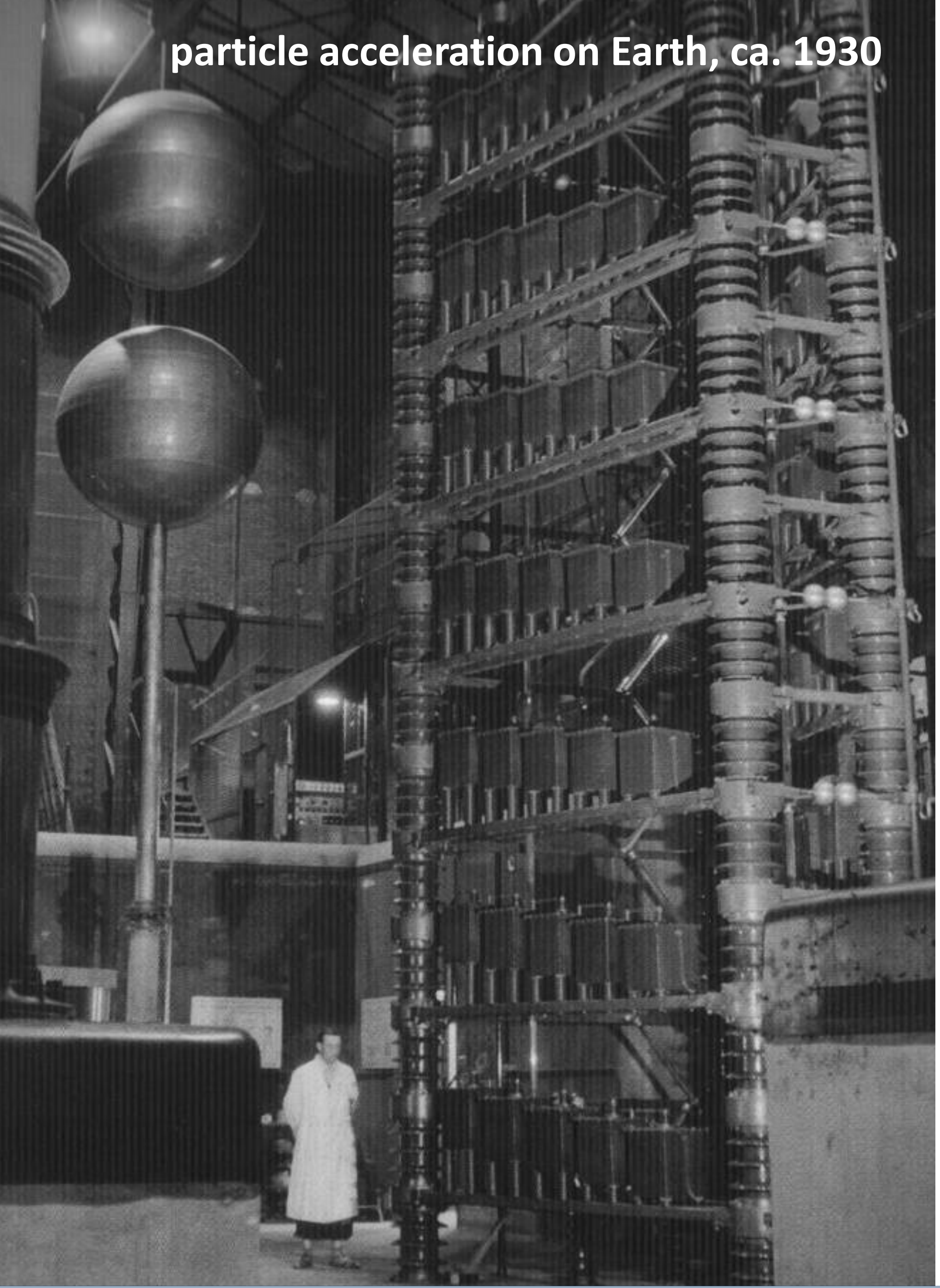

Particle acceleration in the high-energy Universe

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<u>Collaborators:</u>

Virginia Bresci (PhD 2022, Focus Energy), Camilia Demidem (PhD 2019, RIKEN), Arno Vanthieghem (PhD 2019, Obs. Paris), Laurent Gremillet (CEA/DAM)

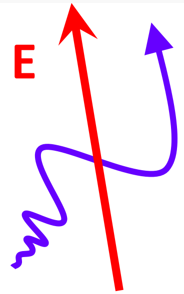
+ G. Pelletier (IPAG), M. Malkov (UCSD), F. Rieger (IPP), K. Murase (Penn State), L. Comisso (Columbia U.), L. Sironi (Columbia U.)

Origin of VHE particles: a multi-pronged approach, from num. exp. to theory to phenomenology

→ a needle in a haystack:

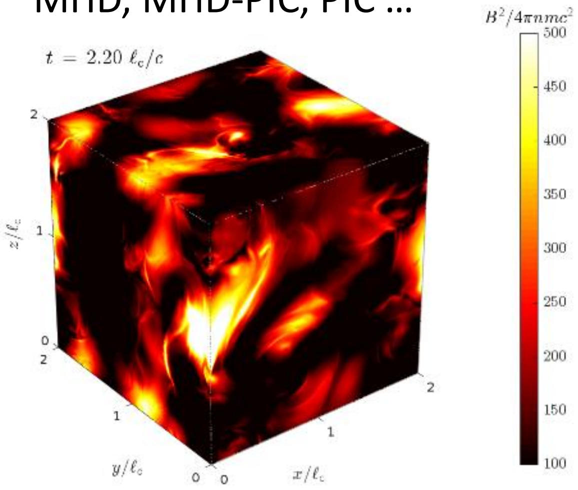
scales(acceleration) $\ll\ll$ scale(source)

+ nonlinear, multiple scale physics



<u>Numerical simulations</u>

MHD, MHD-PIC, PIC …



<u>Theory</u>

schemes: shock, turbulence, reconnection?

test-particle vs self-consistent picture?

extrapolation to large scales?

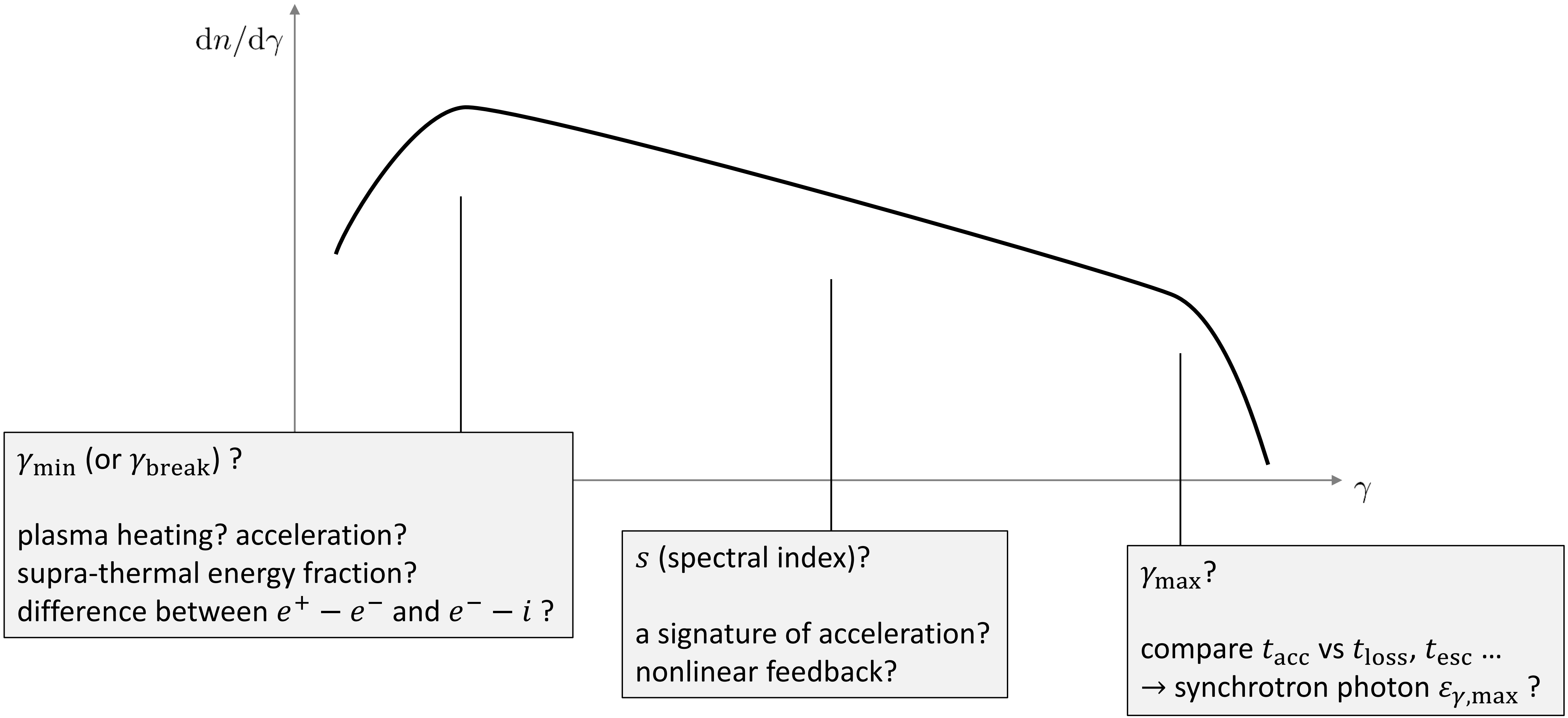
<u>Applications</u>

→ predictions: $t_{\rm acc}$, $\varepsilon_{\rm max}$, $\mathrm{d}n/\mathrm{d}\varepsilon$

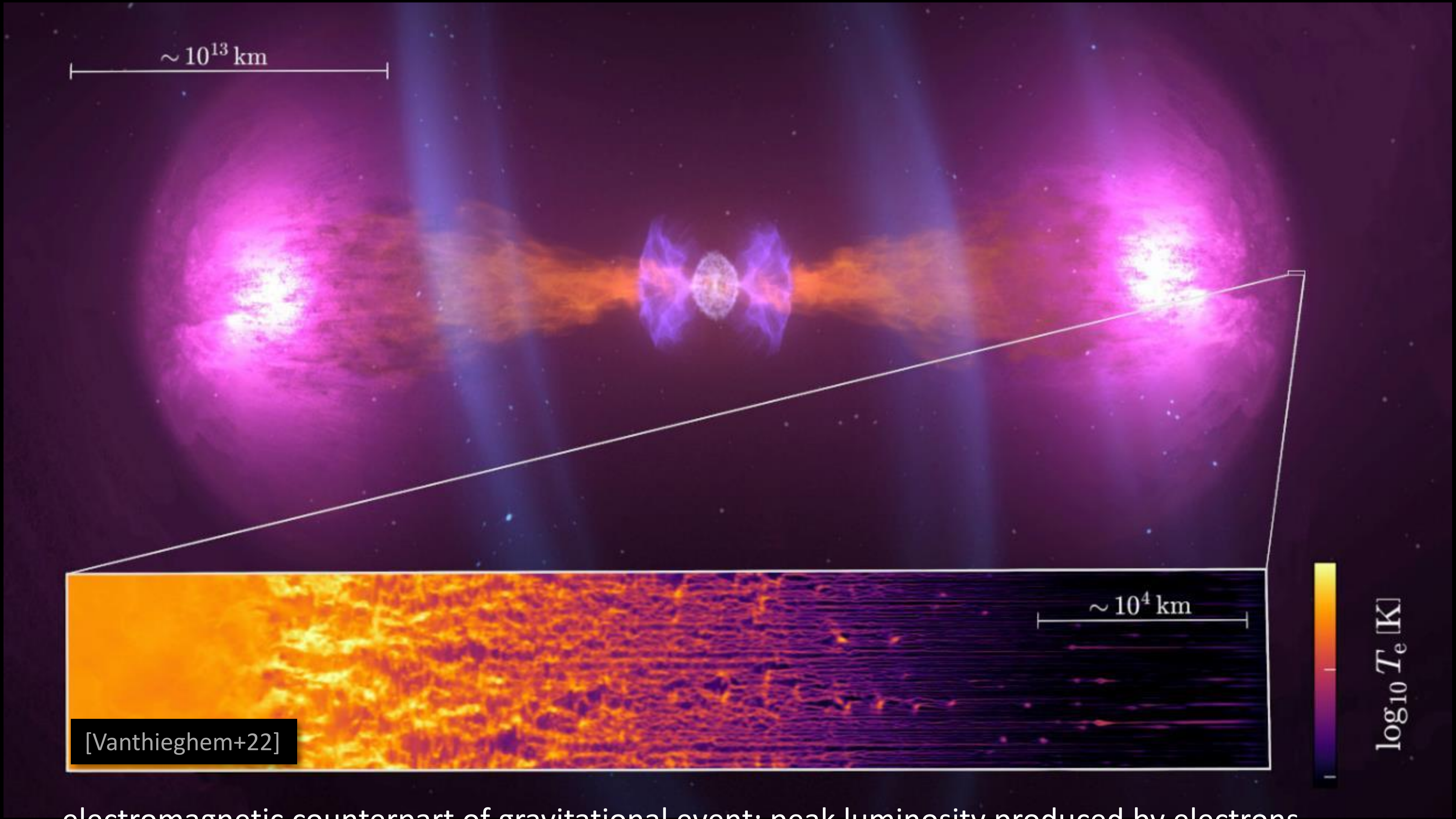
… to be used in transport equations

Minimal model for phenomenological applications

→ supra-thermal particle distribution vs parameters: e.g. magnetization $\sigma = u_B/u_p$, velocity? background B? time?

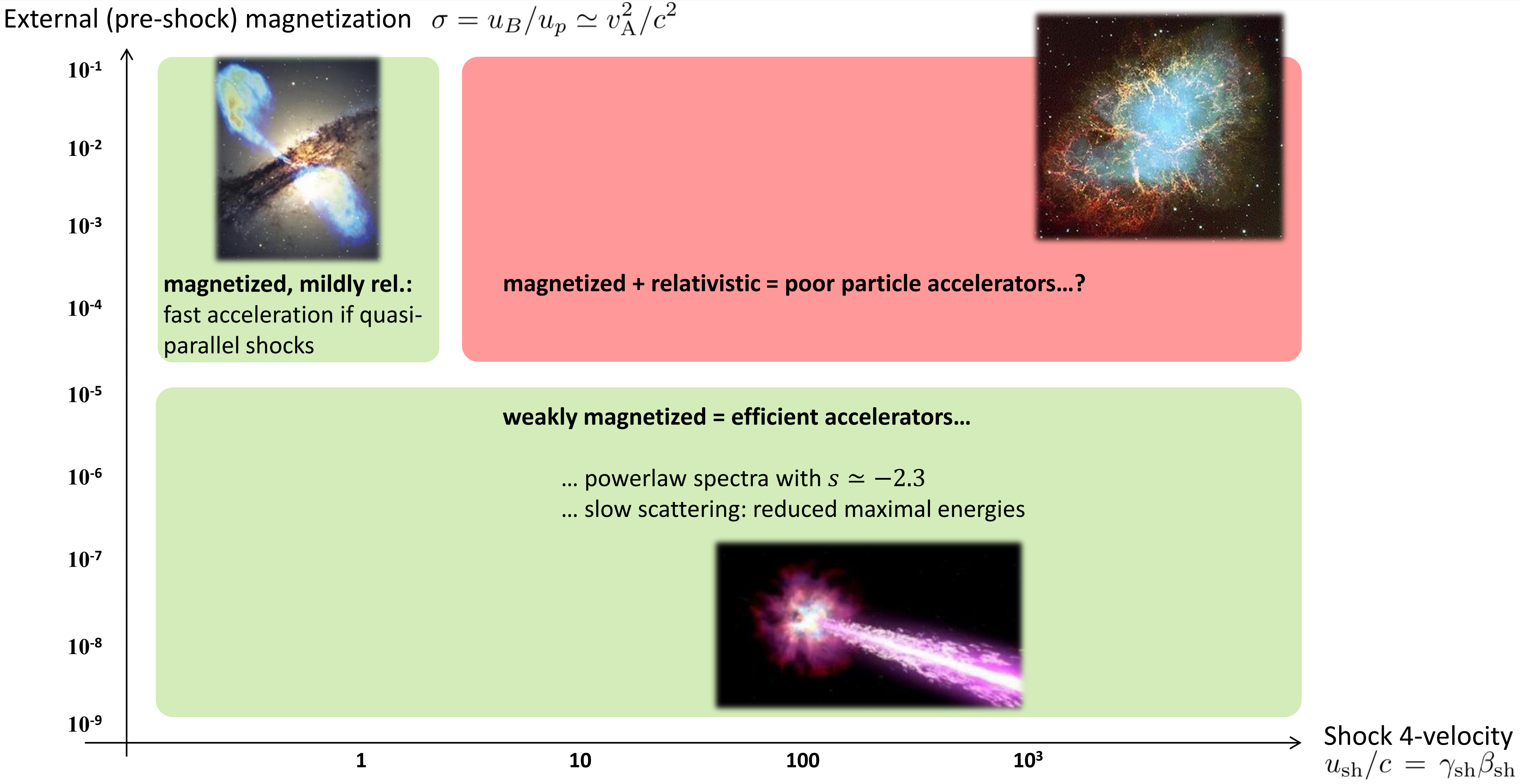


Particle acceleration at (relativistic) shock waves



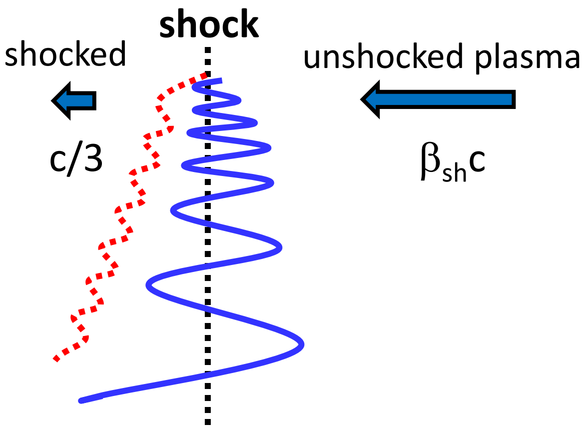
electromagnetic counterpart of gravitational event: peak luminosity produced by electrons heated in a relativistic collisionless shock wave…

Do relativistic shocks accelerate particles… or not?



Onset of particle acceleration at (oblique) relativistic shock waves

→ **competition:** scattering across shock (= acceleration) *vs* escape away w/ plasma



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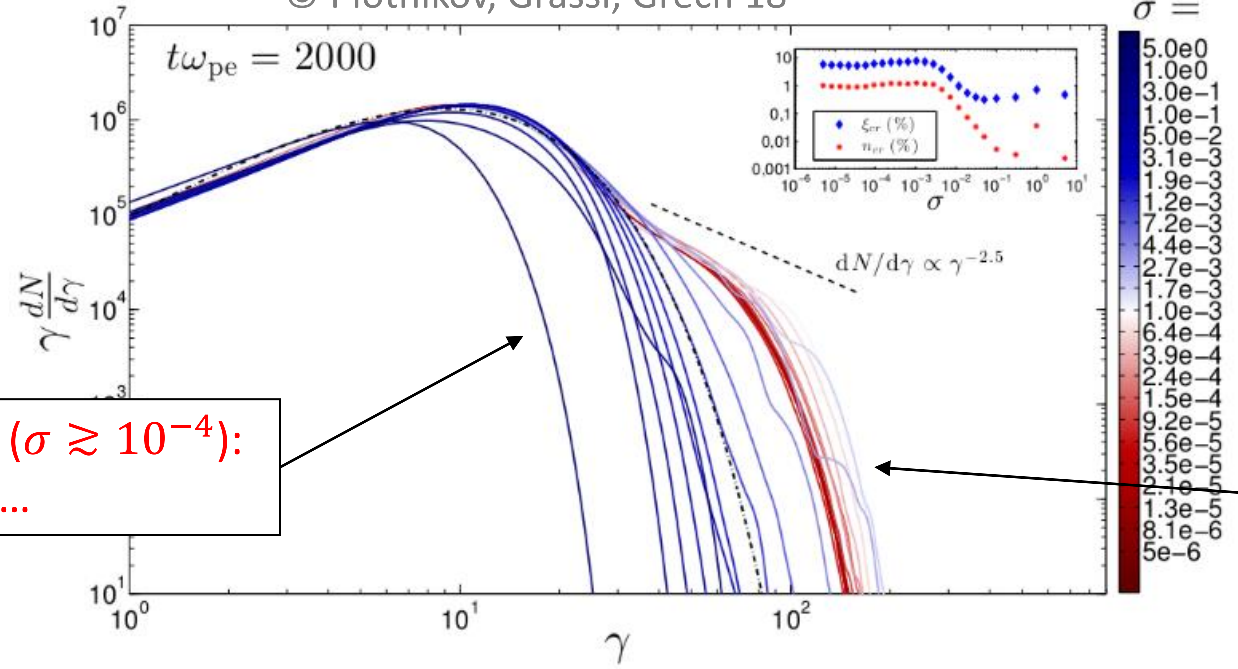


magnetized shocks ($\sigma \gtrsim 10^{-4}$):
⇒ no acceleration[1]…

weakly magnetized shocks ($\sigma \lesssim 10^{-4}$):
⇒ acceleration[1]…
… scattering in self-generated turbulence wins over advection
… application: GRB, microQSO (?) etc

→ **current/open questions:**

… how to understand the Crab SED: inferred e −spectrum ~ relativistic shock acceleration
⇒ reviving acceleration at magnetized shocks[2]: impact of turbulence, reconnection?

Refs.: 1. Spitkovsky 08, ML+Pelletier 06,10, Sironi+11, 13, …
2. Pétri+Lyubarsky 07, Sironi+11, ML 16, Demidem+18, 23, Bresci+23, Cerutti+Giacinti+23, Morikawa+24 …

Mildly relativistic, magnetized shocks: $\Gamma_{\rm shock}\beta_{\rm shock} \sim 0.5\ -5$

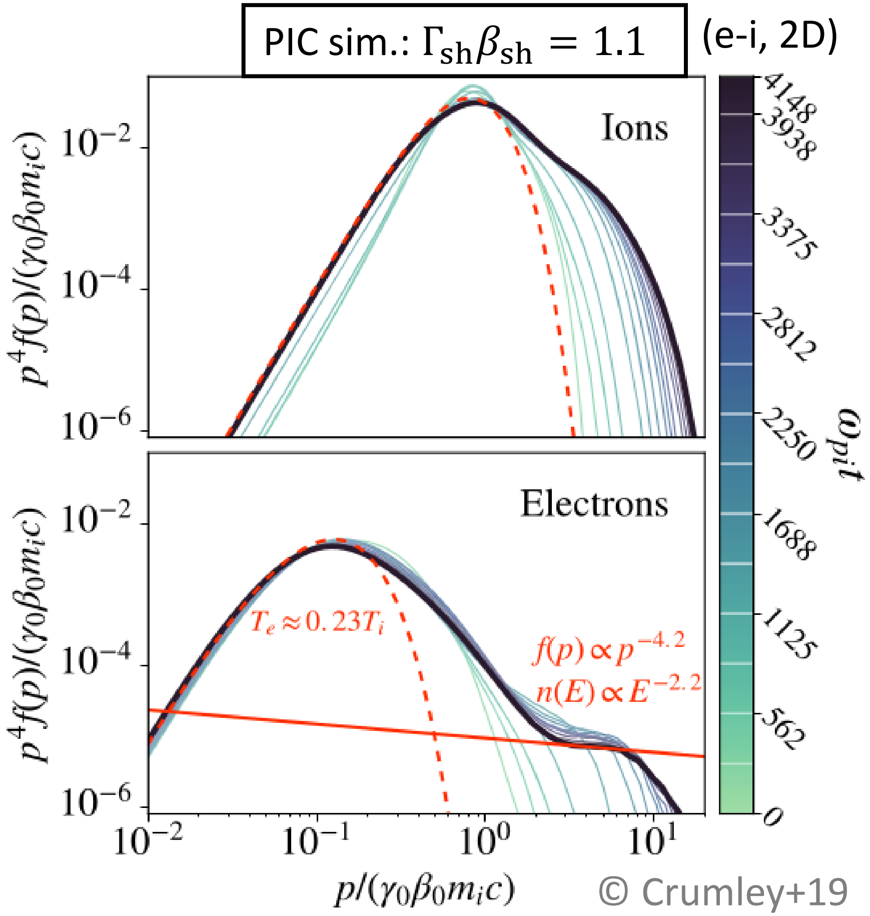
→ acceleration rate[1]:

... quasi-parallel: efficient acceleration, $t_{\rm acc} \propto t_g$ (?)

... quasi-perpendicular: no acceleration

... as $\Gamma_{\rm sh}\ \beta_{\rm sh}$ increases, quasi-perp configuration increasingly likely

⇒ efficient acceleration requires quasi-parallel shocks



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→ electron phenomenology:

... energy fraction in e: $\epsilon_e \sim 0.001$ at $\Gamma_{\rm sh}\beta_{\rm sh} \lesssim 1$ (injection issue)

... but $\epsilon_e \sim 0.1$ at $\Gamma_{\rm sh}\beta_{\rm sh} \gtrsim 3$

⇒ large electron luminosity requires fast shocks (or multiple shocks?)

... $\gamma_{\rm min}$: heating microphysics[2] $kT_e \sim 0.3\ kT_p \sim m_p c^2$

⇒ $\gamma_{\rm min} \sim 10^2 - 10^3$ in e-i plasmas, of relevance to blazars[3] etc.

→ current/open questions:

... long-term evolution w/ development of MHD instabilities in precursor: consequences for $t_{\rm acc}$?

Refs.: 1. Crumley+19, Niemiec+20 2. Vanthieghem+22, 24 3. Zech + ML 21

Weakly magnetized relativistic shocks, e.g. GRB afterglows: the importance of microphysics

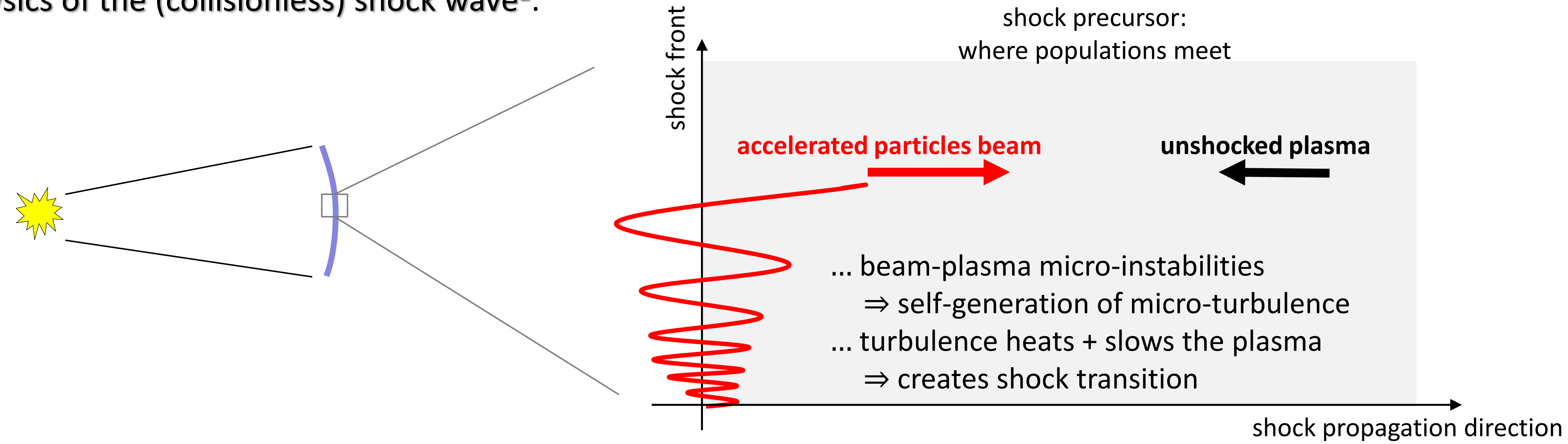
→ generic parameters + physics[1]: $E_{\rm ej}$ and $n_{\rm ext}$ (bulk dynamics); ϵ_e, s, and ϵ_B (microphysics)

… $s \sim 2.3$: electrons are accelerated through relativistic Fermi/shock acceleration

… $\epsilon_e \sim 0.1$: $\gamma_{e,\rm min} \propto \Gamma_{\rm sh}\, m_p/m_e$ ↔ electron heating in the shock transition **(how?)**
+ accelerated particles take $\sim 10\%$ of blast energy **(why?)**

… $\epsilon_B \sim 10^{-4}$: origin of magnetic field at the shock **(how/why?)**

→ microphysics of the (collisionless) shock wave[2]:



Refs.: 1. e.g. Piran 04 +refs, … 2. Moiseev+Sagdeev 63, ……, Medvedev+Loeb 99, Gruzinov 99, …, e.g. Sironi, Keshet, ML 15 + refs

A first-principles model of GRB afterglows

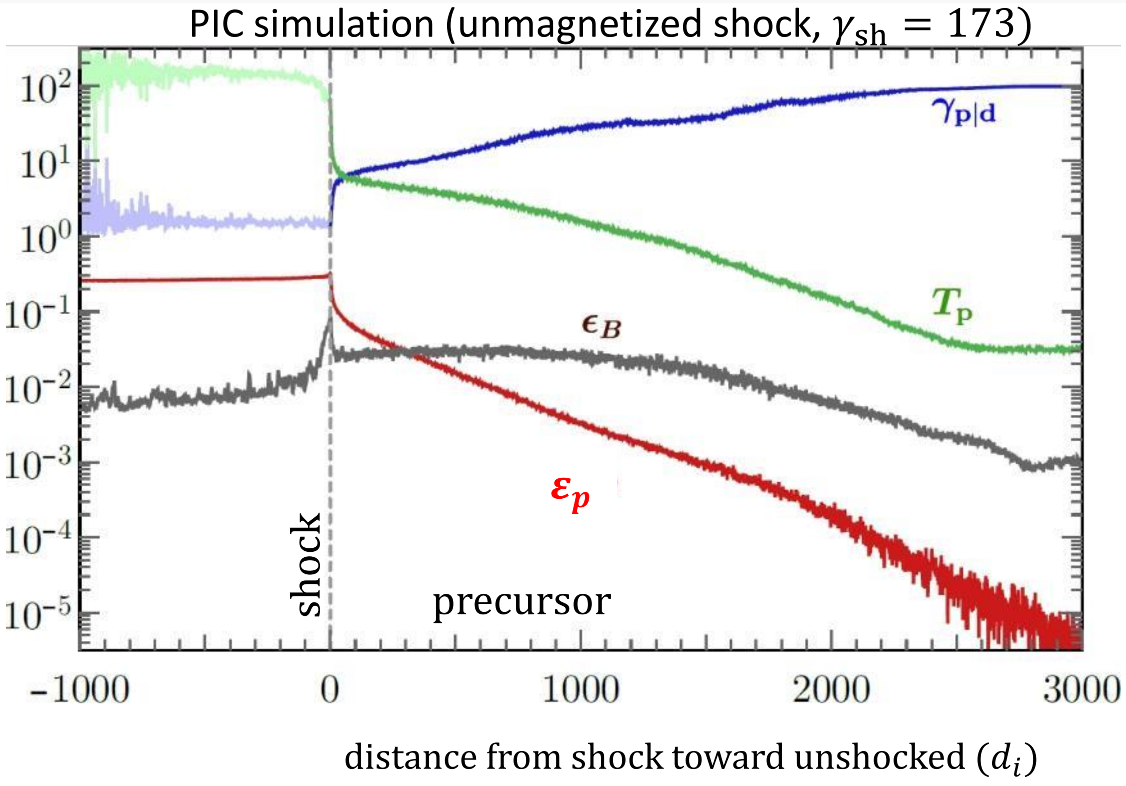
→ microscopic model of an unmagnetized, relativistic collisionless shock wave:

… calculates growth of micro-instabilities in the precursor

… derives a kinetic description of the distribution function in the decelerating frame of the self-generated micro-turbulence: Fokker-Planck + inertial corrections

… models the evolution of mean velocity, temperature, density, magnetized turbulence

… validation against PIC simulations: model reproduces plasma deceleration, heating, injection



→ phenomenology: accelerated particles excite Weibel turbulence, unshocked plasma is trapped in turbulence, scattering of acc. particles on turbulence slows plasma (in shock frame), plasma friction on turbulence generates heating, Weibel turbulence saturates then decays

Refs.: M.L., L. Gremillet, G. Pelletier, A. Vanthieghem, PRL 123, 035101 (2019)
M.L., G. Pelletier, A. Vanthieghem, L. Gremillet, PRE 100, 033210 (2019)
A. Vanthieghem et al., Galaxies 8, 33 (2020)
G. Pelletier, L. Gremillet, A. Vanthieghem, M.L., PRE 100, 013205 (2019)
M.L., A. Vanthieghem, L. Gremillet, G. Pelletier, PRE 100, 033209 (2019)
A. Vanthieghem, M.L., L. Gremillet, ApJL 930, L8 (2022)

A first-principles model of GRB afterglows

→ Predictions/postdictions/interpretations for energy fraction parameters:

$\boldsymbol{\epsilon_{\rm p} \simeq 0.1 - 0.3}$ at injection: blast dissipates 10% of energy into accelerated particles

[pressure in accelerated particles transmitted to plasma through scattering on micro-turbulence, 0.3 of shock energy suffices to decelerate plasma to sound velocity: creates shock]

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

[e-i difference in mass: plasma ions stream through, electrons tied to turbulence and pulled by ions, triggers Joule process transferring energy from ions to electrons, quasi-equipartition]

$\boldsymbol{\epsilon_B \simeq 0.01}$ in precursor, $\ll \mathbf{0.01}$ downstream due to collisionless damping of microturbulence…

[value corresponds to saturation of Weibel inst. in precursor, damping down to values $\sim 10^{-5}$ downstream, depending on long-term evolution]

→ Some consequences for observations:

… $\epsilon_B \ll \epsilon_e$: expect Compton dominance (up to KN effects)

… maximal electron energy: $\boldsymbol{\varepsilon_{e,\rm max} \sim \Gamma_{\rm sh} \times O(1)}$ **TeV**

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

… maximal proton energy: $\boldsymbol{\varepsilon_{p,\rm max} \sim O(1-10)}$ **PeV**

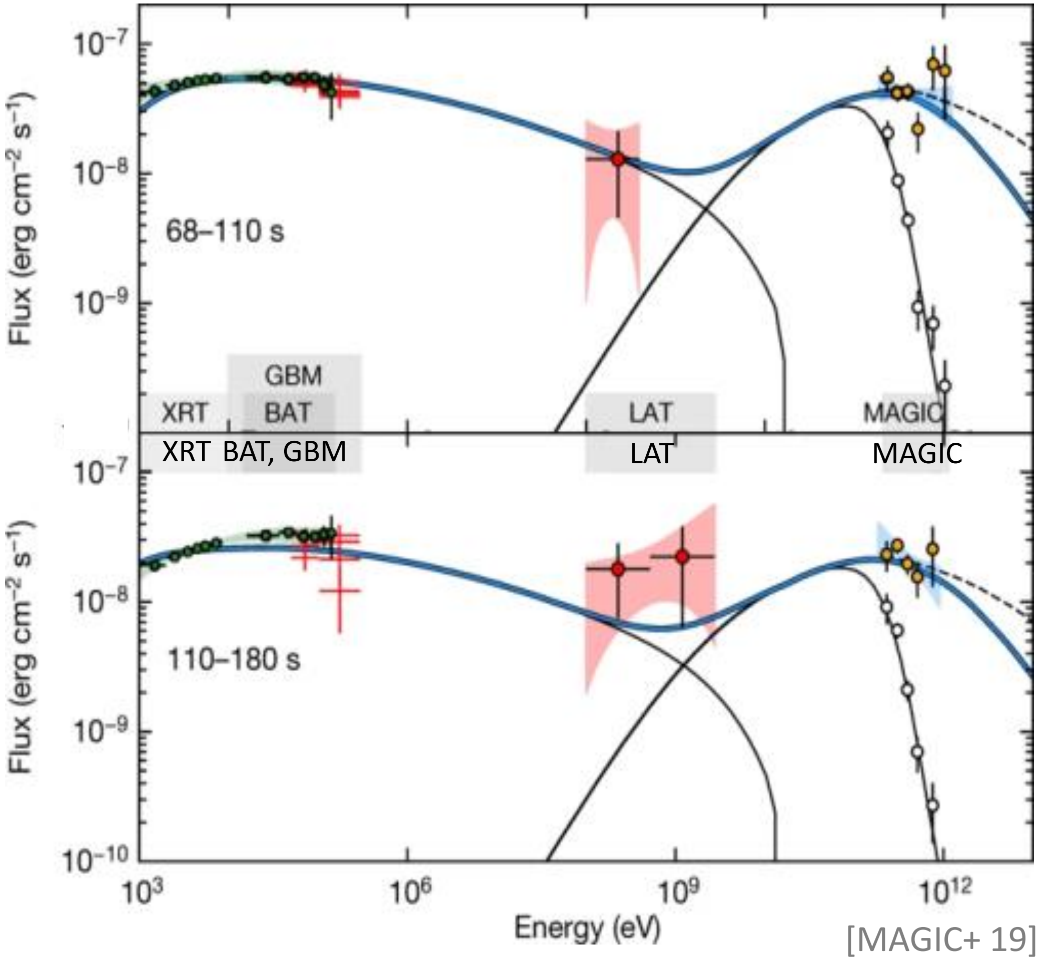
Recent GRB afterglows observed at TeV energies

→ GRB190114C: MAGIC Collaboration

… parameter inference through modeling gives[1]:

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

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



[MAGIC+ 19]

→ GRB221009A: the « BOAT »

… parameter inference through modeling gives[2]:

$p \simeq 2.3, \;\; \epsilon_B \lesssim 10^{-5}, \; \epsilon_e \sim 0.1,$

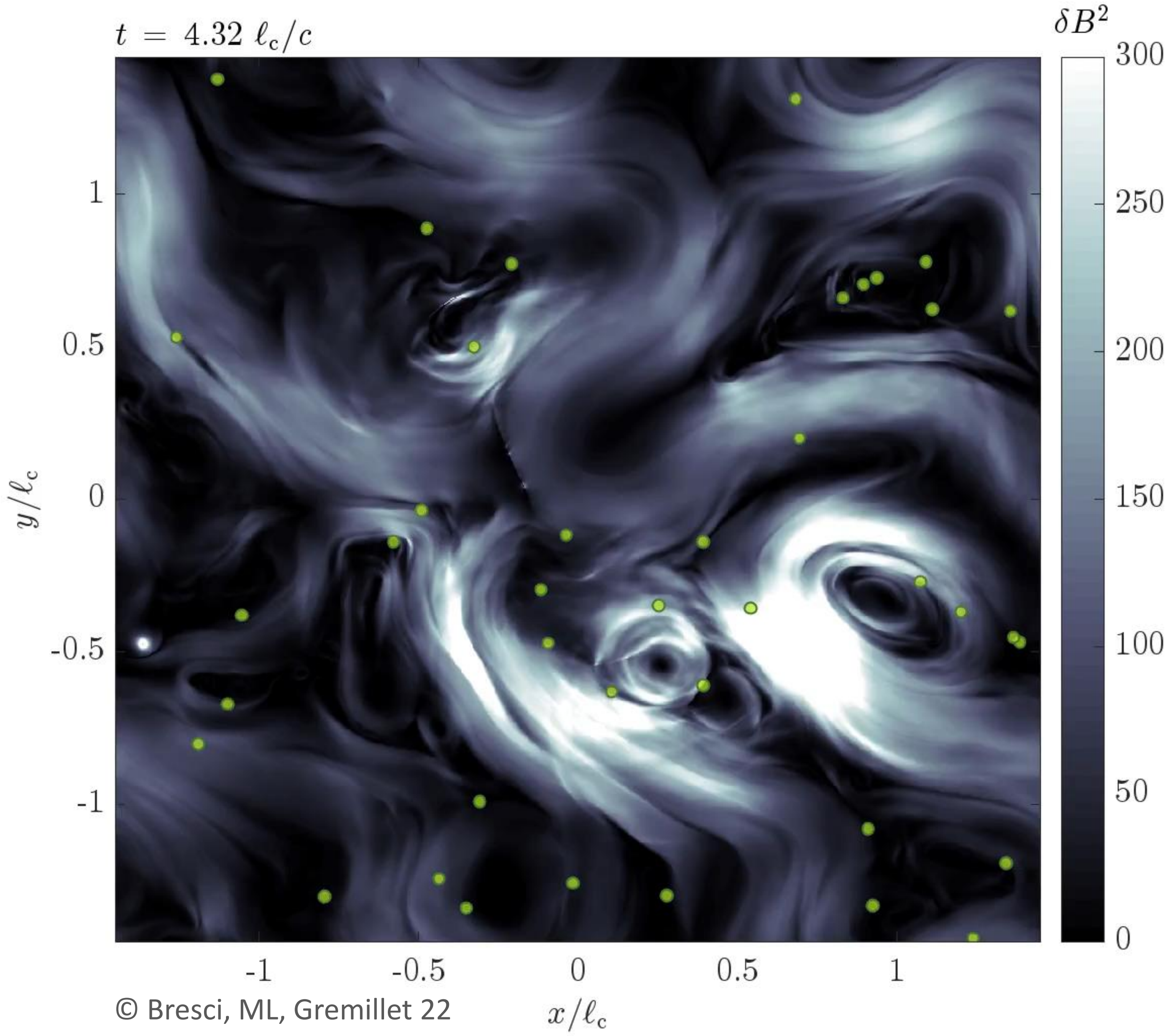
→ caveats and open questions:

… scatter in ϵ_B: degeneracy in inference, or external sources of turbulence? → constraints from polarization[3]

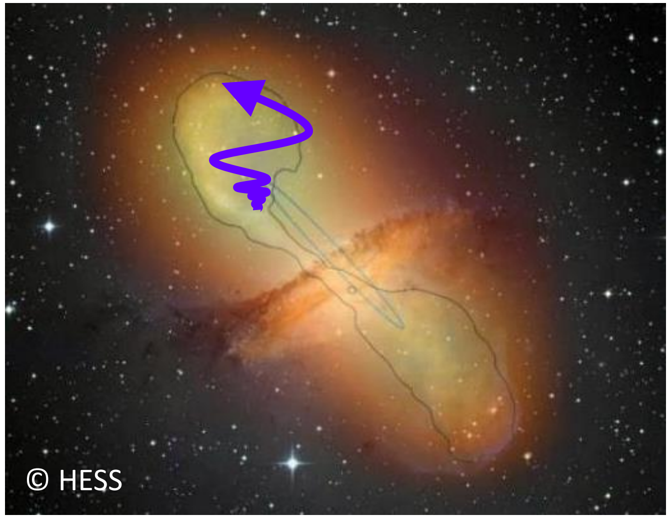
… different models for a given GRB[4] (incl. structured jet, reverse shock, additional MHD instabilities etc.)

Refs.: 1. MAGIC Coll. (2019) 2. O'Connor+23 3. e.g., Kuwata+24 4. e.g. Derishev+Piran 19, Beniamini+20, Derishev 23, Levinson 09, Inoue+11, …

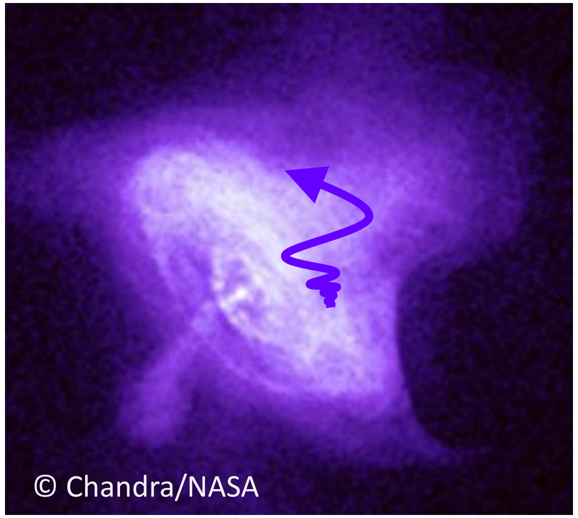
Particle acceleration in (relativistic) turbulence



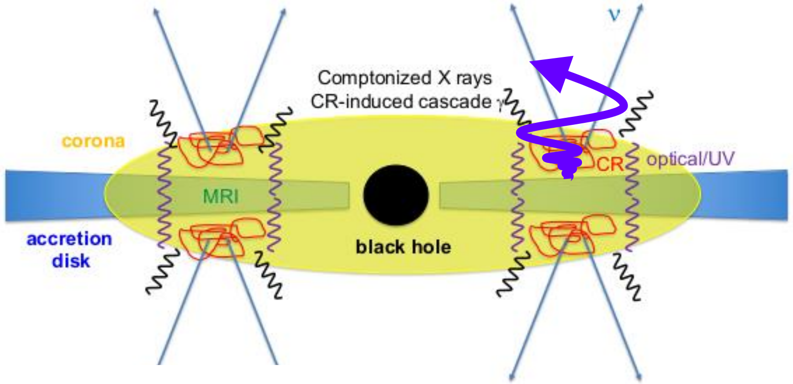
Stochastic particle acceleration in turbulence: a universal scheme in astrophysics



… in extra-galactic jets



… in pulsar wind nebulae



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… in black hole environments

… and any turbulent plasma, with efficient acceleration at large characteristic eddy velocity u_E, large amplitude $\delta B/B$

→ a stochastic process of acceleration:

… particles diffuse in energy space through energy gain- or loss- interactions

… specific virtues: efficient over broad range of physical conditions (unlike shocks, reconnection) + hard spectra

… long-standing questions: acceleration physics? acceleration timescale? particle spectra?

→ here: focus on large-amplitude, large eddy velocity

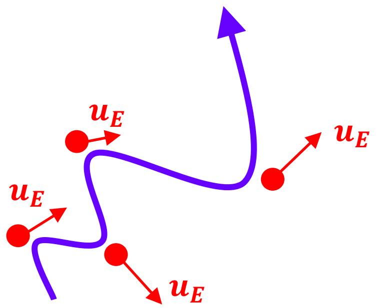
Standard implementation of stochastic acceleration in VHE sources...

→ standard modeling:

… Fokker-Planck approximation for diffusive processes, fully characterized by diffusion coefficient $D_{\varepsilon\varepsilon}$

$$\partial_t n_\epsilon = \partial_\varepsilon \left(D_{\varepsilon\varepsilon} \partial_\varepsilon n_\varepsilon \right) + \ldots \qquad \text{with} \;\; n_\varepsilon \equiv \mathrm{d}n/\mathrm{d}\varepsilon$$

→ functional form of $D_{\varepsilon\varepsilon}(\varepsilon, v_A, \delta\mathrm{B}/\mathrm{B}, \ell_c, \ldots)$ ← acceleration theory… but, which theory?



<u>the Fermi pinball[1]?</u>

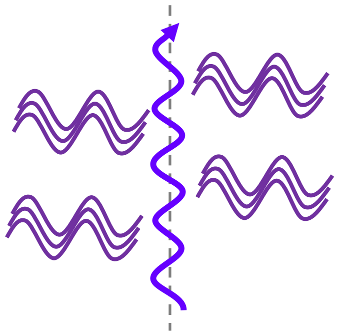
… discrete interactions with scattering centers
… $\mathbf{E} = \mathbf{0}$ in scattering center rest frame
… net gain: head-on vs tail-on (?)

… however, generalization to turbulence?

<u>resonant wave-particle interactions[2]?</u>

… perturbative calculation of $D_{\varepsilon\varepsilon}$

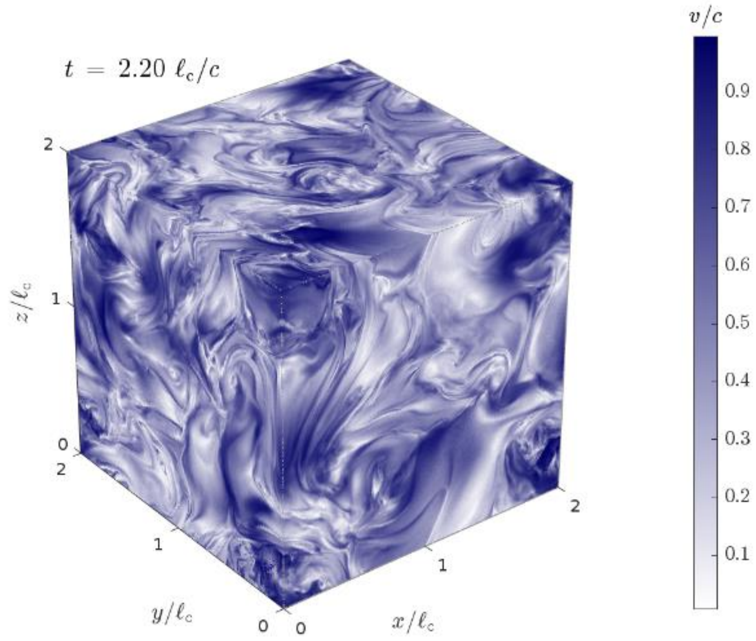
… however, realistic picture?

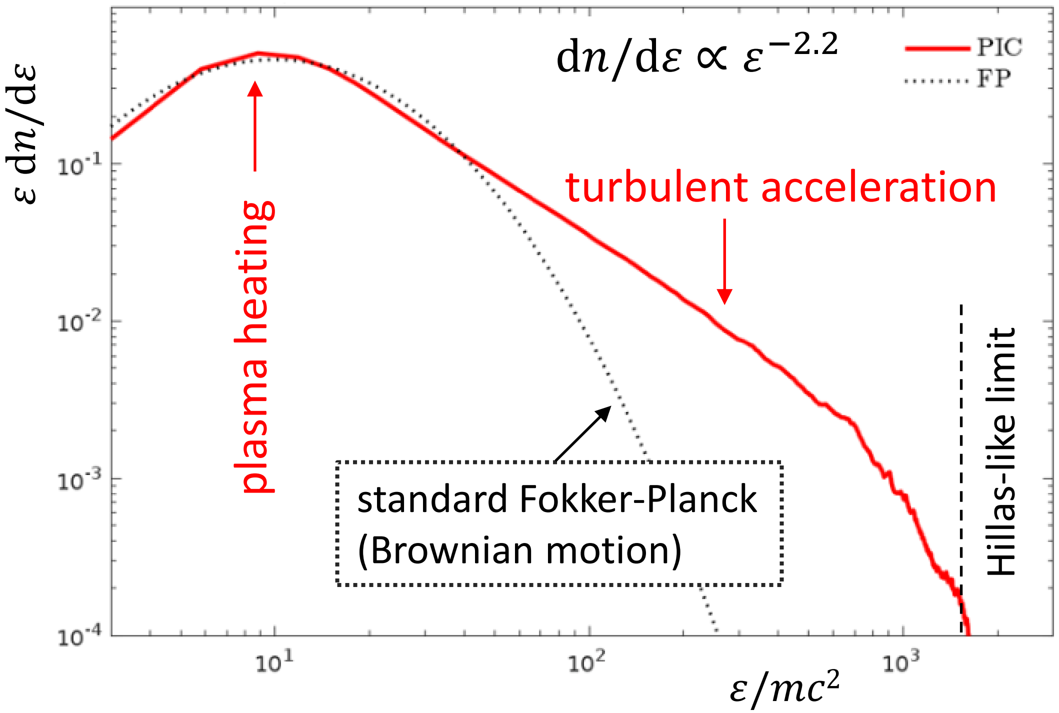


Refs: 1. e.g., Fermi 49, 54, … 2. e.g. Schlickeiser 84, ….

Relativistic stochastic acceleration in silico

→ PIC simulations[1] of particle acceleration: semi- to fully-relativistic (Alfvén $v_A \gtrsim 0.1\,c$, $v_E \sim v_A$) turbulence





→ acceleration to Hillas-limit (w/o losses): $\varepsilon_{\mathrm{Hillas}} \approx e\bar{B}\ell_c$ [w/ ℓ_c outer scale of turbulence]

→ diffusion coefficient $D_{\varepsilon\varepsilon} \sim 0.2\ \varepsilon^2\,\sigma\,c/l_c$ [w/ $\sigma \simeq v_A^2/c^2$ for $v_A \lesssim c$]

→ powerlaw spectra (not Fokker-Planck!): $dn/d\varepsilon \propto \varepsilon^{-s}$ with $s \sim 4$ (sub-relativistic) to $s \sim 2$ (relativistic $\sigma \gg 1$)

… signature of a rich phenomenology[2]…

Refs:

1. fully kinetic (PIC): Zhdankin+17,18,20,… Wong+ 19, Comisso+Sironi 18, 19, Nättilä + Beloborodov 20, Bresci+22, … Groselj+23, Nattila 24
   MHD/hybrid sims: Dmitruk+03, Arzner+06, …, Kowal+12, Isliker+17, Pecora+18, Trotta+20, Pezzi+22
2. M.L. + Malkov 20

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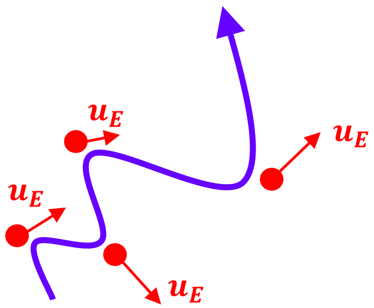

the Fermi pinball[1]?

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resonant wave-particle interactions[2]?

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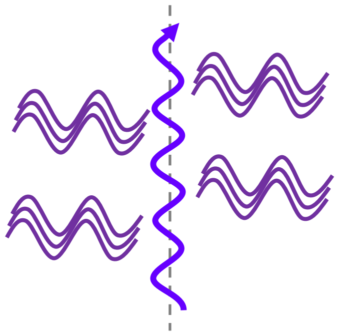


→ here: generalization of Fermi to full (+relativistic) turbulence

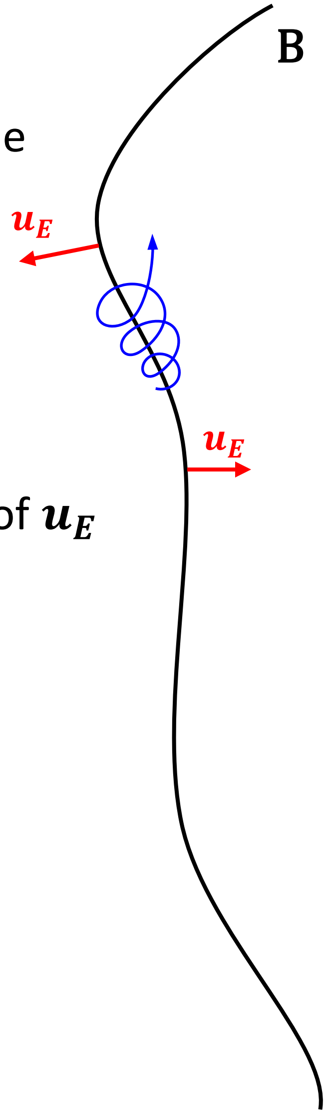
Refs: 1. e.g., Fermi 49, 54, … 2. e.g. Schlickeiser 84, ….

Generalized Fermi acceleration in a random velocity flow

→ Generalized Fermi model[1]:

... scheme = track particle momentum in the (non-inertial) frame moving at $\boldsymbol{u_E}$ where $\mathbf{E} = \mathbf{0}$

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = q\,\boldsymbol{v}\cdot\mathbf{E} \quad \text{in lab frame} \quad \longrightarrow \quad \frac{\mathrm{d}\varepsilon'}{\mathrm{d}t'} = \varepsilon'\ldots\underbrace{\left[\partial_\nu\, u_{E\,\mu}\right]}_{\text{(random) inertial forces at particle location}} \quad \text{(exact) in comoving frame}$$



... a direct generalization of the Fermi picture: pinball → rollercoaster

- $\mathbf{E}$ vanishes in frame moving at $\boldsymbol{u_E}$ ↔ energy changes = random inertial forces = gradients of $\boldsymbol{u_E}$

... benefits:

- effective theory of stochastic acceleration: diffusion coefficient and acceleration physics
- fully covariant → relativistic turbulence
- non perturbative → strong turbulence
- new acceleration channels + specific phenomenological consequences
- new insights for particle transport

Refs: 1. M.L. 19 [PRD 99, 083006 (2019)], 21 [PRD 104, 063020 (2021)], 22 [PRL 129, 215101 (2022)], 25 [PRE 112, 015205 (2025)];
+ previous works by Webb 85, 89
+ other studies in turbulence: Bykov+Toptygin 83, Ptuskin 88, Chandran+Maron 04, Cho+Lazarian 06, Ohira 13, Brunetti+Lazarian 16, …

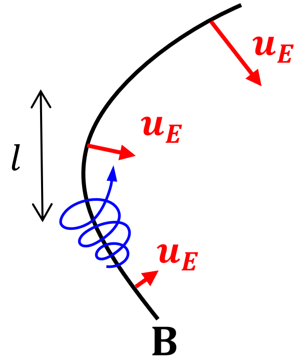
Application to large-amplitude turbulence: $\delta B \sim B$

→ key features:

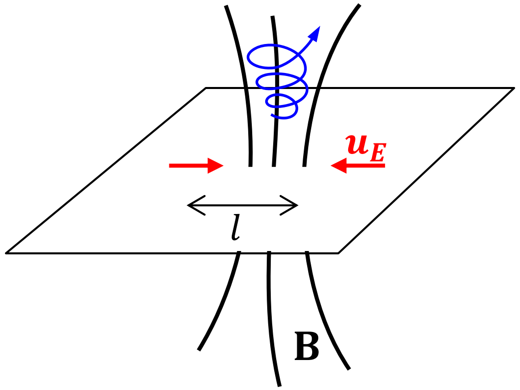
… energy loss/gain from gradients of $\boldsymbol{u_E}$ (on some scale l)

… exponential energy loss/gain while in a structure $\longleftarrow$ $\frac{d\varepsilon'}{dt'} = \varepsilon' \ldots [\partial_\nu u_{E\mu}]$

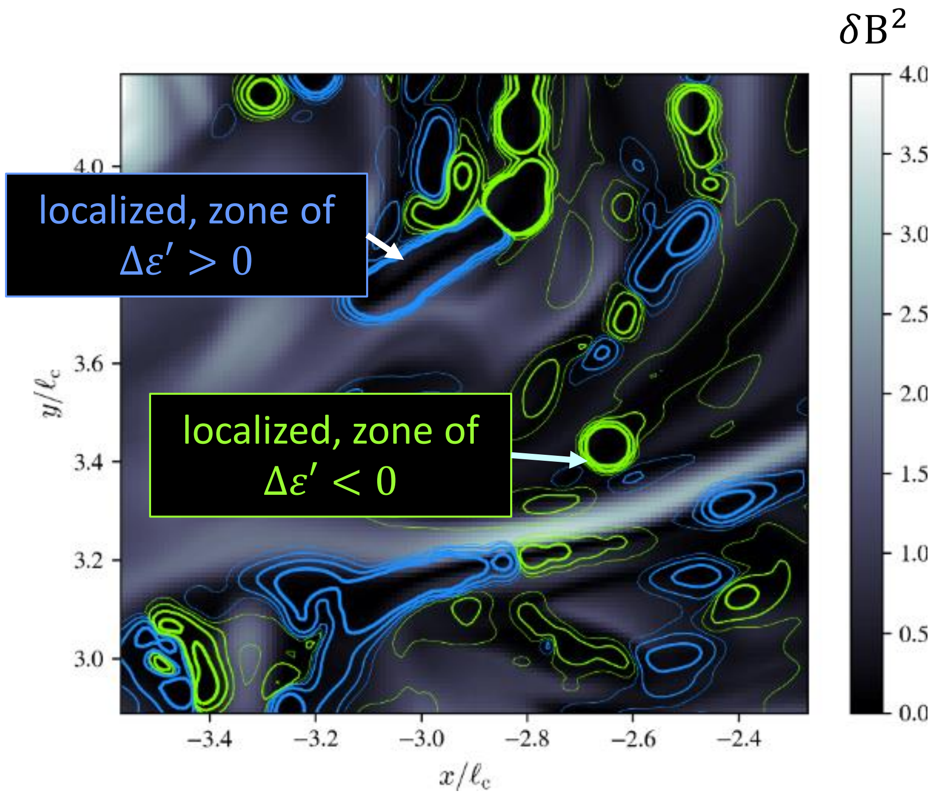
… two examples (dominant contributions):



shear of $\boldsymbol{u_E}$ along B field
(aka curvature drift)



compression of $\boldsymbol{u_E}$ ⊥ B field
(aka betatron, grad-B)



→ consequences:

… particles are accelerated in localized sharp bends (curvature drift) or compressions of the magnetic field

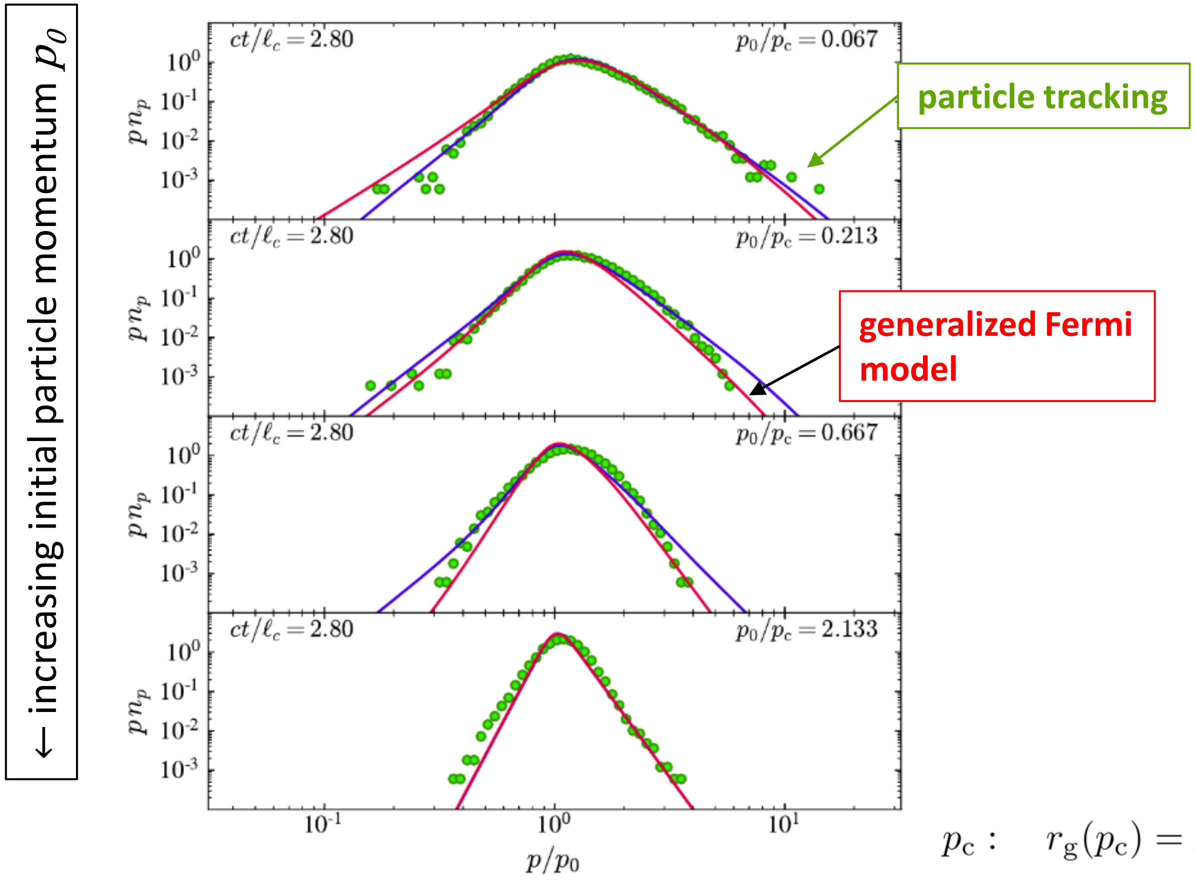
↔ acceleration rate varies through the volume (distributed as a powerlaw)

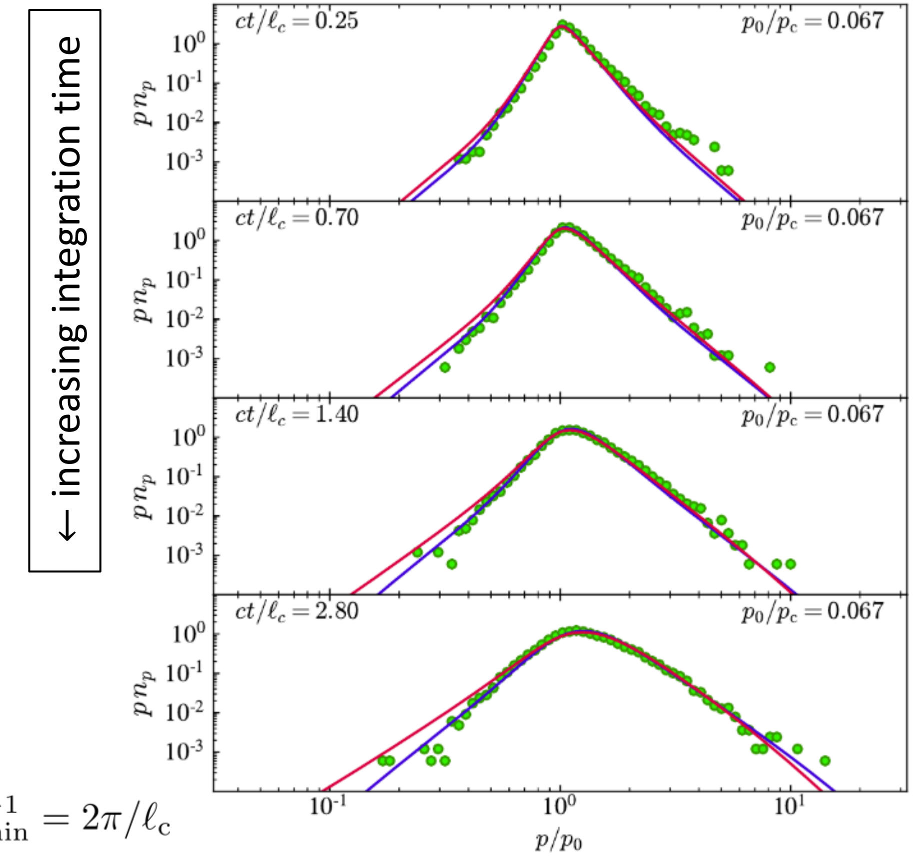
↔ mean acceleration rate ∼ diffusion coefficient = insufficient statistics ⇒ powerlaw spectrum

A transport model reproducing spectra obtained by particle tracking in MHD simulation

→ comparison to numerical data:

1. fit model (here 2: blue & red) to p.d.f. of forces (Γ_l)
2. integrate kinetic equation[1] of generalized Fermi model
3. compare to distribution measured in MHD 1024^3 simulation[2] by time-dependent particle tracking…





$$p_c: \quad r_g(p_c) = k_{min}^{-1} = 2\pi/\ell_c$$

⇒ model supported by MHD (+PIC) numerical experiments of particle tracking

Refs.: 1. ML 22 [PRL 129, 215101 (2022)] 2. no guide field - Eyink+13, JHU database

Impact of energy losses: turbulence as an extreme particle accelerator?

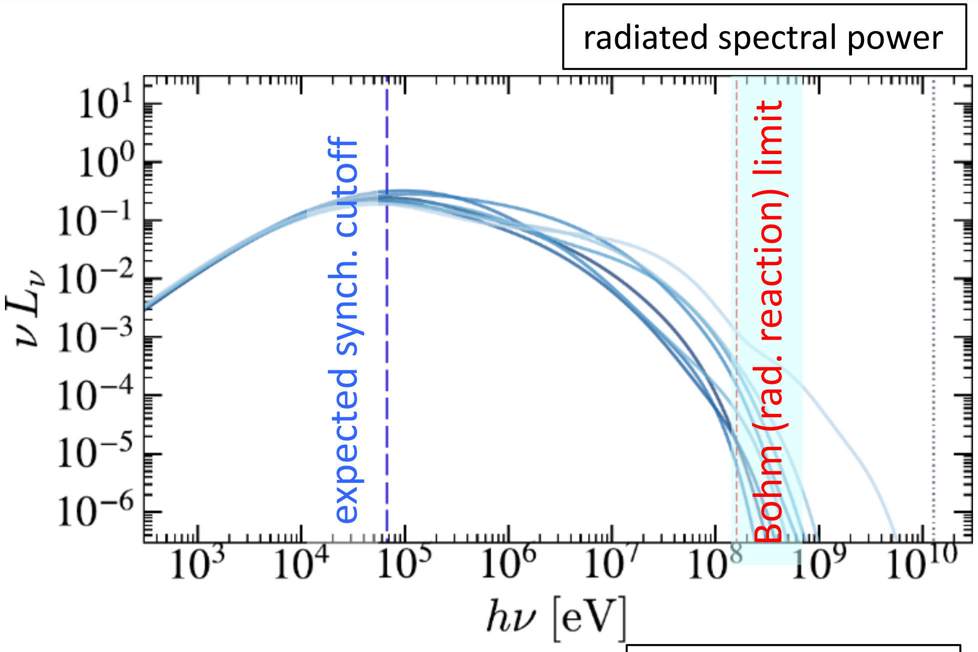
→ maximum energy w/ synchrotron cooling:

… on average, turbulence is a slow accelerator[1]:

$$D_{\varepsilon\varepsilon} \simeq 0.1\,\sigma\,\varepsilon^2 c/\ell_c \quad \Rightarrow \quad t_{\rm acc} \sim l_c/c$$ (turn-around time!)

… vs Bohm limit: $t_B \sim r_g/c \quad \ll \quad t_{\rm acc}$

⇒ expect sharp cut-off $\varepsilon_{\rm cut}$ well below Bohm limit



→ generalized Fermi in strong turbulence[2]:

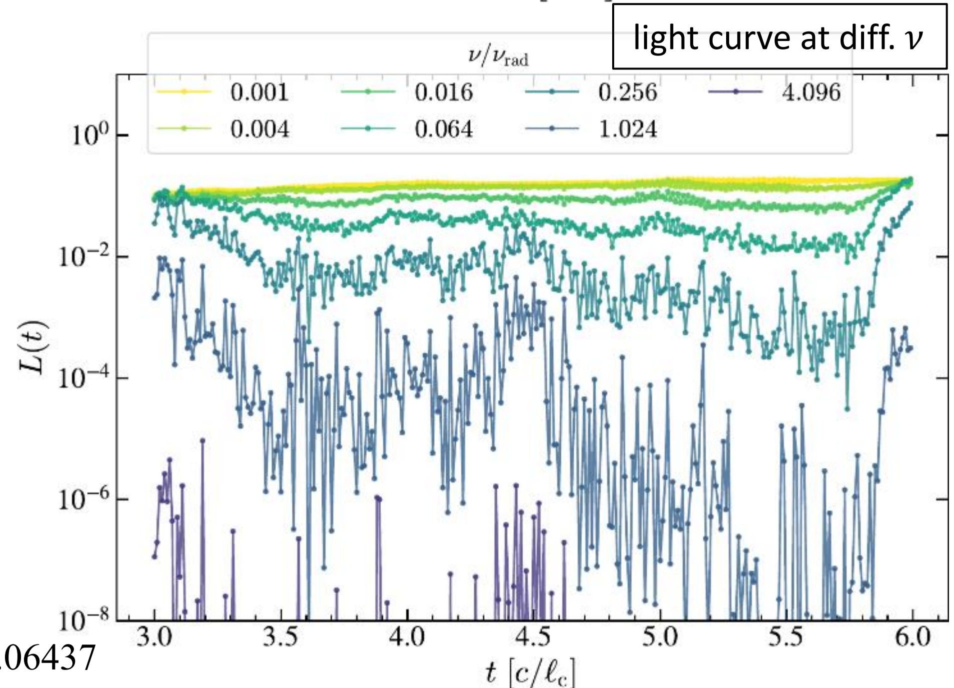
… fast acceleration in localized regions ⇒ extension of spectrum beyond expected $\varepsilon_{\rm cut}$, up to Bohm limit

… characteristic features:

steepening of spectrum,

time variability (weak at low ν, high at high ν)

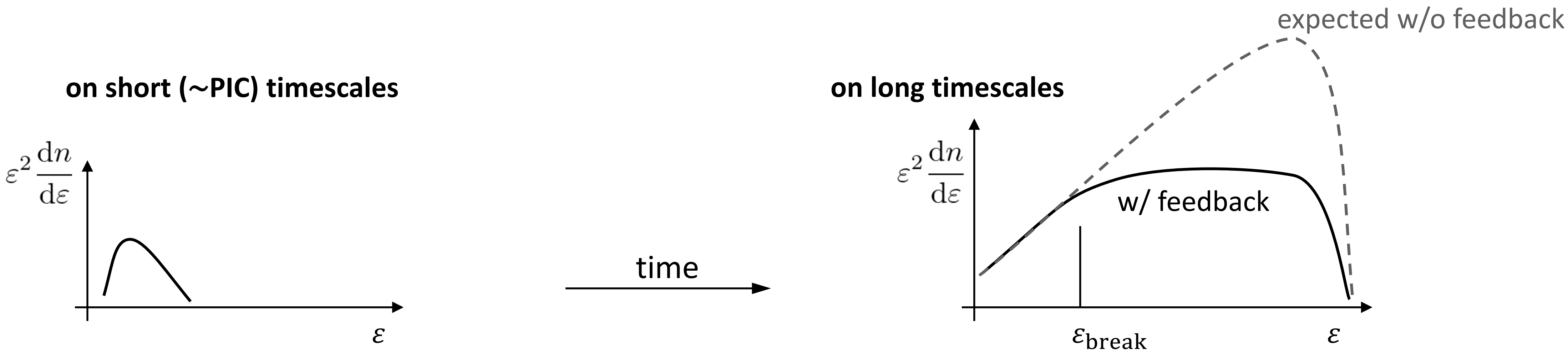
… of direct application to extreme sources, e.g. Crab nebula



Refs: 1. Wong, Zhdankin, Uzdensky + 19, 25 2. M.L., Bresci, Gremillet, arXiv:2509.06437

Evolution on ``long'' timescales: turbulence damping and self-regulated acceleration

→ particle acceleration = sink of energy for turbulence: ⇒ slowdown of acceleration on long timescales
… higher energy particles ↔ larger mean free path ↔ source of viscosity + diffusivity ⇒ turbulence damping



→ consequences:

… damping self-regulates particle acceleration, bounds available energy reservoir to $u_{\rm part.} / u_{\rm turb.} \sim c / v_A$

… w/ feedback, particle energy spectrum changes to broken powerlaw, with flat (index ~ 2) portion

… of direct interest to BH coronae[2], where Ice Cube data suggests that to $u_{\rm part.} / u_{\rm turb.} \sim O(1)$

… or in the context of blazars, PWNe, where $u_{\rm part.} / u_{\rm turb.} > 1$?

Refs.: 1. Eichler 79, Eilek 79, … Kakuwa 16 …, M.L., Murase, Rieger 24 2. ML + Rieger 25

Summary + conclusions

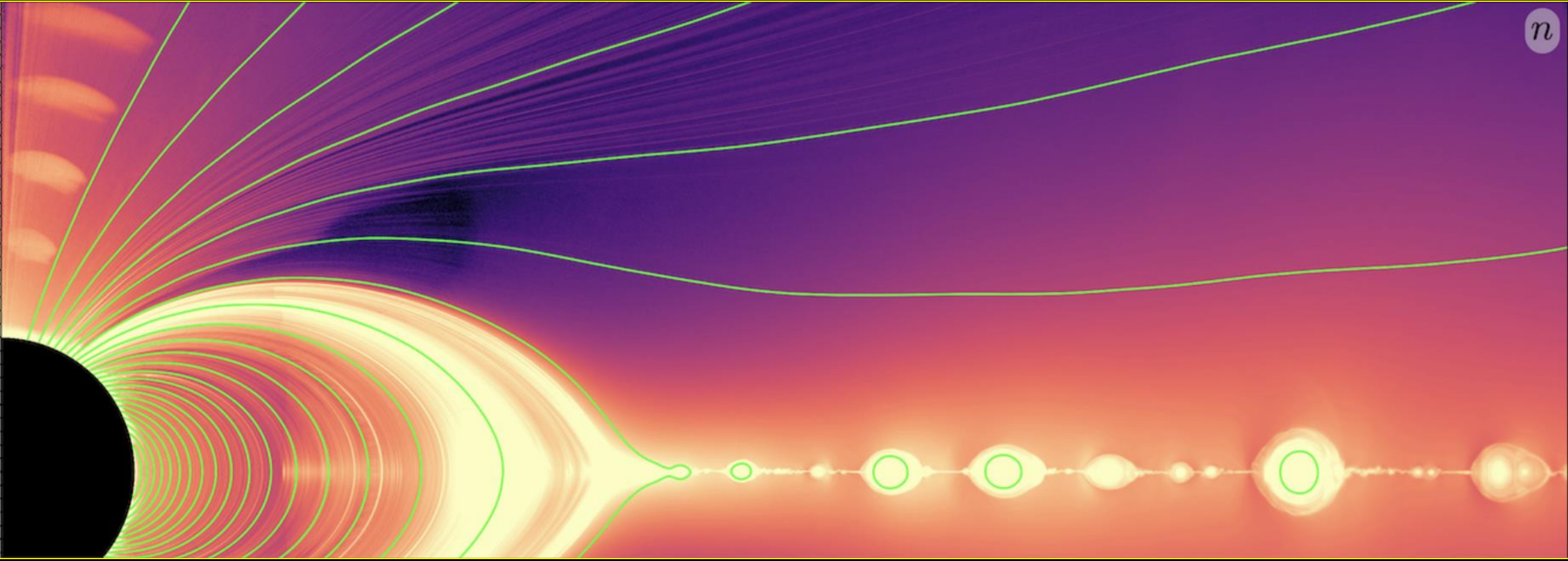
→ shock acceleration (relativistic):
… spectral indices $s \sim 2 - 2.3$
… mildly relativistic: fast (?) acceleration at quasi-parallel, e −injection issue
… relativistic + magnetized: no acceleration (?)
… relativistic + weakly magnetized: acceleration in self-generated turbulence

→ turbulence (strong, relativistic):
… powerlaw spectra on short timescales: indices $s \sim 4$ (sub-rel.) to $s \sim 3$ (rel.), $s \sim 2$ (ultra-rel.)
… long timescales: transition to broken powerlaw at ~equipartition, with $s \sim 2$
… detailed mechanism: generalized Fermi, dominated by sharp dynamic bends of magnetic field lines

→ reconnection (relativistic, no guide field):
… broken powerlaw spectra: break at $\varepsilon_{\rm break} \sim \sigma\, m\, c^2$, indices $s \sim 5$ (sub-rel.) to $s \sim 3$ (rel.), $s \sim 2$ (ultra-rel.)
… acceleration mechanism: partly in non-ideal E, partly à la Fermi in generated turbulence
… w/ guide field: steeper spectra

→ applicability and discrimination between scenarios:
… cannot distinguish acceleration mechanisms on the basis of spectra alone: $s \sim 2$ is not generic to shocks…
… however, different maximum energies based on different acceleration rates
… different signatures in polarization (?)

Particle acceleration in (relativistic) magnetic reconnection



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(Relativistic) collisionless reconnection -- overview

→ general scheme[1]:

… dissipation of magnetic energy through annihilation of alternating component of adjacent field lines…

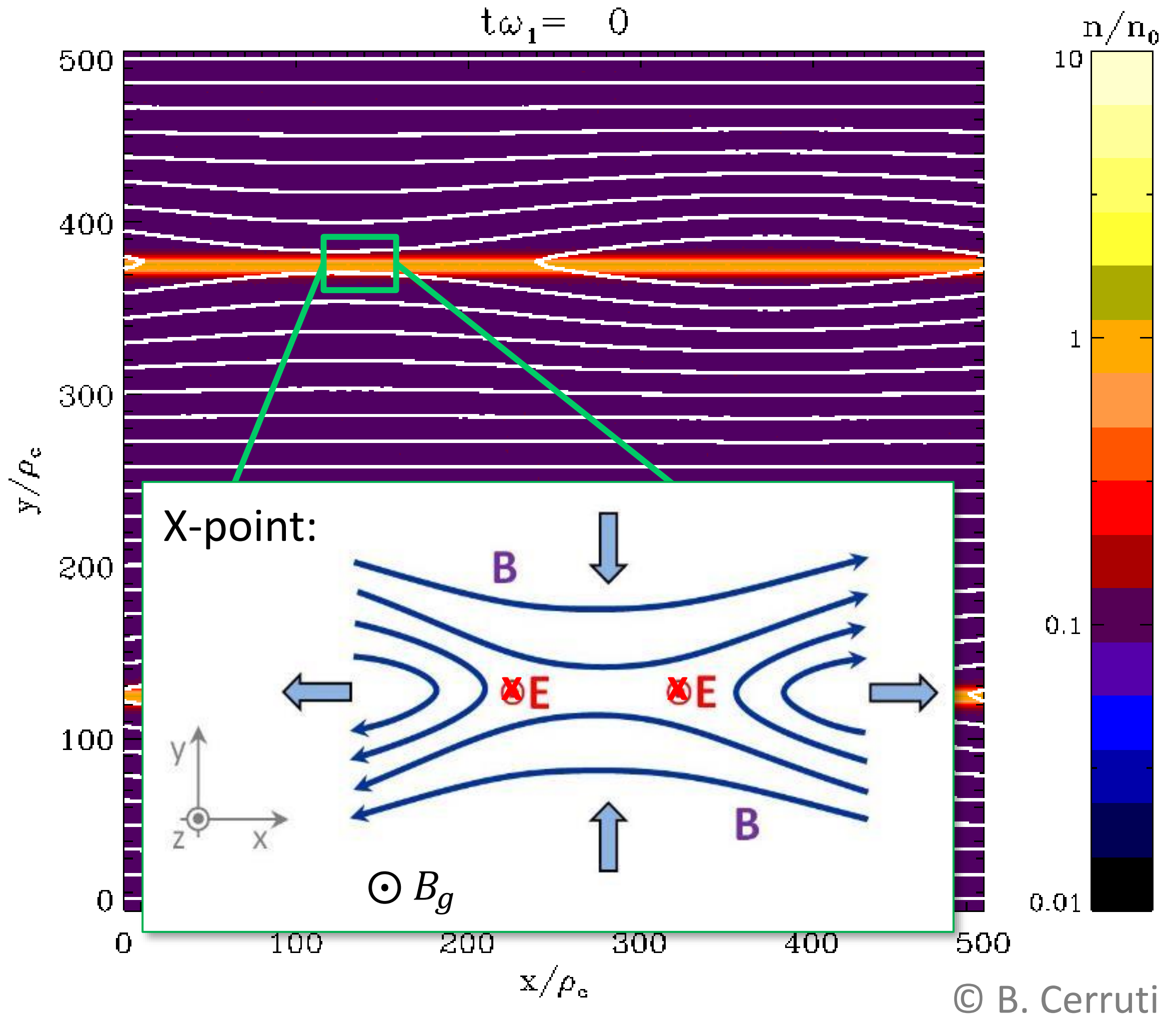
… initialization through instabilities (aka tearing) generating X-point region where dissipation occurs …

… dynamics → near-steady state: inflow of plasma into X-point at velocity $\boldsymbol{v_E}$, outflow along main axis at u_A…

… key parameter: reconnecting electric field, ~ uniform across diffusion region,

$$E_x \simeq (v_E/c)\, B_{\rm rec} \simeq 0.1\, B_{\rm rec}$$

… simplest approximation: $t_{\rm acc} \simeq \dfrac{p}{eE_x} \simeq O(10)\, t_{\rm g,\,rec}$



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… in reality, multiple channels: E_x at X-point, Fermi-type processes in surrounding turbulence…

… key parameters: σ + guiding (non-annihilating) magnetic field B_g

Refs.: 1. Zenitani + Hoshino 01, … , Lyubarsky 05, …, Cerutti+13, Sironi+Spitkovsky 14, Kagan+15, Werner+18, Guo+21, Zhang+23

Spectra of accelerated particles in relativistic reconnection

→ spectral features:

... key parameters: magnetization σ
+ strength of guide field B_g

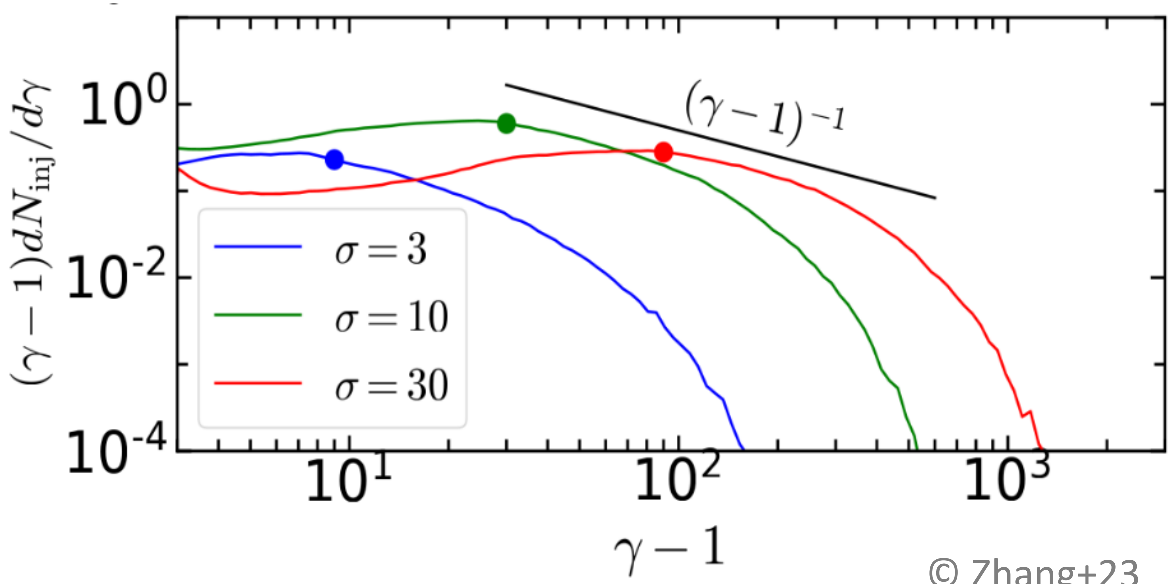
... characteristic spectrum:

mean Lorentz factor: $\gamma_{\rm break} \sim 3\,\sigma$,
[for e in $e - i$ reconnection: $\gamma_{\rm break} \sim 3\,\sigma\, m_p/m_e$]

spectral slope $s \simeq 4 \;\rightarrow 2$ (harder with larger σ, lower B_g)

... acceleration rate: ~Bohm up to mean energy, slower above

→ applications and open questions:
... $\sigma \gg 1$: in vicinity of compact objects (NS, BH),
e.g. rapid flares with mean energy $\sim \sigma\, mc^2$



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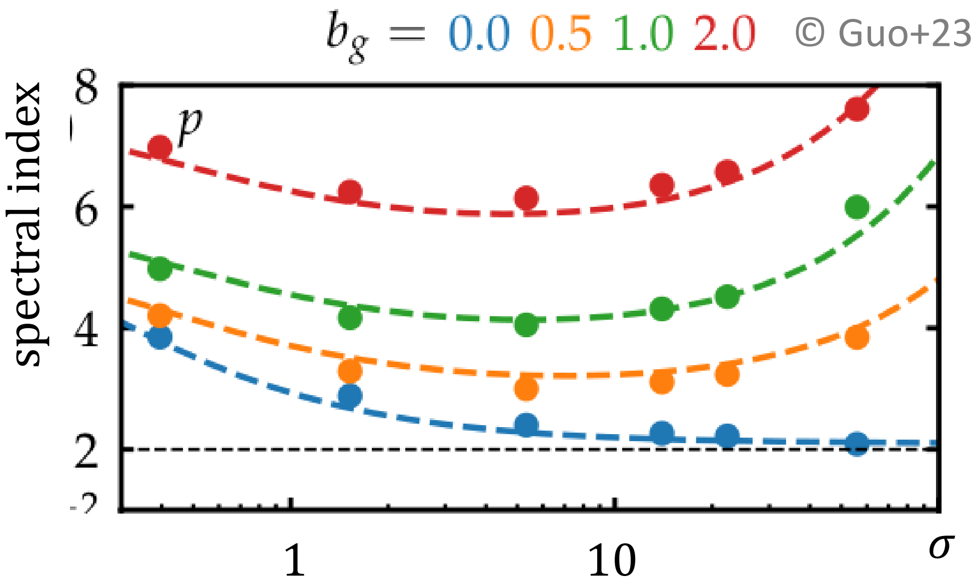

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Open questions: connection to macroscopic (astrophysical) scales

→ reconnection – turbulence:

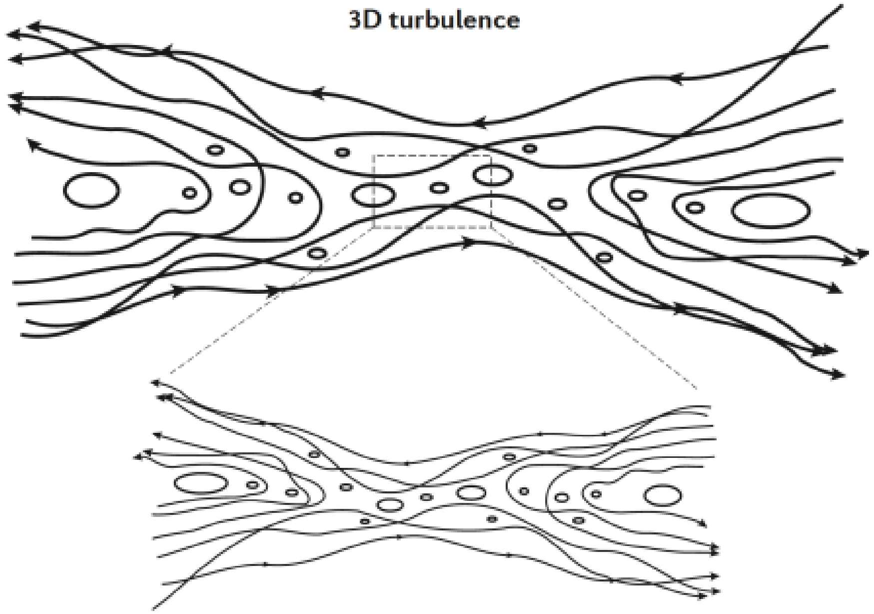
… reconnection generates turbulence, turbulence generates reconnection: does turbulence affect macroscopic reconnection?

… e.g. blazars, emission region $L \sim 10^{16}$cm, vs current-sheet thickness $r_g \sim 10^{6}$cm …??

… if turbulence develops:

→ consequence for reconnection rate ($\Rightarrow E_x$) ?

→ consequence for acceleration physics (t_{acc}, s) ?



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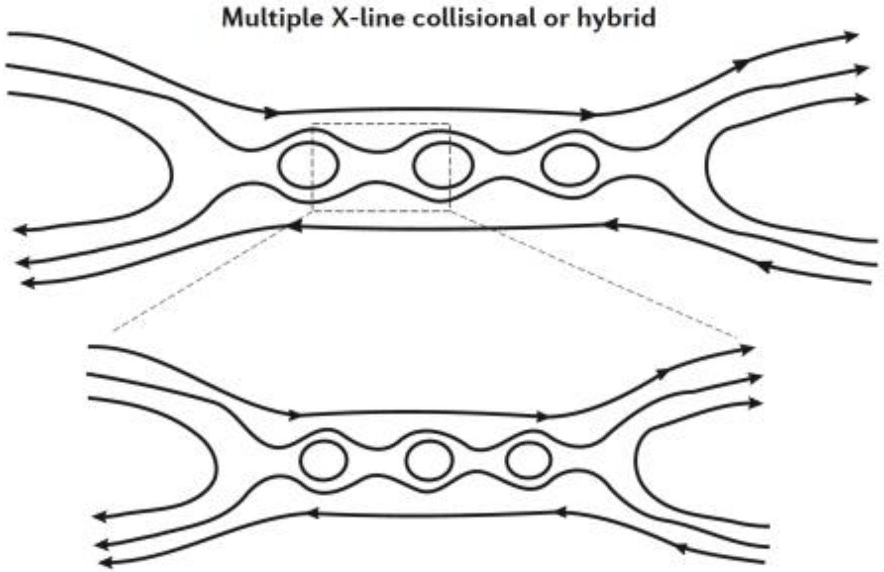

Refs.: 1. Ji+Daughton 22