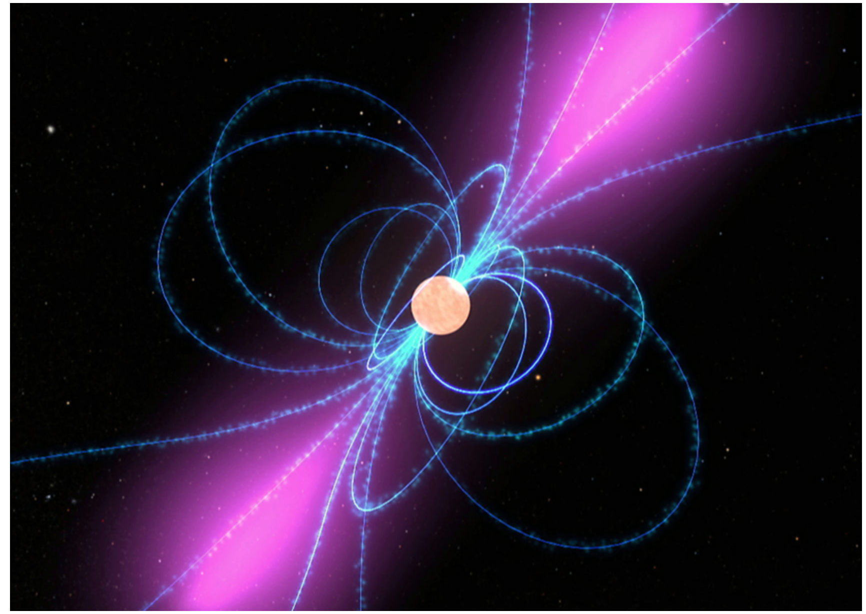


PTA+GR
Using pulsars to detect Gravitational Waves & test Relativistic Gravity

Delphine Perrodin

INAF – Osservatorio Astronomico di Cagliari

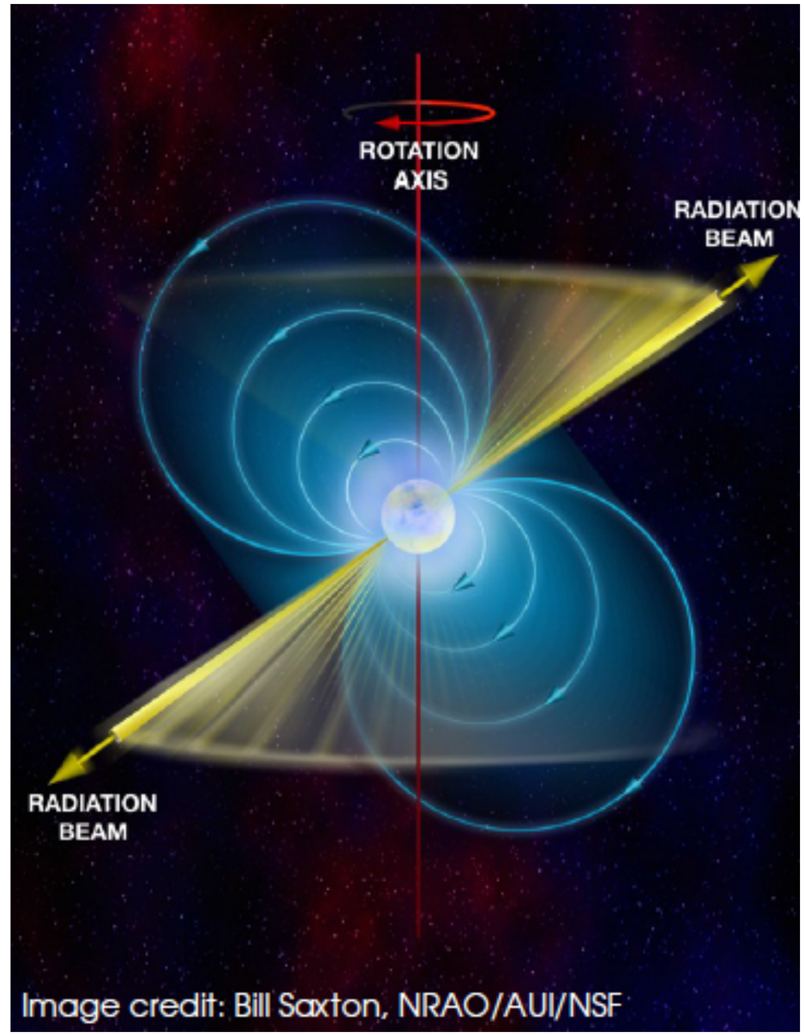
INAF RSN4 auditions, 10/05/2022

Pulsars

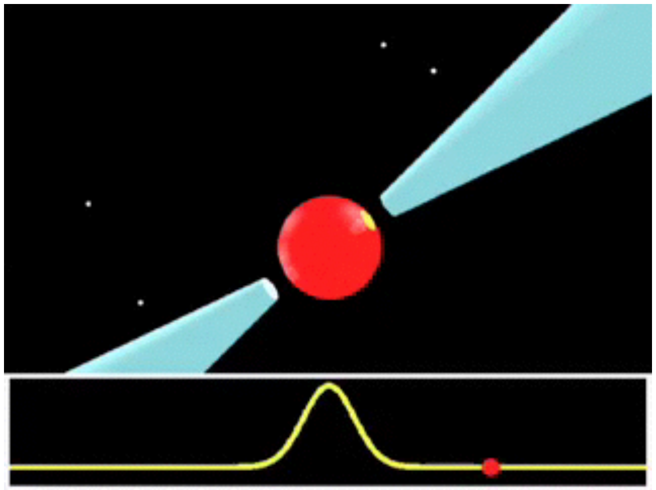
Pulsars are fast-rotating neutron stars
(rotation period: 1 ms–10 s)

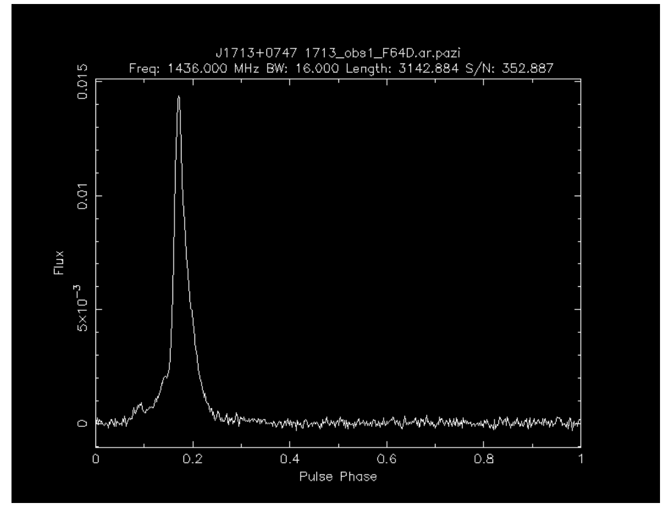
Highly magnetized

Radio beams



Pulsars are “cosmic lighthouses”





SRT observation

We can determine pulsar properties with high accuracy:
- rotation period (up to 15 sig figs!), dispersion measure, orbital parameters if pulsar in binary

The spin period of PSR J1909-3744 is:

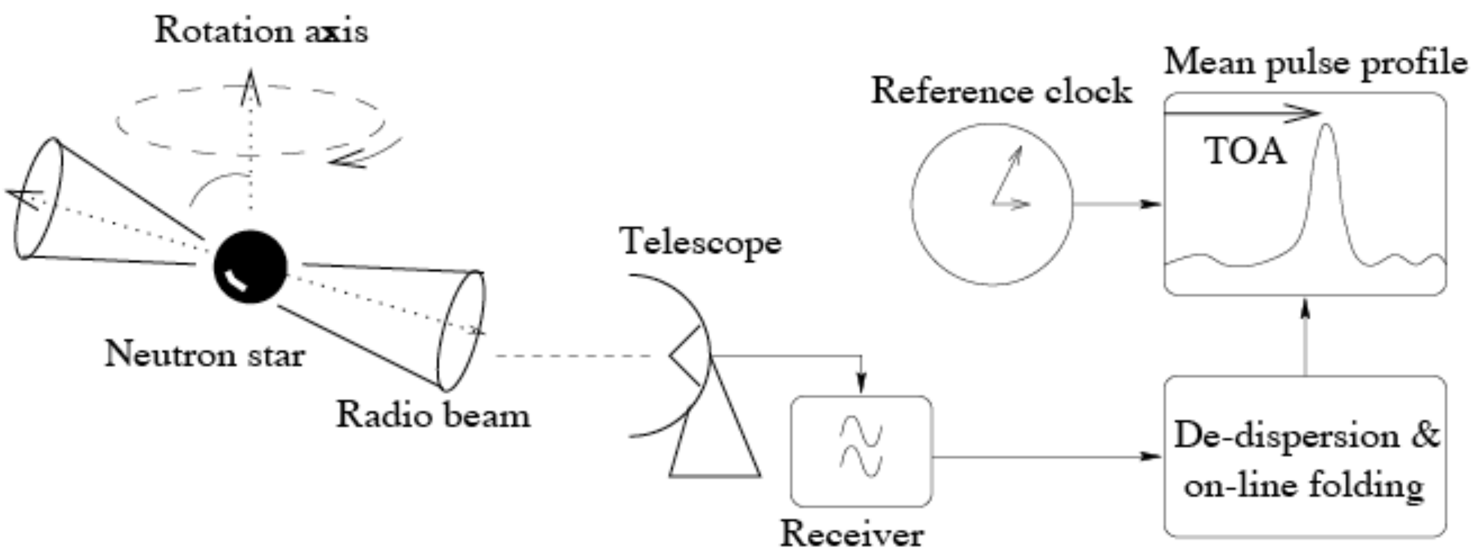
P = 0.002947108068107640 1 ± 0.000000000000000000009 sec

[Verbiest et al 2009]

We can predict the pulse arrival times to ~ 10 ns over 1 year!

Pulsar Timing

Goal: To account for every rotation of the pulsar



(Lorimer & Kramer 2005)

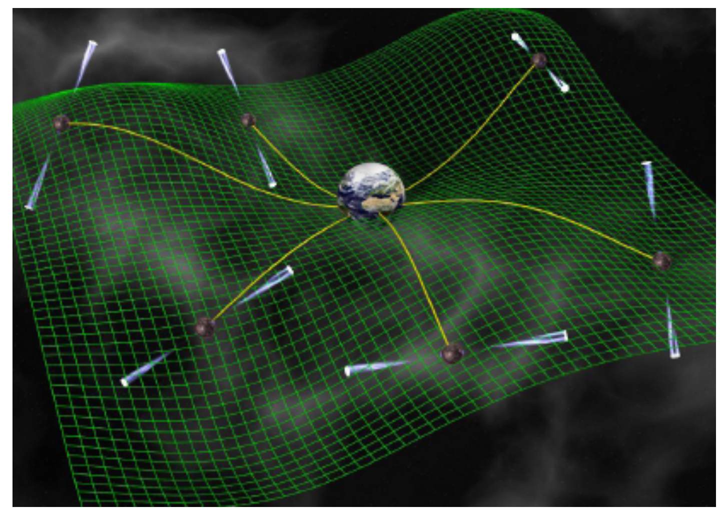
Procedure:

- observe for minutes to hours
- correct for dispersion and fold
- correlate with template profile
- determine time of arrival (TOA)
- improve pulsar timing model
- study residuals

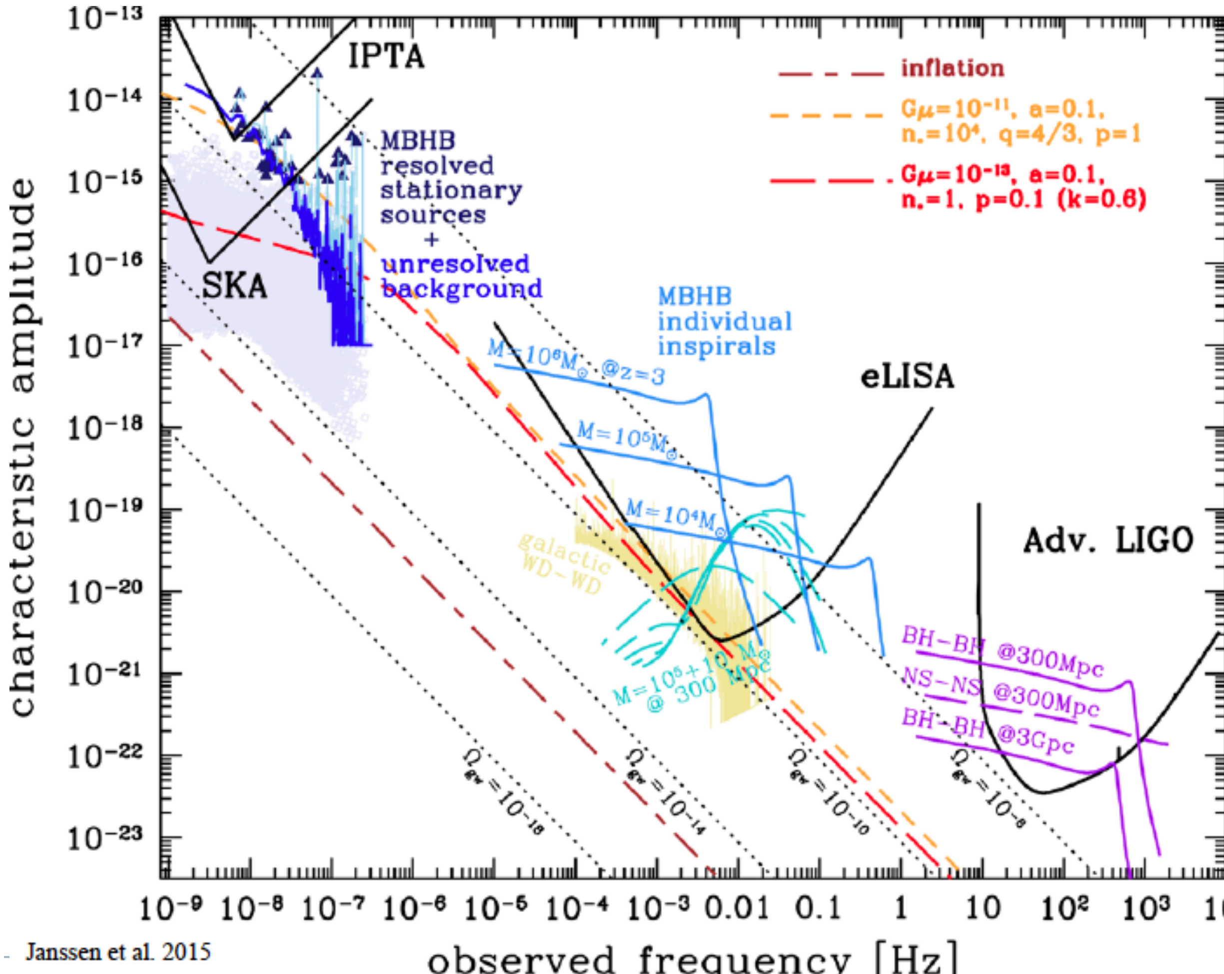
Pulsar Timing Arrays for GW detection

Pulsar Timing Arrays (PTAs) use millisecond pulsars (MSPs) and Earth as test masses.
GWs affect the space-time between Earth and pulsars, introducing offsets in pulsar times-of-arrival (TOAs).

- PTAs sensitive to nHz GWs from supermassive BH binaries and cosmic strings
- PTAs monitor timing residuals of MSPs over 10-30 years
- Detection achieved by studying correlation of residuals between different pulsars



PTAs: complementary to LIGO and LISA

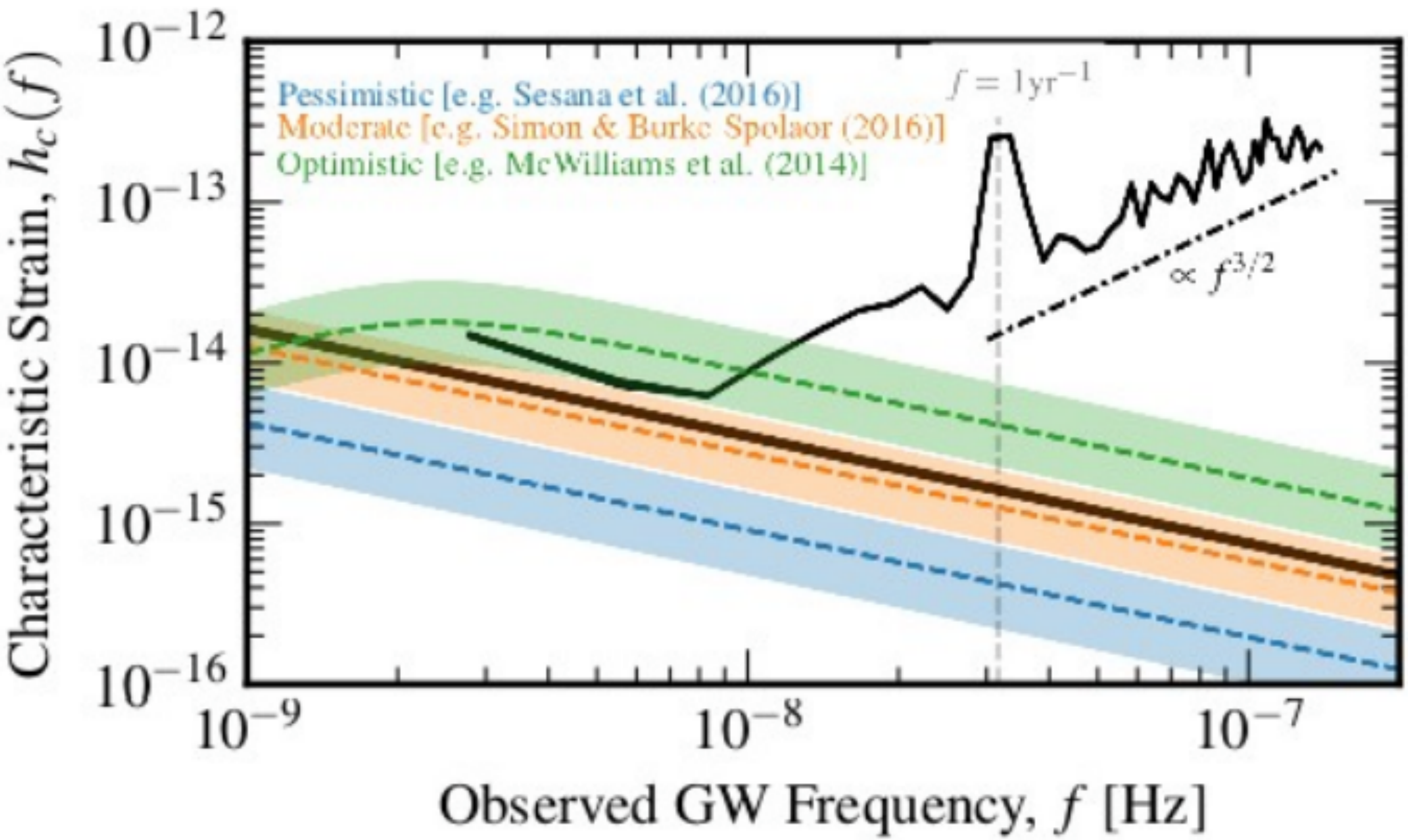


Janssen et al. 2015

PTAs: frequencies in nanohertz regime

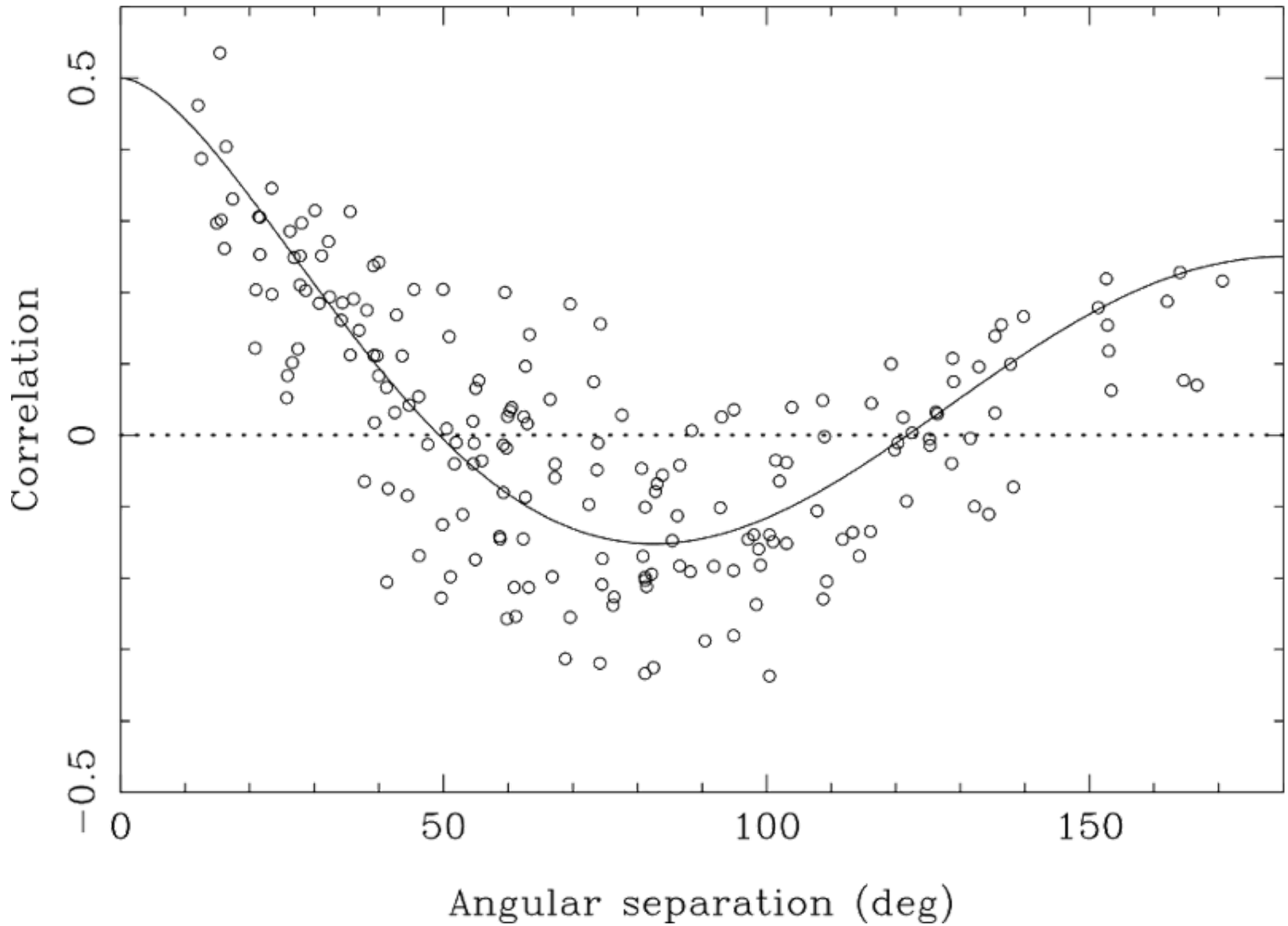
Corresponds to timelines of ~1-30 years

PTAs: constraints on SMBHB background



Arzoumanian et al. 2018

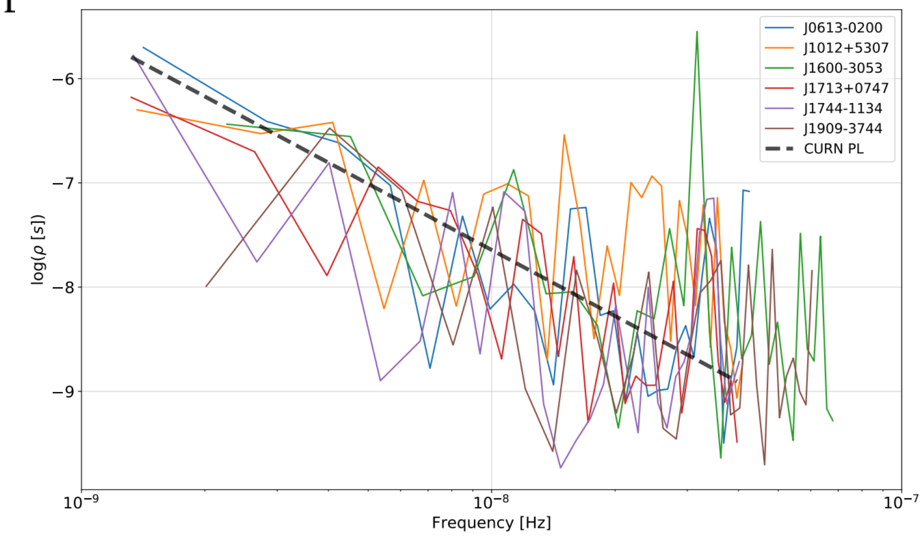
Optimal statistic for GW detection: Hellings & Downs curve



Common red signal: signature of a GW??

Common-red-signal analysis with 24-yr high-precision timing of the European Pulsar Timing Array: Inferences in the stochastic gravitational-wave background search

S. Chen[1,2★], R. N. Caballero[3†], Y. J. Guo[4], A. Chalumeau[5,1,2], K. Liu[4], G. Shaifullah[6,7], K. J. Lee[3,8,4], S. Babak[5,9], G. Desvignes[4,10], A. Parthasarathy[4], H. Hu[4], E. van der Wateren[11,12], J. Antoniadis[13,4,14], A.-S. Bak Nielsen[4,15], C. G. Bassa[11], A. Berthereau[1,2], M. Burgay[16], D. J. Champion[4], I. Cognard[1,2], M. Falxa[5], R. D. Ferdman[17], P. C. C. Freire[4], J. R. Gair[18], E. Graikou[4], L. Guillemot[1,2], J. Jang[4], G. H. Janssen[11,12], R. Karuppusamy[4], M. J. Keith[19], M. Kramer[4,19], X. J. Liu[20,19], A. G. Lyne[19], R. A. Main[4], J. W. McKee[21], M. B. Mickaliger[19], B. B. P. Perera[22], D. Perrodin[16], A. Petiteau[5], N. K. Porayko[4], A. Possenti[16,23], A. Samajdar[6], S. A. Sanidas[19], A. Sesana[6,7], L. Speri[18], B. W. Stappers[19], G. Theureau[1,2,24], C. Tiburzi[11], A. Vecchio[25], J. P. W. Verbiest[15,4], J. Wang[15], I



International Pulsar Timing Array (IPTA)

NANOGrav

Image source, clockwse from upper left: http://www.gb.nrao.edu/; http://www.astron.nl/; http://www.mpifr-bonn.mpg.de/english/index.html; http://gmrt.ncra.tifr.res.in/; http://www.flickr.com/photos/shami_chatterjee/455275921/; http://www.srt.inaf.it/; http://www.obs-nancay.fr/; http://www.jb.man.ac.uk/; http://www.naic.edu/

EPTA

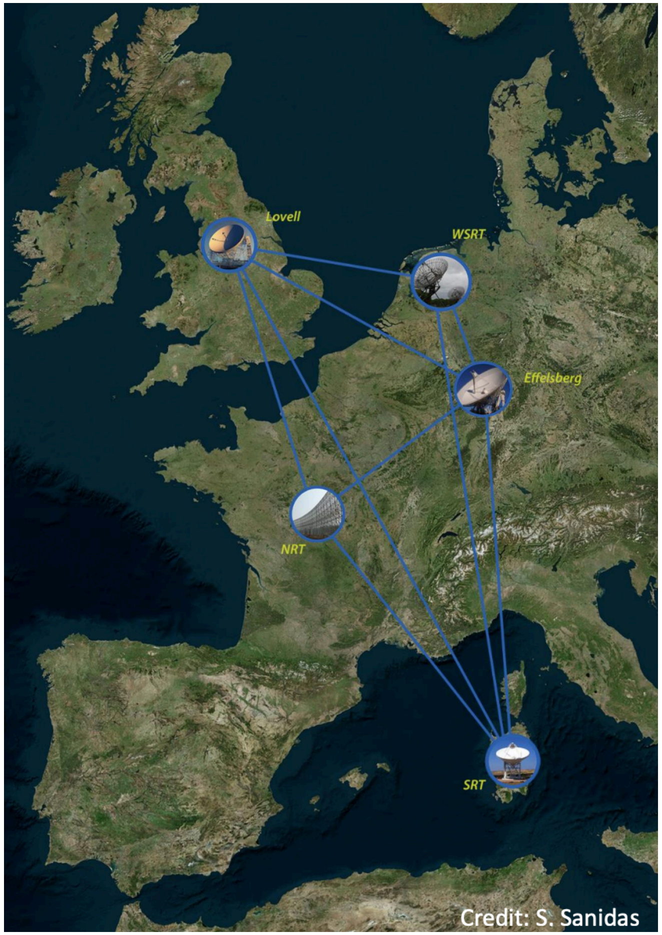
PPTA

The European Pulsar Timing Array

The Sardinia Radio Telescope (SRT) is the latest addition to the European Pulsar Timing Array (EPTA)

and to the Large European Array for Pulsars (LEAP) project that performs simultaneous observations at all 5 EPTA telescopes

Located south of other EPTA telescopes, can observe more southern pulsars such as J1909-3744



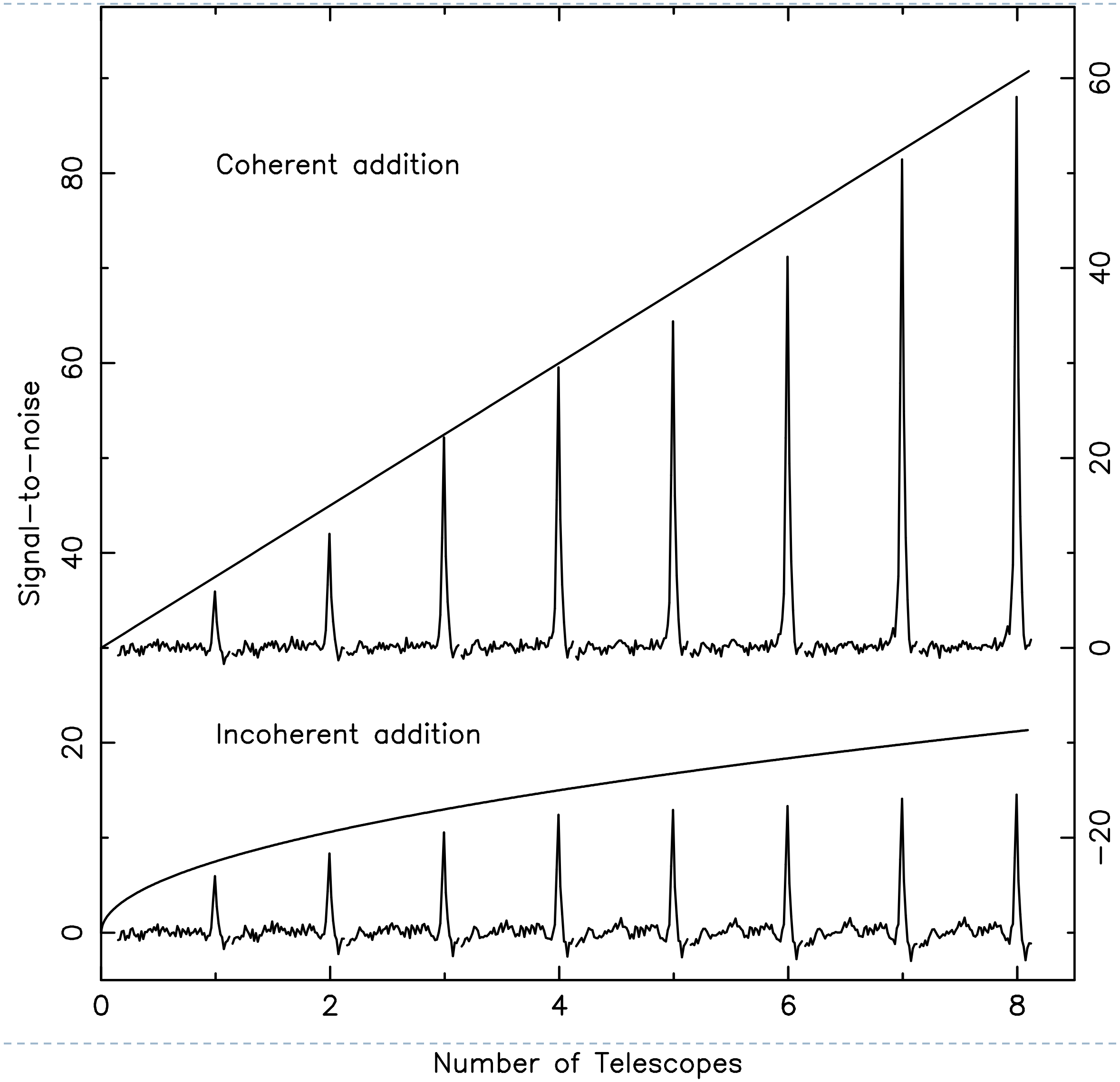
LEAP: the experimental design

➢Coherently combine raw voltage data from the five 100m-class European telescopes to form a phased array

➢Sensitivity equivalent to a 194-m dish, similar to SKA Phase 1. Pathfinder for next generation of radio telescopes

➢Comparable in aperture to the illuminated Arecibo dish, but able to cover $-30 < \mathrm{dec} < 90$

LEAP: the experimental design



The Sardinia Radio Telescope (SRT)

- Fully-steerable 64-m diameter dish
- 3 main focal positions
- Can host 20 receivers
- Wide frequency range (300 MHz to 115 GHz)
- Active surface
- Dual L/P band receiver

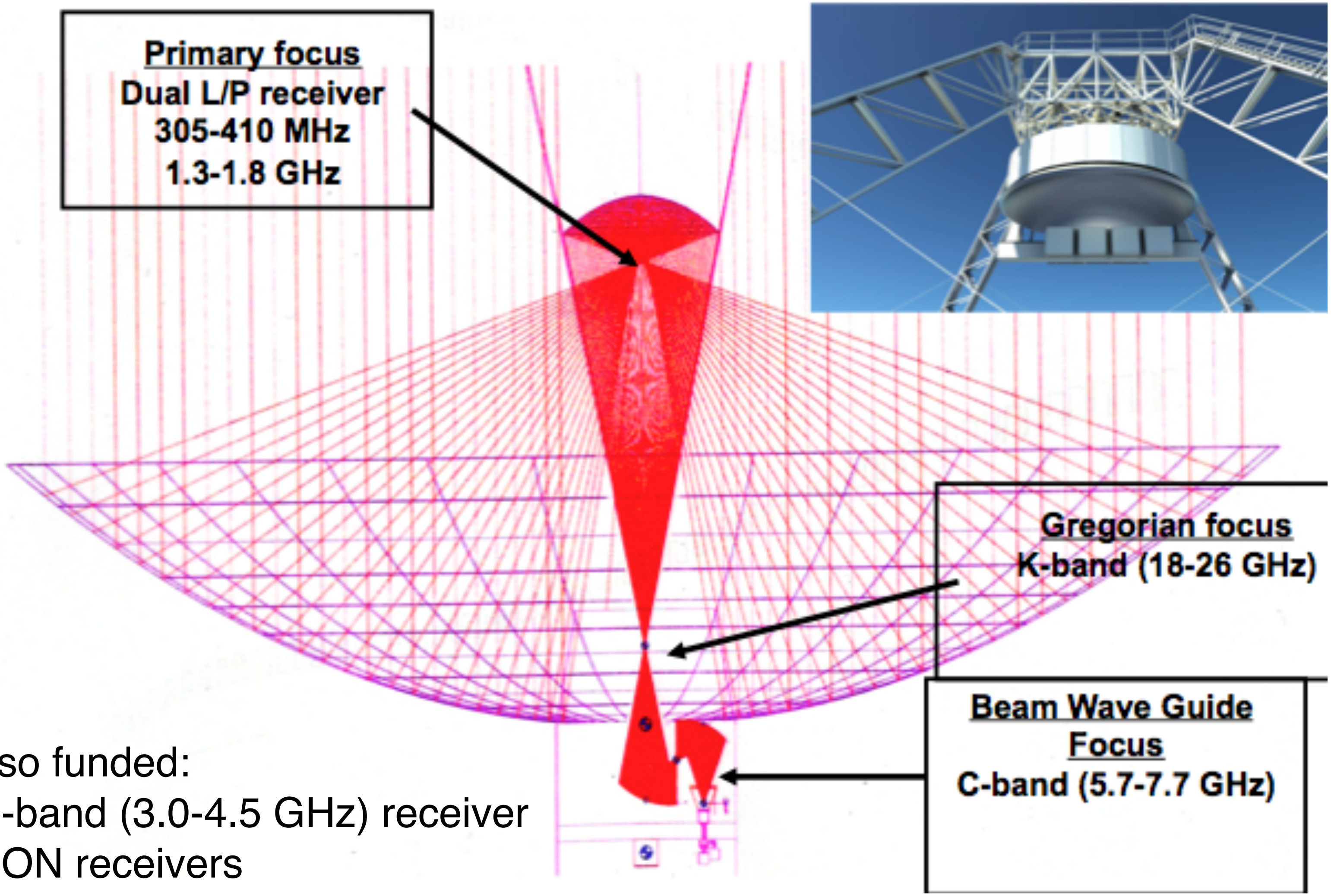
Sardinia Radio Telescope

SRT

INAF

ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

Receiver fleet at SRT

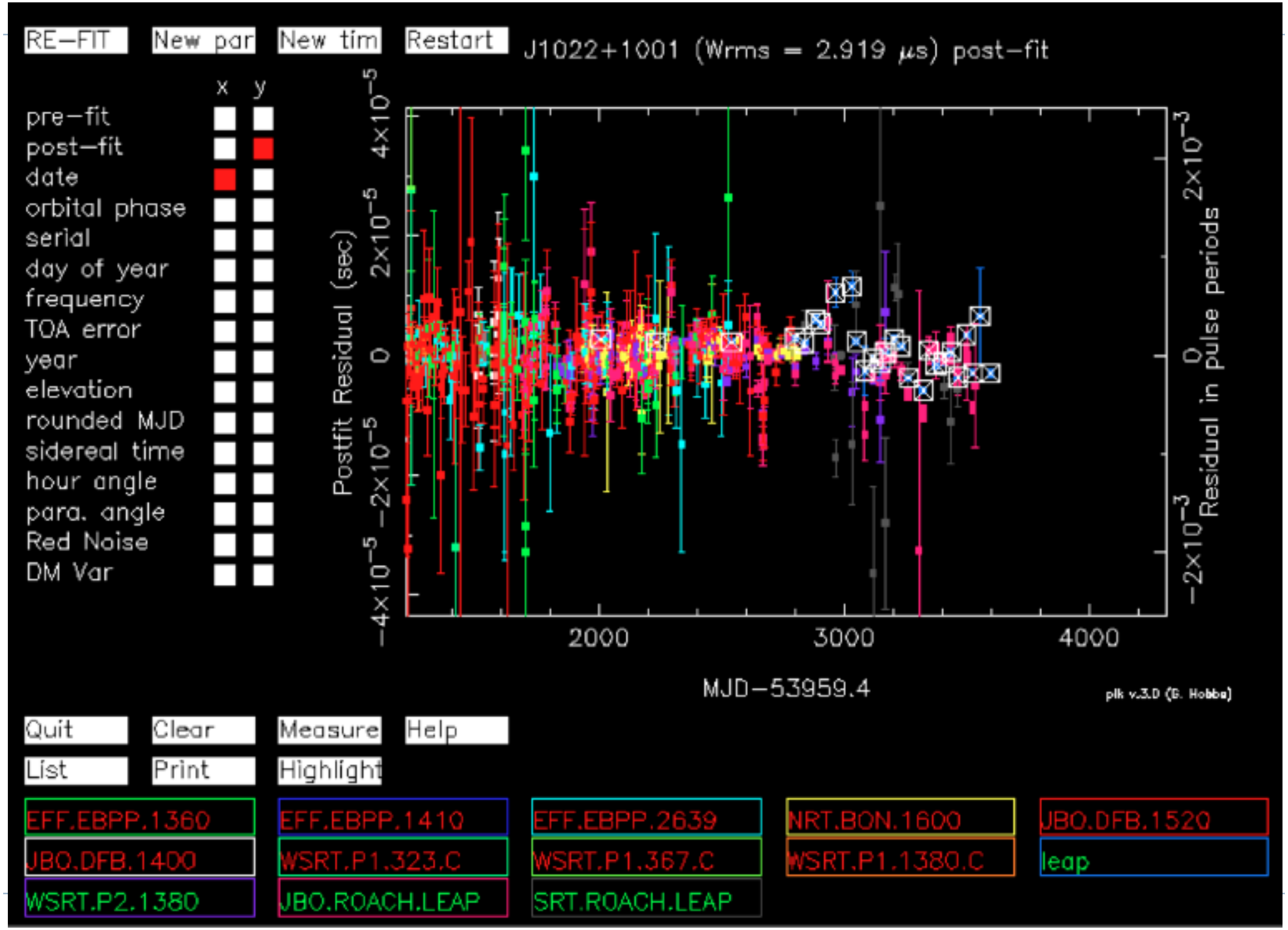


Also funded:
- S-band (3.0-4.5 GHz) receiver
- PON receivers

SRT and PTAs

- Commissioning data since 2013 and ongoing LEAP+EPTA proposals since 2016
- More than 1000 hours of observing so far
- Correlation of SRT data with other LEAP telescopes
- LEAP data has been added to EPTA data for best timing set
- EPTA data is being added to IPTA data for best timing set
- Will get better constraints on background of SMBHBs and possibly detect GWs!

Combine LEAP TOAs with EPTA data



Prospects/planning: Pulsar Timing Arrays

To detect GW, need to achieve higher sensitivity. This can be done by:

- Obtaining longer dataspan —> Continue monthly monitoring of MSPs at L-band for LEAP/EPTA
- Accurately modelling the effects of interstellar medium
- -> with SRT's dual L/P band receiver, continue to perform simultaneous observations and characterize interstellar medium effects (also include more pulsars and higher cadence)
- -> analyse all L/P SRT data from 2016-2021 and compare with LOFAR results
- Accurately modelling the effects of the Solar Wind and incorporate effects into GW search pipeline

We also need to check data formats across telescopes and perfect our efforts at data combination, getting rid of systematic errors

Additionally, PTAs and Gaia can be used synergistically for faster GW detection

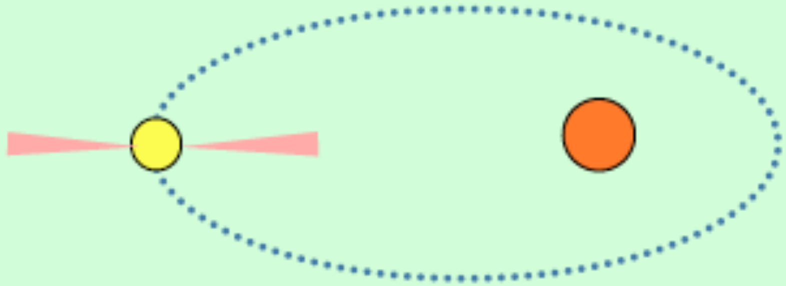
Testing Relativistic Gravity with pulsars

Of about 2500 pulsars,
10% are binaries.

Five Keplerian parameters determined to 4-12 significant figures

Keplerian orbital elements:

Orbital period
Projected semi-major axis
Eccentricity
Angle of periastron
Time of periastron passage

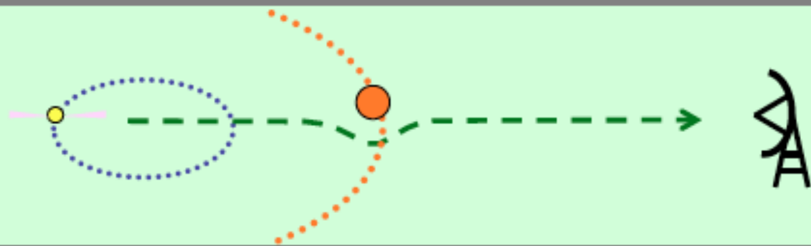


Post-Keplerian formalism

Precession

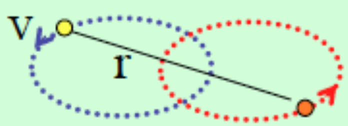
$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{1}{1-e^2} \left[\frac{G}{c^3}(m_1+m_2)\right]^{2/3}$$

Shapiro Delay



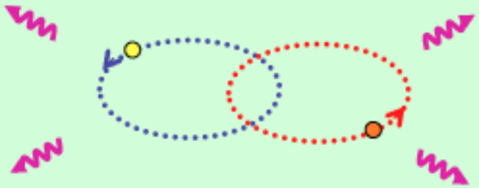
$$\Delta t = 2\frac{G}{c^3} m_2 \ln\left[1 - \sin i \sin(\varphi - \varphi_0)\right]$$

Grav Redshift/Time Dilation



$$\gamma = \frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{1/3} e \frac{m_2(m_1+2m_2)}{(m_1+m_2)^{4/3}}$$

Gravitational Radiation



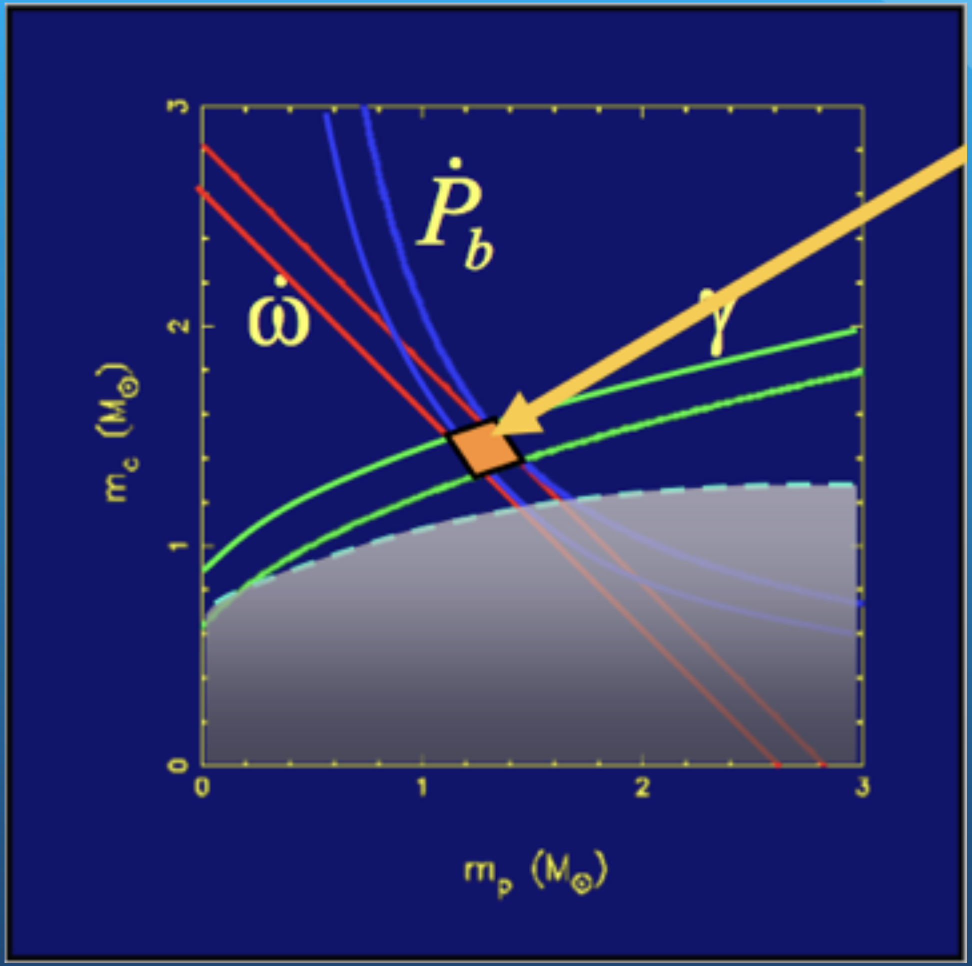
$$\dot{P}_b = -\left(\frac{192\pi}{5}\right)\frac{G^{5/3}}{c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{1}{(1-e^2)^{7/2}}\frac{m_1 m_2}{(m_1+m_2)^{1/3}}$$

Tests of gravity with PK formalism

$$
\begin{aligned}
\dot{\omega} &= 3\left(\frac{P_b}{2\pi}\right)^{-5/3} (T_\odot M)^{2/3} (1-e^2)^{-1}\,, \\
\gamma &= e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_c (m_p + 2m_c)\,, \\
\dot{P}_b &= -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2} T_\odot^{5/3} m_p m_c M^{-1/3}\,, \\
r &= T_\odot m_c\,, \\
s &= x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_c^{-1}\,.
\end{aligned}
$$

PK parameters function of Keplerian parameters and the 2 masses
With 2 PK -> solve for 2 masses
More than 2 PK -> tests of GR
Especially interesting: DNS and PSR-WD

Tests of GR



Double Pulsar

Burgay et al 2003, Lyne et al 2004

PSR+PSR!

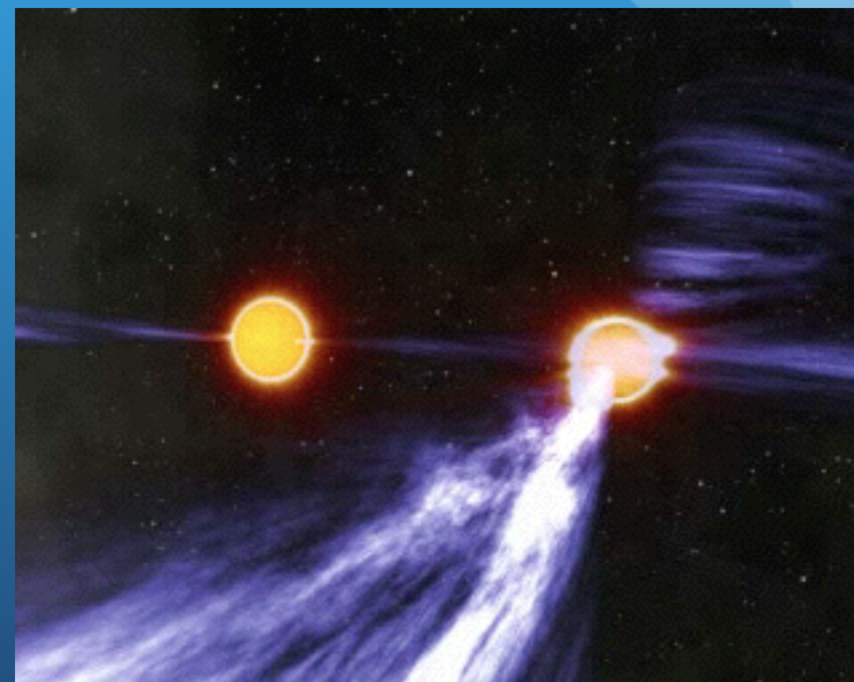
P_{spin} = 23 ms + 2.7 s

P_{orb} = 2.4 hr

Ecc = 0.09

i = 89.29°

Orb vel = 0.01 c !!!



Credits: John Rowe

Strong-field Gravity Tests with the Double Pulsar

M. Kramer,[1,2,*] I. H. Stairs,[3] R. N. Manchester,[4] N. Wex,[1] A. T. Deller,[5,6] W. A. Coles,[7] M. Ali,[1,8] M. Burgay,[9] F. Camilo,[10] I. Cognard,[11,12] T. Damour,[13] G. Desvignes,[14,1] R. D. Ferdman,[15] P. C. C. Freire,[1] S. Grondin,[3,16] L. Guillemot,[11,12] G. B. Hobbs,[4] G. Janssen,[17,18] R. Karuppusamy,[1] D. R. Lorimer,[19] A. G. Lyne,[2] J. W. McKee,[1,20] M. McLaughlin,[19] L. E. Münch,[1] B. B. P. Perera,[21] N. Pol,[19,22] A. Possenti,[9,23] J. Sarkissian,[4] B. W. Stappers,[2] and G. Theureau[11,12,24]

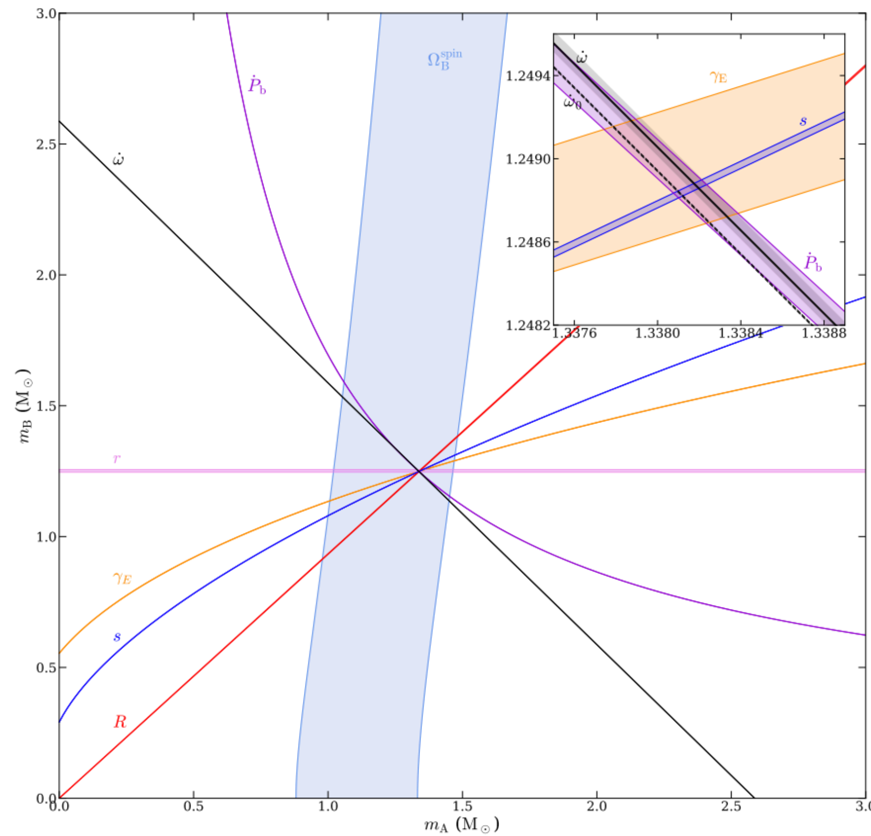
16-year data span

7 PK parameters

This value is in perfect agreement with the observed value given in Eq. (44), leading to a GR test of

$$\dot{P}_{\rm b}^{\rm GW}/\dot{P}_{\rm b}^{\rm GW,GR} = 0.999963(63)\,. \qquad (48)$$

This is by far the most precise test of GW emission, about a factor of 25 better than in the Hulse-Taylor pulsar [150].



Prospects/planning: Gravity tests with pulsars

- Continue Double Pulsar monitoring at Parkes and GBT
- Pulsar surveys with Parkes, discovery of new binary systems
- Involvement in MeerTime project at MeerKAT (precursor of SKA), monitoring of binary systems
- Expand role with MeerKAT+, take advantage of S-band observations
- Planning for the SKA
- Train personnel in order to play key roles in SKA1-MID and SKA1-LOW

TEAM

- 6 permanent staff (TI) + one postdoc (TD) in Cagliari: experts in pulsar timing, pulsar searching and interstellar medium studies; Discovery and monitoring of the Double Pulsar. Expert users and developers of SRT.
- 1 permanent staff from Milano-Bicocca, expert in analysis of PTA data for GW detection
- Staff from INAF-Torino and University Insubria involved in synergy between PTAs and Gaia
- 1 staff from INAF-Roma: expert in study of compact objects and tests of gravity

1	delphine.perrodin	delphine.perrodin@inaf.it	O.A. CAGLIARI	Y	RICERCATORE	Coordinatrice EPTA/LEAP a SRT; analisi dati EPTA/LEAP; studi teorici
2	marta.burgay	marta.burgay@inaf.it	O.A. CAGLIARI	Y	RICERCATORE	Osservazioni, analisi e interpretazione dati
3	andrea.possenti	andrea.possenti@inaf.it	O.A. CAGLIARI	Y	PRIMO RICERCATORE	Osservazioni, analisi e interpretazione dati. Membro del EPTA-SC.
4	alessandro.corongiu	alessandro.corongiu@inaf.it	O.A. CAGLIARI	Y	RICERCATORE	Osservazioni LEAP/EPTA a SRT
5	alessandro.ridolfi	alessandro.ridolfi@inaf.it	O.A. CAGLIARI	N	RICERCATORE	analisi dati binarie/double pulsar Meerkat/Parkes/GBT e osservazioni LEAP/EPTA a SRT

6	maura.pilia	maura.pilia@inaf.it	O.A. CAGLIARI	Y	RICERCATORE	Osservazioni LEAP/EPTA a SRT	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0
7	andrea.melis	andrea.melis@inaf.it	O.A. CAGLIARI	Y	TECNOLOGO	Osservazioni LEAP a SRT	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0
8	raimondo.concu	rconcu@oa-cagliari.inaf.it	O.A. CAGLIARI	Y	C.T.E.R.	Assistenza tecnica	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0
9	mariateresa.crosta	mariateresa.crosta@inaf.it	O.A. TORINO	Y	RICERCATORE	Osservazioni astrometriche e analisi dati Gaia per sinergie con PTA	[0.0, 0.0, 0.0]	[0.2, 0.2, 0.2]	-1.0
10	deborah.busonero	deborah.busonero@inaf.it	O.A. TORINO	Y	TECNOLOGO	Preparazione e analisi dati Gaia per sinergie con PTA	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0
11	ummi.abbas	ummi.abbas@inaf.it	O.A. TORINO	Y	TECNOLOGO	Preparazione e analisi dati Gaia per sinergie con PTA	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0
12	luigi.stella	luigi.stella@inaf.it	O.A. ROMA	Y	DIRIGENTE DI RICERCA	teoria e interpretazione	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0
13	caterina.tiburzi	caterina.tiburzi@inaf.it	O.A. CAGLIARI	Y	RICERCATORE	analisi dati	[0.5, 0.5, 0.5]	[-1.0, -1.0, -1.0]	-1.0

16. Personale Associato INAF coinvolto

#	Nome	E-mail	Struttura	TI	Qualifica	Ruolo nel Progetto	FTE Impegnate (2022/23/24)	FTE Potenziali (2022/23/24)	Extra
1	francesco.haardt	francesco.haardt@uninsubria.it	Università dell'Insubria	Y	Professore ordinario	teoria e interpretazione	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0
2	massimo.dotti	massimo.dotti@unimib.it	Università di Milano Bicocca	Y	Professore Associato	teoria e interpretazione	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0
3	alberto.sesana	alberto.sesana@unimib.it	Università di Milano Bicocca	Y	Professore Associato	teoria e interpretazione	[0.0, 0.0, 0.0]	[-1.0, -1.0, -1.0]	-1.0

Funding

- 130 kEuro from PRIN MIUR (PI: N. D'Amico, 2003)
- 12 kEuro from PRIN INAF (PI: Bandiera, 2005)
- 30 kEuro from Descartes Prize (2005)
- 250 kEuro from ERC Advanced Grant "LEAP" (PI: M. Kramer, 2009-2014)
- 75 kEuro from Regione Sardegna Grant TRG (PI: M. Burgay, 2017-2019)
- 300 kEuro from PRIN INAF SKA_CTA "Opening a new era in pulsars and compact objects science with MeerKat" (PI: A. Possenti, 2017-2022)
- Applied for INAF Large Grant for PTA efforts: "Gravitational Wave Detection using Pulsar Timing Arrays"

Leadership

- Commissioning and development of SRT which is incorporated into the LEAP, EPTA and IPTA networks
- Staff members of LEAP and EPTA collaborations
- Staff members of IPTA working groups
- Staff members of MeerTime project at MeerKAT
- Staff members of working groups planning for SKA

Difficulties/Critical Issues

- Technical difficulties: GW detection requires extremely precise datasets + the correct parametrization of other effects like from the Interstellar Medium + long data spans
- Need continuous dataset at SRT
- Radio Frequency Interference: military radars, 5G
- Need new funding and personnel!