Recent binary-pulsar tests of gravity and comparison with other experiments

Gilles Esposito-Farèse (GRεCO / IAP)

Testing a theory **?**

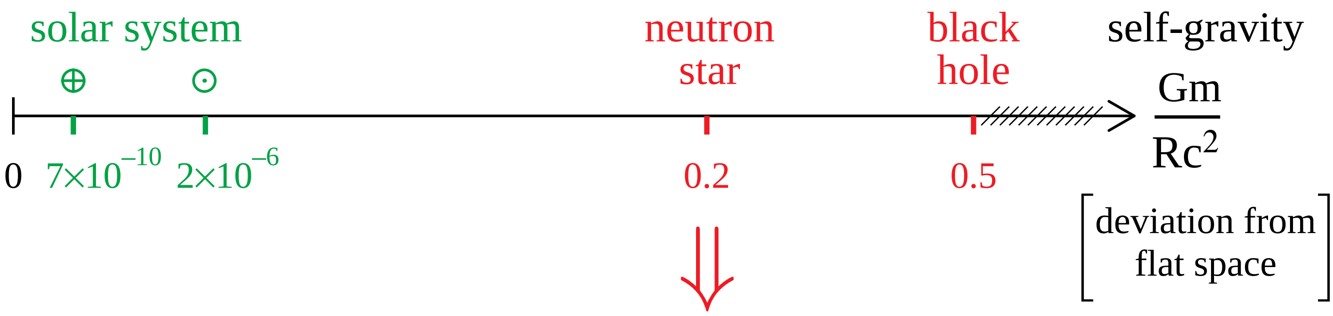
Useful to contrast its predictions with alternative theories

Example: “PPN” formalism to study weak-field gravity (order Newton $\times \frac{1}{c^2}$)

[Eddington, Schiff, Baierlin, Nordtvedt, Will]

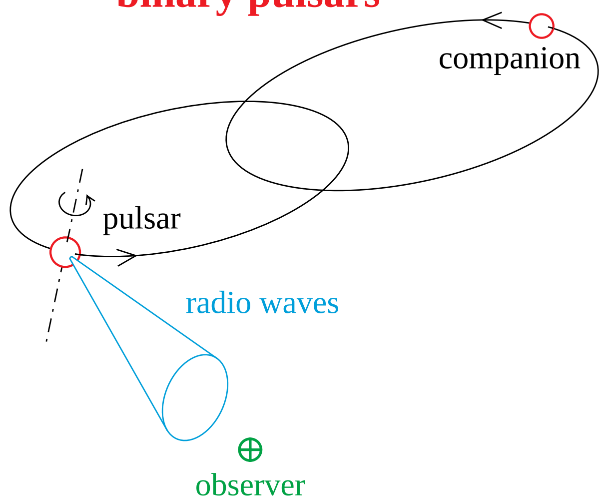
$$\begin{cases} -g_{00} = 1 - 2\dfrac{Gm}{rc^2} + 2\,\beta^{PPN}\left(\dfrac{Gm}{rc^2}\right)^2 + \dots \\ g_{ij} = \delta_{ij}\left[1 + 2\,\gamma^{PPN}\dfrac{Gm}{rc^2} + \dots\right] \end{cases}$$

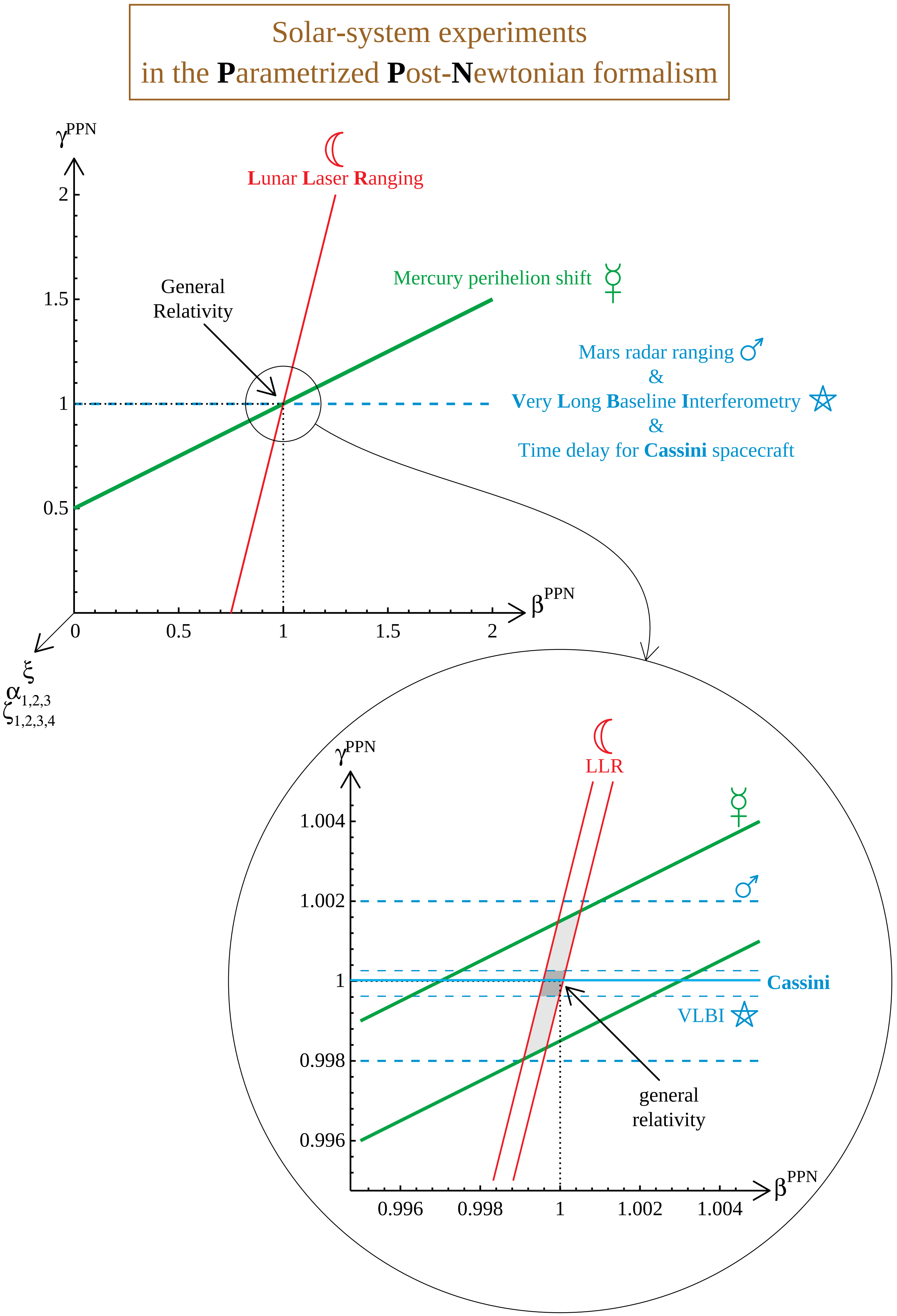
Strong-field tests **?**



binary pulsars

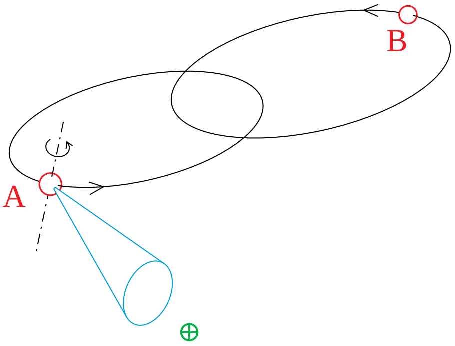
moving clock giving information about this strong-gravity region





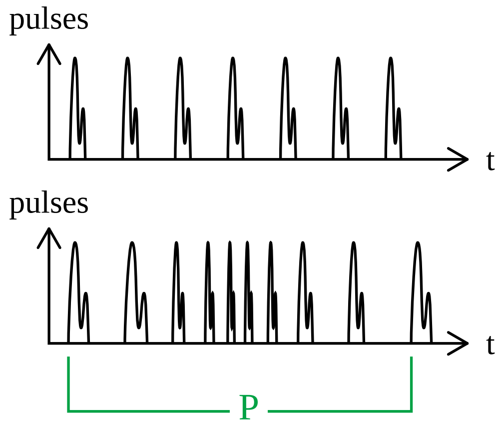
Solar-system experiments
in the Parametrized Post-Newtonian formalism
γPPN
βPPN
Lunar Laser Ranging
Mercury perihelion shift
General Relativity
Mars radar ranging
&
Very Long Baseline Interferometry
&
Time delay for Cassini spacecraft
0
0.5
1
1.5
2
ξ
α1,2,3
ζ1,2,3,4
LLR
Cassini
VLBI
general relativity
1.004
1.002
0.998
0.996

Binary-pulsar tests



pulsar = (very stable) clock

binary pulsar = moving clock



- Time of flight across orbit $\propto \dfrac{\text{size of orbit}}{c}$ ("Roemer time delay")

– orbital period P
– eccentricity e
– periastron angular position ω
– …

} "Keplerian" parameters

- Redshift $\propto \dfrac{G\, m_B}{r_{AB}\, c^2}$ + second order Doppler effect $\propto \dfrac{\vec{v}_A^{\,2}}{2\, c^2}$ ("Einstein time delay")

– parameter γ_{Timing}

- Time evolution of Keplerian parameters

– periastron advance $\dot{\omega}$ (order $\frac{1}{c^2}$)

– gravitational radiation damping $\dot{P}$ (order $\frac{1}{c^5}$)

} "post-Keplerian" observables
[PSR B1913+16 • Hulse & Taylor]

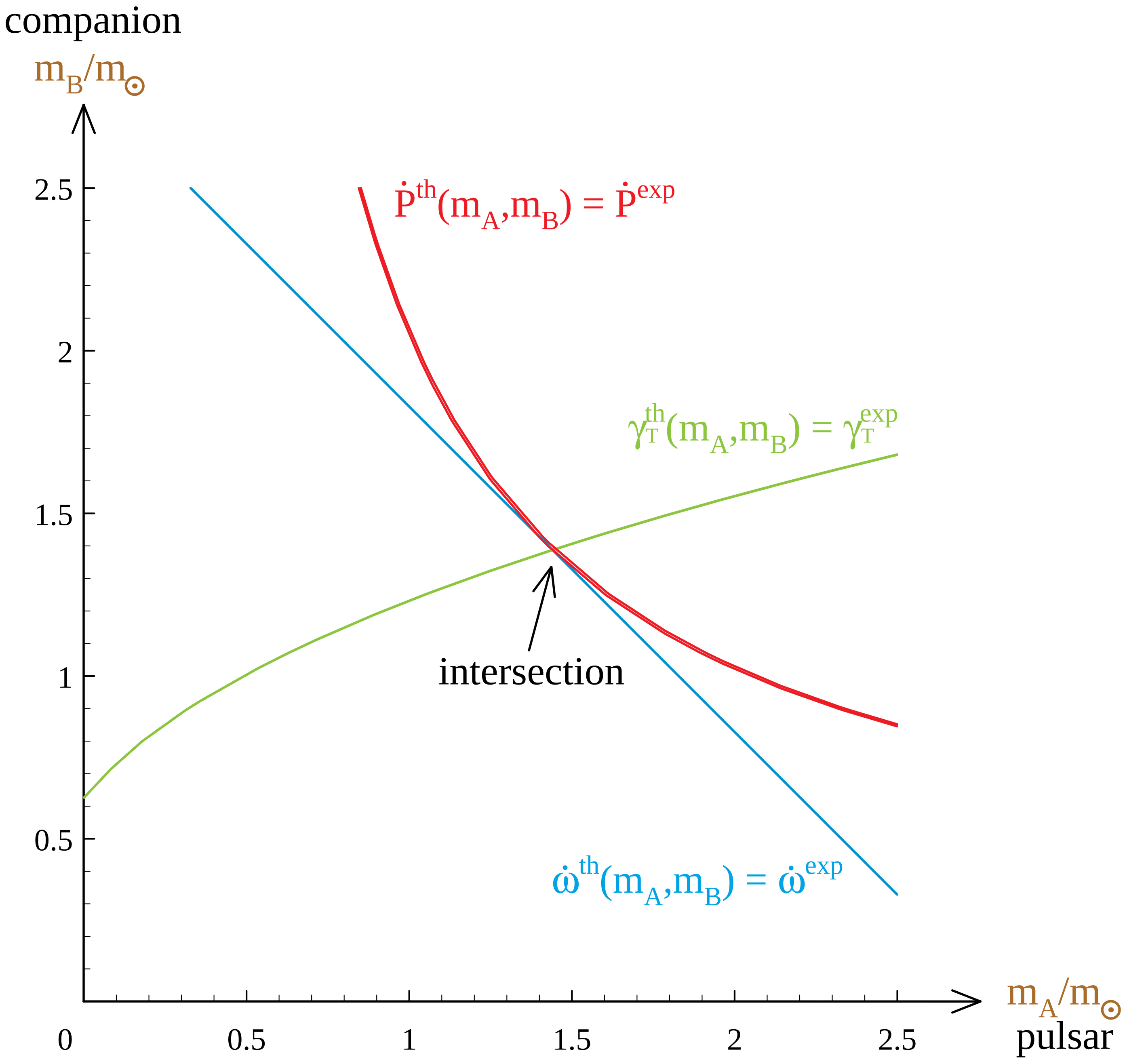
3	–	2	=	1
observables		unknown masses m_A, m_B		test

Plot the three curves [strips]

$$\gamma^{\text{theory}}_{\text{Timing}}(m_A, m_B) = \gamma^{\text{observed}}_{\text{Timing}}$$
$$\dot{\omega}^{\text{theory}}(m_A, m_B) = \dot{\omega}^{\text{observed}}$$
$$\dot{P}^{\text{theory}}(m_A, m_B) = \dot{P}^{\text{observed}}$$

} " γ - $\dot{\omega}$ - $\dot{P}$ test "

PSR B1913+16
in general relativity



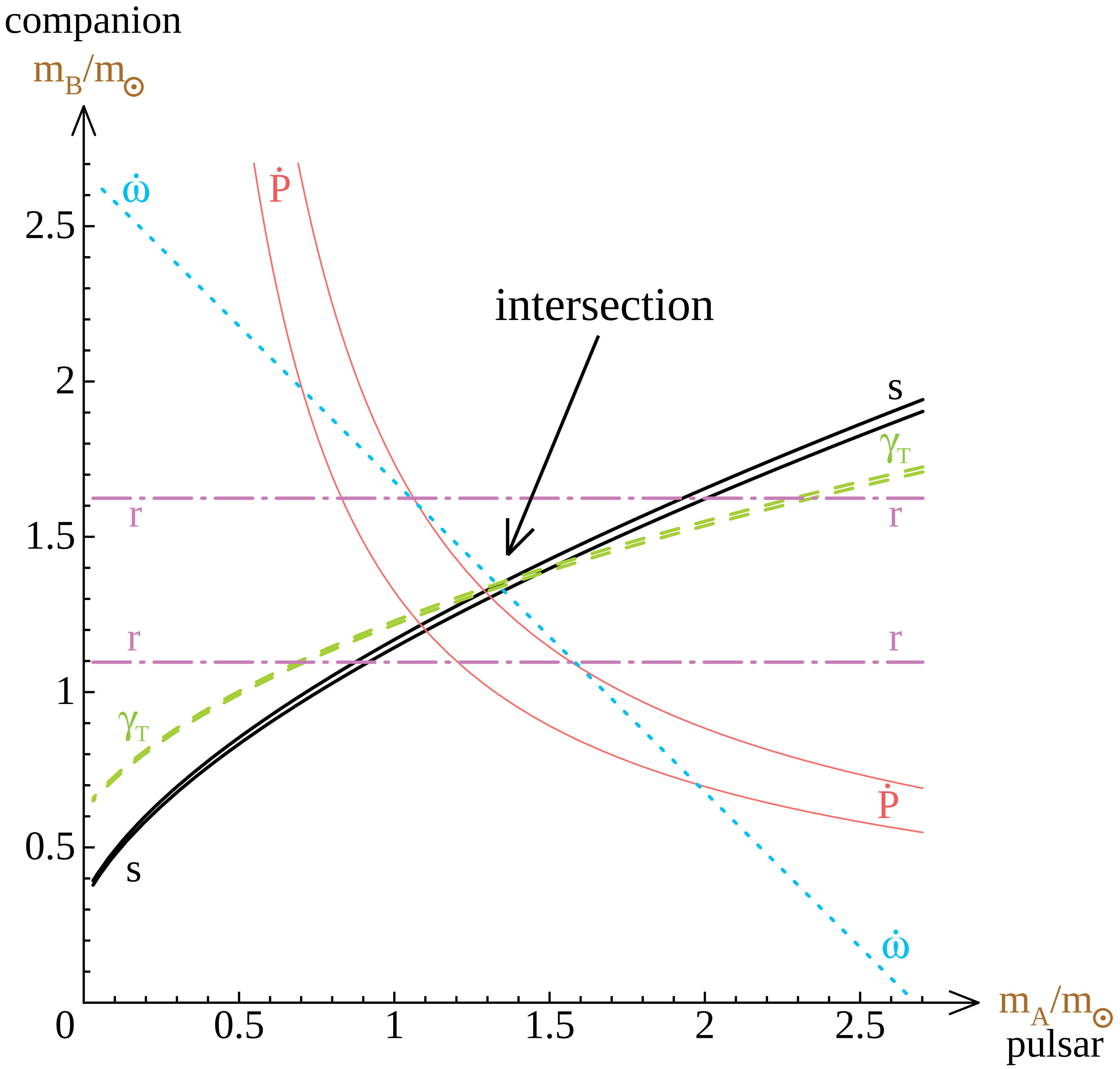
Discovered by R. Hulse and J. Taylor in 1974

$$\dot{\omega} = 4.22661°/\mathrm{yr}$$
$$\gamma_T = 4.294\ \mathrm{ms}$$
$$\dot{P} = -2.421 \times 10^{-12}$$

$$\stackrel{GR}{\Longrightarrow}$$

$$m_A = 1.4408\ m_\odot$$
$$m_B = 1.3873\ m_\odot$$

PSR B1534+12
in general relativity



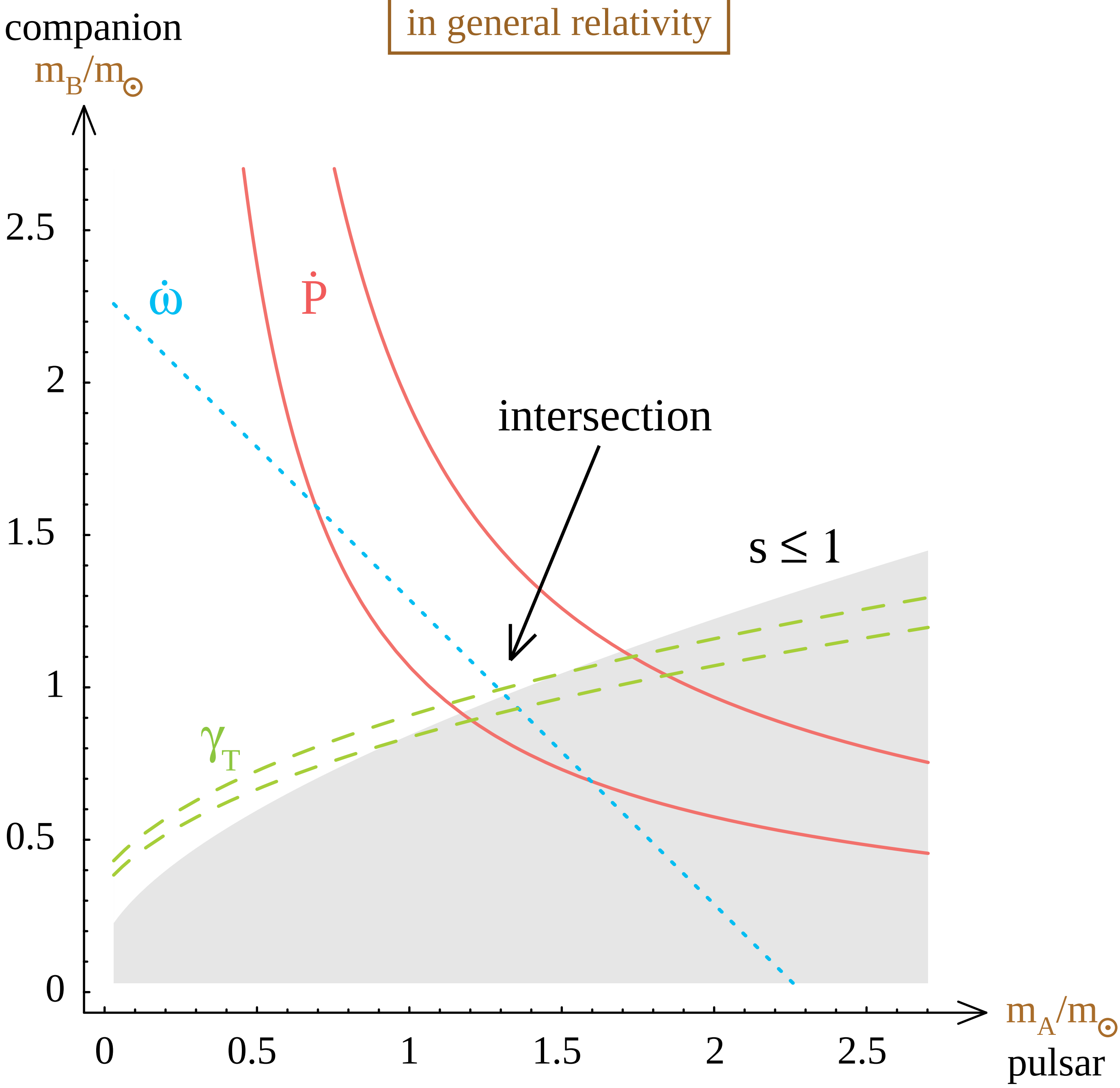
Discovered by A. Wolszczan in 1991

5 observables – **2** masses = **3** tests

"Galactic" contribution to $\dot P$ [Damour–Taylor 1991]

$$\text{Doppler} \propto n.v \Longrightarrow \frac{d\,\text{Doppler}}{d\,t} \propto n.a + \frac{v_\perp^2}{d_{\odot PSR}}$$

PSR J1141–6545
in general relativity



Discovery Kaspi *et al.* 1999,
Timing Bailes *et al.* 2003

$\dot{P} = -4 \times 10^{-13}$

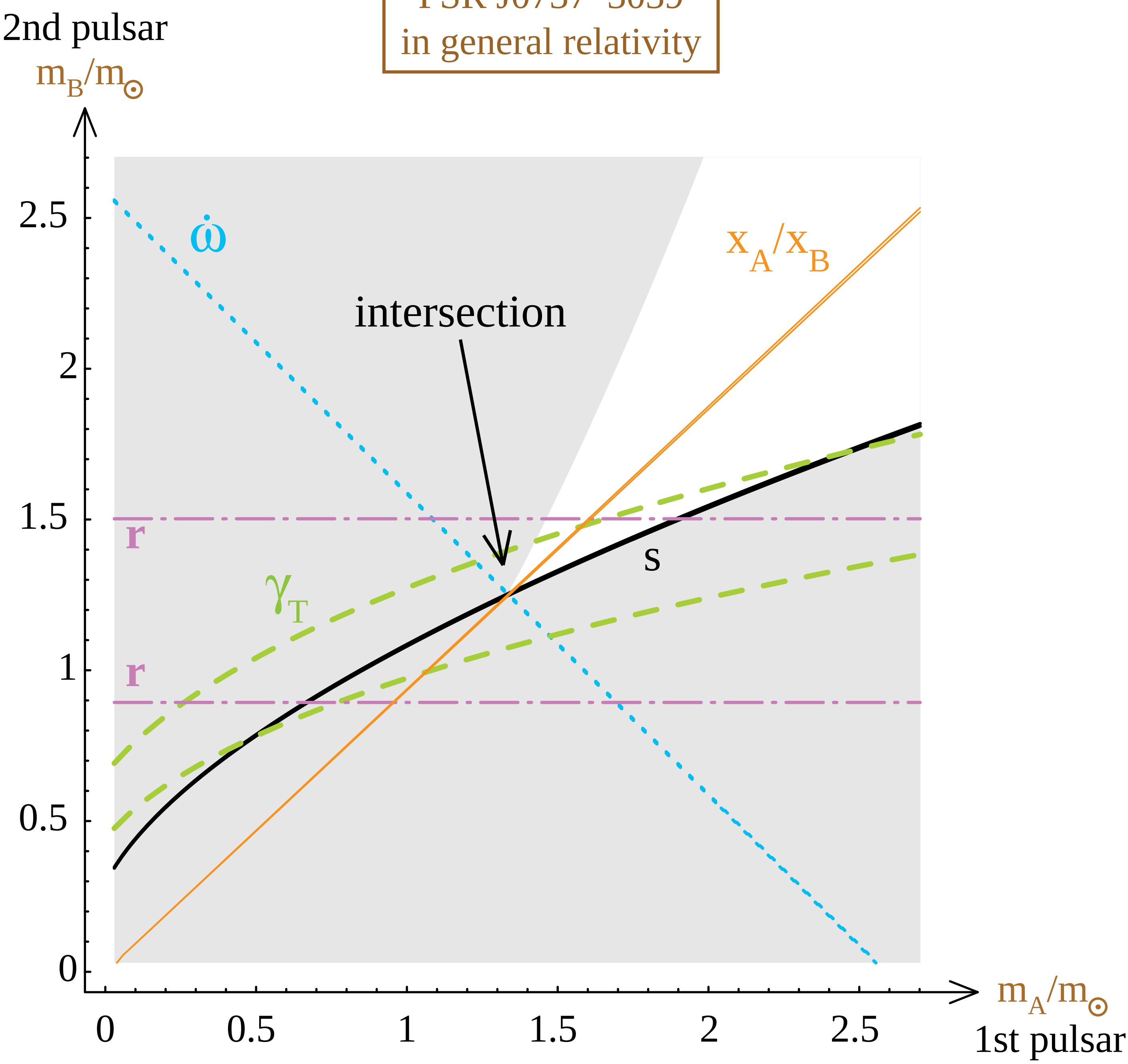
Asymmetrical system
neutron star – **white dwarf**

Neutron star born *after* white dwarf
⇒ eccentricity e = 0.17 large
and nonrecycled pulsar

Mass function

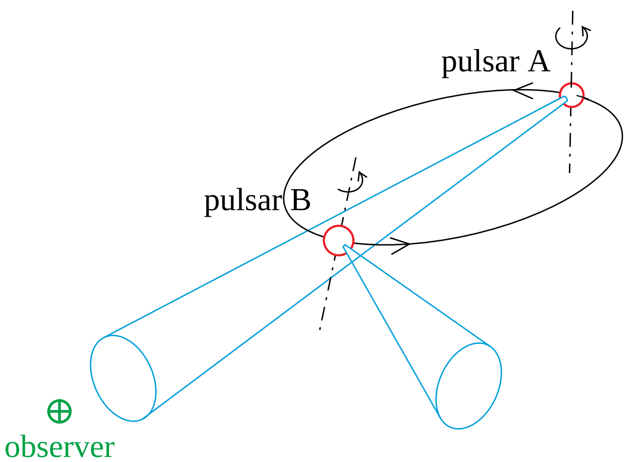
$$\frac{(m_B \sin i)^3}{(m_A + m_B)^2} = \left(\frac{2\pi}{P}\right)^2 \frac{(x\,c)^3}{G}$$

PSR J0737–3039
in general relativity



Timing Burgay *et al.* 2003,
Double pulsar Lyne *et al.* 2004

$P = 2$ h 27 min 14.5350 s



$\dot\omega = 16.90°/\mathrm{yr}$

$$\frac{x_B}{x_A} = \frac{m_A}{m_B} = 1.07$$

The most natural theories of gravity include a scalar field φ besides the metric $g_{\mu\nu}$

- Mathematically **consistent field theories** (no ghost, no adynamical field)

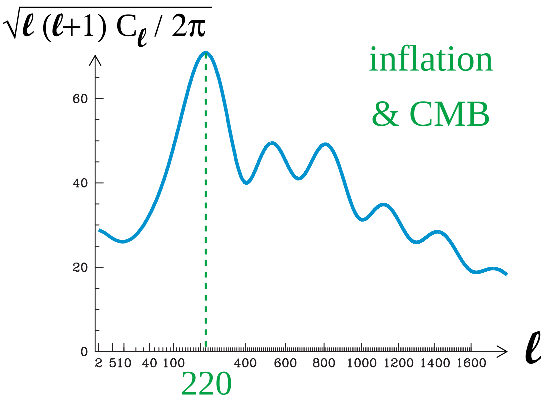
- **Motivated** by superstrings

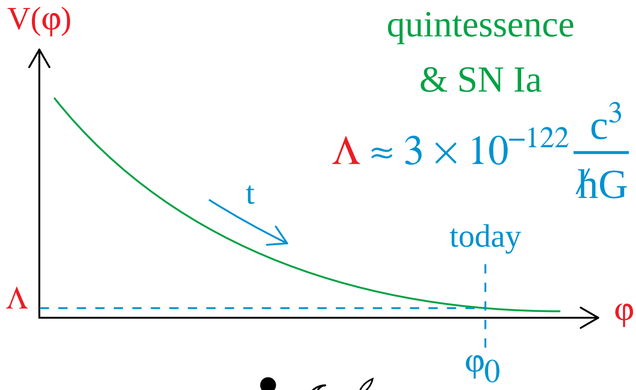
– dilaton in the graviton supermultiplet
– moduli after dimensional reduction

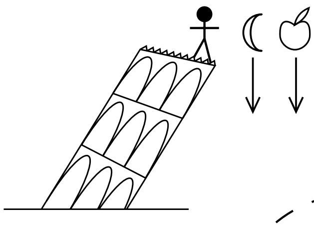
$$g_{mn} = \left(\begin{array}{c|c} g_{\mu\nu} & A_\mu \\ \hline A_\nu & \varphi \end{array}\right)$$

- Scalar fields play a crucial role in modern **cosmology**

(potential $V(\varphi)$ ≈ negative pressure ⇒ accelerated expansion phases of the universe)

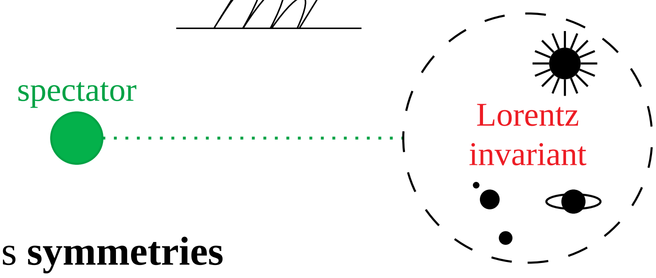






- Only consistent massless field theories able to satisfy the **weak equivalence principle**

- Only known theories satisfying **"extended Lorentz invariance"**



- Preserve most of general relativity's **symmetries**

(explain the key role of β^{PPN} and γ^{PPN})

- Useful as **contrasting alternatives** to general relativity

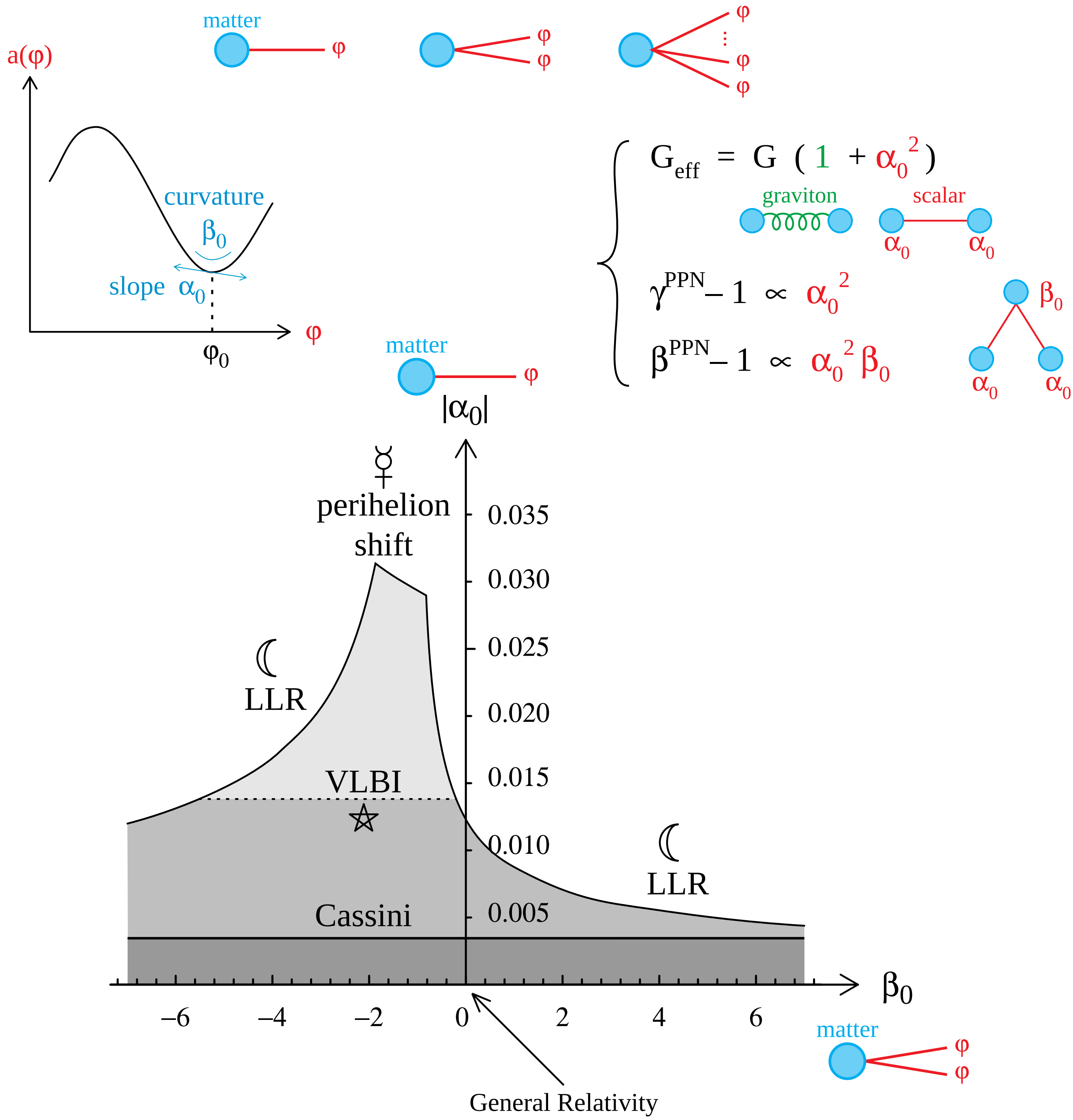
(simple, but general enough ⇒ many possible deviations)

Tensor–scalar theories

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

spin 2 (R) — spin 0 (φ) — physical metric ($\tilde{g}_{\mu\nu}$)

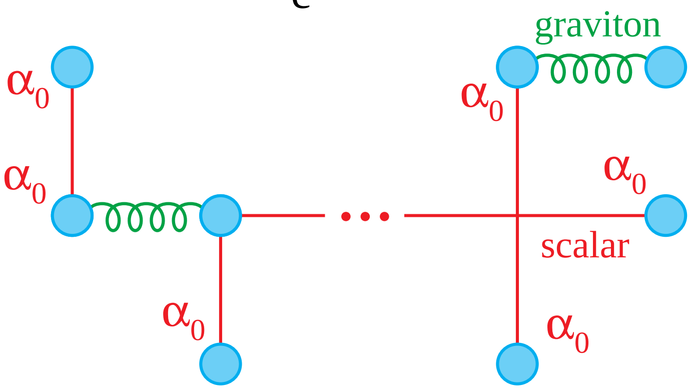
$$a(\varphi) = \alpha_0\,(\varphi-\varphi_0) + \frac{1}{2}\,\beta_0\,(\varphi-\varphi_0)^2 + \ldots$$



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

Deviations from general relativity due to the scalar field

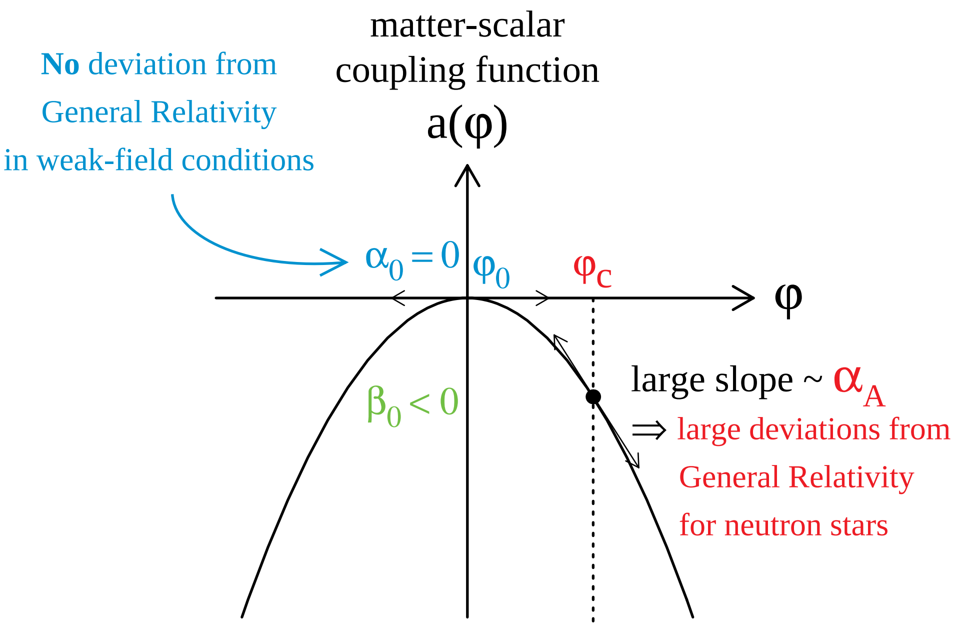
- At any order in $\frac{1}{c^n}$, the deviations involve at least two α_0 factors:

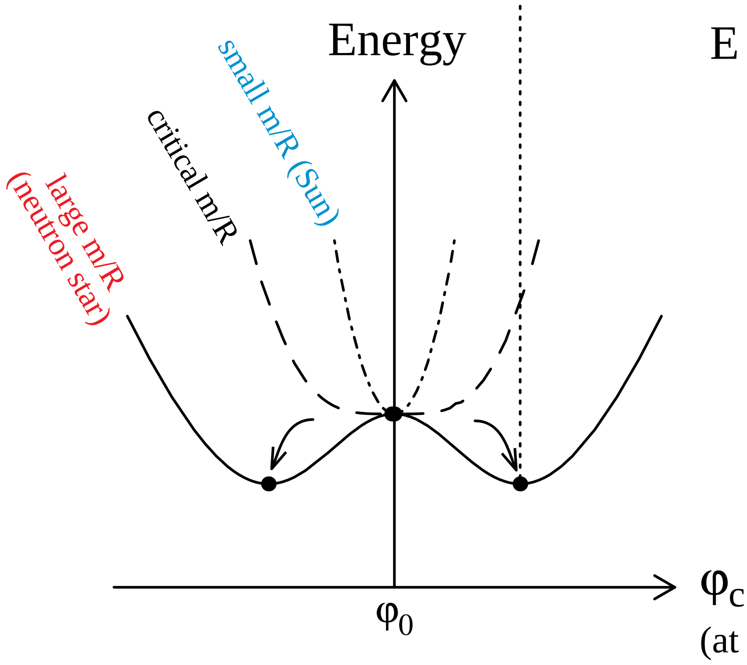


= small deviations!

- But **nonperturbative** strong-field effects may occur:

$$\text{deviations} = \underbrace{\alpha_0^2}_{<10^{-5}} \times \underbrace{\left[a_0 + a_1 \frac{Gm}{Rc^2} + a_2 \left(\frac{Gm}{Rc^2} \right)^2 + \ \ldots \right]}_{\text{LARGE for } \frac{Gm}{Rc^2} \approx 0.2\ ?}$$





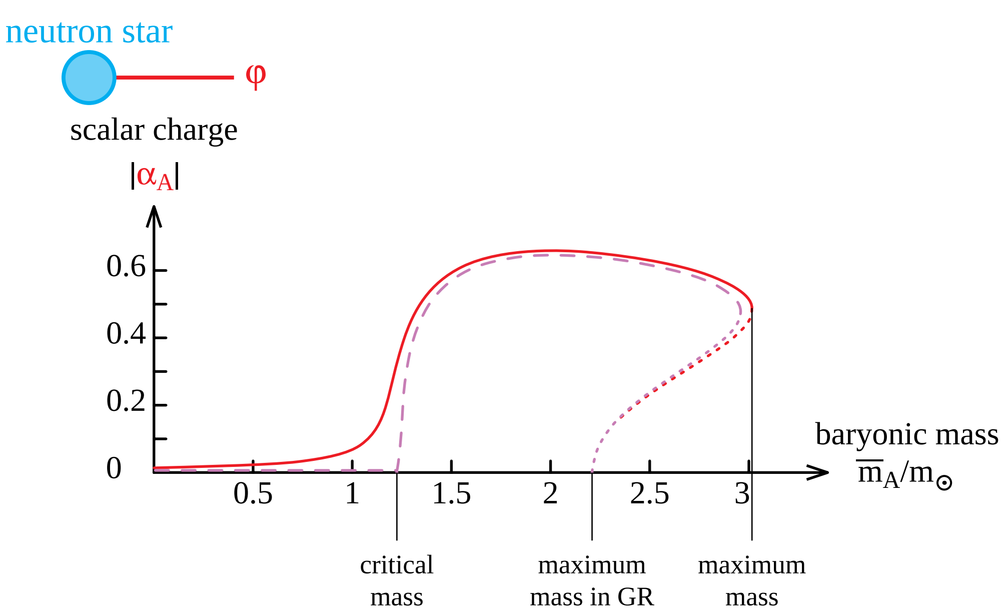
$$E \approx \int \left[\tfrac{1}{2} (\vec{\nabla}\varphi)^2 + \rho\, e^{\beta_0 \varphi^2/2} \right]$$

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

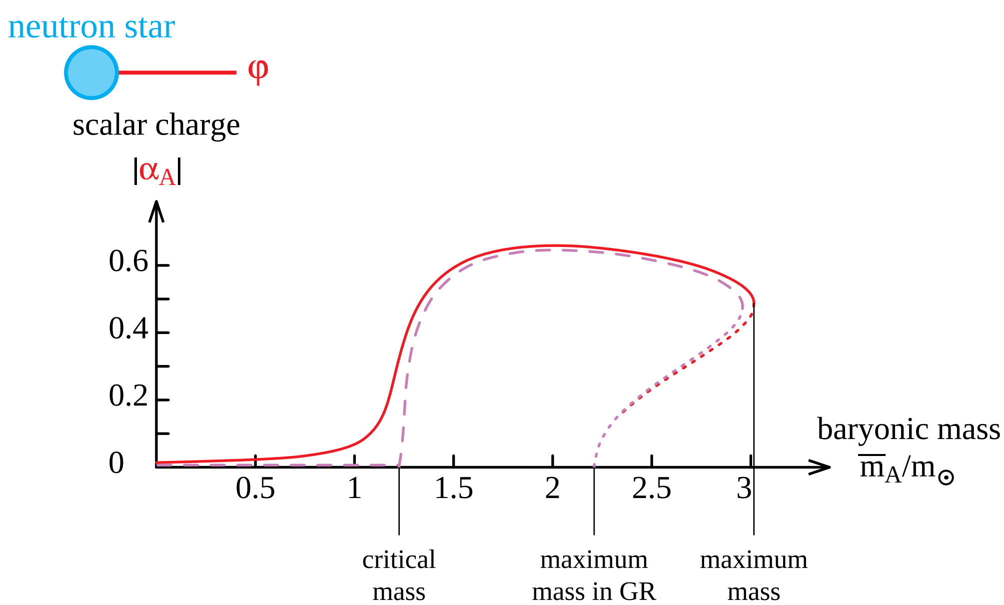
$$\tfrac{1}{2} R\, \varphi_c^{\,2} \; + \; m\, e^{\beta_0 \varphi_c^{\,2}/2}$$

parabola — Gaussian if $\beta_0 < 0$

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

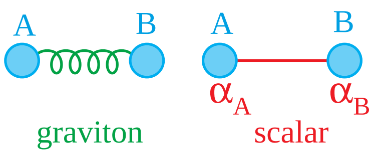


Strong-field effects

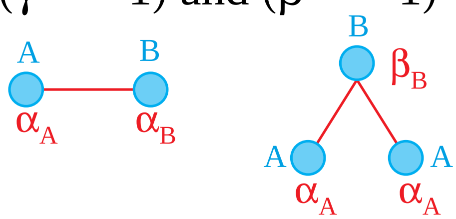


$$G_{AB}^{\text{eff}} = G\,(1 + \alpha_A\,\alpha_B)$$

depends on internal structure of bodies A & B



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



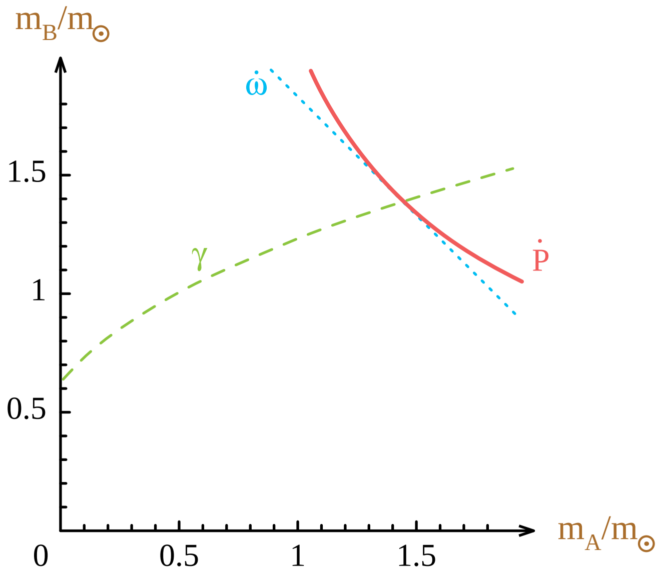
$$\text{Energy flux} = \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \qquad \text{spin 2}$$

$$+ \frac{\text{Monopole}}{c}\left(0 + \frac{1}{c^2}\right)^2 + \frac{\text{Dipole}}{c^3} + \frac{\text{Quadrupole}}{c^5} + O\left(\frac{1}{c^7}\right) \qquad \text{spin 0}$$

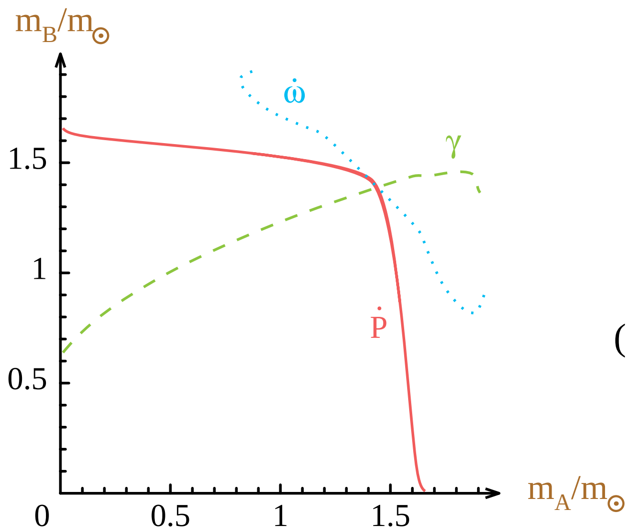
$\uparrow$

$$\propto (\alpha_A - \alpha_B)^2$$

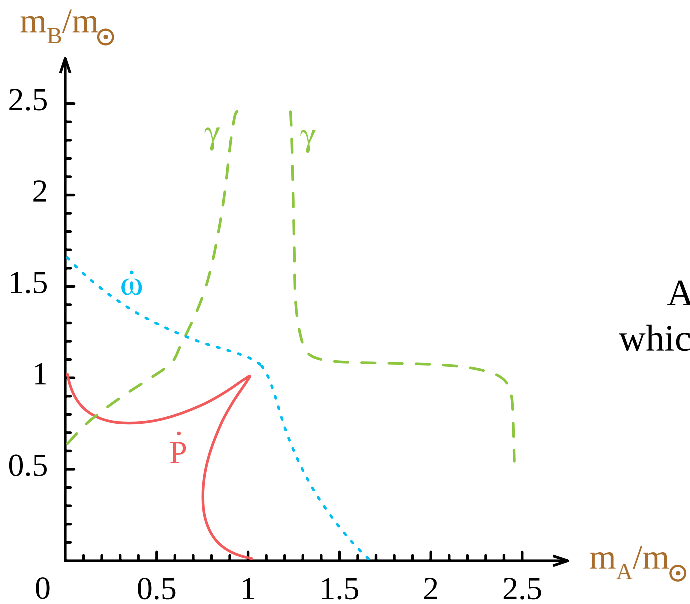
PSR B1913+16
in scalar-tensor theories



General relativity
passes the test

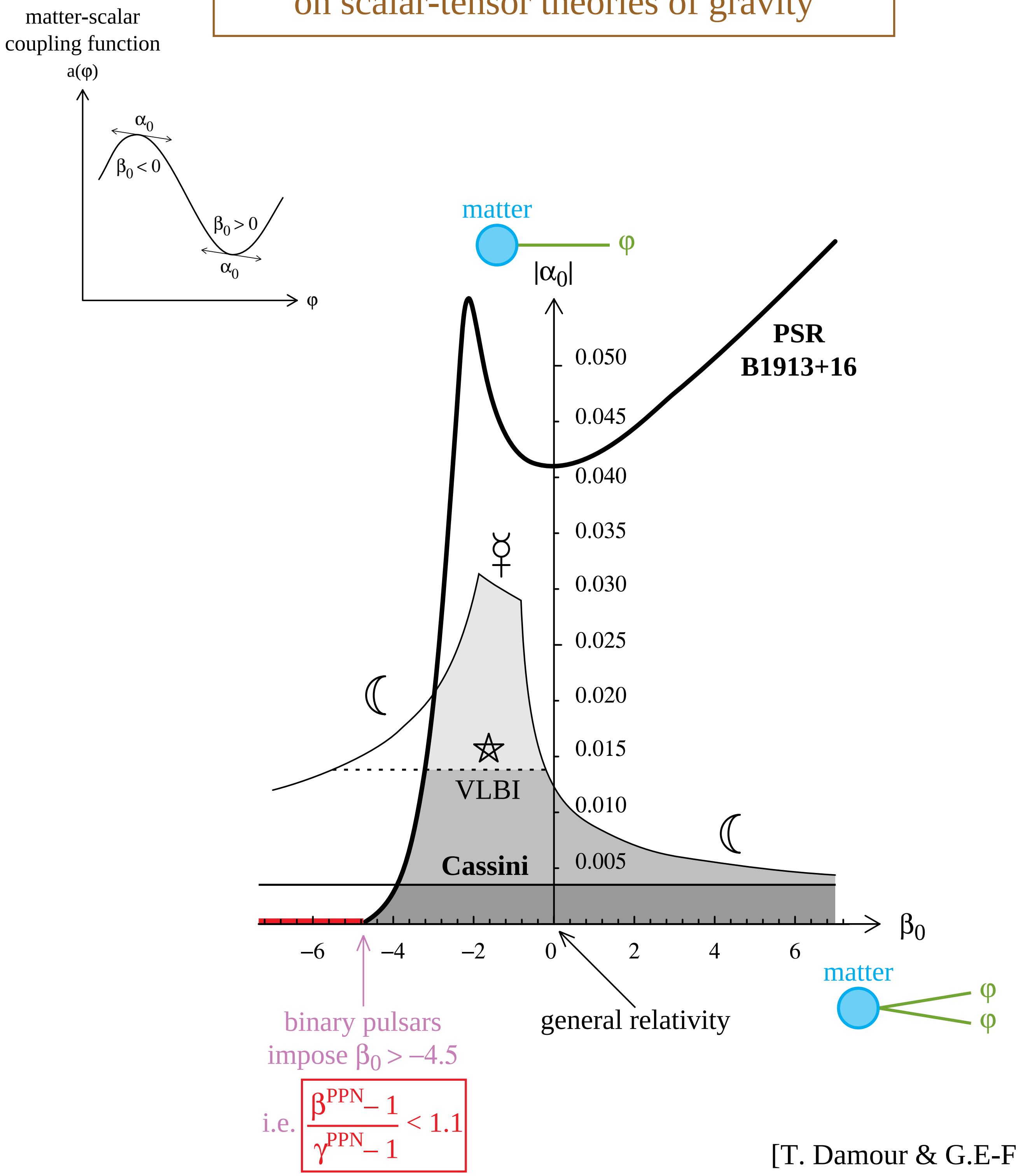


A tensor–scalar theory
which **passes the test**
(β_0 = –4.5, α_0 small enough)



A tensor–scalar theory
which **does not pass the test**
(β_0 = –6, any α_0)

Solar-system & PSR B1913+16 constraints on scalar-tensor theories of gravity

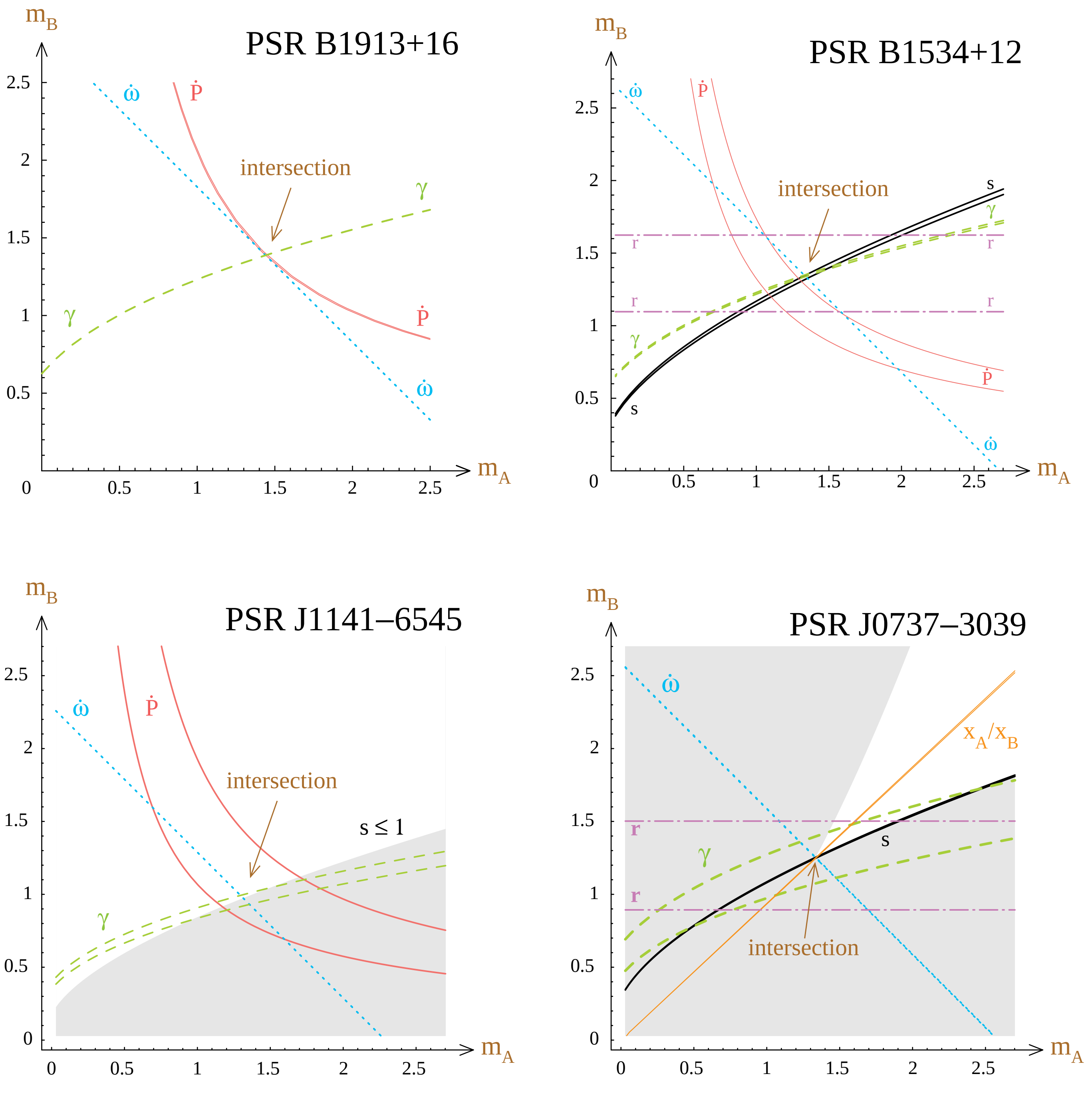


[T. Damour & G.E-F 1998]

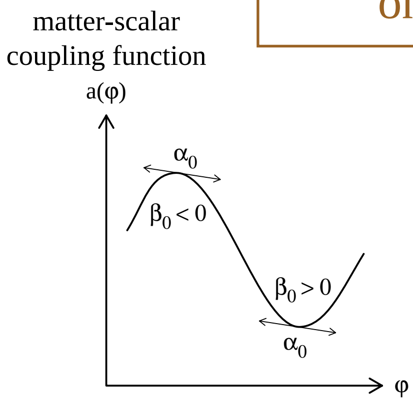
Vertical axis ($\beta_0 = 0$) : Jordan–Fierz–Brans–Dicke theory $\alpha_0^2 = \frac{1}{2\,\omega_{BD} + 3}$

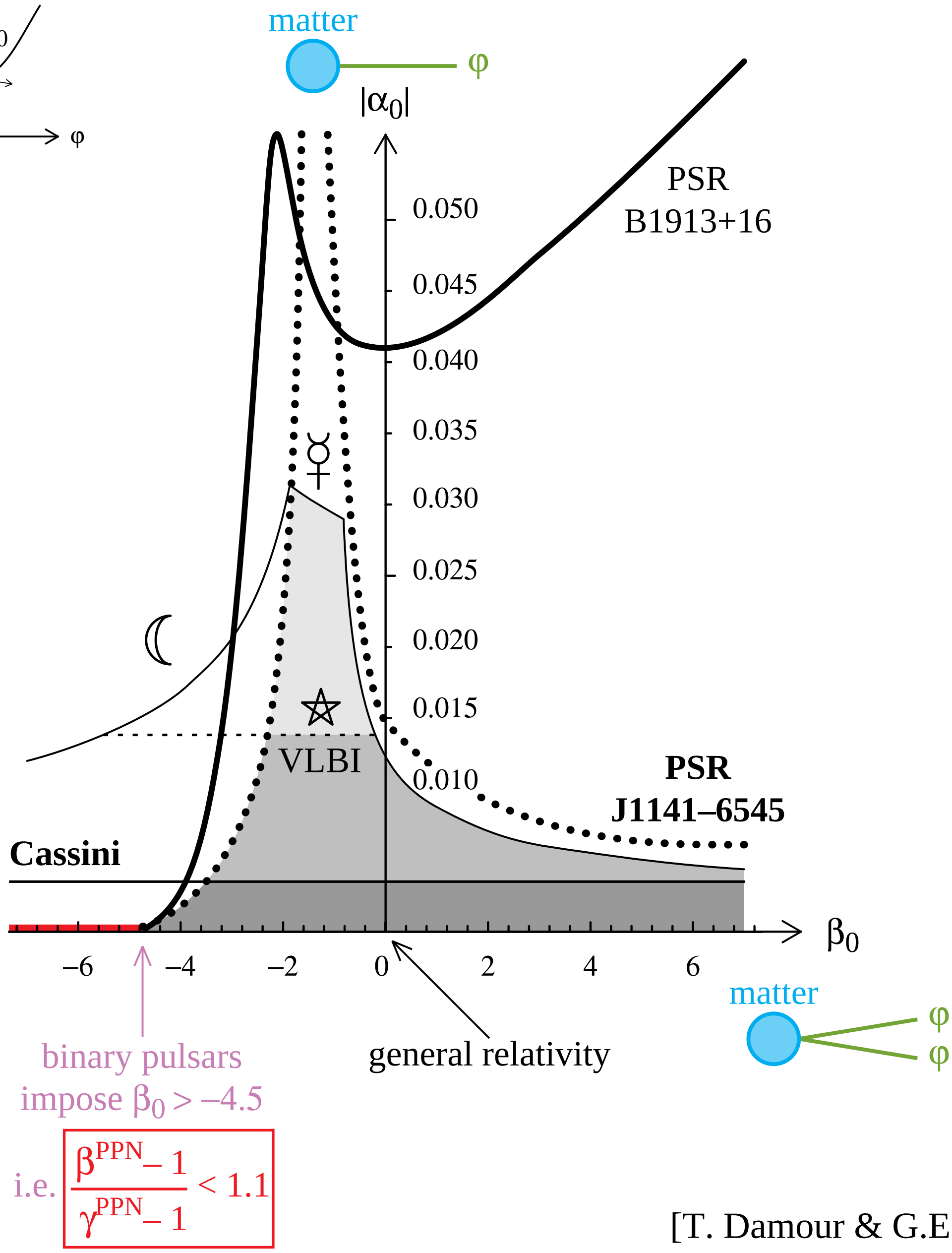
Horizontal axis ($\alpha_0 = 0$) : perturbatively equivalent to G.R.

The four accurately timed binary pulsars in general relativity



Solar-system & best binary-pulsar constraints on scalar-tensor theories of gravity





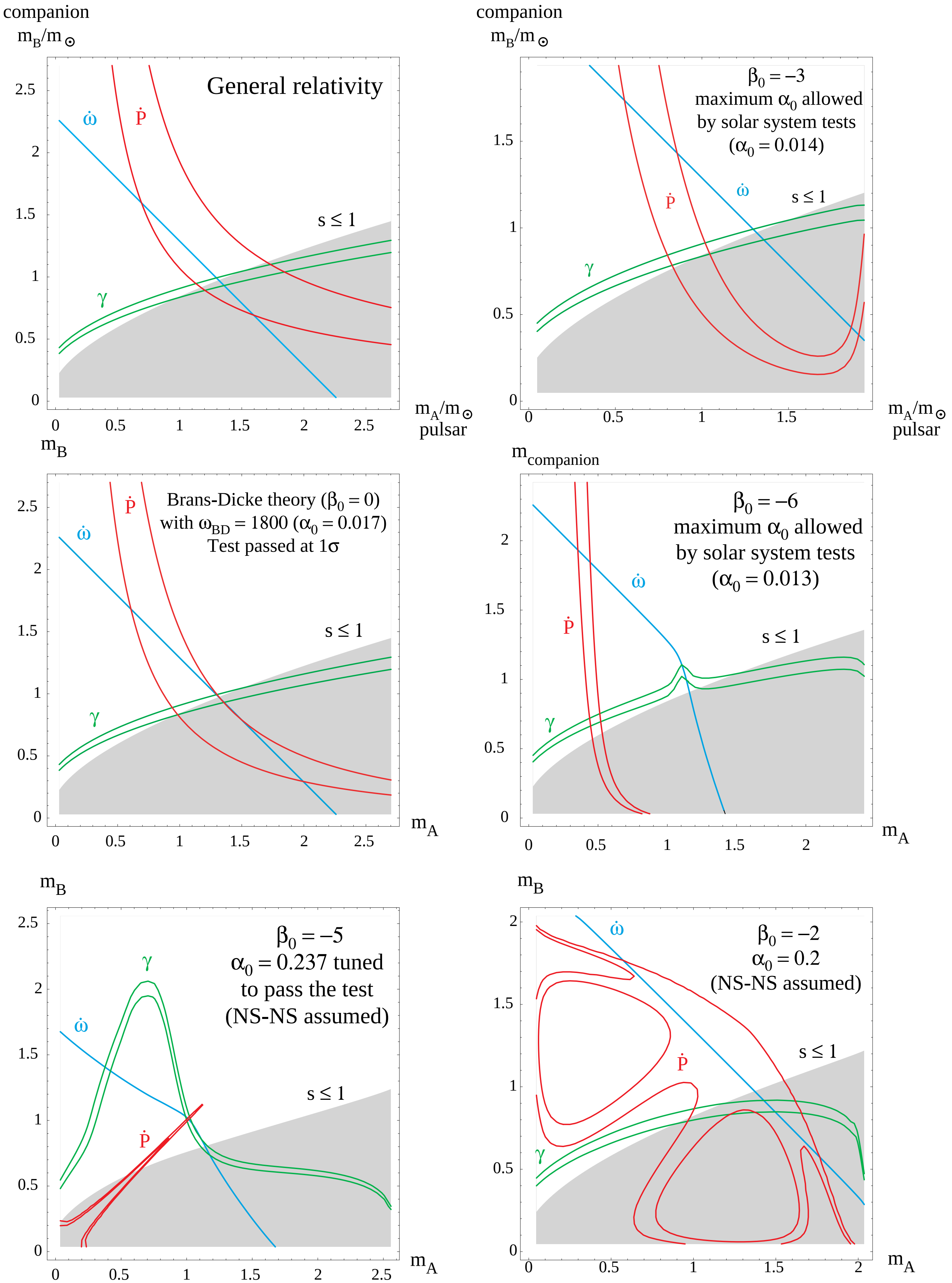
[T. Damour & G.E-F 2004]

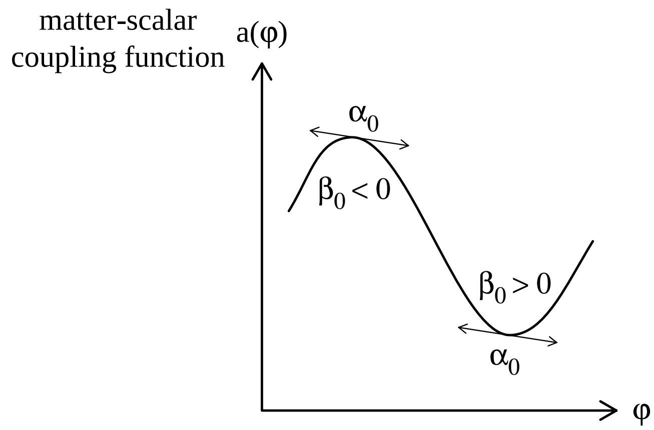
Vertical axis ($\beta_0 = 0$) : Jordan–Fierz–Brans–Dicke theory $\alpha_0^2 = \frac{1}{2\,\omega_{BD} + 3}$

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

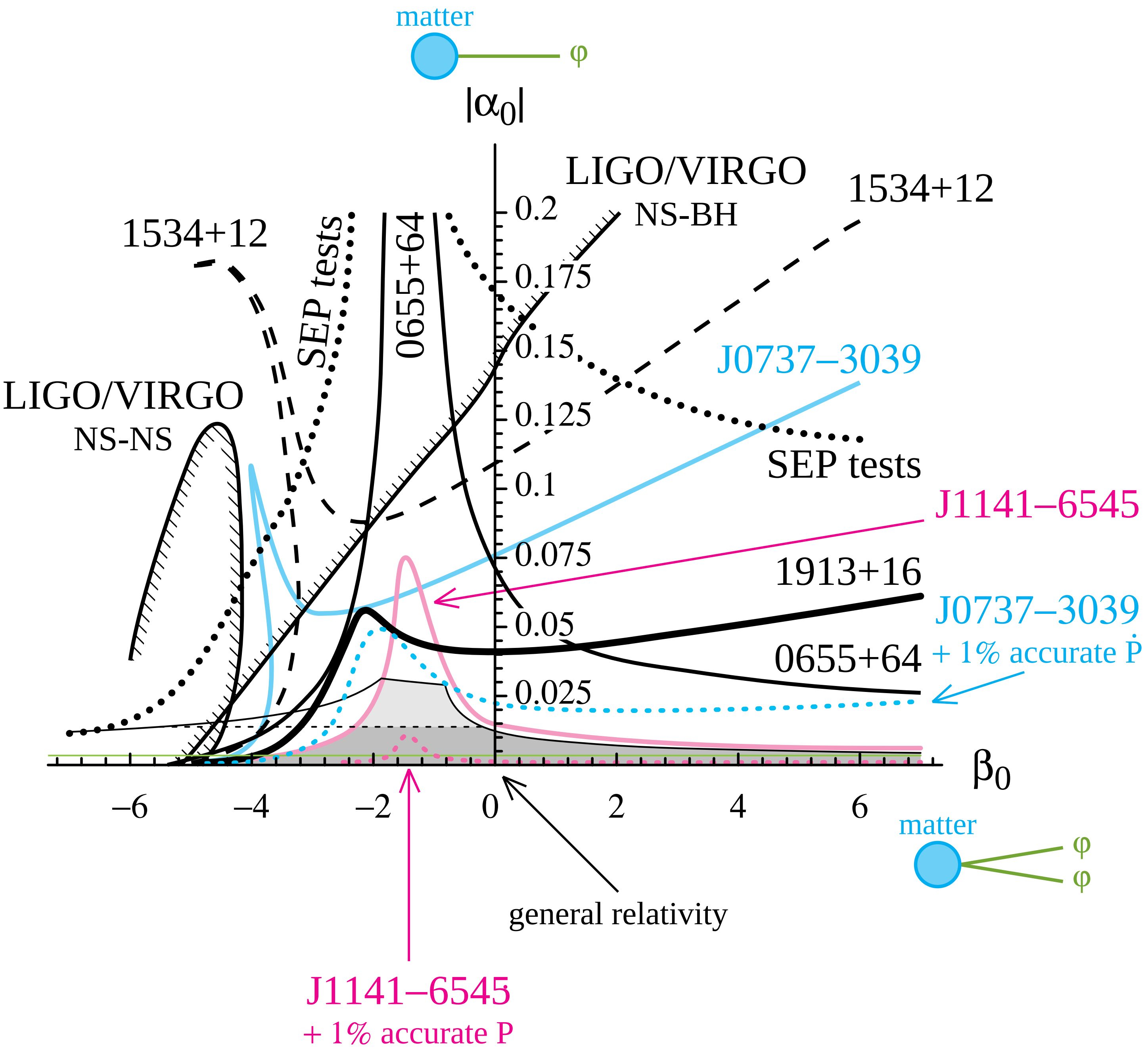
Mass plane for PSR J1141–6545 in various scalar-tensor theories

PSR J1141–6545
rules out (by 5σ) some theories
which were consistent with
all previous experimental data





All solar-system & binary-pulsar constraints on tensor–scalar theories



[T. Damour & G.E-F]

Conclusions

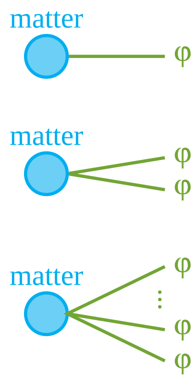
- **Binary pulsars** are ideal tools for testing the **strong-field** regime of gravity.

- **Qualitative** difference between

solar-system, —— first derivative of $a(\varphi)$ ——→

binary-pulsar, —— nonperturbative effects ⇒ second derivative of $a(\varphi)$ ——→

and cosmological observations. —— *a priori* full shape of $a(\varphi)$ but much more noisy ——→



- **Best** available system for constraining scalar-tensor theories: **PSR J1141–6545**.

  Neutron star–white dwarf system ⇒ large emission of **dipolar** scalar waves.

  [Neutron star-black hole system would do even better.]

  Almost as powerful as solar-system tests even in the region $\beta_0 > 0$

  (where scalar-field effects are suppressed in the strong-field regime).

- Douple pulsar **PSR J0737–3039** fantastic system to test GR itself and the physics of neutron stars

  Two pulsars ⇒ direct measure of the mass ratio m_A/m_B

  Fast and close ⇒ { will merge in ~ 85 Myr ⇒ increases estimated merger rate by 10×; very precise soon; ~70 yr geodetic precession }

  Eclipses ⇒ probes pulsar magnetospheres

- **GR wave templates** suffice for **LIGO/VIRGO**, because possible scalar-field effects are already tightly constrained by binary-pulsar tests.

  Small scalar-field effects still possible for **LISA** [Scharre, Will & Yunes]

- **General relativity** passes all the tests with flying colors.