Strong-Field Gravity tests with binary pulsars

Constrains on gravitational dipolar radiation with PSR J1738+0333

John Antoniadis[1]

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Outline

Introduction

GR and the “need” for alternatives
Scalar-Tensor Theories
Timing of binary pulsars

The J1738+0333 system

Characteristics
Constrains on dipolar radiation
Constrains on TeVeS theories?

Future prospects

Surveys for new pulsars
Advances in instrumentation
New systems?

Introduction

GR vs not GR...

GR has passed all tests so far with flying colors!

*Very well tested in the solar system (e.g. Mercury perihelion advance, light deflection, Gravity Probe B, LLR...)

*But...not well tested in the strong-field regime

Credit LST

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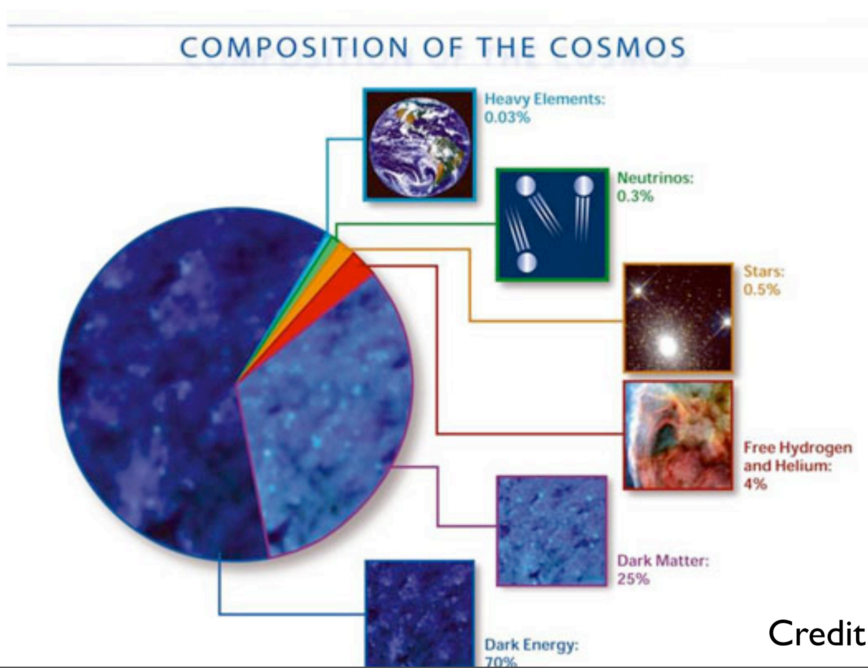
Evidence for breakdown?

*Dark matter - dark energy problem

*inconsistent with modern theories (e.g. super-strings)



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Introduction

Alternative theories

Scalar tensor theories are considered as the most well-founded possible alternatives

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$$S = \frac{c^2}{16\pi G} \int d^4x \sqrt{-g}\, R + S_{\substack{\text{standard}\\ \text{model}}} \left[{}^{\text{all}}\,{}_{\text{fields}}^{\text{matter}}, g_{\mu\nu} \right]$$

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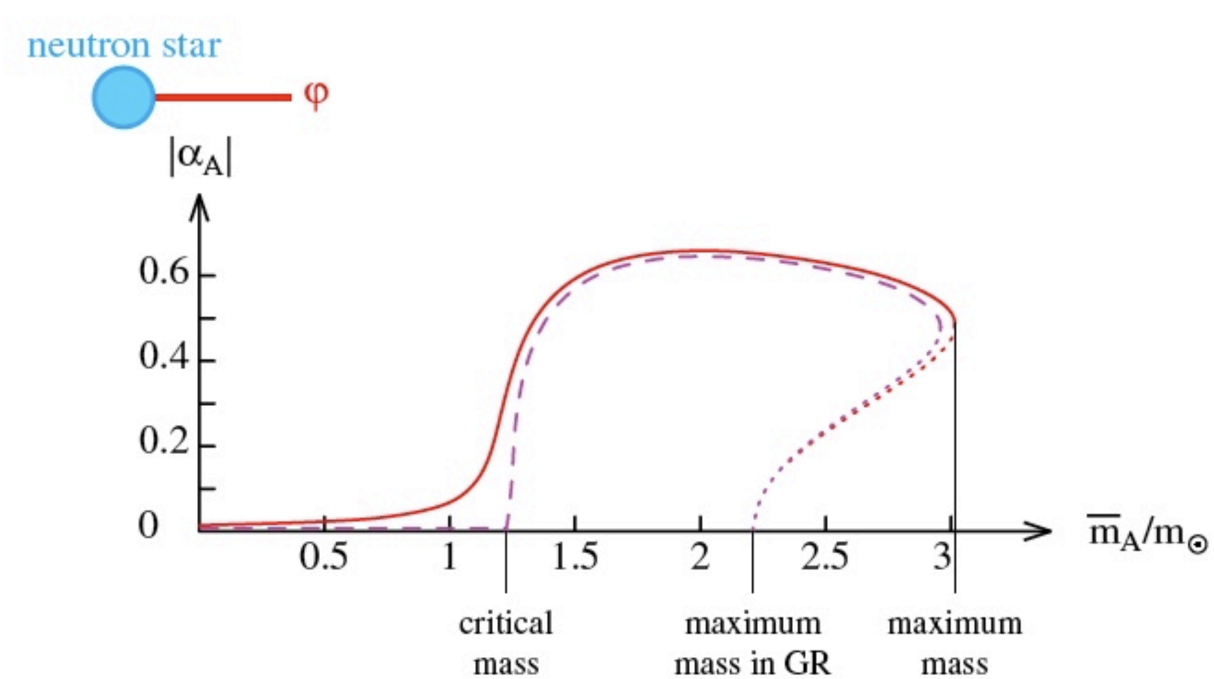
$$S = \frac{c^3}{16\pi G} \int d^4x \sqrt{-g^*} \left(R^* - 2g_*^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi\right) + S_{\text{matter}} \left[\text{matter}; g_{\mu\nu} \equiv A^2(\varphi) g^*_{\mu\nu}\right]$$

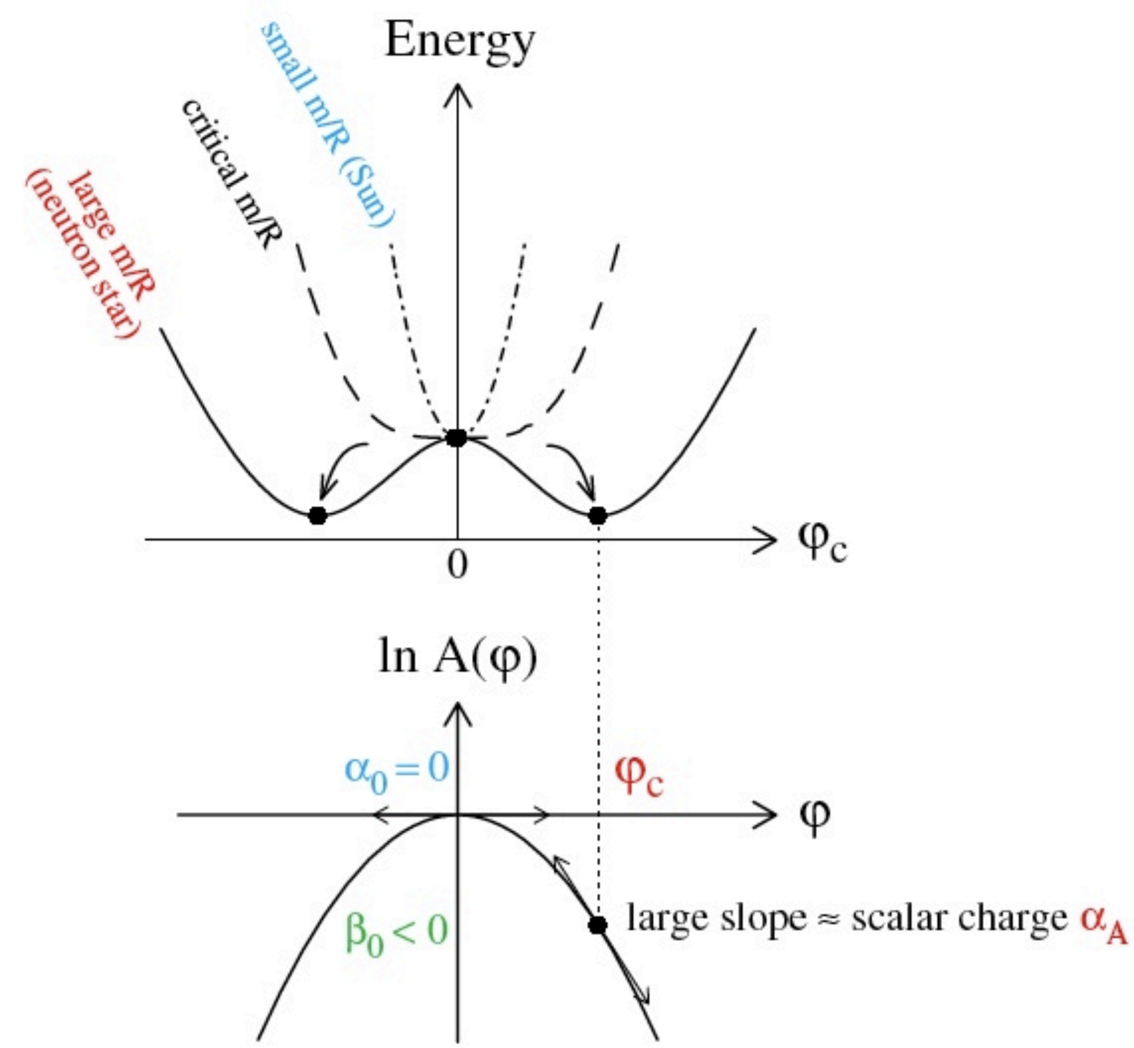
Introduction

Alternative theories

If the mass of the scalar field is small enough it could pass the solar system tests.

For Neutron-stars it could still be energetically favorable to become scalarized





Esposito-Farese (2005)

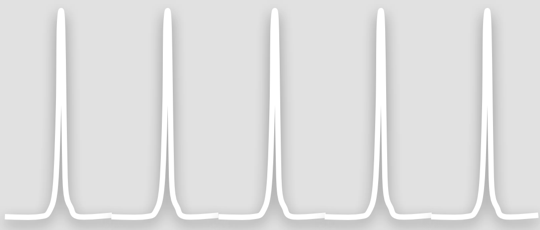
Introduction

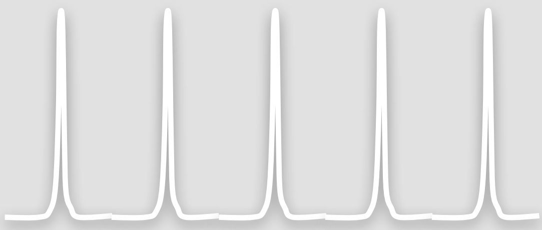
The Pulsar Phenomenon

Credit David Champion

Introduction

The Pulsar Phenomenon





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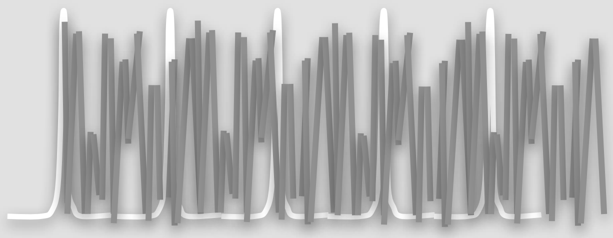

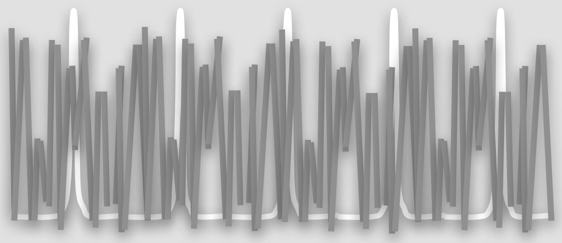

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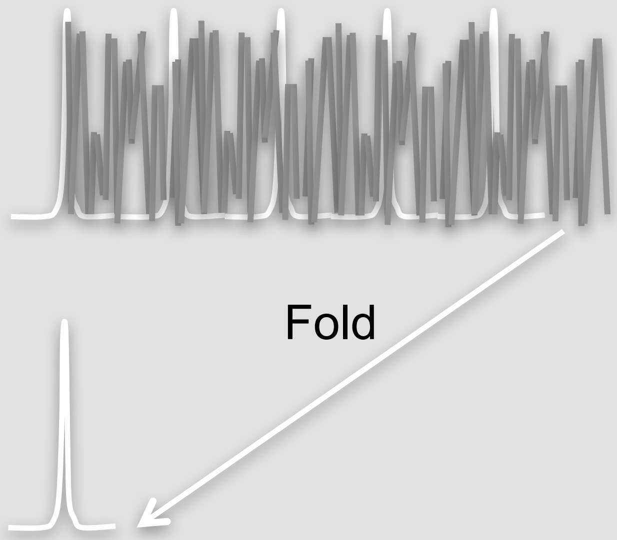

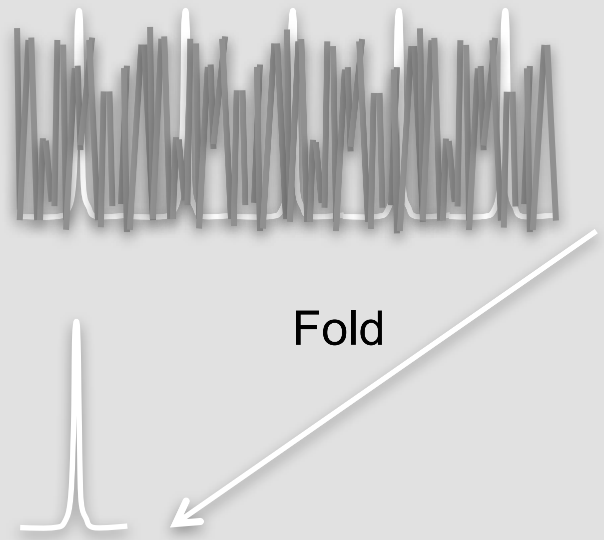

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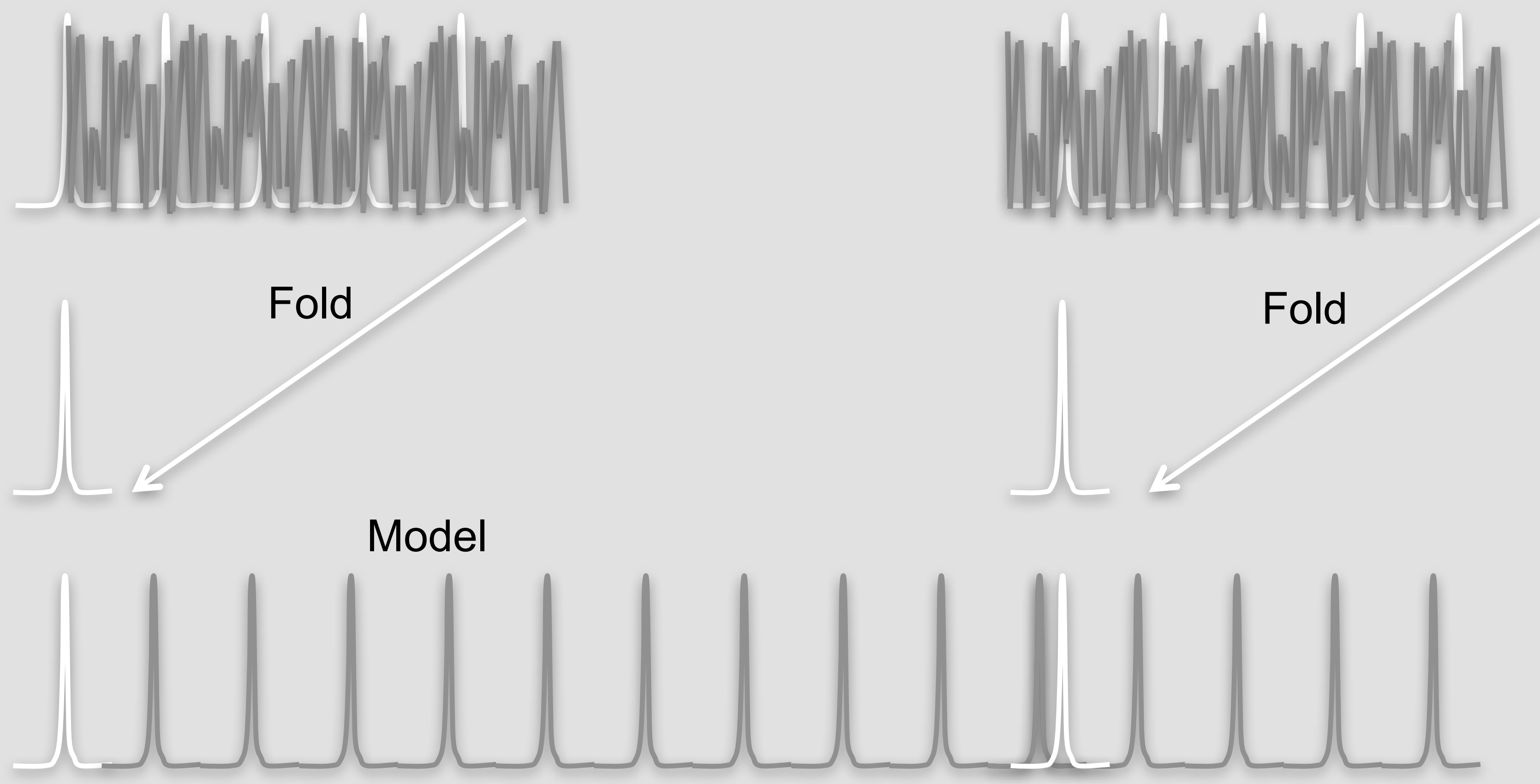

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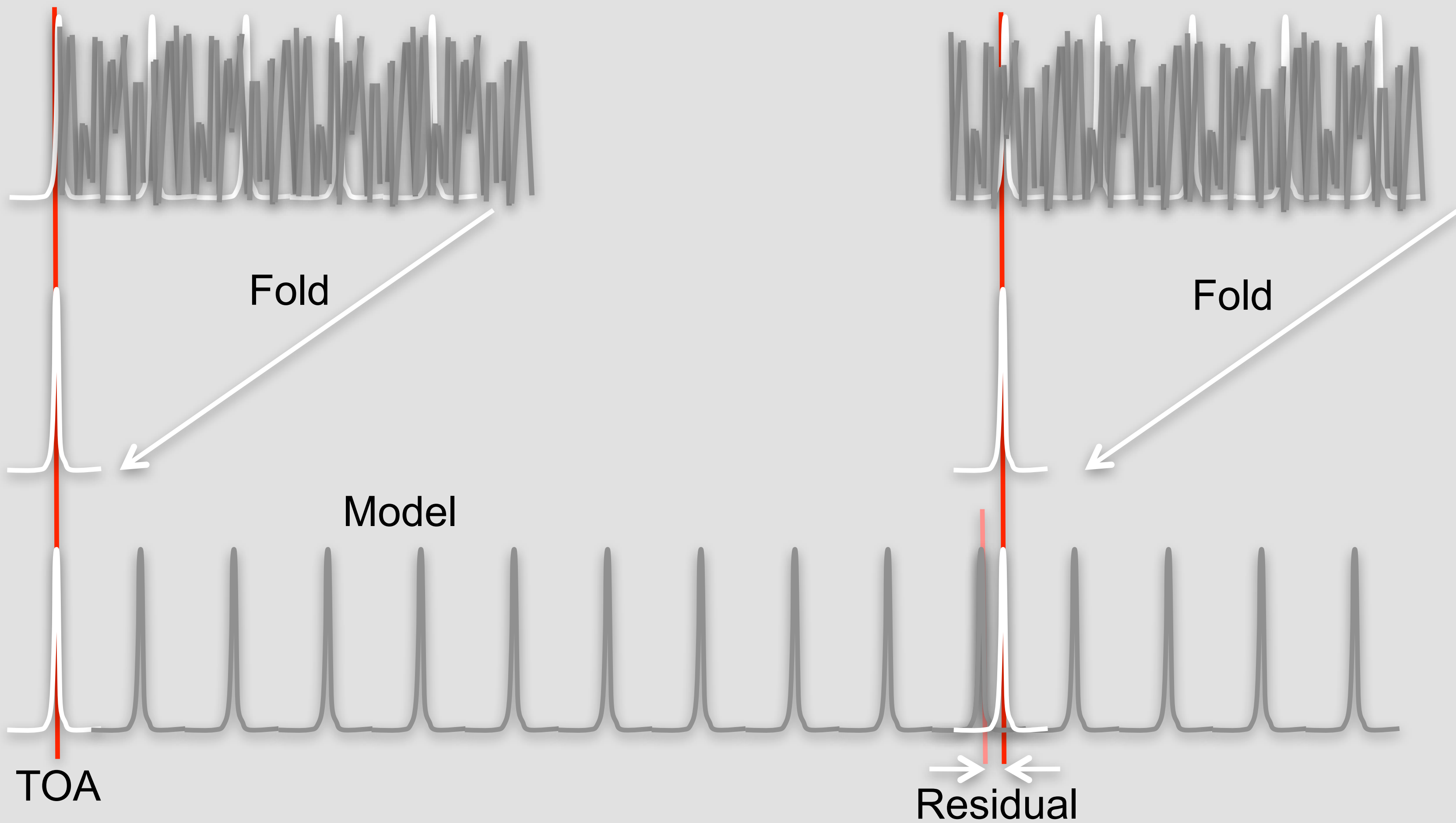

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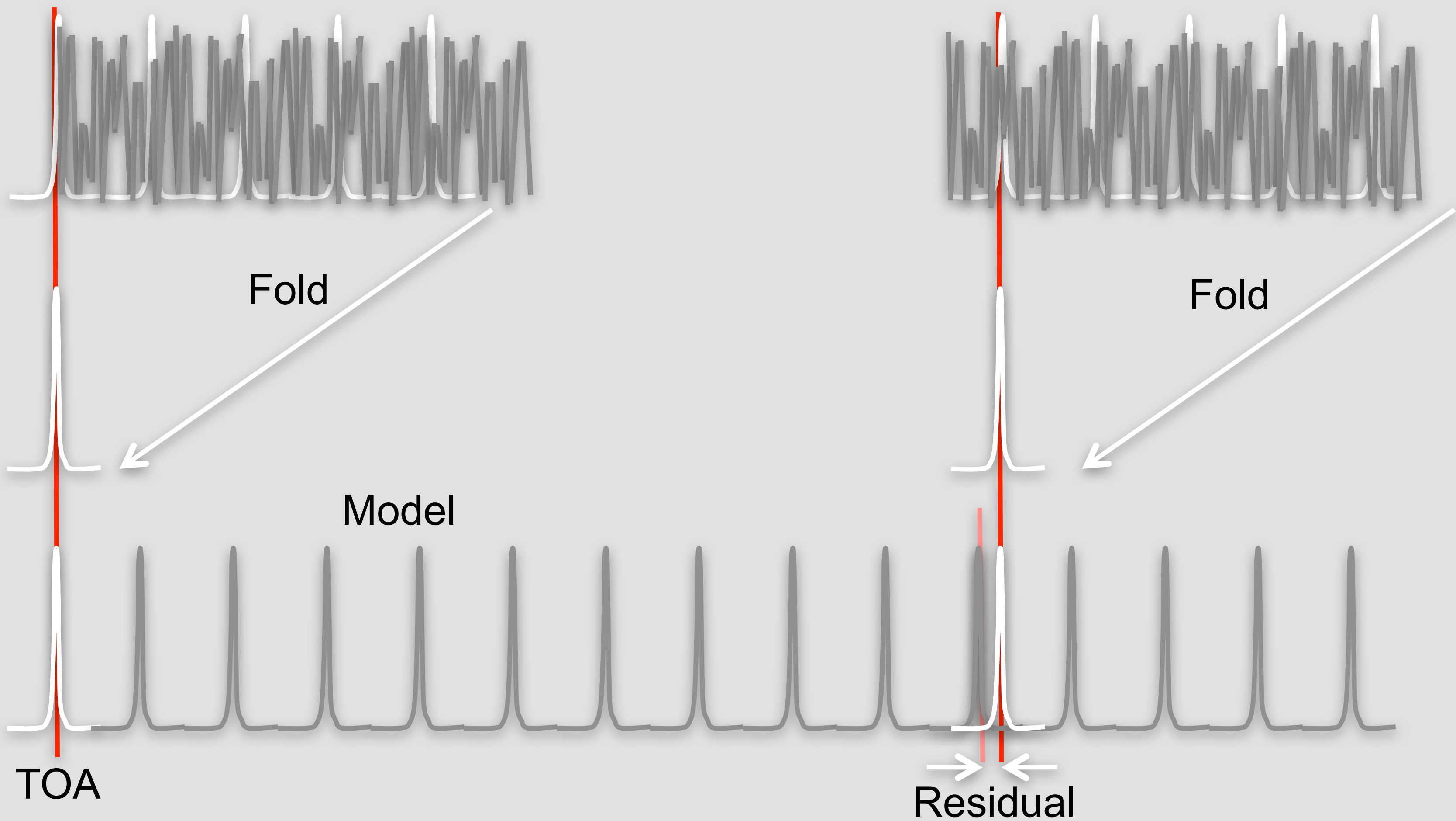

Credit David Champion

Orbital Period, P_b
Eccentricity, e
Inclination, i
Epoch of periastron, T_0
Longitude of periastron, ω
Longitude of ascension, Ω
Projected semi-major axis, x

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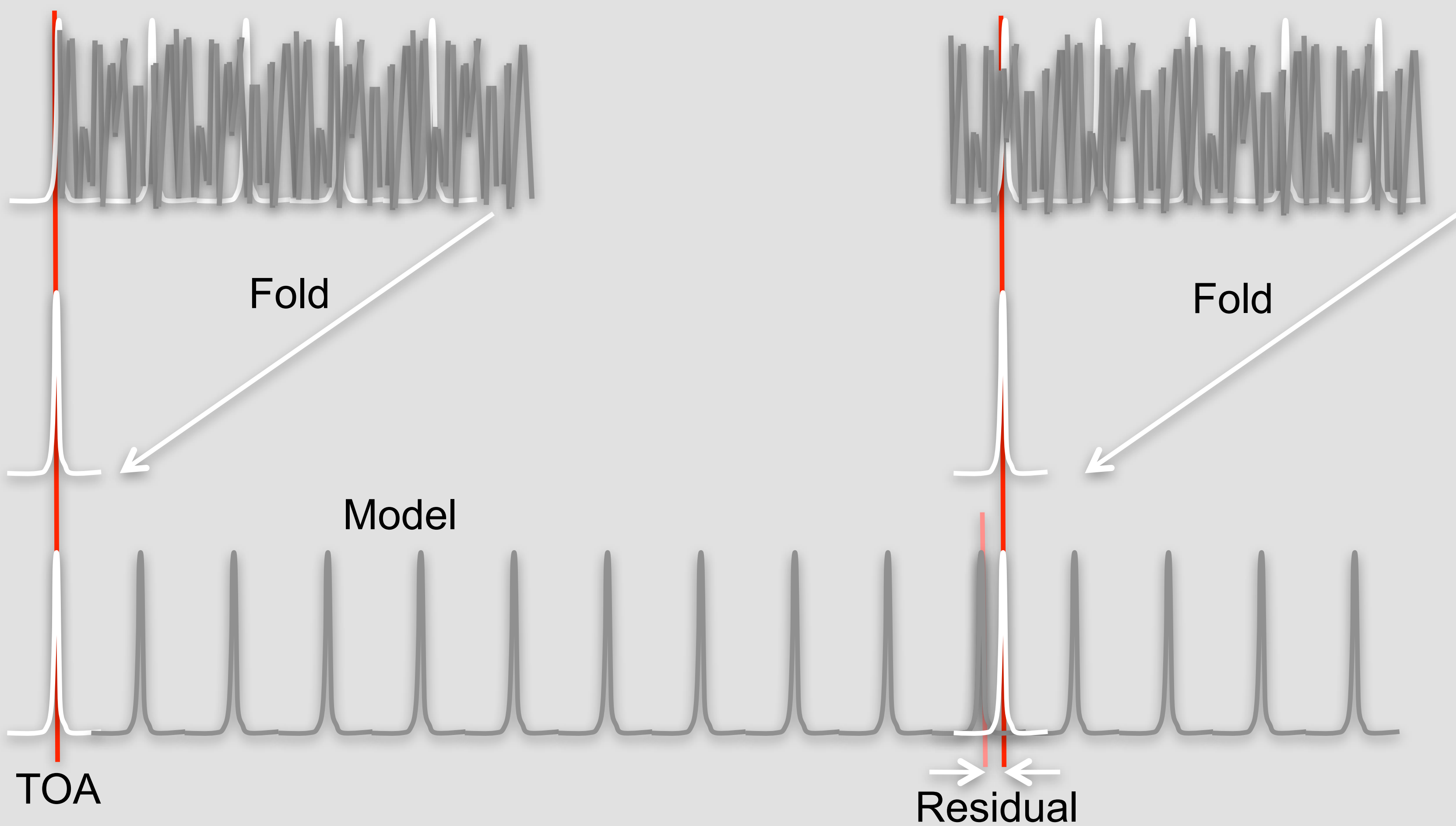

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Orbital decay , $\dot{P}_b$
Precession of periastron, $\dot{\omega}$
Shapiro-delay "range", r
Shapiro-delay "shape", s
relativistic delay, γ
Longitude of ascension, Ω
Projected semi-major axis, x
Spin precession

Introduction

Example: Orbital decay due to the emission of gravitational waves

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GR: Emission of quadropolar gravitational radiation

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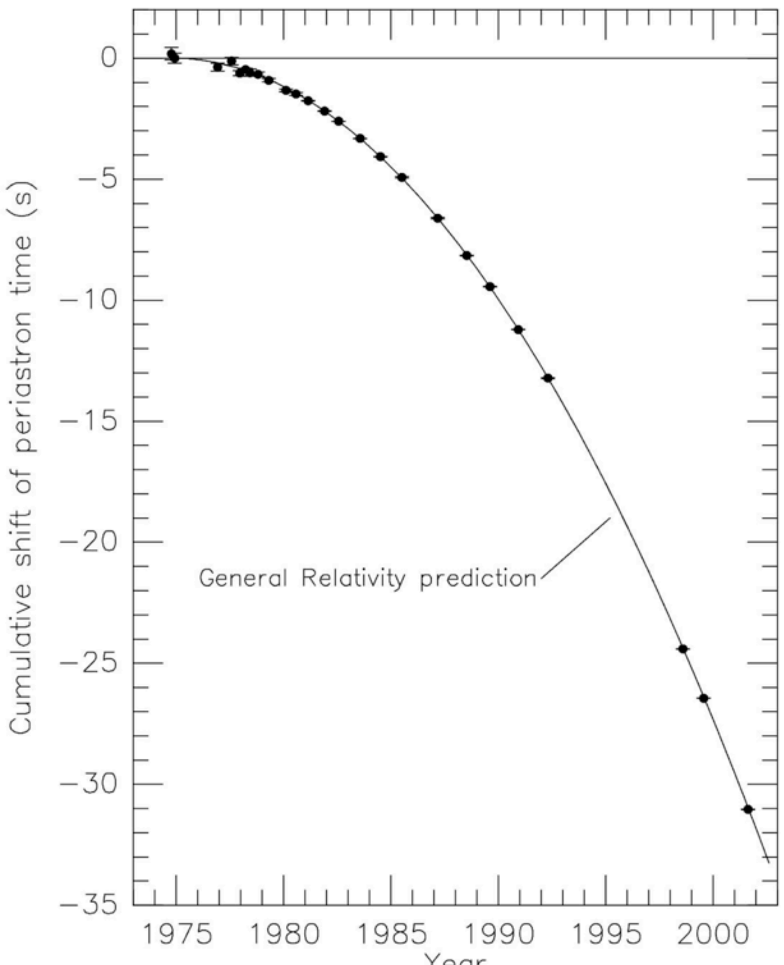
$$\dot{P_b}^{GW} = \dot{P_b}^{GR} = -\frac{192\,\pi}{5}\left(\frac{2\pi}{P_b}\right)^{5/3}\frac{(T_\odot\, m_c)^{5/3} q}{(q+1)^{1/3}}$$



Weisberg & Taylor 2003

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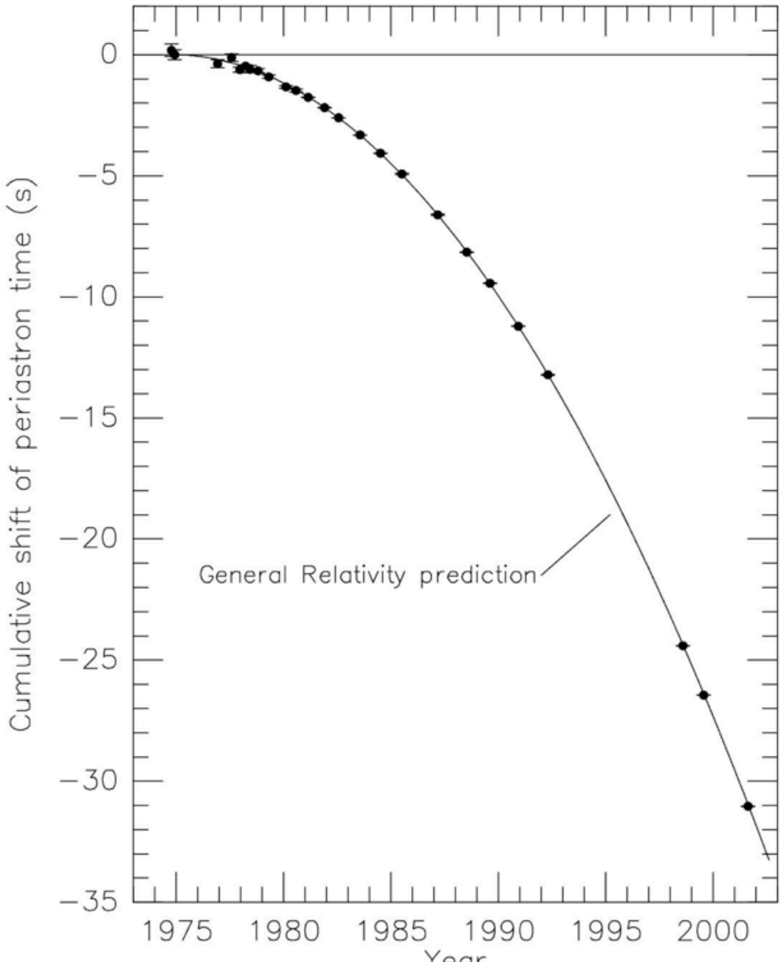

Weisberg & Taylor 2003

Scalar fields: + Dipolar radiation

$$\dot{P}_b^{\rm dipole} \simeq -\frac{4\pi^2 G_*}{c^3 P_b}\frac{m_p m_c}{m_p + m_c}(\alpha_p - \alpha_c)^2$$

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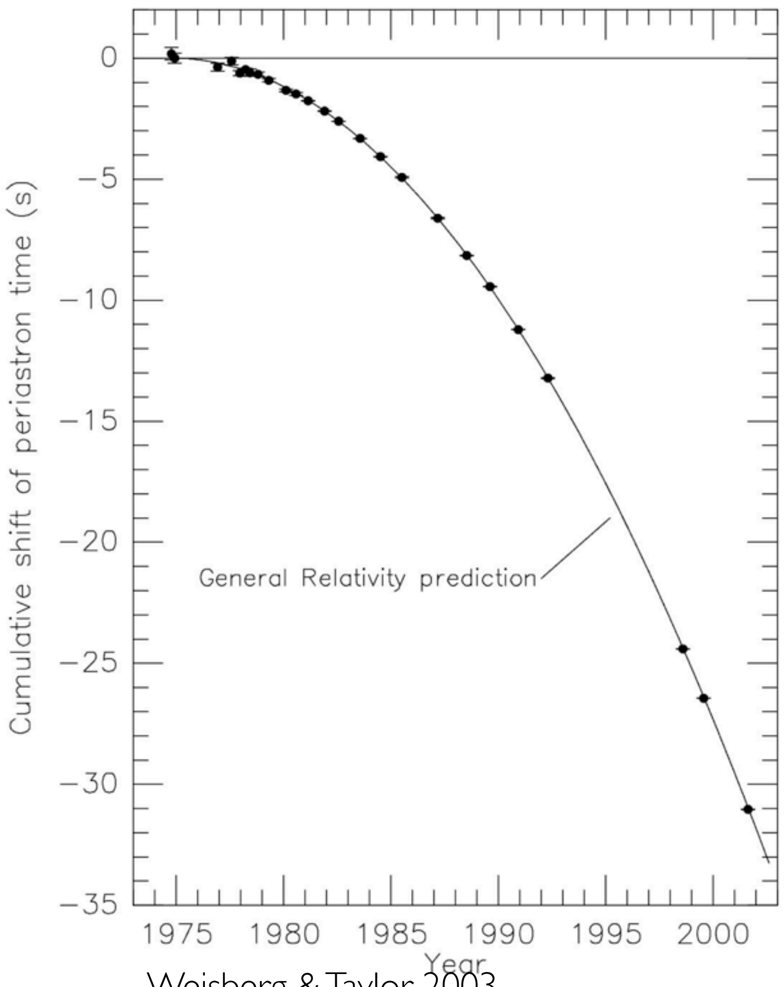

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Scalar fields: + Dipolar radiation

$$\dot{P}_{\rm b}^{\rm dipole} \simeq -\frac{4\pi^2 G_*}{c^3 P_{\rm b}}\frac{m_{\rm p} m_{\rm c}}{m_{\rm p}+m_{\rm c}}(\alpha_{\rm p}-\alpha_{\rm c})^2$$

Needs systems with large difference in scalarization
Effect small: Stable timer
Measurable only in close PSR+WD binaries

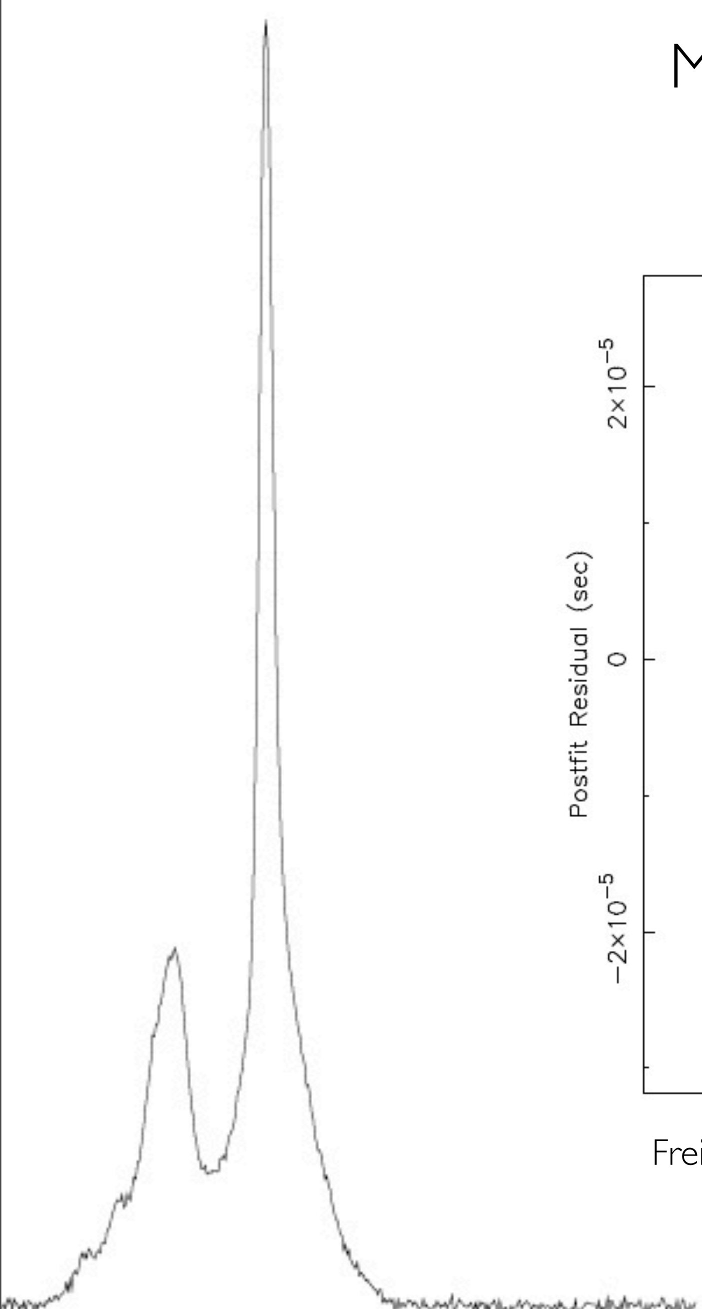
PSR J1738+0333

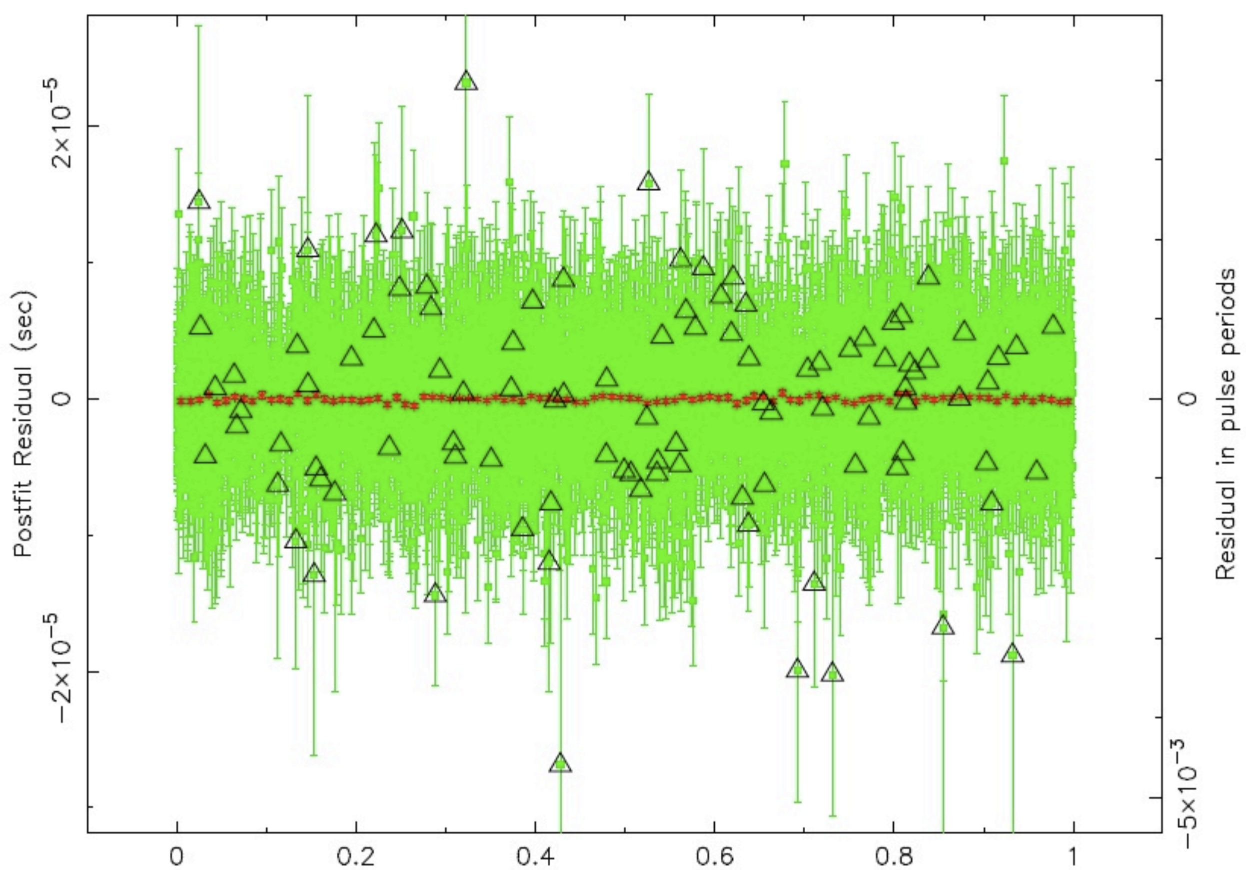
Example: Orbital decay due to the emission of gravitational waves

5.86 ms PSR + white dwarf binary, 8.15 h highly circular orbit

Observed for 7 years with Arecibo

Measured orbital decay , $\dot{P}_b$ = -27.9±3.8 fs/s

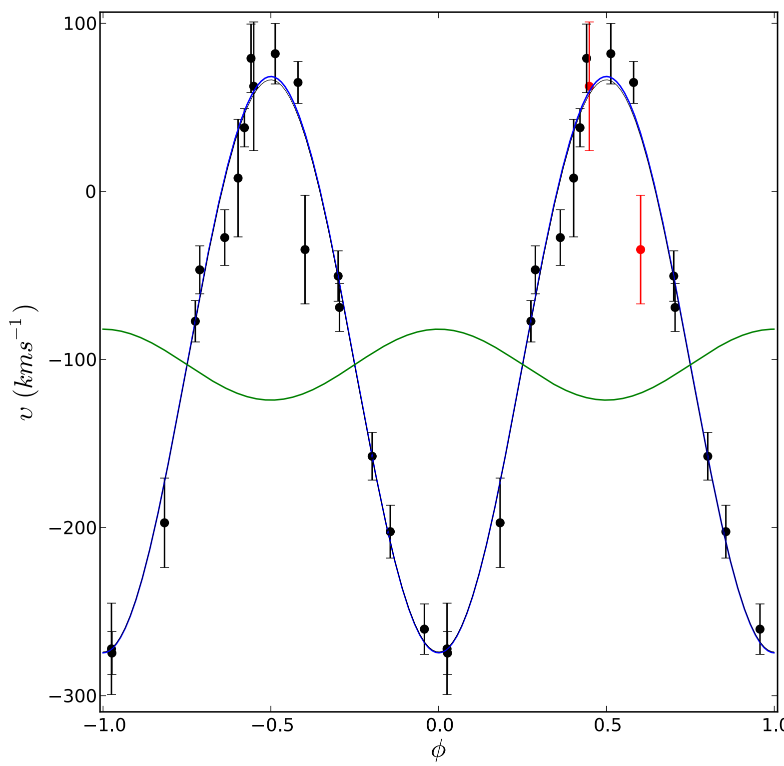




Freire et al. in preperation

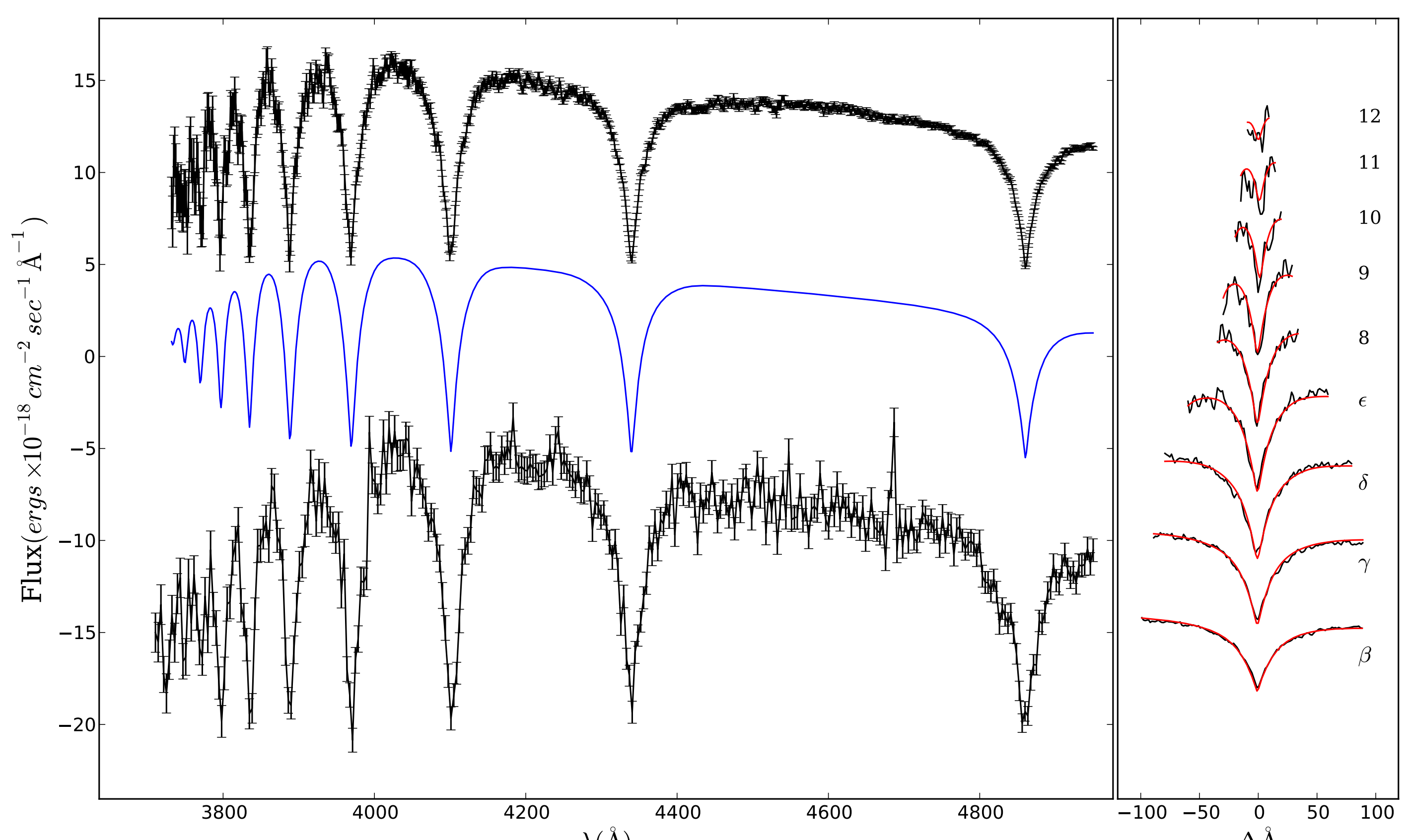
PSR J1738+0333

Antoniadis et al. in preperation



Mass ratio, q	8.1(2)
Companion's mass, $M_{\rm WD}$ ($M_\odot$, spectroscopy) ...	$0.181^{+0.007}_{-0.005}$

$$\dot{P}_{\rm b}^{\rm dipole} \simeq -\frac{4\pi^2 G_*}{c^3 P_{\rm b}} \frac{m_{\rm p} m_{\rm c}}{m_{\rm p} + m_{\rm c}} (\alpha_{\rm p} - \alpha_{\rm c})^2$$



PSR J1738+0333

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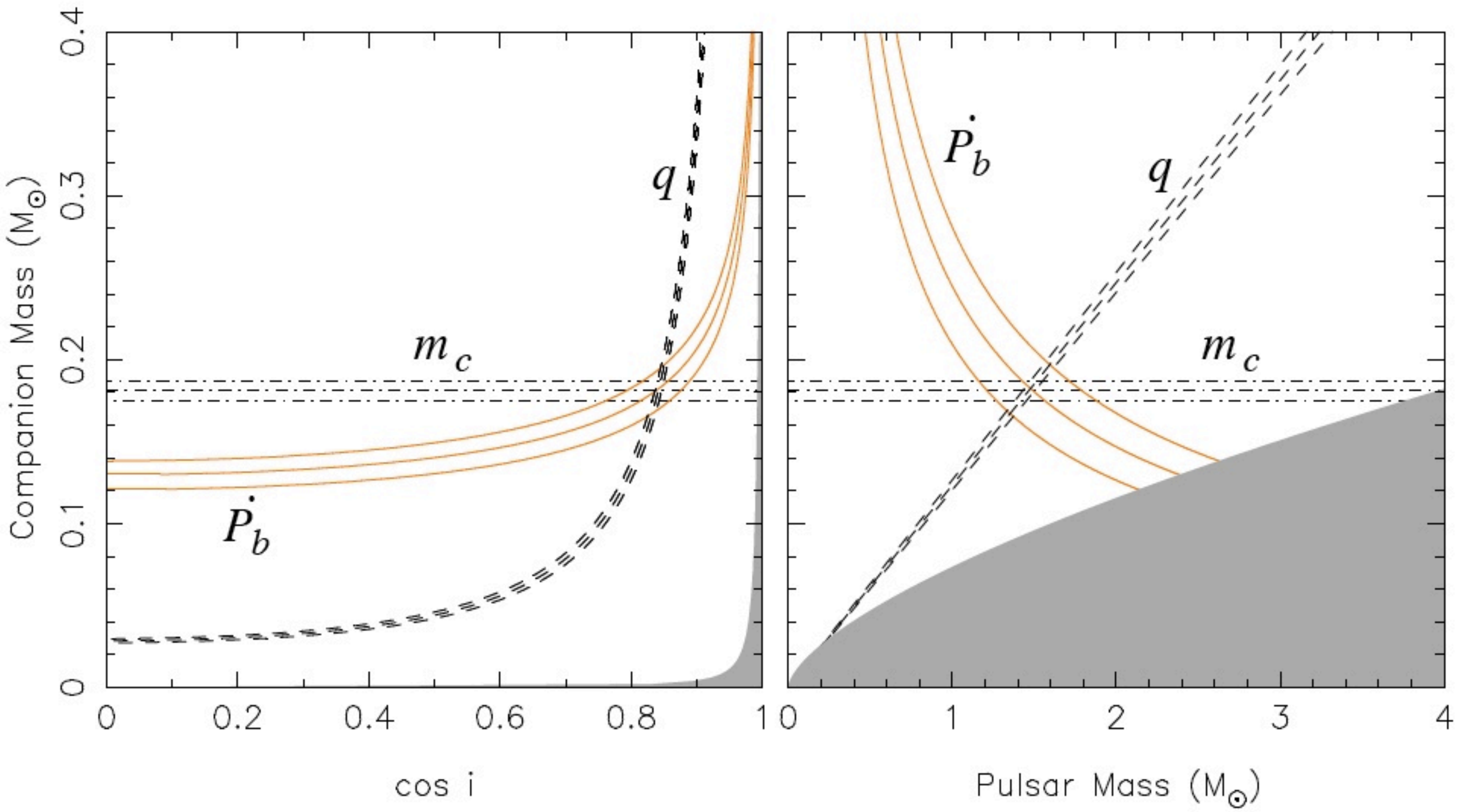

$$\dot{P}_{\rm b}^{\rm dipole} \simeq -\frac{4\pi^2 G_*}{c^3 P_{\rm b}} \frac{m_{\rm p} m_{\rm c}}{m_{\rm p} + m_{\rm c}} (\alpha_{\rm p} - \alpha_{\rm c})^2$$

$$\dot{P}_b^{\rm QGW} = -\frac{192\,\pi}{5} (n_b T_\odot\, m_c)^{5/3} \frac{q}{(q+1)^{1/3}} = -27.3(9)\,{\rm fs\,s^{-1}}$$

PSR J1738+0333

"Excessive" decay:

$$\dot{P}_b^{\rm xs} = (-0.6 \pm 4.0) \times 10^{-15} {\rm s\,s^{-1}}$$

PSR J1738+0333

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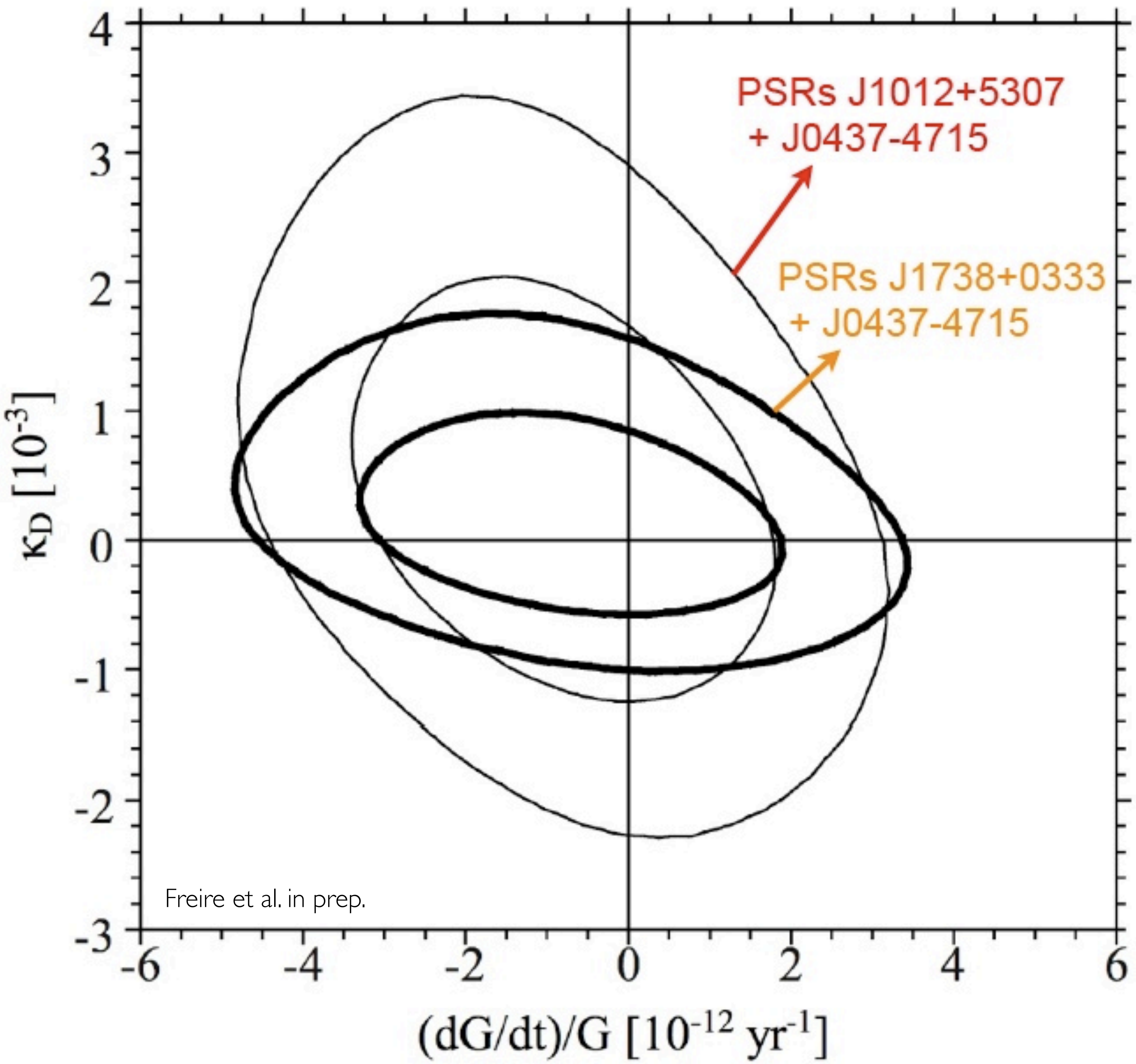
$$\dot{P}_b^{\rm xs} = (-0.6 \pm 4.0) \times 10^{-15} {\rm s\,s^{-1}}$$

Most constraining limit on scalar-matter coupling strength :

$$\alpha_0^2 < 8.3 \times 10^{-5} \ (95\% \ {\rm C.\ L.})$$

PSR J1738+0333

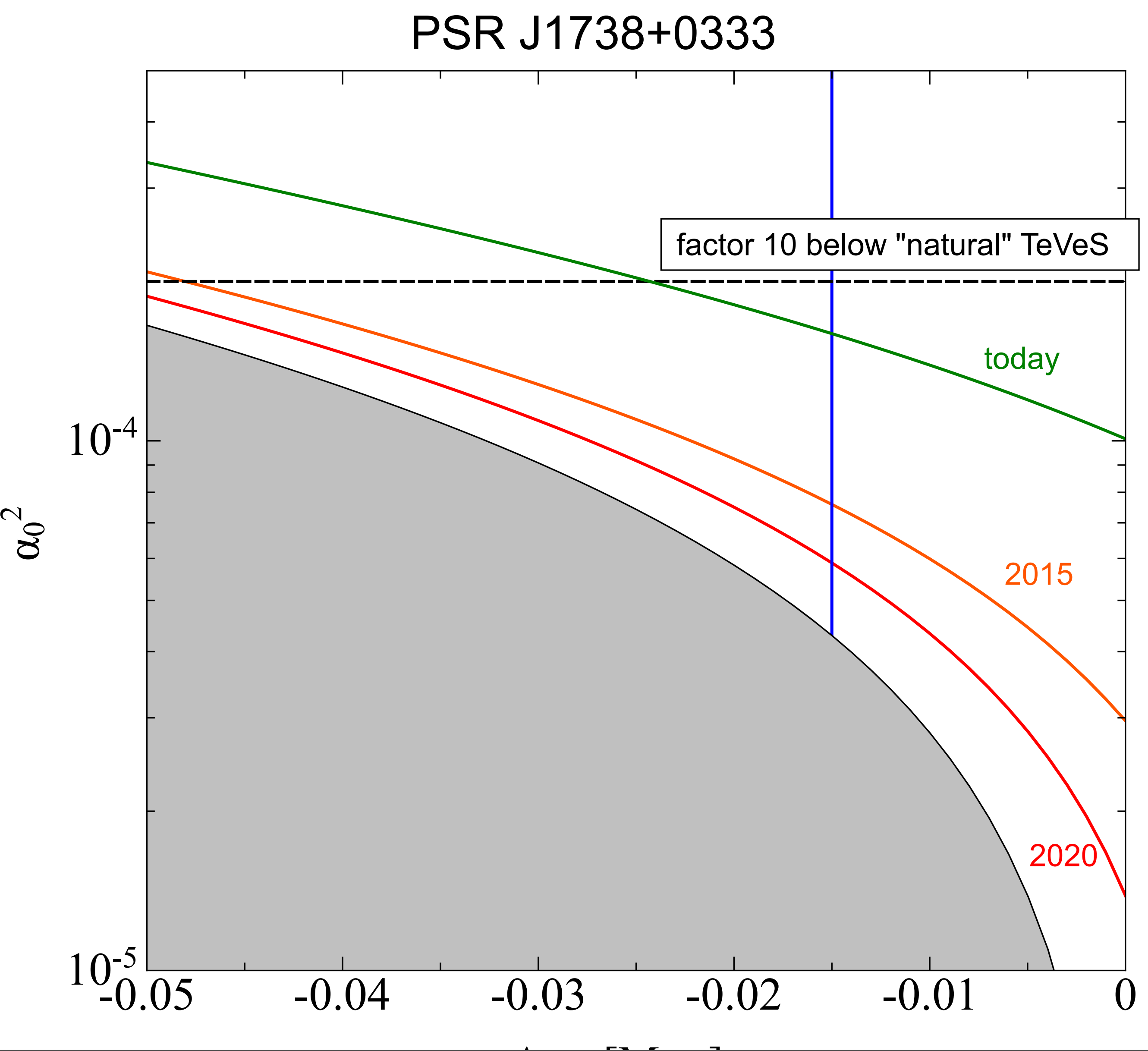


See Lazaridis et al. (2009) for details

PSR J1738+0333

Does the same limit apply to Tensor-Vector-Scalar theories? (relativistic MOND)

If so (Bruneton & Esposito-Farese 2007), the former limit makes these theories "unnatural"



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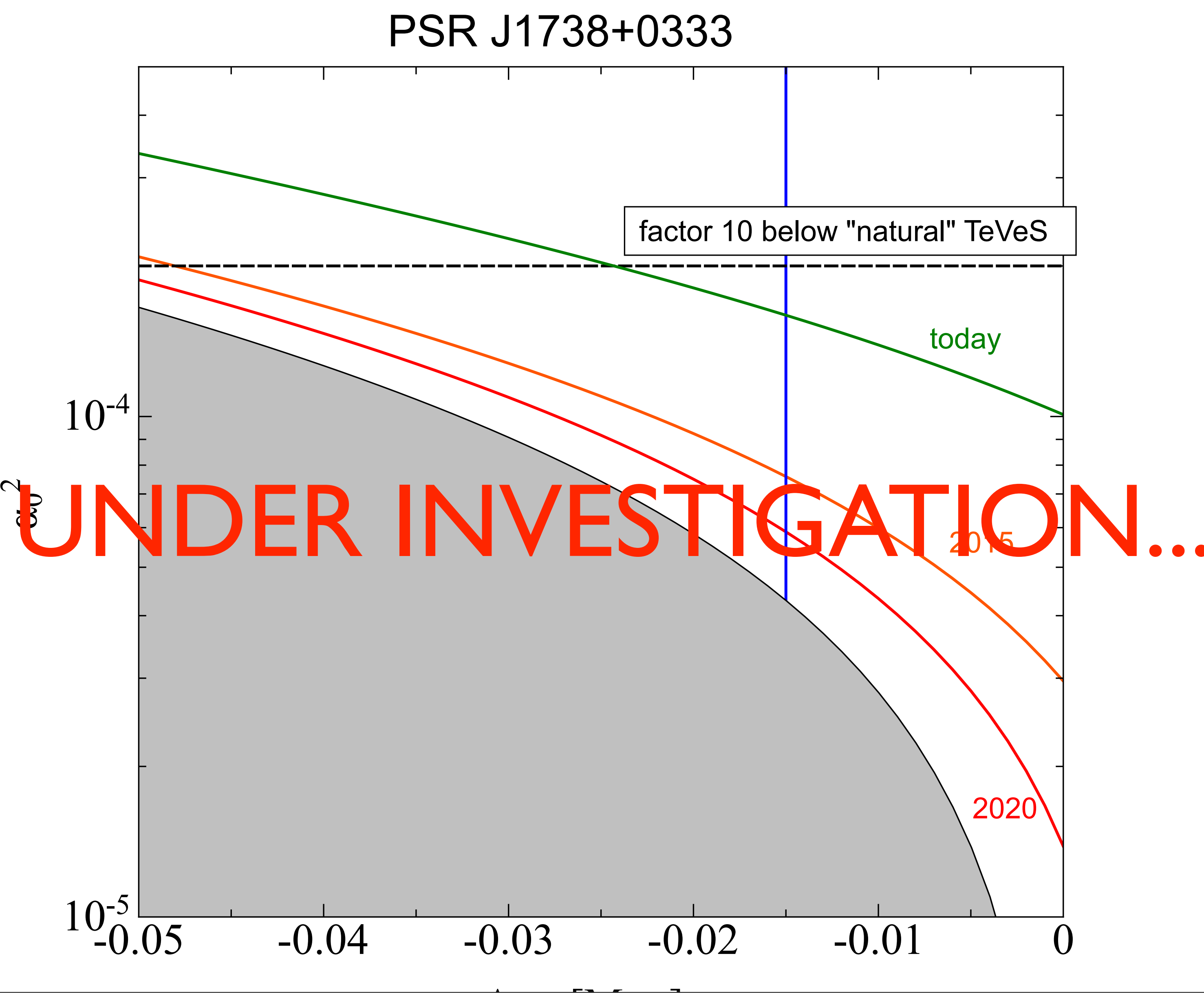
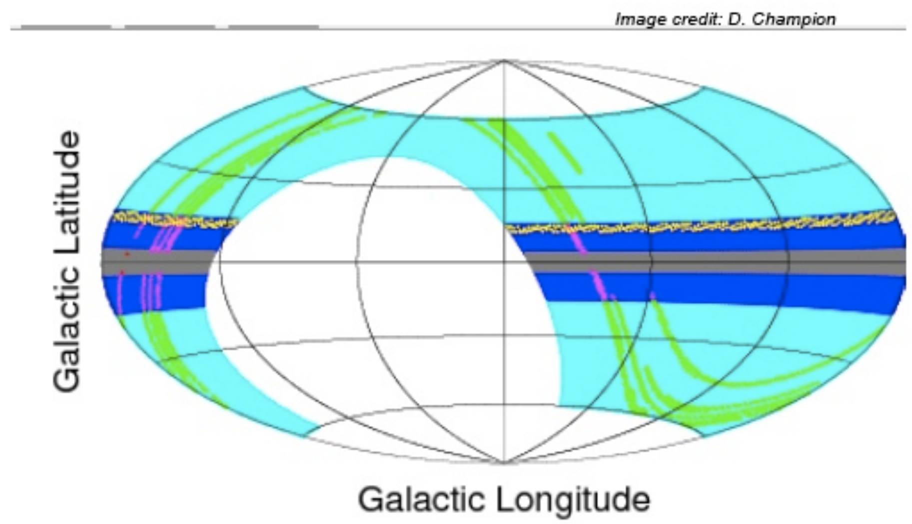
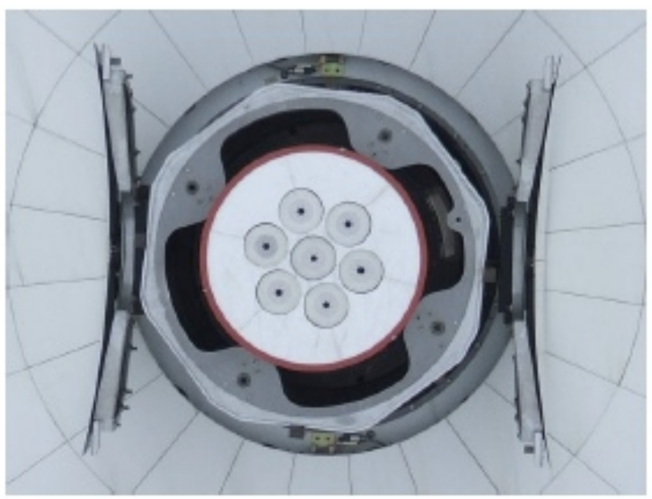


The need for more pulsars..

HTRU survey

Pulsar Fast Fourier Transform Spectrometer (PFFTS)





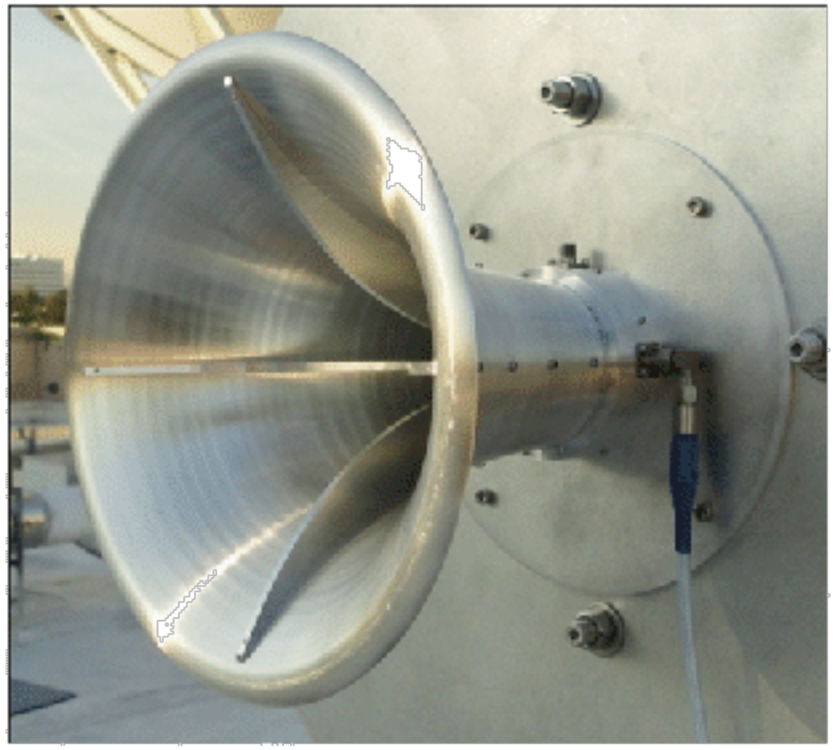
New 7-beam 21-cm primary focus receiver at Effelsberg

Effelsberg (North) + Parkes (South)
>1000 expected new discoveries (>150 MSPs)

D. Champion, E. Bahr, C. Ng, M. Kramer et al.

New instumentation...

Instrumentation



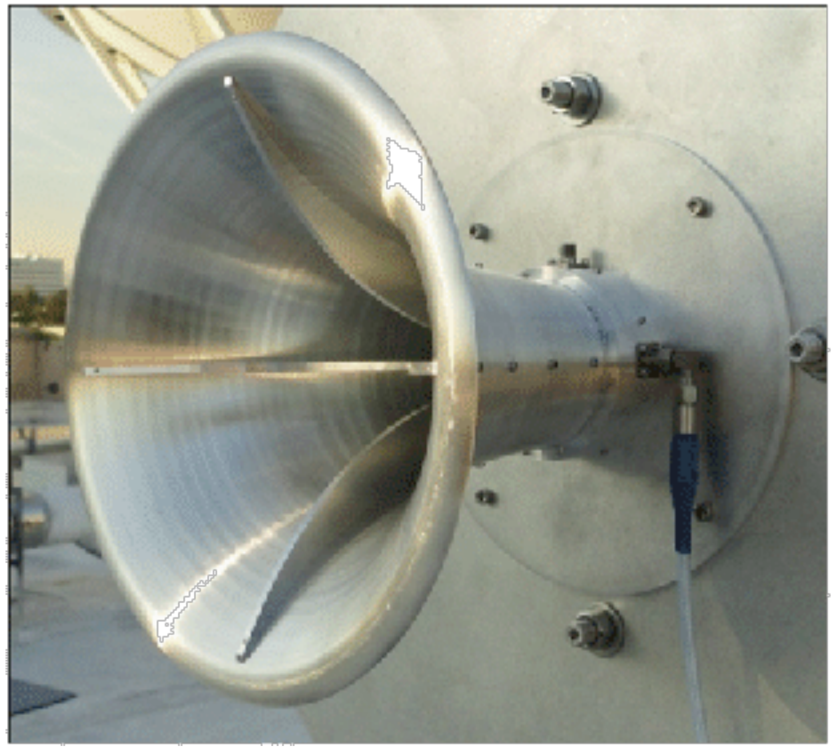
Feed design by Sandy Weinreb (JPL)

New instumentation...

Instrumentation

Being developed:
New 600-3000 MHz ultra-broadband receiver @ Effelsberg
Feed design by Sandy Weinreb (JPL)
ERC consolidated grand (2.1 ME, Paulo Freire)
Whole bandwidth coherently dedispersed!

Higher S/N
ISM effects removal

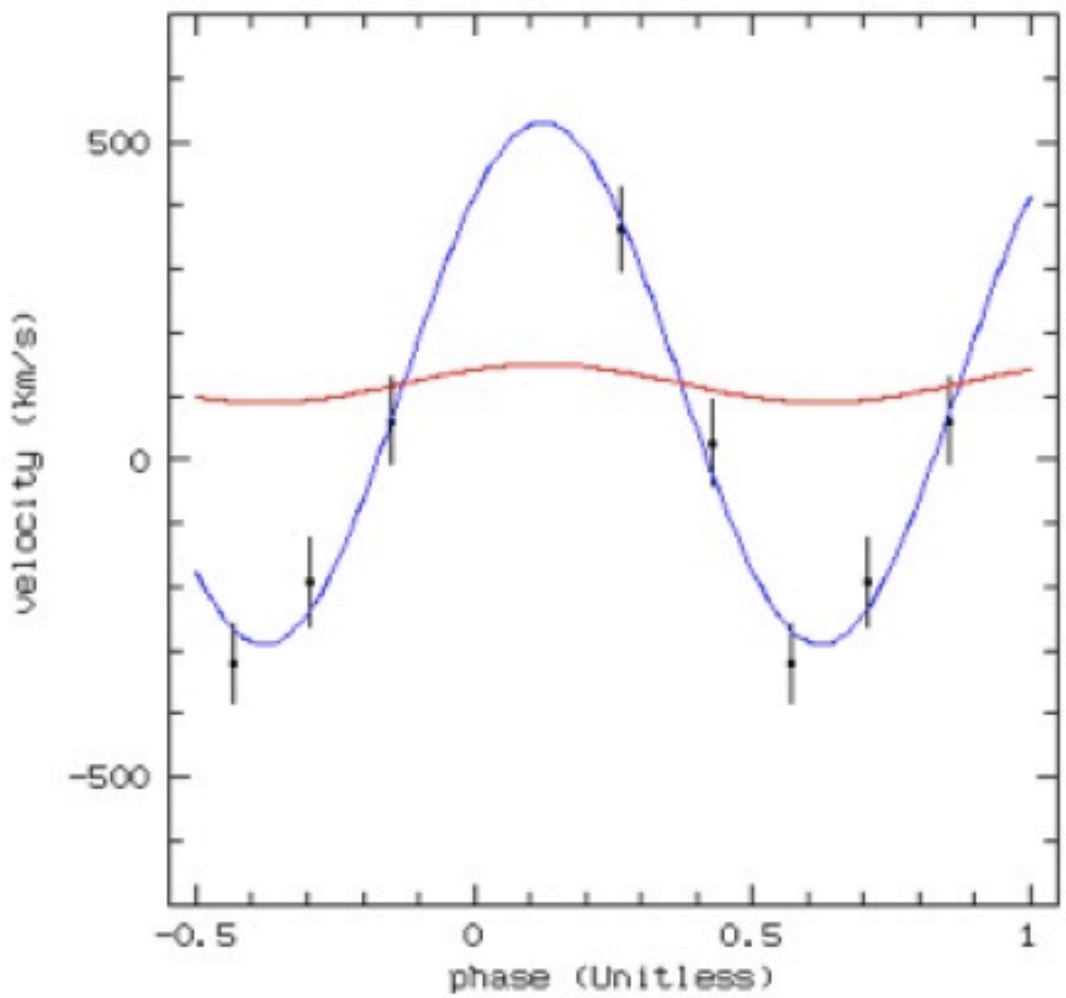


Feed design by Sandy Weinreb (JPL)

New discoveries

New PSR+WD in a 2-hour orbit

Preliminary results show that there is a high chance for the NS to be above 2.2 solar masses



If so ~20 times more luminous in dipolar radiation than J1738

Ongoing observations with Arecibo (Lynch et al.)

Observations with VLT scheduled for this December (Antoniadis et al.)

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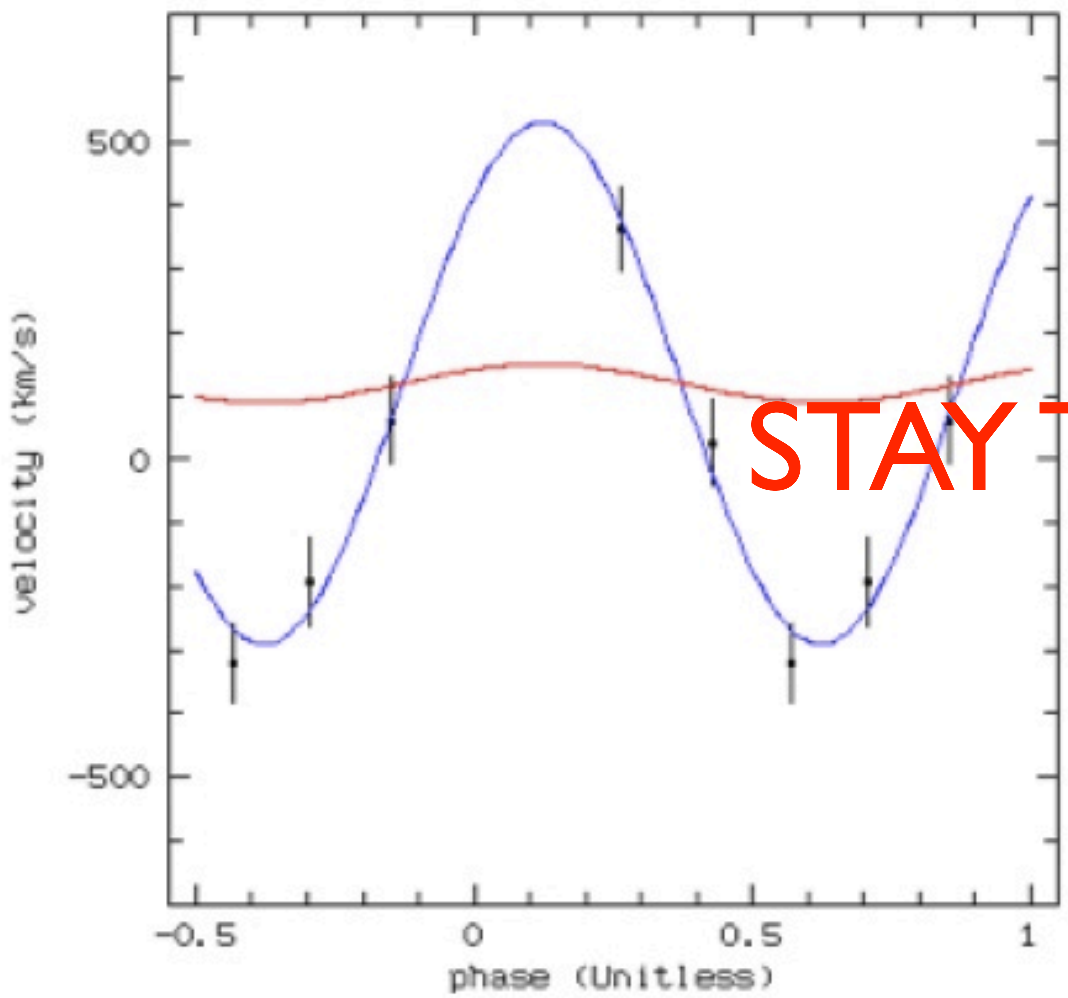

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STAY TUNED!

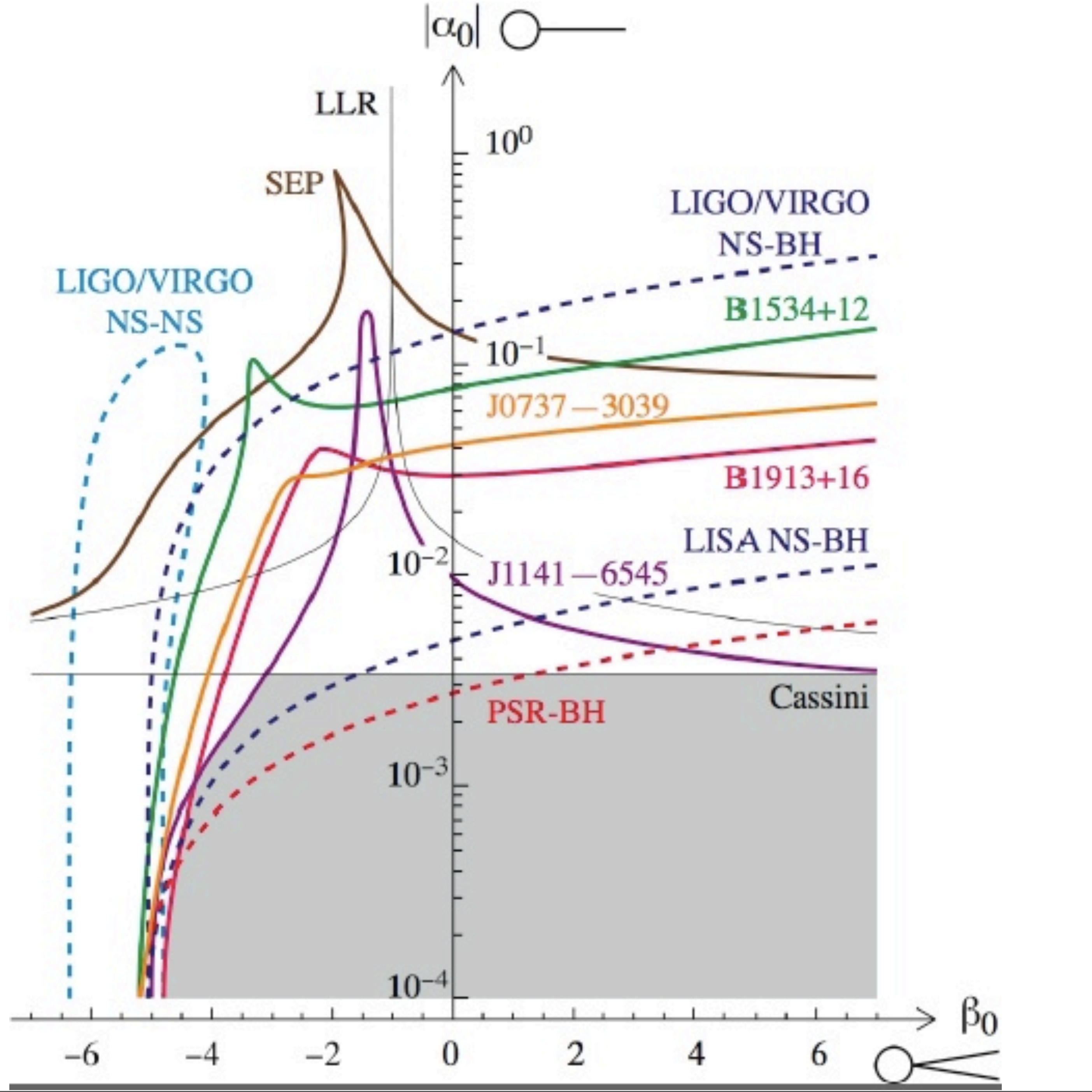
Observations with VLT scheduled for this December (Antoniadis et al.)

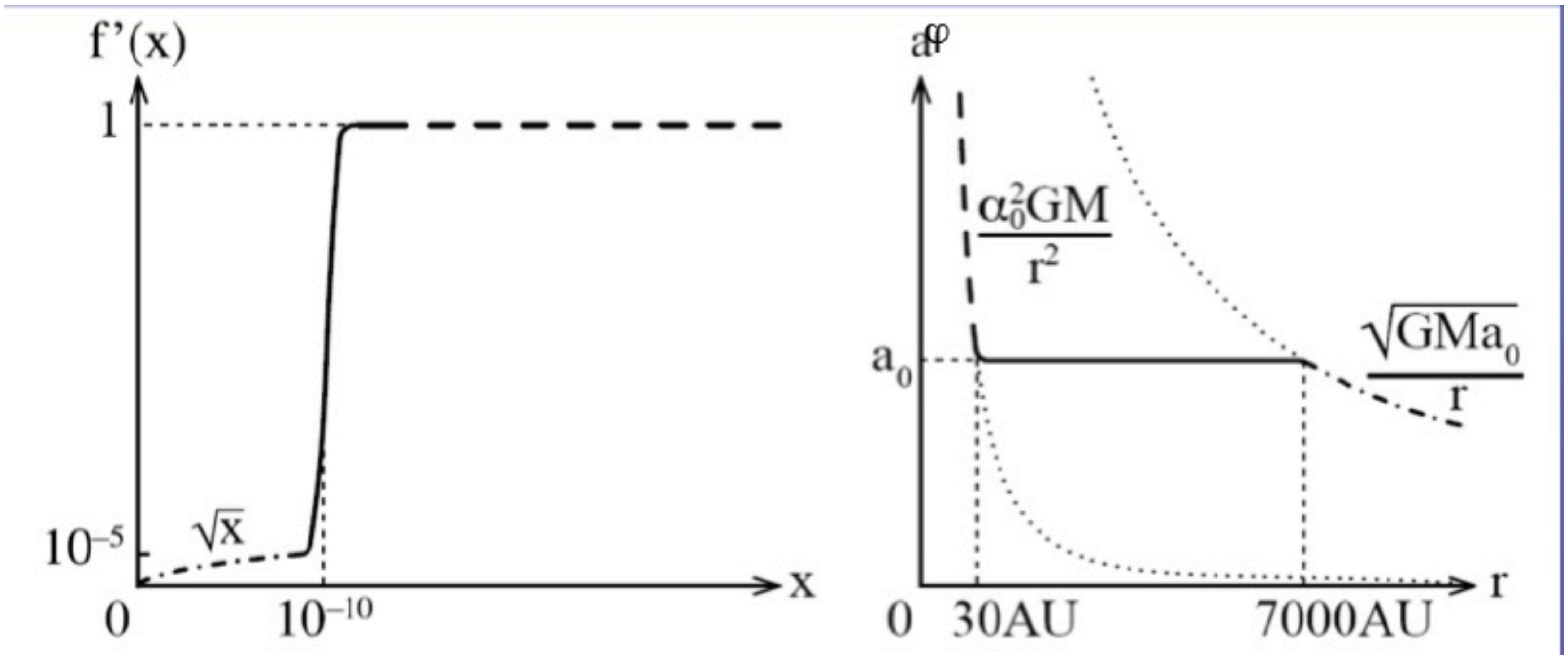
THANK YOU

$$A(\phi) = \exp\left[\alpha_0(\phi - \phi_0) + \frac{1}{2}\beta_0(\phi - \phi_0)^2 + ...\right]$$

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

$$\beta^{PPN} - 1 = \frac{\beta_0\alpha_0^2}{2(1+\alpha_0^2)^2}$$




f'(x)
1
10^{-5}
√x
0
10^{-10}
x
a^φ
α₀²GM / r²
a₀
√(GMa₀) / r
0
30AU
7000AU
r

Timing parameters	
Reference Time (MJD)	54600.000177627541568
Right Ascension, α (J2000)	$17^{\mathrm{h}}\ 38^{\mathrm{m}}\ 53\overset{\mathrm{s}}{.}9658433(6)$
Declination, δ (J2000)	$03^\circ\ 33'\ 10\overset{''}{.}86698(3)$
Proper Motion in α, μ_α (mas yr^{-1})	+7.058(5)
Proper Motion in δ, μ_δ (mas yr^{-1})	+5.176(10)
Parallax, π_x (mas)	0.60(4)
Spin Frequency, ν (Hz)	170.93736991146355(5)
First Derivative of ν, $\dot{\nu}$ (10^{-15} Hz s^{-1})	−7.047742(11)
Dispersion Measure, DM (cm^{-3} pc)	33.77261(3)
Orbital Period P_b (days)	0.3547907398686(19)
Projected Semi-Major Axis, x (lt-s)	0.343429121(17)
Time of Ascending Node, T_{asc} (MJD)	54600.200400109(4)
$\eta \equiv e \sin\omega$	$(-0.3 \pm 1.1) \times 10^{-7}$
$\kappa \equiv e \cos\omega$	$(3.5 \pm 1.1) \times 10^{-7}$
First Derivative of P_b, $\dot{P}_b$ (10^{-15}s s^{-1})	−17.7(3.8)
"range" parameter of Shapiro delay[b], r ($M_\odot$)	0.181
"shape" parameter of Sapiro delay[b], $s \equiv \sin i$	0.5388
Limits (not fitted with other timing parameters)	
Orthometric Amplitude of the Shapiro Delay, h_3 (μs)	0.014(14)
Amplitude of fourth harmonic, h_4 (μs)	0.031(18)
Second Derivative of ν, $\ddot{\nu}$ (10^{-28} Hz s^{-2})	−1.3(6)
Derived Parameters	
Galactic Longitude, l	$27\overset{\circ}{.}7213$
Galactic Latitude, b	$17\overset{\circ}{.}7422$
Distance, d (kpc)	1.66(12)
Total Proper Motion, μ (mas yr^{-1})	8.752(7)
Spin Period, P (ms)	5.850095859775700(17)
First Derivative of Spin Period, $\dot{P}$ (10^{-20}s s^{-1})	2.411993(4)
Characteristic Age, τ_c (10^9 yr)	3.8
Dipolar Magnetic Flux Density at the Poles, B_0 (10^8G)	3.8
Mass Function, f ($M_\odot$)	0.0003455012(12)
Orbital inclination[b], i (°)	32.6(1.0)
Pulsar Mass[b], m_p ($M_\odot$)	$1.46^{+0.05}_{-0.04}$
Total Mass of Binary[b], M_t ($M_\odot$)	$1.64^{+0.06}_{-0.05}$
Eccentricity, e	$(3.5 \pm 1.1) \times 10^{-7}$
Apparent $\dot{P}_b$ due to Shklovskii effect, $\dot{P}_b^{\mathrm{Shk}}$ (fs s^{-1})	9.5(7)[a]
Apparent $\dot{P}_b$ due to Galactic acceleration, $\dot{P}_b^{\mathrm{Gal}}$ (fs s^{-1})	0.73(17)[a]
Intrinsic $\dot{P}_b$, $\dot{P}_b^{\mathrm{Int}}$ (fs s^{-1})	−27.9(3.8)[a]
Predicted $\dot{P}_b$, $\dot{P}_b^{\mathrm{QGW}}$ (fs s^{-1})	−27.3(9)[b]
"Excess" orbital decay, $\dot{P}_b^{\mathrm{xs}} = \dot{P}_b^{\mathrm{Int}} - \dot{P}_b^{\mathrm{QGW}}$ (fs s^{-1})	−0.6(4.0)[a,b]