Injection and Acceleration in Astrophysical Shocks

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with much help from D. Caprioli, J. Park, M. Riquelme, L. Sironi, L. Gargate

Outline

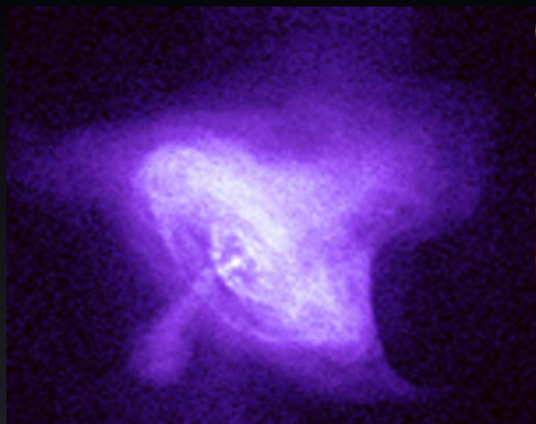
1. Shock acceleration: open problems

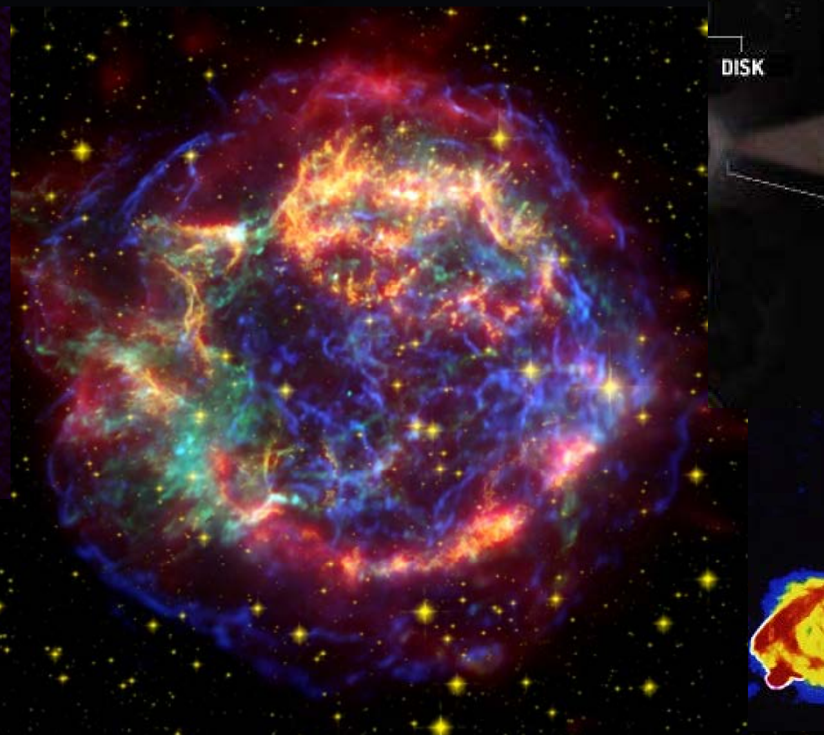
2. Summary of ab-initio simulations of shocks

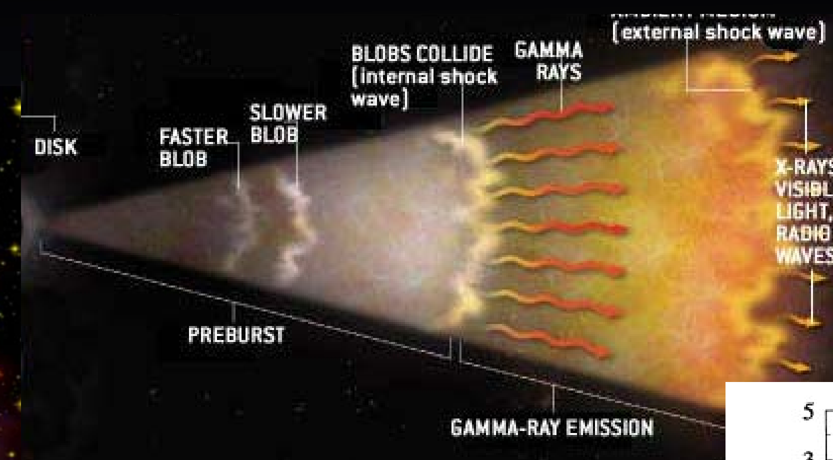
3. Efficiency and injection for ions and electrons: relativistic and non-relativistic shocks

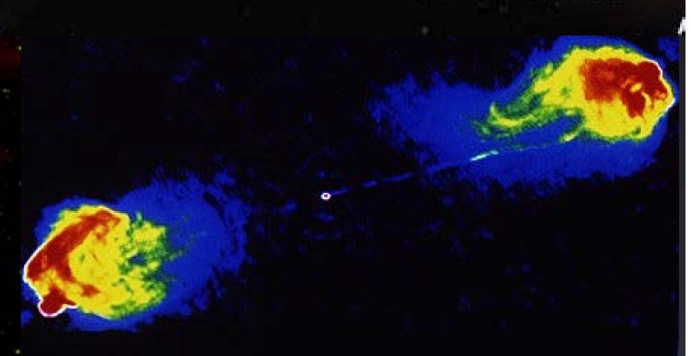
4. Attempt at big picture

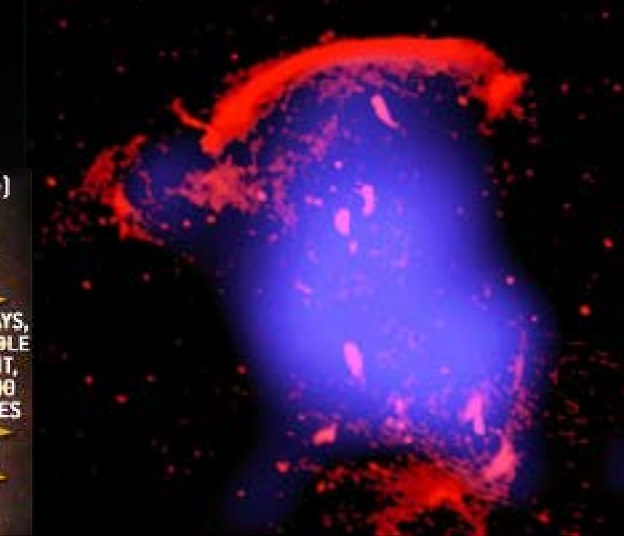
Shocks in astrophysics

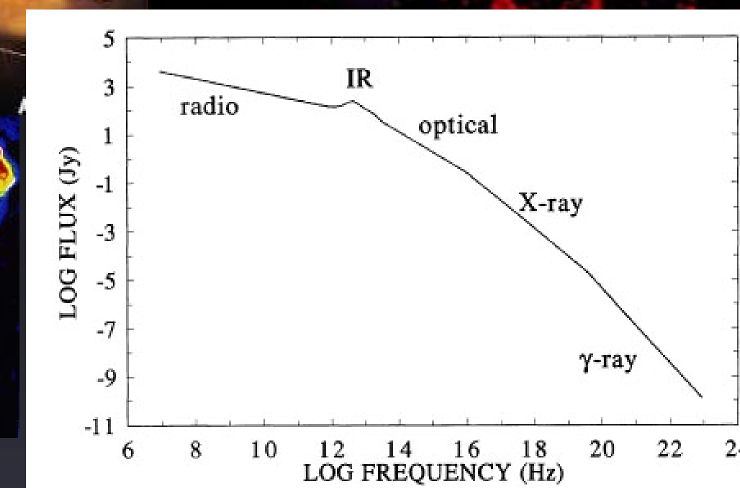


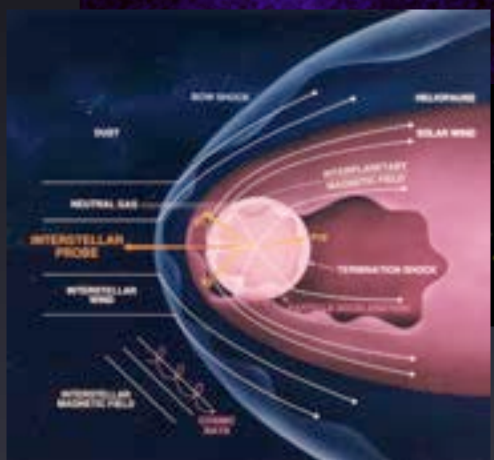










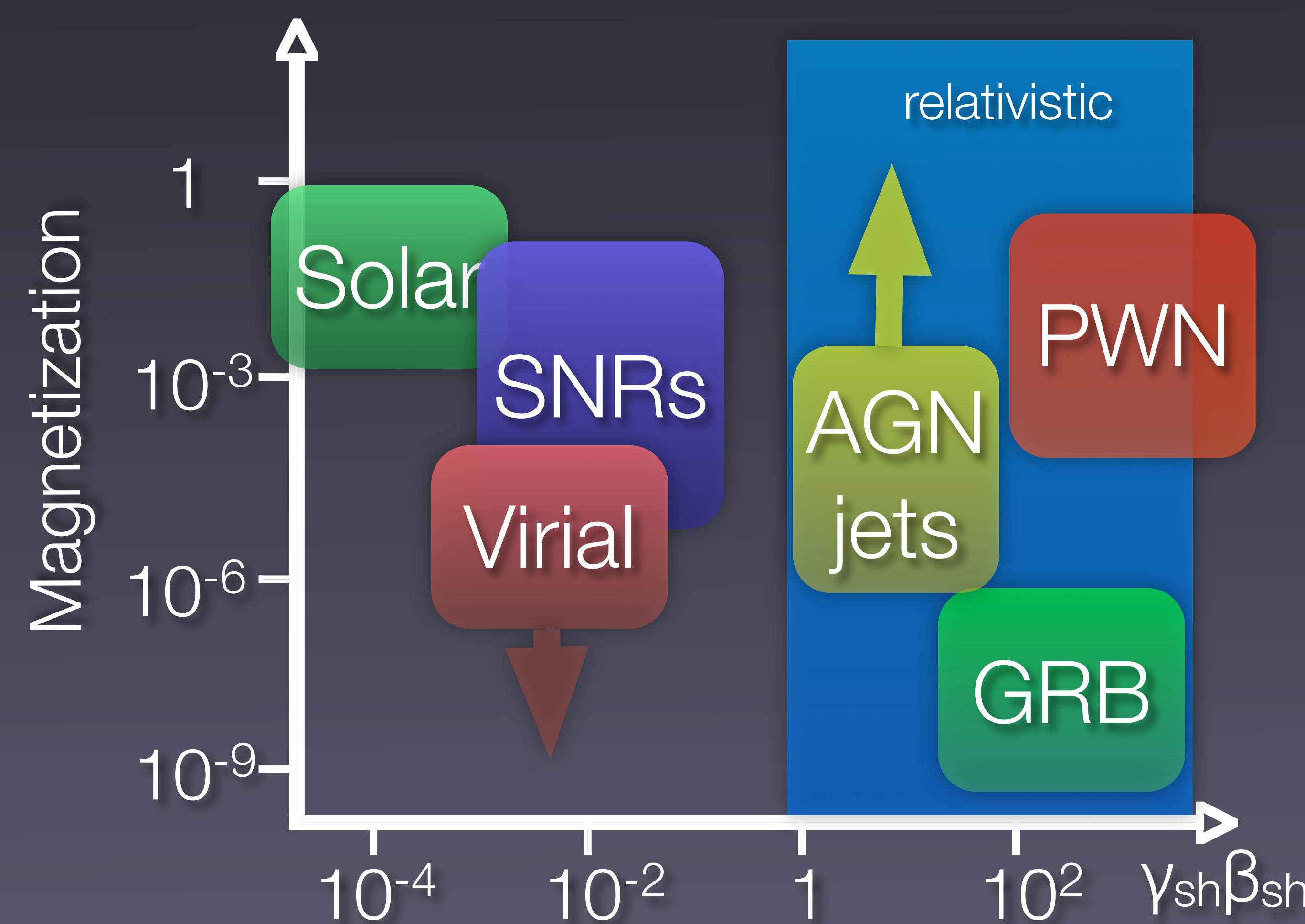


Astrophysical shocks are collisionless

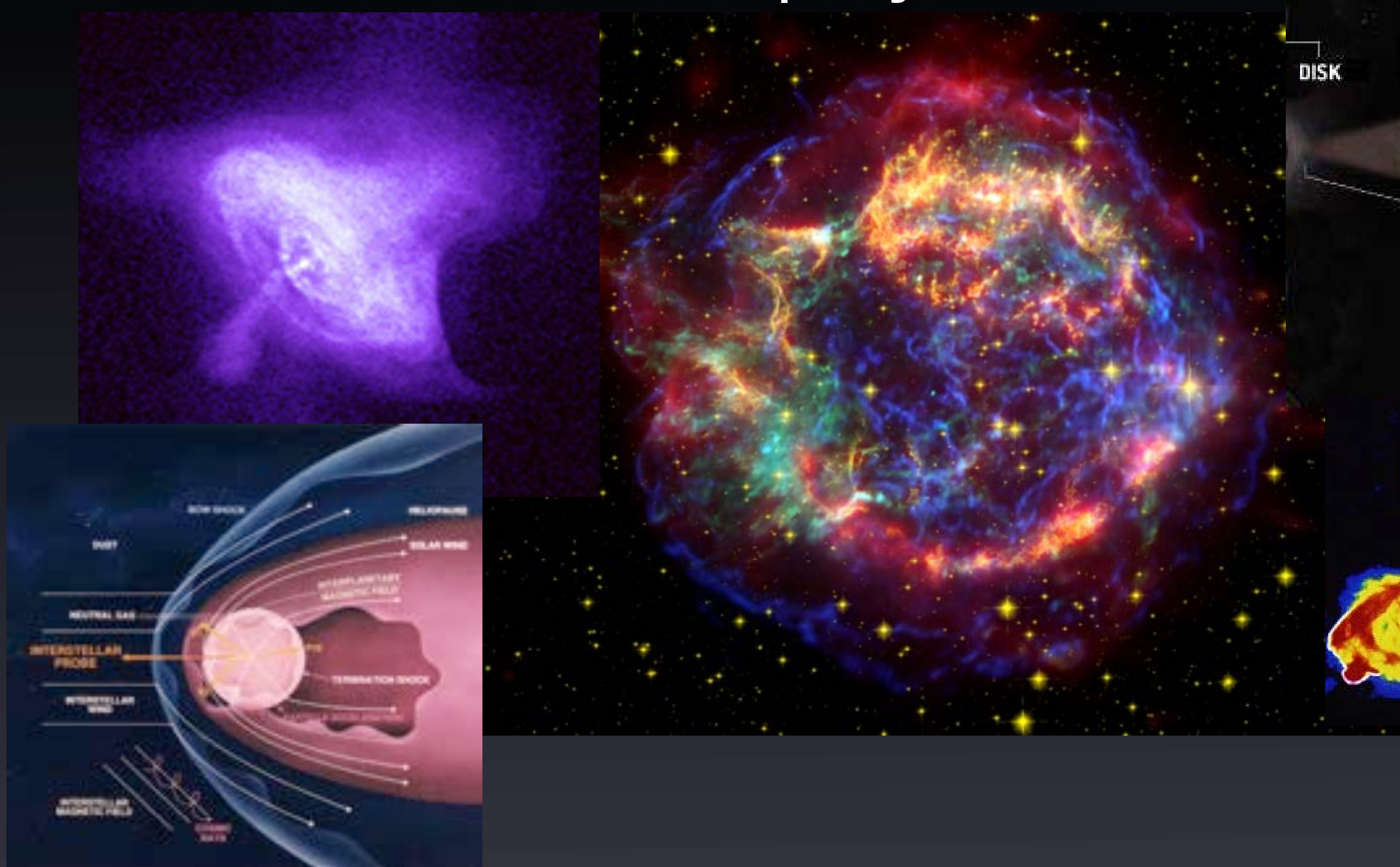
Shocks span a range of parameters: nonrelativistic to relativistic flows

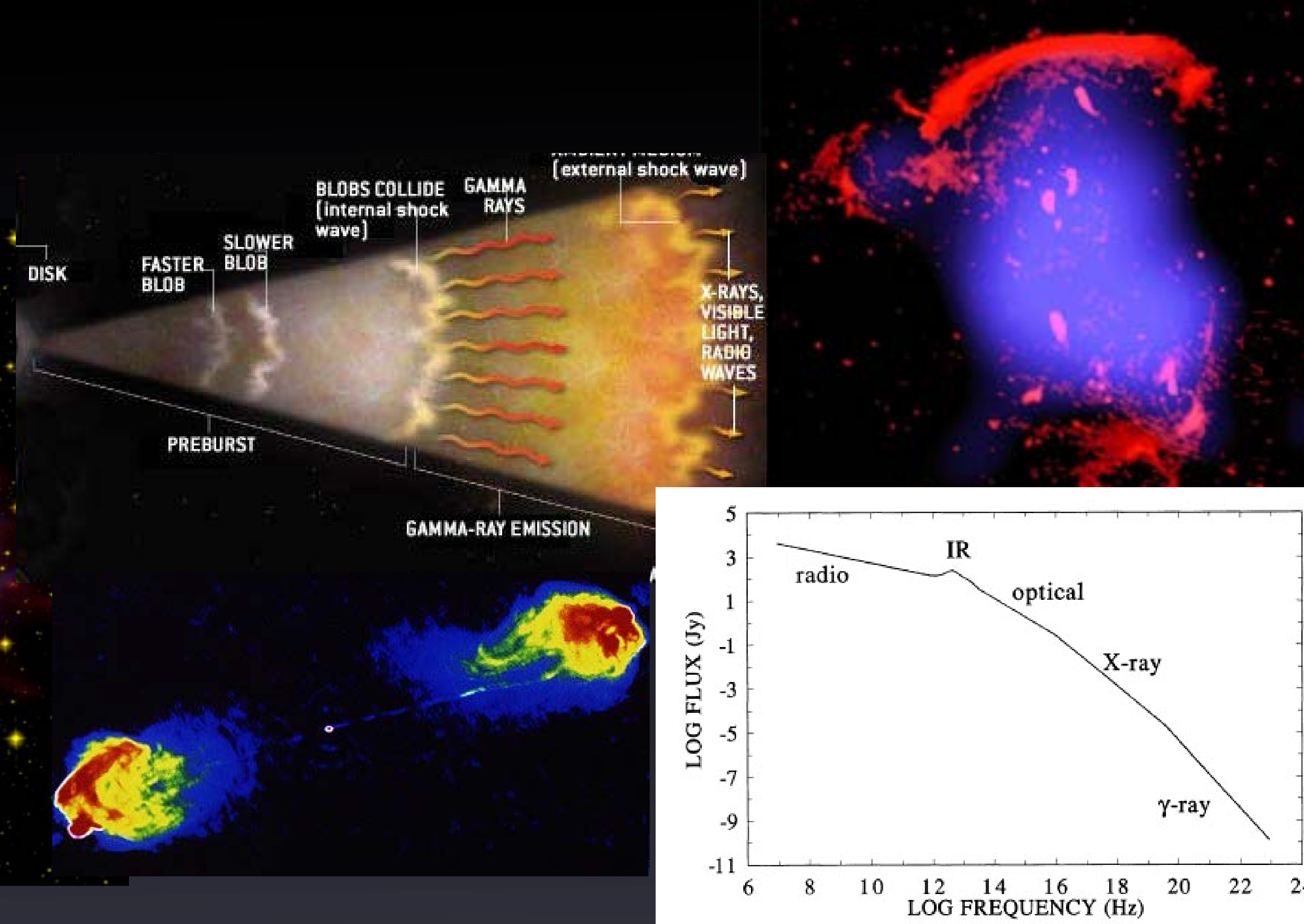
magnetization (magnetic/kinetic energy ratio) and beta

composition (pairs/e-ions/pairs + ions)



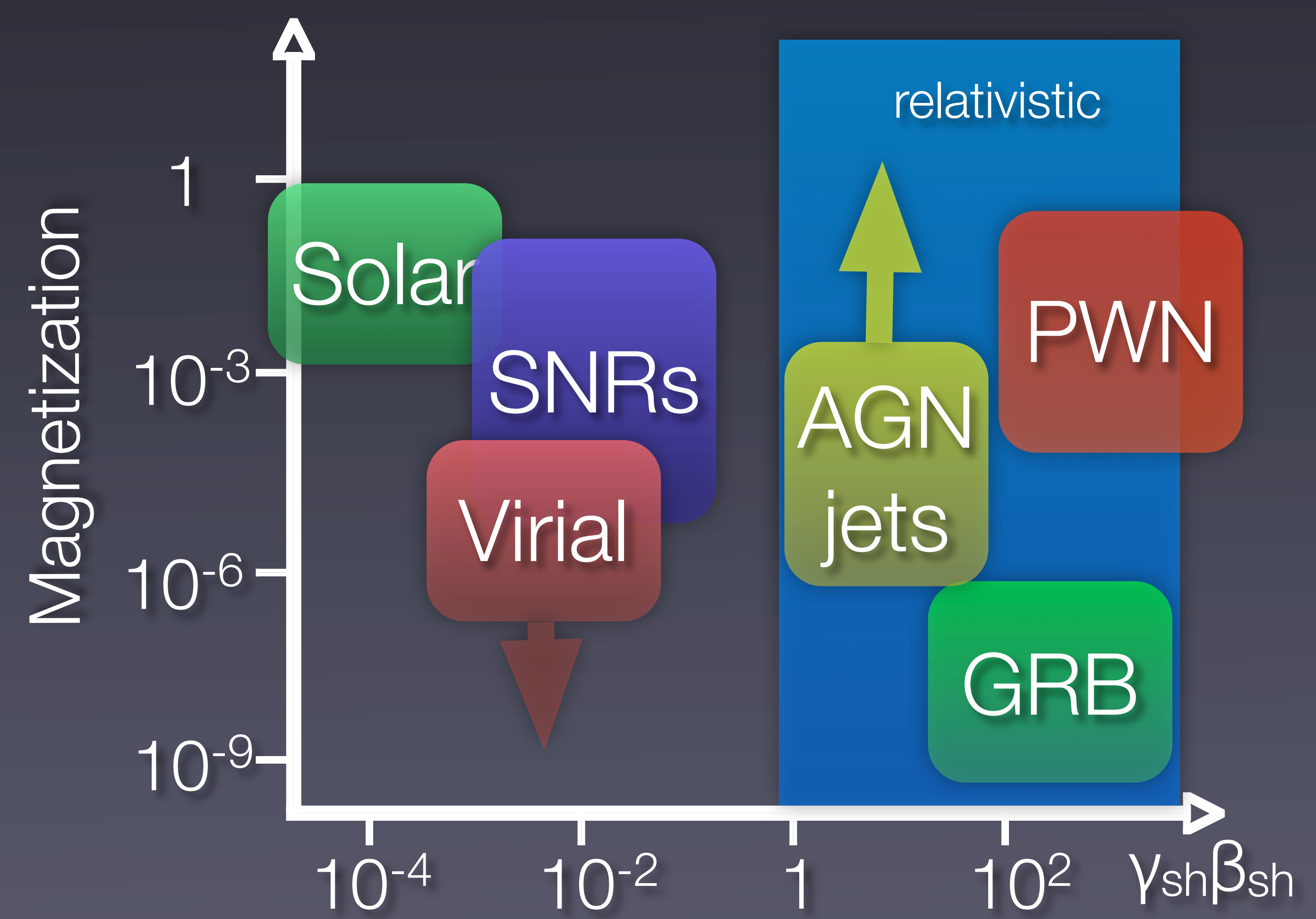
Shocks in astrophysics





Astrophysical collisonless shocks can:

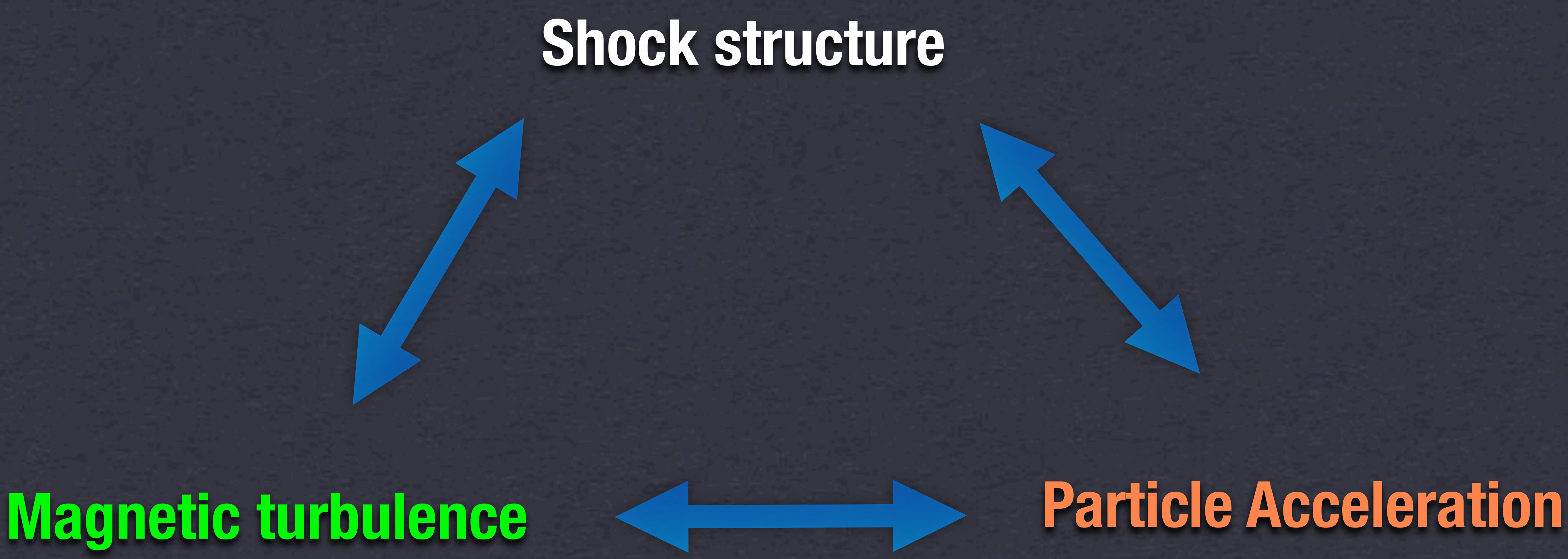
1. accelerate particles
2. amplify magnetic fields (or generate them from scratch)
3. exchange energy between electrons and ions



How? Always? Where?

Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback



Collisionless shocks

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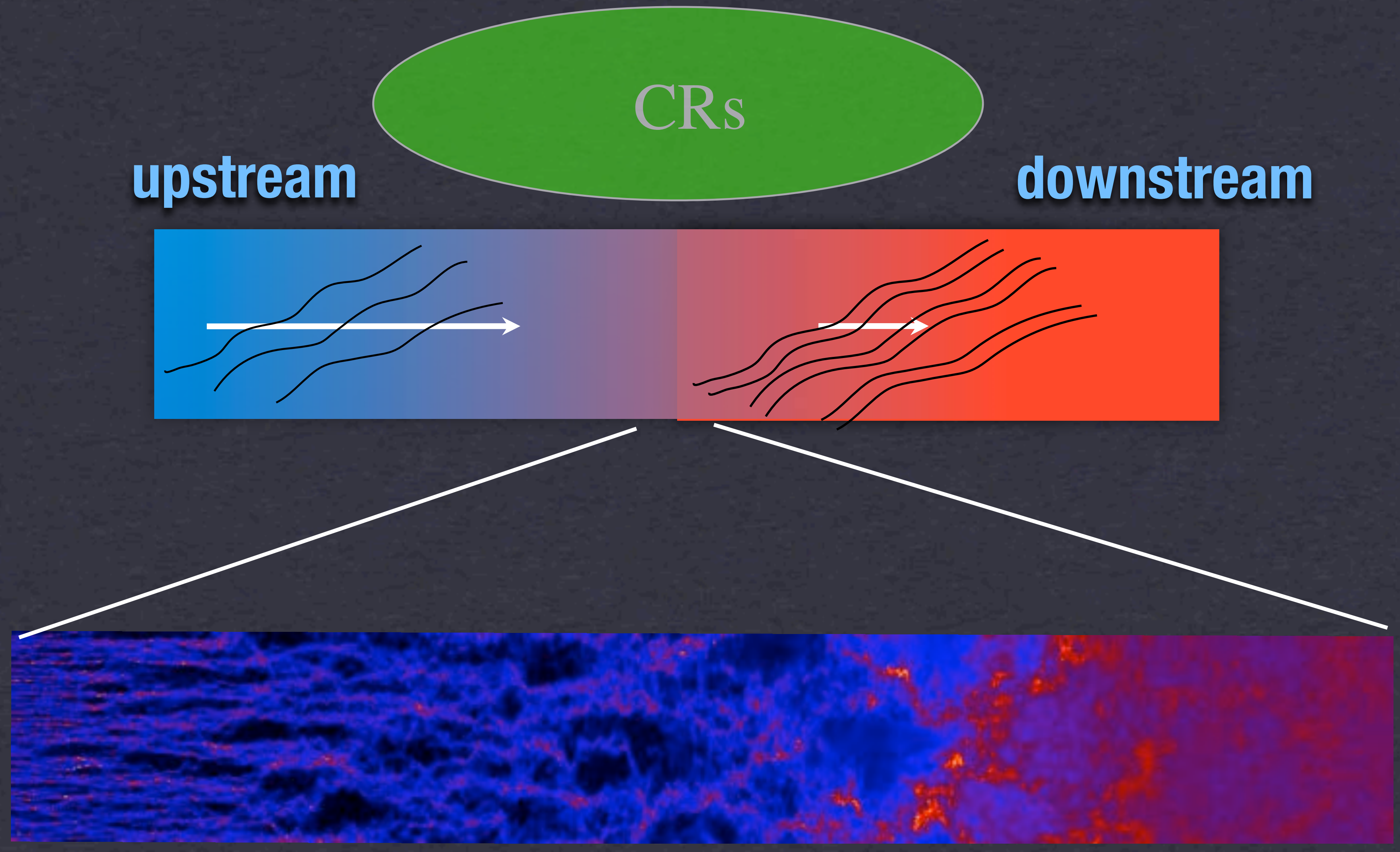
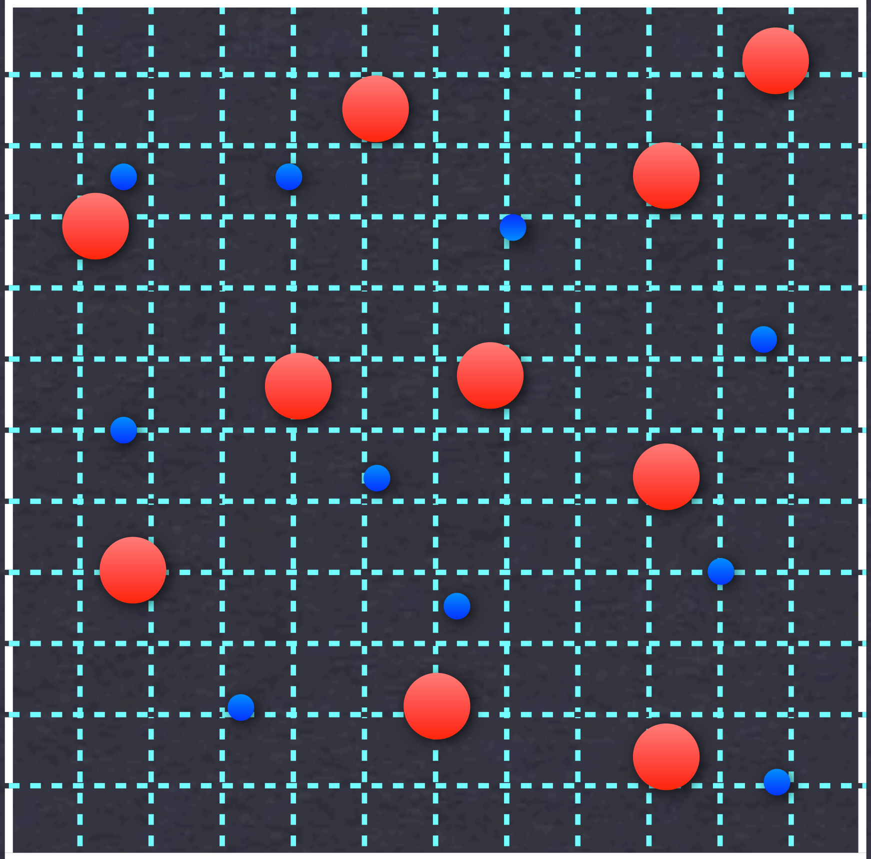
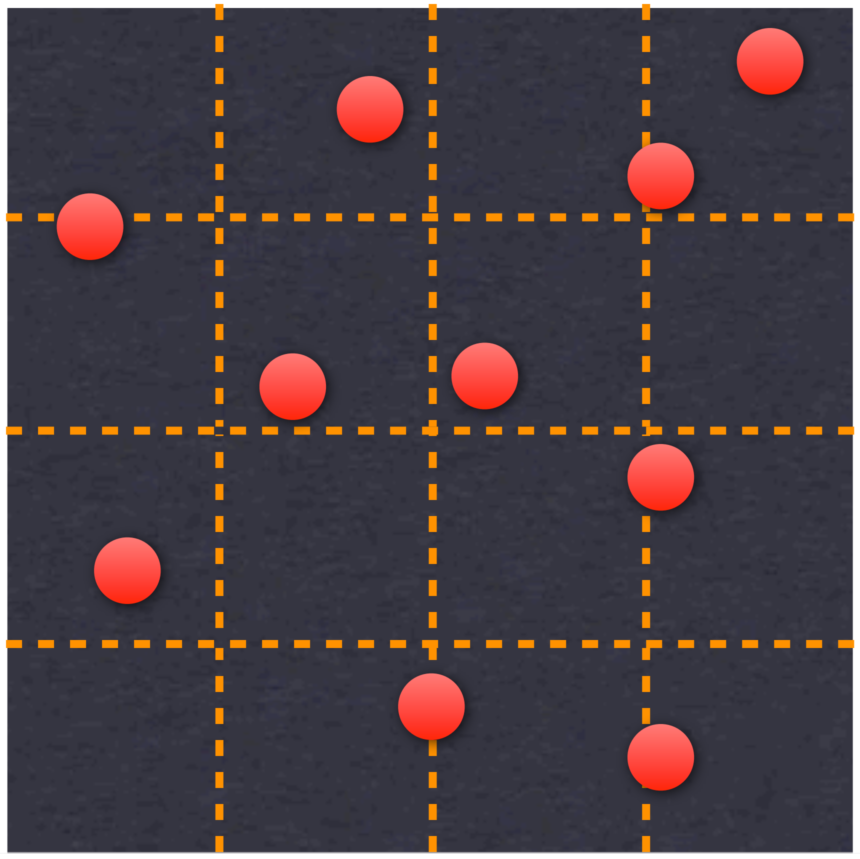


Acceleration from first principles

- 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!

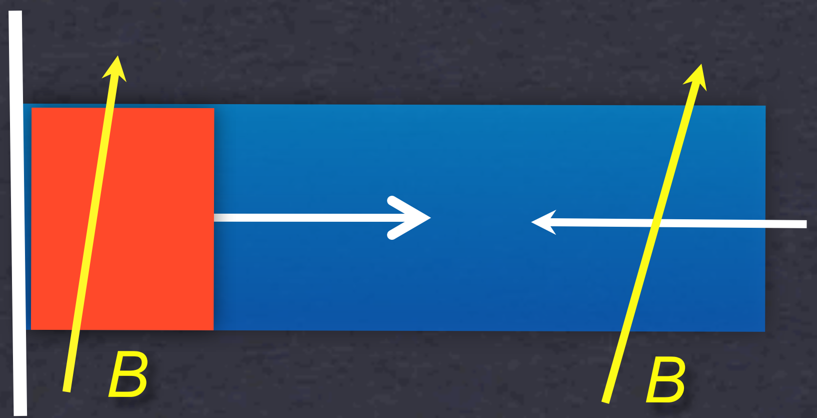


- Hybrid approach: dHybrid code
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, DC & Spitkovsky 2013, 2014)
  - massless electrons for more macroscopic time/length scales



Survey of Collisionless Shocks

We simulated relativistic and nonrelativistic shocks for a range of upstream B fields and flow compositions, ignoring pre-existing turbulence.



Main findings:

Dependence of shock mechanism on upstream magnetization

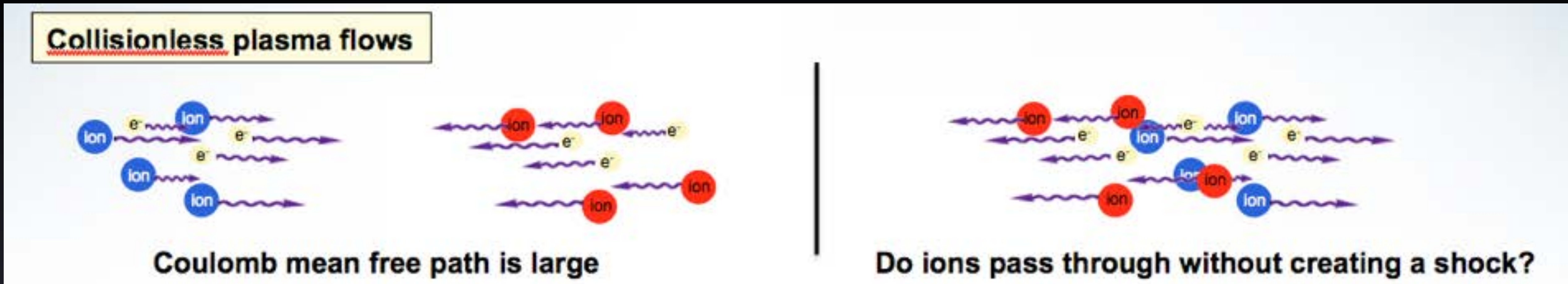
Ab-initio particle acceleration in relativistic shocks

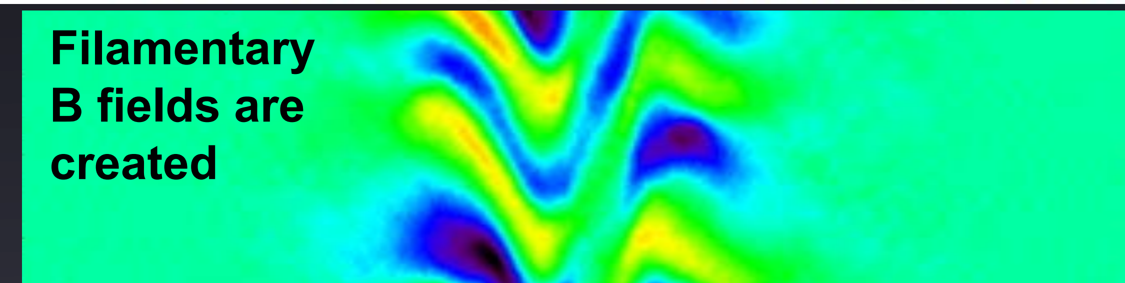
Shock structure and acceleration in non-relativistic shocks

- Ion acceleration vs Mach # in quasipar shocks; DSA; D coeff.
- Evidence for simultaneous e-ion acceleration in parall. shks
- Electron acceleration in quasiperpendicular shocks

FIeld amplification and CR-induced instabilities

How collisionless shocks work

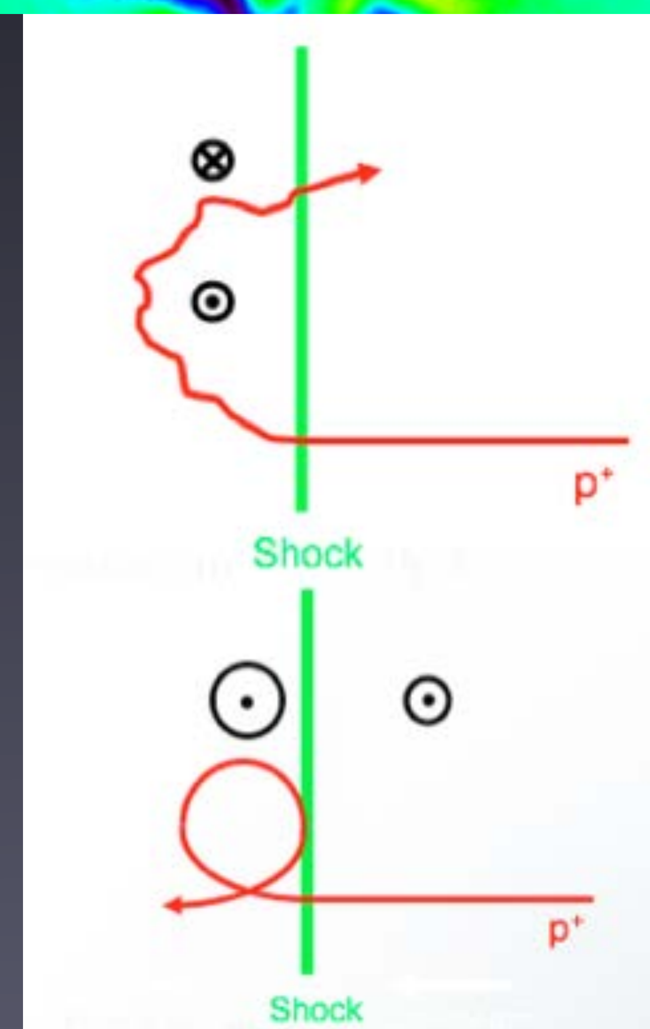




Two main mechanisms for creating collisionless shocks:

1) For low initial B field, particles are deflected by self-generated magnetic fields (filamentation/Weibel instability)

2) For large initial B field, particles are deflected by compressed pre-existing fields

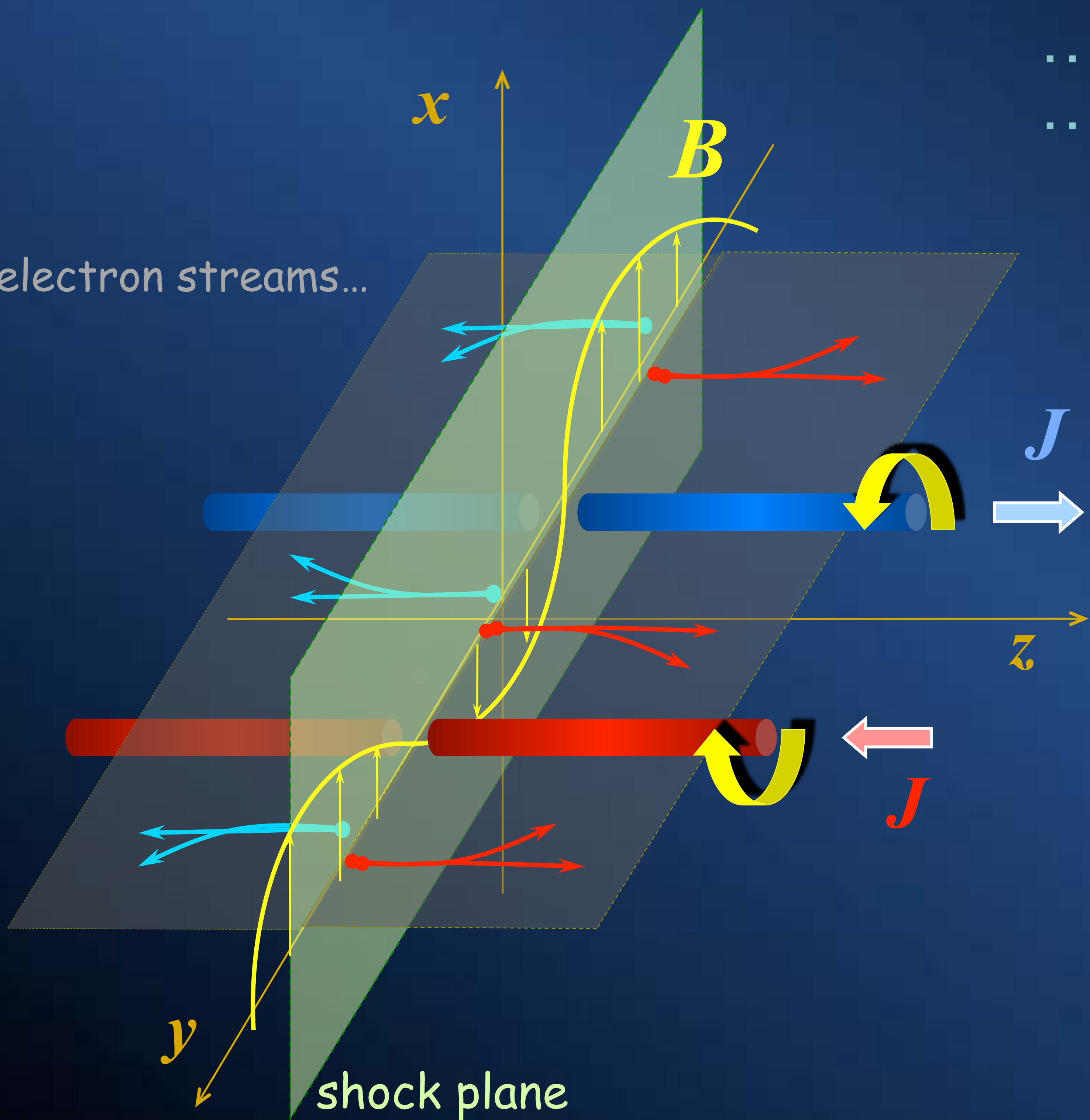


WEIBEL INSTABILITY

(Weibel 1956, Medvedev & Loeb, 1999, ApJ)

… current filamentation …
… *B* – field is generated …

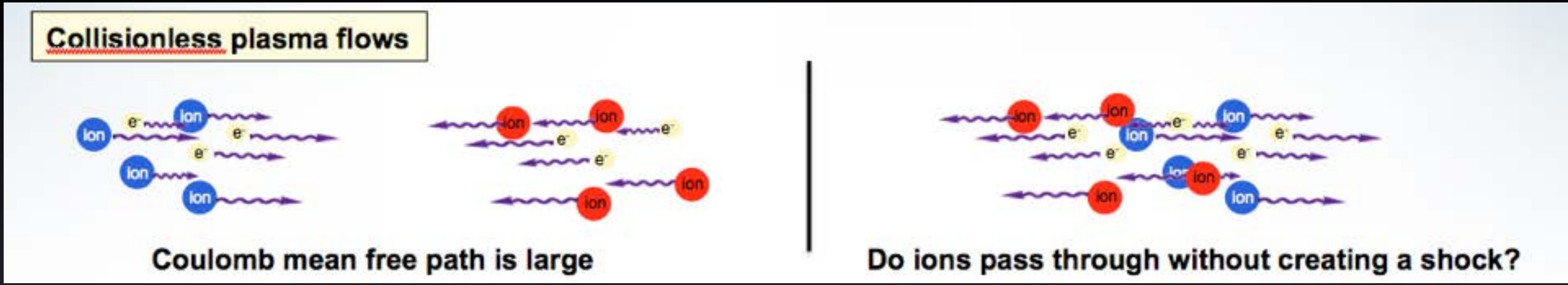
For electron streams…

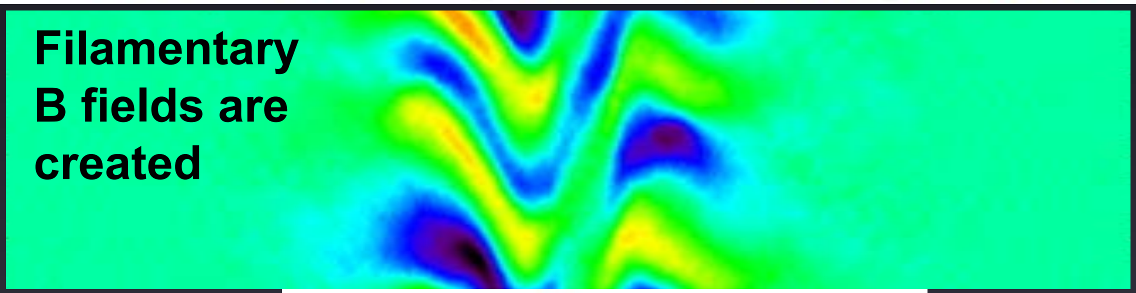


$$\Gamma^2_{\max} \simeq \frac{\omega_p^2}{\gamma}$$

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

How collisionless shocks work





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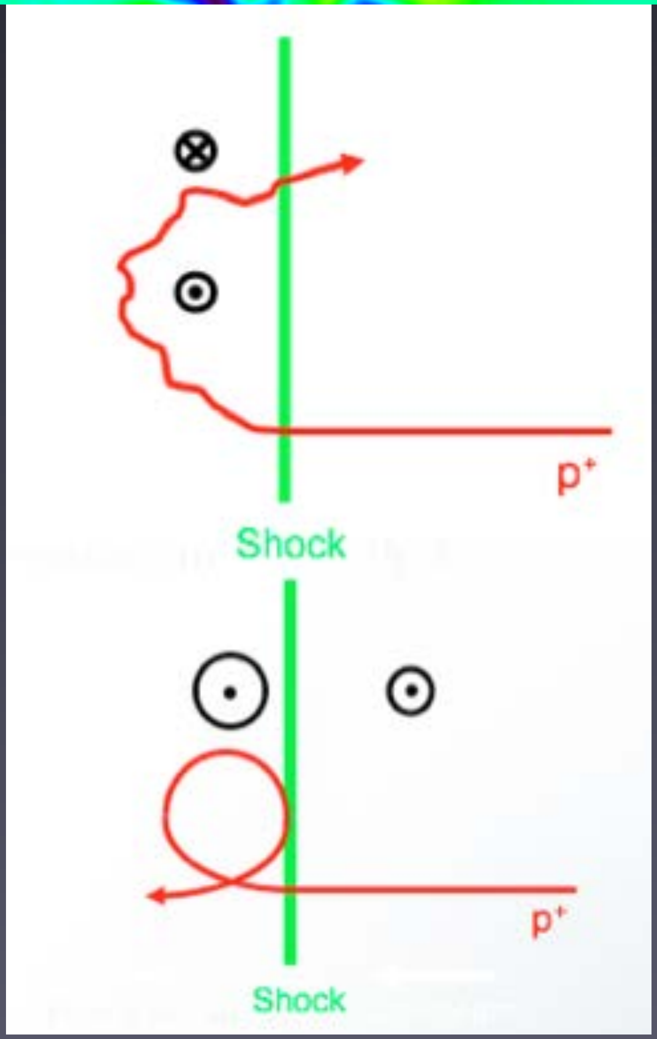
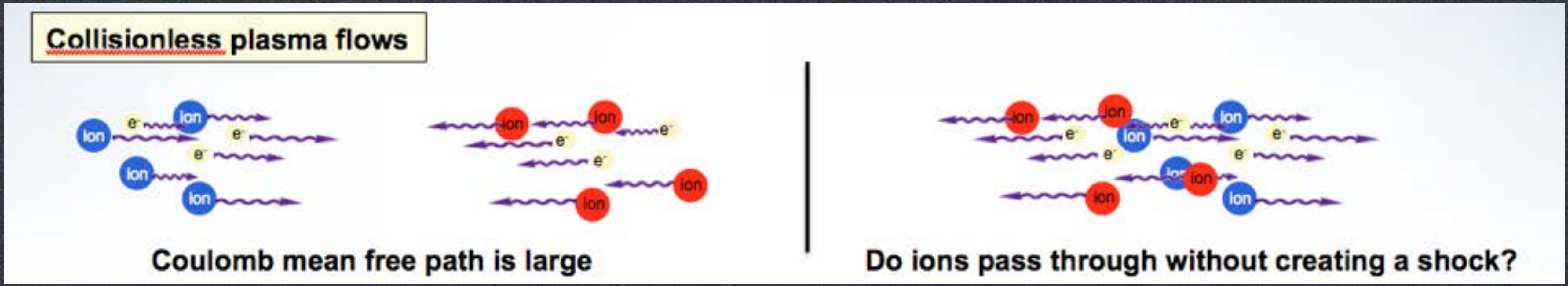


How collisionless shocks work



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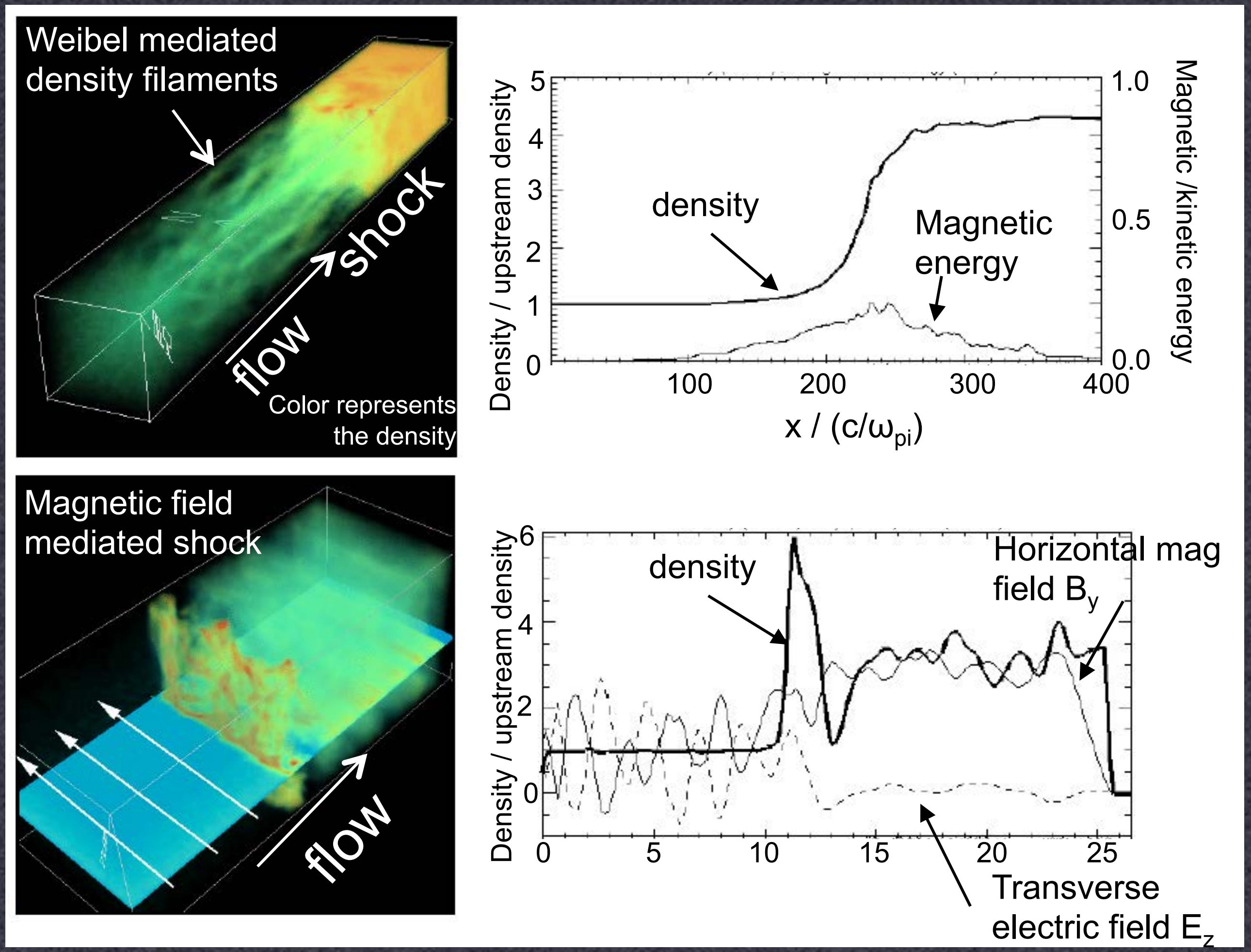
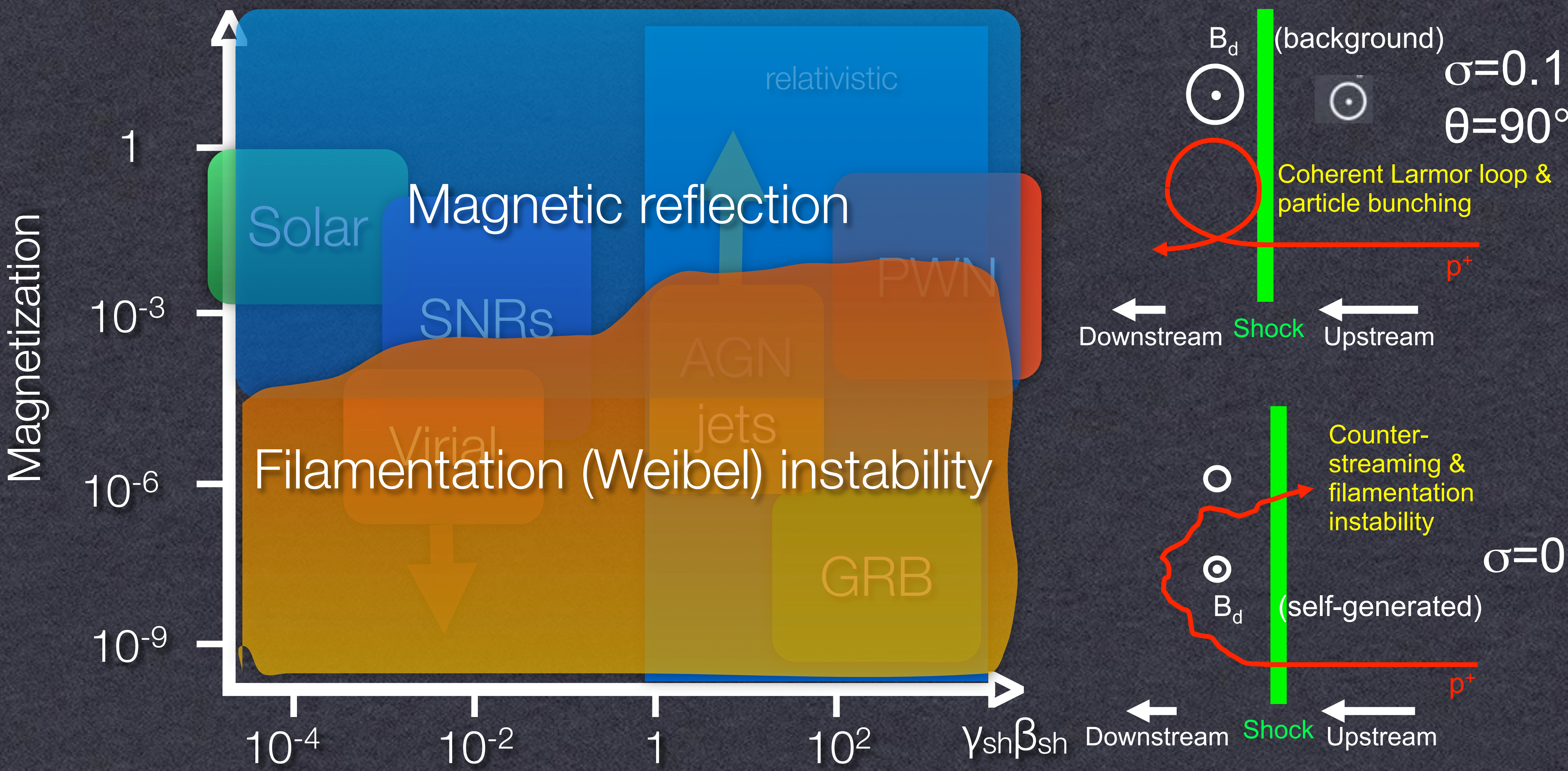
AS (2005)



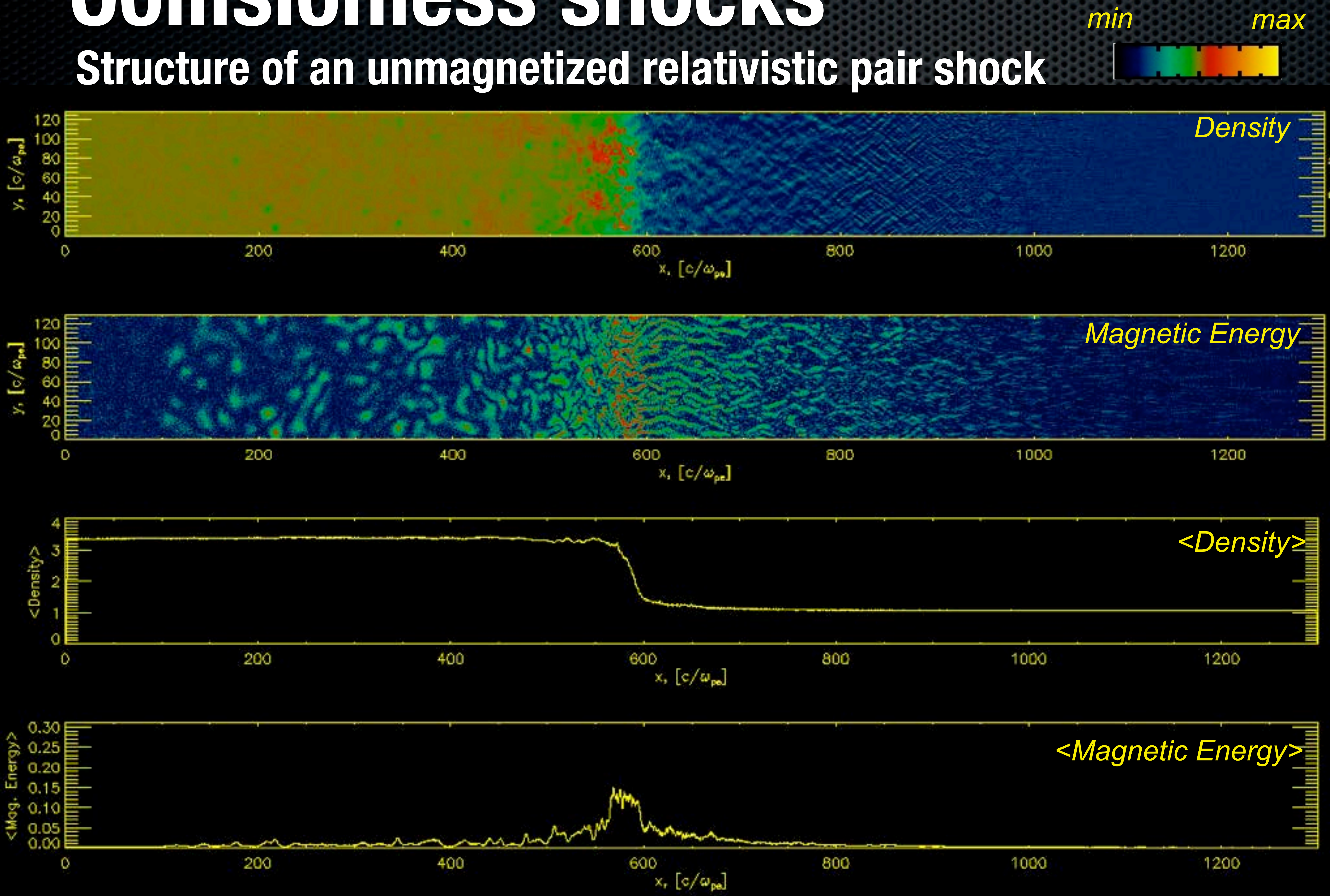
Parameter Space of shocks

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



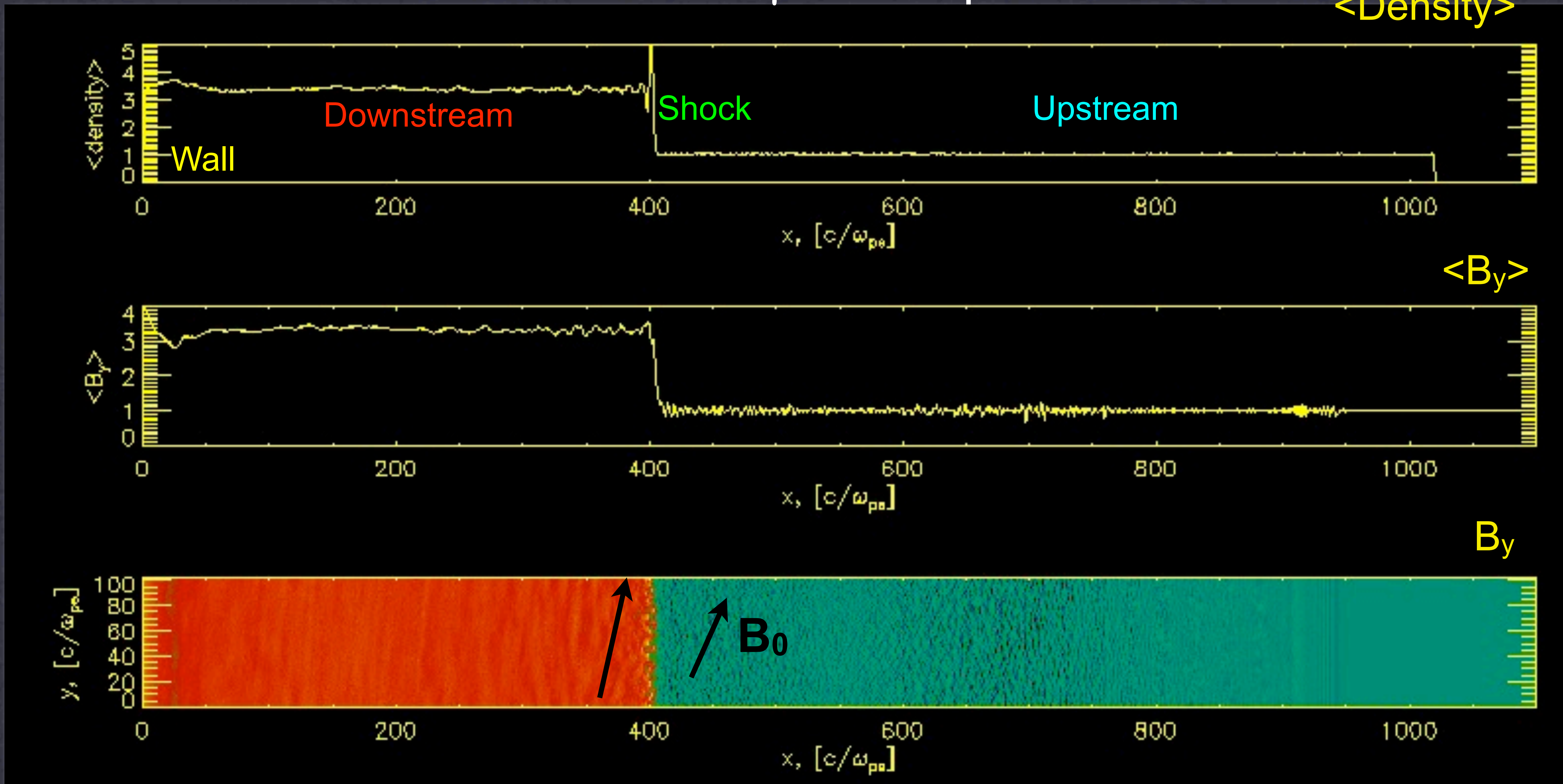
Collisionless shocks

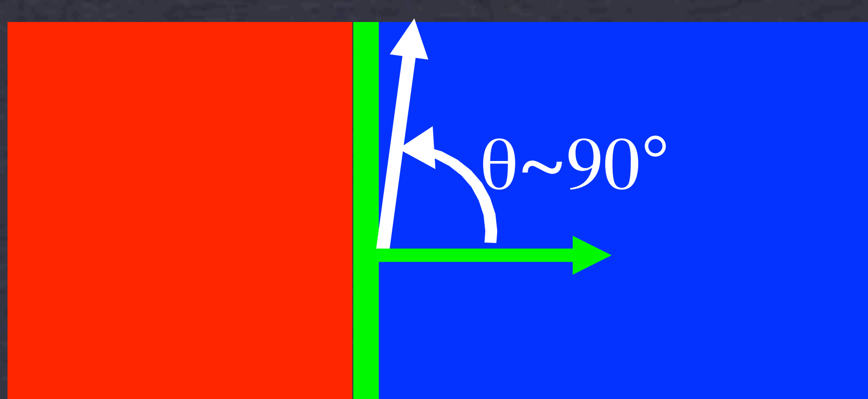
Structure of an unmagnetized relativistic pair shock



High-σ quasi-perpendicular shocks

σ=0.1 θ=75° γ_0=15 e^--p^+ shock





(Sironi and AS 11)

High-σ quasi-perpendicular shocks

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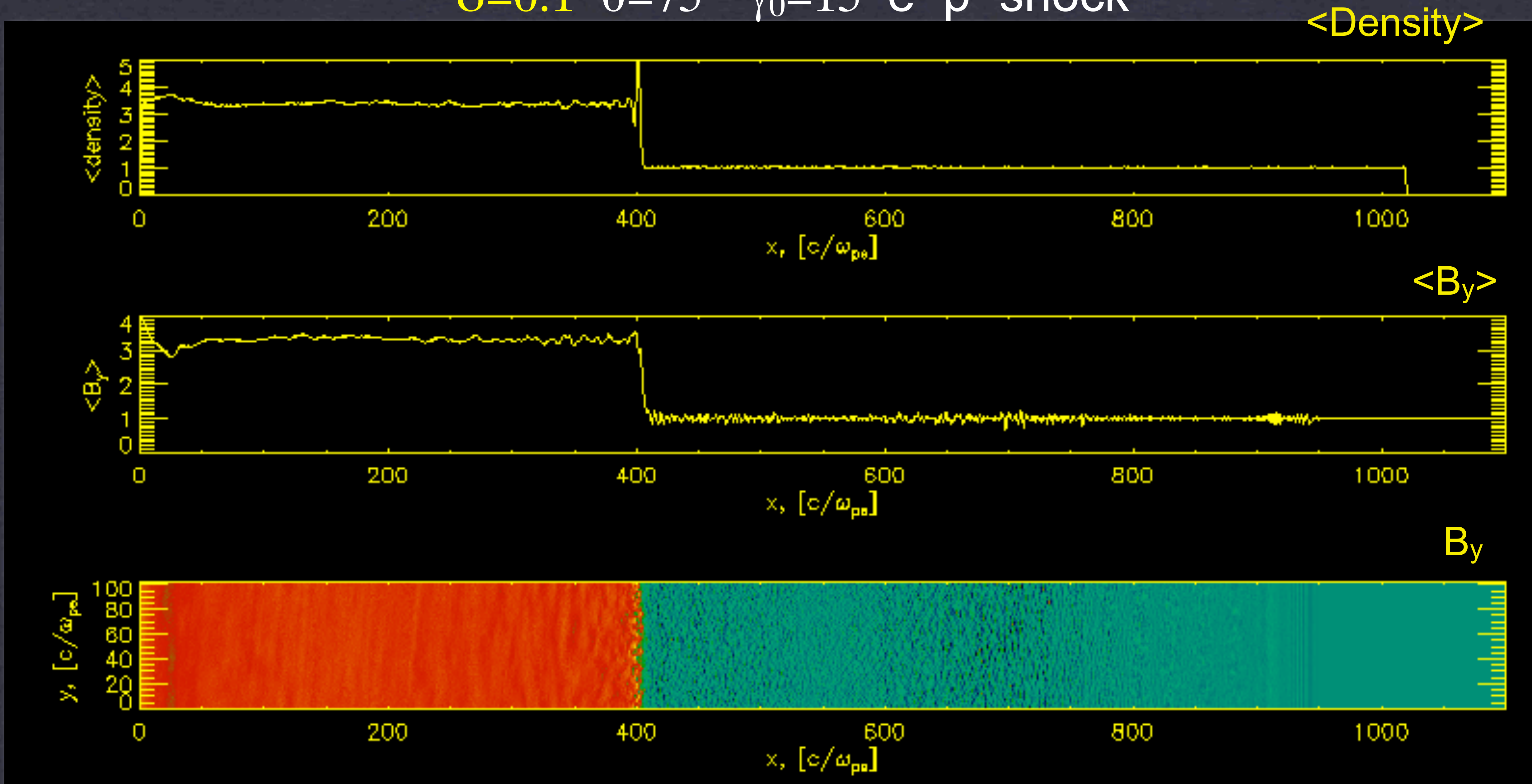
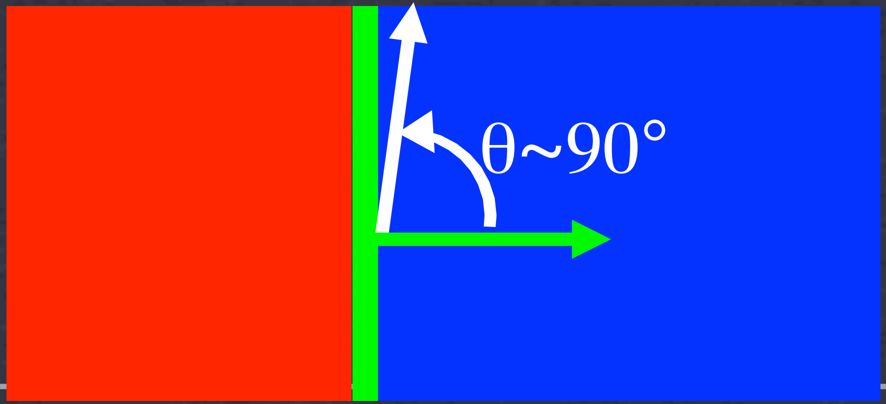
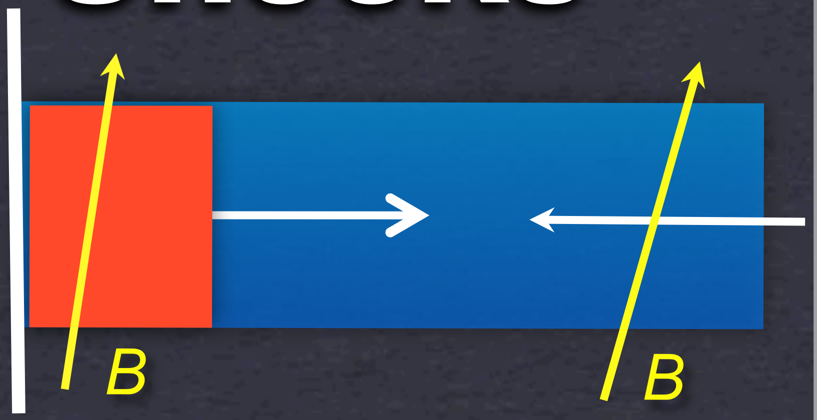




(Sironi and AS 11)

Survey of Collisionless Shocks

- Some findings:

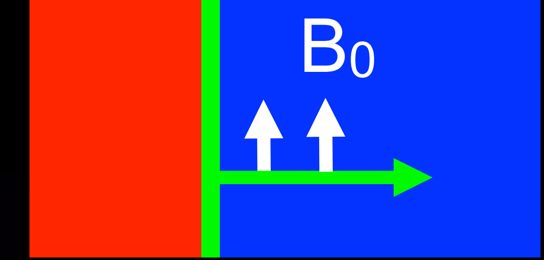


- Magnetized (low Alfvenic Mach #) shocks are mediated by reflection from compressed field
- Unmagnetized (VERY high Alfvenic Mach #) shocks are mediated by filamentation (Weibel) instabilities
- Transition at $\sigma \sim 10^{-3}$
- Acceleration depends on magnetizatoin and obliquity

Returning particles ⇔ Self-generated turbulence

Self-generated turbulence ⇔ Particle acceleration

High-σ vs low-σ shocks



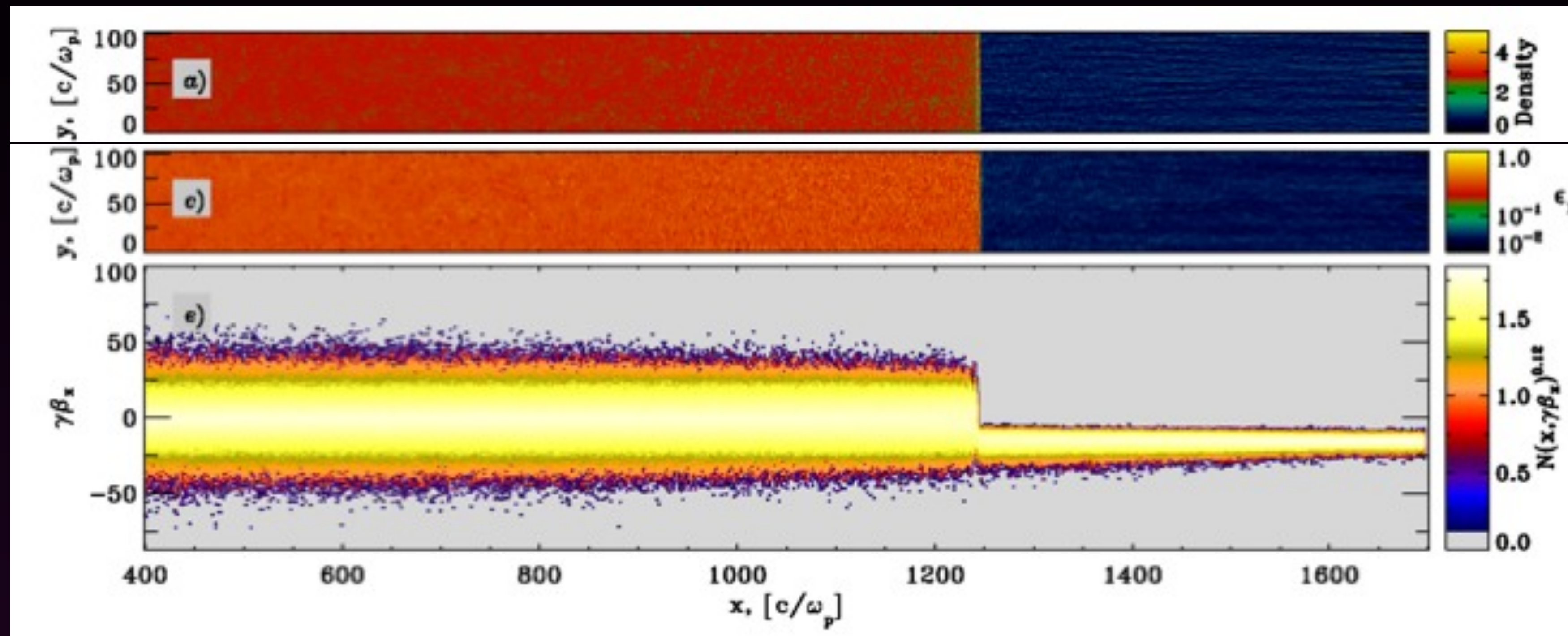
- High-σ shocks: no returning particles → no turbulence

$\sigma=0.1$

perp shock

$\gamma_0=15$

e^--e^+



Density

ε_B

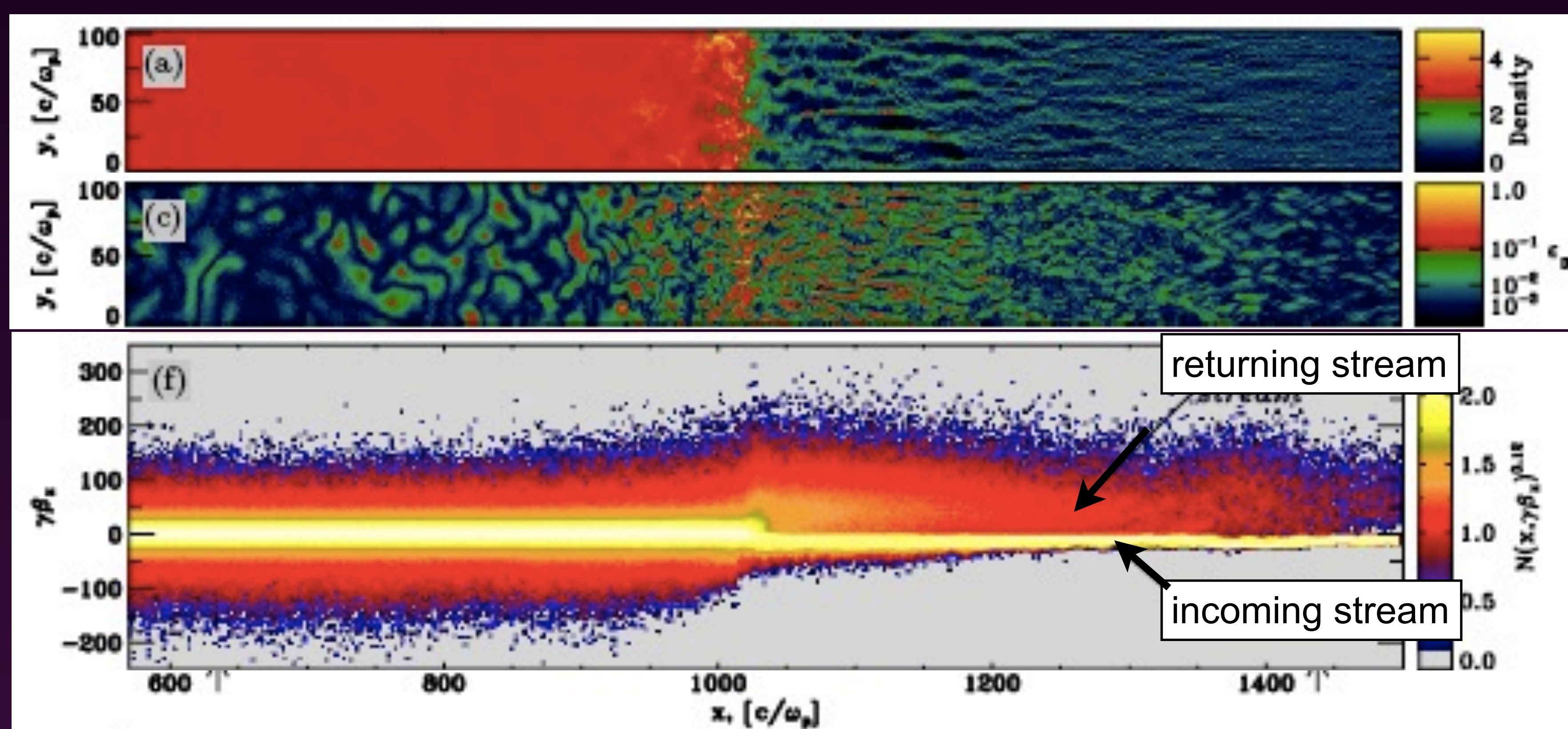
$\gamma\beta_x$

(Sironi & Spitkovsky 11a)

- Low-σ shocks: returning particles → oblique & filamentation instabilities

$\sigma=0$ $\gamma_0=15$

e^--e^+



Density

ε_B

$\gamma\beta_x$

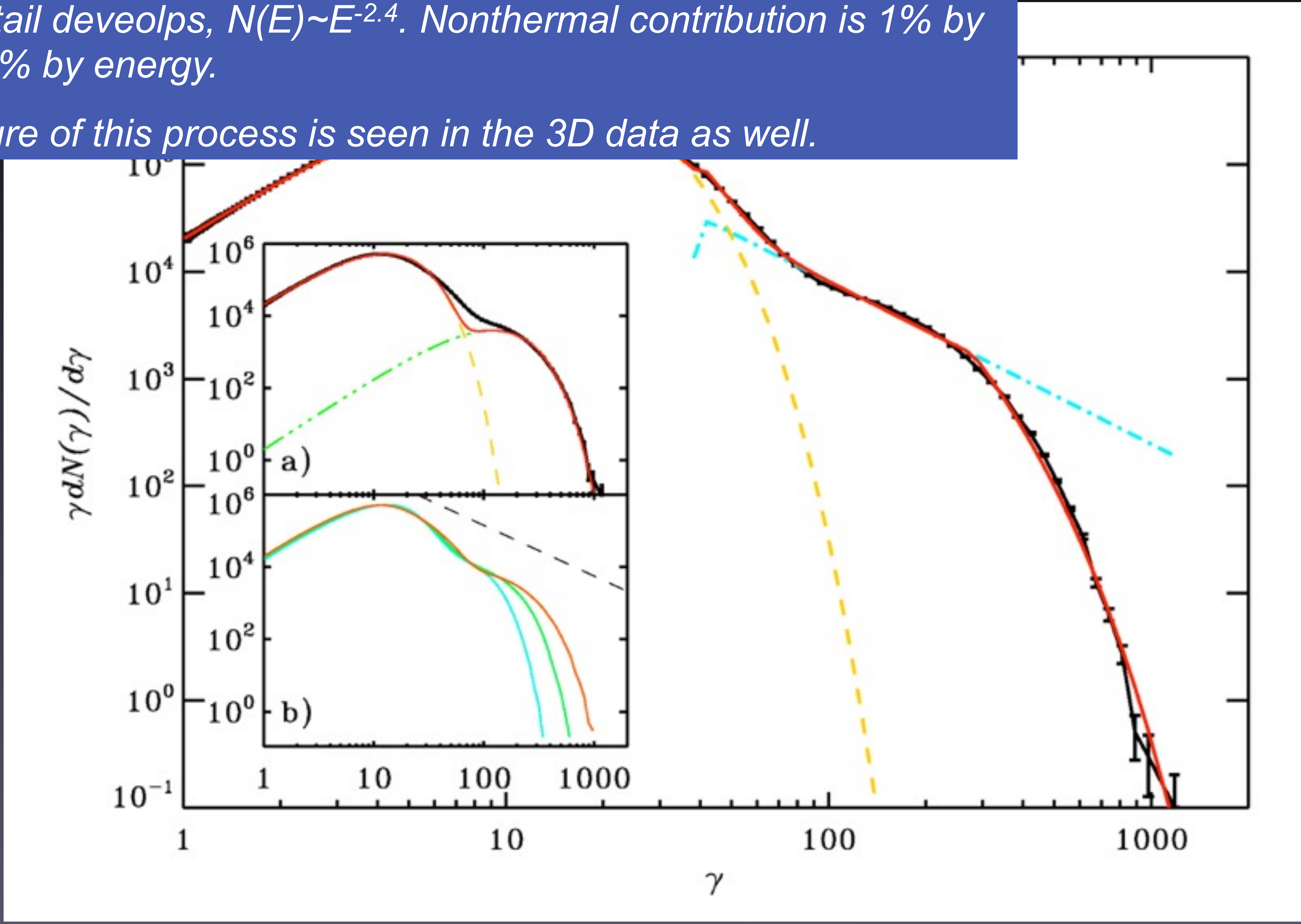
(Sironi & Spitkovsky 09)

Unmagnetized pair shock:

downstream spectrum: development of nonthermal tail!

Nonthermal tail deveolps, N(E)~$E^{-2.4}$. Nonthermal contribution is 1% by number, ~10% by energy.

Early signature of this process is seen in the 3D data as well.



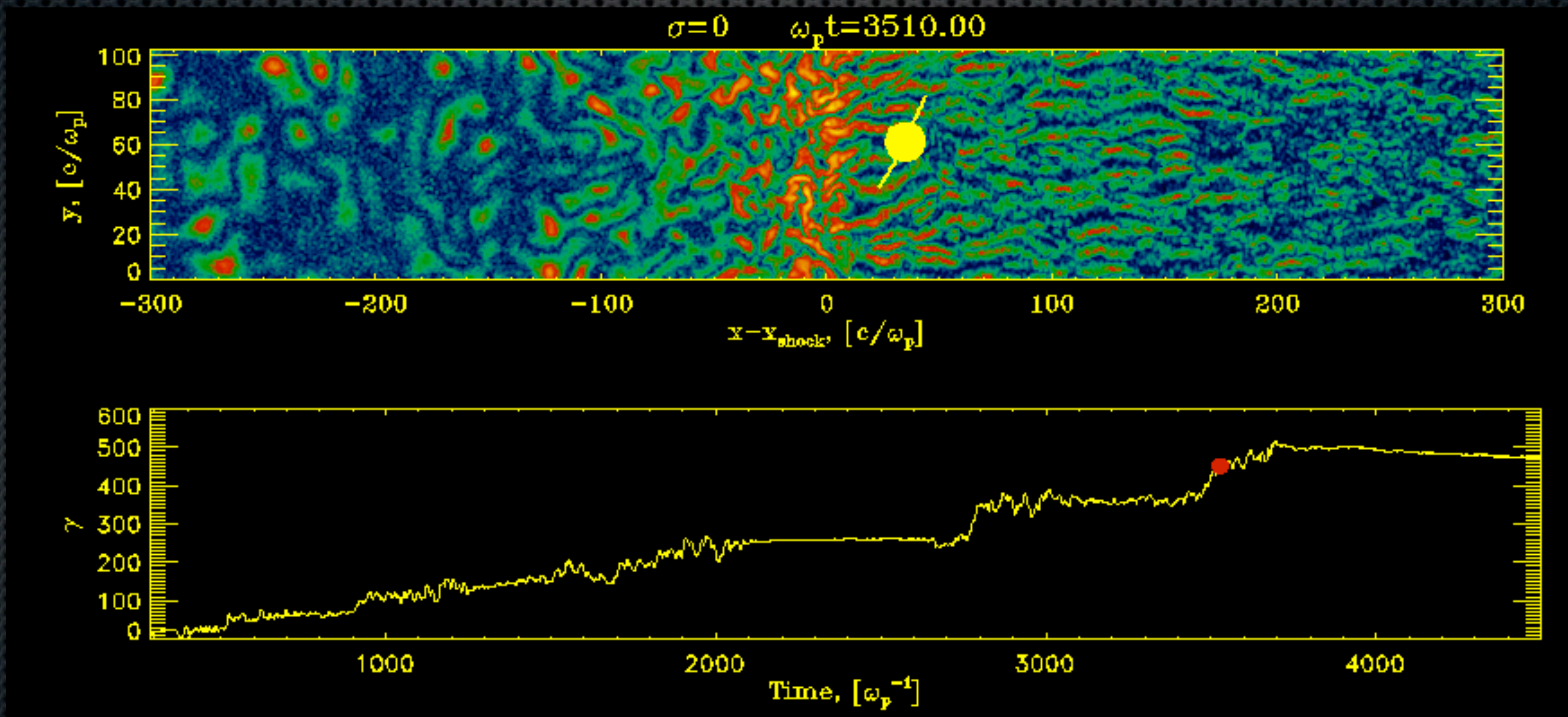
A.S. (2008)

Particle acceleration

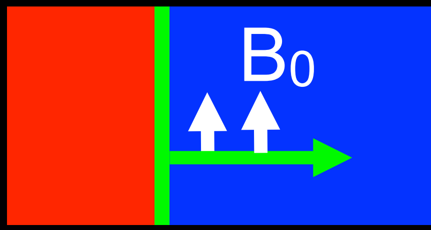
Self-generated magnetic turbulence scatters particles across the shock; each crossing results in energy gain -- Fermi process

Magnetic filaments

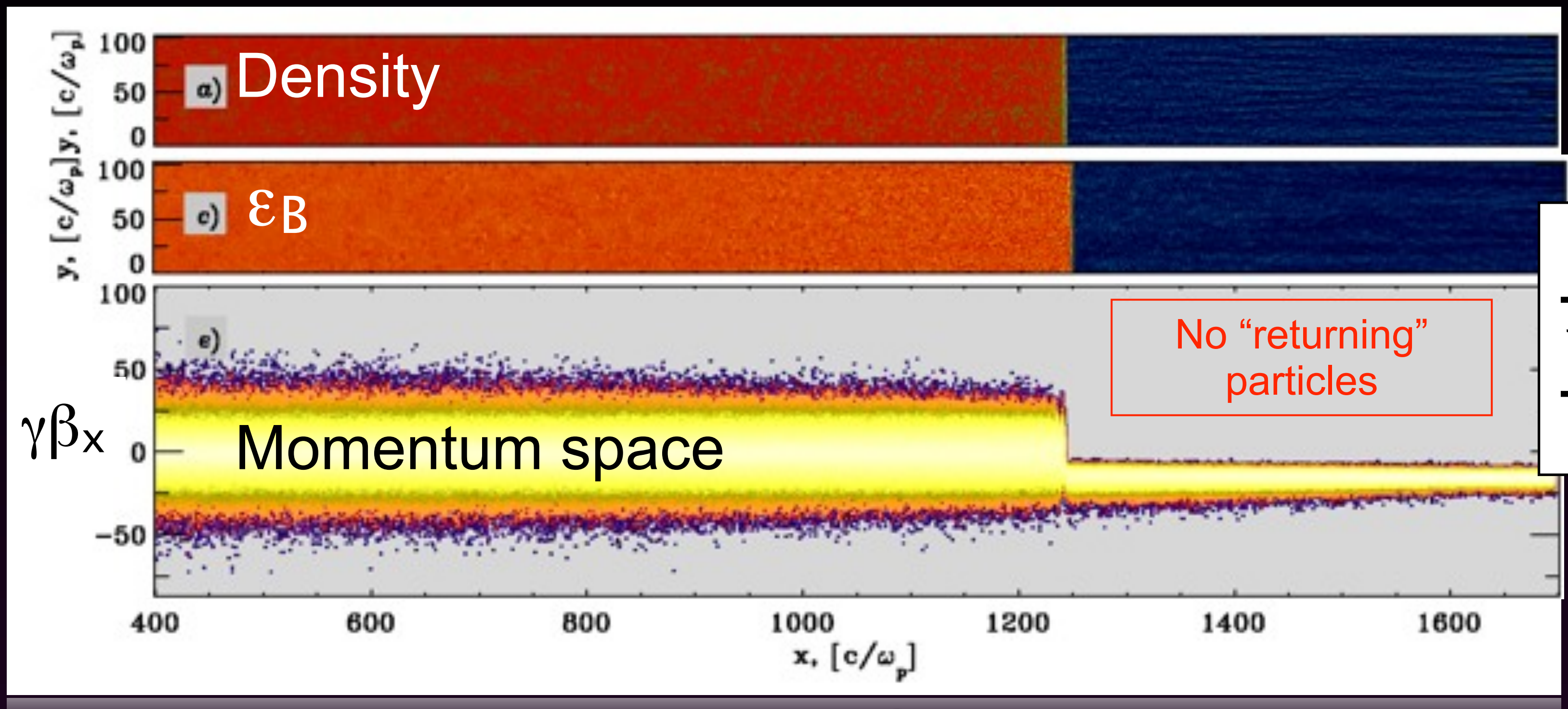
Particle energy

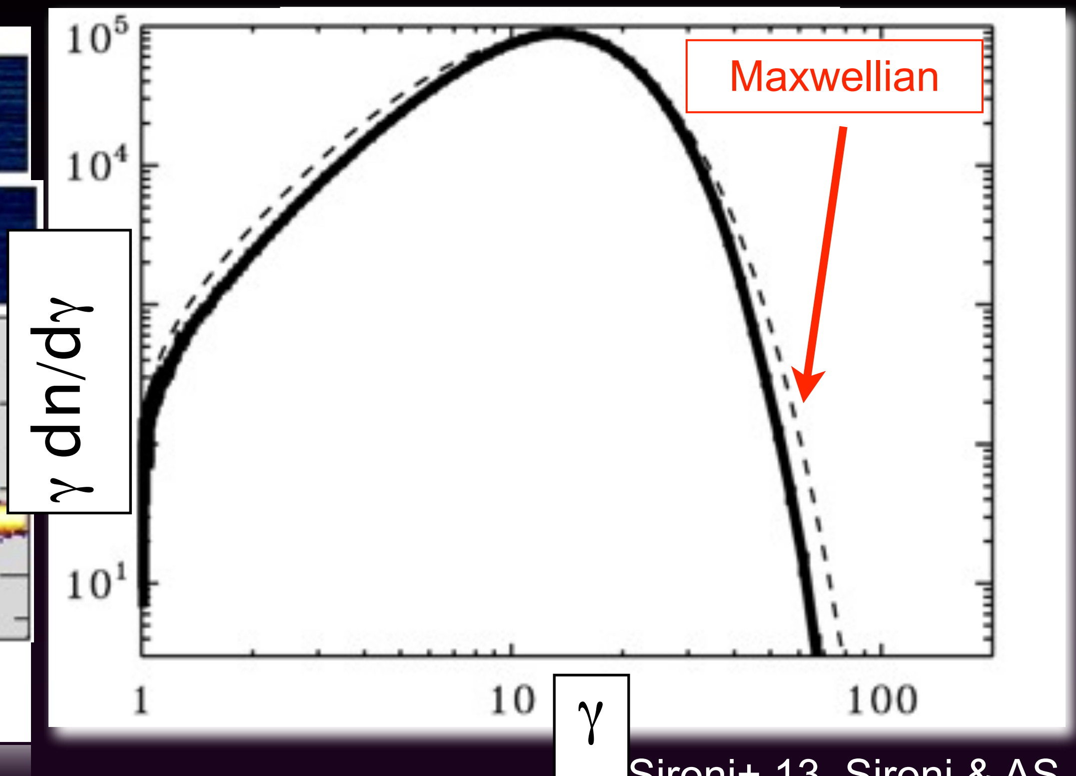


Shocks: no turbulence → no acceleration



σ=0.1 θ=90° γ_0=15 e⁻-e⁺ shock



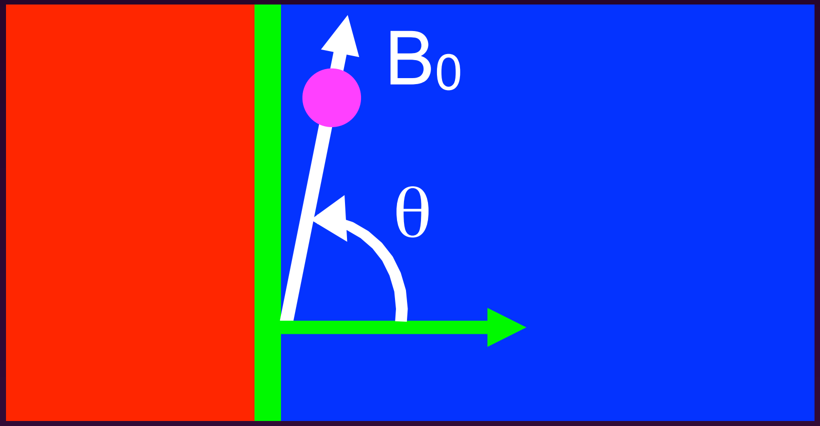


(Sironi+ 13, Sironi & AS 09,11)

No "returning" particles → No self-generated turbulence

No self-generated turbulence → No particle acceleration

Strongly magnetized ($\sigma>10^{-3}$) quasi-perp $\gamma_0 \gg 1$ shocks are poor particle accelerators:



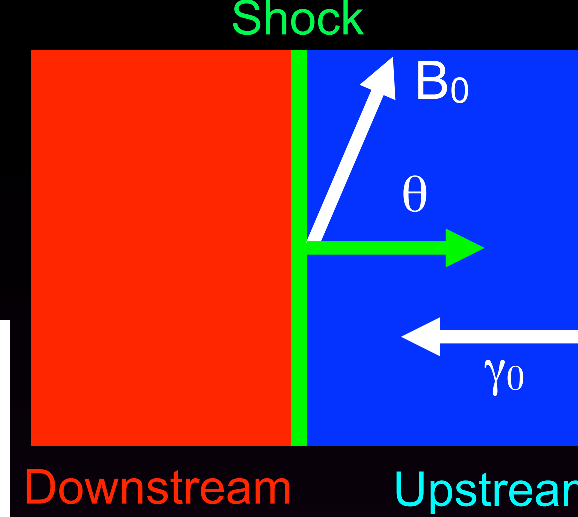
σ is large → particles slide along field lines

θ is large → particles cannot outrun the shock

unless v>c ("superluminal" shock)

→ Fermi acceleration is generally suppressed

Perpendicular vs parallel shocks



- Quasi-perpendicular shocks: mediated by magnetic reflection

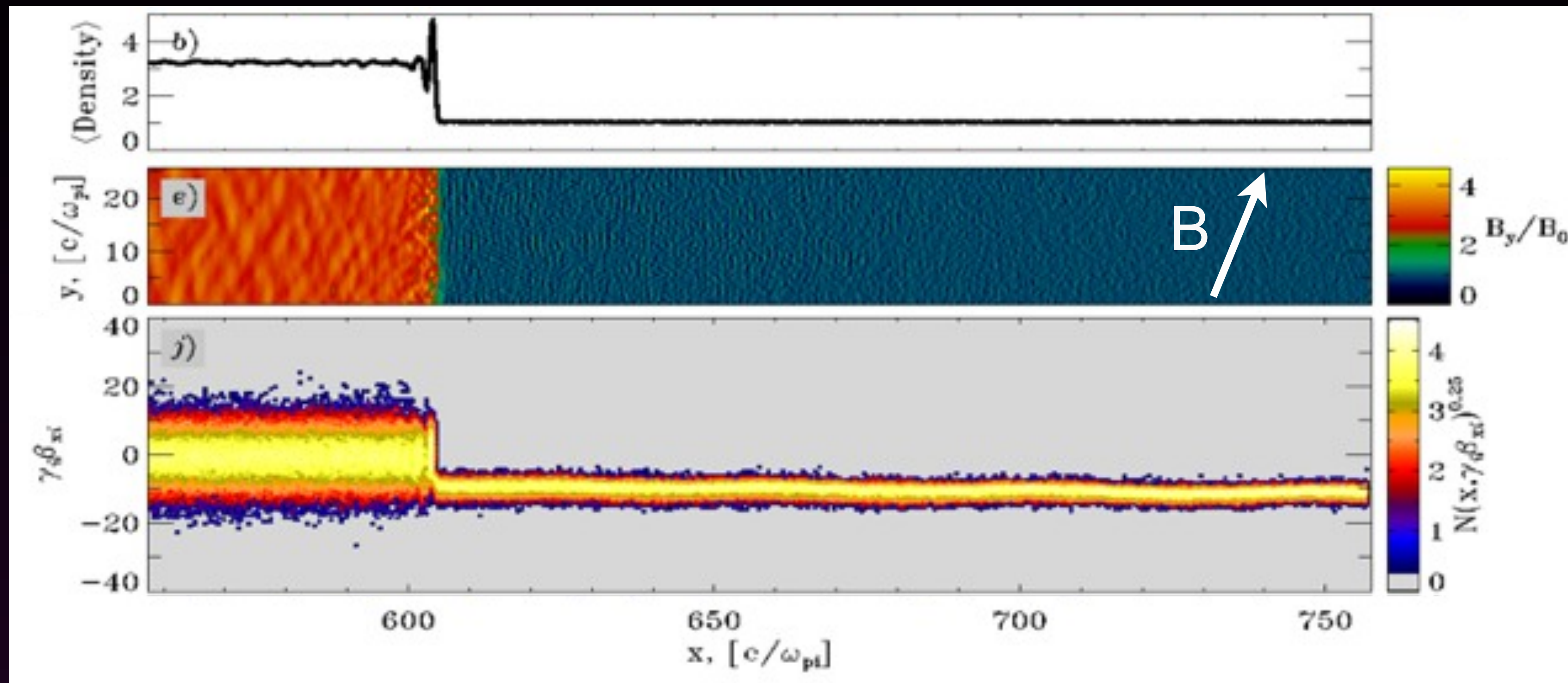
<Density>

$\sigma=0.1$

$\theta=75°$

$\gamma_0=15$

$e^- - p^+$



B_y

$\gamma\beta_x$

(Sironi and AS 11)

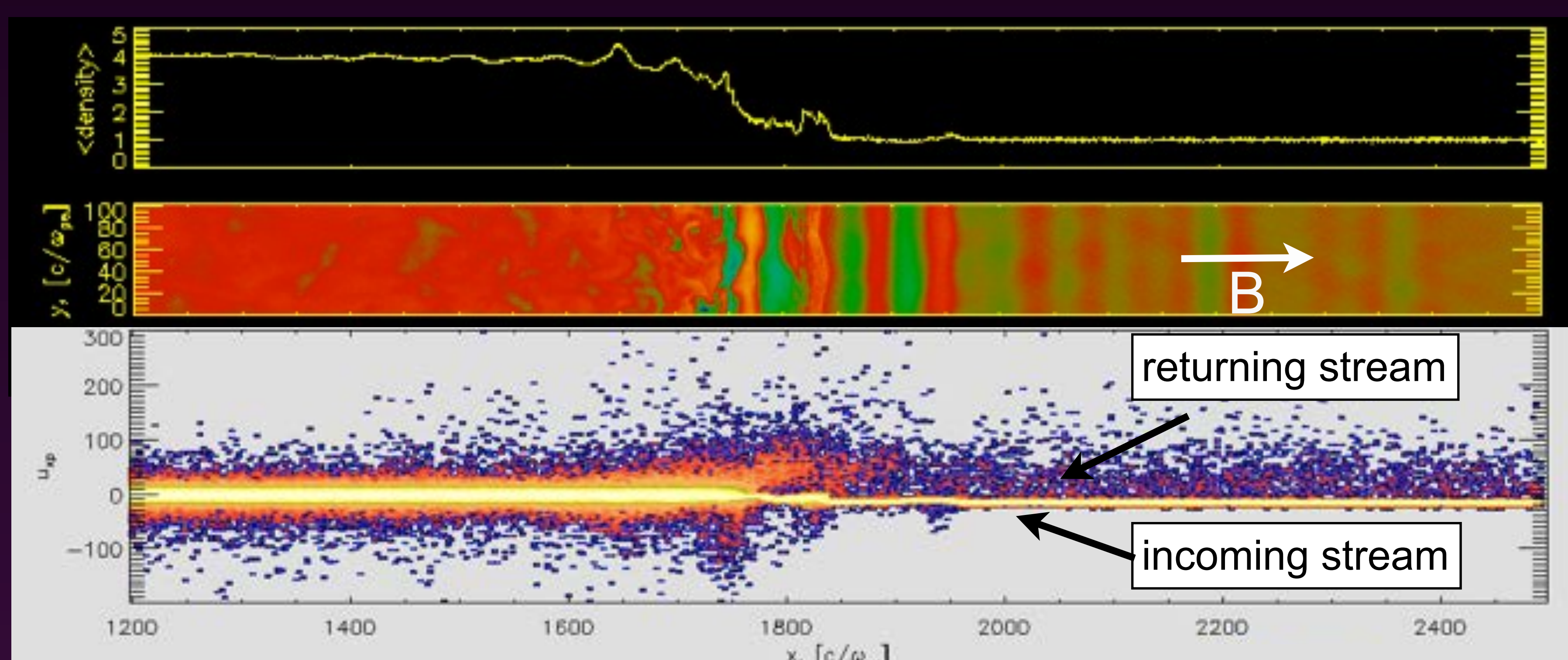
- Quasi-parallel shocks: instabilities amplify transverse field component

$\sigma=0.1$

$\theta=15°$

$\gamma_0=15$

$e^- - p^+$



<Density>

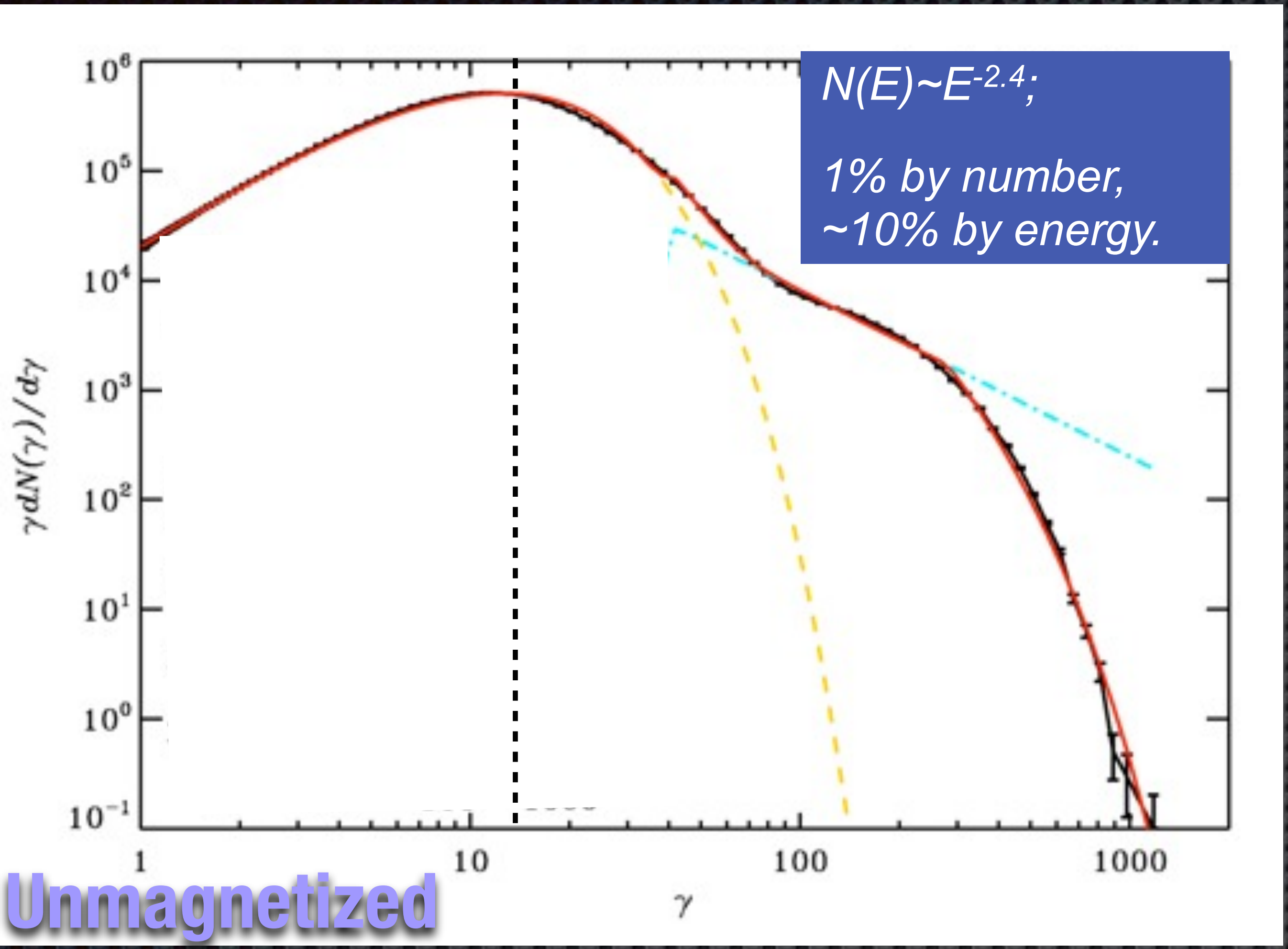
B_y

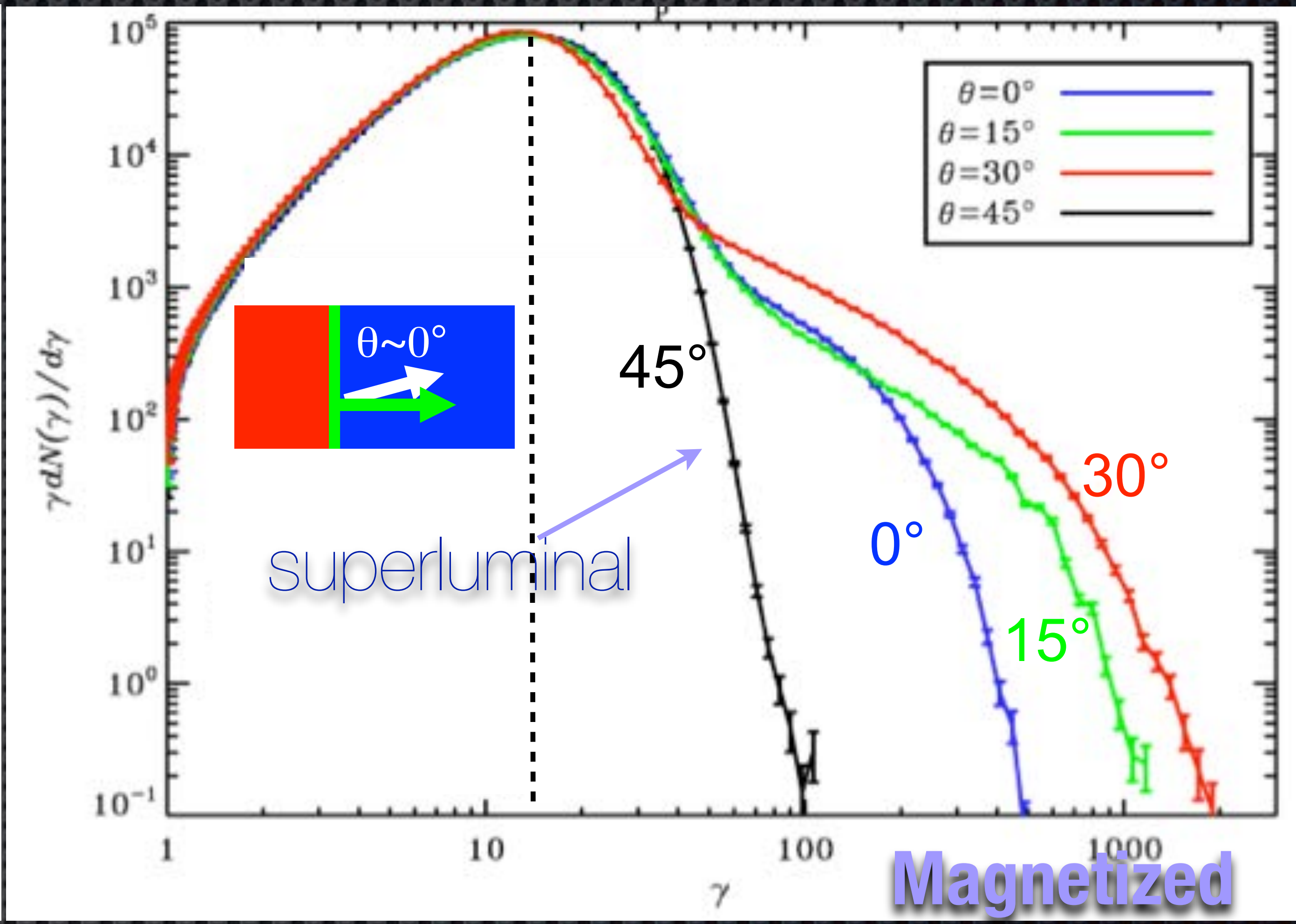
$\gamma\beta_x$

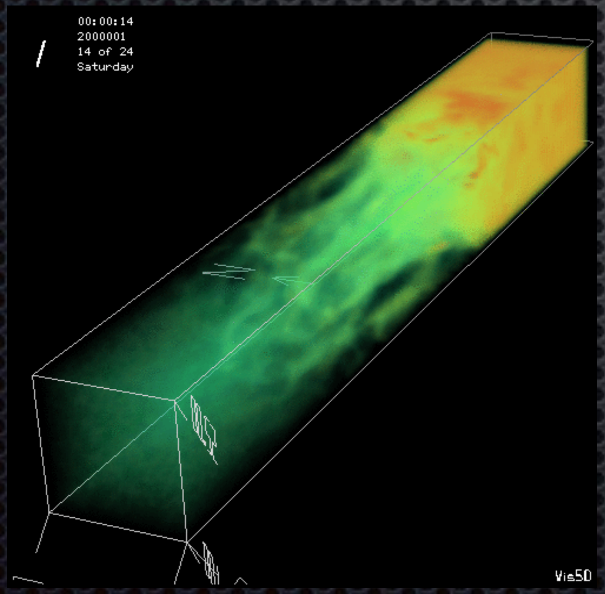
(Sironi & AS 11)

Particle acceleration

Sironi & AS 09



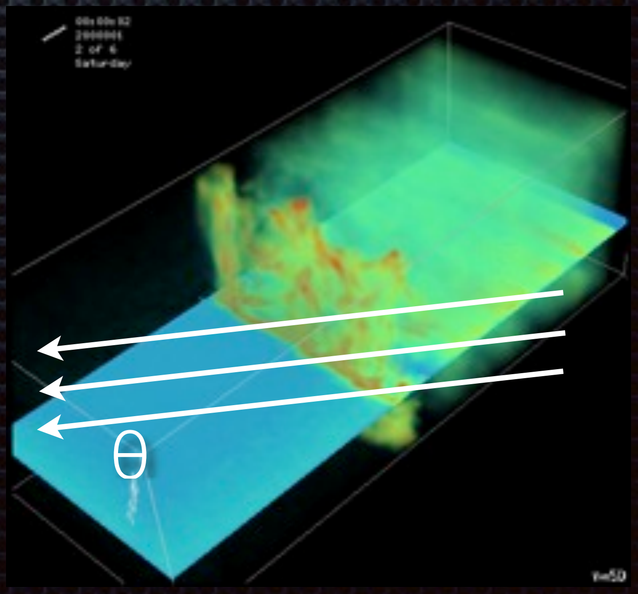




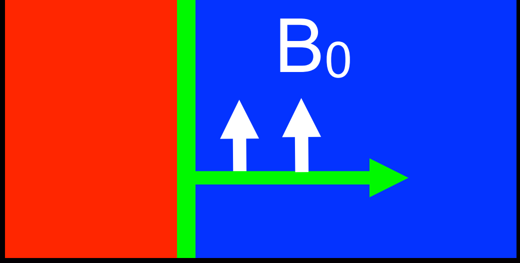
Conditions for acceleration in relativistic shocks:

low magnetization of the flow

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



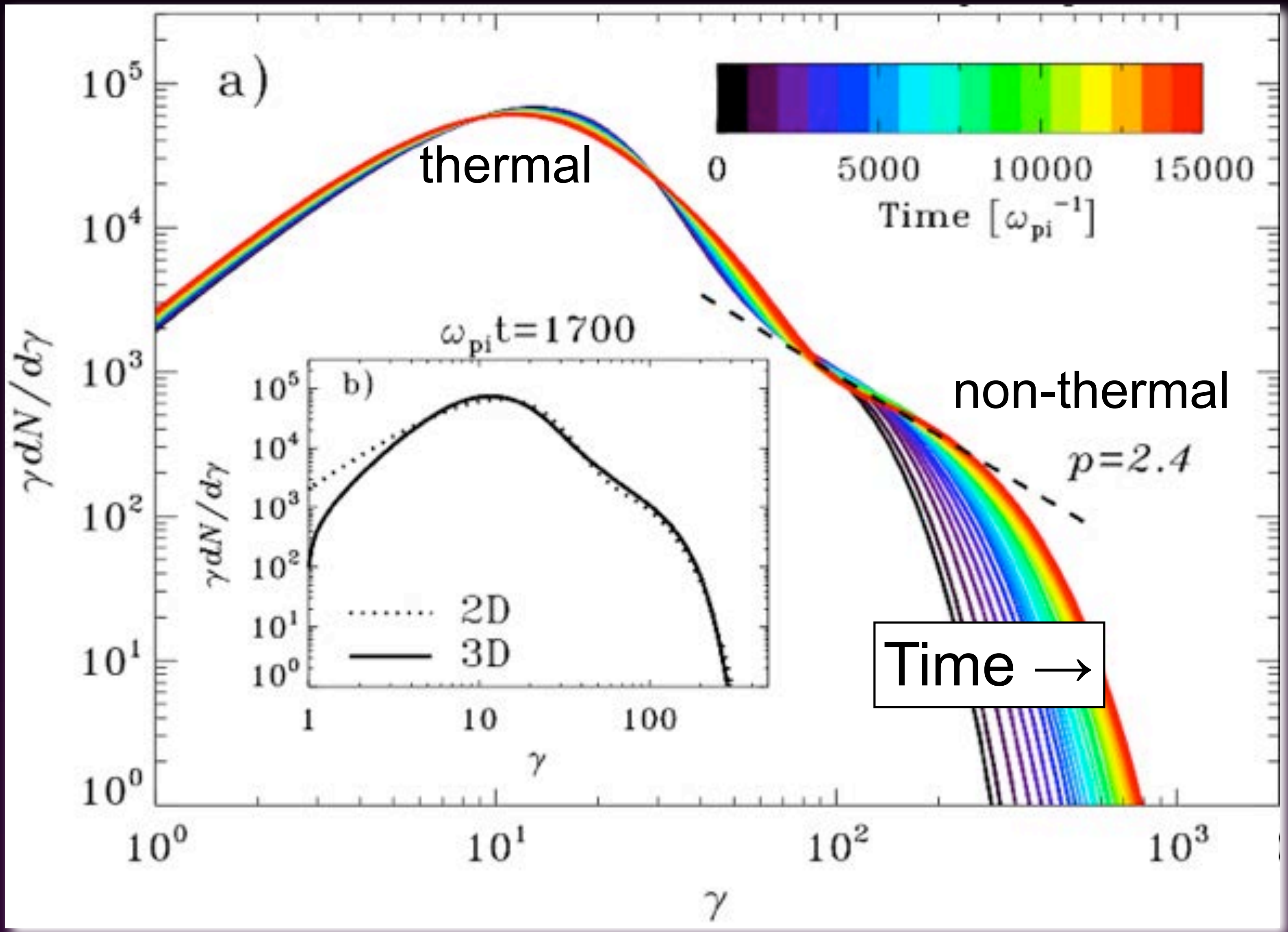
σ=0 shocks are efficient but slow



The nonthermal tail has slope $p=2.4\pm0.1$ and contains ~1% of particles and ~10% of energy.

By scattering off small-scale Weibel turbulence, the maximum energy grows as $\gamma_{max} \propto t^{1/2}$.

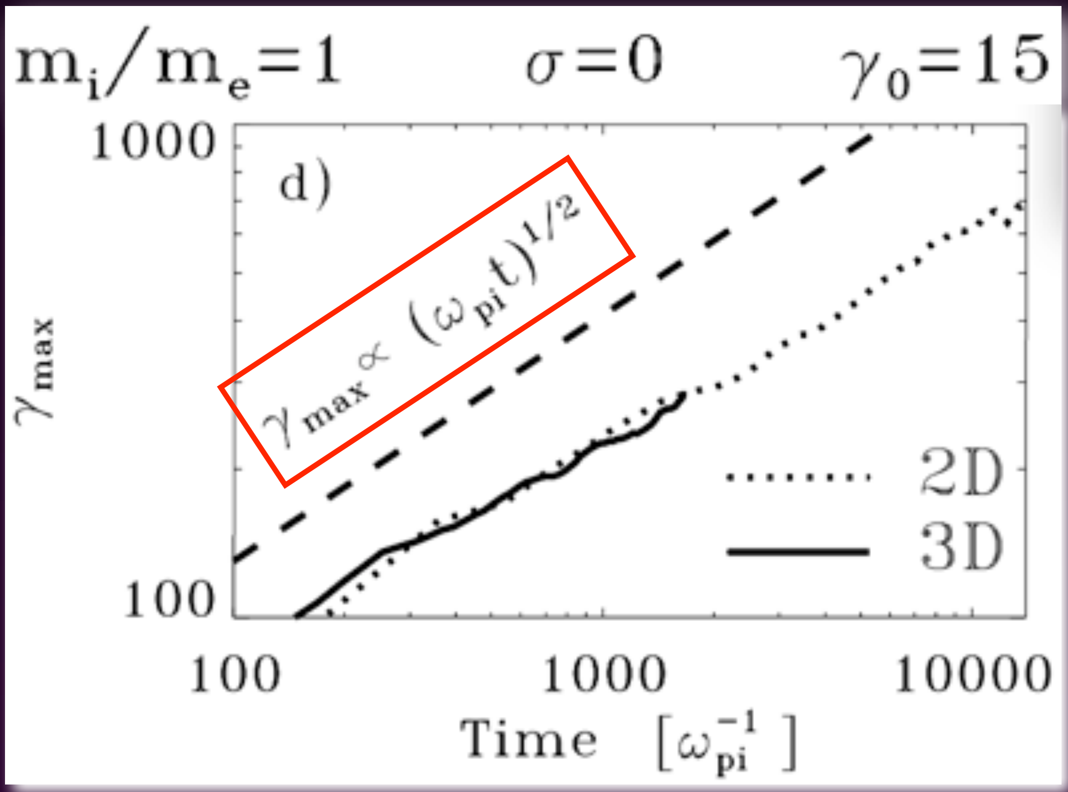
Instead, most models of particle acceleration in shocks assume $\gamma_{max} \propto t$ (Bohm scaling).



$$\gamma_{max} \simeq 0.5\,\gamma_0\,(\omega_{\rm pi}t)^{1/2}$$

$$D \simeq 4\,c\;c/\omega_{\rm pi}(\varepsilon/\gamma_0 m_i c^2)^2$$

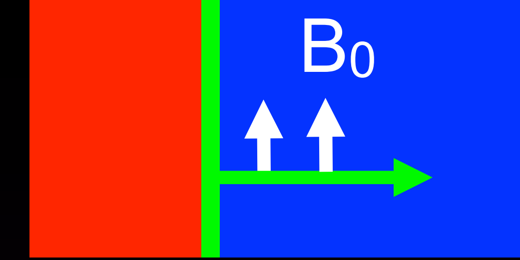
Sironi et al 13, cf. Reville & Kirk 10



(AS08, Sironi et al. 13, Martins et a. 09, Haugbolle 10)

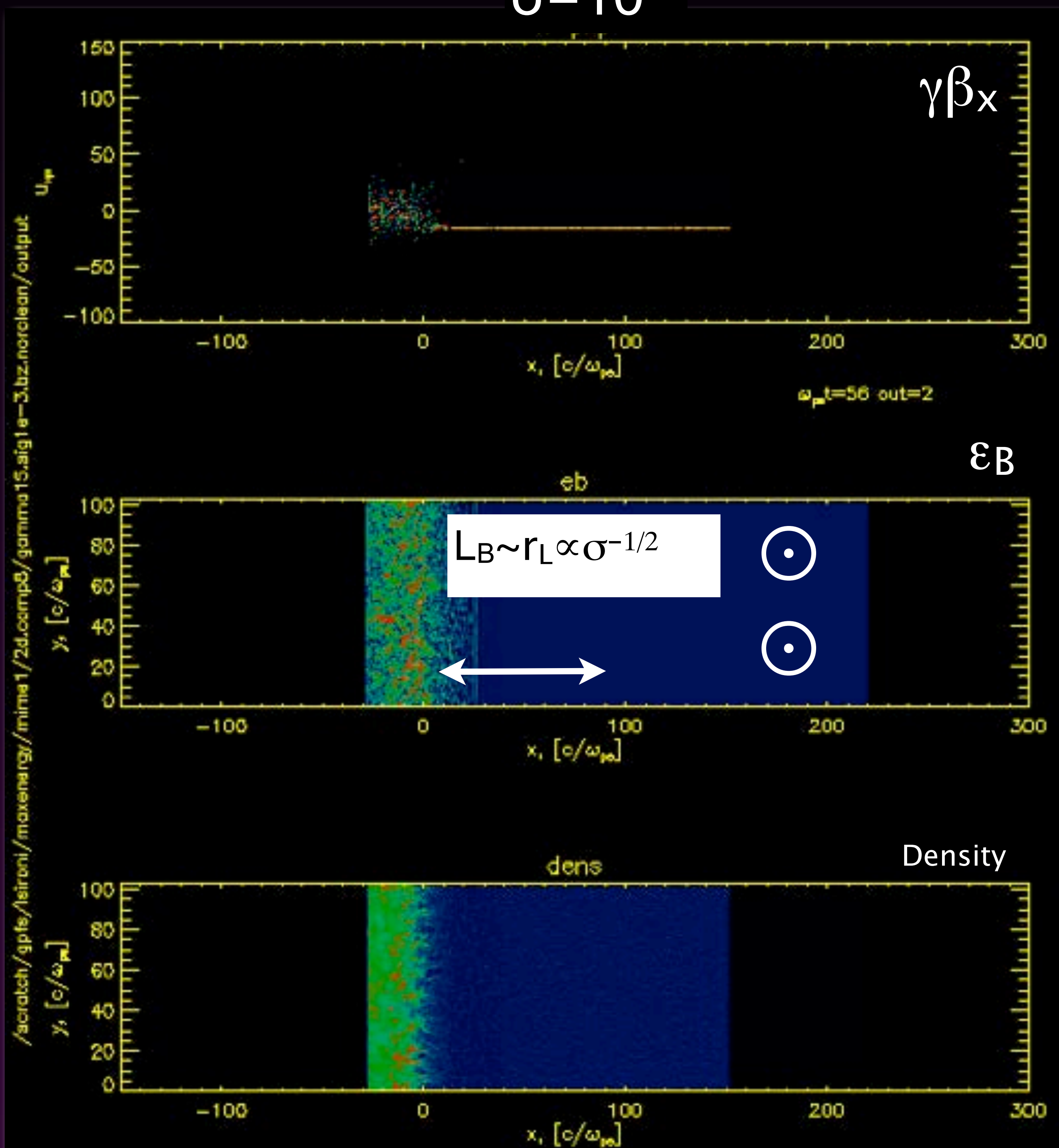
Conclusions are the same in 2D and 3D

Spectral evolution vs magnetization



Thickness of the turbulent layer saturates ⇒ Maximum particle energy saturates

$\sigma=10^{-3}$



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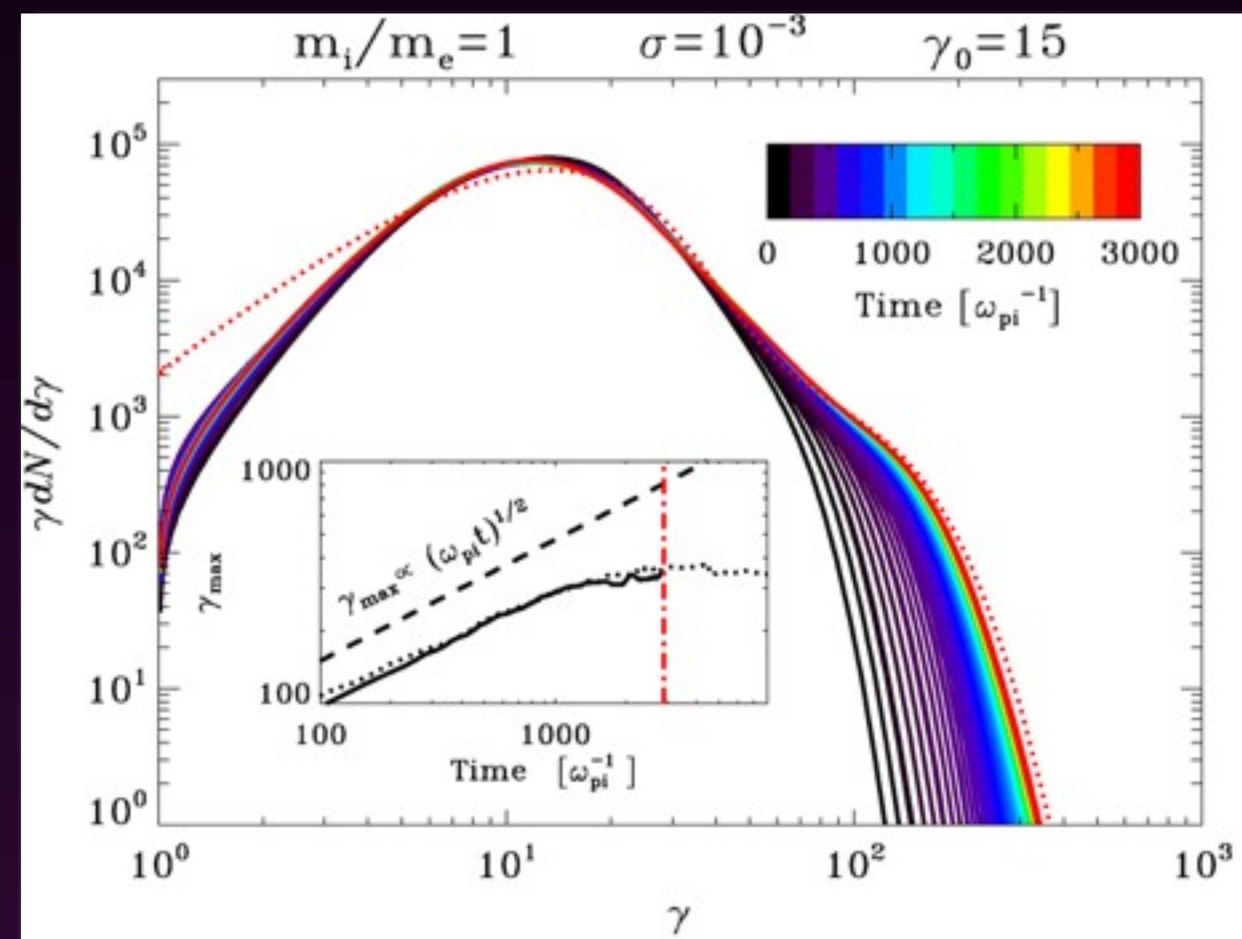
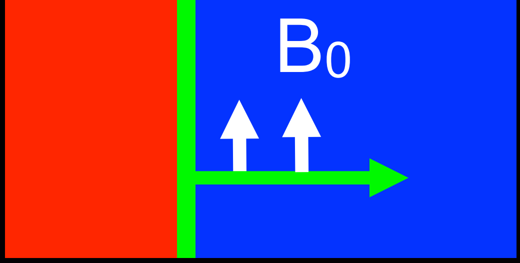


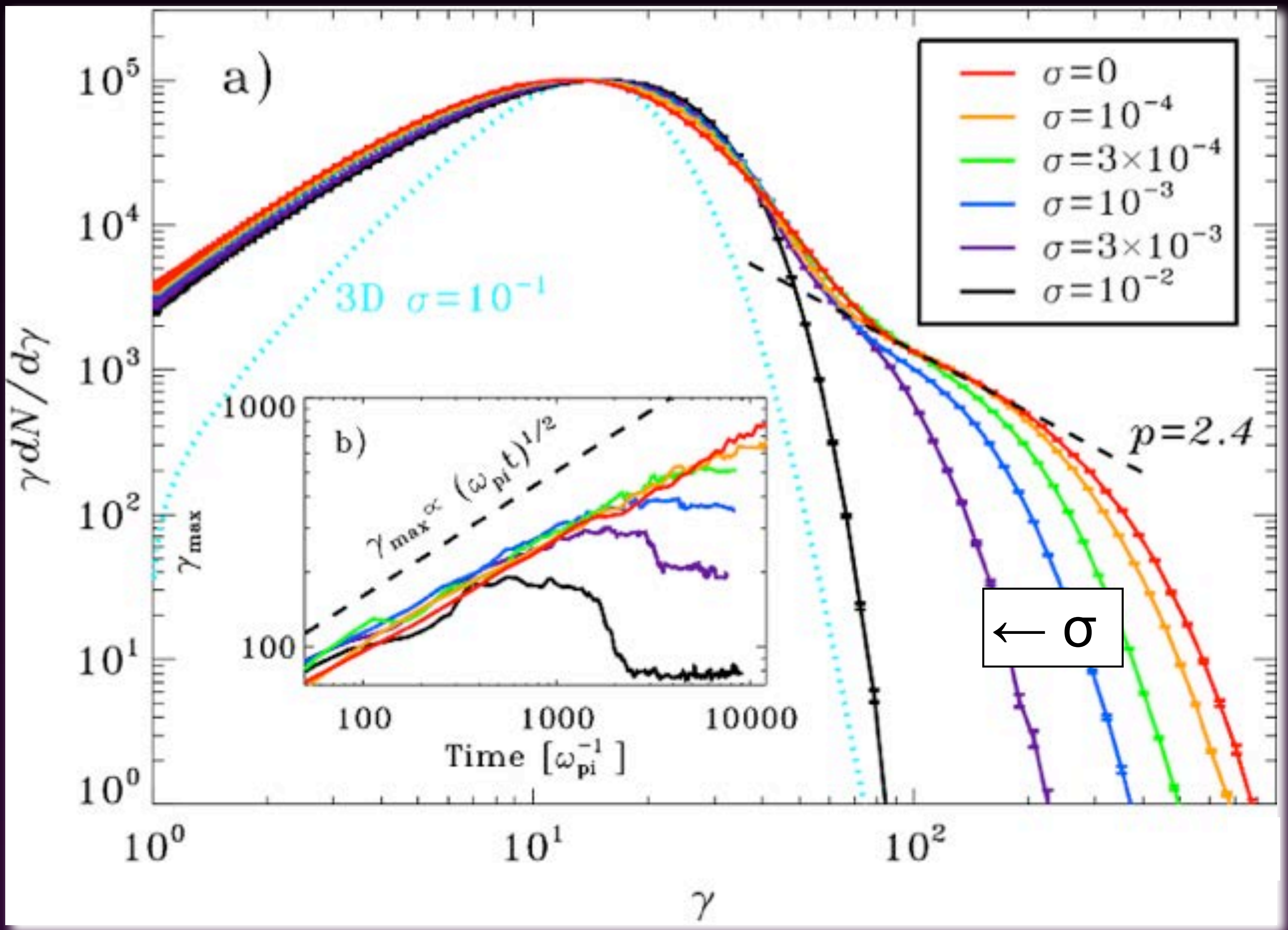
(Sironi et al. 13)

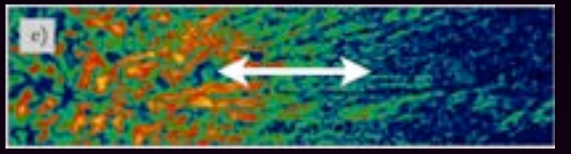
Magnetization inhibits acceleration



Electron-positron perpendicular shocks are efficient particle accelerators if $\sigma \lesssim 10^{-3}$.

If $0 < \sigma \lesssim 10^{-3}$, the Lorentz factor at saturation scales with magnetization as $\gamma_{sat} \propto \sigma^{-1/4}$.





$\gamma_{max} \propto t_{acc}^{1/2}$

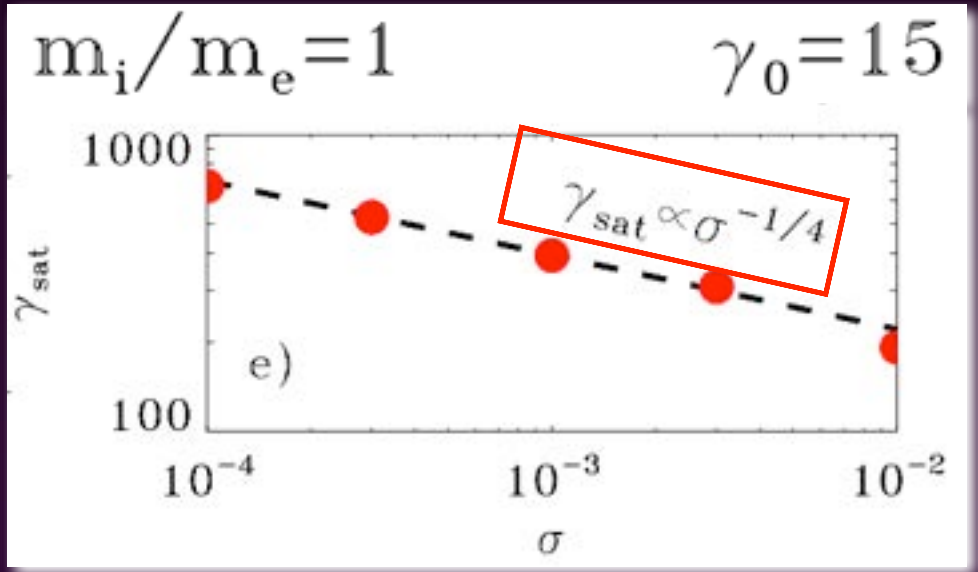
$t_{acc} \propto \gamma_{max}^2$

$L_B \propto \sigma^{-1/2}$

$t_{adv} \propto L_B \propto \sigma^{-1/2}$

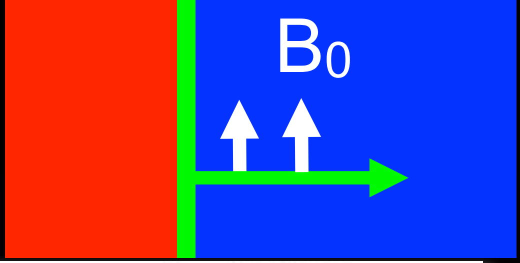
⇓

$$\gamma_{sat} \simeq 4 \gamma_0 \sigma^{-1/4}$$

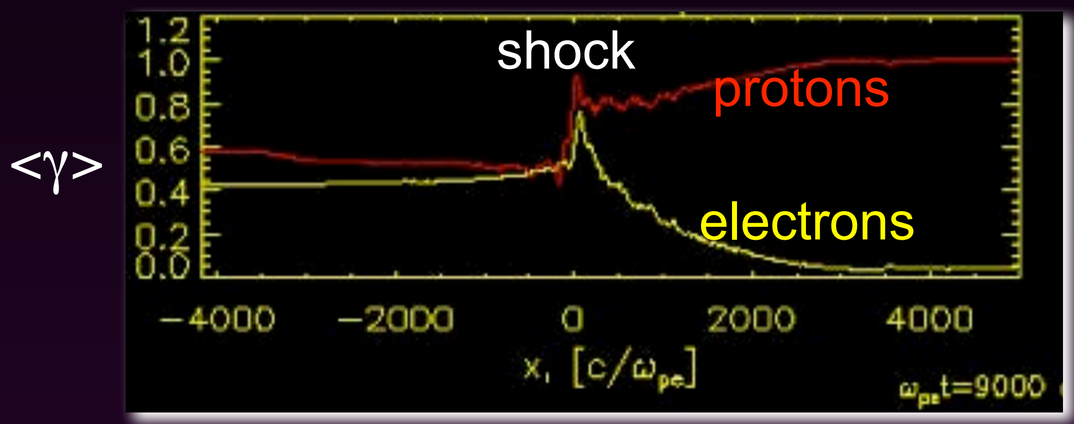


(Sironi et al. 13)

Electron-proton shocks

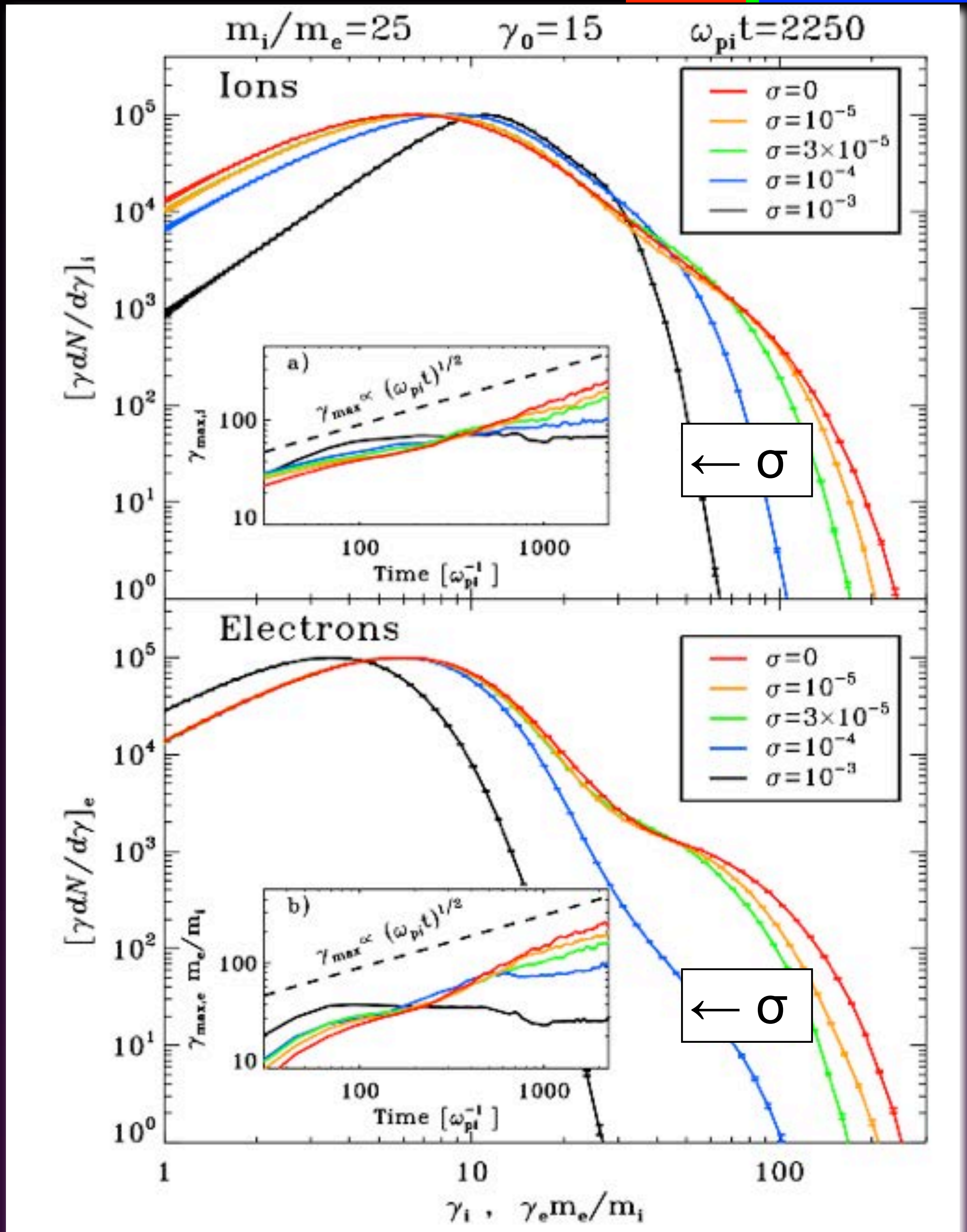


Electrons are efficiently heated ahead of the shock, almost in equipartition with the protons.



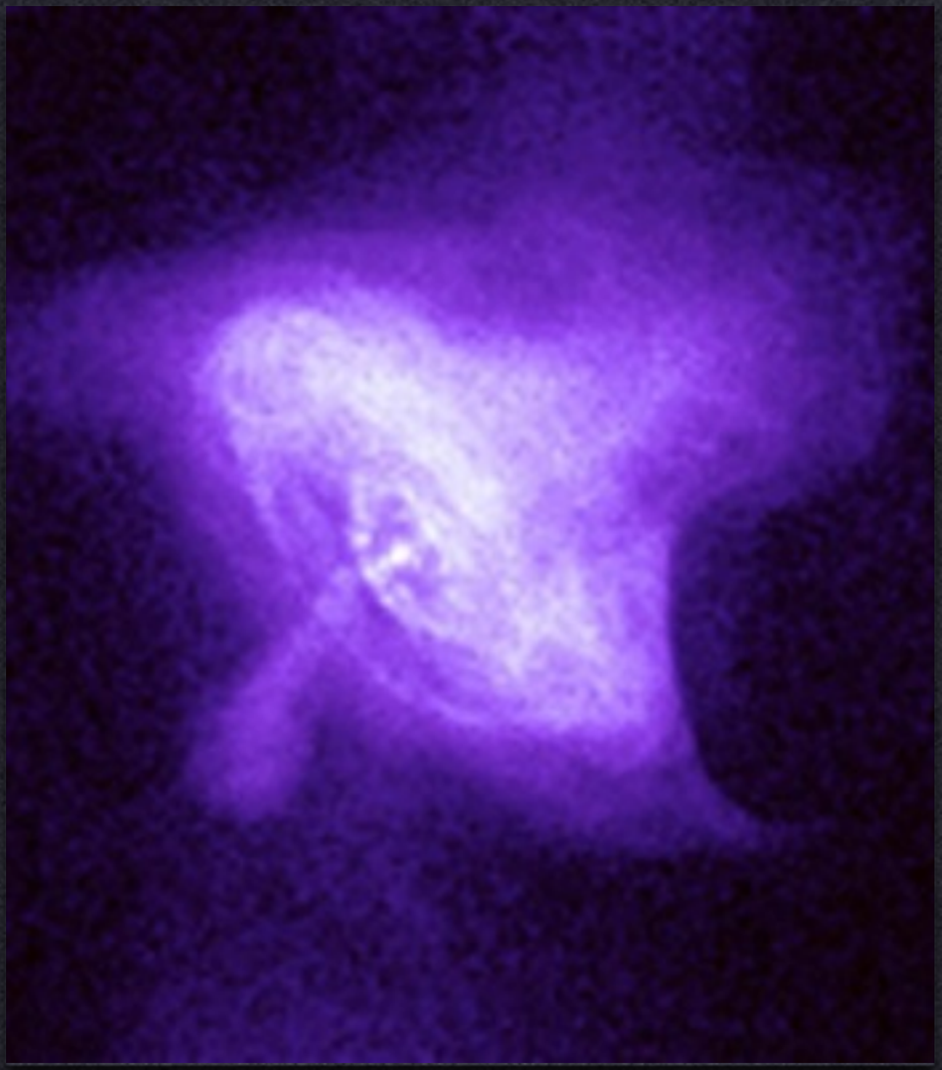
Magnetized electron-proton perpendicular shocks are efficient particle accelerators only if $\sigma \leq 3\times10^{-5}$.

(Sironi et al. 13)



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

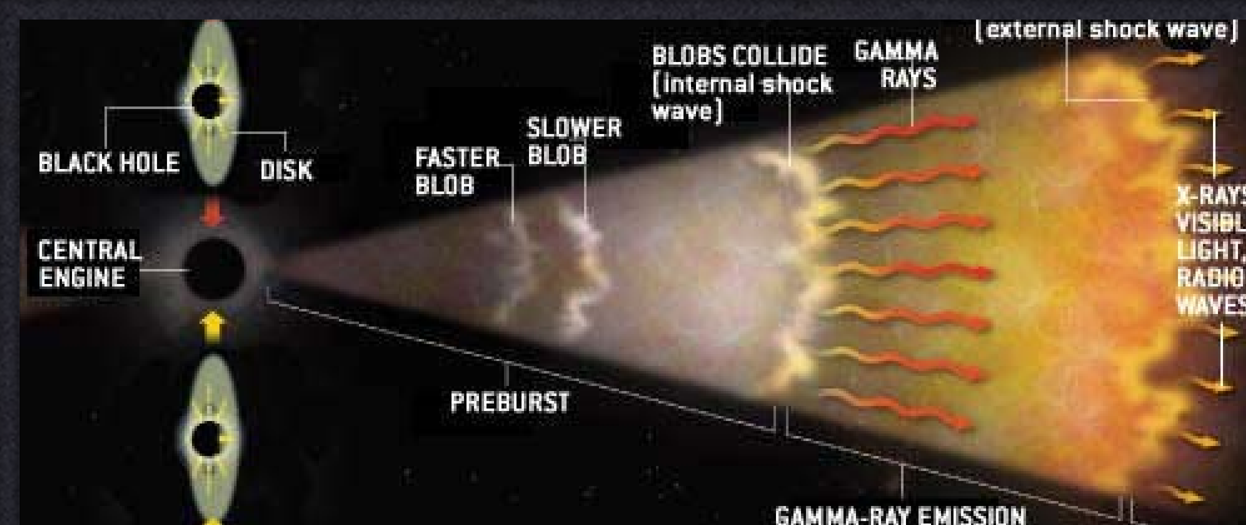
  Either magnetic field is dissipated in the process of acceleration,

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

- GRB jets

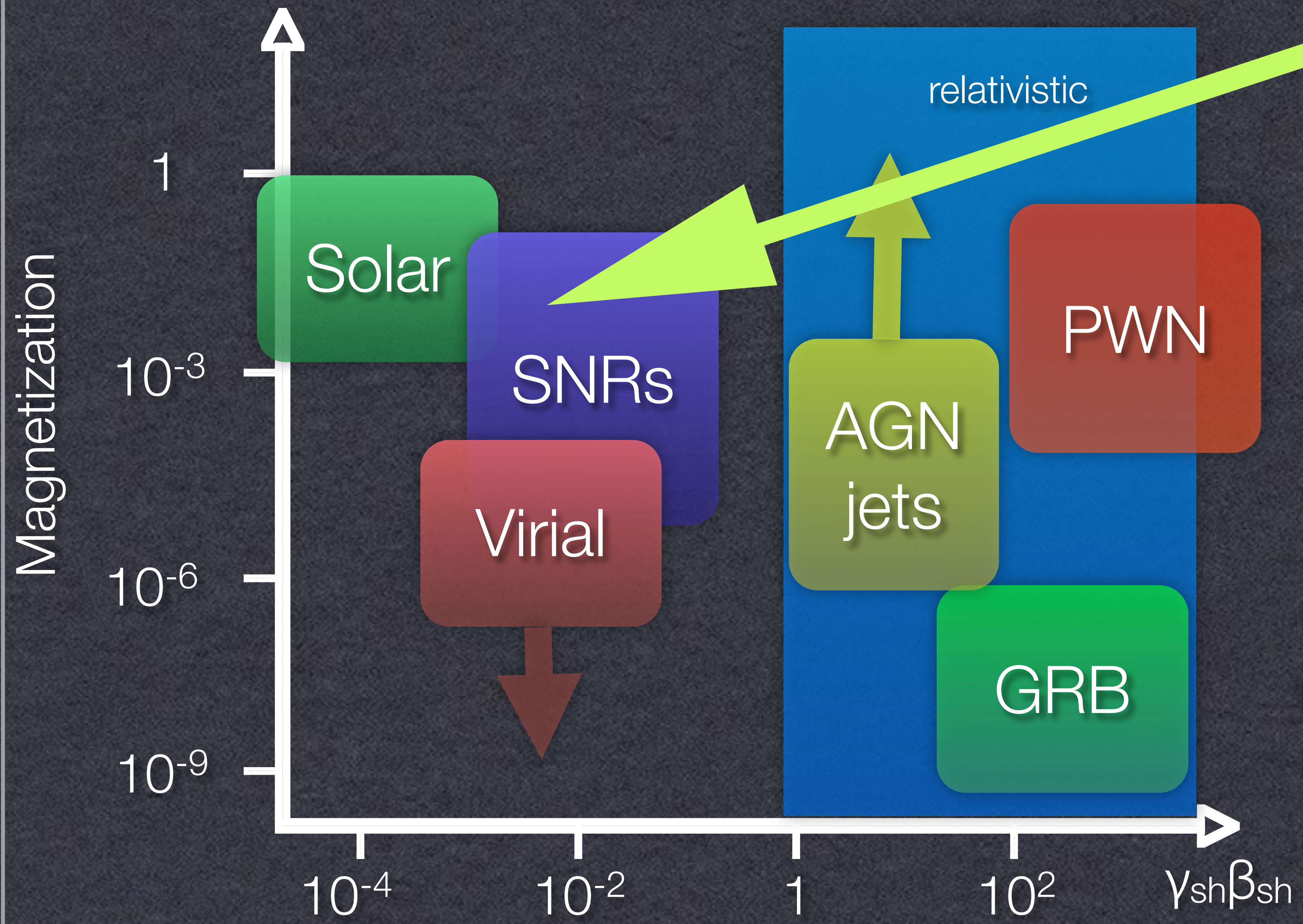
  Low magnetization external shocks can work; Field survival? GeV emission too early?

  Efficient electron heating explains high energy fraction in electrons



Parameter Space of shocks

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



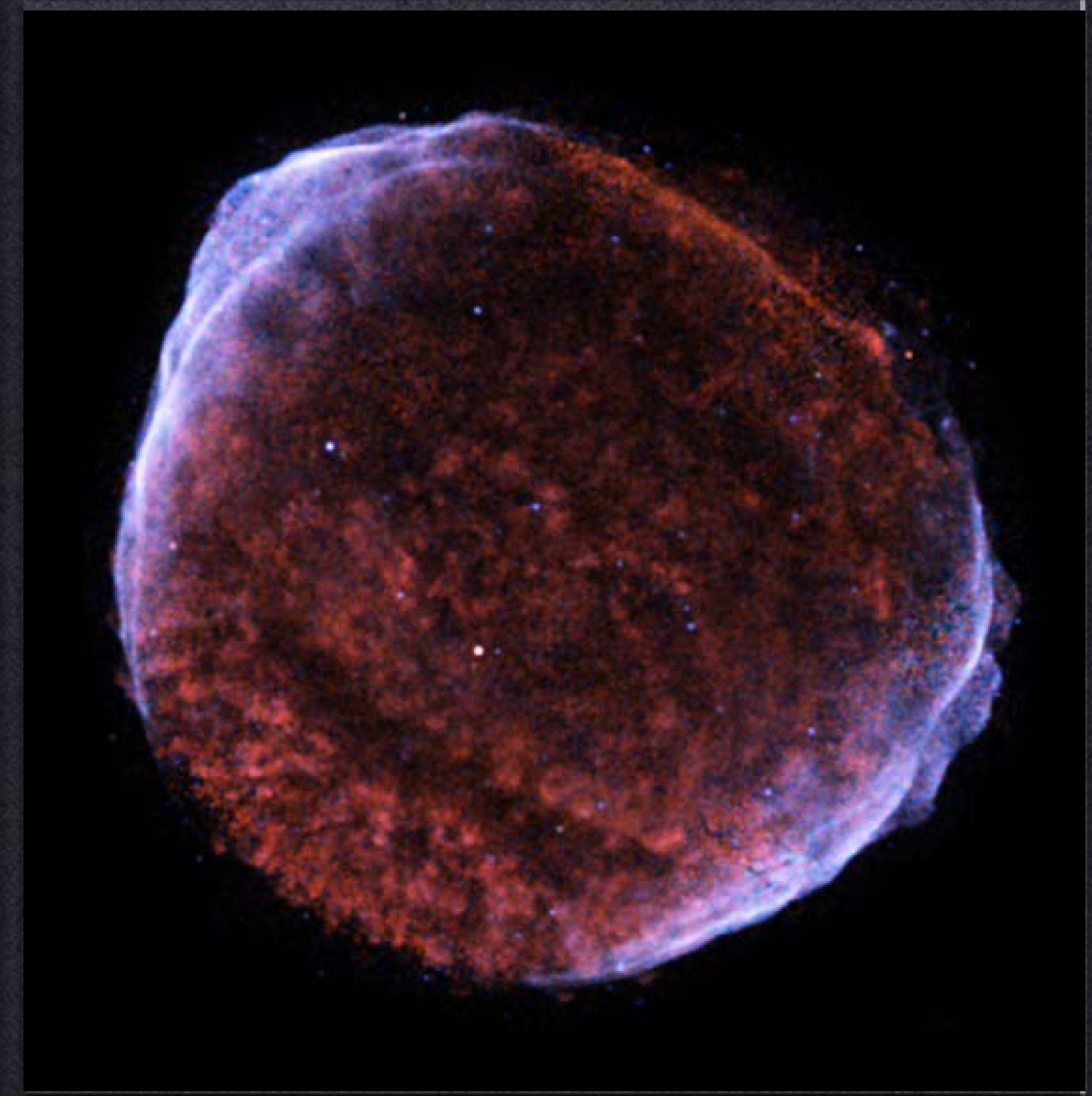
nonrelativistic shocks

e and ions are different in non-relativistic case

most of our PIC runs are still mildly relativistic (v/c~0.03-0.1c)

Nonrelativistic shocks

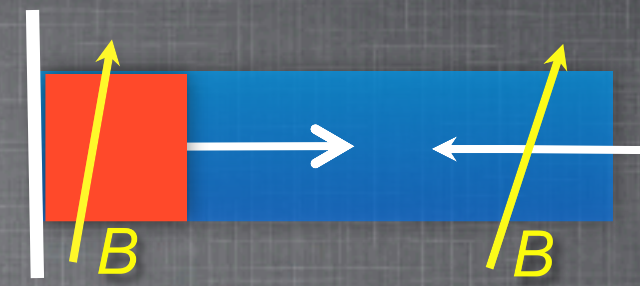
- Thin synchrotron-emitting rims observed in supernove remnants (SNRs)
- Electrons are accelerated to 100 TeV energies
- Cosmic Ray protons are inferred to be accelerated efficiently too (10-40% by energy, up to 10^{16} eV)
- Magnetic field is inferred to be amplified by more than compression at the shock (100 microG vs 3 microG in the ISM)
- Electrons and ions equilibrate post-shock (Te/Ti much larger than 1/1840)

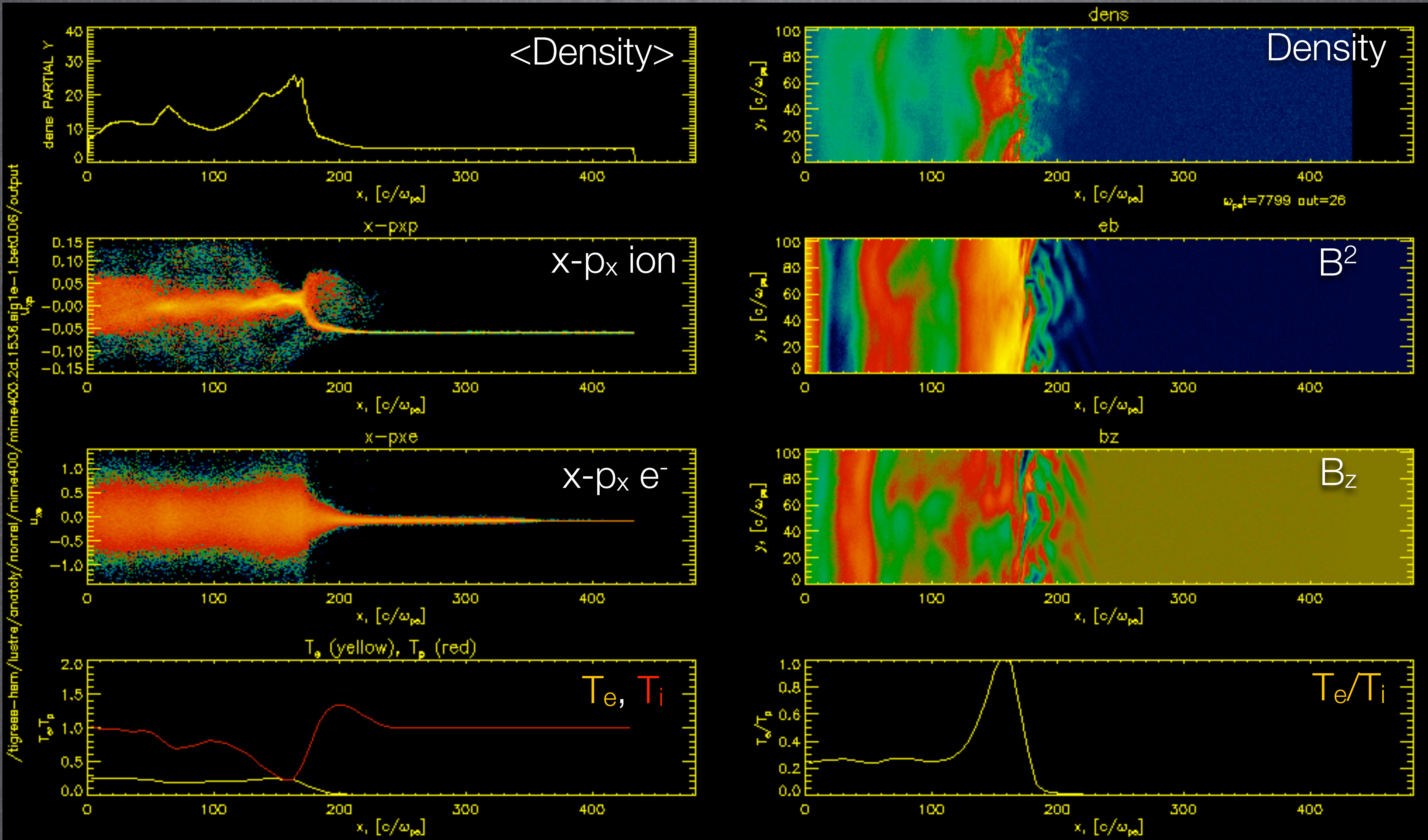


Electron and ion scales are more disparate than in relativistic shocks

Nonrelativistic shocks: shock structure

mi/me=400, v=18,000km/s, Ma=5, quasi-perp 75° inclination

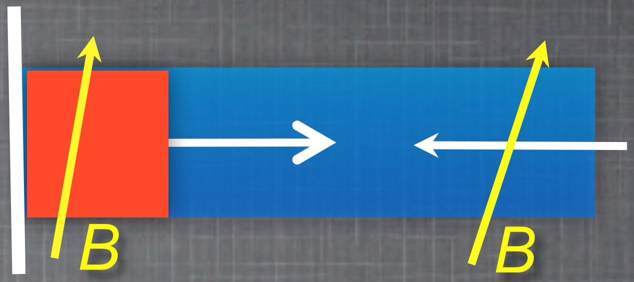


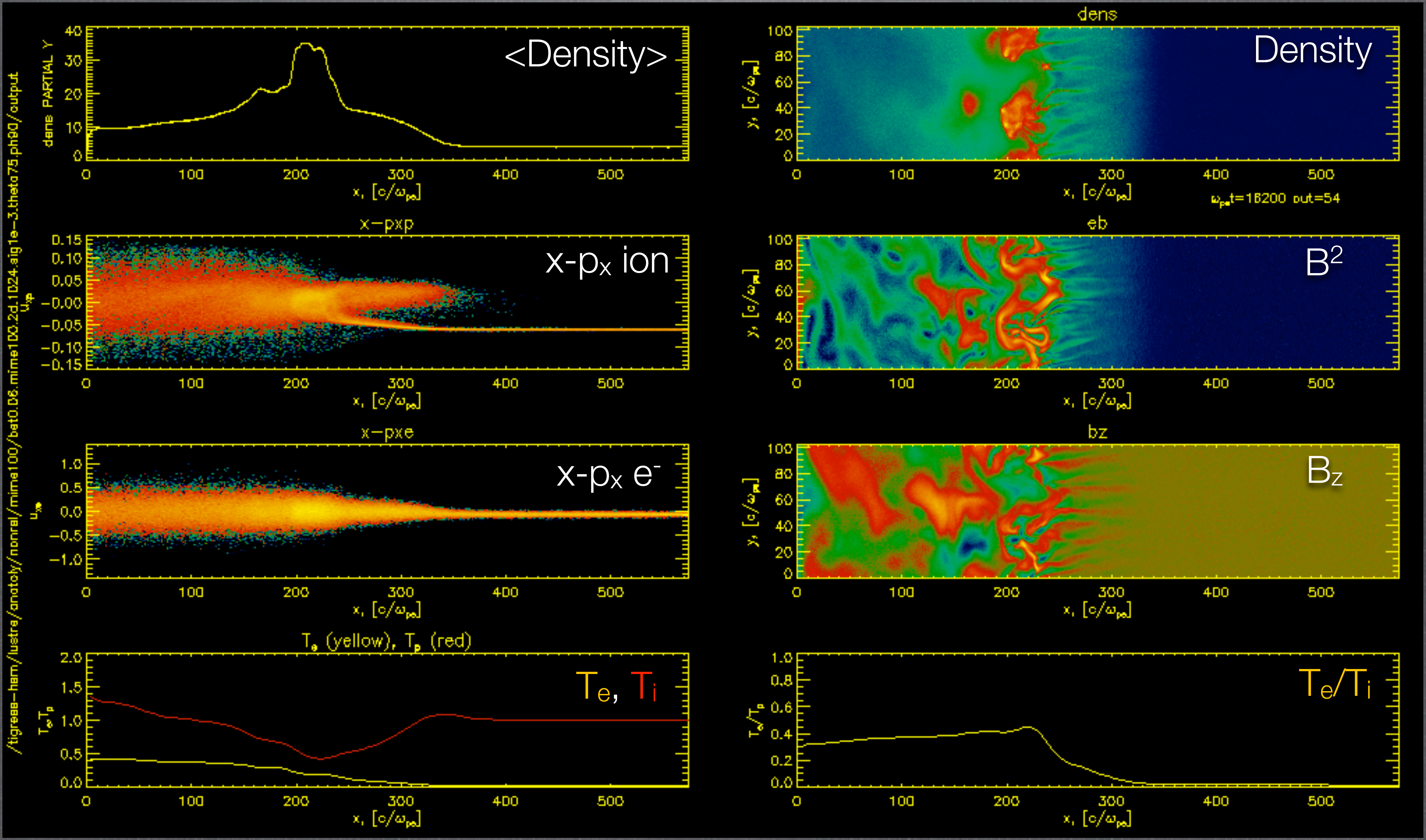


PIC simulation: Shock foot, ramp, overshoot, returning ions, electron heating, whistlers

Nonrelativistic shocks: shock structure

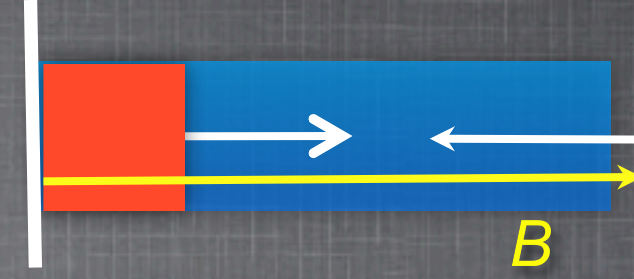
mi/me=100, v=18,000km/s, Ma=45 quasi-perp 75° inclination

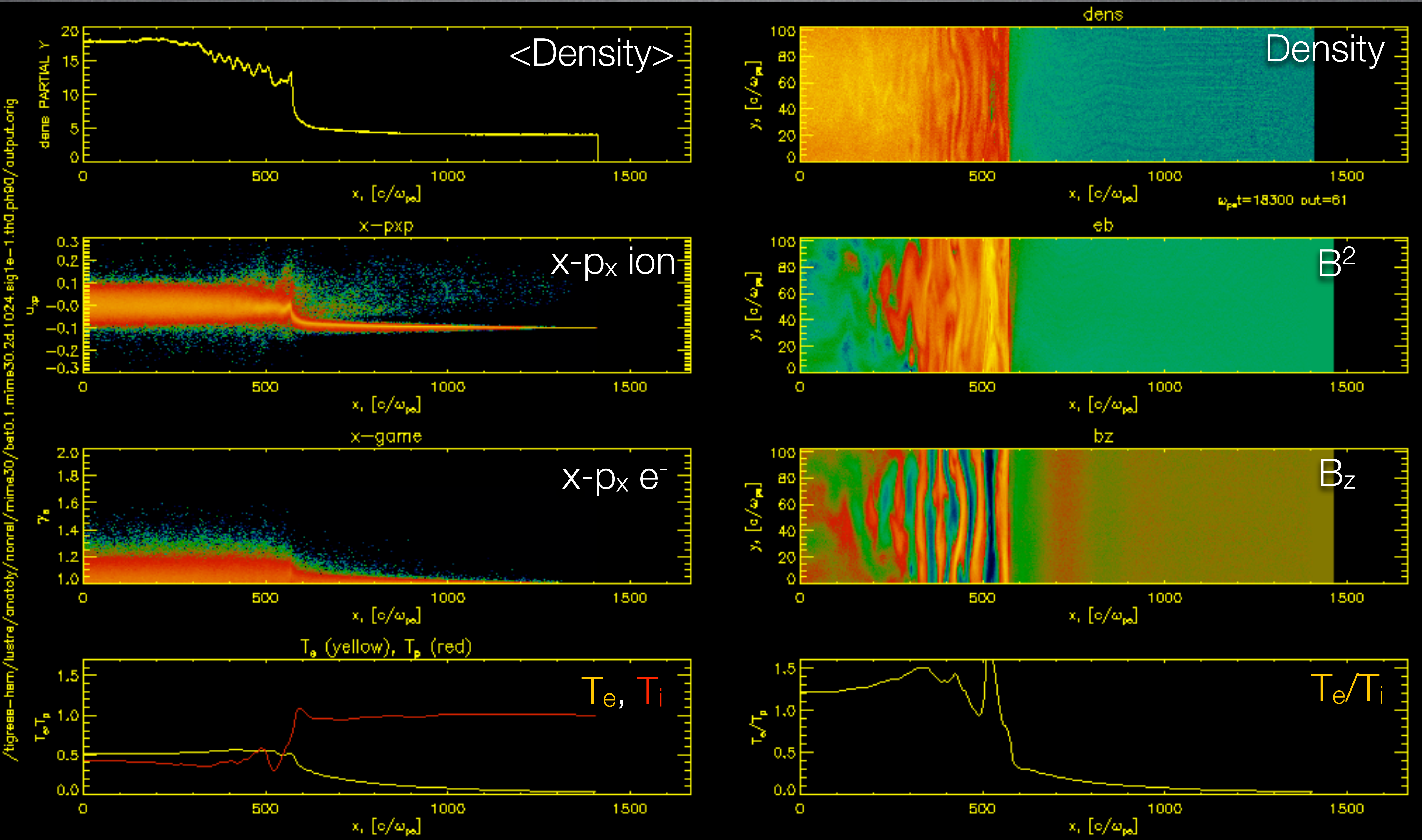




Nonrelativistic shocks: quasiparallel shock

mi/me=30, v=30,000km/s, Ma=5 parallel 0° inclination





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)

Generically, parallel shocks are good for ion and electron acceleration, while perpendicular shocks mainly accelerate electrons.

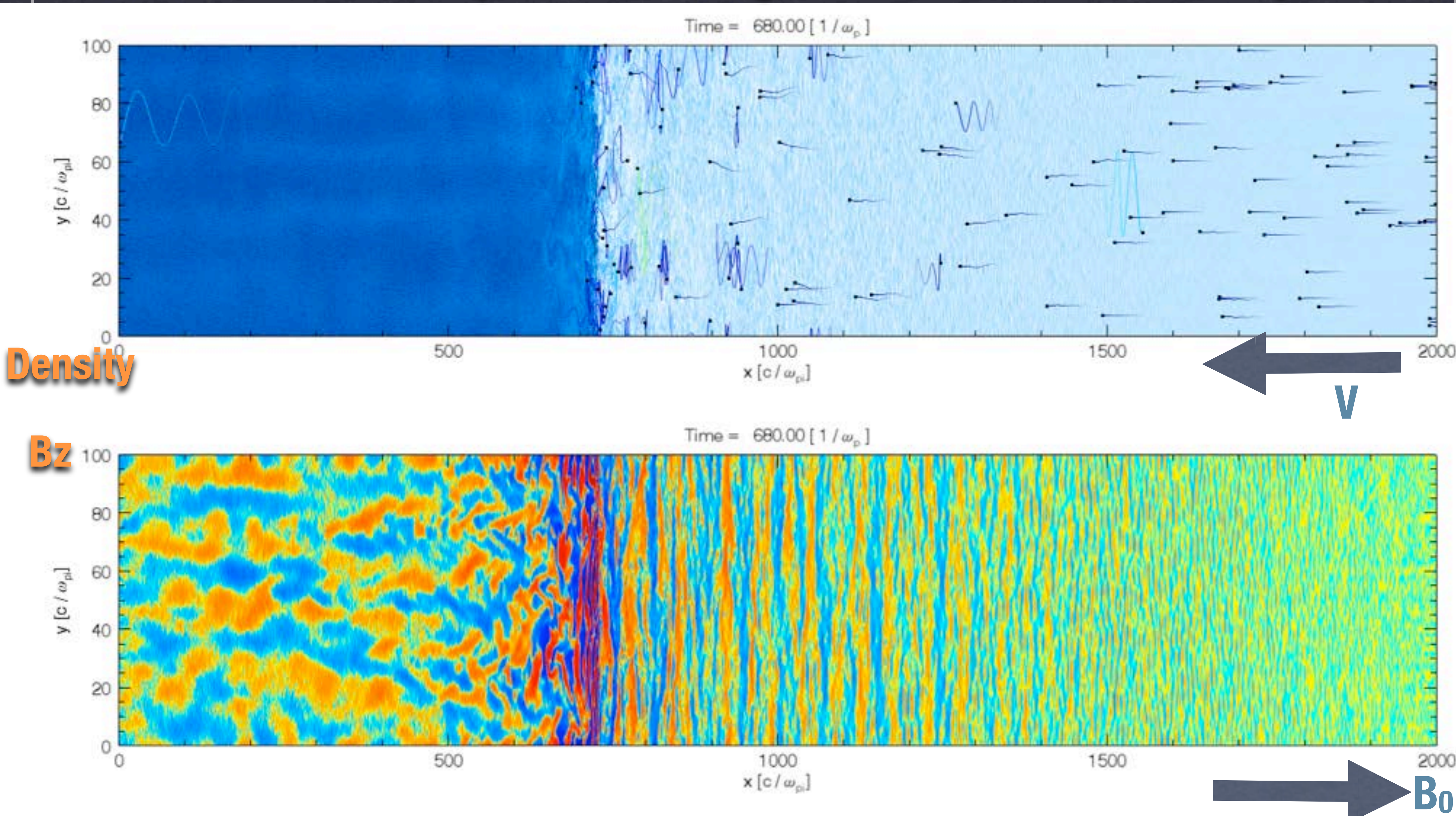
What accelerates ions?

results of non relativistic hybrid simulations
simulations that are sufficiently long to see
nonlinear effects and full acceleration process

Caprioli & Spitkovsky 2014a,b,c

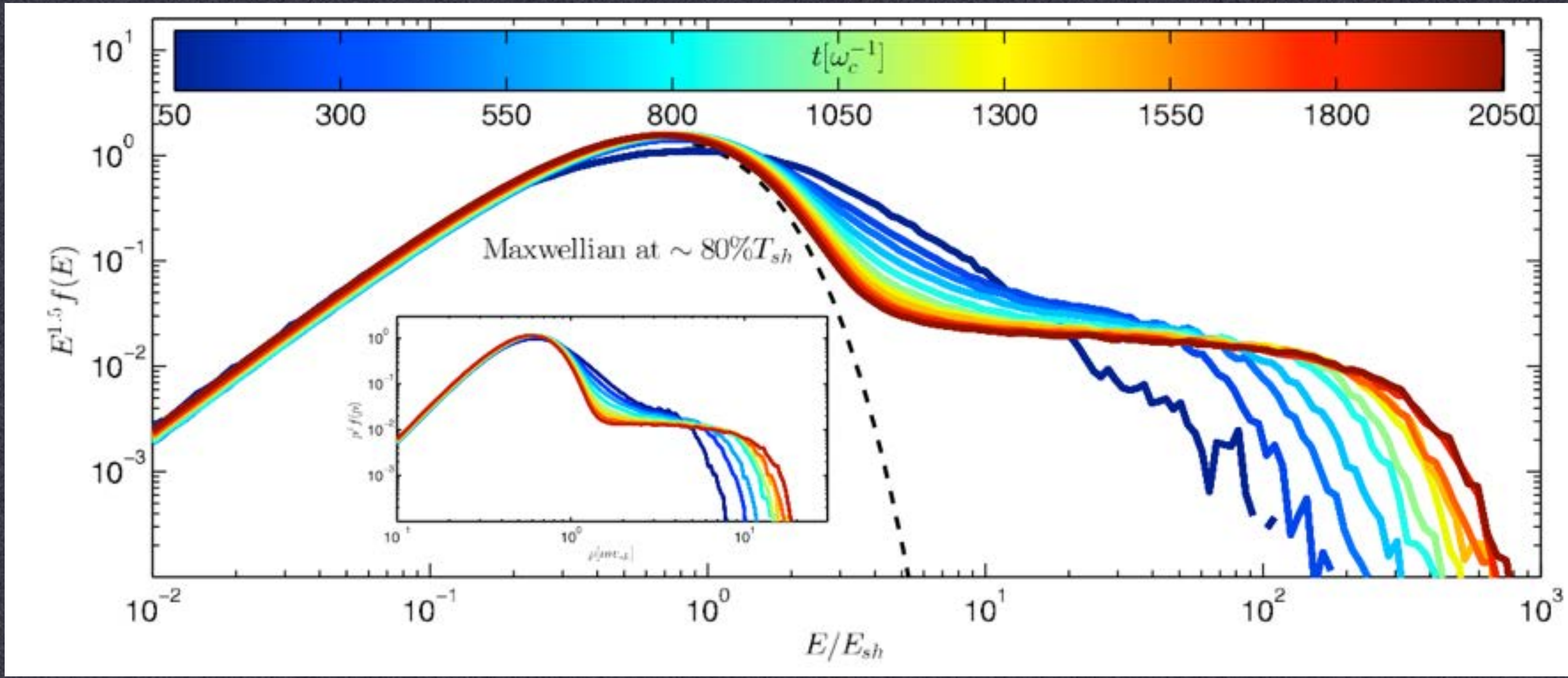
Ion acceleration

M_A=3.1, parallel shock; hybrid simulation. Quasi-parallel shocks accelerate ions and produce self-generated waves in the upstream.



Ion spectrum

Long term evolution: DSA spectrum recovered



First-order Fermi acceleration: $f(p) \propto p^{-4}$ $4\pi p^2 f(p) dp = f(E) dE$

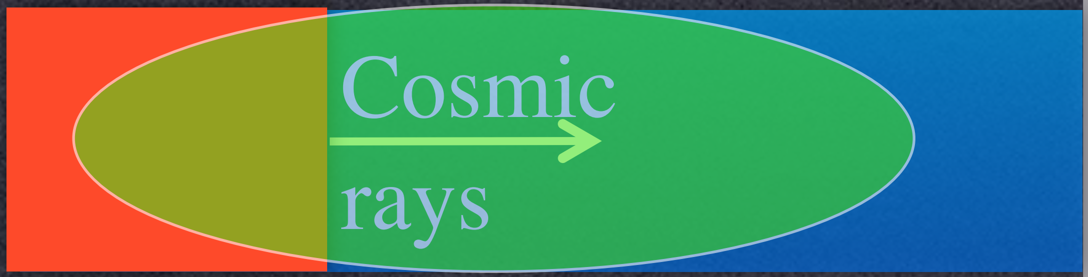
$f(E) \propto E^{-2}$ (relativistic) $f(E) \propto E^{-1.5}$ (non-relativistic)

CR backreaction is affecting downstream temperature

Caprioli & Spitkovsky 2014a

Field amplification

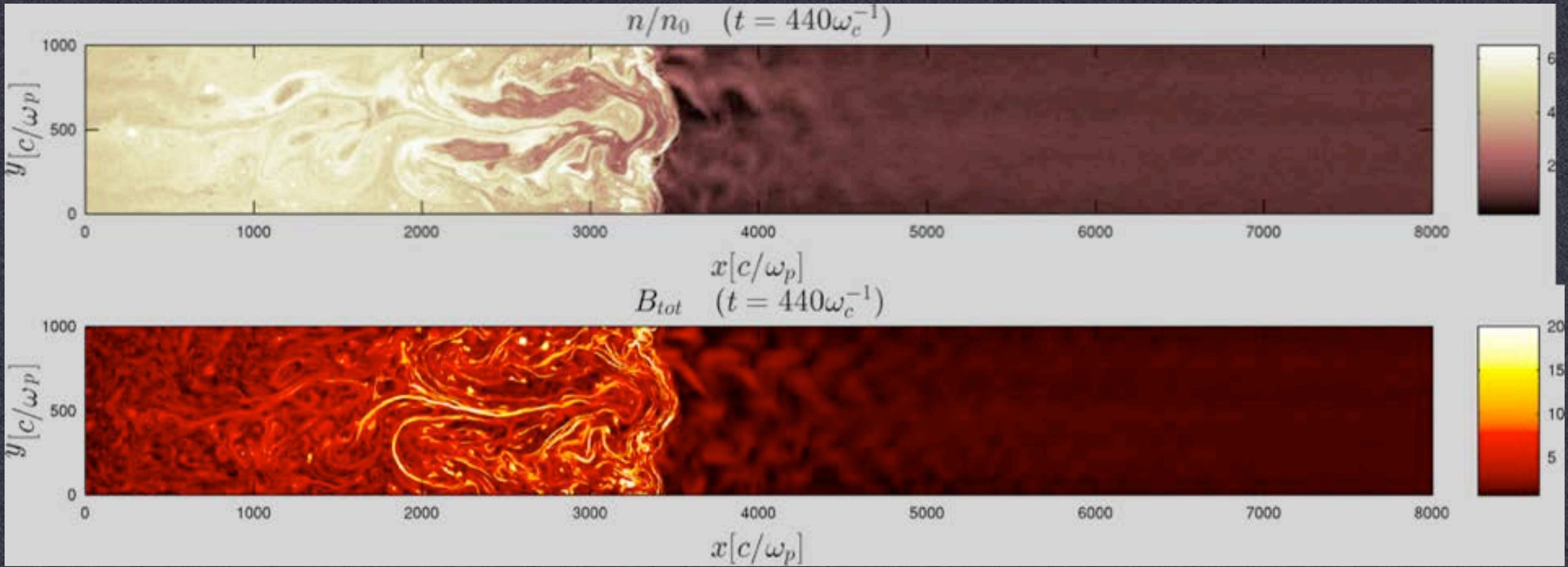
We see evidence of CR effect on upstream.



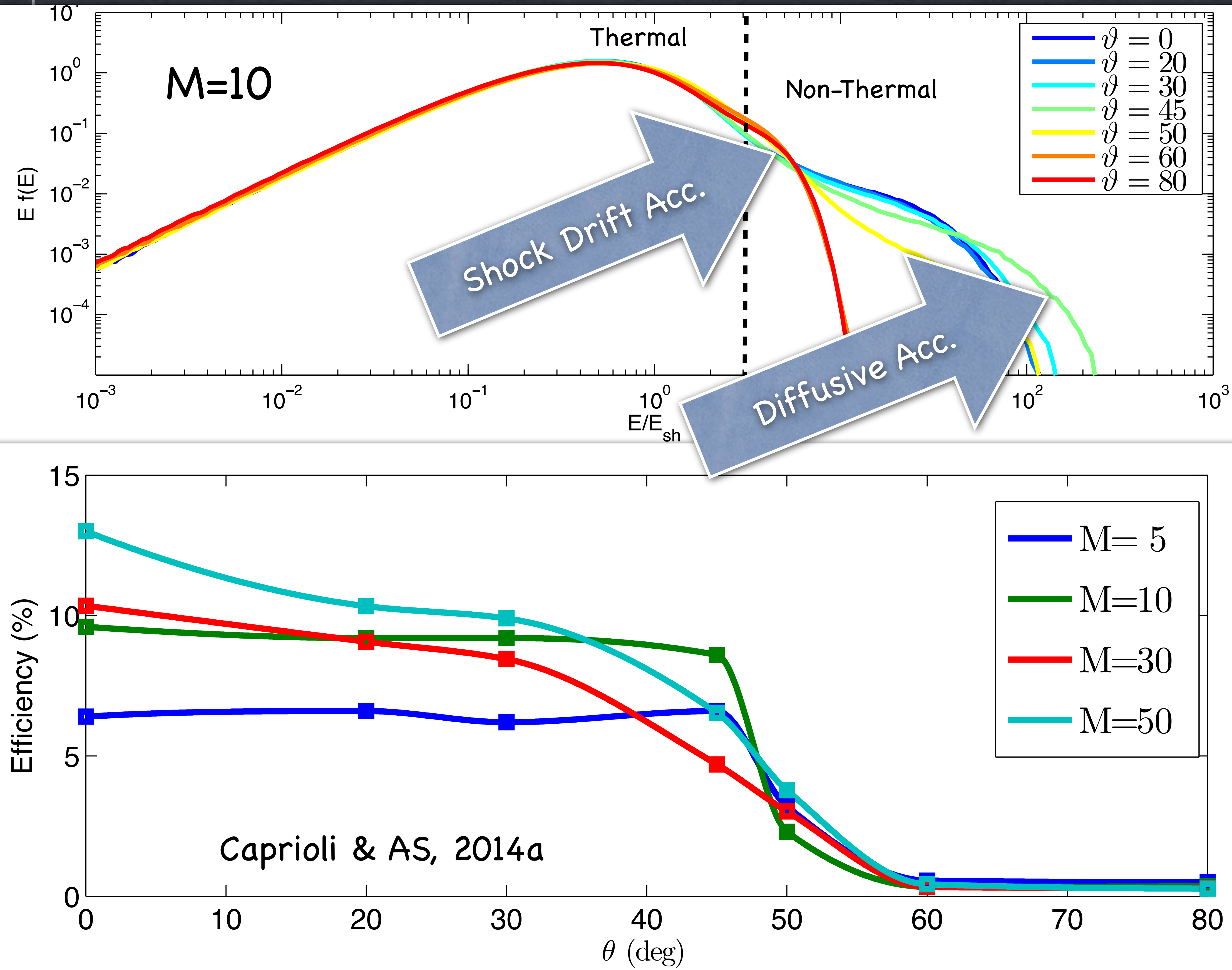
Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

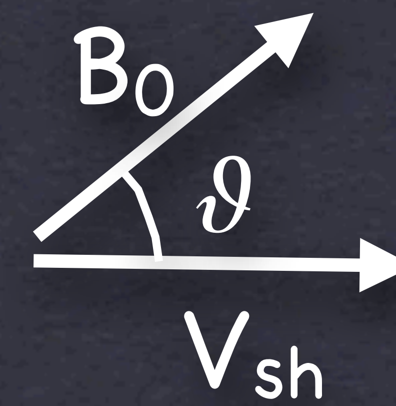
This will lead to “turbulent” shock with effectively lower Alfvenic Mach number with locally 45 degree inclined fields.

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



Parallel vs Oblique shocks

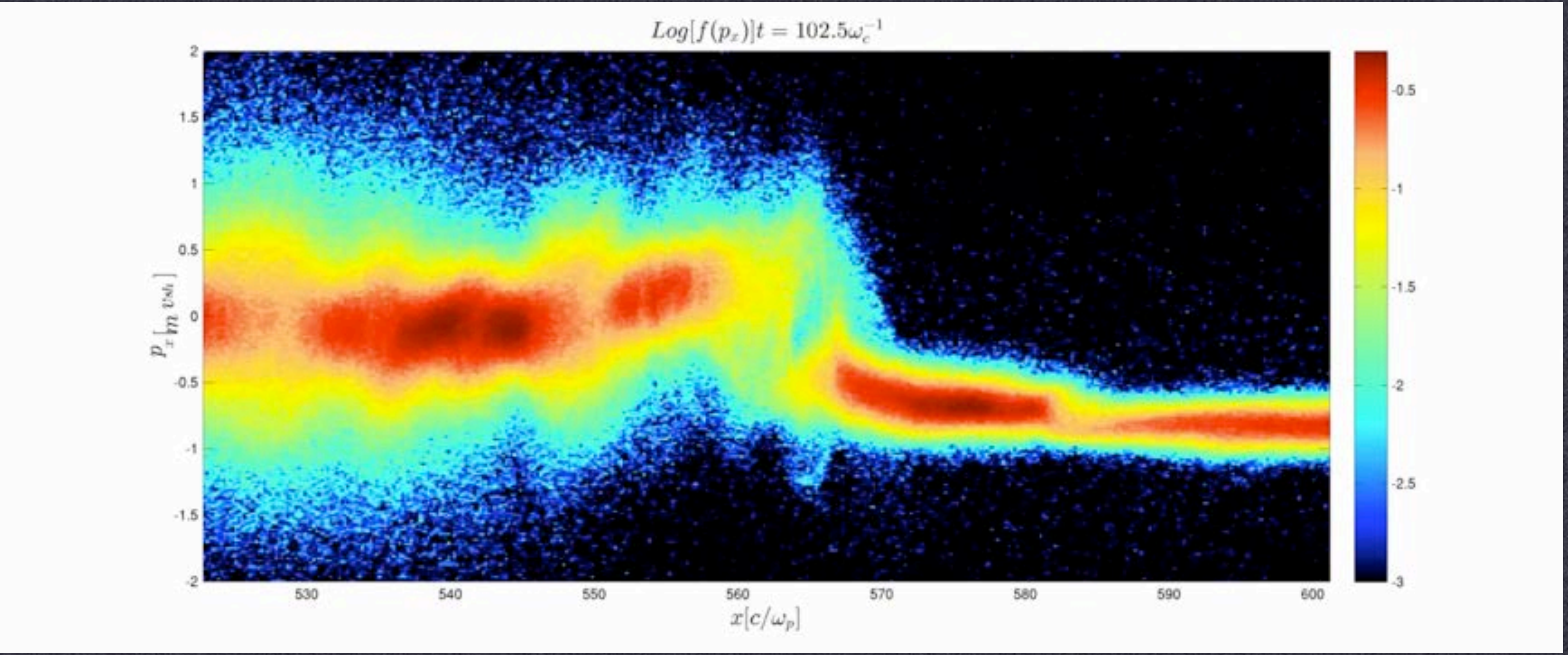




About 1% accelerated ions by number, what is causing that?

Shock structure & injection

Quasiparallel shocks look like intermittent quasiperp shocks

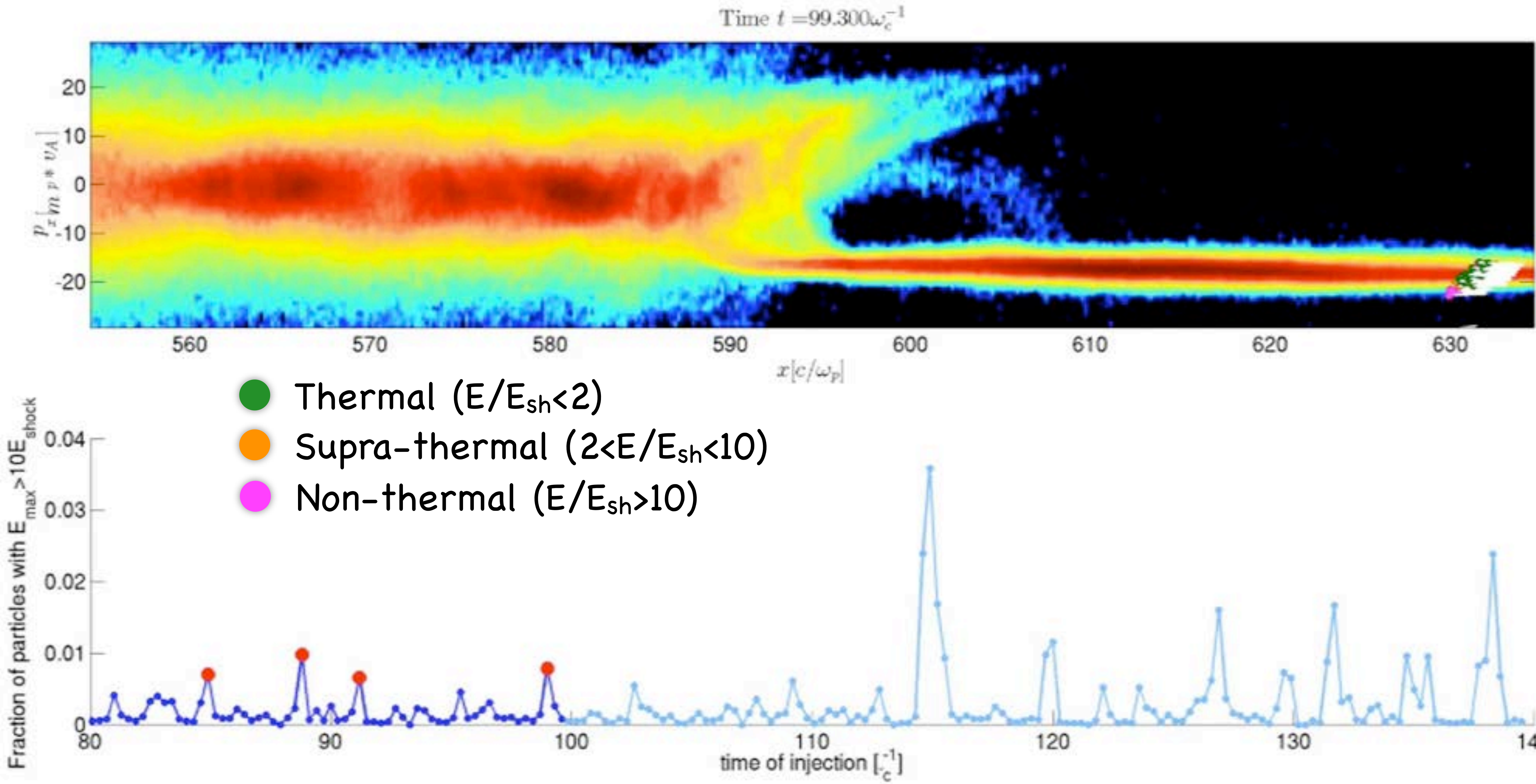


Injection of ions happens on first crossing due to specular reflection from barrier and shock-drift acceleration.

Multiple cycles in a time-dependent shock structure result in injection into DSA; no "thermal leakage" from downstream.

Injection mechanism: importance of timing

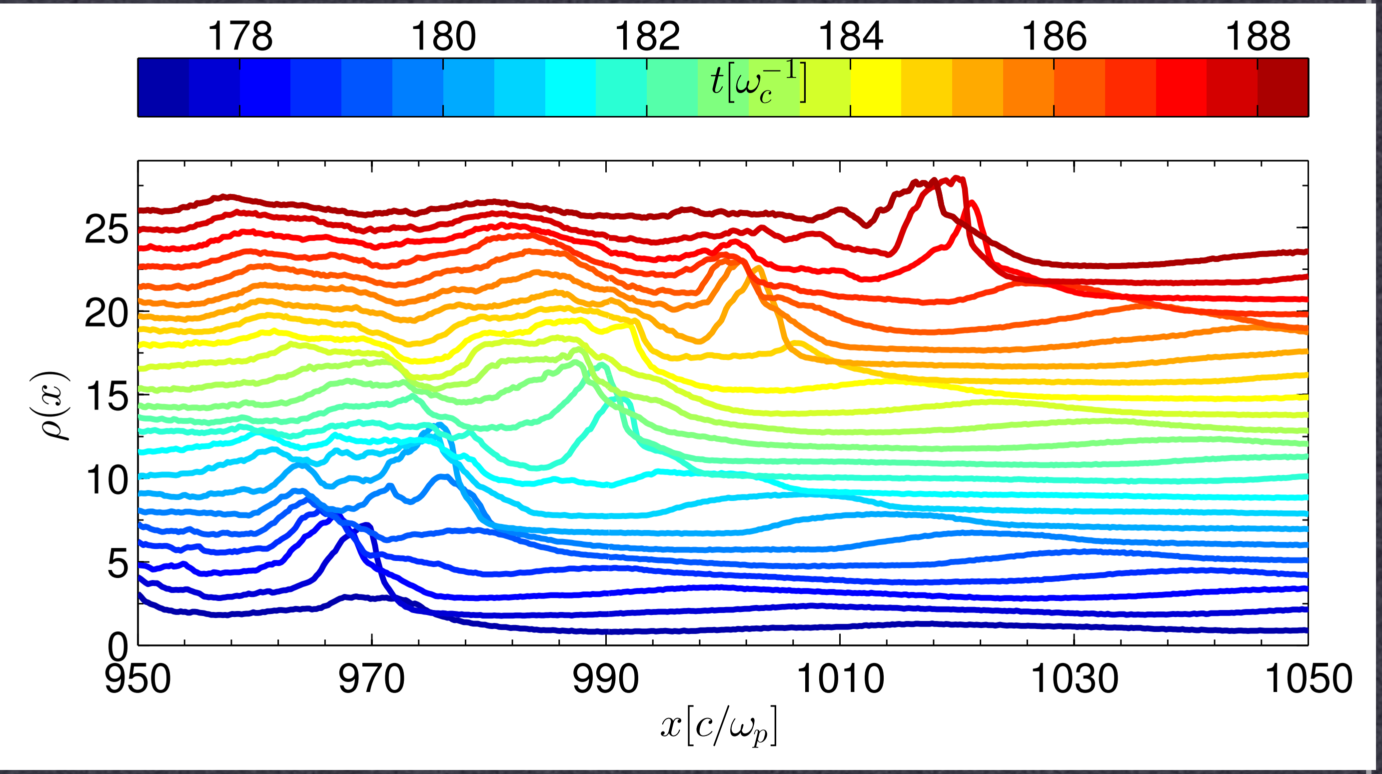
Caprioli, Pop & AS 2015



Ion injection: theory

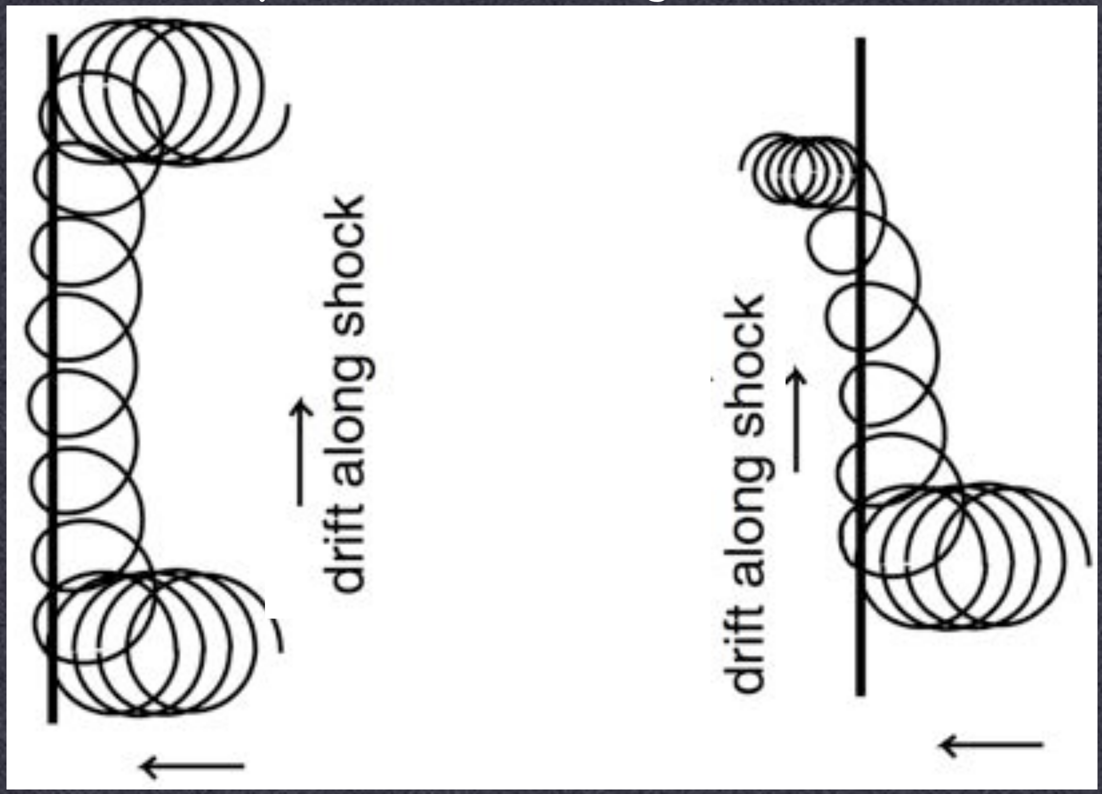
Caprioli, Pop & AS 2015

- Reflection off the shock potential barrier (stationary in the downstream frame)
- For reflection into upstream, particle needs certain minimal energy for given shock inclination;
- Particles first gain energy via shock-drift acceleration (SDA)
- Several cycles are required for higher shock obliquities



Shock-drift acceleration:

downstream upstream Larger B Smaller B

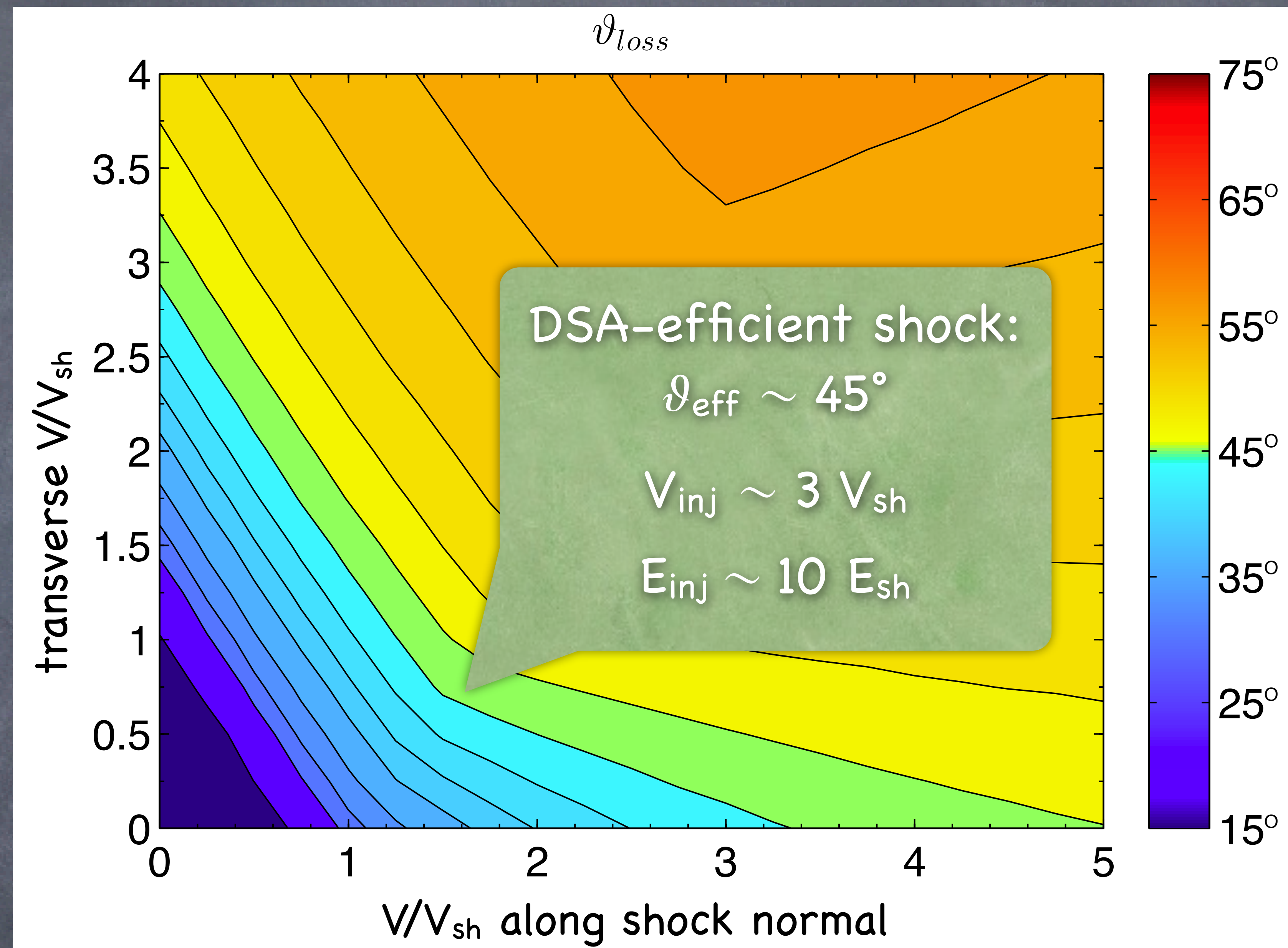


Path of incoming particle

Ion Injection - Theory

- Ion fate determined by
  - barrier duty-cycle (∼25%)
  - pre-reflection V
  - shock inclination
- If $\vartheta<\vartheta_{loss}$, ions escape upstream, and are injected into DSA
- Otherwise, they experience SDA, return to the shock (with larger V), and may be either reflected or advected
  - After N SDA cycles, only a fraction $\eta \sim 0.25^N$ survives
  - For $\vartheta_{eff} \sim 45°$, N∼3 -> $\eta \sim 1\%$

Max ϑ allowing reflection upstream



DC, Pop & Spitkovsky, 2015

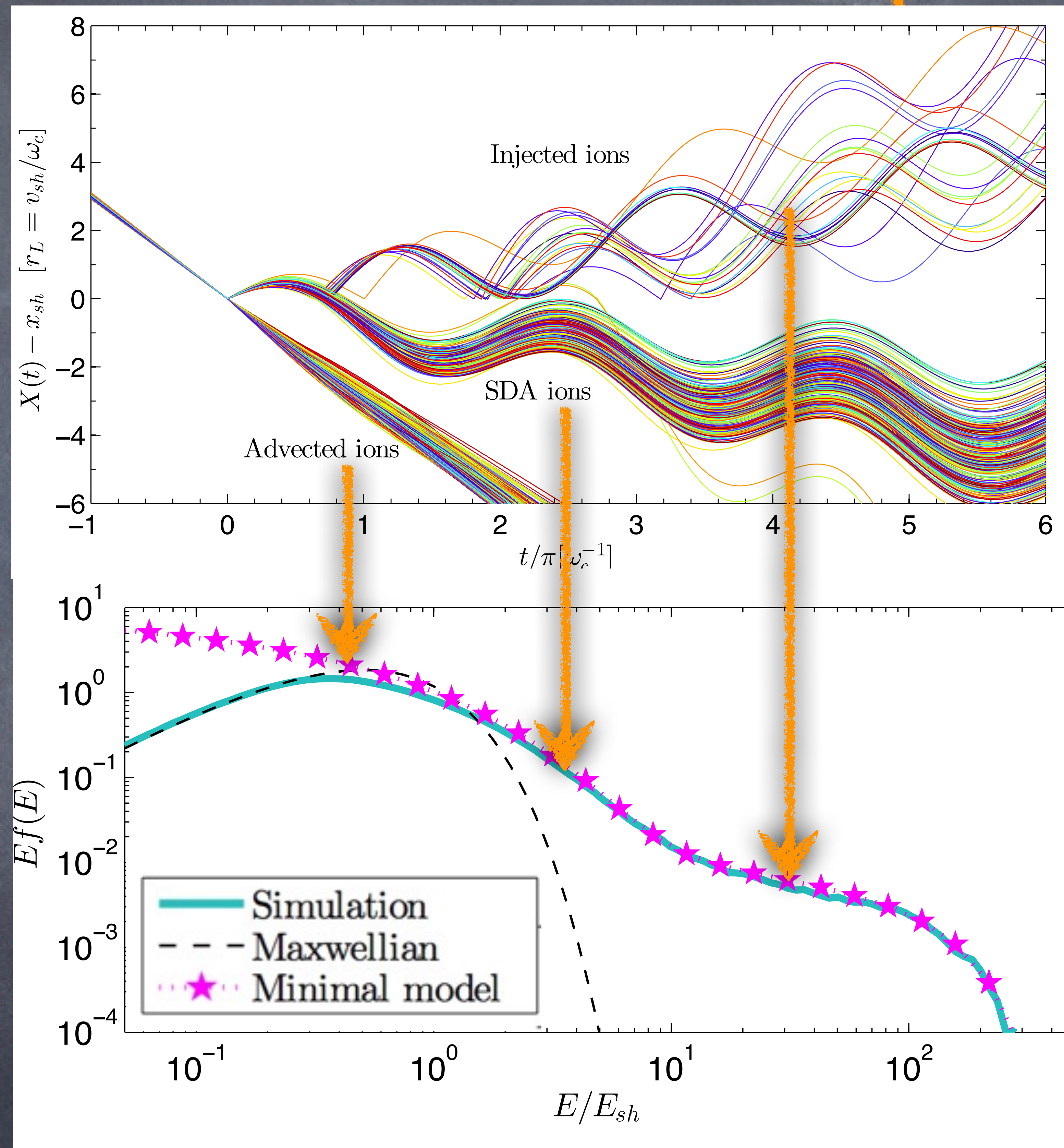
E_{inj} is larger at oblique shocks: injection requires more SDA cycles, and fewer particles can achieve E_{inj}

Minimal Model for Ion Injection

- Time-varying potential barrier
    - **High state** (duty cycle 25%)
      -> Reflection
      -> Shock Drift Acceleration
    - **Low-state** -> Thermalization
- Spectrum à la Bell (1978)

$$f(E) \propto E^{-1-\gamma}; \quad \gamma \equiv -\frac{\ln(1-\mathcal{P})}{\ln(1+\mathcal{E})}$$

- P=probability of being advected
- ε =fractional energy gain/cycle



Caprioli, Pop & Spitkovsky, 2015

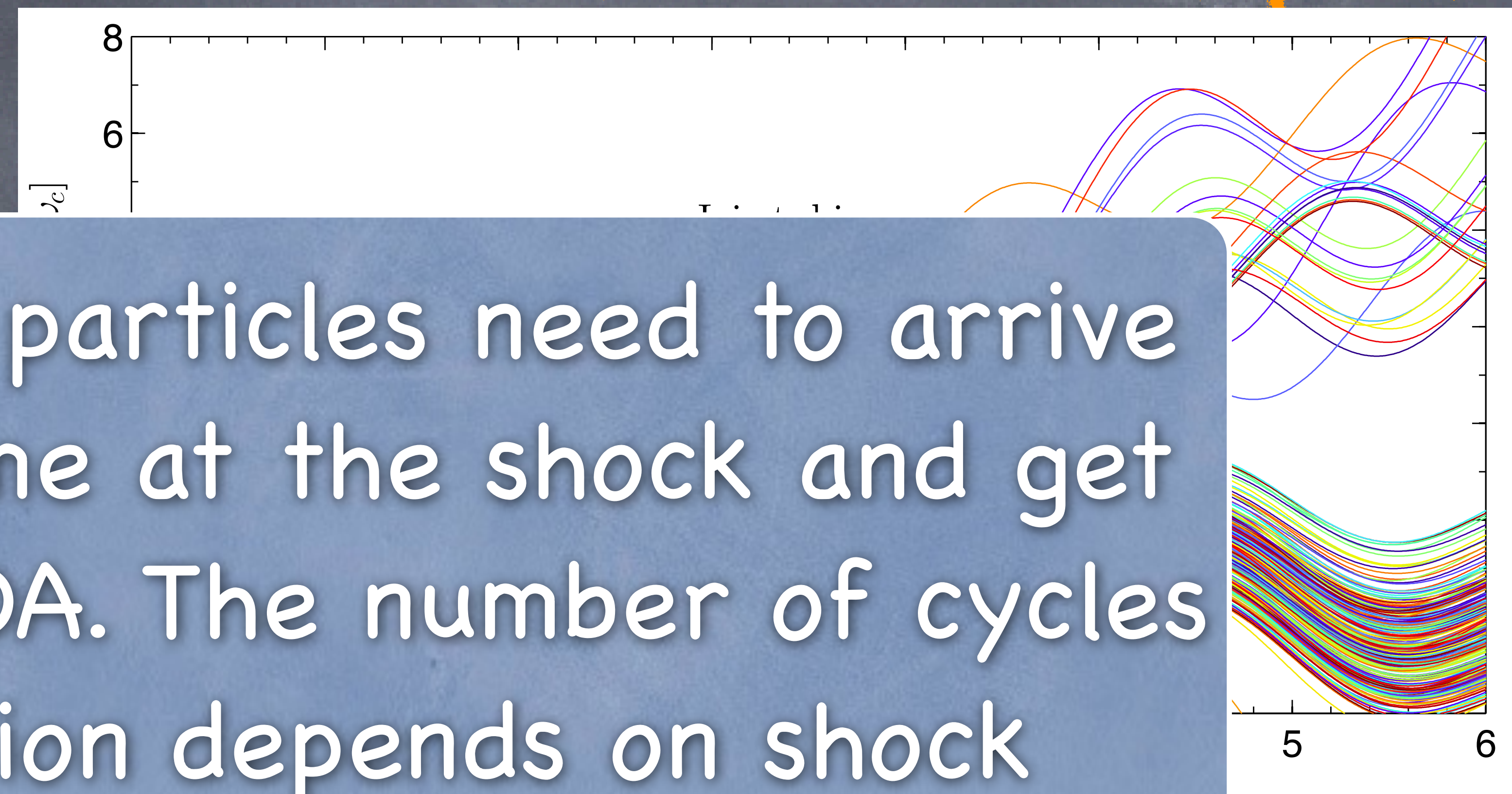
Minimal Model for Ion Injection

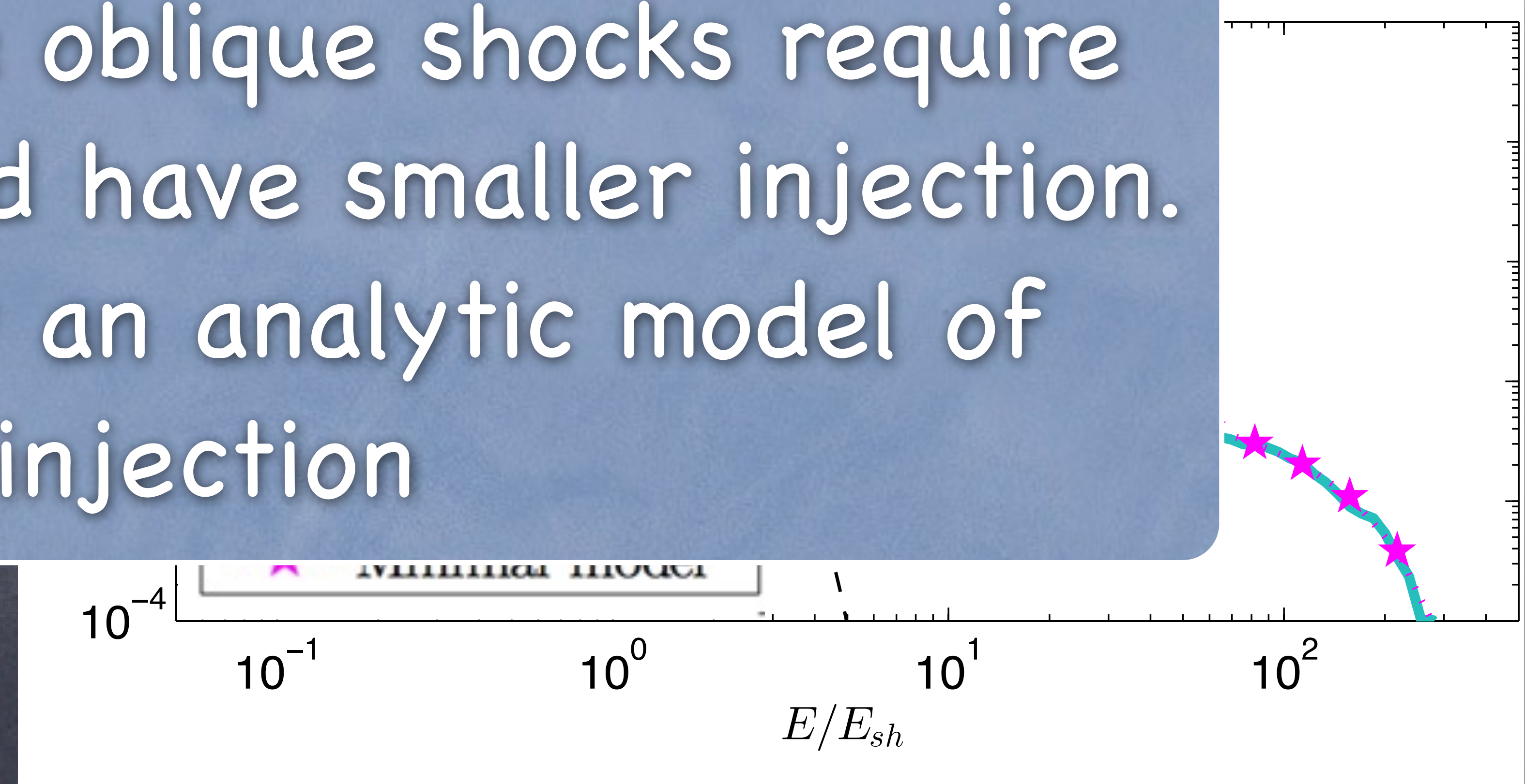
- Time-varying potential barrier
  - Hi
    ->
    ->
  - L
- Spec

$f(E)$

- P=pr
  advected
- ε =fractional energy gain/cycle

To be injected, particles need to arrive at the right time at the shock and get energized by SDA. The number of cycles of energization depends on shock obliquity. More oblique shocks require more cycles, and have smaller injection. There is now an analytic model of injection





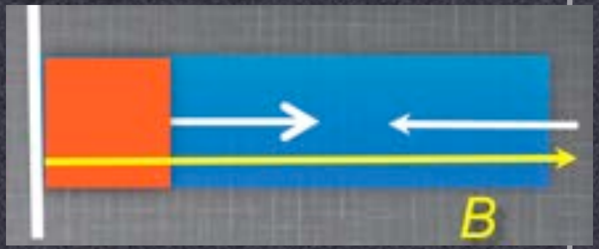
Caprioli, Pop & Spitkovsky, 2015

What accelerates electrons?

results of full PIC simulations simulations

Park, Caprioli & AS 2015

Electron acceleration at parallel shocks



Recent evidence of electron acceleration in quasi parallel shocks.
PIC simulation of quasiparallel shock. Very long simulation in 1D.

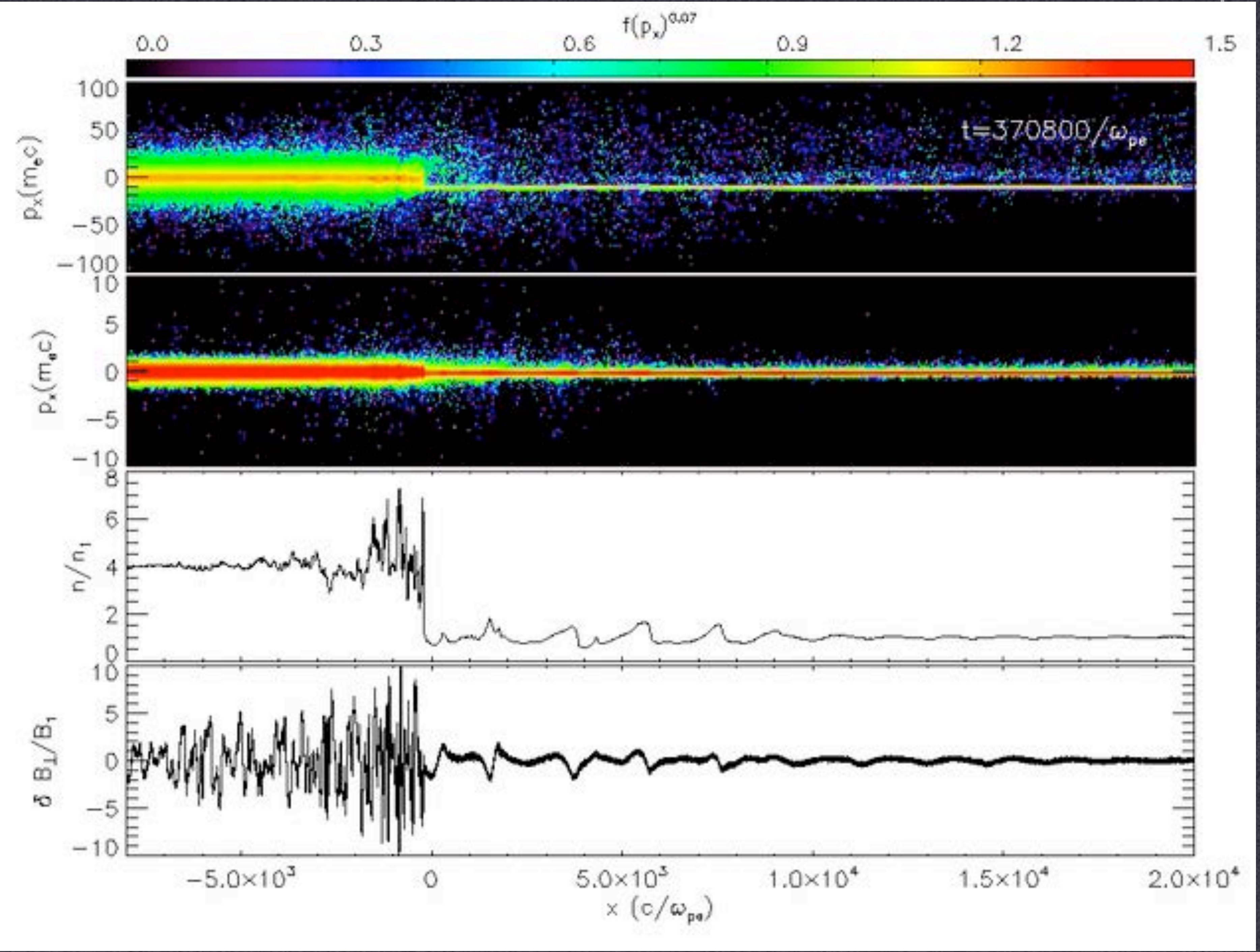
Ion-driven Bell waves drive electron acceleration: correct polarization

Phase space ions

Phase space electrons

Density

Transverse Magnetic field



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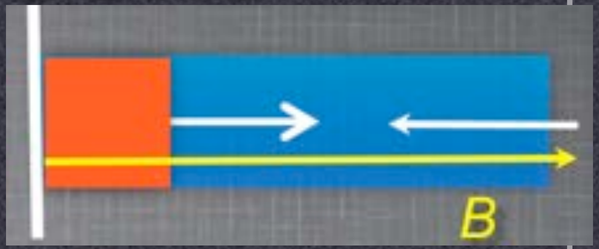

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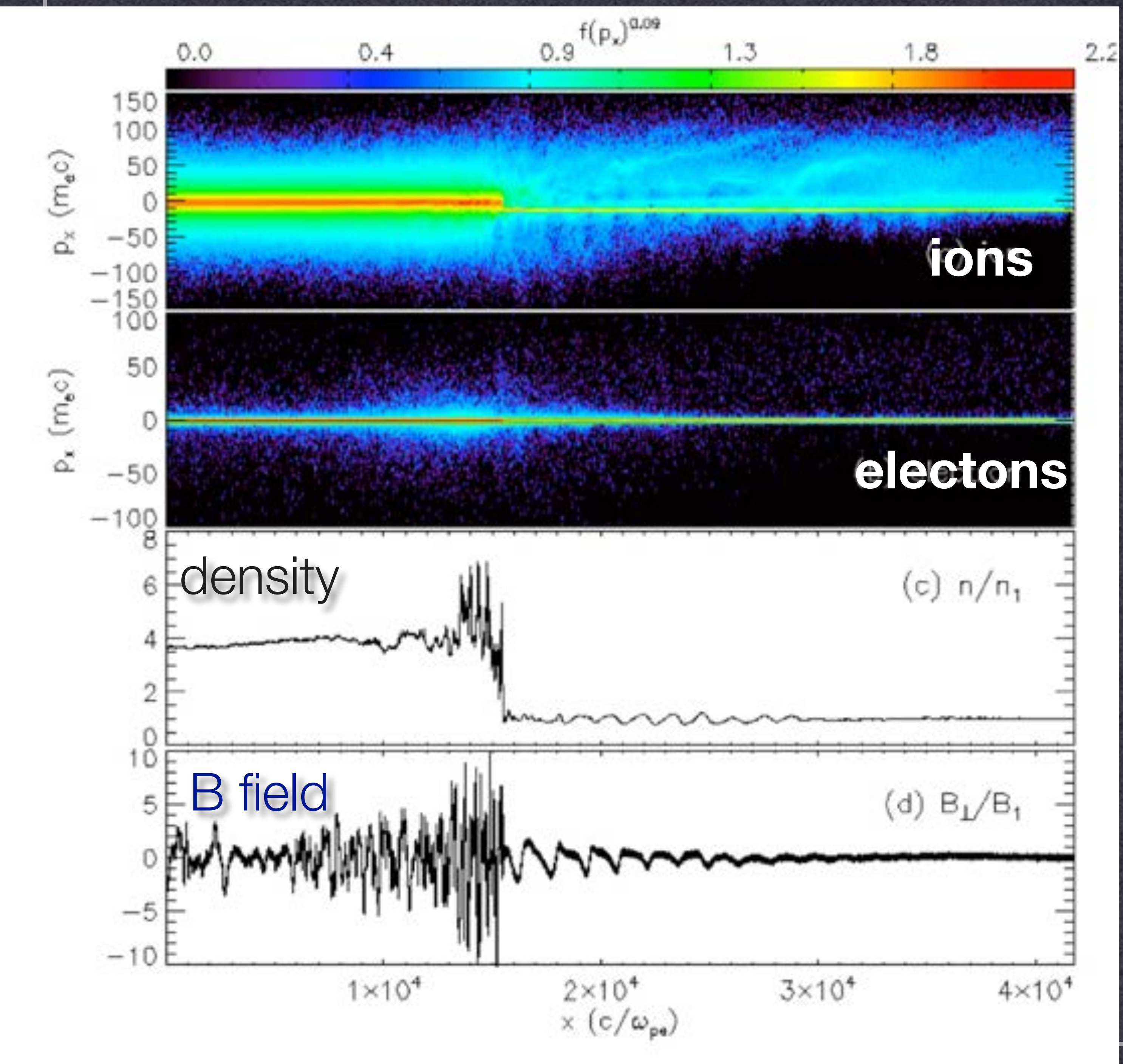
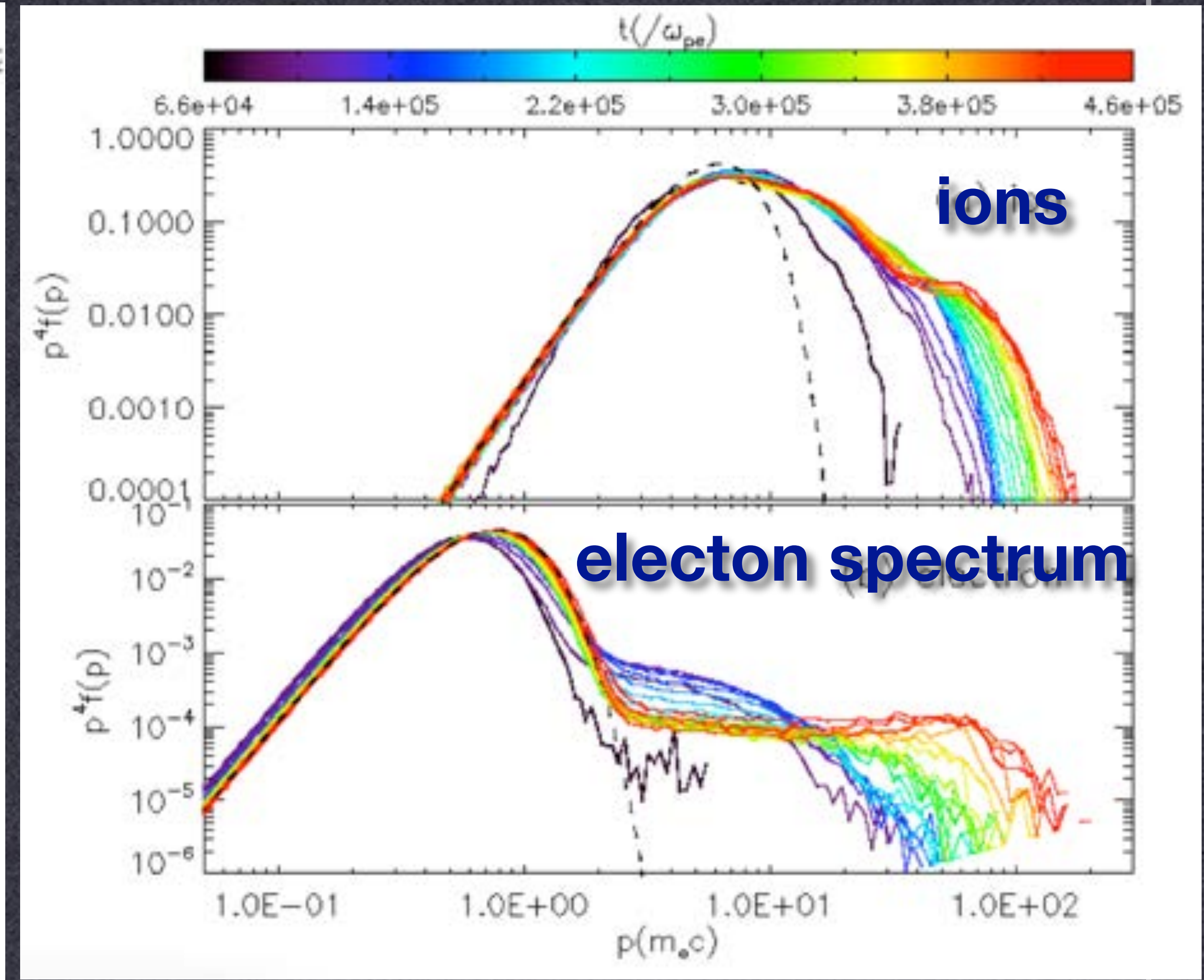


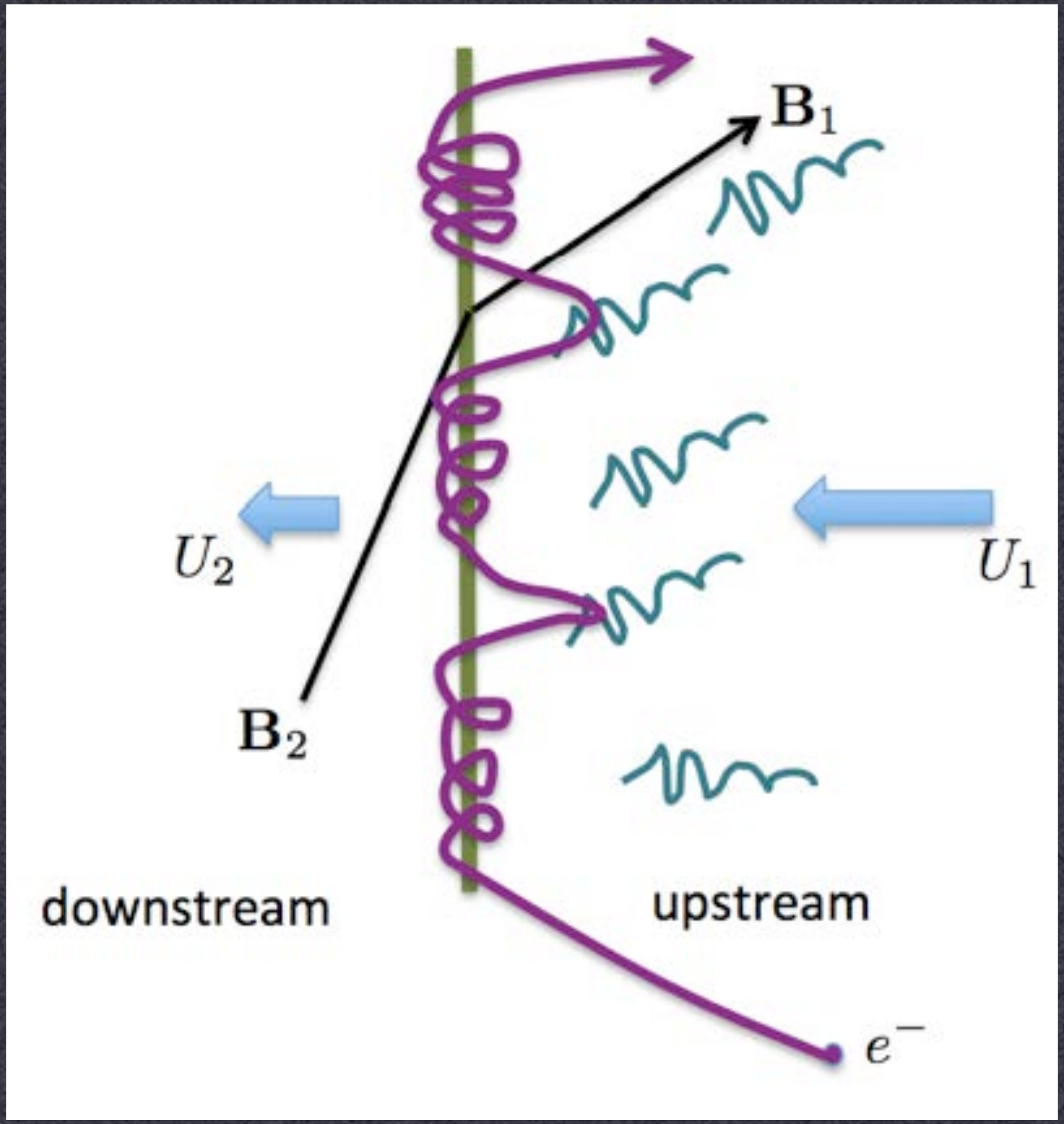


DSA spectrum recovered in _both_ electrons and ions
Electron-proton ratio can be measured!

Park, Caprioli, AS (2015)

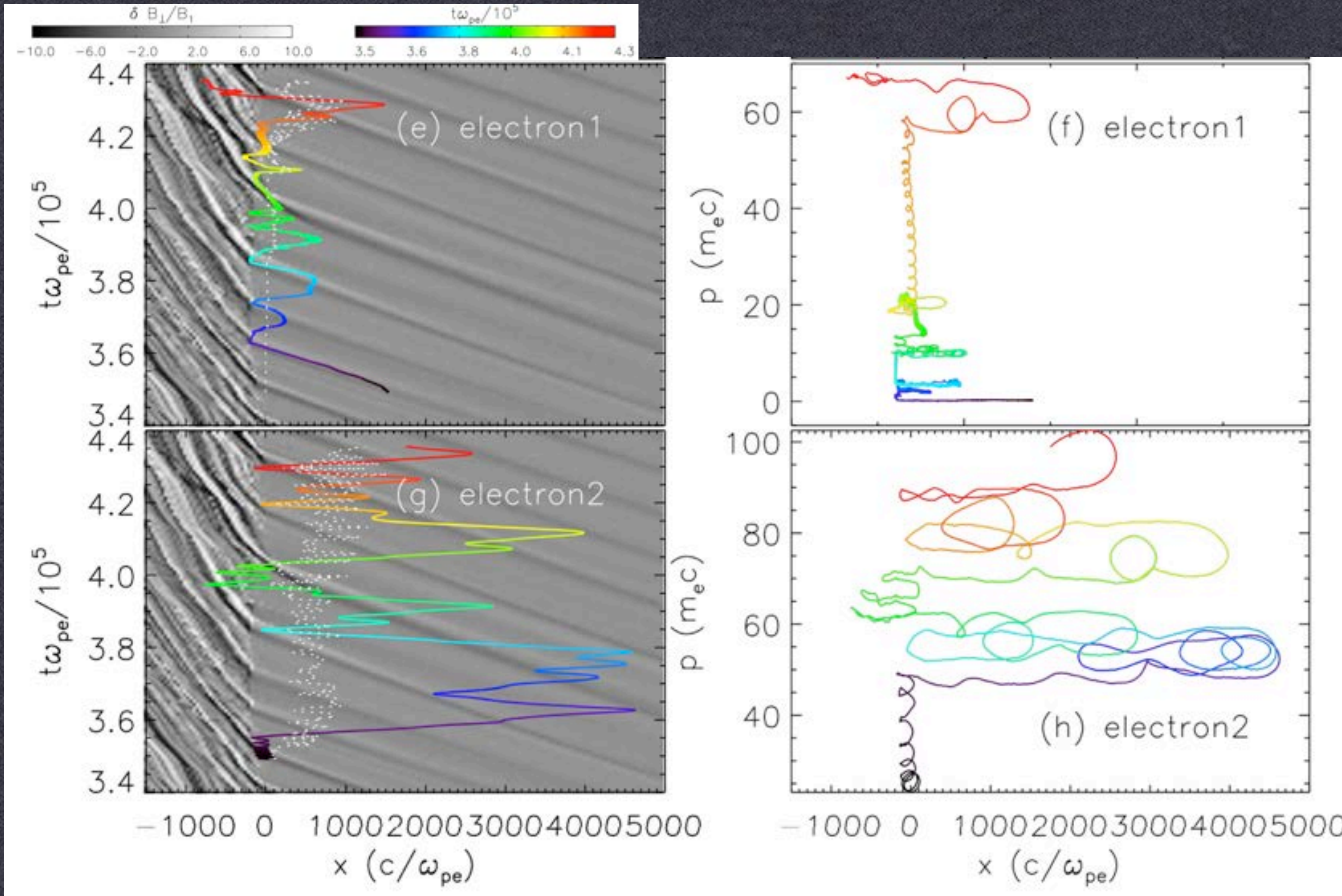
Electron acceleration at parallel shocks

Multi-cycle shock-drift acceleration, with electrons returning back due to upstream ion-generated waves.



Park, Caprioli, AS (2015)

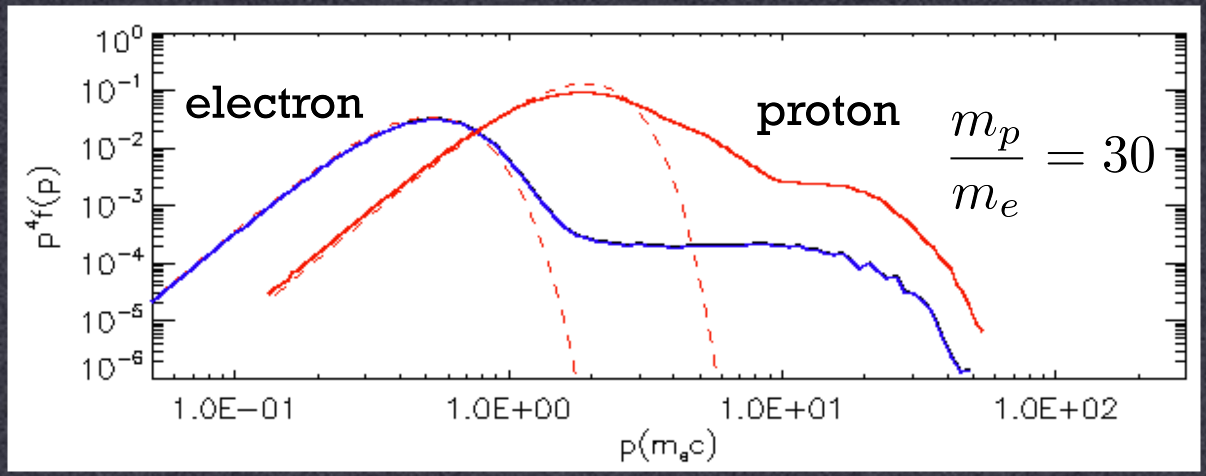
Electron acceleration mechanism: shock drift cycles

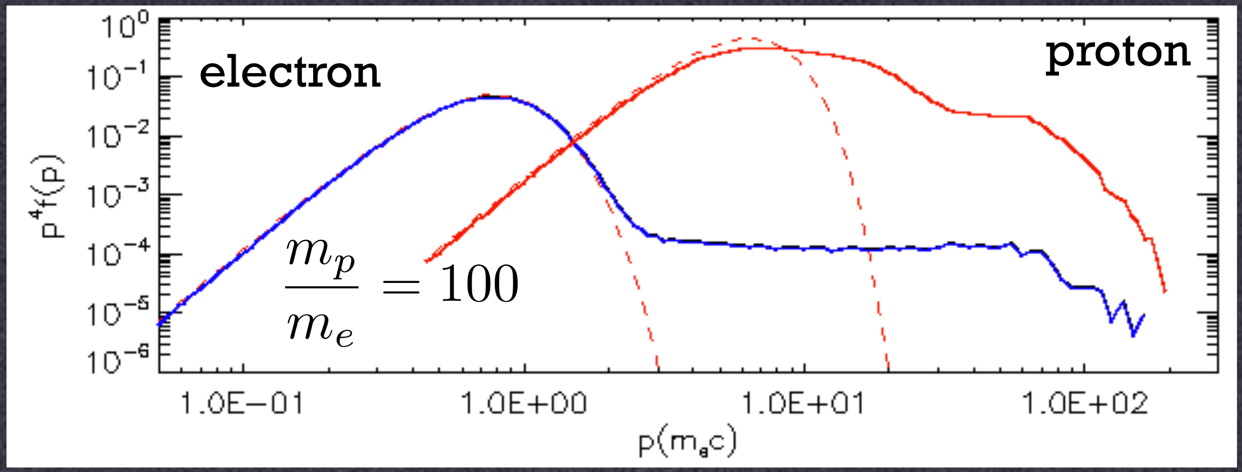


Electron track from our PIC simulation.

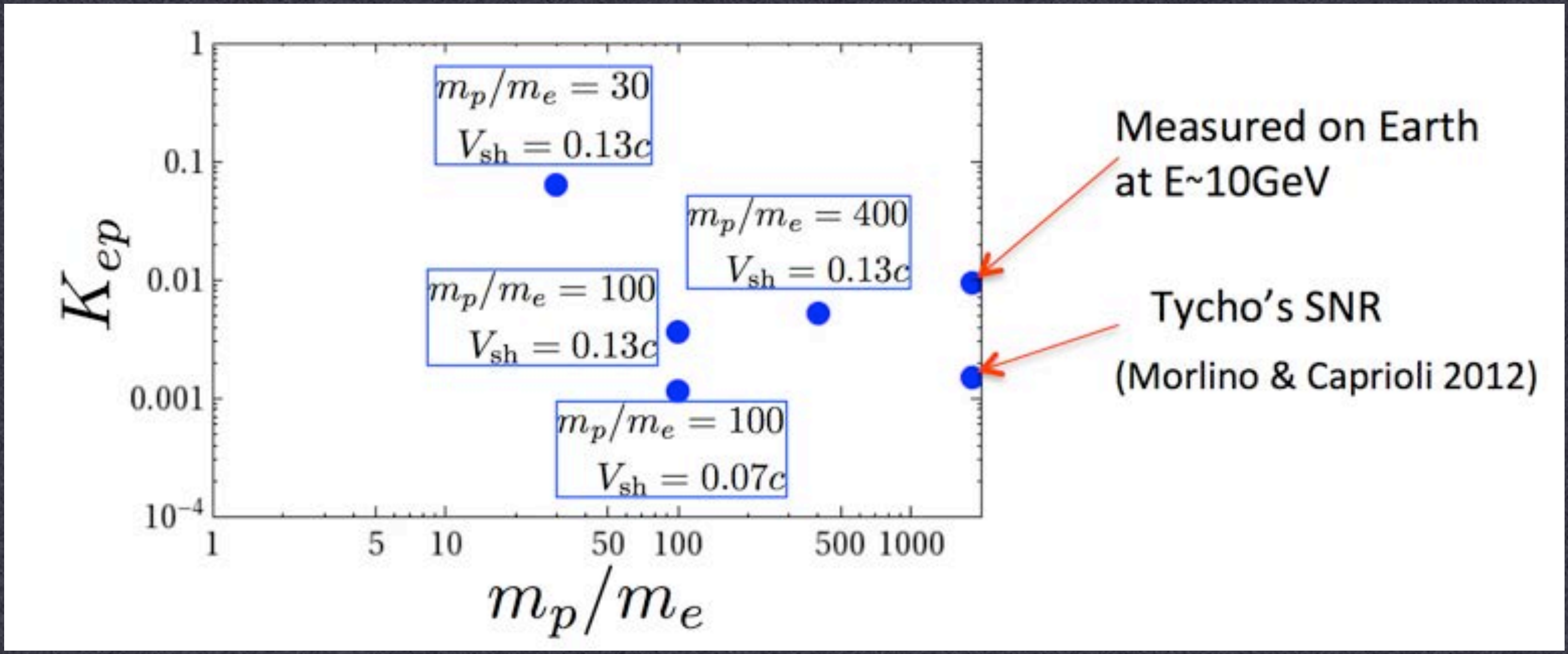
Park, Caprioli, AS (2015)

Electron-proton ratio K_{ep}:



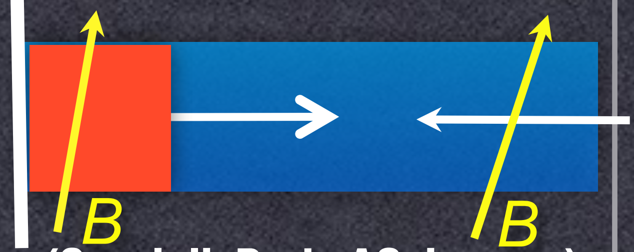


$$K_{\rm ep} \equiv \frac{f_e(p)}{f_p(p)} = \text{const for } p > p_{\rm inj} \quad K_{\rm ep} \approx 3.8 \times 10^{-3} \text{ for } \frac{m_p}{m_e} = 100$$

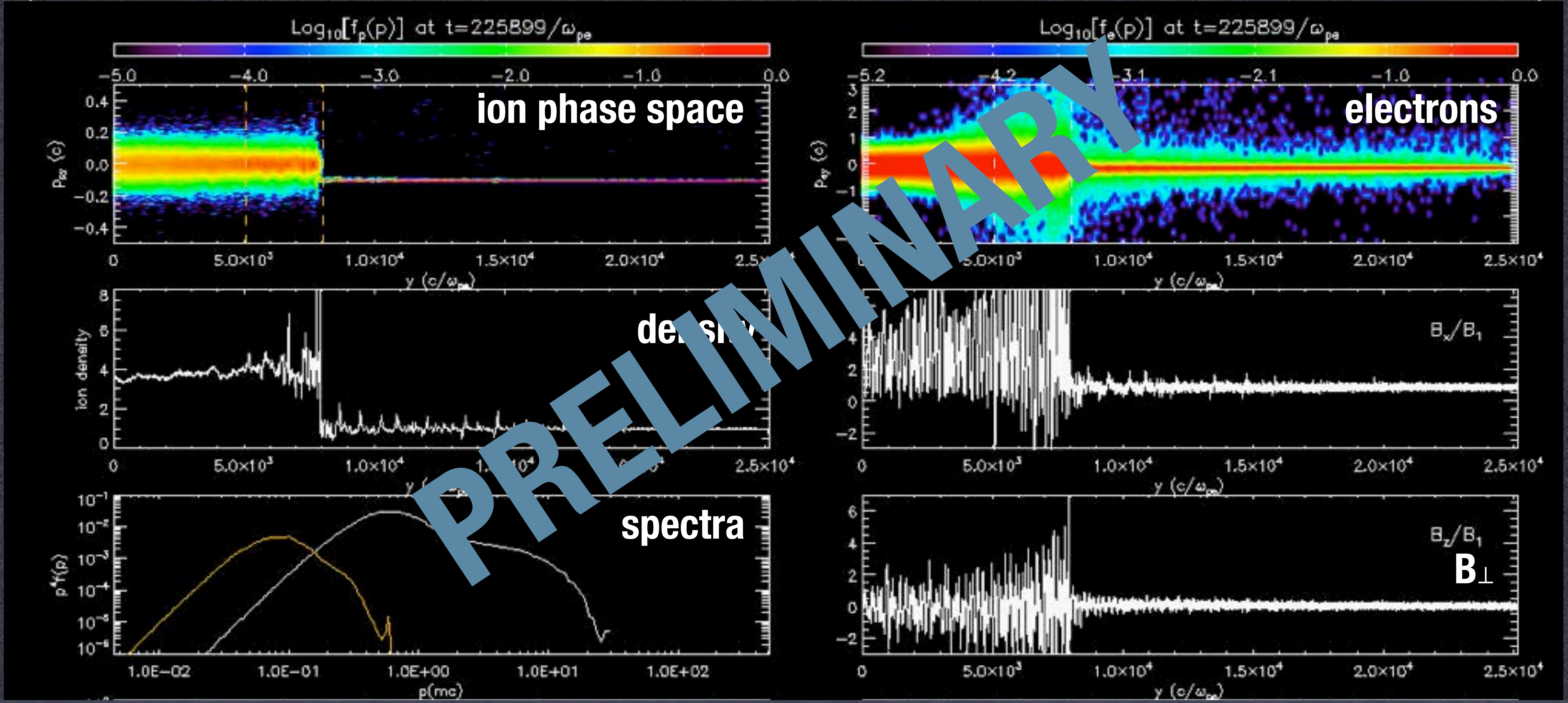


Electron acceleration at ⊥-shocks

60 degrees shock inclination, mi/me=100, Ma=20;
electron-driven waves; cf. Guo, Sironi & Narayan (2014)



(Caprioli, Park, AS, in prep)



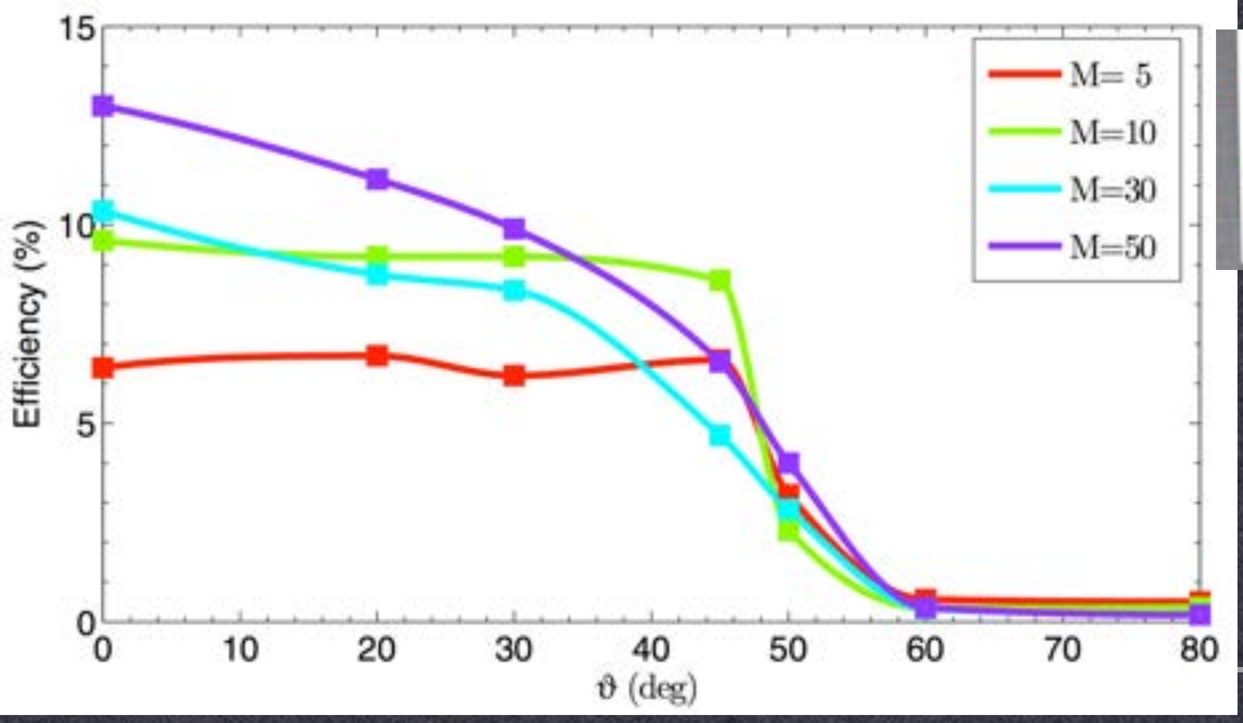
Ions are not injected or accelerated into DSA, while electrons drive their own Bell-type waves. Electrons are reflected from shock due to magnetic mirroring.

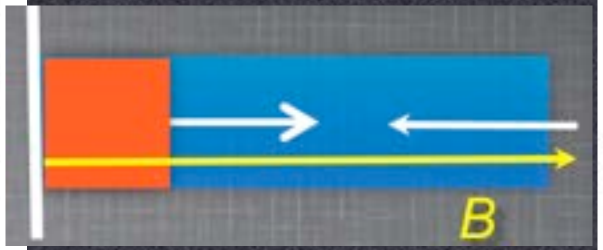
Recover DSA electron spectrum, 0.1-2% in energy, <1% by number.

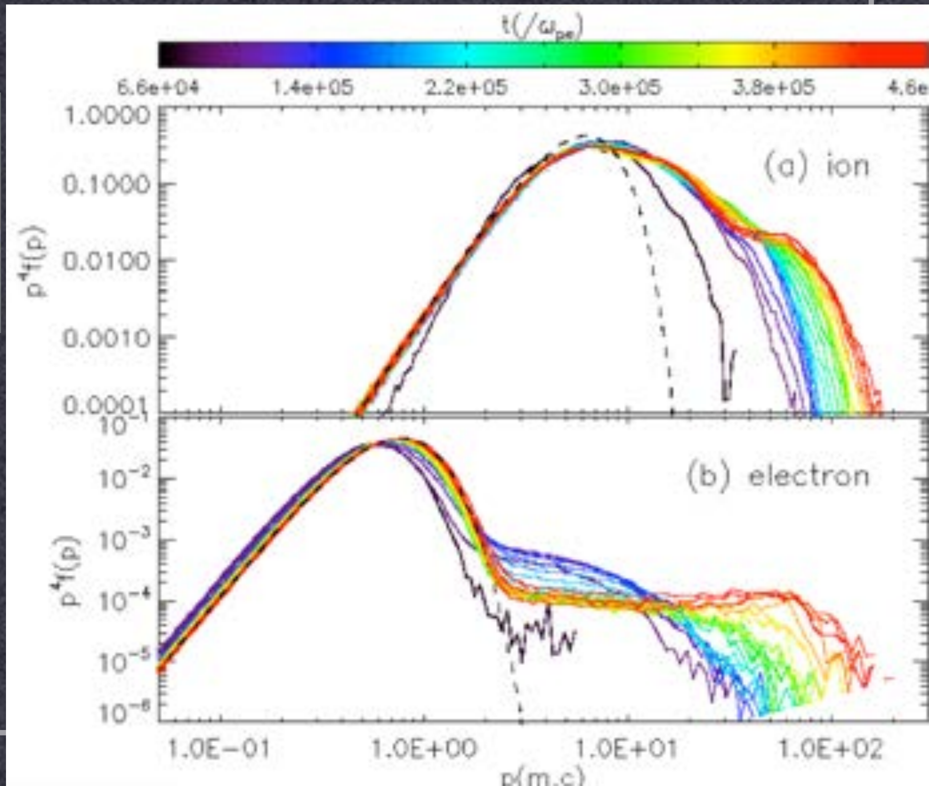
Shock acceleration: emerging picture

Acceleration in laminar field:

quasi-parallel -- accelerate both ions and electrons
(Caprioli & AS, 2014abc; Park, Caprioli, AS 2015)
quasi-perpendicular -- accelerate mostly electrons
(Guo, Sironi & Narayan 2014; Caprioli, Park, AS in prep)







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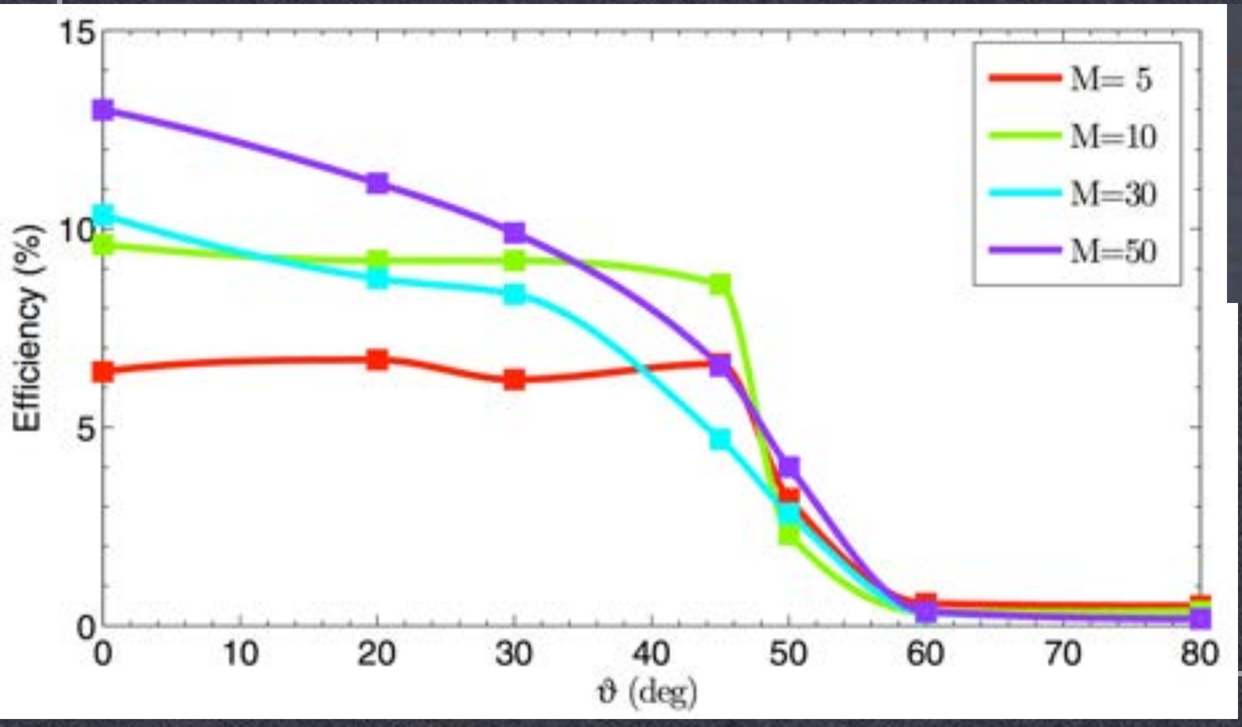
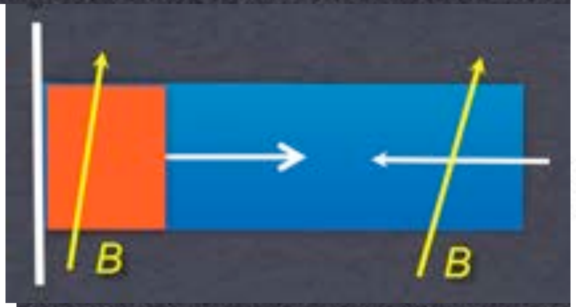
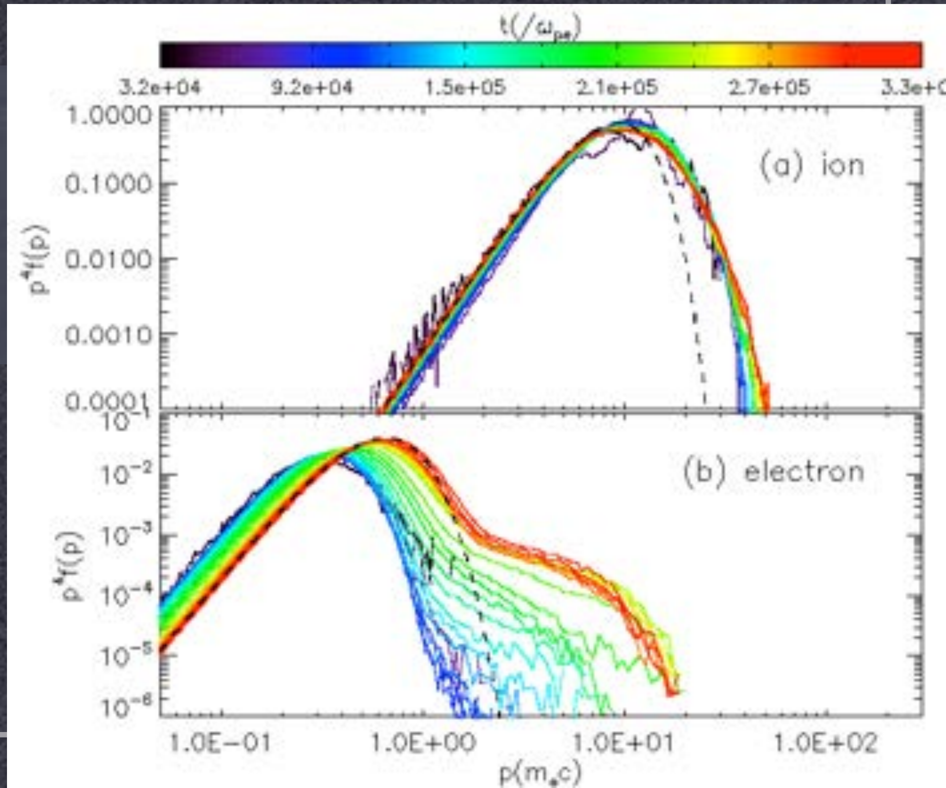




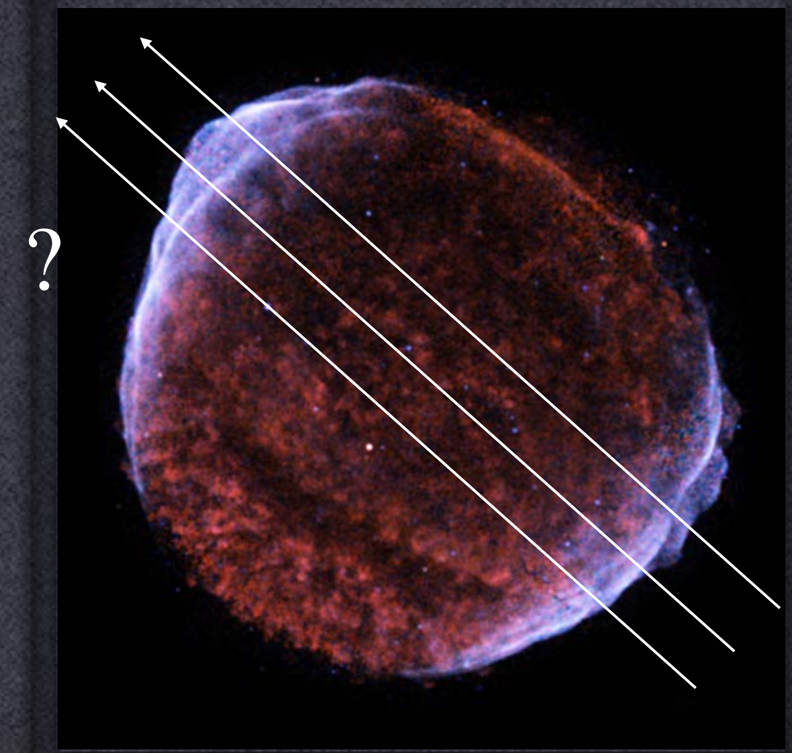


Shock acceleration: emerging picture

Wave driving by escaping particles is crucial
We see both ion-driven waves, and electron-driven waves

When field amplification is large, the shock surface is "turbulent", so understanding interaction of shocks with turbulence is now important.

Conclusions



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

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

Relativistic shocks: slope > 2, percent by #, 10% by energy; low σ or quasiparallel needed

Nonrelativistic shocks accelerate ions and electrons in quasi-par if B fields are amplified by CRs. Energy efficiency of ions 10-20%, number ~few percent; K_{ep}~1e-3; p^{-4} spectrum

Electrons are accelerated in quasi-perp shocks, likely weaker (energy several percent, number <1%).

Long-term evolution, turbulence & 3D effects need to be explored more: more advanced simulation methods are coming