MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

PLASMA
ASTRO

Plasma Astrophysics group – Overview

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PIC simulation informed modeling of blazar emission

Artem Bohdan

Plasma Astrophysics group

Name
Artem
Christian
Daniel
Daniele
Fabien
Frank
Jieshuang
Nikita
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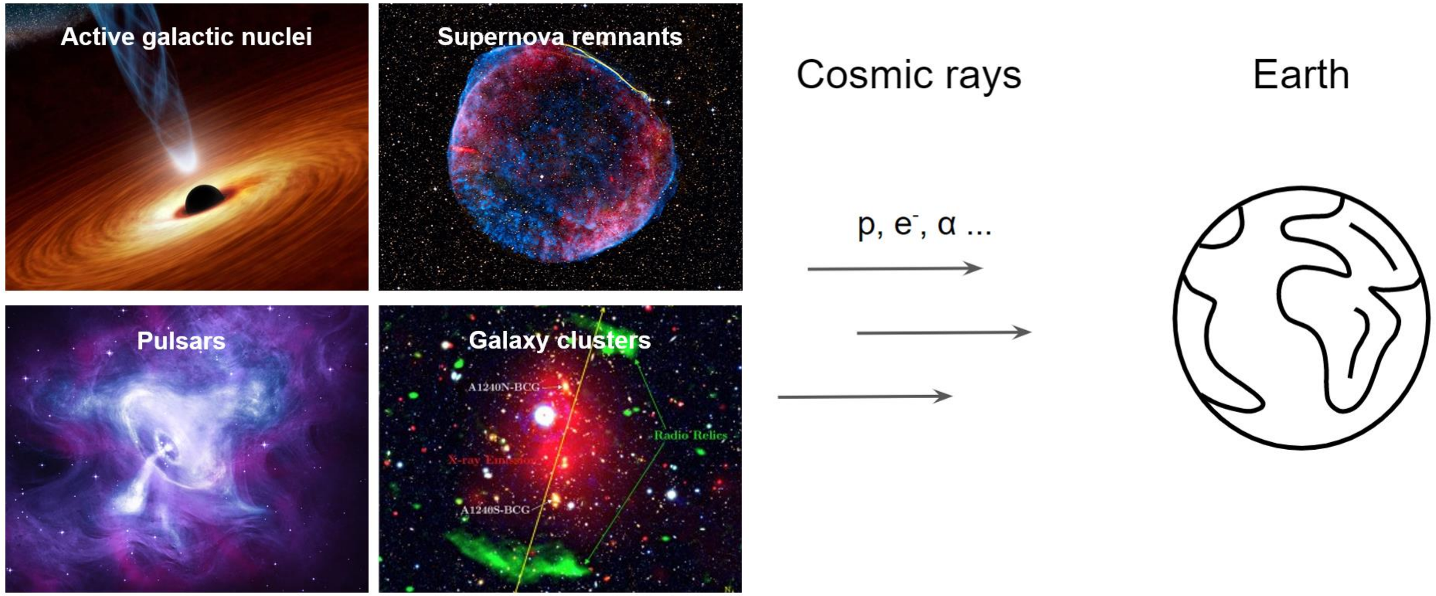
Connector 6: Cosmic accelerators



Plasma Astrophysics group

Name	Phenomena
Artem	shocks
Christian	turbulence
Daniel	turbulence
Daniele	turbulence
Fabien	turbulence, reconnection
Frank	turbulence, shear
Jieshuang	turbulence, shear
Nikita	turbulence, shear
Sreenivasa	turbulence, reconnection
Valentina	shocks
Valentine	shocks

Plasma Astrophysics group

Name	Phenomena	Objects
Artem	shocks	Earth’s bow shock, SNR, AGN
Christian	turbulence	CR, molecular clouds
Daniel	turbulence	Solar wind
Daniele	turbulence	AGN, CR
Fabien	turbulence, reconnection	AGN, accretion
Frank	turbulence, shear	AGN, UHECR, jets
Jieshuang	turbulence, shear	AGN jets, microquasars, UHECR
Nikita	turbulence, shear	AGN jets
Sreenivasa	turbulence, reconnection	Solar wind
Valentina	shocks	Earth’s bow shock
Valentine	shocks	SNR, Earth’s bow shock

Plasma Astrophysics group

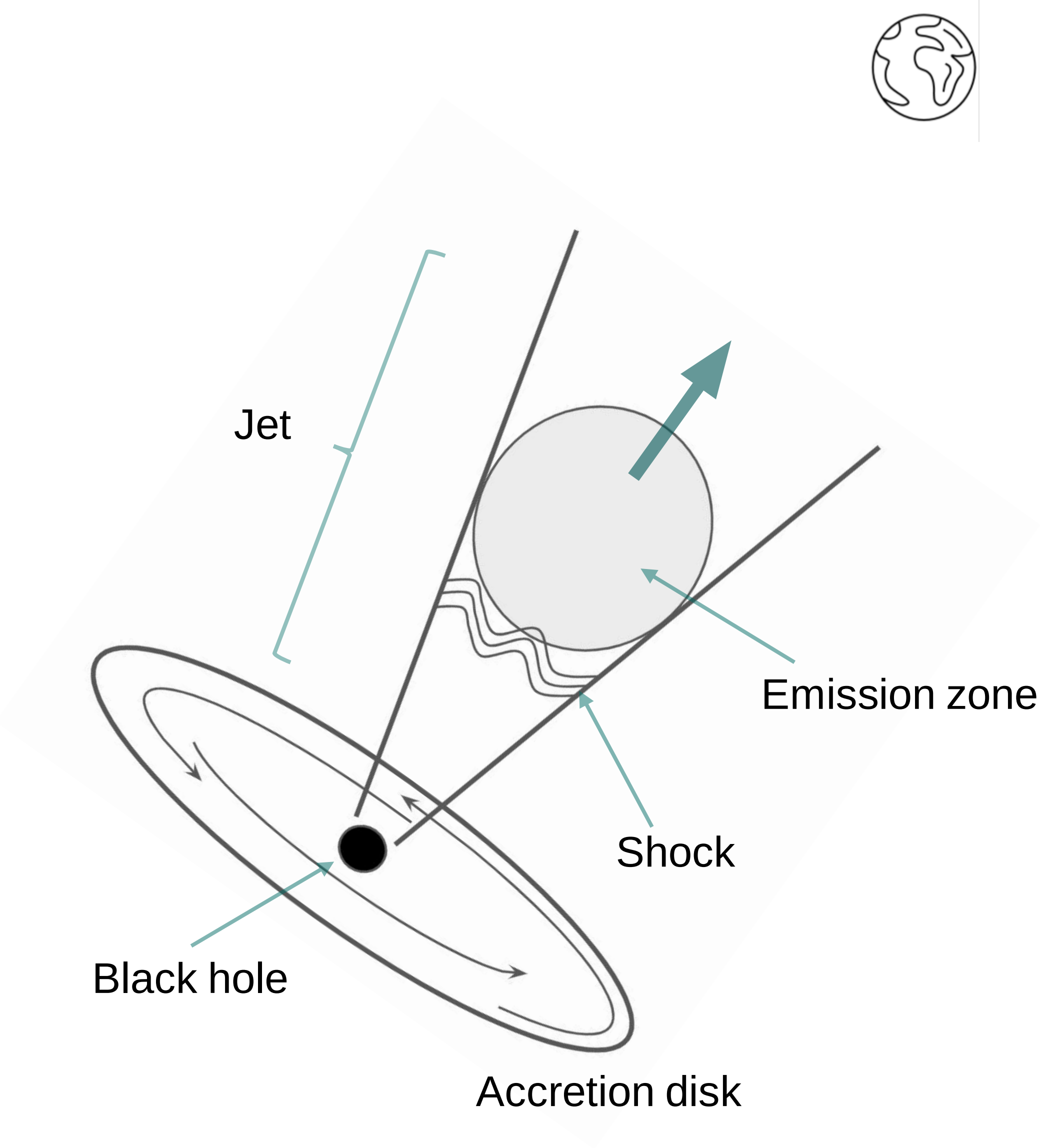
Name	Phenomena	Objects	Methods
Artem	shocks	Earth’s bow shock, SNR, AGN	PIC, semi-analytical
Christian	turbulence	CR, molecular clouds	Two-fluid MHD
Daniel	turbulence	Solar wind	Hybrid-GK
Daniele	turbulence	AGN, CR	GRMHD, test particles, GK
Fabien	turbulence, reconnection	AGN, accretion	MHD
Frank	turbulence, shear	AGN, UHECR, jets	semi-analytical
Jieshuang	turbulence, shear	AGN jets, microquasars, UHECR	MHD, test particles
Nikita	turbulence, shear	AGN jets	MHD
Sreenivasa	turbulence, reconnection	Solar wind	Hybrid-GK
Valentina	shocks	Earth’s bow shock	MMS data analysis
Valentine	shocks	SNR, Earth’s bow shock	PIC

PIC simulation informed modeling of blazar emission

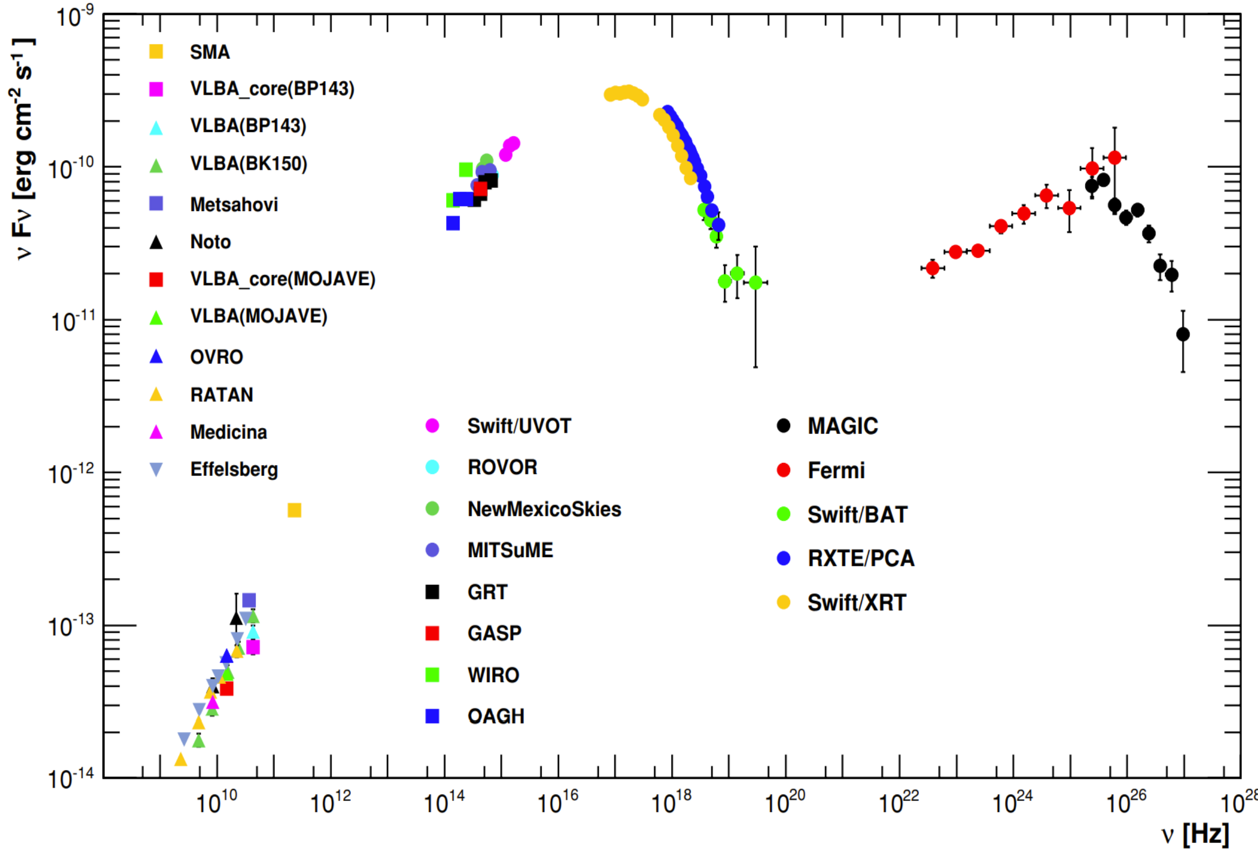
Active Galactic Nuclei (AGN)

AGN is a compact region at the center of a host galaxy that emits a significant amount of energy across the electromagnetic spectrum, which can easily outshine the host galaxy. The most promising candidate is a **supermassive black hole** (SMBH) at the center of the host galaxy.

Blazar emission and shocks in AGN jets

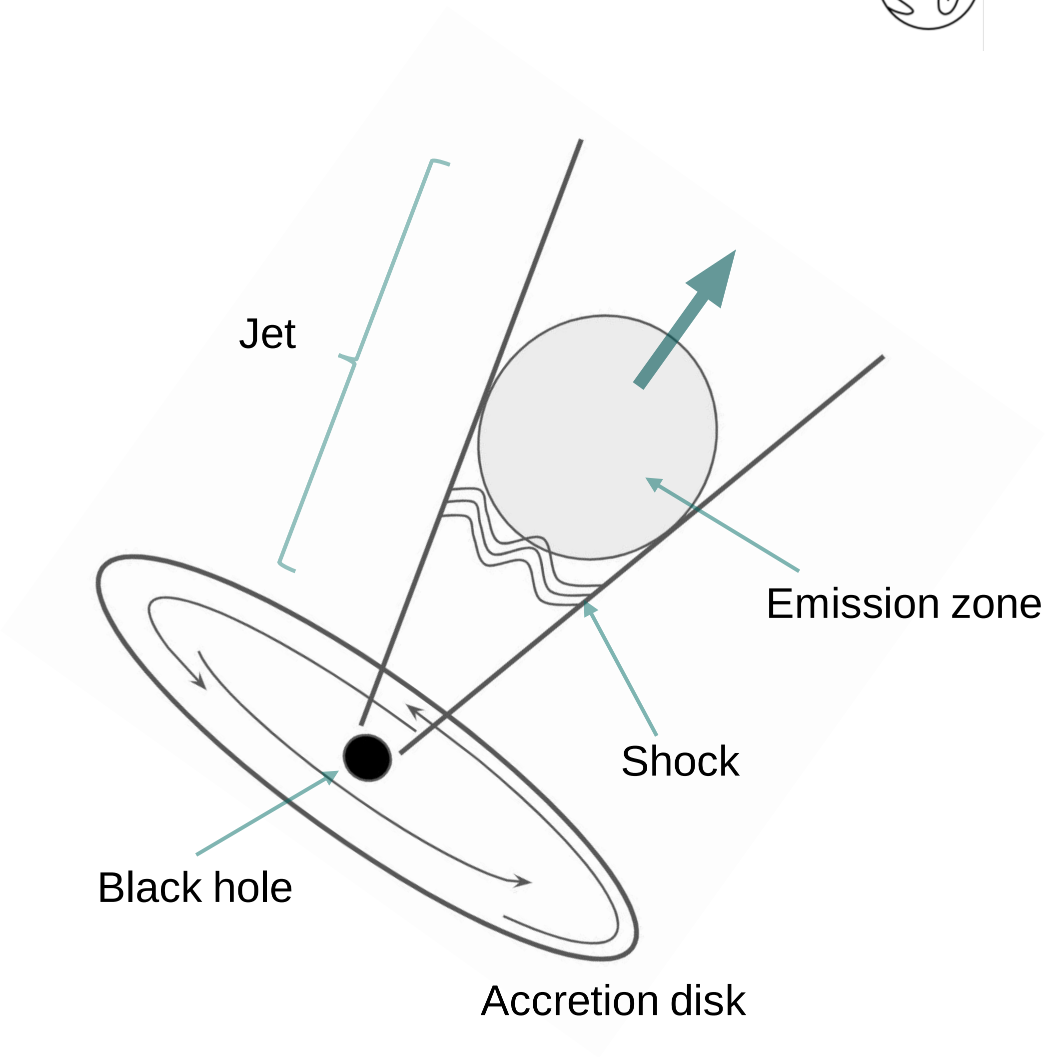


Emission of Mrk421

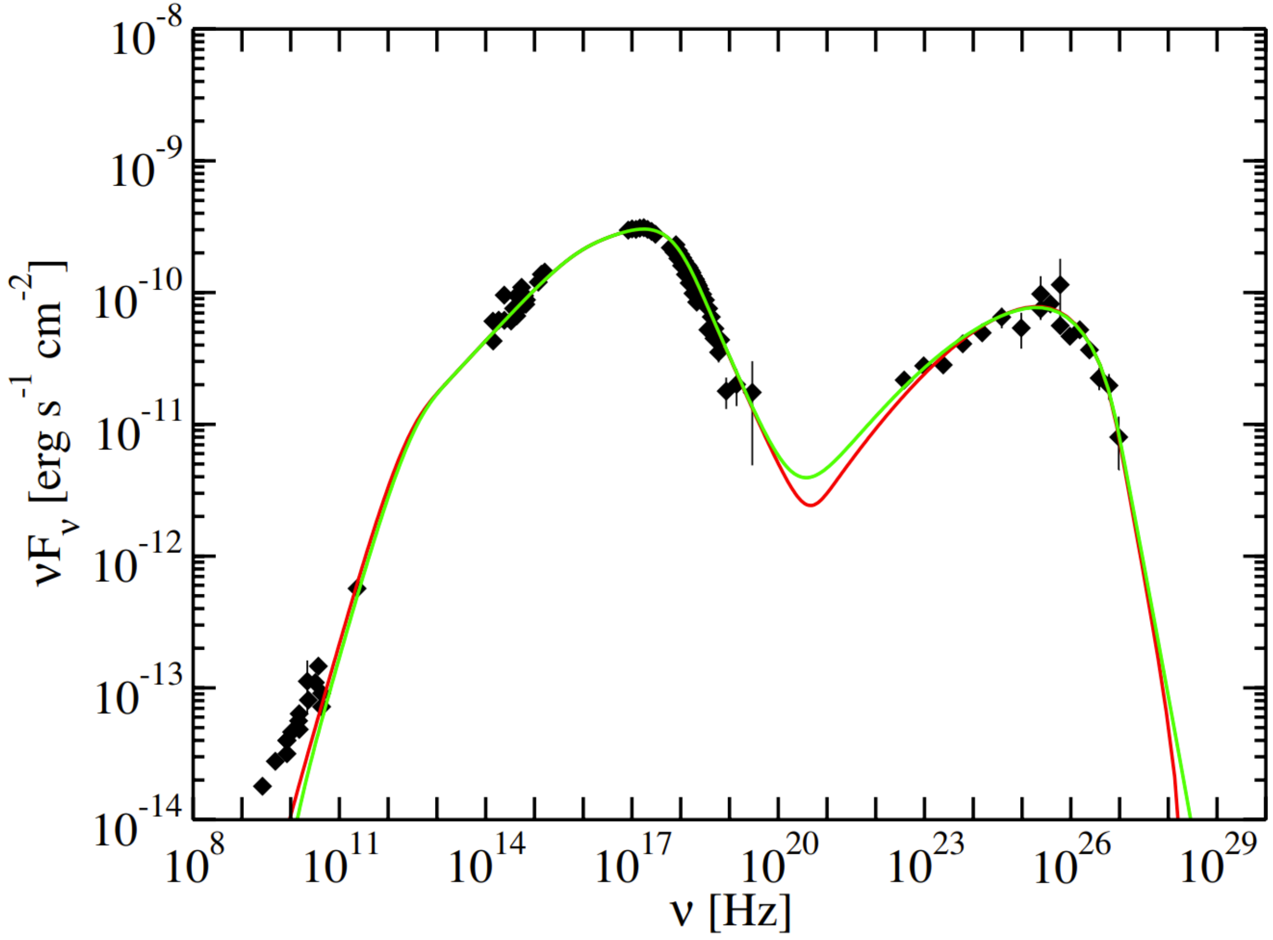


(Abdo et al. 2011)

Blazar emission and shocks in AGN jets



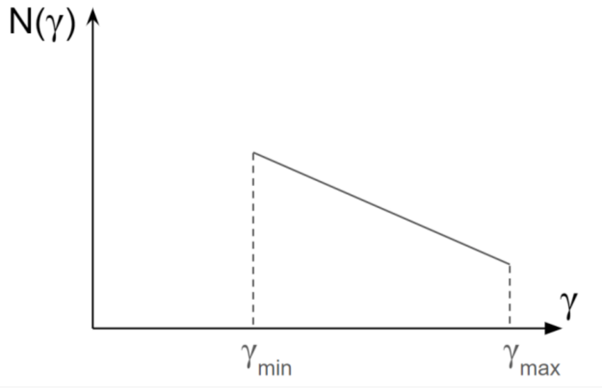
Emission of Mrk421 + synchrotron self-Compton model



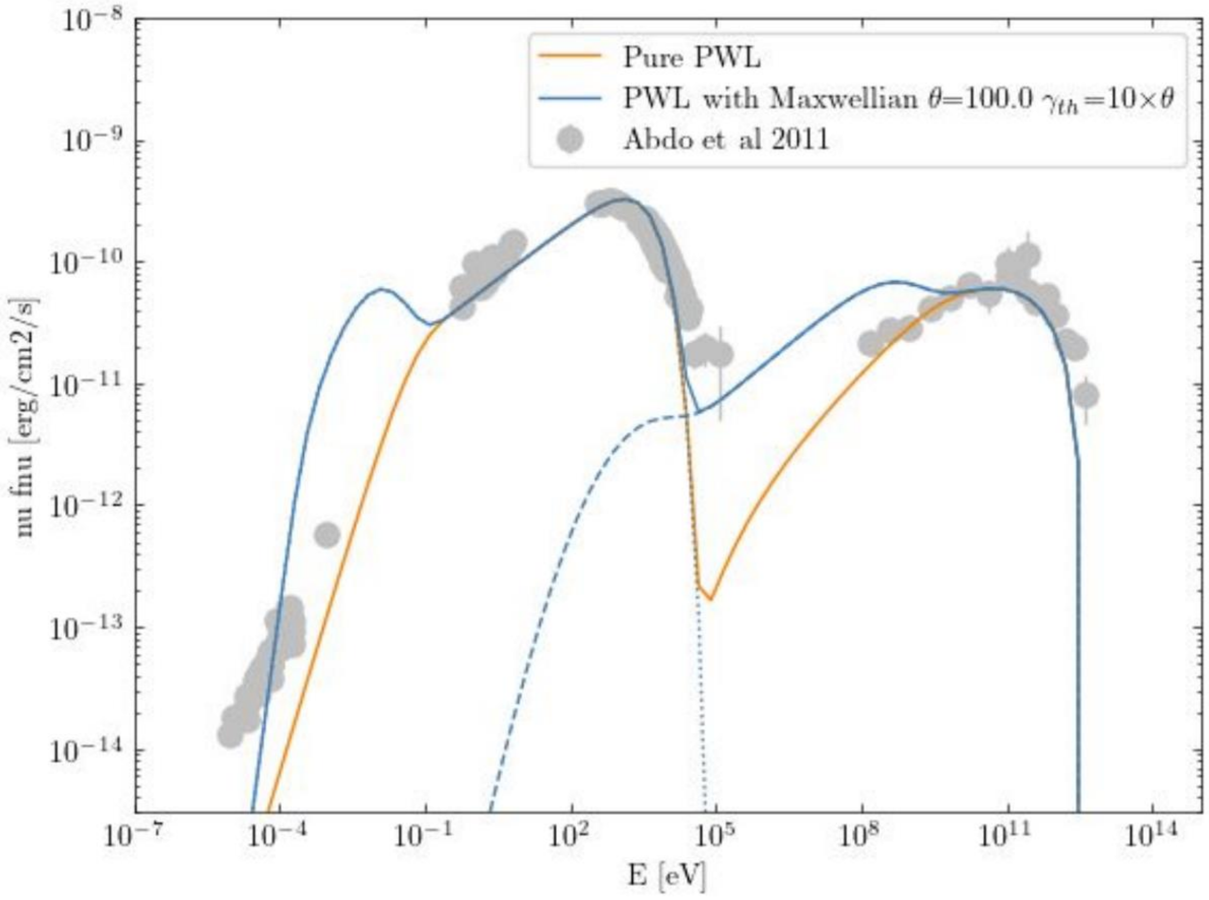
(Abdo et al. 2011)

Blazar emission and shocks in AGN jets

Used electron distribution

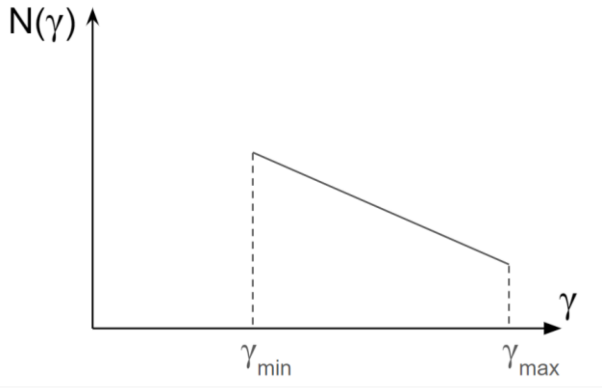


Emission of Mrk421 + synchrotron self-Compton model

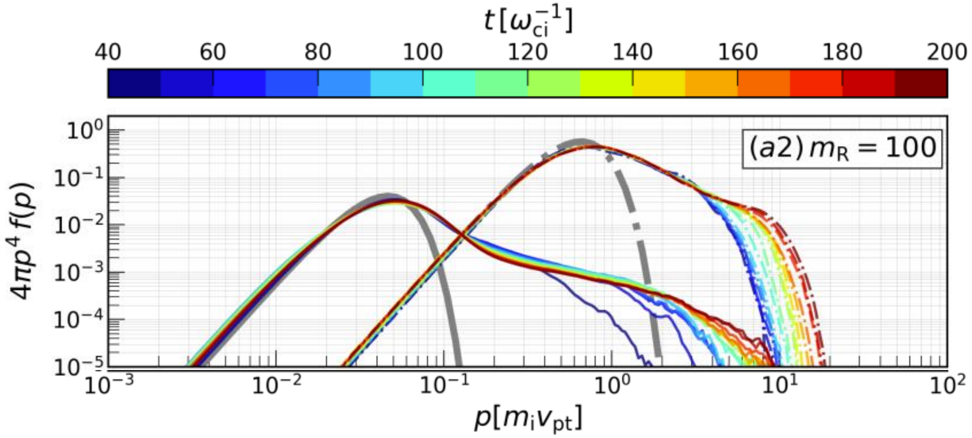


Blazar emission and shocks in AGN jets

Used electron distribution

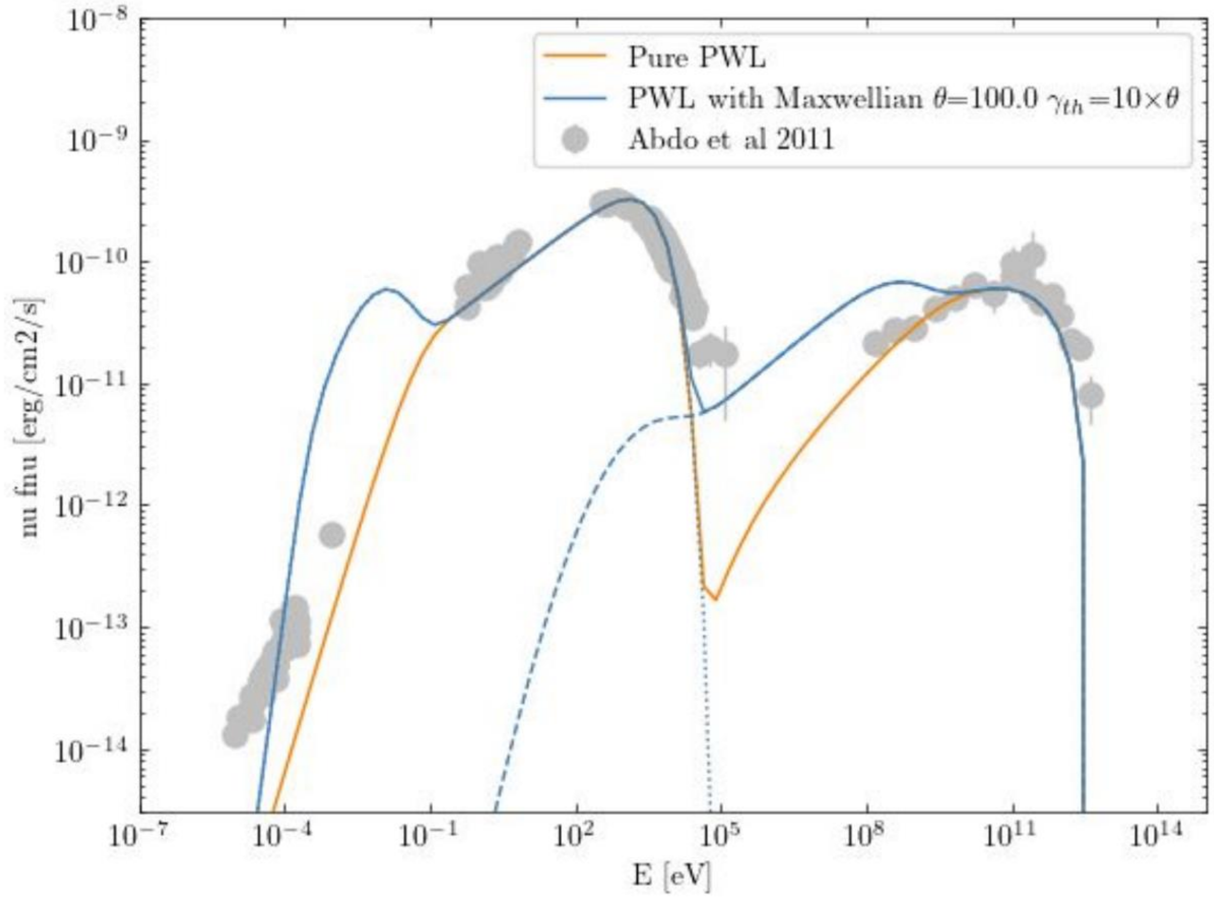


Realistic electron distribution



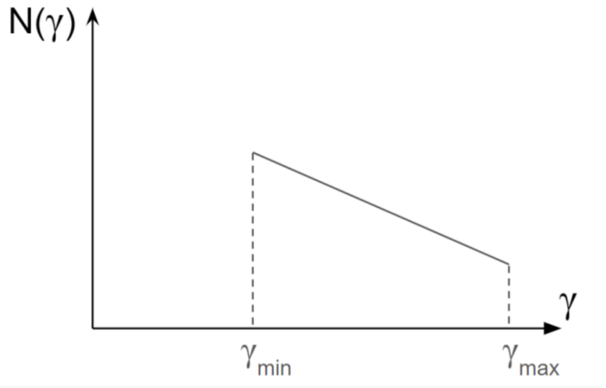
(Gupta et al. 2024)

Emission of Mrk421 + synchrotron self-Compton model



Blazar emission and shocks in AGN jets

Used electron distribution



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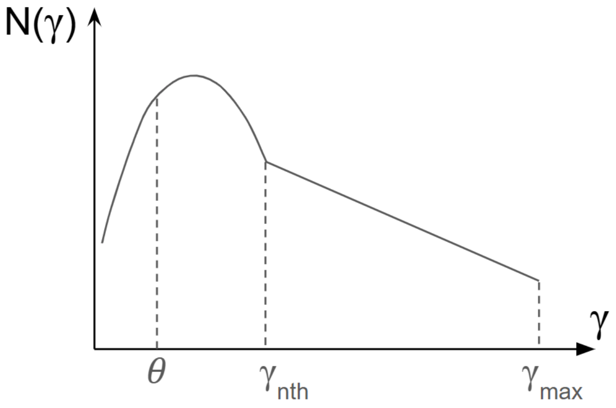
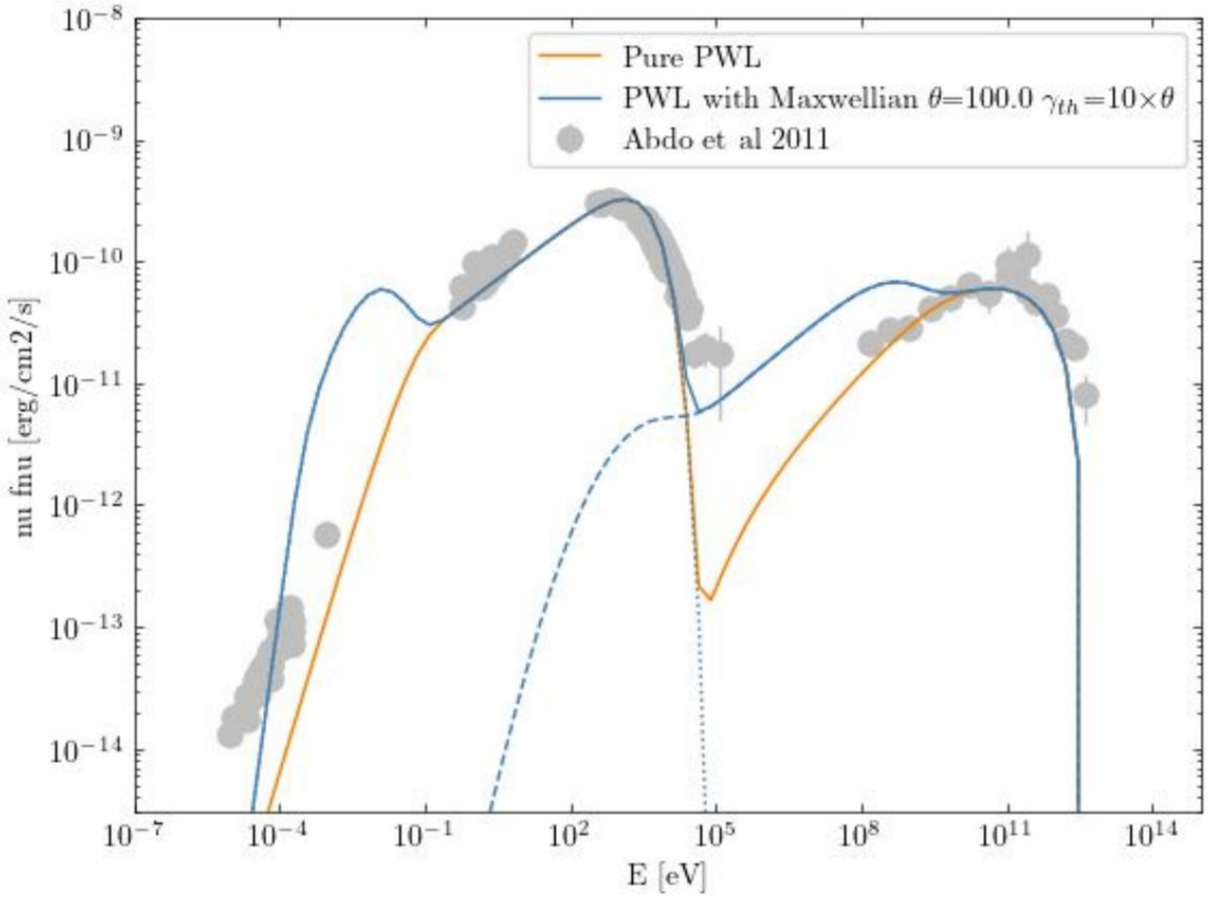


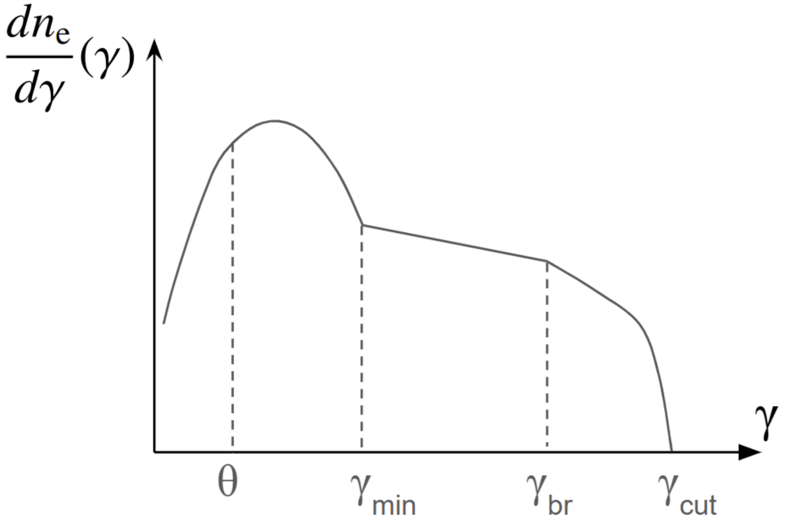
Emission of Mrk421 + synchrotron self-Compton model



Using realistic electron energy distribution

$$\frac{dn_e}{d\gamma}(\gamma) \propto \begin{cases} \mathcal{N}(\gamma,\theta), & 1<\gamma<\gamma_{nth} \\ \mathcal{N}(\gamma_{nth},\theta)\left(\frac{\gamma}{\gamma_{nth}}\right)^{-p_1}, & \gamma_{nth}<\gamma<\gamma_{br}, \\ \mathcal{N}(\gamma_{nth},\theta)\left(\frac{\gamma_{br}}{\gamma_{nth}}\right) e^{\gamma_{br}/\gamma_{cut}} \left(\frac{\gamma}{\gamma_{nth}}\right)^{-p_1-1} e^{-\gamma/\gamma_{cut}}, & \gamma>\gamma_{br} \end{cases}$$

Where $\mathcal{N}(\gamma,\theta) = \frac{\gamma^2}{2\theta^3} e^{-\gamma/\theta}$ is the Maxwell distribution
and $\theta \equiv kT_e/m_e c^2$ is the dimensionless temperature.



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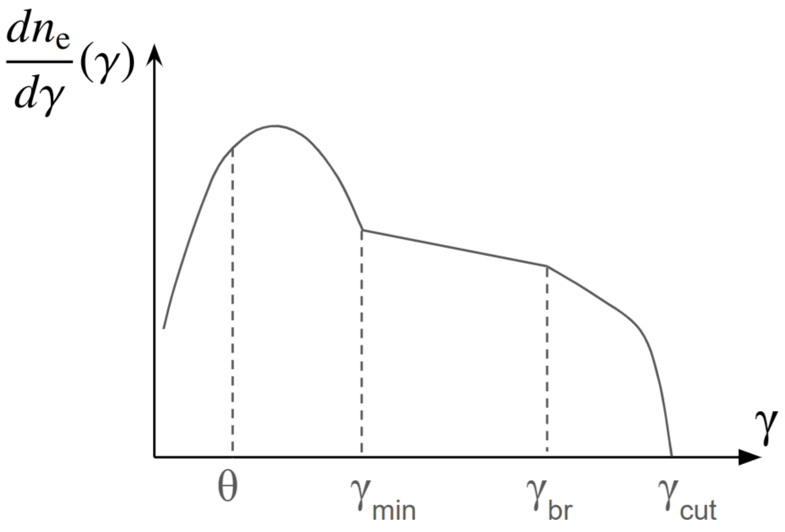
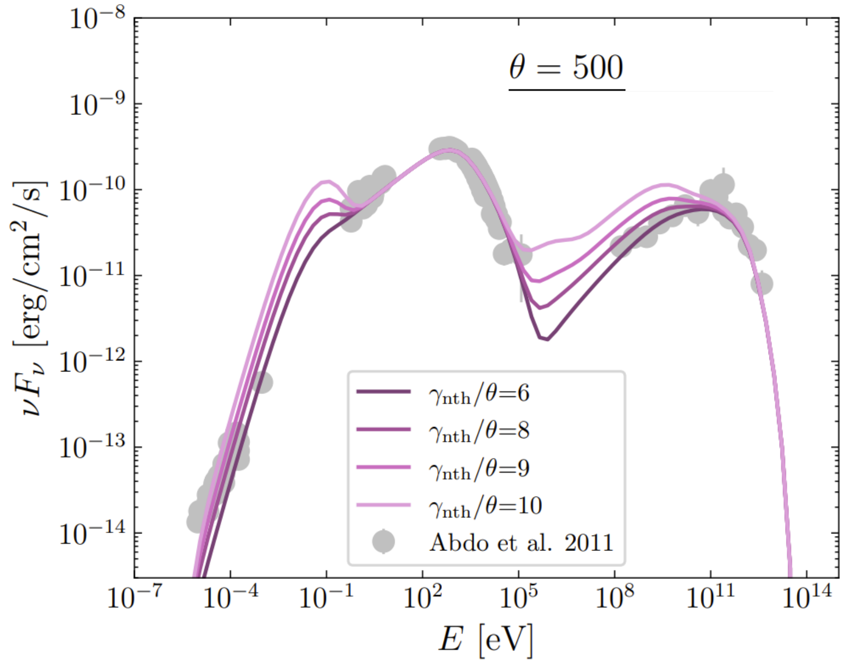
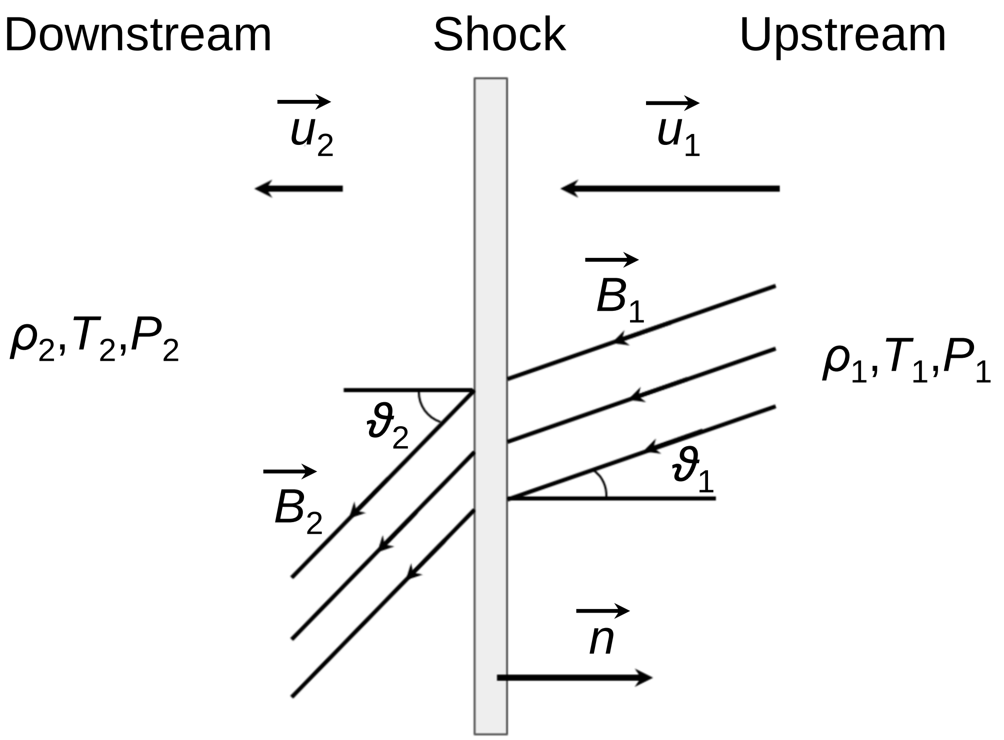


Best-fit parameters:

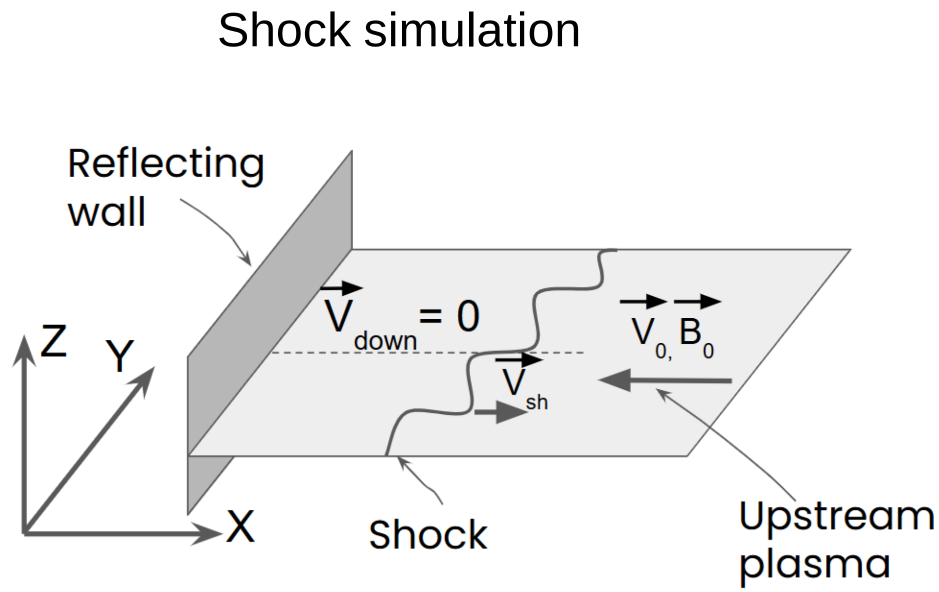
Temperature	$\theta \approx 500$
Nonthermal population	$\gamma_{nth}/\theta \approx 8$
Power-law index	$p_1 \approx 2.4$
Electron density	$n \approx 1\ cm^{-3}$
Magnetic field	$B \approx 0.05\ G$



Shock physics



Velocity transformation



In the simulations reference frame all the upstream kinetic energy goes to:
(1) **thermal ions and electrons** (2) high-energy particles (3) fields.

$$a_{\rm th}(\gamma_0 - 1)\, m_{\rm p}\, c^2 = (\gamma_{\rm th,e} - 1)\, m_{\rm e} c^2 + (\gamma_{\rm th,p} - 1)\, m_{\rm p} c^2$$

Upstream gamma factor and electron temperature

In the simulations reference frame about 80% of the upstream kinetic energy goes to thermal ions and electrons:

$$a_{\rm th}(\gamma_0 - 1)\, m_{\rm p}\, c^2 = (\gamma_{\rm th,e} - 1)\, m_{\rm e} c^2 + (\gamma_{\rm th,p} - 1)\, m_{\rm p} c^2$$

$$\frac{T_{\rm e}}{T_{\rm p}} = \frac{(\gamma_{\rm th,e} - 1)\, m_{\rm e} c^2}{(\gamma_{\rm th,p} - 1)\, m_{\rm p} c^2}$$ (largely unknown, but here we use $T_e/T_i \approx 0.5$)

$$\gamma_0 = 1 + \frac{3\theta}{a_{\rm th}} \frac{m_{\rm e}}{m_{\rm p}} \left(1 + \frac{T_{\rm p}}{T_{\rm e}}\right) \approx 4 \text{ in case of } \theta \approx 500$$

$$\gamma_{\rm sh} = \sqrt{\frac{(\gamma_0 + 1)(\Gamma_{\rm ad}(\gamma_0 - 1) + 1)^2}{\Gamma_{\rm ad}(2 - \Gamma_{\rm ad})(\gamma_0 - 1) + 2}} \approx 5.3$$

Plasma magnetization: plasma density

$$\sigma = \frac{B_0^2}{\mu_0 \gamma_0 n_0 (m_\mathrm{p} + m_\mathrm{e}) c^2}$$

where n_0 and B_0 are the upstream values, however the best fit model gives the downstream values.

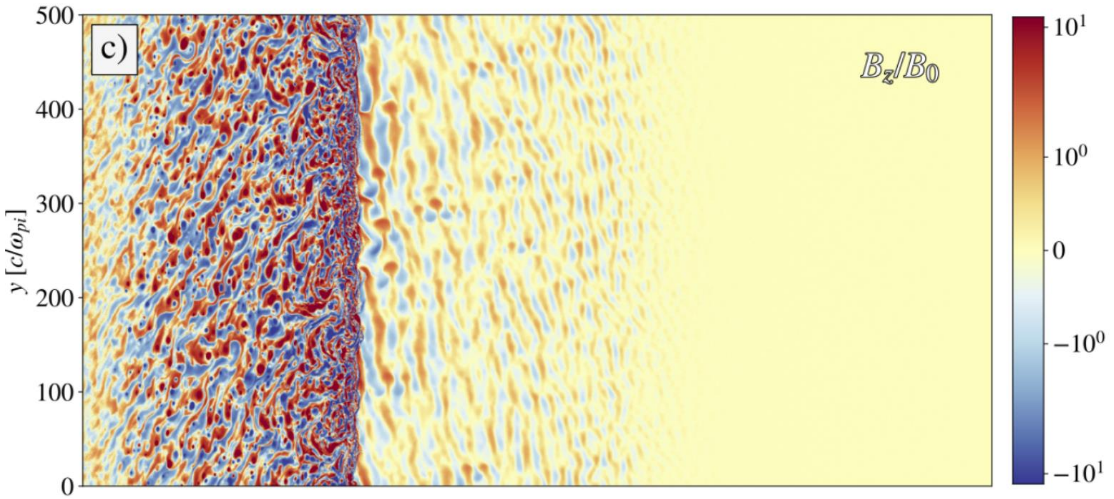
The upstream plasma density can be derived using the shock compression ratio $r = \frac{\Gamma_{ad}(\gamma_0+1)}{\gamma_0(\Gamma_{ad}-1)}$

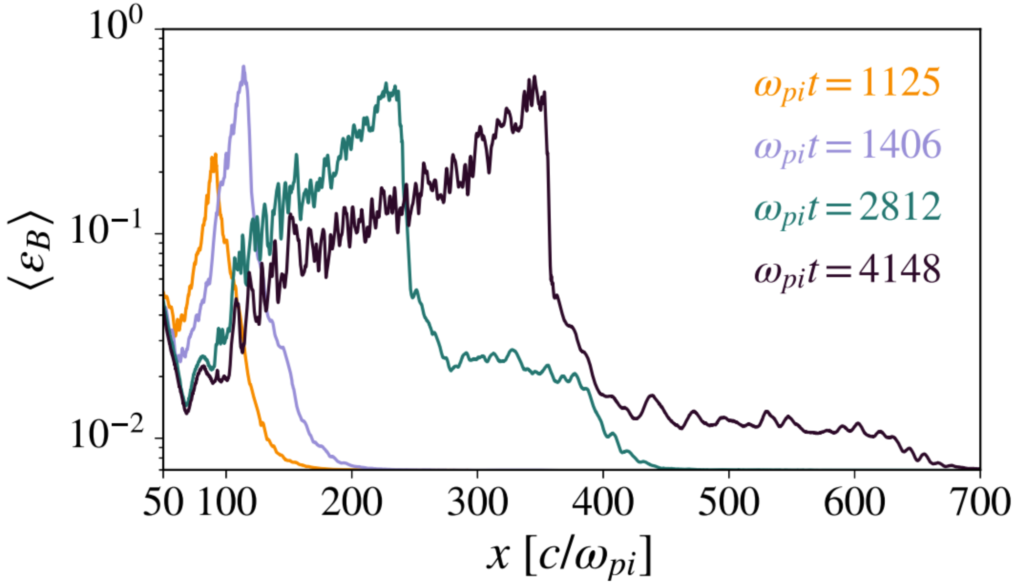
Therefore $n_0 = \frac{n\gamma_0(\Gamma_\mathrm{ad} - 1)}{\Gamma_\mathrm{ad}(\gamma_0 + 1)}$

Plasma magnetization: magnetic field

$$\sigma = \frac{B_0^2}{\mu_0 \gamma_0 n_0 (m_\mathrm{p} + m_\mathrm{e}) c^2}$$

$B_0 = B/a_\mathrm{B}$, where a_B represents magnetic field amplification in front of the shock, compression in the shock and decay behind the shock





(Crumley et al. 2024)

Plasma magnetization

$$\sigma = \frac{(B/a_{\mathrm{B}})^2}{\mu_0 \gamma_0 n (m_{\mathrm{i}} + m_{\mathrm{e}}) c^2} \frac{[\gamma_0 (\Gamma_{\mathrm{ad}} - 1)]}{(\Gamma_{\mathrm{ad}} \gamma_0 + 1)}$$

$$\sigma \sim 0.15/a_{\mathrm{B}}^2$$

(for the best-fit model)

Shock parameters for the best-fit model

Best-fit parameters:

Temperature	$\theta \approx 500$
Nonthermal population	$\gamma_{nth} / \theta \approx 8$
Power-law index	$p_1 \approx 2.4$
Electron density	$n \approx 1\ cm^{-3}$
Magnetic field	$B \approx 0.05\ G$

Shock parameters:

The upstream Lorentz factor in d.r.f.	$\gamma_0 \approx 4$
The shock Lorentz factor	$\gamma_{sh} \approx 5.3$
Magnetization	$\sigma \approx 0.15/a_B$

Assumptions:

Fraction of energy in thermal particles	$a_{th} \approx 0.8$
Downstream temperature ratio	$T_e/T_i \approx 0.5$
Magnetic field amplification	a_B is a free parameter

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Assumptions:

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Downstream temperature ratio	$T_e/T_i \approx 0.5$
Magnetic field amplification	a_B is a free parameter

Things to test with PIC simulations

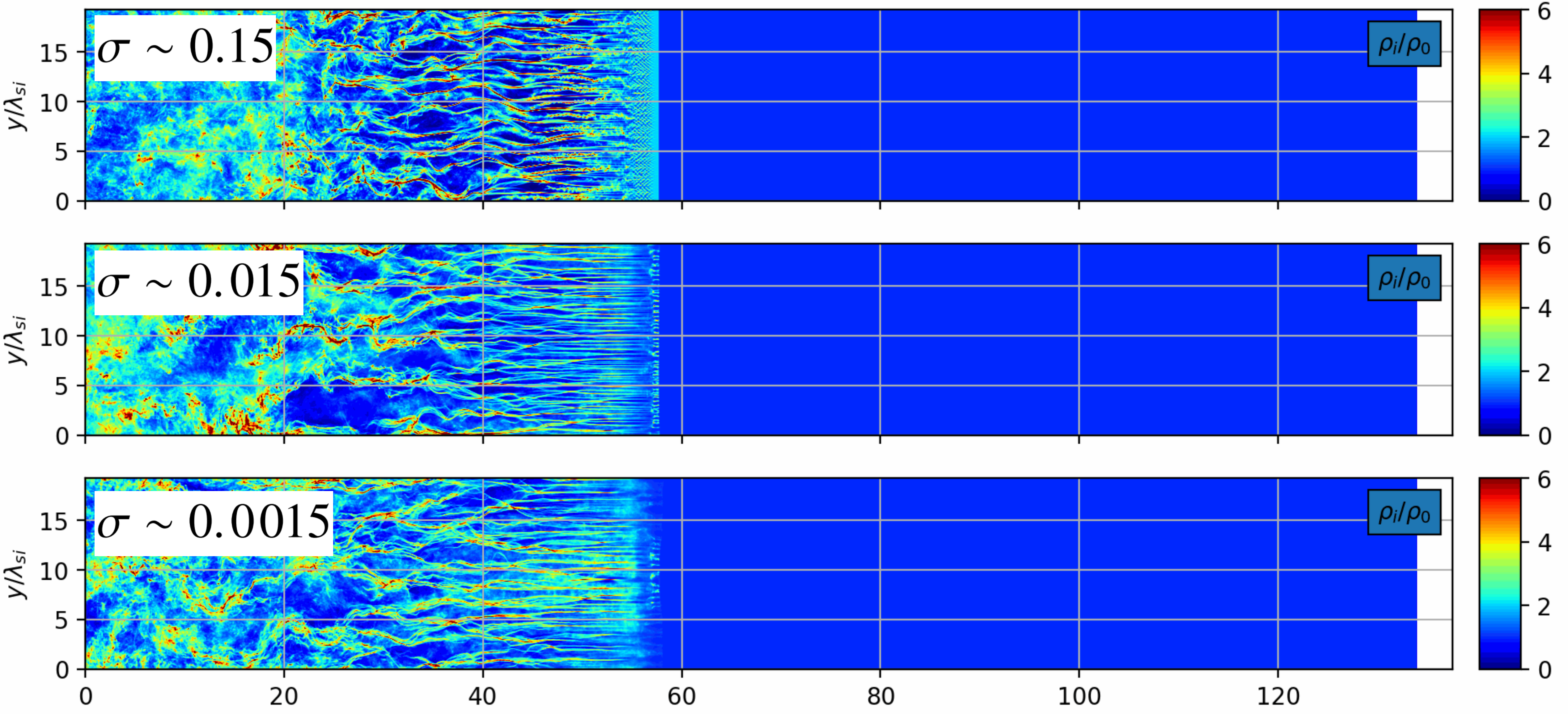
(1) Short simulations

Downstream temperature ratio	T_e/T_i
Fraction of energy in thermal particles	a_{th}

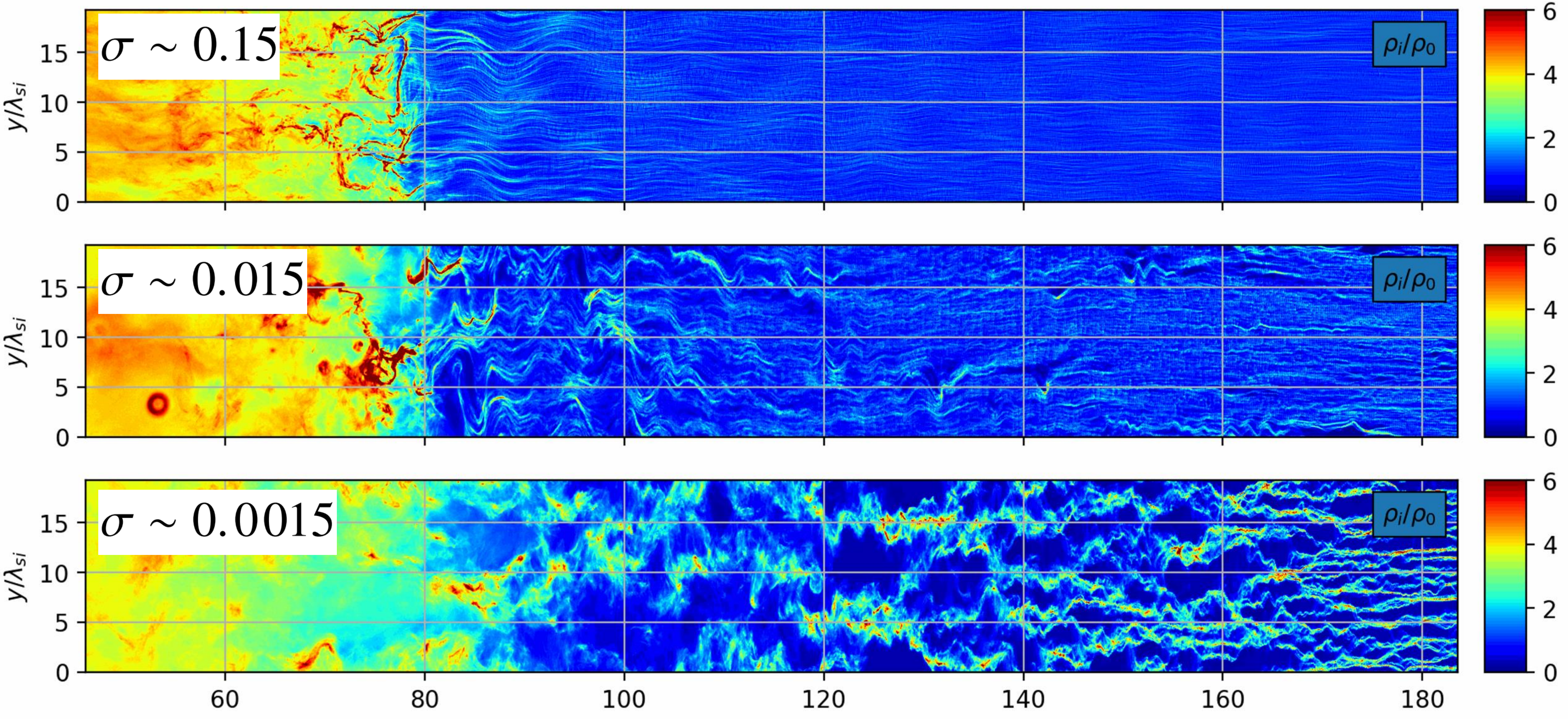
(2) Long simulations

Nonthermal population	γ_{nth}/θ
Power-law index	p_1
Magnetic field amplification	a_B

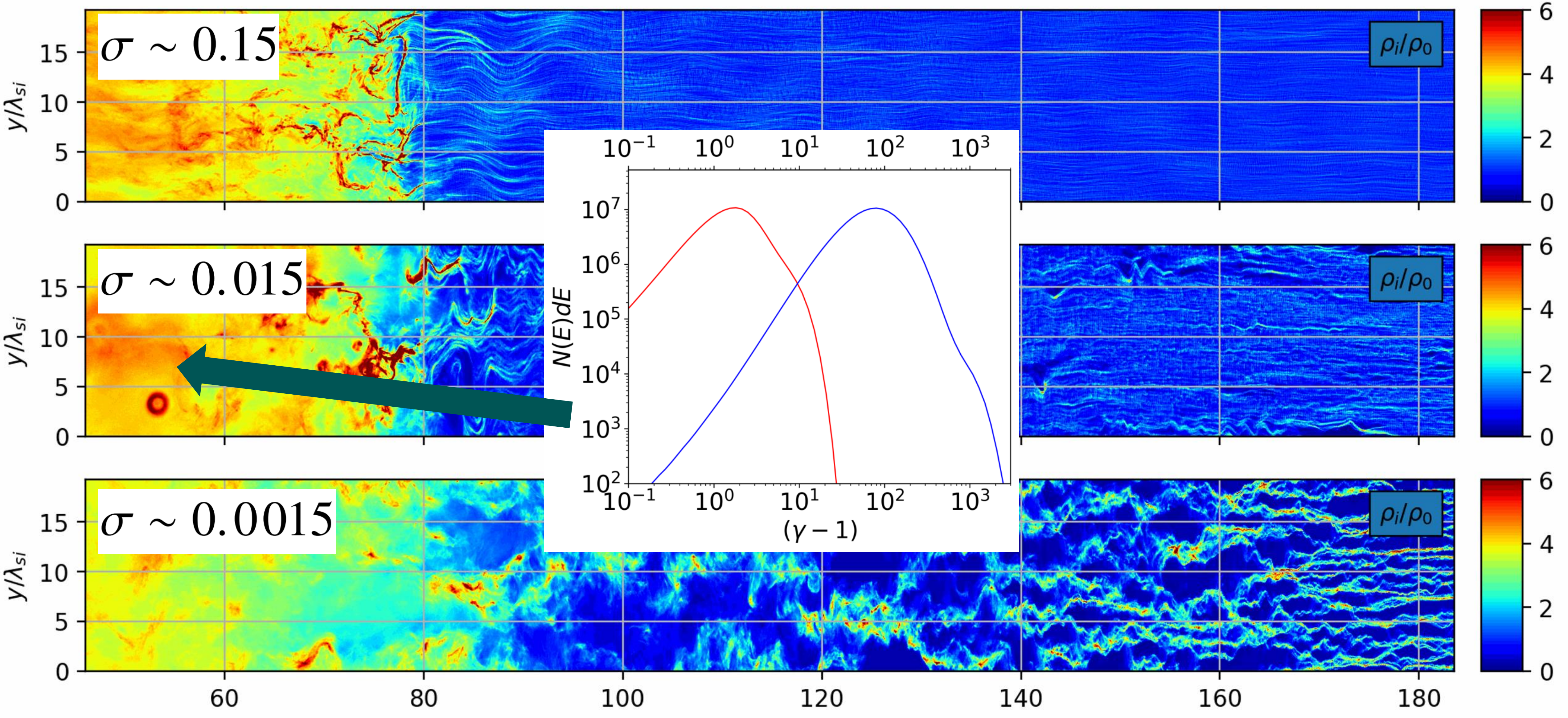
Shock simulations



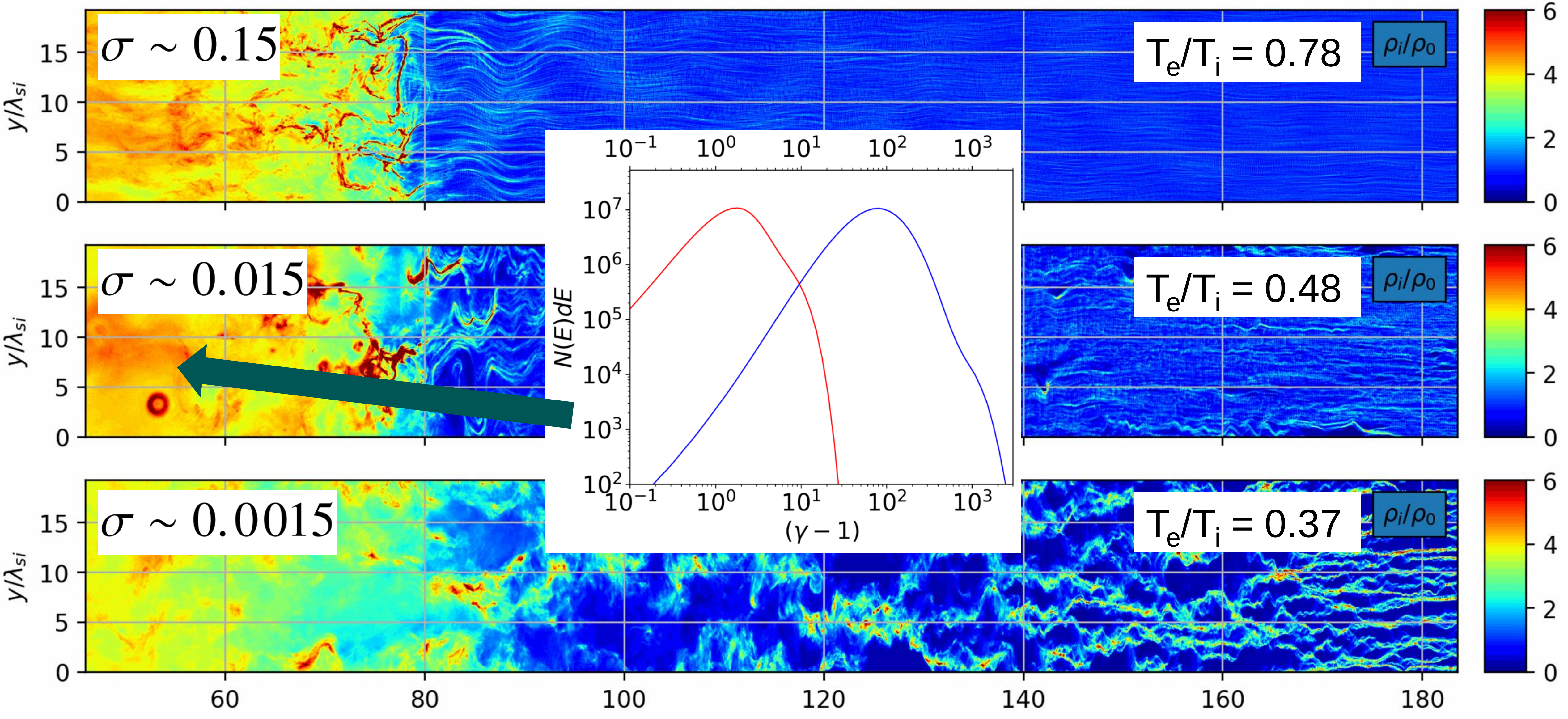
Shock simulations



Shock simulations



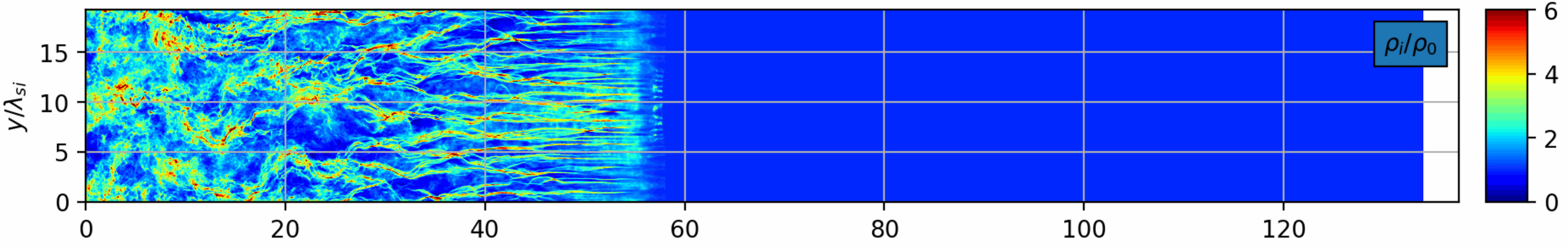
Shock simulations



Conclusions

(1) Connection of nonthermal emission and PIC simulations is possible (paper was submitted)

(2) A lot of simulations needed to determine T_e/T_i , a_{th}, γ_{nth}/θ, p_1 , a_{th}



Thank you

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