Blazar jets:
new clues and old challenges

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Outline

New clues:

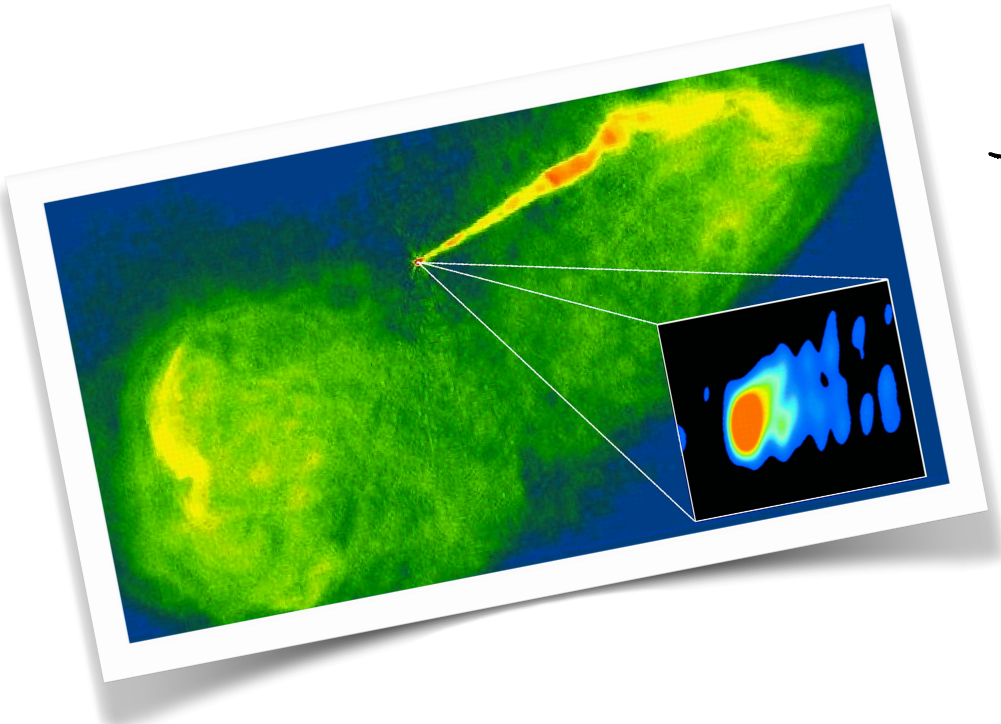
Clues on particle acceleration from X-ray polarization

A stratified shock model for high synchrotron peak BL Lacs

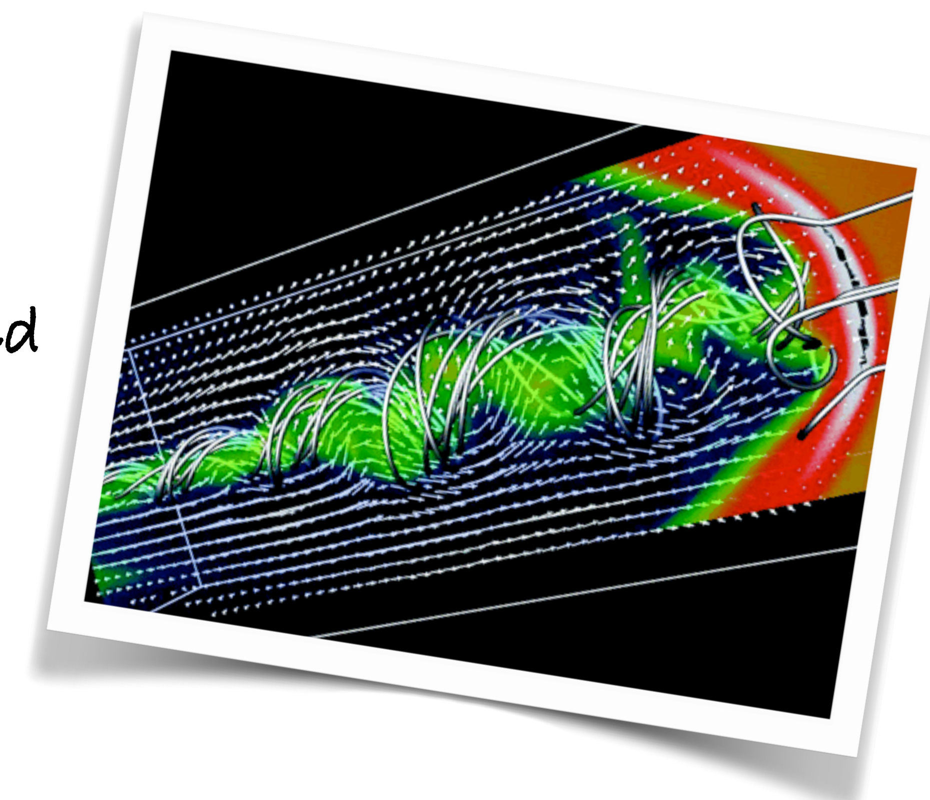
Old challenges:

Extreme blazars: acceleration at recollimation shocks?

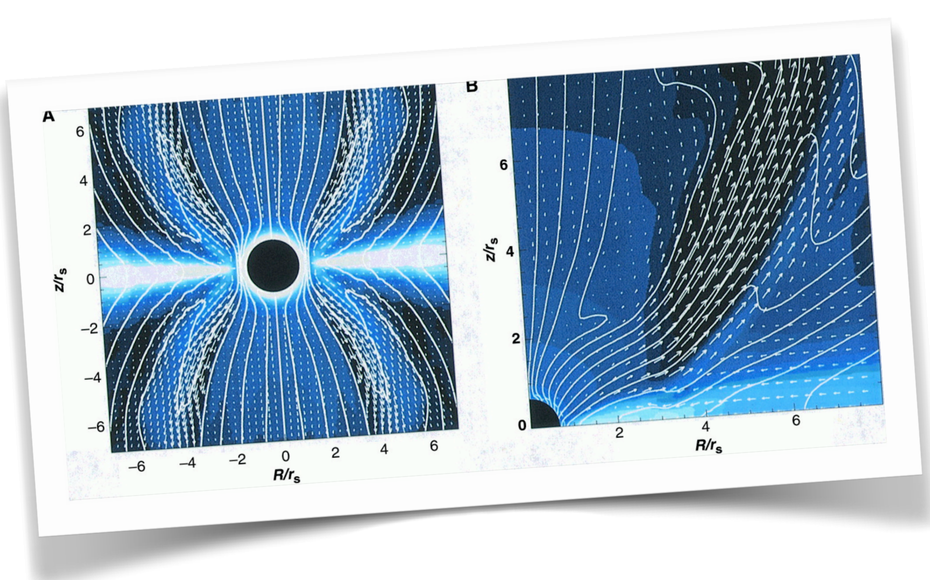
Jets: the fundamental questions



Jet dynamics, speed, composition, power



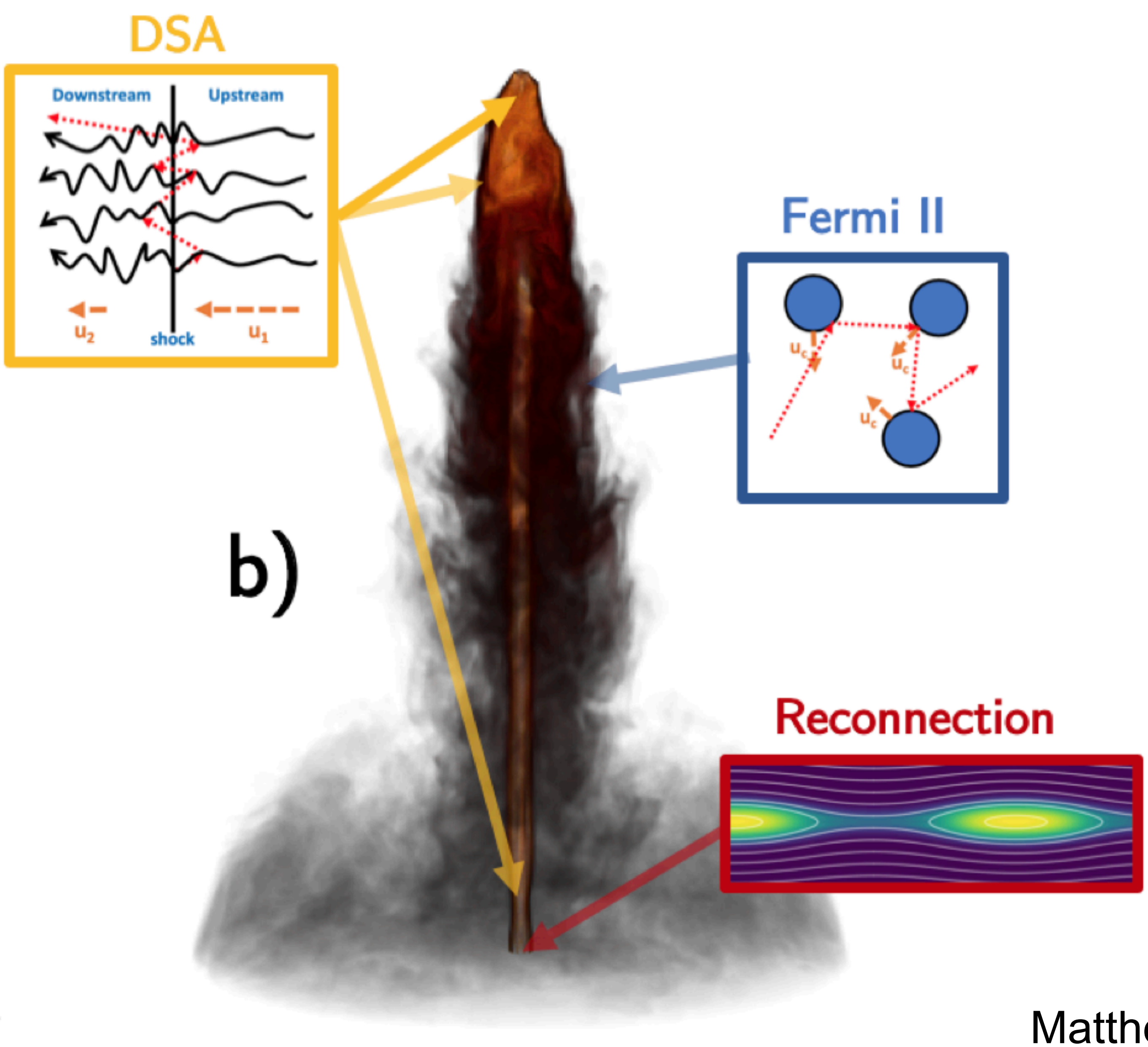
Magnetic fields, dissipation, acceleration and emission mechanisms



Formation, collimation, acceleration

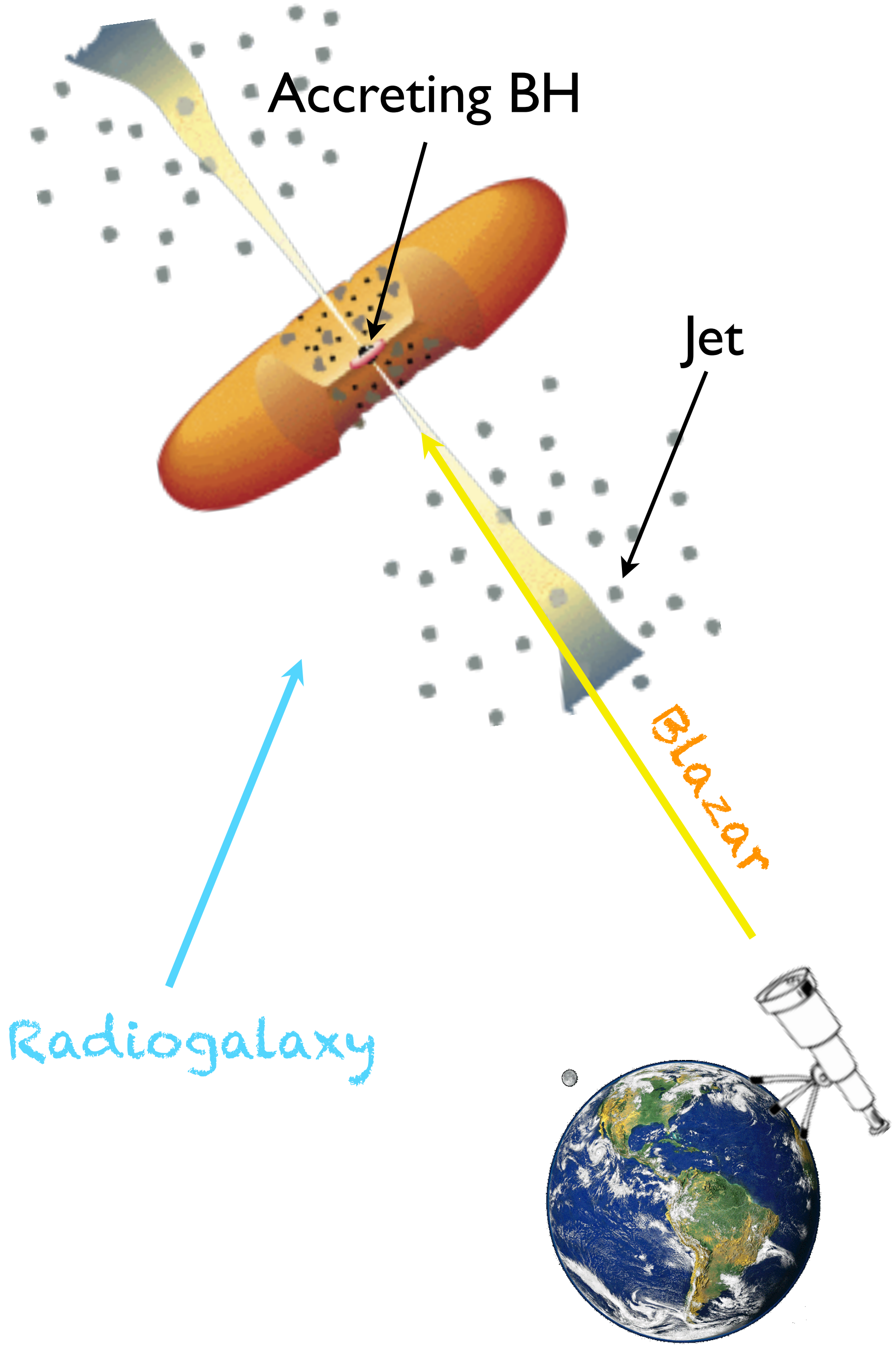
e.g. Blandford et al. 2019
Blackman and Lebedev 2022

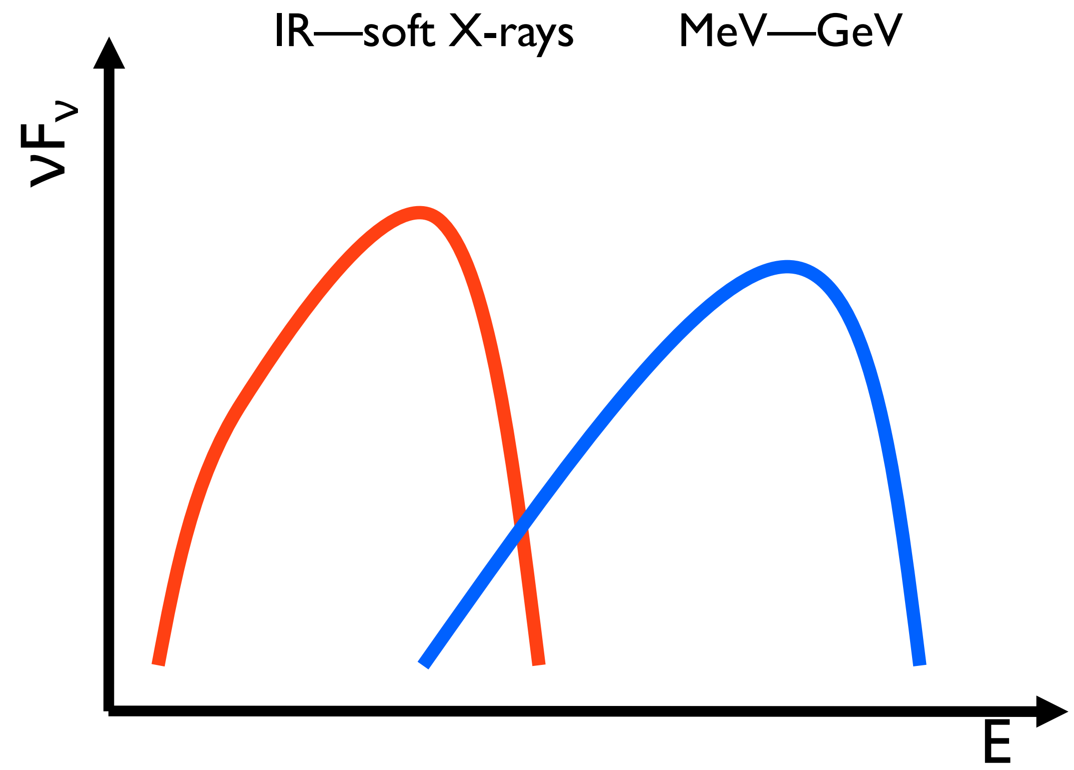
Particle acceleration: many places, several processes



Matthews et al. 2020

Jets pointing at us: blazars





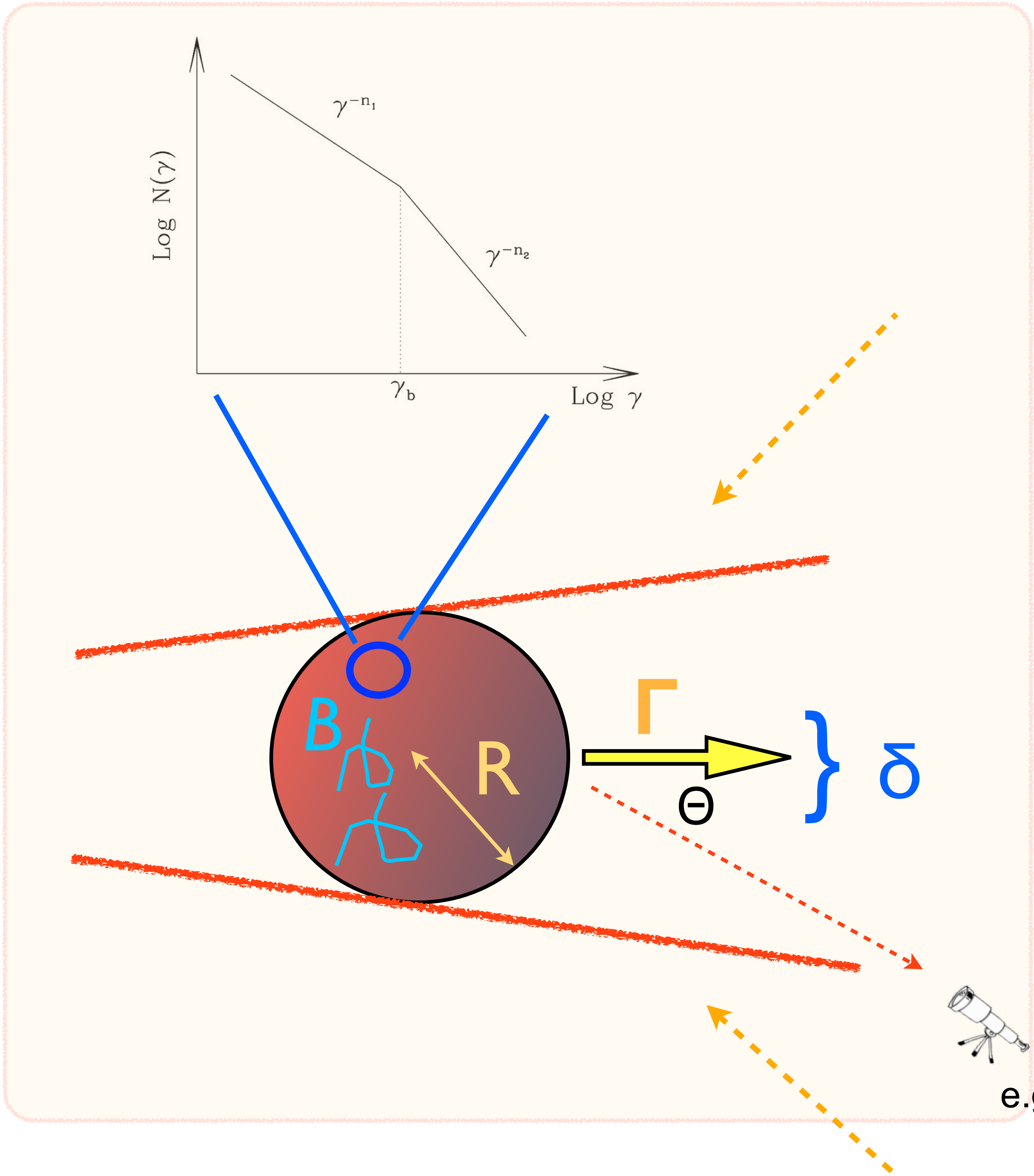
SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

$$L_{\rm obs} = L'\delta^4 \qquad \delta = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm v})}$$

Synchrotron and IC in leptonic models.

Also hadronic scenarios (synchrotron or photo-meson emission)

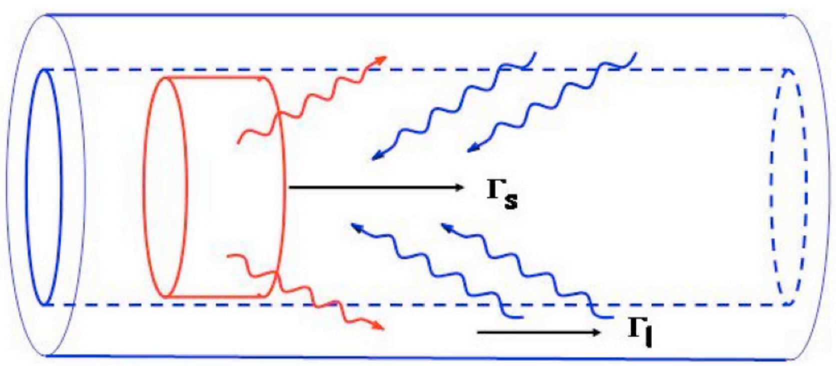
One zone models

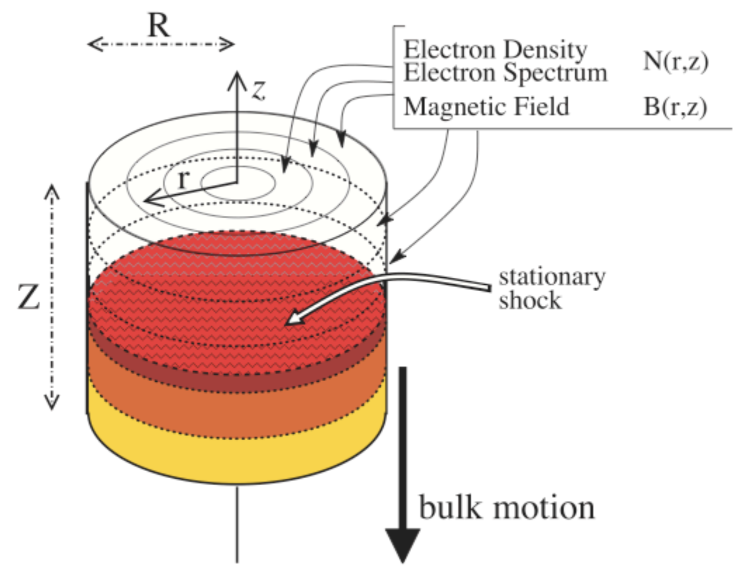


e.g. Tavecchio et al. 1998

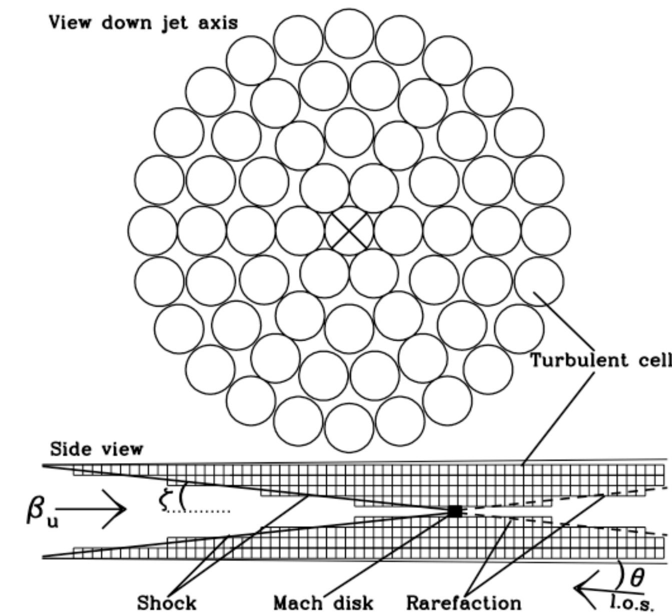
Beyond one-zone *An incomplete list ...*

Ghisellini, FT & Chiaberge 2005





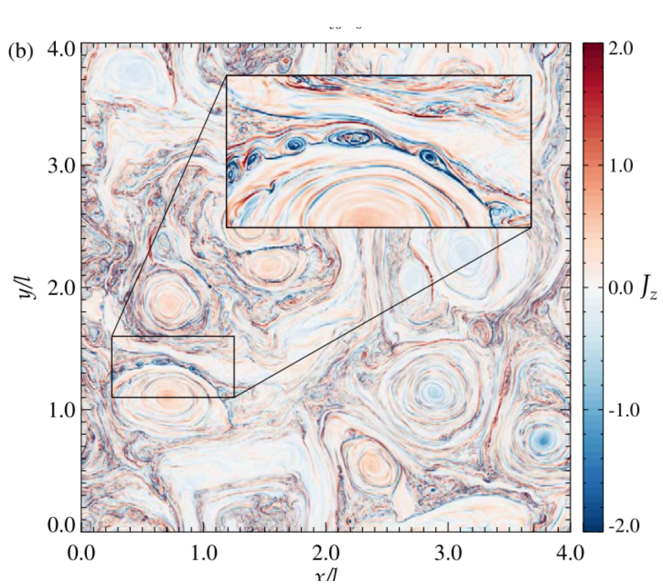
Chen et al. 2011



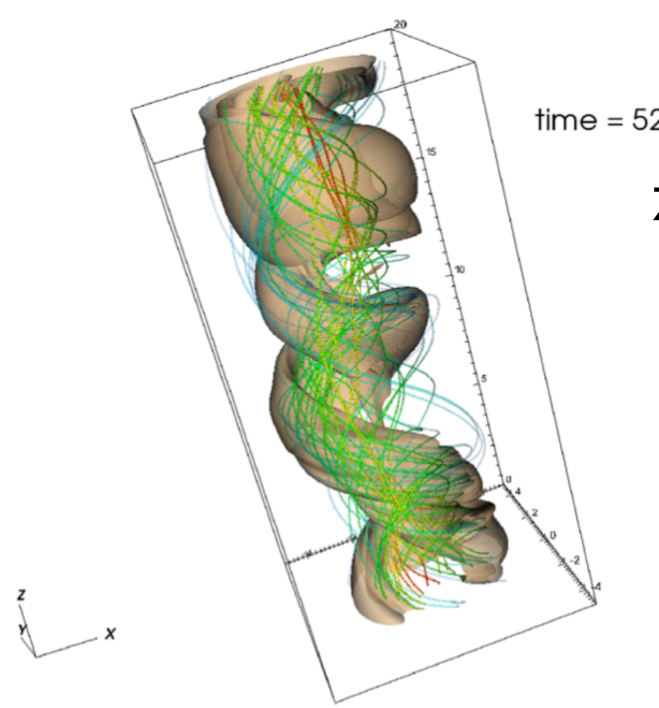
Marscher 2014

Kinetic

Magnetic

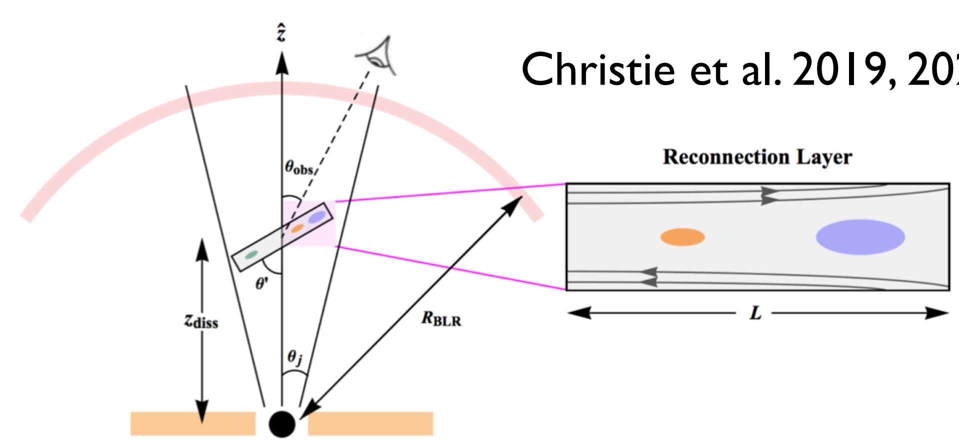


Comisso, Sobacchi et al. 2020

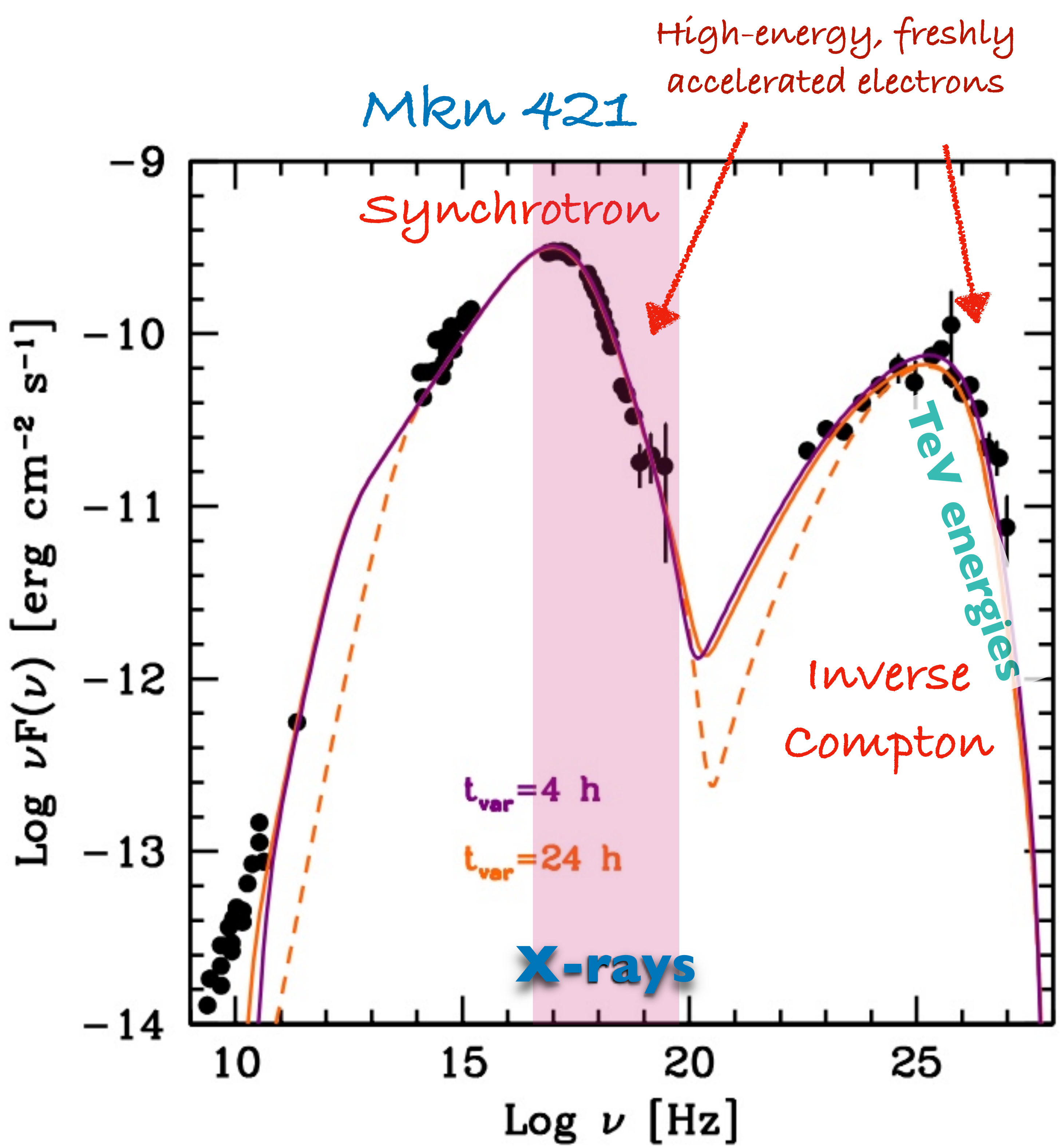


Zhang et al. 2018, Bodo et al. 2020

Christie et al. 2019, 2020



HBLs: extreme accelerators



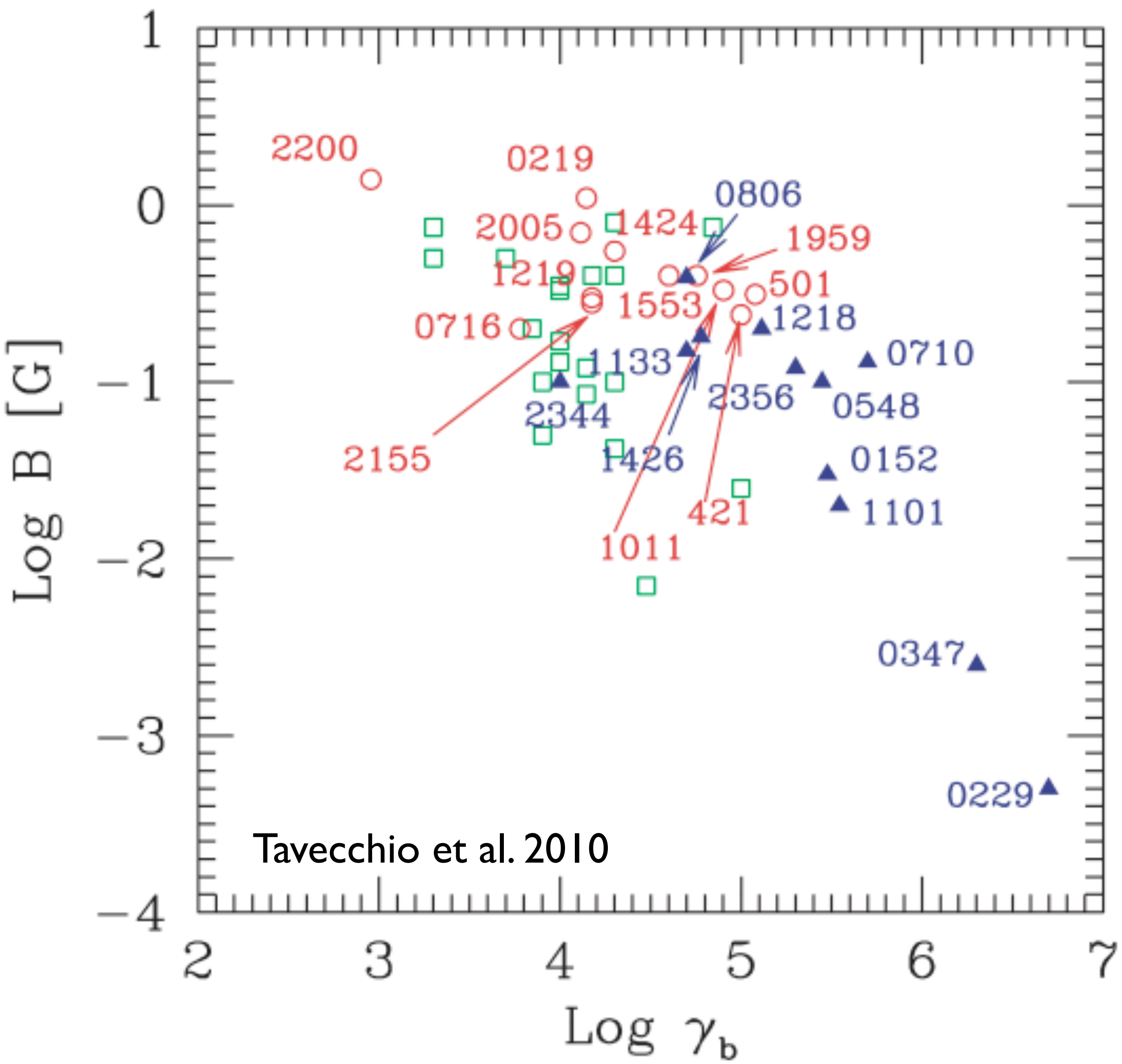
$$h\nu_X = 1 - 10\ \mathrm{keV}$$

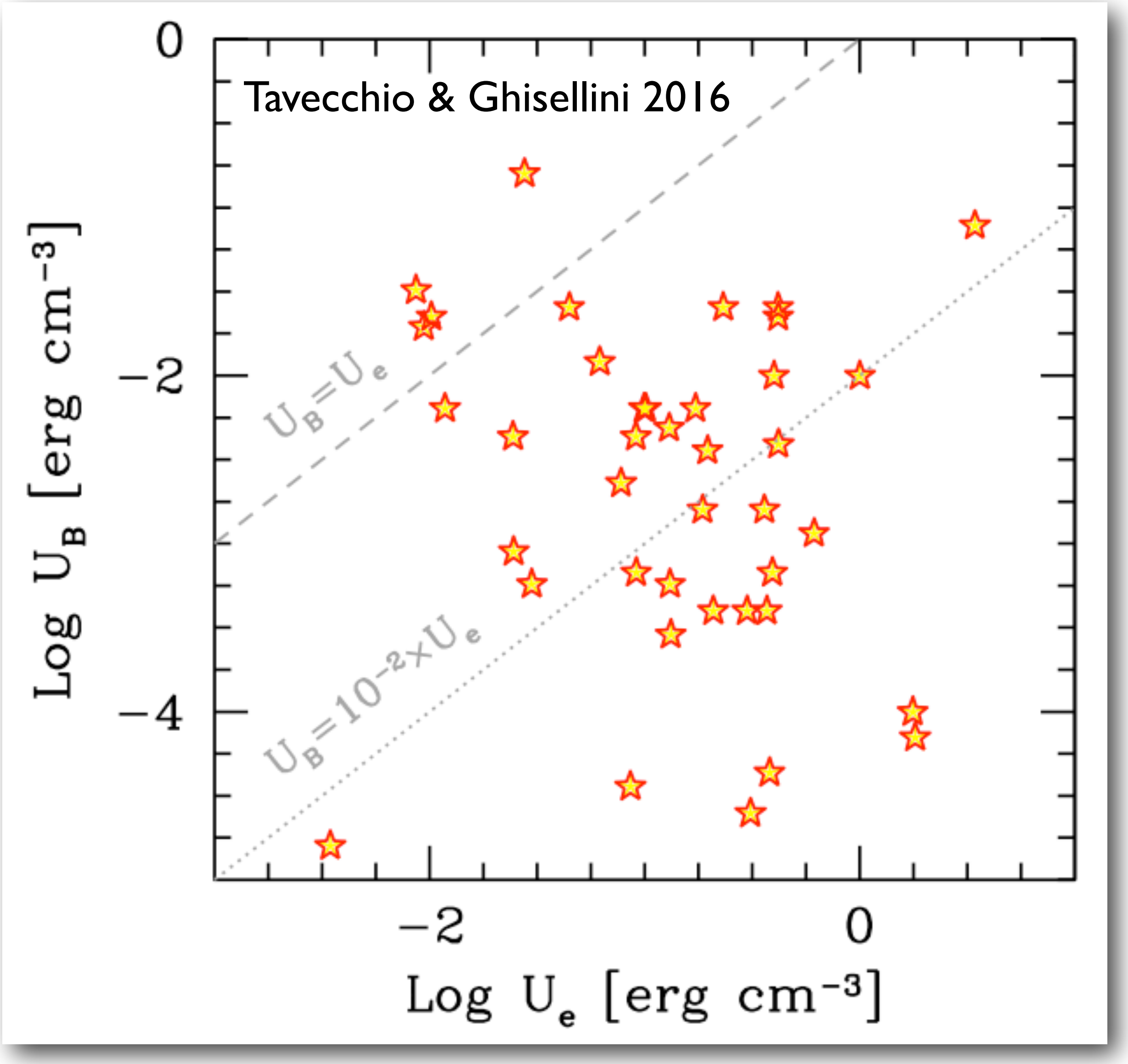
$$\gamma_X = \left(\frac{2\pi m_e c \nu_X}{eB\delta}\right)^{1/2} \sim 10^5 - 10^6$$

$$ct_{cool} = 2.3 \times 10^{15} B_{-1}^{-2} \gamma_{X,6}^{-1}\ \mathrm{cm}$$

Compact regions

One zone modeling: results

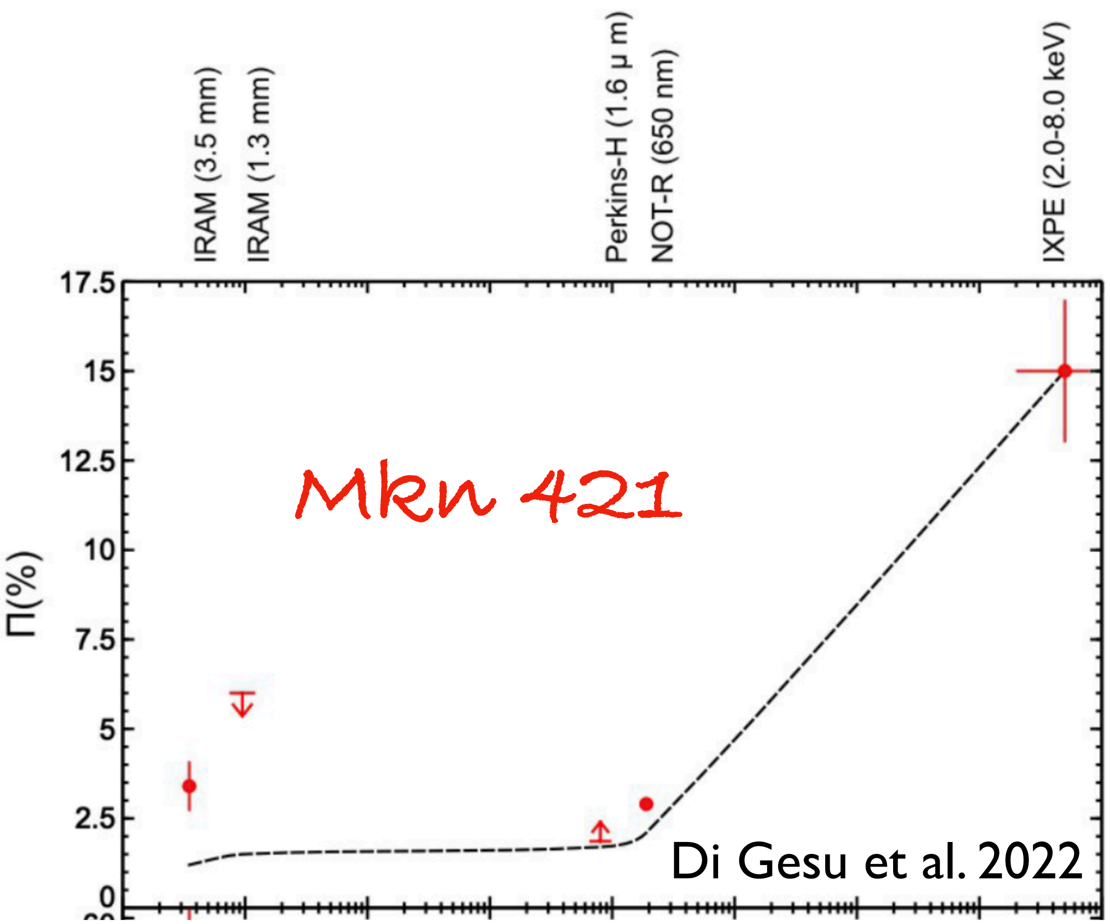


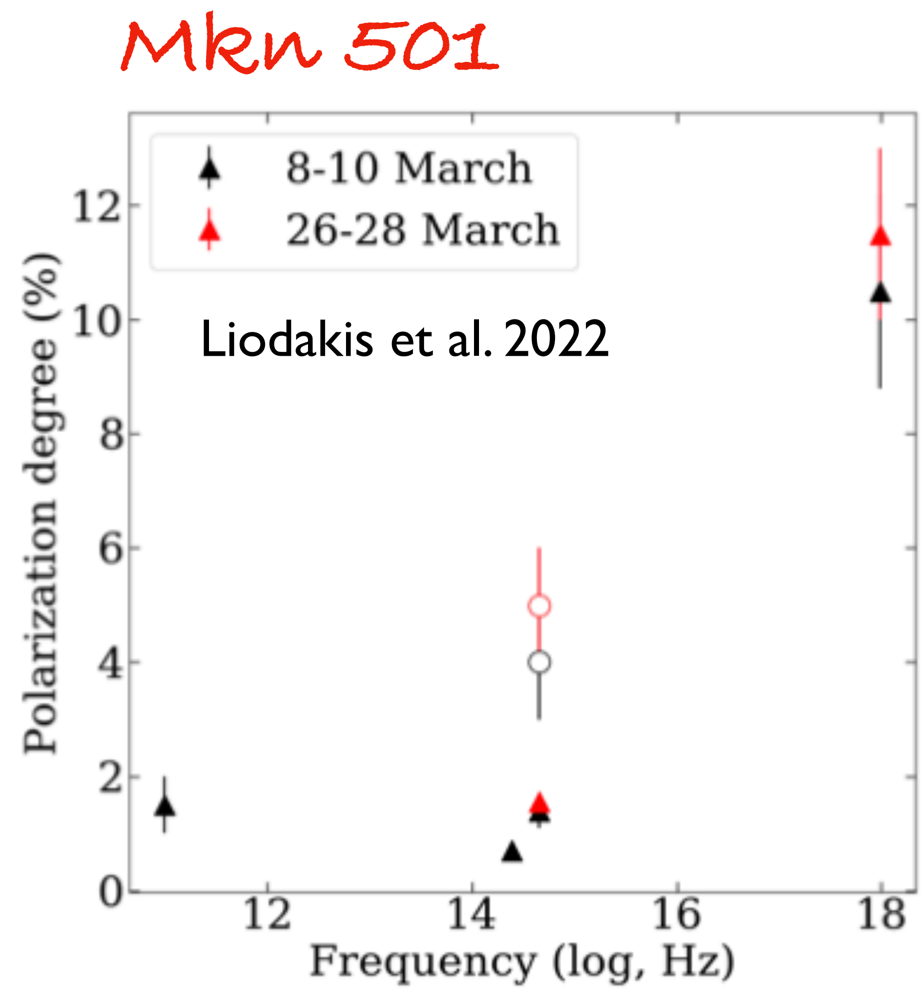


- High electron Lorentz factors
- Low magnetic field (subequipartition)

Hints from IXPE (1)

HSP in low/quiescent flux states





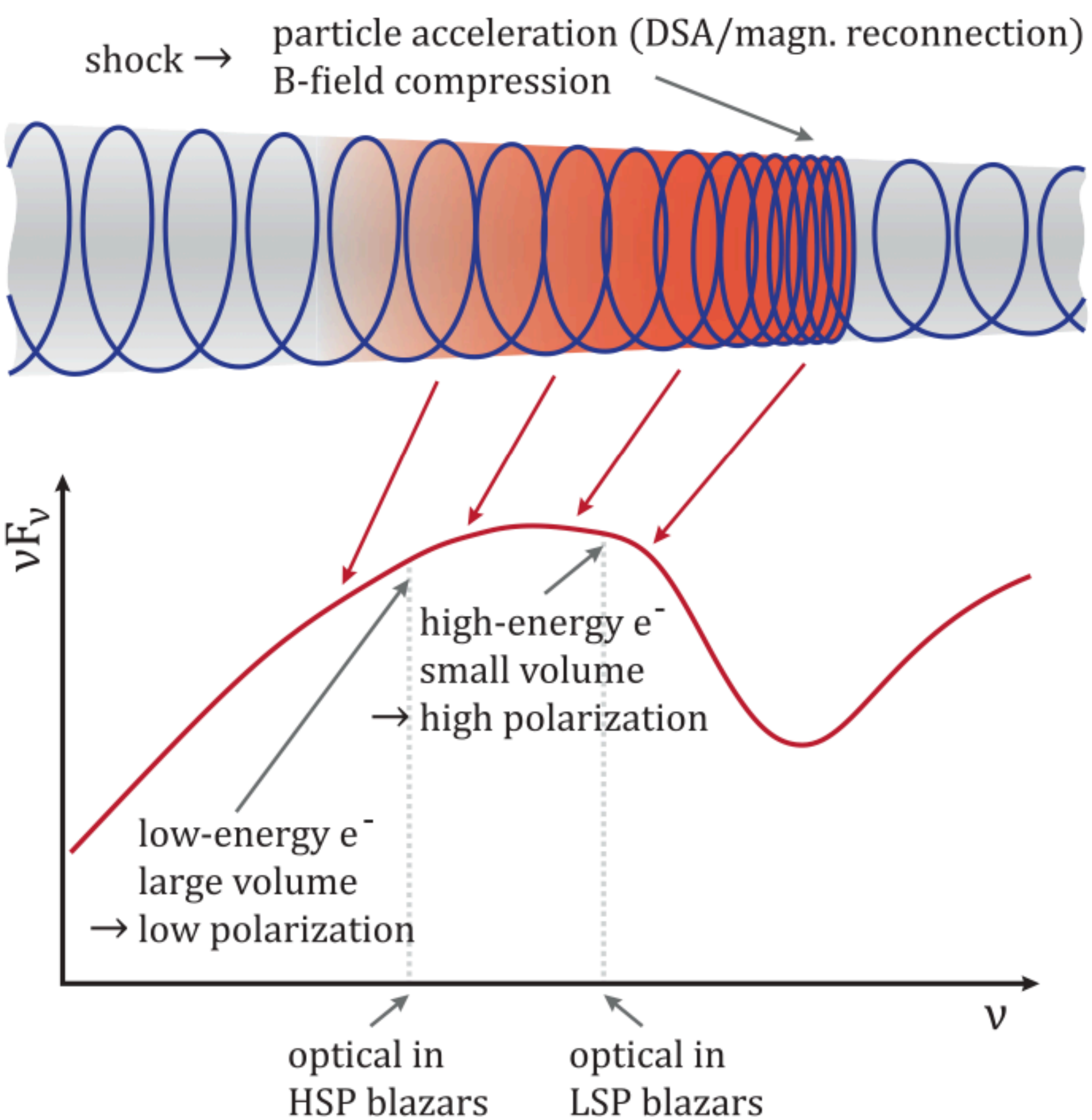
Stratified shock?

Liodakis et al. 2022

Analogue results for:
PG 1553+113 (Middei et al. 2023) ,
1ES 0229+200 (Ehlert et al. 2023),
and others in the pipeline

Magnetic fields at shocks

Compression

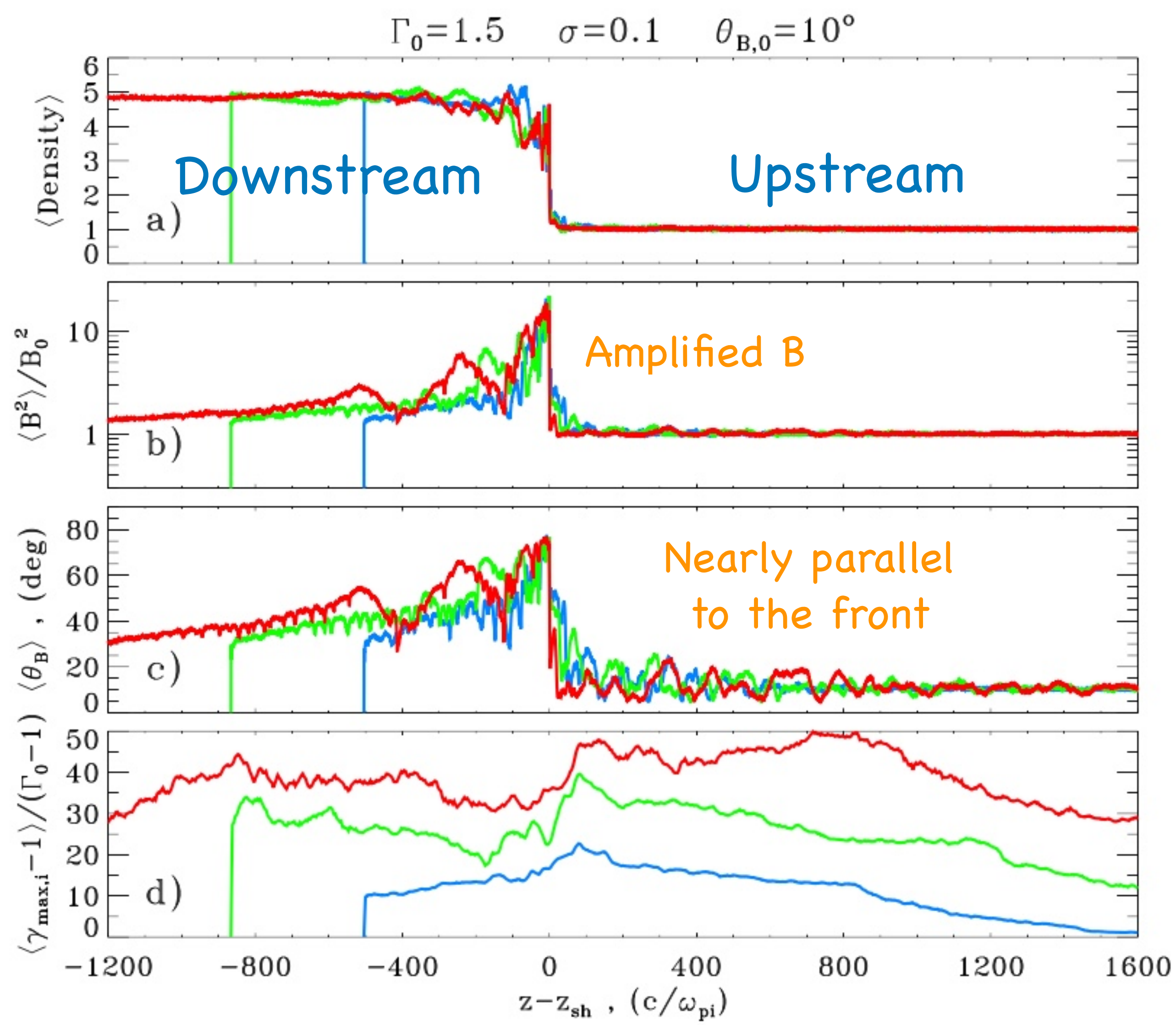


e.g. Laing 1980

Angelakis et al. 2016

Self-generated field

Trans-relativistic, nearly parallel, low σ shock



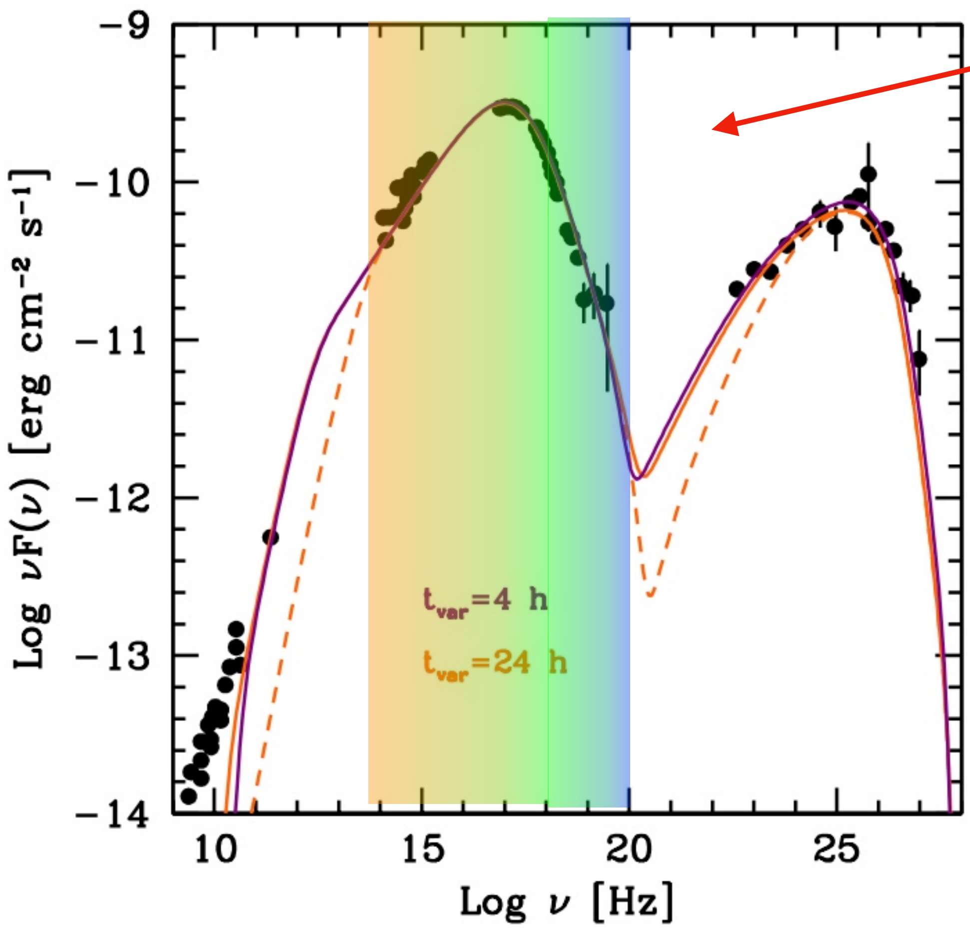
Caprioli & Spitkovsky 2014

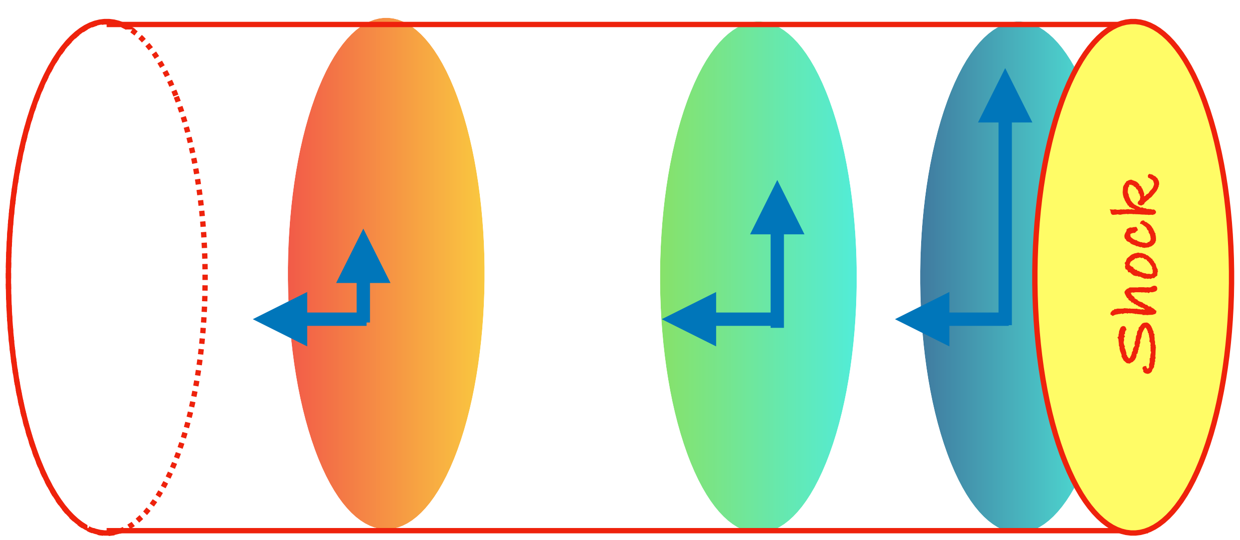
Sironi et al. 2015

Vanthieghem et al. 2020

Stratified shock: a toy model

$$\nu_s \propto \gamma^2 B$$

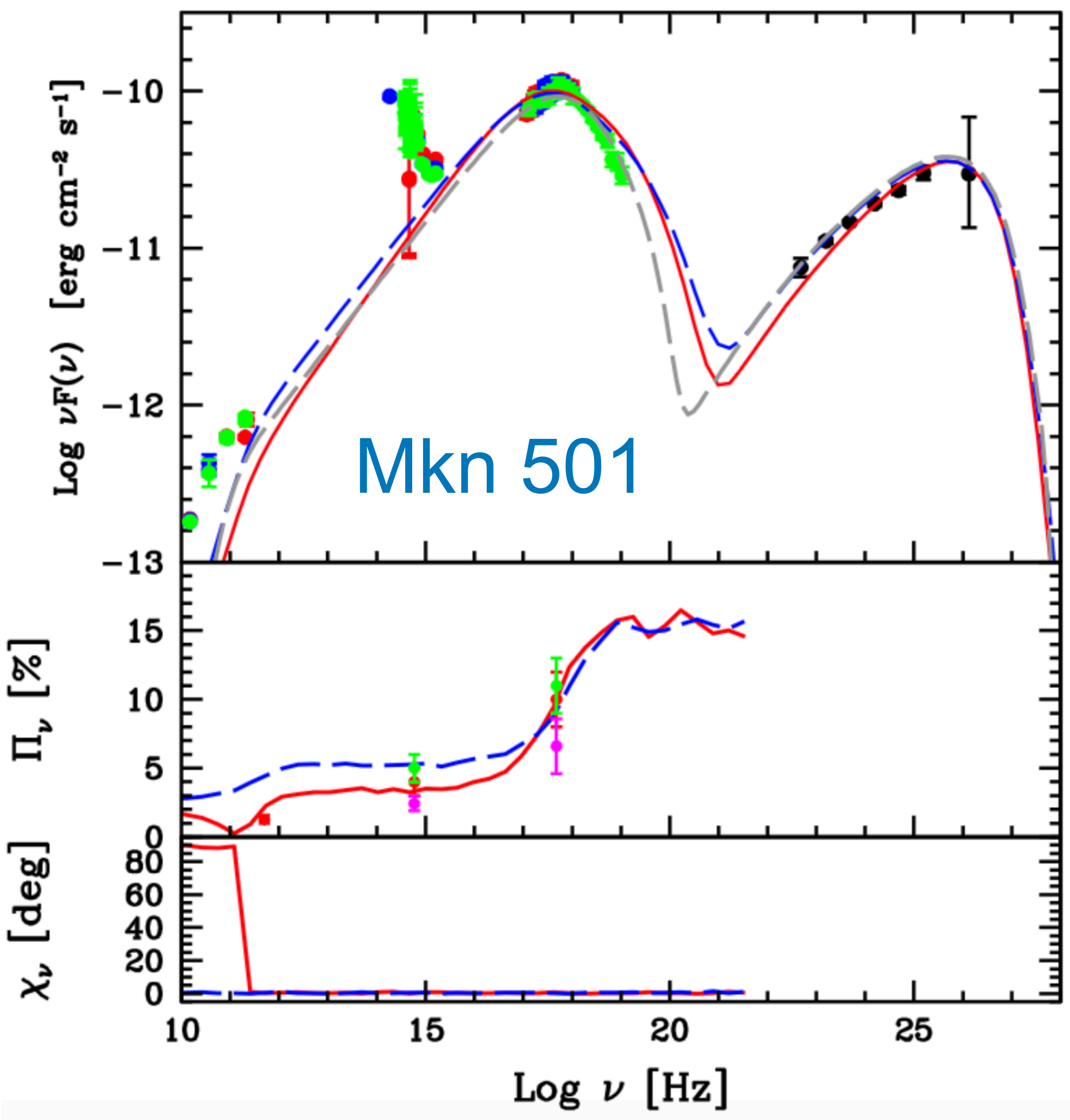




Reminiscent of "X-ray first" behavior in large scale jets? (E. Meyer's talk)

Tavecchio et al. 2018, 2020

Stratified shock: a toy model



Just two possible realizations!
A full exploration of the parameter space is required (MCMC)

$$B_{\perp}(d) = B_{\perp,0}\left[1 + \frac{d}{\lambda}\right]^{-m}$$

Phenomenological law for the field

e.g. Lemoine 2013

$\Gamma = 22,\ \theta_v = 1.3^{\circ}$

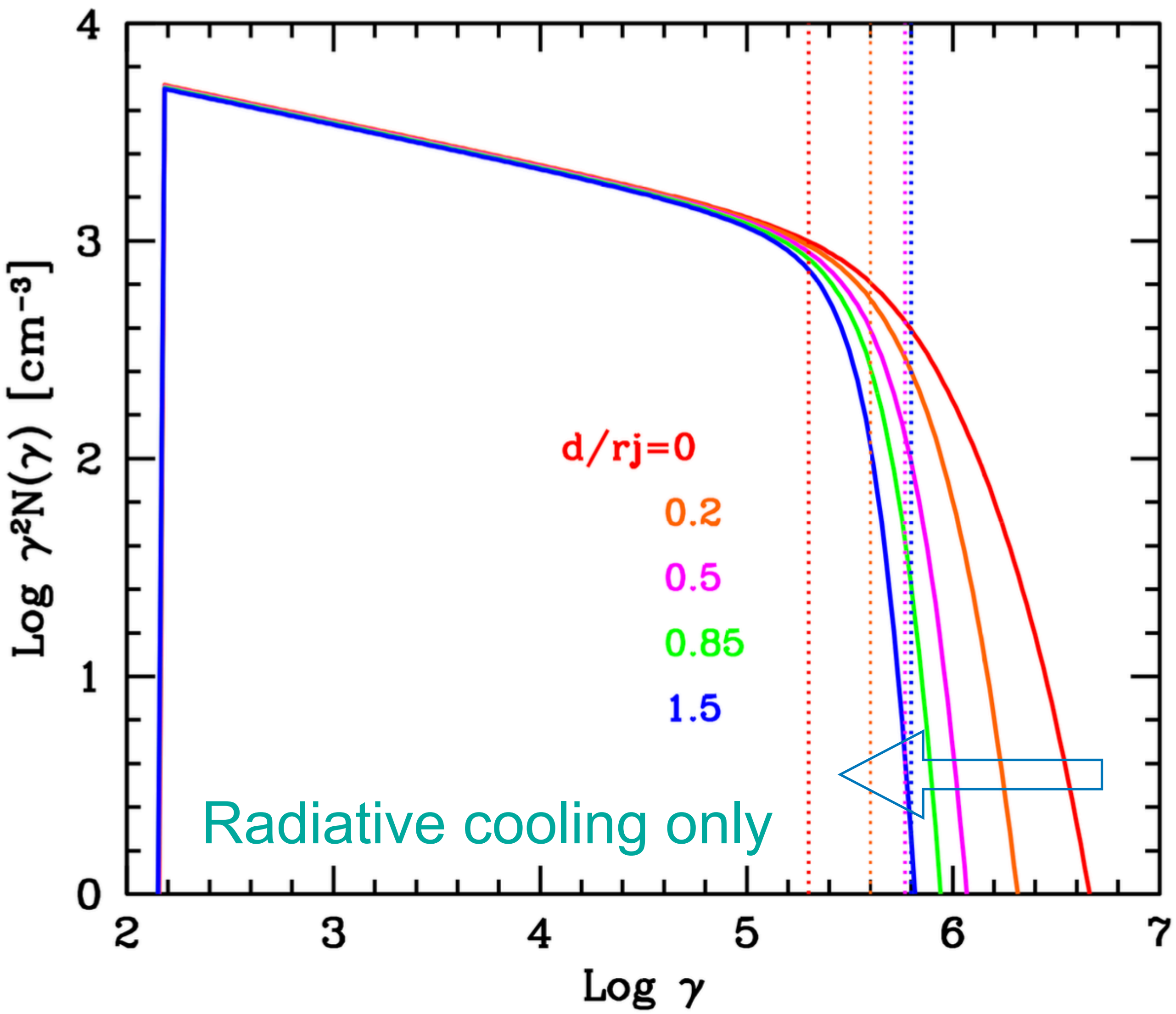
Tavecchio in prep.

Data from Lisalda et al., in prep.

Model	$\gamma_{\rm cut}$ ($\times 10^5$) [1]	n [2]	$n_{e,0}$ [3]	$B_{\perp,0}$ [4]	B_z [5]	$r_{\rm j}$ ($\times 10^{15}$) [6]	λ [7]	m [8]
1	8.5	2.1	20	0.25	0.03	4.3	5×10^{13}	0.5
2	12.6	2.2	30	0.25	0.03	4.8	1.2×10^{12}	0.25

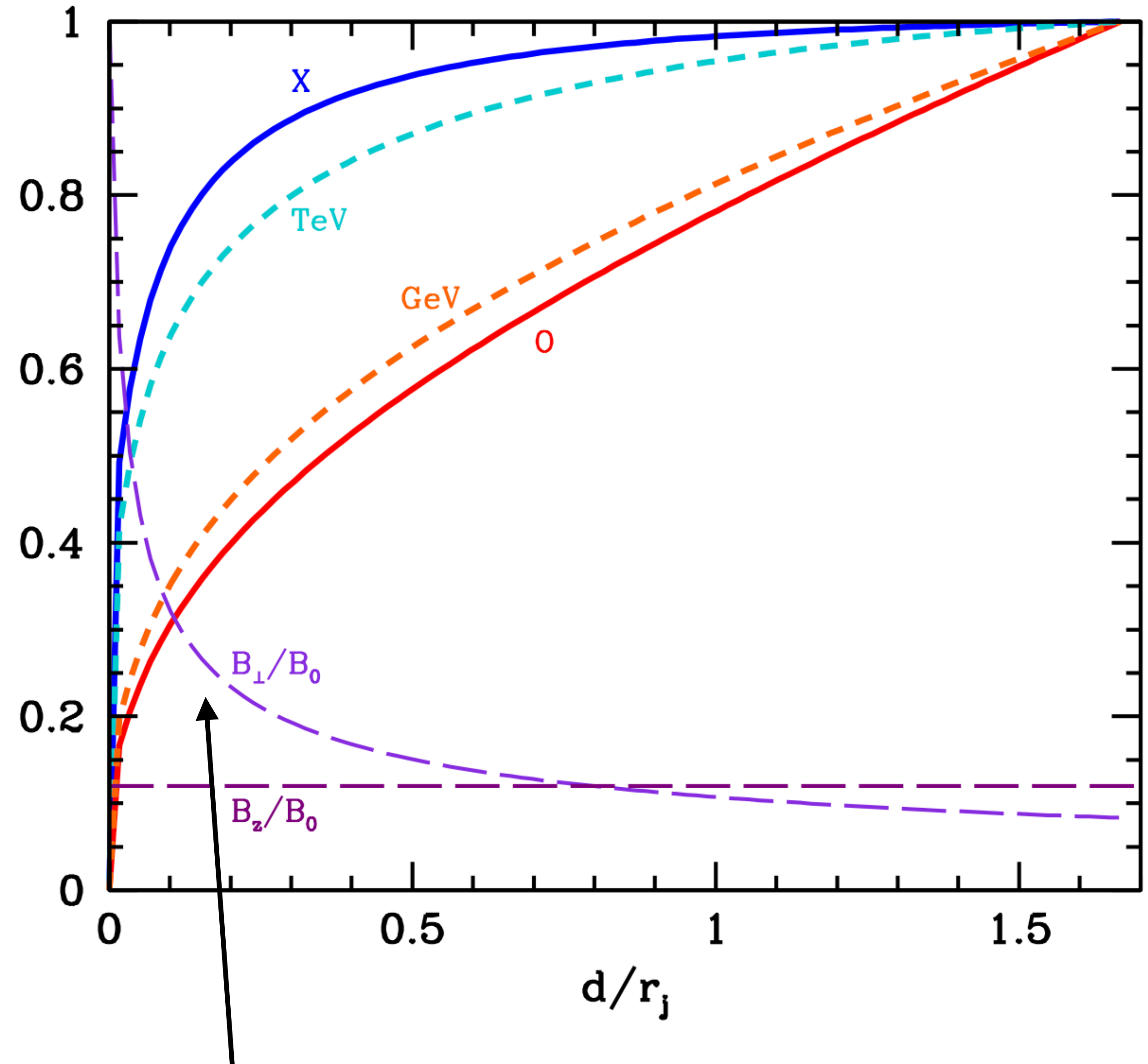
Stratified shock: a toy model

Electron distribution
at different distances



Tavecchio in prep.

Emission profiles



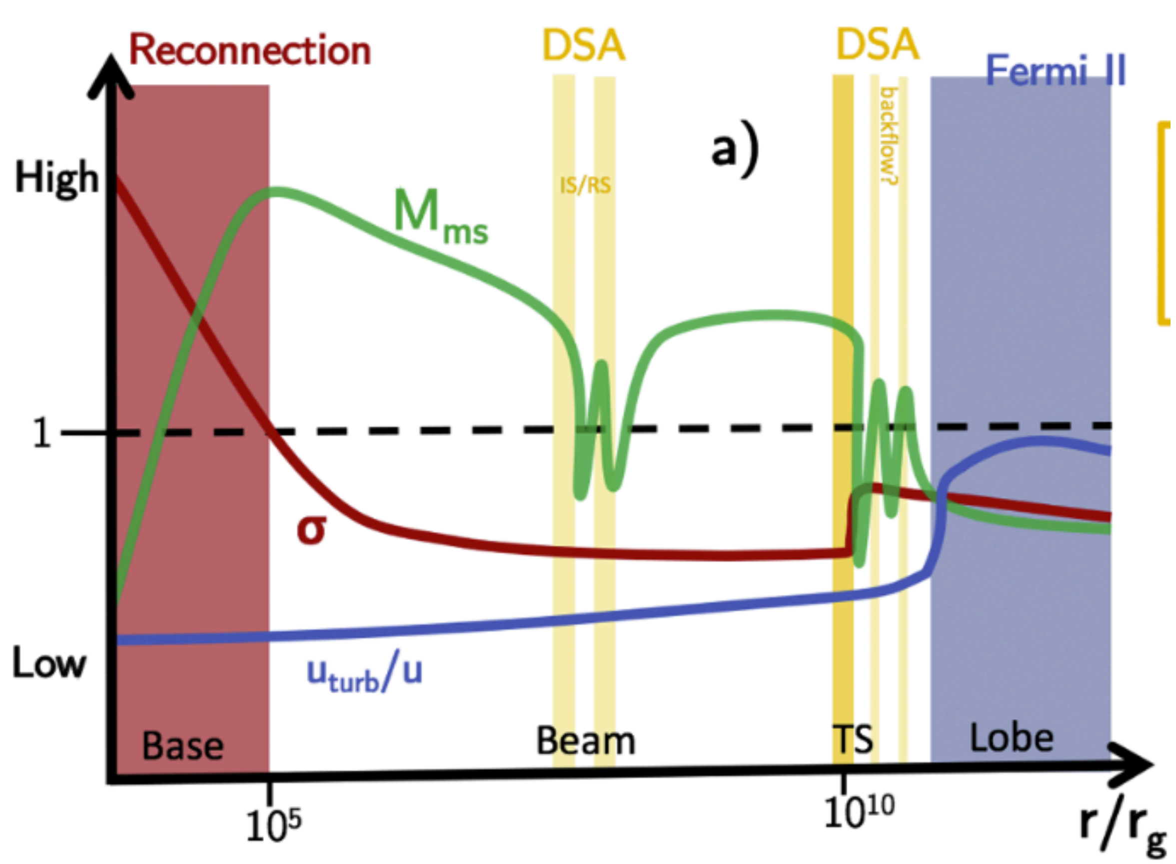
$$B_{\perp}(d) = B_{\perp,0}\left[1 + \frac{d}{\lambda}\right]^{-m}$$

Shock acceleration?

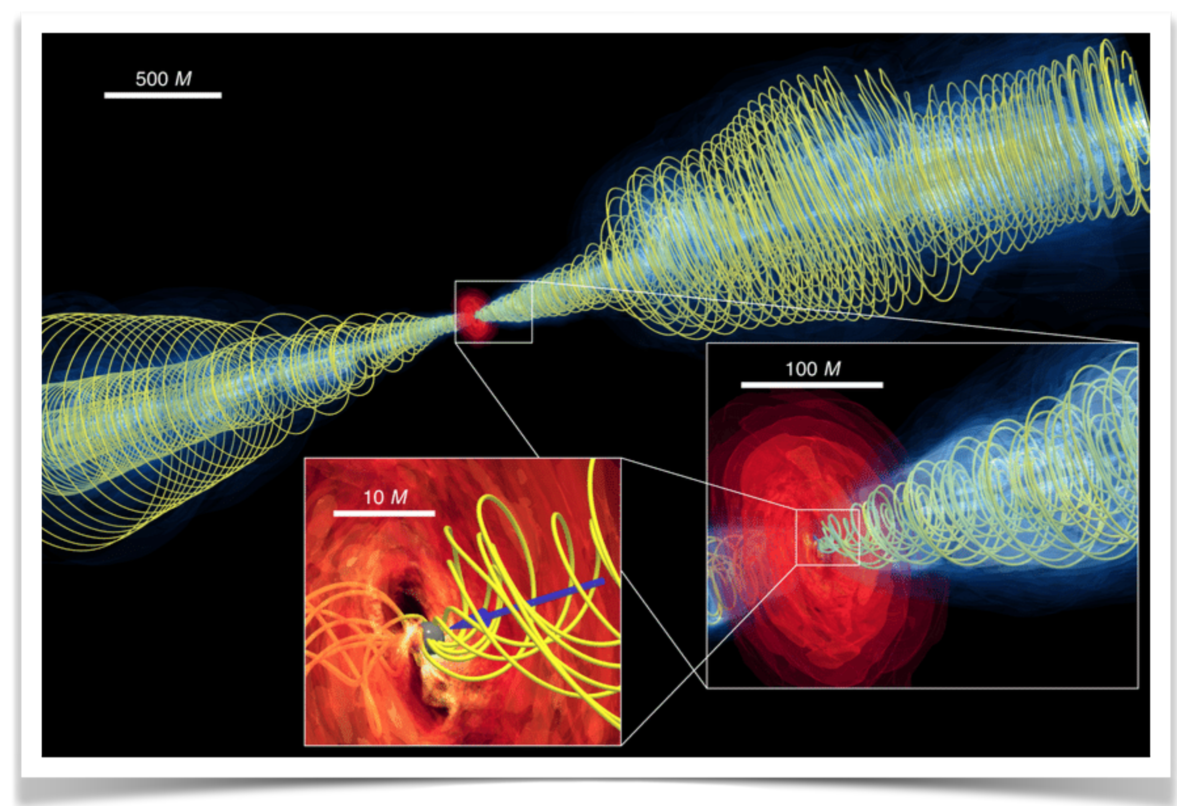
DSA can work efficiently only in weakly magnetized jets (e.g. Sironi+2015)

This is consistent with SED modeling (e.g. FT+2016)

This is inconsistent with jet production models (e.g. Komissarov et al. 2009)

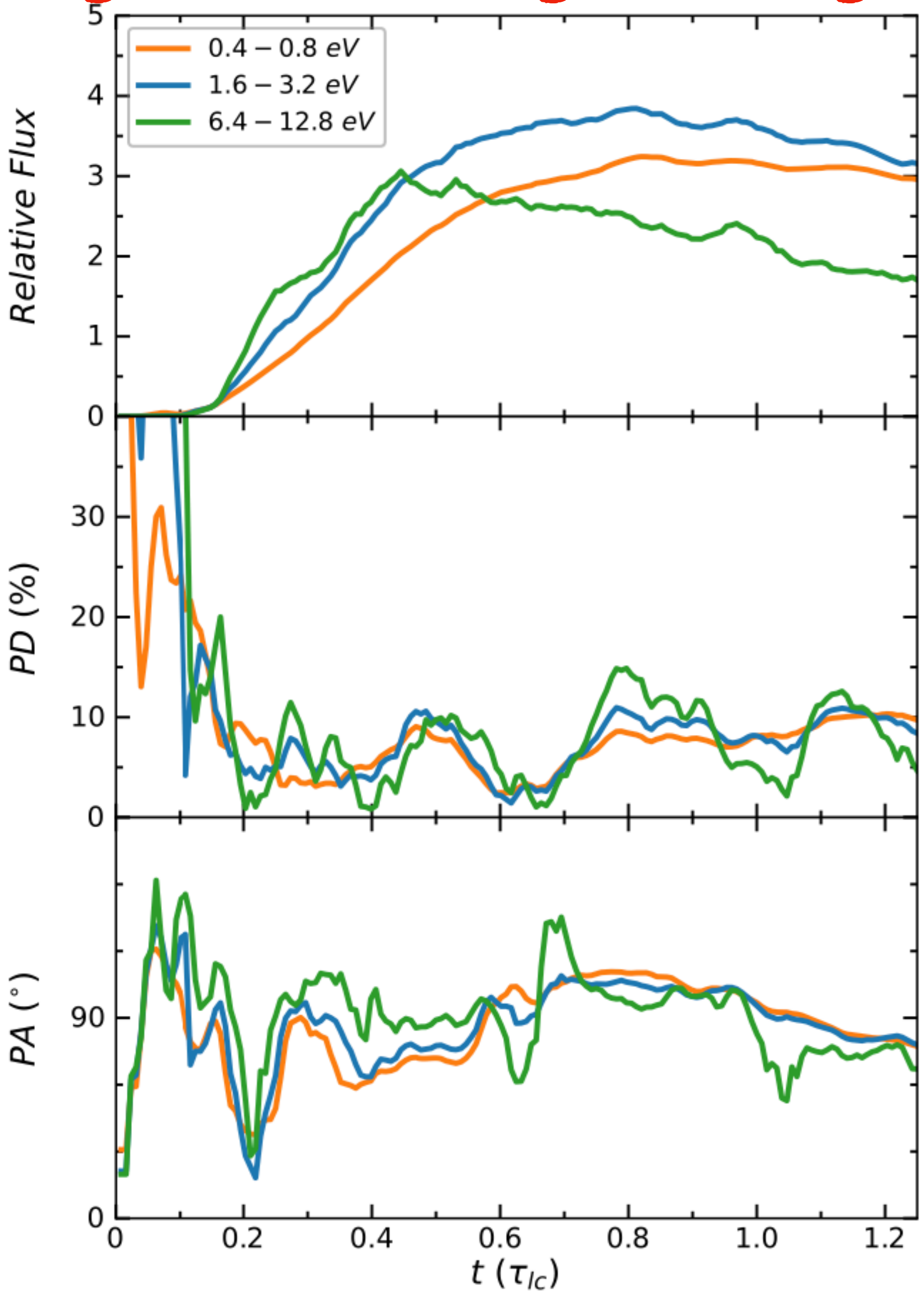


Matthews et al. 2020



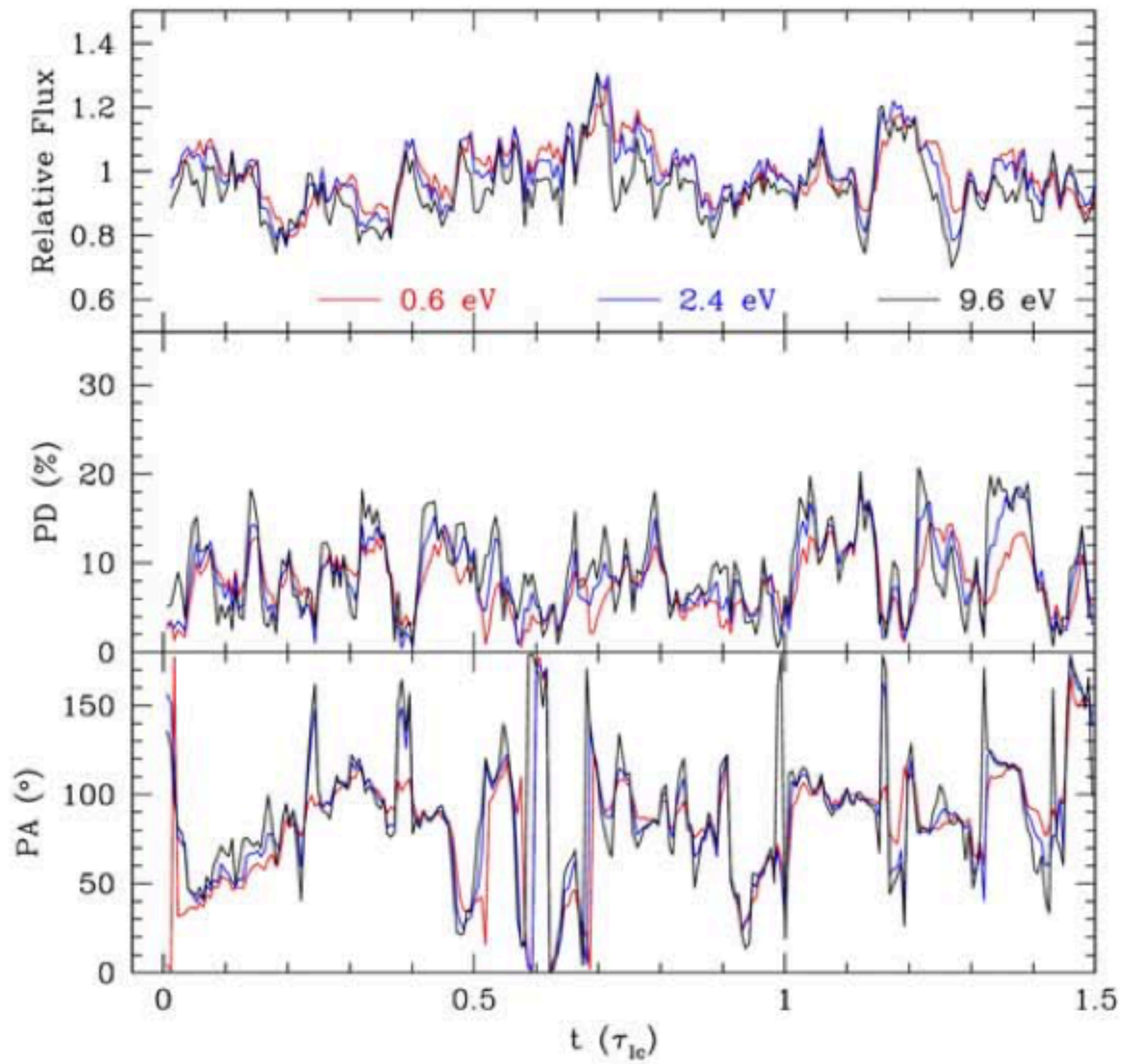
Hints from IXPE: 2) limits to turbulence

Magnetic (high magn.)



Zhang et al. 2023

Kinetic (low magn.)

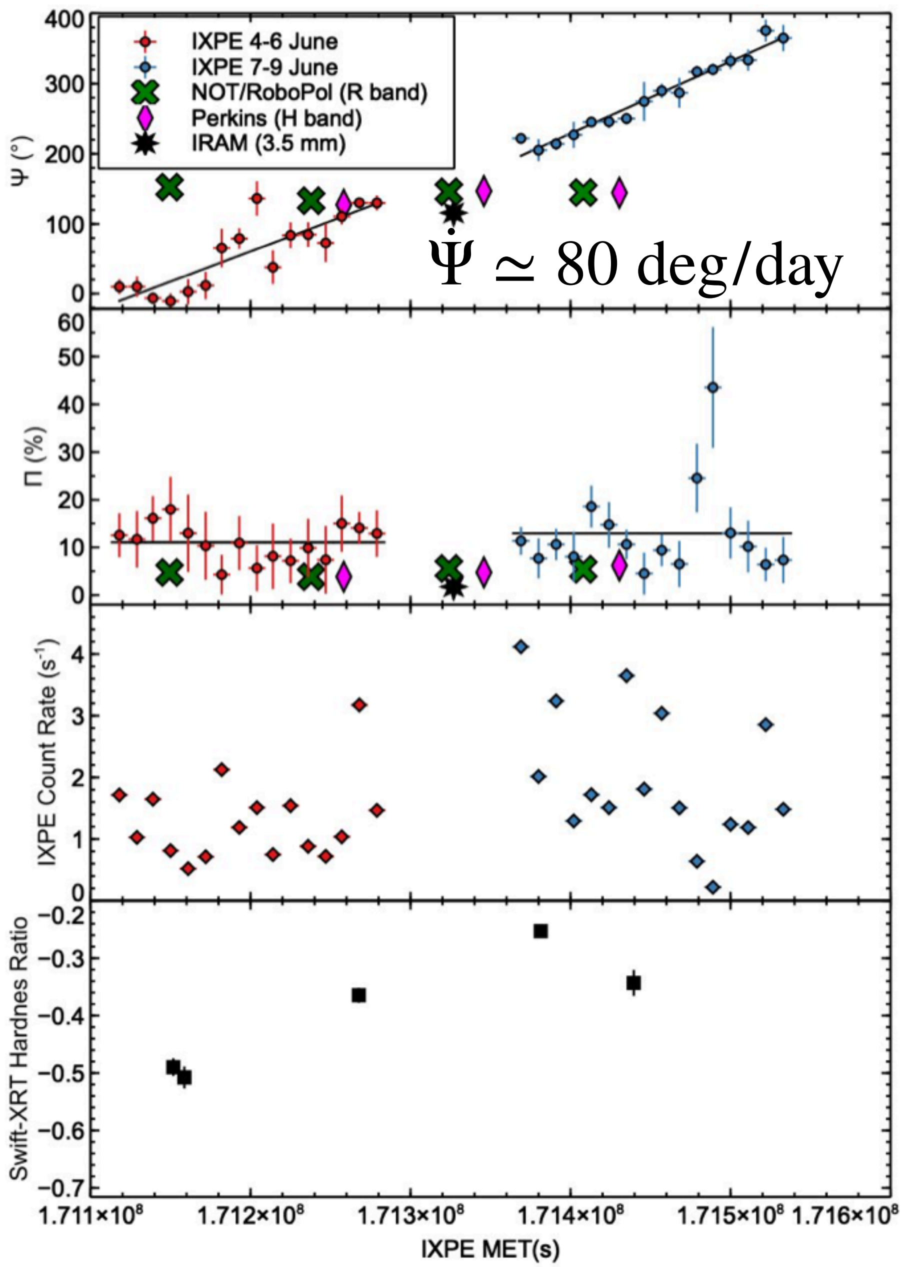


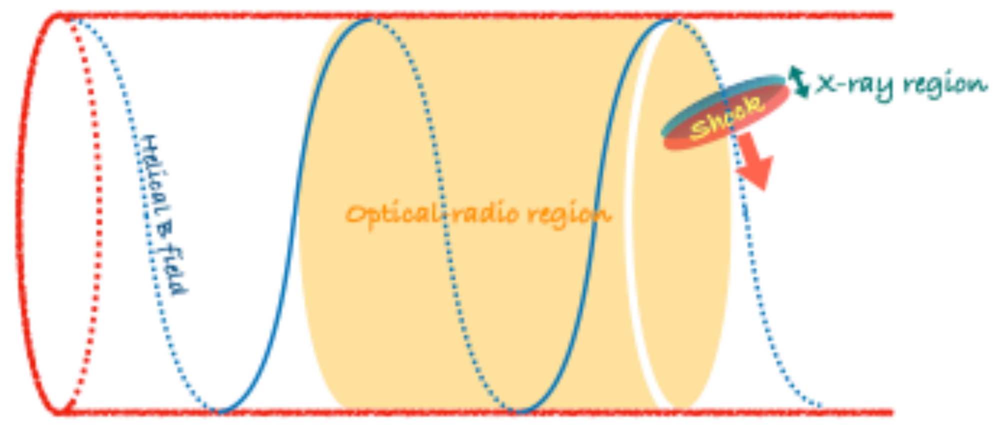
The observed steadiness of the polarization effectively limits the level of (macro)turbulence

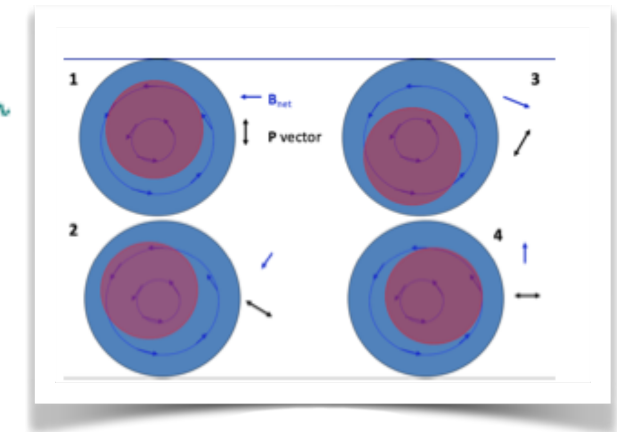
e.g. Marscher & Jorstad 2022

Hints from IXPE: 3) EVPA rotations

Mkn 421

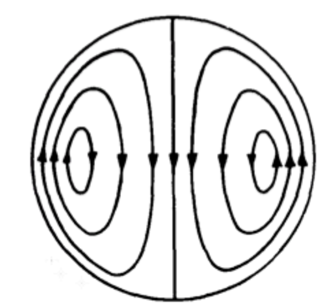


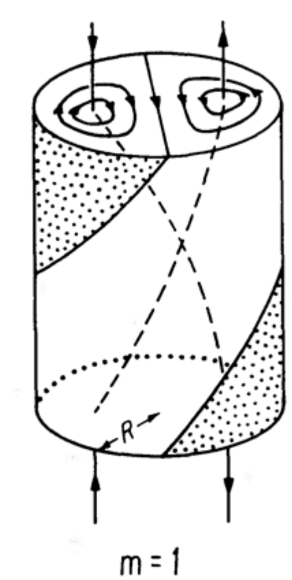




non-axysimmetric feature (e.g. shock)

Marscher et al 2008, 2010





non-axysimmetric field

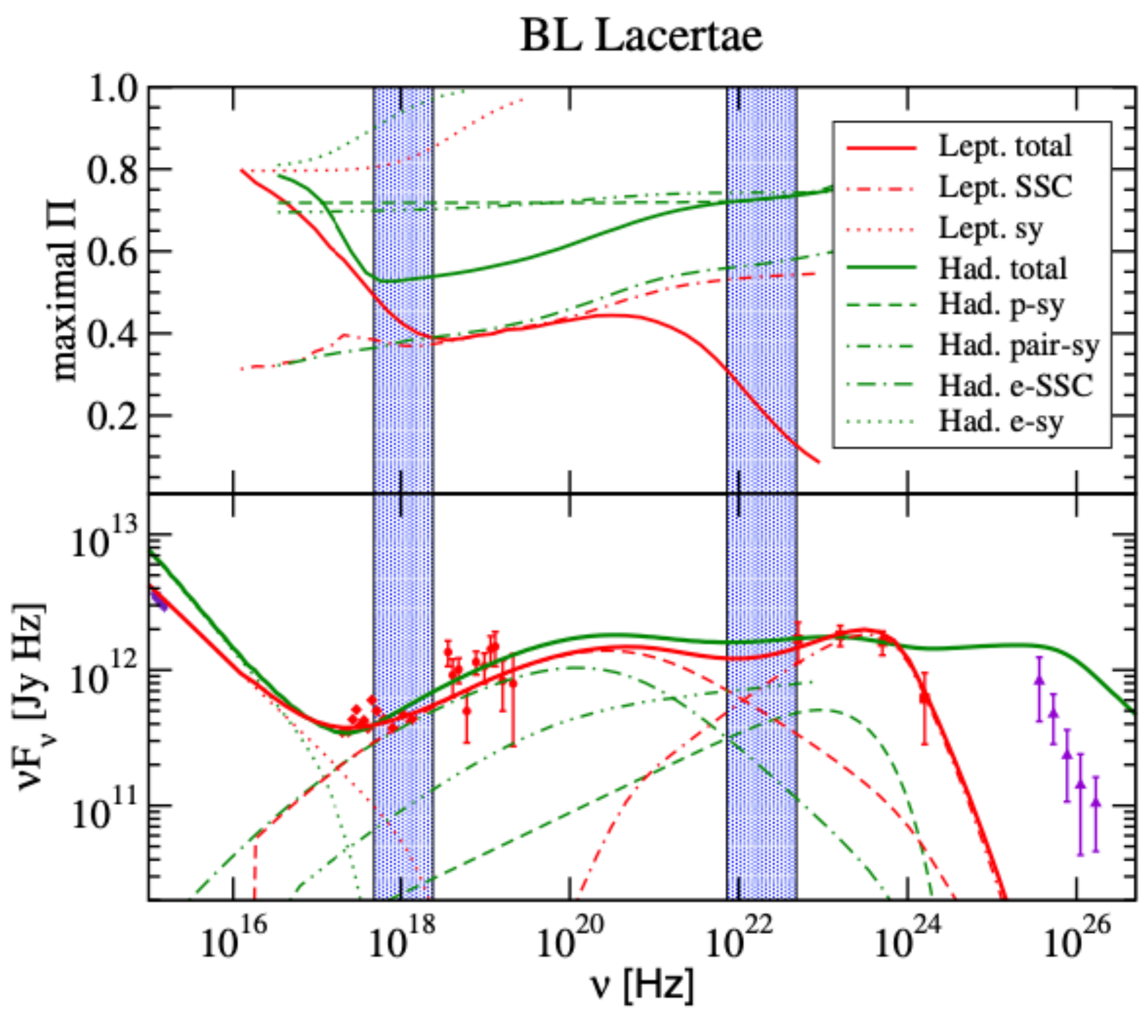
Koenigl & Choudhuri 1985

Observed during relatively high states

Di Gesu et al. 2023

See also Kim et al. 2023

LSP:
emission mechanisms and matter content

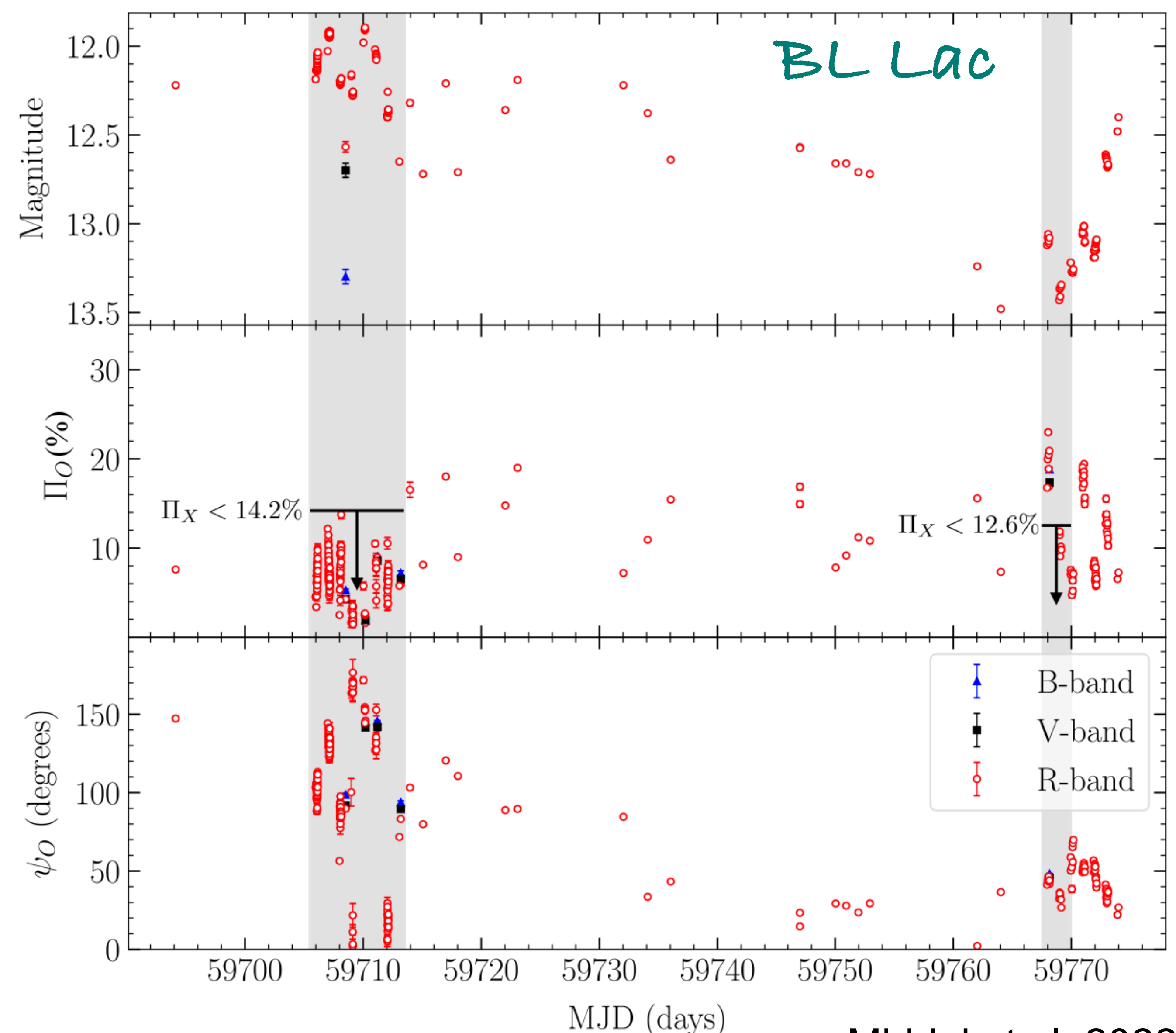


Zhang & Boettcher 2013

(One zone) Hadronic models predicts a relatively large polarization of the raising portion of the high-energy bump (synchrotron from protons and decay products)

Constraining lower limits from IXPE (below optical)

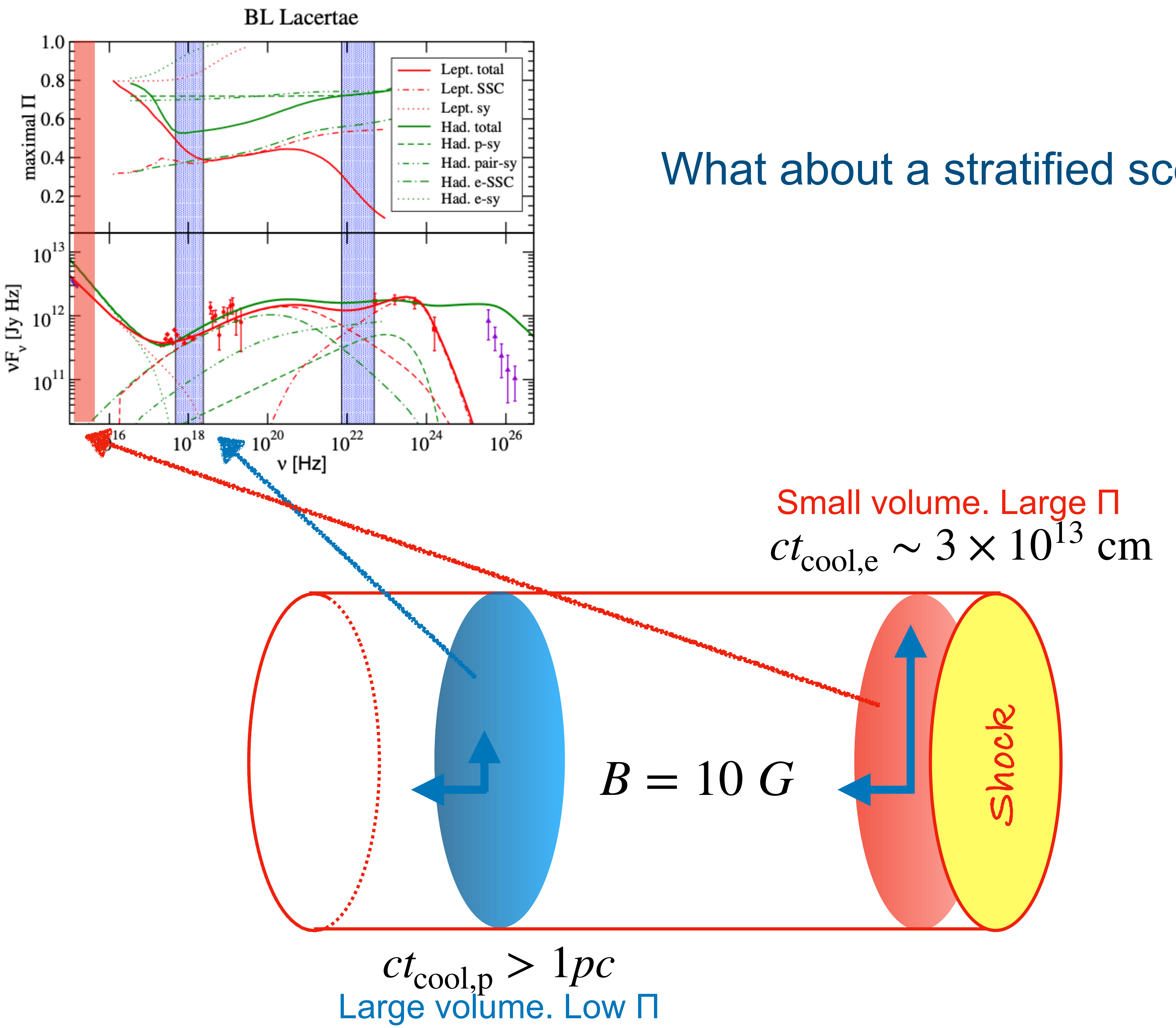
Leptonic (SSC) preferred? Yes, but…



Middei et al. 2022

LSP: emission mechanisms and matter content

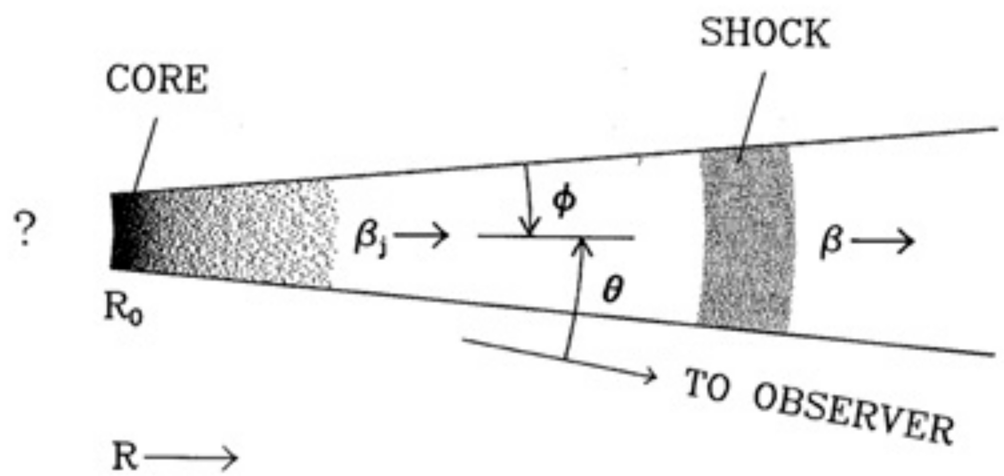
What about a stratified scenario?



Which kind of shock?

(mildy) relativistic shock → Sub-relativistic downstream (in the shock frame)

Substantial beaming of the downstream emission → Large Γ of the shock in the observer frame if the shock is of normal incidence



Traveling relativistic shock

$$\Delta z \sim c\Delta t \Gamma_{sh}^2 \approx 1\mathrm{pc}$$

in 1 day (observed)

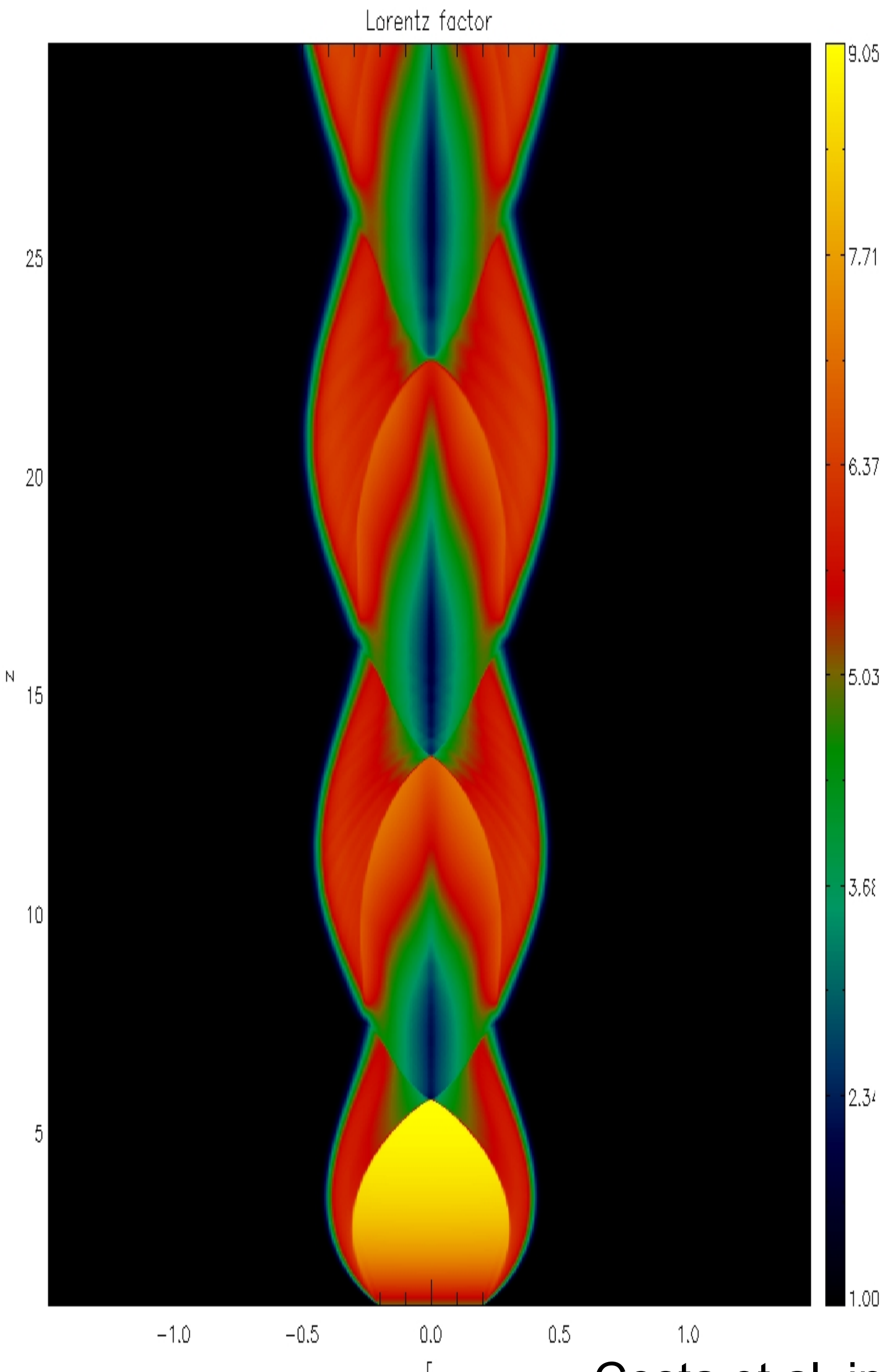
Modeling provides consistent parameters even for very distant epochs (months)

→ oblique standing shock?

Sokolov et al. 2004, 2005
Tagliaferri et al. 2008
Zech & Lemoine 2021

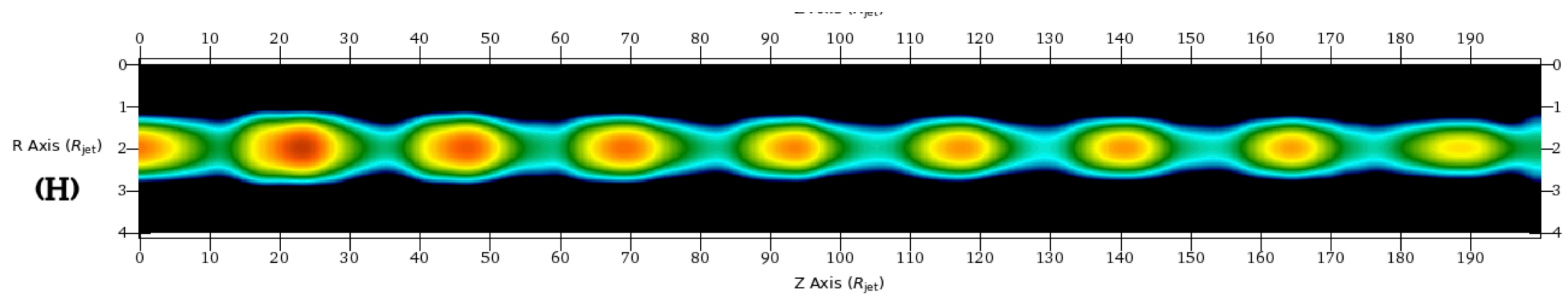
Recollimation shocks

2D simulations
Chain of recollimation shocks



Costa et al. in prep

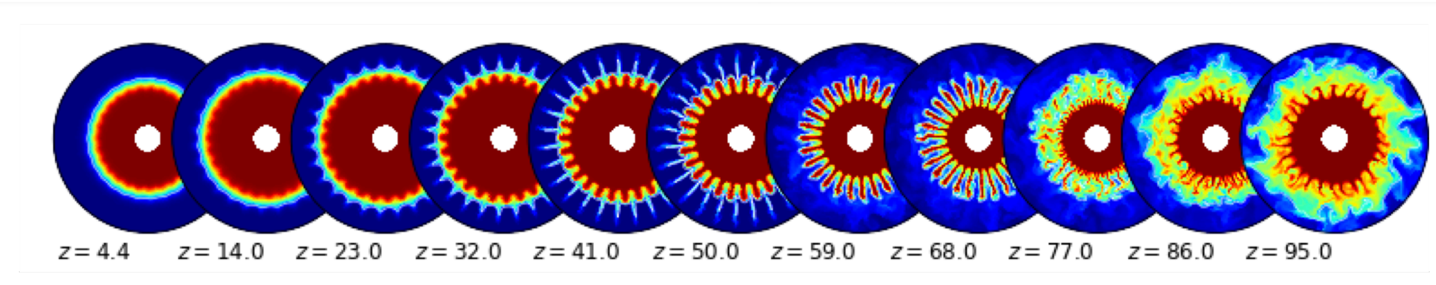
Komissarov & Falle 1997
Bromberg & Levinson 2007

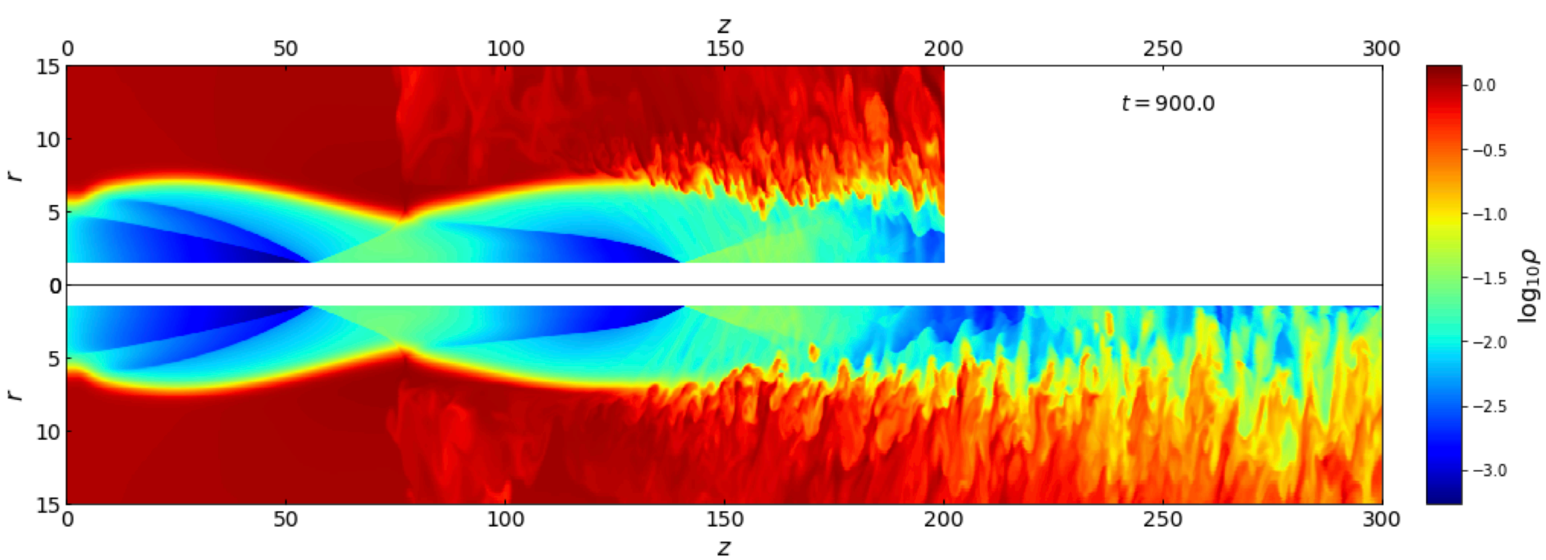


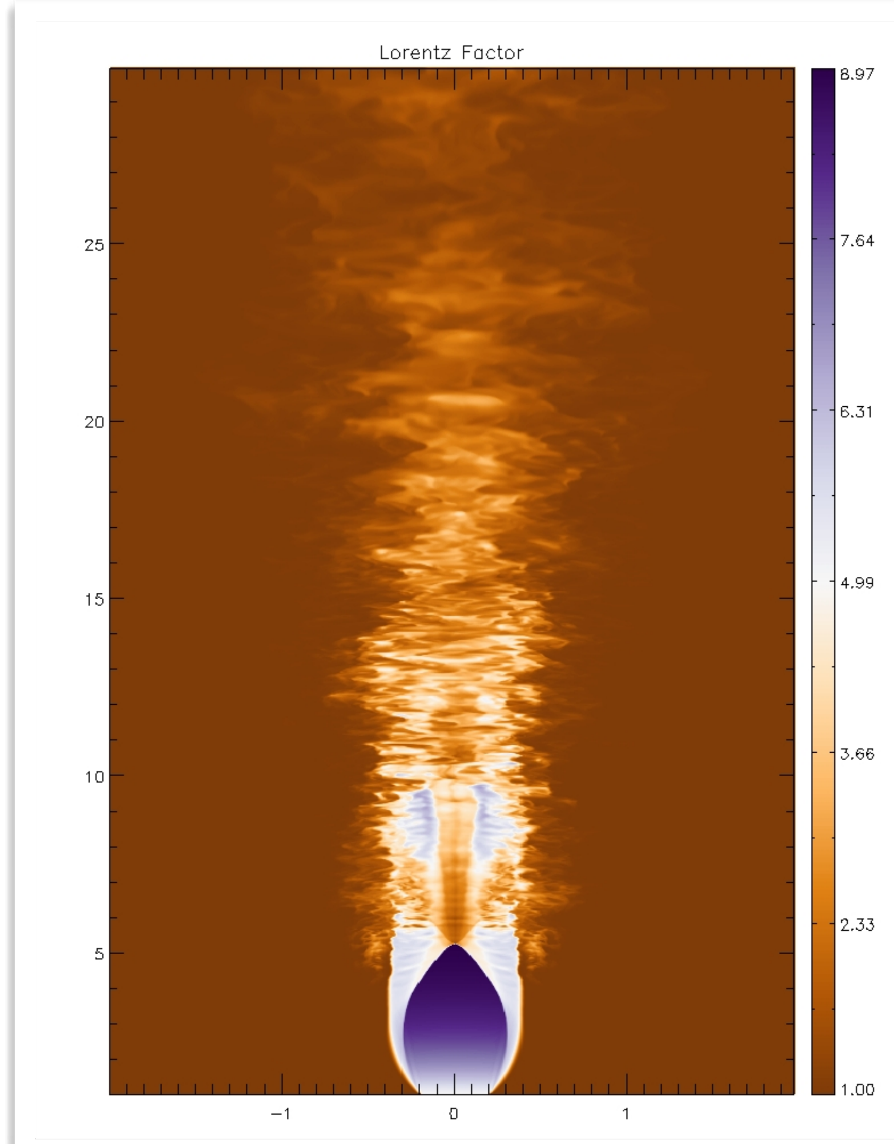
Fichet de Clairfontaine et al. 2021

Instabilities

HD jet







Costa et al. in prep

Rayleigh-Taylor/centrifugal +
Richtmyer-Meskov instabilities

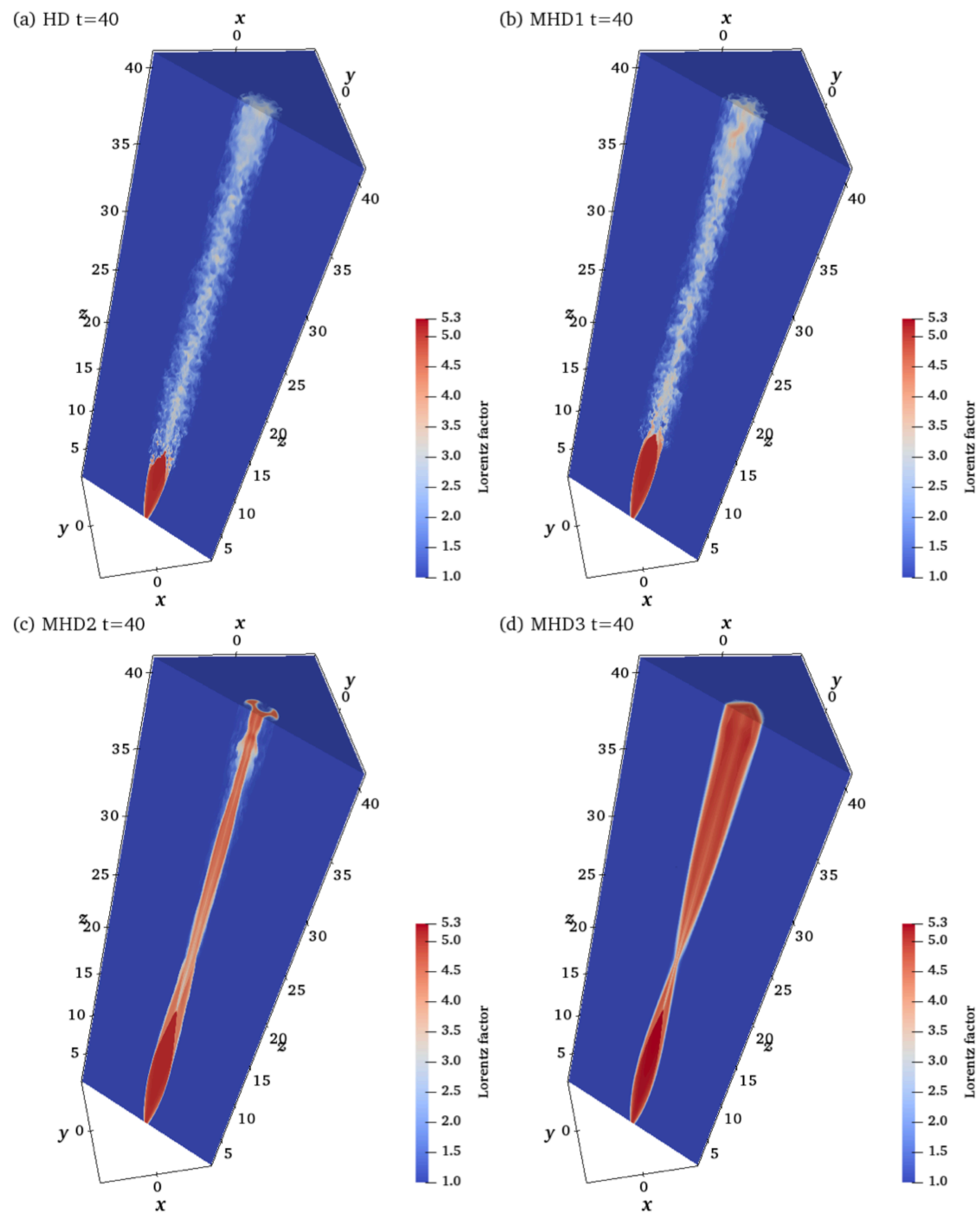
Matsumoto et al. 2017, 2021
Komissarov & Gougouliotos 2018
Abolmasov & Bromberg 2023

Instabilities

MHD jet

Sufficiently large B field can stabilize the jet

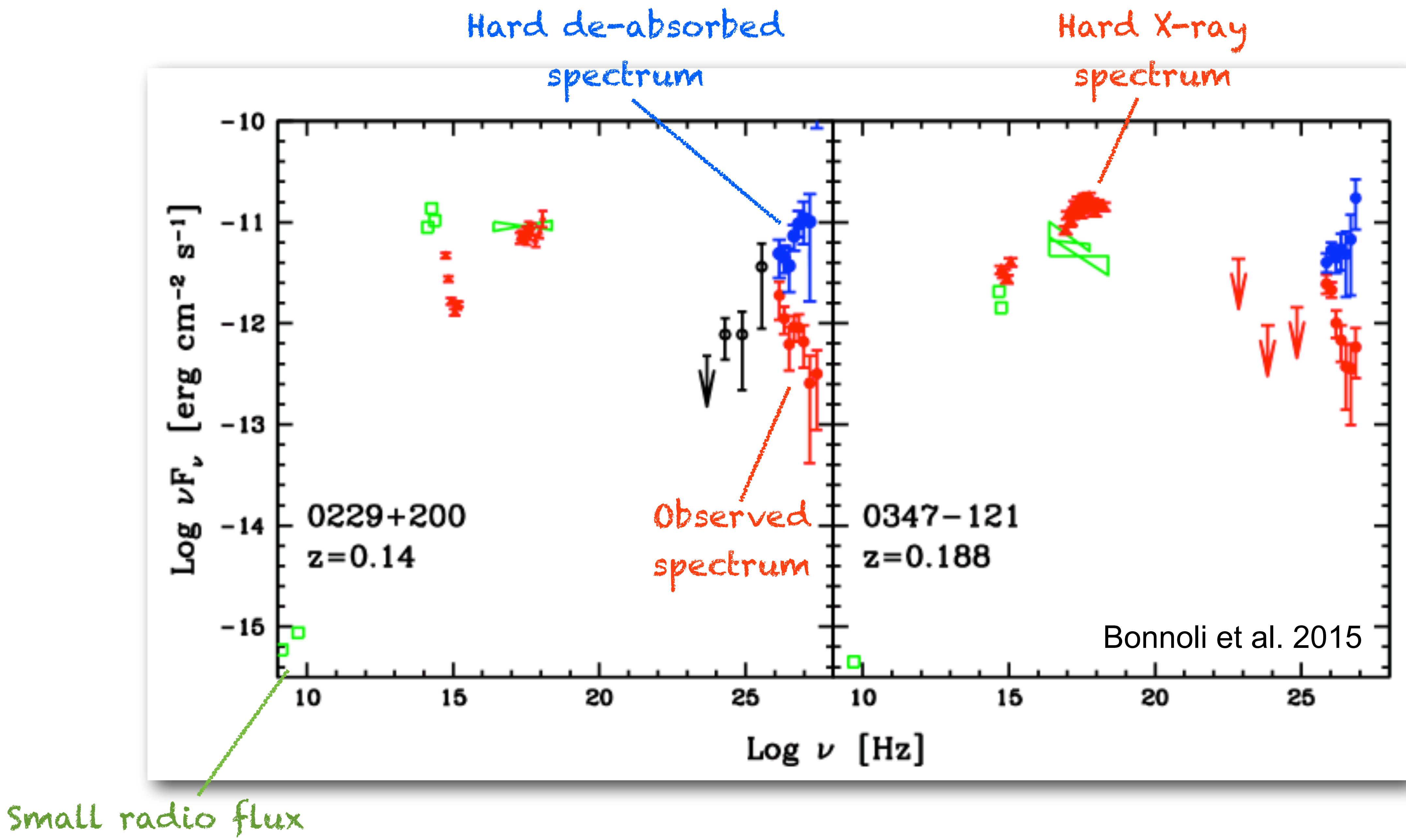
Low magn.



High magn.

Matsumoto et al. 2021

Extreme BL Lacs

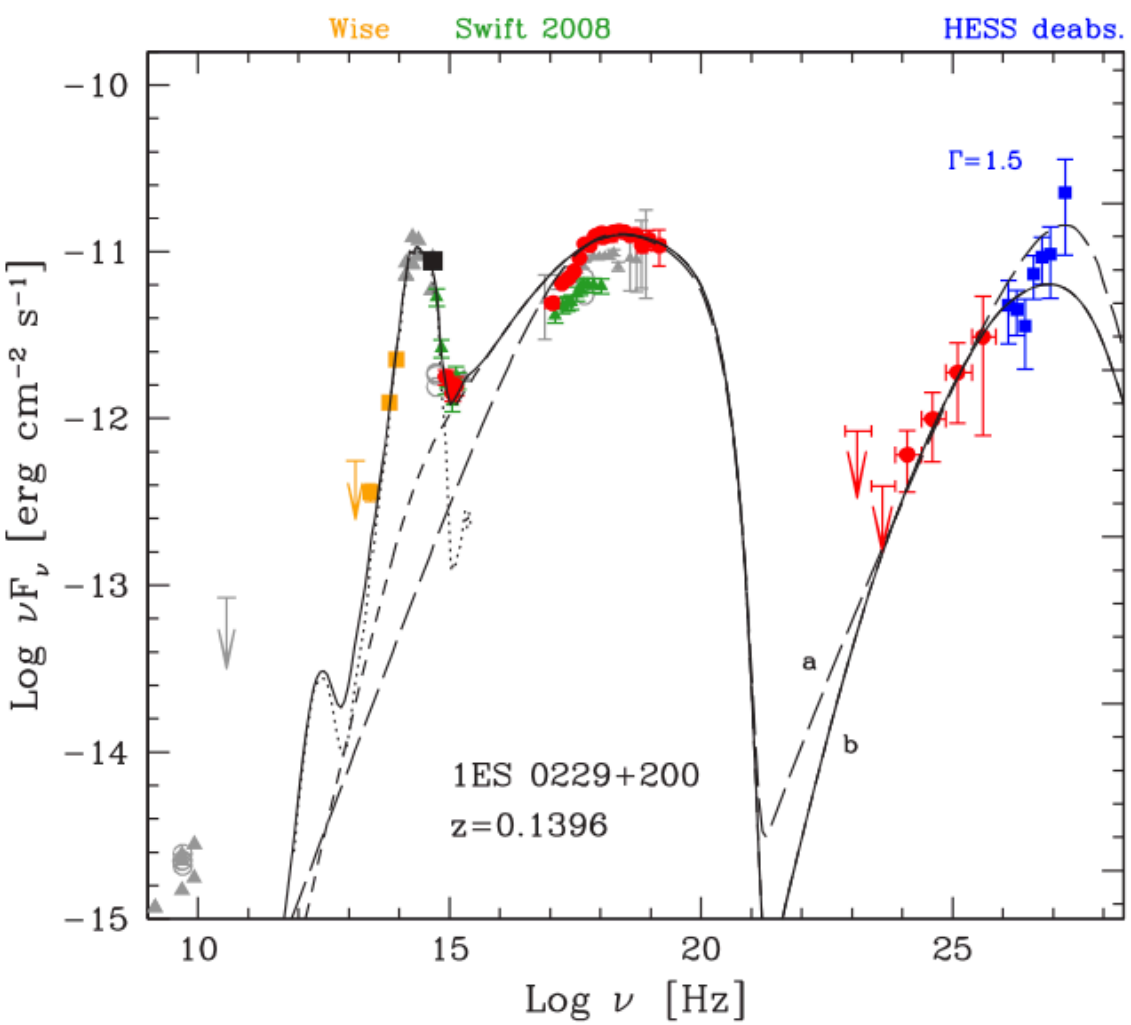


Costamante et al. 2001
Review in Biteau et al. 2020

Stawarz et al. 2004
Zech & Lemoine 2021

Extreme BL Lacs

Costamante et al. 2018



One zone model
Large minimum electron energy
Very low B

Source [1]	γ_0 [2]	n_0 [3]	γ_1 [4]	γ_b [5]	γ_2 [6]	n_1 [7]	n_2 [8]	B [9]	K [10]	R [11]	δ [12]	U_e/U_B [13]
1ES 0229+200[a]	–	–	100	1.1×10^6	2×10^7	1.4	3.35	0.002	6	0.8	50	1.7×10^5
1ES 0229+200[b]	–	–	2×10^4	1.5×10^6	2×10^7	2.0	3.4	0.002	10^3	2.1	50	2.0×10^4

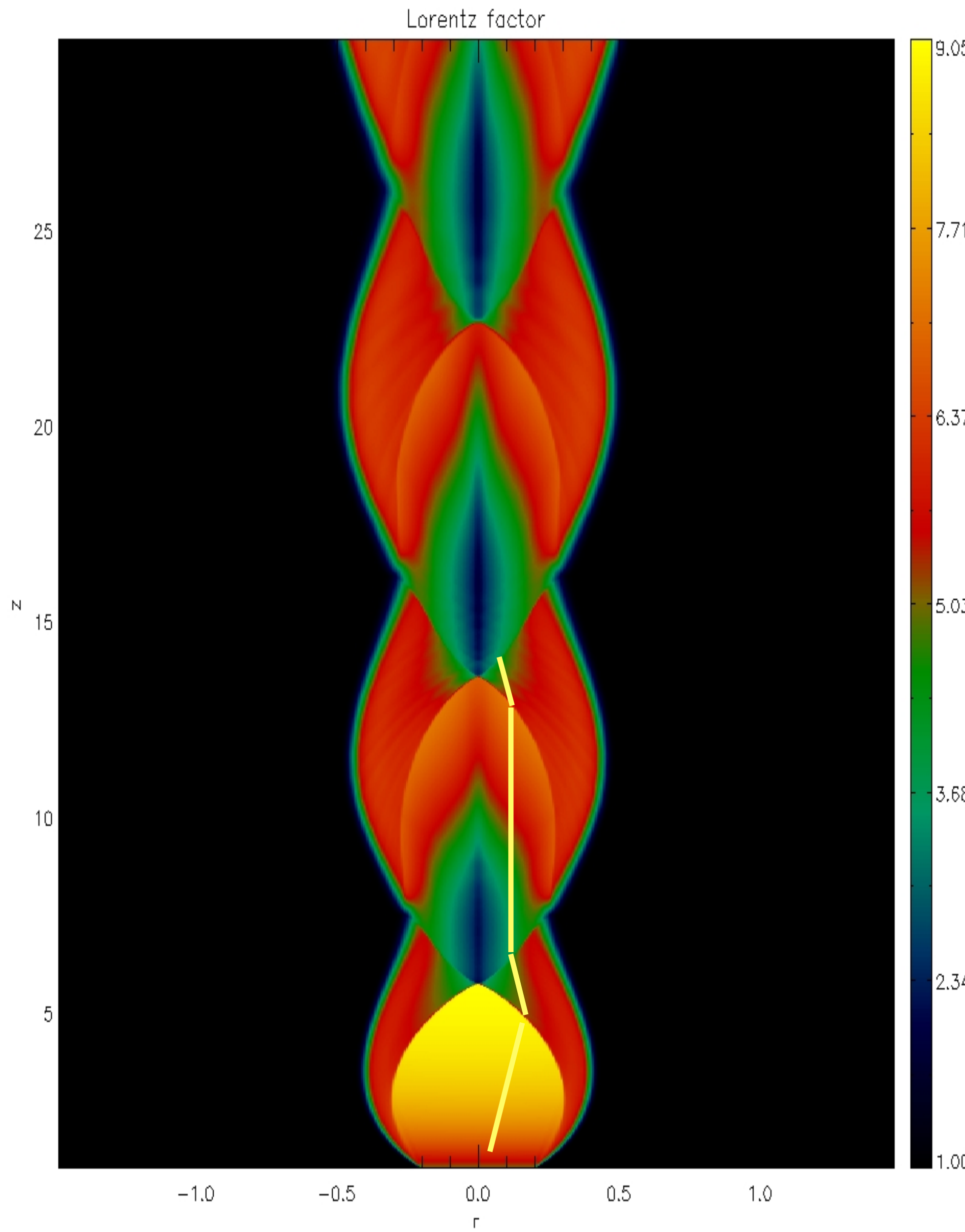
Extreme BL Lacs

Hard electron distribution from multiple shock crossing in a recollimating jet.

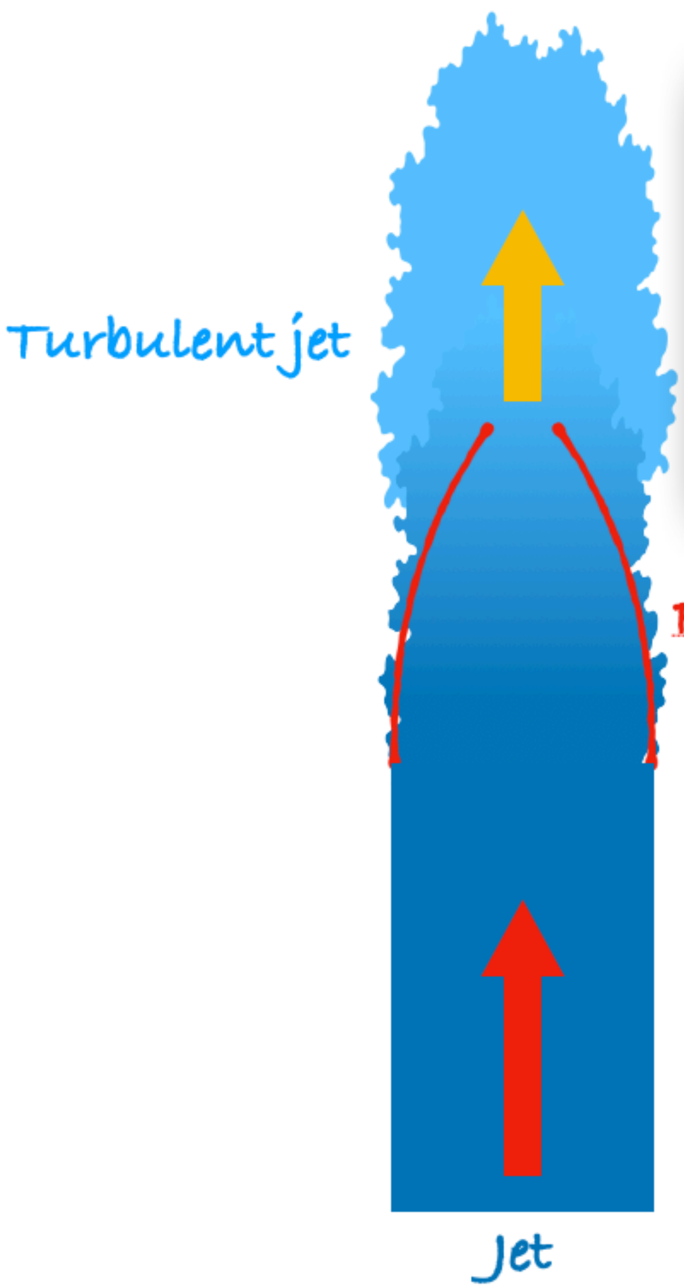
$$\frac{dN_>^{(n)}}{d\gamma_>} = \frac{(s-1)^{n+1}}{n!\, g^n\, \gamma_{\min}} \left(\frac{\gamma_>}{g^n\, \gamma_{\min}}\right)^{-s} \ln\left(\frac{\gamma_>}{g^n\, \gamma_{\min}}\right)^{n}.$$

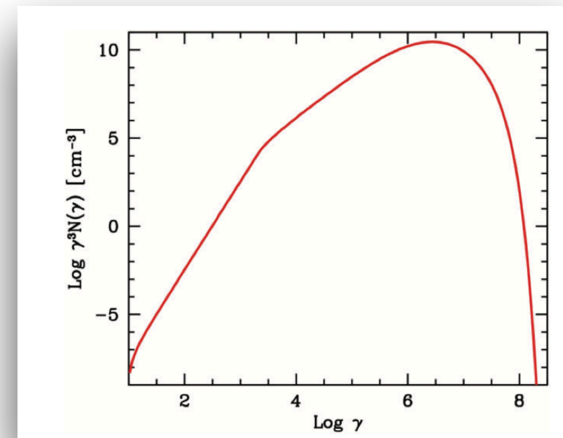
Stawarz et al. 2004
Zech & Lemoine 2021

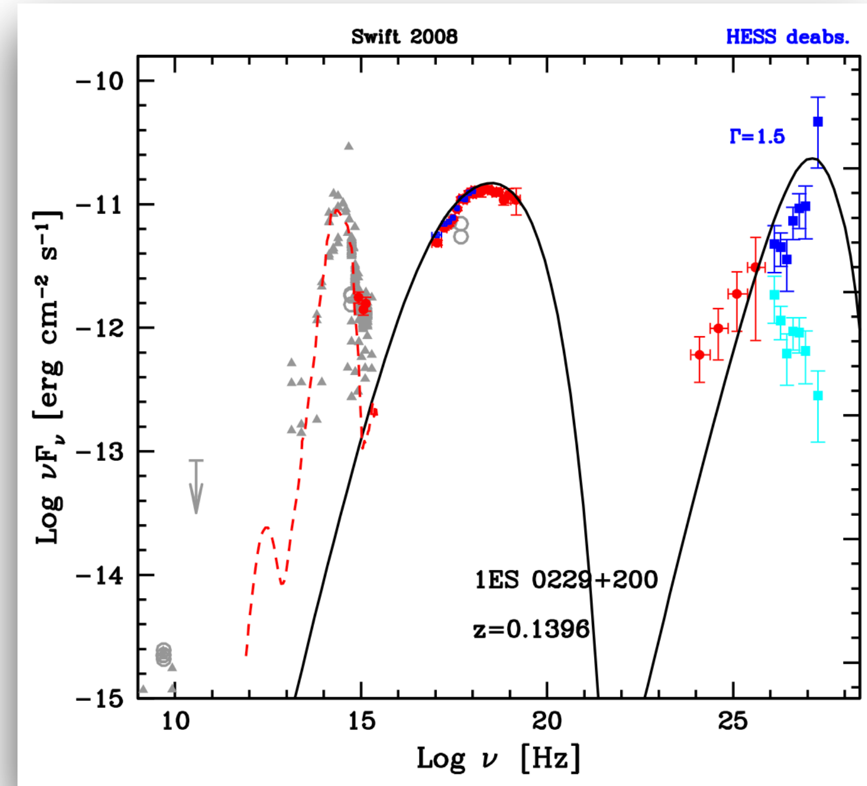
But instabilities?



Extreme BL Lacs: low σ, unstable jets?

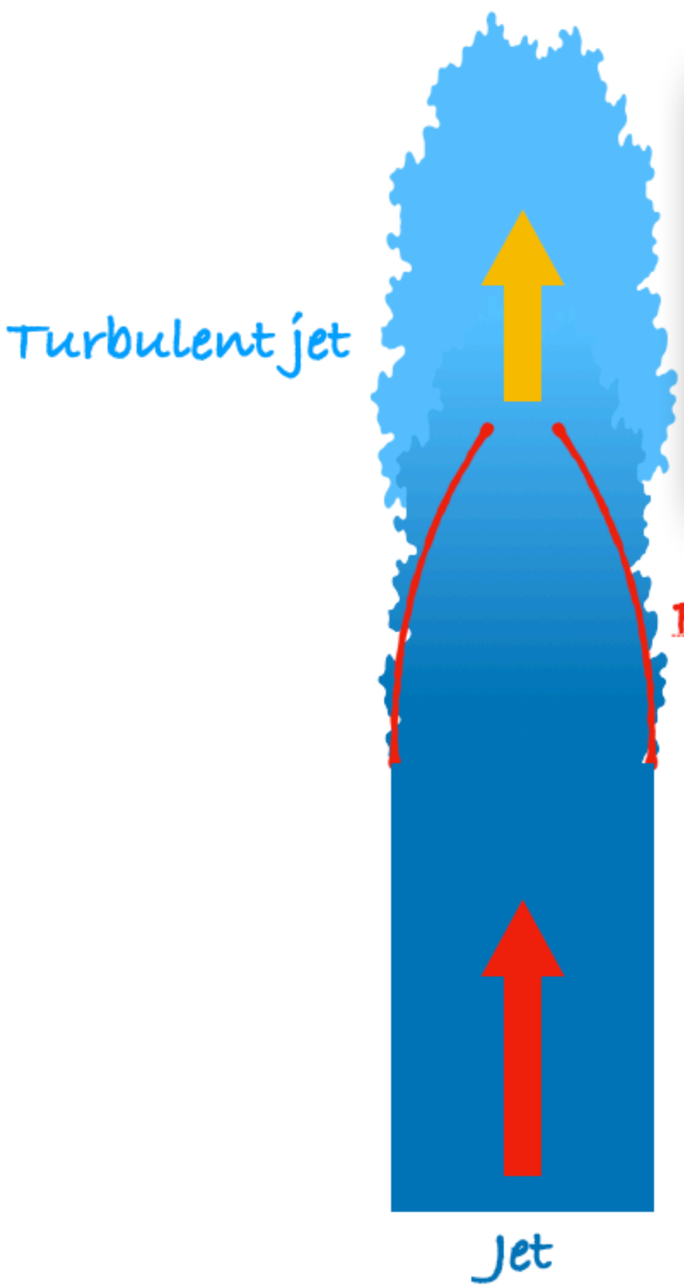


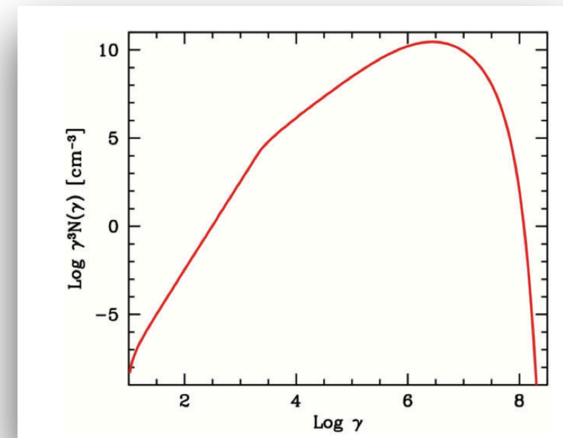


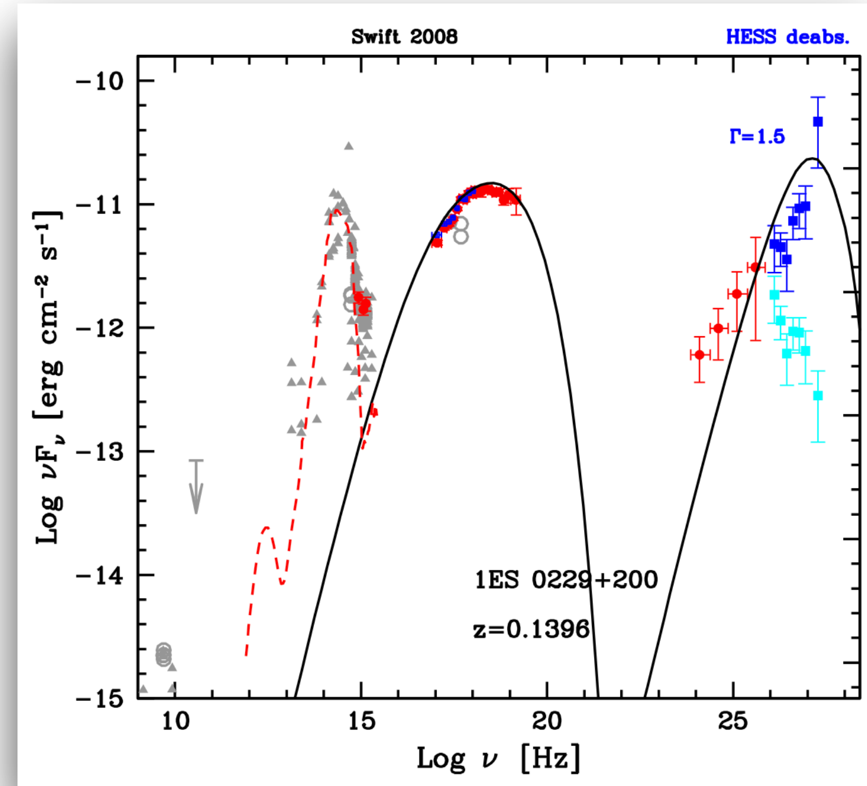


Tavecchio, Costa & Sciaccaluga 2022

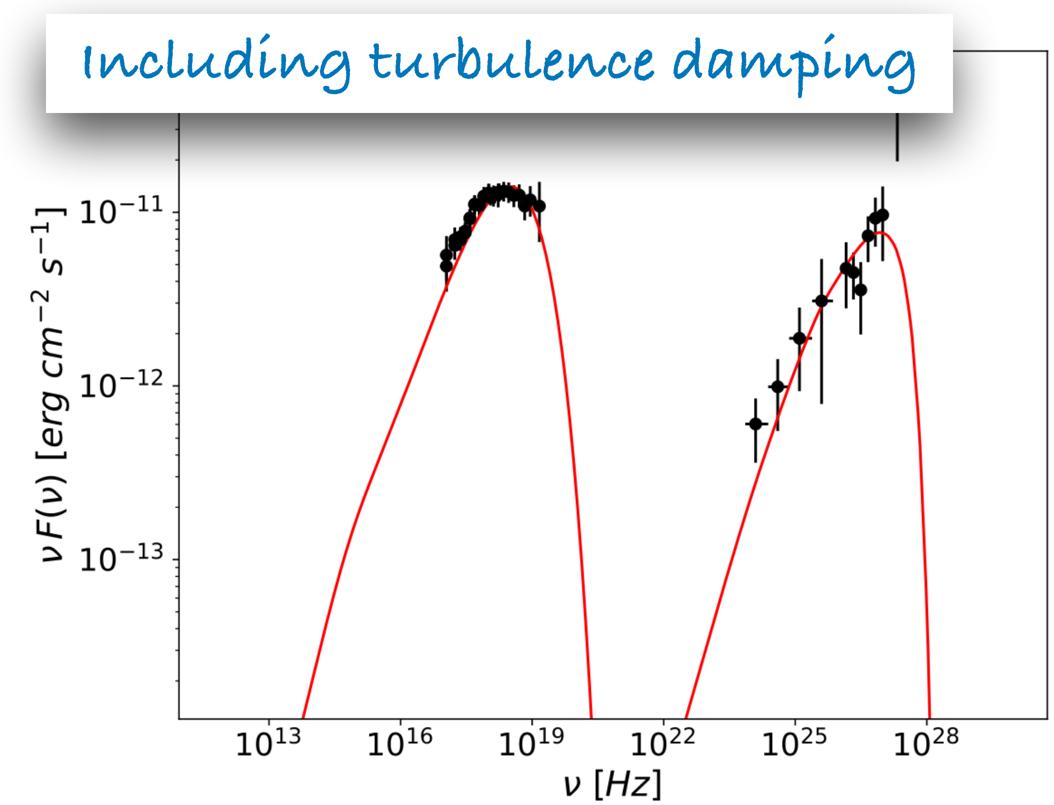
Extreme BL Lacs: low σ, unstable jets?







Tavecchio, Costa & Sciaccaluga 2022



Sciaccaluga & Tavecchio 2022

Extreme BL Lacs: low σ, unstable jets?

But IXPE again…

Π_X=18% In the prototype 1ES 0229+200

Ehlert et al. 2023

The most polarized BL Lac!

Incompatible with turbulence?

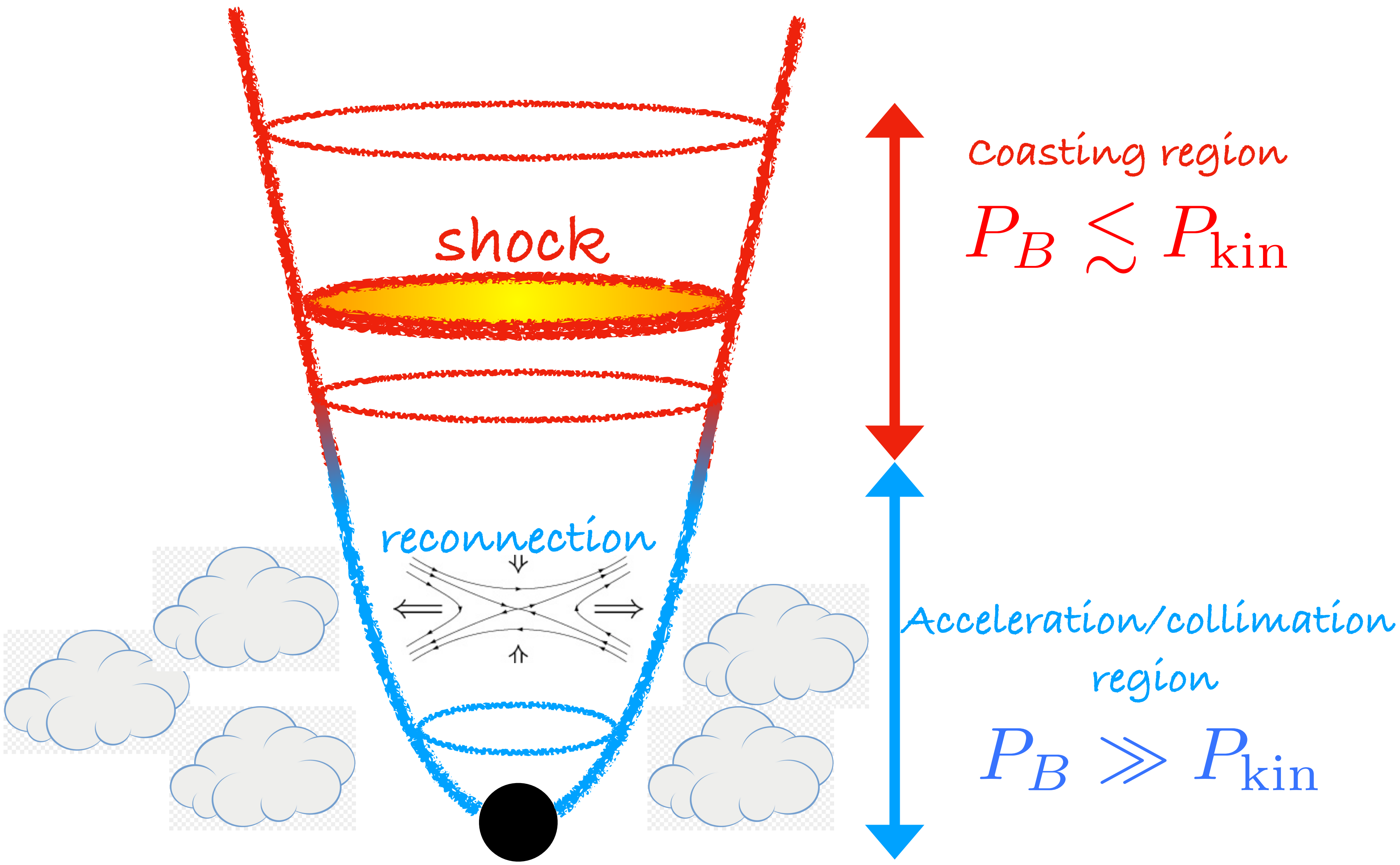
Final thoughts

X-ray polarization of HSP: stratified shock?
Need for realistic physical models!

Extreme blazars: acceleration at recollimation shocks?
Better characterization of role of instabilities/turbulence in particle acceleration


THANK YOU!

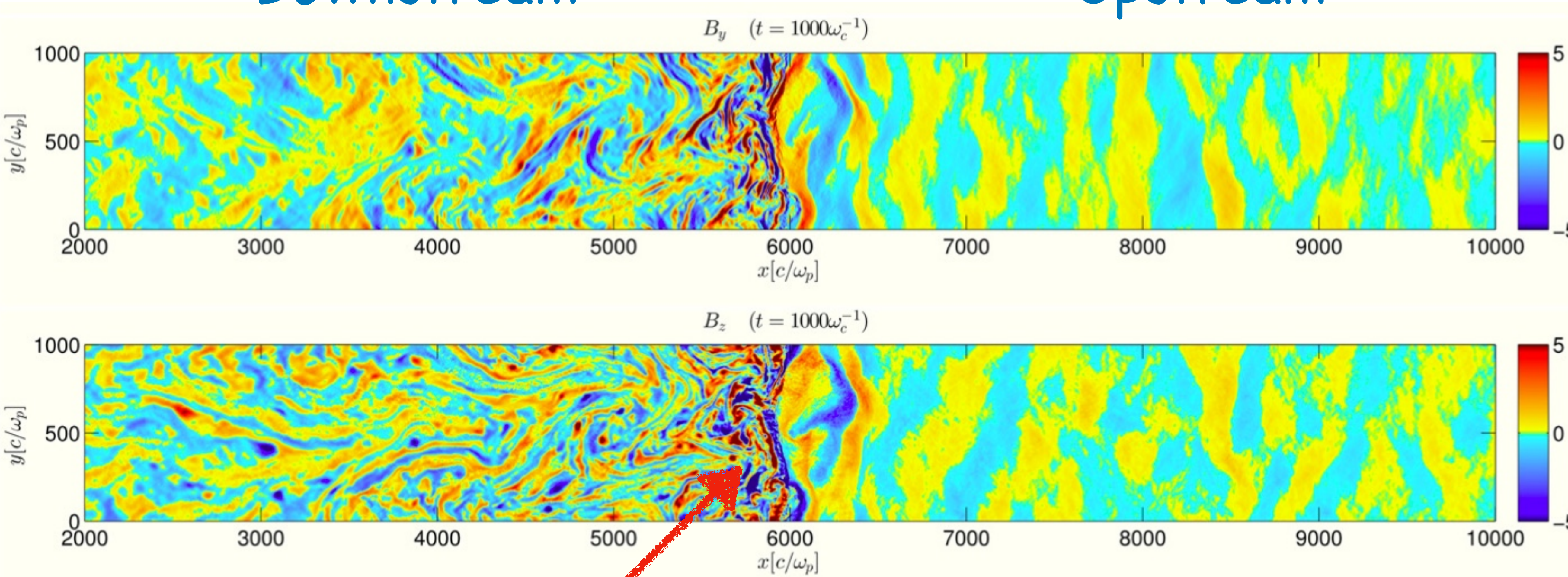
Energizing the particles



Contopoulos 1994
Komissarov et al. 2009
Tchekhovskoy et al. 2009

Magnetic field generation at shocks

Downstream Upstream



Compressed (circularly polarized)
Alfven waves self-generated
by accelerated protons streaming upstream

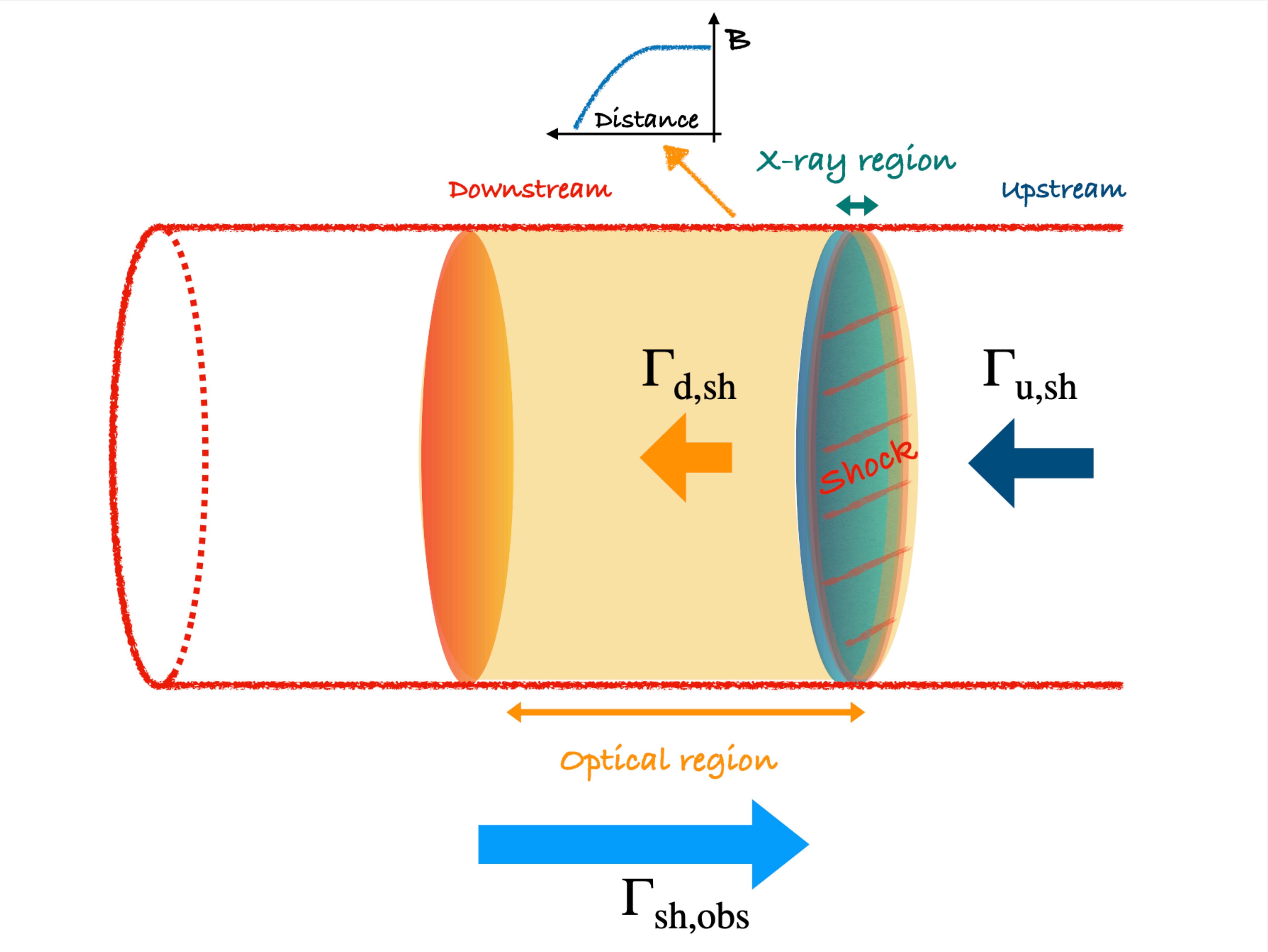
Caprioli & Spitkovsky 2014

Polarimetry in the X-ray band

Possible alternatives and predictions

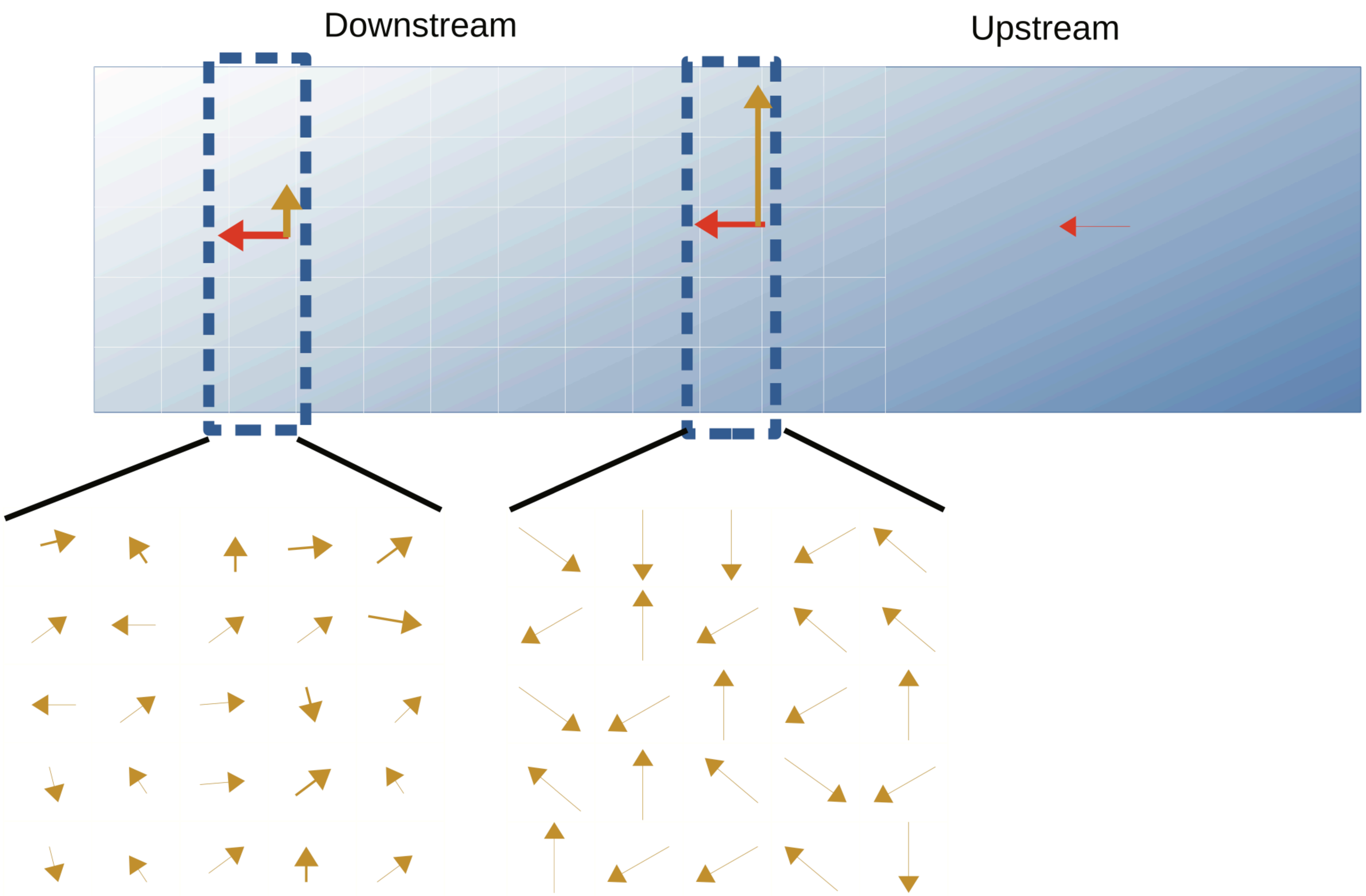
	Optical	Medium-Hard X-Rays
Shock (turbulent)	$\Pi \lesssim 15\%$, variable; χ variable, smooth rotations possible	$\Pi \lesssim 30\%$, highly variable highly and rapidly variable
Shock (self-produced field)	$\Pi \lesssim 20\%$, slowly variable, flips by $\Delta\chi = 90$ deg	$\Pi \gtrsim 40\%$ substantially constant, constant $\chi = 0$
Reconnection (kink-induced)	$\Pi \lesssim 20$–30%, moderately variable smooth rotations, $\Delta\chi \gtrsim 90$ deg	same as optical as optical

Tavecchio 2021



B
Distance
X-ray region
Downstream
Upstream
$\Gamma_{d,sh}$
$\Gamma_{u,sh}$
Shock
Optical region
$\Gamma_{sh,obs}$

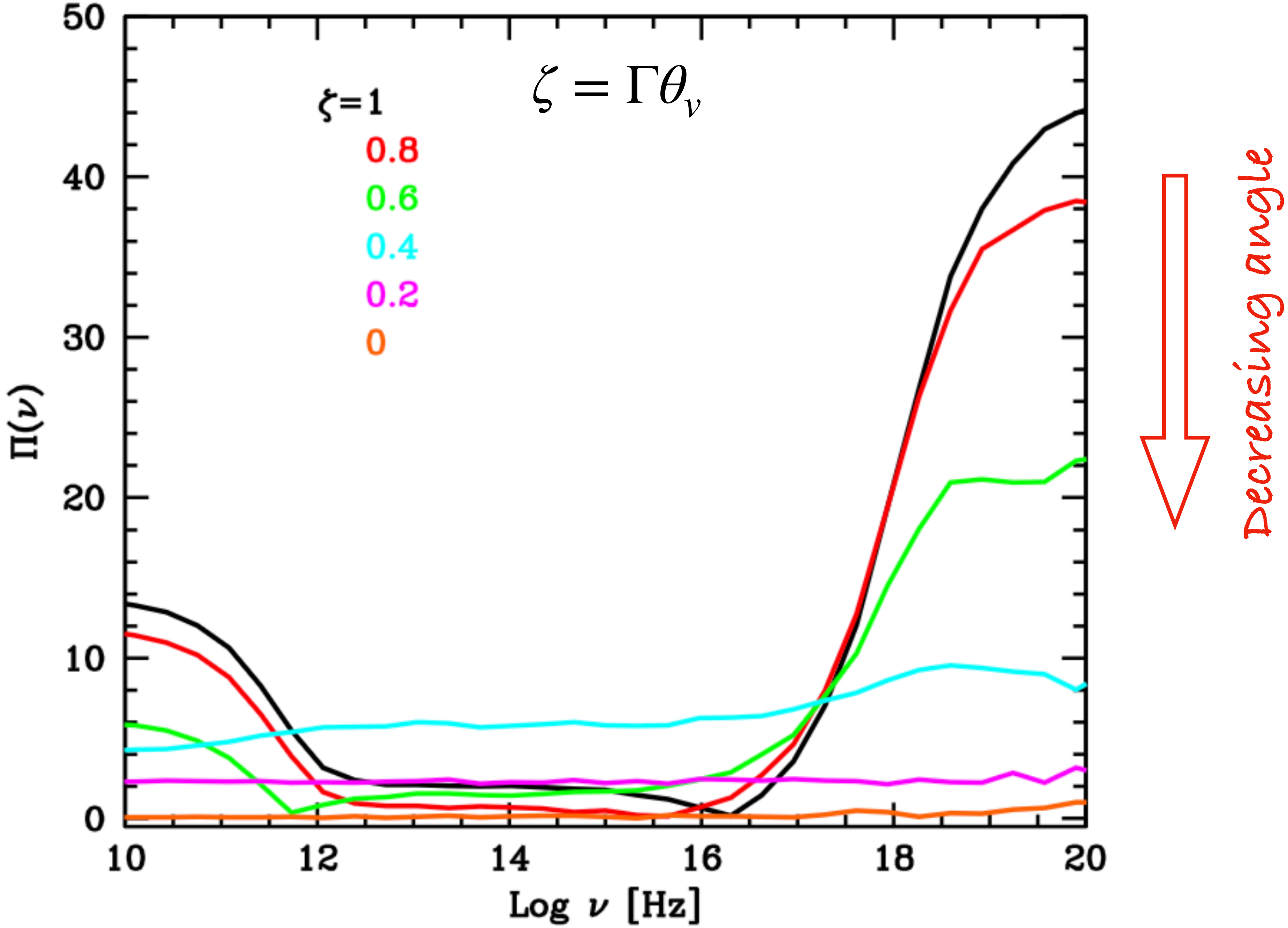
Stratified shock: a toy model



Tavecchio et al. 2018, 2020

Stratified shock: a toy model

For a fixed SED!



Dependence on the observing angle

Tavecchio in prep.