Accreting Millisecond X-ray Pulsars: Insights into accretion and spin evolution

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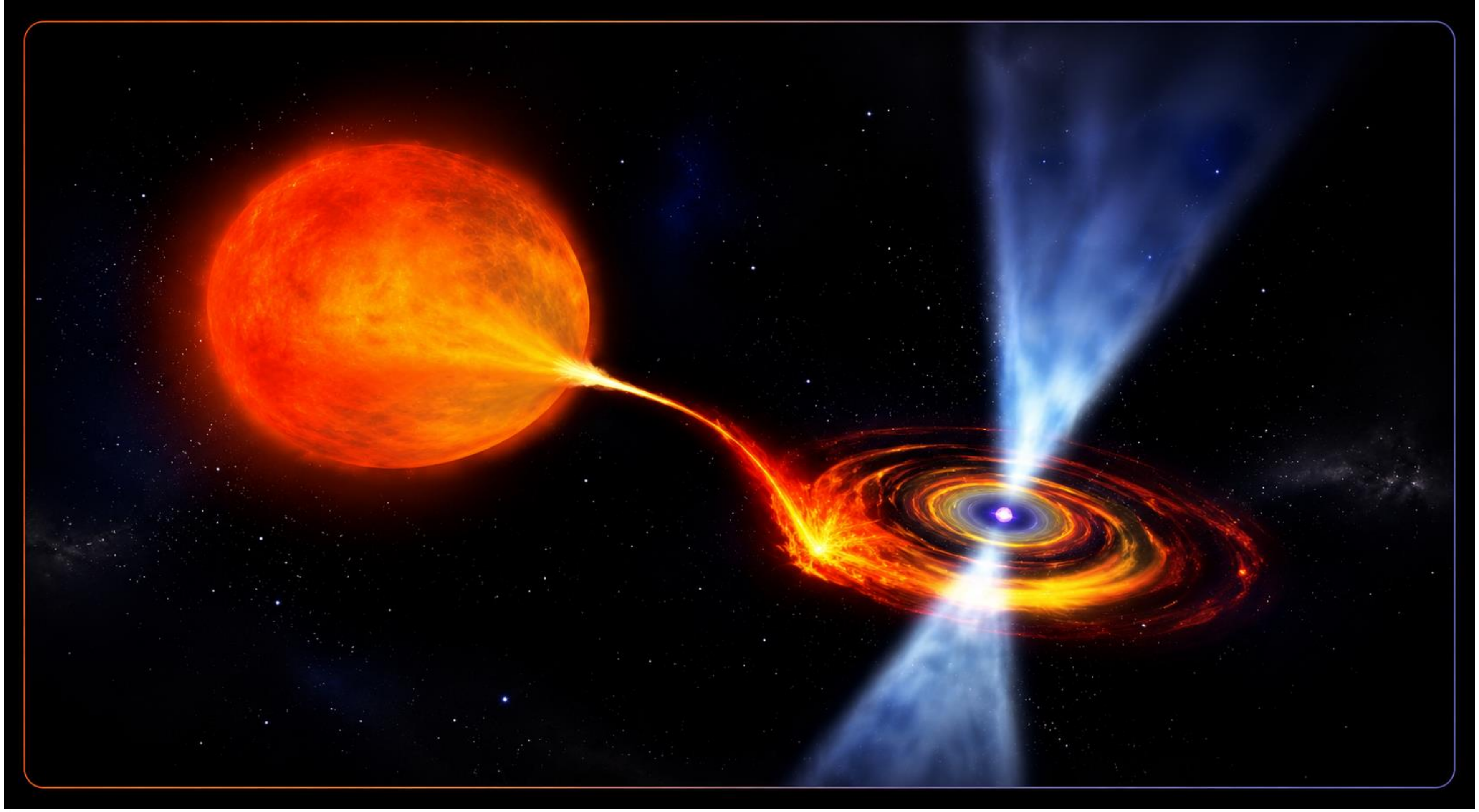
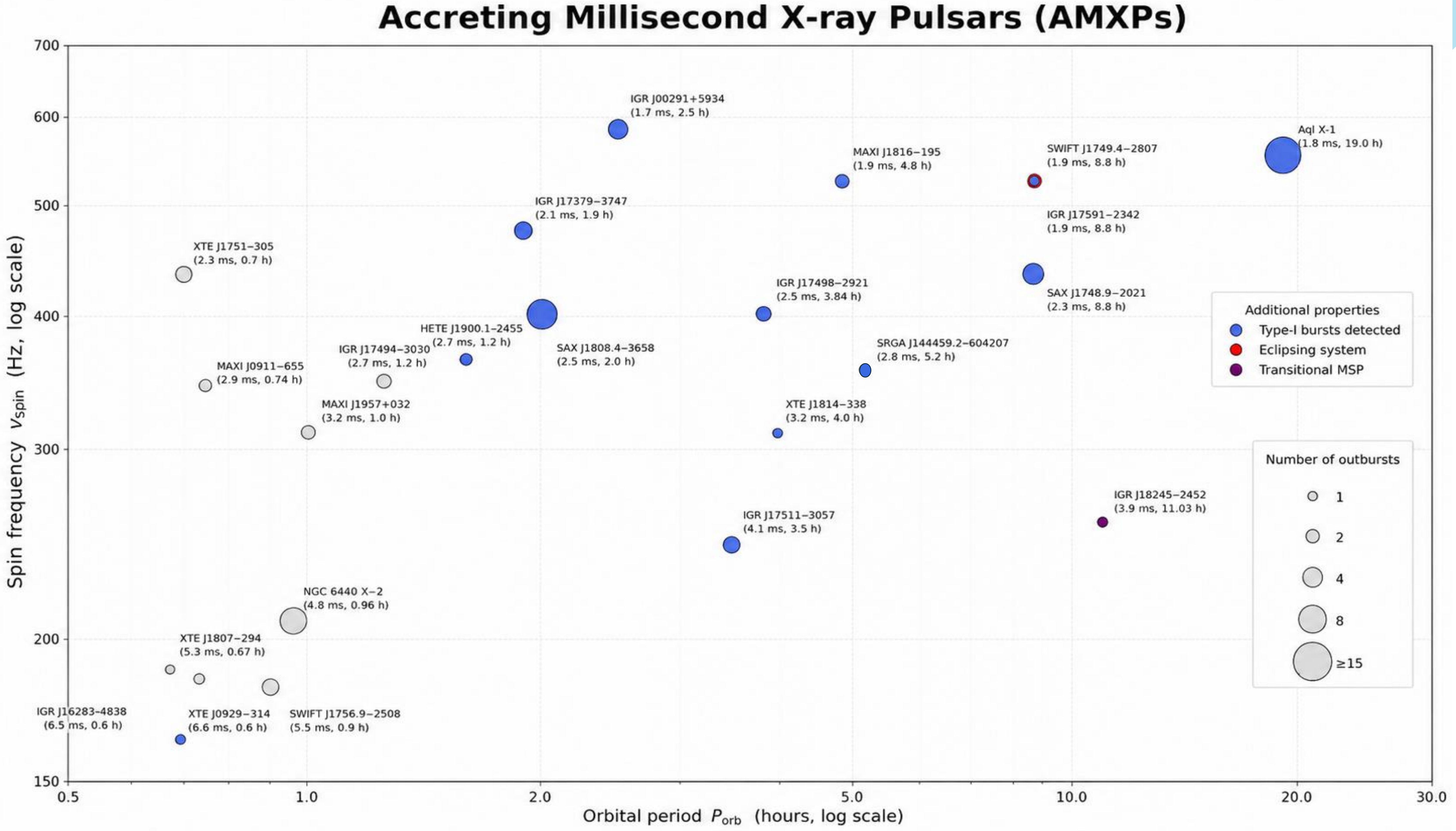
Tomaso

A colleague, a mentor, and a constant presence in our community.

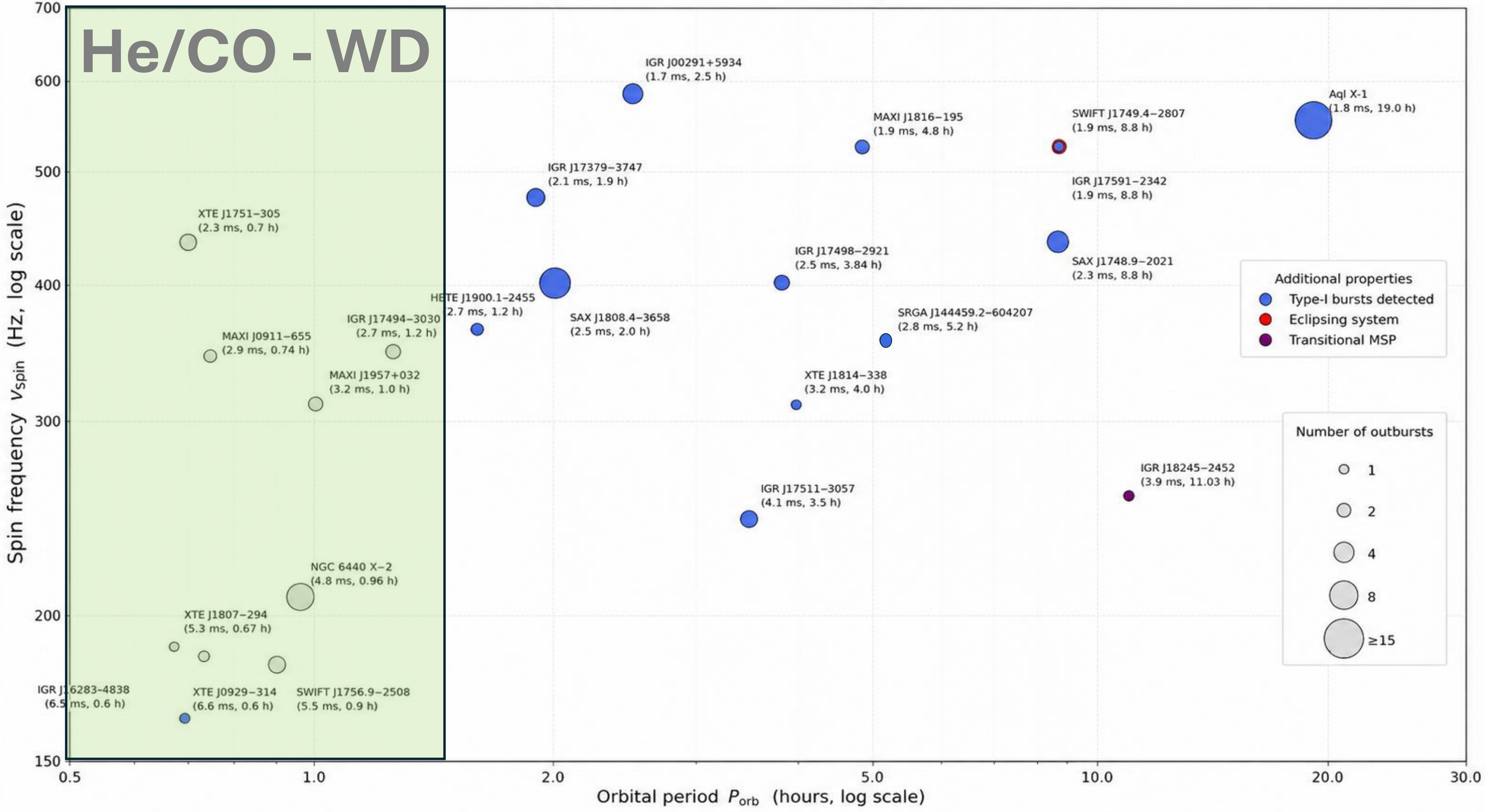


Accreting millisecond X-ray pulsars



Accreting Millisecond X-ray Pulsars (AMXPs)
Spin frequency ν_{spin} (Hz, log scale)
Orbital period P_{orb} (hours, log scale)
700
600
500
400
300
200
150
0.5
1.0
2.0
5.0
10.0
20.0
30.0
IGR J00291+5934 (1.7 ms, 2.5 h)
Aql X-1 (1.8 ms, 19.0 h)
MAXI J1816−195 (1.9 ms, 4.8 h)
SWIFT J1749.4−2807 (1.9 ms, 8.8 h)
IGR J17379−3747 (2.1 ms, 1.9 h)
IGR J17591−2342 (1.9 ms, 8.8 h)
XTE J1751−305 (2.3 ms, 0.7 h)
IGR J17498−2921 (2.5 ms, 3.84 h)
SAX J1748.9−2021 (2.3 ms, 8.8 h)
HETE J1900.1−2455 (2.7 ms, 1.2 h)
IGR J17494−3030 (2.7 ms, 1.2 h)
SAX J1808.4−3658 (2.5 ms, 2.0 h)
SRGA J144459.2−604207 (2.8 ms, 5.2 h)
MAXI J0911−655 (2.9 ms, 0.74 h)
MAXI J1957+032 (3.2 ms, 1.0 h)
XTE J1814−338 (3.2 ms, 4.0 h)
IGR J18245−2452 (3.9 ms, 11.03 h)
IGR J17511−3057 (4.1 ms, 3.5 h)
NGC 6440 X−2 (4.8 ms, 0.96 h)
XTE J1807−294 (5.3 ms, 0.67 h)
IGR J16283−4838 (6.5 ms, 0.6 h)
XTE J0929−314 (6.6 ms, 0.6 h)
SWIFT J1756.9−2508 (5.5 ms, 0.9 h)
Additional properties
Type-I bursts detected
Eclipsing system
Transitional MSP
Number of outbursts
1
2
4
8
≥15

Accreting Millisecond X-ray Pulsars (AMXPs)



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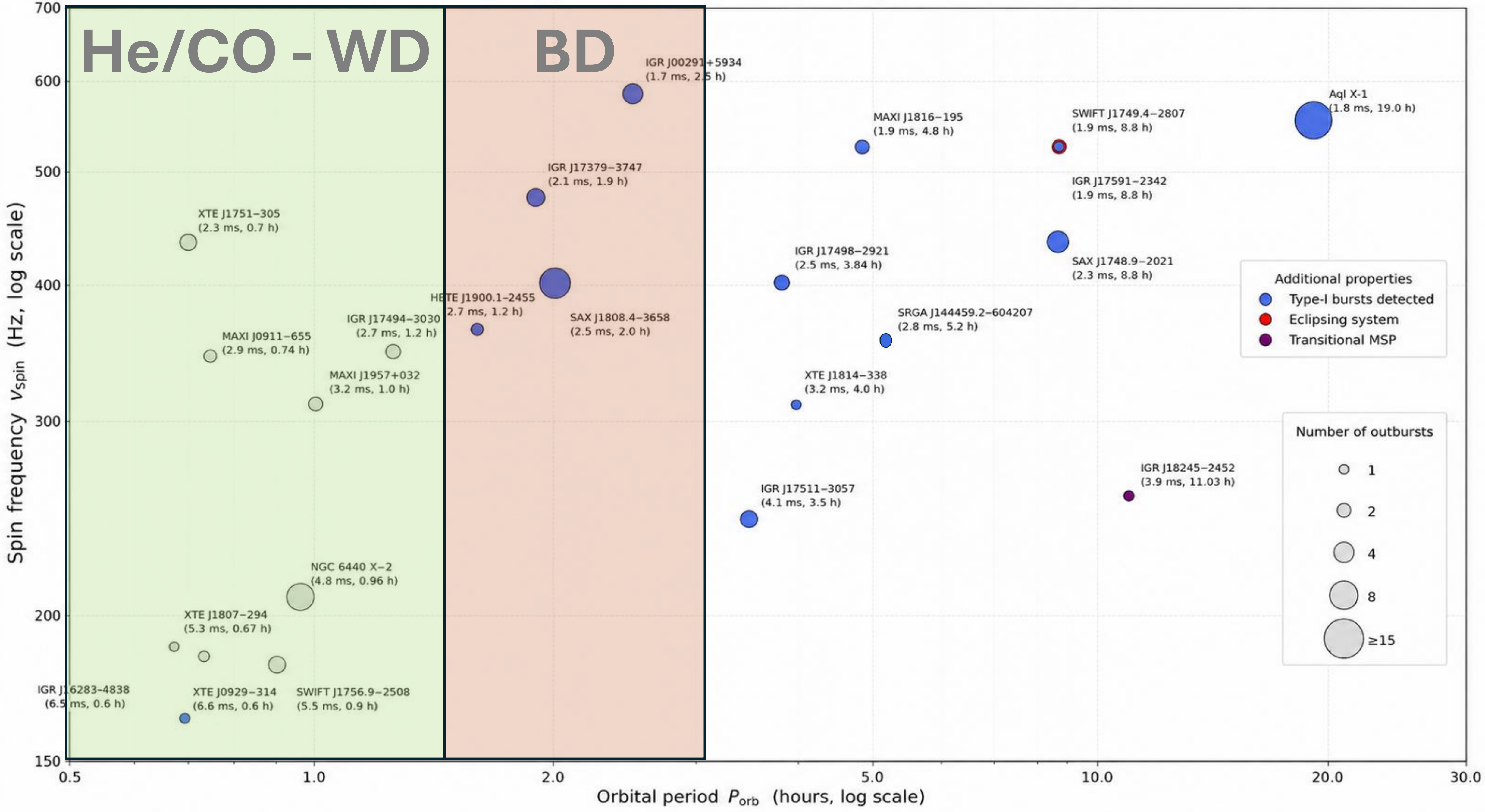

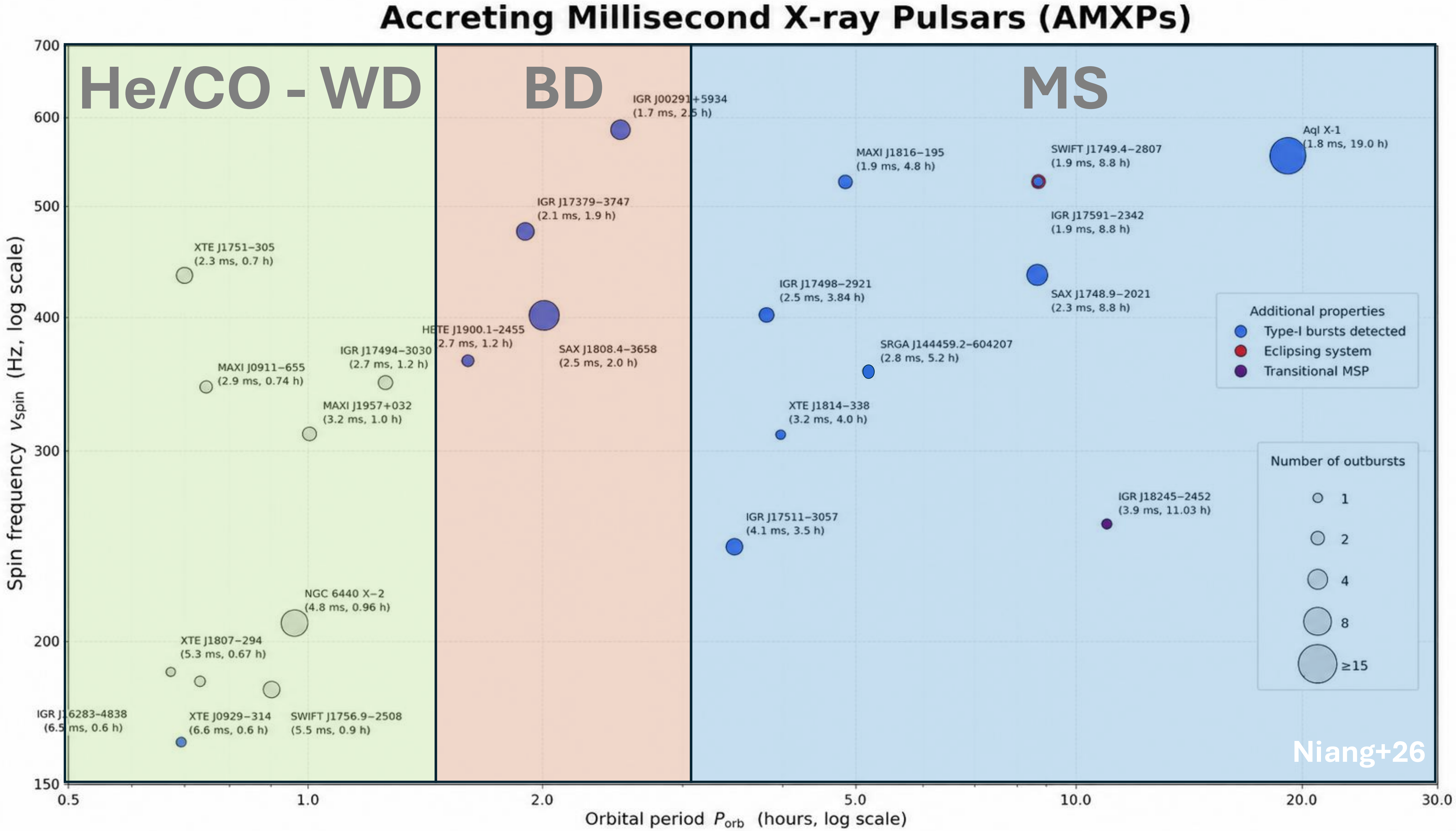
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What timing reveals in AMXPs

1. Measure neutron-star spin evolution

Track pulse arrival times to follow the spin of the neutron star.

2. Track pulse-profile variability and hotspot geometry

Understand changes in the emitting regions and their visibility.

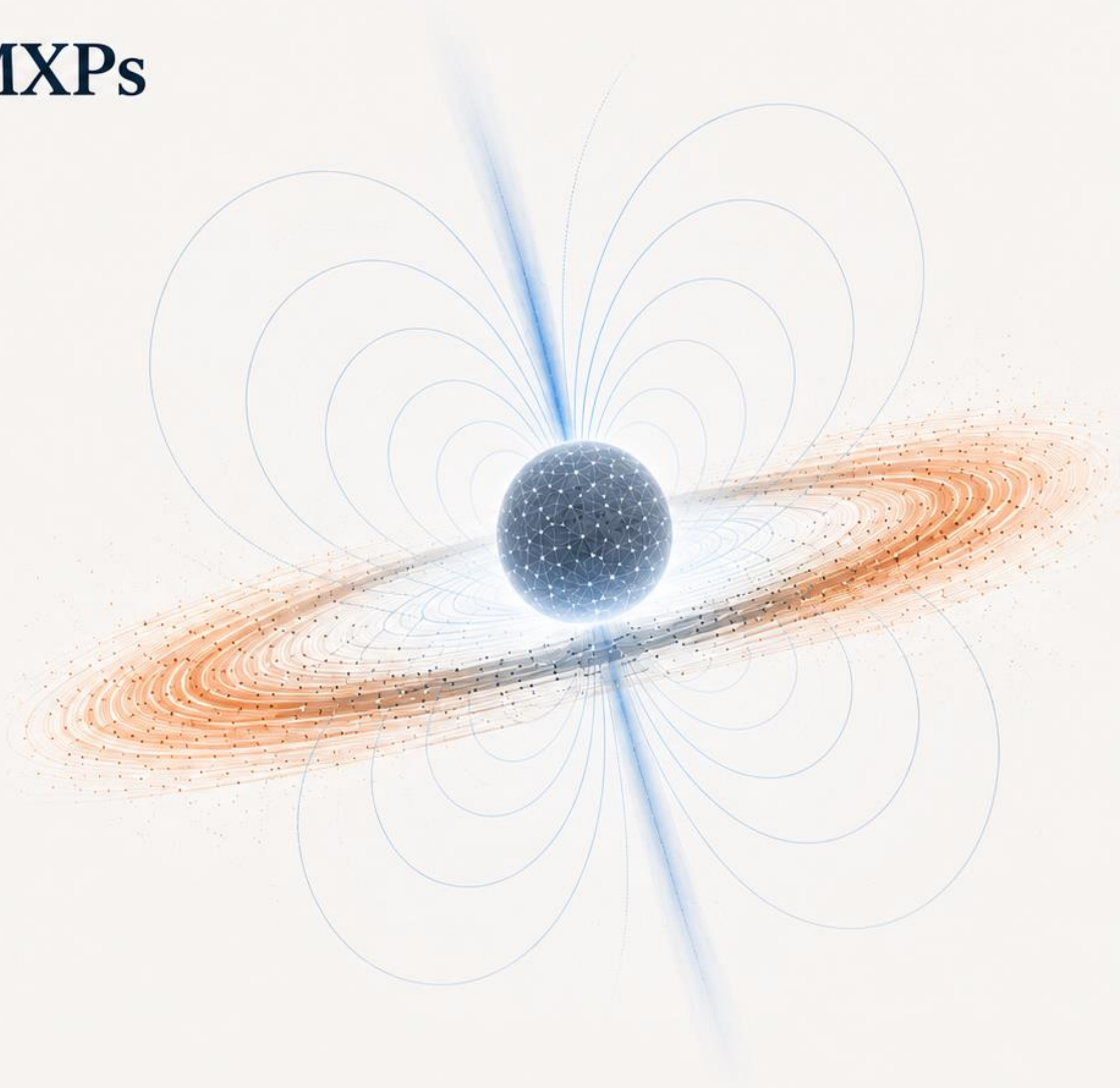
3. Probe accretion torques and magnetosphere–disk coupling

Constrain how matter and magnetic fields exchange angular momentum.

4. Trace secular orbital evolution

Measure long-term changes in orbital period driven by mass transfer, angular momentum losses, and companion evolution.

» *Pulse phases are not always a clean tracer of neutron-star rotation.*



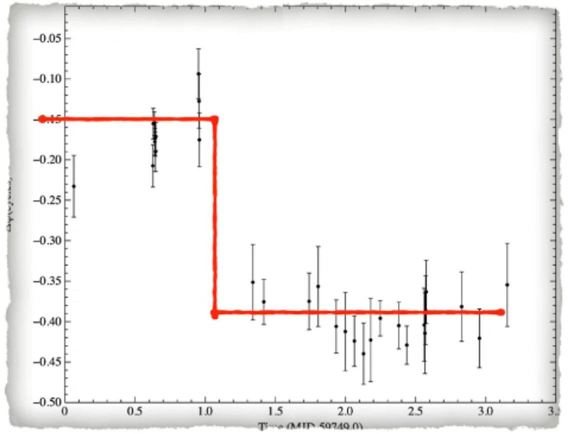
Pulse phase ≠ pure spin phase

Phase behavior reveals more than neutron-star rotation

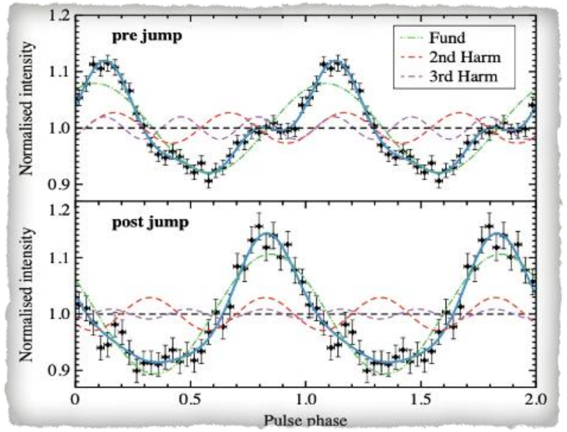
MAXI J1957+032: Pulse phase jumps

- Pulse profiles with high harmonic content
- No clear correlation between phase jumps and X-ray count rate
- Significant variation of the amplitude of harmonic components with time

Phase (fundamental)



Pulse profiles

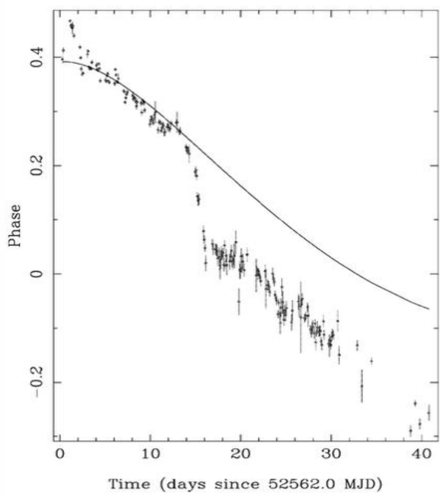


Sanna+22

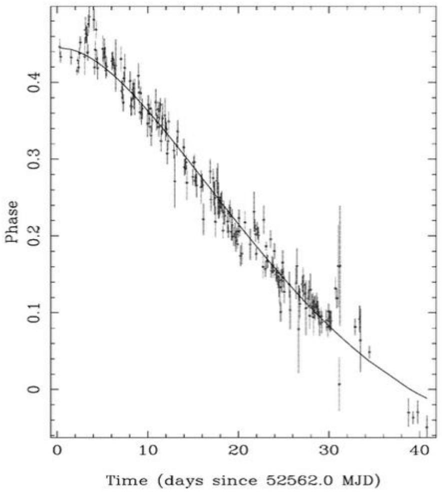
SAX J1808.4-3658: Pulse phase jumps

- The fundamental phase can shift abruptly
- Harmonic component remains more stable
- Jumps coincide with pulse profile and amplitude evolution

Phase (fundamental)



Phase (2nd harmonic)



Burderi+06

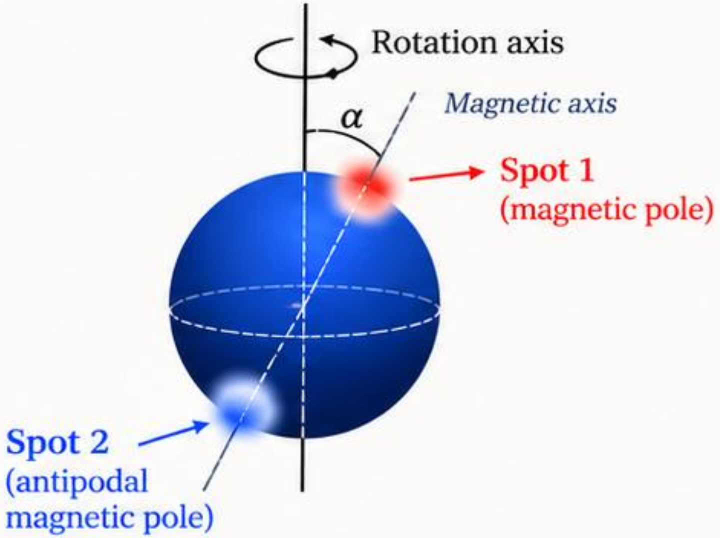
» *Pulse phases are* ***not*** *always a clean tracer of neutron-star rotation.*

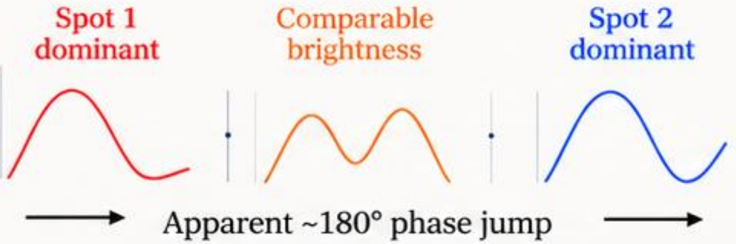
Pulse phase ≠ pure spin evolution

Changes in the emitting geometry can mimic spin-phase variations

A simple geometric picture

Two antipodal hot spots (oblique geometry)

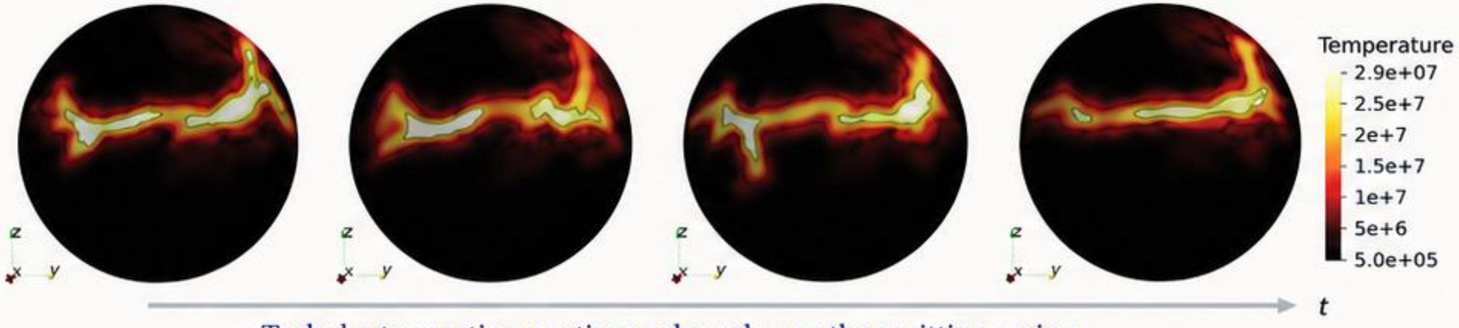




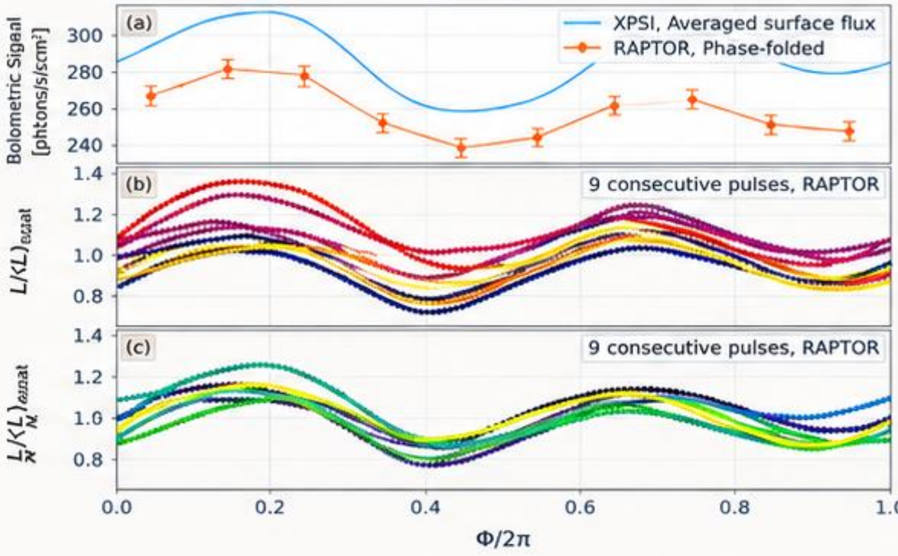
The dominant emitting region can switch without changing the neutron-star rotation.

A more realistic picture: dynamic hotspots

3D GRMHD simulations (Das et al. 2025)



Turbulent accretion continuously reshapes the emitting region.



Hotspots are extended and time-dependent
Their position, shape and temperature vary on timescales comparable to the spin period.

Pulse-to-pulse variability arises naturally
Both amplitude and profile shape change from one pulse to the next.

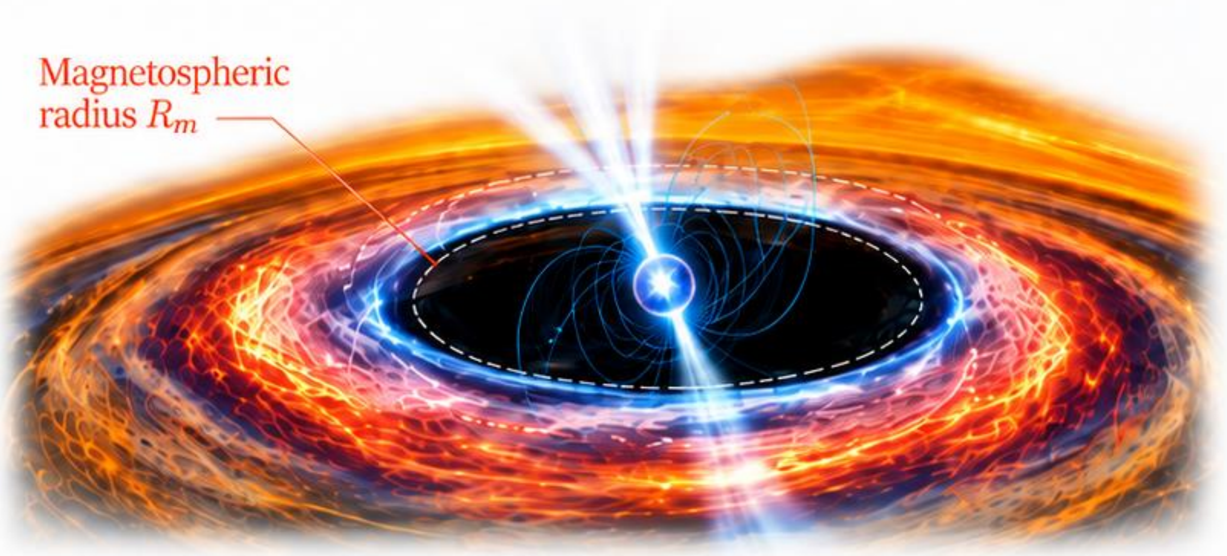
Fundamental phase is particularly sensitive
Variations in hotspot geometry can shift the measured phase, even at fixed stellar spin.

» *Pulse-phase variations do **not** necessarily imply changes in neutron-star spin.*
The measured phase responds to both stellar rotation and the evolving emission geometry.

Spin evolution during outburst: expectation vs observation

Accretion usually spins the neutron star up — but not always.

STANDARD ACCRETION TORQUE (SPIN UP)



Accretion torque (spin-up)

$$\Gamma_{\rm acc} = \dot{M}_* \sqrt{G M r_{in}} > 0$$

Accreted matter transfers angular momentum to the neutron star.

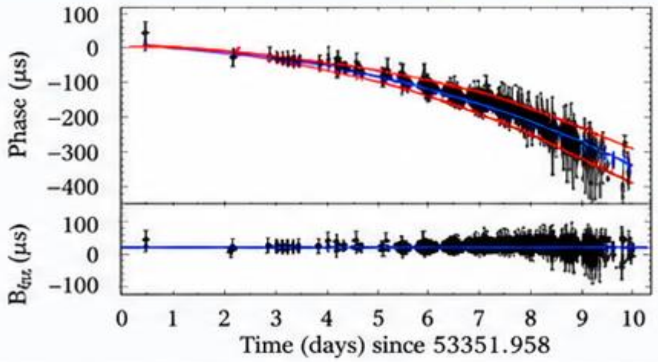
STANDARD EXPECTATION

$$\dot{\nu} > 0$$

Spin-up

OBSERVED SPIN EVOLUTION

IGR J00291+5934 — Spin-up



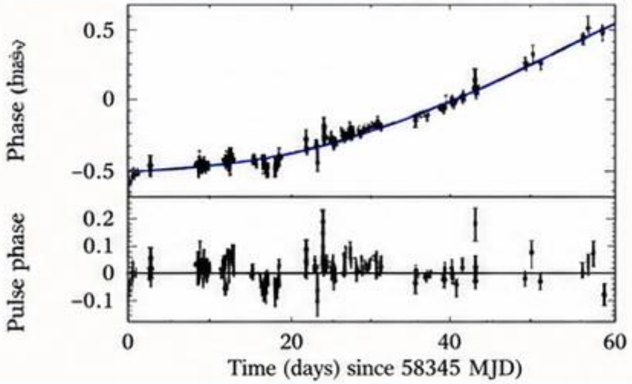
$\dot{\nu} = (5.1 \pm 0.3) \times 10^{-13}$ Hz/s

Spin-up

[Falanga+2005; Burderi+2010; Papitto+2010]

$\dot{\nu} > 0$ vs $\dot{\nu} < 0$

IGR J17591-2342 — Spin-down



$\dot{\nu} = -(7.4 \pm 0.4) \times 10^{-14}$ Hz/s

Spin-down

[Sanna+2020]

Accretion does not guarantee spin-up.

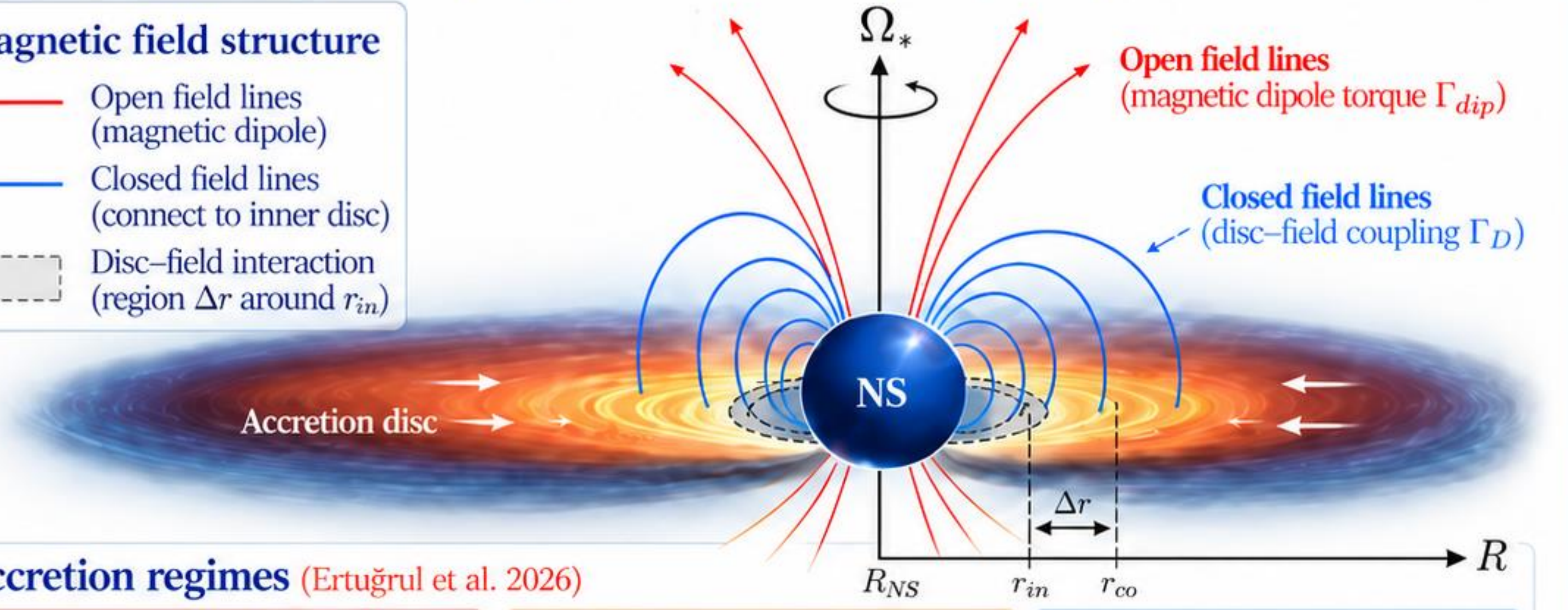
The observed spin evolution measures the net torque acting on the neutron star.

Torques acting on accreting millisecond X-ray pulsars

Accretion and disc-field coupling can drive either spin-up or spin-down.

Magnetic field structure

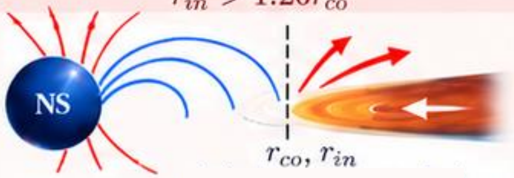
- Open field lines (magnetic dipole)
- Closed field lines (connect to inner disc)
- Disc–field interaction (region Δr around r_{in})



Accretion regimes (Ertuğrul et al. 2026)

Strong propeller (SP)

$r_{in} > 1.26 r_{co}$

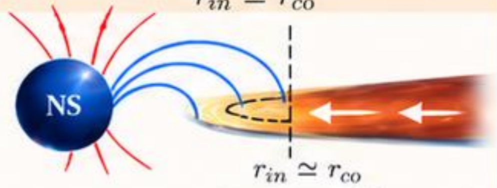


- No accretion onto the neutron star ($\dot{M}_* = 0$)
- $\Gamma = \Gamma_D + \Gamma_{dip} < 0$

Spin-down • no accretion

Weak propeller (WP)

$r_{in} \simeq r_{co}$

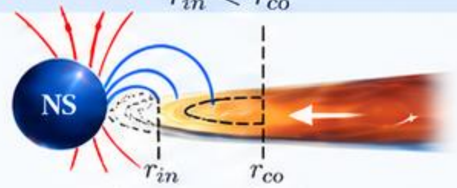


- Accretion is still present ($\dot{M}_* > 0$)
- $|\Gamma_D| > \Gamma_{acc} \Rightarrow \Gamma < 0$

Spin-down while accreting

Spin-up (SU)

$r_{in} < r_{co}$



- Accretion torque dominates
- $\Gamma_{acc} > |\Gamma_D| \Rightarrow \Gamma > 0$

Spin-up • accretion dominated

Torque contributions (Ertuğrul et al. 2026)

$$\Gamma = \dot{M}_* \sqrt{GMr_{in}} - \frac{\mu^2}{r_{in}^3}\left(\frac{\Delta r}{r_{in}}\right) - \frac{2\mu^2\Omega_*^3}{3c^3}$$

Accretion torque Γ_{acc} (spin-up)

$$\Gamma_{acc} = \dot{M}_* \sqrt{GMr_{in}} > 0$$

Transfer of angular momentum by the accreted matter at the inner disc radius.

Disc–field torque Γ_D (spin-down)

$$\Gamma_D = -\frac{\mu^2}{r_{in}^3}\left(\frac{\Delta r}{r_{in}}\right) < 0$$

Magnetic stresses between the star and the inner disc remove angular momentum from the star.

Magnetic dipole torque Γ_{dip} (spin-down)

$$\Gamma_{dip} = -\frac{2\mu^2\Omega_*^3}{3c^3} < 0$$

Open field lines carry away angular momentum. Usually subdominant when the disc is present.

» **Accretion does not necessarily imply spin-up.**
The sign of $\dot{\nu}$ is set by the competition between accretion and disc-field torques.

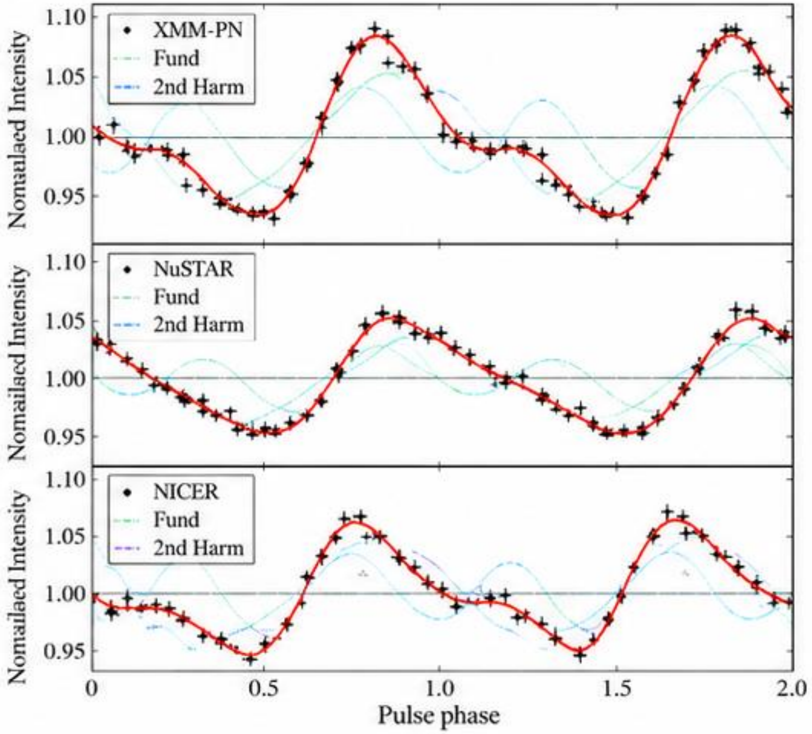
Ertuğrul et al. (2026), *MNRAS* **549**, 1–10

Pulse profiles encode the emitting geometry

Harmonic content and pulse morphology trace the structure of the emitting regions.

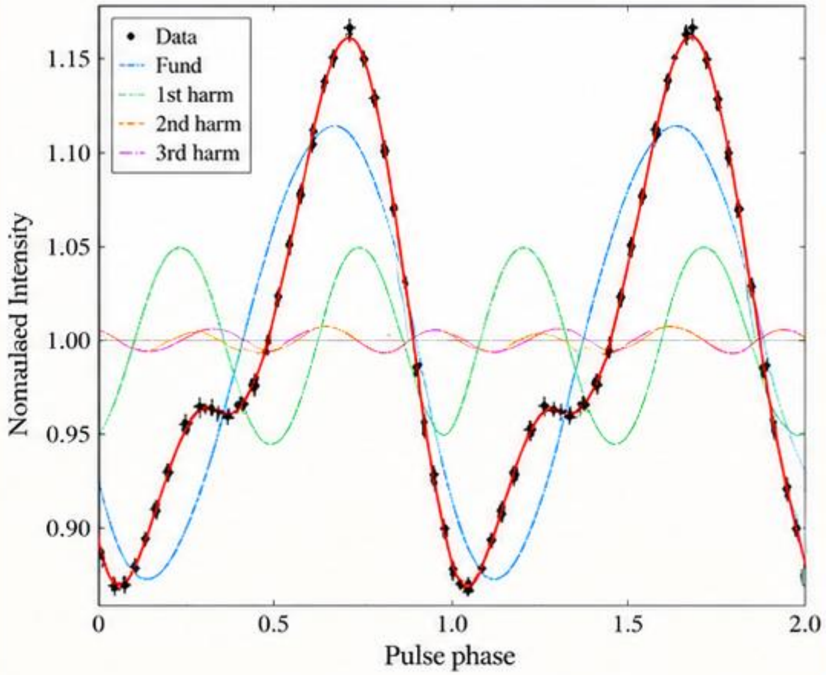
SWIFT J1756.9–2508

Energy- and instrument-dependent harmonic content

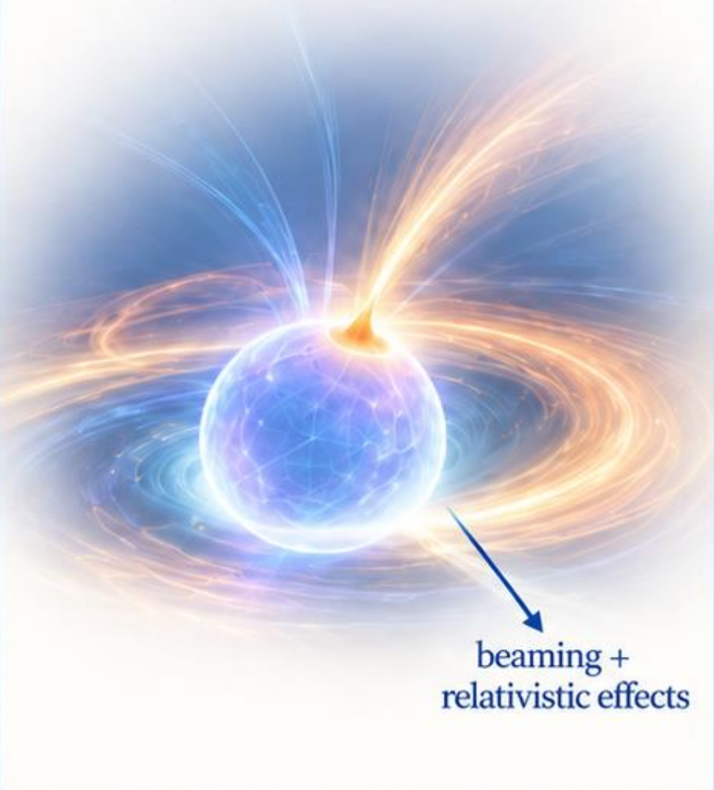


IGR J17591–2342

Strong non-sinusoidal morphology



From pulse profile to geometry



Pulse shape → **Harmonic content** → **Emission geometry** → **But different geometries can produce similar pulse profiles.**

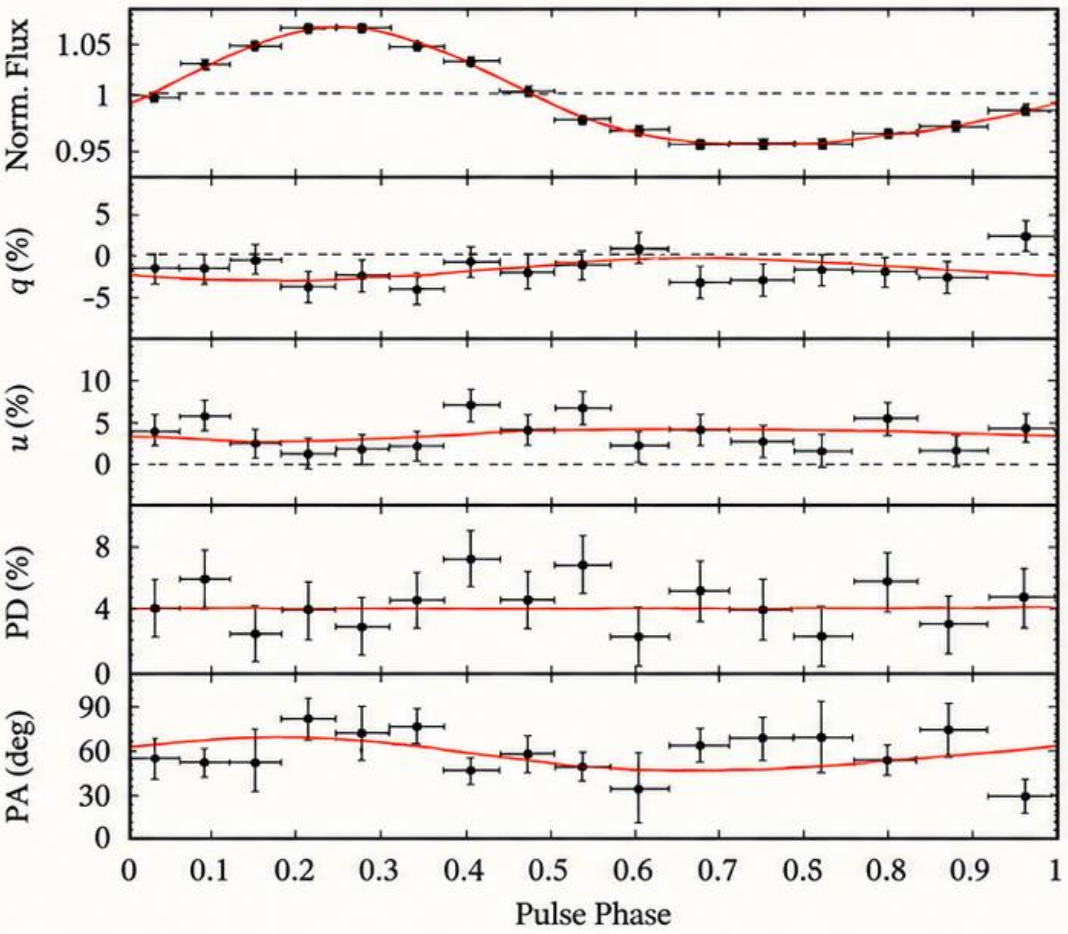
» **Pulse-profile modelling can constrain the hotspot geometry, but degeneracies remain.**
Additional observables are needed to determine the orientation of the emitting regions.

Polarization adds a new view of the hotspot geometry

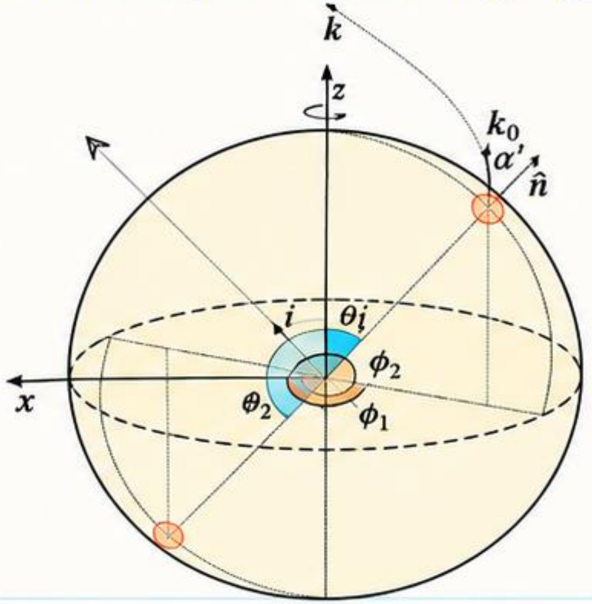
Intensity and polarization probe complementary aspects of the same emitting regions.

SRGA J144459.2−604207

First polarized AMXP



Geometry of the emitting regions



Intensity $I(\phi)$

→ pulse morphology and visibility

Stokes $Q(\phi), U(\phi)$

→ polarization orientation

PD and PA

→ independent geometric information

IXPE detection

$PD_{2-8\ keV} = 2.3 \pm 0.4\%$

$PA = 59° \pm 6°$

$PD_{3-6\ keV} = 4.0 \pm 0.5\%.$

Compatible with two nearly antipodal spots and small magnetic obliquity.

» **Polarization provides an independent handle on the orientation of the emitting regions.**

But weak phase-resolved polarization can still leave substantial degeneracies.

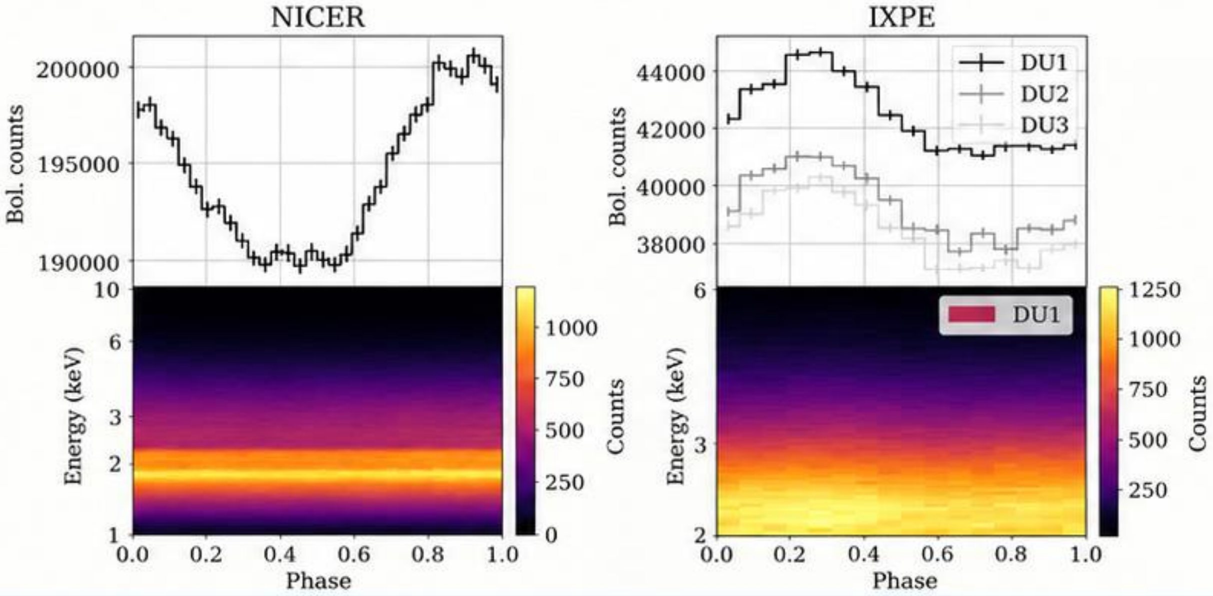
Papitto et al. 2025, A&A 694, A37

From polarization detection to joint inference

NICER intensity and IXPE Stokes data can now probe the same hotspot geometry.

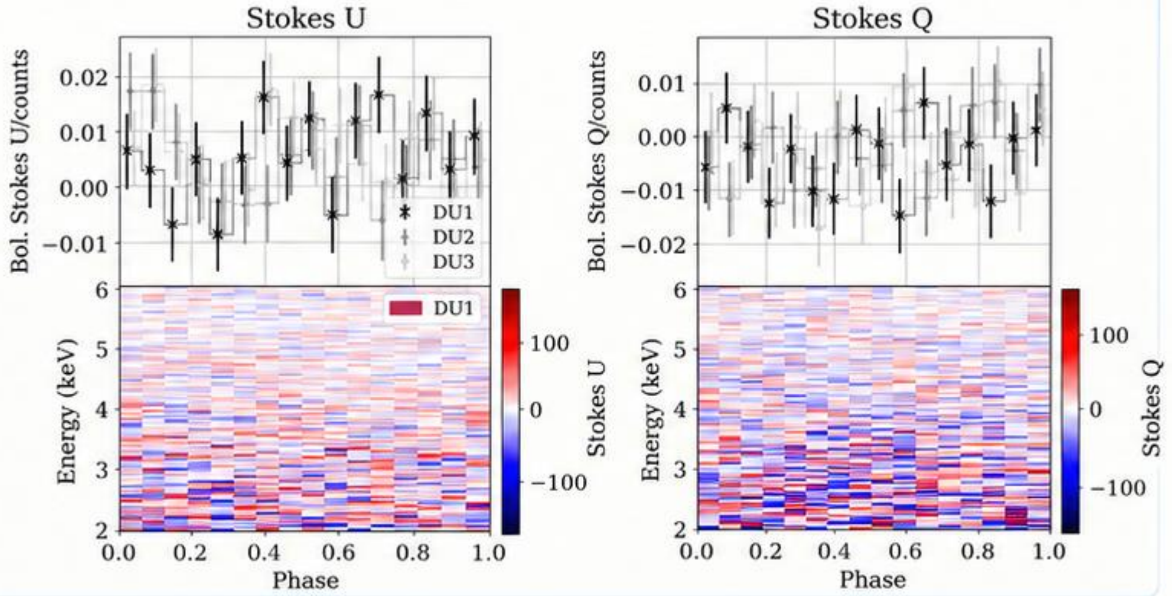
Intensity information

$I(E, \phi)$



Polarization information

$Q(E, \phi),\ U(E, \phi)$



$I(E, \phi)_{NICER}$ + $[I, Q, U](E, \phi)_{IXPE}$ → **joint hotspot inference**

Relativistic pulse-profile modelling

- hotspot geometry
- viewing inclination
- emission properties

Polarization modelling predicts the largest information gain when PD and its phase modulation are sufficiently strong.

Salmi et al. 2025

For SRGA J1444, NICER remains more constraining than IXPE.

The modest polarization degree and weak phase-resolved PA variation limit the current IXPE constraints.

» **Timing and polarimetry now probe the same emitting regions with complementary observables.**

The next limitation is increasingly the realism of the hotspot and accretion-flow model.

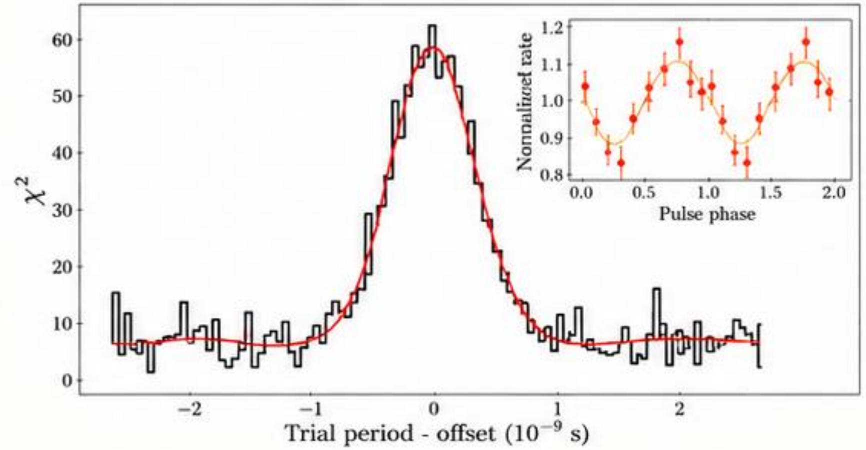
Dorsman et al. 2026, MNRAS 551, stag1340

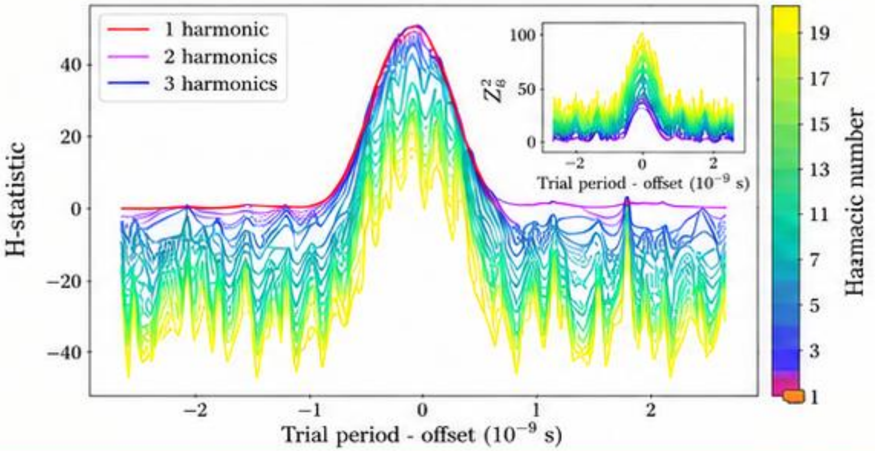
Salmi et al. 2025, MNRAS 538, 2562

How low can accretion-powered pulsations survive?

IGR J17511−3057 probes the transition between accretion and the propeller regime.

Pulsations at very low luminosity





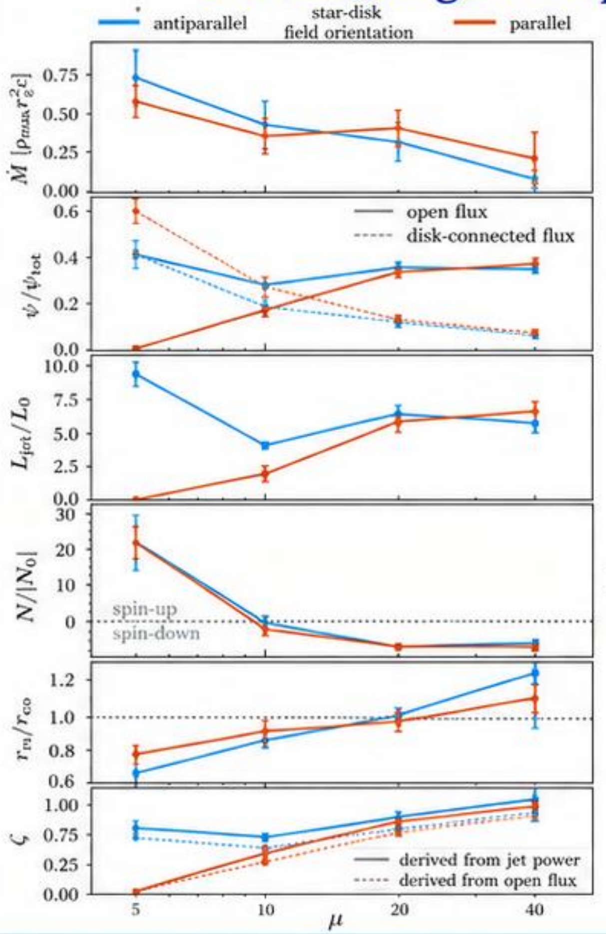
IGR J17511−3057

$L_X \simeq 7 \times 10^{33}$ erg s^{-1}

Coherent pulsations still detected

Illiano et al. 2026

GRMHD: a gradual propeller transition

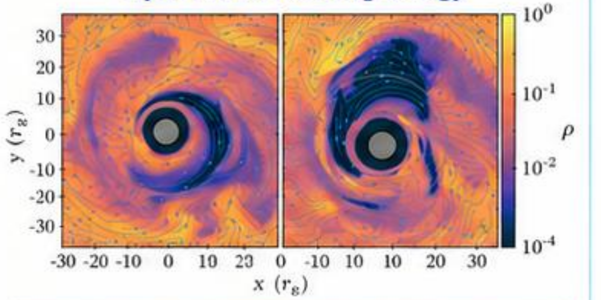


As μ increases, r_m / r_{co} approaches and exceeds 1

The accretion rate onto the star declines, but does not vanish abruptly

The net torque changes sign near the transition

dynamic flow morphology



Intermittent channelled accretion may still occur near the boundary.

Parfrey & Tchekhovskoy 2024, ApJ 975, 57

low $\dot{M}$ → r_m → r_{co} → transition region

the onset of the propeller need not be a sharp switch

» The accretion–propeller transition may be gradual rather than abrupt.

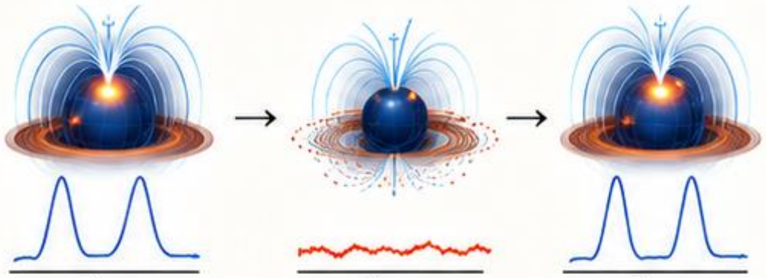
GRMHD suggests that some accretion can persist near the propeller boundary.

AMXPs: what are we still trying to understand?

Timing, pulse profiles and polarimetry are revealing an increasingly dynamic picture of accretion onto neutron stars.

1 What controls the visibility of pulsations?

Why do pulsations appear, disappear, change harmonic content, and survive at unexpectedly low accretion rates?

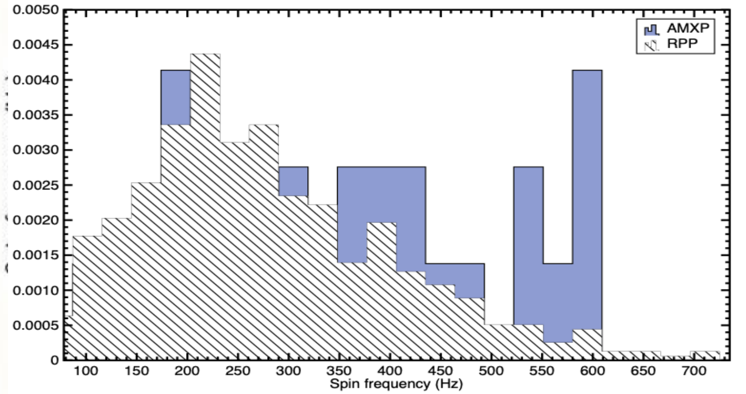


Why it matters

Pulsations are our direct tracer of magnetically channelled accretion and of how matter penetrates the magnetosphere, even at very low luminosities (e.g. IGR J17511–3057).

2 What sets the neutron-star spin distribution?

Why is the observed distribution truncated well below breakup, and which torques determine spin equilibrium?



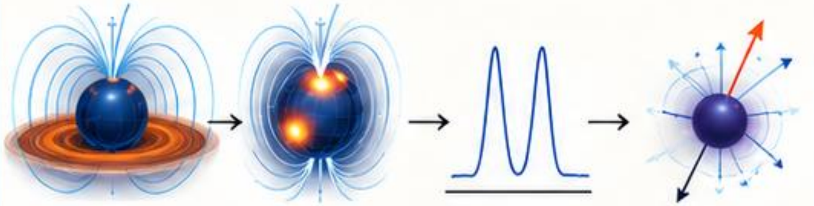
Why it matters

The spin distribution encodes the long-term competition between accretion, disc–field coupling and electromagnetic braking.

$\dot{\nu}_{obs}$ = net outcome of competing torques

3 What is the geometry of the disc–magnetosphere interaction?

How do the inner disc, magnetic field and hotspots reorganize across an outburst and toward the propeller regime?



Why it matters

Geometry drives pulse phases, pulse profiles and polarization, and can mimic changes that would otherwise be attributed to neutron-star spin.

AMXPs are not simply rotating clocks:

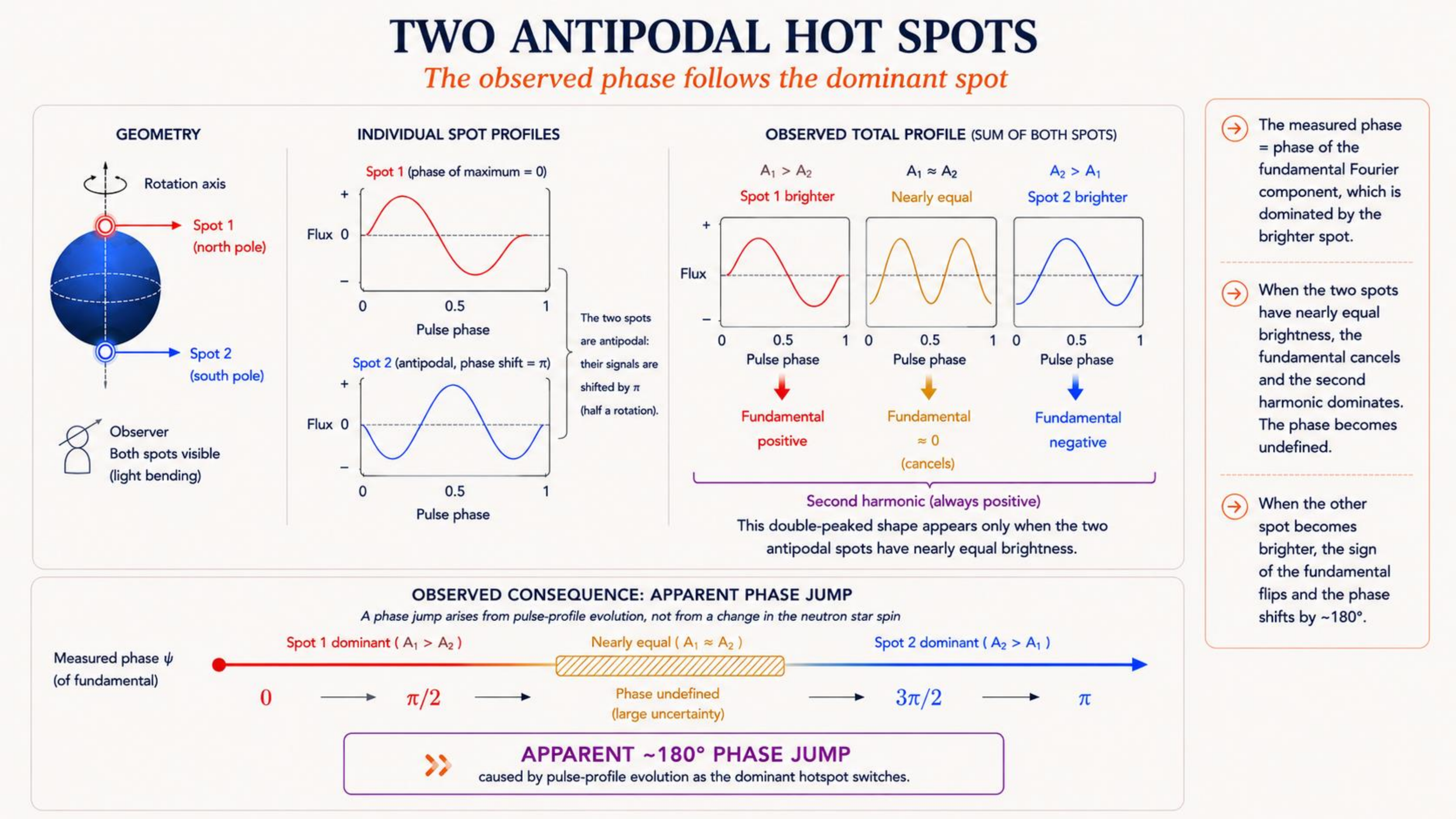
their timing signal is shaped by a dynamic interaction between the neutron star, its magnetic field and the accretion flow.

Connecting spin evolution, pulse morphology and polarization is the route toward disentangling these effects.

Thanks for listening!

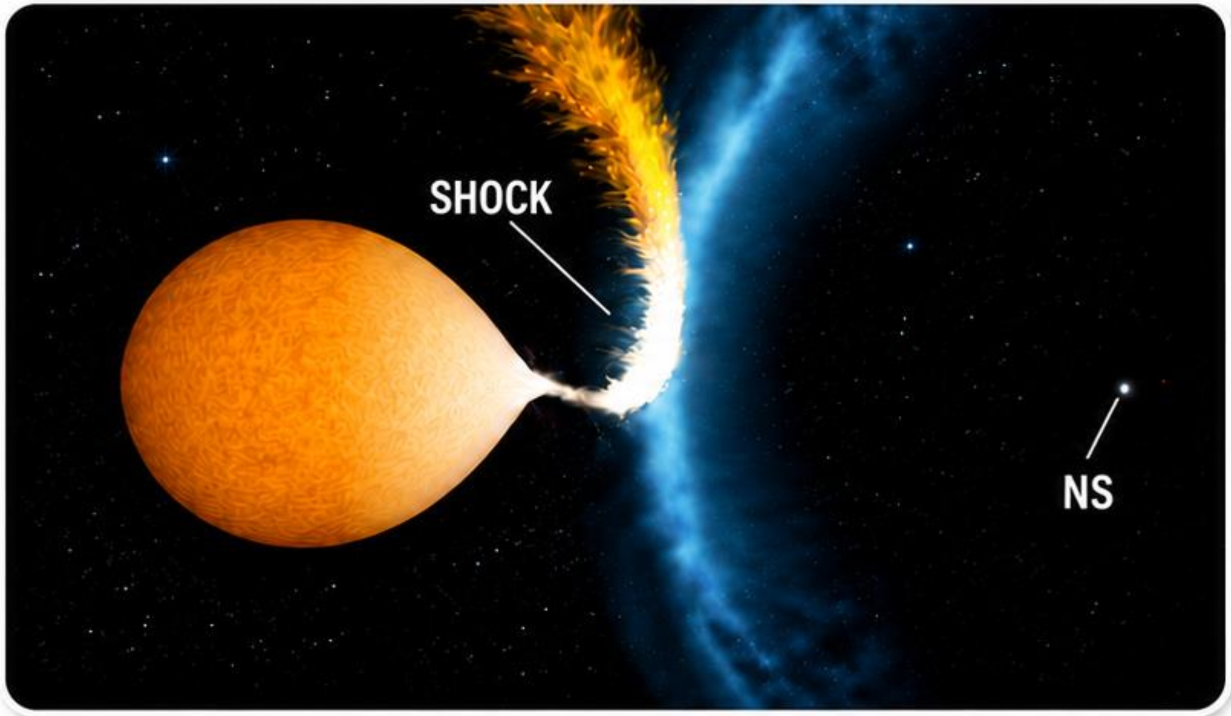
Questions?

Backup slides


TWO ANTIPODAL HOT SPOTS
The observed phase follows the dominant spot
GEOMETRY
Rotation axis
Spot 1
(north pole)
Spot 2
(south pole)
Observer
Both spots visible
(light bending)
INDIVIDUAL SPOT PROFILES
Spot 1 (phase of maximum = 0)
Flux 0
+
–
0
0.5
1
Pulse phase
Spot 2 (antipodal, phase shift = π)
Flux 0
+
–
0
0.5
1
Pulse phase
The two spots are antipodal: their signals are shifted by π (half a rotation).
OBSERVED TOTAL PROFILE (SUM OF BOTH SPOTS)
A1 > A2
Spot 1 brighter
A1 ≈ A2
Nearly equal
A2 > A1
Spot 2 brighter
Flux
+
–
0
0.5
1
Pulse phase
Fundamental positive
Fundamental ≈ 0 (cancels)
Fundamental negative
Second harmonic (always positive)
This double-peaked shape appears only when the two antipodal spots have nearly equal brightness.
The measured phase = phase of the fundamental Fourier component, which is dominated by the brighter spot.
When the two spots have nearly equal brightness, the fundamental cancels and the second harmonic dominates. The phase becomes undefined.
When the other spot becomes brighter, the sign of the fundamental flips and the phase shifts by ~180°.
OBSERVED CONSEQUENCE: APPARENT PHASE JUMP
A phase jump arises from pulse-profile evolution, not from a change in the neutron star spin
Measured phase ψ
(of fundamental)
Spot 1 dominant (A1 > A2)
Nearly equal (A1 ≈ A2)
Spot 2 dominant (A2 > A1)
0
π/2
Phase undefined
(large uncertainty)
3π/2
π
APPARENT ~180° PHASE JUMP
caused by pulse-profile evolution as the dominant hotspot switches.

What can we learn in the long term?

Even in quiescence, compact binaries keep telling us their story.



We study quiescent systems to answer key questions:

Does accretion stop completely?

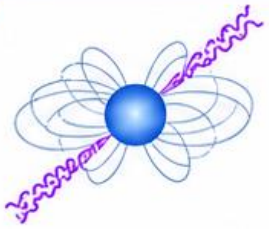
No. We observe **very low X-ray flux** values (below 10^{33} erg/s/cm^2).

Does the NS behave as a millisecond radio pulsar?

Yes. We observe **secular spin-down.**

WHAT WE CAN MEASURE ON LONG TIMESCALES

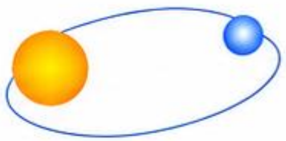
1



SPIN-DOWN IN QUIESCENCE

Measuring the loss of rotational energy of the neutron star over years.

2

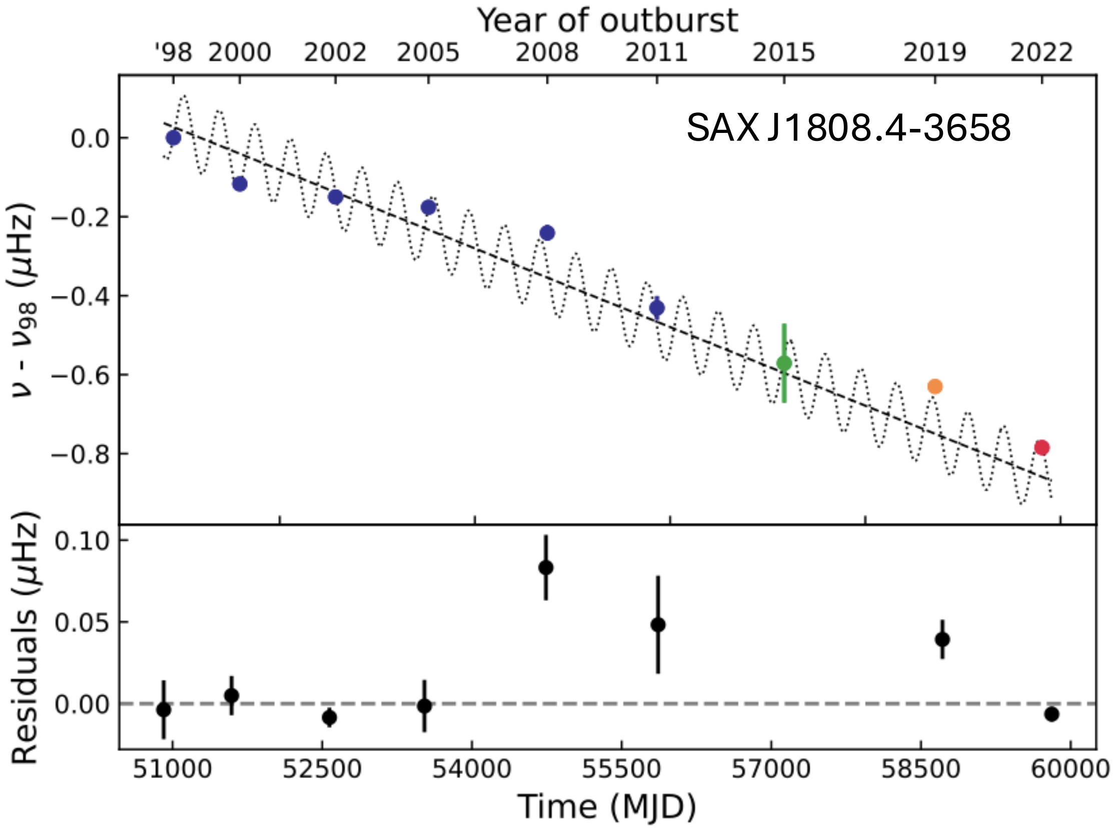


ORBITAL PERIOD VARIATION

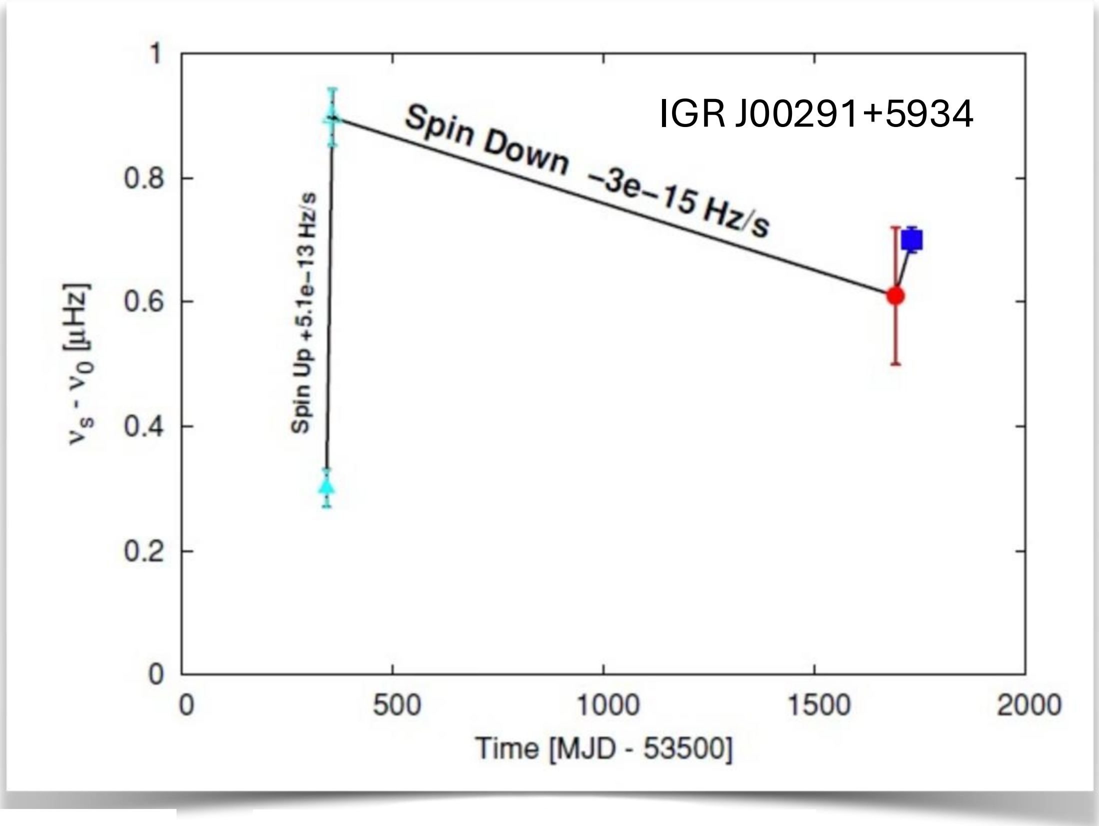
Tracking changes in the orbital period over years to decades.

Long-term (secular) spin evolution

[Illiano+23]



[Hartman+10, Papitto+10,Sanna+17]



$$\dot{\nu} \sim -10^{-15} \text{ Hz/s}$$

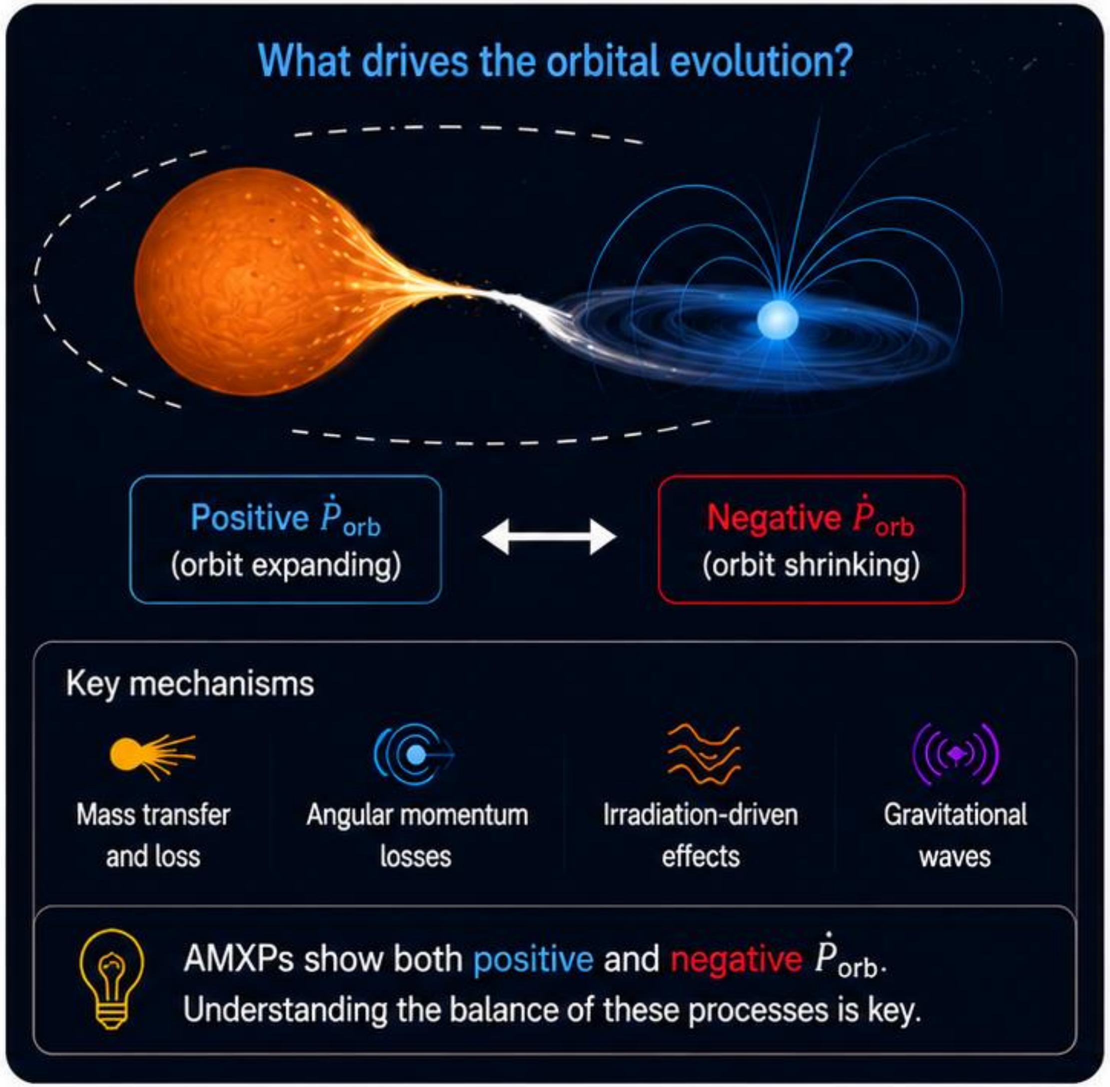
Compatible with rotation-powered spin-down for $B \sim (10^8 – 10^9)$ G

Long-term (secular) spin 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	$-1.1(1)\ 10^{-15}$	Illiano+23
IGR J00291+5934	1.7	2.5	$-4.1(1.2) 10^{-15}$	Patruno+10 Papitto+11
SAX J1748.9-2021	2.3	8.8	$-4.1(2)\ 10^{-15}$	Illiano+24
SWIFT J1756.9-2508	5.5	0.9	$-4.8(6)\ 10^{-16}$	Sanna+18
XTE J1751-305	2.3	0.7	$-5.5(1.2)\ 10^{-15}$	Riggio+11
IGR J17511-3057	4.1	3.5	$-2.3(1.1)\ 10^{-15}$	Sanna+25
MAXI J1957+032	3.2	1.0	$-2.2(0.4)\ 10^{-14}$	Sanna+25
IGR J17494-3030	2.7	1.2	$-2.1(7)\ 10^{-14}$	Ng+21

Secular orbital evolution in AMXPs

Orbital period derivatives measured (or constrained) over years–decades.



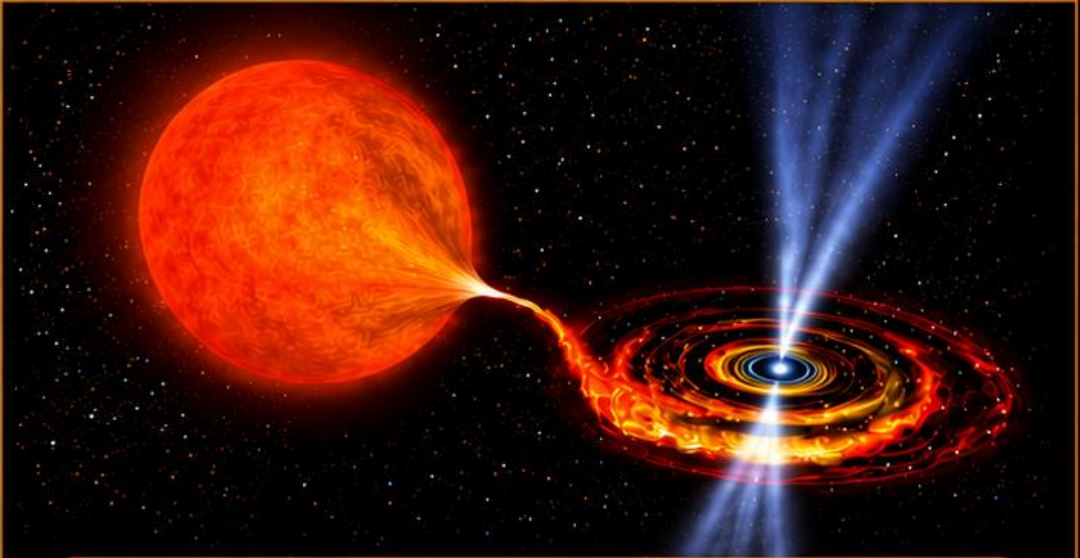
Source	Pspin (ms)	Porb (h)	dPorb/dt (s/s) (u.l. at 3 σ c.l.)	Ref.
SAX J1808.4–3658	2.5	2	$1.7(5) \times 10^{-12}$	Bult+19 Sanna+17
IGR J00291+5934	1.7	2.5	$(-6.6 \div 6.5) \times 10^{-13}$	Patruno+16 Sanna+17
SAX J1748.9–2021	2.3	8.8	$(-0.7 \div 8.4) \times 10^{-11}$	Sanna+22
SWIFT J1756.9–2508	5.5	0.9	$(-4.1 \div 7.1) \times 10^{-12}$	Sanna+18 Bult+18
IGR J17379–3747	2.1	1.9	$(-9.4 \div 4.4) \times 10^{-12}$	Sanna+18
XTE J1751–305	2.3	0.7	$(-2.7 \div 0.7) \times 10^{-11}$	Riggio+11
IGR J17511–3057	4.1	3.5	$-2.55(7) \times 10^{-11}$	Sanna+25

THE RADIO-EJECTION HYPOTHESIS

A unified model for the state transition in accreting millisecond pulsars

OUTBURST: ACCRETION PHASE

- Active accretion from the donor
- Matter accumulates in the inner disc
- X-ray emission is high



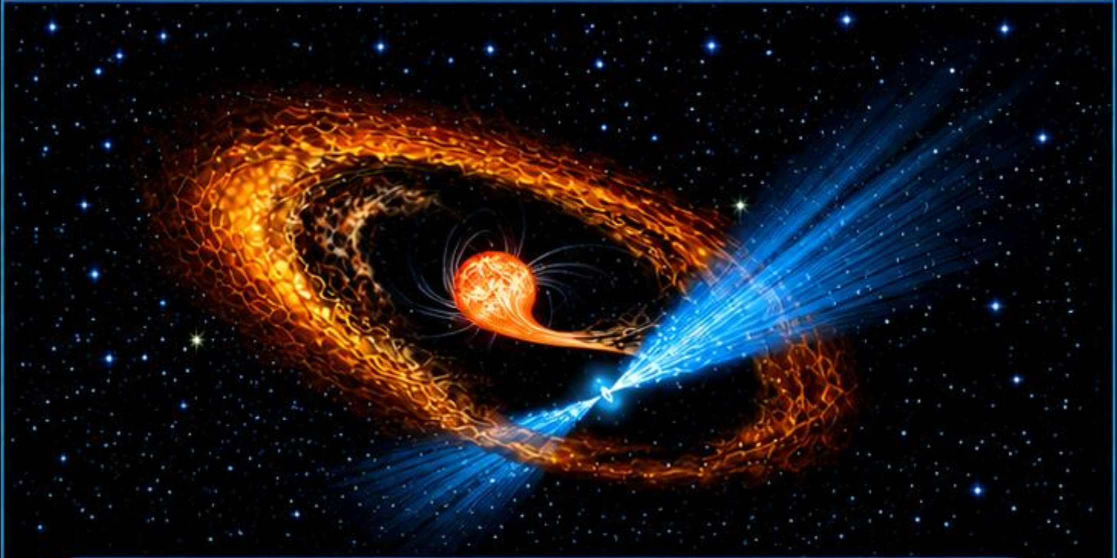
Dominated by accretion-powered X-ray emission

STATE TRANSITION

Drop in accretion rate (below a critical threshold)

QUIESCENCE: RADIO EJECTION

- Accretion is suppressed
- A radio pulsar wind is ejected
- Radio emission dominates



Powered by rotation: radio pulsar wind ejection

KEY IDEA: The system switches from an accretion-dominated (X-ray) state to a rotation-powered (radio) state via the ejection of a radio pulsar wind.

Explains the low X-ray luminosity and is consistent with a rotation-powered state in quiescent AMXPs.

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

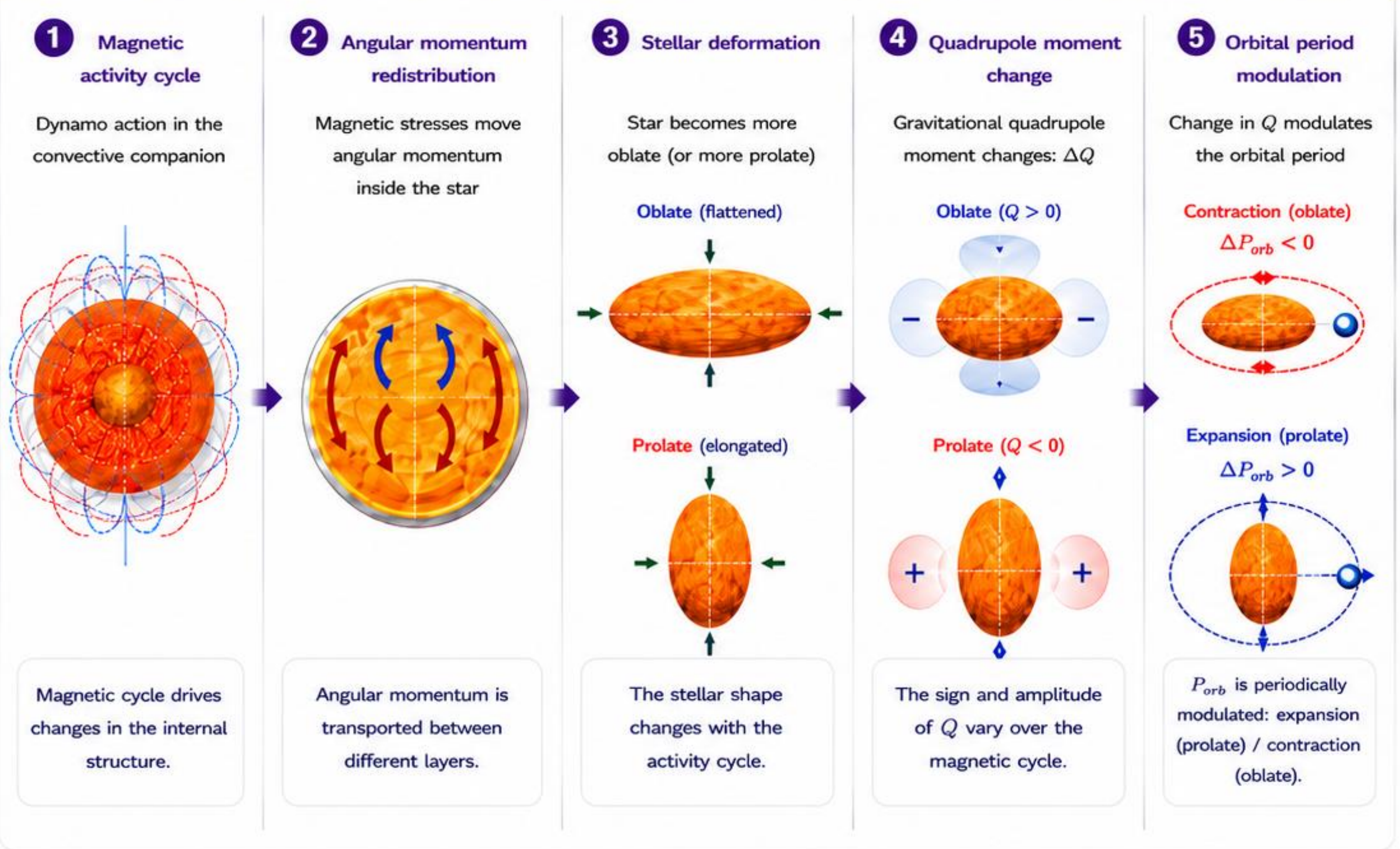
SAX J1808.4-3658: APPLEGATE–SHAHAM MODEL

Periodic Orbital Modulations via Gravitational Quadrupole Changes (GQC)

Magnetic activity cycles in the companion star drive internal angular momentum redistribution, changing its shape and gravitational quadrupole moment.

This **modulates the orbital period**, producing **quasi–sinusoidal** variations in the accumulated delay of T_{star}.

THE APPLEGATE–SHAHAM MECHANISM: FROM MAGNETIC CYCLE TO ORBITAL MODULATION



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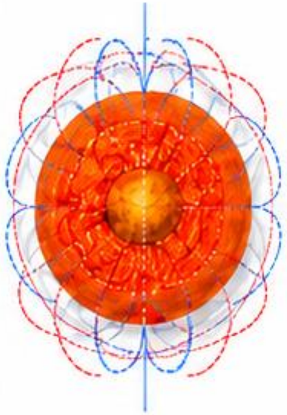
THE APPLEGATE–SHAHAM MECHANISM: FROM MAGNETIC CYCLE TO ORBITAL MODULATION

1 Magnetic activity cycle

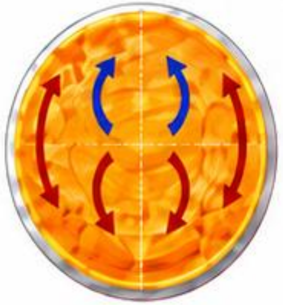
Dynamo action in the convective companion



Magnetic cycle drives changes in the internal structure.

2 Angular momentum redistribution

Magnetic stresses move angular momentum inside the star

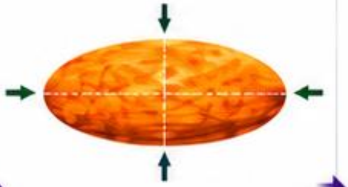


Angular momentum is transported between different layers.

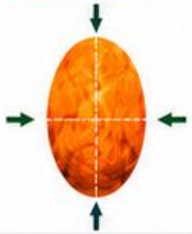
3 Stellar deformation

Star becomes more oblate (or more prolate)

Oblate (flattened)



Prolate (elongated)

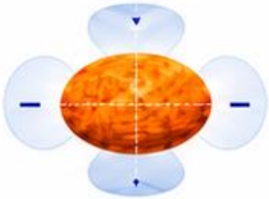


The stellar shape changes with the activity cycle.

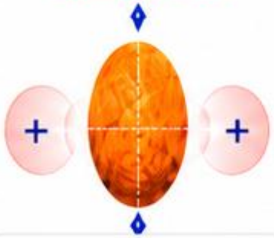
4 Quadrupole moment change

Gravitational quadrupole moment changes: ΔQ

Oblate ($Q > 0$)



Prolate ($Q < 0$)



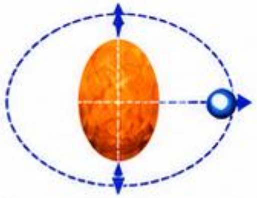
The sign and amplitude of Q vary over the magnetic cycle.

5 Orbital period modulation

Change in Q modulates the orbital period

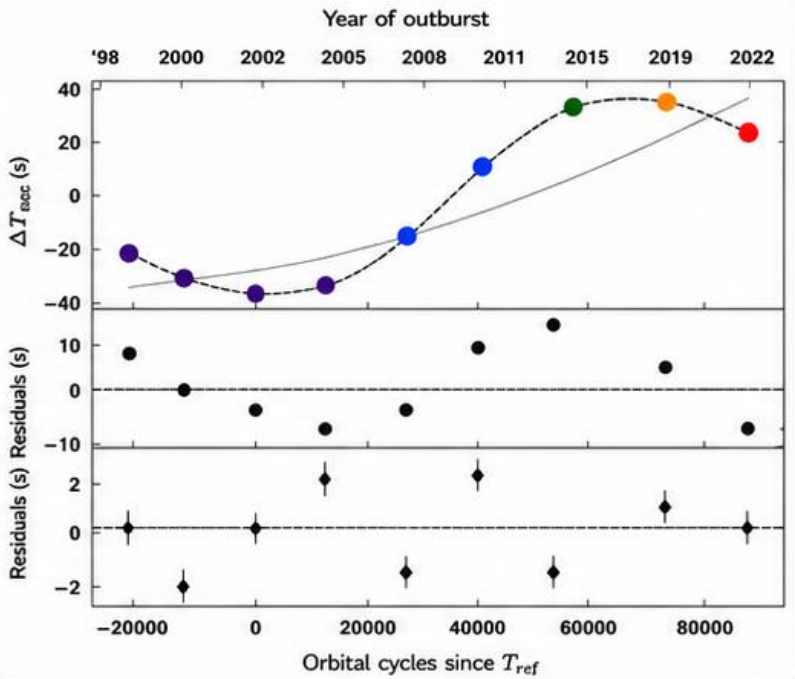
Contraction (oblate)
$\Delta P_{orb} < 0$

Expansion (prolate)
$\Delta P_{orb} > 0$



P_{orb} is periodically modulated: expansion (prolate) / contraction (oblate).

OBSERVED ACCUMULATED DELAY OF T_{star}



BEST–FIT PARAMETERS (ILLIANO+23)

δP_{ref}	$= 4.63(16) \times 10^{-4}$ s	A	$= 11.30(33)$ s
$\dot{P}_{orb}$	$= -2.82(69) \times 10^{-13}$ s s^{-1}	P	$= 20.7(0.6)$ **years**

δP_{ref}: correction to reference spin period
$\dot{P}_{orb}$: secular orbital period derivative
A: semi–amplitude of the modulation
P: modulation period