Probing Microquasar Jet Physics with X-ray Polarization

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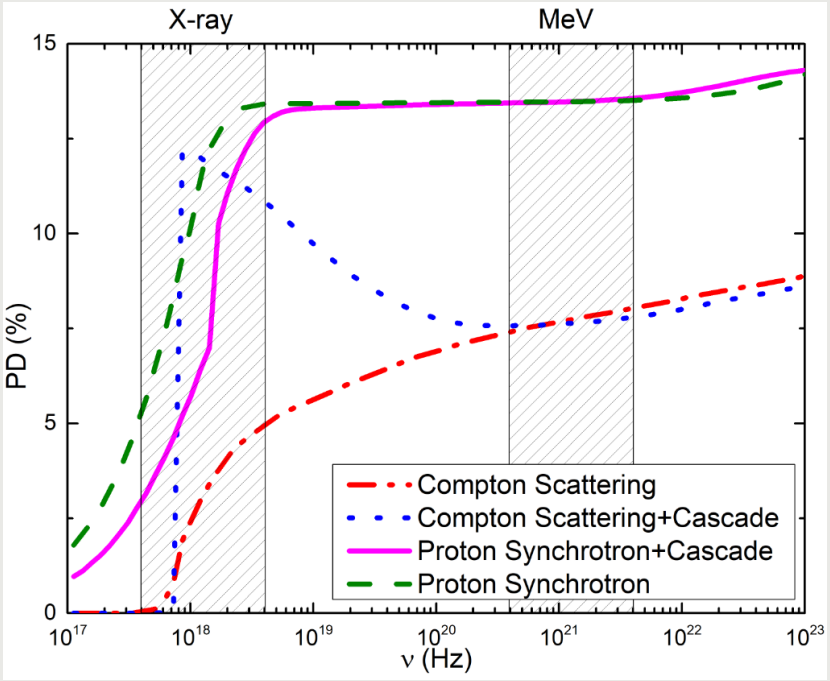
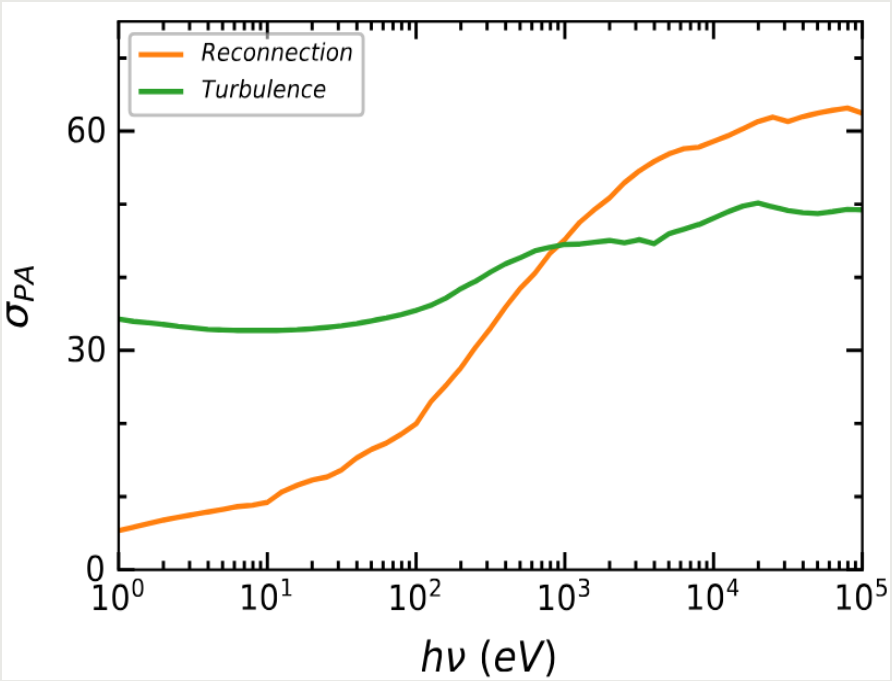
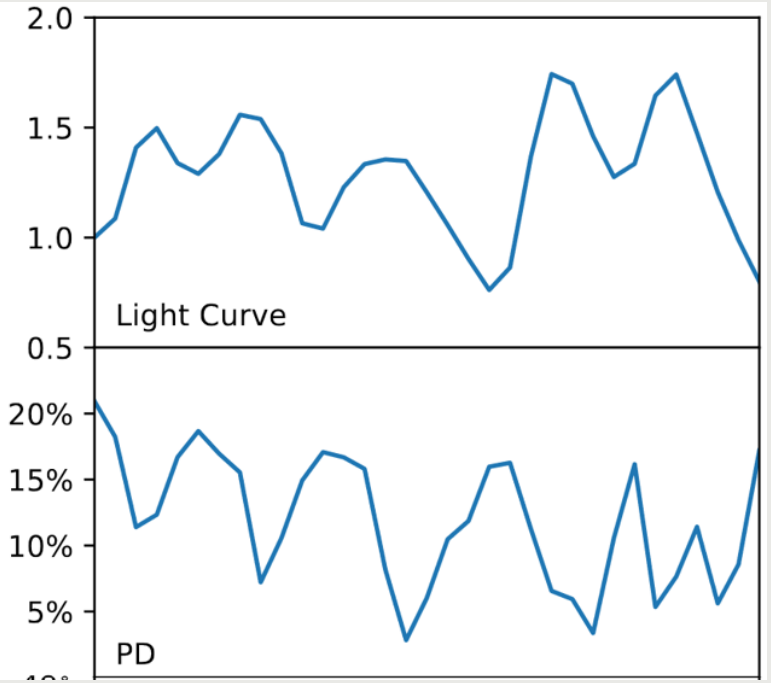
Polarimetry is Essential for Plasma and Particle Dynamics!



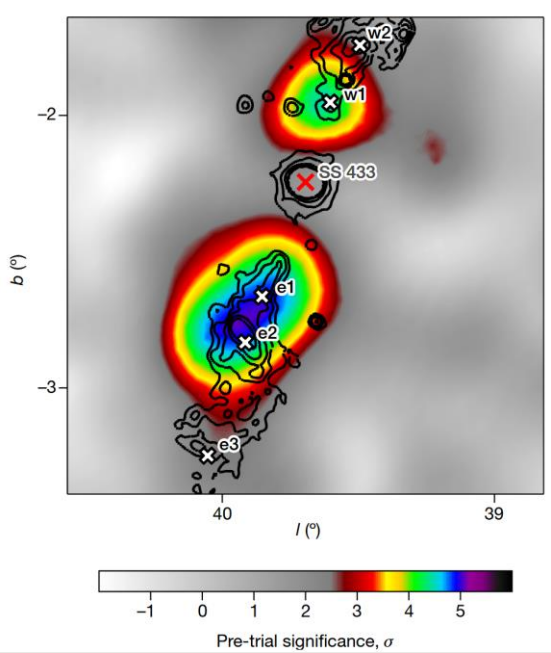


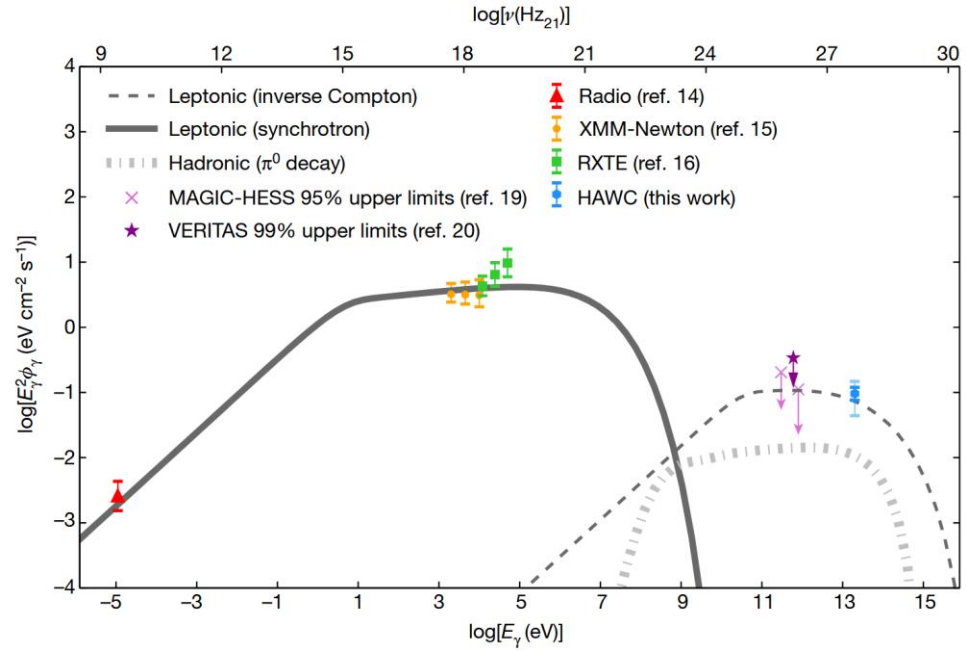


- High-energy polarization can be an alternative proof for hadronic signatures.
- Polarization can distinguish particle acceleration mechanisms.
- Polarization can probe plasma dynamics.

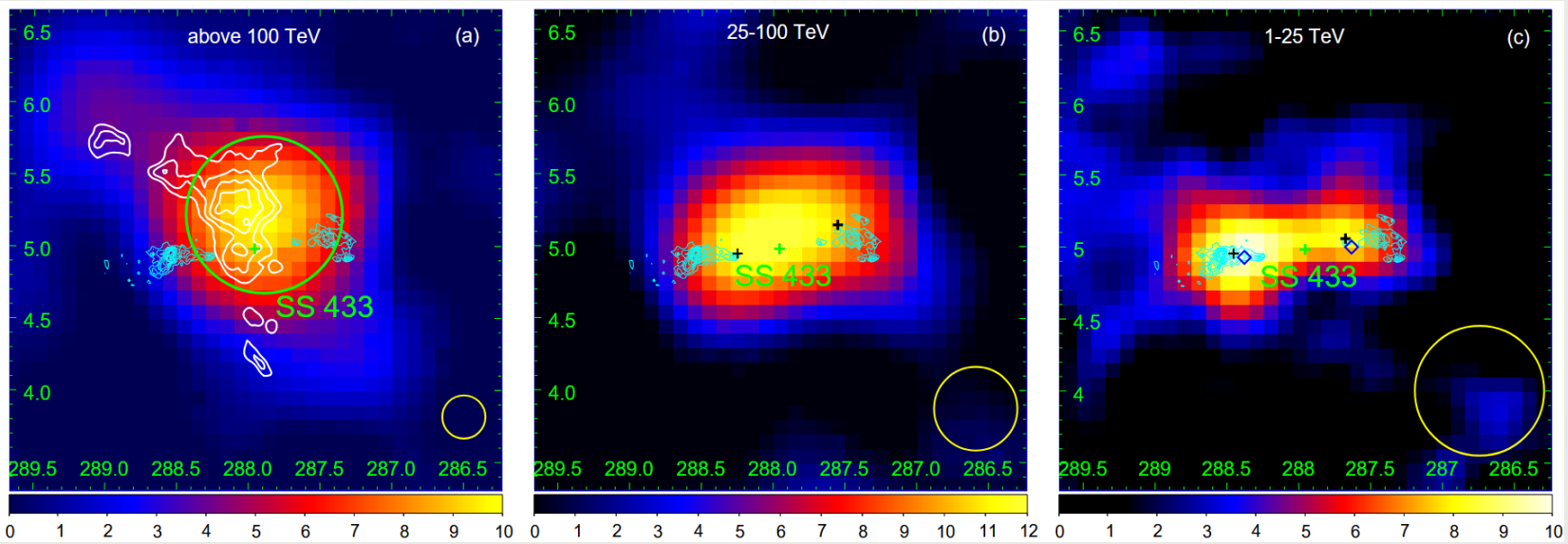
And many more applications!

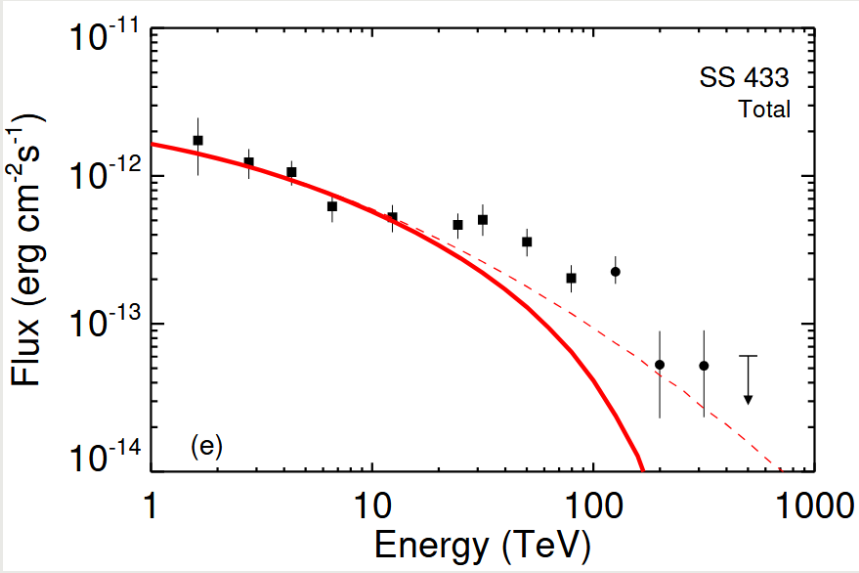
SS 433 Spectrum and Emission Map



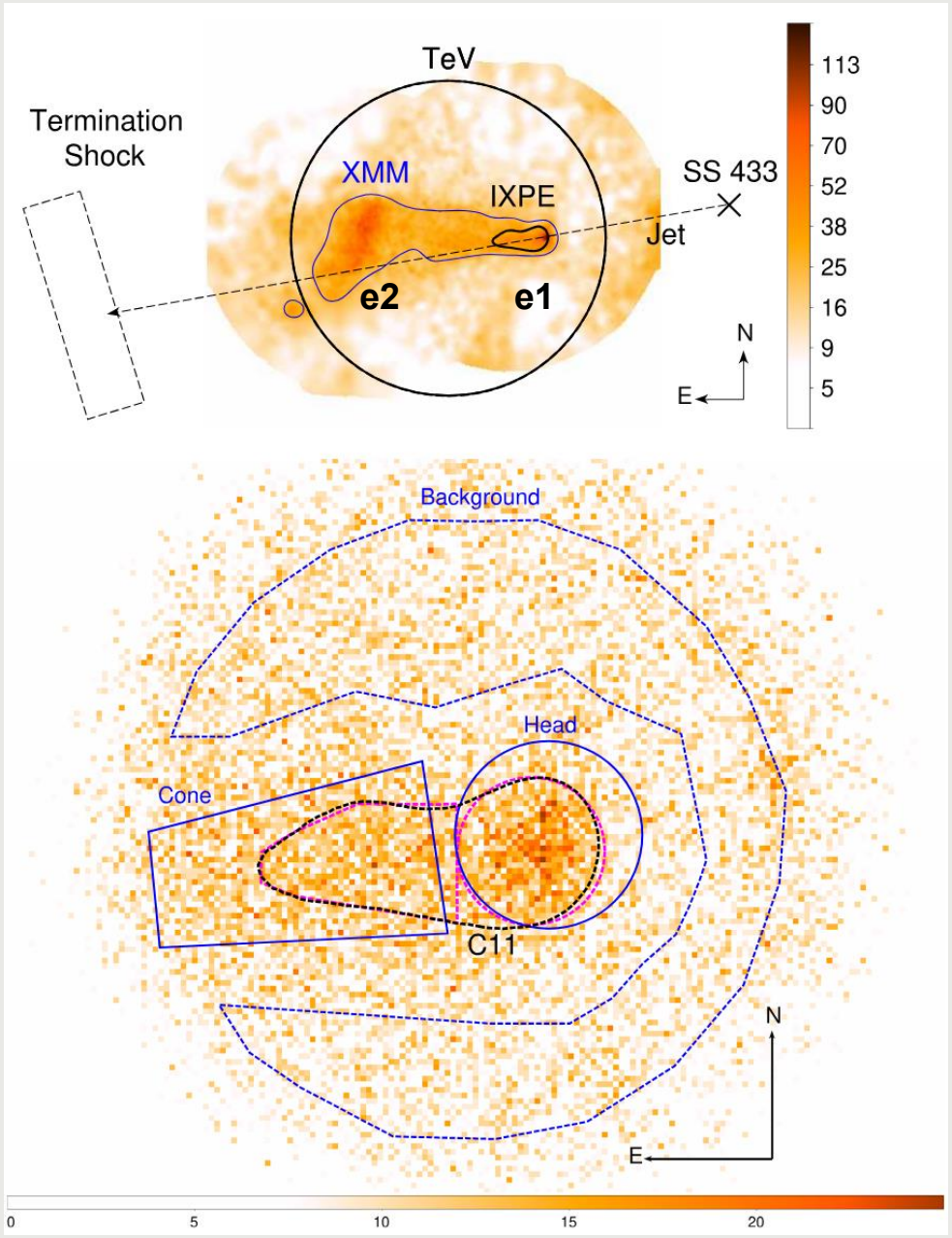


- Emission up to <~100 TeV
- At least some >TeV emission comes from the jet/lobe
- Potential PeVatron accelerator

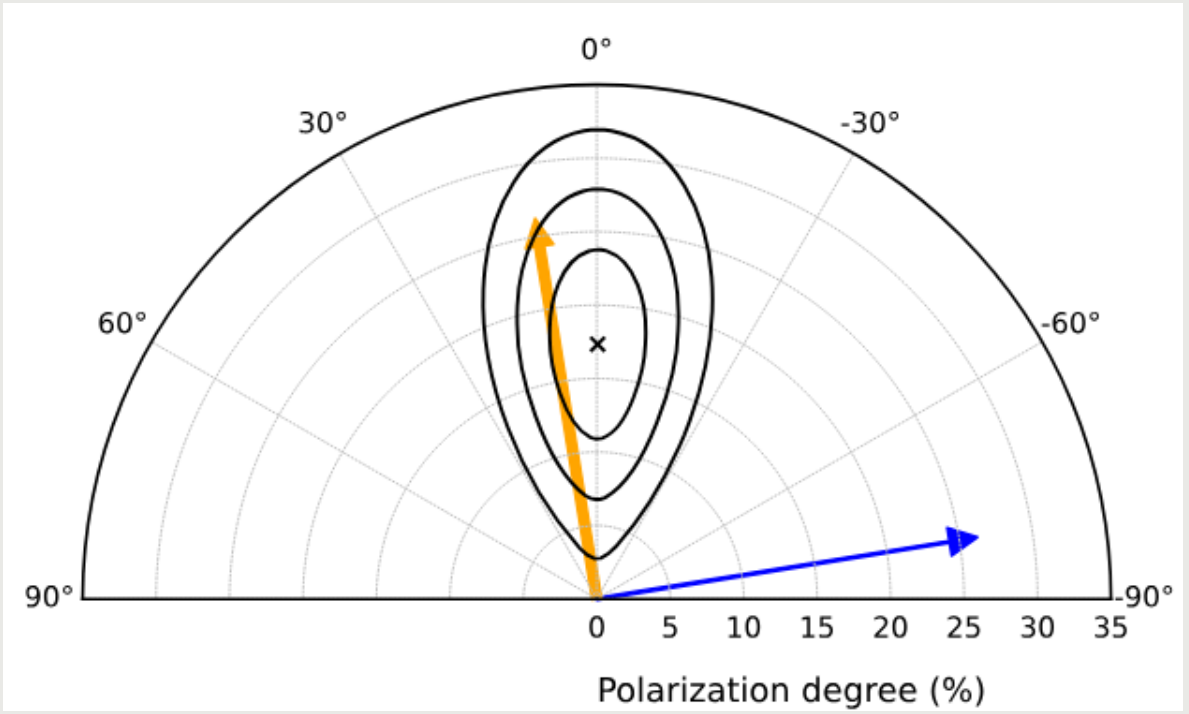




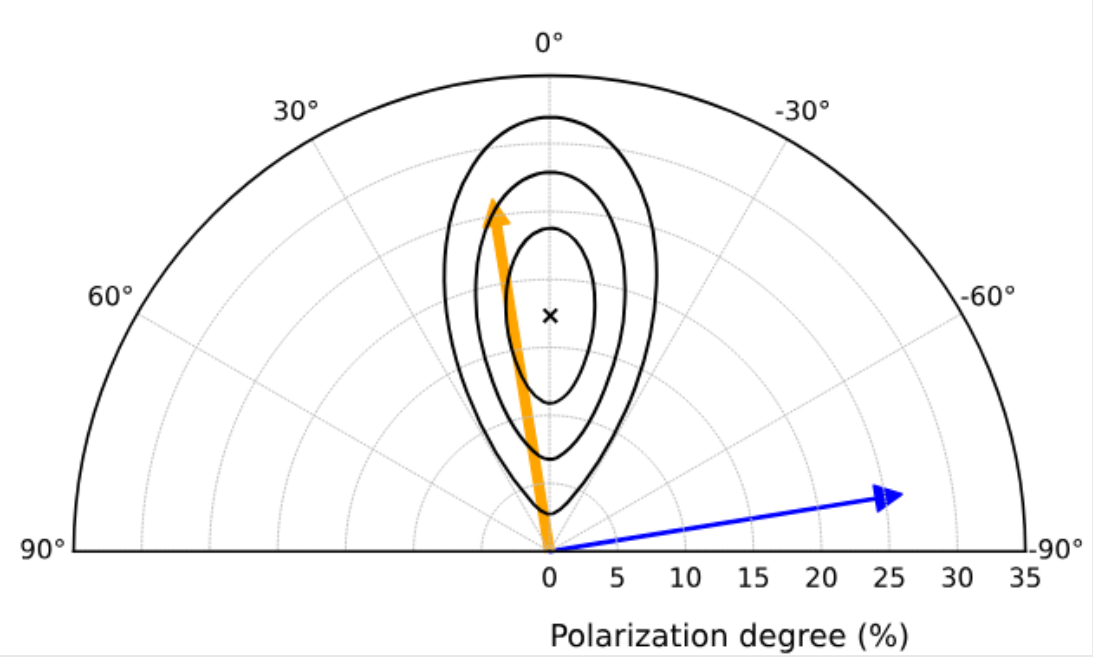
SS 433 X-ray Polarization



- Polarized emission from e1 knot
- $59 \pm 17\%$ polarization in the head region after subtracting background
- Polarization angle perpendicular to the jet, indicating a magnetic field along the jet direction



Surprisingly High Poloidal Magnetic Flux



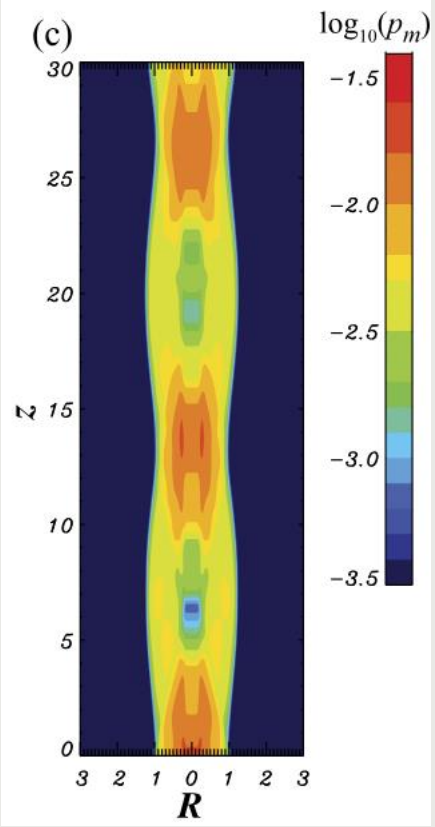
- High polarization indicates a nearly perfect magnetic field along the jet direction.
- Assuming the cross section of the jet is a few pc, and the magnetic field strength is $\sim 10\mu G$ based on HAWC and LHAASO spectral fitting, the poloidal magnetic flux is $\sim 10^{32}\ G\ cm^2$, ten orders of magnitude higher than what can be provided by a stellar-mass black hole.

Two options:

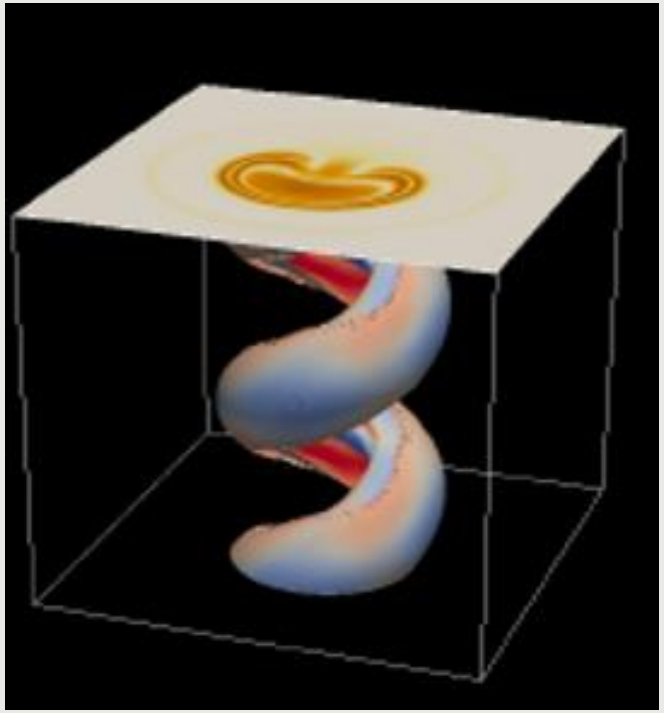
1. It is not a jet/lobe/wind from the central engine.
2. Some physical processes turn the toroidal magnetic flux into poloidal.

Implications on Jet Physics

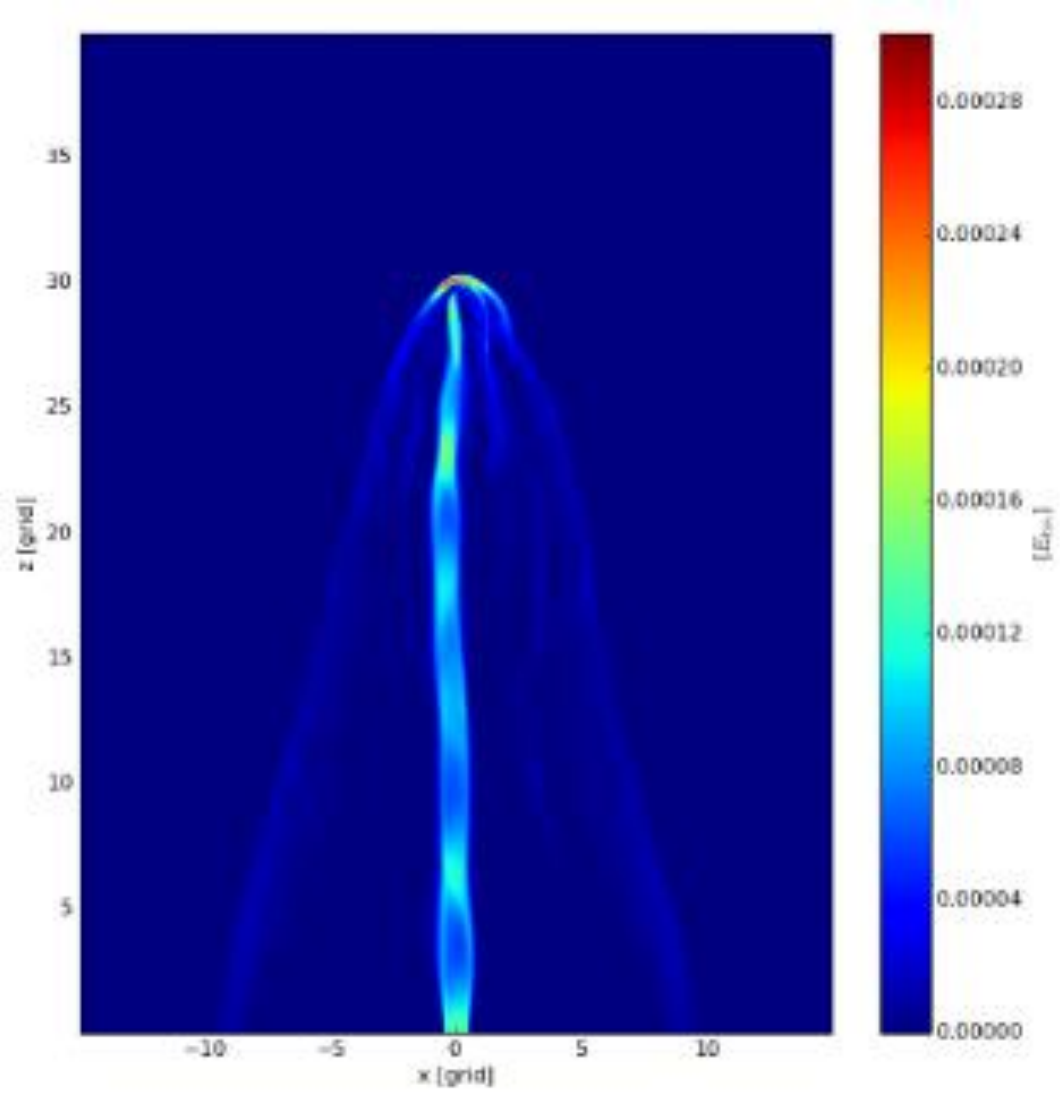
- Kinetic jet: recollimation shocks and velocity shearing enhance the poloidal magnetic component.



- Magnetic jet: kink instabilities twist the magnetic field and alter the polarization signatures.

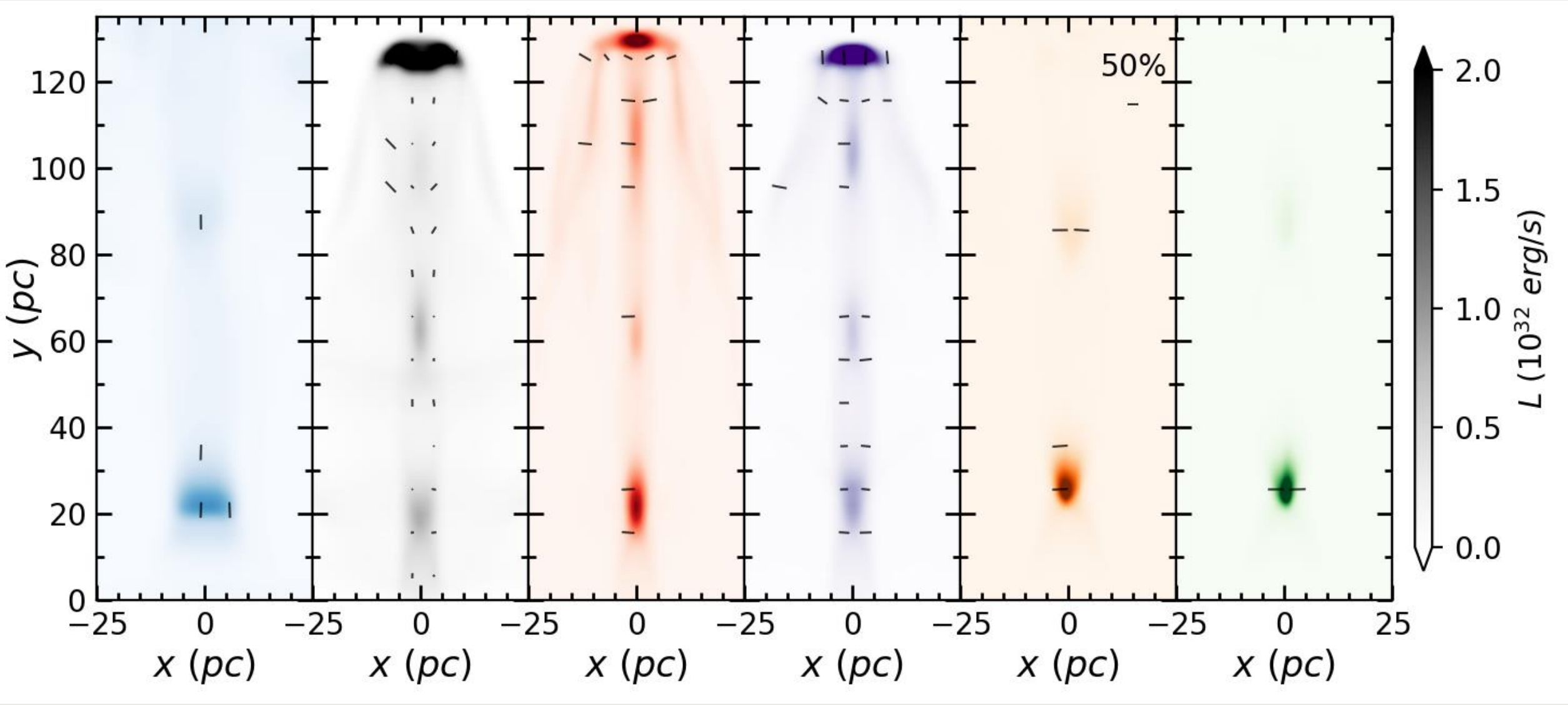


MHD Simulations of Kinetic Jets



- Generic kinetic jet injected from the simulation boundary
- We survey different compositions of initial magnetic field morphology, from purely toroidal to a mixture of toroidal and poloidal components to purely poloidal field.
- Magnetic field strength and X-ray flux are normalized to SS 433 observations.

Polarized Emission Maps of Kinetic Jets



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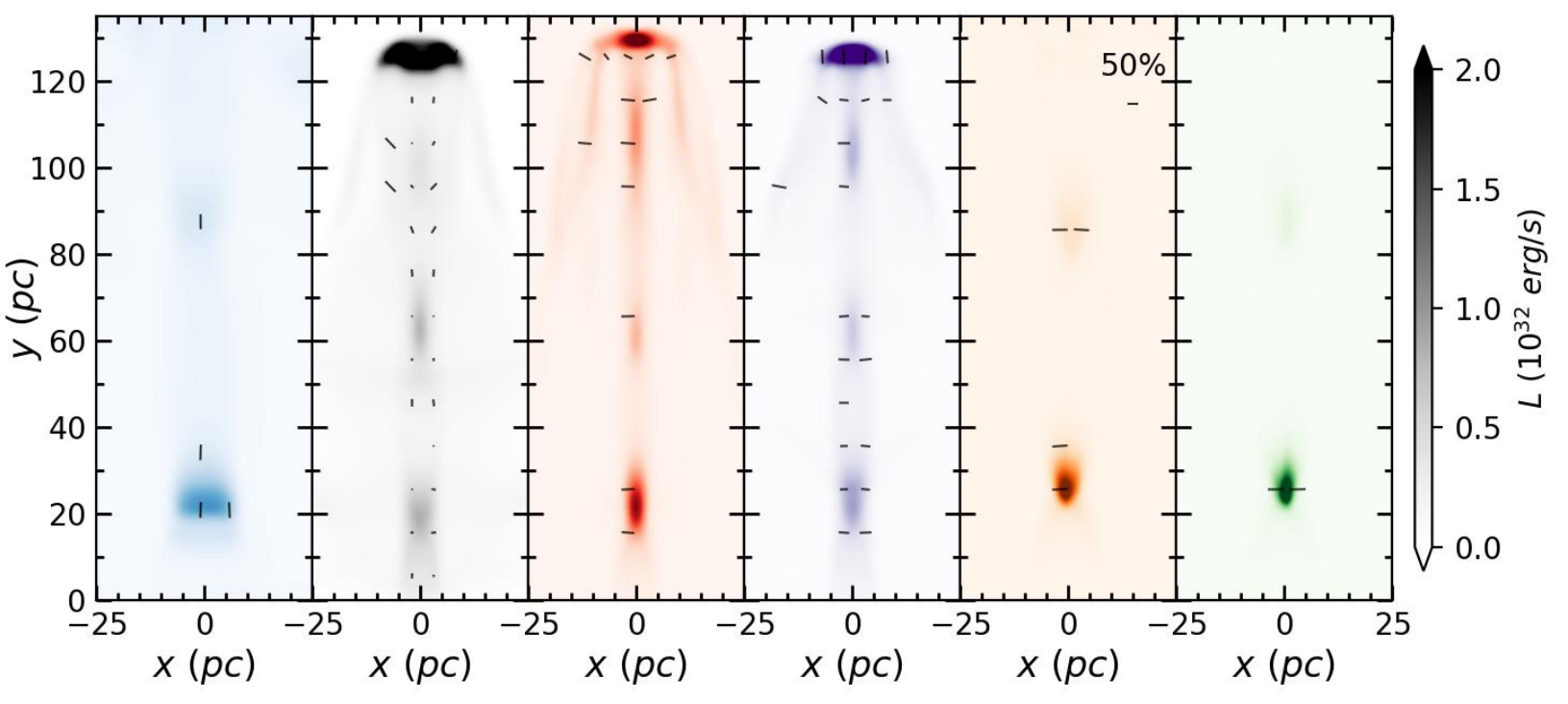
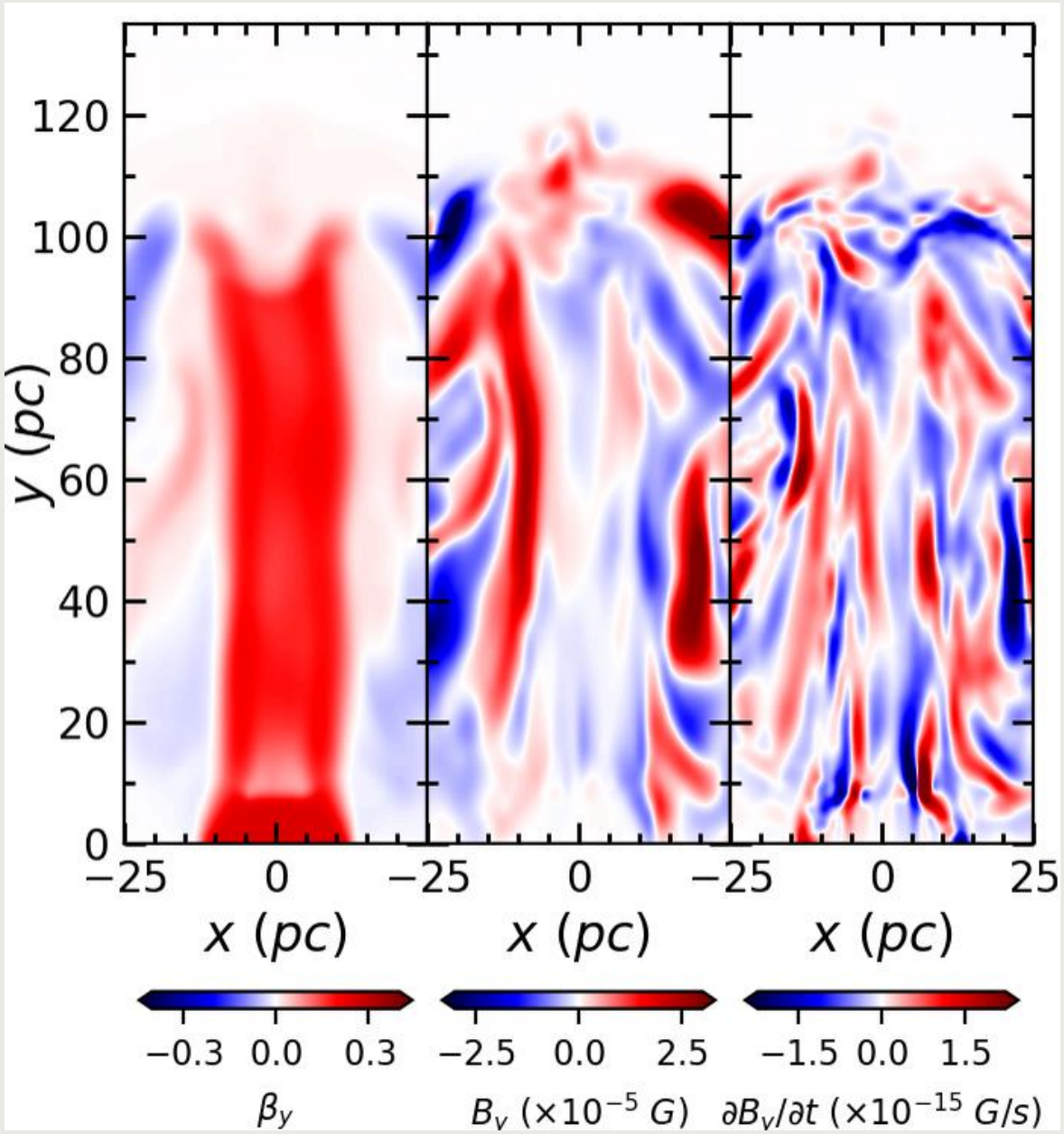


- Enhanced emission in recollimation shock
- Polarization is perpendicular to the jet even with 0.8:0.2 toroidal-to-poloidal ratio.
- 0.6:0.4 and 0.4:0.6 toroidal-to-poloidal ratio are consistent with IXPE data.

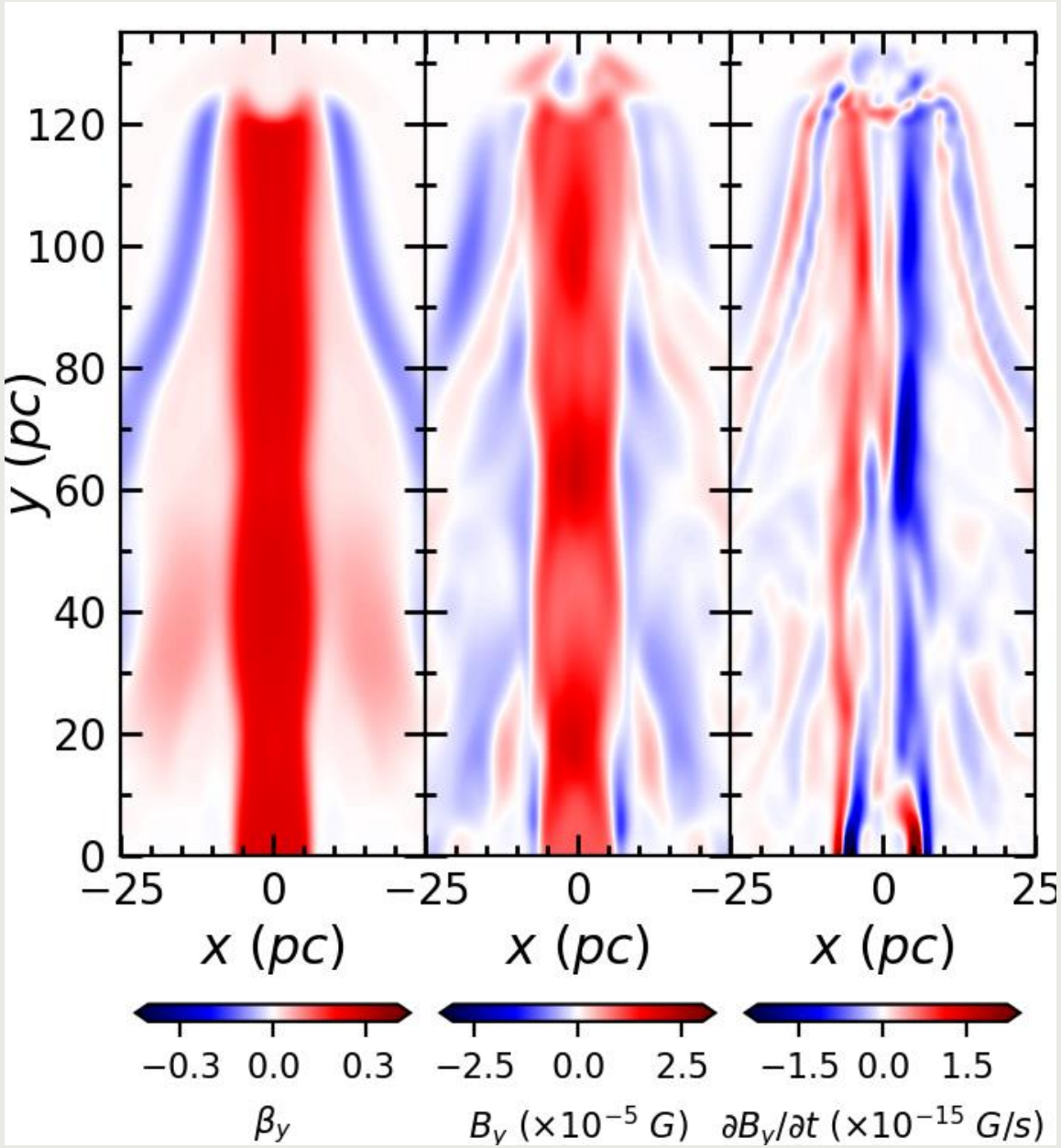
- From left to right have initially purely toroidal field, mixture of toroidal and poloidal components with ratio of 0.8:0.2, 0.6:0.4, 0.4:0.6, 0.2:0.8, and purely poloidal field.
- Polarization in the recollimation shock are ~70% along jet, 2%, ~50%, ~50%, ~70%, and ~70% perpendicular to jet.

Velocity Shearing or Compression?



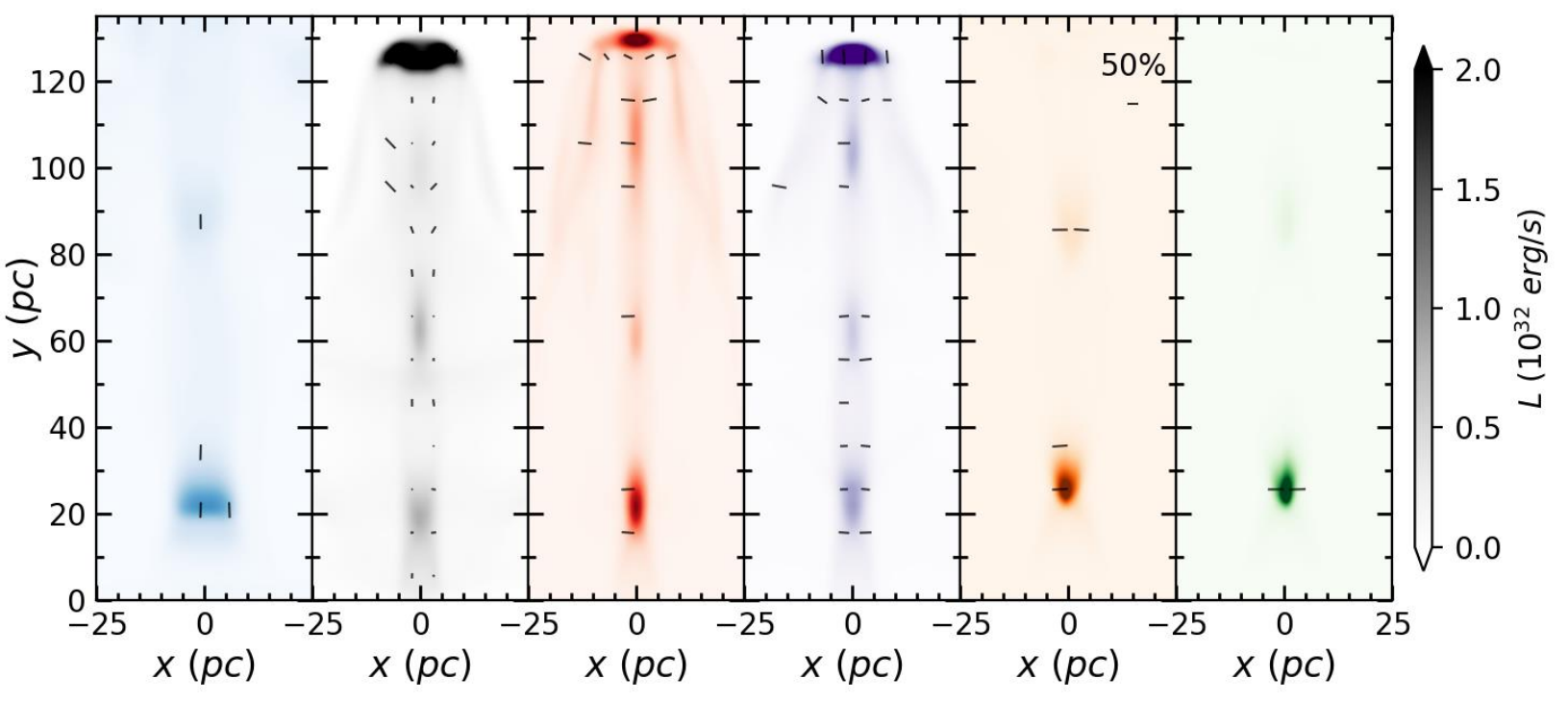
- Examine the case with initially purely toroidal field.
- Poloidal magnetic field strengths roughly match the distribution of induction.
- However, the central spine has only a small amount of poloidal field.
- Velocity shearing is generating poloidal field, but not enough to explain observations.

Velocity Shearing or Compression?



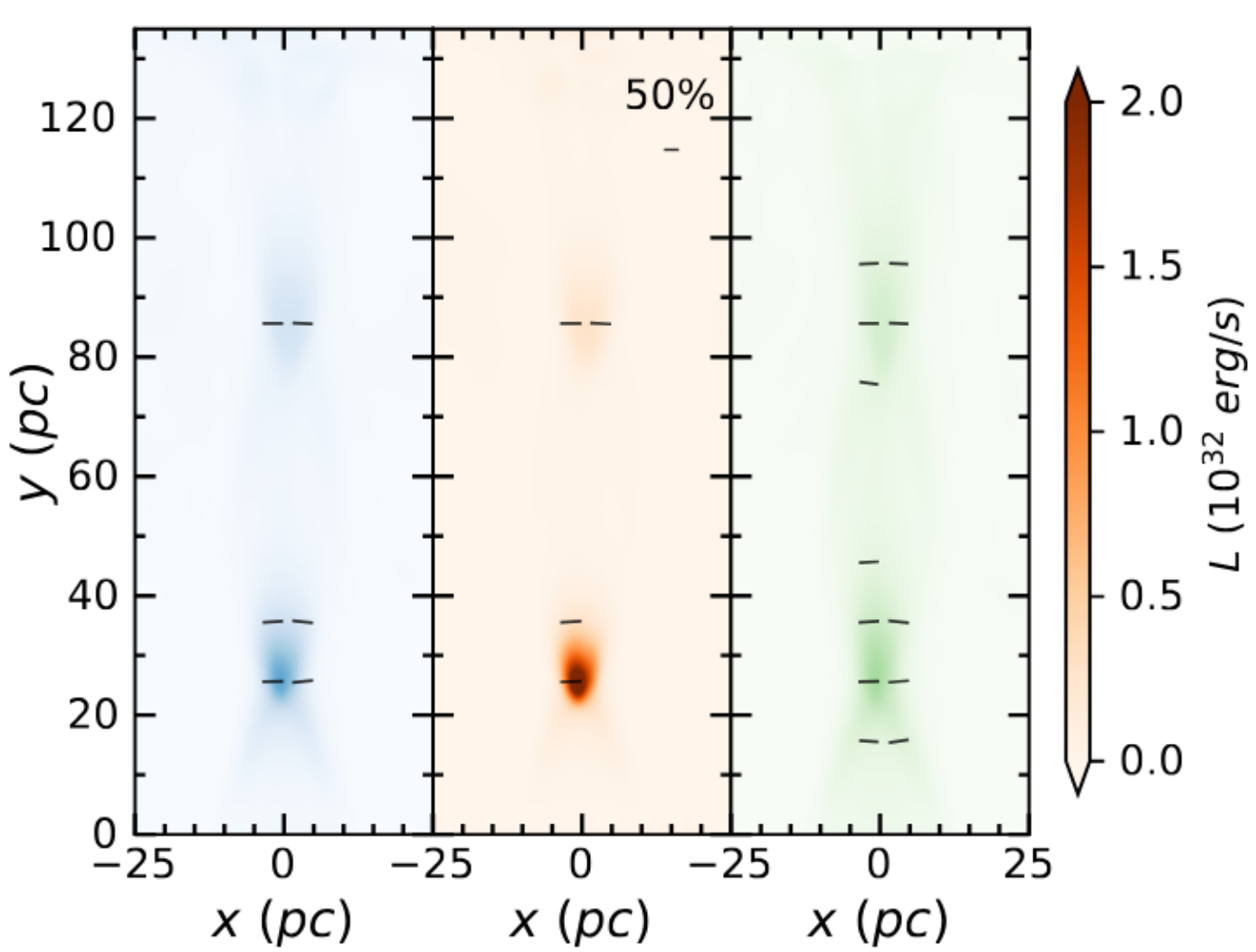
- Examine the case with initially 0.8:0.2 toroidal-to-poloidal ratio.
- Poloidal magnetic field is enhanced in the recollimation shock due to compression.

How to Justify/Rule Out Kinetic Jet?



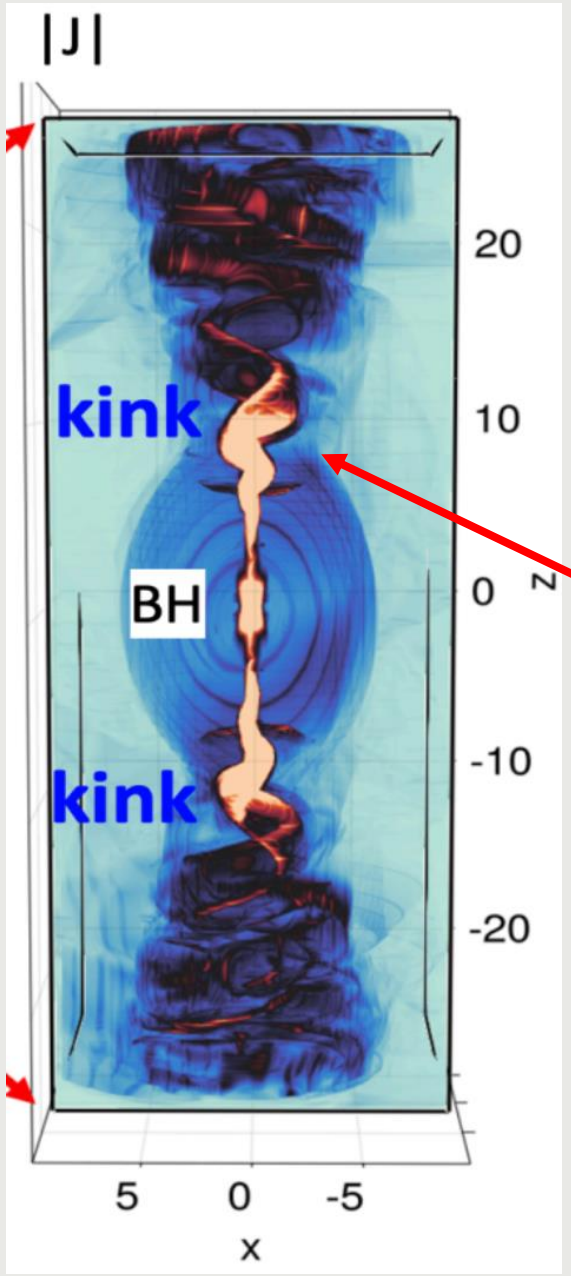
- IXPE polarization data requires roughly half of the magnetic flux in the poloidal direction. Such high poloidal flux has to be converted from toroidal flux very close to the central engine where our simulations cannot resolve. Future simulations can examine if this is possible.
- All recollimation shocks give nearly the same polarization. If IXPE observation of e2 shows different polarization degree/angle from e1, this scenario is ruled out.

Robustness with “Painting” of Electrons

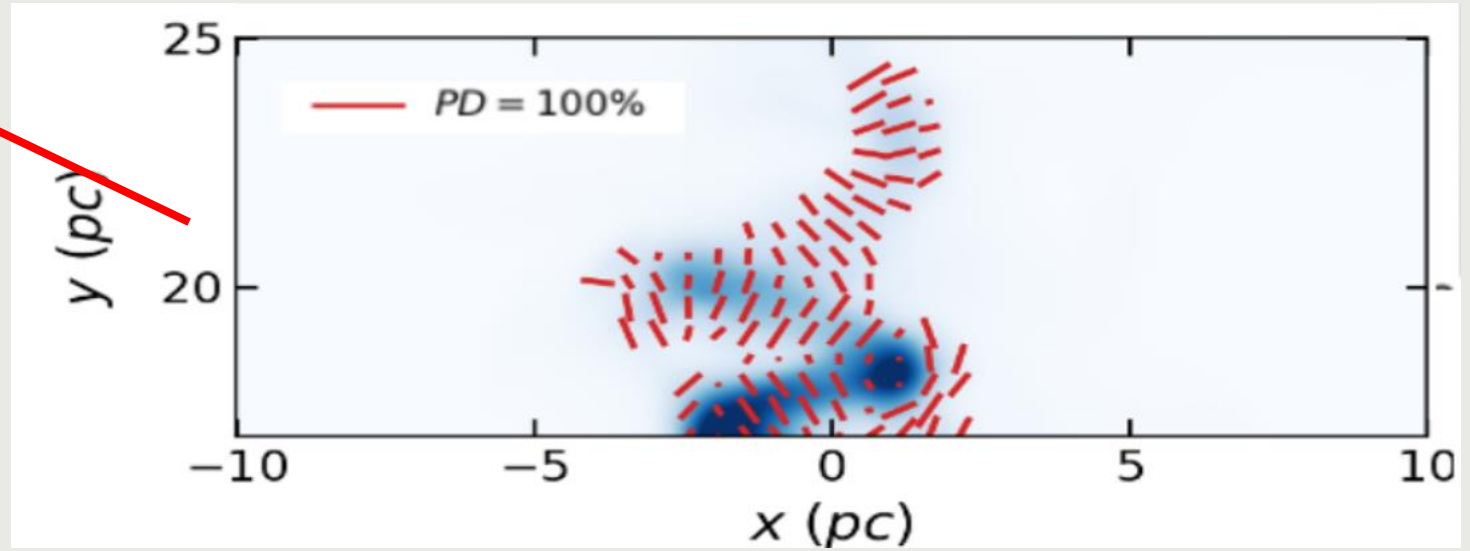


- Changes to the normalization of nonthermal electrons can modify the emission map, but have minor effects on polarization degree and angle.

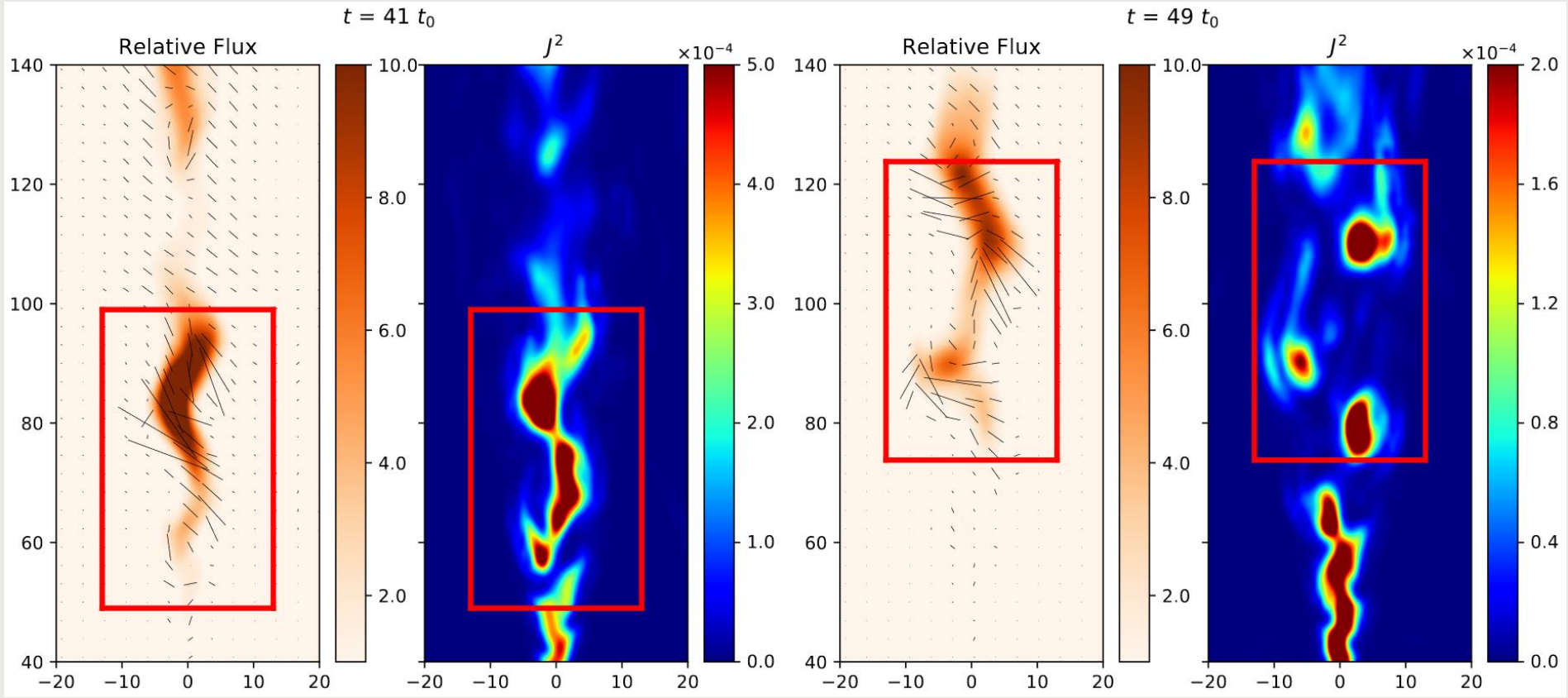
MHD Simulations of Magnetic Jet



- Generic twin magnetic jets injected from the simulation center
- Results are preliminary, we have not performed parameter survey and normalization to the SS 433 data yet.



Kink Instabilities Twist the Magnetic Field Structure



- External kink can bend the jet direction, making the toroidal magnetic component appear along the jet direction in some strongly kinked regions.
- Different kink nodes generally have different polarization. If IXPE observation of e2 shows different polarization degree/angle from e1, this scenario is supported.

Summary

- The very high X-ray polarization degree in SS 433 poses serious challenge on the poloidal magnetic flux.
- Velocity shearing can help to convert toroidal magnetic field into poloidal, and recollimation shock can further enhance the poloidal field via compression.
- Alternatively, kink instabilities can twist the jet magnetic field to make toroidal field appear like poloidal field.
- IXPE observation of e2 knot can distinguish the two scenarios and determine whether the jet is kinetic or magnetic.