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# PIC simulations of SNRs shock waves with a turbulent upstream medium

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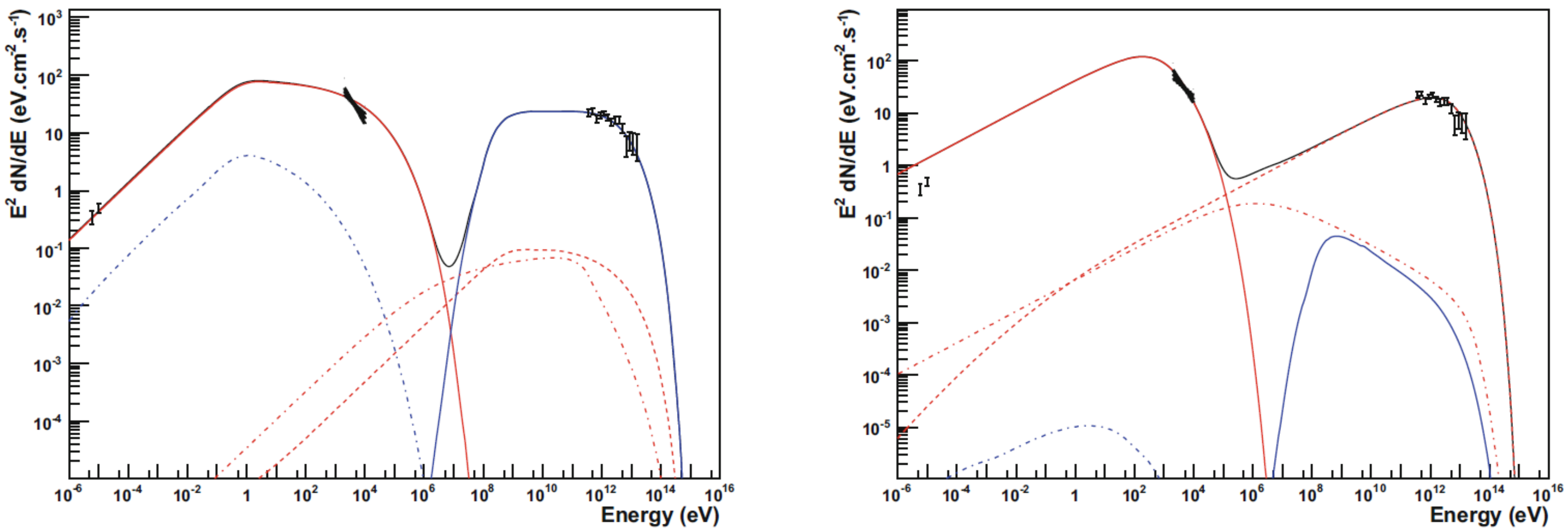
2 August 2022

# Nonthermal radiation from SNRs

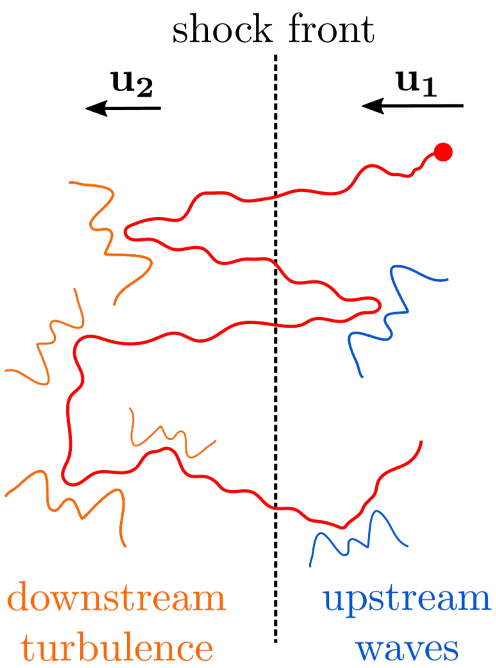
- radio and X-rays → synchrotron emission by relativistic electrons
- γ-rays → inverse-Compton scattering of relativistic electrons
  → decay of neutral pions
- **Hadronic** or **leptonic**?



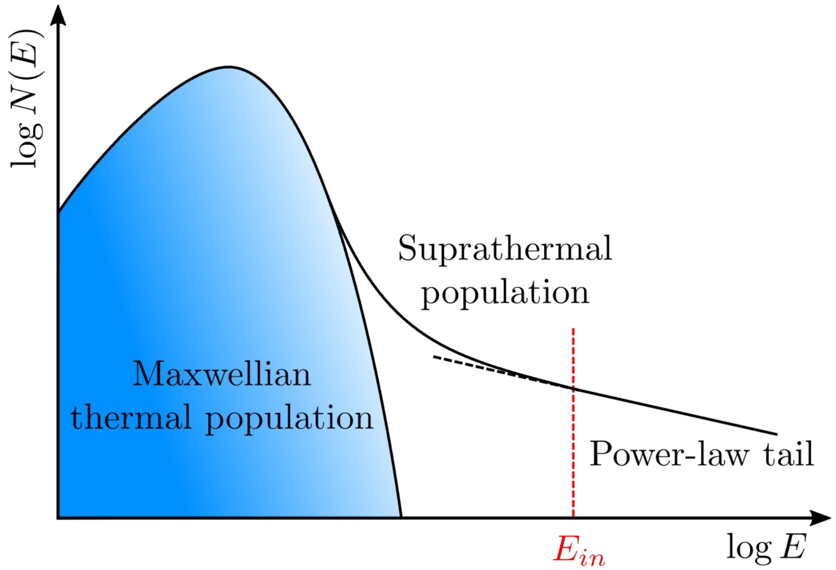

credit: the H.E.S.S. collaboration

# Diffusive shock acceleration

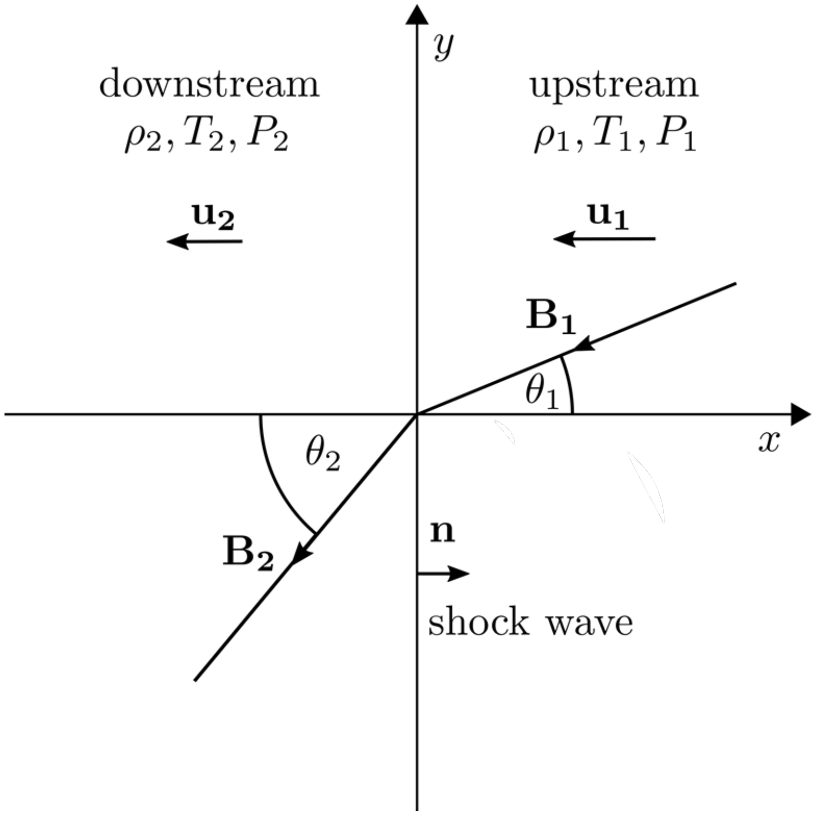
- Particle gains energy crossing the shock




- Power-law energy spectrum
- Initial energy required – **electron injection problem**



# **shock wave** – supersonic discontinuity




$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{4M_S^2}{M_S^2 + 3}$$

Mach numbers:

$$M_S = \frac{v_{sh}}{c_s} \qquad M_A = \frac{v_{sh}}{v_A}$$

plasma beta:

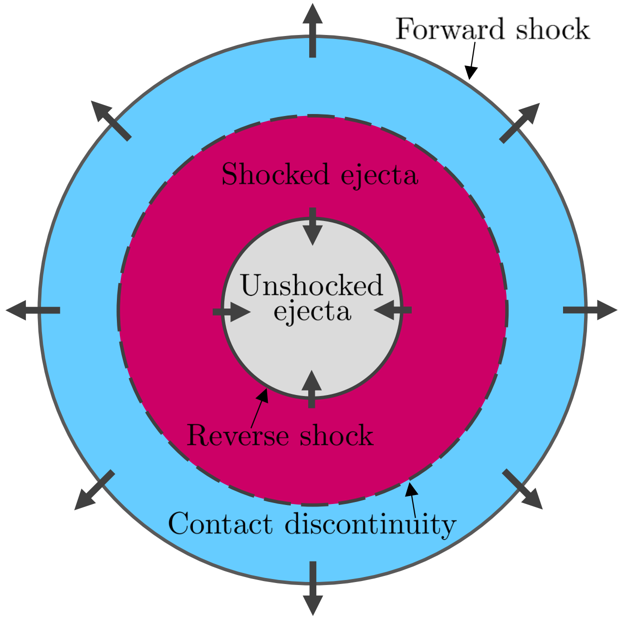
$$\beta = \frac{P_{th}}{P_B}$$

obliquity:

$$0^\circ \leq \theta_1 \leq 90^\circ$$

## SNRs shocks

- Collisionless – particle-wave interactions dominate
- nonrelativistic: $v_{sh} \ll c$
- high Mach numbers: $M_S > 10 \quad M_A > 10$
- low plasma beta: $\beta \lesssim 1$
- variety of obliquity angles



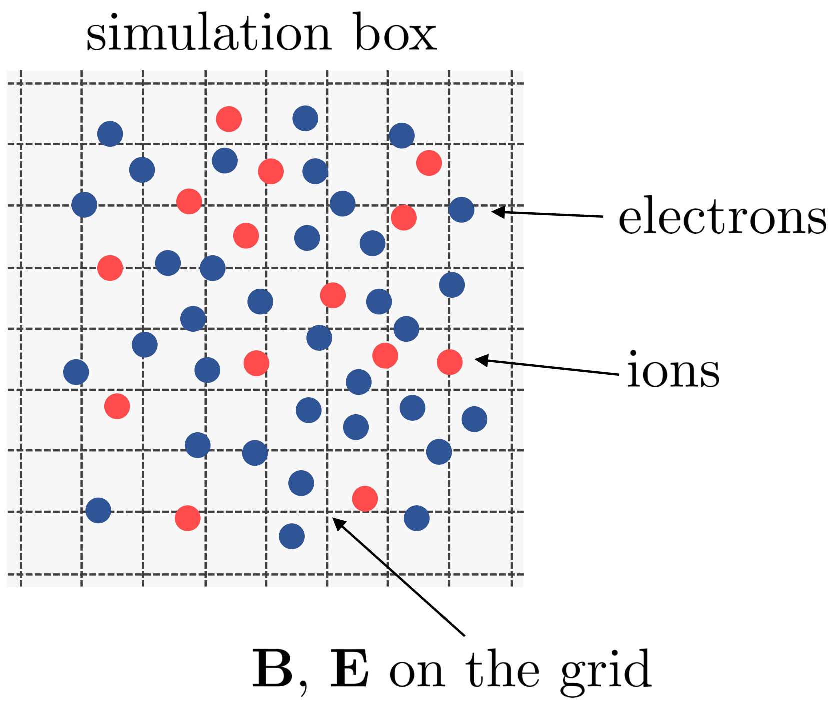

fixed shock parameters $\longrightarrow$ **the obliquity angle** is the most important!

# PIC simulations

Equations of motions of relativistic particles:

$$\dot{\mathbf{r}}(t) = \mathbf{v}(t),$$
$$\gamma m \dot{\mathbf{v}}(t) = \mathbf{F}(\mathbf{r}, t)/m.$$

- Macroparticles – representation of many real particles
- FDTD integration (Yee lattice)



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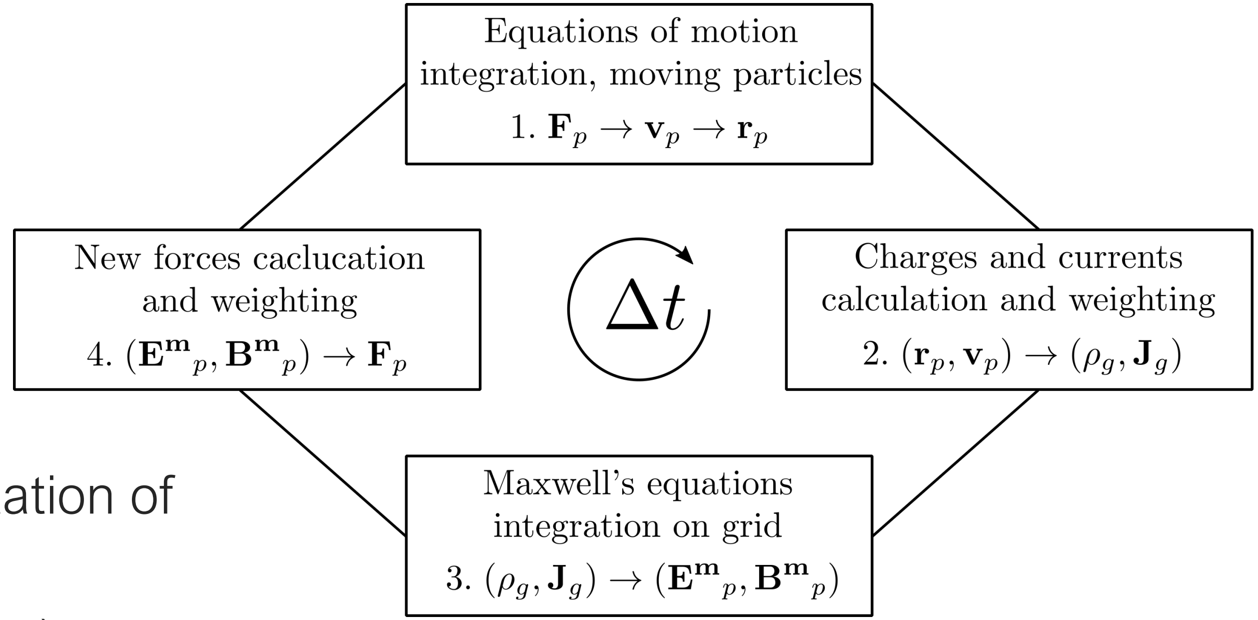


# Motivations

- SNRs shocks are extensively studied
- Assumption: homogenous upstream – turbulence driven by reflected particles
- Space plasma research: importance of pre-existing turbulence

upstream electron dynamics, change of VDF

modification of plasma waves

pre-acceleration conditions

## Parts of the project:

I. the turbulence **generation** in the PIC code

II. the quasi-seamless turbulence **insertion** to shock simulations (layers matching)

III. the shock **simulation**

# The turbulence generation

Particle velocity: $\mathbf{v} = \underbrace{\mathbf{v_b}}_{\text{bulk}} + \underbrace{\delta\mathbf{v_b}}_{\text{local bulk disturbance}} + \underbrace{\mathbf{v_{th}}}_{\text{thermal}}$

Initial velocity disturbance – compressive waves:

$$\delta\mathbf{v_b}(\mathbf{r}) = \sum_k A(k)\cos(kx' + \beta)[\cos\phi\hat{x} + \sin\phi\hat{y}]$$

$$x' = \cos\phi \cdot x + \sin\phi \cdot y$$

Giacalone and Jokipii (1994)

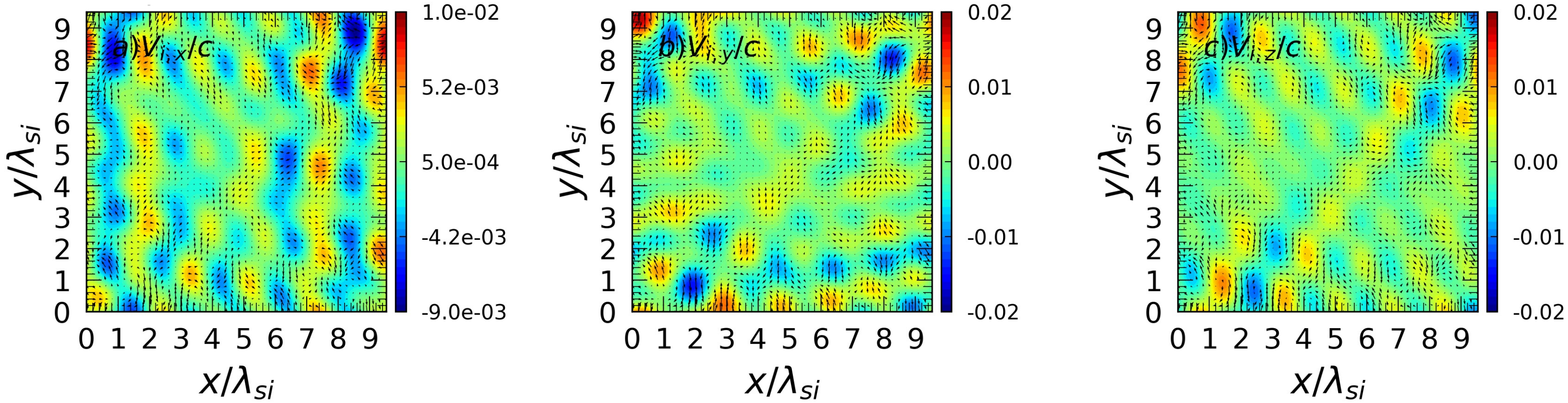
random: $\lambda, \phi, A, \beta$

# The turbulence generation cd.

Periodic box – standing waves: $\mathbf{k} = \left[\frac{n\pi}{L}, \frac{m\pi}{L}\right]$

$n, m-$ random integers

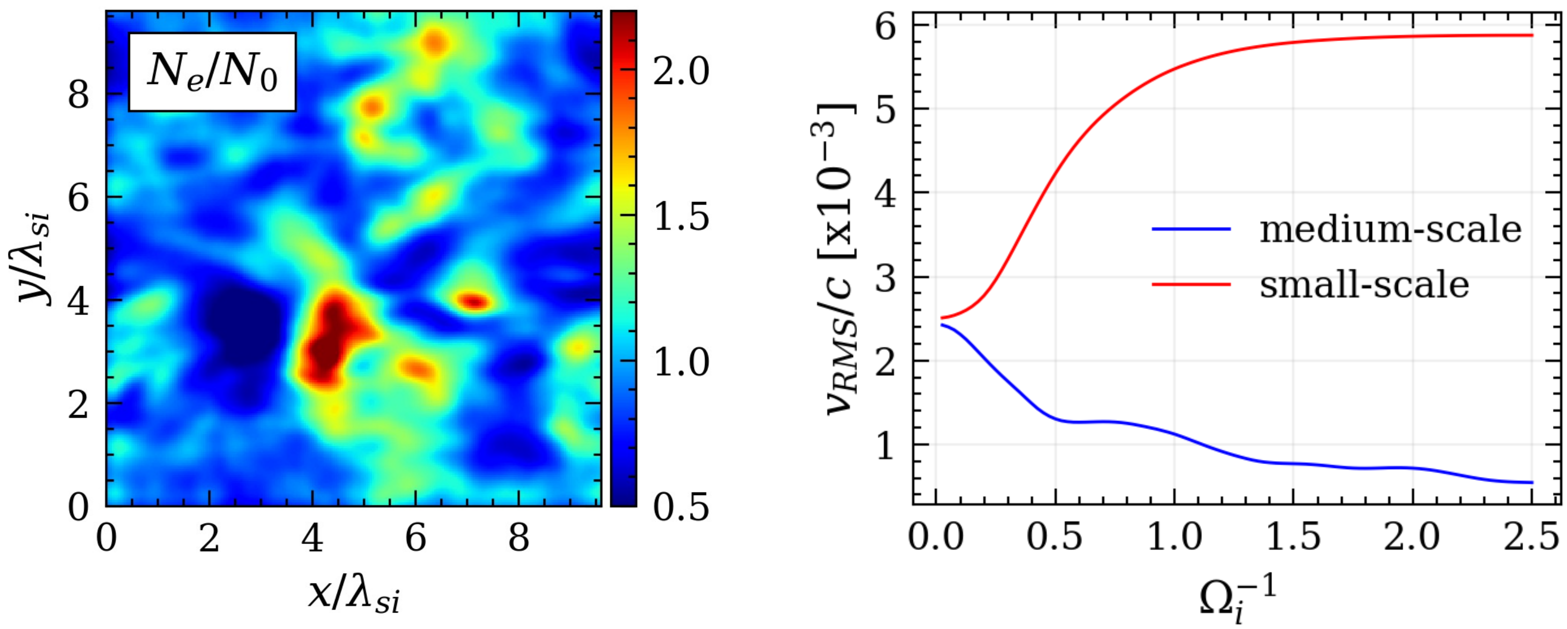
Initial velocity disturbance



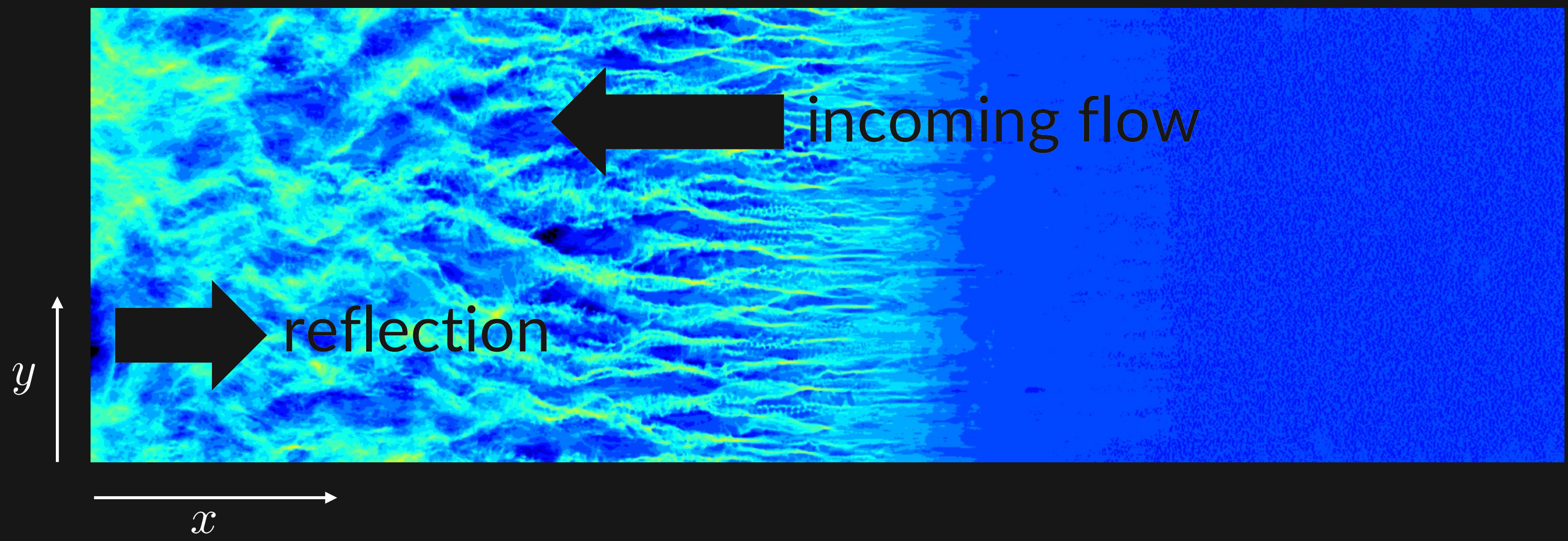

The initial wave spectrum strongly depends on combination of $n, m$ but this changes as the fluctuations evolve.

# Periodic box simulations

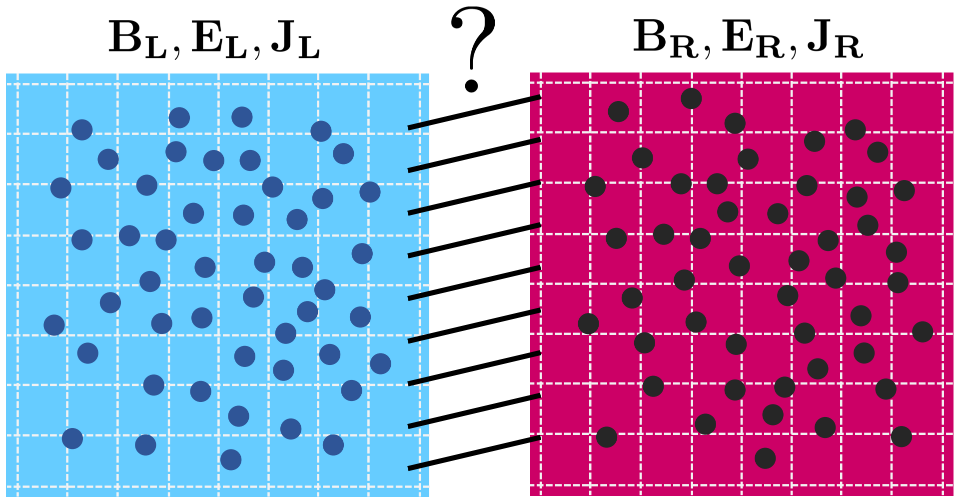
- Long-lived turbulence – density, EM field, currents
- Velocity disturbance turns into  particle heating



# Adding new domains



# Plasma matching method

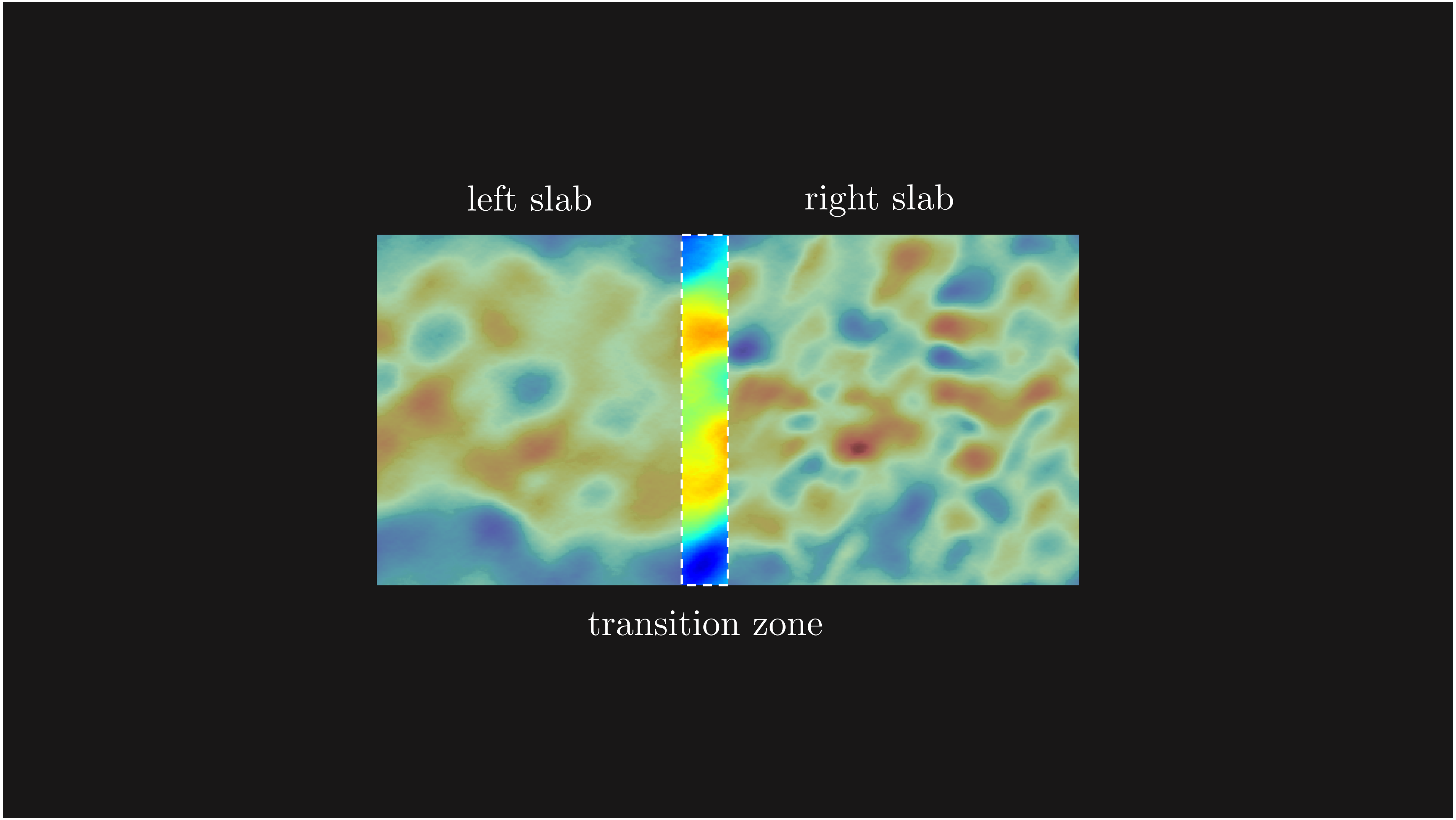



fields: $B = w \cdot B_L + (1 - w) \cdot B_R$

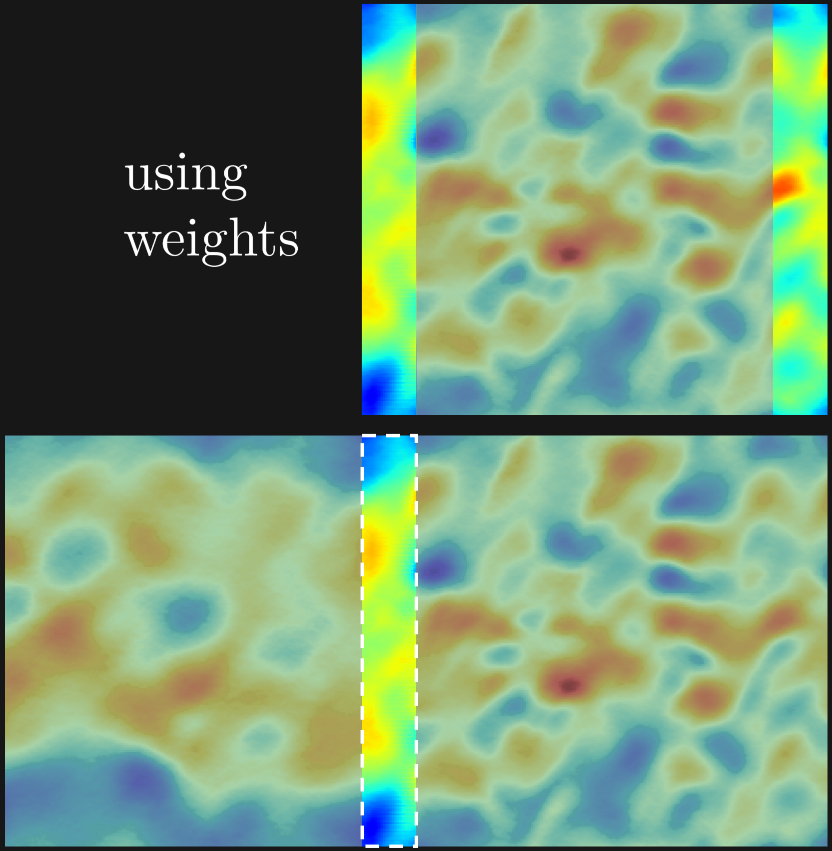
particles: $f_L(\mathbf{r}, \mathbf{v}), f_R(\mathbf{r}, \mathbf{v}) \longrightarrow f(\mathbf{r}, \mathbf{v})$

$\longrightarrow$

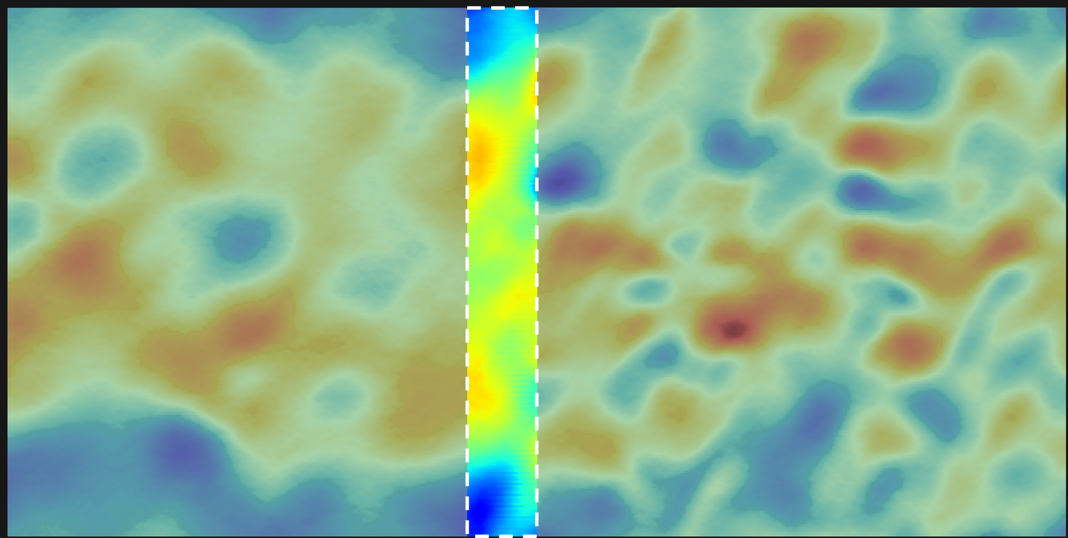
$$\mathrm{div}\mathbf{B} \neq 0$$
$$\rho - \mathrm{div}\mathbf{E} \neq 0$$


left slab
right slab
transition zone

using
weights

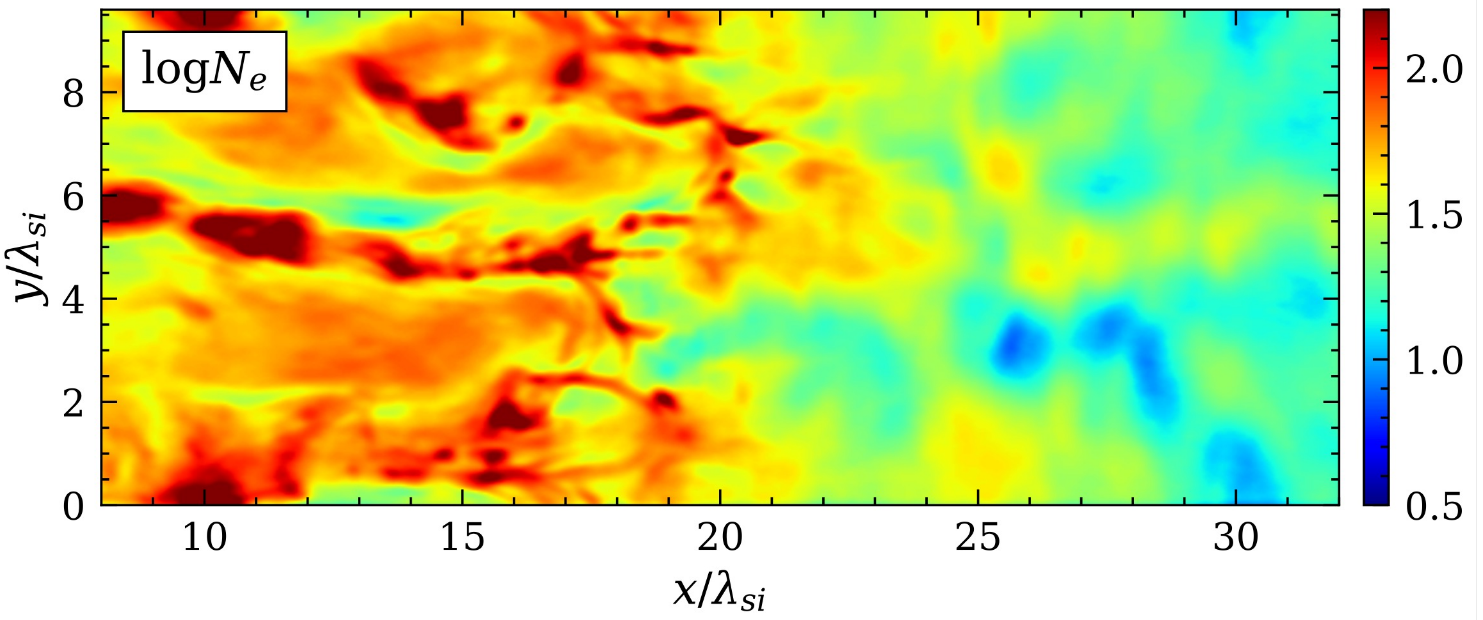


the box is
periodic



matched slabs

# The shock simulation – preliminary results



## Conclusion

Our framework allows to perform more realistic simulations of shock waves in various astrophysical environments.