Microquasars as gamma-ray emitters and powerful particle accelerators

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Outline

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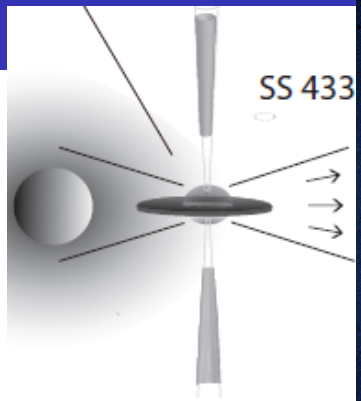
Microquasars

- **Binary with star and accreting BH or low-*B* NS that forms a relativistic jet.**
- MQ are gamma-ray sources with well known large-scale non-thermal jets.
- MQ jet-medium interactions long ago proposed as potential GCR sources.



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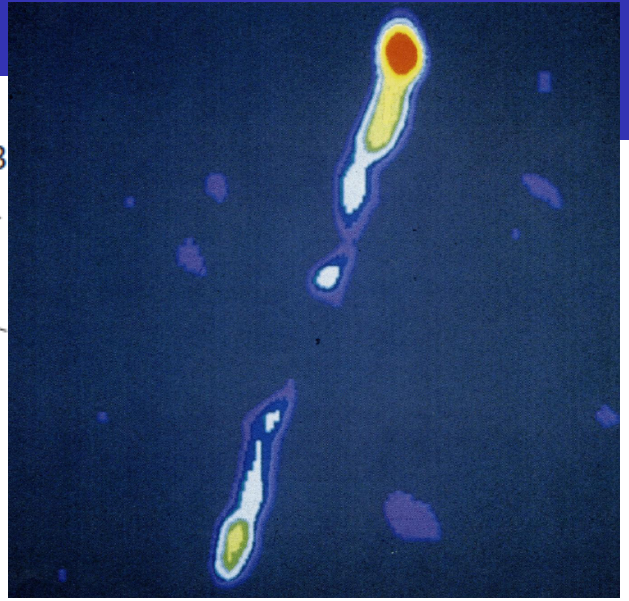

(1E1740.7-2942; Mirabel 1992)

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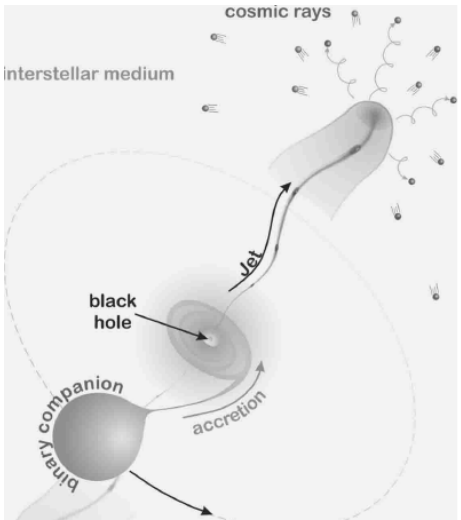

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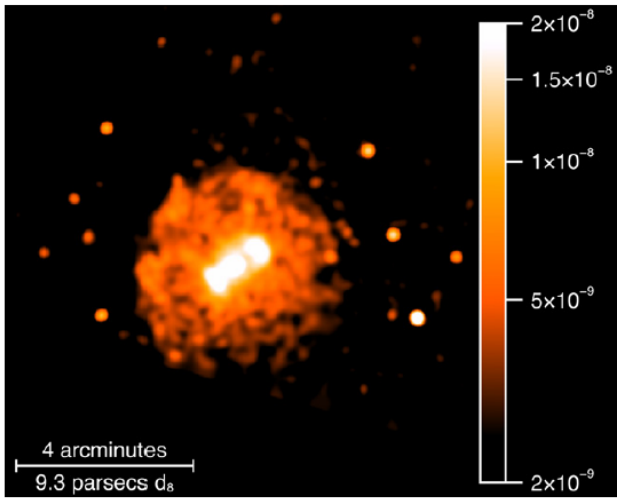

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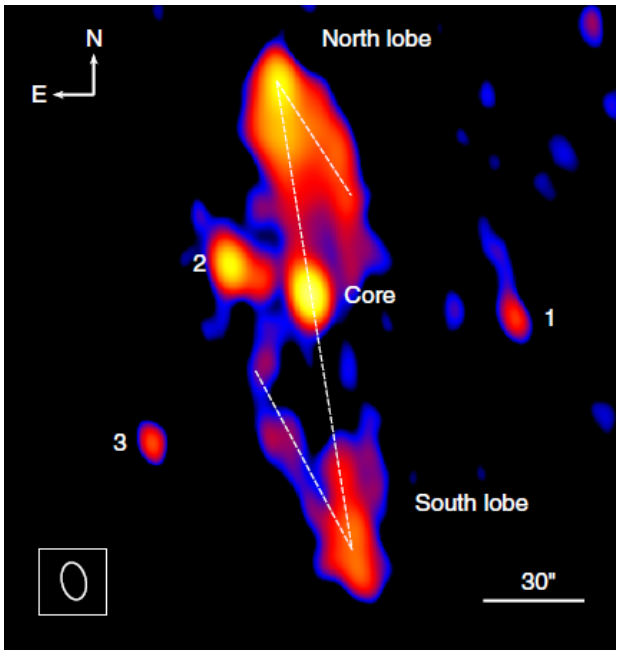

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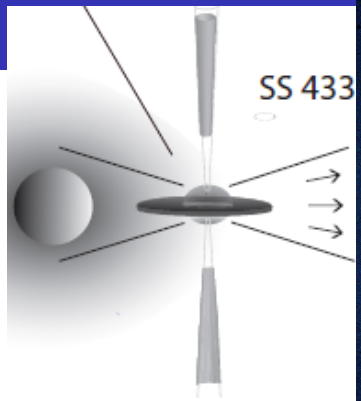

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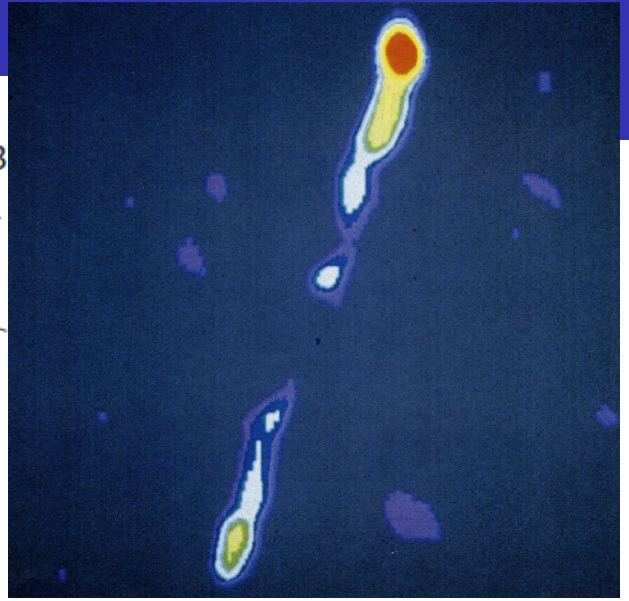

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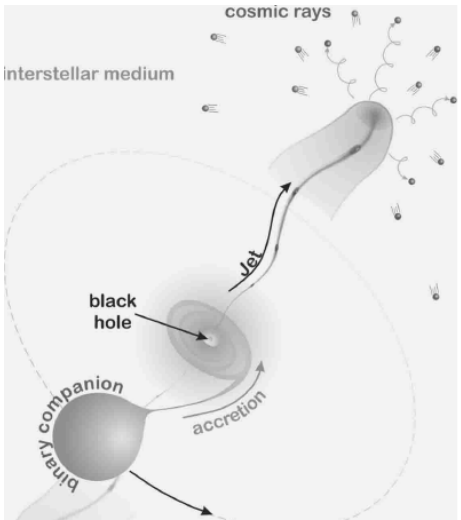

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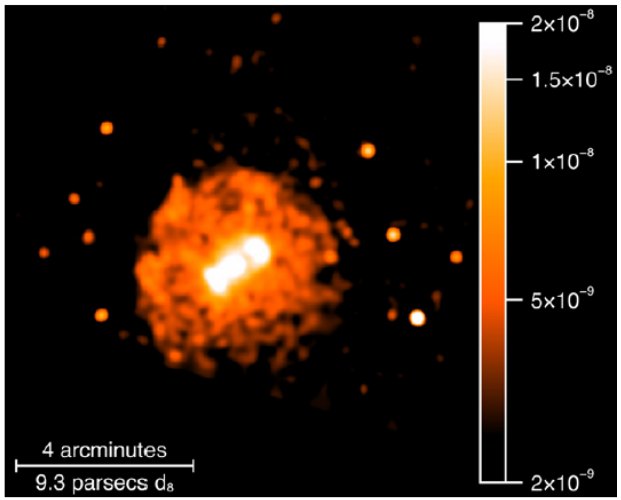

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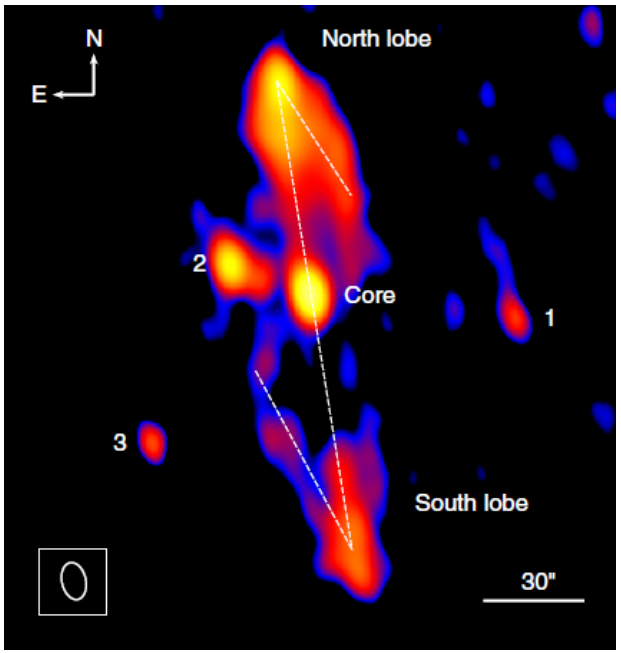

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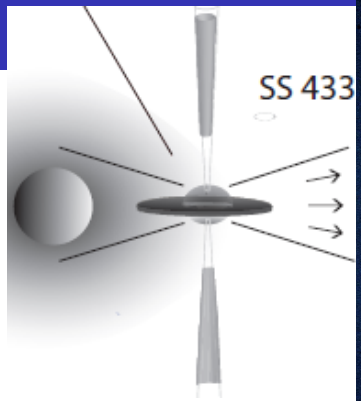

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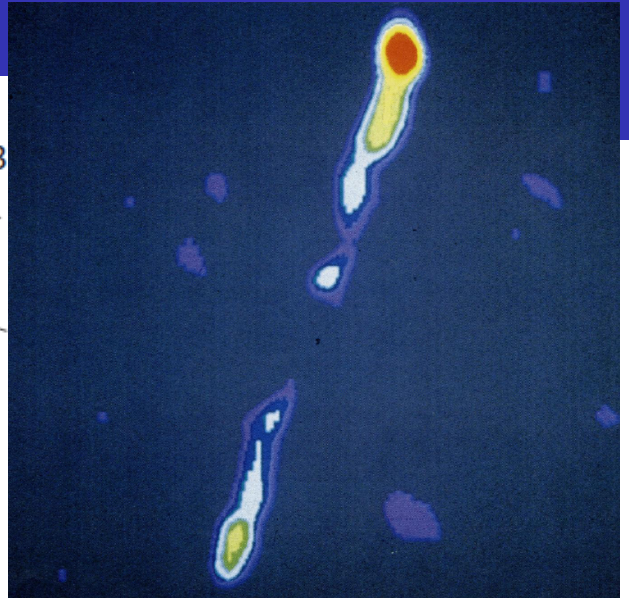

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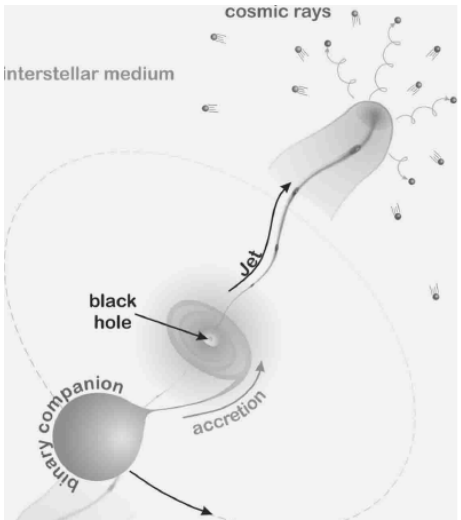

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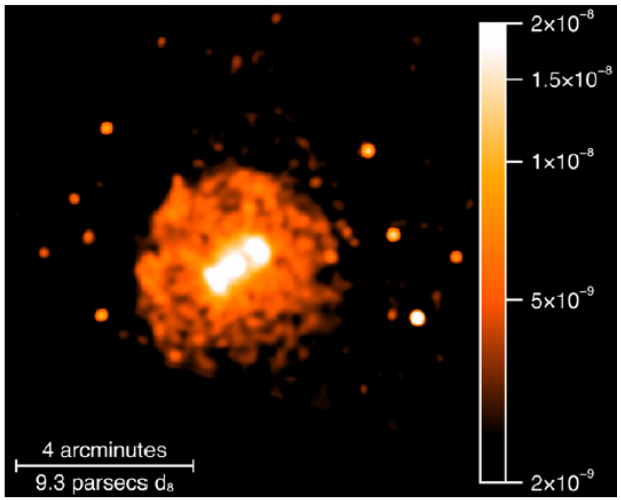

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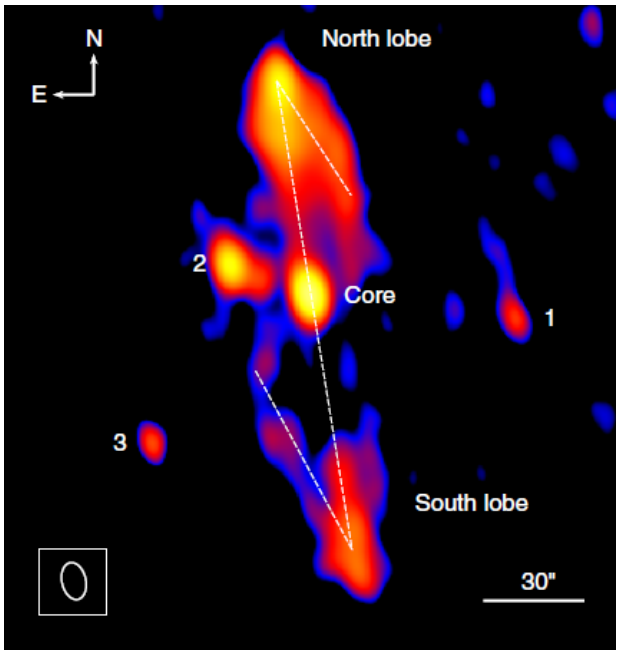

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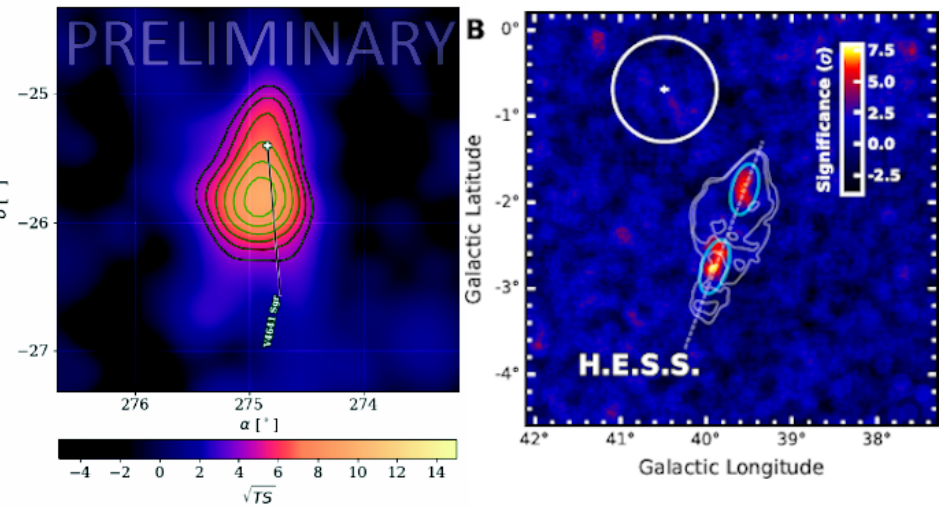
Gamma-rays and CR from large-scale jets

- **No MQ firmly detected at VHE on binary scales yet+adiabatic losses:**

$$E \sim 10^{-4}\, E_{\rm max} \left(z_{\rm acc,AU}/z_{\rm pc}\right)^{2/3}$$ **(conf.?)**

- Total MQ jet power likely dominated by the most powerful sources.
  (e.g. Heinz & Grimm 2005)
- Jet termination shocks are trans relativistic, good for acceleration.
- Large-scale $\gg$ TeV emission from V4641 Sgr (left) and SS 433 (right).

(HESS24; also HAWC18, LHAASO23)



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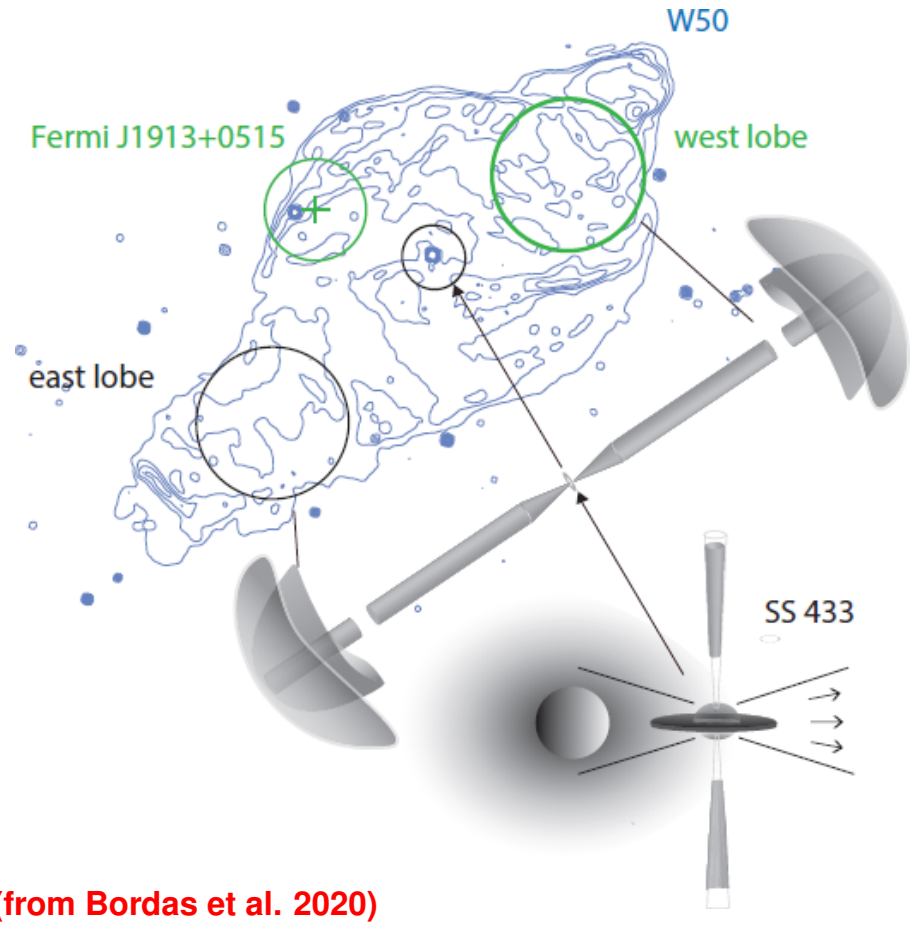

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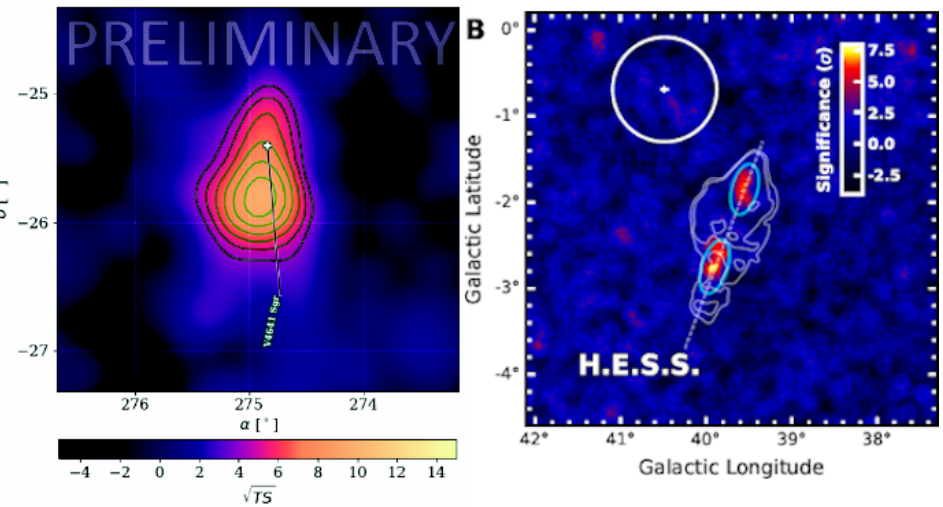

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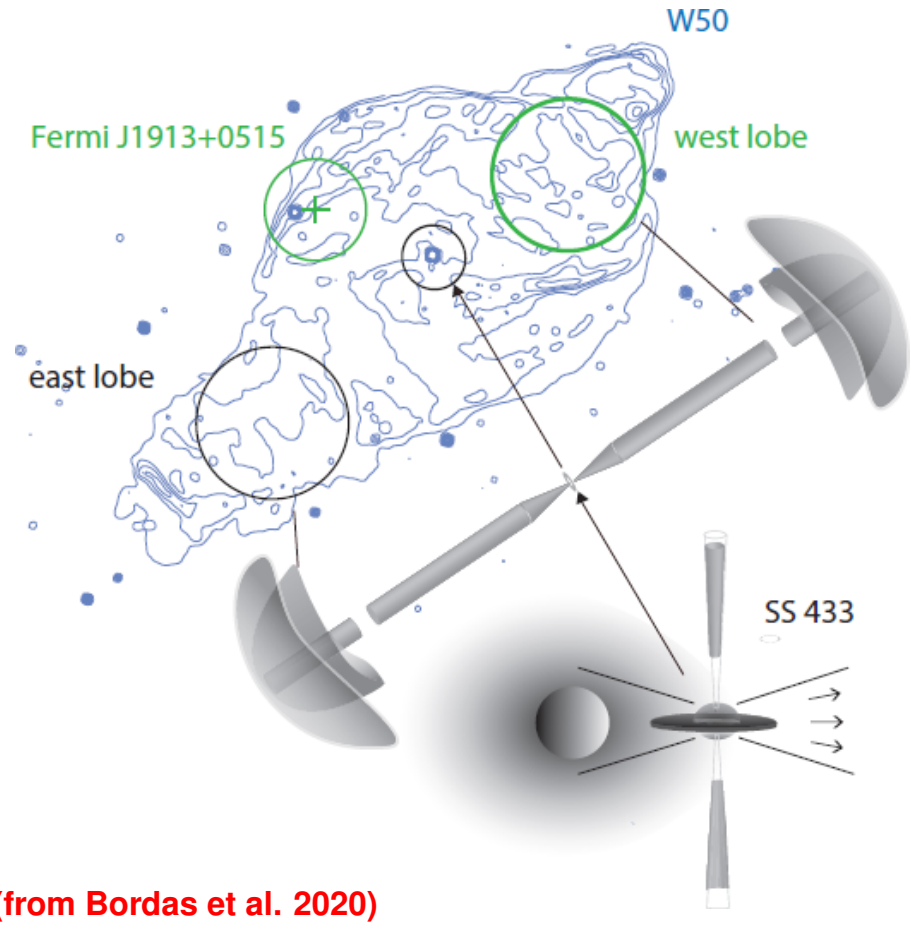

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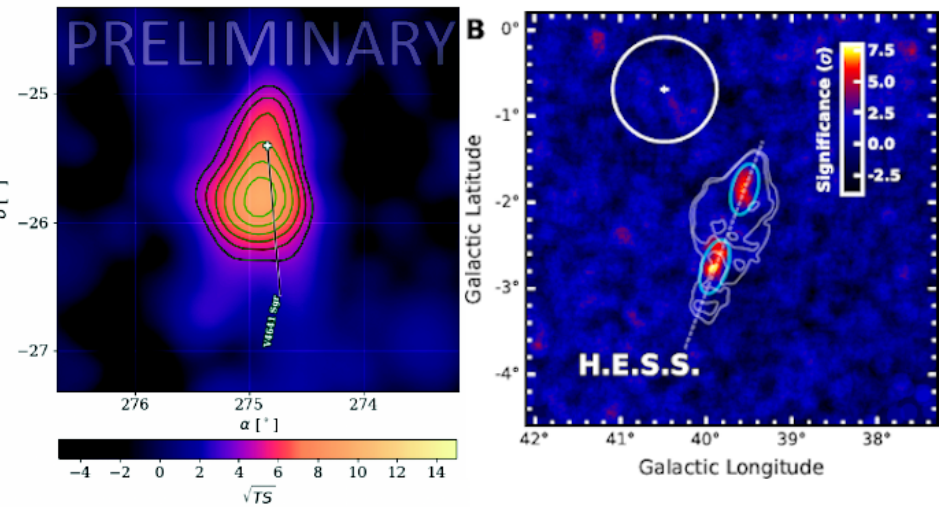

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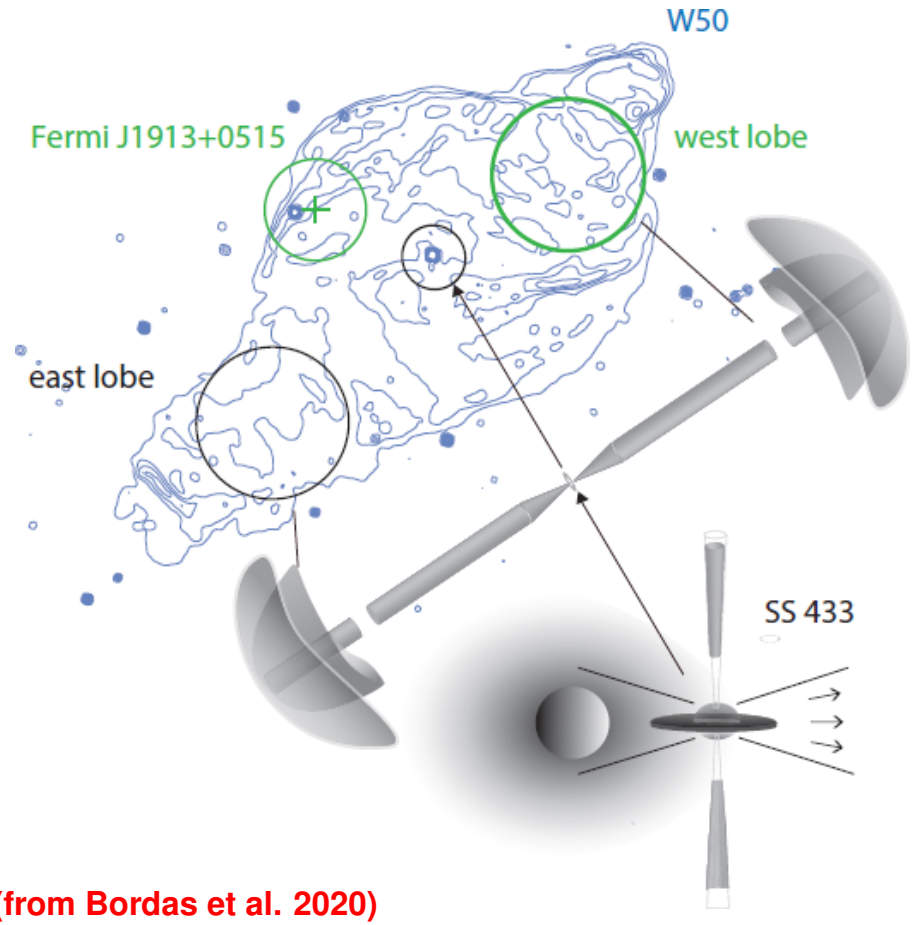

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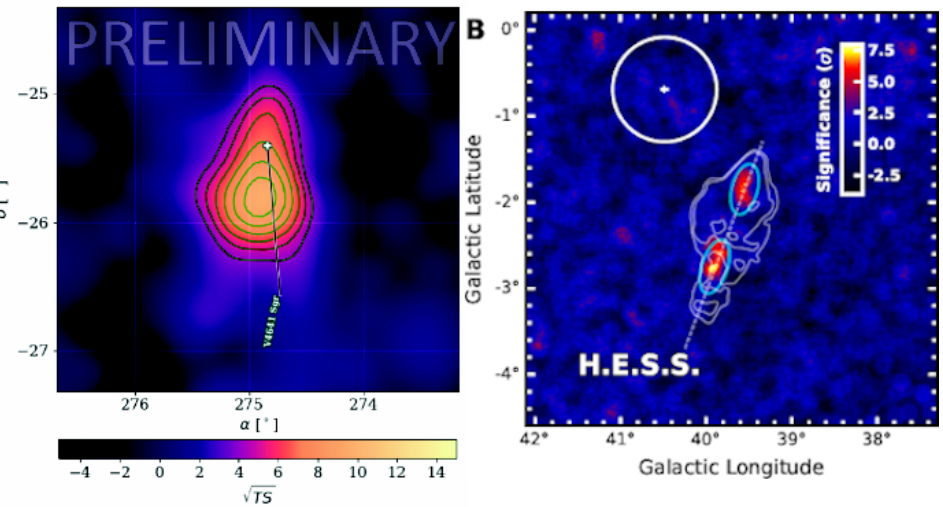

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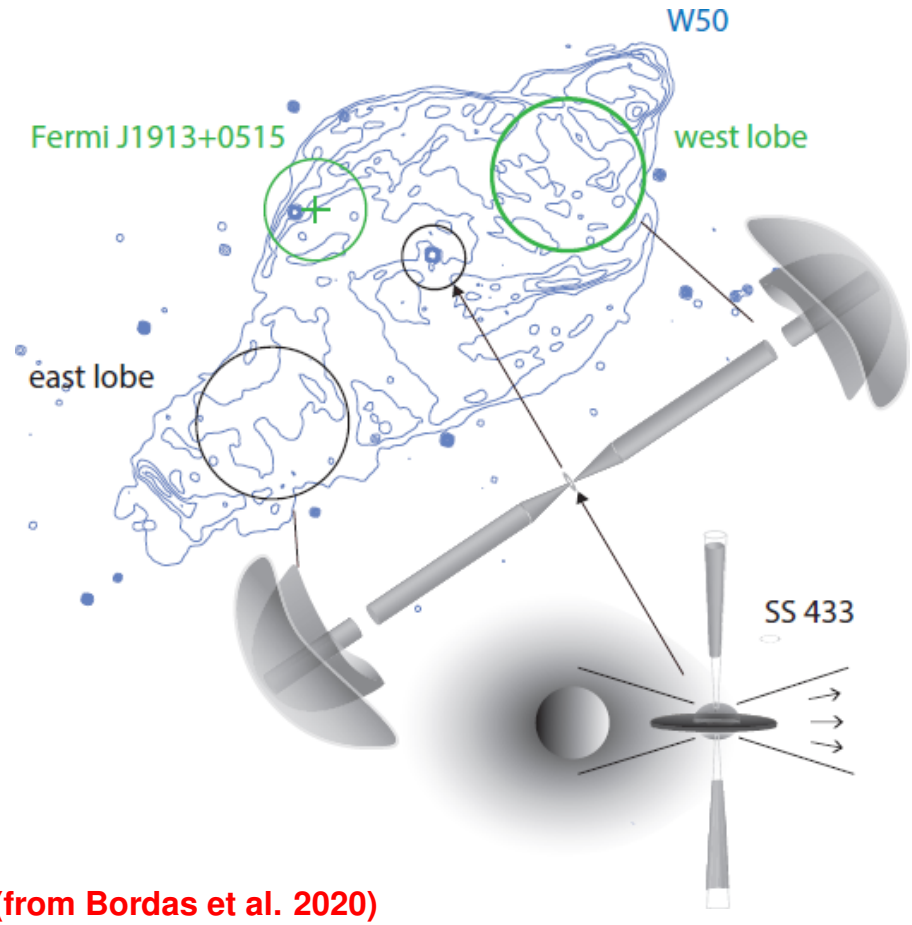

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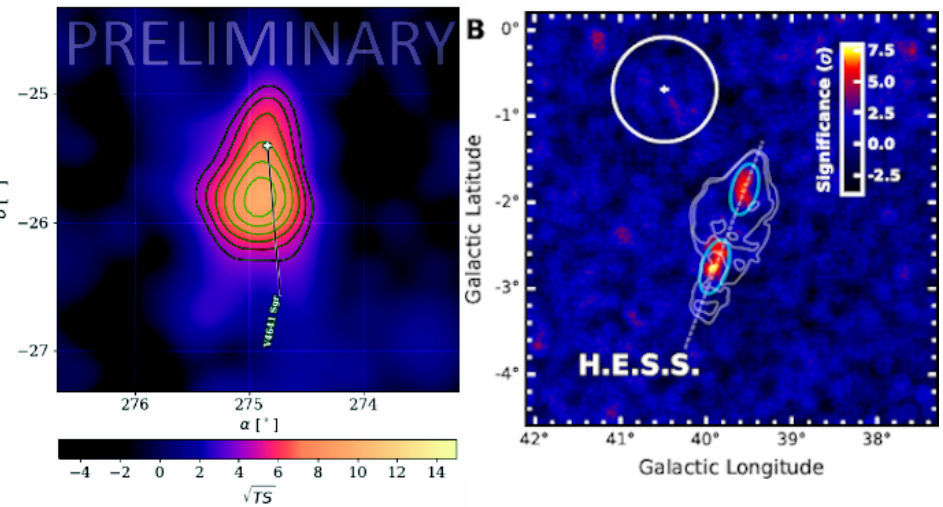

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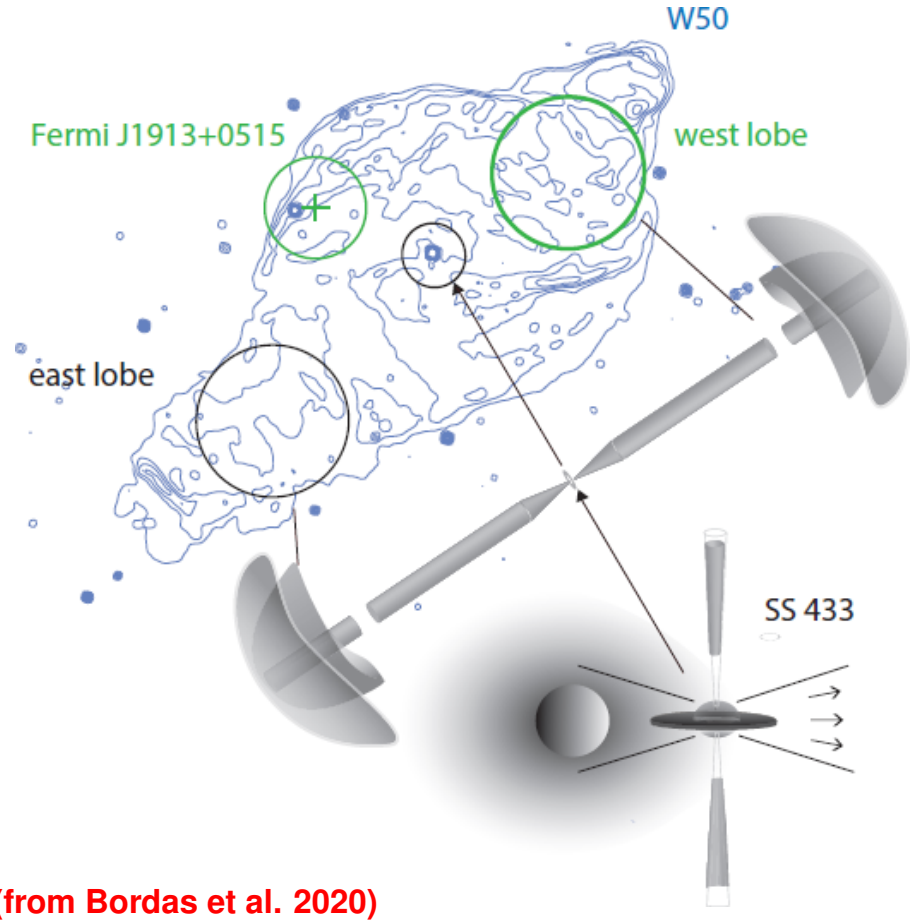

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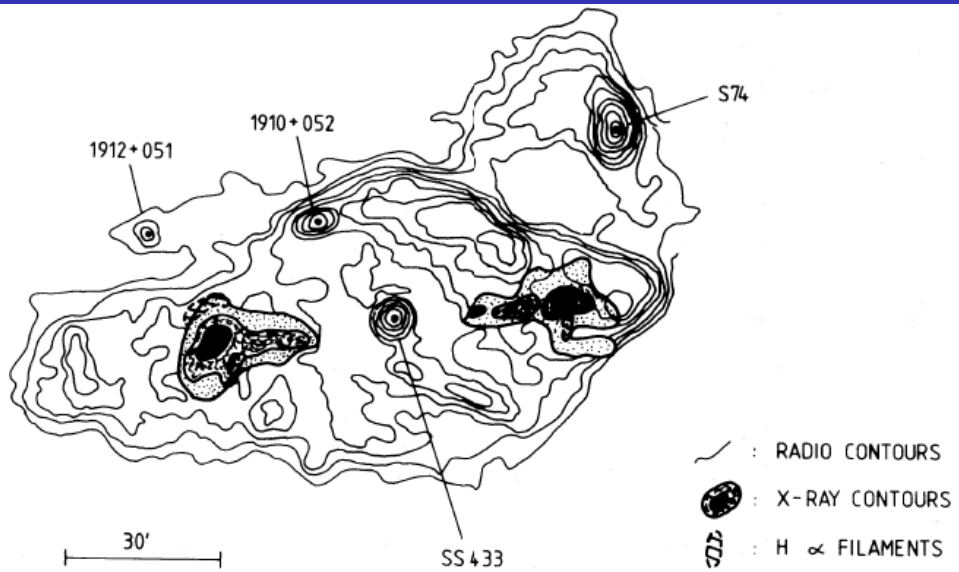
- Synchrotron X-rays proposed in the 80's and 90's, already suggesting $E_{10\mathrm{keV},e} \sim 100 B_{20\mu G}^{-1/2}$ TeV.
- Fermi detected large-scale emission, with evidence of 162 day periodicity.

(e.g., Seward et al. 1980, Watson et al. 1983, Yamauchi et al. 1994, Bordas et al. 2015, Rasul et al. 2019, Li et al. 2020)



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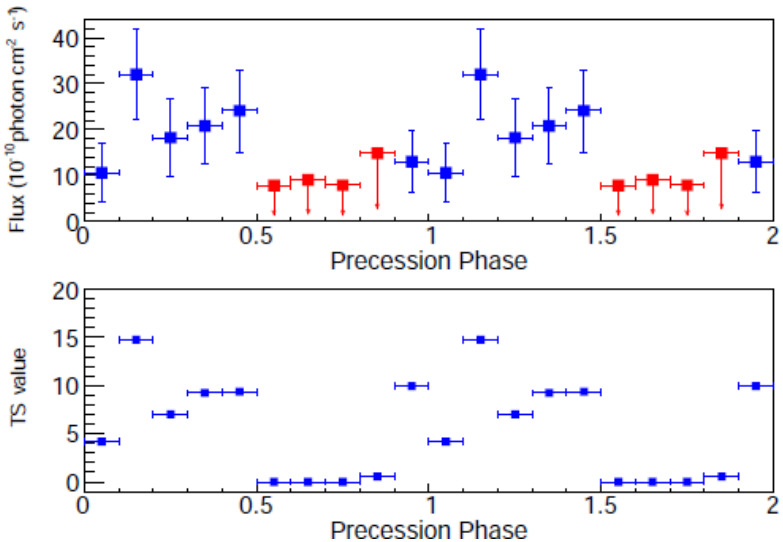

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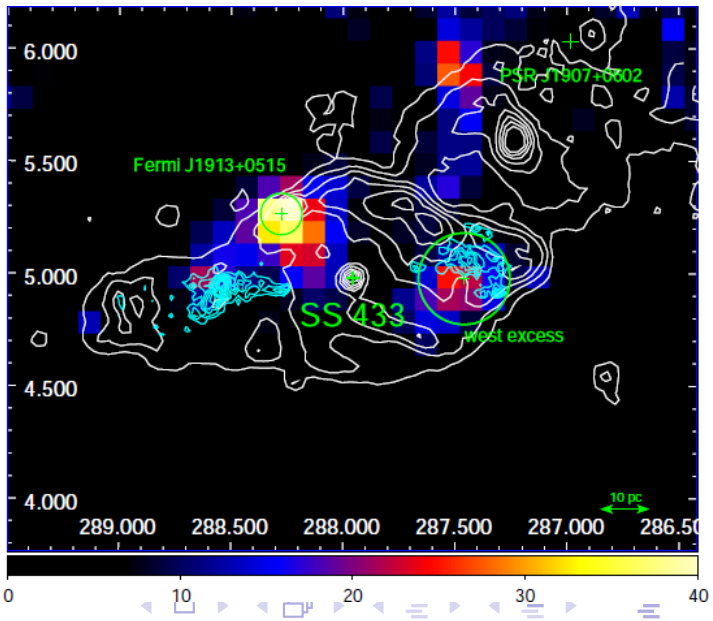

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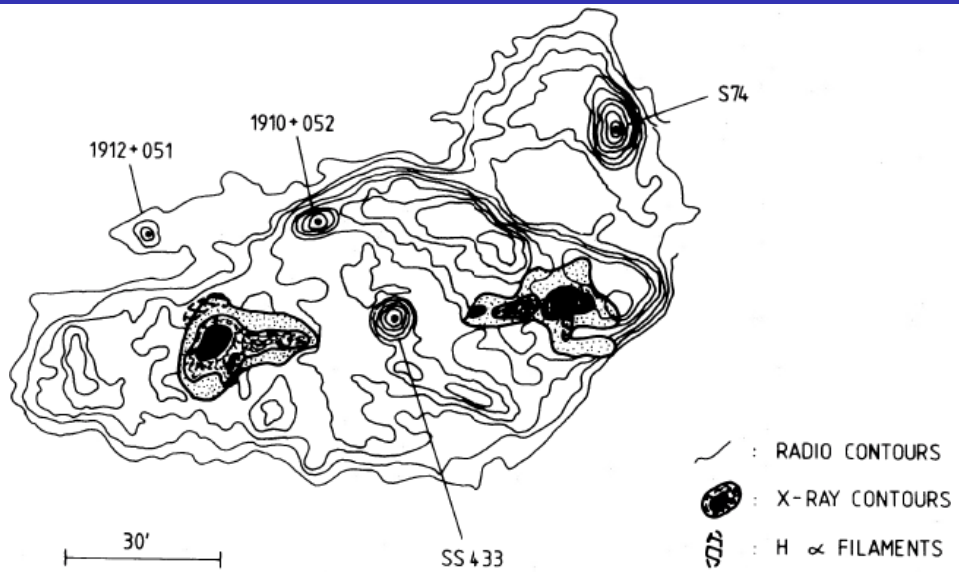

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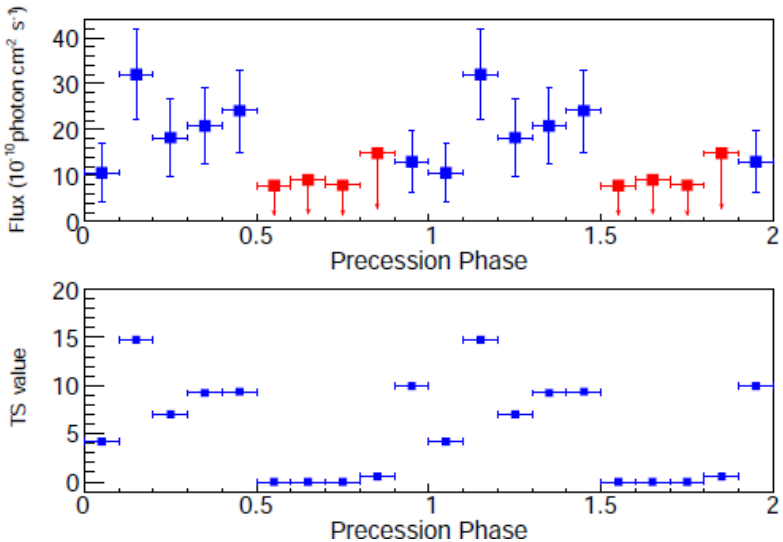

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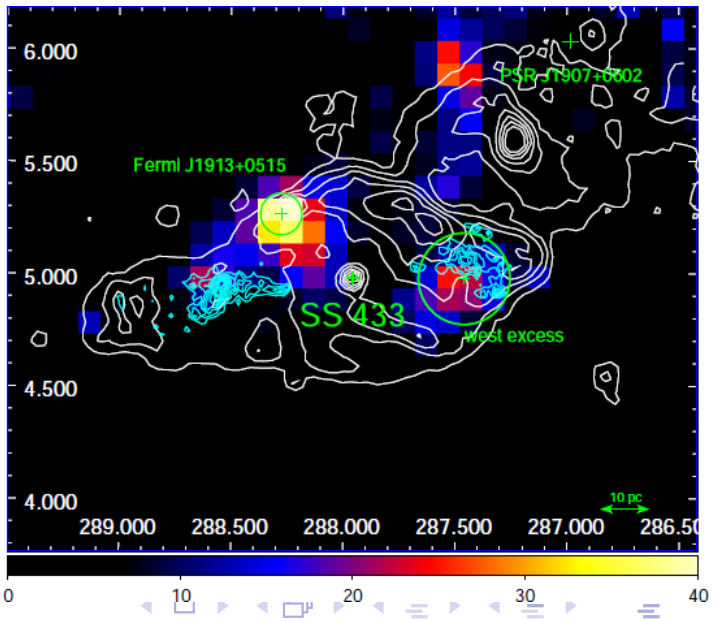

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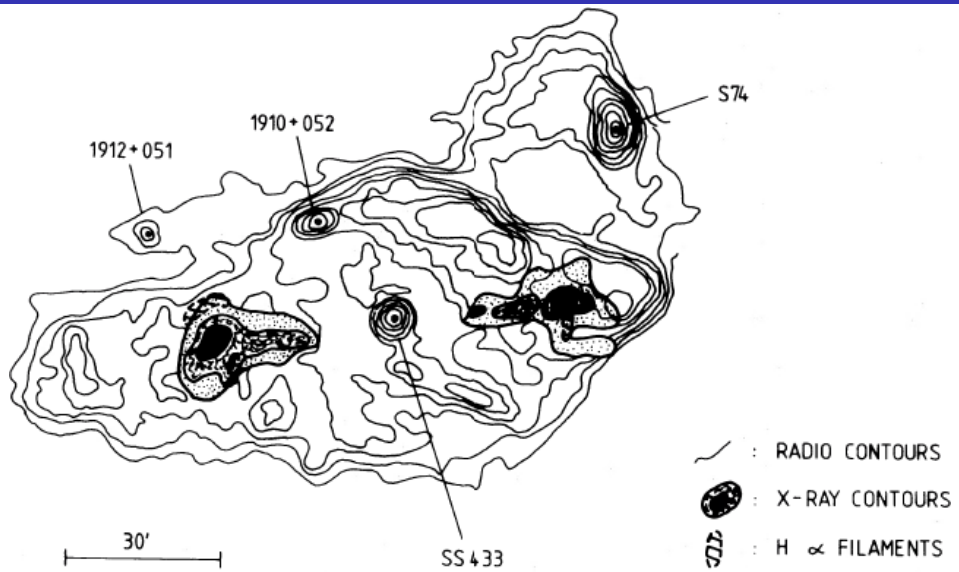

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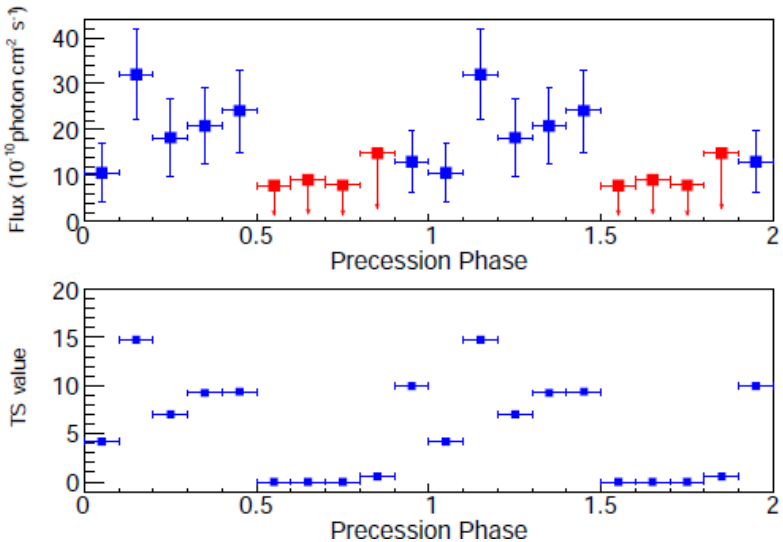

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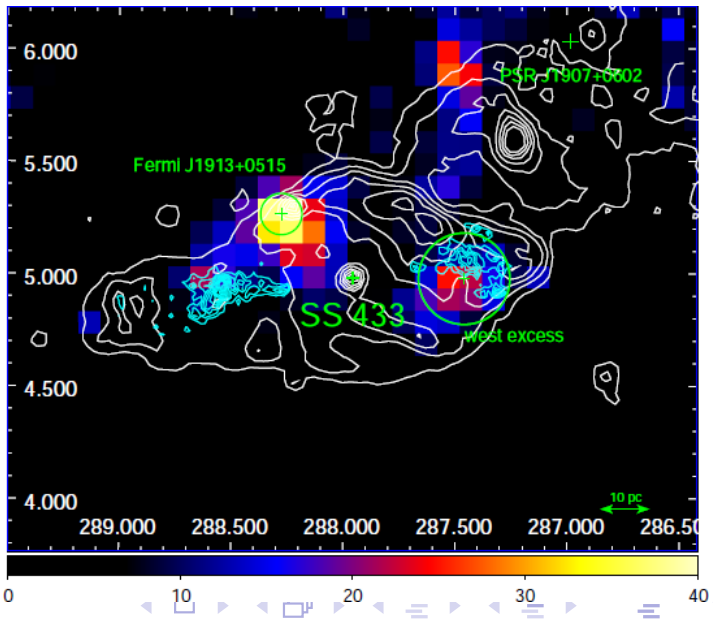

X-rays, Fermi and Hawc

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- The X-ray emission shows energy-dependent morphology.
- There are sub-threshold Fermi excesses on the large-scale jets.

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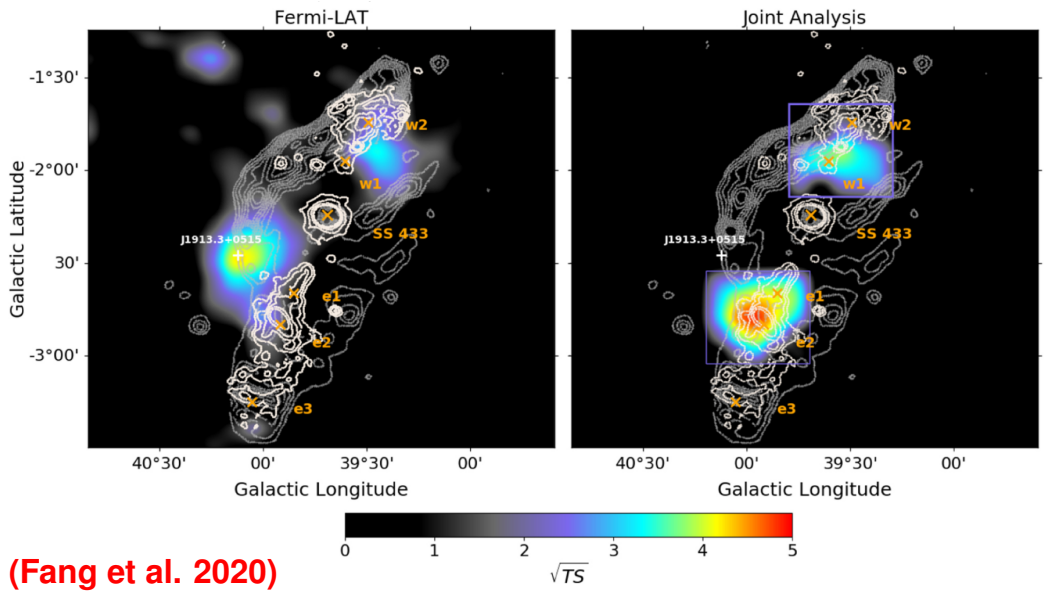

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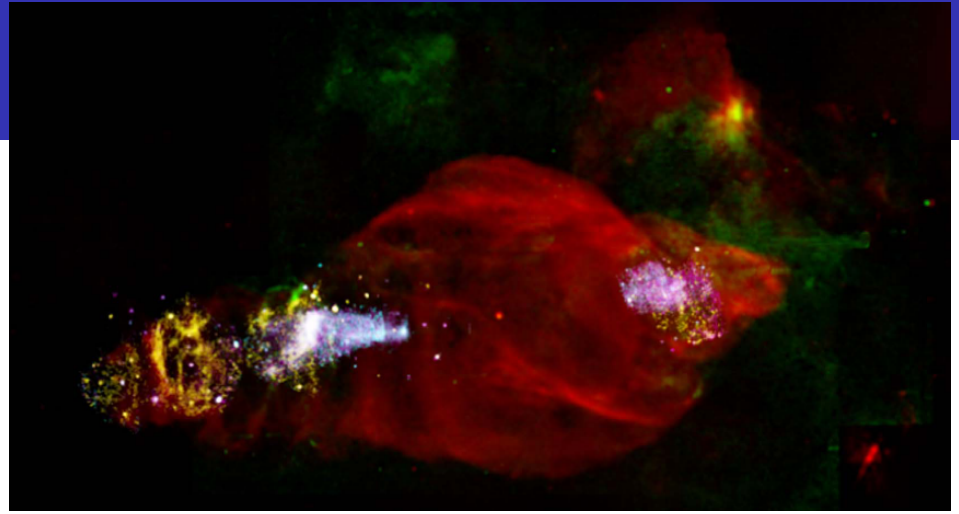

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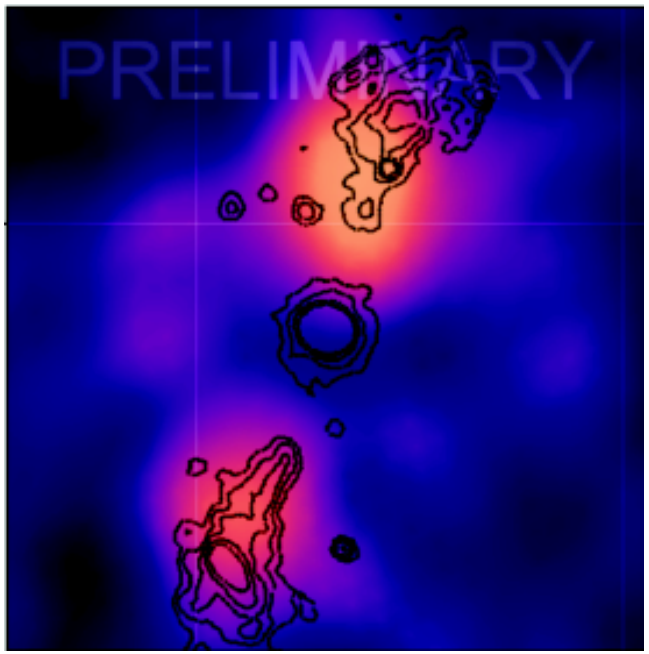

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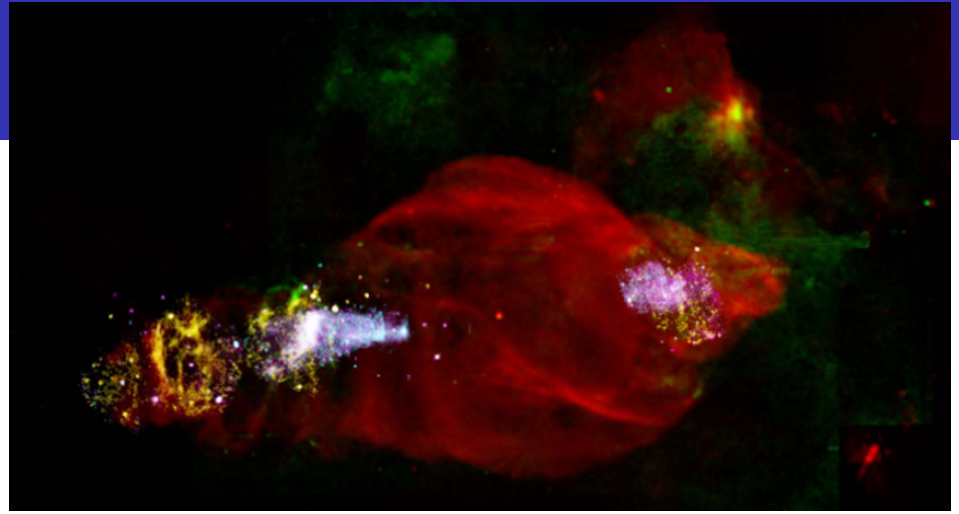

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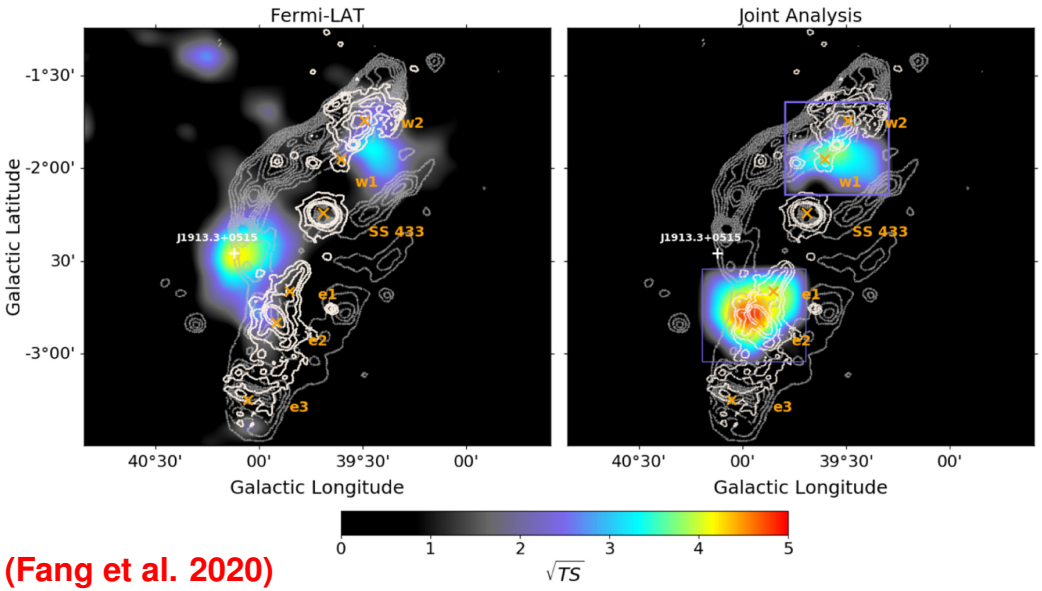

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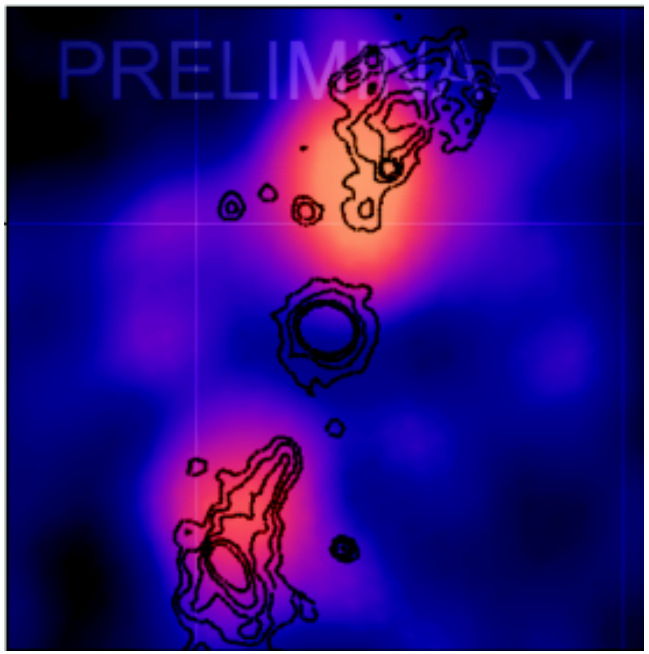

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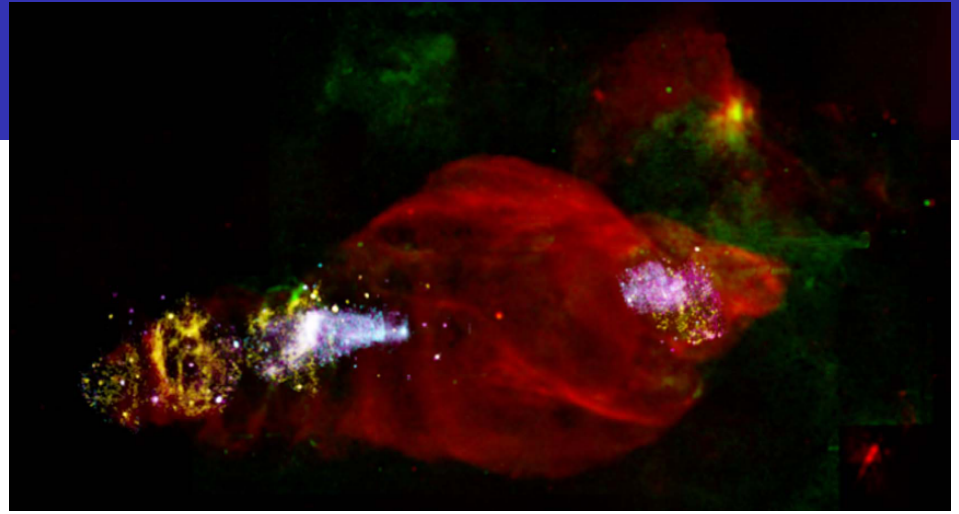

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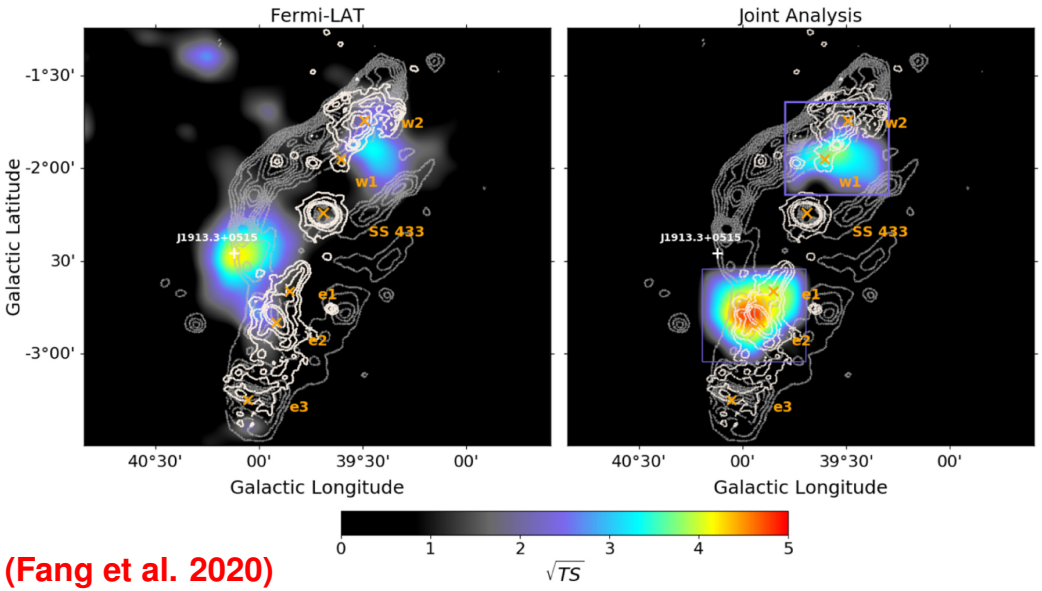

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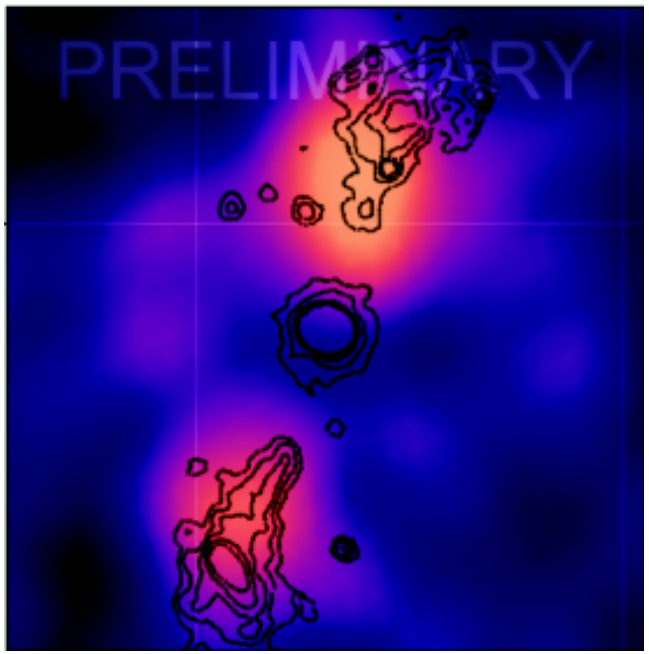

(Rho, HAWC PRELIM., VGGRS VI workshop 2023)

X-rays, Fermi and Hawc

- **The large-scale high-energy emission starts at $\sim$ 30 pc from SS 433.**
- **The X-ray emission shows energy-dependent morphology.**
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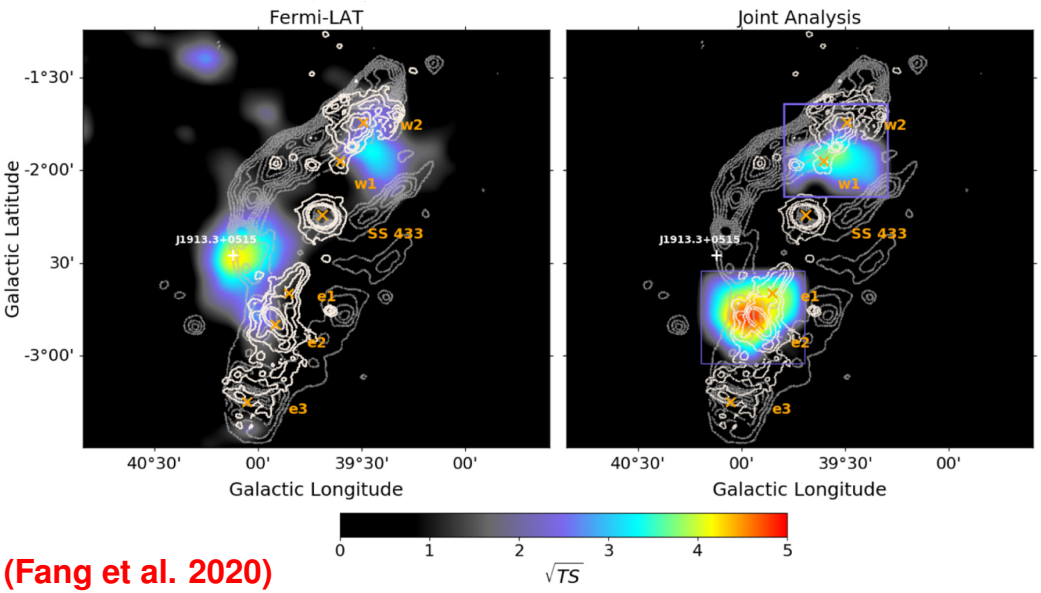

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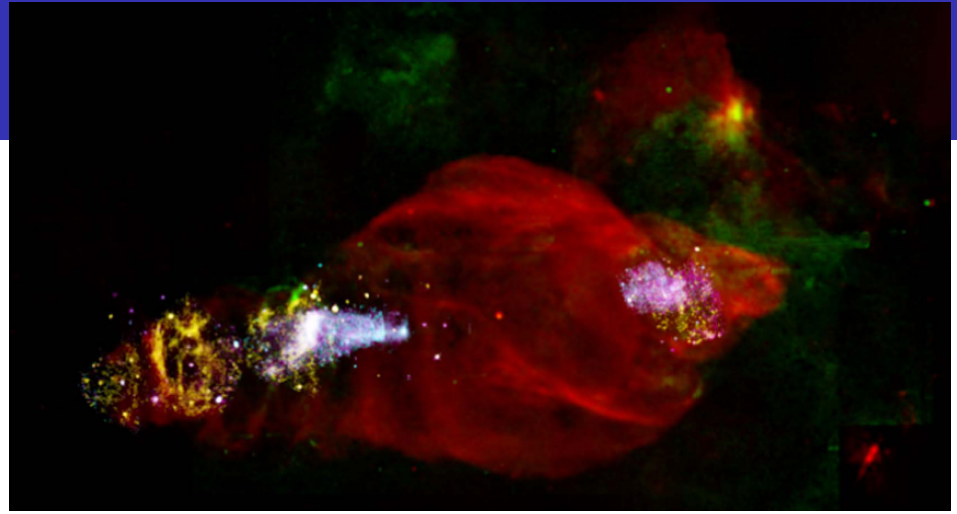

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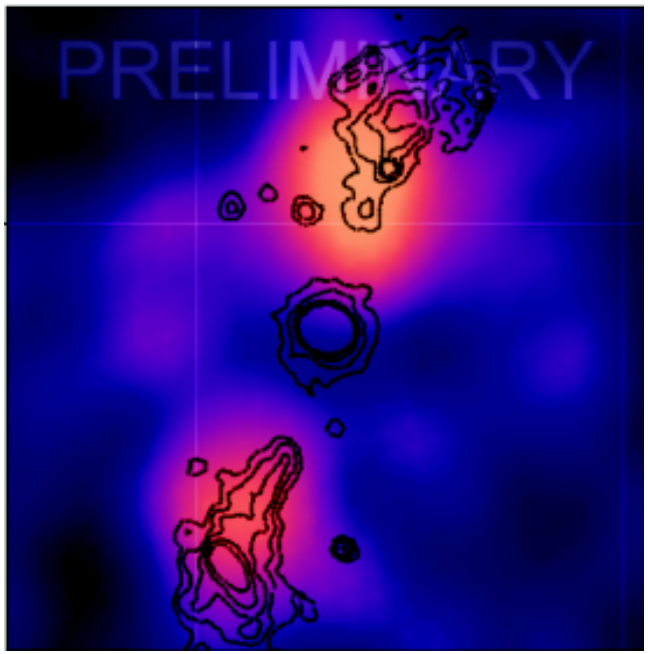

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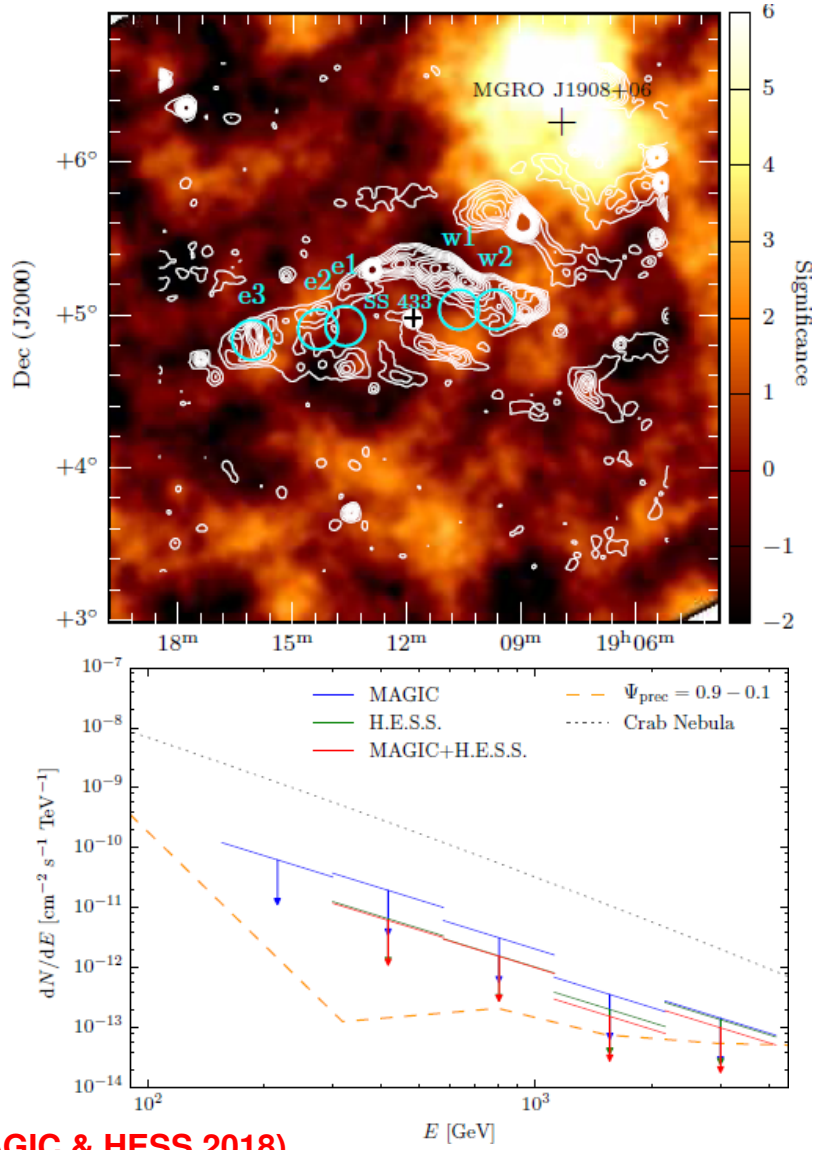

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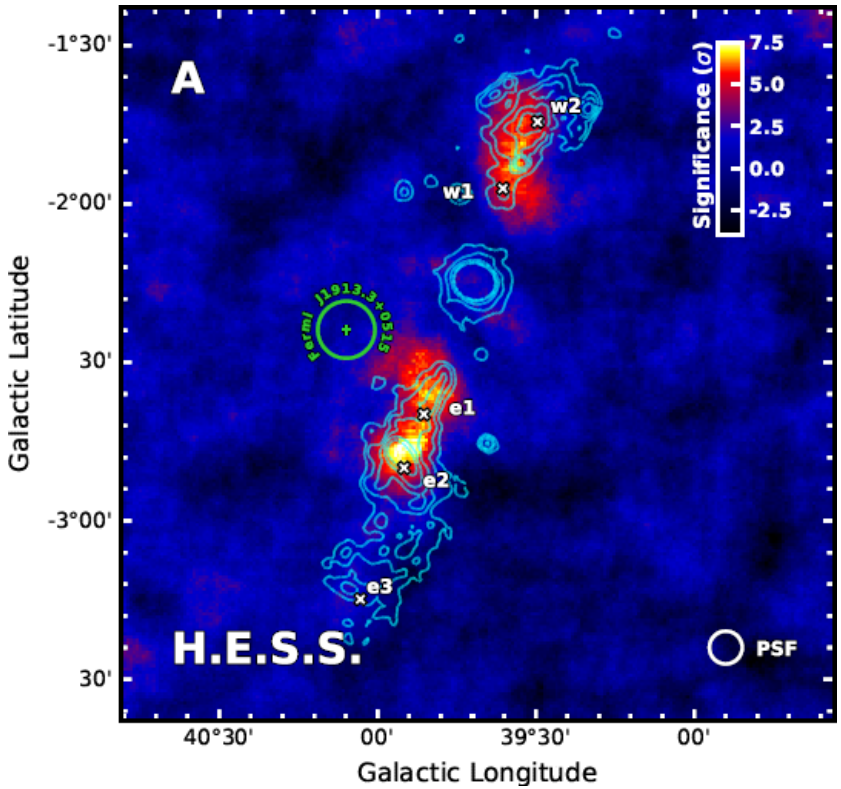

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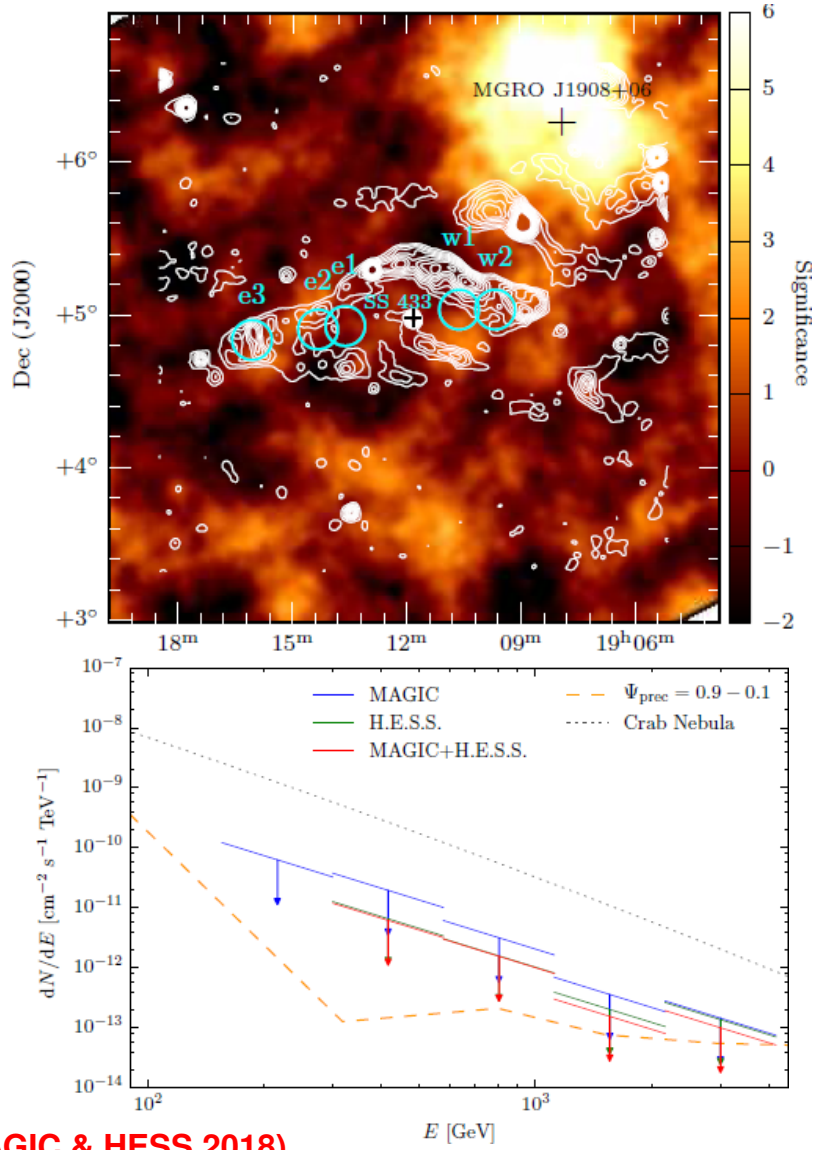

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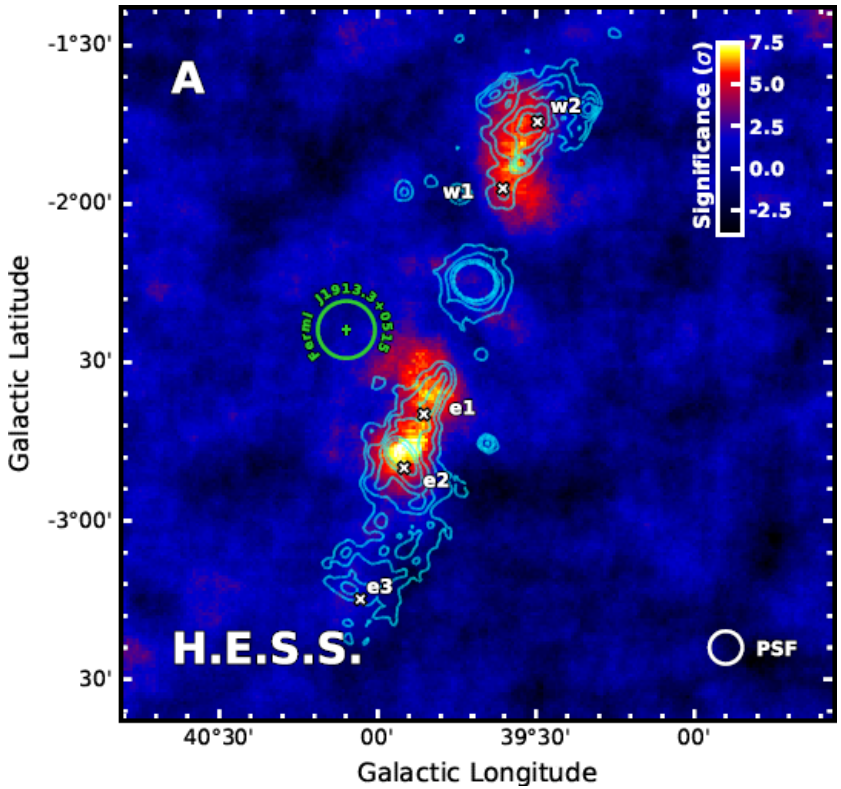

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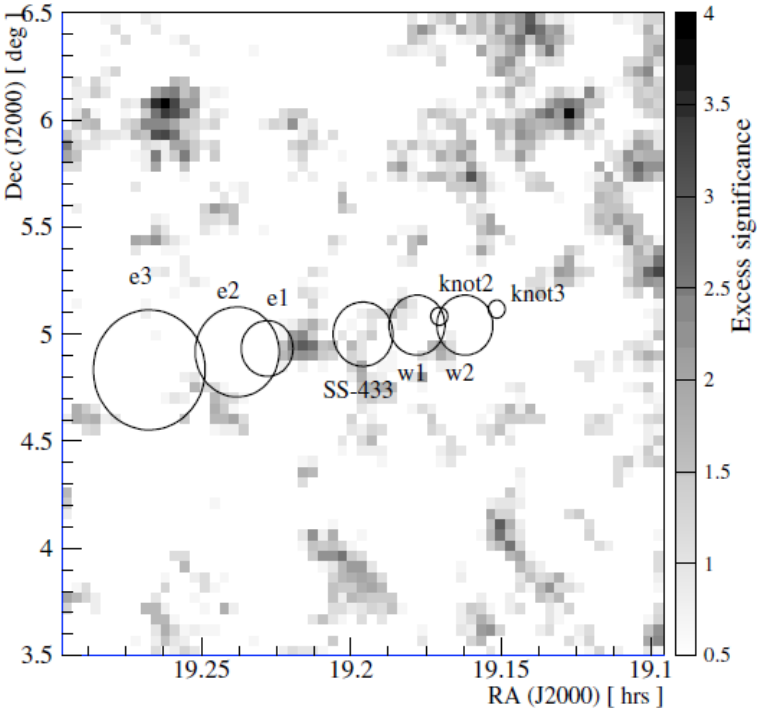

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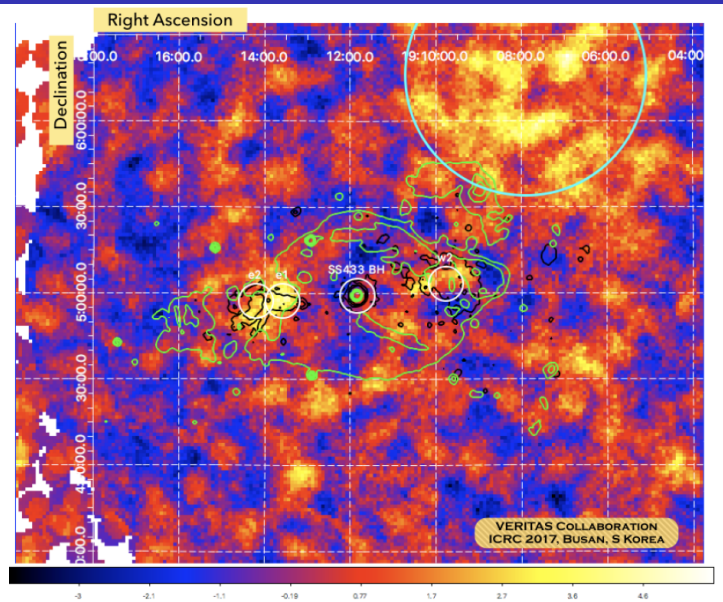

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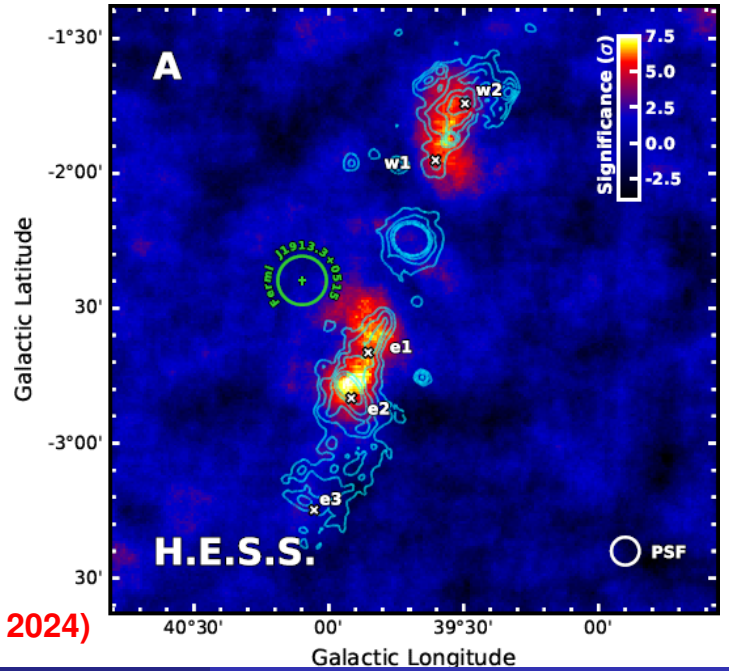

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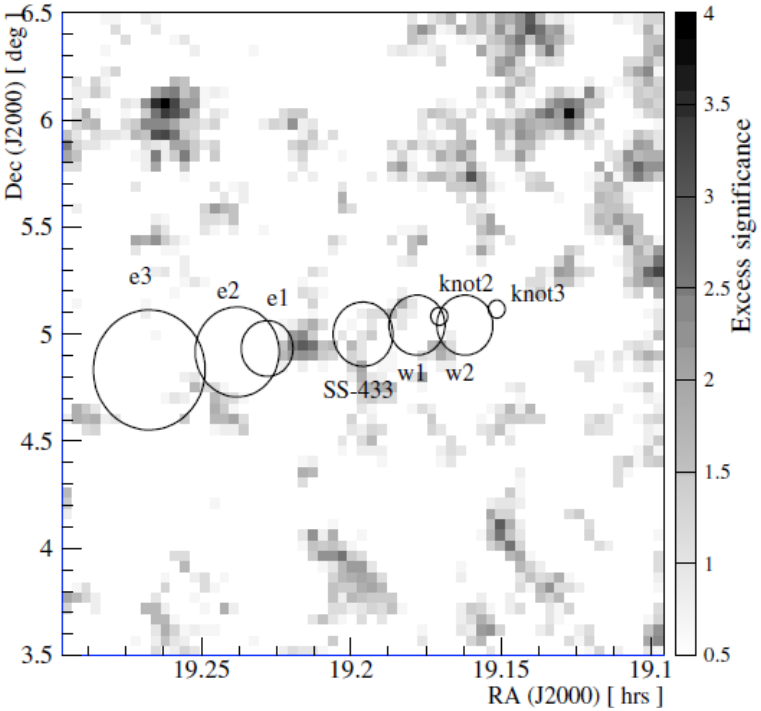

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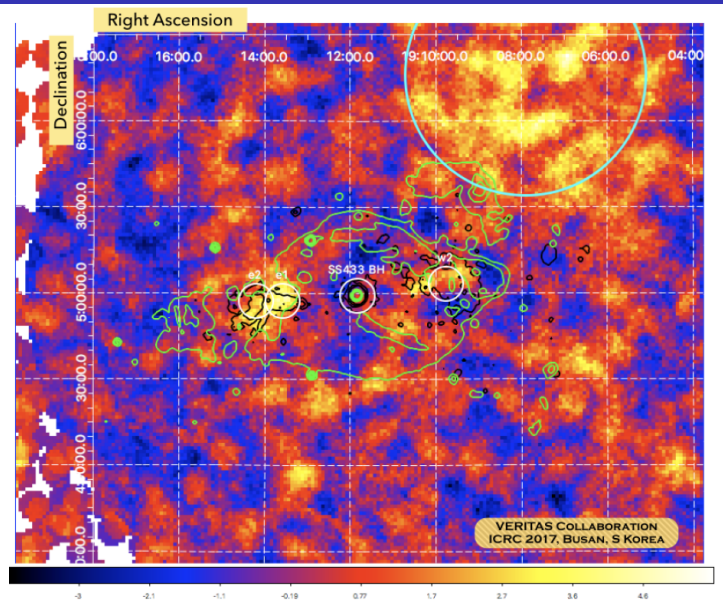

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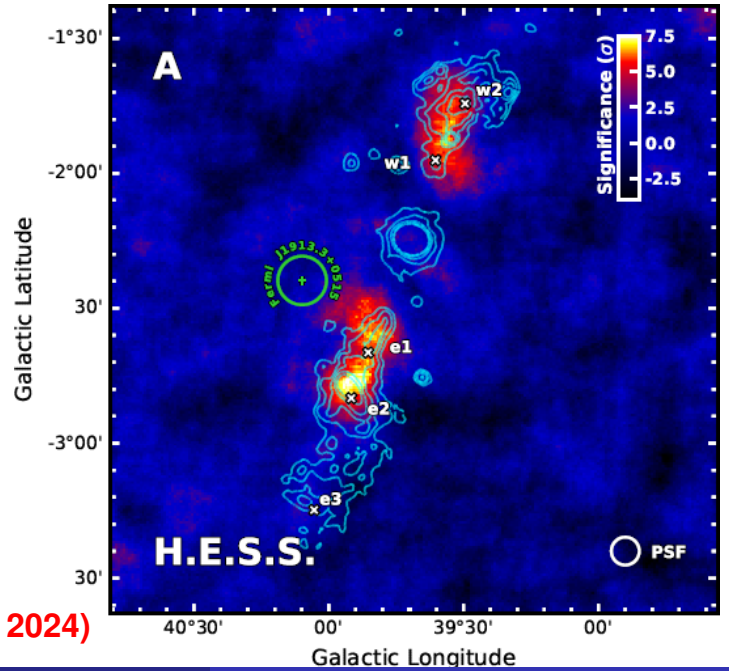

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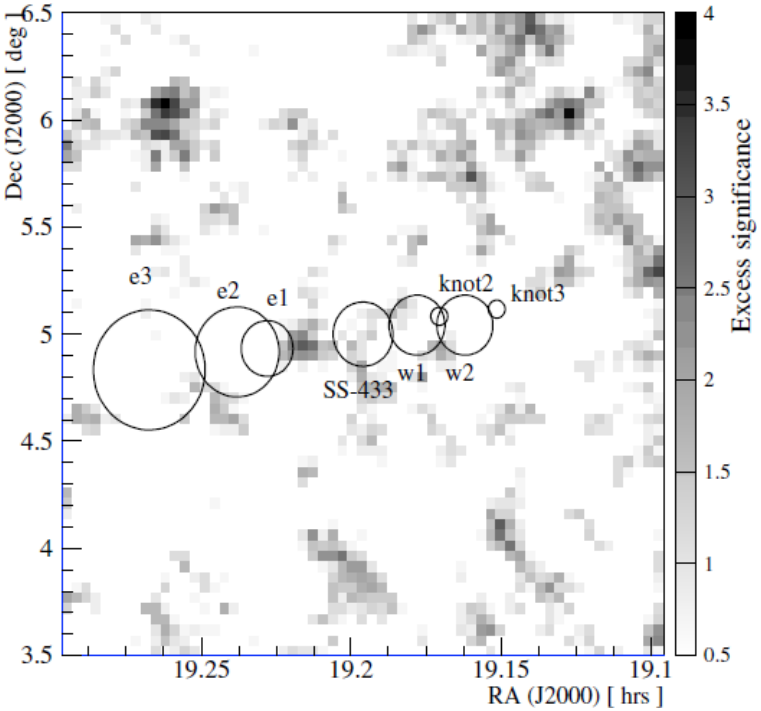

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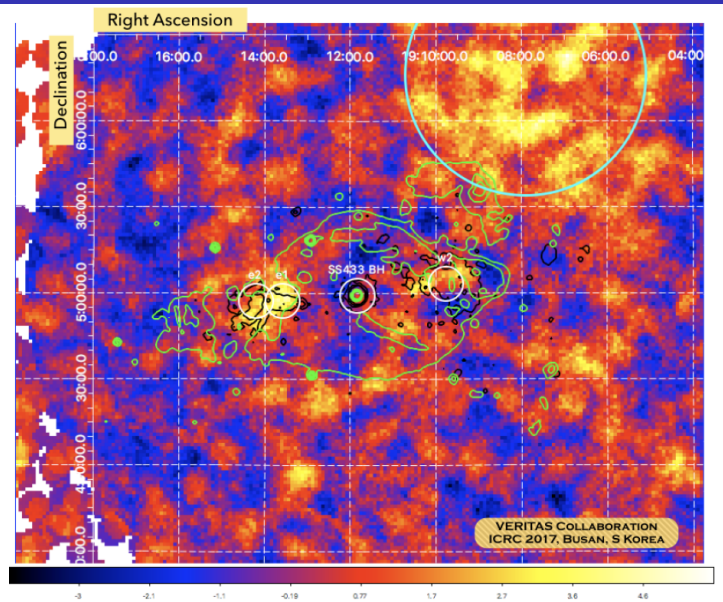

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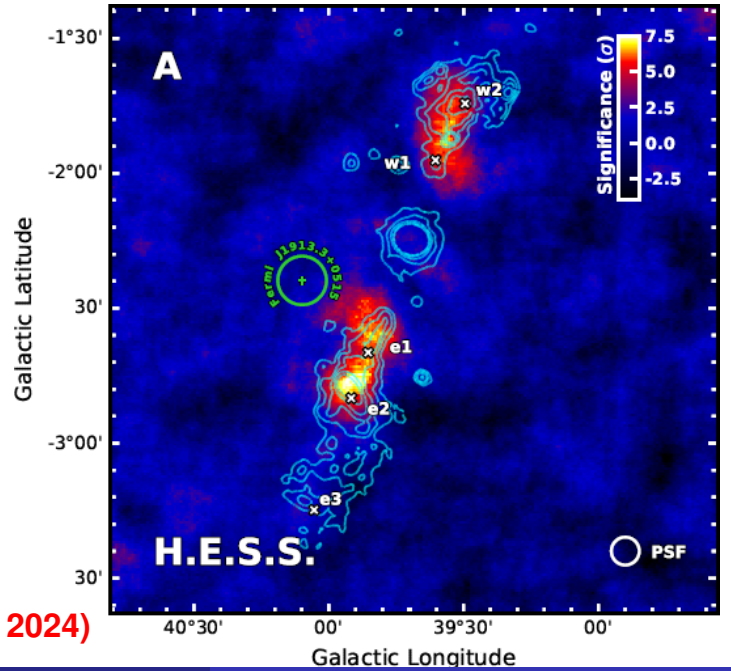

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- **Gamma rays seen by HESS drop in energy with distance from SS 433.**
- Emission from IC off IR photons by $Q_{e\pm,\mathrm{inj}} \propto E^{-2}$ and synchr. losses.
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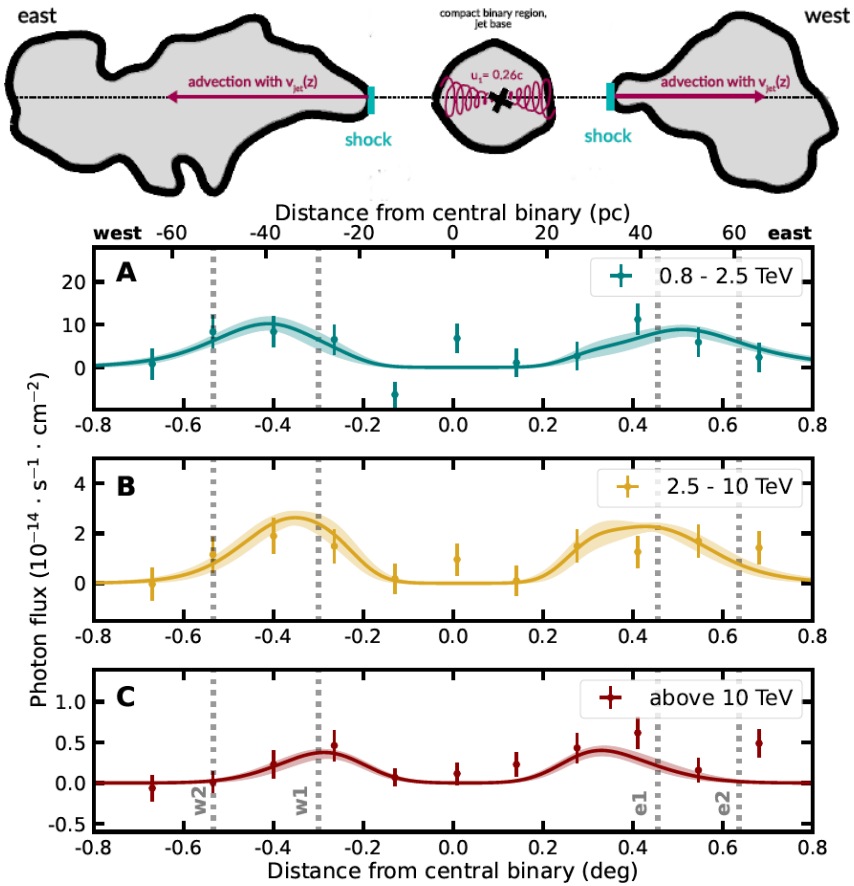

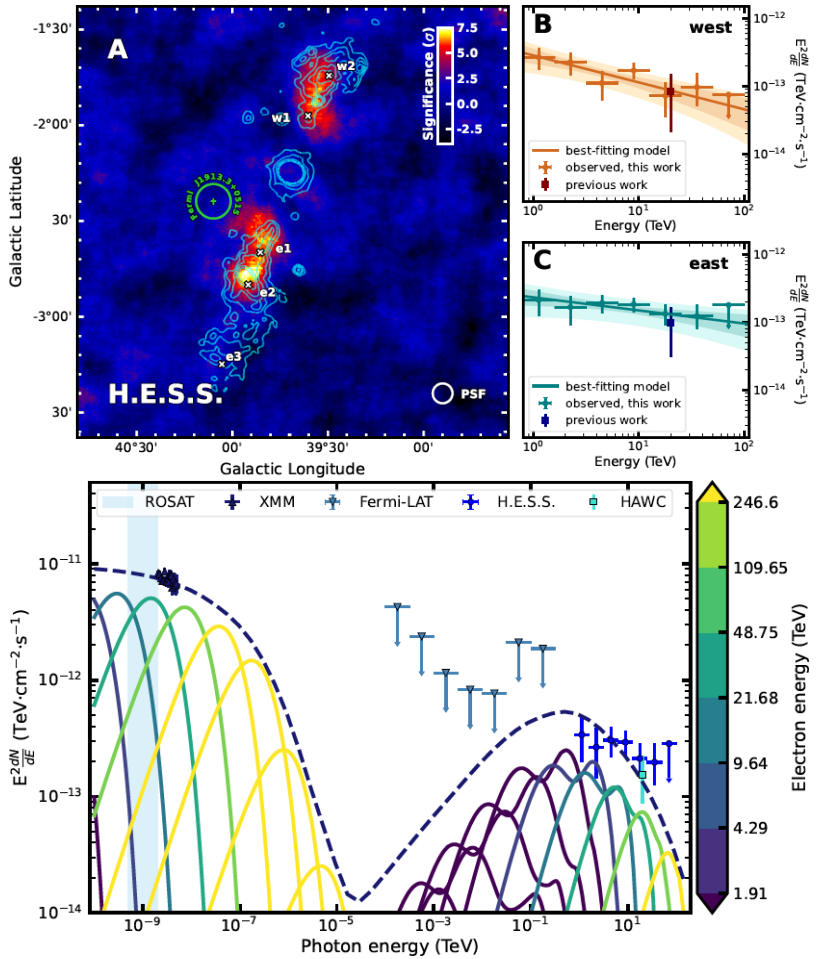

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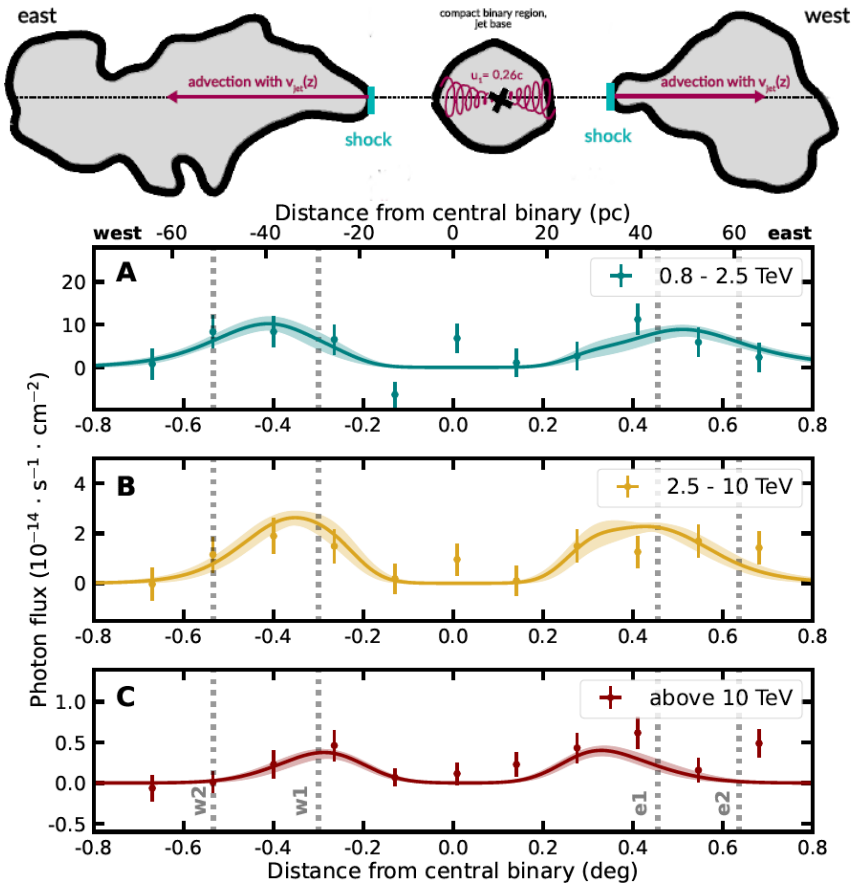

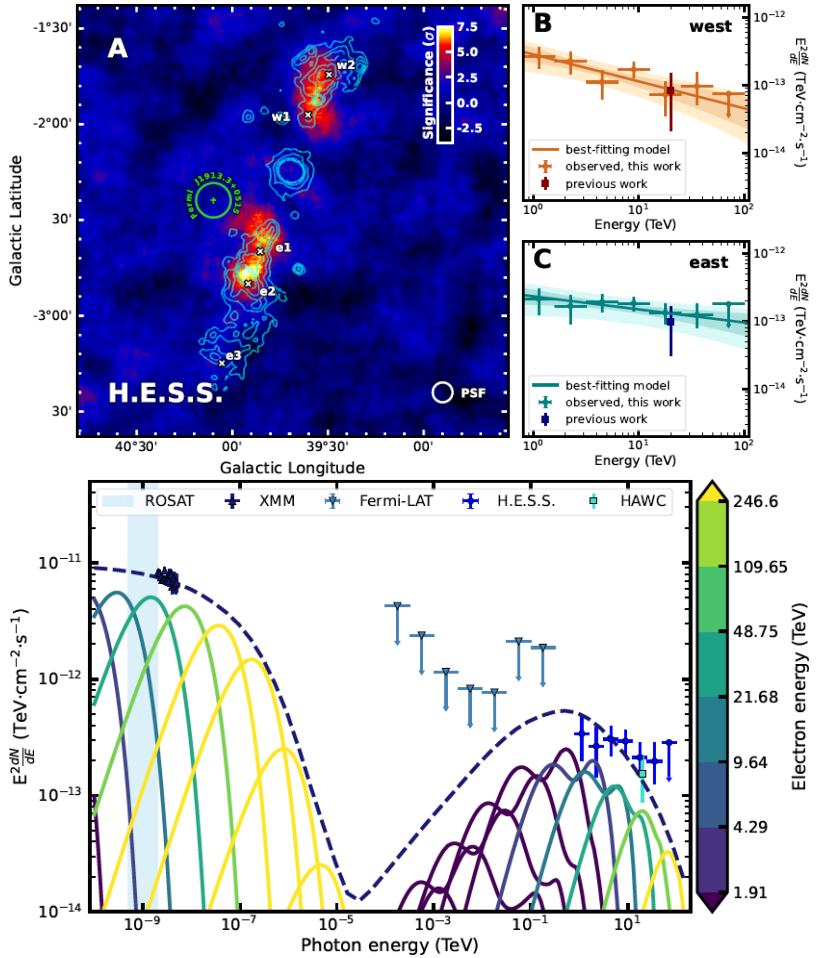

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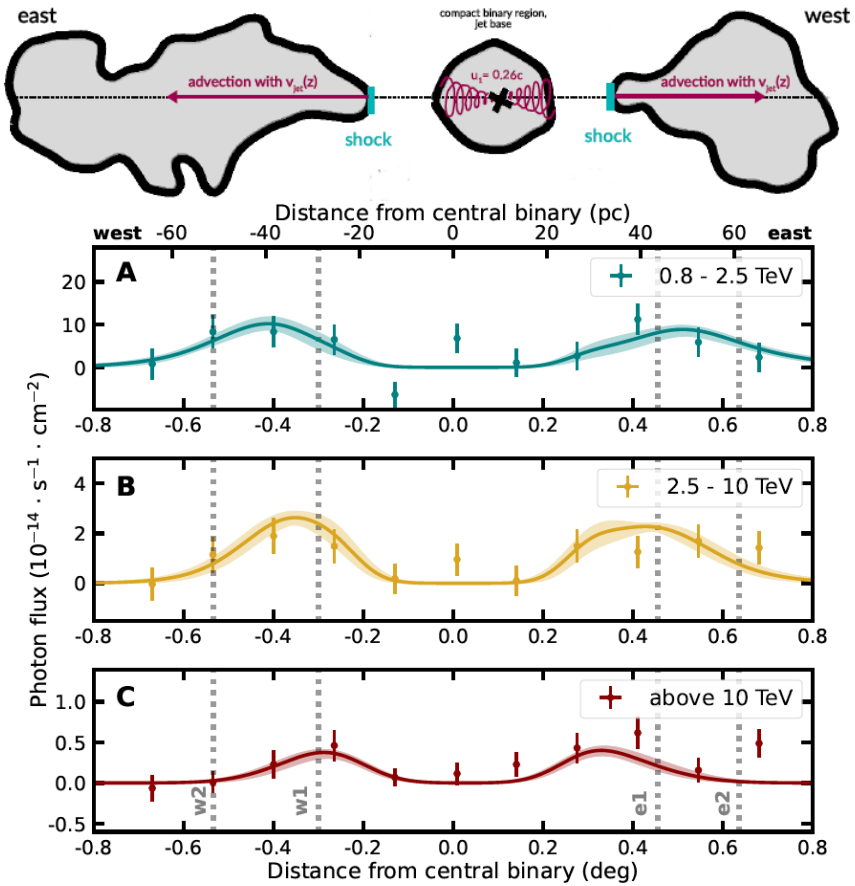

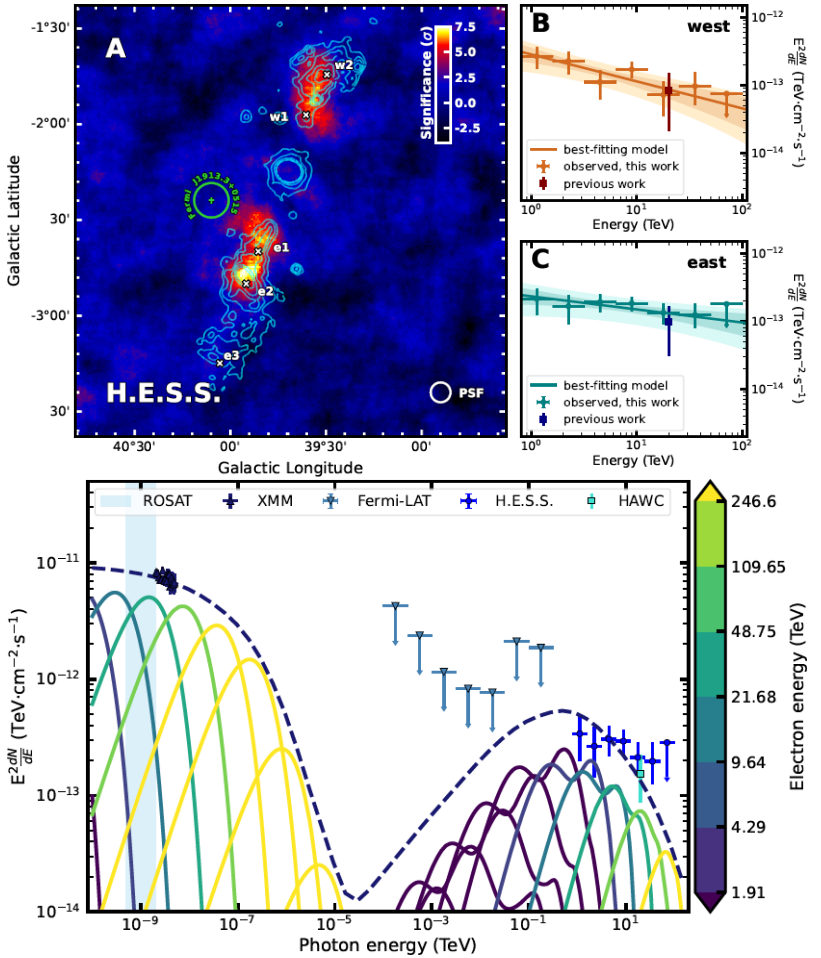

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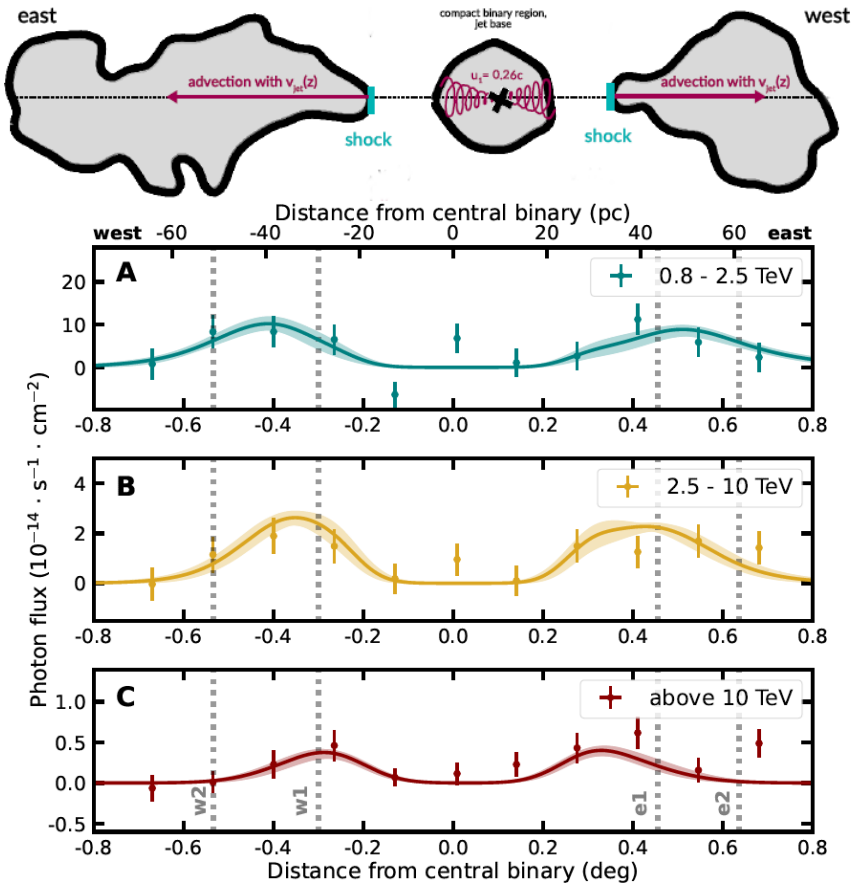

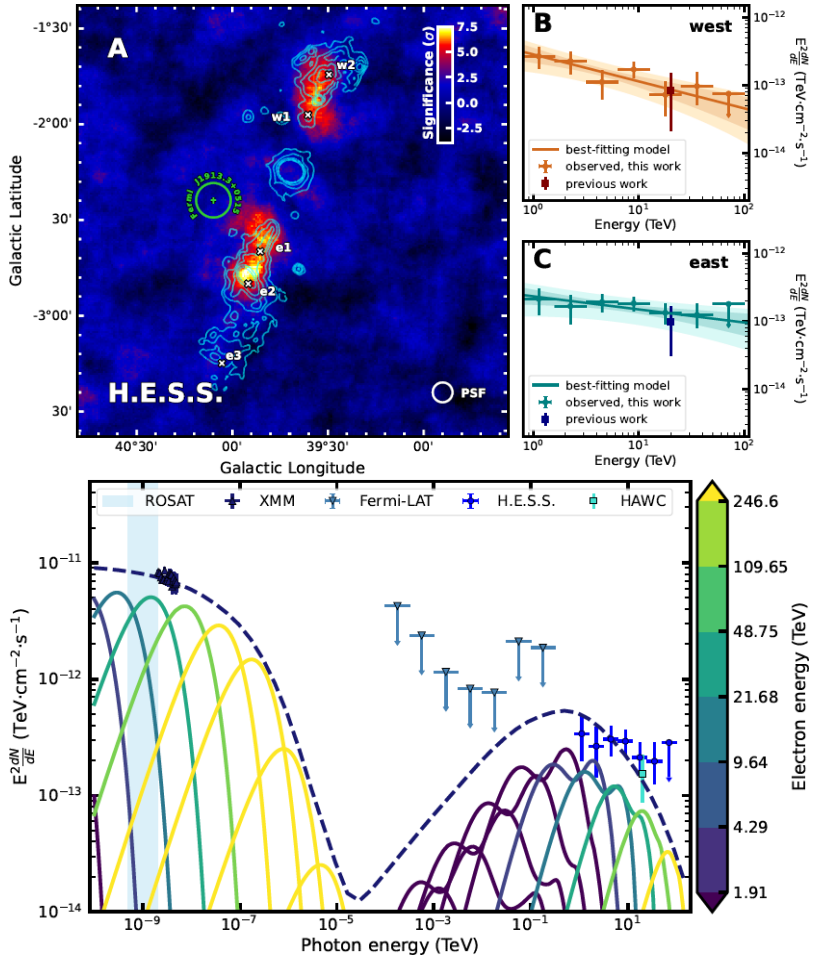

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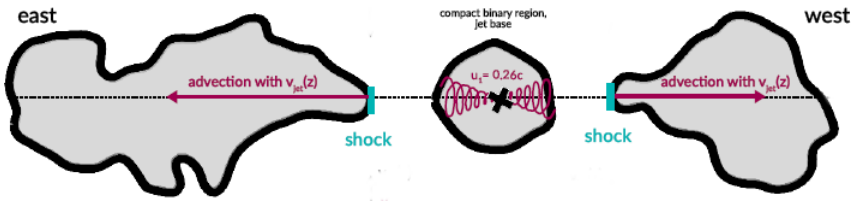

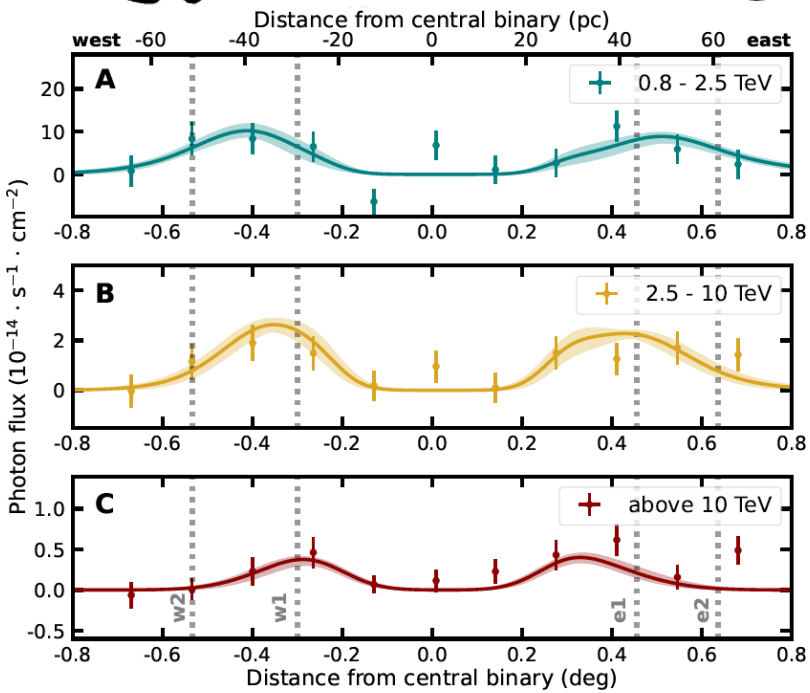

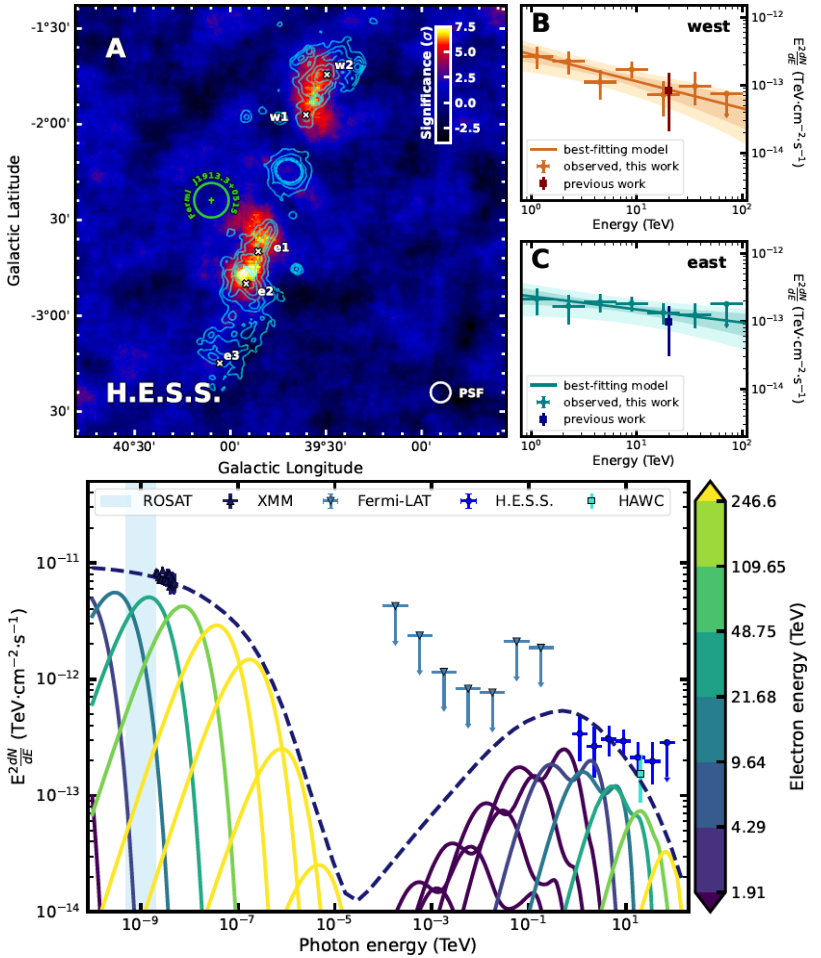

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Outline

Are MQ large-scale jets PeVatrons?

- **In SS 433, for $B_{\rm HESS} \sim 20\,\mu$G, diff. shock acc., and $E_{\rm max,e} > 200$ TeV:**

$$\dot{E}_{\rm DSA} = \dot{E}_{\rm sync} \rightarrow \eta_{\rm Bohm} > 0.01\, u_{0.26c}^{-2} \qquad \textbf{(HESS 2024)}$$

- **From this, for p/N energies, limited by shock escape, one obtains:**

$$E_{\rm max,p/N} \gtrsim 0.4\, Z_0\, R_{\rm 5pc}\, u_{0.26c}^{-1}\ {\rm PeV}$$

- **Population-wise, assuming $n_{p/N}/n_e \sim 100$, for $N_{\rm SS433} \propto E^{-2}$ one gets $L_{\rm SS433,CR,PeV} \sim 10^{37}$ erg/s, so N similar jets always ON could explain**

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- **For $L_{\rm jet} \ll L_{\rm jet,SS433}$: assuming $u_{0.26c} \sim 1$, the fact that $E_{\rm max,p/N}$ is $\propto L_{\rm jet}^{1/2}$ means that $\eta_{\rm Bohm}(L_B/L_{\rm jet})^{1/2} \gg 10^{-3}$ is needed to produce PeV p.**

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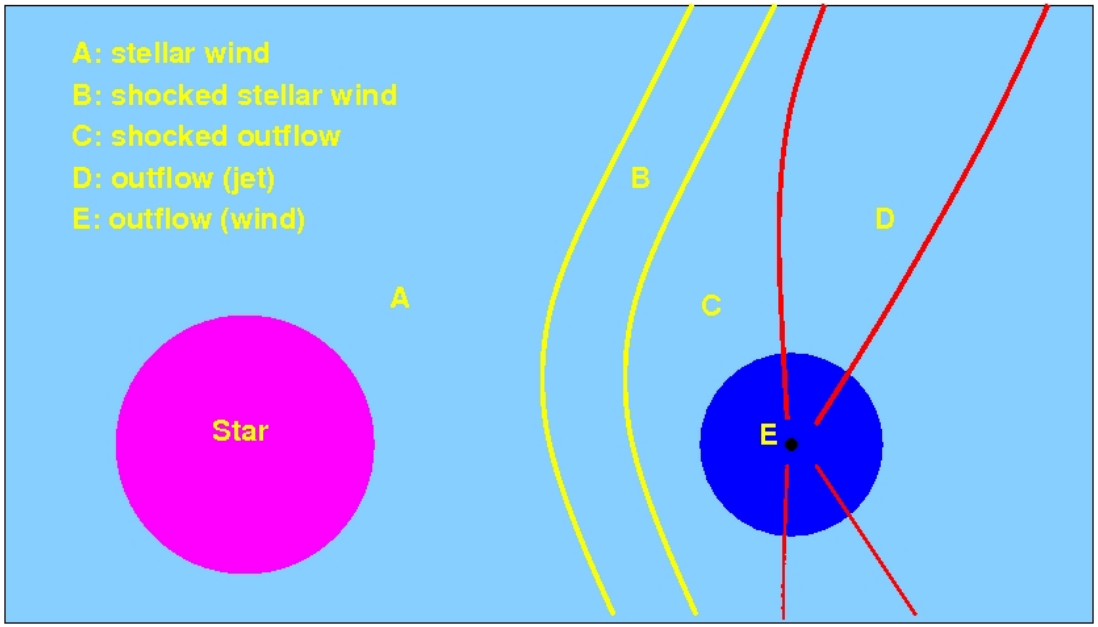
MQ and pulsar gamma-ray binaries

- **MQ on binary scales are seen at least in GeV, and share with pulsar gamma-ray binaries slow and rel. outflows, star photons and orbit.**
- But MQ shocks on those scales are more oblique, more adiabatic, more baryons, so: less efficient $e^{\pm}$accelerators and γ-ray emitters?



- On large scales both sources are similar. Non-MQ outflows are large-scale non-thermal emitters and should be baryon loaded.
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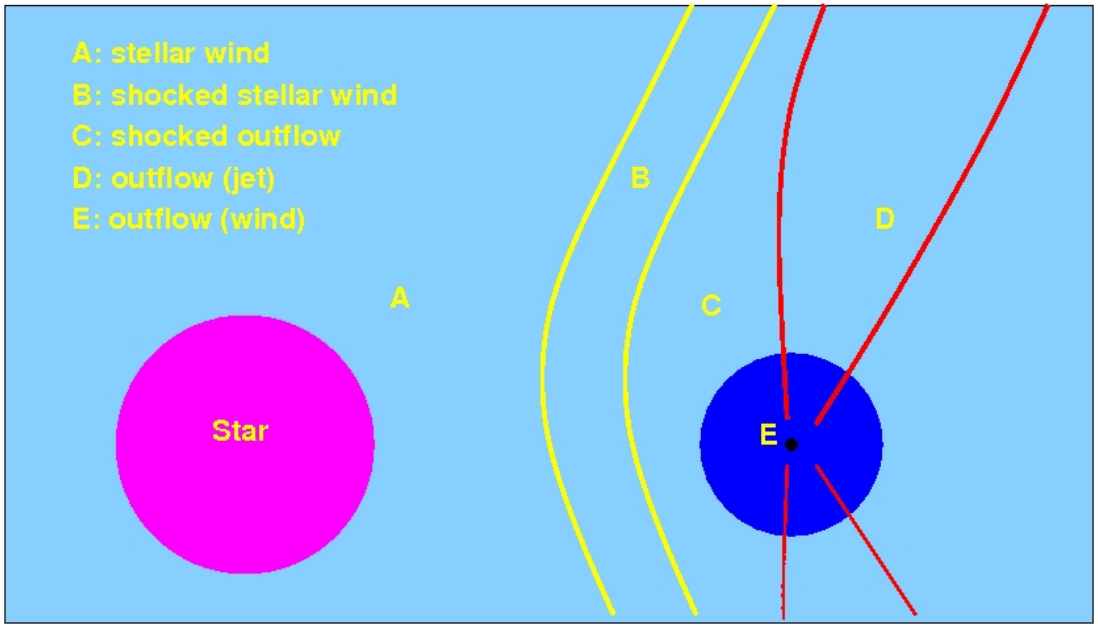

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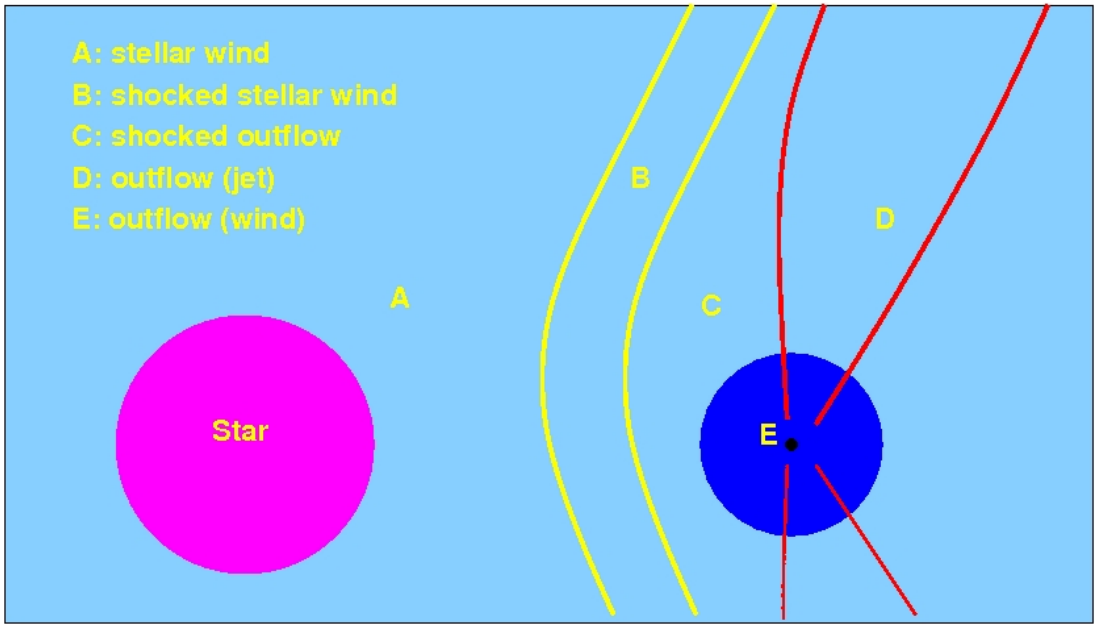

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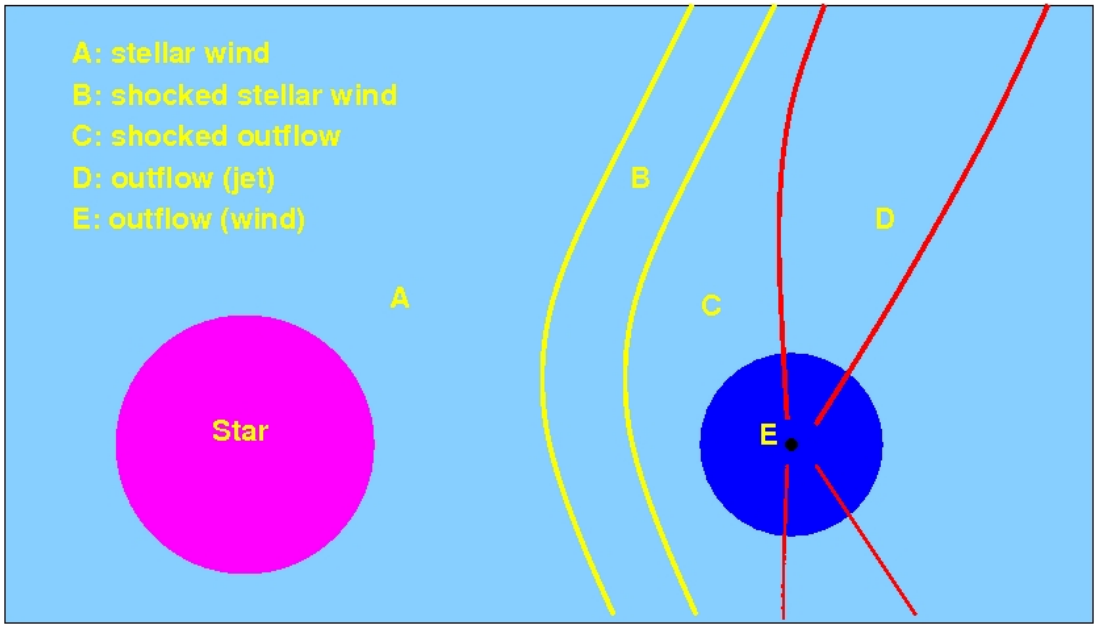

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