Evidence for gravitational quadrupole moment variations of PSR J2051-0827

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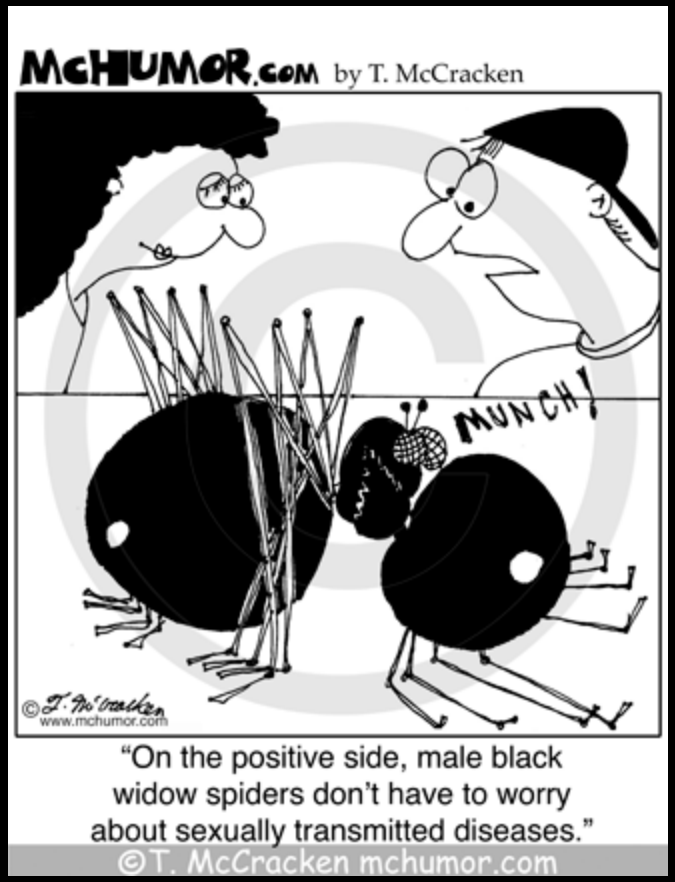
Outline

- Black Widow Pulsars
- PSR J2051-0827
  - EPTA Timing
  - Timing Results
  - Orbital variations
- Conclusions

Black Widow Pulsars

- Low m_c = 0.01-0.04 M_o
- Millisecond periods (< 5 ms)
- Short orbital periods (< 0.4 d)
- Orbital variability
- Possibly heavily recycled
- Eclipses

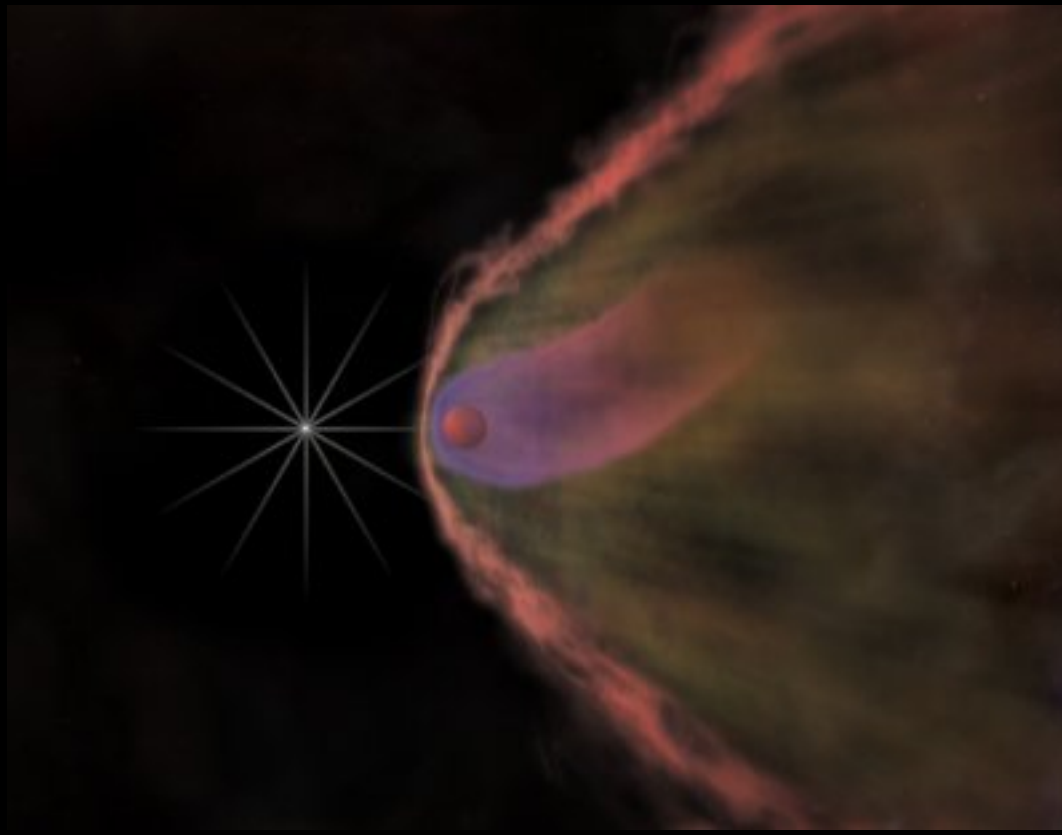


Black Widow Pulsars

First PSR B1957+20

- P=1.61 ms
- P_b=0.382 days
- Orbital period variations
- m_c=0.025 M_o
- Irradiated
- Non-degenerate
- Tidally powered

Applegate & Shaham, 1994
Arzoumanian et al., 1994



Credit: NASA/CXC/M.Weiss

PSR J2051-0827

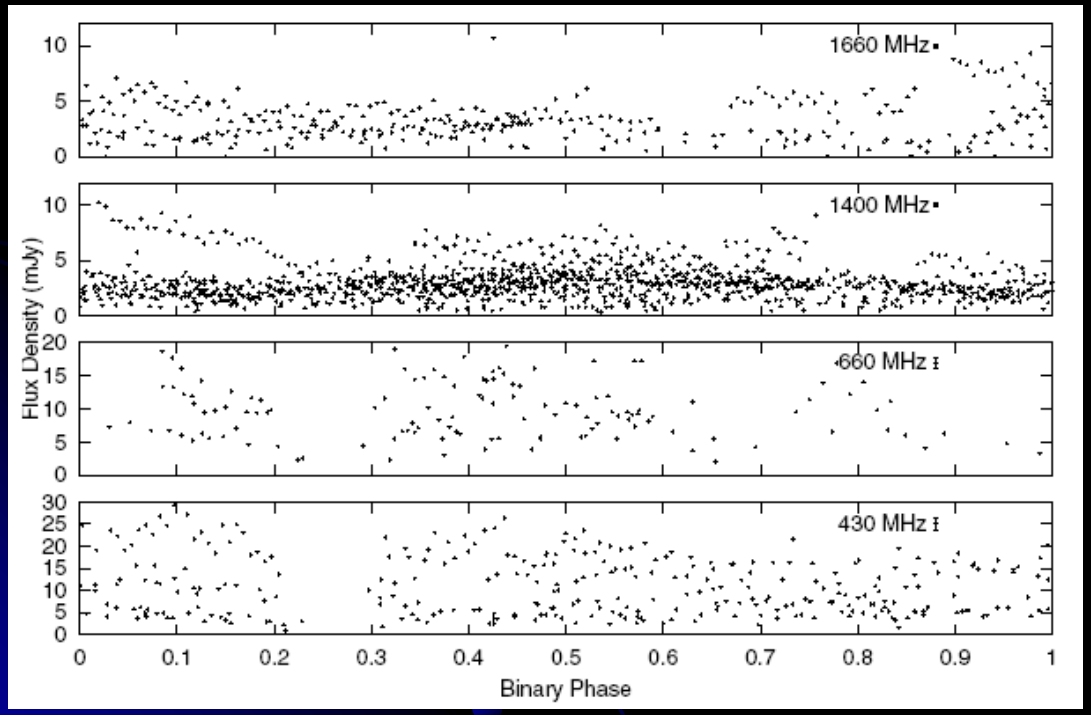
P=4.5 ms P_b=2.4 h

Eclipse duration 10%

Stappers et al., 1996a,b

Variation of P_b and x

Doroshenko et al., 2001



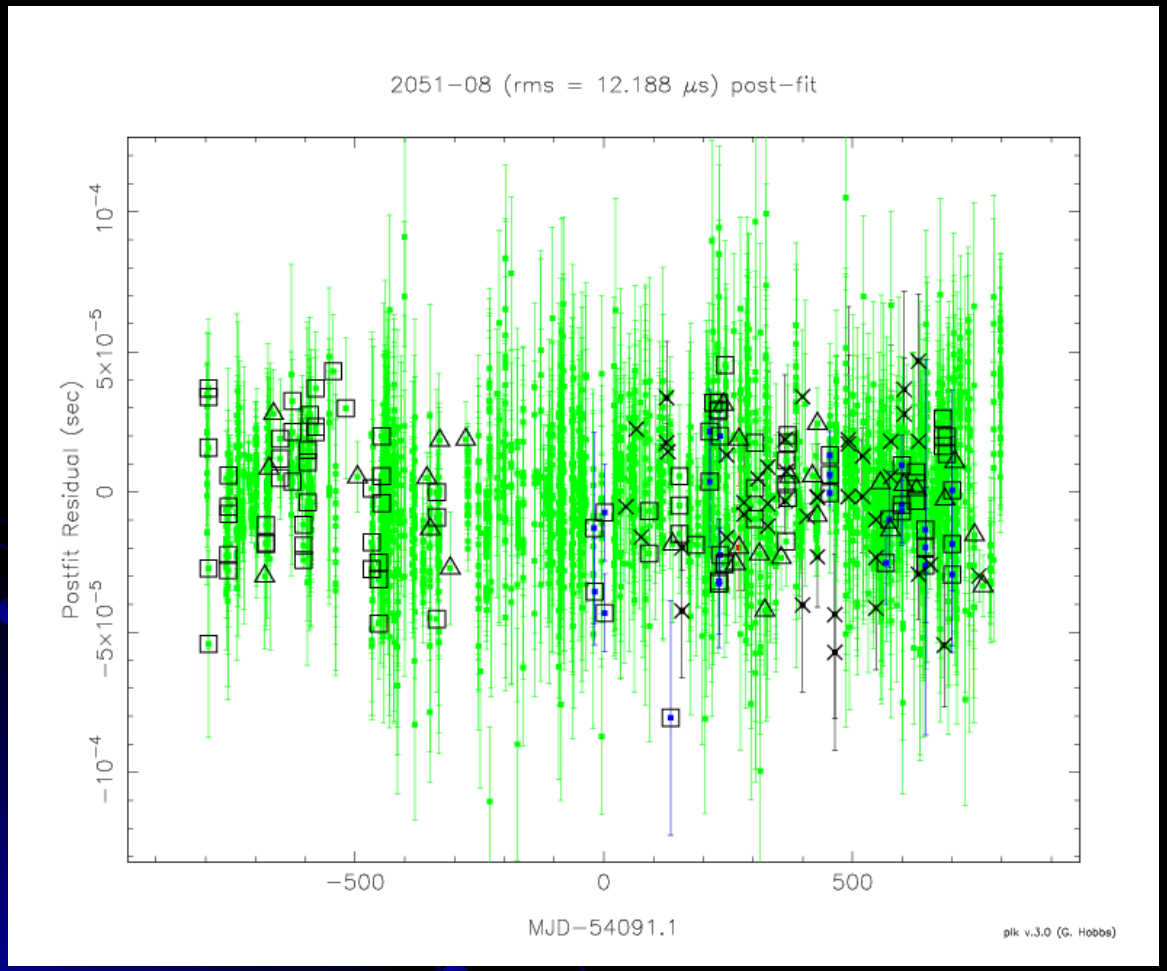
Stappers et al., 2001a

Companion

- Irradiated
- m_c~0.04 M_o
- R_L=0.13 R_o
- i~40^o
- R_c=0.06 R_o
- T_{eff}max ~ 3000 K

Stappers et al., 1996
Stappers et al., 2001b

EPTA Timing



Ntoas = 3680

13 years of data

7 frequencies

Nançay (53293-54888)

Effelsberg (50460-54791)

Lovell (49989-54853)

WSRT (54135-54845)

Parkes (49982-50343)

Lazaridis et al., 2011

Timing Results

1) μ_α (mas yr^{-1}) = 6.6(2)
   μ_δ (mas yr^{-1}) = -3.1(7)
   } $\mu_t = 7.3 \pm 0.4$ mas yr^{-1}

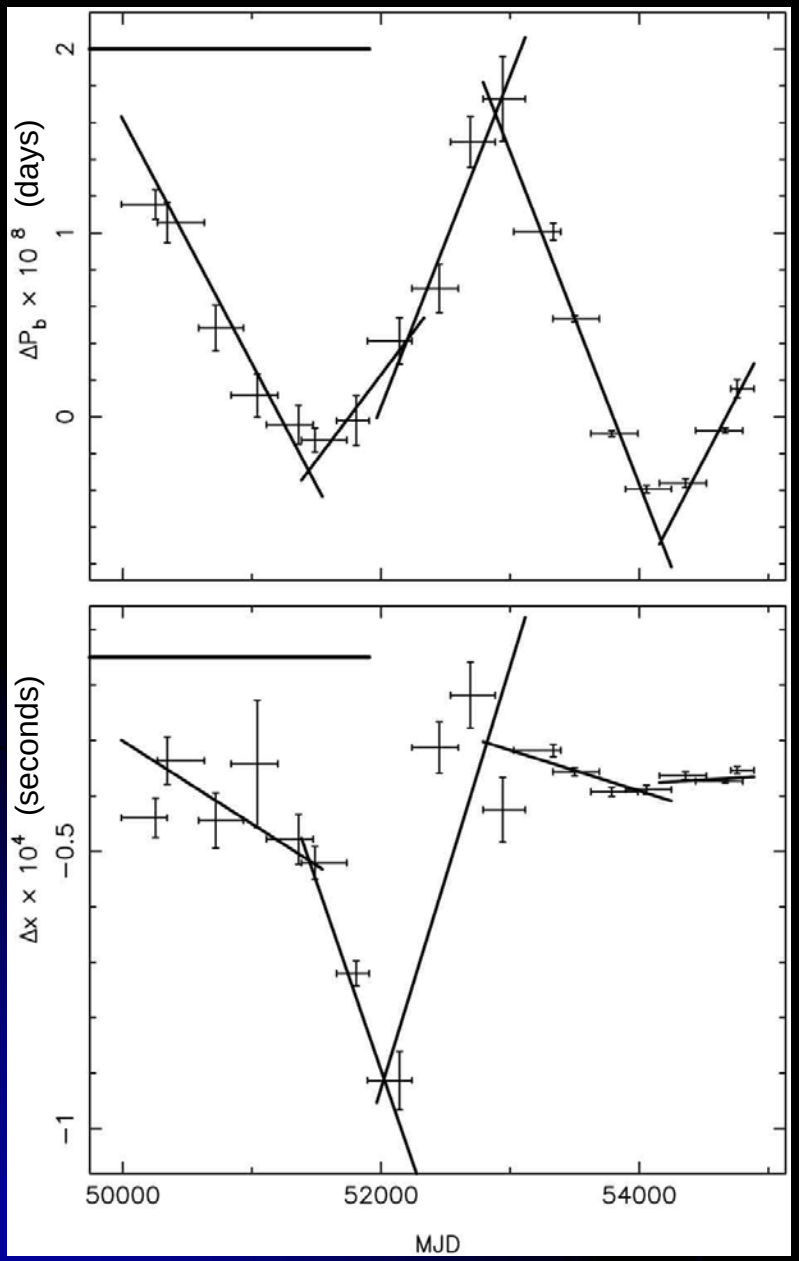
2) $v_t = \mu_t d = 36.1 \pm 7.5$ km s^{-1} ($d_{DM} = 1.04$ kpc)

3) Eccentricity $e = 6(1)\times10^{-5}$

4) Mass function~ $10^{-5}\ M_o$ => m_c=0.05 M_o ($i=40^o$, m_p=1.4 M_o)

5) $\dot{DM}$= $(-4.3 \pm 1.4) \times10^{-4}$ pc cm^{-3} yr^{-1}

Orbital Variations



Extreme orbital period and projected semi-major axis variations

4th epoch

$\dot{P}_b = -1.81(3) \times 10^{-11}$

$\dot{x} = -0.8(2) \times 10^{-13}$

5th epoch

$\dot{P}_b = 1.34(6) \times 10^{-11}$,

$\dot{x} = 0.2(2) \times 10^{-13}$

Orbital Period Variations

$$\dot{P}_b = \dot{P}_b^D + \dot{P}_b^{GW} + \dot{P}_b^{\dot{m}} + \dot{P}_b^Q$$

$\dot{P}_b^D \sim 10^{-15}$

$\dot{P}_b^{GW} \sim -5\times10^{-14}$

$$\dot{P}_b / P_b = -2 * (\dot{m}_c / M)$$

Jeans 1924

$$\dot{m}_c = 4.7\times10^{-8}\ \mathrm{M_{SUN}\ yr^{-1}}$$

Gravitational Quadrupole Coupling

Orbital Period Variations

Gravitational Quadrupole Coupling

$$\left(\frac{\Delta P_b}{P_b}\right)^Q = -9\frac{\Delta Q}{m_c \alpha^2}$$

Applegate, 1992

$$\frac{M_s}{m_c}\frac{\Delta\Omega}{\Omega} = \frac{G m_c}{2R_c^3}\left(\frac{a}{R_c}\right)^2\left(\frac{P_b}{2\pi}\right)\frac{\Delta P_b}{P_b}$$

ΔL/L~0.1

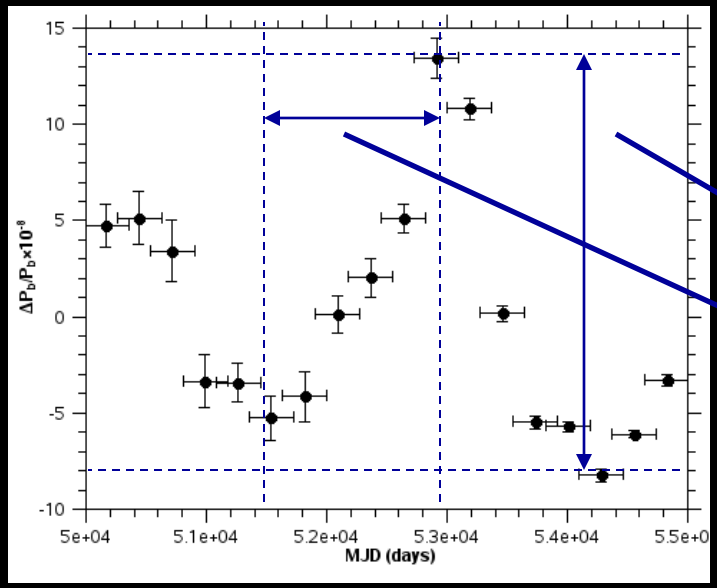
Ω_{dr}~ ΔΩ

M_s~0.1m_c

$$\Delta L = \frac{\pi}{3}\frac{G m_c^2}{R_c P_{\mathrm{mod}}}\left(\frac{a}{R_c}\right)^2\frac{\Omega_{dr}}{\Omega}\frac{\Delta P_b}{P_b}$$

Works for PSR B1957+20. First tidally powered star

Orbital Period Variations



$i=40^o$

$\alpha \sim 7.1\times10^8$ m

$R_c=0.06R_o$

$\Delta P_b/P_b=2.2\times10^{-7}$

$P_{mod}=7.5$ yr

$L\sim10^{30}$ erg s^{-1}

$\Delta\Omega/\Omega\sim4\times10^{-2}$ => $\Delta L\sim10^{33}$ erg s^{-1} => $L\sim10^{34}$ erg s^{-1}

If tidally powered internal luminosity much higher

Alternatively: $R_c=0.12R_o$ => $L\sim10^{31}$ erg s^{-1}

Projected Semi-major axis Variations

$$\dot{x} = \dot{x}^{D} + \dot{x}^{GW} + \frac{d\varepsilon_A}{dt} + \dot{x}^{PM} + \dot{x}^{\dot{m}} + \dot{x}^{SO}$$

$\dot{x}^{D} \sim 10^{-15}$

$\dot{x}^{GW} \sim -2\times10^{-19}$

$\frac{d\varepsilon_A}{dt} \sim 7\times10^{-17}$

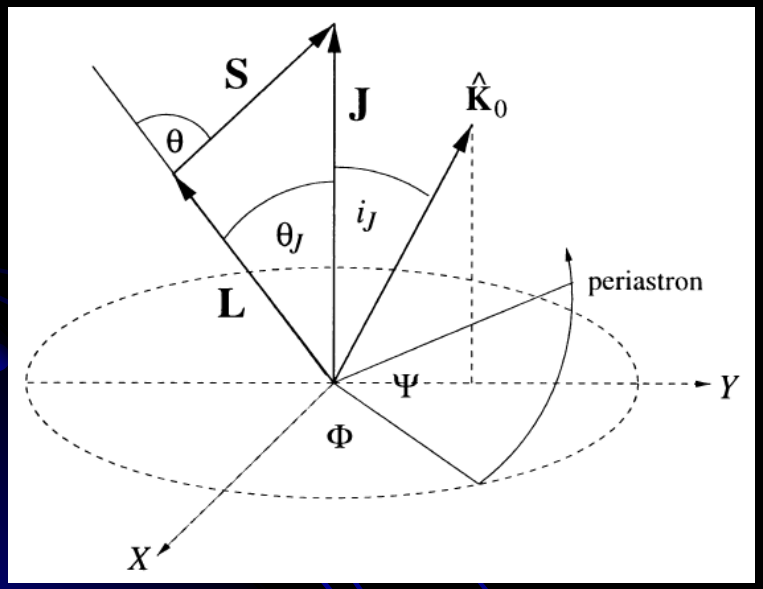
$\dot{x}^{PM} \sim 6\times10^{-17}$

$\dot{m}_c = -5\times10^{-6}\ \mathrm{M_{SUN}\ yr^{-1}}$

Spin Orbit Coupling

Projected Semi-major axis Variations

Classical Spin Orbit Coupling



$$\frac{\dot{x}^{SO}}{x} = n_b \tilde{Q} \cot i \sin\theta \cos\theta \sin\Phi$$

θ : inclination of spin (orbital plane)
Φ: longitude of ascending node (invariable plane)

Smarr & Blandford,1976; Wex, 1998

Projected Semi-major axis Variations

Applegate GQC model with SOC

$$\tilde{Q} = \frac{3}{2} J_2 \left(\frac{R_c}{a} \right), J_2 = \frac{3Q}{m_c R_c^2}$$

Outer shell changing its quadrupole moment and an effective and variable angle θ =>

$$\left(\frac{\Delta P_b}{P_b} \right)^Q = -2\Delta\tilde{Q} \left(1 - \frac{3}{2} \sin^2 \theta \right)$$

$$\frac{\dot{x}}{x} \approx n_b \Delta\tilde{Q}$$

x variations with maximum quadrupole moment variations agree in order of magnitude but not in sign =>

θ must vary strongly from epoch to epoch (unphysical)

Projected Semi-major axis Variations

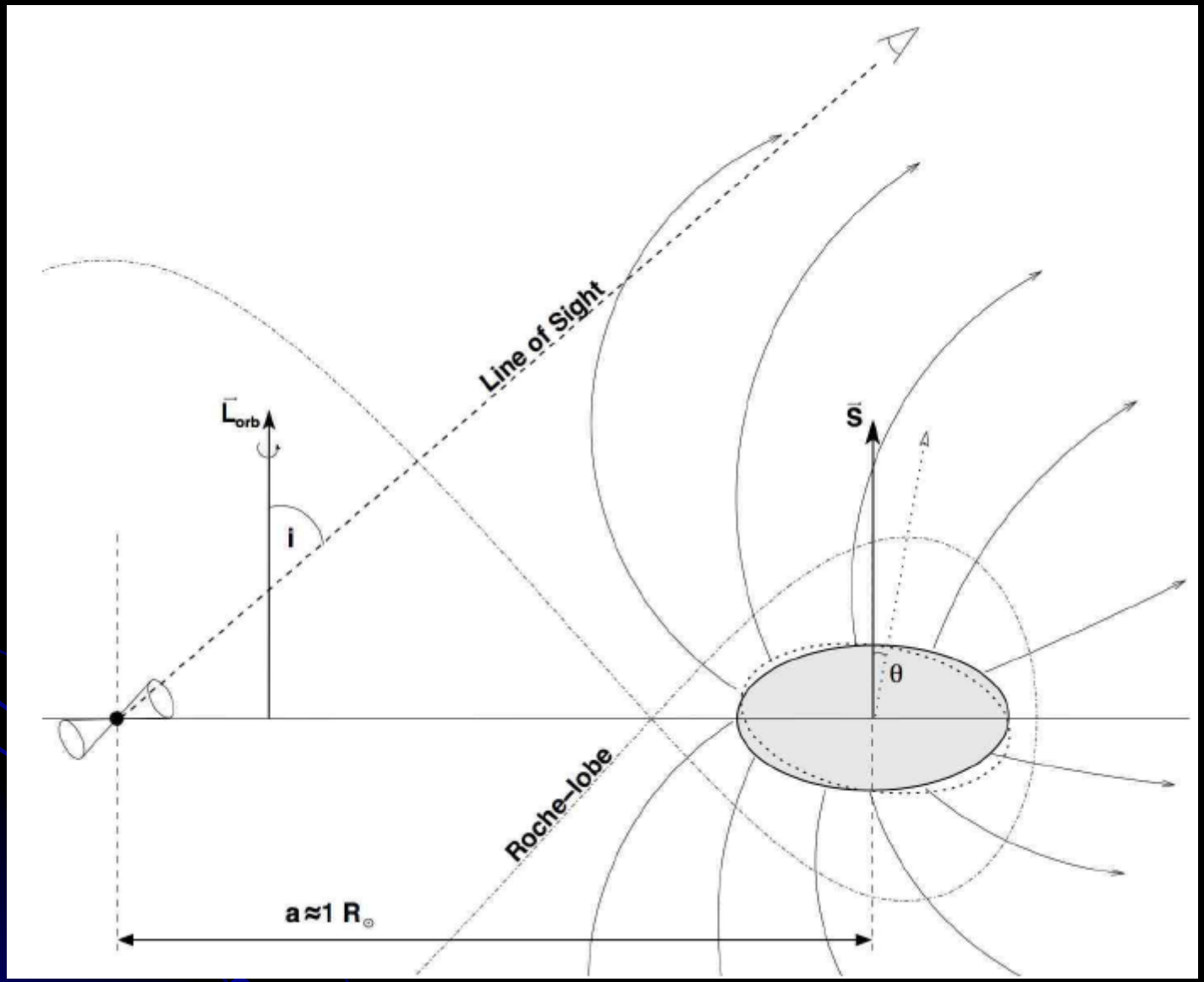
Limited Q changes and tilt of the companion

$$Q = 3.4 \times 10^{47}\ g \cdot cm^2$$

1-2 orders of magnitude > ΔQ for P_b

Epoch	θ (°)	$\Delta Q/Q$
1	−0.14	+0.041
2	−0.64	−0.017
3	+0.73	−0.041
4	−0.06	+0.052
5	+0.02	−0.019

All observed parameter changes can be explained


Line of Sight
$\vec{L}_{orb}$
i
$\vec{S}$
θ
Roche–lobe
a≈1 R⊙

Conclusions

- GQC and SOC can explain the orbital variations under assumptions
- Small orientation & magnitude changes of Q
- What is the physical mechanism?
- The possible nature of the companion
  - Semi-degenerate He-star
  - White dwarf
  - Brown dwarf
- No X-rays. No γ-rays yet (Fermi 1st year).