Theoretical implications of *IXPE* polarimetric measurements for blazars

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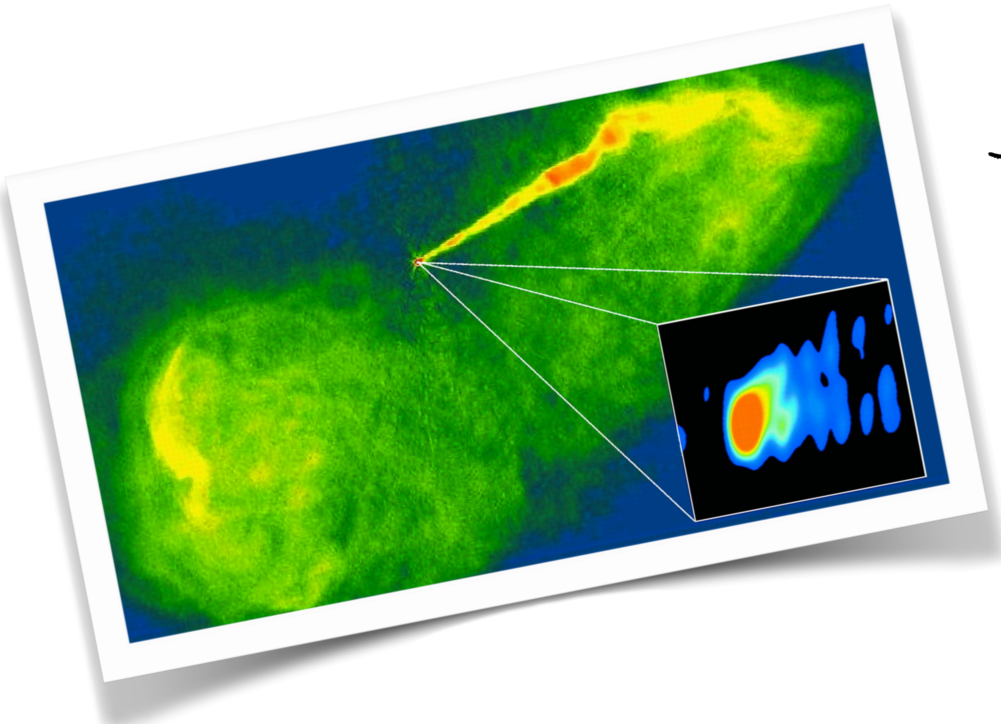
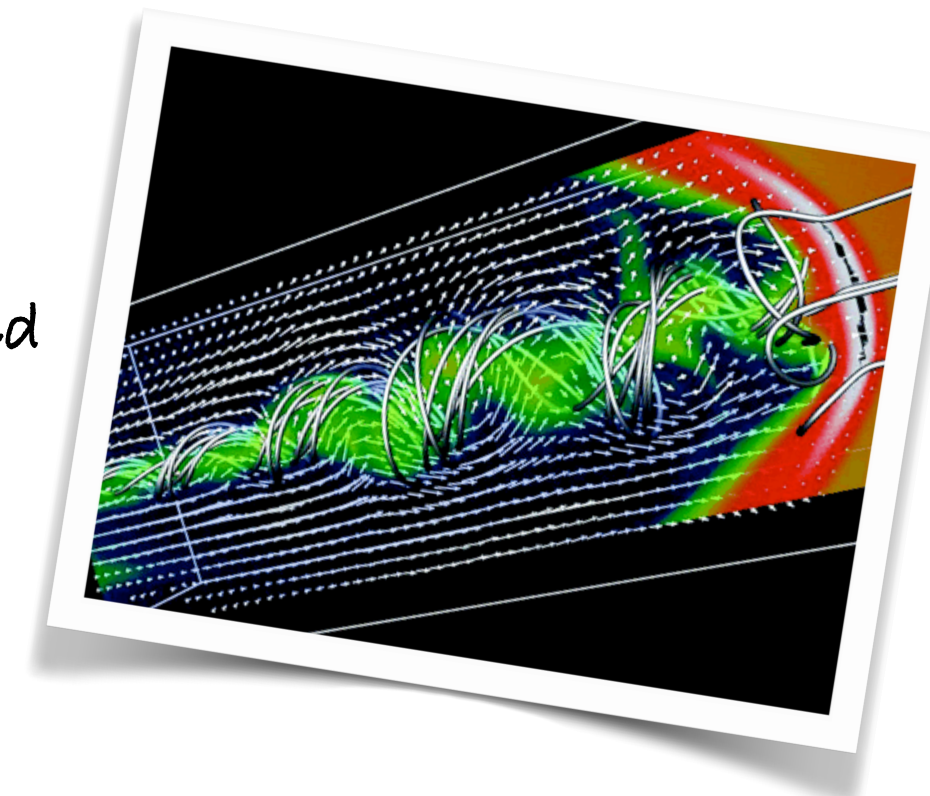
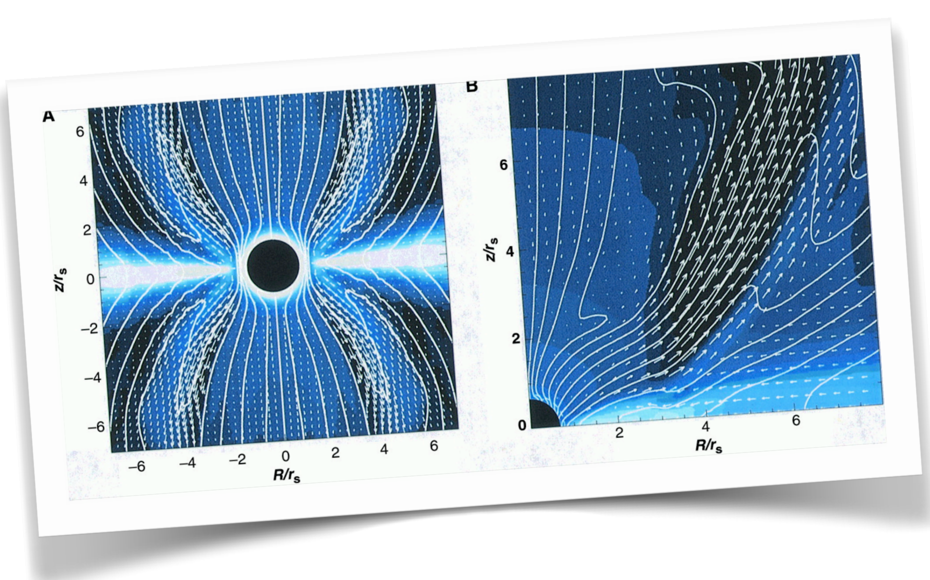
AGN jets: the fundamental questions



Jet dynamics, speed, composition, power



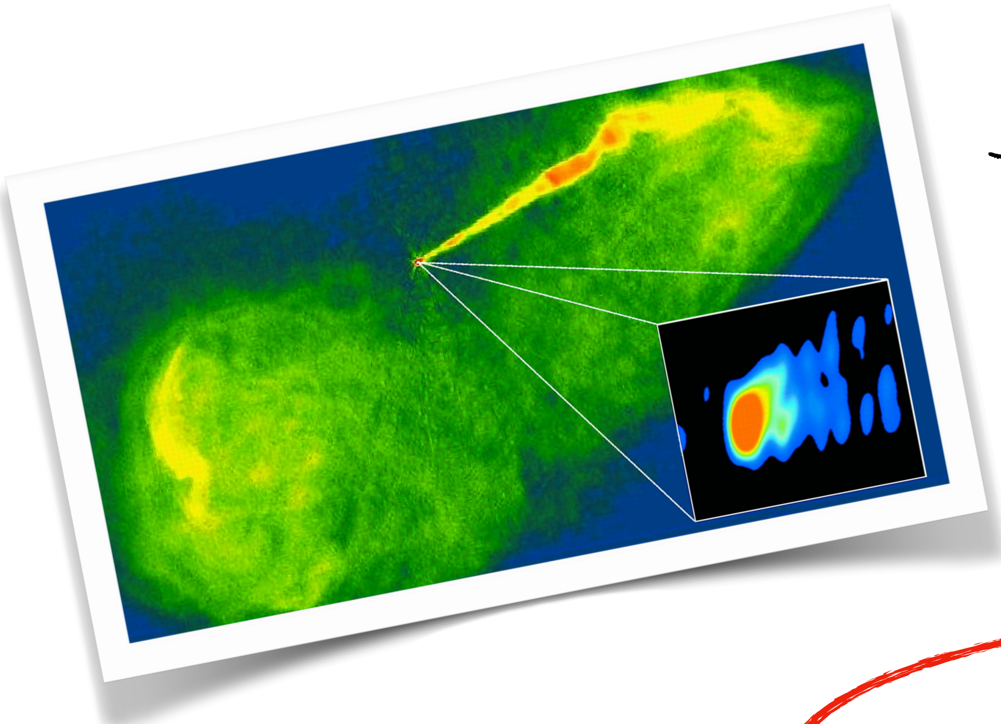
Magnetic fields, dissipation, acceleration and emission mechanisms



Formation, collimation, acceleration

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

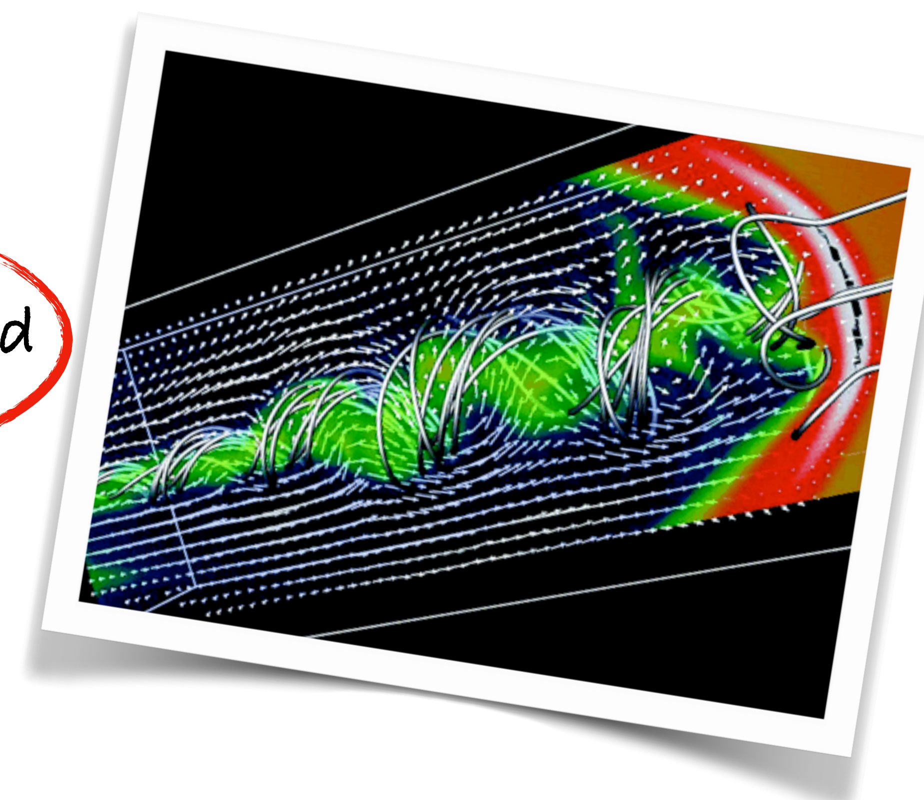
AGN jets: the fundamental questions

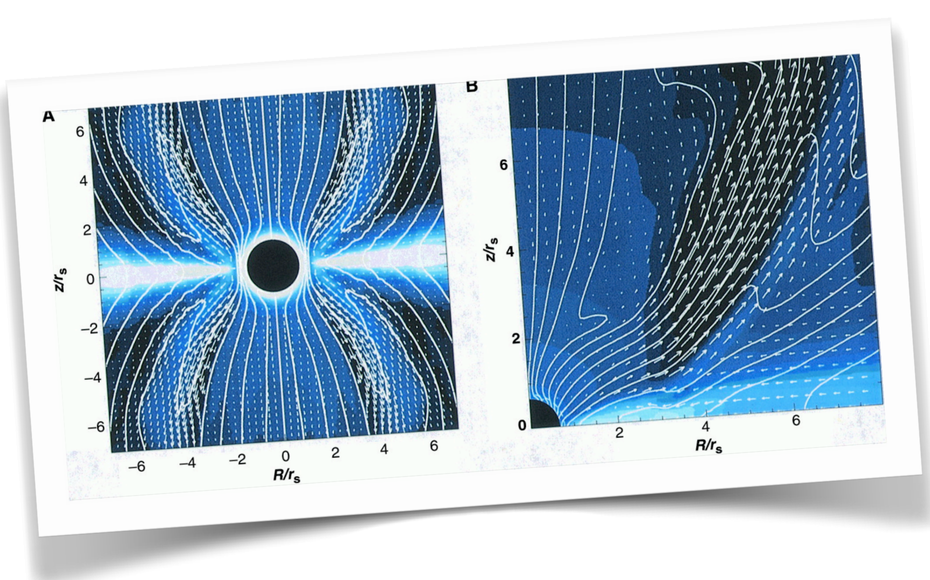


Jet dynamics, speed, composition, power

Polarimetry

Magnetic fields, dissipation, acceleration and emission mechanisms





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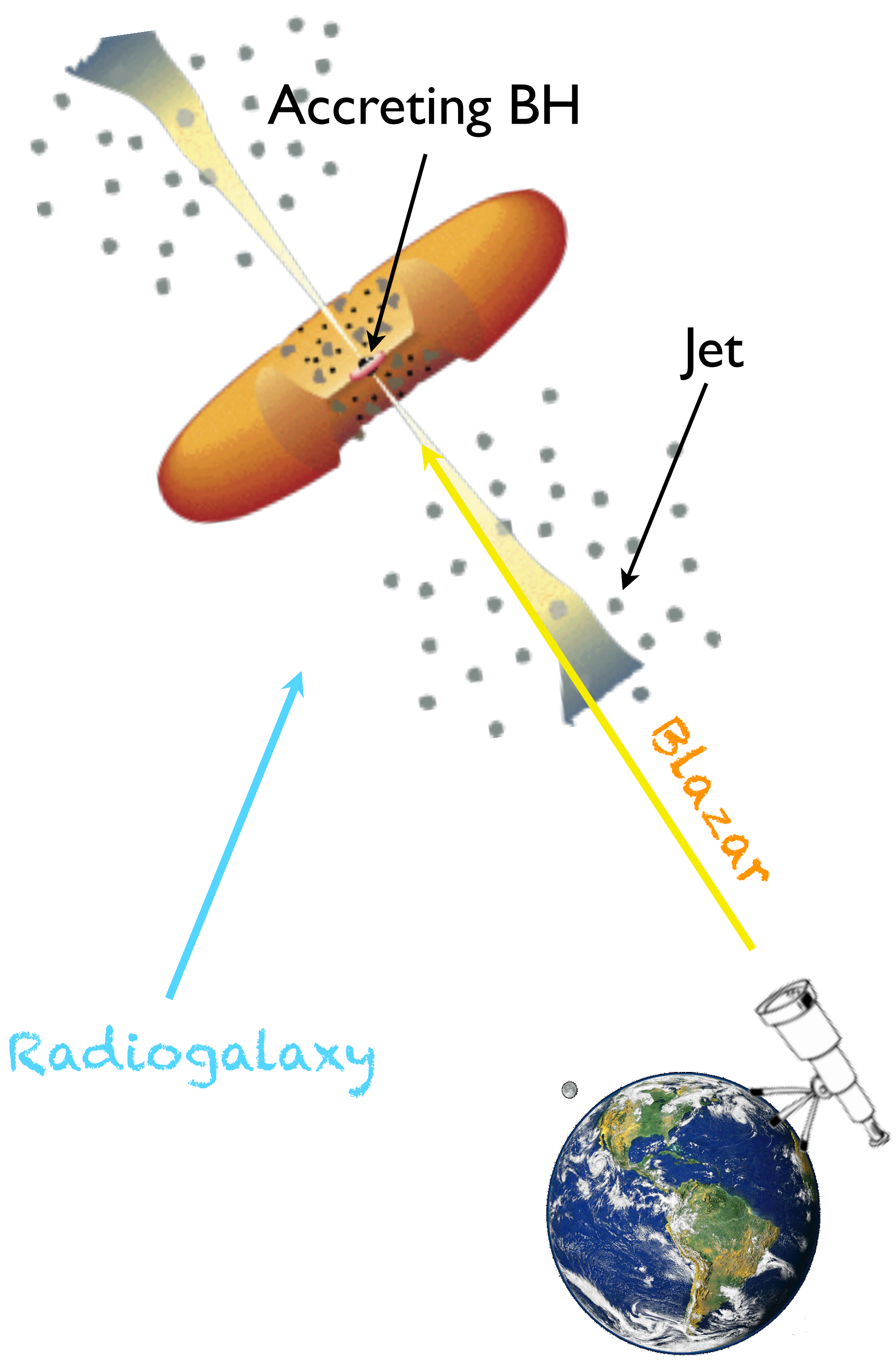
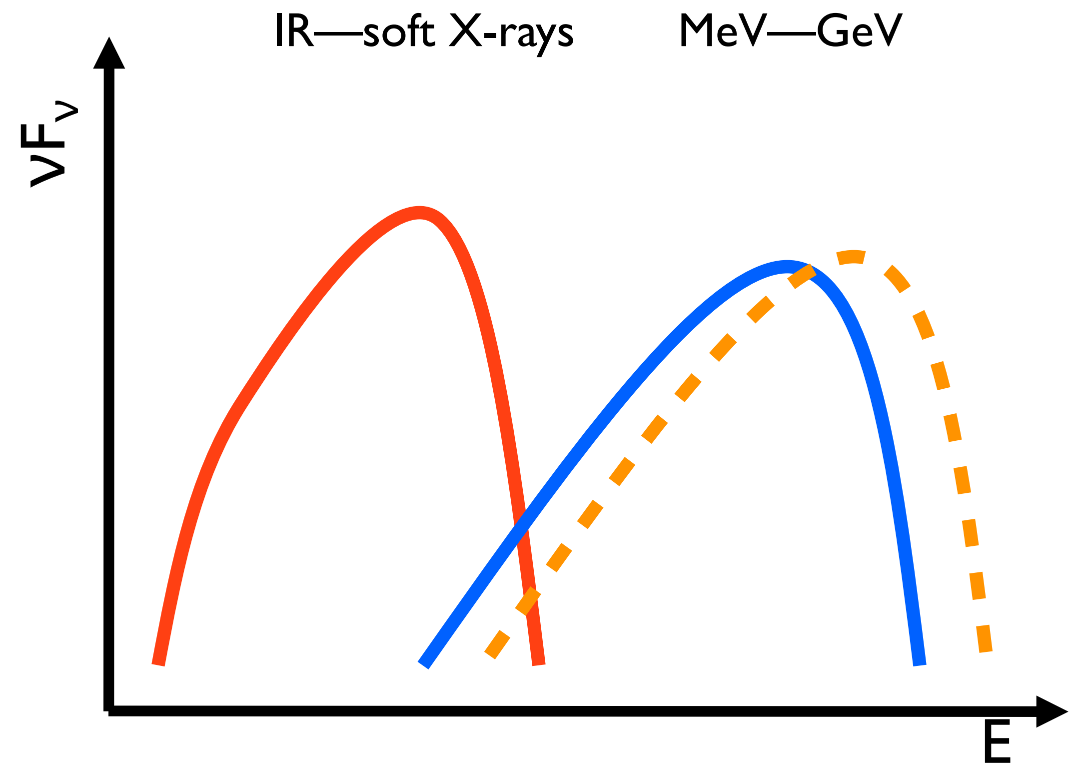
Jets pointing at us: blazars





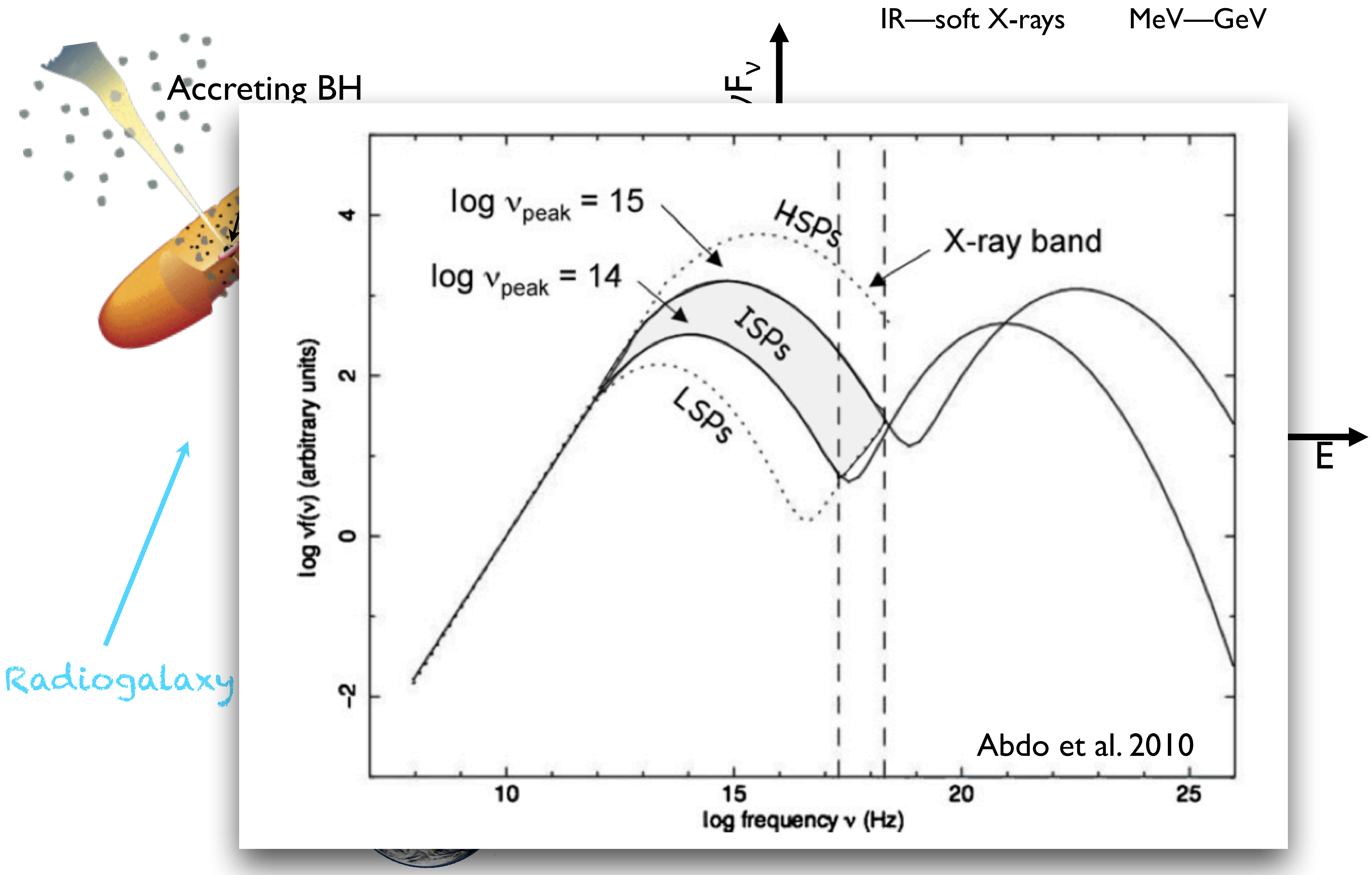
SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

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

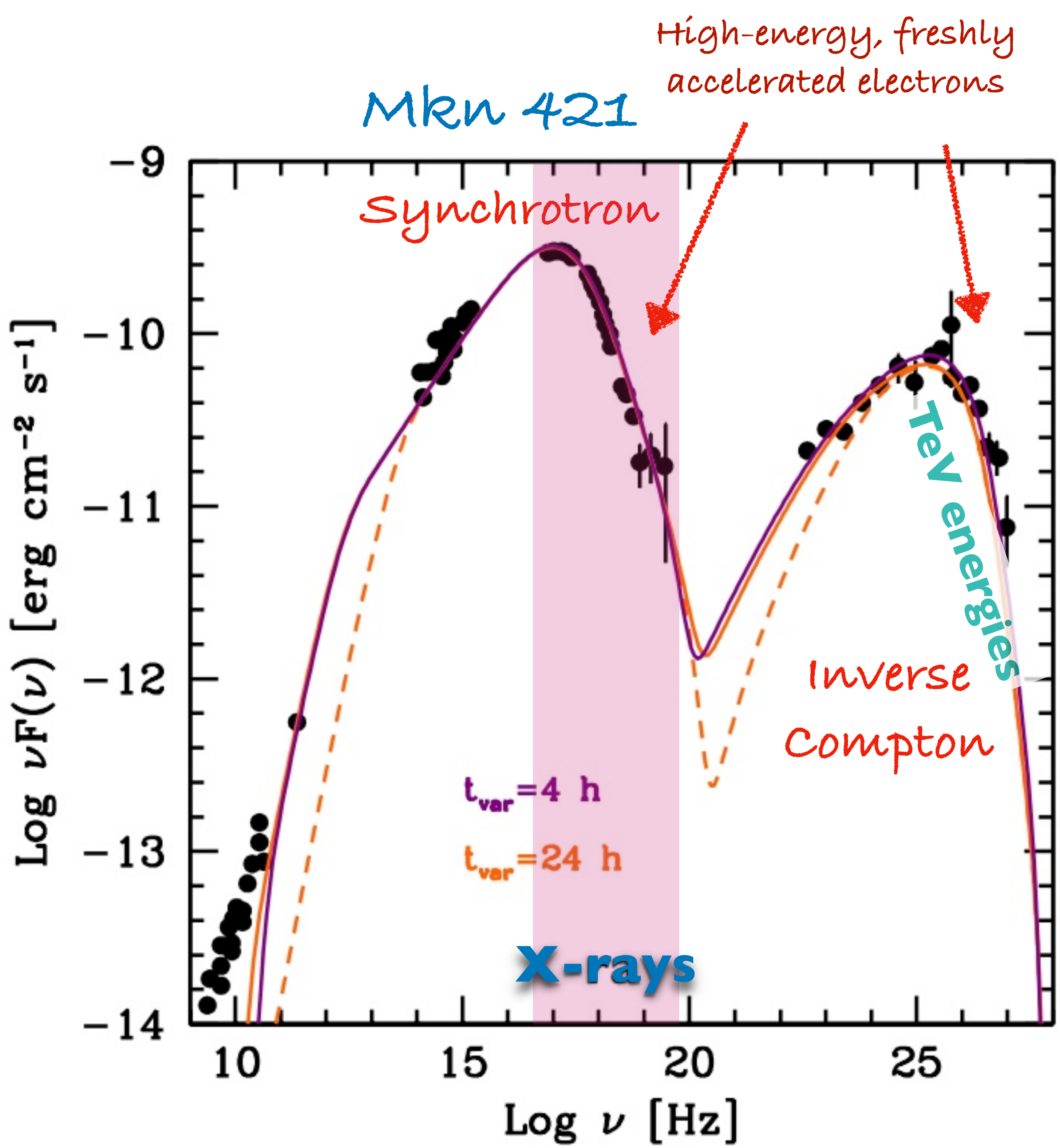
Synchrotron and IC in leptonic models.

Also hadronic scenarios (synchrotron or photo-meson emission)

Jets pointing at us: blazars



HSPs: extreme accelerators



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

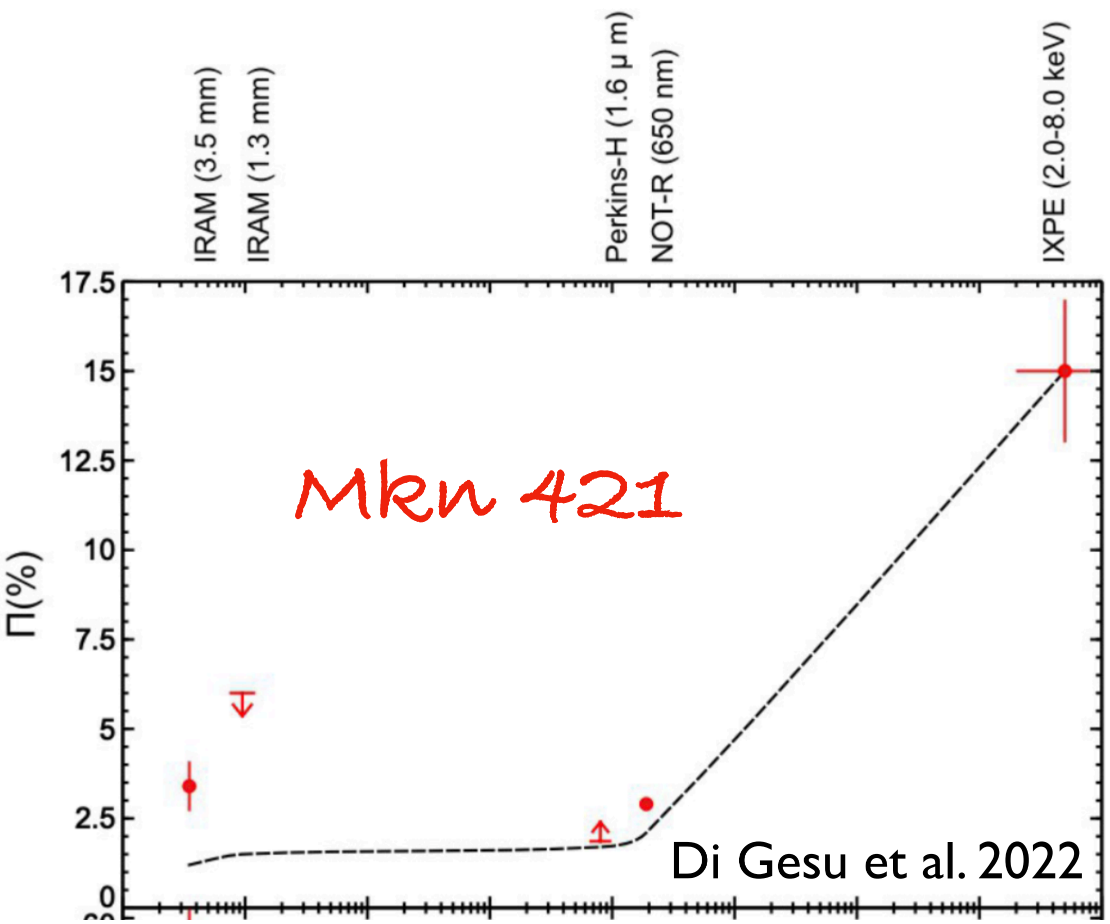
$$\gamma_X = \left(\frac{2\pi m_e c \nu_X}{eB\delta}\right)^{1/2} \sim 10^5 - 10^6$$

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

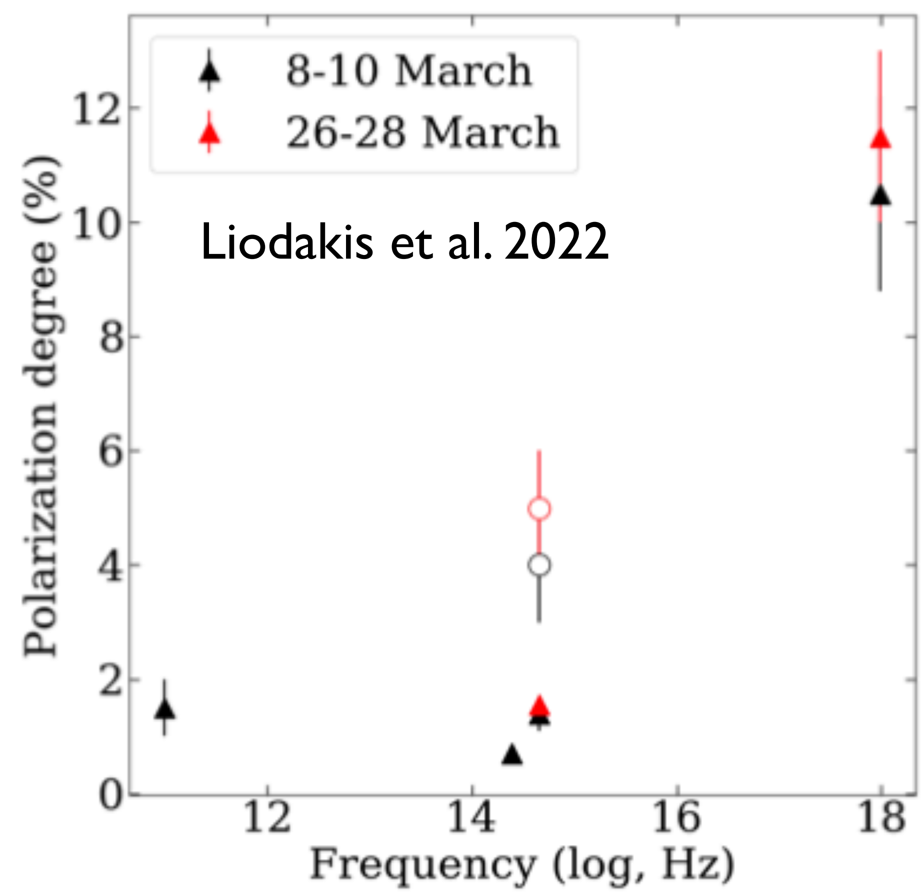
Compact regions

Hints from IXPE (1)

HSP in low/quiescent flux states



Mkn 501



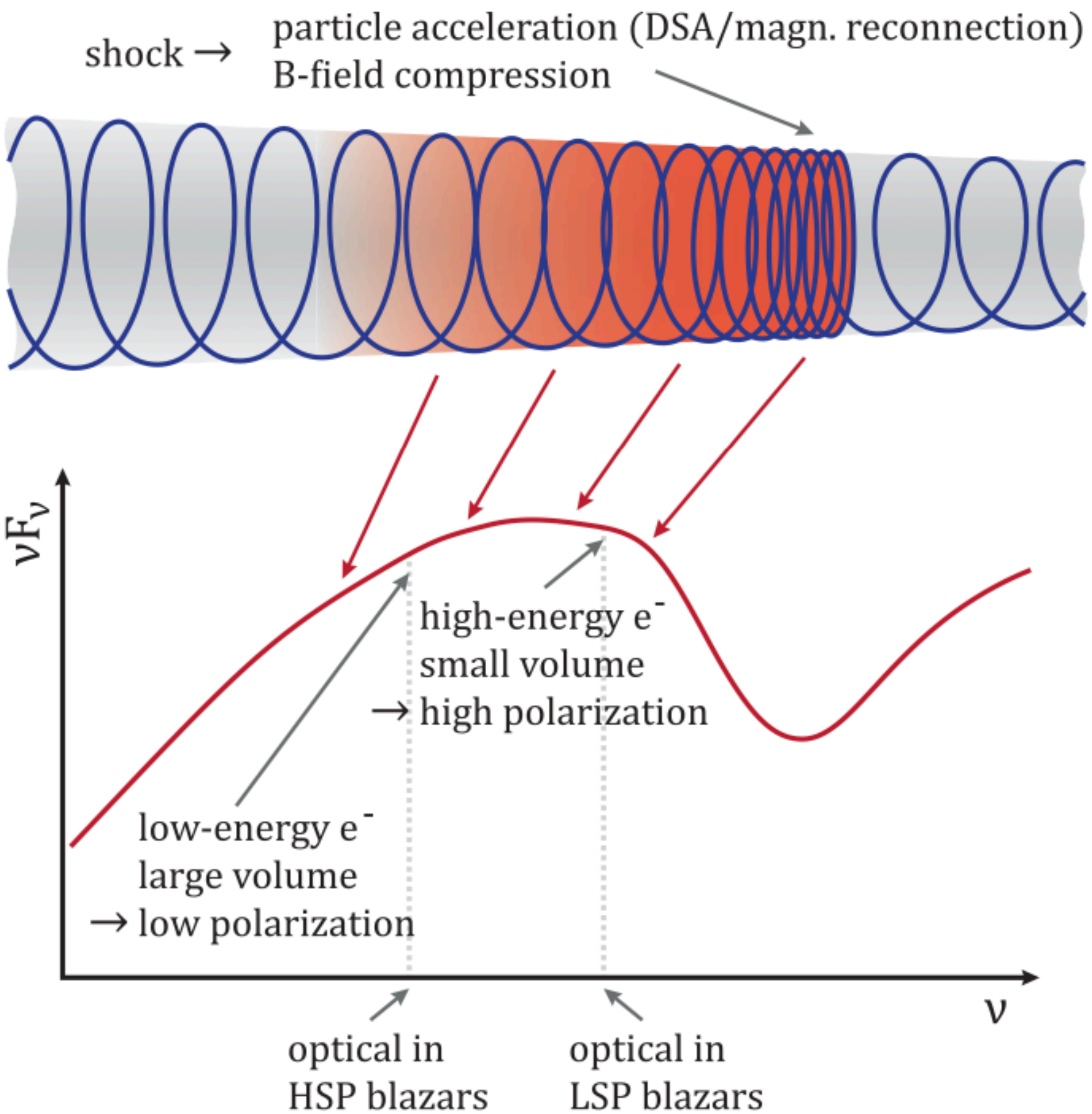
Stratified shock?

Liodakis et al. 2022

Analogue results for:
PG 1553+113 (Middei et al. 2023) ,
1ES 0229+200 (Ehlert et al. 2023),
PKS 2155-304 (Kouch et al. 2024)

Magnetic fields at shocks

Compression

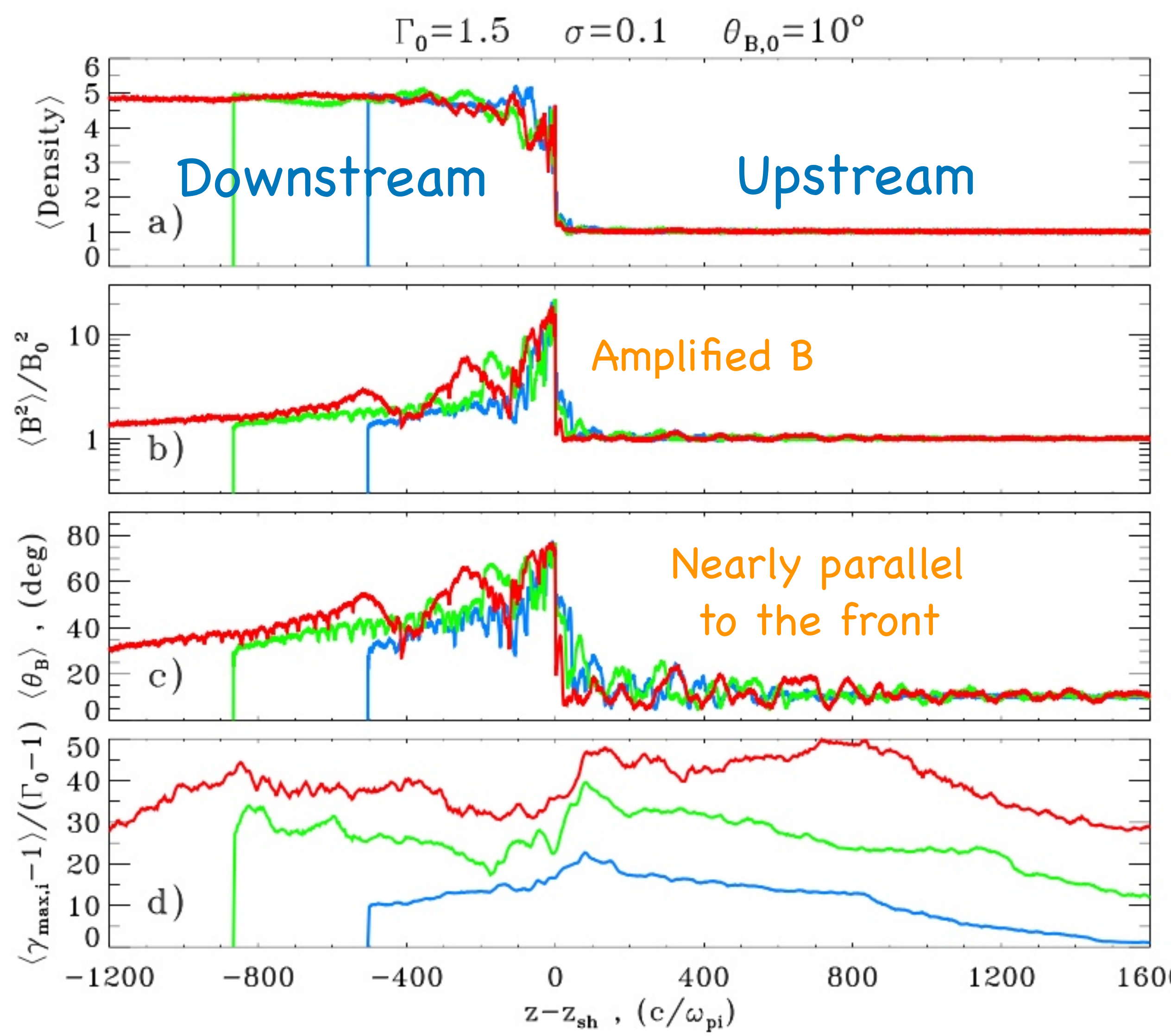


e.g. Laing 1980

Angelakis et al. 2016

Self-generated field

Trans-relativistic, nearly parallel, low σ shock



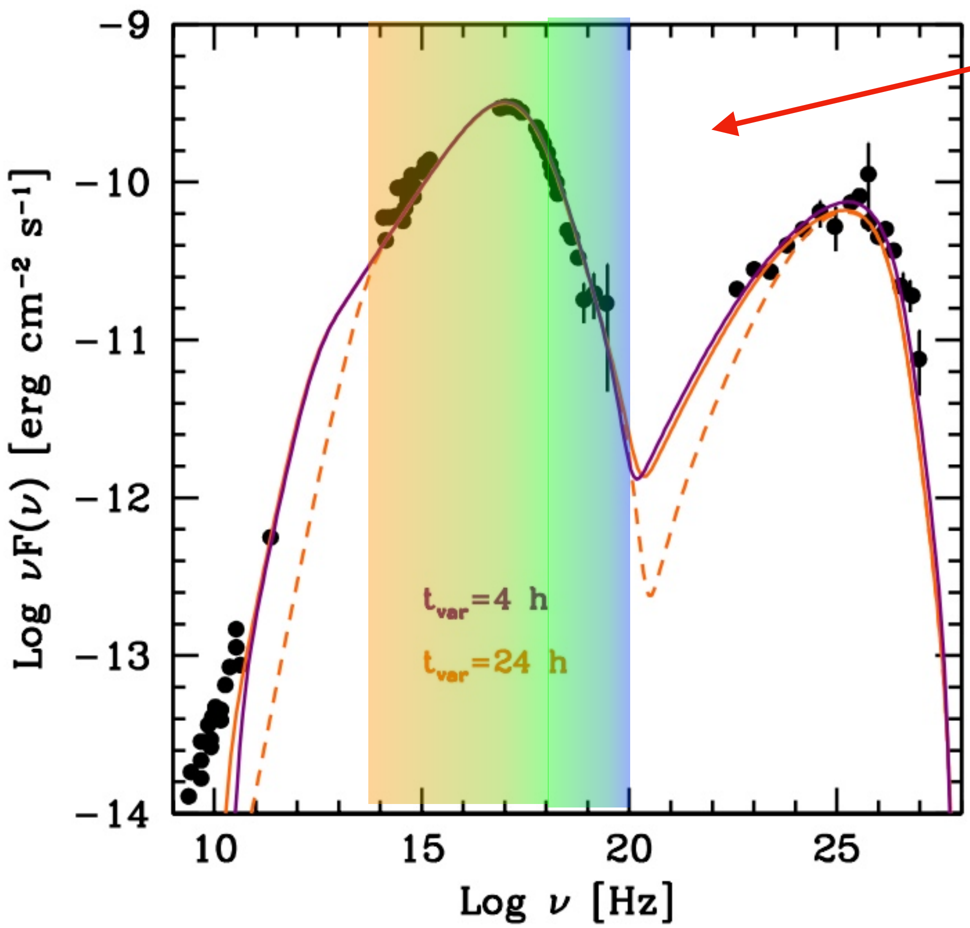
Caprioli & Spitkovsky 2014

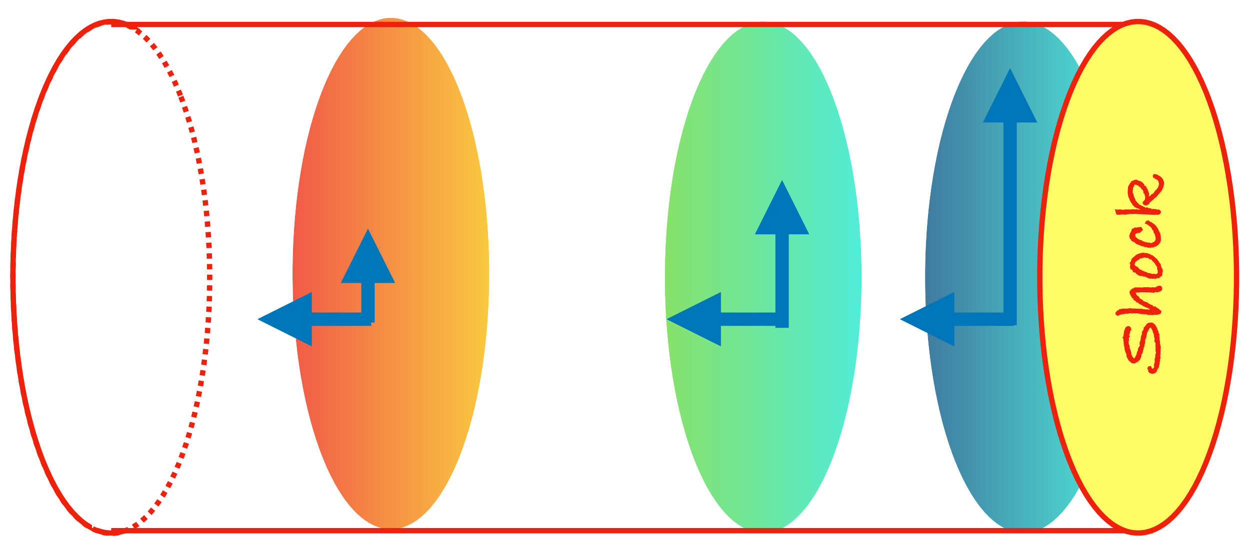
Sironi et al. 2015

Vanthieghem et al. 2020

Stratified shock: a toy model

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

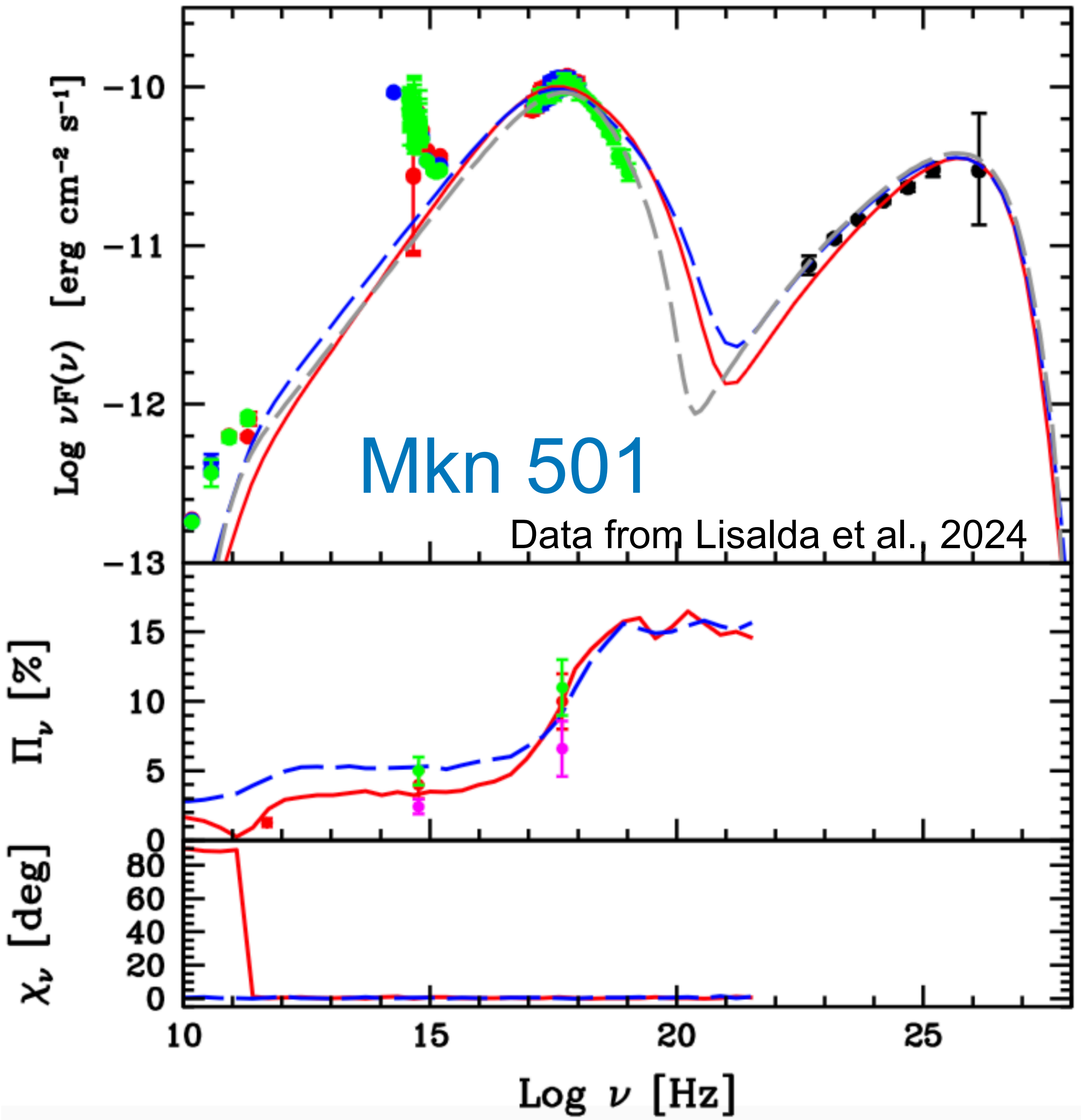




$$ct_{\rm cool} \propto \gamma^{-1}$$

Tavecchio et al. 2018, 2020

Stratified shock: a toy model



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

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

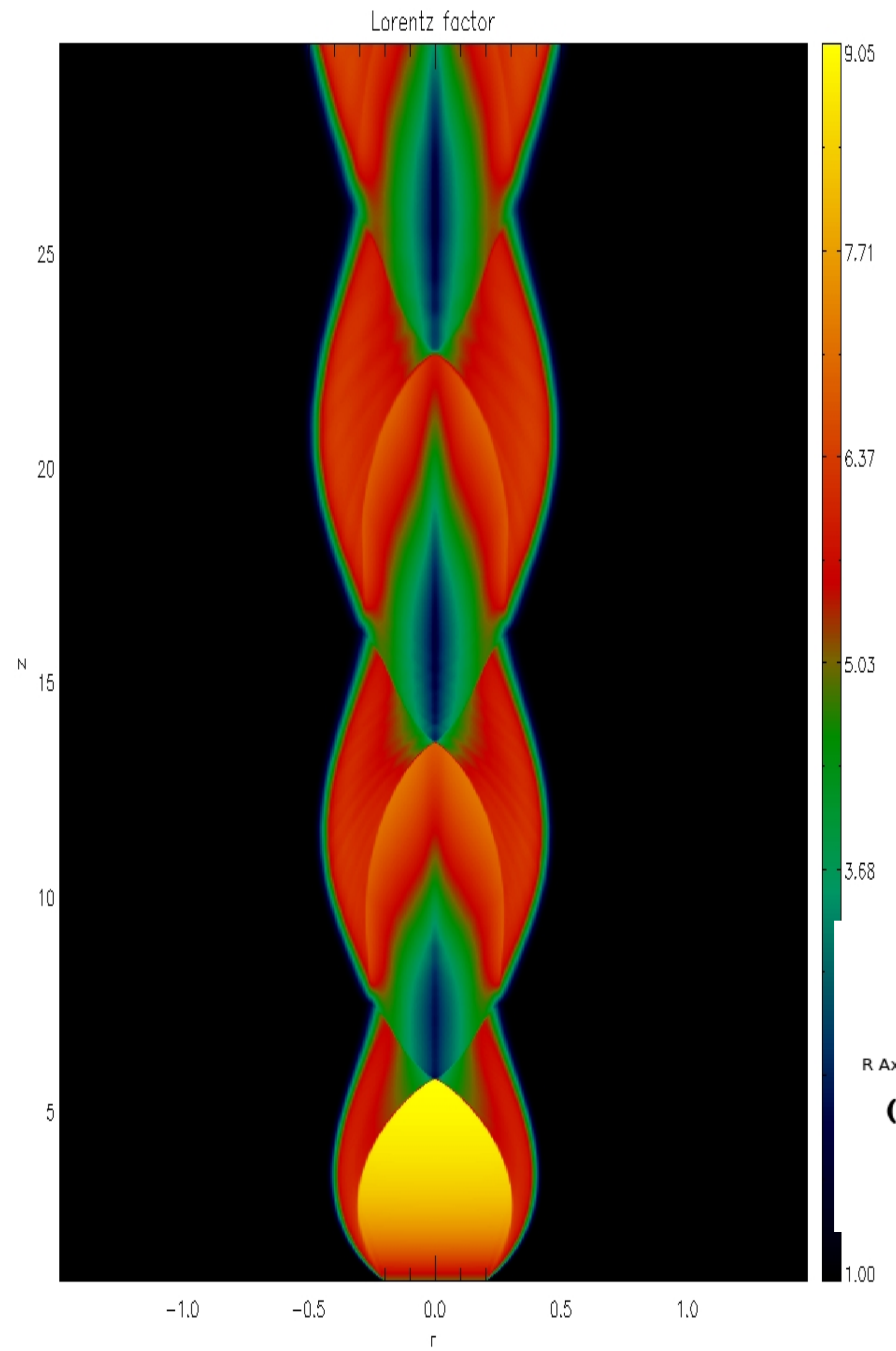
Phenomenological law for the field
e.g. Lemoine 2013

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

Tavecchio, submitted.

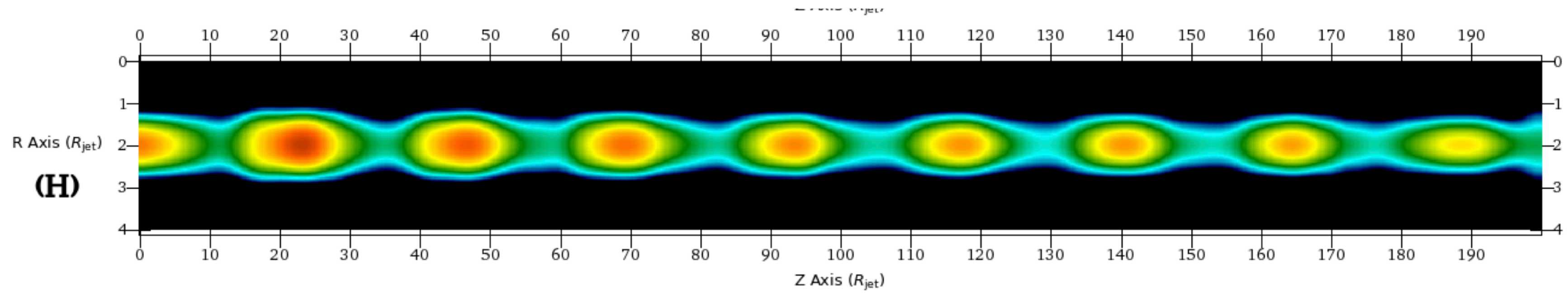
Model	$\gamma_{\rm cut}$ ($\times 10^5$) [1]	n [2]	$n_{e,0}$ [3]	$B_{\perp,0}$ [4]	B_z [5]	$r_{\rm j}$ ($\times 10^{15}$) [6]	λ [7]	m [8]
1	8.5	2.1	20	0.25	0.03	4.3	5×10^{13}	0.5
2	12.6	2.2	30	0.25	0.03	4.8	1.2×10^{12}	0.25

Recollimation shocks



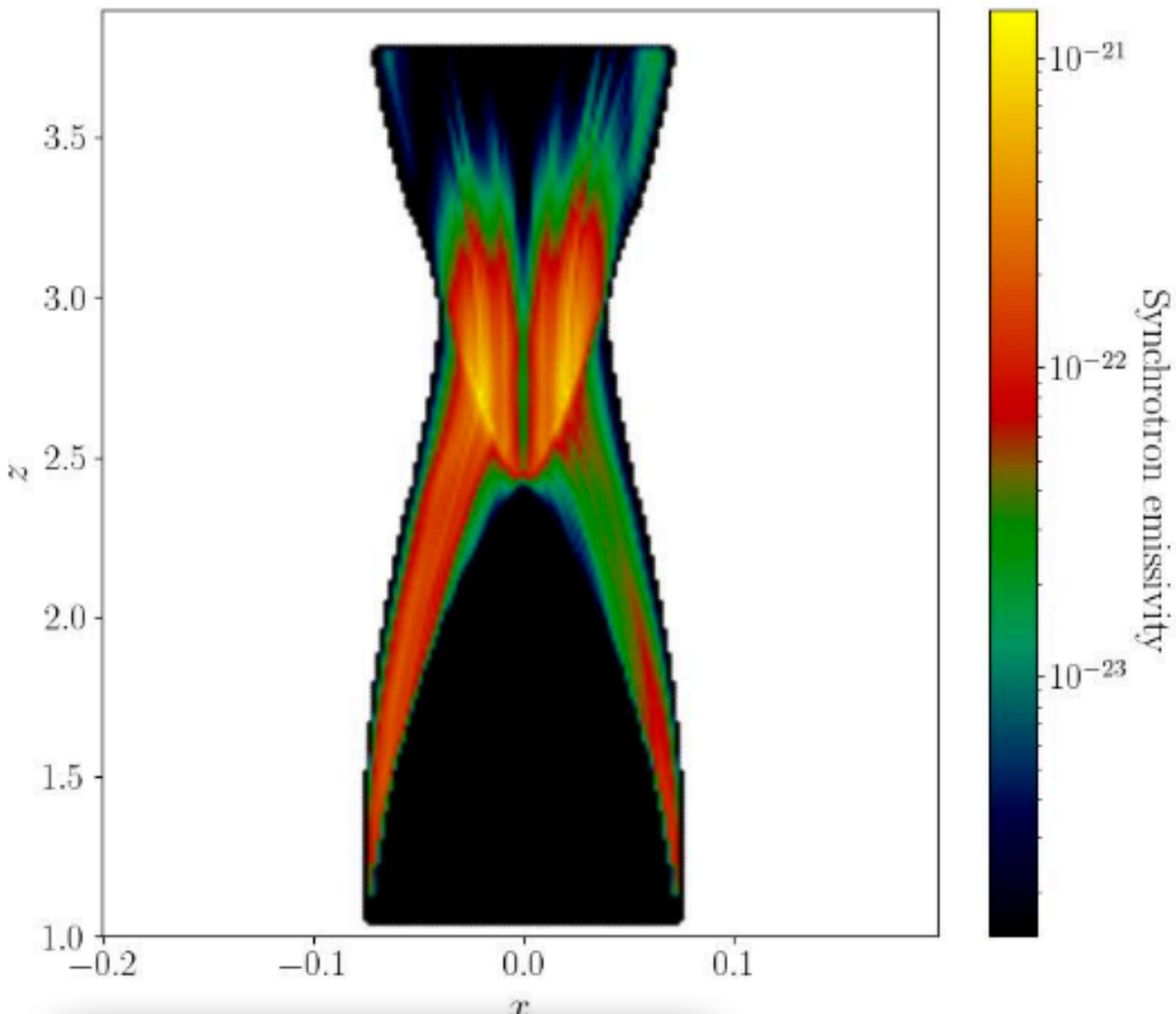
Costa et al. in prep

Komissarov & Falle 1997
Bromberg & Levinson 2007



Fichet de Clairfontaine et al. 2021

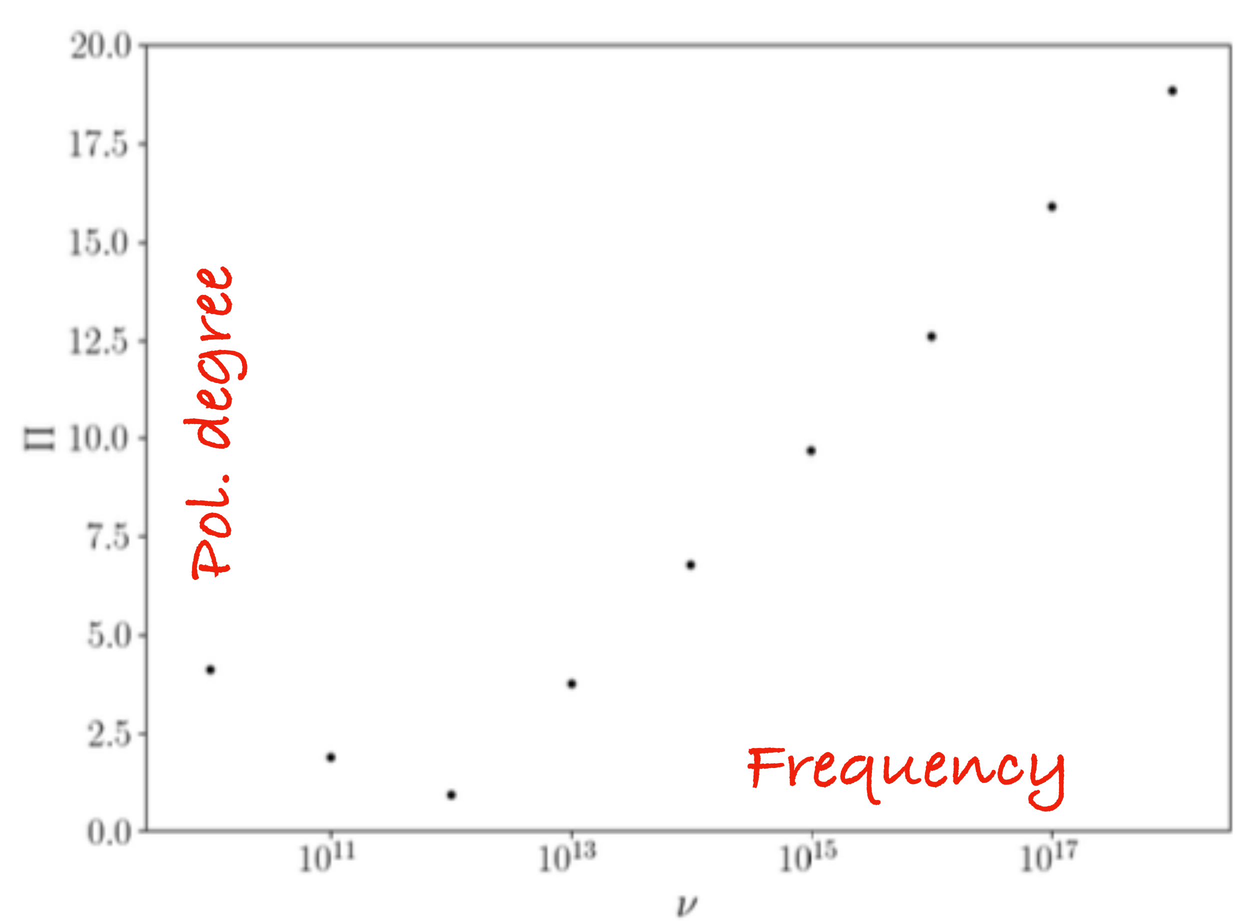
Polarization from recollimation shocks



- Conical under pressured jet
- $B_{\rm tor} \sim B_{\rm pol}$
- Jet power ~ 10^{44} erg/s
- Launch magnetization ~10^{-2}
- Launch radius ~10^{-2} pc

Lagrangian particles are ensembles of relativistic particles following the fluid streamlines. Their energy spectra are updated using sub-grid physics based on local fluid conditions

MHD+PIC

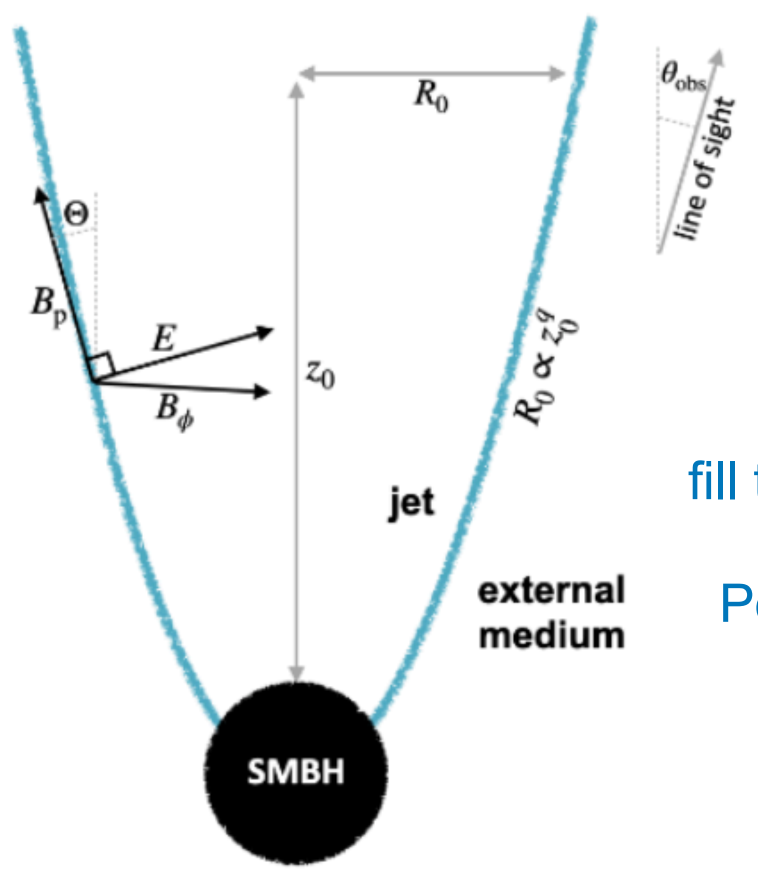


Sciaccaluga et al., in prep.

Shocks & energy stratification? Not necessarily!

Bolis et al., submitted

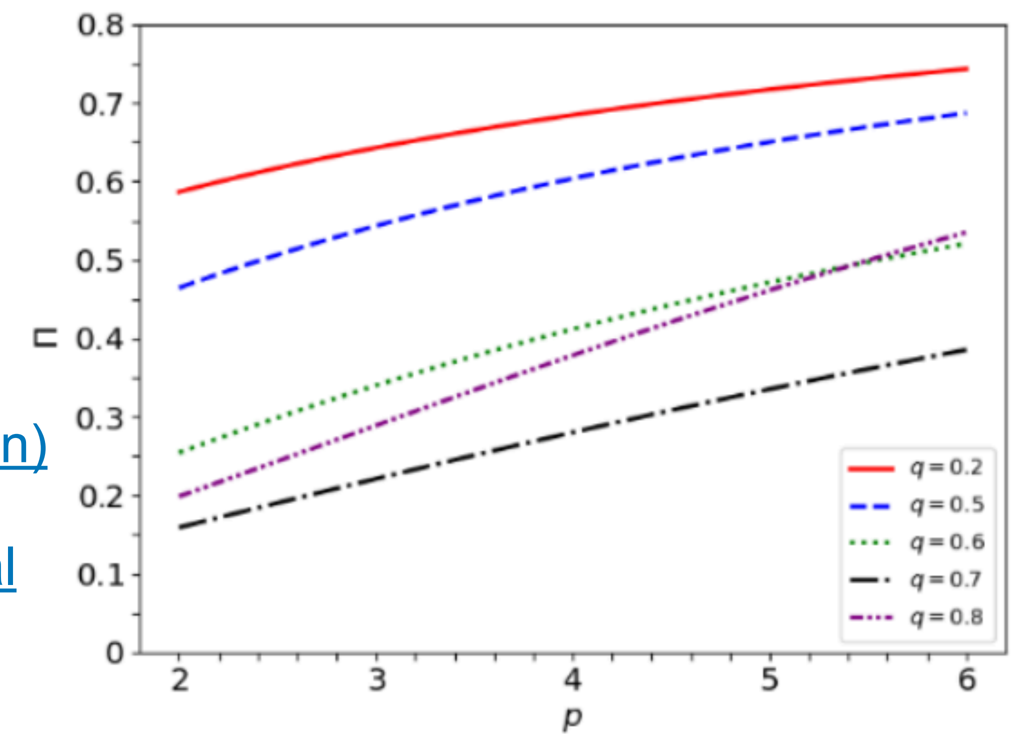
Strong dependence on the electron slope (hence frequency)!

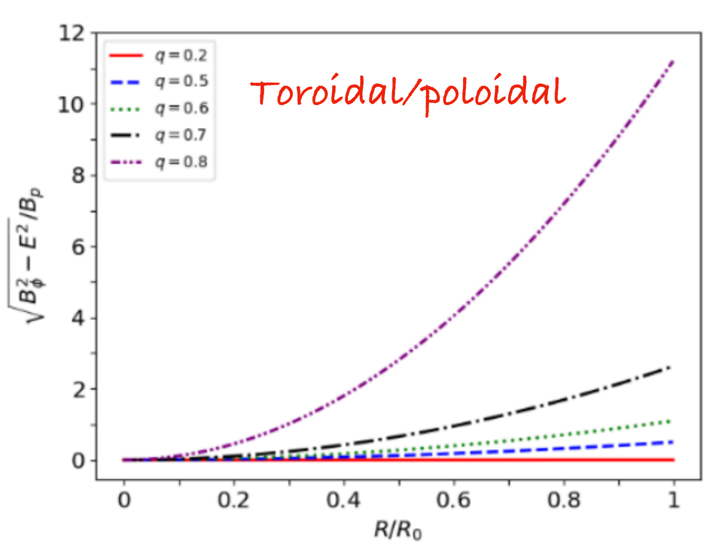


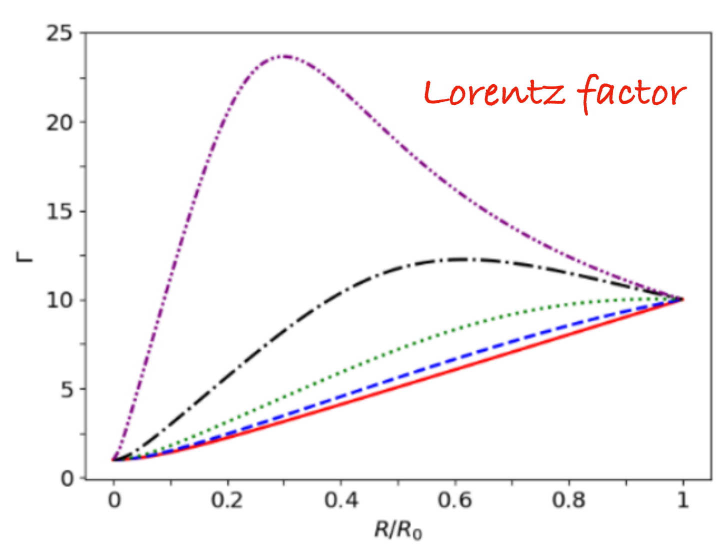
MHD solutions of confined, magnetically dominated jets by Lyubarsky 2009

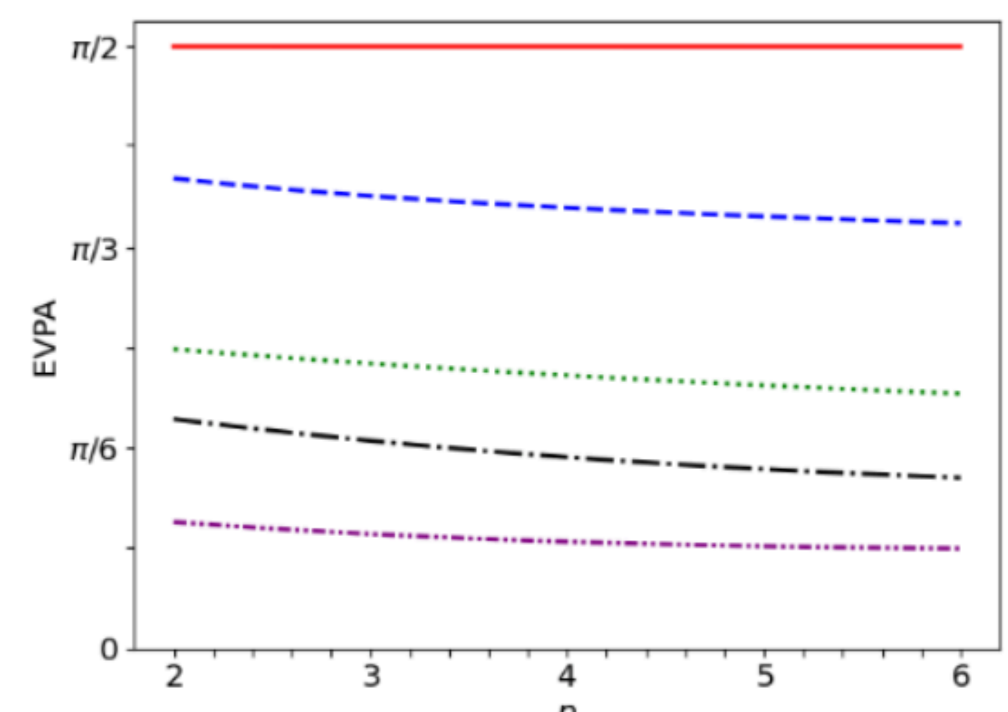
Electrons with different energy fill the <u>same volume (no stratification)</u>

Polarization depends on the <u>global (ordered)</u> B-field structure









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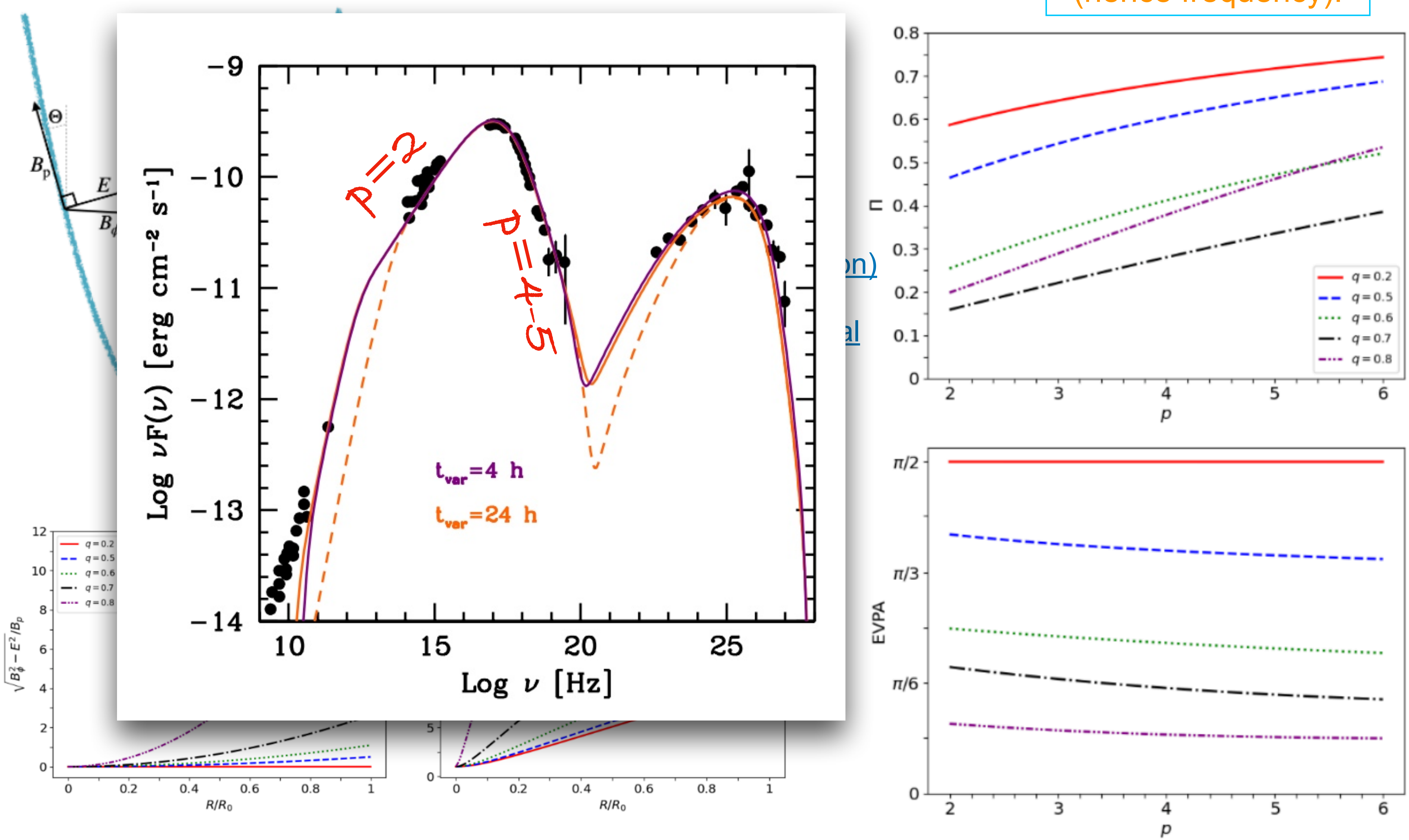
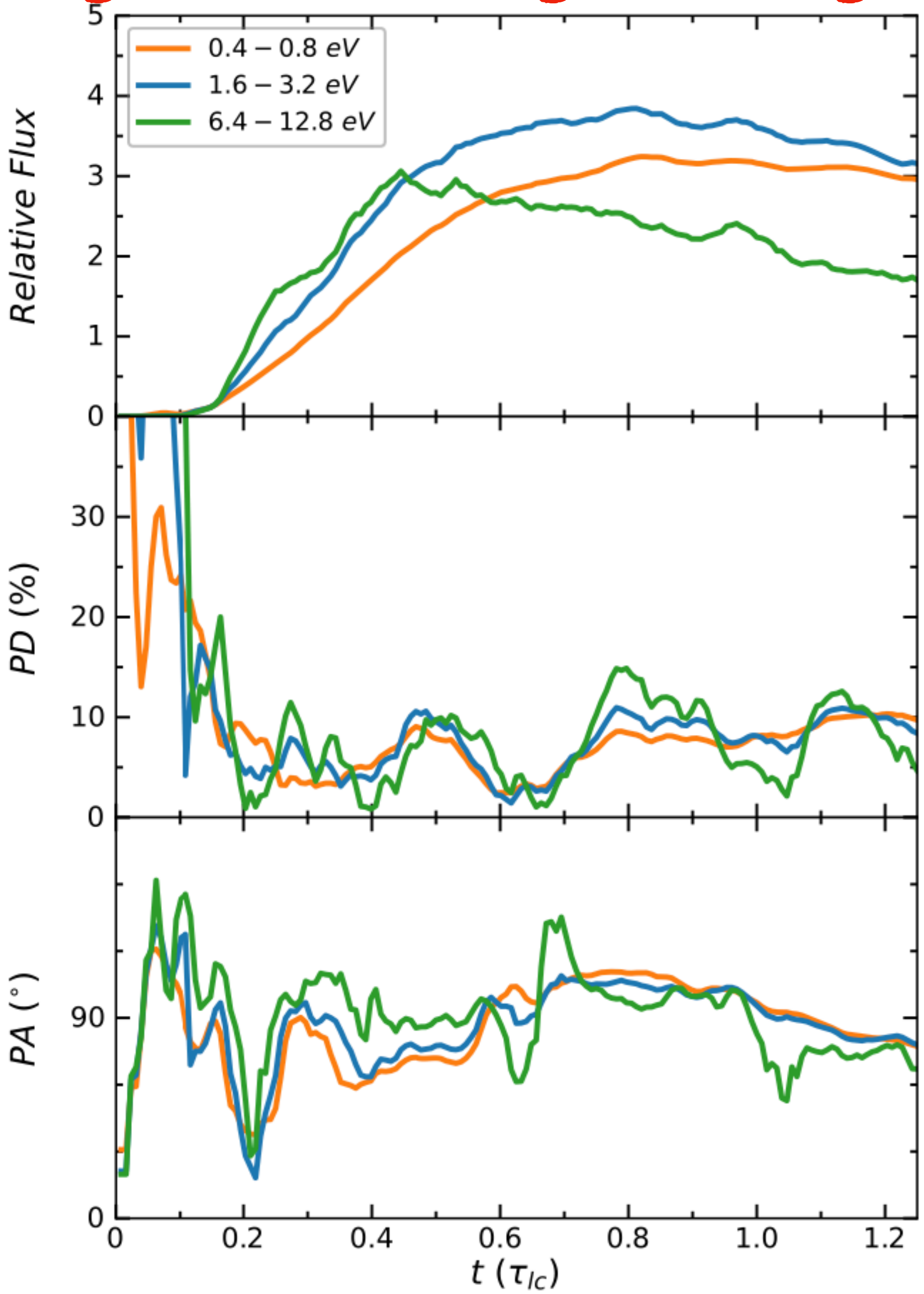


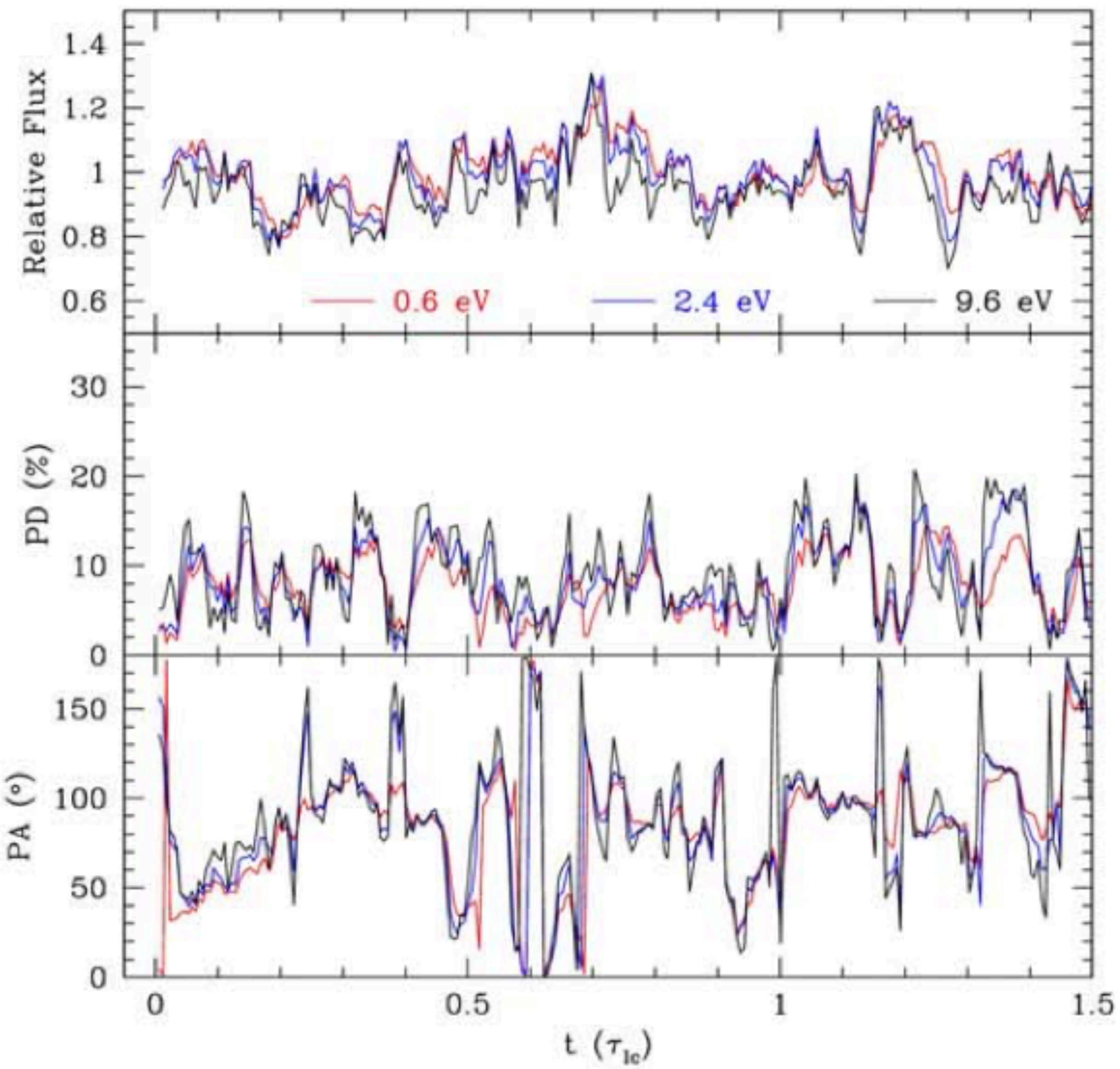
Hints from IXPE: 2) limits to turbulence

Magnetic (high magn.)



Zhang et al. 2023

Kinetic (low magn.)

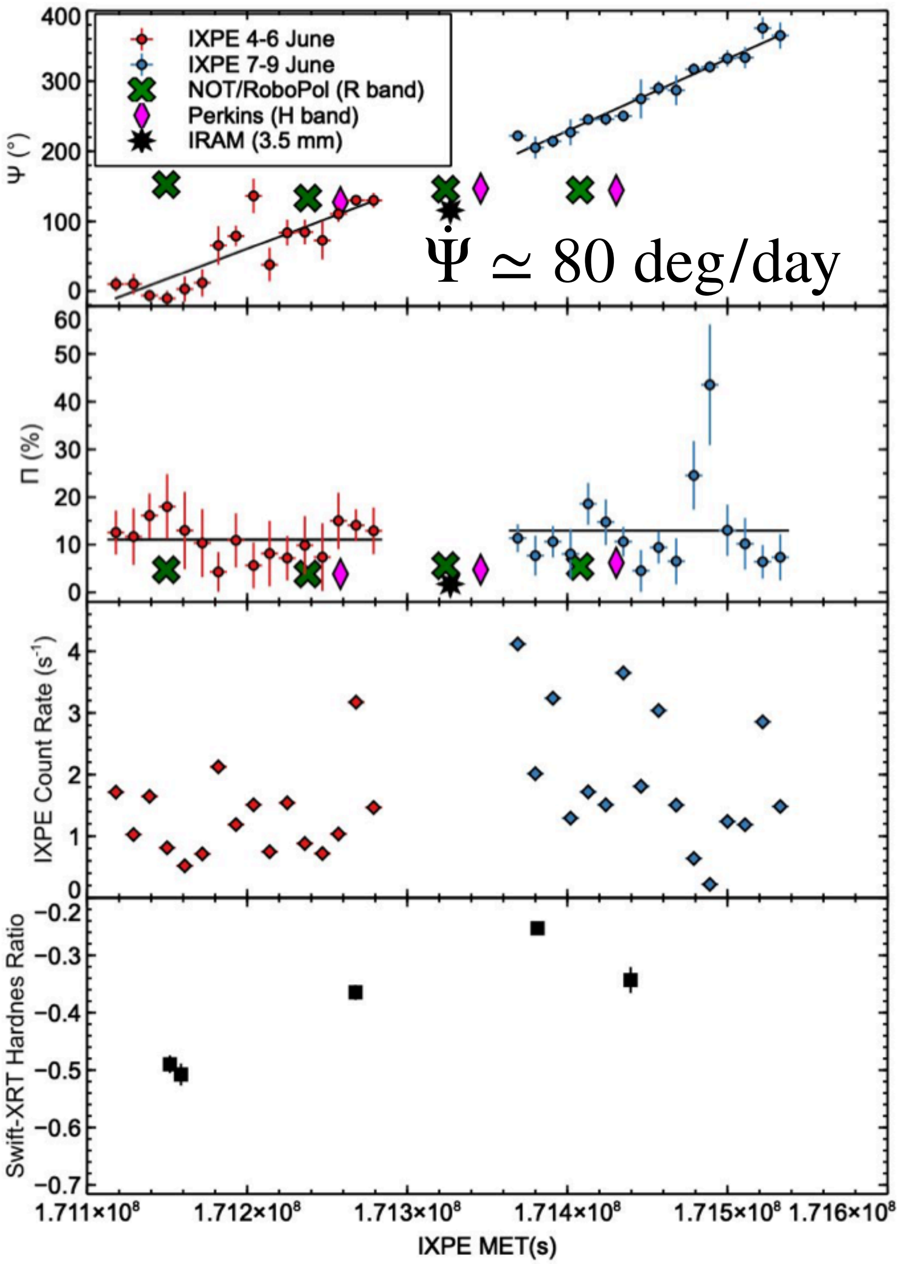


The observed steadiness of the polarization effectively limits the level of (macro)turbulence

e.g. Marscher & Jorstad 2022

Hints from IXPE: 3) EVPA rotations

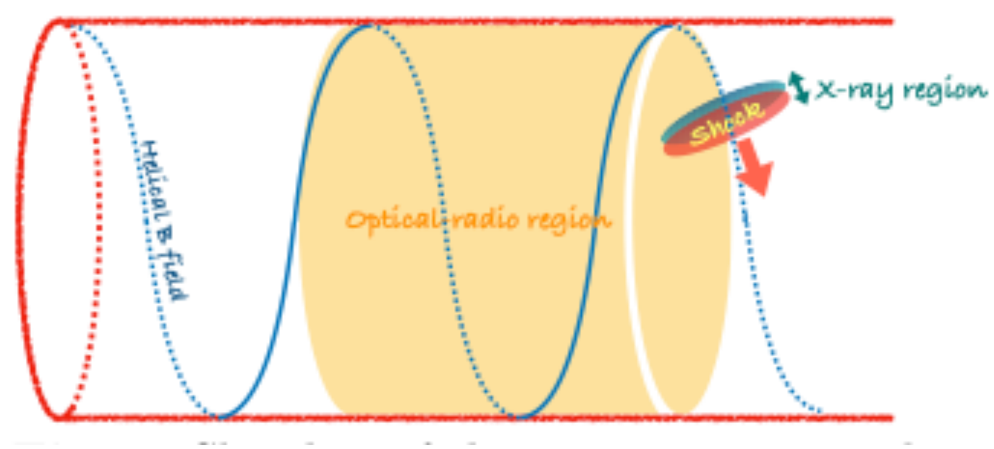
Mkn 421

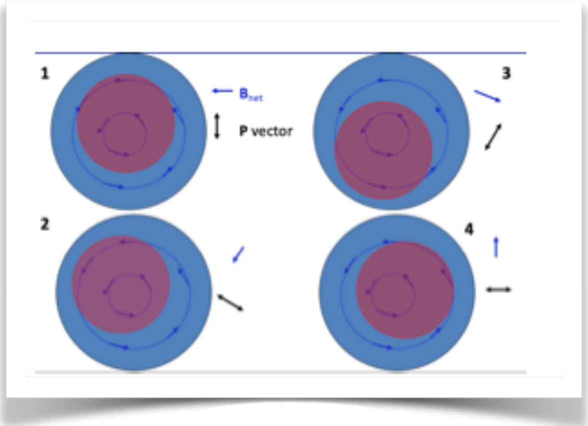


Observed during relatively high states

Di Gesu et al. 2023

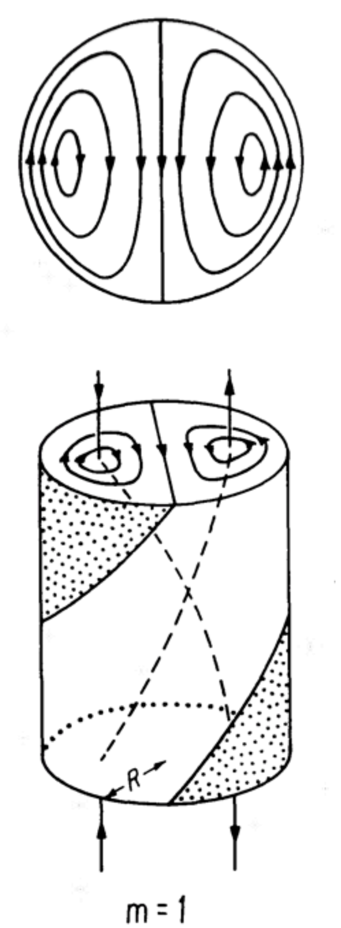
See also Kim et al. 2023





non-axysimmetric feature (e.g. shock)

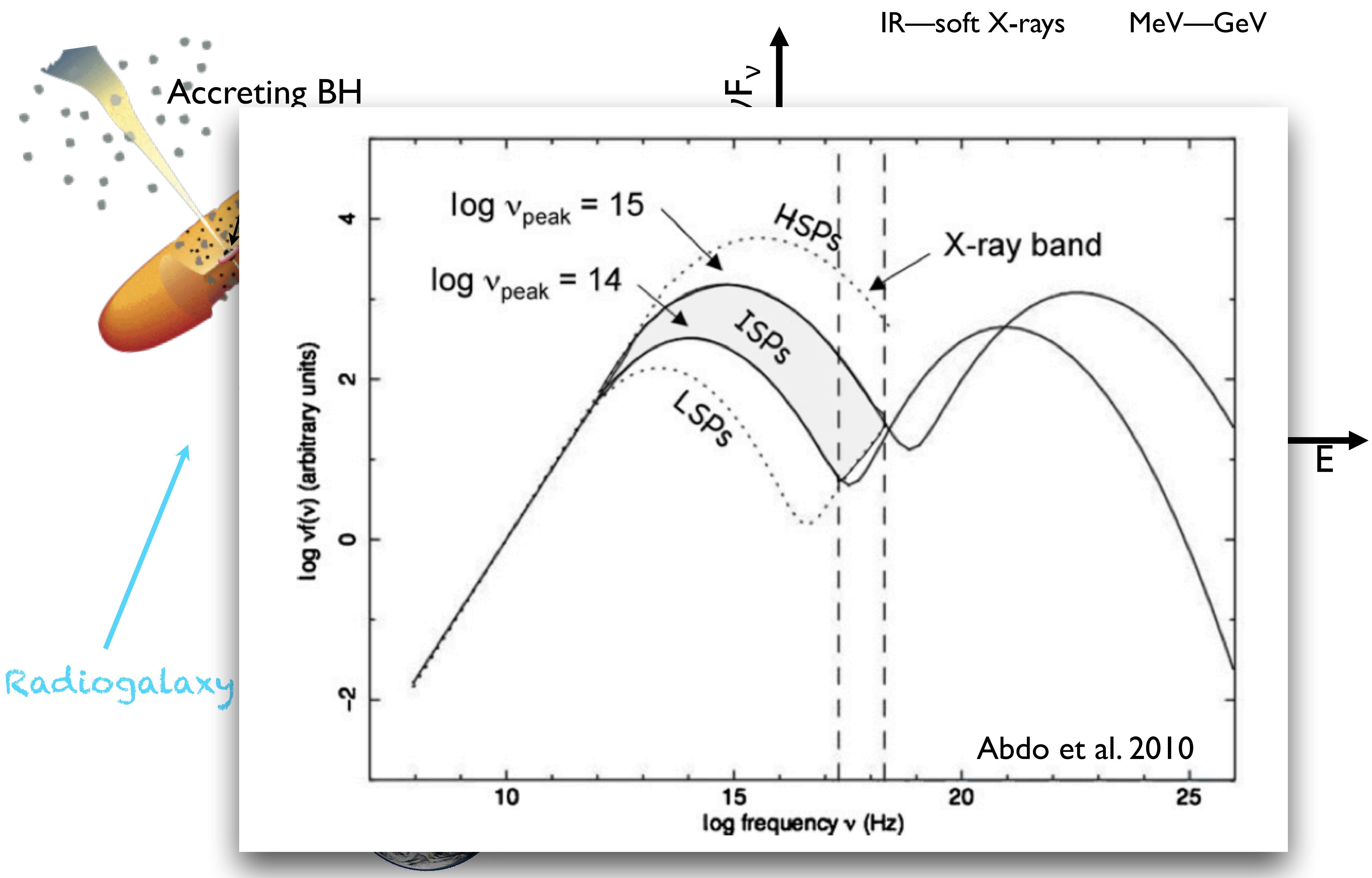
Marscher et al 2008, 2010



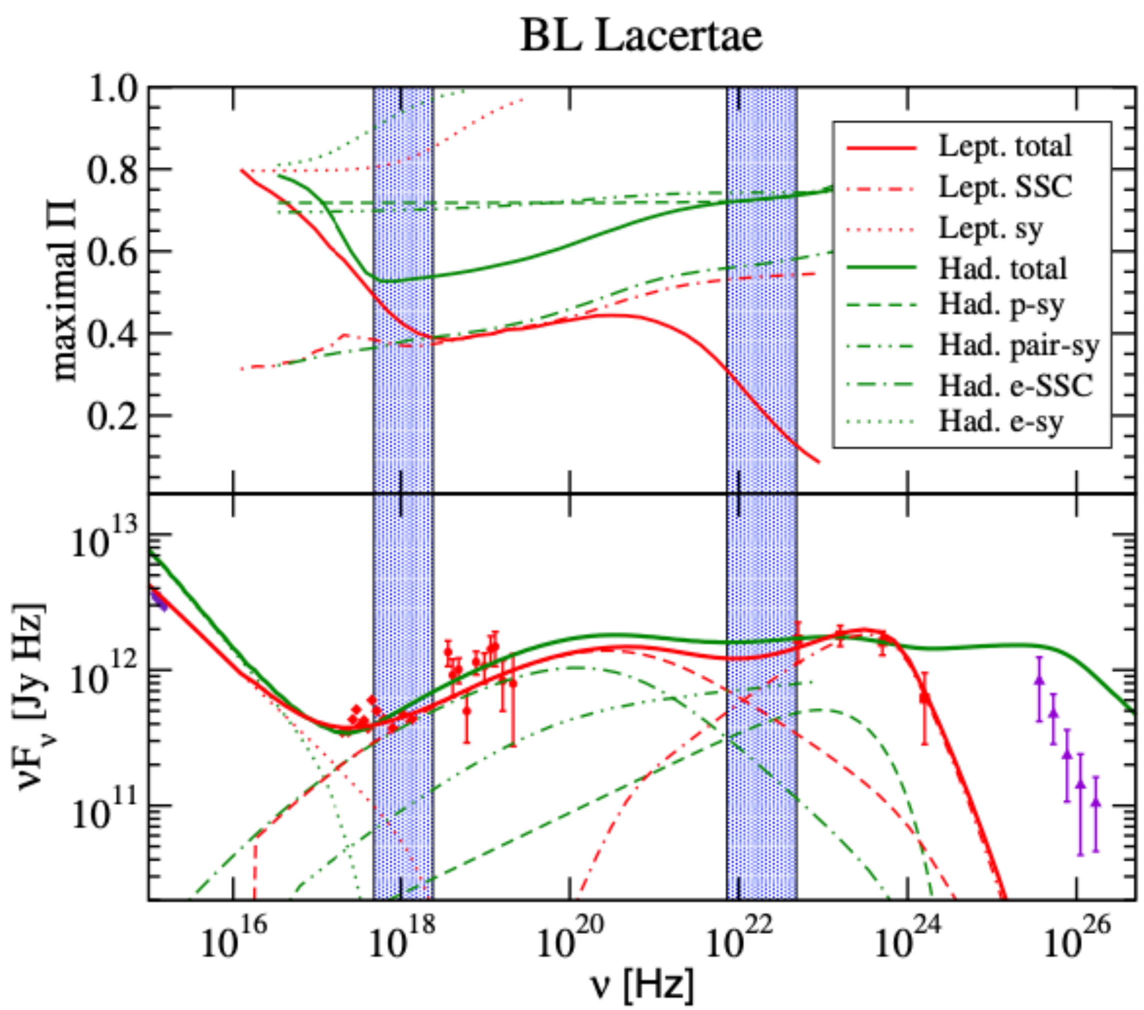
non-axysimmetric field

Koenigl & Choudhuri 1985

Jets pointing at us: blazars



LSP: emission mechanisms and matter content

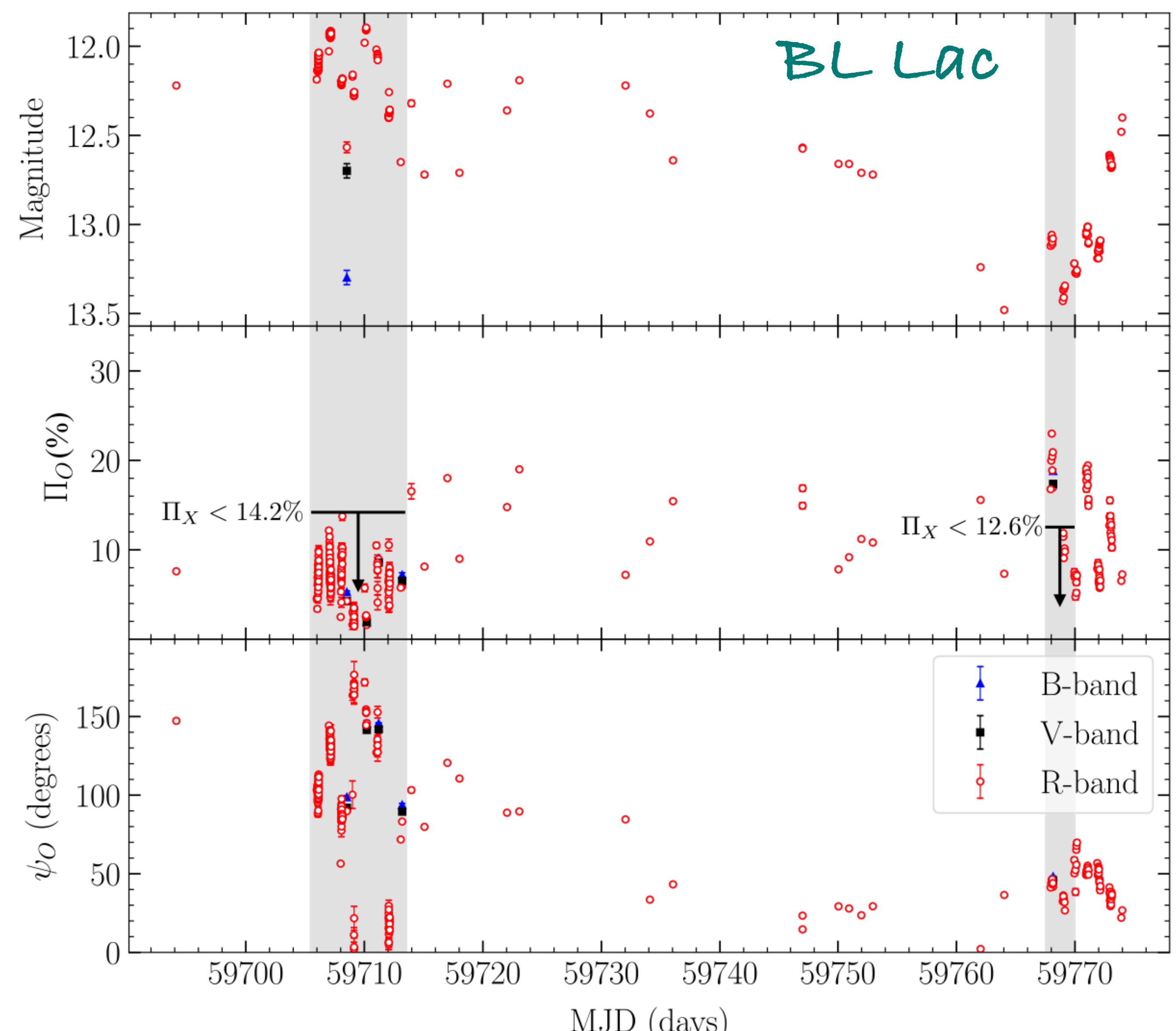


Zhang & Boettcher 2013

(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)

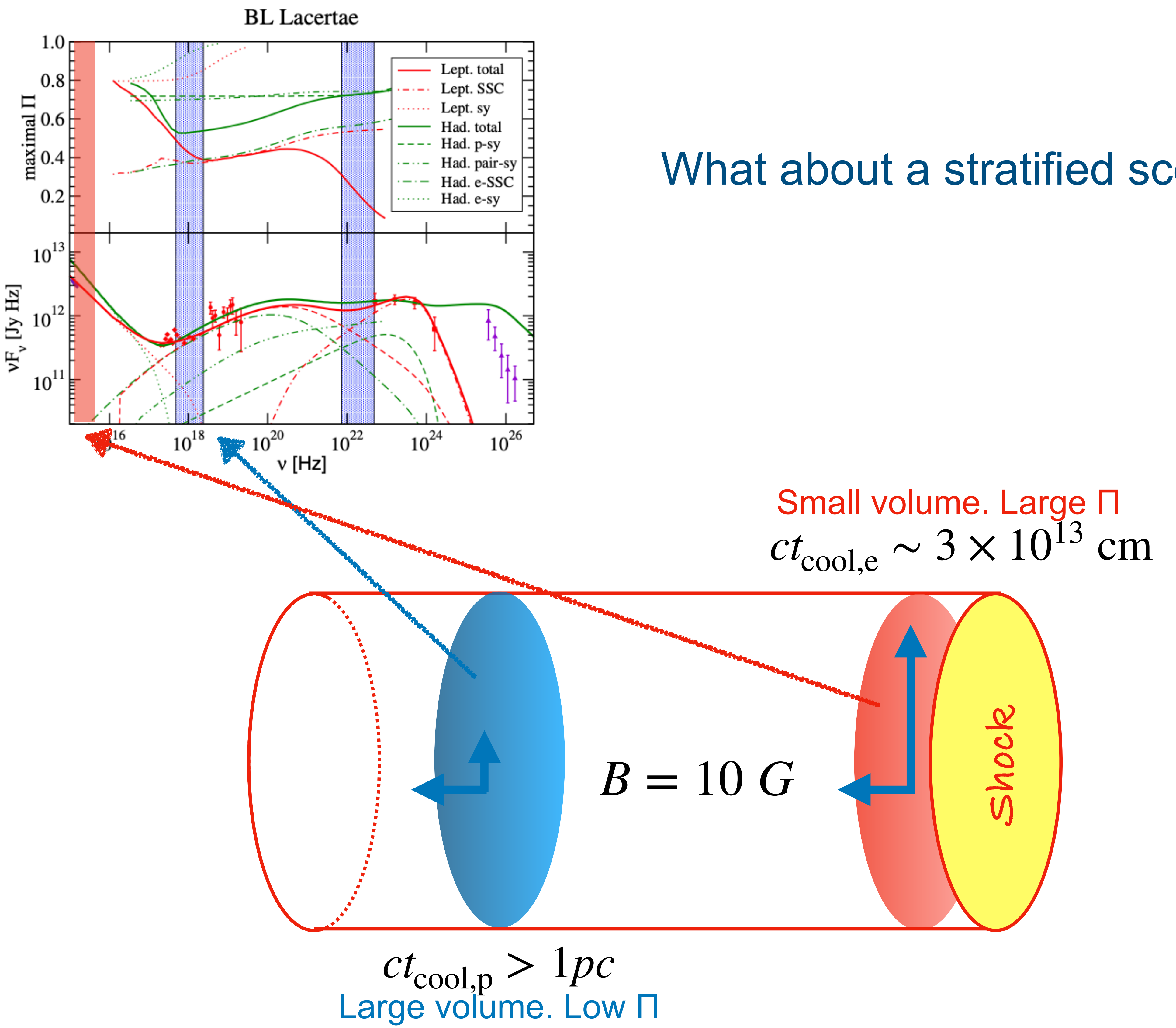
Leptonic (SSC) preferred? Yes, but…



Middei et al. 2022

LSP:
emission mechanisms and matter content

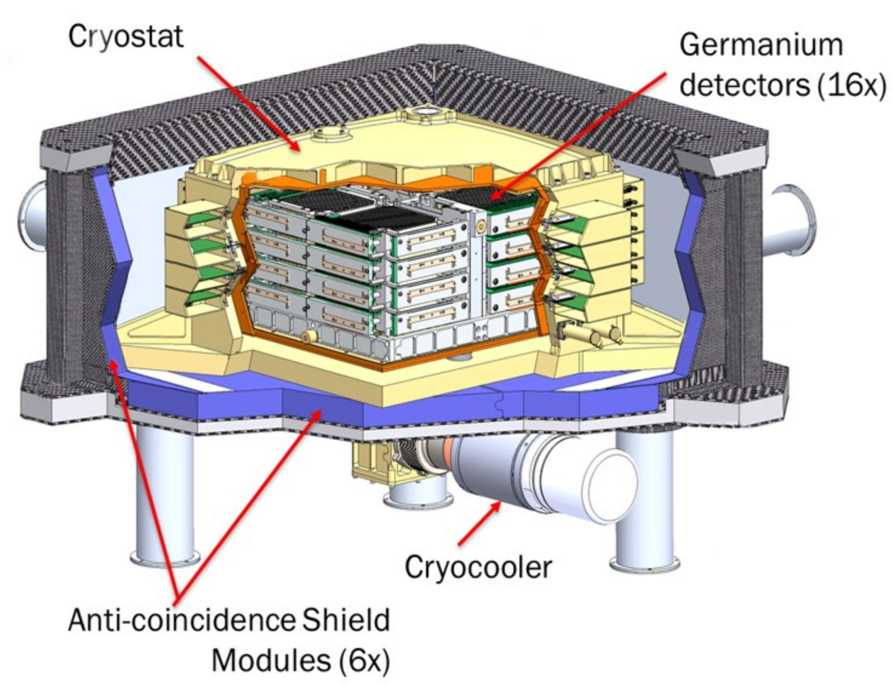
What about a stratified scenario?



Upcoming: polarization at higher energy

NASA-SMEX mission with a Compton Telescope (0.5-2 MeV)

Launch: 2027   Duration: 2 years
PI John Tomsick (UC Berkeley)



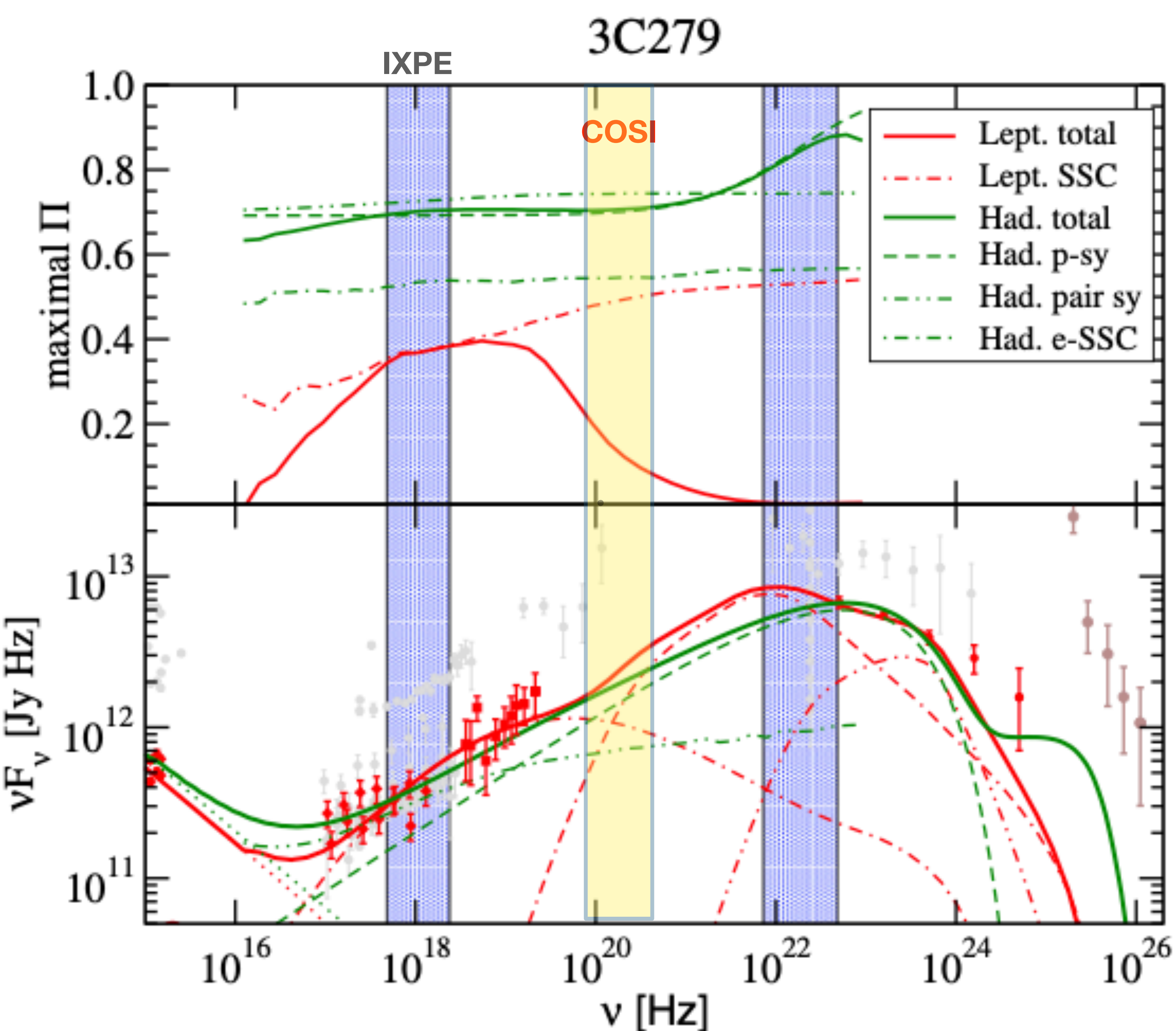
Institutions involved:

U. C. Berkeley
Naval Research Laboratory
Clemson Univ.
GSFC
ASI (Italy)
INAF (Italy)
IRAP (France)
Tokio and Nagoya Univ.

https://cosi.ssl.berkeley.edu

ISP/LSP with COSI

The comparison between IXPE and COSI provides a measure of the SSC/EC relative contribution



Zhang & Boettcher 2013

NB: this assumes a regular B field!

Typical degree of pol. in optical are around 10-20%

Preliminary IXPE results suggest turbulence of moderate level.

We should expect a lower Π

Feasibility still under study

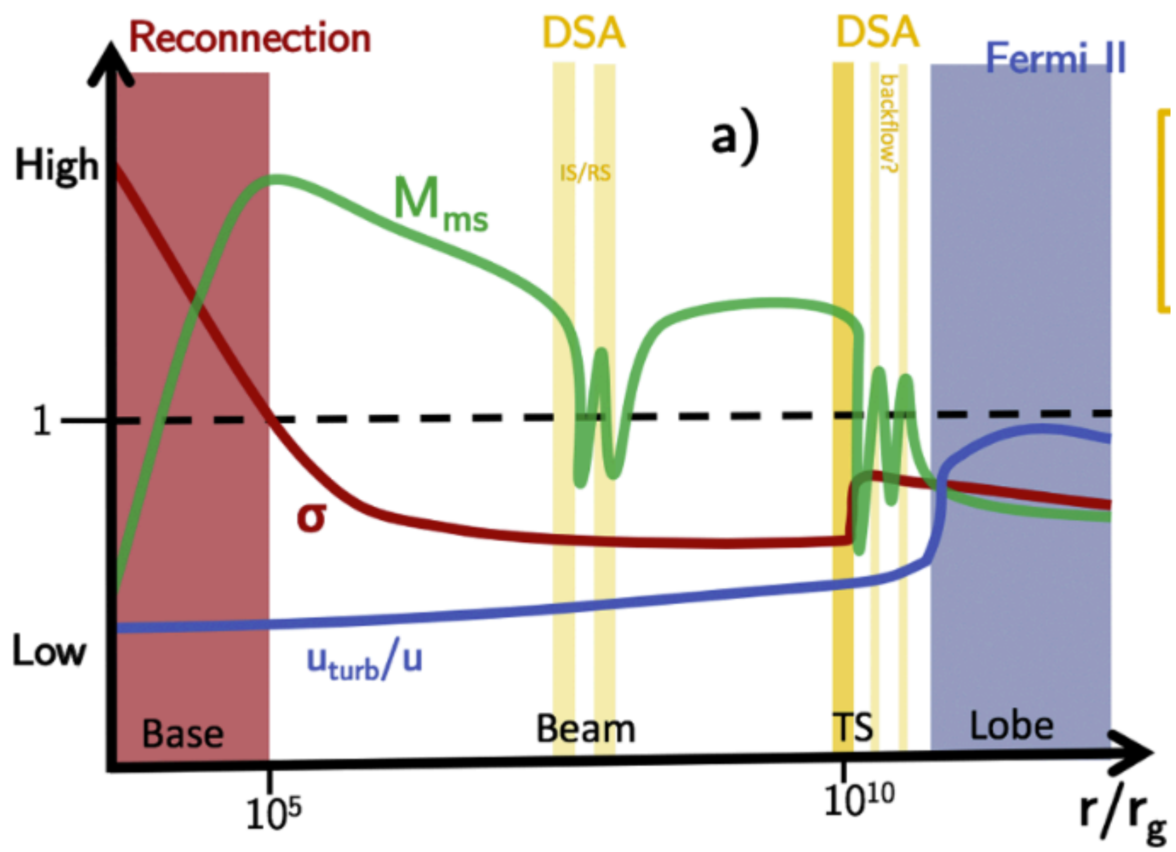

THANK YOU!

Shock acceleration?

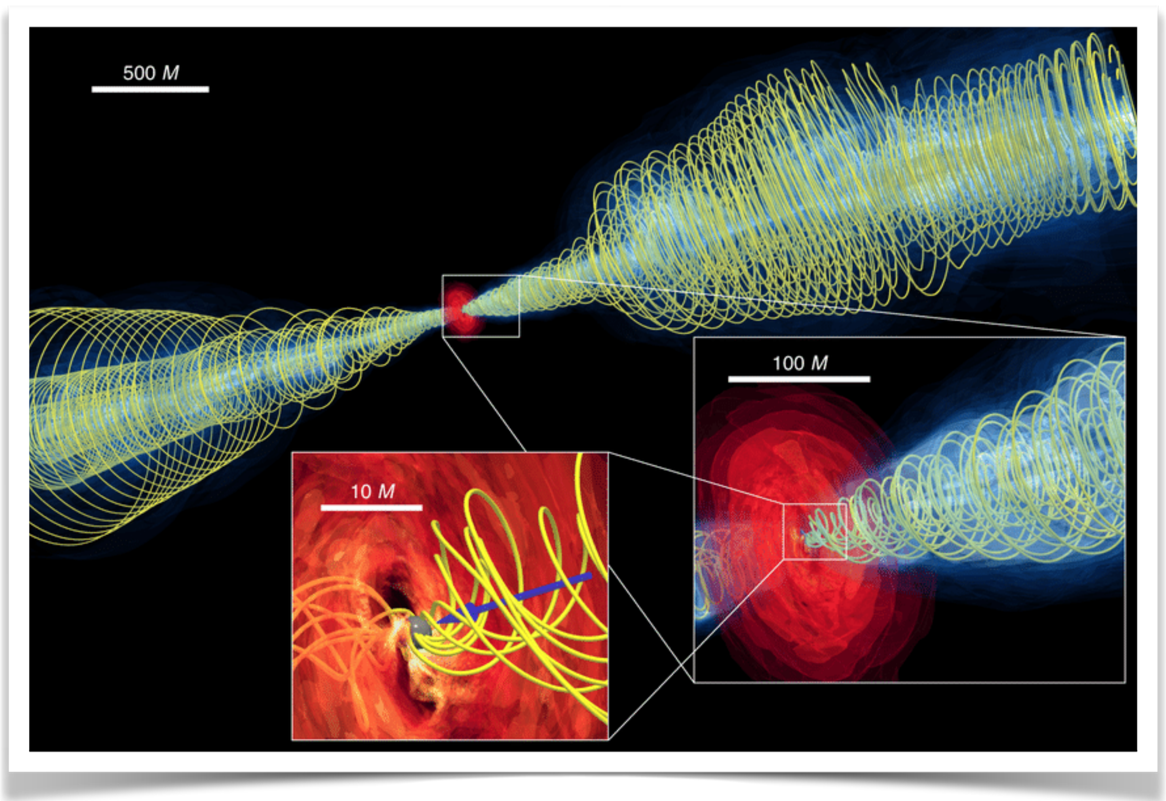
DSA can work efficiently only in weakly magnetized jets (e.g. Sironi+2015)

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

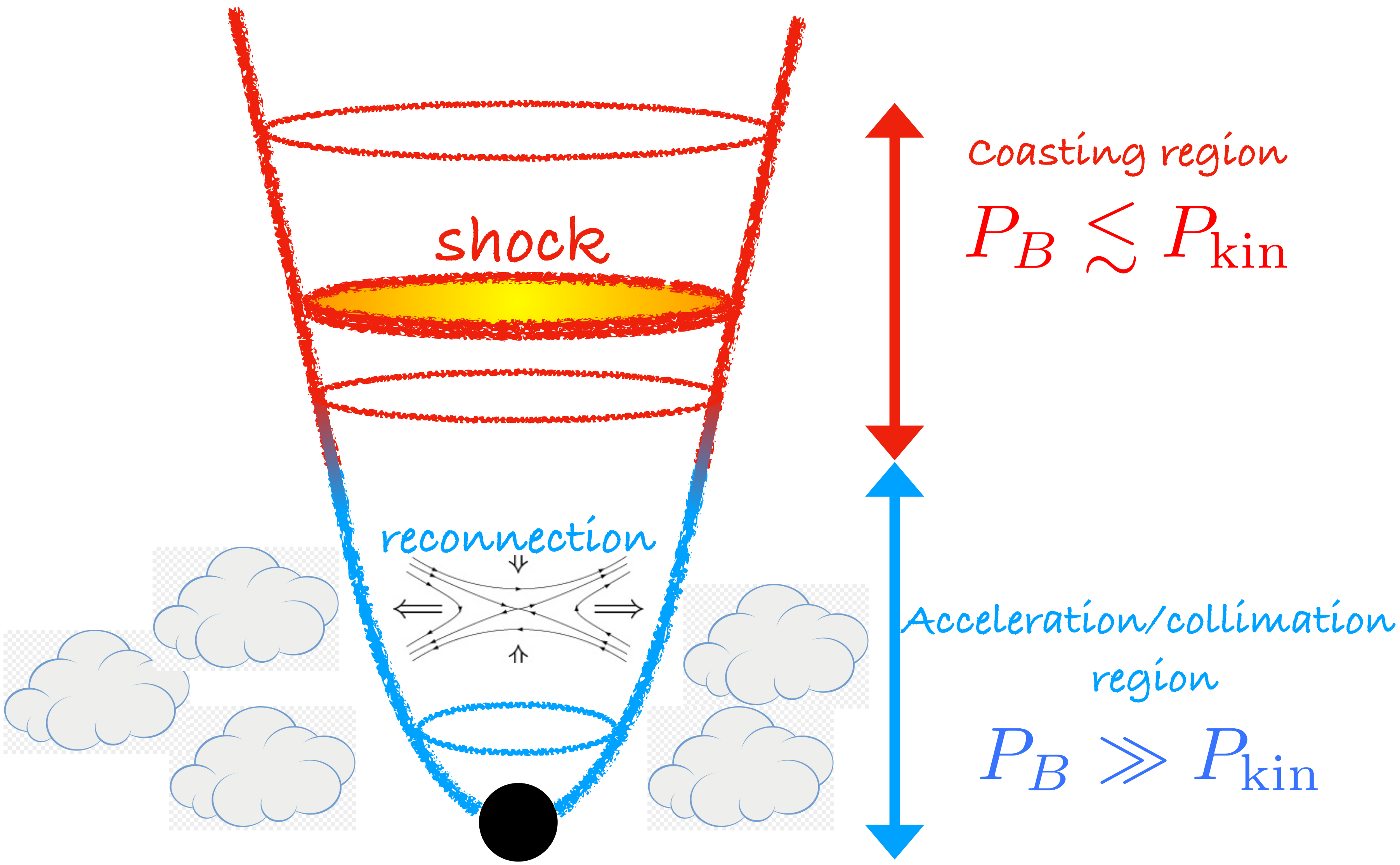
This is inconsistent with jet production models (e.g. Komissarov et al. 2009)



Matthews et al. 2020



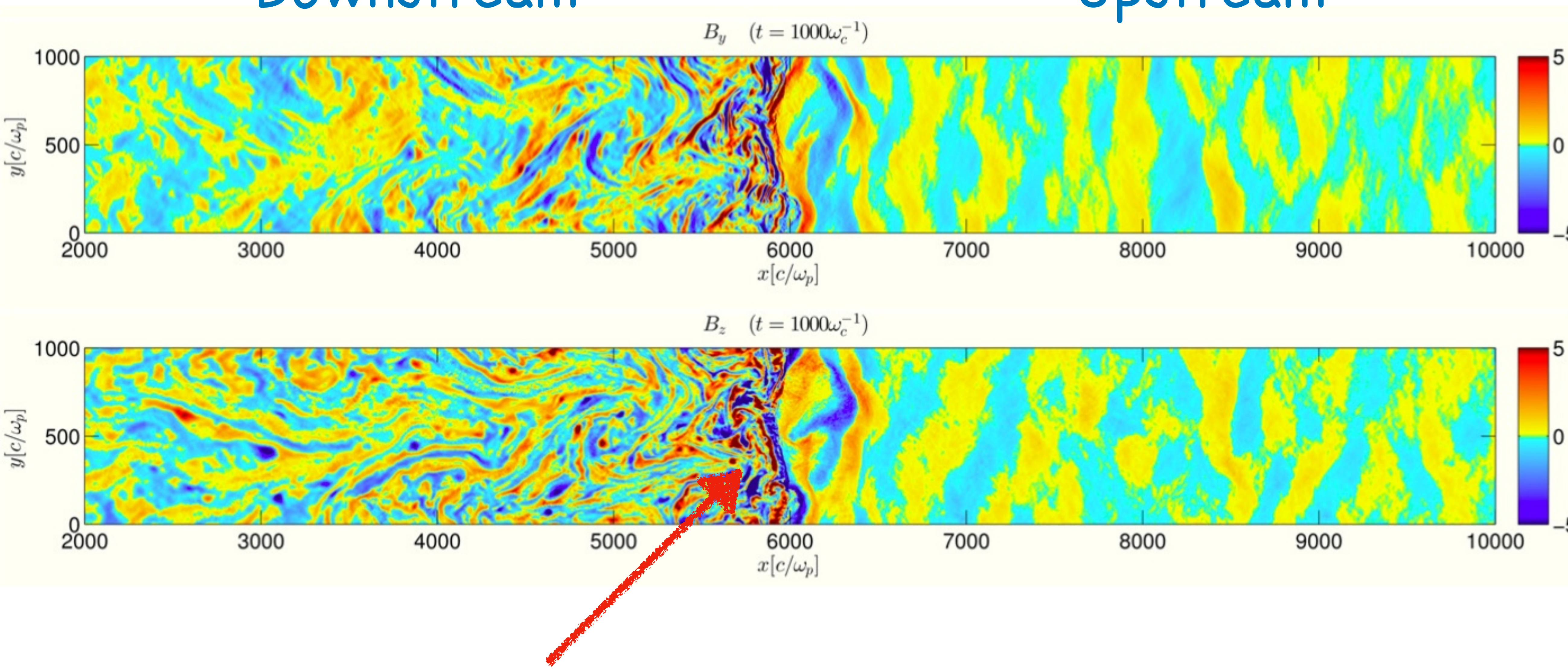
Energizing the particles



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

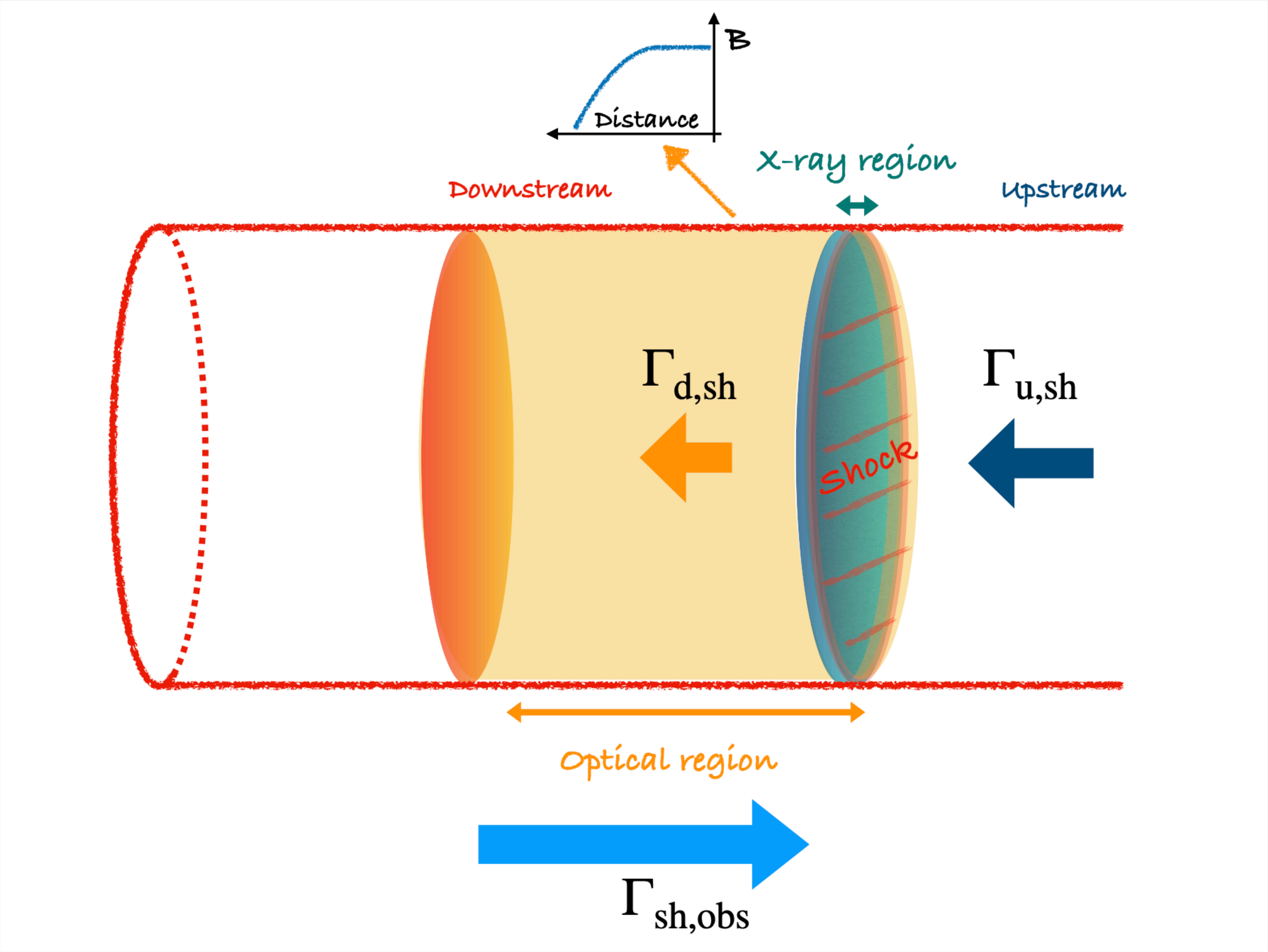
Caprioli & Spitkovsky 2014

Polarimetry in the X-ray band

Possible alternatives and predictions

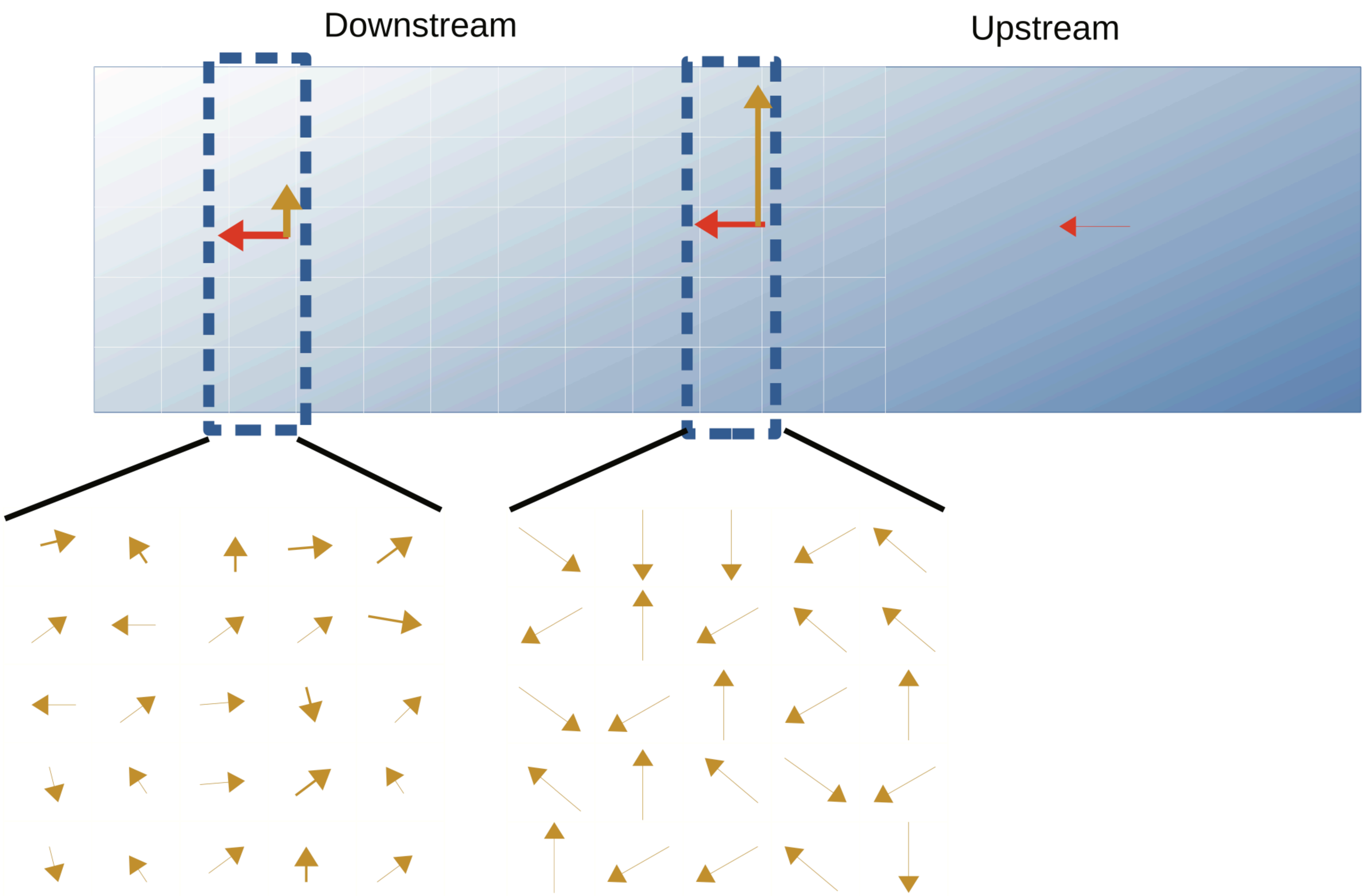
	Optical	Medium-Hard X-Rays
Shock (turbulent)	$\Pi \lesssim 15\%$, variable; χ variable, smooth rotations possible	$\Pi \lesssim 30\%$, highly variable highly and rapidly variable
Shock (self-produced field)	$\Pi \lesssim 20\%$, slowly variable, flips by $\Delta\chi = 90$ deg	$\Pi \gtrsim 40\%$ substantially 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
$\Gamma_{sh,obs}$

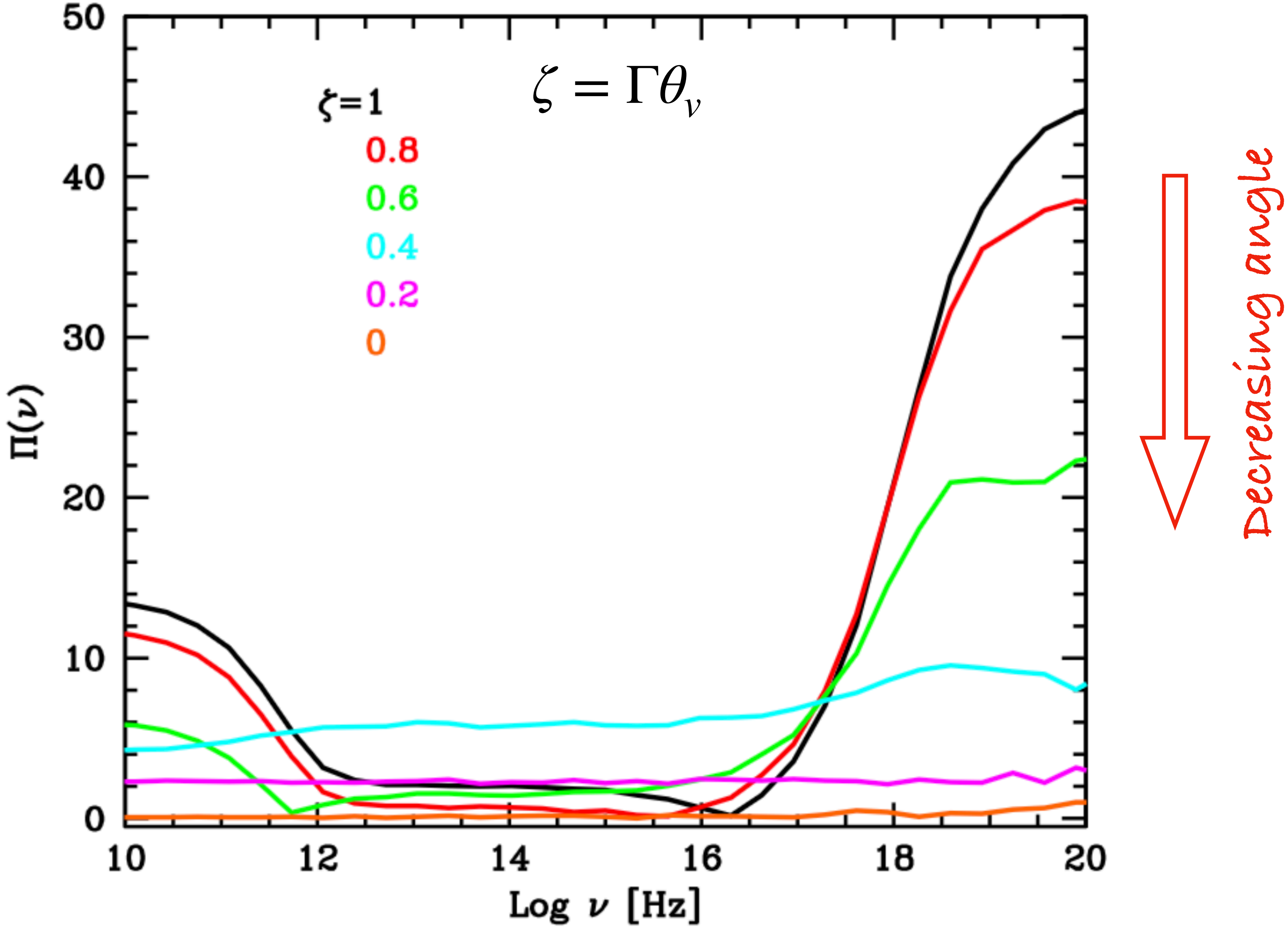
Stratified shock: a toy model



Tavecchio et al. 2018, 2020

Stratified shock: a toy model

For a fixed SED!

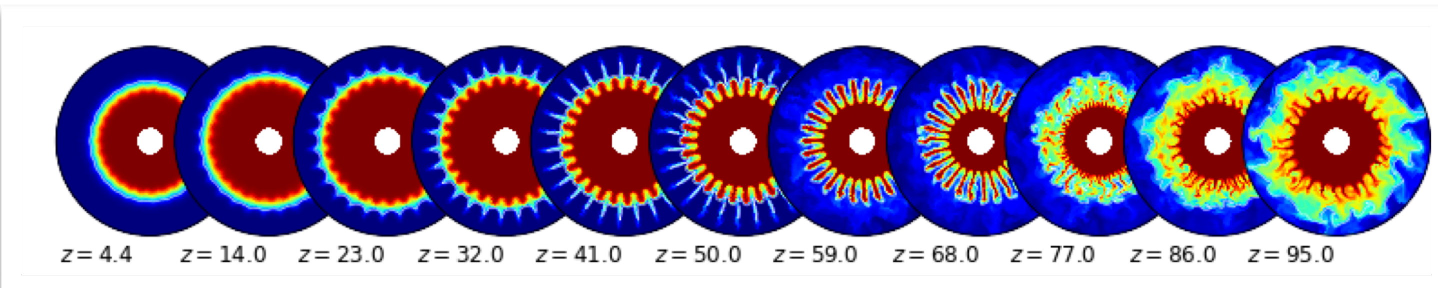


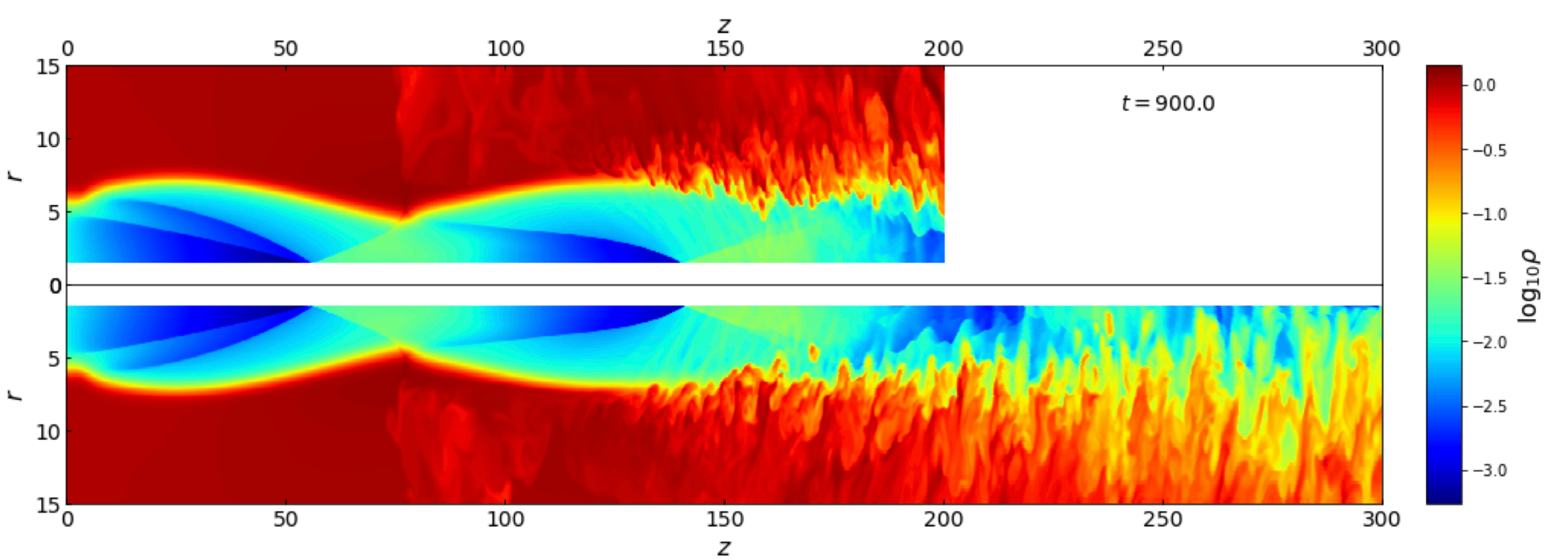
Dependence on the observing angle

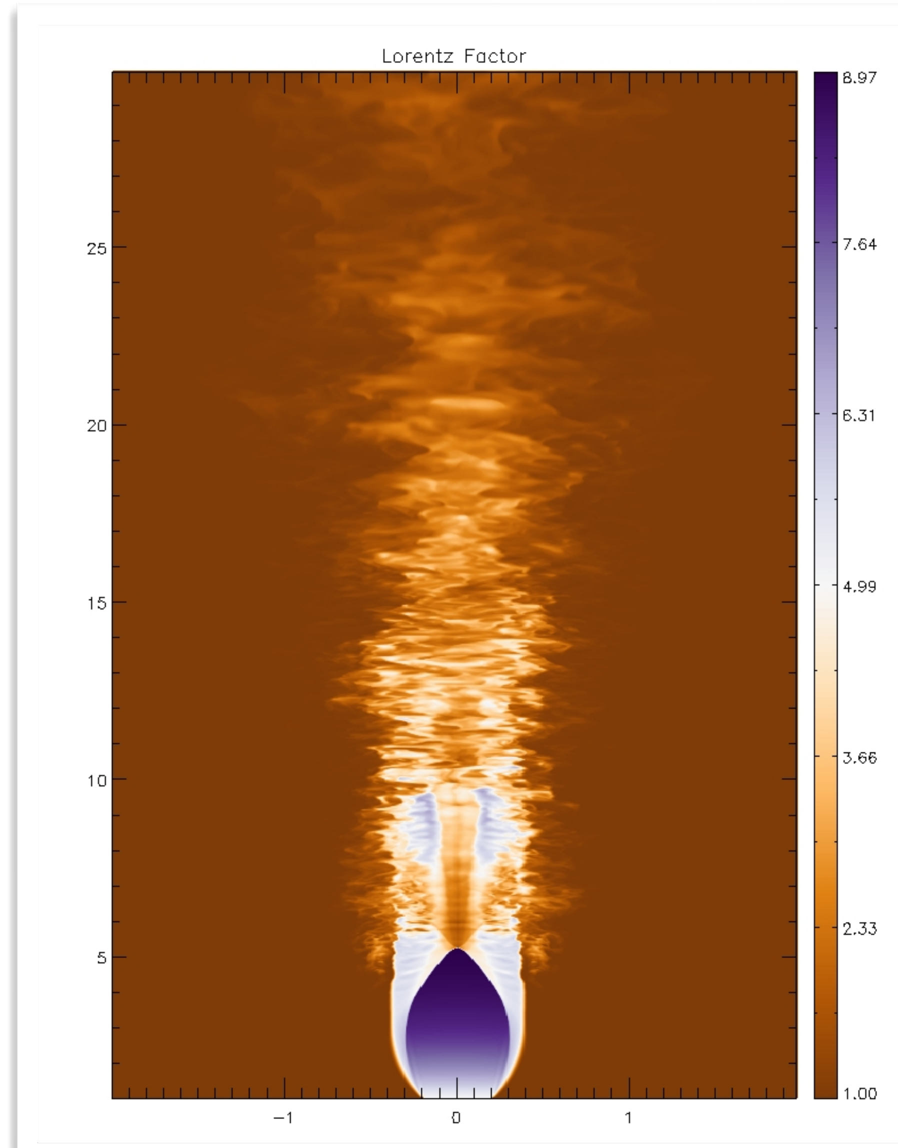
Tavecchio in prep.

Instabilities

HD jet







Costa et al. in prep

Rayleigh-Taylor/centrifugal +
Richtmyer-Meskov instabilities

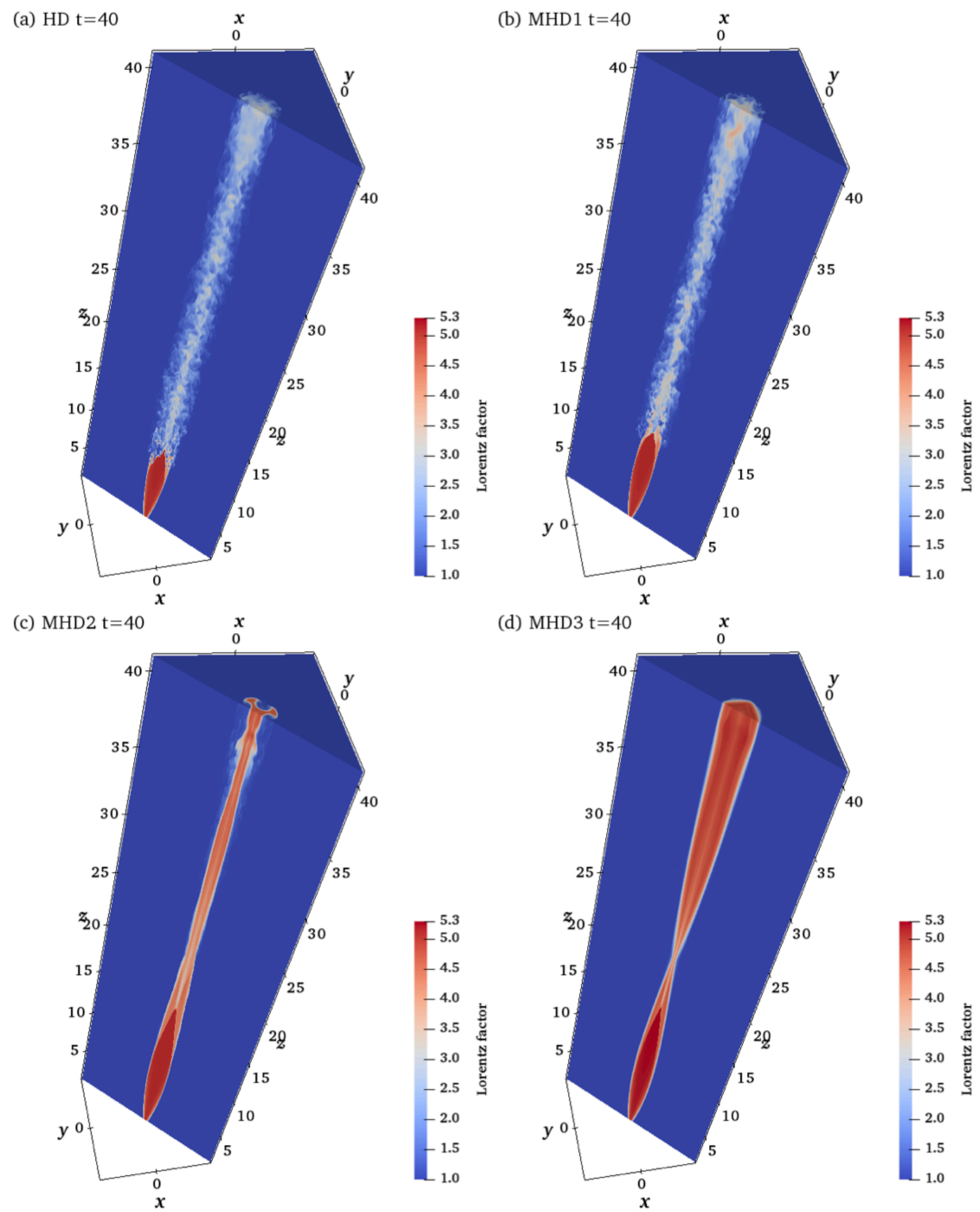
Matsumoto et al. 2017, 2021
Komissarov & Gougouliotos 2018
Abolmasov & Bromberg 2023

Instabilities

Low magn.

MHD jet

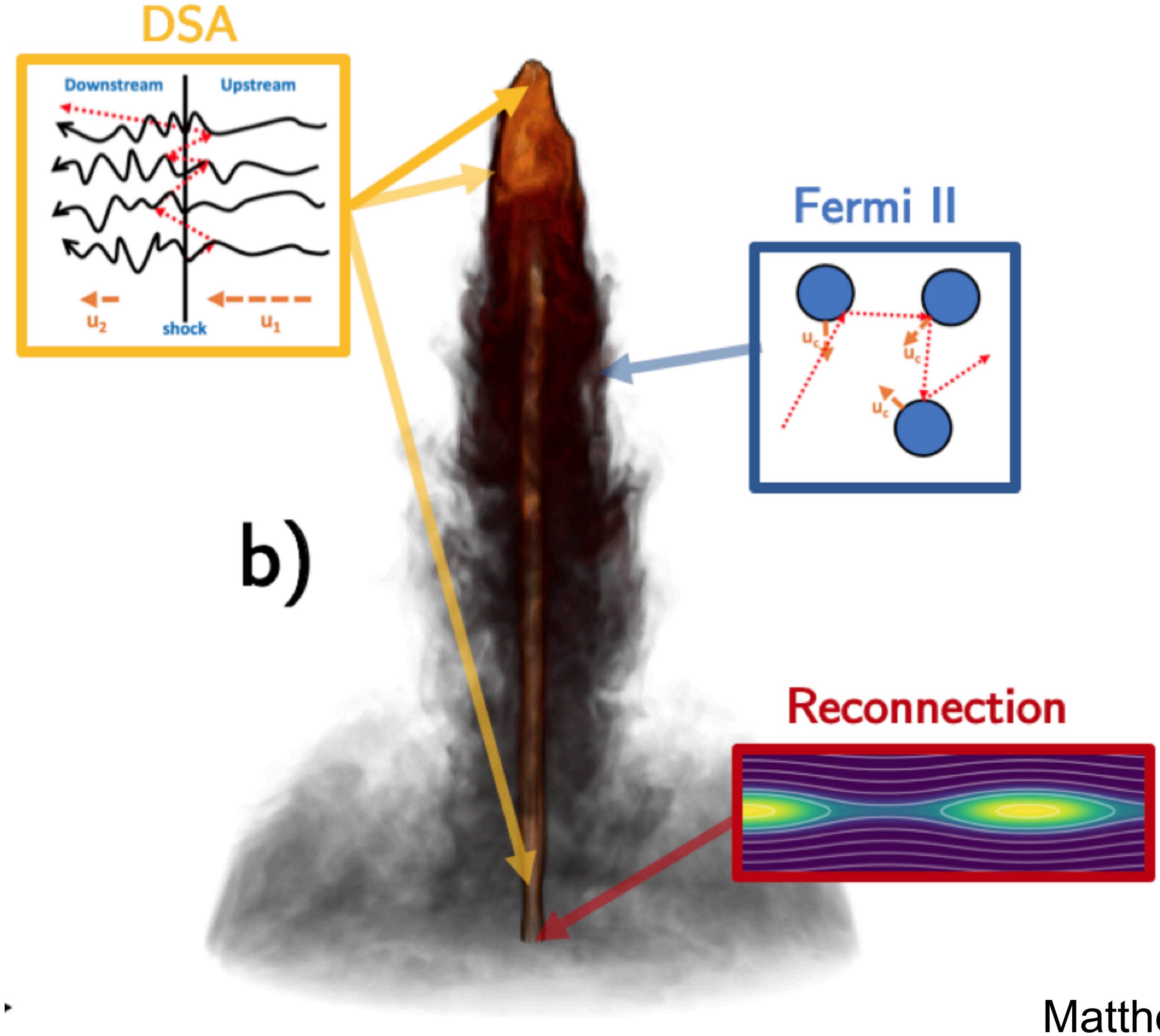
Sufficiently large B field can stabilize the jet



High magn.

Matsumoto et al. 2021

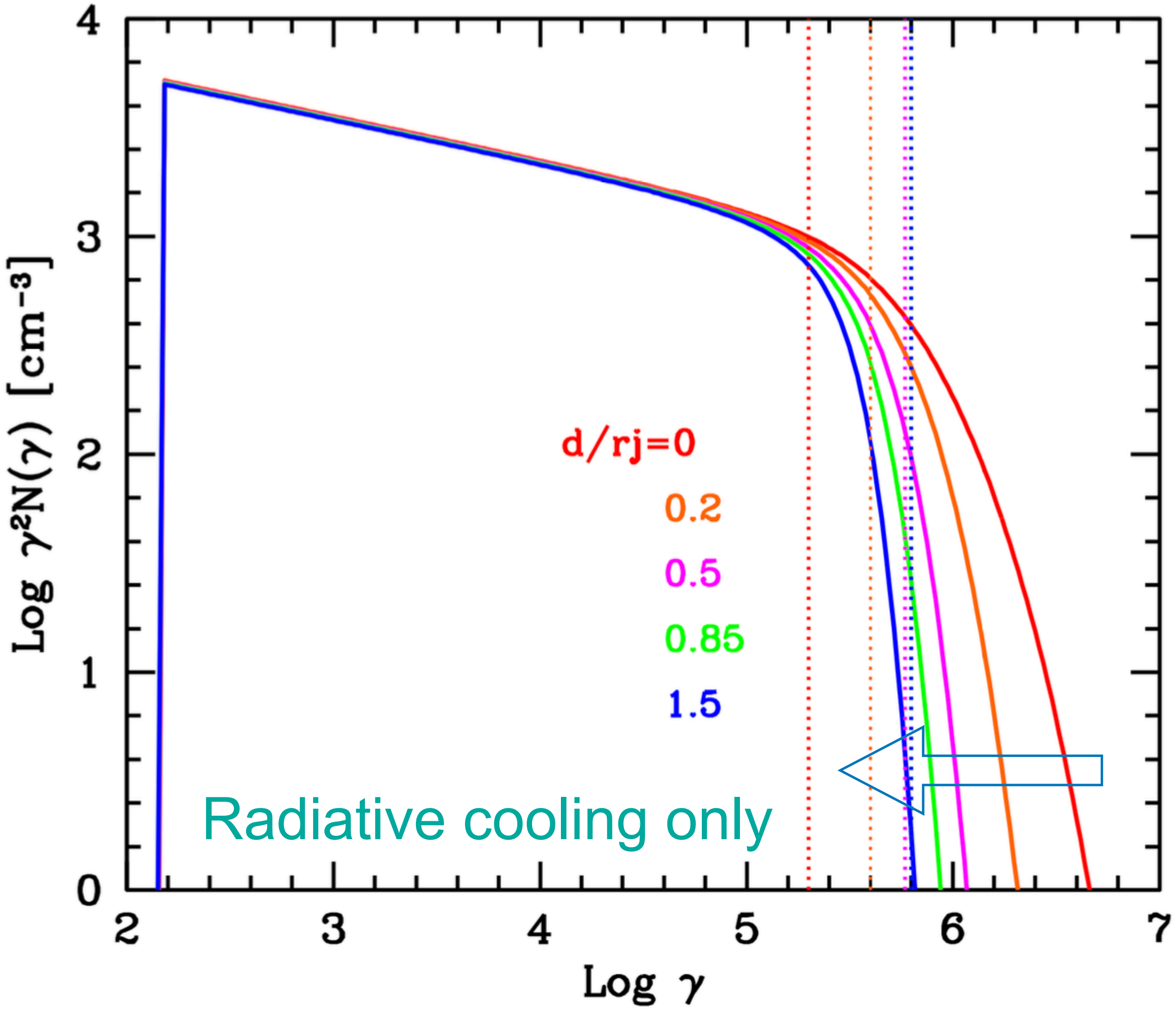
Particle acceleration: many places, several processes



Matthews et al. 2020

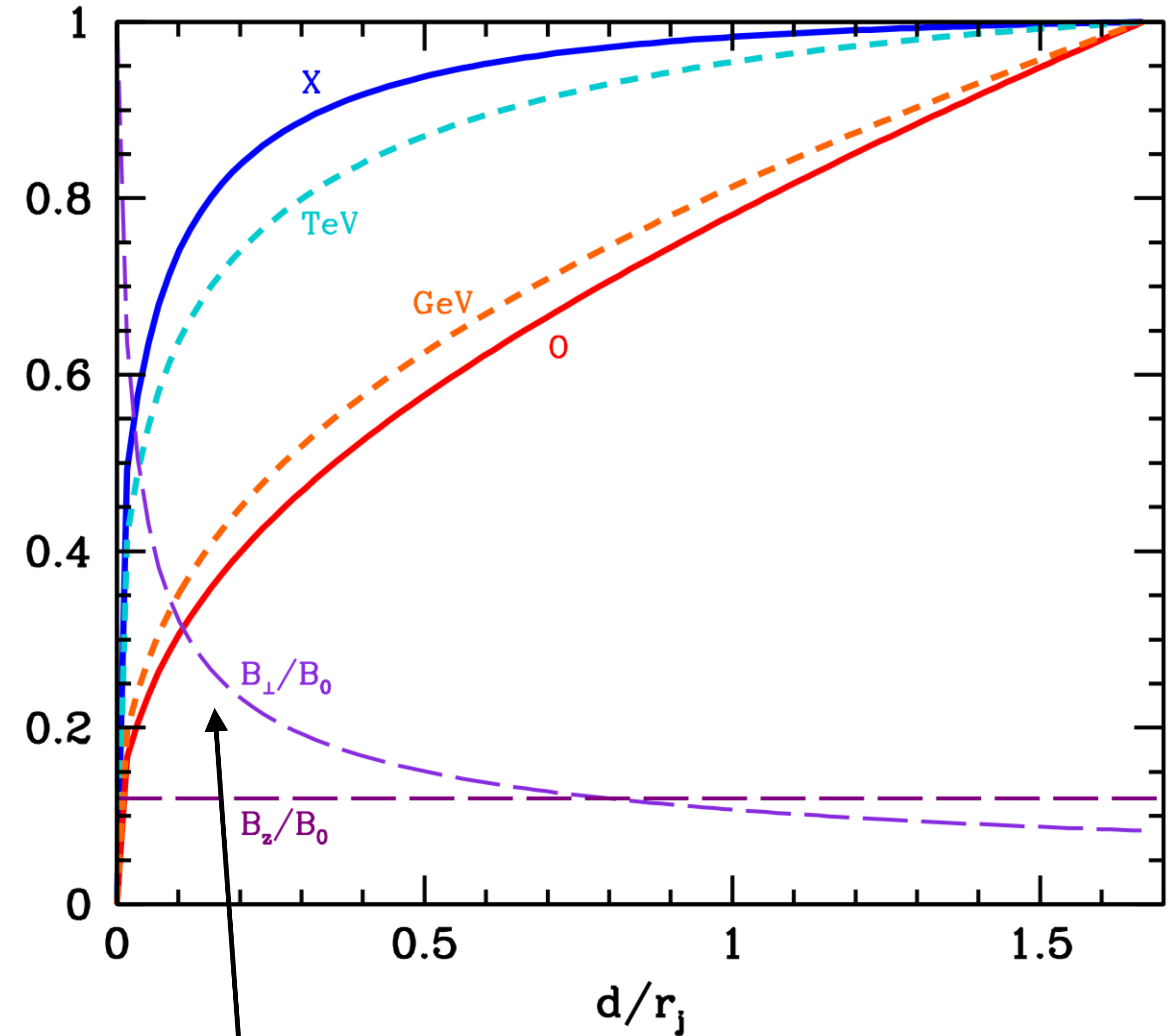
Stratified shock: a toy model

Electron distribution at different distances



Tavecchio in prep.

Emission profiles



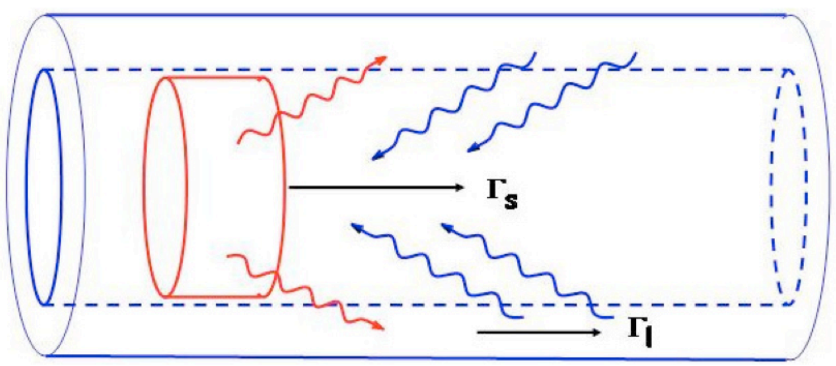
$$B_\perp(d) = B_{\perp,0}\left[1+\frac{d}{\lambda}\right]^{-m}$$

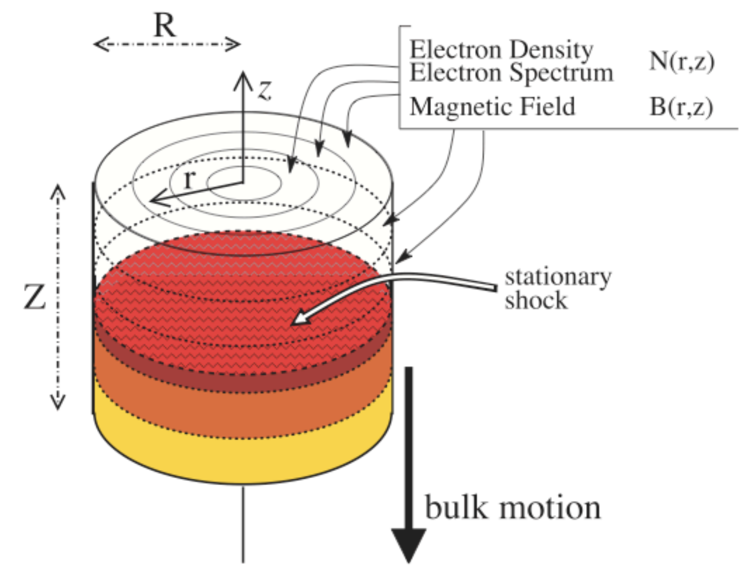
Beyond one-zone

An incomplete list ...

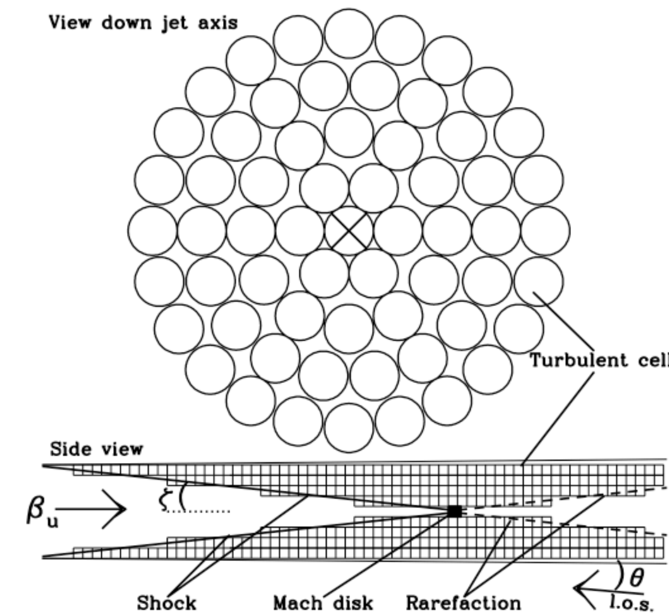
Kinetic

Ghisellini, FT & Chiaberge 2005



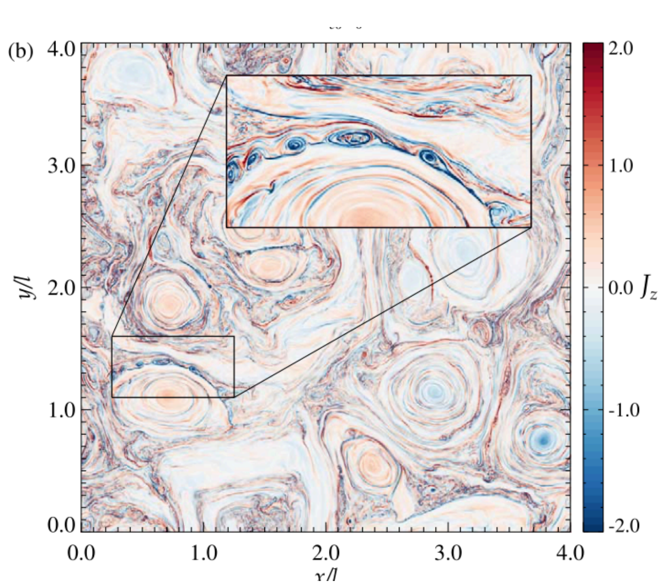


Chen et al. 2011

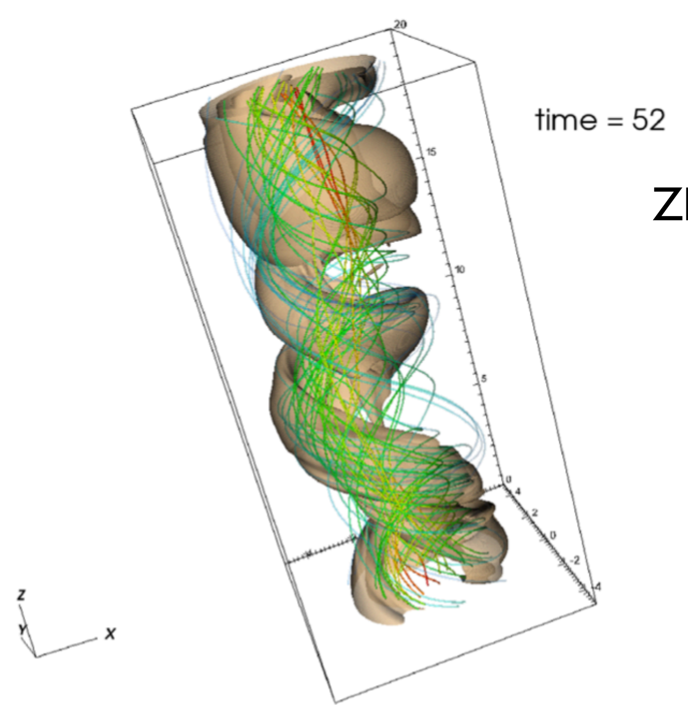


Marscher 2014

Magnetic

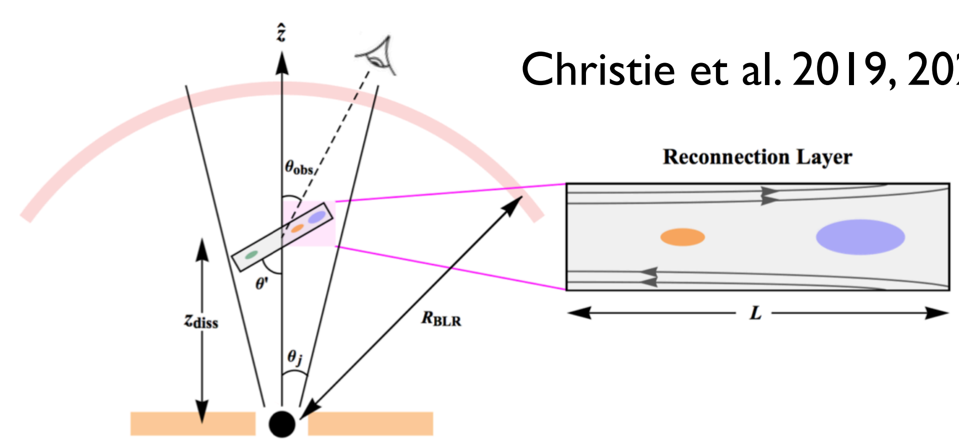


Comisso, Sobacchi et al. 2020



Zhang et al. 2018, Bodo et al. 2020

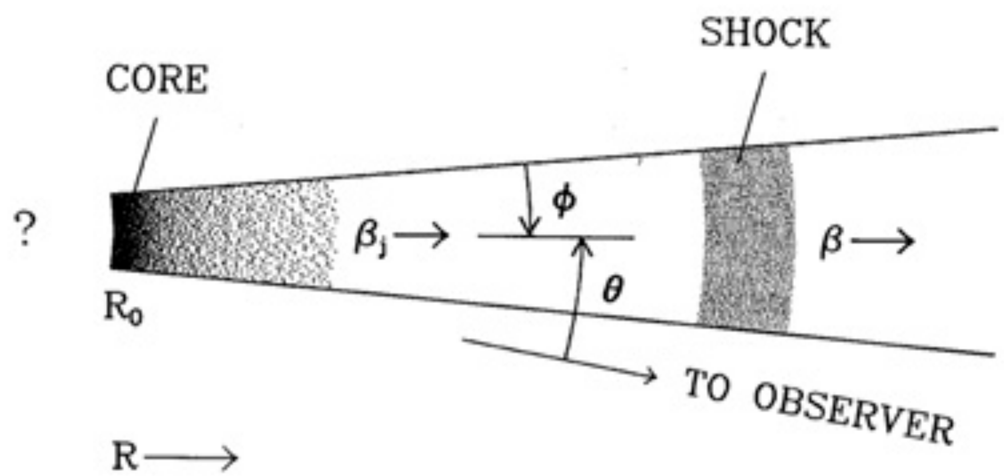
Christie et al. 2019, 2020



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 <u>normal incidence</u>



Traveling relativistic shock

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

in 1 day (observed)

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

→ <u>oblique</u> standing shock?

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