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Unveiling Multimessenger Emission from Hidden Cores of Microquasars

- How do microquasars produce photons above 100 TeV?
- What neutrino signatures should accompany them?

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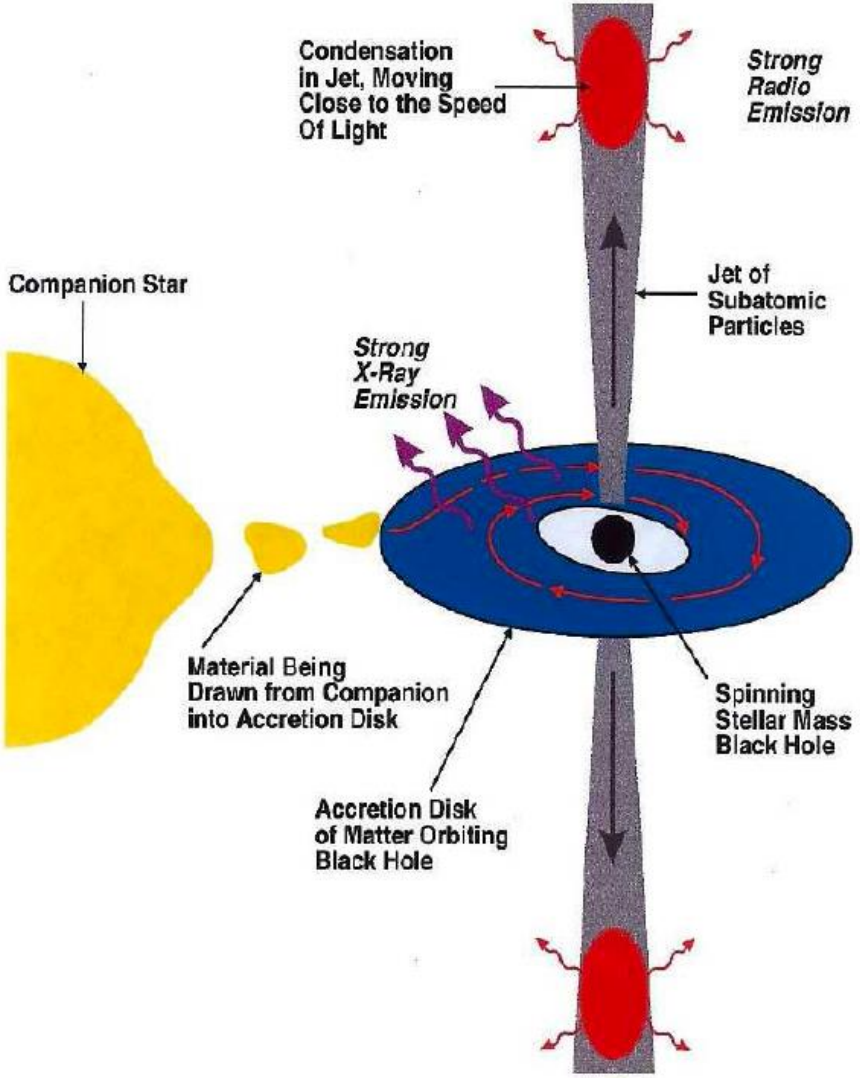
arXiv:2512.23231

TeV Particle Astrophysics (TeVPA) — Tendo, Japan · August 31, 2026

1 Introduction to Microquasars

- **Microquasars:**
  - X-ray binaries: compact object + donor star
  - launch collimated, mildly relativistic jets
  - produce non-thermal emission from radio to γ-rays
  - potential Galactic PeVatron candidates



Costa, E. et al. (2010)

① Microquasars as Cosmic-Ray Accelerators

- **Cosmic rays (CRs):** high-energy (**relativistic**) charged particles from astrophysical sources.

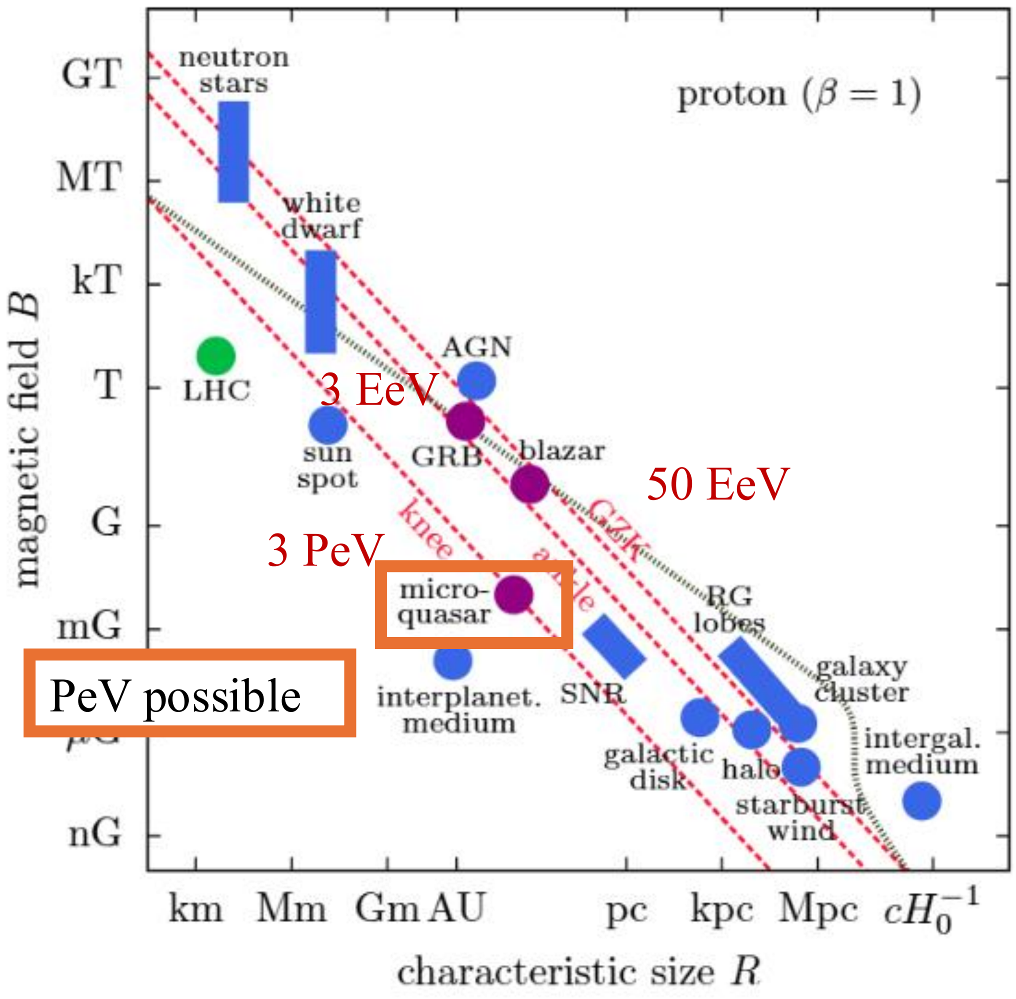
- **Hillas criterion:**

maximum energy — source size — magnetic field

$$E \lesssim Z \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right) \times 10^{9}\ \mathrm{GeV}$$

- Microquasars can in principle accelerate protons to the PeV range.

Aartsen et al. (2017)

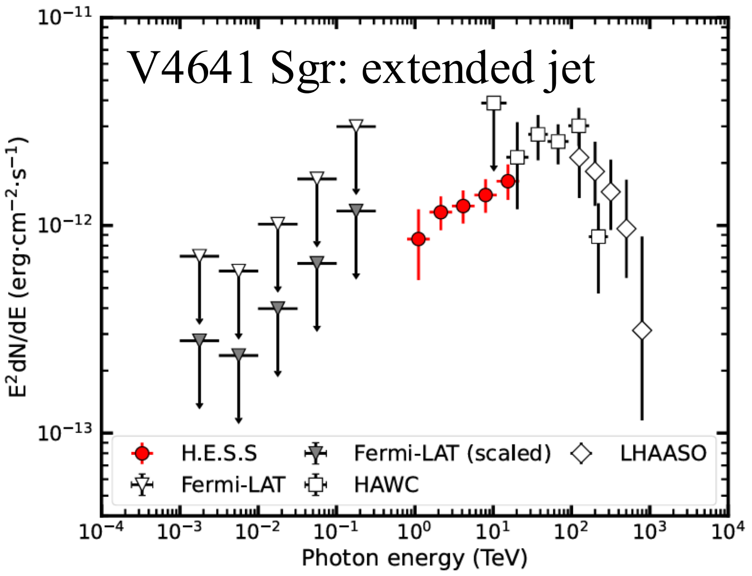


Hillas plot for protons

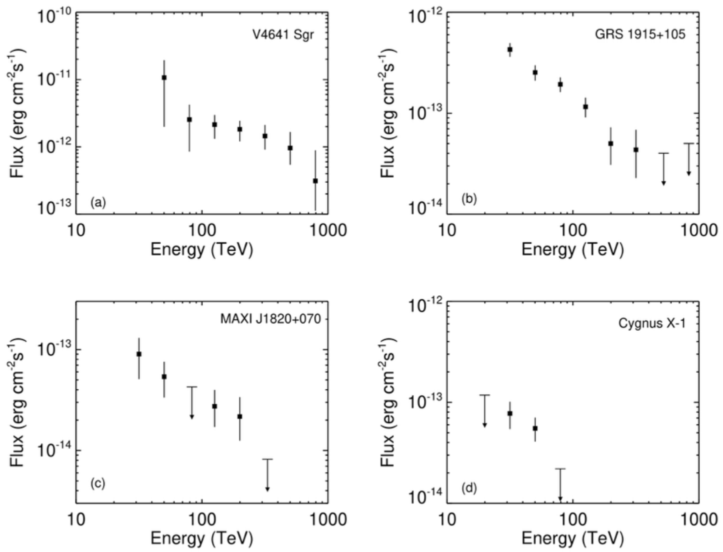
Microquasars as >100 TeV–PeV Gamma-Ray Sources

- **HAWC** and **H.E.S.S.**: **> 100 TeV photons** from the **extended jets** of V4641 Sgr.
- **LHAASO**: ~ 100 TeV photons from several microquasars; **~ PeV photons** from **Cygnus X-3**.

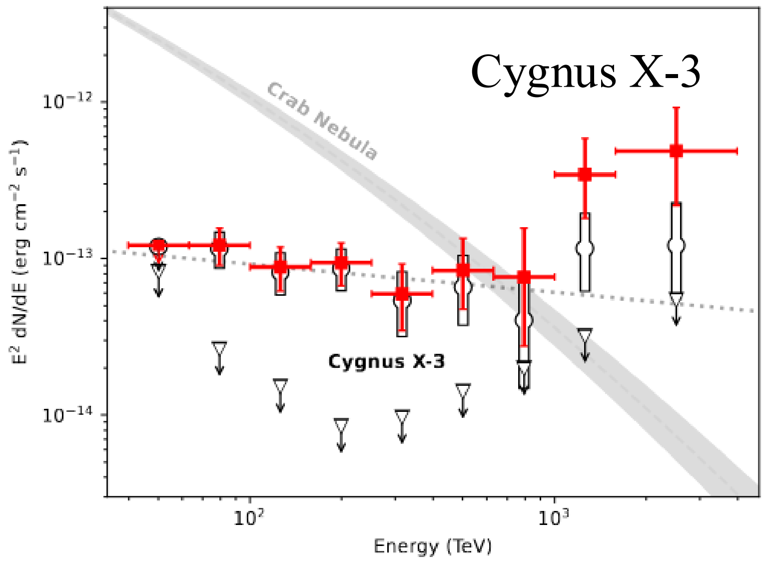
Implication: Microquasars are Galactic PeVatron candidates.



H.E.S.S. Collaboration (2025)



LHAASO Collaboration (2025a)



LHAASO Collaboration (2025b)

Key question: where and how are these >100 TeV / PeV photons produced?

2 Modeling the Multimessenger Emission with AMES

- AMES = Astrophysical Multimessenger Emission Simulator
- **Processes included in AMES**

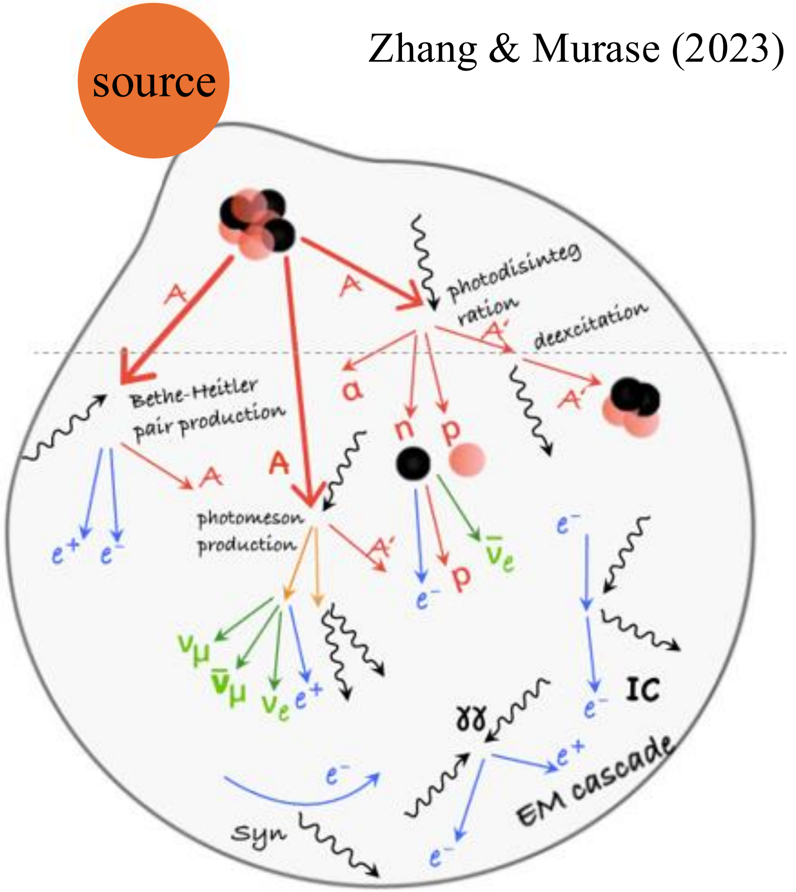
Leptonic

- ✓ synchrotron radiation
- ✓ synchrotron self-absorption
- ✓ inverse Compton scattering
- ✓ photon-photon pair production

Hadronic + secondary particles

- ✓ hadronuclear process
- ✓ photomeson process
- ✓ Bethe-Heitler pair production
- ✓ decay
- ✓ muon / pion cooling

Zhang & Murase (2023)



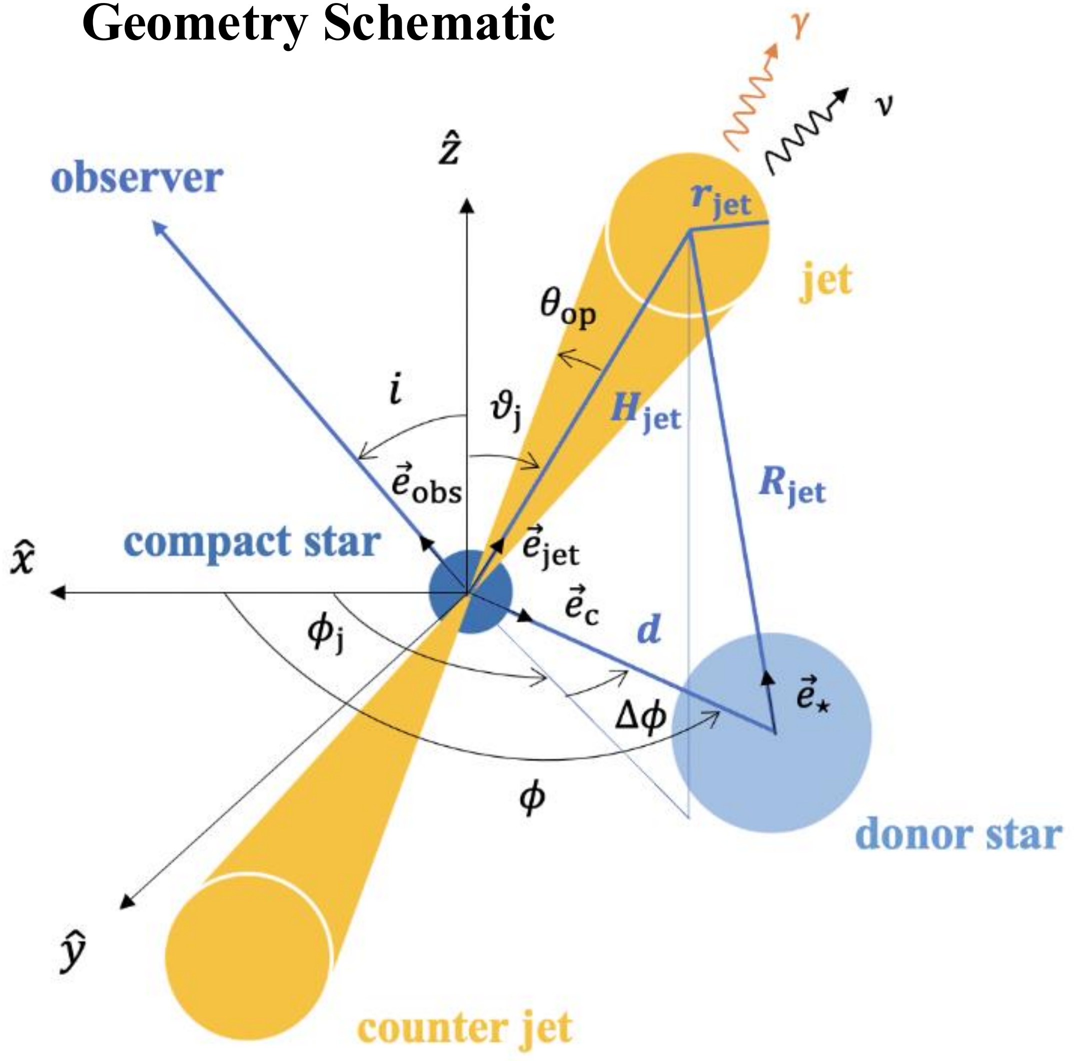
Schematic of coupled particle cascades in AMES.

- We extend **AMES** to include **muon/pion cooling** and apply it to **microquasar** photon–neutrino emission.

3 Model Geometry and Target Photon Fields

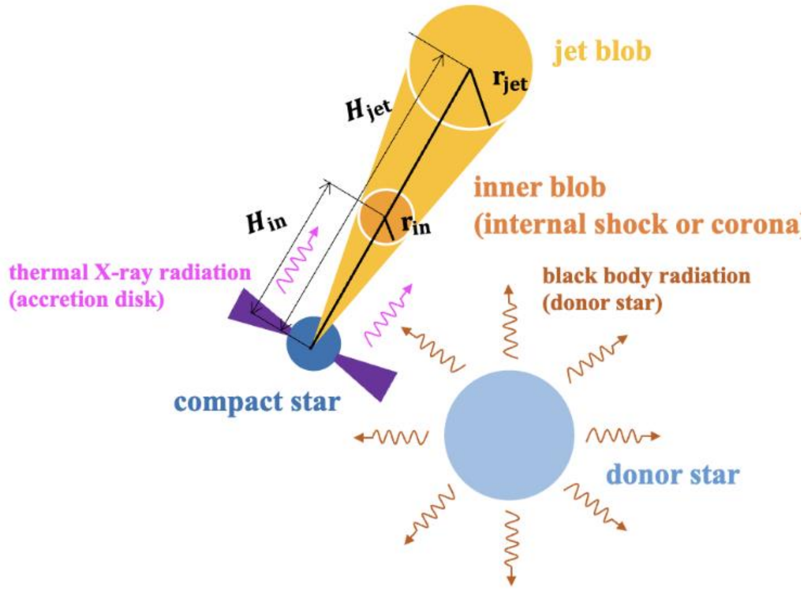
- **Model setup:**
  - Geometry: inclination i, jet direction (ϑ_j, ϕ_j), and orbital phase ϕ.
  - Target photon fields:
    - I. **stellar blackbody photons** from the donor star
    - II. **disk X-ray photons** from the accretion disk
- **Key point:** geometry controls Doppler boosting and external $\gamma\gamma$ absorption.

Geometry Schematic



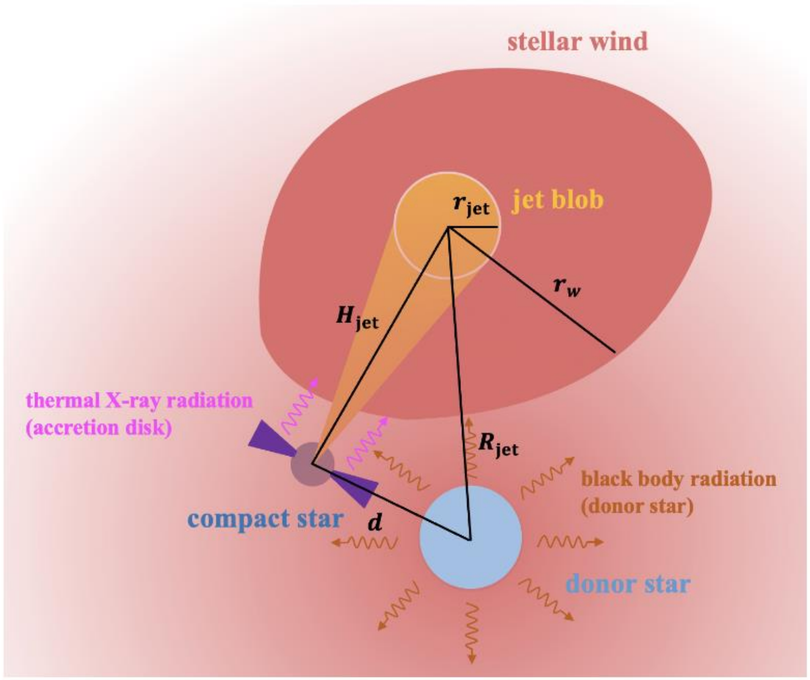
3 Emission Scenarios

Scenario A



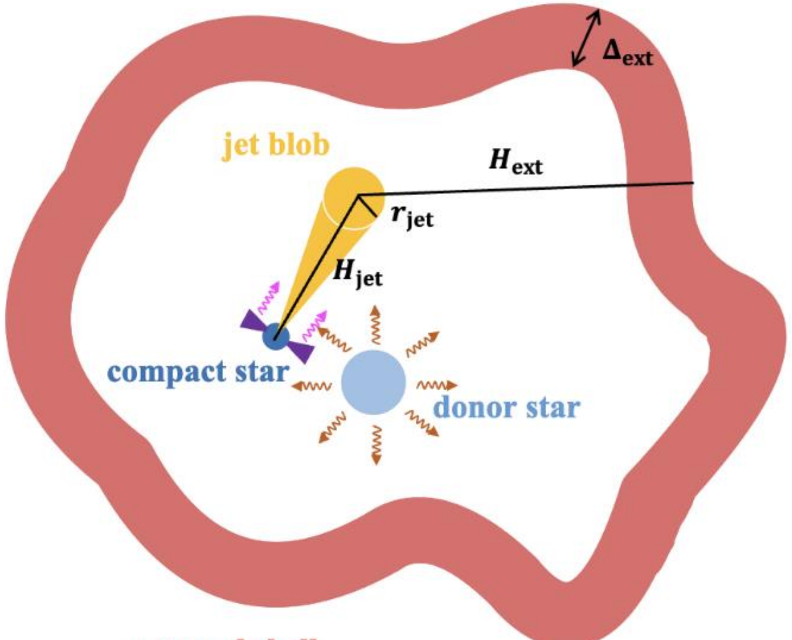
compact *pγ* origin
→ strong variability

Scenario B



stellar-wind *pp* origin
→ moderate variability

Scenario C

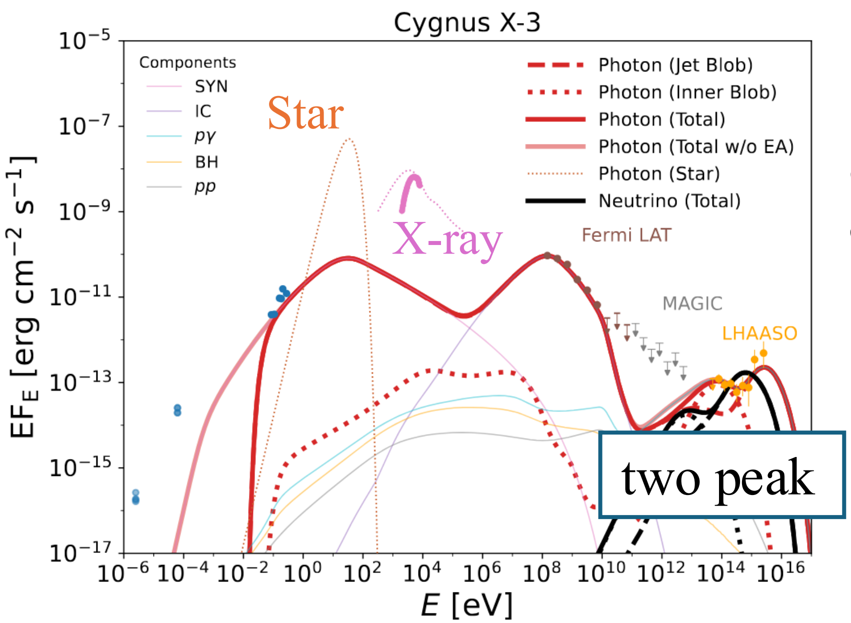


external shell
(interstellar medium or molecular clouds)

extended *pp* origin
→ stable emission

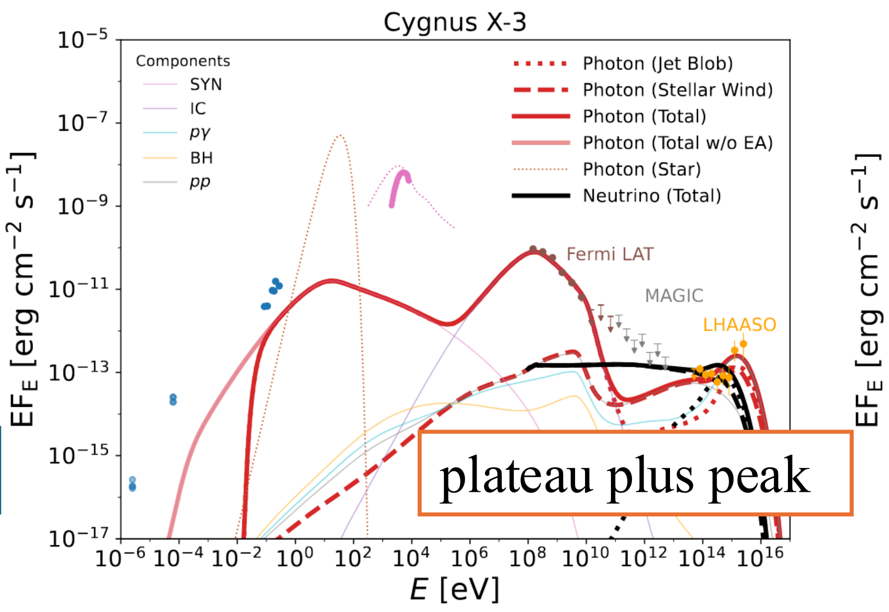
Photon and Neutrino Spectra for Cygnus X-3

Scenario A



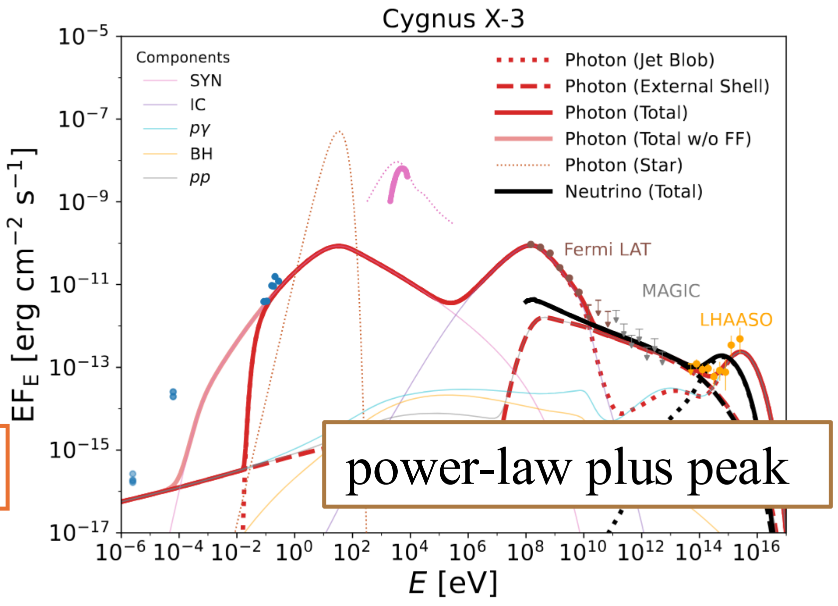
100 TeV: compact *pγ* origin;
10 PeV: compact *pγ* origin.

Scenario B



100 TeV: stellar-wind *pp* origin;
10 PeV: compact *pγ* + stellar-wind *pp* origin.

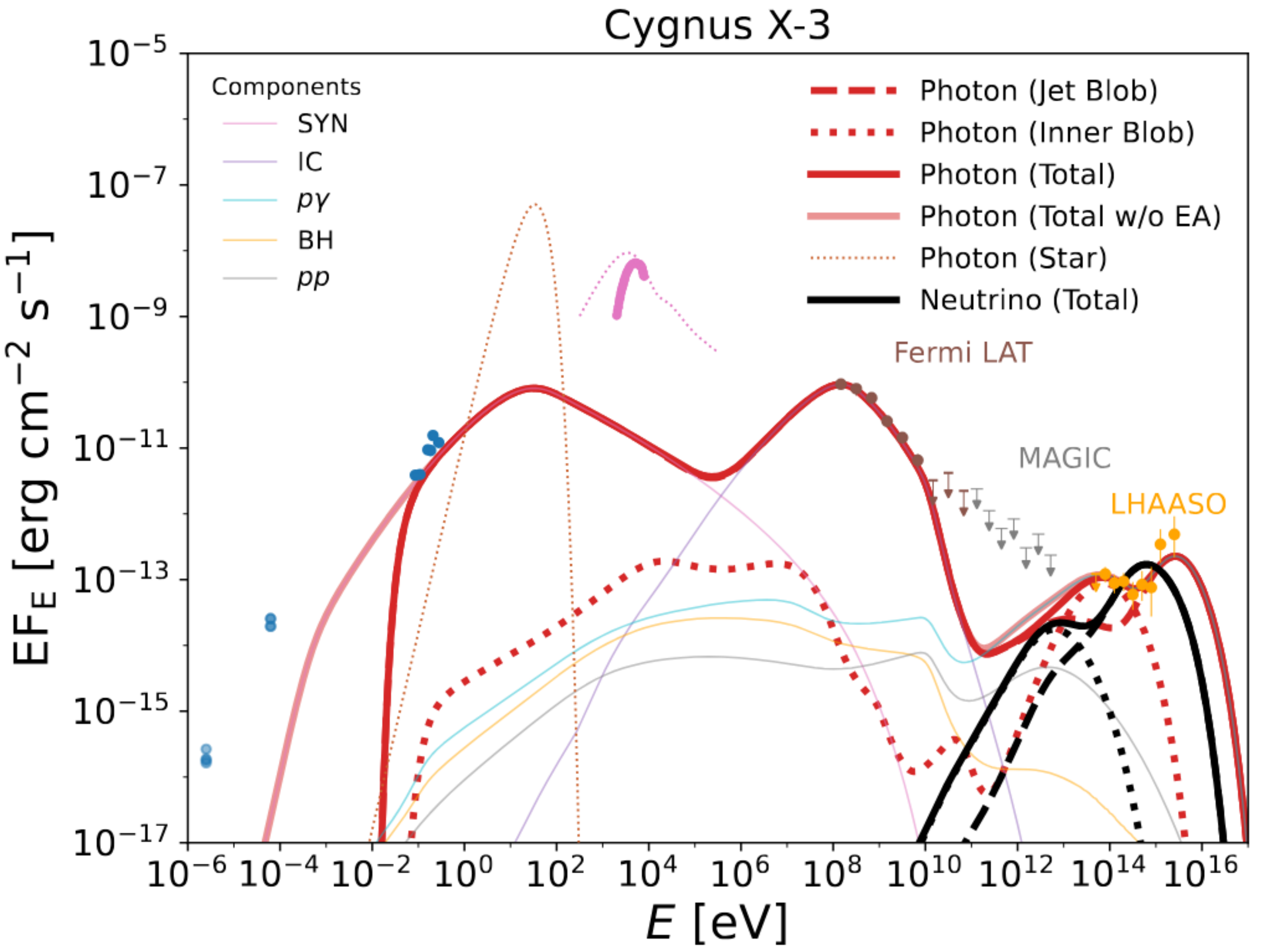
Scenario C



100 TeV: extended *pp* origin
10 PeV: compact *pγ* origin

Magnetic-Field Constraint in the AU-scale Jet Blob

- ~ PeV photons require ~10 PeV protons in the jet blob, implies: $B' \gtrsim 260$ G
- Energy budget constraint gives: $B' \lesssim 1.3 \times 10^4$ G
- Radio/IR synchrotron + GeV EIC emission further suggest: $B' \lesssim 500$ G
- **Takeaway:** $B' \sim$ few $\times\ 10^2$ G is required in the orbital-separation-scale blob.

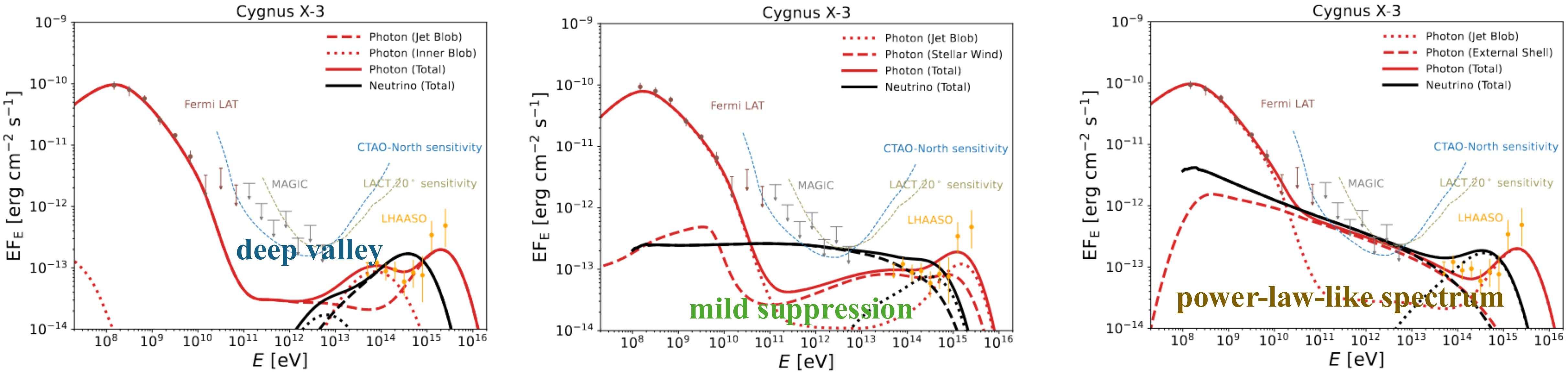


Cygnus X-3 spectrum motivating the PeV magnetic-field constraint.

3 TeV Spectral Predictions: Breaking the Degeneracy

- **0.1-10 TeV range:** predict **a deep valley** in Scenario A, **a mild suppression** in Scenario B, or **a power-law-like spectrum** in Scenario C.

Scenario A **Scenario B** **Scenario C**

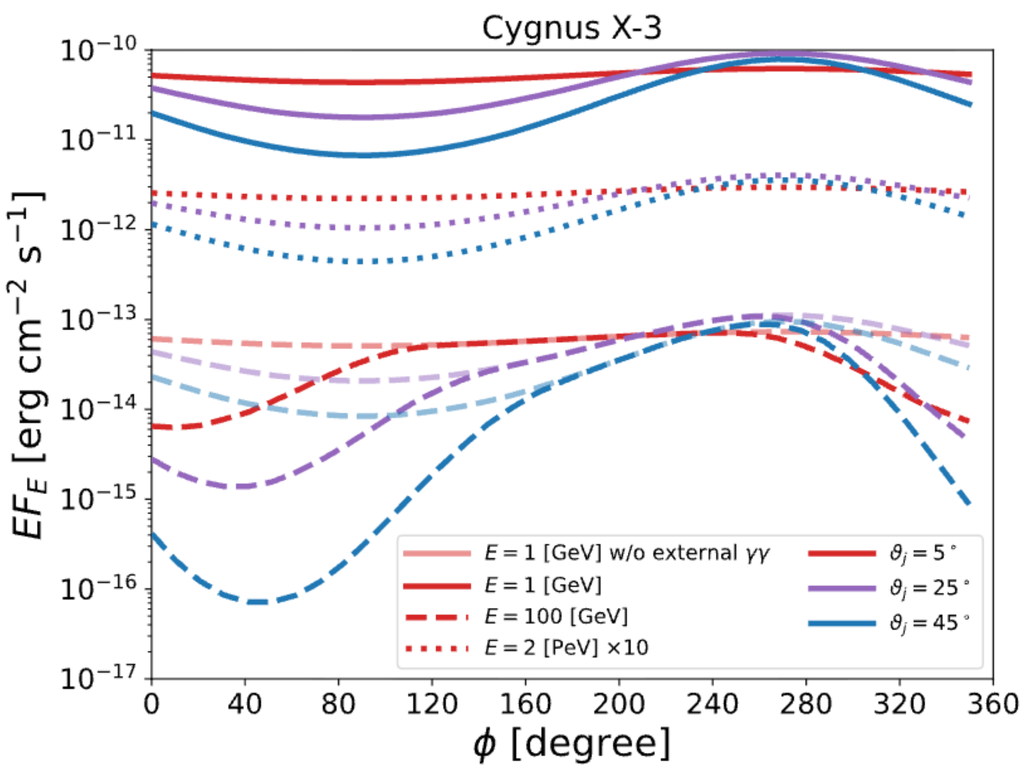


Predicted photon and neutrino spectra for Cygnus X-3.

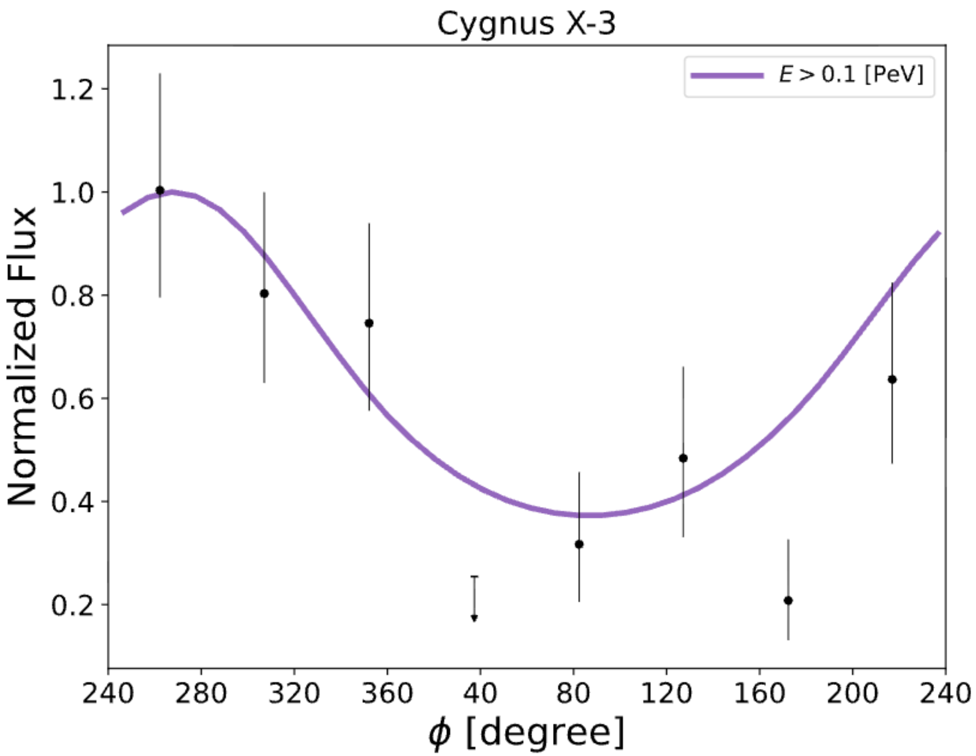
- With ~50-hour CTAO/LACT sensitivity, Scenario C is the most testable TeV prediction.

Energy-Dependent Orbital Modulation: Doppler vs $\gamma\gamma$ Absorption

- Two phase-dependent effects:
  - Doppler boosting: PeV and GeV
  - external $\gamma\gamma$ absorption: GeV
- Result: GeV and PeV bands can peak at different orbital phases.



Phase-dependent fluxes in Scenario A with $\vartheta_j = 25°$.

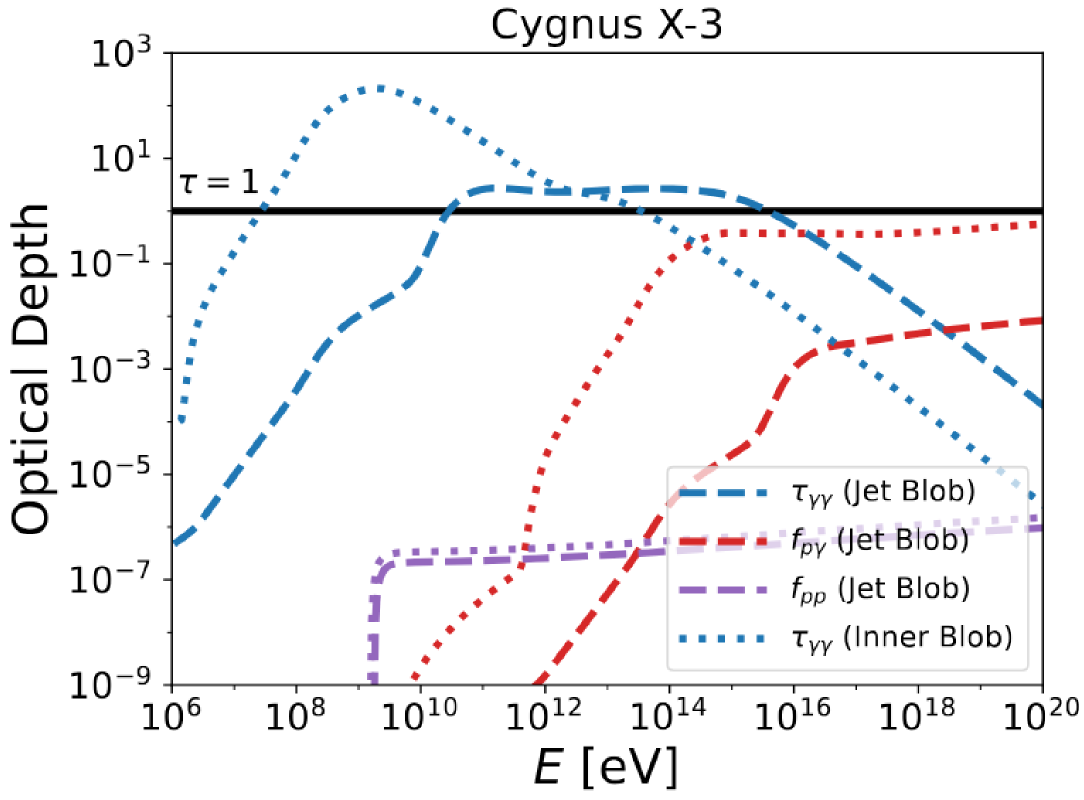


Qualitative comparison with the LHAASO PeV orbital light curve.

3 Why Are High-Energy Neutrinos Suppressed?

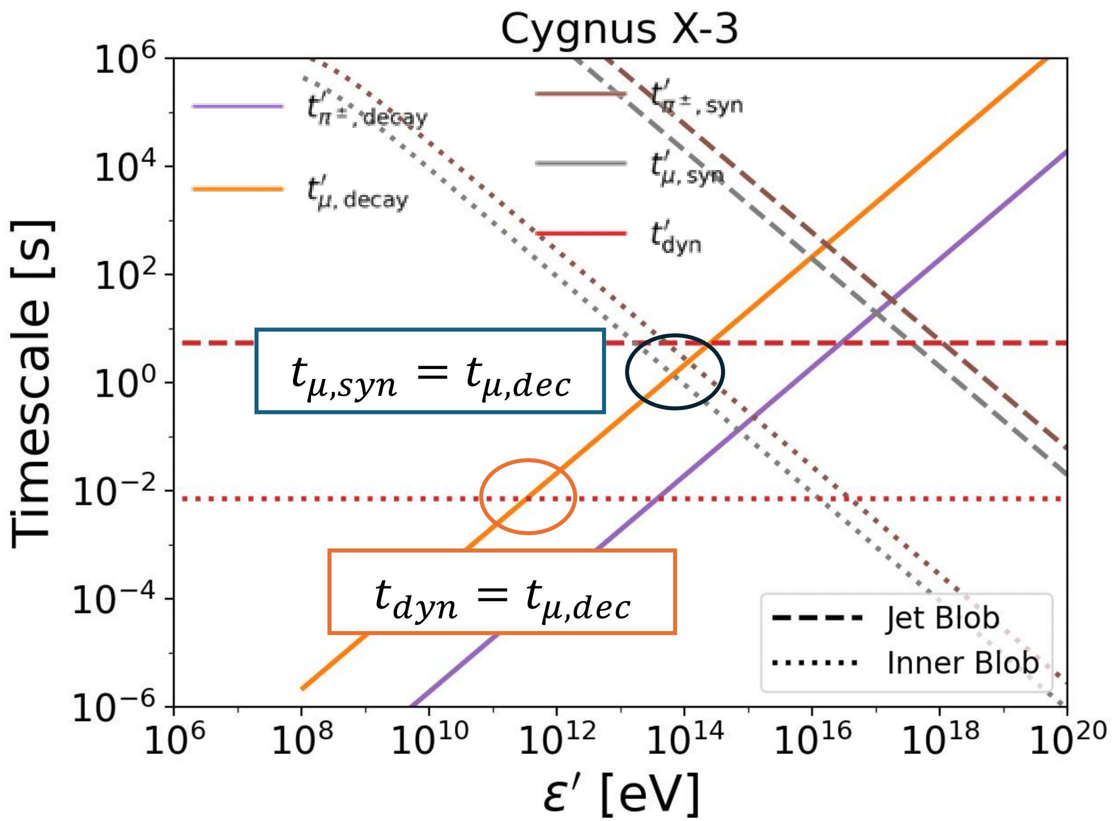
- Hadronic interactions produce secondary pions.

$$pp, p\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu \rightarrow e^{\pm} + 3\nu$$



Interaction efficiencies and $\gamma\gamma$ opacity.

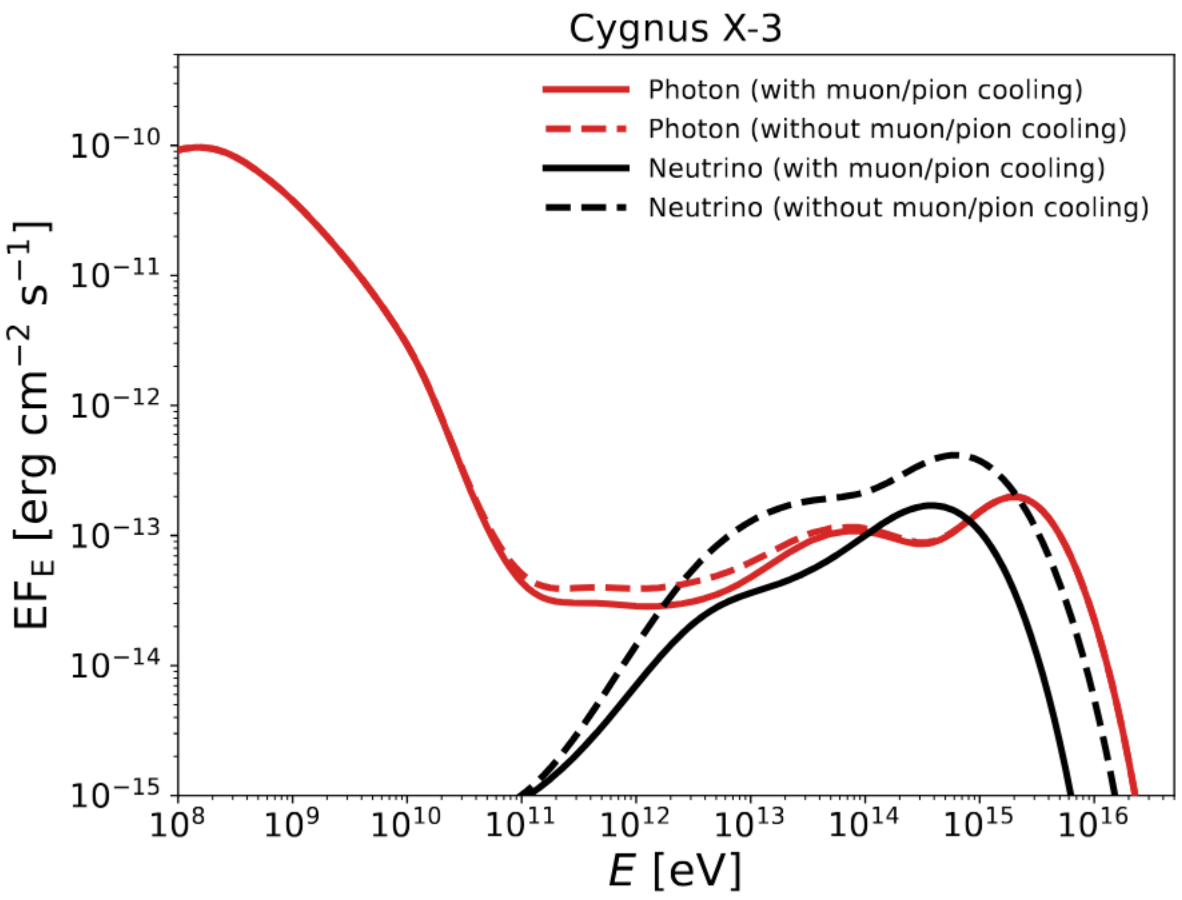
- If $t_{cool} < t_{dec}$ or $t_{dyn} < t_{dec}$, secondaries cool or leave the emission zone before decay, suppressing the high-energy neutrino flux.



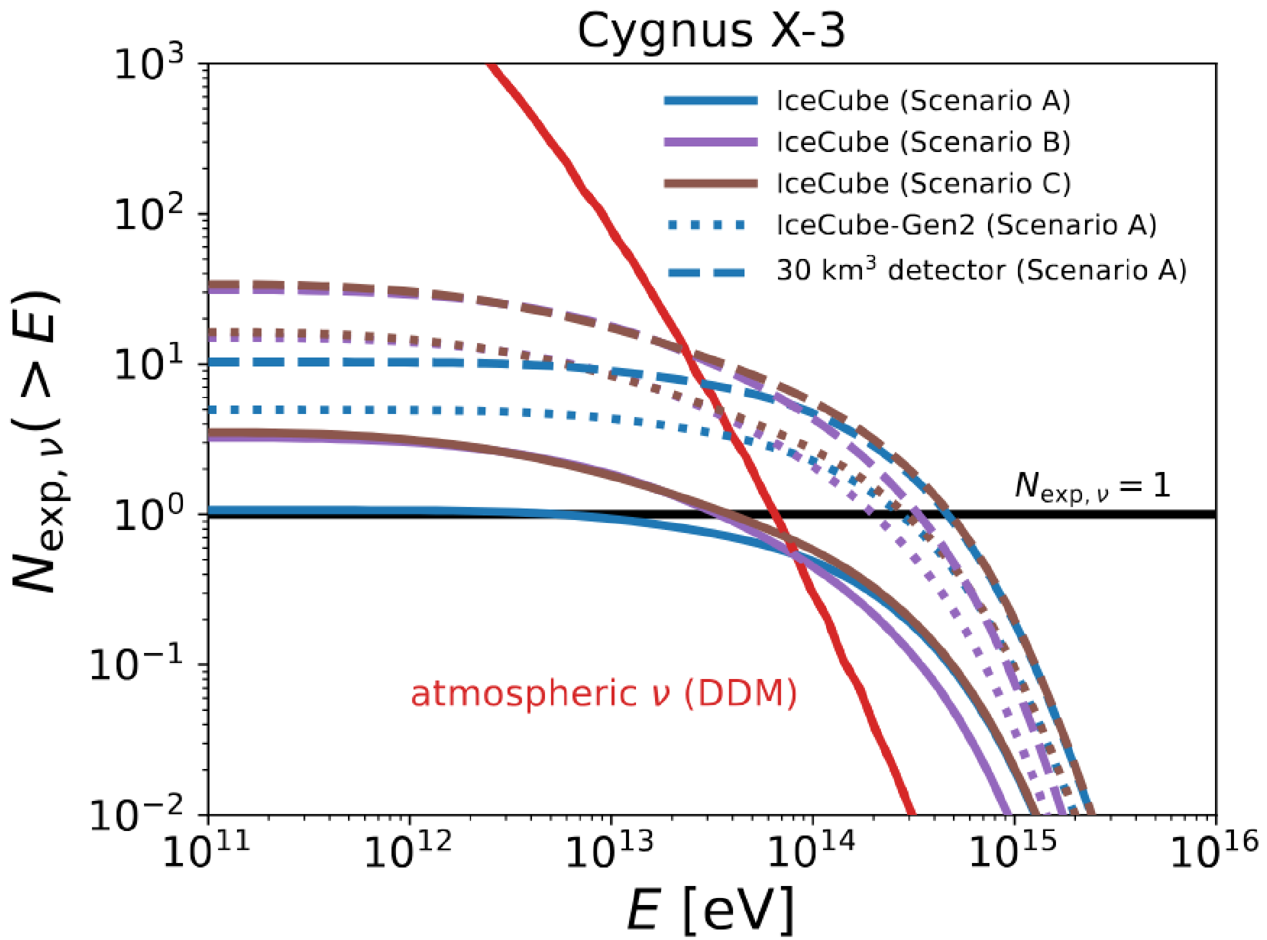
Cooling and decay timescales in the comoving frame.

3 Neutrino Detection Prospects from Microquasars

- Muon/pion cooling suppresses the high-energy neutrino flux, making neutrino detection challenging.



Photon and neutrino spectra with/without muon-pion cooling.



Cumulative expected neutrino events with $\Delta t_{int} = 20$ yr.

4 Summary

- **Main conclusions:**

1. Microquasars are promising Galactic PeVatron candidates.

LHAASO >100 TeV / PeV photons imply proton acceleration up to ~10 PeV.

2. Current broadband data can be reproduced by multiple hadronic scenarios.

- PeV emission from Cygnus X-3: a compact emission region + a magnetic field strength $\sim 10^2$ G
- Particle acceleration is efficient in the jet region

3. Future TeV and timing data can distinguish the models.

- **0.1–10 TeV spectra:** deep dip / mild suppression / power-law-like spectrum
- **Variability:** strong / moderate / stable

4. Muon/pion cooling suppresses neutrino fluxes.

Neutrino detection is challenging; non-detection does not rule out hadronic gamma-ray production.

- **Future tests:** CTAO / LACT, phase-resolved gamma-ray data, IceCube-Gen2 / HUNT