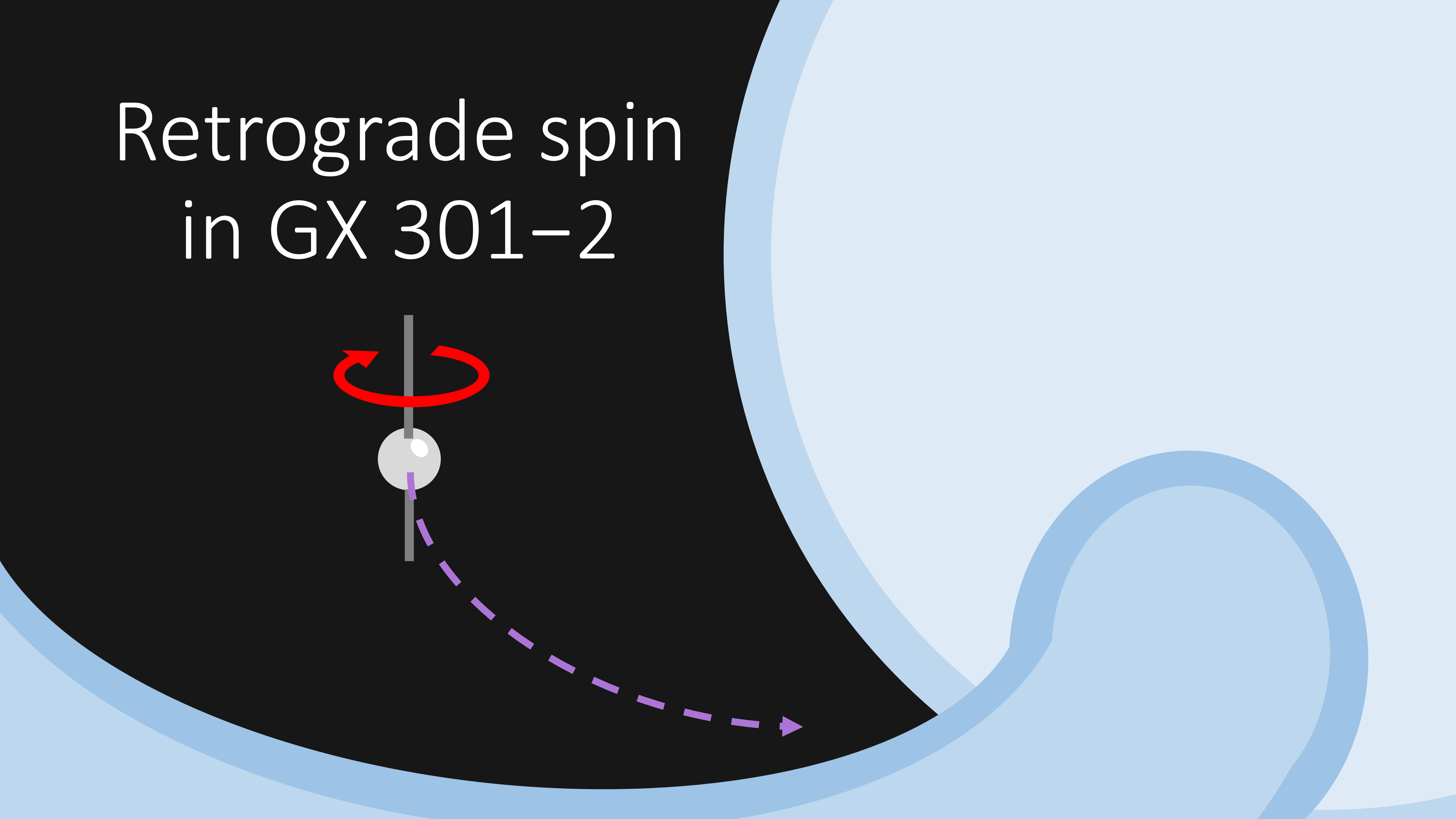
Retrograde spin in GX 301−2

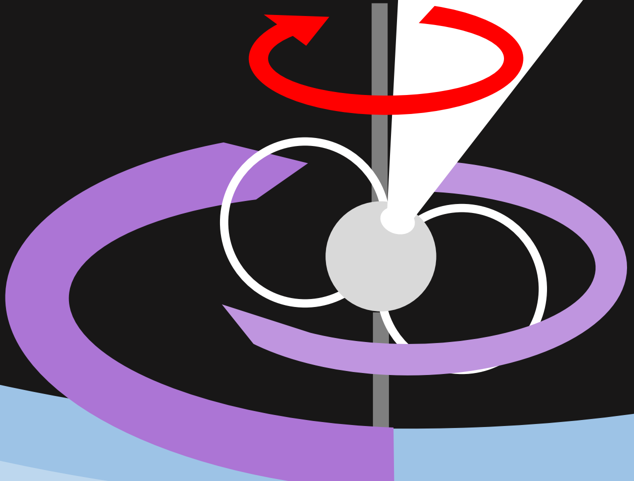


Motivation:

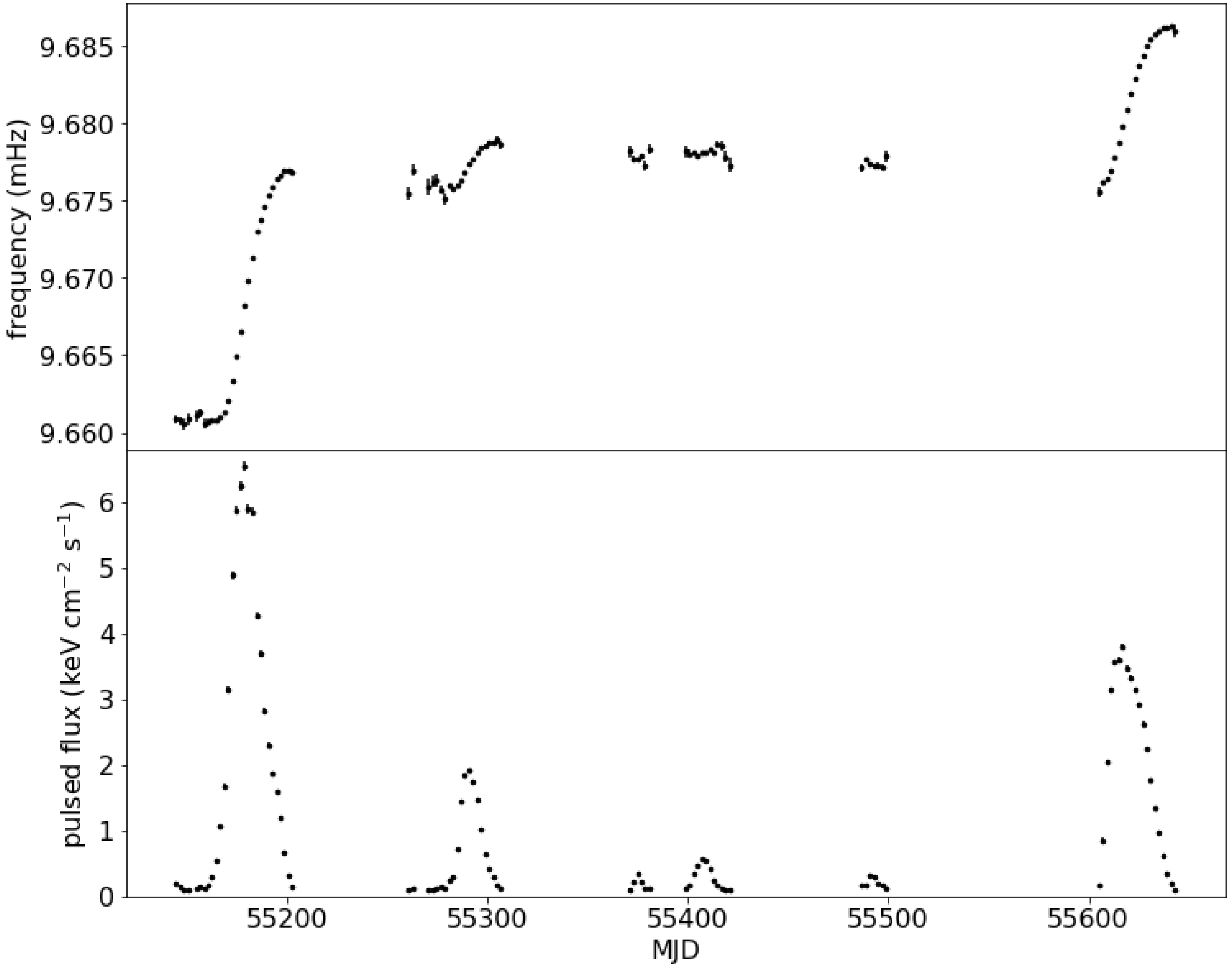
Accretion onto NS releases huge amounts of energy

NS has a low moment of inertia → possible to observe how spin period accelerated by accretion

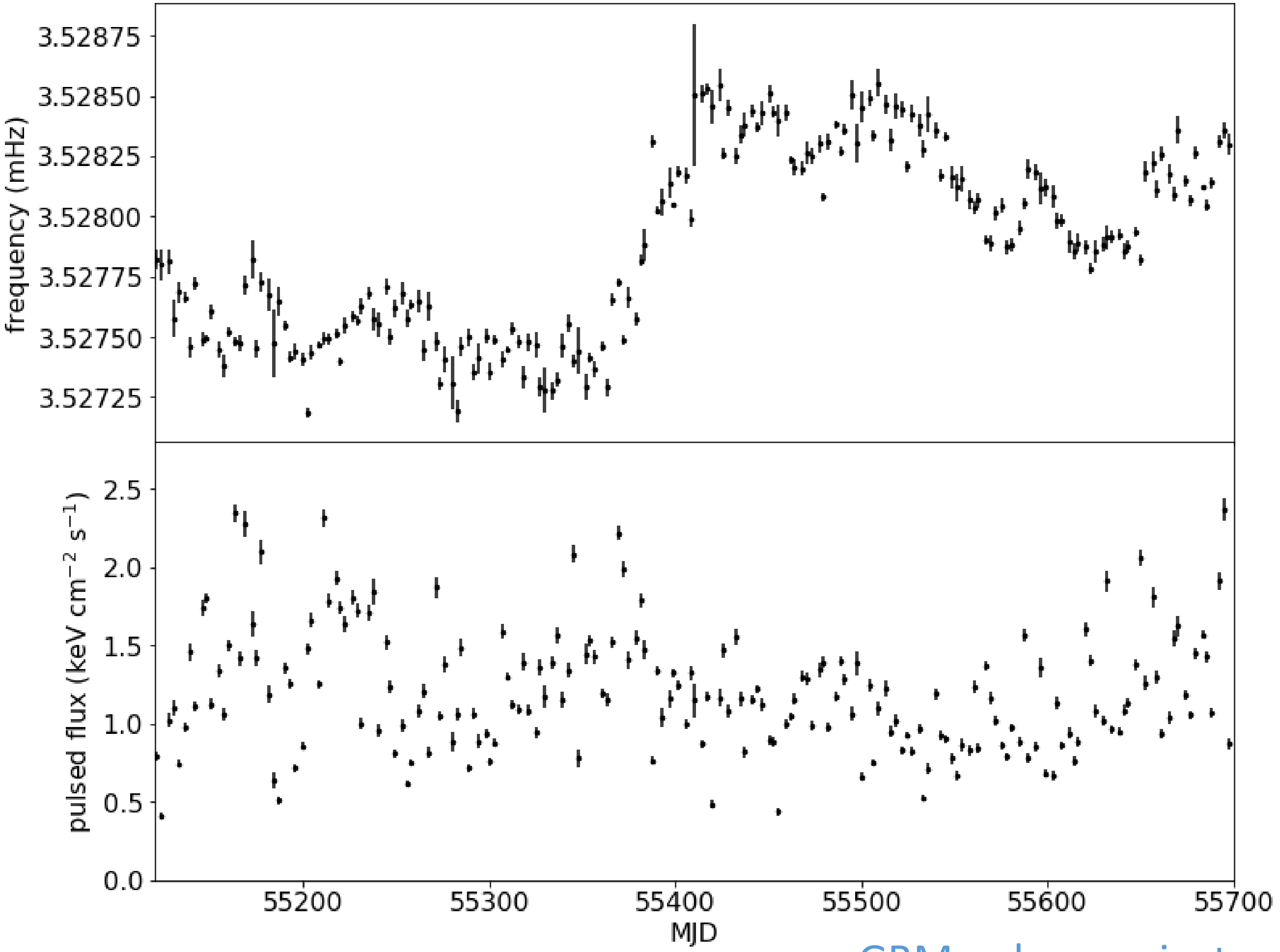
Studying plasma physics in extreme magnetic field strengths



Accretion types in X-ray pulsars



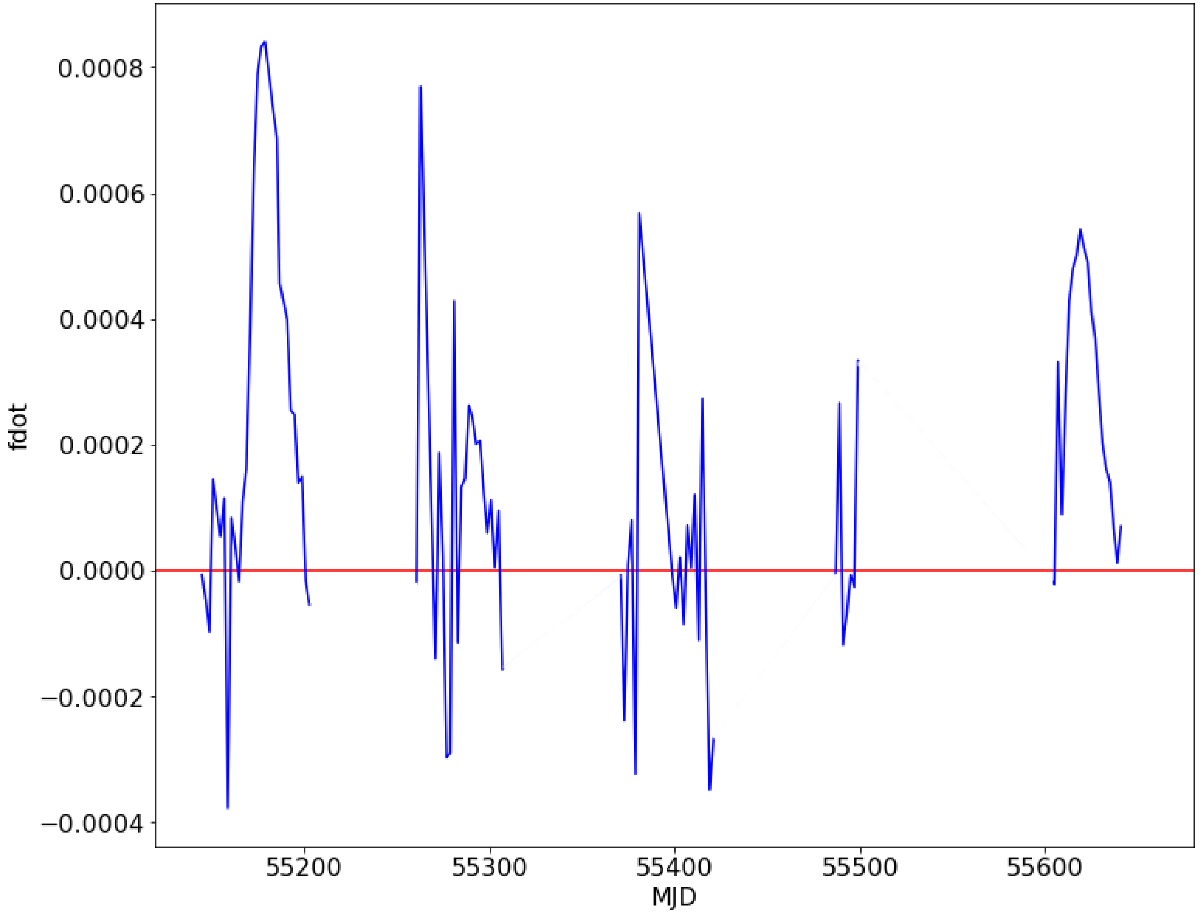
A 0535+262: disc accretion → spin-up



GBM pulsar project

Vela X-1: wind accretion → noisy

Frequency derivatives



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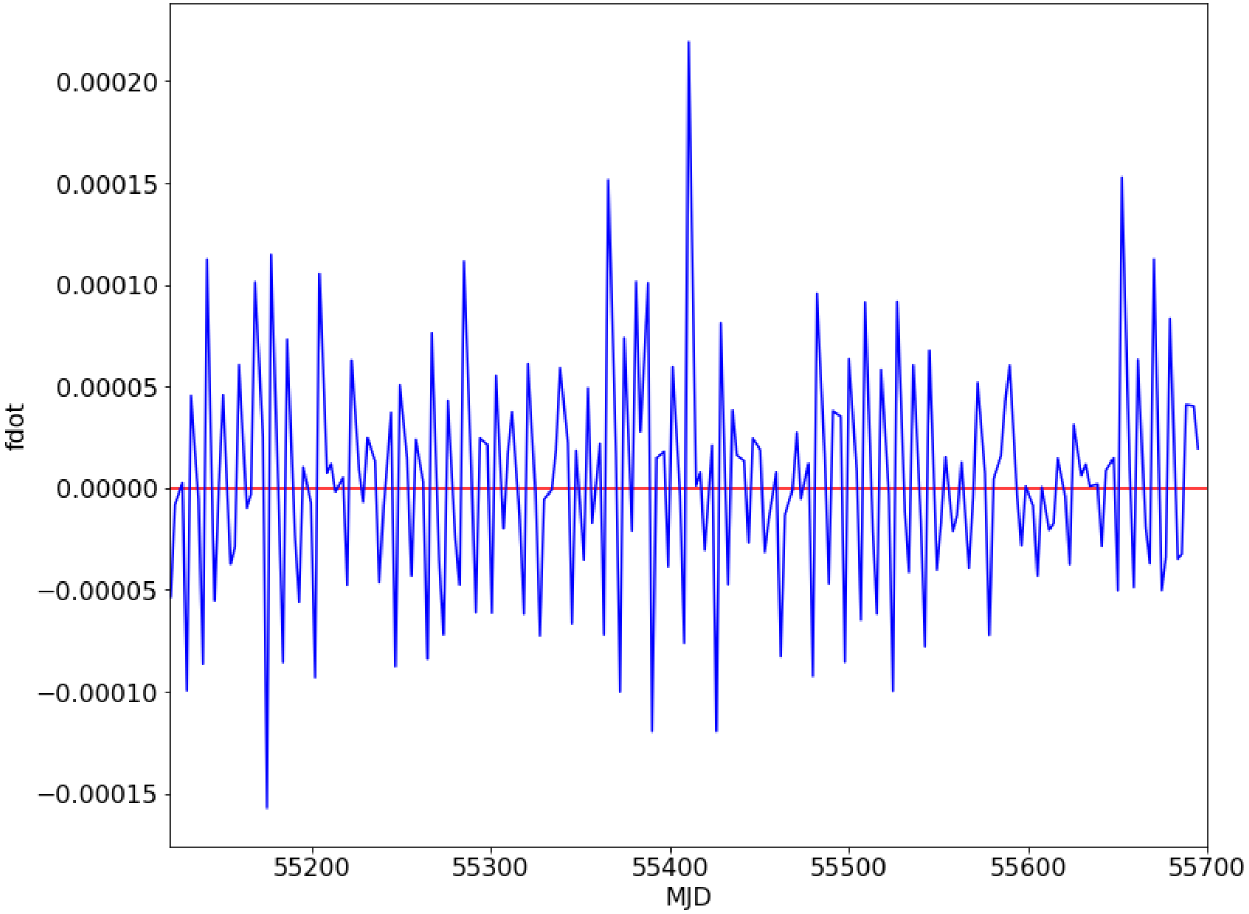


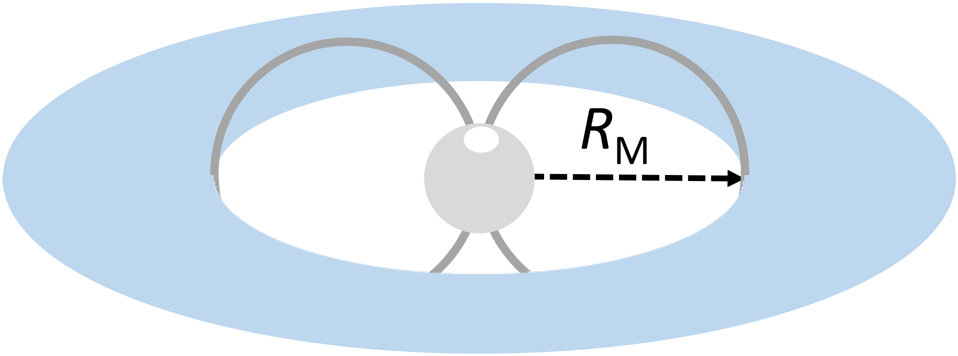
Vela X-1: wind accretion → noisy

Accretion torque models

Torque transferred from disc accretion $2\pi I\dot{f} = \dot{M}(GMR_M)^{1/2}$

where R_M is the **magnetospheric** radius

Successfully applied to determine magnetic field strengths in NSs!



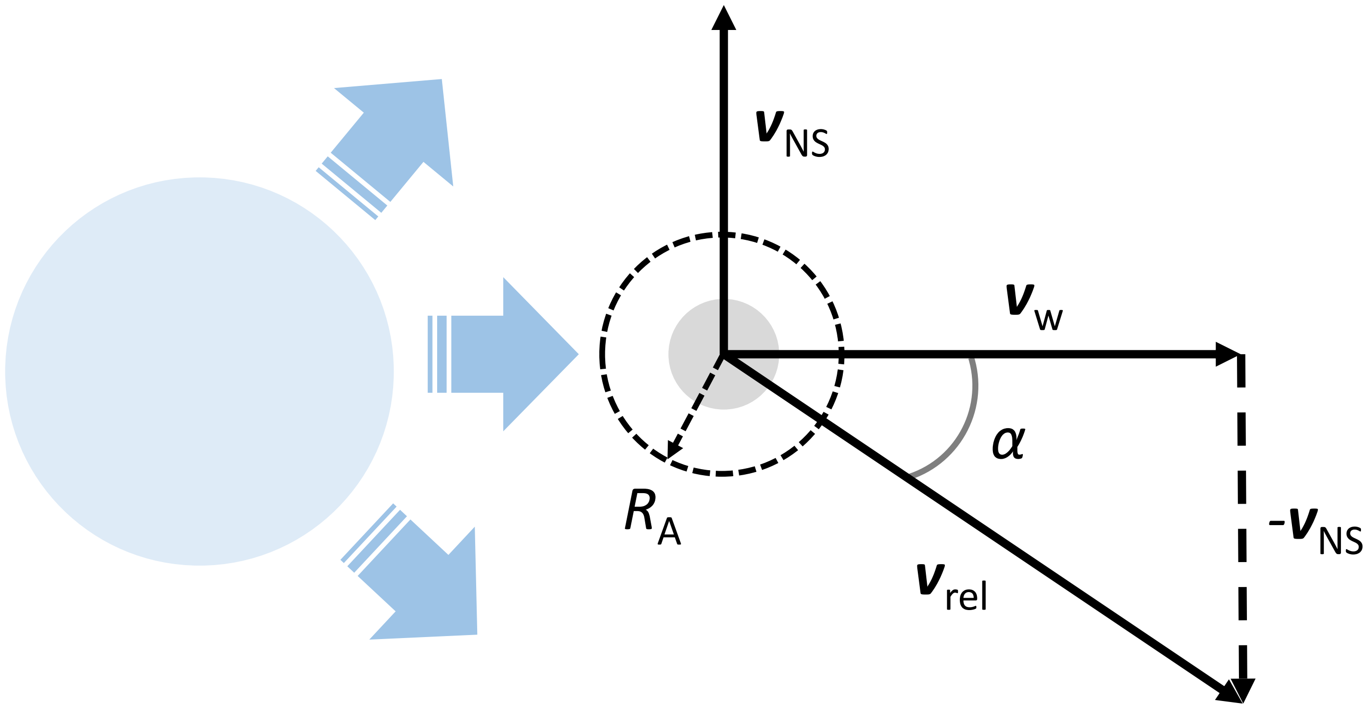
NS in stellar wind

Spherically symmetric wind

Relative velocity v_{rel}

Accretion radius R_{A}

$$R_{\text{A}} = GM_{\text{NS}}/v_{\text{rel}}^2$$



NS in stellar wind

Spherically symmetric wind

Relative velocity $v_{\rm rel}$

Accretion radius $R_{\rm A}$

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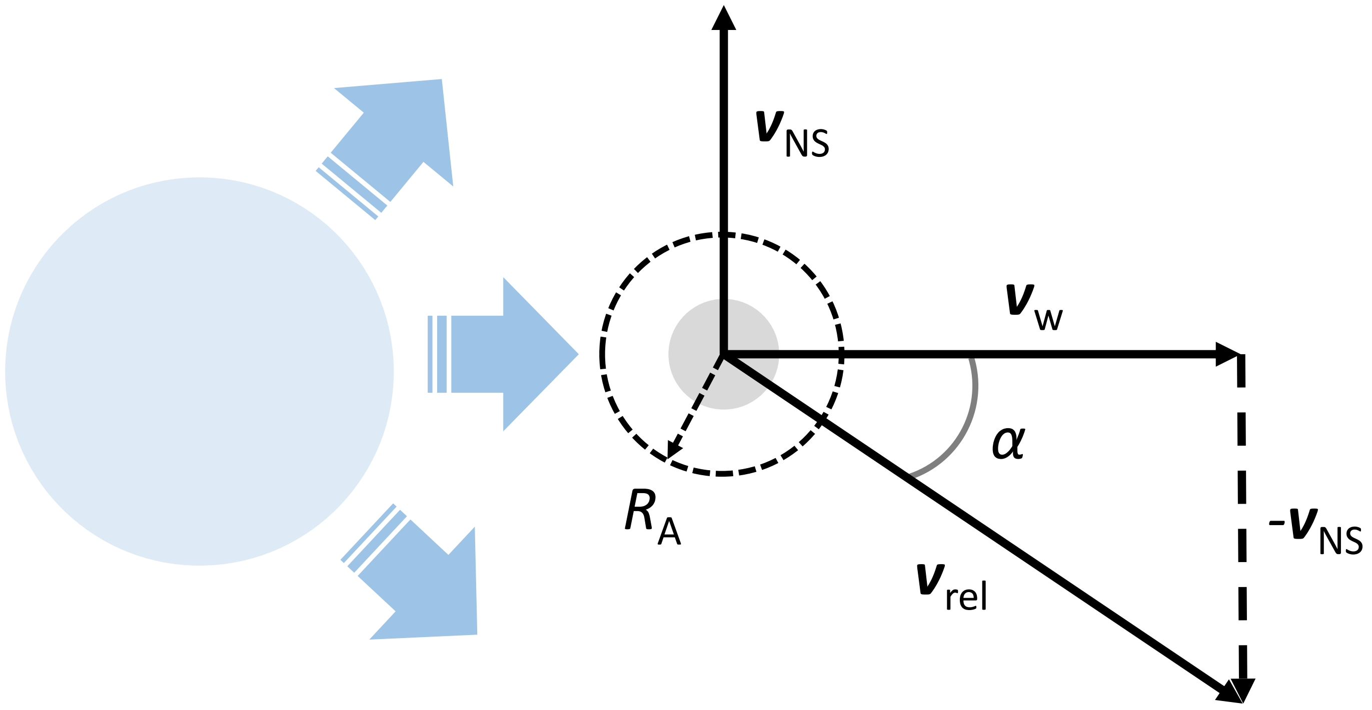


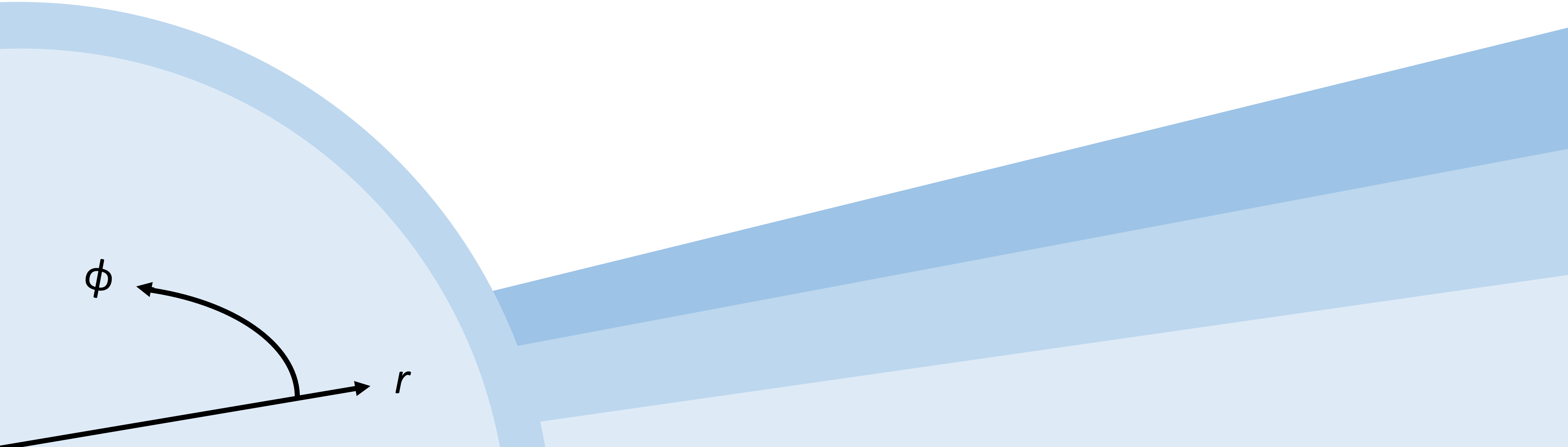
However, **inhomogeneities** affect!

How the NS is accelerated?

Angular momentum transfer after Wang 1981 for $v_{\rm NS} \lesssim v_{\rm w}$

$$l = \frac{\Omega}{2} R_{\rm A}^2 \eta$$

$$\eta \quad = \quad 1 + 3\sin^2\alpha + \frac{1+6\cos^2\alpha}{2}\left(\frac{\partial \ln v_{\rm w}}{\partial \ln r}\right) + \frac{v_{\rm w}}{v_{\rm NS}}\left(-\frac{1}{2}\frac{\partial \ln\rho}{\partial\phi} + 3\cos^2\alpha\,\frac{\partial \ln v_{\rm w}}{\partial\phi}\right)$$



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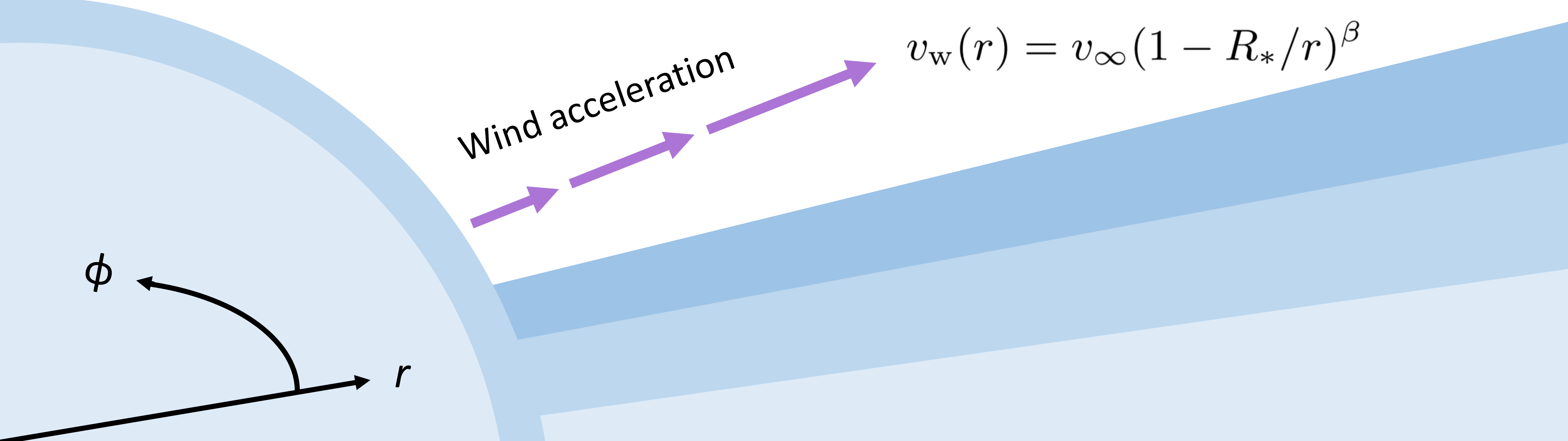
$$v_{\rm w}(r) = v_\infty (1 - R_*/r)^\beta$$



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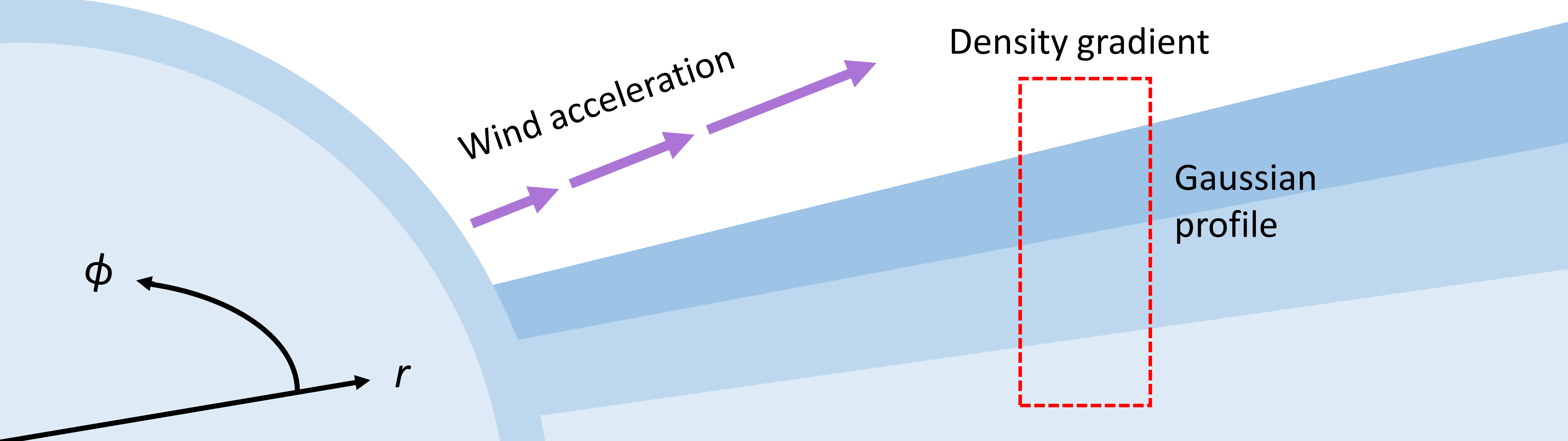

Density gradient

Wind acceleration

Gaussian profile

How the NS is accelerated?

Angular momentum transfer after Wang 1981 for $v_{\mathrm{NS}} \lesssim v_{\mathrm{w}}$

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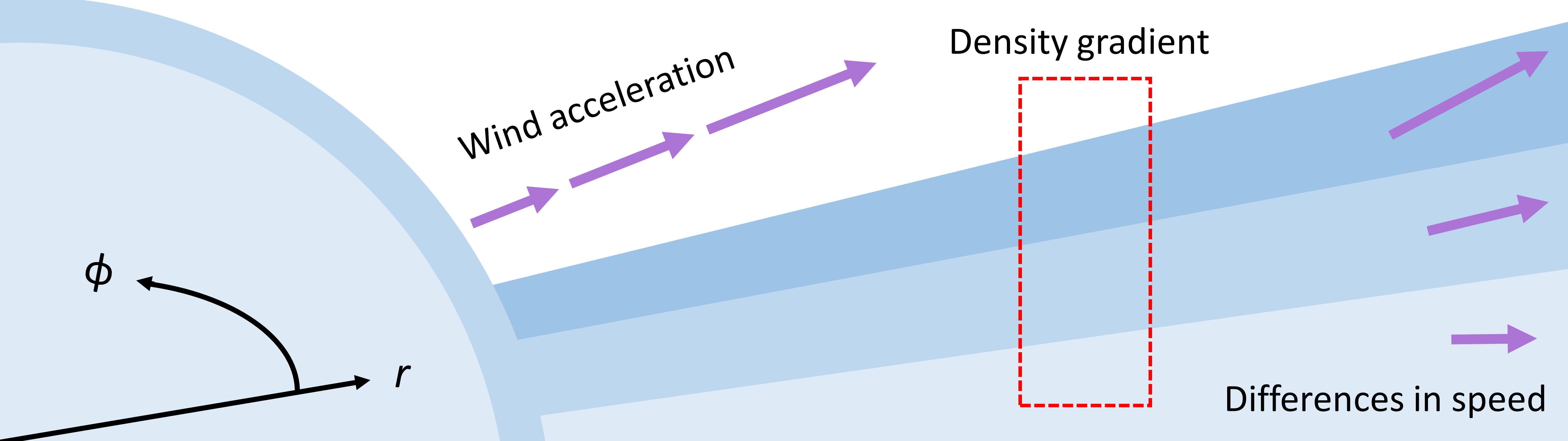


Wind acceleration

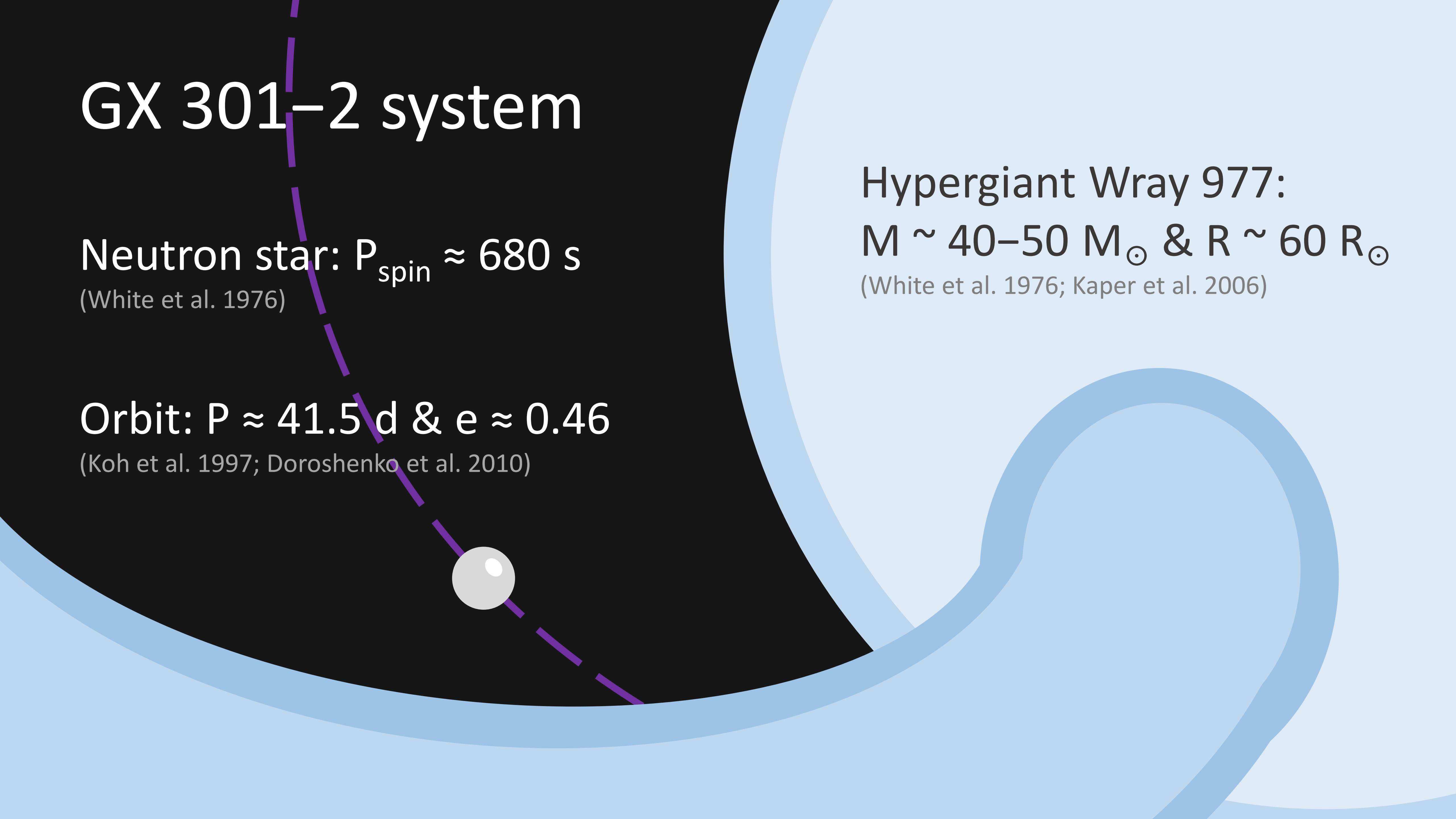
Density gradient

ϕ

r

Differences in speed

GX 301–2 system



Neutron star: $P_{\mathrm{spin}} \approx 680$ s

(White et al. 1976)

Orbit: $P \approx 41.5$ d & $e \approx 0.46$

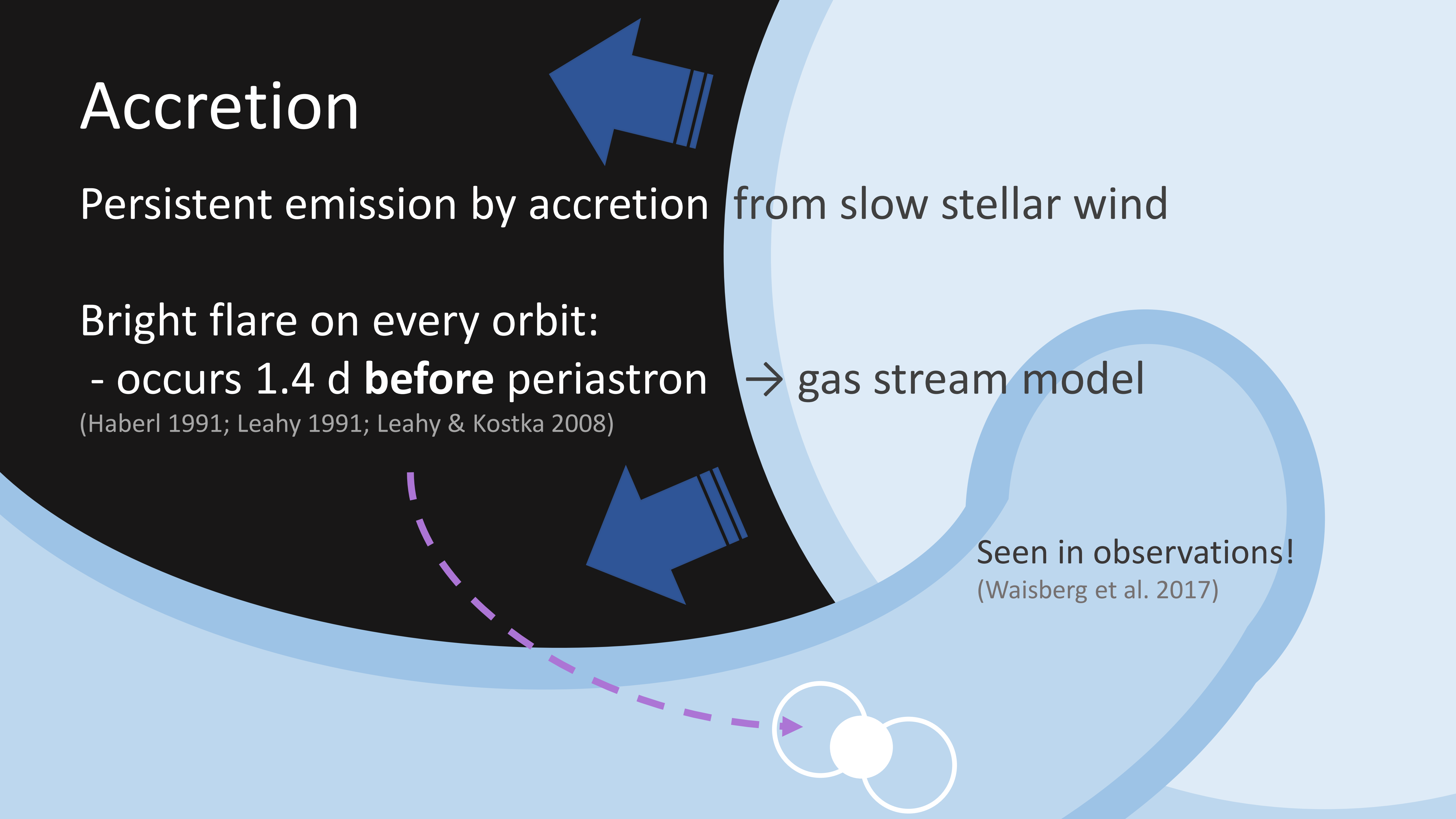
(Koh et al. 1997; Doroshenko et al. 2010)

Hypergiant Wray 977:

$M \sim 40–50\ M_\odot$ & $R \sim 60\ R_\odot$

(White et al. 1976; Kaper et al. 2006)

Accretion



Persistent emission by accretion from slow stellar wind

Bright flare on every orbit:

- occurs 1.4 d **before** periastron → gas stream model

(Haberl 1991; Leahy 1991; Leahy & Kostka 2008)

Seen in observations!
(Waisberg et al. 2017)

(see also Nabizadeh et al. 2019)

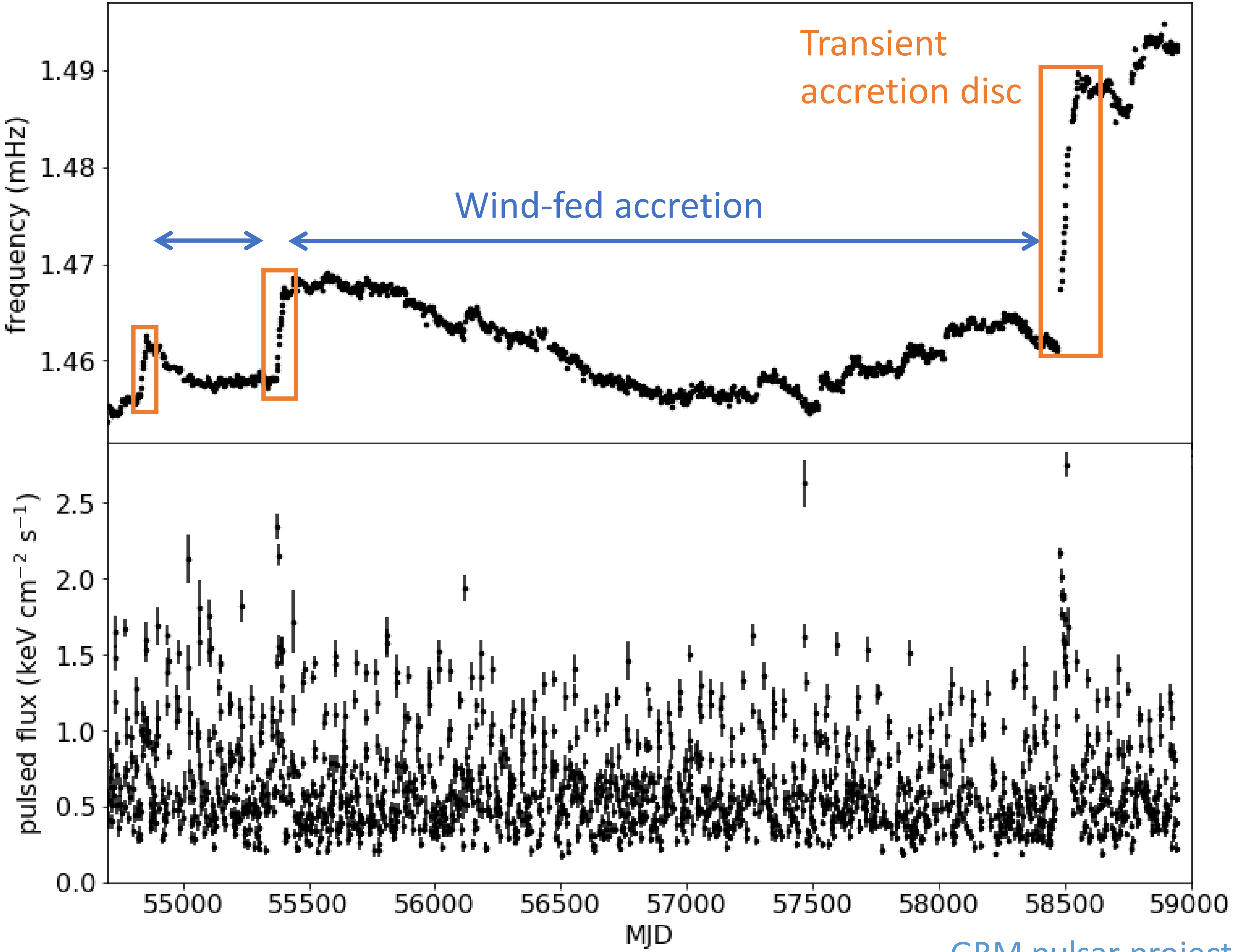
Data

Fermi Gamma-ray Burst Monitor (GBM):
- Pulse frequency
- Many years of data

Swift Burst Alert Telescope (BAT):
- X-ray flux

→ mass accretion rate

$$l = \frac{2\pi \dot{f} I}{\dot{M}}$$

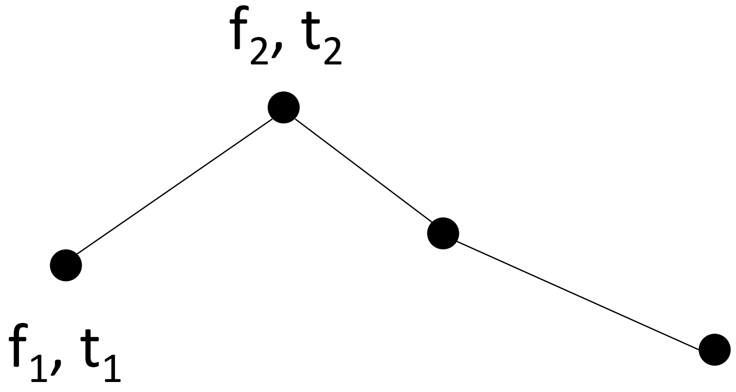


GBM pulsar project

Data reduction

- Frequency derivative calculated from consecutive GBM spin frequency data points

- Folded over the binary orbit (average value per orbital phase)



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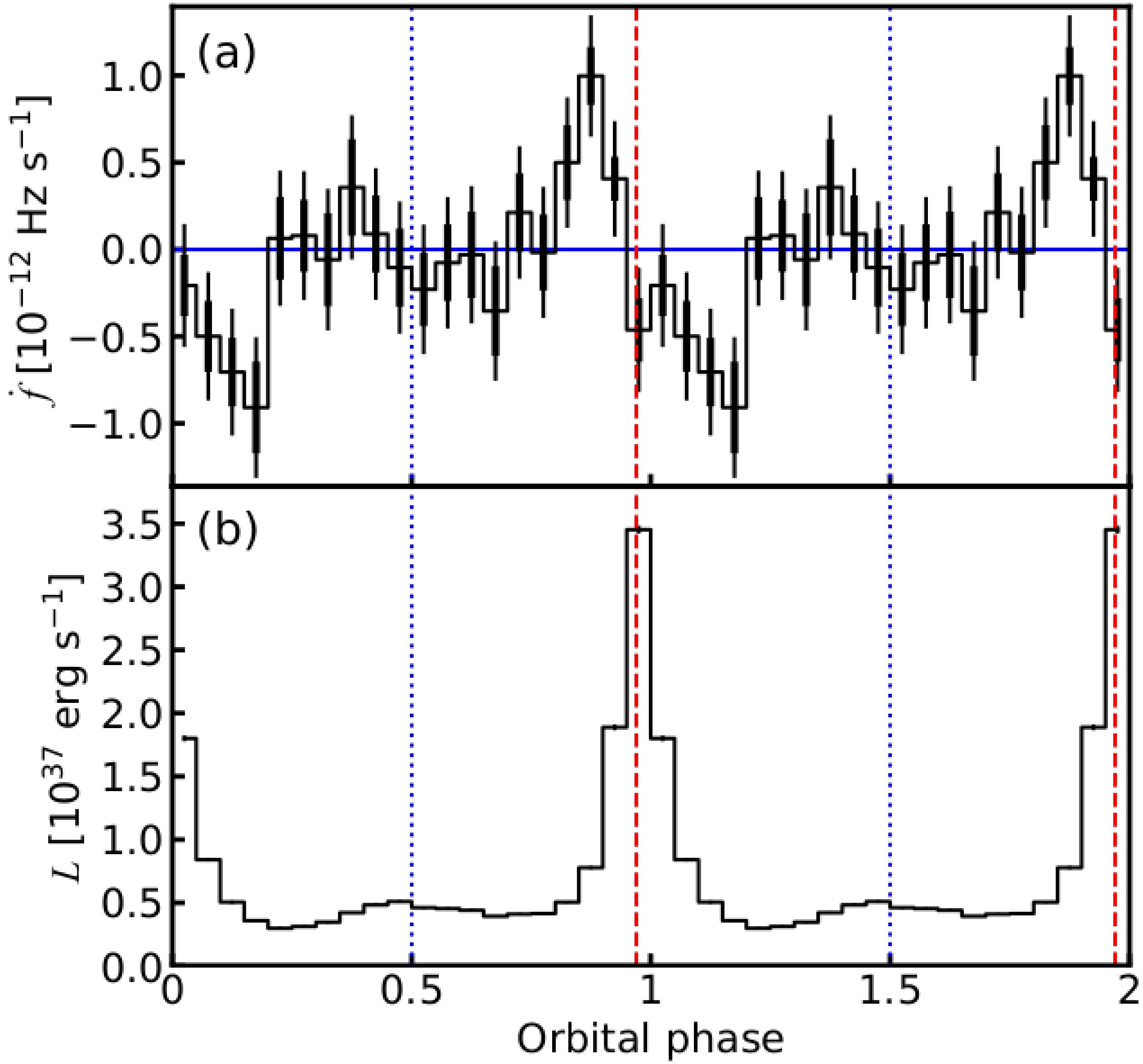
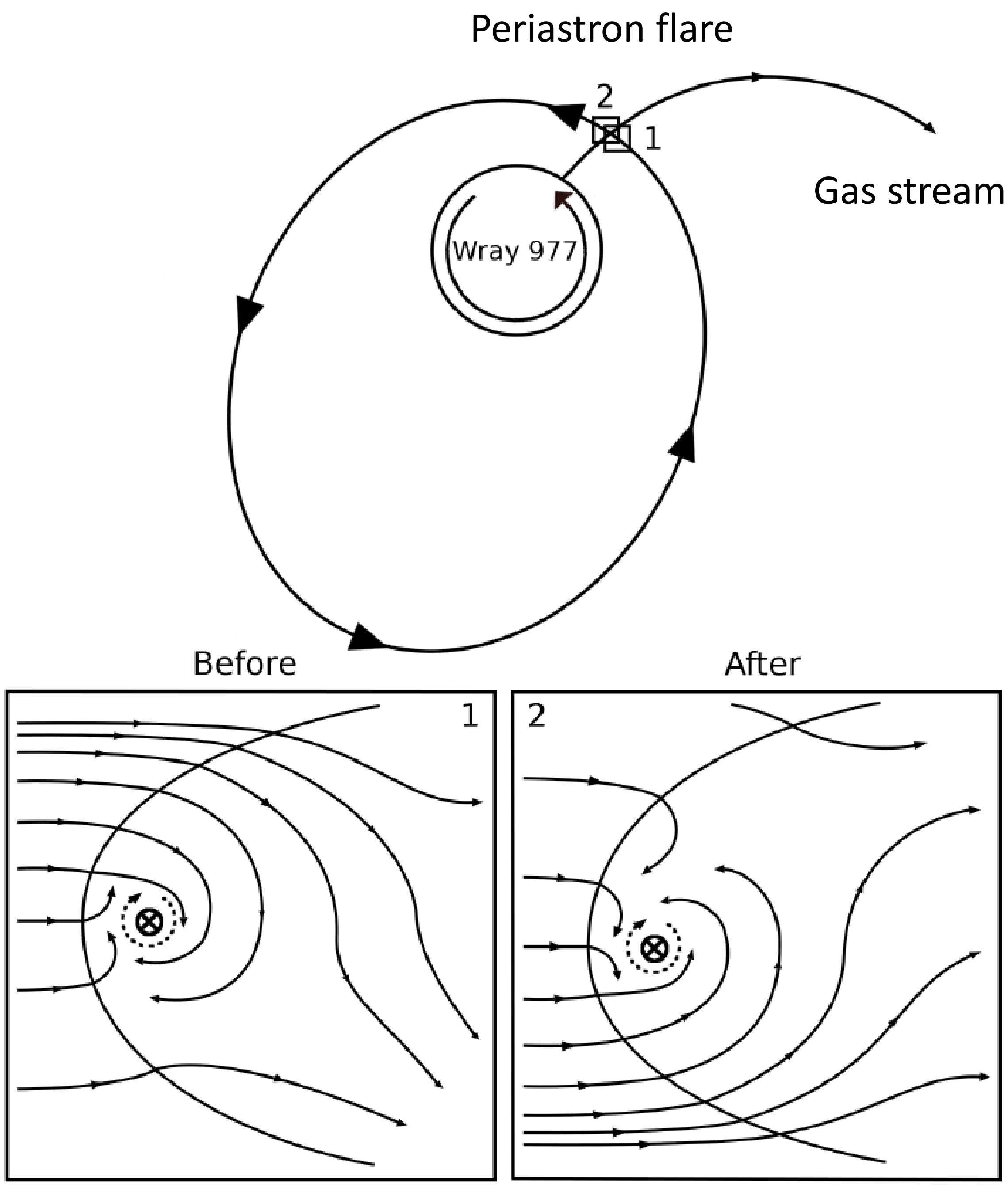


Stream accretion

- Stream model by Leahy (1991, 2002); Leahy & Kostka (2008)

- The accretion wake curves behind the shock front and provides with angular momentum
  (Ruffert 1999; MacLeod & Ramirez-Ruiz 2015)

- Provides torque to the NS
  - depends on the **NS spin direction**



Mönkkönen et al. (2020)

Stream accretion

- Applying the earlier formula of angular momentum transfer to the stream in GX 301−2

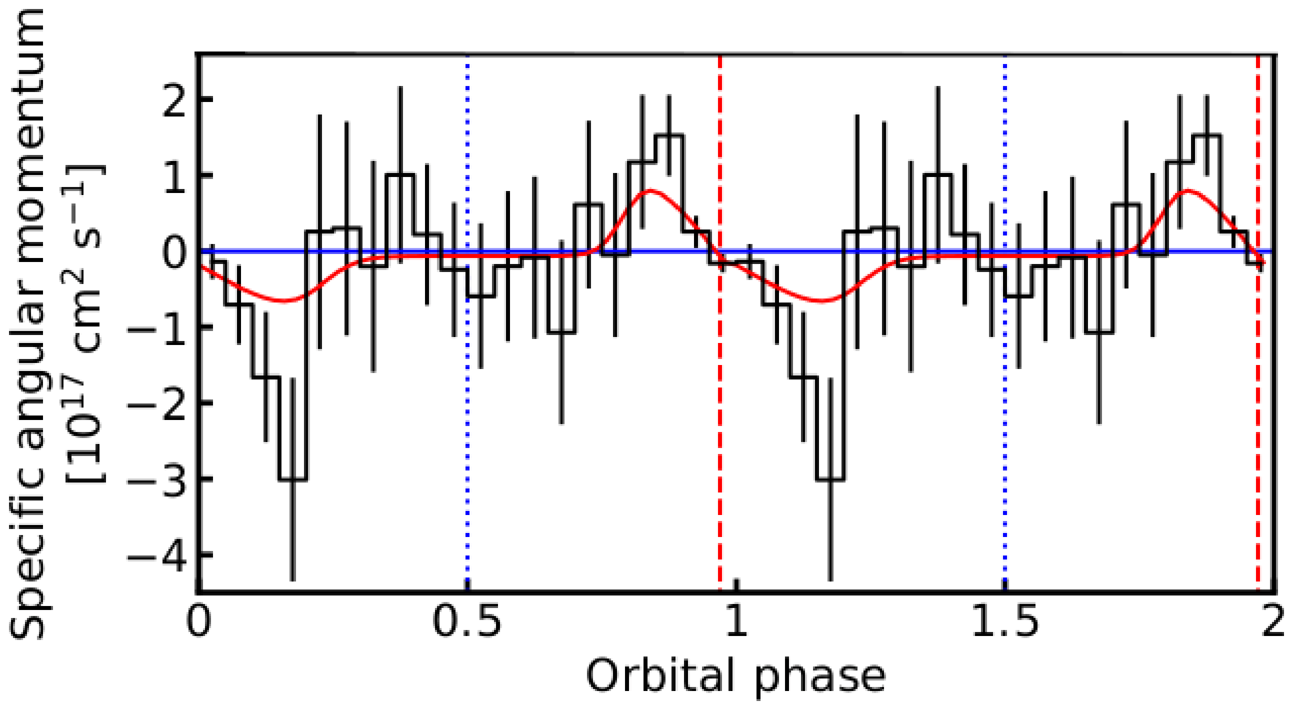
$$\rho\, v_{\mathrm{w}} r^2 = \mathrm{const}$$

$$\eta(\phi) = C_1 - C_2 \frac{\partial \ln \rho}{\partial \phi}(\sigma_1, \sigma_2, R)$$

Set by the wind

Depends on the **spin direction**

Stream parametrization



Mönkkönen et al. (2020)

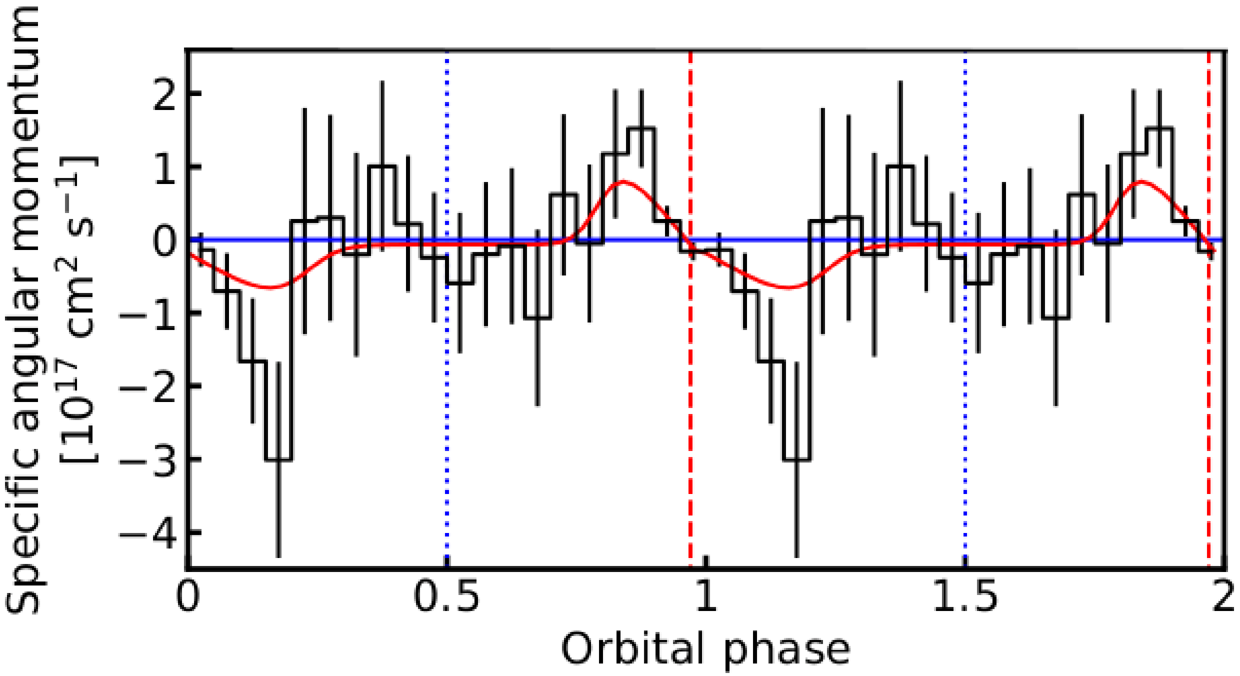
$$l = \frac{2\pi \dot{f} I}{\dot{M}}$$

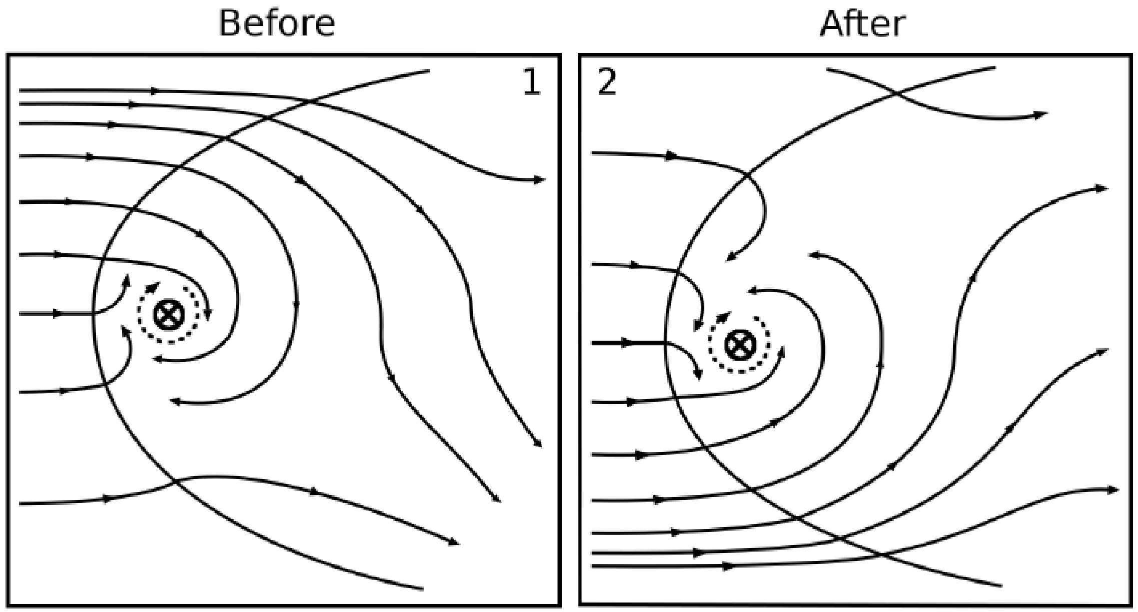
C_1 = −0.1 ± 0.1, **C_2 = −1.0 ± 0.4**,
σ_1 = 0.8 ± 0.2, σ_2 = 1.2 ± 0.4

Stream accretion

- Applying the earlier formula of angular momentum transfer to the stream in GX 301−2

Only possible if the NS spins retrograde with respect to the binary orbit



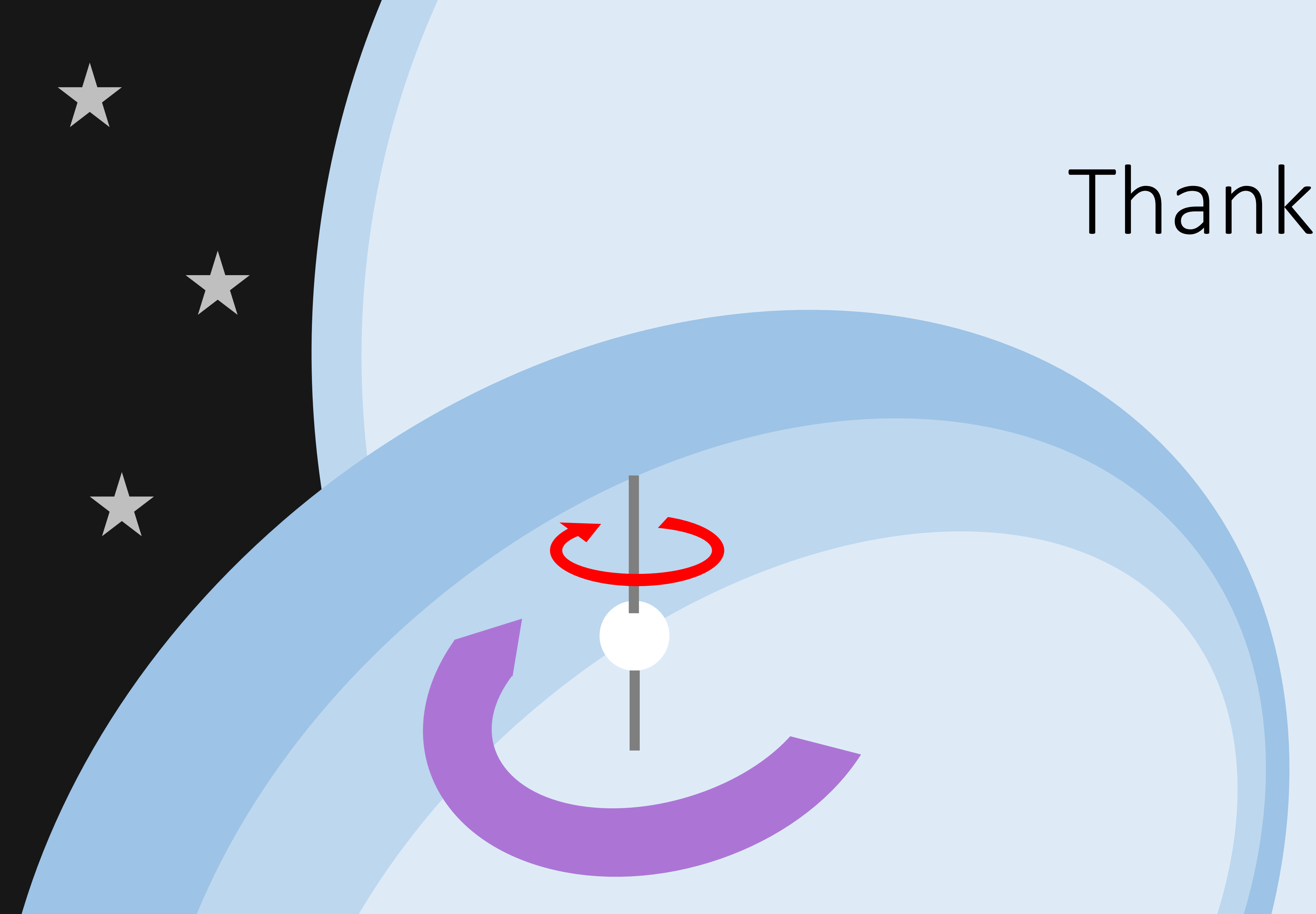


Mönkkönen et al. (2020)

Prospects

- Explaining long spin periods
- Population studies
- Supernova kicks
  - Prediction of retrograde spins (Hills 1983; Brandt & Podsiadlowski 1995)
- Progenitors of gravitational wave sources (East et al. 2019)

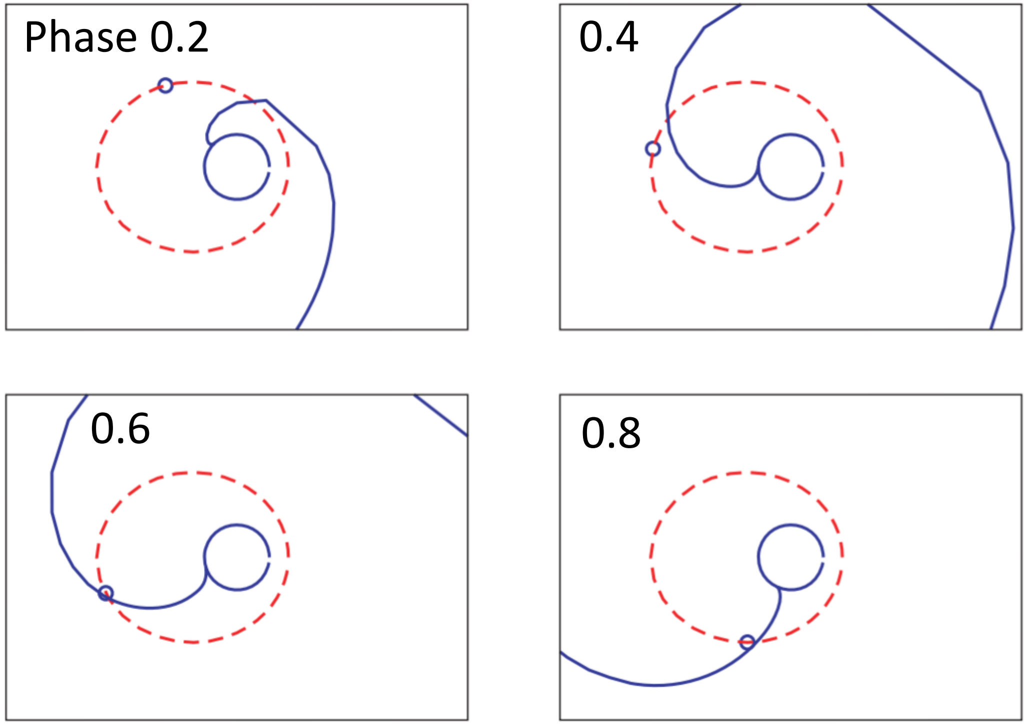
Thank you!



Direction of spin in other pulsars

- The double radio pulsar PSR J0737−3039 prograde (Pol et al. 2018)
- X-ray pulsar 4U 1626−67 prograde? (Middleditch et al. 1981)

Stream



Leahy & Kostka (2008)

Orbital uncertainties

- Caveat: the spin frequency evolution depends on the orbital corrections applied and their accuracy.
- Estimate by reverting back to ”raw” data and re-applying the orbital corrections which were varied within their error range.
- Lowers the significance of observed behaviour but still significant
- Confirmation of the orbital parameters by observing a spin-up episode with high time resolution