Revisiting particle acceleration at ultra-relativistic shocks

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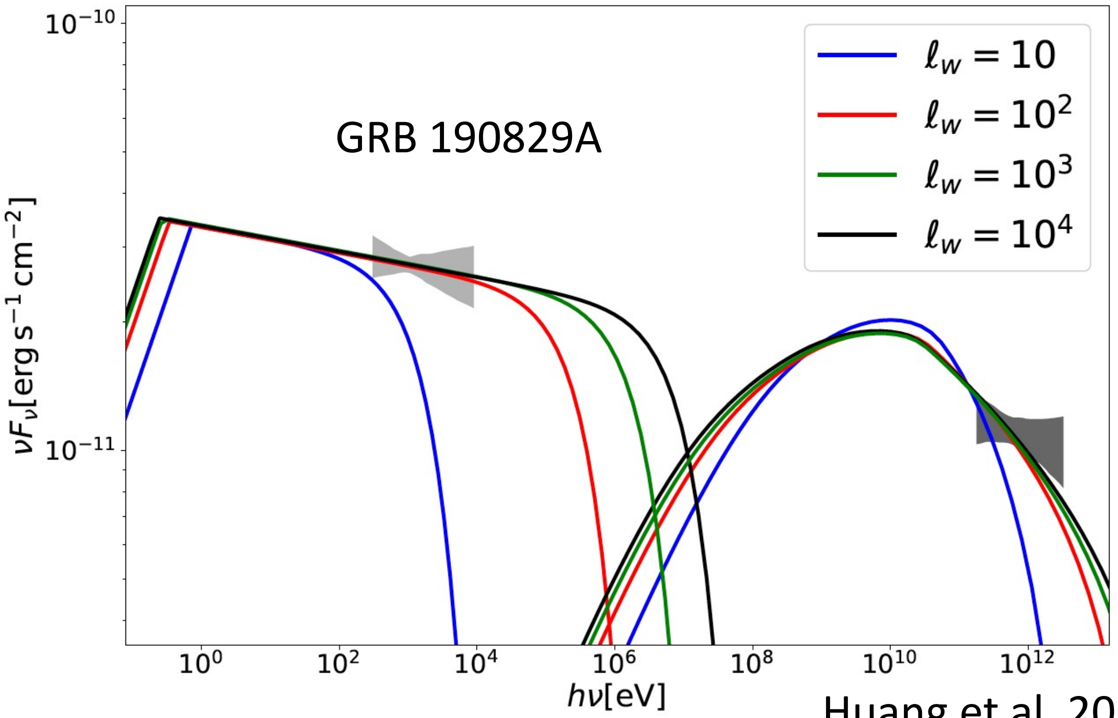
Zhi-Qiu Huang

Brian Reville

John Kirk

Gwenael Giacinti

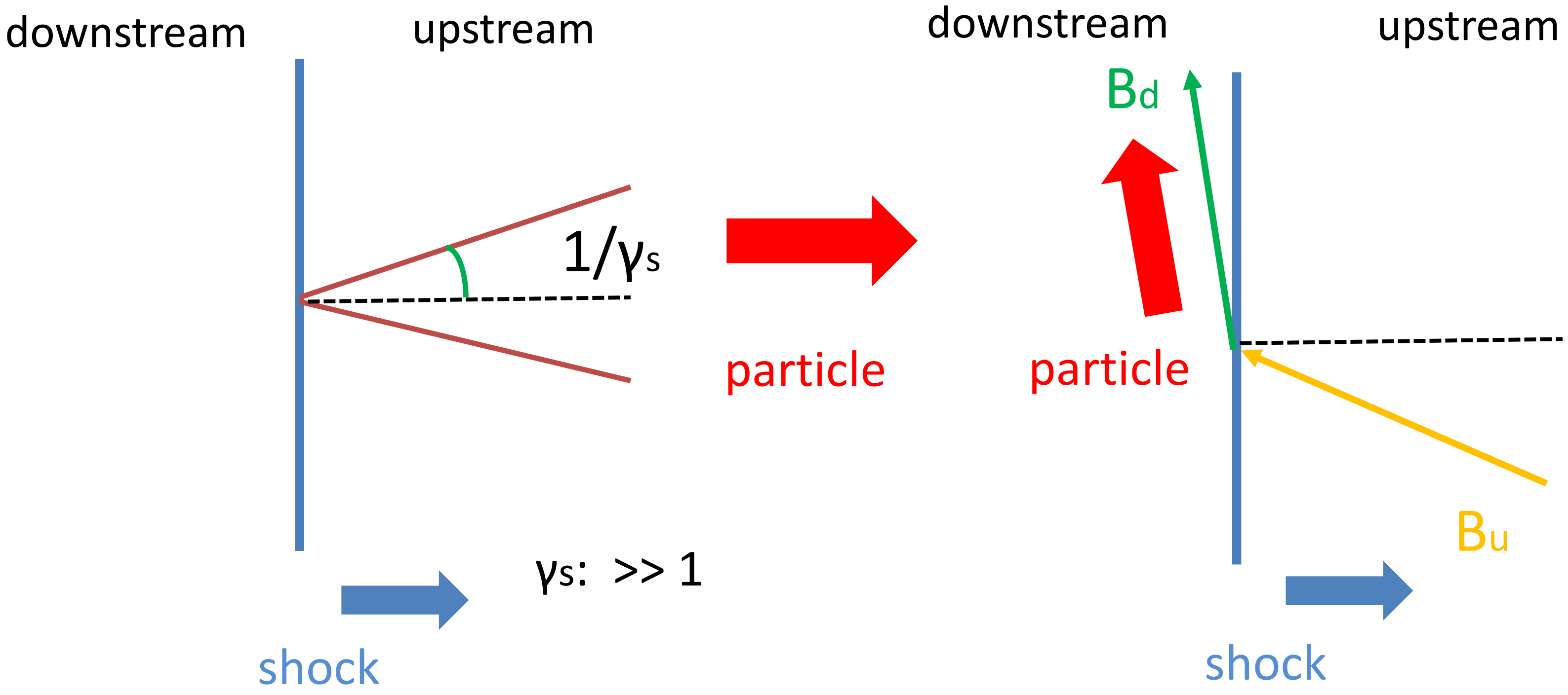
Why do we revisit?



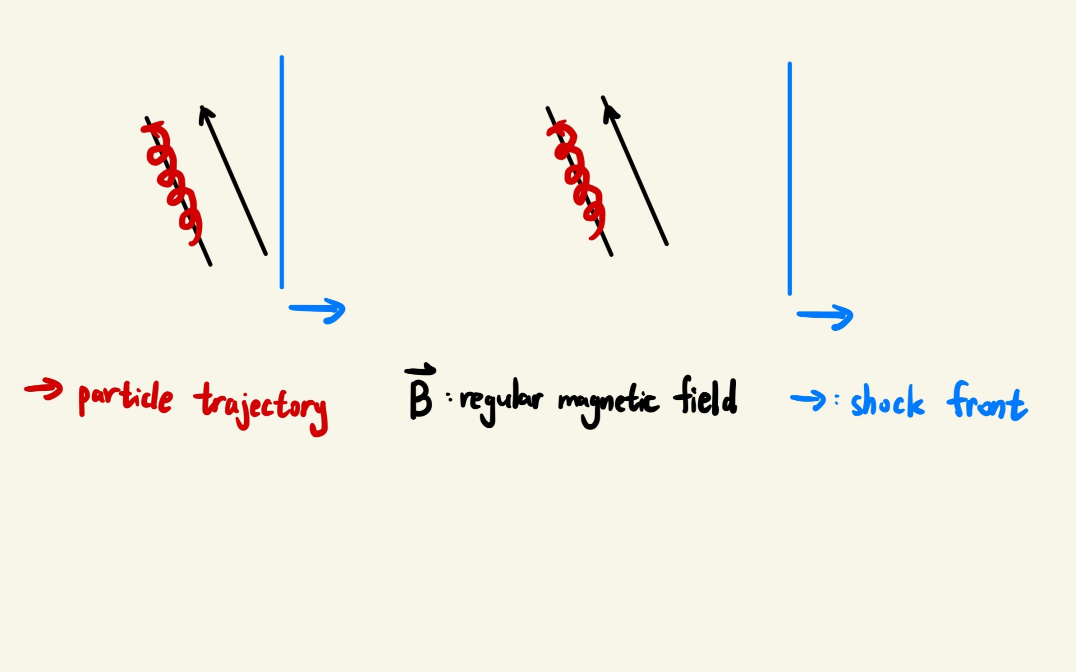
$l_W = 10$: characteristic scale of magnetic fluctuations in terms of ion skin depths from PIC simulations (e.g., Sironi et al. 2013)

Huang et al. 2022
ApJ 925 182

Relativistic shocks



Magnetized limit



For acceleration to proceed, the isotropization rate in downstream must exceed the gyro-frequency.

Achterberg et al. 2001

Magnetized limit: $\nu_{\rm iso} = \omega_{\rm g}$

Code

Monte-Carlo simulation to calculate particle trajectory

✅ Regular magnetic field (jump condition when crossing the shock)

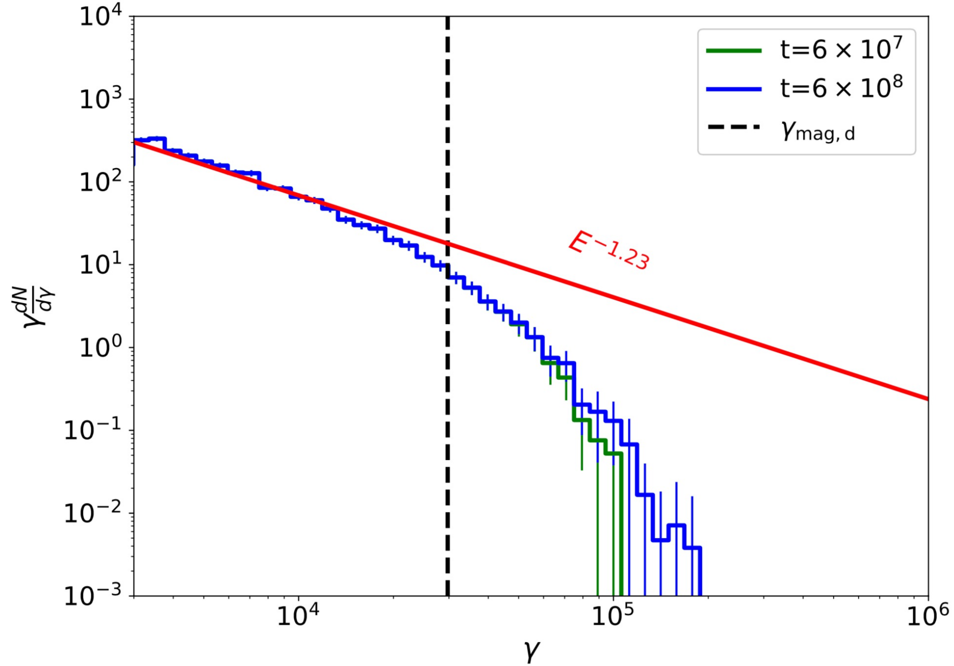
✅ Small angle scattering

✅ Particle splitting method

❎ Energy losses

Perpendicular case

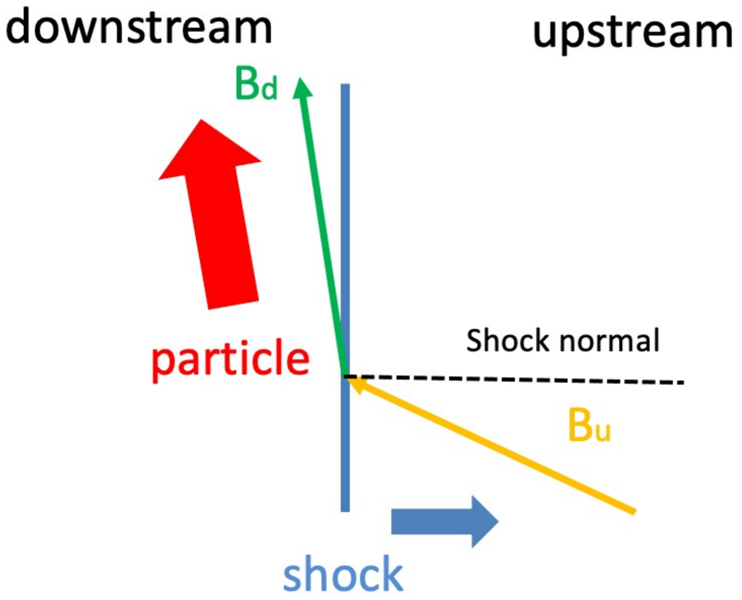
Scattering rates in upstream and downstream are both proportional to γ^-2, as expected for particle scattering in small scale fluctuations



Weak scattering in upstream

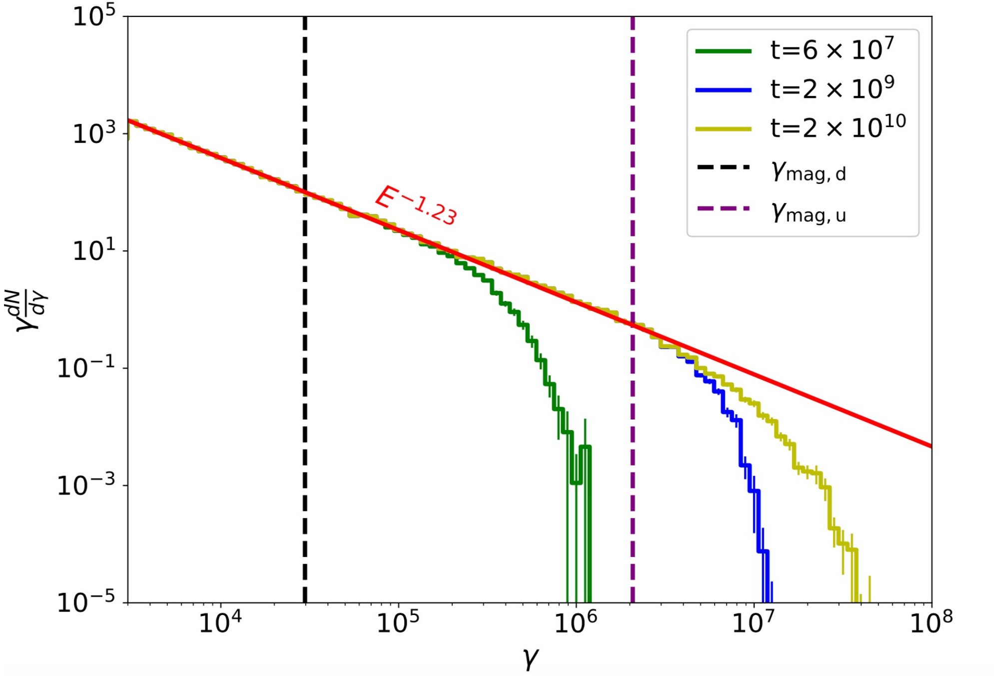
Red: Kirk, Guthmann et al. 2000

Magnetized limit in downstream



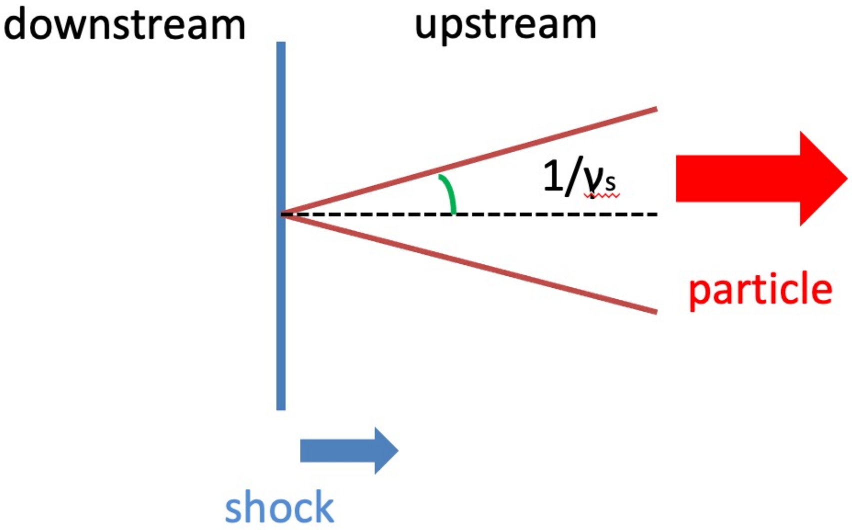
$$t_{\rm sc} = t_{\rm gyro}$$
$$1/\nu = 1/\omega_{\rm g}$$

Perpendicular case



Strong scattering in upstream

Magnetized limit in upstream

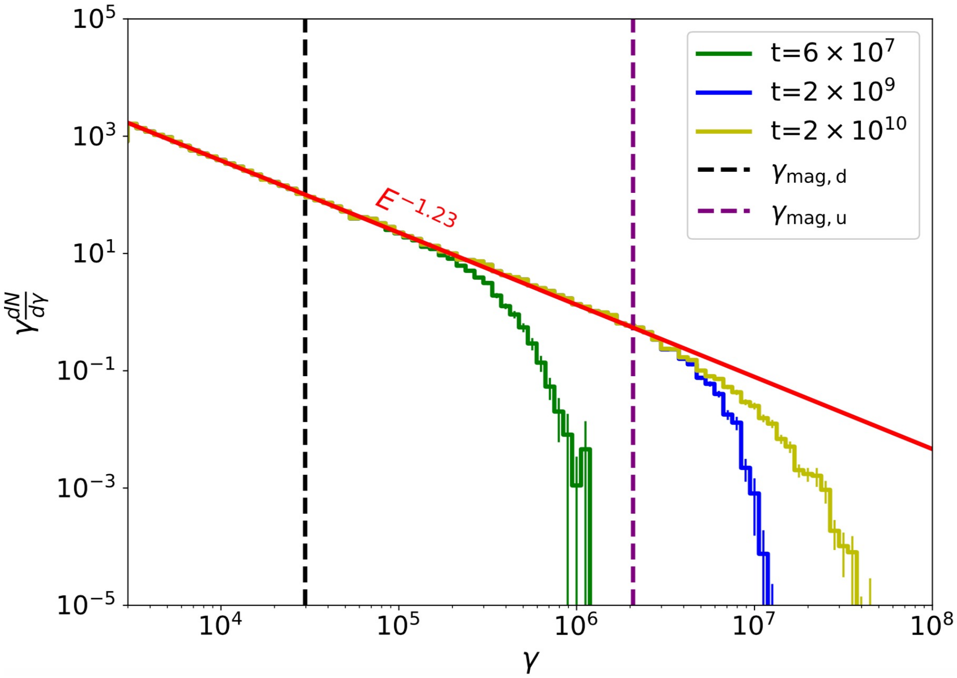


γ_s: >> 1

$$t_{\rm sc} = t_{\rm gyro}$$

$$\frac{1}{\gamma_{\rm s}^2}/\nu = \frac{1}{\gamma_{\rm s}}/\omega_{\rm g}$$

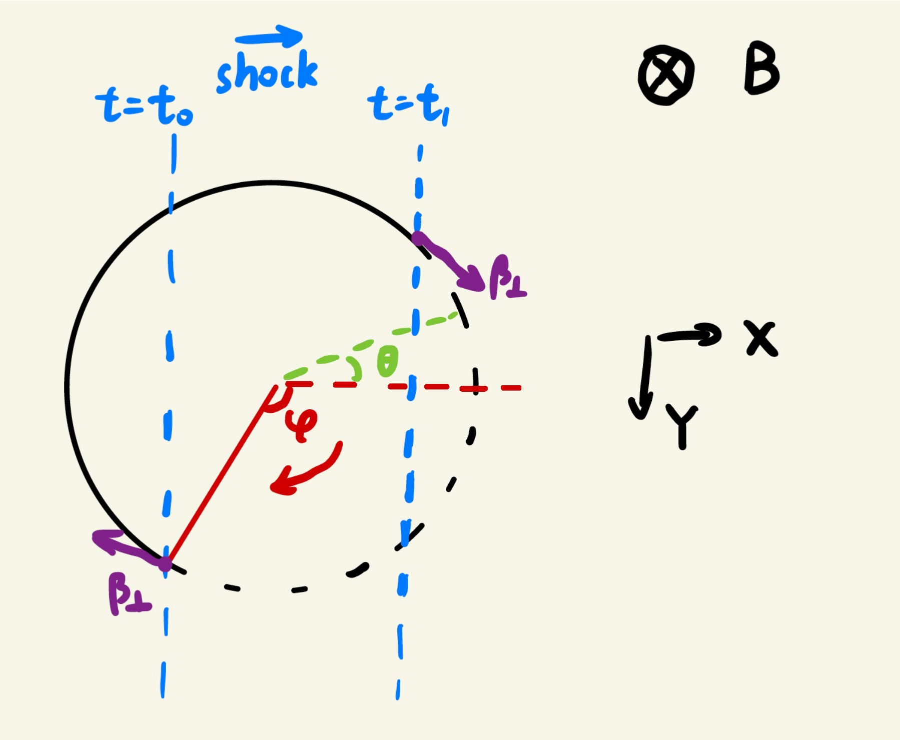
Perpendicular case

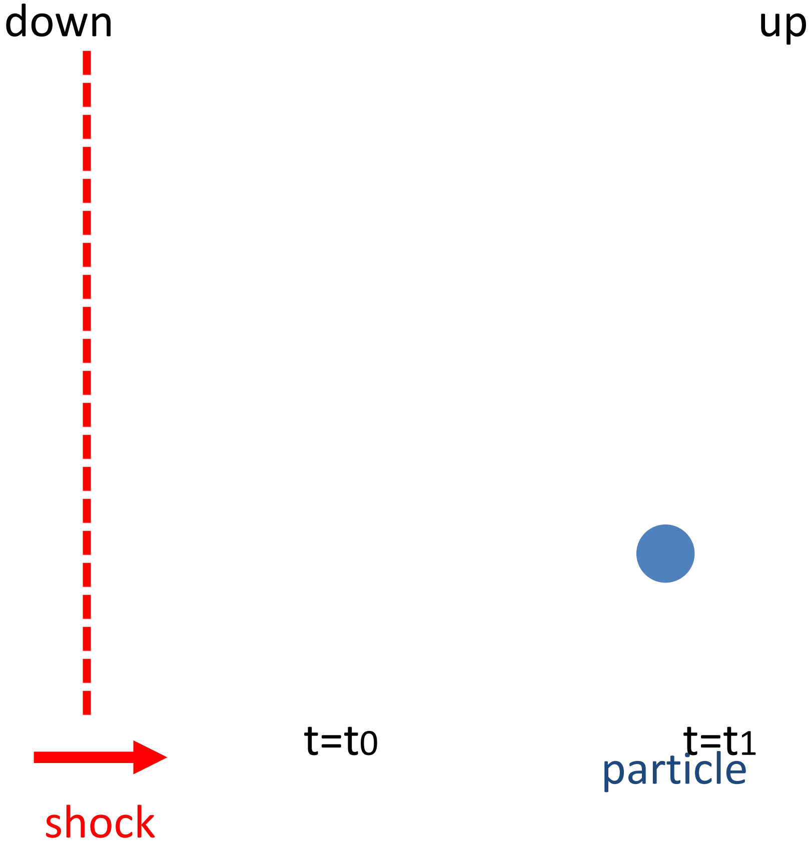


Strong scattering in upstream

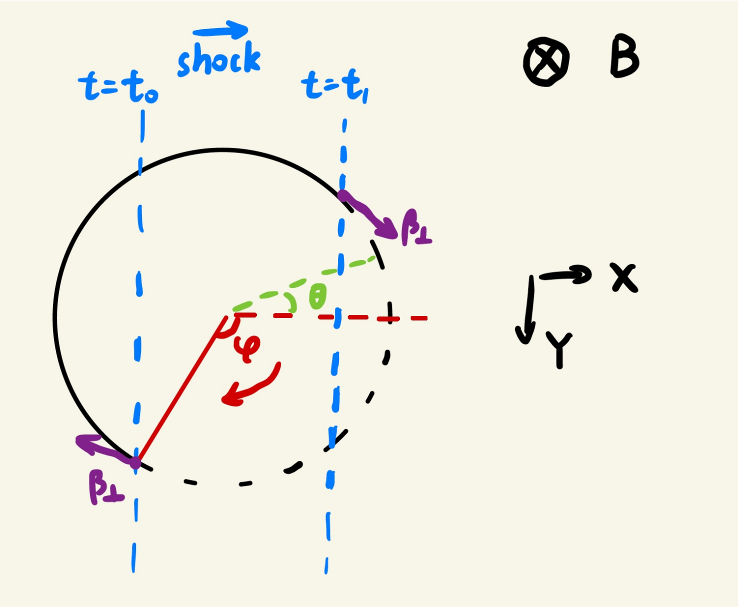
How can these particles return back to upstream?

Particle trajectory





Conditions



When moving to upstream (t=t1)

$$\theta = \arcsin\left(\frac{1}{3\beta_\perp}\right) \qquad \frac{(\cos\theta - \cos\varphi) r_{\mathrm{g}}}{c/3} > \frac{2\pi - \varphi - \theta}{\omega_{\mathrm{g}}}.$$

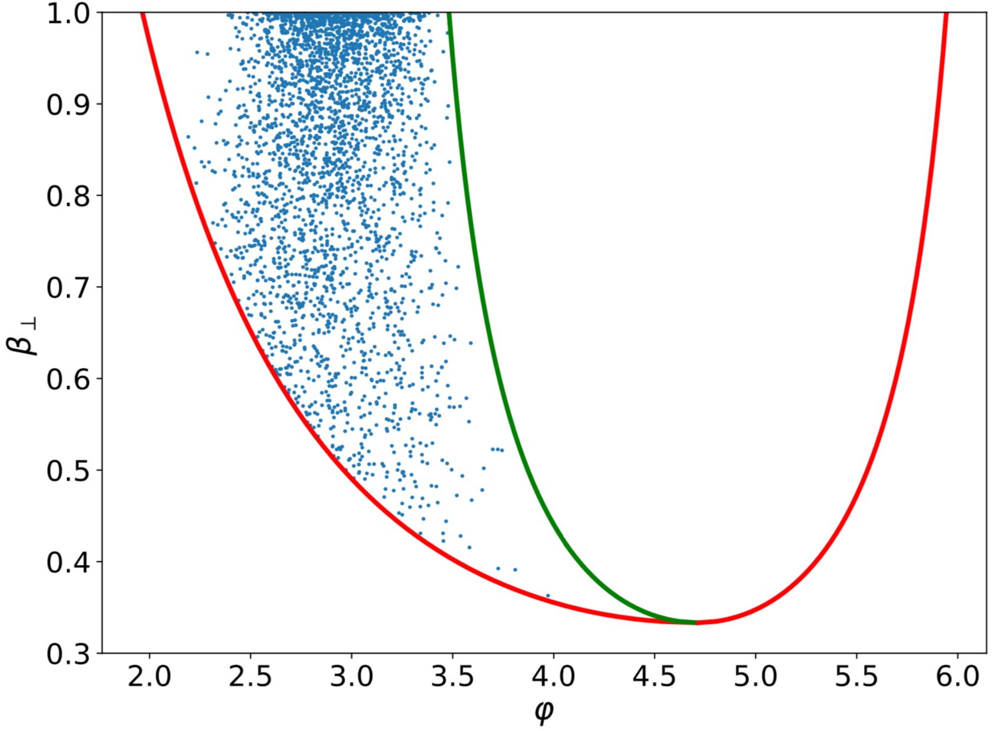
Condition A

When moving to downstream (t=t0)

$$\beta_x < \frac{1}{3}.$$

Condition B

Phase distribution



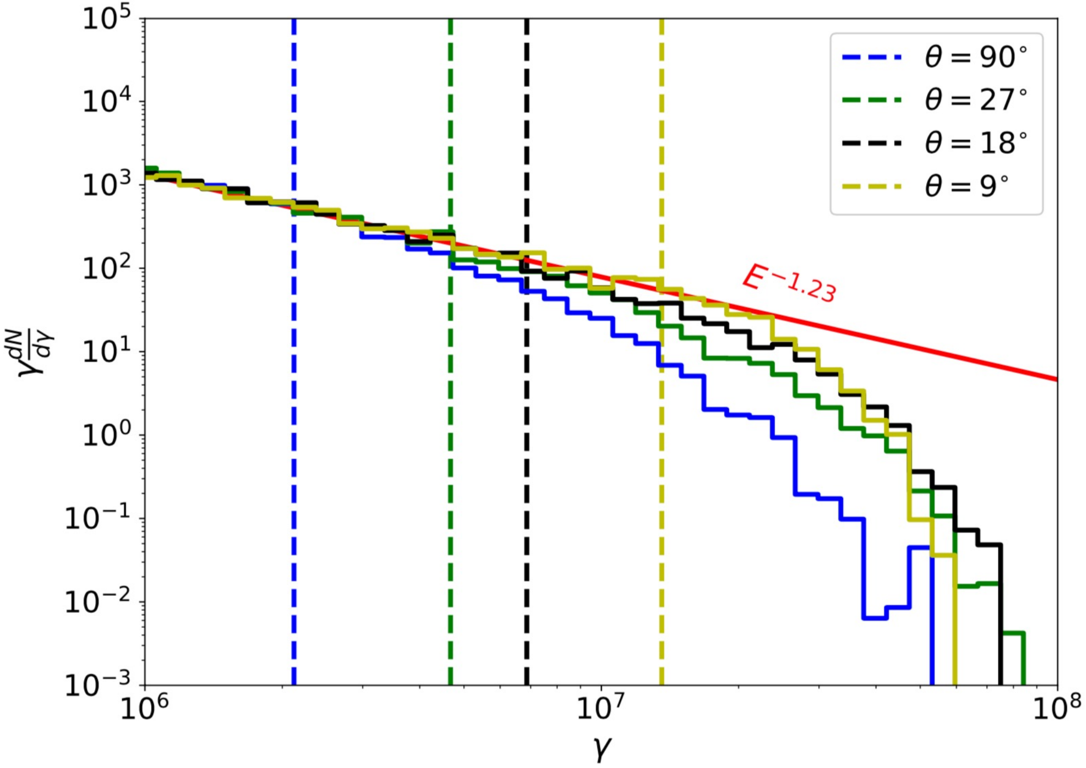
Red: condition A

Green: condition B

Blue: particle phases

Phase distribution is not uniform!

Oblique case



θ: declination angle with shock normal (>> $1/\gamma_s$)

B_{total}: constant

$$E_{\max} \propto \frac{1}{B_{\perp}} \propto \frac{1}{\sin\theta}$$

Role of large scale fields

Consider the existence of a large-scale magnetic field,

$$\nu_{\rm u} = D_1\gamma^{-2} + D_2\gamma^{-1/3}$$

small scale   large scale

$$\omega_{\rm gyro} \propto \gamma^{-1}$$

It is possible that particles are always unmagnetized in upstream. External turbulence in progenitor's environment might be sufficient to provide the necessary upstream scattering at large energies.

Conclusions

- Scattering in upstream is also important for shock acceleration.
- The magnetized limit in downstream is a weak condition.
- The maximum accelerated energy can exceed the magnetized limit in downstream, and may reach the Bohm limit.

Thank you!