TEXAS 2004
STANFORD, 13-17 DEC 2004

BINARY PULSARS
AND
STRONG-FIELD TESTS OF GRAVITY

Thibault Damour
IHES

EXPERIMENT

SUMMER 1974 HULSE, TAYLOR

DISCOVERY OF PSR 1913+16

+ GPB

OBSERVATION OF SECULAR ACCELERATION OF THE ORBITAL MOTION : $\dot{P}_b$

Taylor, Fowler, McCulloch '79;
Taylor, Weisberg '82

DISCOVERY OF PSR 1534+12
Wolszczan '91

EXPERIMENTAL CONSTRAINTS ON STRONG-FIELD RELATIVISTIC GRAVITY
Taylor, Wolszczan, Damour, Weisberg '92

OBSERVATION OF SPIN-ORBIT EFFECTS
Kramer '98 [Weisberg, Romani, Taylor '89]
Weisberg, Taylor '02

THEORY

FRUITFUL DIALOGUE EXPT / THY

SPIN-ORBIT EFFECTS
Dumour, Ruffini '74 ; Esposito, Harrison '75

ENERGY LOSS IN GRAVIT. WAVES
Wagomer '75

P_b PROOF

DIPOLE RADIATION AS TEST OF GRAVITY
Eardley '75 c Will, Eardley '77

RELATIVISTIC "TIMING FORMULA"
Blandford, Teukolsky '76 ;
. . .
Damour, Deruelle '86

RELATIVISTIC MOTION OF COMPACT OBJECTS

$$a = \frac{Gm}{r^2}\left[1 + \frac{v^2}{c^2} + \frac{v^4}{c^4} + \frac{v^5}{c^5}\right]$$

Damour, Deruelle '81 ; Damour '82, '83

STRONG-FIELD TESTS OF GRAVITY AND PARAMETRIZED POST-KEPLERIAN FORM
Damour '87 ; Damour, Taylor '92

SPIN-ORBIT AND NS INERTIA MOMENTS
Damour, Schäfer '88 : 2 NEED 3 ACCURATE OBSERVABLES

TESTS OF STRONG EQUIV. PRINCIPLE
Damour, Schäfer '91

NON-PERTURBATIVE STRONG-FIELD EFFECTS
Damour, Esposito-Farèse '93

T2

RELATIVITÉ. — *Sur certaines vérifications nouvelles de la Relativité générale rendues possibles par la découverte d'un pulsar membre d'un système binaire.* Note (*) de MM. **Thibaut Damour** et **Remo Ruffini**, présentée par M. André Lichnerowicz.

Cette Note montre comment la récente découverte d'un pulsar membre d'un système binaire pourrait fournir des informations très importantes pour la vérification de la Relativité générale ainsi que pour la connaissance de la structure et des processus d'émission des pulsars. On présente des estimations des principaux effets relativistes que l'on peut espérer observer dans un tel système.

Récemment J.H. Taylor (1) a découvert une nouvelle radiosource pulsante (*cf.* tableau pour les paramètres) membre d'un système binaire (comme l'atteste la variation régulière de la période de pulsation P sur des temps $\tau \sim 8$ h). Il est important de vérifier (*a*) que cet objet est bien un pulsar (2), c'est-à-dire que sa période P doit croître lentement avec le temps et satisfaire de plus l'inégalité $(dE/dt)_{em} \leqq I\,(4\pi^2/P^3)\,(dP/dt)$, où I est le moment d'inertie de l'étoile à neutron et $(dE/dt)_{em}$ la puissance émise par le pulsar, (*b*) et ensuite que le compagnon de cet objet est une étoile compacte : naine blanche, étoile à neutron ou black-hole. Si le compagnon n'est pas une étoile compacte les « marées » induites le doteraient d'un moment quadrupolaire qui se signalerait par une rapide précession du périastre (360°/an) (3).

Si ces deux conditions sont remplies, alors on disposera dans cet objet du meilleur outil depuis l'observation des sources de rayons X membres d'un système binaire pour l'étude de la structure des corps compacts plongés dans des champs gravitationnels intenses.

où le deuxième membre est évalué au point d'émission. Le terme $(1 + v^i n_i)$ donne l'effet Doppler ordinaire qui est ici modifié entre autres par l'effet Einstein $(-g_{00})$ et par l'effet transverse $(-g_{ik}\,v^i\,v^k)$. Le dernier terme enfin, usuellement plus faible que les autres peut devenir important si le signal lumineux passe près du compagnon de masse M_2 et de vitesse v_2 (il faut que l'inclinaison $i \simeq 90°$) on peut alors l'estimer à $u^0_{cm}\,(4\,M_2/b_0)\,(v^b_2 - v^b_{cm})$ où b_0 est le paramètre d'impact mesuré sur un axe b abaissé du compagnon sur le rayon.

Le périastre précesse avec la vitesse angulaire

$$\Omega_p \simeq 3\,\Omega_L\,(M_1 + M_2)/a\,(1 - e^2),$$

où $\Omega_L \simeq (M_1 + M_2)^{1/2}\,a^{-3/2}$ est la vitesse angulaire moyenne sur l'orbite, M_1 est la masse du pulsar, M_2 celle du compagnon et a le demi-grand axe de l'orbite relative. Le tableau montre que cet effet est appréciable. Appréciable aussi (tableau) sera la précession du moment cinétique propre du pulsar induite par le couplage spin-orbite :

$$\Omega_{SL} \simeq 3\,\Omega_L\,M_2/\{2\,a\,(1 - e^2)\}.$$

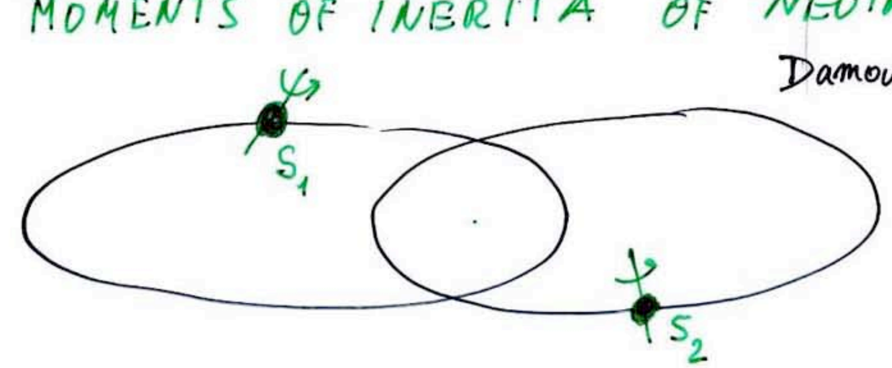
C'est précisément cet effet (ainsi que celui dont on parle plus bas) que cherche à mesurer une expérience terrestre dont la conception est due à Schiff. Cet effet est du plus grand intérêt non seulement pour la vérification de la Relativité générale mais encore pour la connaissance de la structure des étoiles à neutron. En effet pour la première fois il sera possible d'observer les processus d'émission d'un pulsar à des angles variables. Si comme cela a été théoriquement postulé, la radiation est émise dans des cônes issus des pôles magnétiques l'intensité observée sera modulée par la fréquence Ω_{SL}. Elle pourra même s'annuler périodiquement si le faisceau émis est assez étroit.

TABLEAU

Paramètres du pulsar binaire correspondant à une masse de l'étoile à neutron de 0,7 $M_\odot$ en fonction de l'inclinaison i de l'orbite

SPIN-ORBIT COUPLING AND MOMENTS OF INERTIA OF NEUTRON STARS

Damour, Schäfer '88



$$\vec{a} \sim \frac{GM\vec{n}}{r^2}\left[1 + \frac{v^2}{c^2} + \frac{v^4}{c^4}\right] + \text{SPIN-ORBIT TERMS} + \text{SPIN-SPIN ONES}$$

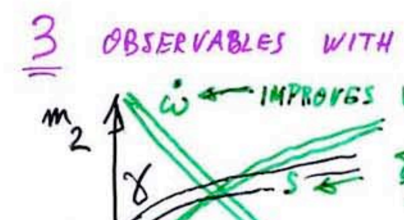
PERIASTRON ADVANCE

$$\frac{\dot{\omega} P_b}{2\pi} = \frac{3(GMn)^{2/3}}{c^2(1-e_T^2)}\left[1 + \underbrace{\frac{(GMn)^{2/3}}{c^2(1-e_T^2)}\left(\frac{39}{4}x_1^2+\frac{27}{4}x_2^2+15x_1x_2\right) - \frac{(GMn)^{2/3}}{c^2}\left(\frac{13}{4}x_1^2+\frac{1}{4}x_2^2+\frac{13}{3}x_1x_2\right) - \frac{\left(\frac{4}{3}x_1^2+x_1x_2\right)(GMn)^{\frac{1}{3}}}{\sqrt{1-e_T^2}}\,\frac{I_1\omega_1}{Gm_1^2}\cdots}_{\text{a few } 10^{-5}}\right]$$

⇒ POSSIBILITY TO MEASURE I_1, AND TEST EQ OF STATE OF N.S.

Damour Schäfer '88, Lattimer Schutz '04, Lyne et al '04, Morrison et al '04

HOWEVER: NEED $\underline{\underline{3}}$ OBSERVABLES WITH $\sim 10^{-5}$ ACCURACY



$\dot{\omega}$ ← IMPROVES WITH TIME $\left(\frac{\delta\dot{\omega}}{\dot{\omega}}\right)_{\text{NOW}} < 10^{-4}$

s ← $\frac{\delta s}{s} \sim 2\times10^{-5}$ FROM SCINTILLATION

Coles et al '04

? WILL A THIRD OBSERVABLE EVER BE MEASURED TO 10^{-5} ?

? IF SO NEED TO WORRY ABOUT $\mathcal{O}(v^2/c^2)$ - ACCURATE DEFINITION OF ALL OBSERVABLES INVOLVED IN THE PROCESS

TESTING RELATIVISTIC GRAVITY WITH BINARY PULSAR DATA

TWO APPROACHES

- "THEORY-INDEPENDENT" OR "PHENOMENOLOGICAL"

  PARAMETRIZED POST-KEPLERIAN

- "THEORY-DEPENDENT"

  - BEYOND USUAL POST-NEWTONIAN PARAMETERS
  - CLASSES OF TENSOR-SCALAR THEORIES

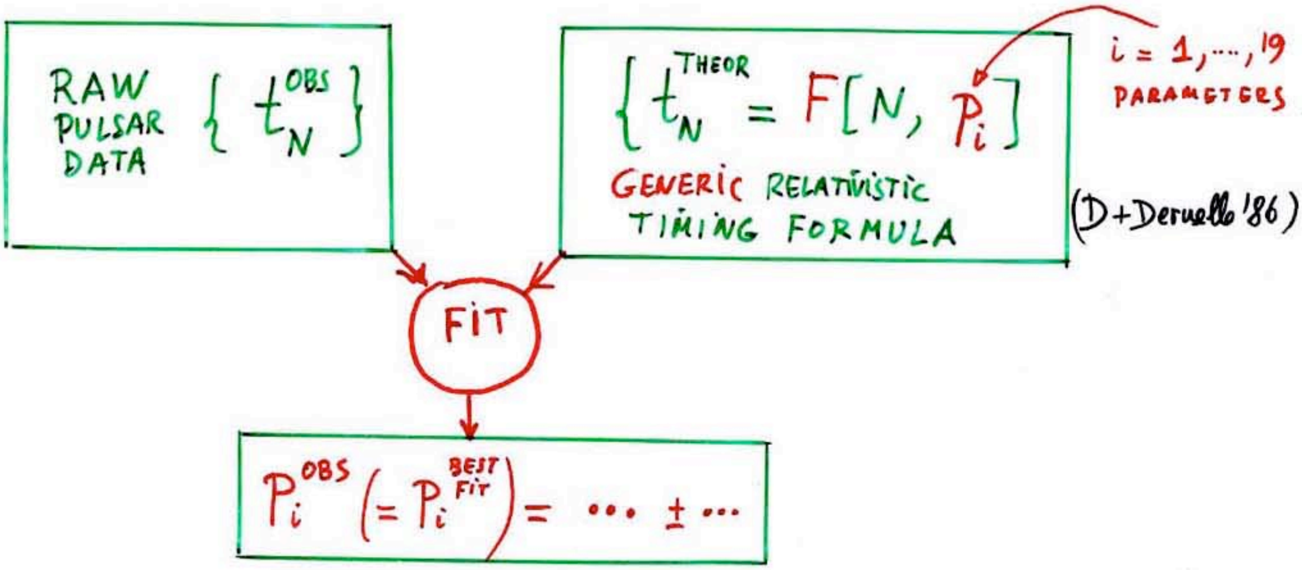
USING BINARY PULSAR MEASUREMENTS TO PROBE RELATIVISTIC GRAVITY

TWO COMPLEMENTARY APPROACHES

①. PHENOMENOLOGICAL ANALYSIS OF BINARY PULSAR DATA

"PARAMETRIZED POST-KEPLERIAN FORMALISM" (PPK)

(Blandford + Teukolsky '76, D + Deruelle '86, D. '88, D + Taylor '92)



RAW PULSAR DATA $\{ t_N^{OBS} \}$

$\{ t_N^{THEOR} = F[N, P_i] \}$

GENERIC RELATIVISTIC TIMING FORMULA

$i = 1, \dots, 19$ PARAMETERS

(D + Deruelle '86)

FIT

$P_i^{OBS} \left(= P_i^{BEST\,FIT} \right) = \cdots \pm \cdots$

EACH RELATIVISTIC THEORY OF GRAVITY PREDICTS

$$P_i^{THEOR} = f_i^{THEORY} \left(m_1, m_2 \left(, \lambda, \eta \right) \right)$$

REDUNDANCY : $19 - 2 \, (-2) = 15$ TESTS OF RELATIVISTIC GRAVITY

MOST PROBE STRONG-FIELD ASPECTS OF GRAVITY

N.B. EACH SUCH TEST IS A POTENTIAL KILLER OF G.R.

RELATIVISTIC TIMING FORMULA

Damour and Deruelle [36, 47] proved that it is possible to describe all of the independent $O(v^2/c^2)$ timing effects in a simple mathematical way common to a wide class of alternative theories. This made it possible to revert to a theory-independent analysis of timing data, and led to the possibility of working within a strong-field analog of the PPN formalism, the so-called [37] "parametrized post-Keplerian" approach. The part of the Damour–Deruelle phenomenological timing model describing orbital effects reads

$$\boxed{t_b - t_0 = F[T; \{p^{\mathrm{K}}\}; \{p^{\mathrm{PK}}\}; \{q^{\mathrm{PK}}\}] \,,} \tag{2.1a}$$

where t_b denotes the solar-system barycentric (infinite frequency) arrival time, T the pulsar proper time (corrected for aberration, see below),

$$\{p^{\mathrm{K}}\} = \{P_b, T_0, e_0, \omega_0, x_0\} \tag{2.1b}$$

is the set of Keplerian parameters,

$$\boxed{\{p^{\mathrm{PK}}\} = \{k, \gamma, \dot{P}_b, r, s, \delta_\theta, \dot{e}, \dot{x}\}} \tag{2.1c}$$

the set of *separately measurable* post-Keplerian parameters, and

$$\{q^{\mathrm{PK}}\} = \{\delta_r, A, B, D\} \tag{2.1d}$$

the set of *not separately measurable* post-Keplerian parameters. The right hand side of Eq. (2.1a) is given by

$$\boxed{\begin{aligned}
F(T) &= D^{-1}[T + \Delta_R(T) + \Delta_E(T) + \Delta_S(T) + \Delta_A(T)] \,, && (2.2\mathrm{a})\\
\Delta_R &= x \sin\omega[\cos u - e(1+\delta_r)] + x[1 - e^2(1+\delta_\theta)^2]^{1/2} \cos\omega \, \sin u \,, && (2.2\mathrm{b})\\
\Delta_E &= \gamma \sin u \,, && (2.2\mathrm{c})\\
\Delta_S &= -2r \, \ln\{1 - e\cos u - s[\sin\omega(\cos u - e) + (1-e^2)^{1/2}\cos\omega \, \sin u]\} \,, && (2.2\mathrm{d})\\
\Delta_A &= A\{\sin[\omega + A_e(u)] + e\sin\omega\} + B\{\cos[\omega + A_e(u)] + e\cos\omega\} \,, && (2.2\mathrm{e})
\end{aligned}}$$

where

$$x = x_0 + \dot{x}(T - T_0) \,, \tag{2.3a}$$

$$e = e_0 + \dot{e}(T - T_0) \,, \tag{2.3b}$$

and where $A_e(u)$ and ω are the following functions of u,

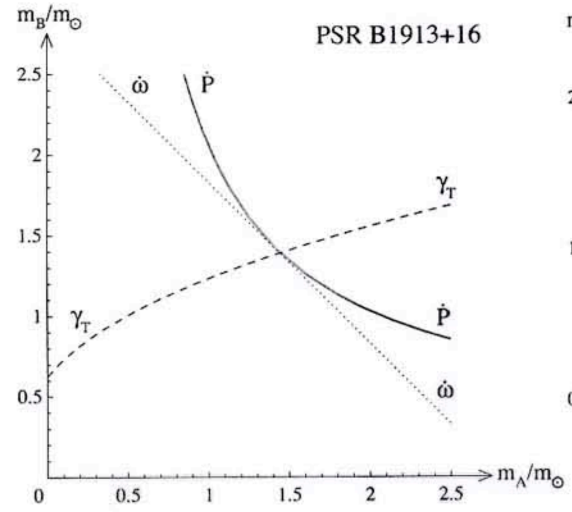
$$A_e(u) = 2\arctan\left[\left(\frac{1+e}{1-e}\right)^{1/2} \tan\frac{u}{2}\right] \,, \tag{2.3c}$$

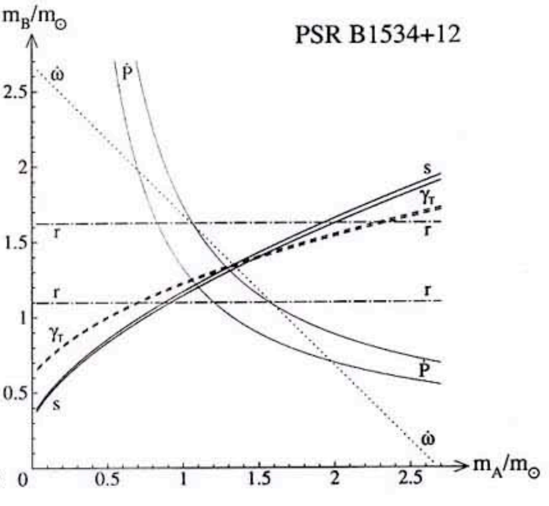
$$\omega = \omega_0 + k\, A_e(u) \,, \tag{2.3d}$$

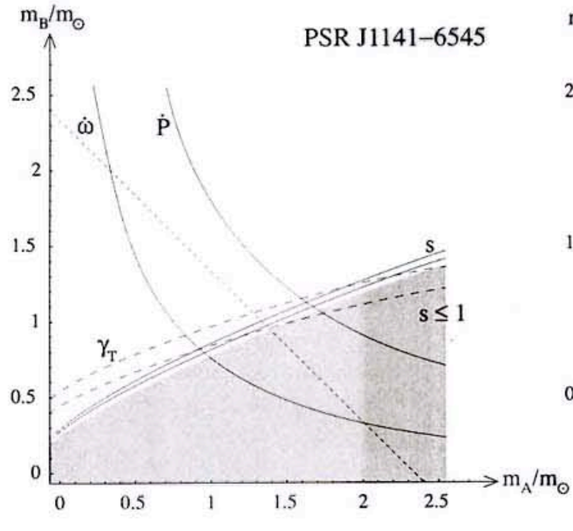
and u is the function of T defined by solving the Kepler equation

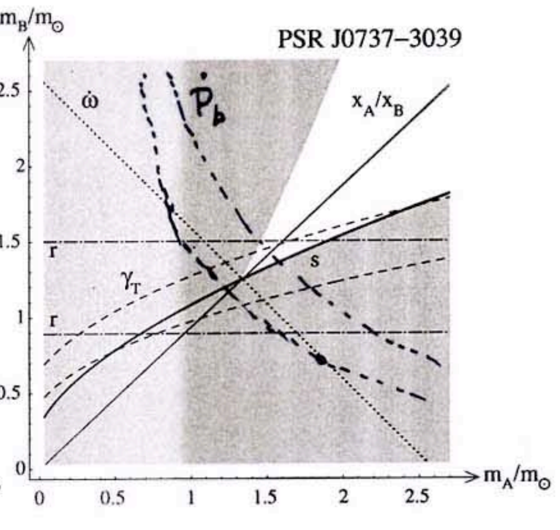
$$u - e\sin u = 2\pi\left[\left(\frac{T - T_0}{P_b}\right) - \frac{1}{2}\dot{P}_b\left(\frac{T - T_0}{P_b}\right)^2\right] \,. \tag{2.3e}$$

T6


PSR B1913+16
m_B/m_⊙
m_A/m_⊙
ω̇
Ṗ
γ_T
0
0.5
1
1.5
2
2.5


PSR B1534+12
m_B/m_⊙
m_A/m_⊙
ω̇
Ṗ
s
γ_T
r
0
0.5
1
1.5
2
2.5


PSR J1141−6545
m_B/m_⊙
m_A/m_⊙
ω̇
Ṗ
s
γ_T
s ≤ 1
0
0.5
1
1.5
2
2.5


PSR J0737−3039
m_B/m_⊙
m_A/m_⊙
ω̇
Ṗ_b
x_A/x_B
r
γ_T
s
0
0.5
1
1.5
2
2.5

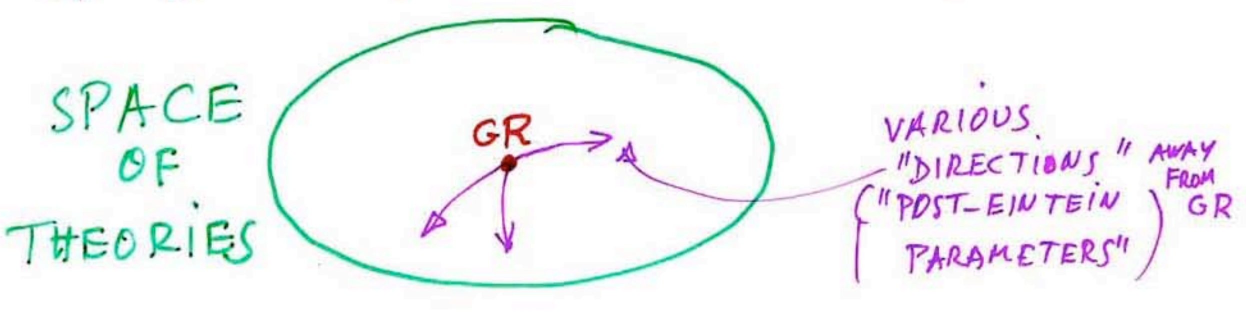
ADVANTAGES OF PHENOMENOLOGICAL APPROACH

- CAN CONFIRM OR INVALIDATE A THEORY WITHOUT MAKING ASSUMPTIONS ABOUT OTHER THEORIES
- GR HAS NO PARAMETER ⇒ ANY TEST IS POTENTIALLY LETHAL

DISADVANTAGES

- DOES NOT TELL US WHICH PART OF THE THEORY IS CONFIRMED
- IN CASE OF FAILURE, DOES NOT TELL US WHICH PART SHOULD BE MODIFIED

⇒ USEFUL TO COMPLEMENT THE PHENOMENOLOGICAL APPROACH BY A THEORY-DEPENDENT ANALYSIS:



FIRST APPROACH TO THEORY-DEPENDENT ANALYSIS

IDEA : GENERALIZE PARAMETRIZED POST NEWTONIAN FRAMEWORK
(Eddington '24, Schiff '60, Baierlein '67, Nordtvedt '68, Will '71)

SOLAR SYSTEM ⇒ WEAK FIELD $\frac{GM}{c^2 r} \lesssim 10^{-6} \ll 1$

MAIN FIRST-ORDER CORRECTIONS PARAMETRIZED BY :

$$\bar{\gamma} \equiv \gamma^{PPN} - 1 \quad : \text{LIGHT DEFLEXION}$$

$$\bar{\beta} \equiv \beta^{PPN} - 1 \quad : \text{PERIASTRON PRECESSION}$$

? GENERALIZATION OF $\bar{\beta}$ AND $\bar{\gamma}$ TO SECOND-ORDER CORRECTIONS $\propto \left(\frac{GM}{c^2 r}\right)^2$?

SEEK INSPIRATION FROM SIMPLEST CLASS OF THEORIES : TENSOR-SCALAR
$g_{\mu\nu}, \varphi_1, \varphi_2, \ldots$

SECOND-ORDER (2PN) CORRECTIONS PARAMETRIZED BY ONLY TWO PARAMETERS
(Damour, Esposito-Farèse '96)

$$\epsilon \qquad \zeta$$

$\sim \beta' \alpha 3$

$\sim \alpha \beta \beta \alpha$

E.G.
EFFECTIVE GRAVITATIONAL COUPLING BETWEEN
A and B

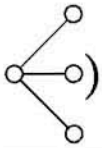
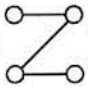
1PN (Nordtvedt '68)

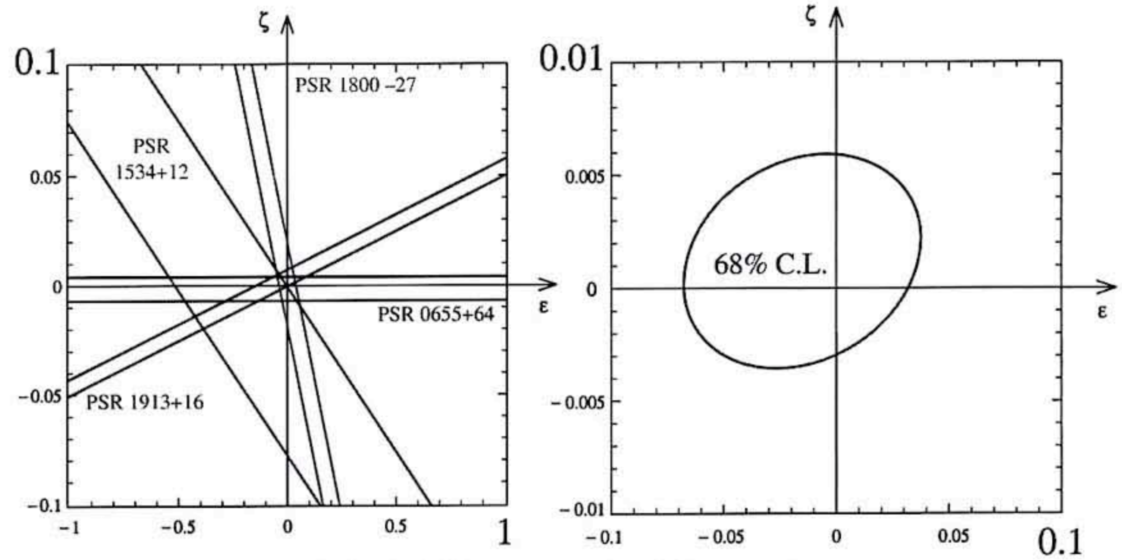
2PN (Damour, Esposito-Farèse '96)

$$\frac{G_{AB}}{G} = 1 + (4\bar{\beta} - \bar{\gamma})\left(\frac{E_A^{grav}}{m_A c^2} + \frac{E_B^{grav}}{m_B c^2}\right) + 4\zeta\left(\frac{E_A^{grav}}{m_A c^2}\right)\left(\frac{E_B^{grav}}{m_B c^2}\right) + \left(\frac{\epsilon}{2} + \zeta\right)\frac{\langle U^2\rangle_A + \langle U^2\rangle_B}{c^4} + \ldots$$

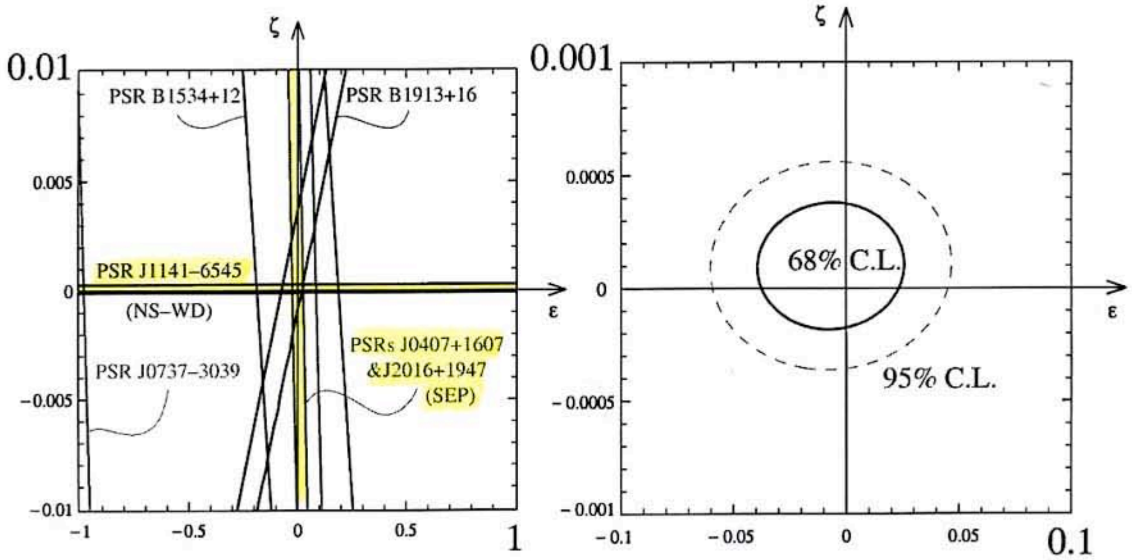
- 2PN TERMS, $\propto \epsilon, \zeta$, ARE TOO SMALL TO BE MEASURABLE IN SOLAR SYSTEM
  [THEY DO NOT ENTER LIGHT DEFLECTION !]
- BINARY PULSARS : $\frac{E_A^{grav}}{m_A c^2} \simeq 0.15$ ⇒ ANALYZE DATA AS CONSTRAINTS ON ϵ, ζ

Binary pulsar constraints on the 2PN parameters

ε (∝ ) and ζ (∝ )



[Damour & Esposito-Farèse, PRD **53** (1996) 5541]



situation in 2004 [T.D. & G.E-F, in preparation]

⇒ 2× tighter constraints on ε ; 15× tighter constraints on ζ

$-4\times10^{-2} < \varepsilon < 3\times10^{-2}$ $-2\times10^{-4} < \zeta < +4\times10^{-4}$

SECOND APPROACH TO THEORY-DEPENDENT ANALYSIS

IDEA: CHOOSE A CLASS OF SIMPLE ALTERNATIVES TO GR,
CONTAINING A SMALL NUMBER OF PARAMETERS,
BUT SUFFICIENTLY MANY TO EXHIBIT INTERESTING EFFECTS

FOR MANY YEARS THE SIMPLEST ALTERNATIVE TO GR WAS:
JORDAN-FIERZ-BRANS-DICKE TENSOR-SCALAR THEORY
CONTAINING ONLY ONE FREE PARAMETER: $\alpha_0^2 = \frac{1}{2\omega_{BD}+3}$

A GENERIC TENSOR-SCALAR THEORY CONTAINS TWO ARBITRARY FUNCTIONS

COUPLING FUNCTION $a(\varphi)$

$$S = \frac{1}{16\pi G}\int d^4x \sqrt{g}\left[R(g) - 2(\partial_\mu \varphi)^2\right] + S_{\text{matter}}\left[\psi; \tilde{g}_{\mu\nu} = e^{2a(\varphi)} g_{\mu\nu}\right]$$
$$- \int d^4x \sqrt{g}\, V(\varphi)$$

POTENTIAL $V(\varphi)$

JORDAN-FIERZ-BRANS-DICKE:

$$\boxed{a(\varphi) = \alpha_0\, \varphi \;;\; V(\varphi) = 0}$$

LINEAR FUNCTION

$\Rightarrow \bar{\gamma} = \gamma^{PPN} - 1 = -\frac{2\alpha_0^2}{1+\alpha_0^2}$

$\bar{\beta} = \beta^{PPN} - 1 = 0$

SIMPLE $\boxed{\text{TWO-PARAMETER}}$ ALTERNATIVE
(Damour, Esposito-Farèse

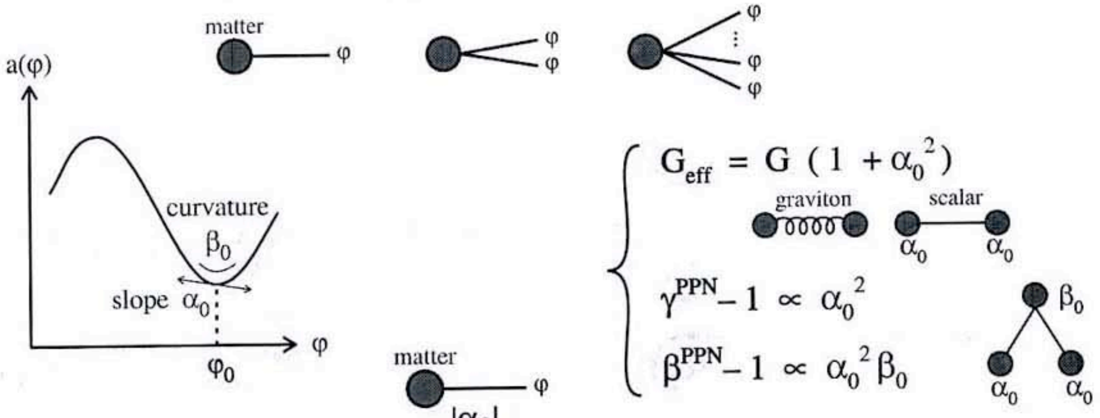
$$\boxed{a(\varphi) = \alpha_0(\varphi - \varphi_0) + \frac{1}{2}\beta_0(\varphi - \varphi_0)^2 \;;\; \begin{array}{l} V'(\varphi_0) = 0 \\ V''(\varphi_0) \simeq 0 \end{array}}$$

$\exists$ OTHER POSSIBILITIES: E.G. $T(\beta', \beta'')$

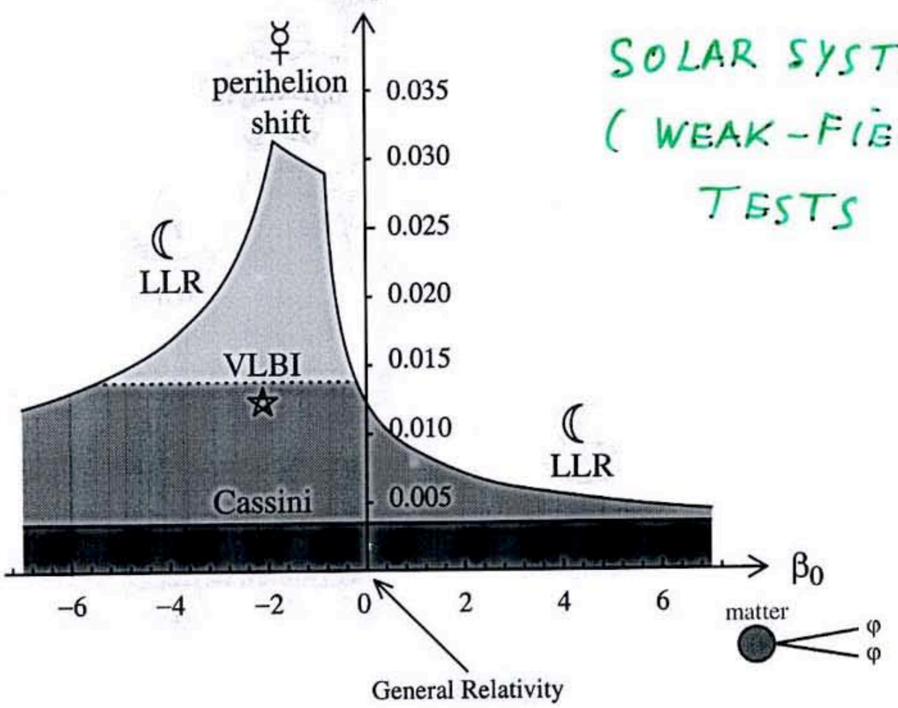
Tensor–scalar theories

$$S = \frac{1}{16\pi G}\int \sqrt{-g}\,\Big\{\underset{\substack{\uparrow\\ \text{spin 2}}}{R} - 2\,\underset{\substack{\uparrow\\ \text{spin 0}}}{\left(\partial_\mu\varphi\right)^2}\Big\} + S_{\text{matter}}\Big[\text{matter}\,;\, \underset{\substack{\uparrow\\ \text{physical metric}}}{\tilde{g}_{\mu\nu}} \equiv e^{2a(\varphi)}\,g_{\mu\nu}\Big]$$

$$a(\varphi) = \alpha_0\,(\varphi-\varphi_0) + \frac{1}{2}\beta_0\,(\varphi-\varphi_0)^2 + \dots$$



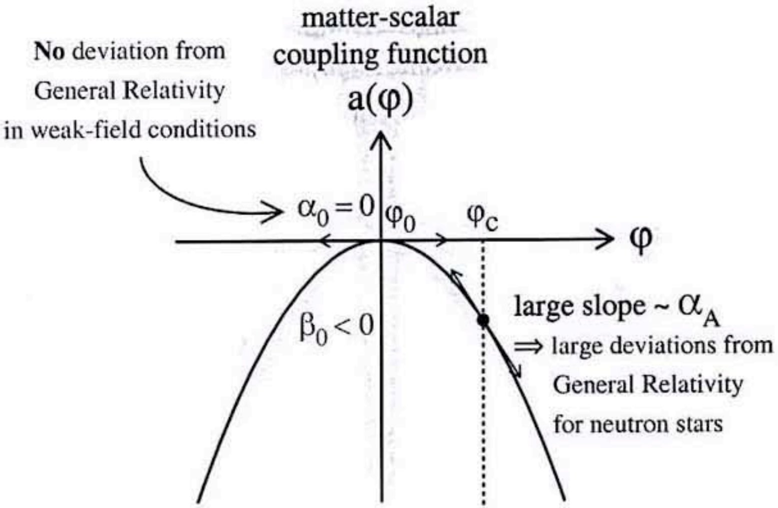
$$\left\{\begin{array}{l} G_{\text{eff}} = G\,(1+\alpha_0^{\,2}) \\ \gamma^{\text{PPN}} - 1 \propto \alpha_0^{\,2} \\ \beta^{\text{PPN}} - 1 \propto \alpha_0^{\,2}\,\beta_0 \end{array}\right.$$

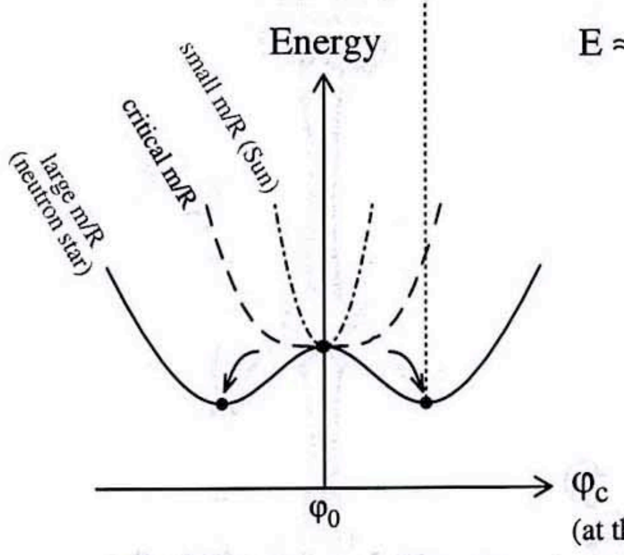


SOLAR SYSTEM
(WEAK-FIELD)
TESTS

Vertical axis ($\beta_0 = 0$) : Jordan–Fierz–Brans–Dicke theory $\alpha_0^2 = \frac{1}{2\,\omega_{\text{BD}} + 3}$

NON-PERTURBATIVE STRONG-FIELD EFFECTS





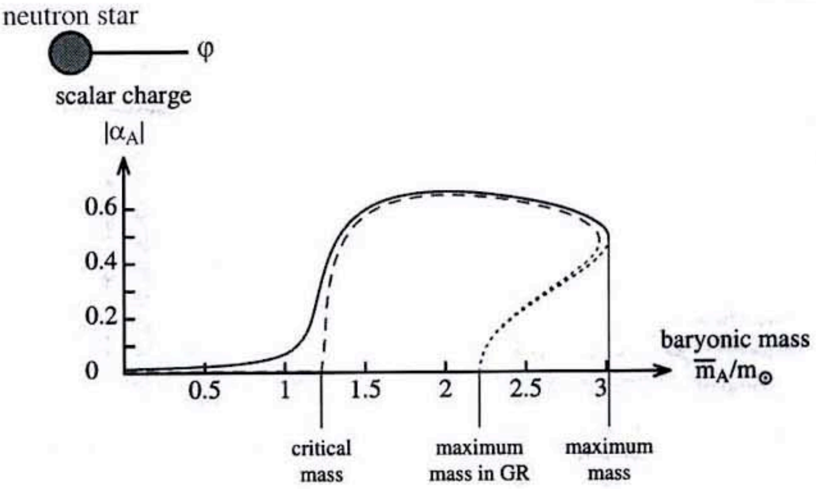
$$E \approx \int \left[\tfrac{1}{2}(\vec{\nabla}\varphi)^2 + \rho\, e^{\beta_0\varphi^2/2} \right]$$

$$\downarrow \qquad\qquad \downarrow$$

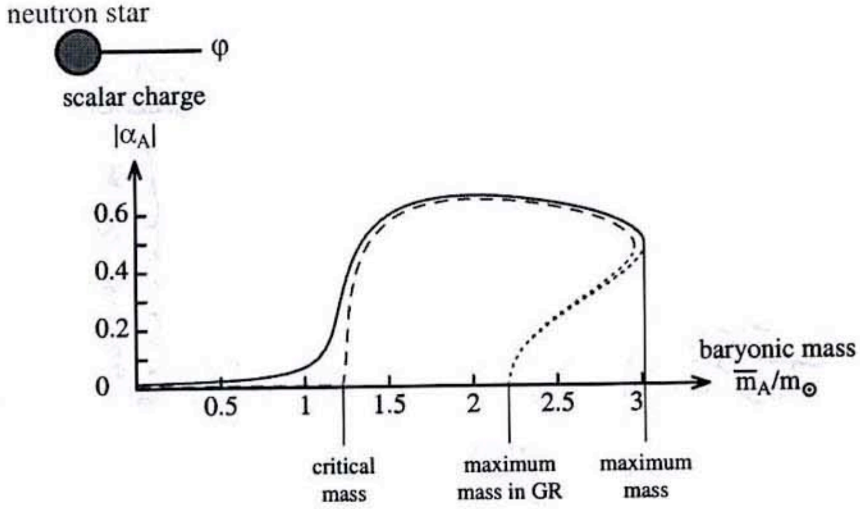
$$\frac{1}{2} R\, \varphi_c^{\,2} \;+\; m\, e^{\beta_0\varphi_c^{\,2}/2}$$

parabola Gaussian if $\beta_0<0$

"spontaneous scalarization" [T. Damour & G.E.F. 1993] Esposito Farèse

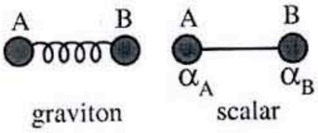


Strong-field effects

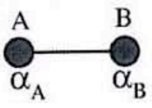


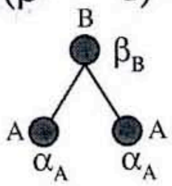
$$G^{\text{eff}}_{AB} = G\,(1 + \alpha_A \alpha_B)$$

depends on internal structure of bodies A & B



similarly for $(\gamma^{\text{PPN}} - 1)$ and $(\beta^{\text{PPN}} - 1)$ ⇒ all post-Newtonian effects





$$\text{Energy flux} = \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \quad \text{spin 2}$$

$$+ \frac{\text{Monopole}}{c}\left(0 + \frac{1}{c^2}\right)^2 + \underset{\underset{\propto(\alpha_A - \alpha_B)^2}{\uparrow}}{\frac{\text{Dipole}}{c^3}} + \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \quad \text{spin 0}$$

DATA

T14 bis

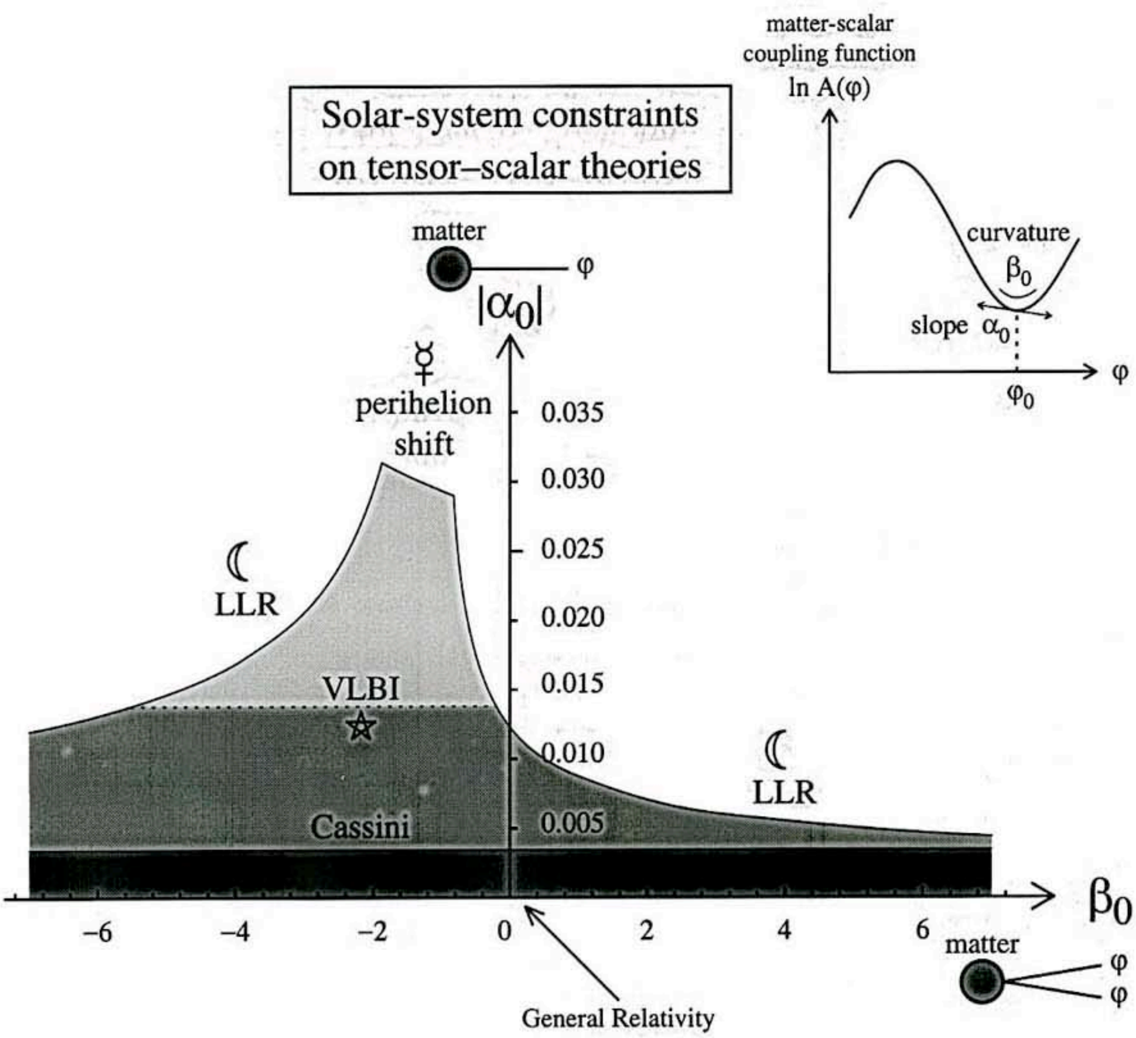
Cassini mission: Bertotti, Iess, Tortora 2003

0737−3039 Burgay et al 2003
Lyne et al. 2004

1141−6545 Bailes et al 2003

Strong Equivalence Principle
Tests on J0407+1607 Lorimer, Freire, 2004
J2016+1947

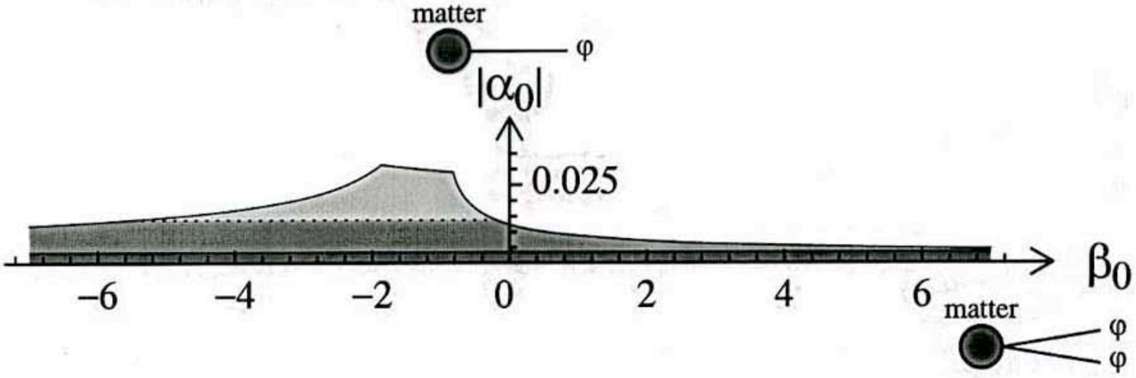
Solar-system constraints on tensor–scalar theories



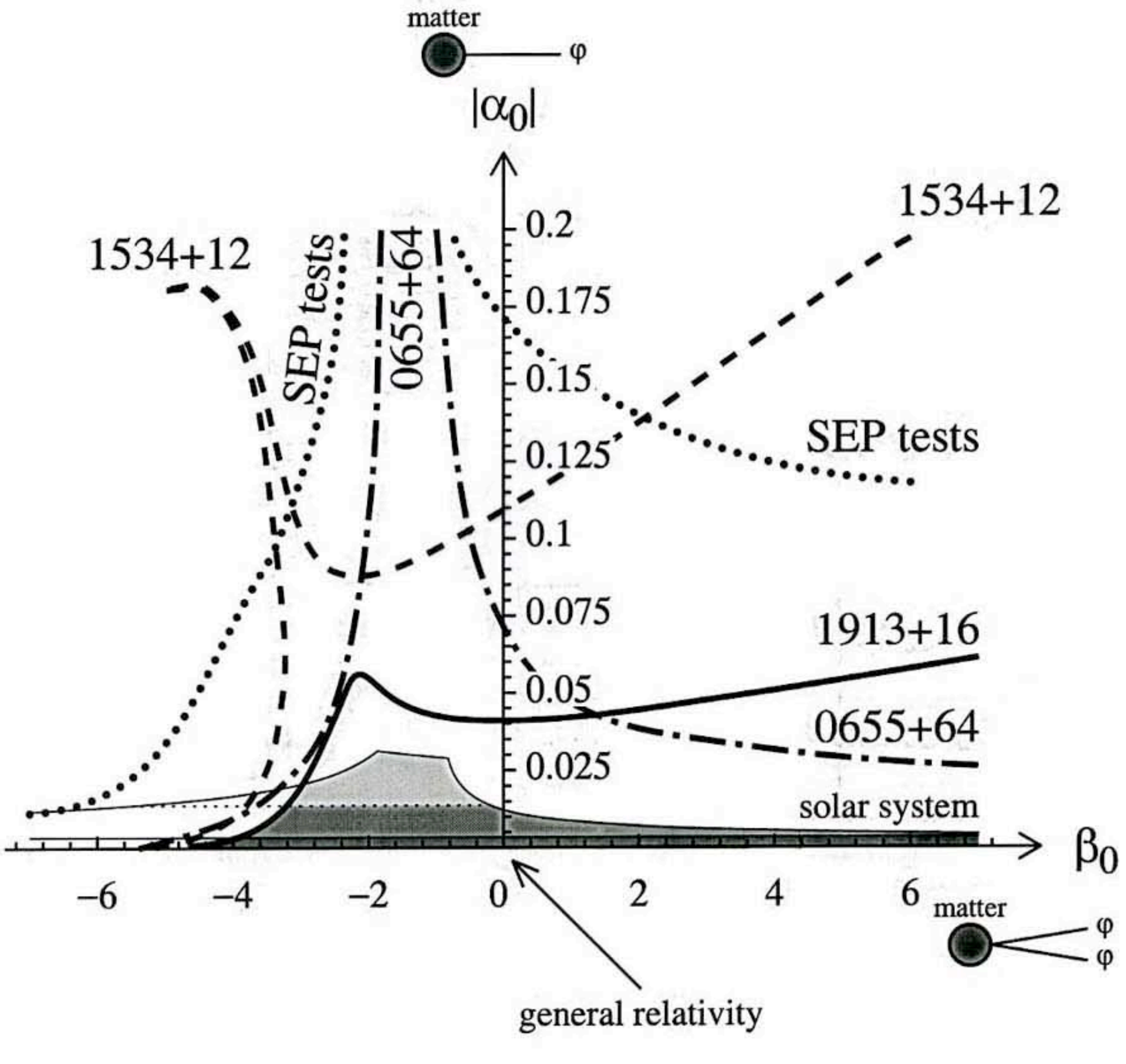
Vertical axis ($\beta_0 = 0$) : Jordan–Fierz–Brans–Dicke theory $\alpha_0^2 = \frac{1}{2\,\omega_{BD} + 3}$

Horizontal axis ($\alpha_0 = 0$) : perturbatively equivalent to G.R.

N.B.: Scale used in next plots

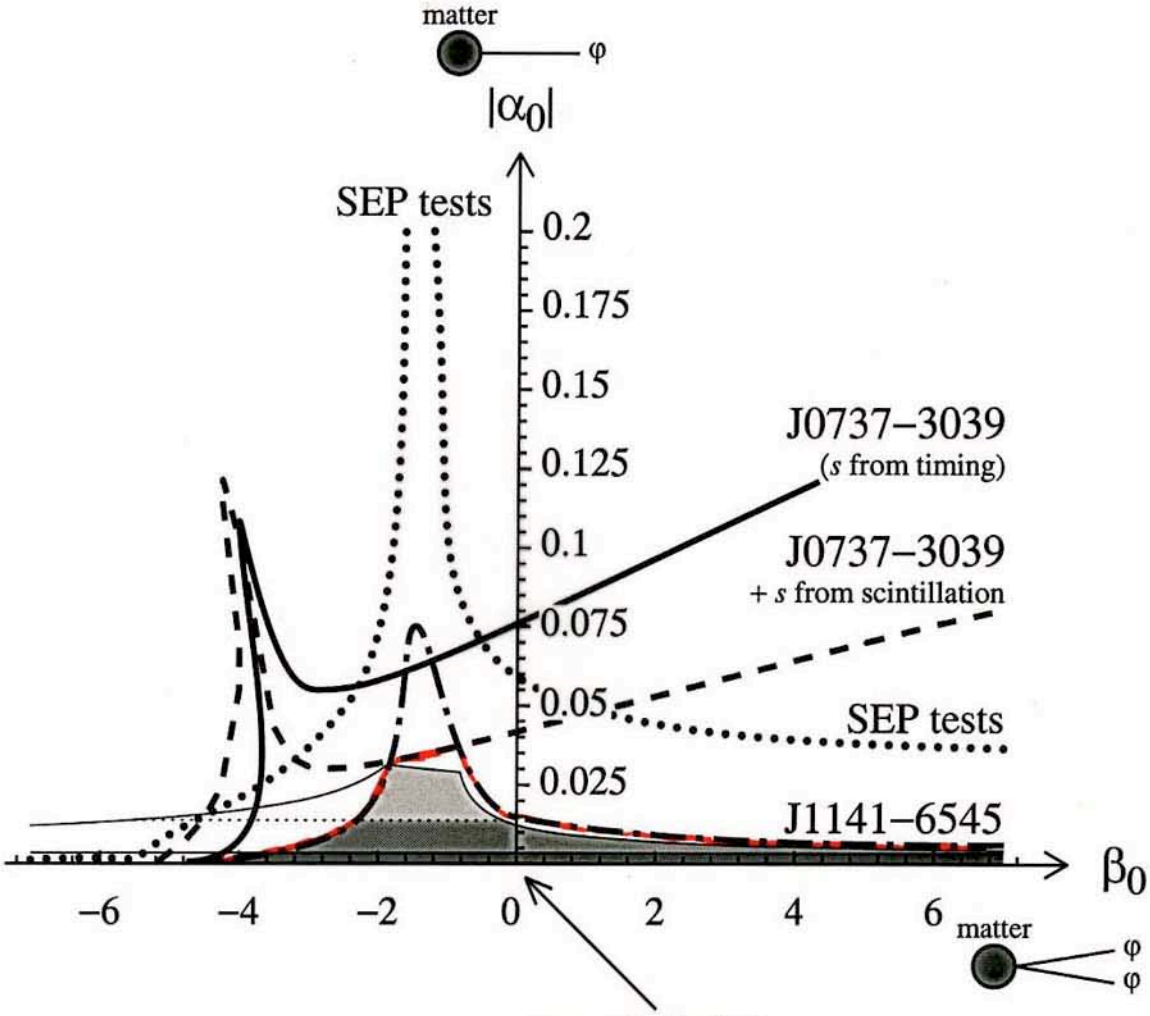


Solar-system and pre-2003 binary-pulsar constraints on tensor–scalar theories

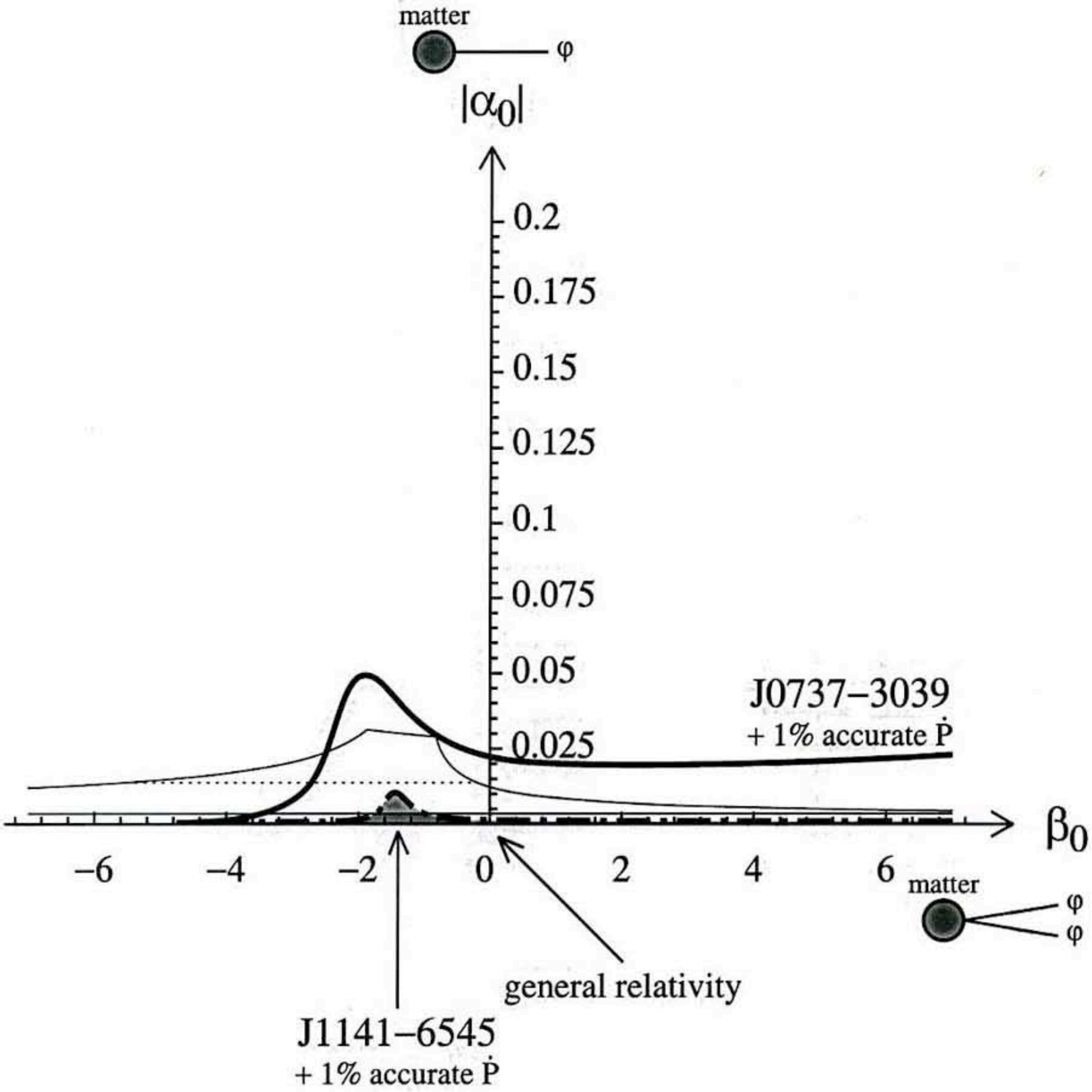


T16

Solar-system and 2003–04 binary-pulsar constraints on tensor–scalar theories

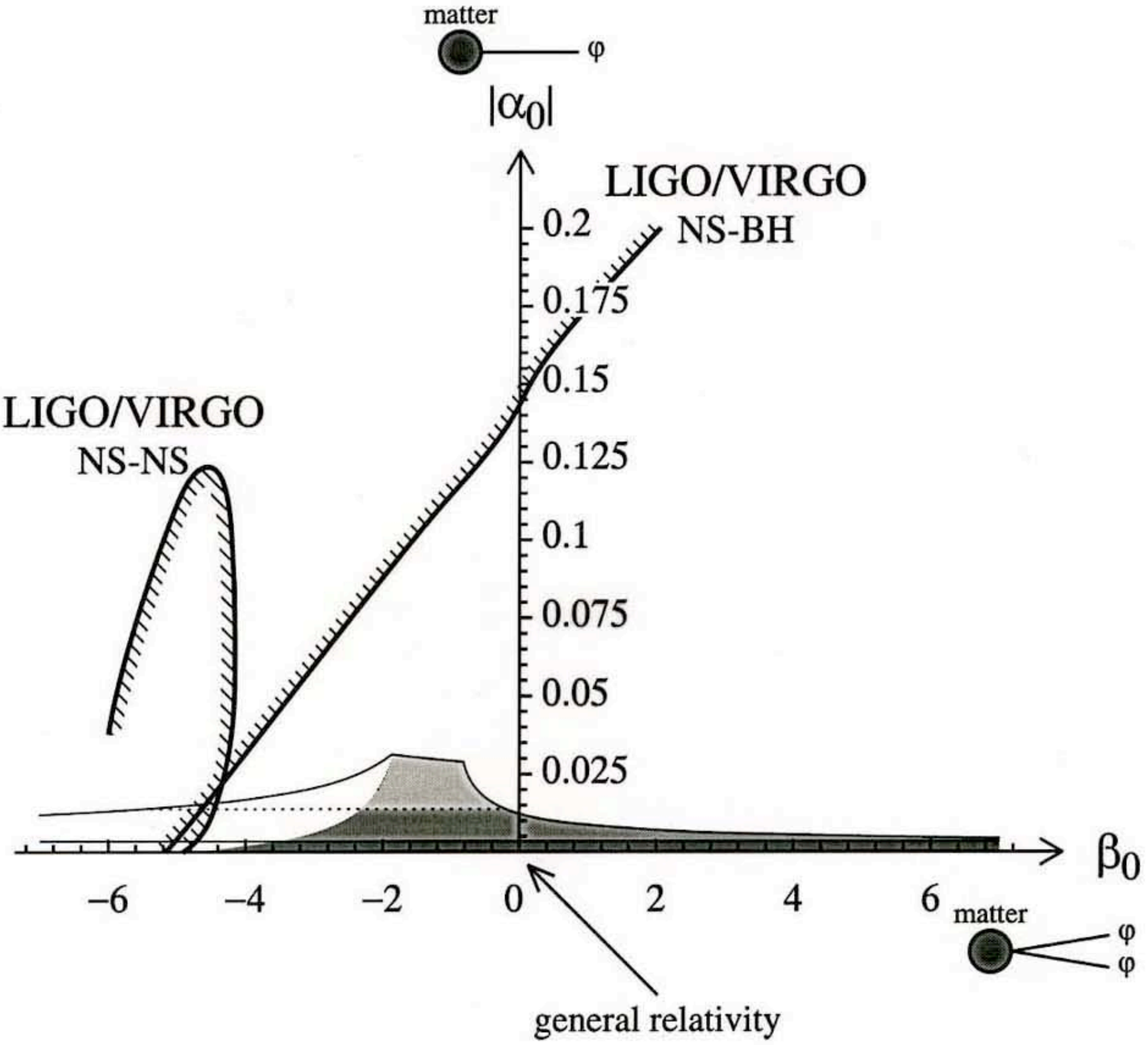


Solar-system and future binary-pulsar constraints on tensor–scalar theories



T18

Solar-system and future LIGO/VIRGO
constraints on tensor–scalar theories

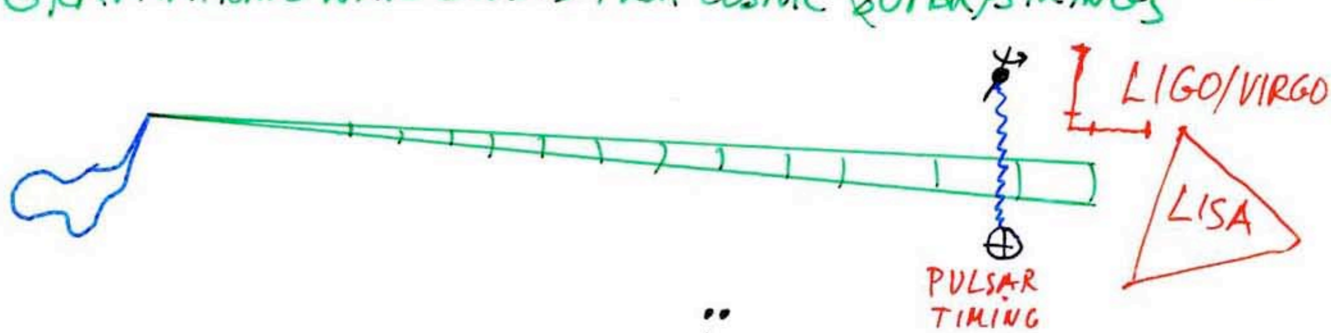


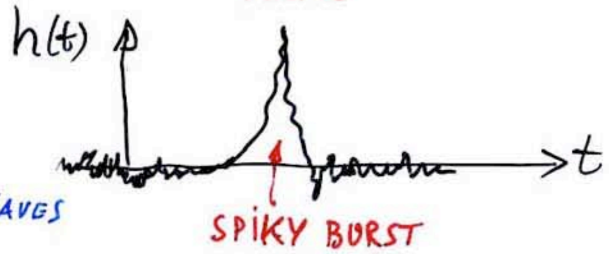
PULSAR TIMING AND GRAVITATIONAL WAVES

T19

EXPERIMENT	THEORY
	Sahzin '78 Detweiler '79 Bertotti, Carr, Rees '83 Blandford, Narayan, Romani '84 COSMIC STRINGS AS SOURCES OF GW Vilenkin '81 ⋮
DISCOVERY OF MILLISECOND PULSARS Backer, Kulkarni, Heiles, Davis, Goss '82	
Stinebring, Ryba, Taylor, Romani '90 Kaspi, Taylor, Ryba '94 $\Omega_g h^2 < 6 \times 10^{-8}$	
CONCEPT AND REALIZATION OF PULSAR TIMING ARRAY Backer Lommen, Backer '2001 Lommen, '2002 $\Omega_g h^2 < 2.8 \times 10^{-6}$ OR $\Omega_g h^2 < 2 \times 10^{-9}$?	NEW COSMOLOGICAL SCENARIOS Dvali, Tye '99 Sarangi, Tye '2002 COSMIC SUPERSTRINGS Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi '03 Copeland, Myers, Polchinski '04 Dvali, Vilenkin '04 GW BURSTS FROM CUSPS ON STRINGS Damour, Vilenkin '00, '04
?	
CONCEPT OF SQUARE KILOMETER ARRAY	

GRAVITATIONAL WAVE BURSTS FROM COSMIC (SUPER)-STRINGS





(STRONGLY) NON GAUSSIAN
STOCHASTIC BACKGROUND OF GRAV. WAVES

UNKNOWN PARAMETERS : μ, p, ϵ.

- STRING TENSION μ . RECENT SCENARIOS $\rightsquigarrow$ $10^{-11} \lesssim G\mu \lesssim 10^{-6}$ Tye et al.
- RECONNECTION PROBABILITY $0 < p \leq 1$ RECENT SCENARIOS $10^{-3} \lesssim p \lesssim 1$ Polchinski et al.
- TYPICAL LENGTH OF NEWLY FORMED LOOPS $\ell = \epsilon \, 50 \, G\mu t$ RECENT SCENARIOS $\epsilon \ll 1$ Siemens et al.

POSSIBILITY OF DETECTING SUCH GW BURSTS
IN LIGO 1, LIGO 2, LISA AND PTA

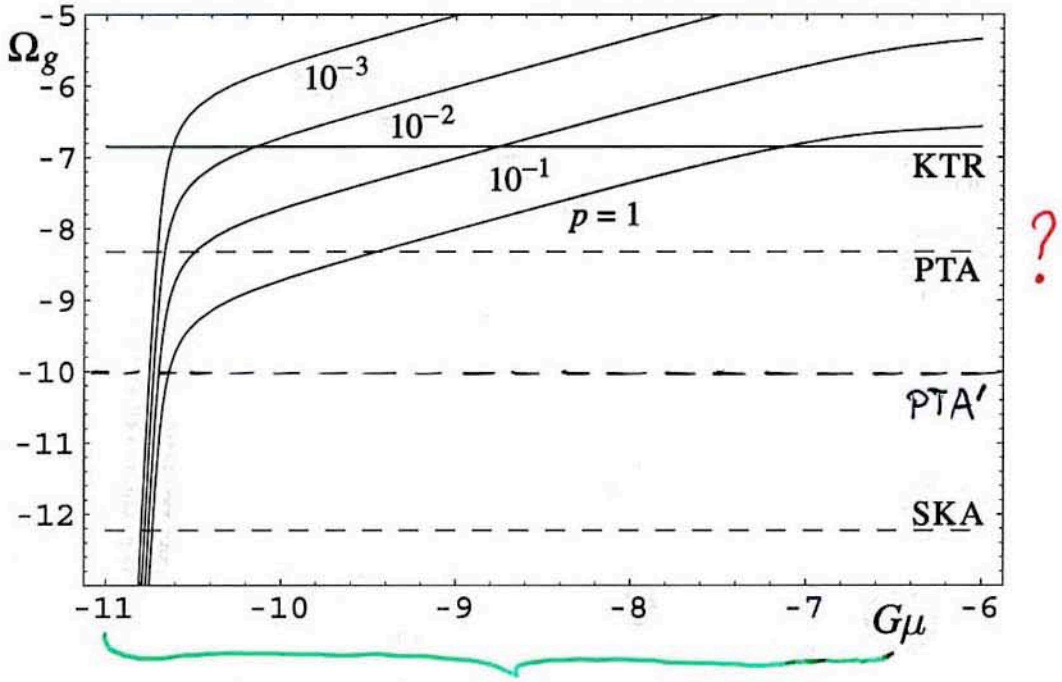
$$\boxed{\Omega_g(f)\, h^2 \sim 10^{-9.13}\, c \left(\frac{G\mu}{10^{-10}}\right)^{2/3} p^{-1} \epsilon^{-1/3} \left(\frac{f}{(10yr)^{-1}}\right)^{-\frac{1}{3}}}$$

OF CUSPS $c \lesssim 1$

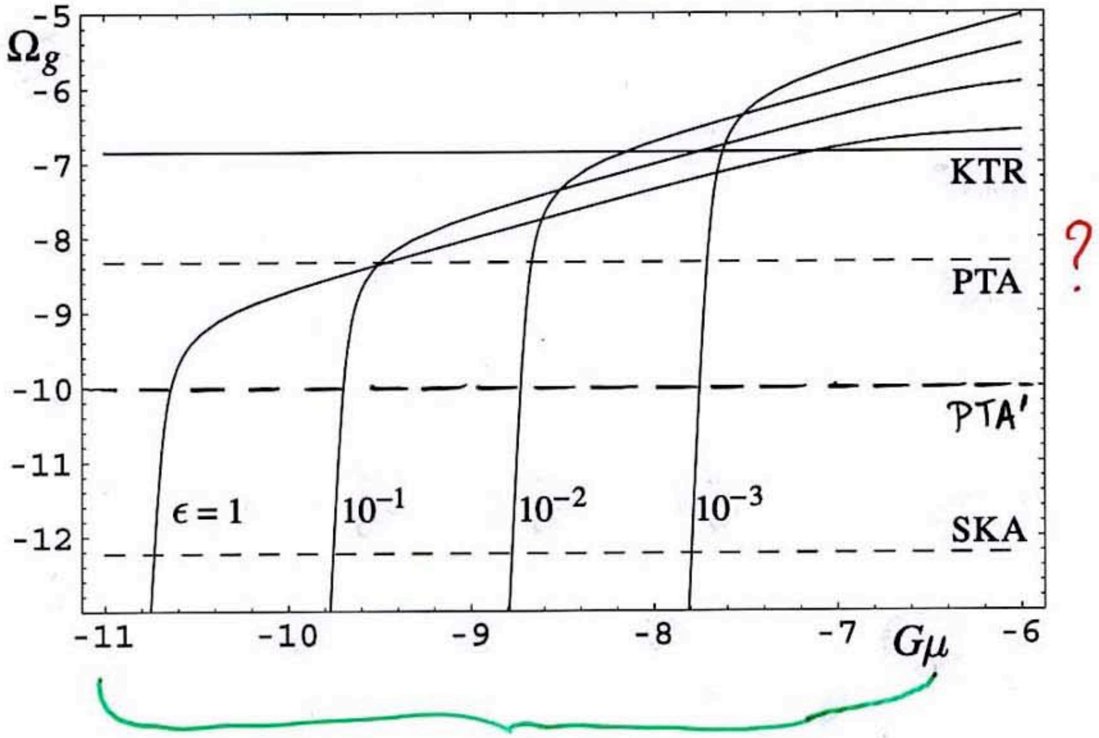
TEND TO INCREASE THE SIGNAL!

Damour, Vilenkin '04

T21



SUGGESTED (ALLOWED) RANGE



SUGGESTED (ALLOWED) RANGE

Z DISAPPEARING SIGNAL IF $50 \epsilon G\mu < 10^{-9}$

"COULD THE LARGE SCATTER IN THE GREEN BANK DATA BE DUE TO A TRANSIENT GRAVIT. WAVE BURST ACTIVITY ?"

Damour, Vilenkin '04

Lommen '01

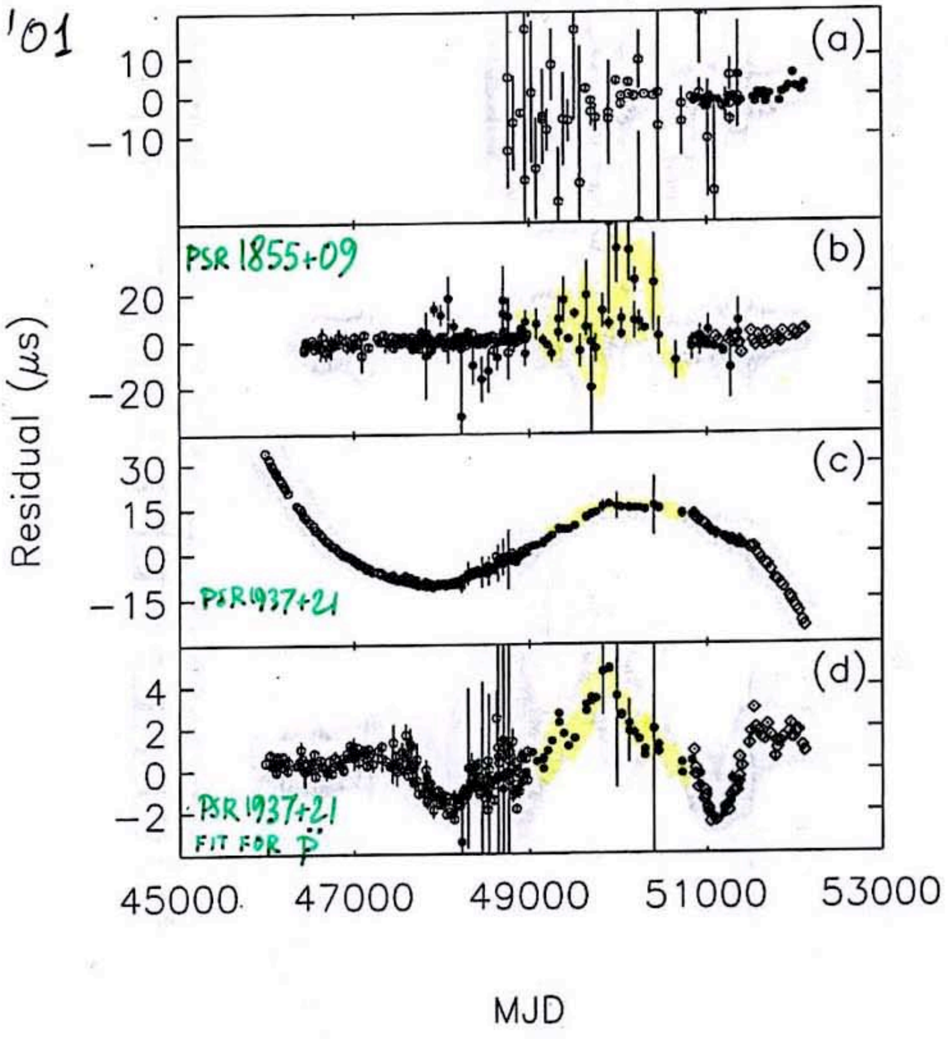


Figure 5.9 (a) PSR J1713+0747, (b) PSR B1855+09, (c) PSR B1937+21 and (d) PSR B1937+21 fit for $\ddot{P}$. The open circles are KTR94 data, the filled circles are Green Bank data, and the open diamonds are ABPP data.

CONCLUSIONS

B1913+16 $\dot\omega\,\dot P\,\gamma$ 1 radiative + strong-field test

B1534+12 $\dot\omega\,\dot P\,r\,s\,\gamma$ 1 radiative + strong-field + 2 PURE STRONG-FIELD TESTS

J1141−6545 $\dot\omega\,\dot P\,\gamma\,s$ 1 radiative + strong-field + 1 PURE STRONG-FIELD

J0737−3039 $\dot\omega\,\gamma\,r\,s\,R\,\dot P$ 1 radiative + strong-field + 3 PURE STRONG-FIELD

[J0407+1607
J2016+1947 $\Delta < 9\times10^{-4}$ 2 PURE STRONG-FIELD]

- ∃ 4 INDEPENDENT DIRECT CONFIRMATIONS THAT GRAVITY PROPAGATES WITH $c_g = c$ AND HELICITY 2, AS GR SAYS

- RECENT PULSAR DATA HAVE MULTIPLIED BY LARGE FACTOR # ACCURATE PURE STRONG-FIELD TESTS

  $2 \rightarrow 2 + 1 + 3 + [2] = 6 + (2] = 8$

- THEORY-DEPENDENT ANALYSES HAVE PROVEN THAT THE PROBING POWER OF PSR EXPTS IS QUALITATIVELY DIFFERENT FROM SOLAR-SYSTEM ONES:
  - ϵ, ζ ANALYSIS : 2PN LEVEL UNREACHABLE IN SOLAR-SYSTEM
  - α_0, β_0 ANALYSIS : $\beta_0 \lesssim -4.5$ EXCLUDED, EVEN IF $\alpha_0 \lll 1$

- FUTURE PSR EXPTS (EG 1141 WITH 1% $\dot P$, OR BH+NS) COULD BEAT SOLAR-SYSTEM EXPTS EVEN AT THE QUANTITATIVE LEVEL : $\alpha_0^2 \sim |\gamma^{PPN} - 1| \lesssim 10^{-6}$

- PRESENT THEORY-DEPENDENT ANALYSES MAY HAVE EXHAUSTED THEIR INTEREST, BUT THE VALUE OF THEORY-INDEPENDENT (PPK) TESTS REMAINS VERY HIGH:

  ANY NEW TEST IS POTENTIALLY LETHAL FOR GR.

- ALL THOSE RADIATIVE + STRONG-FIELD TESTS GIVE A VERY HIGH CONFIDENCE IN USING GR TO PREDICT GWs FROM COALESCING BINARY BLACK HOLES, ETC.

- WE URGE PULSAR OBSERVERS TO REANALYZE THE 17-YR PTA DATA TO SEE WHETHER THE LARGE SCATTER IN GREEN BANK DATA MIGHT BE DUE TO A TRANSIENT GW BURST ACTIVITY OF SOME SORT.

AT STAKES : POTENTIAL CONFIRMATION OF (SUPER-)STRING THEORY