Exploring the Impact of Variabilities in Relativistic Jets dynamics

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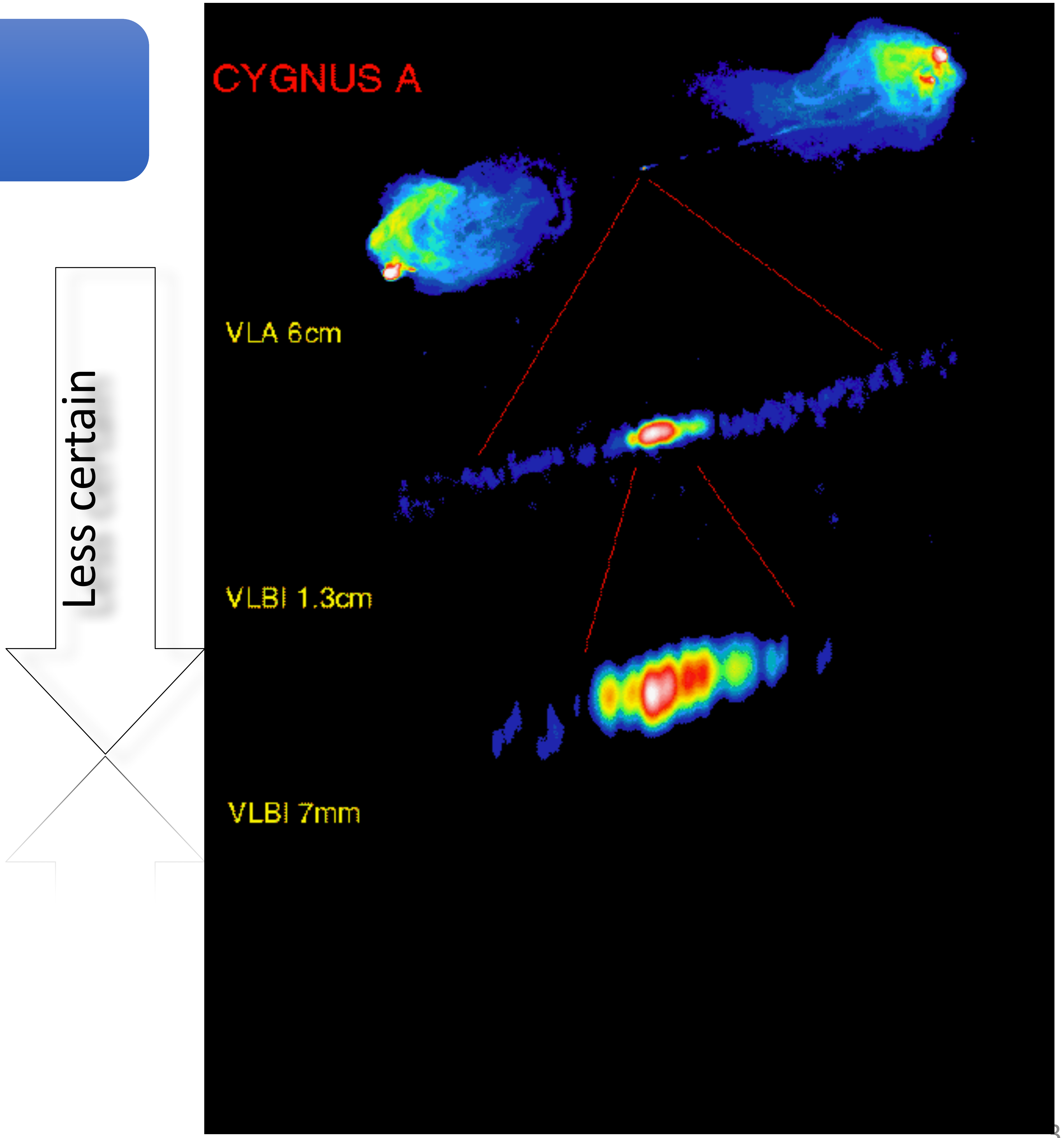
Active galactic nuclei jet

- AGN jets are observed to Mega parsec
- It can be stable to large scale
- Reach a Lorentz factor 3-50
- Magnetic field
- Synchrotron radiation (polarisation)
- Current models focus on GR-SR-MHD



standing and moving radio knots

✓ Standing shocks

- Quasi-stationnary

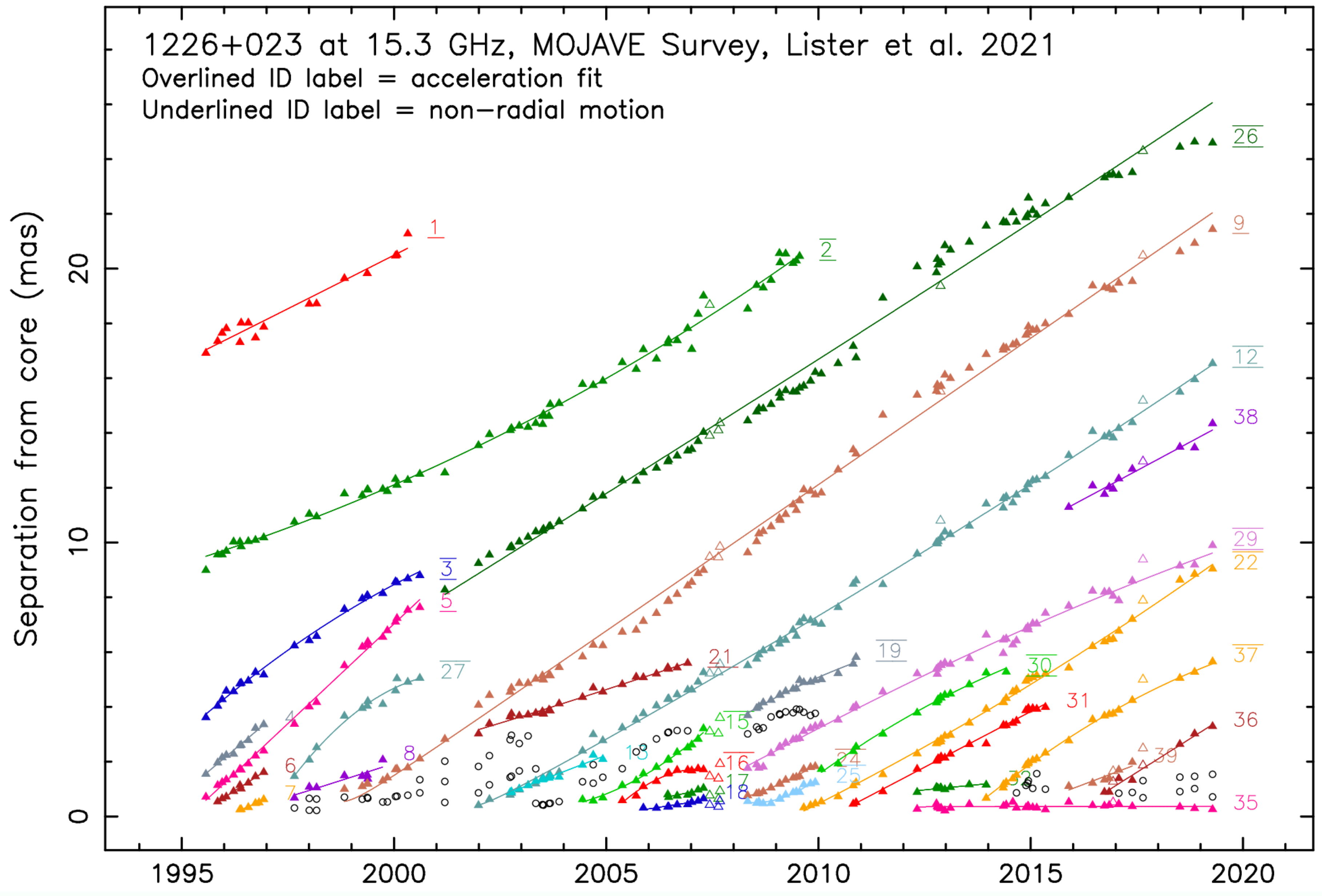
✓ Moving shock

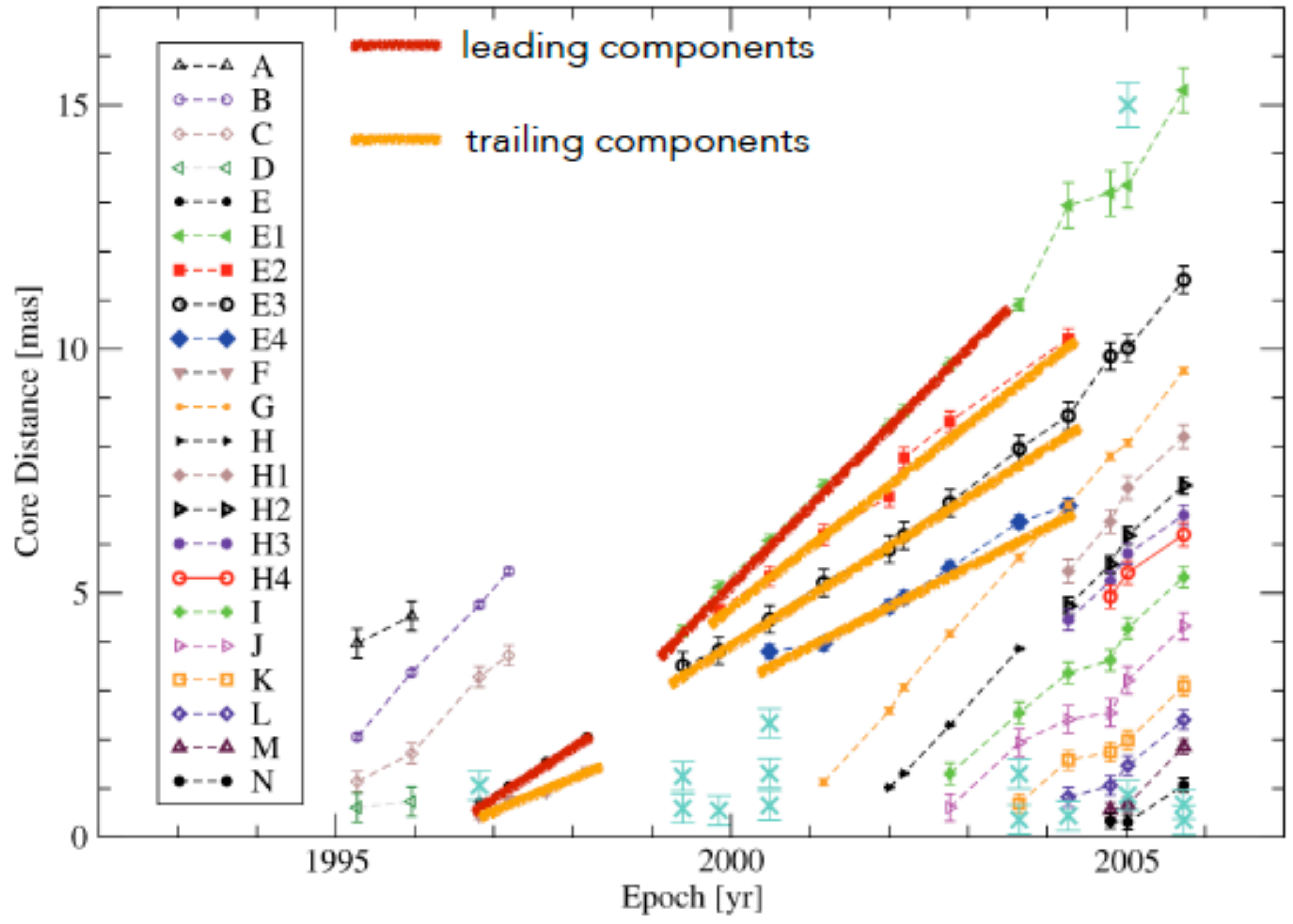
✓ trajectories ballistic

✓ trajectories accelerated

✓ trajectories bended

✓ Trailing components.





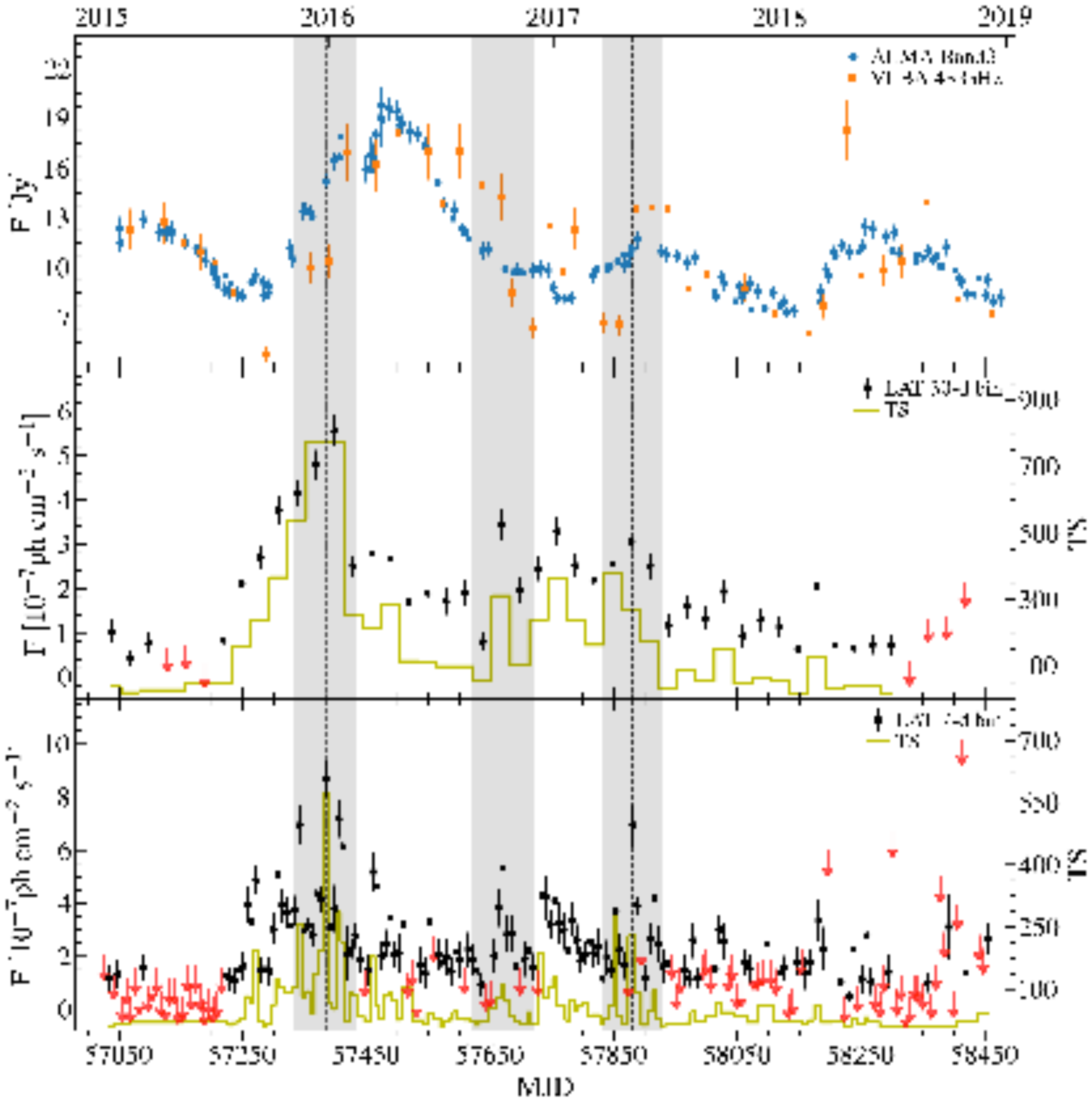
Link between flars and shocks

✓Evidence of MWL flare emission during interaction between standing and moving knots (Kim et al. 2020).

✓Apparent displacement of the standing shock + increase in brightnes

✓Rotation of EVPAs during such interactions.

- Several interpretations exist to explain such variabilities : **interaction between moving and standing knots.**



Stationnary shocks

The relativistic jet covered a large distances covered in galactic medium

- Jet becomes over pressured

Result

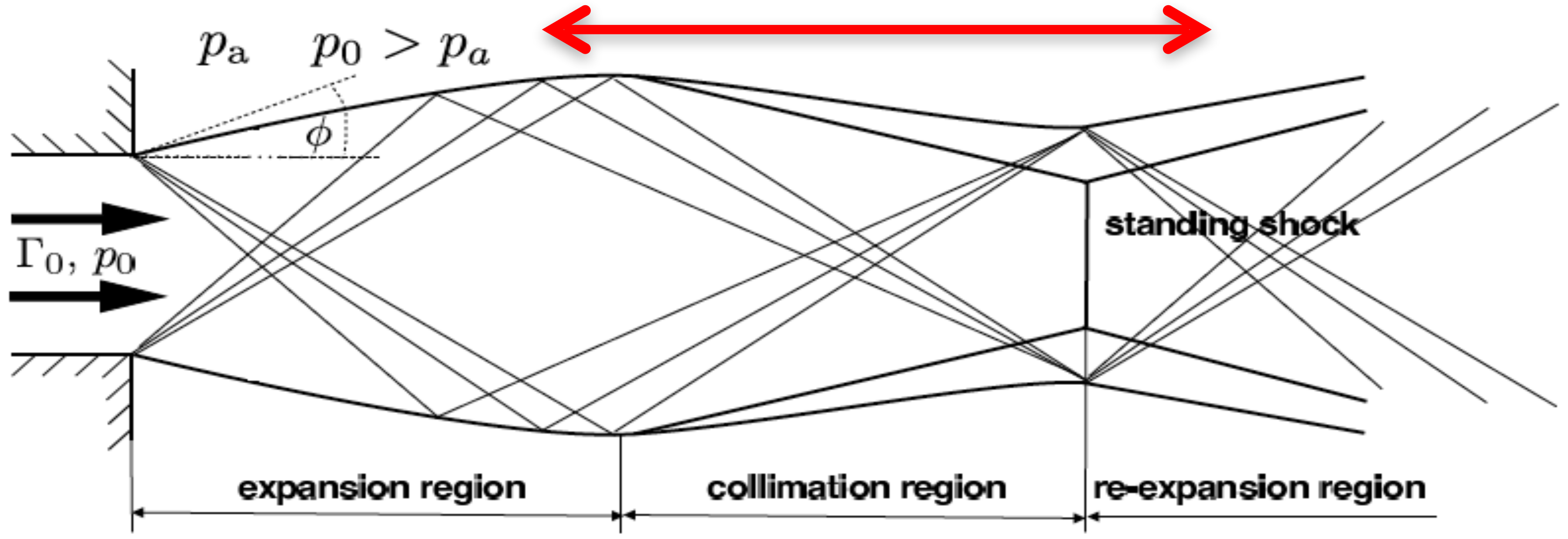
- re-collimation shocks
- Re-acceleration of the jet

Uniform jet

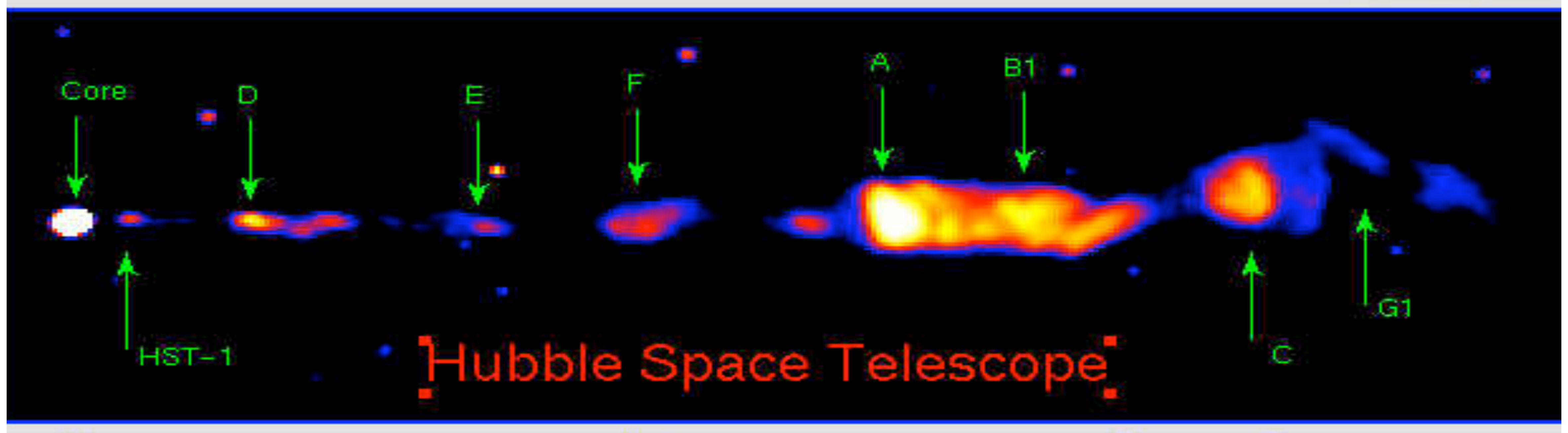
- Equidistance for cylindrical jet
- Increasing distance for the conical jet

Gómez et al 1996, Agudo et al. 2001, Mimica et al. 2009, Fromm et al. 2016, …

$$dZ=2MR$$



Daly & Marscher 1988



Interaction shock model

Jet

- Relativistic jet with Lorentz factor 3
- Cylindrical jetchecking variations of the Mach number
- Over-pressured jet

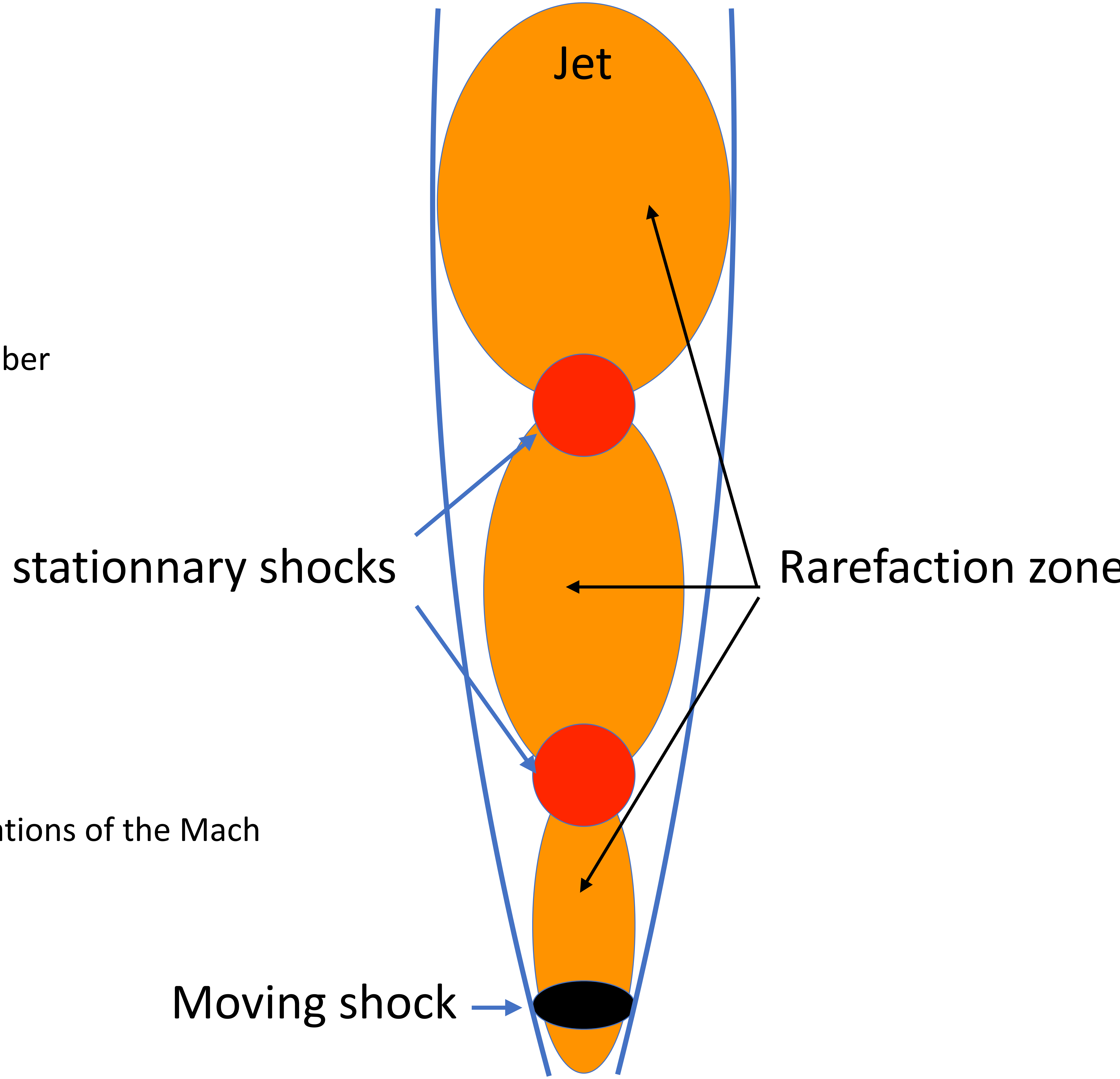
Moving shock

- Set at the jet base with Lorentz factor 12
- Radius = 1 jet radius

Electrons population

- Detect the shock regions in the jet by checking variations of the Mach number

1. Inject relativistic electrons population at shocks.
2. Radiative cooling of electrons



Moving shock

Phase 1

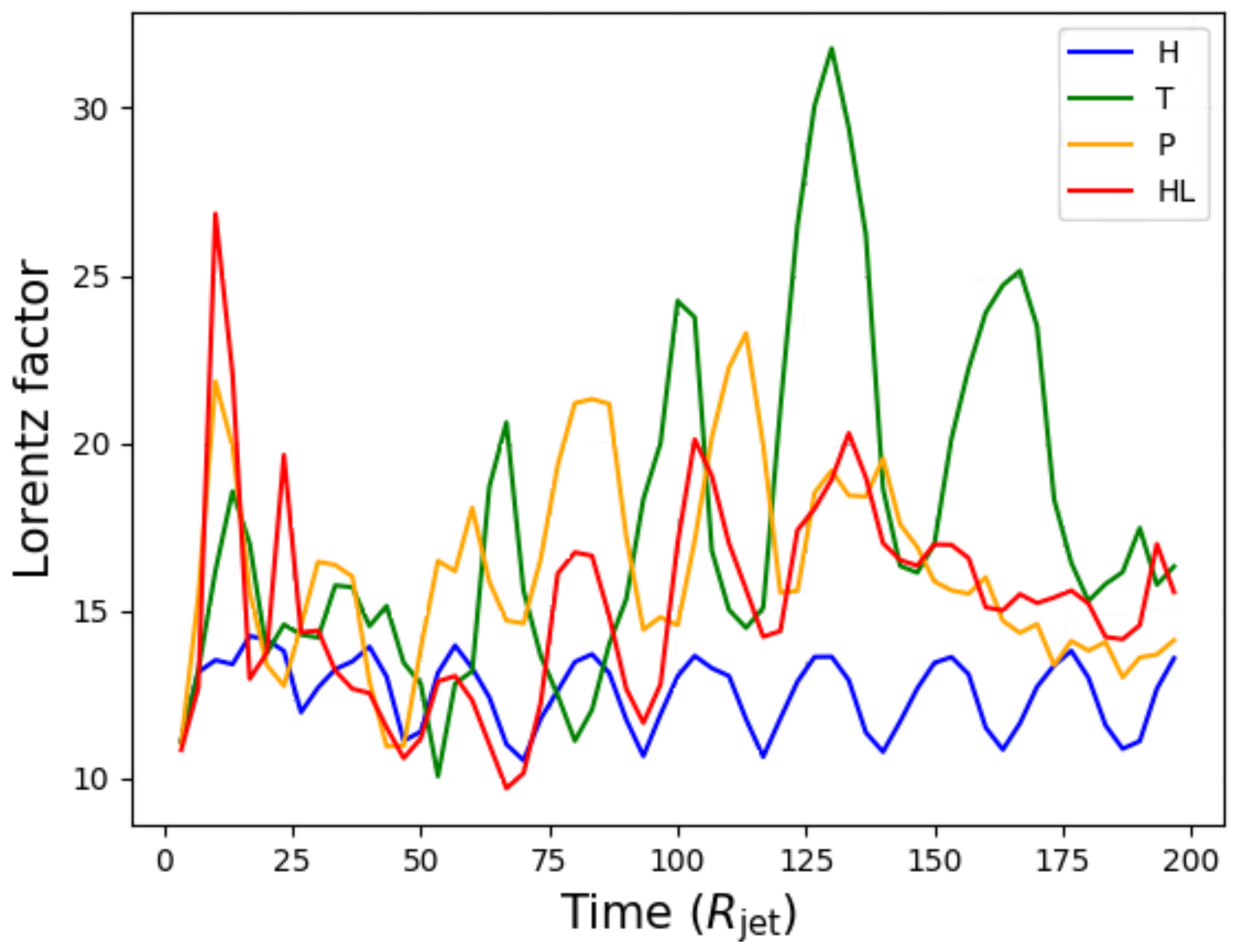
- Adiabatic acceleration

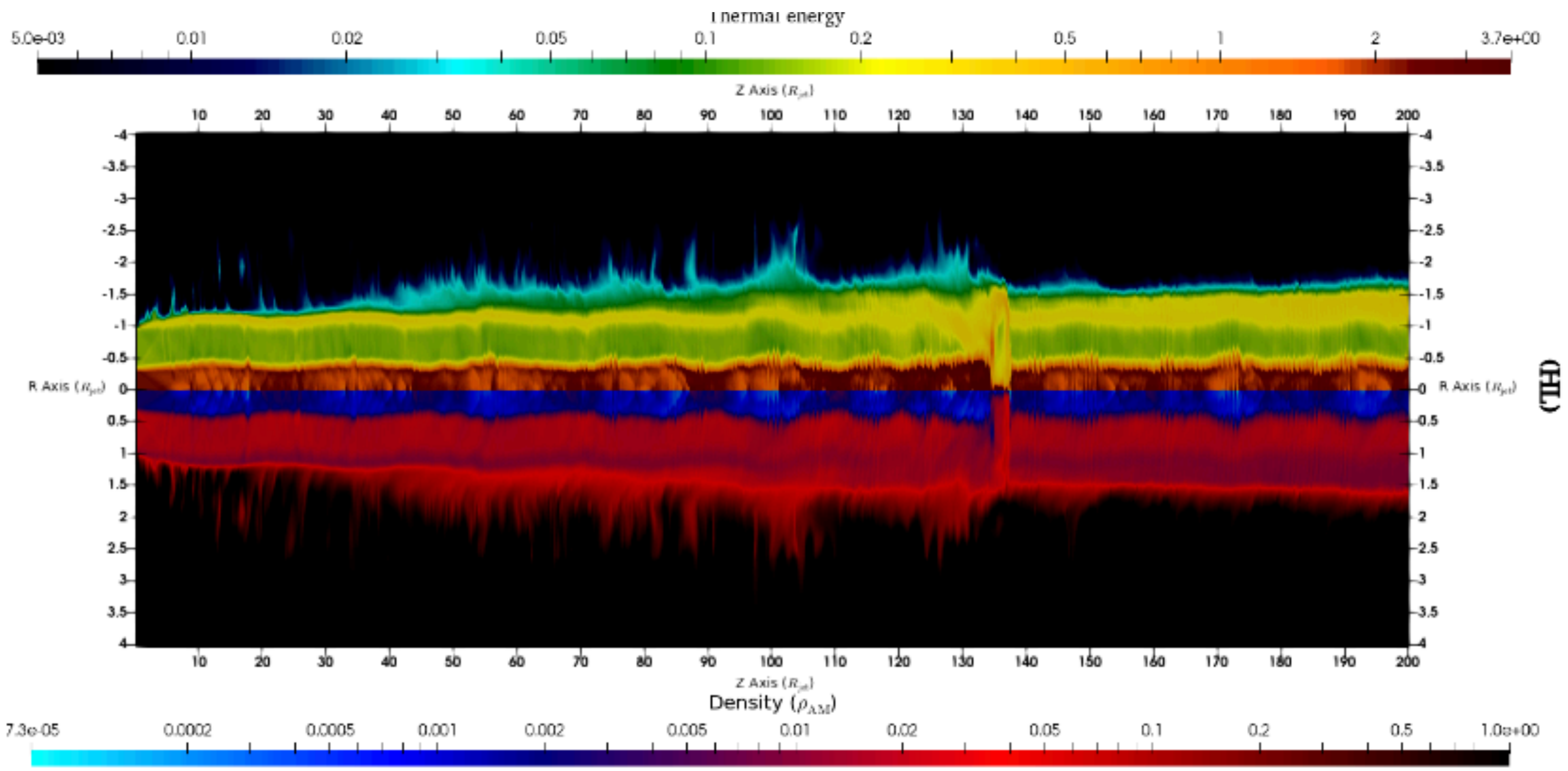
Phase 2

- Interaction with internal shocks

Phase 3

- Shock wave

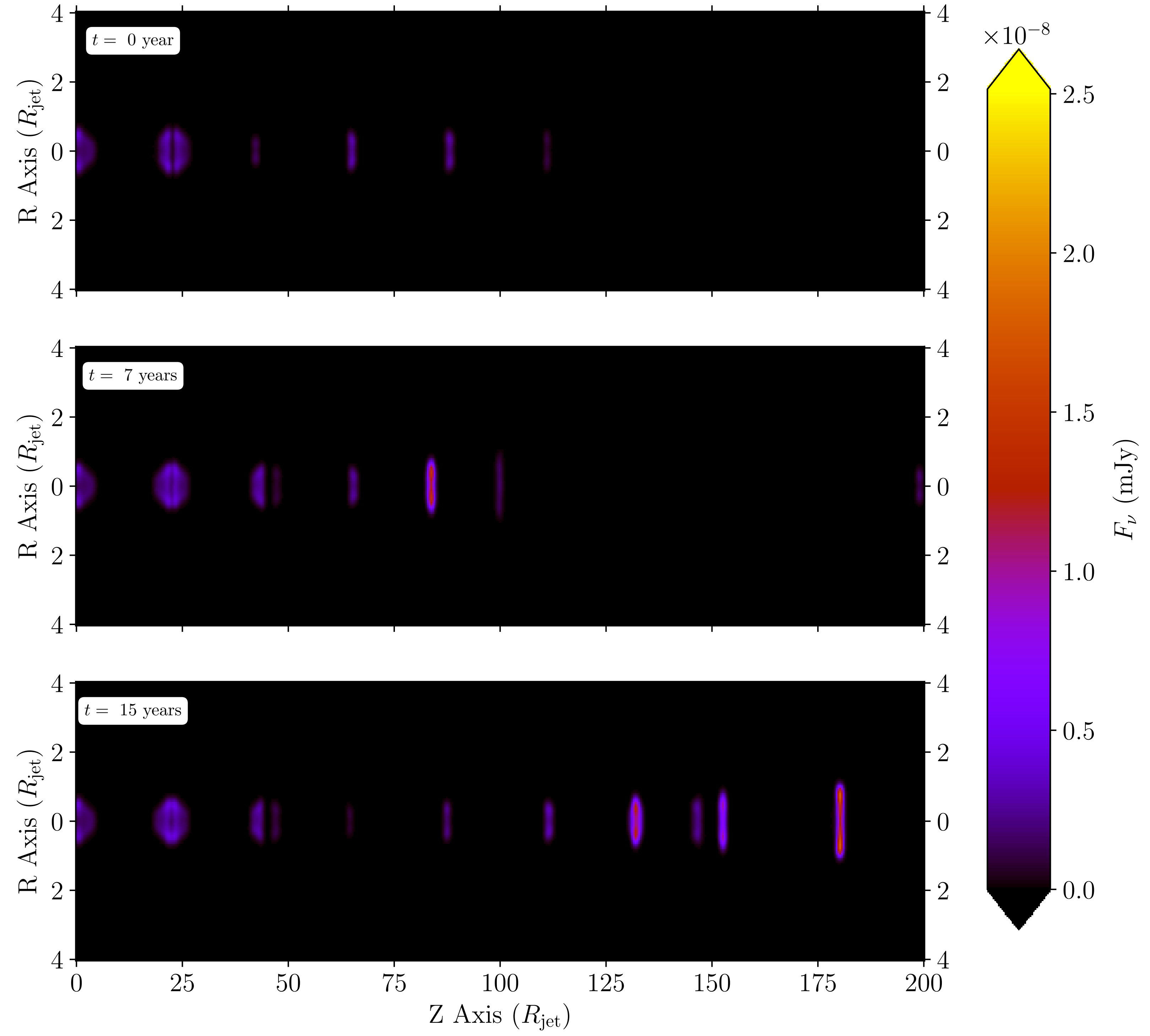




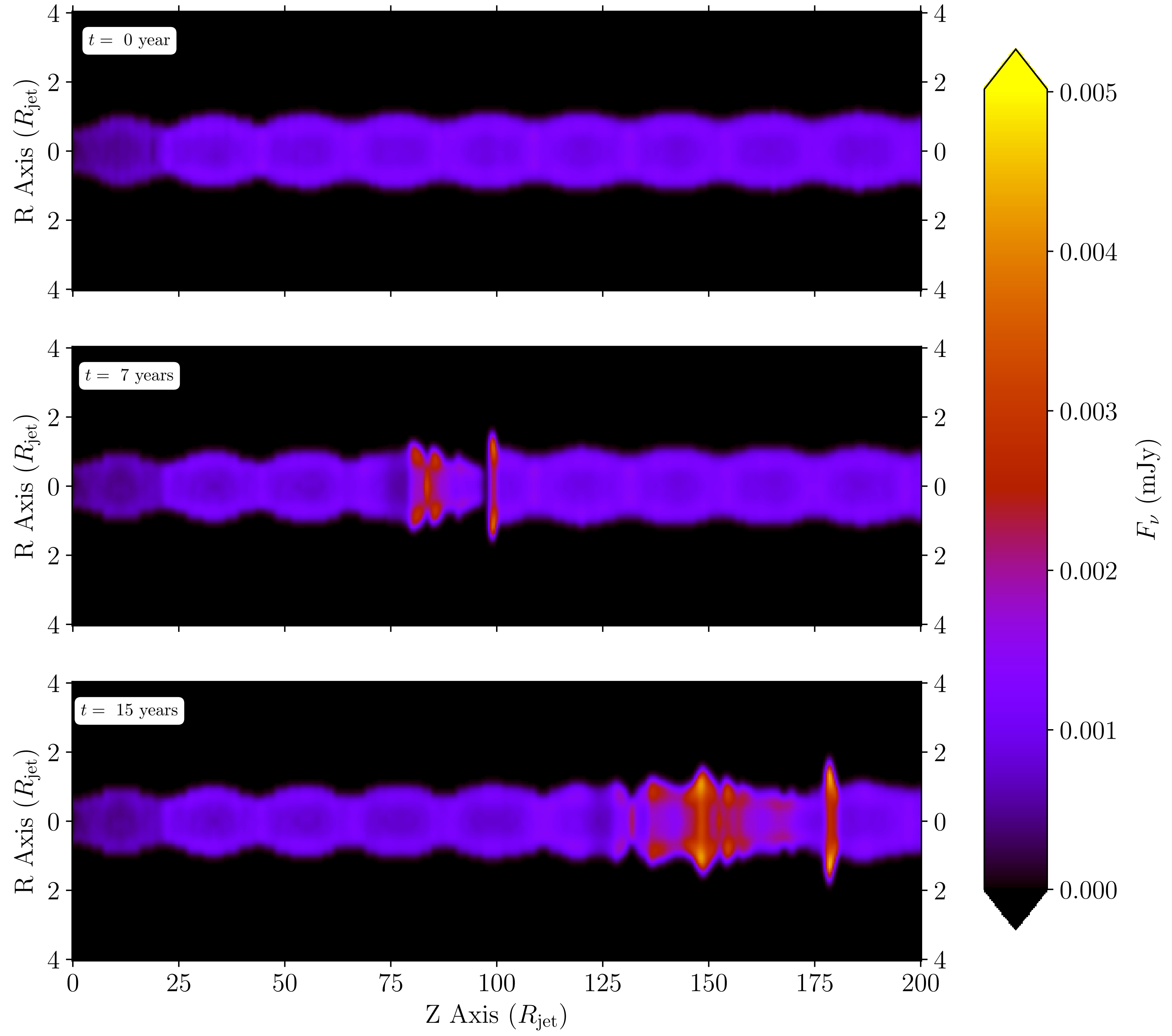
Synthetic Image

Moving shocks induces oscillation of knots

Oscillating knot responsible for the intense flare.



X-Ray $\nu = 10^{18}\mathrm{Hz}$

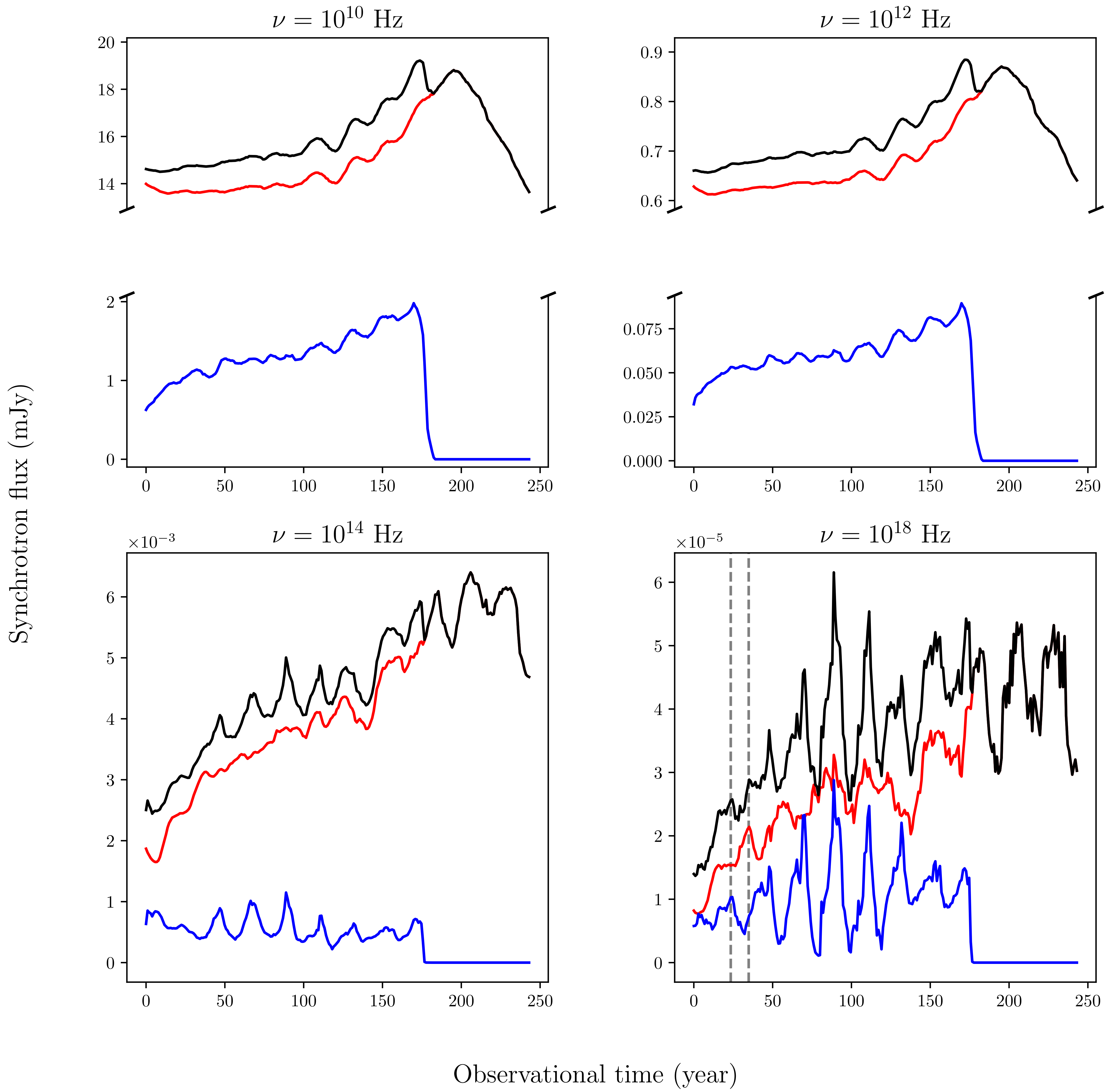


Radio $\nu = 10^{10}\mathrm{Hz}$

Light curves

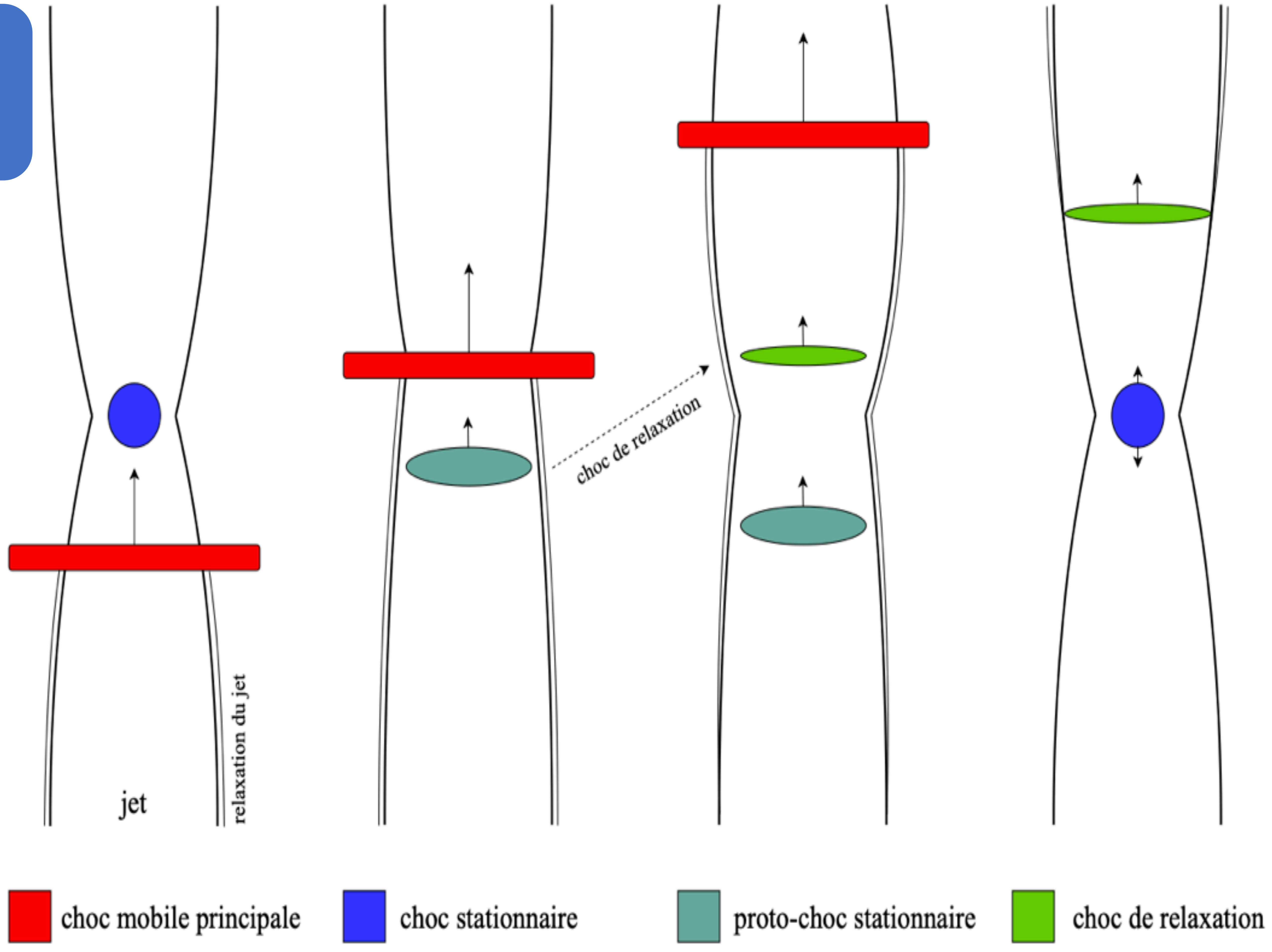
Four Different Emitting Zones

- Stationary jet, emitting from electrons (more or less extensive emission).
- Leading moving shock causing flare emission during shock-shock interactions.
- Perturbed standing shocks resulting in remnant emission.
- Relaxation shocks, each with its potential emission signature.



Relaxation shock formation :

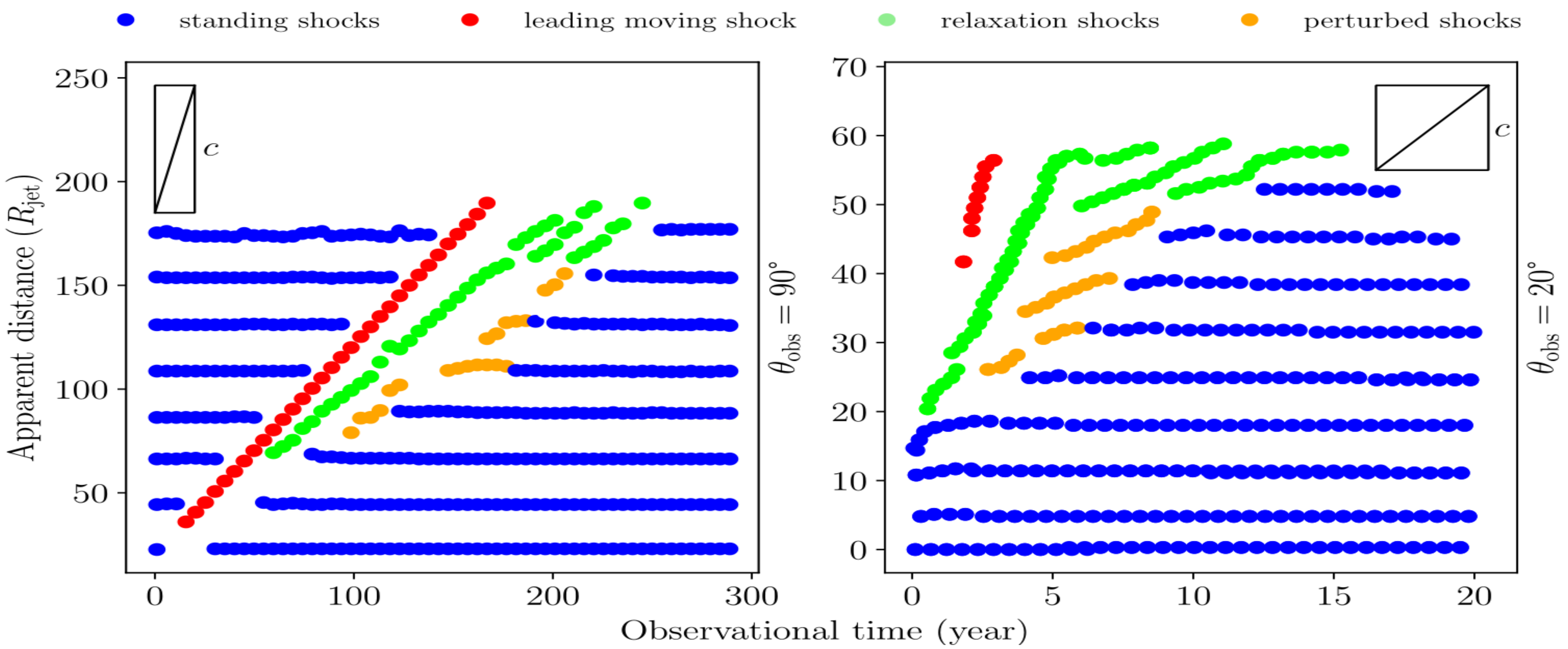
- Moving shock disturbs a standing shock.
- Standing shock relaxes by releasing a new moving shock.



Fichet de Clairfontaine, G. et al. 2022

Relaxation shock

- Relaxation shock velocities always lower than the leading one.
- Apparent motion of perturbed standing shocks.

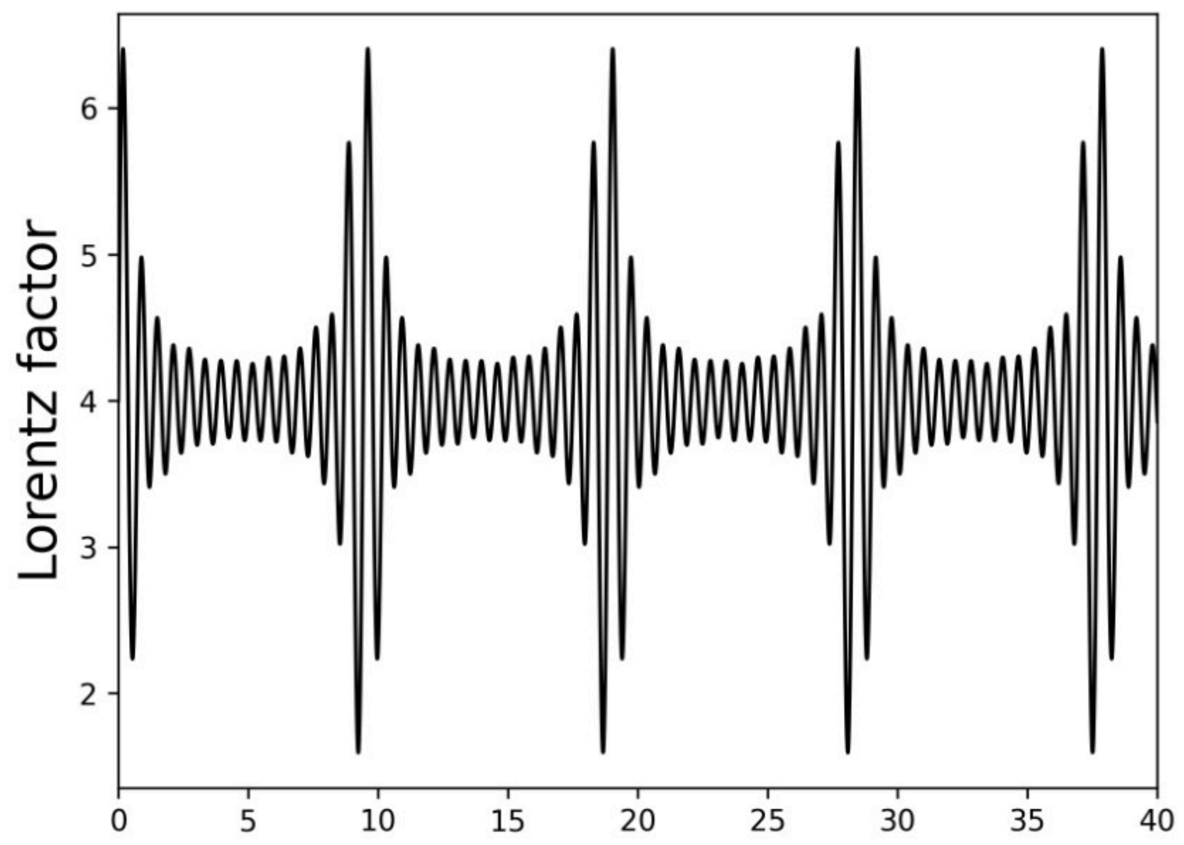


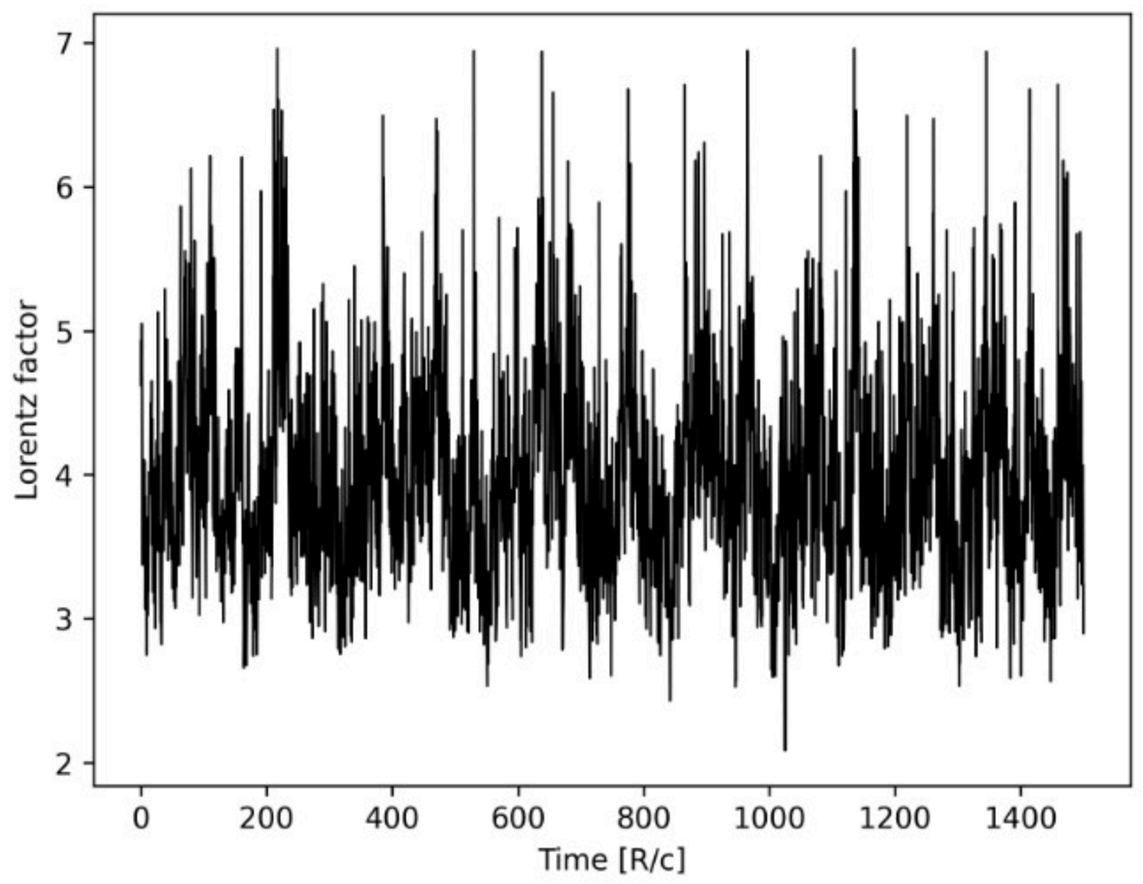
Variability Induces Internal Shocks

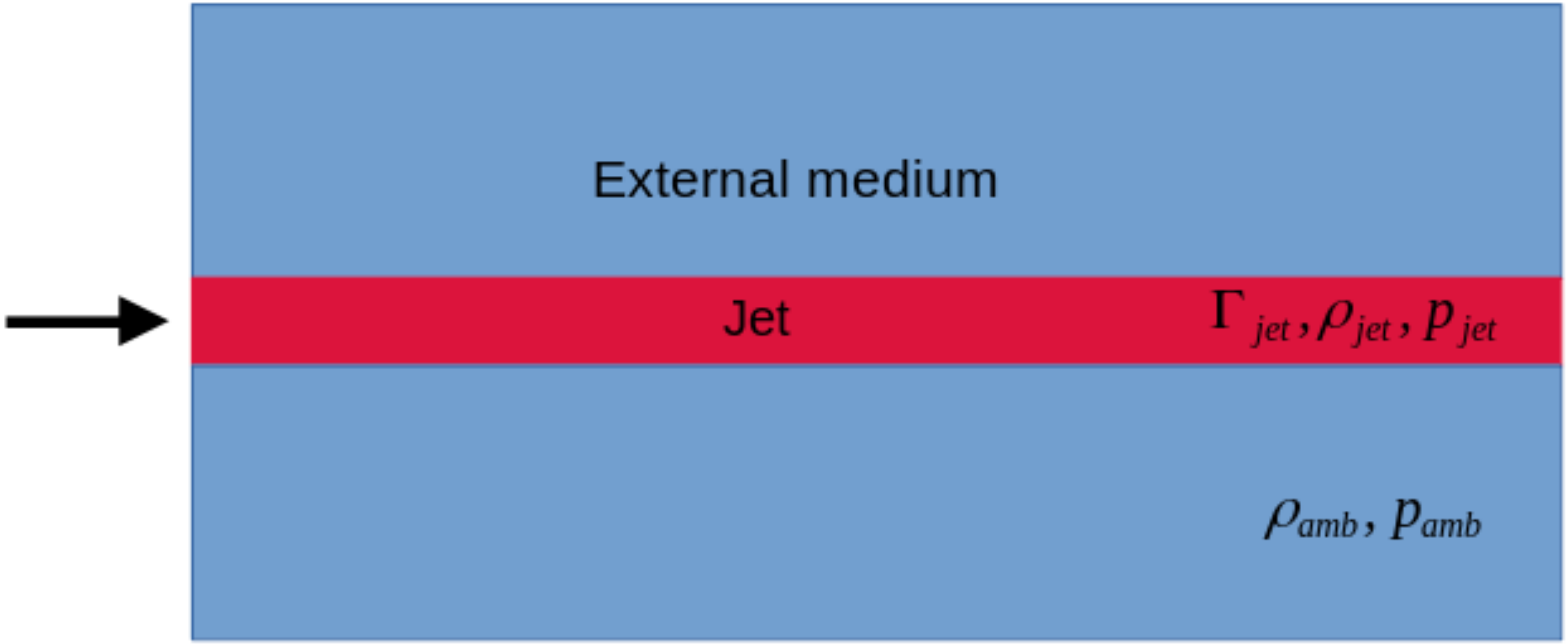
Variability at jet inlet

$$F(t) = \Gamma_{\text{jet}} + \sum_{i=1}^{N} (\Gamma_i - \Gamma_{\text{min}}) \sin(\omega_i t)$$

$\omega_{min} = 4, \omega_{max} = 10$ *and* $\Gamma_{\text{jet}} = 3.0$, $\Gamma_{min} = 2, \Gamma_{max} = 2.5$.



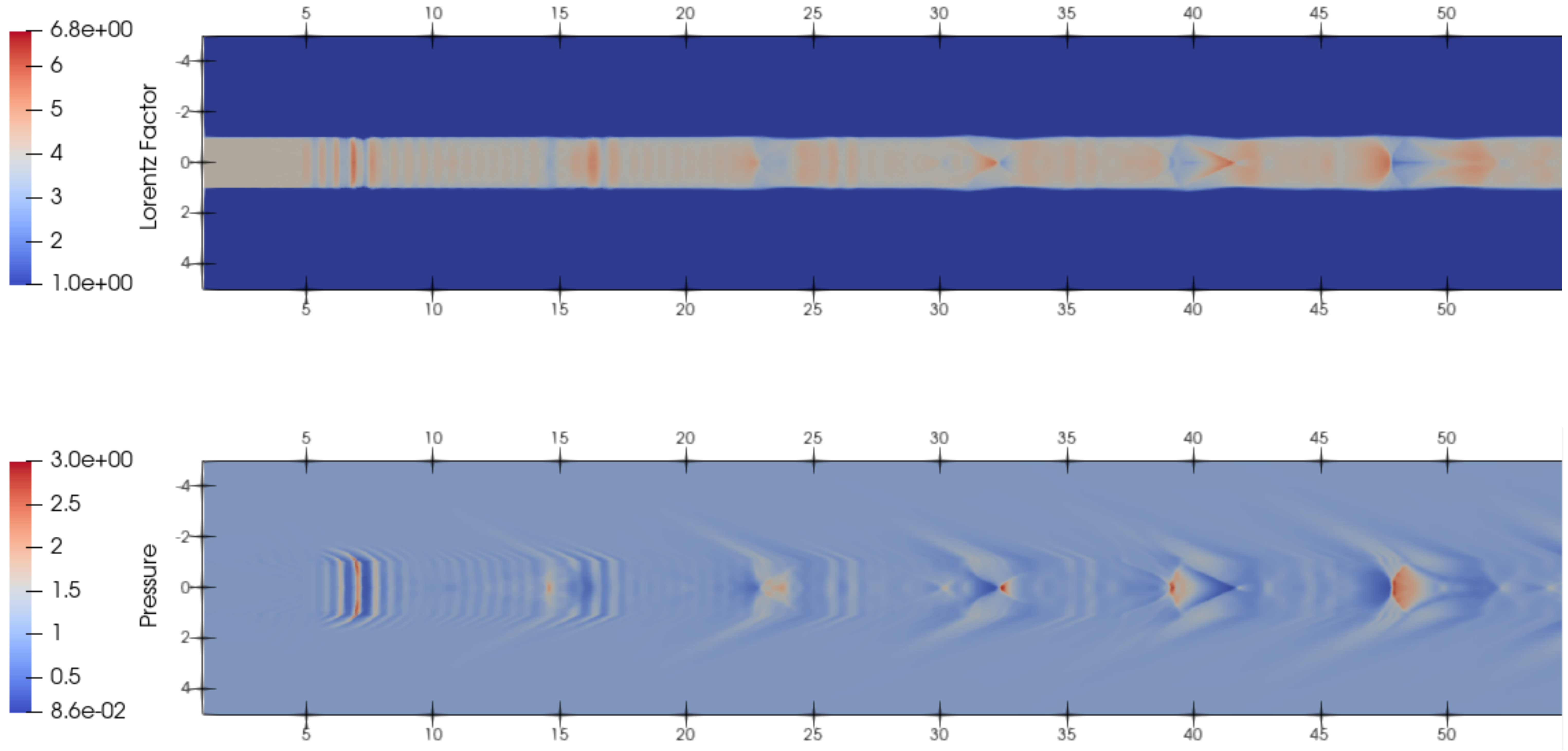




Under dense jet $\rho_{\text{jet}}/\rho_{\text{amb}} = 10^{-3}$; Pressure equiliblrium .

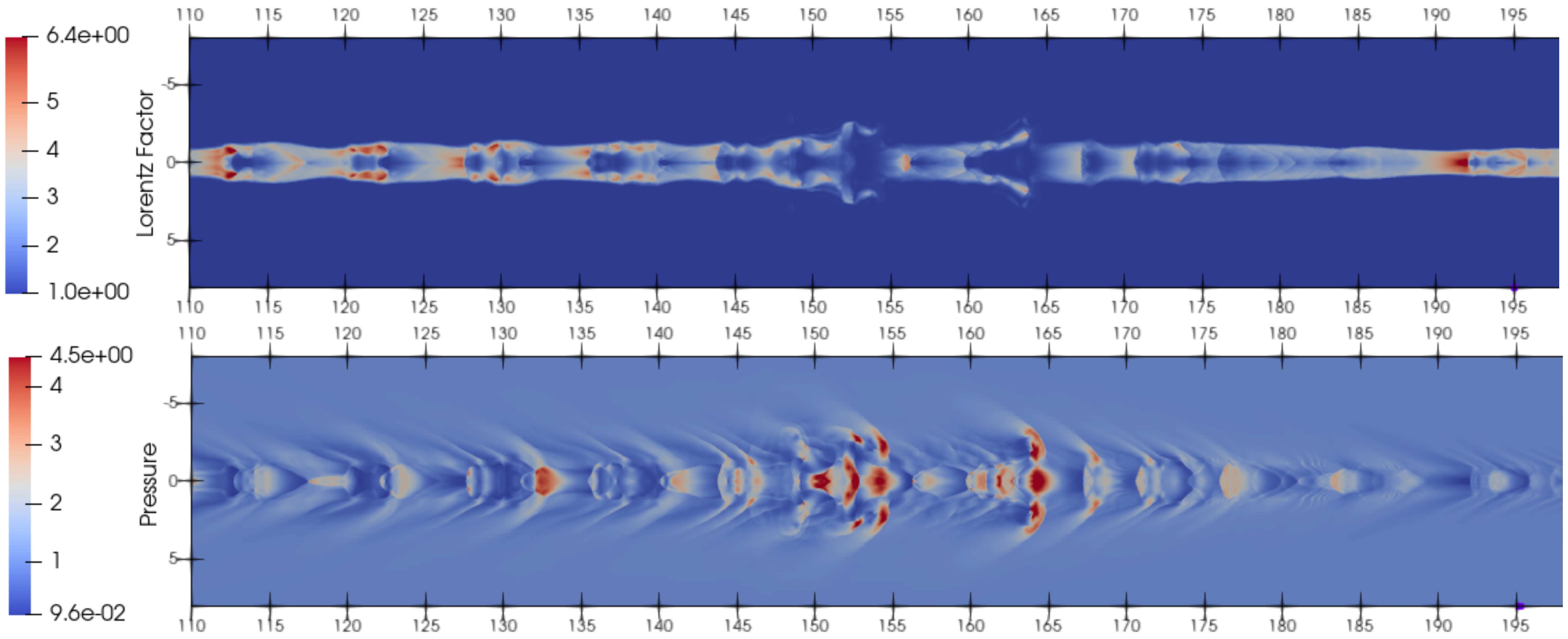
Flicker noise power spectrum (Timmer & König 1995, Malzac, J. 2012)

Periodic Variability (near the jet inlet)



- *Evolving Shock Regions in the Wake of High-Velocity Shells*
- *Sustaining and Amplifying Mobile Shock Zones Through Injected Variability at t = 100 R/c*

Rising of standing shocks



- Jet thermalisation at large scale
- Rising of Slow-Moving Shocks
- Development of slow flow regions

Dynamics of Jet Shockwaves

Downstream

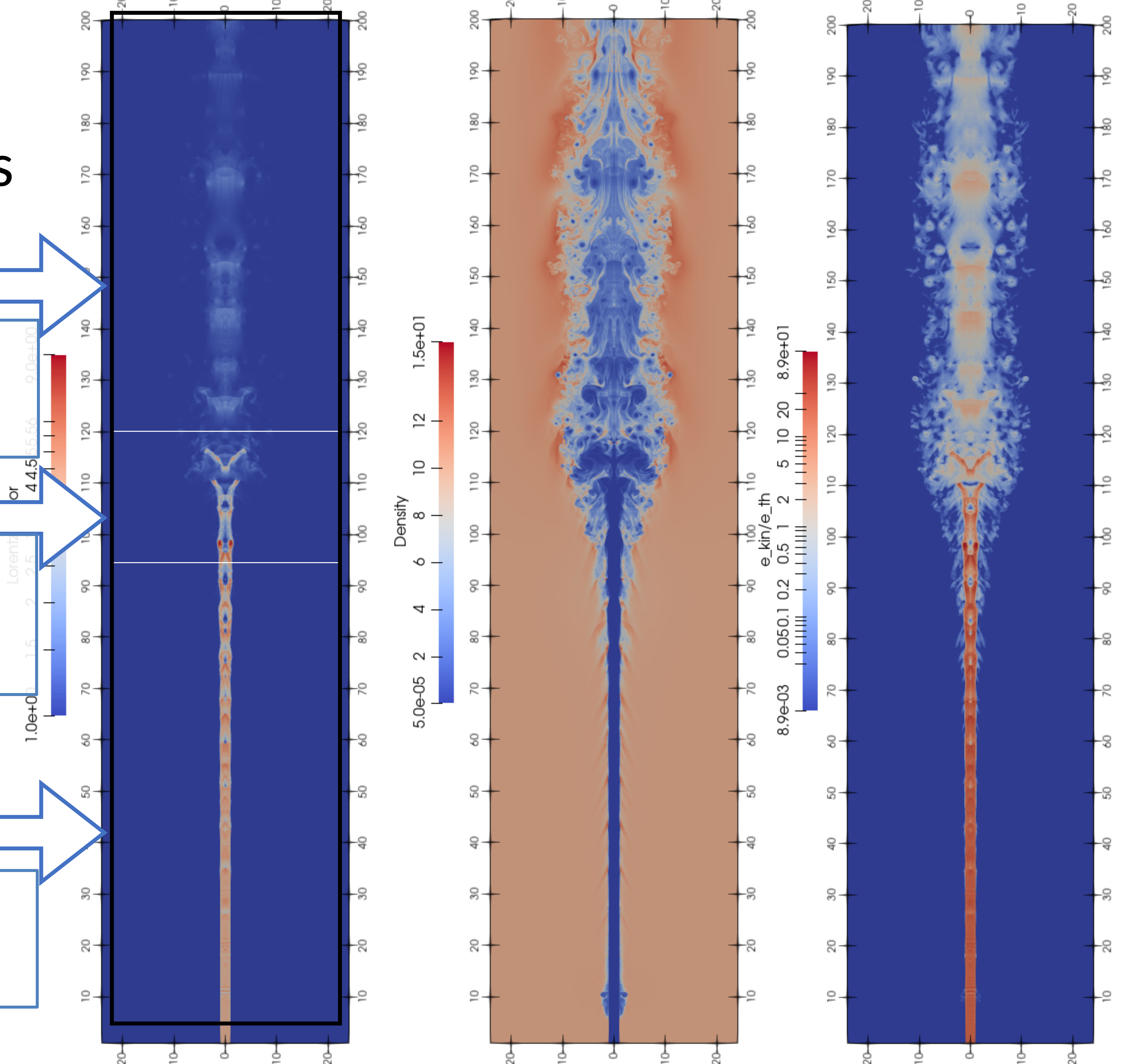
- Steady shocks
- Turbulent flow

Stationary Shock

- Jet decollimation
- Jet Deceleration and Thermalization

Upstream : Moving Shock Region

- Compression waves
- Moving Shocks

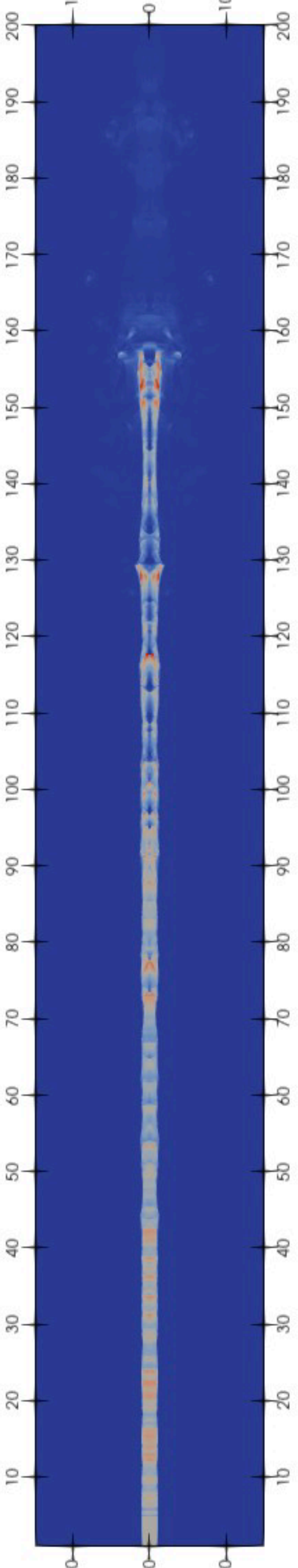


Perturbation: Flicker Noise

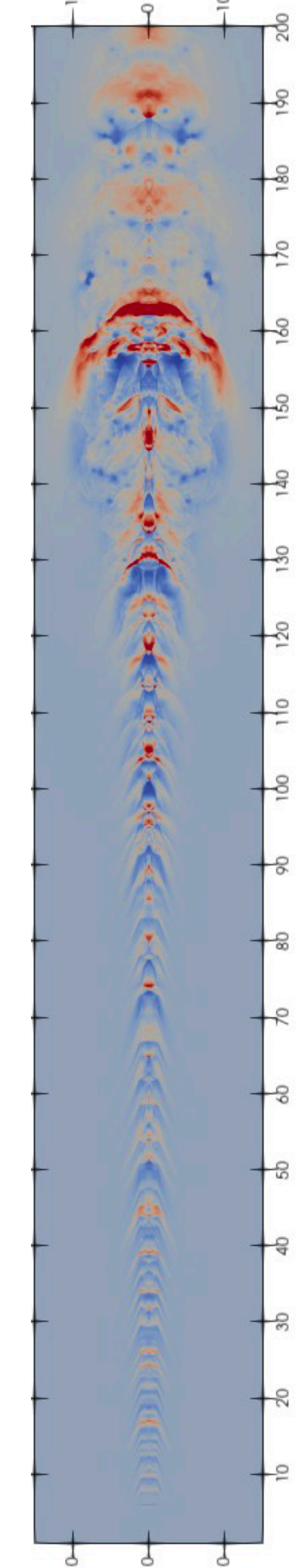
- Same Behavior as Cases with Periodic Variability

- Downstream Region
  - Reduced Turbulence
  - More Pronounced Quasi-Stationary Shocks

Lorentz Factor



Density



Synthetic Image (Periodic Variability)

Moving Shock Region

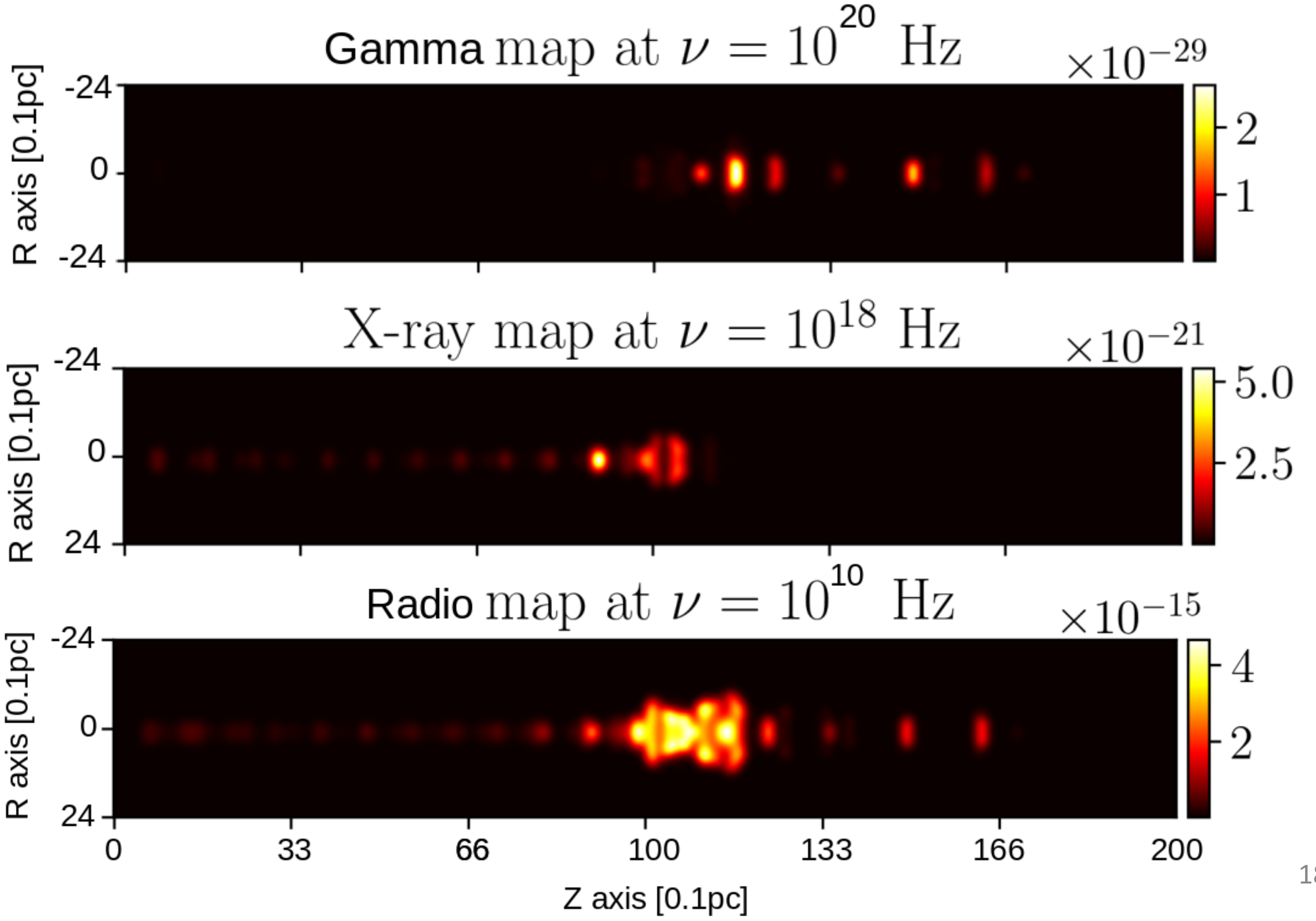
Radio
X-ray

Stationary Shock

Extended Radio
X-ray at the Shock Region

Downstream

- Steady Shocks with Radio and X-Ray



Synthetic Image (Flicker Noise)

Moving Shock Region

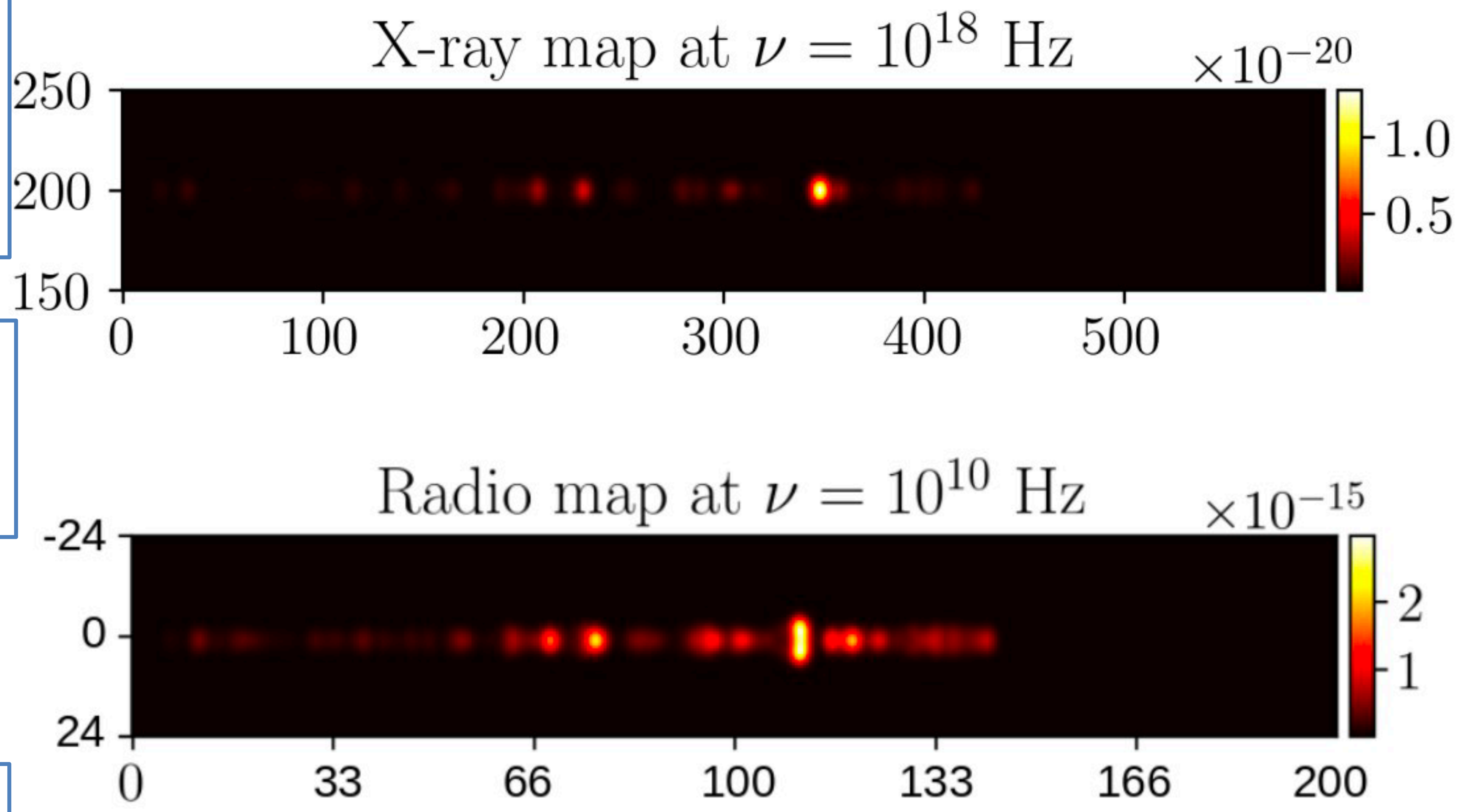
All Compression Region Emits in Radio
Shock Region Emits in X-ray

Stationary Shock

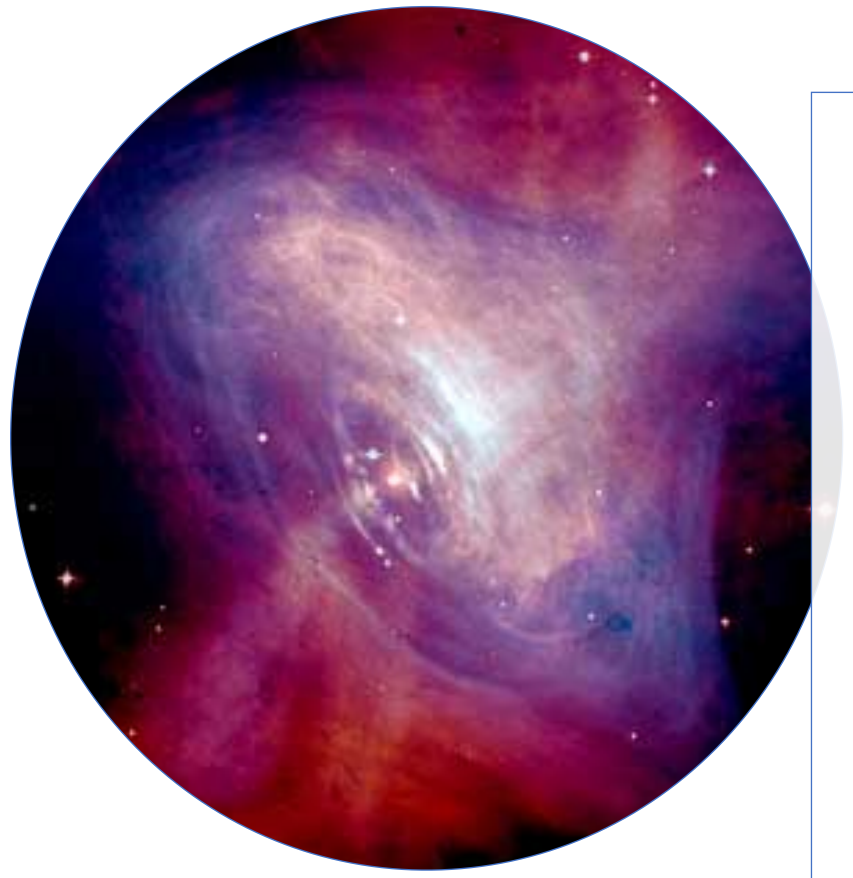
Extended Radio
X-ray at the Shock Region

Downstream

- Steady Shocks with Diffuse Radio Emission



Meliani, Z. et al. in preparation



Unveiling the Jet through Shock-Shock

- Strong shock-shock interactions result in diverse emission regions.
- Fork events and flare echoes serve as observational indicators of relaxation shocks.
- Characterizing relaxation shocks contributes to constraining jet physics and verifying the plausibility of the "shock-shock" scenario.
- Strong variability at the jet inlet could induce terminal shock and a succession of quasi-stationary shocks.