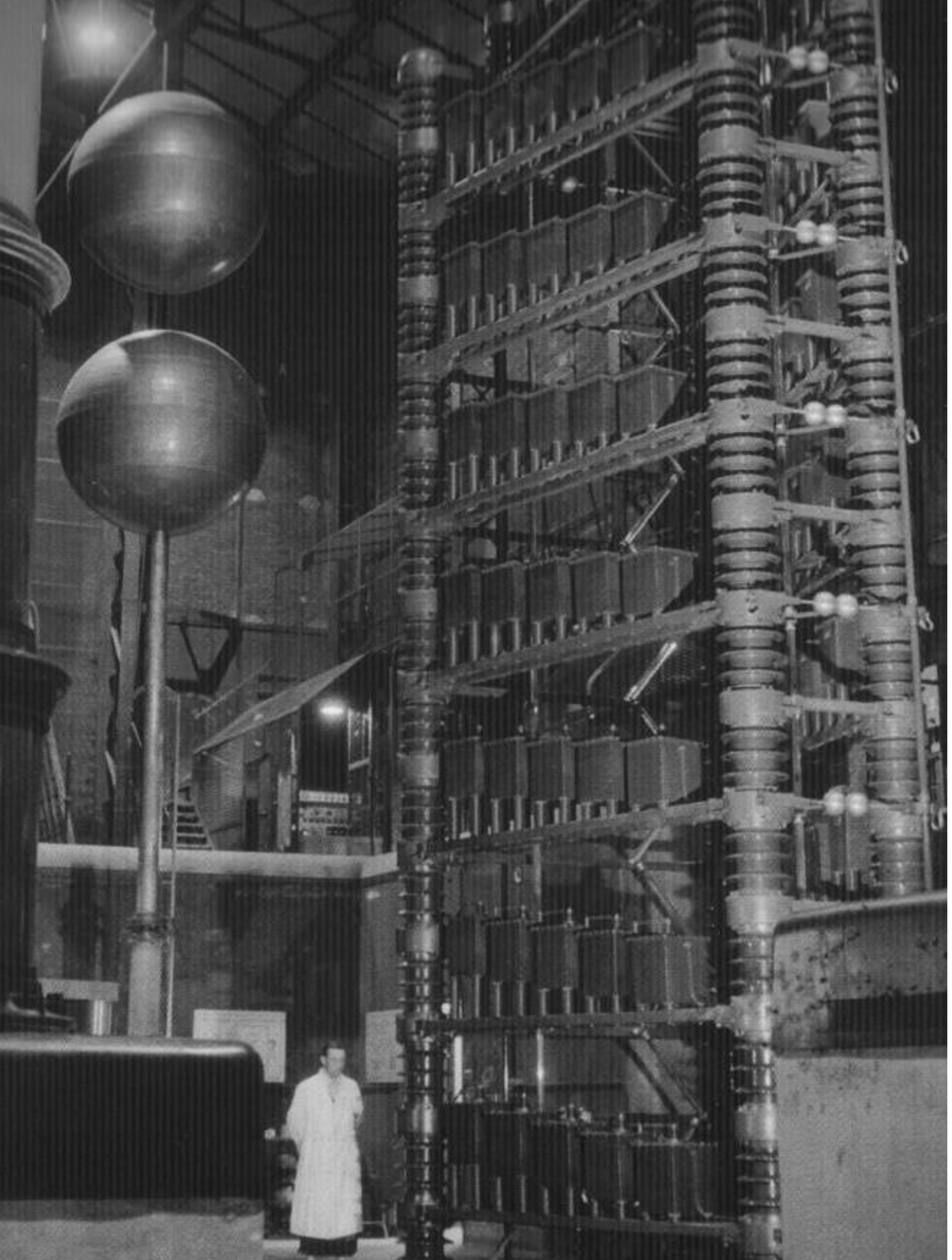

particle acceleration on Earth, ca. 1937

Turbulent plasmas as high-energy particle accelerators

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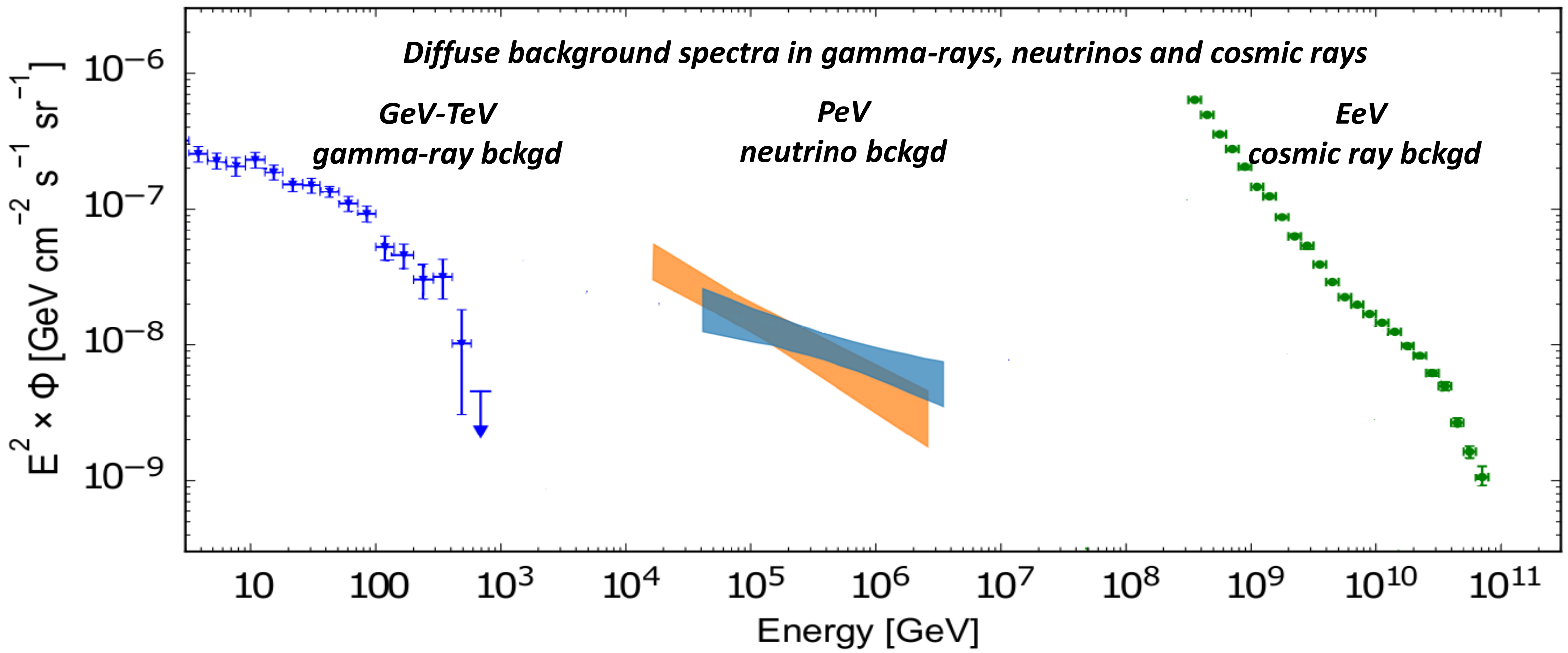
+ A. Bykov (Ioffe), L. Comisso (Columbia U.), M. Malkov (UCSD), K. Murase (Penn State), G. Pelletier (IPAG), F. Rieger (MPIPP), L. Sironi (Columbia U.)

Physics of particle acceleration: a cornerstone of high-energy multi-messenger astrophysics

→ $\nu - \gamma -$ CR connection: acceleration of ions → cosmic rays, photons and neutrinos

→ *what are the accelerating machine(s) and the acceleration process(es) at work ?*



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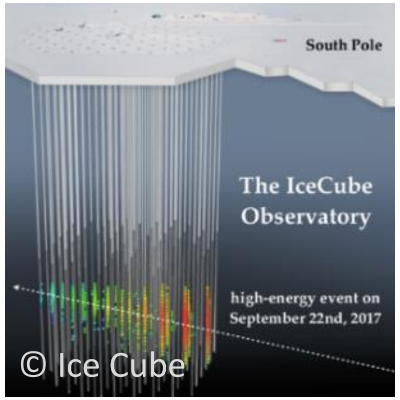
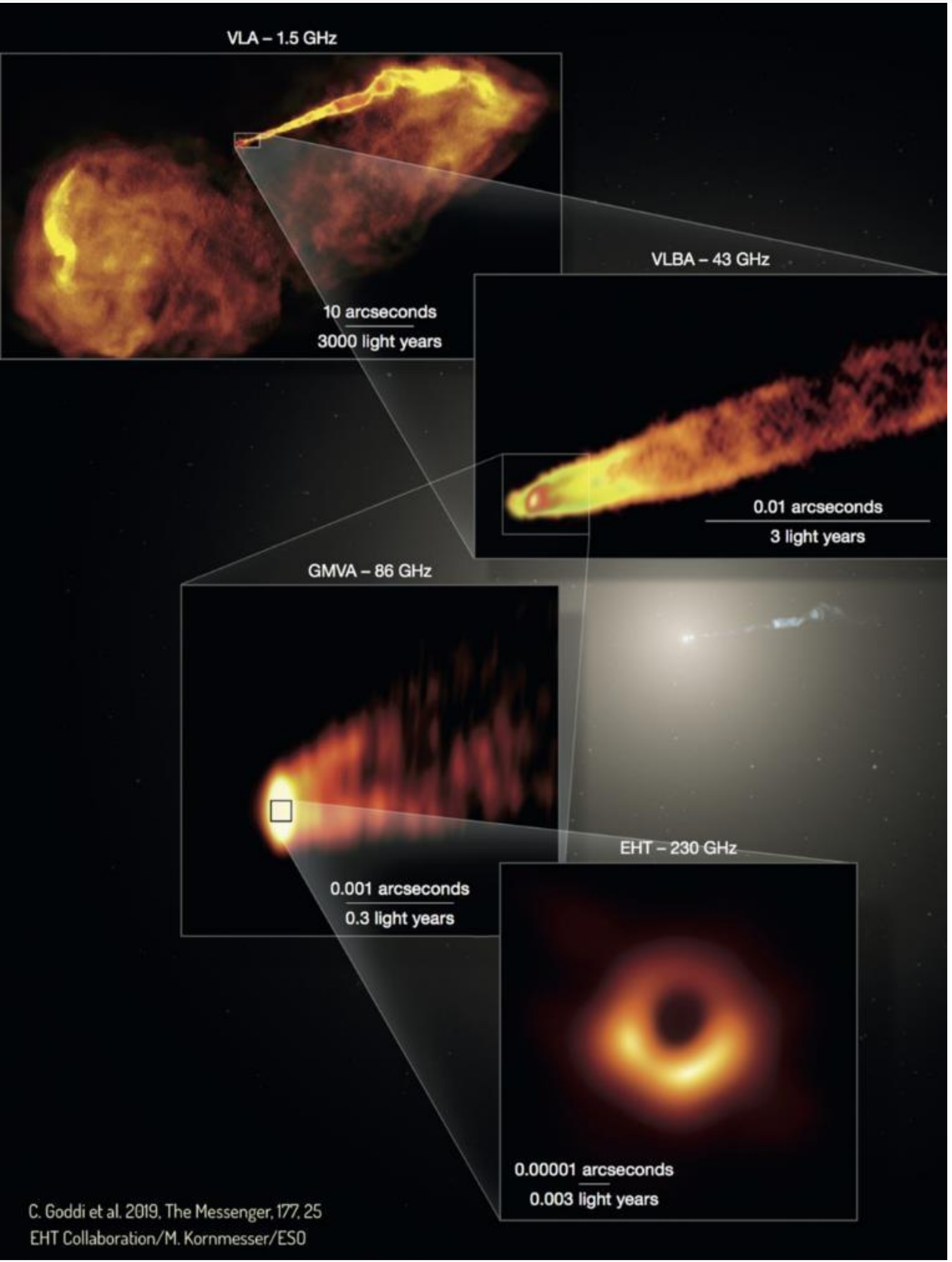


Particle acceleration in the high-energy Universe



→ 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

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

→ Fermi's solution (1949):

$\boldsymbol{E} = 0$ 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 $\boldsymbol{E}, \boldsymbol{v_E}$)

e.g.: acceleration at shock waves, in turbulent plasmas etc.

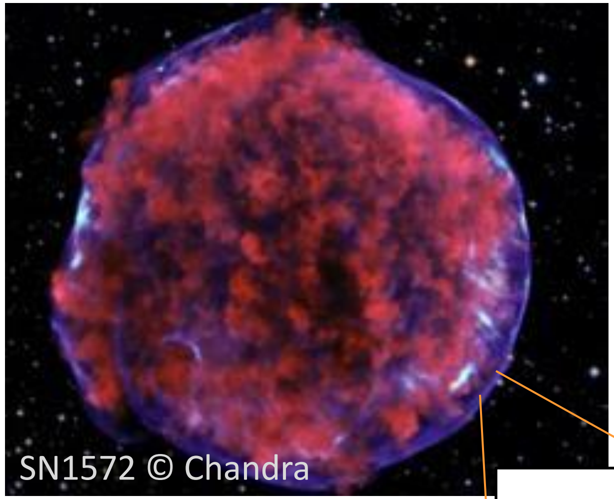
Shock waves as particle accelerators in HE astrophysics: the standard scheme

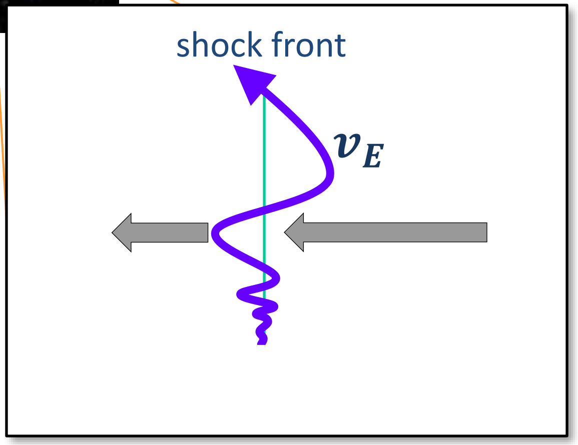
→ particle acceleration in MHD flows:

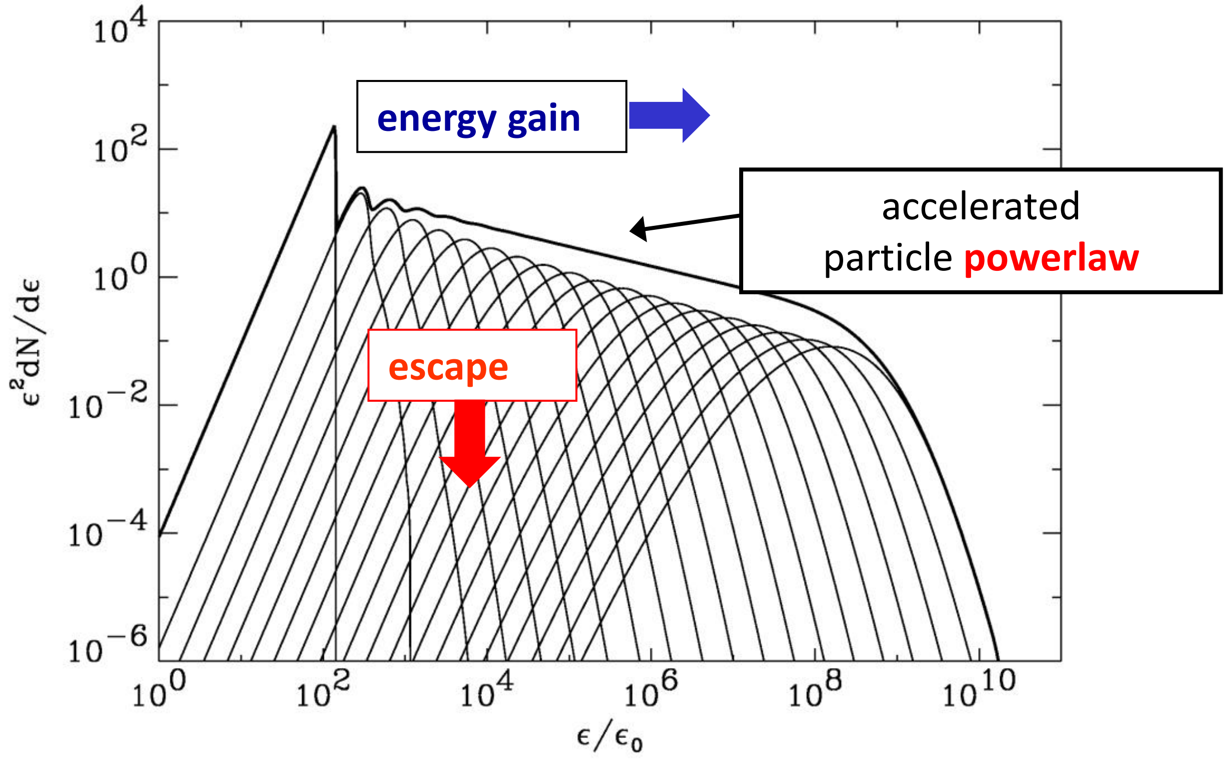
… particles draw energy from electric field carried by plasma (ideal Ohm's law): $\boldsymbol{E} = -\boldsymbol{v}_{\boldsymbol{E}} \times \boldsymbol{B}/c$

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

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



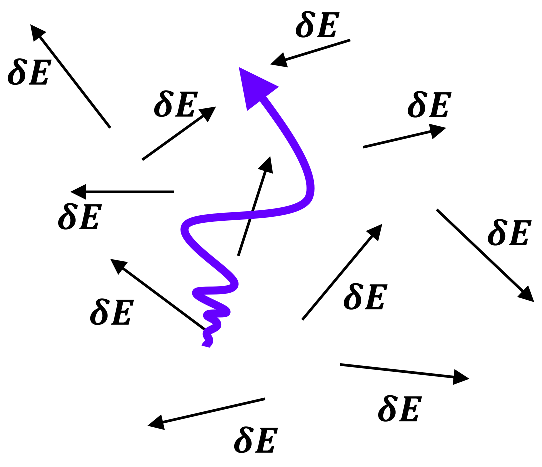




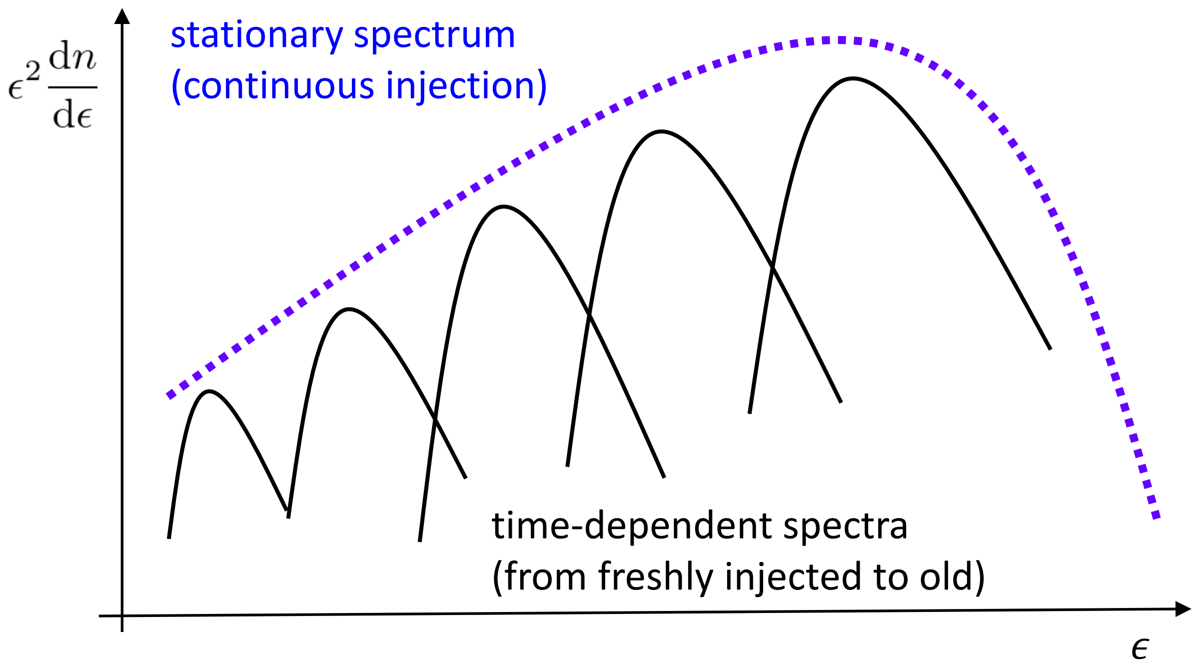
Stochastic particle acceleration in astrophysics

→ **stochastic Fermi acceleration**[1]**:** particles interact with random motional electric fields (← random velocity and magnetic fields in a turbulent plasma)

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

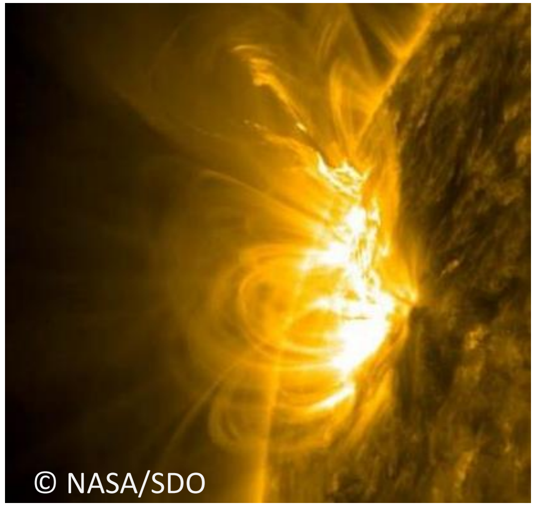


… **a well-known signature:** hard spectra = most of the energy at the highest energies…

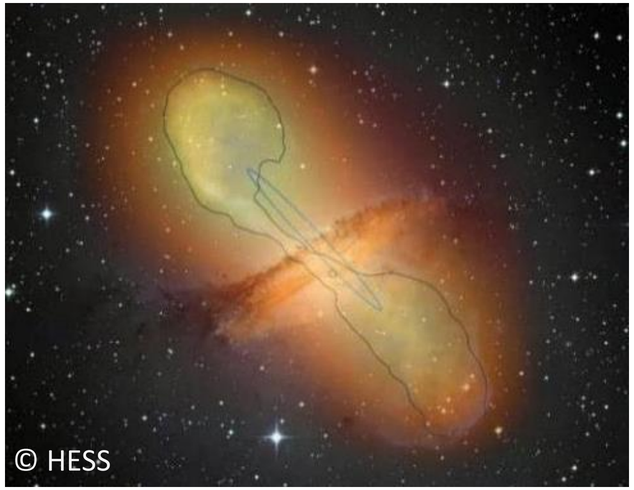


Refs: 1. Fermi 49, 54

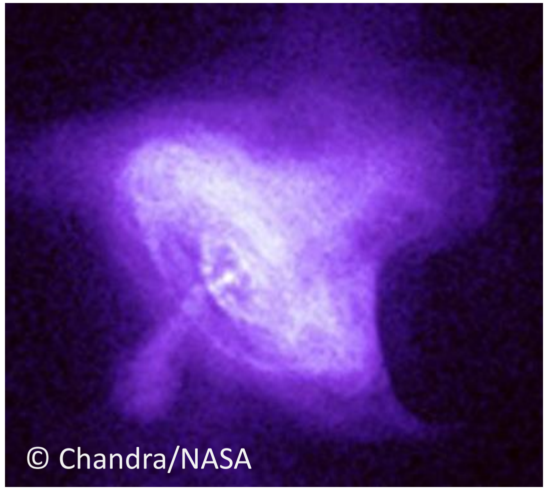
Fermi stochastic acceleration: a standard acceleration scheme in astrophysics



… in solar flares ($v_A \sim 0.1c$)…



… in extra-galactic jets ($v_A \sim 0.1c$)…



… in pulsar wind nebulae ($v_A \sim 0.1 - 1\ c$)…

… acceleration near black holes ($v_A \sim 0.1 - 1\ c$)…

… key parameter: velocity of largest eddies $v_E \sim v_A$

… long-standing issues:

detailed acceleration mechanism? … consequences? …

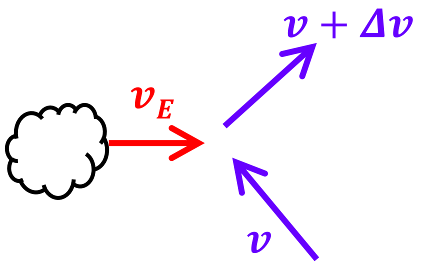
acceleration in relativistic regime ($v_A \sim c$)?

… a non-linear (particles ↔ fields), multi-scale problem…

Stochastic/Fermi-II acceleration – kinematics of interactions

→ a stochastic process: particles interact with discrete, randomly moving magnetized structures carrying $\boldsymbol{E} = -\boldsymbol{v_E} \times \boldsymbol{B}/c$

→ in detail: Lorentz transform to structure rest frame and back, elastic scattering gives energy change / interaction:



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

"net energy gain because more head-on than tail-on collisions…"

→ a diffusive process characterized by energy diffusion coefficient: $D_{\epsilon\epsilon} \equiv \dfrac{\langle\Delta\epsilon^2\rangle}{\Delta t} \sim \epsilon^2 \dfrac{(v_E/c)^2}{t_{\mathrm{int}}}$

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

→ some open questions:

is this the true acceleration process, what about wave-particle resonant interactions?

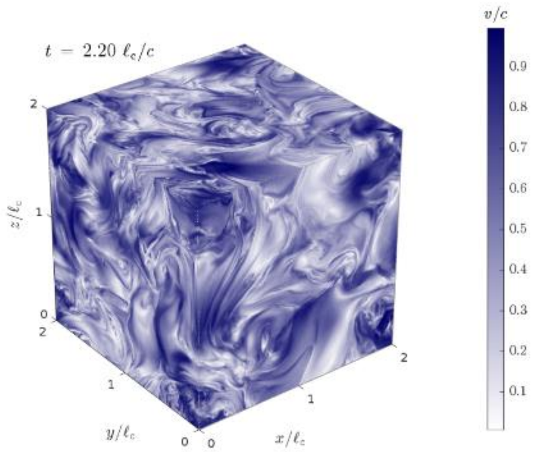
how to generalize Fermi to turbulence, where where $\boldsymbol{v_E}$ = continuous random field with power on all scales?

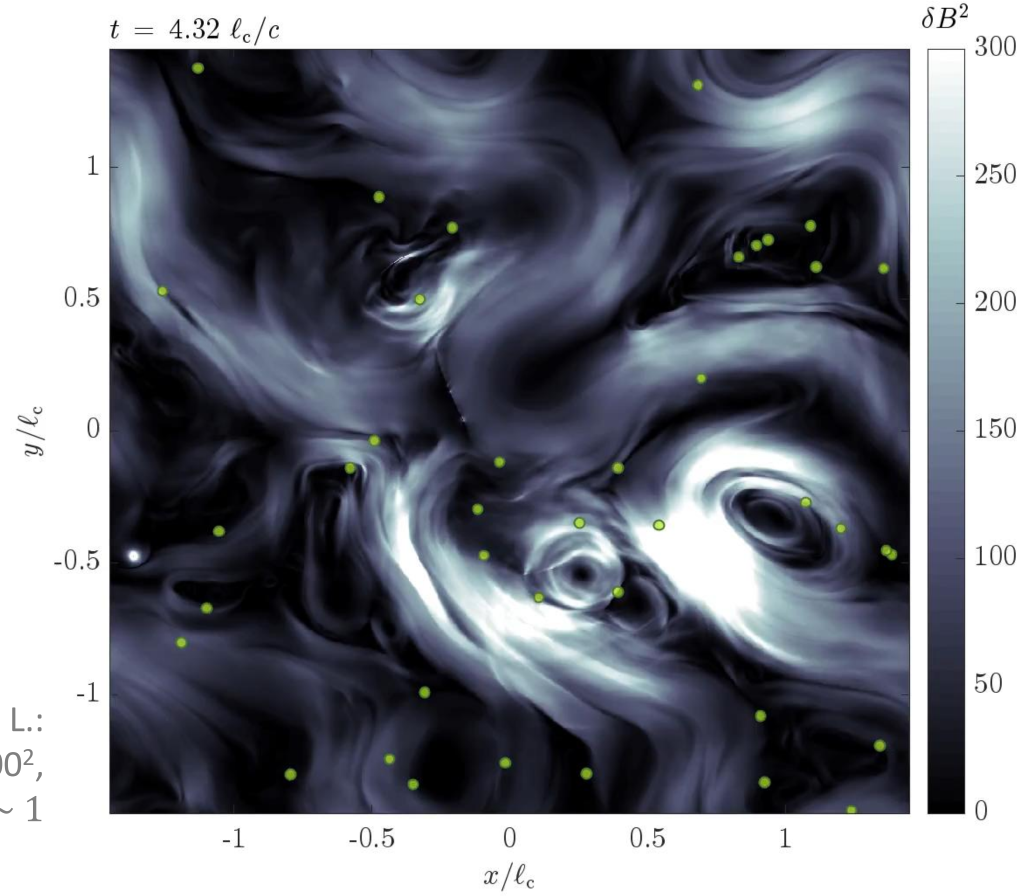
Numerical studies of particle acceleration in collisionless magnetized turbulence

→ a non-linear, multi-scale problem:

… e.g. in turbulence: a fully nonlinear interplay between particles and e.m. fields…

⇒ HPC numerical simulations[1]





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

<u>tracked particles:</u>
symbol size ∝ particle momentum

- p ~3-5 x thermal
- p ~20-40 x thermal

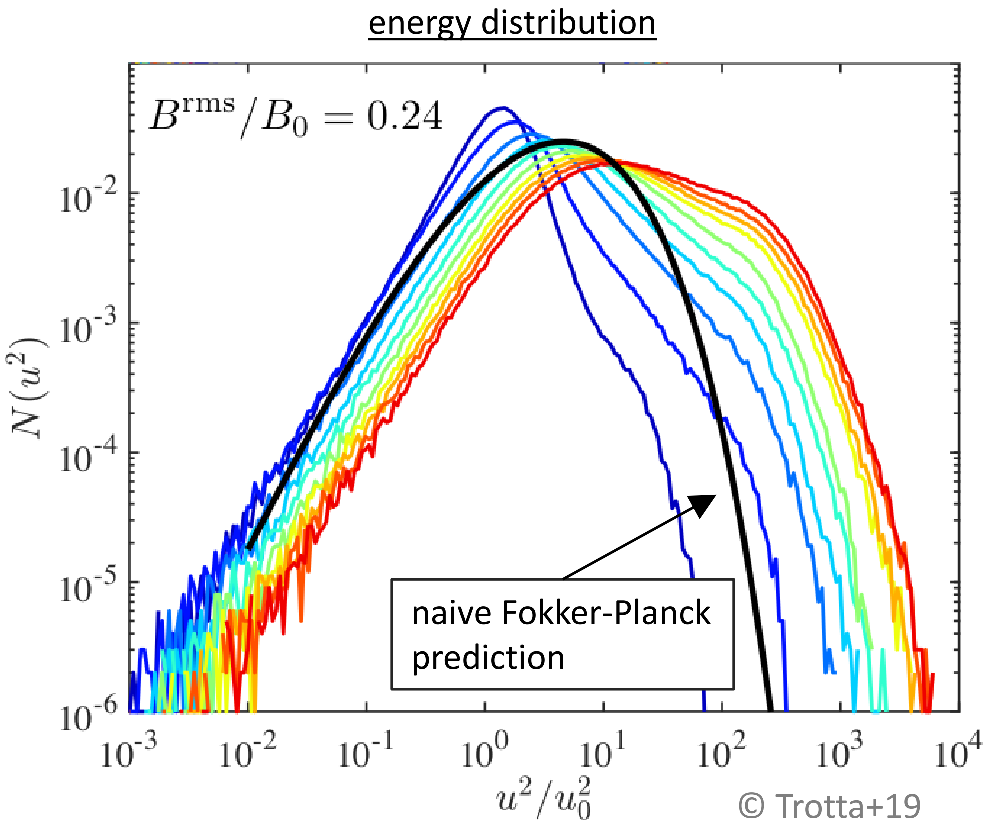
Refs: 1. fully kinetic (PIC): Zhdankin+17,18,20,… Wong+ 19, Comisso+Sironi 18, 19, Nättilä + Beloborodov 20, … Groselj+23
MHD/hybrid sims: Dmitruk+03, Arzner+06, …, Isliker+17, Pecora+18, Trotta+20, Pezzi+22

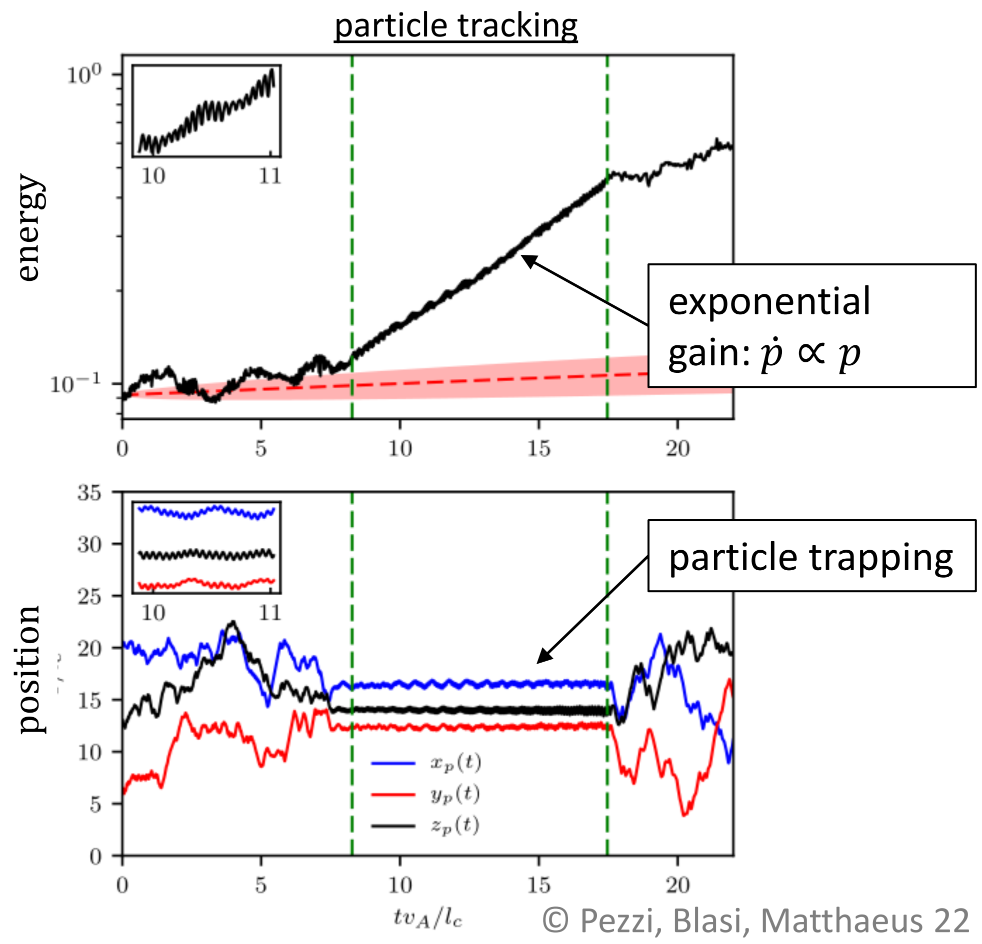
Insights from particle tracking in MHD numerical simulations

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

… for fast (~ exponential!) acceleration in localized regions …

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

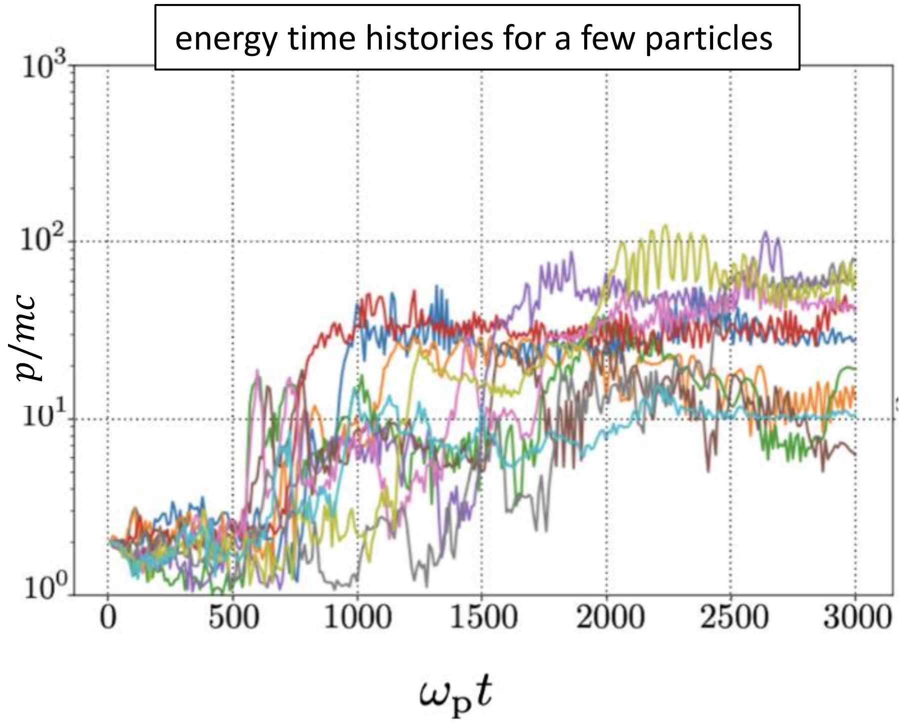


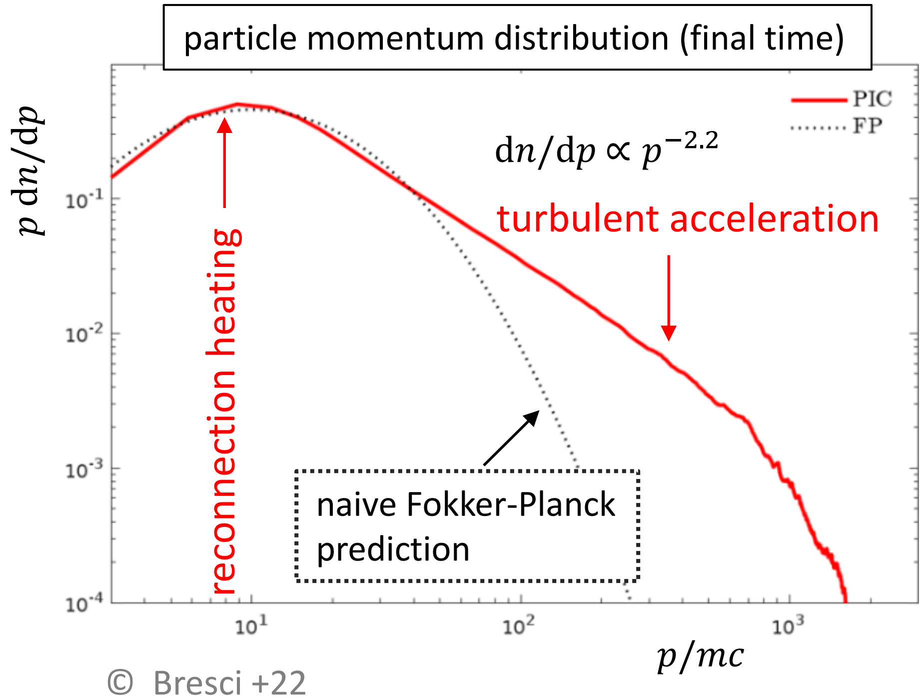


Refs: 1. Dmitruk+03, Arzner+06, …, Isliker+17, Pecora+18, Trotta+20, Pezzi+22, Pugliese+23

Insights from fully kinetic numerical simulations

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





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

→ in relativistic regime, diffusion coefficient $D_{pp} \sim 0.2\ \sigma\ p^2\ c/l_c$ (scaling w/ Alfven 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, Pugliese+23)
2. discussion in M.L. + Malkov 20

Generalized Fermi acceleration in a random velocity flow

→ Generalized Fermi model[1]:

… scheme = track particle momentum along particle word line in the (non-inertial) frame moving at $\boldsymbol{v_E}$

$$\frac{\mathrm{d}\epsilon'}{\mathrm{d}\tau} = -\Gamma^0_{a\,b}\,\frac{p'^a\,p'^b}{m} = -e_a{}^\mu\,e_b{}^\nu\,u_{E\,\mu,\nu}\,\frac{p'^a\,p'^b}{m}$$

(vs $d\epsilon/dt = q\,\boldsymbol{v}\cdot\boldsymbol{\delta E}$ in lab frame)

… motivations:

- $\boldsymbol{E}$ vanishes in frame moving at $\boldsymbol{v_E} = c\,\boldsymbol{E}\times\boldsymbol{B}/B^2 \Rightarrow$ particles are accelerated by visiting regions of different $\boldsymbol{v_E} \leftrightarrow$ acceleration controlled by gradients of $\boldsymbol{v_E}$ [= velocity of magnetic field lines]
- scheme connects $\Delta\epsilon'$ to inertial corrections ↔ gradients of $\boldsymbol{u_E}$ ($u_E \equiv \gamma_E v_E$ 4-velocity)
- direct generalization of Fermi process (boost to reference frame of scattering center)

… benefits:

- connection to velocity structures: on scale $l \gtrsim r_g$, regions with net gradient of $\boldsymbol{v_E}$
- fully covariant implementation of Fermi acceleration in turbulence, non perturbative scheme
- diffusion coefficient $\propto (u_E/c)^2$ validated by numerical sims, while $\propto (v_E/c)^2$ expected from wave-particle interactions[3]

Refs:

1. M.L. 19 [PRD 99, 083006 (2019)], 21 [PRD 104, 063020 (2021)]; see also previous works by Webb 85, 89
2. other studies in turbulence: Bykov+Toptygin 83, Ptuskin 88, Chandran+Maron 04, Cho+Lazarian 06, Ohira 13, Brunetti+Lazarian 16, …
3. Demidem, ML, Casse 20

Effective model describing Fermi acceleration in magnetized turbulence

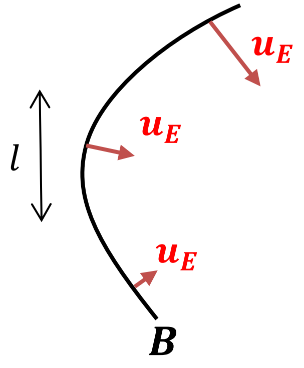
→ effective model[1]:

$$\frac{\mathrm{d}\epsilon'}{\mathrm{d}\tau} = -\frac{p'^a\, p'^b}{m}\, e_a{}^{\mu}\, e_b{}^{\nu}\, u_{E\,\mu,\nu}\,[\boldsymbol{x}(t), t]$$

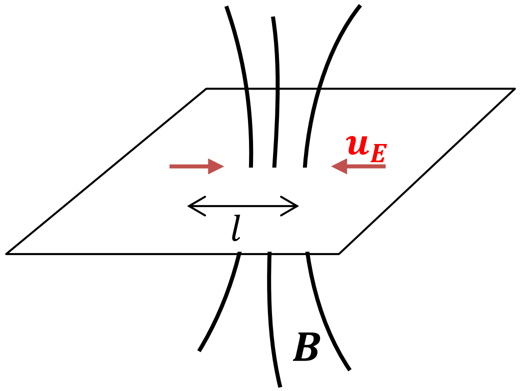
… decomposition of $u_{E\,\mu,\nu}$ ⇒ particle accelerated in regions of compression and shear (mostly)

… stochastic differential equation: random force = gradients of u_E … integrate to obtain advection + diffusion coefficients … model captures all forms of non-resonant acceleration (in ideal fields) …

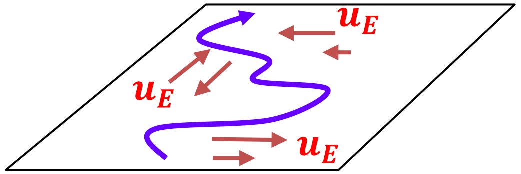
→ examples on different scales (small to large):



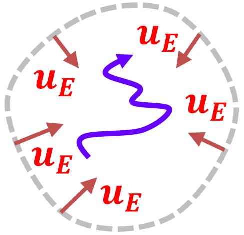
shear along B field
(aka curvature drift)
(close to Fermi type-B)



compression ⊥ B field
(aka betatron)
(close to Fermi type-A)



turbulent shear flow



large-scale compression
(aka magnetic pumping)

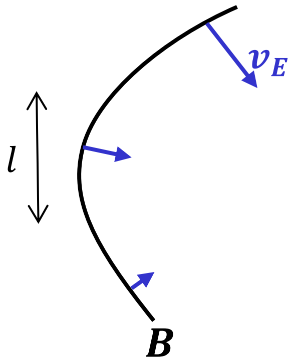
Refs: 1. M.L. 19 [PRD 99, 083006 (2019)], M.L. 21 [PRD 104, 063020 (2021)], M.L. 22 [PRL 129, 215101 (2022)], M.L. 25 [arXiv:]

Application to strong turbulence: $\delta B \gtrsim B$, dominant contribution from curved field lines

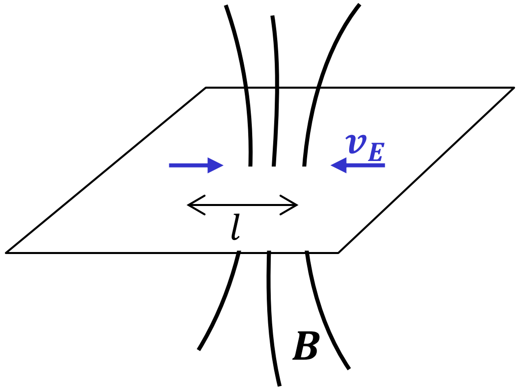
→ theoretical model[1]: $\dot{p} = \Gamma_l \, p$ (simplified expression in comoving frame)

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

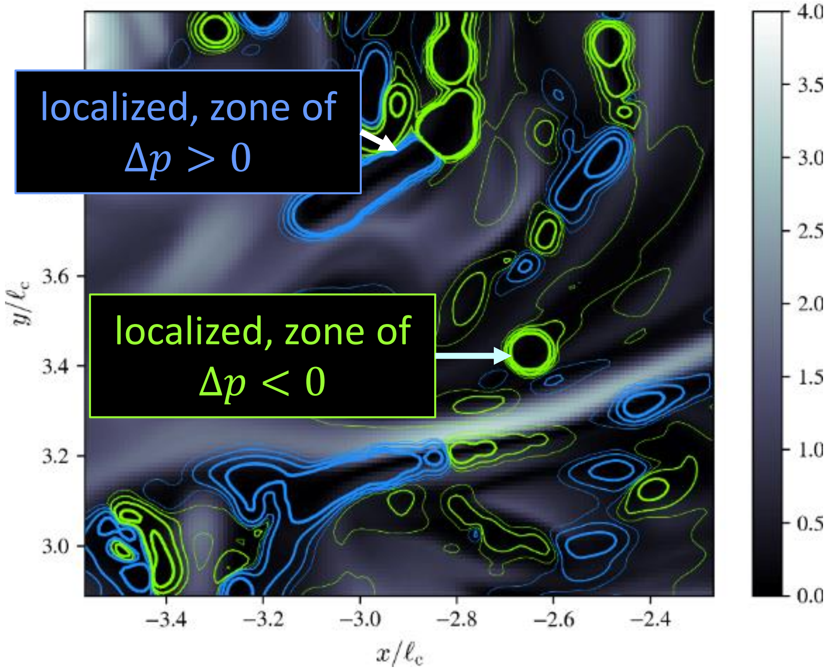
Γ_l from dynamic curved field lines, or dynamic perp. gradients (mirrors), or acceleration of field lines



$\Gamma_l \sim \Delta v_E / l$



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



→ 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

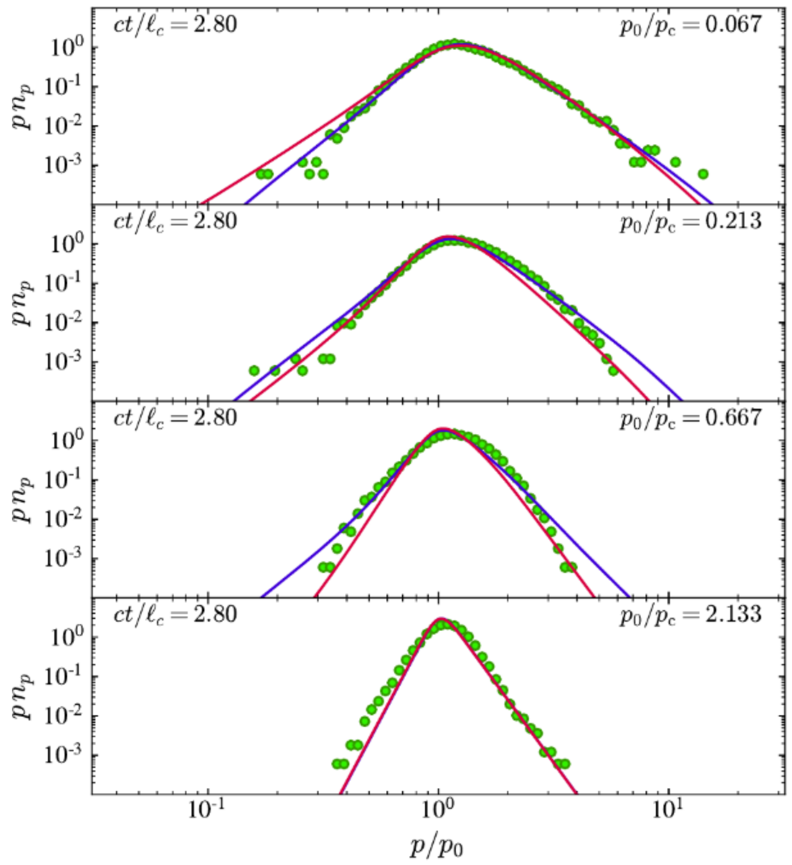
Refs.: 1. ML 21 [PRD 104, 063020 (2021)], ML 22 [PRL 129, 215101 (2022)] 2. Eyink+13, JHU database

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

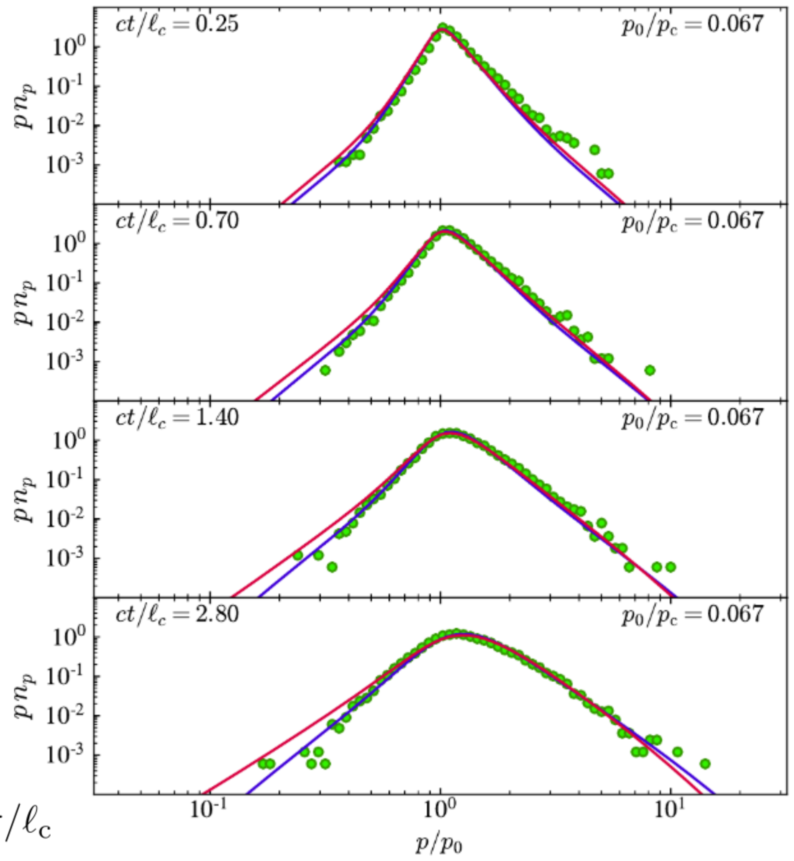
→ comparison to numerical data:

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



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

⇒ 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

Some perspectives and phenomenological consequences

→ executive summary:

… acceleration in turbulent plasmas can be described as a generalized Fermi process: model supported by PIC+MHD simulations … ⟺ acceleration through exploration of random velocity flows (shear and compression) + a generalized Fermi transport equation in strong turbulence …

→ some consequences:

… statistics of sharp bends of field lines in strong turbulence: can contribute to spatial transport as well, m.f.p. comparable to naive prediction of quasi-linear theory …

… acceleration is fast (exponential) in localized regions, e.g. trapping of particles in compressive fluctuations, diffusion in momentum is heterogeneous …

… phenomenological consequences: powerlaw spectra are generic …

… in relativistic turbulence, fast acceleration, local Lorentz boosts → distorted + non-isotropic radiative spectra

→ many open questions and perspectives:

… in-depth understanding of acceleration, origin of spectra vs turbulence conditions → application to different sources

… turbulent acceleration combined with radiative losses → radiative (+polarized) spectra?

… extrapolation to large timescales ? (a strong limit of current numerical simulations)

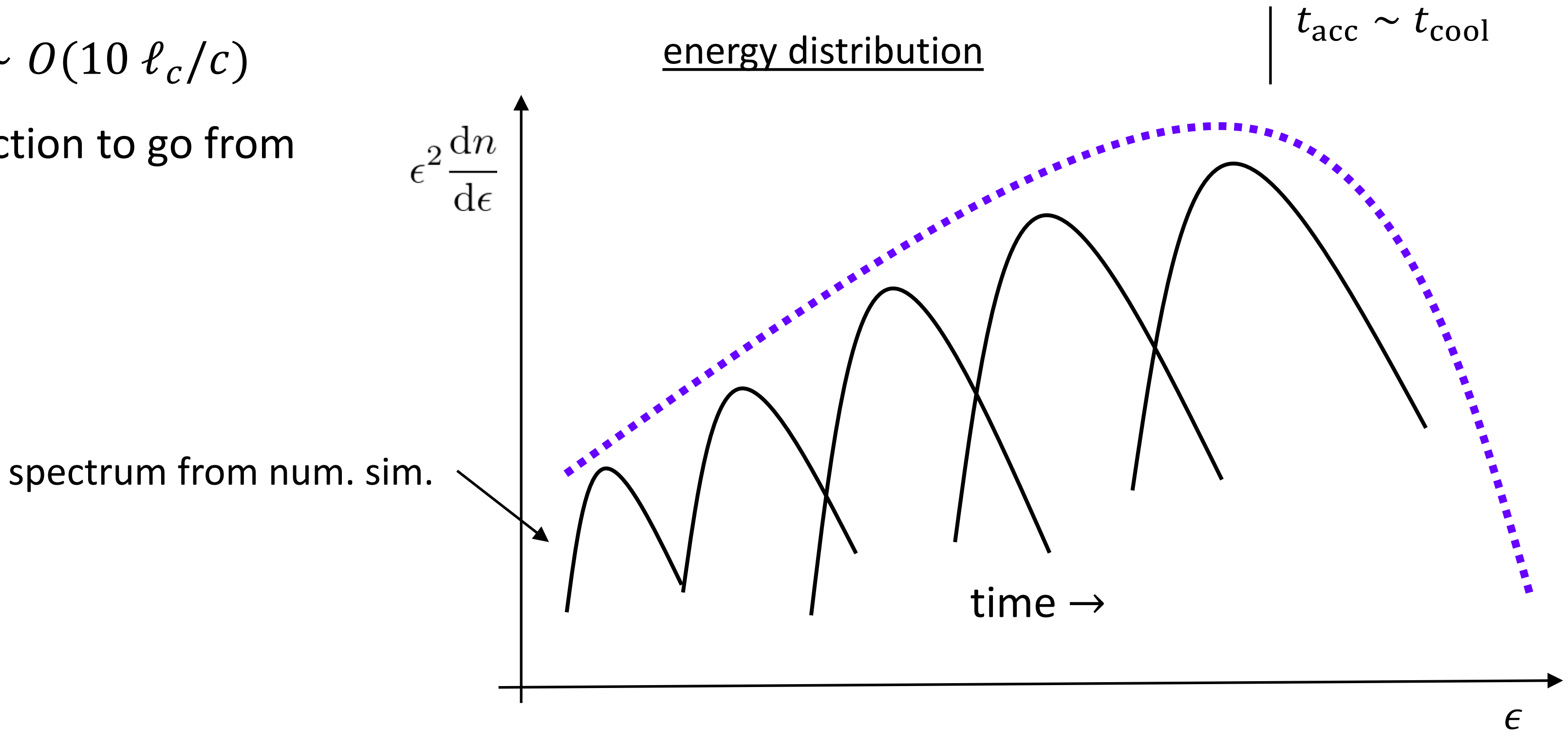
… derive recipes to implement generalized Fermi acceleration in MHD/GRMHD simulations (acceleration in complex velocity flows)

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

→ limited duration of simulations:

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

… numerical 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: accelerated particles can modify the turbulence structure…

→ particle acceleration in turbulence, up to feedback[1]:

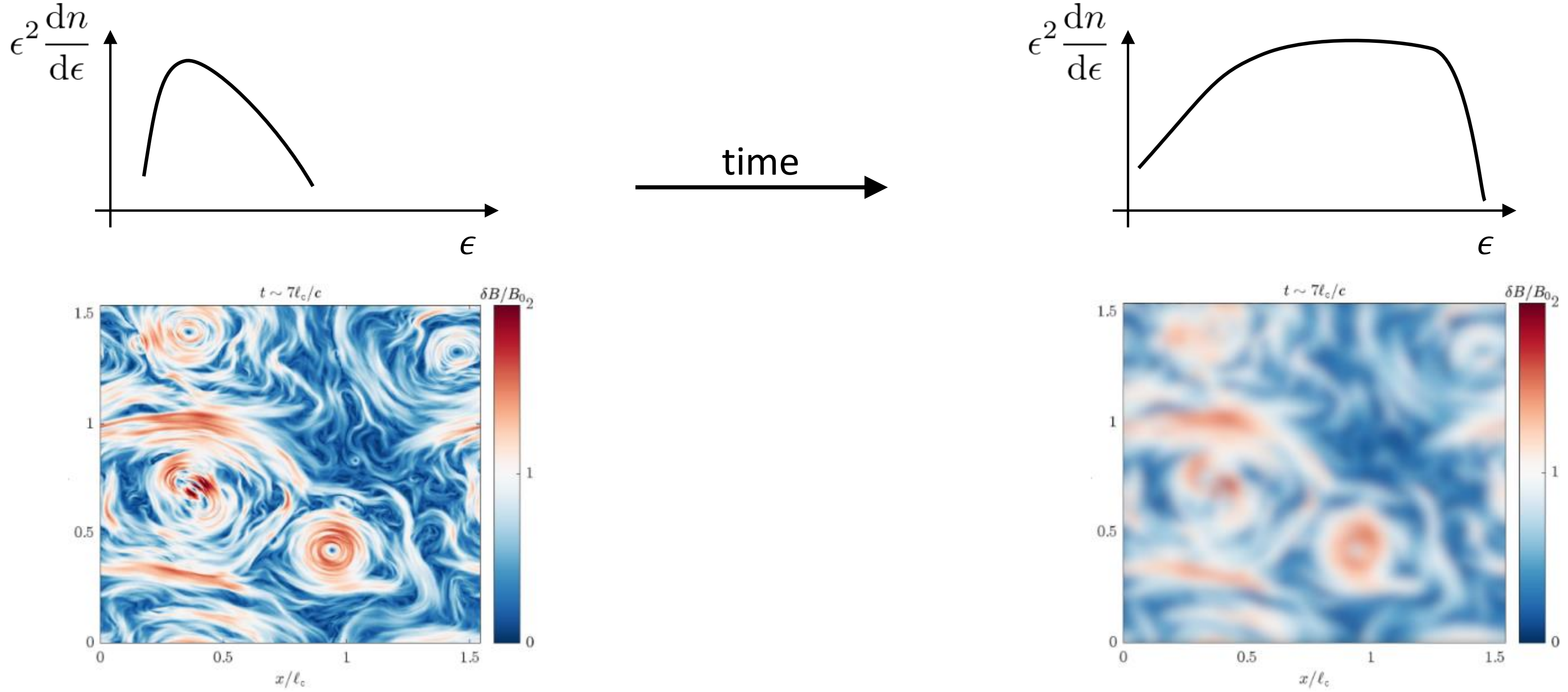
… acceleration = loss of energy for turbulence + most of energy given to highest energy particles

… higher energy particles ↔ larger mean free path ↔ source of viscosity + diffusivity

⇒ consequences: (1) self-regulation of acceleration impacts distribution function $f(\epsilon, t)$

(2) removes turbulent power on short scales, modifies plasma heating rate

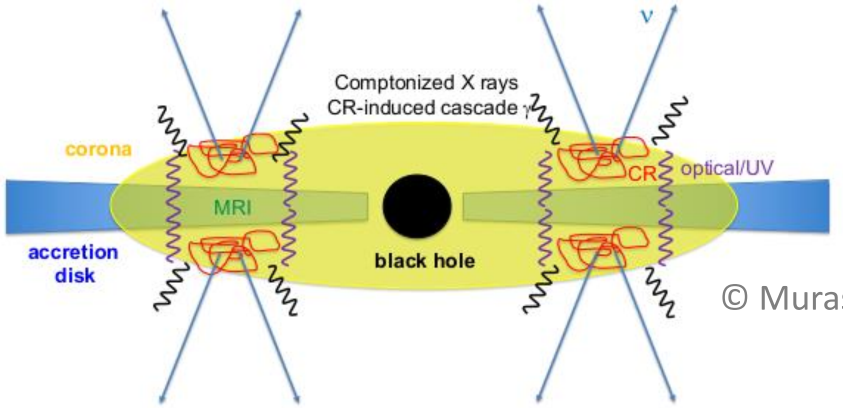
(3) pressure in accelerated particles can become comparable to plasma pressure



Refs.: 1. Eichler 79, Eilek 79, … Kakuwa 16 …, 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 + $p-\gamma$ neutrino production[1]



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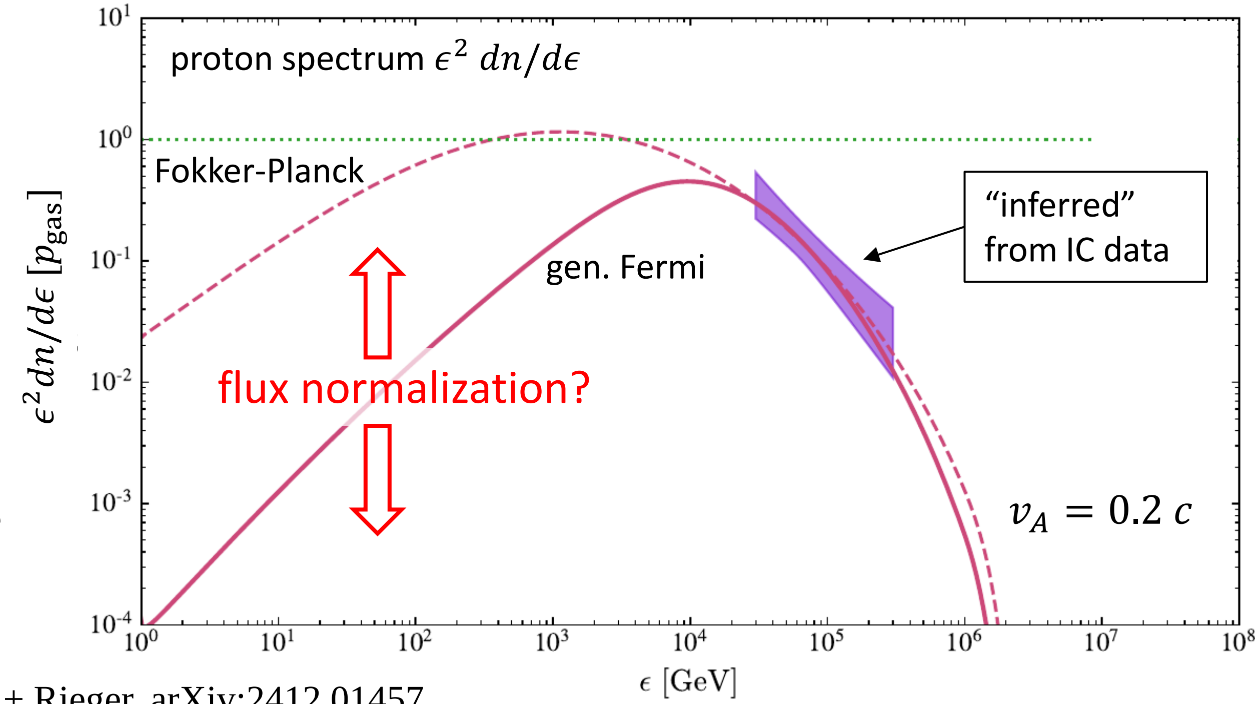
→ model[2]: integrate spectra through transport eqn…
… including relevant energy losses

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

→ issue: ad-hoc normalization of the flux…

… particle feedback on turbulence appears unavoidable



Refs.: 1. e.g. Murase 22 + refs.,… Padovani+24 2. M.L. + Rieger, arXiv:2412.01457

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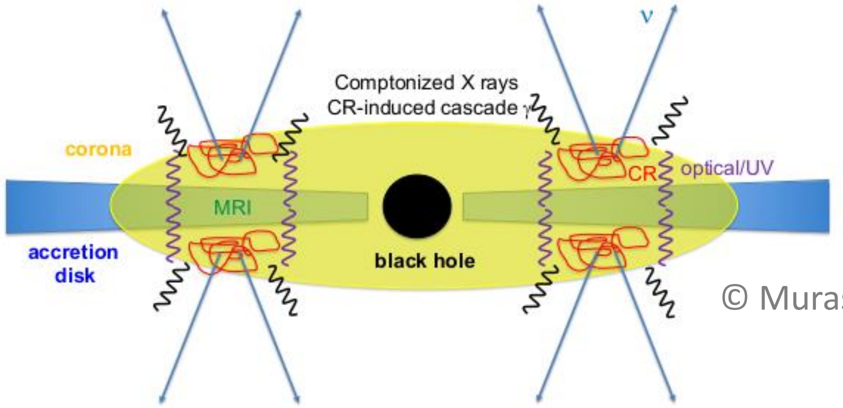

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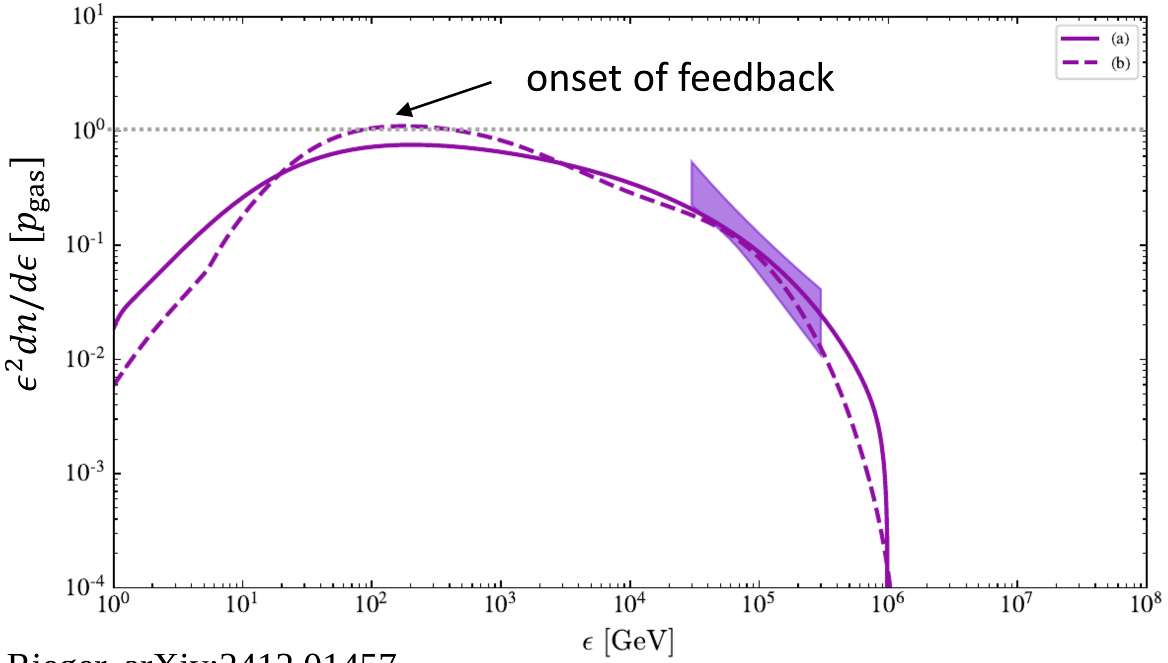
→ model[2]: integrate spectra through transport eqn…
… including relevant energy losses

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

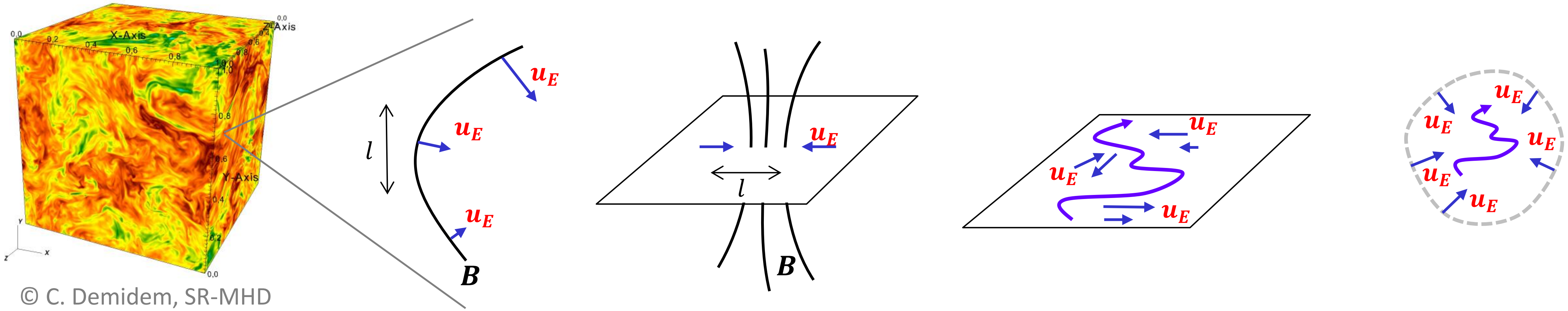


Refs.: 1. e.g. Murase 22 + refs.,… Padovani+24 2. M.L. + Rieger, arXiv:2412.01457

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 …



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→ 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