Acceleration, radiation, and transport of relativistic particles in the jets of SS433

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Talk intention and content

Substitute Talk

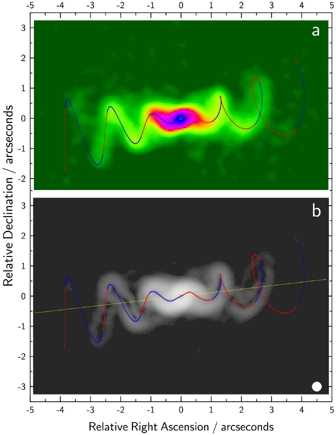
Unfortunately Samar had to cancel her talk, so although I cannot substitute her expertise, I will occupy the slot and will talk about SS 433. Namely about attempts to constrain the magnetic properties of its jets using X-ray observations with Chandra (western jet) and XMM-Newton (eastern jet).

The talk will be based on

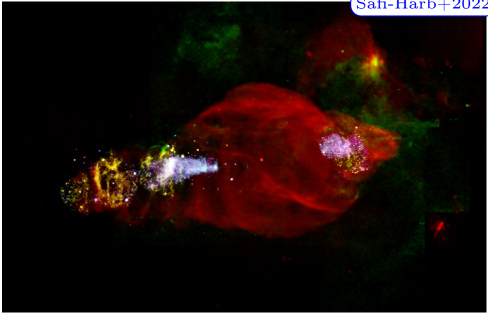
- Sudoh et al 2020 (the transport model)
- Kayama et 2022 (western jet)
- Kayama et 2025(?) (eastern jet, submitted to PASJ)

SS433@Radio

Blundell&Bowler2004

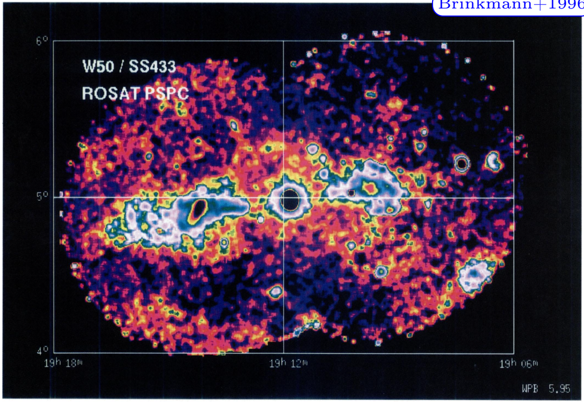


Safi-Harb+2022



- For a source distance of 5.5 kpc, corresponds to 3×10^{-2} pc
- The scale of the W50 and jets is $\sim$ 100 pc
- So we see a coherent structure that extends over four orders of magnitude

SS433@X-rays



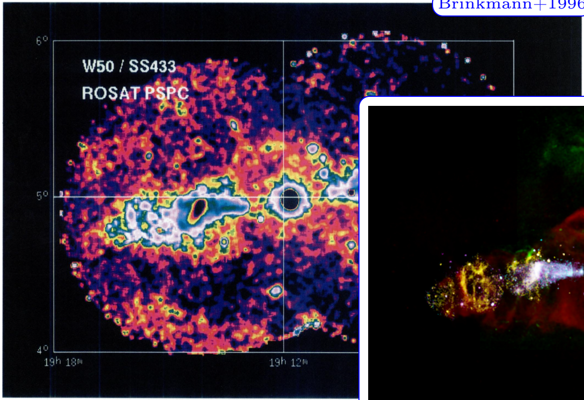
Brinkmann+1996

@5.5 kpc $1^\circ \rightarrow 100$ pc

- Although there is a clear coherence between the small and large scales the source doesn't look continuous
- Already with ROSAT data it was clear that there a kind of discontinuity between the center source and large scale structure

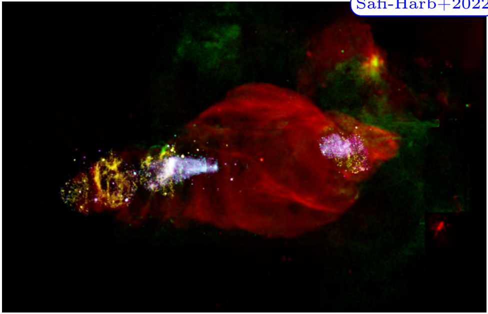
SS433@X-rays

Brinkmann+1996



@5.5 kpc 1° → 100 pc

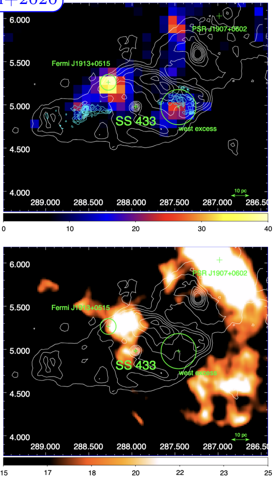
Safi-Harb+2022



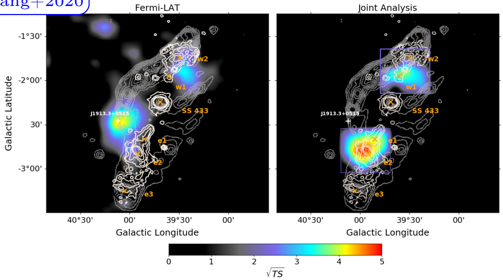
- ☞ Although there is a clear coherence between the small and large scales the source doesn't look continuous
- ☞ Already with ROSAT data it was clear that there a kind of discontinuity between the center source and large scale structure

SS433@GeV

Li+2020



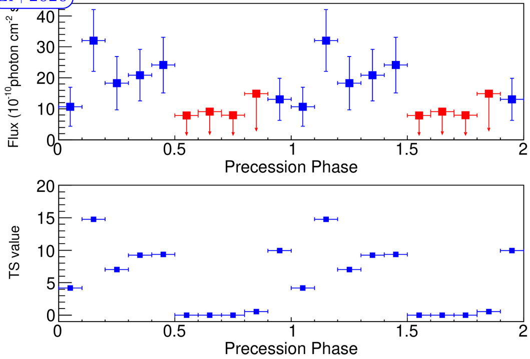
Fang+2020

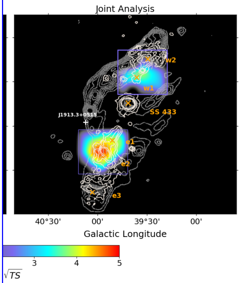


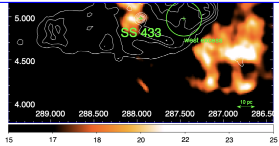
- ☞ Detection in the GeV band remains the most contradictory at the present moment
- ☞ Concensus still need to be established regarding the source morphology and potential variability

SS433@GeV

Li+2020







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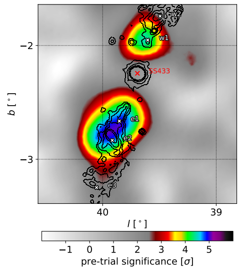
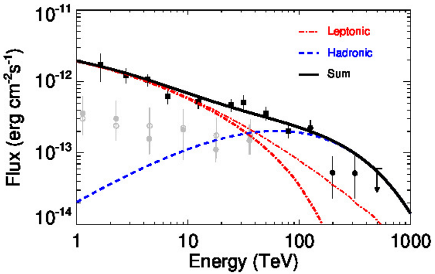
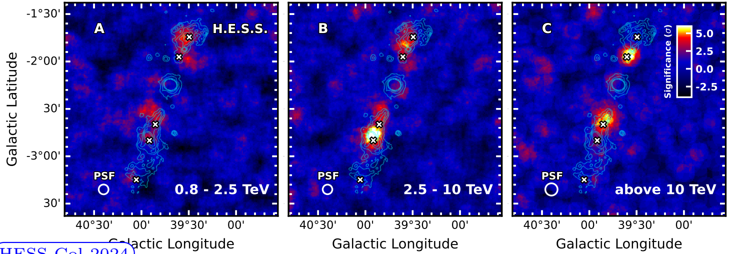
SS433@TeV

HAWC Col 2018



LHAASO Col 2024

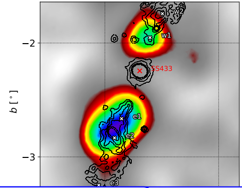




HESS Col 2024

SS433@TeV

HAWC Col 2018



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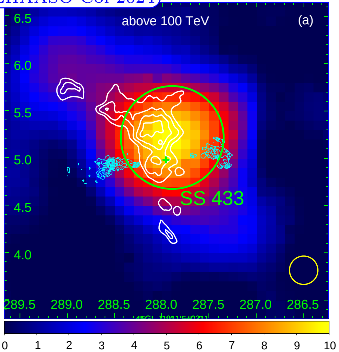

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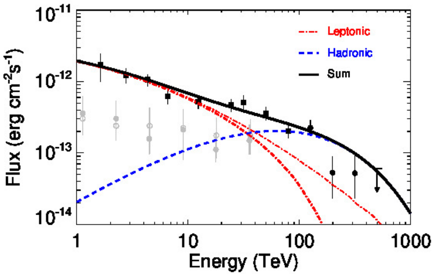

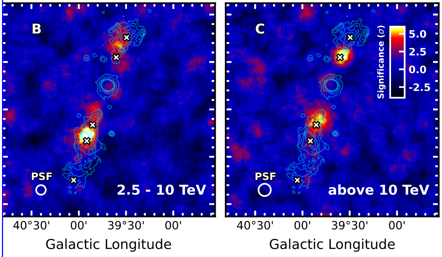

MWL view at SS433

What can we learn from a quick look at the data?

- ☞ Jet launched (likely) on the binary scale is an essential feature of the system [radio+X-ray]
- ☞ The jet has excavated its funnel to a significant distance, ~ 10 pc, until it eventually terminates / passes through a recollimation shock [X-ray+TeV]
- ☞ Electrons are accelerated to multi-TeV energies [TeV]
- ☞ The jet remains a coherent outflow in the downstream reagion for significant distance [X-ray+TeV(?)]
- ☞ Acceleration of protons may accompany the acceleration of leptons [PeV]

Physical scales for the problem

- Jet power is $L_j \approx 10^{39}\,\mathrm{erg\,s^{-1}}$
- Jet "termination radius" $Z_j \approx 10\,\mathrm{pc}$
- Jet "opening angle" $\theta_j \approx 10^\circ$
- Jet radius $R_j \approx 1.5\,\mathrm{pc}$
- Jet precession angle $\theta_p \approx 20^\circ$

- Jet ram pressure

$$P \sim \frac{L}{\pi R_j^2 c} \sim 300\,\mathrm{eVcm^{-3}}$$

- Equivalent magnetic field strength

$$B \sim 100\,\mu\mathrm{G}$$

- Photon fields: multi-temperature CMBR+FIR+NIR

$$w_{ph} \sim 5\,\mathrm{eVcm^{-3}}$$

- Jet mass-loss rate

$$\dot{M} \approx 10^{-6} M_\odot\,\mathrm{yr^{-1}}$$

- Jet initial speed $v_0 \approx 0.26c$
- Typical density $\rho \sim 10^{-4}\,\mathrm{cm^{-3}}$
- Sound speed $v_s \sim 10^9\,\mathrm{cm\,s^{-1}}$

- Synchrotron cooling time

$$t_{syn} \approx 10^5\,\mathrm{yr}\left(\frac{B}{10\,\mu\mathrm{G}}\right)^{-2}\left(\frac{E}{1\,\mathrm{TeV}}\right)^{-1}$$

- X-ray typical energy (for 10keV in 10µG field): 100TeV
- TeV typical energy (for 10TeV photons from T = 100K photon field): 25TeV

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$\approx 0.26c$

$10^{-4}\,\mathrm{cm^{-3}}$

$0^{9}\,\mathrm{cm\,s^{-1}}$

- X-ray and TeV data indicates the presence of 100 TeV electrons in the jet
- Synchrotron cooling distance for these electrons is

$$l_{syn} \approx 20\,\mathrm{pc}\left(\frac{B}{10\,\mu G}\right)^{-2}\left(\frac{E}{100\,\mathrm{TeV}}\right)^{-1}\left(\frac{v_{ad}}{0.07c}\right)$$

- Thus particle transport plays important role in the formation of the high-energy emission in the jest of SS 433

- Jet ra

P

- Equiva

$$B \sim 100\,\mu G$$

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$$w_{ph} \sim 5\,\mathrm{eVcm^{-3}}$$

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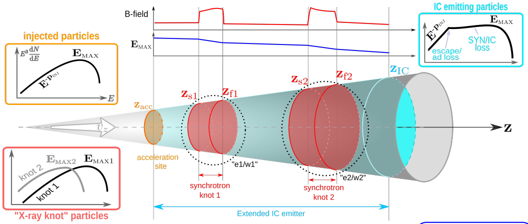
- ☞ One needs to assume particle accelerator(s), their spectra and locations
- ☞ One needs to adopt (or calculate) field of the velocities
- ☞ One needs to adopt (or calculation) the strength of magnetic field
- ☞ One needs to account for adiabatic cooling (depends on the model for the speed)
- ☞ One needs to account for IC losses (external Compton)



Sudoh+2020

$$\Gamma\left(\frac{\partial}{\partial t}+v_z\frac{\partial}{\partial z}\right)n(\gamma,t,z)$$

$$+\frac{\partial}{\partial\gamma}[\dot\gamma_{cool}(\gamma,t,z)n(\gamma,t,z)]=\dot q_{inj}(\gamma,t,z),$$

$$\dot\gamma=\dot\gamma_{syn}+\dot\gamma_{ad}+\dot\gamma_{ic}$$

For injection the simplest assumption is a δ-function approximation:

$$q_{inj}\propto E^{-\alpha}\theta(t)\delta(z-z_{acc})$$

Describing the particle transport

- One needs to a
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calculate) field
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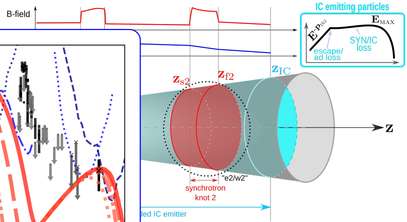
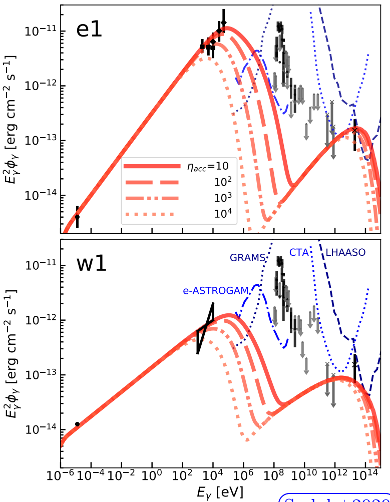


Sudoh+2020



Sudoh+2020

$) \, n(\gamma, t, z)$

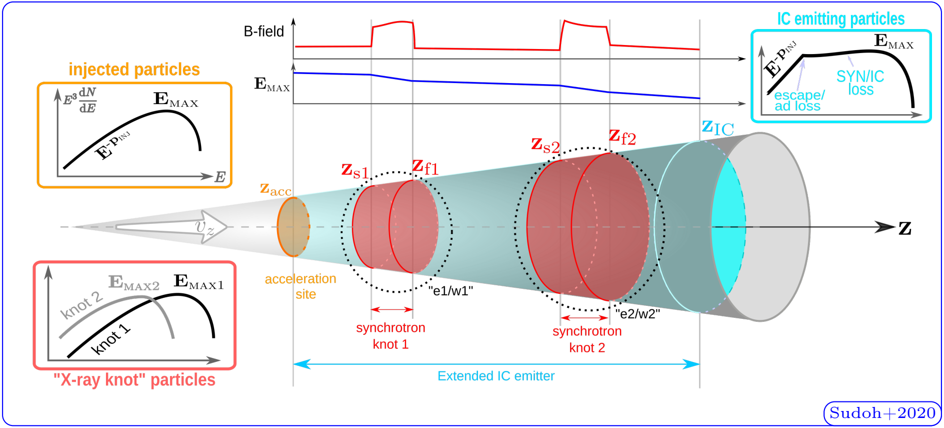
$, z)] = \dot{q}_{inj}(\gamma, t, z),$

$\gamma_{ad} + \dot{\gamma}_{ic}$

st assumption is a δ-

$q_{inj} \propto E^{-\alpha}\theta(t)\delta(z - z_{acc})$

The inner structure of the jet



X-ray typical energy (for 10keV in 10μG field): 100TeV

TeV typical energy (for 10TeV photons from T = 100K photon field): 25TeV

Studying the structure of the jet

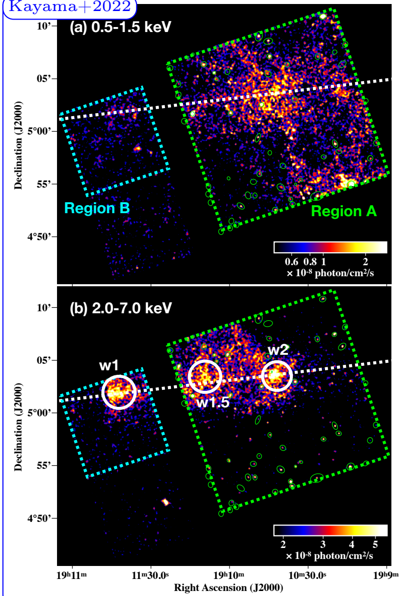
How to constrain the structure of the jet in SS 433?

- ☞ Emission detected in the X-ray band is likely generated by higher-energy electrons than 10TeV gamma-ray emission
- ☞ X-ray telescopes have much better angular resolution
- ☞ There are data spanning over several decades, which allows one to study the evolution of fine features in the jet (in particular Naomi Tsuji works on that topic)

Thus, it seems that for the modeling of the particle transport in the jets of SS 433 one needs primarily aim at reproducing the X-ray data

Study of the west jet

Kayama+2022



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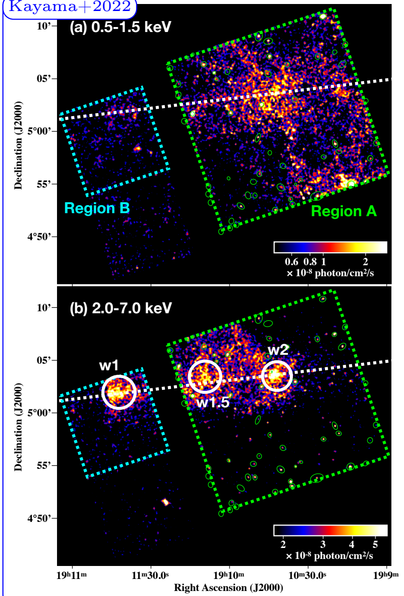

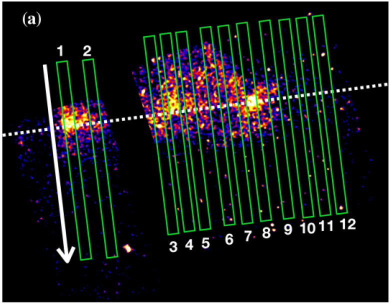

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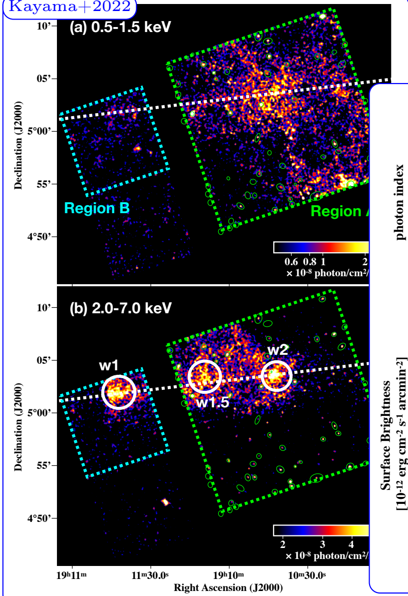
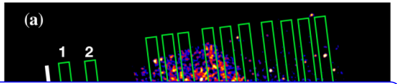
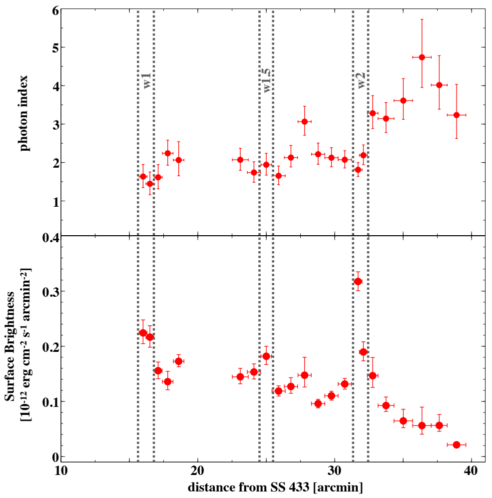
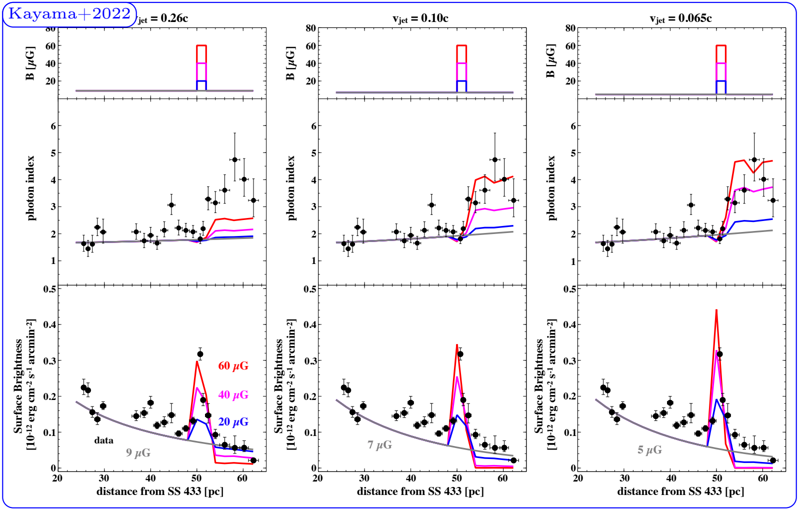




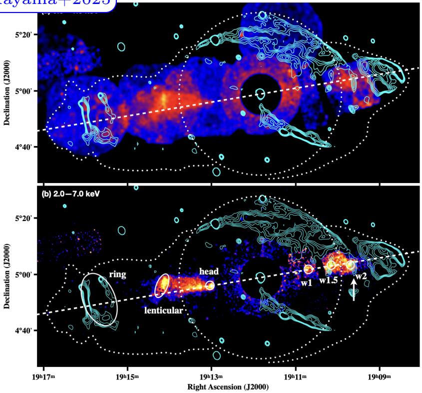


Magnetic Field in the West Jet



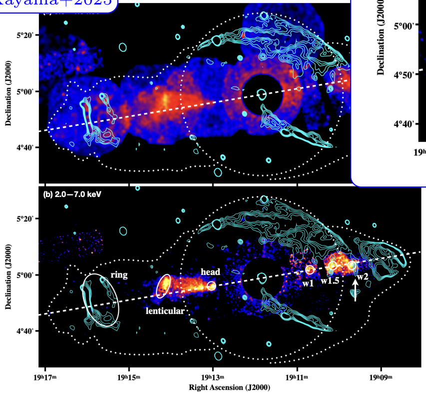
Study of the east jet

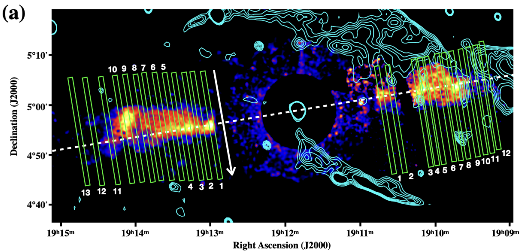
Kayama+2025



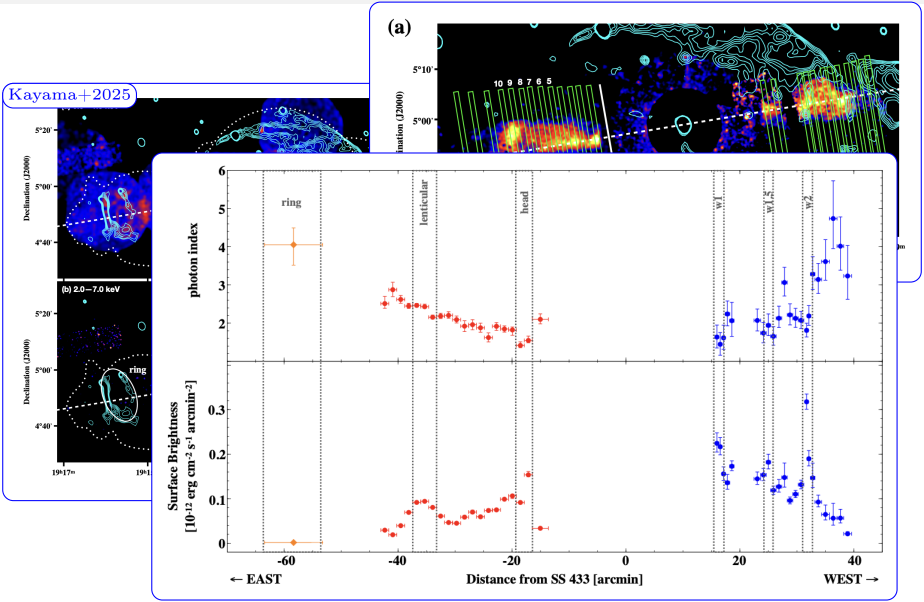
Study of the east jet

Kayama+2025



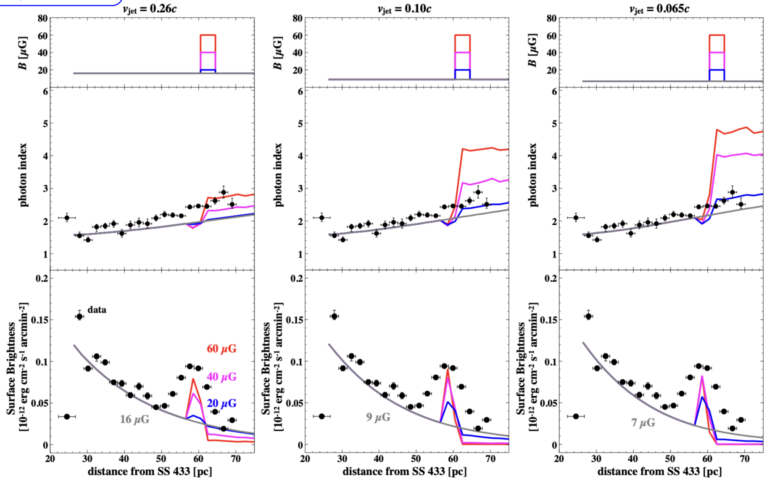


Study of the east jet



Magnetic Field in the West Jet

Kayama+2025



Summary

- Estimates for the physical conditions in the jets of SS 433 suggest that its X-ray emission is generated by ~ 100TeV electrons
- The inferred cooling length for multi-TeV electron is comparable to the scale of the jet, thus one need to use a cooling / transport model for particles in the jet
- X-ray emission detected from the jets is likely generated by higher-energy (or at least comparable) electrons than the TeV emission detected from the jets
- X-ray instruments feature significantly better angular resolution, larger set or archival data
- Thus transport models that aim primarily on explaining the X-ray data seem to have a larger potential
- Kayama+2022 adopted model by Sudoh+(2020) to study the distribution of X-ray emission from the Eastern jet of SS 433 and found acceptable agreement provided that magnetic field in w2 is noticeably amplified
- Kayama+2025 used a similar approach to study the Eastern jet, however it appeared that the data cannot be explained by models used earlier
- In particular, the emission from the lenticular knot cannot be explained by enhancement of the magnetic field and likely requires particle (re)acceleration