NICER updates on Accreting Millisecond X-ray Pulsars

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in collaboration with:

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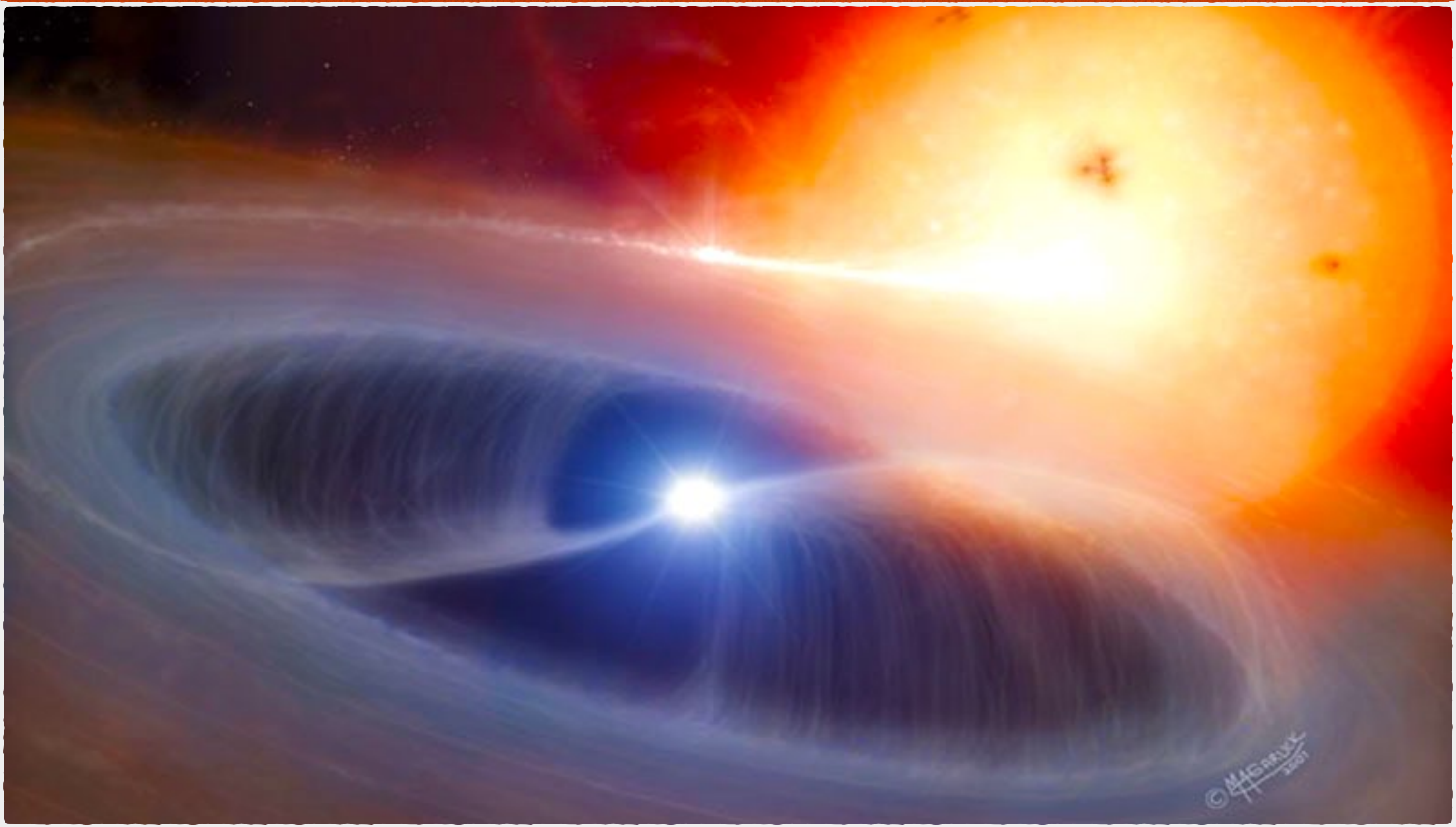
NICER ANALYSIS WORKSHOP - 11 May 2021

Accreting millisecond X-ray pulsars



Accreting Millisecond X-ray pulsars

Name	P_spin (ms)	P_orb (h)	Ref
SAX J1808.4-3658	2.5	2.0	Wijnands & van der Klis 1998
XTE J0929-314	5.4	0.73	Galloway et al. 2002
XTE J1751-305	2.3	0.7	Markwardt et al. 2002
XTE J1814-338	3.2	4.0	Markwardt et al. 2003
XTE J1807-294	5.3	0.67	Markwardt et al. 2003
IGR J00291+5934	1.7	2.5	Galloway et al. 2005
HETE J1900.1-2455	2.7	1.4	Kaaret et al. 2005
SWIFT J1756.9-2508	5.5	0.9	Markwardt et al. 2007
Aql X-1	1.8	19	Casella et al. 2007
SAX J1748.9-2021	2.3	8.8	Altamirano et al. 2007
NGC 6440 X-2	4.8	0.96	Altamirano et al. 2010
IGR J17511-3057	4.1	3.5	Markwardt et al. 2009
SWIFT J1749.4-2807	1.9	8.8	Altamirano et al. 2010
IGR J1749.8-2921	2.5	3.84	Papitto et al. 2011
IGR J18245-2452	3.9	11.03	Papitto et al. 2013
XSS J12270	1.7	6.9	Bassa et al. 2014
PSR J1023+0038	1.7	4.75	Archibald et al. 2015
MAXI J0911-655	2.9	0.74	Sanna et al. 2017
IGR J17062-6143	6.1	0.63	Strohmayer & Keek 2017
IGR J16597-3704	9.5	0.77	Sanna et al. 2017
IGR J17379-3747	2.1	1.9	Strohmayer 2018 - Sanna et al. 2018
IGR J17591-2342	1.9	8.8	Sanna et al. 2018
IGR J17494-3030	2.7	1.2	Ng et al. 2020

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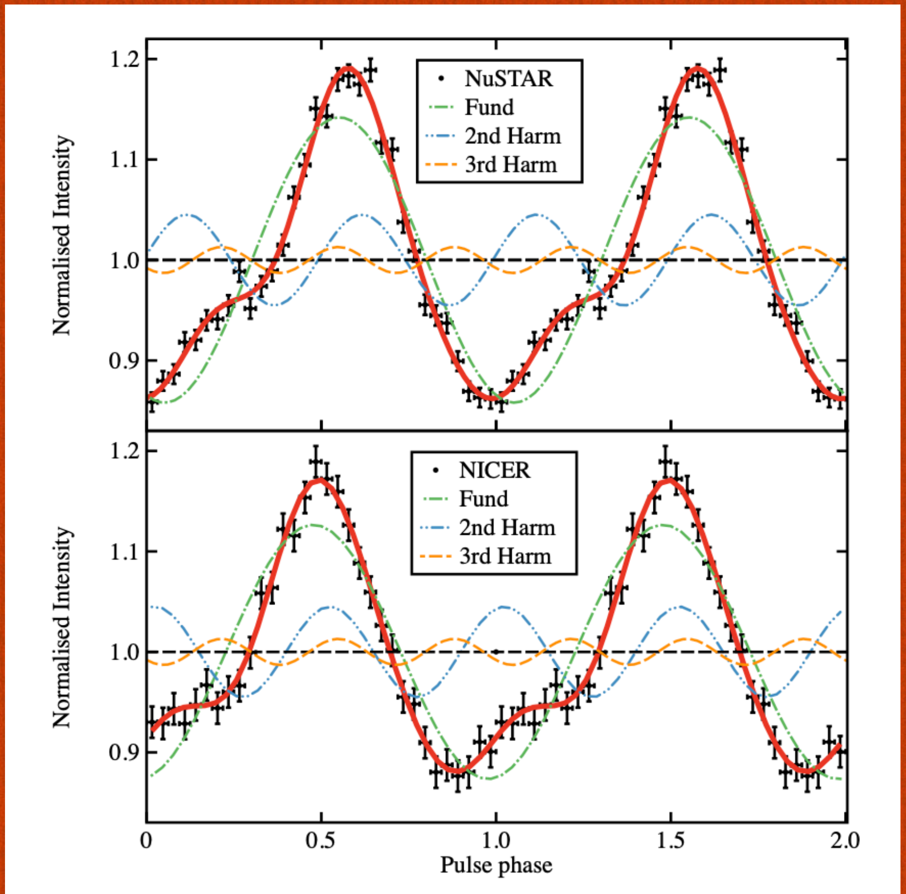
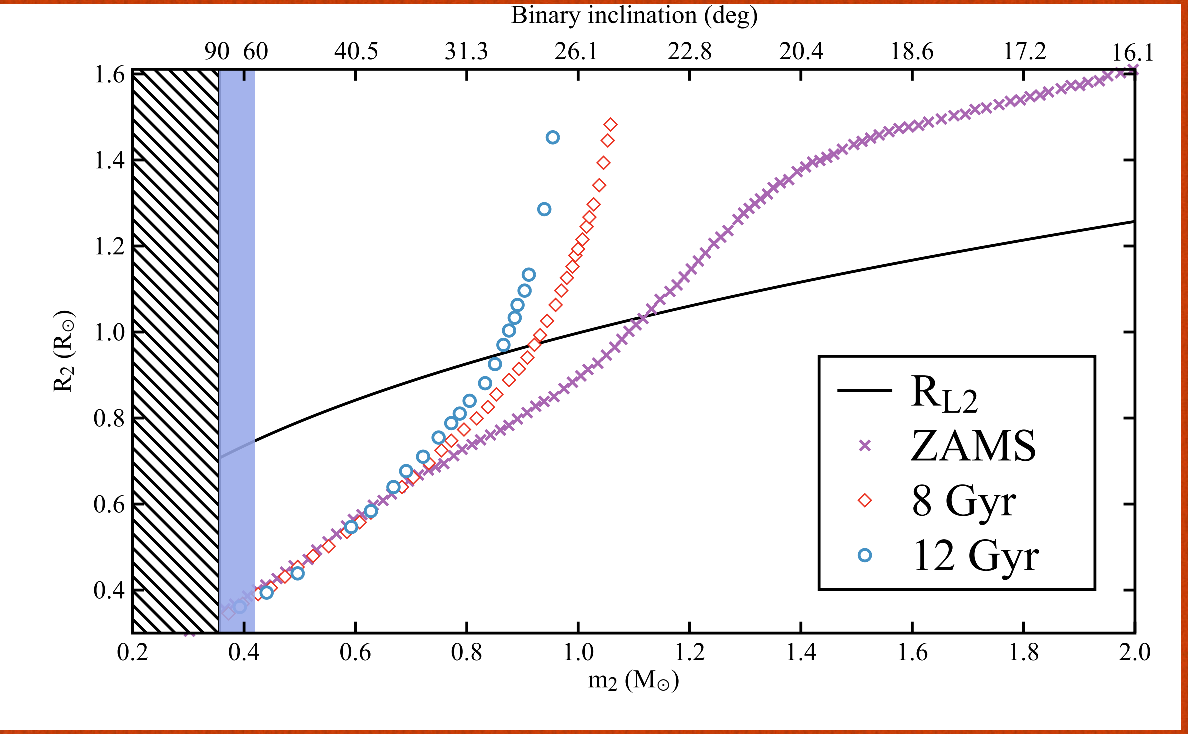
IGR J17591-2342

- **Discovered on 2018 Aug 10 by INTEGRAL IBIS/ISGRI**
- **12th of Aug 2018 Swift/XRT starts monitoring the source**
- **14th/15th of Aug 2018 NuSTAR and NICER detect coherent X-ray pulsation**

ν ≃ 527 Hz

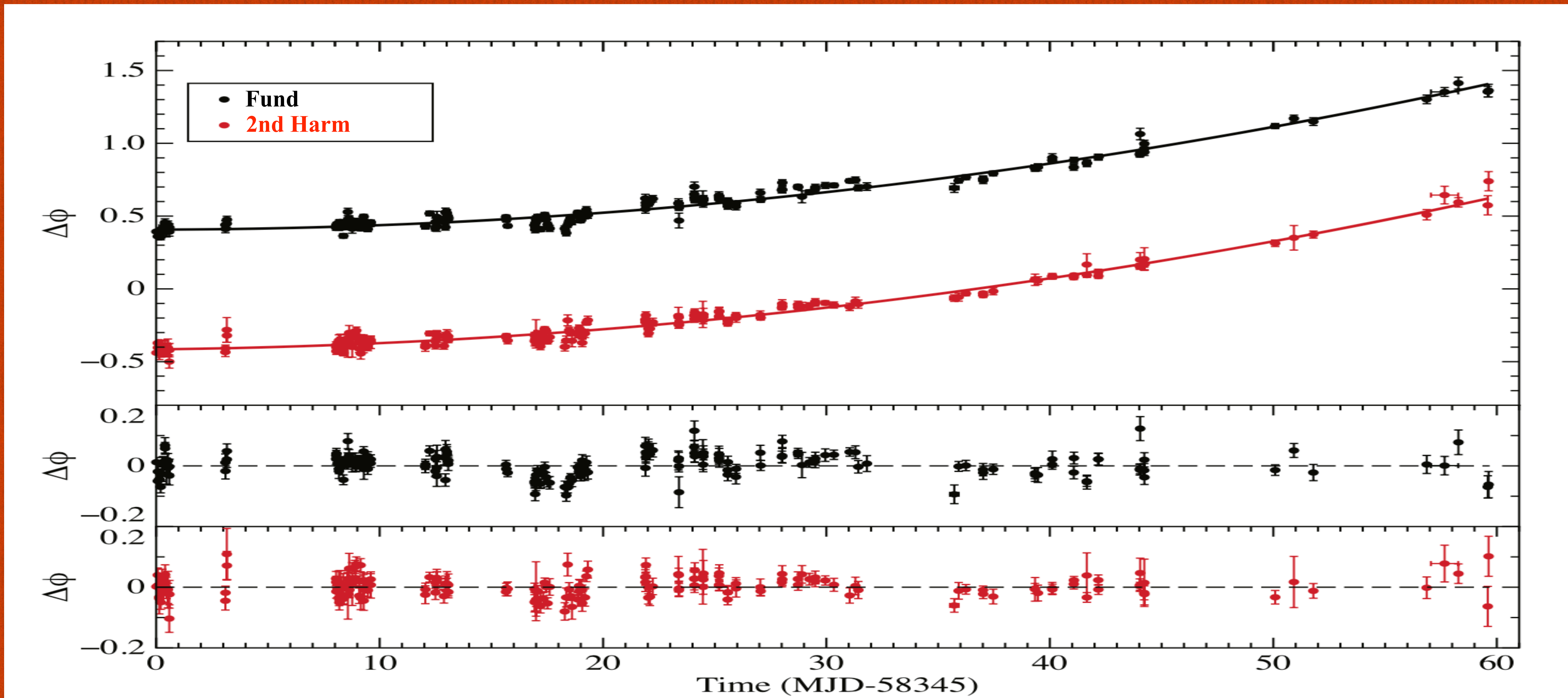
m2 ≥ 0.42 M⊙





Sanna et al. 2018, A&A, 617, L8

IGR J17591-2342



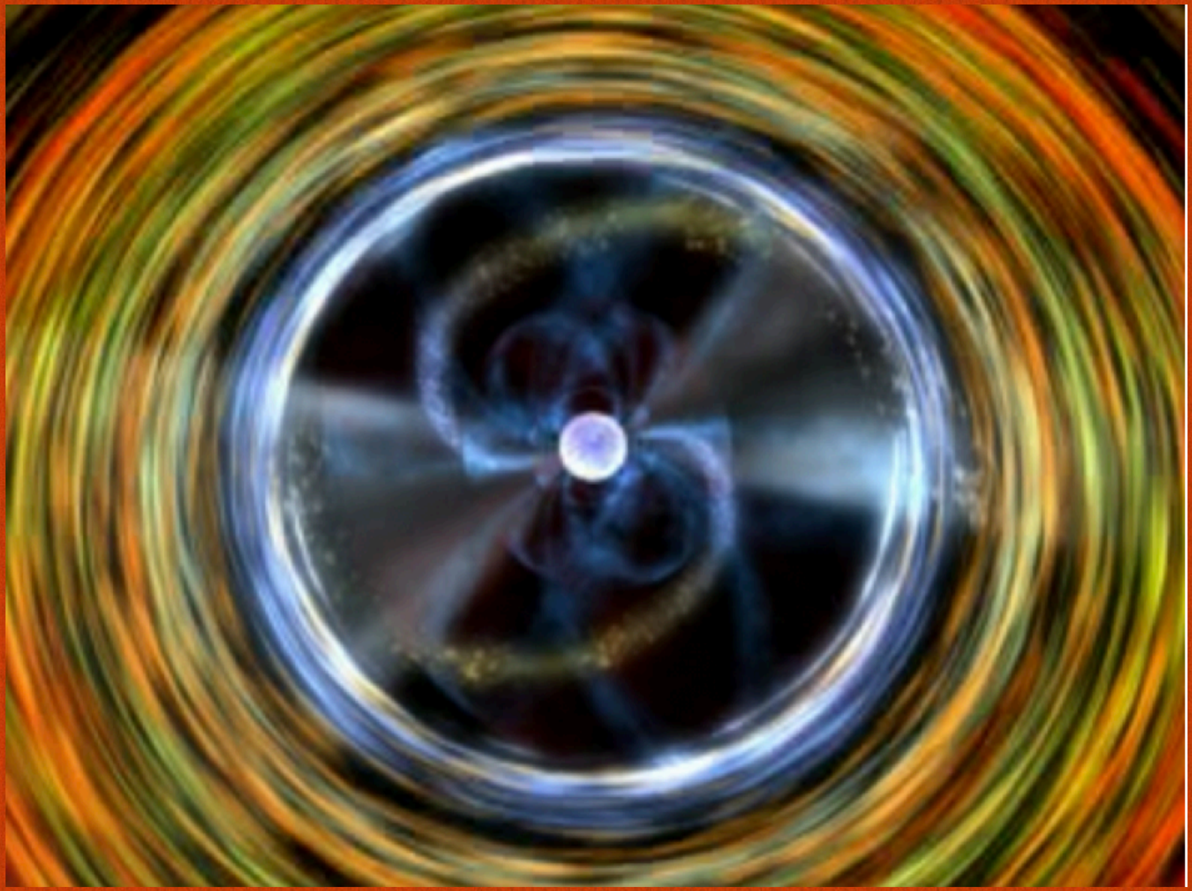
Parameters	S18	This work
RA (J2000)	$17^h59^m02\overset{s}{.}86 \pm 0.04^s$	
Dec. (J2000)	$-23°43'08\overset{''}{.}3 \pm 0.1''$	
Orbital period P_{orb} (s)	31684.743(3)	31684.7503(5)
Projected semimajor axis $a\sin i/c$ (lt-s)	1.227716(8)	1.227714(4)
Ascending node passage T_{NOD} (MJD)	58345.1719787(16)	58345.1719781(9)
Eccentricity (e)	$<6 \times 10^{-5}$	$<5 \times 10^{-5}$
χ^2/d.o.f.	123.75/99	876.4/355
Fundamental		
Spin frequency ν_0 (Hz)	527.42570042(8)	527.425700578(9)
Spin frequency 1st derivative $\dot{\nu}_0$ (Hz s^{-1})	$2.0(1.6) \times 10^{-13}$	$-7.4(4) \times 10^{-14}$
First Harmonic		
Spin frequency ν_0 (Hz)	–	527.42570056(1)
Spin frequency 1st derivative $\dot{\nu}_0$ (Hz s^{-1})	–	$-7.1(4) \times 10^{-14}$

$$\dot{\nu} \simeq -7 \times 10^{-14} Hz/s$$

SPIN DOWN

Sanna et al. 2020, MNRAS, 495, 1641

Accretion Torque



$$\tau_{acc} = \ell \dot{M} =$$
$$= \sqrt{GMR_m}\dot{M}$$

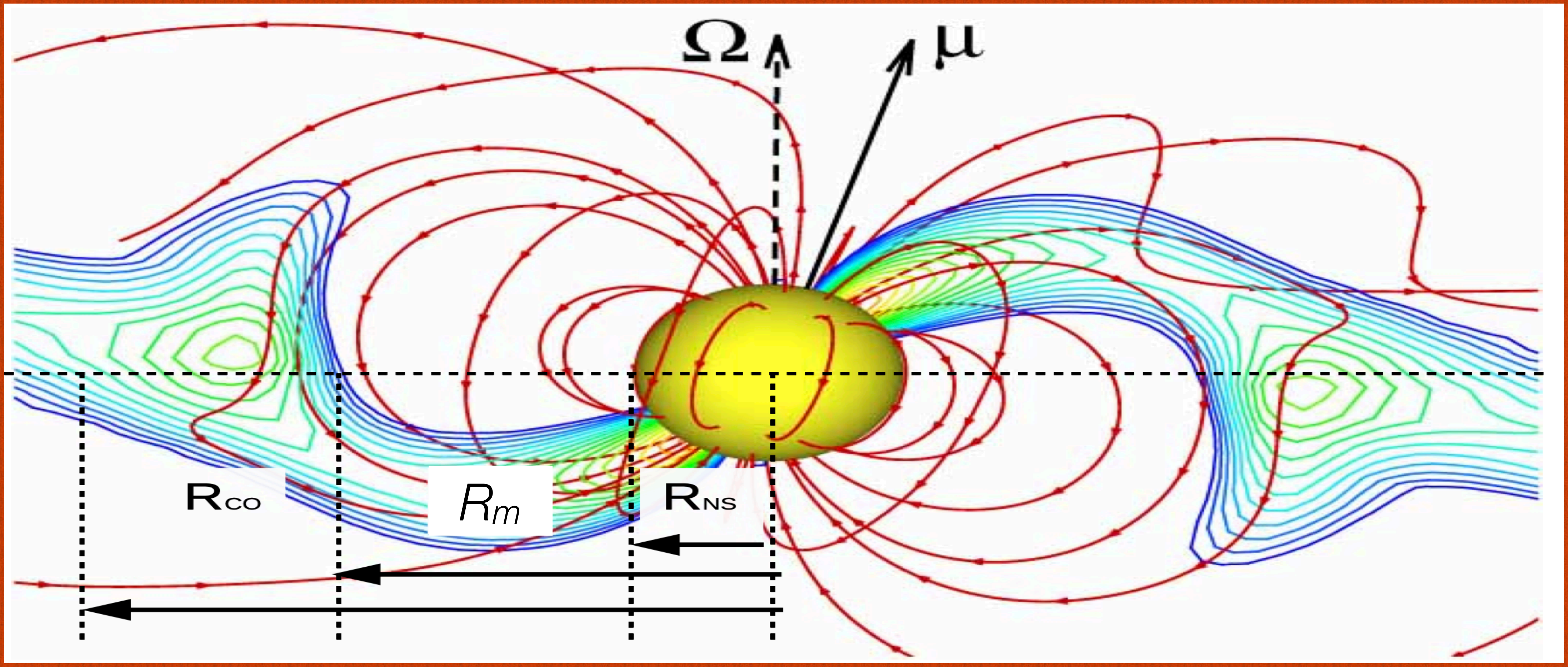
$$R_m \propto \mu^{4/7} \dot{M}^{-2/7} M^{-1/7}$$

$$\tau_{acc} = I\dot{\Omega} = 2I\pi\dot{\nu}$$

$$\dot{\nu} \propto \mu^{2/7} \dot{M}^{6/7} M^{3/7} I^{-1} > 0$$

SPIN UP

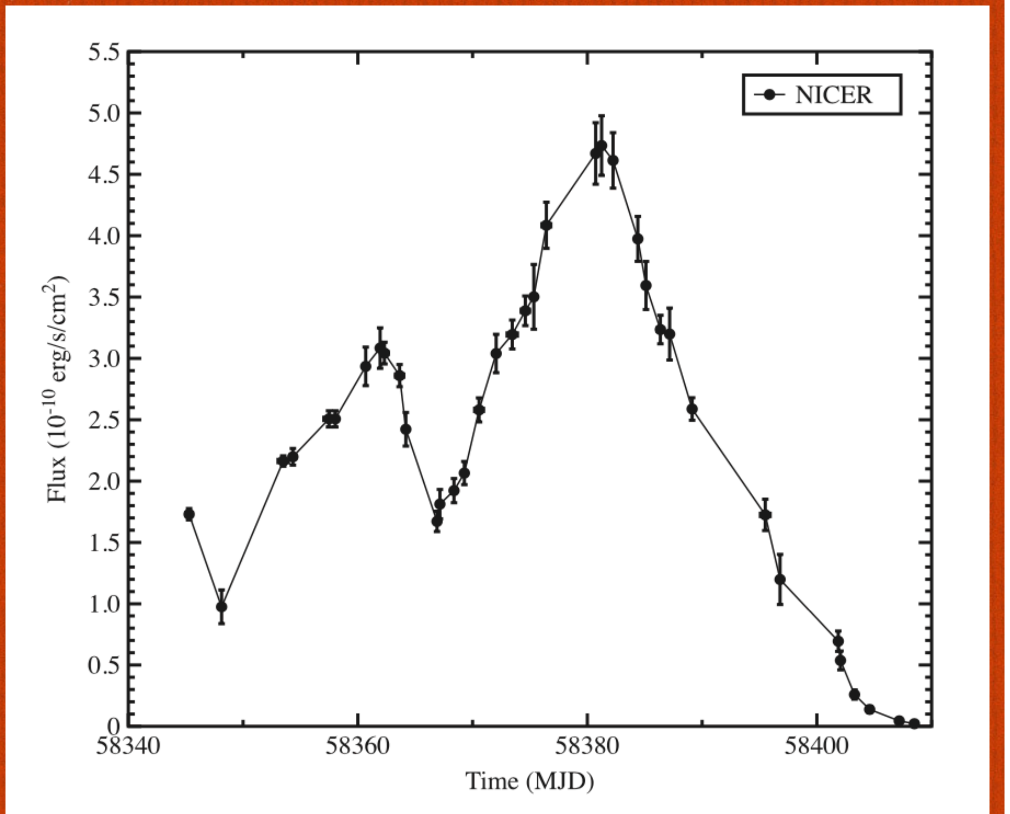
Torque on threaded discs

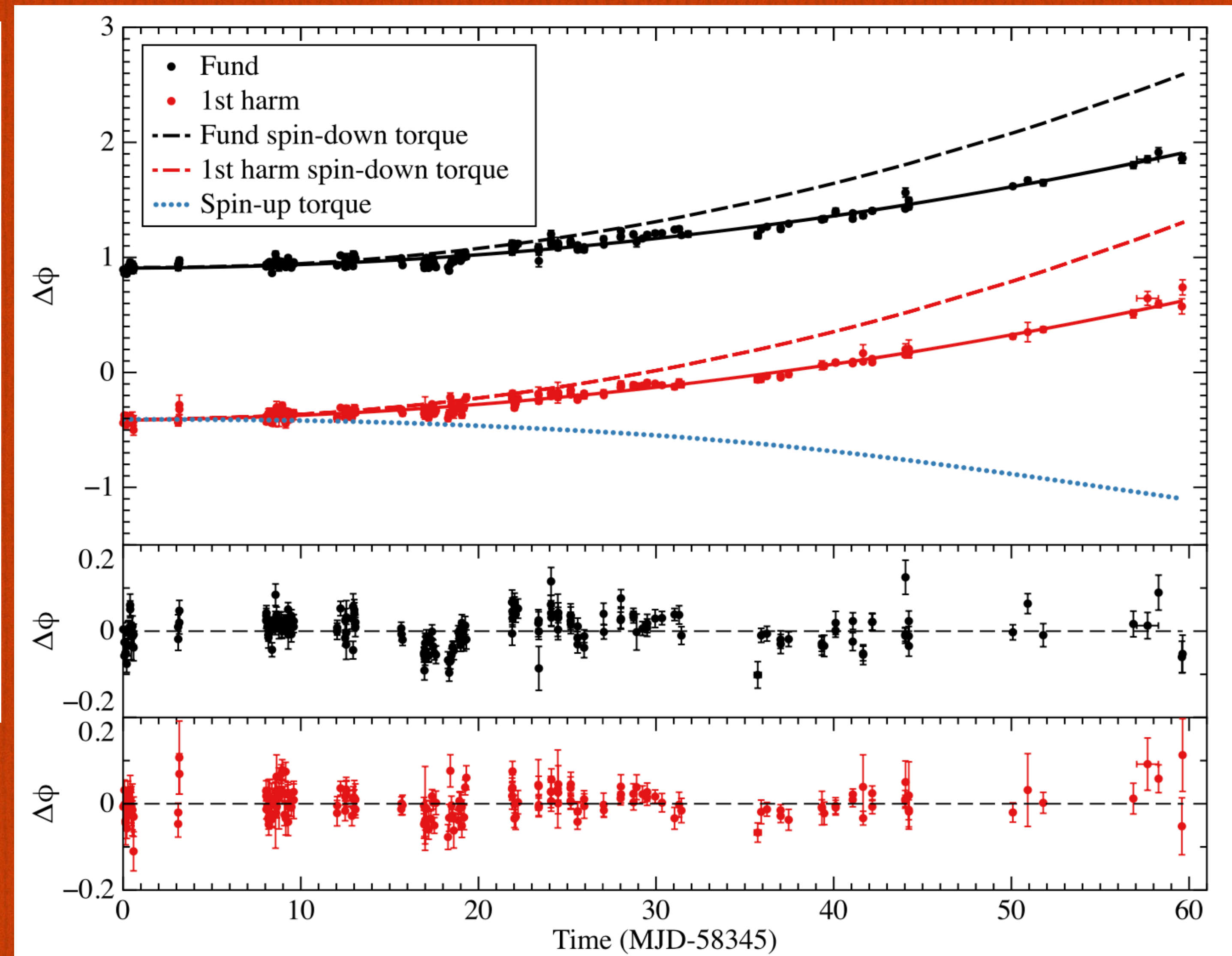


- **Ghosh&Lamb (1979), Wang (1987): for $R_m \simeq R_{CO}$ the field lines are able to thread the disc in regions where they are faster than matter → negative torque on the NS**
- **Rappaport et al. (2004):**

$$\tau = \ell \dot{M} - \gamma \frac{\mu^2}{9 R_{CO}^3}$$

IGR J17591-2342





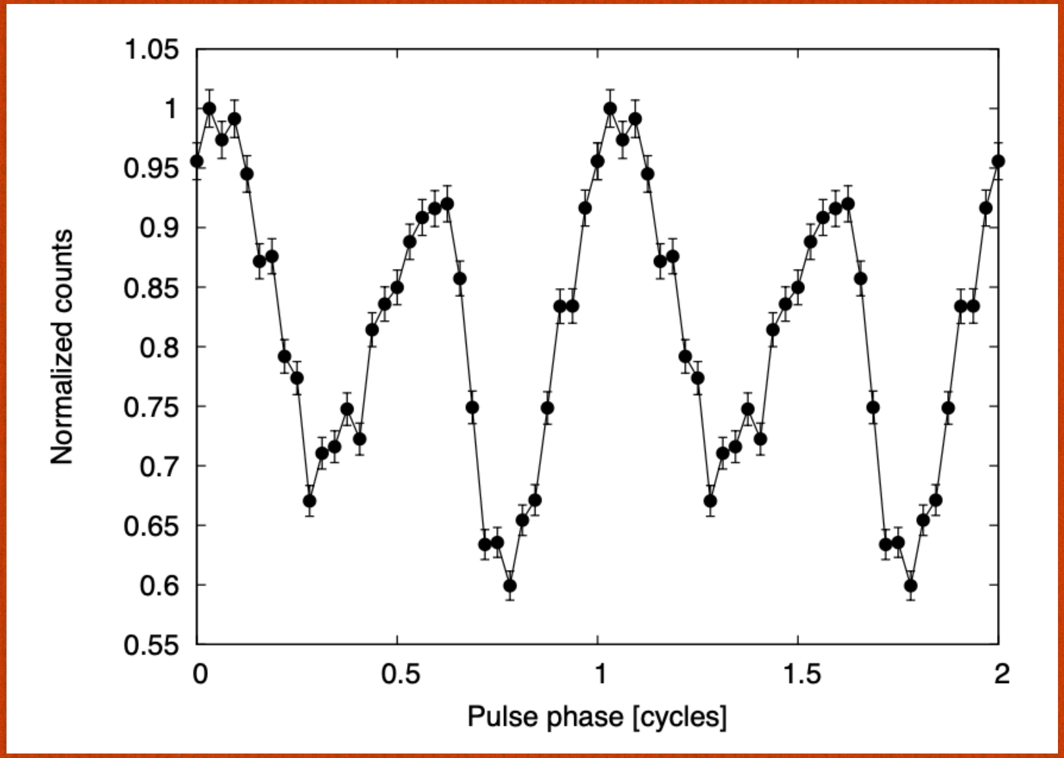
Sanna et al. 2020, MNRAS, 495, 1641

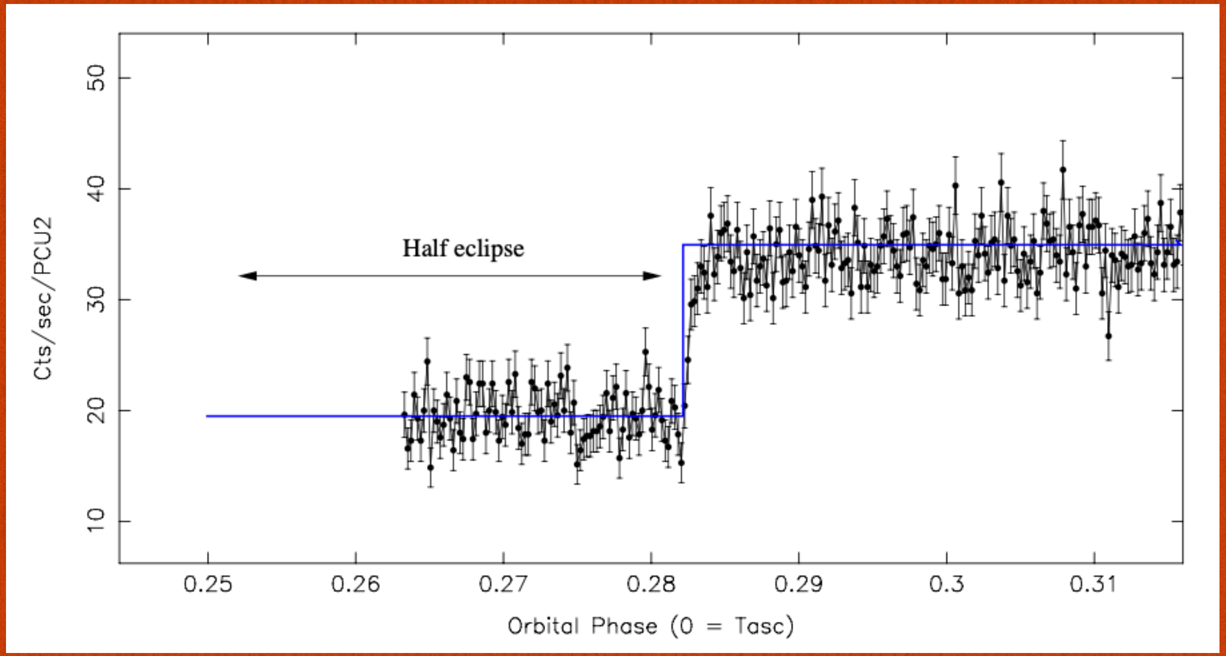
$$\dot{\nu}(t) = \frac{1}{2\pi I_{NS}} \left[\Omega R_{CO}^2 \, \epsilon d^2 F_{0.5-10\mathrm{keV}}(t) - \gamma \frac{\mu^2}{9R_{CO}^3} \right]$$

NS magnetic field $B_{eq} = 2.4(4) \times 10^8 \mathrm{G}$

SWIFT J1749.4-2807

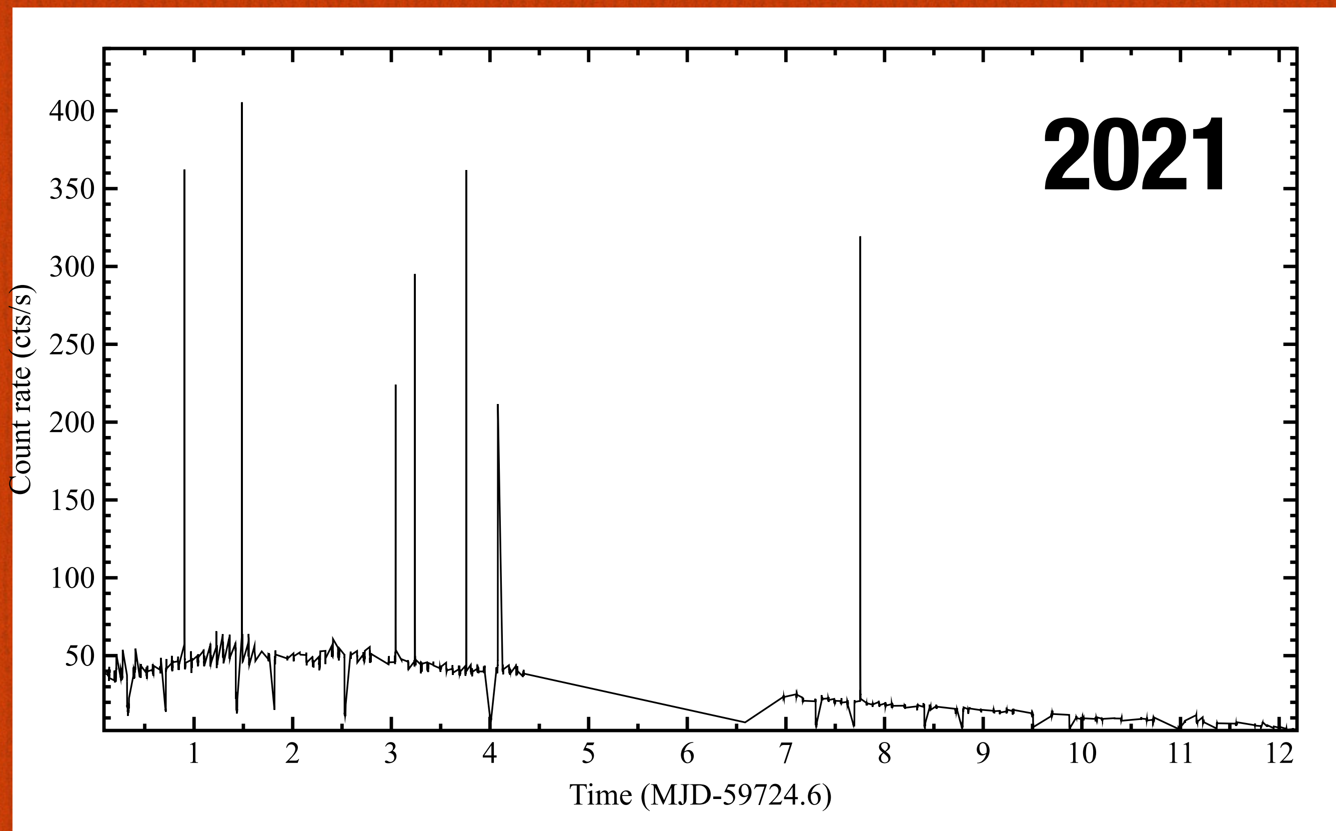
- Discovered on 2006 June 2 by Swift/BAT
- 10th of April 2010 detection of 2nd outburst
- 14th of April 2010 RXTE detects coherent X-ray pulsation at $\nu \simeq 528$ Hz
- First and only AMXP to show X-ray eclipses from which inclination is constrained in the range 74-77 degrees



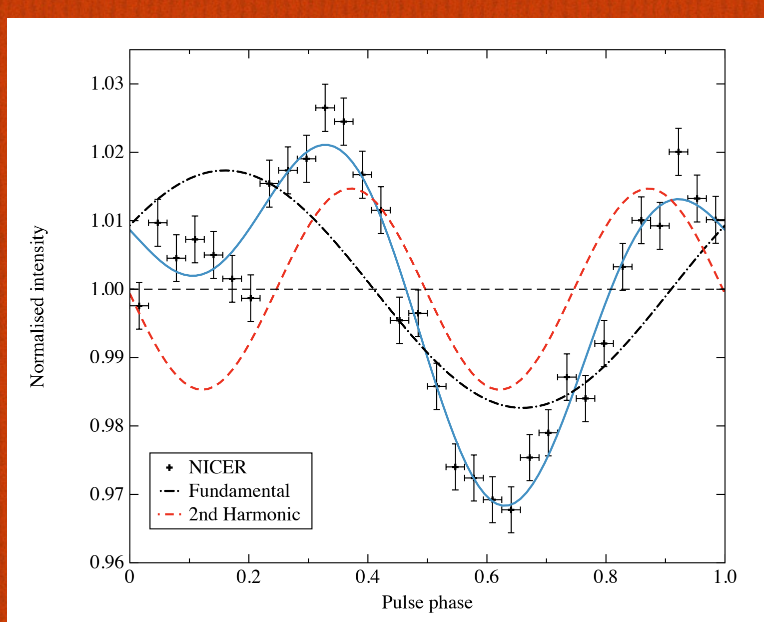


Altaminaro et al. 2010, Markwardt & Strohmayer 2010

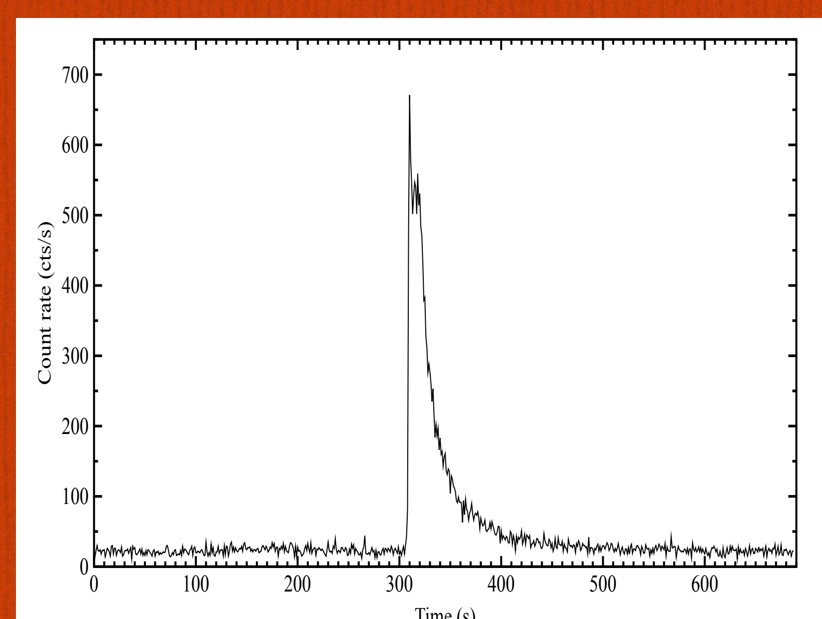
SWIFT J1749.4-2807



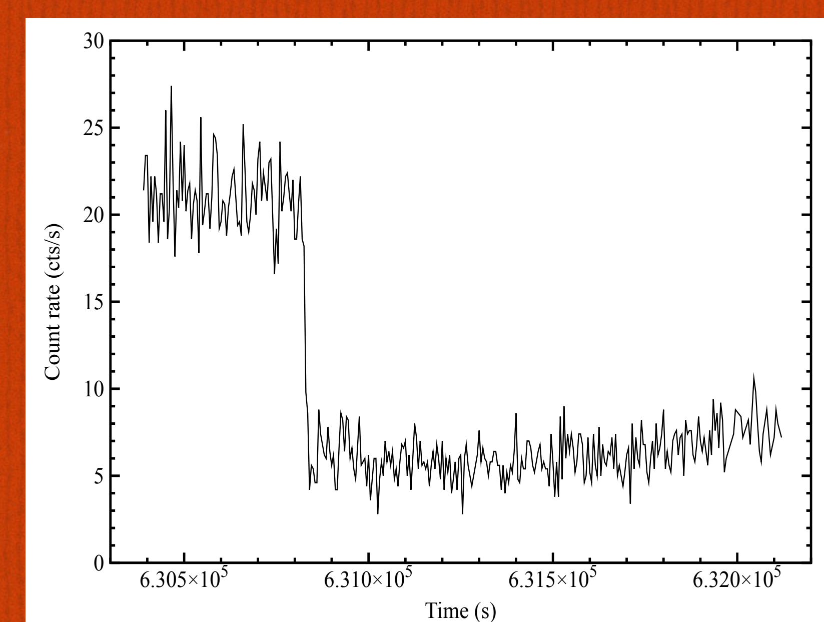
X-ray pulsations



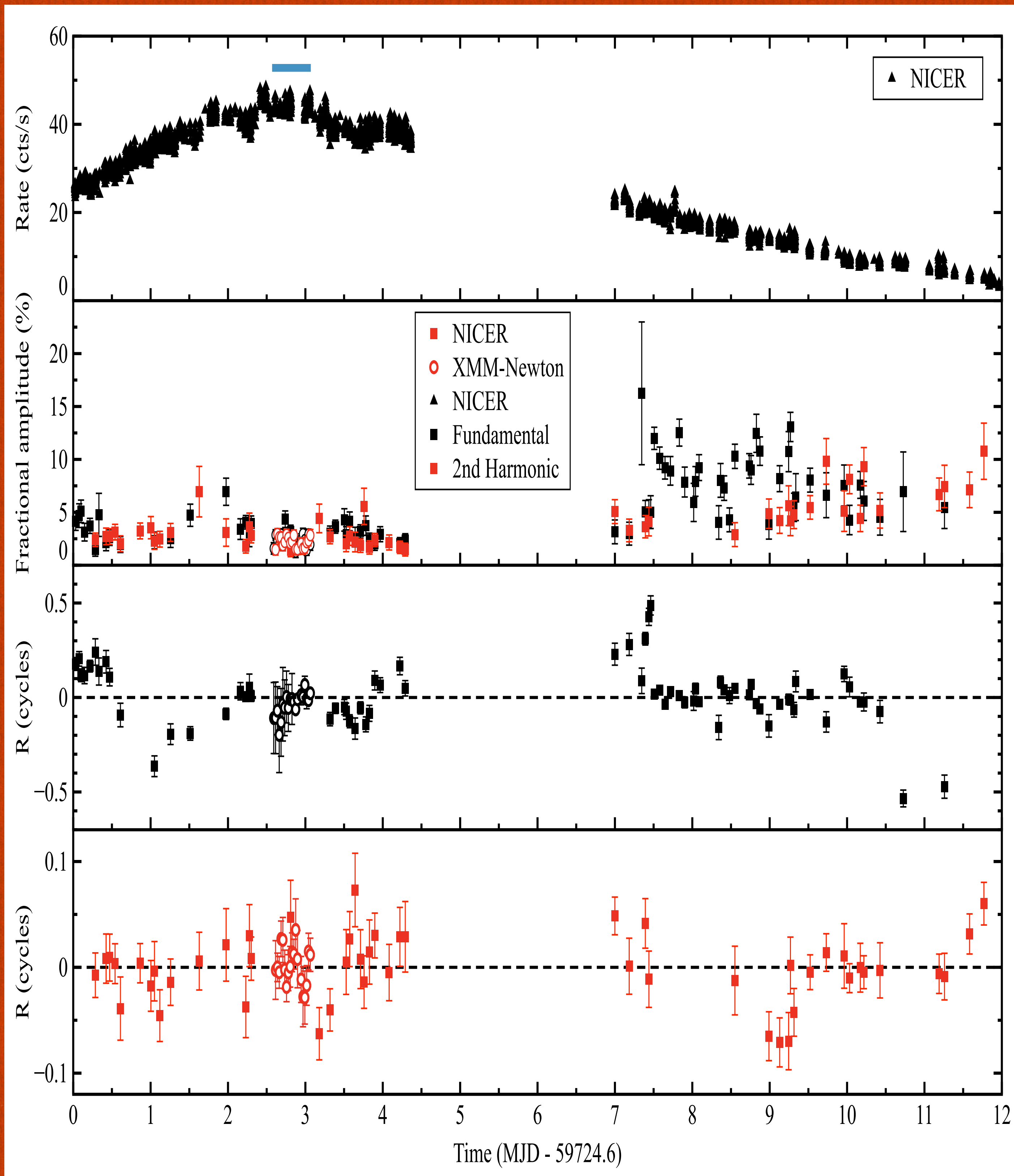
X-ray bursts



X-ray eclipses



SWIFT J1749.4-2807



Phase-coherent timing

Parameters	Fundamental	Second Harmonic
R.A. (J2000)	$17^h 49^m 31^s.73 \pm 0.6^s$	
Decl. (J2000)	$-28°08'05''.08 \pm 0.6''$	
Orbital period P_{orb} (s)	31740.84(1)	31740.8417(27)
Projected semi-major axis $a \sin i/c$ (lt-s)	1.89956(3)	1.899568(11)
Ascending node passage $T_{\rm NOD}$ (MJD)	59274.494176(5)	59274.4941787(14)
Eccentricity (e)	$3.7(3.3) \times 10^{-5}$	$4.1(1.1) \times 10^{-5}$
χ^2/d.o.f.	1001.6/84	97.8/60
Spin frequency ν_0 (Hz)	517.92001572(25)*	517.92001385(16)*
Spin frequency 1st derivative $\dot{\nu}_0$ (Hz/s)	$-4.0(5)\times10^{-12*}$	$-0.6(1.1) \times 10^{-13*}$

Sanna et al. 2021, in prep.

Long-term (secular) orbital evolution

Parameters	2010	2021
Asin(i)/c (lt-s)	1.899494(12)	1.899568(11)
TASC (MJD)	55300.6522542(5)	59274.4941787(14)
Porb (s)	31740.719(8)	31740.8417(27)
Ecc	4.2(1.5)e-5	4.1(1.1)e-5
Spin frequency (Hz)	517.920013925(65)	517.92001385(16)
Spin freq. derivative (Hz/s)	<1.2e-12	-0.6(11)e-13

Sanna et al. 2021, in prep.

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Ecc	4.2(1.5)e-5	4.1(1.1)e-5
Spin frequency (Hz)	517.920013925(65)	517.92001385(16)
Spin freq. derivative (Hz/s)	<1.2e-12	-0.6(11)e-13

$\Delta P_{orb} = 0.123(8)\ s$ ⇒ $\dot{P}_{orb} = 3.6(2) \times 10^{-10}\ s/s$

Sanna et al. 2021, in prep.

Theory of Dynamical (Orbital) evolution

1. J_{TOT} conservation
2. Kepler's third law
3. Contact condition $\dot{R}_{L2}/R_{L2} = \dot{R}_2/R_2$
4. Companion well described by $R_2 \propto M_2^n$
5. $\dot{J}/J$ driven by GR and MB

$$\dot{P}_{ORB} = -1.4 \times 10^{-12}\, m^{5/3}\, q(1+q)^{-1/3}\, P_{2h}^{-5/3} \left[\frac{n-1/3}{n-1/3+2g}\right] [1+T_{MB}]$$

assuming

$$m_{NS} = 0.8 - 2.2M_\odot$$

$$m_c = 0.45 - 0.8M_\odot$$

$$-\frac{1}{3} \leq n < \frac{1}{3}$$

we estimate

Sanna et al. 2021, in prep.

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1. J_{TOT} conservation
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4. Com
5. $\dot{J}/J$

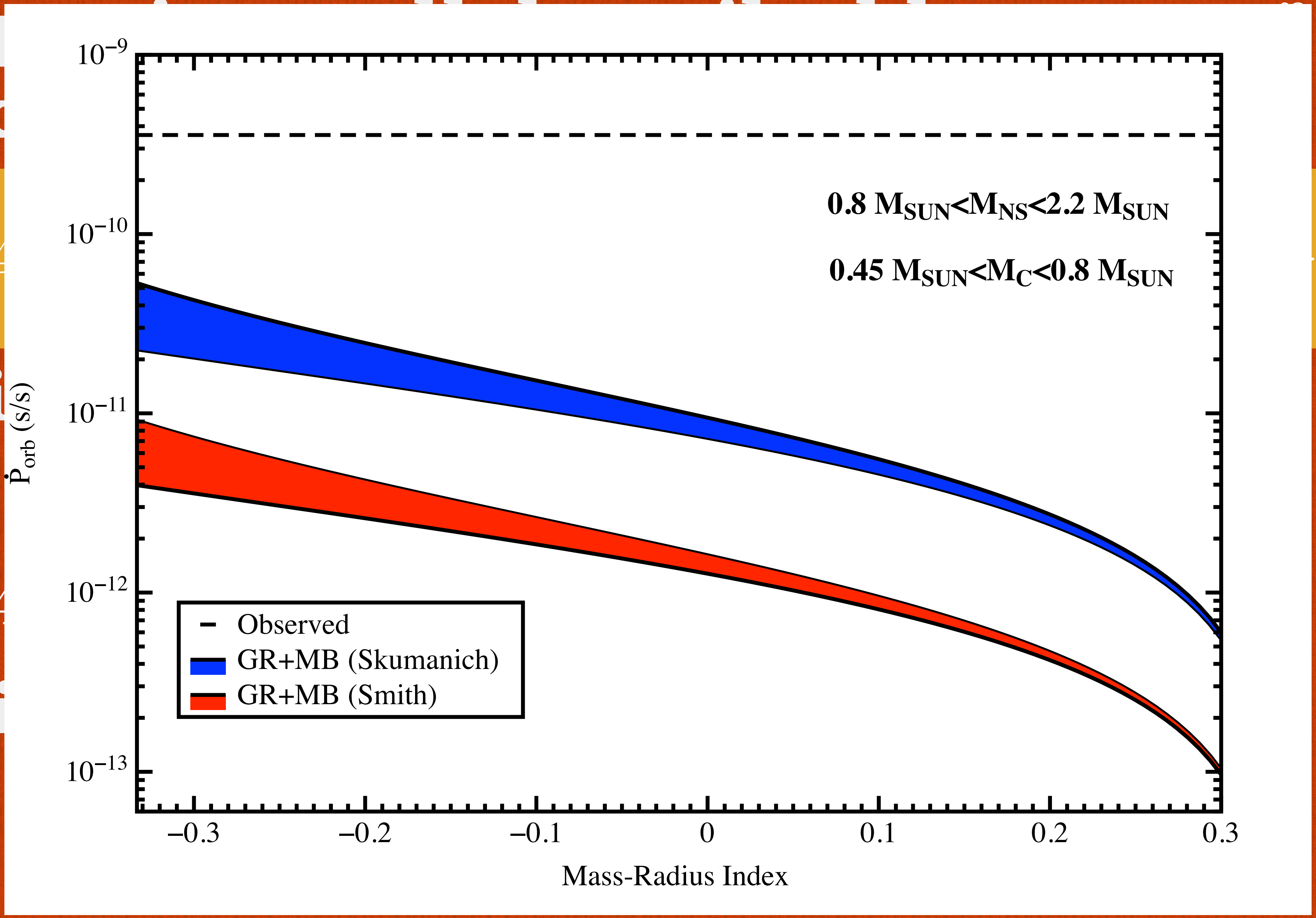
$\dot{P}_{ORB} = -1.4$ … $T_{MB}]$

assumi

$m_{NS} =$

$m_c = 0.4$

we esti



Sanna et al. 2021, in prep.

Predictions vs Observations

2. Fully non-conservative mass transfer

$$\beta = 0 \quad \Rightarrow \quad g = 1 - (\alpha + q/3)/(1+q)$$

assuming

$$m_{NS} = 0.8 - 2.2 M_\odot$$

$$m_c = 0.45 - 0.8 M_\odot$$

$$-\frac{1}{3} \leq n < \frac{1}{3}$$

we find that

$$\dot{P}_{orb} \simeq \dot{P}_{orb_{obs}} for\, \alpha > 0.8$$

matter ejected in the vicinity of the companion star

Sanna et al. 2021, in prep.

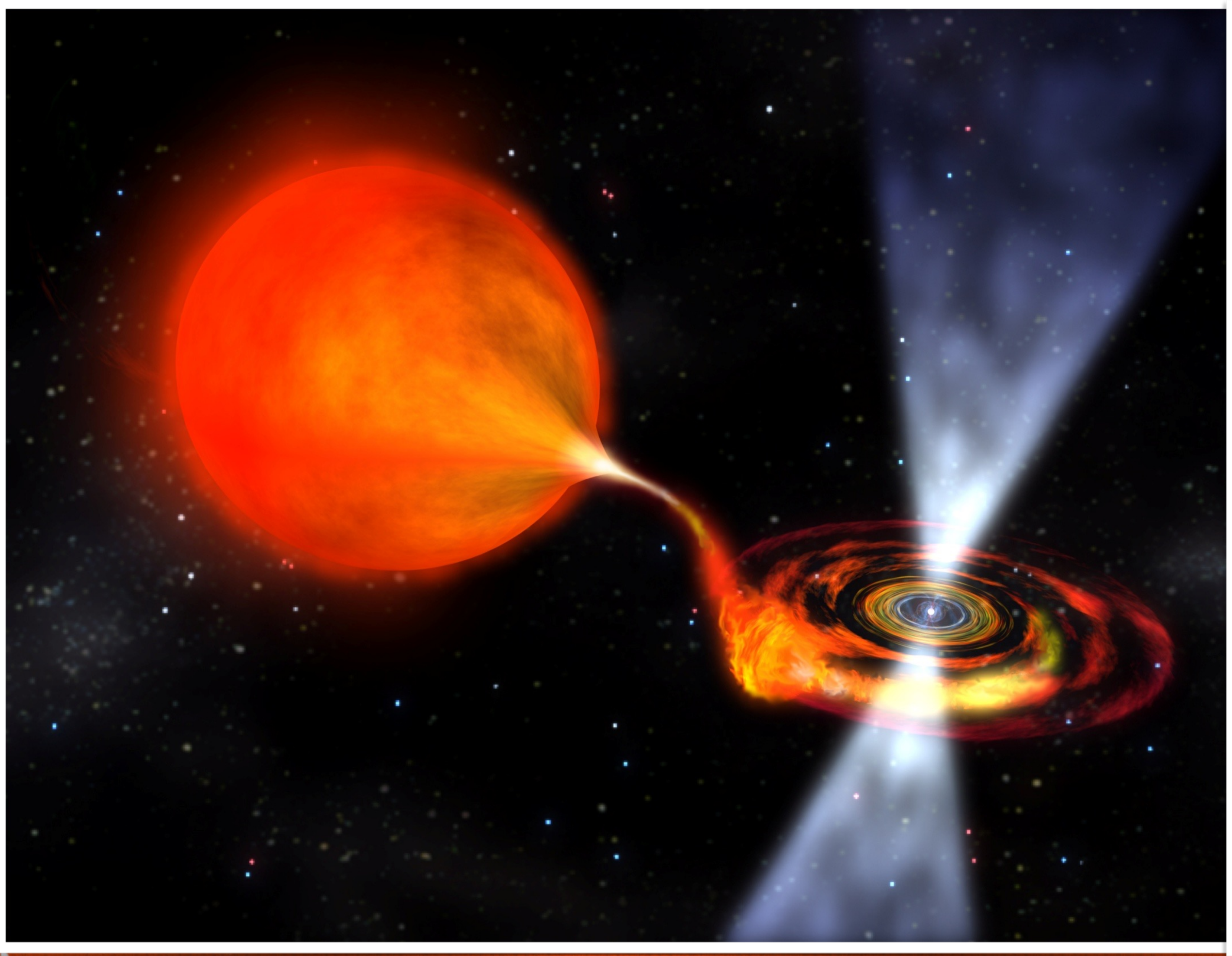
Secular orbital evolution

Source	Pspin (ms)	Porb (h)	dPorb/dt (s/s) (u.l. at 3 σ c.l.)	Ref.
SAX J1808.4-3658	2.5	2	1.7(5) 10^{-12}	Bult+19 Sanna+17
IGR J00291+5934	1.7	2.5	(-6.6÷6.5) 10^{-13}	Patruno+16 Sanna+17
SAX J1748.9-2021	2.3	8.8	(-0.7÷8.4) 10^{-11}	Sanna+21
SWIFT J1756.9-2508	5.5	0.9	(-4.1÷7.1) 10^{-12}	Sanna+18 Bult+18
IGR J17379-3747	2.1	1.9	(-9.4÷4.4) 10^{-12}	Sanna+18
XTE J1751-305	2.3	0.7	(-2.7÷0.7) 10^{-11}	Riggio+11

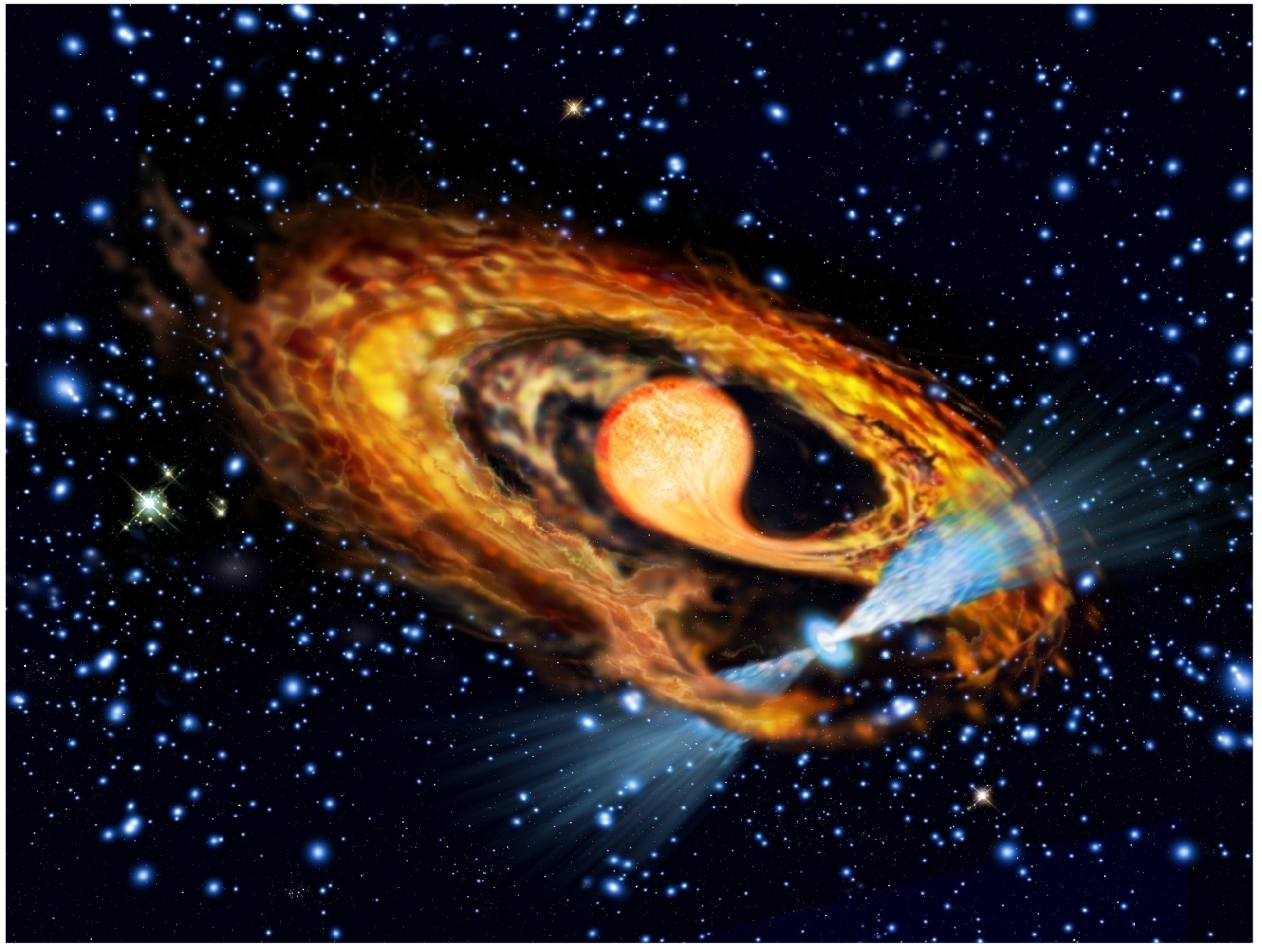
see also Marino+17, 19 for an alternative method

The Radio-Ejection hypothesis

Outburst:
accretion phase



Quiescence:
radio ejection



(Burderi et al. 2001, Di Salvo et al. 2008)

Thanks for the attention!