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AGENCIA ESTATAL DE INVESTIGACIÓN

MAGIC

Results of the long-term campaign on Cygnus X-3 with the MAGIC telescopes.

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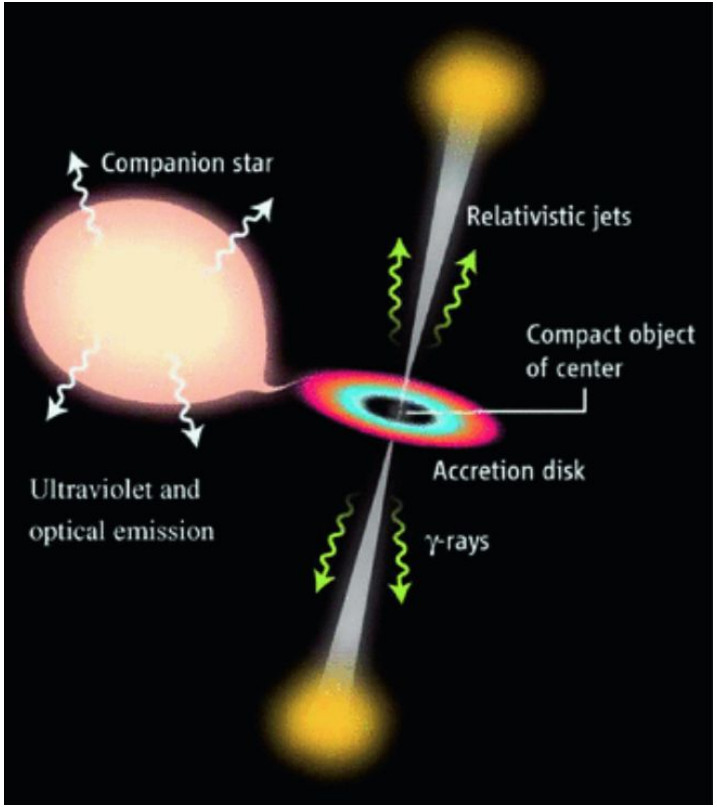
Introduction: Microquasars

Microquasars (MQs):

- Binary systems made of a compact object (CO) accreting material from a companion star and emitting relativistic jets [Fender, R., 2006].

- Jets are launched at the vicinity of the CO and can accelerate particles up to relativistic energies [Fender, R., 2006].

- Emission detected from radio to TeV [Mirabel, I. F. +, 1993, H.E.S.S. Collaboration, 2024].



[Mirabel, I. F., 2006]

Introduction: Microquasars as PeV particle accelerators

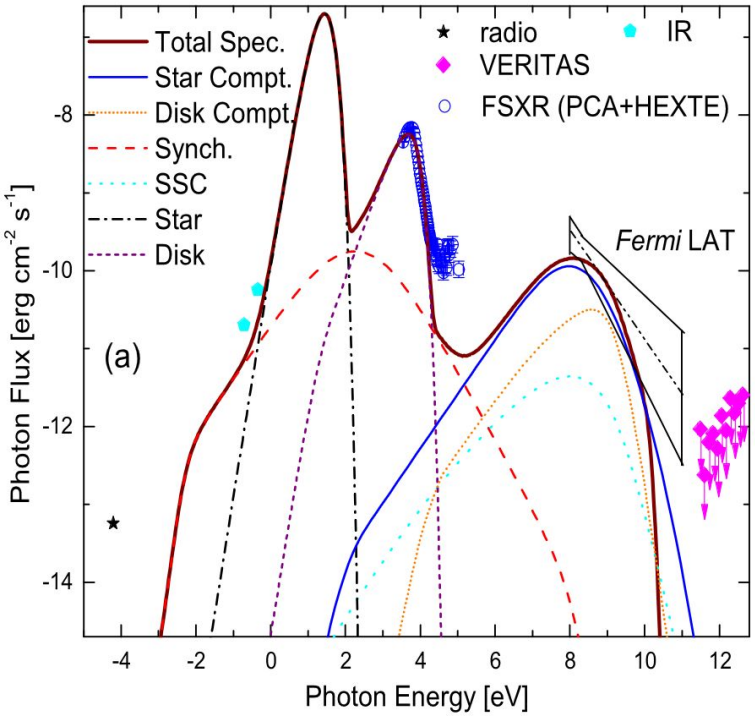
- 5 microquasars detected up to 100s of TeV [LHAASO Collaboration, 2024].

Microquasar	Distance (kpc)	LHAASO Source	Significance (σ)	Photon Index	Energy Range (TeV)	Extension[a]	Flux[b] (Crab Unit)
SS 433 E.		J1913+0457	9.7[c]	2.78 ± 0.19	$25 - 100$	$0.70°$	0.10
SS 433 W.	4.6 ± 1.3[33]	J1910+0509	8.6[c]	2.92 ± 0.21	$25 - 100$		0.082
SS 433 central		J1911+0513	9.8	4.03 ± 0.29	$100 - 400$	$0.32°$	0.32
V4641 Sgr	6.2 ± 0.7[34]	J1819-2541	8.1	2.67 ± 0.27	$40 - 1000$	$0.36°$	3.9
GRS 1915+105	9.4 ± 0.6[35]	J1914+1049	6.1	3.07 ± 0.15	$25 - 400$	$0.33°$	0.17
MAXI J1820+070	2.96 ± 0.33[36]	J1821+0726	5.9	3.19 ± 0.29	$25 - 400$	$< 0.28°$	0.13
Cygnus X-1	2.2 ± 0.2[37]	J1957+3517	4.0	4.07 ± 0.35	$25 - 100$	$< 0.22°$	< 0.01

- Accreting BHs and their environments can operate as extremely efficient accelerators of particles up to and above 1 PeV [LHAASO Collaboration, 2024].

Introduction: Cygnus X-3. General Properties

- Microquasar located at 9.7 kpc and with an orbital period of 4.8 h [Reid, M. J. +, 2023; van der Klis, M. +, 1981].
- Nature of the CO still unknown (black hole or neutron star) [Zdziarski, A. A. +, 2013].
- Donor star is a Wolf-Rayet with M ≃8-14 $M_{\odot}$ [Koljonen, I. I. +, 2017].
- Brightest and most variable radio source among the MQs, with highly energetic jets [Mioduszewski, A.J. +, 2001; Miller-Jones, J. C. A. +, 2004].



Zhang, F. +, 2015

Introduction: Cygnus X-3 at HE (E > 100 MeV)

- *Fermi*-LAT detects High Energy (HE; E > 100 MeV) emission from the jets during flaring states [*Fermi*-LAT collaboration, 2009].

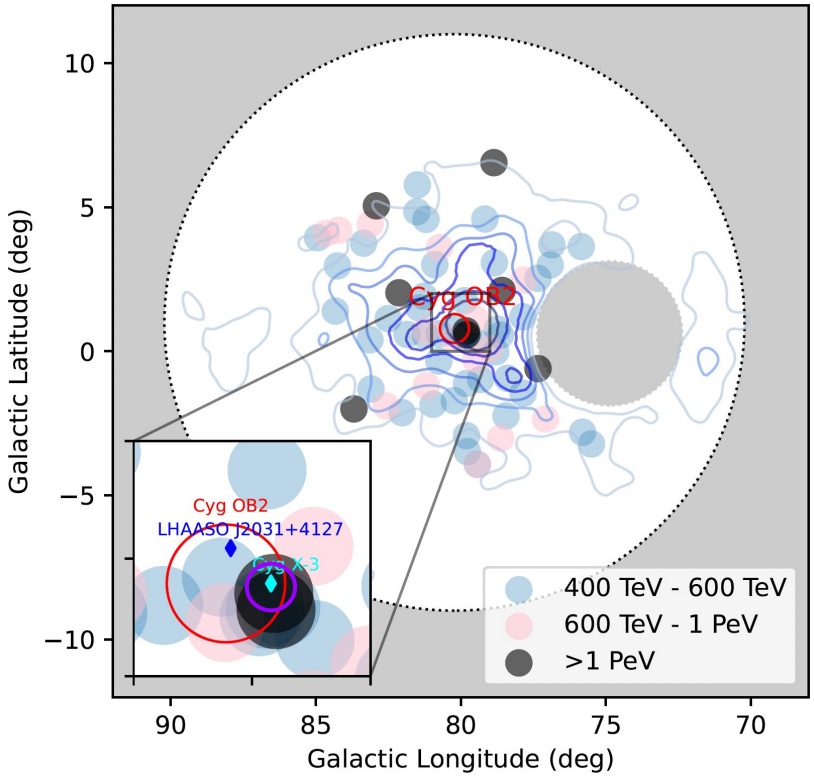
- Gamma-ray emission likely occurs due to IC between high energy e^- from the jet with optical photons from the star [Dubus, G. +, 2010].

- HE emission strongly orbitally modulated [Dubus, G. +, 2010].

- **Never detected at Very High Energies (VHE; E > 100 GeV) but conditions are very favourable for IC emission (also for gamma-gamma absorption, however)** [Bosch-Ramon +, 2018; Aleksic, J. +, 2010; Archambault, S. +, 2013].

Introduction: Cygnus X-3 at UHE (E > 100 TeV).

- **Cygnus Bubble:** 6º region around Cygnus X-3 observed by LHAASO.
- Contains Cygnus X-3 among other gamma-ray sources.
- Detection of 2 photons above 1 PeV coincident with the position of Cyg X-3 (also with Cyg OB2).
  [LHAASO, 2024]



[LHAASO, 2024]

Introduction: The MAGIC telescopes

- Two 17 m Cherenkov telescopes located in the island of La Palma, Spain.
- Photomultiplier cameras with a ~ 3.5º FoV.
- Energy range: ~ 30 GeV - 100 TeV.
- Angular resolution: ~ 0.09º at 100 GeV.
- Energy resolution: 15-23%

[Aleksić, J. +, 2016]

https://magic.mpp.mpg.de/

Previous observations

- Already observed with MAGIC and VERITAS.

MAGIC: 56.7 h mono (2006-2009)

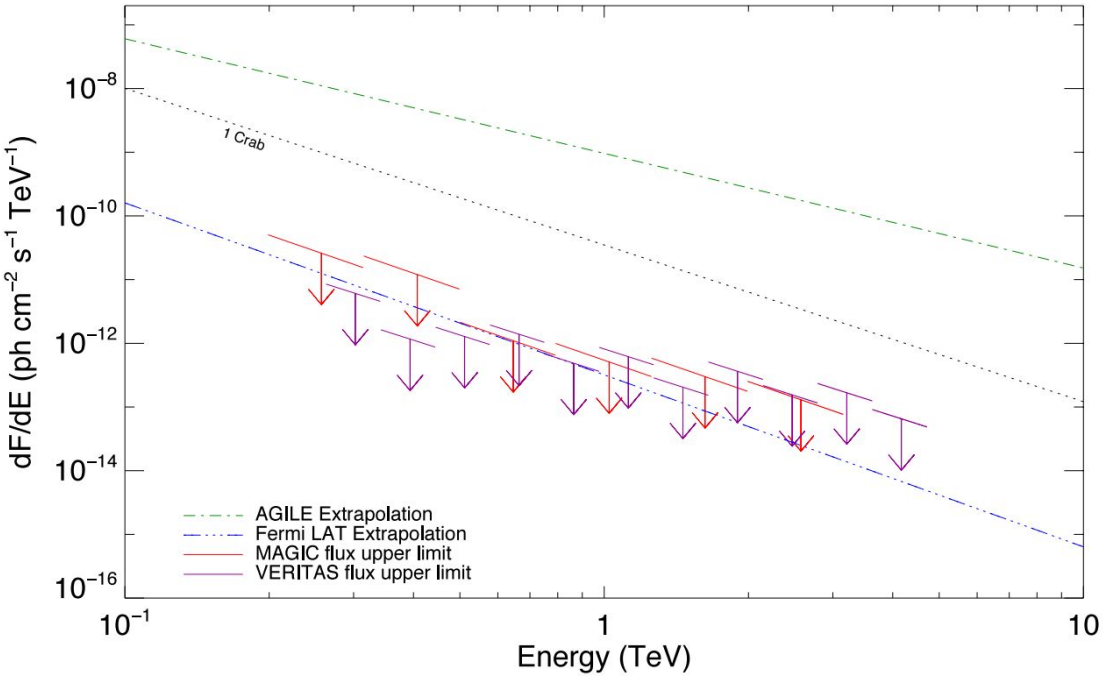
$F(E>250\ \text{GeV}) < 2.2 \cdot 10^{-12}\ \text{ph cm}^{-2}\ \text{s}^{-1}$

[Aleksic, J. +, 2010]

VERITAS: 44 h (2007-2011)

$F(E>263\ \text{GeV}) < 0.7 \cdot 10^{-12}\ \text{ph cm}^{-2}\ \text{s}^{-1}$

[Archambault, S. +, 2013]



[Archambault, S. +, 2013]

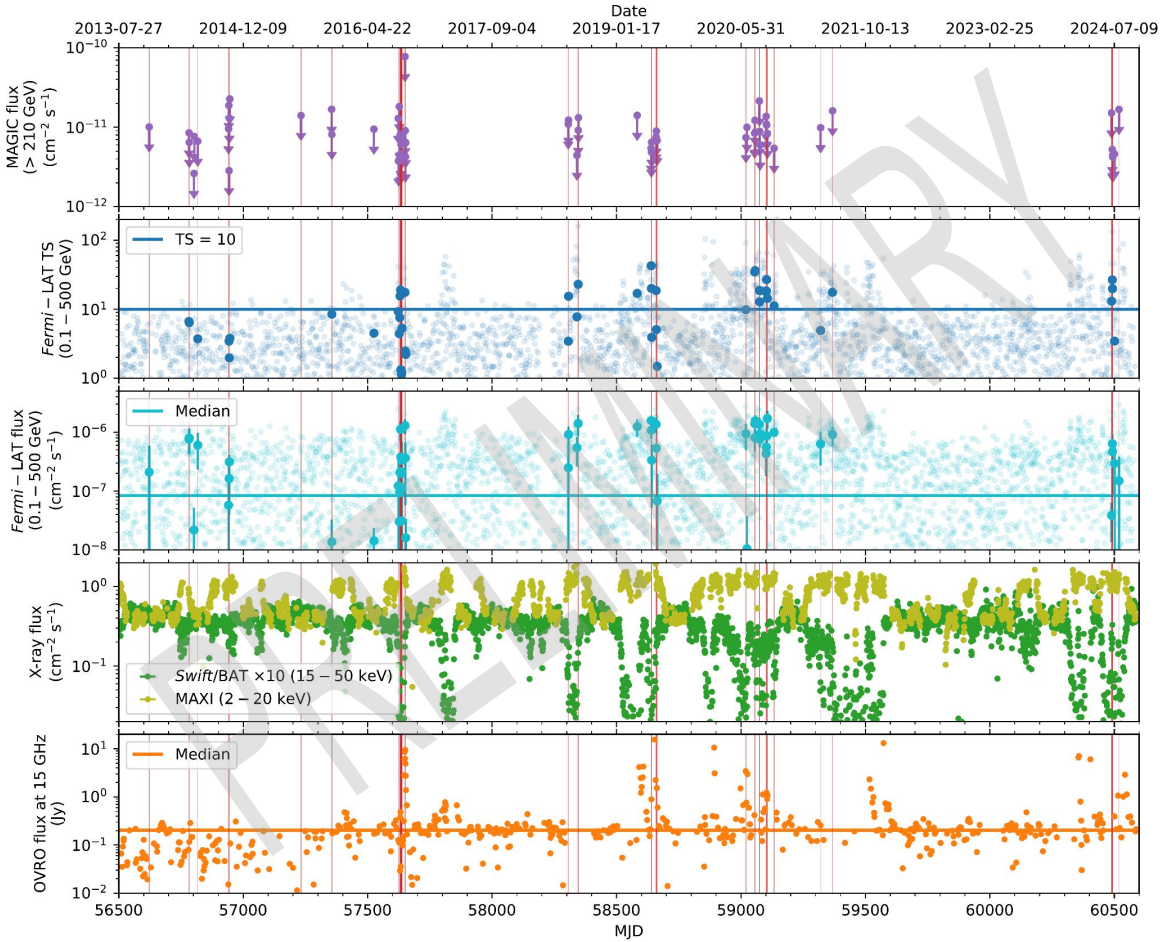
MAGIC observations (2013-2024):

- A total of 190 h of MAGIC observations.
- 129.7 h of data after quality cuts.
- Observations cover zenith distances from 10º to 58º.
- Significant part of the observations were done during flaring states at HE.
- Largest available sample of Cygnus X-3 at VHE.

Year	Month	Obs. time (h)	Zenith angles (°)
2013	Nov	1.3	31 – 49
2014	May	6.6	15 – 40
	Oct	3.3	11 – 58
2015	Jul	0.8	12 – 39
	Nov	1.3	33 – 47
2016	May	1.0	19 – 31
	Aug	9.6	12 – 45
	Sep	42.8	11 – 52
2018	Jul	2.1	12 – 37
	Aug	6.2	11 – 22
2019	Apr	1.0	38 – 50
	Jun	11.3	11 – 51
2020	Jun	4.4	12 – 25
	Jul	5.0	12 – 23
	Aug	3.2	12 – 30
	Sep	8.0	12 – 20
	Oct	1.9	22 – 44
2021	Apr	1.2	29 – 46
	Jun	1.9	27 – 50
2024	Apr	0.7	53 – 58
	Jun	2.0	23 – 49
	Jul	14.1	12 – 47
Total		129.7	11 – 58

Results: daily light curve

MAGIC Observations

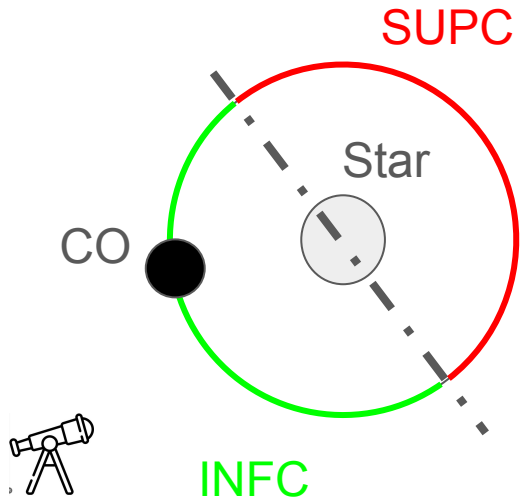


Gamma-ray datasets

- **Global**: includes all observed hours after quality cuts. **129.7 h**

Flaring

- **Inferior conjunction (INFC)**: flaring activity in *Fermi*-LAT + Inferior conjunction. **24.6 h**
- **Superior conjunction (SUPC)**: flaring activity in *Fermi*-LAT + Superior conjunction. **28.9 h**



Results: Significances

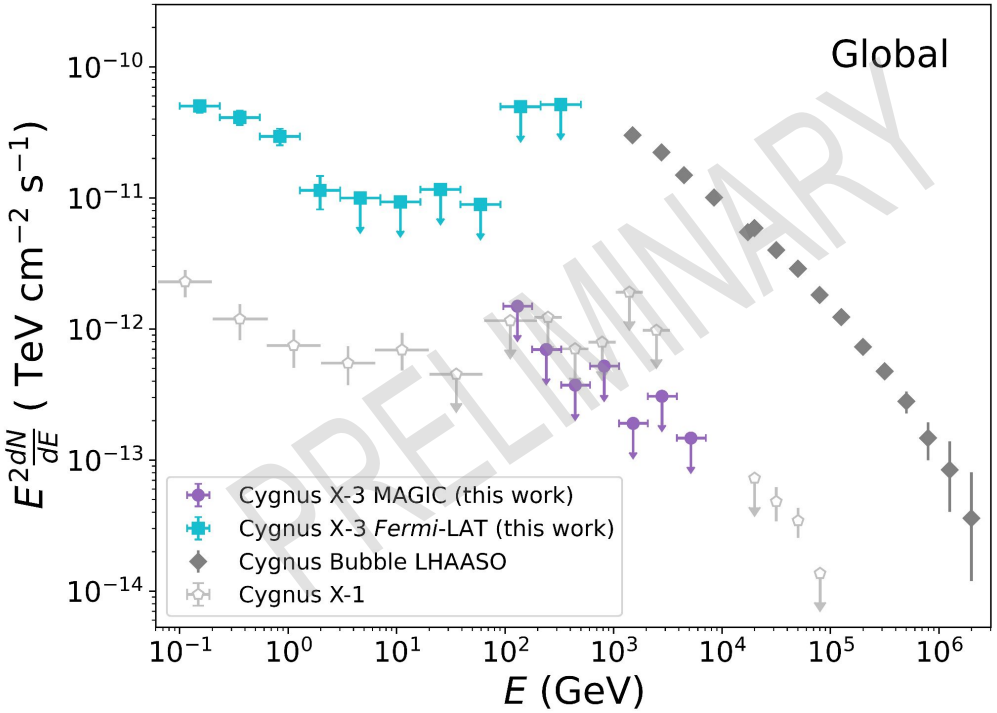
Dataset / E range*	Low Energy	Medium Energy	High Energy
Global	0.90 σ	0.25 σ	1.76 σ
INFC	0.76 σ	1.82 σ	0.84 σ
SUPC	0.03 σ	1.08 σ	1.22 σ

- All significances are positive. In some cases near 2 σ.
- May indicate a real excess in the VHE emission.

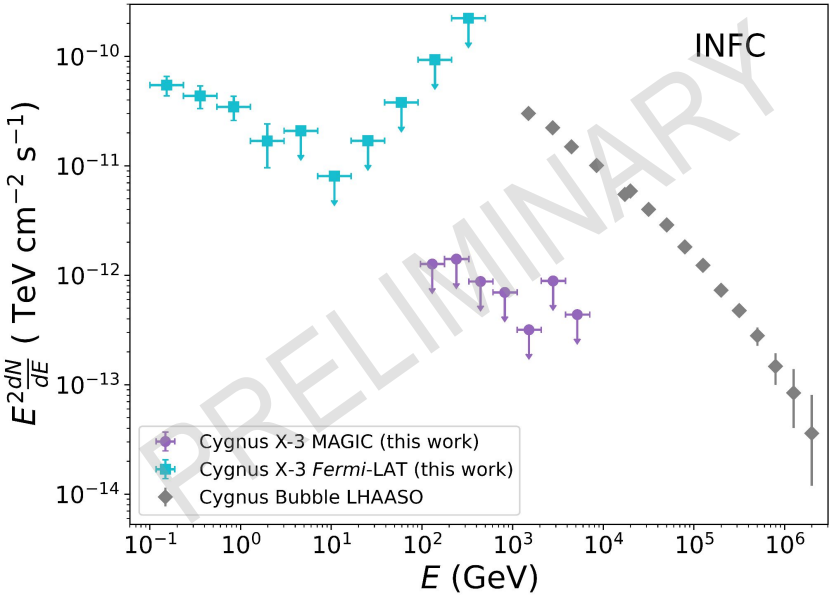
* Low Energy:E ≳ 100 GeV; Medium Energy: E ≳ 250 GeV; High Energy: E ≳ 1 TeV

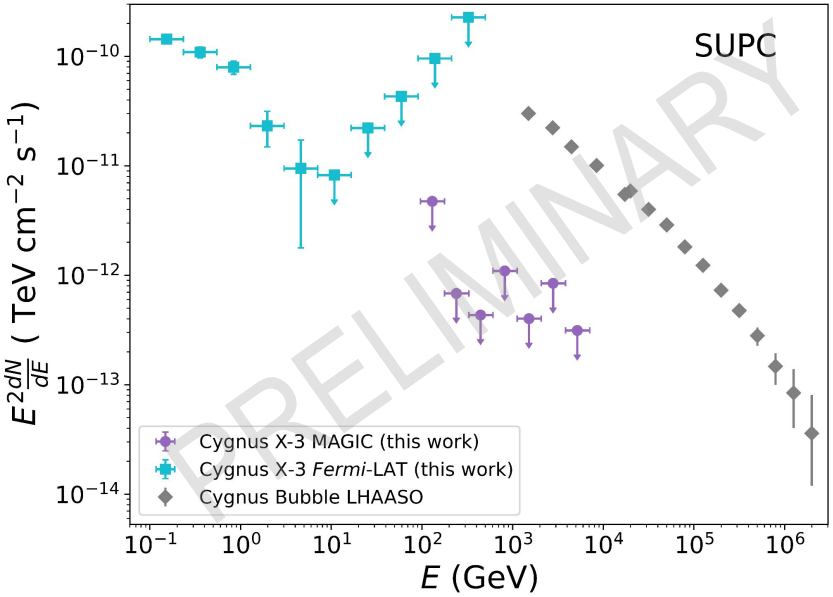
Results: Global Spectral Energy Distribution

- MAGIC ULs compatible with the extrapolation of *Fermi*-LAT spectrum.
- Below 10 TeV, the contribution of Cyg X-3 to the Cygnus Bubble has to be below ~1%
- Cyg X-1 SED also shown for comparison. The 4 sigma hint from LHAASO serve as a reference lower limit for Cyg X-3 flux at UHE.



Results: Spectral Energy Distribution by orbital phase





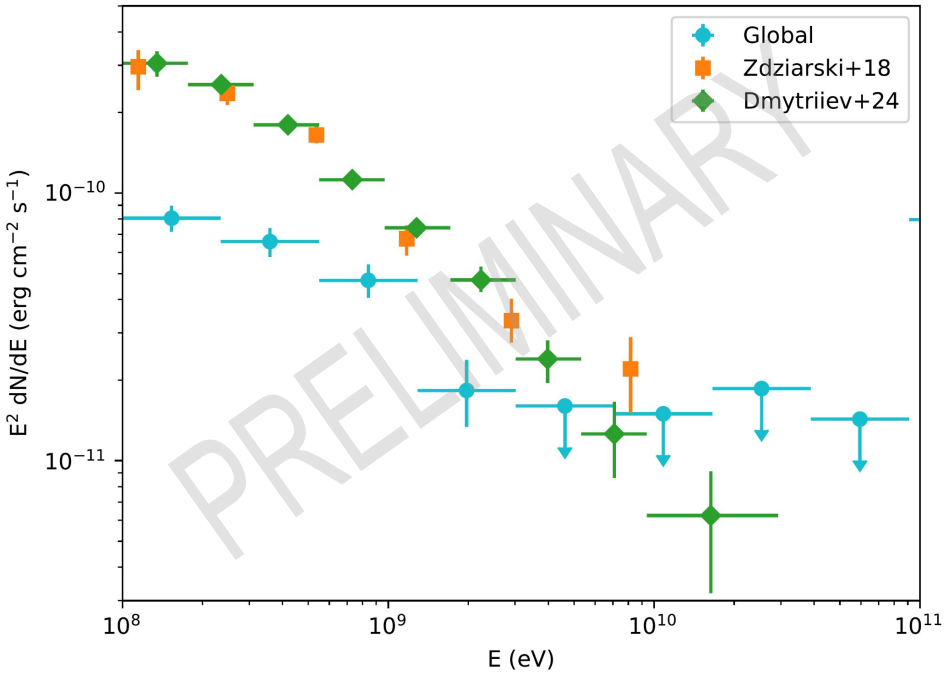
- *Fermi*-LAT fluxes ~2 times higher for SUPC.
- Similar MAGIC ULs.

Discussion and summary

- ★ No significant detection between ~ 100 GeV and ~ 7 TeV.
- ★ Largest available sample at VHE for Cygnus X-3 (~ 130 h).
- ★ Most constraining VHE ULs up to date.
- ★ Detection at UHE would increase significantly the relevance of the results.
  - ➡ Physical constraints on source properties and emission mechanism.

Backup: Spectral Energy Distribution at HE

- *Fermi*-LAT data **coincident with the MAGIC** observations were also analysed (Edgar Molina).
- Complex region that need some care with the analysis.
- Our fluxes are a factor ~2 below those in the literature, which **only use flaring states**.
  - Discrepancies likely explained by **different datasets** and choice of analysis parameters.



Backup: Differential Flux at VHE

- More constraining ULs than previous observations.
  - Wider energy range.
  - Larger amount of observed hours.