Title: Numerical simulations of accreting neutron stars in a general relativistic framework.

Speakers: Pushpita Das

Collection/Series: Magnetic Fields Around Compact Objects Workshop

Subject: Strong Gravity

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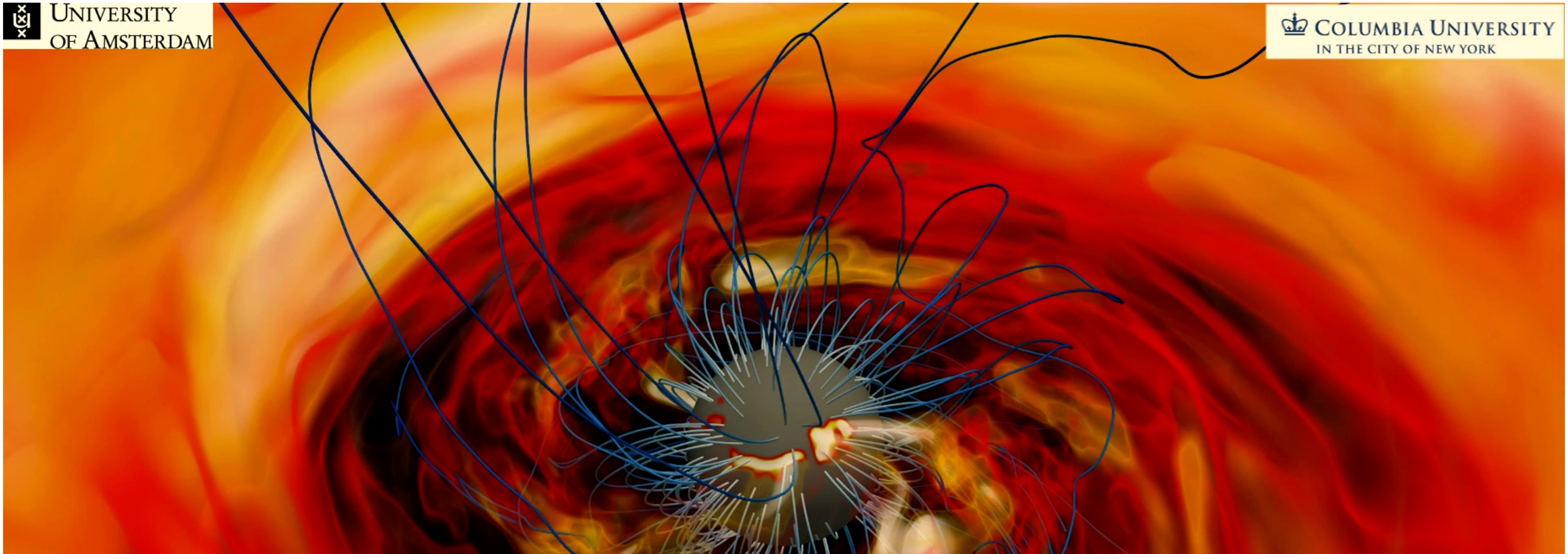
Abstract:

Numerical modeling of accreting millisecond X-ray pulsars (AMXPs) allows us to understand the physical origin of different observational signatures detected from these systems. Since the birth sites of these signals are strongly influenced by the gravitational potential of the star, magnetohydrodynamic (MHD) simulations in full GR

(GRMHD) are essential to accurately capture space-time curvature effects and inherent variations in the X-ray spectra. In this talk, I will present results from 3D GRMHD simulations of accreting neutron stars with oblique magnetospheres. I will discuss the pulse profiles generated from the GRMHD simulations and their implications for mass-radius inference in the accreting sources. Apart from the surface features, AMXPs are also good candidates for studying neutron star jet formation mechanisms. Though there have been extensive investigations into black hole jets, neutron star jets remain highly unexplored. Our 2D axisymmetric study in the quiescent regime suggests that the thick disk collimates the initial open stellar flux, leading to jets like the Blandford-Znajek mechanism proposed for black holes. However, much remains to be done before we can draw a complete picture of jets launched from neutron stars. The global 3D GRMHD simulations of the accreting neutron stars allow us to explore the jet formation mechanisms in these systems in detail for the first time.



Numerical simulations of accreting neutron stars in a general relativistic framework

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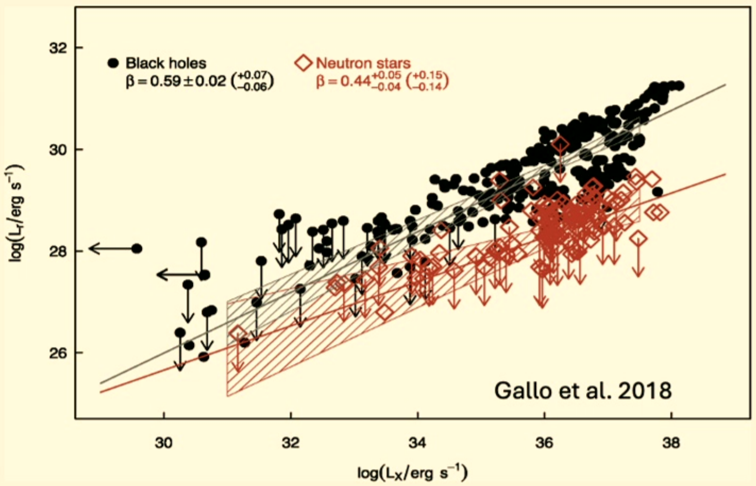
Astrophysical Processes in X-ray Binaries

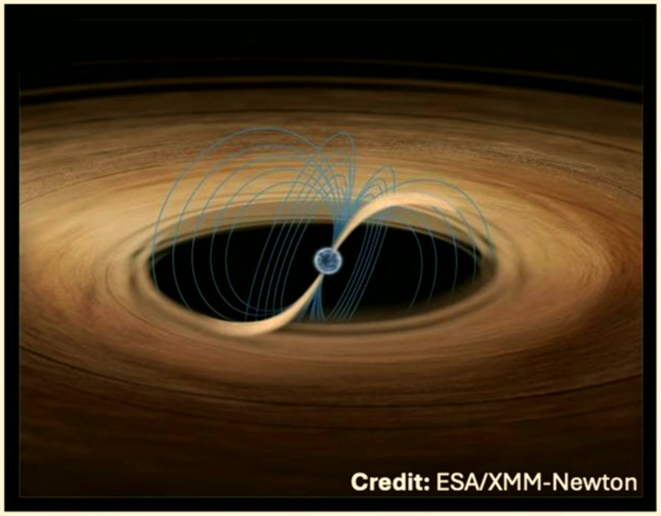
Outflows

- Simillar to Black hole X-ray binaries, relativistic jets has also been observed from NS X-ray binaries



X-ray Pulses

- Complicated surface emission
- Candidates for Pulse profile Modelling



Critically depends on star-disk magnetic field interactions!

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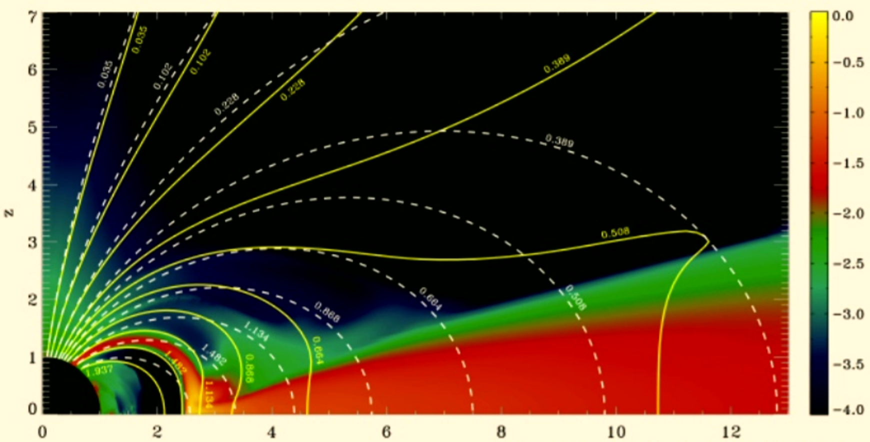
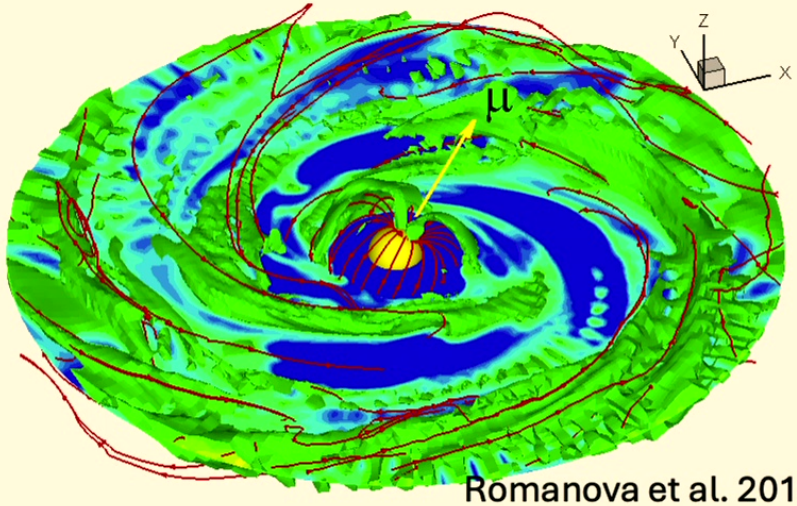
Numerical Simulations

- Accretion onto magnetized stars have been extensively studied in the non-relativistic regime.
  - Non-magnetized (*Romanova et al. 2002; Bessolaz et al. 2008; Fendt 2009; Zanni & Ferreira 2009; Romanova et al. 2021*)
  - Magnetized disks (*Romanova et al. 2012, Takasao et al. 2018*)



Zanni & Ferreira 2009



Romanova et al. 2012

- General Relativistic Studies (Parfrey 2017, 2024; Murguia-Berthier 2024; Das 2022, 2024, 2025)

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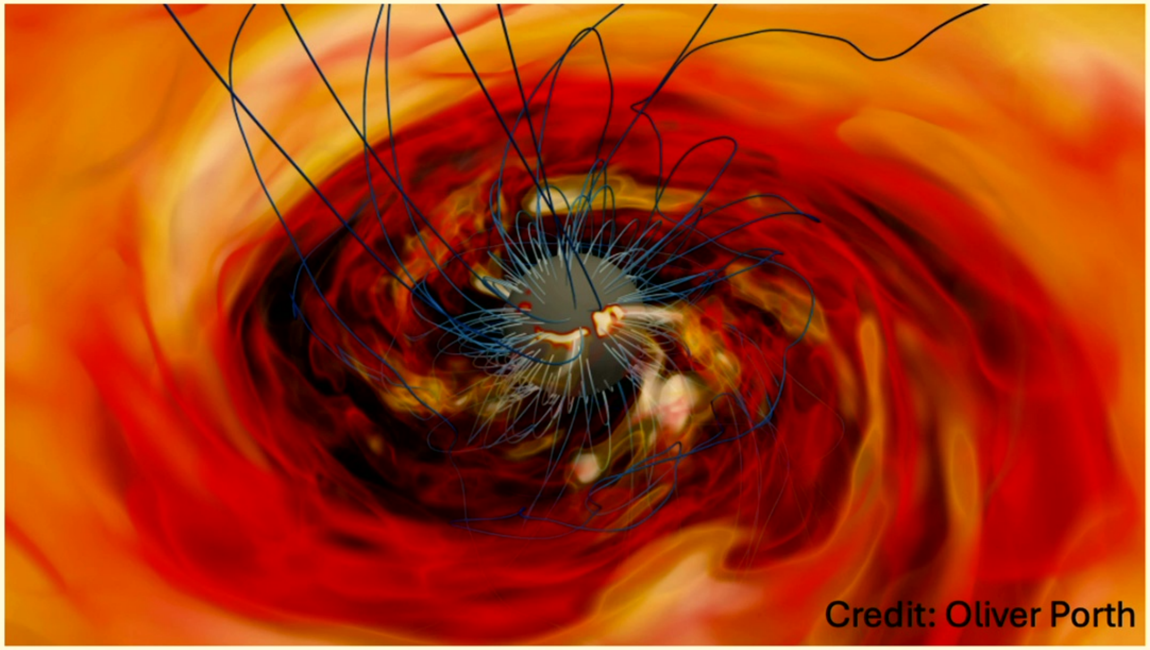
GRMHD Simulations

- Neutron star jet formation mechanisms.
- Magnetospheric Interactions.
- Hotspot shapes in accreting pulsars.
- Accretion variability.
- Pulse properties.

- Schwarzschild Spacetime.
- Initialize the domain with a stellar magnetic field and a weakly magnetised torus.
- Self-consistantly handle the force-free and MHD regions.



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3D Cartesian Simulations

Evolution:

- Force free coupled magnetosphere
- Inside the light cylinder, “drive” the solution to force free state, $\rho \to \rho_t$, $p \to p_t$, $v_{||} \to 0$ ($\sigma = 70$, $\beta = 1.4 \times 10^{-2}$)

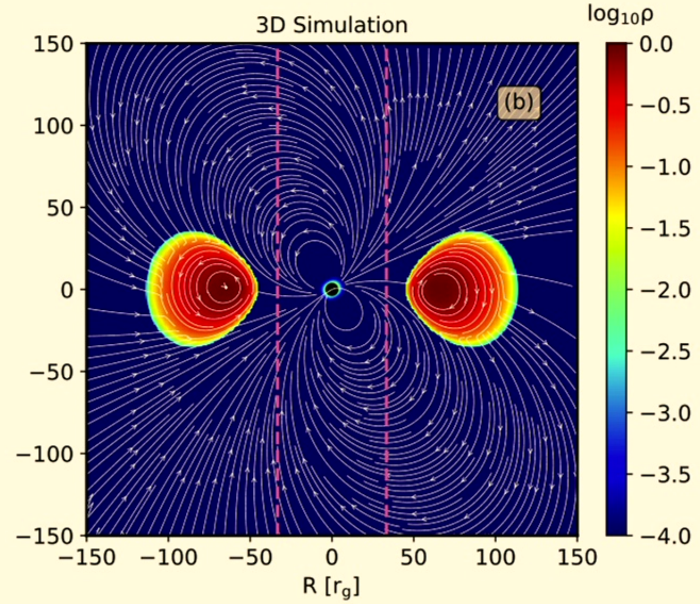
Komissarov (2006), Tchekhovskoy et al., (2013)

At the Stellar surface:

- $\rho \to \rho_{star}$, $p \to p_{star}$, $\vec{v} = v_{star}$
- Accreting matter fall into the stellar surface without any obstructions.

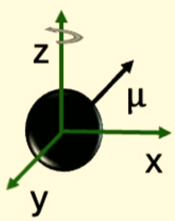
Numerical Setup

- Cartesian Coordinates
- Schwarzschild Spacetime

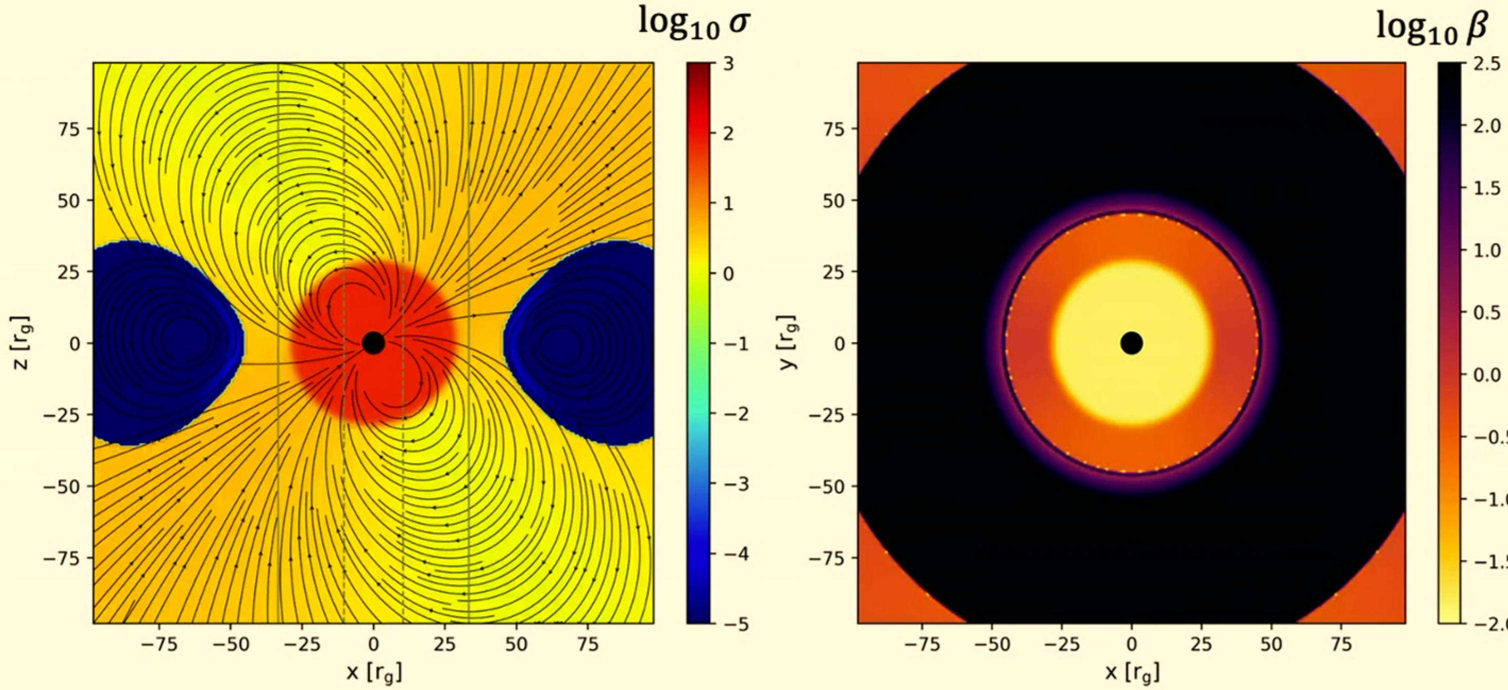


What role does inclination play?

- Matter accreted through one column in the upper and lower magnetic hemisphere.



Inclined Dipole $\chi_{star} = 60°$



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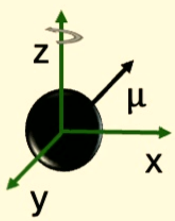
What role does inclination play?

- Matter accreted through one column in the upper and lower magnetic hemisphere.
- Rayleigh–Taylor Instability manifesting in the equatorial plane.



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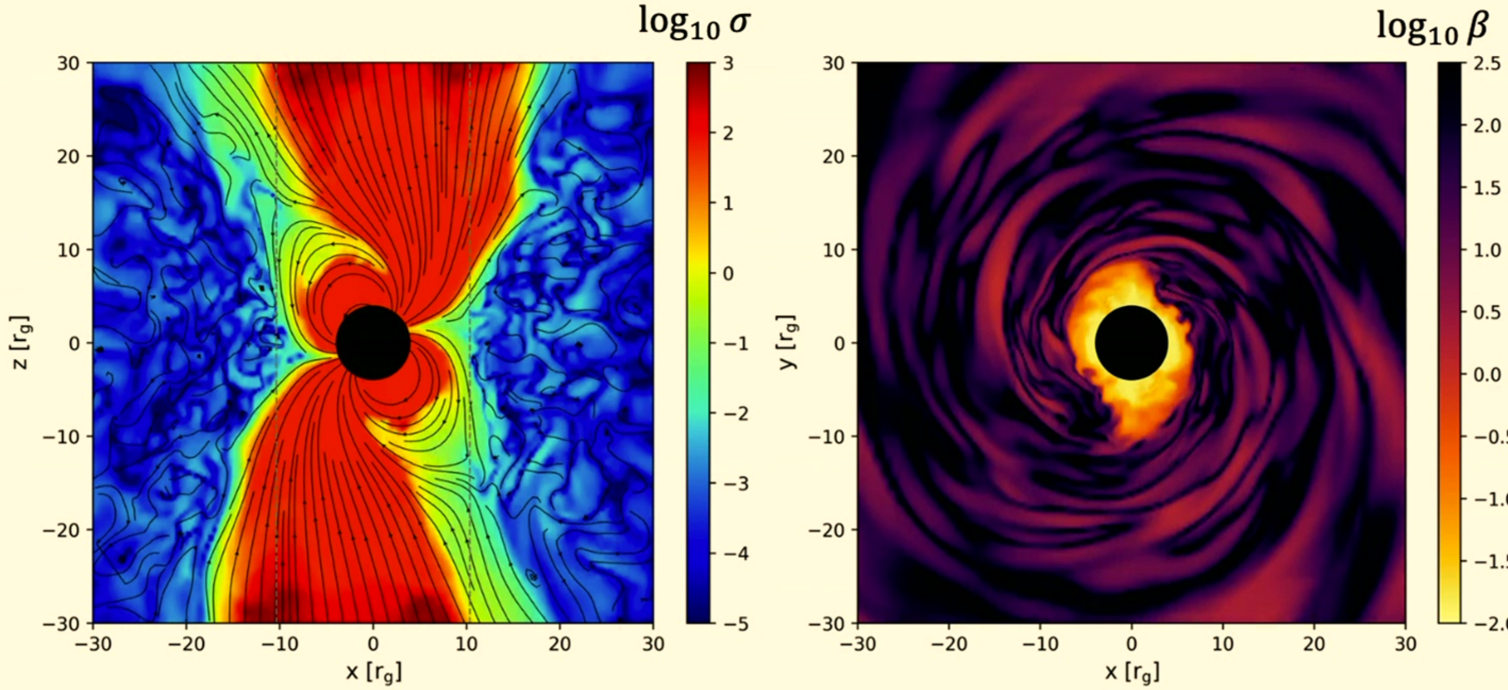

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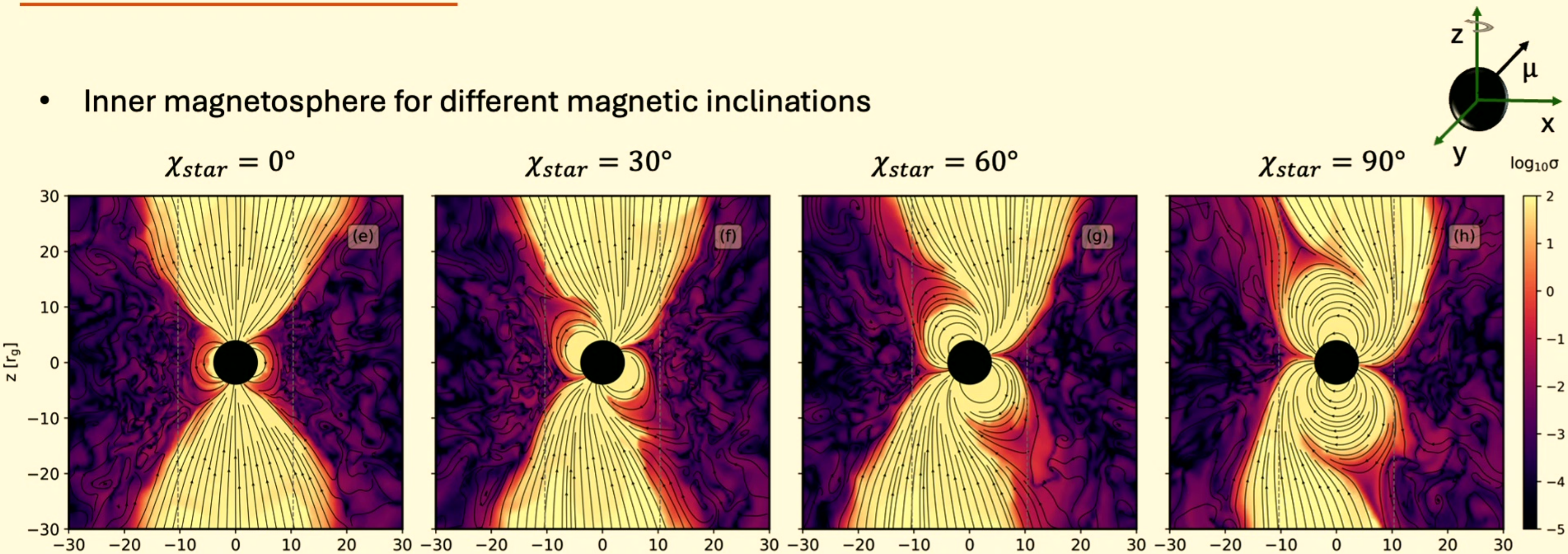
Different Magnetic Inclinations..

- Inner magnetosphere for different magnetic inclinations



- The accretion column preferably moves towards the location of anti-parallel fieldlines..

Das P., and Porth O., 2024

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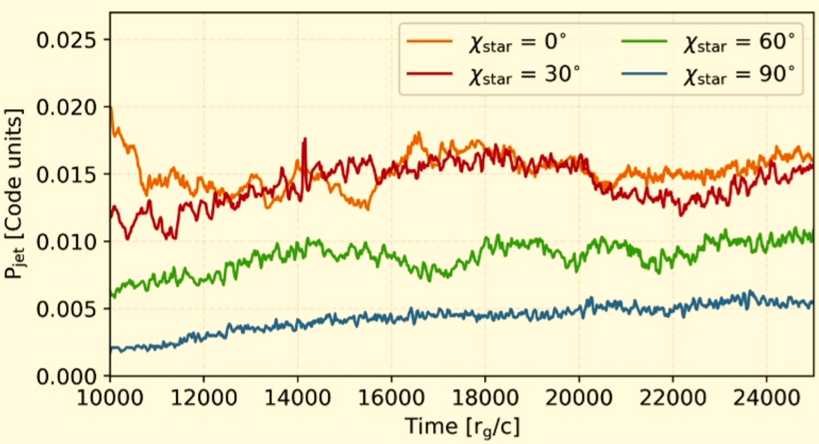
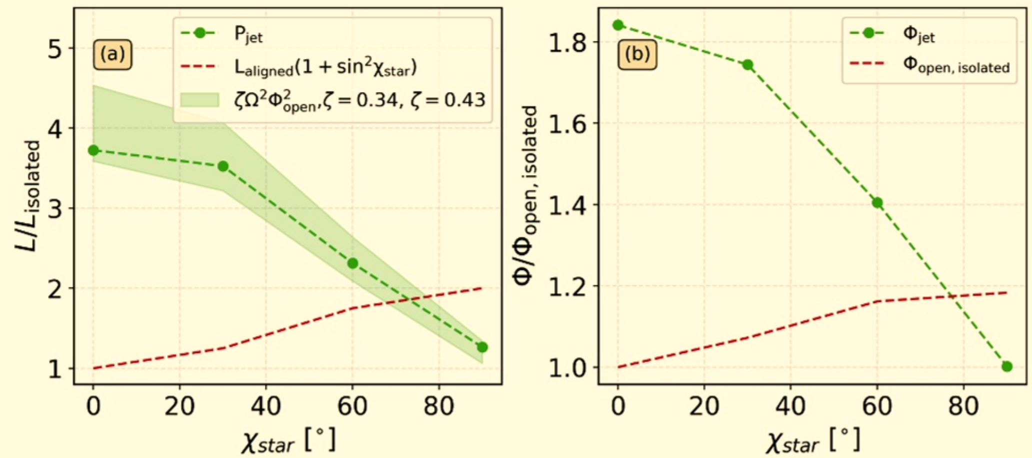
Neutron Star Jets in 3D



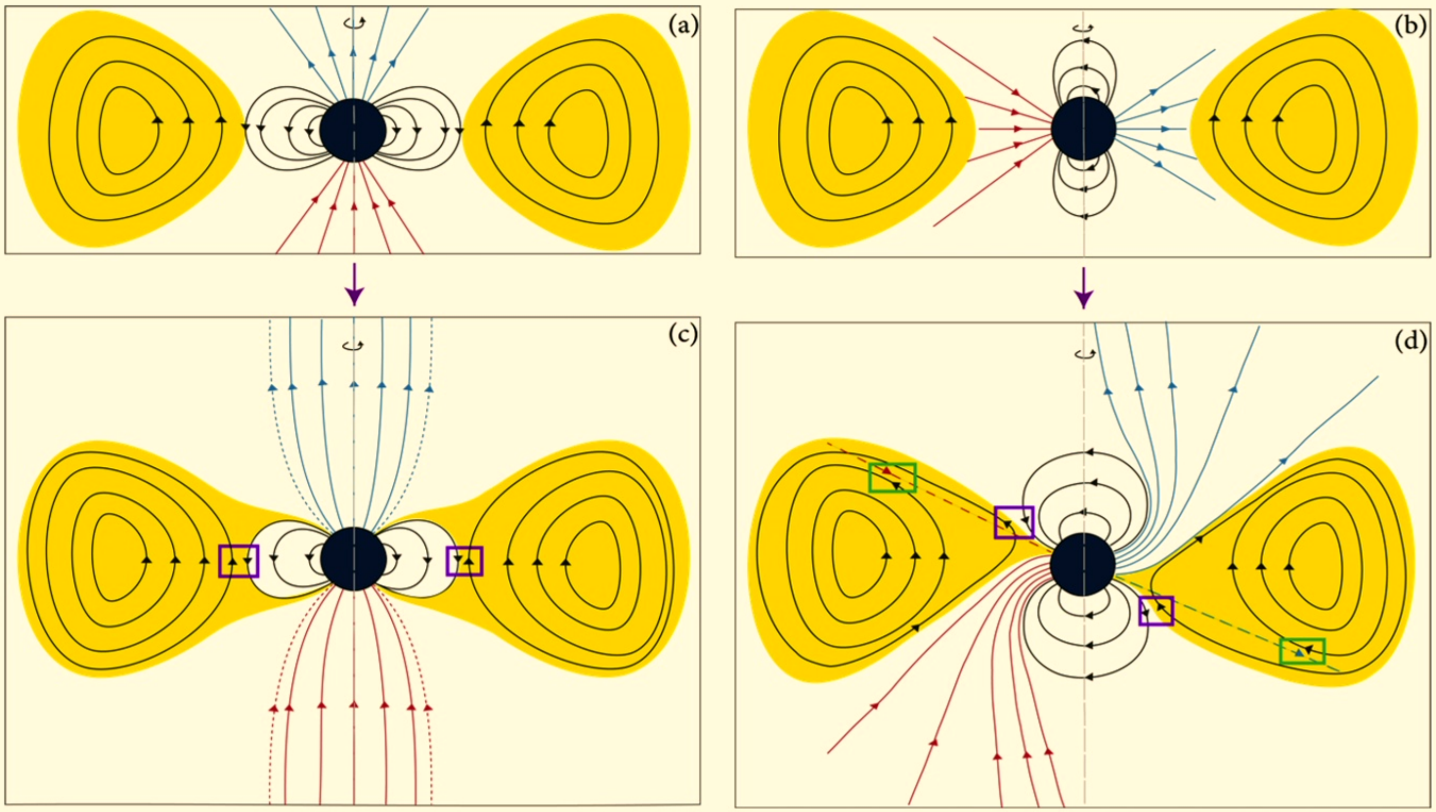


- Jet power decreases with increasing magnetic inclination
- For $\chi_{star} = 90°$, $P_{jet} \simeq 8 \times 10^{36}$ erg/s

- $L = \xi\Omega^2\Phi^2_{open}$, $\xi \in [0.34, 0.43]$

Das P., and Porth O., 2024

Flux opening in 3D



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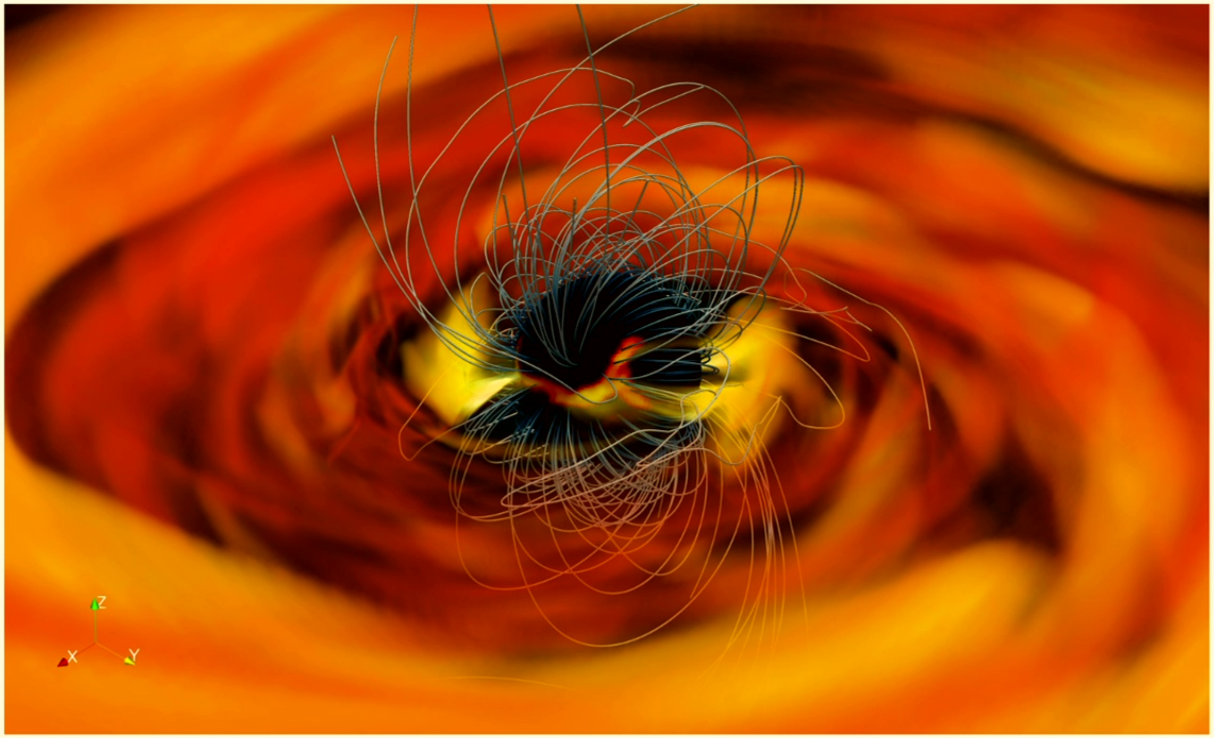
Inner Magnetosphere..

- Inner magnetosphere for $\chi_{star} = 60°$
- Complicated non axisymmetric accretion flow.



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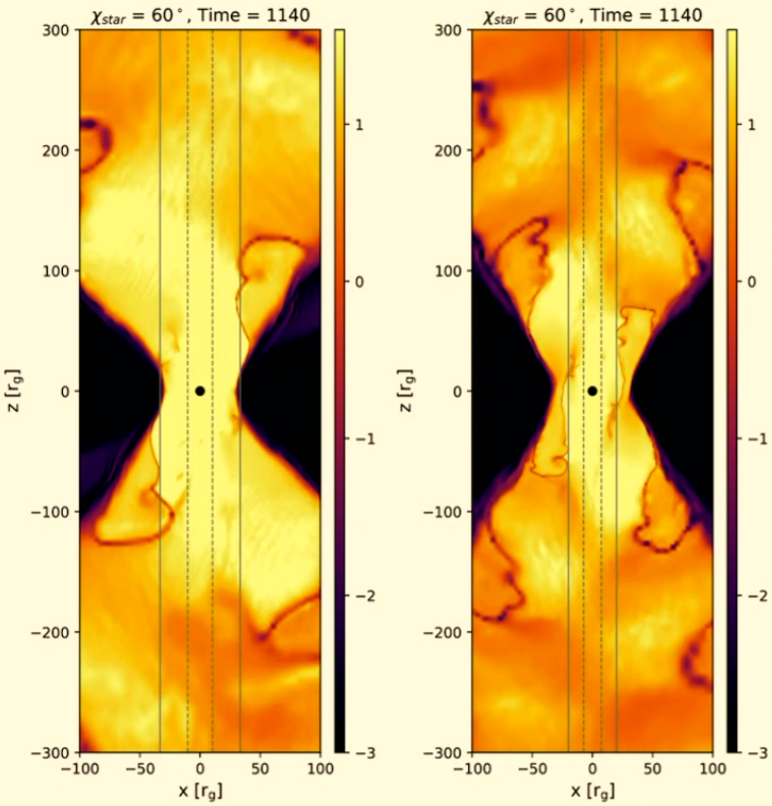
Jets in different regimes



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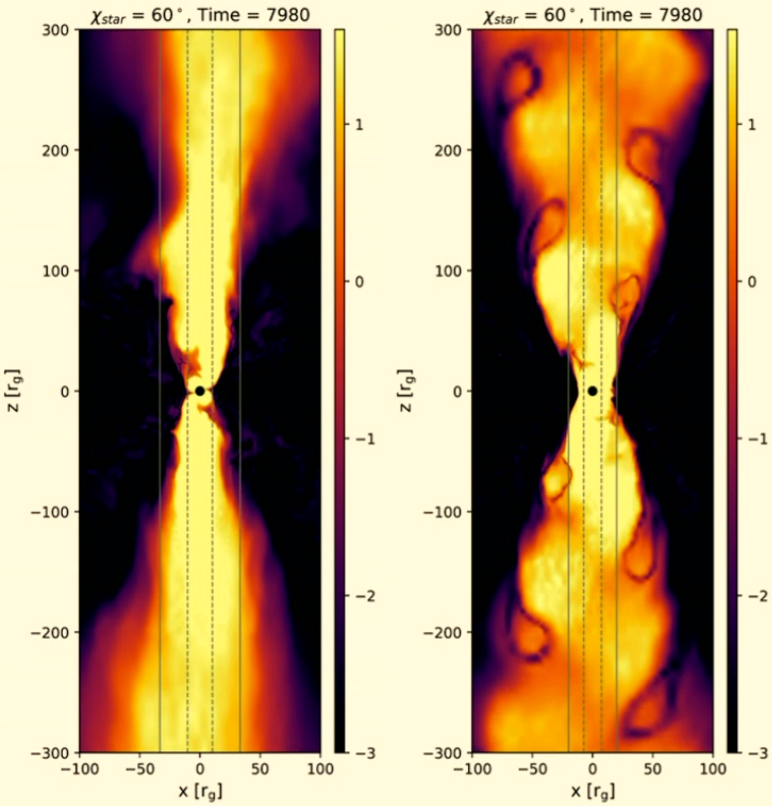
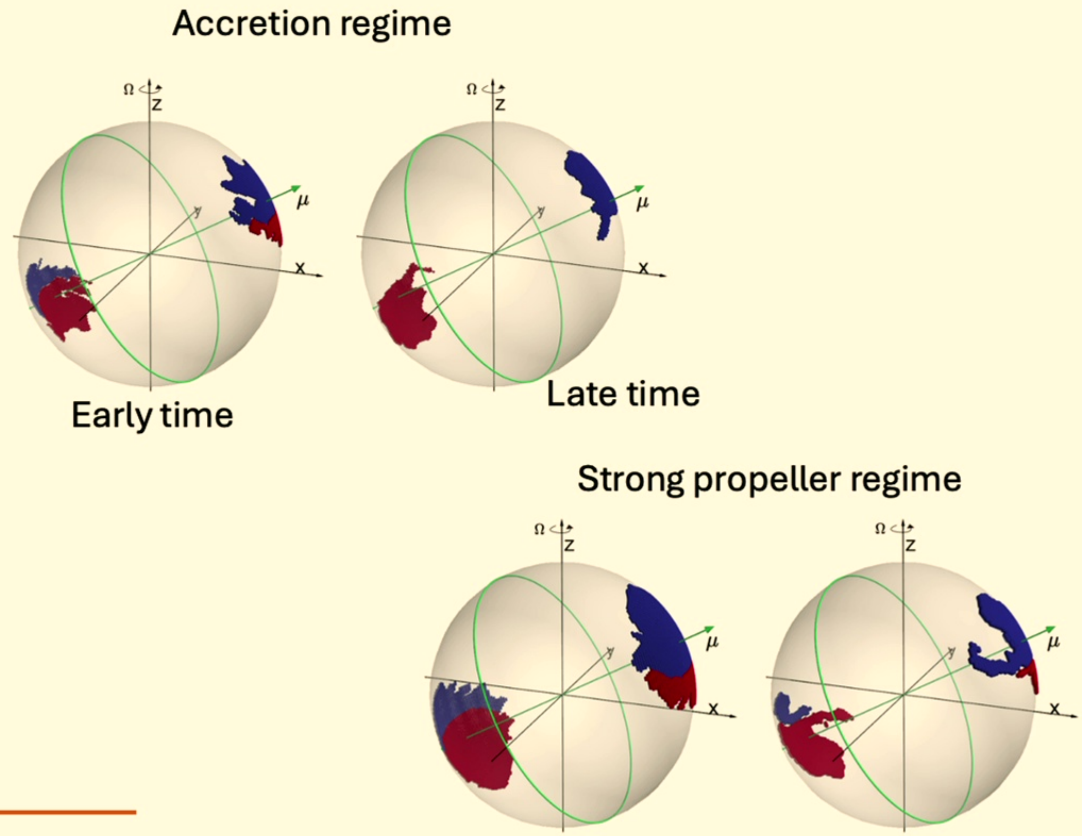
Jets in different regimes





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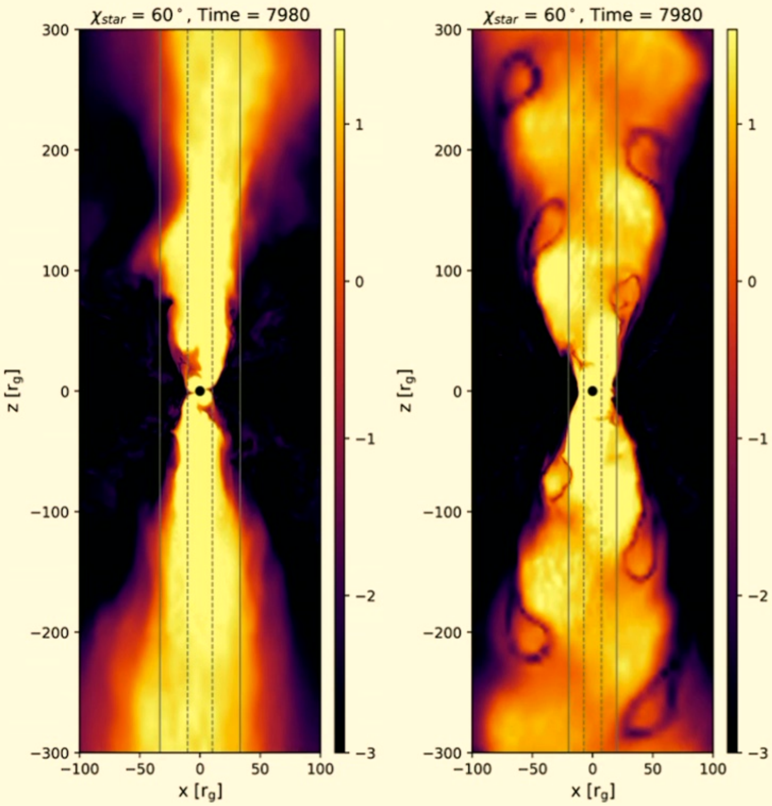
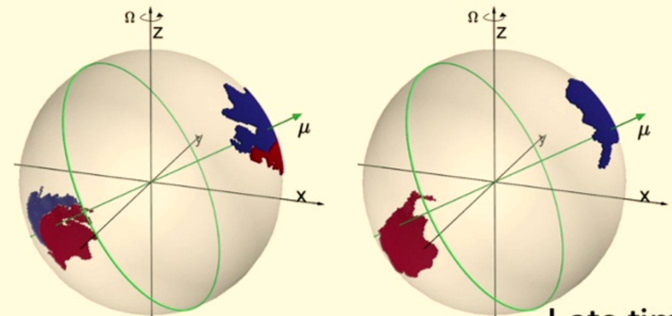
Jets in different regimes



Accretion regime



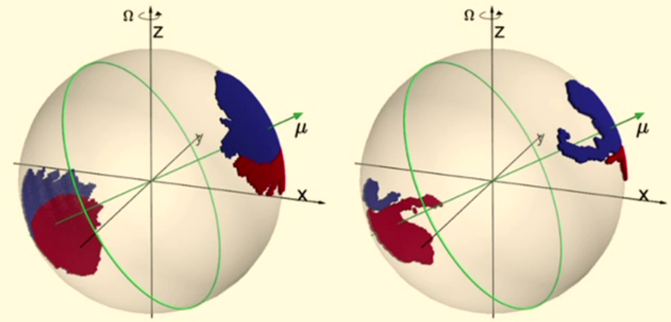
Early time

Late time

Strong propeller regime

Blue ⟶ Upper Hemisphere

Red ⟶ Lower Hemisphere



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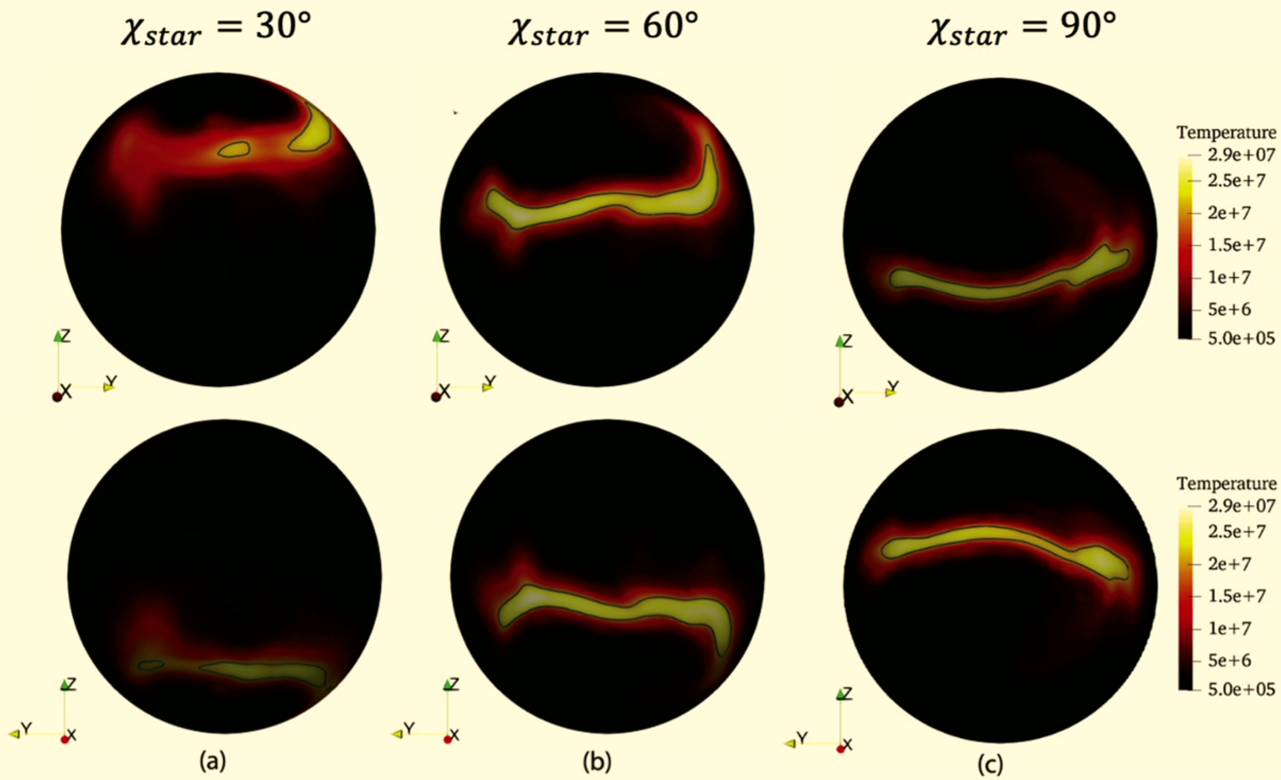
Zooming in at the surface

- How do the hotspot shapes depend on stellar magnetic inclination?

- Hotspots always form at the below the open fieldline regions in both hemispheres.



Das, et al., 2025 (https://arxiv.org/abs/2411.16528)

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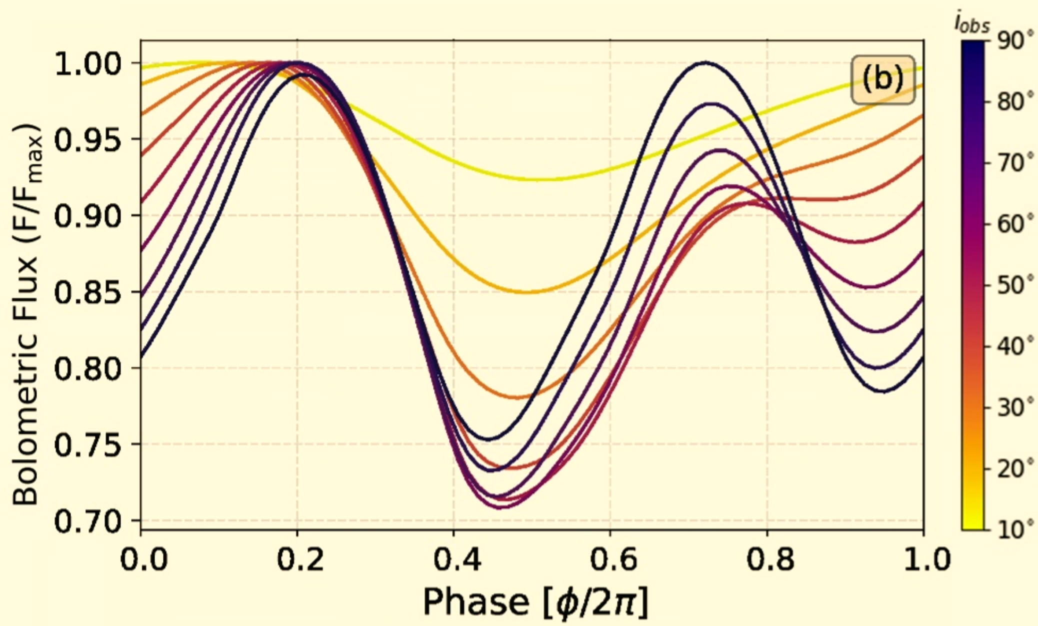
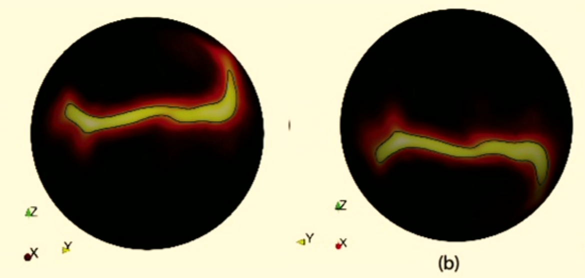
Pulse profiles

- Bolometric Pulse Profiles from the averaged accretion hotspots



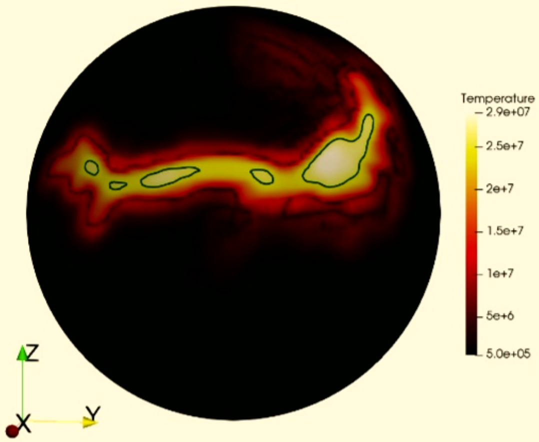


- Using XPSI, https://github.com/xpsi-group/xpsi
  - Fundamental: $\simeq 3-10\%$ rms
  - First Harmonic: $\simeq 0.5-12\%$ rms

Das, et al., 2025 (https://arxiv.org/abs/2411.16528)

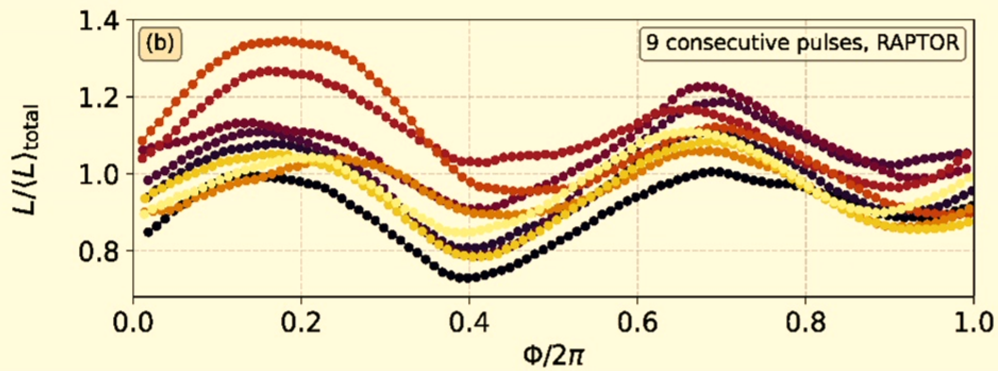
But the hotspots are variable!

- Hotspot shapes



How does this impact the pulses?

- Using a GRRT code, RAPTOR https://github.com/jordydavelaar/raptor
- M = 1.69 $M_{\odot}$, R_{eq} = 10.75 km at $i_{obs} = 70°$



Das, et al., 2025 (https://arxiv.org/abs/2411.16528)

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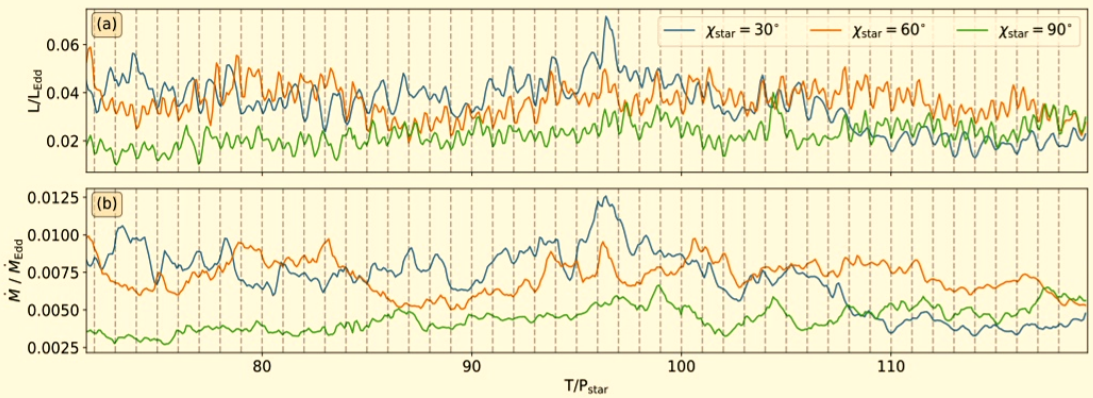
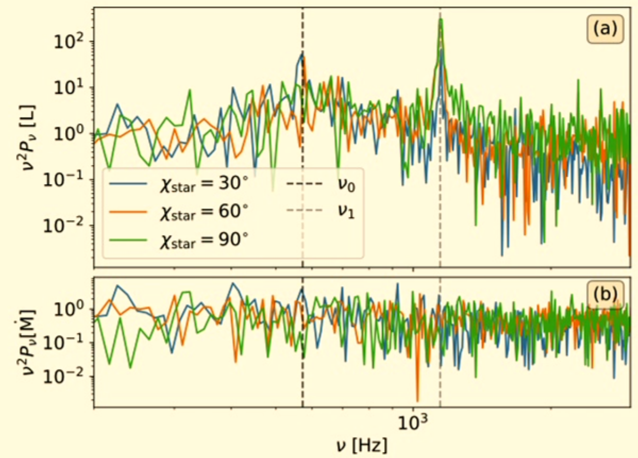
Pulse variability

- Light curve for $i_{obs} = 70°$





- Accretion noise dominates the overall light-curve variability
- The fractional rms amplitudes of the fundamental and the first harmonic show a similar trend as the averaged accretion spots with χ_{star}

$$rms_{\nu_0} = [0.054, 0.045]$$

$$rms_{\nu_1} = [0.027, 0.073, 0.083]$$

Das, et al., 2025 (https://arxiv.org/abs/2411.16528)

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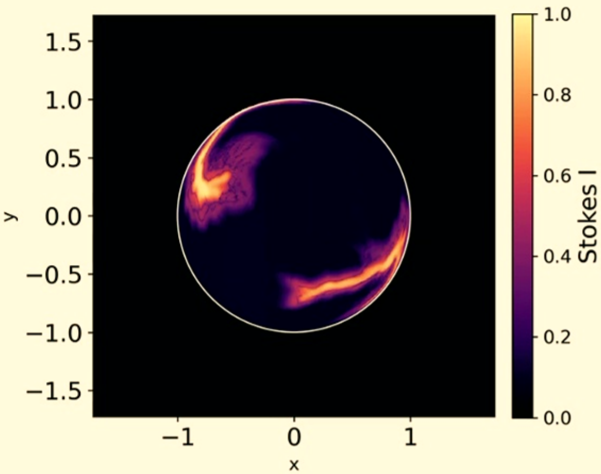
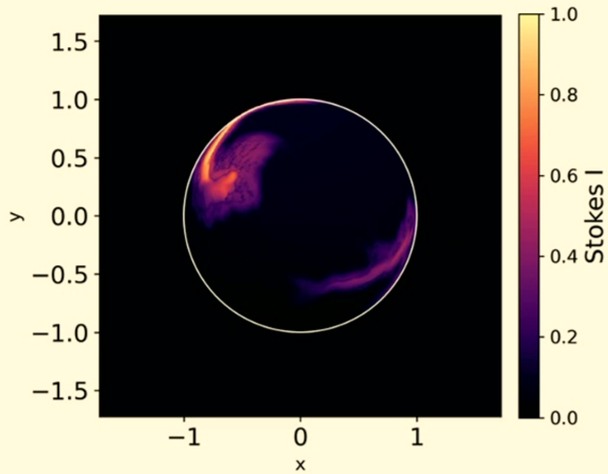
Accretion Columns

- How does the accretion column impact the pulses?





- $M = 1.69\ M_{\odot}$, $R_{eq} = 10.75$ km
  - Ray-traced images for $\chi_{star} = 60°$, at $i_{obs} = 50°$

- Obscures the lower spot in the antipodal geometry
- Full radiative transfer including all the necessary emission, absorption and scattering, along with better boundary conditions for MHD simulations is required to complete this picture

Das, et al., 2025 (https://arxiv.org/abs/2411.16528)

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Summary

- The disk plays a dominant role in determining the jet power.
- Jet power decreases with increasing magnetic axis inclination (with respect to the rotation axis).
- We get stripped jets with an inclined star ($\chi_{star} = 60°$) in propeller regime.
- Harmonic contents of the simulated pulses are consistent with the values observed for AMXPs.
- We observe significant pulse variability in all cases.
- Absorption in the accretion columns significantly impacts the pulse properties and introduces higher harmonics in the pulses.