Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Constraining Dipolar Gravitational Radiation
through Pulsar Timing

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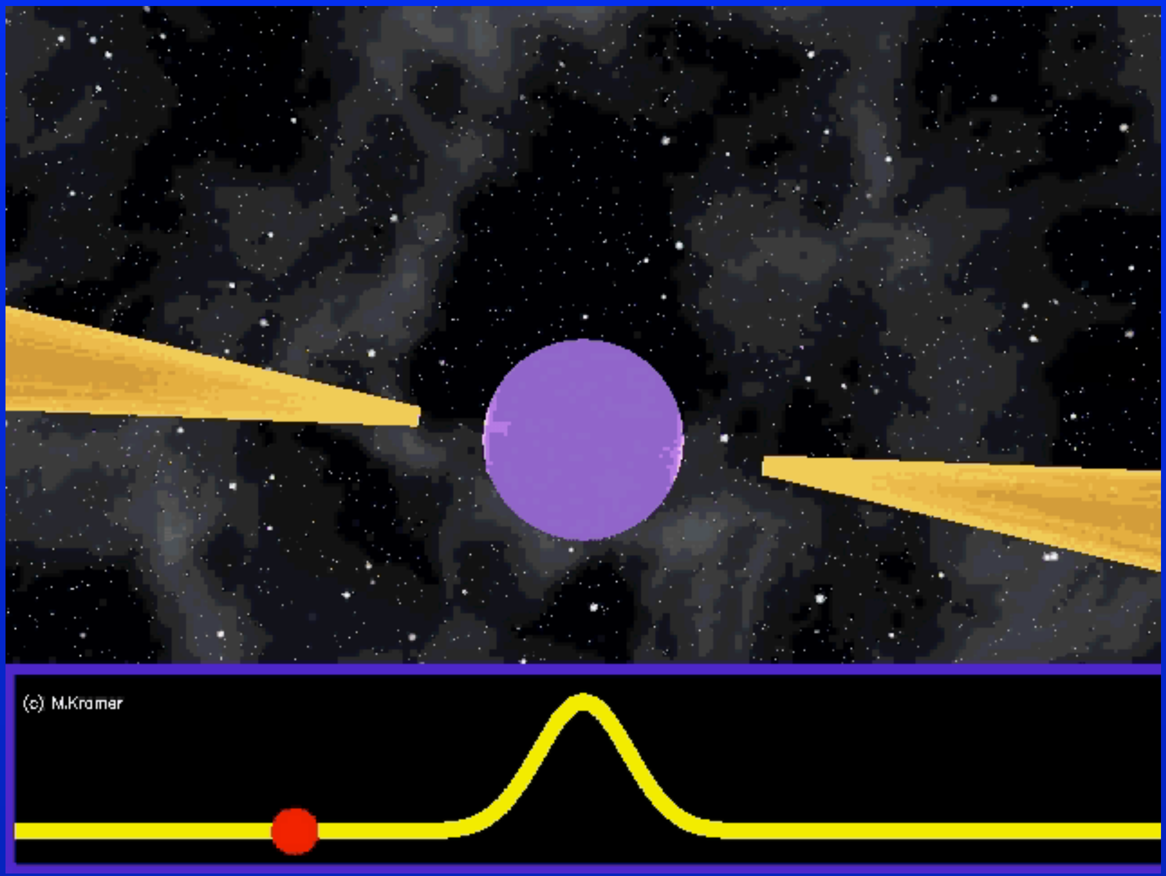
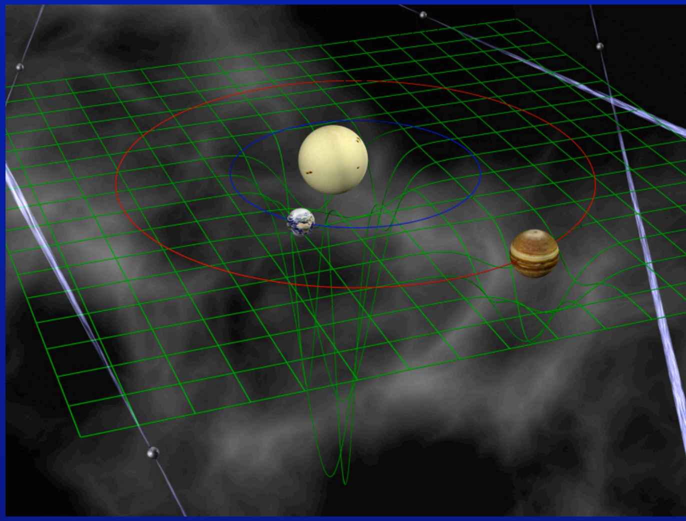
Outline

- Pulsar Timing
- Tensor-Scalar Theories: J1141-6545
- Generic Tests for Dipole Radiation
  - Introduction
  - Why not 1141?
  - J1012+5307 & J1738+0333
- Anticipated Results

Pulsar Timing





Champion et al., 2010

PSR J1012+5307: 15 years of observations with EPTA

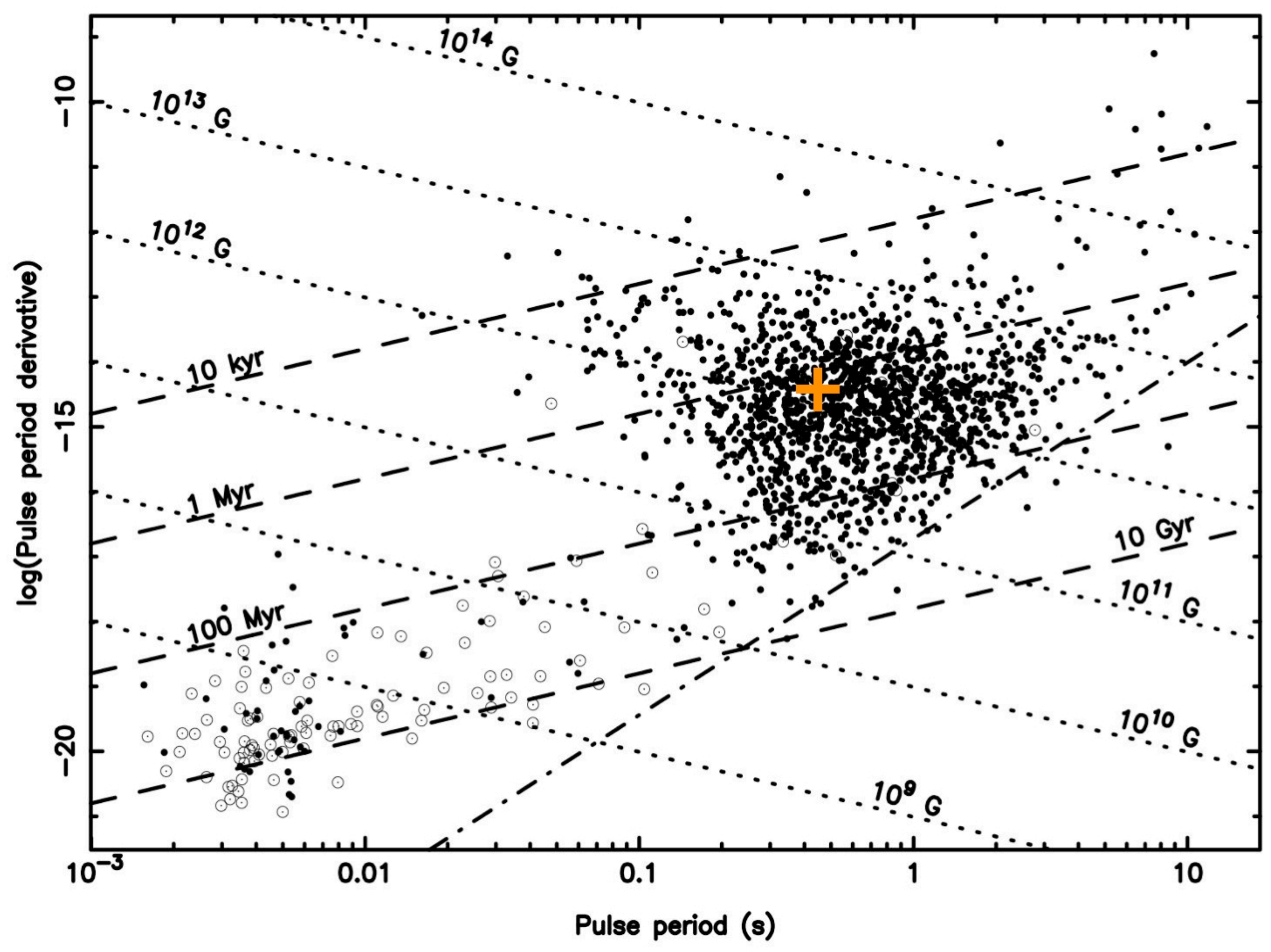
$$P = 5.2557490141154 10 \pm 0.000000000000015 \text{ ms}$$
$$P_{\text{orb}} = 52243.722450 \pm 0.000003 \text{ s}$$

[*Lazaridis et al. 2009*]

The PSR J1141-6545 System

- Pulse period
  P ~ 400 ms
- Binary period
  P_b ~ 4.7 hr
- Ecc ~ 0.17
- Dist > 3.7 kpc
- WD-NS binary

(Antoniadis et al., 2010)



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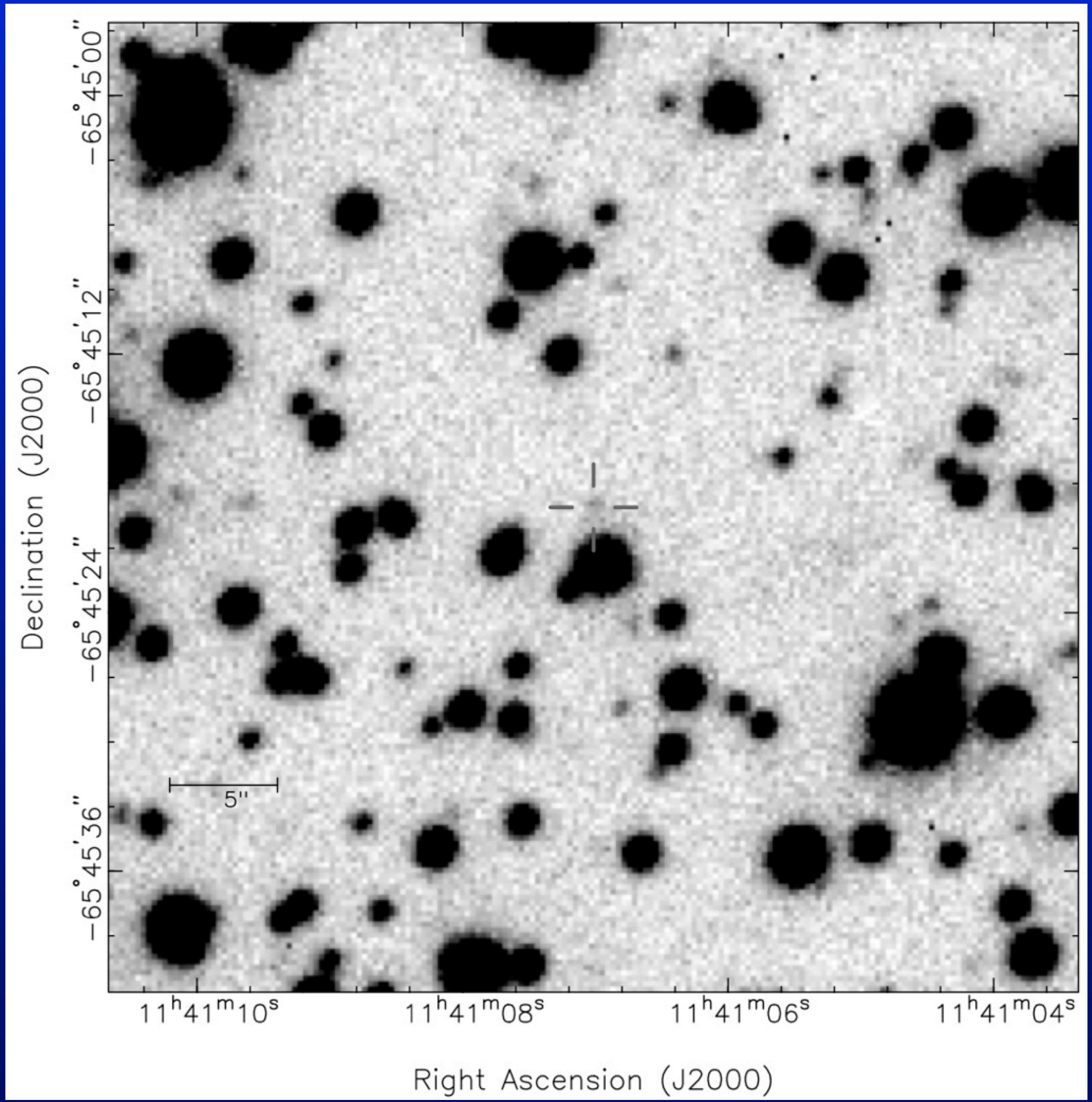

Observable Relativistic Effects

Periastron Advance: $$\dot{\omega} \propto \frac{M_{Tot}^{2/3}}{P_b^{5/3}(1-e^2)}$$

Shapiro Delay (shape): $$s \propto \frac{M_{Tot}^{2/3}\, a \sin i}{P_b^{2/3}\, M_c}$$

Orbital Period Decay: $$\dot{P}_b \propto \frac{M_{psr}\, M_c}{M_{Tot}^{1/3}\, P_b^{5/3}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)$$

Gravitational Redshift: $$\gamma \propto P_b^{1/3}\, e\, \frac{M_c\left(M_{Tot}+M_c\right)}{M_{Tot}^{4/3}}$$

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Determined through scintillation studies (Ord et al., 2002)

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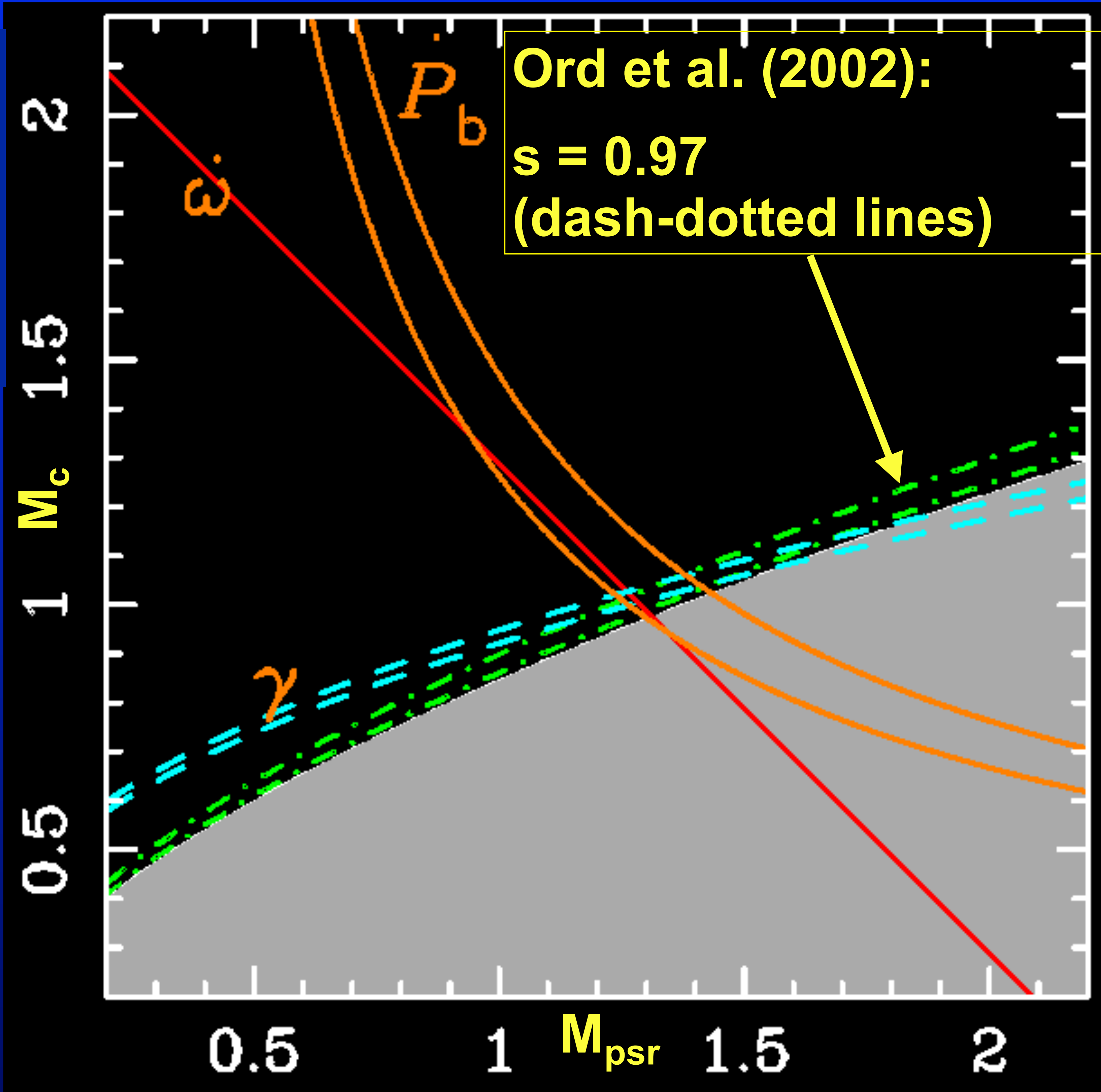
Mass-Mass Diagram

$$\dot{\omega} = 5^o.3096(4)\,yr^{-1}$$

$$\gamma = 0.000773(11)\,ms$$

$$i = asin(s) = 73^o \pm 1^o.5$$



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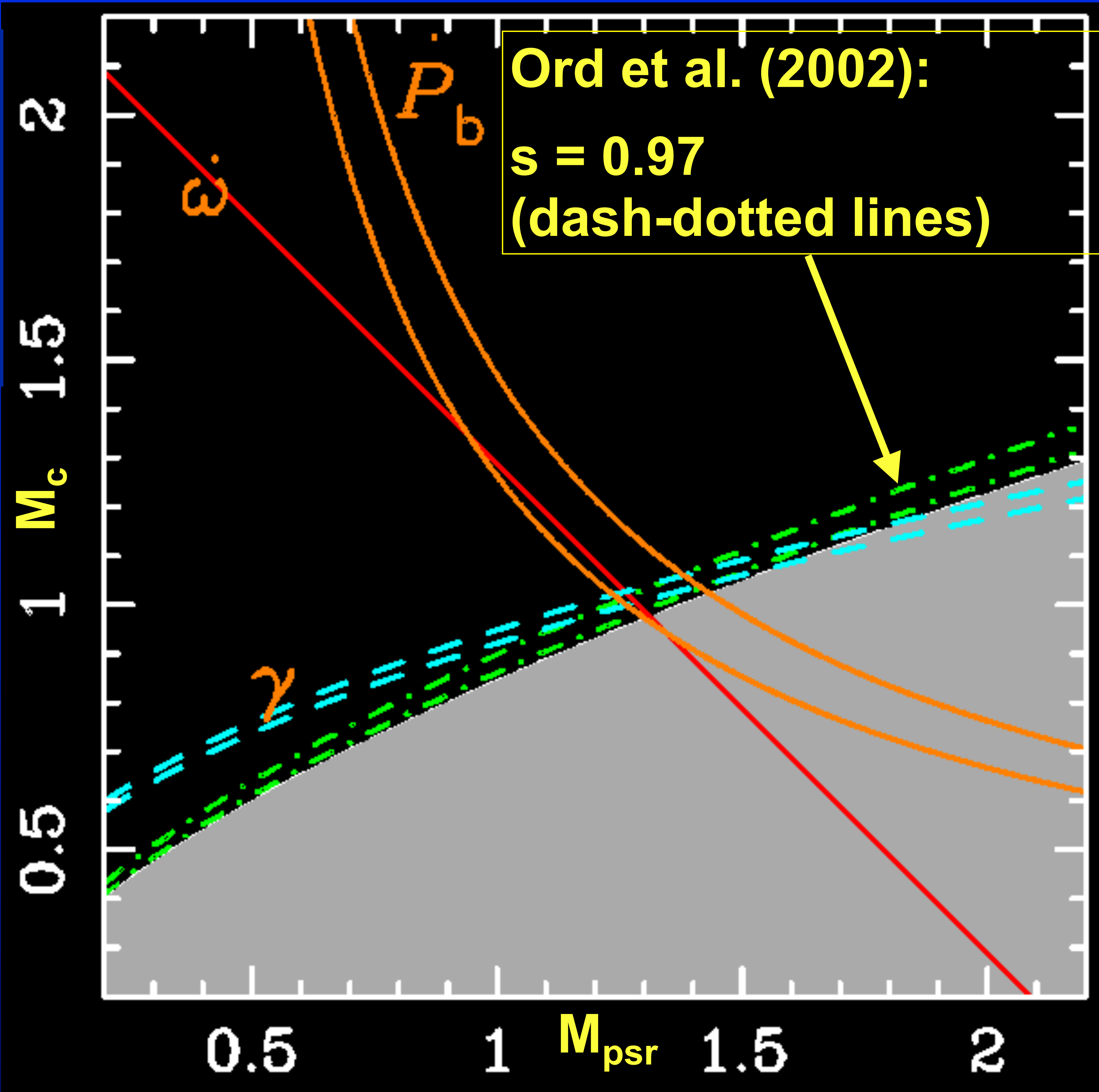
$$\gamma = 0.000773(11)\,ms$$

$$i = asin(s) = 73^o \pm 1^o.5$$

$$M_{psr} = 1.27 \pm 0.01\,M_{Sun}$$

$$M_c = 1.02 \pm 0.01\,M_{Sun}$$



Tensor-Scalar Theories

- **Amongst the most well-founded alternatives to GR**

- **Coupling strength btw. scalar field & matter,**
  e.g. quadratic: a$(\psi) = \alpha_0\ \psi$ **+0.5** $\beta_0\ \psi^2$ **;**
  GR: $(\alpha_0; \beta_0) = (0;0)$
  JFBD: $(\alpha_0; \beta_0) = (\alpha_0;0)$

- **Predict emission of dipolar GWs, depending on difference in compactness** $(\Delta\varepsilon)$ **of objects**

- **J1141-6545: WD** $(\varepsilon \sim 10^{-4})$ **- NS** $(\varepsilon \sim 0.2)$

See e.g. Esposito-Farèse (2004)

Tensor-Scalar Theories - Limits

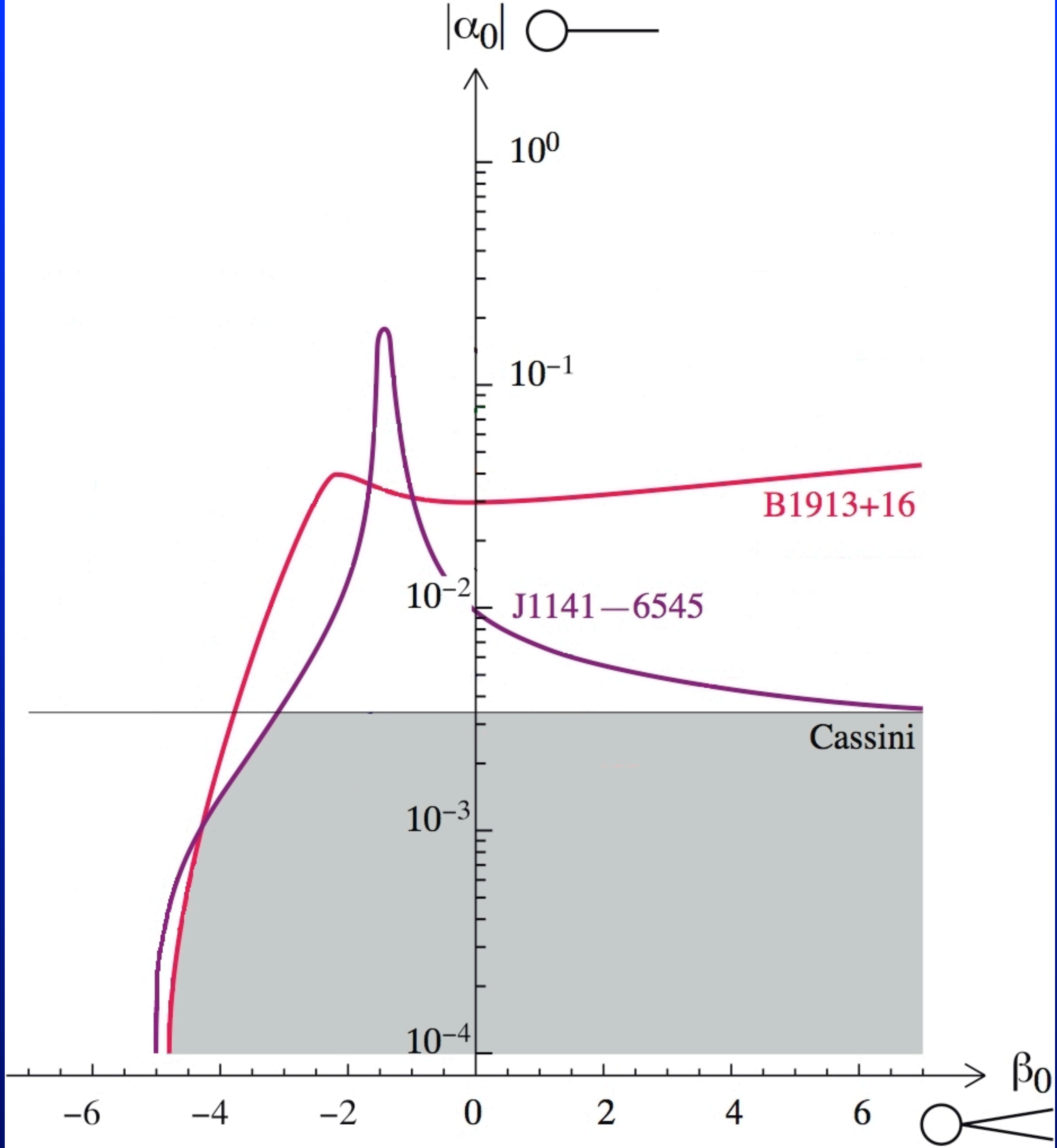


Figure:
Esposito-Farèse (2009) arXiv:0905.2575;
Data: Bhat, Bailes & Verbiest (PRD, 2008)

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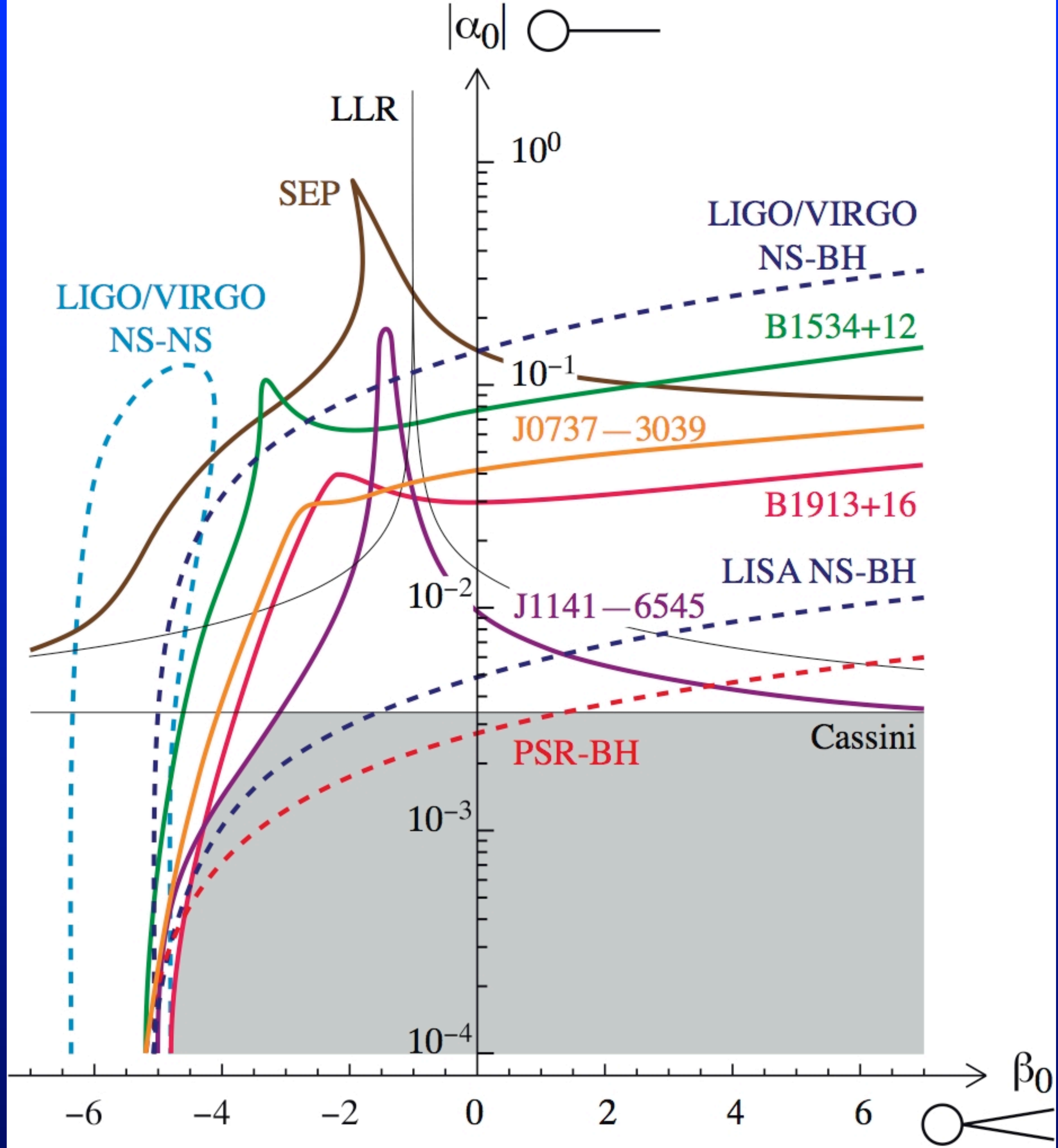

Figure: Esposito-Farèse (2009) arXiv:0905.2575;
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PSR J1141-6545 Forecast

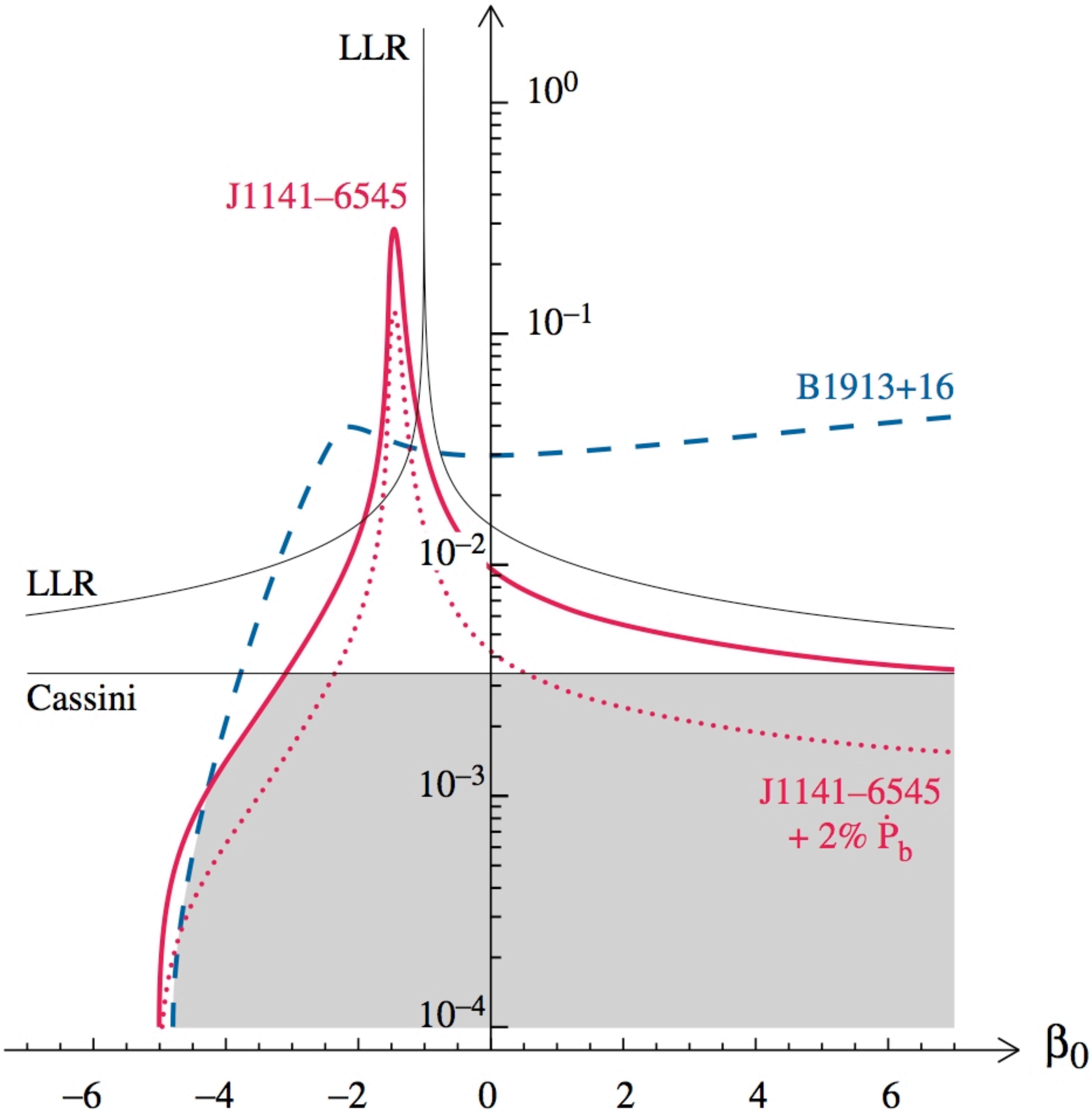


Figure courtesy of Gilles Esposito-Farèse

Problems with J1141-6545

- No theory-invariant mass estimates
- Not applicable in generic frameworks
- Practical problems: geodetic precession, glitch, unknown proper motion, ...

Generic Limits on dipolar GW Emission

- Dipolar GW emission is predicted by most alternative gravitational theories
- Strongly dependent on difference in effective scalar coupling:

$$\dot{P}_{\mathrm{b}}^{\mathrm{dipole}} = -\frac{4\pi^2}{P_{\mathrm{b}}}\frac{G\mu}{c^3}\frac{1+e^2/2}{(1-e^2)^{5/2}}\left(\alpha_{\mathrm{p}}-\alpha_{\mathrm{c}}\right)^2$$

Negligible if NS-NS

Substantial if NS-WD

Generic Test with PSR J1012+5307

Pulsar timing observations

$P \;\; = \;\; 5.3$ ms

$P_{orb} = 14.5$ h

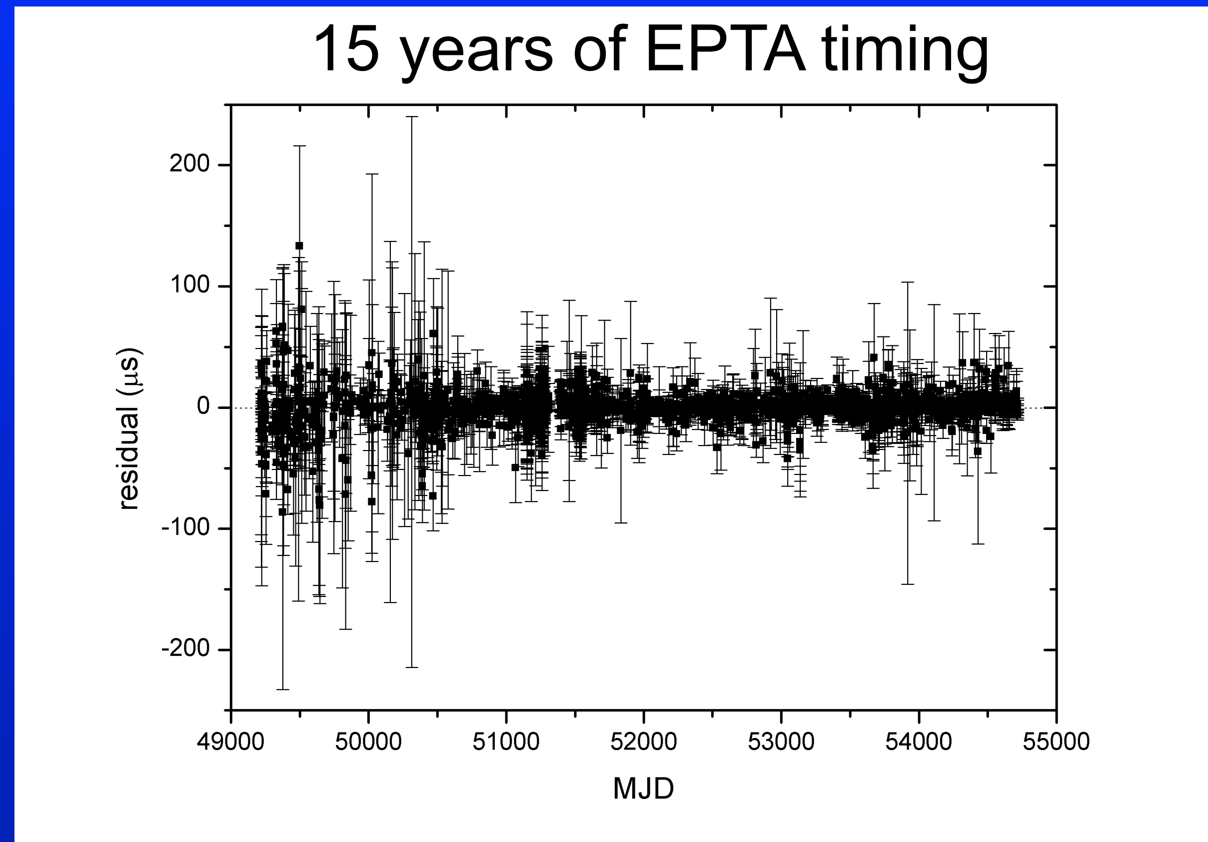
e < 0.000001

Helium white dwarf optical observations

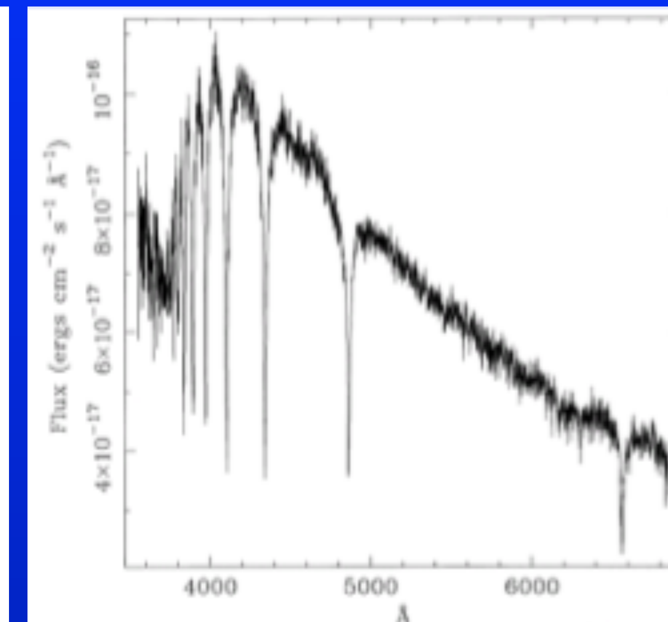
$m_c = 0.16 \pm 0.02\, M_{sun}$

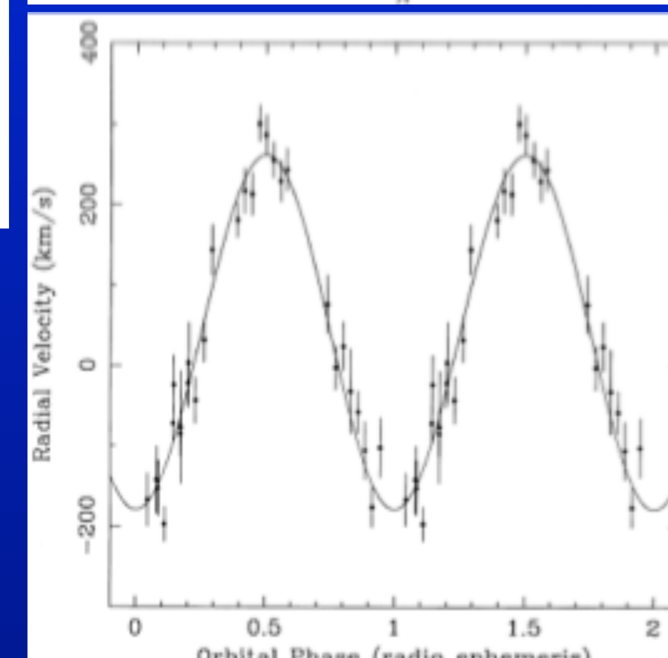
$q = m_p/m_c = 10.5 \pm 0.5$

$d = 840 \pm 90$ pc



[*Lazaridis et al. 2009*]





[*Callanan et al. 1998*]

LLR / PSRs

$$\dot{P}_b^{\rm obs} = \dot{P}_b^{\rm Shk} + \dot{P}_b^{\rm Gal} + \dot{P}_b^{\dot{G}} + \dot{P}_b^{\rm GW}$$

$$-4\pi^2 \frac{G m_c}{c^3 P_b} \frac{q}{q+1} (\alpha_{\rm p} - \alpha_0)^2$$

⇨ $$|\alpha_{\rm p} - \alpha_0| < 0.008$$

[*Lazaridis et al. 2009*]

Even tighter limit expected from PSR J1738+0333

[*Freire et al. 2011*]

Combined Limits for a Variation in G and Dipole Radiation

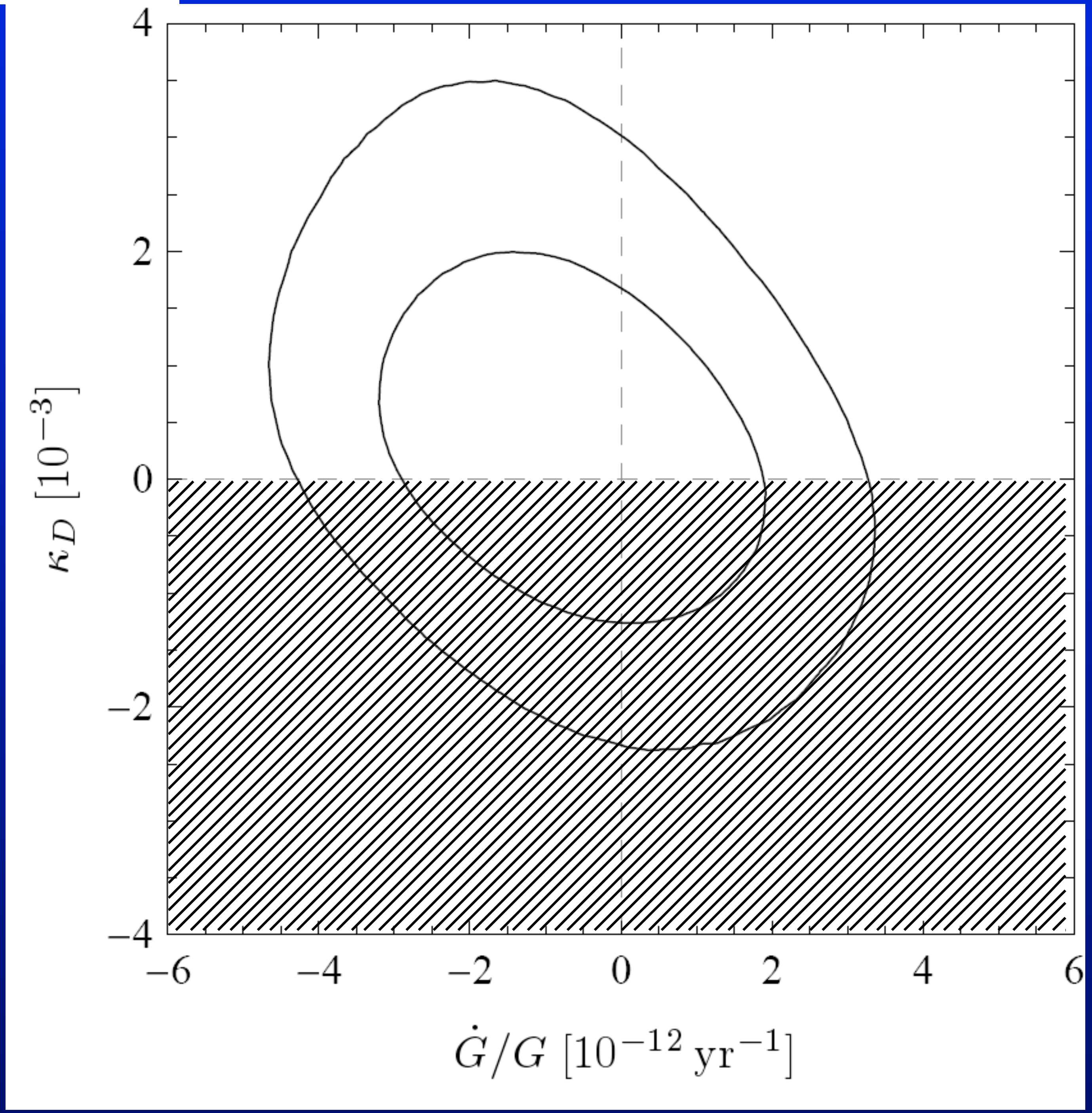
$$\frac{\dot{P}_b^{exc}}{P_b} = -2\boxed{\frac{\dot{G}}{G}}\left[1-\left(1+\frac{m_c}{2M}\right)s_p\right] - 4\pi^2\frac{T_\odot \mu}{P_b^2}\boxed{\kappa_D} s_p^2$$

PSR J1012+5307

Orbital period = 0.605 days

PSR J0437-4715

Orbital period = 5.75 days

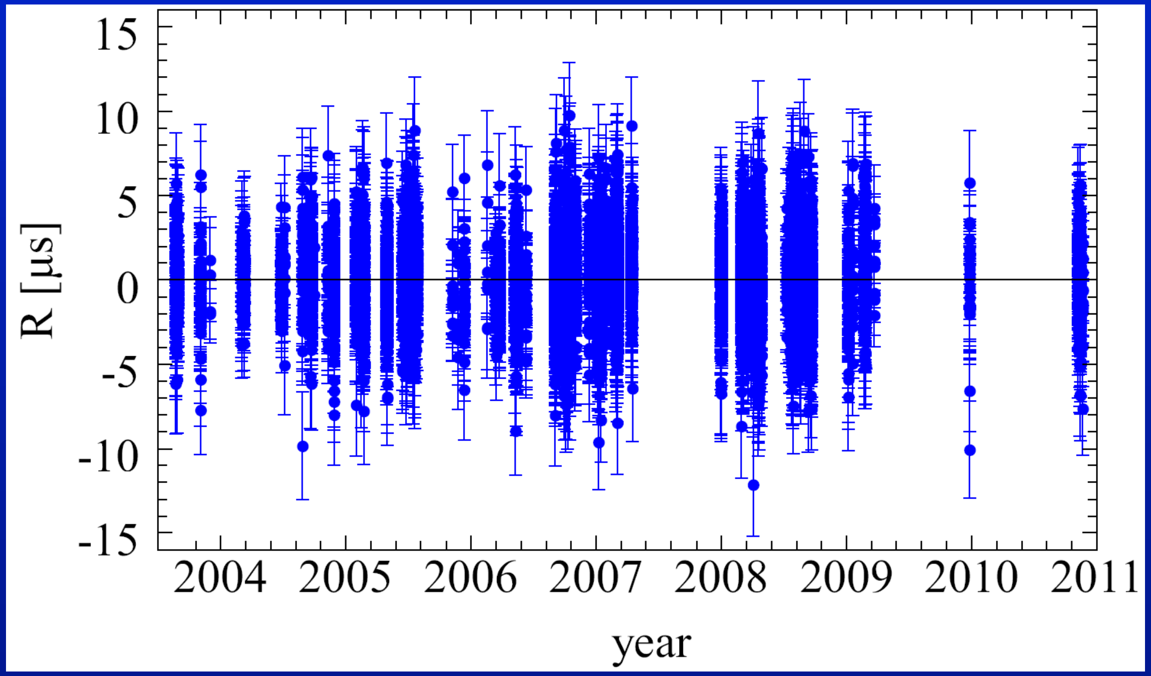


[*Lazaridis et al. 2009*]

PSR J1738+0333

Timing observations of the pulsar

[*Freire et al. 2011*]



P = 5.85 ms

P_b = 8.51 h

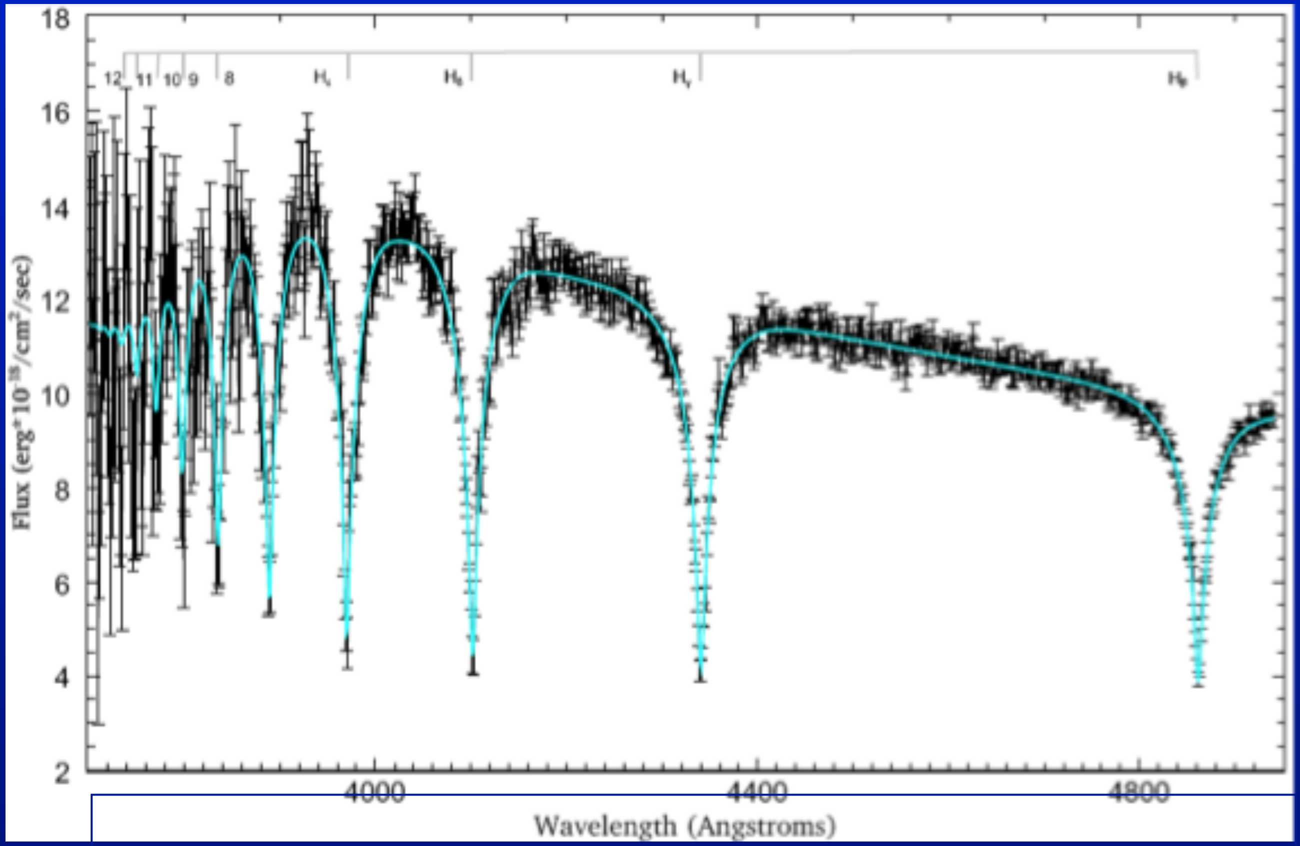
e ~ 10^{-7}

D_π = 1.4 ± 0.1 kpc

$dP_b/dt = (-3 \pm 1) \times 10^{-14}$

Optical observations of the WD companion

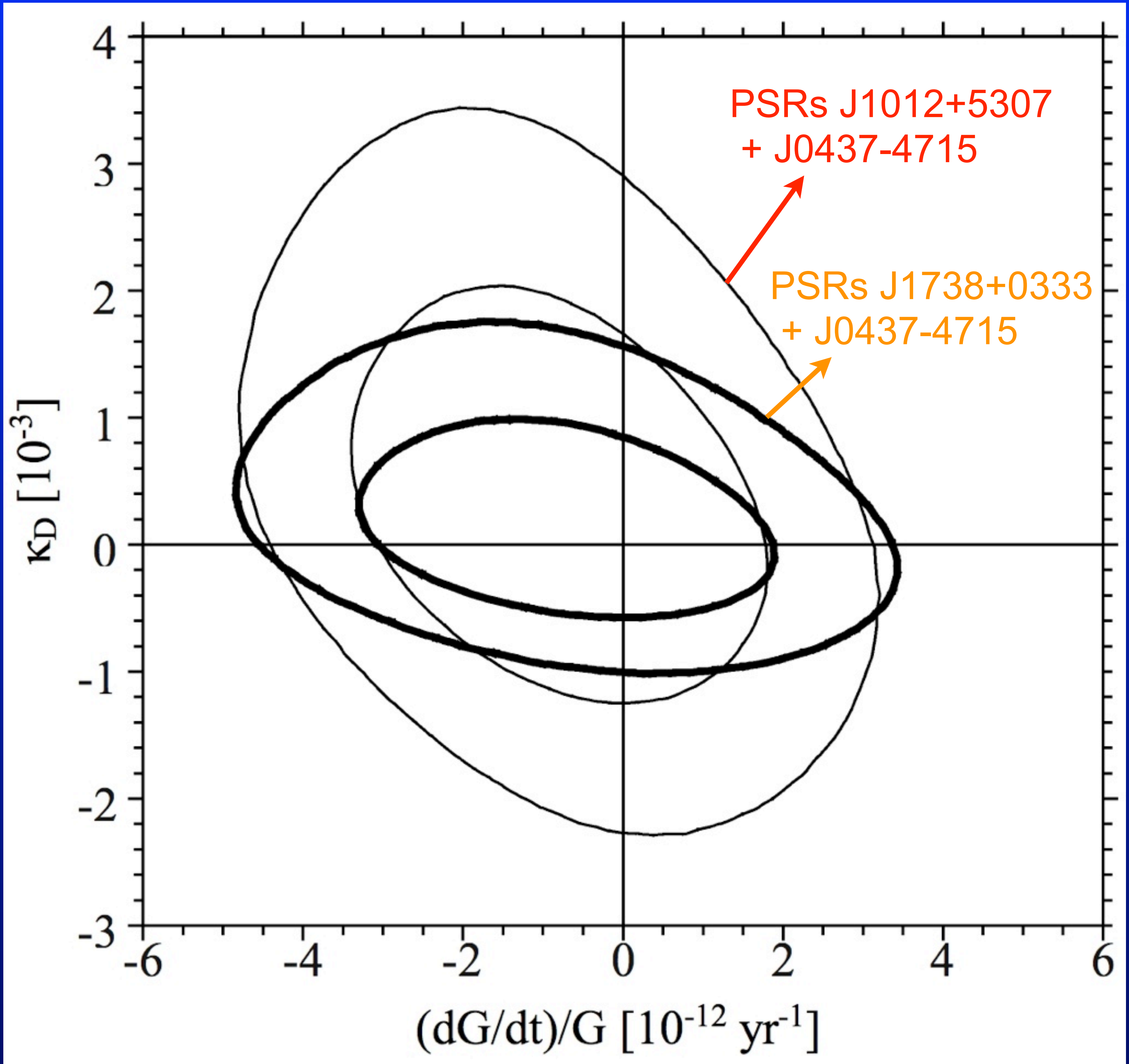
[*Antoniadis et al. 2011*]



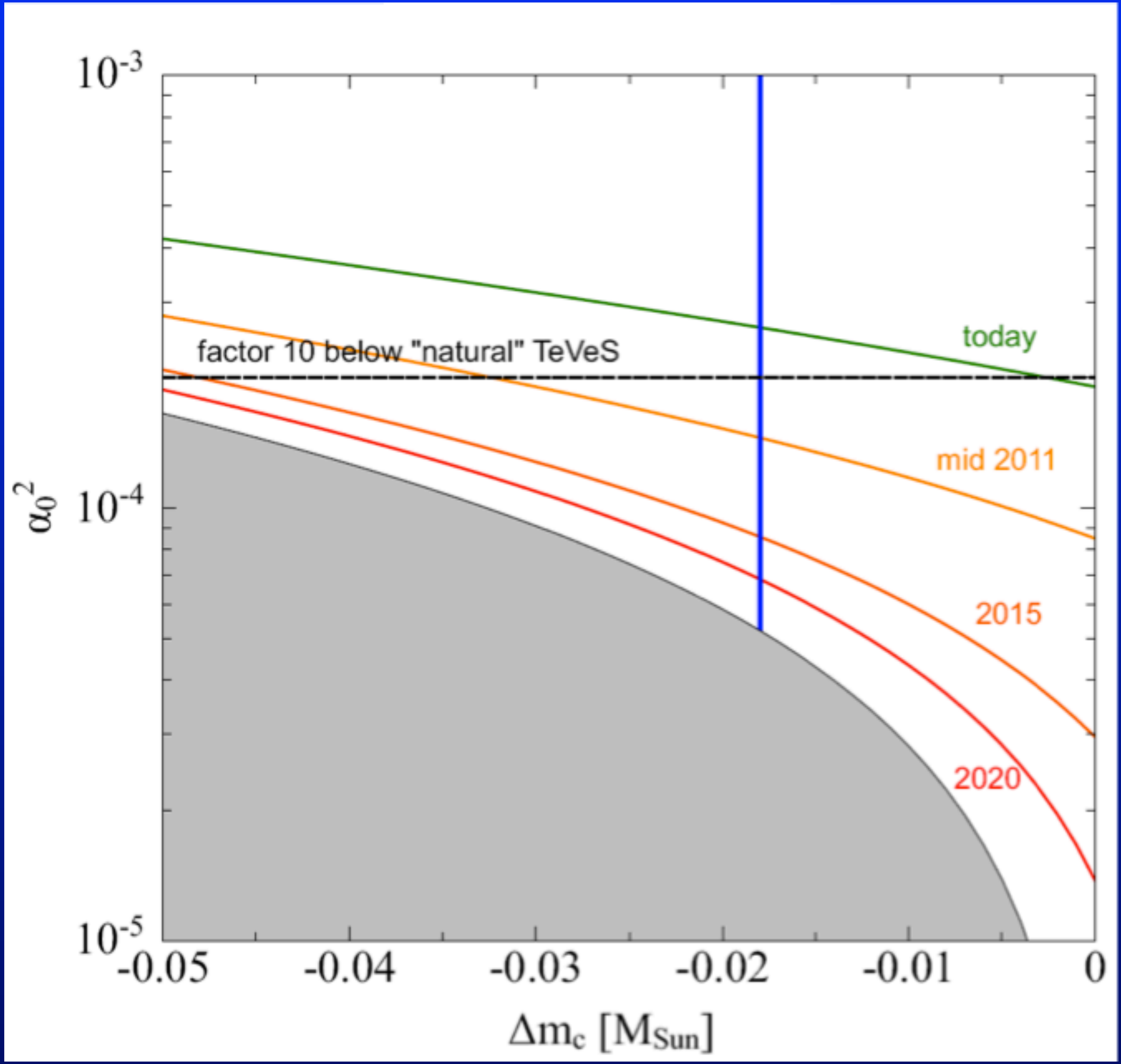
$m_c = 0.178 +0.015/-0.009\ M_{sun}$

$m_p/m_c = 8.20 \pm 0.19$

PSR J1738+0333 - GW Limit



TeVeS Limits from J1738+0333



See also Bruneton & Esposito-Farèse 2007

Summary & Outlook

- Generic Strong-Field Tests
  of Gravity
  with Binary Pulsar Systems

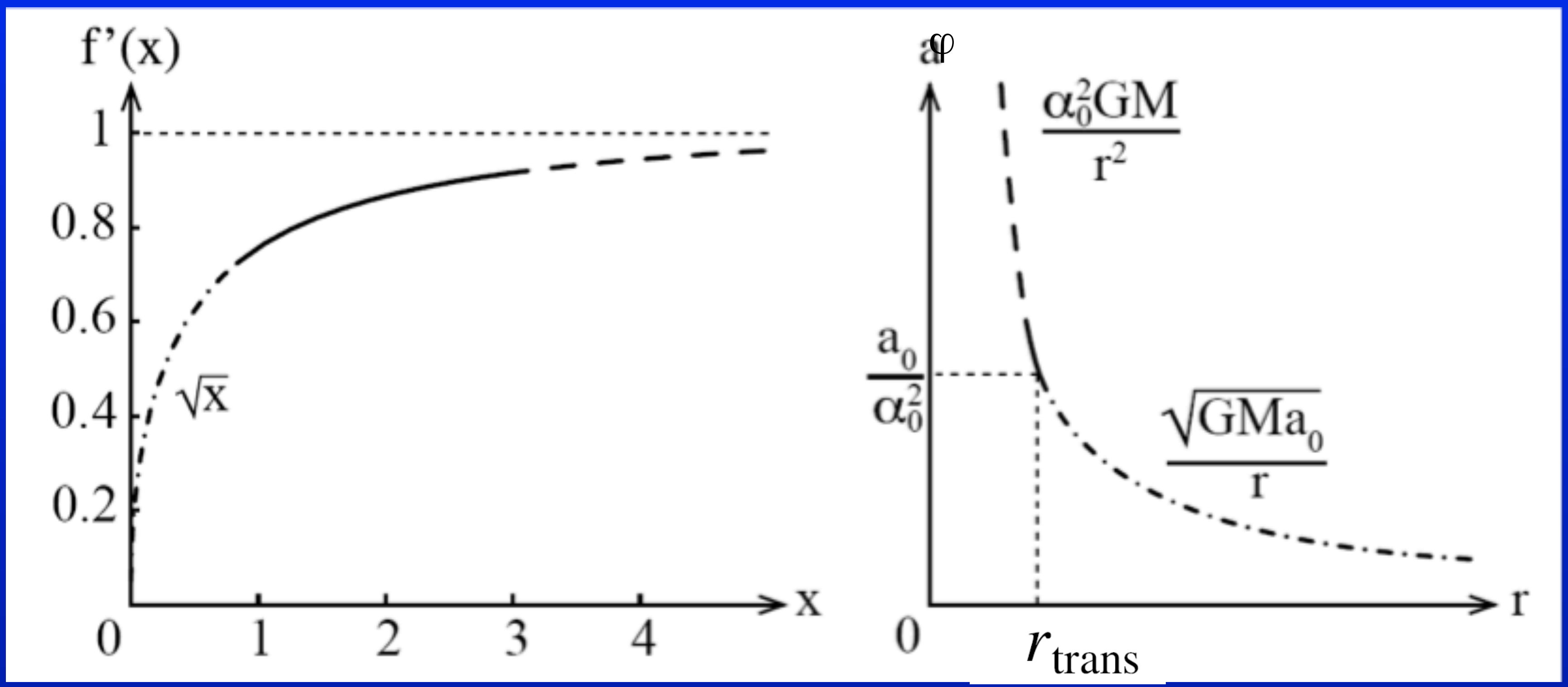
- PSR J1141-6545:
  Quadratic Tensor-Vector Theories

- PSR J1738+0333:
  TeVeS Theories — Must be “unnatural”

Additional Slides

"Natural" MOND and Binary Pulsars

[*Bruneton & Esposito-Farese 2007*]



MOND potential appears at a distance: $r_{\text{trans}} = \alpha_0^2 \sqrt{\frac{GM}{a_0}} \gg 7000\,\text{AU} \times \alpha_0^2$

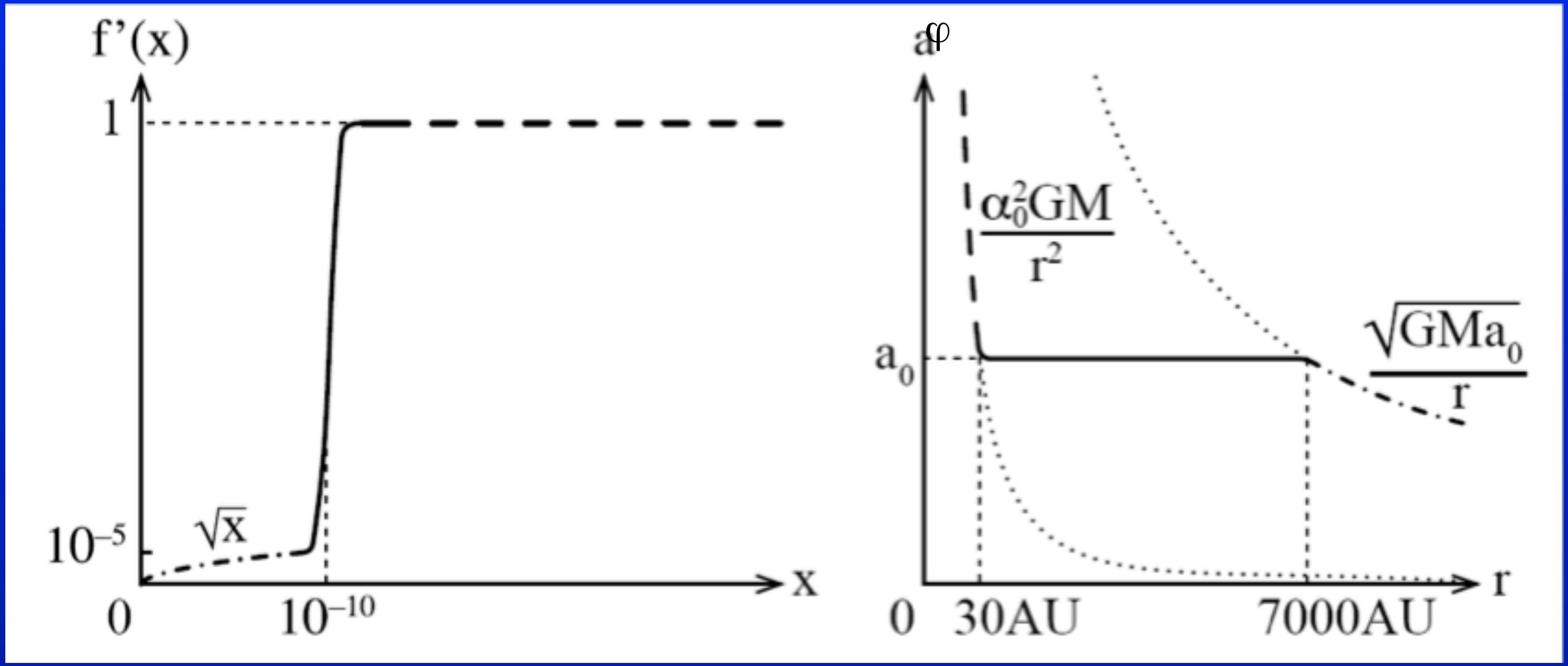
If $\alpha_0^2 < 0.002$ MOND effects should be apparent in the solar system dynamics

$\alpha_0^2 > 0.002$ would lead to a significant emission of dipolar gravitational radiation in pulsar-white dwarf binaries with ~1 day orbital period:

$$\dot{P}_{\text{b}}^{\text{dipole}} = -\frac{4\pi^2}{P_{\text{b}}} \frac{G\mu}{c^3} \frac{1+e^2/2}{(1-e^2)^{5/2}} (\alpha_0 s_{\text{p}})^2$$

TeVeS Becomes Unnatural

$\alpha_0^2 = 10^{-4}$ **requires an extremely unnatural behaviour of** $f(x)$**:**



[*Bruneton & Esposito-Farese 2007*]

If $\alpha_0^2 \sim 10^{-5}$ **stability and consistency conditions violated.**

The vector field U_μ **has to be parallel to the matter proper time, in order to prevent preferred frame effects. This leads to additional gravitational wave damping. Therefore constraints on TeVeS are most likely even tighter.**

TeVeS Theories and Binary Pulsar Experiments

MOND (MOdified Newtonian Dynamics) is not a relativistic theory of gravity (cannot explain lensing, cosmology, etc.)

To be an alternative to GR, a relativistic theory is needed that

- Consistent and stable
- Has MOND as a weak-field, slow motion limit
- Can explain existing experimental and observational results

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Most promising attempt so far: tensor-vector-scalar (TeVeS) theories (Bekenstein).

With sufficient fine-tuning (free function, free parameters) TeVeS theories can pass solar system tests

- Post-Newtonian dynamics of the planets
- Light-deflection and light-propagation effects
- Preferred-frame effect (PFE) tests

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However, general considerations by Bruneton & Esposito-Farese (2007) already show, that the scalar coupling used to explain solar system tests ($\alpha^2 = 2\times10^{-3}$) is in stark contrast to gravitational wave tests with binary pulsars: ($\alpha^2 < 2\times10^{-4}$).

Further, there is an issue with PFEs due to the vector field. If the vector field is adjusted to the matter frame to prevent PFEs, it would lead to additional GW damping in binary pulsars.