Recent developments on particle acceleration in magnetized turbulence

1. Comisso, L., & Sironi, L. : The Interplay of Magnetically Dominated Turbulence and Magnetic Reconnection in Producing Nonthermal Particles, ApJ, 886, 122 (2019).

2. Comisso, L., & Sironi, L. : Particle Acceleration in Relativistic Plasma Turbulence, PRL, 121, 255101 (2018).

3. Zhdankin, V. : Particle energization in relativistic plasma turbulence: solenoidal versus compressive driving, arXiv e-prints, arXiv:2106.00743 (2021).

4. Zhdankin, V., Uzdensky, D. A., Werner, G. R., & Begelman, M. C. : Electron and Ion Energization in Relativistic Plasma Turbulence, PRL, 122, 055101 (2019).

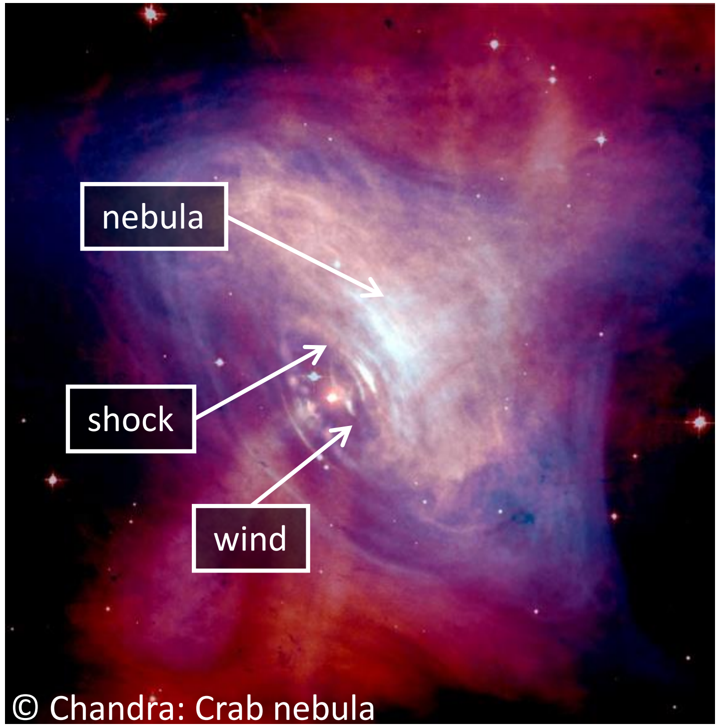
5. Zhdankin, V., Uzdensky, D. A., Werner, G. R., & Begelman, M. C. : System-size Convergence of Nonthermal Particle Acceleration in Relativistic Plasma Turbulence, ApJ, 867, L18 (2018).

6. Zhdankin, V., Werner, G. R., Uzdensky, D. A., & Begelman, M. C. : Kinetic Turbulence in Relativistic Plasma: From Thermal Bath to Nonthermal Continuum, PRL, 118, 055103 (2017).

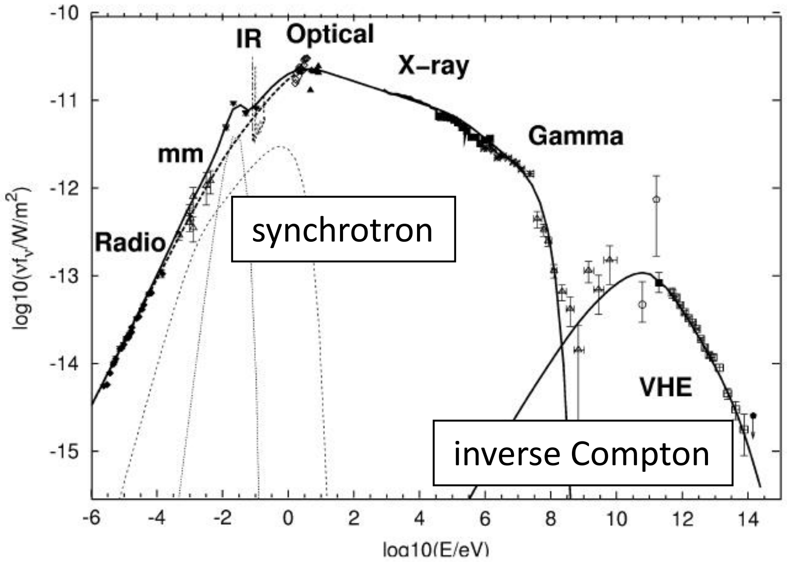
7. Wong, K., Zhdankin, V., Uzdensky, D. A., Werner, G. R., & Begelman, M. C.: First-principles Demonstration of Diffusive-advective Particle Acceleration in Kinetic Simulations of Relativistic Plasma Turbulence, ApJ, 893, L7 (2020).

+ Lemoine, M., Malkov, M. A.: Powerlaw spectra from stochastic acceleration, MNRAS, 499, 4972 (2020).
Lemoine, M.: Particle acceleration in strong MHD turbulence, arXiv:2104.08199 (2021).

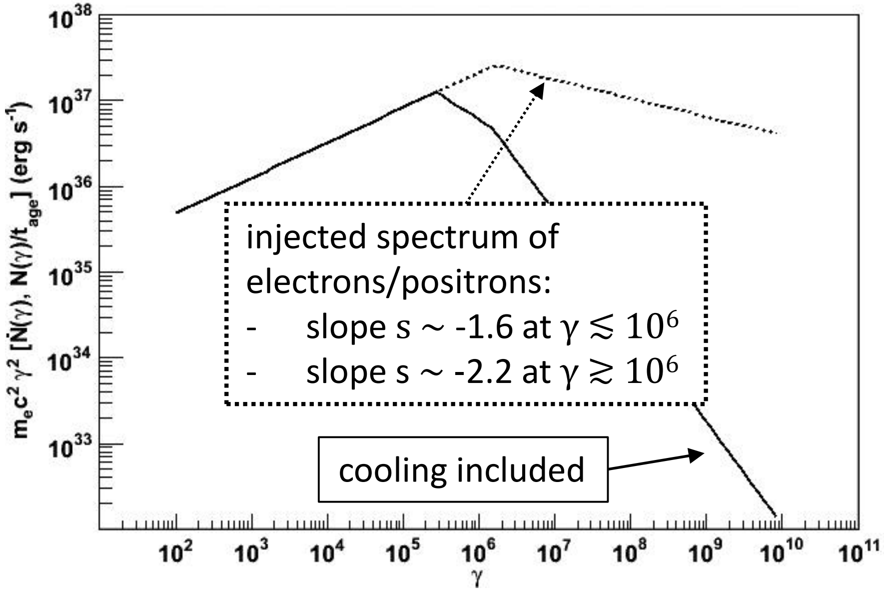
Pulsar wind nebulae as extreme lepton accelerators…



spectral energy distribution



reconstructed e^+e^- spectrum



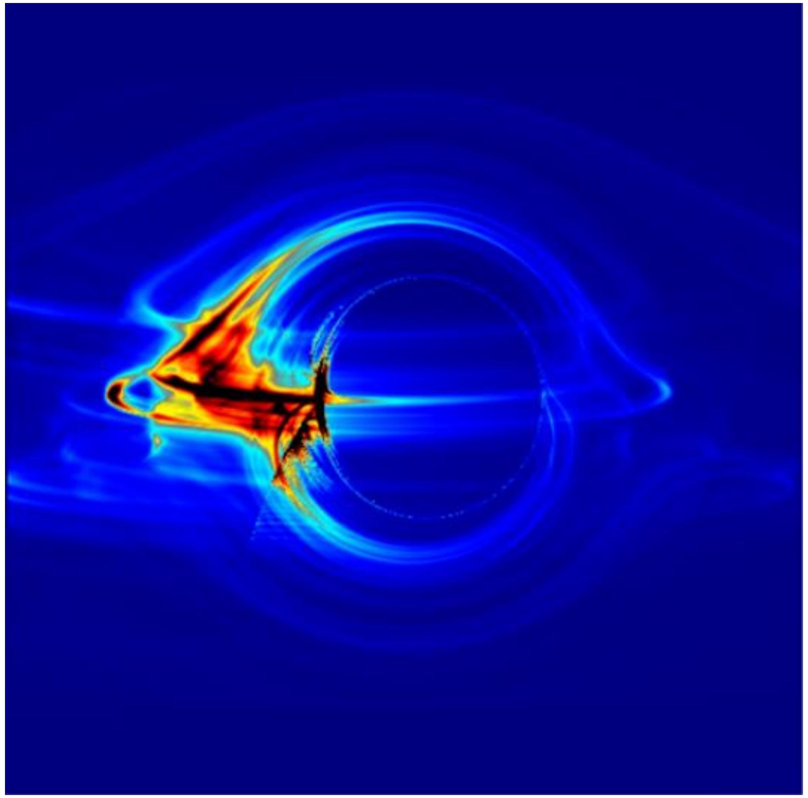
→ in the nebula: magnetization $\sigma = \frac{u_{magnetic}}{u_{plasma}} \sim 1$ (relativistic turbulence!),

… composition pair plasma, $\ell_c \sim 0.1$ pc, $\frac{c}{\omega_p} \sim 10^{-6}$pc

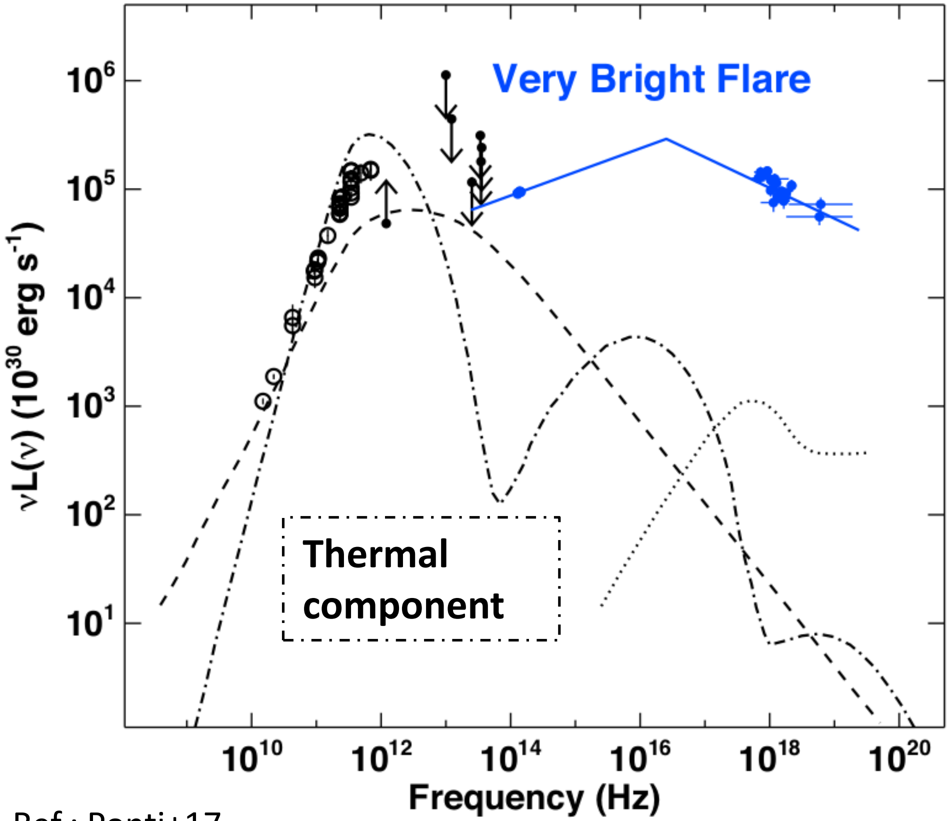
Ref.: e.g. Horns & Aharonian 04; Kirk+09

Evidence for non-thermal electron acceleration in BH environments…

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



Ref.: Petersen+Gammie20



Ref.: Ponti+17

NB: as in many astrophysical sources, a huge hierarchy between macroscopic scales (l_c turbulence scale, r_g) and microscopic scales (r_L): $r_g/r_L \sim 10^6$ for a GeV electron in 1G field… a challenge for numerical simulations!

Non-thermal electrons in jets… on all scales!

© Chandra: X-ray jet from Cen A

→ in large-scale jets:

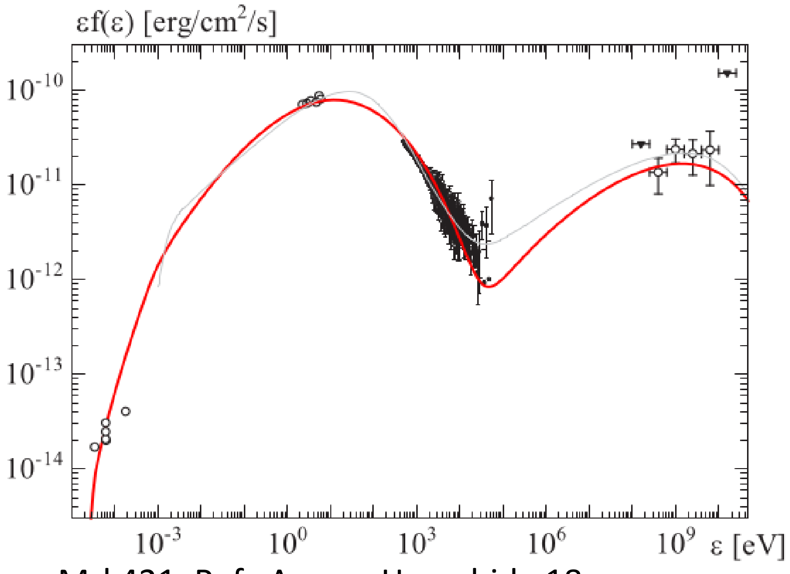
radiation in X-ray over length scales ≫ synchrotron cooling length requires some continuous acceleration, with index ~ -2 … -3, e.g. turbulence or shear?

Refs.: Liu+17, Rieger 19

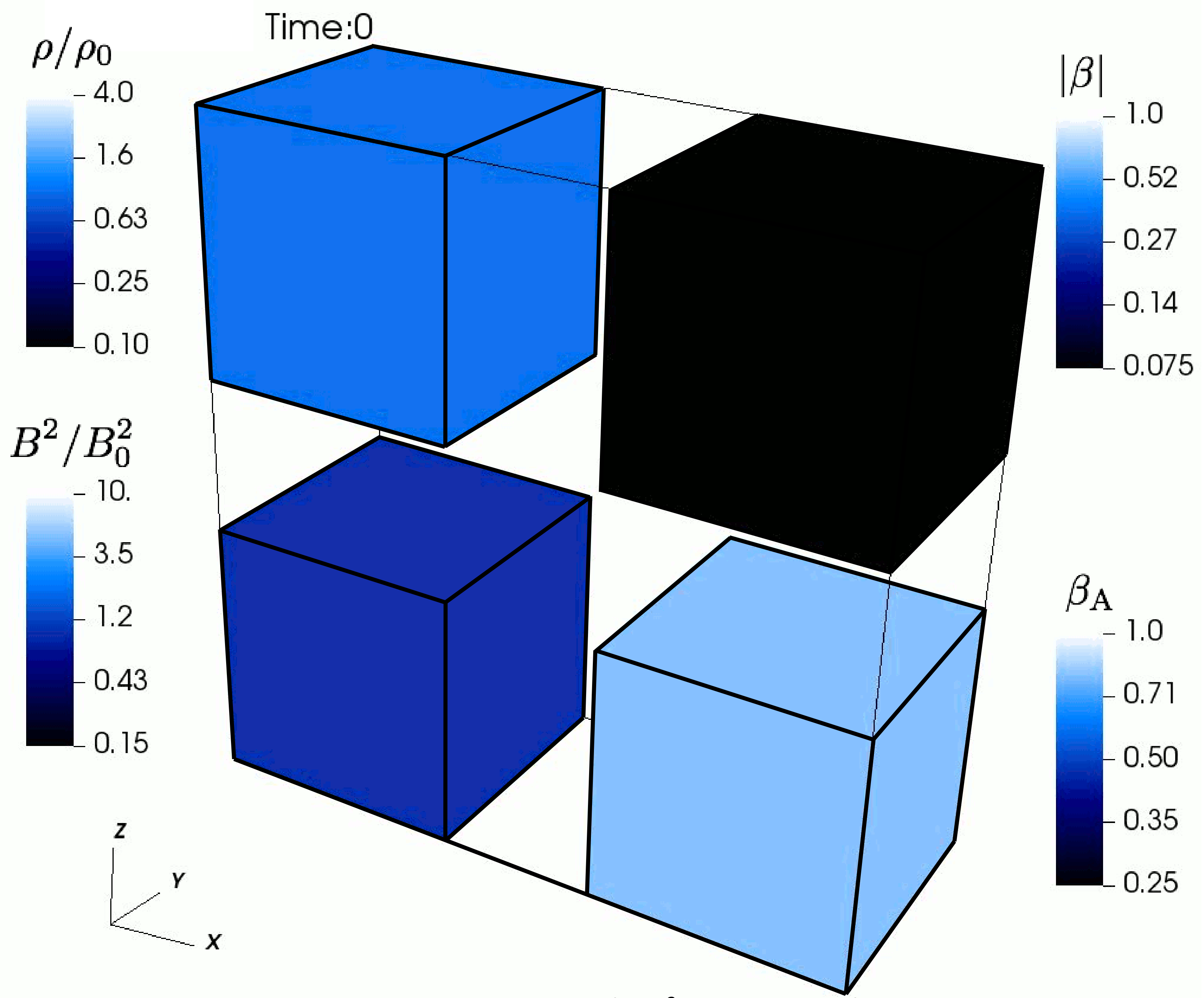
→ in blazars:

generic SSC or synchrotron+EC model from non-thermal electrons… acceleration physics: reconnection, turbulence, shocks?

e.g. for turbulence:



Mrk421, Ref.: Asano+Hayashida 18



Relativistic MHD simulation (256^3, σ_0=30, u_A~5) © C. Demidem

Turbulence characteristics:

→ energy injection scale: ℓ_c

→ magnetization: $\sigma = \frac{u_{\mathrm{magnetic}}}{u_{\mathrm{plasma}}}$

→ Alfvén 4-velocity: $u_A = \sqrt{\sigma}$

⇒ relativistic turbulence: $\sigma > 1$

→ dissipation scales: at plasma Larmor or skin depth scale c/ω_p

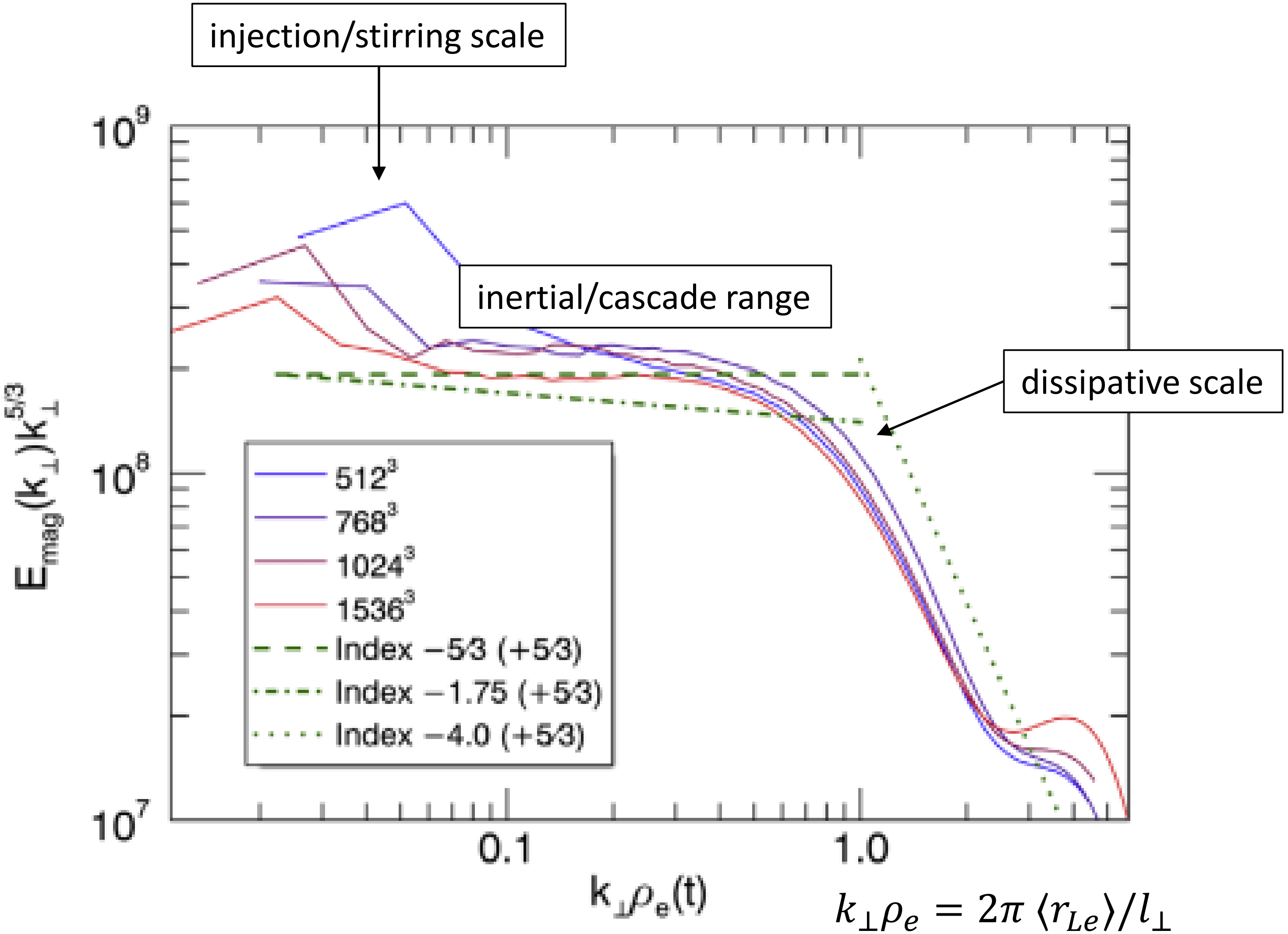
⇒ dynamic range in PIC:

$$\frac{\ell_c}{c/\omega_p} \sim \mathcal{O}(100)$$

… using PIC (~ electromagnetic N-body code) to perform self-consistent, ab initio virtual experiments of relativistic magnetized turbulence

magnetic
power spectrum

$$\langle \delta B^2 \rangle \propto \int \mathrm{d}k_\perp E_{\mathrm{mag}}(k_\perp)$$



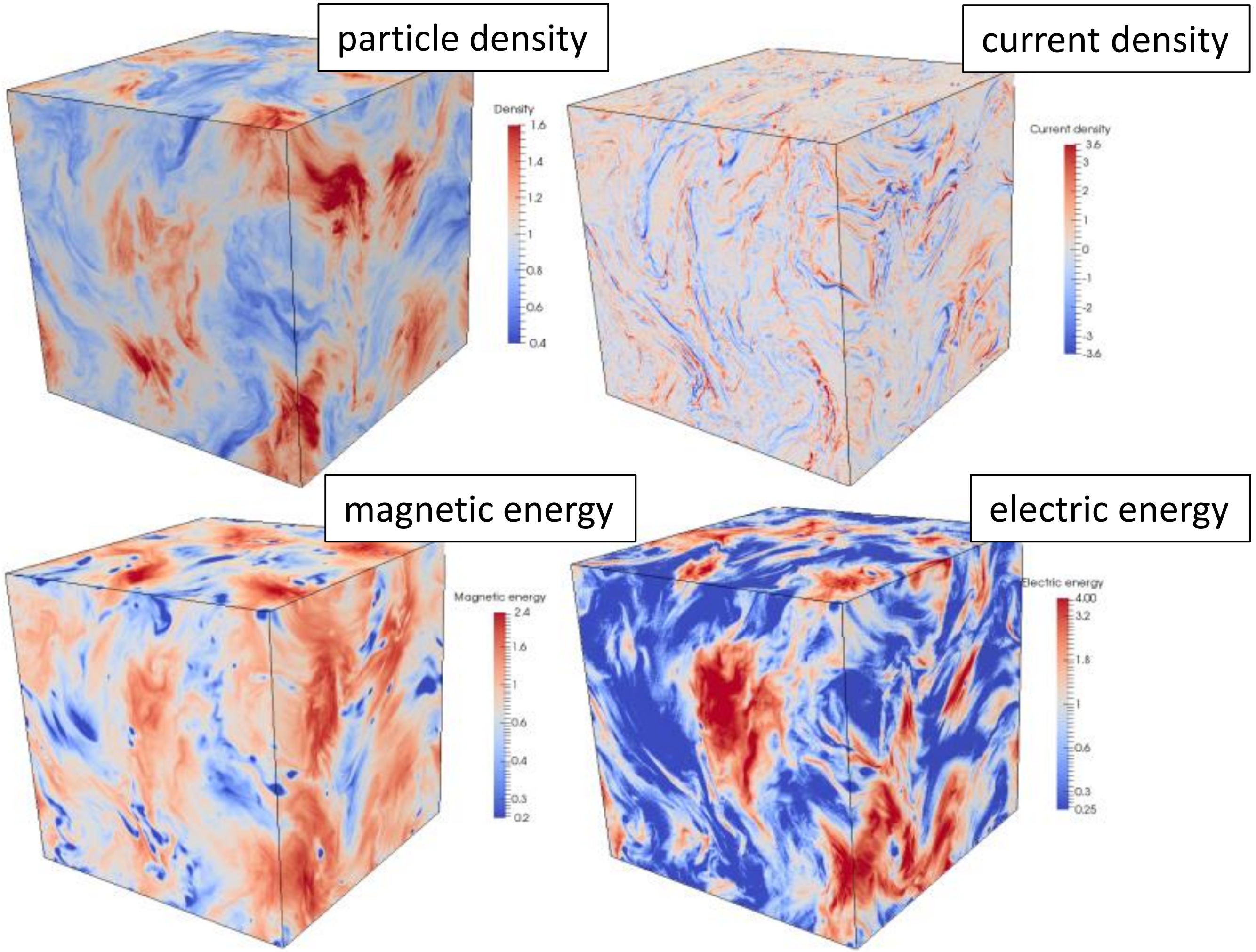
$k_\perp \rho_e = 2\pi \langle r_{Le} \rangle / l_\perp$

inertial range: MHD-type turbulent cascade
kinetic scales: dissipative processes (reconnection)
+ self-consistent particle-turbulence interaction → particle acceleration

Zhdankin+18

Table 1. List of largest simulations

Case	N^3	$L/2\pi\rho_{e0}$	σ_0	Tc/L	$N_{\rm ppc}$	$R_{{\rm err},T}(\%)$	$R_{{\rm err},L/c}(\%)$
A2	1024^3	108.6	0.5	22.3	128	3.7%	0.16%
A4	1024^3	108.6	2	13.4	192	3.0%	0.23%
B1	768^3	61.1	0.25	22.3	256	3.7%	0.16%
B2	768^3	81.5	0.5	10.1	256	0.6%	0.06%
B3	768^3	81.5	1	11.2	128	2.3%	0.21%
B4	768^3	81.5	2	9.2	128	3.3%	0.36%
B5	768^3	81.5	4	13.4	96	2.4%	0.18%
C1	512^3	40.7	0.25	22.3	256	2.3%	0.10%
C2	512^3	54.3	0.5	17.9	128	0.8%	0.05%
C3	512^3	54.3	1	14.1	128	2.0%	0.14%
C4	512^3	54.3	2	15.1	128	2.6%	0.17%
C5	512^3	54.3	4	15.6	128	2.5%	0.16%



Zhdankin+18

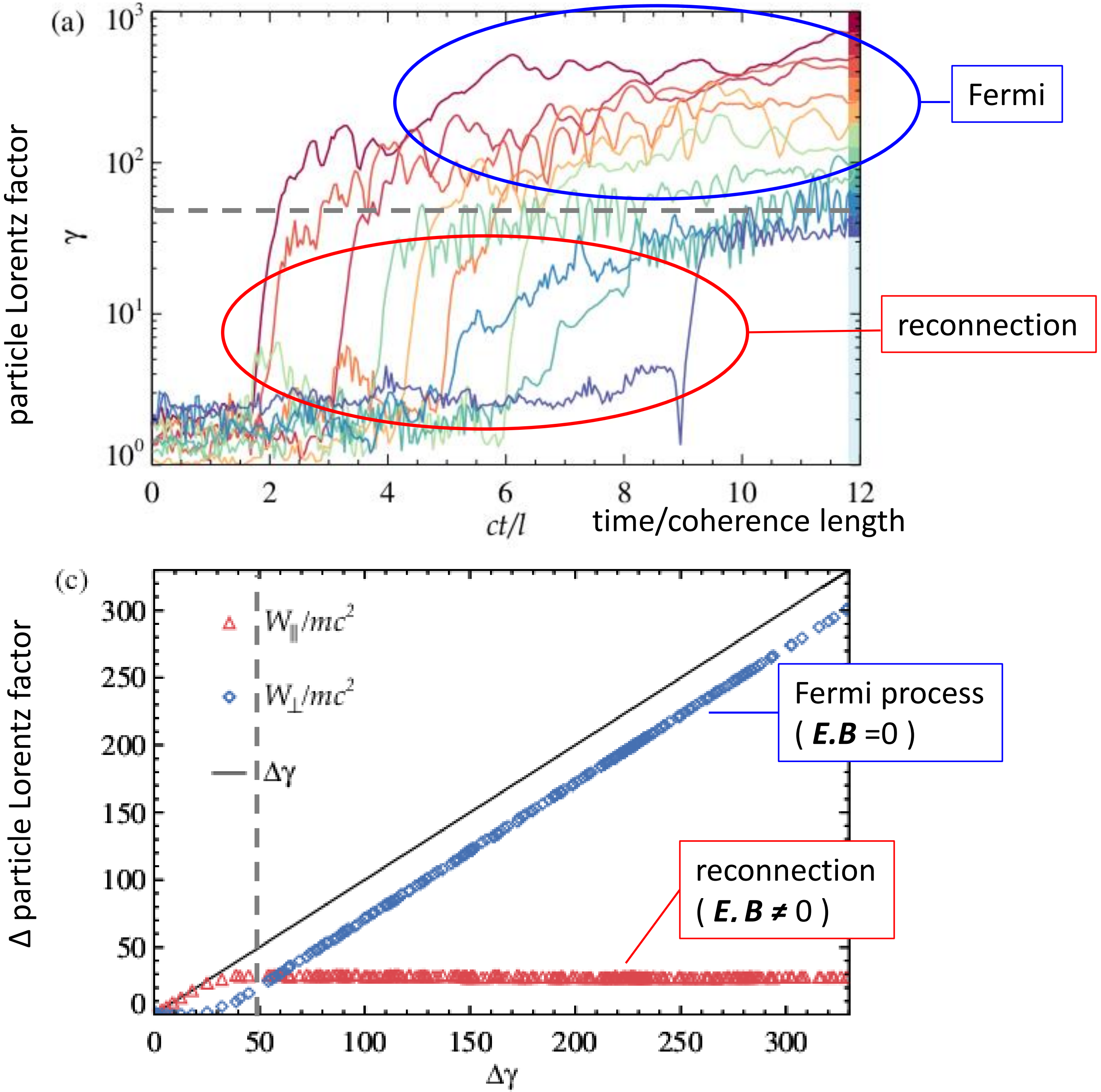
A two-stage acceleration process:

- initially, plasma is thermal: $\langle\gamma_0\rangle \sim 3$

[gyroradius ~ skin depth at $\sigma \sim O(1)$]

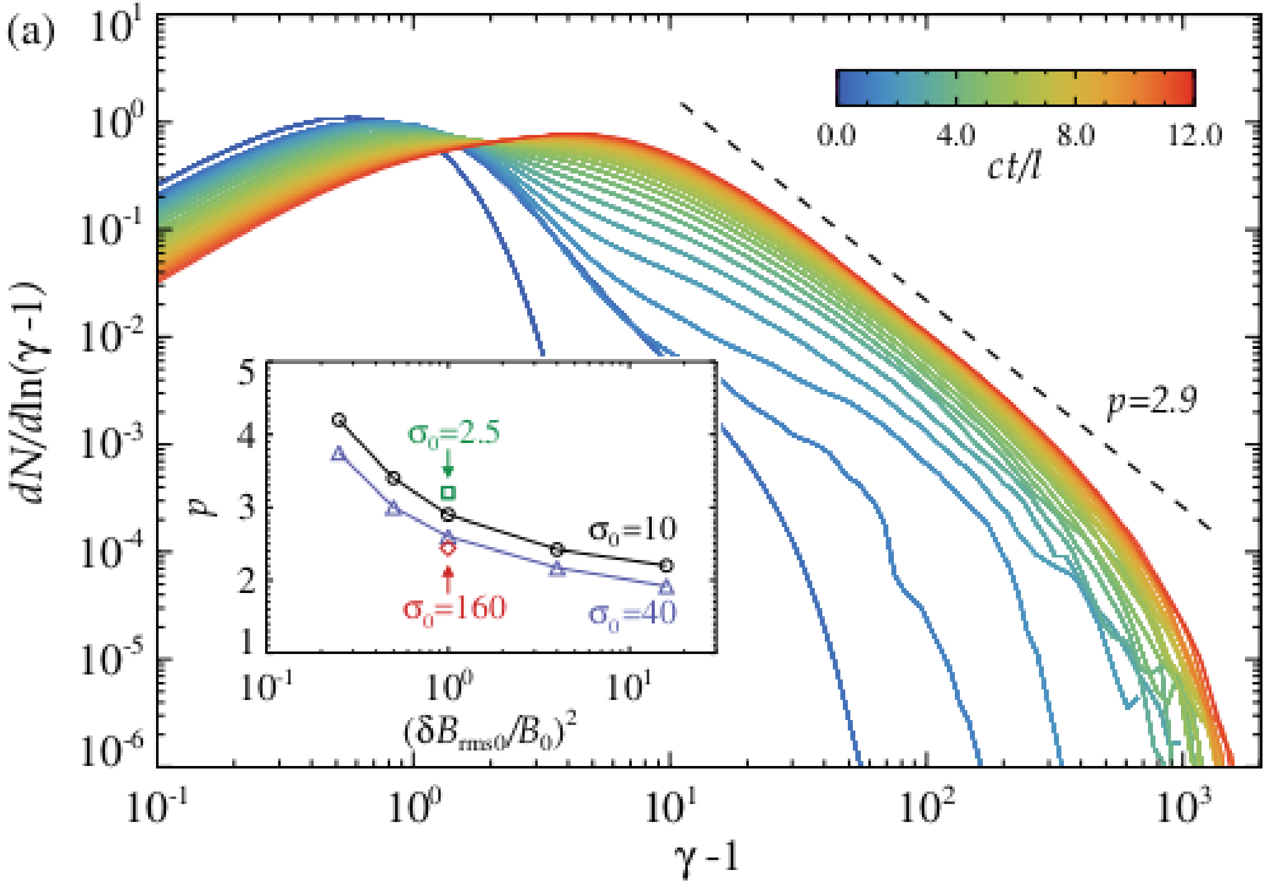
- first stage: particles are accelerated to $\langle\gamma\rangle \sim 4\sigma \langle\gamma_0\rangle$ in reconnection layers (dissipative physics on kinetic scales)

- second stage: particles are accelerated to larger energies through Fermi-type (stochastic Fermi acceleration) processes...



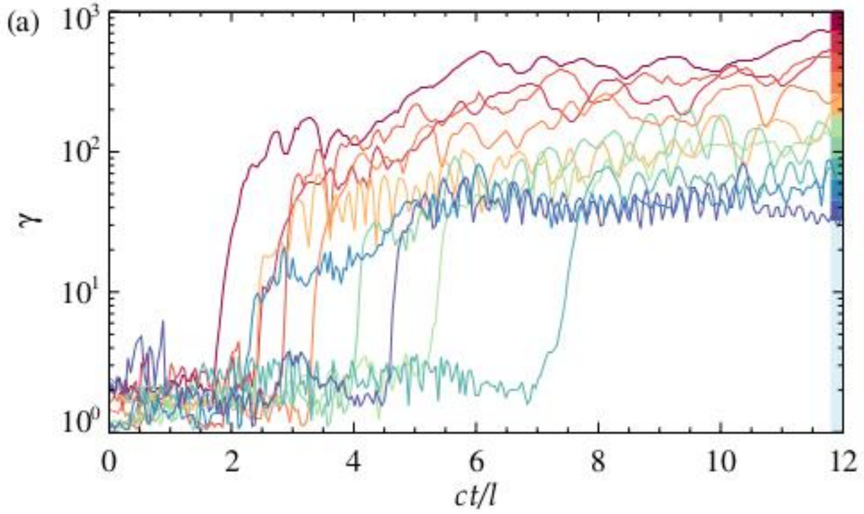
Comisso+Sironi 18,19

<u>Generation of a non-thermal powerlaw spectrum</u>



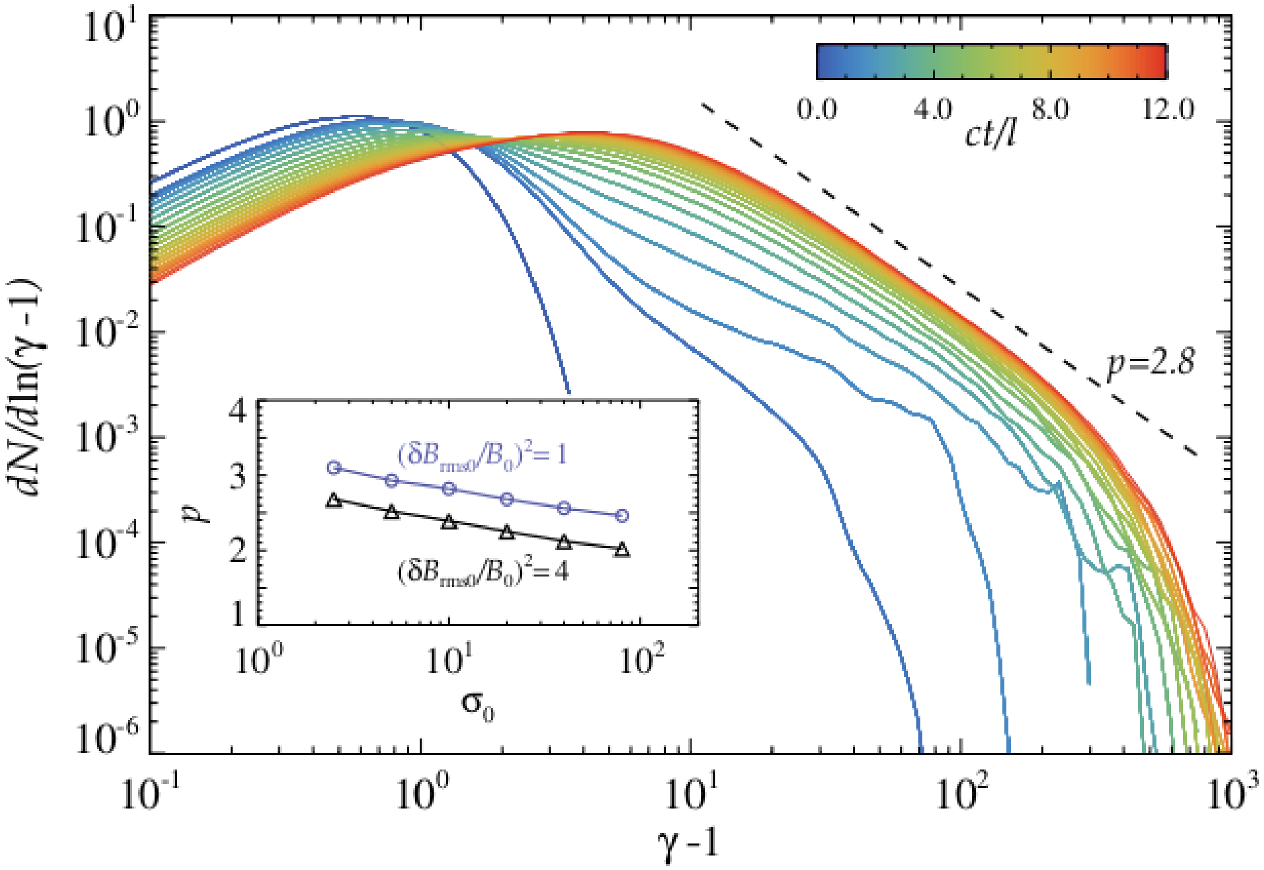
- a thermal core, heating through dissipative processes at kinetic scales (reconnection)…

- a non-thermal (soft) powerlaw tail from Fermi acceleration



Comisso+Sironi 18,19

Generation of a non-thermal powerlaw spectrum



- a thermal core, heating through dissipative processes at kinetic scales (reconnection)…

- a non-thermal (soft) powerlaw tail from Fermi acceleration

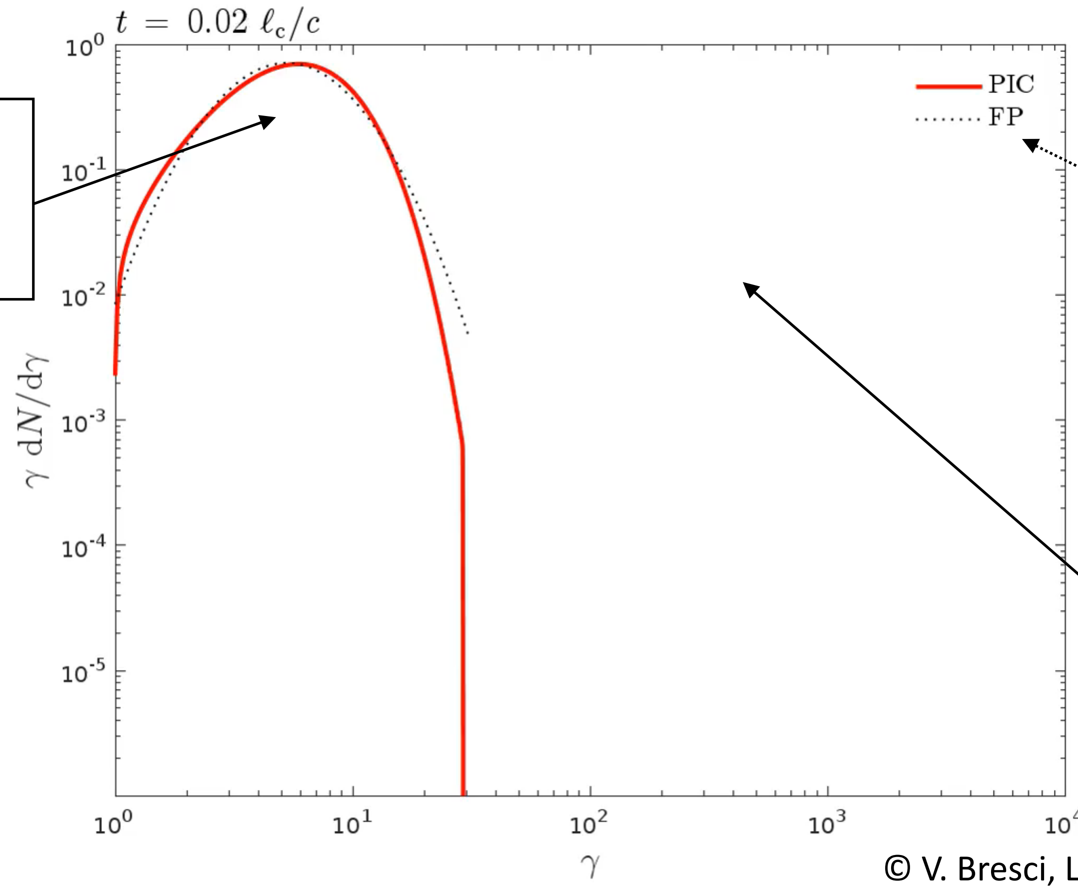
- tendency: spectrum becomes harder with increasing magnetization (= increasing v_A/c), with increasing amplitude $(\delta B/B)$…

Measured momentum diffusion coefficient (in supra-thermal tail): $$D_{pp} \sim 0.1 \,\langle \delta u^2 \rangle \,\frac{p^2}{\ell_c/c}$$

→ a powerlaw spectra from Fermi acceleration in a closed box?

Comisso+Sironi 18,19

PIC simulations invalidate the Fokker-Planck description of stochastic acceleration[1]



<u>injection in thermal core:</u>
from dissipation at kinetic (microscopic) scales, mostly reconnection

<u>QLT/Fokker-Planck prediction:</u>

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

⇒ sol.: $$p^3 f(p,t) \propto \exp\left[-\frac{\left(\ln p - \frac{3}{2}t/t_{acc}\right)^2}{2t/t_{acc}}\right]$$

$$t_{acc} = p^2/D_{pp}$$

<u>non-thermal tail:</u>
from Fermi-type mechanism (no parallel E field)

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

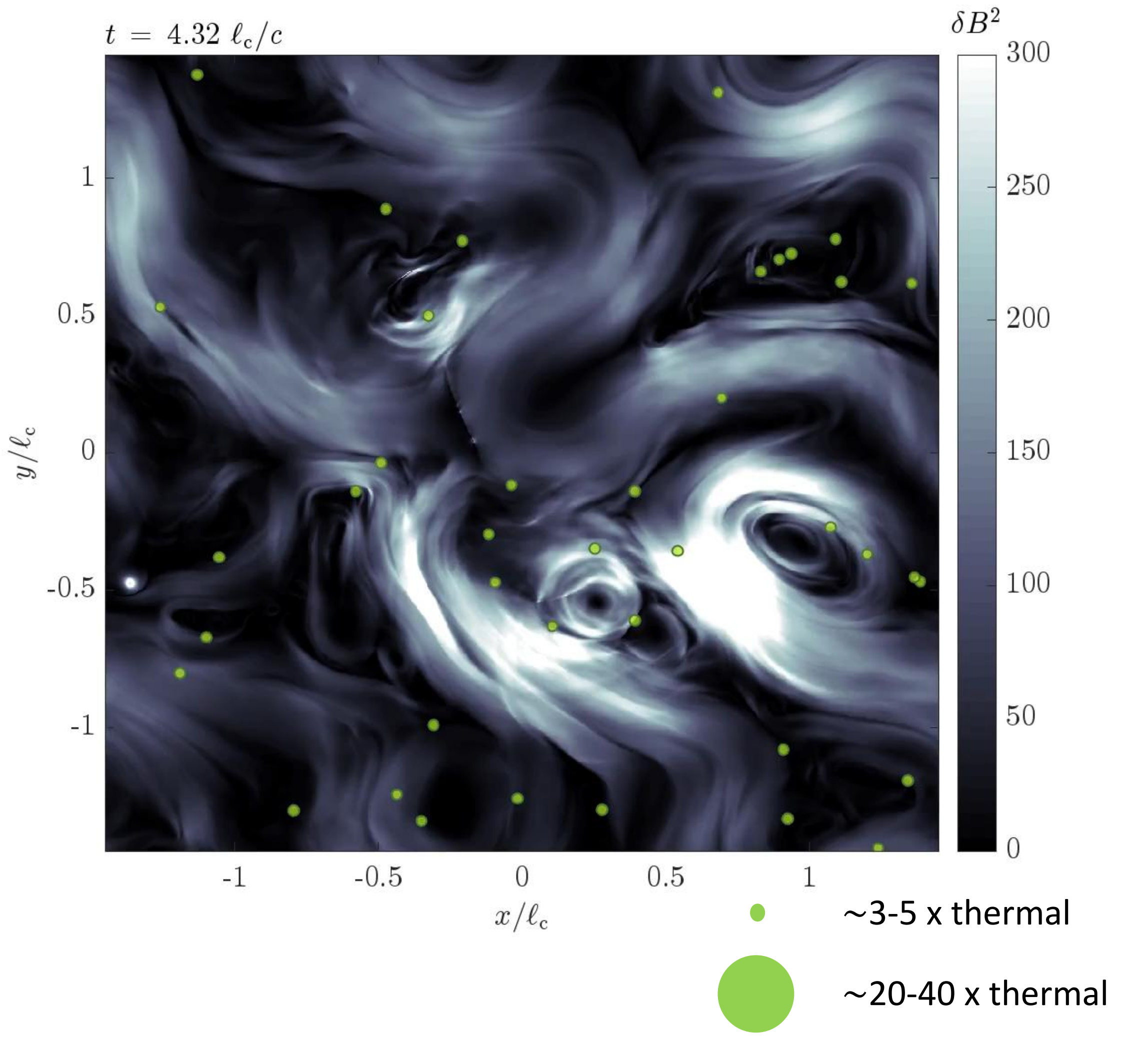
→ consequence: Fokker-Planck is not a good model... a powerlaw tail develops, drift is slow, unlike predictions!

→ Interpretation[2]: segregation in t_{acc} among particle population...

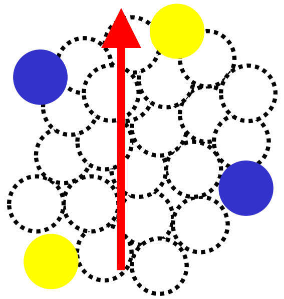
Refs: 1. Zhdankin+17-19, Wong+19, Comisso+Sironi 18,19; Nättilä+Beloborodov21 2. M.L. & Malkov 20

Stochastic particle acceleration is shaped by the intermittency of the turbulence

Fokker-Planck: derives from a Langevin process with Gaussian noise, zero time coherence…
… here non-Gaussian noise, macroscopic coherence time



→ acceleration sites are localized in sparse regions, with small filling fraction, large excursions in strength



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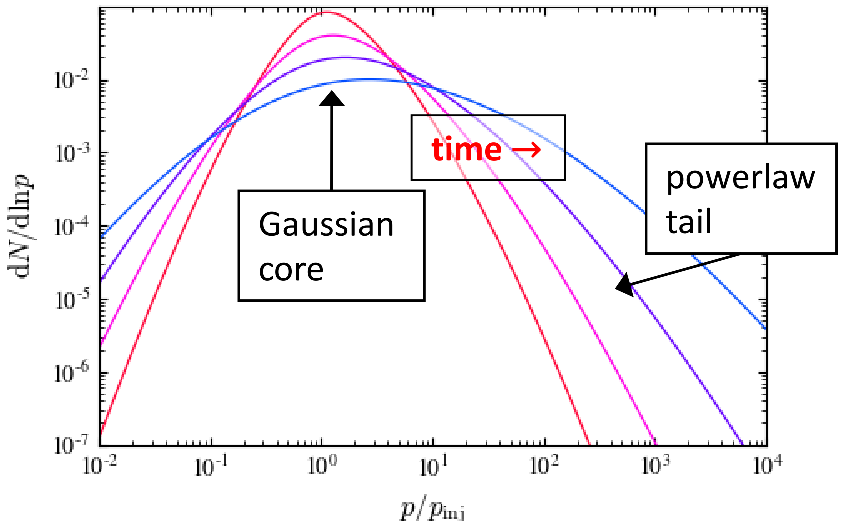


© V. Bresci, L. Gremillet, M. L.: 2D PIC, driven turb., e^+e^-, 10 000^2, $\delta B/B \sim 3$, $\sigma \sim 1$

Some consequences for phenomenology and open questions

1. spectrum differs noticeably from std Fokker-Planck predictions

→ no pile-up distribution, quasi-powerlaw, slow drift: impact on phenomenology?
→ w/ improved model, including effects of radiative losses → recipe for inclusion in MHD/GRMHD simulations?

2. extrapolation to large hierarchy $\ell_c/(c/\omega_p)$… and other physical conditions

→ quasi-powerlaw (log-running), hardening in time vs PIC sims limited in dynamic range…
→ dependence on magnetization, beta-parameter, physics of stirring, composition etc.

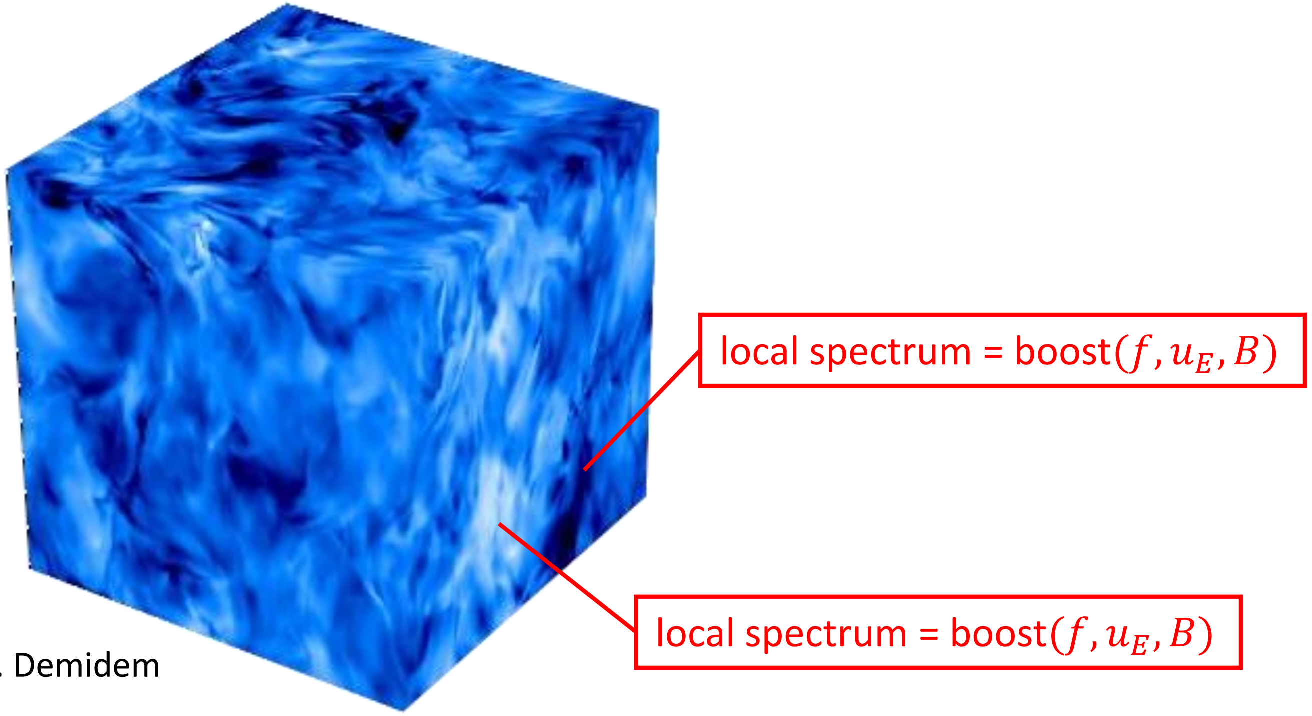
3. impact of intermittency on transport, acceleration and radiative spectra

→ first experimental indication of ``anomalous'' transport: distribution of acceleration/scattering timescales ⇒?
→ on timescale ℓ_c/c, only a small fraction of particles has scattered ⇒ expect anisotropies on ℓ_c scales!
→ inhomogeneous particle spectra in one volume ℓ_c^3… consequences for flaring? (time profile?)
→ inhomogeneous spectra, u_E and B in one volume ℓ_c^3… consequences for radiative spectra?

Some consequences for phenomenology and open questions

3. impact of intermittency on transport, acceleration and radiative spectra

→ no one-to-one relation t_{acc} (γ) : distribution of acceleration/scattering timescales ⇒?
→ on timescale ℓ_c/c, only a small fraction of particles has scattered ⇒ expect anisotropies on ℓ_c scales!
→ inhomogeneous particle spectra in one volume ℓ_c^3… consequences for flaring? (time profile?)
→ inhomogeneous spectra, u_E and B in one volume ℓ_c^3… consequences for radiative spectra?



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

Some consequences for phenomenology and open questions

3. impact of intermittency on transport, acceleration and radiative spectra

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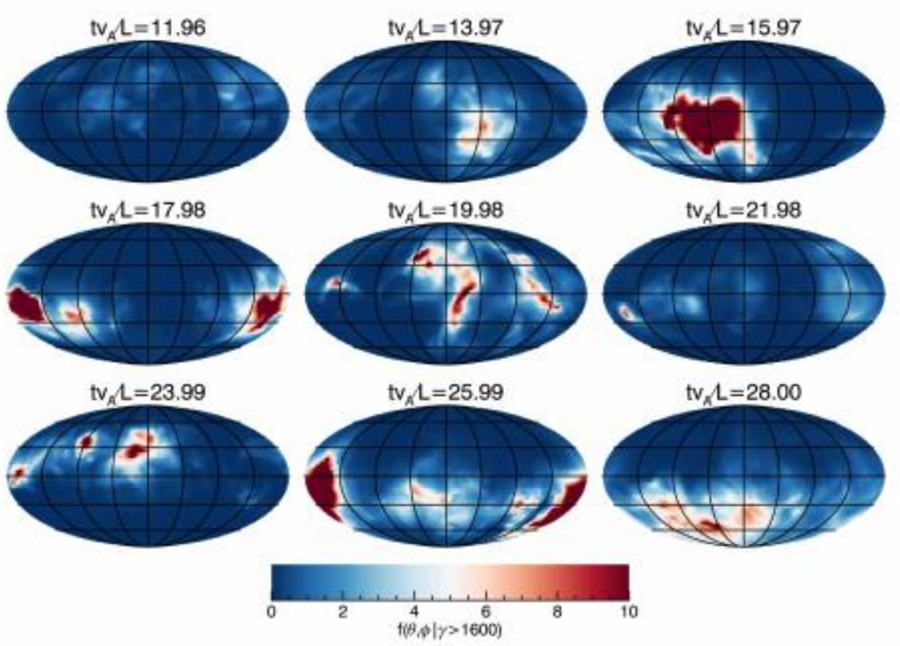
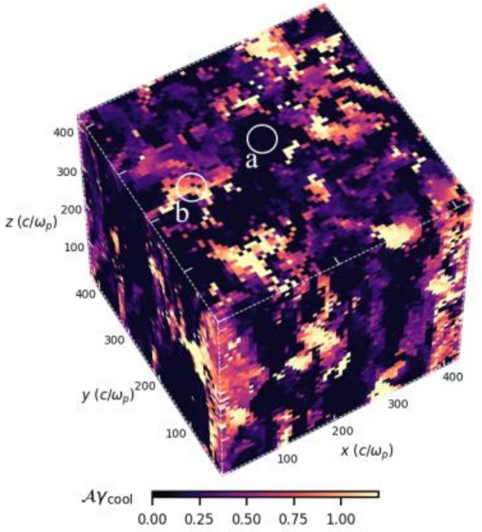
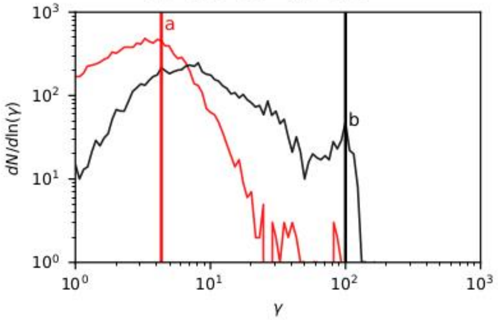
<u>Zhdankin+18:</u>
PIC, relativistic + radiative sims,



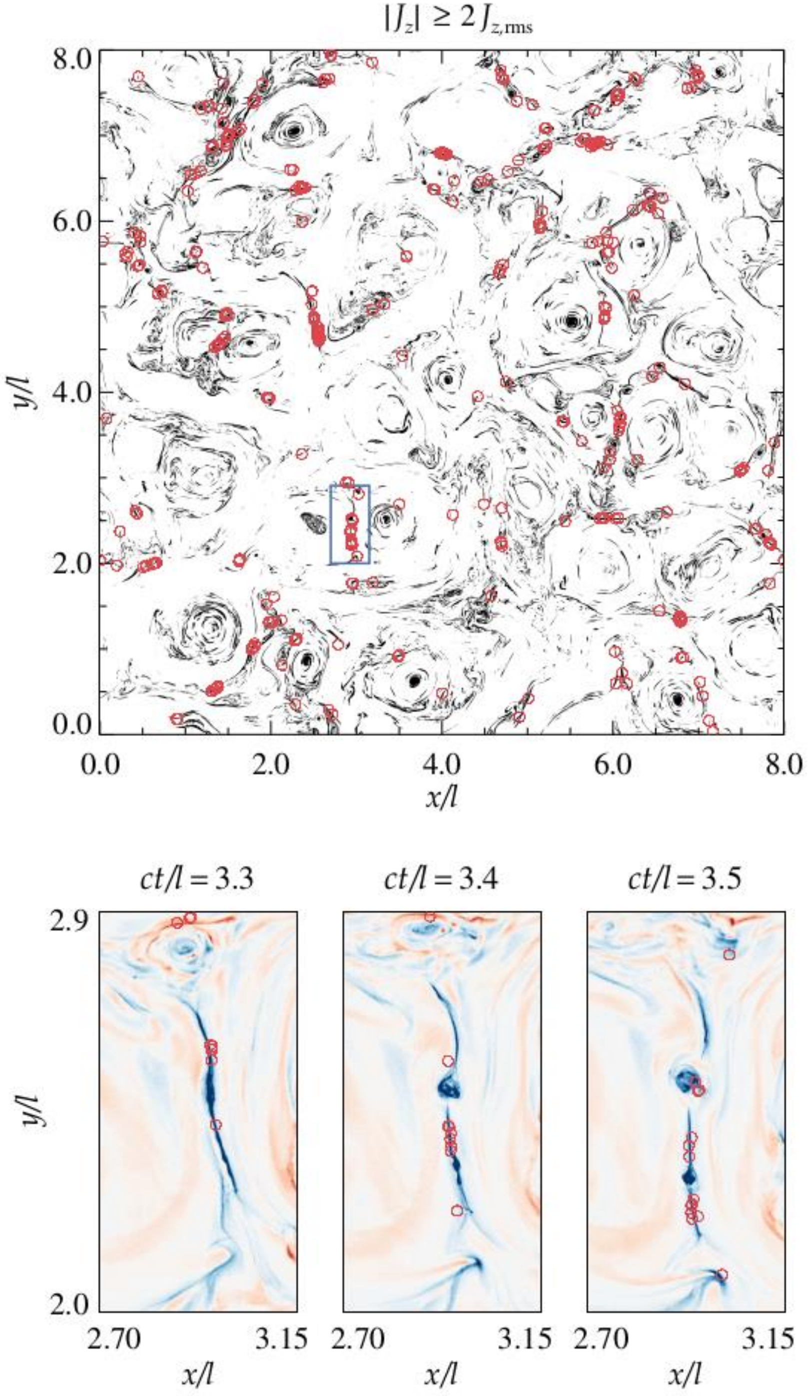
anisotropic momentum distribution at large momenta

<u>Nättilä+Beloborodov 20:</u>
PIC, relativistic + radiative sims,



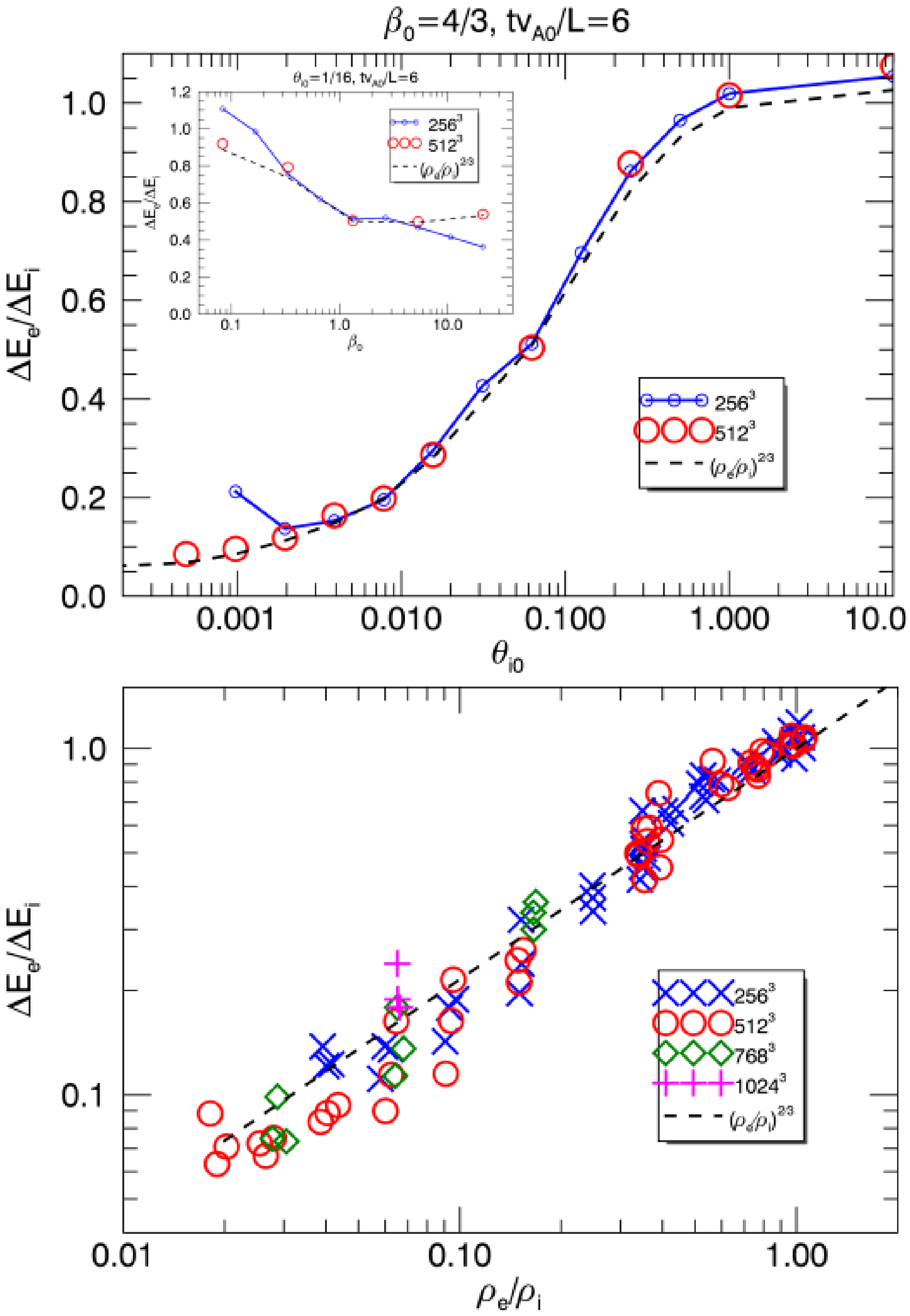


Injection in reconnection layers



Comisso+Sironi 19

Turbulence in e-ion plasmas: differential heating



Zhdankin+19