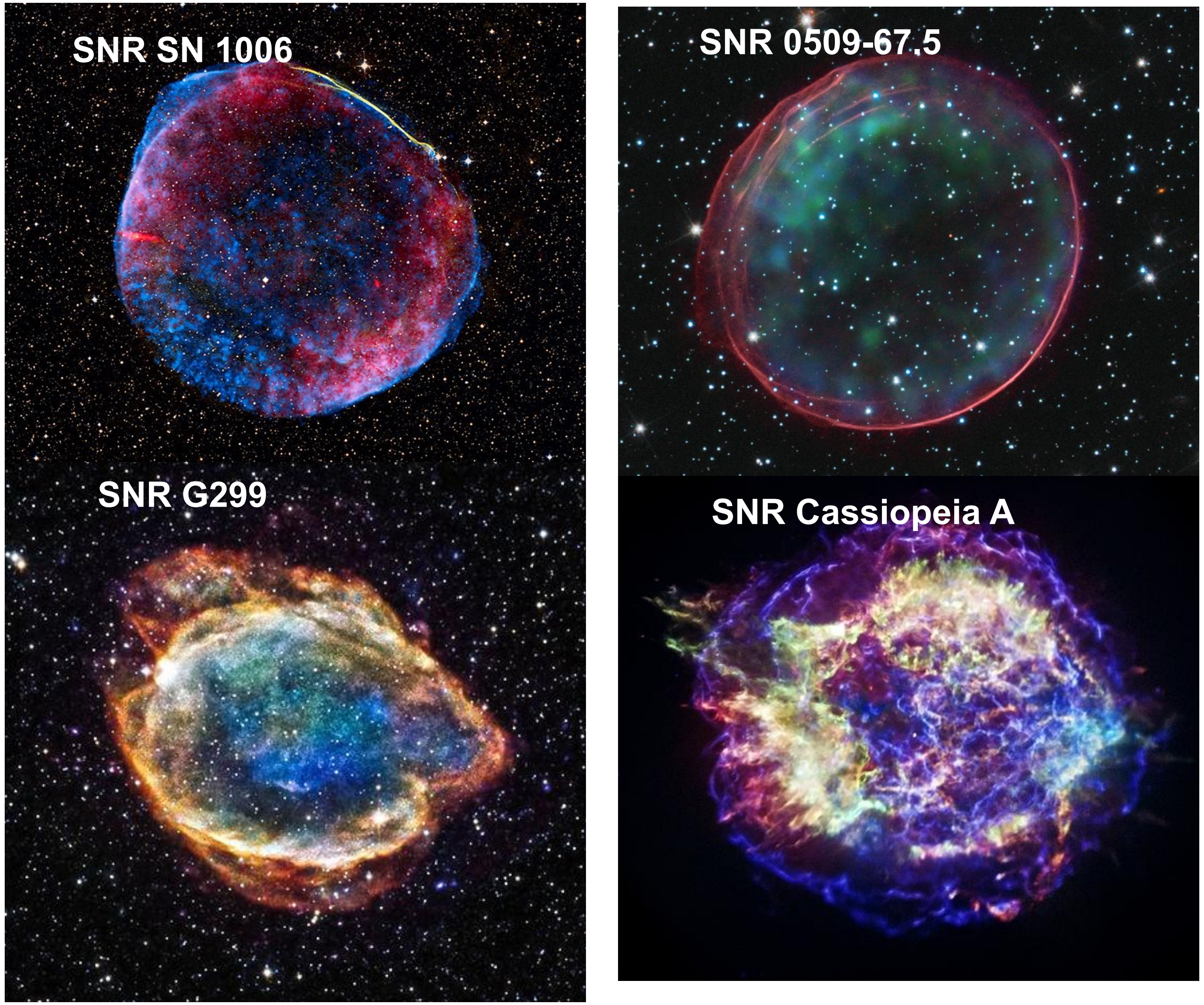
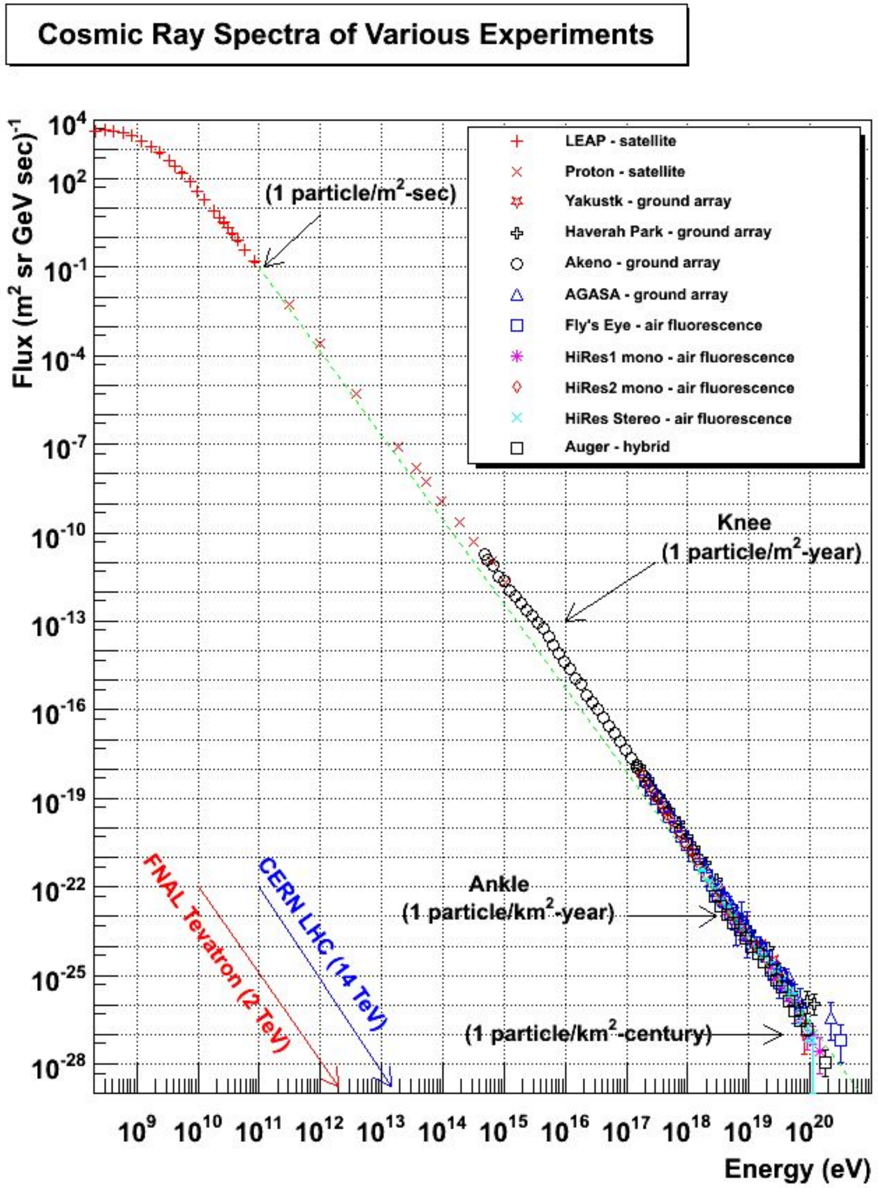
Electron injection in Tycho's SNR.

Artem Bohdan, Martin Pohl

SNR paradigm of CR production

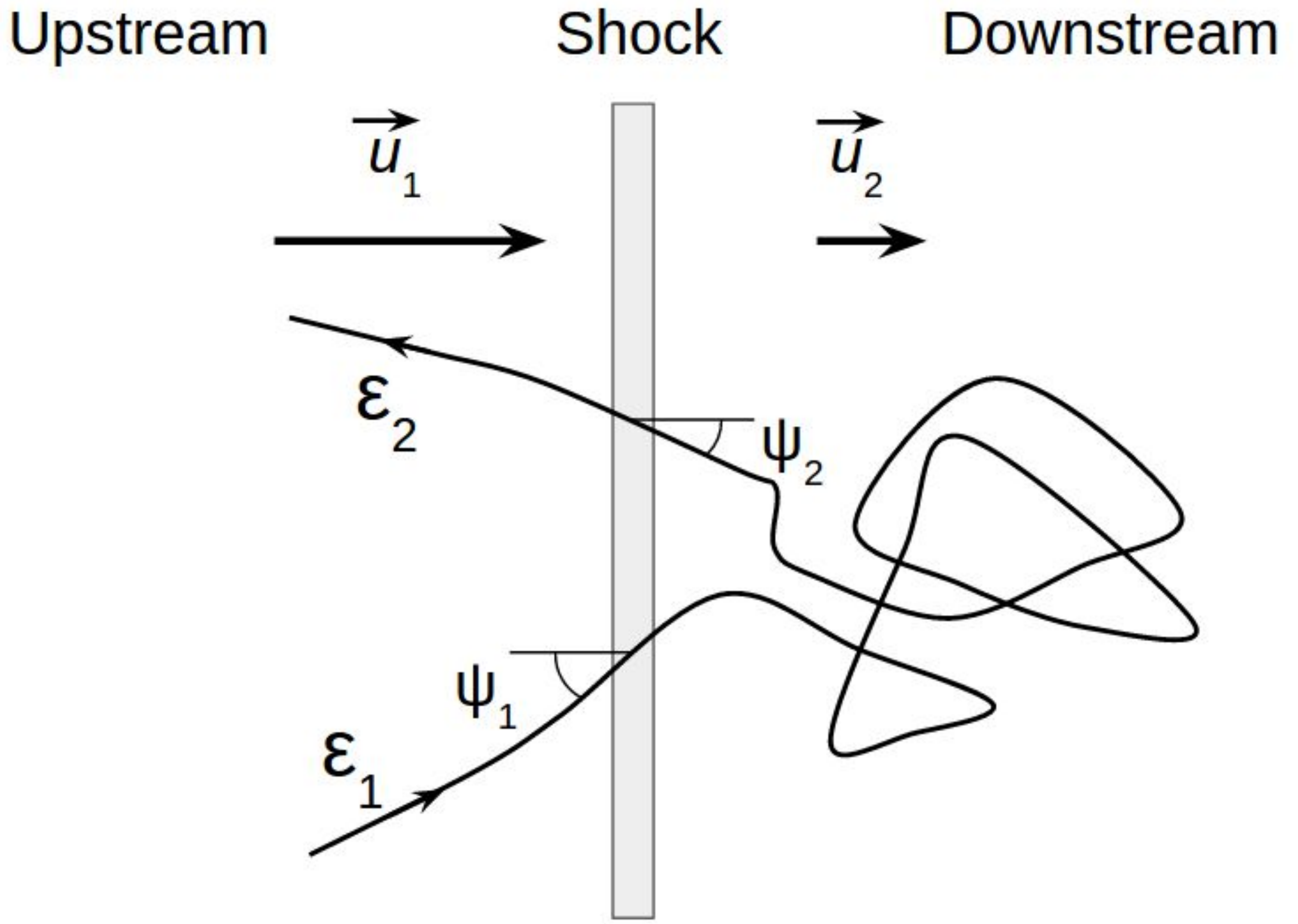




Diffusive shock acceleration

Diffusive Shock Acceleration (DSA)
is the first-order Fermi acceleration process at young SNR shocks assumed to provide the main part of Galactic cosmic-ray flux.

- Particles are bouncing between upstream and downstream plasmas
- Particle scattering process has diffusive nature
- Relativistic particles are involved
- Predicted spectrum: $N(\varepsilon) \propto \varepsilon^{-2}$

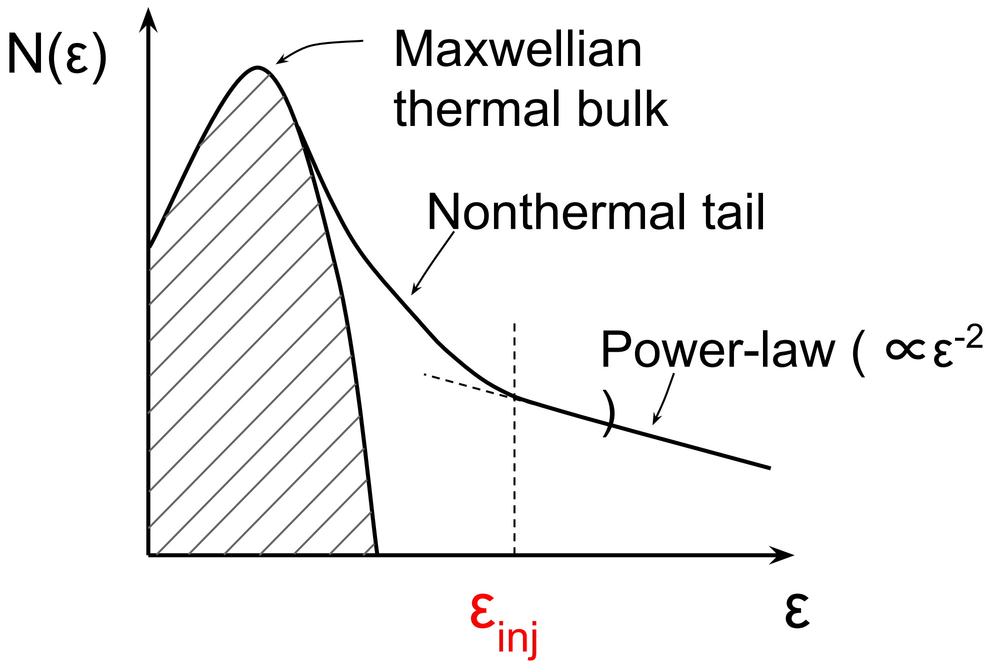


$d_{sh} \sim (1\text{-}100)\ \lambda_{gi}$

Particle injection problem

Particle pre-acceleration is needed to accelerate particles via DSA. Only particles with energy greater than ε_{inj} ($r_g(\varepsilon_{inj}) > d_{sh}$) can cross the shock unaffected. Some pre-acceleration is thus required, in particular for electrons.

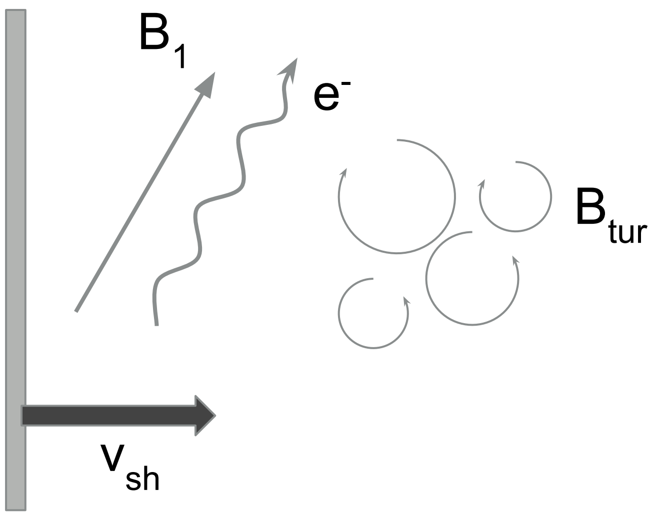
Questions: mechanism, efficiency (N_{nt}/N_{tot})



Generation of scattering turbulence

In simulations with oblique magnetic field (subluminal case) particles can escape the shock. Electrons require less energy than ions to achieve relativistic velocity and escape shock region moving along magnetic field lines.

This current is capable to produce Alfvenic waves or induce nonresonant Bell instability.



Parameters of SNR shocks

Shock velocity: v_{sh} ~ 10 000 km/s
Particle density: $N_{i,e}$ ~ 1 particle/cm^3
Upstream magnetic field: B_1 ~ 1 - 10 μG
Upstream plasma temperature: T_i ~ (0.1-1) eV
Plasma beta: β_p ~ 1

- Nonrelativistic shocks: $\boldsymbol{v_{sh} \ll c}$
- Sonic Mach number: $\boldsymbol{M_S = v_{sh}/c_s \sim 20 - 200}$
- Alfvén Mach number: $\boldsymbol{M_A = v_{sh}/v_A \sim 50 - 500}$
- **Perpendicular** or parallel shocks

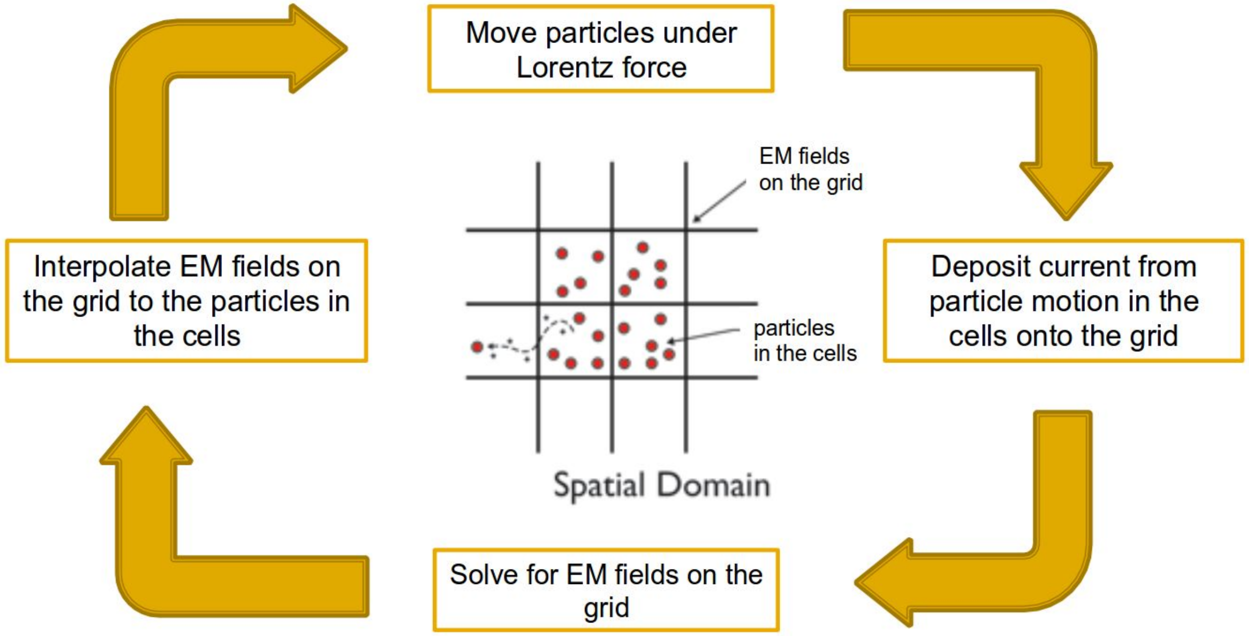
Particle-In-Cell Simulations

Particle-In-Cell modeling - an ab-initio method of Vlasov equation solution through:

- integration of Maxwell's equations on a numerical grid
- integration of relativistic particle equations of motion in collective self-consistent EM field

Particle-In-Cell simulations are designed to explore cases when:

- self-consistent treatment is needed
- electron dynamic is important (electrostatic waves, instabilities generated by electrons)
- electron acceleration processes are investigated



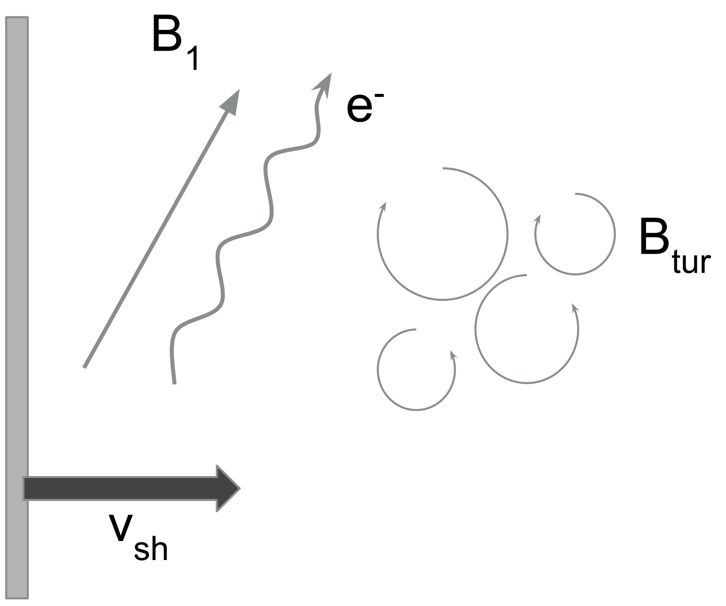
Generation of scattering turbulence

Generation of scattering turbulence

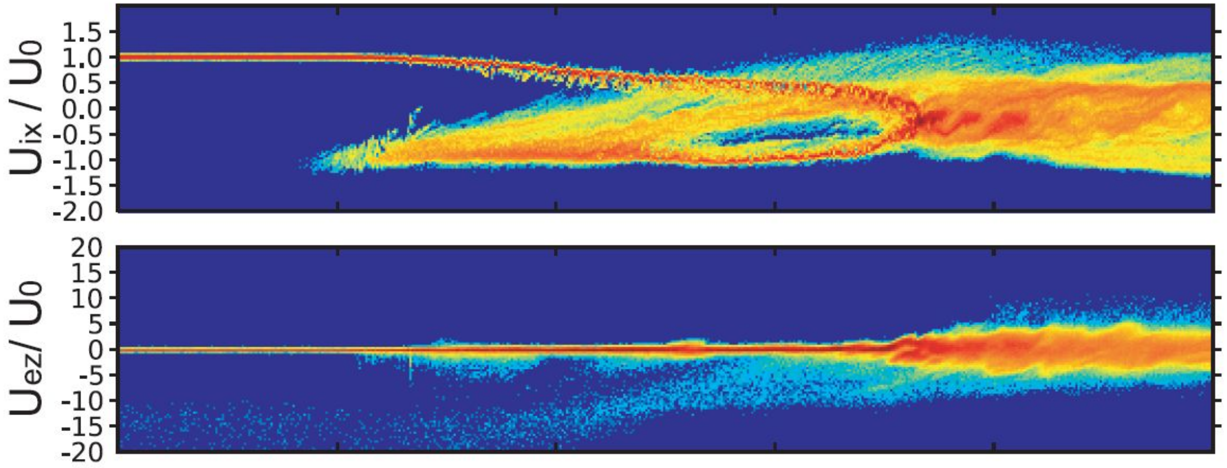
If $c/\tan\theta_{Bn} > v_{sh}$ (subluminal case) particles can escape the shock.

Electrons are reflected due to magnetic mirror effect.

When the reflected electrons are capable to induce turbulence upstream?



Oblique shock simulation: 1D case (Amano & Hoshino, 2007)



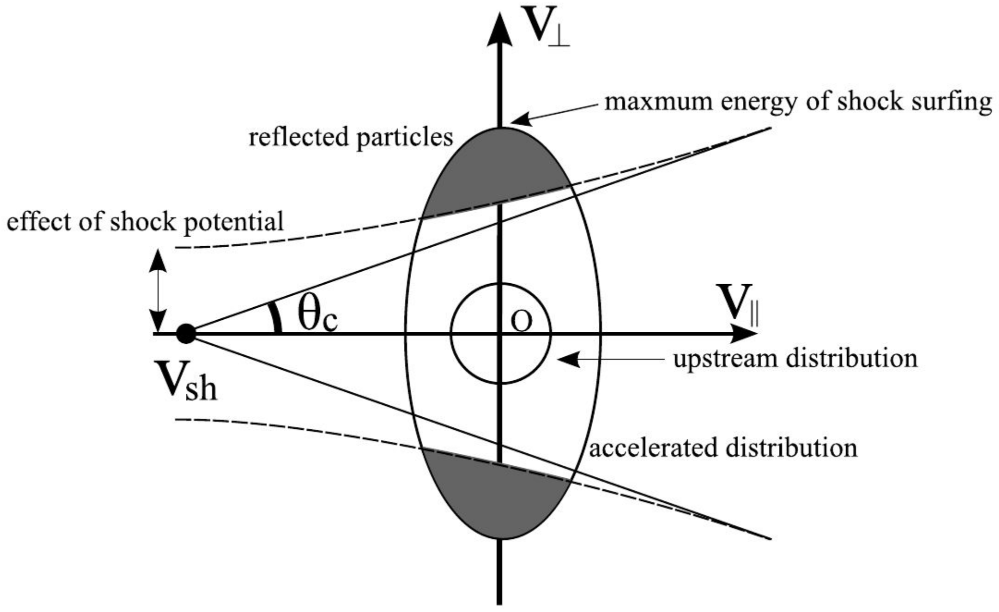


FIG. 5.—Schematic illustration of surfing and drift acceleration.

θ_{Bn} = 80°, m_i/m_e= 100, M_A = 15

Propagating upstream electrons are produced by combination of shock surfing acceleration (SSA) and shock drift acceleration (SDA). This current is capable to produce Alfvenic waves.

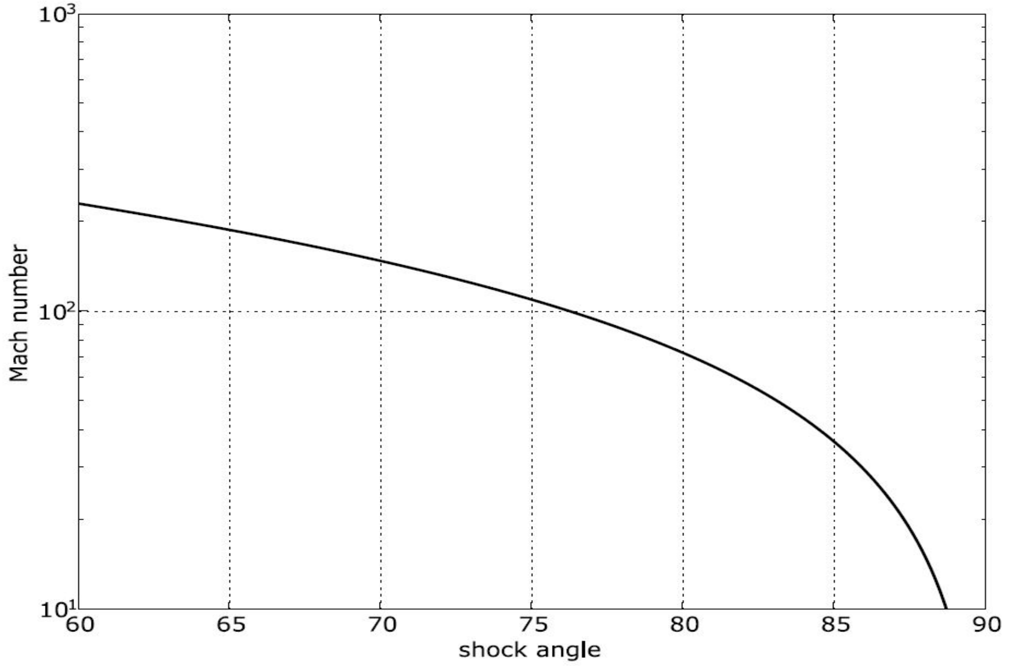
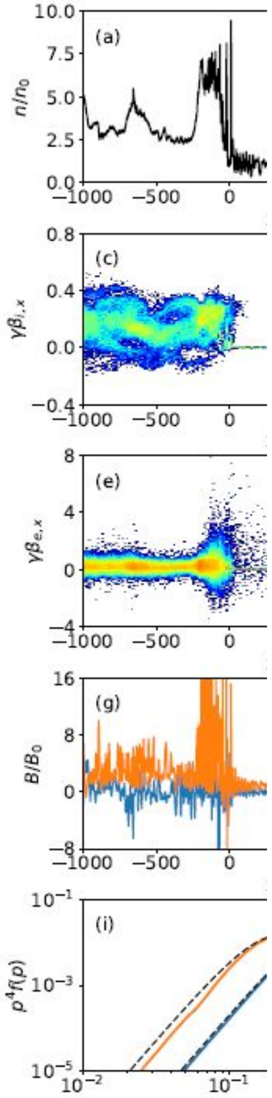
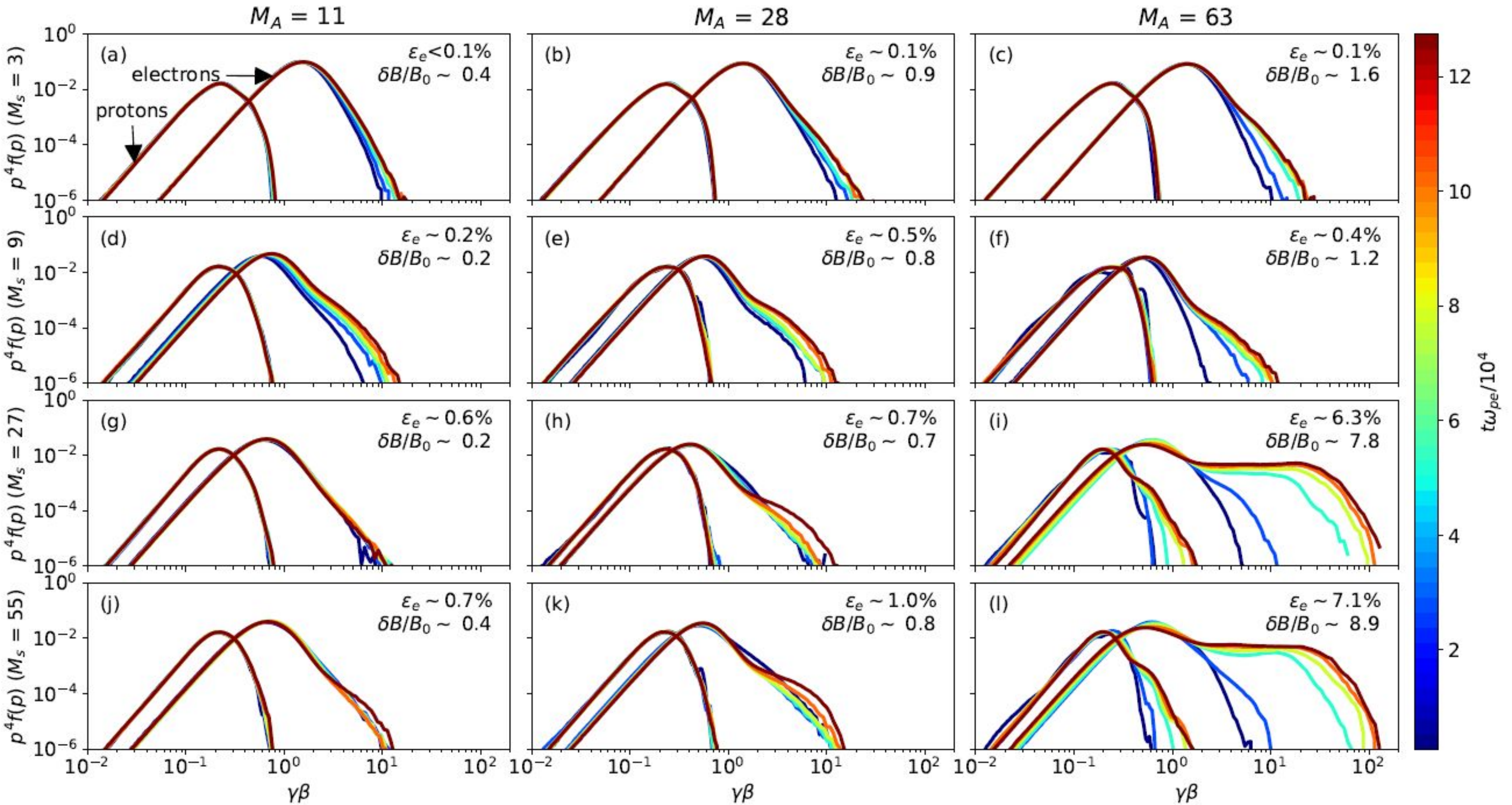


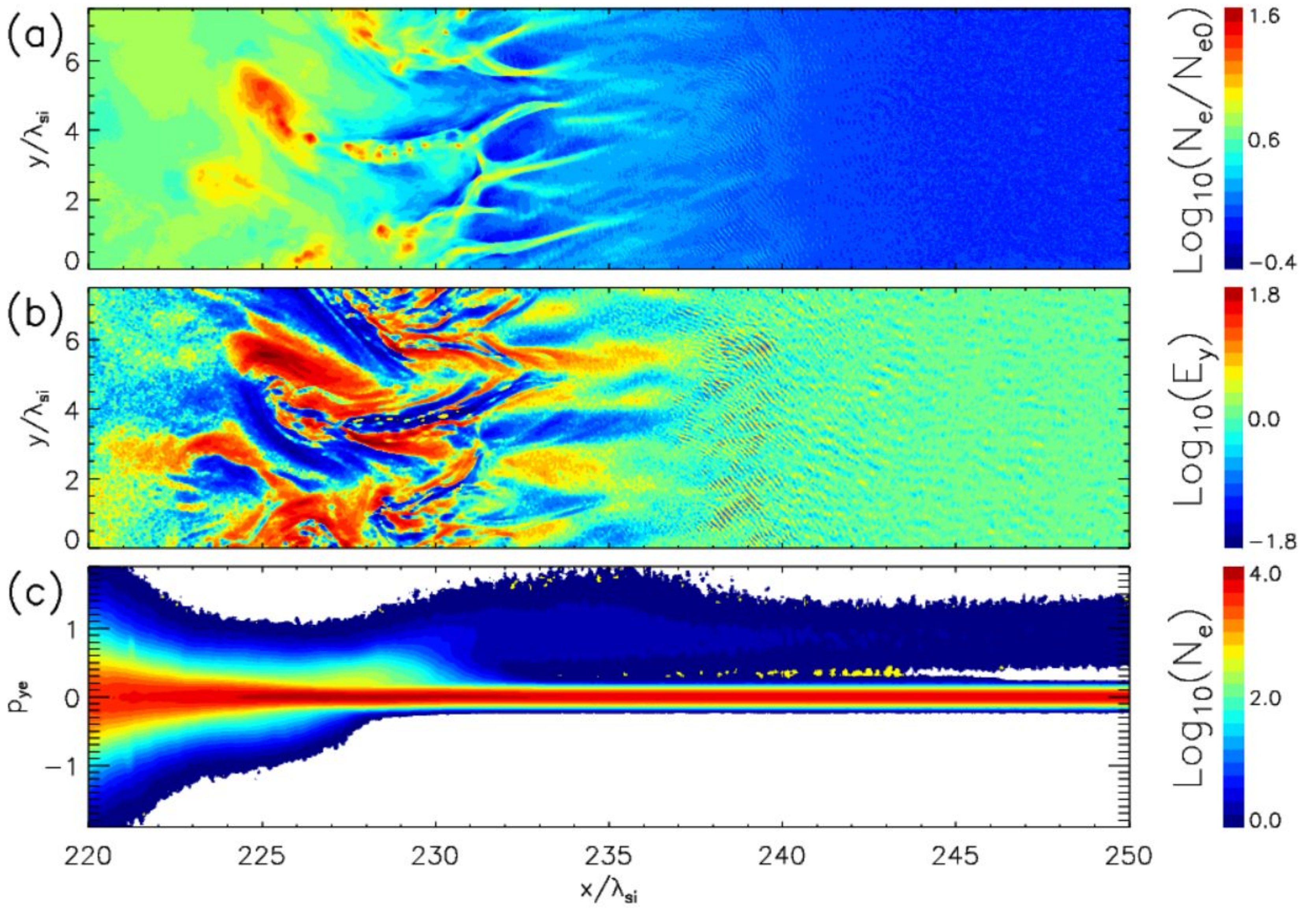
FIG. 9.—Critical Mach number above which the self-generation of upstream waves becomes possible.

Oblique shock simulation: 1D case (Xu et al. 2019, arXiv:1908.07890)





Oblique shock simulation: 2D case (early results)



θ_{Bn} = 63°, m_i/m_e= 100, M_A = 35

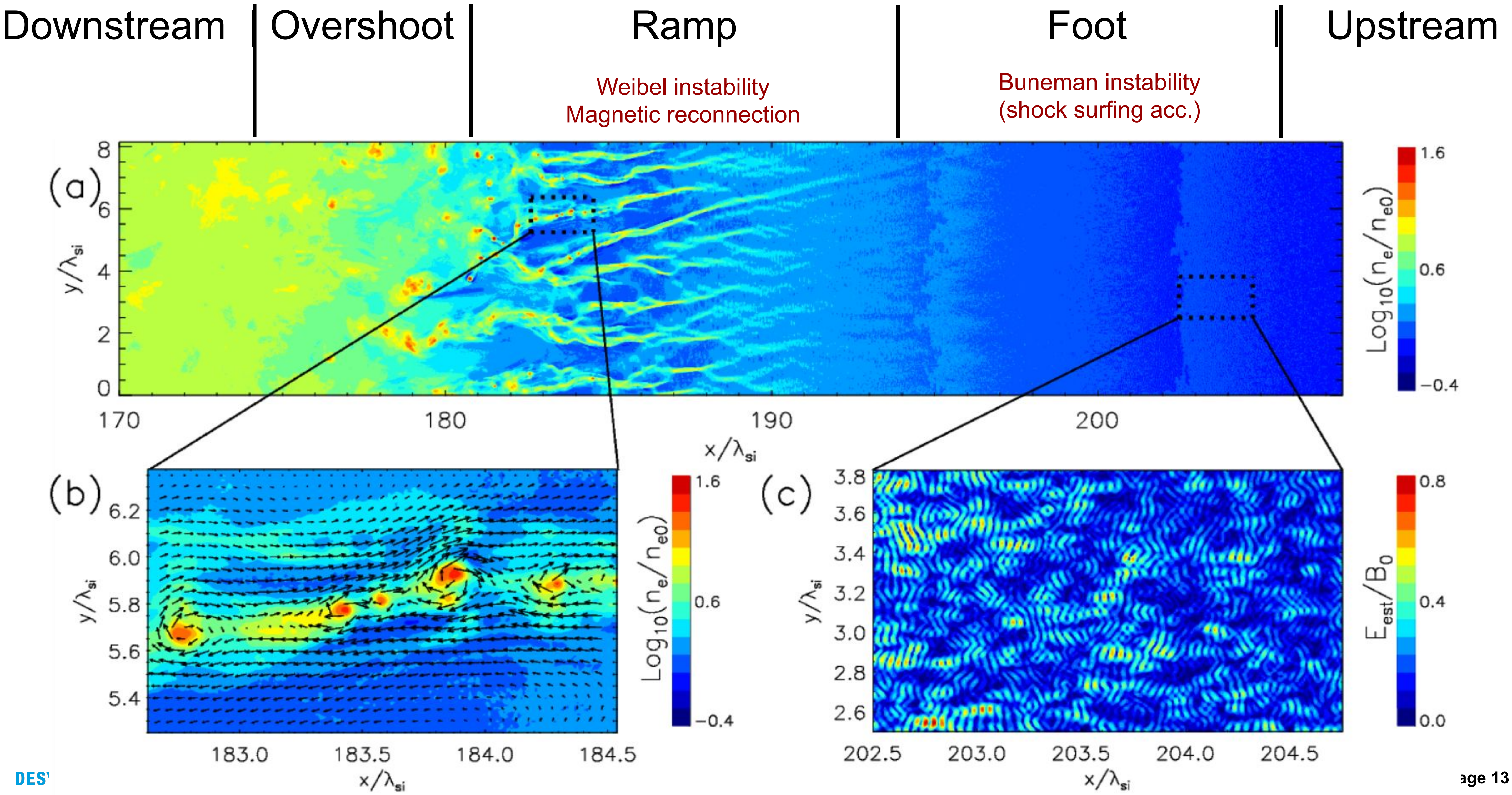
Propagating upstream relativistic electrons are observed. Reflection mechanism is similar to 1D case.

Both Buneman instability (SSA) and magnetic reconnection are important for reflection of relativistic electrons.

More simulations with different θ_{Bn} are needed.

Electron injection mechanisms

Microstructure of perpendicular shocks: 2D3V PIC simulations



Parameters of PIC simulations

Common parameters: $\theta_{Bn} \lesssim 90^o$, $v_{sh} \approx 0.2c$, $\beta_e \approx 0.5$, $N_{ppc} \approx 20$

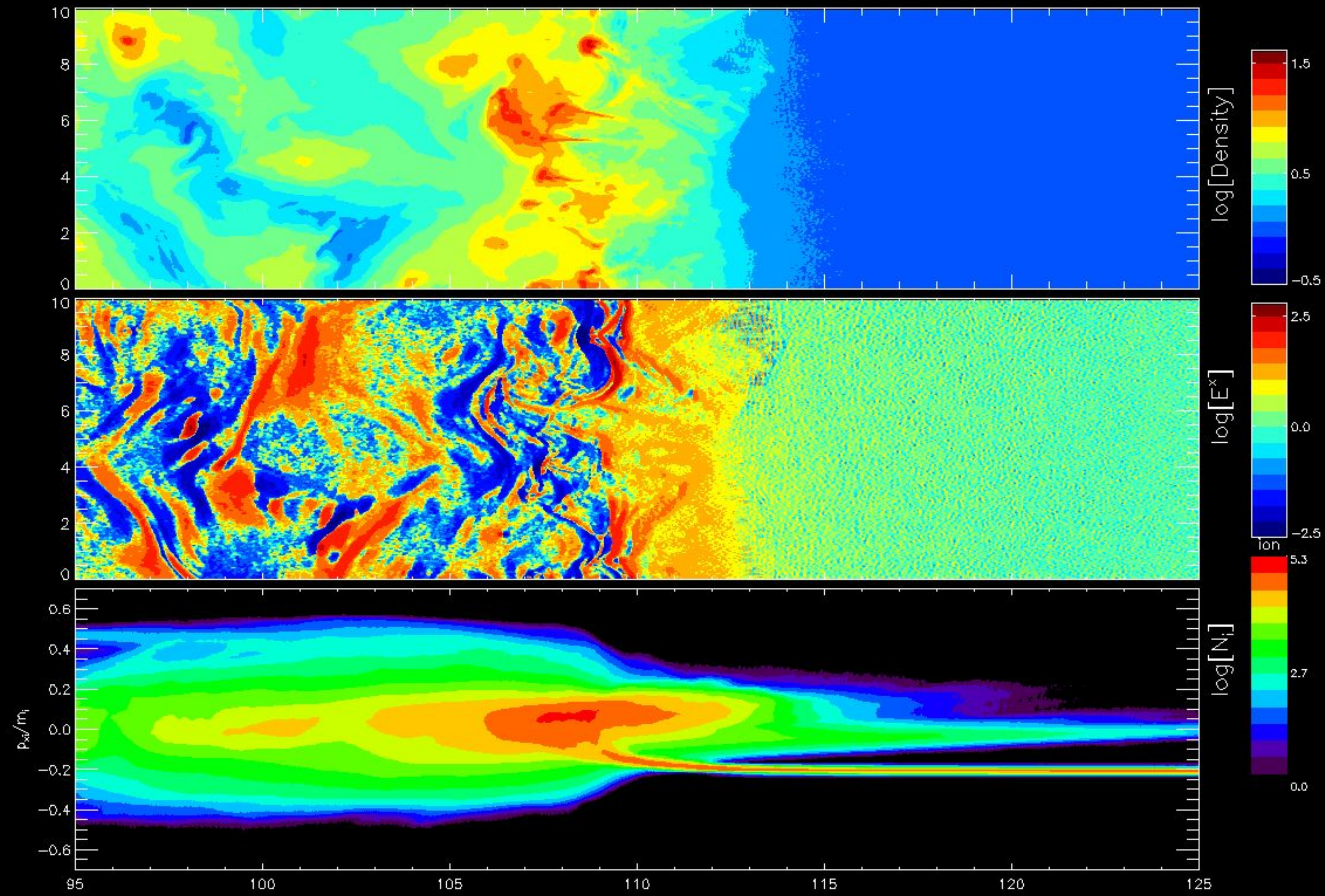
1D: $M_A = 32$, $m_i/m_e = 20$ (Hoshino 2002)
$M_A = 15$, $m_i/m_e = 100$ (Amano 2007)

2D: $\varphi = 90^o$, $M_A = 14$, $m_i/m_e = 25$ (Amano 2009)
$\varphi = 90^o$, $M_A = 15\text{-}30$, $m_i/m_e = 25\text{-}100$ (Matsumoto 2012)
$\varphi = 0^o$, $M_A = 42$, $m_i/m_e = 225$ (Matsumoto 2015)
$\varphi = 45^o$, $M_A = 28$, $m_i/m_e = 50$ (Wieland 2016)
$\varphi = 0^o\text{-}90^o$, $M_A = 33$, $m_i/m_e = 100$ (Bohdan 2017) 1 mln CPU-h.
$\varphi = 0^o\text{-}90^o$, $M_A = 23\text{-}69$, $m_i/m_e = 50\text{-}400$ (Bohdan 2019) 5 mln CPU-h.

3D: $M_A = 21$, $m_i/m_e = 64$, (Matsumoto 2017) 25 mln CPU-h. and 3PB of disk space

Fully realistic simulation: $M_A = 150$, $m_i/m_e = 1836$, $v_{sh} \approx 0.02c$

20 billions CPU-h.!!!


log[Density]
1.5
0.5
−0.5
log[E^x]
2.5
0.0
−2.5
ion
log[N_i]
5.3
2.7
0.0
p_{xi}/m_i
95
100
105
110
115
120
125

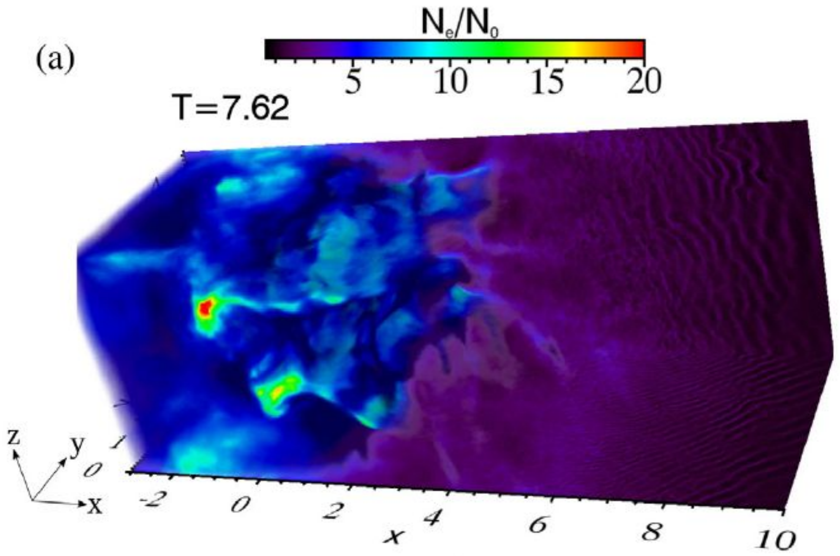
Electron injection processes in PIC simulations

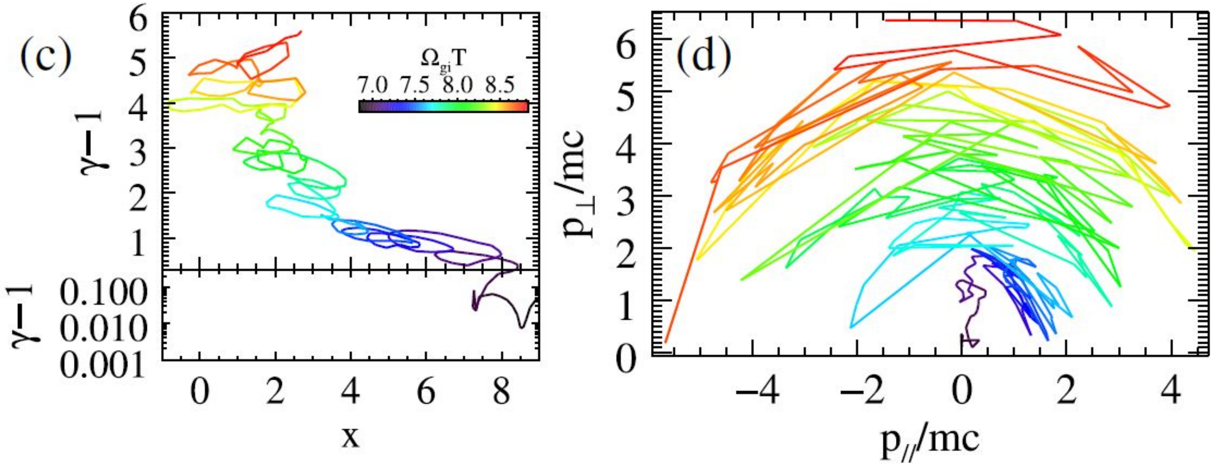
Leading edge of the foot: **SSA** (1D, 2D*, 3D)

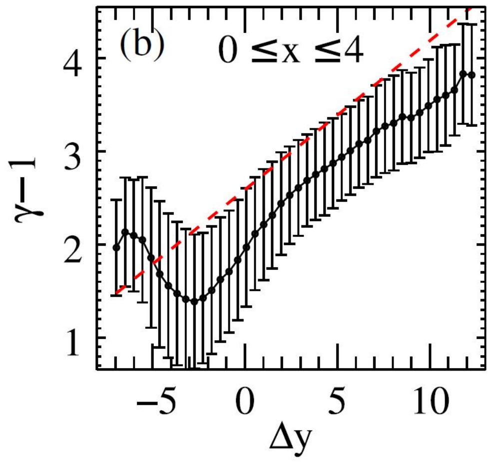
Foot/Ramp: **stochastic scattering** (2D,3D) + **drift** (3D oblique)

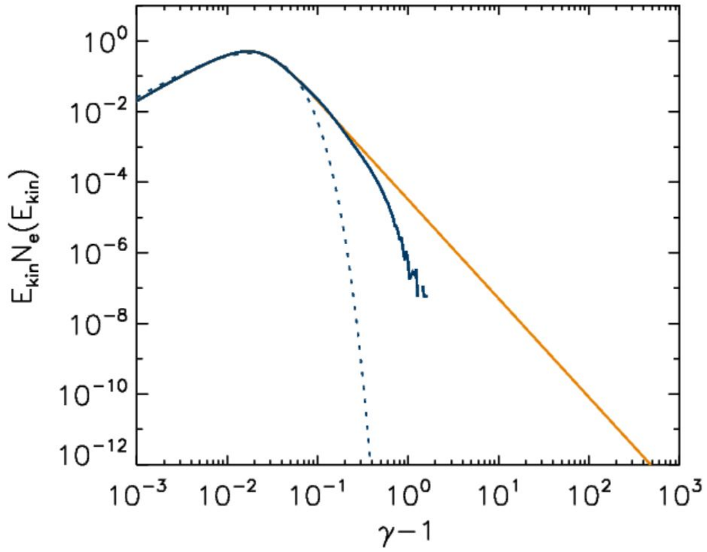
Ramp: **magnetic reconnection** (2D*, 3D*)

Stochastic shock drift acceleration (Matsumoto 2017)









Tycho's SNR

Tycho's SNR

The X-ray luminosity (Einstein Observatory, Reid et al., 1982, ApJ, 261, 485) of Tycho's SNR is $L_{xray} = 3 \cdot 10^{29} Js^{-1}$ at about 2keV.

Other parameters of Tycho's SNR (Völk et al. 2002, A&A, 396, 649) are:

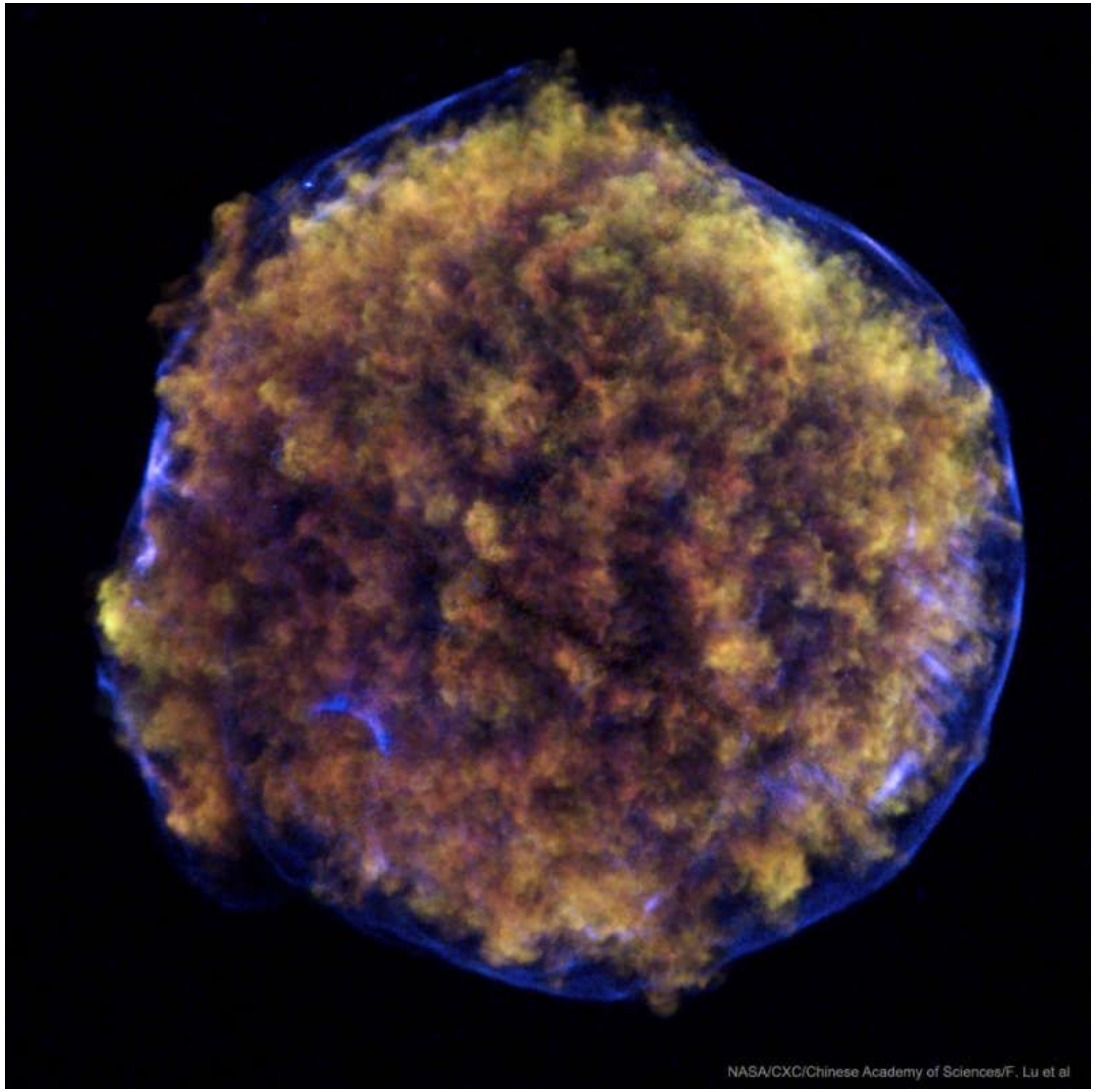
$v_{sh} = 4.4 \cdot 10^6$ m/s

$R = 2.72pc = 8.2 \cdot 10^{16}$ m

$n_{ISM} = 5 \cdot 10^5\ m^{-3}$

$B = 240\ \mu G$

$D = 2.3kpc = 6.9 \cdot 10^{19}$ m



Tycho's SNR: electron injection (observations)

2keV X-ray photons are emitted by electrons with energy about 10 TeV: $\gamma_{xrey} = \sqrt{\frac{2\pi E_{ph} m_e}{eBh}}$

Number of electrons emitting in X-ray is: $N_{xray} = \frac{L_{xray}}{\frac{dE}{dt}}$,where $\frac{dE}{dt} = \frac{4}{3}\sigma_T c \frac{B^2}{2\mu_0}\frac{V^2}{c^2}\gamma_{xrey}^2$

Assuming the power low spectrum for nonthermal electrons with index -2 the number of electrons above injection energy equals:

$$N_{inj} = \frac{\gamma_{xray}}{\gamma_{inj}} N_{xray}$$

Total number of electrons: $N_{tot} = n_{ISM}\frac{4}{3}\pi R^3$

Injection efficiency: $N_{inj}/N_{tot}(observation) = (2-30)\cdot 10^{-9}$

Tycho's SNR: electron injection (simulations)

The main question "How to fill the gap?" is still unresolved and requires a lot of efforts, but we can do some math.

An electron is injected if its gyroradius is comparable with the shock width (ξ≈2-3):

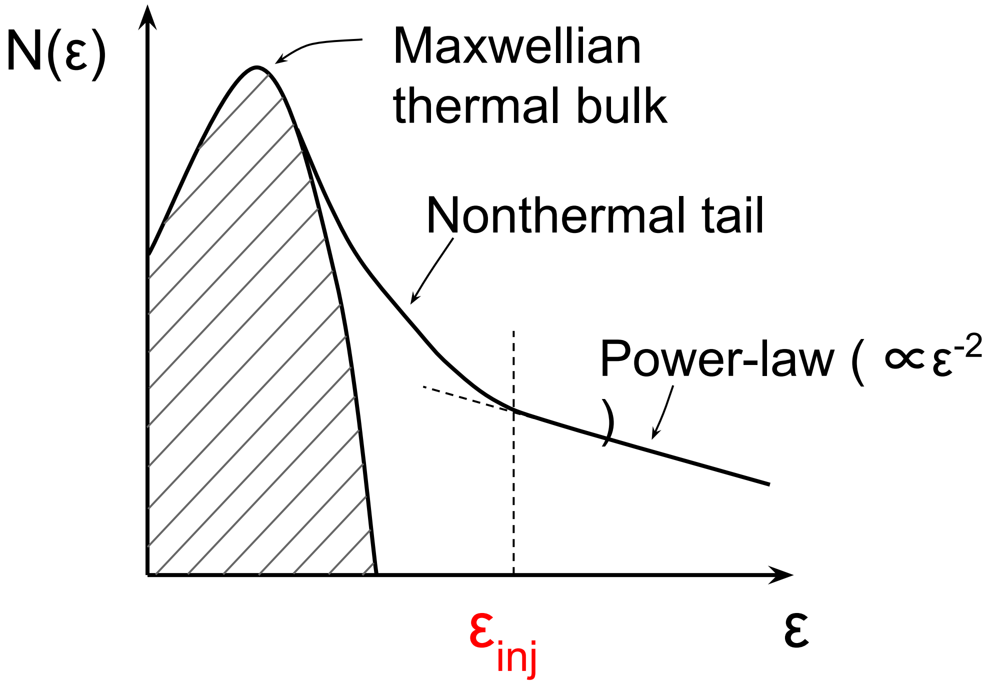
$$m_i \xi v_{sh} = m_e \gamma_{inj} c \qquad \gamma_{inj} = \frac{\xi v_{sh}}{c} \frac{m_i}{m_e}$$

The downstream temperature estimated from RH condition is (α≈0.3-0.5):

$$\gamma_{th} - 1 = \frac{k_B T_{RH}}{m_e c^2} \alpha = \frac{3\alpha}{32} \frac{m_i}{m_e} \frac{v_{sh}^2}{c^2}$$

The ratio below defines "the gap":

$$\frac{\gamma_{inj} - 1}{\gamma_{th} - 1} \approx \frac{32\xi}{3\alpha} \frac{c}{v_{sh}} \approx 15 \frac{c}{v_{sh}}$$

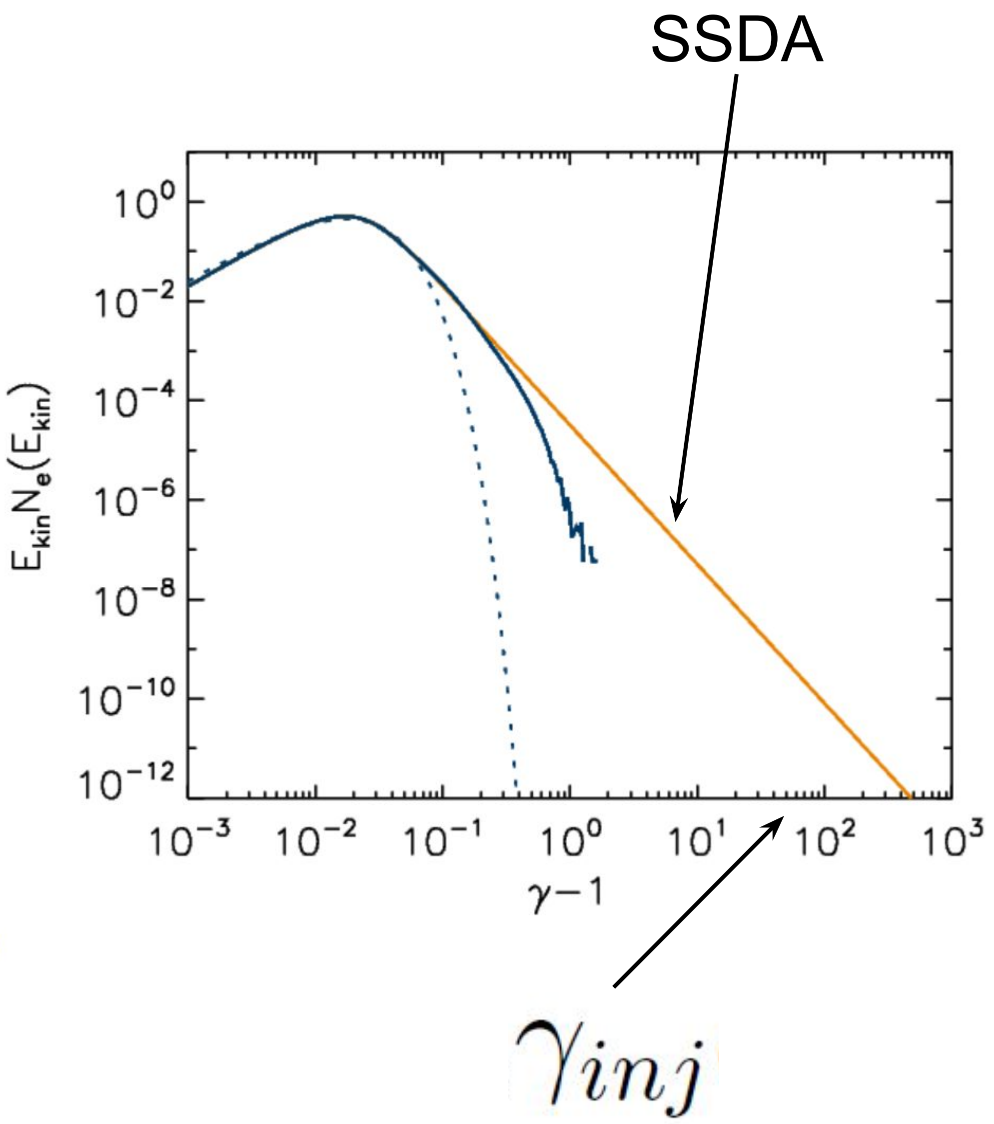


Tycho's SNR: electron injection (simulations)

The downstream electron spectra (3D simulation, blue line) rescaled for realistic parameters. Scaling is based on 2D simulations with m_i/m_e=50-400 and v_{sh}= (0.053-0.263)*c.

Power-law with index -3.8 for electrons produced via SSDA (3D simulation, orange line).

Injection energy for DSA is about γ_{inj}≈50-80.



Injection efficiency:

$$N_{inj}/N_{tot}(simulation) = (0.2 - 2) \cdot 10^{-9}$$

Conclusions

1. Quasi-perpendicular shocks are capable to produce turbulence around the shock transition, but more simulation are needed

2. Electrons potentially can be accelerated up to injection energy, but longer simulations are needed

3. Observational data can be explained by simulation results

Thank you

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

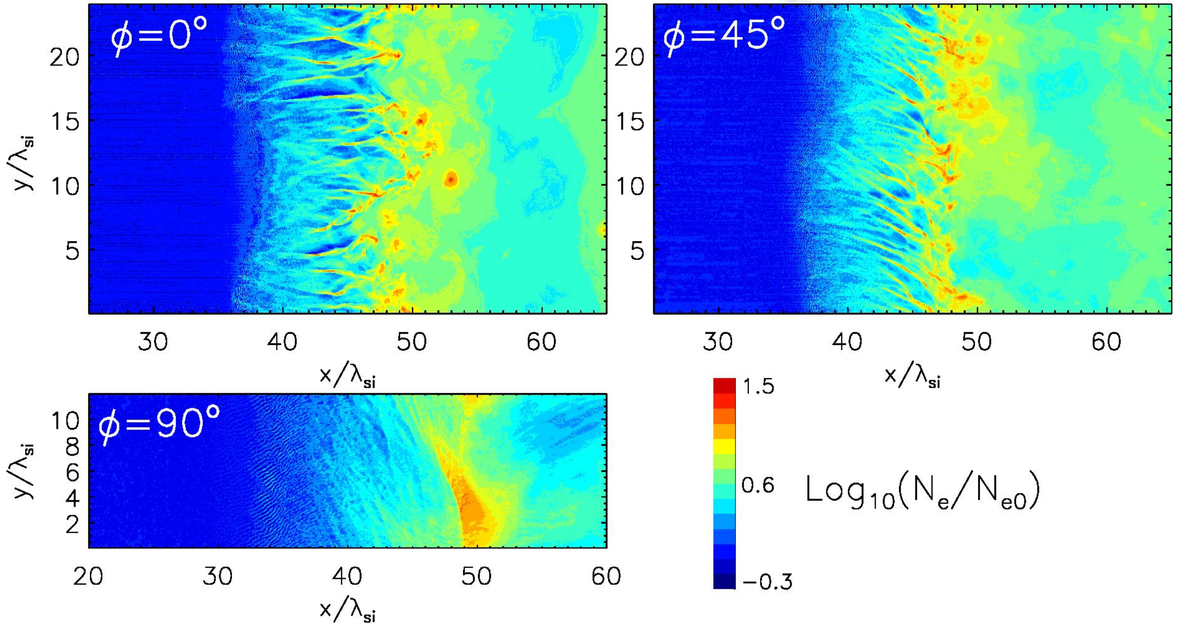
Artem Bohdan
Astroparticle Physics
artem.bohdan@desy.de
+49 33762 7-7193

2D vs 3D PIC simulations

2D: Bohdan et al. (2017)

V_0 = 0.2c
θ = 90°
φ = 0° ; 45° ; 90°
m_i/m_e = 100
M_A = 35

2D simulations reproduce ramp/overshoot region (Weibel instability) with φ=0° and foot region (Buneman instability) with φ=90°



3D: Matsumoto et al. (2017)

V_0 = 0.2c
θ = 74°
φ - not valid
m_i/m_e = 64
M_A = 21