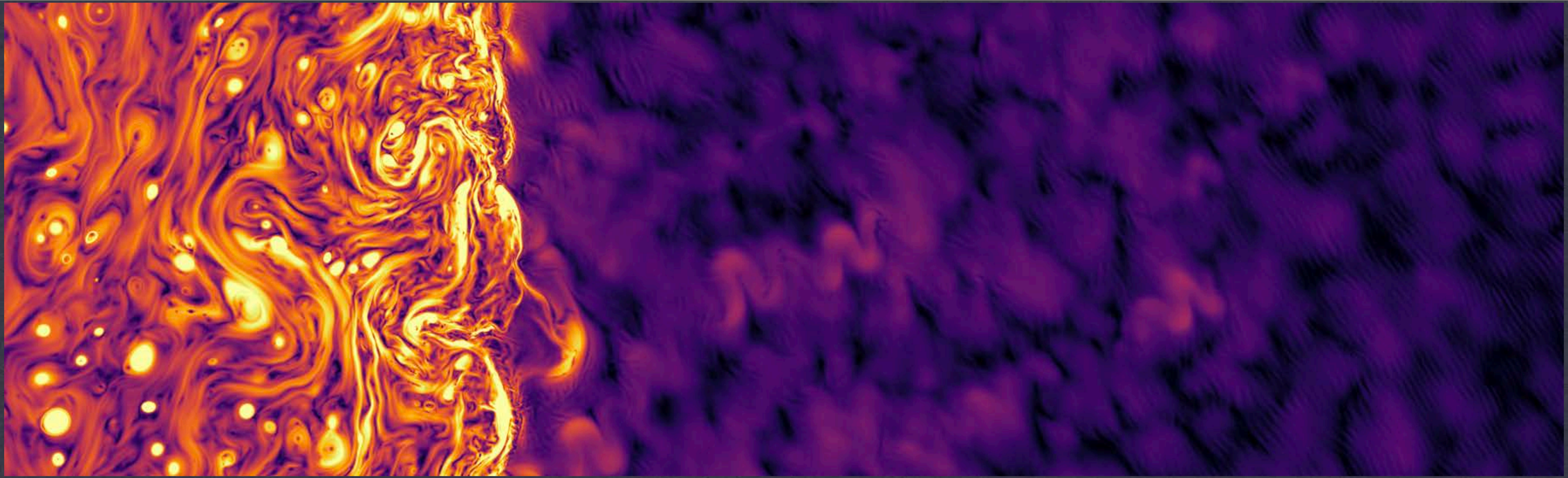


Kinetic Modeling of Particle Acceleration

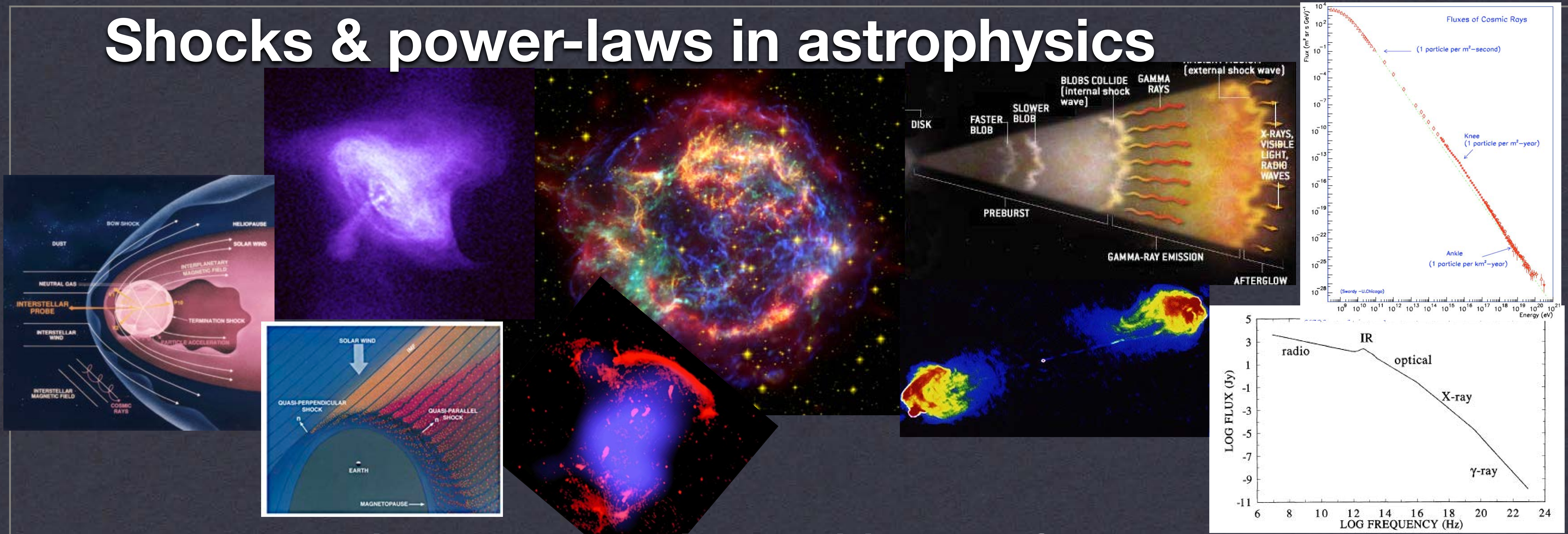
Anatoly Spitkovsky (Princeton University)

with much help from D. Caprioli, J. Park, V. Zekovic, A. Galishnikova, V. Tsiolis, Z. Hemler,
M. Riquelme, L. Sironi, P. Crumley, R. Kumar, X. Bai, H-S. Park, F. Fiuza

Outline

1. Acceleration problem: the need for kinetics to validate assumptions
2. Regimes of particle acceleration: ion and electron acceleration in parallel vs perpendicular shocks
3. Long-term and nonlinear effects in shocks on small and large scales: slams, postcursors, MHD-PIC
4. Reconnection + Turbulence
5. Open questions and prospects

Shocks & power-laws in astrophysics



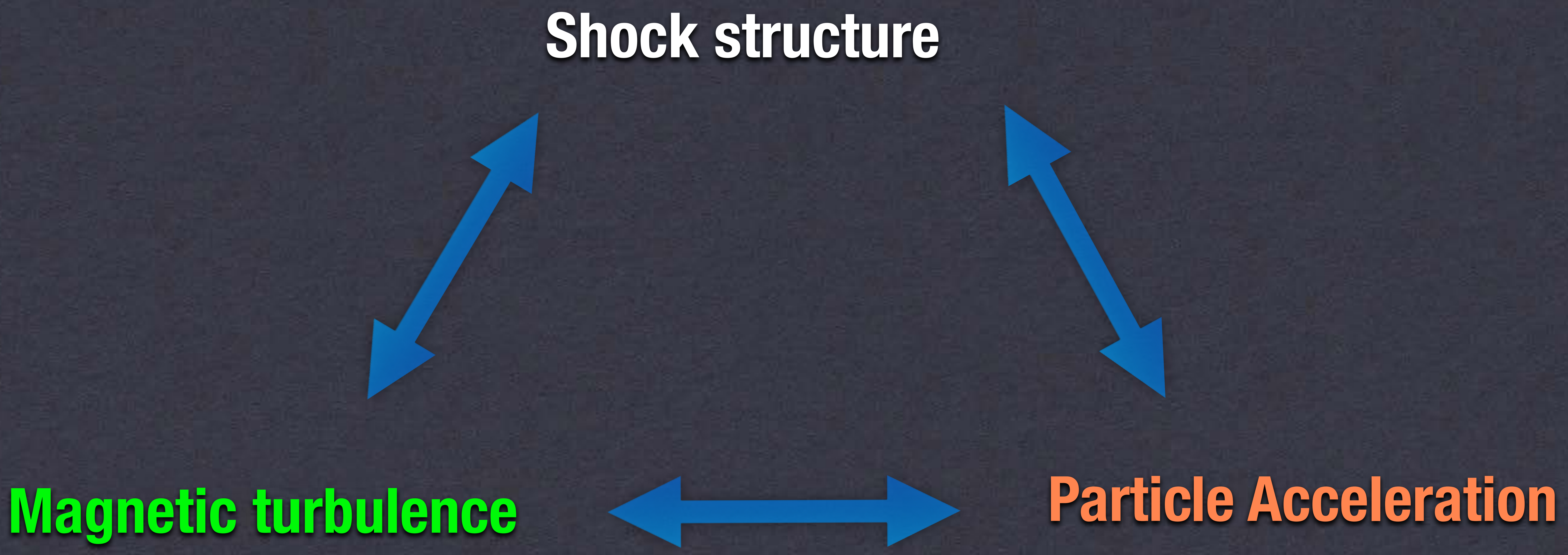
Astrophysical shocks are typically collisionless (mfp >> shock scales).
Many astrophysical shocks are inferred to:

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

How do they do this? Mechanisms, efficiencies, conditions?…

Collisionless shocks

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



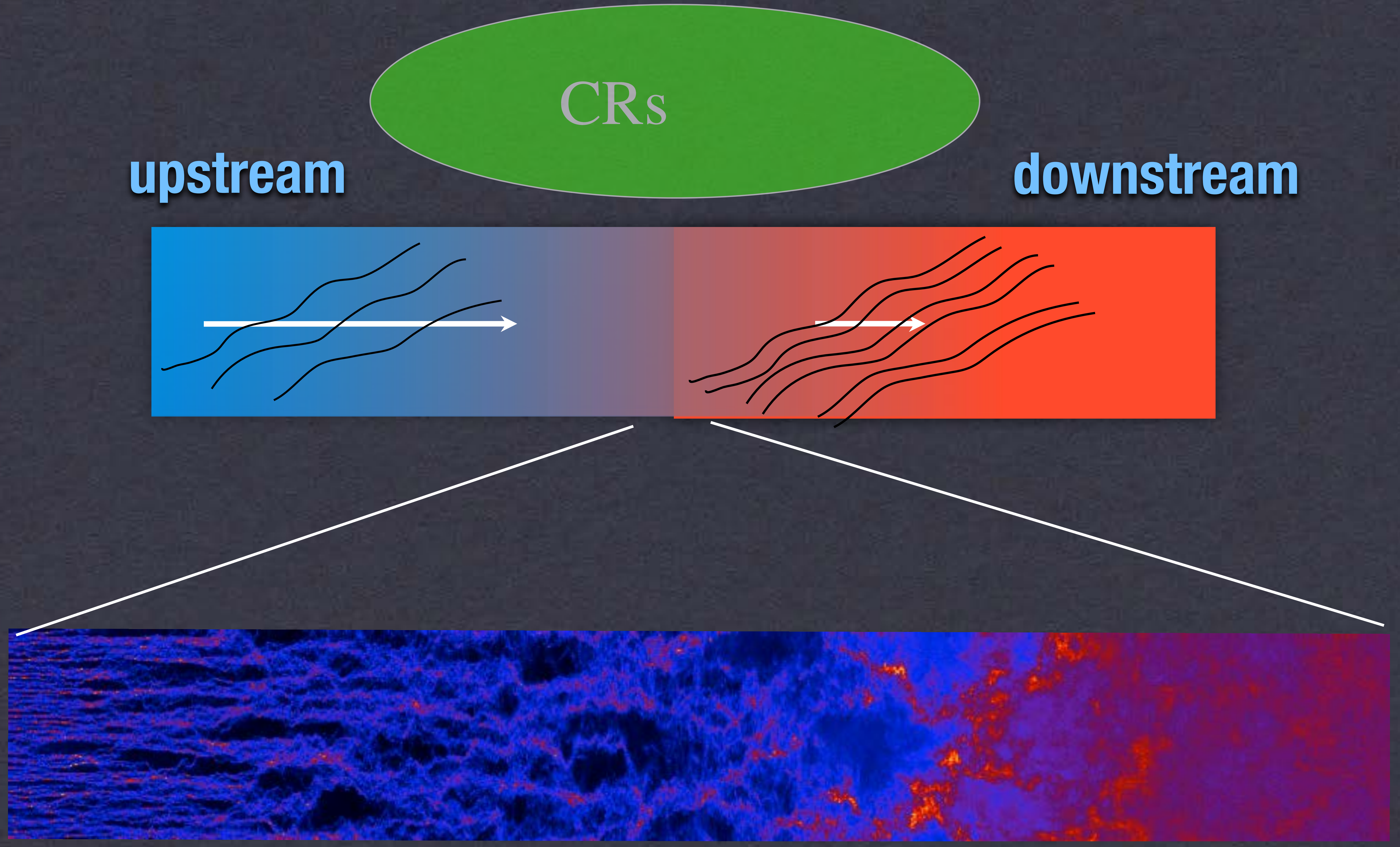
Shock structure

Magnetic turbulence

Particle Acceleration

Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback

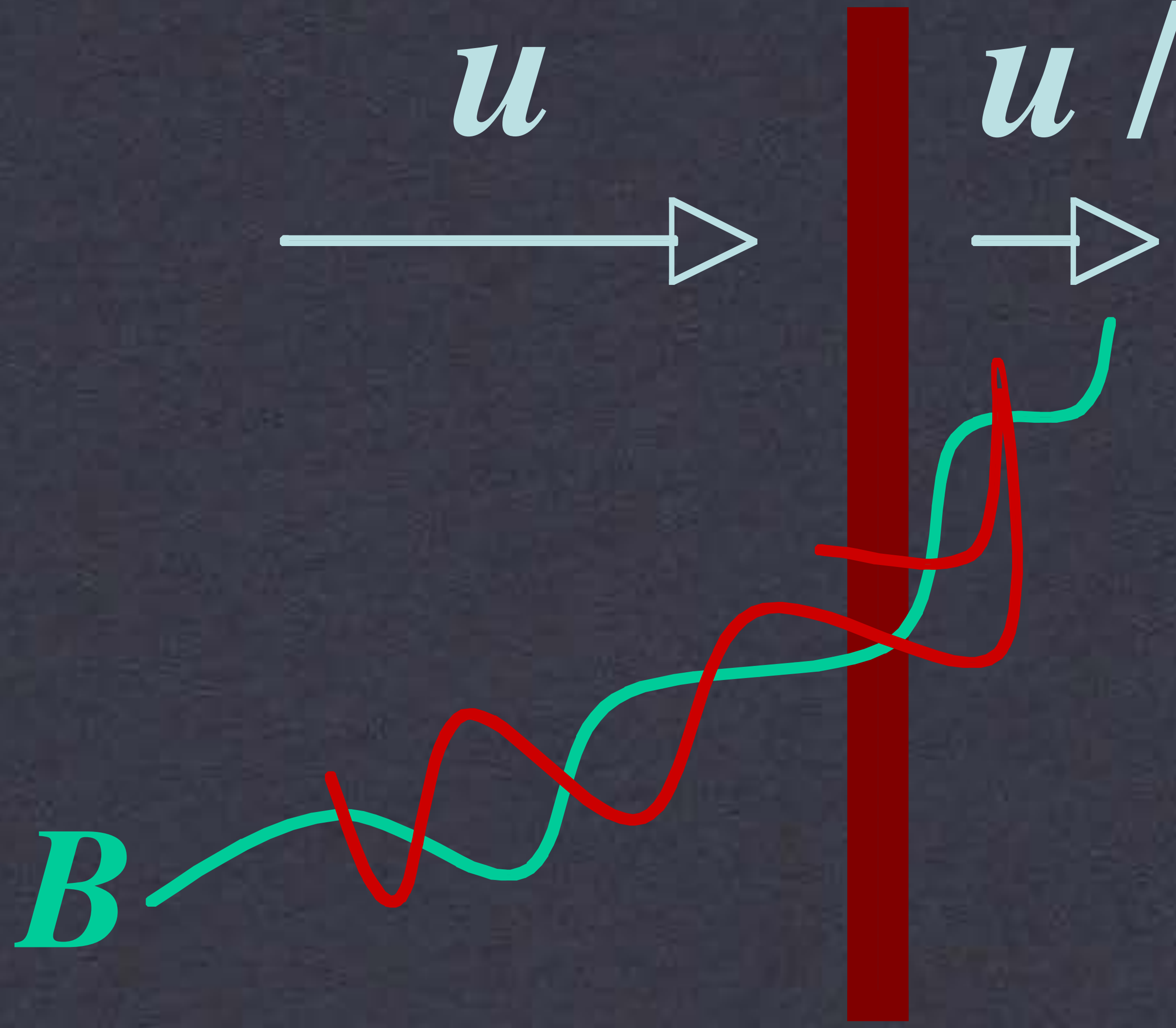


CRs

upstream

downstream

Particle acceleration:



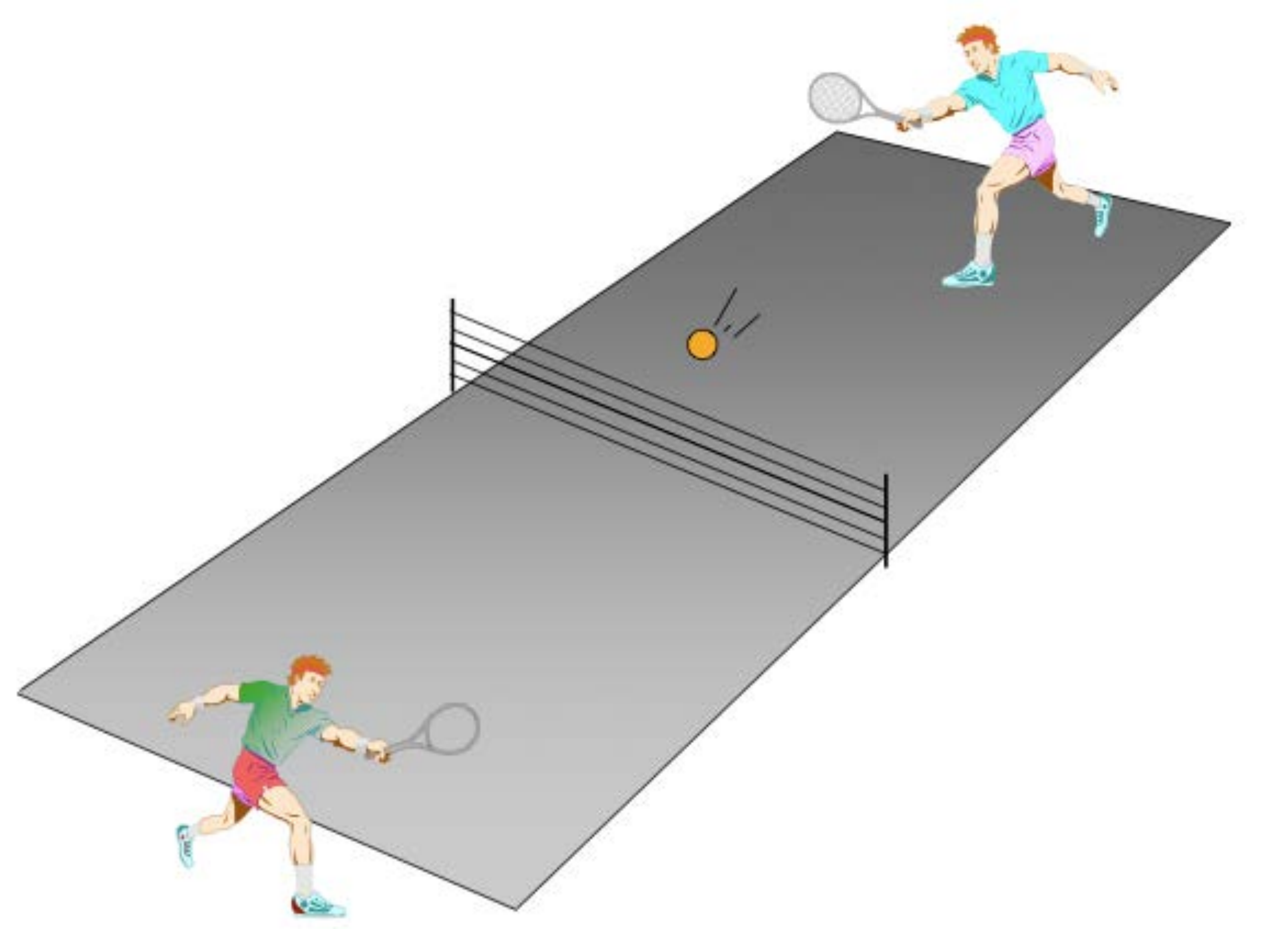
$\Delta E/E \sim v_{shock}/c$

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

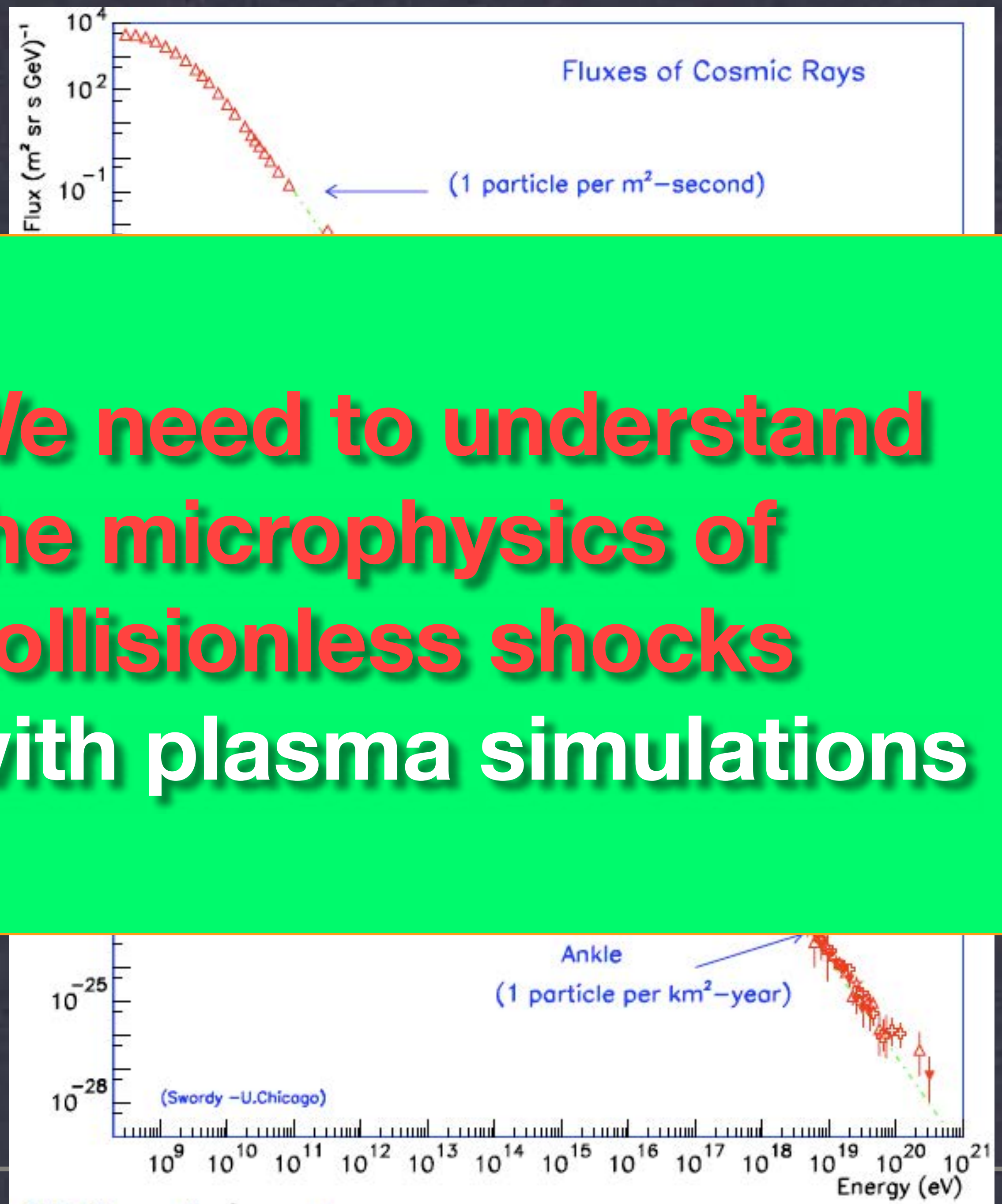
$K(r)=3\,r/(r-1)$

Strong shock:
$r=4$
$N(E) \sim N_0 E^{-2}$

- Original idea -- Fermi (1949) -- scattering off moving clouds. Too slow (second order in v/c) to explain CR spectrum, because clouds both approach *and* recede.
- In shocks, acceleration is first order in v/c, because flows are always converging (Blandford & Ostriker 78,Bell 78, Krymsky 77)
- Efficient scattering of particles is required. Particles diffuse around the shock. Monte Carlo simulations show that this implies very high level of turbulence. Is this realistic? Are there specific conditions?



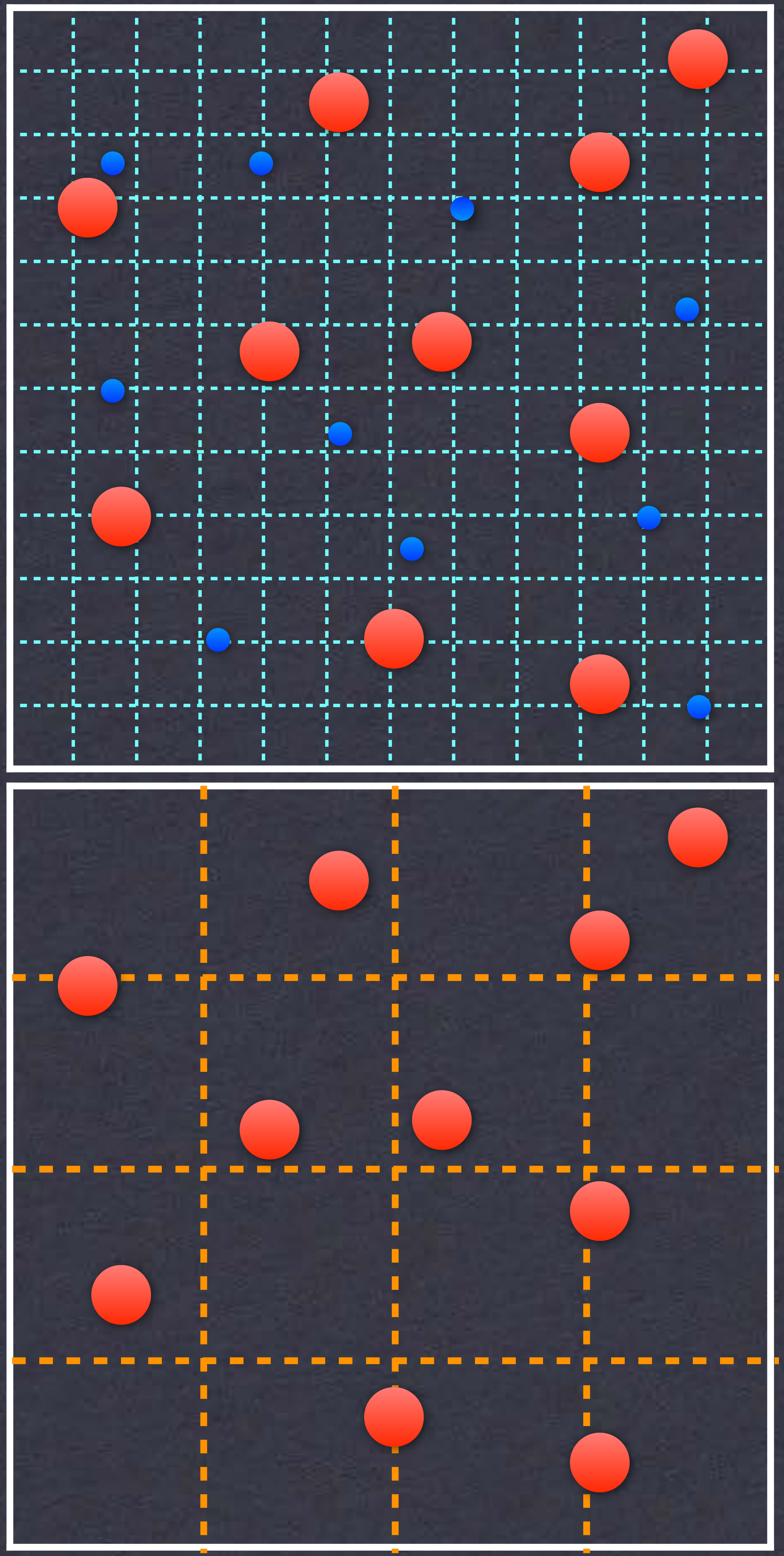
Free energy: converging flows



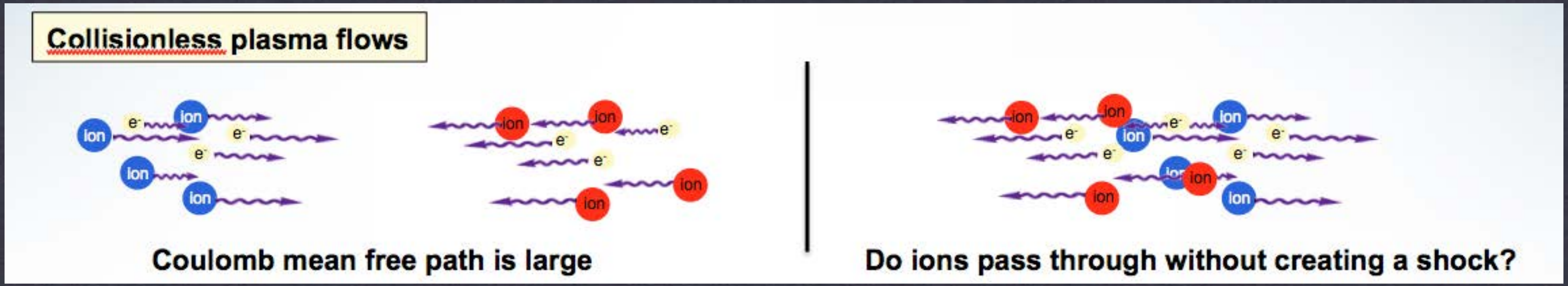
We need to understand the microphysics of collisionless shocks with plasma simulations

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

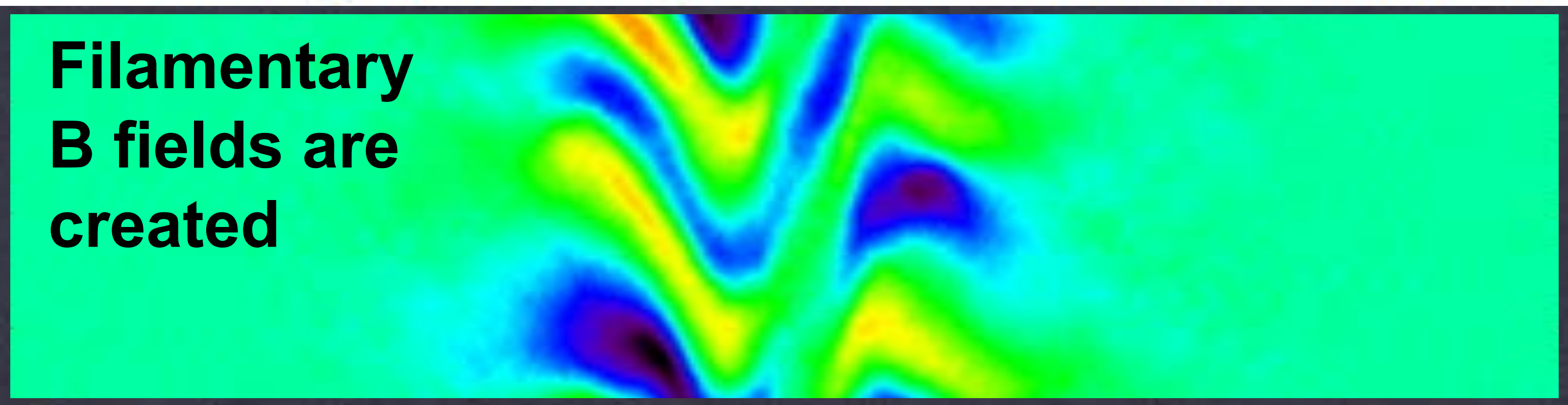


How collisionless shocks work


Collisionless plasma flows

Coulomb mean free path is large

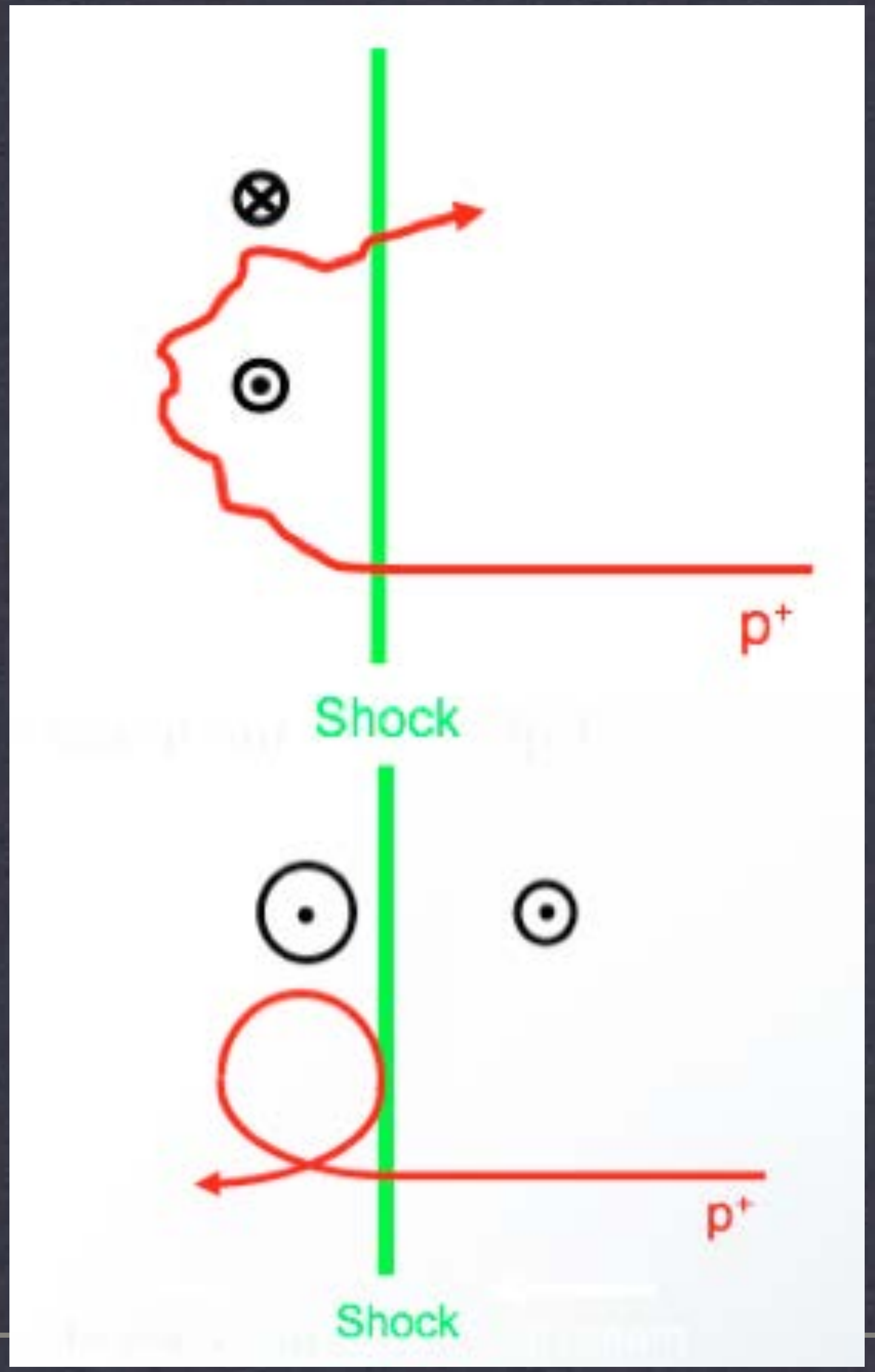
Do ions pass through without creating a shock?


Filamentary B fields are created

Two main mechanisms for creating collisionless shocks:

1) For low initial B field, particles are deflected by self-generated magnetic fields (filamentation/Weibel instability); Alvenic Mach # > 100

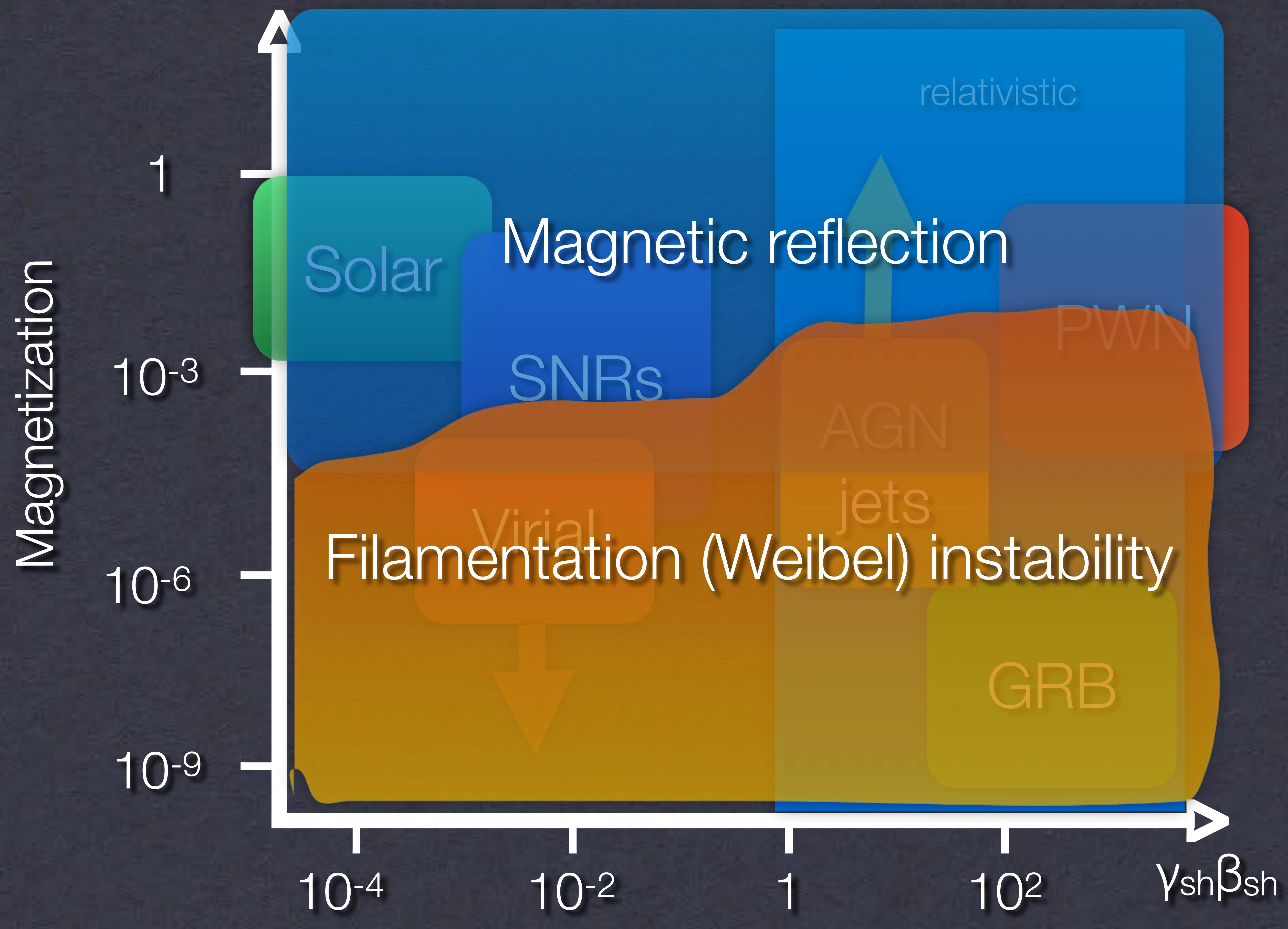
2) For large enough initial B field, particles are deflected by compressed pre-existing fields; Alfvenic Mach # < 100

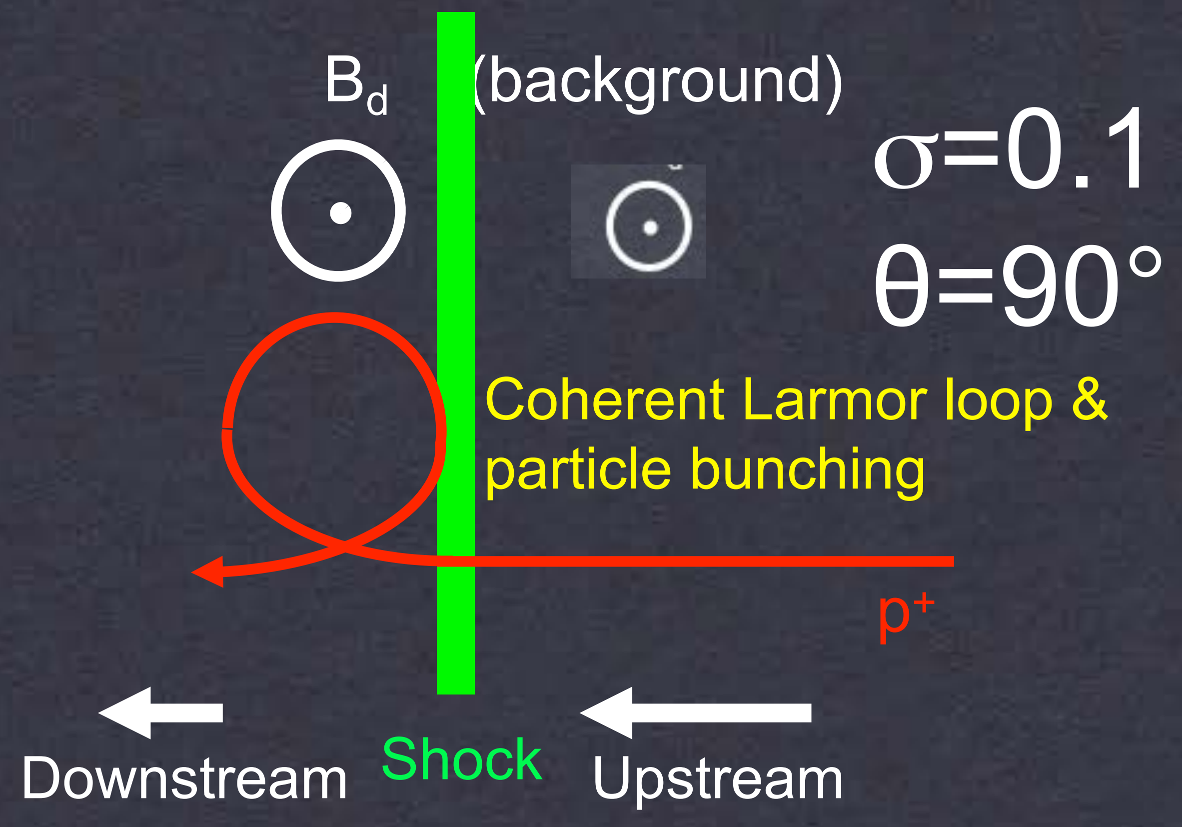


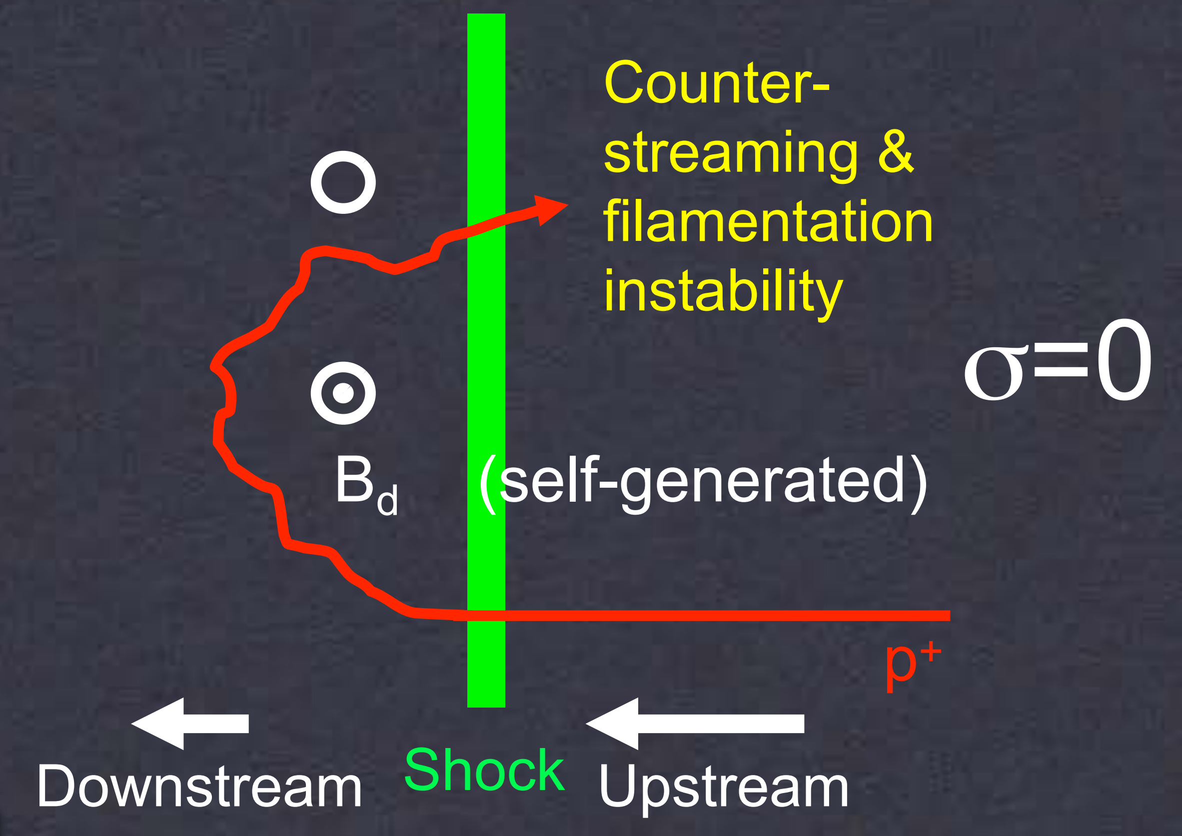
Parameter Space of shocks

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

$$M_A = \frac{v}{v_A} \qquad M_s = \frac{v}{v_{th}} \qquad \beta = \frac{M_A^2}{M_s^2} \qquad \frac{m_i}{m_e}$$

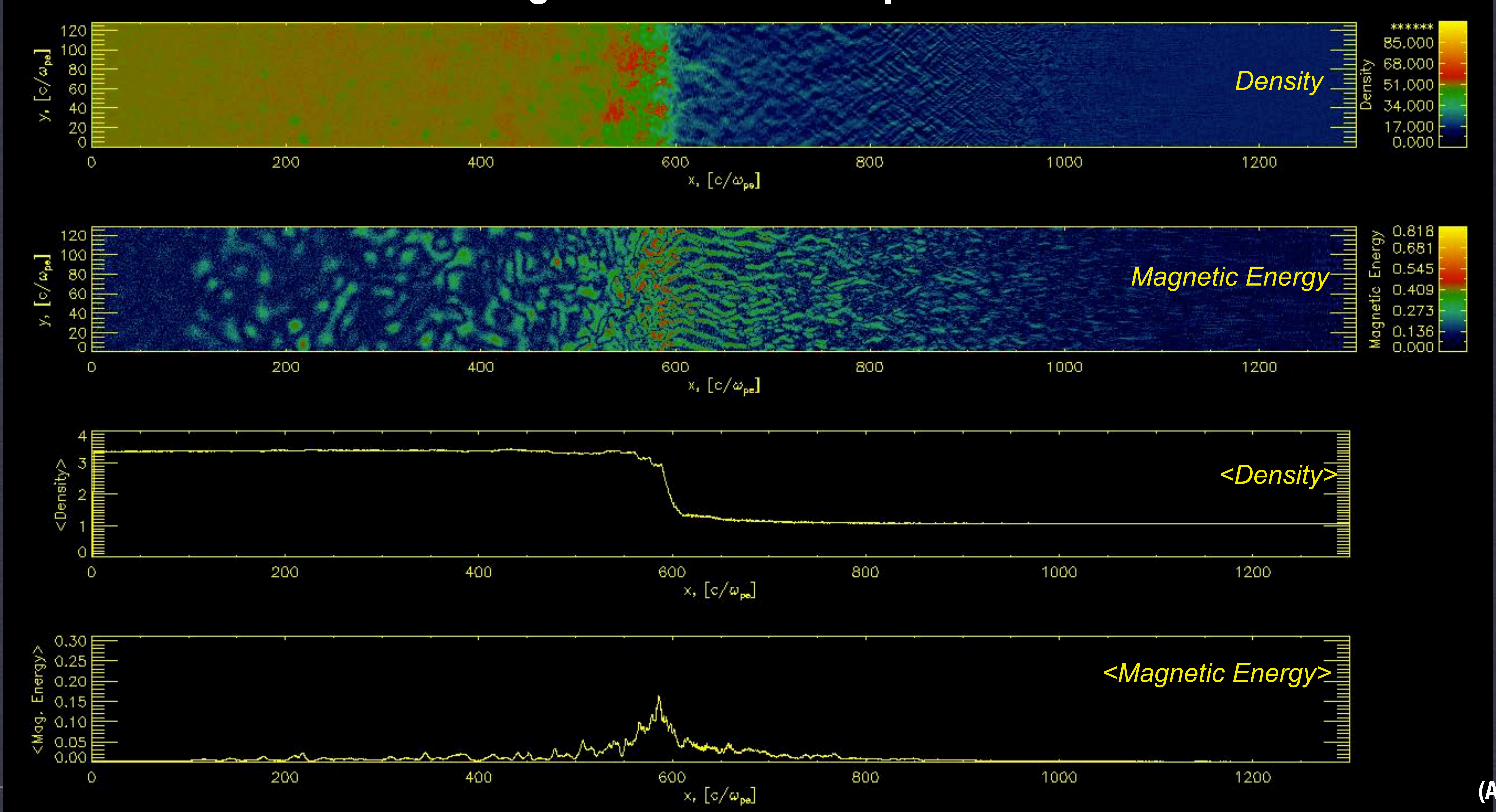






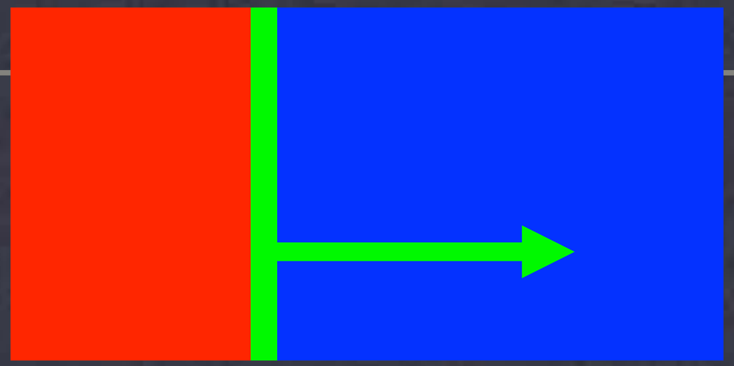
Collisionless shocks

Structure of an unmagnetized relativistic pair shock



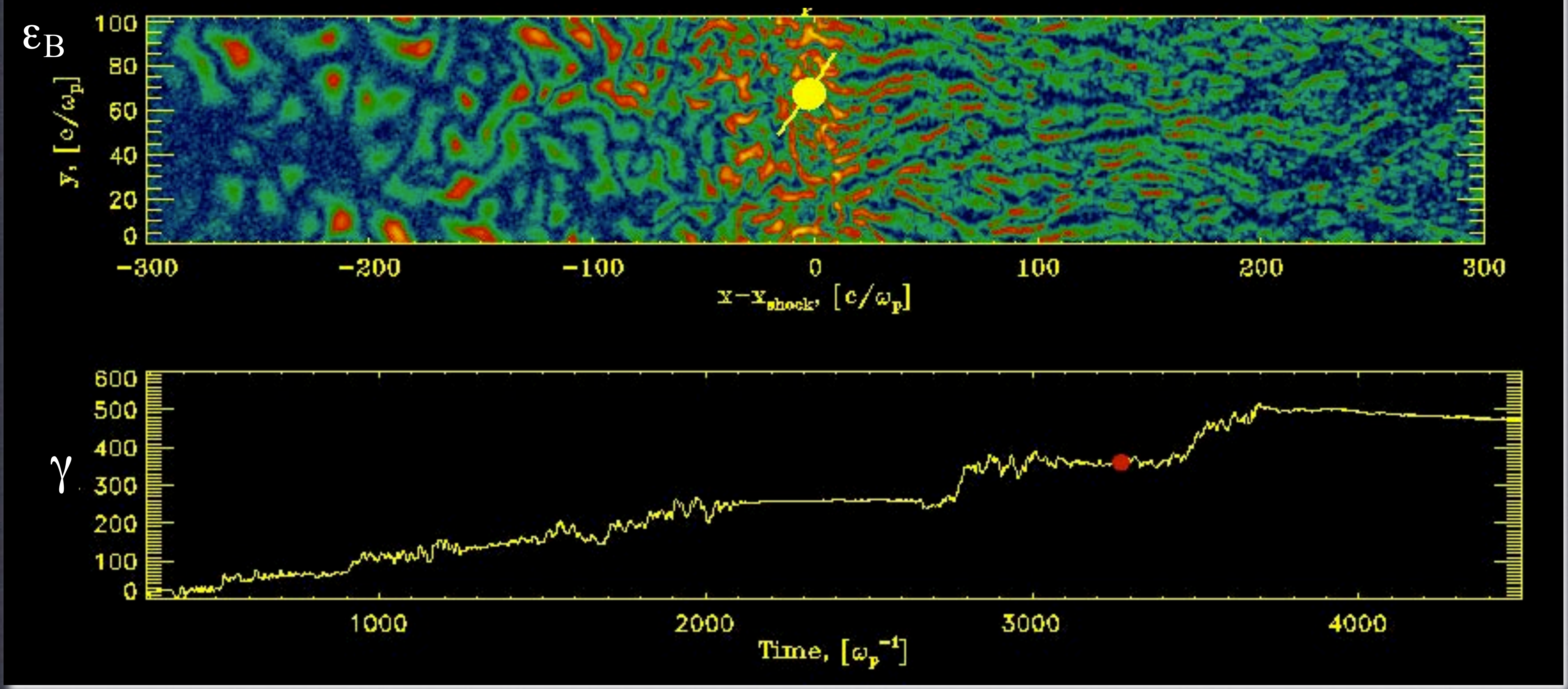
(AS 2008)

Fermi process in action

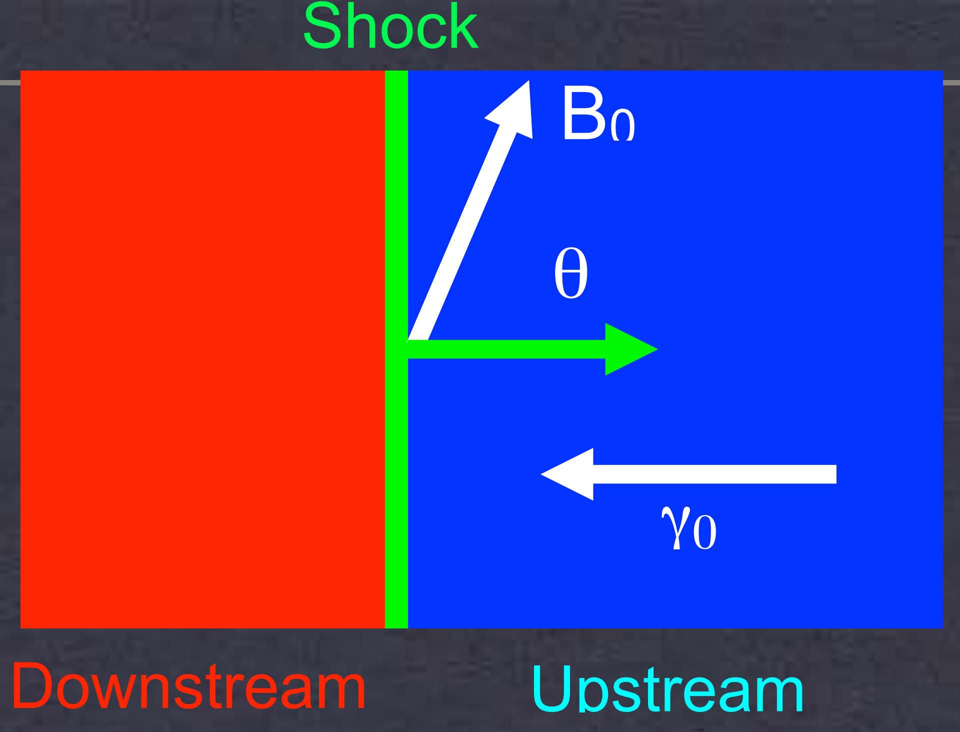


Particles scatter off magnetic turbulence produced self-consistently as part of the shock evolution

$\sigma=0$ $\gamma_0=15$ e^--e^+ shock



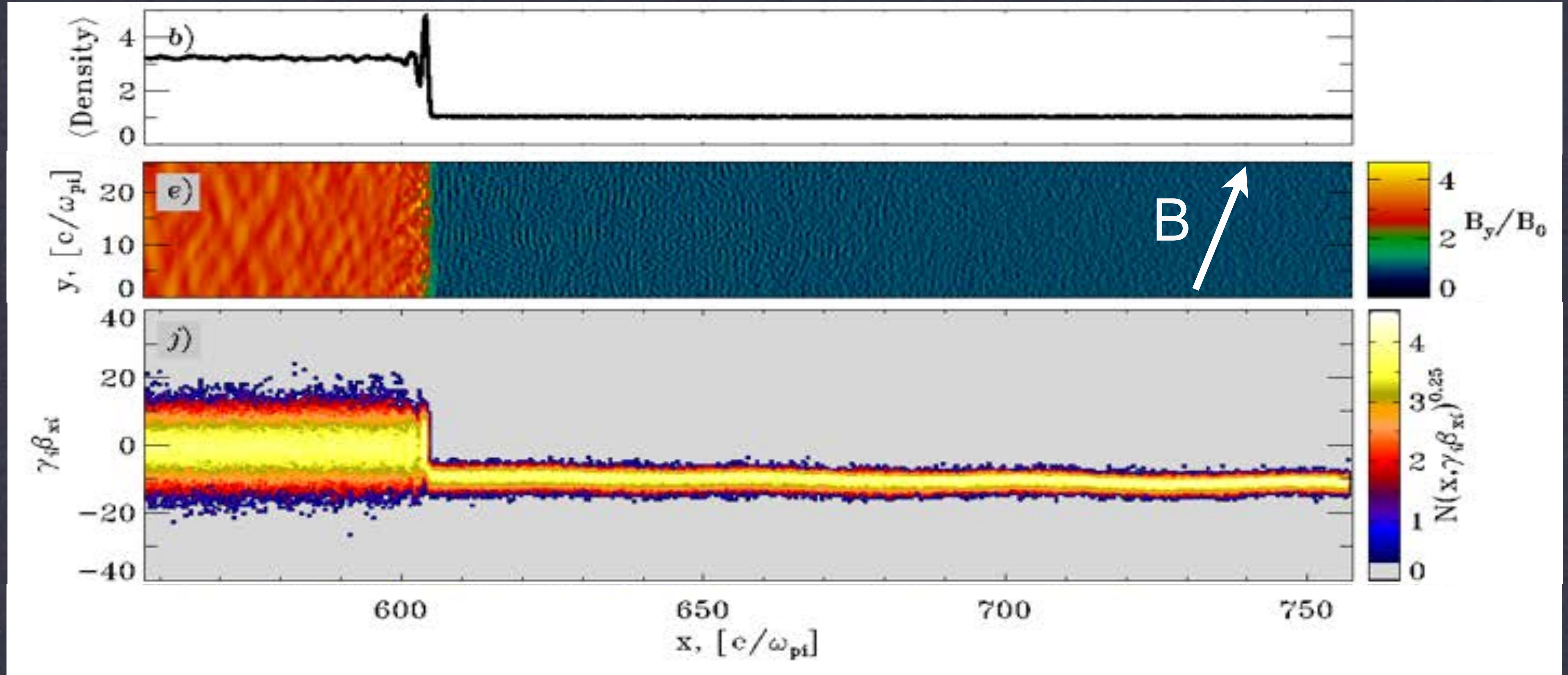
Finite B: perpendicular vs parallel shocks



- Quasi-perpendicular shocks: mediated by magnetic reflection

<Density>

$\sigma=0.1$
$\theta=75°$
$\gamma_0=15$
e^--p^+



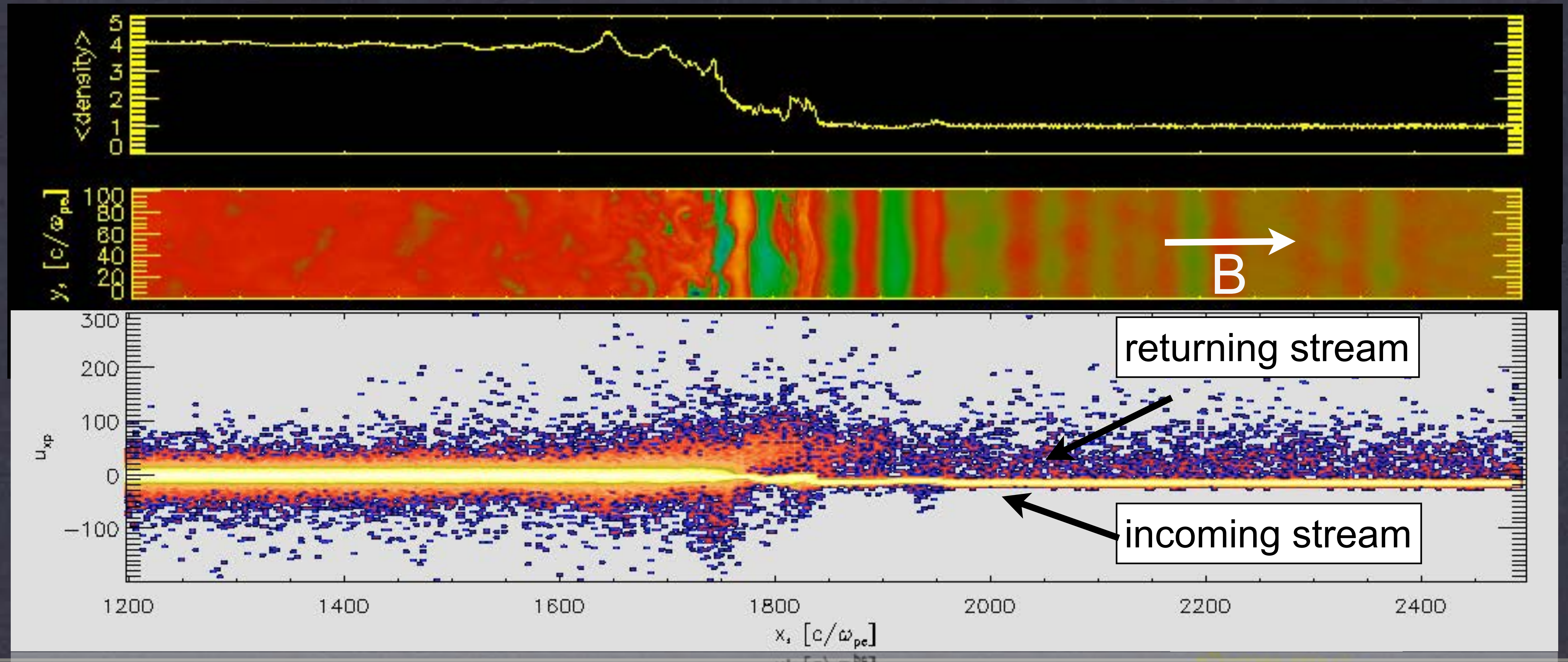
B_y

$\gamma\beta_x$

(Sironi and AS 11)

- Quasi-parallel shocks: instabilities amplify transverse field component

$\sigma=0.1$
$\theta=15°$
$\gamma_0=15$
e^--p^+



<Density>

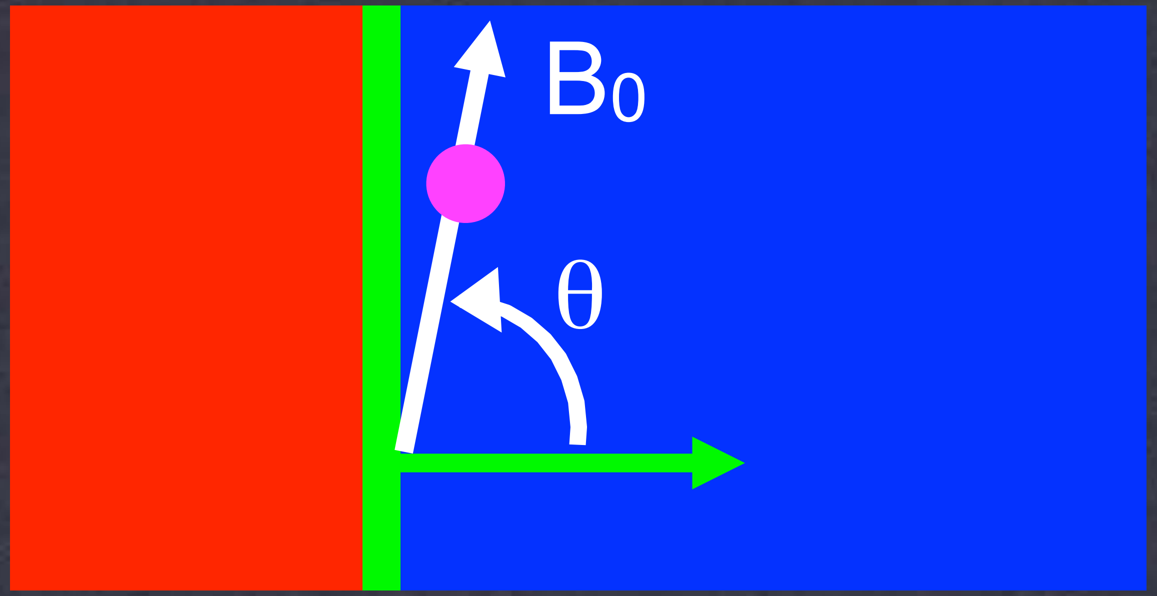
B_y

•Reflected particles

$\gamma\beta_x$

(Sironi & AS 11)

Superluminal vs subluminal shocks



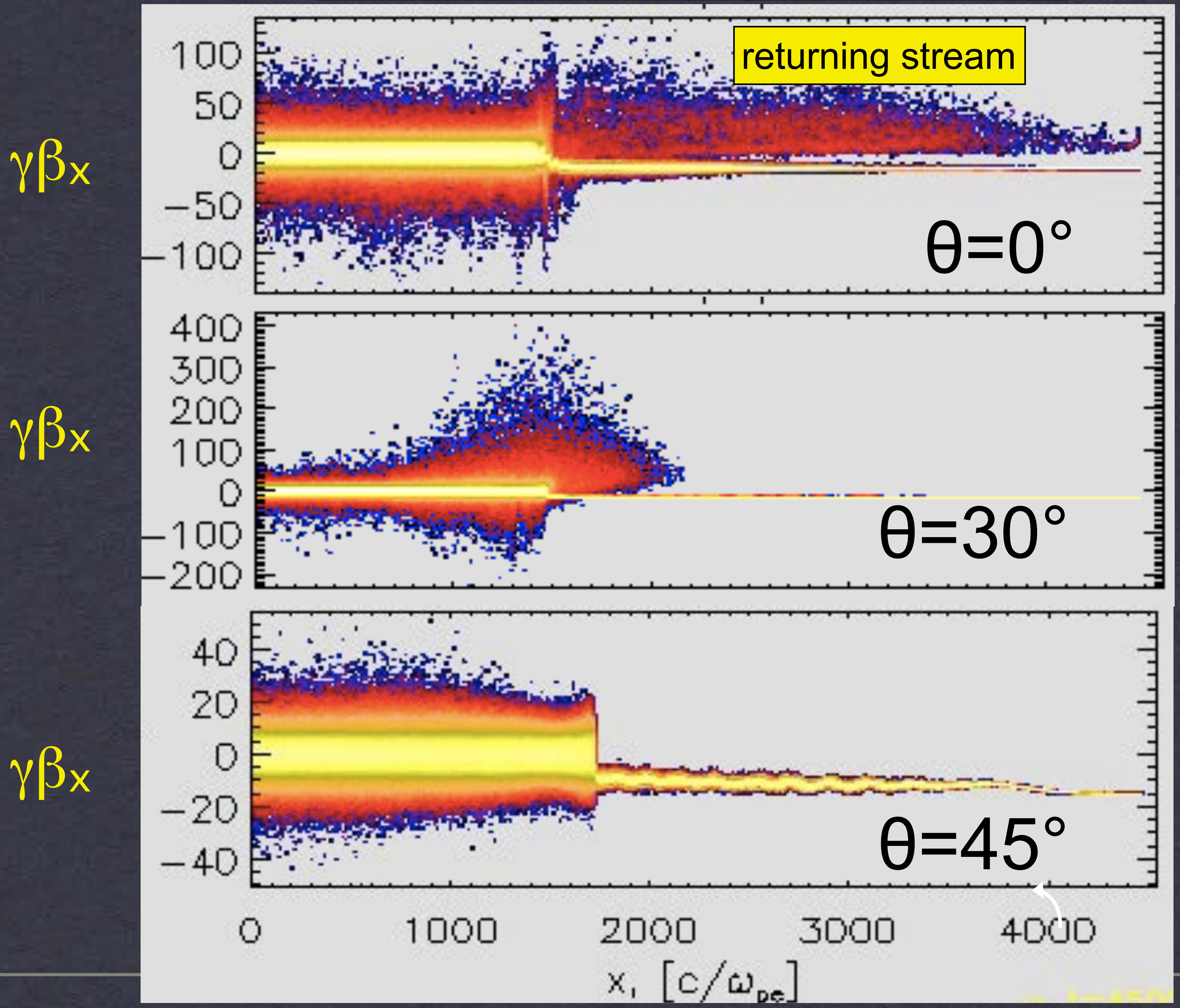
σ is large → particles slide along field lines

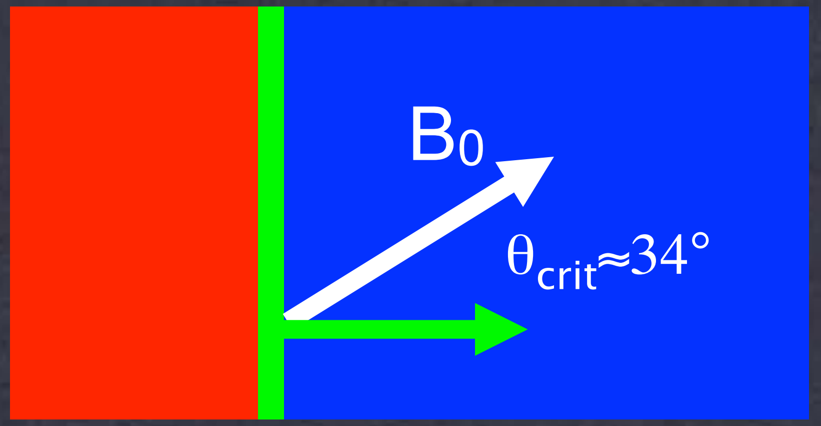
θ is large → particles cannot outrun the shock

unless v>c (“superluminal” shock)

⇒ no returning particles in superluminal shocks

$\sigma=0.1$ $\gamma_0=15$ e^--p^+ shock





Subluminal / superluminal boundary
at $\theta\sim34°$

→ Fermi acceleration should be suppressed in superluminal shocks!

If $\sigma>10^{-3}$, particle acceleration only for:

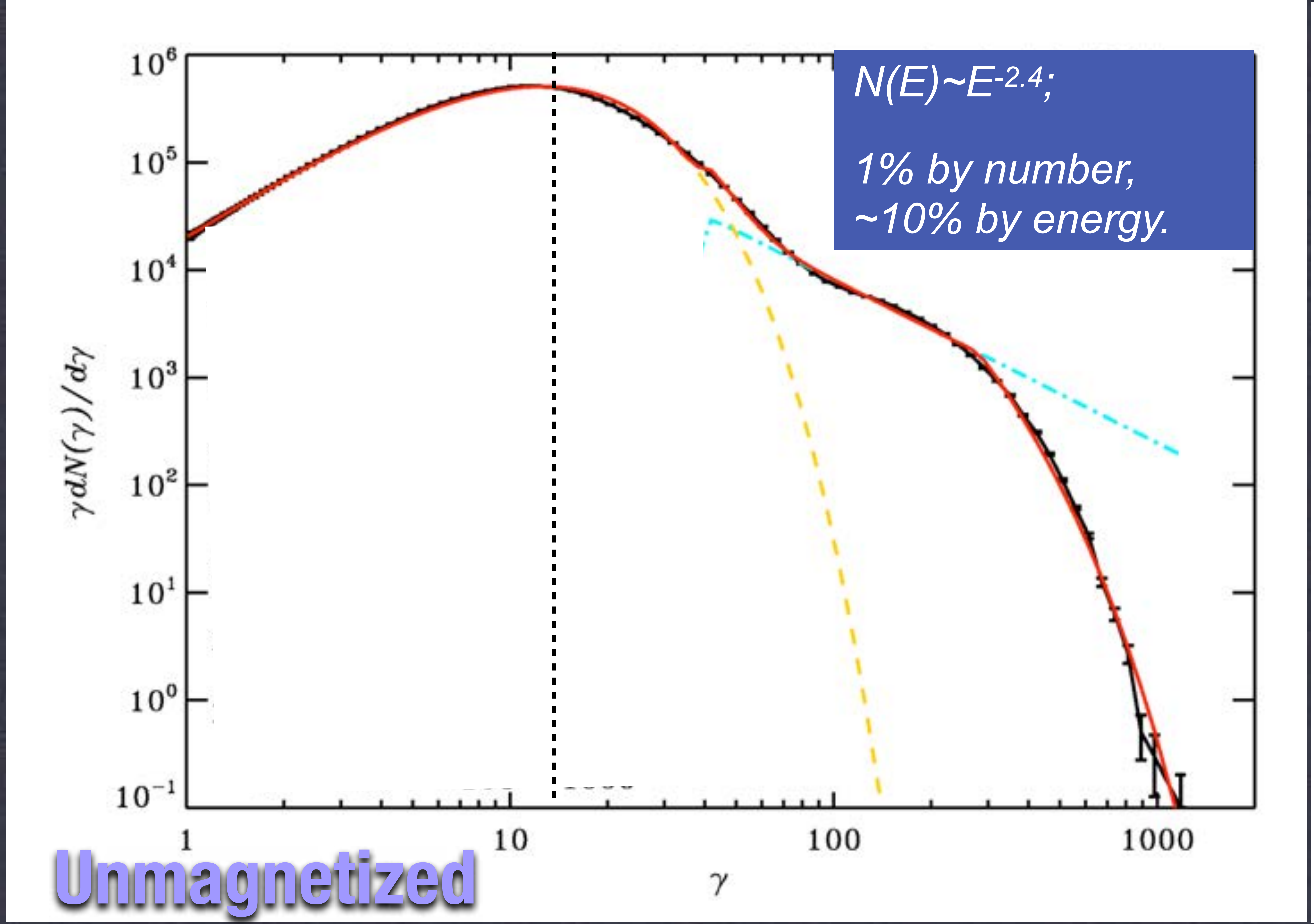
$\theta<\theta_{crit}\approx34°$ (downstream frame)

$\theta'<34°/\gamma_0<<1$ (upstream frame)

Easy to kill!

RELATIVISTIC SHOCKS ACCELERATION

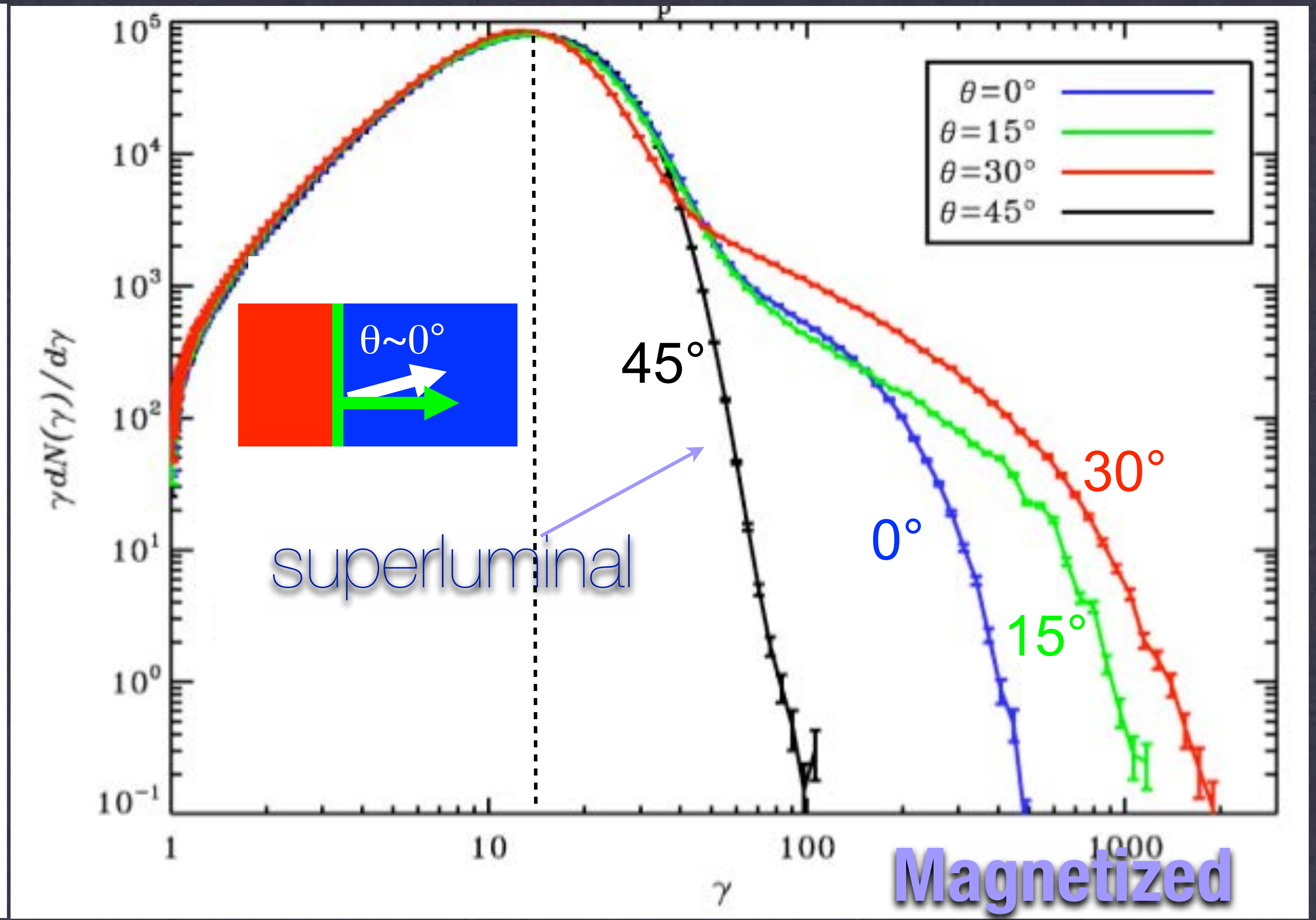
Sironi & AS 09



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

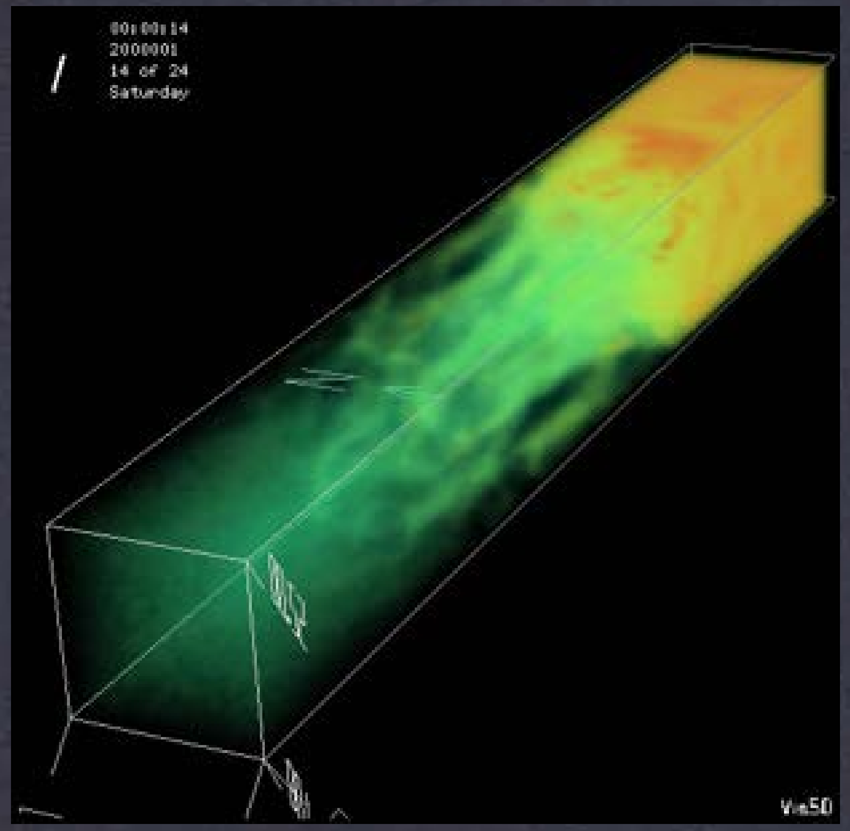
1% by number,
~10% by energy.

Unmagnetized



superluminal

Magnetized

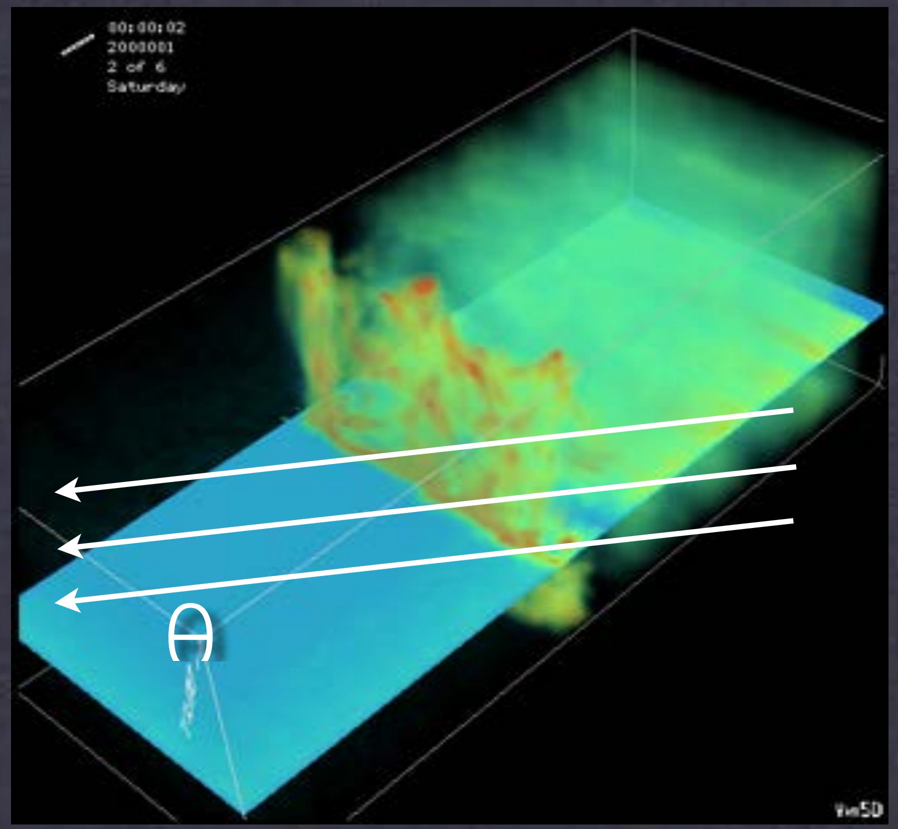


Conditions for acceleration in relativistic shocks:

low magnetization of the flow

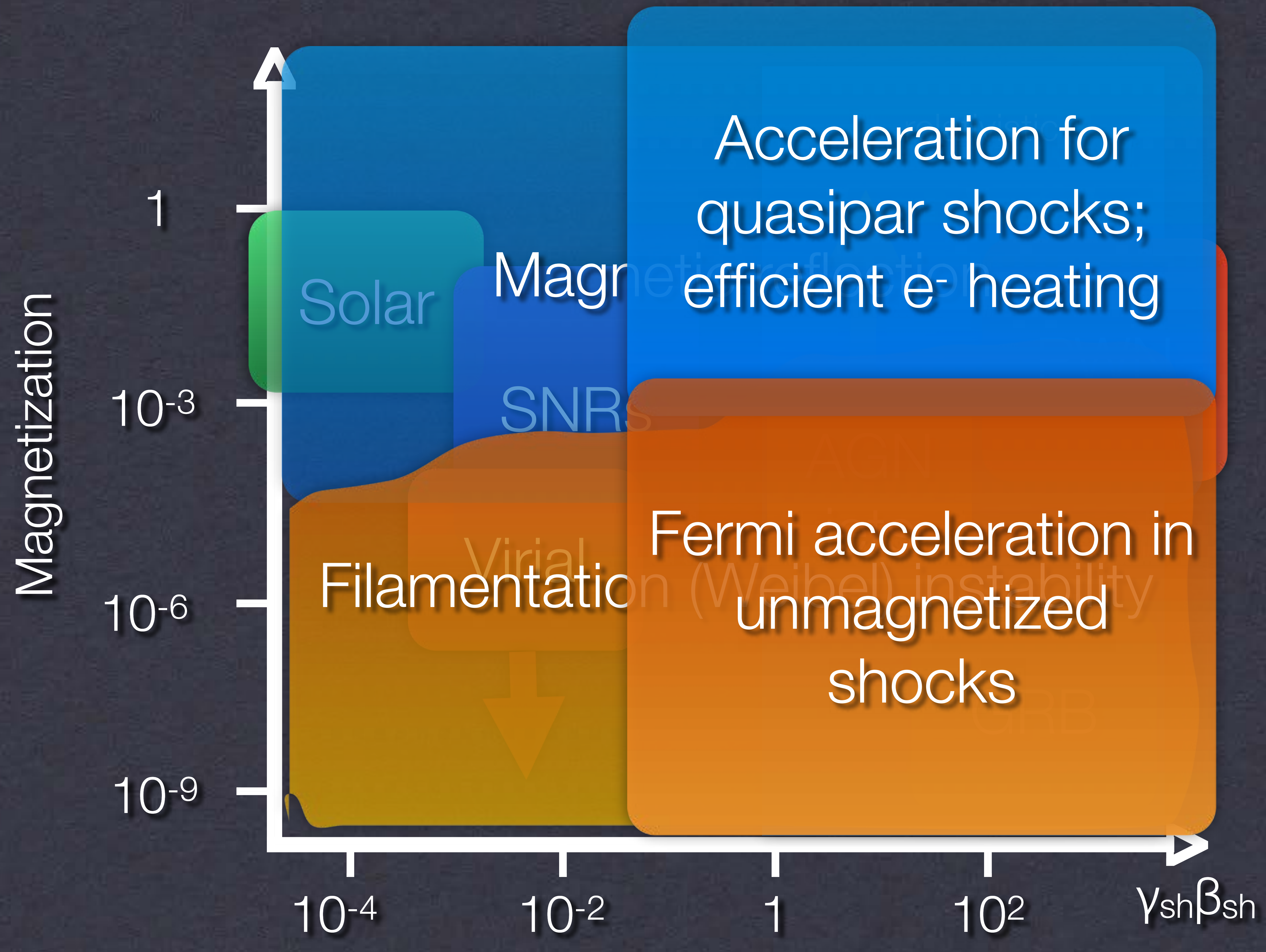
or quasi-parallel B field ($\theta<34°/\Gamma$);

electrons & ions behave similarly



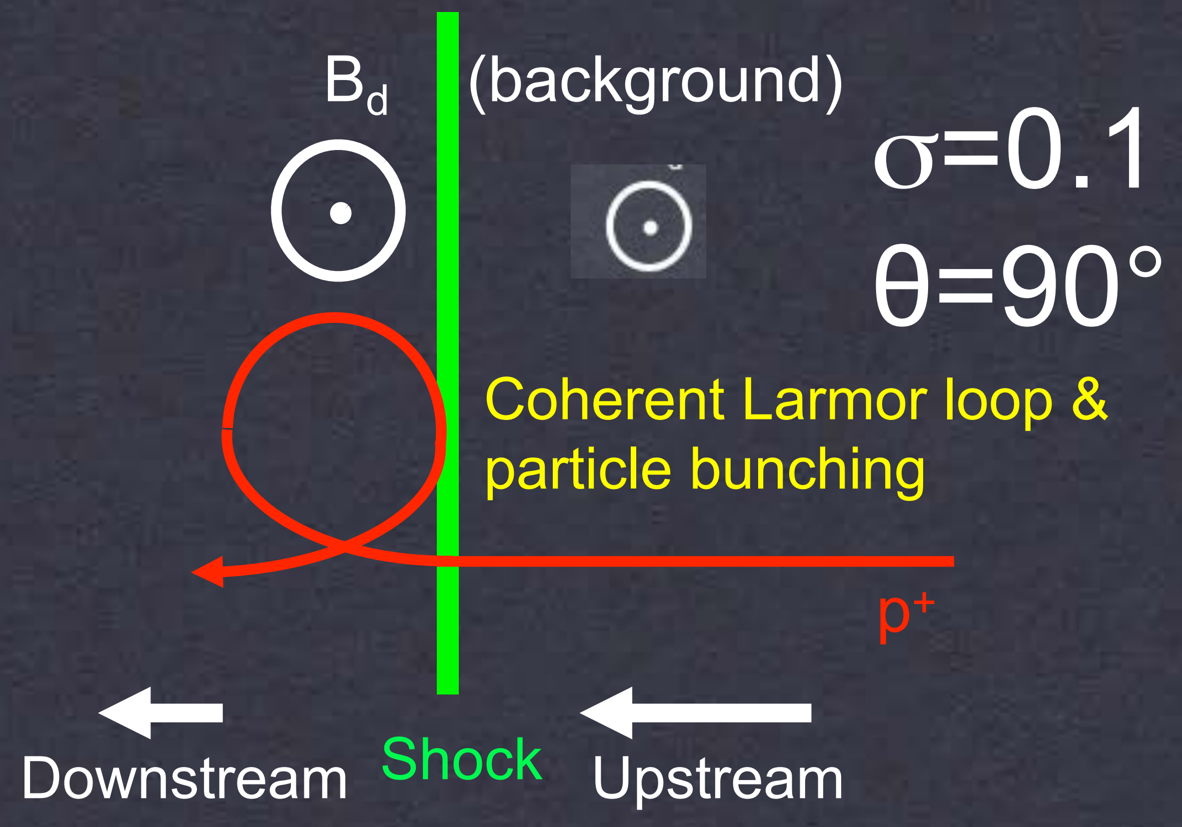
Parameter Space of shocks

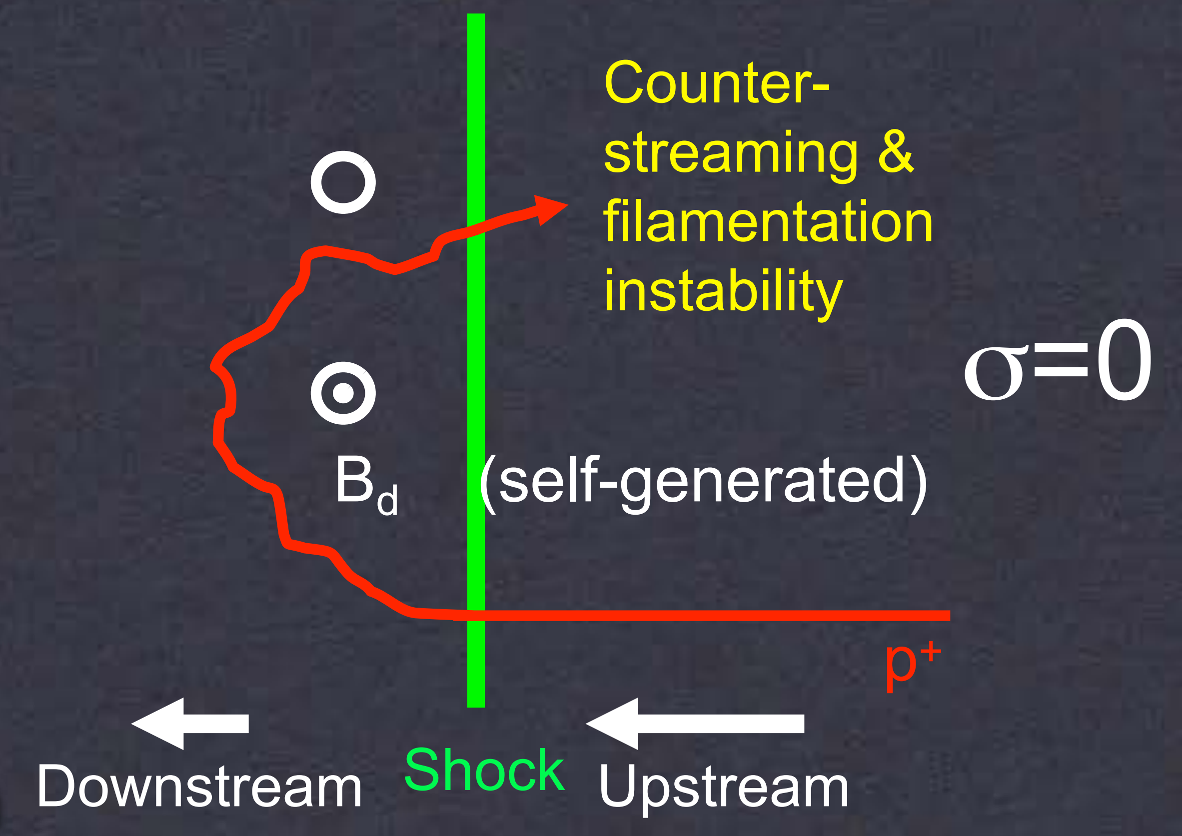
$$\sigma \equiv \frac{B^2/4\pi}{(\gamma-1)nmc^2} = \frac{1}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2\left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$



Acceleration for quasipar shocks; efficient e- heating

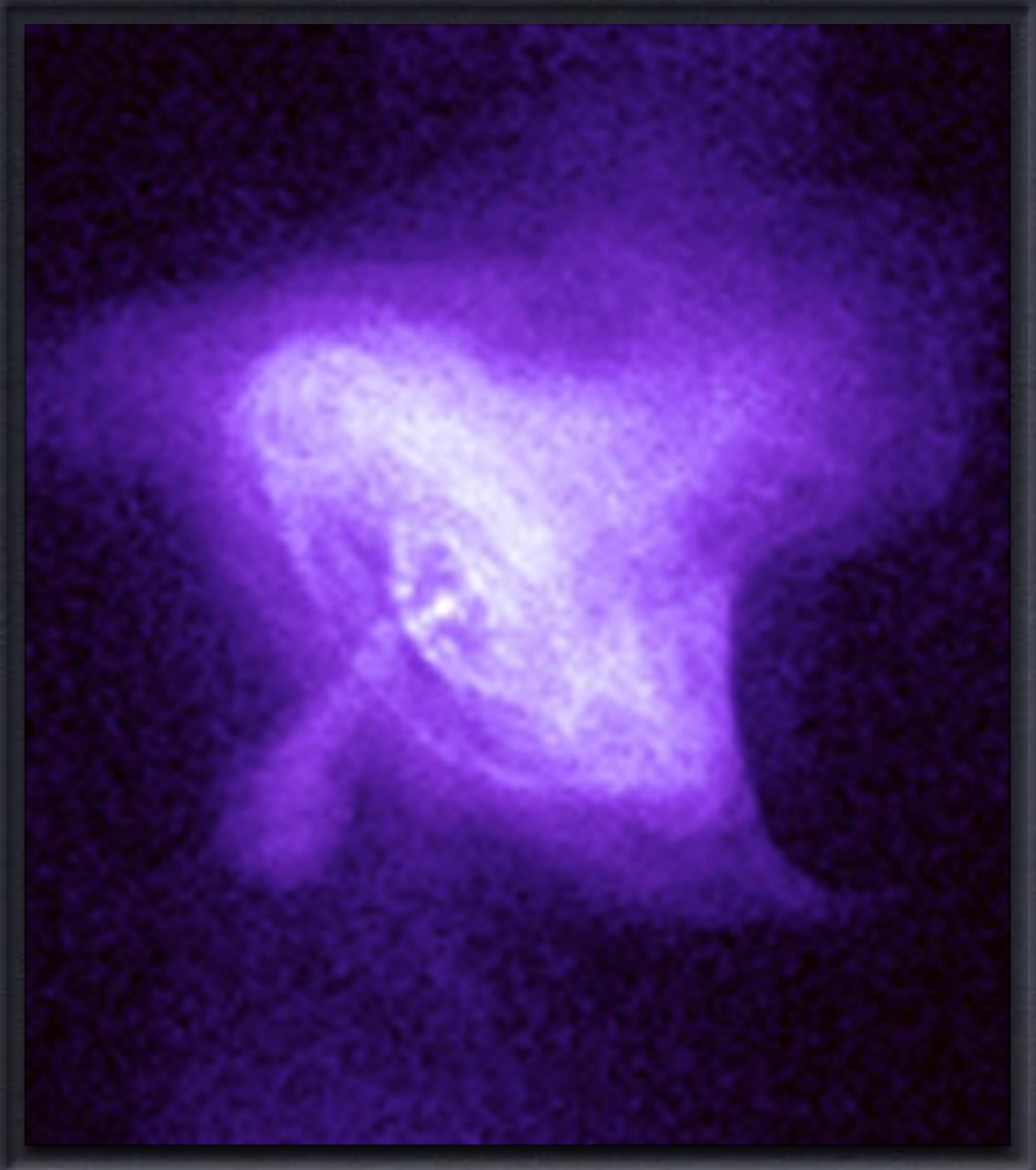
Fermi acceleration in unmagnetized shocks





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)



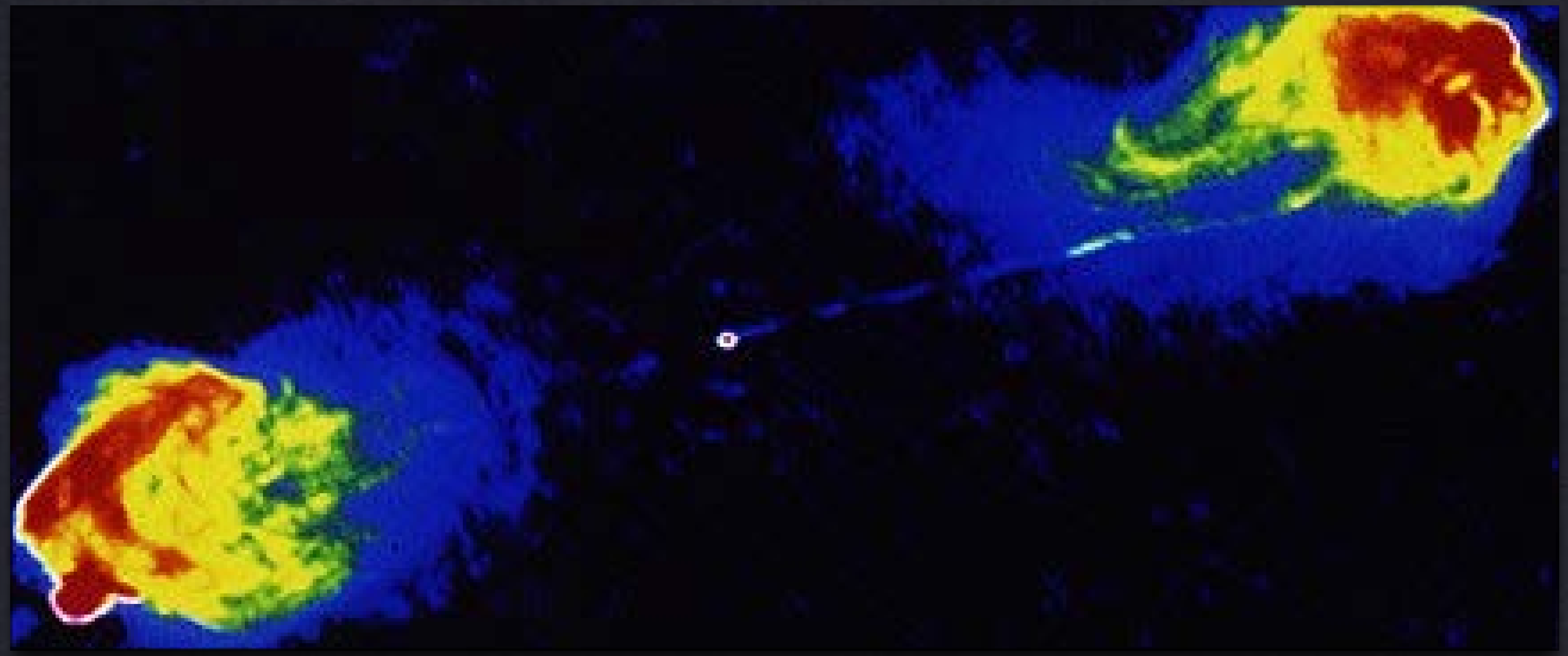
Astrophysical implications

- AGN Jets

  High magnetization toroidal field configuration is disfavored

  Either magnetic field is dissipated in the process of acceleration,

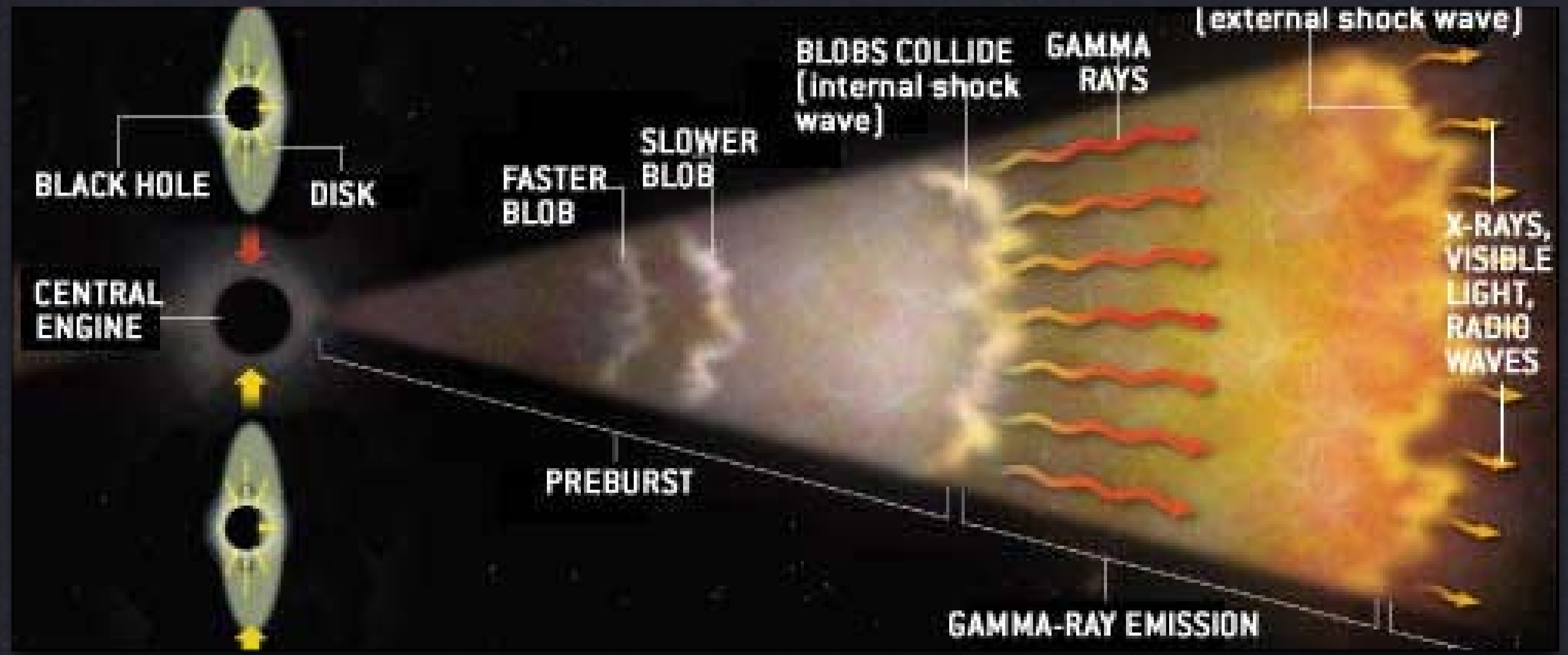
  or field is reoriented to lie along the flow (sheath vs spine flows?)



- GRB jets

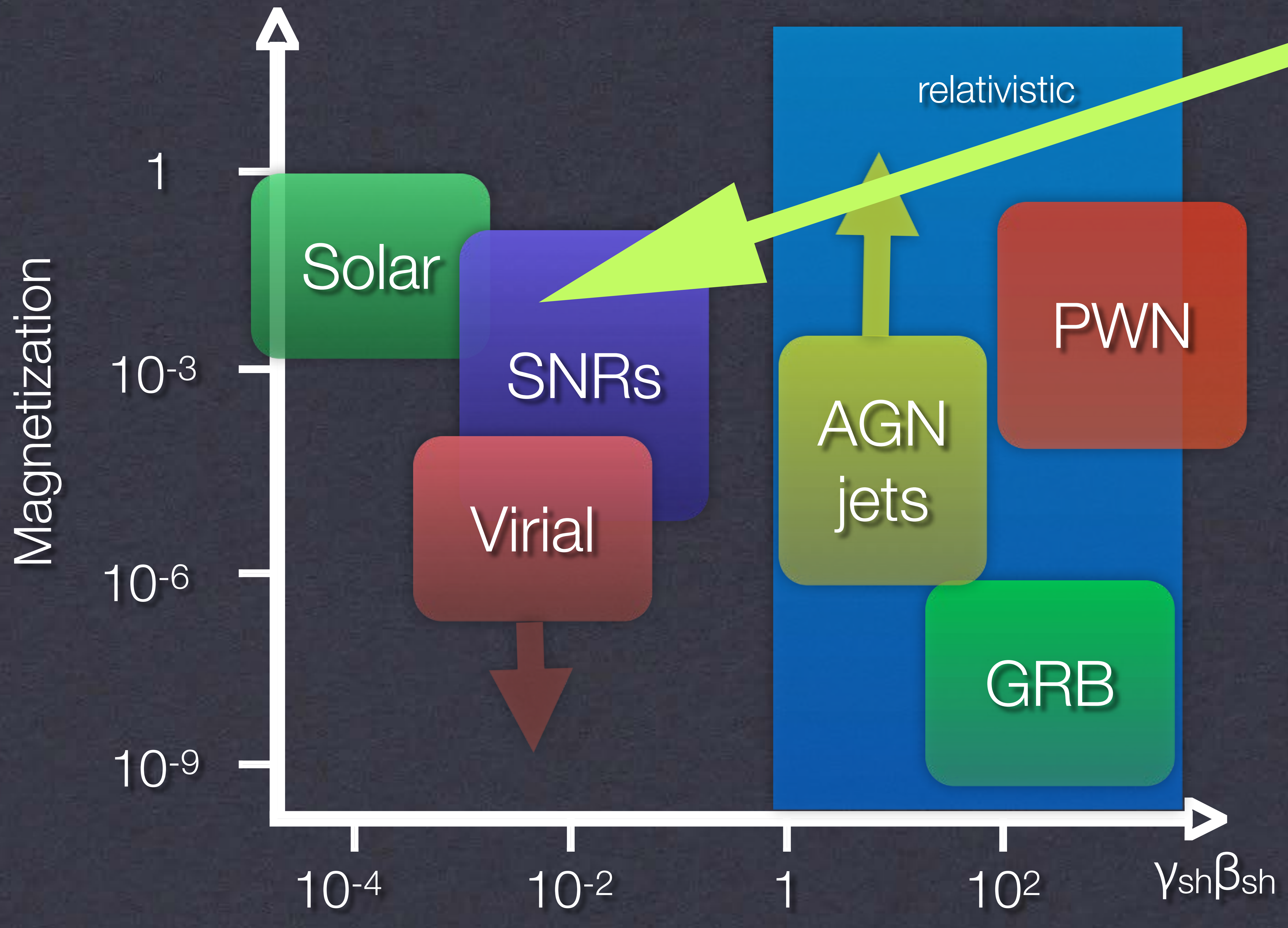
  Low magnetization external shocks can work; Field survival?

  Efficient electron heating explains high energy fraction in electrons



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 still mildly relativistic (v/c~0.03-0.1c)

SHOCK ACCELERATION

Two crucial ingredients:

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

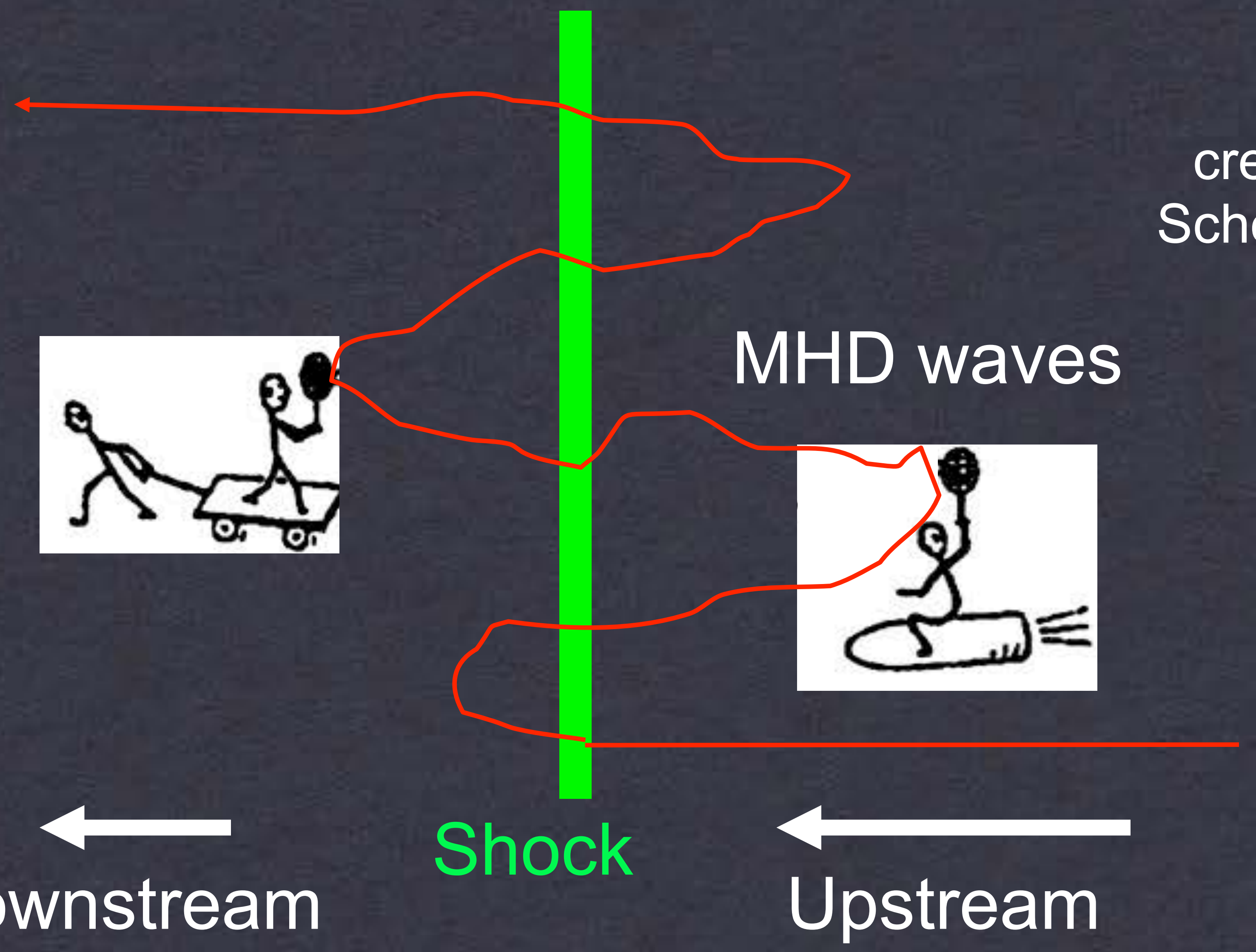
2) ability of these particles to scatter and return to the shock (pre-existing or generated turbulence)

Similarly to relativistic shocks, parallel shocks are good for ion and electron acceleration, while perpendicular shocks are either superluminal or mainly accelerate electrons. *There are many sub-regimes, not fully mapped yet.*

Acceleration processes in shocks

- Diffusive Shock Acceleration (DSA) or Fermi acceleration:

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

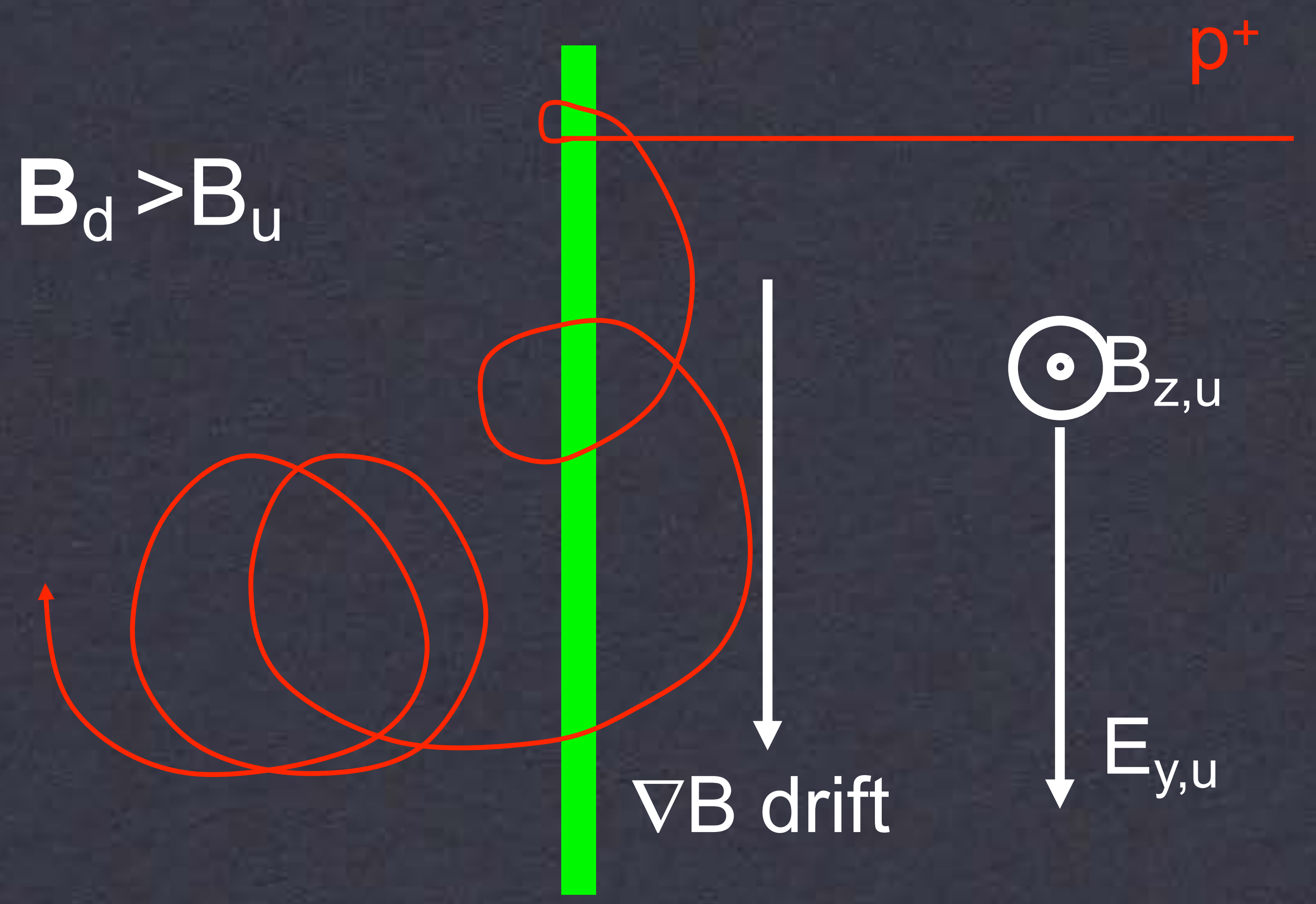


credit: Scholer

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

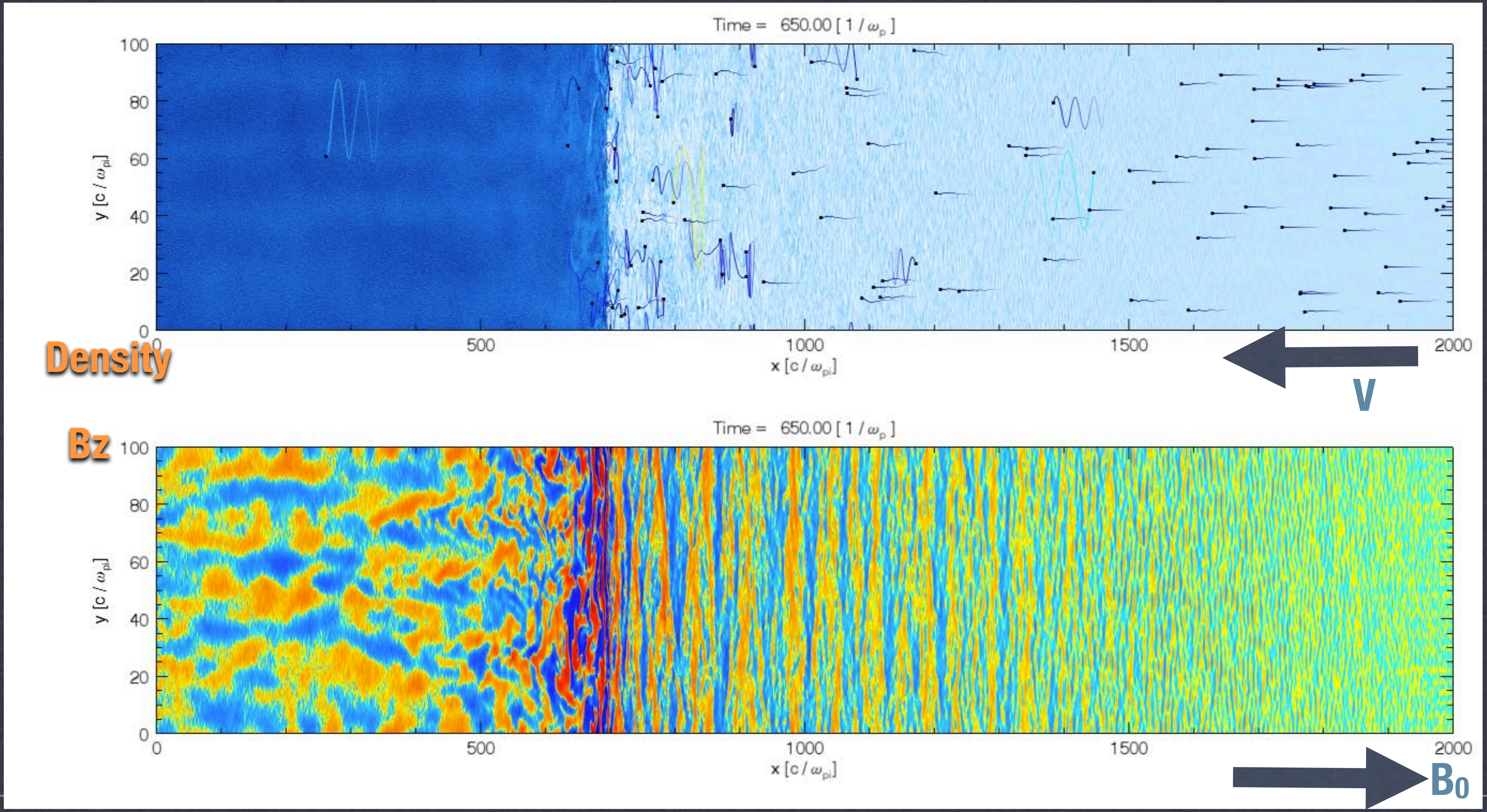
Shock-reflected particles are accelerated by the background electric field while drifting along the shock surface: Larmor radius is finite compared to shock thickness

Obliquity angle important for escaping shock



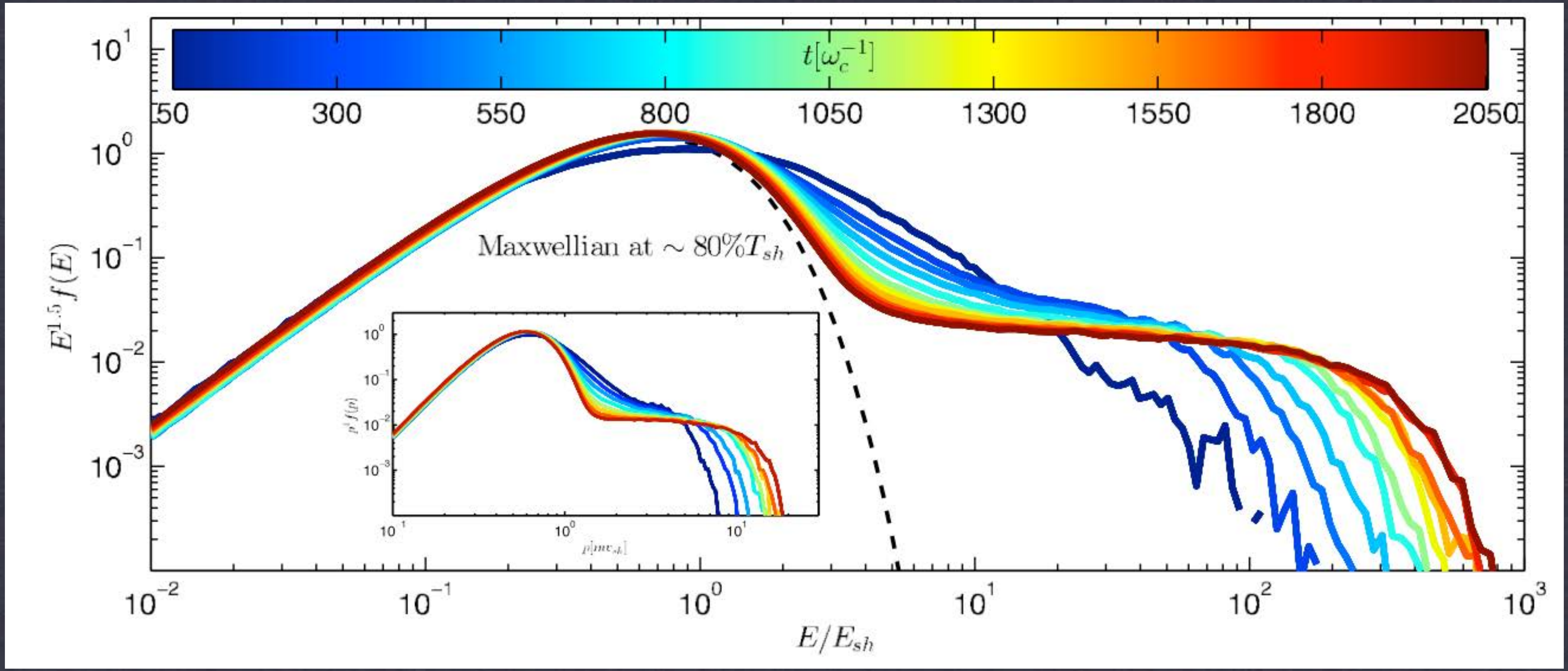
Quasiparallel shocks: proton and electron accelerators

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)

10-20% of energy going to nonthermal CRs.

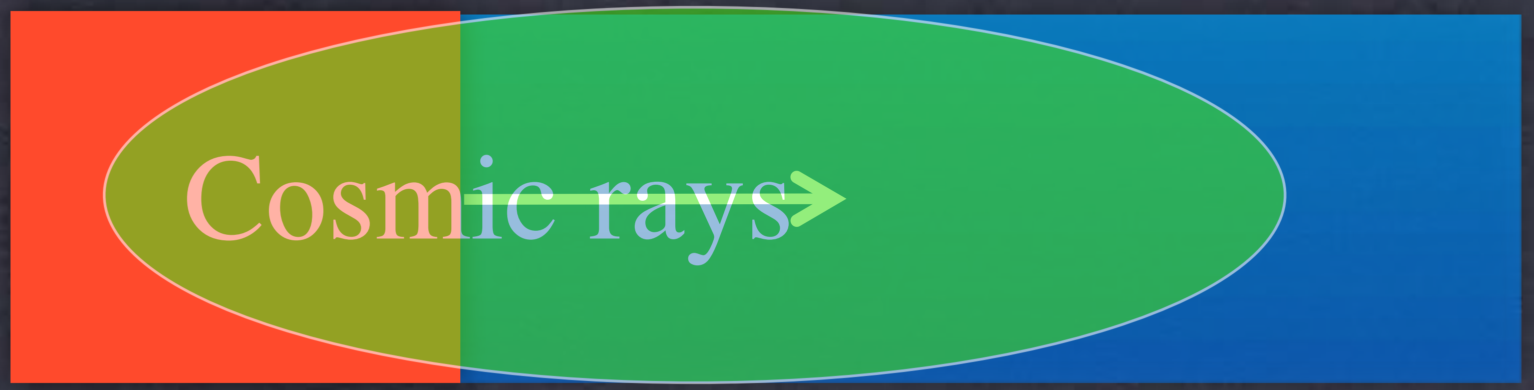
CR backreaction is affecting downstream temperature

Caprioli & AS 2014a

Field amplification

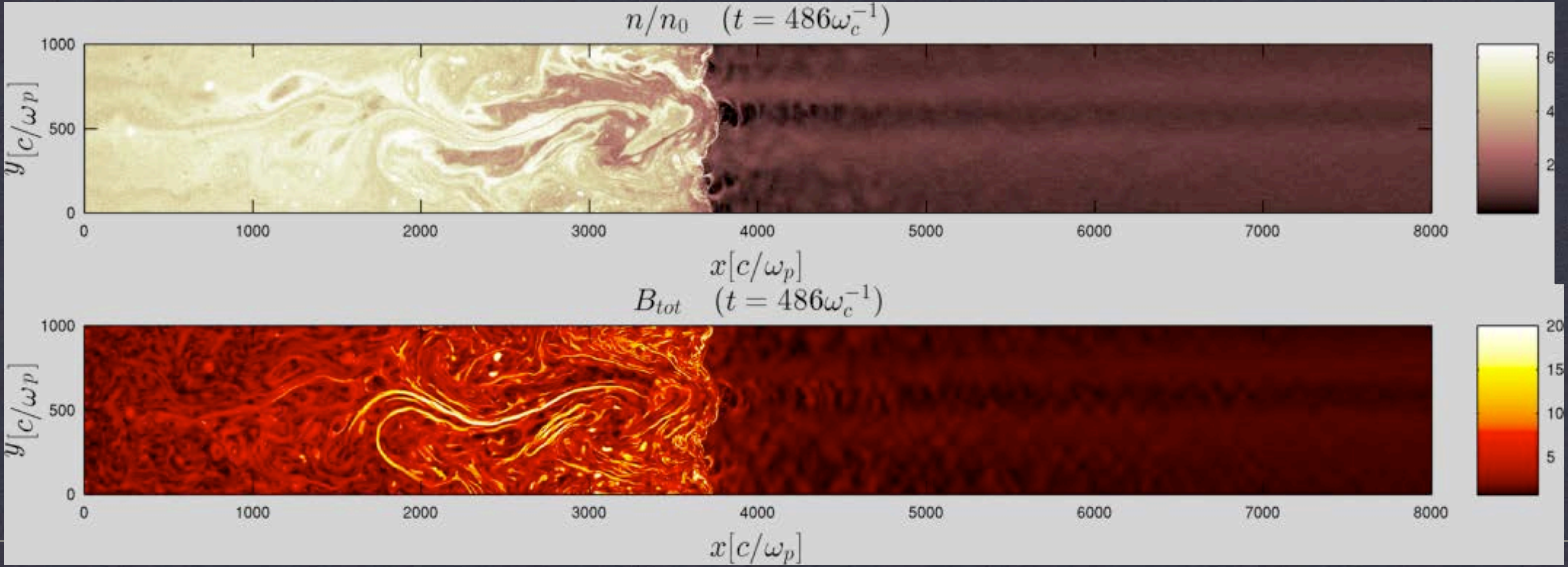
We see evidence of CR effect on upstream.

This will lead to “turbulent” shock with effectively lower Alfvenic Mach number with locally 45 degree inclined fields.

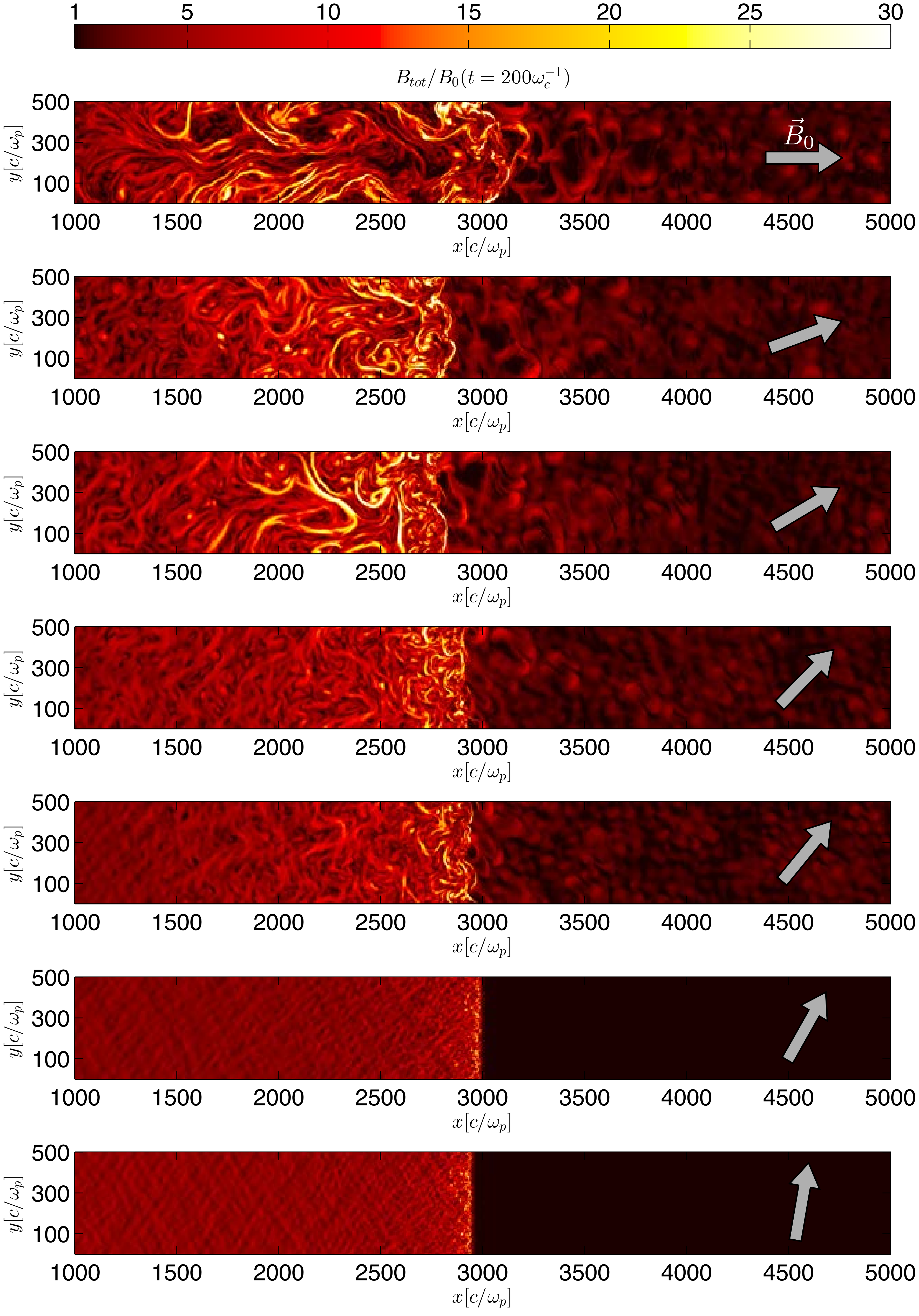


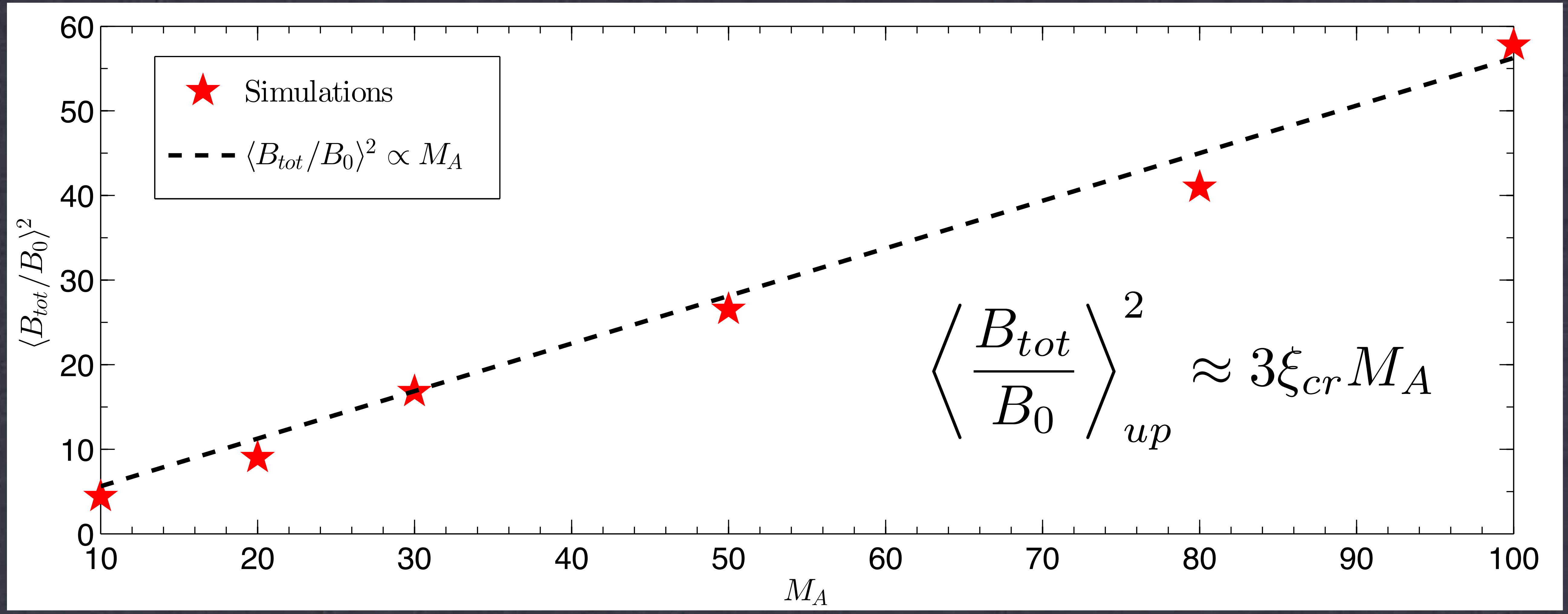
Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

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



Dependence of field amplification on inclination and Mach



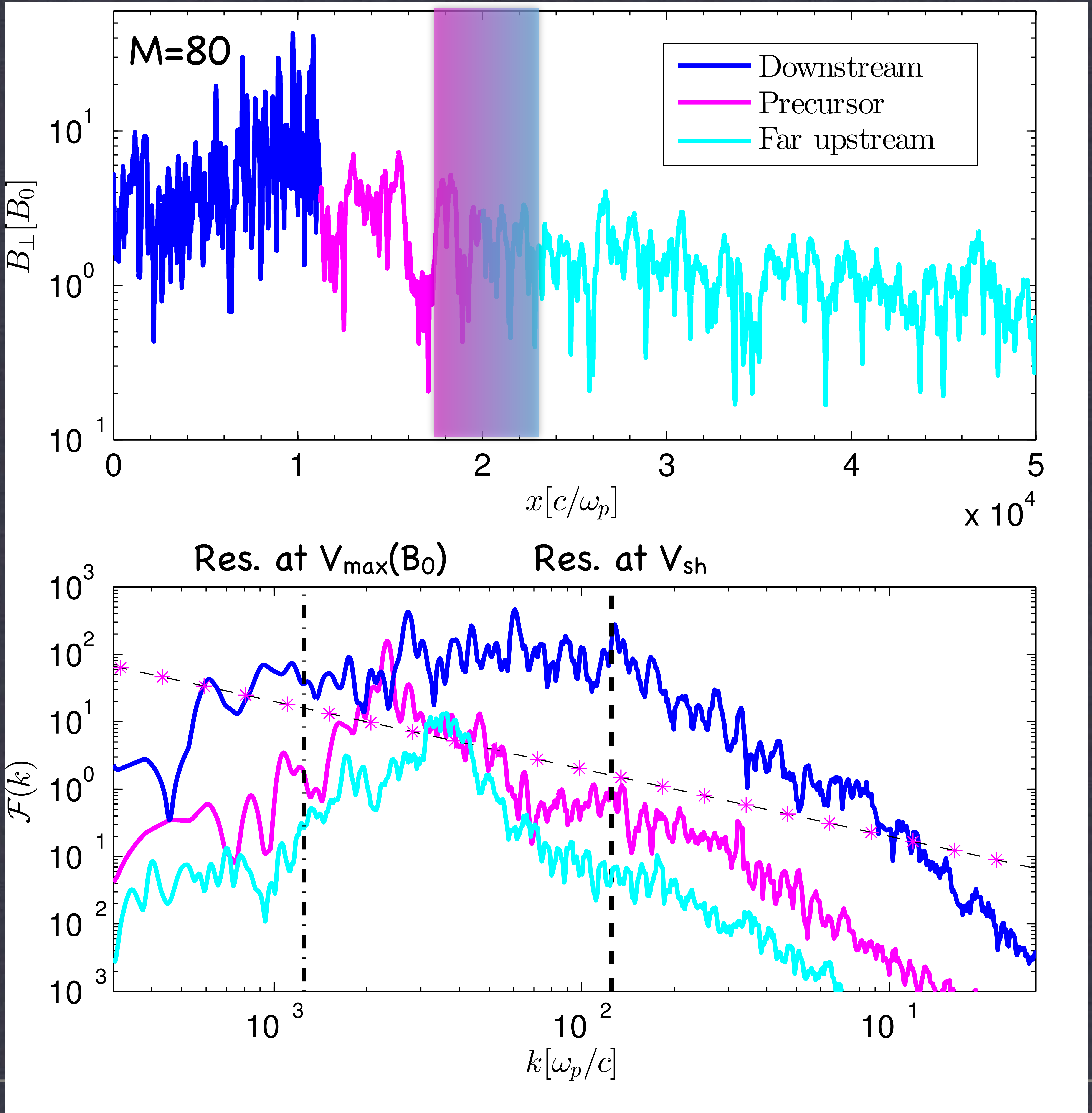


$$\left\langle \frac{B_{tot}}{B_0} \right\rangle^2_{up} \approx 3\xi_{cr} M_A$$

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's): strongly non-linear!
- Bohm-like diffusion in the self-generated B
  (Reville & Bell 2013; Caprioli & AS 2014c)

Magnetic field spectrum, high M_A



- Bell modes (short-wavelength, right-handed) grow faster than resonant
- Far upstream: escaping CRs at $\sim p_{max}$ (Bell)
- For large $b=\delta B/B_0$ $k_{max}(b) \sim k_{max,0}/b^2$
- There exist a b^* such that $k_{max}(b^*) r_L(p_{esc}) \sim 1$

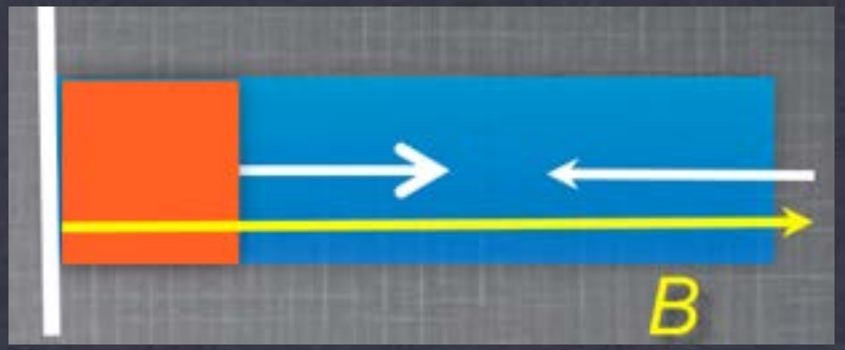
Free escape boundary

- Precursor: diffusion + resonant

Caprioli & AS, 2014b

Quasiparallel shocks: electron acceleration

Recent evidence of electron acceleration in quasi parallel shocks.
PIC simulation of quasiparallel shock. Very long simulation in 1D.
Alfven Mach = Sonic Mach = 20; mi/me=100-400;
Ion-driven Bell waves drive electron acceleration: correct polarization

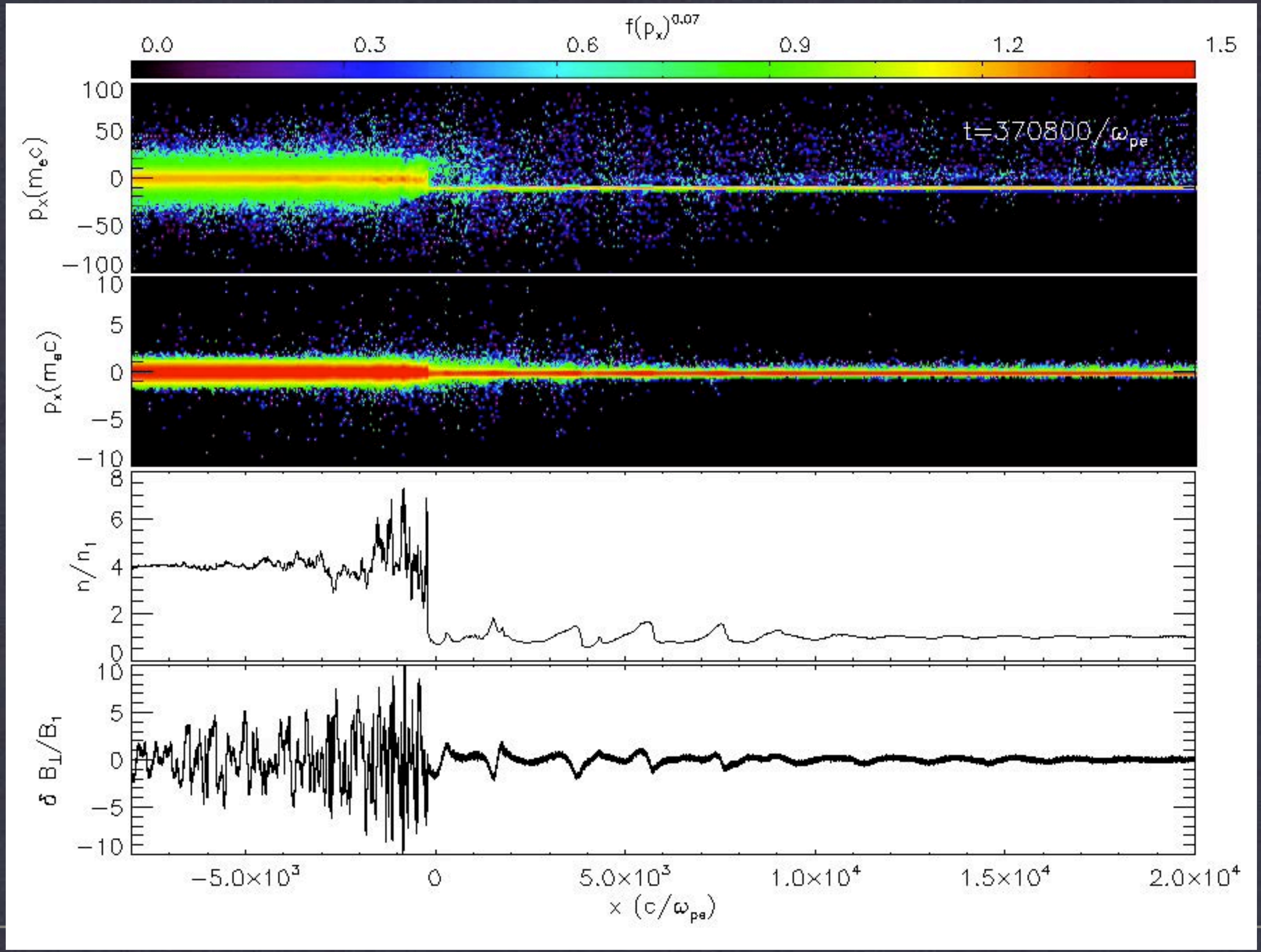


Ion phase space

Electron phase space

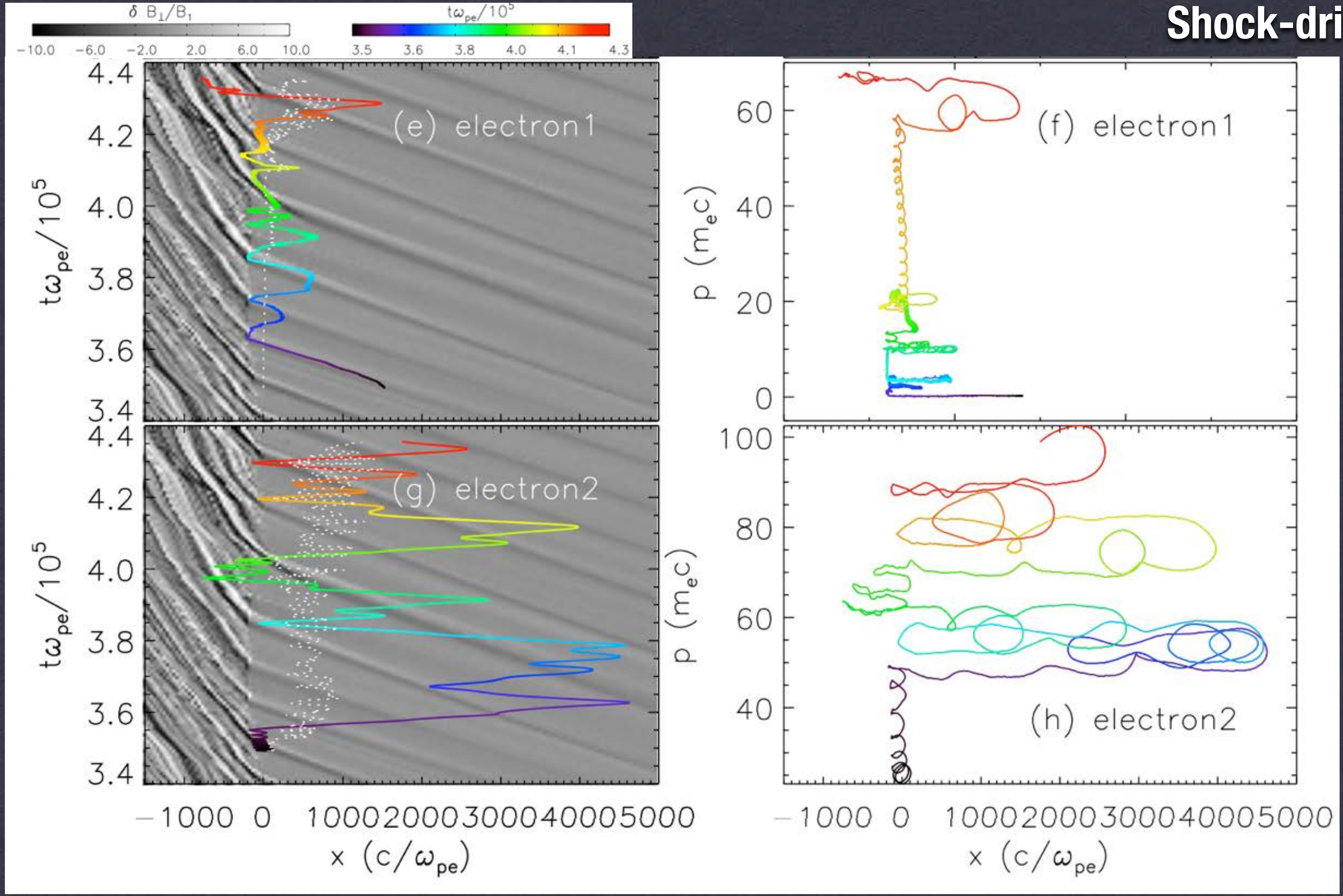
Density

Transverse Magnetic field



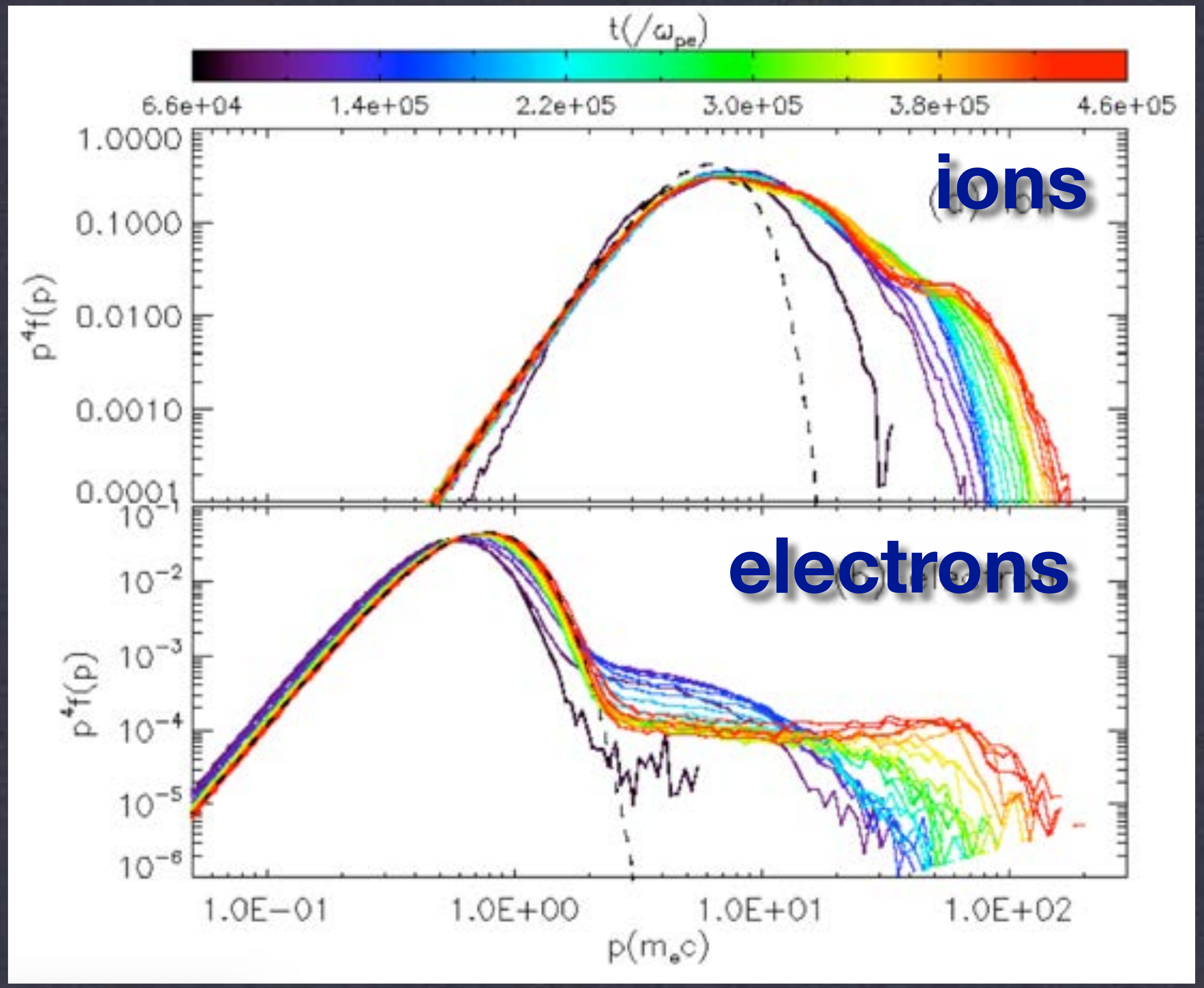
Electron acceleration mechanism: shock drift cycles + upstream diffusion

Shock-drift



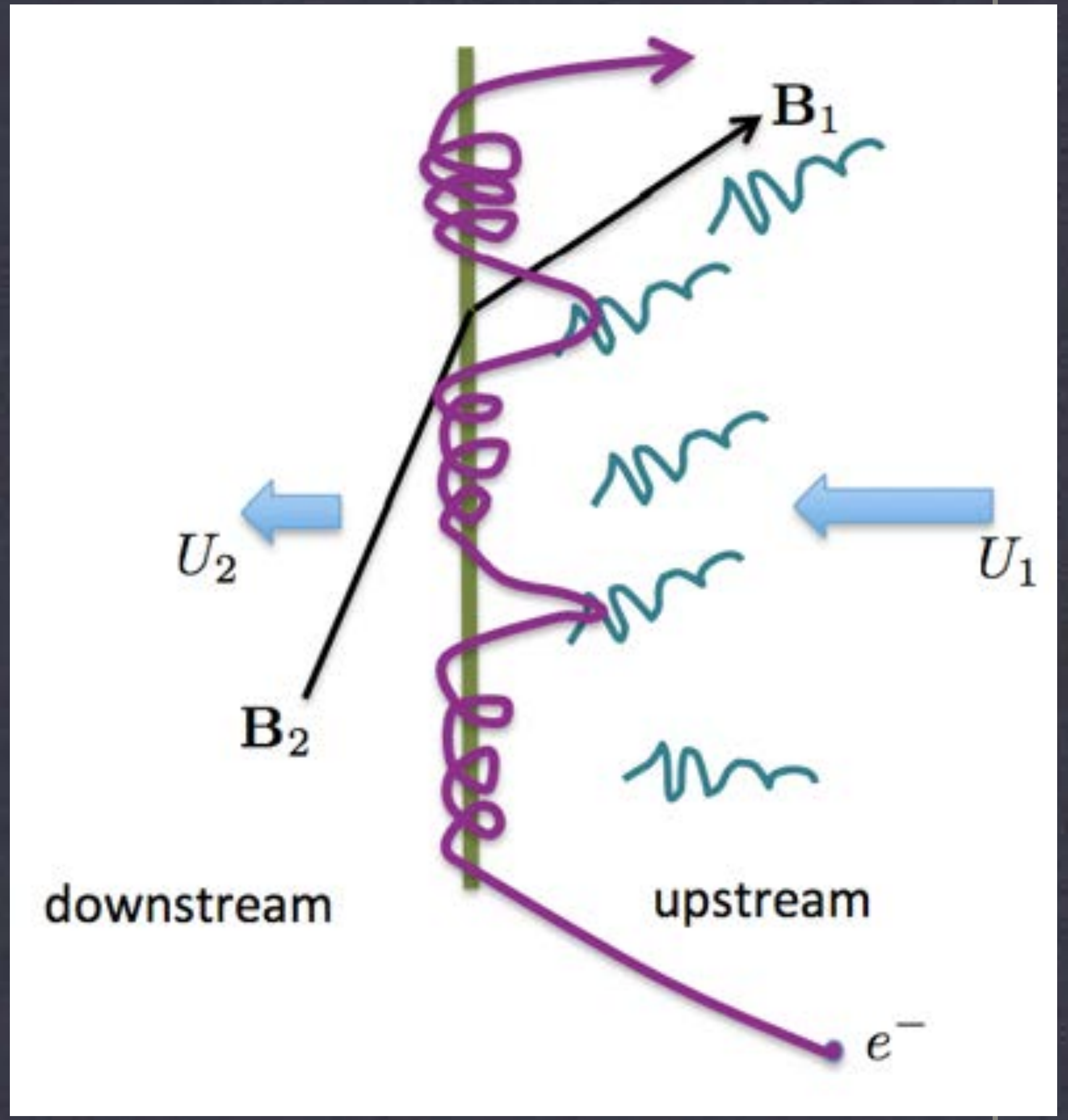
Diffusive

Electron track from PIC simulation



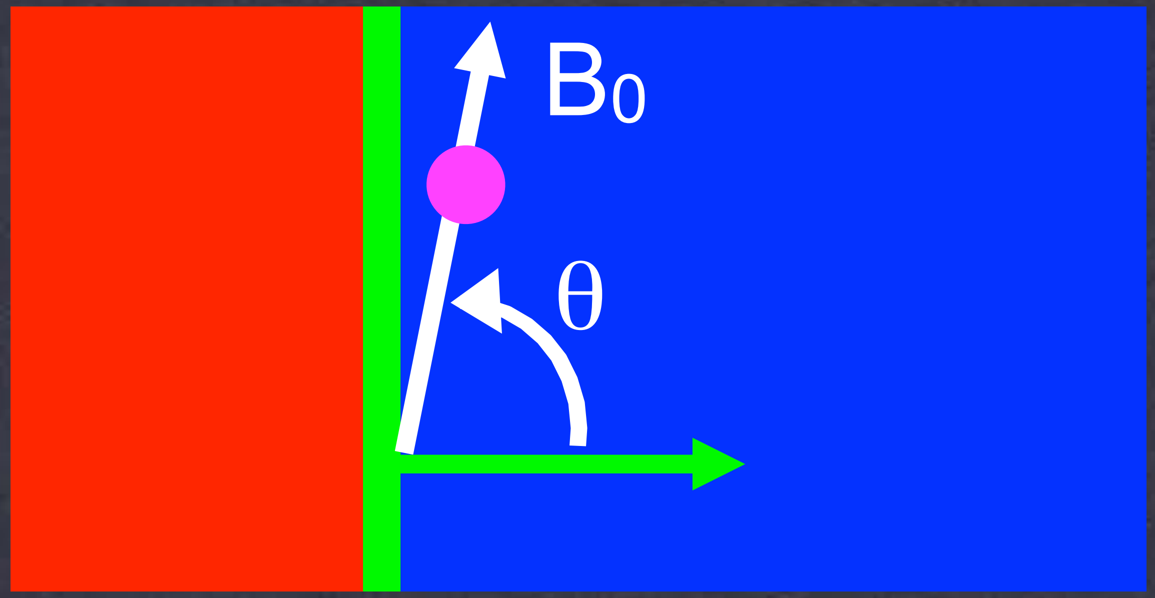
Electron efficiency:

Kep~10^{-3}



Quasiperpendicular shocks: electron acceleration

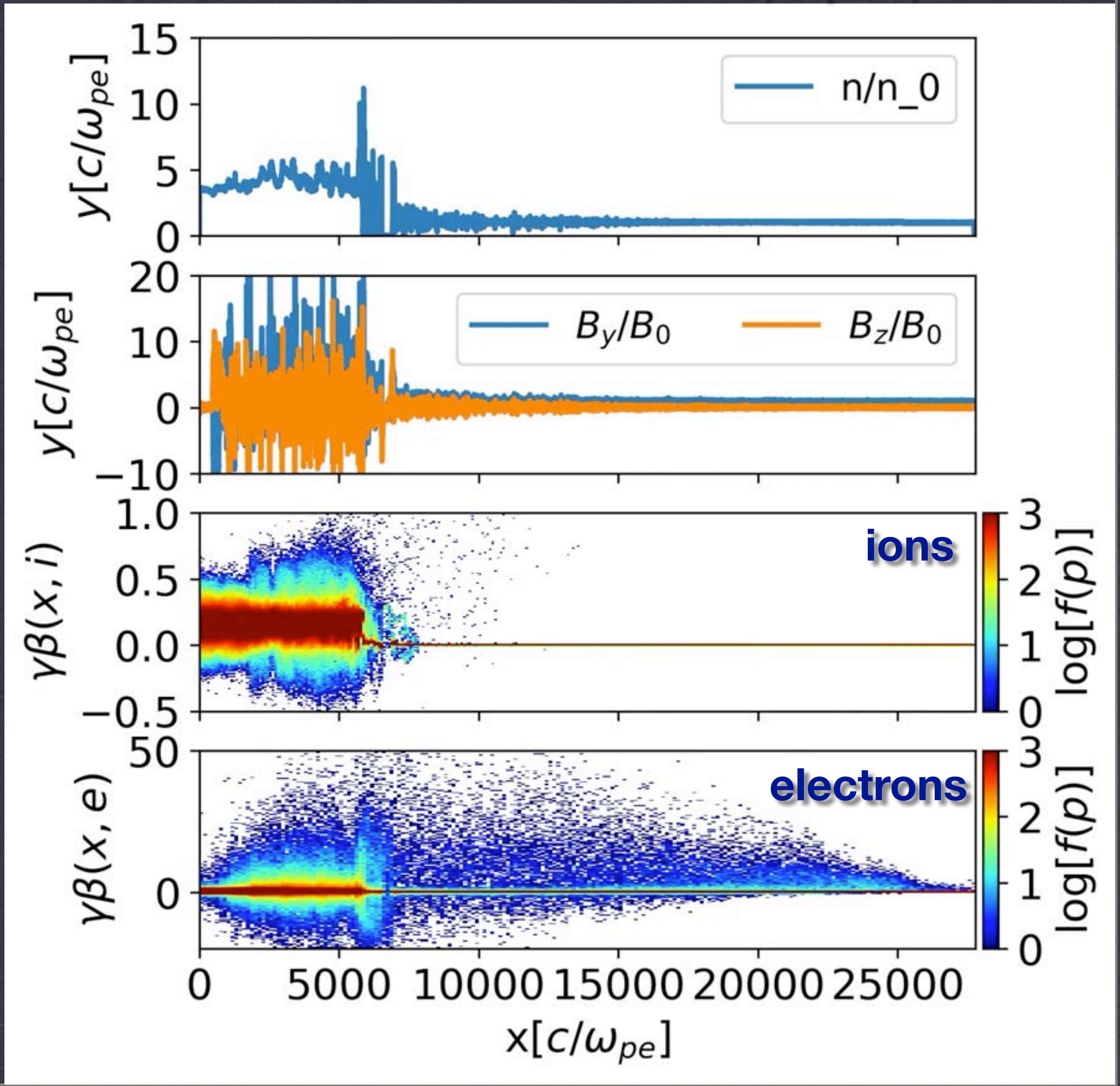
Particles can outrun the shock along oblique field if $v \cos\theta > v_{sh}$. This is easier for electrons than protons after mirroring and SDA pre-acceleration.



High Mach numbers:
Sonic Mach # = Alfvenic = 50; 63 degrees shock inclination, mi/me=100. Acceleration proceeds even with cold upstream.
Electrons are reflected into the upstream and can cause instabilities that scatter them.

Beginning of this process seen in previous PIC work (Matsumoto+ 17, Bohdan+ 20)

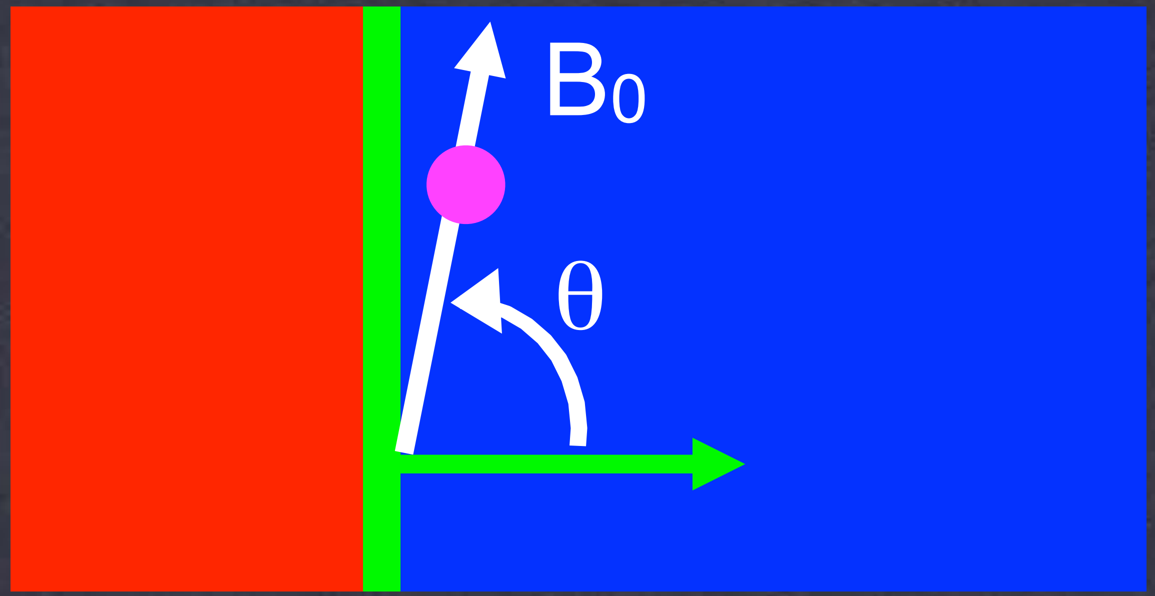
Xu, Caprioli, AS '20

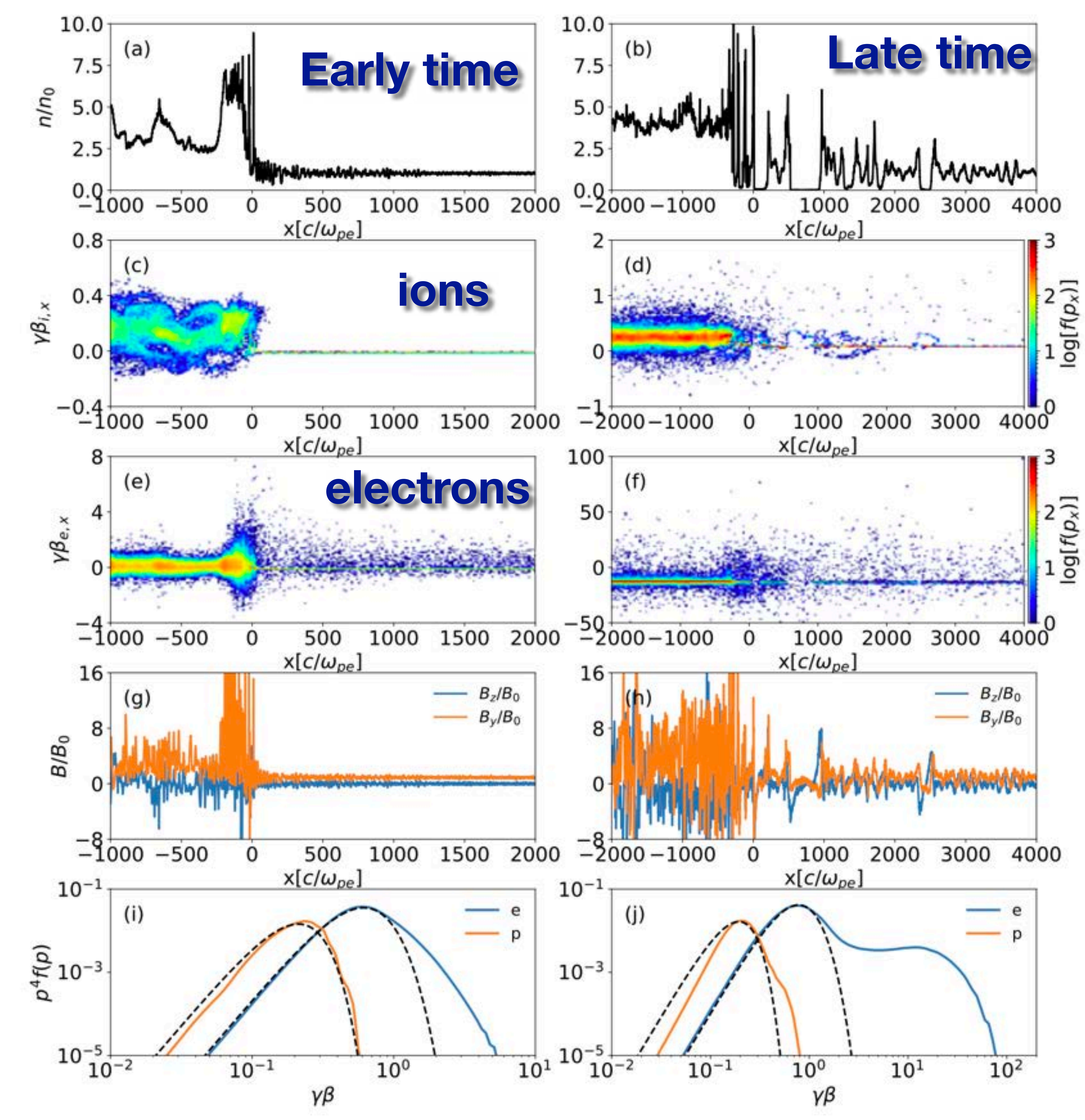


Quasiperpendicular shocks: electron acceleration

Xu, Caprioli, AS ‘20

Particles can outrun the shock along oblique field if $v\cos\theta > v_{sh}$. This is easier for electrons than protons after mirroring and SDA pre-acceleration.





High Mach numbers:
Sonic Mach # = Alfvenic = 50; 63 degrees shock inclination, mi/me=100. Acceleration proceeds even with cold upstream.
Electrons are reflected into the upstream and can cause instabilities that scatter them.

DSA electron spectrum, 0.1-5% in energy, <1% by number.

Electron acceleration in quasi-perp shocks: 2D

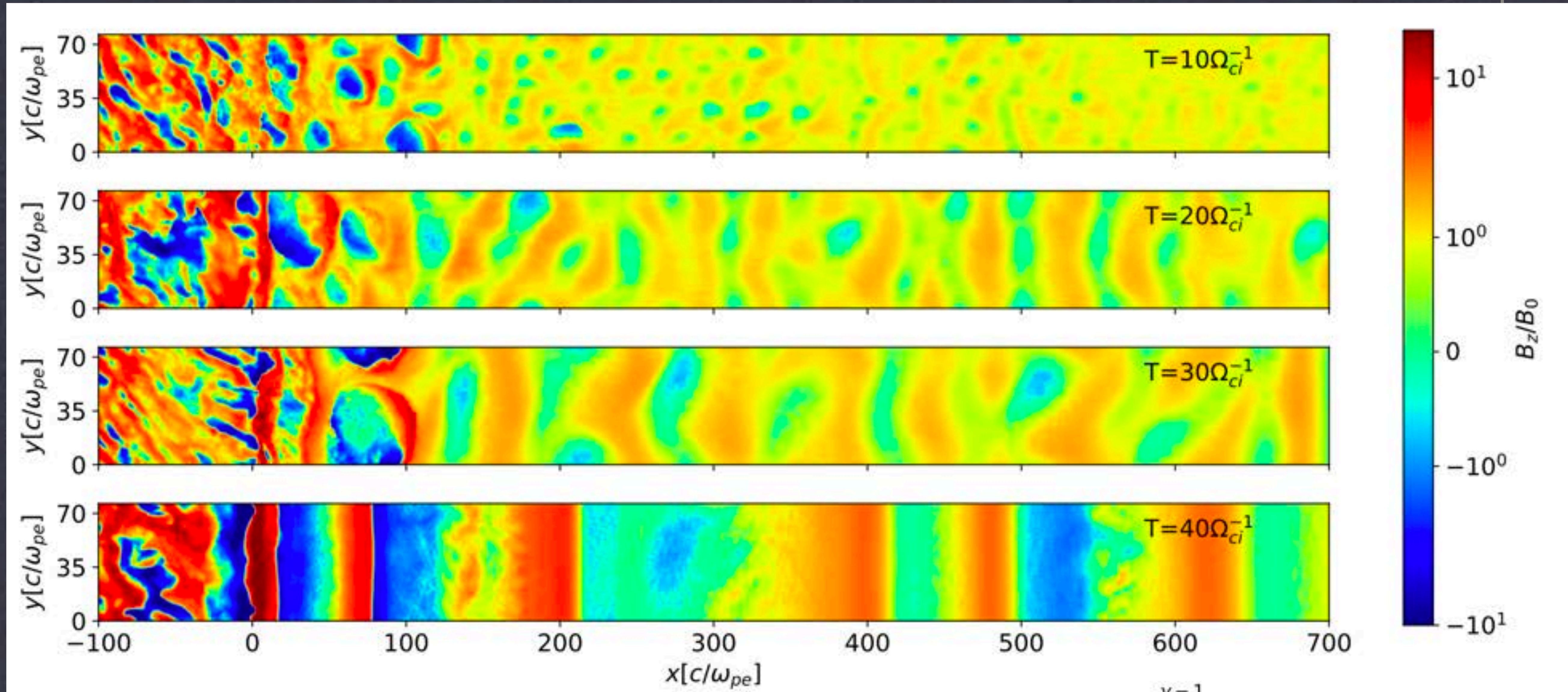
Electron acceleration depends on Mach number — can reach 4% by number, 5% by energy for high Machs.

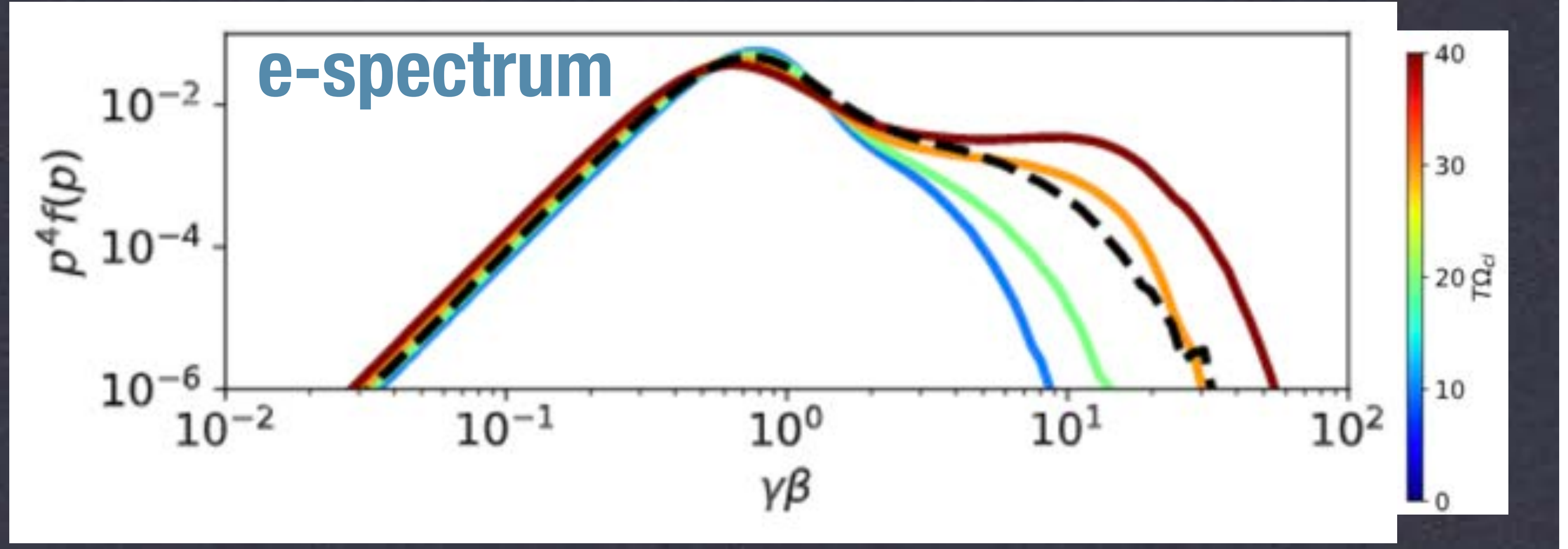
Electrons drive firehose-like upstream waves

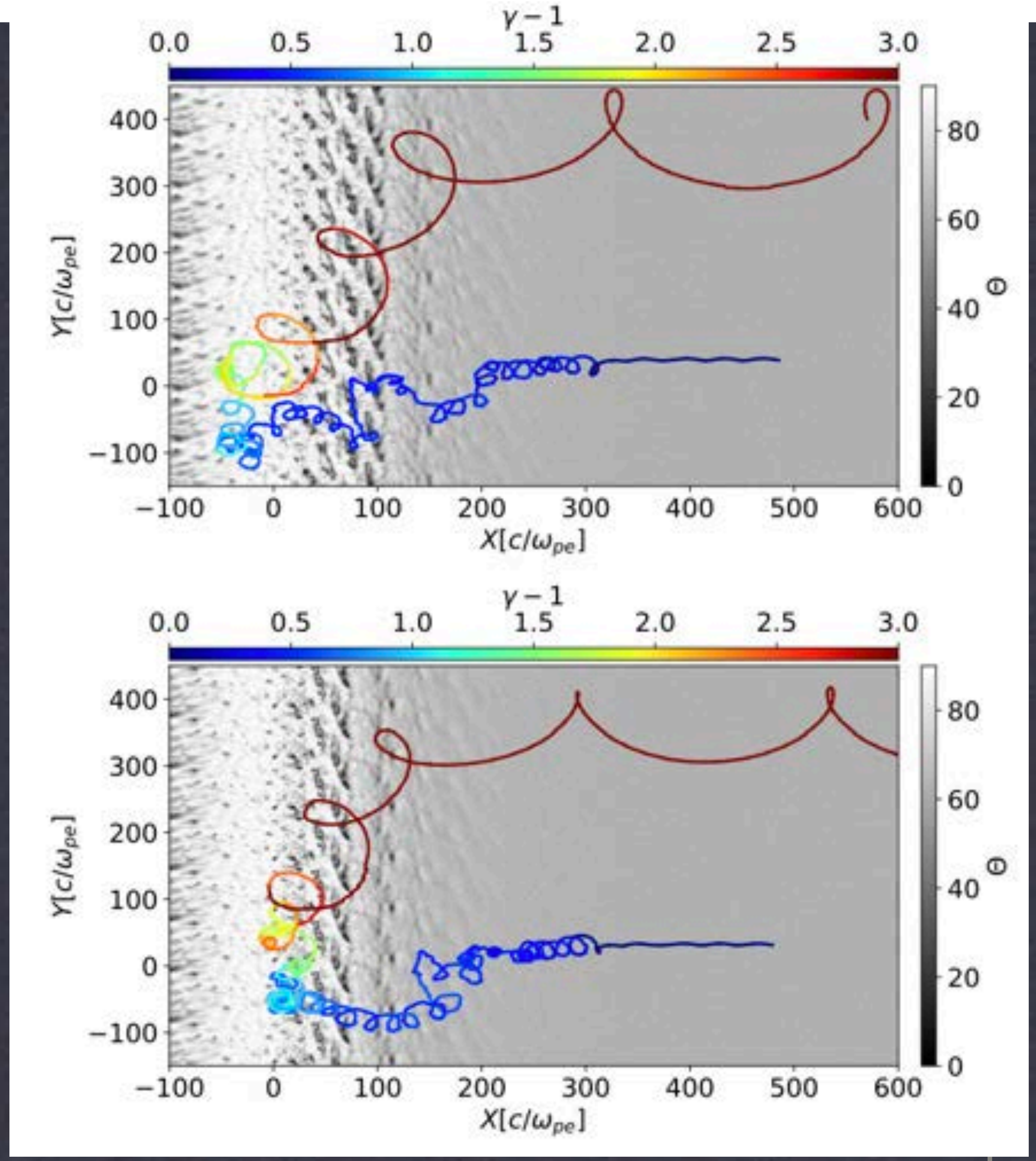
For injection, electrons are pre-heated in the shock foot and are accelerated through cycles of SDA before escaping upstream.

Picture survives in 2D and 3D

Transverse box size is still limited in PIC







Xu+AS, in prep

COLLISIONLESS SHOCKS

Kinetic simulations have shown:

- Formation of collisionless shocks from first principles
- Presence of reflected particles
- Generation of self-turbulence: resonant and non-resonant waves
- Acceleration of reflected particles

All of these are on fairly early time scales

Feedback mechanisms

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

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

Global deceleration of upstream

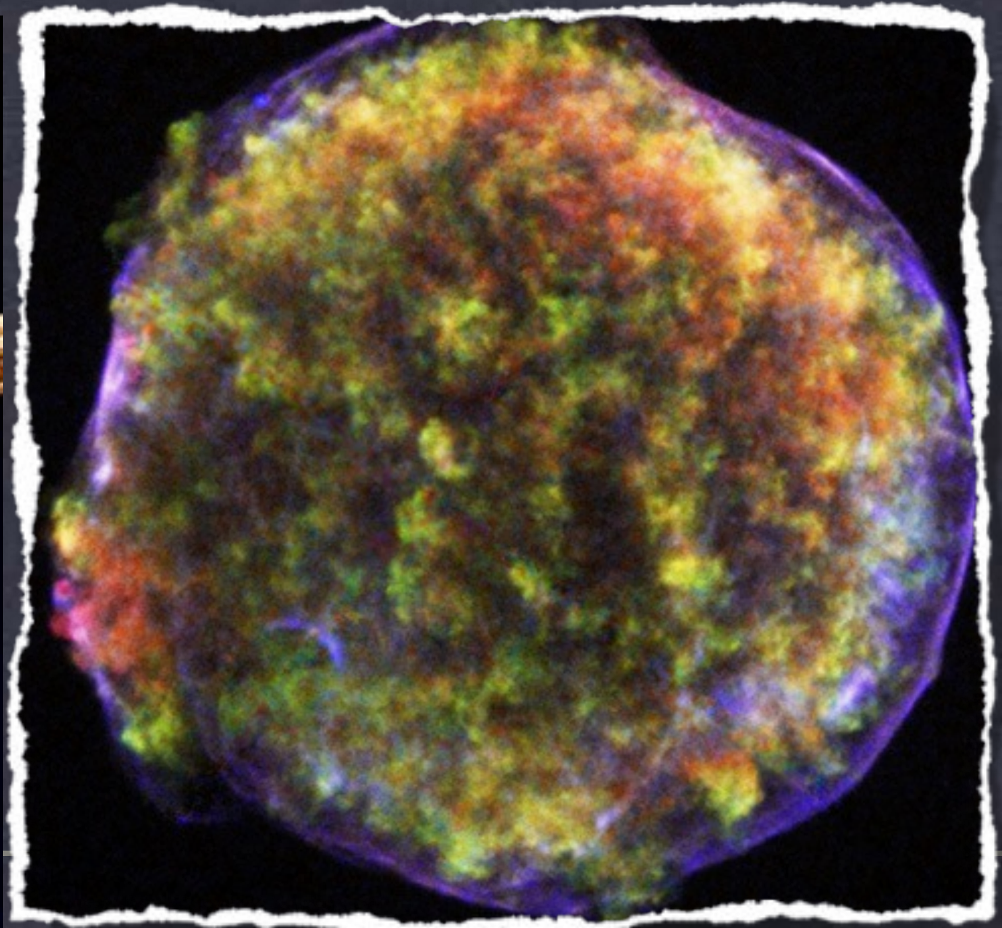
Shock reformation, nonlinear structures, SLAMs (short large amplitude magnetic structures)

Over time as max energy grows, the dominant wavelength at the shock also increases, does that prevent further acceleration?

Nonlinear DSA — Theory vs Observations

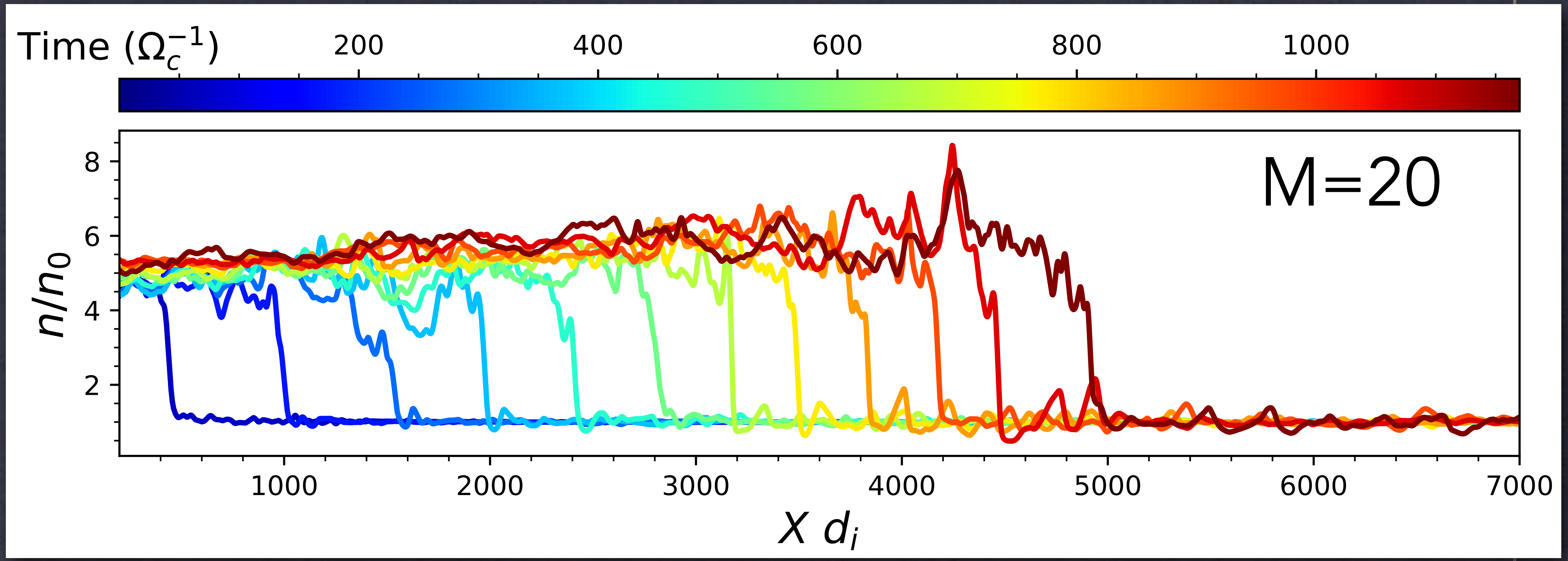
Caprioli, Haggerty, Blasi ‘20

- ***Efficient DSA*** (Drury 1983, Jones & Ellison 1991, Malkov & Drury 2001,…) should return:
  - Compression ratios $r > 4$;
  - CR spectra flatter than p^{-4} (flatter than E^{-2} for relativistic particles)
- **Observations**, instead, point to significantly steeper spectra:
  - Hadronic γ-rays from historical and middle-age SNRs: $p^{-q}, \ q \sim 4.3 - 4.7$ (e.g., Caprioli11,12; Aharonian+19);
  - Synchrotron emission from radio SNe: $q \sim 5$ (e.g., Chevalier & Fransson06, Bell+11, Margutti+18, …);
  - Propagation of Galactic CRs suggests source spectra with $q \sim 4.3 - 4.4$ (e.g., Blasi-Amato11a,b; Evoli+19).



CR-Modified Shocks: Enhanced Compression

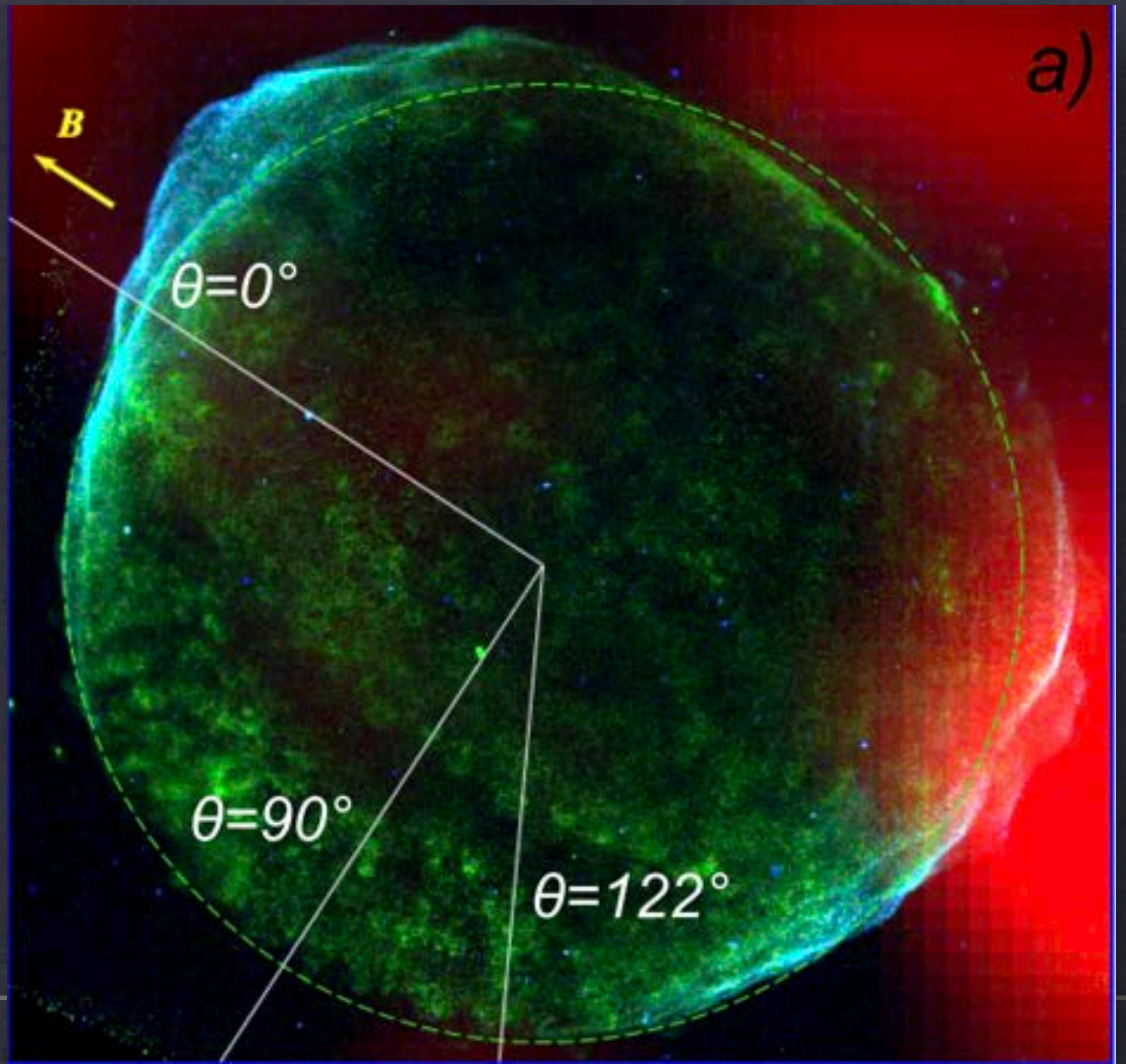
- Hybrid simulations (Haggerty & Caprioli20)
  - Efficiency $\lesssim 15\,\%$ at parallel shocks
  - Formation of upstream precursor
  - *R* increases with time, up to ~ 6

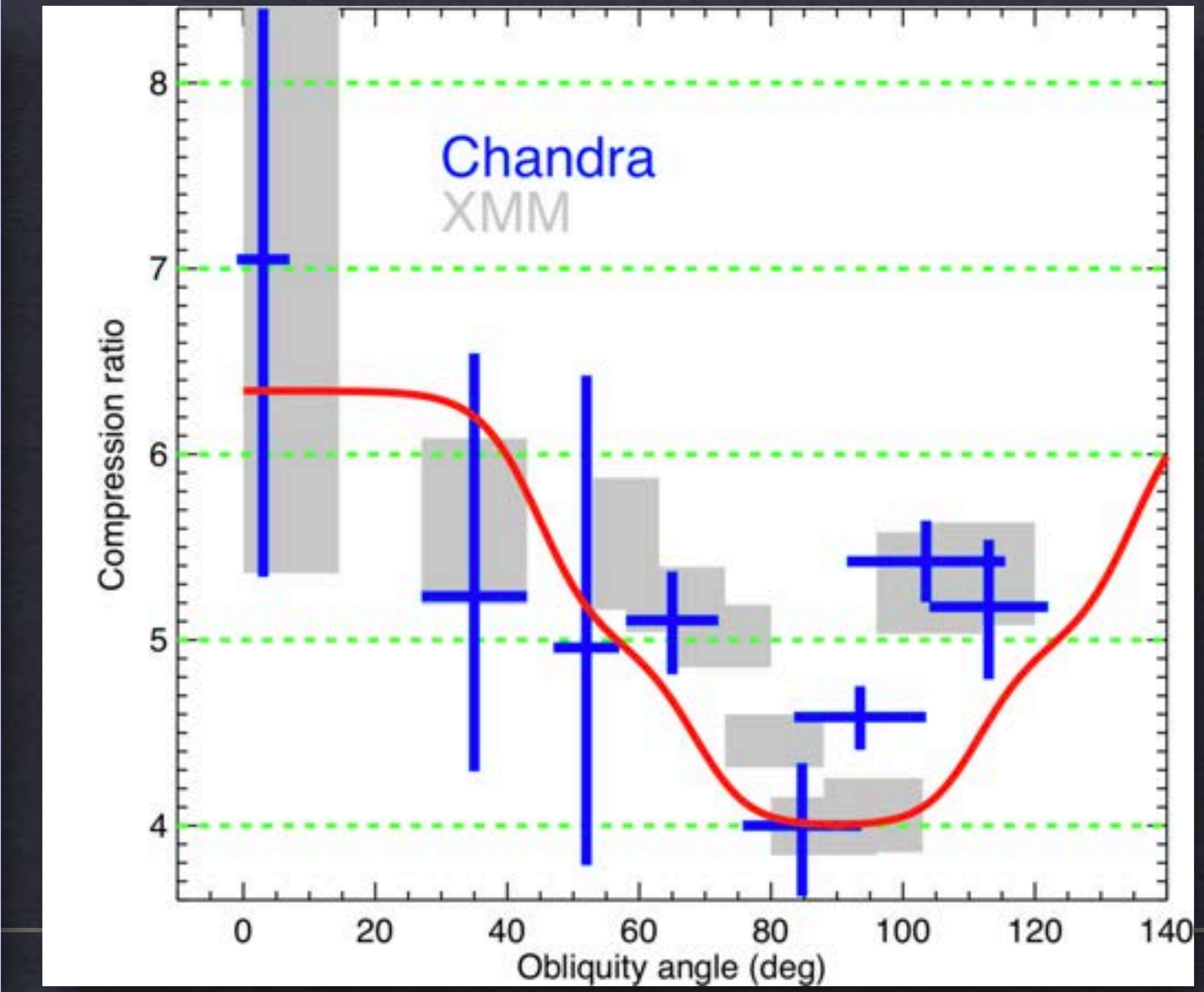


- $r \sim 6 - 7$ inferred in Tycho (Warren+05). In SN1006: $r \sim 4 - 7$, modulated with the azimuth/shock inclination (Giuffrida, Miceli, Caprioli+21)
  - If $r \simeq 7 \rightarrow q_{\text{expected}} \simeq 3.5$
  - SNRs: radio to γ-ray observations:

$$q_{\text{inferred}} \simeq 4.3$$

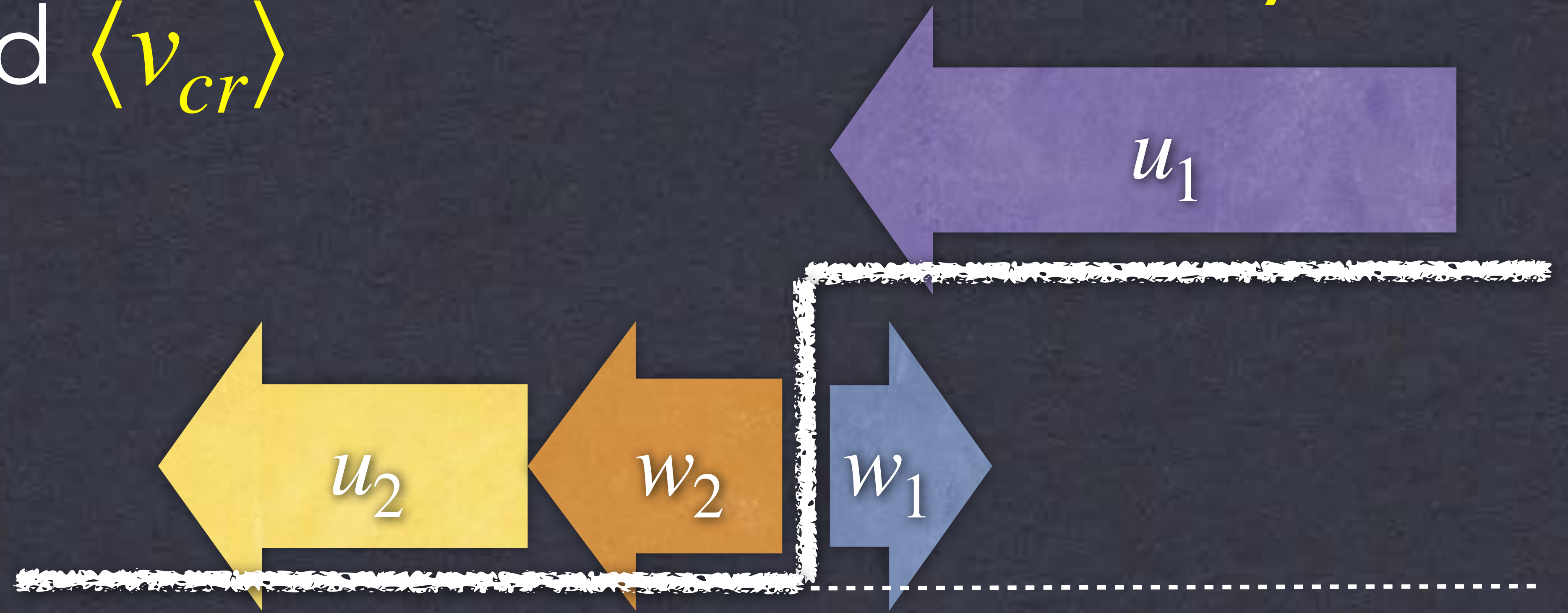
A challenge to DSA theory!

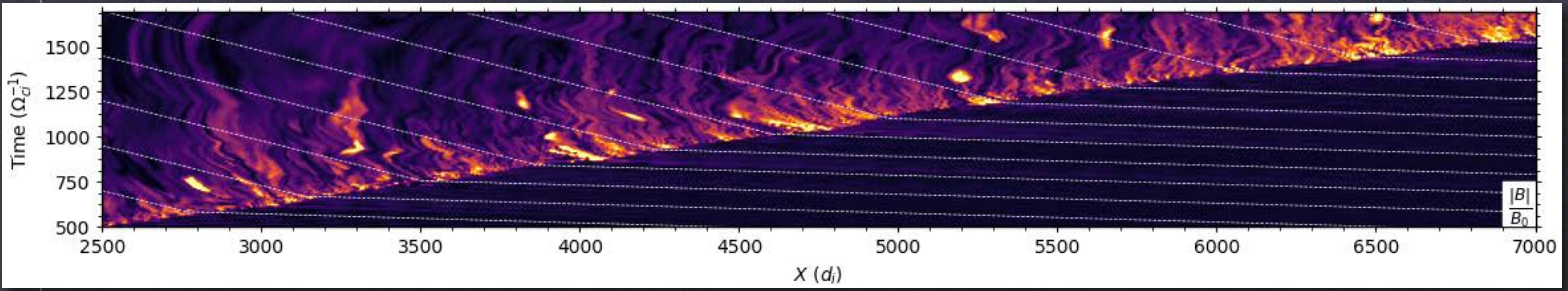




The Role of Amplified Magnetic Fields

- CRs feel an effective compression $r_{cr} = \frac{u_1 + w_1}{u_2 + w_2}$; w = wave speed $\approx v_A = \frac{B}{4\pi\rho}$
- We can measure both w and the effective CR speed $\langle v_{cr} \rangle$
  - Upstream: $w_1 \simeq - v_{A,1}(\delta B_1) \ll u_1$
  - Downstream: $\langle v_{cr} \rangle \simeq w_2 \simeq + v_{A,2}(\delta B_2) \equiv \alpha\ u_2$



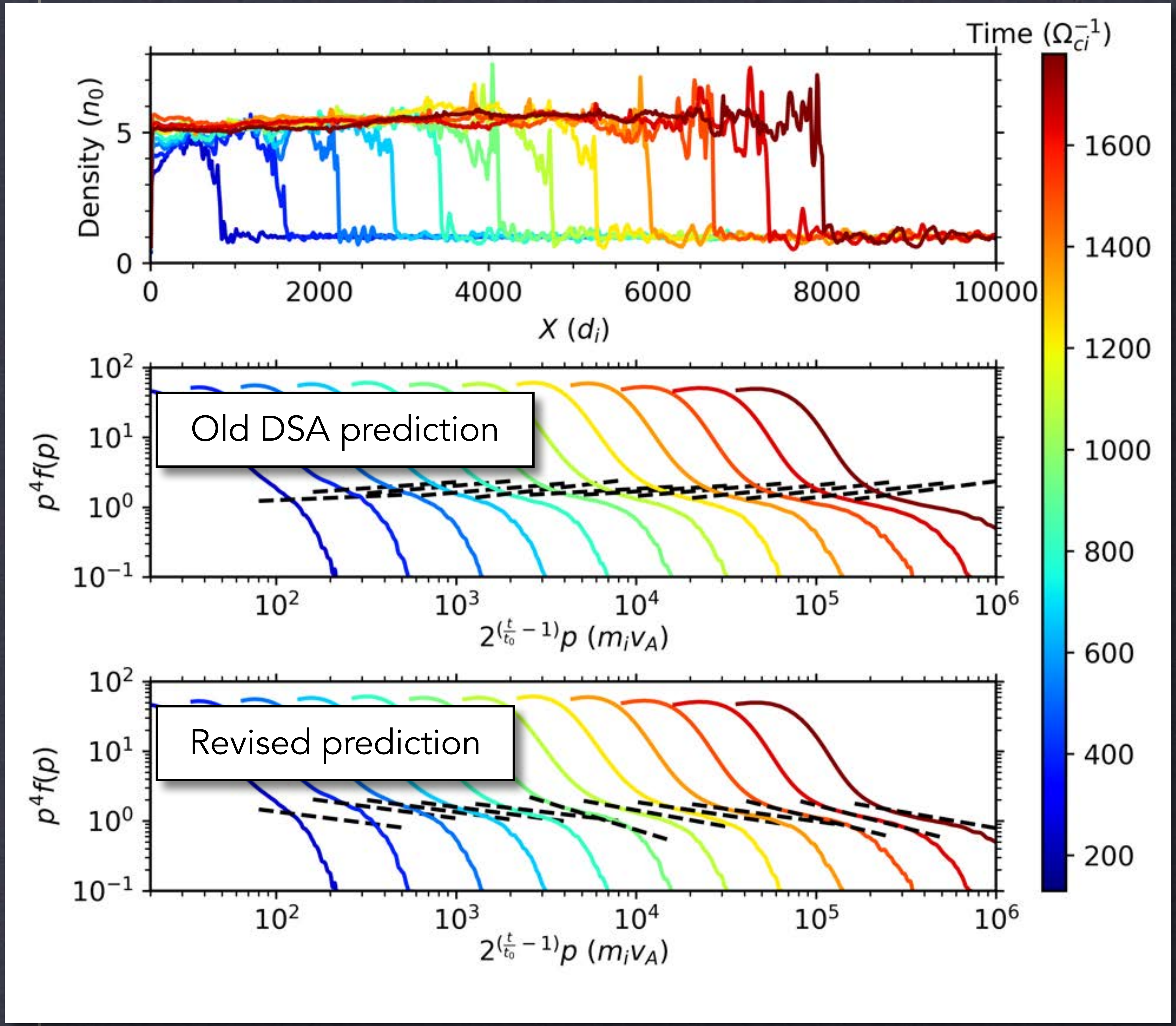


Haggerty-Caprioli20

- B fields (and hence CRs) drift downstream with respect to the thermal gas
  - First evidence of the formation of a *postcursor*
  - CRs *feel* a compression ratio *smaller* than the gas

$$r_{cr} \simeq \frac{u_1}{u_2(1+\alpha)} < r_{gas}$$

A Revised Theory of Diffusive Shock Acceleration



Old DSA prediction

Revised prediction

Caprioli, Haggerty & Blasi 2020

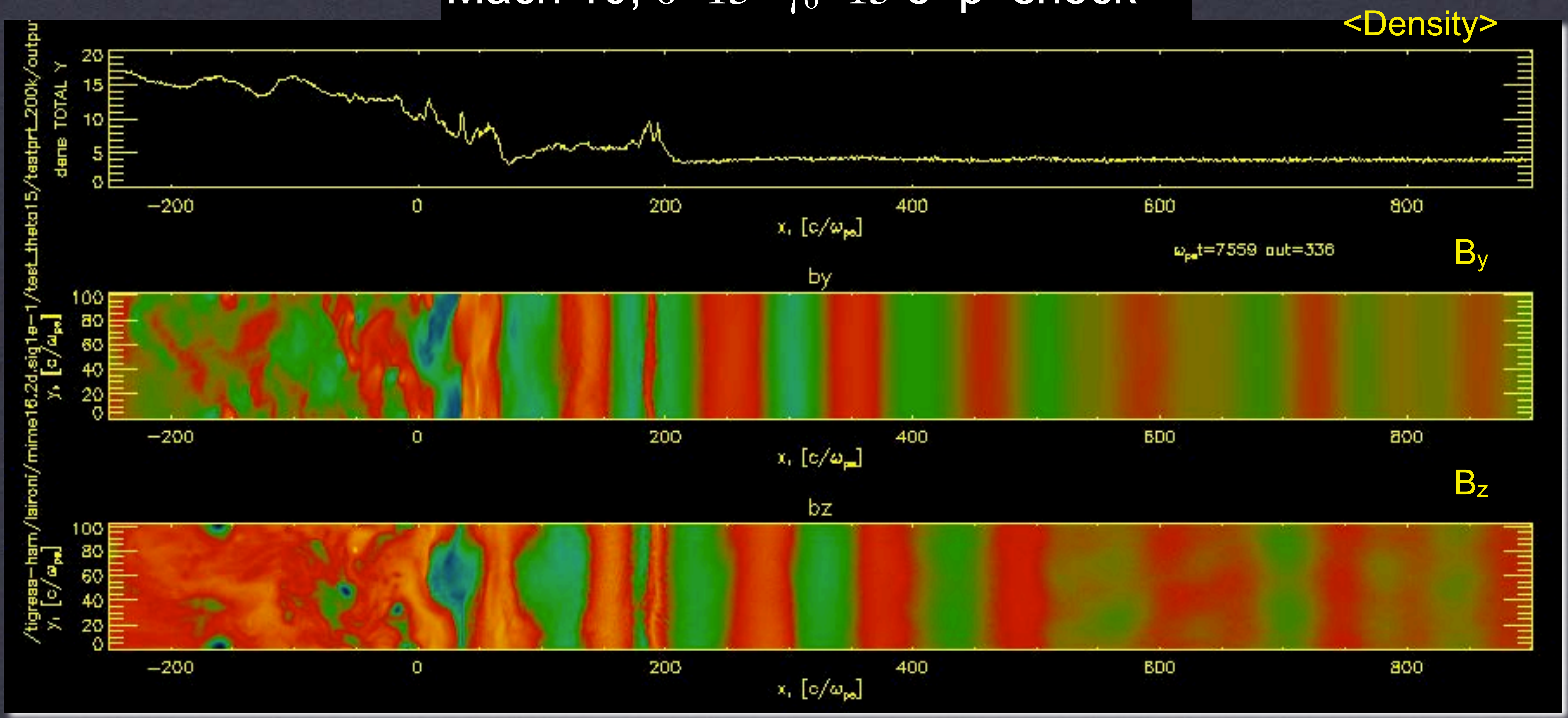
- With the effective compression felt by CRs

$$q = \frac{3r_{cr}}{r_{cr}-1} = \frac{3r_{gas}}{r_{gas}-1-\alpha} > q_{DSA}$$

- CRs feel $r_{cr} < r_{gas}$: the power-law index is *not universal, but depends on the (CR-produced) B field*
- *Ab-initio* explanation for the steep spectra observed?

Nonlinear evolution: reformation and feedback

Mach 10, $\theta=15°$ $\gamma_0=15$ e^--p^+ shock

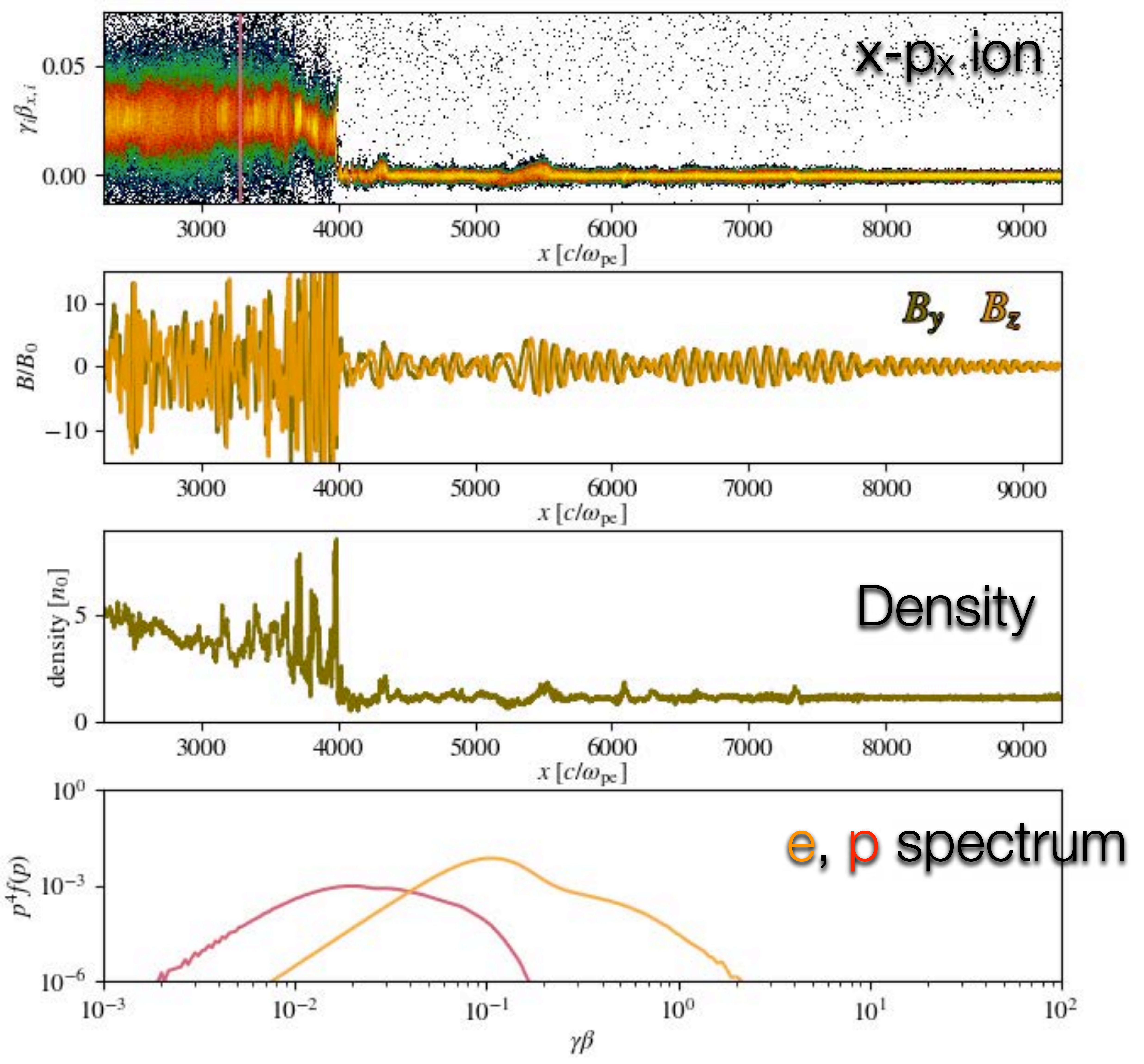


(Sironi & AS 11)

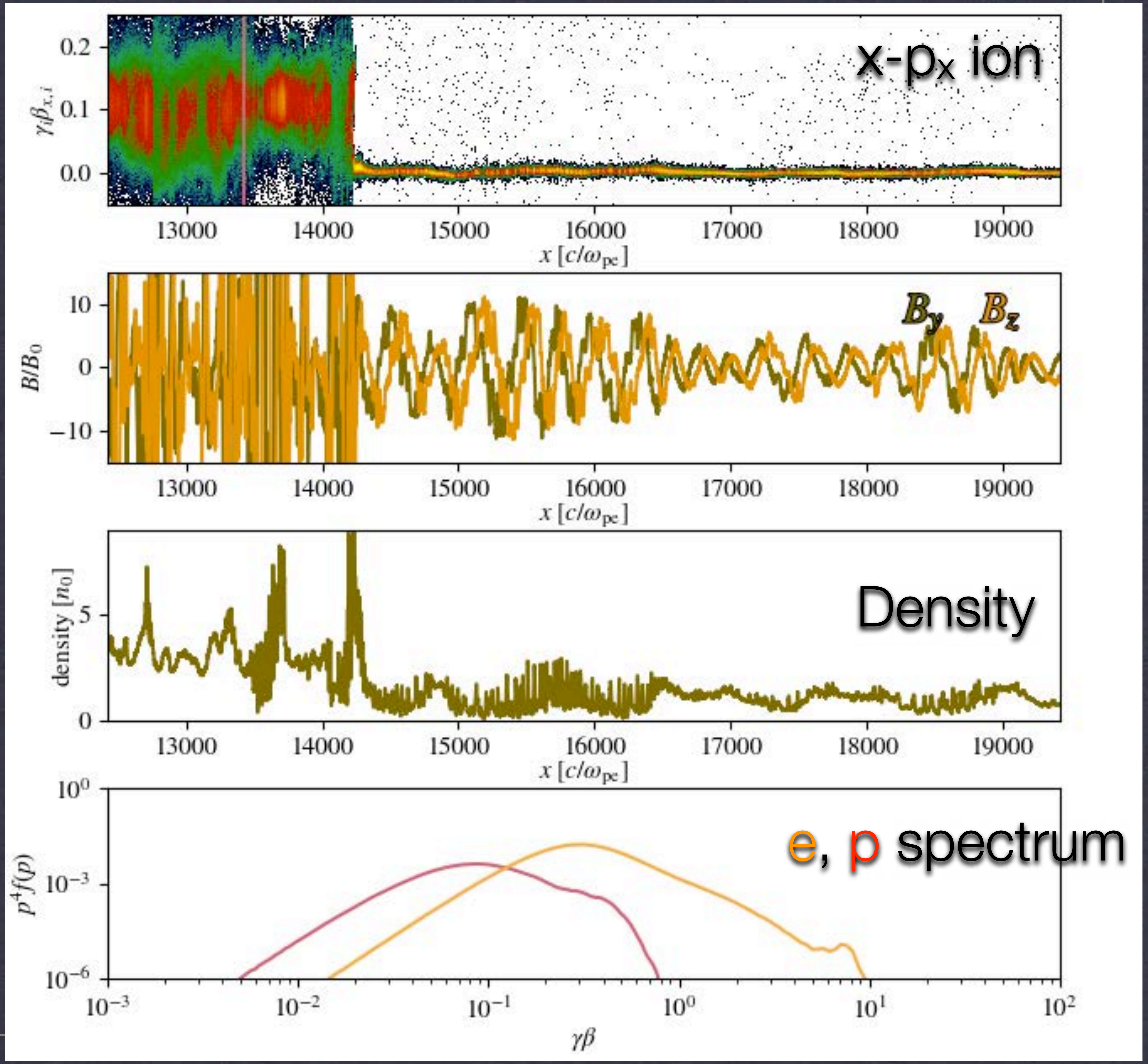
- Parallel shock with efficient injection drives large amplitude upstream waves
- Shock reformation (and SLAMS) seen in the density profile at late times

Short Large Amplitude Magnetic Structures (SLAMS)

Ma=20: large waves in the upstream



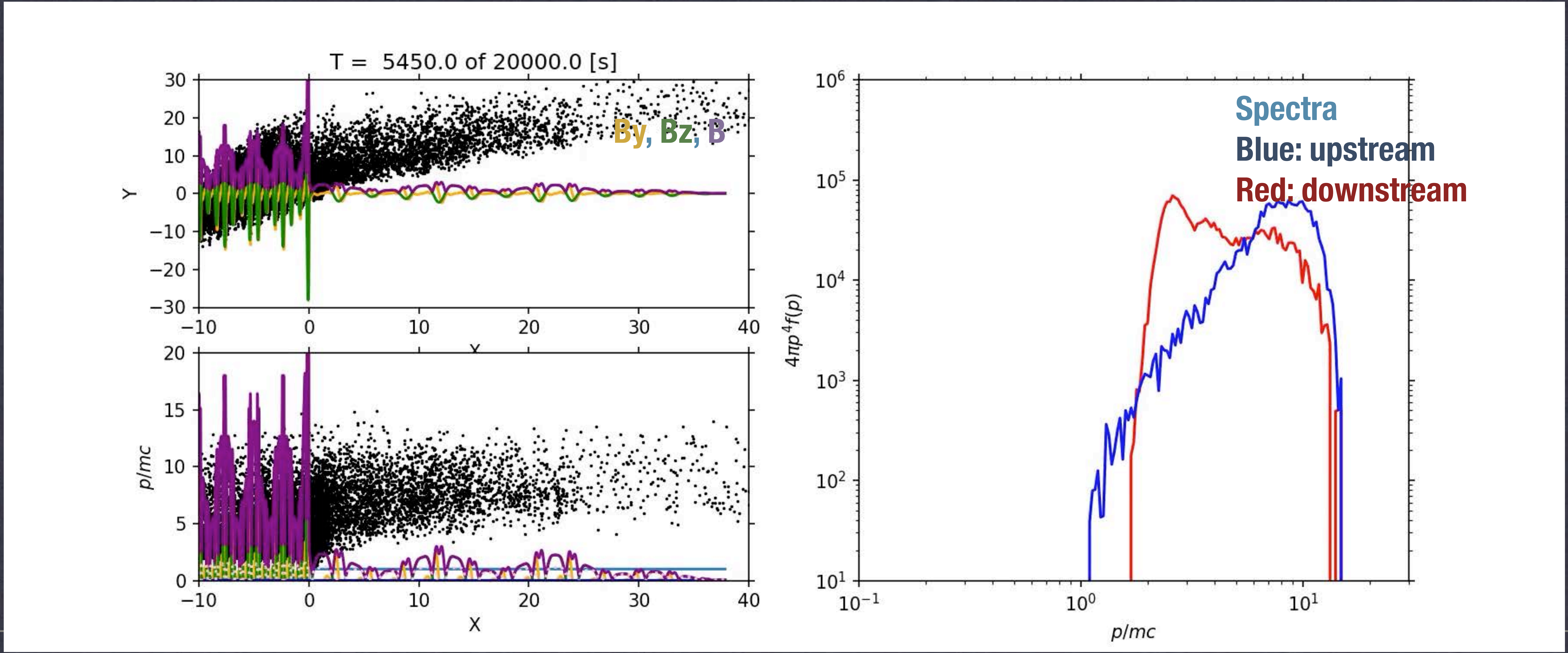
Ma=80: SLAMs lead to steeper electron spectra?



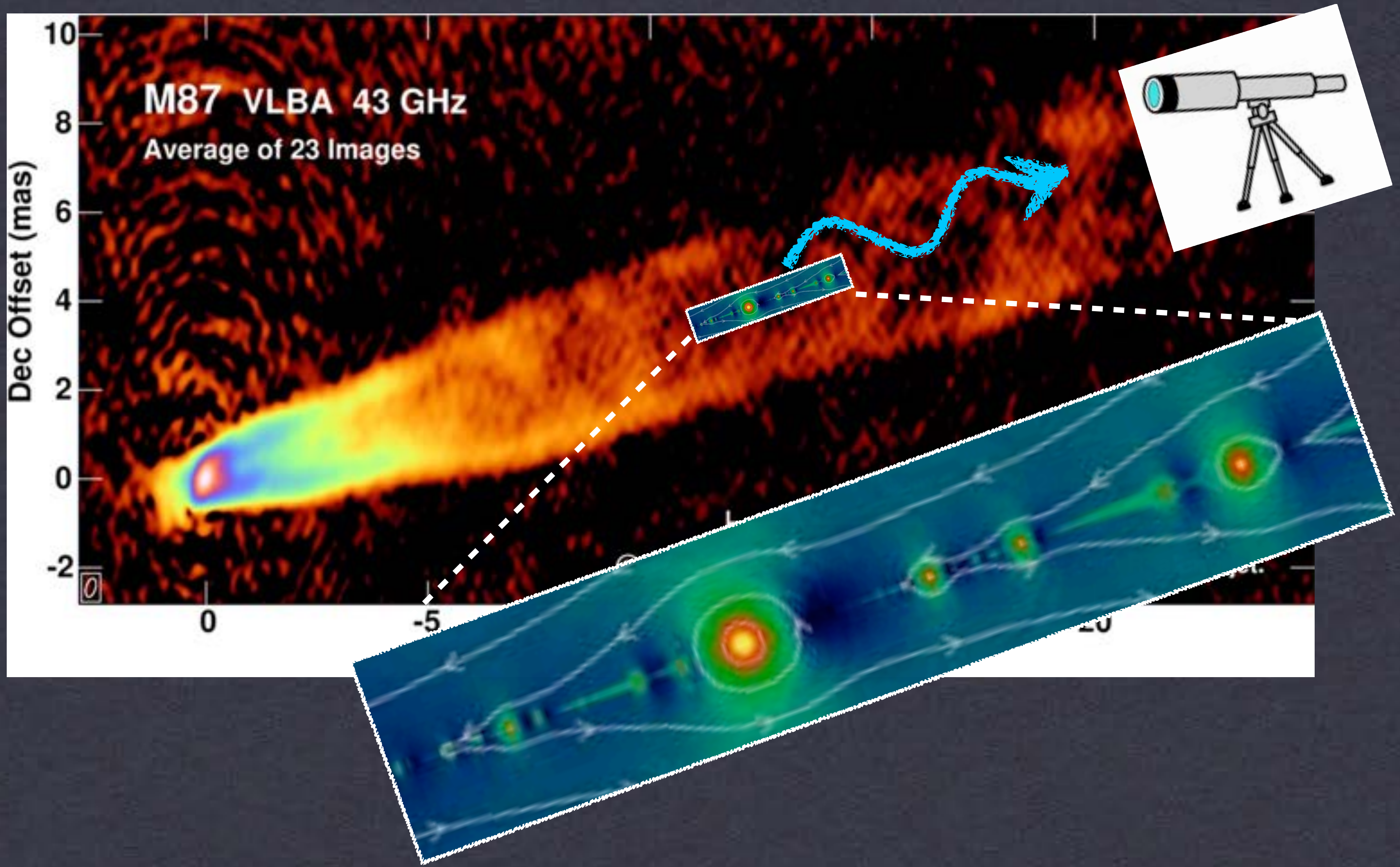
Wave packets help injection

Even though maximum amplitude in a strong wave makes the local field direction very oblique, and thus unlikely to easily inject particles, amplitude modulation in a wave packet creates regions of smaller obliquity that are favorable for injection. Thus, the filling fraction of favorable obliqueness (both spatial and temporal) determines and regulates injection fraction.

Test particle simulation in prescribed circularly polarized wave packet (Zekovic, Hemler, AS, in prep)



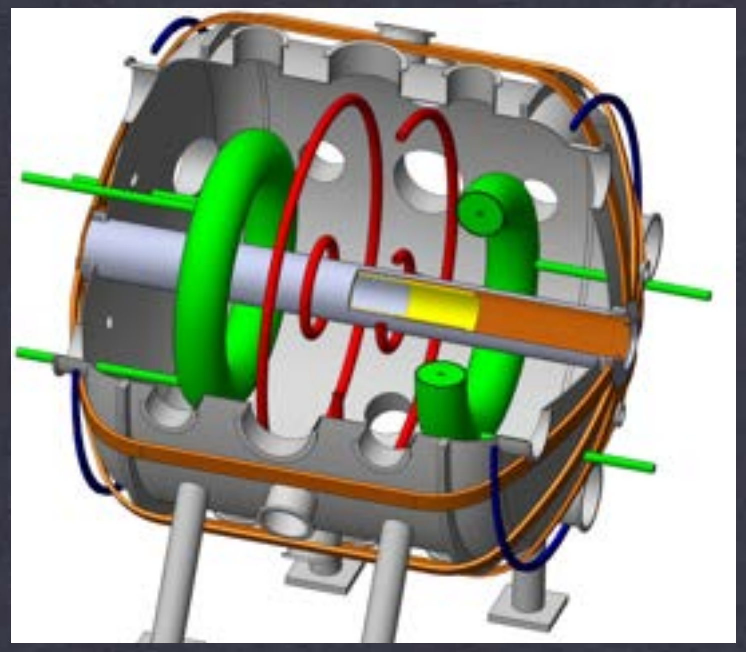
ACCELERATION IN RECONNECTION

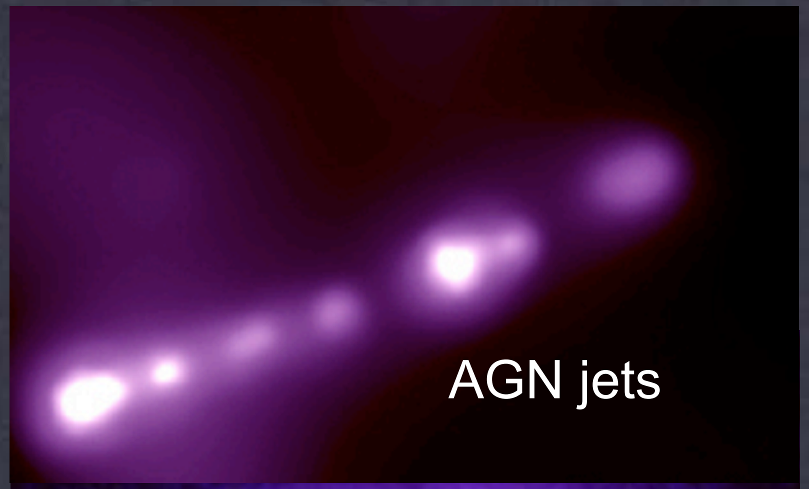


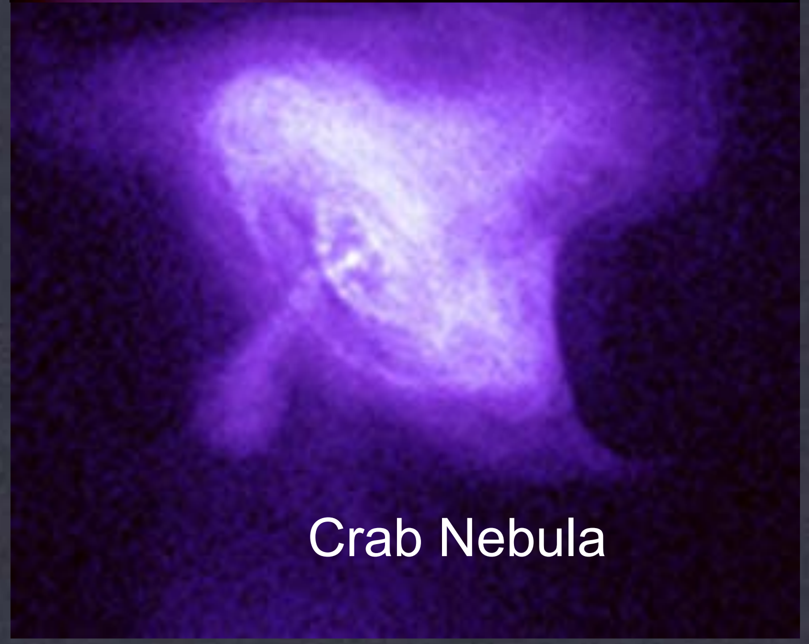
$$\sigma = \frac{B_0^2}{4\pi\rho c^2}$$

σ≪1

σ≫1







Relativistic reconnection in magnetically-dominated plasmas:

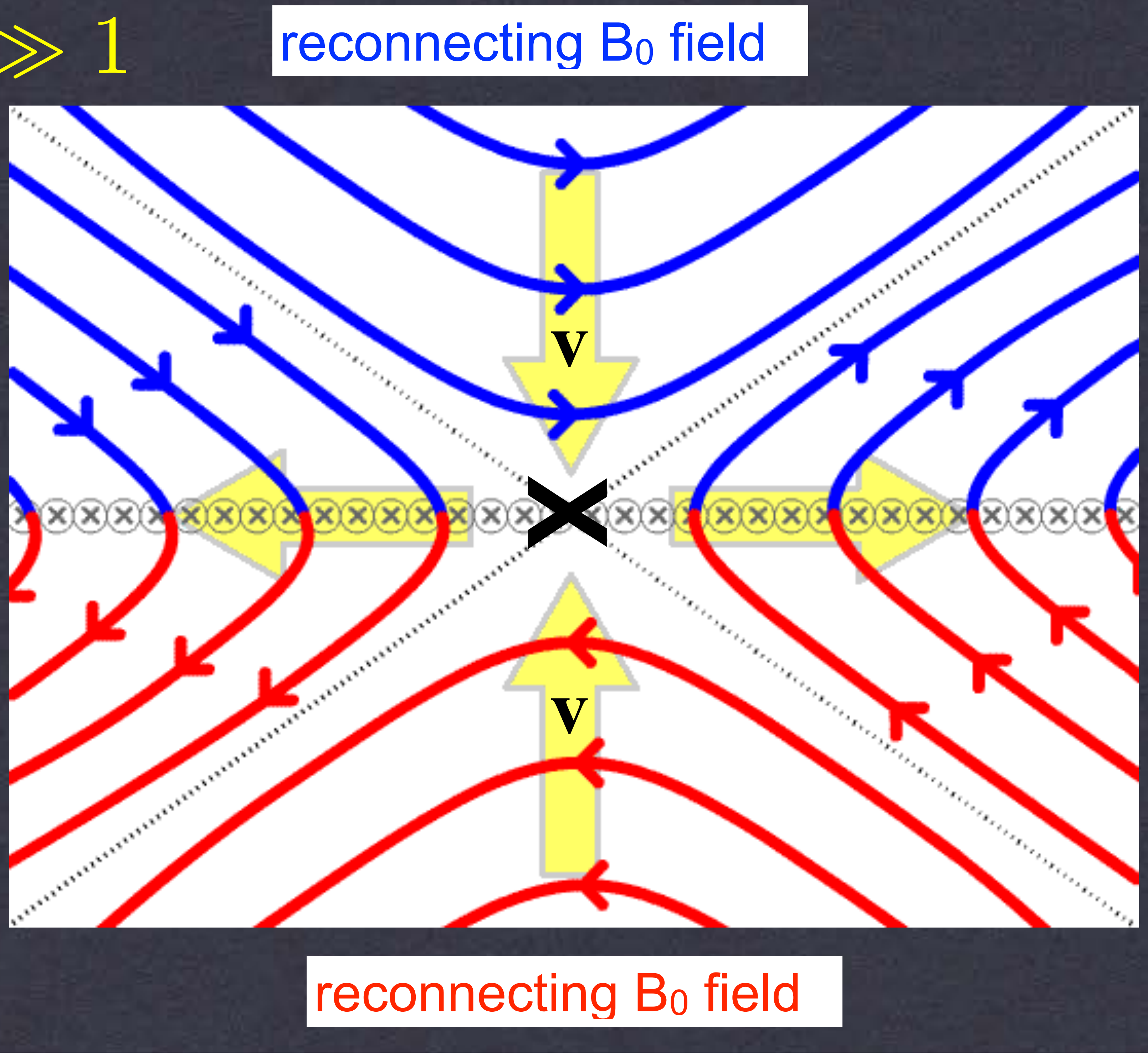
$$\sigma = \frac{B_0^2}{4\pi\rho c^2} \gg 1 \quad v_A \sim c$$

High-energy astro sources are our best “laboratories” of relativistic plasma physics

ACCELERATION IN RECONNECTION

$$\sigma = \frac{B_0^2}{4\pi\rho c^2} \gg 1$$

$$v_A \sim c$$



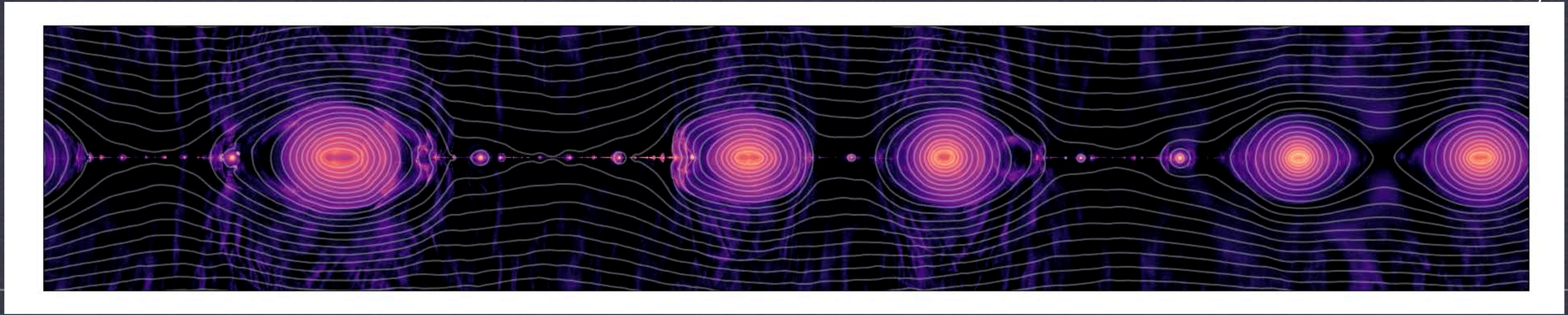
- The plasma flows into the reconnection region with $\frac{v_{\rm in}}{v_A} = \frac{E_{\rm rec}}{B_0} \sim 0.1$

→ Rel. reconnection can efficiently dissipate the field energy (at rate ~ 0.1 c).

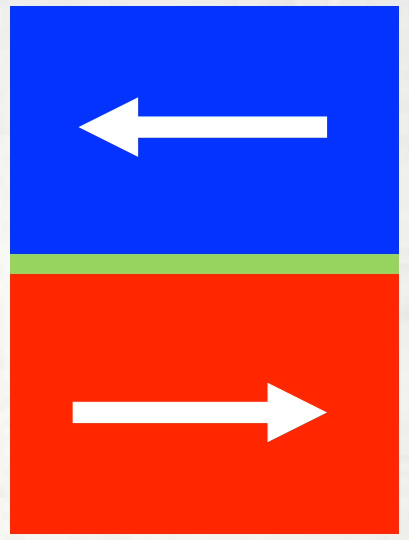
→ Rel. reconnection may accelerate particles, via $E_{\rm rec} \sim 0.1 B_0$.

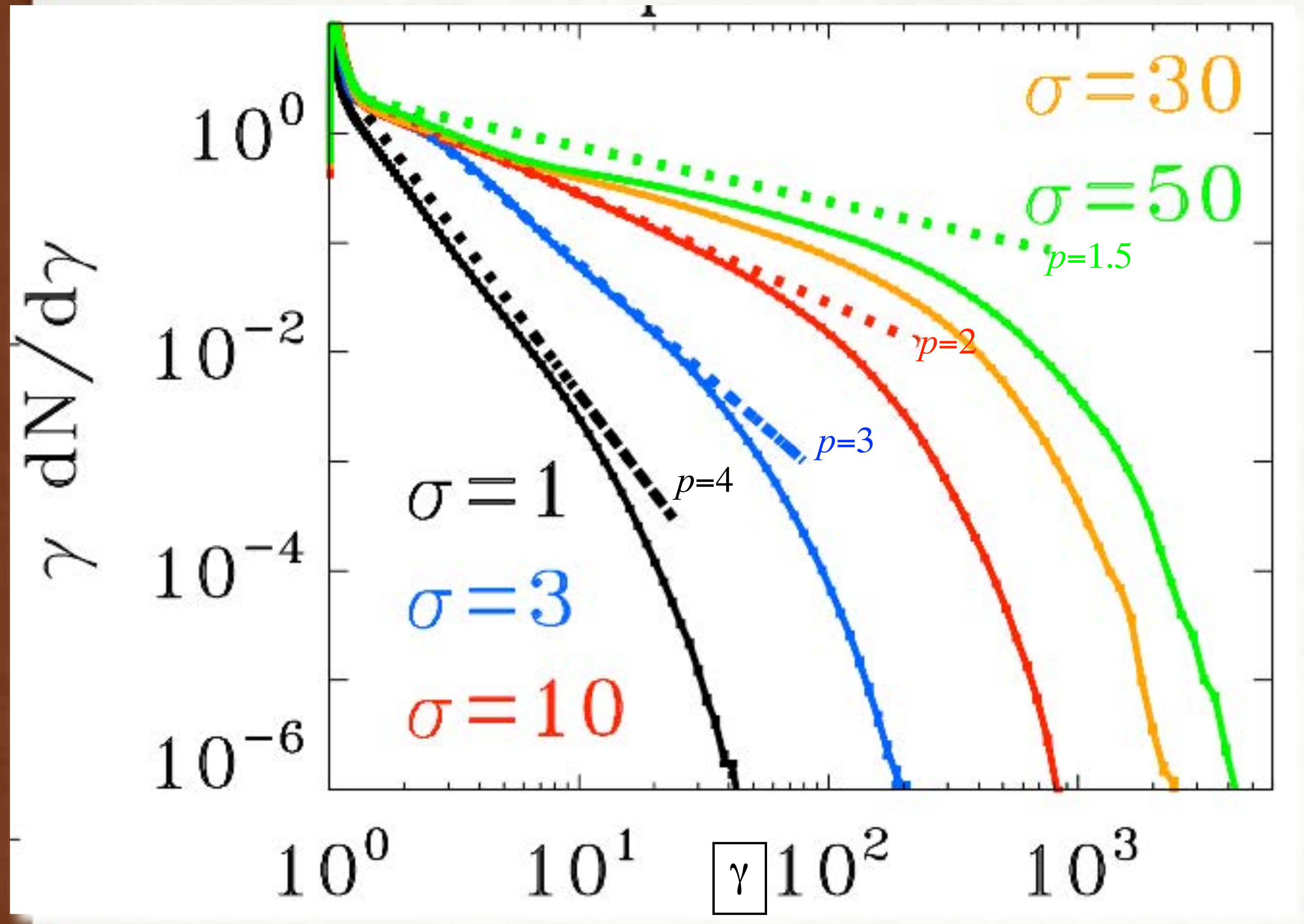
Plasmoid instability:

Hakobyan+ 2019

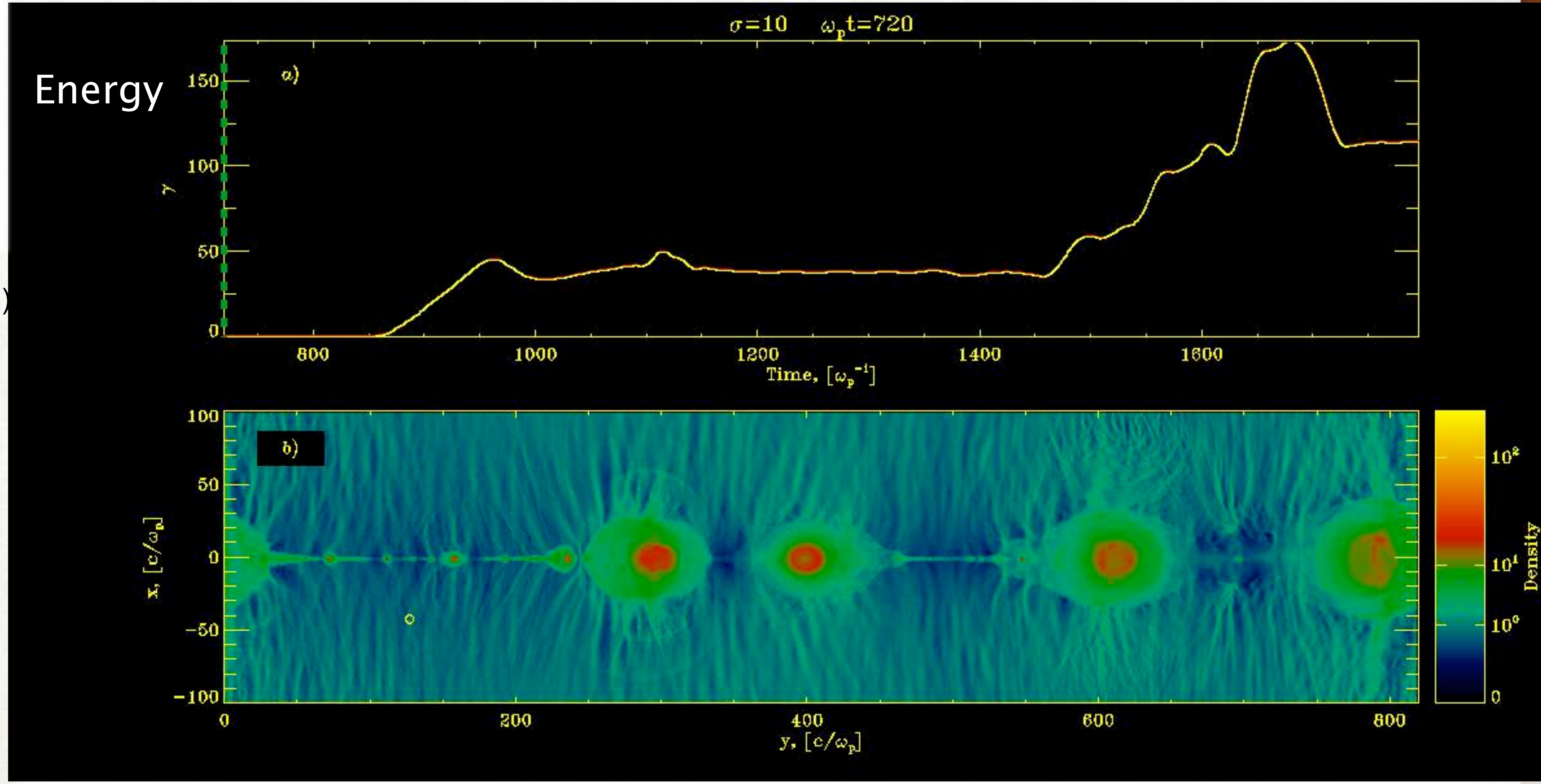


PARTICLE ACCELERATION IN RECONNECTION





(Sironi & AS 14, Guo et al. 14, Werner et al. 14)



Relativistic reconnection produces extended non-thermal tails of accelerated particles, whose power-law slope is harder than *p*=2 for high magnetizations (σ>10)

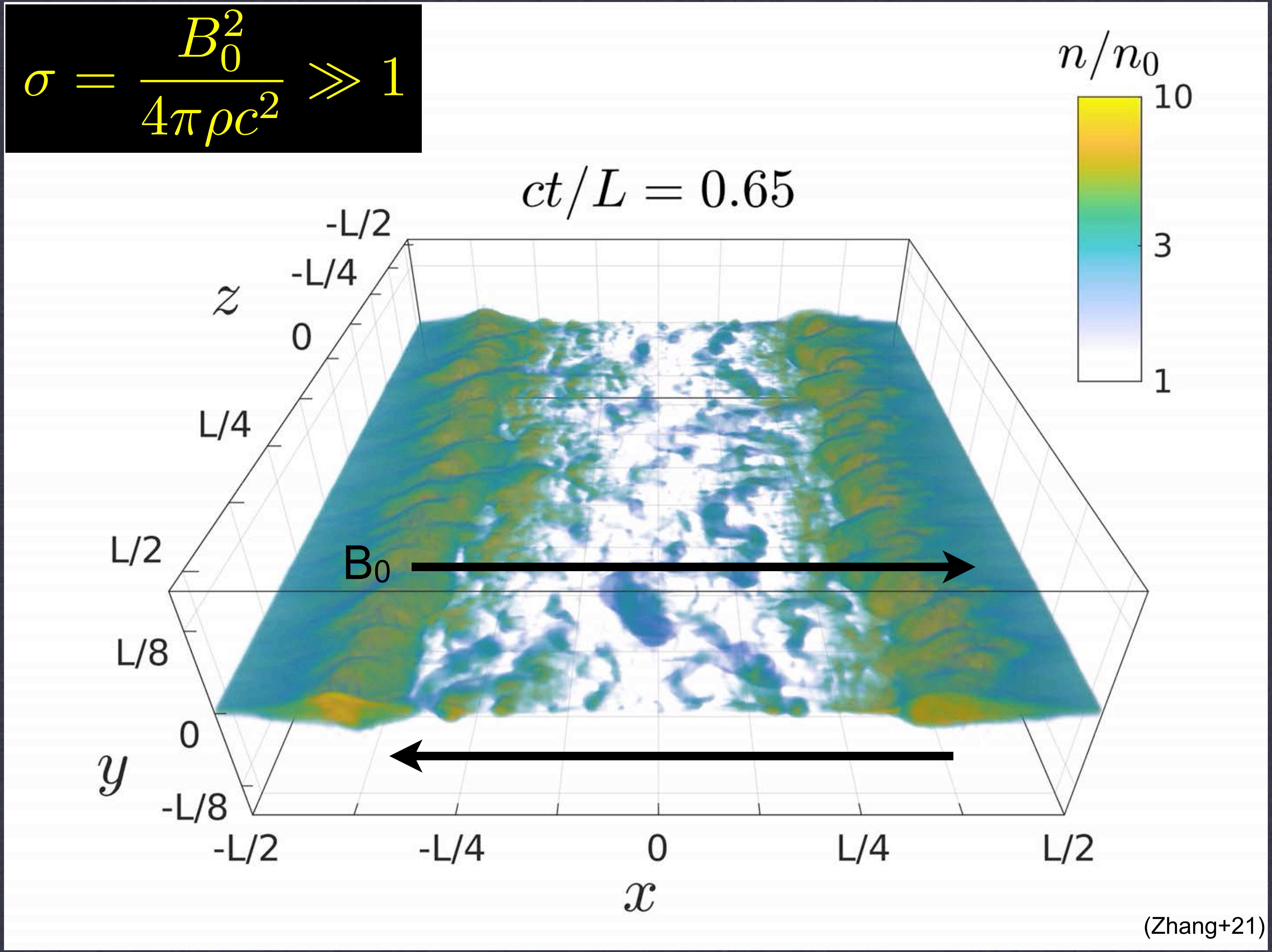
Magnetization:

$$\sigma = \frac{B^2}{4\pi n m c^2}$$

Two acceleration phases: 1) at the X-point; 2) in between merging islands

PIC simulation of σ=10 (relativistic) reconnection

Zhang, Sironi, Giannios 21

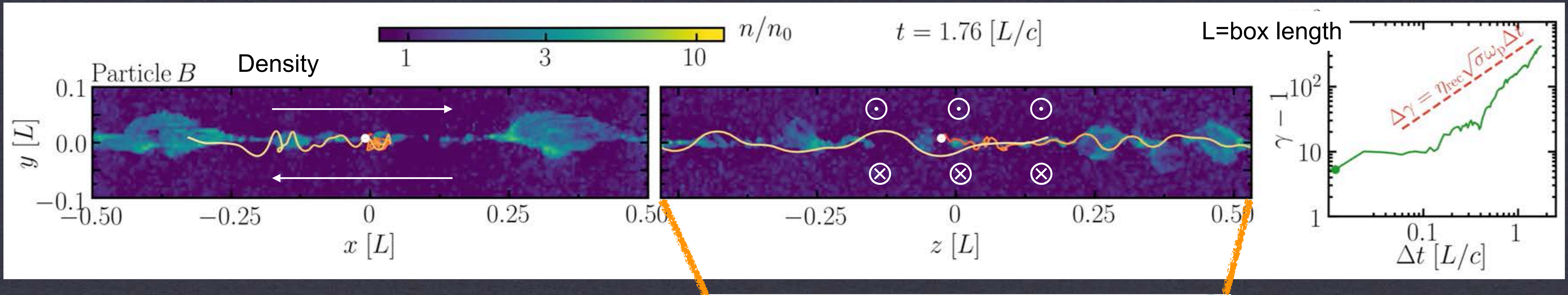


$$\sigma = \frac{B_0^2}{4\pi\rho c^2} \gg 1$$

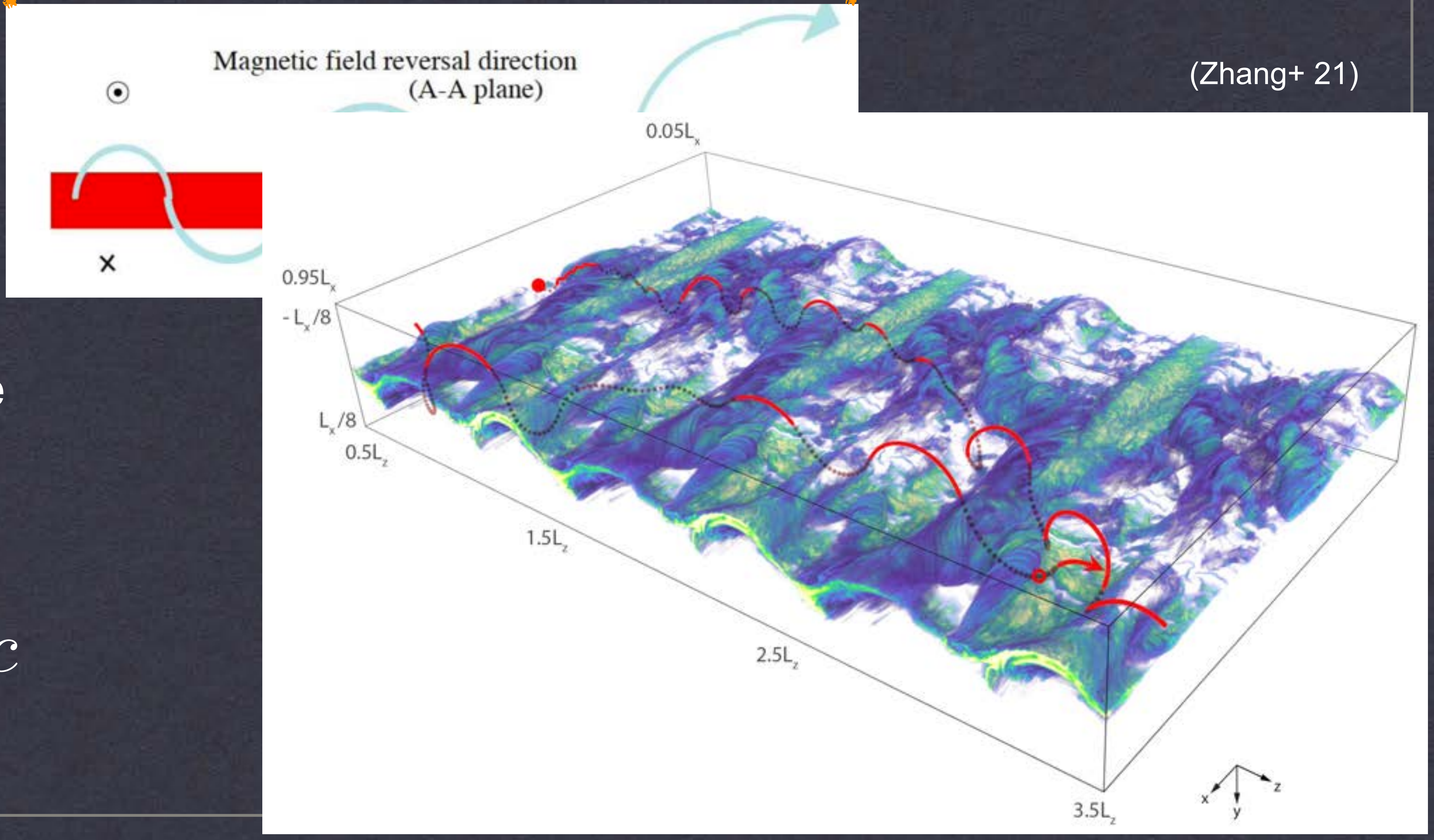
(Zhang+21)

The reconnection layer breaks into a chain of magnetic islands / plasmoids

Particle acceleration to $\gamma \gg 3\sigma$



- In 3D, lucky particles escape from plasmoids (Dahlin+15) and wiggle “free” around the layer.

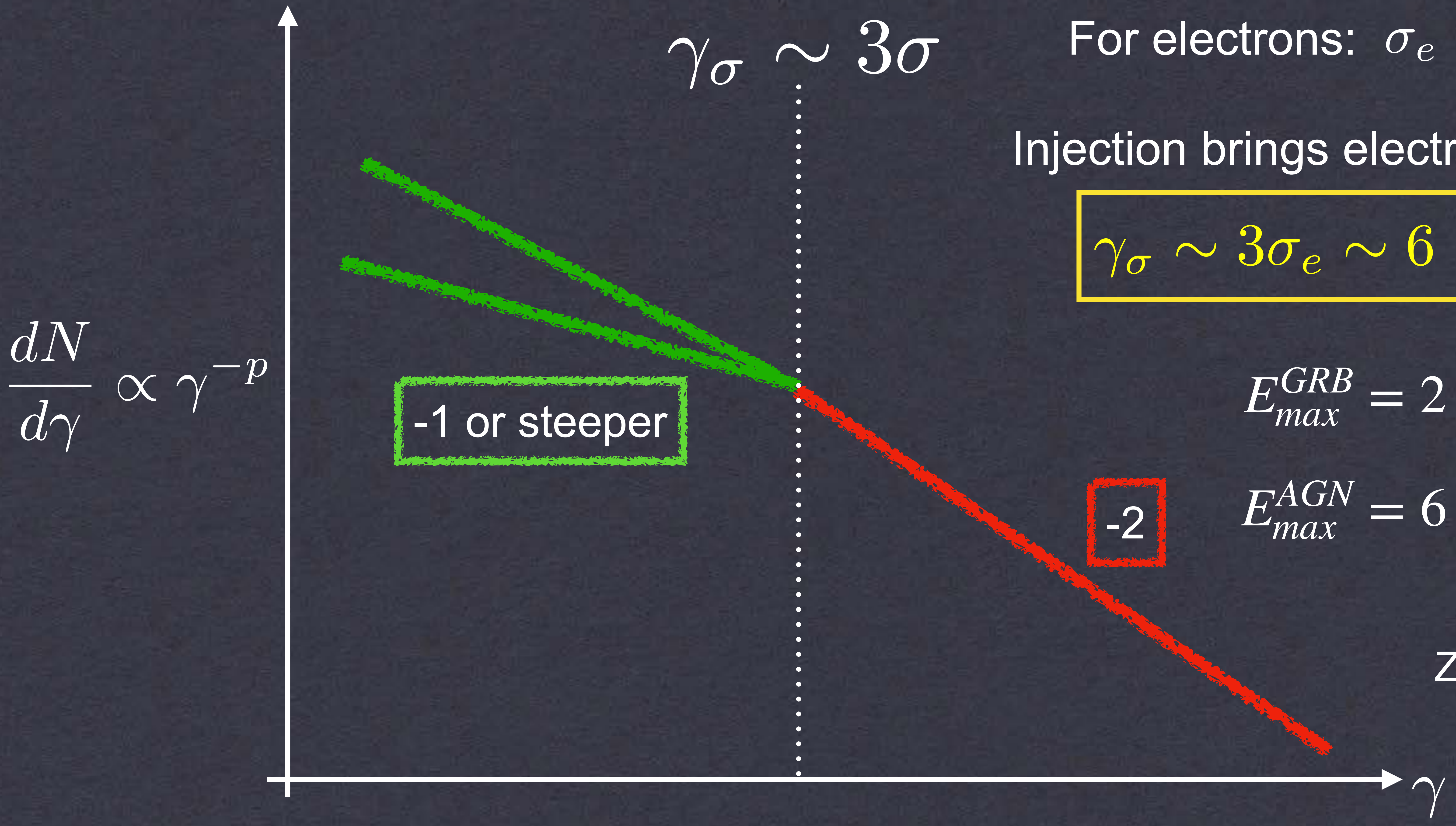


(Zhang+ 21)

- They get accelerated linearly in time, $\gamma \propto t$, by the large-scale <u>ideal</u> electric field in the upstream.
- The energy gain rate approaches $\sim eE_{\rm rec}c$

$$\sim 0.1eB_0c$$

Reconnection makes broken power laws



For electrons: $\sigma_e = \frac{m_p}{m_e}\sigma$

Injection brings electrons up to

$$\boxed{\gamma_\sigma \sim 3\sigma_e \sim 6 \times 10^3 \sigma}$$

$$E_{max}^{GRB} = 2 \times 10^{20} \eta_{rec,-1} L_{P,52}^{1/2} \Gamma_2^{-1} \text{ eV}$$

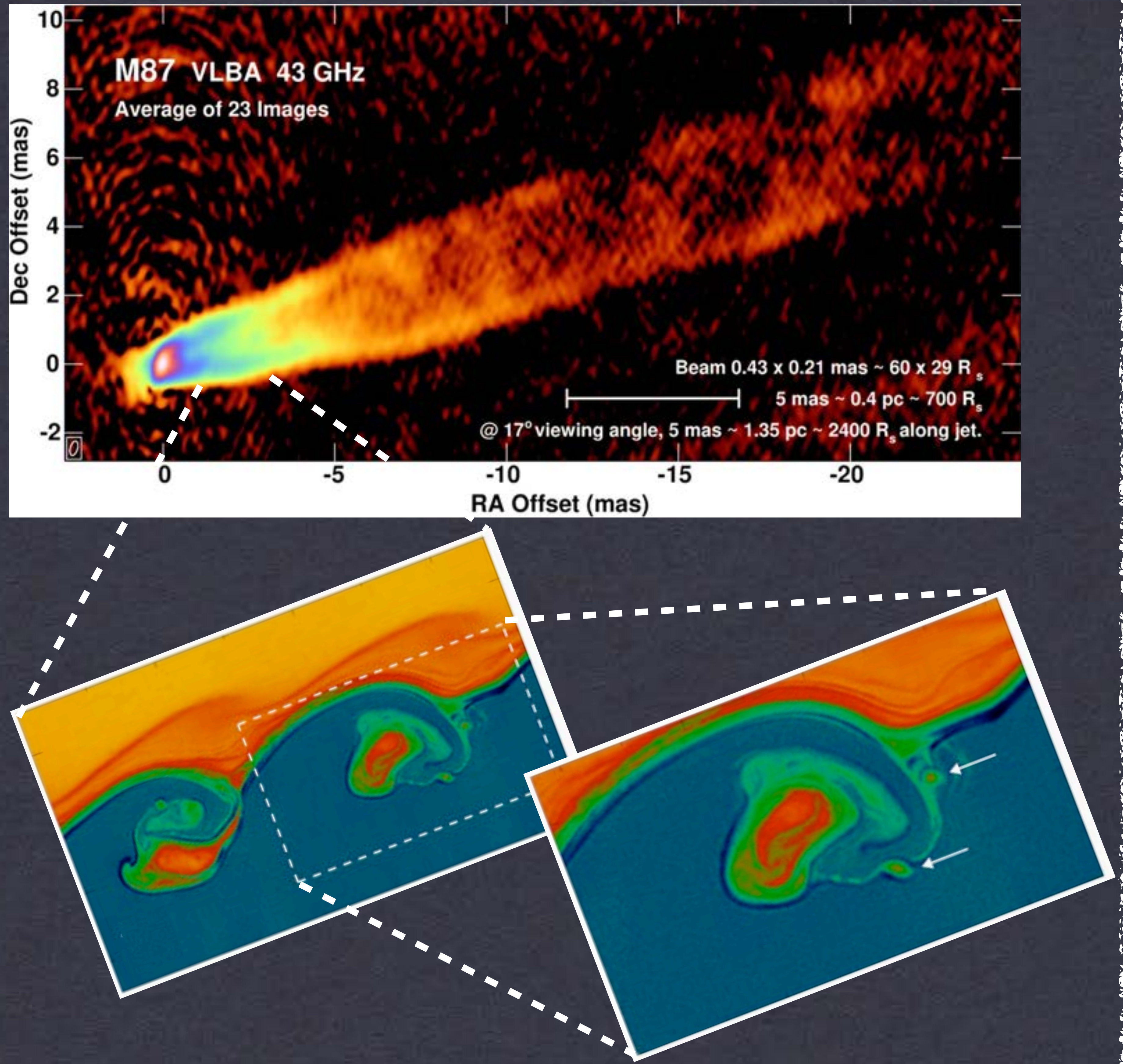
$$E_{max}^{AGN} = 6 \times 10^{19} \eta_{rec,-1} L_{P,48}^{1/2} \Gamma_{0.5}^{-1} \text{ eV}$$

Zhang, Sironi, Giannios 21

At $\gamma \lesssim 3\sigma$ “injection” in reconnection leads to σ-dependent slopes, with *p*≳*1*.

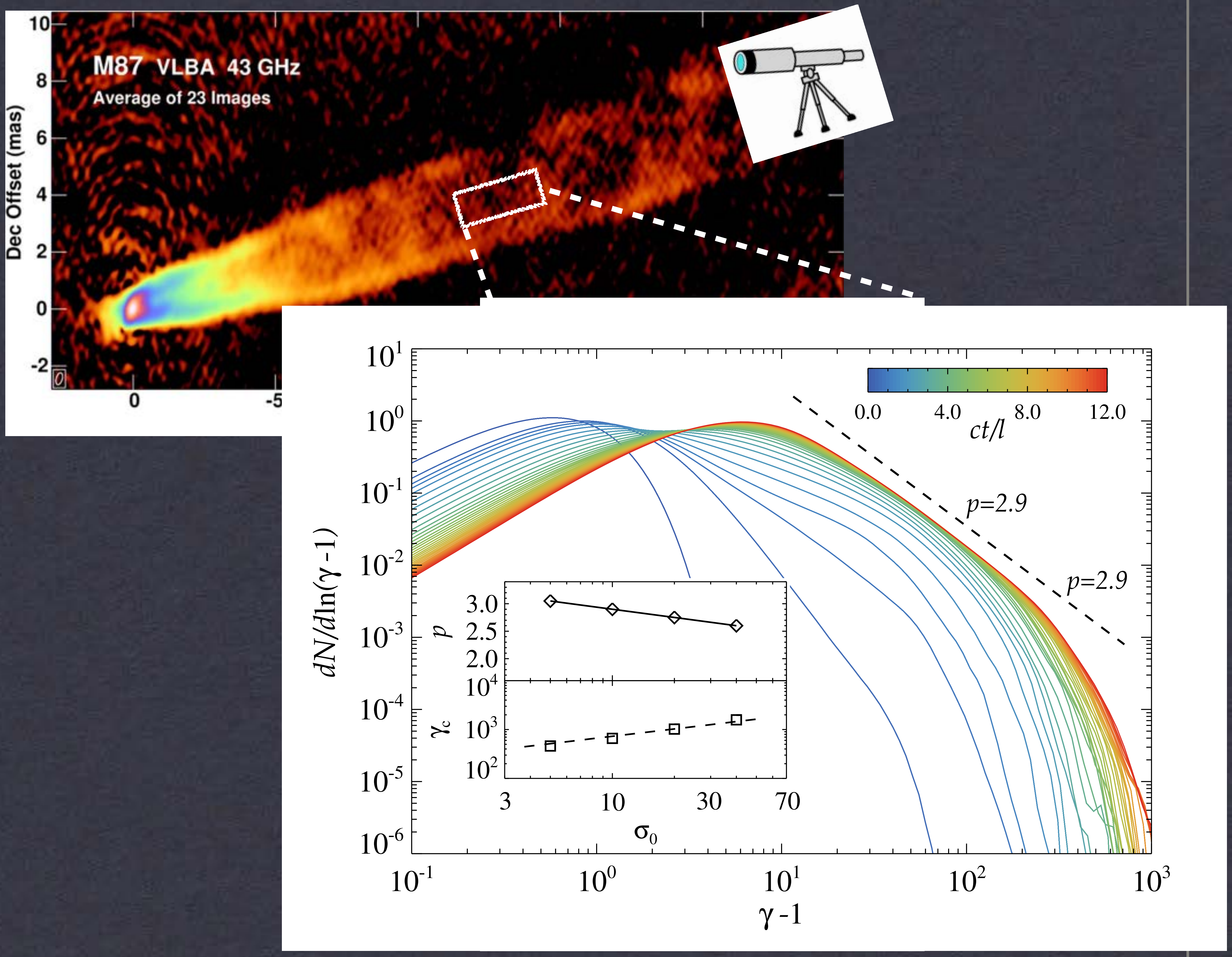
At $\gamma \gtrsim 3\sigma$ 3D reconnection leads to a universal (σ-independent) slope of *p*~2.

KH-driven relativistic reconnection



KH instability at jet boundaries
→ relativistic reconnection
→ particle injection
→ shear-driven acceleration

Turbulence-driven relativistic reconnection



Magnetized turbulence in the jet core
→ relativistic reconnection
→ particle injection
→ stochastic acceleration

Sironi+ 21

Comisso+Sironi 18-20
Zhdankin+ 18-21

Conclusions

Kinetic simulations allow to calculate particle injection and acceleration from first principles, constraining injection fraction

Magnetization (Mach #) of the shock and B inclination control the shock structure

Nonrelativistic shocks accelerate ions and electrons in quasi-par shocks if B fields are amplified by CRs. Energy efficiency of ions 10-20%, number ~few percent; $K_{ep}\sim10^{-3}$

Electrons are accelerated in quasi-perp shocks, could be stronger (energy ~ several percent, number <~1%). Electrons drive instabilities.

Long-term evolution & 3D effects need to be explored more, new multi-scale simulation ideas to come

Relativistic reconnection and turbulence is a promising source of nonthermal power-laws