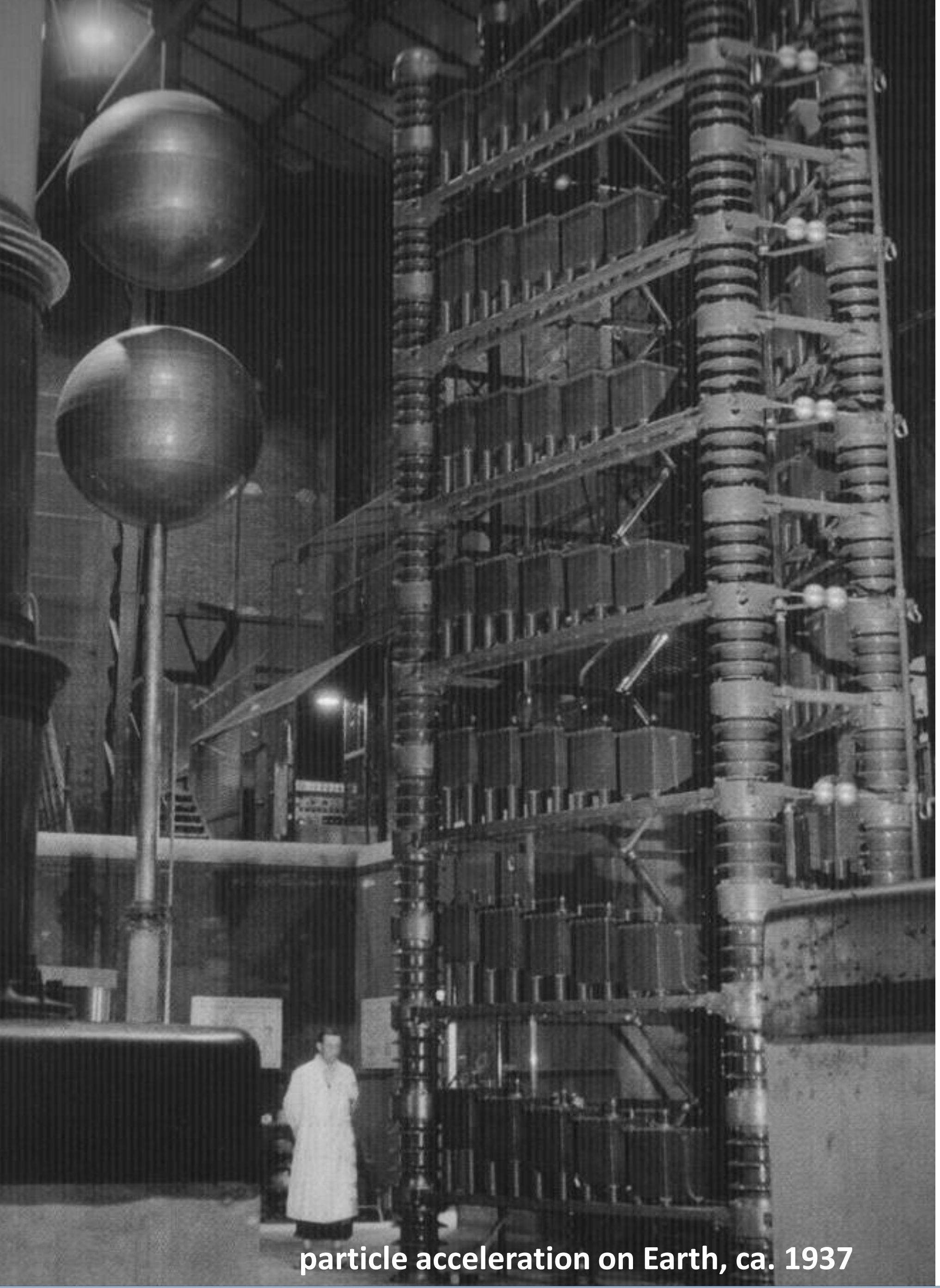
Magnetized turbulent plasmas as high-energy particle accelerators



particle acceleration on Earth, ca. 1937

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+ A. Bykov (Ioffe), M. Malkov (UCSD), L. Comisso (Columbia U.), K. Murase (Penn State), F. Rieger (MPIPP), L. Sironi (Columbia U.)

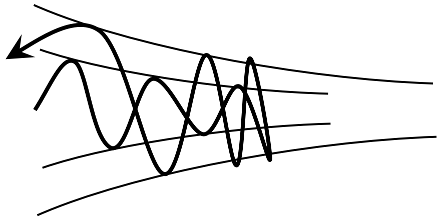
The pioneering studies of E. Fermi (1949, 1954)

→ a key problem for particle acceleration in astrophysical plasmas: high conductivity implies small electric fields… in practice $\boldsymbol{E} \sim 0$ everywhere on length/time scales of interest

Debye length scale: $\lambda_{\rm D} \sim 10^3\,{\rm cm}\;\; T_4^{1/2} n_0^{-1/2}$

ion plasma time scale: $1/\omega_{\rm pi} \sim 10^{-3}\,{\rm s}\;\; n_0^{-1/2}$

→ Fermi's solution: $\boldsymbol{E} = 0$ in plasma rest frame, but $\boldsymbol{E} = -\boldsymbol{v_E} \times \boldsymbol{B}/c$ in magnetized plasmas moving at $\boldsymbol{v_E}$
… particles can gain energy from motional electric fields *(more precisely: differences in $\boldsymbol{E}$, or $\boldsymbol{v_E}$!)*



Fermi type A reflection of a cosmic-ray particle

→ details: assume interaction of particle with "magnetized cloud" moving at $\boldsymbol{v_E}$ in lab frame…
in cloud rest frame: elastic scattering ($\boldsymbol{E} \sim 0$)
in lab frame: energy gain, or loss

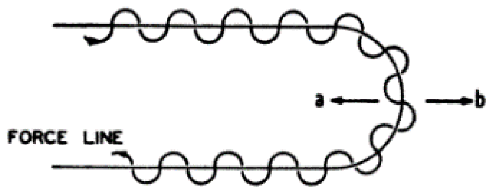


FIG. 1. Type *B* reflection of a cosmic-ray particle.

→ kinematics: Lorentz transform to center frame, scattering and back gives

$$\Delta\epsilon/\epsilon = \gamma_E^2 \left(1 + \boldsymbol{v_E}\cdot\boldsymbol{v}'/c^2\right)\left(1 - \boldsymbol{v_E}\cdot\boldsymbol{v}/c^2\right) - 1 \simeq \mathcal{O}(v_E^2/c^2)$$

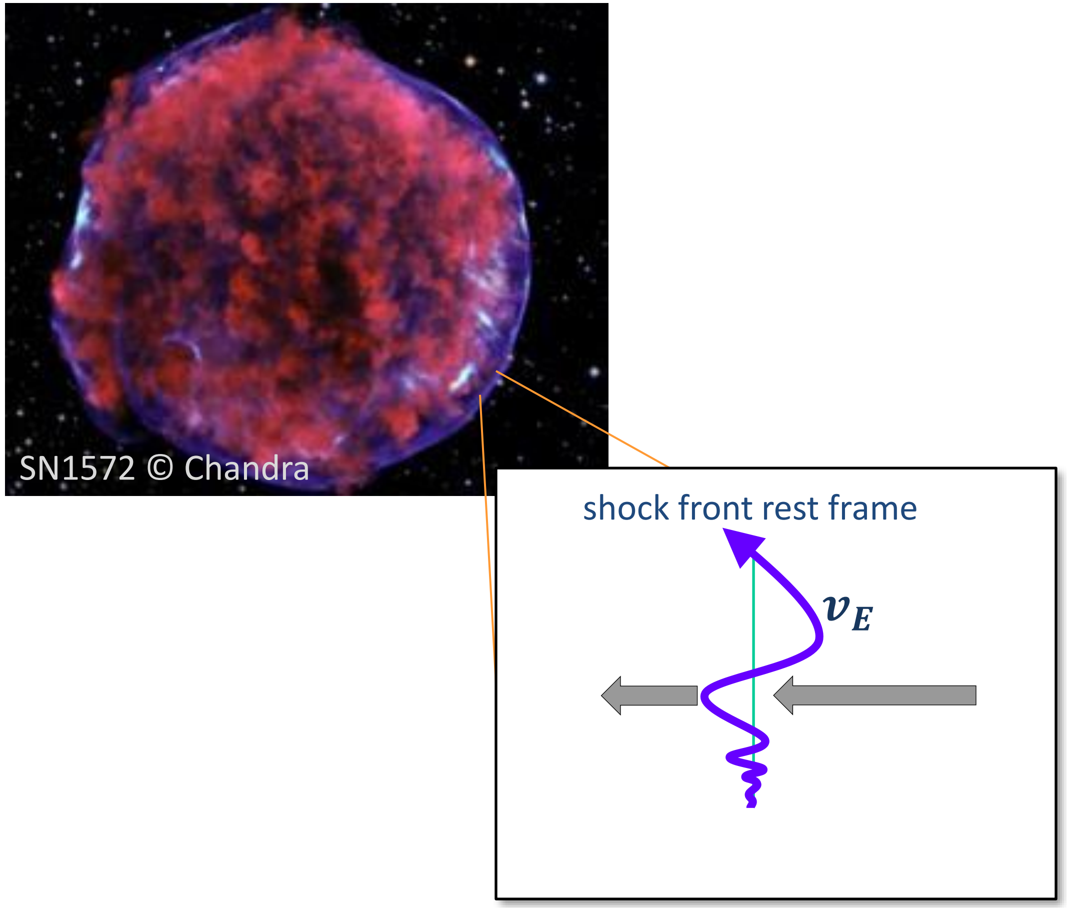
Shock waves as particle accelerators in HE astrophysics: the standard scheme

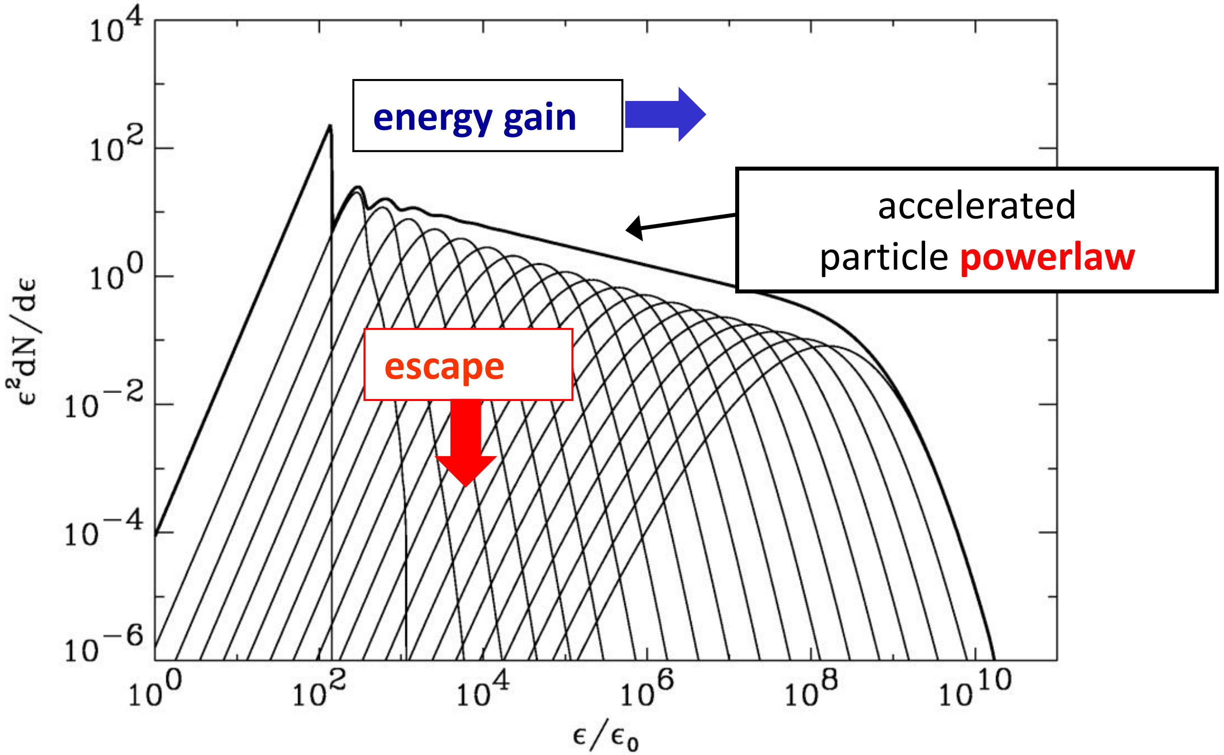
→ particle acceleration in MHD flows:

… particles draw energy from electric field carried by plasma (ideal Ohm's law): $\boldsymbol{E} = -\boldsymbol{v}_{\boldsymbol{E}} \times \boldsymbol{B}/c$

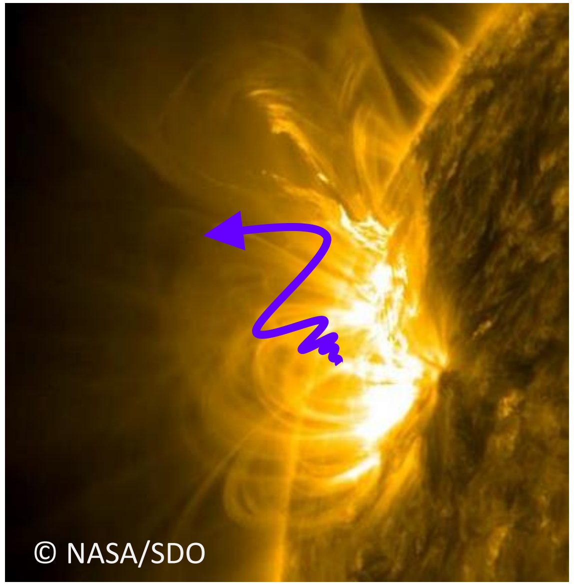
… often picture as kinematics of interactions back and forth across shock front…

… shapes spectrum $dn/d\epsilon \propto \epsilon^{-2\ldots}$

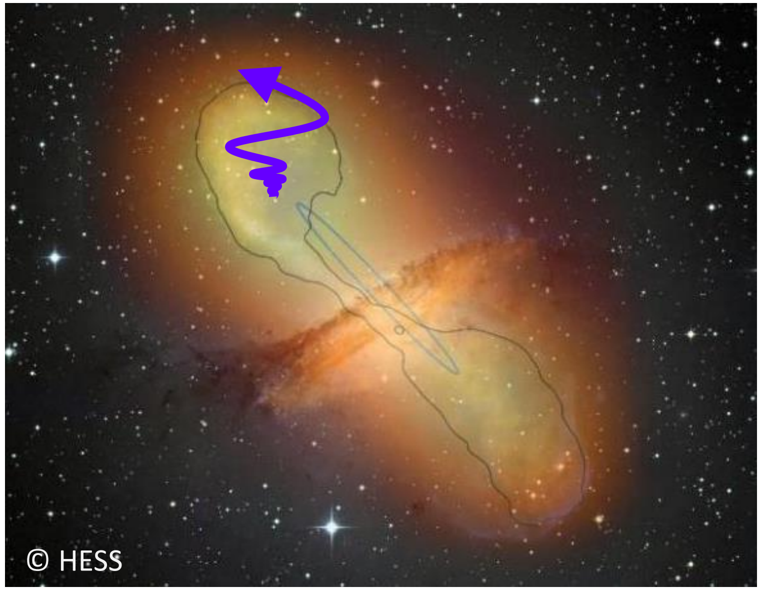




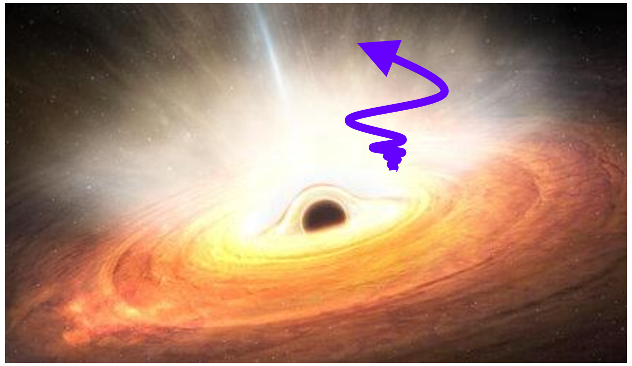
Stochastic particle acceleration à la Fermi: a standard acceleration scheme in astrophysics



… from acceleration in solar flares



… to acceleration in extra-galactic jets…



… to AGN cores…

→ a stochastic process of acceleration:

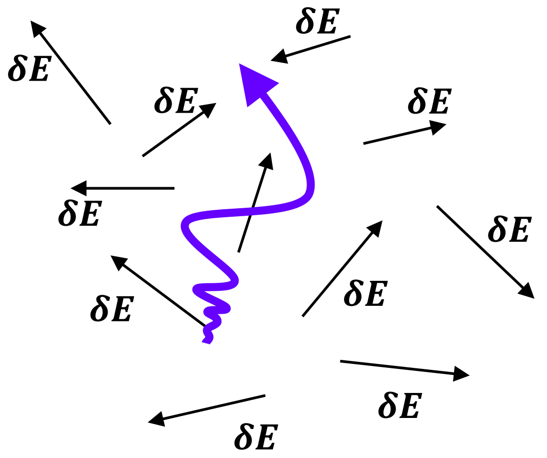
… particles diffuse in momentum space through energy gain- or loss-interactions

… expected acceleration timescale $t_{\mathrm{acc}} \propto 1/v_E^2$ with v_E characteristic random velocity (e.g. Alfvén)

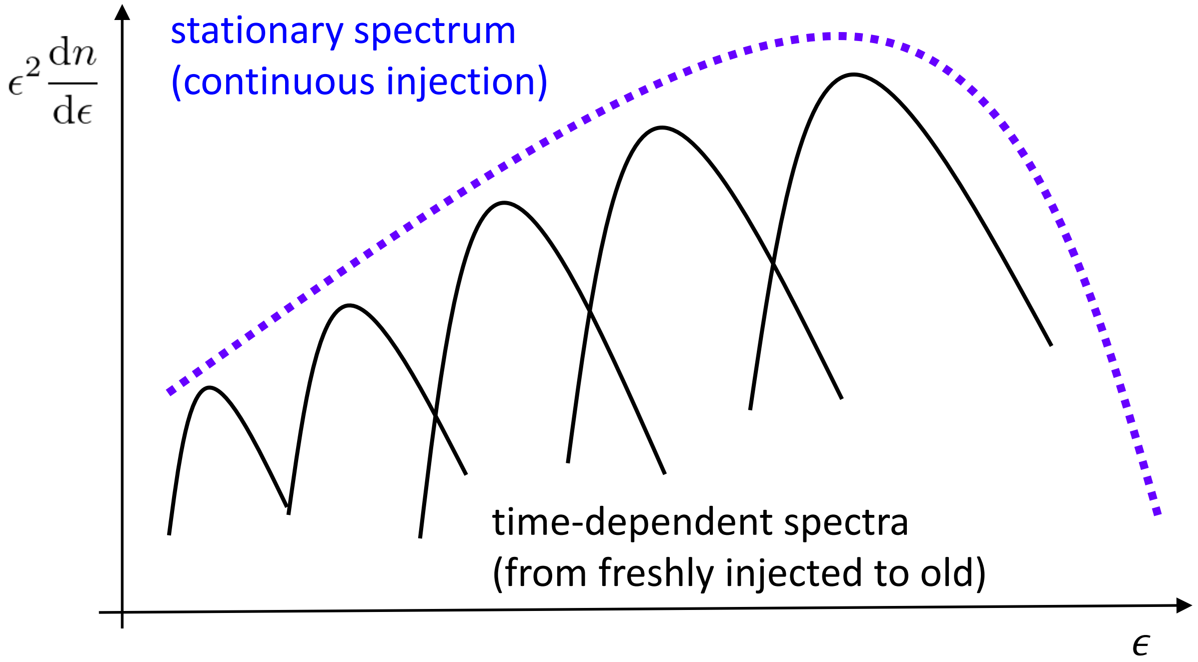
… long-standing issue: acceleration mechanism? … origin of electric field? … consequences? … relativistic regime?

Stochastic particle acceleration in astrophysics

… **a key question:** how to describe stochastic acceleration in random electric fields…



… **a well-known signature:** hard spectra = most of the energy at the highest energies…



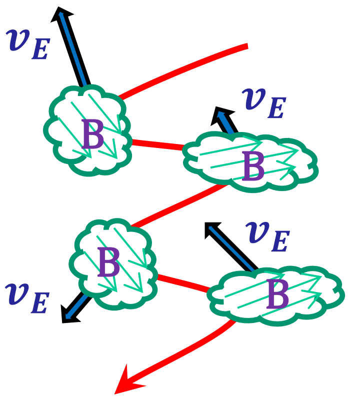
→ **a non-linear, multi-scale problem:**

… e.g. in turbulence: charged particles build the e.m. fields that transport them …

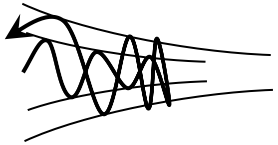
⇒ HPC numerical simulations, e.g. MHD or « particle-in-cell » (PIC) method

Detailed mechanism of acceleration in turbulent plasmas?

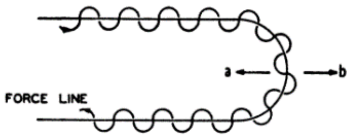
2nd order Fermi (49,54) acceleration: scattering off discrete **magnetized structures**, with $\boldsymbol{E} = 0$ in local rest frame



$$\boldsymbol{E} = -\boldsymbol{v}_E \times \boldsymbol{B}/c$$

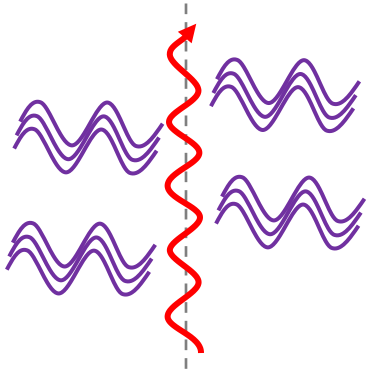


Fermi type A: bounce on magnetic mirror



Fermi type B: bounce on curved field line

Quasilinear picture: transport in a bath of small-amplitude **linear waves** (e.g. Alfvén, magnetosonic)…
… energy gain through resonant interactions



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

$$\boldsymbol{\delta E} = -\boldsymbol{v}_\varphi \times \boldsymbol{\delta B}/c$$

… a schizoid pattern connected to an old debate in turbulence physics: structures vs waves …

… in practice, assume diffusion coefficient and use Fokker-Planck:

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

A recurring debate: waves vs structures… impact on cosmic-ray transport + acceleration?

→ Quasilinear calculations of diffusion coefficients:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = q\,\hat{\boldsymbol{p}}\cdot\boldsymbol{\delta E} \Rightarrow \langle \Delta p^2 \rangle = \int_0^{\Delta t} \mathrm{d}t_1 \int_0^{\Delta t} \mathrm{d}t_2 \ldots \langle \delta E_i\left(\boldsymbol{x}(t_1),\,t_1\right)\delta E_j\left(\boldsymbol{x}(t_2),\,t_2\right)\rangle$$

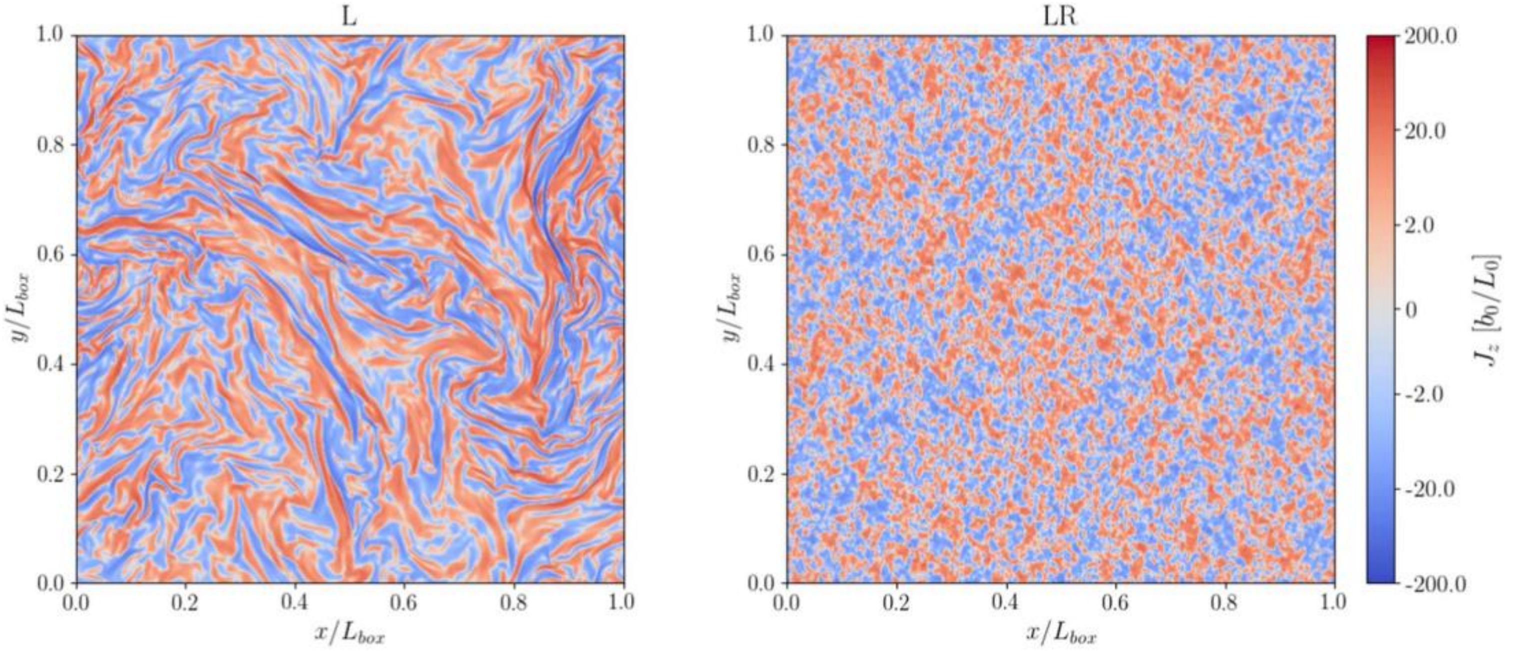
$$\sim \Delta t \int \mathrm{d}\boldsymbol{k} \int^{+\infty} \mathrm{d}\tau\, \mathcal{R}_{\boldsymbol{k}}(t)\, \mathcal{P}_{\delta B_{\boldsymbol{k}}}$$

⇒ diffusion coefficient: $D_{pp} \equiv \dfrac{\langle \Delta p^2 \rangle}{\Delta t}$

(key) assumption for practical calculations:
$\boldsymbol{\delta B}$ ~ Gaussian random field
[as sum of random phased δB_k]
… all information in power spectrum $P_{\delta B_{\boldsymbol{k}}}$

→ Waves or structures: RPA means waves are incoherent, while phase coherence builds up structures … as outliers to the distribution (non-Gaussianity – intermittency)

left: actual MHD simulation



right: quasilinear vision, randomized phases

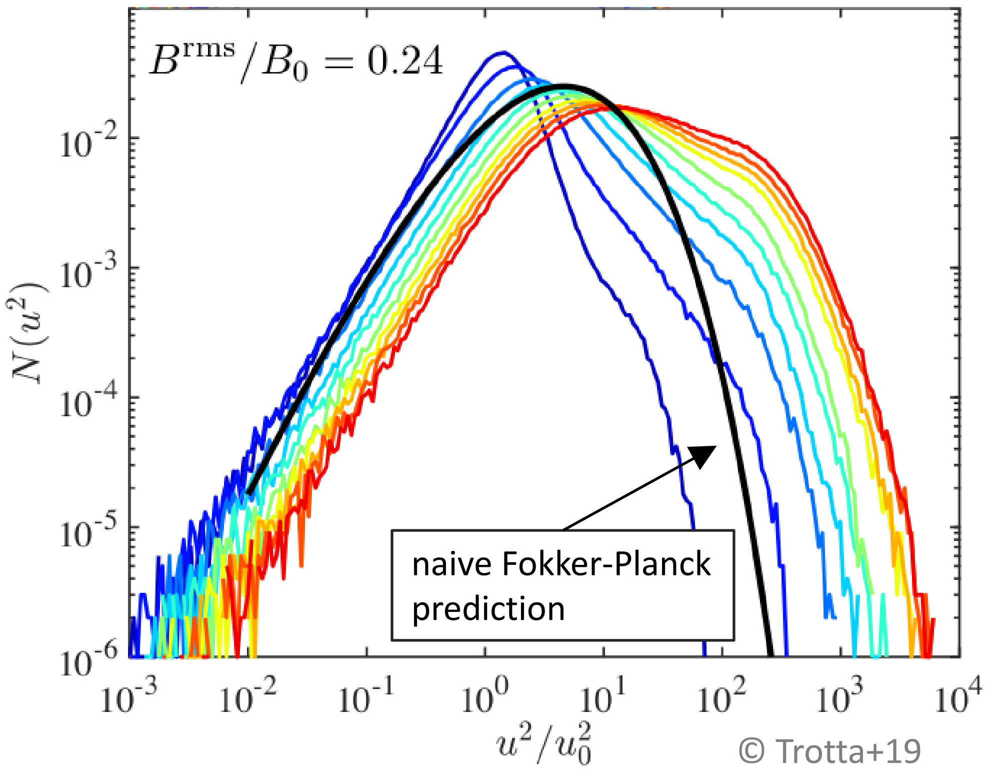
Insights from particle tracking in MHD numerical simulations

→ MHD / hybrid simulations[1] of magnetized turbulence + particle tracking:

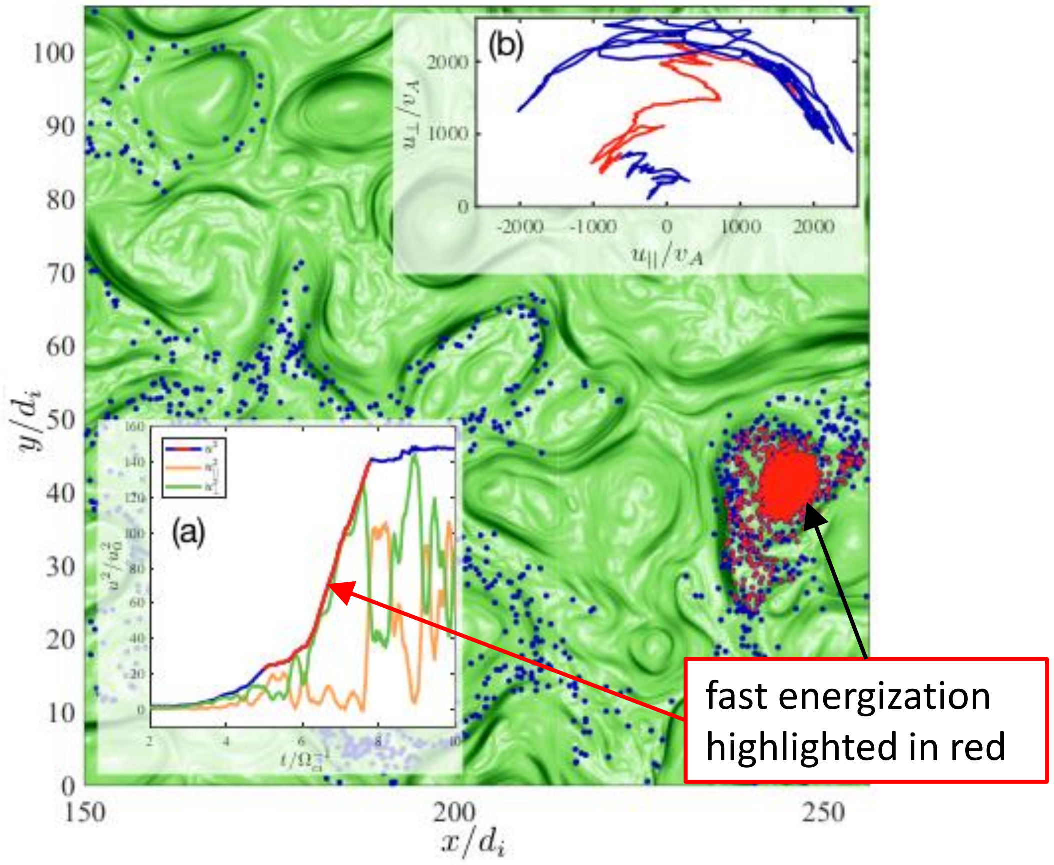
… recent simulations provide evidence for fast acceleration in localized regions …

… non-trivial energy distributions (~not simple Fokker-Planck)[2] …

energy distribution



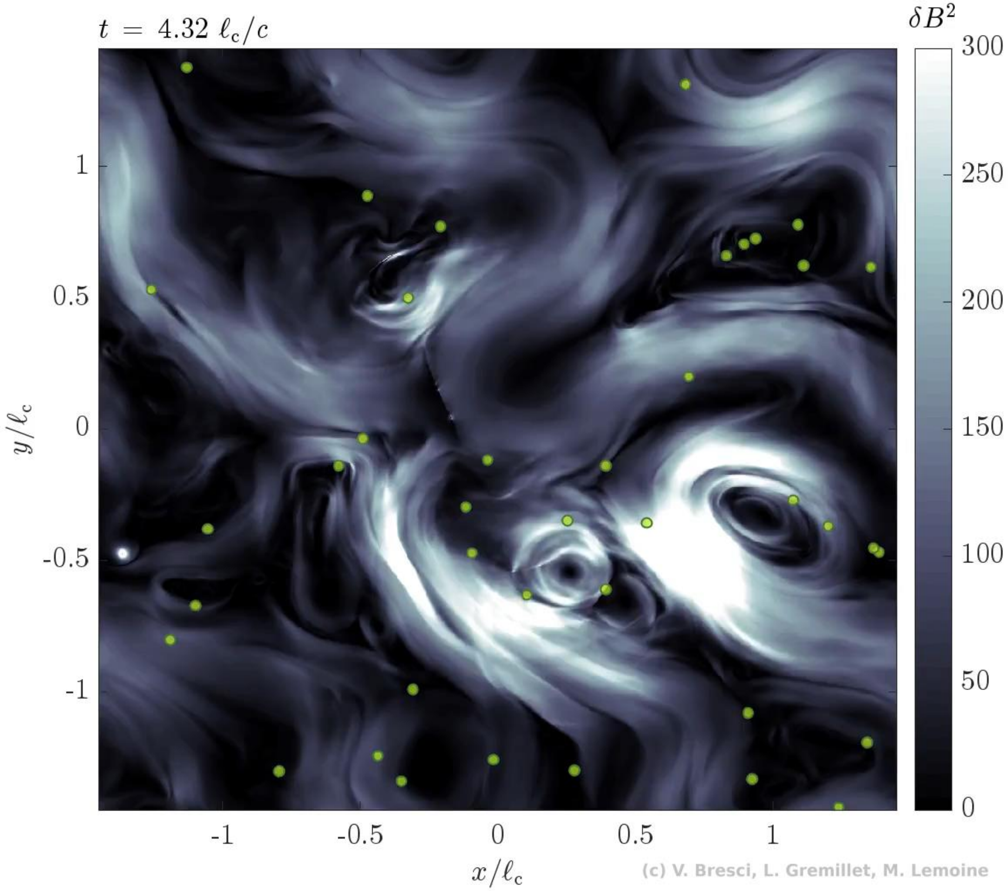
particle tracking in 2D sim.

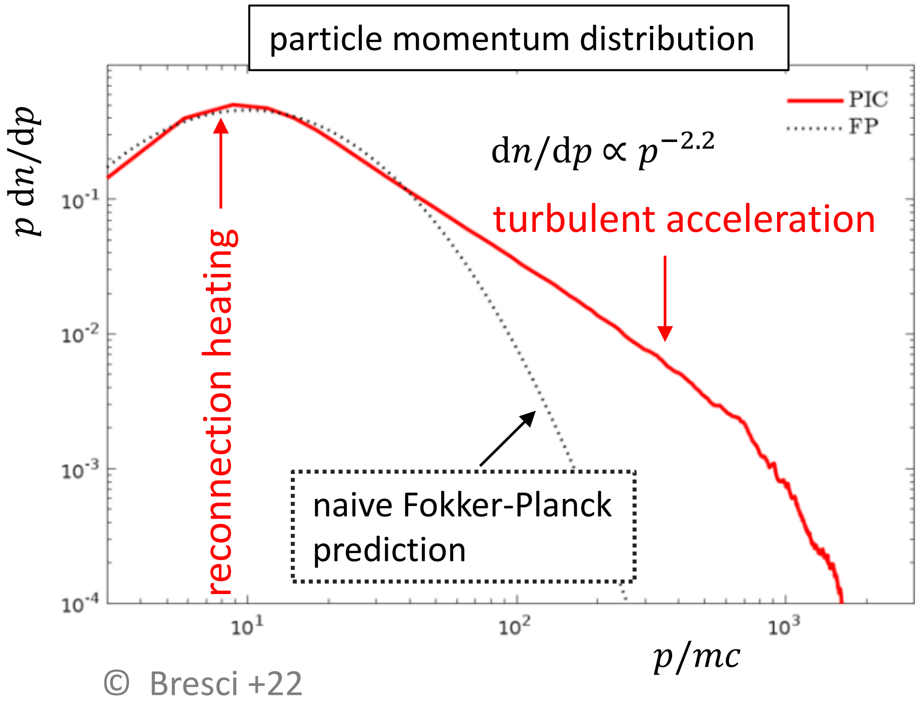


Refs: 1. Dmitruk+03, Arzner+06, …, Isliker+17, Trotta+19, Pezzi+22 2. see however results by X. Sun, C. Demidem

Insights from numerical simulations

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





→ unexpected[2] emergence of powerlaws, $dn/dp \propto p^{-s}$ with $s \sim 2$ … 4, signature of a rich phenomenology…

→ in relativistic regime, diffusion coefficient $D_{pp} \sim 0.2\, \sigma\, p^2\, c/l_c$ (scaling w/ Alfvén 4-velocity)

Refs: 1. Zhdankin+17,18,20, … Wong+ 19, Comisso+Sironi 18, 19, Nättilä + Beloborodov 20, Vega+20, … Bresci+22
+ many MHD/hybrid (Dmitruk+03, Arzner+06, …, Isliker+17, Trotta+19, Pezzi+22)
2. discussion in M.L. + Malkov 20

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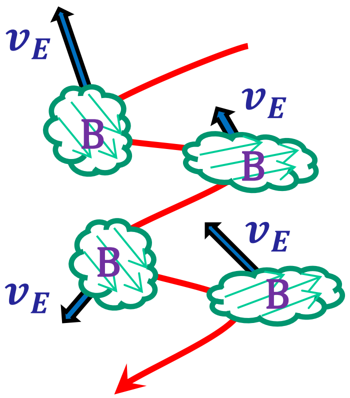
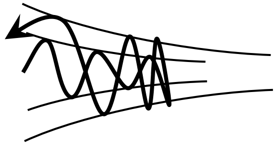


$$\boldsymbol{E} = -\boldsymbol{v}_E \times \boldsymbol{B}/c$$



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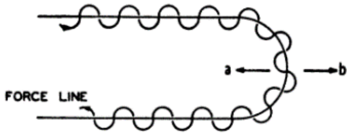

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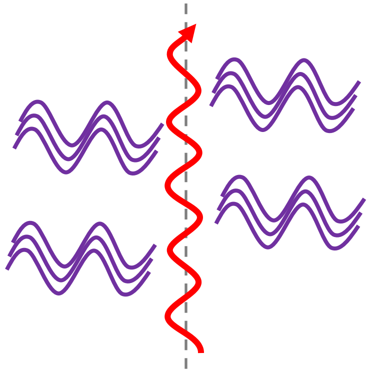


… interactions dominated by resonances e.g. $k\, r_g \sim 1$ …

$$\boldsymbol{\delta E} = -\boldsymbol{v}_{\boldsymbol{\varphi}} \times \boldsymbol{\delta B}/c$$

… in practice, assume diffusion coefficient and use Fokker-Planck: $$\frac{\partial}{\partial t} f(p,t) = \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p} f(p,t)\right]$$

→ outline:

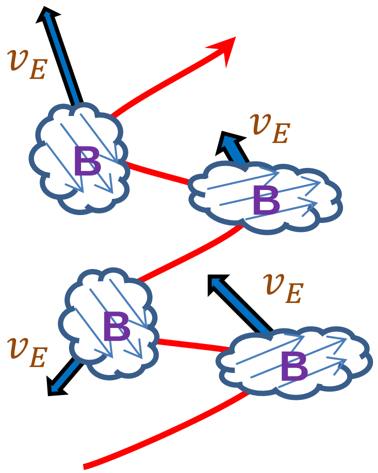
1. generalize Fermi acceleration to turbulence, including relativistic ($v_A \sim c$)…
   ⇒ Fermi prevails in strong turbulence due to strong intermittency of velocity structures
   … and Fokker-Planck fails.
2. phenomenological application: acceleration in black hole coronae and Ice Cube neutrinos

Generalized Fermi acceleration in a random velocity flow

→ **Fermi acceleration:** in original Fermi scheme, particles gain energy by point-like, discrete interactions with moving scattering centers (carrying electric fields!)

… key difference for turbulence (or large-scale random velocity flow):

velocity flow $\boldsymbol{v_E} = \boldsymbol{c\, E \times B / B^2}$ is continuous…



→ **generalization to turbulence[2]:**

… many models[1], a direct connection to structures on various scales…

… follow particle momentum in the (non-inertial) frame where $\boldsymbol{E} = 0$

$$\frac{\mathrm{d}\gamma'}{\mathrm{d}\tau} = -\Gamma^0_{a\,b}\,\frac{p'^a\,p'^b}{m^2c^2}$$

… **inertial forces:** $\Gamma^0_{a\,b} \propto \partial_a u_{E\,b}$

… γ' comoving particle Lorentz factor

… in that frame, energy variation ∝ non-inertial forces characterized by velocity shear of $\boldsymbol{u_E}$ (4-velocity!)

→ fully covariant implementation of Fermi acceleration in turbulence, diffusion coefficient ∝ $(u_E/c)^2$

Refs: 1. Fermi 49,…, Bykov+Toptygin 83, Ptuskin 88, Chandran+Maron 04, Cho+Lazarian 06, Ohira 13, Brunetti+Lazarian 16, …

2. M.L. 19 [PRD 99, 083006 (2019)], 21 [PRD 104, 063020 (2021)]; see also previous works by Webb 85, 89

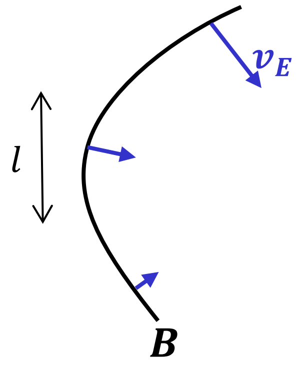
Generalized Fermi acceleration in magnetized turbulence

→ theoretical model[1]: $\dot{p} = \Gamma_l\, p$ (simplified expression in comoving frame)

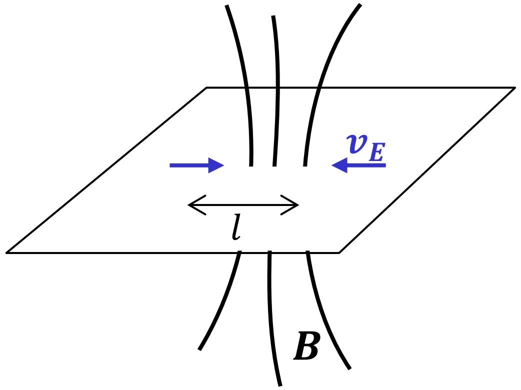
with Γ_l a random field: gradients of $\boldsymbol{v_E}$ coarse-grained on scale $l \gtrsim r_g$ …

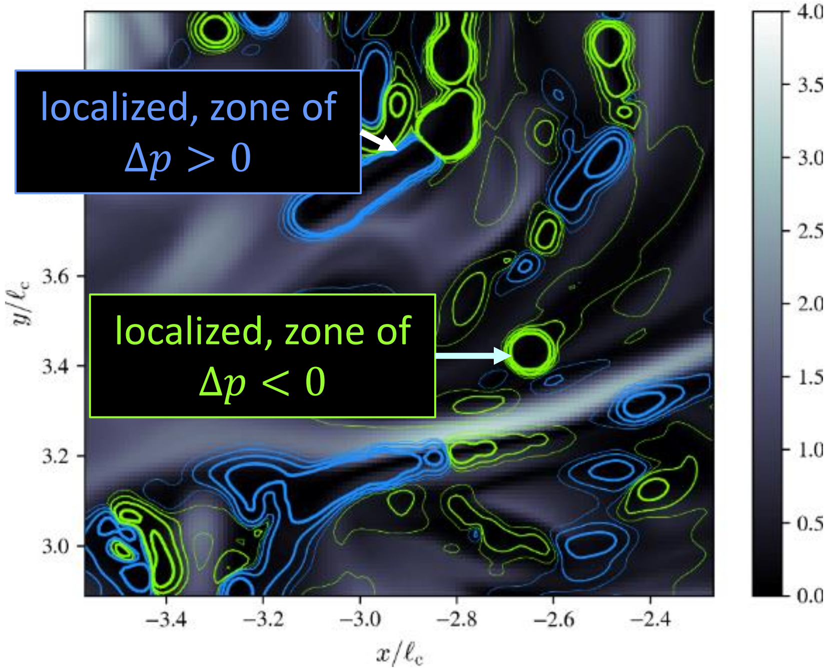
Γ_l from dynamic curved field lines, or dynamic perp. gradients (mirrors), or acceleration of field lines

Map of $\ln|\Gamma_l|$ in MHD 1024^3 sim.[2]
(no guide field: large-amplitude turb.)



$\Gamma_l \sim \Delta v_E / l$





→ Properties of the random force:

… (exponential) energy gain if $\Gamma_l > 0$, loss if $\Gamma_l < 0$

… Γ_l is non-Gaussian, highly localized in specific regions… (in large-amplitude turbulence)

… different particles experience different histories ⇒ powerlaw spectrum

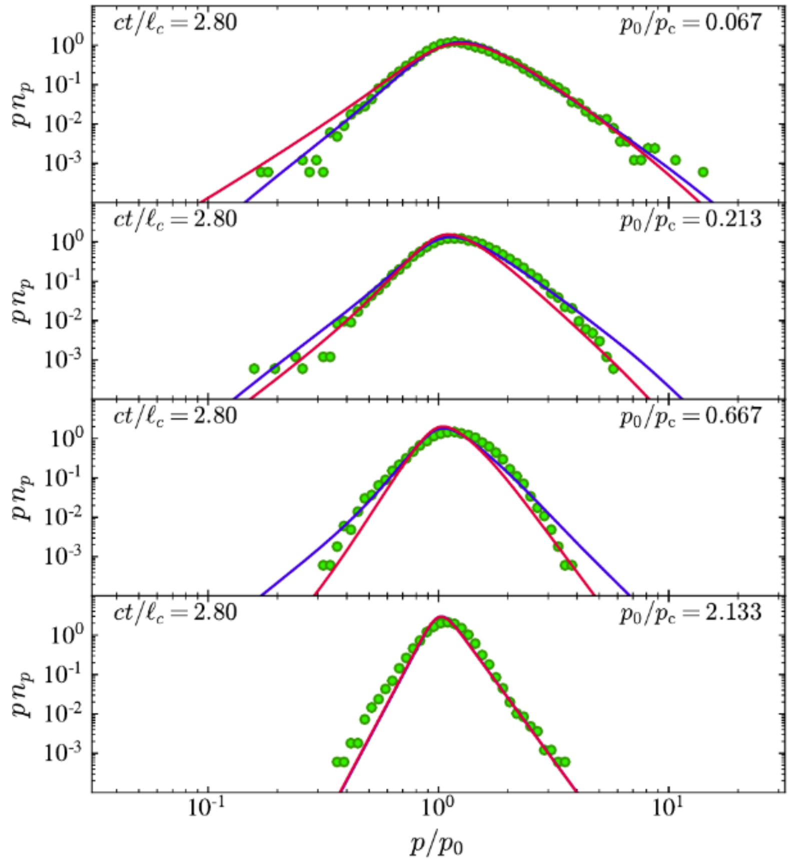
Refs.: 1. ML 21 [PRD 104, 063020 (2021)], ML 22 [PRL 129, 215101 (2022)] 2. Eyink+13, JHU database

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

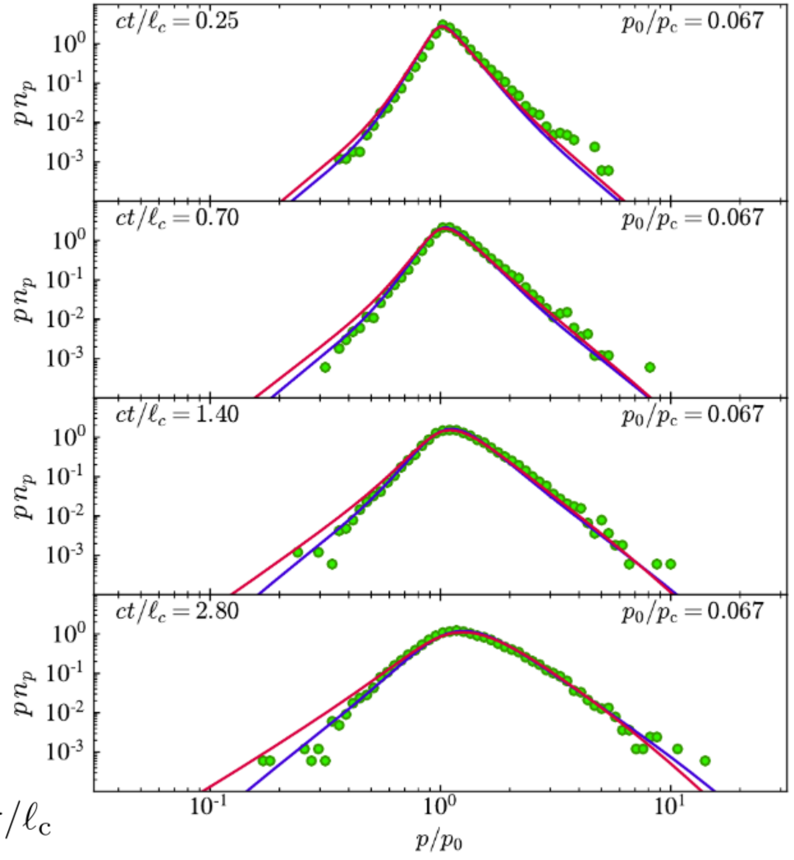
→ comparison to numerical data:

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

← increasing initial particle momentum p_0



← increasing integration time



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

⇒ model reproduces time- and energy- dependent Green functions… + produces powerlaw spectra $dn/dp \propto p^{-4}$

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

The (dominant?) role of the field line curvature

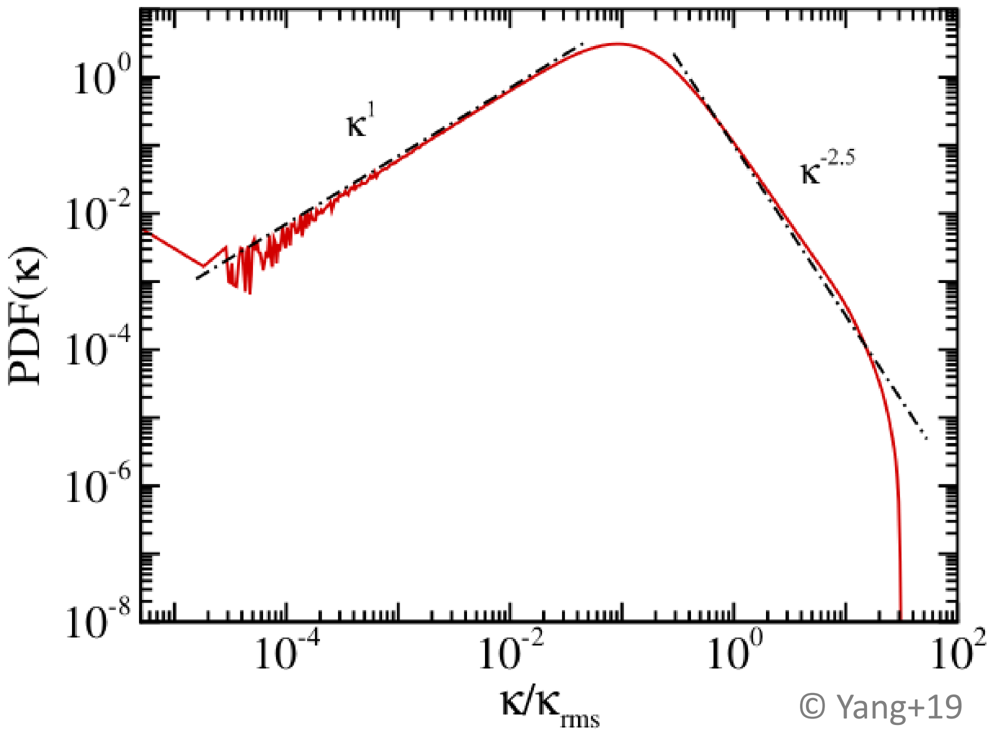
→ energization through curvature drift:

… a dominant process in reconnection physics[1]

… field line curvature: $\boldsymbol{\kappa} = \boldsymbol{b} \cdot \nabla \boldsymbol{b} \qquad (\boldsymbol{b} \equiv \boldsymbol{B}/|\boldsymbol{B}|)$

… statistics of κ: a powerlaw a large values[2], p.d.f.(κ) $\propto \kappa^{-2.5}$ ⇒ origin, connection to statistics of random force?

3D MHD simulation[2]



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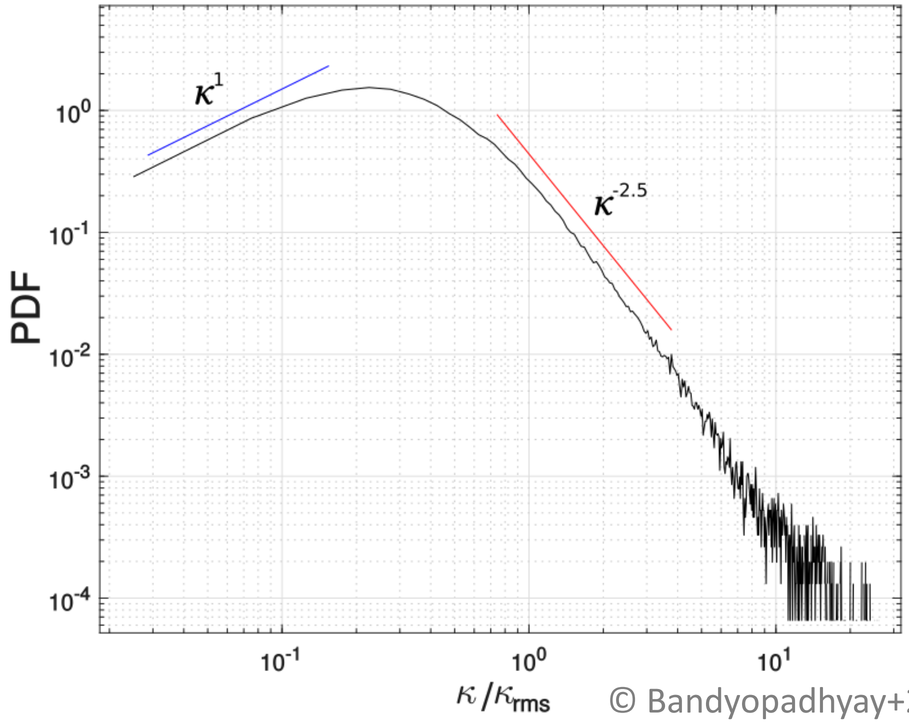
Solar wind data[3]



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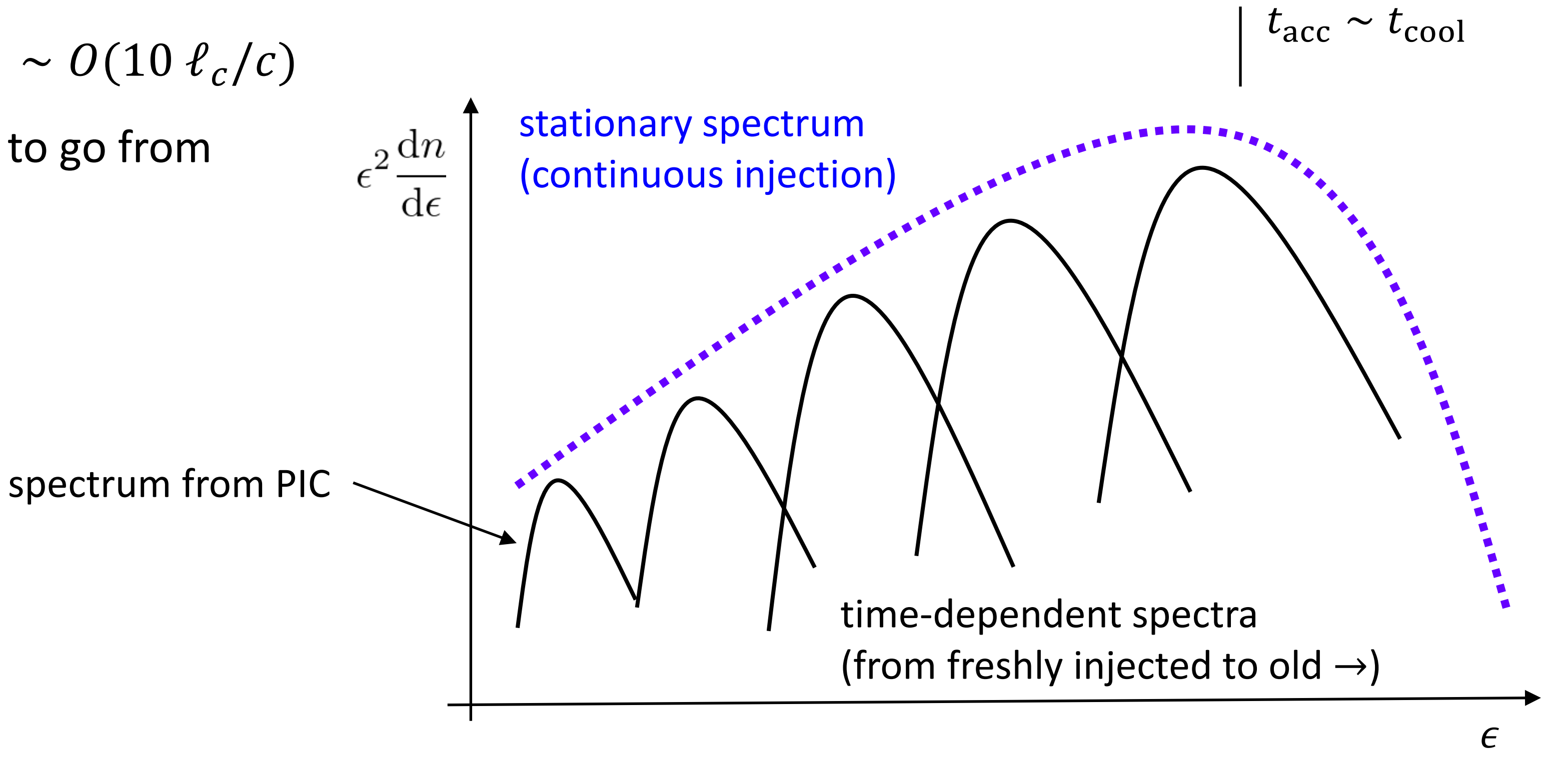
Refs.: 1. e.g. Drake+06, …, Dahlin+14, … 2. Schekochihin+01, Yang+19, Yuen+Lazarian20 3. Bandyopadhyay+20, Huang+20

Evolution on ``long'' timescales: from simulations to astrophysical objects

→ limited duration of simulations:

… in practice, simulations run for $T \sim O(10\, \ell_c/c)$

… PIC spectrum ~ Green's function to go from thermal to supra-thermal over T



… important:

(1) stochastic acceleration is diffusion + advection in momentum space…

(2) final spectrum depends on injection history + whether turbulence is sustained or not ("decaying")

(3) high-energy particles take most of the energy… until they exhaust the turbulence that feeds them!

Evolution on ``long'' timescales: self-regulation through turbulence damping

→ damping of turbulence by stochastic particle acceleration[1]:

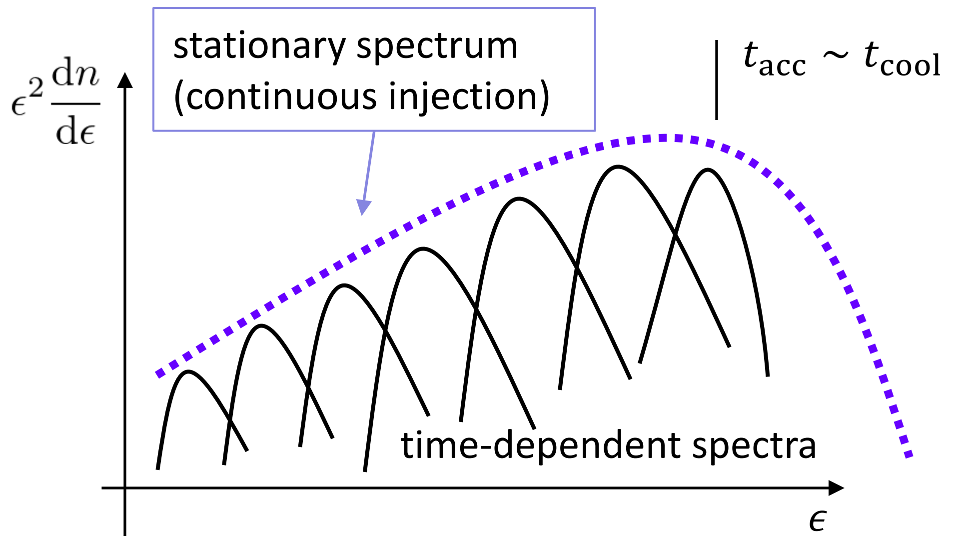
… wave-particle picture: cyclotron damping of resonant waves…

… in non-resonant Fermi: suprathermal particles bring in effective viscosity + diffusivity

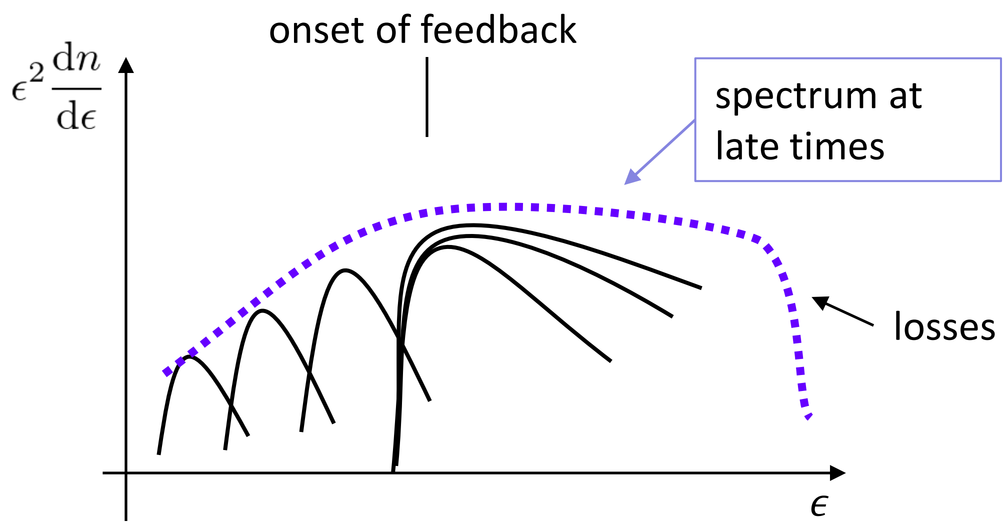
… simplified model[2]: incorporate energy loss in turbulent cascade through kernel describing where energy is drawn form in k-space for particles of momentum p…

⇒consequences for particle spectra: remodeled to broken powerlaw, constant energy/decade $dn/dp \propto p^{-2}$

particle acceleration w/o feedback



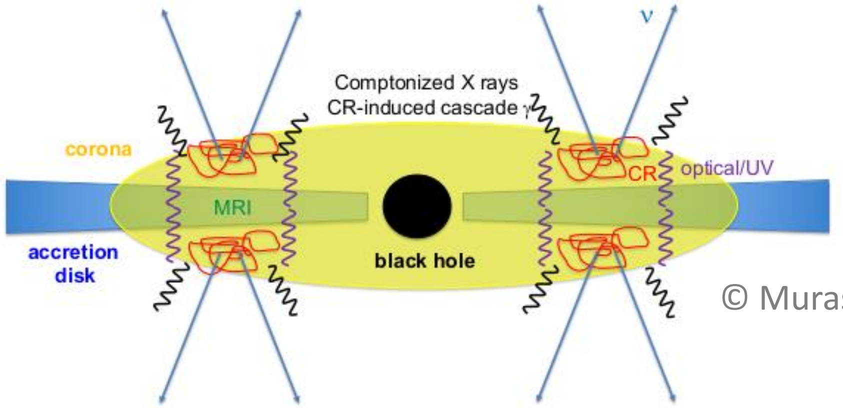
particle acceleration w/ feedback



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

Stochastic Fermi acceleration & high-energy neutrinos from NGC 1068

→ Ice Cube 22: excess of high-energy (1-10 TeV) neutrinos from nearby AGN NGC 1068…
… a possible scenario: stochastic acceleration in turbulent corona + $p-p, p-\gamma$ neutrino production[1]



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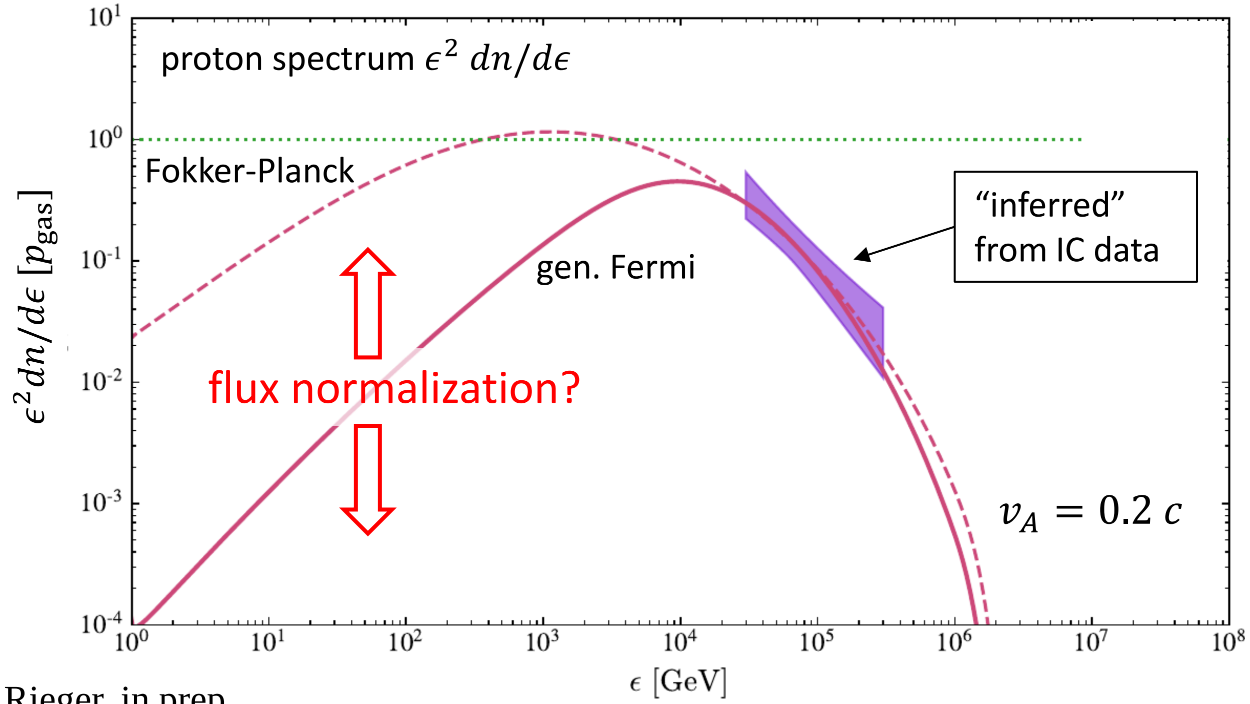
→ model[2]: integrate spectra through transport eqn…
… including relevant energy losses

→ p acceleration to >100TeV possible for turbulent Alfvén velocity $v_A \gtrsim 0.1c$

→ issue: ad-hoc normalization of the flux…

… particle feedback on turbulence appears unavoidable



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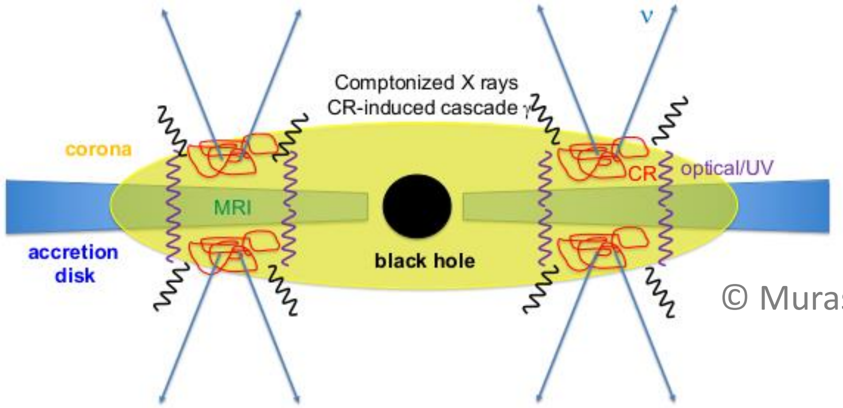

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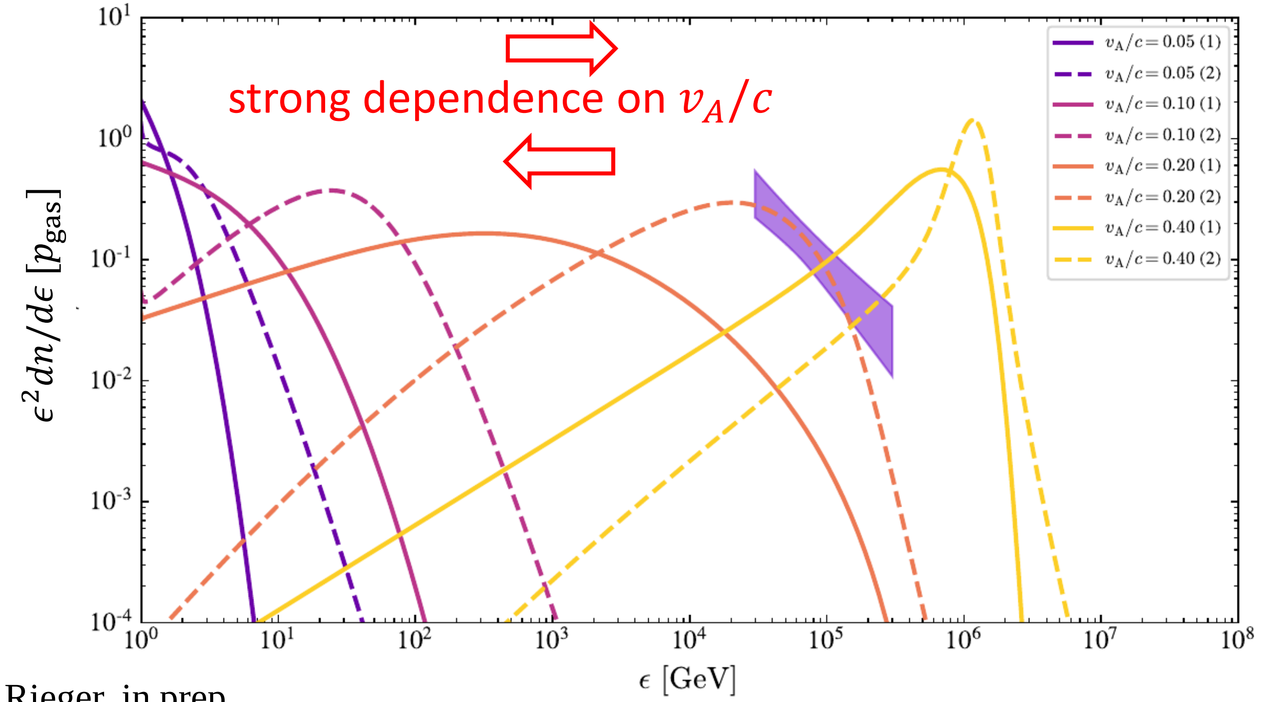
→ model[2]: integrate spectra through transport eqn…
… including relevant energy losses

→ p acceleration to >100TeV possible for turbulent Alfvén velocity $v_{\rm A} \gtrsim 0.1c$

→ issue: sensitivity to acceleration rate…

$$\langle\epsilon\rangle \propto \exp\left(4D_{pp}t/p^2\right)$$



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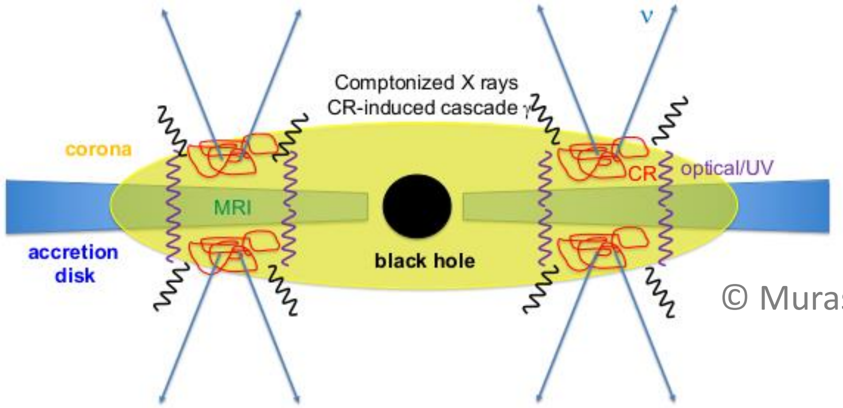

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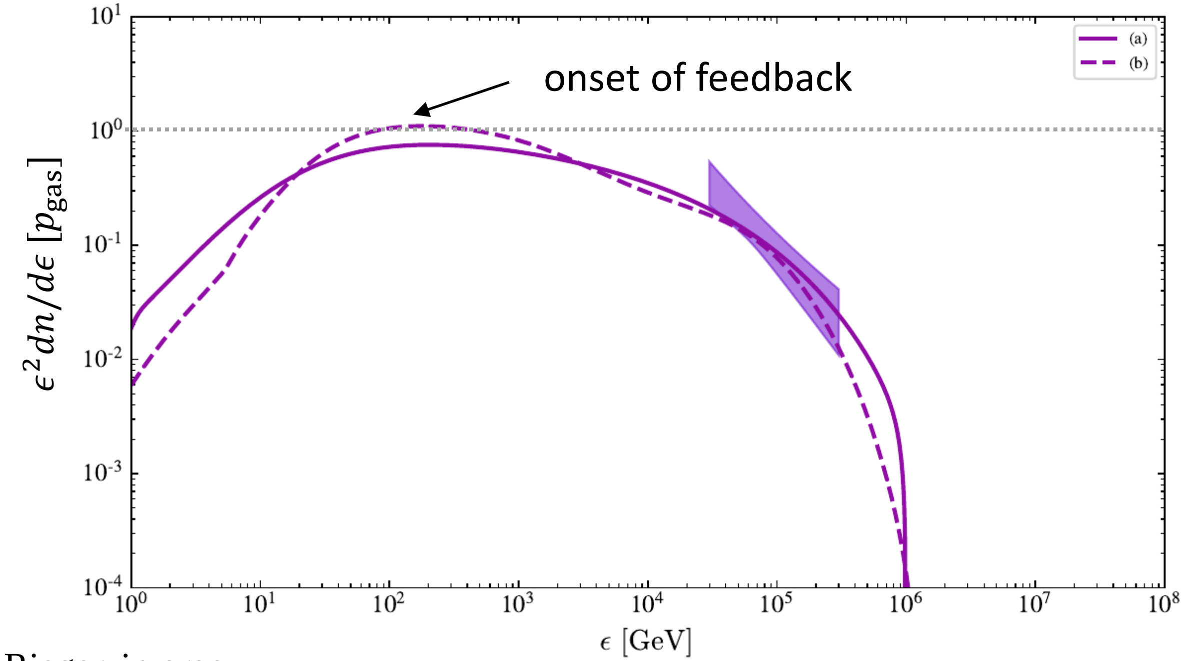
→ model[2]: integrate spectra through transport eqn…
… including relevant energy losses

… proper account of feedback of particles on turbulence (damping) ⇒ reasonable fit to Ice Cube data, without fine-tuning of normalization…

… high-energy tail likely shaped by distribution of acceleration rates (e.g. v_A) inside corona… ?

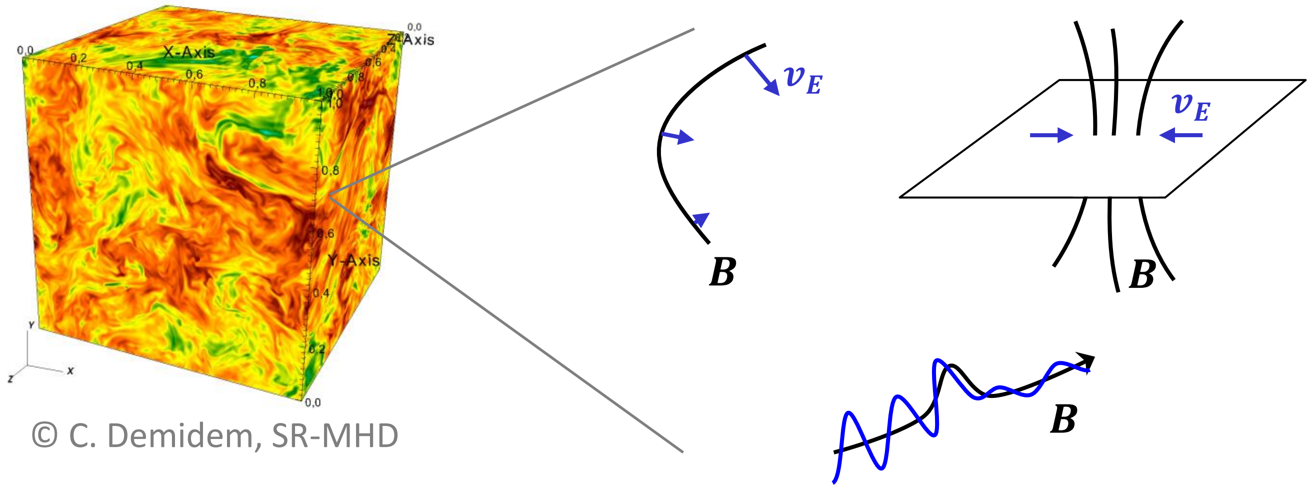


Refs.: 1. e.g. Murase 22 + refs.,… Padovani+24 2. ML + Rieger, in prep.

Summary + discussion: generalized Fermi acceleration in turbulent plasmas

→ Summary (1): particle acceleration in turbulence as generalized Fermi process

… Fermi acceleration generalized to turbulence: acceleration in localized regions of strong (field line) velocity gradients … model supported by PIC+MHD simulations …
… generalization to transport: interaction with (static) regions of strong curvature leads to strong scattering events … can sustain scattering with m.f.p. $\lambda_{\rm s} \sim \ell_{\rm c}^{0.7}\, r_{\rm g}^{0.3}$



→ Summary (2): application to phenomenology of Ice Cube neutrinos from Seyferts

… (generalized Fermi) transport equation allows to model spectra …
… an important effect in (many) sources: account for feedback of particles on turbulence… acceleration process becomes self-regulated