INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

THE ACCRETING MILLISECOND PULSAR SAX J1808.4-3658 DURING ITS 2022 OUTBURST

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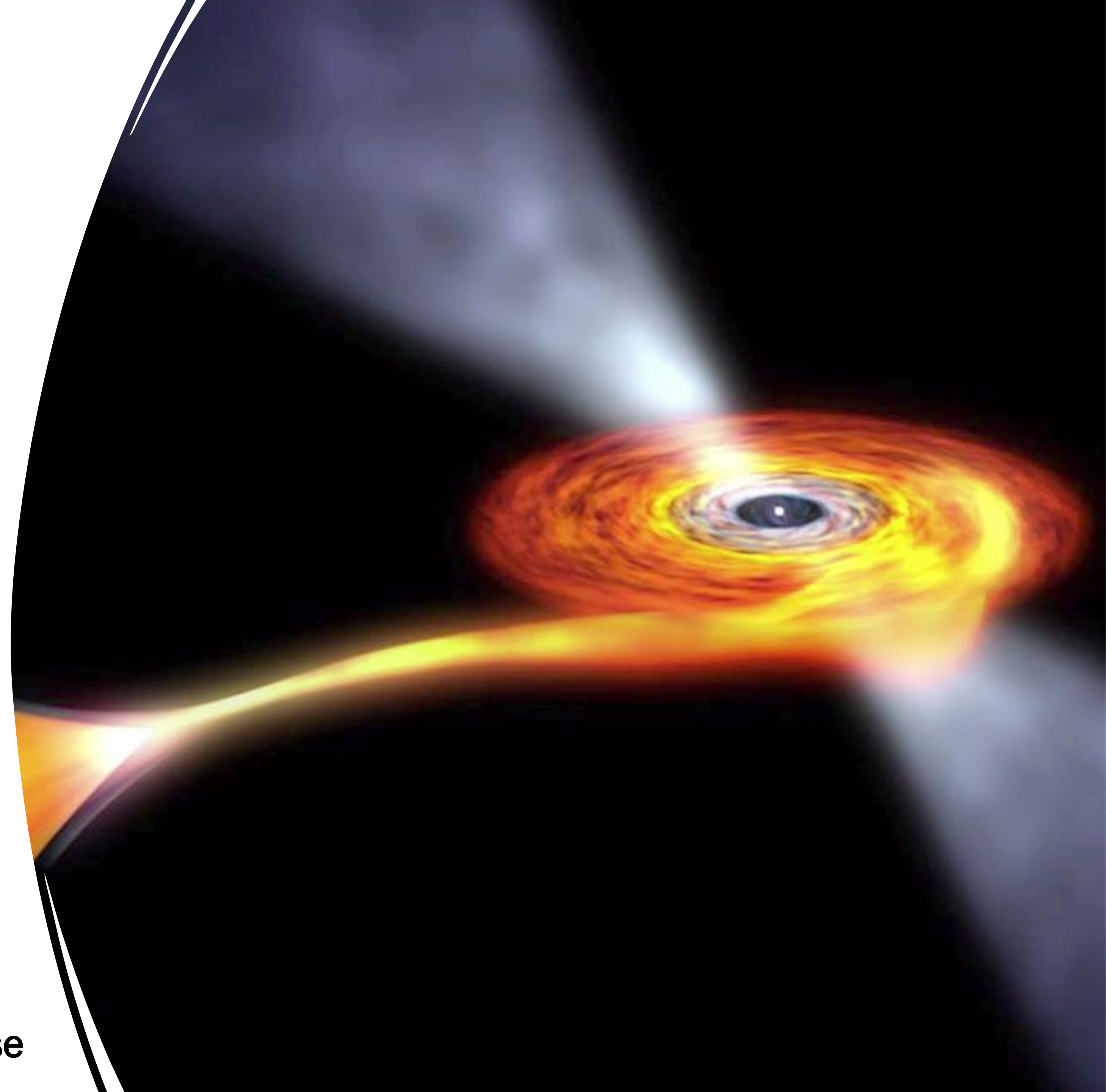
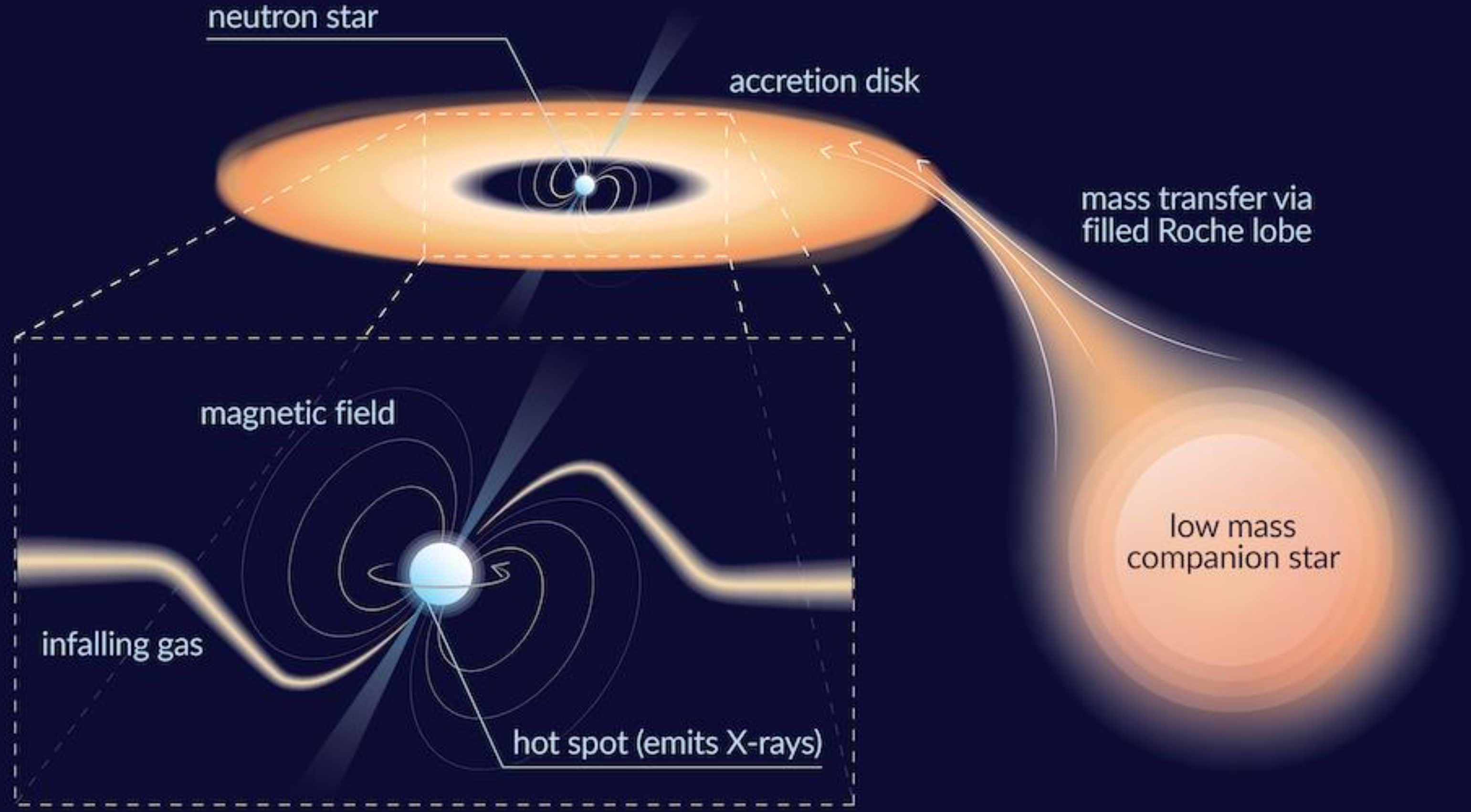
Collaborators: A. Sanna, P. Bult, F. Ambrosino, A. Miraval Zanon, L. Stella, and many more

The Transient Universe 2023 IESC Cargèse



ACCRETING MILLISECOND PULSARS



Credit: S. Galaudage

- Transient systems: active (accretion outburst) and quiescent phases
- X-ray pulsations detected only during outbursts so far
- Low-mass companion: $M \lesssim 1\ M_\odot$
- Mass accretion spins up the neutron star to ms periods
- Orbital periods $P_{orb} < 1$ day
- Rare systems (~ 20 discovered)

SAX J1808: YEARS OF OUTBURSTS

1996
Discovery X-ray transient
[in ‘t Zand+ 1998, 2001]

1998
Discovery of 401 Hz pulsations: FIRST AMXP
[Wijnands & van der Klis 1998]

2000
[Papitto+ 2005; Hartman+ 2008]

2002
[Papitto+ 2005; Burderi+ 2006; Hartman+ 2008]

2005
[Hartman+ 2008]

2008
[Hartman+ 2009; Burderi+ 2009; Patruno 2009]

2011
[Patruno+ 2012]

2015
[Sanna+ 2017; Patruno+ 2017; Di Salvo+ 2019]

2019
[Bult+ 2020; Baglio+ 2020]
Discovery of optical and UV pulsations
[Ambrosino, Miraval Zanon+ 2021]

2022
Latest outburst
[**Illiano+ 2023, ApJL**; Miraval Zanon+ (in prep.)]

2022 OUTBURST: MULTI-WAVELENGTH OBSERVATIONAL CAMPAIGN

NuSTAR (PI Papitto)

- 22-23 August 2022
- 3-79 keV
- Duration: 120 ks

NICER (PI Papitto)

- 23 August – 31 October 2022
- 0.2-12 keV
- Duration: 163 ks

XMM-Newton (PI Papitto)

- 9-10 September 2022
- 0.3-10 keV
- Duration: 120 ks

TNG/SiFAP2 (PI Miraval Zanon)

- 26-27 August 2022
- 320-900 nm
- Duration: 4 hr

HST/STIS (PI Miraval Zanon)

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Accepted coordinated ToO with IXPE
but not executed due to visibility constraints

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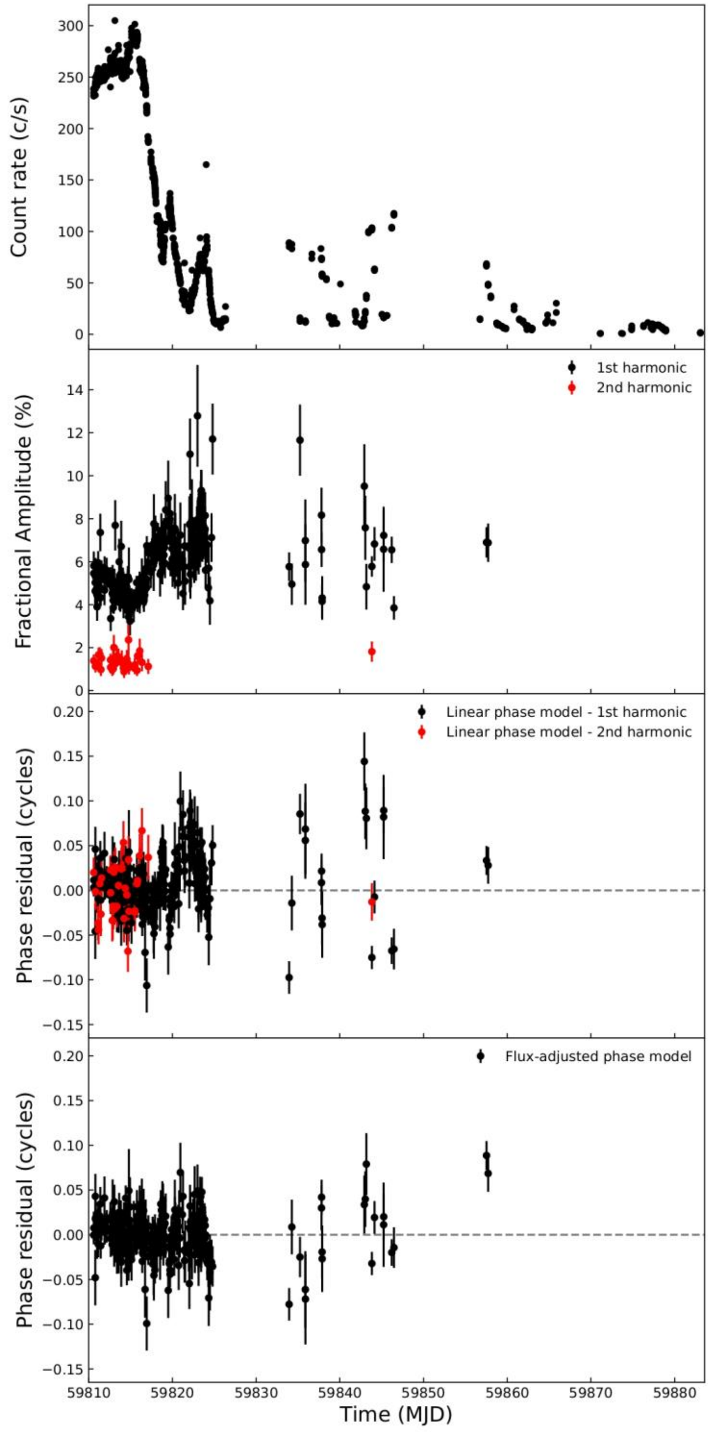
TIMING ANALYSIS

$$\Delta\phi(t) = \phi_0 - \Delta\nu(t - T_0) - \frac{1}{2}\,\dot{\nu}\,(t - T_0)^2 + R_{\rm orb}(t)$$

Parameter	Value
Epoch (MJD)	59810.5956860
$a_1 \sin i$ (lt-s)	0.0628033(57)
$P_{\rm orb}$ (s)	7249.1600(13)
$T_{\rm asc}$ (MJD)	59810.6179996(17)
Linear phase model	
ν (Hz)	400.975209557(50)
χ^2/dof	699.1/285
Flux-adjusted phase model	
ν (Hz)	400.975209535(50)
b	1.44(49)
Γ	−0.81(12)
χ^2/dof	450.0/283

← $R_{\rm flux}(t) = bF_X(t)^\Gamma$

[Illiano+ 2023, ApJL]



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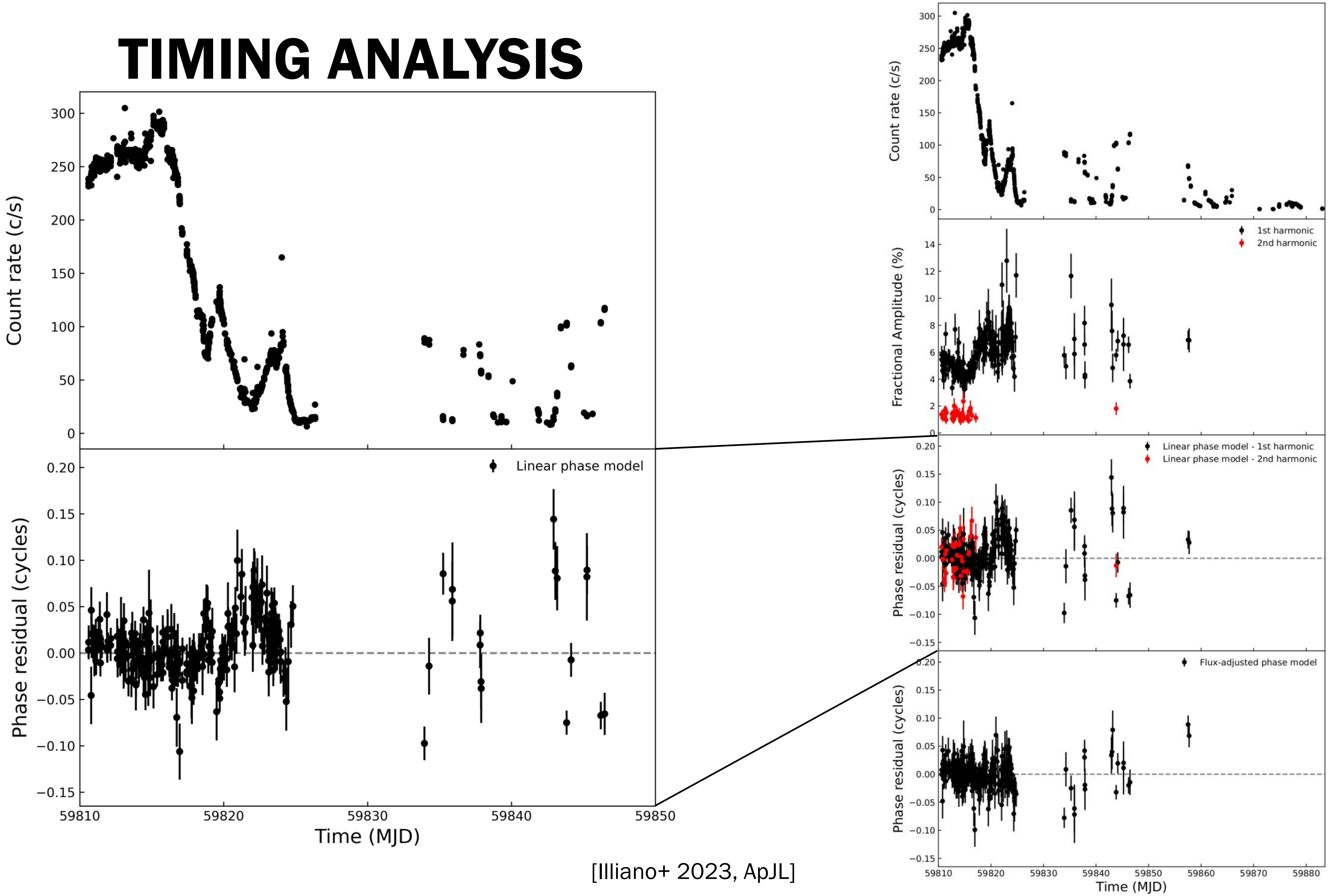
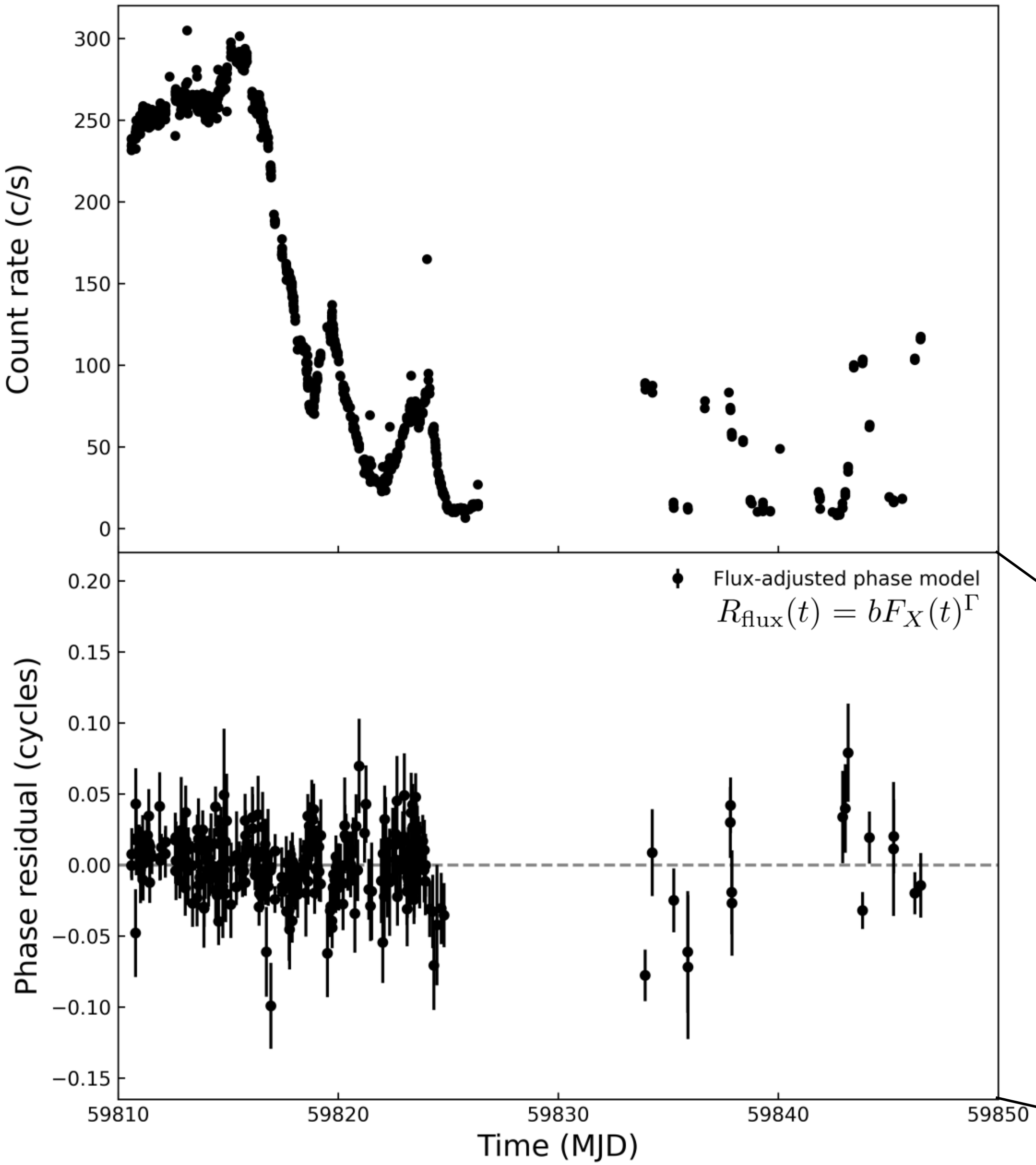
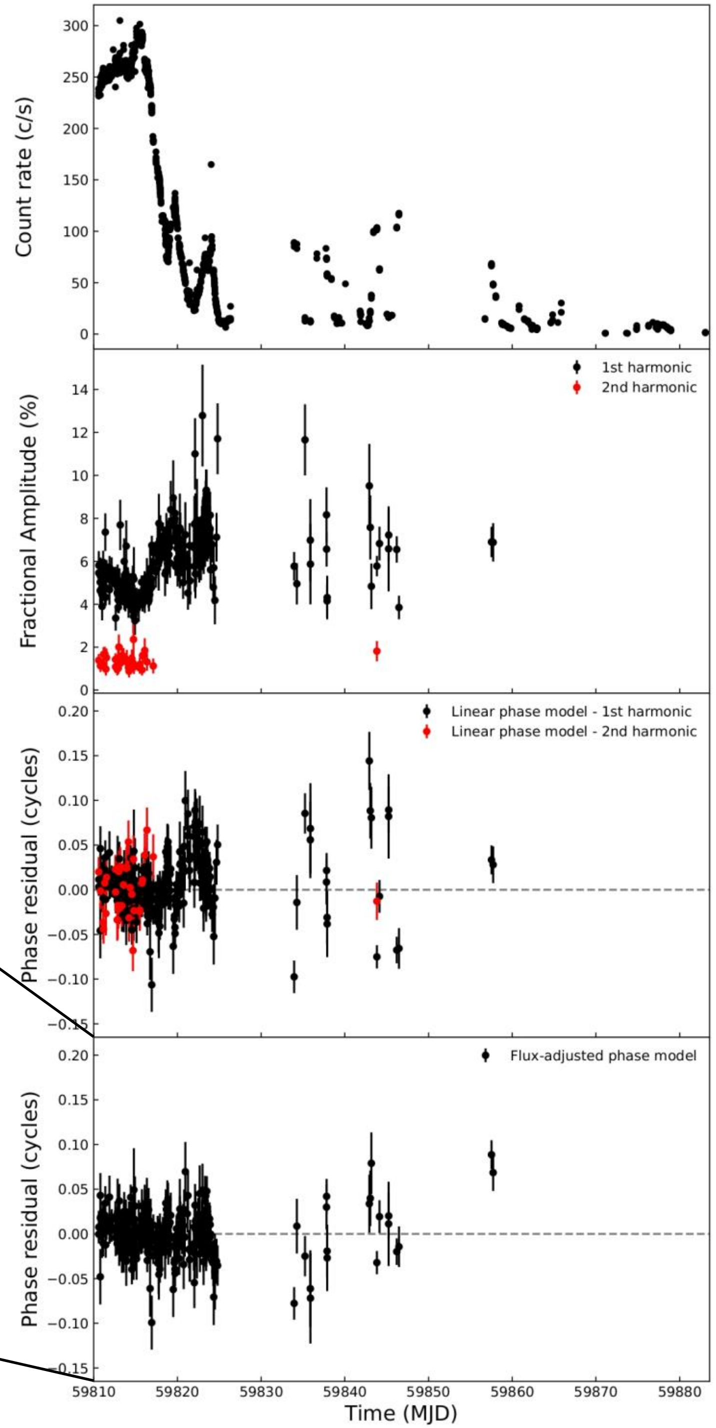


[Illiano+ 2023, ApJL]

TIMING ANALYSIS





[Illiano+ 2023, ApJL]

LONG-TERM SPIN FREQUENCY EVOLUTION

SAX J1808: most thoroughly studied AMXP

↓

Detailed study of the long-term spin frequency evolution

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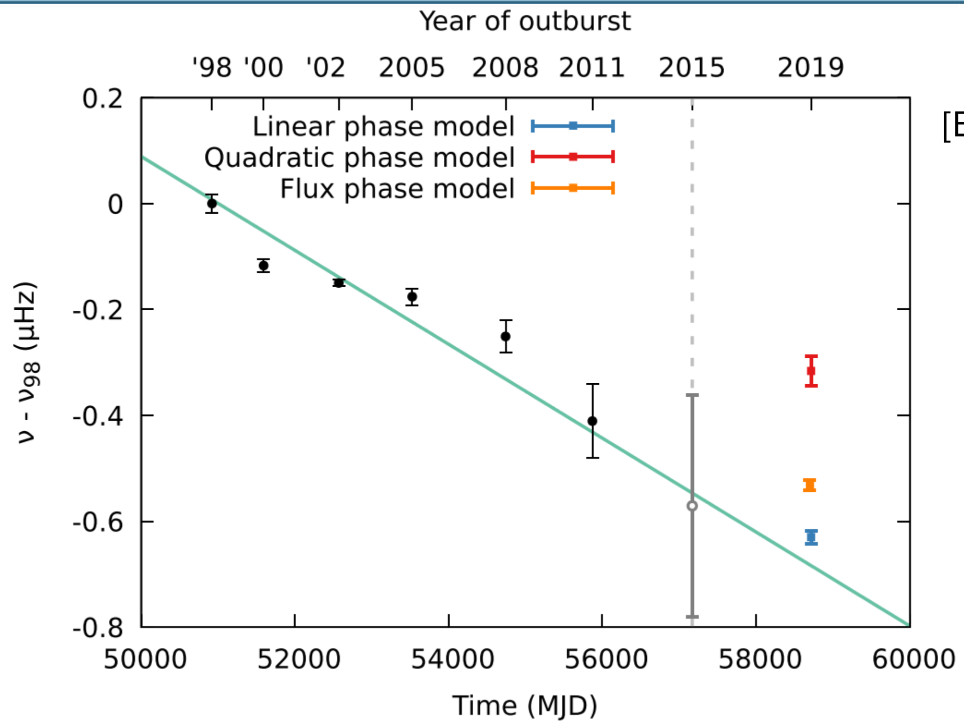
Previous works: average **spin-down** rate of

$\dot{\nu}_{SD} \simeq 10^{-15}$ Hz/s

[Patruno+ 2012; Sanna+ 2017; Bult+ 2020]



[Bult+ 2020]

LONG-TERM SPIN FREQUENCY EVOLUTION

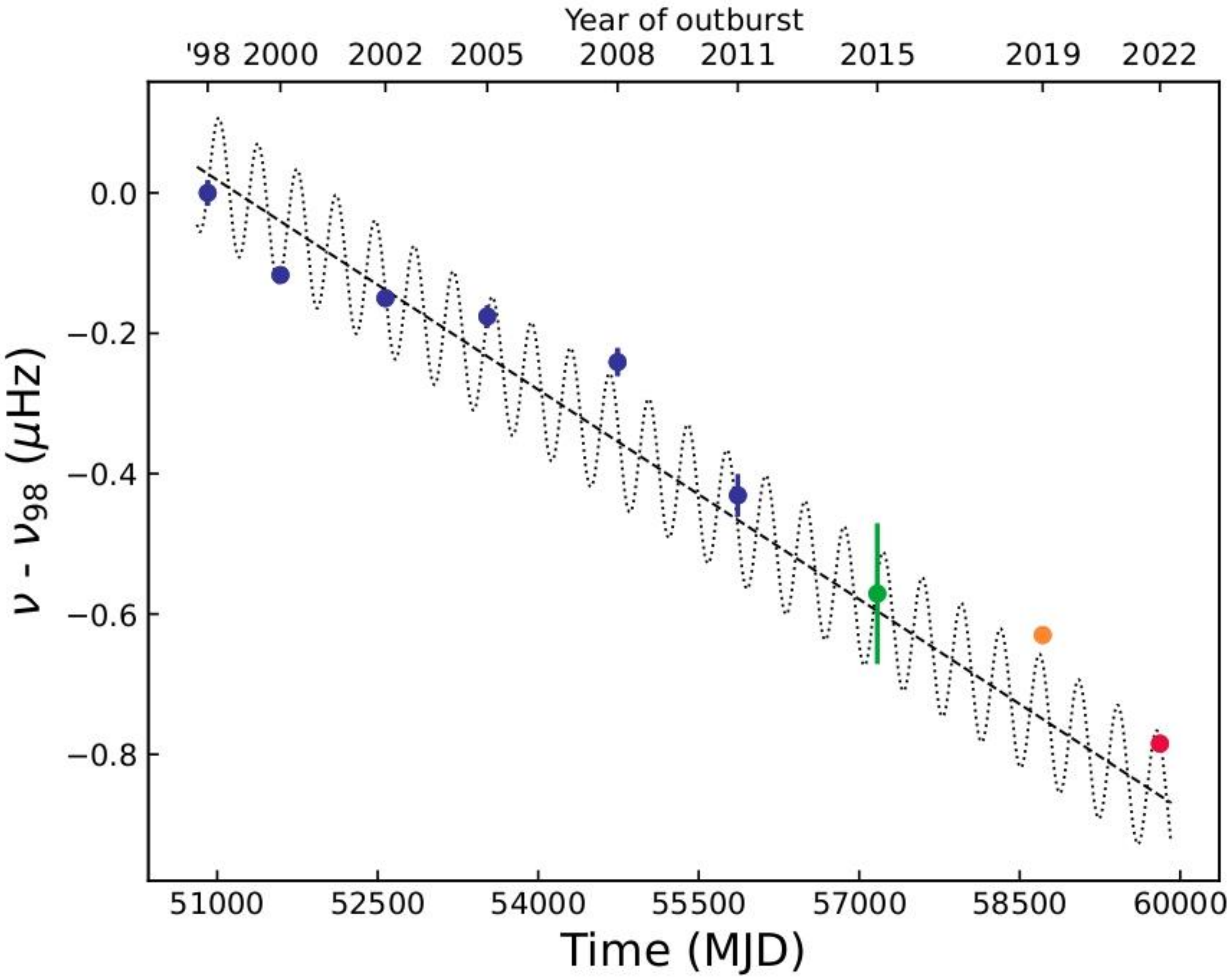
$$\Delta\nu(t) = \delta\nu_{98} + \dot{\nu}_{SD}(t - T_{98}) + \delta\nu_{pos}(t, \lambda, \beta)$$

$$\begin{cases} \delta\nu_{98} = 2.7(1.9) \times 10^{-8}\,\text{Hz} \\ \dot{\nu}_{SD} = -1.152(56) \times 10^{-15}\,\text{Hz/s} \\ \delta\beta = -0''.93(38) \\ \delta\lambda = 0''.42(15) \\ \chi^2/\text{dof} = 34.9/5 \end{cases}$$

↓

$$\text{R.A.(J2000)} = 18{:}08{:}27.656(12)\text{s}$$

$$\text{DEC.(J2000)} = -36{:}58{:}44.222(89)\text{s}$$

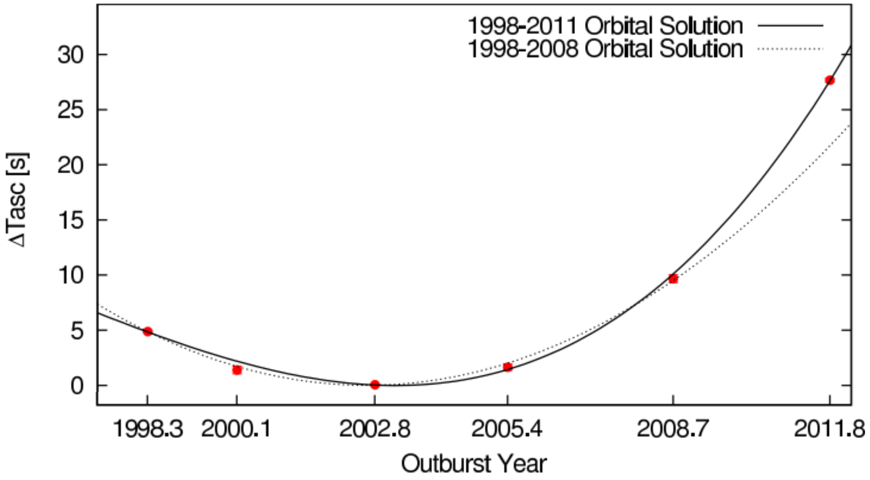


[Illiano+ 2023, ApJL]

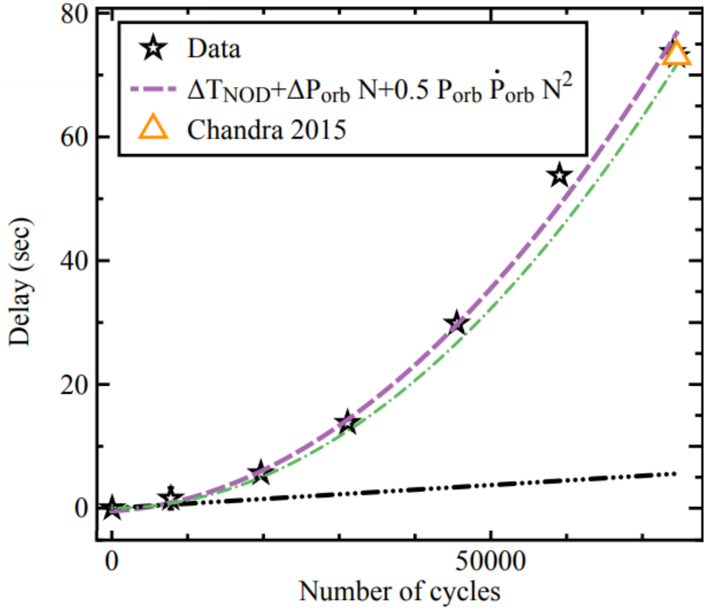
LONG-TERM ORBITAL PERIOD EVOLUTION

SAX J1808's **orbital evolution** highly discussed

- Until 2008, **orbital expansion** at $\simeq 4 \times 10^{-12}$ s s^{-1} [e.g. Di Salvo+ 2008; Hartman+ 2008, 2009; Burderi+ 2009]
- Suggestion of an **acceleration of the expansion** in 2011 [Patruno+ 2012]
- **Slower evolution** since 2015 [Sanna+ 2017; Patruno+ 2017]

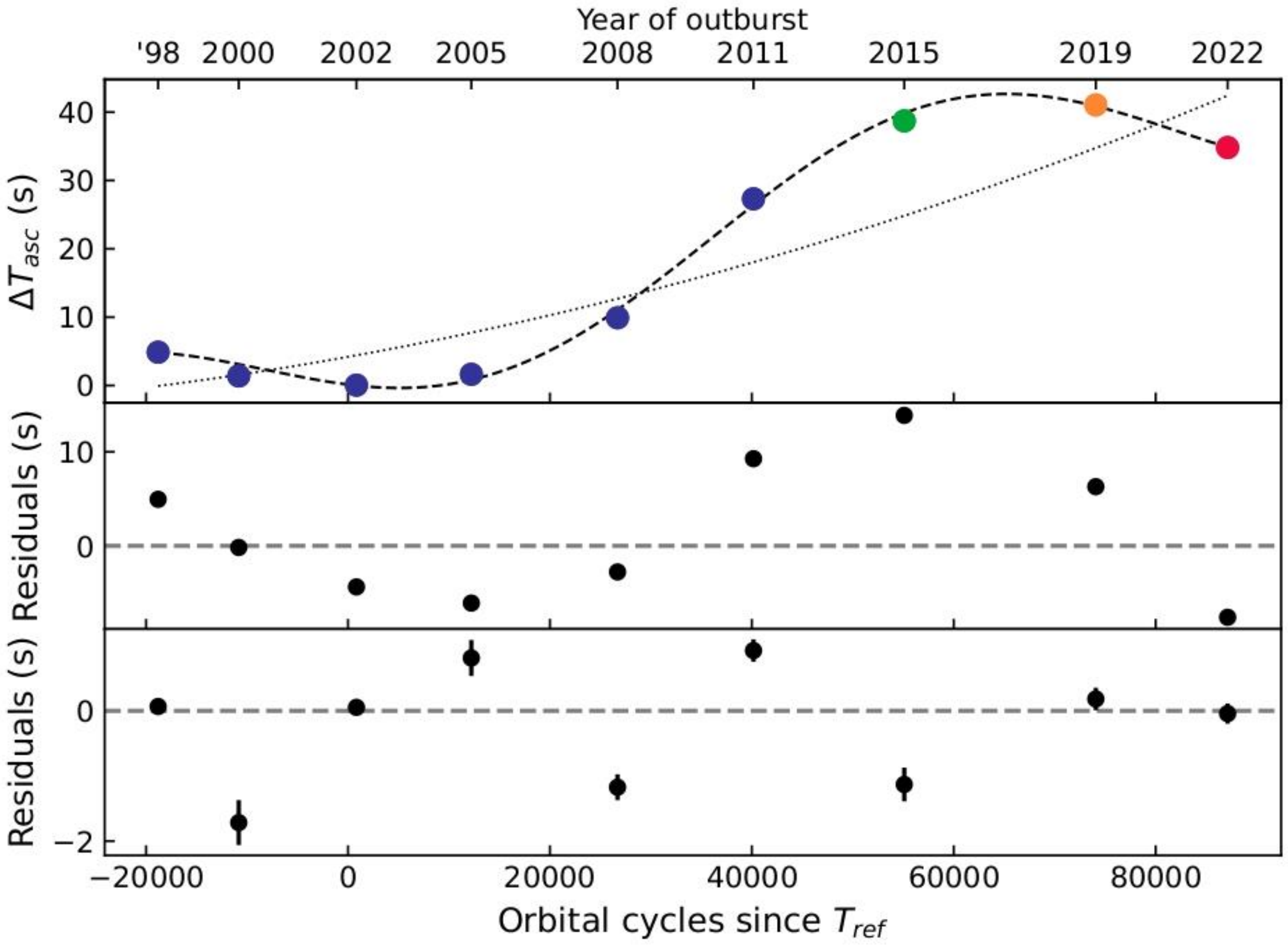


[Patruno+ 2012]



[Sanna+ 2017]

FIRST INDICATION OF ORBITAL CONTRACTION IN THE LAST TWENTY YEARS

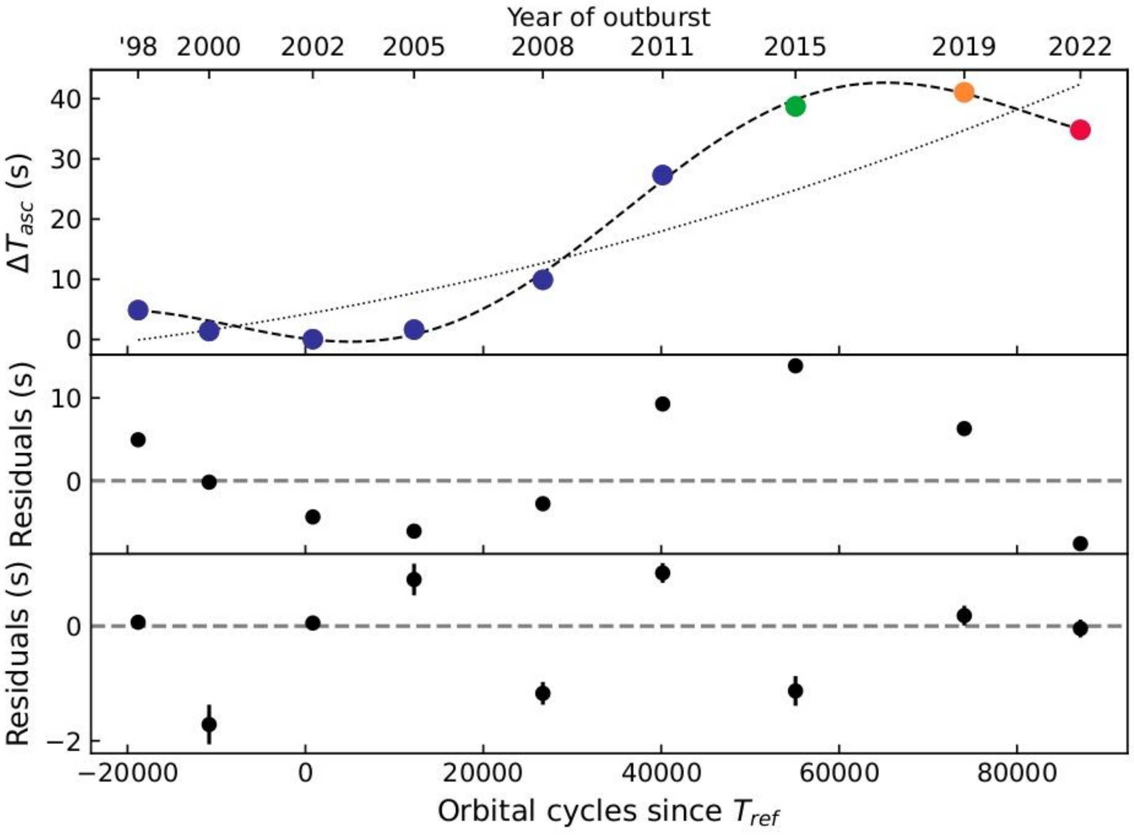


$$\Delta T_{asc}(N_{orb}) = \delta T_{ref} + \delta P_{ref}\, N_{orb} + $$
$$+ \frac{1}{2}\, \dot{P}_{orb}\, P_{ref}\, N_{orb}^2 + A\, \sin\left[\frac{2\,\pi}{P}\,(N_{orb} - N_0)\right]$$

$$\begin{cases} \delta P_{ref} = 4.63(16) \times 10^{-4}\,\mathrm{s} \\ \dot{P}_{orb} = -2.82(69) \times 10^{-13}\,\mathrm{s\,s^{-1}} \\ A = 11.30(33)\,\mathrm{s} \\ P = 7567(213)\,\mathrm{d} \\ \chi^2/\mathrm{dof} = 117.9/3 \end{cases}$$

[Illiano+ 2023, ApJL]

ORBITAL PERIOD EVOLUTION



[Illiano+ 2023, ApJL]

$$\begin{cases} A = 11.30(33)\,\mathrm{s} \\ P = 7567(213)\,\mathrm{d} \end{cases}$$

Sinusoidal modulation due to a **third body**?
Hardly explained

- Hypothetical third body mass: $\sim 0.004\,\mathrm{M}_\odot$
- **Doppler modulation** of the pulsar spin frequency:

$$\delta\nu \sim 2\pi/P_{orb}\, a_1 \sin i/c\, \nu_0 \sim 42\,\mu\mathrm{Hz}$$

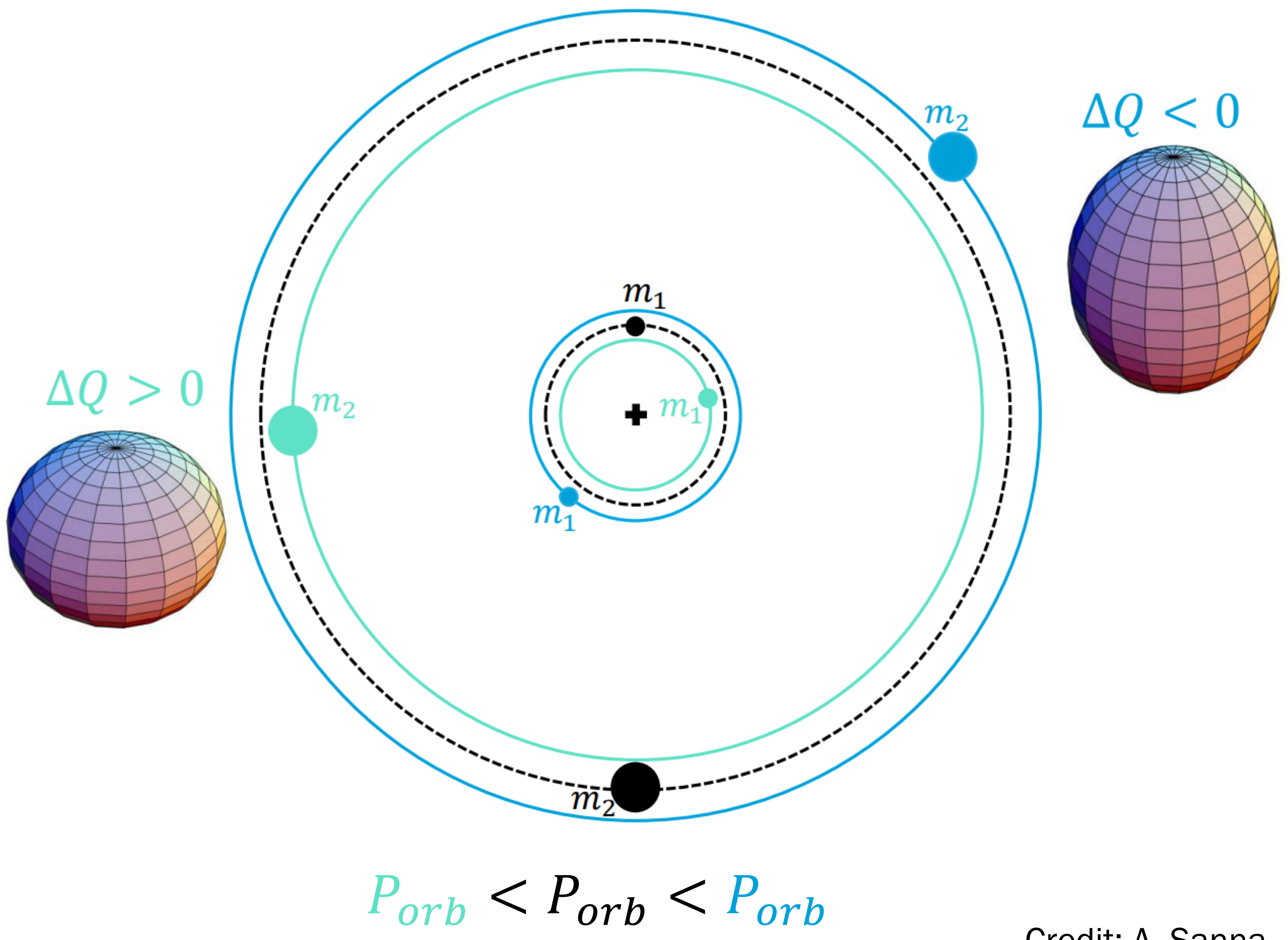
↓

Two orders of magnitude higher than observed

GRAVITATIONAL QUADRUPOLE COUPLING (GQC) MODEL

[Applegate 1992; Applegate & Shaham 1994]

- $\Delta Q < 0 \rightarrow$ Companion less oblate $\longrightarrow$ the orbit expands ($\dot{P}_{orb} > 0$)
- $\Delta Q > 0 \rightarrow$ Companion more oblate $\longrightarrow$ the orbit shrinks ($\dot{P}_{orb} < 0$)



Credit: A. Sanna

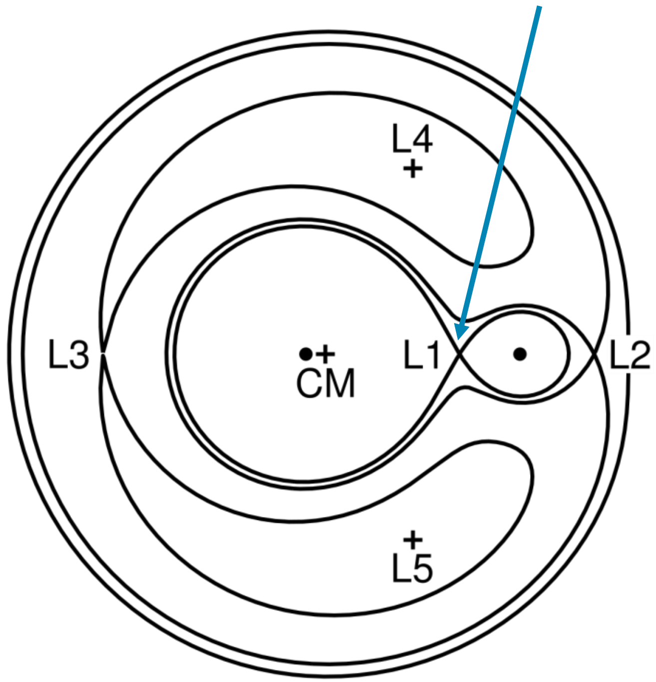
GRAVITATIONAL QUADRUPOLE COUPLING (GQC) MODEL

[Applegate 1992; Applegate & Shaham 1994]

First scenario: **mass ejected with the specific angular momentum of the inner Lagrangian point**

↓

$\dot{P}_{orb}$ **too large for the observed orbital evolution**



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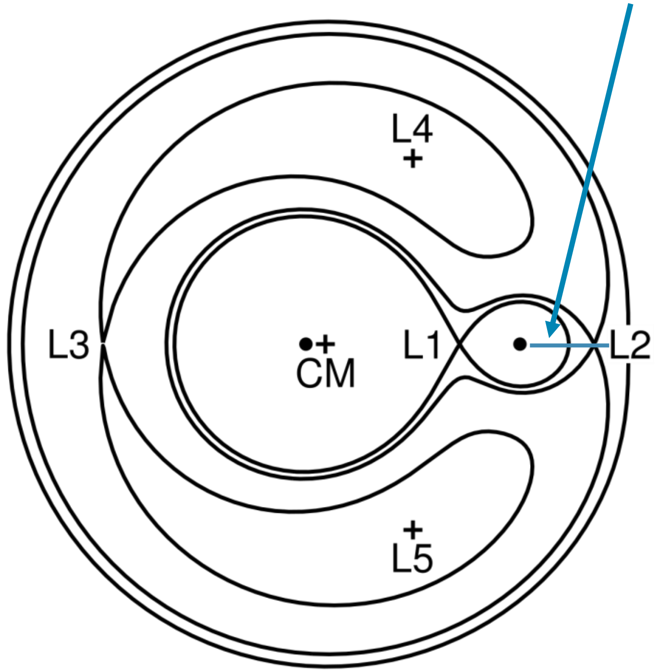
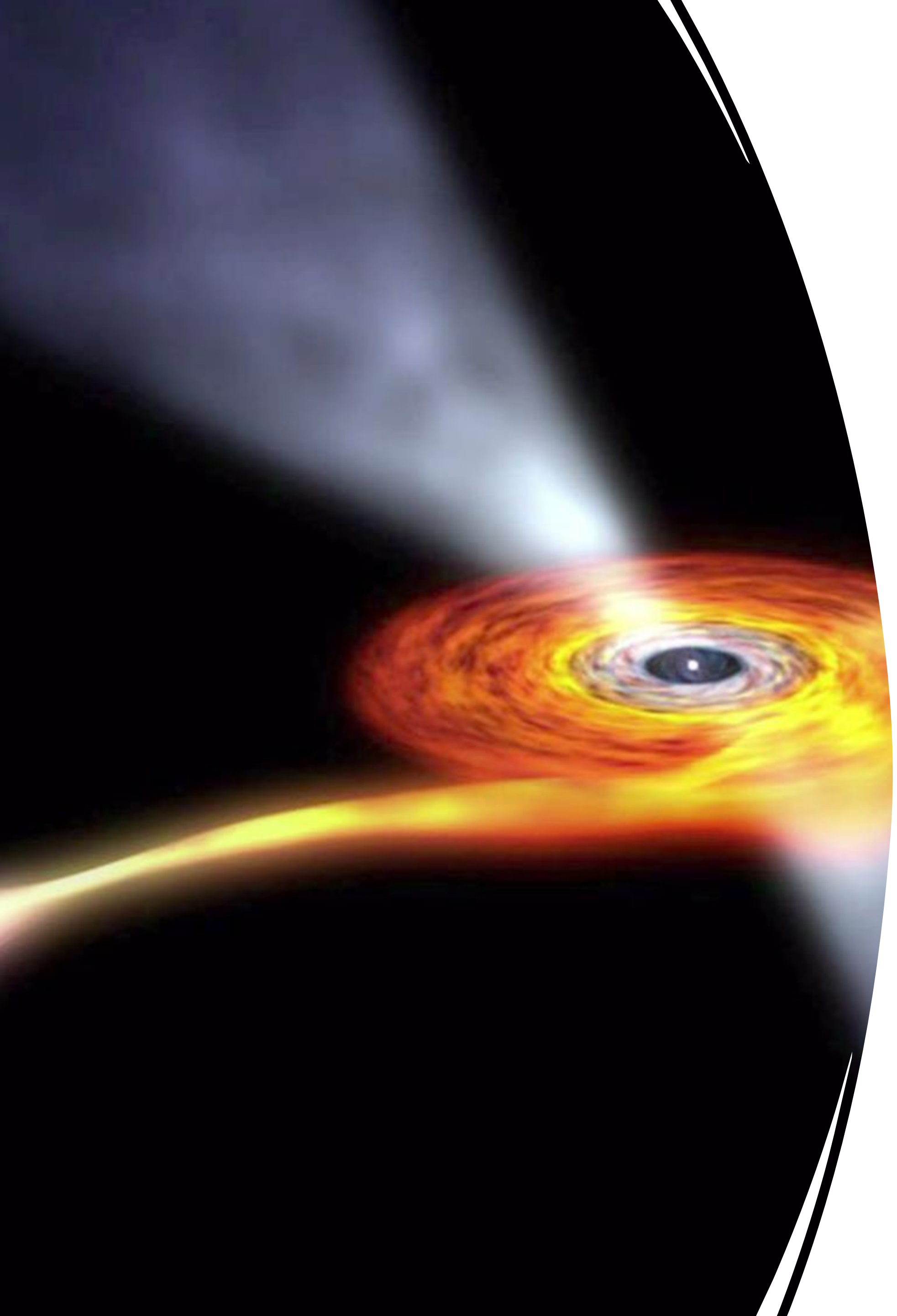
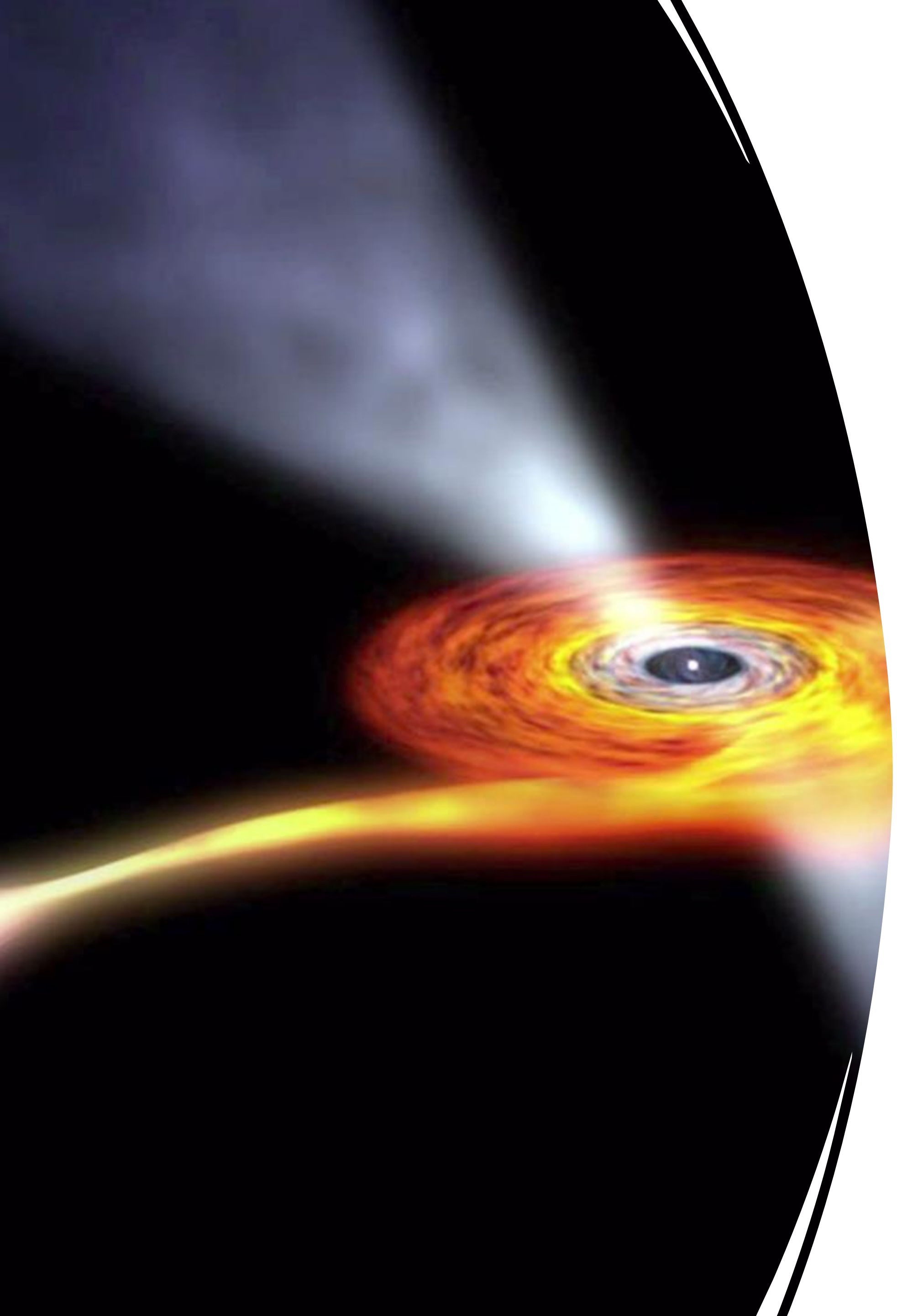
The mass has to leave the system with an angular momentum equal to or greater than that of the secondary centre of mass





CONCLUSIONS

- Timing analysis of the 2022 outburst: confirmation of the secular spin-down and hints of an orbital decay
- Next outburst crucial to confirm the orbital evolution
- Detecting (optical) pulsations during quiescence would increase our ability to monitor the pulsar evolution



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THANK YOU FOR THE ATTENTION!