Stochastic acceleration in Extreme TeV BL Lacs

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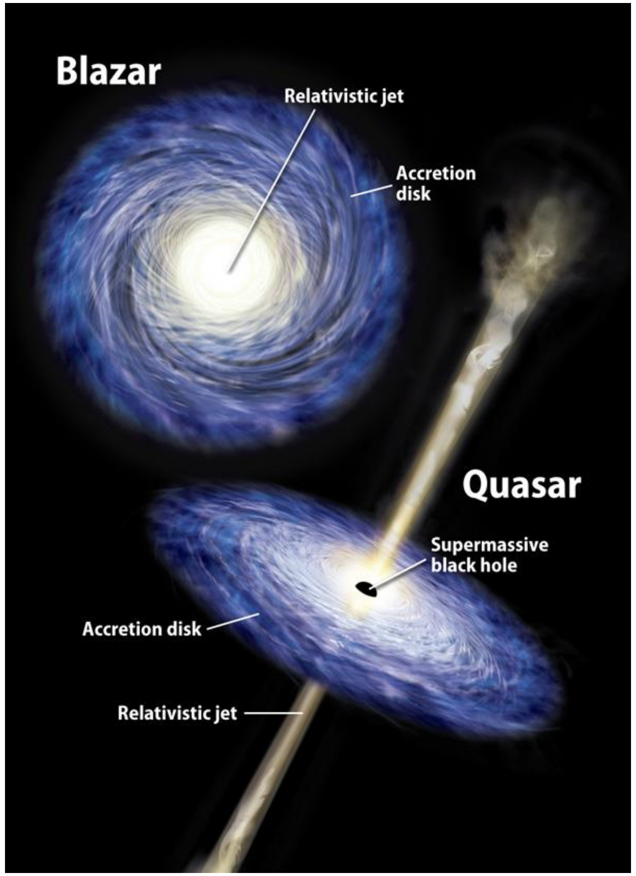
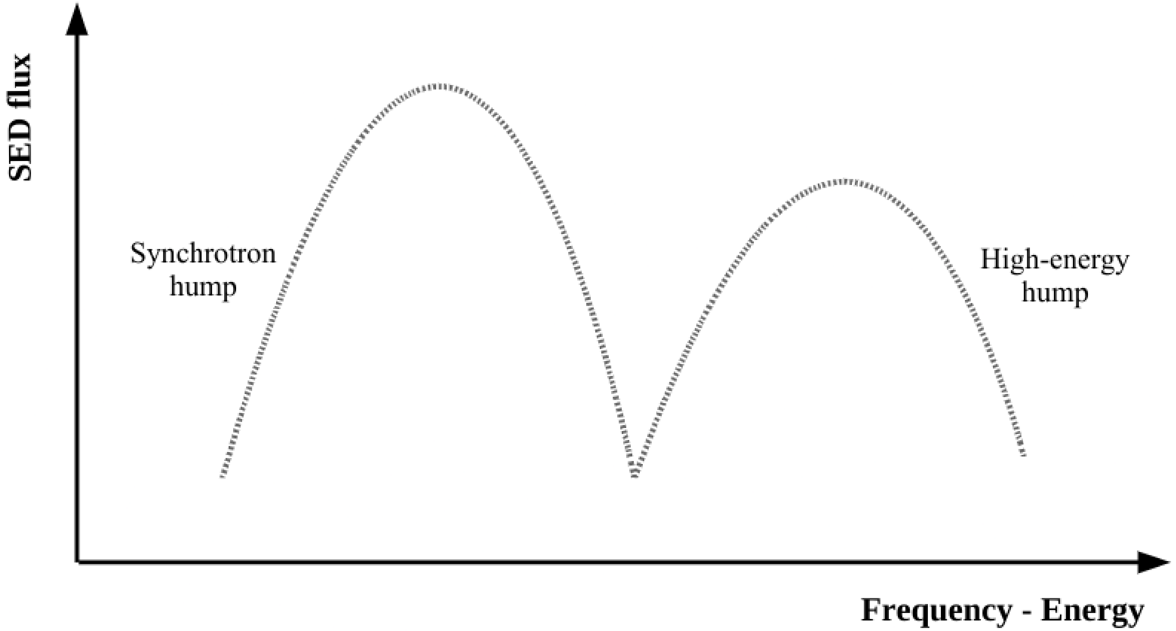
Introduction to Blazars

Blazars are radio-loud Active Galactic Nuclei (AGN) whose jet is pointing towards the observer. Their Spectral Energy Distribution (SED) presents two broad humps. Blazars can be classified using the two peak frequencies (Blazar sequence).



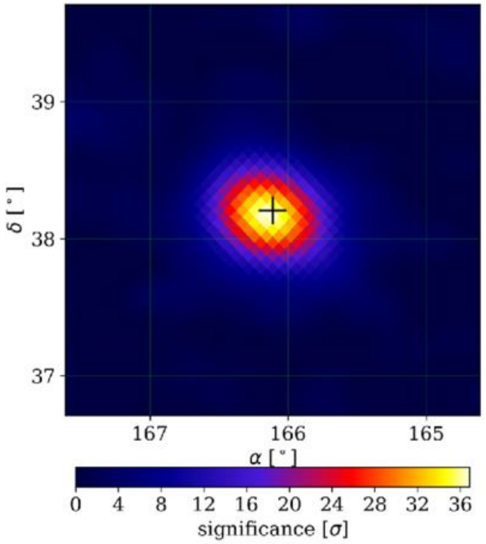


High and Extreme frequency peaked Bl Lacs

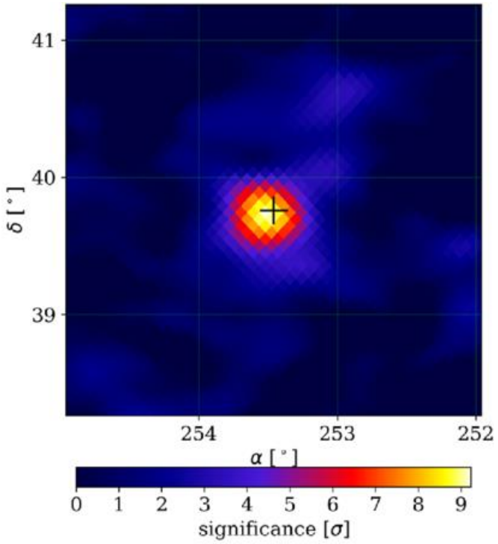
The first peak ranges from infrared to X-rays, the second from MeV to TeV energies. The end of the sequence is populated by the High and Extreme frequency peaked BL Lacs (HBL and EHBL).

HBL

$$\nu_1 \gtrsim 10^{15}\ \mathrm{Hz}$$



Mrk 421



Mrk 501

EHBL

Extreme Synchrotron BL Lacs

$$\nu_1 \gtrsim 10^{17}\ \mathrm{Hz}$$

Extreme Tev BL Lacs

$$\nu_2 \gtrsim 10^{26}\ \mathrm{Hz}$$

[Biteau+ 2020, Albert+ 2022]

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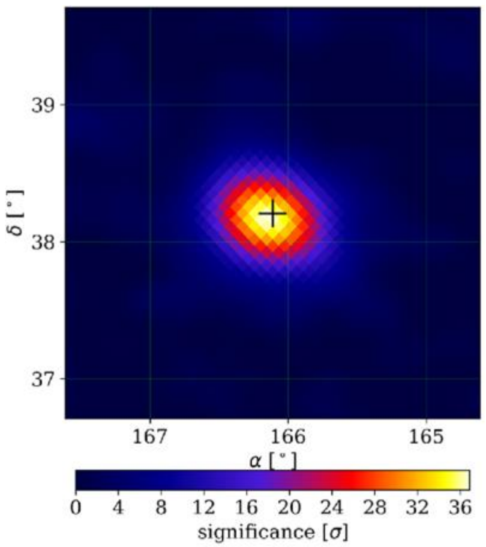

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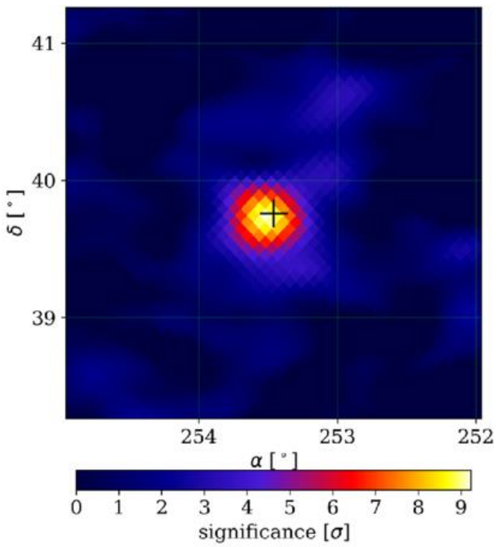

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Extreme TeV BL Lacs

In the one-zone leptonic framework, two ingredients are needed to obtain a good agreement with data

1. Low magnetic field, far from equipartition
2. High average Lorentz factor

→

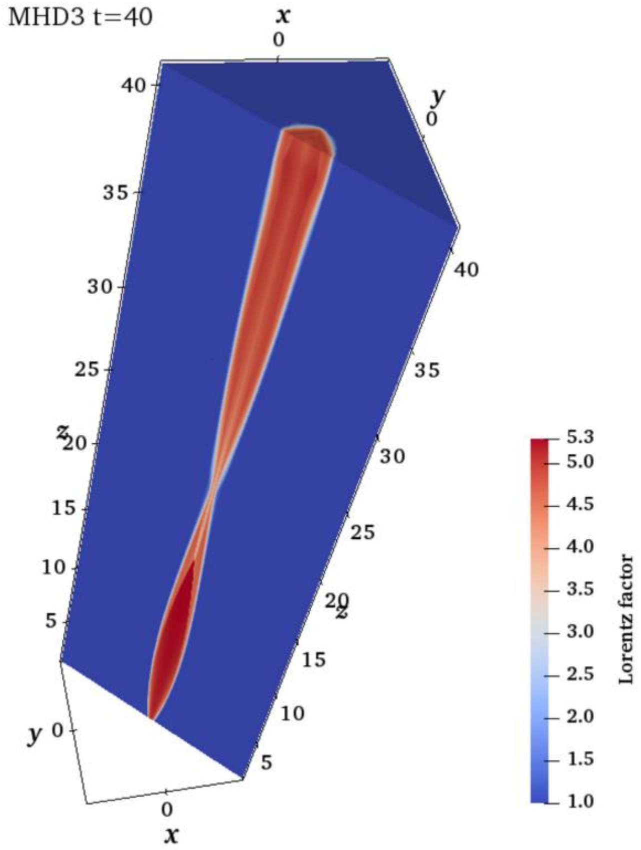
1. Hardening of gamma spectrum and large separation between peaks
2. Steep gamma spectrum and high peak frequency

[Biteau+ 2020, Zech&Lemoine 2021]

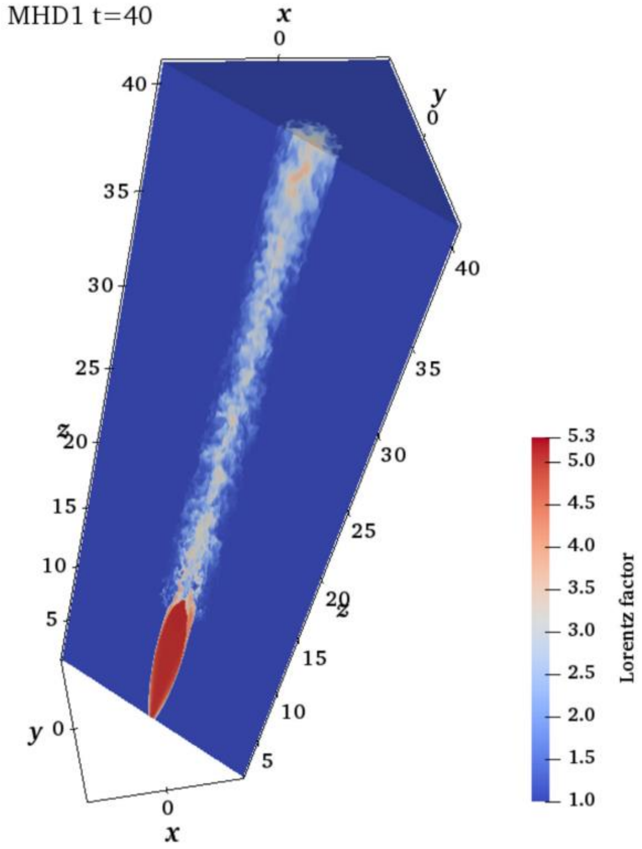
Starting point

Many alternative models have been proposed, our model
is based on recent simulations of magnetized recollimated jets

$\sigma \sim 10^{-2}$



$\sigma \sim 10^{-4}$



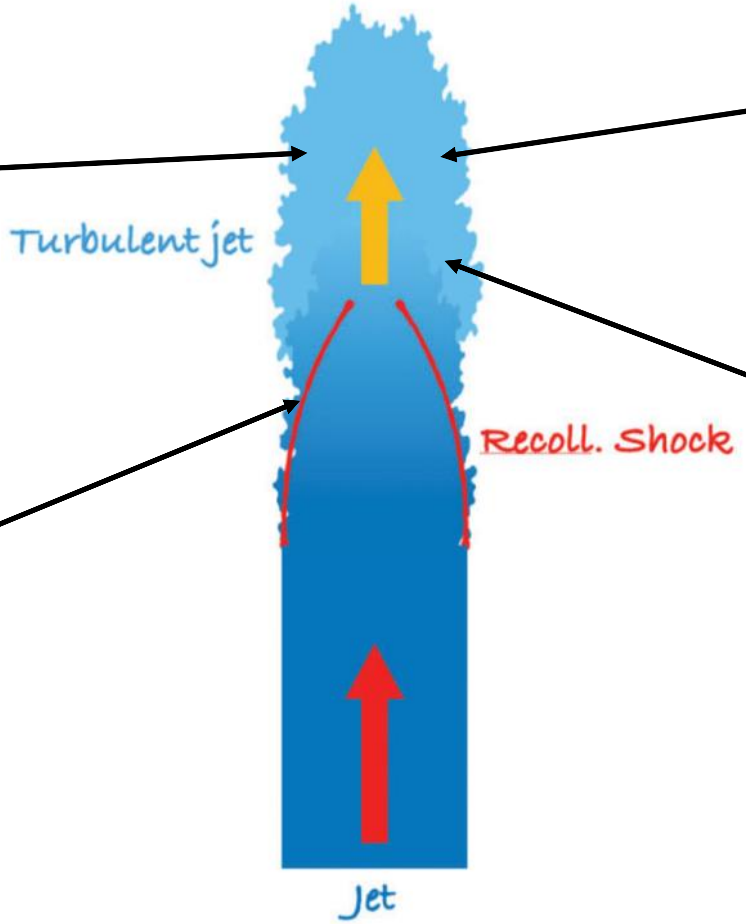
[Matsumoto+ 2021]

Modeling

We consider a one-zone leptonic model, where non-thermal particles are first accelerated by the shock (via DSA), then they are further energized by the downstream turbulence (via SA)

Turbulence = SA

DSA acceleration
=
Emission
region injection



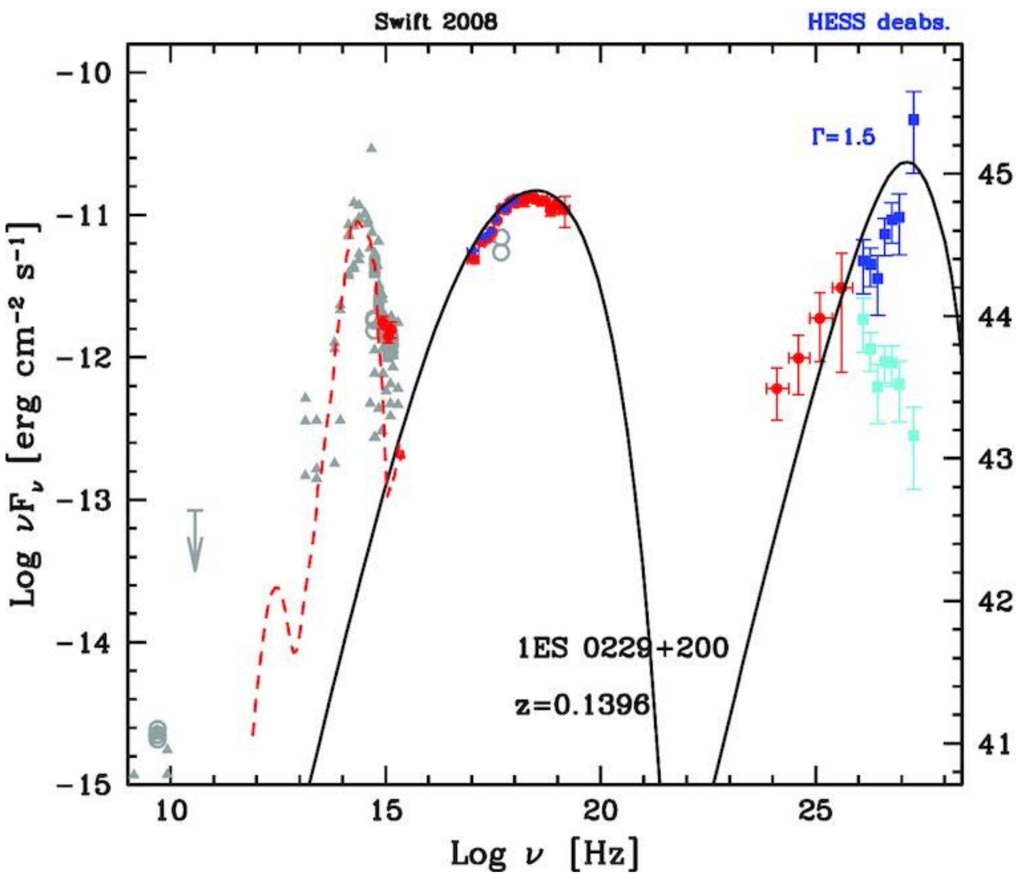
Emission zone
=
Shock downstream

Synchrotron
& IC cooling
+
Escape

[Tavecchio+ 2021]

No damping

Since particles gain energy from turbulence, turbulence spectrum is damped. At the zeroth order, this effect can be neglected



1. The gamma spectrum is too hard
2. The damping time is much shorter than the cascading time

We must consider damping to obtain a self-consistent model

[Kakuwa 2016, Tavecchio+ 2021]

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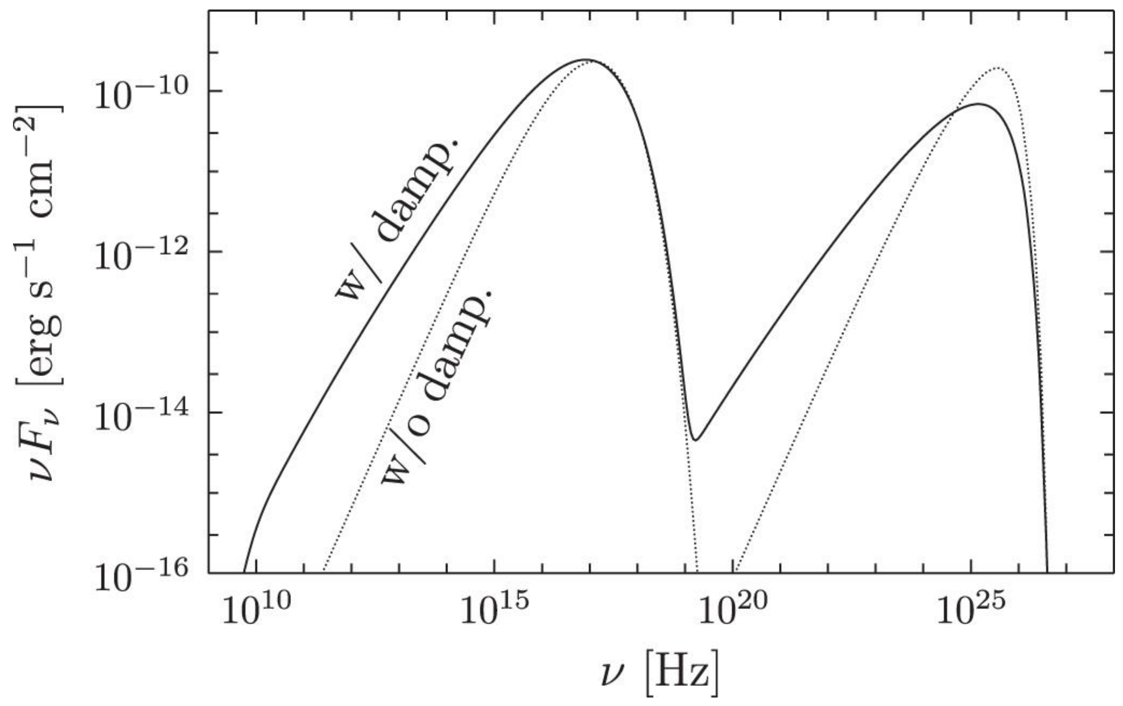

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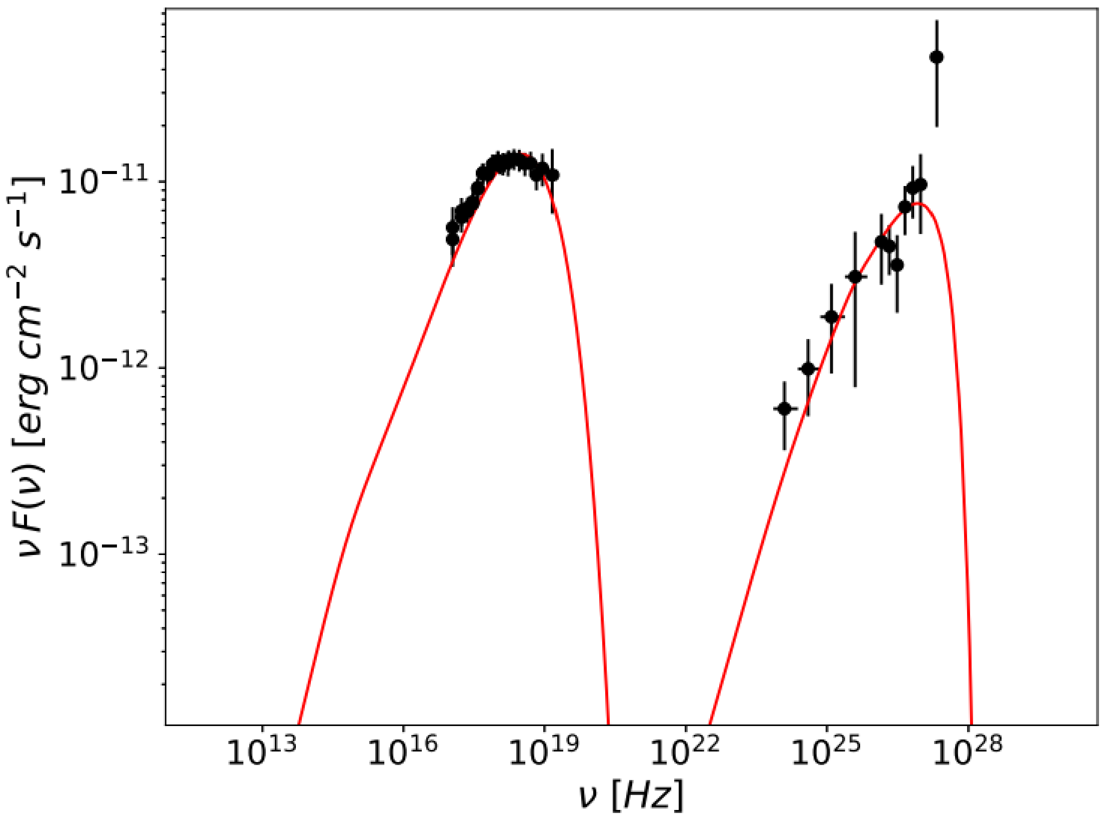
[Kakuwa 2016, Tavecchio+ 2021]

Damping

We added the turbulence damping in our model, which was tested with the prototypical Extreme TeV BL Lac, 1ES0229+200



Softening of the gamma spectrum by the turbulence damping

$$
\begin{aligned}
R &= 1.2 \times 10^{16}\ \mathrm{cm} \\
v_a &= 2 \times 10^{9}\ \mathrm{cm/s} \\
B &= 1.6 \times 10^{-2}\ \mathrm{G} \\
P_n &= 7 \times 10^{39}\ \mathrm{erg/s} \\
P_w &= 7 \times 10^{39}\ \mathrm{erg/s} \\
\delta &= 25
\end{aligned}
$$

[Sciaccaluga&Tavecchio 2022]

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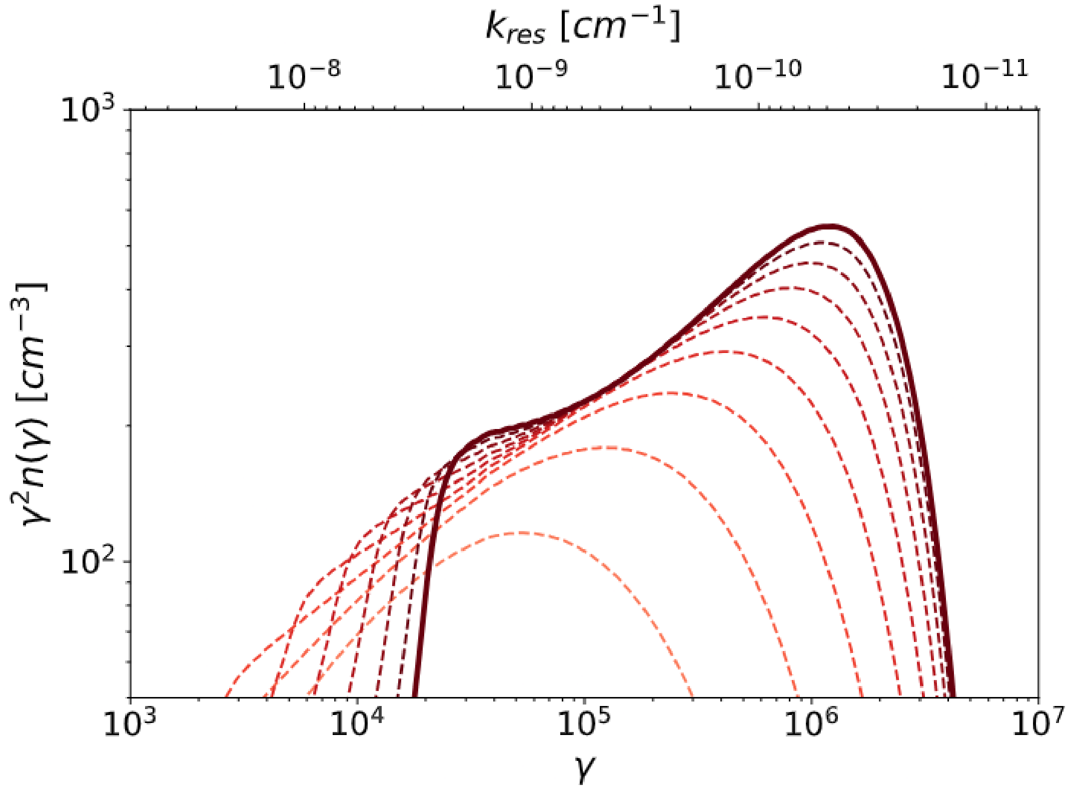
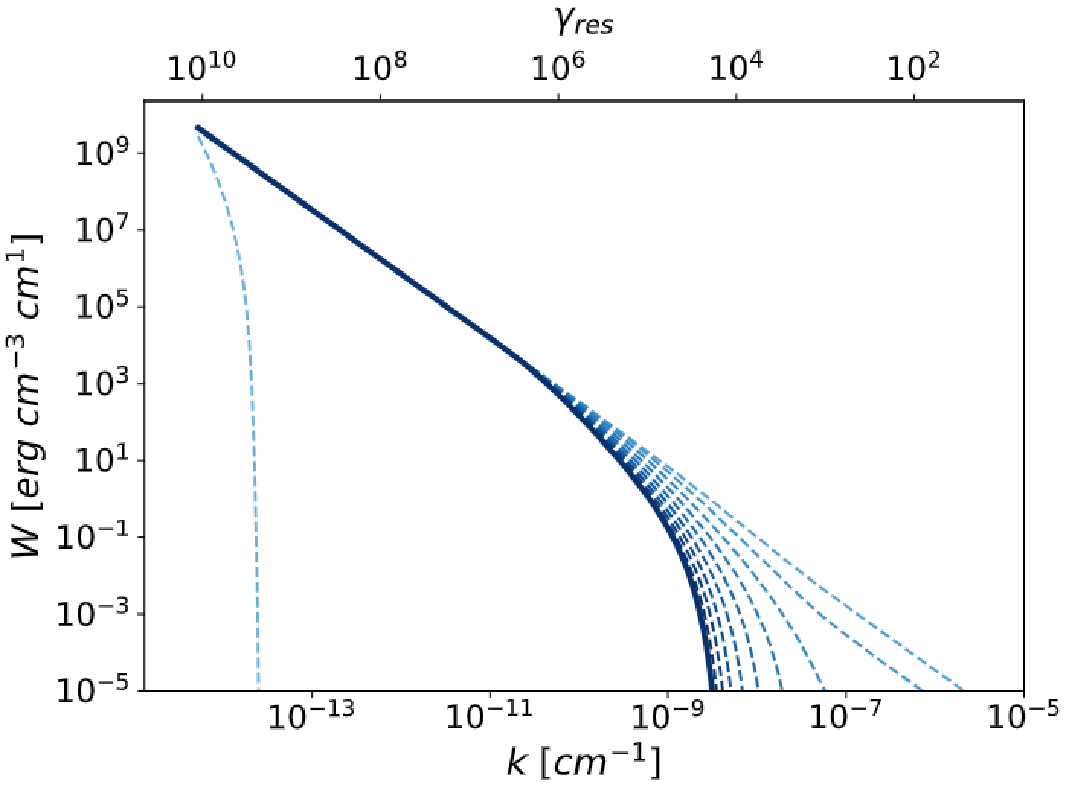


Shock accelerated electrons are further energized by turbulence

Turbulence is strongly damped by injected electrons

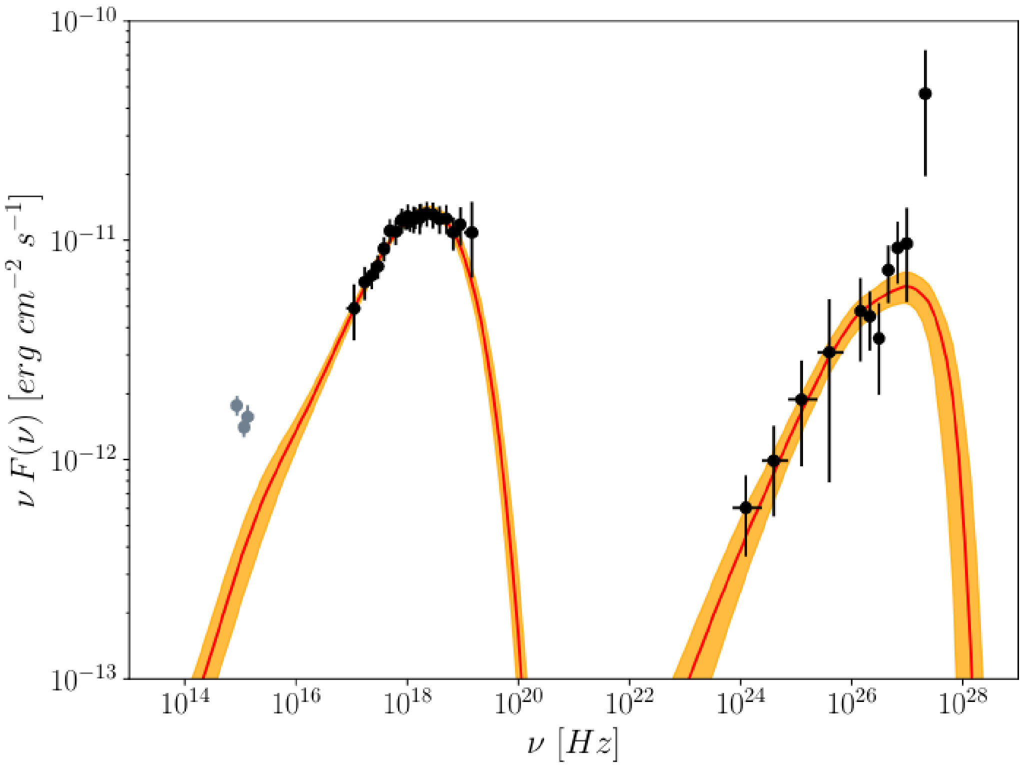


[Sciaccaluga&Tavecchio 2022]

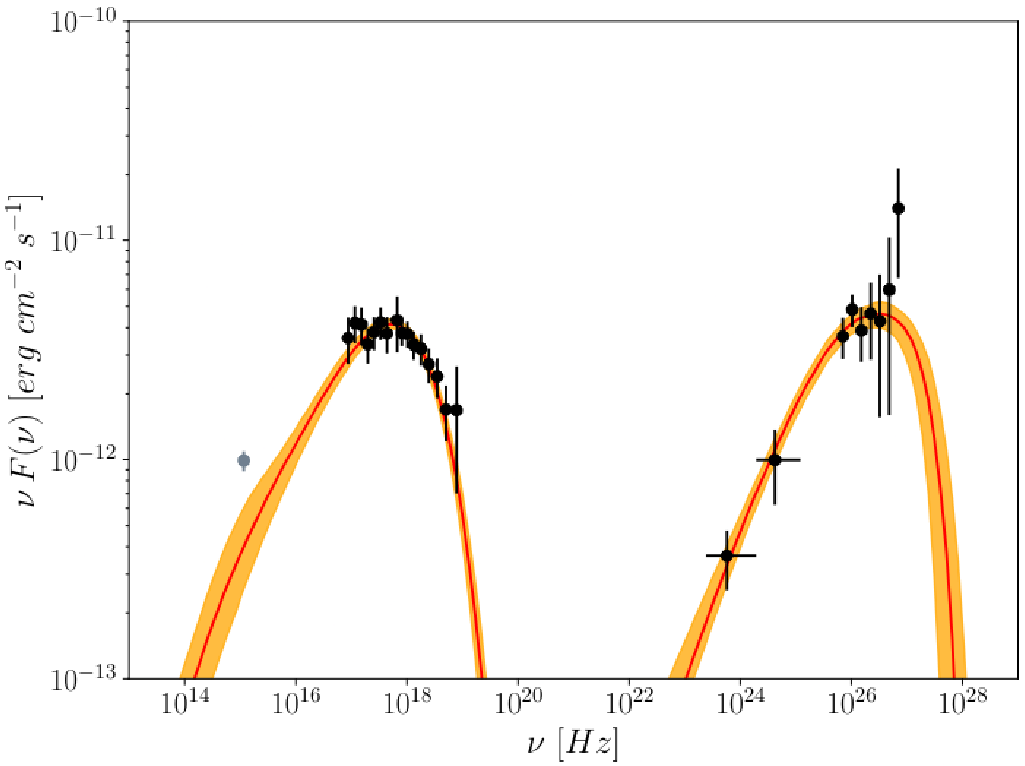
MCMC

Models are usually adjusted on the data via visual inspection. MCMC sampling can automatize this procedure, exploring the full parameter space.

1ES0229+200



1ES0347-121



Parallel evaluation

[Sciaccaluga+ 2024]

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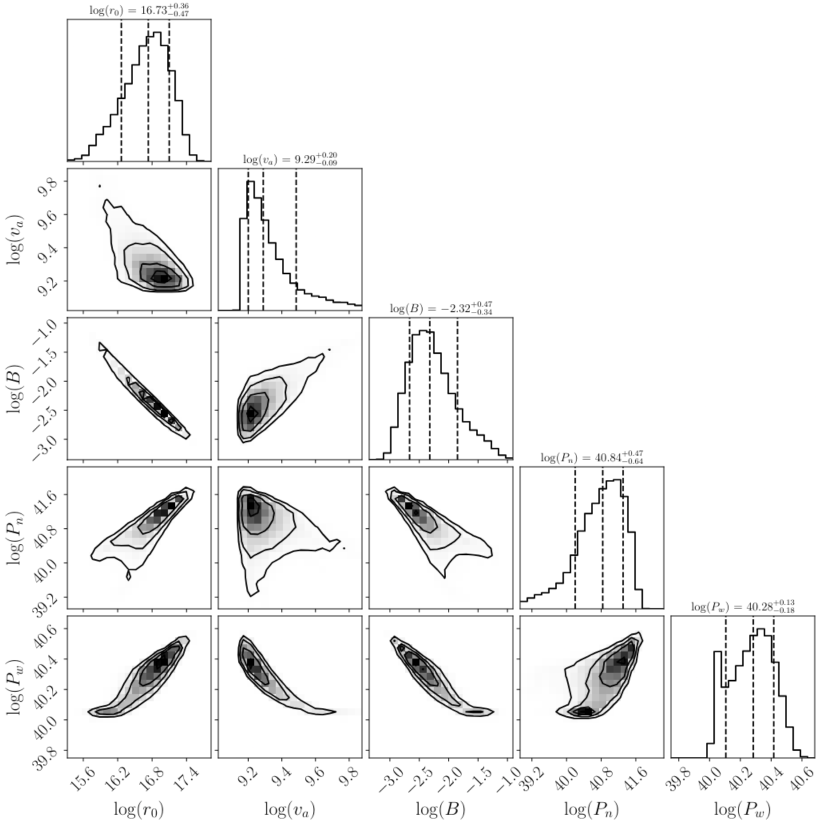

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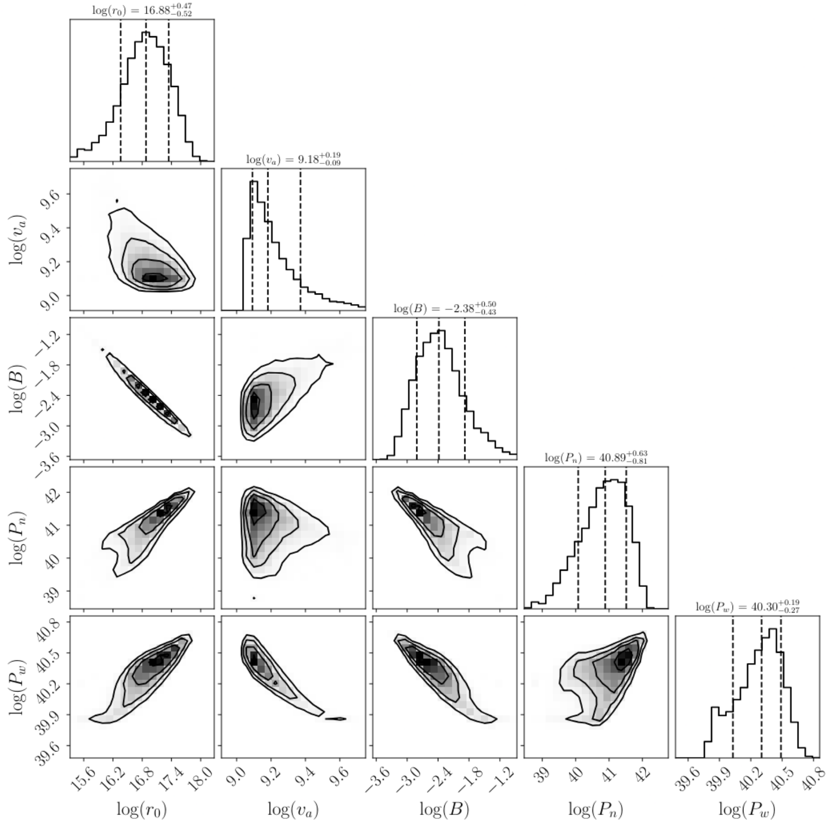

Priors, uncertainties and cross-correlations

[Sciaccaluga+ 2024]

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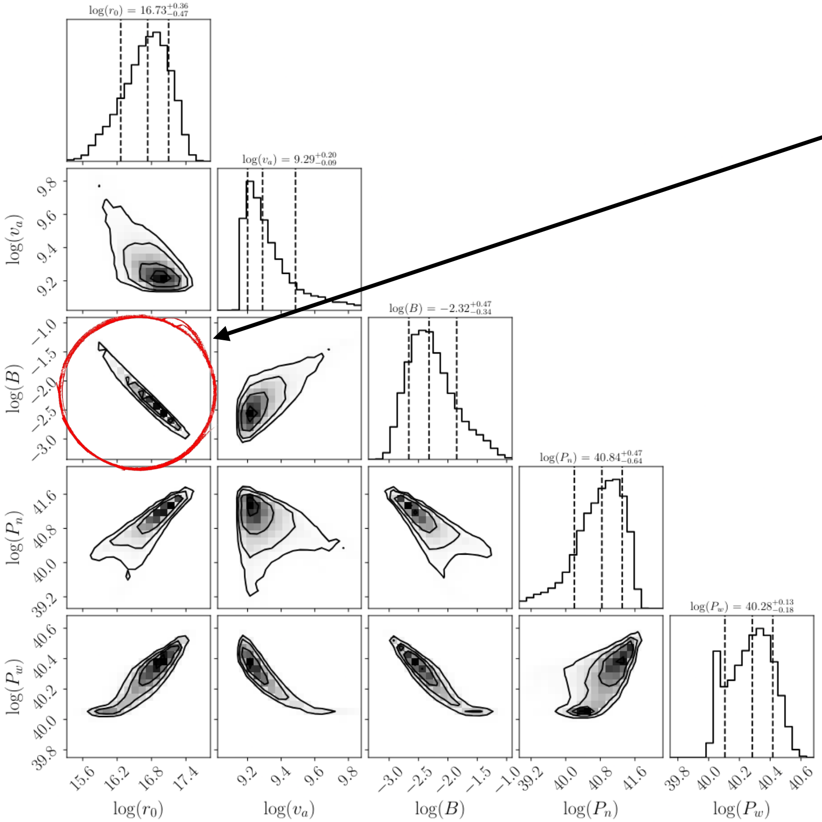
Luminosity ratio

1ES0229+200



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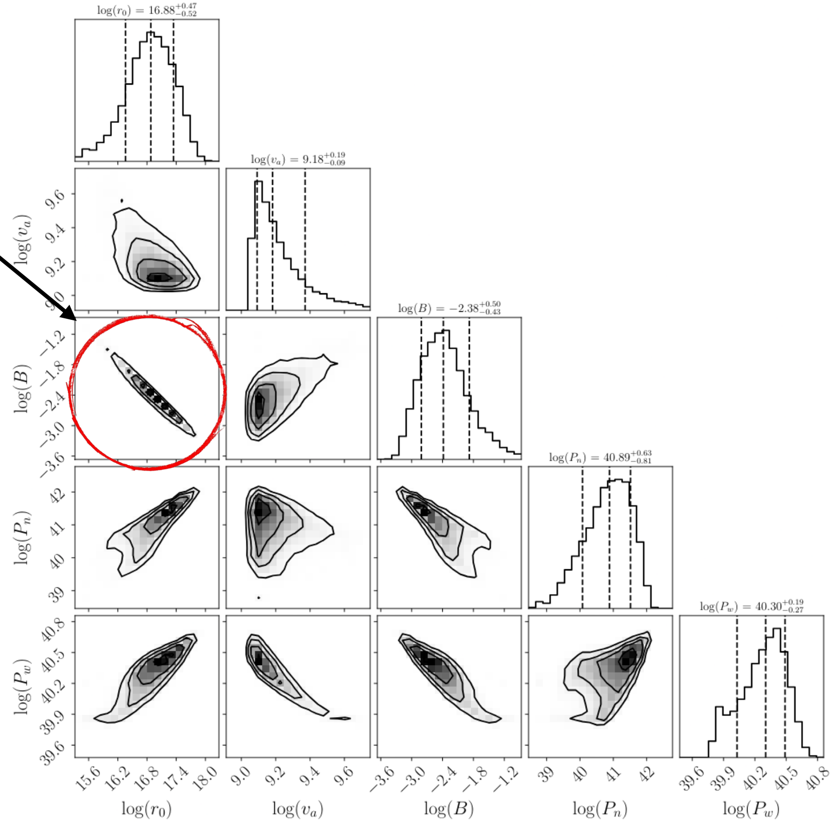
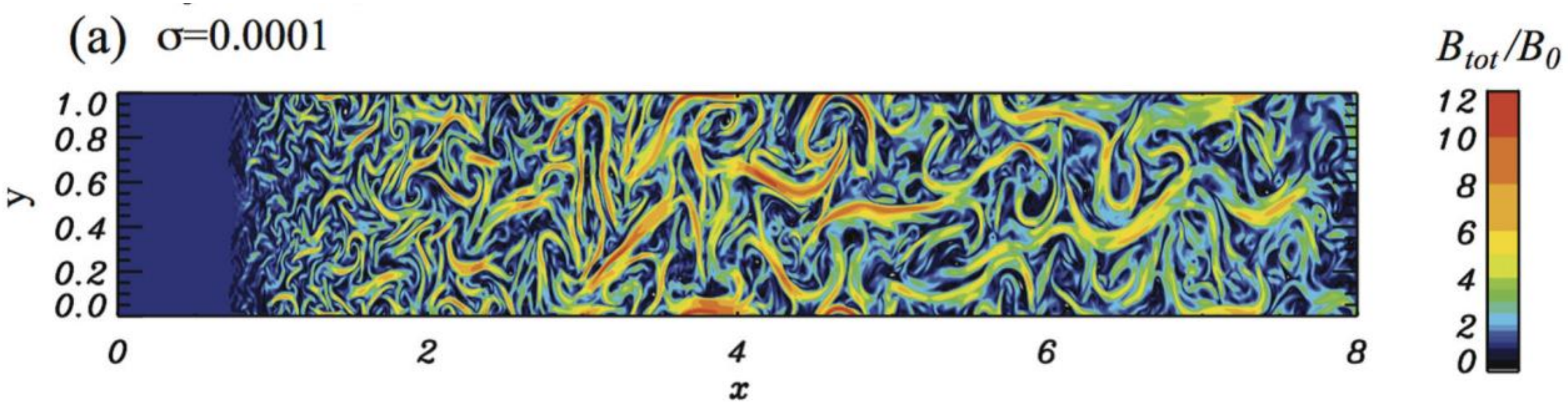


Priors, uncertainties and cross-correlations

[Sciaccaluga+ 2024]

Polarization

IXPE Observations of 1ES 0229+200 show that the X-ray polarization is rather high (~18%) and strongly chromatic. Moreover, the high relativistic Doppler factor (~20) is incompatible with a global recollimation instability that disrupts the jet flow.



Upstream inhomogeneities favor the development of downstream instabilities: small eddies form at the shock front, growing in size farther in the downstream. Since the jet does not mix with the external medium, it maintains a moderate relativistic Doppler factor.

[Mizuno+ 2014, Ehlert+ 2023, Sciaccaluga+ 2024]

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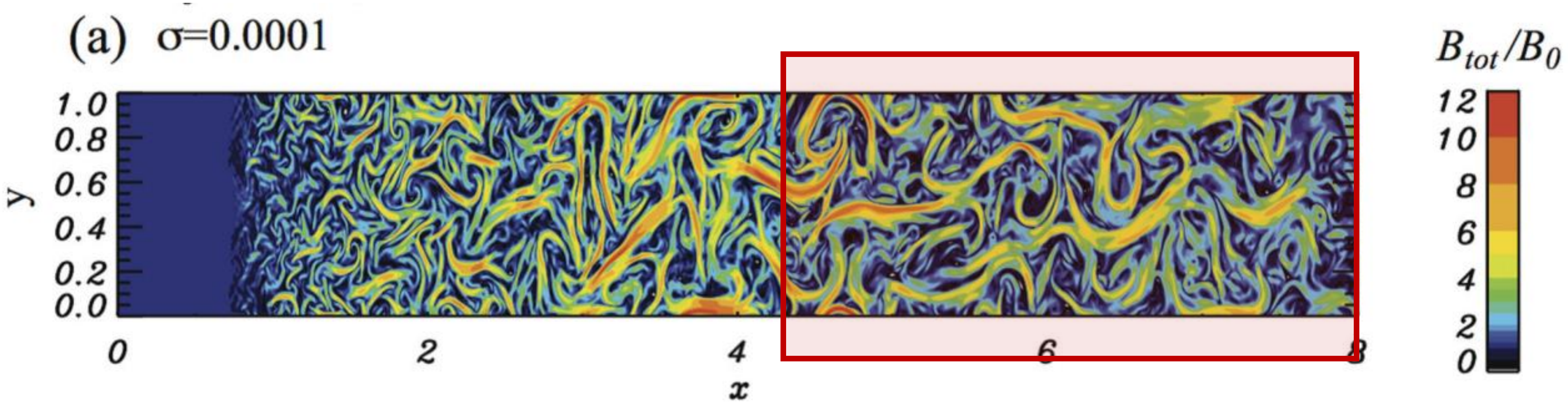

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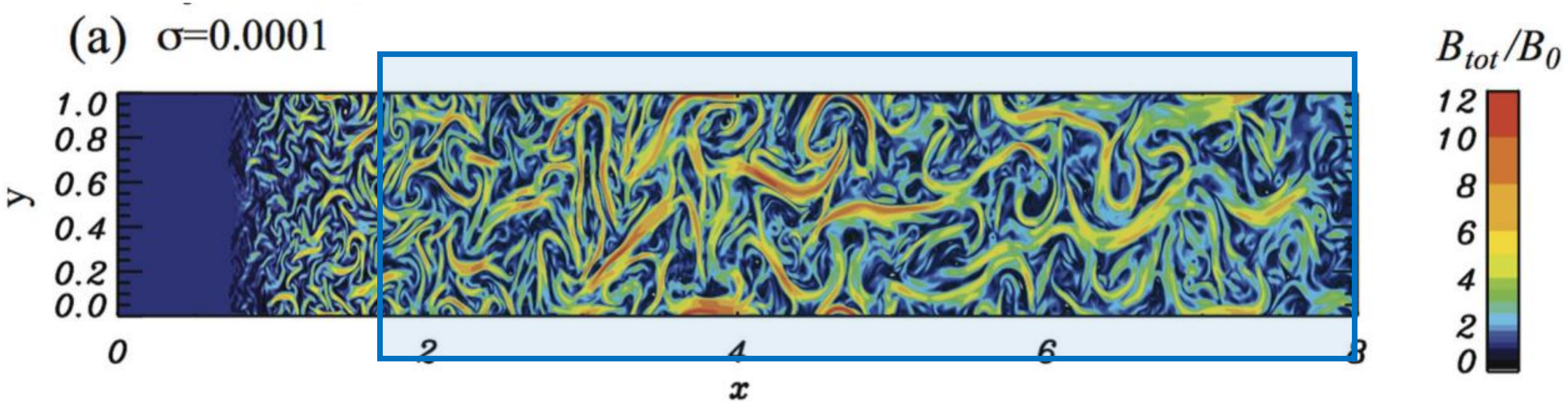

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What's next?

LIMITATIONS

- Based on MHD evidences
- No spatial resolution
- Simple shock interpretation

IMPROVEMENTS

- Directly on MHD simulations
- Spatial effects
- Shocks from PIC