From GeV to PeV: Orbital Modulation and Wind-Regulated Ultrahigh-energy Emission in Cygnus X-3

Speaker: Su-Yu Wan
Nanjing University

Ruo-Yu Liu, Xing-Fu Zhang, Dmitriy Khangulyan

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Outline

Outline

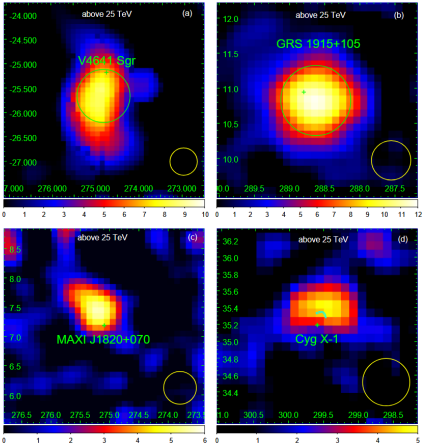
Introduction

Model Setup

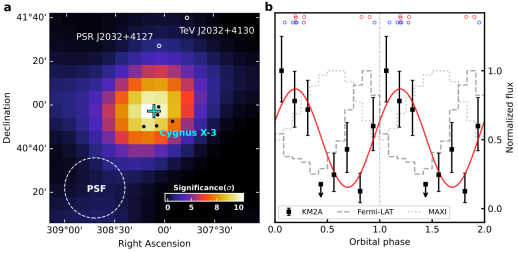
Environmental Regulation

Conclusions

Probing UHE microquasars



LHAASO observations of microquasars [Lhaaso Collaboration et al., 2025].



Cygnus X-3 in the UHE γ-ray sky [Cao et al., 2026].

- TeV–PeV γ-ray emission has been detected from several Galactic microquasars.
- **Point-like source Cygnus X-3 Orbitally modulated !**

Microquasar system: Cygnus X-3

- **High-mass X-ray binary:** a Wolf–Rayet (WR) star and a compact object; $P_{\rm orb} = 4.8$ hr, $d \simeq 9$ kpc.
- **Circum-binary environment:** $a \sim 2.7 \times 10^{11}$ cm; strong WR wind ($\dot{M}_{\rm WR} = 0.4 - 2.0 \times 10^{-5} M_\odot\ {\rm yr}^{-1}$).
- **Accretion funnel:** IXPE polarization, possibly associated with accretion-driven outflows.

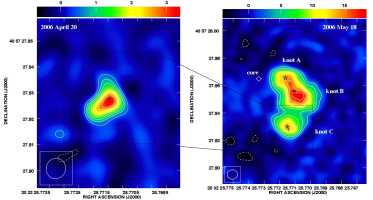


Figure: 5-GHz e-VLBI radio jets [Tudose et al., 2007].

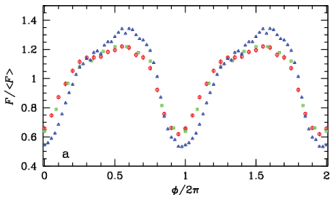


Figure: Folded X-ray orbital modulation [Zdziarski et al., 2012].

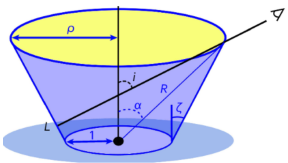


Figure: Accretion funnel geometry (Veledina et al. 2024).

Gamma-ray variability

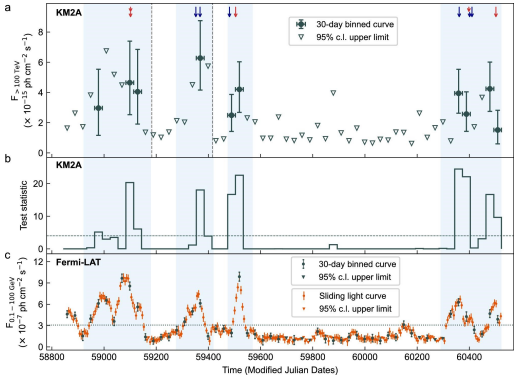


Figure: Long-term GeV–PeV variability [Cao et al., 2026].

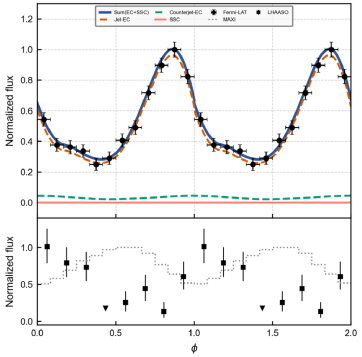


Figure: Folded GeV orbital modulation [Zhang et al., 2026].

- **Month-scale variability:** the PeV emission is variable and enhanced during GeV high states.
- **GeV emission:** Explained by anisotropic IC scattering.

Why escaping PeV protons?

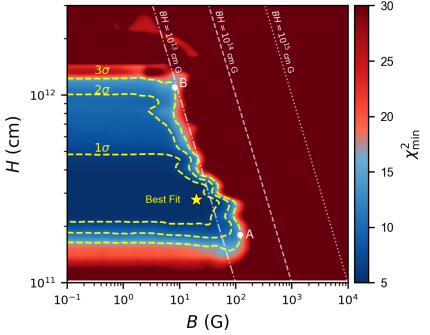


Figure: GeV-zone magnetic constraints [Zhang et al., 2026].

GeV-zone 3σ constraints:
$(BH)_{\rm GeV} \lesssim 10^{13.3}$ G cm

- **Magnetic deconfinement:** For a rapidly decaying jet field $B(H) \propto H^{-\delta}$ ($\delta > 2$), protons confined in the inner jet can escape before reaching the GeV zone !
- **Advection vs. cooling:** $t_{\rm adv} < t_{\rm cool,p}$: a substantial fraction of proton energy can survive.
- **GeV–PeV connection:** Jet electrons produce GeV gamma rays via anisotropic IC, while escaping protons produce PeV emission via hadronic processes ($p\gamma + pp$).

Can explain the GeV–PeV orbital phase offset !

Unified GeV–PeV emission model

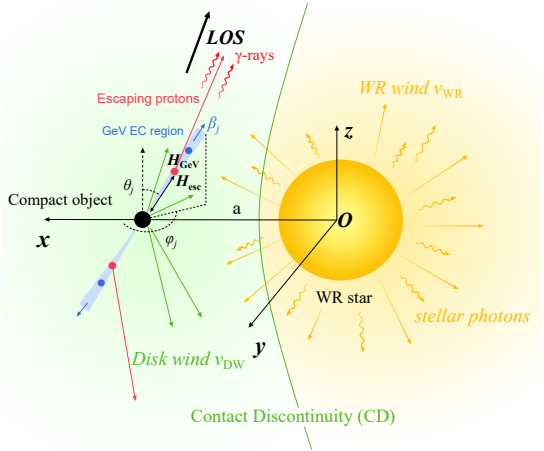


Figure: Sketch of binary–jet geometry

- **GeV emission:** Anisotropic IC scattering of stellar photons by jet electrons; constrains the common jet geometry.
- **Escaping protons:** Comoving-isotropic injection transformed to the observer. Ballistic propagation after escape.
- **Photon-hadronic yields:** SOPHIA++ Monte Carlo 20000 samples per interaction.
- **Wind environment:** WR wind + Accretion-driven disk wind + Contact discontinuity (CD)

Joint spectral and orbital fits

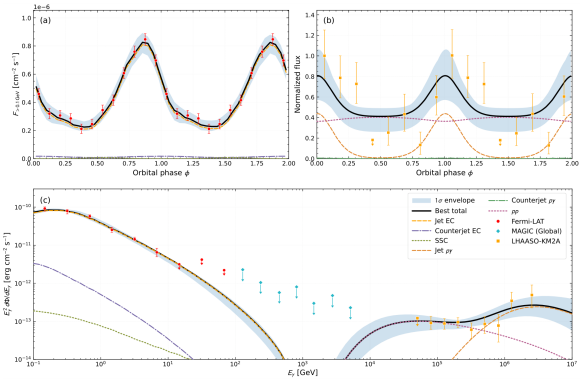


Figure: Joint GeV–PeV spectral and orbital fits, with a low-energy cutoff at 10 TeV.

Parameter	Best fit (1σ)
GeV / Jet parameters	
$H_{\rm GeV}/10^{11}$ cm	$2.751^{+0.327}_{-0.600}$
β_j	$0.603^{+0.076}_{-0.071}$
θ_j [°]	$44.97^{+10.71}_{-3.50}$
φ_j [°]	$196.32^{+6.08}_{-2.25}$
p_e	$3.639^{+0.135}_{-0.061}$
$K_{\rm inj}/10^{48}\,{\rm s}^{-1}$	$0.995^{+1.390}_{-0.258}$
UHE / Wind parameters	
$H_{\rm esc}/10^{10}$ cm	$2.971^{+3.026}_{-2.699}$
$\beta_{\rm DW}$	$0.142^{+0.187}_{-0.015}$
$L'_p/10^{38}\,{\rm erg\,s}^{-1}$	$0.583^{+2.574}_{-0.355}$
s_p	$2.461^{+0.213}_{-0.165}$
$E'_{p,\rm cut}$ [PeV]	$107.78^{+439.66}_{-80.48}$

L'_p is integrated above 1 TeV.

$$E_p^2 Q_p(1\,{\rm PeV}) = 2.02^{+2.78}_{-0.75} \times 10^{36}\,{\rm erg\,s}^{-1}$$

Wind-regulated PeV emission

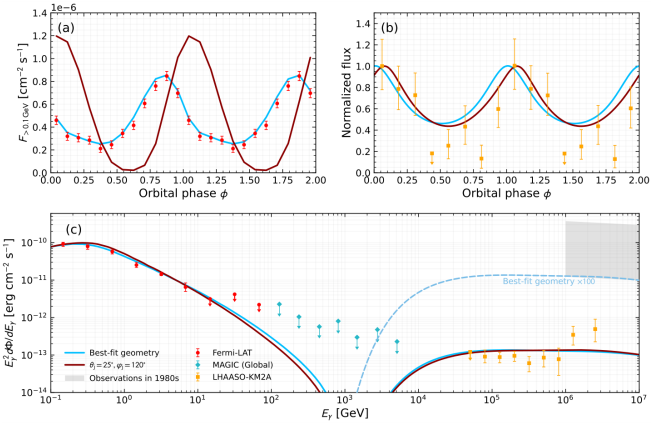


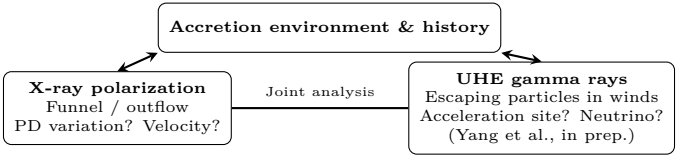
Figure: Pure WR-wind scenario: solid curves use $L_p \sim 2 \times 10^{36}\,\mathrm{erg\,s^{-1}}$; blue dashed uses $L_p \sim 2 \times 10^{38}\,\mathrm{erg\,s^{-1}}$. Gray band: PeV reports from the 1980s.

- **Pure WR-wind:** Reproduces the spectrum below 1 PeV, but fails to explain the observed **PeV bump**.
- **Historical PeV emission:** With proton power comparable to our joint fit, the enhanced pp emission approaches the **1980s reported flux**.
- **Environmental regulation:** Wind geometry modulates the hadronic emission by orders of magnitude.

Takeaway messages

- **Cygnus X-3 — compact hadronic emission:** Jet electrons reproduce the GeV orbital modulation through anisotropic IC, while escaping PeV protons produce UHE gamma rays via hadronic processes. The photon-hadronic interactions dominate the orbital modulation $> 100\,\mathrm{TeV}$, and interactions of WR and disk wind could regulate the PeV emission.

- The binary environment plays a crucial role in shaping UHE emission from Galactic microquasars. Long-term, coordinated multi-wavelength observations are essential to link accretion and wind-state changes to UHE gamma-ray variability, providing deeper insights into cosmic-ray acceleration and propagation.



Thanks for listening !

Link for this work: arXiv:2610.11881

Contact me: **sywan2002@smail.nju.edu.cn**

Backup 1

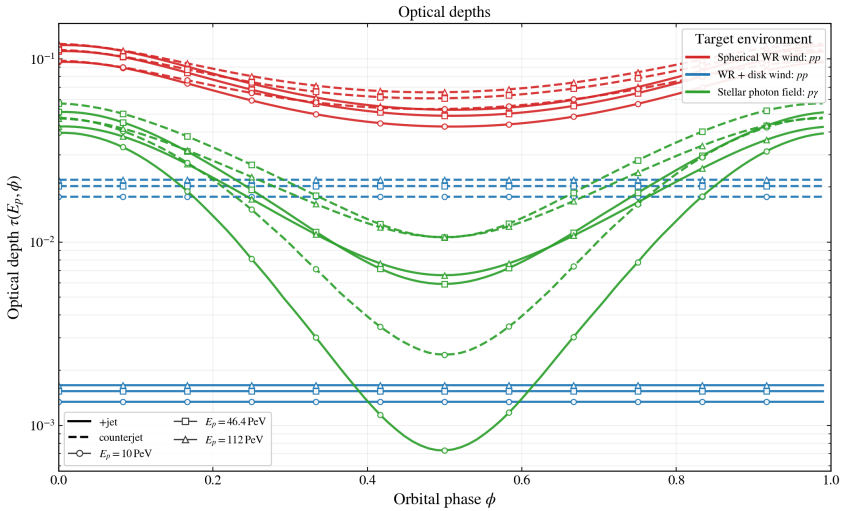


Figure: Optical depths for the best-fit case

Backup 2

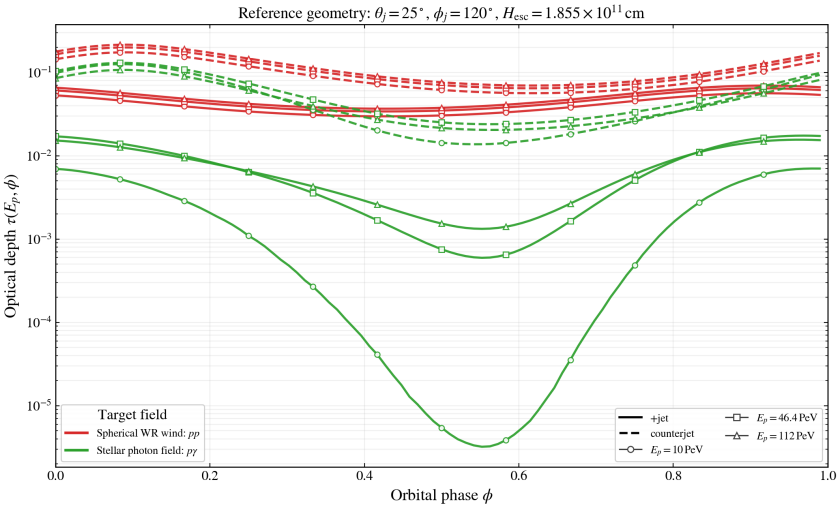
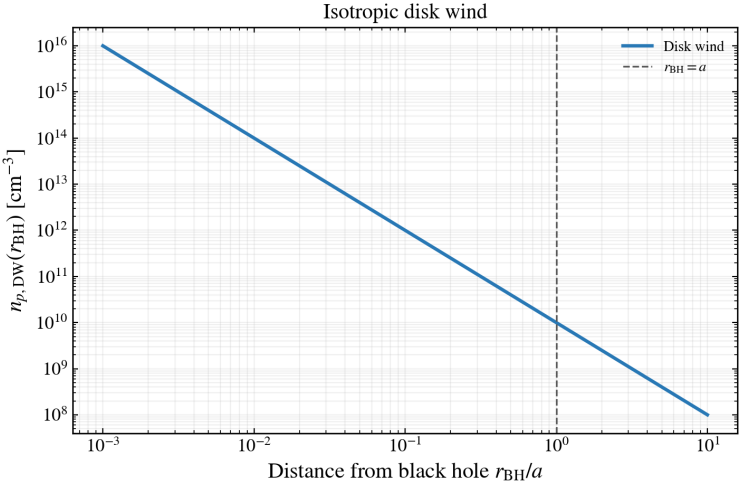
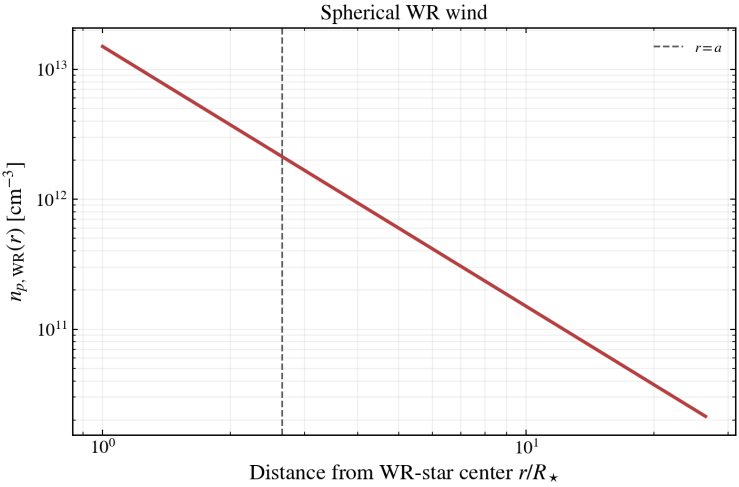


Figure: Optical depths for the reference case

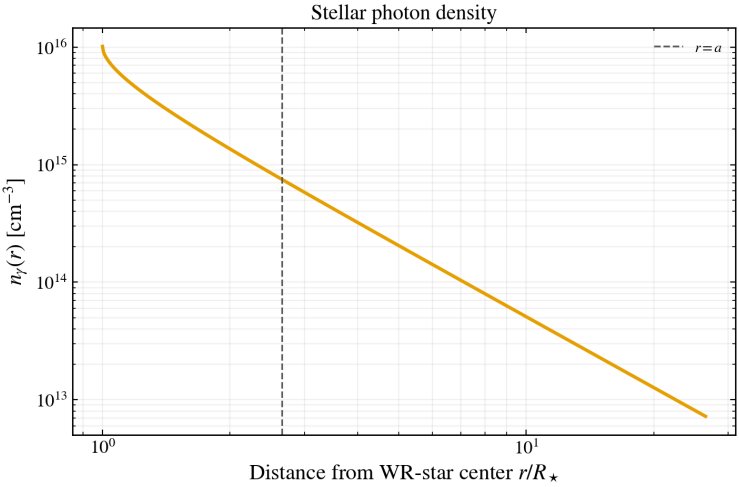
Backup 3


Isotropic disk wind
Disk wind
$r_{\rm BH} = a$
$n_{p,\rm DW}(r_{\rm BH})$ [cm^{-3}]
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Distance from black hole $r_{\rm BH}/a$

Backup 4


Spherical WR wind
$r=a$
10^{13}
10^{12}
10^{11}
$n_{p,\mathrm{WR}}(r)$ [cm^{-3}]
10^{0}
10^{1}
Distance from WR-star center $r/R_\star$

Backup 5


Stellar photon density
$r=a$
10^{16}
10^{15}
10^{14}
10^{13}
$n_\gamma(r)$ [cm^{-3}]
10^0
10^1
Distance from WR-star center $r/R_\star$