Kinetic studies of particle acceleration in shocks

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Executive summary

- **Good news:** ab-initio simulations show self-consistent injection and acceleration under favorable conditions

- **Not so good news:** all simulations are relatively short and suggest that further evolution is likely

- **Hopeful news:** new multiscale methods are showing promising results in acceleration modeling

- **Coming soon:** Multimessenger astrophysics meets multiscale simulations.

Shocking astrophysics

Astrophysical shocks are typically collisionless (mfp >> shock scales).
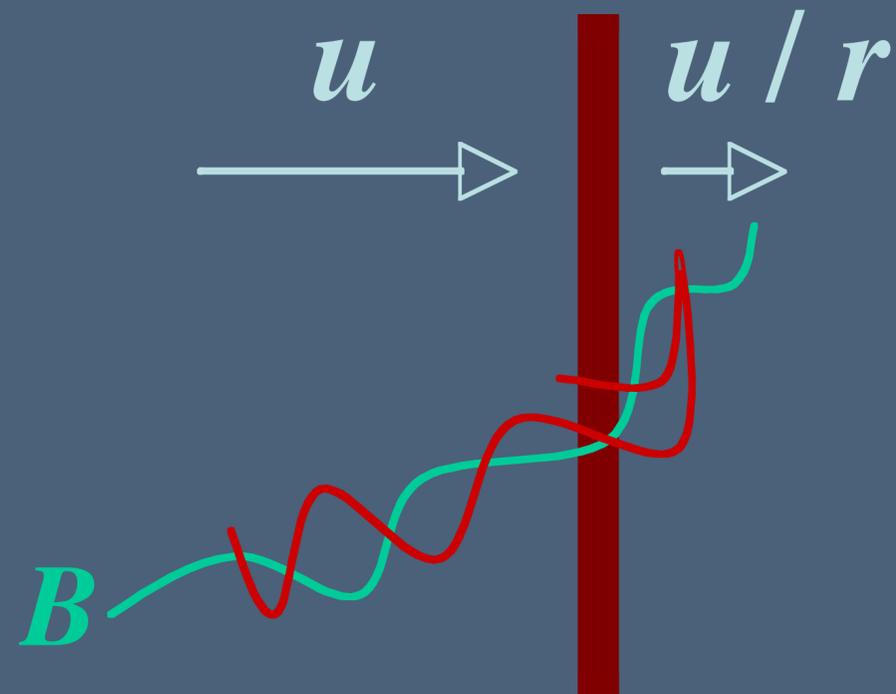Many astrophysical shocks are inferred to:

1) accelerate particles to power-laws
2) amplify magnetic fields
3) exchange energy between electrons and ions

How do they do this? Is it all inevitable?
Inside-out vs top-down

Particle acceleration
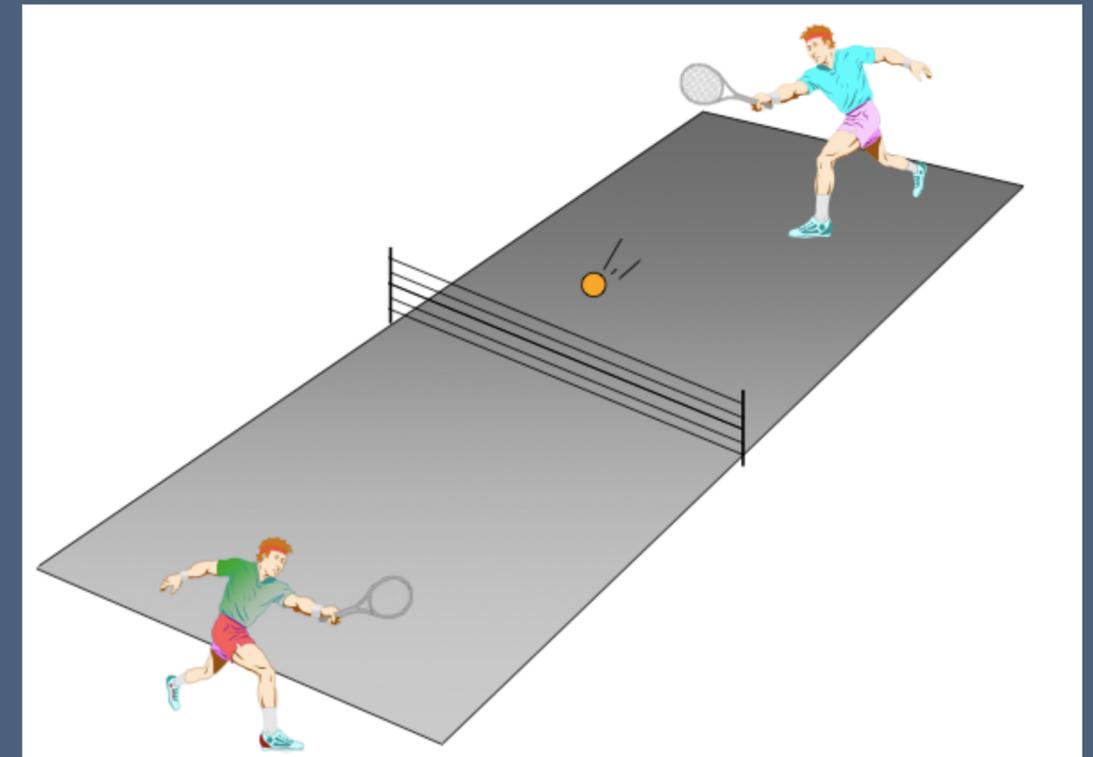
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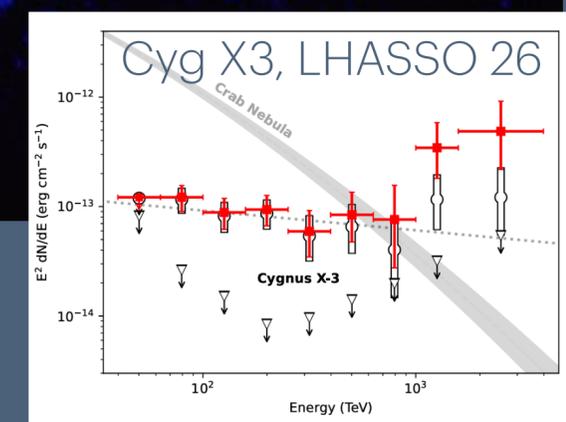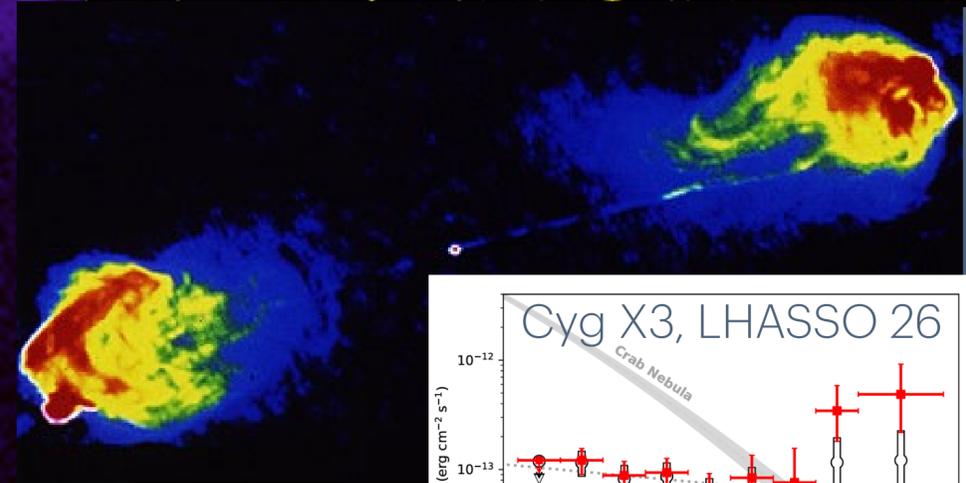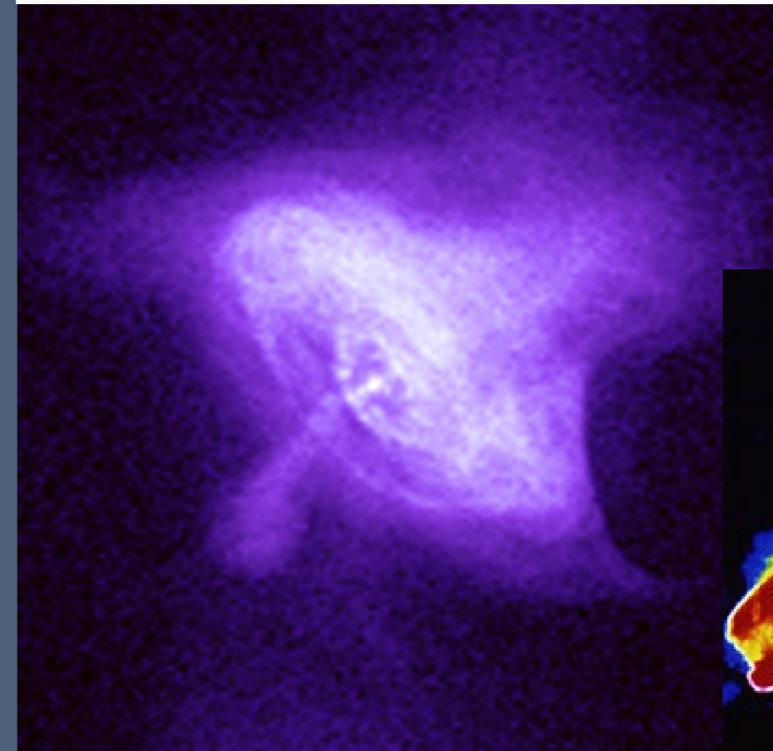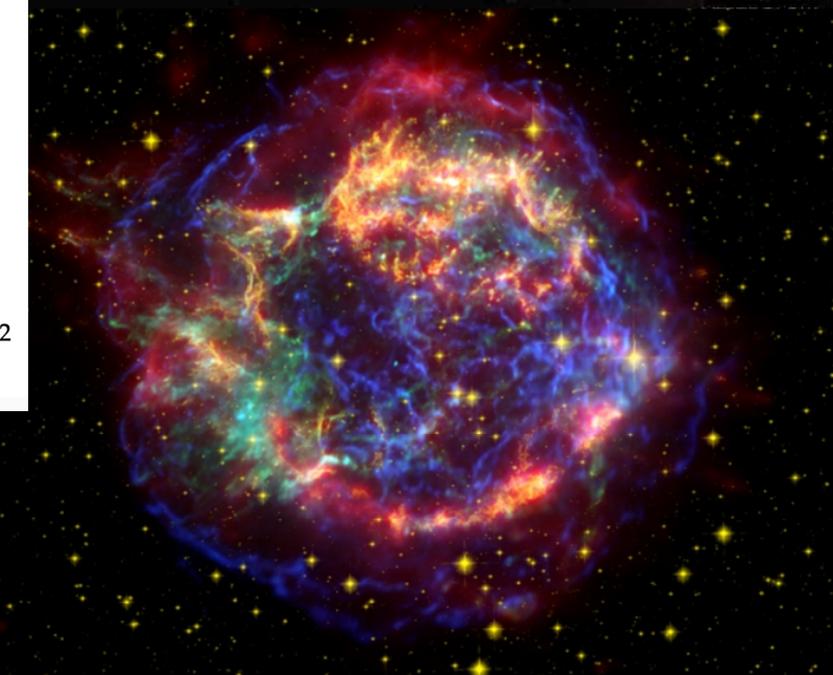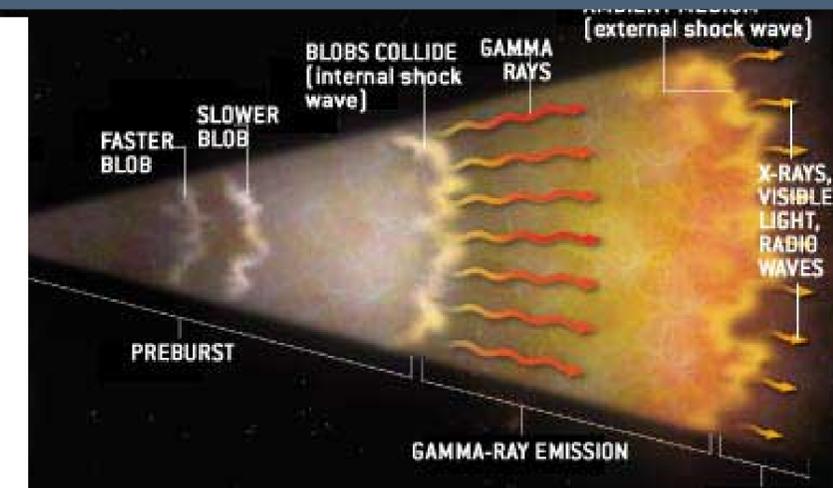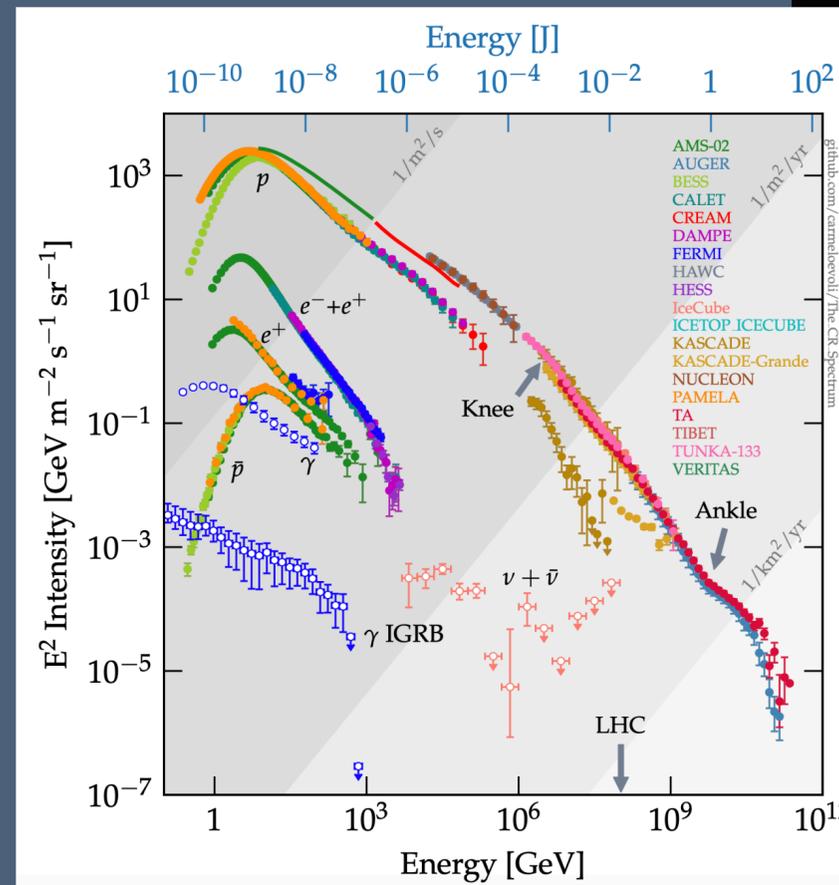
$\Delta E/E \sim v_{shock}/c$

$N(E) \sim N_0 E^{-K(r)}$

Strong shock:
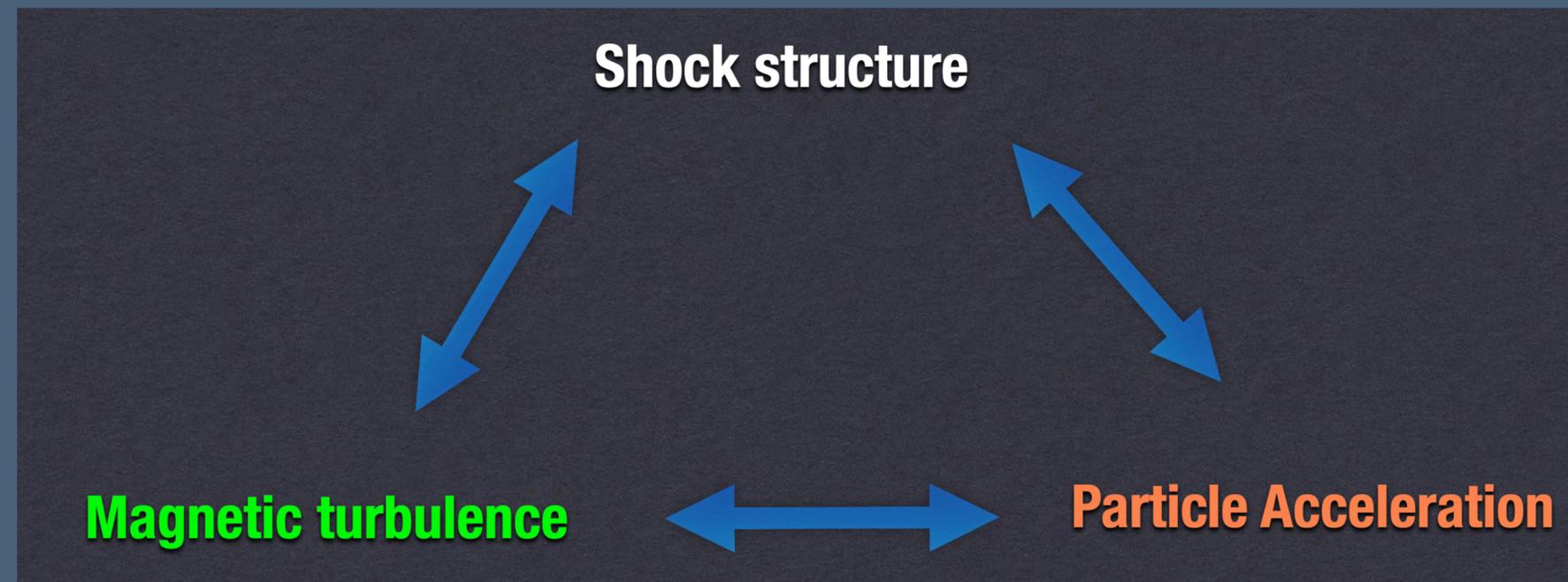$N(E) \sim N_0 E^{-2}$

Equivalently,
$f(p) \sim p^{-4}$

Free energy: converging flows

- Diffusive Shock Acceleration (DSA) — Bell 78, Blandford & Ostriker 78.

- Efficient scattering of particles is required. Particles diffuse around the shock. Advection-diffusion balance in the upstream

- Implies high level of turbulence

Shock structure

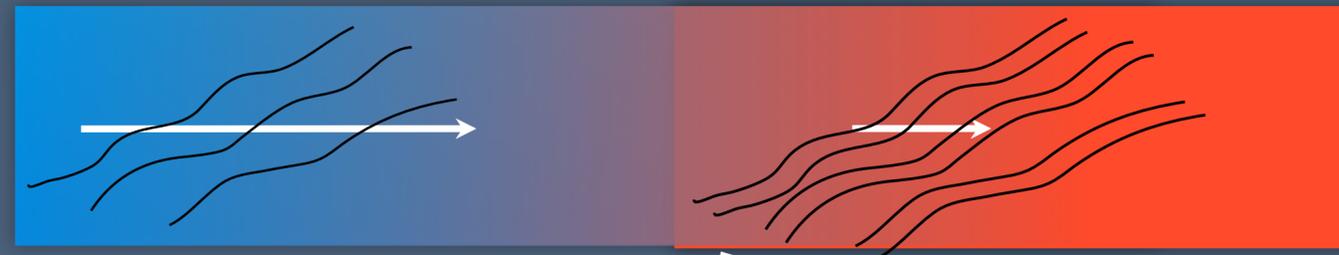**Magnetic turbulence**

Particle Acceleration
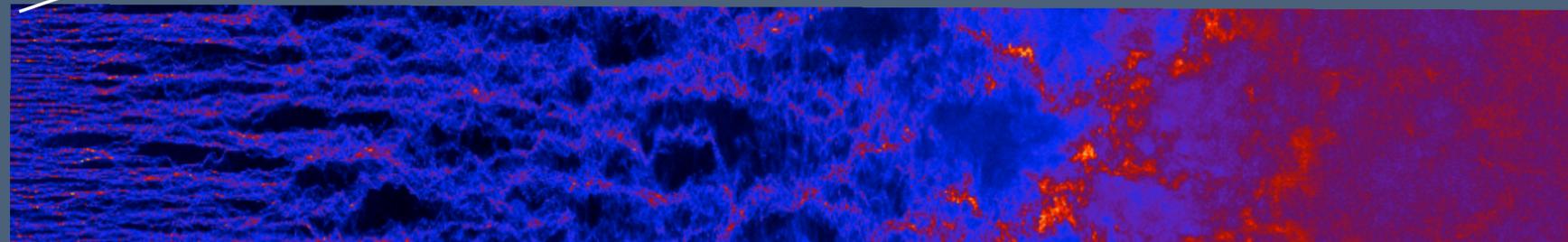
Collisionless shock: nonlinear system

- Complex interplay between micro and macro scales and nonlinear feedback: self-sustaining and replicating

upstream

downstream

Long evolution is often required
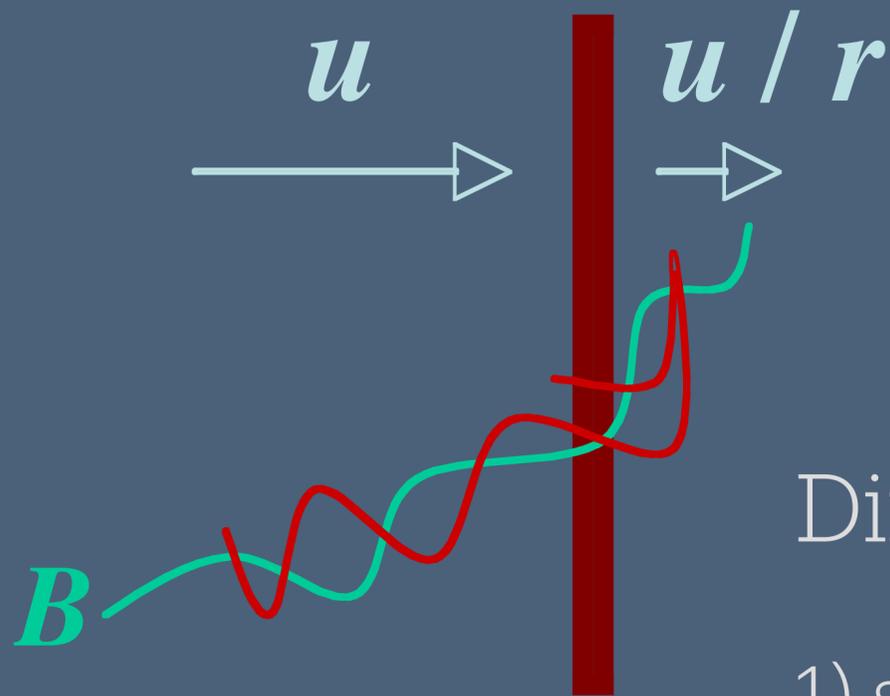
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SHOCK ACCELERATION

Diffusive shock acceleration (DSA) predictions

1) self-generated turbulence, resulting in diffusion of particles in the upstream, balanced by advection towards the shock

2) universal p^{-4} spectrum downstream (for nonrel strong shocks)

3) injection fraction for e and p not known — determined by microphysics?

4) nonlinear effects (backreaction on the flow)

We check these with a suite of kinetic simulations

Plasma physics on computers

- **Full particle in cell**: TRISTAN-MP code
  (Spitkovsky 2008, Niemiec+2008, Stroman+2009, Amano & Hoshino 2007-2010, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park+2012, Niemiec+2012, Guo+14,...)

  - Define electromagnetic field on a grid

  - Move particles via Lorentz force

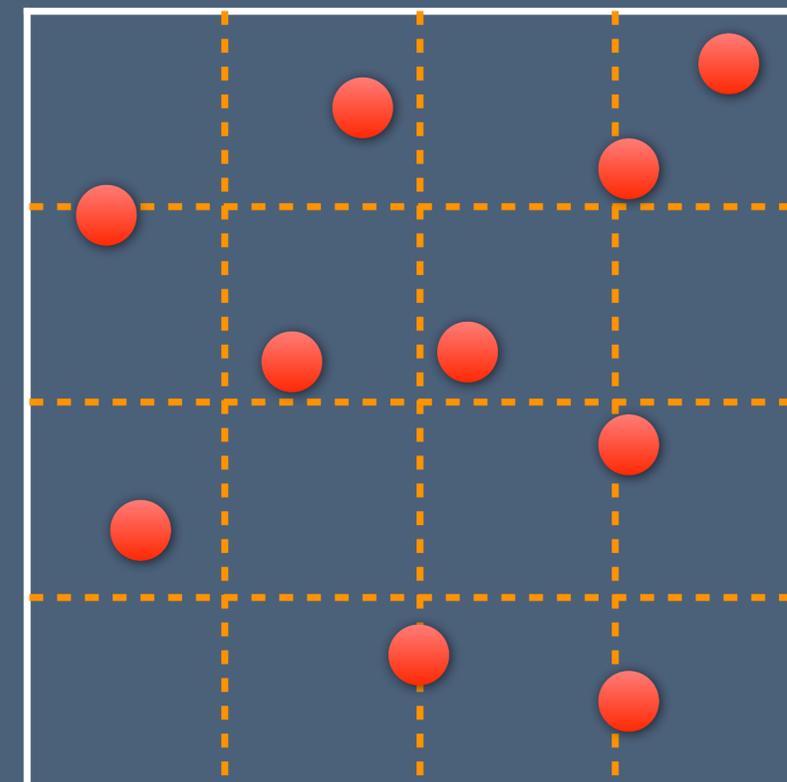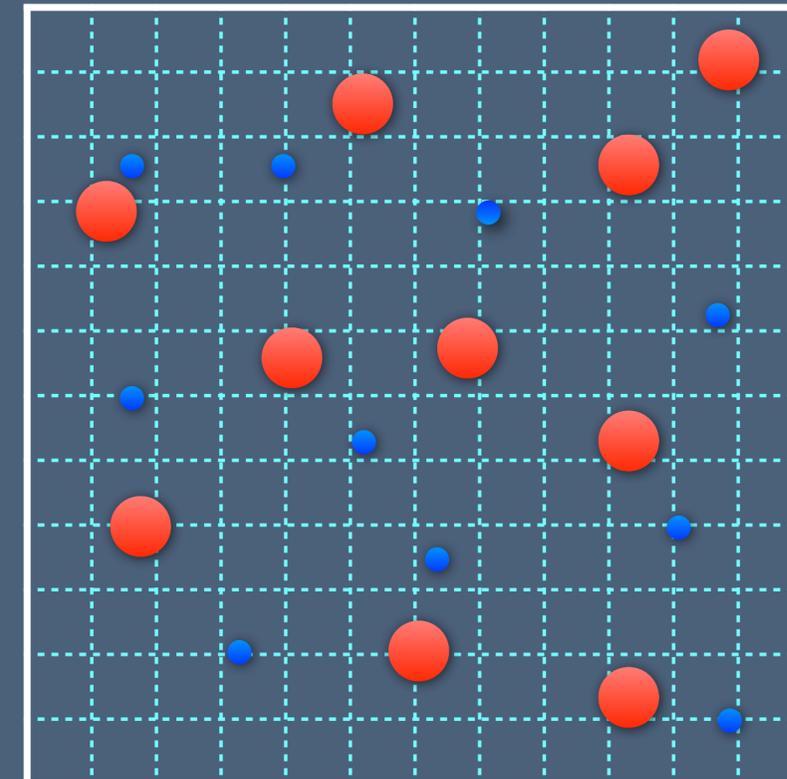 - Evolve fields via Maxwell equations

  - Computationally expensive!

- **Hybrid approach**: dHybrid code
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, Caprioli & Spitkovsky 2013, 2014)

  - massless electrons for more macroscopic time/length scales

Characteristic time and length scales

$$\omega_P = \left(\frac{4\pi \, ne^2}{m} \right)^{1/2}$$

$$\lambda_D = \frac{V_{thermal}}{\omega_p} \propto \left(\frac{T}{n} \right)^{1/2}$$

$$\lambda_{skin} = c/\omega_p$$

$$\omega_c = \frac{eB}{mc}$$

Plasma frequency   Debye length   skin depth   Larmor
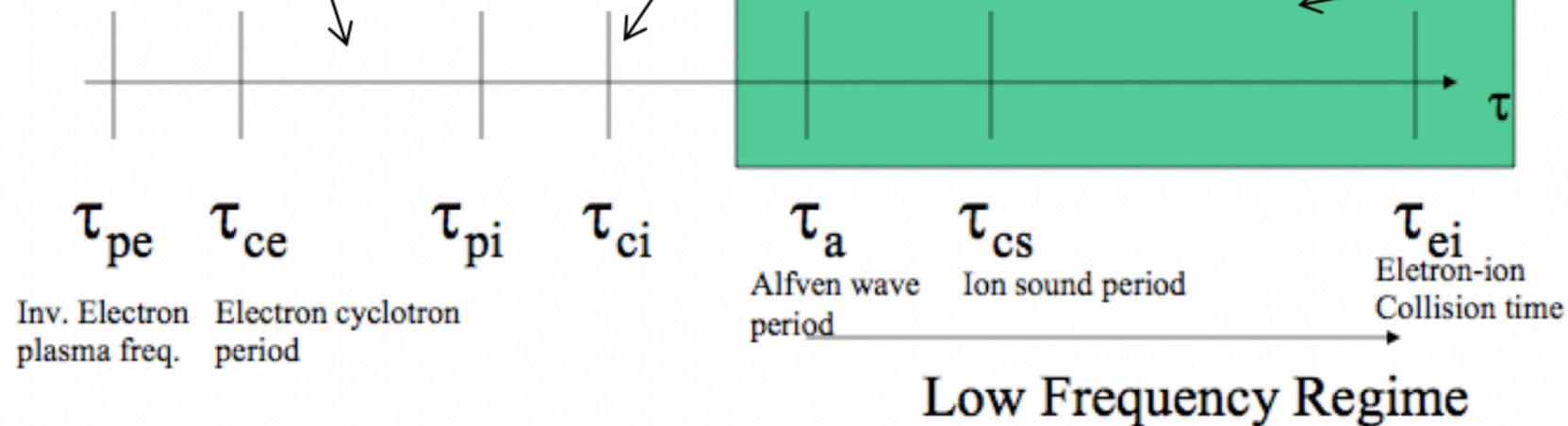
$$\frac{c}{\omega_p} = 5 \times 10^5 \left(\frac{n}{1\text{cm}^{-3}} \right)^{\frac{1}{2}} \text{cm}$$

$$\frac{1}{\omega_p} = 1.8 \times 10^{-5} \left(\frac{n}{1\text{cm}^{-3}} \right)^{\frac{1}{2}} \text{s}$$

Full kinetic models   Hybrid models   Fluid models

•Time Scales

τ_{pe} τ_{ce} τ_{pi} τ_{ci} τ_a τ_{cs} τ_{ei}

Inv. Electron   Electron cyclotron   Alfven wave   Ion sound period   Eletron-ion
plasma freq.   period   period   Collision time

Low Frequency Regime

•Length Scales

λ_{De} ρ_e c/ω_{pe} ρ_s ρ_i c/ω_{pi} L_n L_J L

where $\rho_s = \sqrt{\frac{T_i}{T_i}}\rho_i$ where $L_n = |\nabla n/n|^{-1}$

Parameter Space of shocks

$$\sigma \equiv \frac{B^2/4\pi}{(\gamma-1)nmc^2} = \frac{2}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$

$$M_A = \frac{v}{v_A} \qquad M_s = \frac{v}{v_{th}} \qquad \beta = \frac{M_A^2}{M_s^2} \qquad \frac{m_i}{m_e}$$
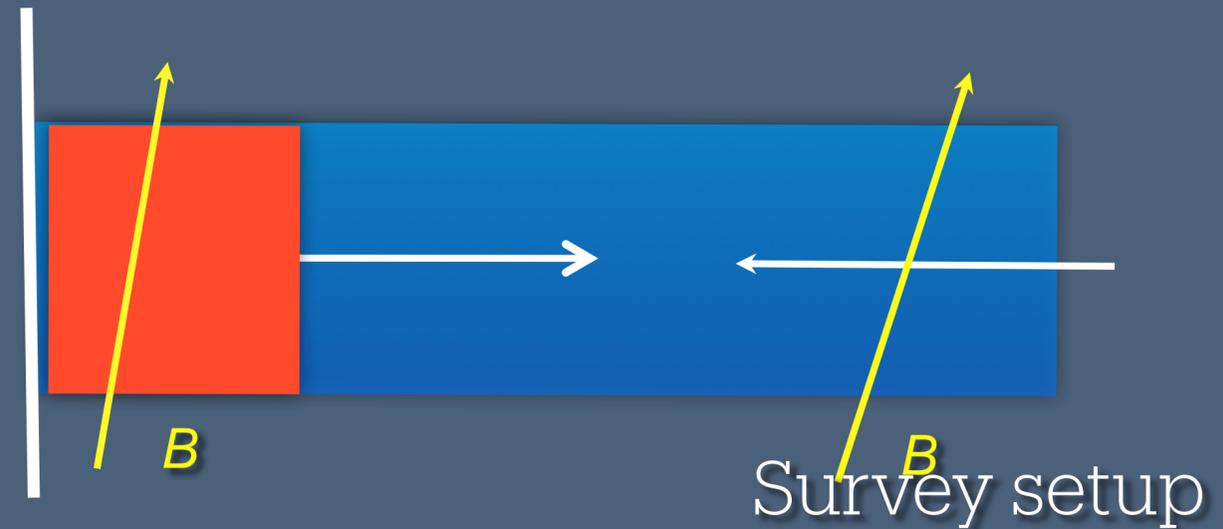
In Solar wind: beta < 1, $M_s = M_A = 1\text{-}10$

In ISM: beta ~ 1, $M_s = M_A$, $c_s \sim v_A \sim 10$ km/s
SNRs: v=2000-30000+ km/s, $M_s = M_A = 100\text{-}1500$; With B amplification M_A can decrease to 10-30.
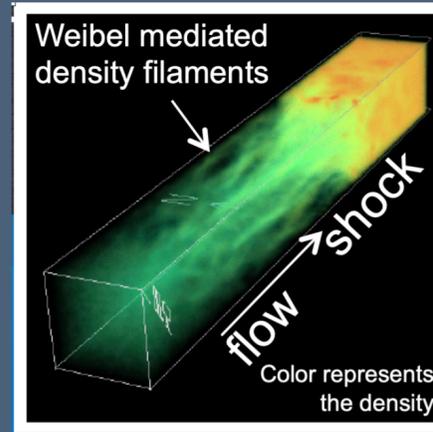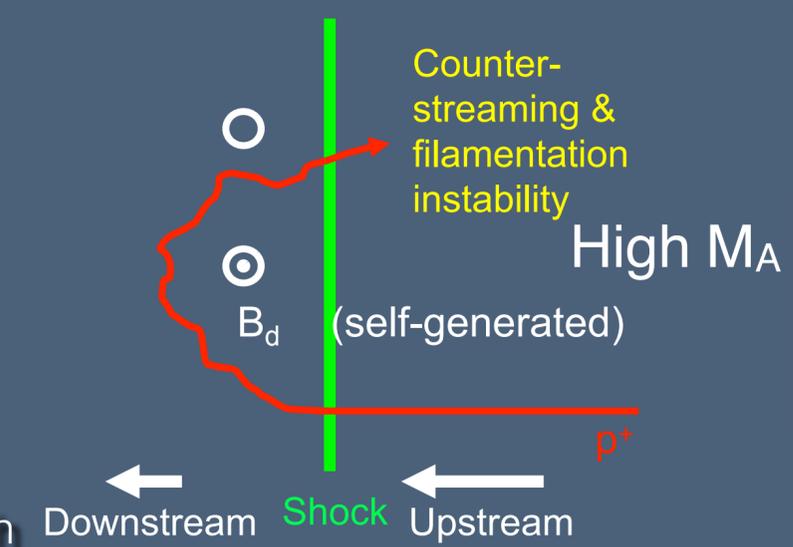
GRBs: $\Gamma \approx 100, \ \sigma < 10^{-6}$
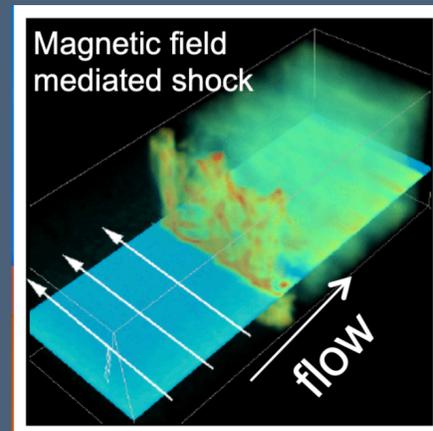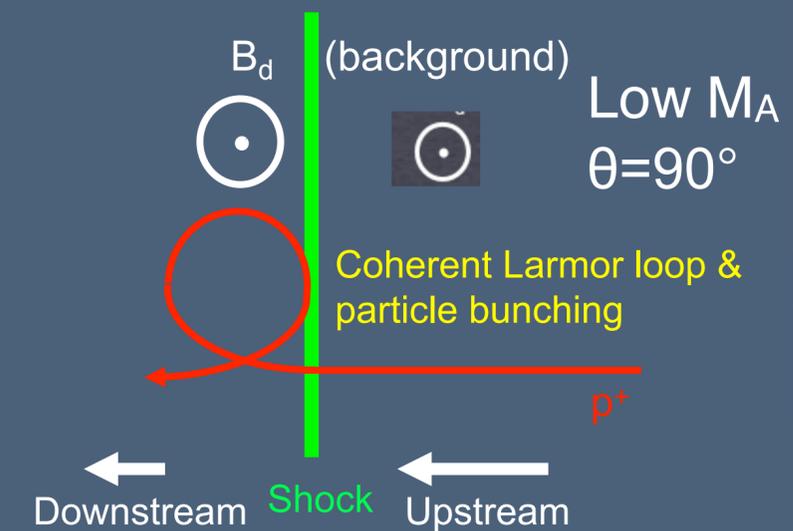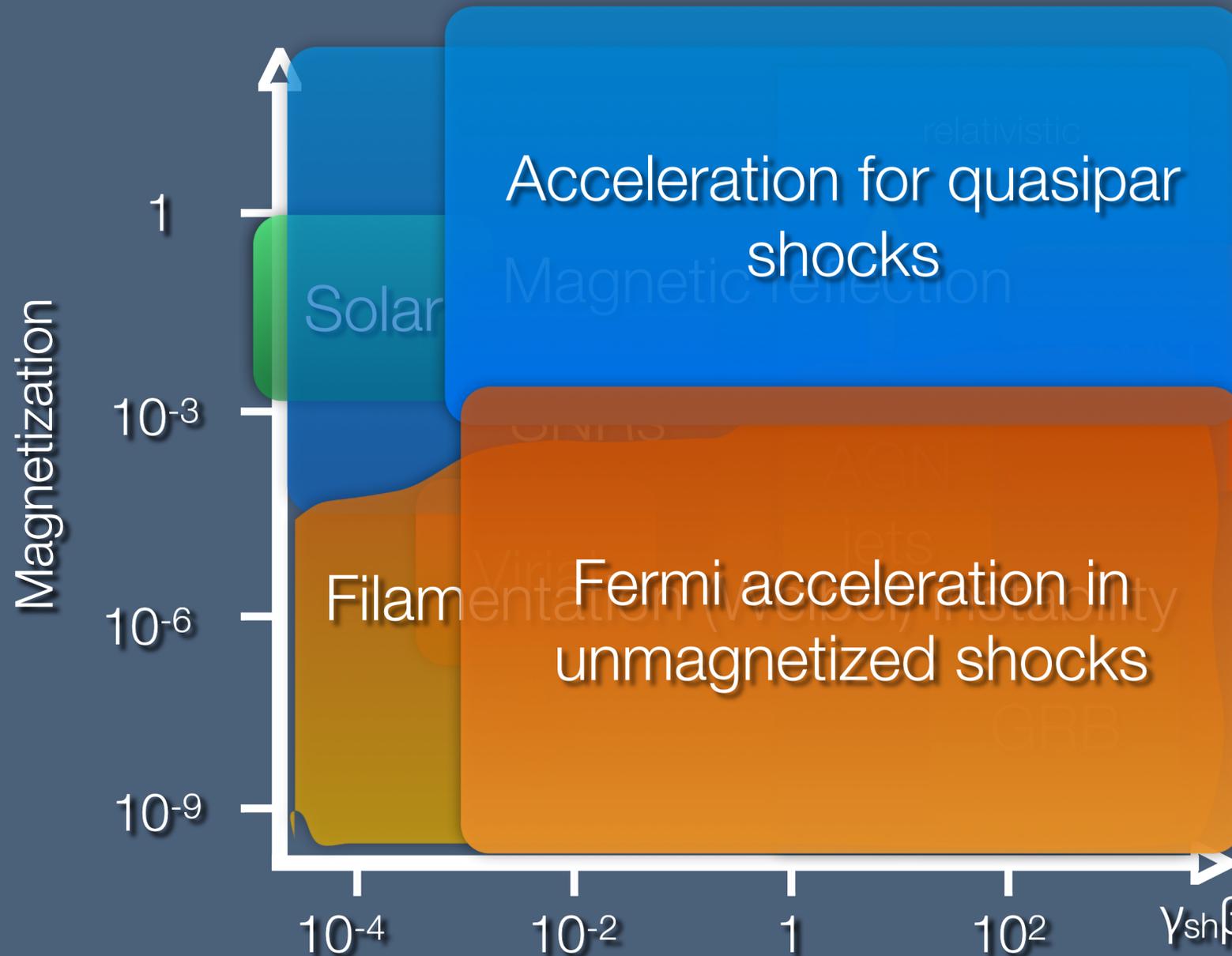

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Survey setup

Field orientation:
can be anything in viral shocks and SNRs, mostly transverse in jets.

Parameter Space of shocks

Magnetization $\quad \sigma \equiv \dfrac{B^2/4\pi}{(\gamma-1)nmc^2} = \dfrac{1}{M_A^2} = \left(\dfrac{\omega_c}{\omega_p}\right)^2\left(\dfrac{c}{v}\right)^2 = \left[\dfrac{c/\omega_p}{R_L}\right]^2$

Acceleration for quasipar shocks

Magnetic reflection

Solar

relativistic

Magnetization

10⁻³

10⁻⁶

10⁻⁹

Filam

Fermi acceleration in unmagnetized shocks

entation (Weibel) instability

Virt

jets

AGN

GRB

10⁻⁴   10⁻²   1   10²   γ_sh β_sh

B_d (background)

Low M_A
θ=90°

Coherent Larmor loop & particle bunching

p⁺

Downstream   Shock   Upstream

Magnetic field mediated shock

flow

Counter-streaming & filamentation instability

High M_A

B_d (self-generated)

p⁺

Downstream   Shock   Upstream

Weibel mediated density filaments

shock
flow

Color represents the density

Shock Acceleration

Two crucial ingredients:

1) ability of a shock to reflect particles back into the upstream (injection)

2) ability of these particles to scatter and return to the shock (pre-existing or generated turbulence). Instabilities: resonant, non-resonant (Bell), Weibel

Magnetic obliquity and field strength determine whether a shock accelerates

Generally, parallel shocks are good for both ion and electron acceleration, while quasi-perpendicular shocks mainly accelerate electrons.
There are many sub-regimes, not fully mapped yet.

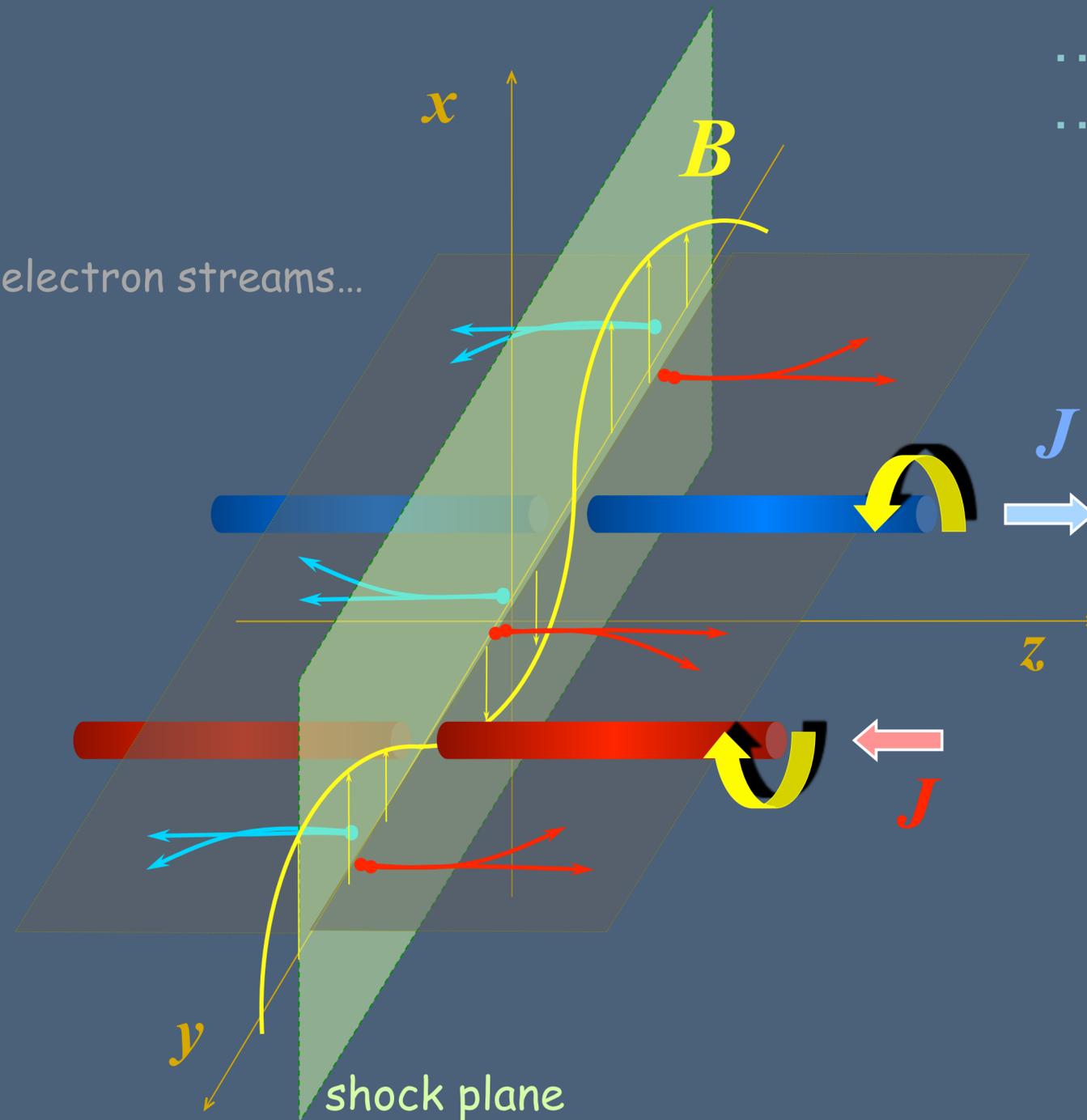# Structure of an unmagnetized relativistic pair shock

(AS 2008)
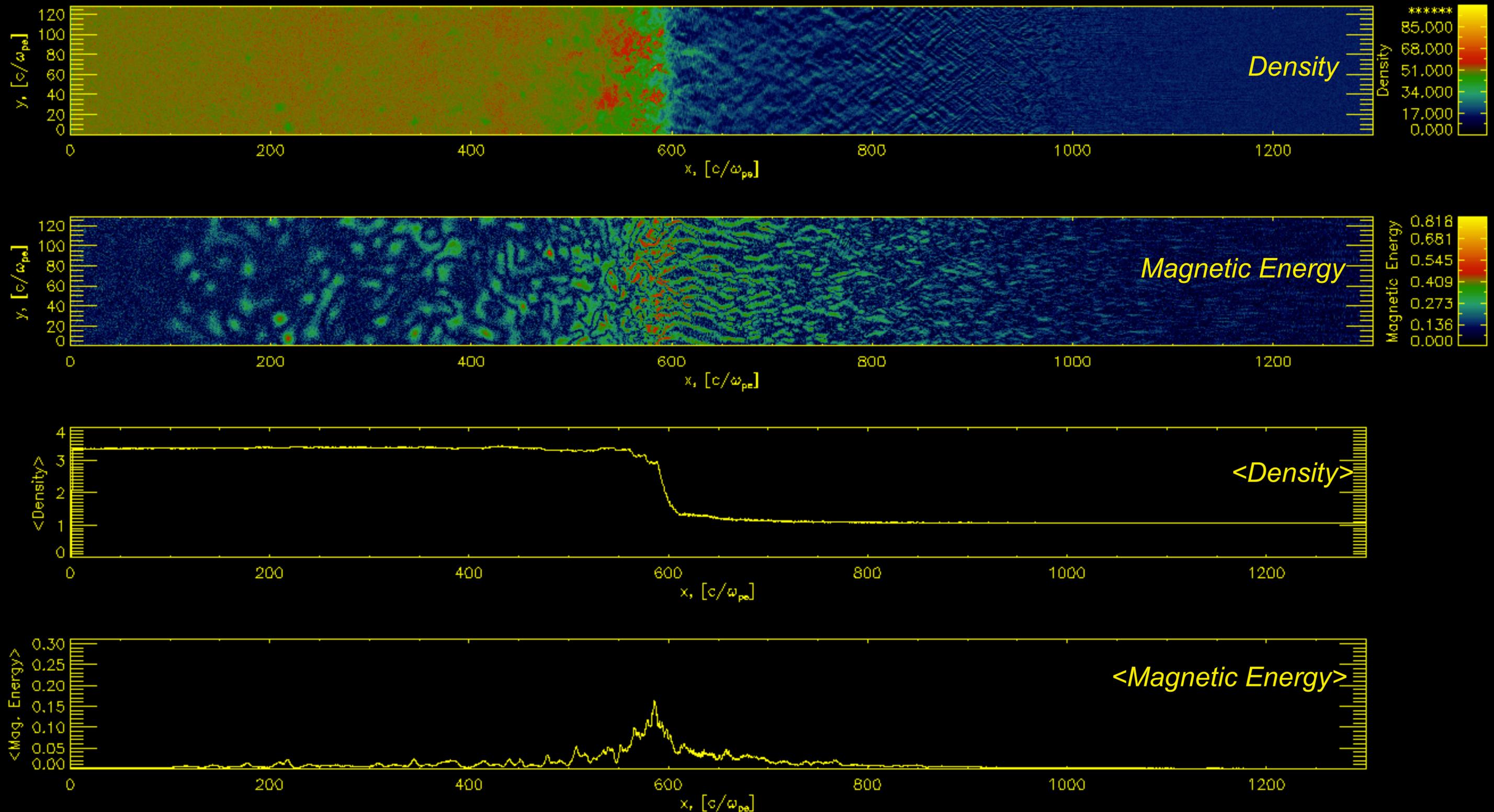
Weibel instability

… current filamentation …
… B – field is generated …

For electron streams…

x

B

J

z

J

y

shock plane

$$\Gamma^2_{max} \simeq \frac{\omega_p^2}{\gamma} \qquad k^2_{max} \simeq \frac{1}{\sqrt{2}} \frac{\omega_p^2}{\gamma_\perp c^2}$$

Structure of an unmagnetized relativistic pair shock

Magnetic energy in 3D.

Filaments on skin depth scale c/ω_p
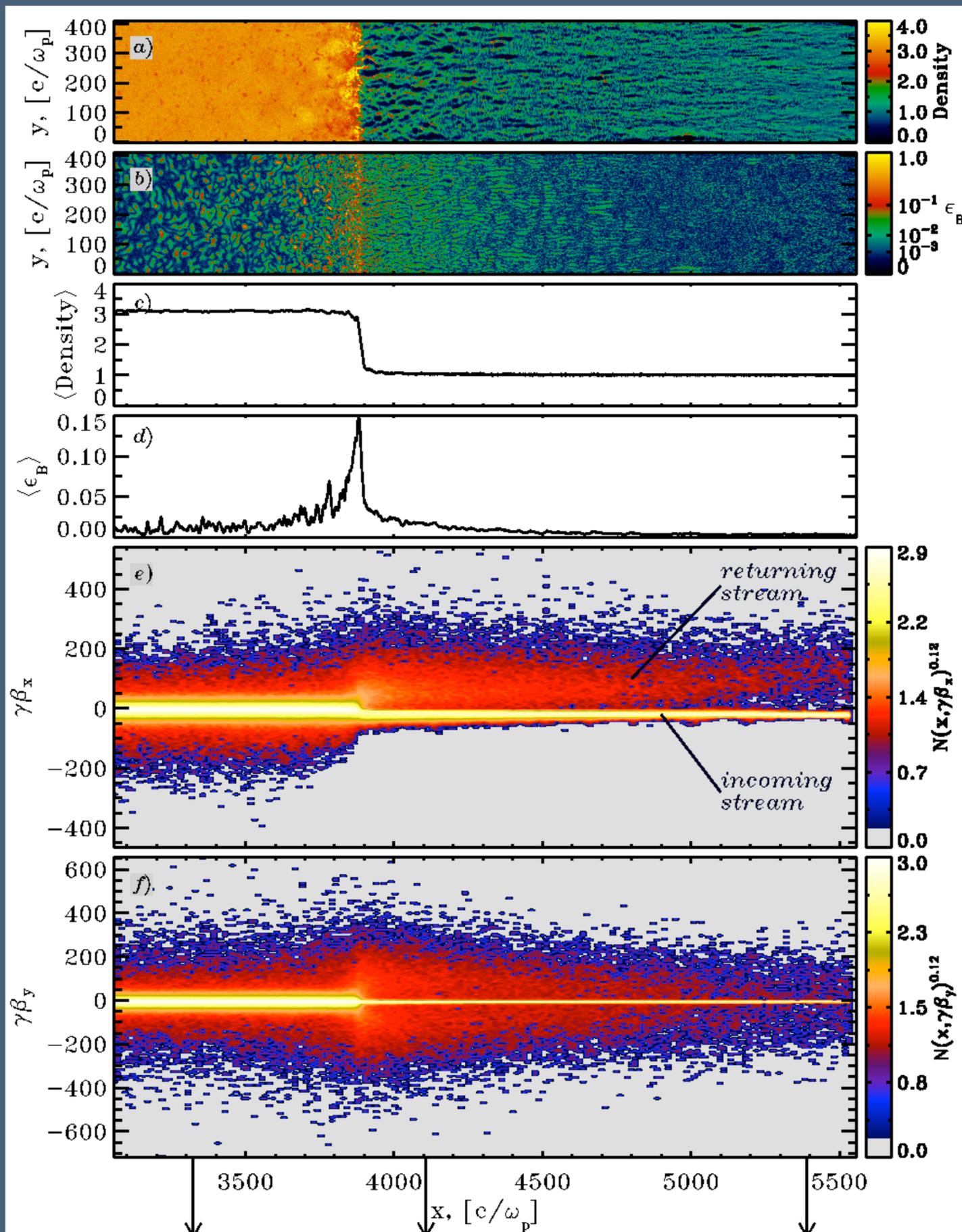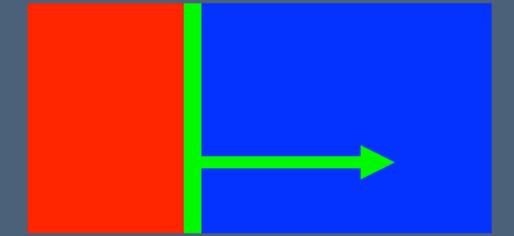
Density

Shock formation from counterstreaming

shock is driven by returning particle precursor
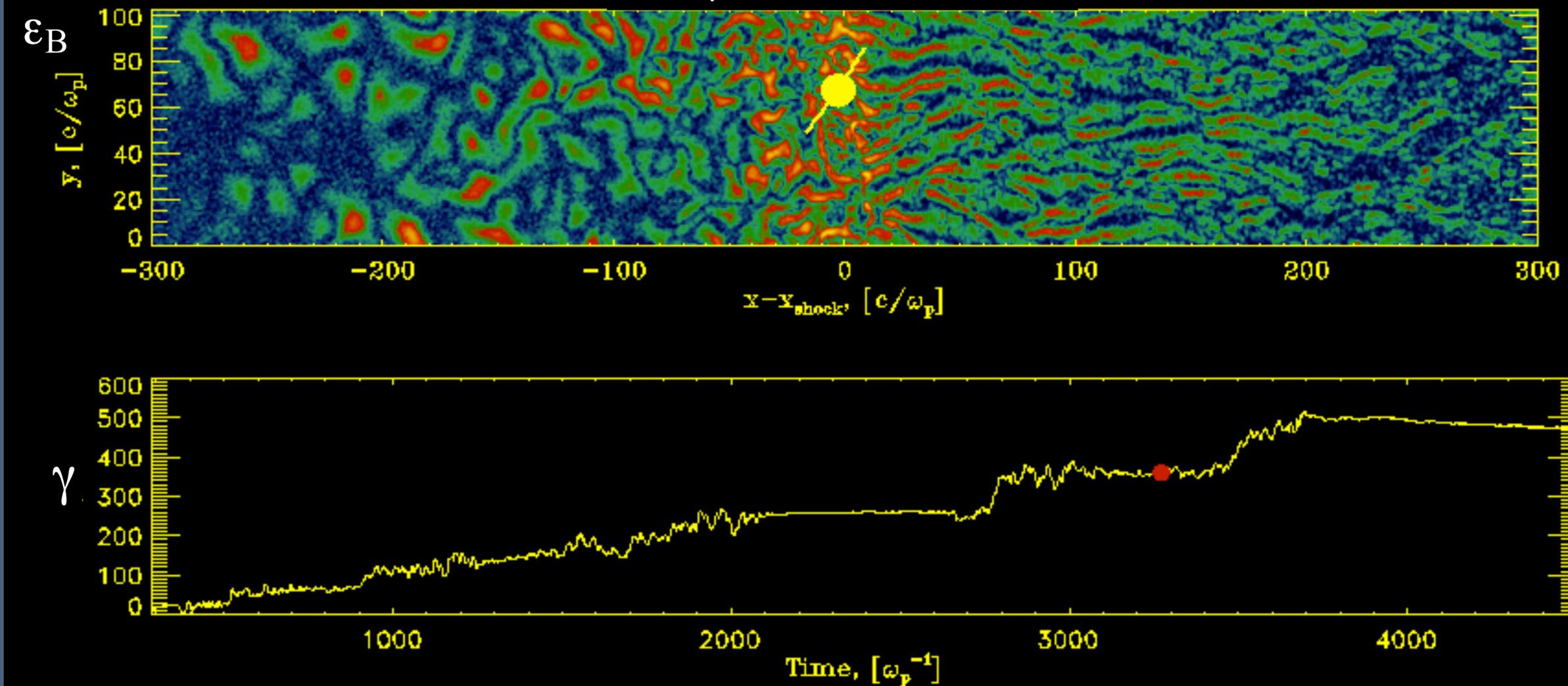
x- px momentum space

x- py momentum space

Shock structure for σ=0 (AS '08)

Acceleration in self-generated turbulence

Fermi process from first principles: particles scatter off magnetic
turbulence produced self-consistently as part of the shock evolution

σ=0 γ₀=15 e⁻-e⁺ shock

Perpendicular vs parallel shocks

- Quasi-perpendicular shocks: mediated by magnetic reflection

Shock

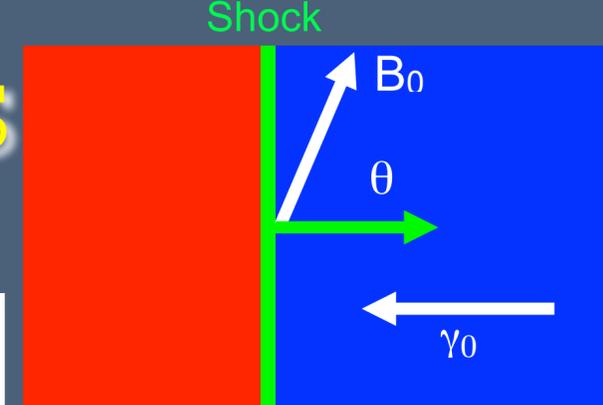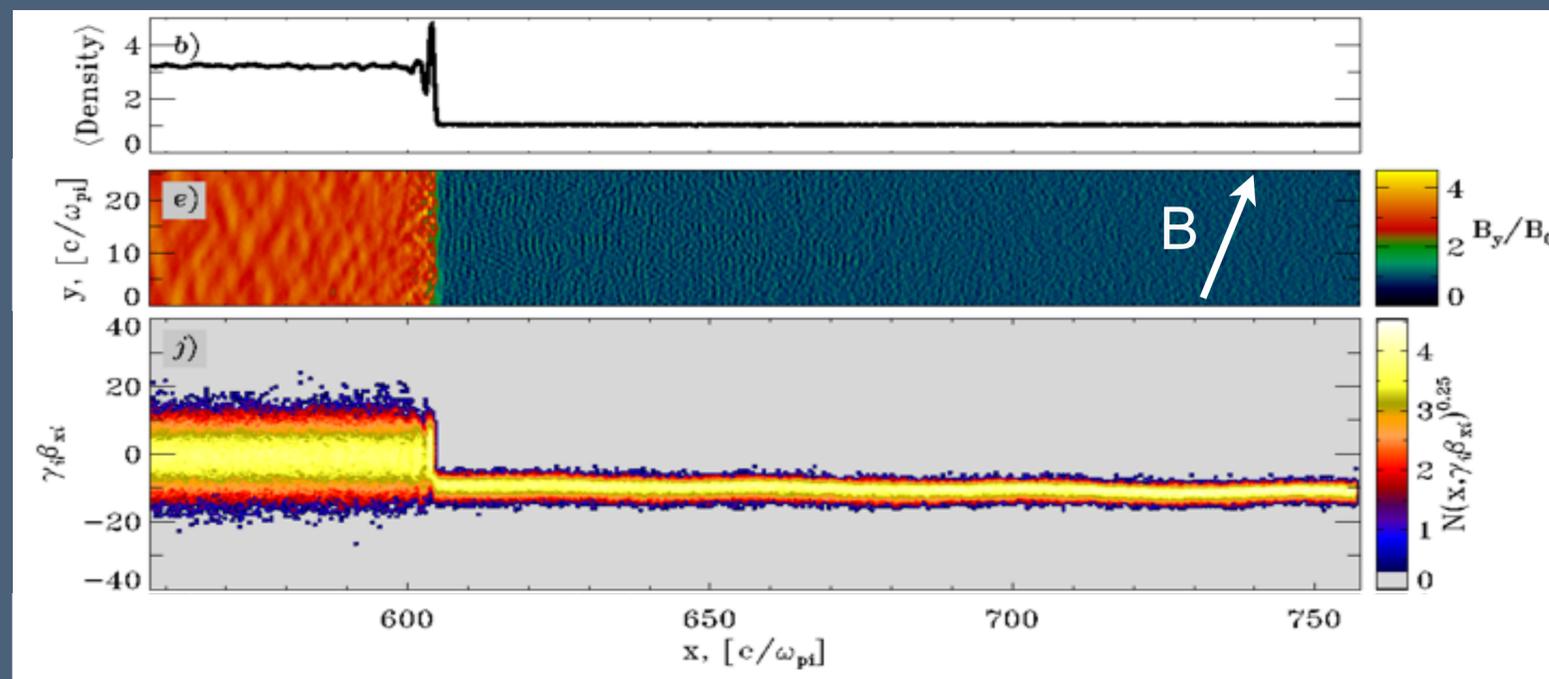B₀

θ

γ₀

Downstream   Upstream

<Density>

σ=0.1

θ=75°

γ₀=15

e⁻-p⁺

B

Bᵧ

γβₓ

- Quasi-parallel shocks: instabilities amplify transverse field component

<Density>

σ=0.1

θ=15°

γ₀=15

e⁻-p⁺

Bᵧ

B

returning stream

incoming stream
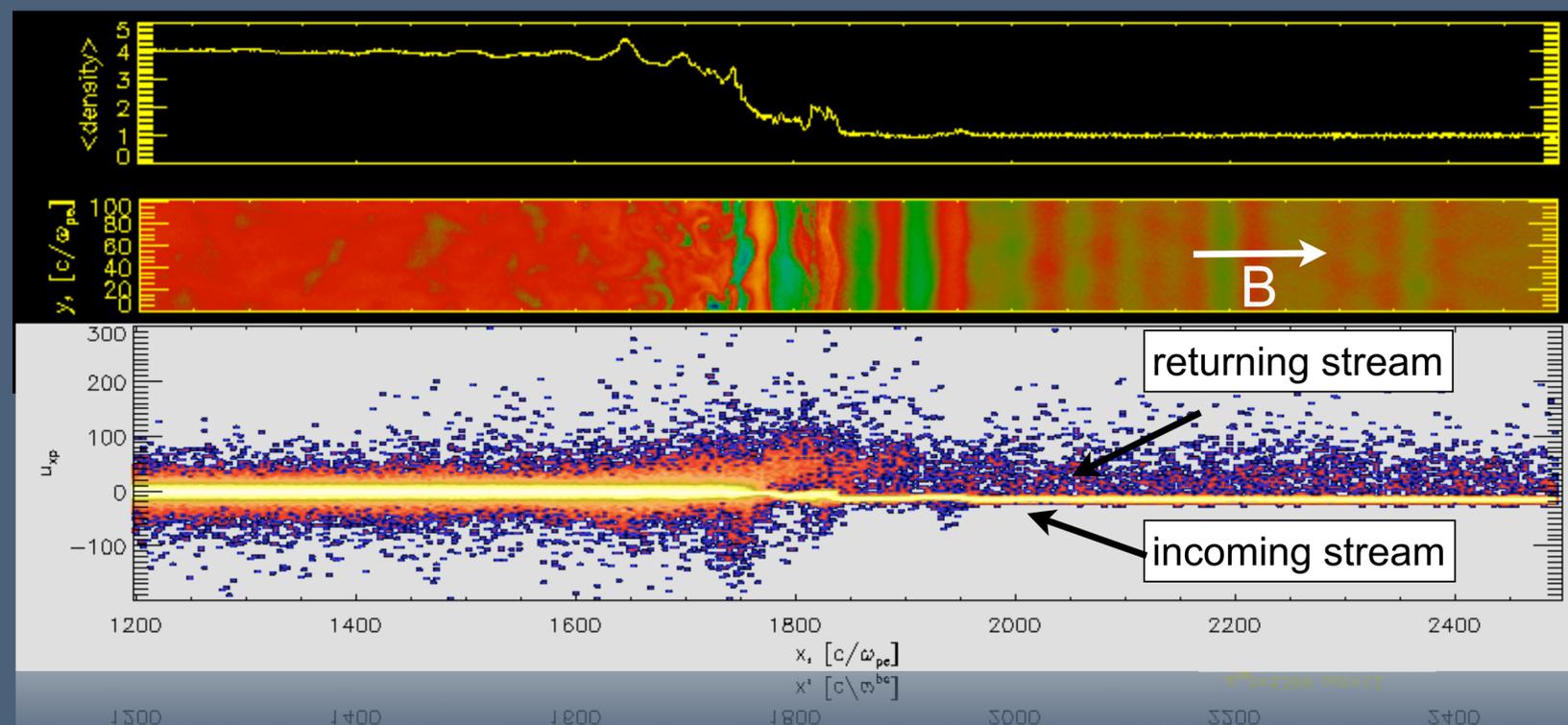
γβₓ

(Sironi & AS 11)

Relativistic shock acceleration

Sironi & AS 09

$N(E) \sim E^{-2.4}$;

1% by number, ~10% by energy.

Unmagnetized

Magnetized

superluminal

$\theta = 0°$
$\theta = 15°$
$\theta = 30°$
$\theta = 45°$

45° 30° 0° 15°

$\theta \sim 0°$
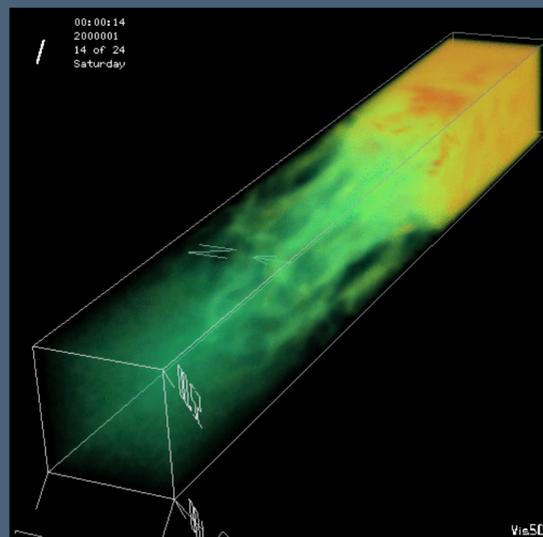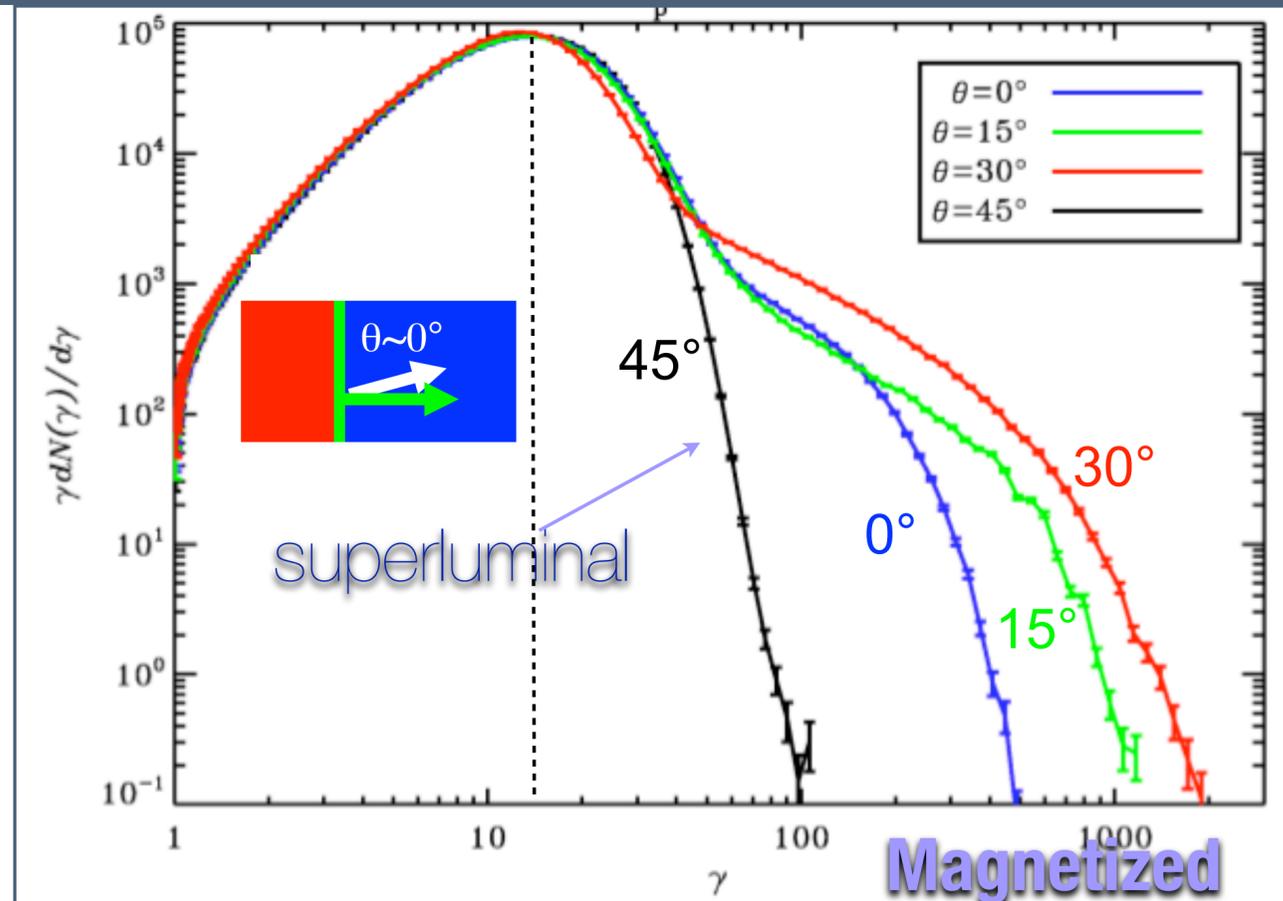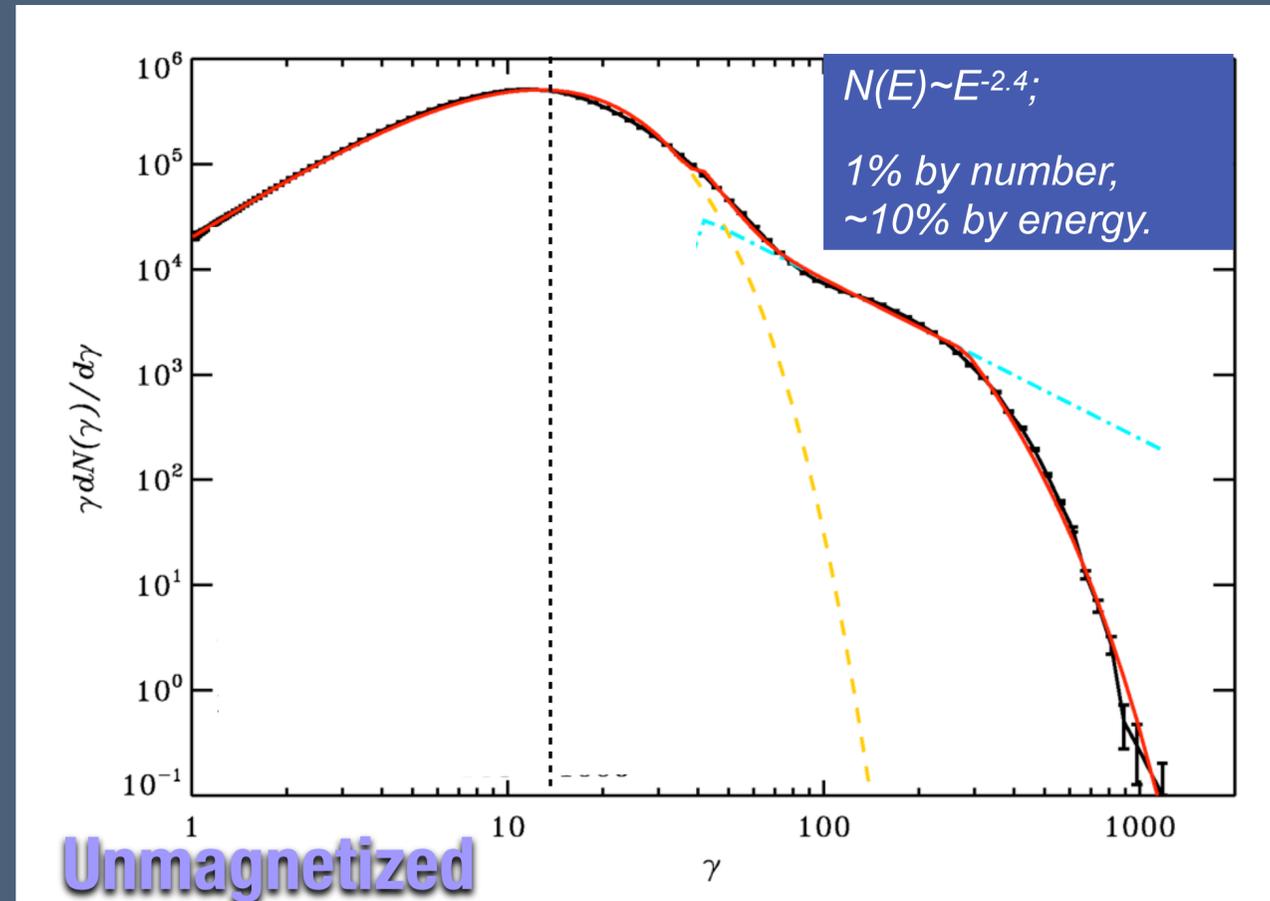
Conditions for acceleration in relativistic shocks:

low magnetization of the flow

or quasi-parallel B field ($\theta < 34°/\Gamma$);

electrons & ions behave similarly

B

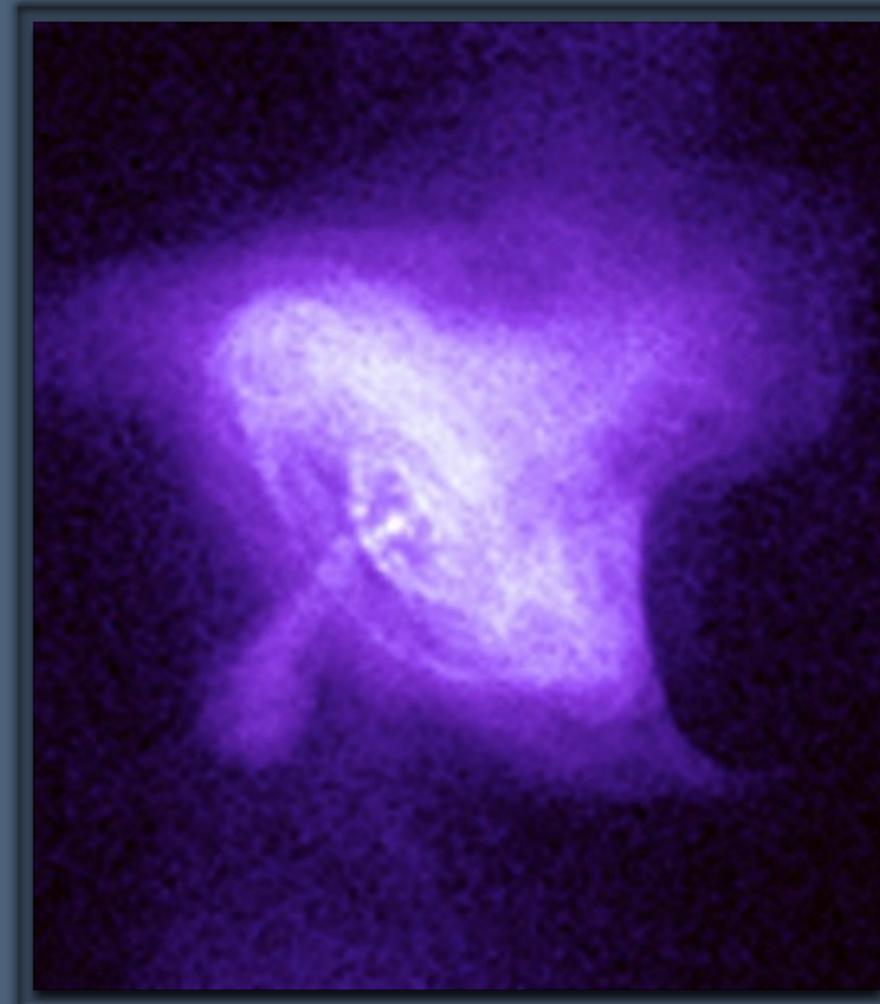$\theta_{crit} \approx 34$
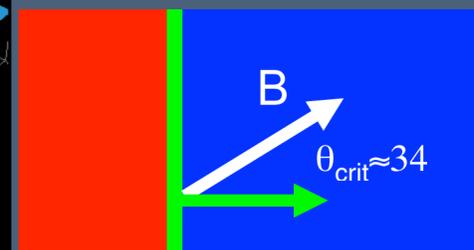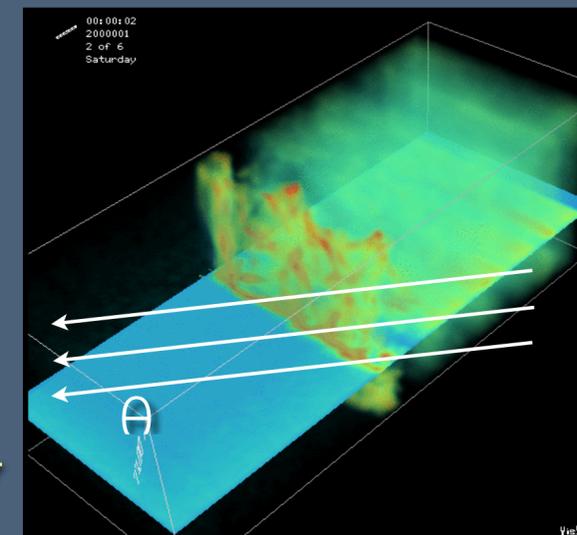
Astrophysical implications

- Pulsar Wind Nebulae

  Toroidal magnetic geometry will accelerate particles if field is weak at the shock

  Implies efficient magnetic dissipation in the wind

  Low equatorial magnetization -- consistent with PWN morphology

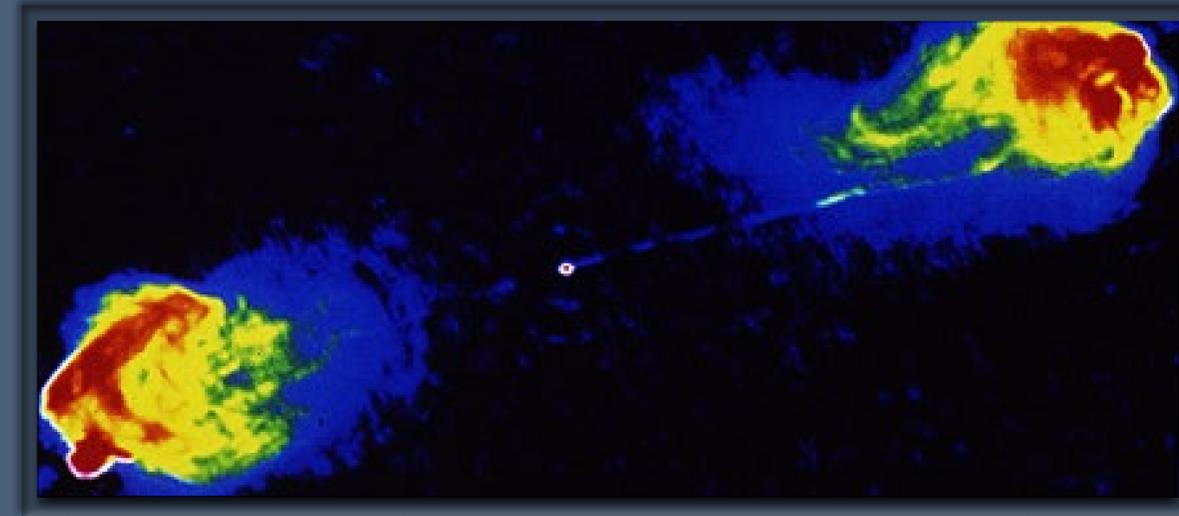 Alternative: magnetic dissipation at the shock (reconnection/striped winds)

Astrophysical implications

- AGN Jets

  High magnetization toroidal field
  configuration is disfavored

  Either magnetic field is dissipated
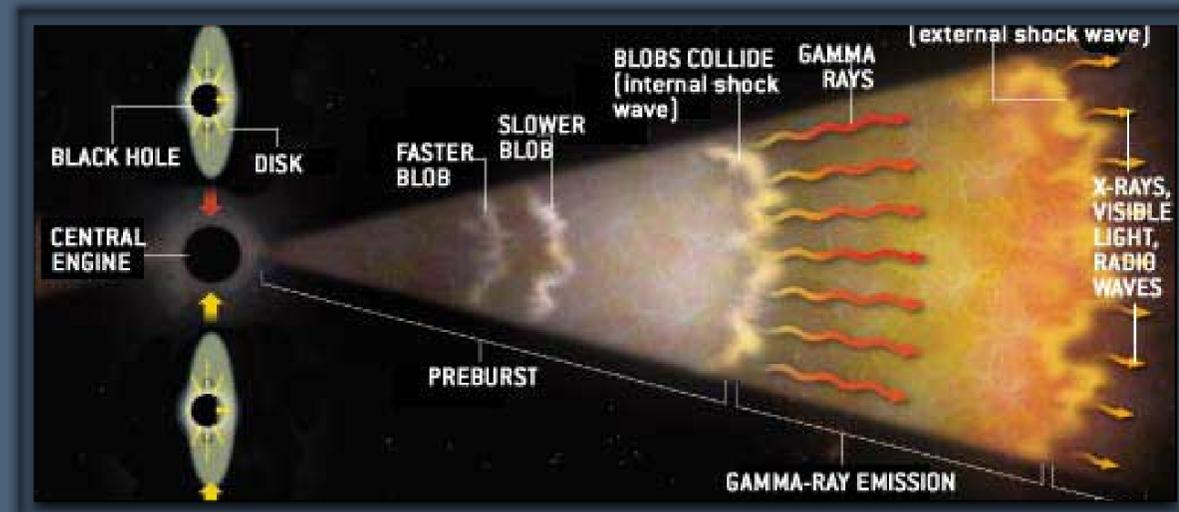 in the process of acceleration,

  or field is reoriented to lie along
  the flow (sheath vs spine flows?)

- GRB jets

  Low magnetization external
  shocks can work; Field survival?
  GeV emission too early?

  Efficient electron heating
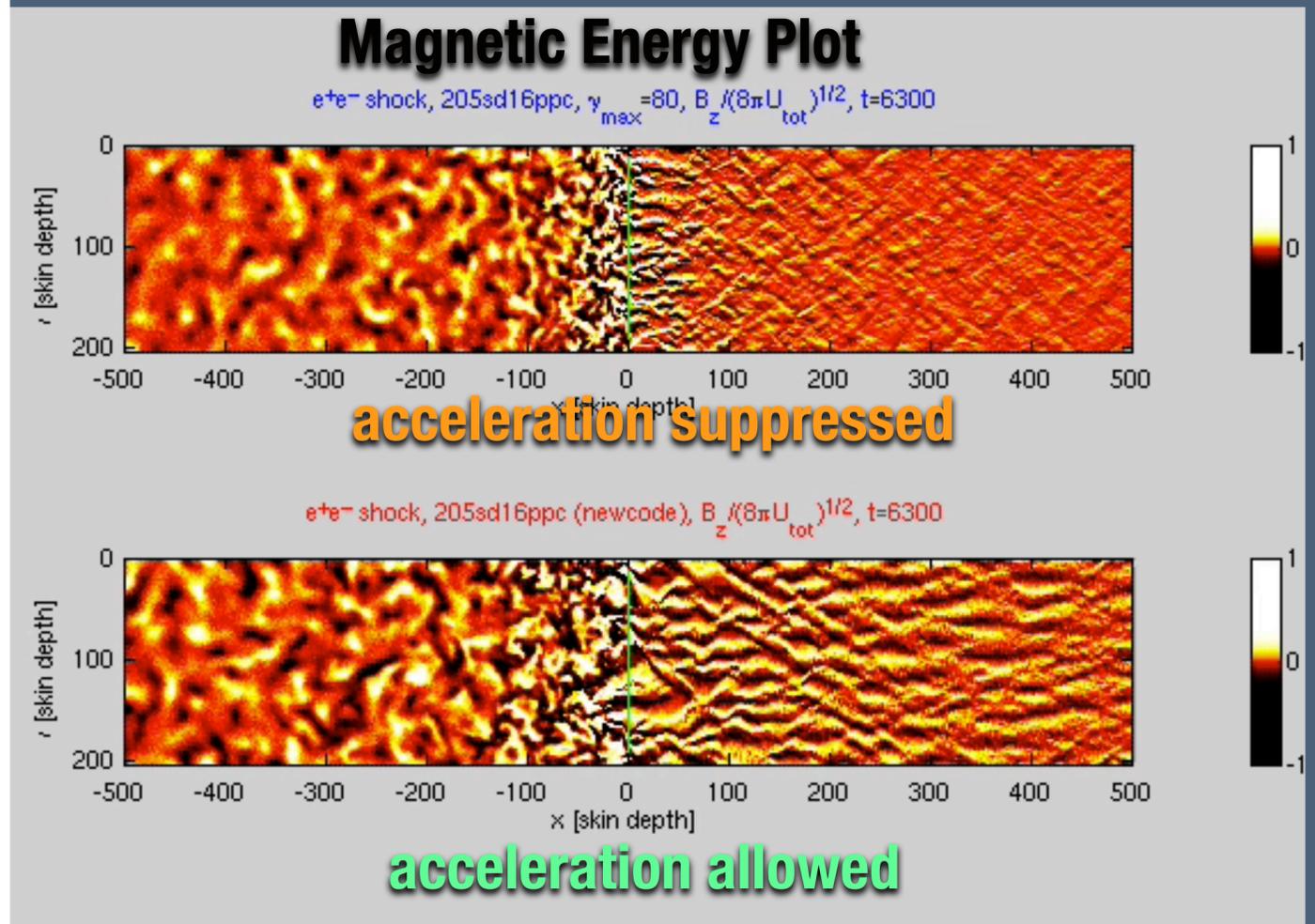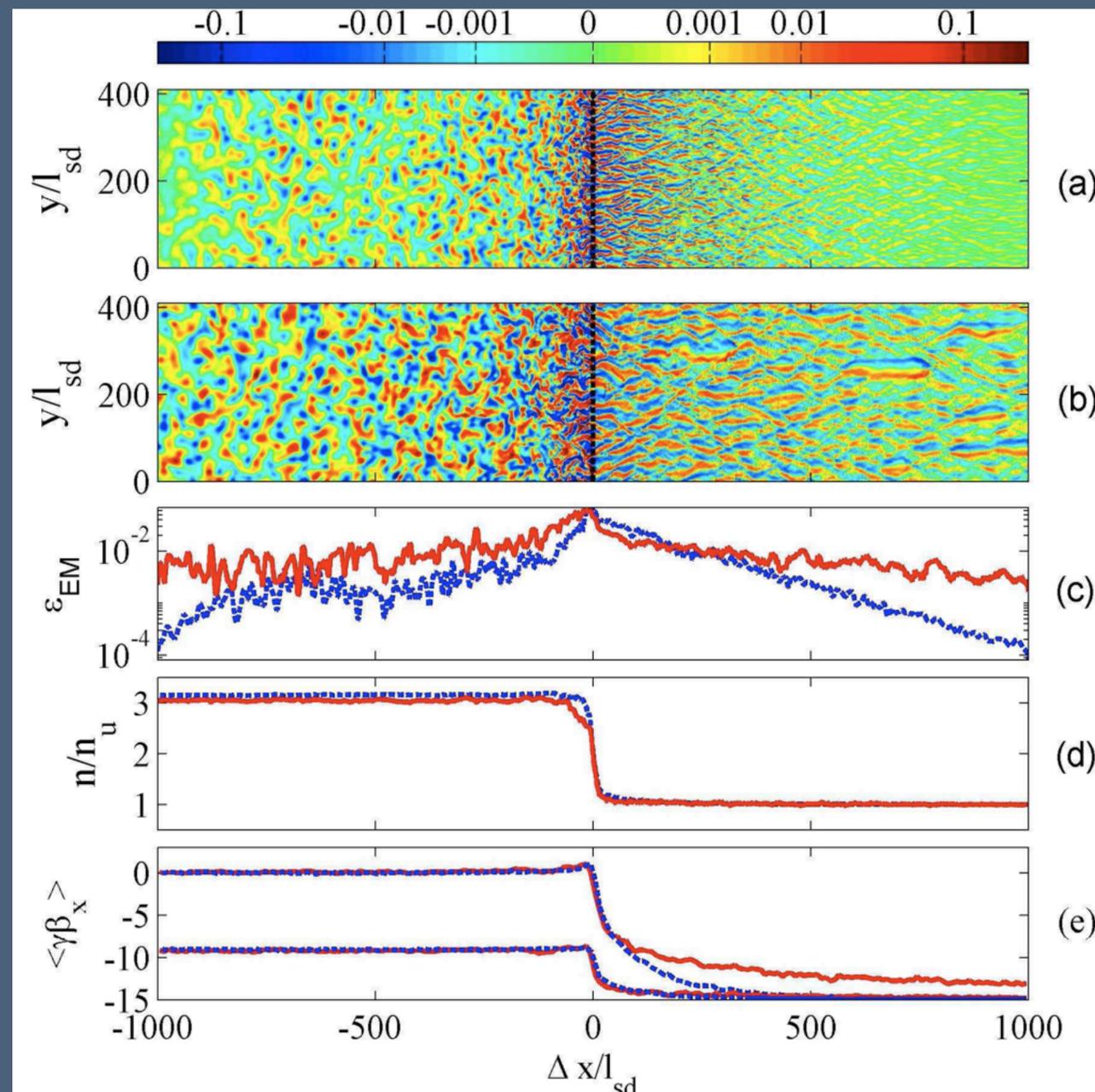 explains high energy fraction in
  electrons

Field survival long term?

In unmagnetized shocks field is created on plasma scale and then decays.
Need to make it on larger scale. Accelerated particles feedback?

(Keshet, Katz, A.S., Waxman 2009)

Is there self-similarity? (Keshet & Waxman 08)

Effective 1% downstream magnetization possible?

Magnetic Energy Plot

e^+e^- shock, 205sd16ppc, γ_{max} =80, $B_z/(8\pi U_{tot})^{1/2}$, t=6300

acceleration suppressed

e^+e^- shock, 205sd16ppc (newcode), $B_z/(8\pi U_{tot})^{1/2}$, t=6300
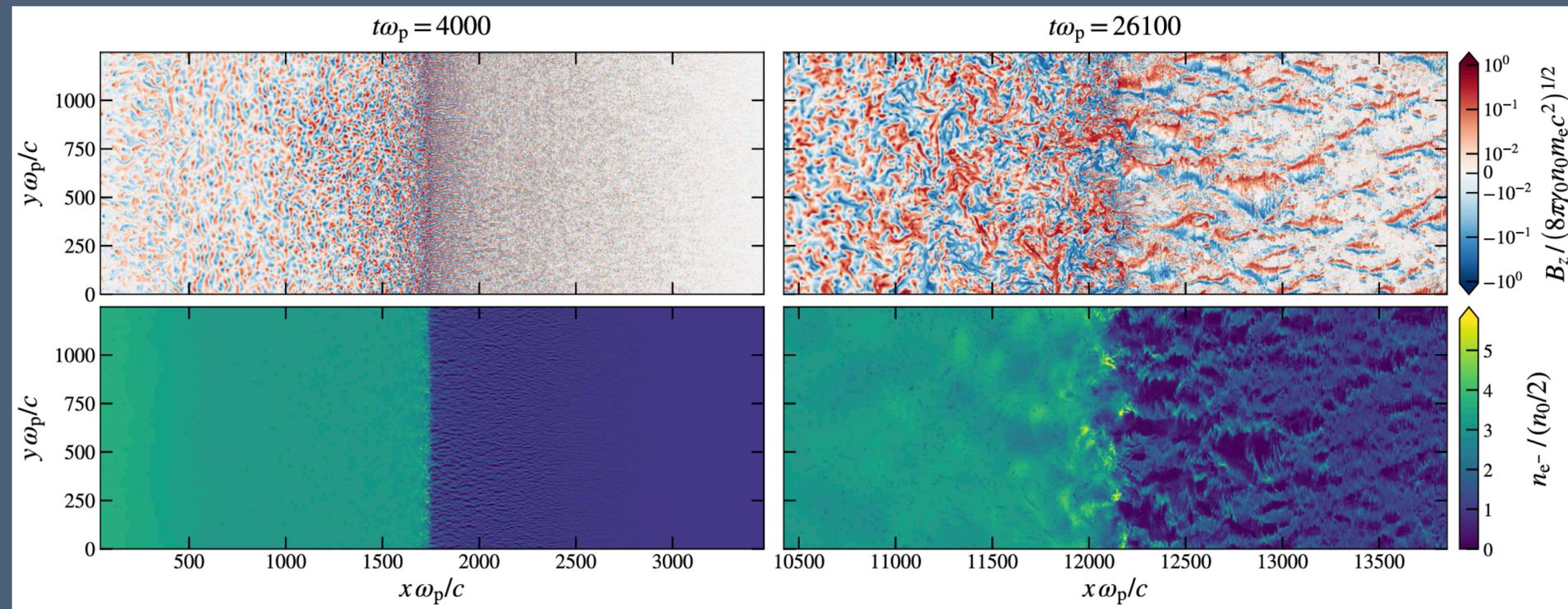
acceleration allowed

Long simulation of a relativistic pair shock
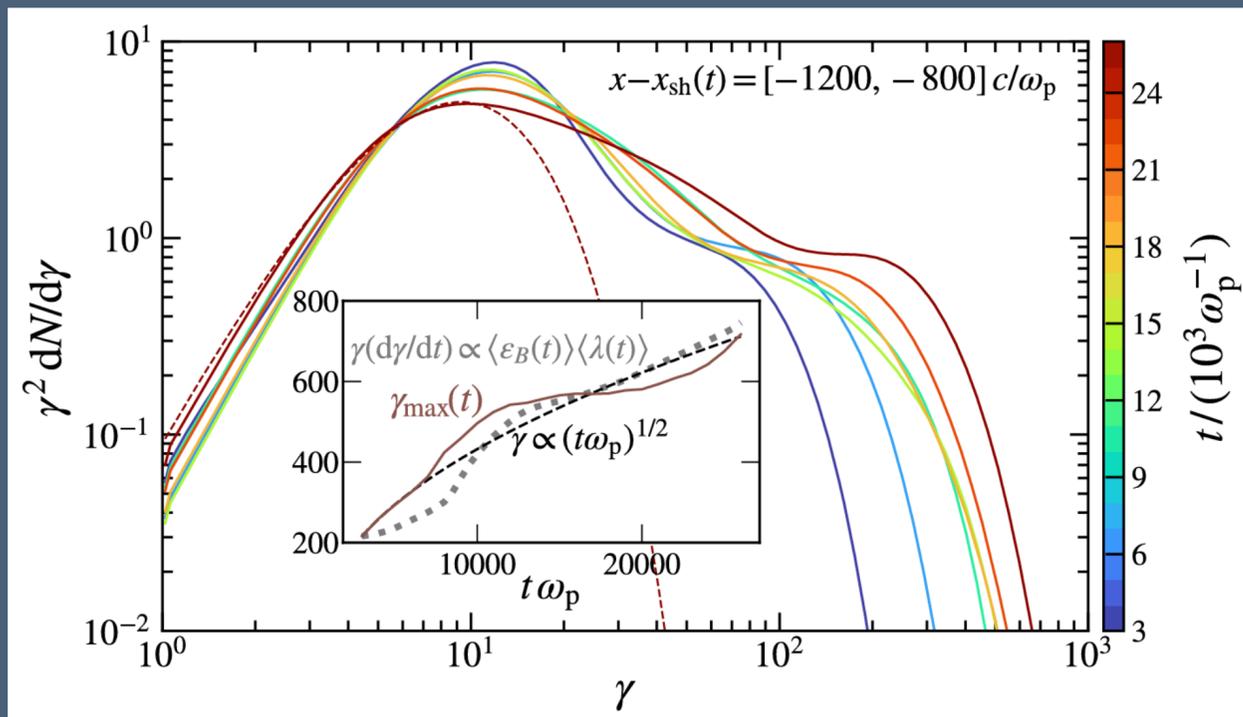
$t\omega_\mathrm{p} = 26100$
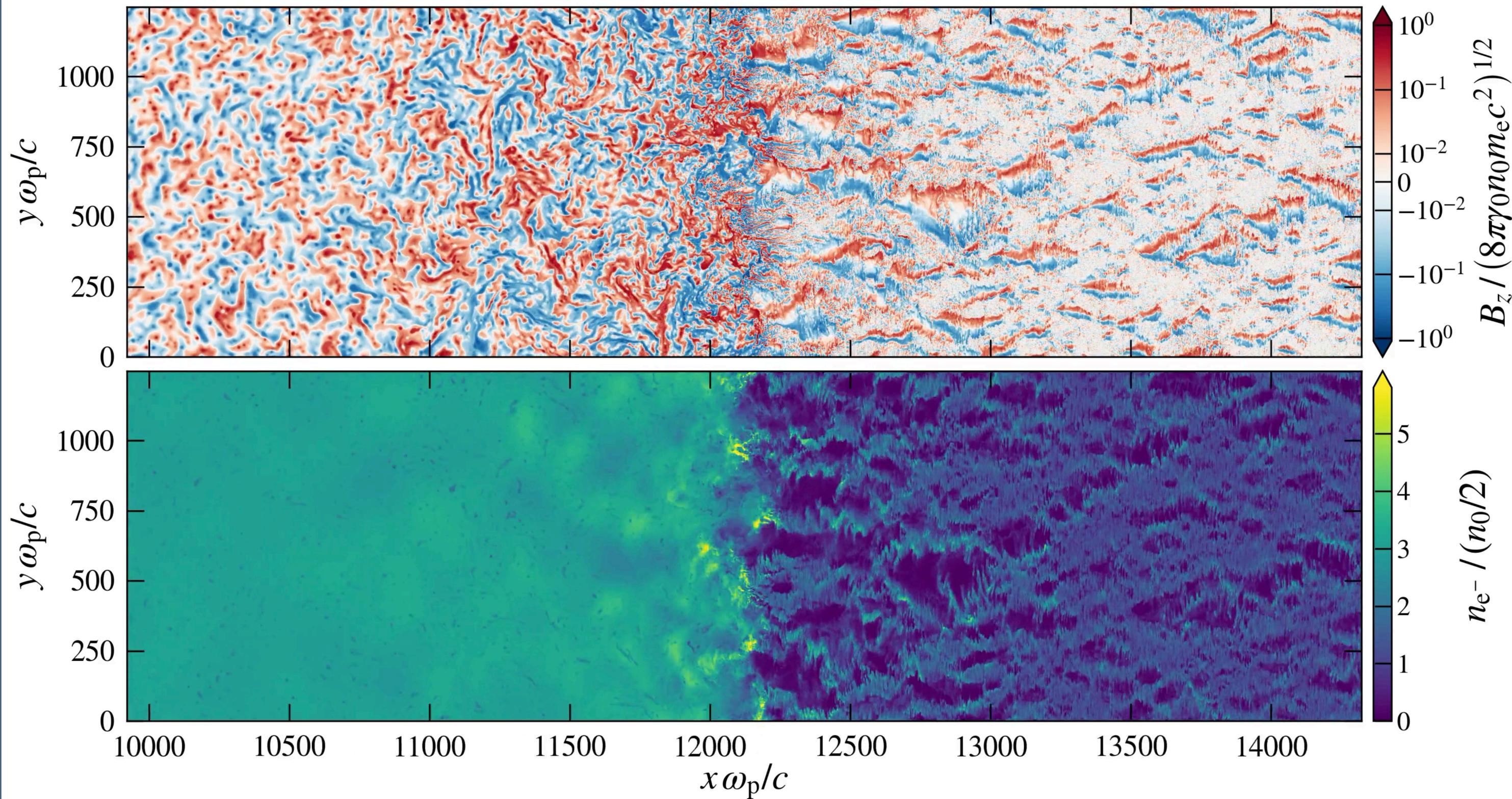
Long term evolution of unmagnetized pair shock
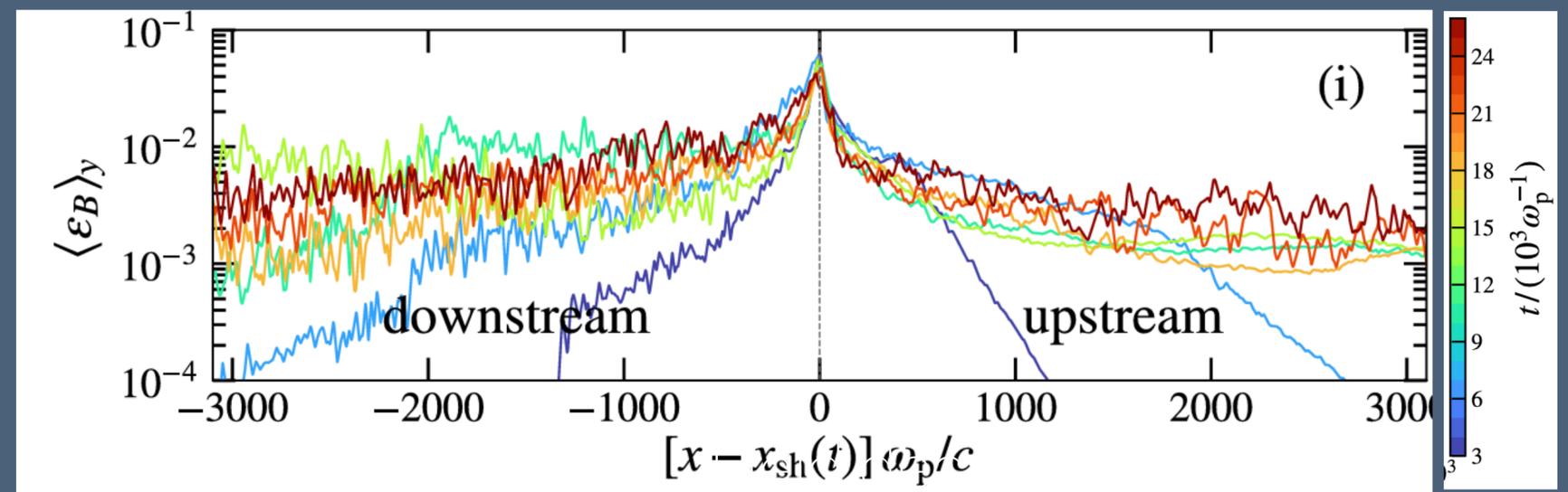

Groselj, Sironi, AS 24

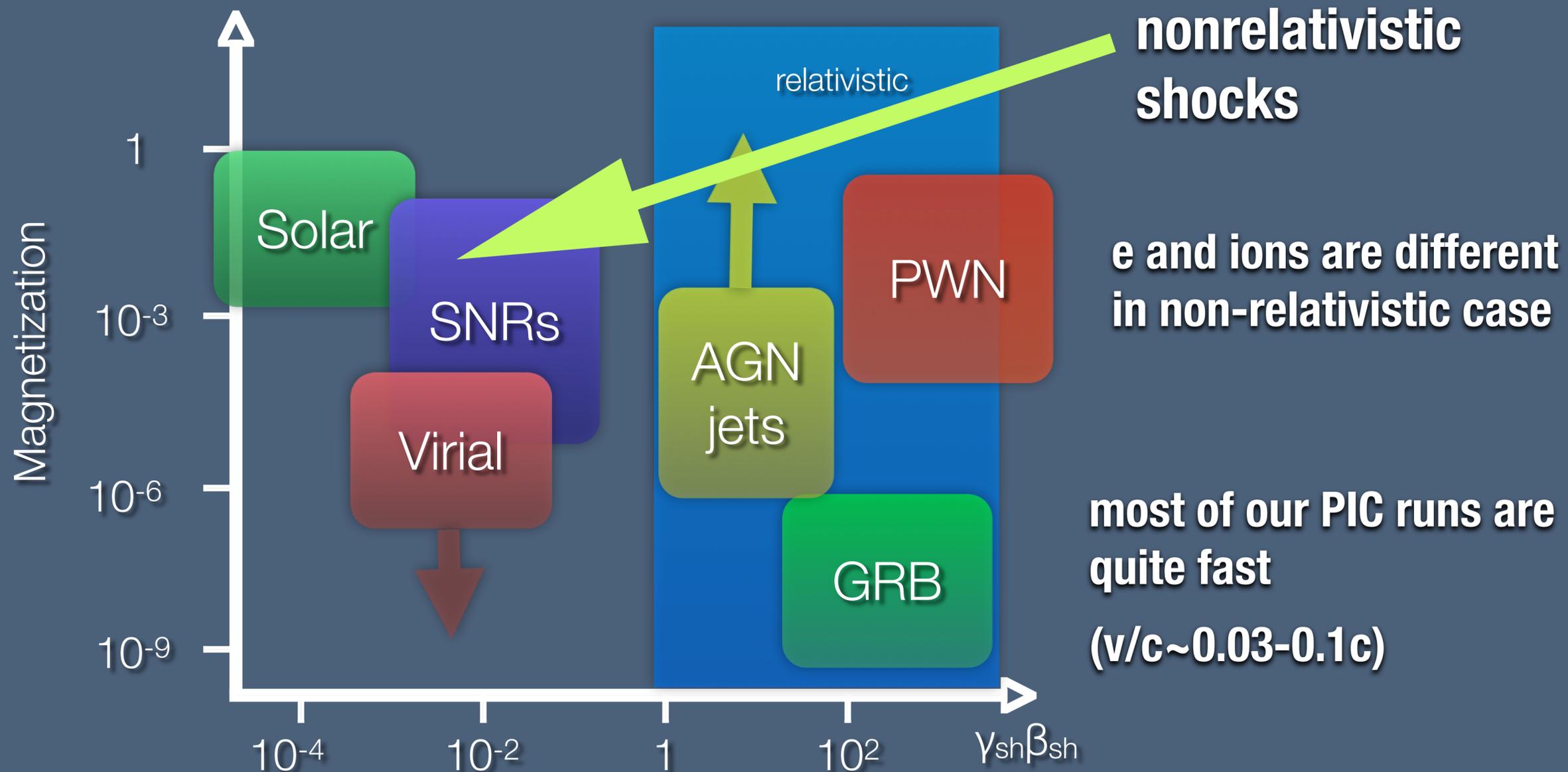## Spectrum: suprathermal component

Field evolution: decay slows down

Downstream radiation is dominated by strong field regions

Parameter Space of shocks

$$\sigma \equiv \frac{B^2/4\pi}{(\gamma-1)nmc^2} = \frac{1}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$

nonrelativistic shocks

e and ions are different in non-relativistic case

most of our PIC runs are quite fast

(v/c~0.03-0.1c)

relativistic

Solar

SNRs

Virial

AGN jets

PWN

GRB

Magnetization

1

10^{-3}

10^{-6}

10^{-9}

10^{-4} 10^{-2} 1 10^2 $\gamma_{sh}\beta_{sh}$

Nonrelativistic shocks: shock structure

mi/me=400, v=18,000km/s, M$_A$=5, quasi-perp 75° inclination
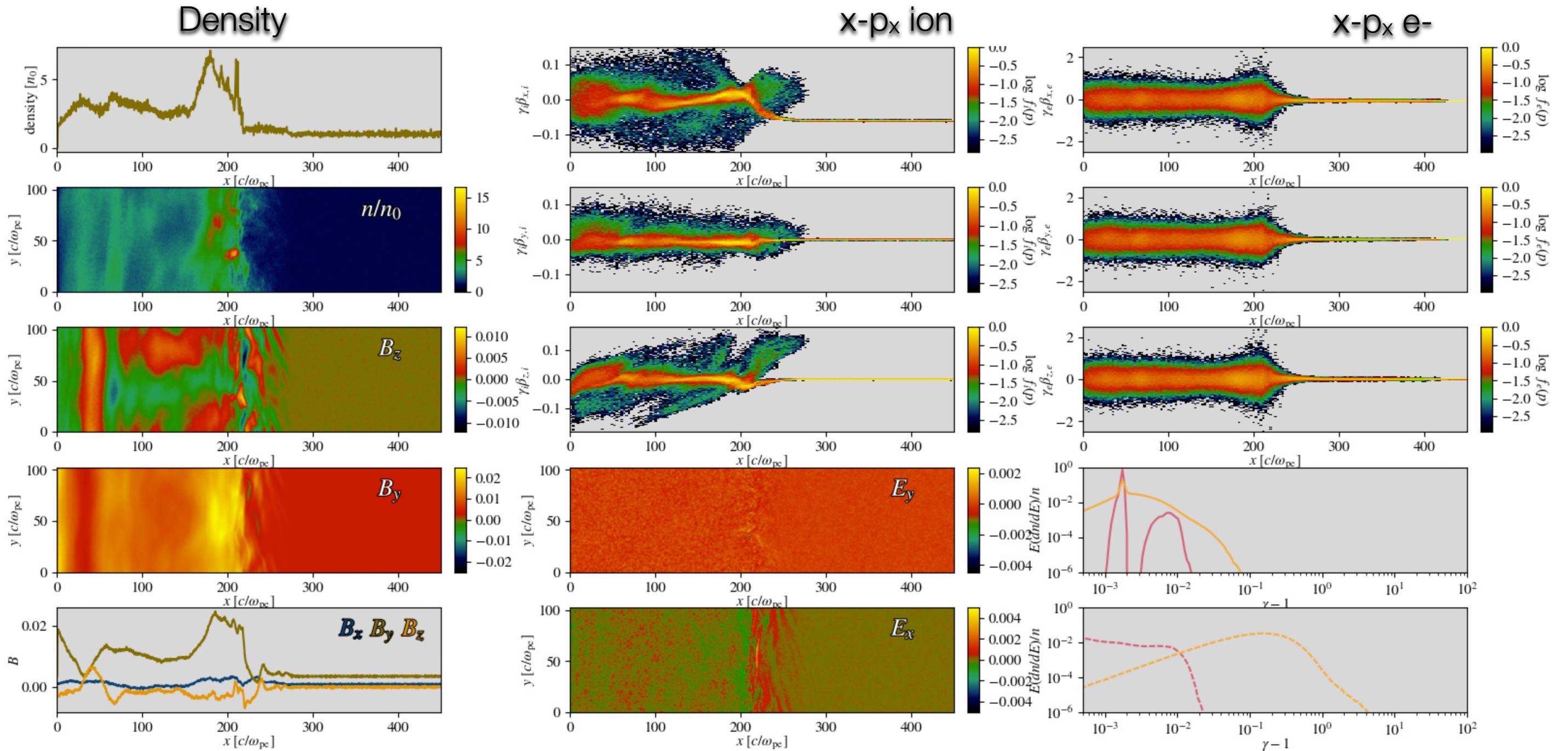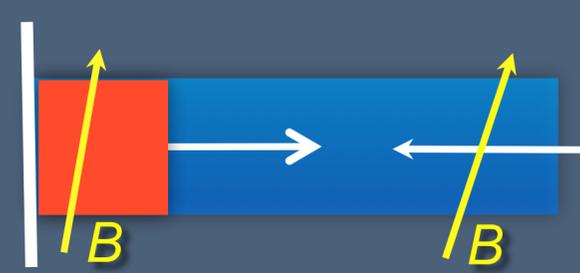
PIC simulation: Shock foot, ramp, overshoot, returning ions, electron heating, whistlers

Nonrelativistic shocks: quasiparallel shock

mi/me=30, v=30,000km/s, M$_A$=5   parallel 0° inclination
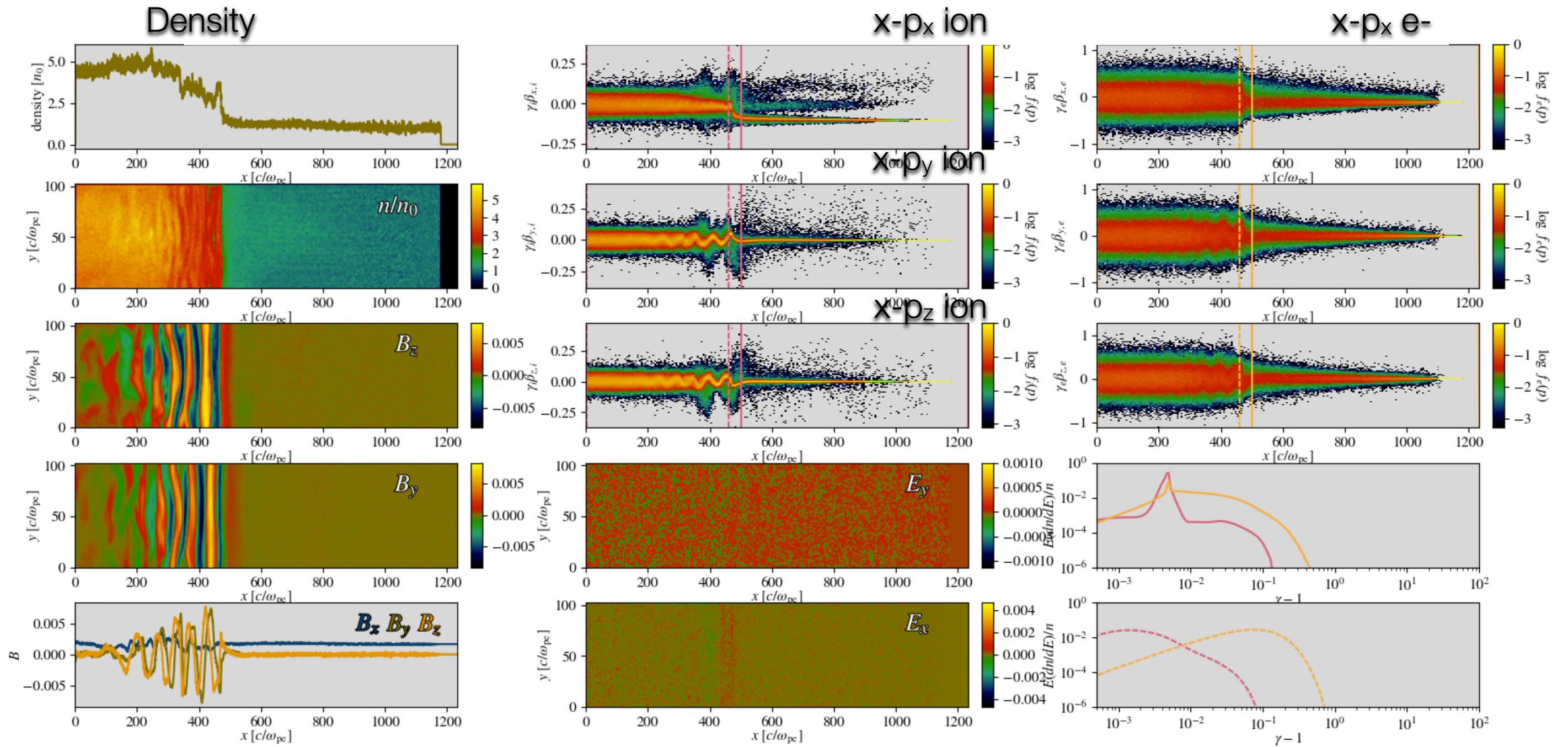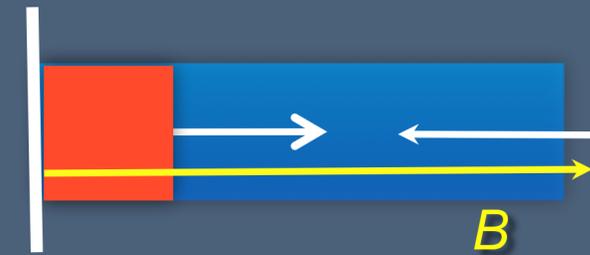
Quasiparallel shocks: proton and electron accelerators

Mach 10 nonrelativistic hybrid simulation of proton acceleration
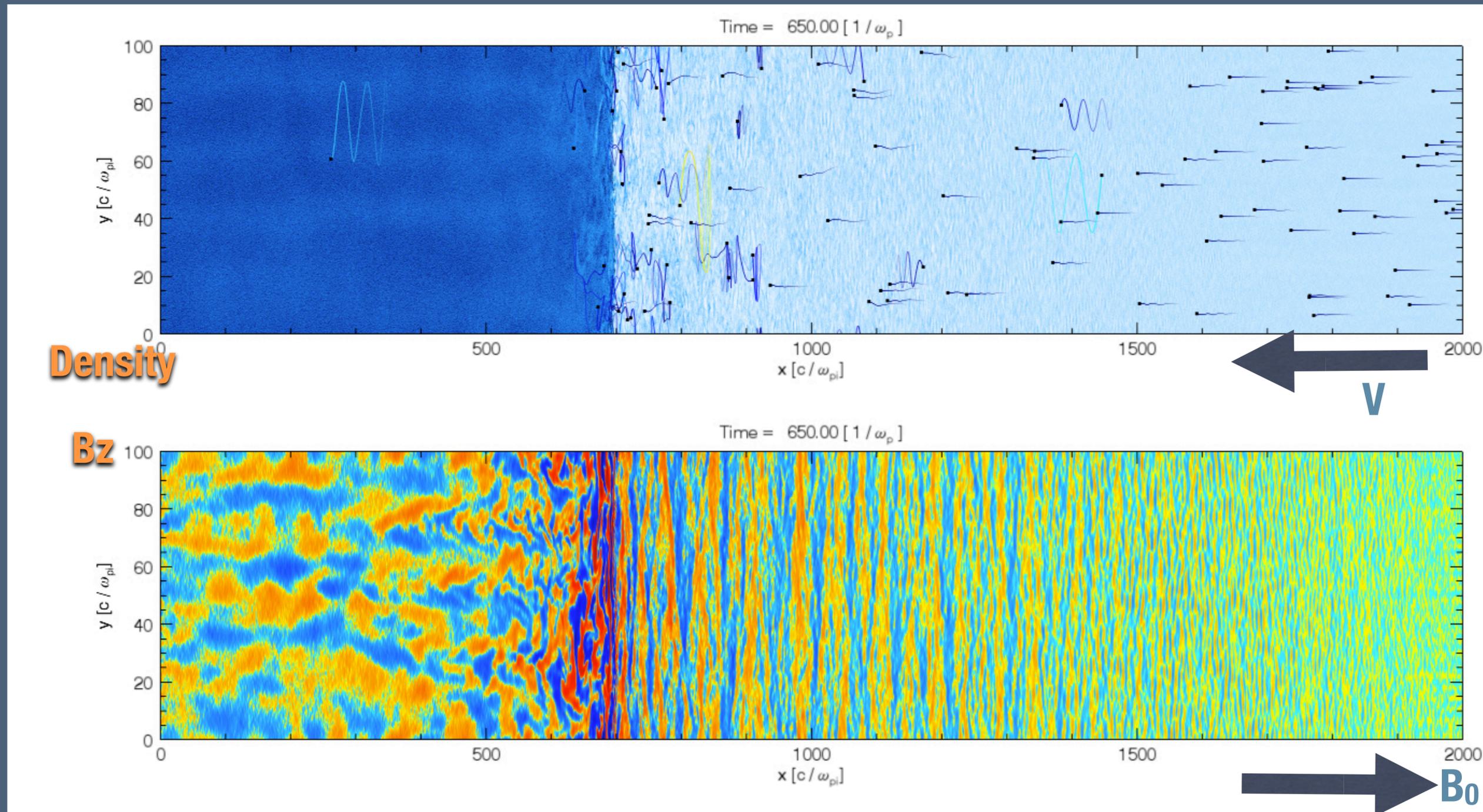
Proton spectrum

Long term evolution: Diffusive Shock Acceleration spectrum recovered
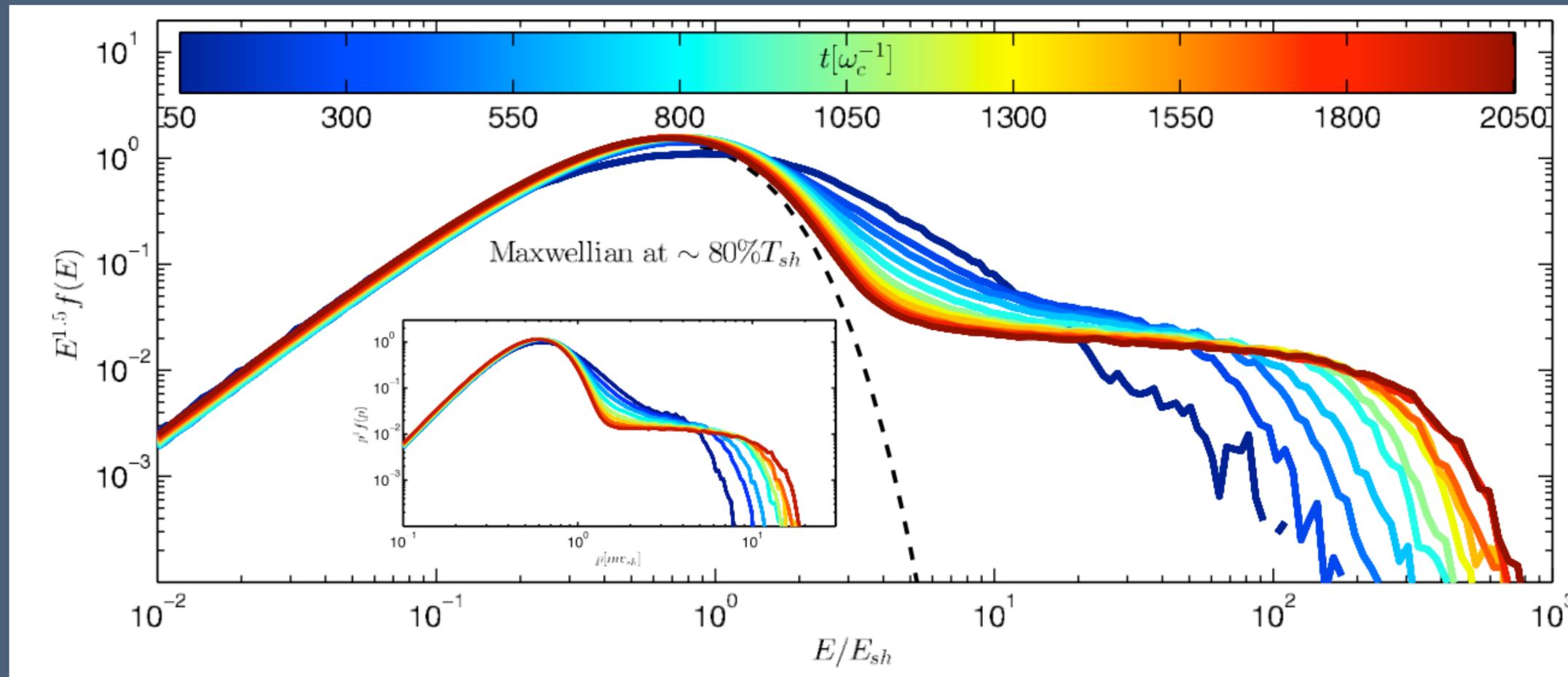
First-order Fermi acceleration: $f(p) \propto p^{-4}$ $4\pi p^2 f(p)dp = f(E)dE$

$f(E) \propto E^{-2}$ (relativistic) $f(E) \propto E^{-1.5}$ (non-relativistic)

Few percent by number, 10-20% by energy in the tail!

Field amplification

We see evidence of CR effect on upstream.

This will lead to a shock with effectively lower Alfvenic Mach number with locally 45 degree inclined fields for Ma<80.
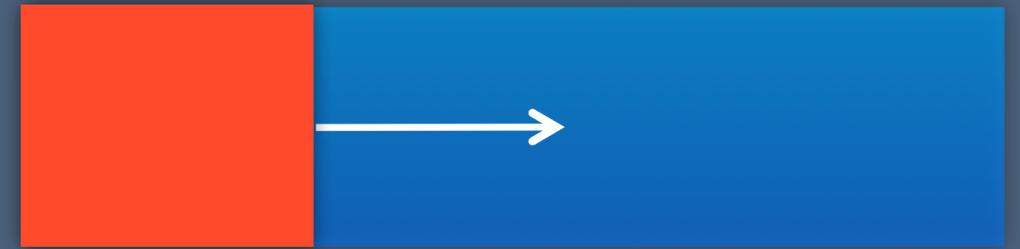
Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

Combination of nonresonant (Bell), resonant, and firehose instabilities + CR filamentation

Field amplification

We see evidence of CR effect on upstream.

This will lead to ... of nonresonant (Bell),
lower Alfvenic ... firehose instabilities
degree inclined ... ation

Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

Cosmic ray Nonresonant/resonant streaming instability

References: e.g., Achterberg 1983, Lucek & Bell 2000, Bell 2004,05

Field amplification

We see evidence of CR effect on upstream.

This will lead to a shock with effectively lower Alfvenic Mach number with locally 45 degree inclined fields for Ma<80.
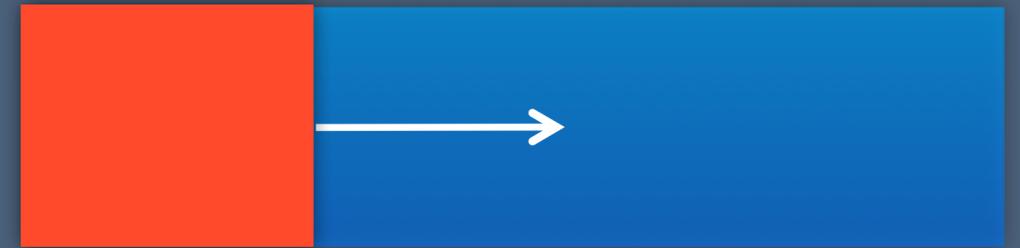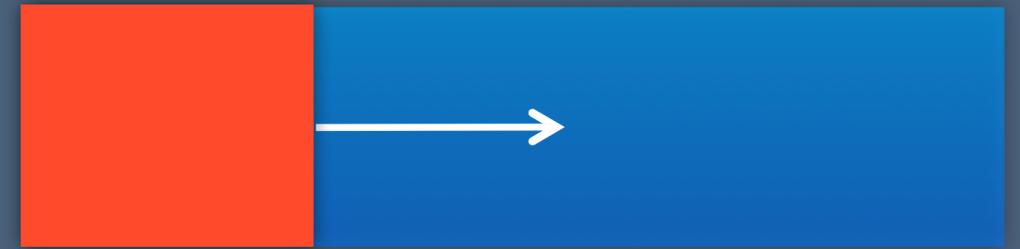
Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

Combination of nonresonant (Bell), resonant, and firehose instabilities + CR filamentation
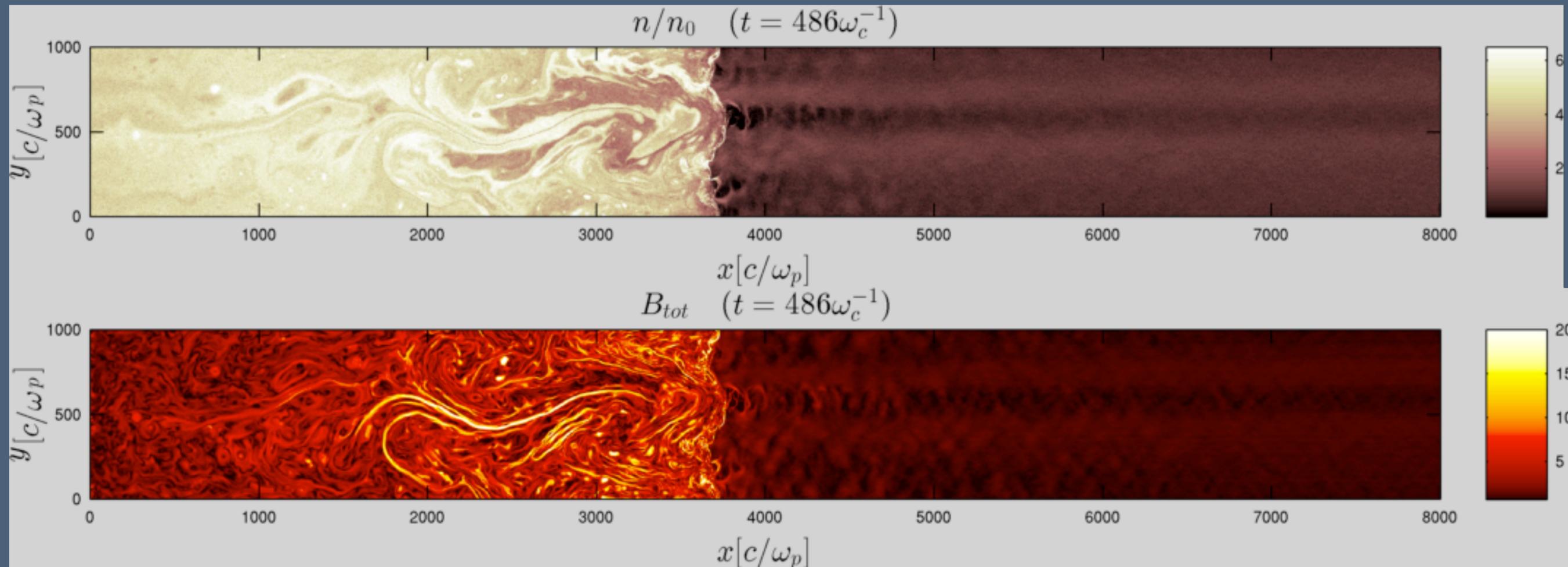
Dependence of field am...
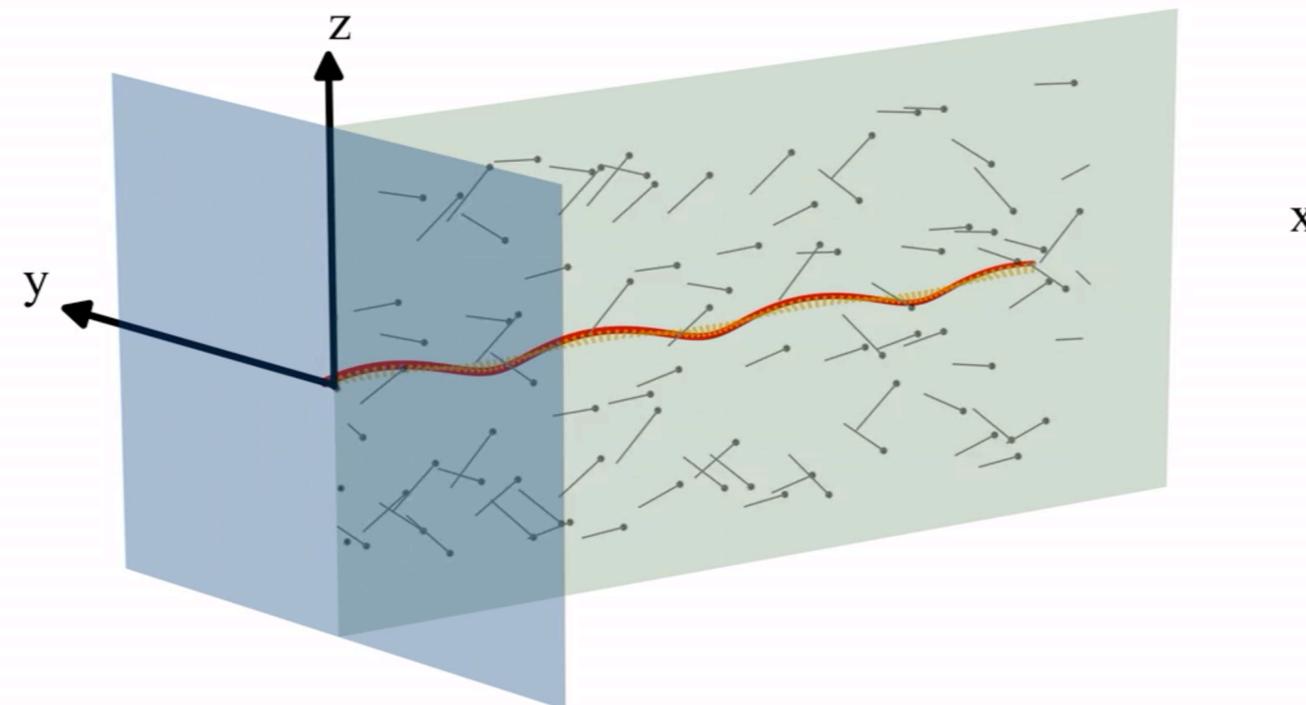

$$\left\langle \frac{B_{tot}}{B_0} \right\rangle_{up}^2 \approx 3\xi_{cr} M_A$$
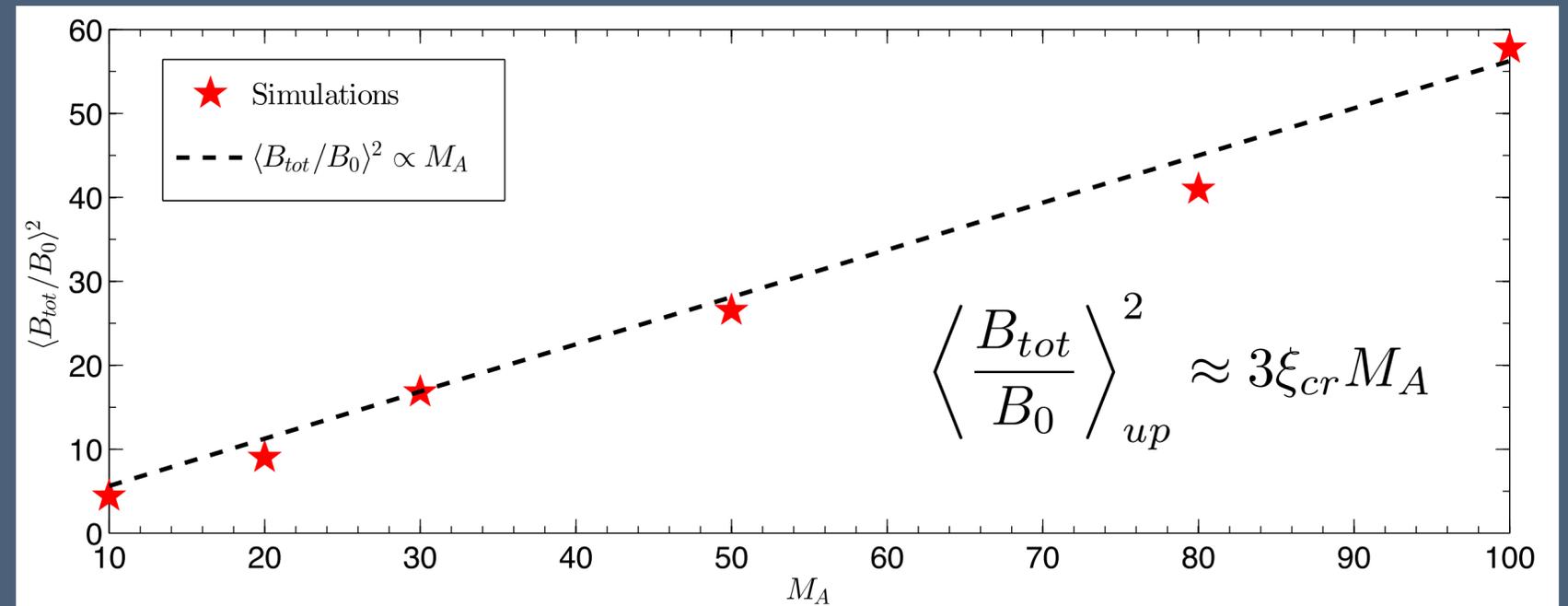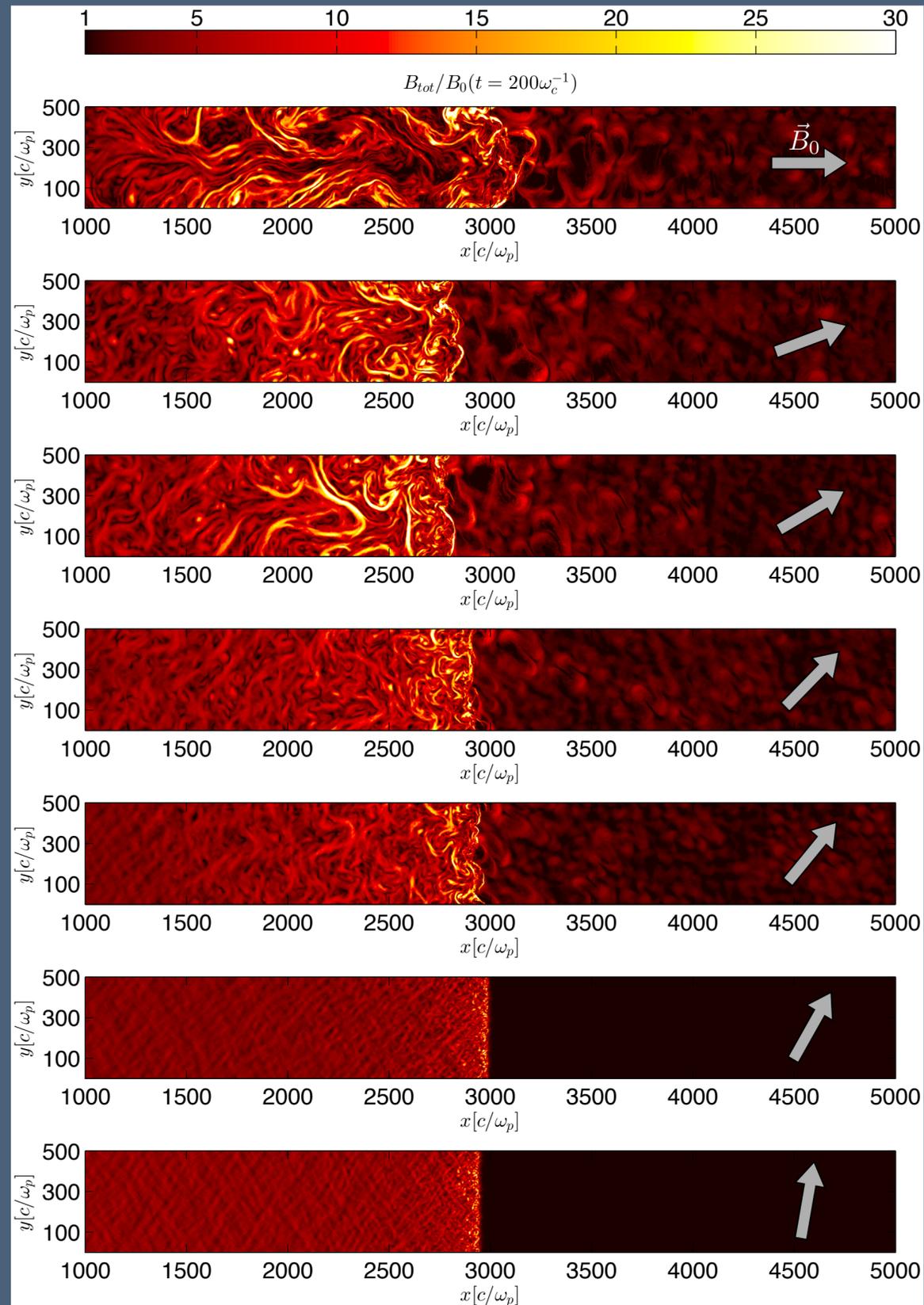
More B amplification for stronger (higher M_A) shocks

- Different flavors of CR-driven streaming instabilities
  (Amato & Blasi 2009; Caprioli & AS 2014b)

  - For $M_A < 30$, resonant (cyclotron)

  - For $M_A > 30$, non-resonant (Bell): strongly non-linear!

- Bohm-like diffusion in the self-generated B
  (Reville & Bell 2013; Caprioli & AS 2014c)

Caprioli & AS, 2014a
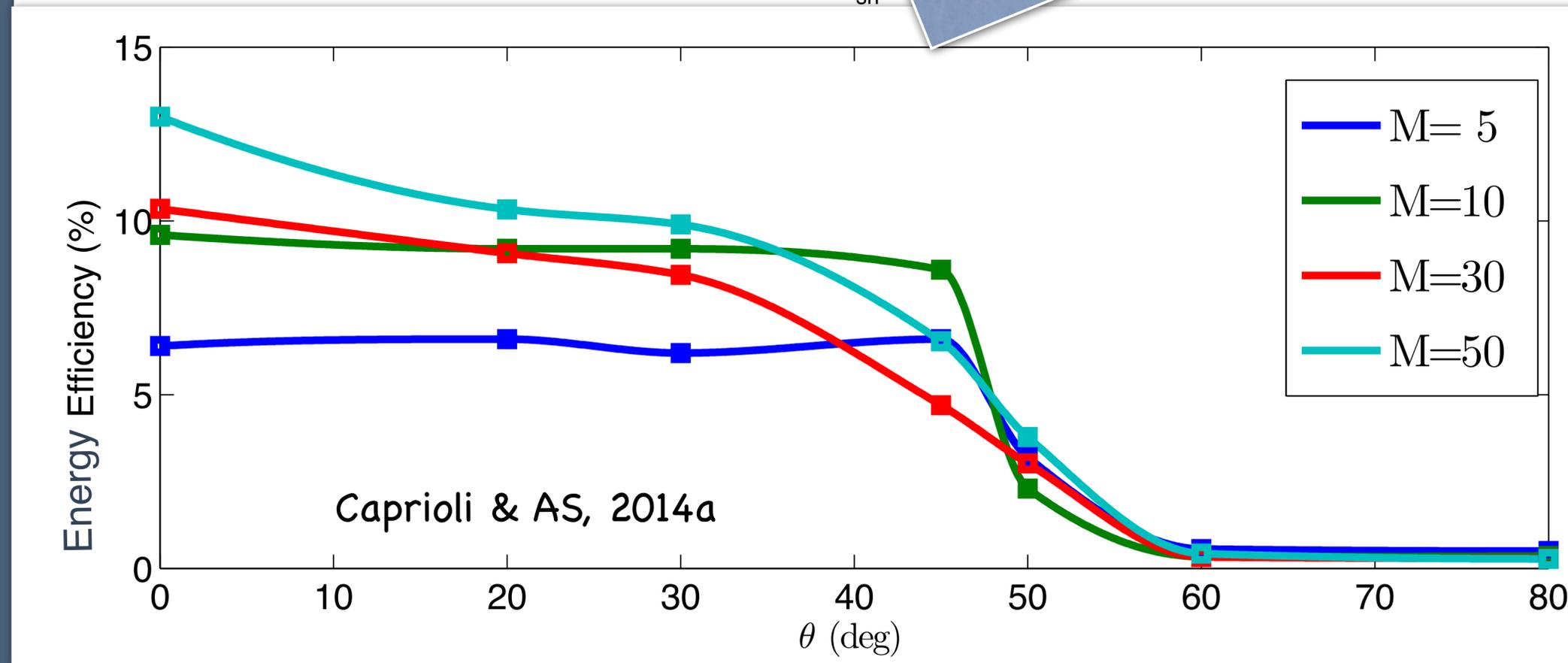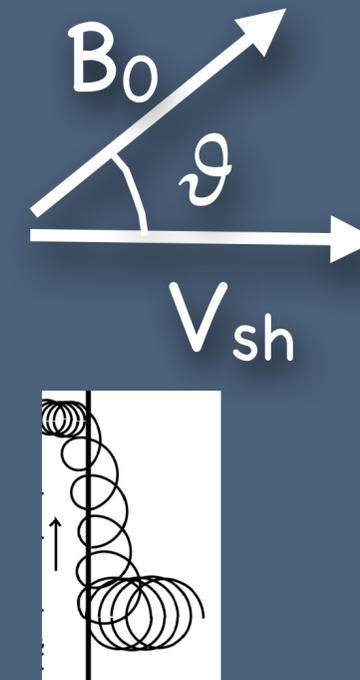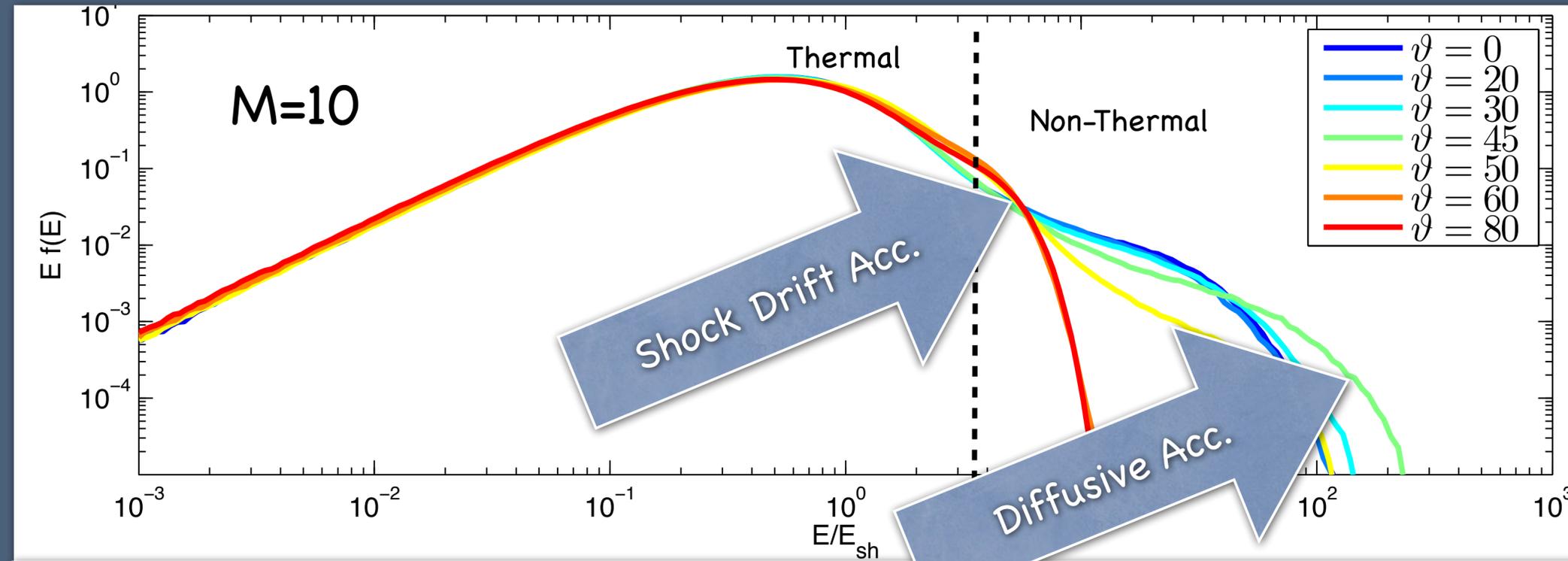
About 1% accelerated protons by number, 10% by energy

Caprioli & AS, 2014a
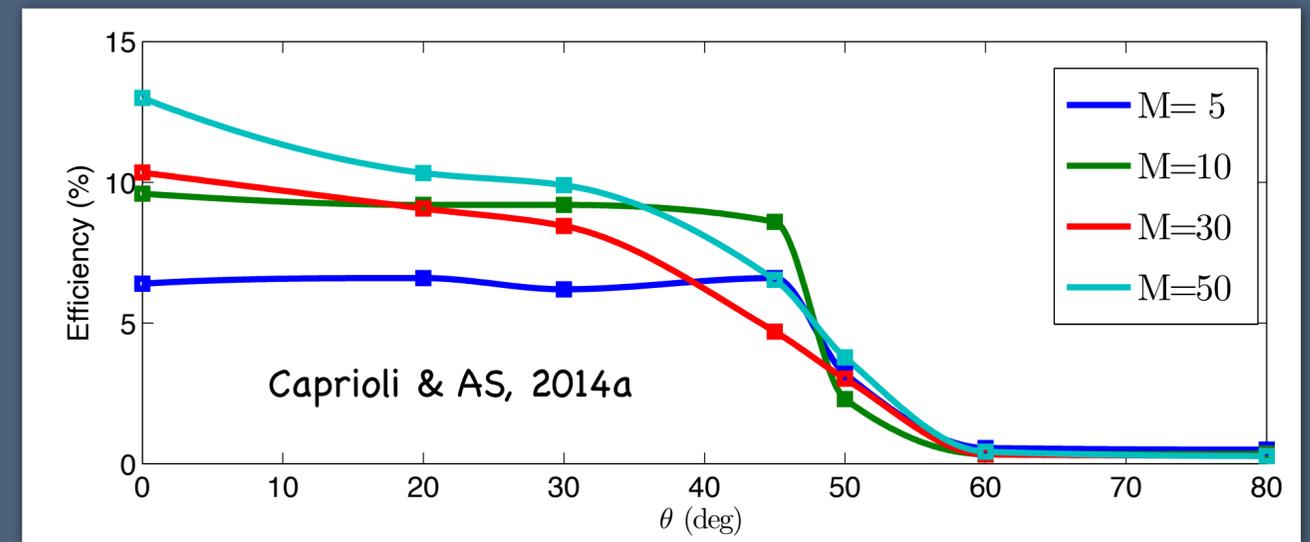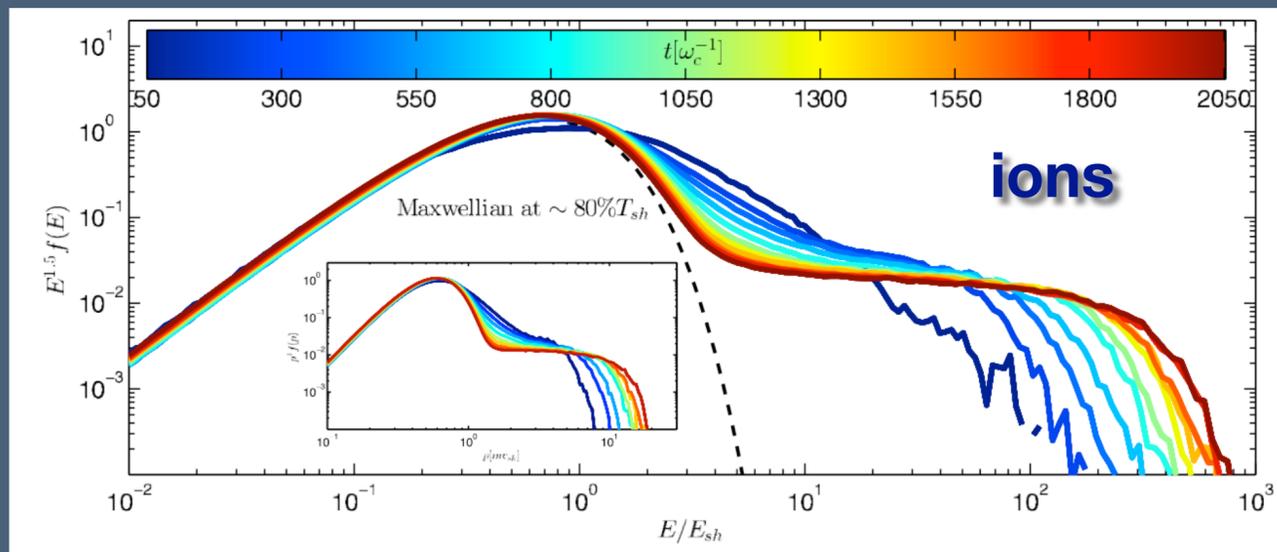
Modeling nonrelativistic DSA across regimes:

1) PIC and Hybrid have been indispensable for microphysics: Weibel shocks vs magnetized shocks.

2) What we learned: efficiency of injection vs Mach # and magnetic obliquity for magnetized shocks.

3) For q-par shocks: Ma < 50 results in 10-15% by energy in CRs (Caprioli & AS 20).

4) Both e and ions are accelerated, κ_{ep}~0.1-1% (Park et al 15, Gupta et al 24) at Ma < 40.

Park et al 2015

ion

electon spectrum
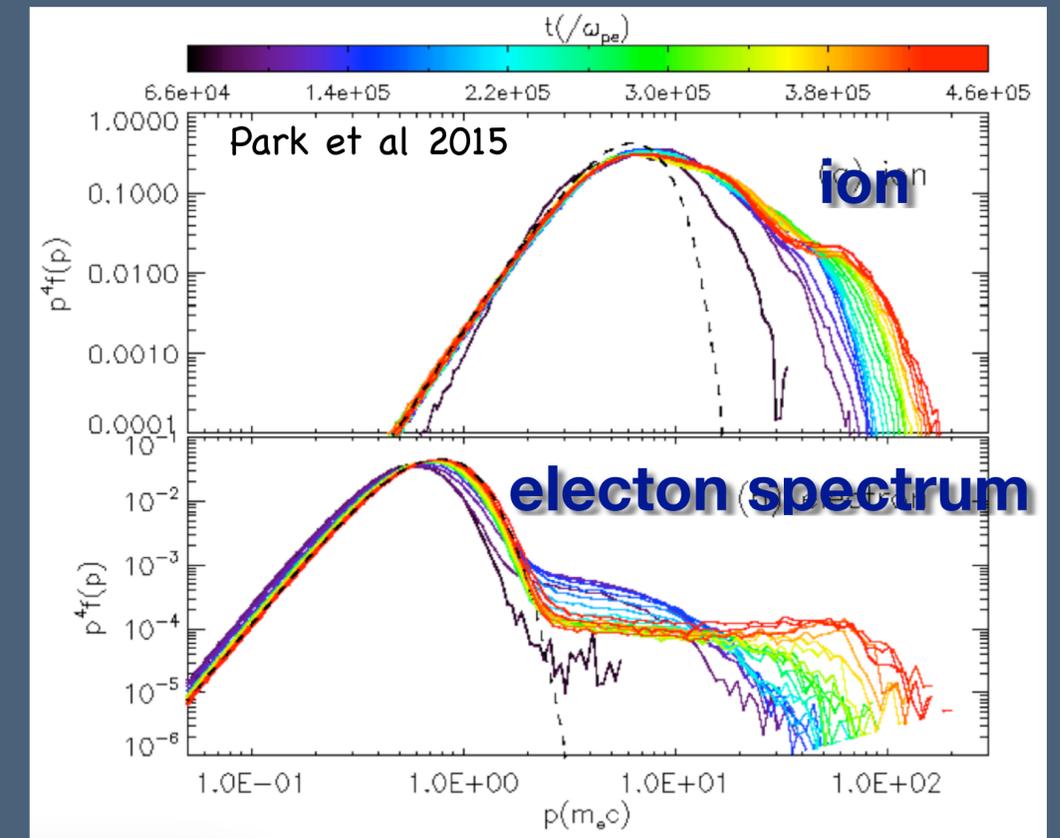
Injection physics: ions

- Ions are injected through cycles of Shock-Drift acceleration (SDA), where ions probe coverging flows around the shock, as their Larmor radius is comparable to the thickness of the shock. Shock transition is "breathing" and is dynamical on ion gyration scale.

- After several cycles of SDA, lucky energetic ions have enough velocity to outrun the shock along field line into the upstream.

- The SDA process is lossy, and the fraction of particles that can stay for the needed number of cycles is small, near 1%.

- More oblique shocks require longer SDA process, so fewer particles remain.

Acceleration processes in shocks

- Diffusive Shock Acceleration (DSA) or Fermi acceleration:

Particles bounce between the upstream and the downstream, diffusively scattered by magnetic turbulence

credit: Scholer

MHD waves

Downstream

Shock

Upstream
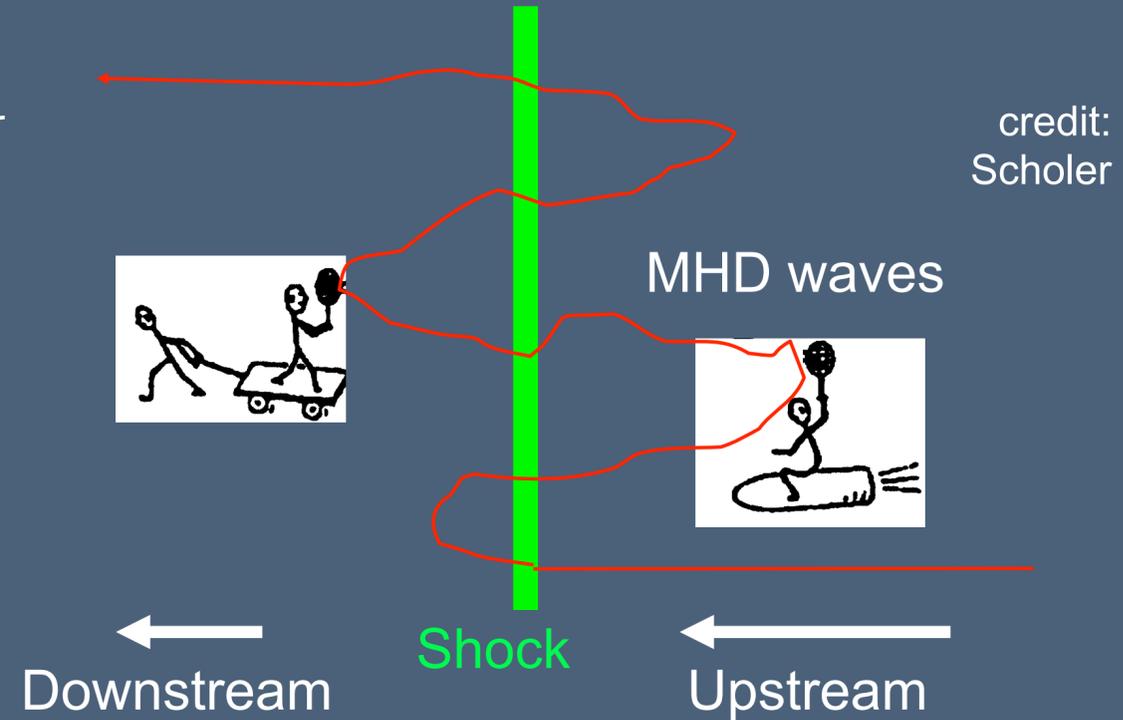
- Shock-drift acceleration (SDA): oblique shocks only!

Shock-reflected particles are accelerated by the background electric field while drifting along the shock surface: Larmor radius is finite compared to shock thickness

p^+

$B_d > B_u$

$\odot B_{z,u}$

∇B drift

$E_{y,u}$
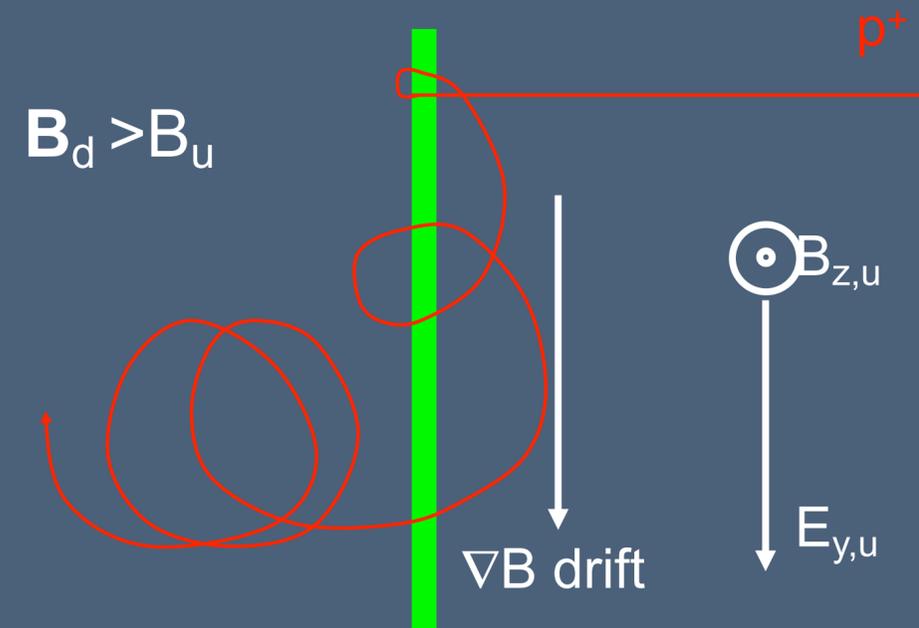
Shock structure & injection

Quasiparallel shocks look like intermittent, reforming quasiperpendicular shocks
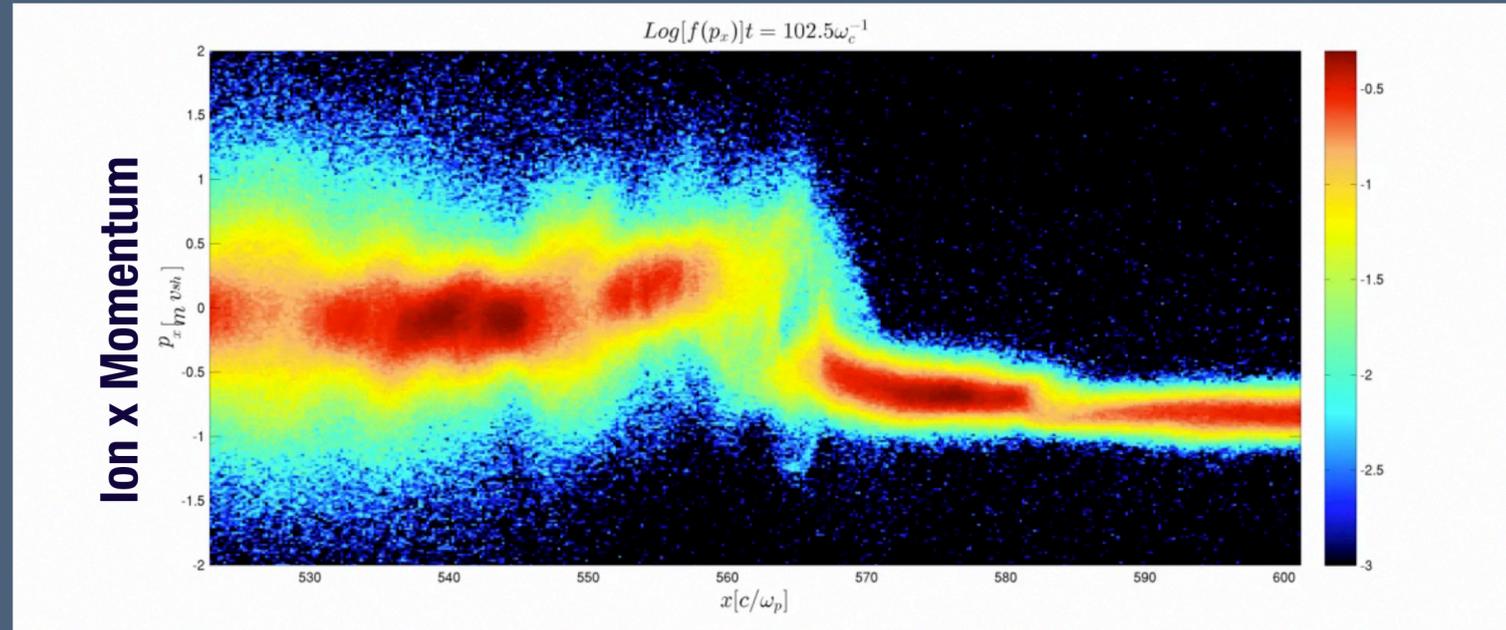
Injection of ions happens on first crossing due to specular reflection from reforming magnetic and electric barrier and shock-drift acceleration.

Multiple cycles in a time-dependent shock structure result in injection into DSA; oblique shocks require more "leaky" cycles of pre-acceleration, leading to 1% by number (Pop, Caprioli, AS 15).
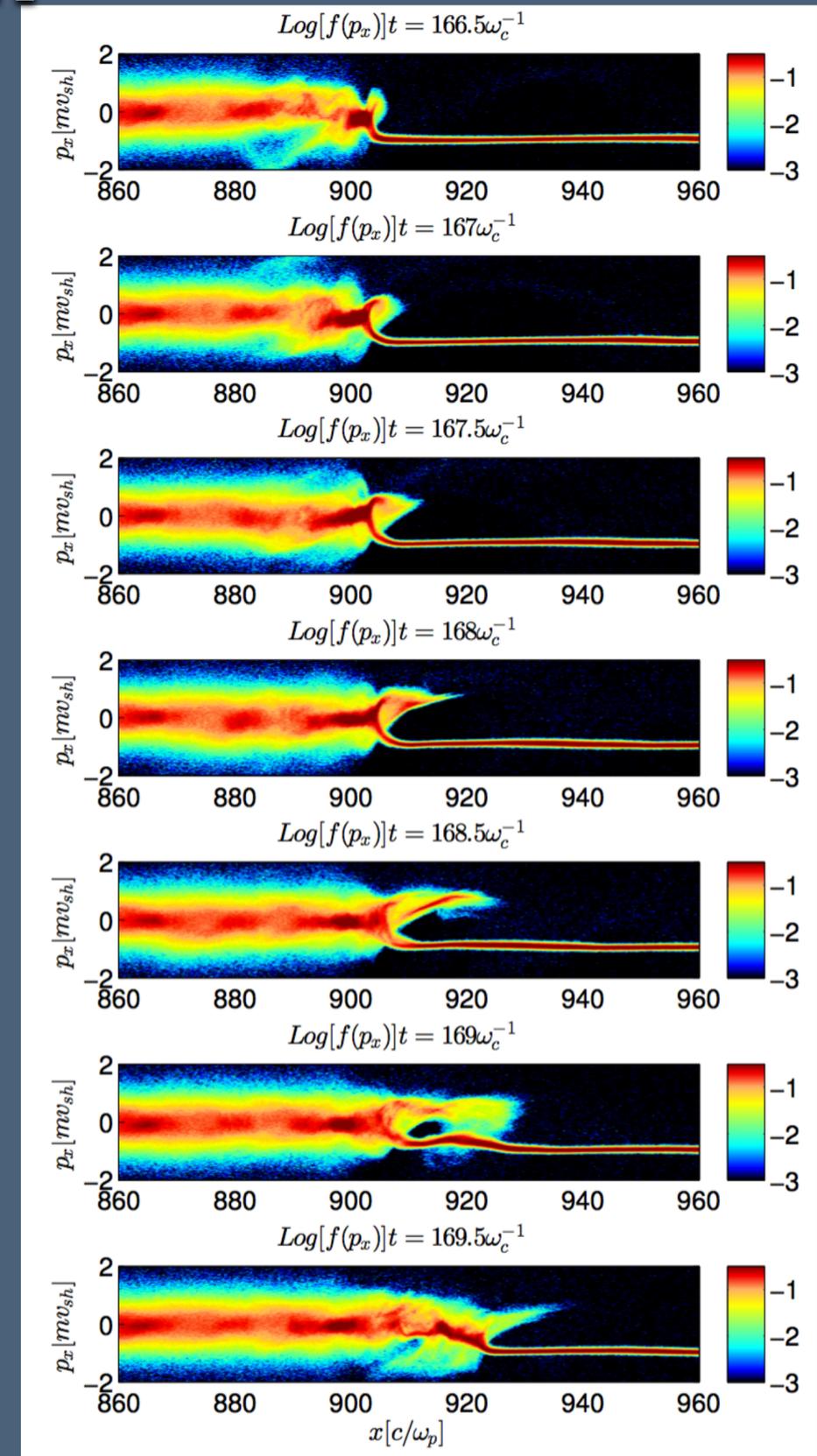
Injection physics: electrons

- Electrons are injected relatively easily — they mirror off the shock compression and gain velocity until they can outrun the shock. They need to reach 2-3 times the shock speed (Gupta, Caprioli, AS 25)

- Electrons need to be hot to have large pitch angle to mirror — preheating by ions

$$M_{s,e} = \frac{shock\ speed}{thermal\ speed} \lesssim 3$$

- To reflect from the shock electrons do not need large Larmor radius, just a few times thermal velocity is enough. The injection criterion is 3x v_th.

- Energy gain through bounces from the shock (a kind of SDA), until they gain enough energy to enter diffusive acceleration by scattering on upstream ion-created waves.

Electron acceleration at parallel shocks

Multi-cycle shock-drift acceleration, with electrons returning back due to upstream ion-generated waves. 1D PIC simulation, mass ratio 100 (Park et al 15)

Ion phase space

Electron phase space

Density

Transverse Magnetic field
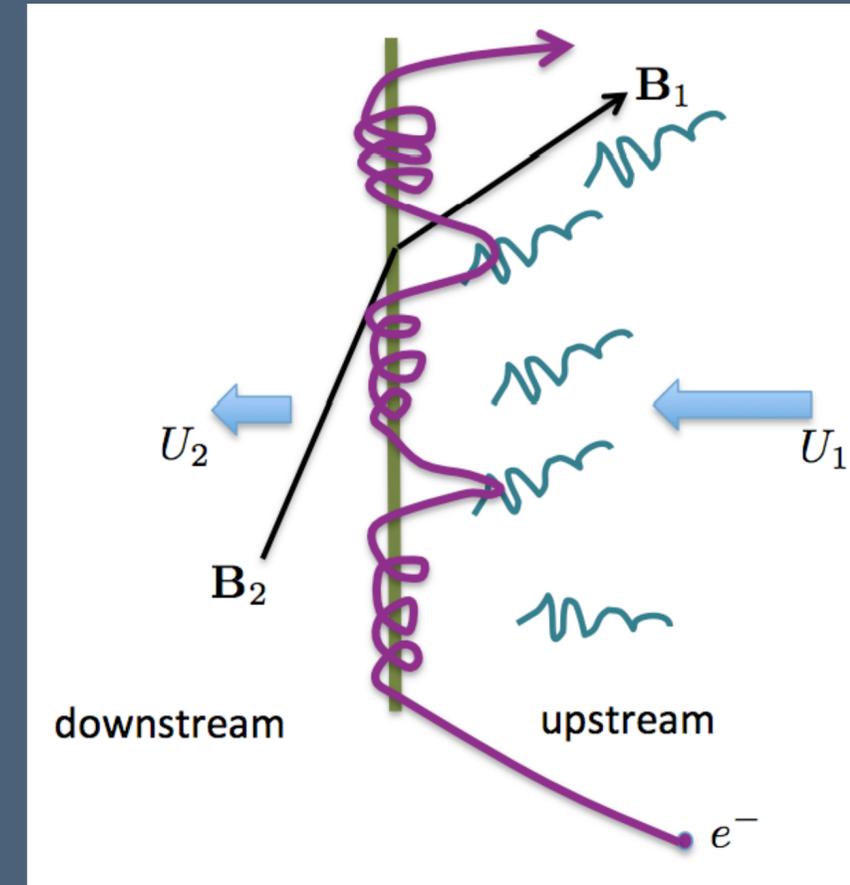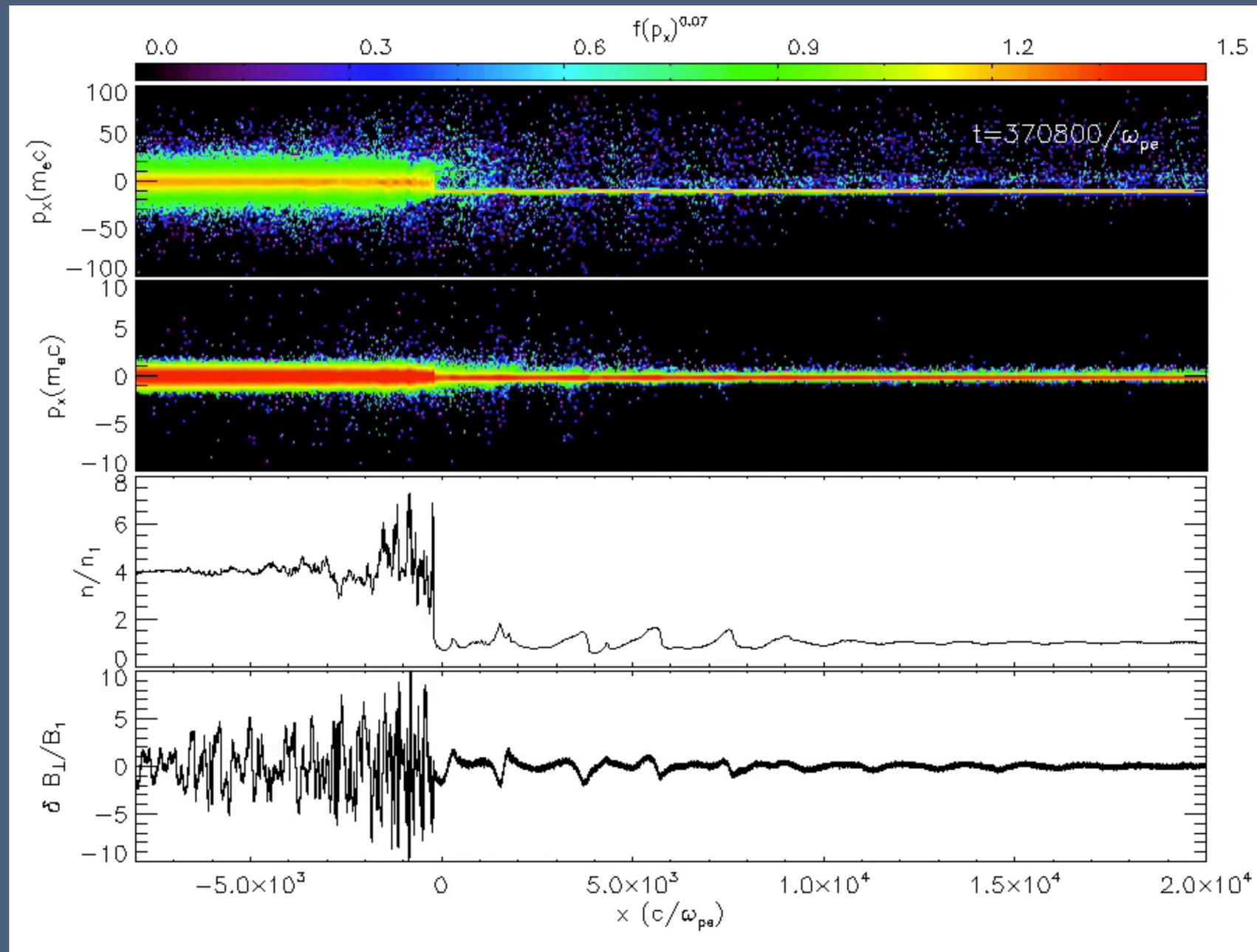
Electron acceleration at parallel shocks

Inject 0.1% by number of electrons into the tail and 1% of ions. Tail is defined as >5 thermal momentum. Electron DSA tail connects to the maxwellian.

Gupta, Caprioli, AS 24
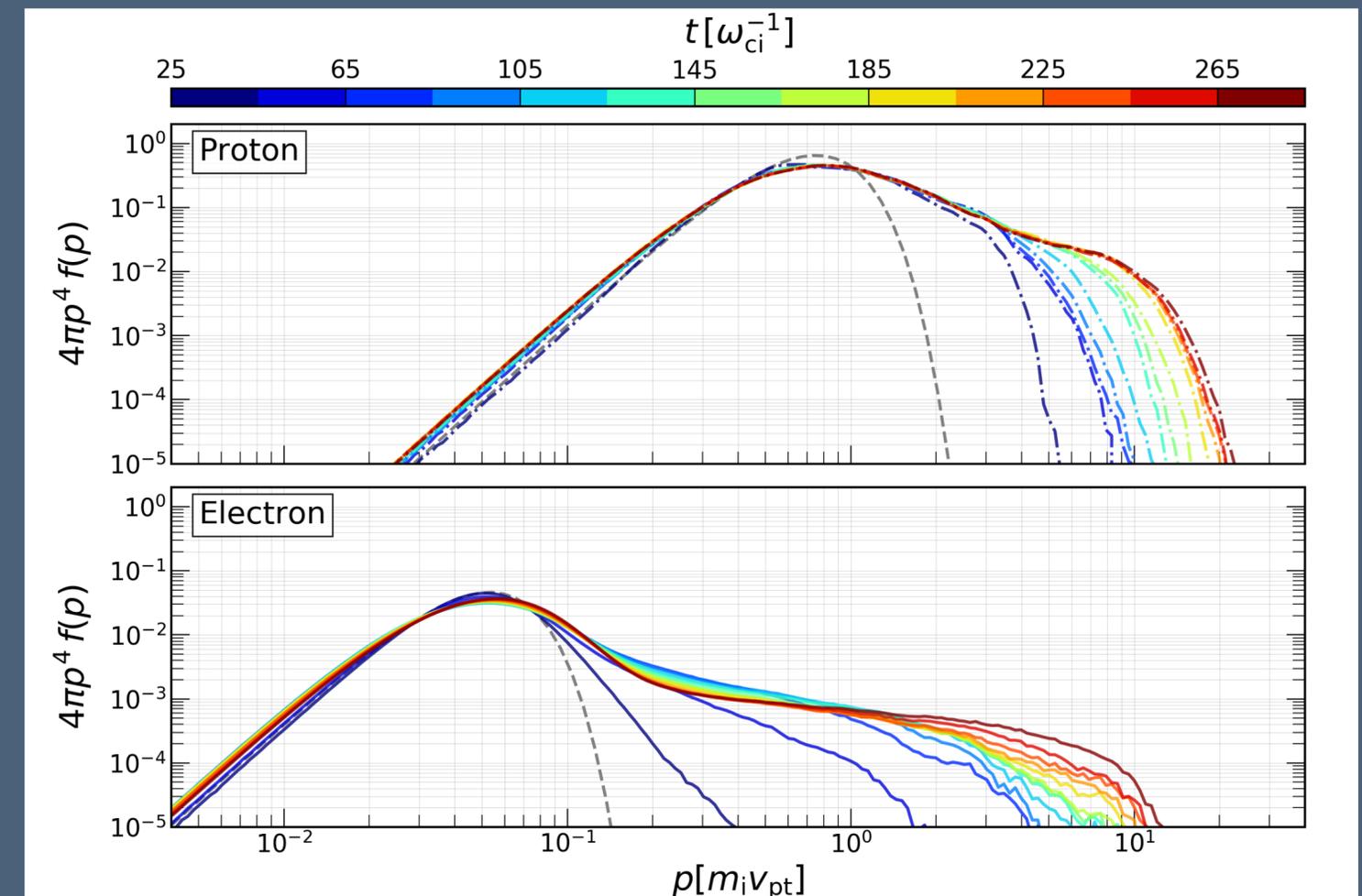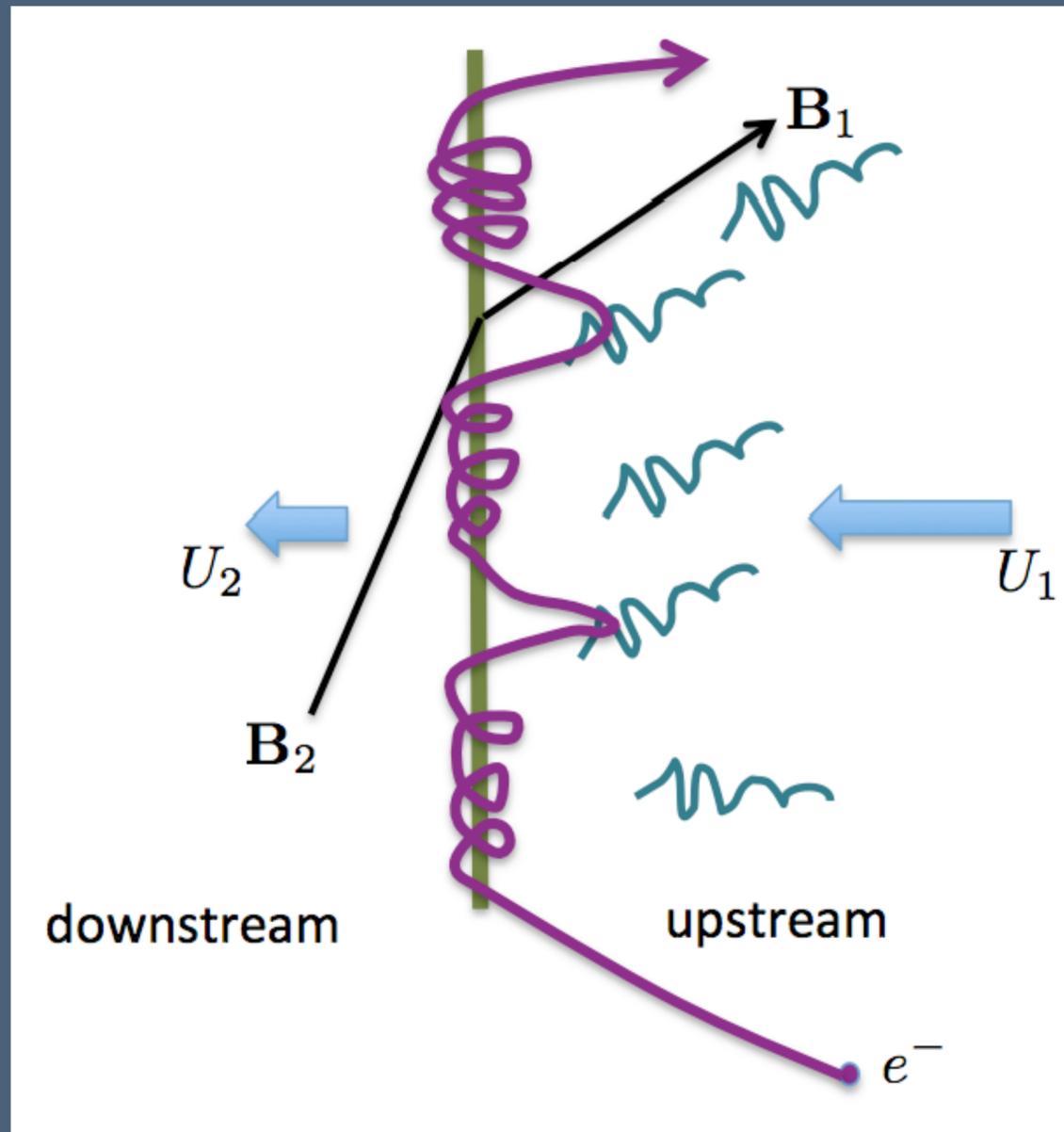
e/p ratio:

- Construct minimal model for e- energization (Gupta, Caprioli, AS 25)
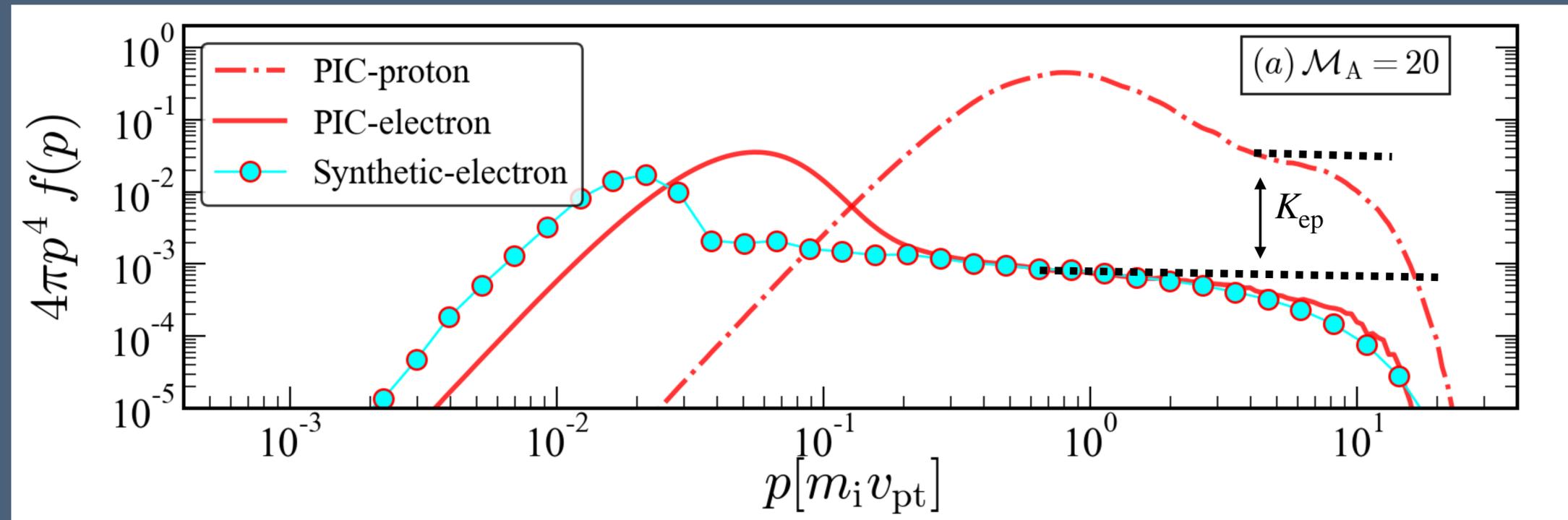
Electron-to-proton ratio:

$$K_{ep} \equiv \frac{f_e(p)}{f_i(p)} \approx \frac{\eta_e}{\eta_i} \left(\frac{p}{p_{inj}} \right)^{q_i - q_e} \frac{1}{(m_i/m_e)^{(q_e-3)/2}},$$

For the spectral indices $q_e = q_i = 4$, and $m_i/m_e = 1836$, $K_{ep} \sim 10^{-3}$ Consistent with SNR observations

Shock acceleration: emerging picture

Acceleration in laminar field for non-relativistic shocks:

quasi-parallel -- accelerate both ions and electrons (Caprioli & AS, 2014abc; Park, Caprioli, AS 2015; Gupta, Caprioli, AS 2024)

Energy efficiency of ions 10-20%, number ~few percent; $K_{ep} \sim 10^{-3}\text{-}10^{-2}$

quasi-perpendicular -- accelerate mainly electrons (Guo, Sironi & Narayan 2014; Xu+20)

Electron energy efficiency ~ up to 10-20 percent, number <~5% (Xu, Caprioli, AS 20); but may be 1D is too efficient
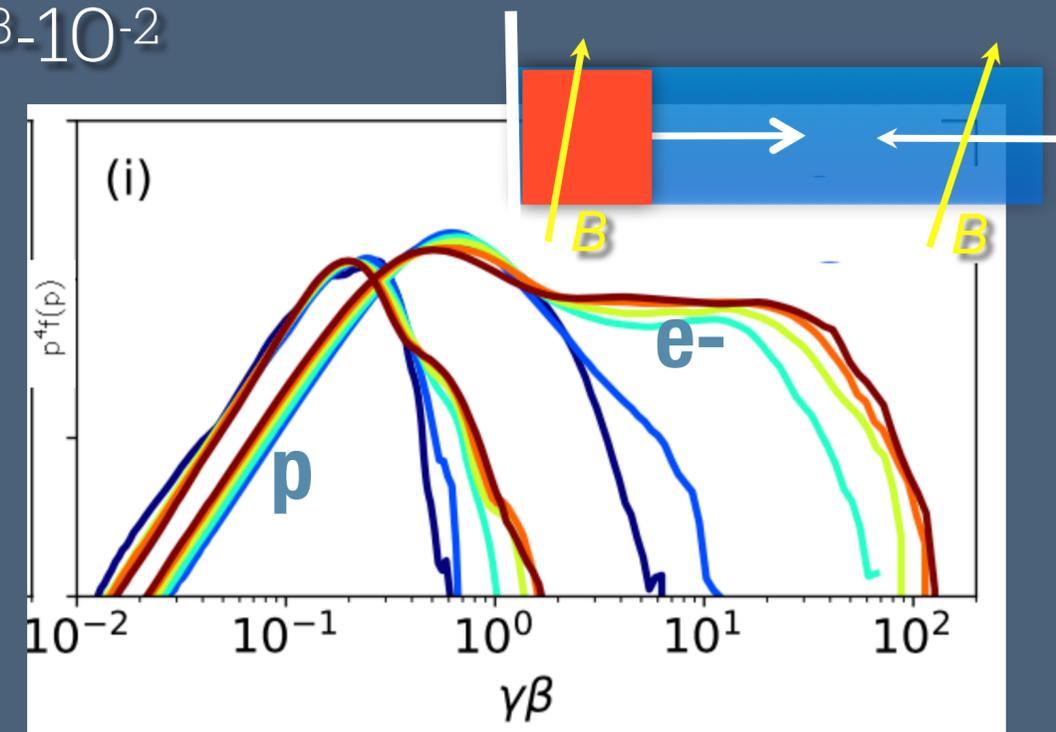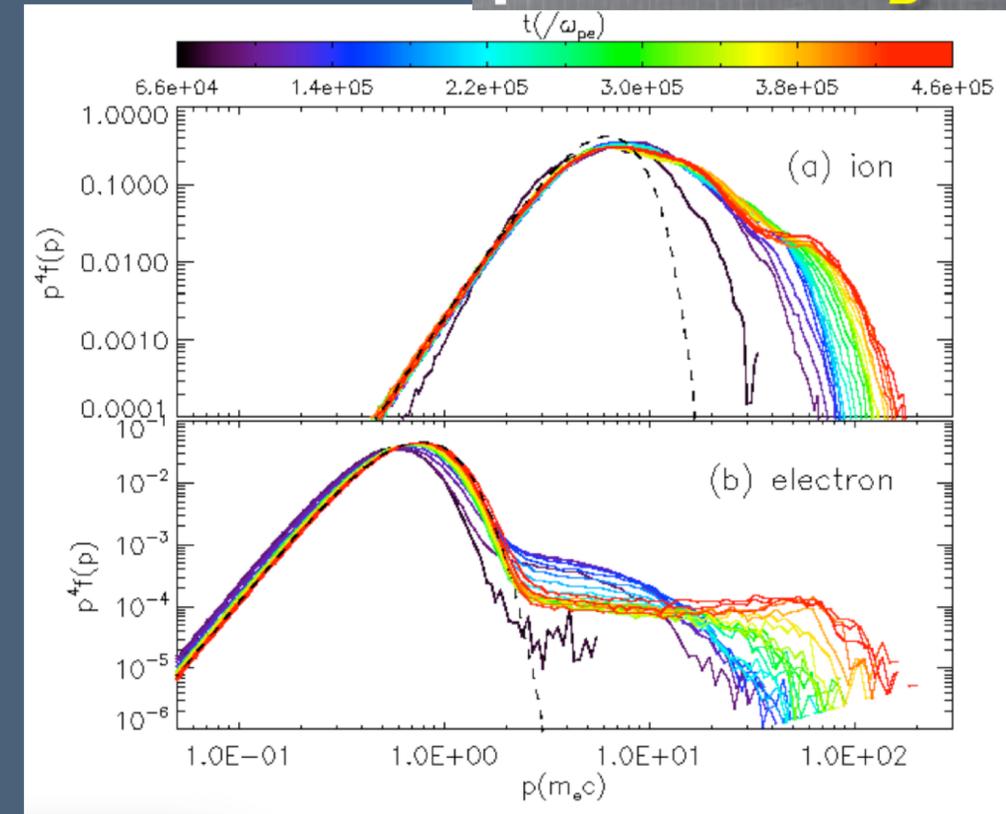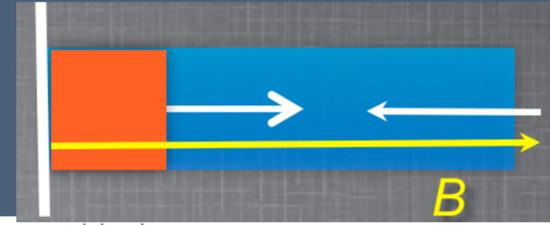
Caveats

- All conclusions so far are based on lower Mach numbers, Ma < 40.

- High Mach number frontier — new effects and nonlinear structures

- Quasi-perp shocks at high Mach number accelerate ions better in 3D (work by Orusa et al)

- This may affect conclusions about e- acceleration at q-perp shocks
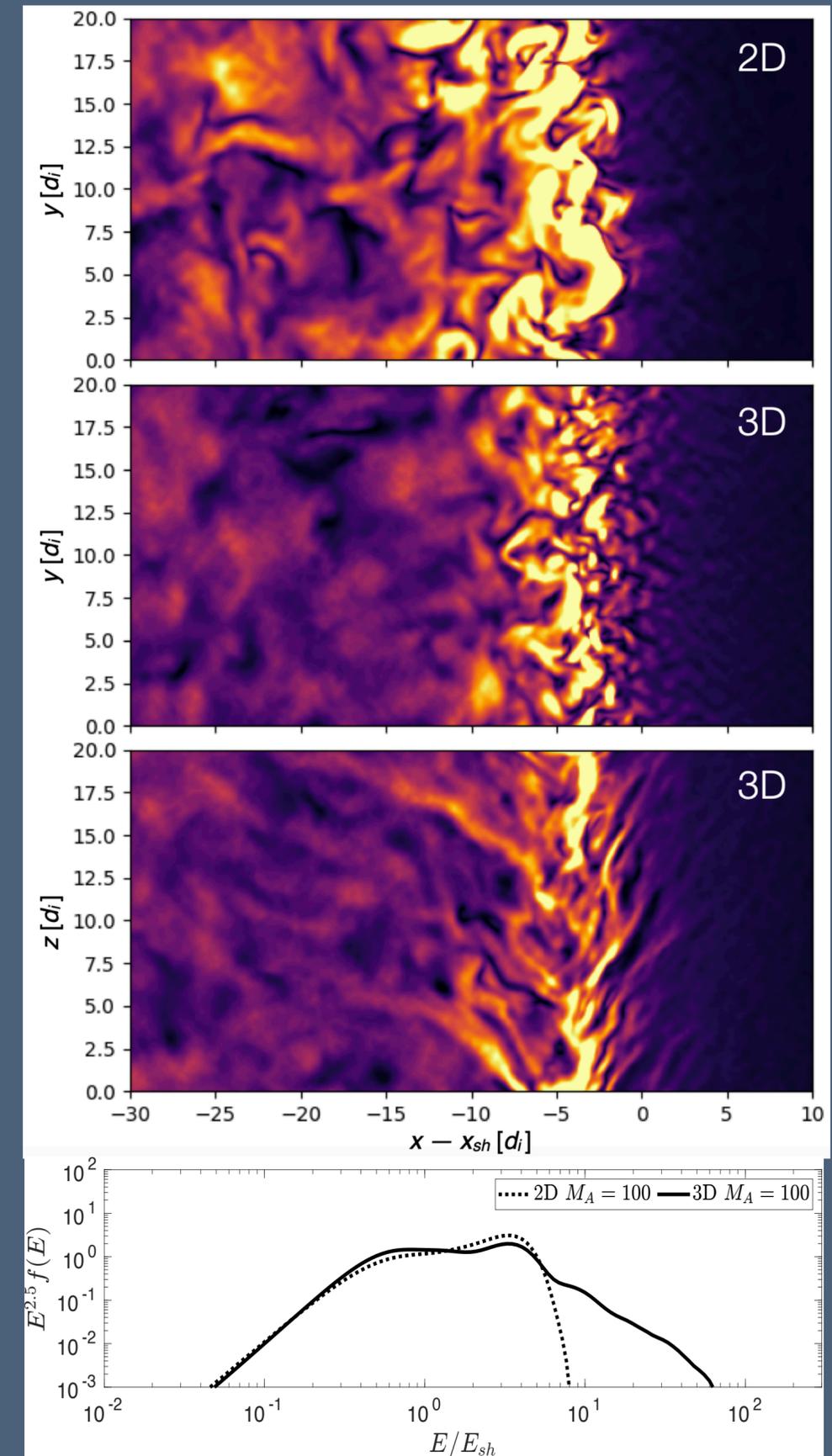
SHOCK ACCELERATION

Diffusive shock acceleration (DSA) predictions

✓ 1) self-generated turbulence, resulting in diffusion of particles in the upstream, balanced by advection towards the shock

✓ 2) universal p^{-4} spectrum downstream (for strong shocks)

✓ 3) injection fraction for e and p not known — determined by microphysics?

4) nonlinear effects (backreaction on the flow)

Feedback mechanisms

Are injection levels always fixed or do they respond to the state of magnetic turbulence? There must be regulation and feedback.

In the order of increasing energy in accelerated particles:

Magnetic obliquity affects chances of reflection from the shock: larger obliquity ok for electrons, bad for ions.

Global deceleration of upstream — origin of nonlinear DSA theory (Blandford & Eichler, Drury)

Shock reformation, SLAMs (Short Large Amplitude Magnetic Structures)

High Machs: Short Large Amplitude Magnetic Structures (SLAMS)

Q-par Ma=20: large waves in the upstream

Q-par Ma=80: SLAMs lead to steeper electron spectra?
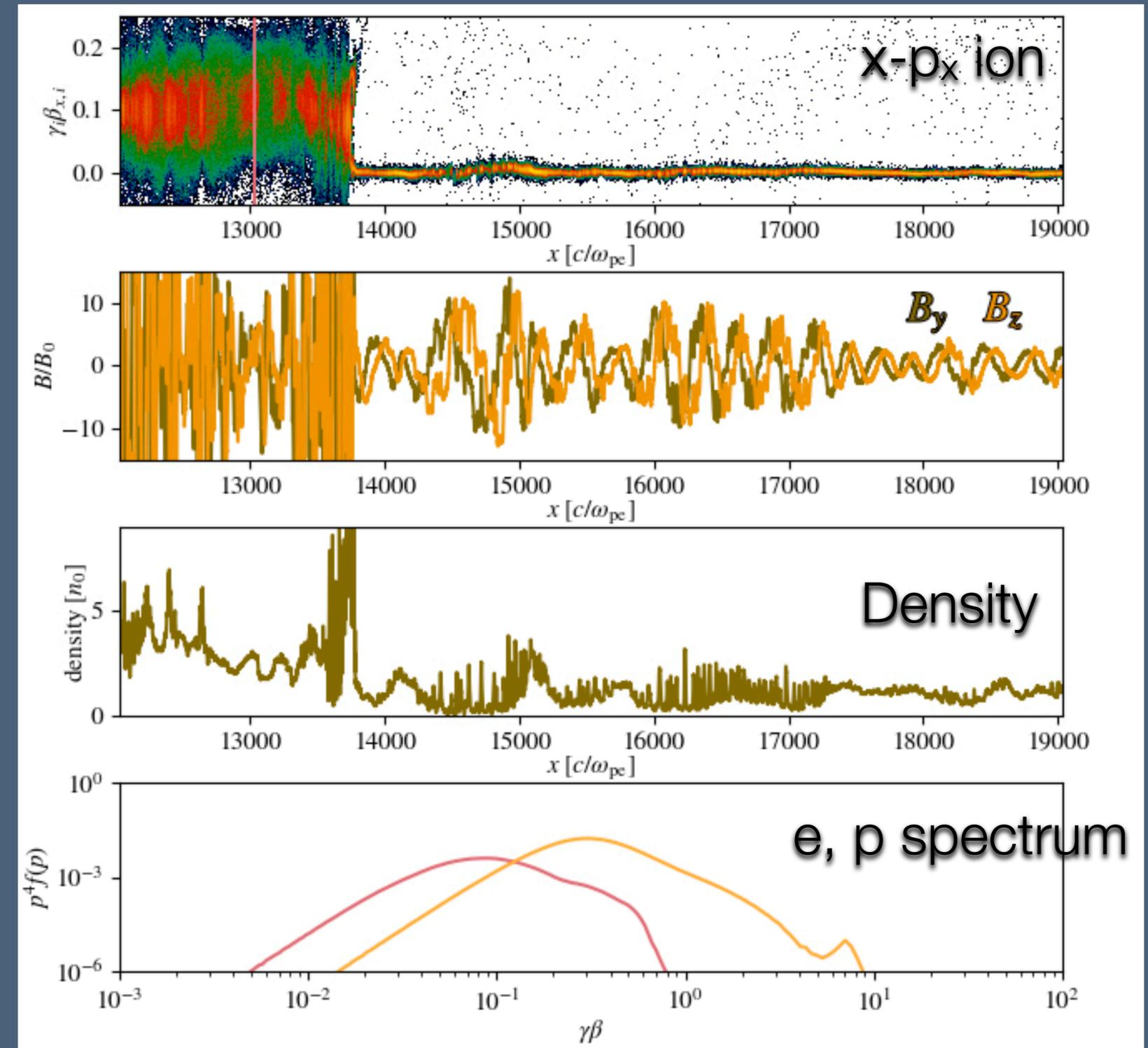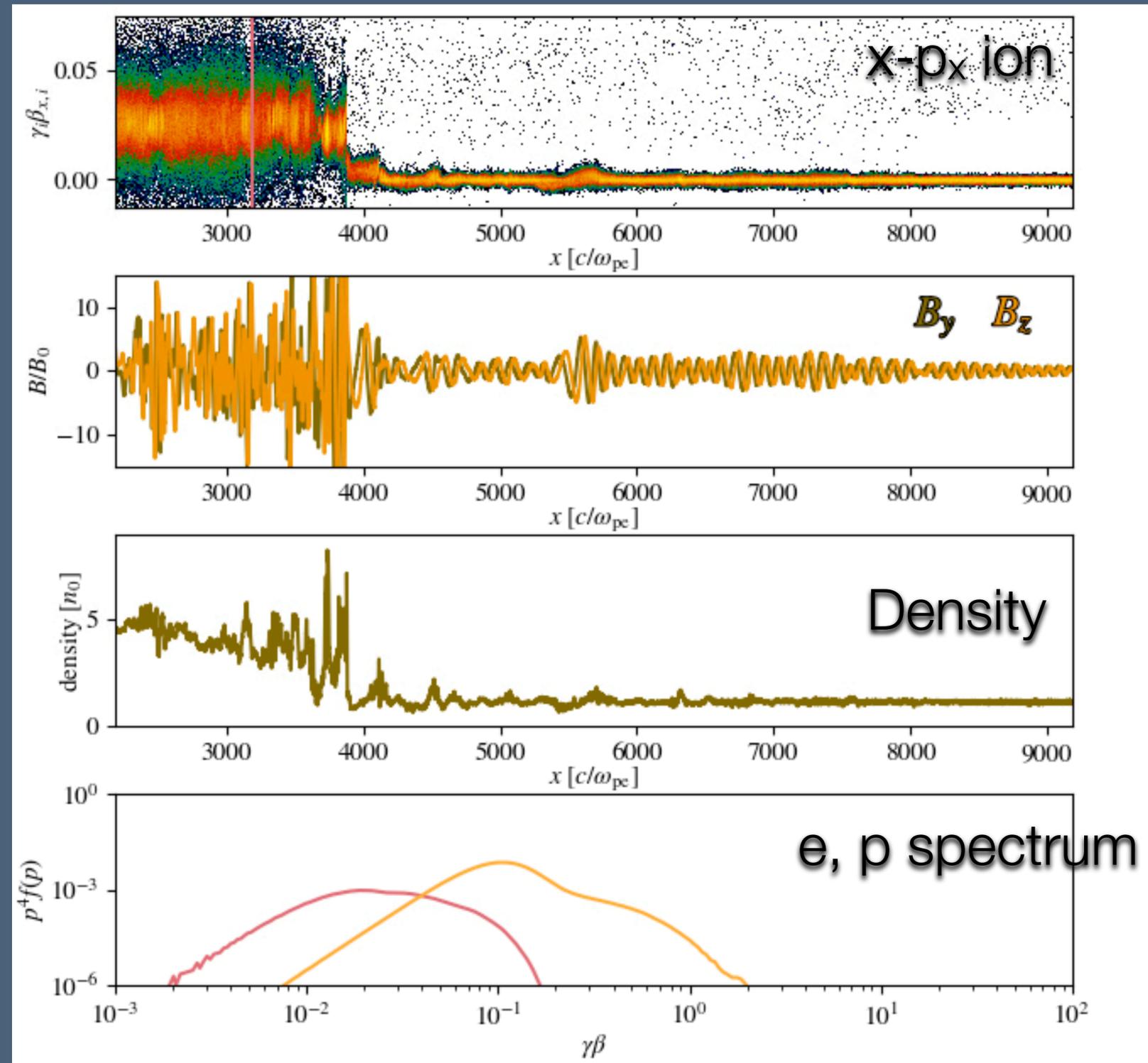
SLAMs and trapping

Particle tracking in a SLAM simulation shows trapping and "superluminal" regions (Zekovic, AS, Hemler 25)
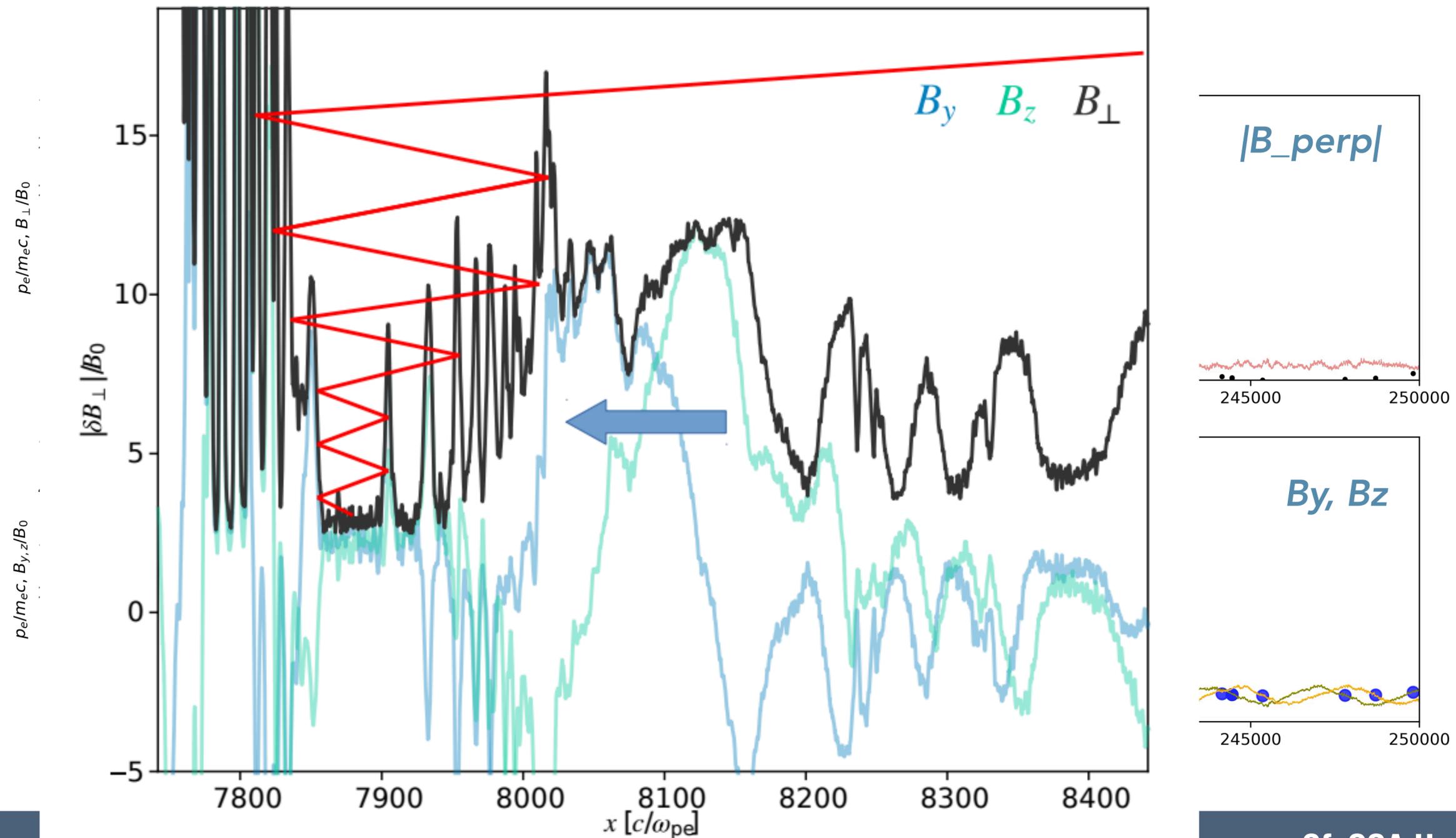
Electron Spectra
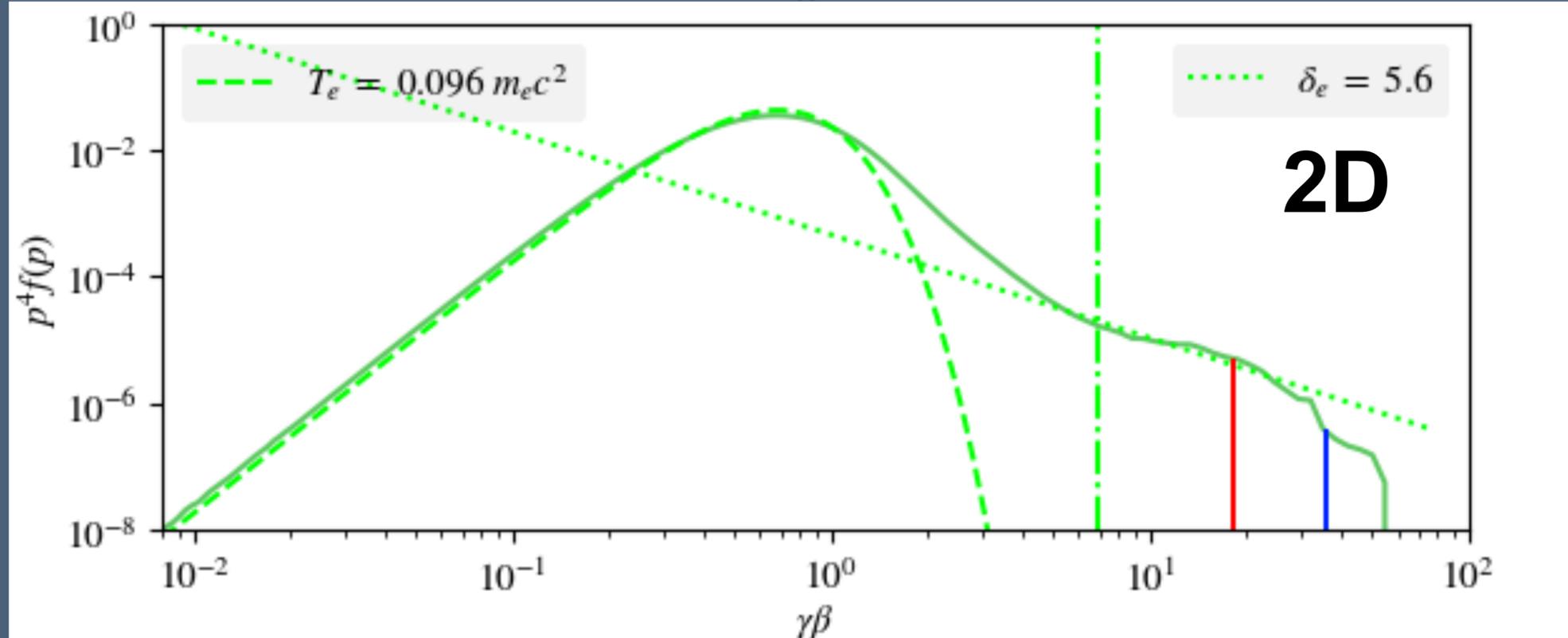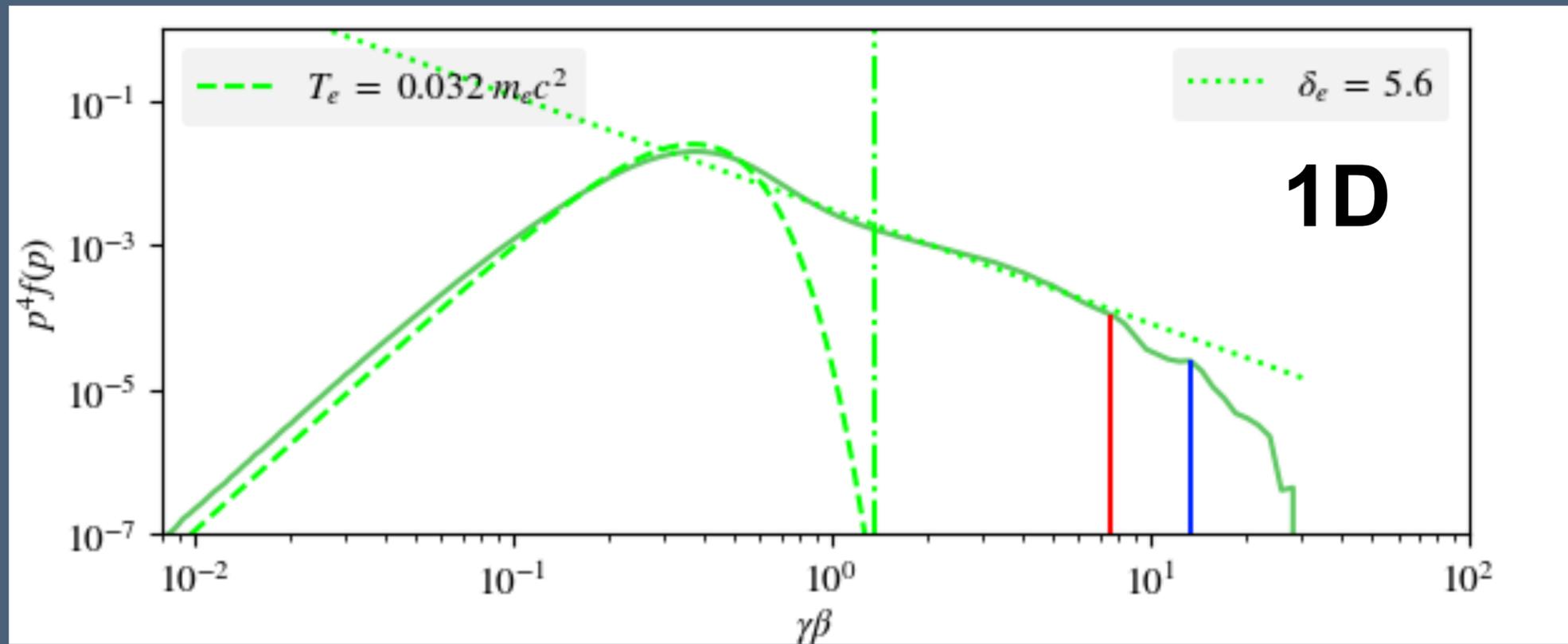
We observe steepening of electron spectrum to $p^{-5.6}$.

Combination of SDA and DSA — come with different time dependence and lead to steeper spectra in nonrel shocks.

Expect steepening till energy resonant with the wavelength of SLAMS. Beyond that — join DSA spectrum.
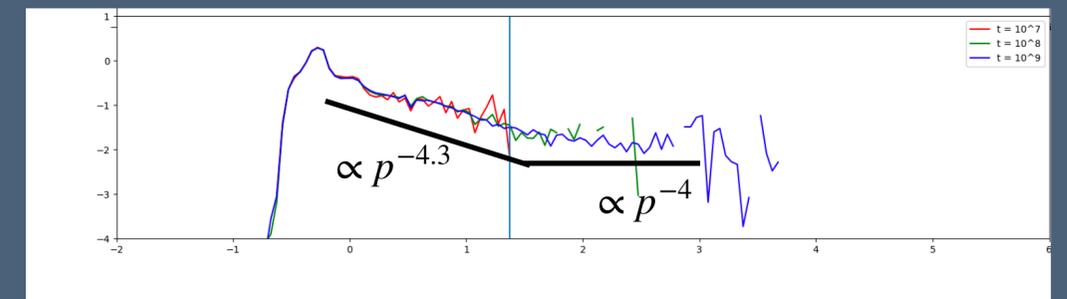
Resonance with SLAMS

(Zekovic, AS, Hemler *2025*)

Mach=80 quasi-parallel shock: 2D

/scratch/09021/tg883203/2d.w800.parallel.comp5.ppc128.mime32.sig8.89e-5.v0.1.M80/output/*.124 at time t = 111600 ω_{pe}^{-1}
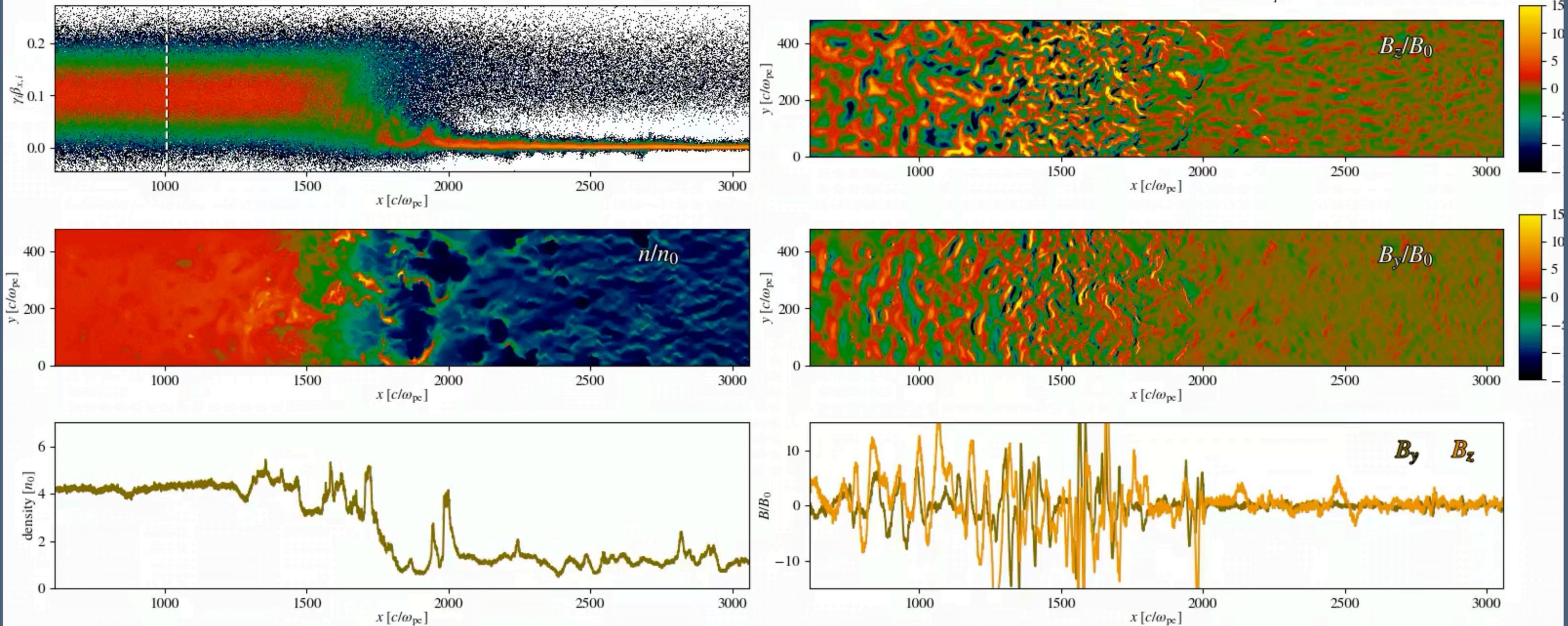
(Zekovic, AS, Hemler 2025)

SLAMS form: short large-amplitude magnetic structure. In multi-D cause intermittent cavitation

SLAMS and Electron Acceleration

Large amplitude (>10) SLAMs are possible in high Mach # shocks (M_A>80).

To get a steep e- spectrum:

> High Mach # shock with SLAMS

> Quasiperiodic Shock Acceleration (QSA) — electrons trap between shock and first SLAM. Probability of escape is different than in DSA, so steep spectrum.

> Superluminality (expected in shocks of young SNRs). Electrons are stuck for longer near the shock, so transition to DSA is delayed to higher energy.

Scaling: expect steep electron spectra (~E^{-3}) up to ~10GeV, switching to DSA at higher energy

Next steps: multiscale

Although we see the beginnings of nonlinear feedback, the current computing is insufficient to push kinetic simulations much further.

We need to resolve both shock physics for injection and far upstream for wave growth (above and below Larmor radius of CRs)

We need to study larger scale multi-dimensional effects

We need to add upstream turbulence and potential non-local effects from field-line connections to different parts of the shock, or global curvature of the shock (see, e.g. Guy & Giacalone '15)

Hybrid and PIC scheme spend most of their time evolving "boring" thermal particles. Can we bypass/accelerate this? … Yes!
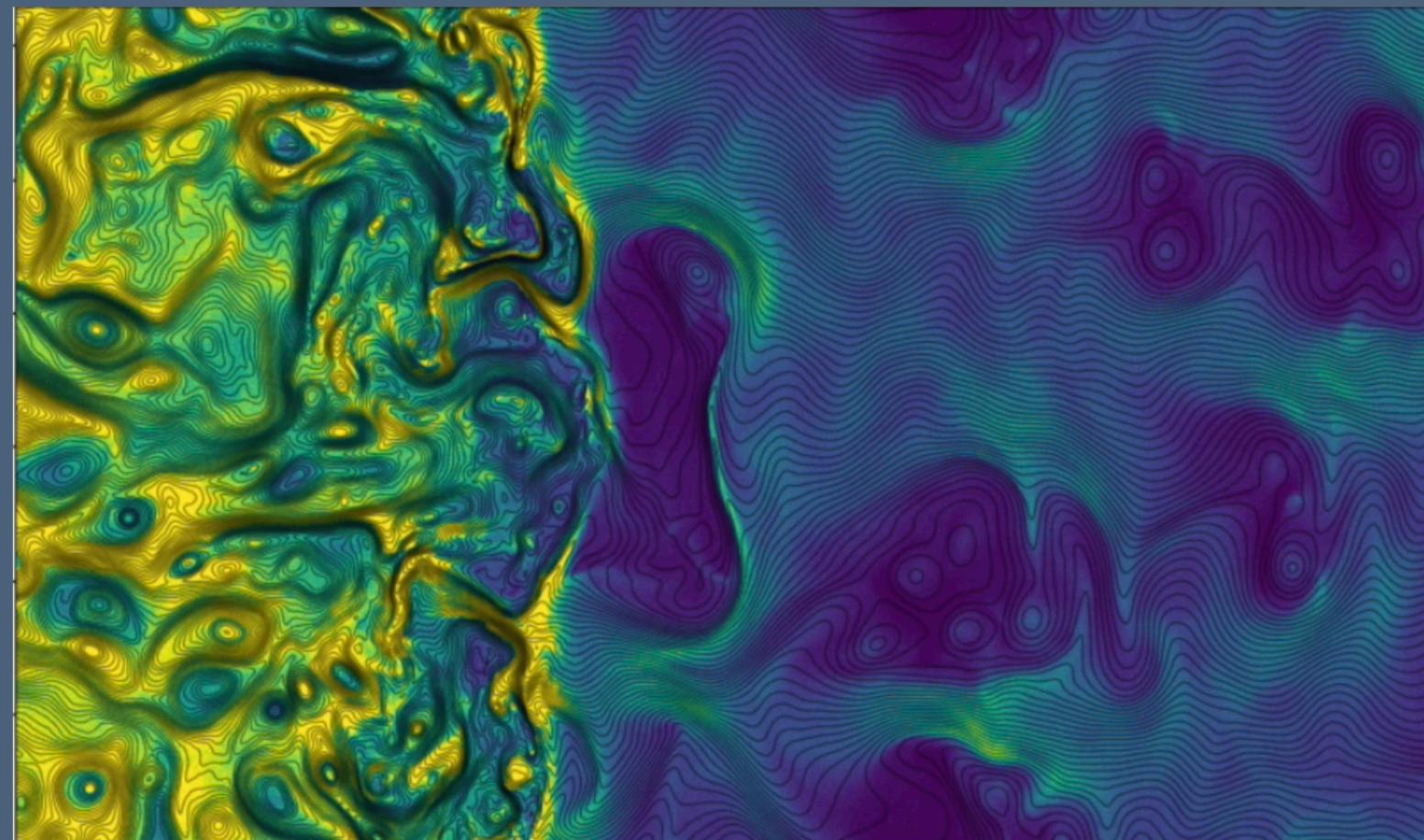
New ideas: MHD-PIC: MHD with CR particles

Full equations for the CR particles:

$$\frac{d(\gamma_j \boldsymbol{u}_j)}{dt} = \frac{q_j}{m_j}\left(\boldsymbol{E} + \frac{\boldsymbol{u}_j}{c} \times \boldsymbol{B}\right)$$

Relativistic Boris pusher, subcycling (~10 particle steps per MHD).

Specify the numerical speed of light c >> any velocities in MHD.

Full equations for the gas:

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{vv} - \boldsymbol{BB} + \mathbf{P}^*) = \text{- Lorentz force on the CRs}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = \text{- energy change rate of the CRs}$$

Momentum and energy source terms reflect Newton's 3rd law.

We coupled particles to Athena MHD code   Bai, Caprioli, Sironi, AS (2015)
Similar recent codes by   van Marle et al 2017; Mignone et al 2018

Example: constant fraction of flow is injected as particles at the shock: nonlinear evolution, but no feedback on injection.

"Injecting at a shock" is hard to define for turbulent shocks.

Log(Density)

Log(T)

Bx field

By field

Bz field

Bai et al 2015, cf. van Marle et al 2022
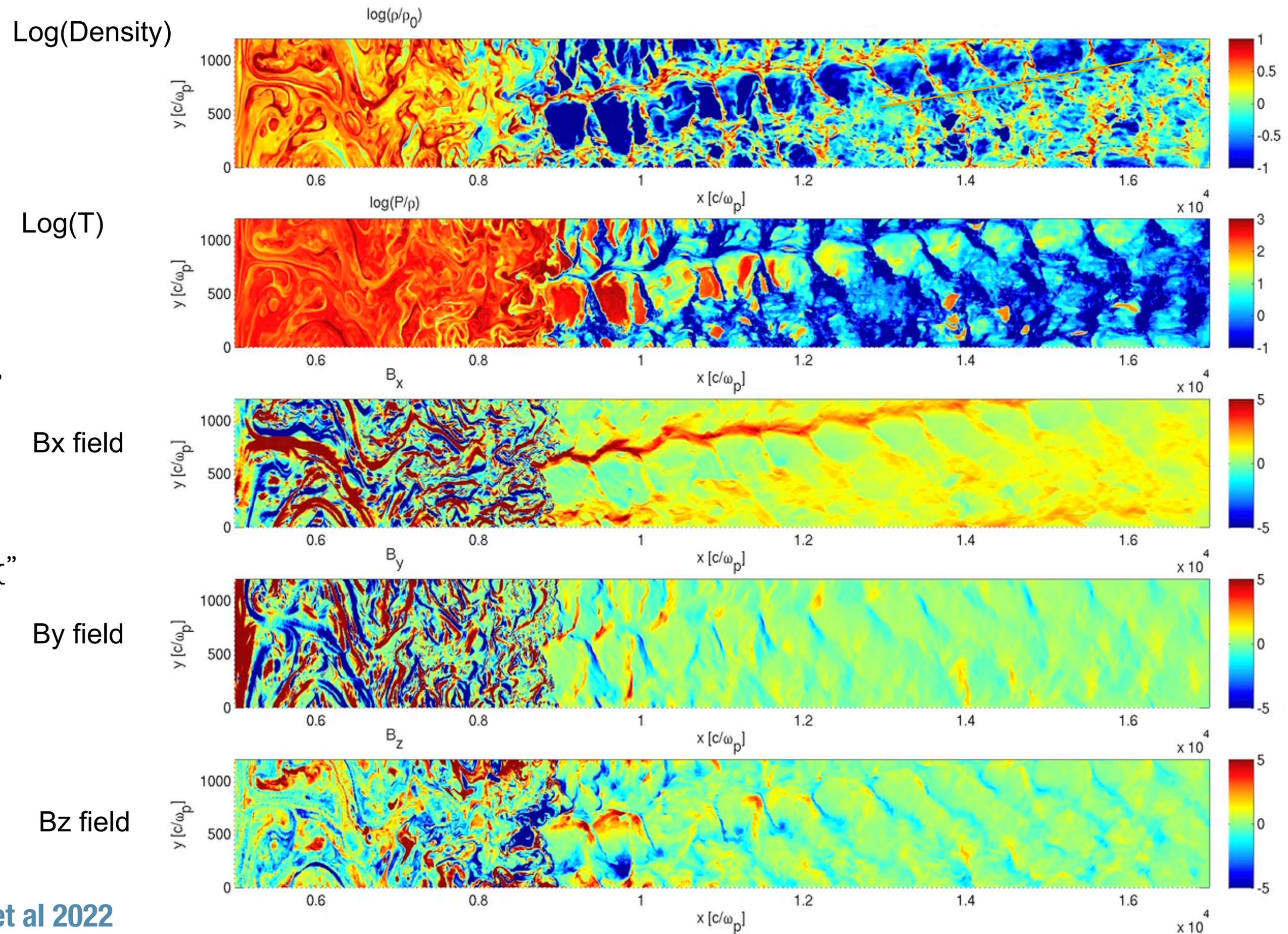
New Particle Injection Prescription

Simulate an MHD shock

Inject hot test particles in the shock upstream, representing pre-heating by upstream instabilities.

Promote test particles to real particles if they are reflected & accelerated

Remove un-promoted test particles far upstream/downstream

MHDPIC 2D SIMULATION: TIME=56.0
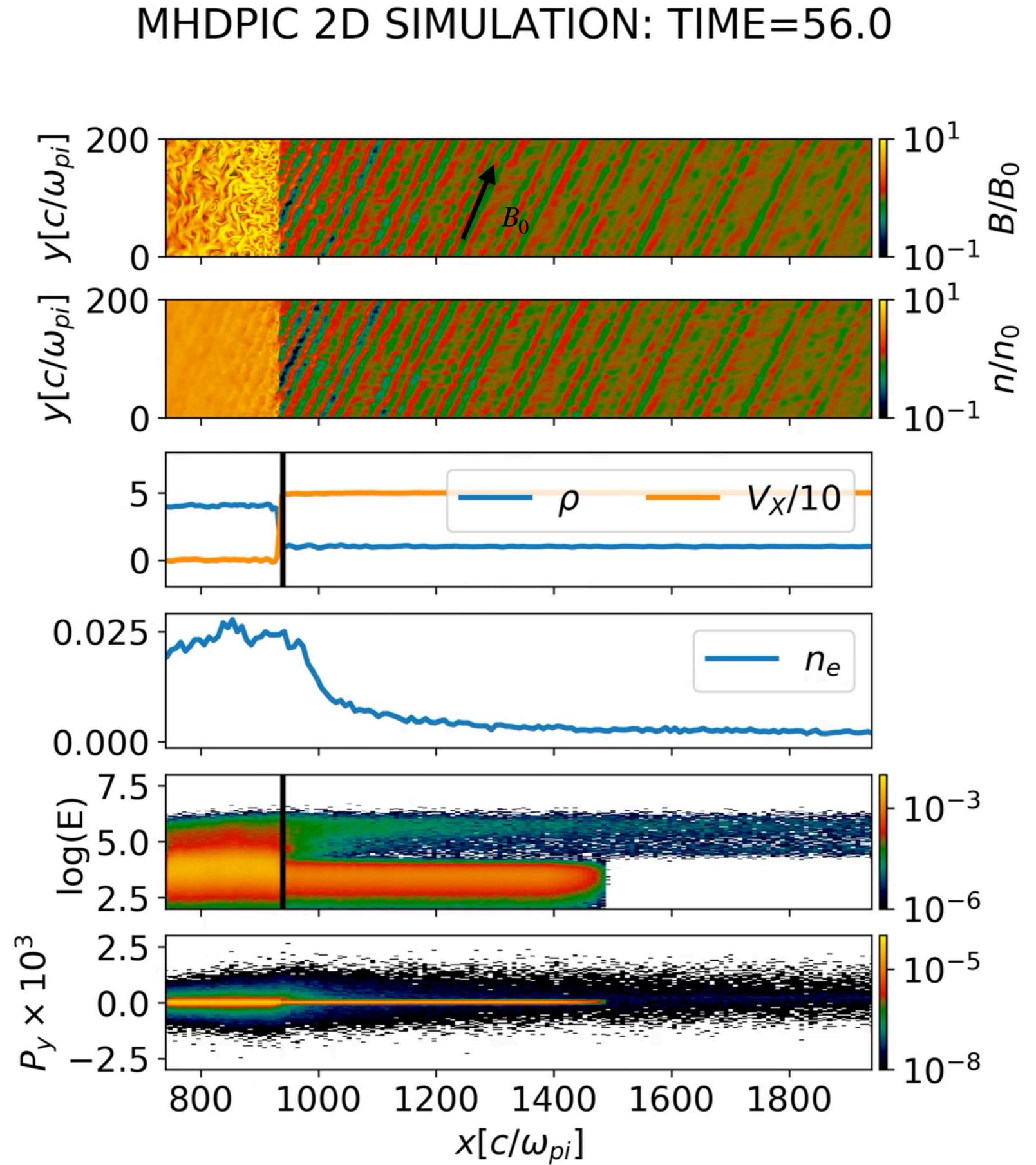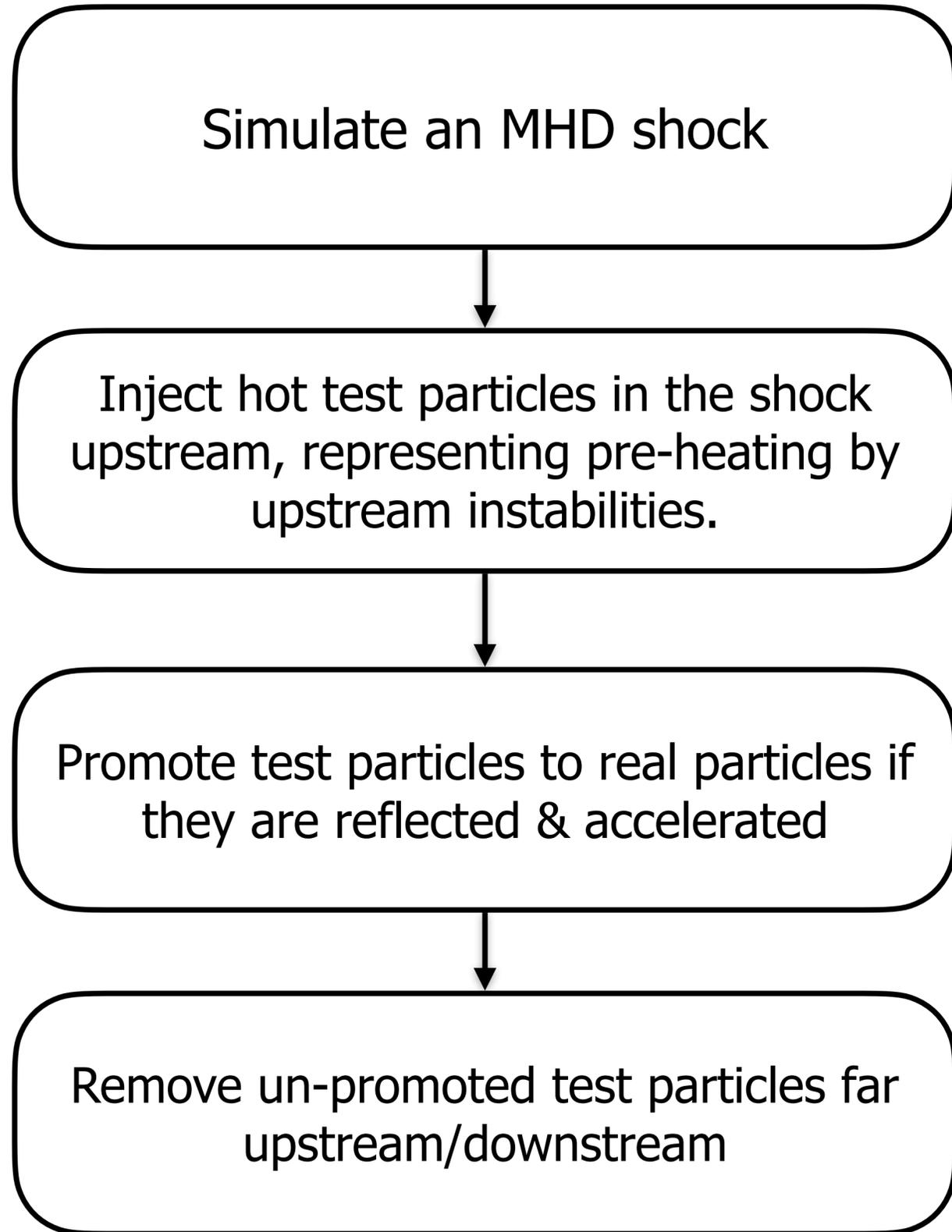
Quasi-parallel M_A=50 shock

Test particles promoted when they accelerate to 3x the speed of the shock.

X-domain: 100x larger than in PIC

file number = 43; $t = 3000 + 1075.0\,[\omega_{ci}^{-1}]$, $v_0 = 50.0$, $x_{sh} = 69902.5\,[d_i]$, $(n_{cr}/n_g)_{up} = 0.100$, ppc = 1000, $\Delta = 5.0\,d_i$
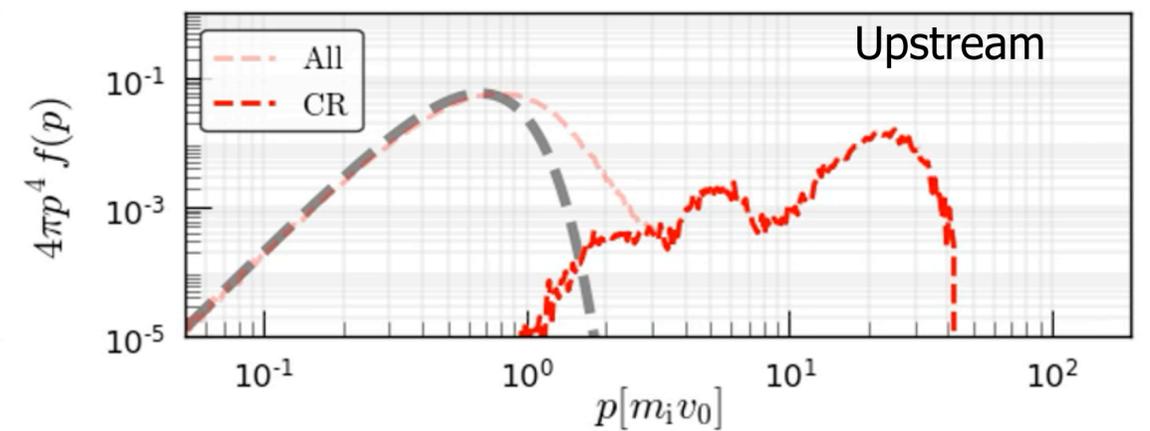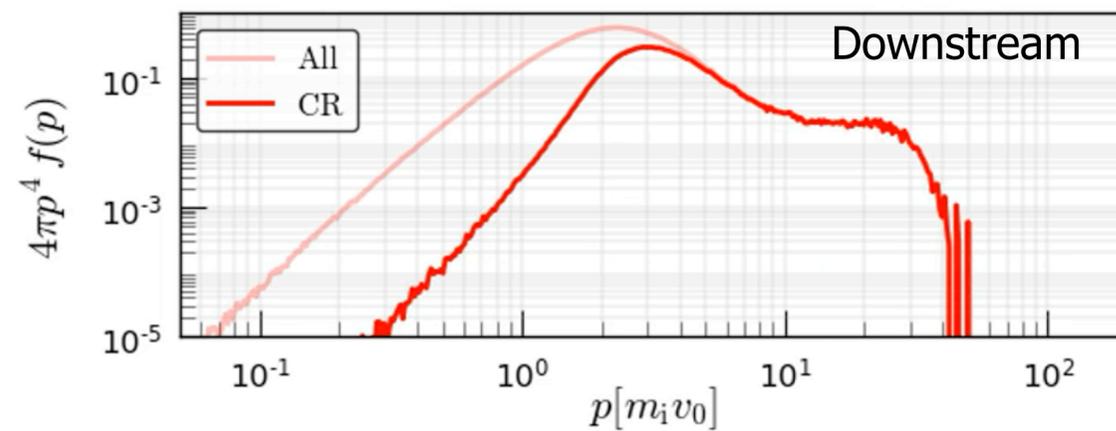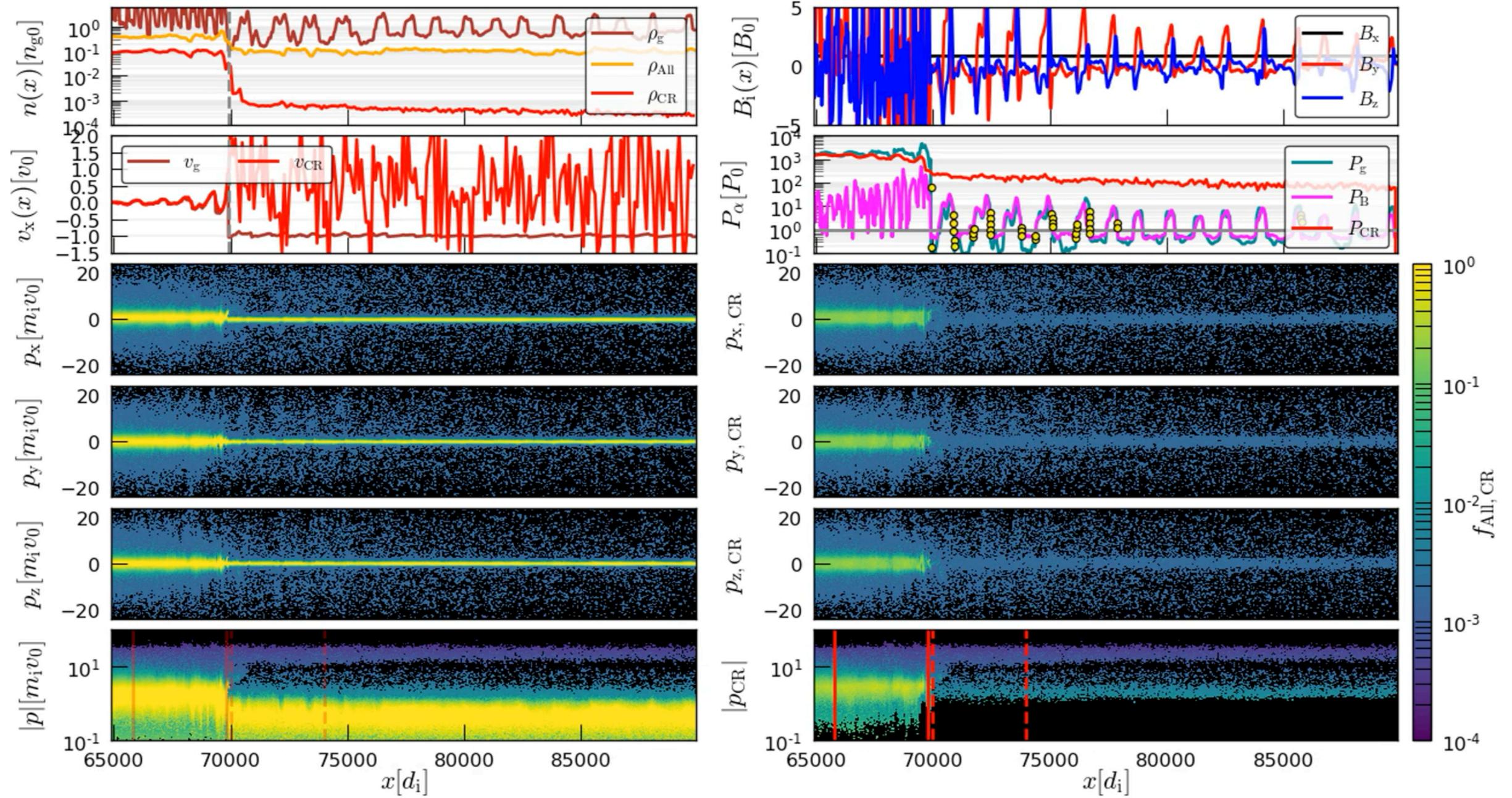
Downstream

Upstream

Quasi-parallel M_A=150 shock

Test particles promoted when they accelerate to 3x the speed of the shock.
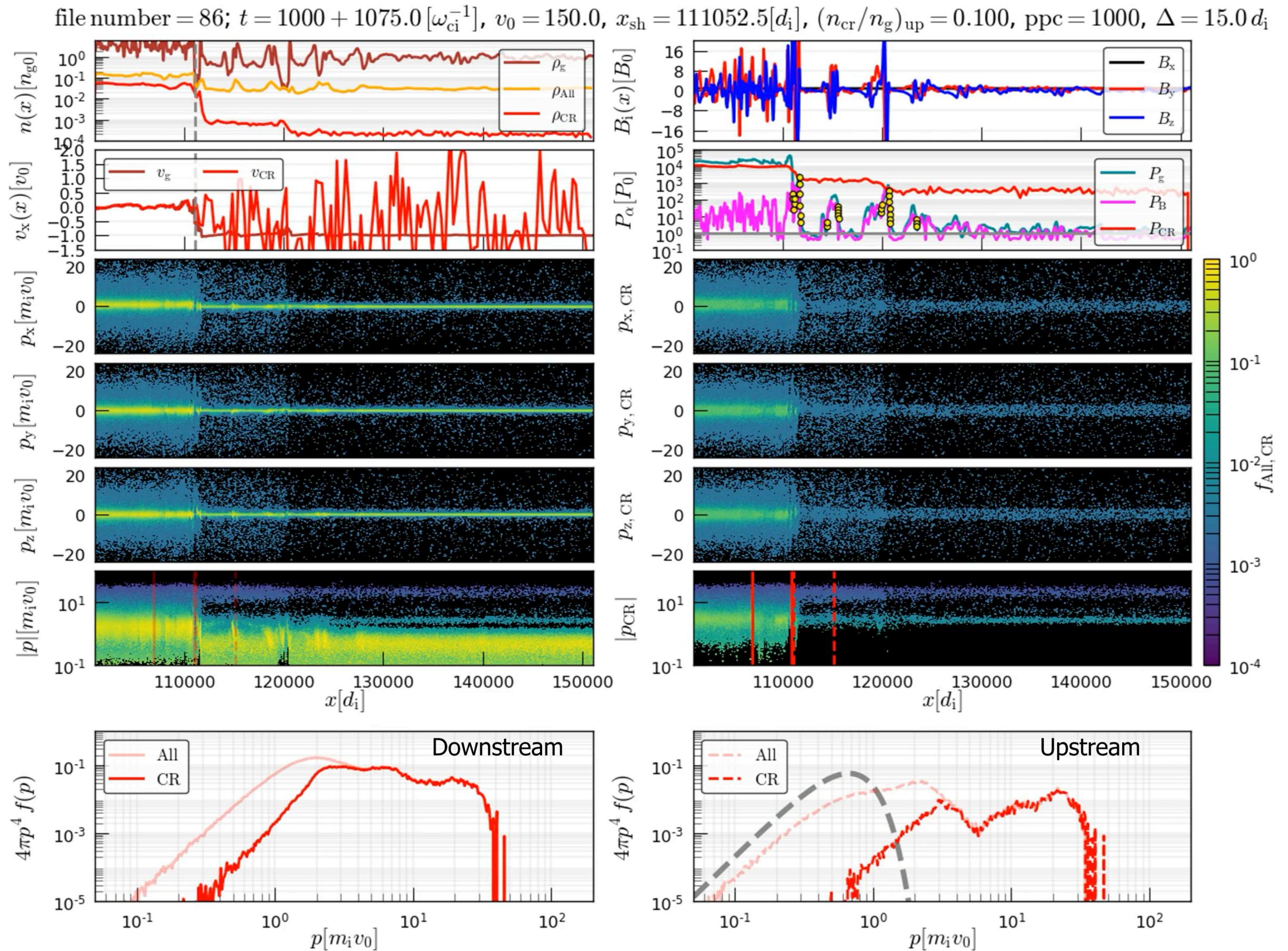
Periodic "reformation"

file number $= 86$; $t = 1000 + 1075.0 \, [\omega_{ci}^{-1}]$, $v_0 = 150.0$, $x_{sh} = 111052.5 \, [d_i]$, $(n_{cr}/n_g)_{up} = 0.100$, ppc $= 1000$, $\Delta = 15.0 \, d_i$

Downstream

Upstream

Quasi-parallel $M_A=50$ shock

Comparison of 4 different levels of injection: from 0.5% to 3% of all particles

Promotion condition:

velocity of particle in upstream frame > 3 * v0

Is there self-regulation?

Spectra do not strongly depend on the available charge supply

file number = 150; $t = 300 + 3000\,[\omega_{\rm ci}^{-1}]$, $v_0 = 50.0$, $x_{\rm sh} = 59315, 54995, 54475, 54585\,[d_{\rm i}]$
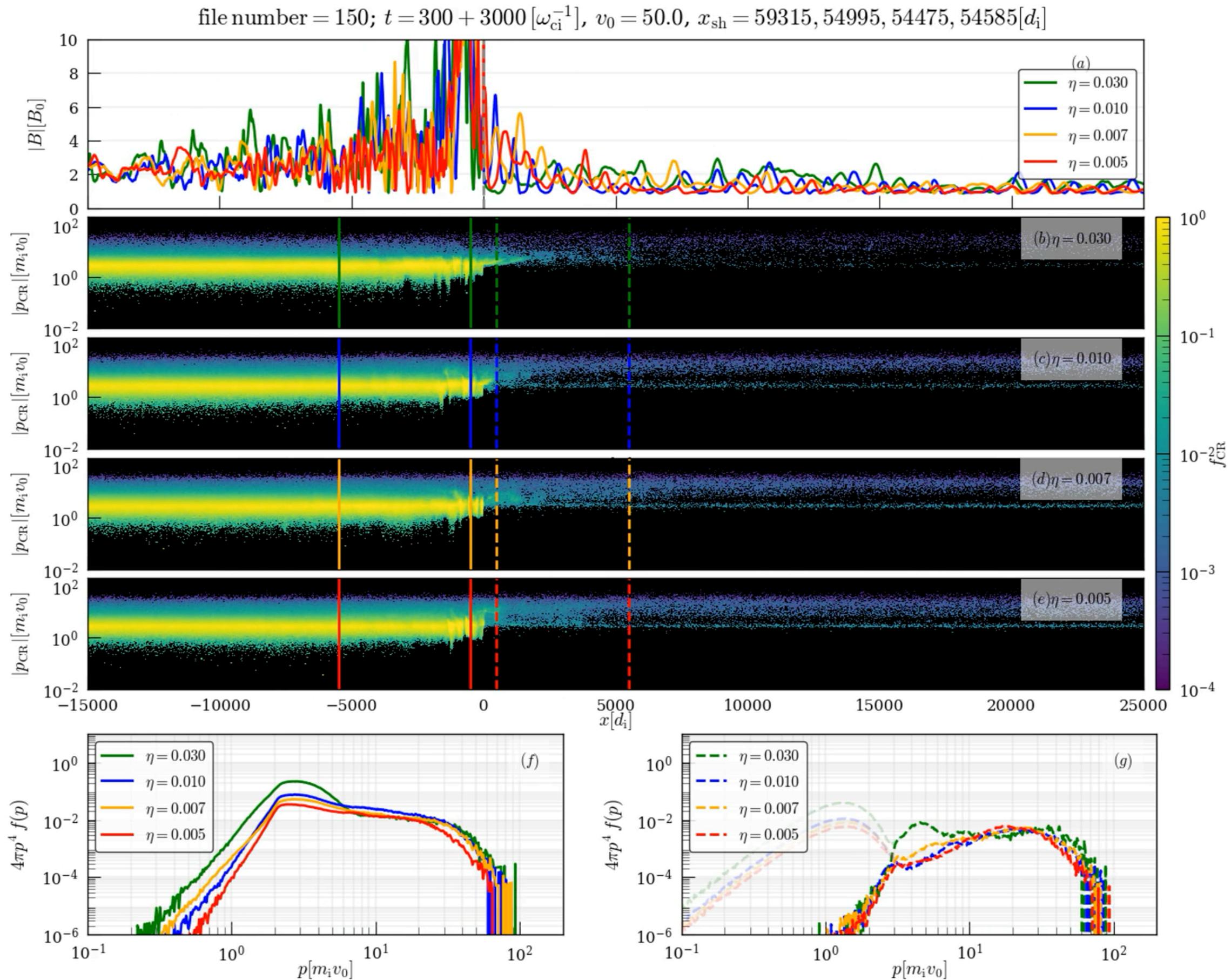
Quasi-parallel M_A=50 shock

Start with already promoted particles in the upstream

SLAMS trap low energy particles, controlling normalization of the power-law

Time-dependent trapping and advection of accelerated particles

Nonlinear backreaction
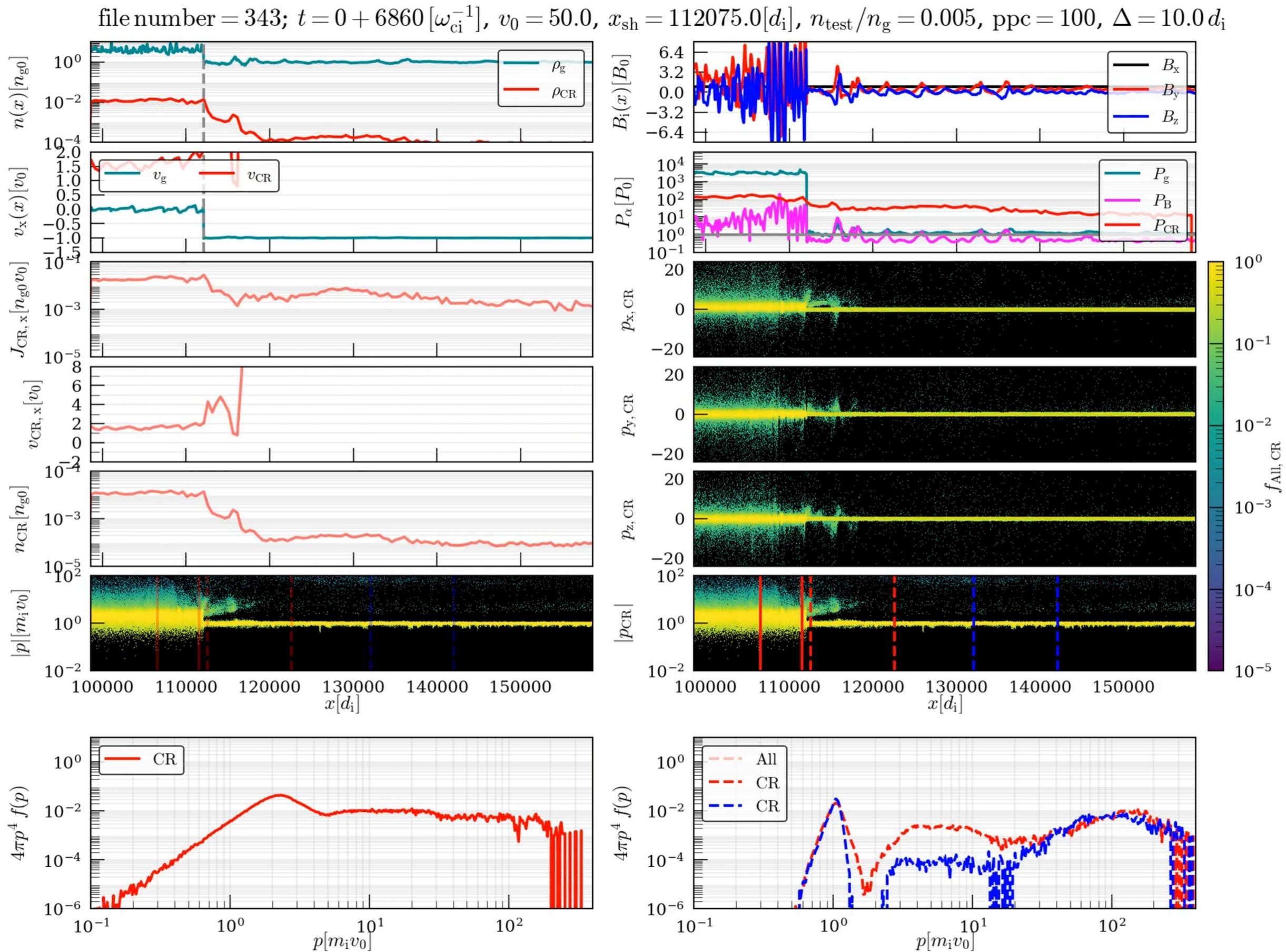
- Large-amplitude upstream waves have periodic modulation — SLAMs come in trains. Sometimes field is strong, sometimes not.

- Periodically particles are trapped between the shock and SLAM and are advected downstream. The field inclination is nearly superluminal — can trap particles well.

- This regulates effective injection — even if more ions are "promoted" into acceleration, they don't make it to the far upstream. As injection fraction increases, far upstream turbulence saturates.

- Regulation exists for finite range of reflected particle flux — too small and turbulence is weak; intermediate — self-regulation; too high — strong modification of the shock (shock speed-up). Energy in tail ~20%.

- We do not see canonical gradual upstream deceleration in strong shocks as expected in nonlinear-DSA.

- SLAM-mediated advection can cause steeper spectra in e and p — interesting for young SNRs.
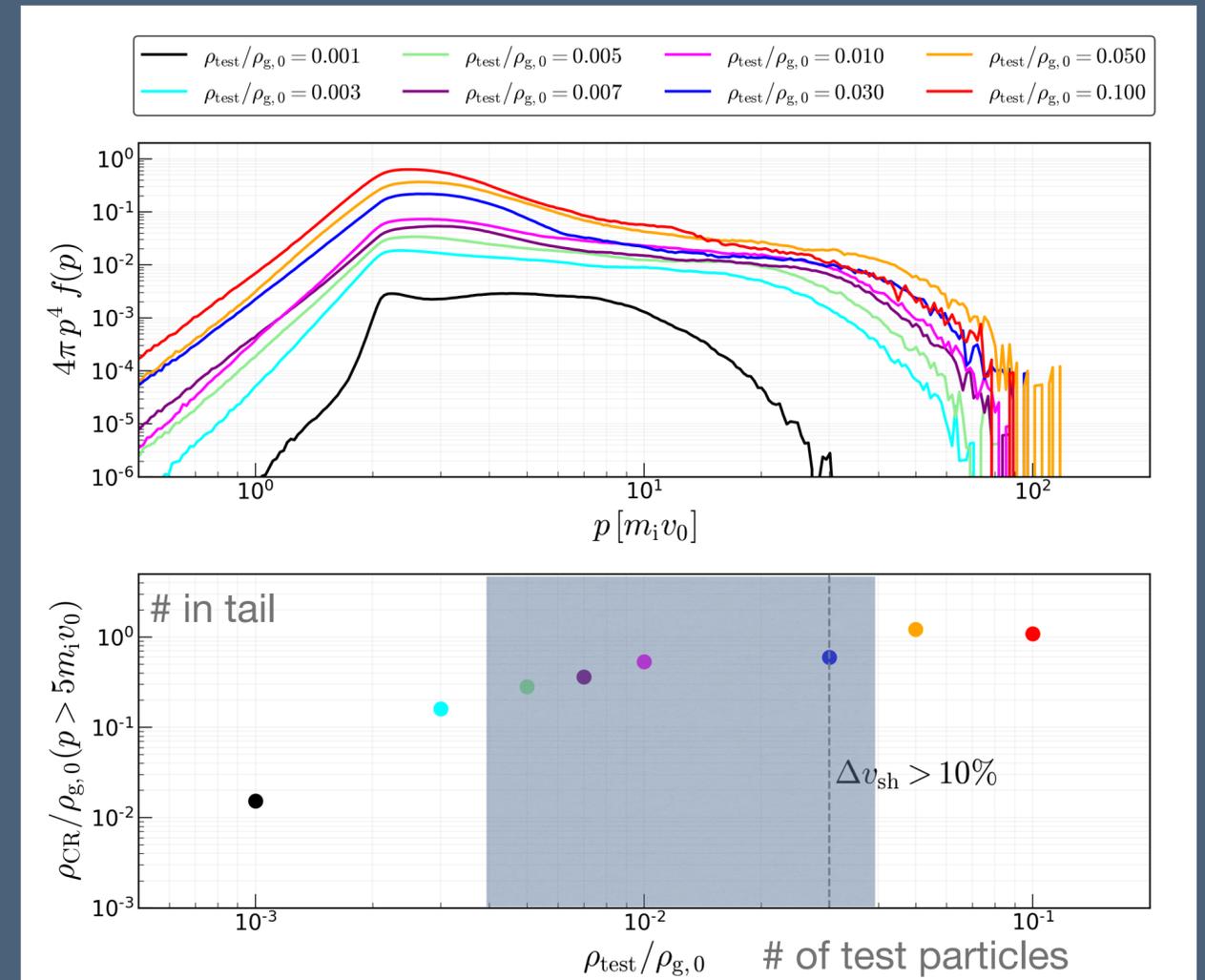
Conclusions

- Simulations predict distinct regimes of shock formation: unmagnetized (Weibel) shocks, magnetized shocks, and high-Mach # "turbulent" magnetized shocks.

- Acceleration efficiency is set by physics of the shock transition or by collective feedback of turbulence

  - Local injection depends on field strength and orientation: 1% by number (p), 10% by energy

  - When magnetic amplification is large, shock surface is "turbulent" and intermittent.

  - Self-regulation is possible at high Mach numbers

  - Long term effects of self-regulation of injection, microphysics of heating in strong waves need to be studied

- MHD-PIC with self-consistent injection prescriptions is a promising technique for studying long-term evolution of shock acceleration.

- Multi-D effects to come!