



folded profile cross-correlated with a noise-free **template** (« template matching »)

$$\sigma_{\mathrm{TOA}} \propto \frac{P}{S_{\mathrm{PSR}}} \frac{T_{\mathrm{sys}}}{\Delta f}$$

Good receiver

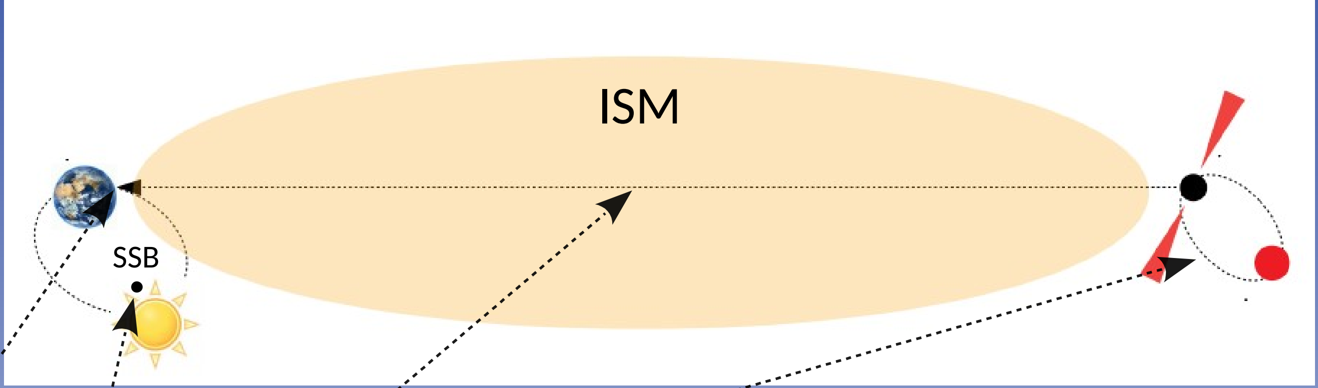
Choose good the pulsars

Observe in a large bandwidth

σ_{TOA} ~ 200 ns

Pulsar timing

Build a timing model and get residuals



$$t_e^{psr} = t_a^{obs} - \Delta_\odot - \Delta_{\mathrm{ISM}} - \Delta_{\mathrm{B}}$$

t_e^{psr} : Time of emission from the center of the pulsar

t_a^{obs} : TOA at observatory time after clock correction

$\Delta_\odot$: Transformation to the solar system barycenter (SSB)

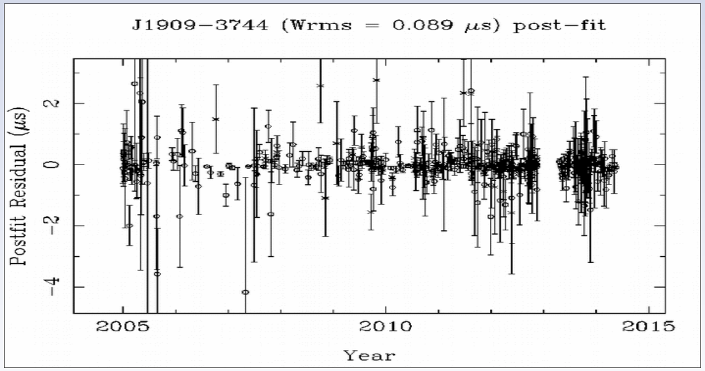
Δ_{ISM} : Transformation to the binary barycenter (dispersion from the ISM)

Δ_{B} : Transformation to the pulsar proper time of emission

Timing model

- Rotational params
- Astrometric params
- Orbital params
- ISM effects
- Clock correction
- Transformation to the SSB

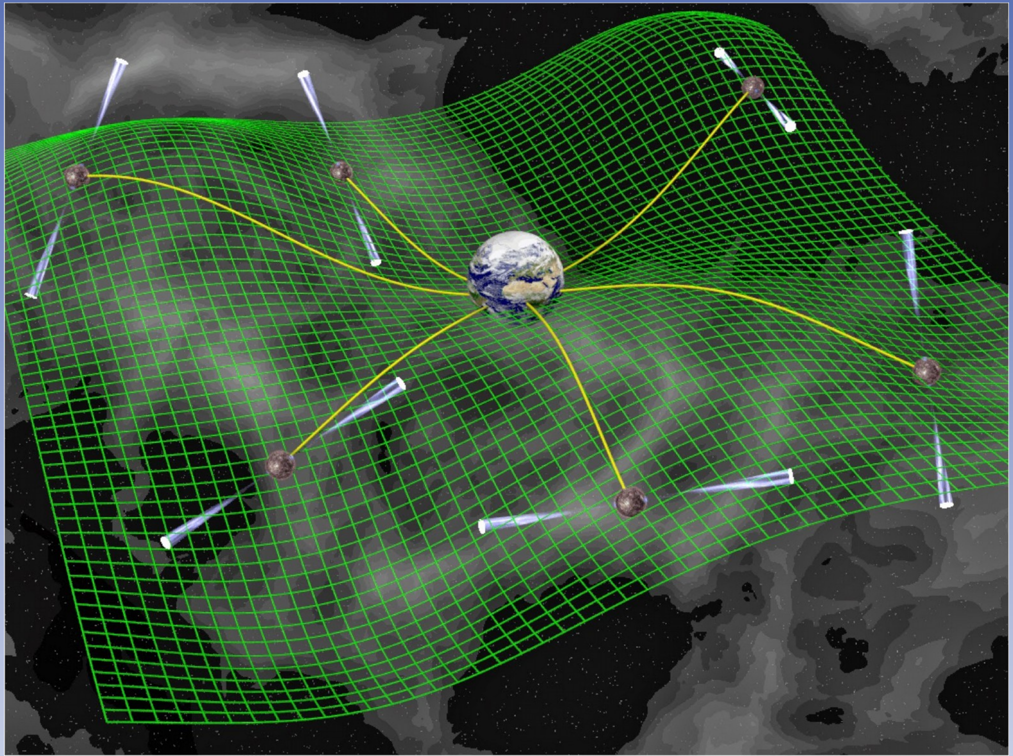
TOAs – predicted TOAs from timing model
=
Residuals



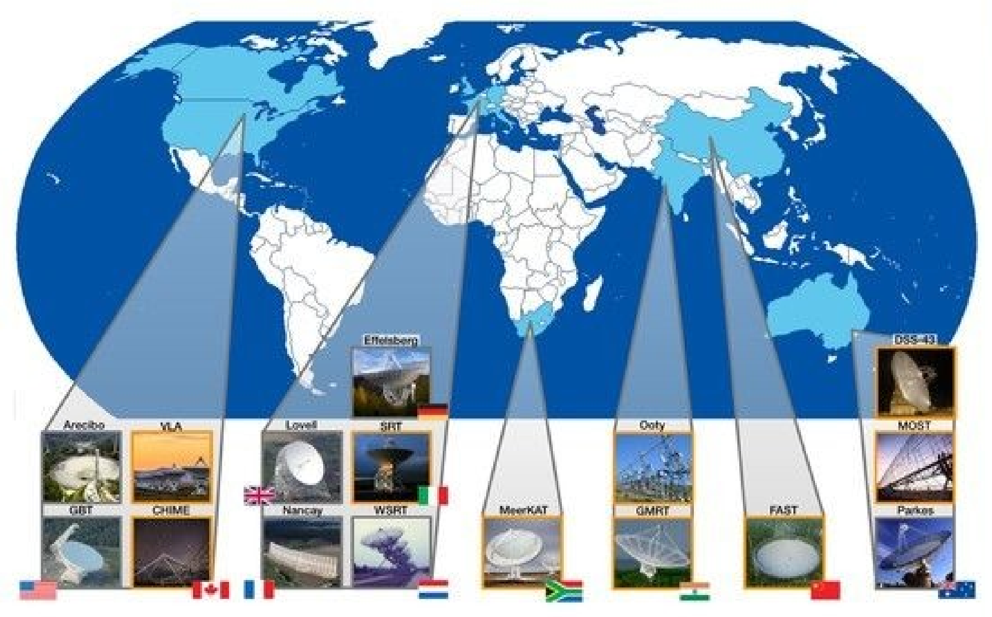
Pulsar Timing Arrays

Probe very low-frequency gravitational waves effects in a combined set of residuals of a full array of pulsars !

PTA_NRAO_Outreach_animation



Credit : D. Champion



NANOGrav

EPTA

PPTA

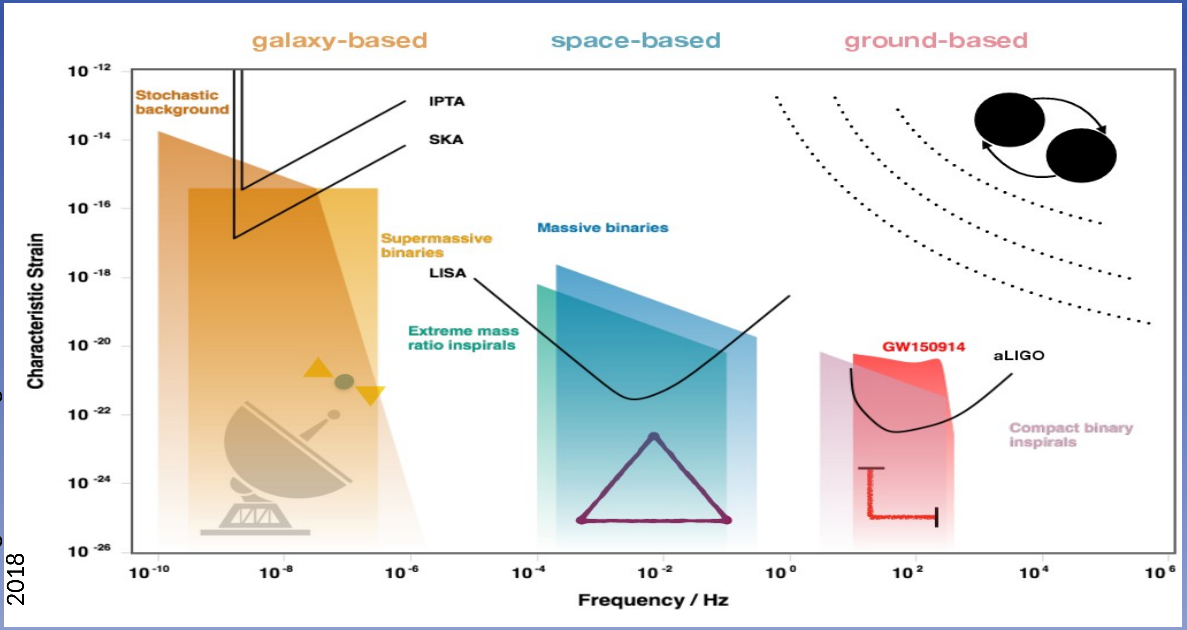
INTERNATIONAL PULSAR TIMING ARRAY

IPTA

**SMBHB
(stochastic background +
single sources)**

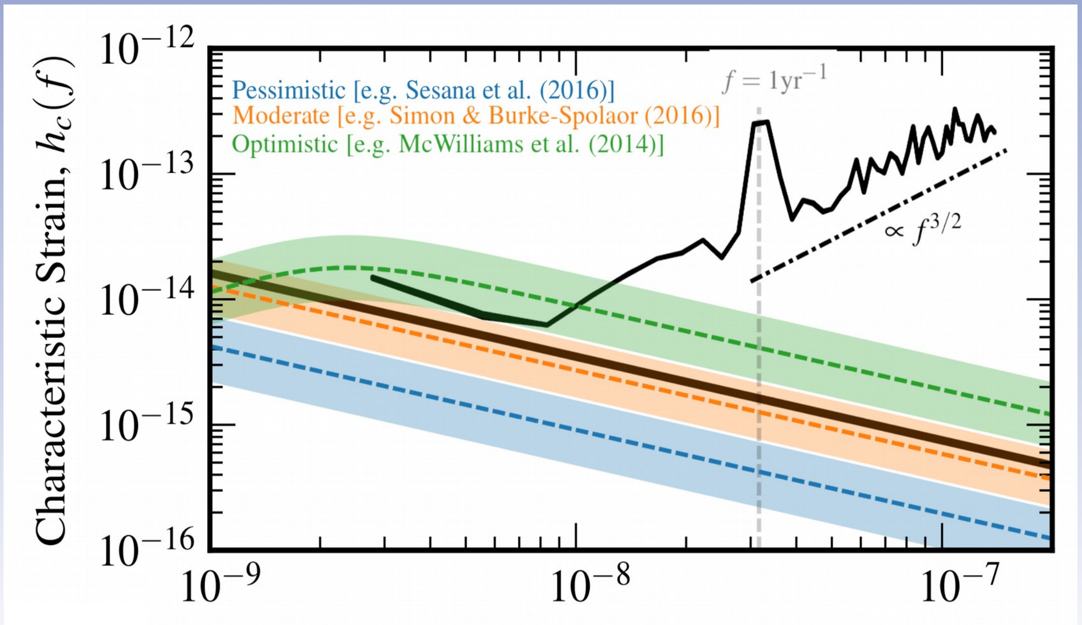
**Cosmic strings,
primordial GWs, ...**

Pulsar Timing Arrays



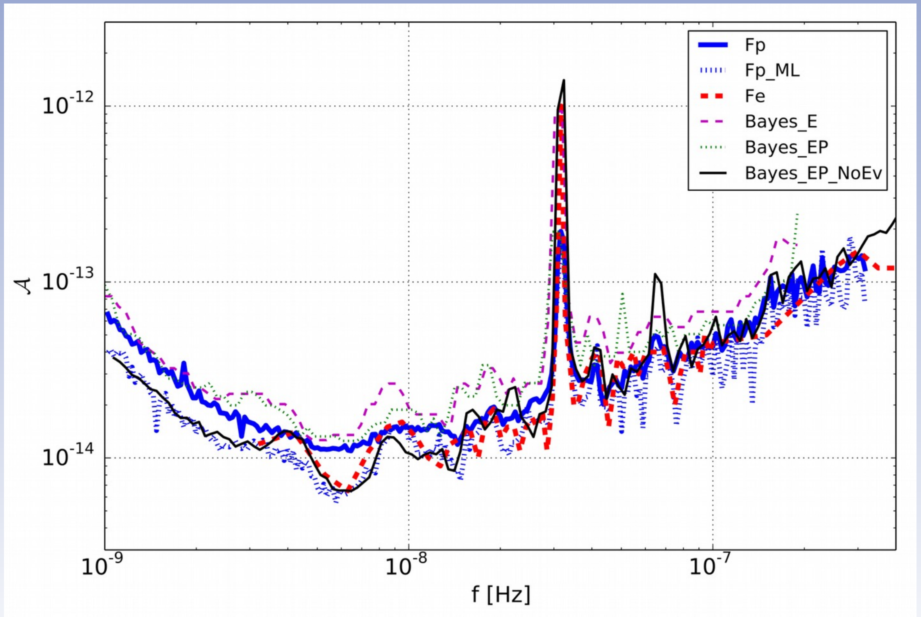
cf. Migarellli & Mingarelli 2018

Gravitational wave background (GWB) upper-limits



[Arzoumanian et al. 2018]

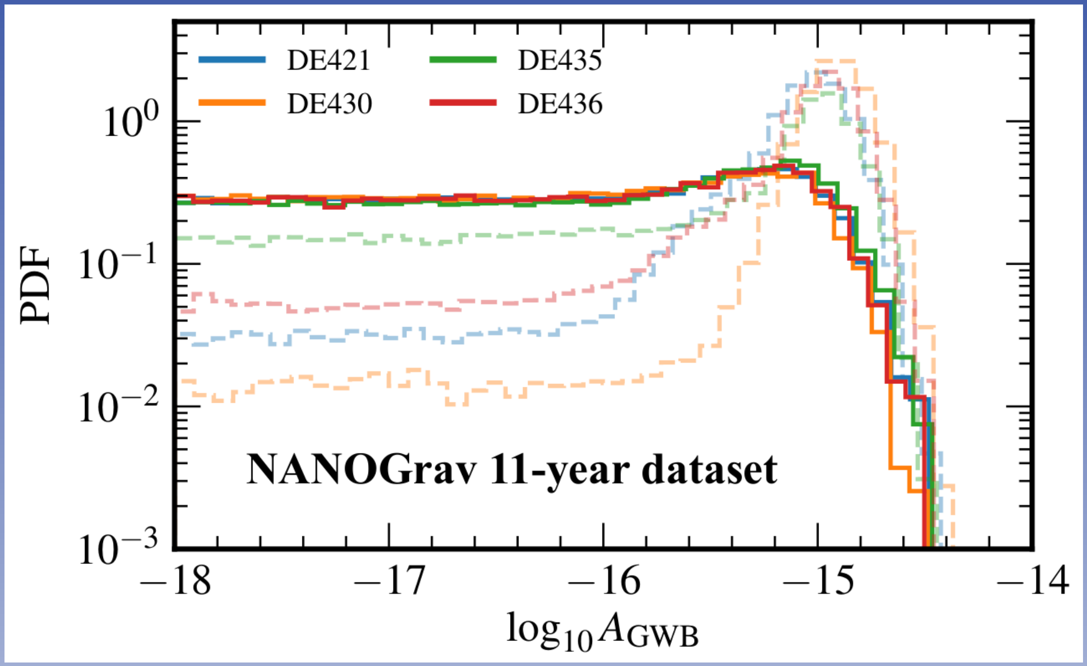
Individual sources upper-limits



[Babak et al. 2016]

Our motivations

GWB Amplitude PDF vs. Solar-system ephemerides (SSEs)



[Arzoumanian et al. 2018]

Problem : GWB results seem dependent of the chosen ephemeris model !

Possible to fix it by modelling some SSE parameters

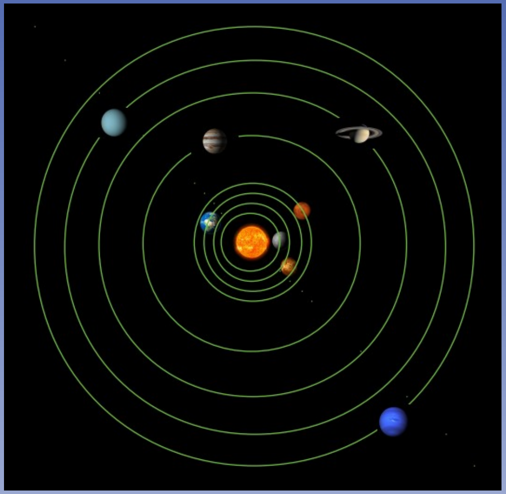
→ **BAYESEPHEM** model (11 params) to « unfix » ephemeris parameters

→ GWB constraint gets robust against SSE errors

→ **But modelling SSE errors can absorb some of the GWB signal**

Solar system ephemerides

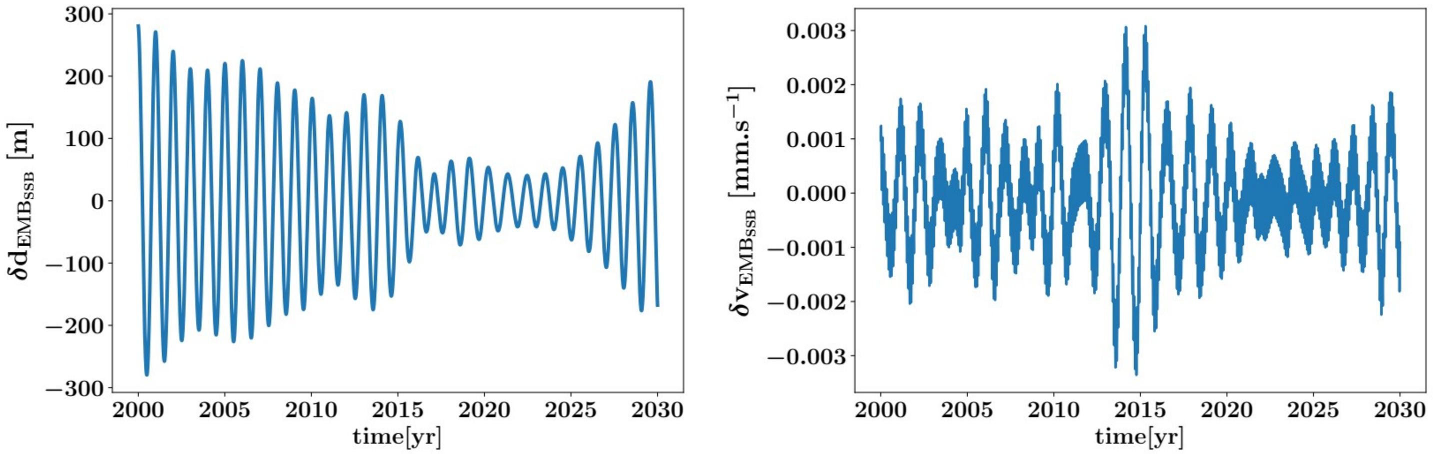
Pos. & vel. predicted from numerical integration of eq. of motions fitted to the observational data



Various solutions given by various collaborations !
JPL, IMCCE (INPOP),...

- Different data
- Different uncertainties
- Different models (i.e. eq. & params)

Difference of Earth-Moon barycenter (EMB) position (left) & velocity (right) w.r.t. SSB frame between by INPOP17a & JPL DE436



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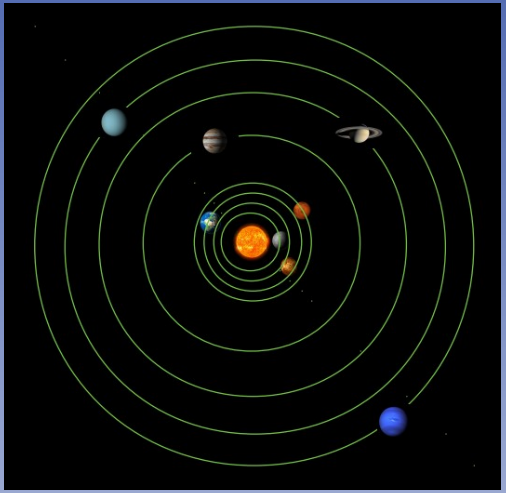

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Work with **INPOP** data (cf. A. Fienga)

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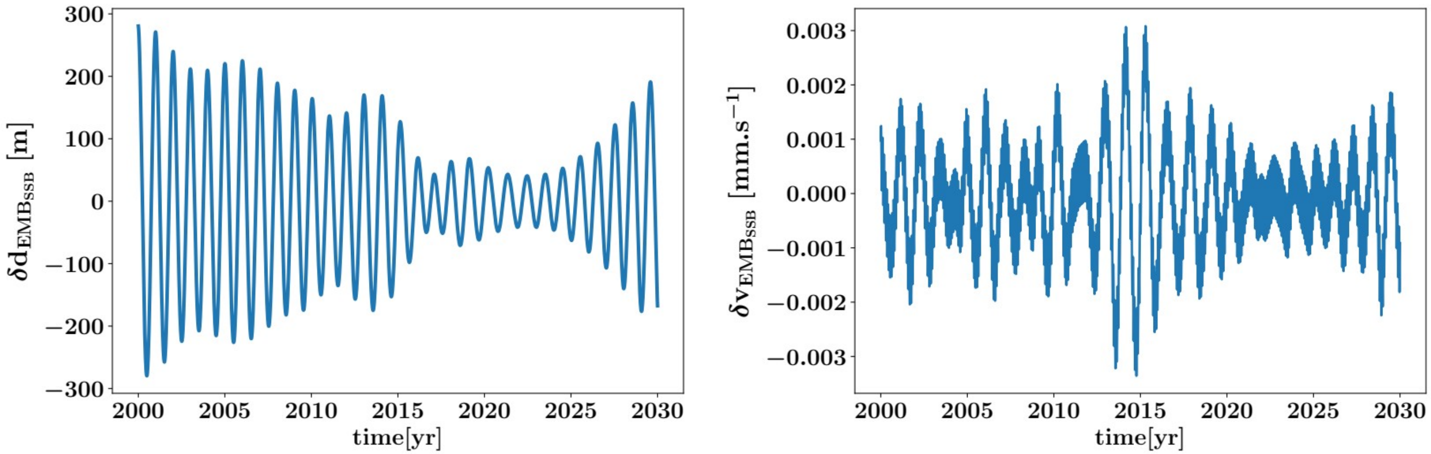


A first approach – SSE perturbation

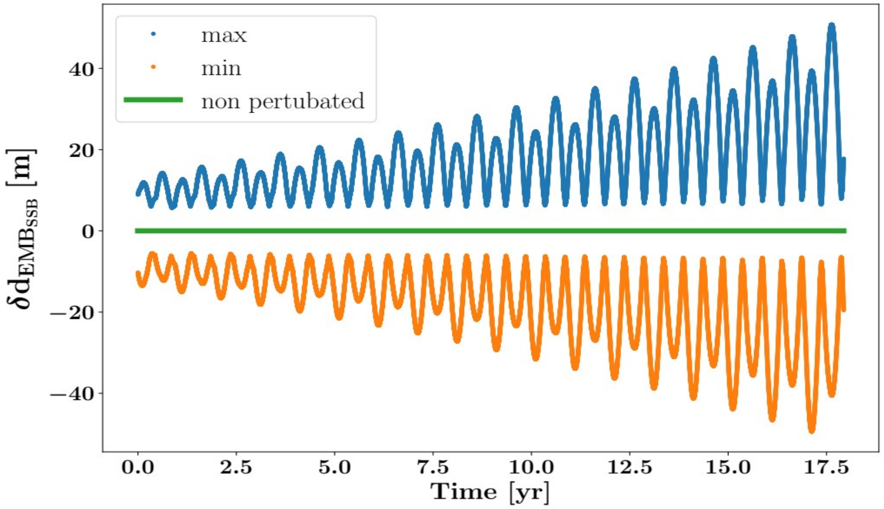
INPOP data (cf. A. Fienga)

- Covariance matrix of orbital parameters
- Linear model coefficients

→ **Linear approximation + perturbation of planet positions (EMB & 4 outer planets) at initial conditions**

$$\vec{x}_{new}(\vec{\theta}) = \vec{x}_{ref}(\vec{\theta}) + \frac{\partial \vec{x}_{ref}(\vec{\theta})}{\partial \vec{\theta}} \delta\vec{\theta}$$

Max & min values of EMB position errors after perturbations at 1σ (2000 perturb.)



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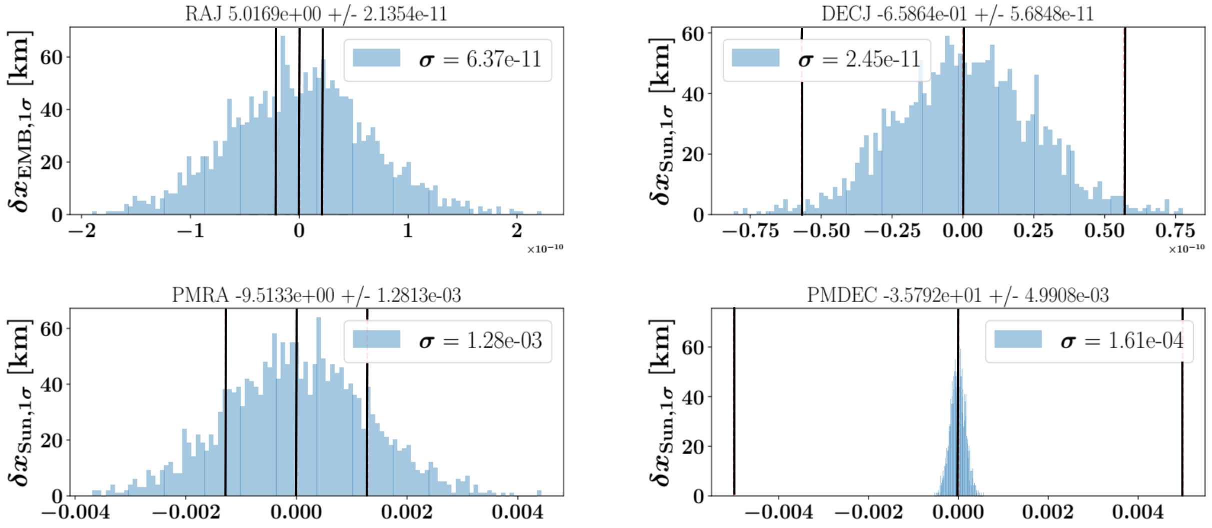
Post-fit astrometric parameters of J1909-3744
after perturbations at 1σ vs. Non perturbed (2000 perturb.)



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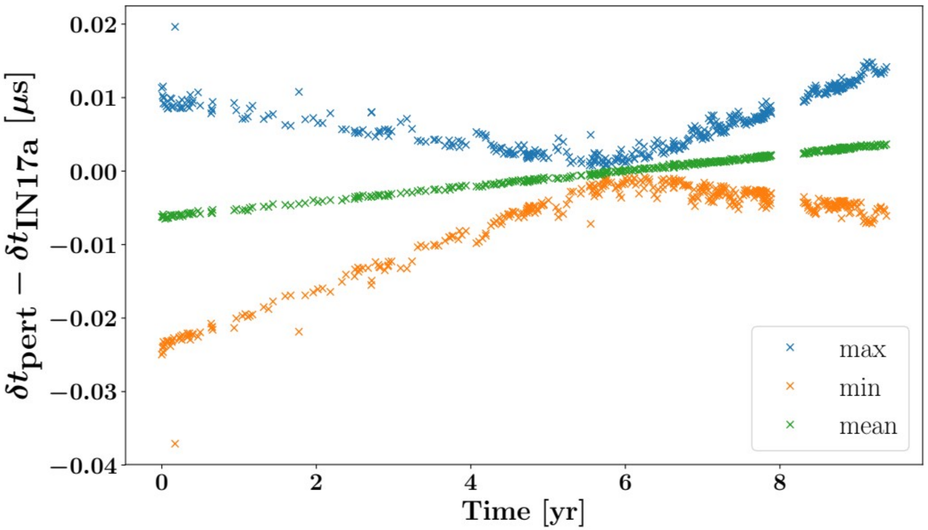
Max & min values of post-fit residuals of J1909-3744 after perturbations at 1σ (2000 perturb.)



Model SSE uncertainties as gaussian process

Description of SSE noise as <u>Gaussian process</u> in residuals with the PTA analysis Bayesian framework software : <u>enterprise</u> (cf. M. Vallisneri)

Method(s)

Marginalize over the SSE parameters (orbital elements) → **Perform a GW searches**

Sample for SSE parameter uncertainties & GW parameters together

Get SSE uncertainties params by marginalizing over other signals

Get constraints on priors that take into account possible <u>systematic biases</u>

Add SSE errors into a full noise model using <u>dipolar correlations</u>

Conclusions

- SSE studies very important to increase PTA sensibility
- Need to take into account ephemeris uncertainties in GW analysis
- Possible to model ephem uncertainties as Gaussian process

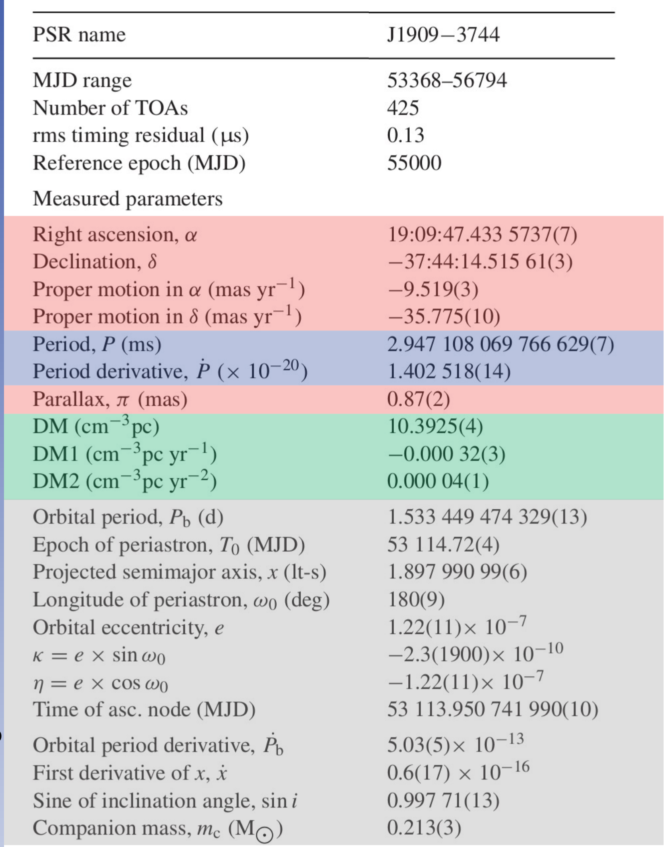
Next steps :

  - Study systematics between SSEs (importance of probing several ephemeris solutions)
  - Find an optimal model for ephemeris uncertainties which takes into account dipolar spatial correlations

Thank you for your attention

Annexe 1

A timing model



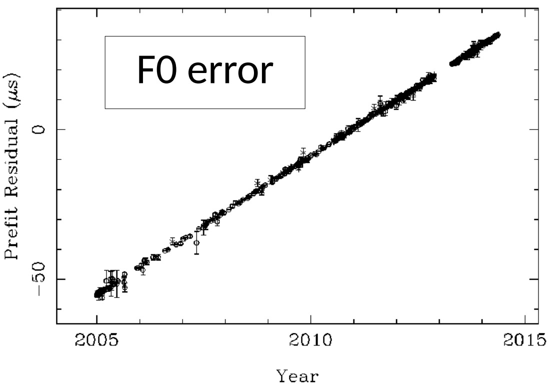
PSR name	J1909−3744
MJD range	53368–56794
Number of TOAs	425
rms timing residual (µs)	0.13
Reference epoch (MJD)	55000
Measured parameters	
Right ascension, α	19:09:47.433 5737(7)
Declination, δ	−37:44:14.515 61(3)
Proper motion in α (mas yr^{-1})	−9.519(3)
Proper motion in δ (mas yr^{-1})	−35.775(10)
Period, P (ms)	2.947 108 069 766 629(7)
Period derivative, $\dot{P}$ ($\times\ 10^{-20}$)	1.402 518(14)
Parallax, π (mas)	0.87(2)
DM (cm^{-3}pc)	10.3925(4)
DM1 (cm^{-3}pc yr^{-1})	−0.000 32(3)
DM2 (cm^{-3}pc yr^{-2})	0.000 04(1)
Orbital period, P_b (d)	1.533 449 474 329(13)
Epoch of periastron, T_0 (MJD)	53 114.72(4)
Projected semimajor axis, x (lt-s)	1.897 990 99(6)
Longitude of periastron, ω_0 (deg)	180(9)
Orbital eccentricity, e	1.22(11)$\times\ 10^{-7}$
$\kappa = e \times \sin \omega_0$	−2.3(1900)$\times\ 10^{-10}$
$\eta = e \times \cos \omega_0$	−1.22(11)$\times\ 10^{-7}$
Time of asc. node (MJD)	53 113.950 741 990(10)
Orbital period derivative, $\dot{P}_b$	5.03(5)$\times\ 10^{-13}$
First derivative of x, $\dot{x}$	0.6(17) $\times\ 10^{-16}$
Sine of inclination angle, $\sin i$	0.997 71(13)
Companion mass, m_c ($M_\odot$)	0.213(3)

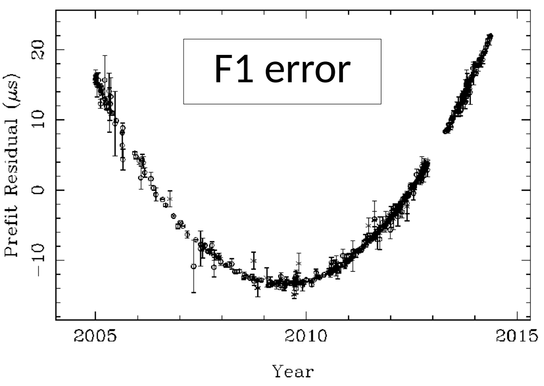
cf. Desvignes et al. 2016

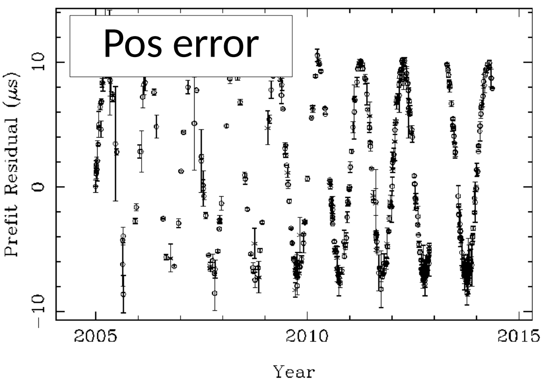
- Astrometric parameters
- Rotational parameters
- Dispersion measure
- Orbital parameters

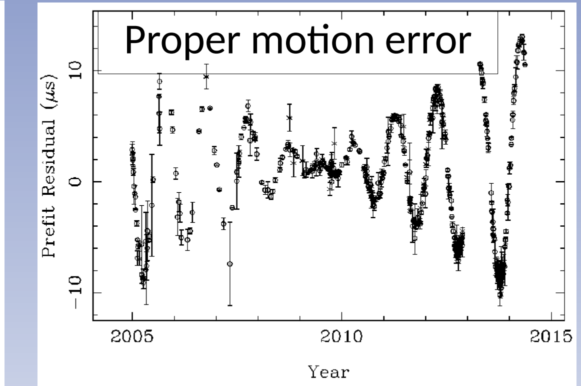
+ solar system ephemerides and clock correction

Effect of param errors on residuals









Annexe 2

Transformation to the SSB

From the topocentric to the quasi-inertial solar system barycenter frame

Atmospheric delay

Parallax

Einstein delay

$$\Delta_\odot = \Delta_A + \Delta_{R\odot} + \Delta_p + \Delta_{D\odot} + \Delta_{E\odot} + \Delta_{S\odot}$$

Rømer delay

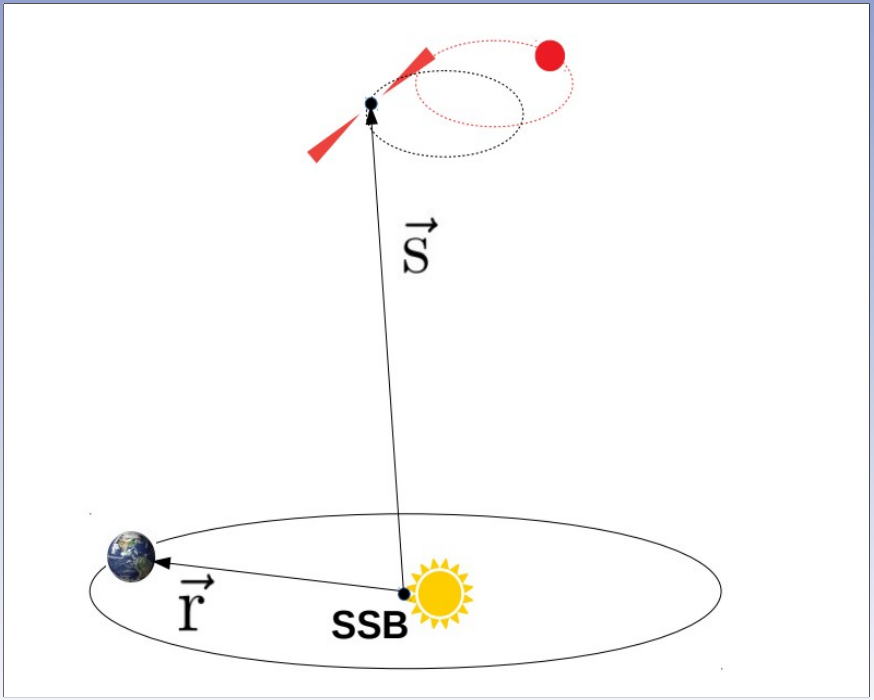
Solar-system dispersion

Shapiro

Dominant term

$$\Delta_{R\odot} = -\frac{1}{c}\,\vec{r}\cdot\hat{s}$$

Orbits of solar system bodies needed !



Annexe 3

Gaussian processes

« Collection of random variables such that every finite collection of these has a multivariate normal distribution »

Set of basis functions
« design matrix »

$$\sum_\mu \phi_\mu(x) w_\mu$$

Weights : Gaussian random variables
« parameter errors »

ω^{0}_{μ} **Mean vector**

$\Sigma_{\mu\nu}$ **Covariance matrix**

Signals modelization

Approx. to the dominant term : Rømer delay

EMB displacement

$$\delta t_{R\odot} = -\frac{\delta \boldsymbol{x}.\hat{\mathbf{n}}_{\mathrm{p}}}{c}$$

Pulsar position

Residuals represented as Gaussian processes

$$y(\theta) = \sum_{(A)} y^{(A)}(\theta^{(A)}) + \epsilon$$

Gaussian Process with hyp. Params. θ

Measurement noise vector

$\mathcal{N}(\boldsymbol{\mu}_\epsilon, N)$

[Van Haasteren & Vallisneri 2014]

Annexe 4

Marginal likelihood of data (n TOAs) with GP noise description subject to Gaussian measurement noise ε$_i$ with covariance matrix *N*

$$\log p(y|\theta, \mathrm{GP}) = -\frac{1}{2} y^T (N + \sum_{(A)} K^{(A)})^{-1} y - \frac{n}{2} \log(2\pi) - \frac{1}{2} \log \det \left(N + \sum_{(A)} K^{(A)} \right)$$

Gaussian process covariance matrices

Gaussian process « duality »

$$p(y_i|w_\mu, \mathrm{GP}) = \frac{\mathrm{e}^{-\frac{1}{2}\sum_{i,j}\left(y_i - \sum_\mu \phi_\mu(x_i) w_\mu\right)(N_{ij})^{-1}\left(y_j - \sum_\mu \phi_\mu(x_j) w_\nu\right)}}{\sqrt{(2\pi)^n \det N}} \times \frac{e^{-\frac{1}{2}\sum_{\mu\nu} w_\mu (\Sigma_{\mu\nu})^{-1} w_\nu}}{\sqrt{(2\pi)^m \det \Sigma}}$$

$$p(y_i|\mathrm{GP}) = \frac{\mathrm{e}^{-\frac{1}{2}\sum_{i,j} y_i \left(N_{ij} + K_{ij}\right)^{-1} y_j}}{\sqrt{(2\pi)^n \det(N + K)}}, \quad \text{with} \quad K_{ij} = k(x_i, x_j) = \sum_{\mu\nu} \phi_\mu(x_i) \Sigma_{\mu\nu} \phi_\nu(x_j),$$

Marginal likelihood of the data given the Gaussian process