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Multi-wavelength Polarization Analysis of Relativistic Over-pressured Jets

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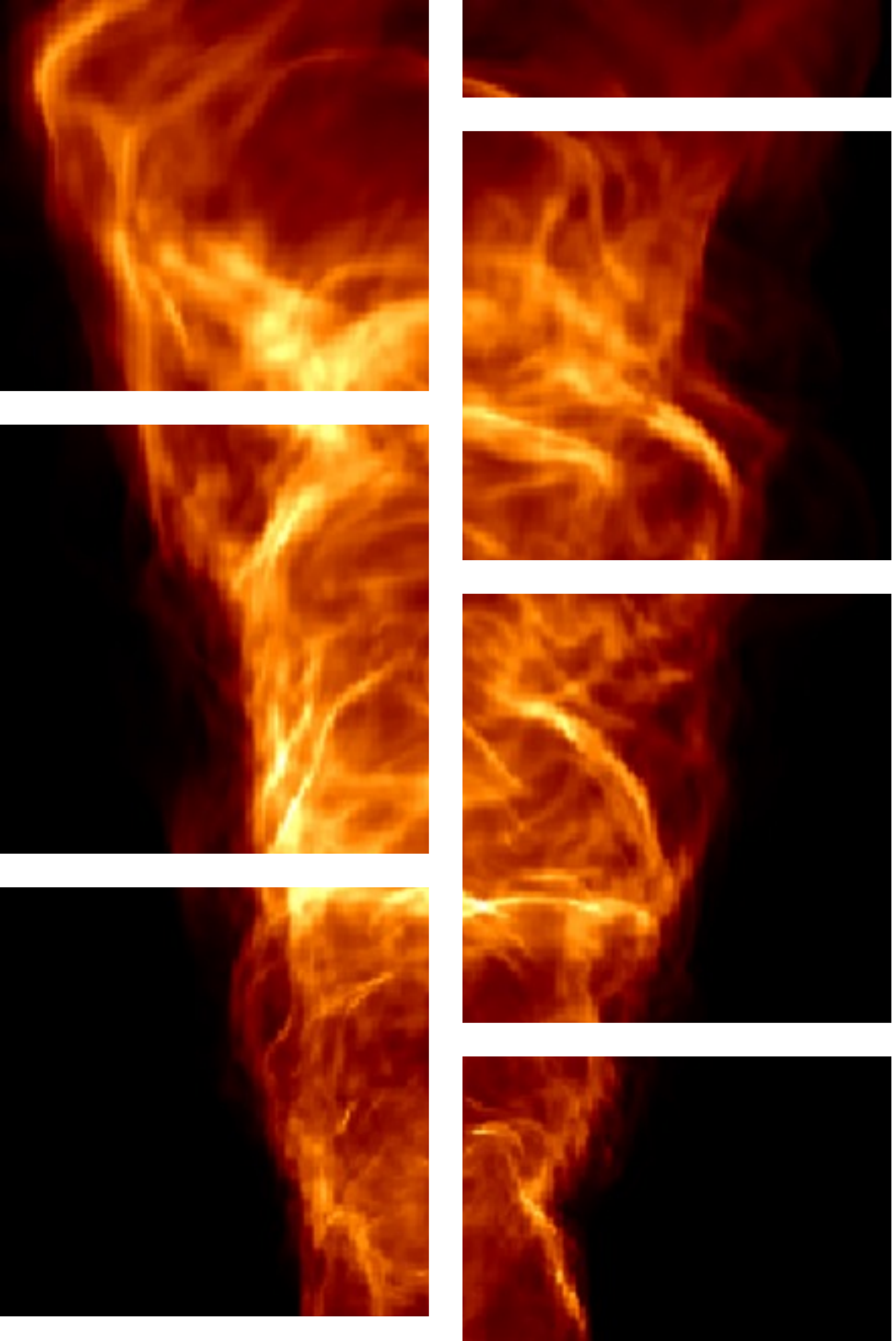
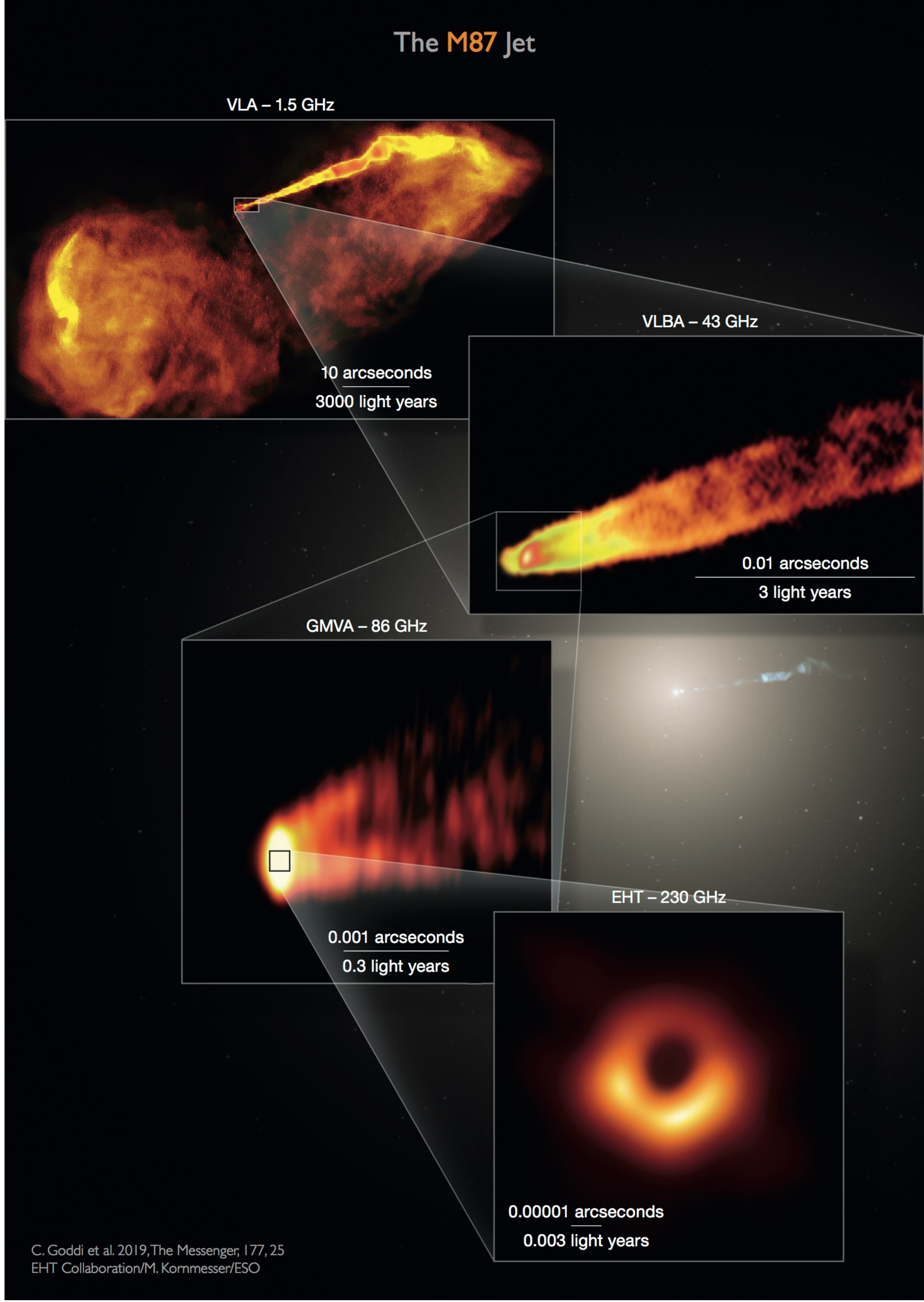


- **Introduction:** relativistic jets, Blazar
- **RMHD**: recollimation shock, kink instability
- **Radiation transfer:** multi-frequency images, Qusai-Periodic Oscillations (QPOs)
- **Summary**

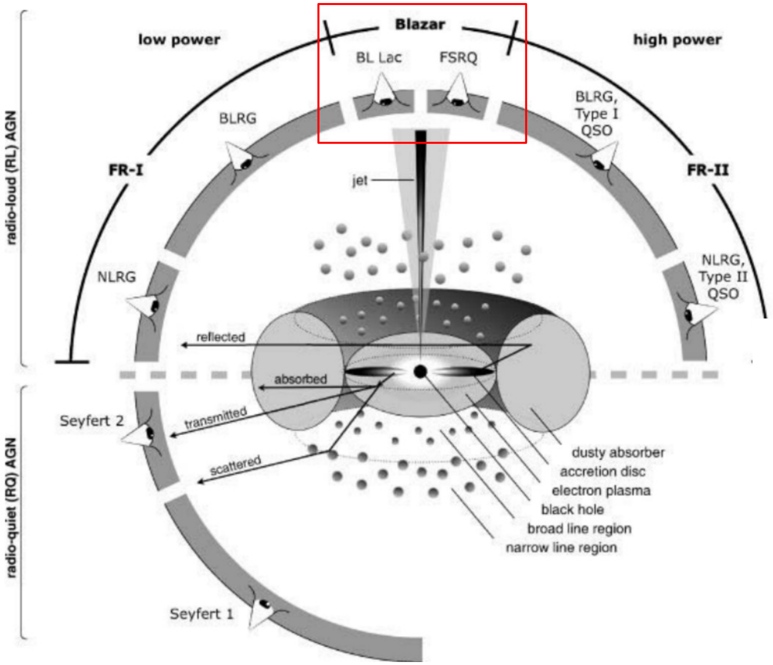
Relativistic jet

- Outflow of highly collimated plasma
  - Microquasars, Active Galactic Nuclei, Gamma-Ray Bursts, Jet velocity ~ c
  - Generic systems: Compact object (Neutron Star, Black Hole) + accretion flows
- Key Issues of Relativistic Jets
  - Launch & Acceleration (General Relativistic MHD)
  - Propagation & Stability (Speical Relativistic MHD)
  - Radiation profile & Particle acceleration mechanism (Radiation Transfer, Particle In Cell)

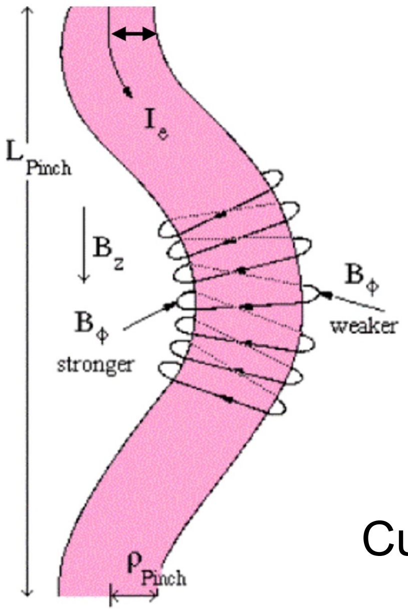


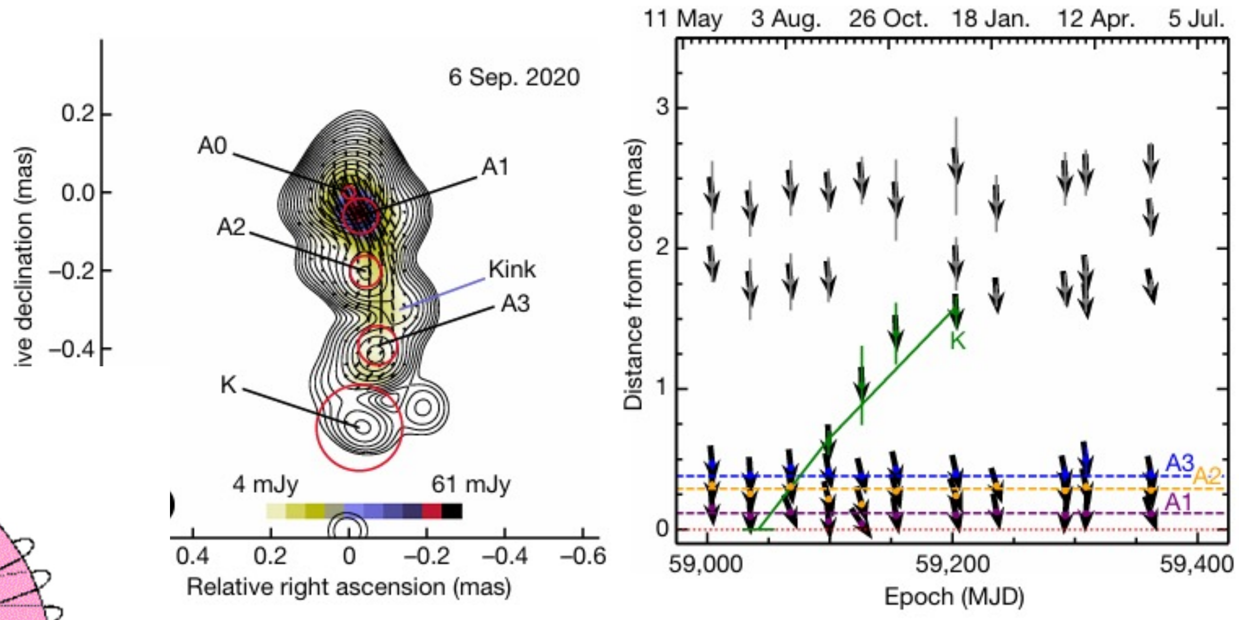
Blazar

- Blazar: characterized by highly relativistic jets nearly along our line of sight, which exhibit highly variable, non-thermal emission from radio to TeV γ-rays



AGN unified model (credit:Beckmann+12)





BL Lac in R-band (credit: Jorstad+22)

Current Driven kink instability

Stationary knots interpreted as recollimation shocks

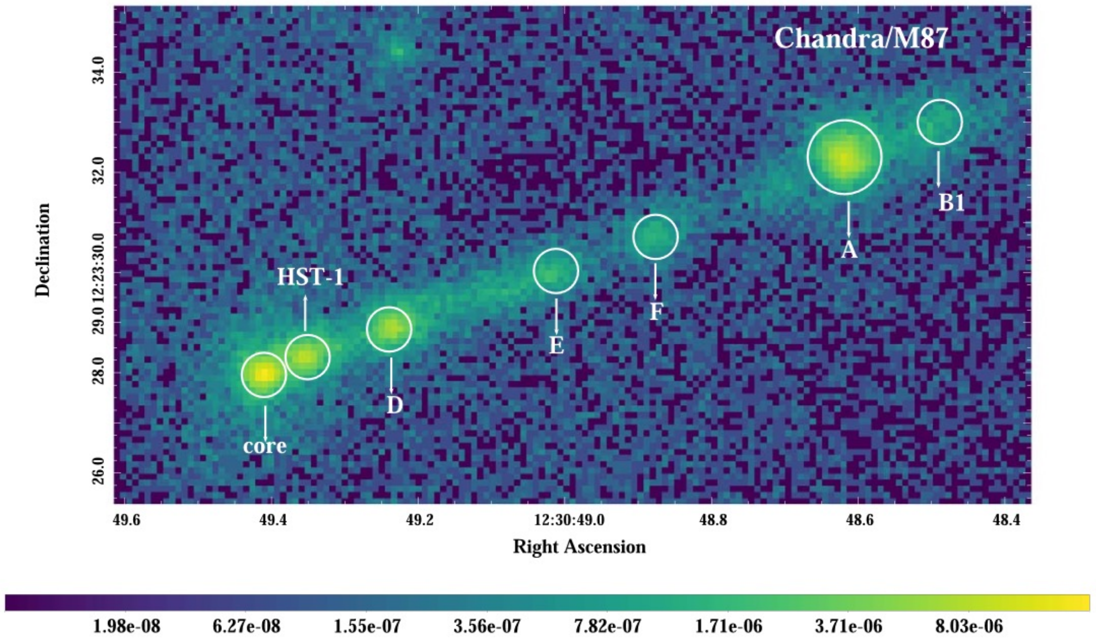
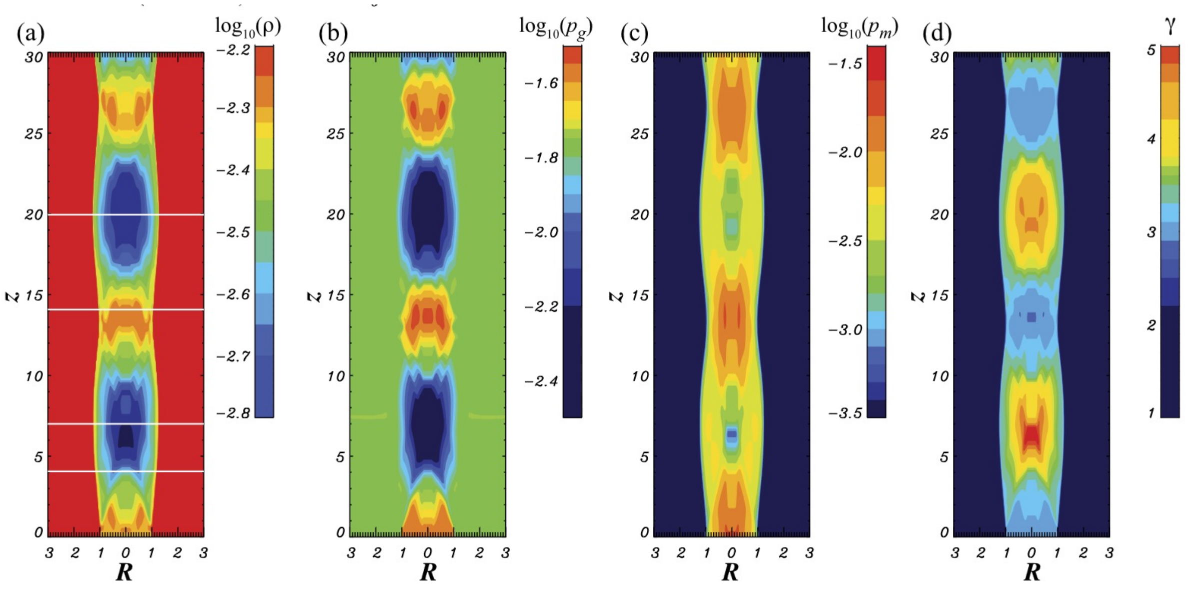


Figure 1. The exposure-corrected 0.4 – 8.0 keV image of the jet in M87, binned to 0.25 px resolution for ObsID 352.

(Credit: Thimmappa+24)

- HST-1 is located downstream of the Bondi radius (Asada+12)
- X-ray observations of M87 suggest a flattening of the density profile potentially accompanied with a factor of few jump in density (Russell +15)

- Recollimation shock is triggered when the pressure is mis-matched between the jet and the ambient environment.



(Credit: Miuzno+15)

3D RMHD Simulations of Over-Pressured Jets

- Code: PLUTO (Mignone+07)

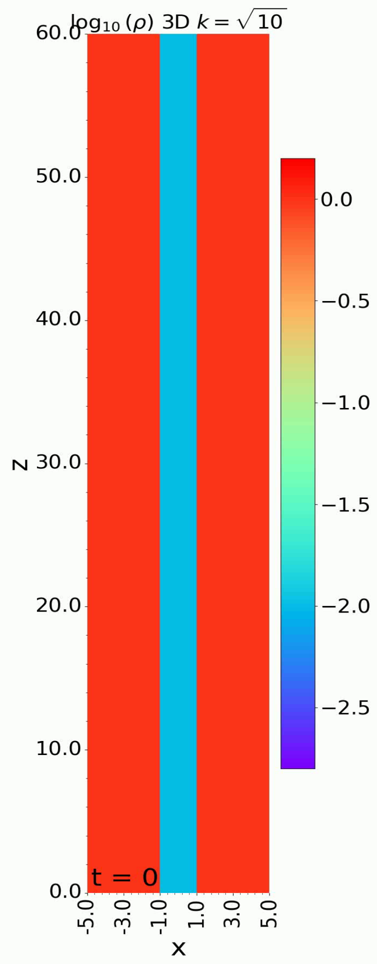
$$\frac{\partial}{\partial t}\begin{pmatrix} D \\ \boldsymbol{m} \\ E_t \\ \boldsymbol{B} \end{pmatrix} + \nabla\cdot\begin{pmatrix} D\boldsymbol{v} \\ w_t\gamma^2\boldsymbol{v}\boldsymbol{v} - \boldsymbol{b}\boldsymbol{b} + \mathsf{I}p_t \\ \boldsymbol{m} \\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} \end{pmatrix}^T = \begin{pmatrix} 0 \\ \boldsymbol{f}_g \\ \boldsymbol{v}\cdot\boldsymbol{f}_g \\ \boldsymbol{0} \end{pmatrix}$$

$$\begin{aligned} D &= \gamma\rho \\ \boldsymbol{m} &= w_t\gamma^2\boldsymbol{v} - b^0\boldsymbol{b} \\ E_t &= w_t\gamma^2 - b^0 b^0 - p_t \end{aligned} \quad , \quad \begin{cases} b^0 = \gamma\boldsymbol{v}\cdot\boldsymbol{B} \\ \boldsymbol{b} = \boldsymbol{B}/\gamma + \gamma(\boldsymbol{v}\cdot\boldsymbol{B})\boldsymbol{v} \\ w_t = \rho h + \boldsymbol{B}^2/\gamma^2 + (\boldsymbol{v}\cdot\boldsymbol{B})^2 \\ p_t = p + \dfrac{\boldsymbol{B}^2/\gamma^2 + (\boldsymbol{v}\cdot\boldsymbol{B})^2}{2} \end{cases}$$

- Initial Condition:
  - a preexisting over-pressured jet ($p_j > p_a$)
  - helical magnetic field but torodial component dominates

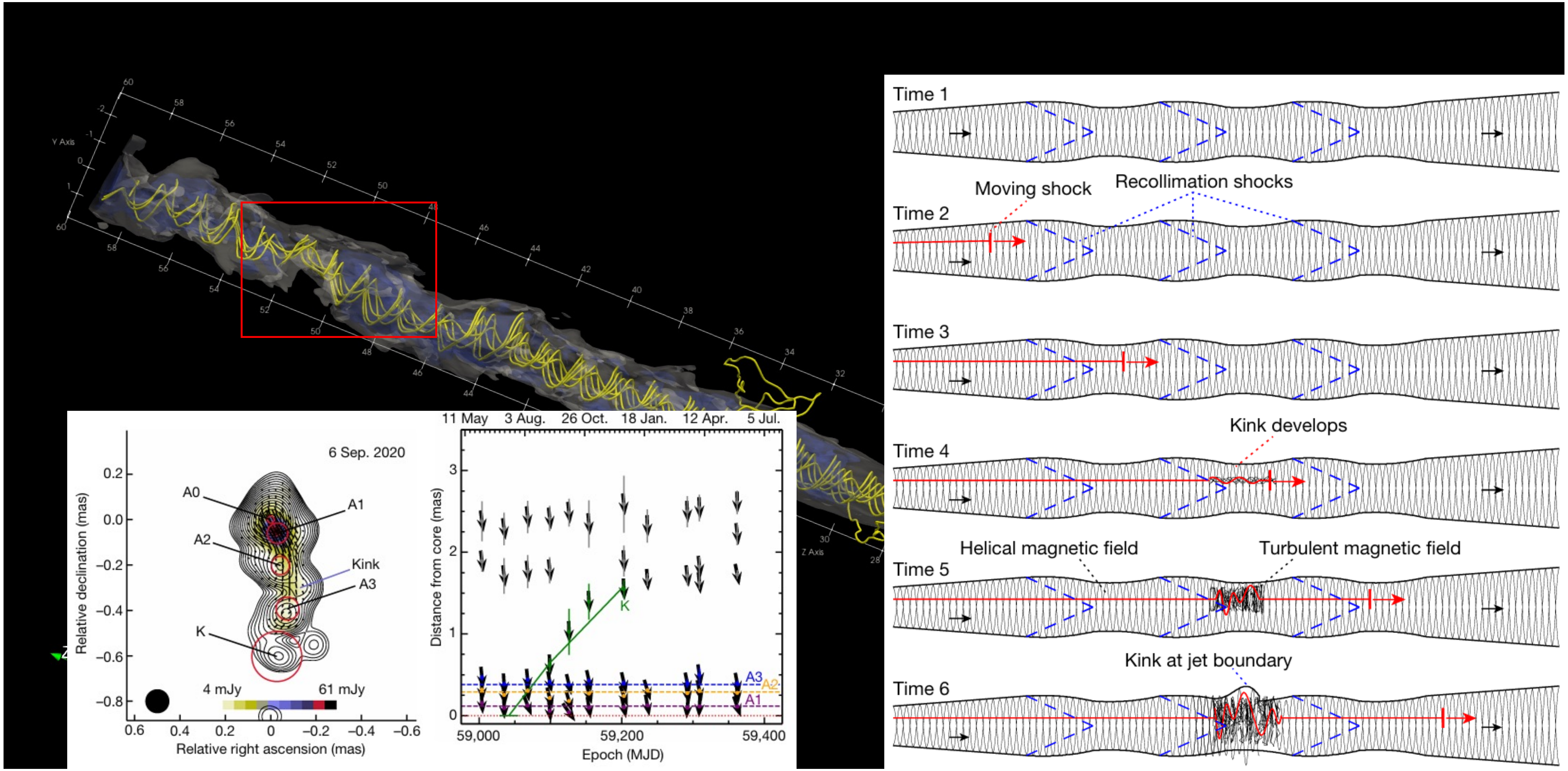
- z<30 Recollimation shocks
- z>30 Rayleigh-Taylor Instability

  Current Driven Kink Instability



Hu, YM, & Fromm (2025)

Kink instability develops after passing recollimation shocks



(credit: Jorstad+22)

- However, RMHD simulation is only the half of the story...the other half is Radiation Transfer.

power-law + local emissivity

Absence of aborption and Faraday rotation

Neglect of relativistic effects (except for Doppler beaming)

Dependence on the assumption of a power-law eDF.

$$\left.\frac{\mathrm{d}}{\mathrm{d}\lambda}\right|_P \begin{pmatrix} \mathcal{I} \\ \mathcal{Q} \\ \mathcal{U} \\ \mathcal{V} \end{pmatrix} = \begin{pmatrix} j_I \\ j_Q \\ j_U \\ j_V \end{pmatrix} - \begin{pmatrix} \alpha_I & \alpha_Q & \alpha_U & \alpha_V \\ \alpha_Q & \alpha_I & \rho_V & -\rho_U \\ \alpha_U & -\rho_V & \alpha_I & \rho_Q \\ \alpha_V & \rho_U & -\rho_Q & \alpha_I \end{pmatrix} \begin{pmatrix} \mathcal{I} \\ \mathcal{Q} \\ \mathcal{U} \\ \mathcal{V} \end{pmatrix},$$

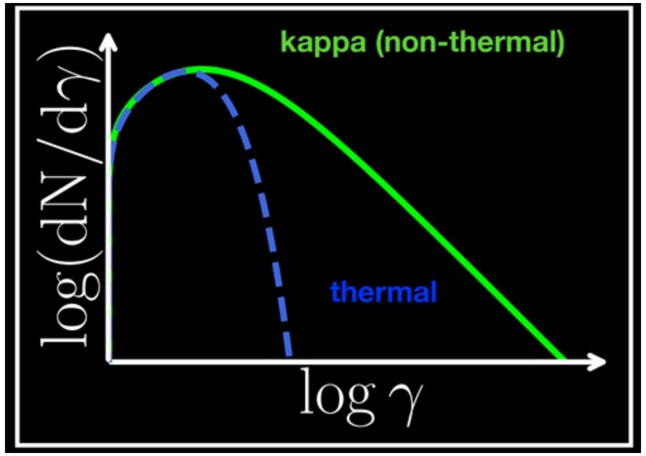
determine geodesic in Minkowski metric (like GRRT)

incoporate subgrid models from PIC simulations

RaptorP: SRRT Imaging

- based on General Relativistic Radiation Transfer (GRRT) code **RAPTOR** (Bronzwaer+18,20)
- read both uniform and non-uniform Cartesian data from **PLUTO**
- calculate synchrotron emission
- κ eDF (thermal core + power-law tail):

$$\frac{dN}{d\gamma} \propto \gamma\sqrt{\gamma^2-1}\left(1+\frac{\gamma-1}{\kappa w}\right)^{-(\kappa+1)}. \quad \epsilon = \frac{\int_{\gamma_0}^{\infty}(dN/d\gamma - f_{MJ}(\gamma,\Theta_e))(\gamma-1)d\gamma}{\int_{\gamma_0}^{\infty}(dN/d\gamma)(\gamma-1)d\gamma},$$



(credit: Fromm+25)

non-thermal efficiency & spectral index from PIC simulations

- turbulence (Meringolo+23)
- magnetic reconnection (Ball+18)

- derive a self-consistent determination of nonthermal electron temperature w

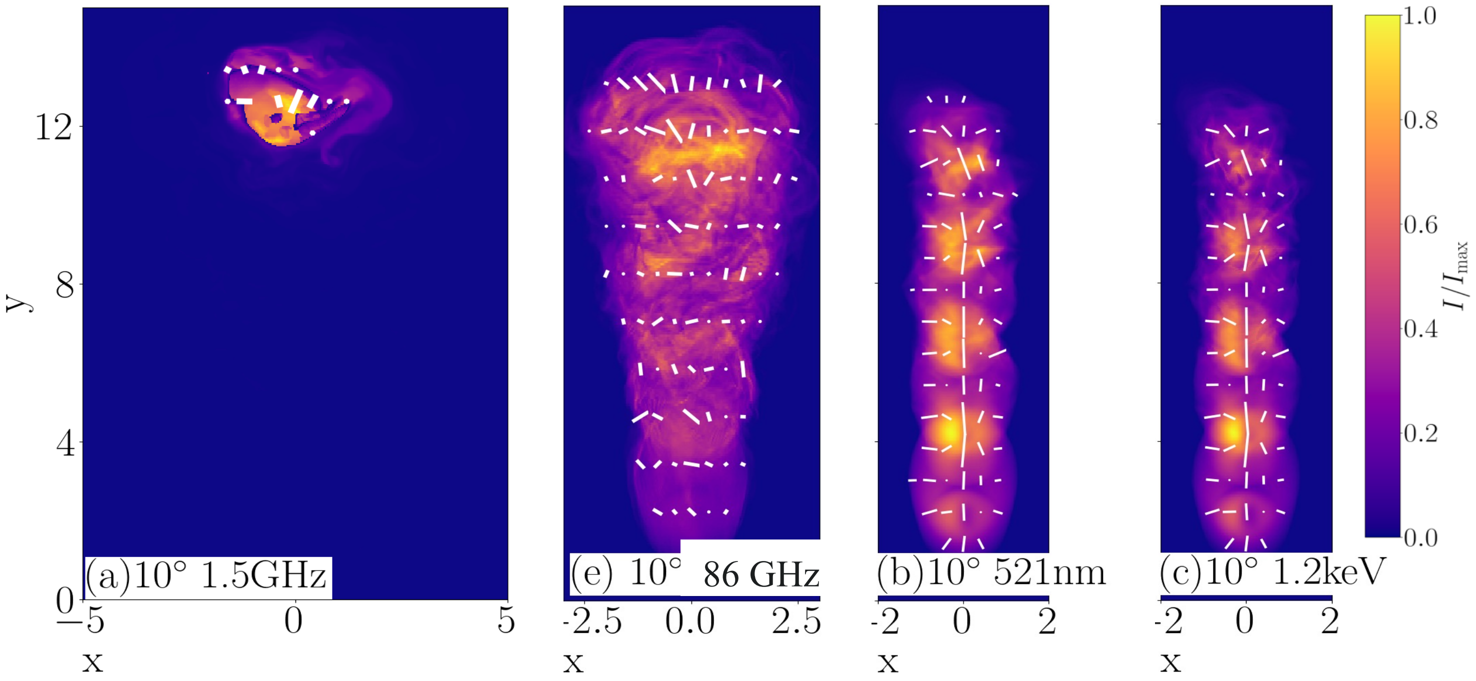
Hu et al. (2025) submitted

Multi-Frequency Snapshot Images

- 1.5 GHz: optically thick by the ambient medium, only see the jet head
- 86 GHz: still optically thick, turbulence gas surrounding the jet dominates emission
- 521nm and 1.2keV: we see bright knots caused by recollimation shocks and twisted kink

- EVPA is parallel to the jet direction at the jet spine and perpendicular at jet boundary (consistent with Kramer & McDonald 2021)

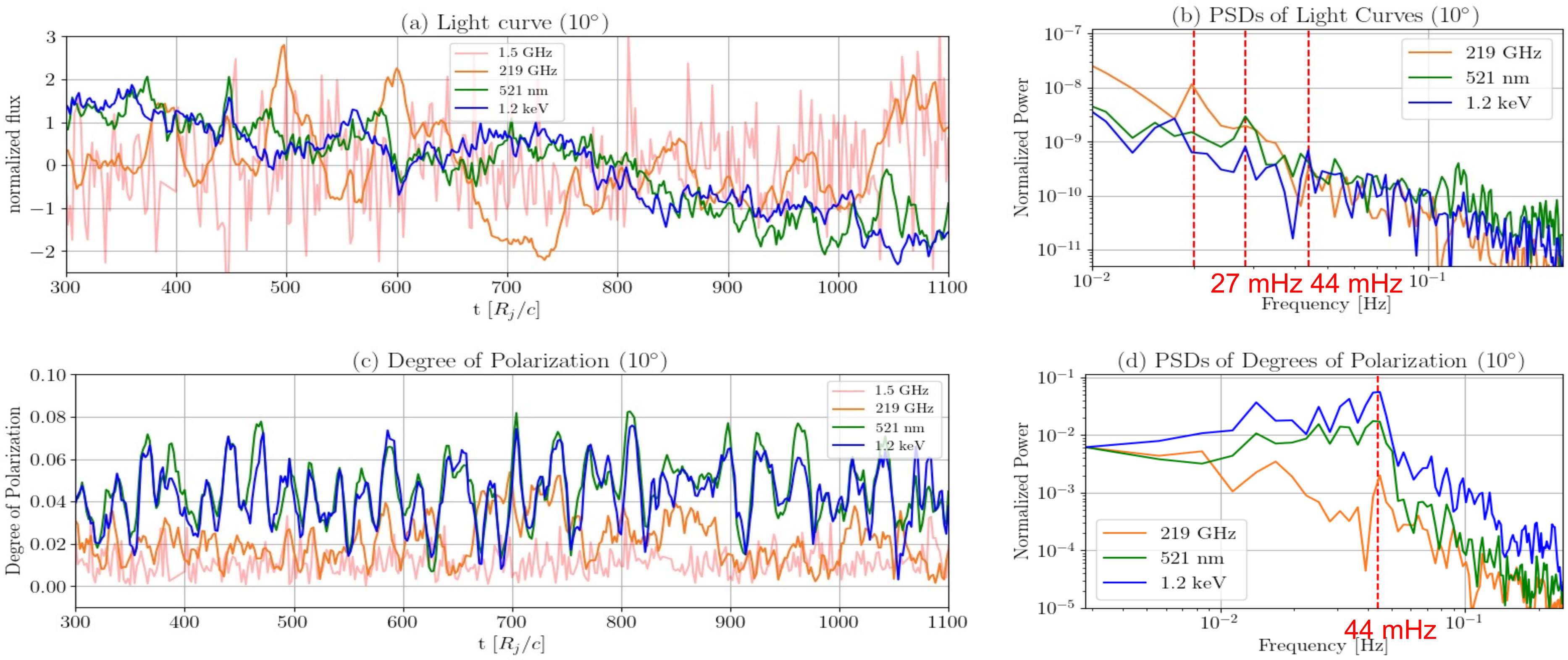
Intensity (color) + EVPA at 10°



Hu et al. (2025) submitted

Qusai-Periodic Oscillation

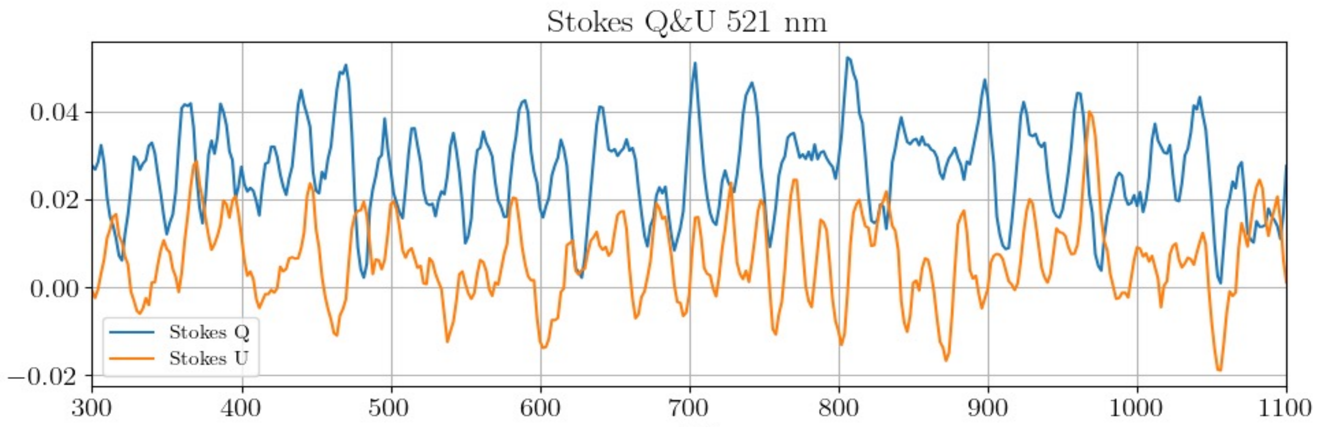
- RaptorP supports locally imaging, so we focus on the kink structure region

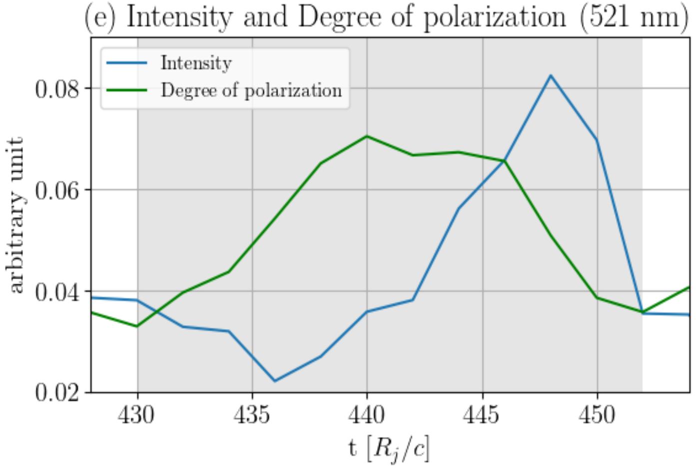


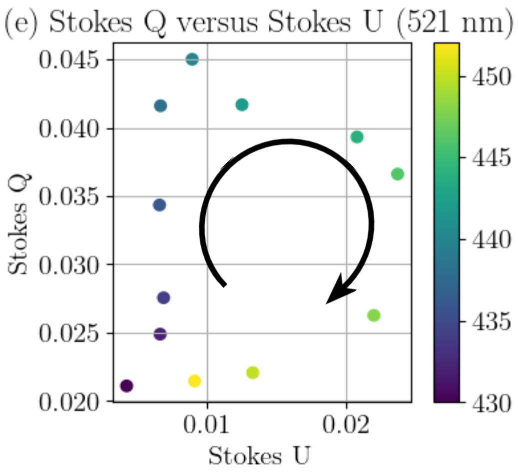
- **Intensity:** 521nm (1.2 keV) have a peak at 29 (44) mHz, well-matched with kink rotation frequencies (27 & 46 mHz)
- **Degree of polarization:** a peak around 40-50 mHz

Hu et al. (2025) submitted

Inspiration for observations







- We found an **anti-correlation** between the time evolution of intensity and polarization degree (similar to Dong et al. 2020).
- We saw QU loop pattern (**clockwise** rotation)
- Two phenomenons have the same origin: **the dissipation of torodial magneitc field** when kink develops

Hu et al. (2025) submitted

Summary

- We performed 3D RMHD simulations of over-pressured magnetized jets. The **recollimation shock** structure transformed into a mixture of the **Rayleigh-Taylor Instability** and the **Curren Driven kink instability**.
- We present **RaptorP**(will be open-sourced soon), a special relativistic module of polarized GRRT code RAPTOR. Then we calculate the multi-frequency images of the jet.
- We see **knot-like** structures caused by recollimation shocks and **kink** structures in images
- Time variability of intensity and polarization degree presents **quasi-periodic oscillations** whose frequencies are well-matched with the kink rotation frequency. In particular, we predict an **anticorrelation between intensity and degree of polarization**, and a **clockwise** pattern in Q-U plane

Derivation of w

By employing $\gamma_0 \gg 1$, we rewrite Eq. 1 as

$$\int_{\gamma_0}^{\infty} \frac{dN}{d\gamma}\gamma d\gamma = \frac{\int_{\gamma_0}^{\infty} f_{MJ}(\gamma, \Theta_e)\gamma d\gamma}{1-\epsilon}. \tag{B6}$$

and we simplify the expressions of the thermal distribution as $\frac{\gamma^2}{\Theta_e K_2(1/\Theta_e)} e^{-\gamma/\Theta_e}$ and κ distribution as $\gamma^2(1+\frac{\gamma}{\kappa w})^{-(\kappa+1)}$. Then we rewrite Eq. B6 with normalization:

$$\frac{\int_{\gamma_0}^{\infty} \gamma^3(1+\frac{\gamma}{\kappa w})^{-(\kappa+1)}}{\int_{\gamma_0}^{\infty} \gamma^2(1+\frac{\gamma}{\kappa w})^{-(\kappa+1)}} = \frac{1}{1-\epsilon} \frac{\int_{\gamma_0}^{\infty} \frac{\gamma^3}{\Theta_e K_2(1/\Theta_e)} e^{-\gamma/\Theta_e} d\gamma}{\int_{\gamma_0}^{\infty} \frac{\gamma^2}{\Theta_e K_2(1/\Theta_e)} e^{-\gamma/\Theta_e} d\gamma} \tag{B7}$$

$$\frac{6\gamma_0(w\kappa)^2 + \gamma_0^3(-2+\kappa)(-1+\kappa) + 3w\gamma_0^2(-1+\kappa)\kappa + 6w^3\kappa^2}{(-3+\kappa)[\gamma_0^2(-1+\kappa) + 2w^2\kappa + 2\gamma_0 w\kappa]} = \frac{1}{1-\epsilon}(3\Theta_e + \frac{\gamma_0^3}{\gamma_0^2 + 2\gamma_0\Theta_e + 2\Theta_e^2}) \tag{B8}$$

Define C equals the right hand of Eq. B8, and we reorganize Eq. B8 into a cubic equation:

$$aw^3 + bw^2 + cw + d = 0, \tag{B9}$$

$$\begin{cases} a &= 6\kappa^2, \\ b &= 6\gamma_0\kappa^2 - 2\kappa C(-3+\kappa), \\ c &= 3\gamma_0^2(-1+\kappa)\kappa - (-3+\kappa)C\gamma_0\kappa, \\ d &= \gamma_0^3(-2+\kappa)(-1+\kappa) - C(-3+\kappa)\gamma_0^2(-1+\kappa), \end{cases} \tag{B10}$$

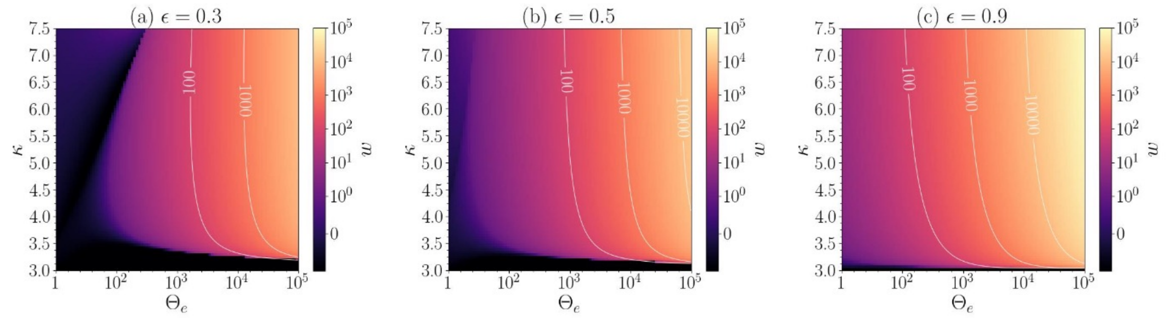


Figure 6. Dependency of w on Θ_e and κ at different efficiency $\epsilon = 0.3$ (a), 0.5 (b), and 0.9 (c), which is the solution of Eq. (B9). Contour lines at 10^2,10^3, and 10^4 are plotted.

To guarantee the existence of at least one positive real root, the condition $d < 0$ is a sufficient condition:

$$\gamma_0^3(-2+\kappa)(-1+\kappa) < C(-3+\kappa)\gamma_0^2(-1+\kappa) \tag{B11}$$

$$\gamma_0(\kappa-2) < C(\kappa-3) \tag{B12}$$

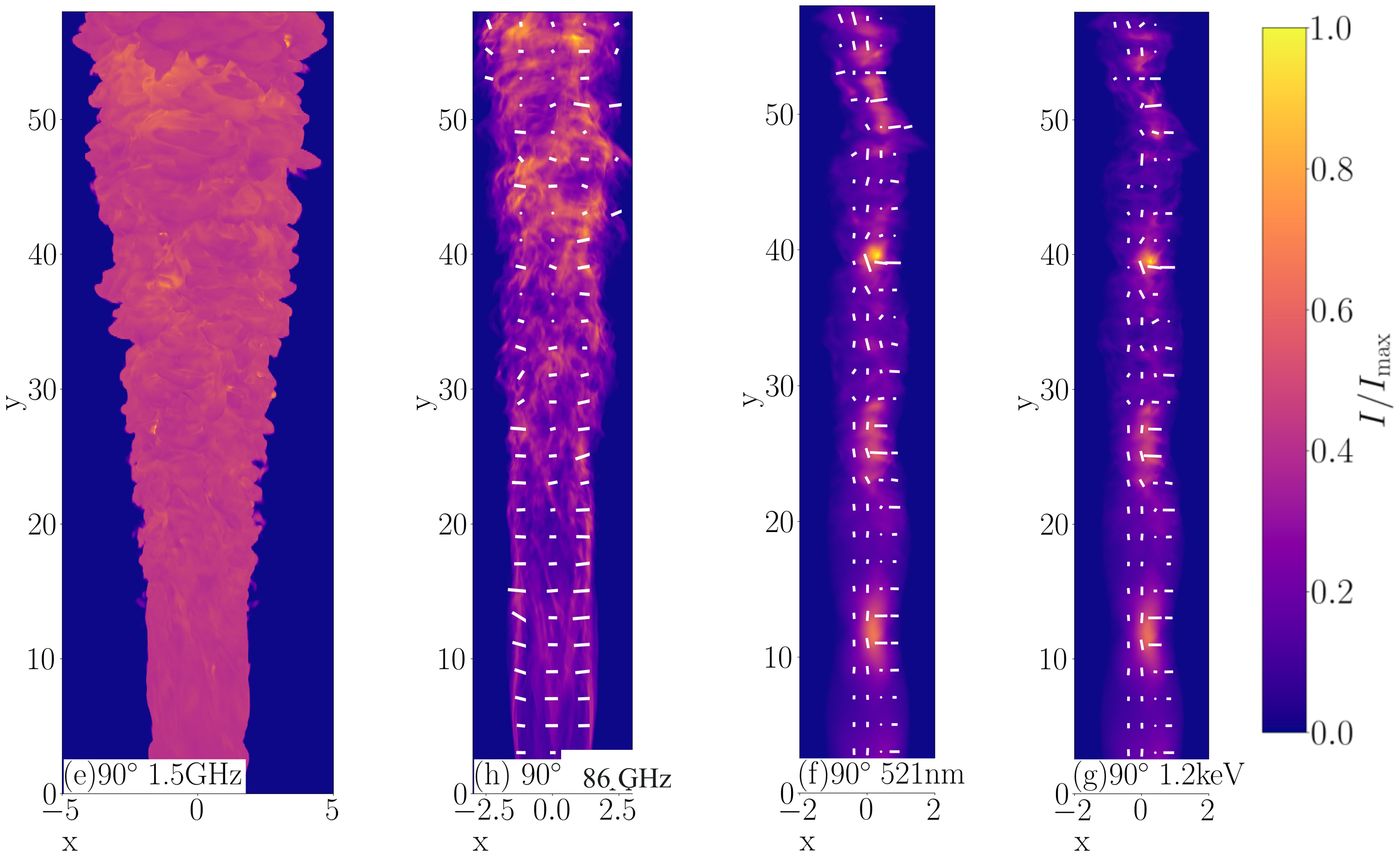
$$\gamma_0\frac{\kappa-2}{\kappa-3} < \frac{1}{1-\epsilon}(3\Theta_e + \frac{\gamma_0^3}{\gamma_0^2 + 2\gamma_0\Theta_e + 2\Theta_e^2}) \tag{B13}$$

$$3\Theta_e\frac{\kappa-2}{\kappa-3} < \frac{3\Theta_e}{1-\epsilon}(1+\frac{9}{17}) \tag{B14}$$

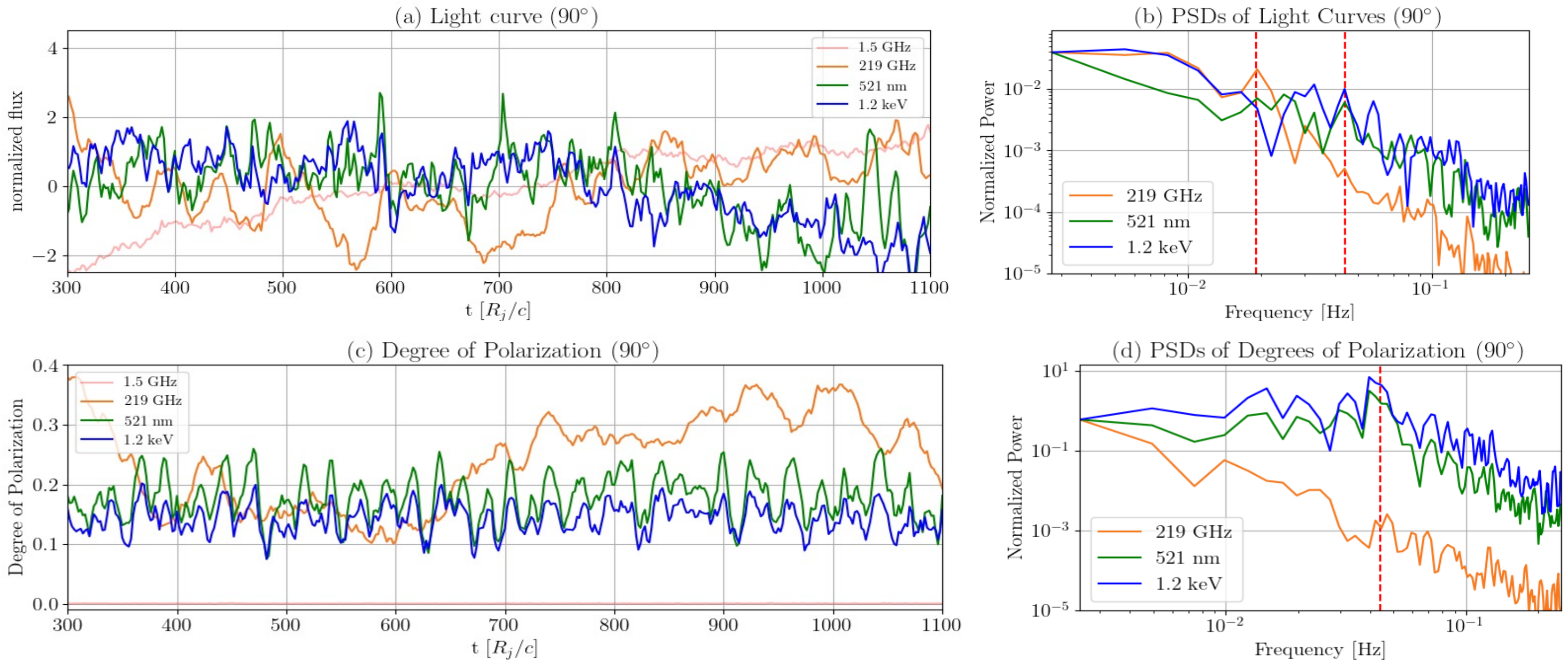
$$1 + \frac{1}{\kappa-3} < \frac{1.529}{1-\epsilon} \tag{B15}$$

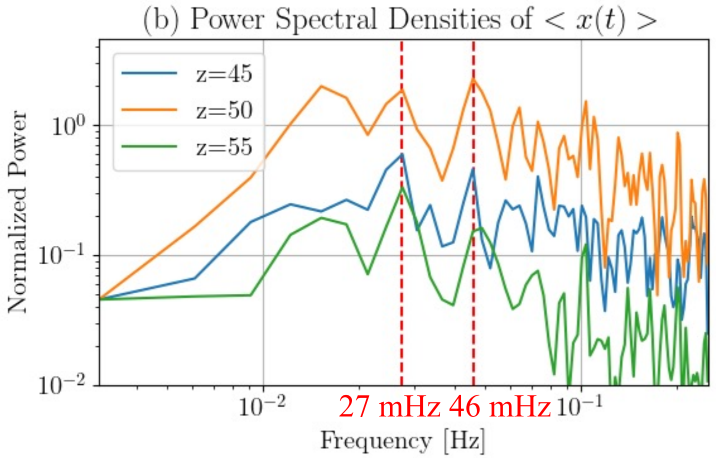
$$\kappa > 2 + \frac{1.529}{0.529+\epsilon} \tag{B16}$$

Multi-Frequency Snapshot Images at 90°

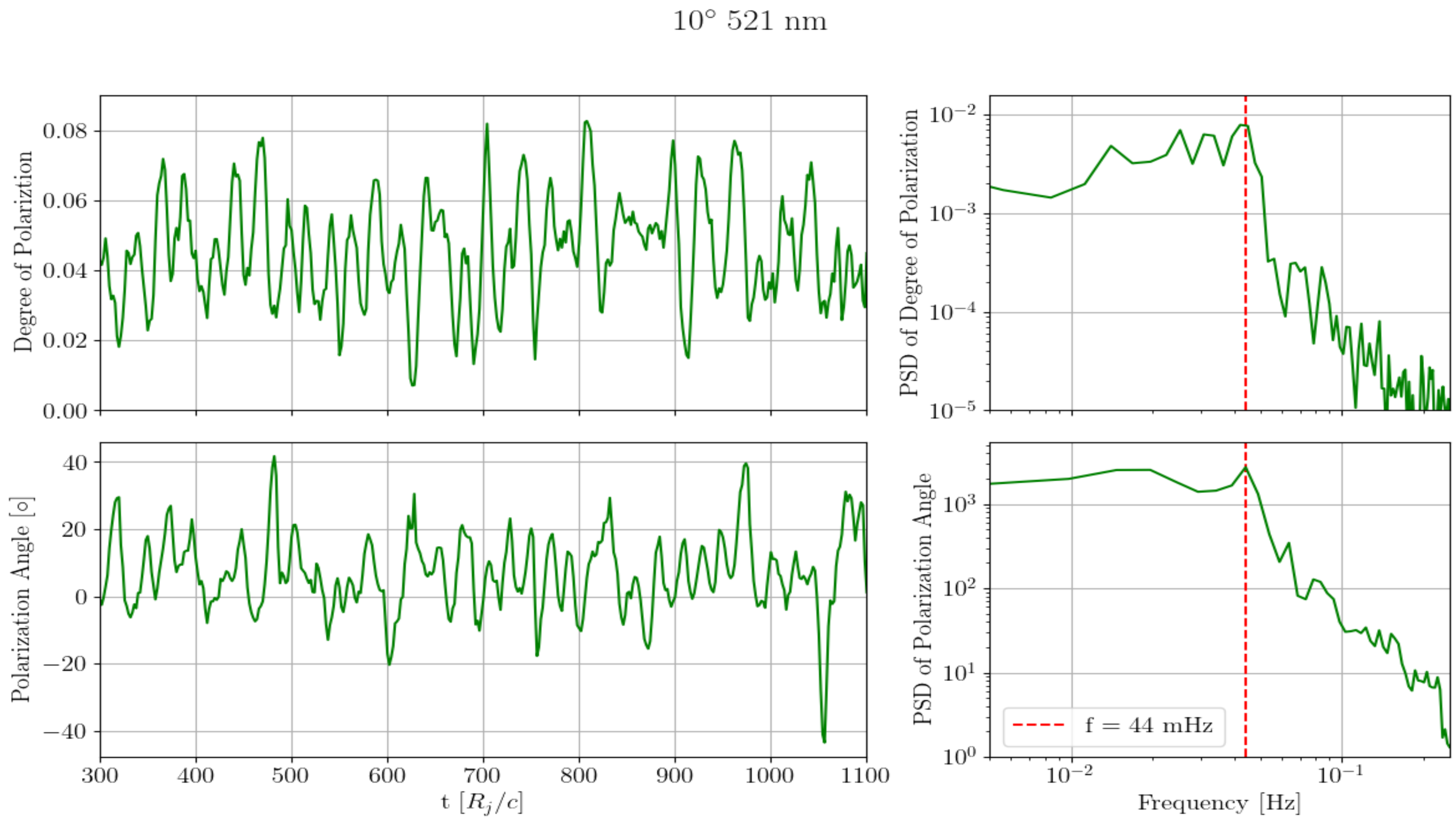


Time series analysis at 90°





optical polarization degree and angle



- Polarization degree & polarization angle shows similar quasi-periodic oscillations
- PSDs have a peak around 44 mHz

Time evolution of kink feature