Fermi acceleration in relativistic outflows

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Fermi acceleration in relativistic outflows

Outline:

1. General remarks
2. Fermi acceleration at relativistic shock waves
3. Fermi acceleration in turbulence (+shear)

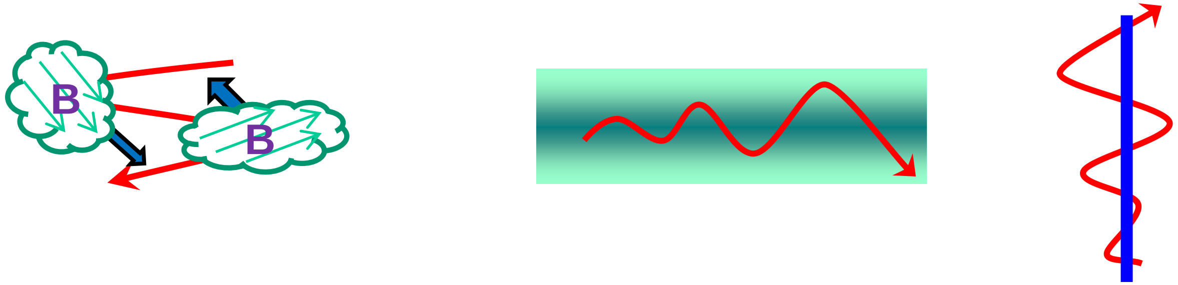
Microphysics of particle acceleration in the high-energy Universe

→ Lorentz force: $\frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right)$ … what is the origin of ***E***?

1. Acceleration à la Fermi: **highly conducting plasma…**

→ large scale physics (↔ very high energies?): corresponds to ideal Ohm's law $\boldsymbol{E} = -\boldsymbol{v}_p \times \boldsymbol{B}/c$…

→ **Fermi-type scenarios: magnetized turbulence,** **shear flows,** **shock waves**



2. "Linear" accelerators: **non-MHD flows:** $\exists\, \boldsymbol{E}_{\parallel}$

→ acceleration can proceed unbounded along **E** (or at least $\mathbf{E}_{\parallel}$)…

→ **gaps in magnetospheres, reconnection**

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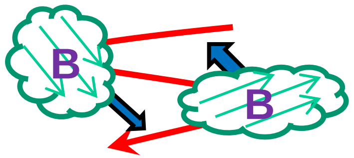
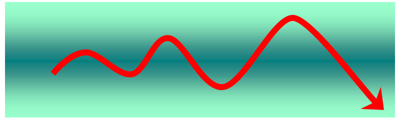
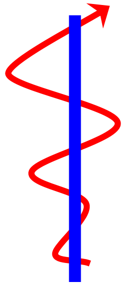






→ acceleration timescale $t_{\mathrm{acc}} \propto 1/\beta_s^2$ (β_s = velocity/c of accelerating agents)

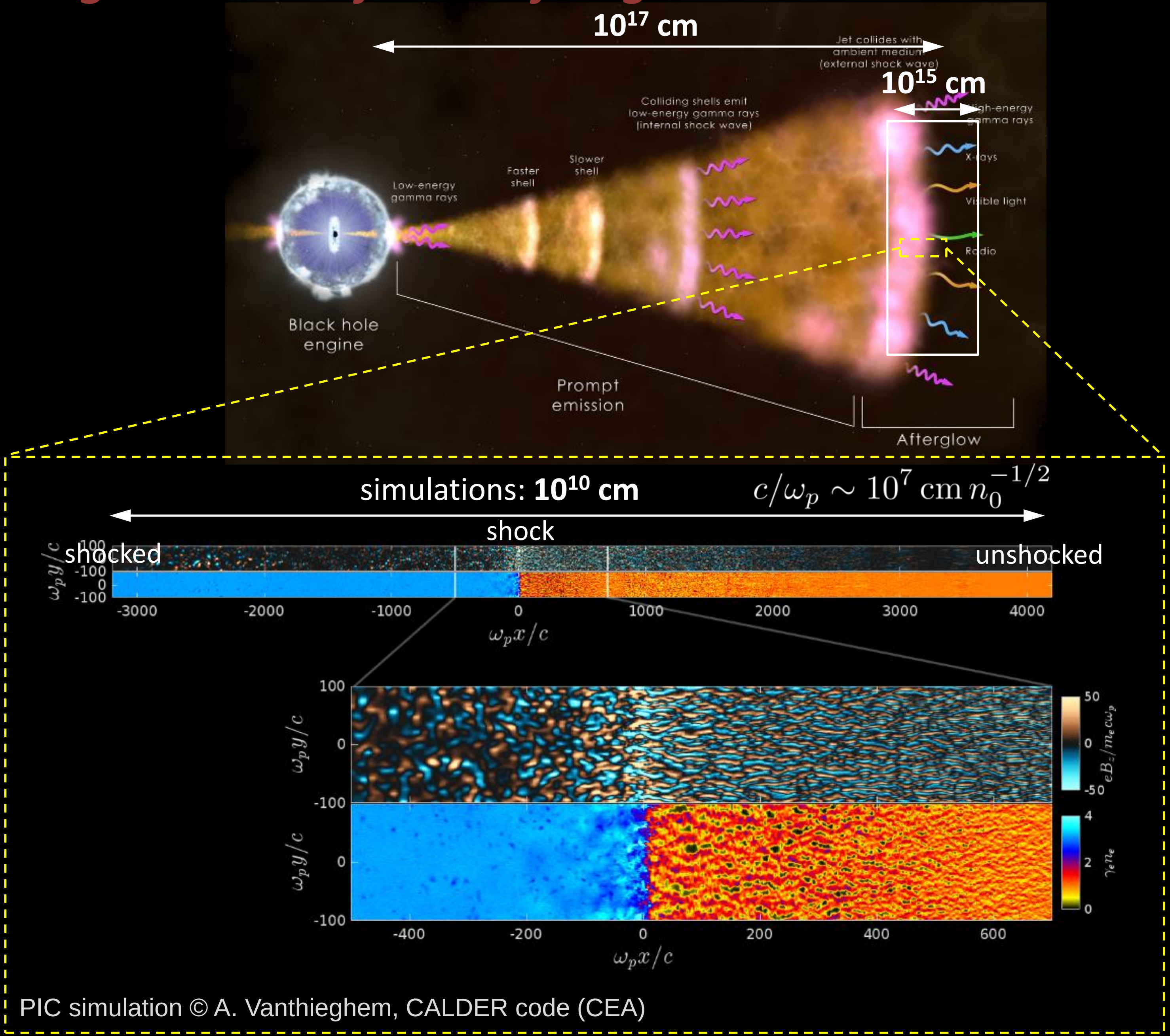
⇒ extreme plasma physics: relativistic + collisionless plasmas, highly magnetized etc.

→ scattering is essential to explore *E* fields through cross-*B* transport: **turbulence**!

⇒ a non-linear, multi-scale challenge in realistic conditions…

→ significant progress from particle-in-cell (PIC) numerical simulations… BUT: probe tiny length/time scales!

Length scales of GRB afterglows



PIC simulation © A. Vanthieghem, CALDER code (CEA)

... afterglow: SSC radiation from electrons accelerated in a self-generated electromagnetic turbulence...

... **a huge gap in scales** $\gtrsim \mathbf{10^5}$:

$L_{\mathrm{radiation}}$	$\gg$	$L_{\mathrm{acceleration}}$
macrophysics (~ source)		microphysics (~ shock width)

... macro to micro: parameterize physics of acceleration and derive constraints on the parameters from observations, e.g.

E: energy of the blast
n: density of circumburst medium

ϵ_e: energy fraction of suprathermal electrons
ϵ_B: energy fraction of magnetized turbulence

... micro to macro: model acceleration from ab-initio principles, using e.g. PIC numerical experiments, and derive physical parameters for phenomenology...

but, **PIC limited to small scales: theory needed!**

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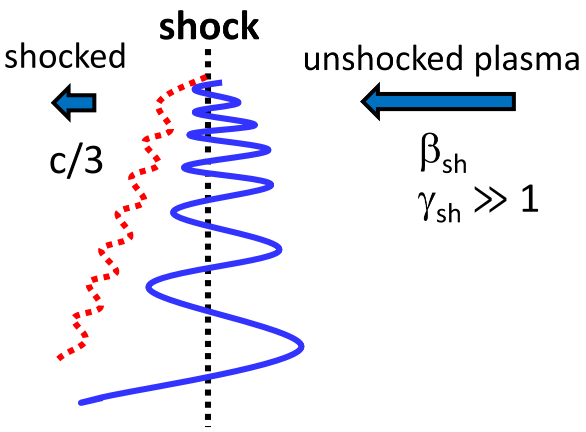
Particle acceleration at relativistic shock fronts

→ Acceleration … or not?

… acceleration = particle scatters around the shock[1] (——): $\Delta p/p \sim 1$

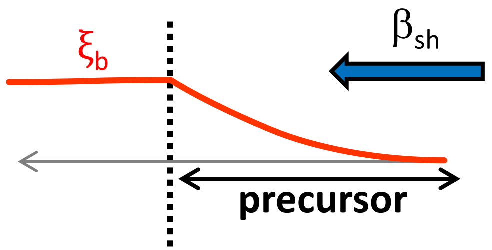
… w/ background field, generic superluminal nature implies escape (⋯⋯),
⇒ advection away from shock, no acceleration

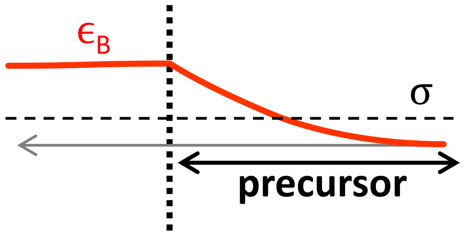


→ Way out to acceleration[2,3]: **low ambient magnetization** $\sigma \equiv \frac{\text{magnetic energy density}}{\text{plasma energy density}}$

… at low magnetization: scattering wins over advection

… at low magnetization: precursor large enough to allow growth of microinstabilities through the mixing of accelerated particles + unshocked plasma… [e.g. Weibel]



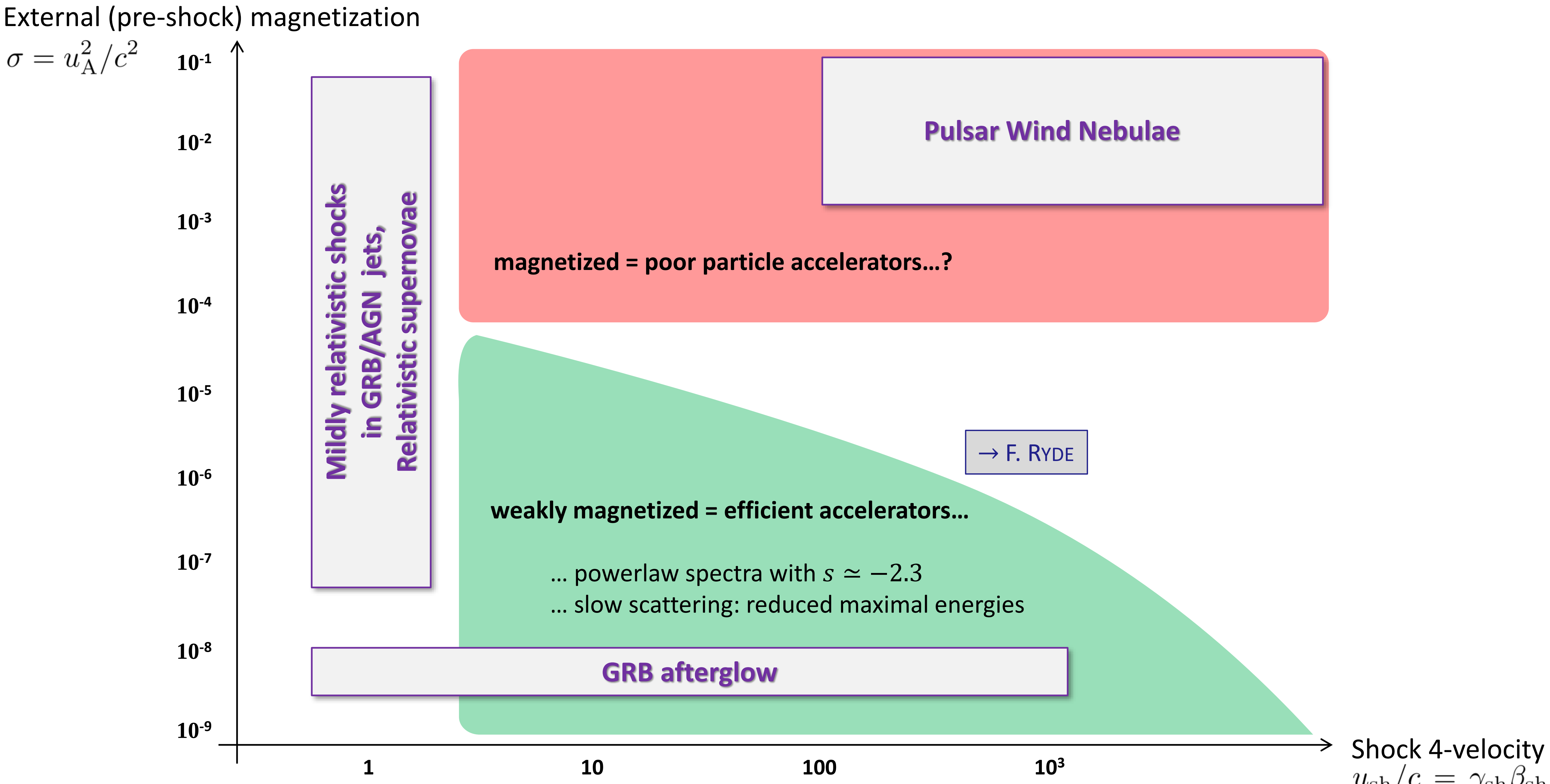


⇒ particle acceleration at relativistic shock waves of low magnetization ($\lesssim 10^{-4}$)

… in agreement with PIC simulations (Spitkovsky 08, Martins+09, Keshet+09, Sironi+11, 13, Sironi+15)

Refs.: 1. Begelman+Kirk90, Gallant+Achterberg99, Achterberg+01 2. ML+06, Niemiec+06, Pelletier+09, …
3. Milosavljevic+Nakar06, ML+Pelletier 10,11, Plotnikov+13, ML+14

The high-energy astrophysical shock landscape



magnetized = poor particle accelerators…?

weakly magnetized = efficient accelerators…

… powerlaw spectra with $s \simeq -2.3$

… slow scattering: reduced maximal energies

Refs: e.g. ML+ 06, Niemiec+ 06, Kato 07, Spitkovsky 08, Keshet+ 09, Pelletier+09, ML+Pelletier 10, Sironi+Spitkovsky 11,13, …

Ab-initio model of weakly magnetized, relativistic collisionless shocks

→ Key features of weakly magnetized ($\sigma \ll 10^{-5}$), relativistic shock waves:

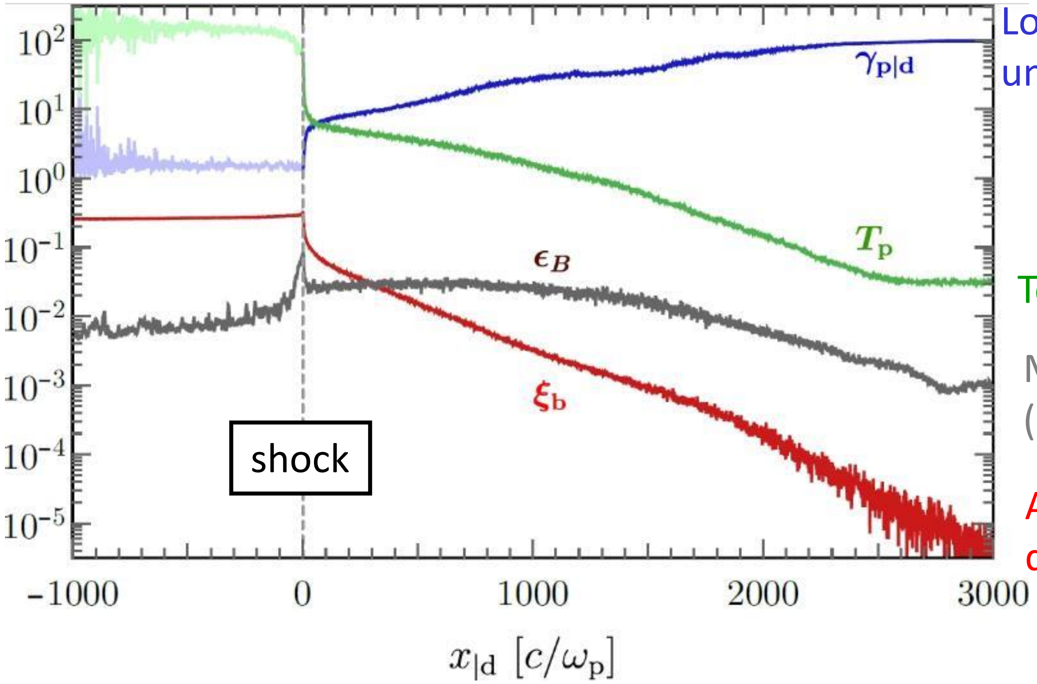
1. the shock builds its own magnetization (ϵ_B) through plasma micro-instabilities generated by mixing of accelerated particles (fraction e. density ξ_b) and unshocked plasma in shock precursor…

2. microturbulence mediates shock physics and sustains particle acceleration

→ Shock profile from a 2D PIC numerical experiment:

shock precursor: where accelerated particles and bckgd plasma meet

downstream
(shocked plasma)



Lorentz factor of unshocked plasma

Temp. of unshocked plasma

Magnetic energy density (microturbulence)

Accelerated particle energy density

upstream
(unshocked plasma)
←

Refs.: Moiseev+Sagdeev 63 … Medevedev+Loeb99, …, ML+19a, b, c, Pelletier+19, Vanthieghem+22 … see Vanthieghem+20 for a review

From ab-initio shock physics toward phenomenology of GRB afterglows

→ Predictions/postdictions/interpretations for energy fraction parameters[1]:

$\boldsymbol{\epsilon}_{\mathbf{accelerated}} \simeq \boldsymbol{\xi_b} \sim \mathbf{0.1} - \mathbf{0.3}$ at injection[2]: blast dissipates 10% of energy into accelerated particles!

(condition to form shock: sufficient pressure in accelerated particles!)

$\boldsymbol{\epsilon_e} \simeq \mathbf{0.1}$ due to efficient electron heating[3]… relativistic shock waves = highly efficient radiation engines

(electron heating in shocks through Joule process: $\gamma_{e\,\mathrm{min}} \sim \epsilon_e \gamma_{\mathrm{sh}} m_p/m_e$!)

Refs.: 1. Vanthieghem+20 2. ML+19 3. Spitkovsky 08, Kumar+15, Vanthieghem+22

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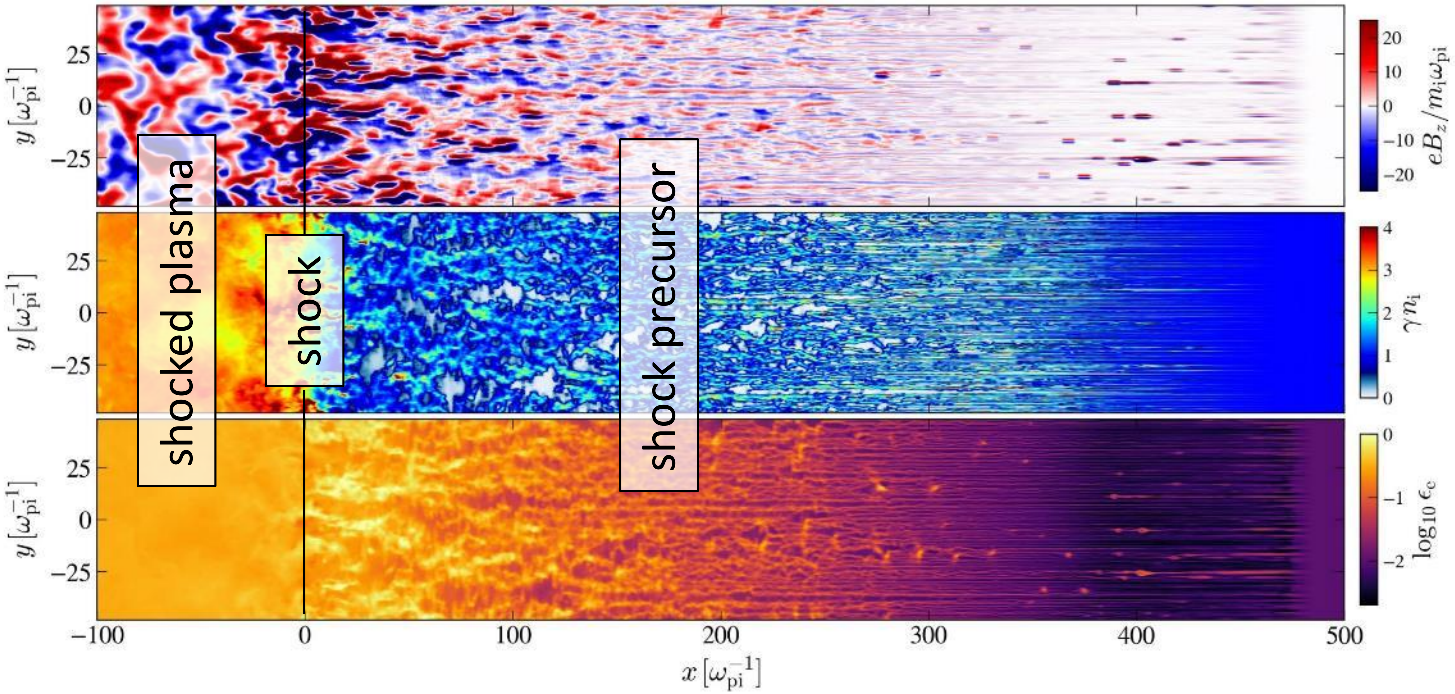

… w/o e heating:

$$\gamma_{e\,\rm min} \sim \gamma_{\rm sh}$$

… but, heating efficient:

$$\gamma_{e\,\rm min} \sim \epsilon_e \gamma_{\rm sh} m_p/m_e$$

… note: relevant to other classes of objects, e.g. blazars (Zech+ML 21)

Refs.: 1. Vanthieghem+20 2. ML+19 3. Spitkovsky 08, Kumar+15, Vanthieghem+22

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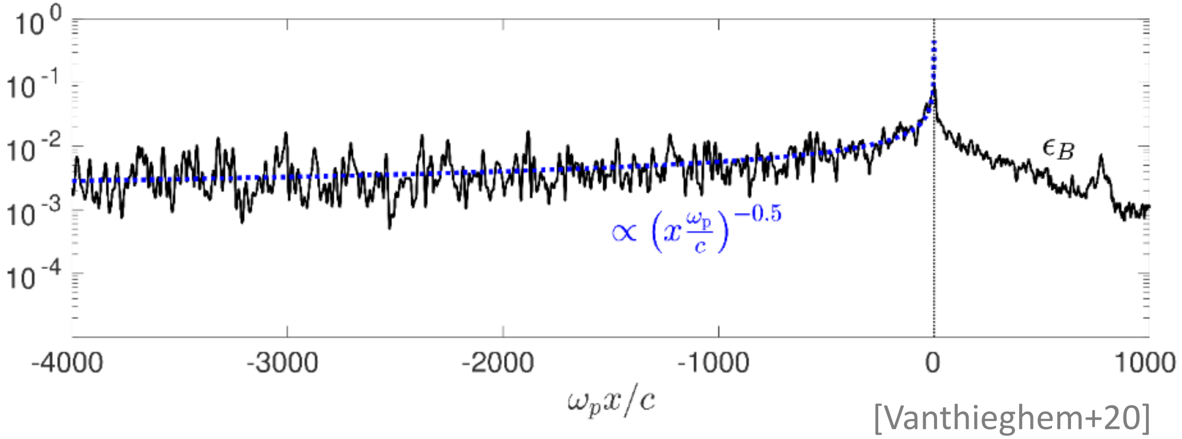
$\boldsymbol{\epsilon_B} \simeq \mathbf{0.01}$ in precursor, $\simeq 0.1$ at shock, but much less downstream due to collisionless damping of microturbulence…



[Vanthieghem+20]

$\epsilon_B \ll \epsilon_e$ in radiation zone $\omega_p x/c \sim 10^8$
… expect Compton dominance[4]

… particles radiate in decaying turbulence: interesting signatures on GRB afterglows[5]

Refs.: 1. Vanthieghem+20 2. ML+19 3. Spitkovsky 08, Kumar+15, Vanthieghem+22 4. Sari+Esin01 etc.
5. Rossi+Rees03, Derishev 07, M.L. 13, 15

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(saturation of instability leads to 0.01 value… much less in radiation region)

powerlaw spectrum index[4] $\boldsymbol{p} \sim \mathbf{2.3}$

maximal electron energy[5]: $\boldsymbol{E_{e,max}} \sim \mathbf{1}$ **TeV** (scattering in microturbulence … not Bohm regime!)

… maximal synchrotron photon energy: $\boldsymbol{\epsilon_{\gamma,max}} \sim \mathbf{1}$ **GeV** at ∼100sec, then decreases in time

maximal ion energy: $\boldsymbol{E_{p,max}} \sim \mathbf{1} - \mathbf{10}$ **PeV** (scattering in microturbulence … not Bohm regime!)

Refs.: 1. Vanthieghem+20 2. ML+19 3. Spitkovsky 08, Kumar+15, Vanthieghem+22 4. Kirk+00 … Keshet+Waxman 05
5. Kirk+Reville 09, Eichler+Pohl 11, Plotnikov+13, ML+19

Observations: a first gamma-ray burst seen at TeV energies!

GRB190114C: an afterglow seen up to TeV energies by the MAGIC Collaboration

… parameter inference through modeling gives:

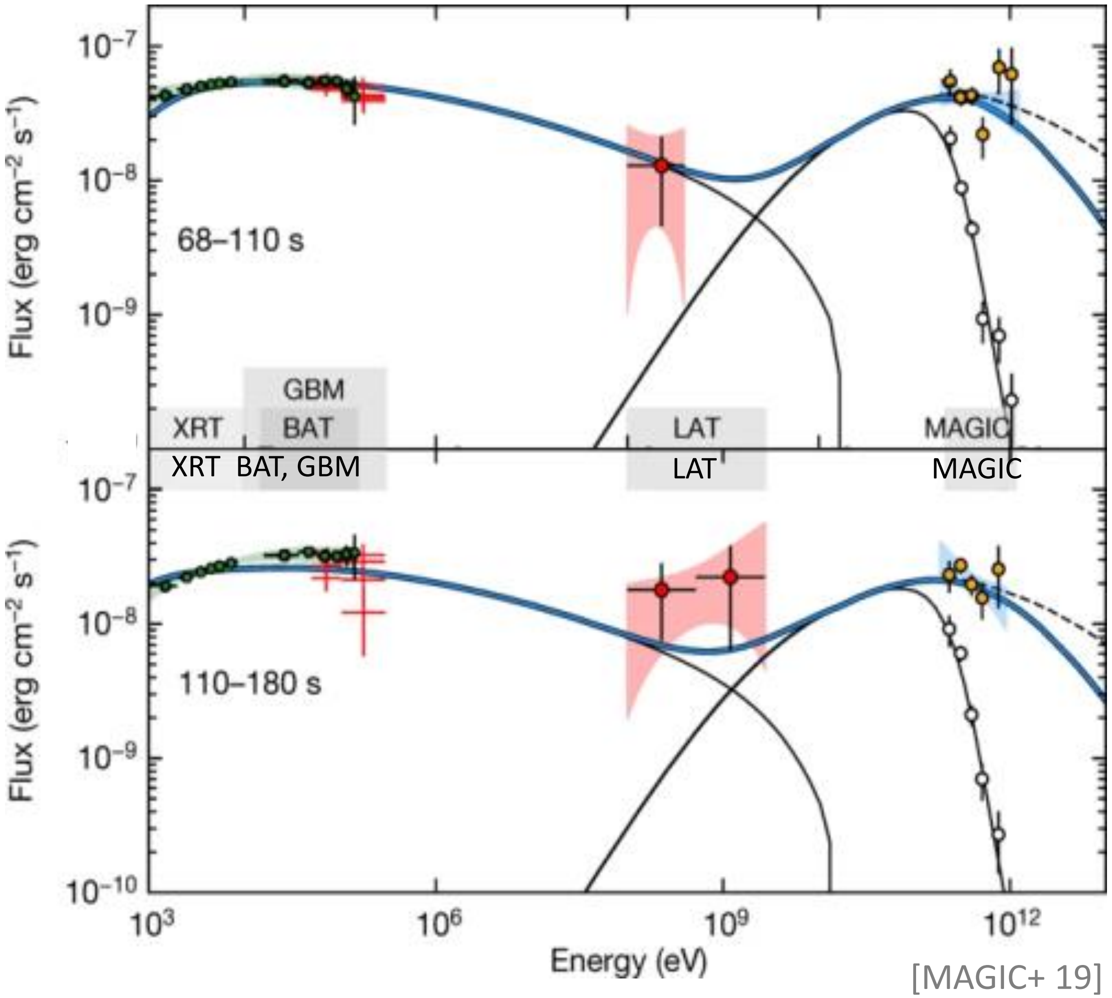
$$p \simeq 2.3,\ \ \epsilon_B \lesssim 10^{-4},\ \ \epsilon_e \sim 0.1,$$

… note: SED (+evolution) suggests a synchrotron cut-off at GeV at early times, significant Compton emission in accord with low ϵ_B…

… much to be learned on afterglow physics from SSC component![1]

→ J. GRANOT

Note: other GRBs seen at TeV, by H.E.S.S. and MAGIC… to be continued!



[MAGIC+ 19]

Refs.: [1] e.g., Nava 21, Gill+Granot 22

Some key open questions...

→ Evolution of the magnetic on long timescales, far from the shock:

… expect powerlaw decay from damping of turbulence with generic value $\epsilon_B \sim 10^{-5}$? Amplification by large-scale instability modes (e.g., R-T at contact discontinuity[1], R-M at shock[2], …)? Pollution by magnetized ejecta?

→ Evolution of instabilities (turbulence) on long timescales:

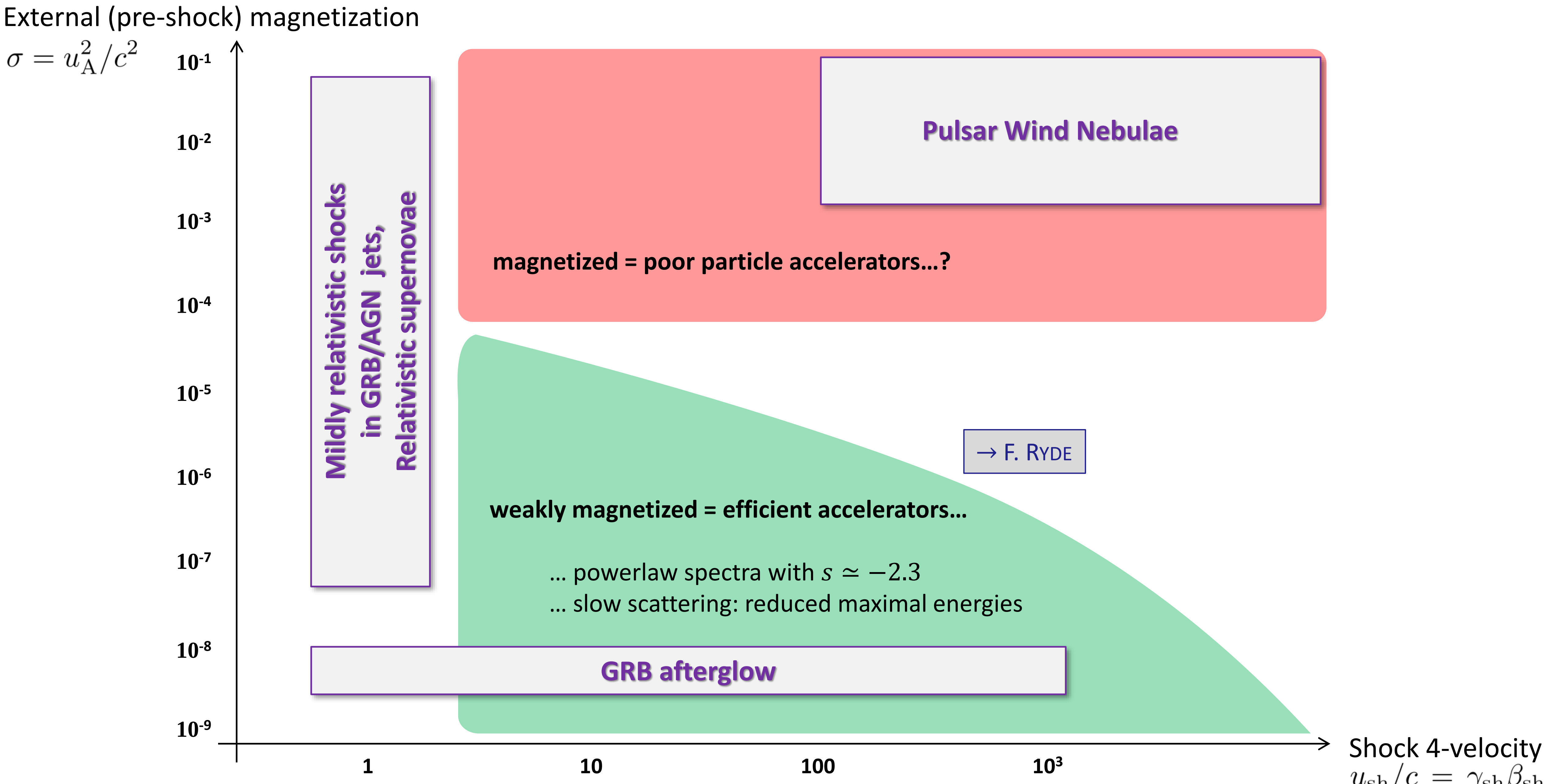
… evolution of the generic scale toward larger values[3], with positive impact on maximum energies (enhanced scattering)?

→ Radiative feedback … photon-photon pair creation upstream of the shock:

… either from prompt photons[4], or afterglow photons[5]?
… pair loading can change dramatically the shock structure and acceleration physics[5]!

Refs.: 1. Levinson 10, Duffell+MacFadyen14 2. Inoue+11, Tomita+22 3. Medvedev 05, Ruyer+15, Naseri+18, Peterson+21,22, Groselj+21, Bresci+22 4. e.g. Beloborodov 05, Hascoet+14 5. Derishev+Piran 16, 21, Groselj+22

The high-energy astrophysical shock landscape



External (pre-shock) magnetization

$\sigma = u_{\rm A}^2/c^2$

Pulsar Wind Nebulae

magnetized = poor particle accelerators…?

Mildly relativistic shocks in GRB/AGN jets, Relativistic supernovae

→ F. RYDE

weakly magnetized = efficient accelerators…

… powerlaw spectra with $s \simeq -2.3$
… slow scattering: reduced maximal energies

GRB afterglow

Shock 4-velocity
$u_{\rm sh}/c\,=\,\gamma_{\rm sh}\beta_{\rm sh}$

Refs: e.g. ML+ 06, Niemiec+ 06, Kato 07, Spitkovsky 08, Keshet+ 09, Pelletier+09, ML+Pelletier 10, Sironi+Spitkovsky 11,13, Sironi+15,…

Going beyond the standard shock model … to find acceleration?

→ Including radiation backgrounds:

e.g. « converter » mechanism, Fermi-type acceleration through charged – neutral conversions by photo-interactions… (Derishev+ 03, Derishev+Piran16)

→ Electromagnetic (non-MHD) shocks:

conversion of the pulsar wind into a superluminal e.m. wave, destabilized in the shock precursor… (Arka+ 12, Amano+Kirk 13)

→ Including magnetic annihilation (shock+reconnection):

e.g. particle acceleration at the demagnetized termination shock of PWNe through reconnection of the striped wind… (Lyubarsky 03, Sironi +11, Lu+21)

→ Corrugation of the shock front (shock+turbulence):

deformation of the shock front, converting incoming ordered magnetic energy into downstream turbulence… (ML+16, ML 16, Demidem + 18, Bresci+22, Demidem+22)

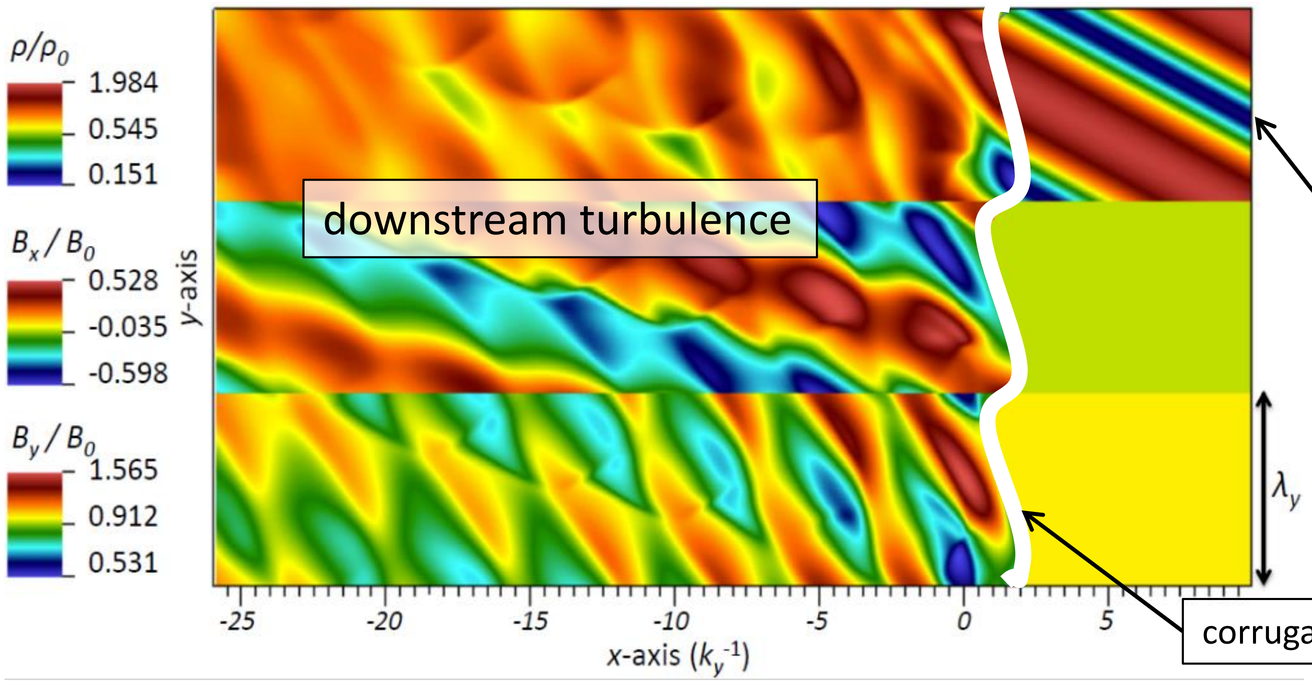
→ Sheared magnetic field configuration (shock+shear):

orbits in a strongly sheared magnetic field (alternate polarity)… (Cerutti+Giacinti 20)

Corrugation of shock waves by external turbulence

→ shock-turbulence interaction:

... at a corrugated shock front, incoming energy is (partly) converted into turbulence, with potentially significant phenomenological consequences for particle acceleration...



density perturbation interacting with relativistic magnetized shock front ... tuned to resonance!
(ML+16, Demidem+18)

corrugated shock front

... shock becomes a dissipative turbulent layer ⇒ dissipation of magnetic energy into particles?

... particles with $r_g > l_c$ are injected in shock acceleration?

... relation to PWNe: pulsar wind may turn turbulent before passing through termination shock?

Zrake 16, ML 16, Zrake+Arons17

(Mildly) relativistic shock interacting with turbulent plasma: simulations

→ PIC simulations:

1. inject plasma moving at $u_\infty \simeq -2\ c$ from RHS
2. drive turbulence in rest frame of plasma
3. plasma reflects off mirror on LHS

… mimics 2 equal counterstreaming plasmas (Spitkovsky 08)

⇒ triggers shock interacting with turbulence

→ in detail:

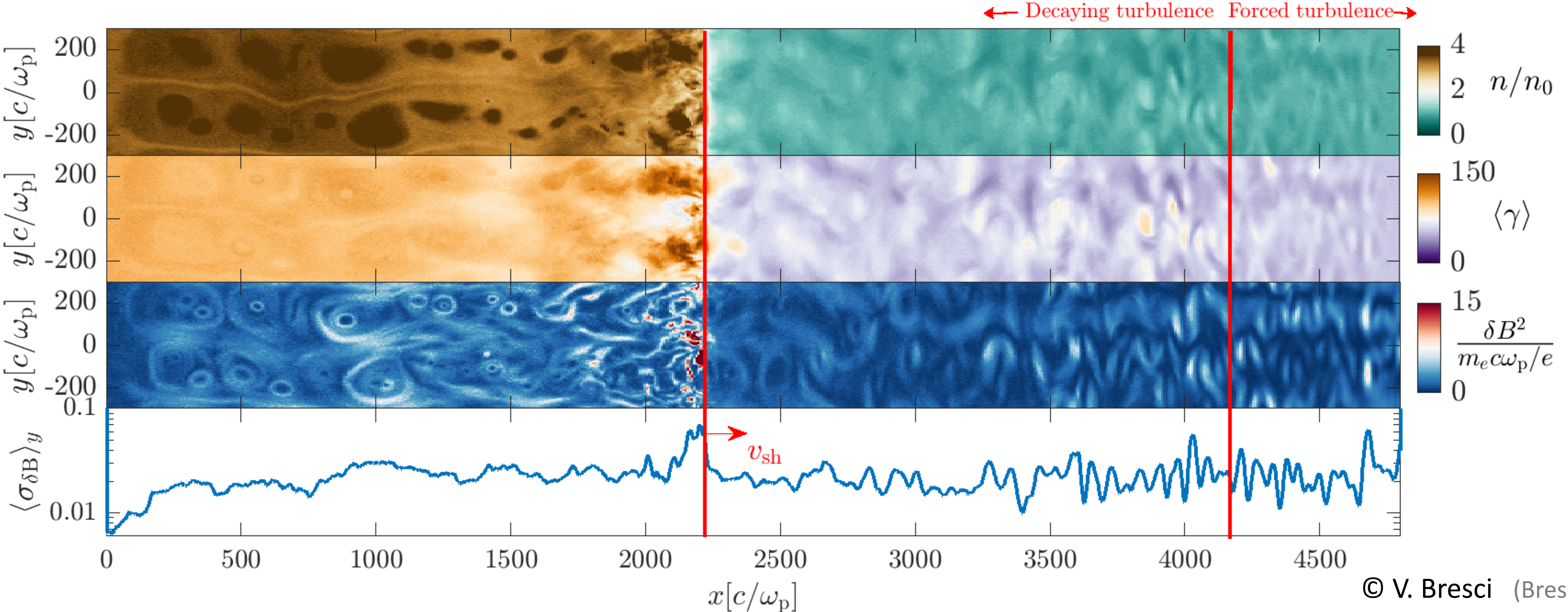
$L_x \times L_y \times T = 4\,800 \times 600 \times 12\,000\ \ c^2/\omega_p^3$

(in cells: 48 000 x 6 000 over 120 000 time steps)

$N_{ppc} = 20$, composition: pairs

$u_\infty \simeq -2c,\ \sigma_{\delta B} \simeq 0.03, \sigma_B \simeq 0.001, \ell_c \simeq 300\ c/\omega_p$

… main parameters: $\sigma_{\delta B}, u_\infty, \ell_c$ (here $\delta B > B$)



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(Mildly) relativistic shock interacting with turbulent plasma: particle acceleration

→ key features:

1. in absence of turbulence (dashed), particle acceleration does not happen: particles are locked on (perpendicular) magnetic field lines and advected away from shock…

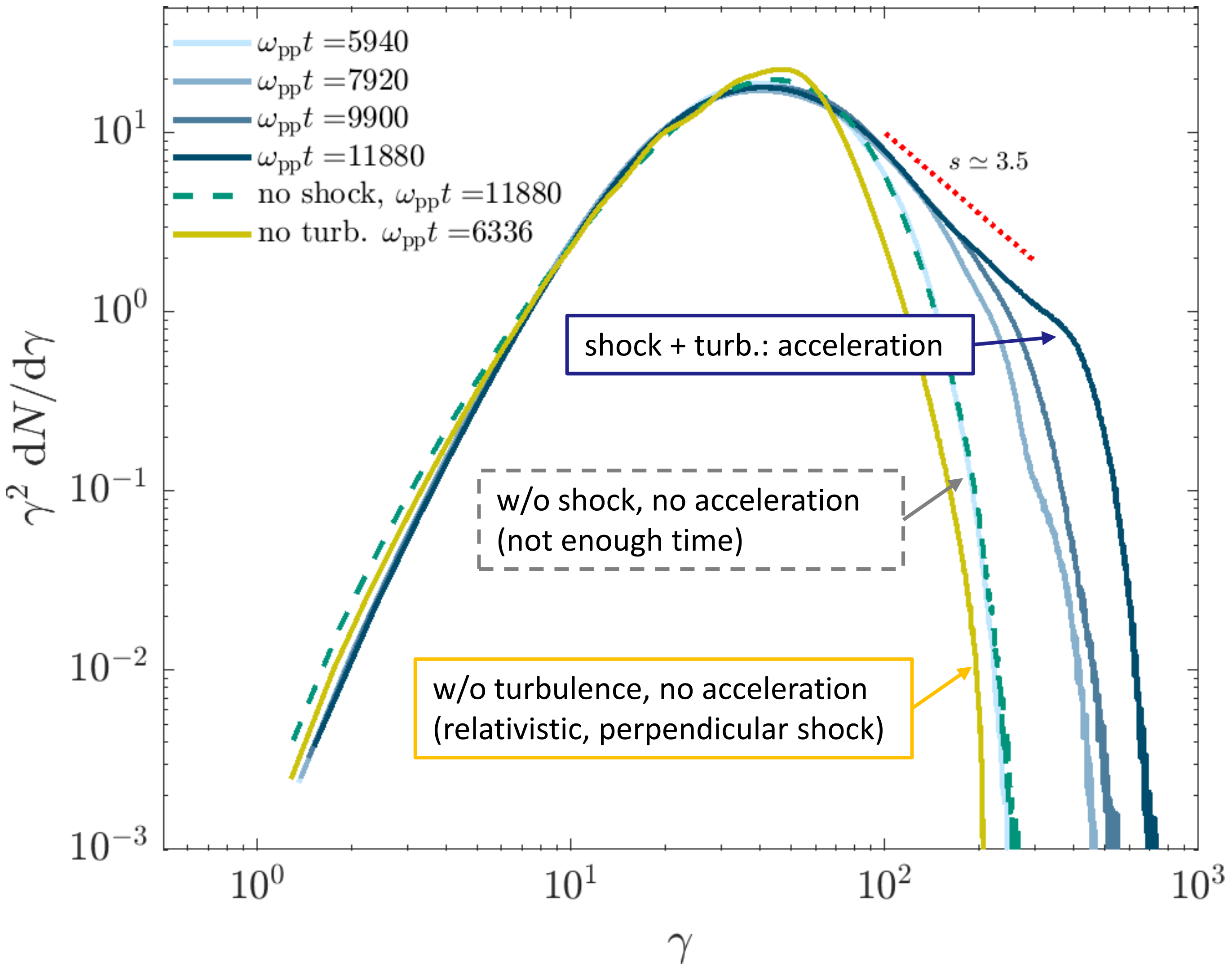
2. in absence of shock, particle acceleration has not taken place in turbulence on simulation timescale: $t_{\rm acc} \sim \ell_c/\sigma_{\delta B} \sim 10^4/\omega_p$

(magnetization: $\sigma_{\delta B} \simeq v_A^2/c^2$)

3. in shock+turbulence configuration: particle acceleration takes place, develops powerlaw with index $s \simeq 3.5$ $(\frac{dN}{dp} \propto p^{-s})$

(shock formation time = 5940 ω_p^{-1})

4. at large magnetizations $\sigma_{\delta B} \gtrsim 0.1$, particle acceleration in pre-shock turbulence takes over…



shock + turb.: acceleration

w/o shock, no acceleration (not enough time)

w/o turbulence, no acceleration (relativistic, perpendicular shock)

© V. Bresci [V. Bresci, ML, L. Gremillet, 22, submitted]

⇒ interesting prospects for particle acceleration in magnetized, relativistic environments… (to be continued)

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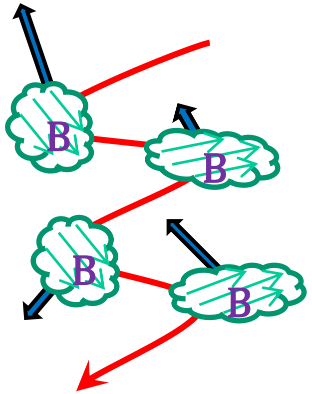
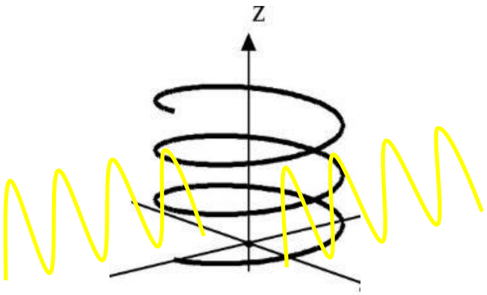
Two pictures for particle acceleration in magnetized turbulence

→ Original Fermi acceleration[1]: scattering off moving magnetic scatterers, with **E=0** in local rest frame



isotropic + elastic scattering in scattering center rest frame
⇒ $\Delta p > 0$ for head-on, $\Delta p < 0$ tail-on

→ Quasilinear theory: transport in a bath of linear waves (e.g. Alfvén, magnetosonic)… energy gain through resonant interactions[2]



… interactions dominated by resonances, e.g. $k\, r_g \sim 1$

→ in phenomenology… Fokker-Planck equation:

$$\frac{\partial}{\partial t} f(p,t) = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\, D_{pp}\, \frac{\partial}{\partial p} f(p,t)\right]$$

→ issues:

1. how to calculate the diffusion coefficient D_{pp} in realistic environments + strong turbulence?
2. solution to Fokker-Planck with $D_{pp} \propto p^2$ does not reproduce observed spectra from PIC simulations…
3. relativistic regime?

Refs: 1. Fermi 49, 54. 2. e.g. Kennel + Engelmann 66, … Jokipii et al., … , R. Schlickeiser 02 + refs;

Particle acceleration in magnetized turbulence

… HPC kinetic simulations have started to probe particle acceleration in large-scale turbulence[1]…

→ L. COMISSO

→ **Key features:** (here: assume pair plasma)

… particle acceleration fast in relativistic regime $\sigma \gtrsim 1$ ($v_A \sim c$)

$$t_{\rm acc} \sim \frac{c\,\ell_c}{\langle \delta u^2 \rangle} \sim \frac{\ell_c}{\sigma c}$$

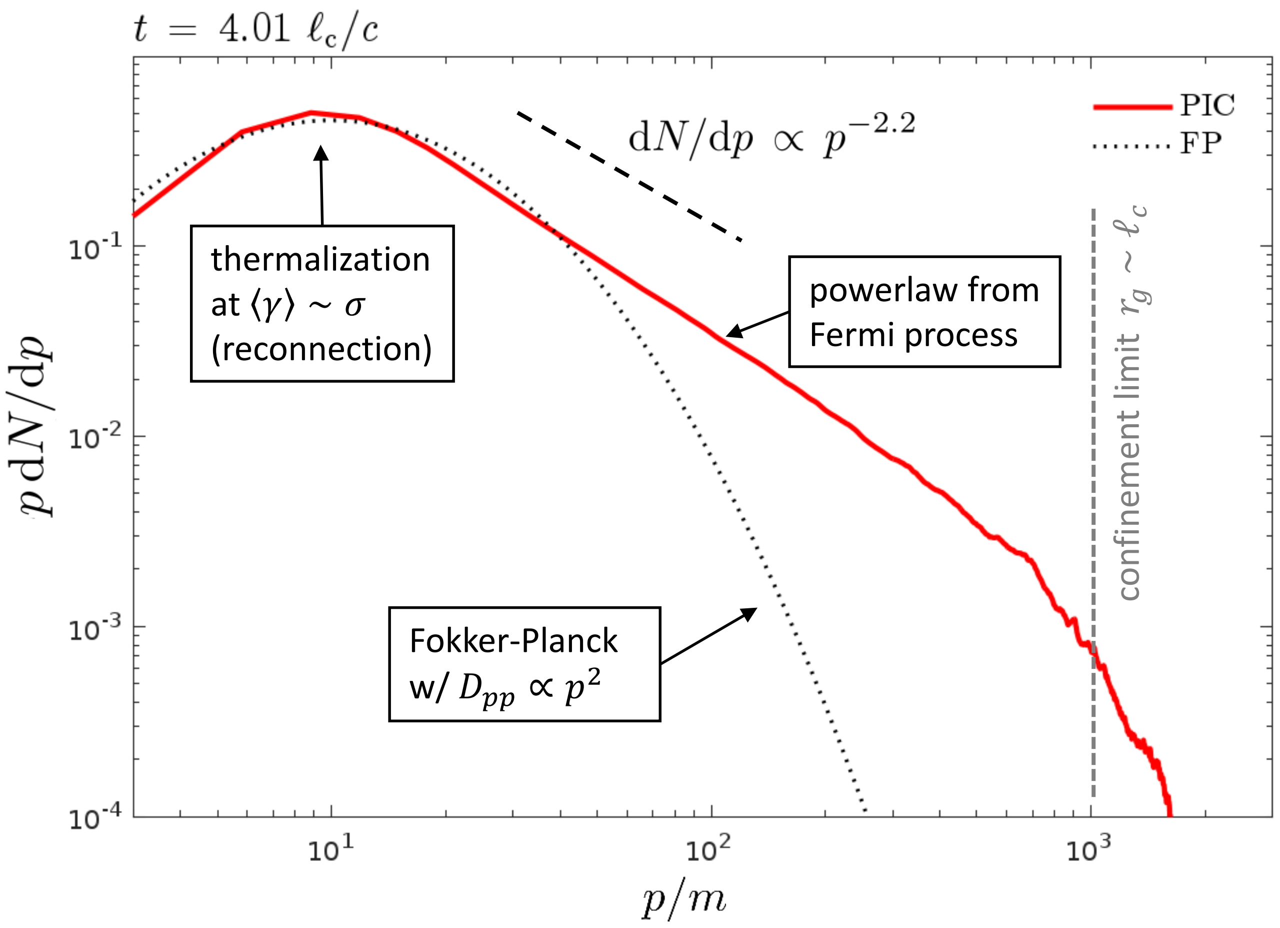
ℓ_c : coherence scale, $\langle \delta u^2 \rangle \sim u_A^2 = \sigma$

… acceleration in two stages:

reconnection up to $\gamma \sim$ few $\times\, \sigma$,
then Fermi-type in turbulence

… diffusion coefficient: $D_{pp} \propto p^2$

… energy spectrum: broad powerlaw tails with index $s \sim 3 \dots 2$ … writing $dN/dp \propto p^{-s}$



thermalization at $\langle \gamma \rangle \sim \sigma$ (reconnection)

powerlaw from Fermi process

Fokker-Planck w/ $D_{pp} \propto p^2$

© V. Bresci, M. L., L. Gremillet: 2D PIC, driven turb., e^+e^-, $10\,000^2$, $\delta B/B \sim 3$, $\sigma \sim 1$

Refs.: 1. e.g. Zhdankin+17,18,19, Comisso+Sironi19,20, Wong+19, …, Bresci+22 +MHD sims: Dmitruk+03, Yang+19, Trotta+20, Pezzi+22,…

Generalized Fermi acceleration in magnetized turbulence

→ **original Fermi model** (= discrete interactions with “magnetic clouds”):

… to compute energy gain/loss, follow momentum in “magnetic cloud” frame where $\boldsymbol{E} = 0$ (ideal MHD: $\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B}\,/c$)

… jump from cloud frame to cloud frame by Lorentz transform

→ **generalization to turbulence**[1] (= continuous random flow):

… follow momentum in instantaneous frame where $\boldsymbol{E} = 0$ … velocity $\boldsymbol{u_E} \propto \boldsymbol{E}\times\boldsymbol{B}/B^2$

in that frame, no electric field…

⇒ Δ energy ∝ non-inertial forces characterized by velocity shear of **u$_E$**

→ **model**[2]:

$$\boxed{\frac{\mathrm{d}\gamma'}{\mathrm{d}\tau} = -\gamma' u'_\parallel\, \boldsymbol{a_E}\cdot\boldsymbol{b} - {u'_\parallel}^2\,\Theta_\parallel - \frac{1}{2}{u'_\perp}^2\Theta_\perp}$$

energy change

effective gravity along field line

$$\boldsymbol{a_E} = u_E^\alpha\,\partial_\alpha\,\boldsymbol{u_E}$$

velocity shear along field line

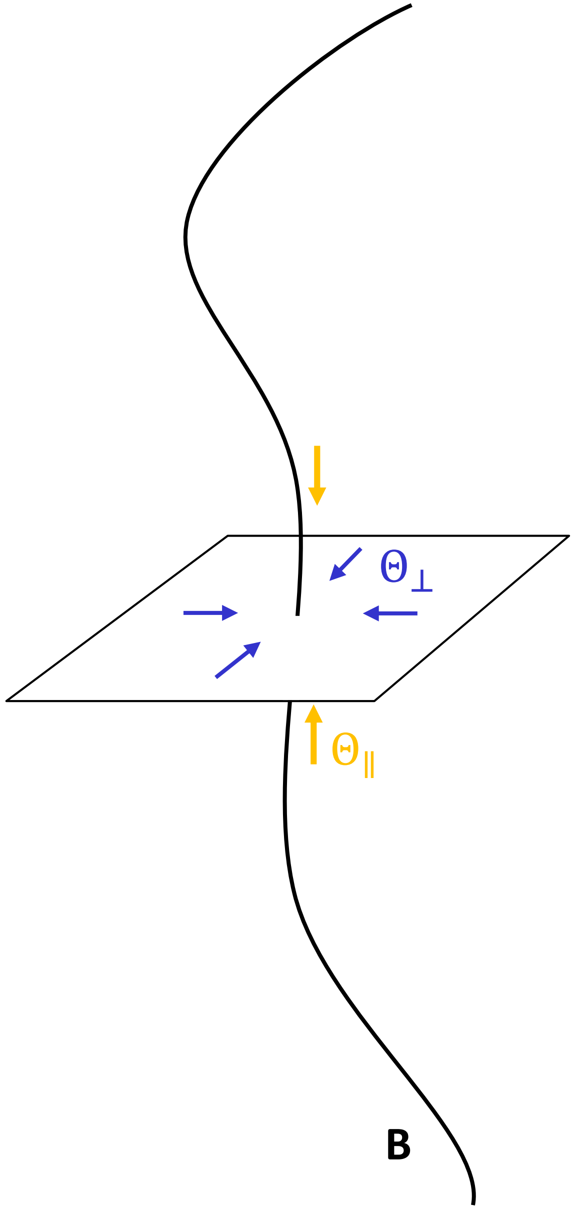
$$\Theta_\parallel = b^\alpha b^\beta \partial_\alpha u_{E\,\beta}$$

[Fermi type-B]
[field line curvature]

compression transverse to field line

$$\Theta_\perp = \left(\eta^{\alpha\beta} - b^\alpha b^\beta\right)\partial_\alpha u_{E\,\beta}$$

[Fermi type-A]
[magnetic mirrors]



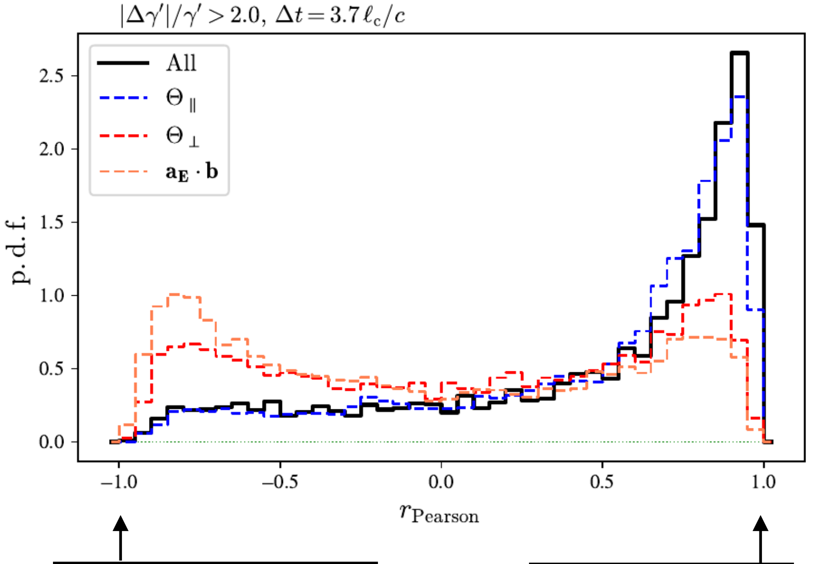
Refs: 1. ML19 2. ML21 (assumes gyroradius ≪ coherence scale of turbulence)

Comparison between model and simulations

→ model: $$\frac{\mathrm{d}\gamma'}{\mathrm{d}\tau} = -\gamma' u'_{\parallel}\, \boldsymbol{a_E} \cdot \boldsymbol{b} \;-\; {u'_{\parallel}}^{2}\, \Theta_{\parallel} \;-\; \frac{1}{2} {u'_{\perp}}^{2} \Theta_{\perp}$$

→ test[1]: for each particle history in a simulation, reconstruct $\gamma'(t)$ using above model and velocity gradients measured in the simulation at **x**, t, then measure degree of correlation r_{Pearson} between the observed and reconstructed $\gamma'(t)$

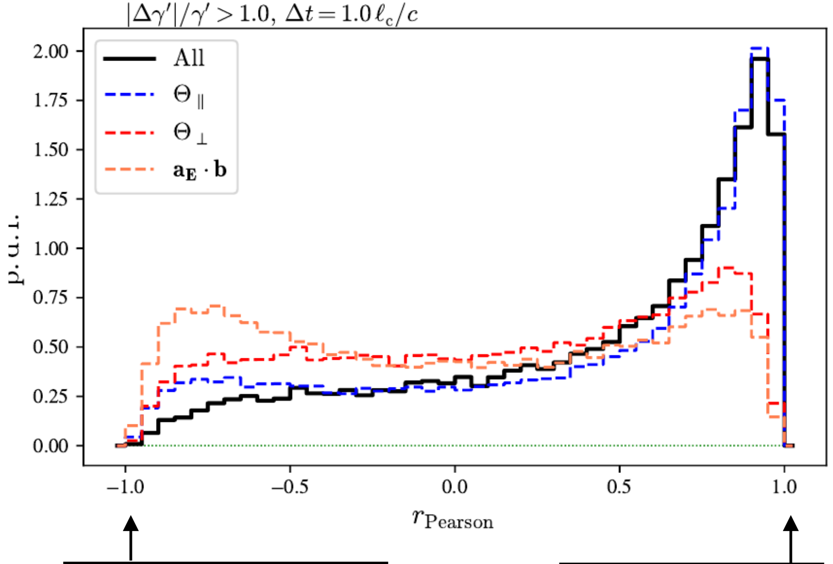
PIC simulation: 3D, $1\,080^3$, e^-e^+, $\delta B/B \sim 3$, $\sigma \sim 1$



100% anti-correlation

100% correlation

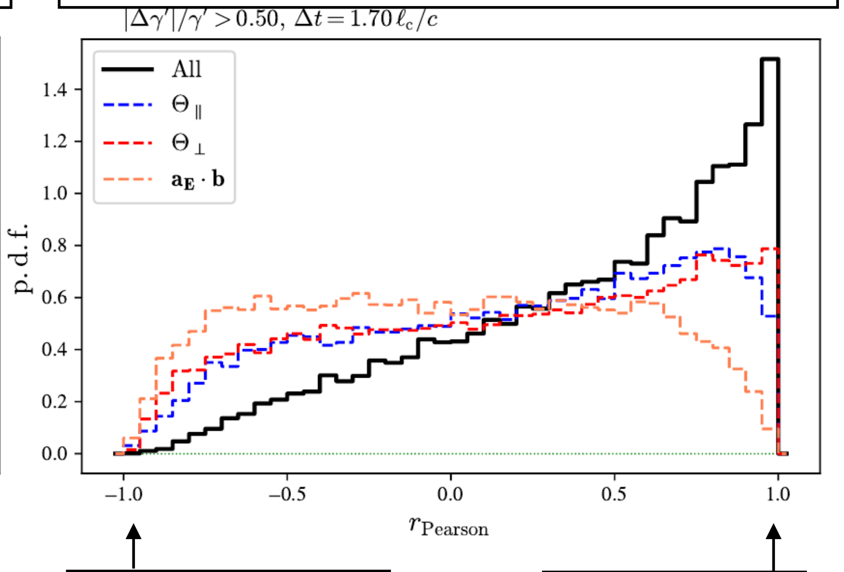
PIC simulation: 2D, $10\,000^2$, e^-e^+, $\delta B/B \sim 3$, $\sigma \sim 1$



100% anti-correlation

100% correlation

driven incompress. MHD[2], 3D, 1024^3, $v_A = 0.4c$



100% anti-correlation

100% correlation

⇒ model captures the dominant contribution to particle energization

Refs.: 1. V. Bresci, ML, L. Gremillet, L. Comisso, L. Sironi, C. Demidem 22 2. Eyink+13, JHU database

Powerlaw spectra: a consequence of turbulence intermittency

→ statistics of the random force (~velocity gradient):

… velocity gradients become increasingly non-Gaussian (intermittent) at small scales (↔ small gyroradii), taking large values in localized regions…

→ particle acceleration[1]:

… some particles interact frequently with strong scattering centers, some not at all over long timescales

⇒ anomalous transport + powerlaws in momentum

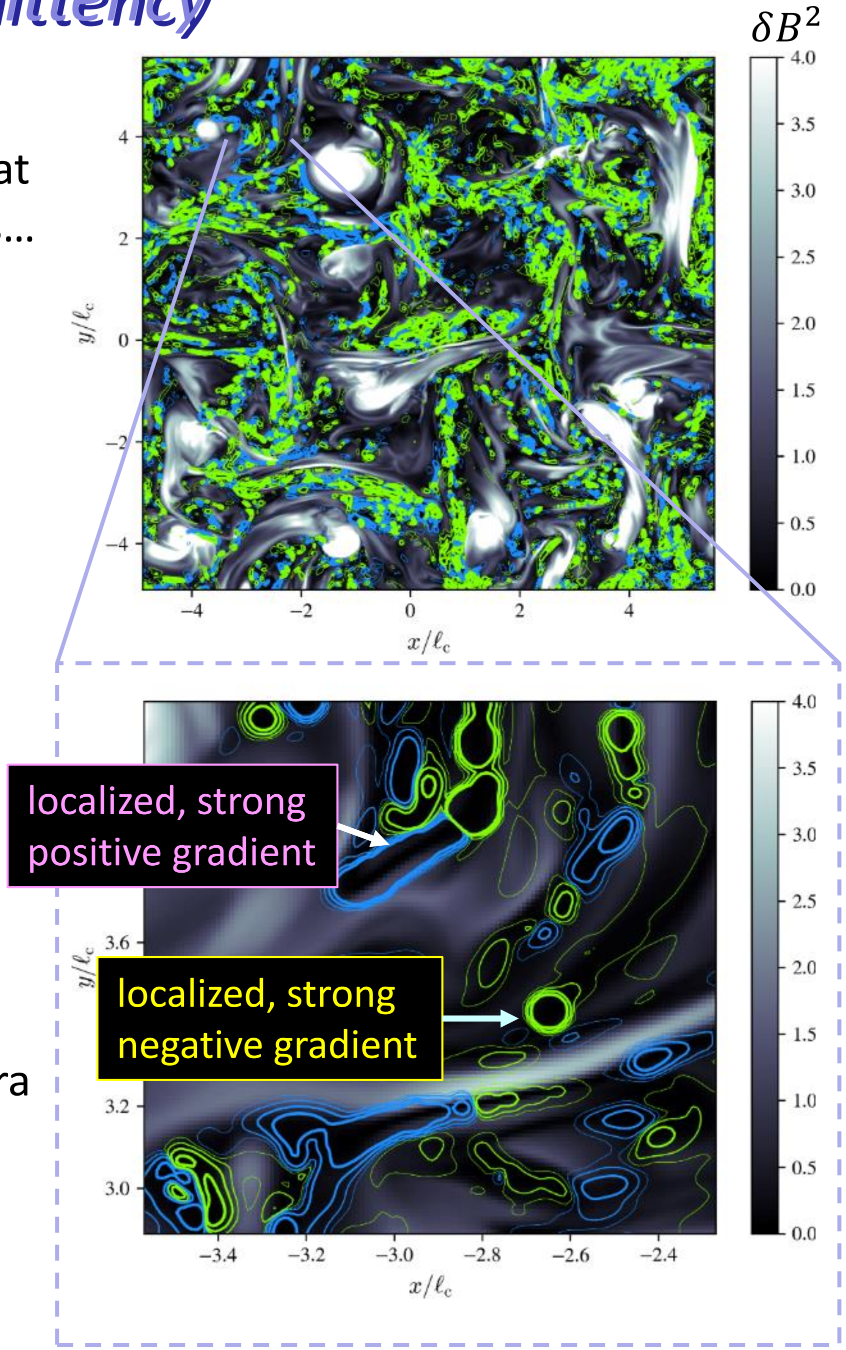
→ transport equation for distribution function[2]:

… failure of Fokker-Planck: noise is non-Gaussian, not white noise…

… derivation of a new transport equation:

pdf(momentum jump) ~ intermittency statistics

… transport equation produces powerlaws, accounts for particle spectra from time-dependent tracking in MHD simulation



localized, strong positive gradient

localized, strong negative gradient

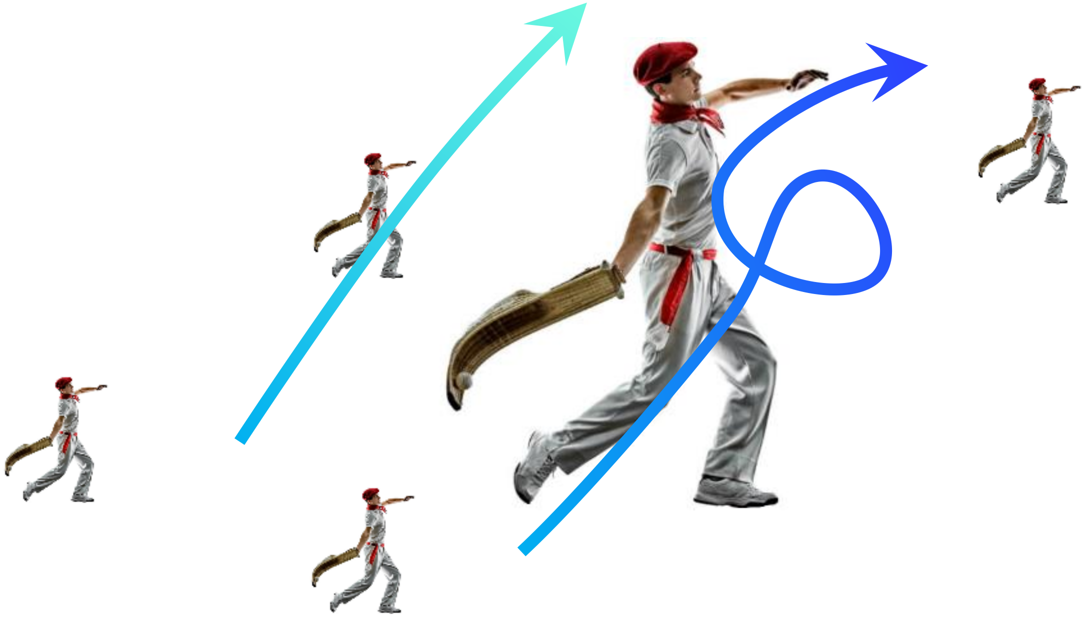
Refs.: 1. Trotta+19, ML + Malkov 20, Maiti+21, Pezzi+22 2. ML 22 (submitted)

Colourizing the Fermi picture…

→ **the original picture:** stochastic acceleration as Brownian motion…

Brownian motion ⟷ Fokker-Planck description,
characterized by one diffusion coefficient D_{pp} (+advection)

→ **the colourized picture:** stochastic interactions with *intermittent gradients*…



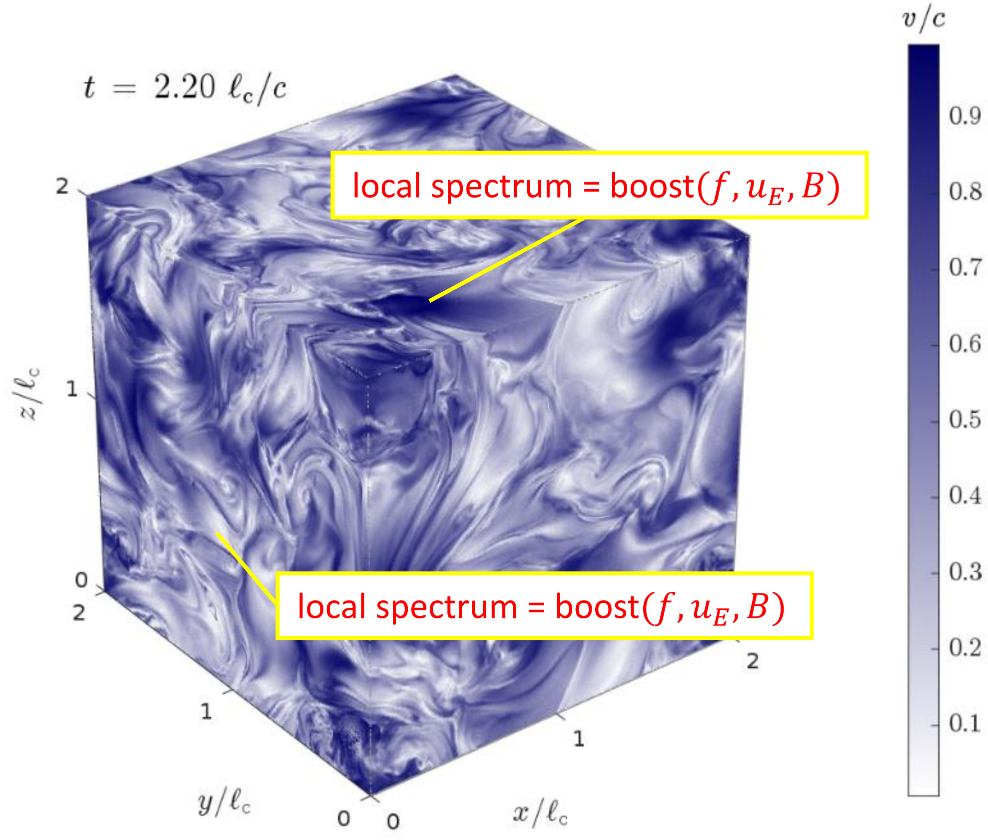
one diffusion coefficient D_{pp} does not describe spectra…
… particle acceleration dominated by intermittency…
… spectra exhibit powerlaw shapes…
… dominant acceleration: field line curvature…

Stochastic acceleration… some implications for phenomenology

→ interesting signatures:

→ inhomogeneous, fast moving structures… consequences for flaring? (time profile?)

→ inhomogeneities (spectra, B, etc.) in one volume ℓ_c^3… consequences for radiative spectra?



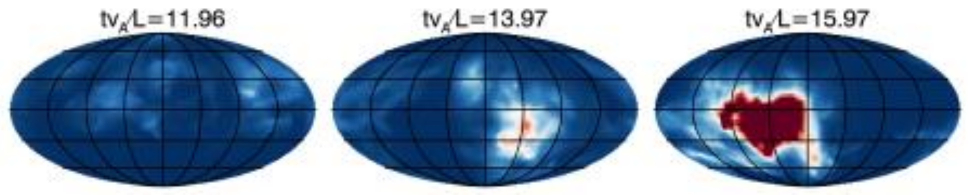
local spectrum = boost(f, u_E, B)

local spectrum = boost(f, u_E, B)

anisotropies of the distribution function

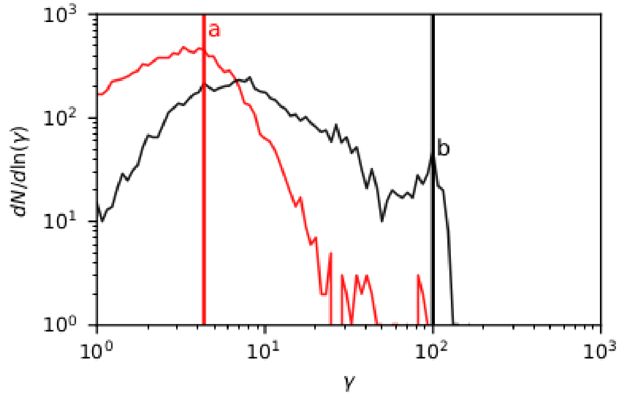
e.g., synchrotron spectra (Comisso+20,Sobacchi+21)

velocity space anisotropies at large momenta



Zhdankin+20

location-dependent spectra



Nättilä+Beloborov 20

consequences for maximal energy (synchrotron photon energy?)

e.g., Bykov+13 in connection to Crab flares,
Khangulyan+21 for synchrotron in inhomogeneous B

Shear acceleration… in one slide

→Fermi shear acceleration:

… the electric field in a sheared velocity flow (Δu) cannot be boosted away globally: particles gain energy by exploring the shear gradient…

… acceleration timescale: $t_{\rm acc} \sim \dfrac{\Delta r^2}{t_{\rm scatt}}\dfrac{1}{\Delta u^2/\gamma_u^2}$

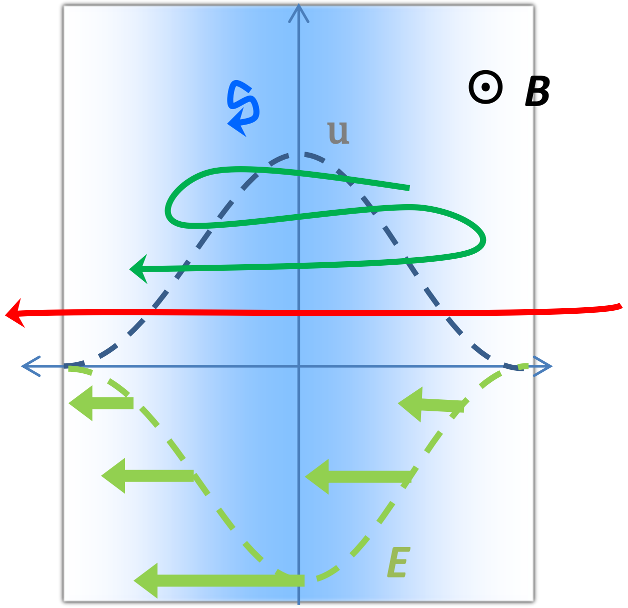
inefficient at low energies (↻), as particles cannot explore shear…

⇒ requires a seed population of particles

optimal efficiency at « confinement energy » (↻ $c\, t_{\rm scatt} \sim r_g \sim \Delta r$):

$t_{\rm acc} \sim r_g/c$ (Bohm) for $\Delta u \sim u \sim c$

inefficient at higher energies (↻ decoupling from turbulence)



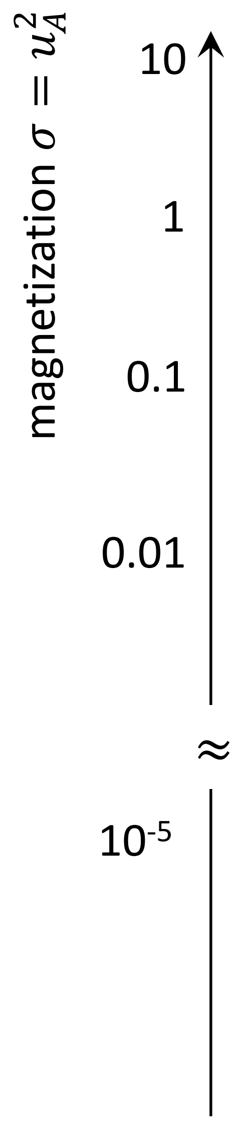
particles with larger mean free paths explore larger gradient of **E**
⇒ faster acceleration…

⇒ shear may provide sustain energy population of electrons over distances > cooling length…

⇒ reacceleration of a population of energetic CRs in mildly relativistic shear may reach confinement energy…

Refs.: e.g., Rieger+Duffy 04, 06, 08, Liu+ 17, Rieger 19, Webb+ 18,19, ML 19, Rieger + Duffy 22

Summary + perspectives: Fermi acceleration in relativistic outflows



relativistic reconnection:
… fast up to few x σ,
… hard powerlaw spectra at $\sigma \geq 10$,

$$t_{\rm acc} \sim 10\, r_g/c$$

turbulence:
… efficient at large Alfvén velocity $u_A = \sqrt{\sigma}$
… hard powerlaw spectra at large $\delta B/B$, $\sigma_{\delta B}$ …

$$t_{\rm acc} \sim 10\, \ell_c/\sigma_{\delta B} c$$

→ mechanism: generalized Fermi in random velocity flow…
→ promising phenomenological signatures

relativistic, magnetized shock+turbulence:
… acceleration observed, in spite of superluminal configuration…

→ s ~ 2.5 - 3.5 for mildly relativistic
→ extension to truly relativistic regime?
→ promising phenomenological signatures

weakly magnetized, relativistic shocks:
… acceleration in self-generated turbulence,

$$t_{\rm acc} \sim 10\, r_g\, (r_g \frac{c}{\omega_p})$$

⇒ increasingly slow at high energies…
… nicely accounts for GRB afterglow