Modeling Cosmic-Ray Transport and Nonthermal Emission in the Jets of SS 433

A Spatially Dependent Approach

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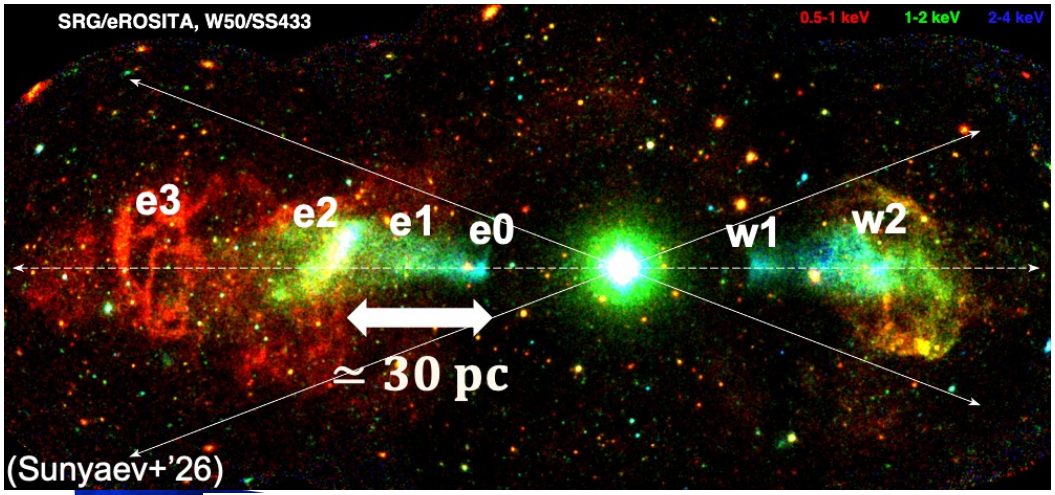
SS 433: A Jet-Driven PeVatron Candidate

- SS 433 launches mildly relativistic jets ($0.26c$)
  - Extended X-ray jets accompanied by TeV gamma rays
    (e.g., Abeysekara+'18; Safi-Harb+'22; H.E.S.S., '24; LHAASO, '25; Mac Intyre+'26)
  - LHAASO detects > 0.1 PeV gamma rays (LHAASO, '25)

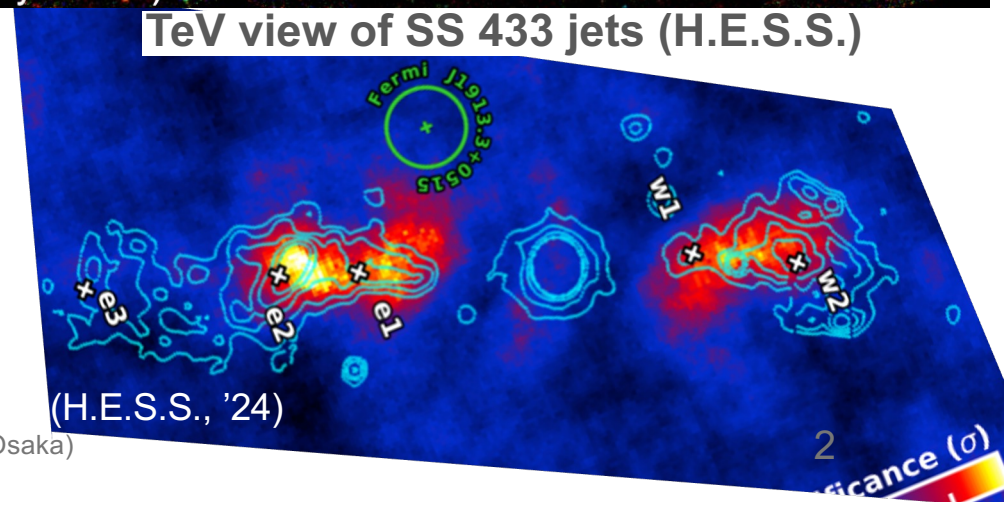
→ PeVatron candidate

- Multi-TeV electrons likely produce nonthermal emission from the jets
  (e.g., Sudoh+'20; Kimura+'20; H.E.S.S., '24)

X-ray view of SS 433 jets (eROSITA)



TeV view of SS 433 jets (H.E.S.S.)

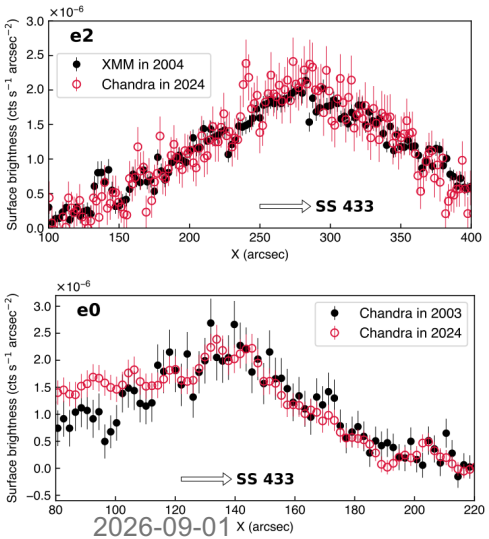


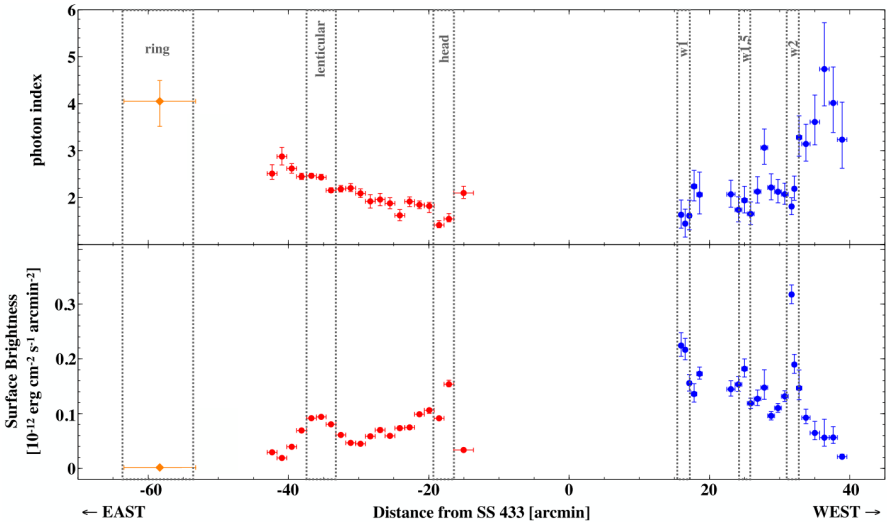
Advances from New Observations

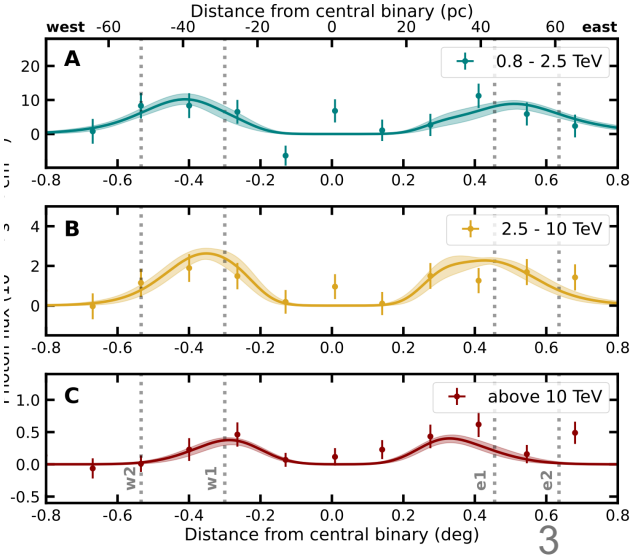
- Implication of spatially resolved observations:
  - CR accelerator → standing recollimation shocks
    - Proper motion measurement using 20-yr Chandra data (Tsuji+'25)
  - CR transport & cooling in the jets
    - X-ray profiles & TeV morphology (Kayama+'22, '25; Tong+'26; H.E.S.S., '24)

→ Explain these profiles, SED & morphology with spatially-dependent modeling

(beyond one-zone simplified transport models: Sudoh+'20, Kimura+'20)

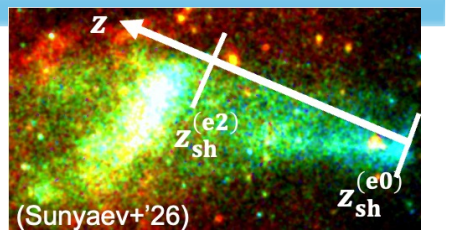




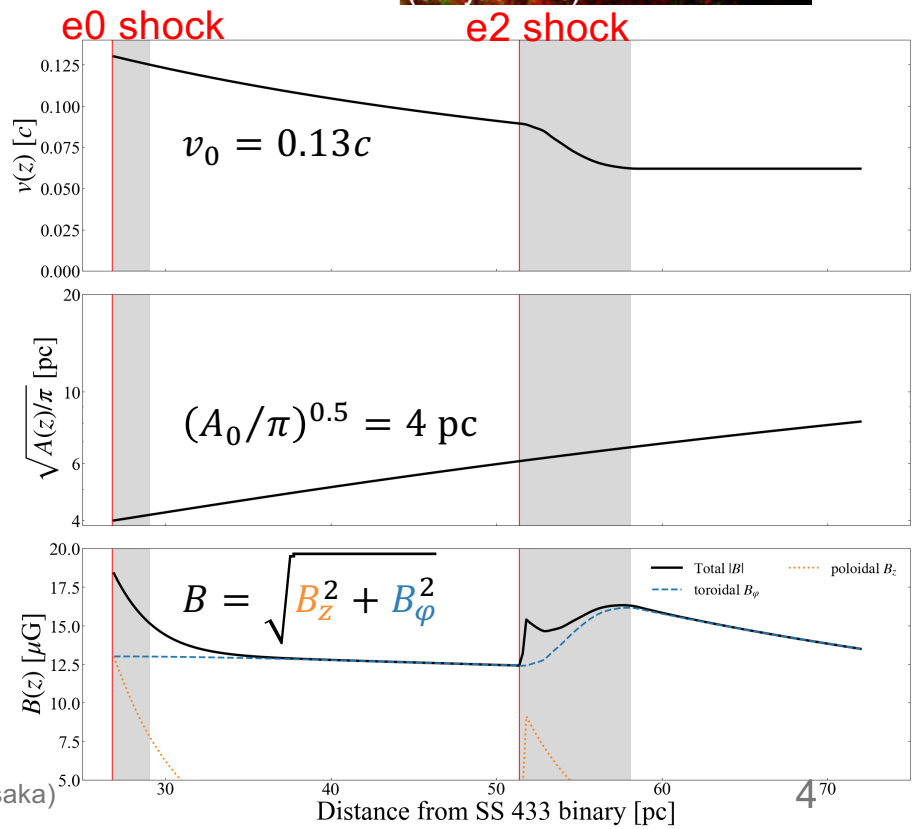


1D Steady-State CR Transport Model

$$\underbrace{\frac{1}{A(z)}\frac{\partial}{\partial z}[Av(z)\psi_e]}_{\text{Advection}} + \underbrace{\frac{\partial}{\partial p}\left[\dot{p}(z,p)\psi_e - \frac{p}{3}\frac{1}{A}\frac{\mathrm{d}(Av)}{\mathrm{d}z}\psi_e\right]}_{\text{Syn/IC + Adiabatic } (\rightarrow \mathrm{X}/\gamma)} = \underbrace{\dot{q}_{\mathrm{inj}}(z,p)}_{\text{Injection}}$$



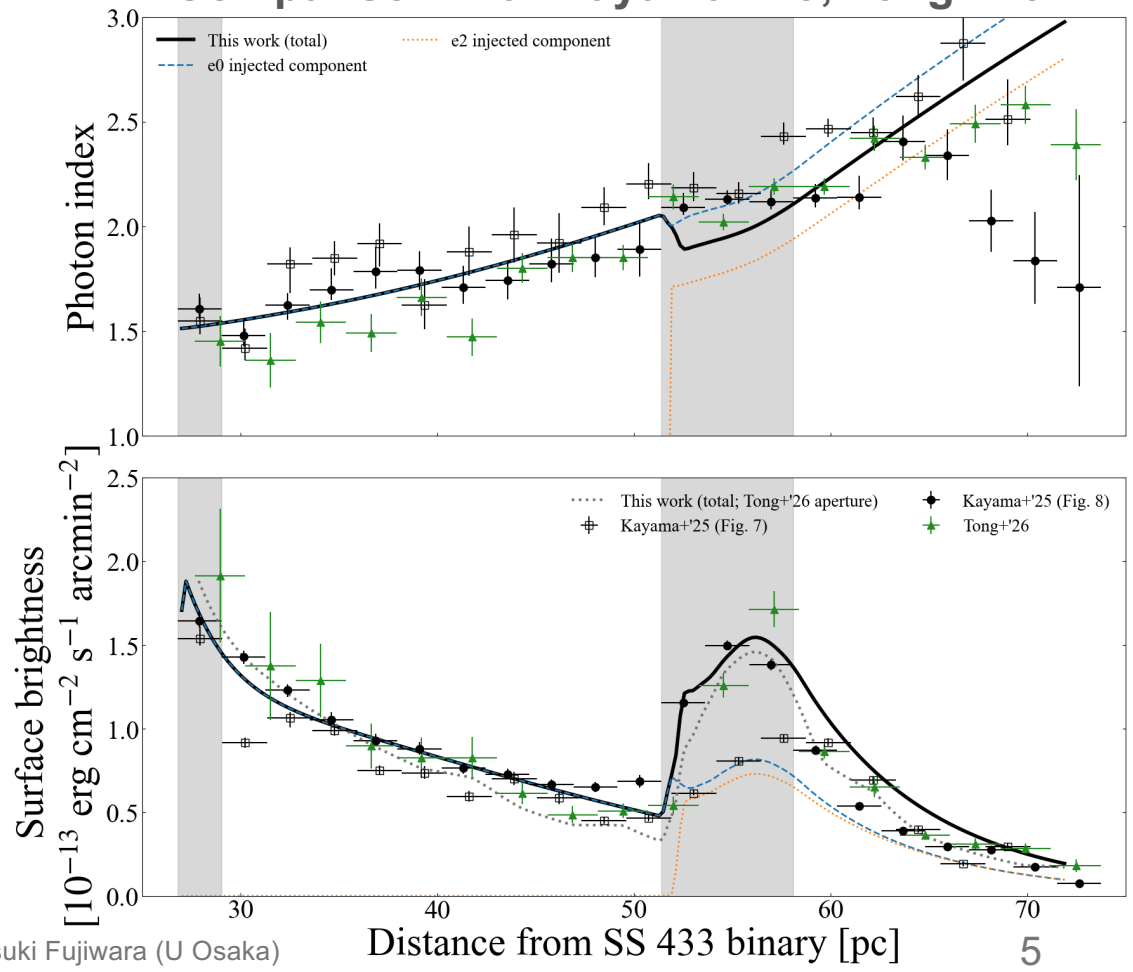
- Setup for the eastern jet:
  - Two e^- injection sites @ e0 & e2
    - $\dot{q}_{\mathrm{inj}} \propto \gamma_e^{-2} \exp\left[-(\gamma_e/\gamma_{e,\mathrm{max}})^2\right] \delta(z - z_{\mathrm{sh}})$
  - Decelerating conical jet
    - $v \propto [1 + (z/z_{\mathrm{e0sh}})]^{-1}$, $(z < z_{\mathrm{e2sh}})$
    - $A \propto [1 + (z/z_{\mathrm{e0sh}})^2]$
  - Poloidal @ e0 & e2 + Toroidal $B(z)$
    - $B_{z,\mathrm{e0}} = B_{\varphi,\mathrm{e0}} = 13$ μG, $B_{z,\mathrm{e2}} = 10$ μG
  - Radiation fields: CMB, ISRF, disk



X-ray Profiles (1–7 keV) along Eastern Jet

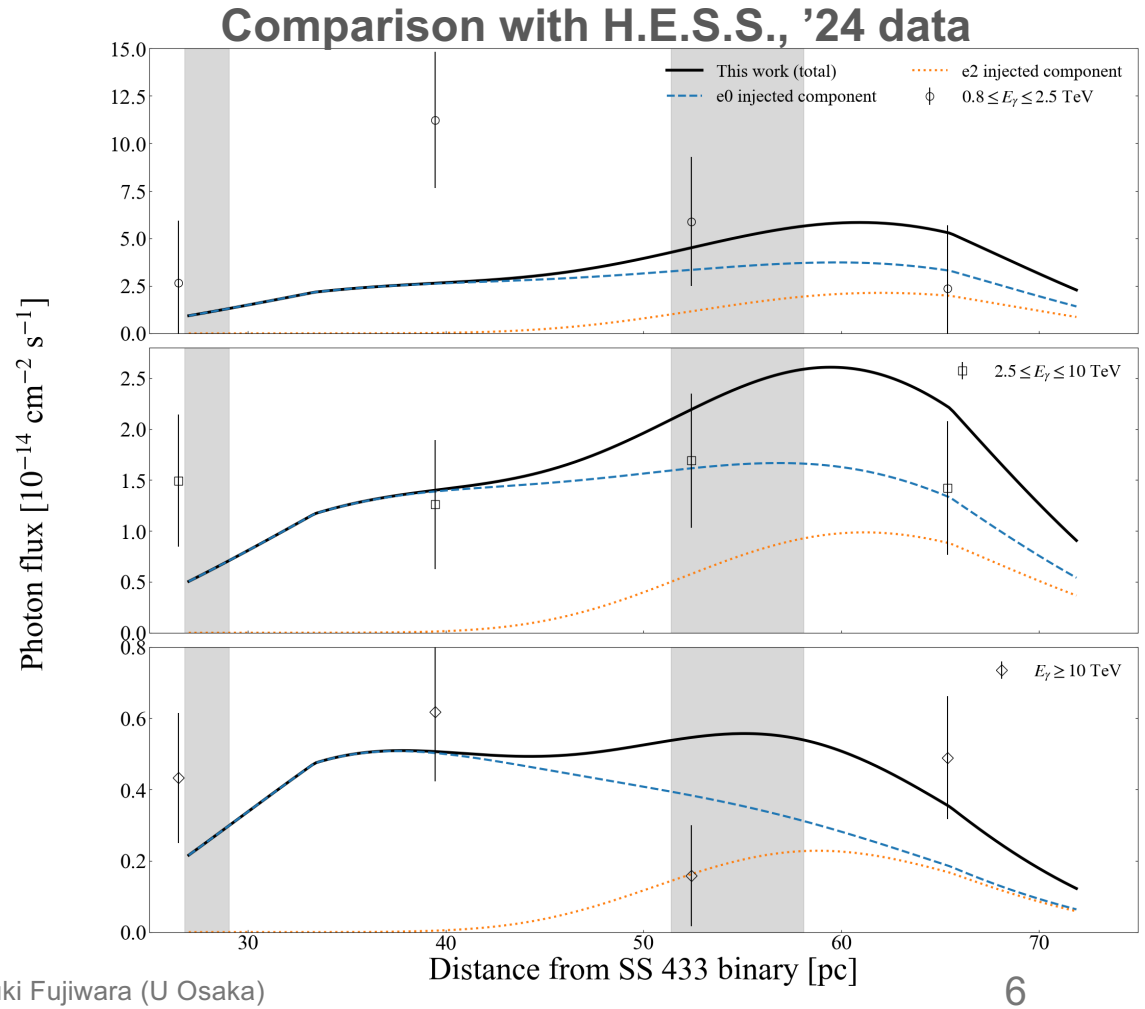
- Reproduces photon index Γ & surface brightness over ~27–65 pc
  - Observed Γ beyond ~65 pc harder than model → Data systematics? Thermal contamination?
- e0 injection alone cannot explain emission out to e2
  - Local process @ e2 region is required

Comparison with Kayama+'25; Tong+'26



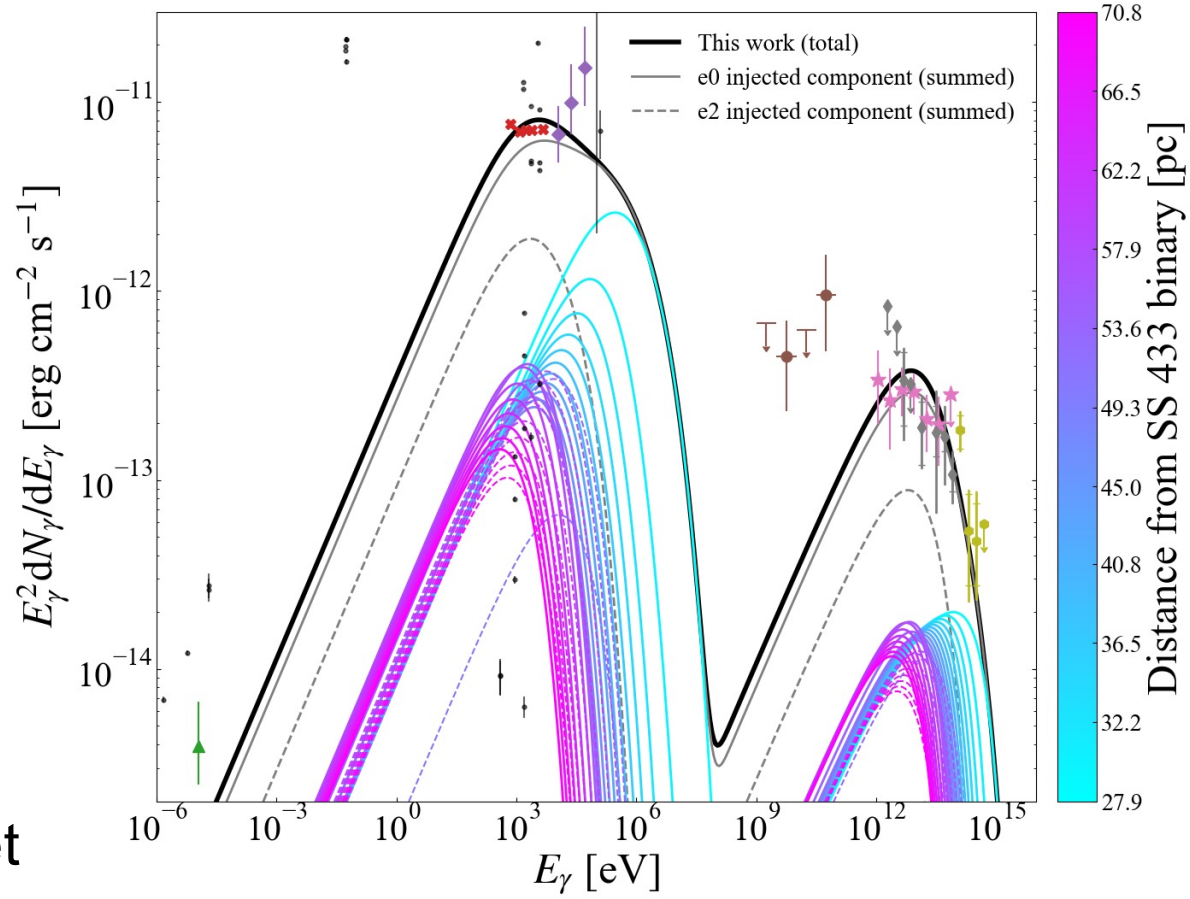
Gamma-Ray Profiles (TeV) along Eastern Jet

- Broadly reproduces energy-dependent TeV profile
  - Roughly consistent with H.E.S.S. morphology
- e2 injection enhances gamma-ray fluxes @ e2
- Two injection sites (e0+e2) picture remains consistent within uncertainties



Global SED of Eastern Jet

- TeV data (H.E.S.S. + LHAASO) reproduced near the Bohm limit
- GeV: exceeds our model prediction
  - Suggested as IC from the same e^- (Sun+'26)
    → Under investigation
- Total $L_e \approx 10^{-3} L_{\rm jet}$
  - 20× less than the previous model (Sudoh+'20)
  - Transport spreads one population along the jet

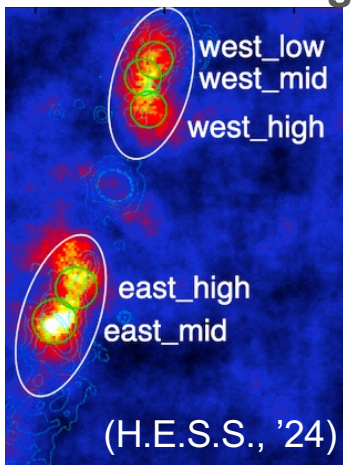


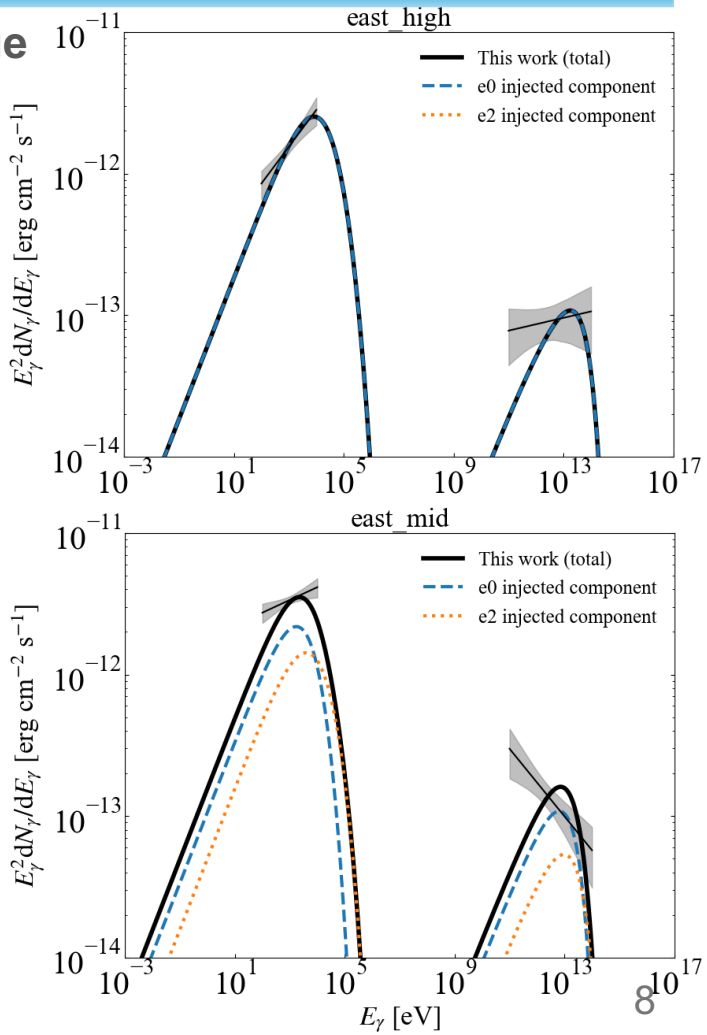
(Geldzahler+'80; Tong+'26; Safi-Harb & Petre, '99; Sun+'26; H.E.S.S., '24; LHAASO, '25)

Spatially Resolved SED of Eastern Jet

- Comparison with SEDs of H.E.S.S. circular regions @ energy-band centroids
  - east_high
    → >10 TeV, $r = 0.08^\circ$
  - east_mid (~e2)
    → 2.5–10 TeV, $r = 0.085^\circ$
- Simultaneously reproduces X-ray & TeV in both regions
  - Note: integrated over the same sky circles

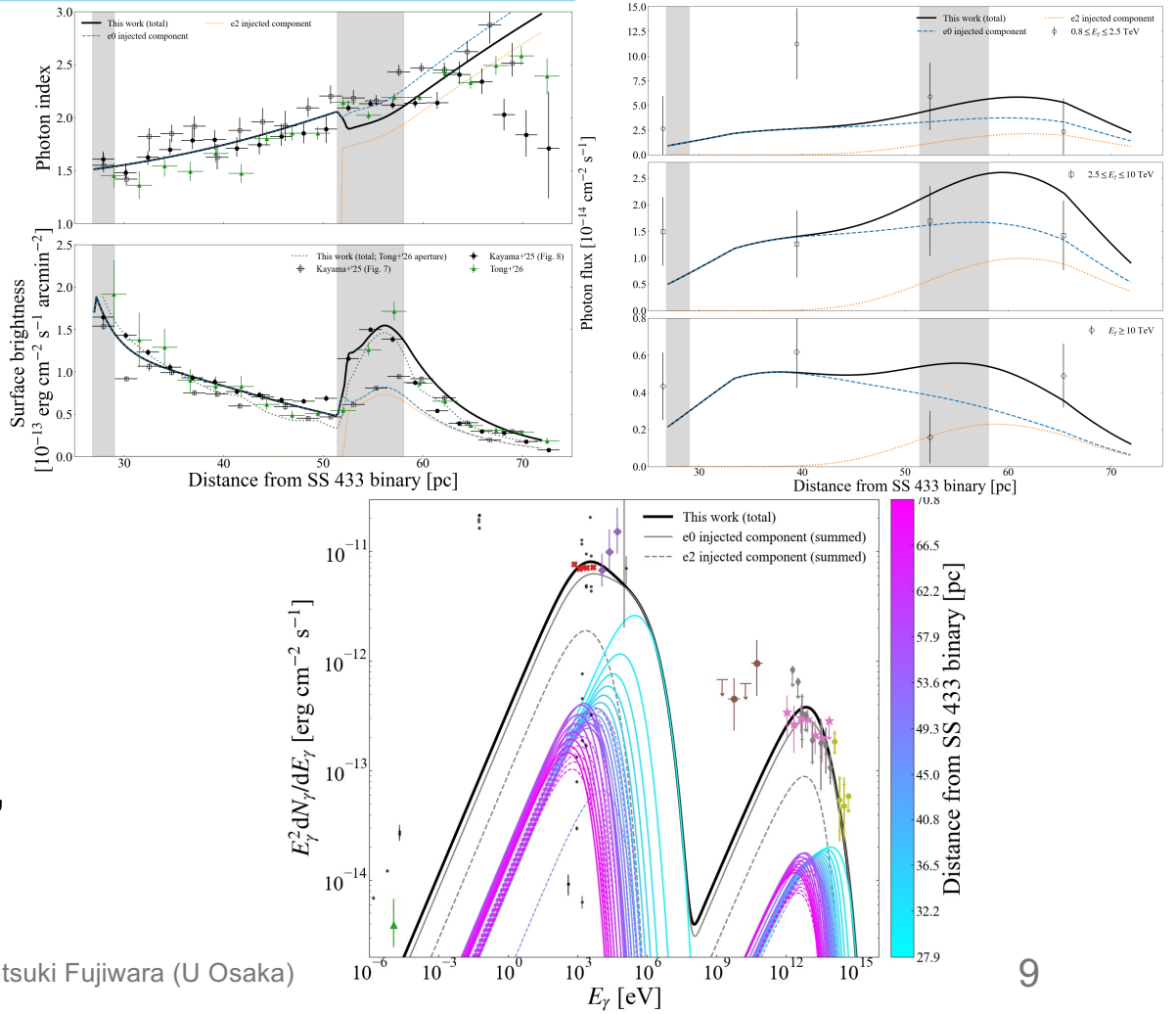
H.E.S.S. circle image





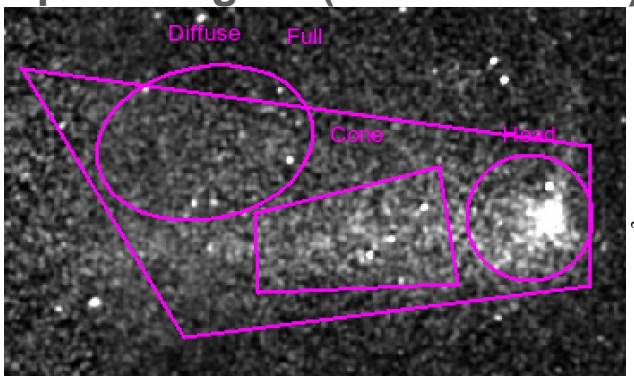
Summary

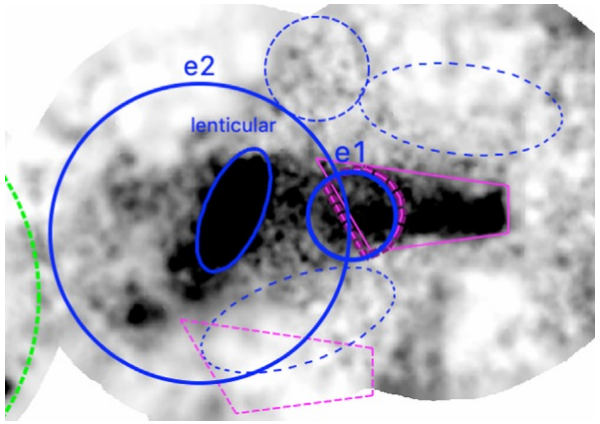
- SS 433 modeling enters the spatially resolved era
  - Simplified transport (Sudoh+'20) → 1D CR transport (Fujiwara+ in prep)
- X-ray & TeV profiles and morphology are reproduced simultaneously by a single solution
- Spatially-dependent approach is important for deeper understanding of jet-driven PeVatrons
- **Next**: western jet, cutoff shape, other microquasars



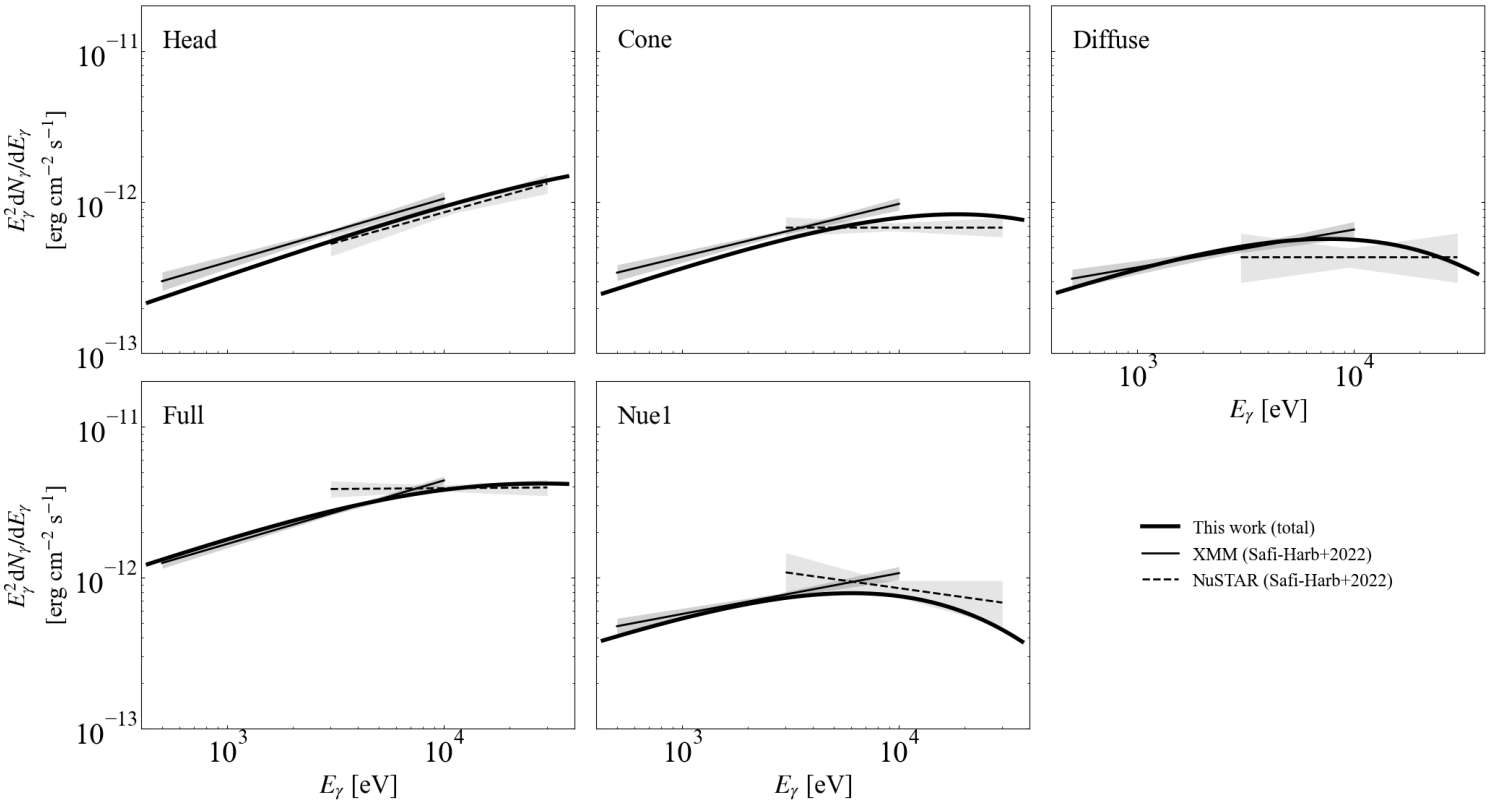
Comparison with Spatial X-ray SEDs

Spatial region (Safi-Harb+'22)



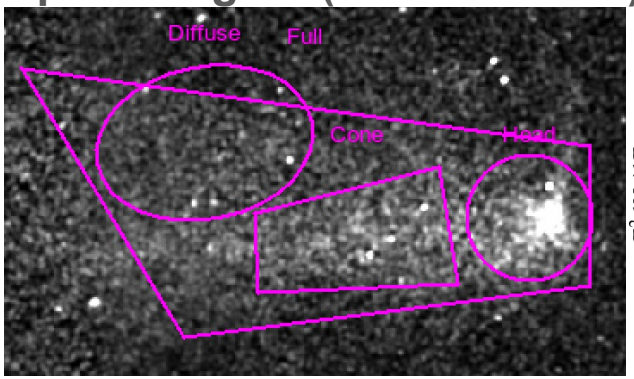


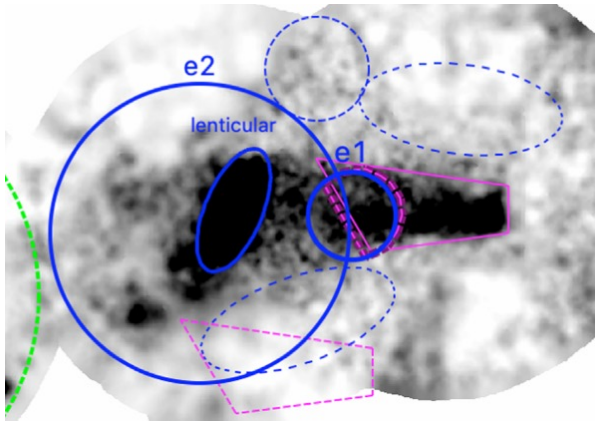
Comparison with joint XMM+NuSTAR data (Safi-Harb+'22)



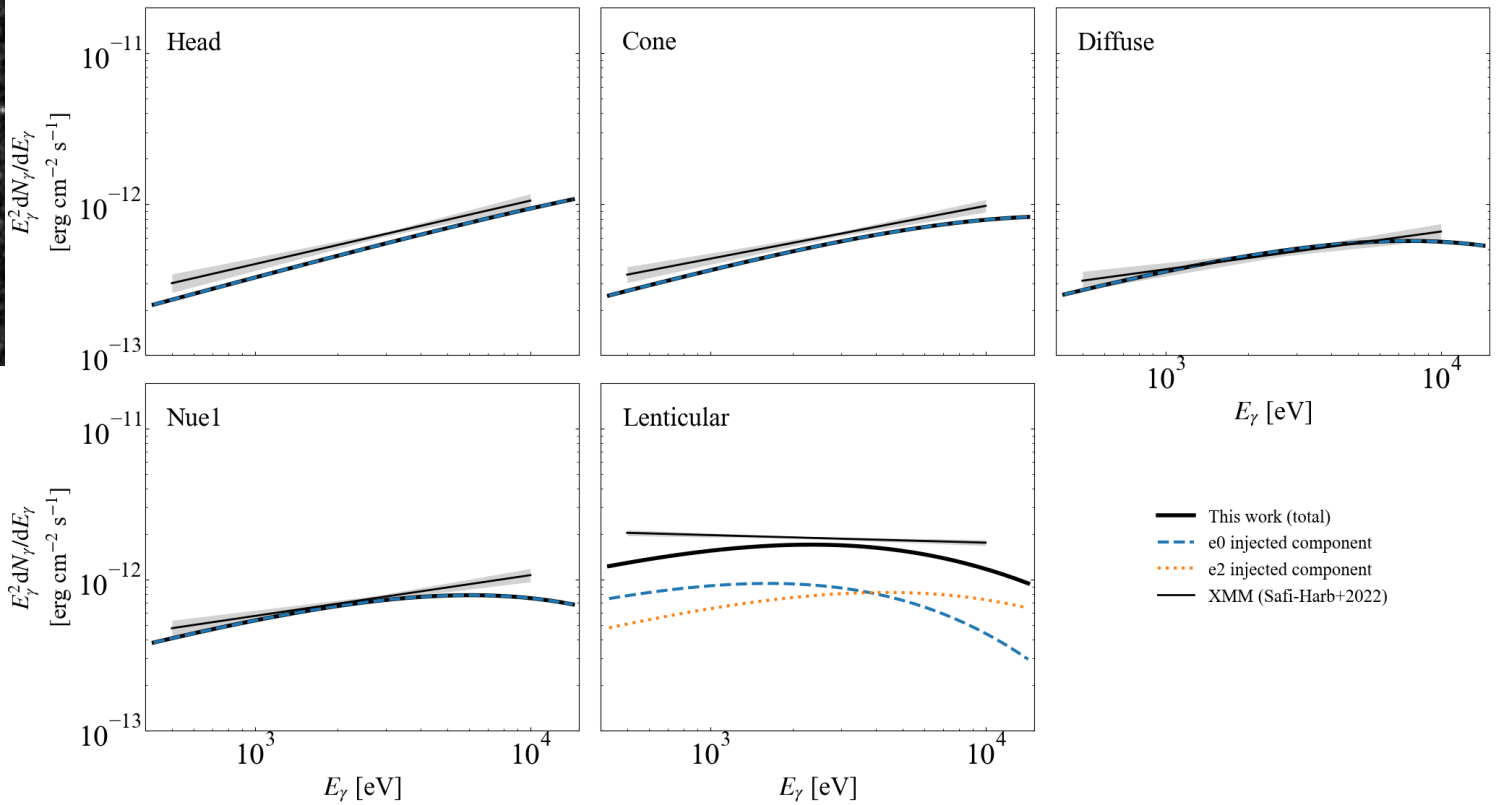
Comparison with Spatial X-ray SEDs

Spatial region (Safi-Harb+'22)





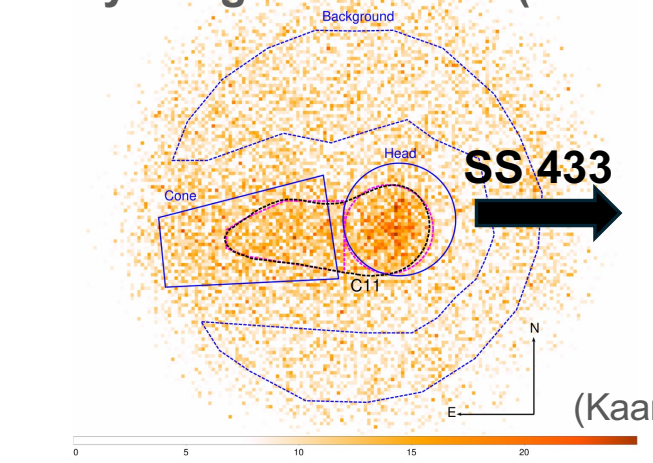
Comparison with XMM-only view data (Safi-Harb+'22)



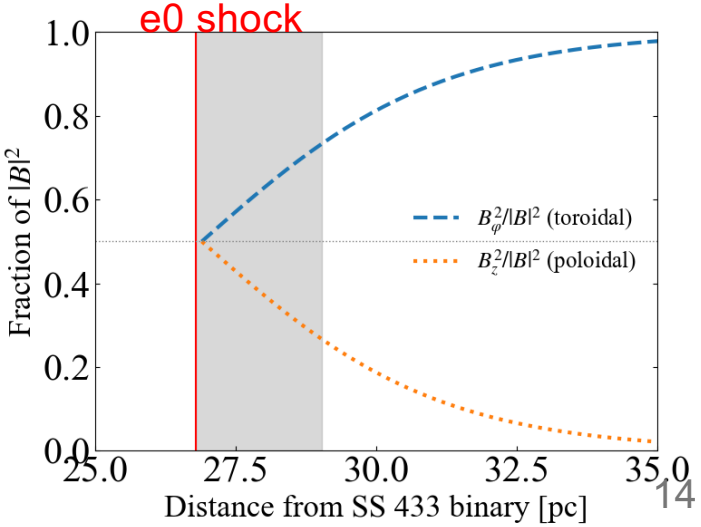
X-Ray Polarization of Eastern Jet (IXPE)

- X-ray polarization around e0 (Kaaret+'24):
  - Ordered B field parallel to the jet (poloidal) → efficient DSA?
  - $\gtrsim 50\%$ of magnetic energy in the uniform component
- Our model
  - $B_z = B_\varphi = 13\ \mu\mathrm{G}$ at e0 shock (50% poloidal)
  - B_z survives across the "Head"
  - Qualitatively consistent with IXPE
  - Further adjustment needed to quantitatively match PD

X-ray image from IXPE (2-5 keV)



(Kaaret+'24)



Hadronic Contribution in SS 433

- pp cooling time in the jet: $t_{pp} \approx 300\ \mathrm{Gyr}\ (n/10^{-4}\ \mathrm{cm}^{-3})^{-1}$
  (for n, see e.g. Safi-Harb & Petre, '99; Panferov, '17)
  - $n_{\mathrm{gas}} \sim 2L_{\mathrm{jet}}/(m_p v^3 A) \sim 10^{-4}\ \mathrm{cm}^{-3}\ (L_{\mathrm{jet}}/10^{39}\ \mathrm{erg\ s}^{-1})(v/0.13c)^{-3}(A/50\ \mathrm{pc}^2)^{-1}$
  - Protons accumulated over $t_{\mathrm{jet}} \sim \Delta z/v \sim 3\ \mathrm{kyr}$ → efficiency $\sim 10^{-8}$
  - $F_\gamma \sim 10^{-16}\ \mathrm{erg\ cm}^{-2}\ \mathrm{s}^{-1}\ (n/10^{-4}\ \mathrm{cm}^{-3})$ (cf., see also Sudoh+'20)

→ Low pp efficiency in the jets

  - Can be efficient only with localized dense gas
    (see also e.g. Kimura+'20; Sun+'26)

- LHAASO suggests that total emission (up to sub-PeV energies) may require more than a single leptonic component (LHAASO, '25)
- GeV emission: West excess and J1913+0512 favor hadronic (or bremsstrahlung) origin (Sun+'26)