# NON-RESONANT PARTICLE ACCELERATION IN STRONG TURBULENCE: COMPARISON TO NUMERICAL SIMULATIONS

Journée SF2A 2022 - S20: Cosmic turbulence

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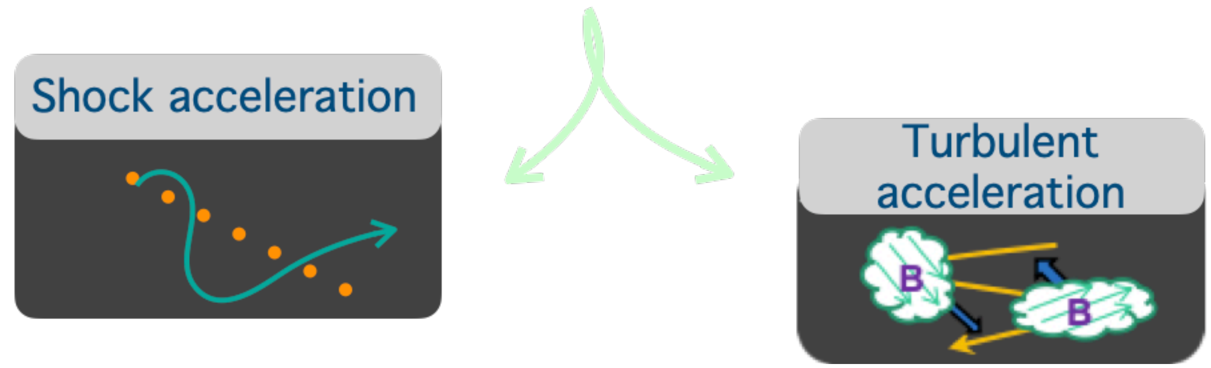
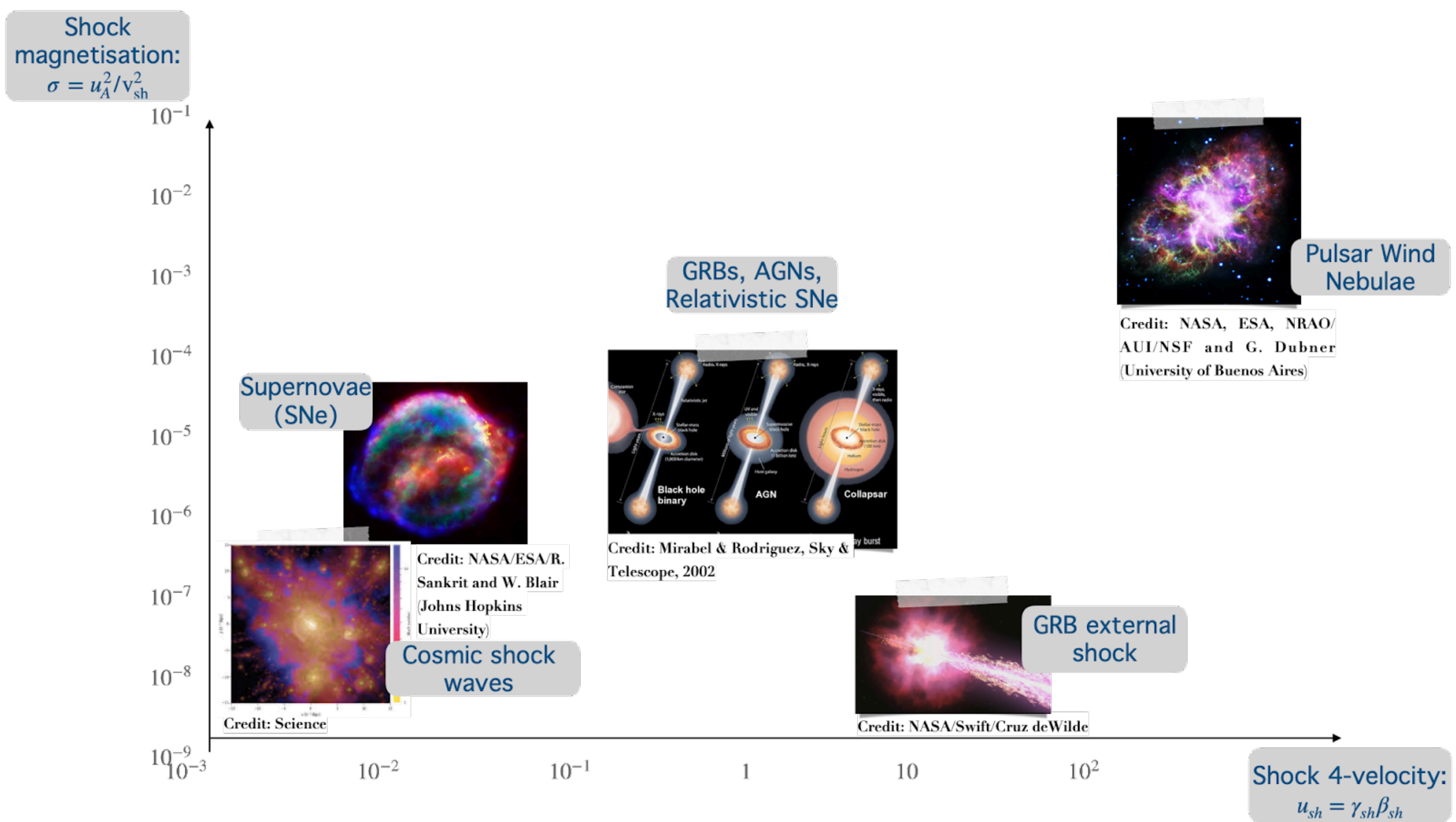
# PARTICLE ACCELERATION TO EXTREME ENERGIES



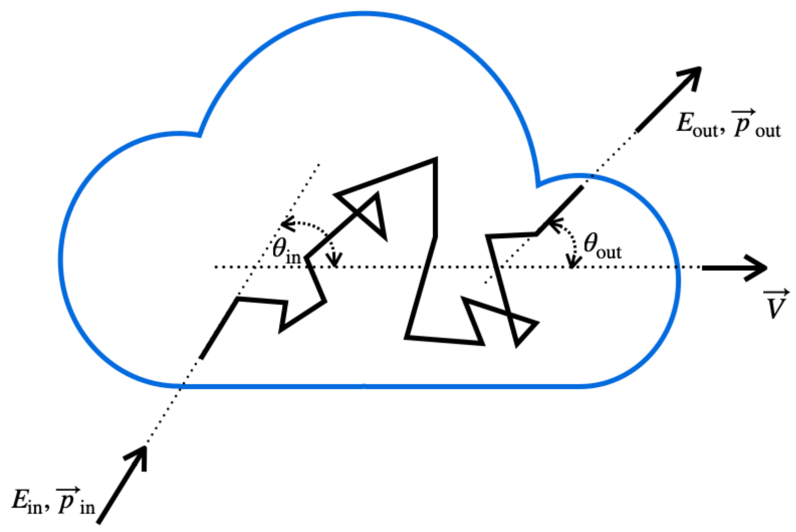
# FERMI-II ACCELERATION

- Particles are accelerated by **electric fields**
- Interstellar medium (ISM) almost a perfect conductor, $\langle E \rangle = 0$

**BUT** a time varying magnetic field induces electric fields

**AND** a pure magnetic field transforms in a magnetic + electric field in another reference frame moving relative to it by Lorentz transform

$$\left\{ \nabla \times E = -\frac{\partial B}{\partial t} \right.$$




Fermi in 1949: ISM is filled with "clouds" of ionized gas, in movement with respect to the "Galactic frame", ables to accelerate on average particles encountering them

↓

Stochastic acceleration ⟷ Diffusion in momentum space

# QUASI LINEAR THEORY (QLT)

Sum of linear eigenmodes of the plasma:
- Alfvén waves
- Fast & slow magnetosonic modes

## QLT:

- **First-order** perturbation theory: small amplitude limit of fluctuations
- **Uncorrelated** fluctuations
- Particles followed on **unperturbed** orbits
- **Resonant** wave-particle interactions

Fokker-Plank equation

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

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

$$D_{pp} \propto p^q \qquad t_{\rm acc} \equiv \frac{p^2}{D_{pp}} \propto \frac{p^{2-q}}{\beta_A^2}.$$

Spectrum of magnetic fluctuations $\propto k^{-q}$

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## NUMERICAL SIMULATIONS:

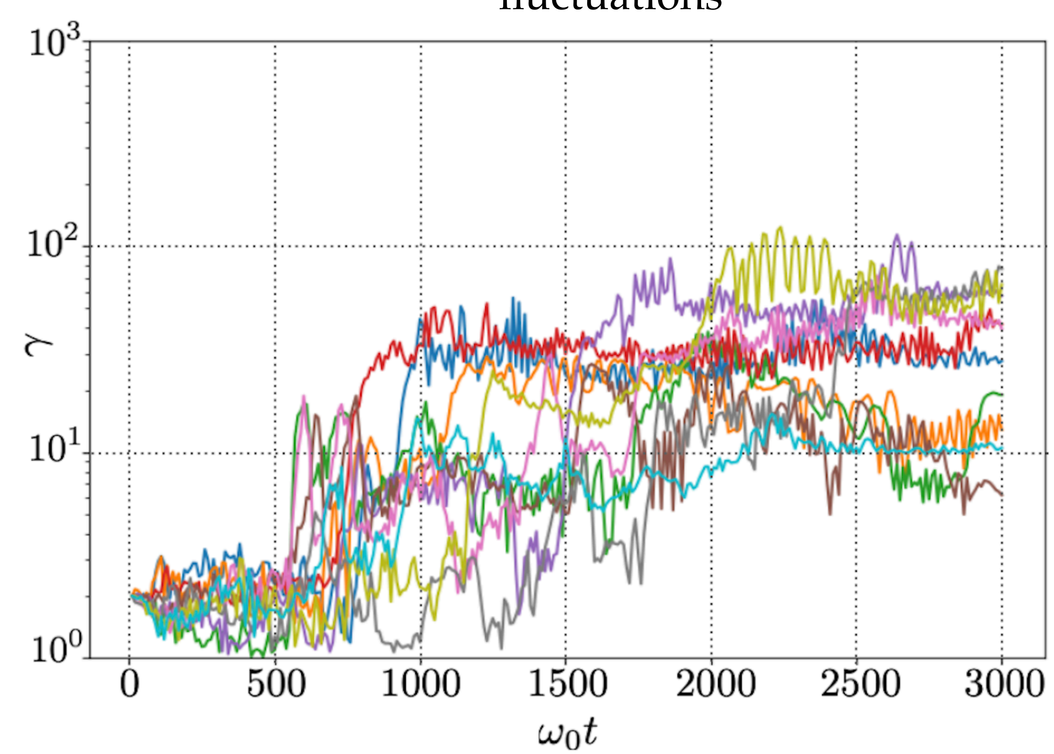
$$t_{\rm acc} \sim \frac{\ell_c}{\langle \delta u^2 \rangle} \sim \frac{\ell_c}{\sigma c}$$

fast acceleration in the relativistic regime

$\langle \delta u^2 \rangle \sim u_A^2 \propto B^2 \sim \sigma$

Coherence length

$D_{pp} \propto p^2$




Two-stage acceleration: reconnection + Fermi II resulting in power law distributions $dN/dp \propto p^{-s}\,,\ s \sim 2-3$

# GENERALIZED FERMI ACCELERATION

Original Fermi picture of discrete point-like interactions ⟷ interaction with fluctuating $\boldsymbol{E}$ fields connected to **random velocity fluctuations** by ideal Ohm's Law

**Not** uniform

There **non** exists a **global** frame where $\boldsymbol{E} = \boldsymbol{0}$, but different frames $\mathscr{R}_E$ moving at $u_E \propto \boldsymbol{E} \times \boldsymbol{B}$

**Gradients of the velocity field**:
- Shear along field velocities
- Compression/expansion
- Vorticity
- Acceleration of the velocity field

## PARTICLE ACCELERATION

by inertial forces induced by the varying velocity fluctuations as $\boldsymbol{E}$ vanishes in $\mathscr{R}_E$

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## NON-RESONANT MODEL

follows particles in different $\mathscr{R}_E$ frames:

- Ideal MHD, frame where the $\boldsymbol{E}$-field vanishes coincides with the plasma bulk rest frame
- Fluctuations on scale $\ll$ gyroradius ignored
- Local gyromotion around $\boldsymbol{B}$-field lines

## PARTICLE ACCELERATION

by inertial forces induced by the varying velocity fluctuations as $\boldsymbol{E}$ vanishes in $\mathscr{R}_E$

In $\mathscr{R}_E$: $$\frac{1}{c}\frac{d\gamma'}{d\tau} = -\gamma' u'_{\parallel} \boldsymbol{a}_E \cdot \boldsymbol{b} - u'^2_{\parallel}\Theta_{\parallel} - \frac{1}{2}u'^2_{\perp}\Theta_{\perp}$$

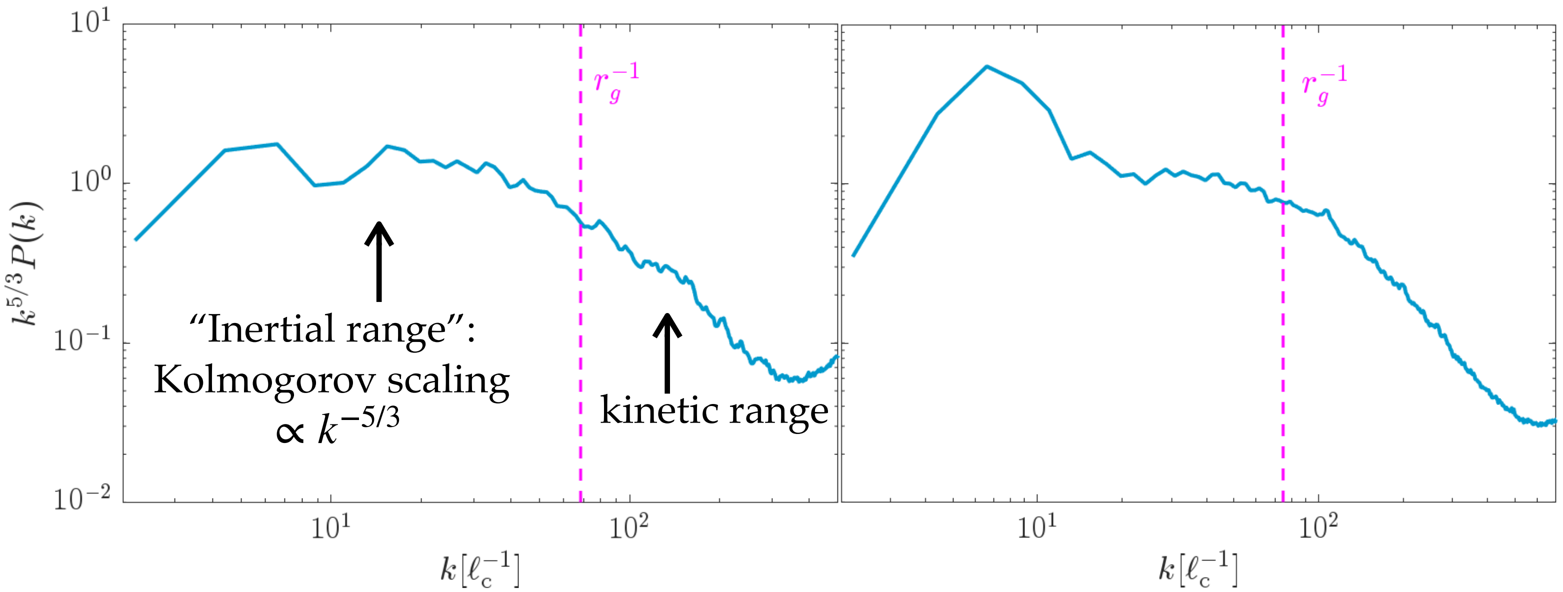
$\boldsymbol{a_E} = u_E^{\alpha}\,\partial_\alpha\,\boldsymbol{u_E}$
Effective gravity along the field line

$\Theta_{\parallel} = b^\alpha b^\beta \partial_\alpha u_{E\,\beta}$
Velocity shear along the field line

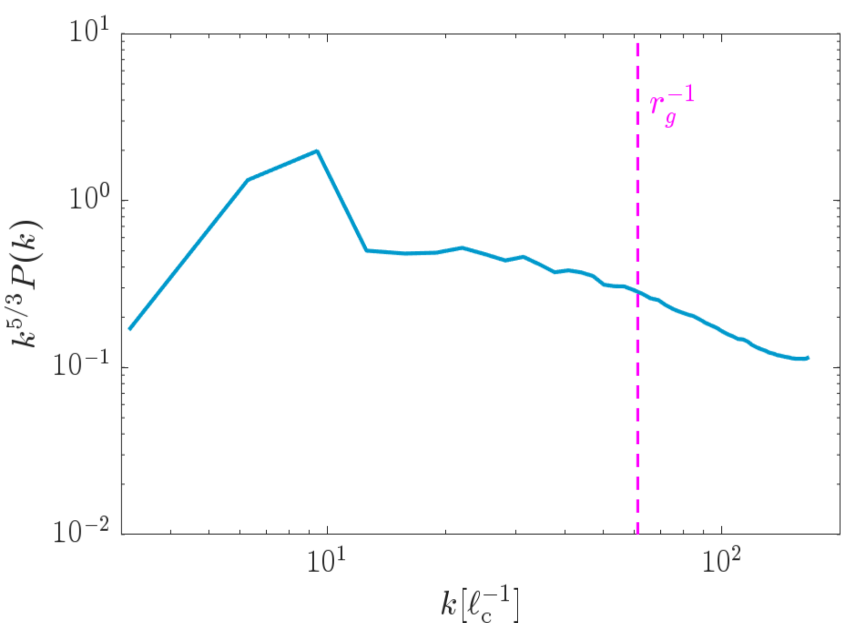
$\Theta_{\perp} = (\eta^{\alpha\beta} - b^\alpha b^\beta)\partial_\alpha u_{E\,\beta}$
Compression in the plane transverse to the field line

Refs.: Lemoine '19, Lemoine '21

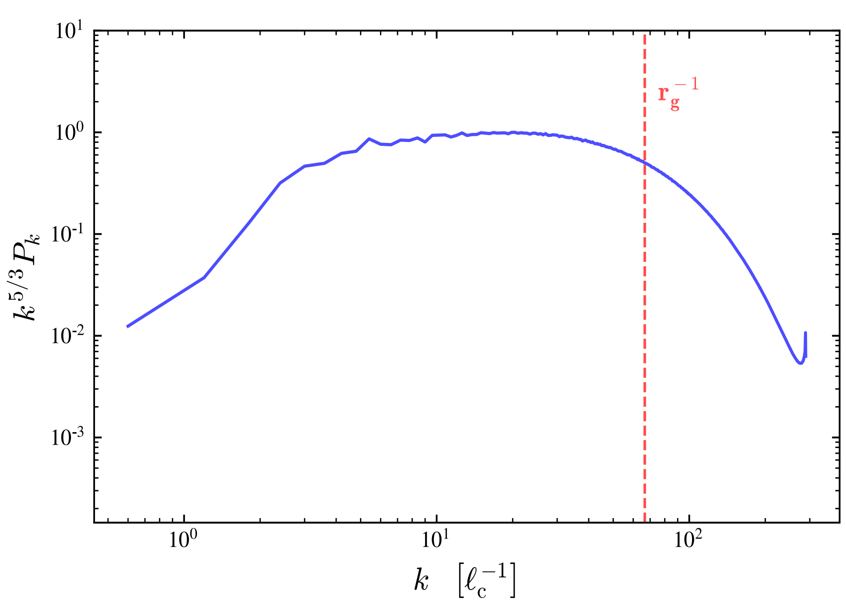
# COMPARISON WITH NUMERICAL SIMULATIONS - METHOD




**2D PIC** simulations of decaying (left) and forced (right) periodic turbulence, $1000^2$, $e^{\pm}$, $\sigma \sim 2$, $\delta B/B \sim 3$




**3D PIC** forced periodic turbulence, $1\,080^3$




**3D MHD** forced periodic turbulence, $1\,024^3$

## THE "LANGEVIN ANTENNA" SCHEME

The oscillating Langevin antenna models the magnetic **fluctuations** at the domain scale generated by the transfer of energy caused by non-linear interaction of Alfvén waves

Superposition of plane waves whose temporal profiles satisfy a Langevin equation with white noise

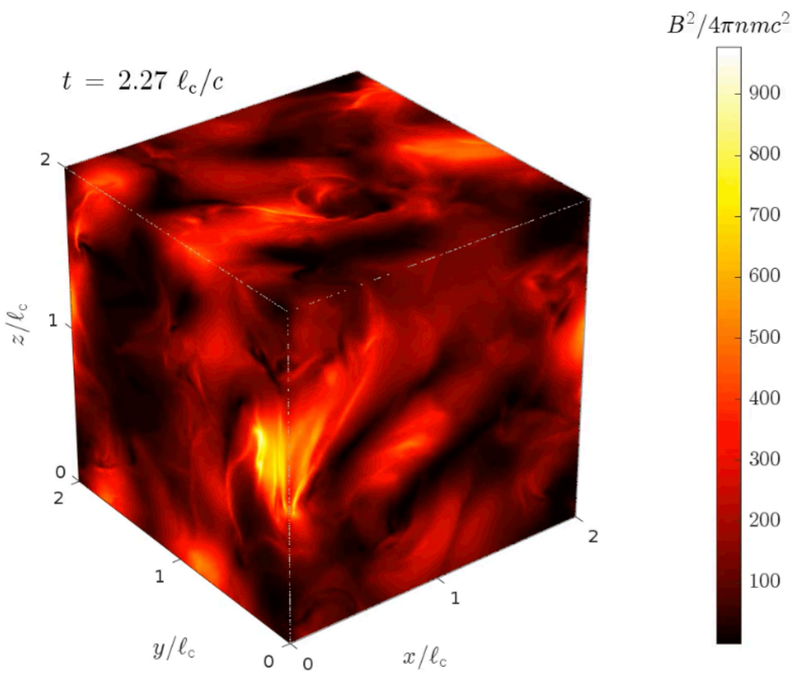
$$j_{z,\mathrm{ext}} = \nabla^2 A_z\,,\ A_z = \sum_{i=1}^{N_w} a_i(t) e^{i\mathbf{k}_i\cdot\mathbf{r}}$$

$$a_i(t) = a_i(t-\Delta t)e^{-i(\omega_i-\gamma_i)\Delta t} + F_i\Delta t$$

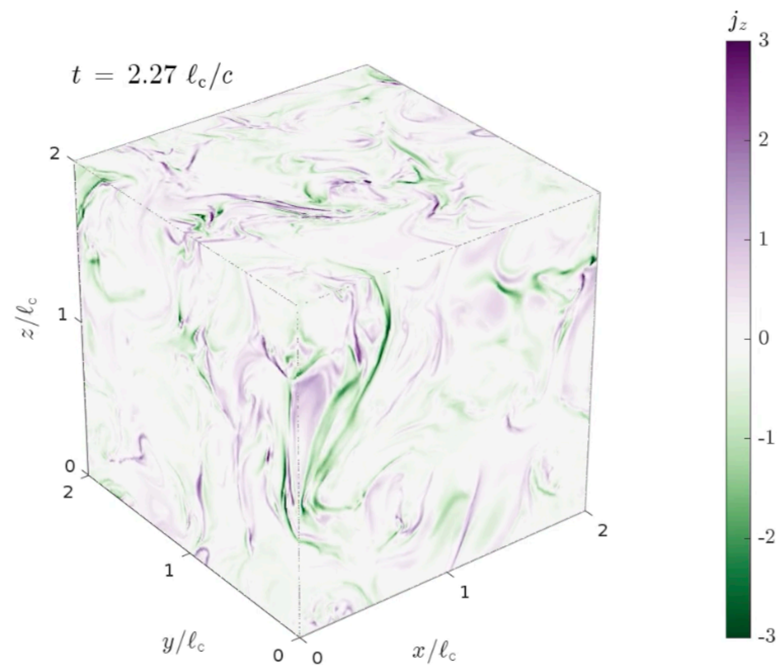
Refs.: TenBarge+ '14

# COMPARISON WITH NUMERICAL SIMULATIONS - METHOD

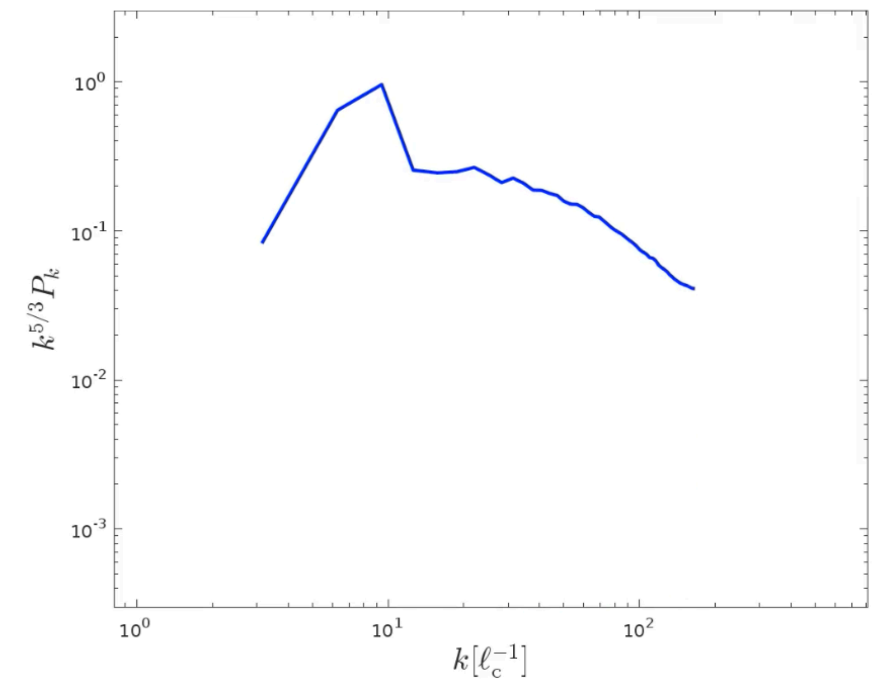
Magnetic energy density



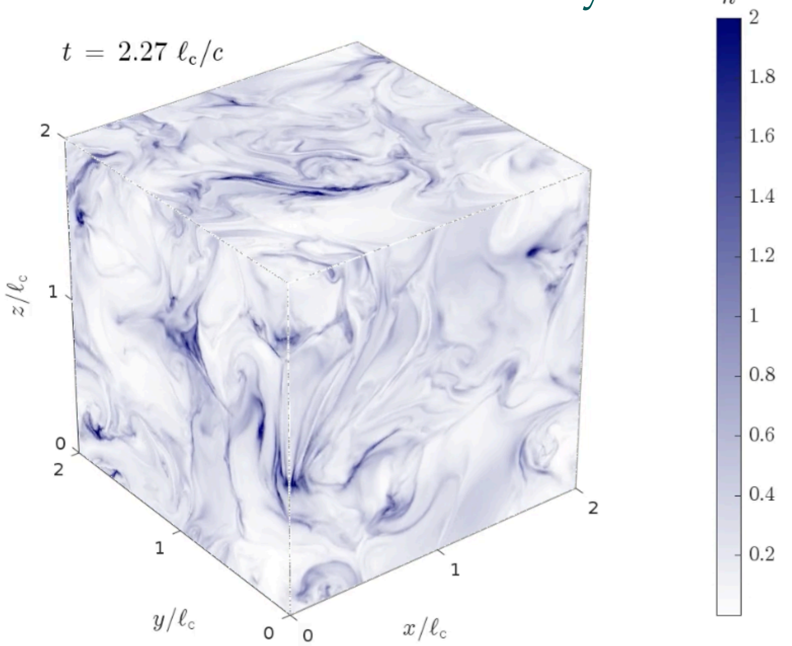

Current density



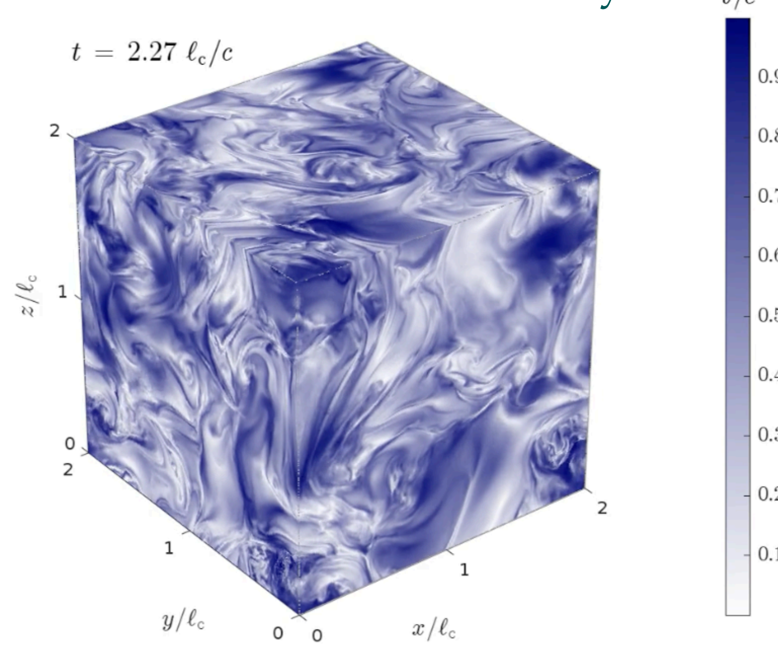

Power spectrum



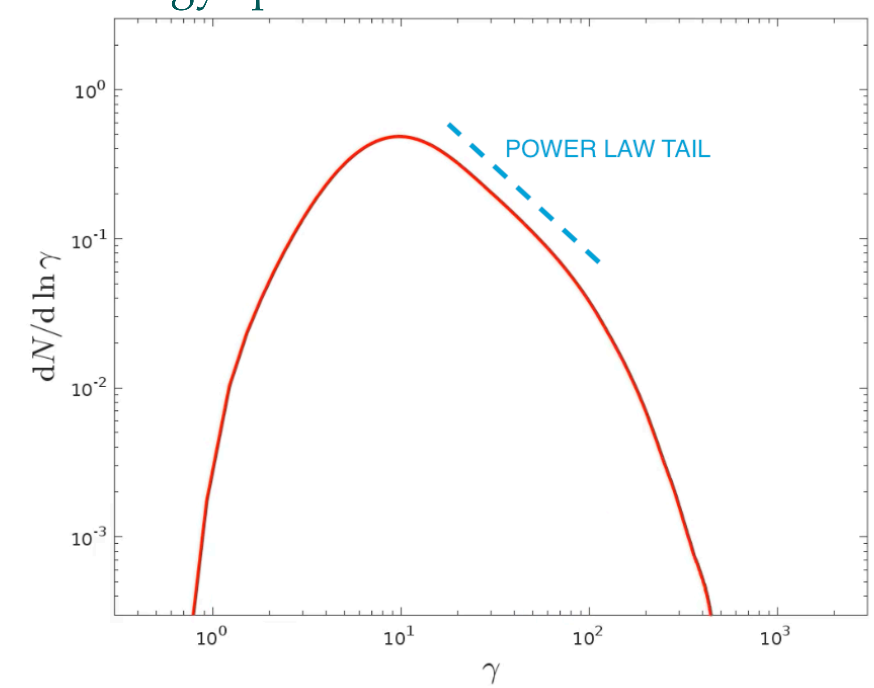

Density




Velocity




Energy spectrum

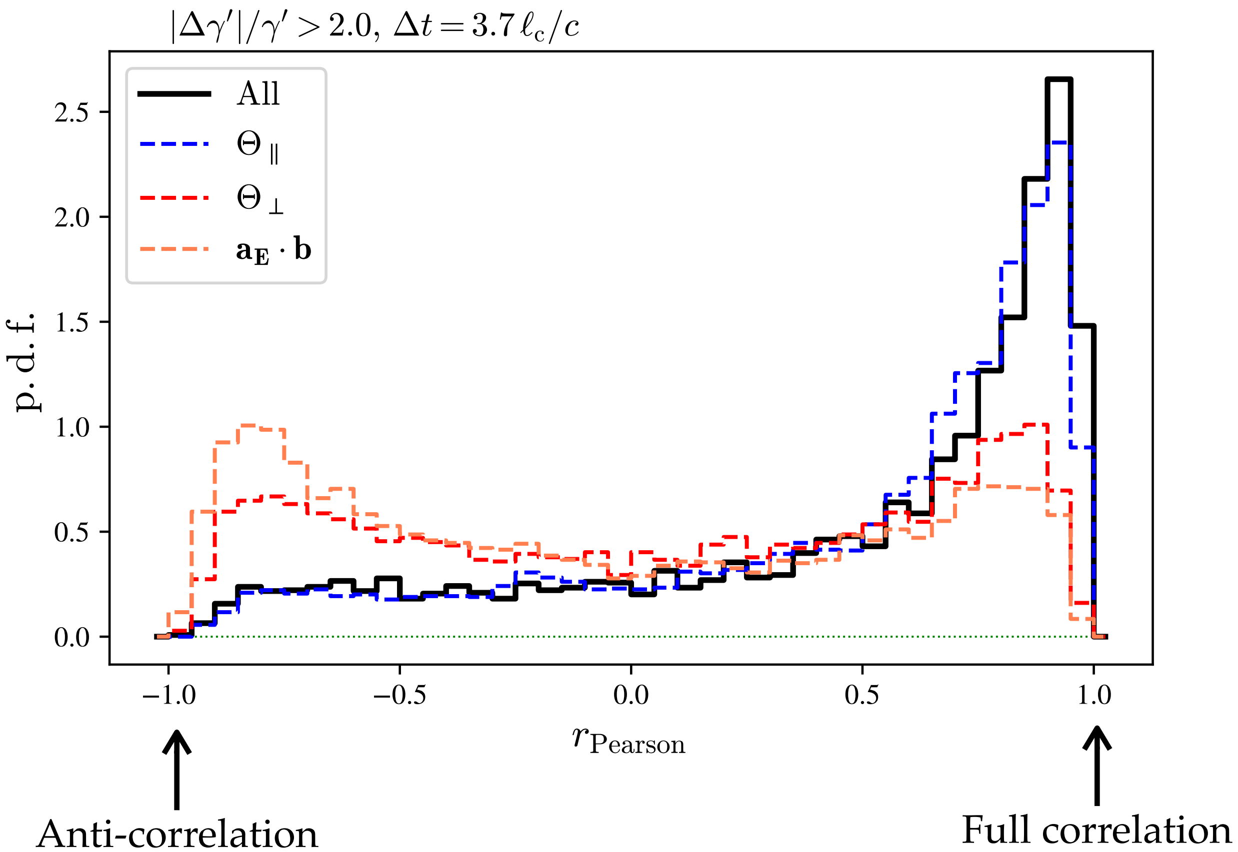


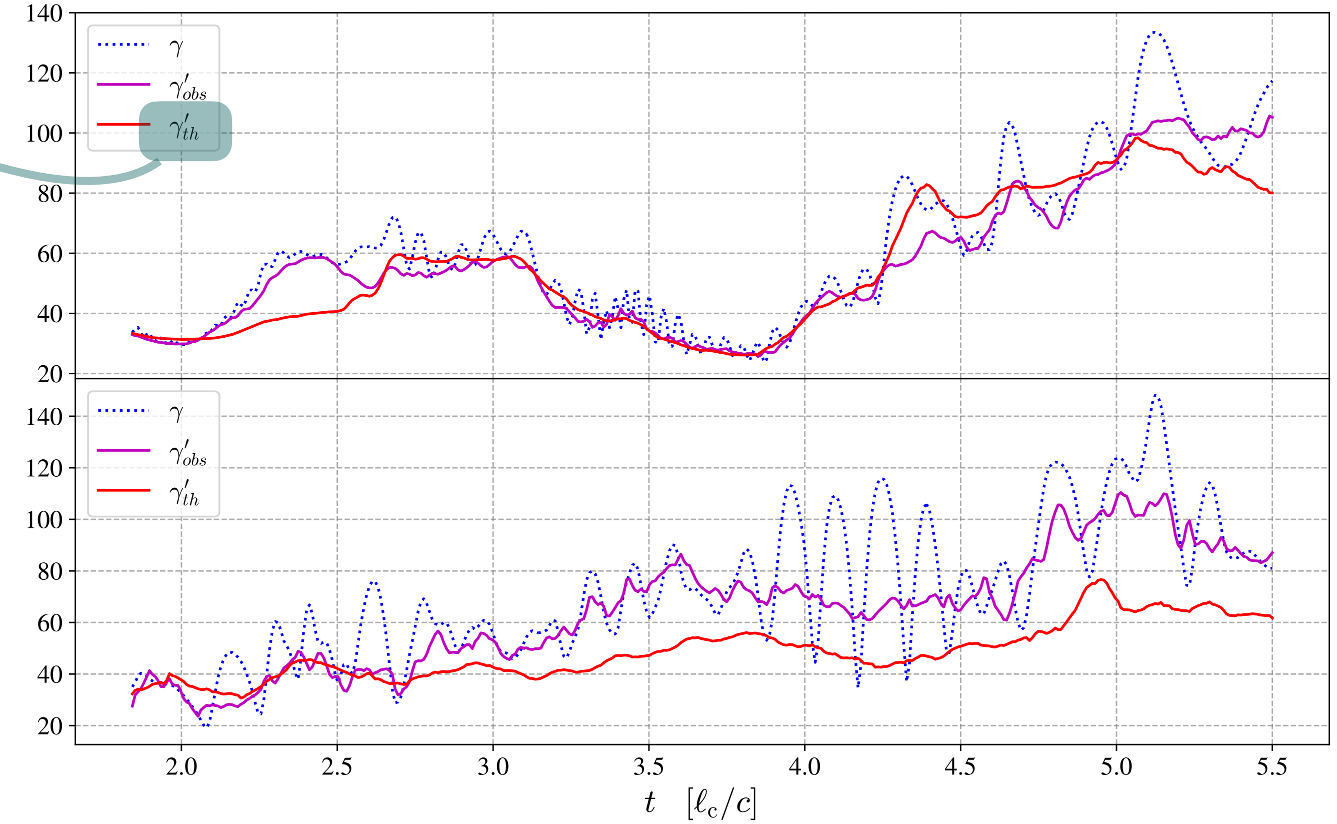

**3D PIC** forced periodic turbulence, $1\,080^3$

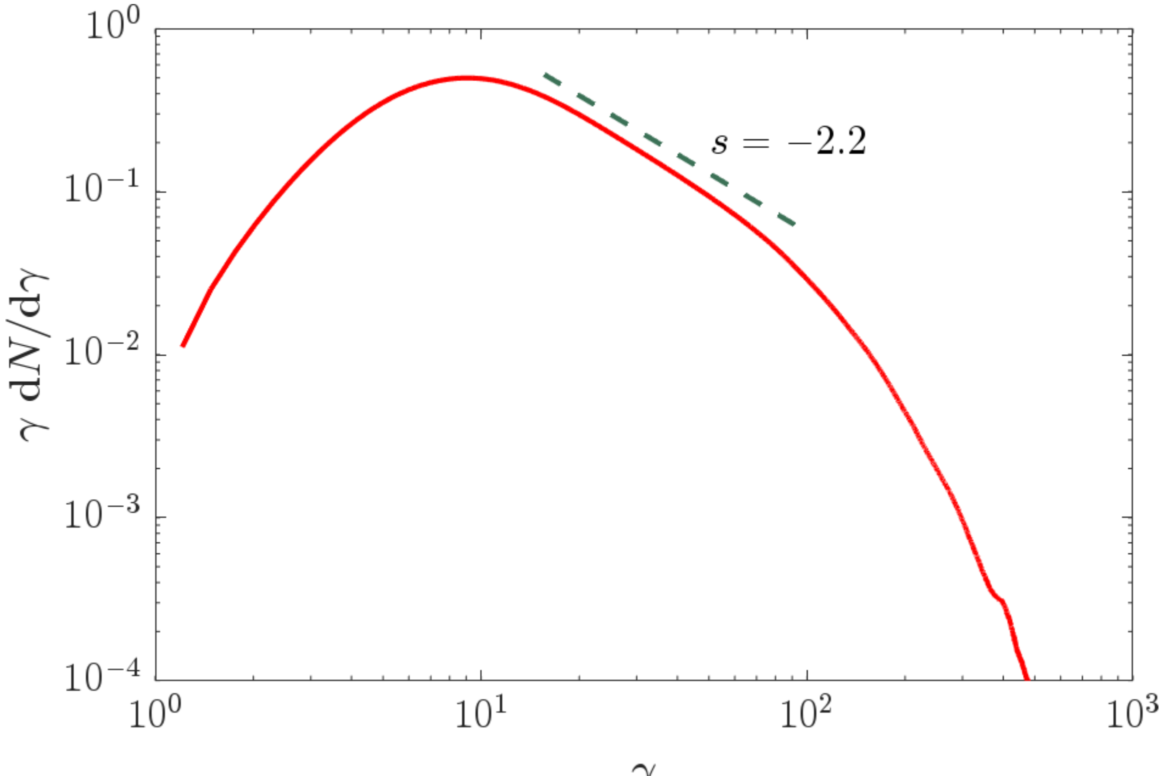
# COMPARISON WITH NUMERICAL SIMULATIONS - RESULTS

$$\int\left(\frac{1}{c}\frac{d\gamma'}{d\tau} = -\gamma' u'_{\parallel} \boldsymbol{a}_E \cdot \boldsymbol{b} - u'^2_{\parallel}\Theta_{\parallel} - \frac{1}{2}u'^2_{\perp}\Theta_{\perp}\right)$$

Degree of correlation between **observed** and **reconstructed** particle trajectories from velocity gradients:



# CONCLUSION

- **Non-resonant model** of acceleration: all energy gains or losses are related to inertial forces deriving from the non-inertial nature of the frame where the motional electric field vanishes

- Reconstruction of the particle energy evolution due to the velocity gradient of the non-inertial frame to lowest order in the ratio $r_g/\ell_c$ neglecting fluctuations on scales much lower than the particle gyroradius

- Comparison with test particles energy evolution

- **Clear correlation** between the two histories in both **2D and 3D PIC** simulations and **3D MHD** simulations

⟶ non-resonant model can **account for the bulk of particle energisation** through stochastic Fermi processes, in particular, longitudinal shear term is the dominant contribution in PIC and mirroring effects slightly prevail in MHD (physic of acceleration depends on how turbulence is stirred)

VB, M. Lemoine, L. Gremillet, C. Demidem, L. Comisso, L. Sironi: "Particle acceleration in strong turbulence: comparison to kinetic and MHD simulations" submitted (2022)

# PERSPECTIVES

- Analytical prediction of the accelerated spectrum?
- Radiative spectra from inhomogeneous fast-moving structures?
- Interplay of turbulence and shock fronts?