3rd IEEE International Workshop on

Metrology for Aerospace

Florence, Italy, June 22 - 23, 2016

22 June 2016

URSI in Italy

University of Florence

U.R.S.I.

The clock-like nature of the Radio Pulsars

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Layout

- Pulsar rudiments
- Pulsar timing concepts
- Fundamental physics applications
- A pulsar-based time scale

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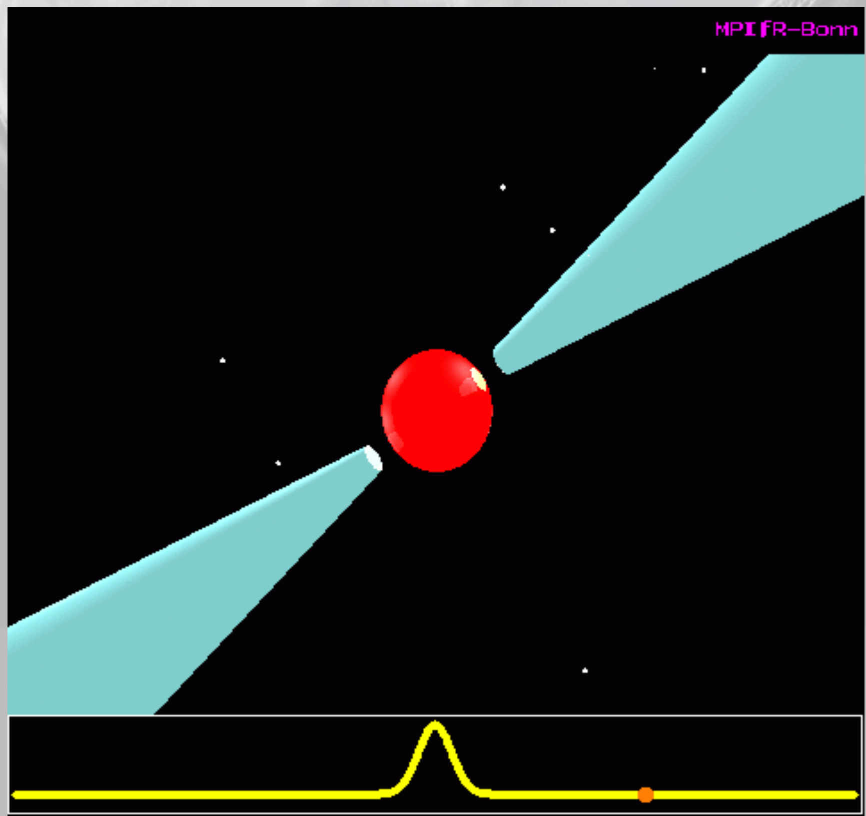
Pulsar rudiments

What is a Radio Pulsar

A **PULSAR** is a rapidly rotating and highly magnetized neutron star, emitting a pulsed radio signal as a consequence of a light-house effect



@Kramer

The "inferred" radio pulsar basic parameters

Spin-down age: $\tau_c = 1.6 \cdot 10^7 \; P / \dot{P}_{-15}$ yr

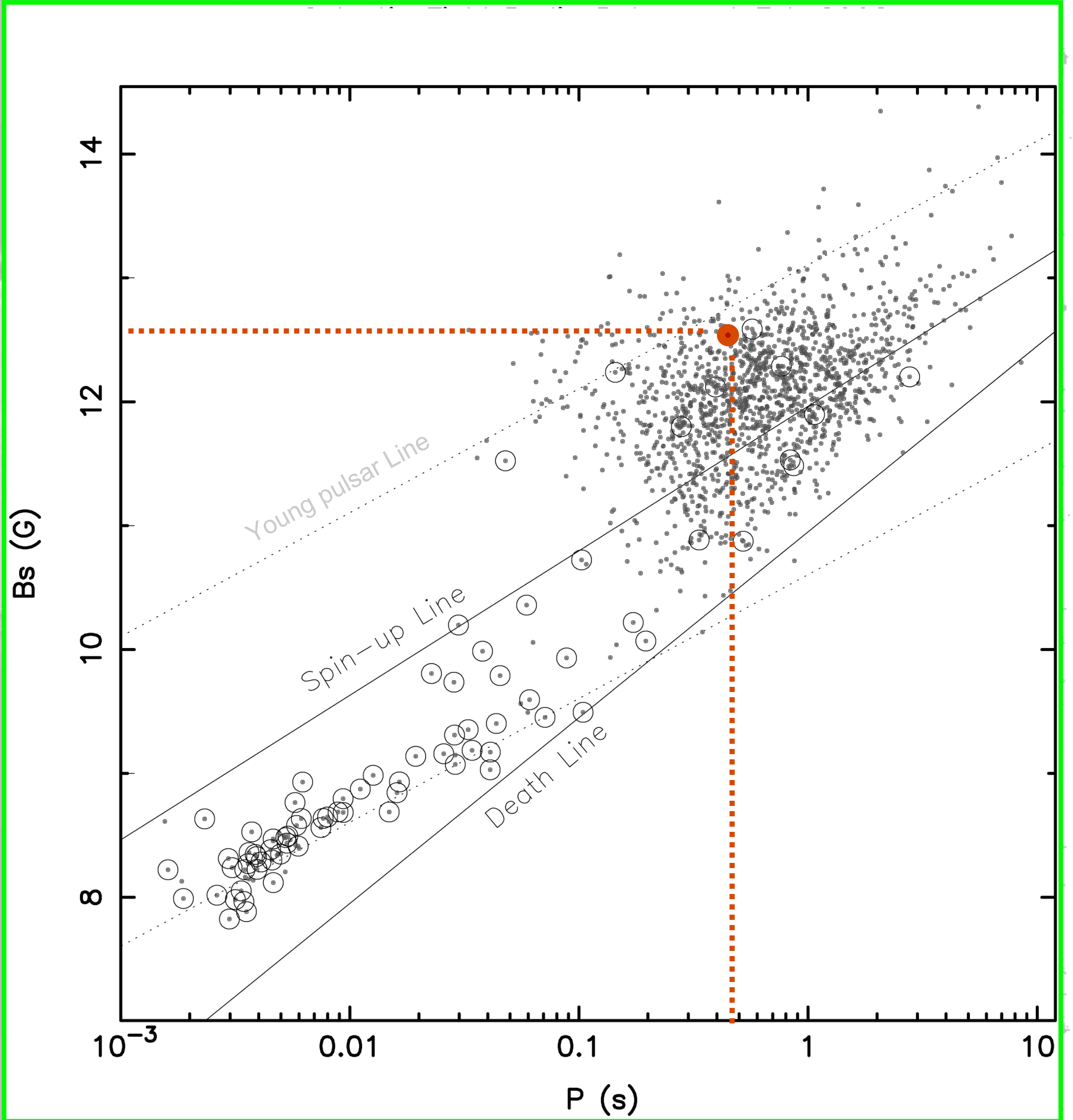
Spin-down power: $L_{sd} = 3.9 \cdot 10^{31} \; P^{-3} \dot{P}_{-15}$ erg/s

Surface magnetic field: $B_{surf} = 1.0 \cdot 10^{12} \; [\, P \dot{P}_{-15} \,]^{1/2}$ Gauss

The observation of the spin period P and of its derivative $\dot{P}$ allows one to give an estimate of the quantities above...

...and allows one to place a pulsar on the basic P vs $\dot{P}$ [or P vs B_{surf}] diagram...

The B_s vs P diagram



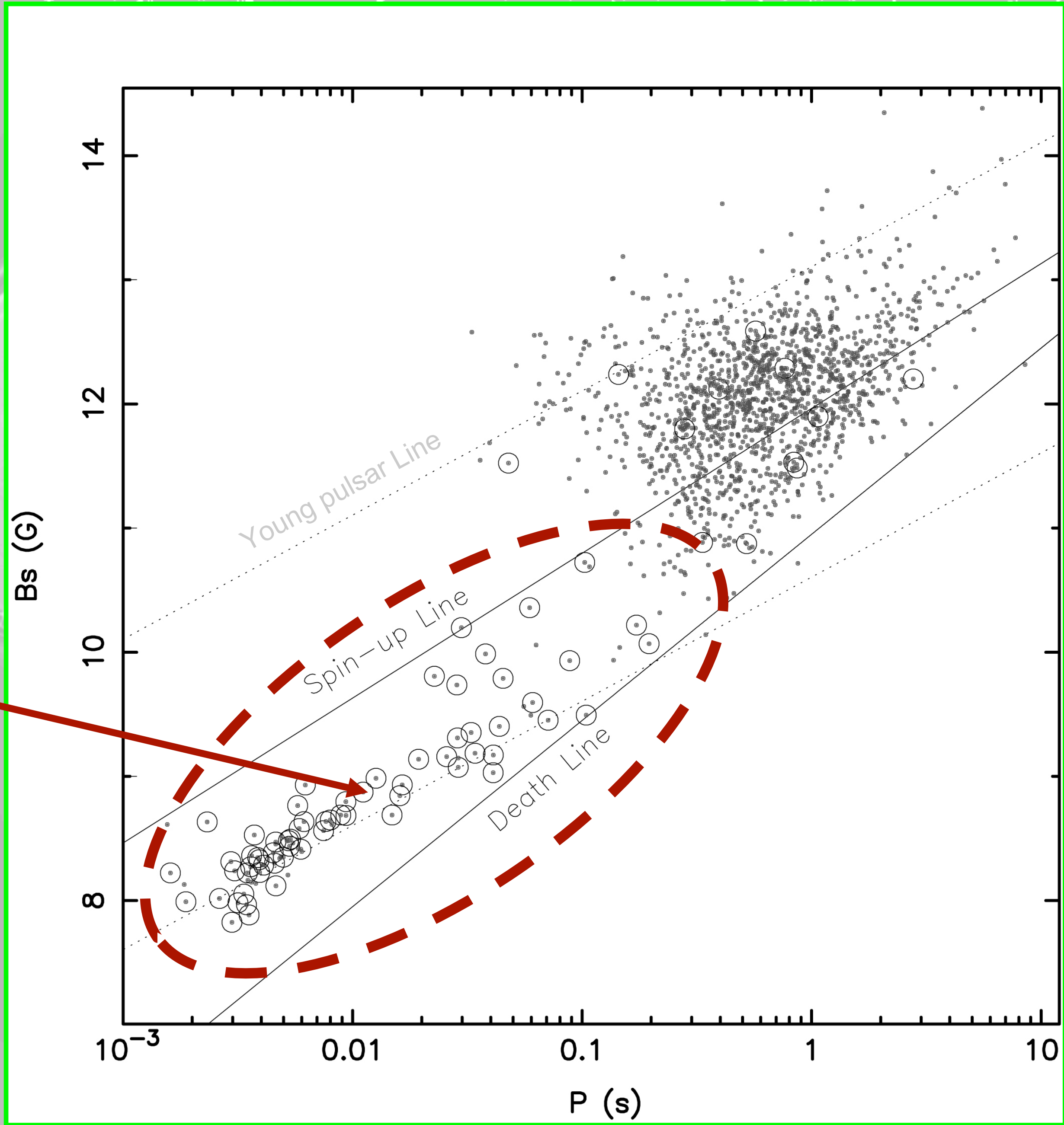
ATNF Pulsar Catalogue

A pulsar is put on it once both P and dP/dt are measured, from which

$$B_s = 3.2 \cdot 10^{19} [\, P \dot{P} \,]^{1/2} \text{ G}$$

A dichotomy in the population

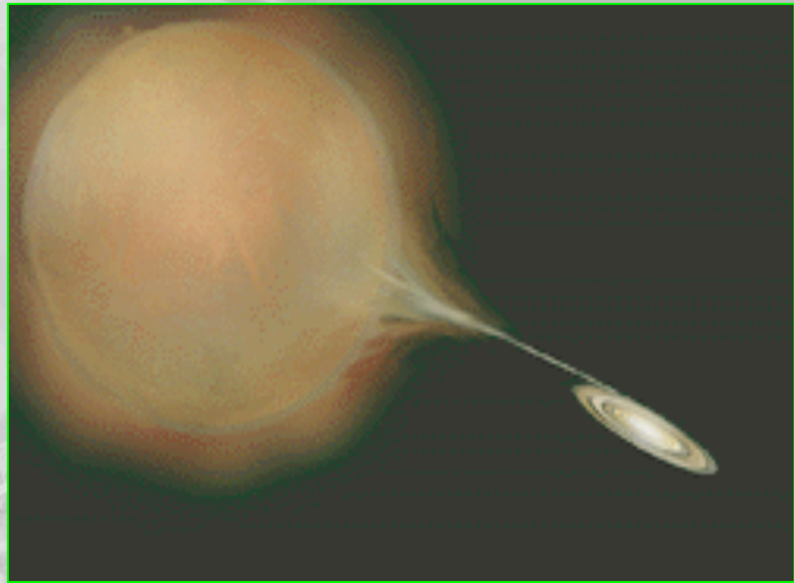
How to explain this group of pulsars ?

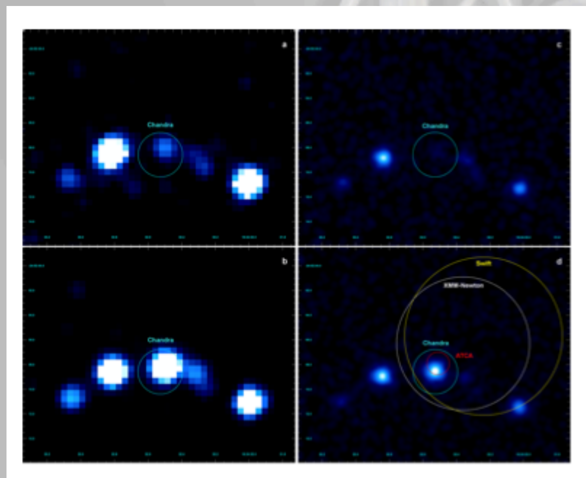


ATNF Pulsar Catalogue

The MSP formation paradigm

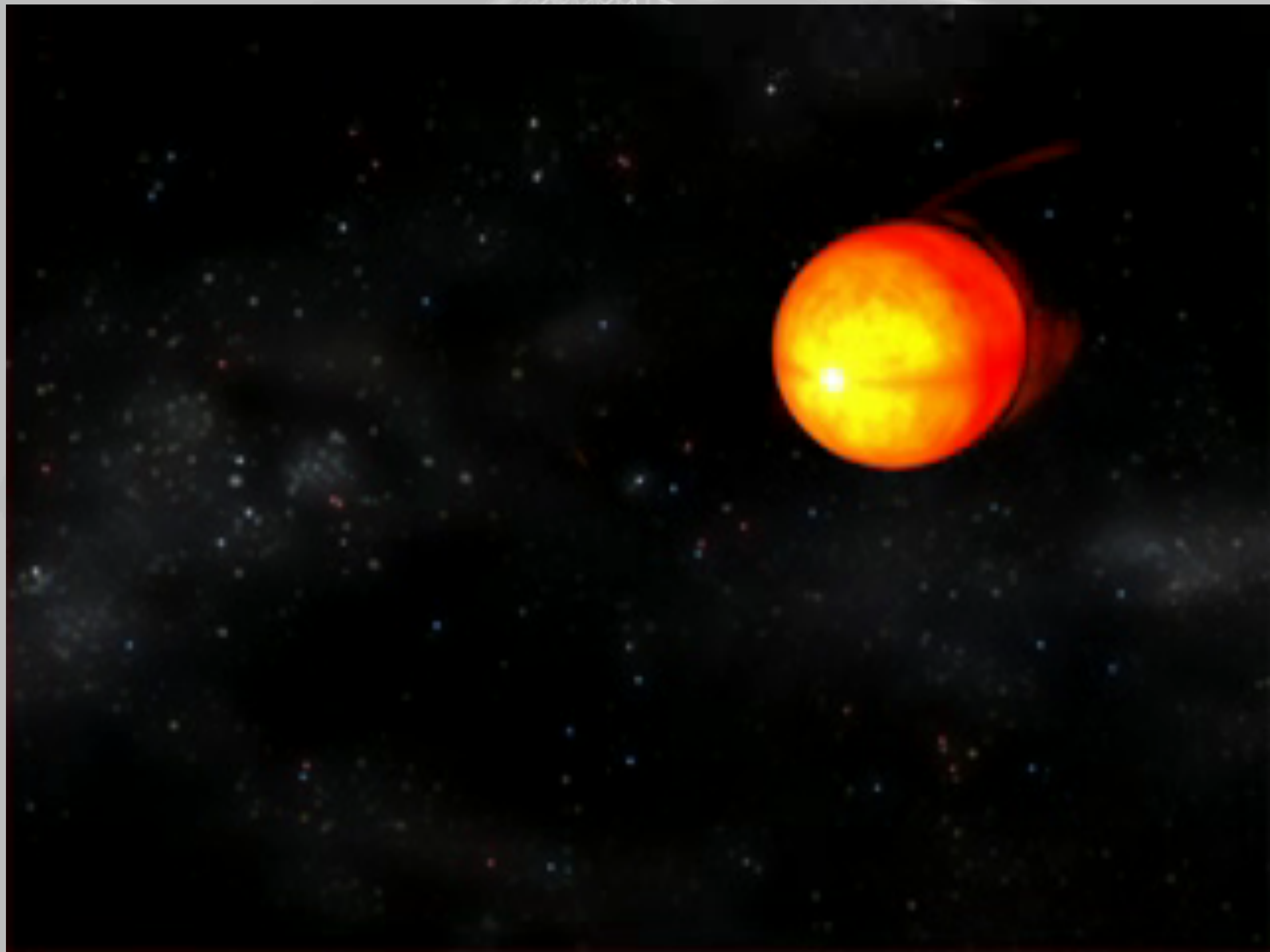
Recycling scenario: Millisecond pulsars are old neutron stars spun up by accretion of matter and angular momentum from a companion star in a multiple system [Bisnovati-Kogan & Kornberg 1974, Alpar et al. 1982]





Swinging btw X-ray and radio MSP

The case of M28I: a direct proof... finally! [Papitto et al Sept 2013]



Dana Berry @ NASA

A died pulsar could be spun up and rejuvenated by an evolving binary companion

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Pulsars timing concepts

Timing concept

1. Performing repeated observations of the Times of Arrival (ToAs) at the telescope of the pulsations from a given pulsar

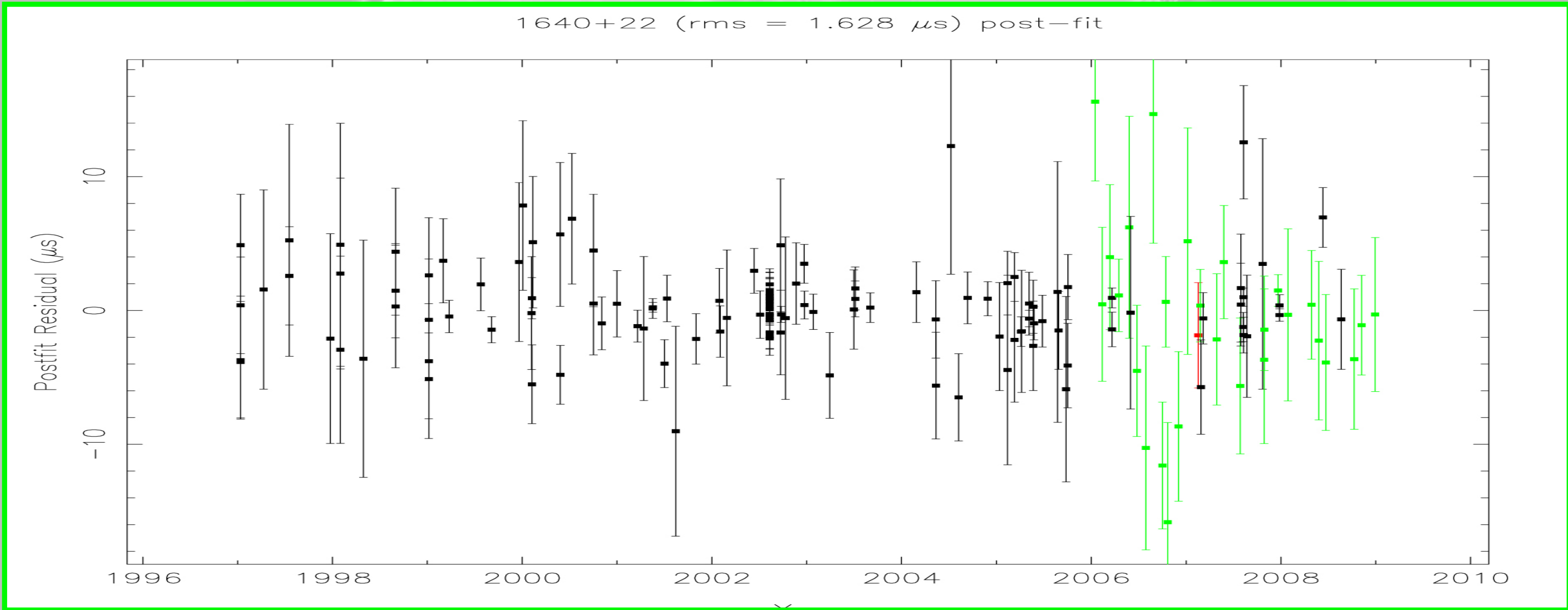
2. Searching the ToAs for systematic trends on many different timescales, from minutes to decades

If a physical model adequately describes the trends, it is applied with the smallest number of parameters

When a model finally describes accurately the observed ToAs, the values of the model's parameters shed light onto the physical properties of the pulsar and/or of its environment

Timing analysis quality: residuals

Quality factor in a timing observation:
uncertainty σ_{TOA} in the Time Of
Arrival of the pulse, known as TOA



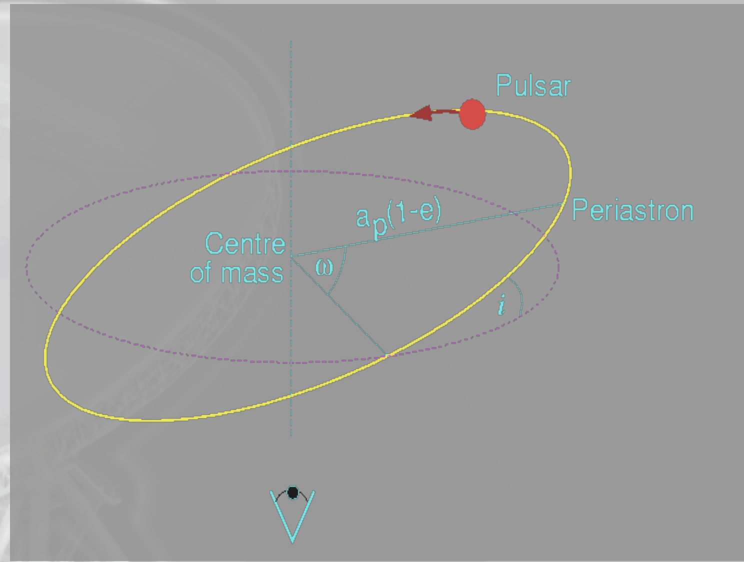
(OBSERVED TOAs - MODEL TOAs) $\rightarrow$ residuals

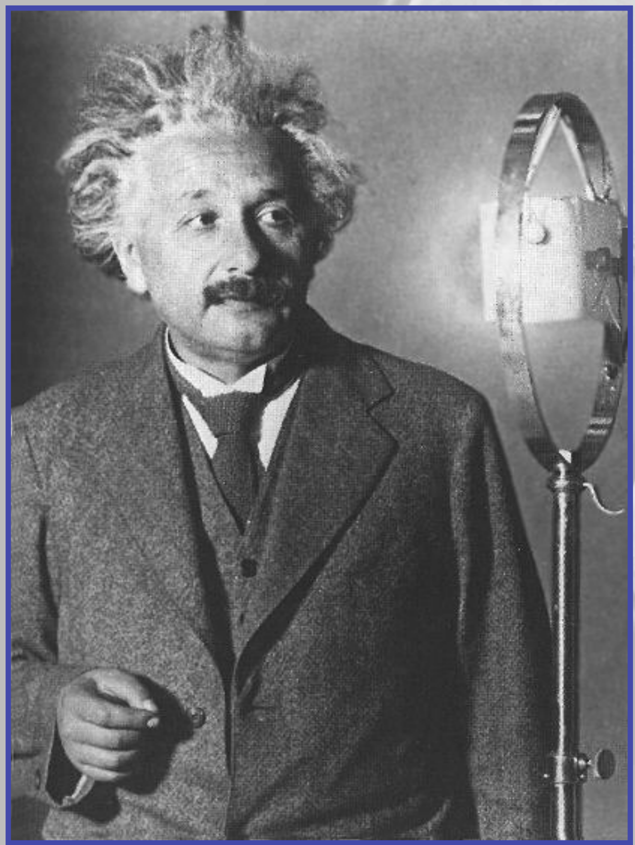
Good timing solution $\rightarrow$ no evident trend in the residuals

Pulsar Timing applied to binary pulsars

- By using repeated observations of the time of arrival of the pulses (Timing) one can measure 5 Keplerian parameters:

P_{orb}, a_p, e, ω, T_0





... and, in few cases, one or more post-Keplerian parameters:

$\dot{\omega}$, γ, $\dot{P}_{orb}$, s, r

plus additional GR effects:

Ω_{prec}, ...

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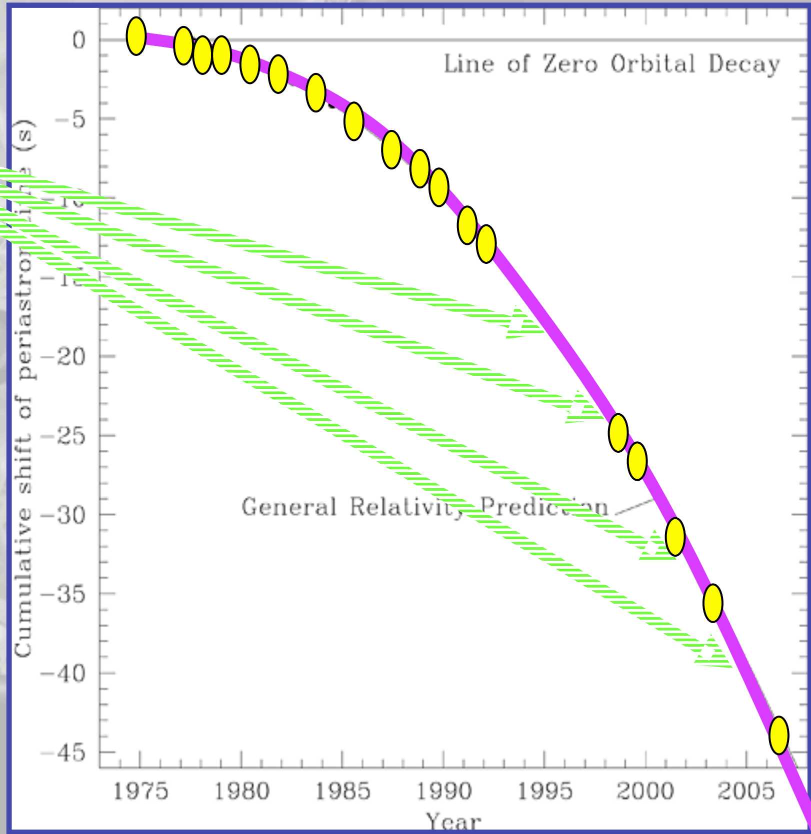
A quick-look to some fundamental physics applications

The measurements of Russell Hulse and of Joe Taylor…

The prediction of the Einstein's equations…

The (in?)direct proof of GW existence: PSR B1913+16



[Weisberg 2010]

GR provides an accurate

des … as

orb … e.

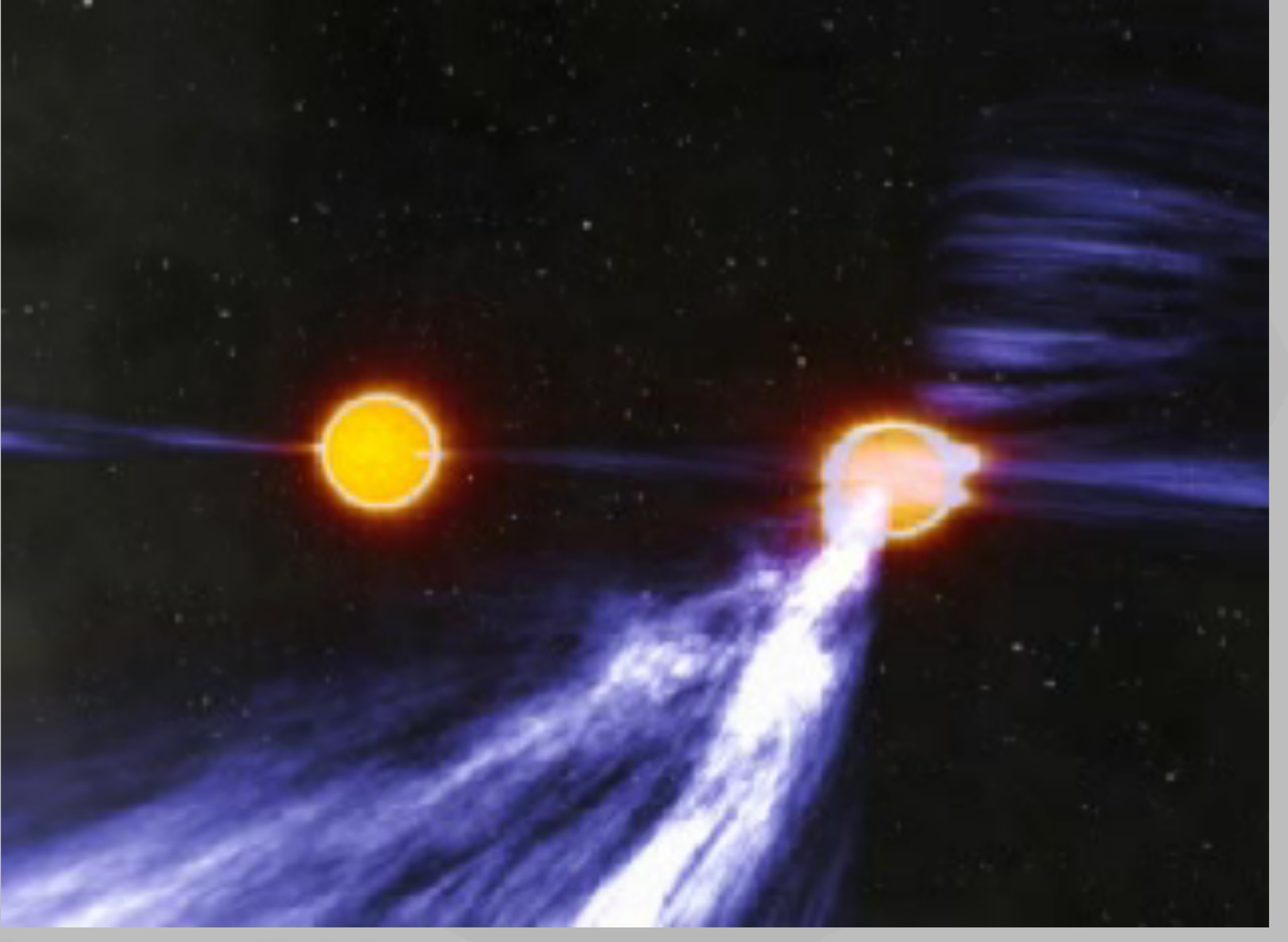
NS … ct

NOBEL PRIZE 1993

Taylor & Hulse

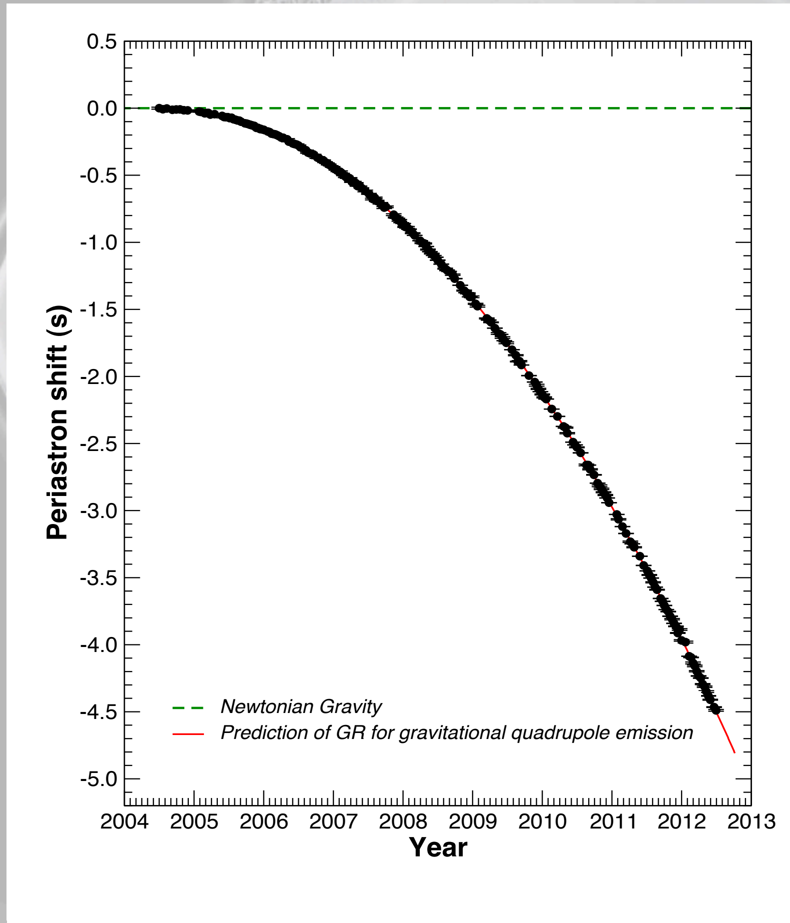
The best binary so far: J0737-3039A/B

[Burgay et al 2003, Lyne at al 2004]



[© Howe, ATNF]

Current radiative GR test for J0737-3039 system is at ~ 0.03% level



[Kramer et al 2016 (in prep.)]

Precision measurements, e.g.

P (ms) = 22.69937884809636 ± 0. 00000000000003 (measured to 30 atto-seconds!)

P_b (d) = 0.102251562465 ± 0.000000000002 (i.e. 2.45h measured to 173 ns!)

...some other tests on fundamental physics with binary pulsars

Time derivative of G
PSR J0437-4715

$[dG/dt]/G = (-5 \pm 18) \cdot 10^{-12}\ yr^{-1}$
(about 10 times weaker than lunar ranging but much simpler and in strong-field)
[Damour & Taylor 1991, Verbiest et al 2008]

Strong Equivalence Principle
21 highly circular WD-MSP

$|\Delta| = 5.6 \cdot 10^{-3}$ (weaker than solar system tests, but in strong-field regime)
[Wex 1997, Stairs et al 2005]

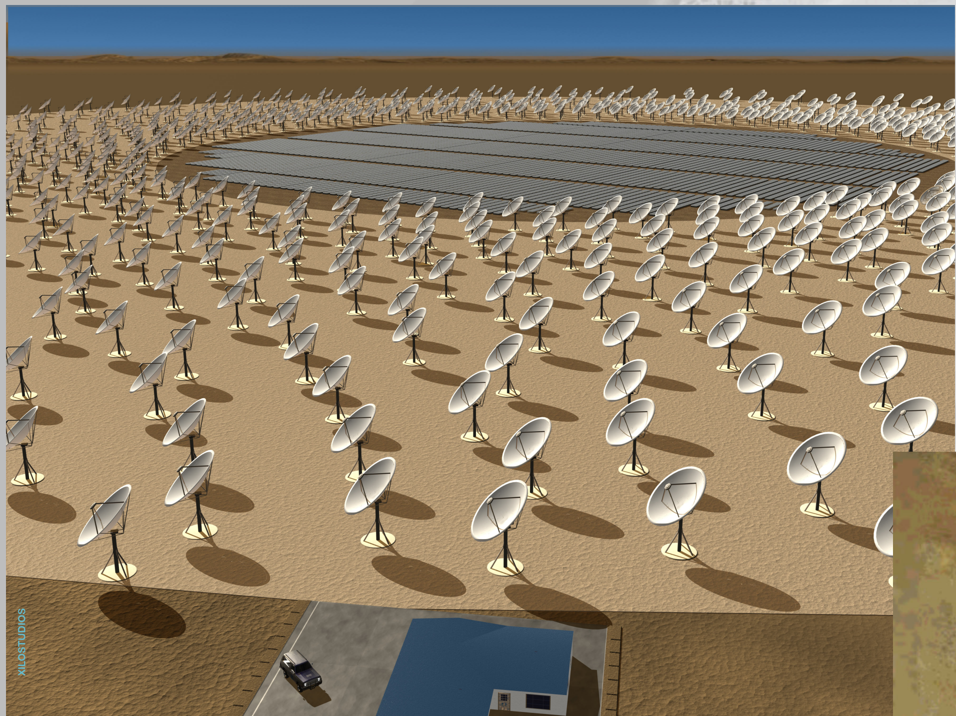
Momentum conservation
21 highly circular WD-MSP

$|\hat{\alpha}_3| = 4.0 \cdot 10^{-20}$ (10^{13} better than Earth or Mercury perhelion shifts)
[Bell & Damour 1996, Stairs et al 2005]

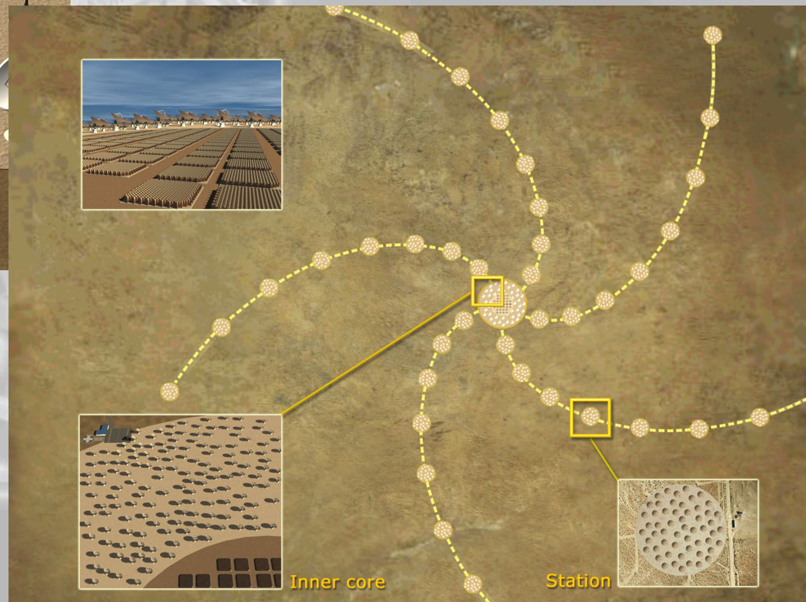
Existence of preferred frame
PSR J1012+5307

$|\hat{\alpha}_1| = 1.4 \cdot 10^{-4}$ (slighlty weaker than lunar laser ranging, but in strong-field regime)
[Wex 2000]

The prospects of new timing experiments with the Square-Kilometre-Array (SKA)



To be built in Australia & South Africa



@ www.skatelescope.org

Available ≈ 2020

What might be feasible to measure:
Moment of Inertia of J0737-3039A

Total periastron advance to 2PN level: [Damour & Schaefer 1988]

$$k^{tot} = \frac{3\beta_0^2}{1-e_T}\left[1 + f_0\beta_0^2 - g_S{}^A\beta_0\beta_S{}^A - g_S{}^B\beta_0\beta_S{}^B\right]$$

1PN 2PN Spin A Spin B

Neutron star dependent

Equation-of-State
for the nuclear matter!!

$$\beta_S = \frac{2\pi c}{G}\frac{1}{P}\frac{I}{m^2}$$

A 10% accuracy on I
would exclude most EoS
[Lattimer & Schutz 2004]
[Morrison et al. 2004]

Some of the promises of SKA...

FINDING AND TIMING A PSR-BH BINARY (AND MAYBE A PSR-MSP BINARY IN A GLOBULAR CLUSTER [Clausen et al. 2014])

From the ordinary PK parameters — **BH mass with precision < 0.1%**

From precessional effects on semi-major axis and longitude of periastron — **BH spin S with precision < 1%**

From M & S $\chi \equiv \frac{c}{G}\frac{S}{M^2}$ — $\chi \le 1$ *Test of* Cosmic Censorship Conjecture” [Penrose 1969]

FINDING AND TIMING A PSR CLOSELY ORBITING SGR A*

From only 1 PK parameter — **BH mass with precision < 0.001%**

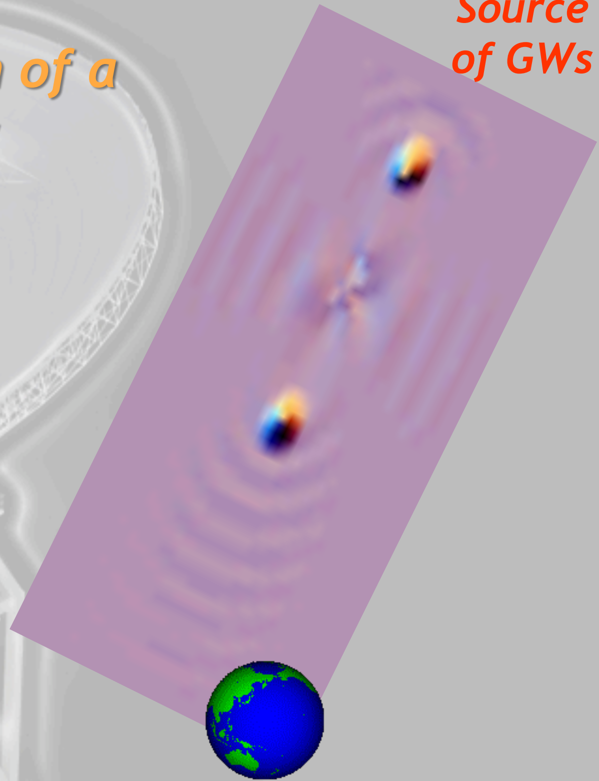
From BH oblateness — **BH quadrupole moment Q with precision ~ 1%**

From M & Q $q \equiv \frac{c^4}{G^2}\frac{Q}{M^3}$ — $q = -\chi^2$ *Test of* No Hair theorem”

Pulsars as GW detectors

The Pulsar-Earth path can be used as the arm of a huge cosmic gravitational wave detector

Source of GWs



Earth

Perturbation in space-time can be detected in timing residuals over a suitable long observation time span

Radio Pulsar

Sensitivity (rule of thumb):

$$h_c(f) \sim \frac{\sigma_{TOA}}{T}$$

where

$h_c(f)$ is the dimensionless strain at freq f

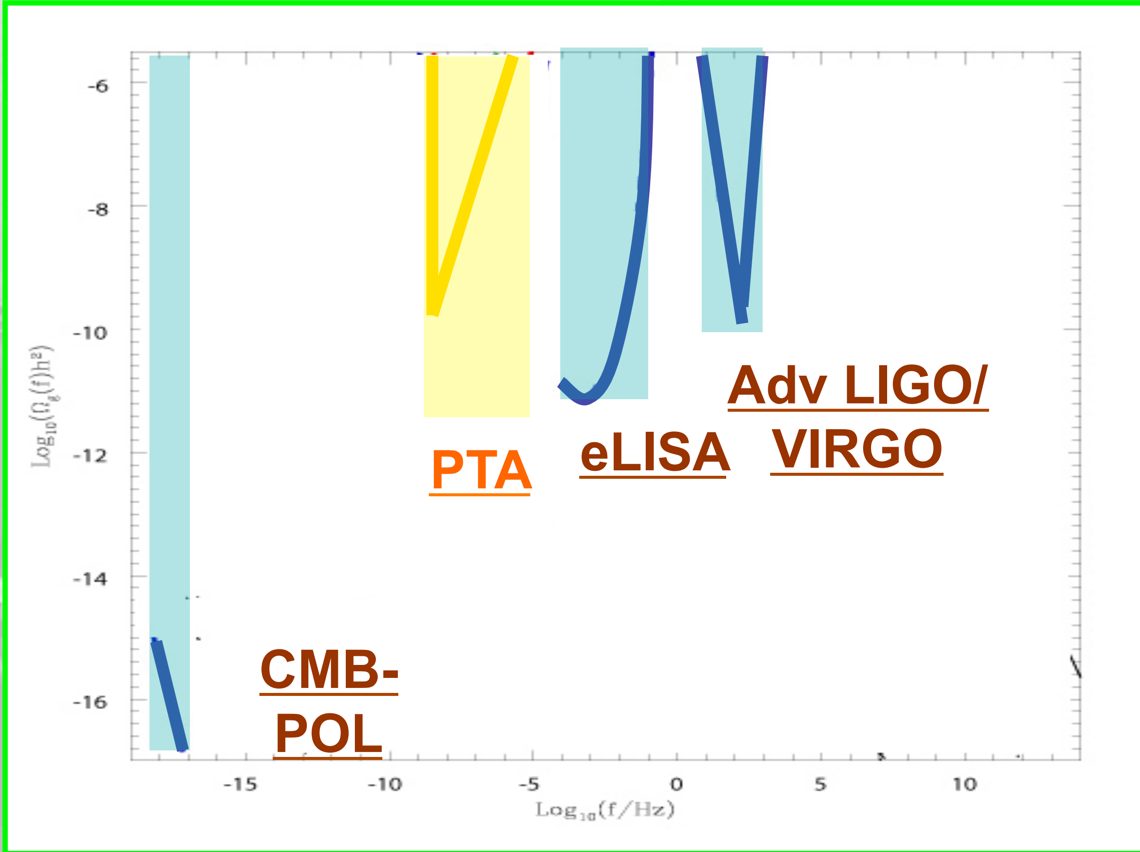
σ_{TOA} is the rms uncertainty in Time of Arrival

T is the duration of the dataspan

Pulsar Timing array(s): the frequency space and the sources

Note the complementarity in explored frequencies with respect to the current and the future GW observatories, like LIGO, advLIGO, advVIRGO and LISA-like

- Expected sources:
  - Binary super-massive black holes in early Galaxy evolution
  - Cosmic strings
  - Cosmological sources
- Types of signals:
  - Stochastic (multiple)
  - Periodic (single)
  - Burst (single)



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A Pulsar Timing Array timescale TT(PTA)

Millisecond pulsars (MSPs) as cosmic clocks

Pulsar periods can sometimes be measured with unrivalled precision

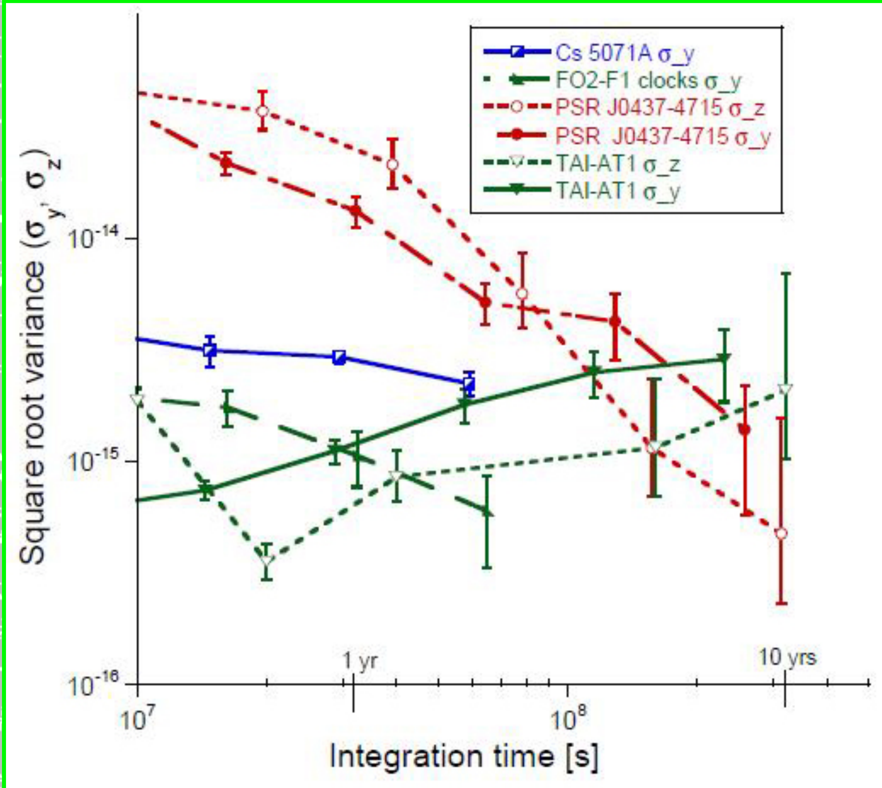
e.g. on Jan 16, 1999, at 00:00 UT, PSR J0437-4715 had a period of

5.757451831072007 ± 0.000000000000008 ms

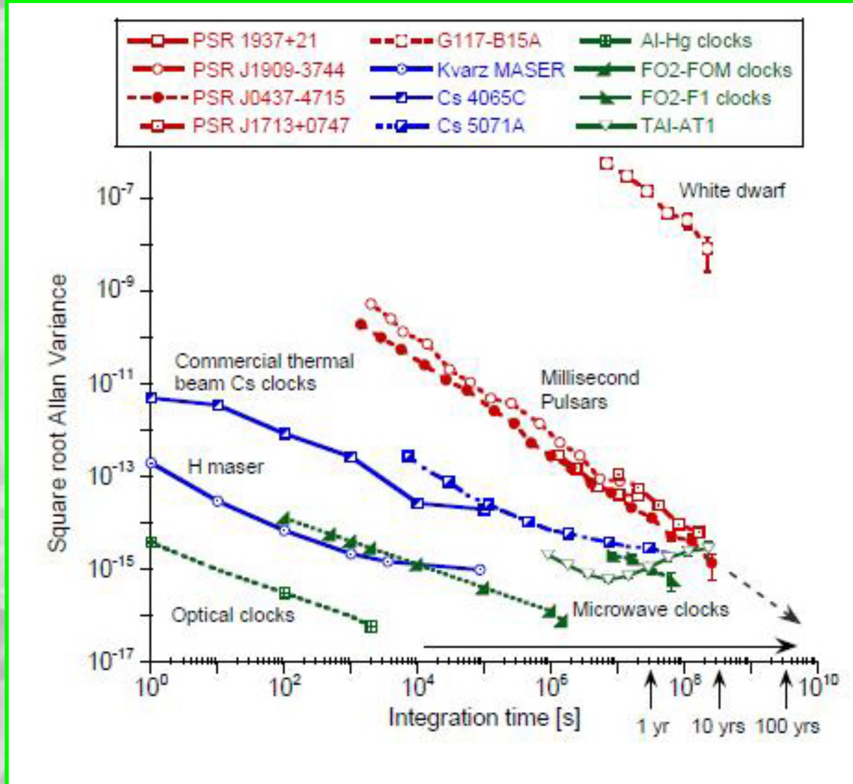
15 significant digits!

... and for “good” MSPs that steadily improves with the timespan !

Atomic clocks vs pulsar timing



[Hartnett & Luiten 2010]



Unfortunately only a subsample of the recycled pulsars is able to achieve such a rotational stability

The majority of the ordinary pulsars undergo timing irregularities

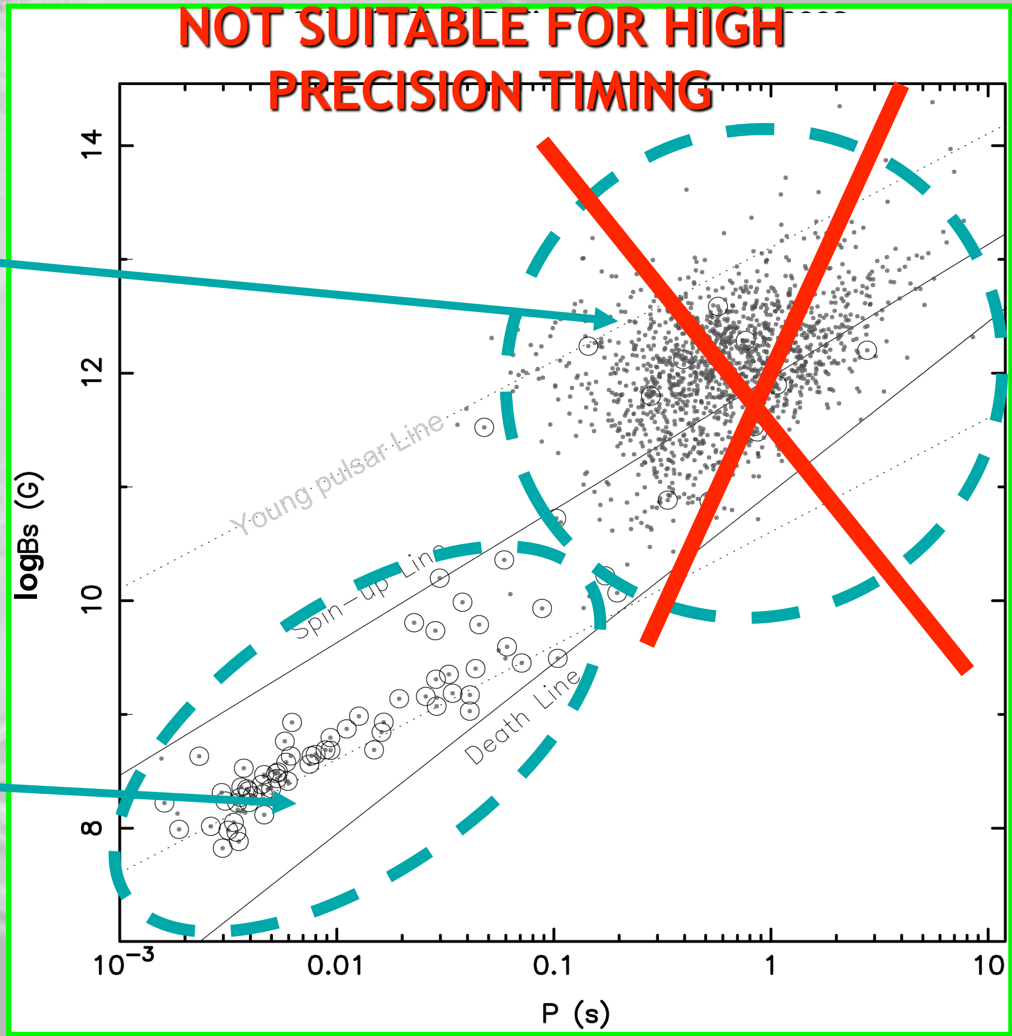
High precision pulsar timing: which targets?

Ordinary pulsars:
~ 2200 known objects;
NS_{age} < few 10^7 yr

relatively long pulses &
rotational irregularities

Recycled pulsars:
~ 300 known objects;
NS_{age} > 10^8-10^9 yr

The most rapidly rotating are known as millisecond pulsars



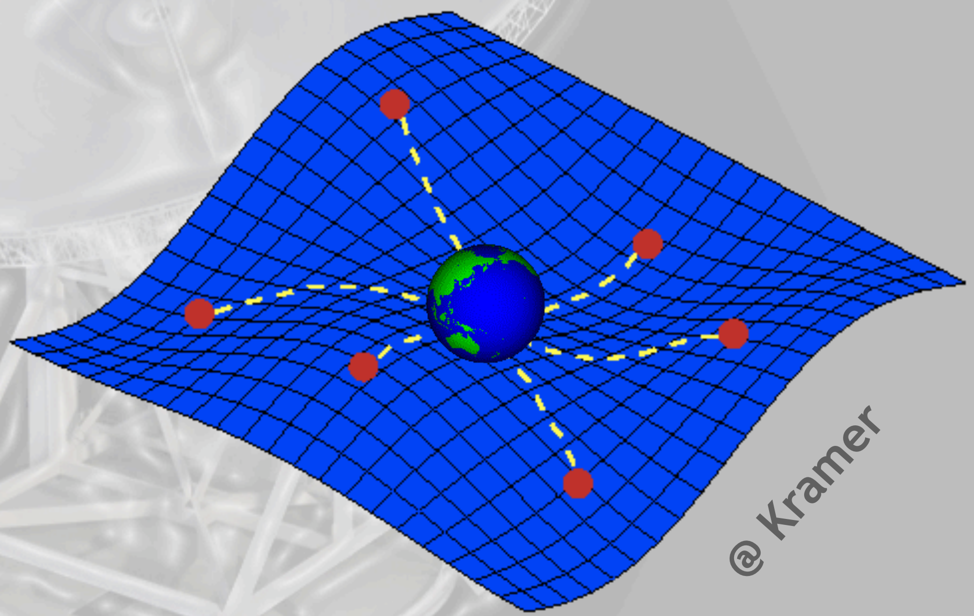
ATNF Pulsar Catalogue

A pulsar timing array (PTA)

Using a number of pulsars distributed across the sky it is possible to create a time scale based on pulsar rotation dubbed e.g.

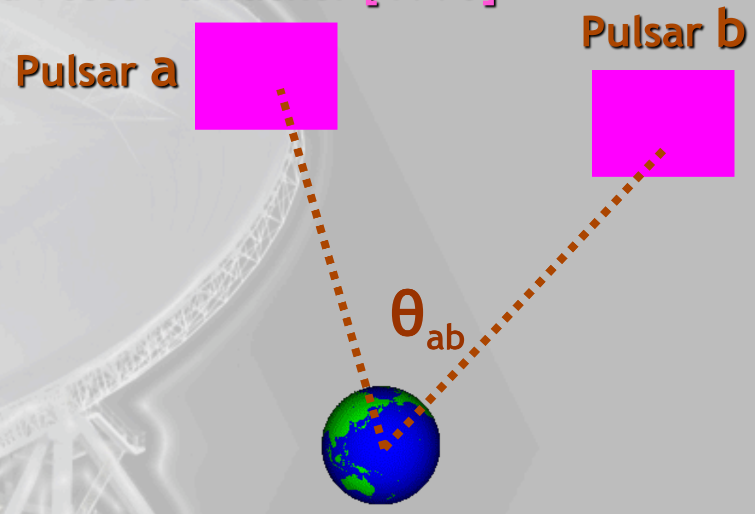
Ensemble Pulsar Scale

In practice, by LOOKING AT MANY PULSARS it is possible to separate the intrinsic “timing noise” contribution from each pulsar from other contributions: e.g. the signature of a clock effect manifests as a distortion in the times of arrival of the pulses which is common to the signal from all pulsars



The correlations among timing residuals for a Pulsar Timing Array

Idea first discussed by Romani [1989] and Foster & Backer [1990]



- **Clock errors**

  All pulsars have common variations in the residuals: **Monopole** signature

- **Solar-System ephemeris errors**

  Dipole signature

- **Gravitational waves background**

  Quadrupole signature

$$\zeta(\theta_{ab}) = \frac{3}{2}\left(\frac{1-\cos\vartheta_{ab}}{2}\right)\log\left(\frac{1-\cos\vartheta_{ab}}{2}\right) - \frac{1}{4}\left(\frac{1-\cos\vartheta_{ab}}{2}\right) + \frac{1}{2} + \frac{1}{2}\delta_{ab}$$

Hellings & Downs [1983]: correlation that an isotropic and stocastic GWB leaves on the timing residuals of 2 pulsars a and b separeted by an angle θ_{ab} in sky

Can separate these effects provided there is a sufficient number of widely distributed pulsars

[adapted from Manchester]

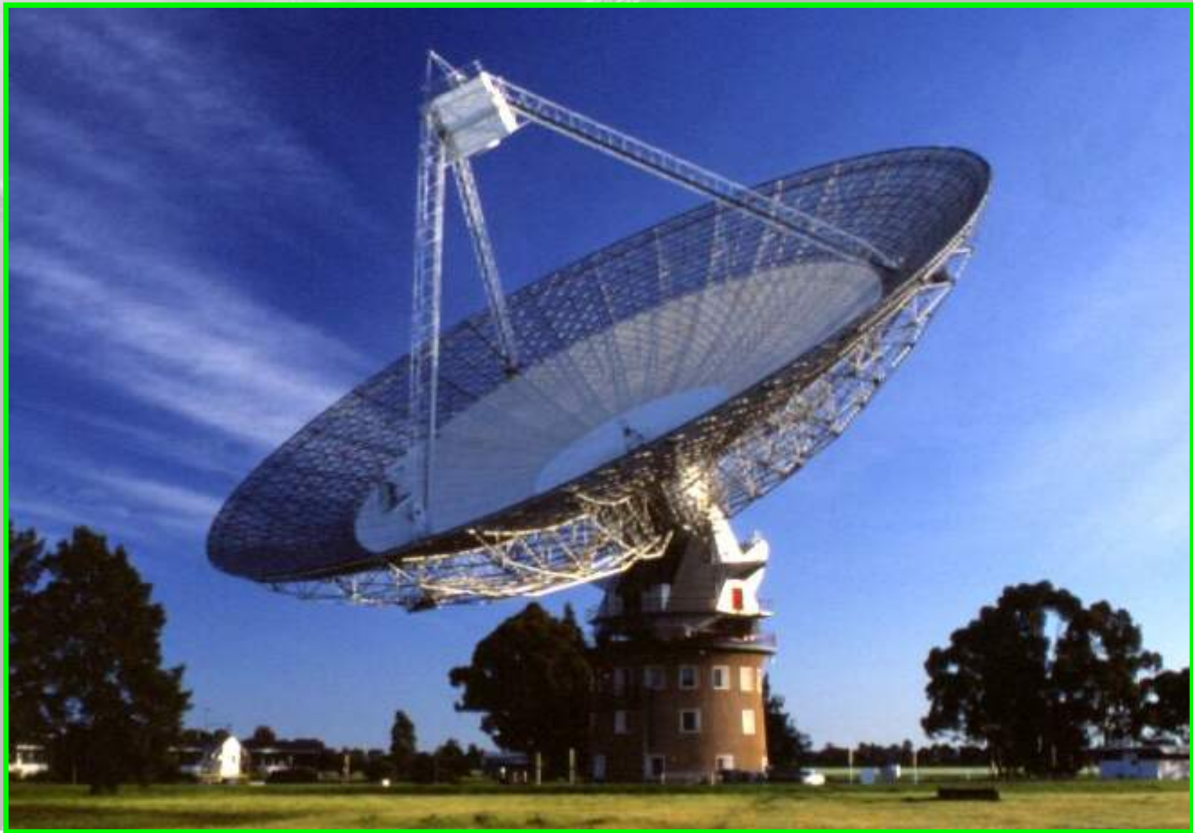
I. Current projects: PPTA

Parkes Pulsar Timing Array: PPTA

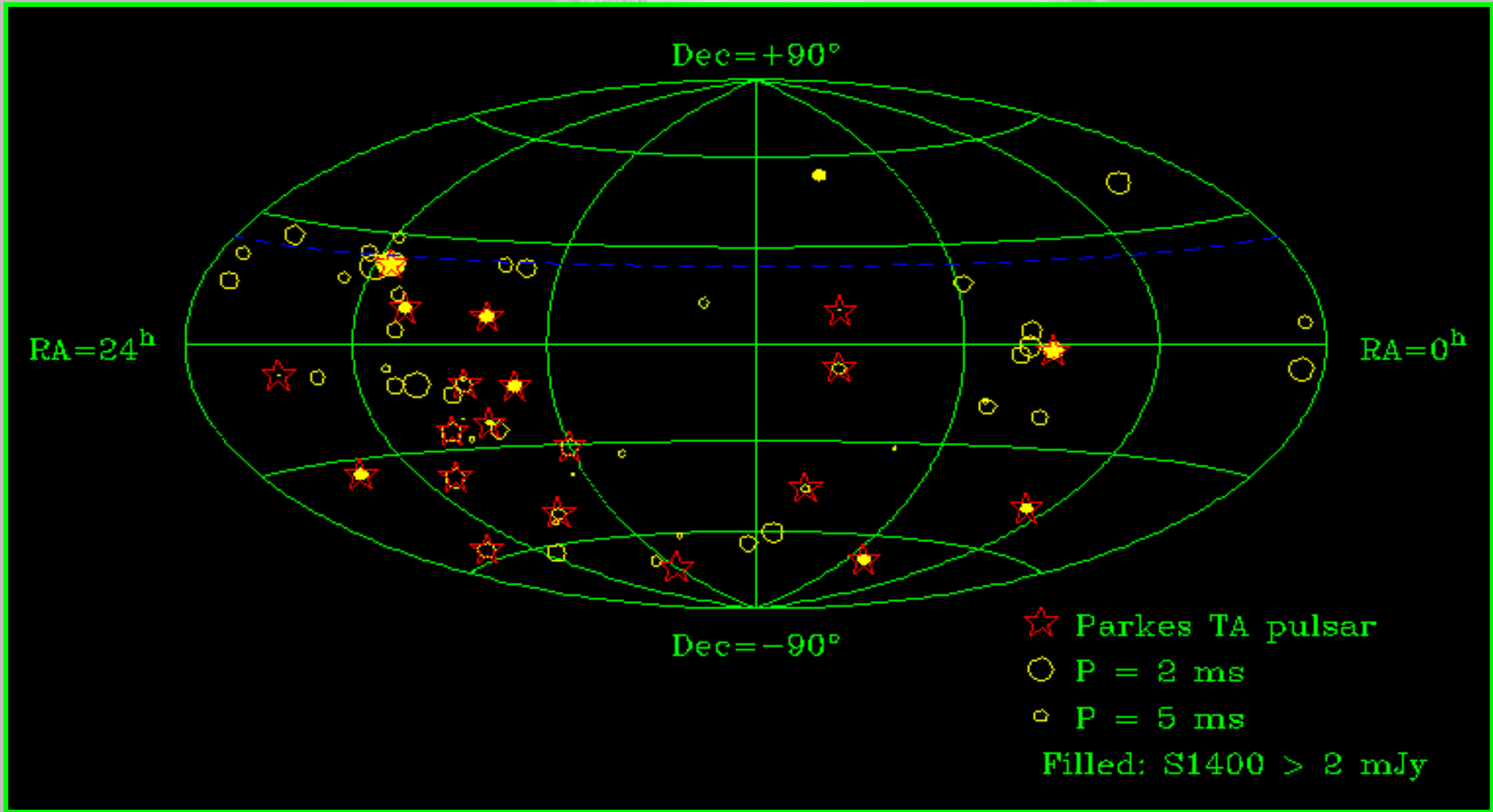
Australian based, using Parkes 64m dish

Running since ~ 2003

@ M.Burgay



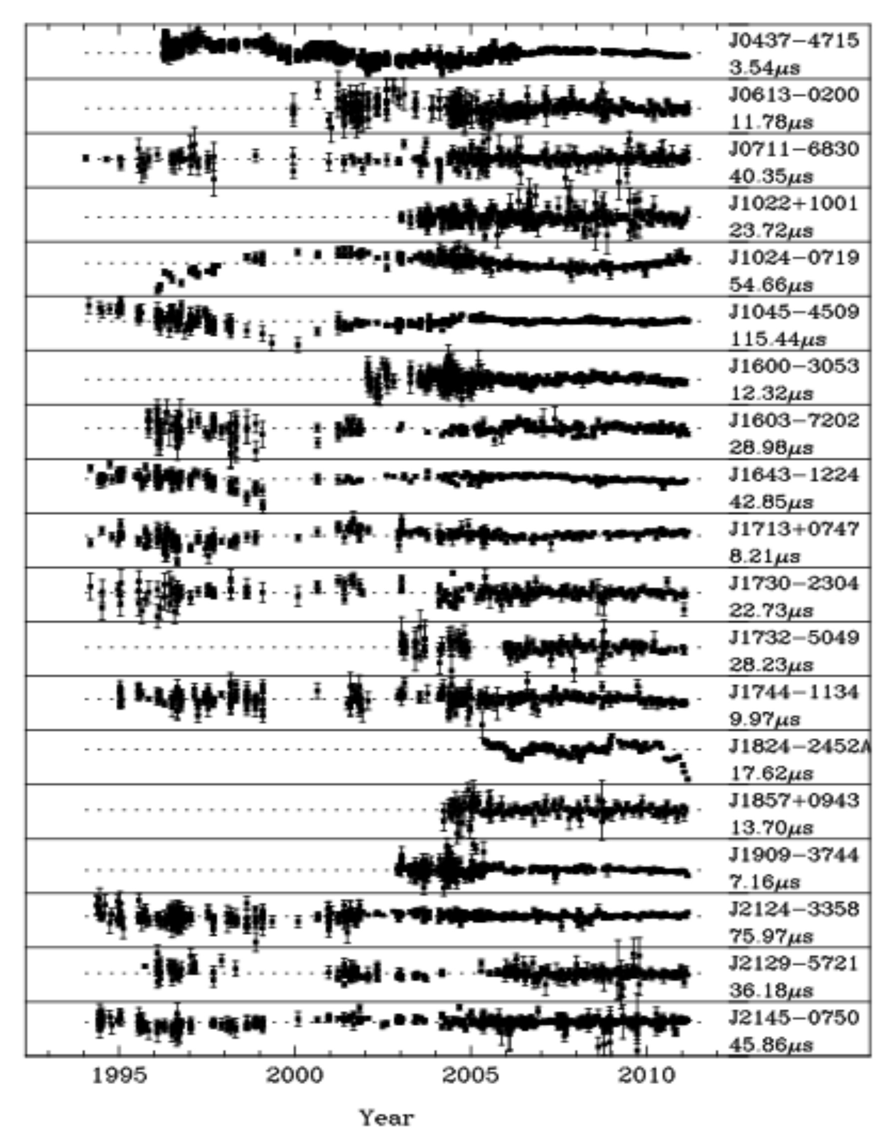
The currently used set of observed millisecond pulsars in the PPTA australian project



[@ D.Manchester]

P < 20 ms and not in globular clusters

Timing residuals for the PPTA pulsars over a 17-yr timespan



[Hobbs at al 2012]

... from the PPTA observations it was possible to create a

time scale based on pulsar rotation dubbed e.g.

Ensemble Pulsar Scale (PPTA)

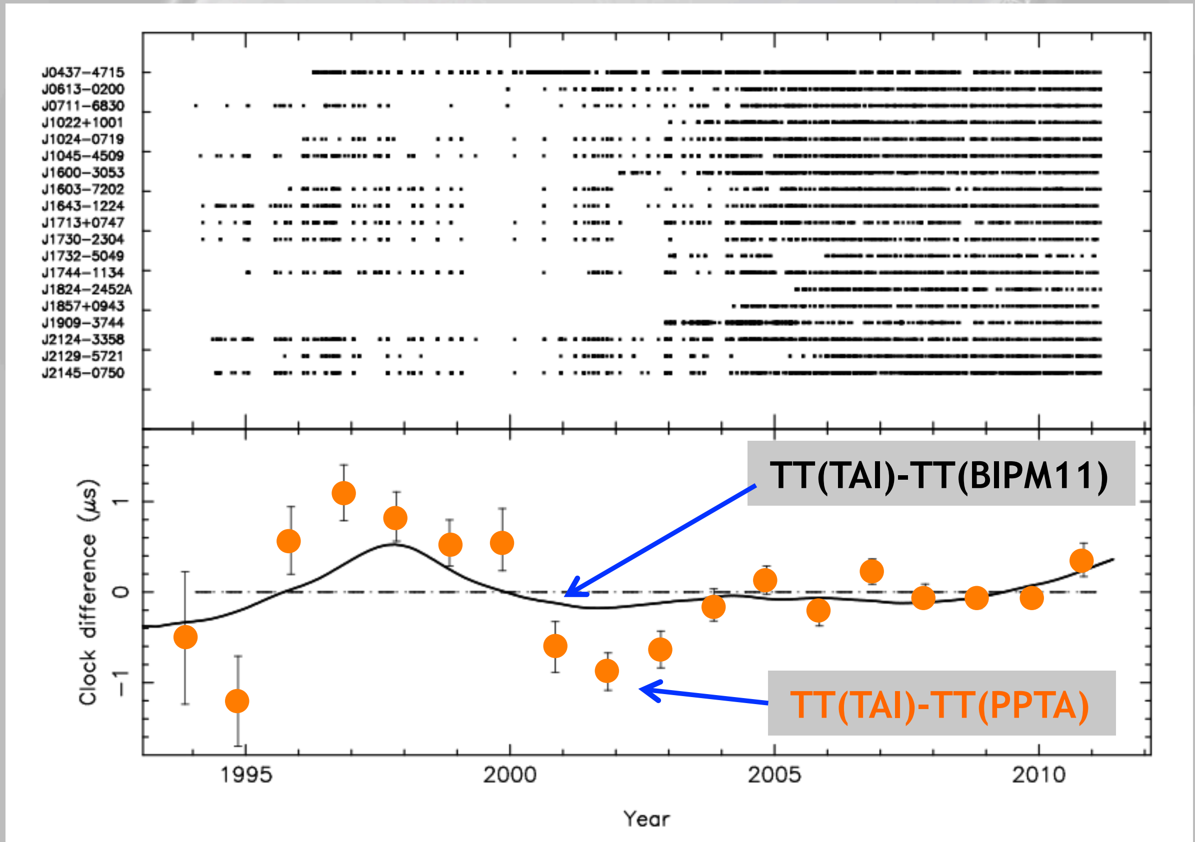
...similar to the Échelle Atomique Libre (EAL)

from which the International Atomic Time (TAI) is built (after applying corrections to satisfy the SI definition of second)

and in turn a realization of the Terrestrial Time is obtained TT(TAI) (by referencing clocks to the Earth geoid)

as well as the post-corrected realization of TT published each year and known as TT(BIPMyy)

The Ensemble Pulsar Scale (ESP) can be linked ("steered") to e.g. TT(TAI) [or to TT(BIPMyy)] and then fluctuations of the reference time scale wrt ESP can be spotted and used for creating a pulsar based realization of the terrestrial time TT(PulsarTimingArray)



[Hobbs at al 2012]

II. Current projects: NANOGrav

North American Nanohertz Observatory for Gravitational Waves: NANOGrav

USA & Canada based, using the excellent Arecibo 300m dish and GBT 101m dish and state-of-art backends

Running only since ~ 2008

@ NRAO

@ Cornell

III. Current projects: EPTA-LEAP

European Pulsar Timing Array

+

Large European Array for Pulsar

European based

Running since ~ 2006

EPTA

The telescopes

Effelsberg(100 m)-Westerbork(96 m)-Nancay (92 m)-Lovell(76 m)-Sardinia(64 m)

The IPTA collaboration

The plan for the IPTA pulsar timescale project

1st: We wish to search for correlated signals in the whole IPTA data sets and use this to form a realisation of terrestrial time, TT(IPTAyy)

2nd: We are aiming to measure the stability of the timescale compared with terrestrial timescales and discuss how to combine the new timescale with TT(BIPMyy) in an optimal manner.

G. Hobbs is chairing an IAU working group (which, among others, includes D. Matsakis, G. Petit and R. Manchester) on related topics (with a particular emphasis on comparing and combining terrestrial time standards with a pulsar time standard). IAU members may join this working group.

What the Ensemble Pulsar Scale (ESP) and a pulsar based realization of the terrestrial time TT(IPTAyy) could be worth for

- Independent check on TT(BIPMyy) with a non terrestrial “device”
- A timescale not based on quantum effects on clocks
- Never ending time scale

Thank you !

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