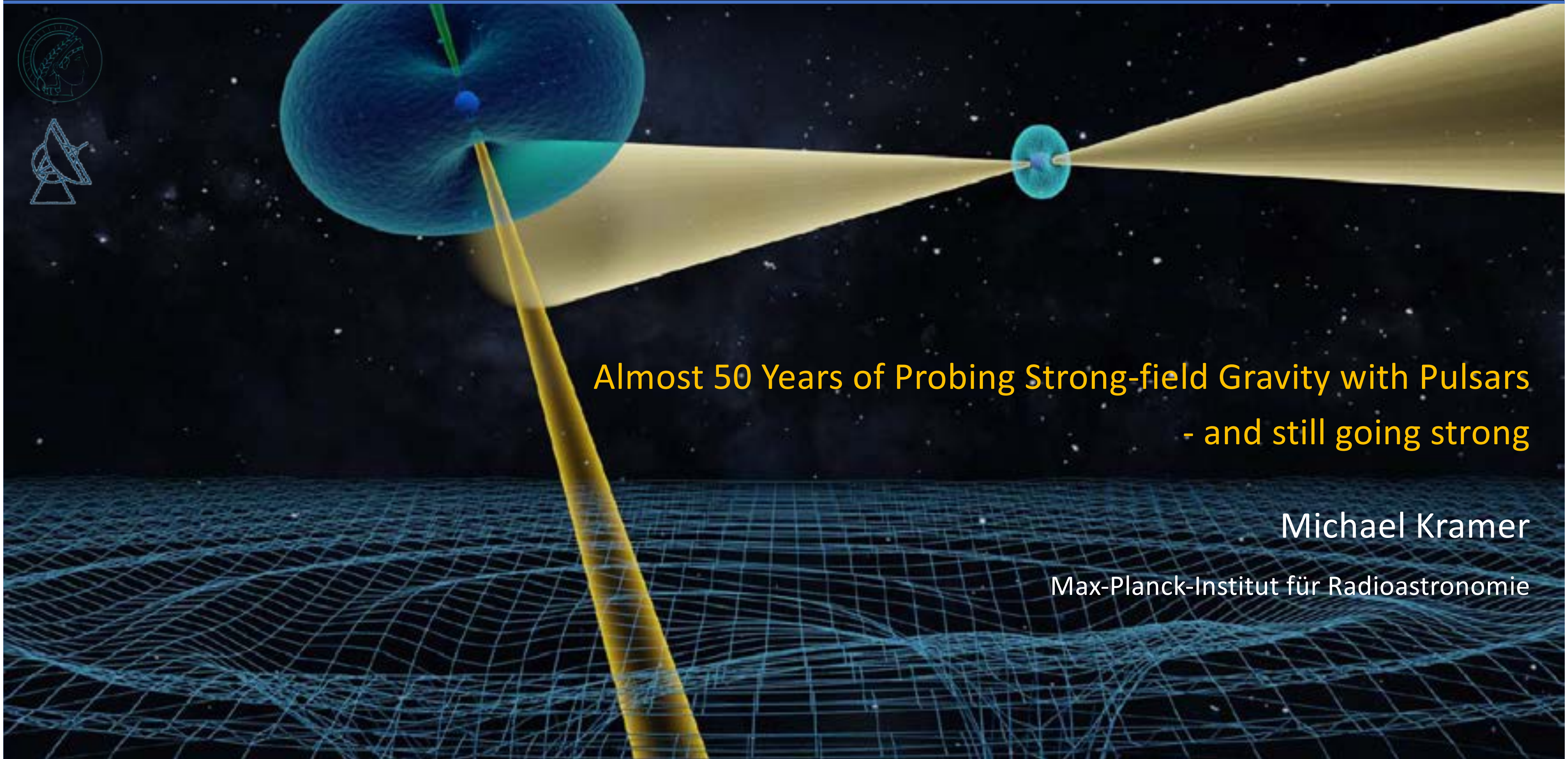


Almost 50 Years of Probing Strong-field Gravity with Pulsars
- and still going strong

Michael Kramer

Max-Planck-Institut für Radioastronomie

PSR J0737-3039 A/B

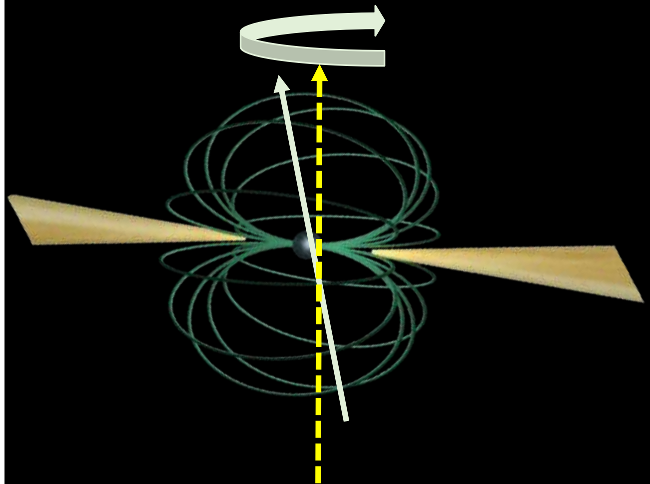
Almost 50 Years of Probing Strong-field Gravity with Pulsars - and still going strong

This also applies to Thibault himself.

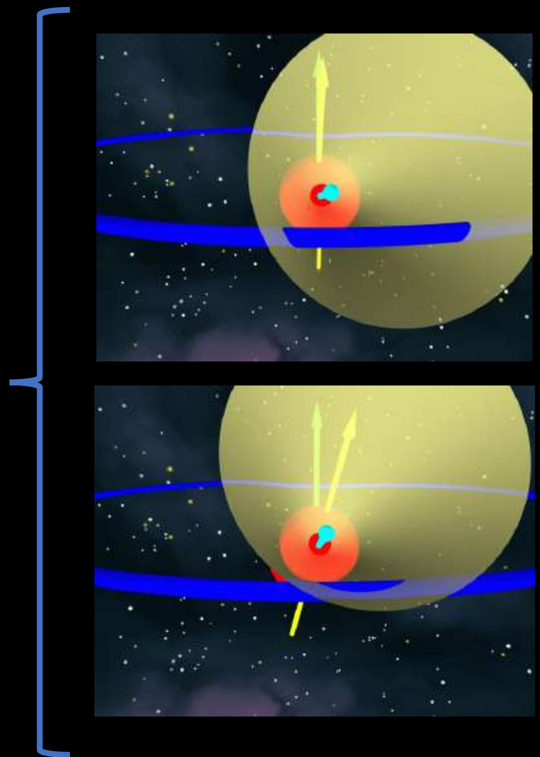
Indeed, there are so many seminal contributions, that we are grateful for.

I have treasured them from the beginning of my career and I haven’t stopped doing so.

Some appeared even before the discovery paper of the first binary pulsar was published : geodetic precession



Damour & Ruffini (1974)



C. R. Acad. Sc. Paris, t. 279 (23 décembre 1974) — Série A — 971

RELATIVITÉ. — ...

MM. Thibault Damour et Remo Ruffini, présentée par M. André Lichnerowicz.

The “DD“ timing model

We present a new method for solving explicitly the equations of motion of a binary system at the first post-Newtonian approximation of General Relativity. We show how to express the solution in a simple, quasi-Newtonian form.

...We derive a new « timing formula » ...simpler and more complete ... than presently existing timing formulas. ... This should lead to additional tests ... (and) ... to the first test of relativistic theories of gravity independent of any hypothesis of « cleanness » of the system.

All modern timing formulae derive from “DD“!

Ann. Inst. Henri Poincaré.
Vol. 43, n° 1, 1985, p. 107-132 *Physique théorique*

General relativistic celestial mechanics of binary systems I. The post-Newtonian motion

by

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Observatoire de Paris-Meudon, 92195 Meudon Principal Cedex (France)

and

N. DERUELLE
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ABSTRACT. — We present a new method for solving explicitly the equations of motion of a binary system at the first post-Newtonian approximation of General Relativity. We show how to express the solution in a simple, quasi-Newtonian form. The results are compared and constrasted with other results existing in the literature.

RÉSUMÉ. - Nous présentons une nouvelle méthode de résolution explicite des équations du mouvement d'un système binaire à la première approximation post-newtonienne de la Relativité Générale. Nous montrons comment exprimer la solution sous une forme particulièrement simple, quasi-newtonienne. Les résultats sont confrontés à ceux précédemment obtenus dans la littérature.

1. INTRODUCTION

The non-relativistic two-body problem consists in two sub-problems: 1) deriving the equations of orbital motion for two gravitationally inter-

Annales de l'Institut Henri Poincaré - Physique théorique - Vol. 43, 0246-0211
85.01/107/26/$ 4.60/© Gauthier-Villars

Damour & Deruelle (1985)

Ann. Inst. Henri Poincaré,
Vol. 44, n° 3, 1986, p. 263-292. *Physique théorique*

General relativistic celestial mechanics of binary systems II. The post-Newtonian timing formula

by

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ABSTRACT. - Starting from a previously obtained « quasi-Newtonian » solution of the equations of motion of a binary system at the first post-Newtonian approximation of General Relativity, we derive a new « timing formula » giving the arrival times at the barycenter of the solar system of electromagnetic signals emitted by one member of a binary system. Our timing formula is simpler and more complete than presently existing timing formulas. We propose to use it as a timing model to be fitted to the arrival times of pulses from binary pulsars. Specifically we show that the use of this timing model in the analysis of the timing measurements of the Hulse-Taylor pulsar could determine more parameters than is presently done. This should lead to additional tests of the simplest model of this binary system and to the first test of relativistic theories of gravity independent of any hypothesis of « cleanness » of the system.

RÉSUMÉ. — A partir d'une solution « quasi-newtonienne » des équations du mouvement d'un système binaire à la première approximation post-newtonienne de la Relativité Générale précédemment obtenue, nous déri-

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Damour & Deruelle (1986)

The "DT92" paper

... a detailed account of the "parametrized post-Keplerian" (PPK) formalism, a general phenomenological framework designed to extract the maximum possible information from pulsar timing and pulse-structure data. The PPK approach allows dynamical information to be obtained from the data in a theory-independent way, and encoded in a certain number of fitted post-Keplerian parameters ... The prospects for extracting some of these tests from observations of known or yet-to-be-discovered binary pulsars is quantitatively assessed ... by combining the PPK approach with the predictions of a rather generic class of tensor-biscalar theories, one can bring together tests based on observations of several different pulsars.

It has been the standard reference ever since...!


PHYSICAL REVIEW D VOLUME 45, NUMBER 6 15 MARCH 1992

ARTICLES

Strong-field tests of relativistic gravity and binary pulsars

Thibault Damour

J. H. Taylor

I. INTRODUCTION

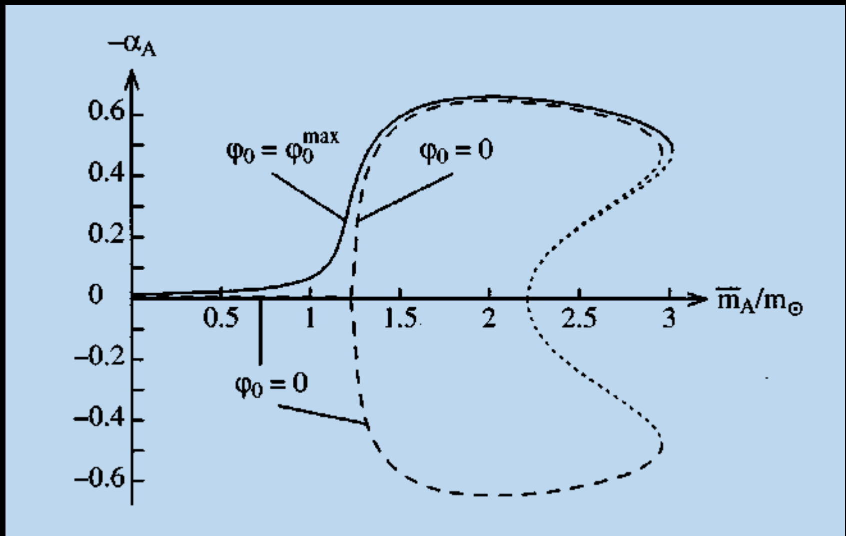
45 1840 ©1992 The American Physical Society

Damour & Taylor (1992)

Alternative theories and "Spontaneous scalarization":

Damour & Esposito-Faresese (1993)

...non-perturbative strong-field effects in tensor-scalar theories ... are interpreted as a scalar analogue of ferromagnetism: ''spontaneous scalarization.'' (...leading to...) very significant deviations from general relativity in conditions involving strong gravitational fields, notably binary-pulsar experiments...



VOLUME 70, NUMBER 15 PHYSICAL REVIEW LETTERS 12 APRIL 1993

Nonperturbative Strong-Field Effects in Tensor-Scalar Theories of Gravitation

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(Received 15 January 1993)

It is shown that a wide class of tensor-scalar theories can pass the present weak-field gravitational tests and exhibit nonperturbative strong-field deviations away from general relativity in systems involving neutron stars. This is achieved without requiring either large dimensionless parameters, fine tuning, or the presence of negative-energy modes. This gives greater significance to tests of the strong gravitational field regime, notably binary pulsar experiments.

PACS numbers: 04.50.+h, 97.60.Jd

PHYSICAL REVIEW D VOLUME 54, NUMBER 2 15 JULY 1996

Tensor-scalar gravity and binary-pulsar experiments

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(Received 28 February 1996)

Some recently discovered nonperturbative strong-field effects in tensor-scalar theories of gravitation are interpreted as a scalar analogue of ferromagnetism: ''spontaneous scalarization.'' This phenomenon leads to very significant deviations from general relativity in conditions involving strong gravitational fields, notably binary-pulsar experiments. Contrary to solar-system experiments, these deviations do not necessarily vanish when the weak-field scalar coupling tends to zero. We compute the scalar ''form factors'' measuring these deviations, and notably a parameter entering the pulsar timing observable γ through scalar-field-induced variations of the inertia moment of the pulsar. An exploratory investigation of the confrontation between tensor-scalar theories and binary-pulsar experiments shows that nonperturbative scalar field effects are already very tightly constrained by published data on three binary-pulsar systems. We contrast the probing power of pulsar experiments with that of solar-system ones by plotting the regions they exclude in a generic two-dimensional plane of tensor-scalar theories. [S0556-2821(96)04314-7]

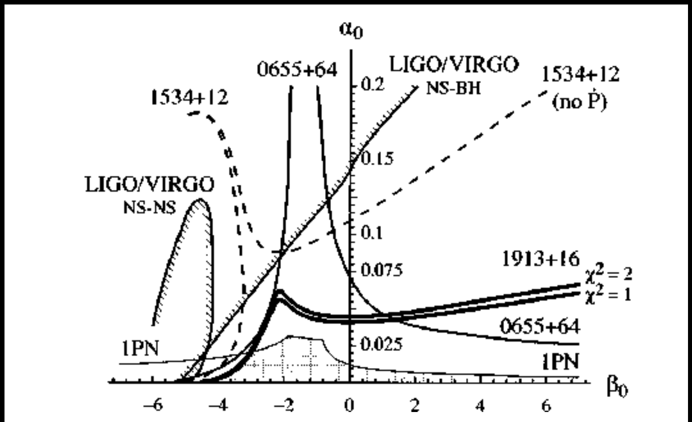
PACS number(s): 04.50.+h, 04.80.Cc, 97.60.Gb

Damour & Esposito-Faresese (1996)

And many more highly relevant papers by Thibault and Gilles...!

Alternative theories and comparison to gravitational wave detectors

Binary systems comprising at least one neutron star contain strong gravitational field regions and thereby provide a testing ground for strong-field gravity. Two types of data can be used to test the law of gravity in compact binaries: binary pulsar observations, or forthcoming gravitational-wave observations of inspiralling binaries.



PHYSICAL REVIEW D, VOLUME 58, 042001

Gravitational-wave versus binary-pulsar tests of strong-field gravity

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(Received 9 March 1998; published 16 July 1998)

Binary systems comprising at least one neutron star contain strong gravitational field regions and thereby provide a testing ground for strong-field gravity. Two types of data can be used to test the law of gravity in compact binaries: binary pulsar observations, or forthcoming gravitational-wave observations of inspiralling binaries. We compare the probing power of these two types of observations within a generic two-parameter family of tensor-scalar gravitational theories. Our analysis generalizes previous work (by us) on binary-pulsar tests by using a sample of realistic equations of state for nuclear matter (instead of a polytrope), and goes beyond a previous study (by C. M. Will) of gravitational-wave tests by considering more general tensor-scalar theories than the one-parameter Jordan-Fierz-Brans-Dicke one. Finite-size effects in tensor-scalar gravity are also discussed. [S0556-2821(98)08616-0]

PACS number(s): 04.80.Cc, 04.30.−w, 97.60.Gb

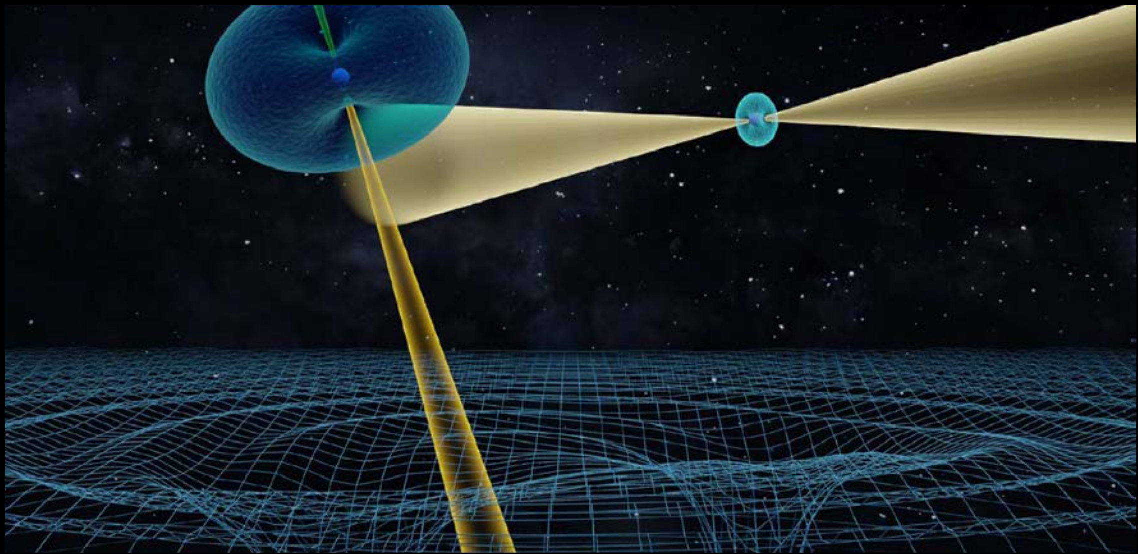
I. INTRODUCTION

The detection of gravitational waves by kilometric-size laser-interferometer systems such as the Laser Interferometric Gravitational Wave Observatory (LIGO) in the US and VIRGO in Europe will initiate a new era in astronomy. One of the most promising sources of gravitational waves is the inspiralling compact binary, a binary system made of neutron stars or black holes whose orbit decays under gravitational radiation reaction. The observation of these systems will provide important astrophysical information, e.g. masses of neutron stars, and direct distance measurements up to hundreds

has studied the quantitative constraints on the coupling parameter α_0 of Jordan-Fierz-Brans-Dicke theories that could be brought by gravitational-wave observations. His result is that in most cases the bounds coming from gravity-wave observations will be comparable to presently known bounds coming from solar-system experiments (namely, $\alpha_0^2 < 10^{-3}$). This result of Ref. [8] seems to suggest that gravitational-wave-based *strong-field* tests of gravity do not go really beyond the solar-system *weak-field* tests of gravity. We wish, however, to emphasize that this seemingly pessimistic conclusion is mainly due to having restricted one's attention to the special, one-parameter Jordan-Fierz-Brans-Dicke theory. Indeed, in this theory the strength of the coupling of the

Damour & Esposito-Faresese (1998)

And still going strong...



In the following:

Some of the milestones & current state of art...

and some more important work by Thibault!

Strong-field Gravity Tests with the Double Pulsar

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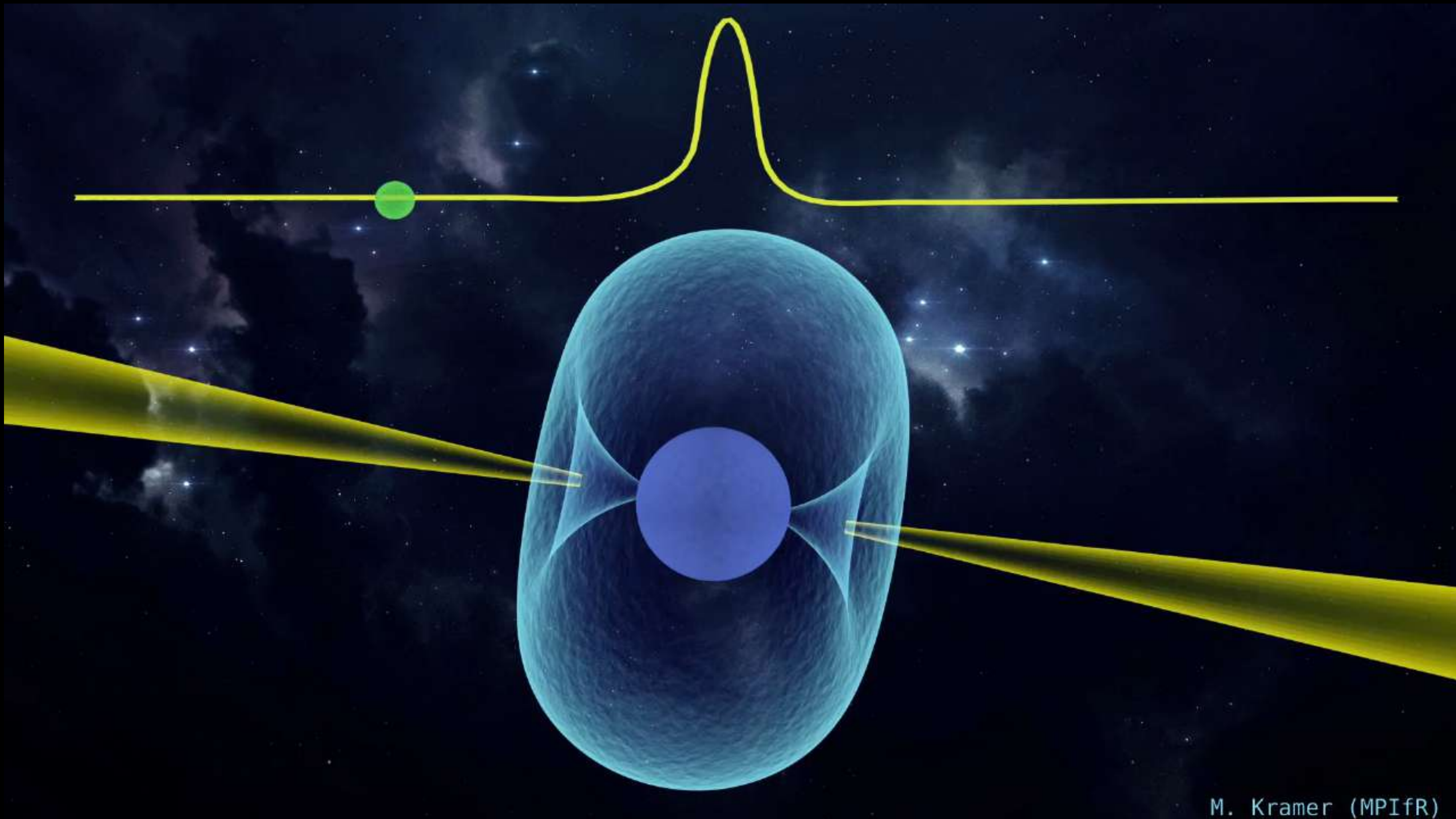
(Dated: October 12, 2021)

Continued timing observations of the Double Pulsar, PSR J0737−3039A/B, which consists of two active radio pulsars (A and B) that orbit each other with a period of 2.45 hr in a mildly eccentric ($e = 0.088$) binary system, have led to large improvements in the measurement of relativistic effects in this system. With a 16-yr data span, the results enable precision tests of theories of gravity for strongly self-gravitating bodies and also reveal new relativistic effects that have been expected but are now observed for the first time. These include effects of light propagation in strong gravitational fields which are currently not testable by any other method. In particular, we observe the effects of retardation and aberrational light-bending that allow determination of the spin direction of the pulsar. In total, we have detected seven post-Keplerian parameters in this system, more than for any other known binary pulsar. For some of these effects, the measurement precision is now so high that for the first time we have to take higher-order contributions into account. These include the contribution of the A pulsar's effective mass loss (due to spin-down) to the observed orbital period decay, a relativistic deformation of the orbit, and the effects of the equation of state of super-dense matter on the observed post-Keplerian parameters via relativistic spin-orbit coupling. We discuss the implications of our findings, including those for the moment of inertia of neutron stars, and present the currently most precise test of general relativity's quadrupolar description of gravitational waves, validating the prediction of general relativity at a level of 1.3×10^{-4} with 95% confidence. We demonstrate the utility of the Double Pulsar for tests of alternative theories of gravity by focusing on two specific examples and also discuss some implications of the observations for studies of the interstellar medium and models for the formation of the Double Pulsar system. Finally, we provide context to other types of related experiments and prospects for the future.

Kramer ...Damour ... et al. (2021)

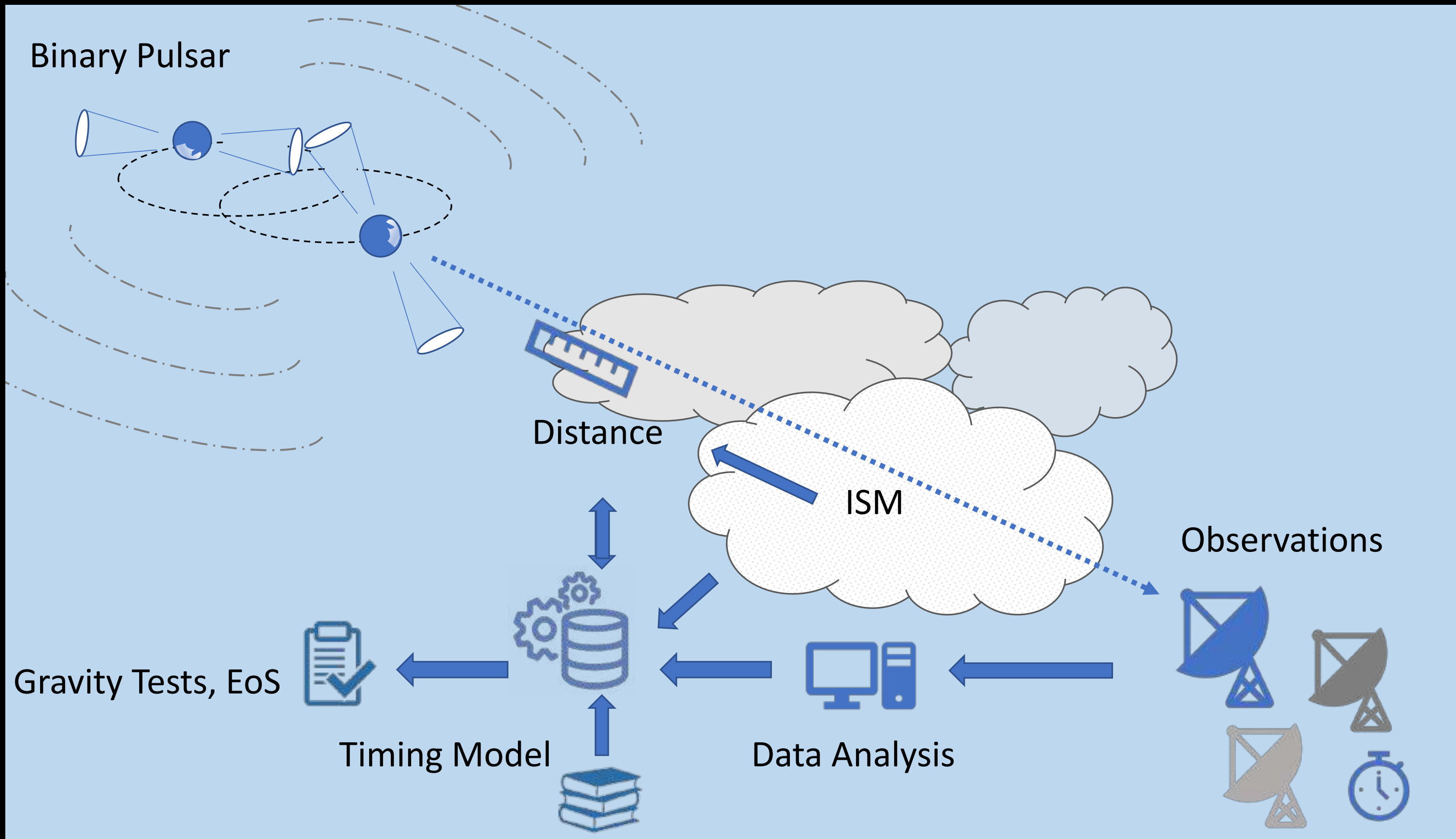
Binary Pulsar experiments are rather simple...

We start with a precise clock attached to a compact massive object...



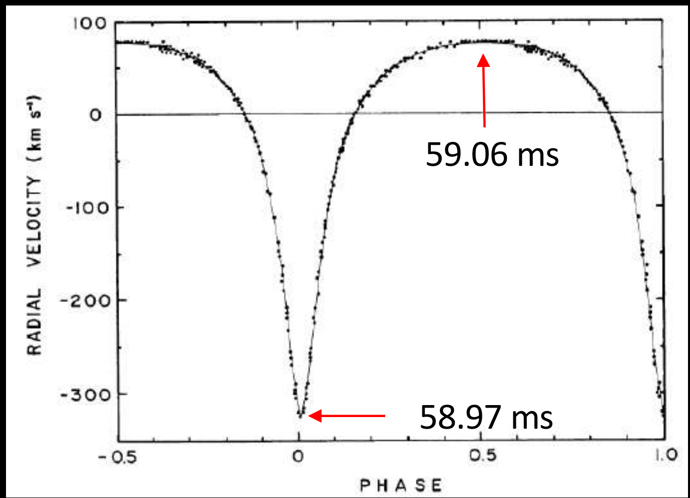
Binary Pulsar experiments are rather simple...

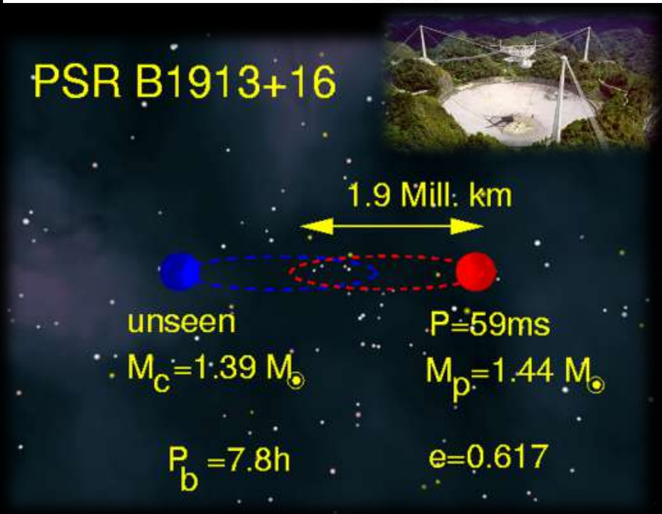
...which we put in a binary system and watch from "safe" distance:



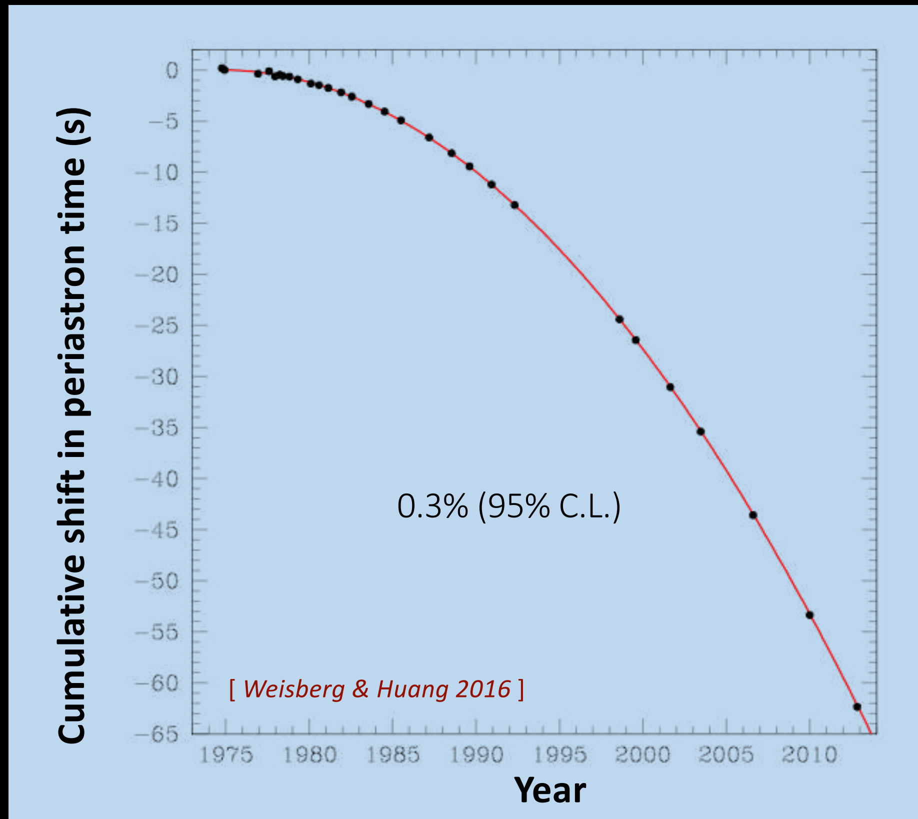
How it all started… & first evidence for gravitational waves

Hulse & Taylor (1975)





- Gravitational waves exist
- Their energy is as predicted by GR
- Gravity propagates with the speed of light
- GR holds for strongly self-gravitating bodies
- Existence of double neutron star mergers



Post Keplerian (PK) - Parameters

- Theory-independent strong-field analogue of PPN formalism: "parametrized post-Keplerian" approach (Damour & Deruelle ’86, Damour & Taylor ’92)
- Theory independent, but given theory makes specific prediction for values as functions of Keplerian parameters and (a priori) unknown masses of pulsar and companion
- Simultaneous measurement of n PK parameters allows (n-2) independent tests of given theory

Post-Keplerian Parameters in GR (leading order)

Periastron advance

$$\dot{\omega} = 3T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{(m_p+m_c)^{2/3}}{1-e}$$

Gravitational wave damping

$$\dot{P}_b = \frac{192\pi}{5}T_\odot^{5/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1+(73/24)e^2+(37/96)e^4}{(1-e^2)^{7/2}}\frac{m_p m_c}{(m_p+m_c)^{1/3}}$$

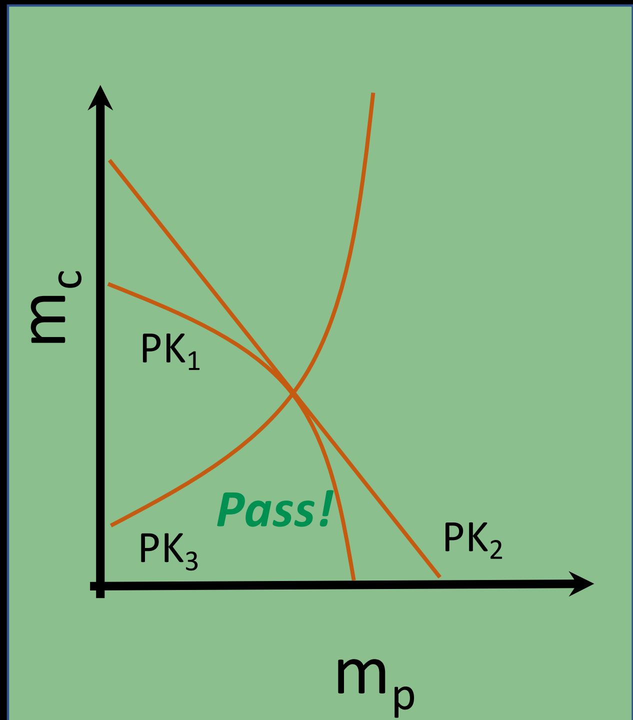
Time dilation

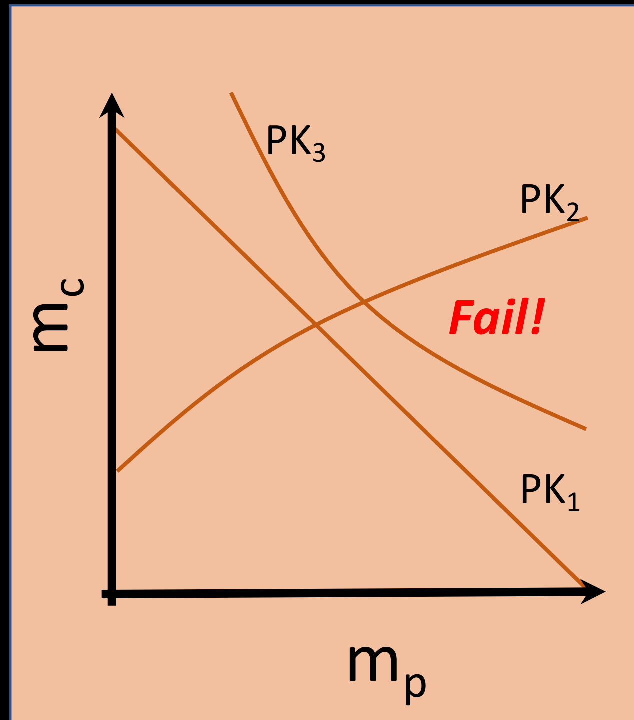
$$\gamma = T_\odot^{2/3}\left(\frac{P_b}{2\pi}\right)^{1/3} e\,\frac{m_c(m_p+2m_c)}{(m_p+m_c)^{4/3}}$$

Shapiro delay (range, shape)

$$r = T_\odot m_c \qquad s = T_\odot^{-1/3}\left(\frac{P_b}{2\pi}\right)^{-2/3} x\,\frac{(m_p+m_c)^{2/3}}{m_c}$$

where $T_\odot = GM_\odot/c^3 \simeq 4.92549\ \mu s$





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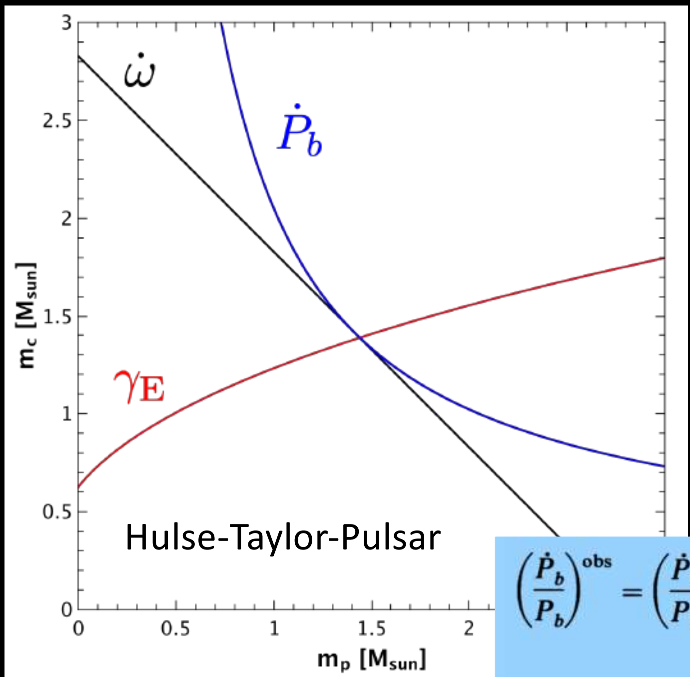

ON THE ORBITAL PERIOD CHANGE OF THE BINARY PULSAR PSR 1913+16

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Joseph Henry Laboratories; and Physics Department, Princeton University

Received 1990 April 10; accepted 1990 June 29

ABSTRACT

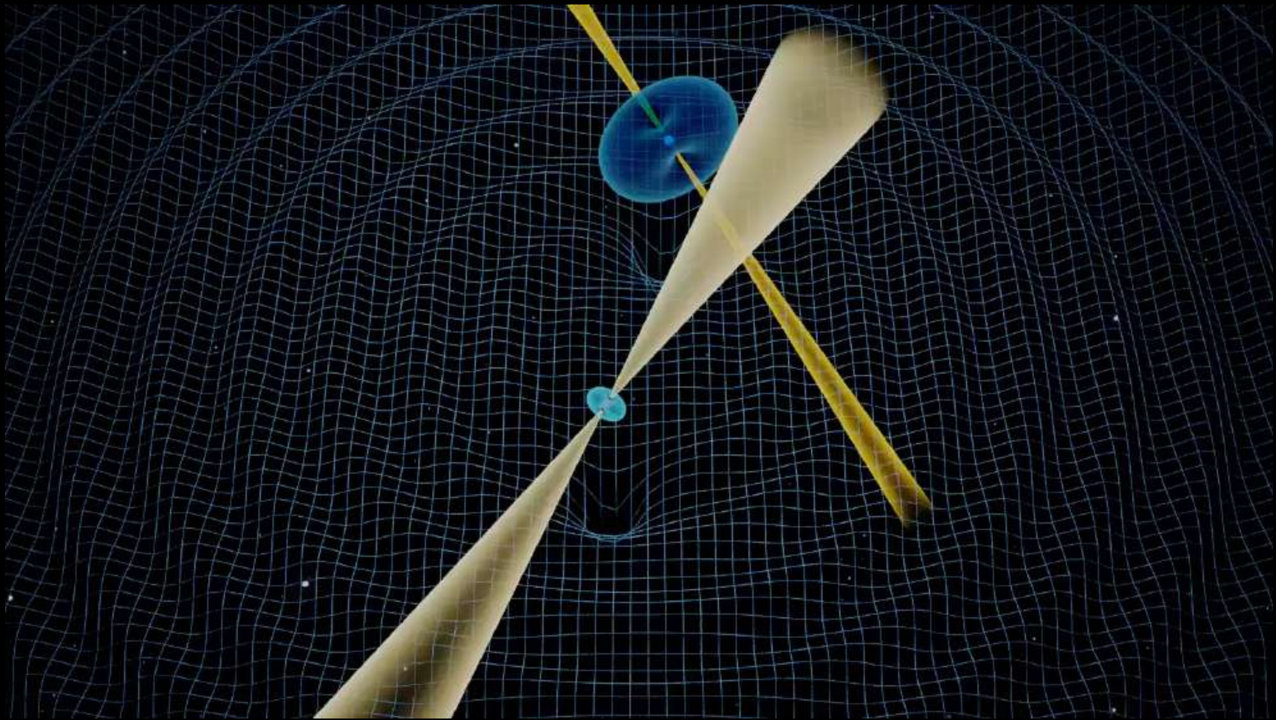
We reexamine the theoretical significance of the raw observational parameter called the “rate of orbital period change,” $\dot P_b^{obs}$, of the binary pulsar PSR 1913+16. We show that the current precision (~0.8%) on the determination of $\dot P_b^{obs}$ makes it necessary to take explicitly into account the effects of the galactic accelerations of the pulsar and the Sun, and that of the proper motion of the pulsar. Several other possible contributions to $\dot P_b^{obs}$ are (re)examined and found negligible. As the value of the galactic contribution to $\dot P_b/P_b$ depends explicitly on the distance to the pulsar, say d, we have been led to reexamine the determination of d from dispersion measurements. We find that recent progress in H I absorption measurements in the first galactic longitude quadrant allows one to constrain the mean electron density along the line of sight to PSR 1913+16 ($l = 50°$) to the range $\bar n_e(50°) = ([6.39 \pm 0.93][R_0/1\ \text{kpc}])^{-1}\ \text{cm}^{-3}$, where R_0 is the galactocentric distance of the Sun. This value for $\bar n_e$ is smaller than the “standard” one and leads to a galactic-reduced distance to PSR 1913+16, $d/R_0 = 1.08 \pm 0.16$. After subtraction of the galactic effects, the latest experimental results yield a … prediction: $\dot P_b^{obs-gal}/\dot P_b^{GR} = 1.0081 \pm 0.0022$(galactic) … an upper bound to the rate of change of Newton’s … ^{1}, which, in the long term, may be limited to the … rtainties in the values of the galactic constants, R_0

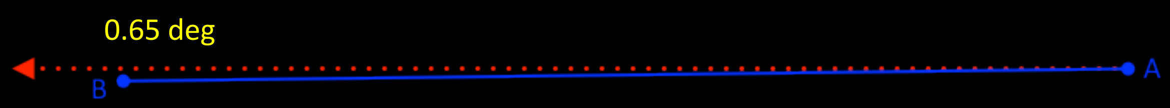
$$\left(\frac{\dot P_b}{P_b}\right)^{\text{obs}} = \left(\frac{\dot P_b}{P_b}\right)^{\text{theor}} + \left(\frac{\dot P_b}{P_b}\right)^{\text{gal}} + \left(\frac{\dot P_b}{P_b}\right)^{\text{accel}} + \left(\frac{\dot P_b}{P_b}\right)^{\dot m_1} + \left(\frac{\dot P_b}{P_b}\right)^{\dot m_2} + \cdots . \quad (1.4)$$

Damour & Taylor (1991)

The Double Pulsar (Burgay et al. 2003, Lyne et al. 2004)

- Mildly recycled 23-ms pulsar in a 147-min orbit with young 2.8-s pulsar - orbital velocities of 300 km/s
- Eclipsing binary in compact (3-lts), slightly eccentric (e=0.088) and edge-on orbit (tilt only 0.65 deg!)
- Ideal laboratory for gravitational physics





<u>Relativistic effects measured:</u>

- Orbital precession
- Time dilation
- Shapiro delay (incl. next-to-leading order)
- Aberrational light bending
- Spin precession
- Relativistic deformation of orbit
- GW emission

Plus theory-independent mass-ratio

The Double Pulsar (Burgay et al. 2003, Lyne et al. 2004)

- Mildly recycled 23-ms pulsar in a 147-min orbit with young 2.8-s pulsar - orbital velocities of 300 km/s
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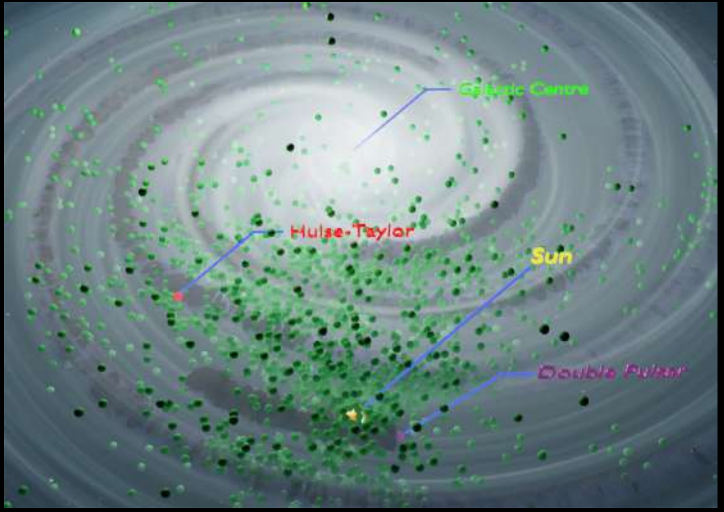
- Ideal laboratory for gravitational physics

Most recent results:

Precision astrometry including parallax

Kramer et al. (2021)

Parameter	Value
Right ascension, α (J2000)	$07^{h}37^{m}51^{s}.248115(10)^{\dagger}$
Declination, δ (J2000)	$-30°39'40''.70485(17)^{\dagger}$
Proper motion R.A., μ_{α} (mas yr^{-1})	$-2.567(30)^{\dagger}$
Proper motion Dec., μ_{δ} (mas yr^{-1})	$2.082(38)^{\dagger}$
Parallax, π_c (mas)	$1.36(+0.12,-0.10)^{\dagger}$
Position epoch (MJD)	55045.0000



Distance = 735 ± 60 pc

Transverse velocity:

11.5 ± 1.5 km/s

Relativistic effects measured:

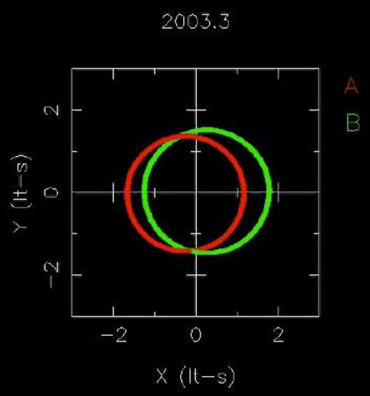
- Orbital precession
- Time dilation
- Shapiro delay (incl. next-to-leading order)
- Aberrational light bending
- Spin precession
- Relativistic deformation of orbit
- GW emission

Plus theory-independent mass-ratio

The Double Pulsar (Burgay et al. 2003, Lyne et al. 2004)

- Mildly recycled 23-ms pulsar in a 147-min orbit with young 2.8-s pulsar - orbital velocities of 300 km/s
- Eclipsing binary in compact (3-lts), slightly eccentric (e=0.088) and edge-on orbit (tilt only 0.65 deg!)
- Ideal laboratory for gravitational physics

Most recent results:



>300 deg of precession of the orbit:

2PN contribution at 35σ

(important for MoI)

Kramer et al. (2021)

Parameter	Value
Right ascension, α (J2000)	$07^{\mathrm{h}}37^{\mathrm{m}}51\overset{\mathrm{s}}{.}248115(10)^{\dagger}$
Declination, δ (J2000)	$-30^{\circ}39'40\overset{\prime\prime}{.}70485(17)^{\dagger}$
Proper motion R.A., μ_α (mas yr^{-1})	$-2.567(30)^{\dagger}$
Proper motion Dec., μ_δ (mas yr^{-1})	$2.082(38)^{\dagger}$
Parallax, π_c (mas)	$1.36(+0.12,-0.10)^{\dagger}$
Position epoch (MJD)	55045.0000
Orbital period, P_b (day)	0.1022515592973(10)
Projected semimajor axis, x (s)	1.415028603(92)
Eccentricity (Kepler equation), e_T	0.087777023(61)
Epoch of periastron, T_0 (MJD)	55700.233017540(13)
Longitude of periastron, ω_0 (deg)	204.753686(47)
Periastron advance, $\dot{\omega}$ (deg yr^{-1})	16.899323(13)
Change of orbital period, $\dot{P}_b$	$-1.247920(78)\times10^{-12}$
Einstein delay amplitude, γ_E (ms)	0.384045(94)
Logarithmic Shapiro shape , z_s	9.65(15)
Range of Shapiro delay, r ($T_\odot$)*	1.2510(43)
NLO factor for signal prop., q_{NLO}	1.15(13)
Relativistic deformation of orbit, δ_θ	$13(13)\times10^{-6}$

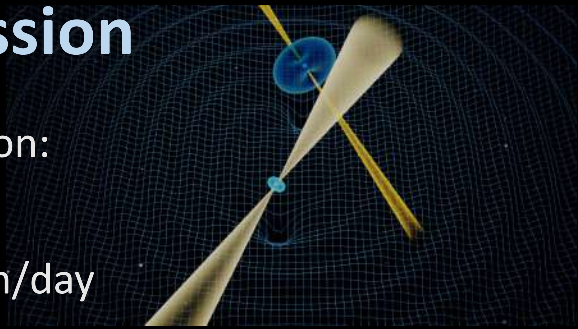
Relativistic effects measured:

- Orbital precession
- Time dilation
- Shapiro delay (incl. next-to-leading order)
- Aberrational light bending
- Spin precession
- Relativistic deformation of orbit
- GW emission

Plus theory-independent mass-ratio

Based on about 1 Million Times of Arrival measurements
“Average cadence” < 10 min

Gravitational wave emission



- Shrinkage of orbit due to GW emission:

  $\Delta P_b = 107{,}820 \pm 7$ ps/day!
- Pulsars approach each other by 7mm/day
- Merger in 85 M years
- Precision will still improve with time - and new telescopes

Most precise test of GR's quadrupole formula

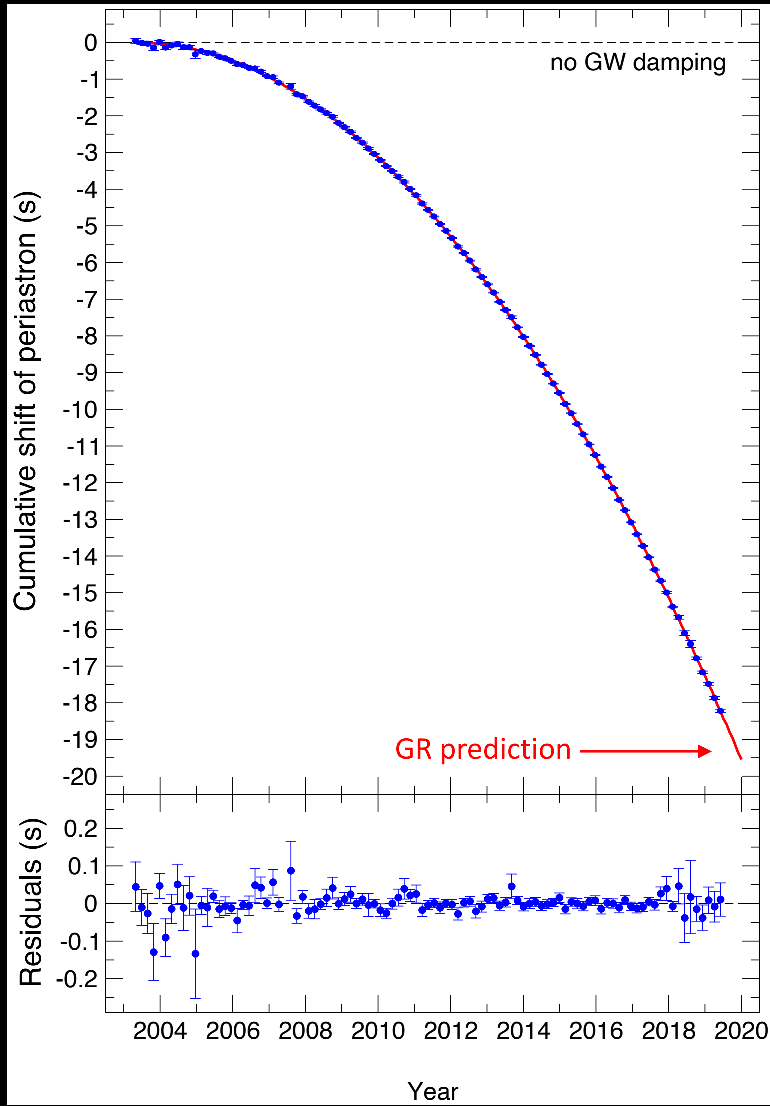
Observed/Expected = 0.99996 ± 0.00006

validating at 1.3×10^{-4} (95% c.l.)

Precision is so high that we need to take mass loss due to rotational spin-down into account:

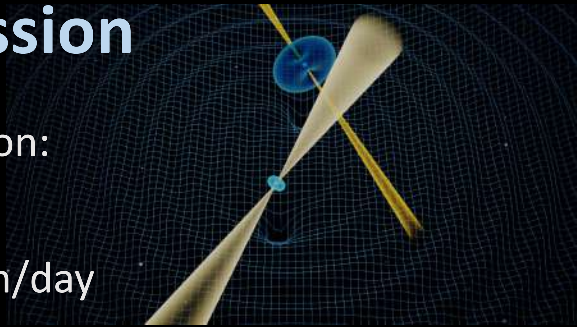
Pulsar loses rotational energy & $E = mc^2$,

i.e. 8.4 Million tons/second = 3.2×10^{-21} M_A per second



Kramer et al. (2021)

Gravitational wave emission



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Most precise test of GR's quadrupole formula

Observed/Expected = 0.99996 ±0.00006

$$\dot{P}_0 = -\frac{192\pi}{5c^5}\left(\frac{2\pi G}{P_0}\right)^{5/3}\frac{mm'}{(m+m')^{1/3}}\left(1+\frac{73}{24}e_0^2+\frac{37}{96}e_0^4\right)\left(1-e_0^2\right)^{-7/2},$$

VOLUME 51, NUMBER 12 PHYSICAL REVIEW LETTERS 19 SEPTEMBER 1983

Gravitational Radiation Reaction in the Binary Pulsar and the Quadrupole-Formula Controversy

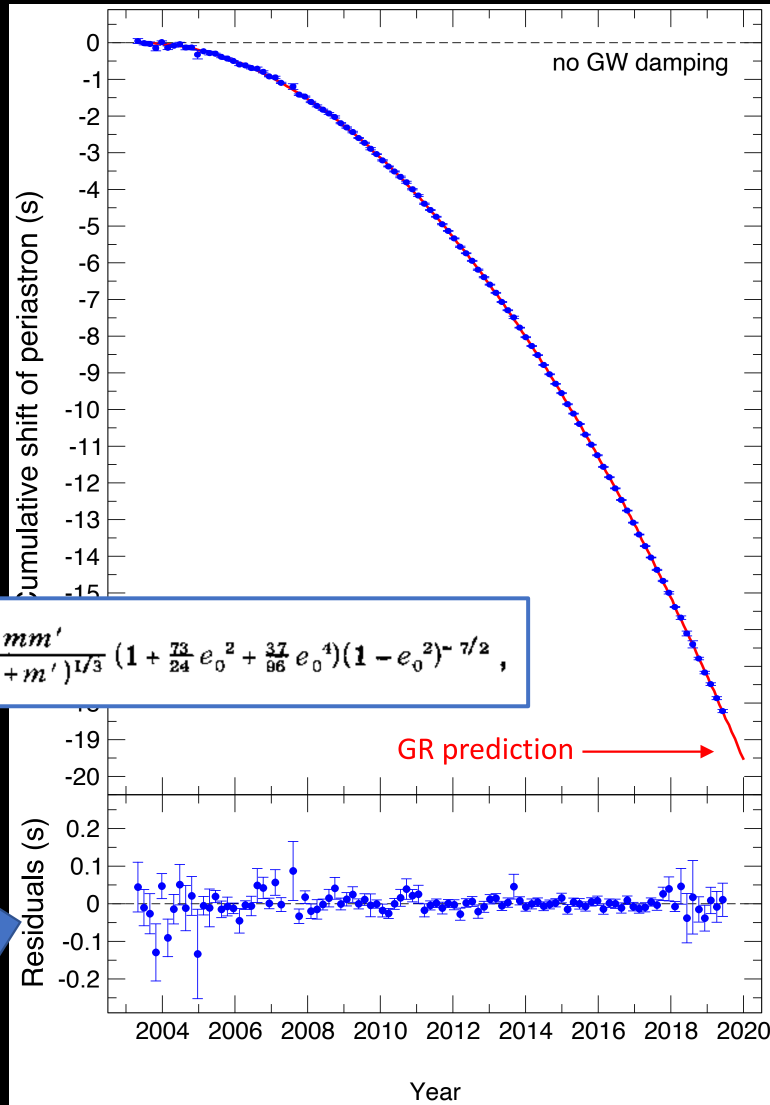
Thibaut Damour

Groupe d'Astrophysique Relativiste, Observatoire de Paris-Meudon, F-92195 Meudon Principal Cedex, France

(Received 31 May 1983)

The evolution of the orbit of a binary pulsar under the action of gravitational radiation reaction is calculated. No approximation is made of weak gravity inside the individual stars; the details of the orbital motion are given directly (to order c^{-5} and G^3). The calculation reveals no acceleration of the center of mass of the system, and a secular decrease of the time of return to periastron. The quantitative results agree both with the well-known "quadrupole formula" and with observations.

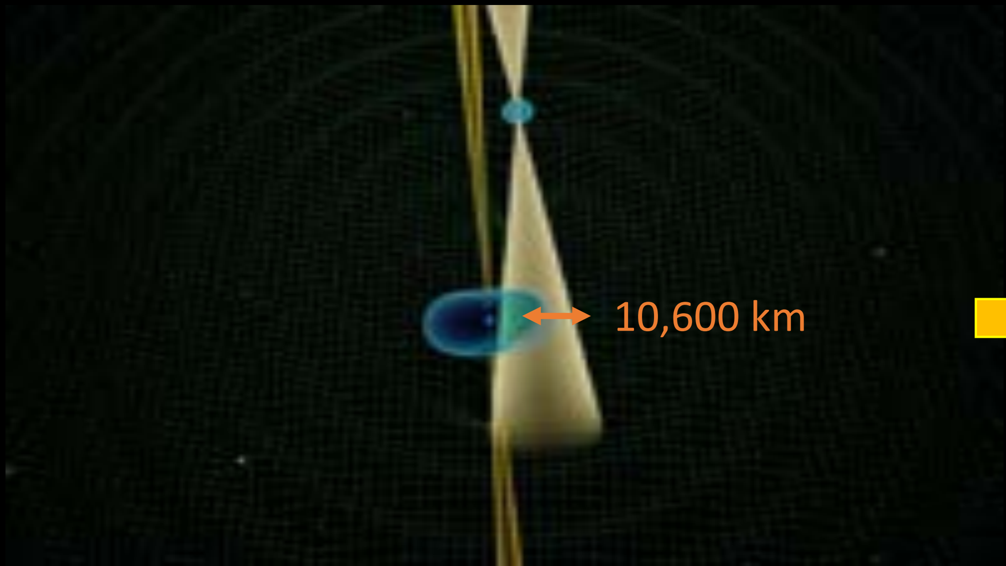
PACS numbers: 04.20.Me, 04.80.+z

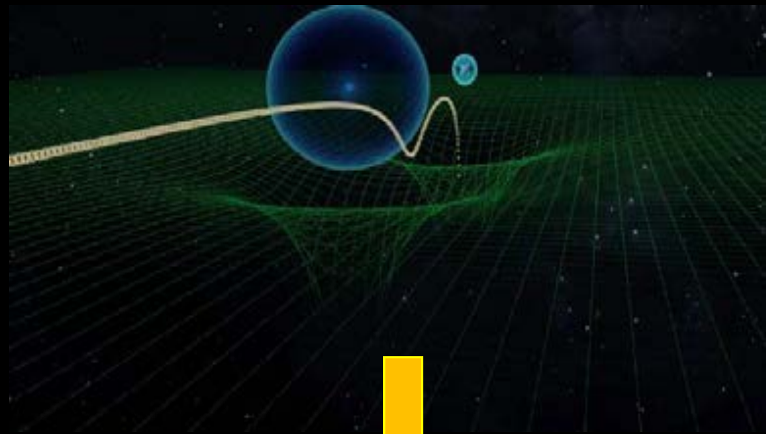


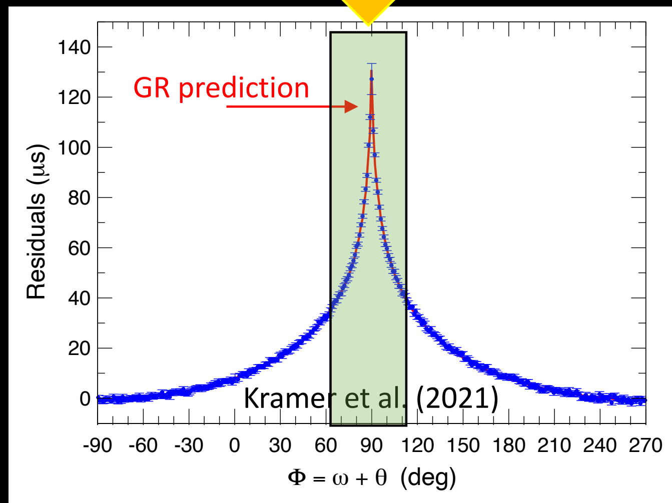
Kramer et al. (2021)

Light-propagation in strong gravitational fields

Shapiro delay in edge-on orbit: $s = \sin i = 0.99994 \pm 0.00001$ - Orbital inclination angle: I = 89.35(5) deg



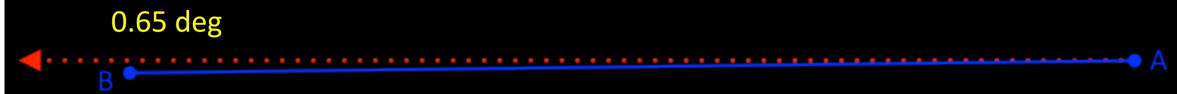




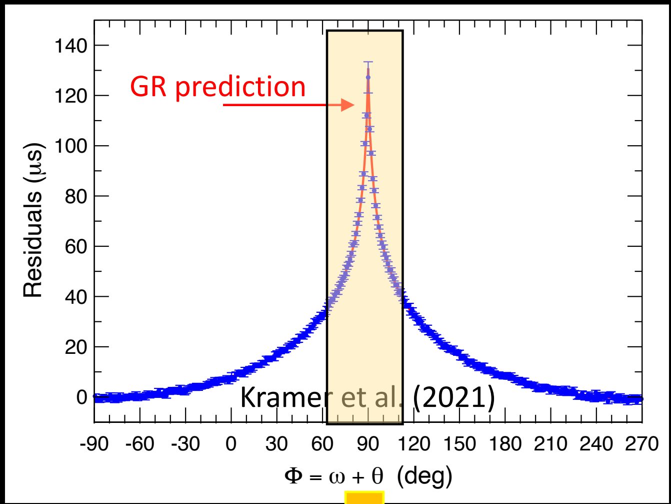
Two tests of GR:

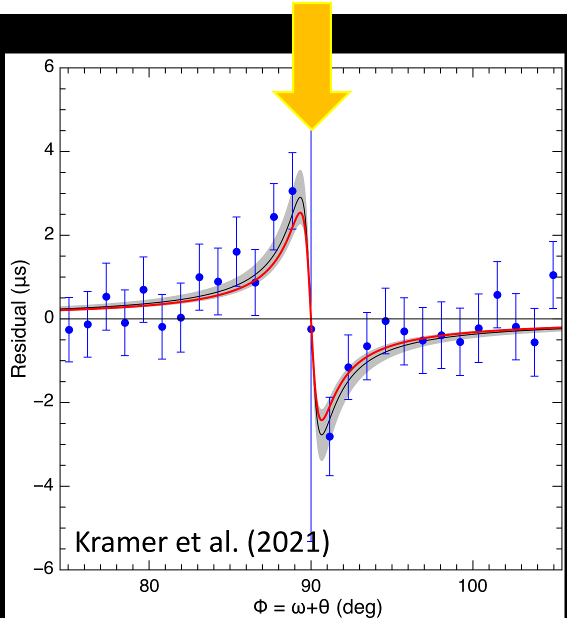
"Shape" Obs./Exp. = 1.00009(18)

"Range" Obs./Exp. = 1.0016(34)

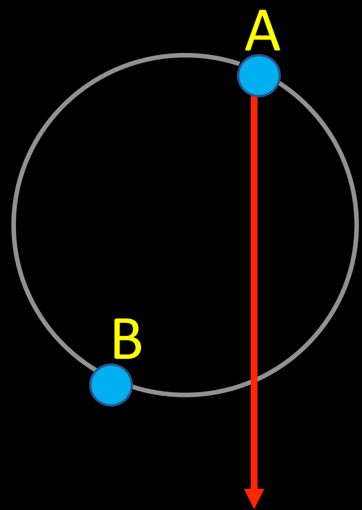


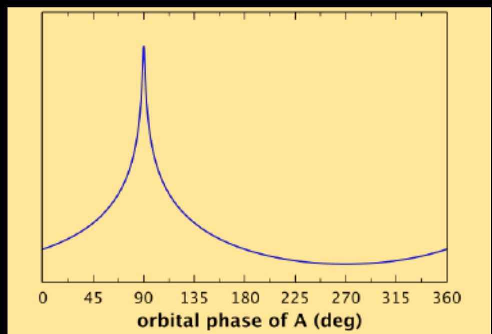
Light-propagation in strong gravitational fields: next-to-leading order (NLO) effects



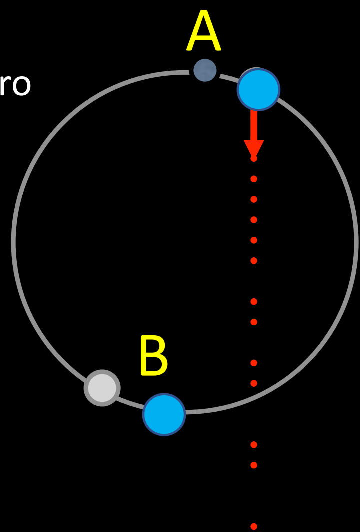


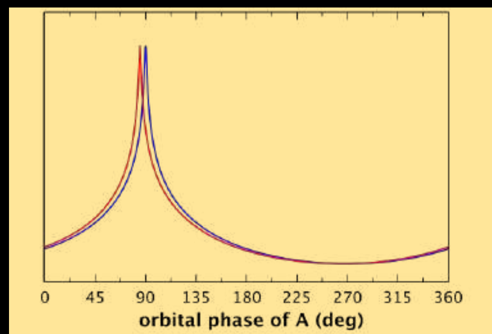
Two additional effects: Retardation & Light-bending





1.5 PN Shapiro





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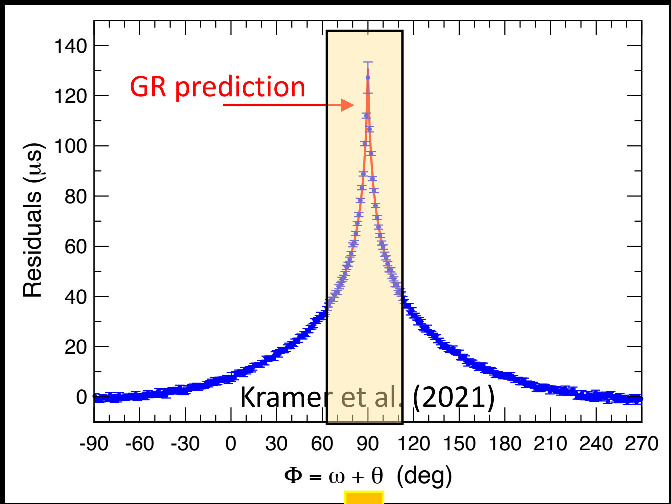

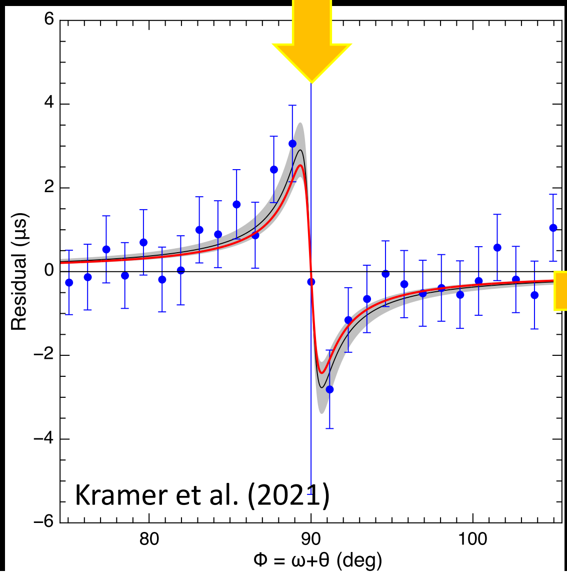

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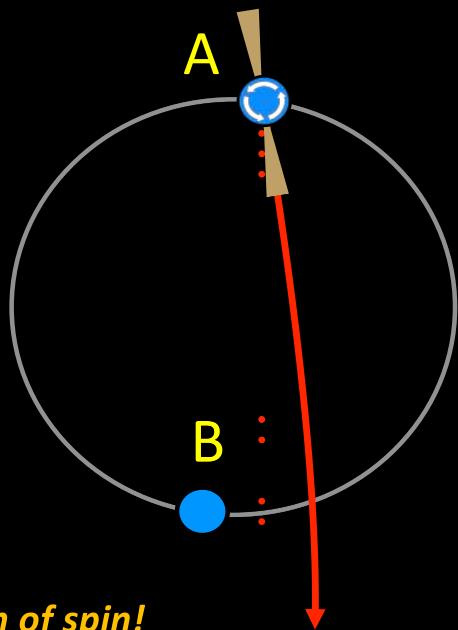
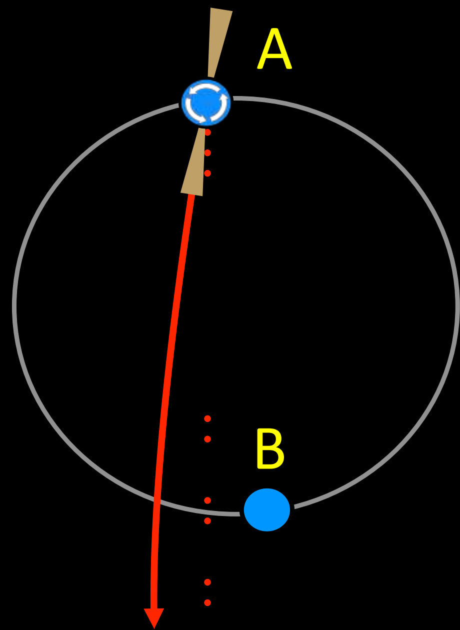
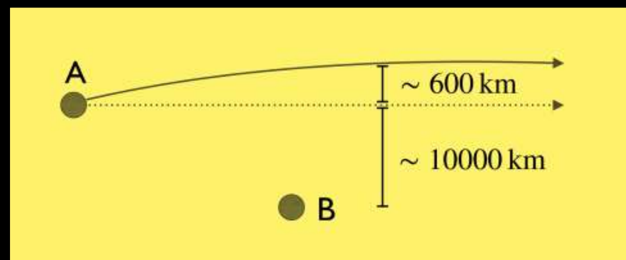




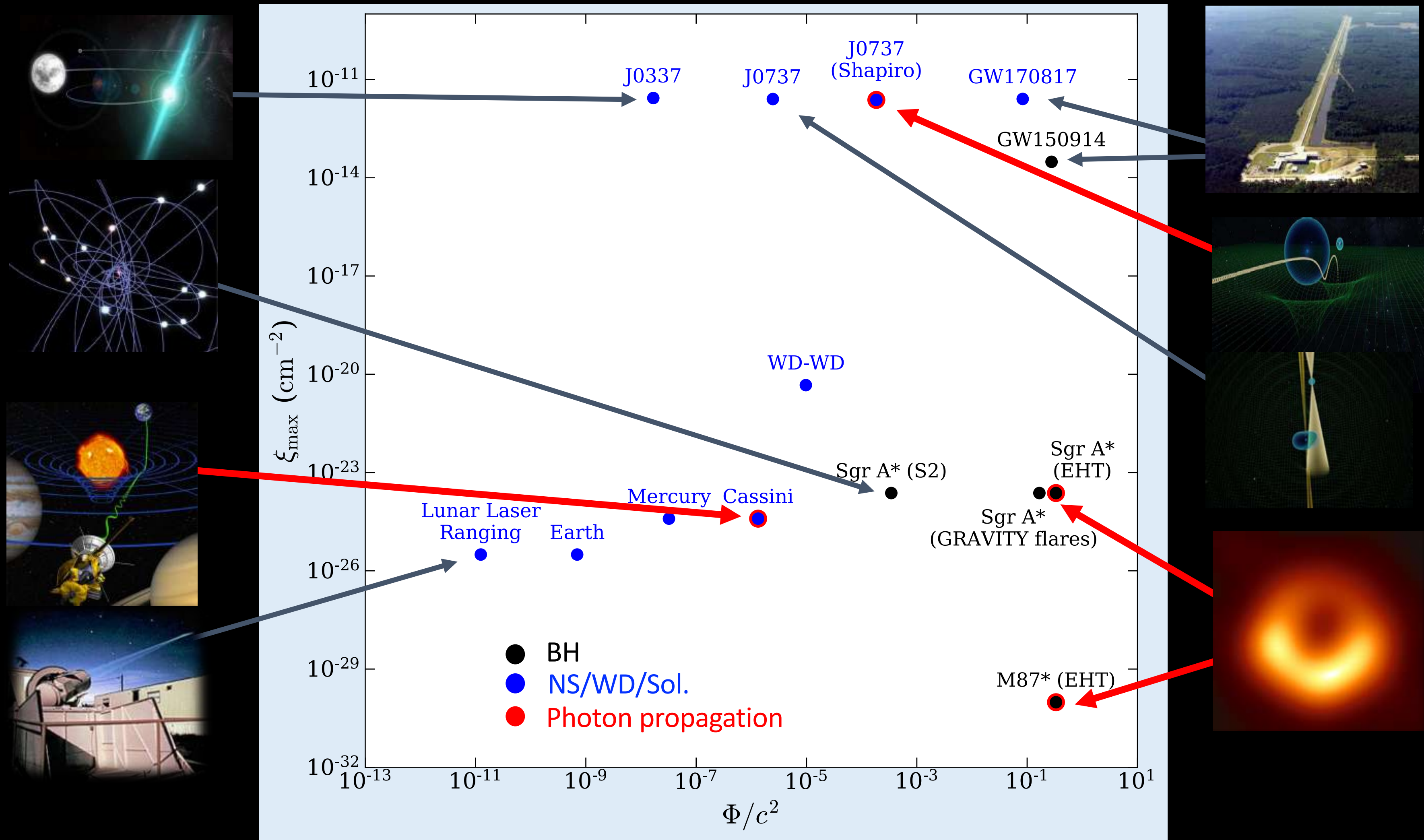
Direction of spin!



Obs./Exp:

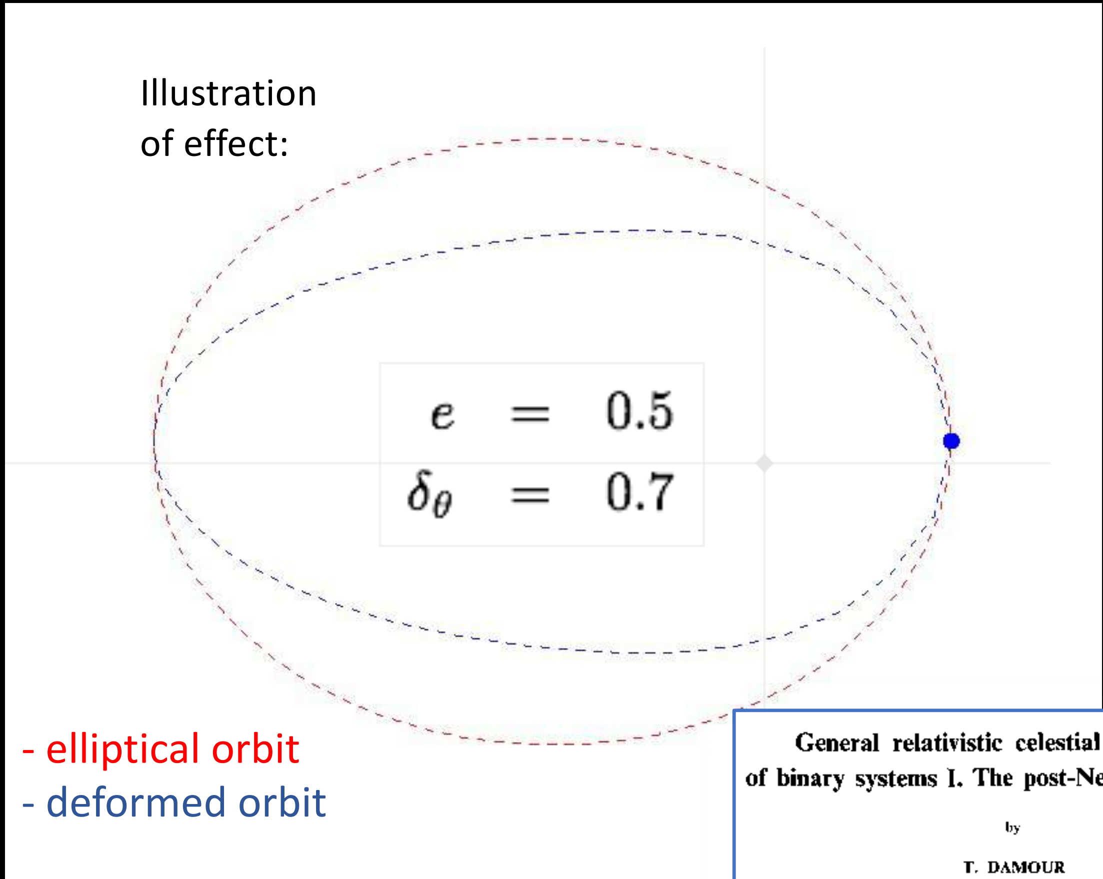
NLO signal propagation	q_{NLO}[total]	1.15(13)
... from signal deflection	q_{NLO}[deflect.]	1.26(24)
... from signal retardation	q_{NLO}[retard.]	1.32(24)

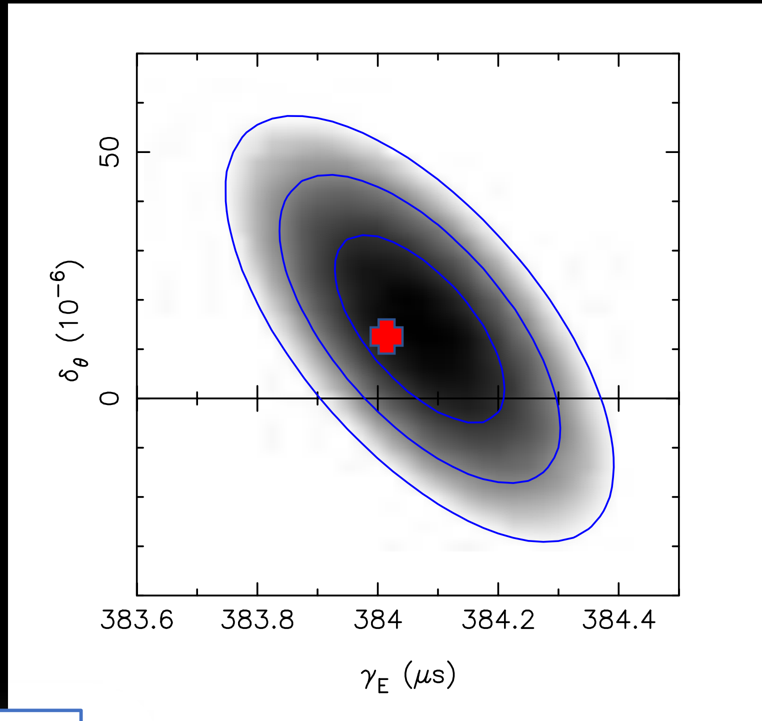
Pulsar photon propagation tests probe largest spacetime curvatures



Relativistic deformation of the orbit

Kramer et al. (2021)





General relativistic celestial mechanics of binary systems I. The post-Newtonian motion

by

T. DAMOUR

Groupe d'astrophysique relativiste. E. R. n° 176 du CNRS.
Observatoire de Paris-Meudon. 92195 Meudon Principal Cedex (France)

and

N. DERUELLE

Laboratoire de gravitation et cosmologie relativistes, E. R. A. n° 533 du CNRS,
Institut Henri Poincaré, 11 rue Pierre et Marie Curie. 75005 Paris (France)

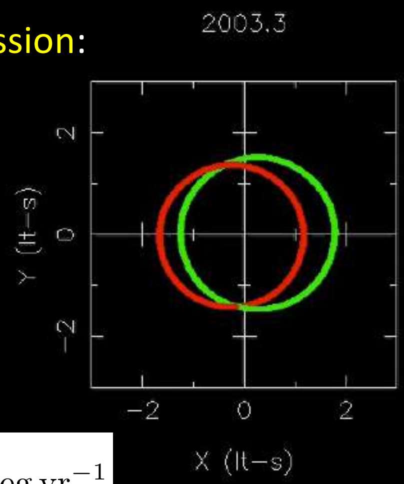
Without taking this correlation into account, gamma appears to be deviating from GR. In fact, it is in perfect agreement

Lense-Thirring Effect: rel. spin-orbit coupling of spin of A

Contributing to the observed orbital precession:

$$\dot{\omega} = \dot{\omega}^{1\mathrm{PN}} + \dot{\omega}^{2\mathrm{PN}} + \dot{\omega}^{\mathrm{LT,A}}$$

= 16.899323(13) deg/yr



Whereas: $\dot{\omega}^{\mathrm{LT,A}} \simeq -3.77 \times 10^{-4} \times I_{\mathrm{A}}^{(45)}\ \mathrm{deg\,yr}^{-1}$

Moment of inertia

C. R. Acad. Sci. Paris, t. 305, Série II, p. 839-842, 1987 839

Relativité/*Relativity*

Le problème des deux corps en relativité générale

Thibault Damour et Gerhard Schäfer

Résumé — On étudie la dynamique d'un système de deux masses comparables, à l'approximation post-post-newtonienne de la relativité générale, c'est-à-dire, au dernier niveau où le système est encore conservatif. On obtient les expressions explicites de la période radiale, et de l'avance séculaire du périastre, en fonction de l'énergie et du moment cinétique. On en déduit l'expression de l'avance du périastre en fonction des masses et de quantités directement observables. Le résultat ainsi obtenu est observationnellement significatif au vu de la grande précision atteinte aujourd'hui dans les mesures du pulsar binaire PSR 1913+16.

The two-body problem in general relativity

Abstract — We study the dynamics of a system of two comparable masses, at the second post-Newtonian approximation of general relativity (i.e. at the last level where the system is still conservative). We obtain explicit expressions of the radial period and secular periastron advance in terms of energy and angular momentum. We then deduce the expression of the periastron advance in terms of the masses and directly observable quantities. The latter result is of observational significance in view of the high precision now obtained in meas[...] binary pulsar PSR 1913+16.

$$(9)\quad k = \frac{3\,(\mathrm{GM}\,n)^{2/3}}{c^2\,(1-e_{\mathrm{T}}^2)}\left[1 + \frac{(\mathrm{GM}\,n)^{2/3}}{c^2\,(1-e_{\mathrm{T}}^2)}\left(\frac{39}{4}x^2 + \frac{27}{4}x'^2 + 15\,xx'\right) - \frac{(\mathrm{GM}\,n)^{2/3}}{c^2}\left(\frac{13}{4}x^2 + \frac{1}{4}x'^2 + \frac{13}{3}xx'\right)\right],$$

IL NUOVO CIMENTO Vol. 101 B, N. 2 Febbraio 1988

Higher-Order Relativistic Periastron Advances and Binary Pulsars.

T. Damour and G. Schäfer (*)

Groupe d'Astrophysique Relativiste, CNRS
DARC, Observatoire de Paris, Section de Meudon - 92195 Meudon Principal Cedex, France

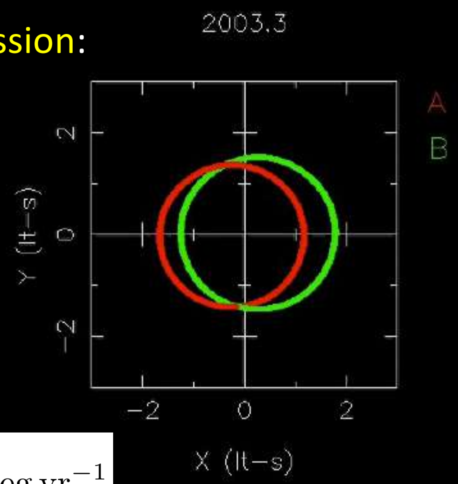
(ricevuto il 14 Marzo 1988)

Lense-Thirring Effect: rel. spin-orbit coupling of spin of A

Contributing to the observed orbital precession:

$$\dot{\omega} = \dot{\omega}^{\mathrm{1PN}} + \dot{\omega}^{\mathrm{2PN}} + \dot{\omega}^{\mathrm{LT,A}}$$

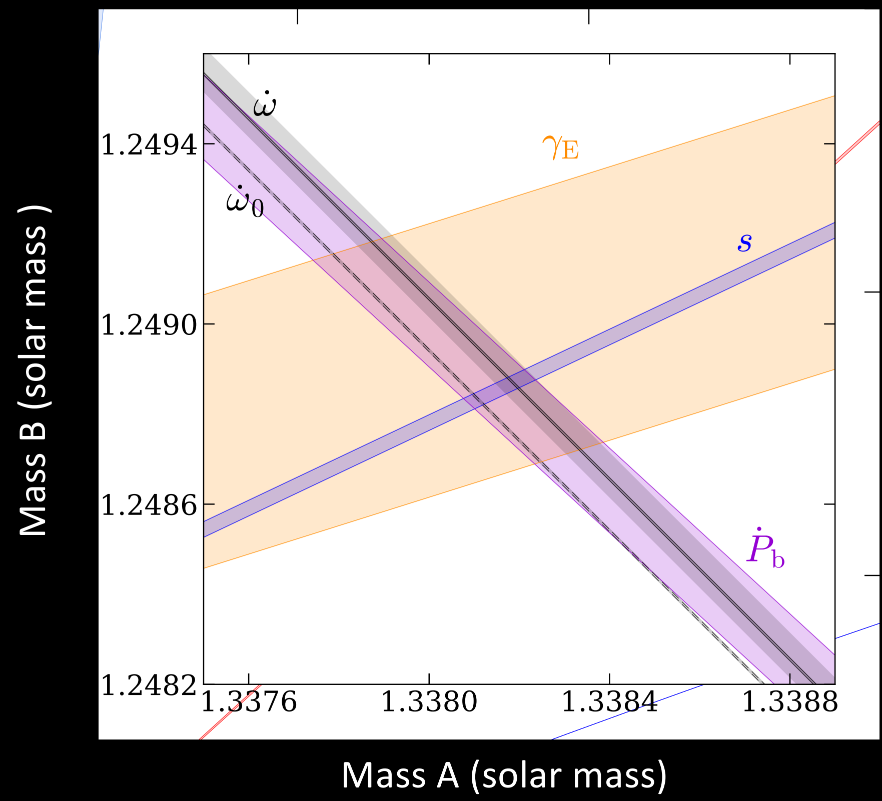
= 16.899323(13) deg/yr



Whereas: $\dot{\omega}^{\mathrm{LT,A}} \simeq -3.77 \times 10^{-4} \times I_{\mathrm{A}}^{(45)}\,\mathrm{deg\,yr}^{-1}$

Moment of inertia

Kramer et al. (2021)



Taking EOS uncertainties into account:

m_A = 1.338185 (14) M_{sun}

m_B = 1.248868 (13) M_{sun}

Lense-Thirring Effect: rel. spin-orbit coupling of spin of A

Contributing to the observed orbital precession:

$$\dot{\omega} = \dot{\omega}^{1PN} + \dot{\omega}^{2PN} + \dot{\omega}^{LT,A}$$

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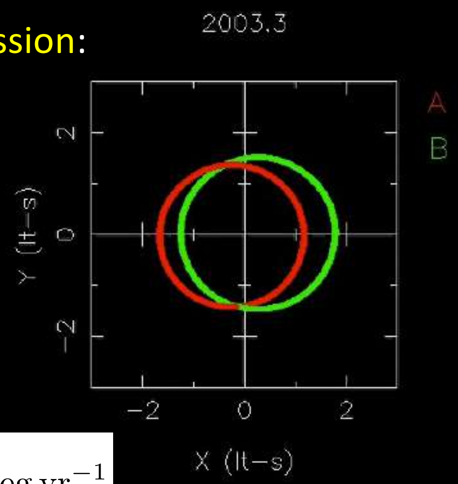

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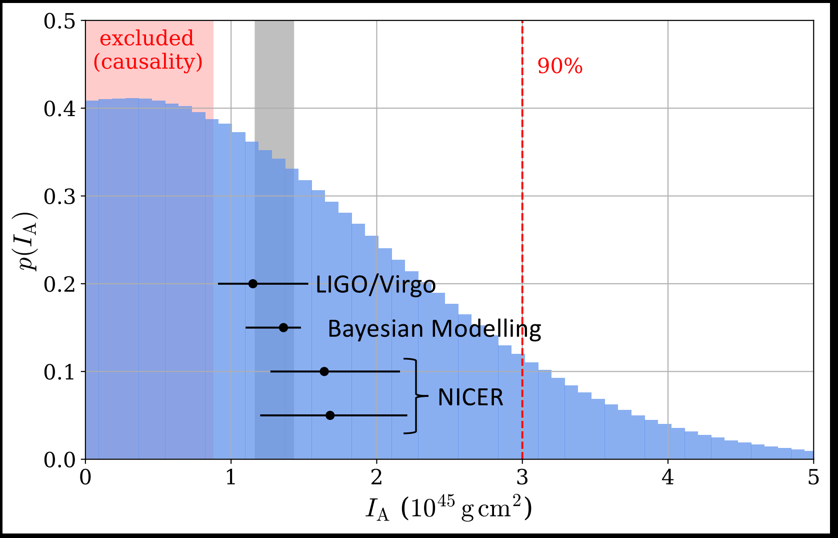
Moment of inertia



Kramer et al. (2021)

Taking EOS uncertainties into account:

m_A = 1.338185 (14) M_{sun}

m_B = 1.248868 (13) M_{sun}

Grey regions: estimates from Dietrich et al. (2020) using Lattimer (2019):

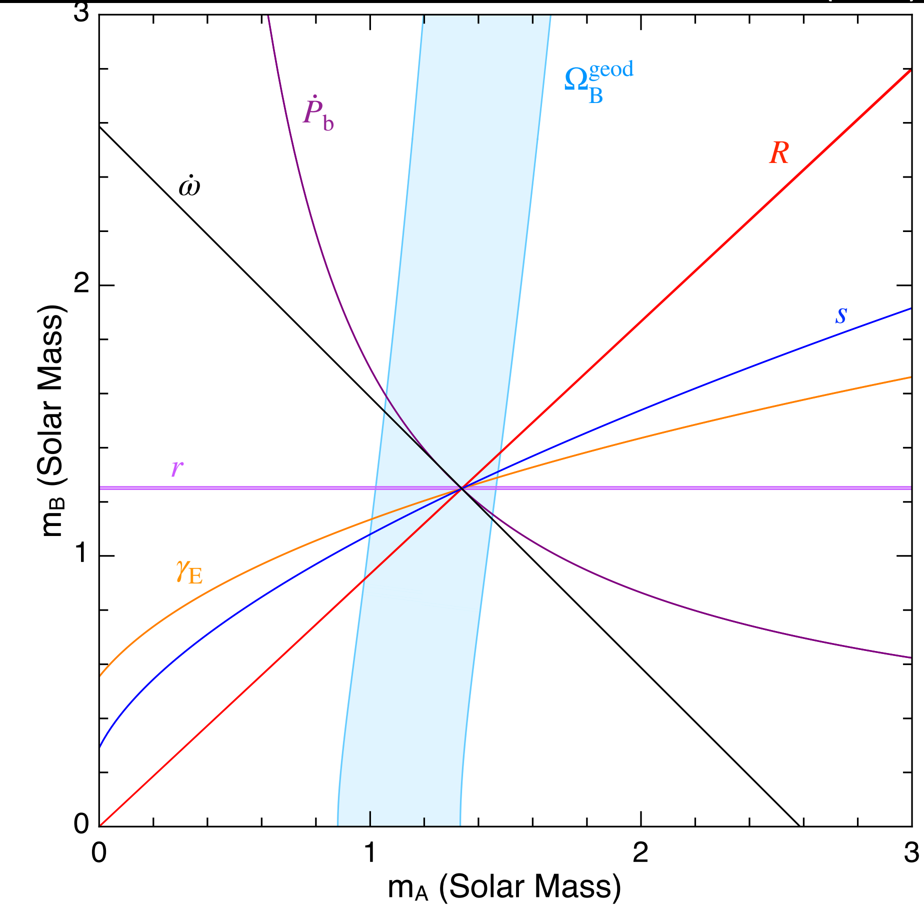
limit on R_A is < 22 km at 90% confidence.

See also Hu et al. (2020)

Putting it all together:

After 18 years since its discovery:

Kramer et al. (2021)



Kramer et al. (2021)

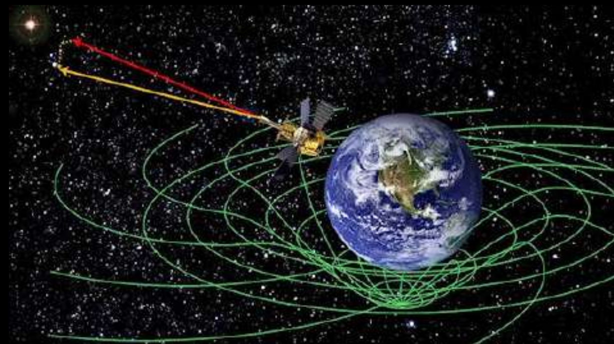
Relativistic effect	Parameter	Obs./GR pred.
Shapiro delay shape	s	1.00009(18)
Shapiro delay range	r	1.0016(34)
Time dilation	γ_E	1.00012(25)
Periastron advance	$\dot{\omega} \equiv n_b k$	1.000015(26)
GW emission	$\dot{P}_b$	0.999963(63)
Orbital deformation	δ_θ	1.3(13)
Spin precession	Ω_B^{spin}	0.94(13)*
Tests of higher order contributions		
Lense-Thirring contrib. to k	λ_{LT}	0.7(9)
NLO signal propagation	q_{NLO}[total]	1.15(13)
...from signal deflection	q_{NLO}[deflect.]	1.26(24)
...from signal retardation	q_{NLO}[retard.]	1.32(24)

- 7 Post-Keplerian parameters
- Next-to-leading order in signal propagation
- Most precise strong-field test of GR
- Start to probe MoI and Equation-of-State
- Need to take mass loss into account
- MeerKAT improves timing by factor 2-3!

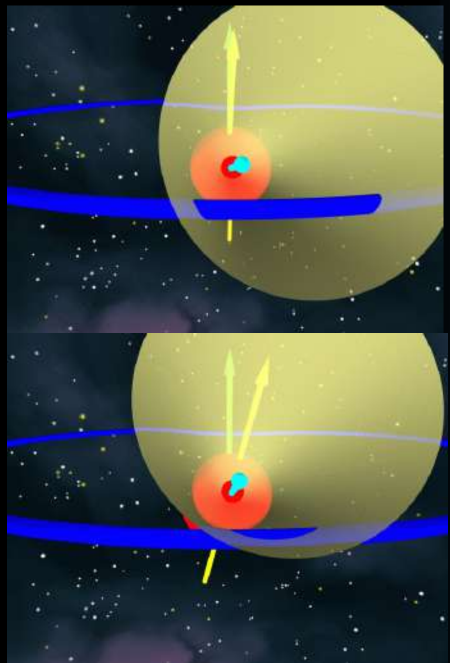
Relativistic spin precession

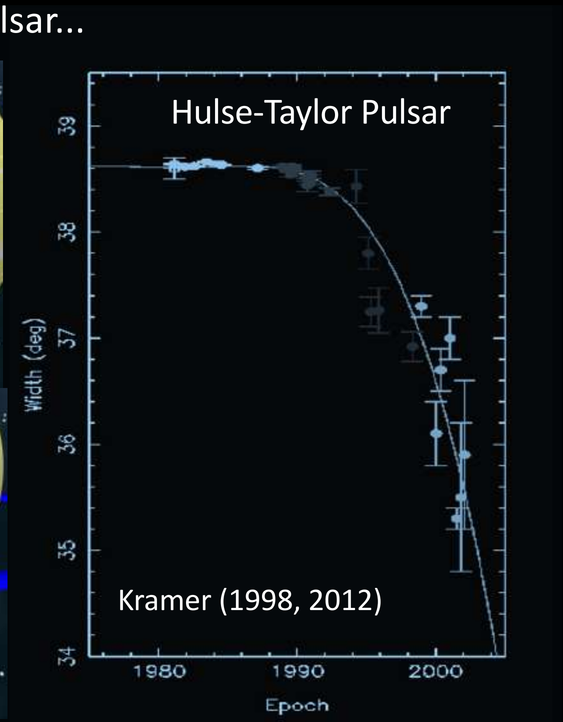
Experiments made in Solar System provide precise weak-field tests and confirm it, e.g. LLR or GRAVITY Probe-B

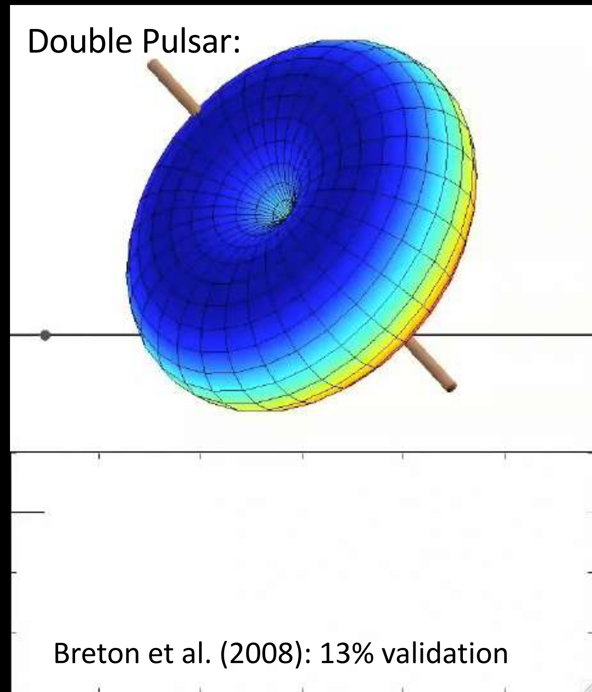
Predicted for pulsars by Damour & Ruffini (1974) and first seen for such strongly self-gravitating bodies in HT-Pulsar (Kramer'98) but no significant measurement of precession rate until Double Pulsar...



Damour & Ruffini (1974)



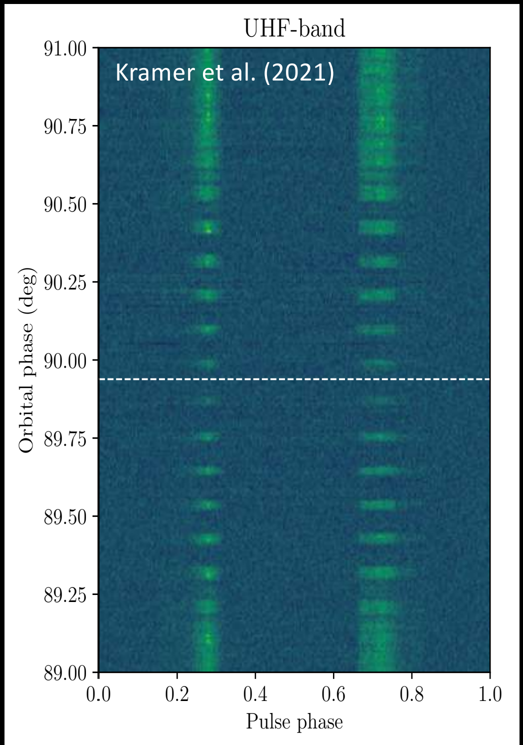


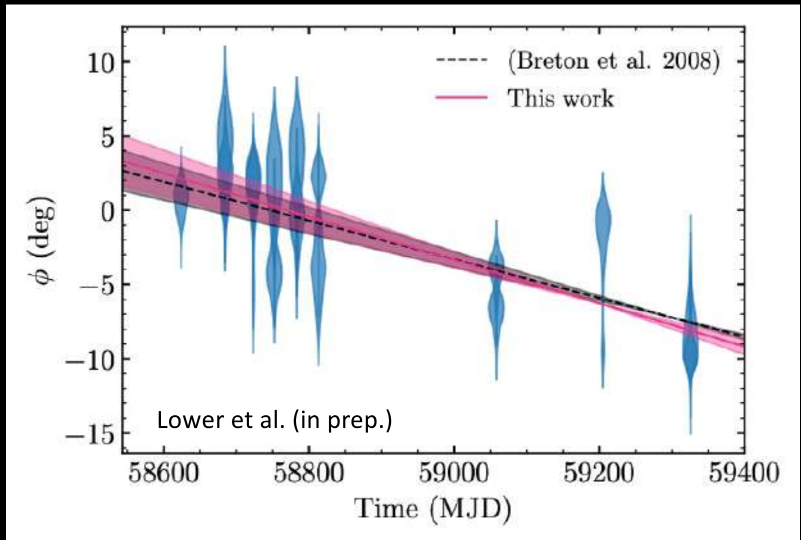


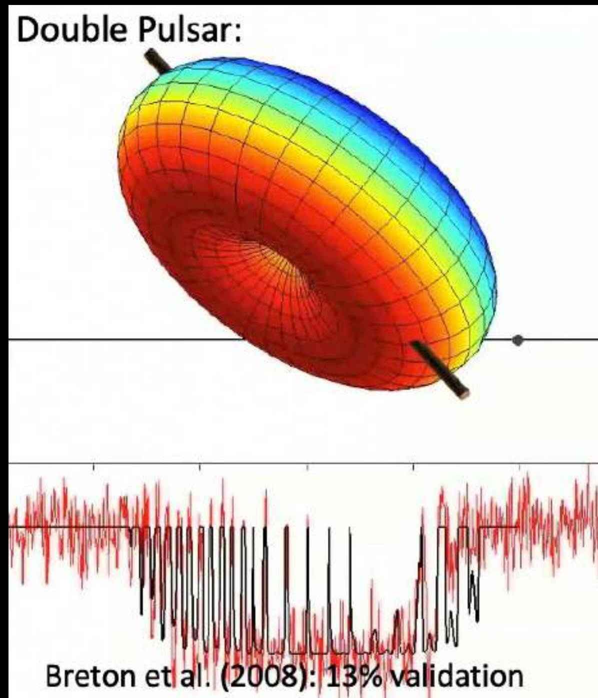
Relativistic spin precession in Double Pulsar

Measurement going to be much improved with MeerKAT

MeerTime's (Bailes et al. 2020) "RelBin" programme (Kramer et al. 2021b) studies Double Pulsar's timing (Hu et al.) and eclipses (Lower et al.)







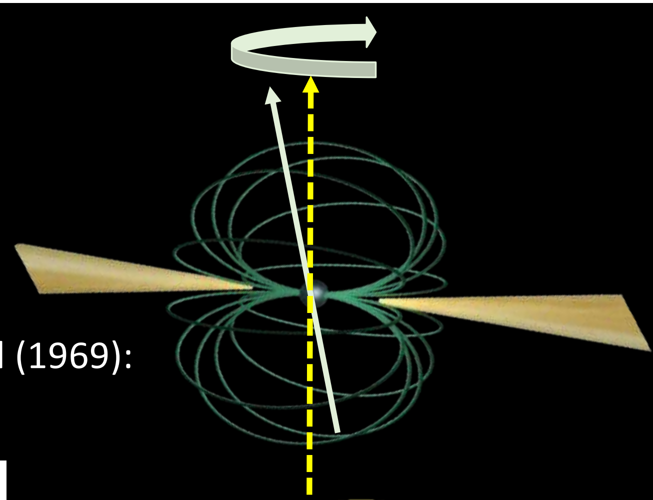
Eclipses will also allow us to track "B"'s rotation without its radio emission: improvement also on the mass ratio – (see Lower et al., in prep.)

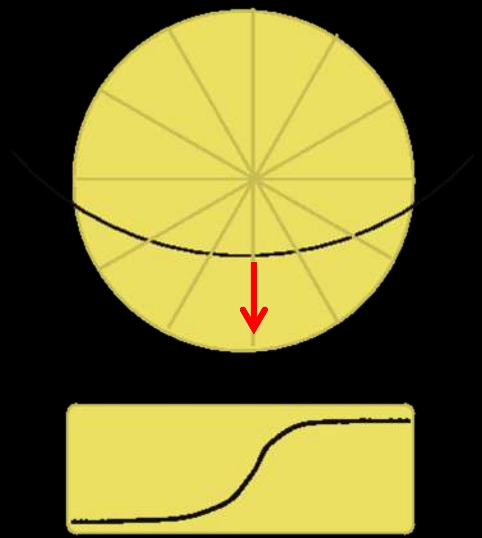
PSR J1906+0746: Deciphering pulsars with GR

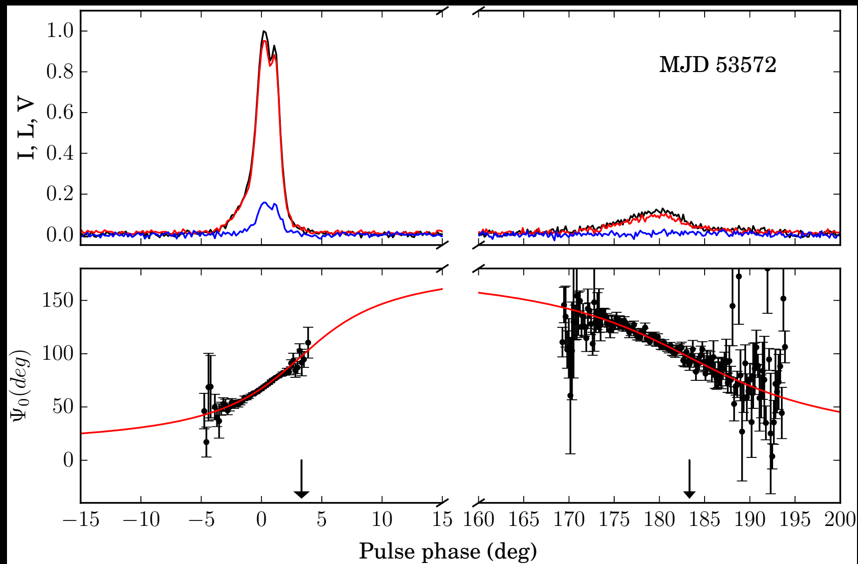
Unique results on relativistic binary (Desvignes et al. 2019):

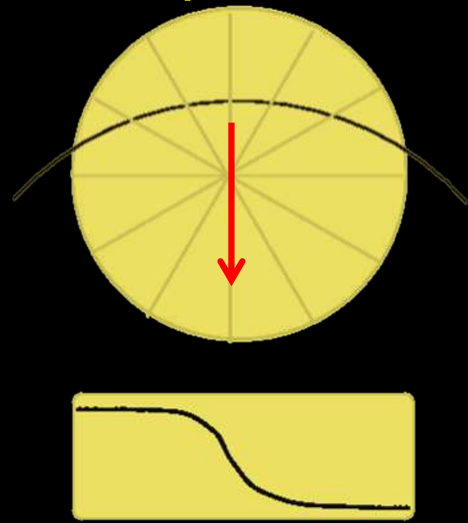
Our line-of-sight has crossed the pole of interpulse! First glance ever.

Using ideas of DR74 & Dass & Radhakrishnan (1975) to look at Rotating Vector Model (1969):









PSR J1906+0746: Deciphering pulsars with GR

Unique results on relativistic binary (Desvignes et al. Science 2019):

Our line-of-sight has crossed the pole of interpulse! First glance ever.

Best test of GR for spin-precession of strongly - self-gravitating gyroscope

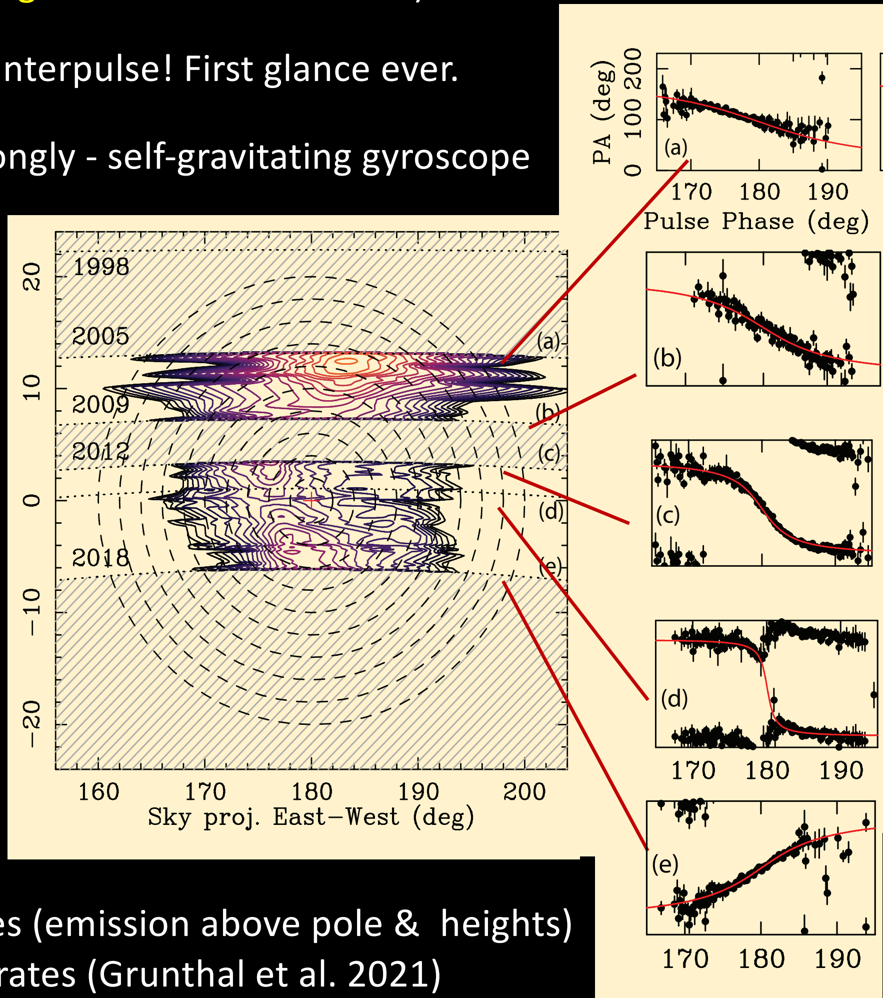
From accurate tracking of geometry vs time:

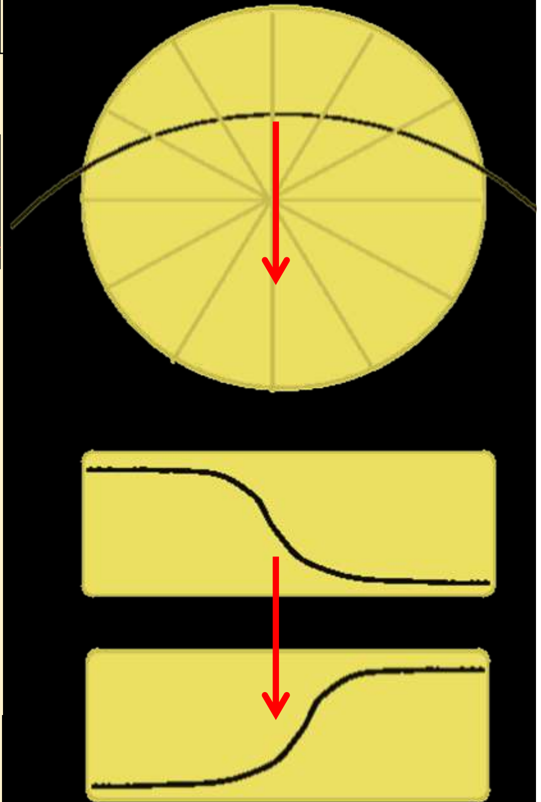
$$\boxed{\Omega_{\mathrm{p}} = 2.17 \pm 0.11\ \mathrm{deg/yr}}$$

Compare to GR expectation:
2.234 ± 0.014 deg/yr

Radio emission from a pulsar's magnetic pole revealed by general relativity

Gregory Desvignes[1,2*], Michael Kramer[1,3], Kejia Lee[4], Joeri van Leeuwen[5,6], Ingrid Stairs[7], Axel Jessner[1], Ismaël Cognard[8,9], Laura Kasian[7], Andrew Lyne[3], Ben W. Stappers[3]





- Confirming also magnetospheric theories (emission above pole & heights)
- Update on GW-detector NS/NS-merger rates (Grunthal et al. 2021)

Universality of Free Fall (UFF)

Weak Equivalence Principle
(test masses)

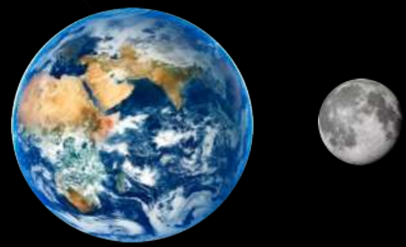
$$E_{\text{grav}} = 0$$

MICROSCOPE Satellite

$$|\Delta| \lesssim 10^{-14}$$

Touboul et al.2017

Strong Equivalence Principle
weak field



$$\epsilon \equiv \frac{E_{\text{grav}}}{mc^2} \approx -5 \times 10^{-10}$$

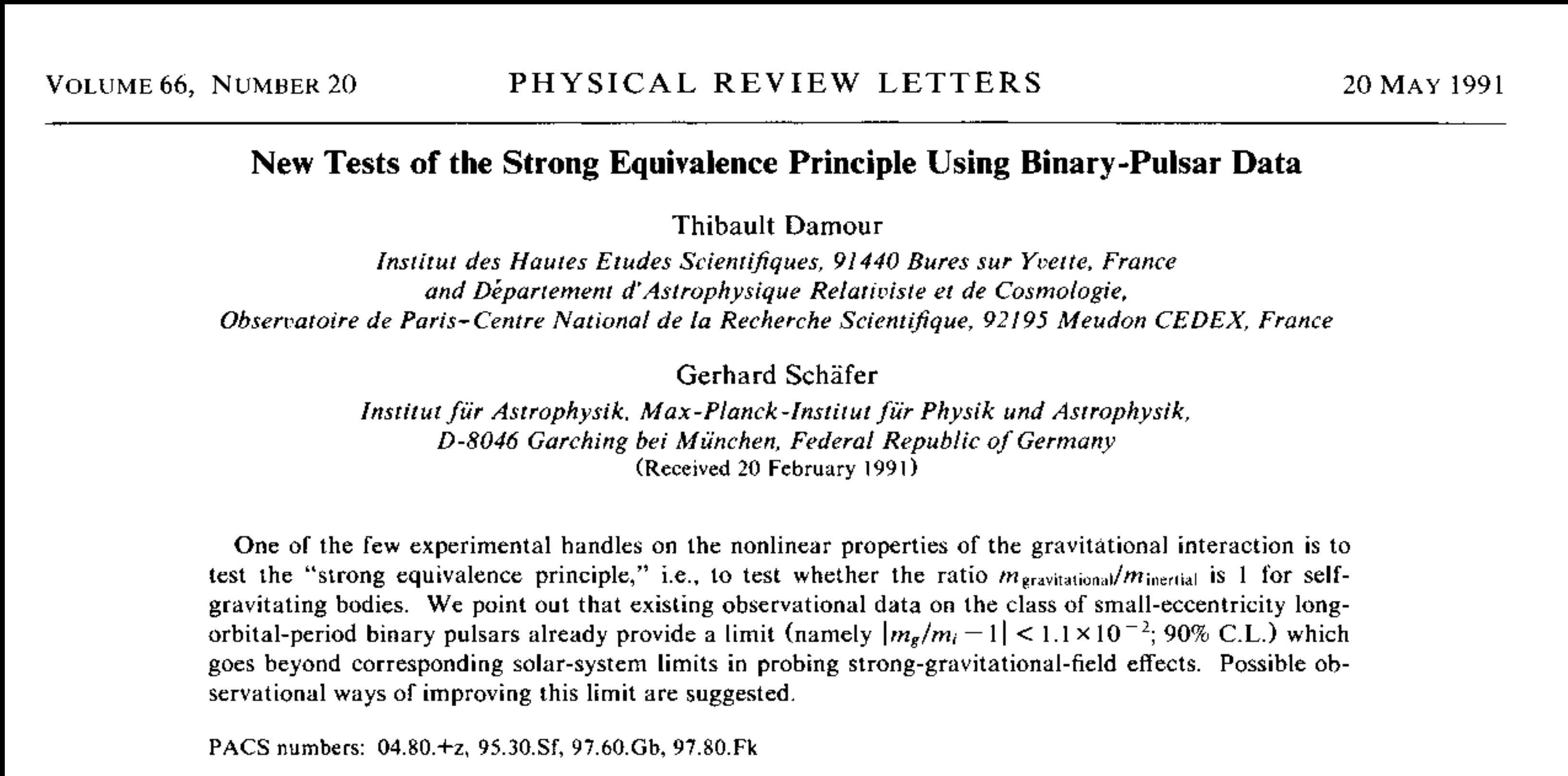
Lunar Laser Ranging

$$|\Delta| \lesssim 2 \times 10^{-13} \qquad |\Delta|/\epsilon \lesssim 0.04\%$$

Williams et al.2009/Hofmann & Müller 2018

and pulsars?

Universality of Free Fall (UFF)


VOLUME 66, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1991

New Tests of the Strong Equivalence Principle Using Binary-Pulsar Data

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(Received 20 February 1991)

One of the few experimental handles on the nonlinear properties of the gravitational interaction is to test the "strong equivalence principle," i.e., to test whether the ratio $m_{\text{gravitational}}/m_{\text{inertial}}$ is 1 for self-gravitating bodies. We point out that existing observational data on the class of small-eccentricity long-orbital-period binary pulsars already provide a limit (namely $|m_g/m_i - 1| < 1.1\times10^{-2}$; 90% C.L.) which goes beyond corresponding solar-system limits in probing strong-gravitational-field effects. Possible observational ways of improving this limit are suggested.

PACS numbers: 04.80.+z, 95.30.Sf, 97.60.Gb, 97.80.Fk

Here: small eccentricity systems – which we have indeed used until recently

Universality of Free Fall (UFF)

Strong Equivalence Principle
strong field

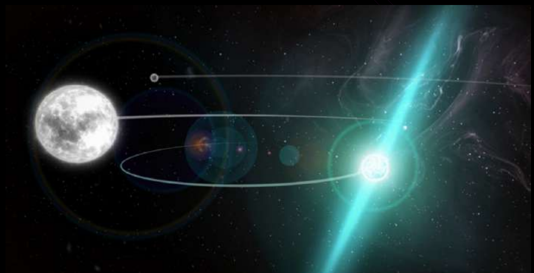


Illustration: NRAO/AUI/NSF/S. Dagnello

$$\epsilon \equiv \frac{E_{\text{grav}}}{mc^2} \approx -0.15$$

Triple System (aka PSR J0337+1715) discovered by Ransom et al. (2014)

PSR J0337+1715:	P = 2.7 ms, M_{PSR} = 1.436 $M_\odot$
Inner orbit:	1.63 d, M_{WD} = 0.197 $M_\odot$
Outer orbit:	327 d, M_{WD} = 0.410 $M_\odot$

Strong-field Nordtvedt parameter (cf. Damour & Schäfer 1991):

$$\Delta = \eta_{(1\text{PN})}\,\varepsilon + \eta'_{(2\text{PN})}\,\varepsilon^2 + \mathcal{O}(\varepsilon^3)$$

$$|\Delta| \lesssim 2.6 \times 10^{-6}$$

$$|\Delta|/\epsilon \lesssim 0.002\%$$

Archibald et al.2018

Recent important update by Voisin et al. (2020):

A&A 638, A24 (2020)
https://doi.org/10.1051/0004-6361/202038104

Astronomy & Astrophysics

An improved test of the strong equivalence principle with the pulsar in a triple star system★

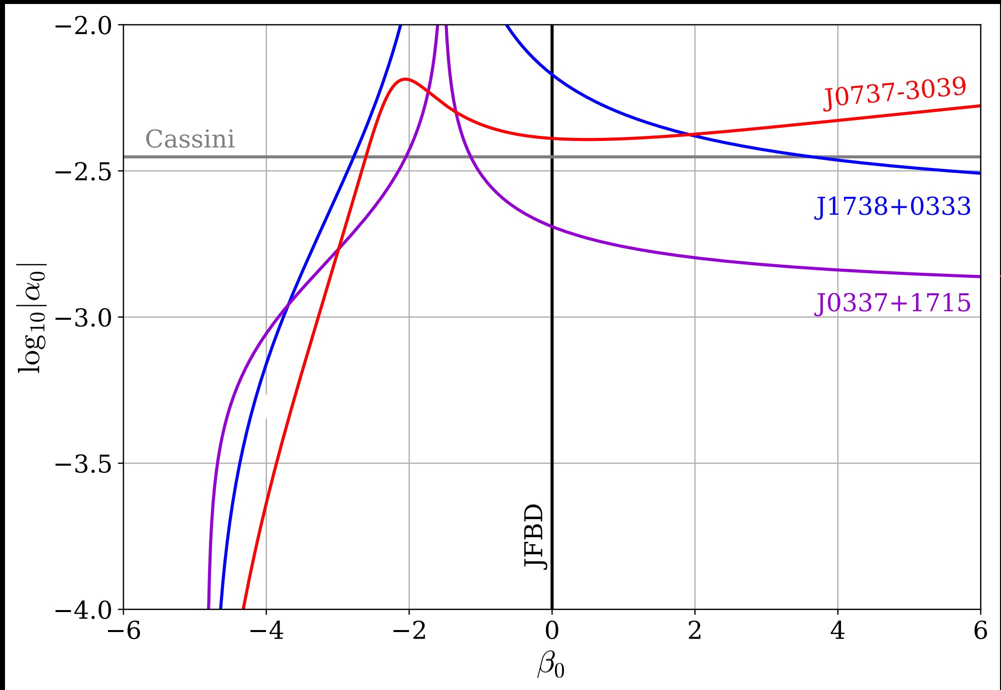
G. Voisin[1,2], I. Cognard[3,4], P. C. C. Freire[5], N. Wex[5], L. Guillemot[3,4], G. Desvignes[6,5], M. Kramer[5,1], and G. Theureau[2,3,4]

$$\Delta = (0.5 \pm 1.8) \times 10^{-6} \qquad (95\%)$$

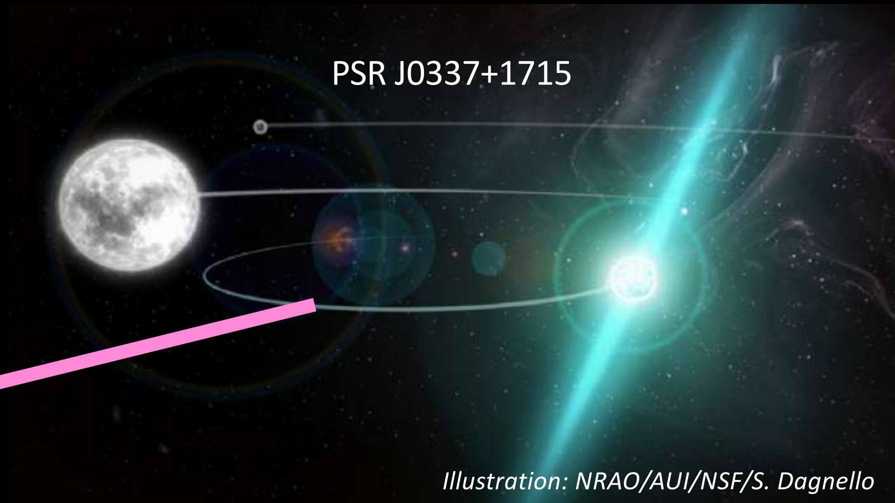
Voisin et al. (2020)

Testing Damour-Esposito-Farèse Gravity

A two parameter mono-scalar-tensor gravity $T_1(\alpha_0, \beta_0)$



Kramer et al. (2021)



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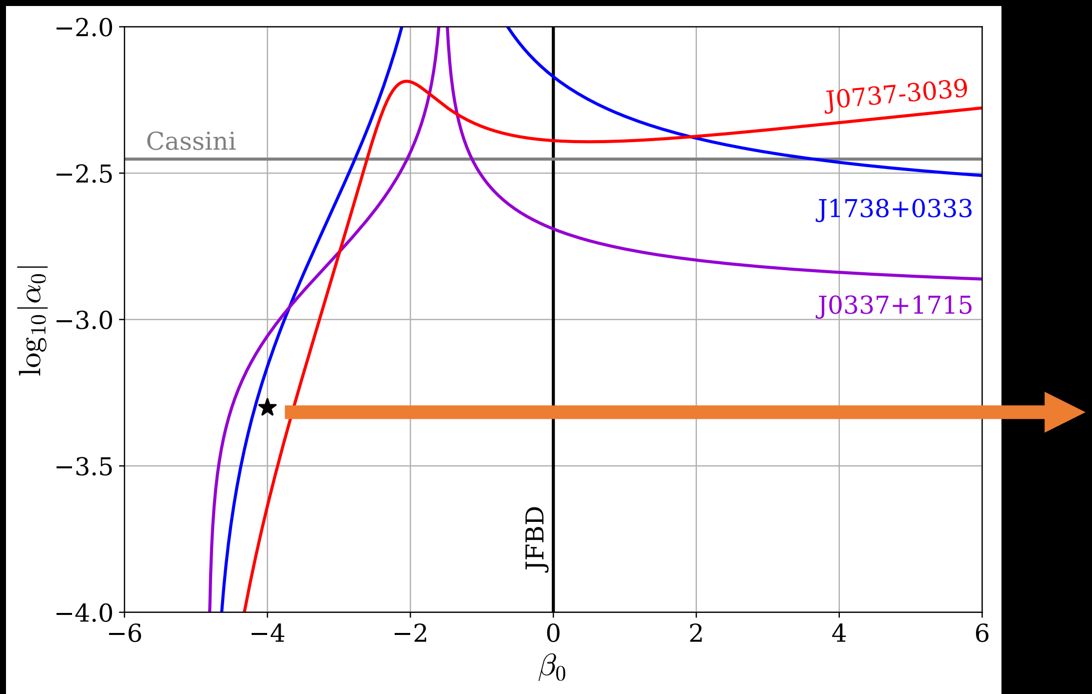
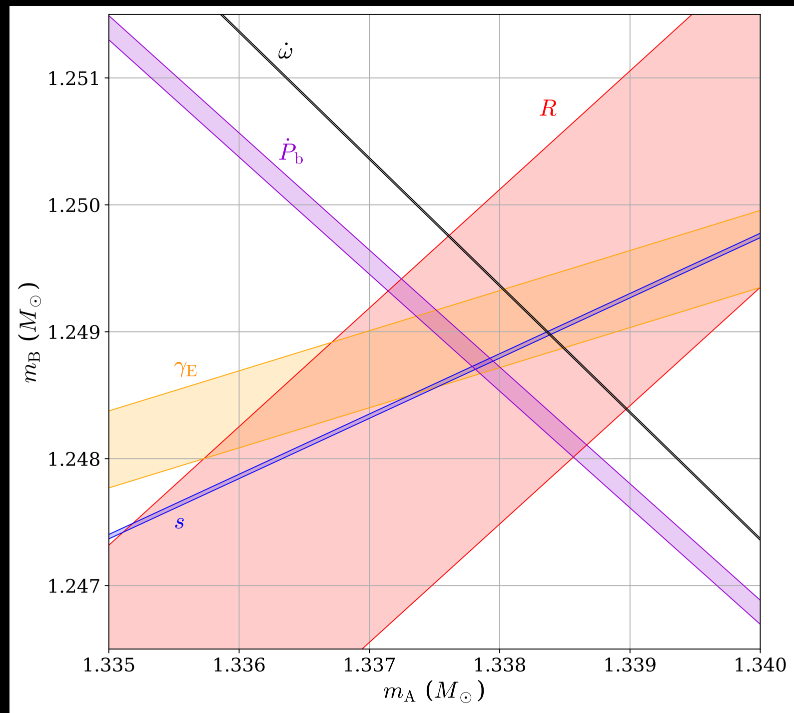


Kramer et al. (2021)

Double Pulsar



Kramer et al. (2021)

A lot more can be tested with binary pulsars – recent examples:

Universality of Free Fall (UFF):

- Triple System (aka PSR J0337+1715): Archibald et al. (2018) & Voisin et al. (2020)
- Towards Dark Matter: Shao et al. (2018)

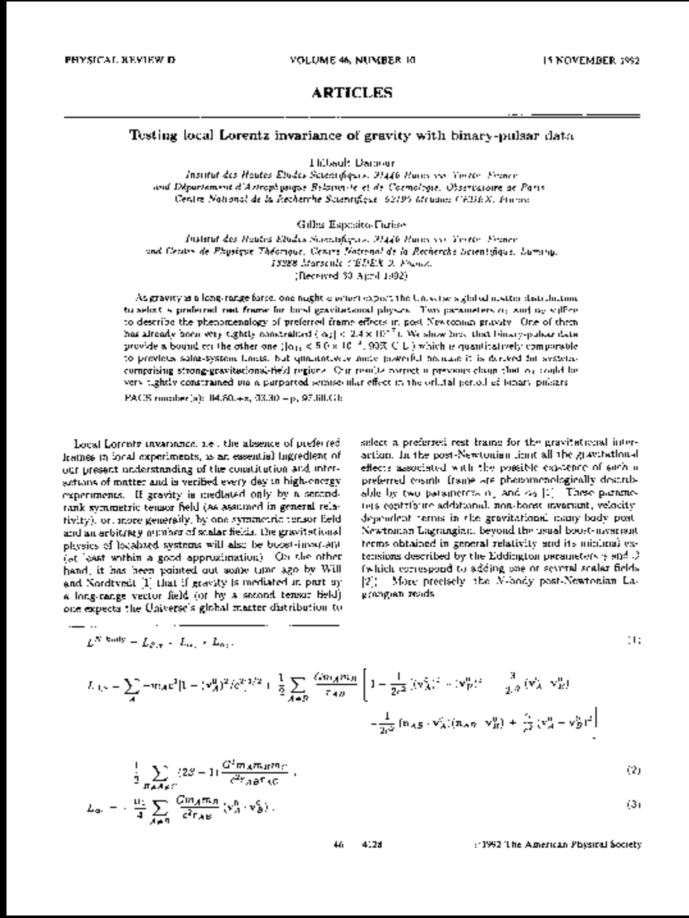
Local Lorenz Invariance Damour & Esposito-Farese (1992), Shao & Wex (2016)

Existence of gravitational dipole radiation Freire et al. (2012)

Variation of gravitational constant Zhu et al. (2019)

Graviton mass bound from binary pulsars Shao et al. (2020)

…and more: see reviews by Shao & Wex (2016) or Wex & Kramer (2020)


PHYSICAL REVIEW D VOLUME 46, NUMBER 10 15 NOVEMBER 1992

ARTICLES

Testing local Lorentz invariance of gravity with binary-pulsar data

Thibault Damour

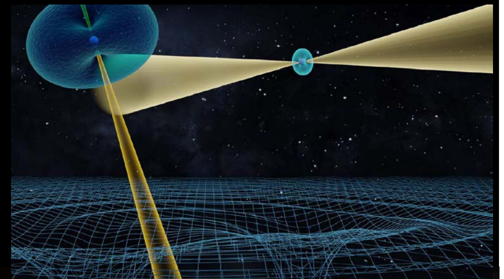
Gilles Esposito-Farèse

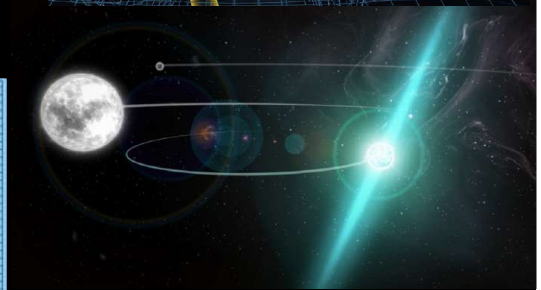
(Received 30 April 1992)

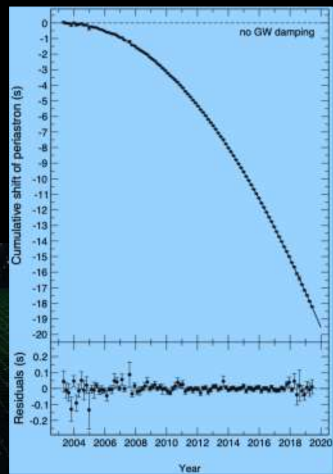
Damour and Esposito-Farese (1992)

Summary & Conclusions

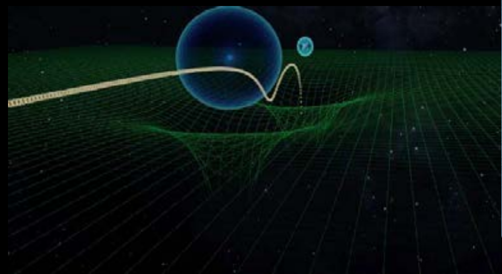
- Unfortunately, Einstein did not live to see discovery of pulsars and their usage to test relativistic gravity
- Binary pulsars provide most precise – and often unique - tests for strongly self-gravitating bodies
- Measurements are usually clean and precise – confirming GR so far
- Tight constraints on alternative theories which need to pass binary pulsar tests
- Recent very significant progress, e.g. Double Pulsar or Triple System
- We have transcended to the next level of precision (&effects)
- Even more systems are being discovered
- With MeerKAT, FAST and later SKA a new era has begun
- Thibault has helped enormously to exploit them



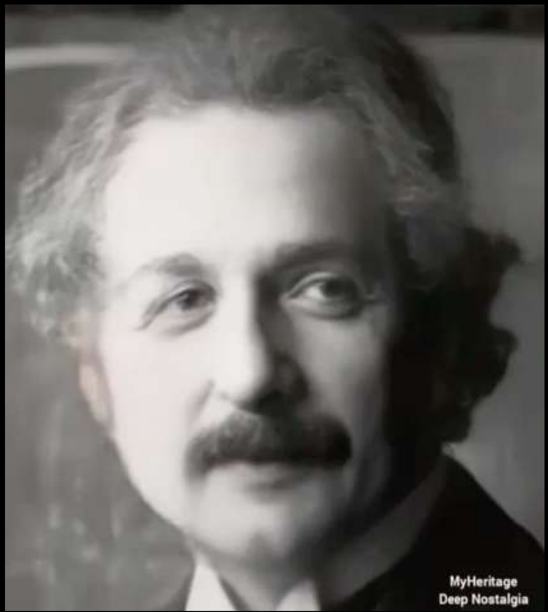




Many more years more to come.



“Famous” Words...



“Wie kommt uns da die pedantische Genauigkeit der Astronomie zu Hilfe, über die ich mich im Stillen früher oft lustig machte!”

“There comes the pedantic precision of astronomy to the rescue, which I have ridiculed silently so often in the past!”

(Albert Einstein in letter to Arnold Sommerfeld , 9.12.1915)

Thank you, Thibault.

from *Mysteries of the Quantum World* (Damour & Burniat)