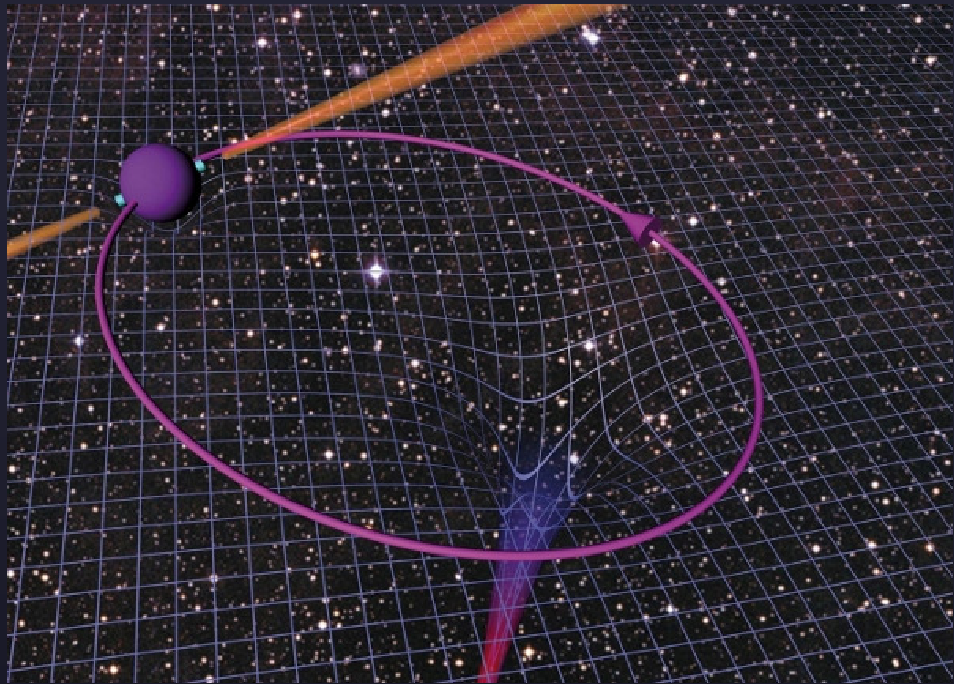


Gravity Tests with Pulsar-Black Hole Systems

Norbert Wex

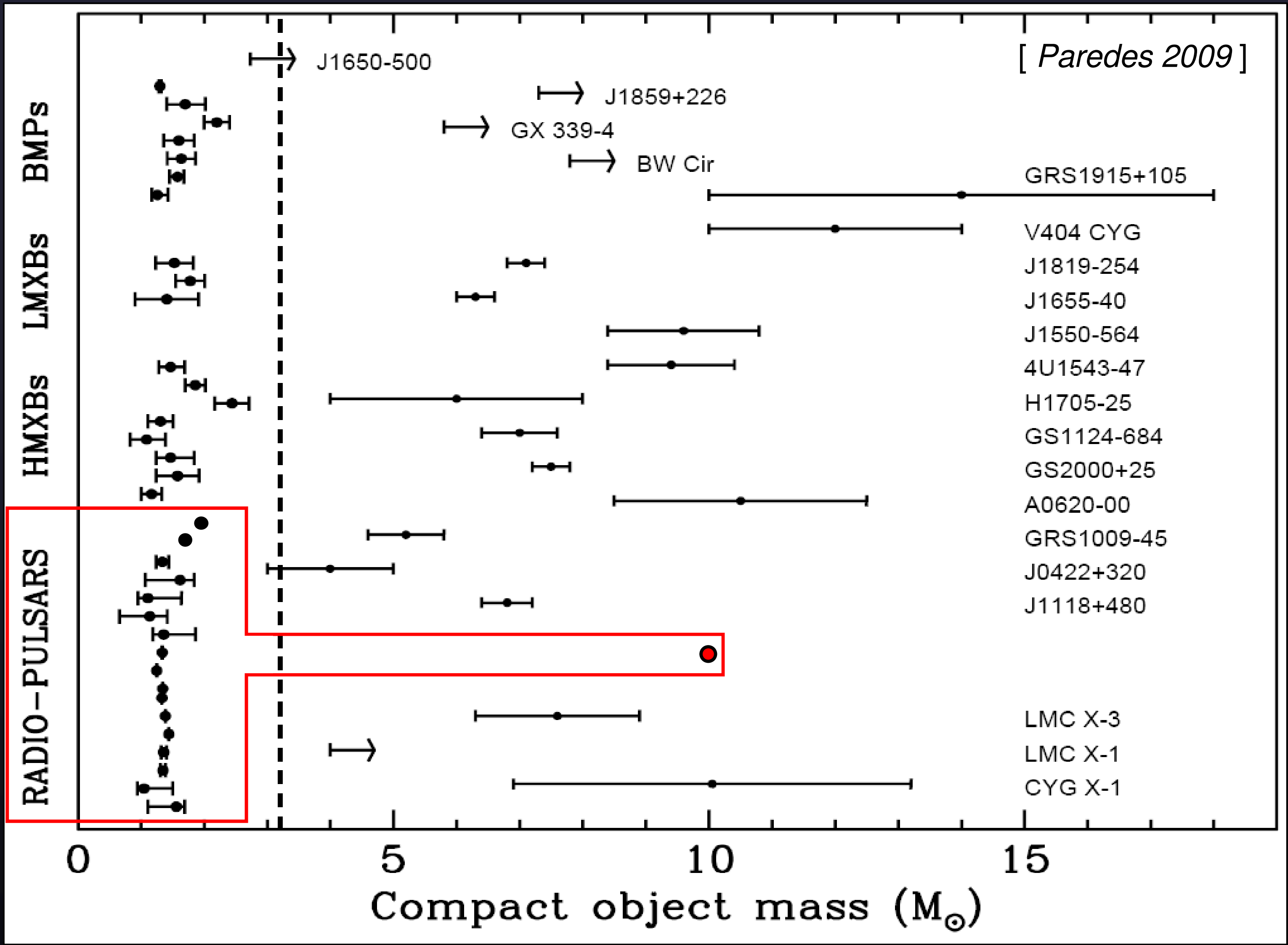
Valencia, Nov. 2010

Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Black Hole Mass

Masses of Compact Objects in X-ray Binaries

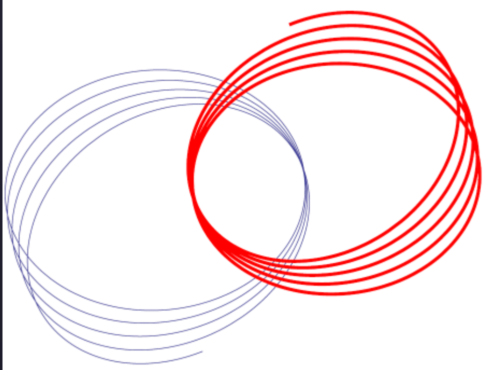


Most massive stellar-mass BH: IC 10 X-1 → M ~ 33 M_{Sun}

[*Silverman & Filippenko 2008*]

Mass Determination in the Hulse-Taylor Pulsar

Advance of periastron



$$\langle\dot{\omega}\rangle = 3G^{2/3}c^{-2}(P_b 2\pi)^{-5/3}(1-e^2)^{-1}\boxed{(m_1+m_2)^{2/3}}$$

Observed value: 4.226598 ± 0.000005 deg/yr

Gravitational redshift and transverse Doppler shift amplitude

$$\gamma = G^{2/3}c^{-2}e(P_b/2\pi)^{1/3}\boxed{m_2(m_1+2m_2)(m_1+m_2)^{-4/3}}$$

Observed value: 4.2992 ± 0.0008 ms

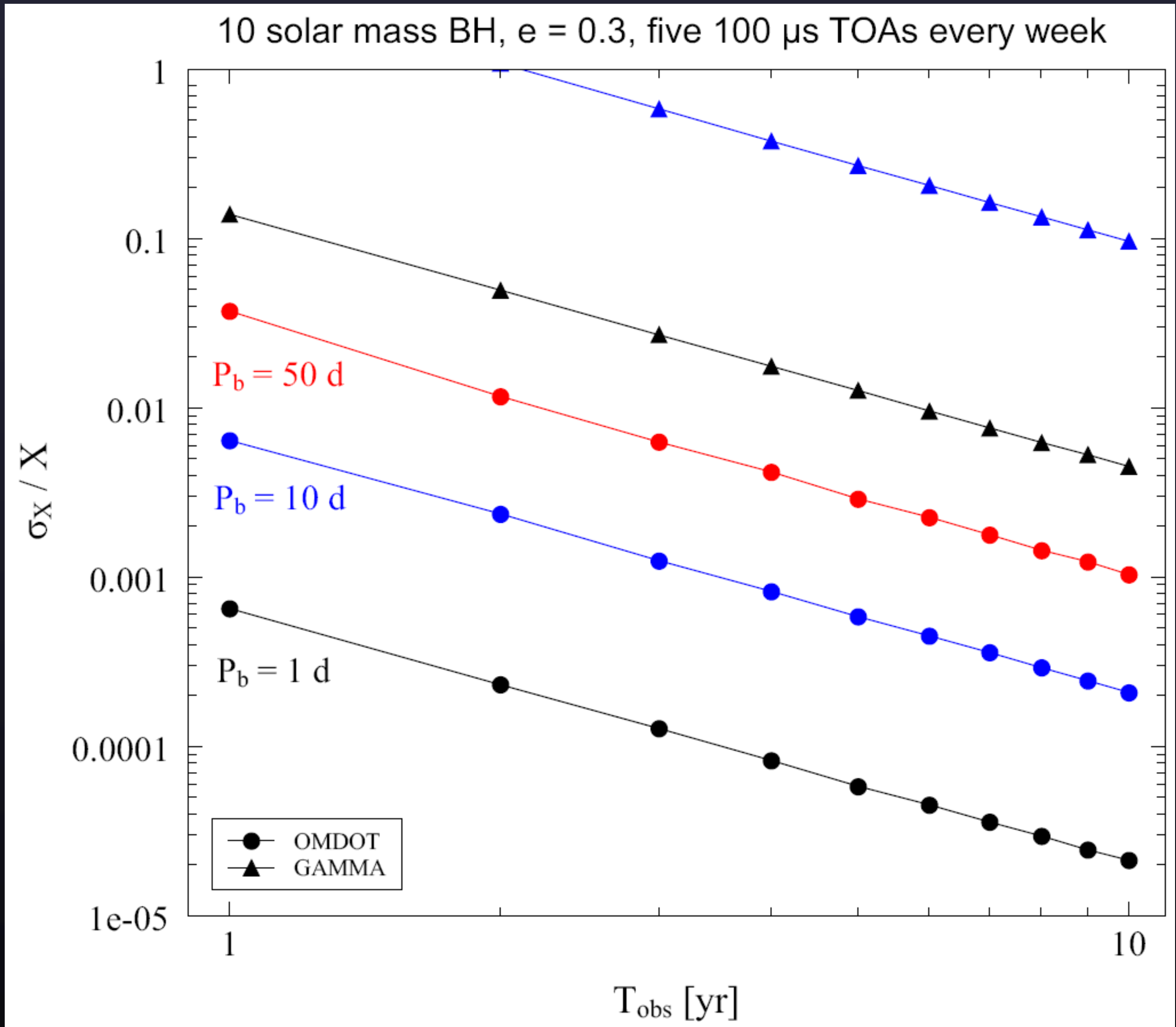
Calculating the neutron star masses

$$m_1 = 1.4398 \pm 0.0002\, M_\odot \text{ and } m_2 = 1.3886 \pm 0.0002\, M_\odot$$

[*Weisberg et al. 2010*]

Mass Determination in a Pulsar-Black Hole System

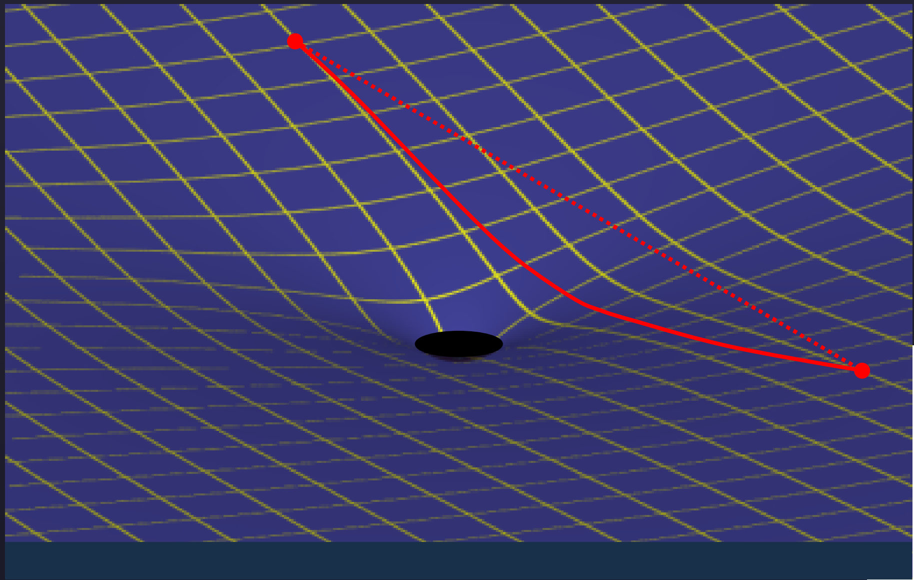
$10\ M_\odot$ BH, weekly $5 \times 100\ \mu s$ TOAs



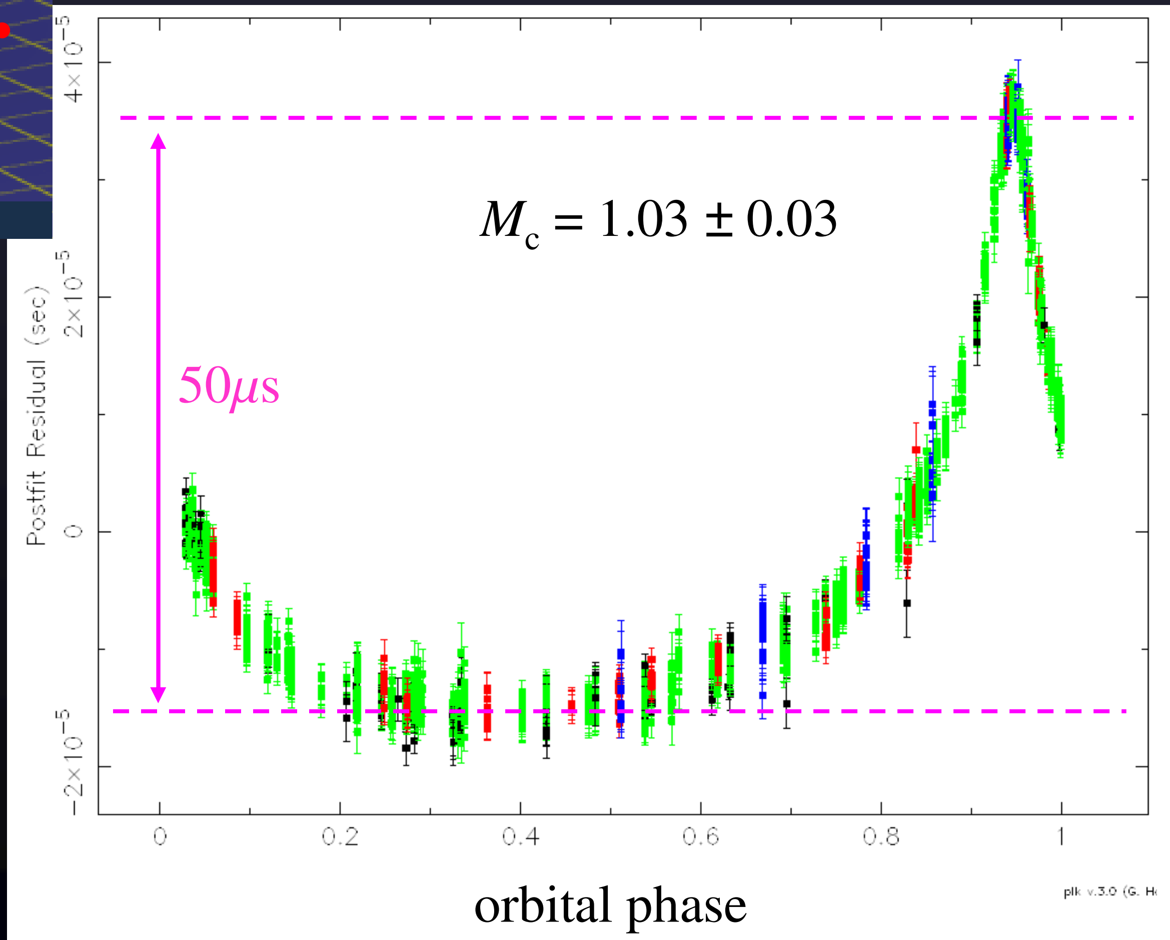
$$\dot{\omega} \;\Rightarrow\; M \;\Rightarrow\; \mathrm{m_{BH}} \approx M - 1.35\ M_\odot$$

$$\dot{\omega}, \gamma \;\Rightarrow\; m_{\mathrm{PSR}}\ \&\ m_{\mathrm{BH}}$$

Mass Determination via the Shapiro Delay



PSR J1903+0327



PSR-BH System
and
Alternative Gravity Theories

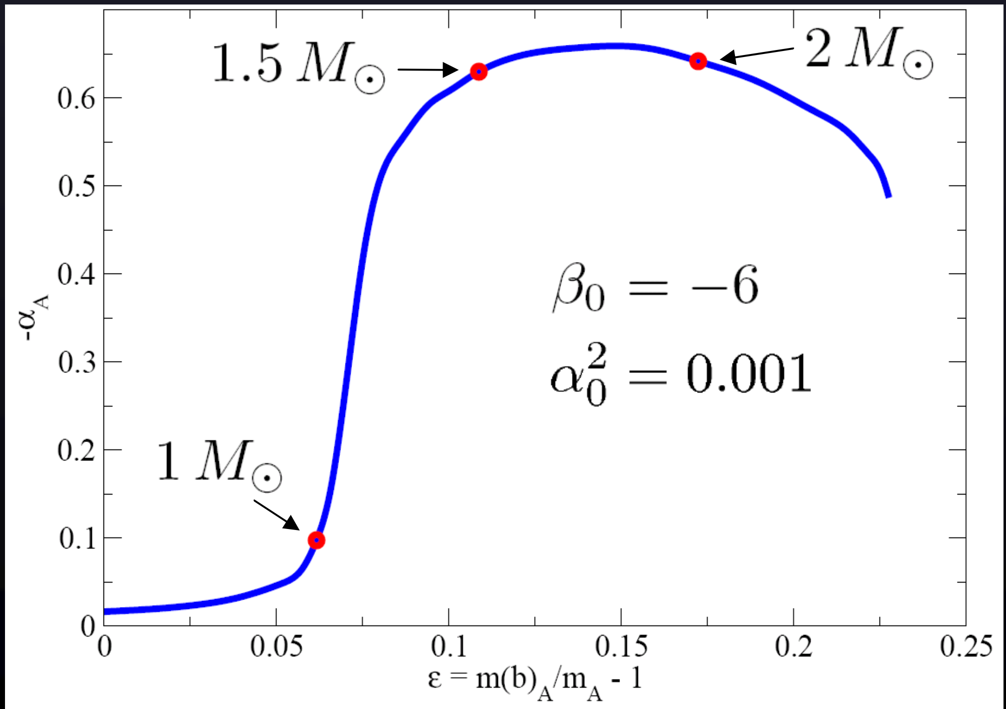
``Quadratic Model´´ by Damour & Esposito-Farèse – $T_1(\alpha_0,\beta_0)$

$$R^*_{\mu\nu} = \frac{8\pi G_*}{c^4}\left(T^*_{\mu\nu} - \frac{1}{2}T^* g^*_{\mu\nu}\right) + 2\partial_\mu\varphi\partial_\nu\varphi$$

$$g_*^{\mu\nu}\nabla^*_\mu\nabla^*_\nu\varphi = -\frac{4\pi G_*}{c^4}\left(\alpha_0 + \beta_0\varphi\right) T_*$$

Physical metric: $\tilde{g}_{\mu\nu} = g^*_{\mu\nu} \exp\left(2\alpha_0\varphi + \beta_0\varphi^2\right)$

Effective coupling constant $\alpha_A = -q_A / m_A$:

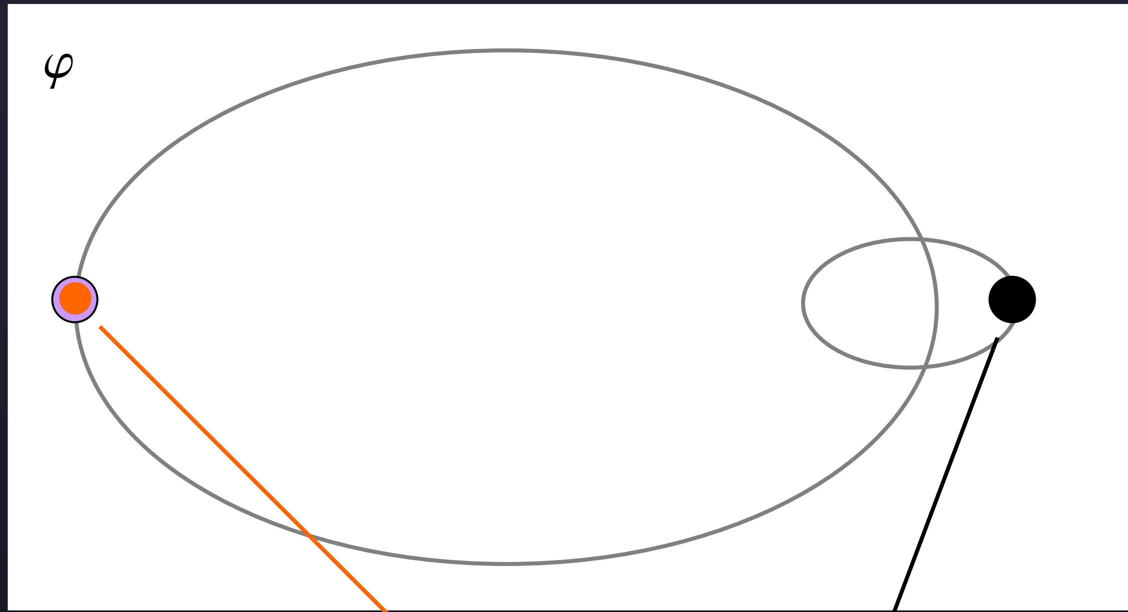


Can reach order unity in <u>neutron stars</u>, even if α_0 is extremely small (spontaneous scalarization)

<u>Black holes</u> have no scalar charge (no-hair theorem)

[*Damour & Esposito-Farèse 1996*]

Dipolar Gravitational Radiation in a PSR-BH System



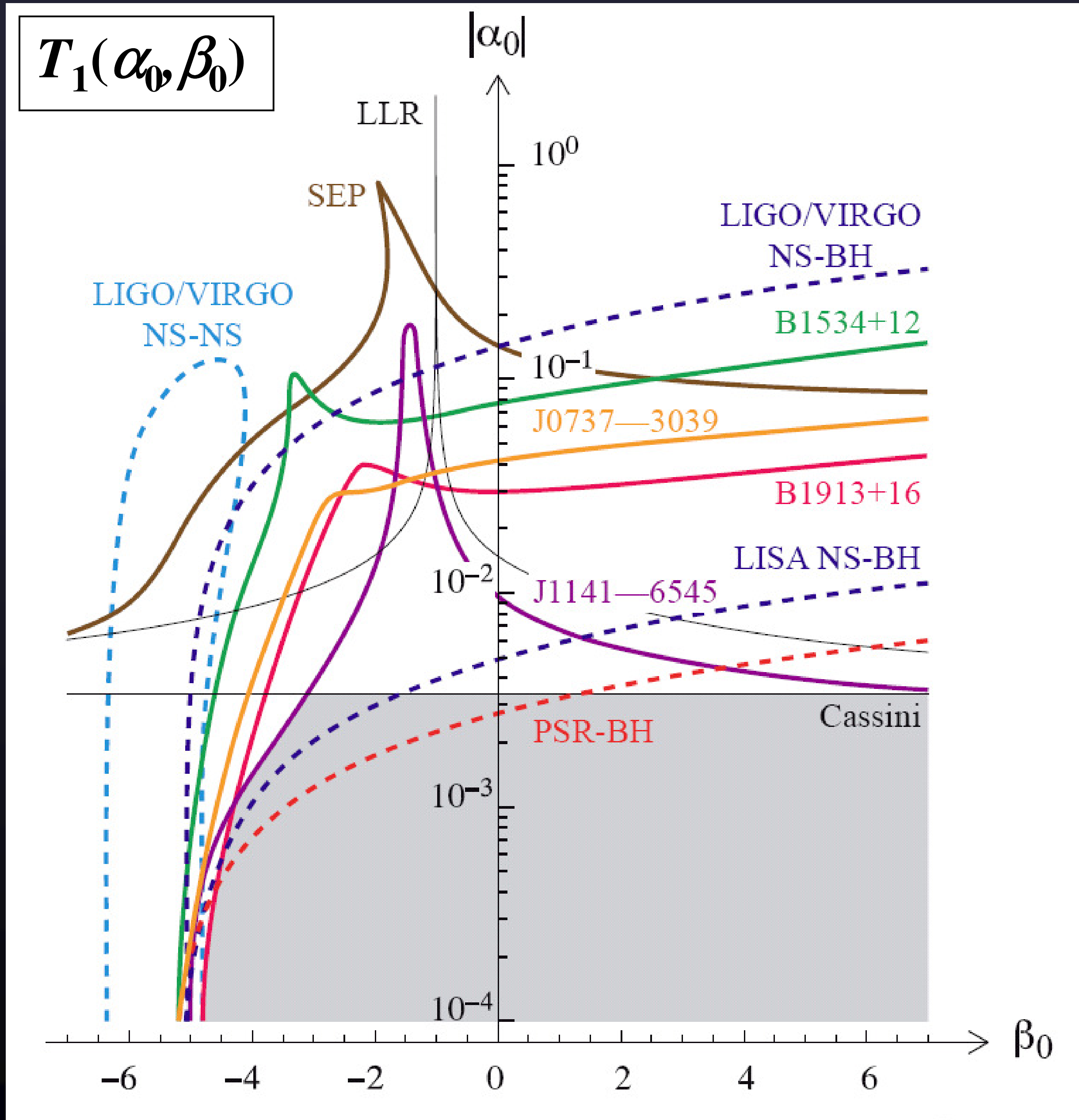
$$\dot{P}^{\rm dipole}_{b\varphi}(m_A, m_B) = -2\pi \, \frac{G_* \, m_A \, m_B \, n}{c^3(m_A + m_B)} \, \frac{1 + e^2/2}{(1 - e^2)^{5/2}} \, (\alpha_A - \alpha_B)^2$$

0

no (regular) ‘scalar hair’

→ efficient emitter of dipolar radiation

Limits on ``Quadratic´´ Tensor-Scalar Theories

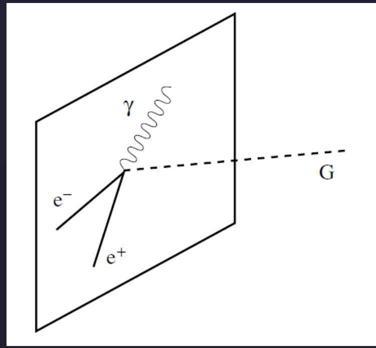


[*Esposito-Farèse 2009*]

Testing for Extra Spatial Dimensions

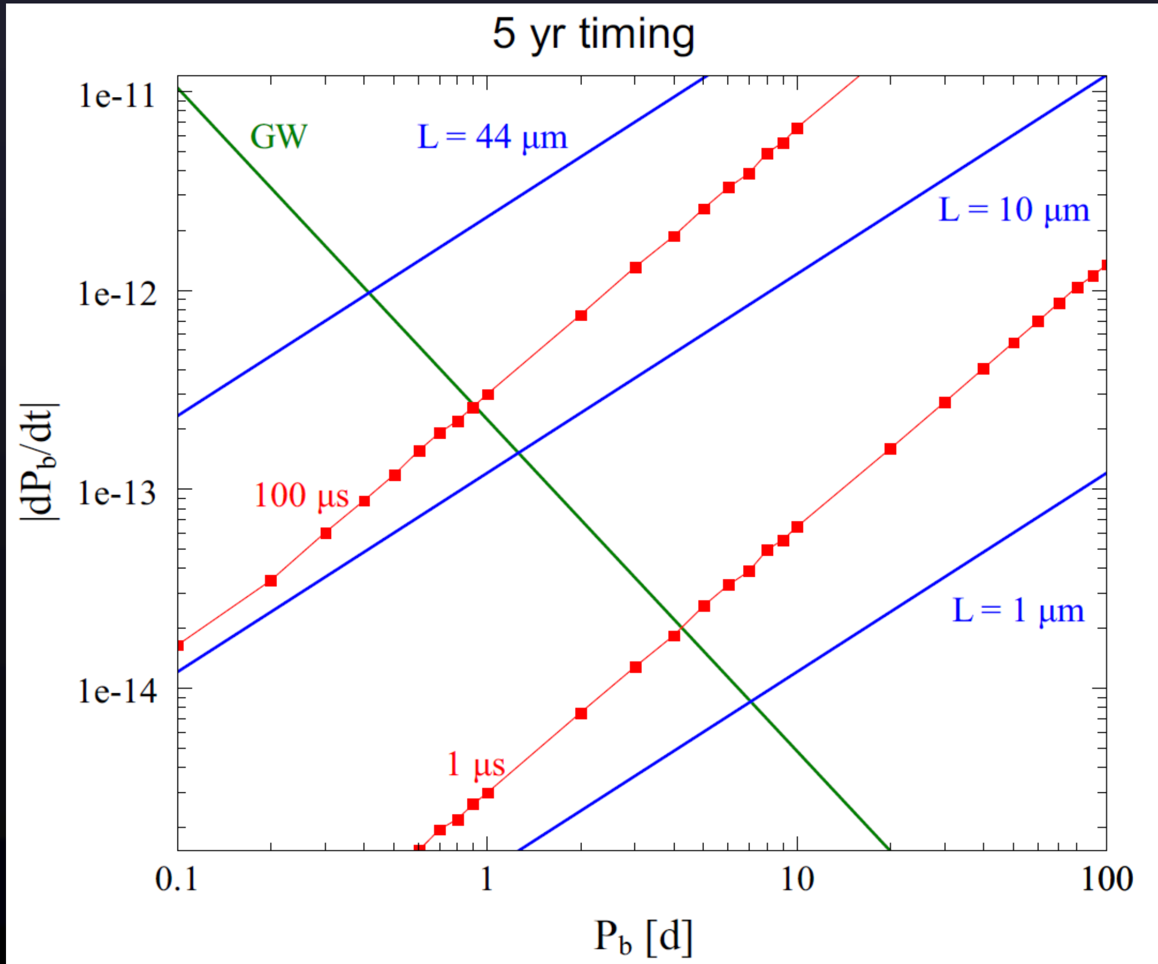
BH evaboration rate in the braneworld scenario

$$\dot{M}_{\rm BH} = -2.8 \times 10^{-7} \left(\frac{M_{\rm BH}}{M_\odot}\right)^{-2} \left(\frac{L}{10\,\mu{\rm m}}\right)^{2} M_\odot/{\rm yr}$$



... can lead to significant changes in the orbital period

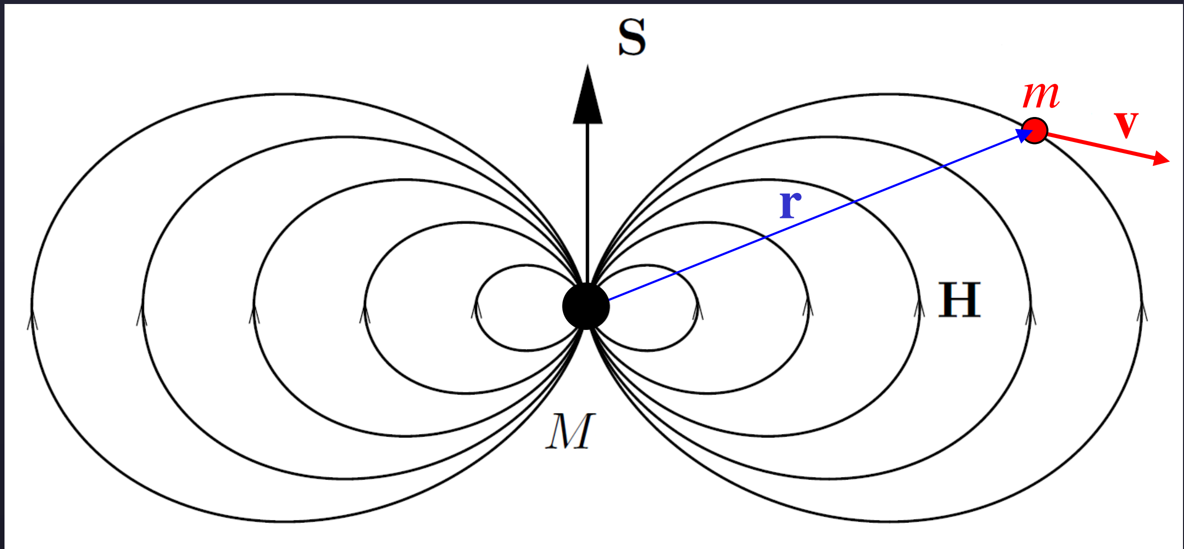
$$\frac{\dot{P}_{\rm b}}{P_{\rm b}} = -2\frac{\dot{M}_{\rm BH}}{M_{\rm BH}+M_{\rm p}}$$



[*Johannsen et al. 2009, Simonetti et al. 2010*]

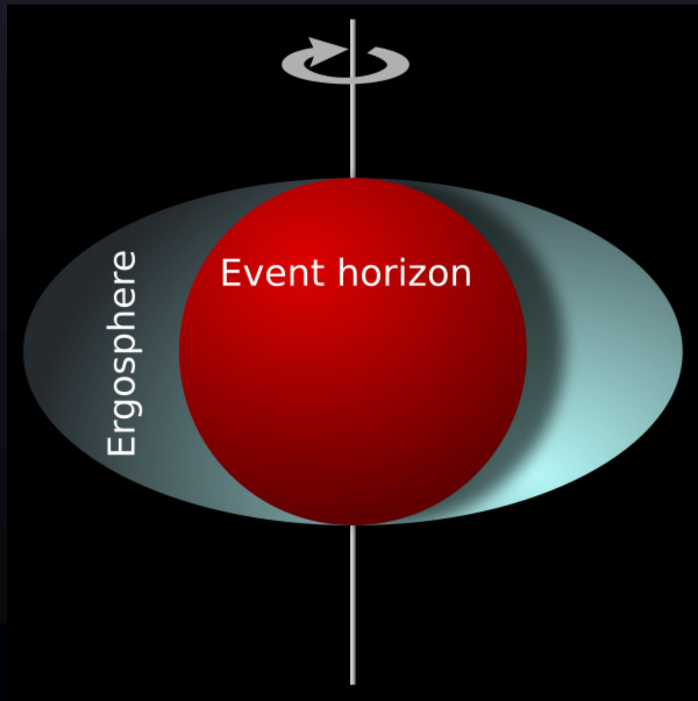
Lense-Thirring Effect
and
Cosmic Censorship

The Gravitomagnetic Field of a Rotating Body

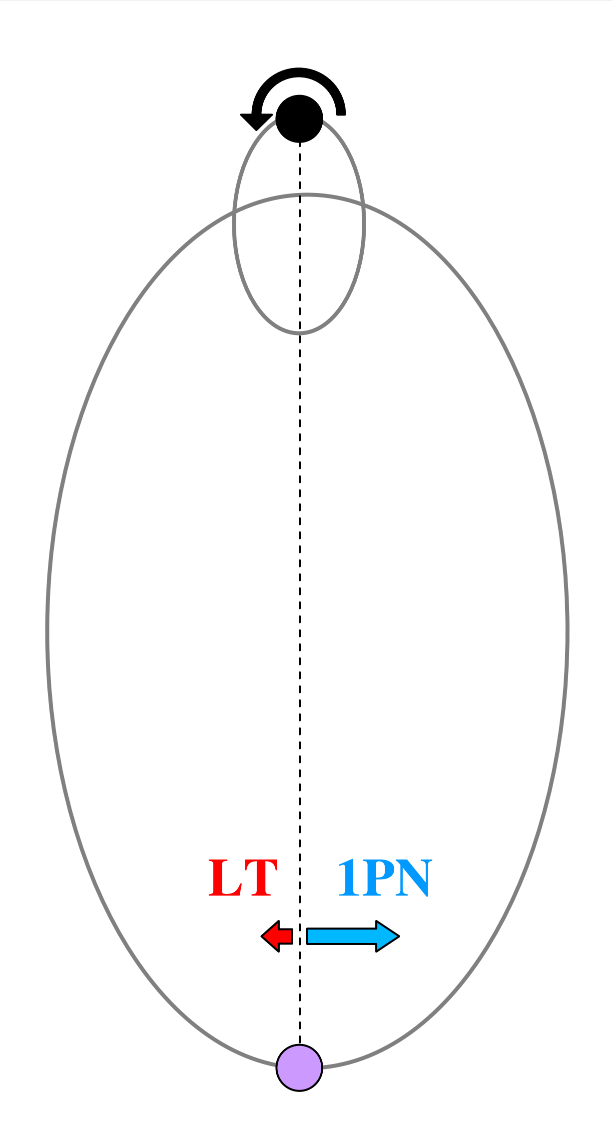


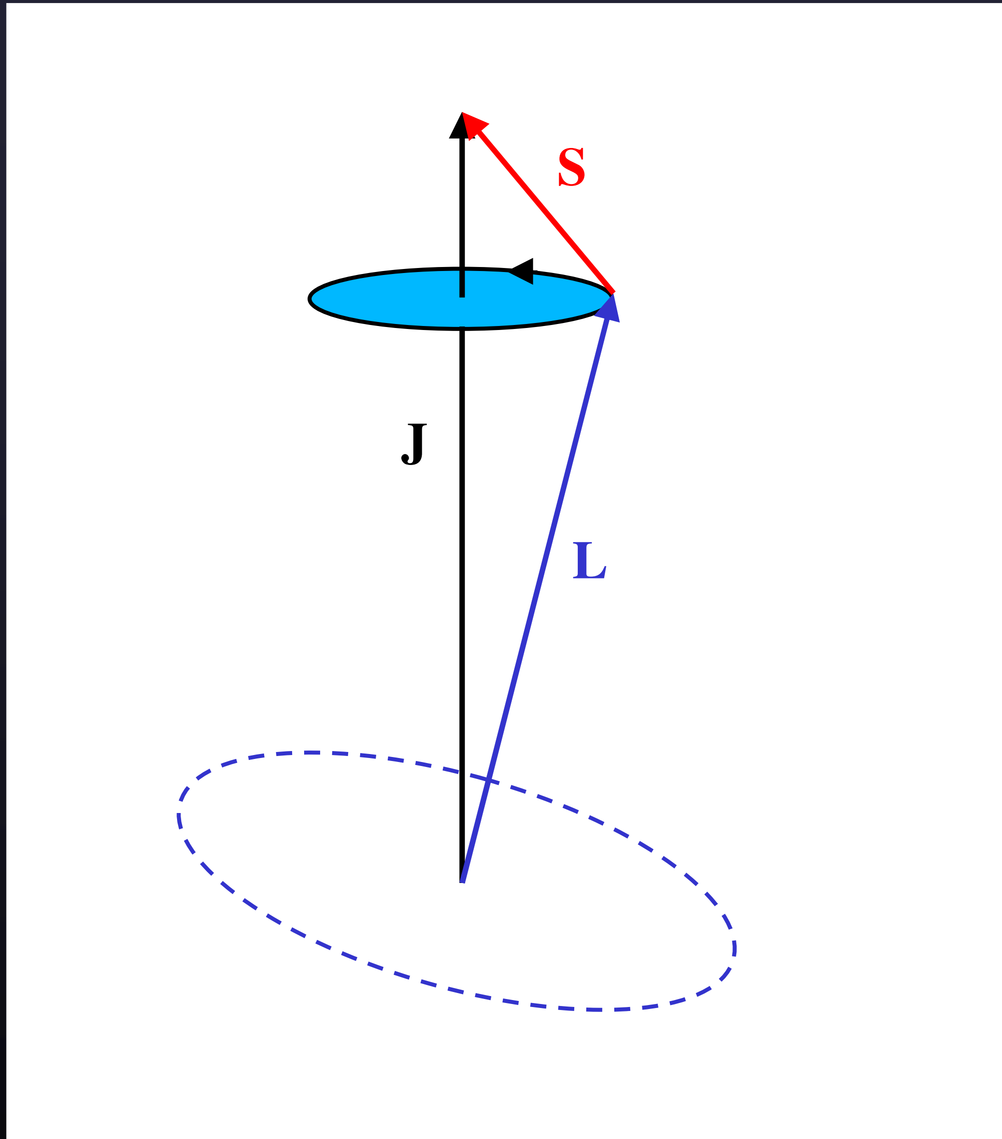
$$\mathbf{a} = \mathbf{a}_{\mathrm{PN}}^{(\mathrm{M})} + \mathbf{v} \times 2\mathbf{H}$$

$$\mathbf{H} = \frac{G}{2c^2} \frac{\mathbf{S} - 3(\mathbf{S}\cdot\mathbf{r}/r)\mathbf{r}/r}{r^3}$$



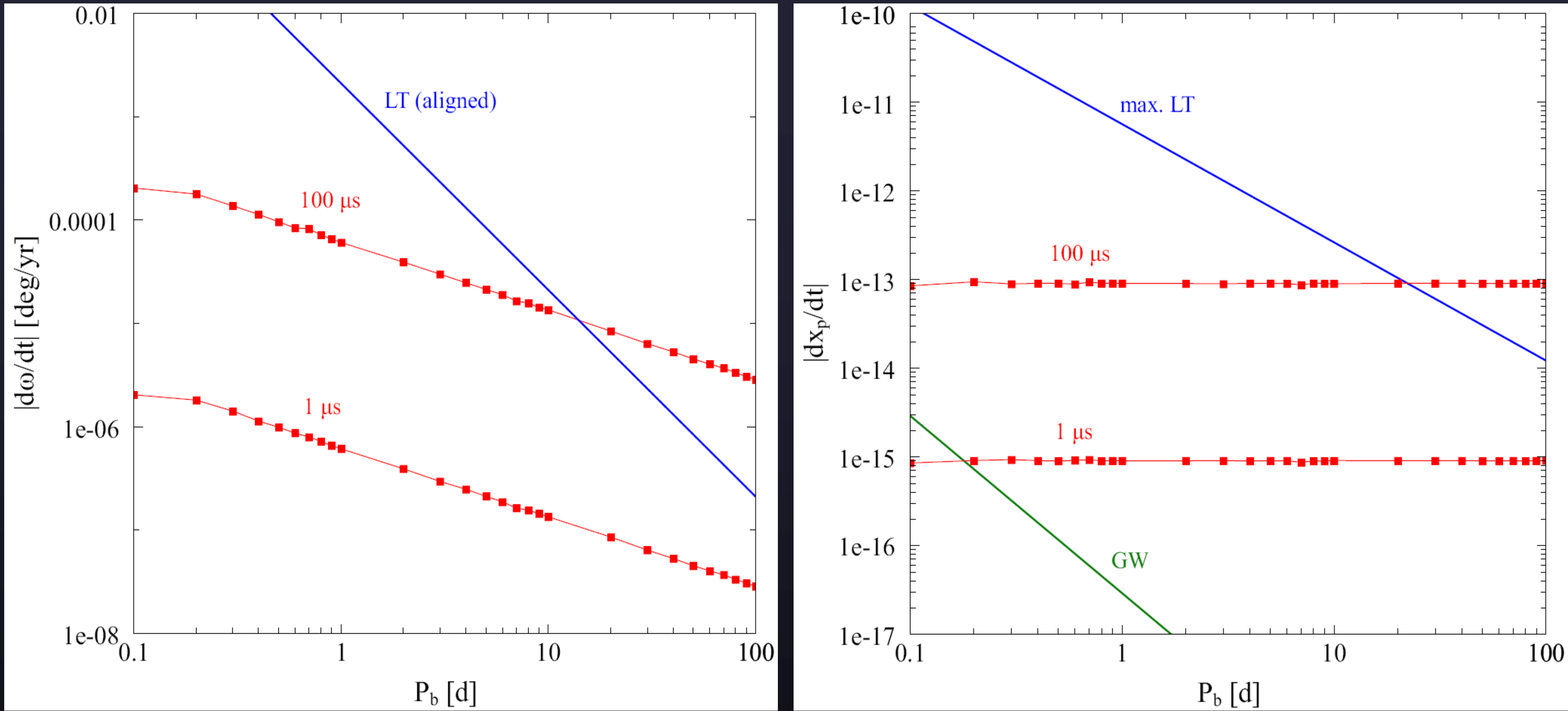
Lense-Thirring Precession





$$\frac{\Omega_{\rm LT}}{\Omega_{\rm 1PN}} \approx 0.001 \left(\frac{P_{\rm b}}{1\,{\rm day}}\right)^{-1/3} \left(\frac{M_{\rm BH}}{10\,M_\odot}\right)^{1/3}$$

Frame Dragging Measurement



Measurement of $\dot{x}$ → lower limit for S

Second time derivatives in ω and x → S and orientation of the BH

Cosmic censorship → if GR is correct:

$$\chi \equiv \frac{c}{G}\frac{S}{M^2} \leq 1$$

Simulations

$\chi = 1$, $\tau_{\mathrm{merger}} = 100$ Myr

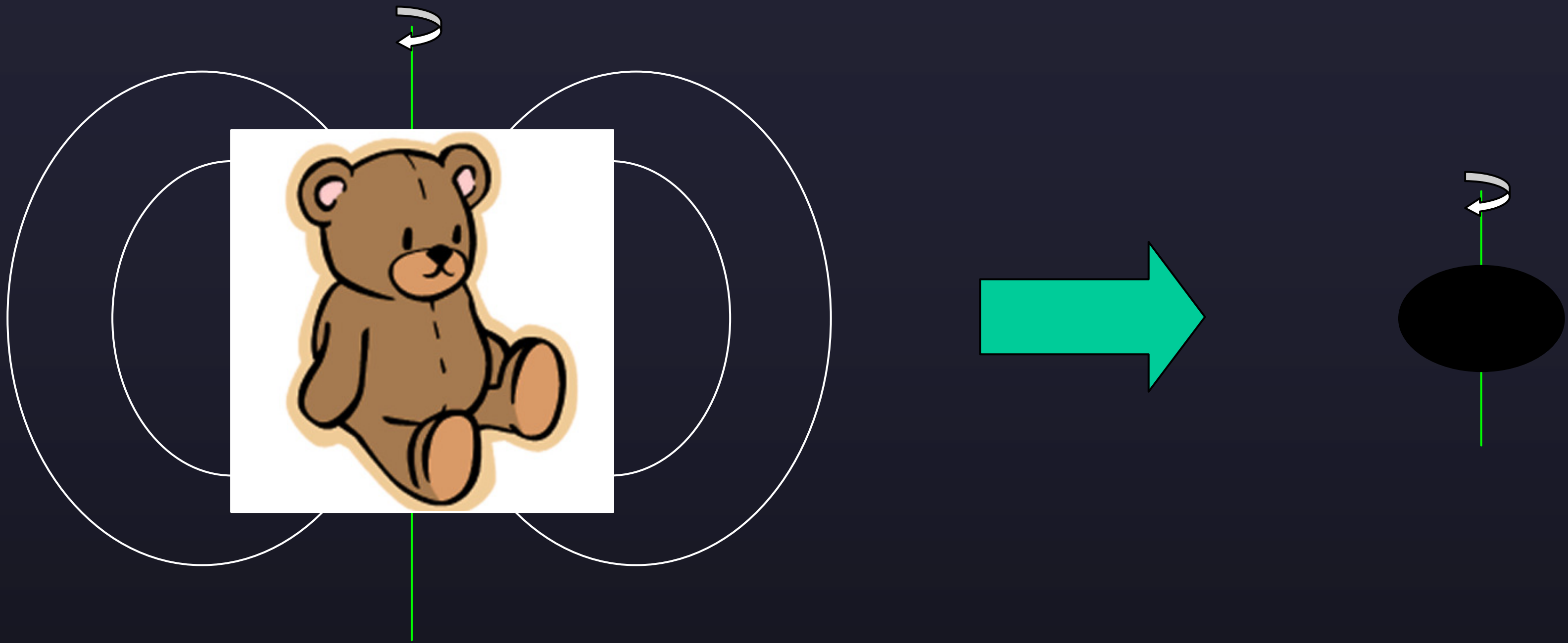
	A_{eff} (m^2)	T_{sys} (K)	$\sigma_{30\mathrm{min}}$ (μs)
Parkes	2.2×10^3	23.5	4
FAST	7.1×10^4	20.0	0.1
SKA	2.5×10^5	30.0	0.04

e	M_{BH} $(M_\odot)$	P_{b} (day)	θ	Telescope	$\hat{\sigma}_{5\mathrm{yr}}$ $(\chi\|\theta)$	$\hat{\sigma}_{10\mathrm{yr}}$ $(\chi\|\theta)$	$\hat{\sigma}_{20\mathrm{yr}}$ $(\chi\|\theta)$
0.1	5	0.166	20°	Parkes	NM | NM	NM | NM	3.0% | 3.0%
				FAST	3.0% | 2.6%	0.44% | 0.53%	0.08% | 0.08%
				SKA	1.2% | 1.0%	0.18% | 0.21%	0.03% | 0.03%
			70°	Parkes	NM | NM	6.5% | NM	1.1% | 2.4%
				FAST	1.1% | 0.73%	0.16% | 0.33%	0.03% | 0.06%
				SKA	0.43% | 0.29%	0.06% | 0.13%	0.01% | 0.02%
	30	0.266	20°	Parkes	NM | NM	1.9% | 2.0%	0.33% | 0.35%
				FAST	0.31% | 0.35%	0.05% | 0.05%	0.01% | 0.01%
				SKA	0.12% | 0.14%	0.02% | 0.02%	<0.01% |<0.01%
			70°	Parkes	4.5% | 9.9%	0.69% | 1.5%	0.12% | 0.27%
				FAST	0.11% | 0.25%	0.02% | 0.04%	<0.01% | <0.01%
				SKA	0.04% | 0.10%	<0.01% | <0.01%	<0.01% | <0.01%

[*Liu et al. 2010*]

The Quadrupole Moment and the No-hair Theorem

The No-hair Theorem



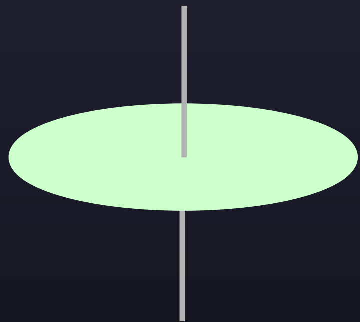
"A black hole has no hair" (J. A. Wheeler)

The Quadrupole Moment of a Black-Hole

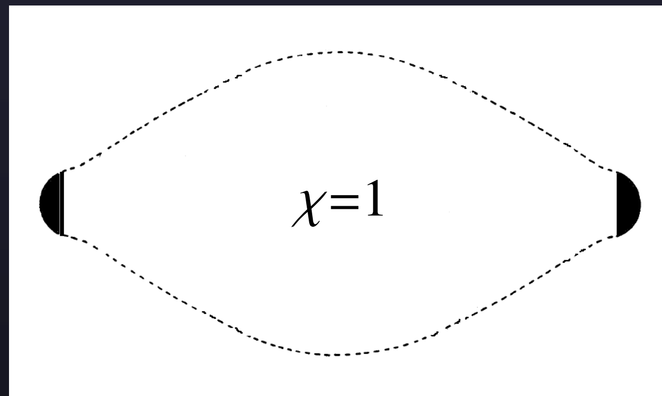
$$\Phi(r,\theta) = -G\frac{M}{r} + G\frac{QP_2(\cos\theta)}{r^3} + O\left(\frac{1}{r^4}\right)$$

[*Smarr 1973*]

$J_2 \simeq 0.001$



$J_2 = 0.25$



$q = 1$

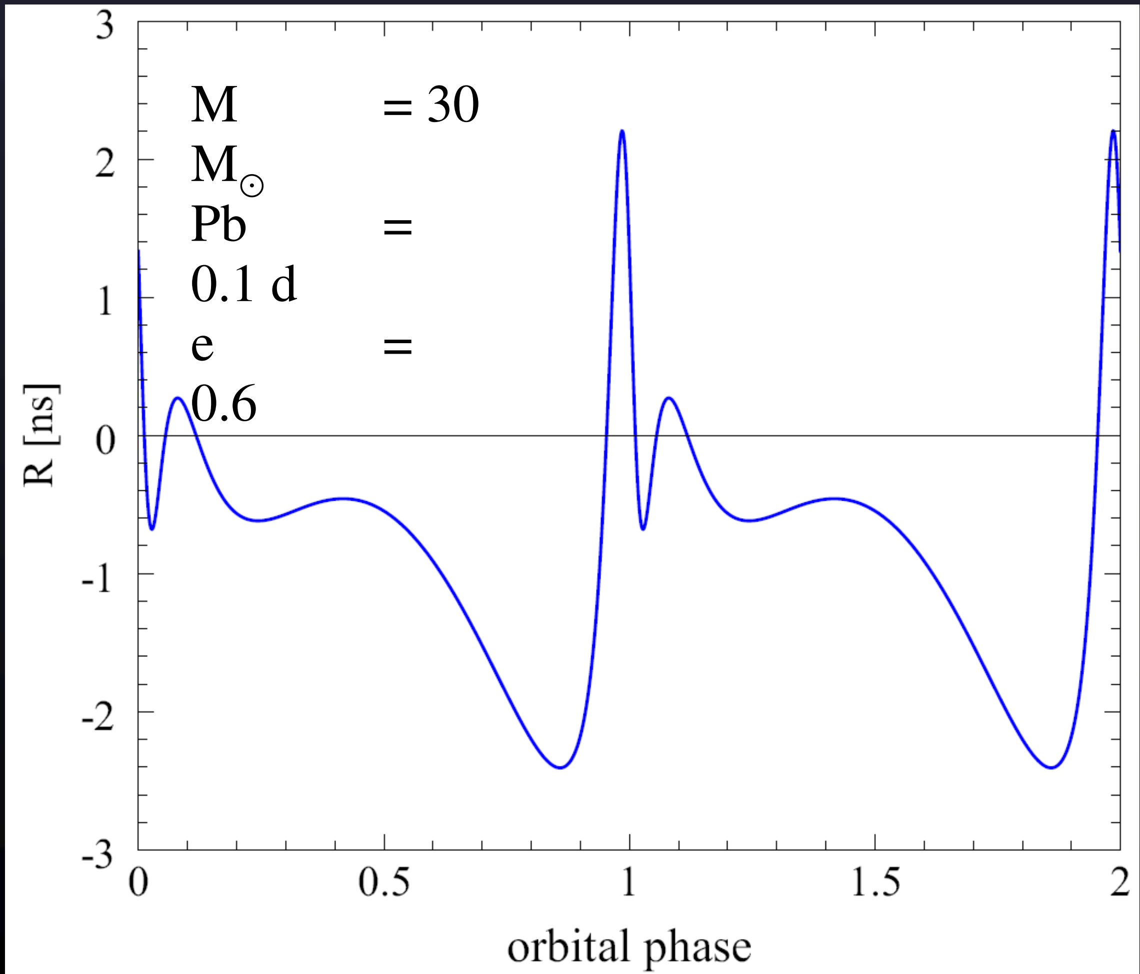
Black hole <u>"no-hair" (uniqueness) theorem</u> of general relativity implies:
all multipole moments of the gravitational field are determined by M and S

e.g. the quadrupole moment: $\boxed{q = \chi^2}$

Measuring the Quadrupole Moment of a Black-Hole

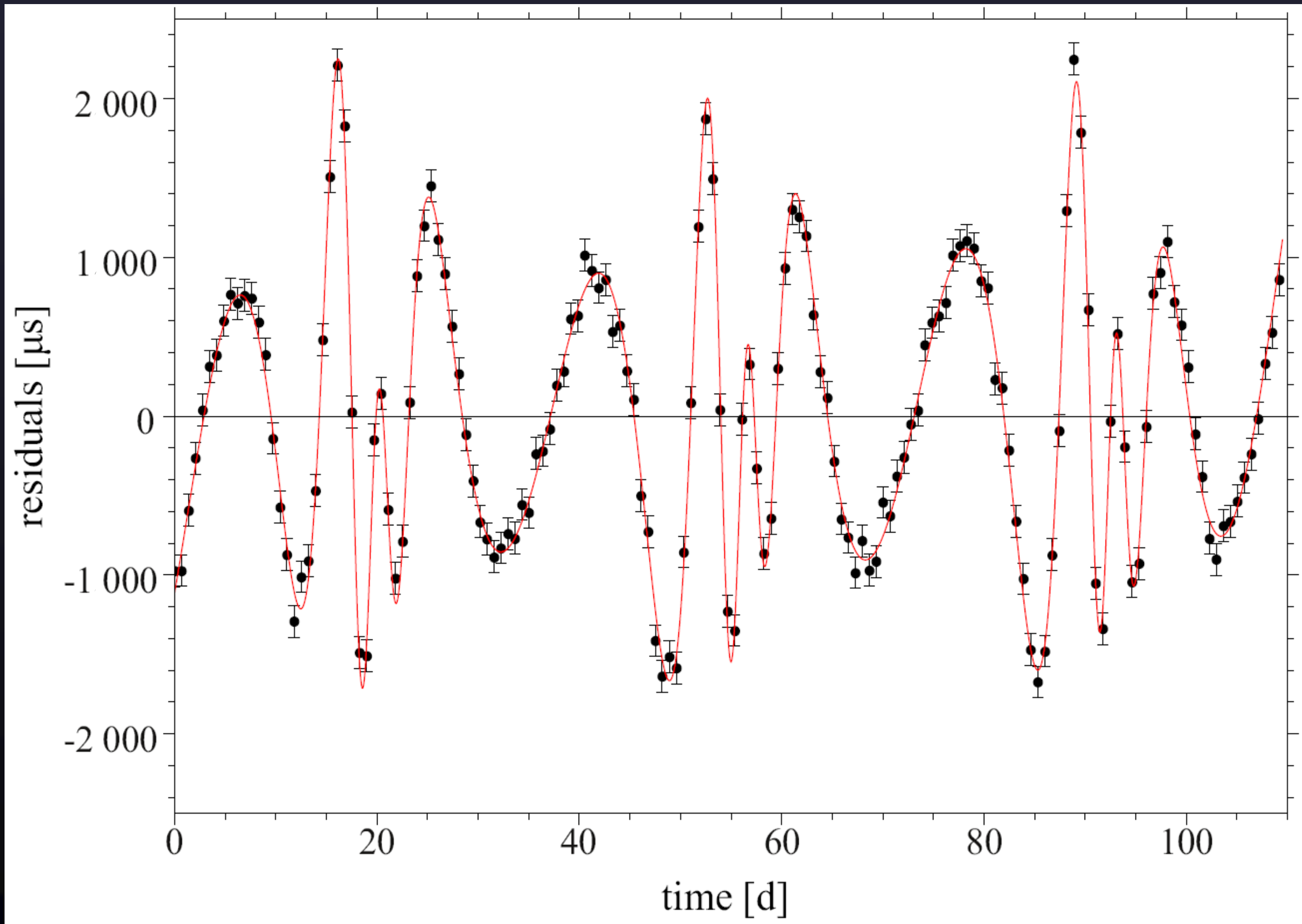
Secular precession much smaller than frame dragging and can therefore not be separated from the Lense-Thirring precession.

Quadrupole moment leads to characteristic periodic terms in the orbital motion, but…



Measuring the Quadrupole Moment of the Black Hole

Pulsar in a 0.1 yr orbit around Sgr A*:
Extreme Kerr, 3 orbits, 160 TOAs with 100 μs error, e = 0.4



→ $\delta Q/Q = 0.008$

Conclusions

A pulsar-black hole system

- …will give a precise value for the black hole mass
- …will provide a unique laboratory for gravity theories
- …will allow the measurment of frame dragging for orbital periods < 10 days
- …can provide a full spin determination in case of a tight orbit
- …needs to host a black hole $\gtrsim 100\ M_\odot$ for a no-hair theorem test