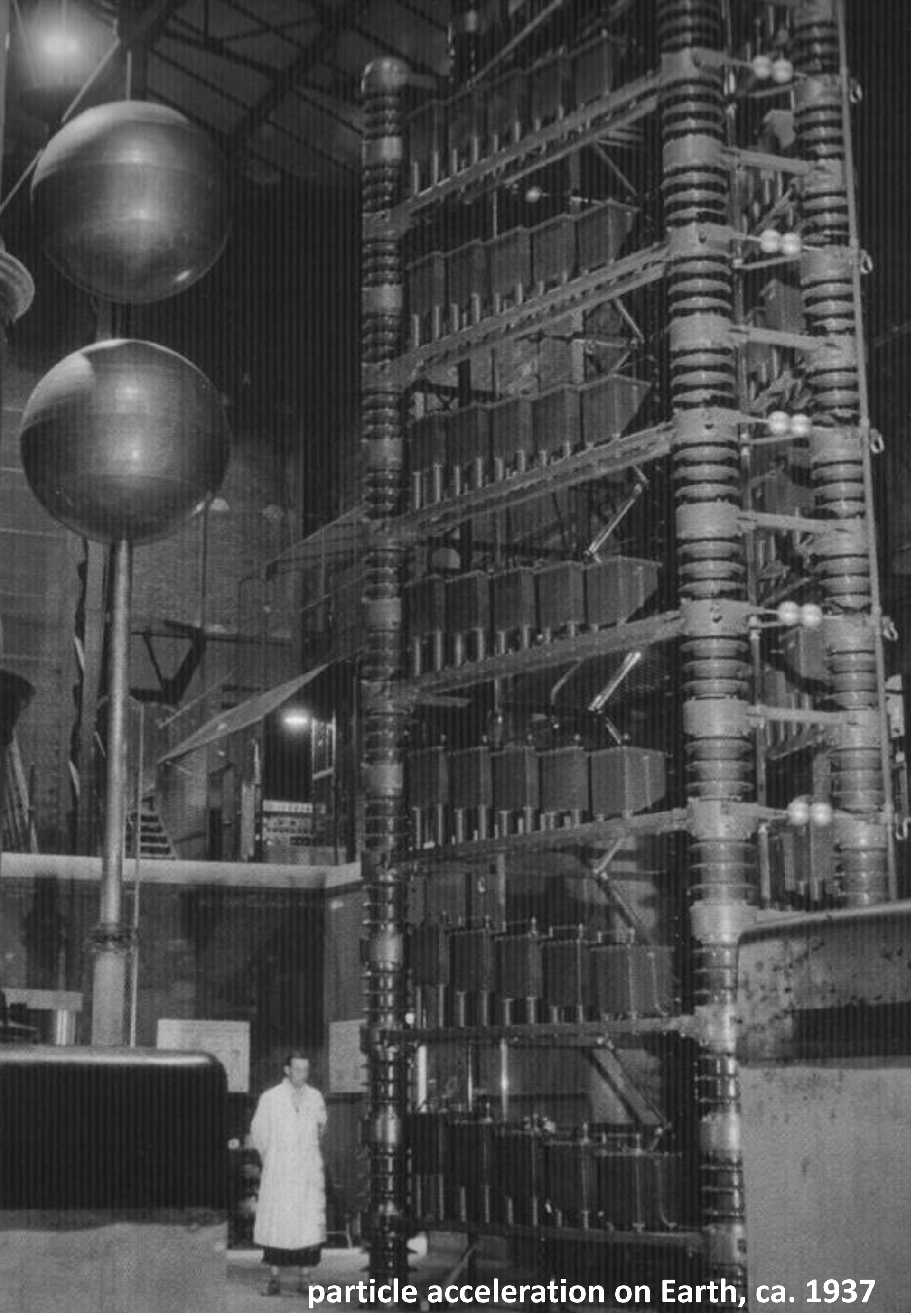
particle acceleration on Earth, ca. 1937

Particle acceleration in magnetized, astrophysical turbulent plasmas

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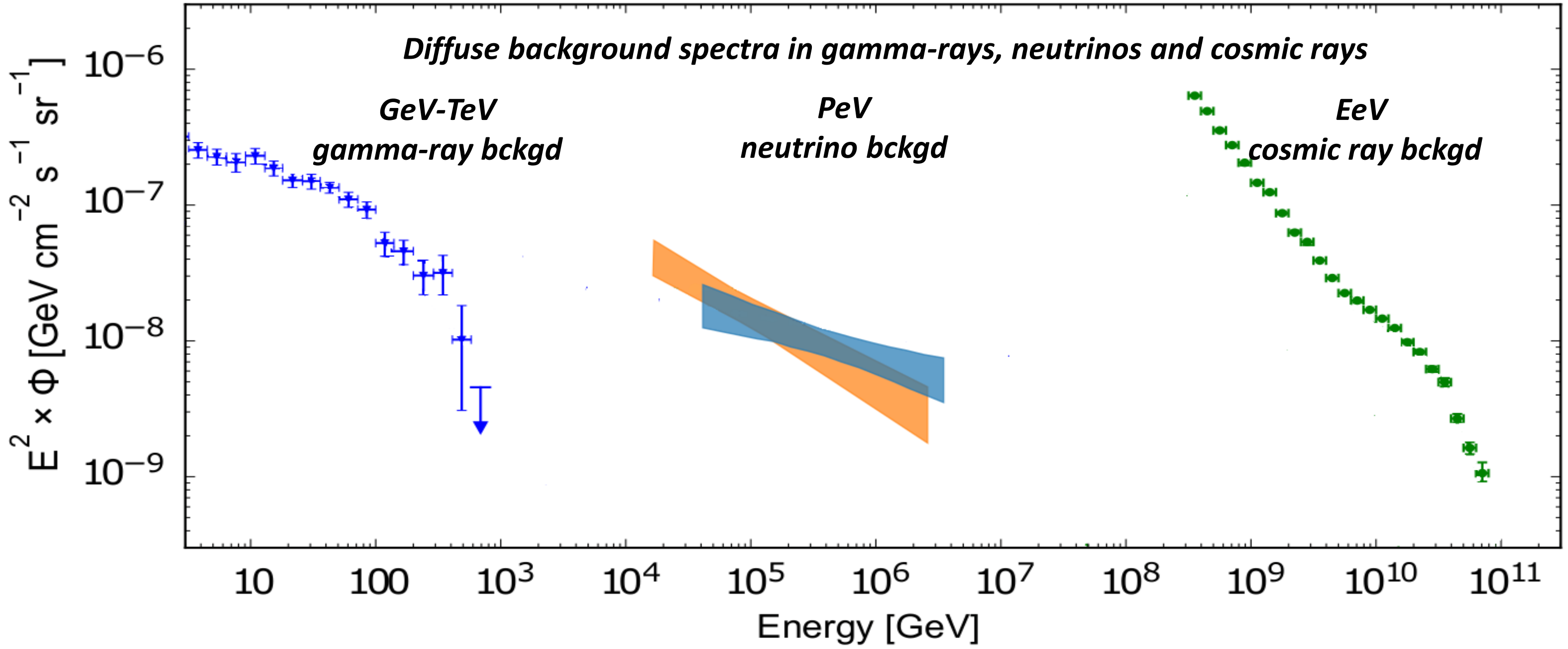
  L. Comisso & L. Sironi (Columbia)

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

→ $\nu - \gamma -$ CR connection: acceleration of ions → cosmic rays, photons and neutrinos [e.g. Waxman + Bahcall 97, 98]

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



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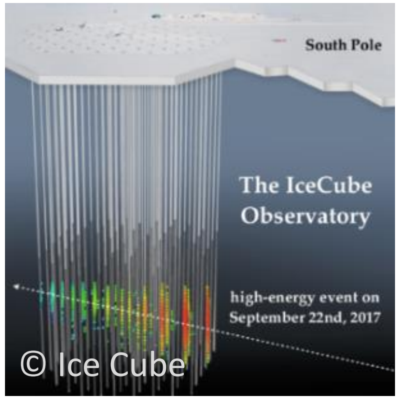
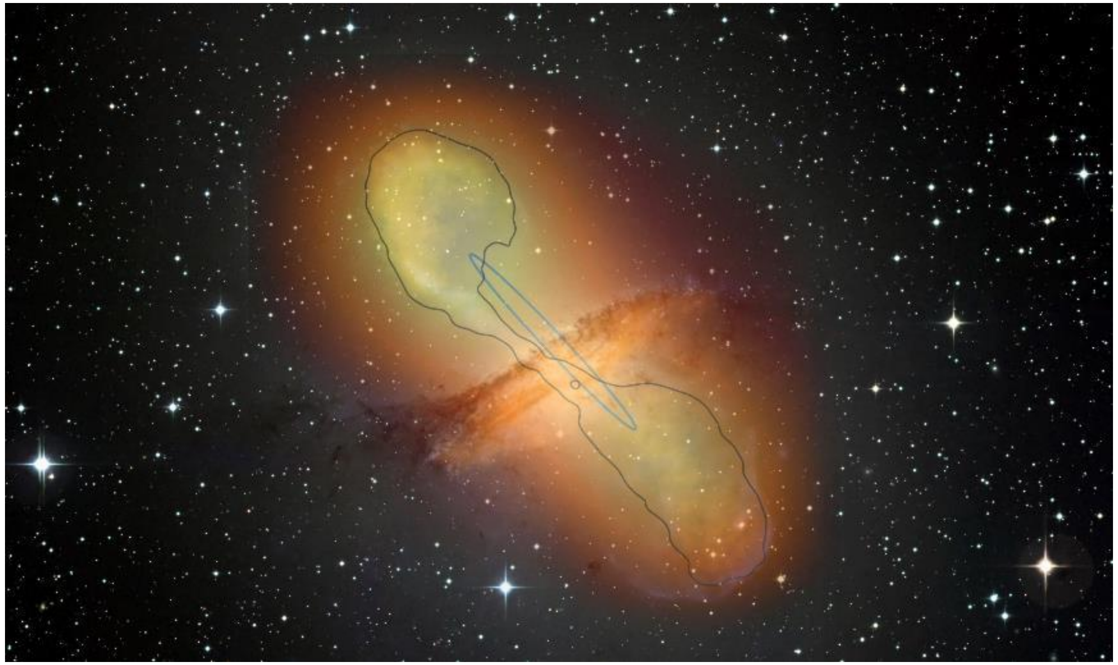
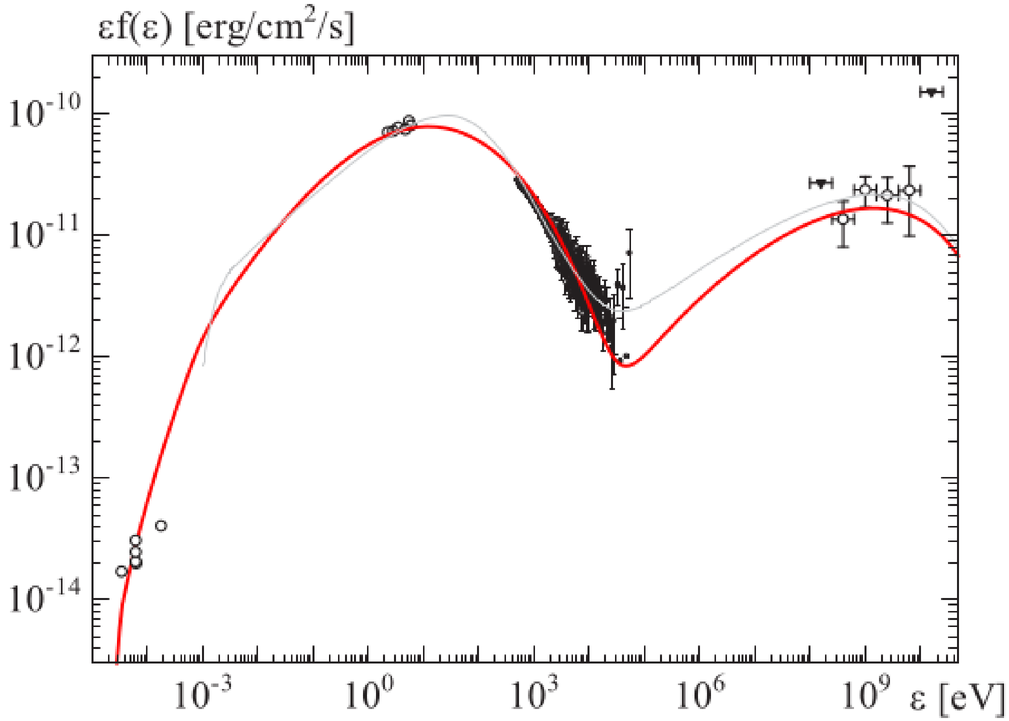


Stochastic Fermi acceleration on all scales: from large-scale jets to the blazar zone

→ in large-scale jets: continuous acceleration in turbulent flows invoked to explain the non-thermal emission seen on scales exceeding the cooling length scale of high-energy electrons… Refs.: e.g. Liu+17, Rieger 19, Webb+18,20

→ in blazars (radio-galaxies with jet head-on to observer): characteristic double-hump spectrum (synchrotron – inverse Compton) from non-thermal electrons… acceleration physics: reconnection, turbulence, shocks?



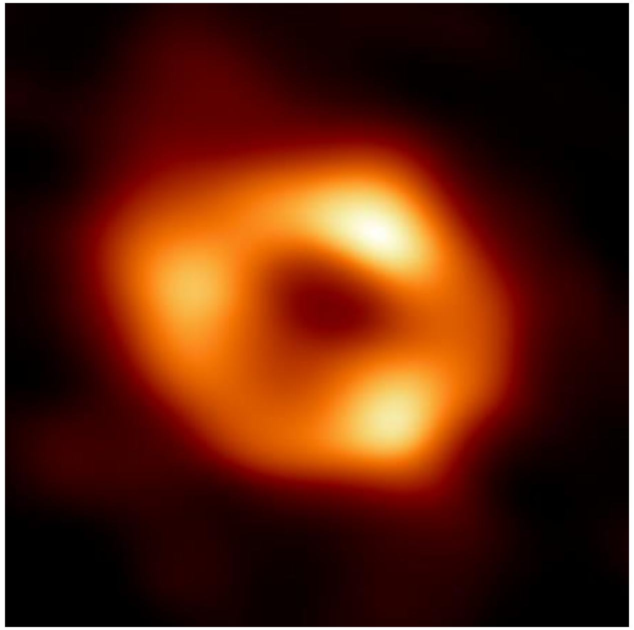


PKS2155-304 [Asano+Hayashida 18]

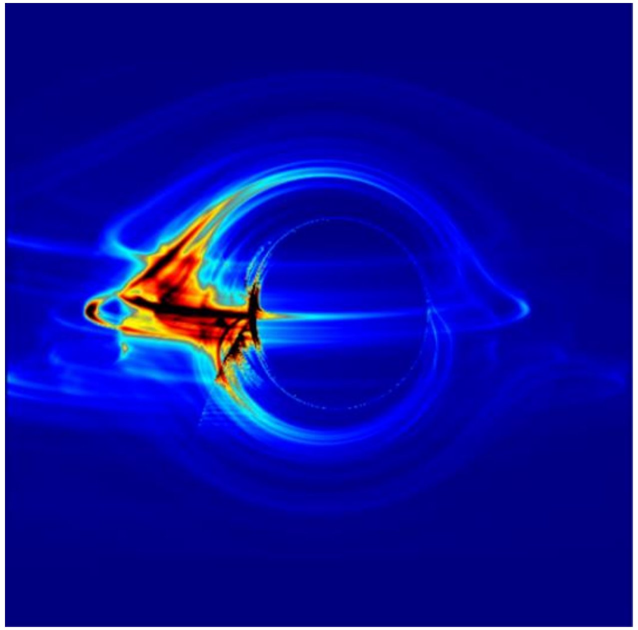
Stochastic Fermi acceleration on all scales: down to black hole surroundings

→ **Importance of microphysics:** radiation of black hole flows shaped by the physics of dissipation in collisionless turbulence…

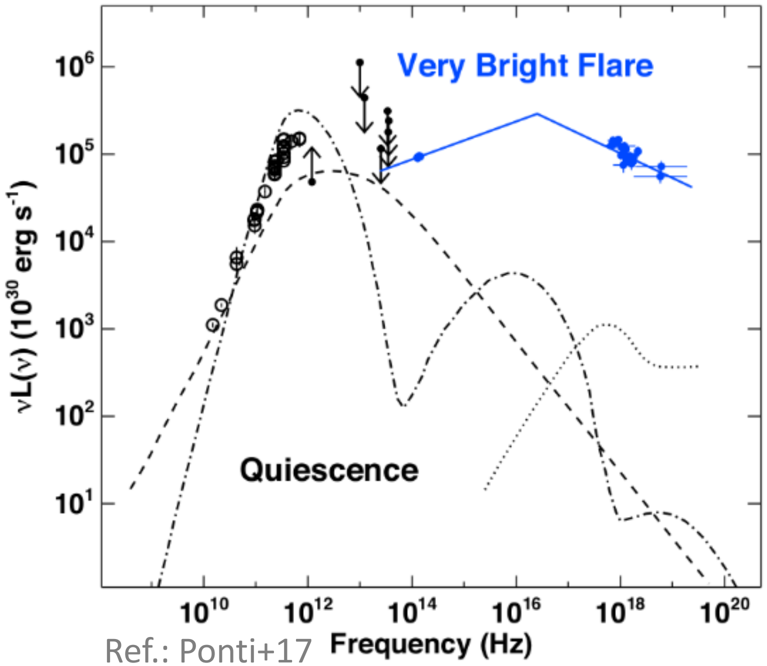
→ **Flares seen in NIR and X around SgrA*:** suggest powerlaw extension with slope $\sim -3 \ldots -2$, + synchrotron cooling …
⇒ key scenarios: reconnection (at large magnetization), or turbulence (if large fluctuations)?



Ref.: Event Horizon Telescope 22



Ref.: Petersen+Gammie20

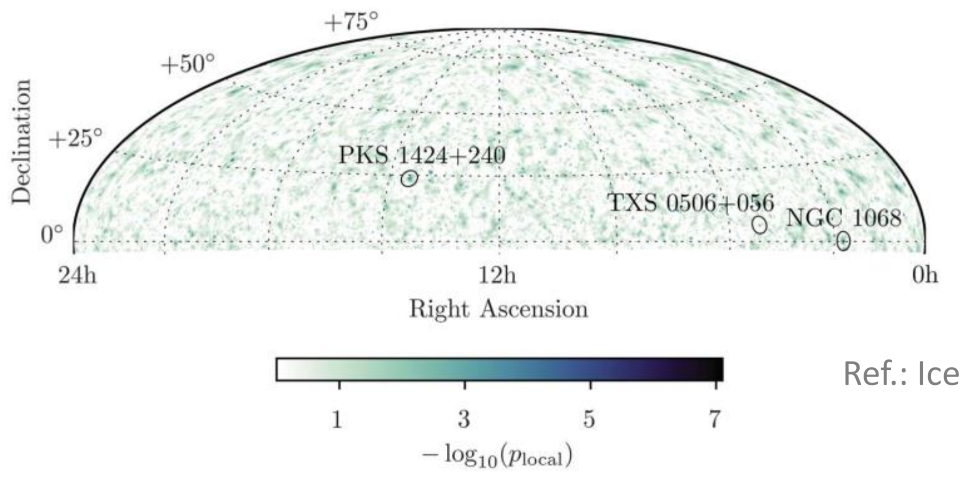


Ref.: Ponti+17

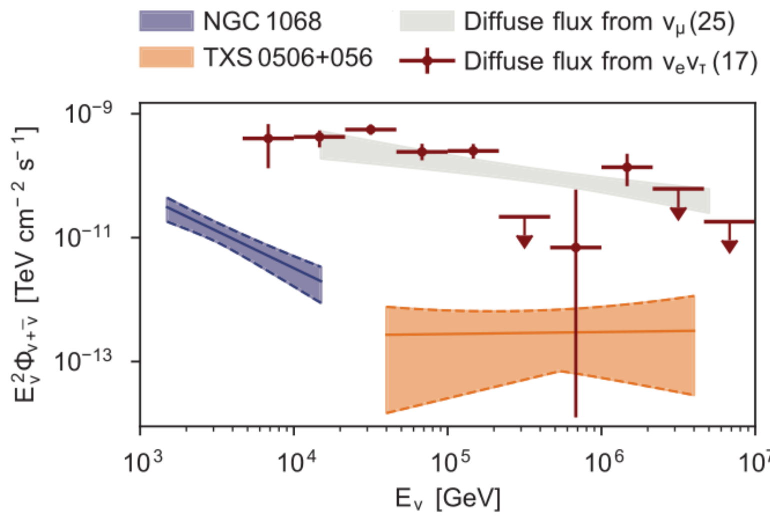
Note: EHT image well reconstructed by GRMHD simulations… which however use recipes to describe particle heating + acceleration!

Stochastic Fermi acceleration as an origin for the high-energy neutrinos from NGC1068

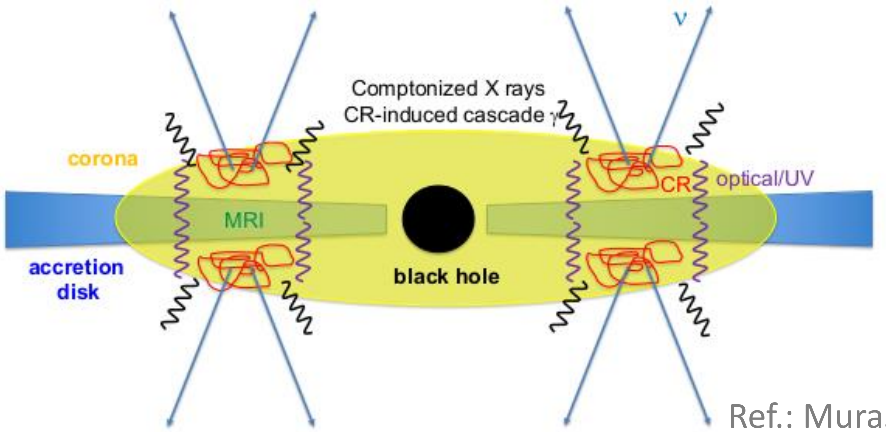
→ Ice Cube 22: a clear excess of high-energy (1-10 TeV) neutrinos from nearby AGN NGC7068



Ref.: Ice Cube 22



→ interpretation: e.g. [Murase+], particle acceleration in corona of accretion disk + neutrino production in $p-\gamma$ process



Ref.: Murase+Stecker 22

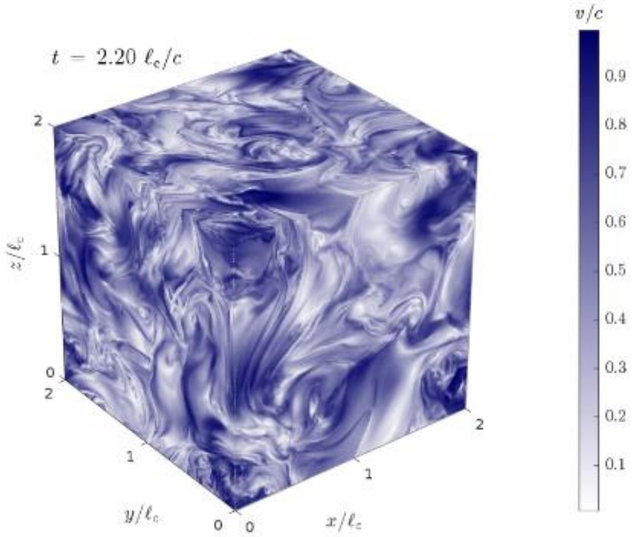
→ particle acceleration: turbulence, shocks?

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…

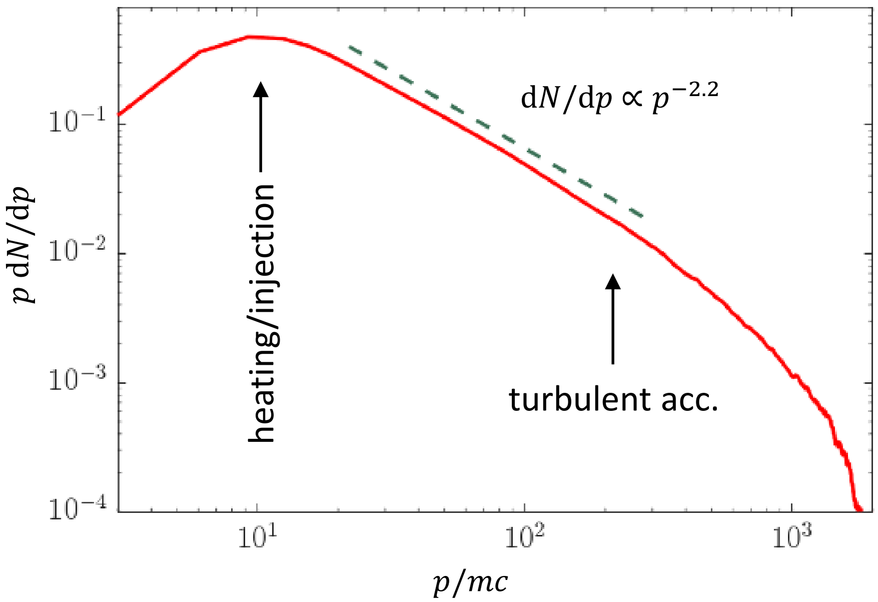
⇒ HPC numerical simulations using « particle-in-cell » (PIC) method



→ numerical experiments of particle acceleration in magnetized, collisionless turbulence:

… recent breakthrough results in (trans- and fully-) relativistic turbulence[1]

… meaning: magnetization parameter $\sigma \equiv \dfrac{B^2/4\pi}{n\,mc^2} = (u_A/c)^2 \sim 1$



<u>main findings:</u>

1. two-stage particle acceleration:
   first, injection through reconnection up to $p \sim \sigma\, m\, c$ …
   then, particle acceleration in “ideal” fields

2. unexpected[2] emergence of powerlaws
   with $\mathrm{d}N/\mathrm{d}p \propto p^{-s}$ and $s \sim 2\ \dots\ 4$

Refs: 1. Zhdankin+17,18,20,… Wong+ 19, Comisso+Sironi 18, 19, Nättilä + Beloborodov 20, … Groselj+23 (+ many MHD sims)
2. discussion in M.L. + Malkov 20

Challenges in modeling particle acceleration from first-principles

→ a challenge of scales:

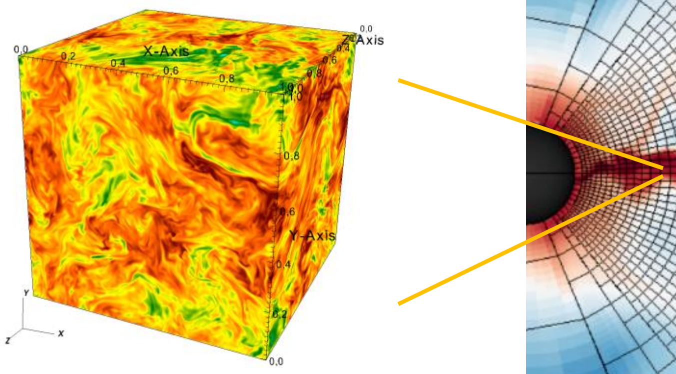
... microscopic acceleration scales: ... gyroradius: $r_{\rm g} \sim 3 \times 10^6\,{\rm cm}\,E_{\rm GeV}\,B_{\rm G}^{-1}$

... macroscopic source scales: ... e.g. blazar zone $R \sim 10^{16}\,{\rm cm}$

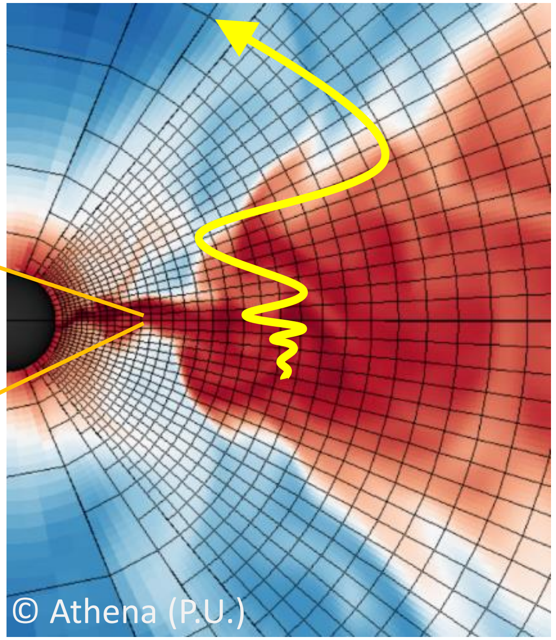
⇒ a strong limitation for applicability of PIC simulations: $1\,000^3 \sim 2$ orders of magnitude in dynamic range..

... in practice: phenomenology (macro → micro) vs theory (micro → macro)

→ a need for microscopic recipes to model particle acceleration in complex, random velocity flows:



© C. Demidem, rel. MHD turb.



→ multi-stage acceleration:

... scattering m.f.p. increases with energy ⇒ particle probes different velocity flows as energy increases

... from non-ideal/reconnection → turbulence → sheared velocity flows

Particle acceleration in magnetized, astrophysical turbulent plasmas

<u>Outline:</u>

1. General motivations and context

2. A colourized picture for stochastic Fermi acceleration:

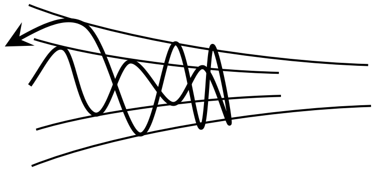
   → contribution of non-resonant acceleration supported by numerical simulations

   → physics of acceleration shaped by the intermittency of turbulence

3. Discussion + remarks toward phenomenology

The Fermi picture for particle acceleration (1949, 1954)

→ assumption: perfectly conducting magnetized plasma composed of moving scattering centers…
particle acceleration on motional electric fields $\boldsymbol{E} = -\boldsymbol{v_E} \times \boldsymbol{B}/c$



Fermi type A reflection of a cosmic-ray particle

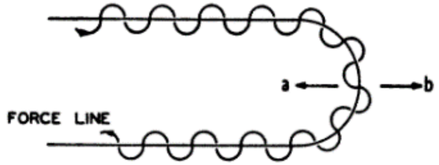
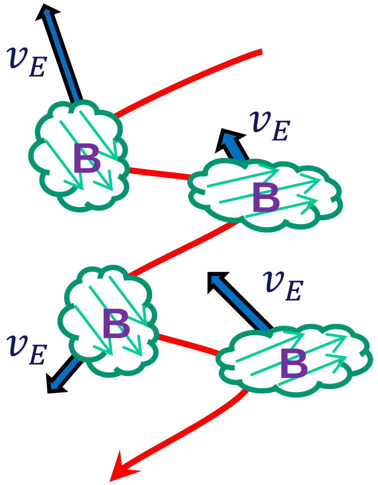


FIG. 1. Type B reflection of a cosmic-ray particle.



→ sequence of discrete interactions with point-like scattering centers… in each scattering center rest frame: elastic collision (ideal MHD ⇒ $\boldsymbol{E} = 0$ in rest frame)

→ kinematics: two-body collision, isotropic + elastic scattering in scattering center rest frame
⇒ $\Delta p > 0$ for head-on, $\Delta p < 0$ tail-on

→ stochastic acceleration (diffusion in momentum space)…
e.g. Fokker-Planck equation:

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

momentum diffusion coefficient: $D_{pp} \sim \frac{v_E^2}{c^2}\frac{p^2}{t_{\rm int}}$

→ an issue: implementing stochastic acceleration in turbulence?

Generalized Fermi acceleration: implementation in a large-scale, random velocity flow

→ what matters is the shear of the velocity flow $\partial_\alpha u_E{}^\beta$:

ideal MHD conditions: $\boldsymbol{E}$ vanishes in (comoving) frame moving at $\boldsymbol{u_E} \propto \boldsymbol{E} \times \boldsymbol{B}$

⇒ no acceleration in absence of shear…

… in original Fermi scenario:
shear ↔ difference in velocity of scattering centers

… in turbulent flow:
$\partial_\alpha u_E{}^\beta \supset$ compression, shear, vorticity…
with contributions from all scales of cascade…

→ follow the particle momentum in the (non-inertial) frame where $E = 0$ [1]:

in that frame, no electric field…

⇒ momentum variation ∝ non-inertial forces characterized by velocity shear of $\boldsymbol{u_E}$

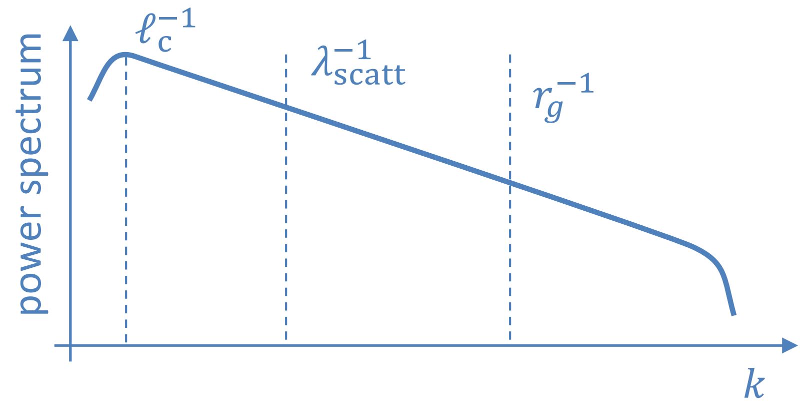
… ~instantaneous Lorentz transform to non-inertial frame where interaction with e.m. field is elastic

(+ mandatory in relativistic settings)

Refs: 1. M.L. 19, 21; see also previous works by Webb 85, 89

Generalized Fermi acceleration: interaction with large scale modes

→ what (also) matters is how a particle experiences different scales:

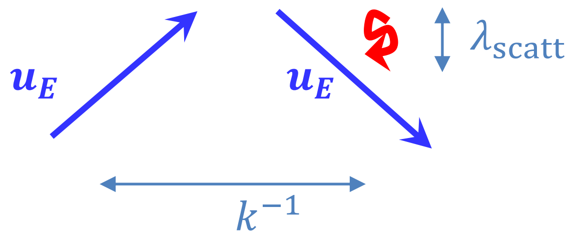


… e.g.: for $r_g/\ell_c \to 0$ adiabatic limit (MHD)
for $r_g/\ell_c \to \infty$ decoupling from turbulence

… for large scale modes: k (mode wavenumber) $\ll \lambda_{\rm scatt}^{-1}$ (scattering m.f.p.) $\ll r_g^{-1}$ (gyroradius)

⇒ momentum diffusion coefficient[1]:

$$D_{pp} \sim \underbrace{\frac{u_E^2}{c^2}\frac{p^2}{\lambda_{\rm scatt}/c}}_{\text{Fermi scaling}} \underbrace{\left(\frac{\lambda_{\rm scatt}}{k^{-1}}\right)^2}_{\ll 1}$$



… u_E gradient weak on scale $\lambda_{\rm scatt}$
⇒ inefficient acceleration in comoving frame…

⇒ "shielding" from large scale modes $k \ll \lambda_{\rm scatt}^{-1}$

Refs: 1. Bykov+Toptygin 83, Ptuskin 88, …, M.L. 19, Rieger 20 + refs, Demidem+20

Generalized Fermi acceleration: interaction with intermediate scale modes

→ **dominant contribution:** intermediate-scale modes with $\lambda_{\rm scatt}^{-1} < k \leq$ gyroradius r_g^{-1}

... transport ~ gyration around local magnetic field lines, i.e. coarse-grained on scale r_g

→ **model**[2]**:**

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

energy change in local comoving frame

$u'_{\parallel} = \boldsymbol{p'} \cdot \boldsymbol{b}/mc$

$u'_{\perp} = \left[u'^2 - {u'_{\parallel}}^2 \right]^{1/2}$

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]

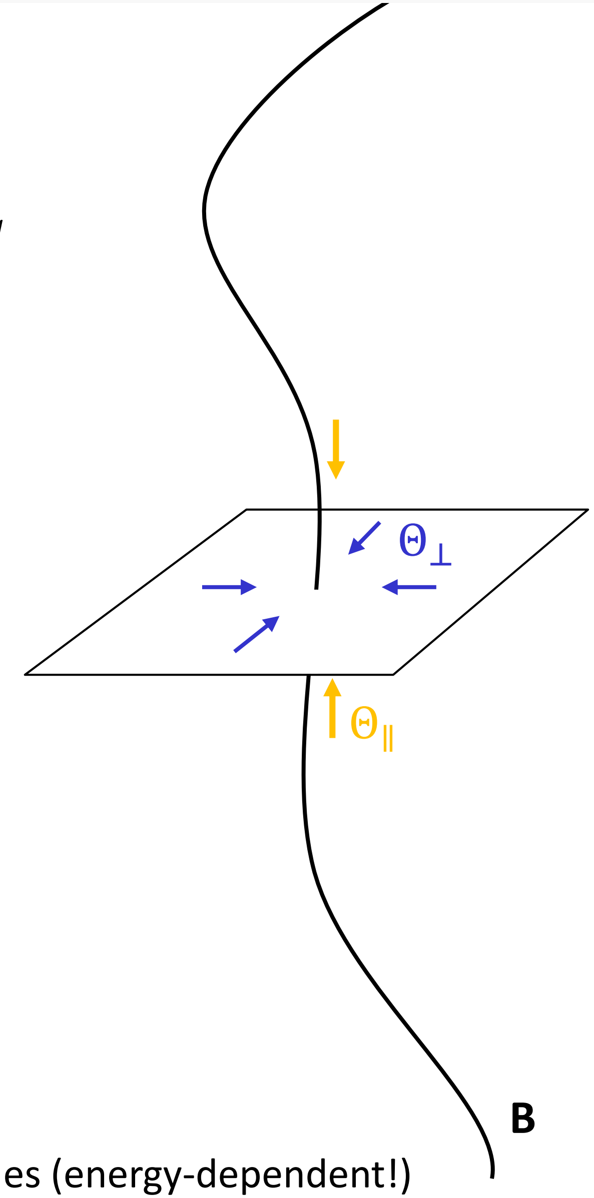
[field line curvature]

compression transverse to field line

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

[Fermi type-A]

[magnetic mirrors]



→ **remarks:**

... terms $a_E \cdot B$, $\Theta_{\parallel}$ and $\Theta_{\perp}$ are random forces: ⇒ random walk in momentum space

⇒ provides the required generalization of Fermi model to turbulent modes...

... average over gyro-orbit: ~drift-kinetic theory in magnetic field coarse-grained on r_g scales (energy-dependent!)

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

Non-resonant Fermi-type acceleration in velocity gradients: distinctive features

→ acceleration scales with gradient of magnetic energy density

… unlike quasi-linear theory: ∝ magnetic energy density

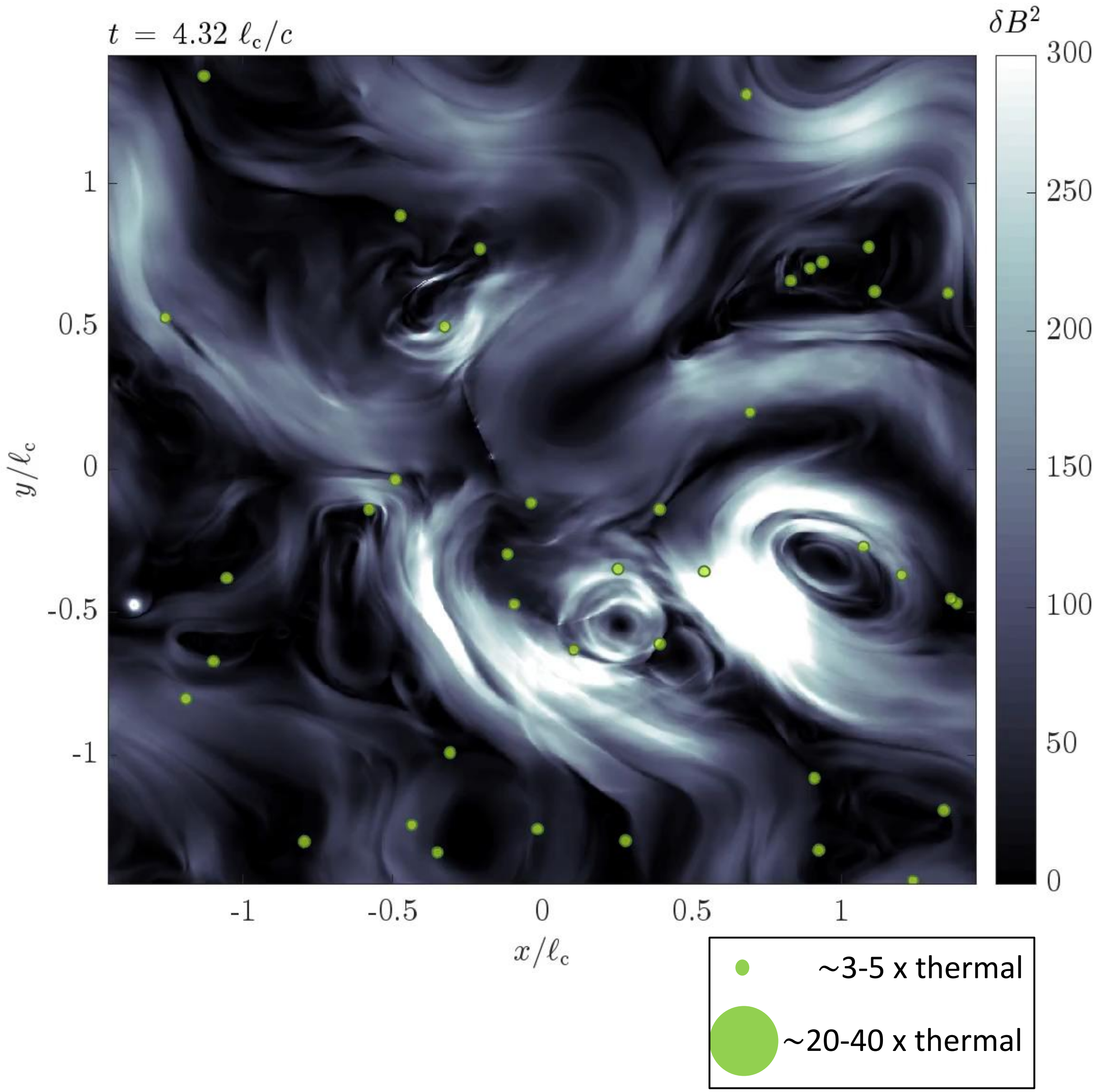
→ in each site, particle gains or loses energy regularly, according to sign of gradient

… unlike Fermi: head-on vs tail-on

→ acceleration sites occupy only a small filling fraction of the total volume

⇒ direct connection to intermittency

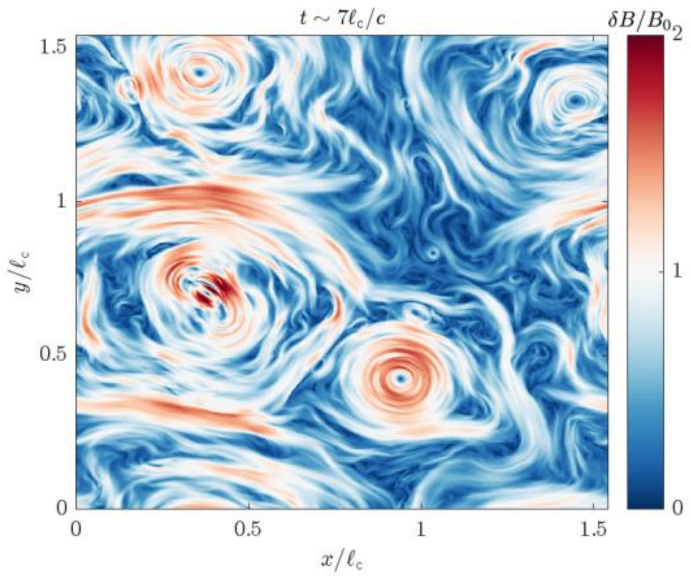
… unlike quasi-linear theory: homogeneous statistics



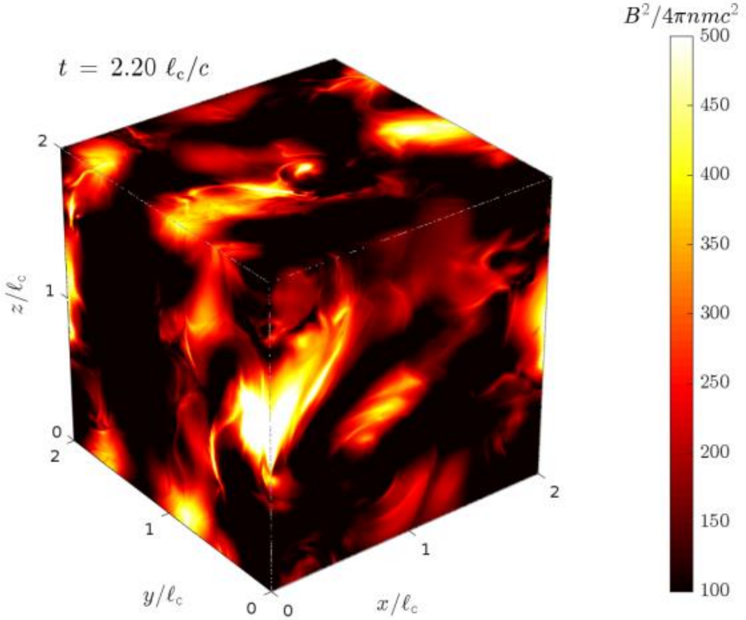
© V. Bresci, L. Gremillet, M. L.: 2D PIC, driven turb., e^+e^-, $10\,000^2$, $\delta B/B \sim 3$, $\sigma \sim 1$

Non-resonant Fermi-type acceleration: comparison to numerical experiments

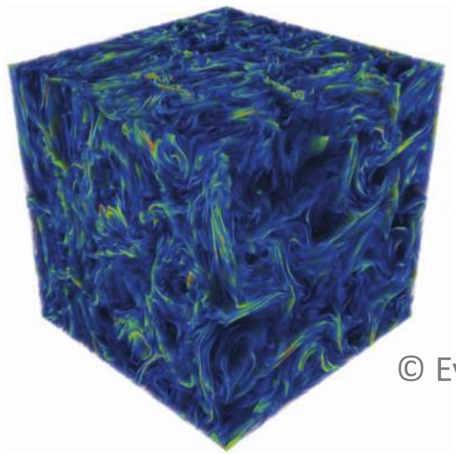
2D PIC simulation[1]: forced and decaying, 10 000^2, e^-e^+, $\delta B/B \sim 3, \sigma \sim 1$



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



3D MHD simulation[2]: forced, 1 024^3 x 1 024, $< B >= 0, v_A/c = 0.4$



+ synthetic turbulence[3] : sum of plane waves (Alfvén or fast magnetosonic)

Note: magnetization parameter $\sigma = \dfrac{\text{mag. energy dens.}}{\text{plasma energy dens.}}$

Refs: 1. V. Bresci, ML, L. Gremillet, L. Comisso, L. Sironi, C. Demidem 22 2. JHU database 3. Demidem+ 20

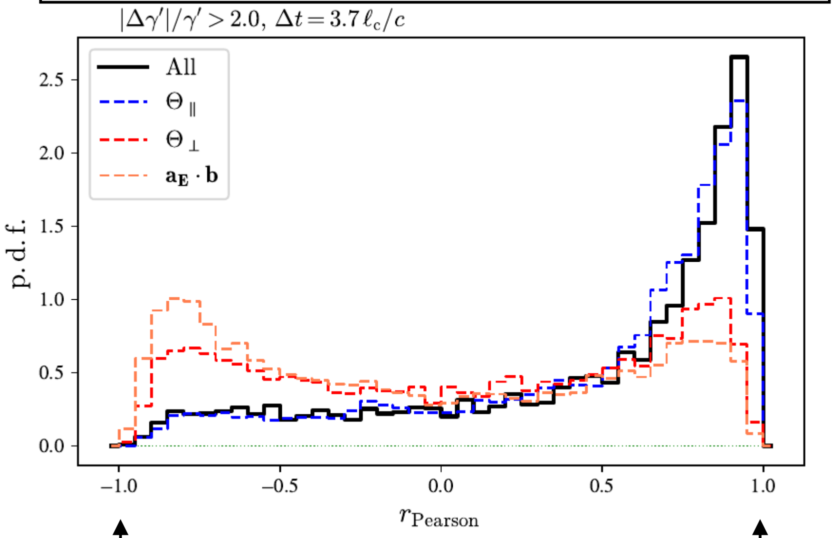
Non-resonant Fermi-type acceleration: comparison to numerical experiments

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

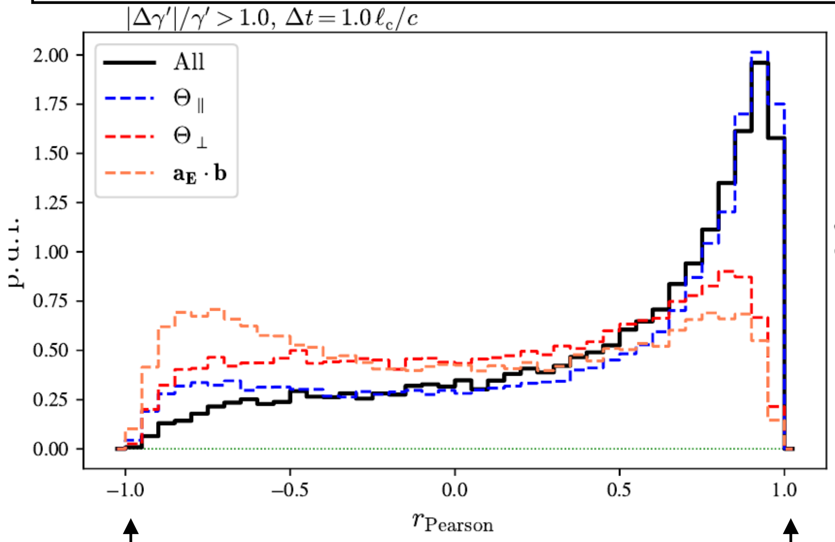
$$u'_{\|} = \boldsymbol{p'}\cdot\boldsymbol{b}/mc$$
$$u'_{\perp} = \left[u'^{2} - {u'_{\|}}^{2}\right]^{1/2}$$

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

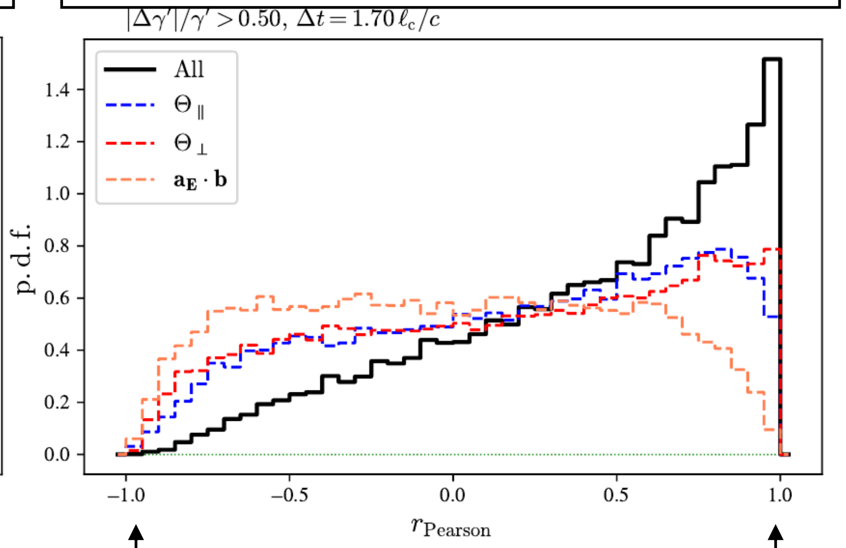
PIC simulation: 3D, 1 080^3, e$^-$e$^+$, δB/B ~ 3, σ ~ 1



PIC simulation: 2D, 10 000^2, e$^-$e$^+$, δB/B ~ 3, σ ~ 1



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



100% anti-correlation | 100% correlation | 100% anti-correlation | 100% correlation | 100% anti-correlation | 100% correlation

⇒ model captures the dominant contribution to particle energization

+ note: in wave turbulence w/ resonant wave-particle interactions, no apparent correlation seen (as expected)

Powerlaw spectra: shaped by the intermittency of turbulence

→ 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:

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

⇒ anomalous transport[1] + powerlaws in momentum

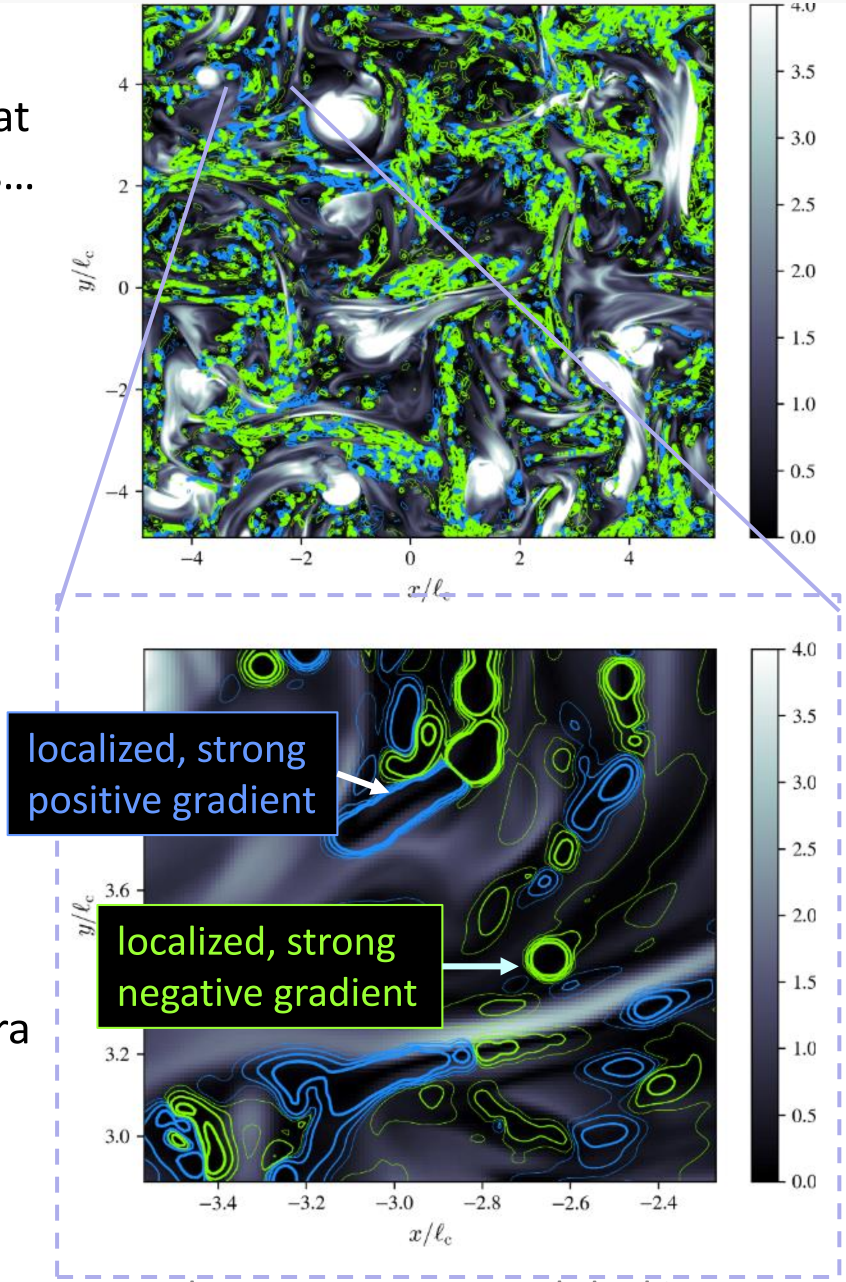
→ transport equation for distribution function[2]:

… failure of Fokker-Planck[3]: noise is non-Gaussian + non-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



Refs.: 1. Trotta+19, ML + Malkov 20, Maiti+21, Pezzi+22 2. ML 22 3. see however Wong+19, Zhdankin+20

A transport equation for non-resonant particle acceleration in intermittent turbulence

→ **note:** random forces $(a_E \cdot b, \Theta_{\parallel}, \Theta_{\perp}) \sim \Gamma_l \neq$ Gaussian white noise
⇒ transport equation deviates from Fokker-Planck…
intermittency ~ origin of powerlaw

→ **scheme:** random force Γ_l (coarse-grained on scale $l \sim r_g$), p.d.f. Prob(Γ_l)

⇒ momentum p jumps on timescale $\sim l/c$ by

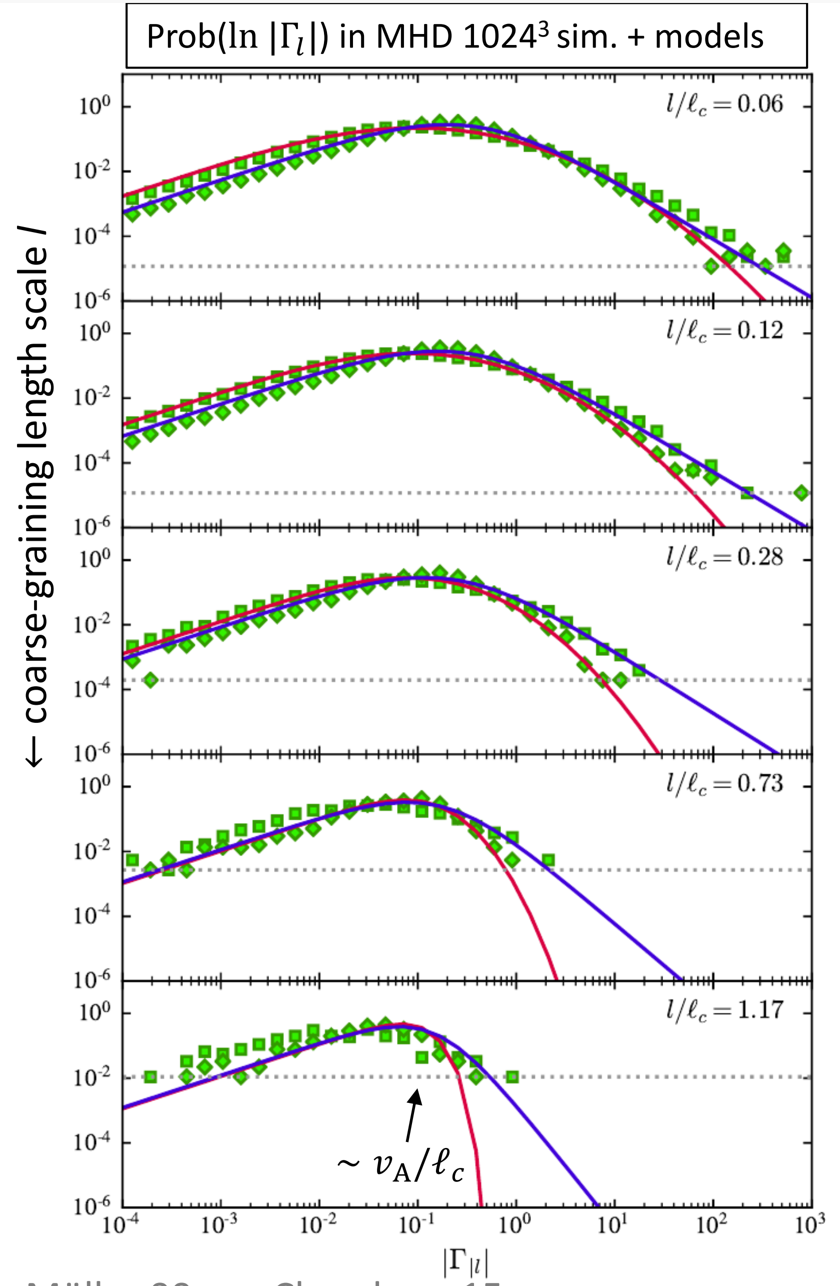
$$\Delta \ln p \sim \Gamma_l \; \Delta t \;\Rightarrow\; \mathrm{Prob.}\,(\Delta \ln p) \sim \mathrm{Prob.}\,(\Gamma_l)$$

→ **kinetic equation**[1]:

$$\partial_t\, n_p = \int_0^{+\infty} \mathrm{d}p' \left[\frac{\varphi\,(p|p')}{t_{p'}} n_{p'}(t) - \frac{\varphi\,(p'|p)}{t_p} n_p(t) \right]$$

$$n_p = \frac{\mathrm{d}N}{\mathrm{d}p} \qquad\qquad t_p \sim l/c$$

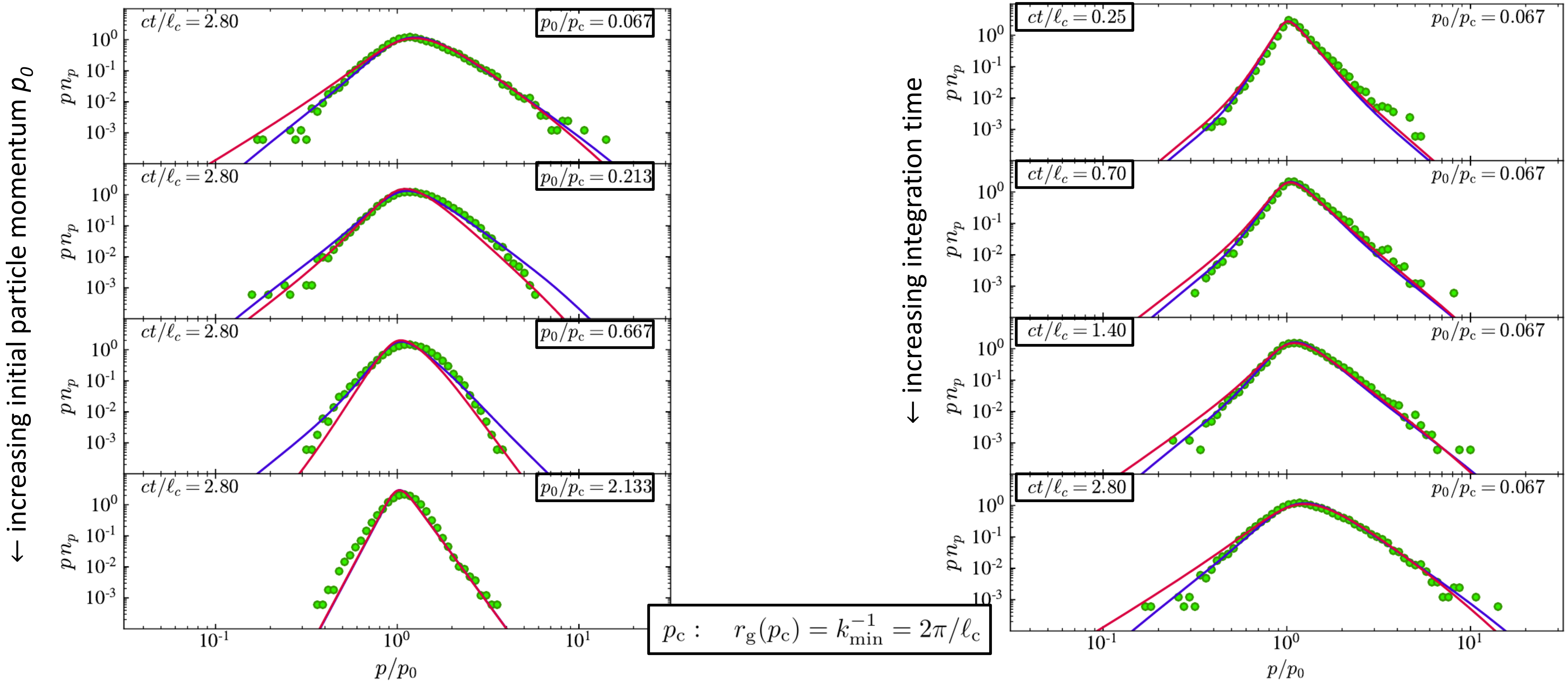
… hope: gain fundamental knowledge on Prob(Γ_l) to model acceleration (e.g. intermittency studies[2])



Refs.: 1. M.L. 22 2. Parisi+Frisch 85, …, She+Levêque 94, Dubrulle 94, … Biskamp+Müller 00, … , Chandran+15, …

Accelerated particle spectra from phase space transport in intermittent turbulence

→ comparison to numerical data: integrate kinetic equation and compare solution (Green function) to distribution measured in MHD 1024^3 simulation by time-dependent particle tracking…



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

⇒ transport equation can reproduce time- and energy- dependent Green functions… + capture powerlaw spectra

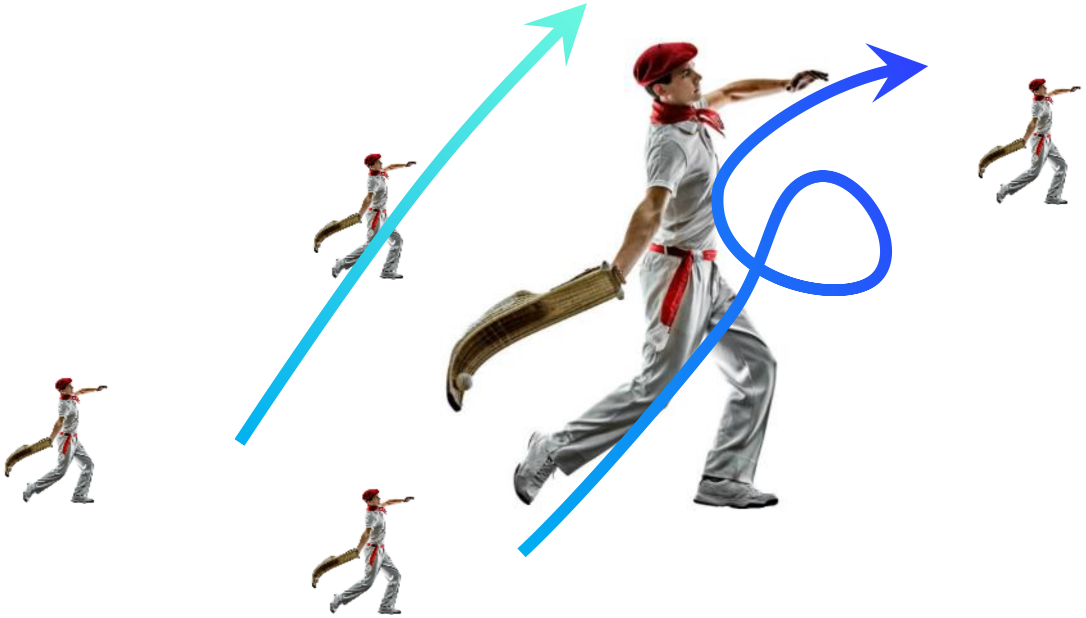
… in sub-relativistic regime: $\mathrm{d}N/\mathrm{d}p \propto p^{-4}$ and acceleration timescale $\sim \ell_c/v_A^2$ [see also Comisso + Sironi 22]

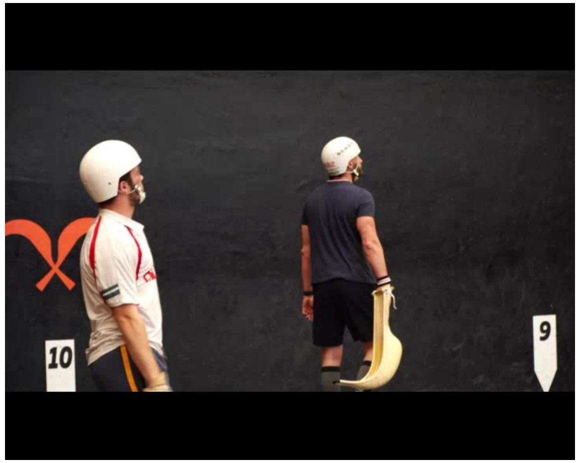
Colourizing the Fermi picture…

→ **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…

Summary + discussion

→ Implementing (non-resonant) Fermi-type acceleration in a realistic turbulence setting:

… track particle history in frame in which ***E=0****…*

… particles are accelerated in regions of strong velocity gradients

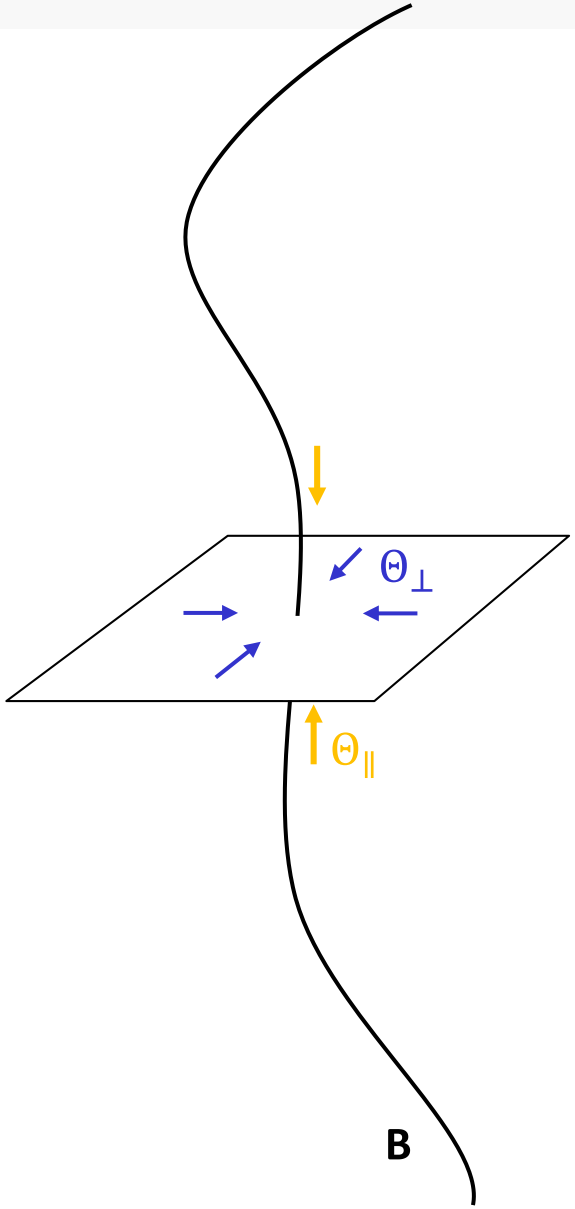
→ Test on PIC + MHD simulations: the Fermi picture is well alive

… model captures bulk of energization in supra-thermal powerlaw region… at $\sigma \gtrsim 0.1$

→ Deriving a transport equation for Fermi acceleration:

… velocity gradients are non-Gaussian on small scales: intermittency rules…

… a multi-fractal model of gradient statistics, and a transport equation…



→ Some limitations:

… extrapolation to small spatial length scales ?

… role of turbulence anisotropy, particle trapping in structures?

→ Some perspectives:

… better understanding the role and nature of intermittency wrt acceleration…

… consequences for phenomenology: flares etc…

… generalization to transport: e.g., role of intermittent magnetic mirrors…

… recipes for incorporating particle phase space transport in large-scale numerical simulations?

Statistics of turbulence intermittency

→ intermittent statistics: e.g. $\langle|\delta u_l^2|\rangle \propto l^{2\,h}$ but $\langle|\delta u_l|^n\rangle \not\propto l^{n\,h}\ (n>2)$

… structure functions: $S_n \equiv \langle|\delta u_l|^n\rangle = l^{\zeta_n}$

ζ_n in one-to-one correspondence with p.d.f. of δu_l

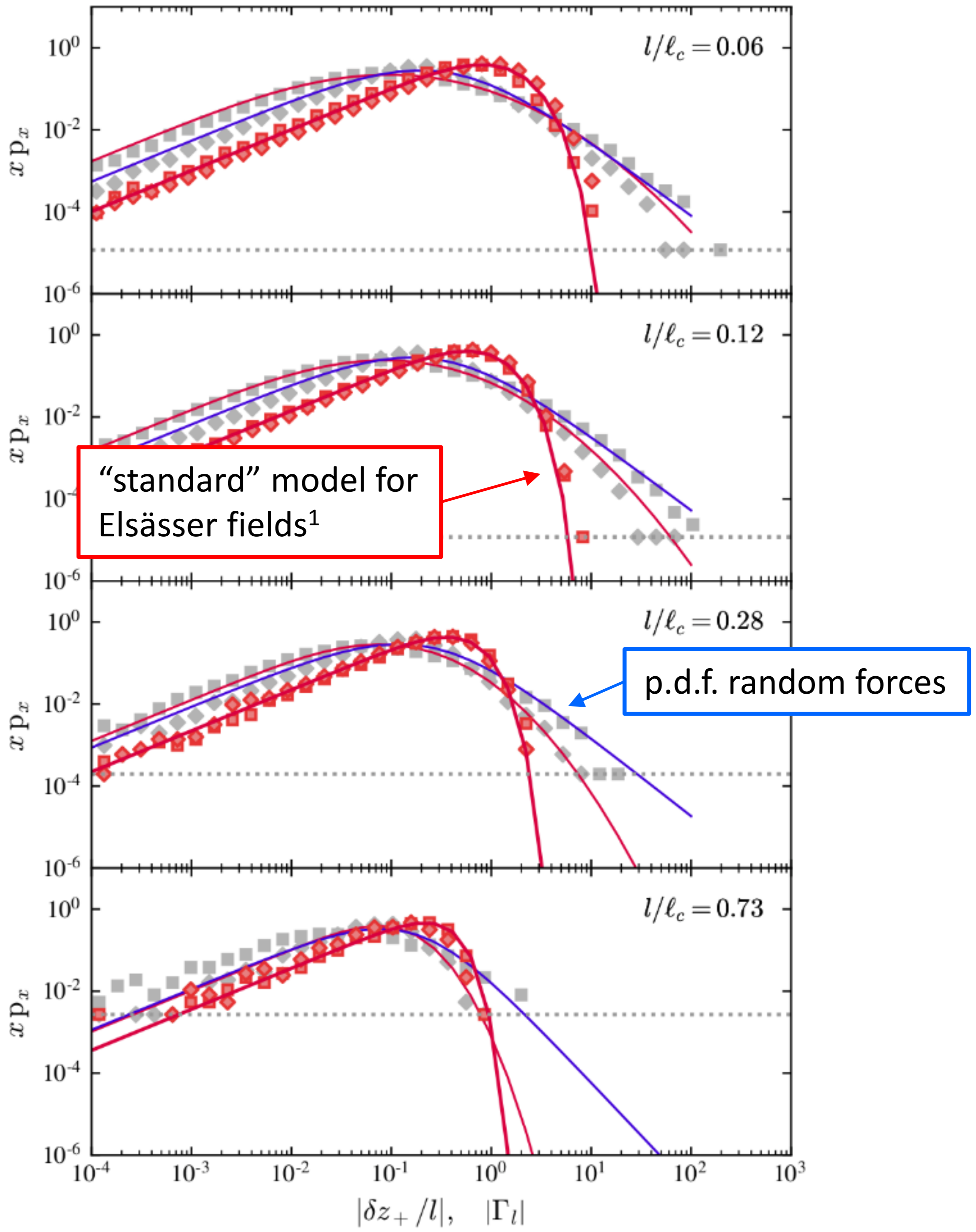
→ intermittent statistics of random forces:

… more extended, broader powerlaw tails than “standard” statistics for Elsässer fields $\delta z_{\pm} \equiv \delta v_l \pm \delta b_l$

… p.d.f. of random forces connected to field line curvature, which displays powerlaw behavior[2]

… a model for statistics of field line curvature: see [3]

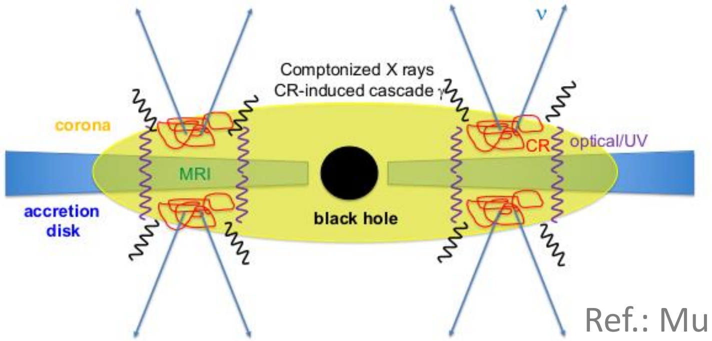
→ in different types of turbulence (e.g. compressive vs incompressible), different spectra[4] because of different statistics?



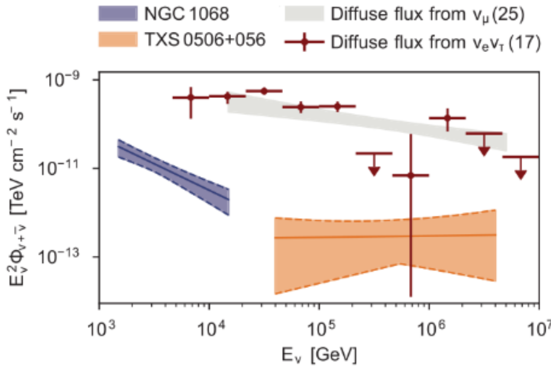
Refs.: 1. e.g. She+Levêque 94, Dubrulle 94,…, Müller+ 03,…, Chandran+15 2. Yang+19, Yuen+Lazarian20 3. Schekochihin+01 4. Zhdankin 20

Stochastic Fermi acceleration as an origin for the high-energy neutrinos from NGC 1068

→ **Ice Cube 22:** a clear 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]



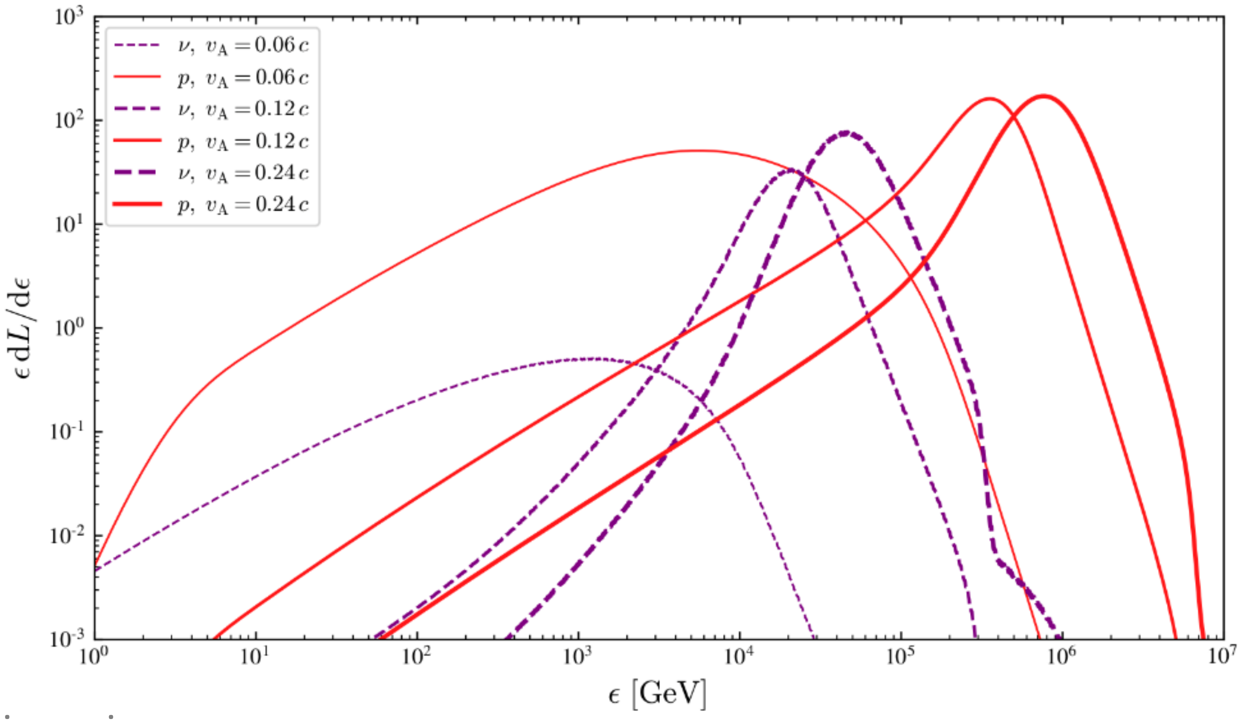
Ref.: Murase+Stecker 22



Ref.: Ice Cube 22

→ **model:** integrate spectra through transport eqn…
… including relevant energy losses[1]

⇒ p acceleration to >100TeV possible for turbulent Alfvén velocity $v_A \gtrsim 0.1c$
… +shear contribution?[2]



Refs.: 1. e.g. Murase 22 + refs. 2. M.L. + Rieger, in prep.

Does intermittency affect spatial transport?

→ anomalous spatial transport by scattering on intermittent structures?

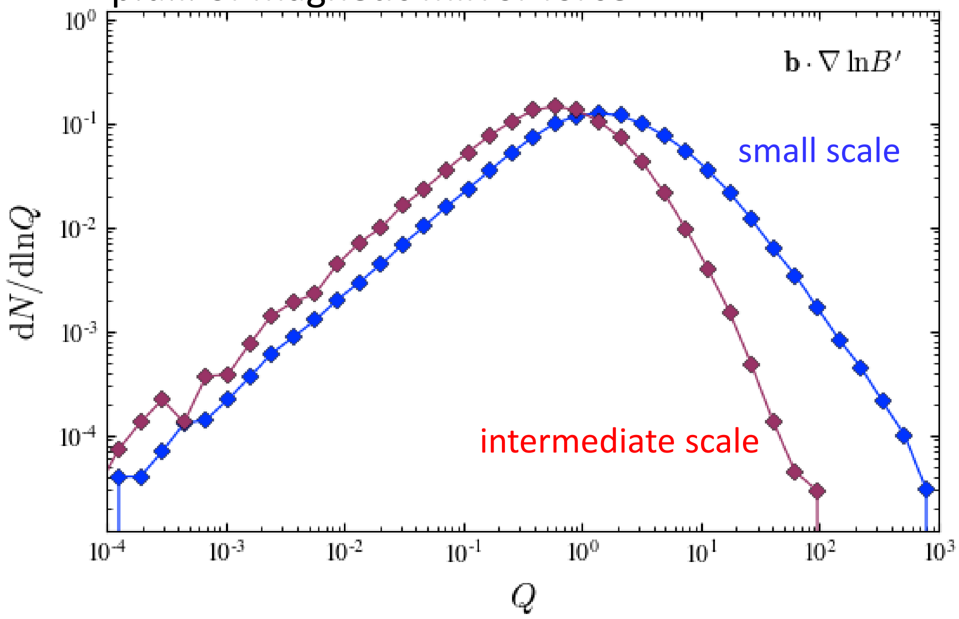
→ in absence of resonant wave-particle interactions: scattering ← magnetic mirrors[1]

⇒ subject to intermittency…

⇒ expect spatial anomalous diffusion on scales $\sim \ell_c$:
… superdiffusion for some particles,
… trapping for others… seen in some simulations[3]

⇒ phenomenological consequences for e.g. pulsar halos, cosmic-ray anisotropies at high energies etc.?

p.d.f. of magnetic mirror force

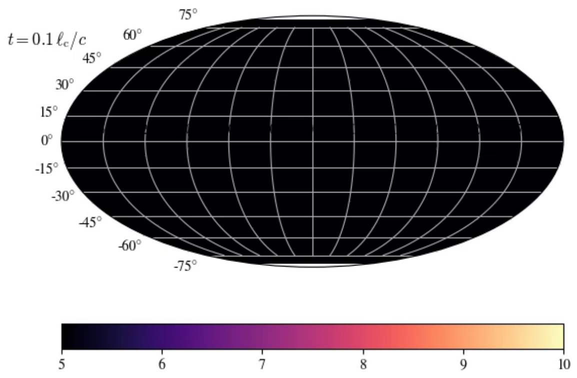


→ **note:** for low-energy cosmic rays, no intermittency effect because of very large travel time…

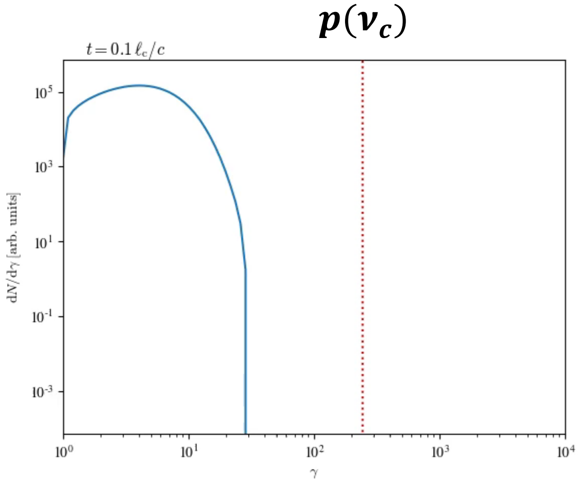
Refs.: 1. e.g. Chandran 00, Malyshkin + Kulsrud 01, …, Xu+Lazarian 20 3. Trotta+20, Maiti+21, Pezzi+22, …

Consequence of intermittency for radiative signatures

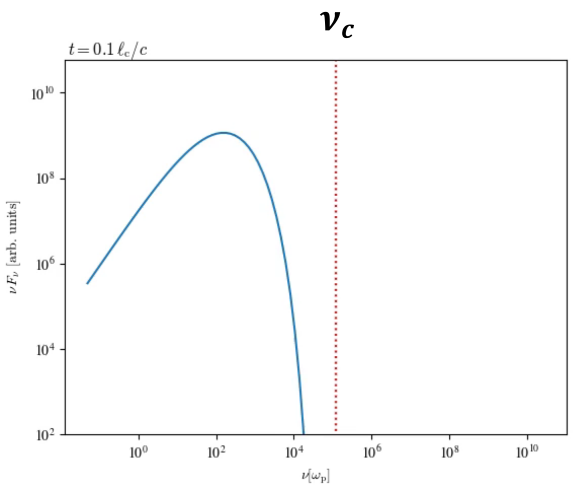
→ intermittency and high-energy flares: particle distribution highly anisotropic with spectral shape non-uniform in space close to the maximal energy[1]…



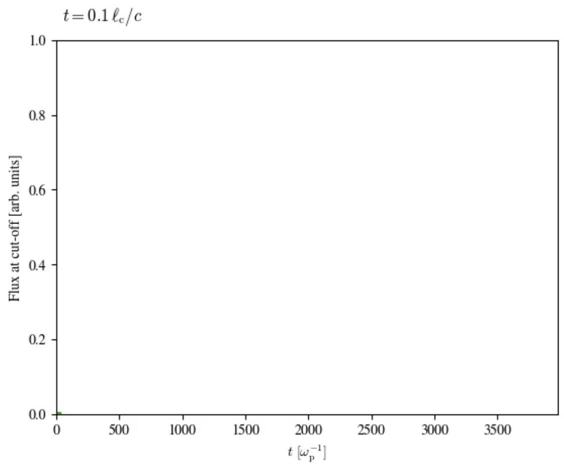
synchrotron map at cut-off ν_c



$p\ \mathrm{d}N/\mathrm{d}p$ vs p



νF_ν vs ν



light curve at cut-off ν_c

→ important phenomenological consequences for time-dependent flaring sources at high energies (e.g. blazars, GRBs etc.)

→ a potential realization of [Bykov+13] scenario for Crab flares: injection of high-energy pairs in turbulence?

→ note: in relativistic turbulence $\sigma \gtrsim 1$, acceleration timescale $t_{\rm acc} \propto 1/u_E^2 \propto 1/\sigma$!

Refs.: 1. Zhdankin+19, 20, Nättilä + Beloborodov 20, Comisso+Sironi 21

Summary and perspectives

→ Implementing (non-resonant) Fermi-type acceleration in a realistic turbulence setting:

… track particle history in frame in which ***E=0****…*

… particles are accelerated in regions of strong velocity gradients

→ Test on PIC + MHD simulations: the Fermi picture is well alive

… model captures bulk of energization in supra-thermal powerlaw region…

→ Deriving a transport equation for Fermi acceleration:

… non-Gaussian velocity gradients on small scales: intermittency rules…

… a multi-fractal model of gradient statistics, and a transport equation…

→ Some limitations:

… extrapolation to small spatial length scales ?

… role of turbulence anisotropy, particle trapping in structures?

→ Some perspectives:

… role and nature of intermittency wrt acceleration…

… consequences for phenomenology: flares etc…

… generalization to transport: e.g., role of intermittent magnetic mirrors…

… recipes for particle phase space transport in numerical simulations?