Chania
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Particle acceleration in shocks: insights from kinetic simulations

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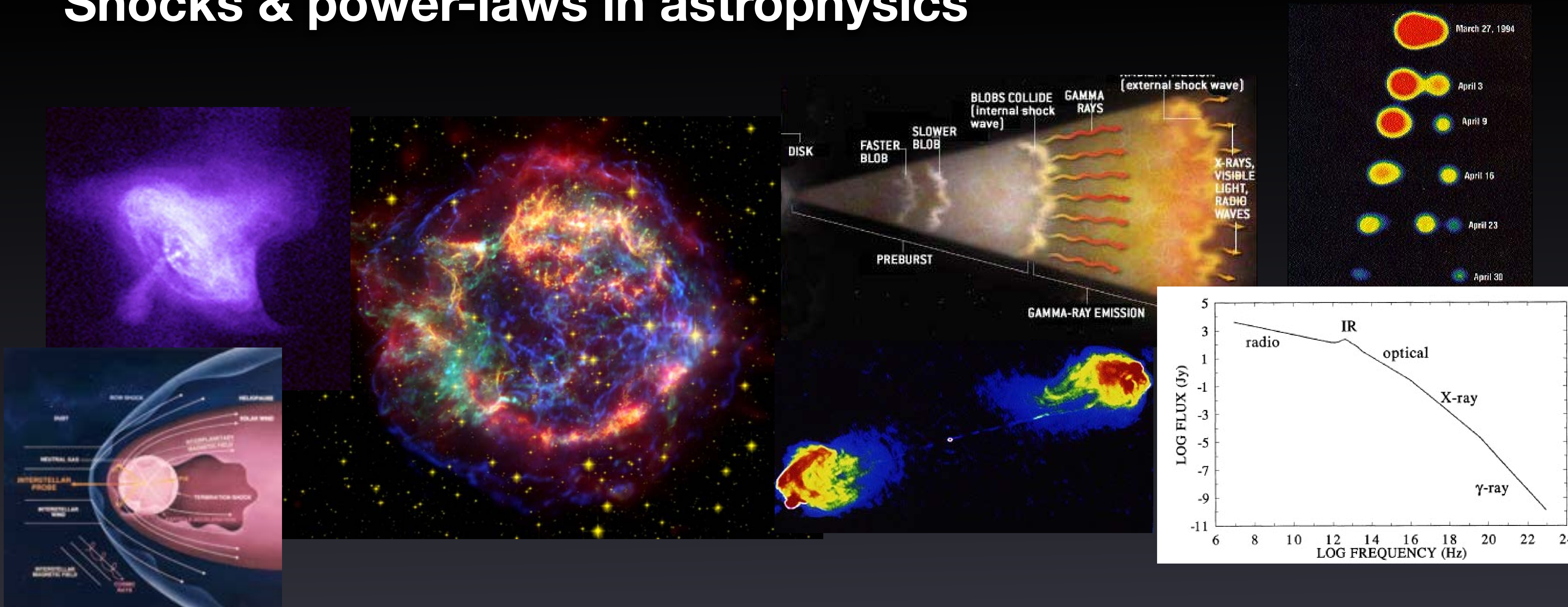
Shocks & power-laws in astrophysics



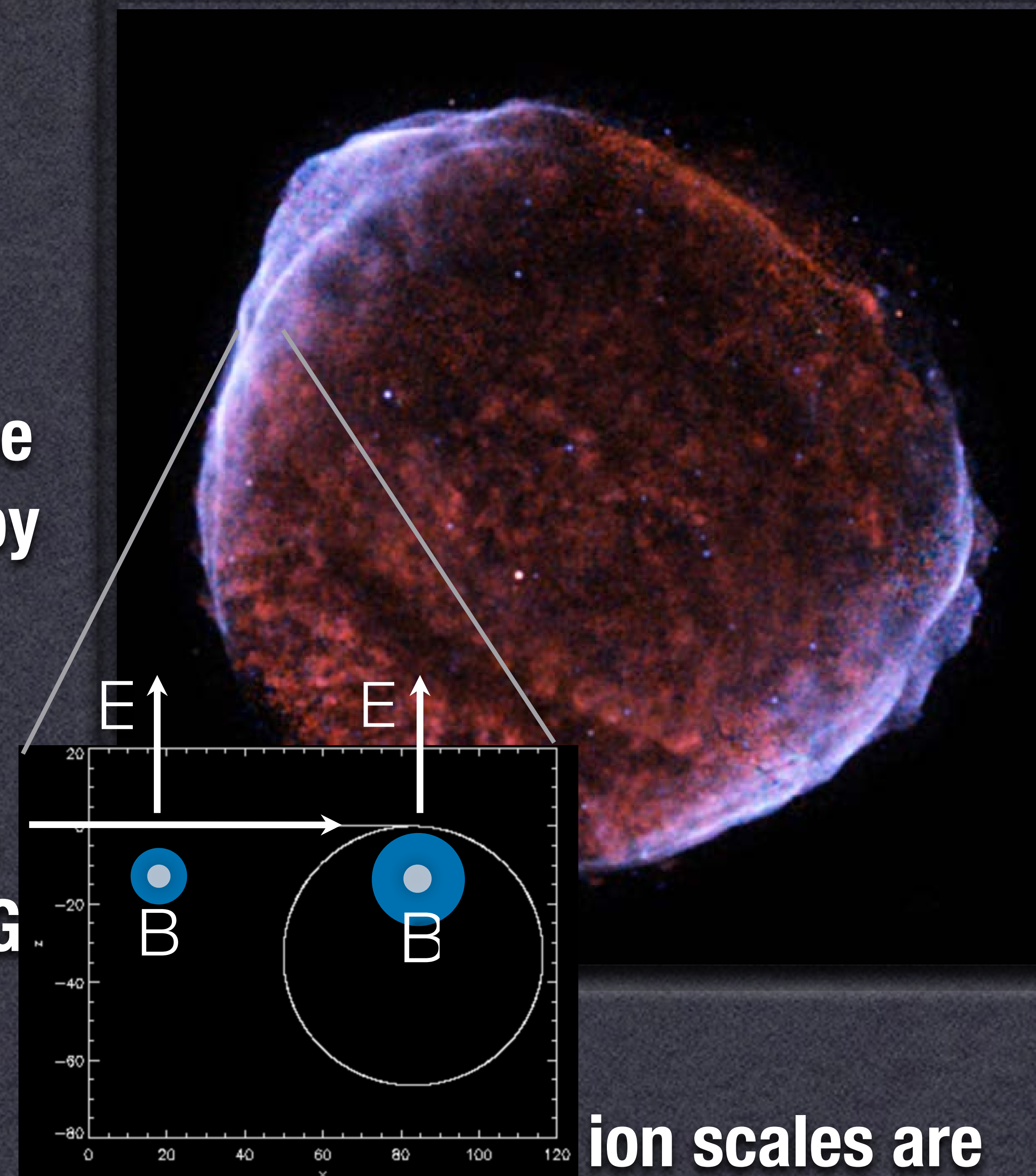
Astrophysical shocks are typically collisionless (mfp >> shock scales).
Many astrophysical shocks are inferred to:

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?…

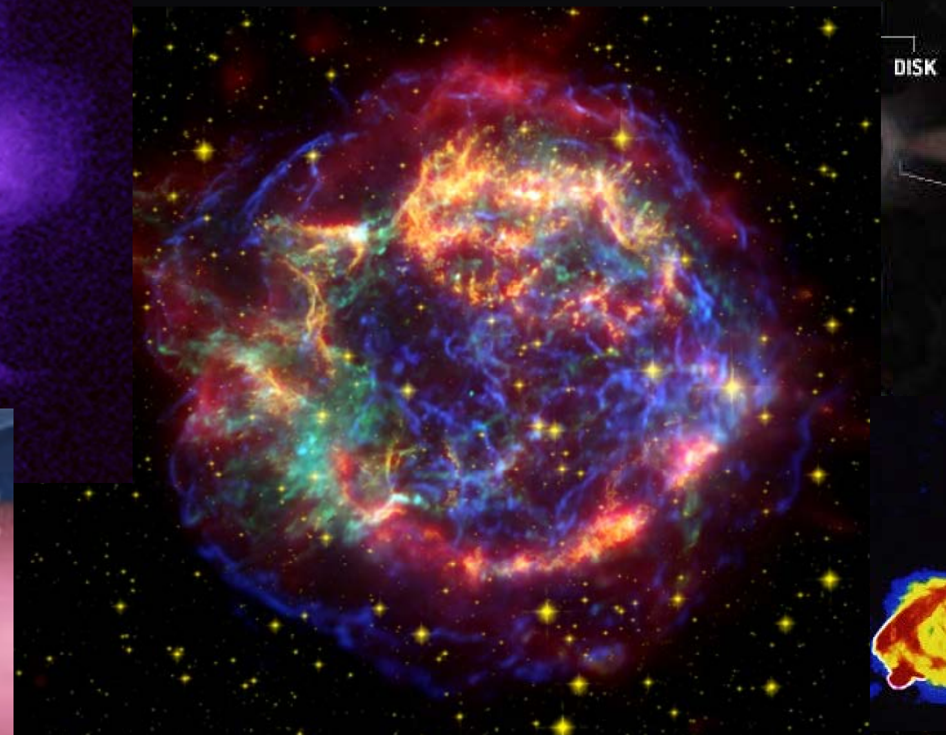
Nonrelativistic SNR shocks

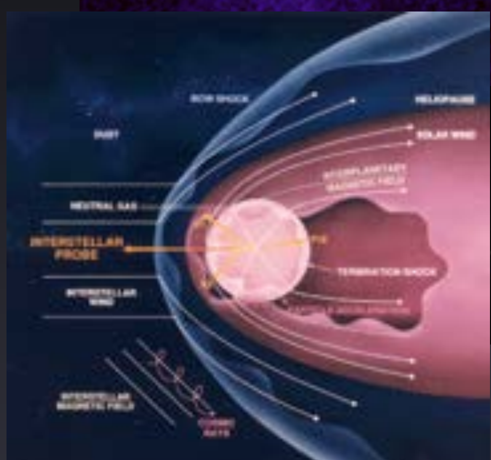
- Thin synchrotron-emitting rims observed in supernove remnants (SNRs)
- Electrons are accelerated to 100 TeV energies
- Cosmic Ray protons are inferred to be accelerated efficiently too (10-40% by energy, up to 10^{16}(?) eV)
- Magnetic field is inferred to be amplified by more than compression at the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

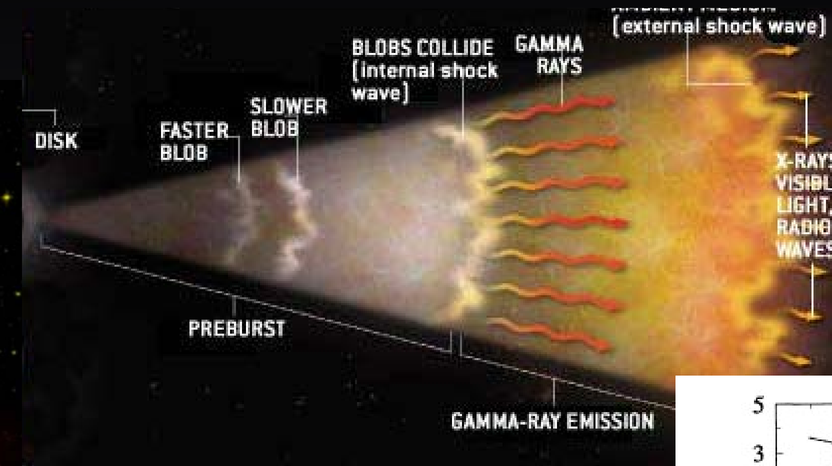


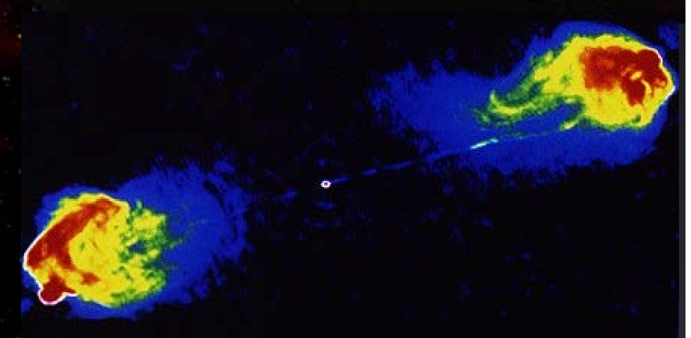
ion scales are disparate

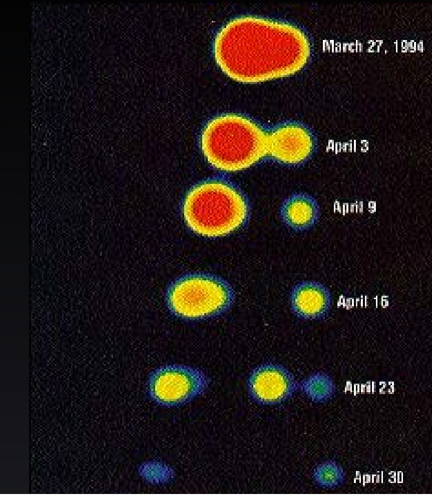
Shocks & power-laws in astrophysics

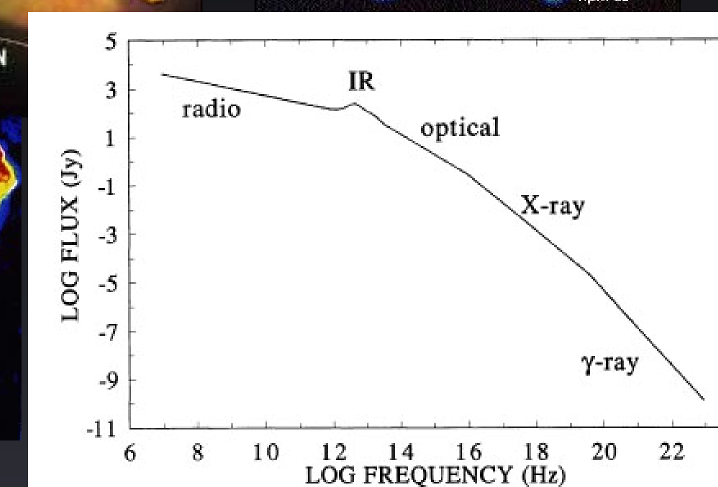












Open issues:

What is the structure of collisionless shocks? Do they exist? Are there different regimes?

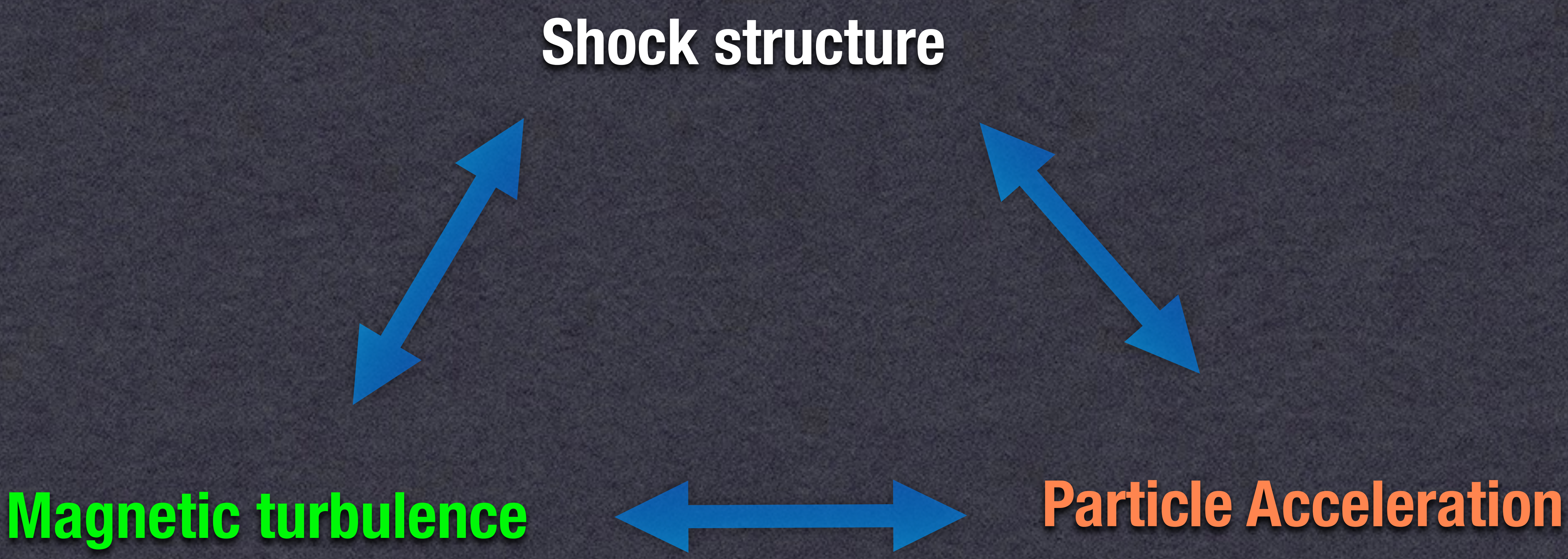
Particle acceleration -- Fermi mechanism? Other? Efficiency? Injection problem: what determines if particle is accelerated?

Generation/amplification of magnetic fields?

All are coupled through the structure of turbulence in shocks and acceleration

Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback



Collisionless shocks

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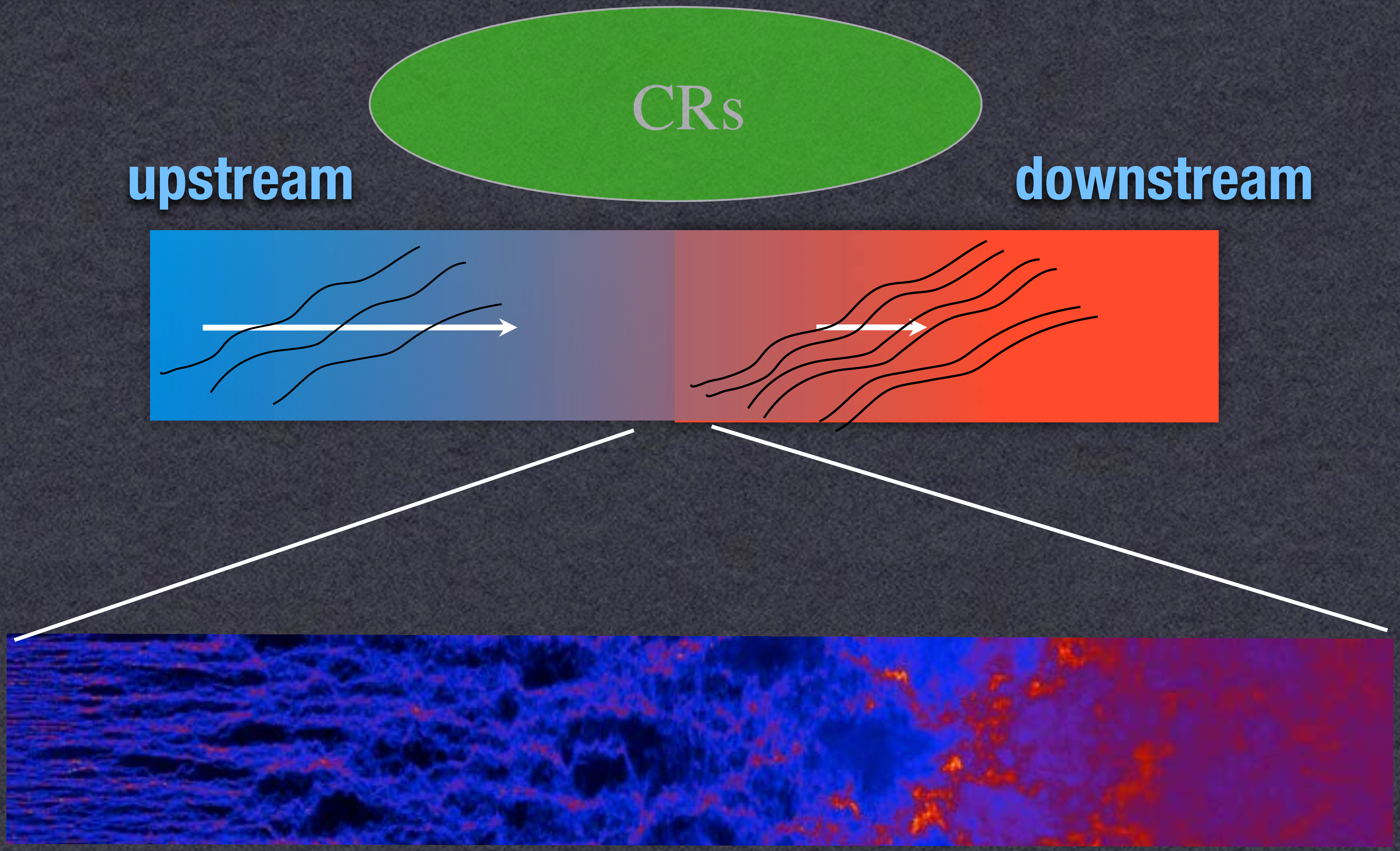
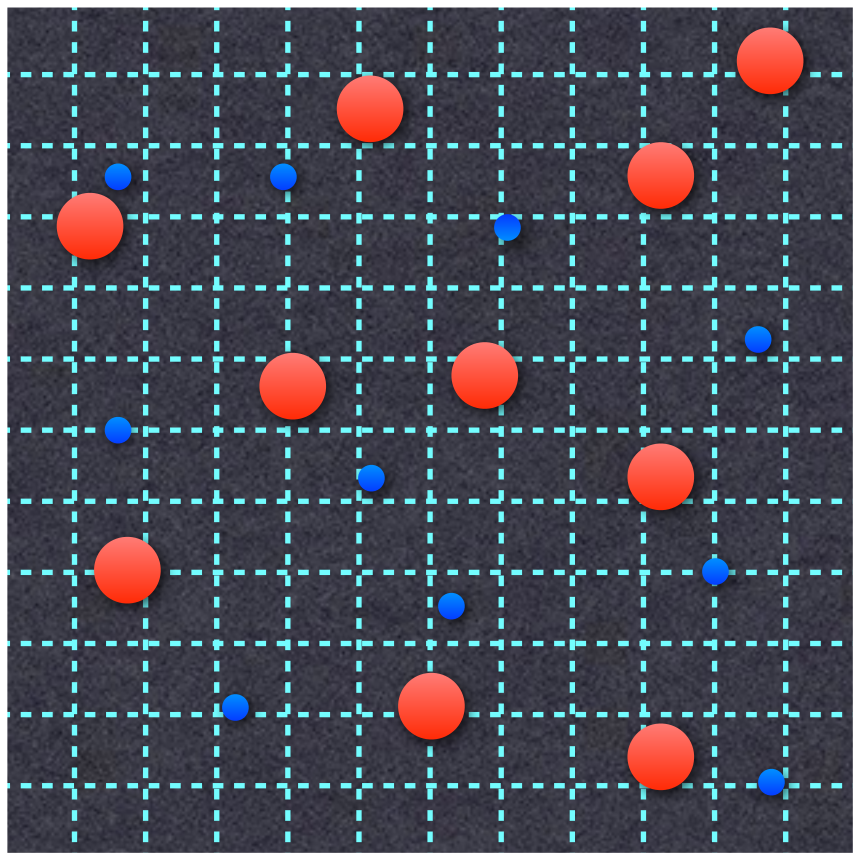
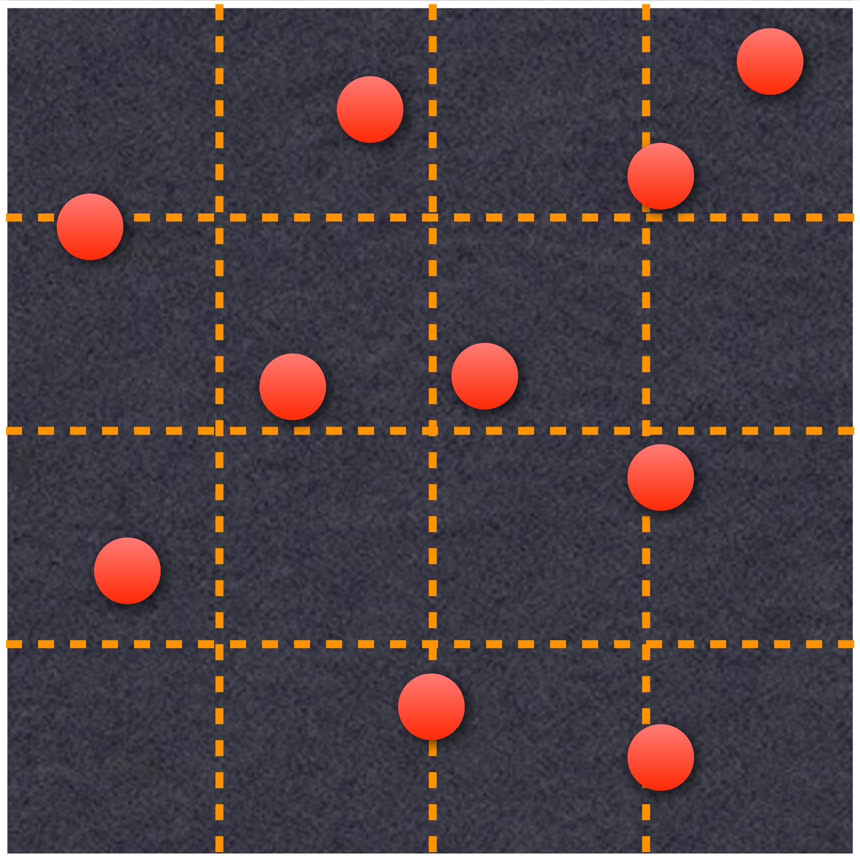


Collisionless shocks from first principles

- 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

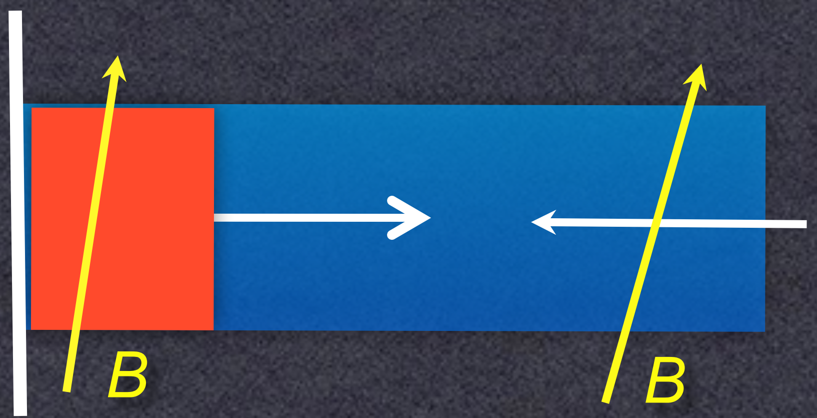




Survey of Collisionless Shocks

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

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



Main findings:

Dependence of shock mechanism on upstream magnetization

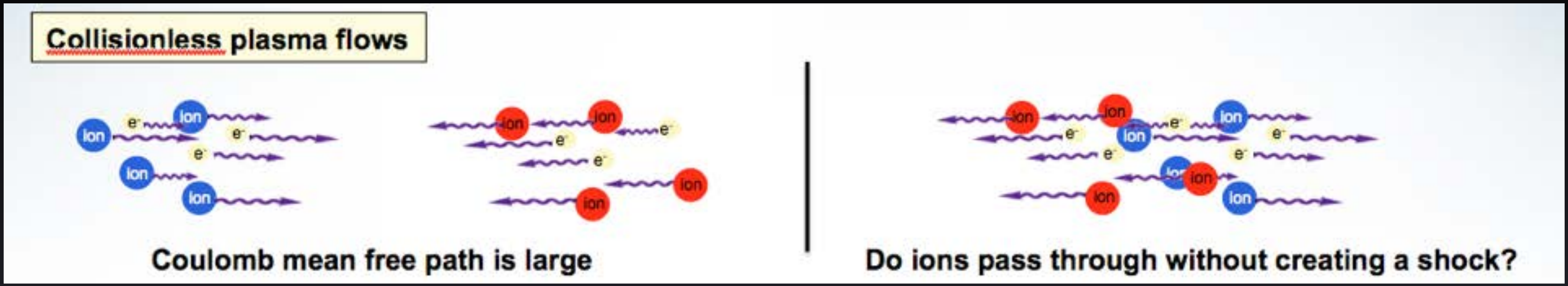
Ab-initio particle acceleration in relativistic shocks

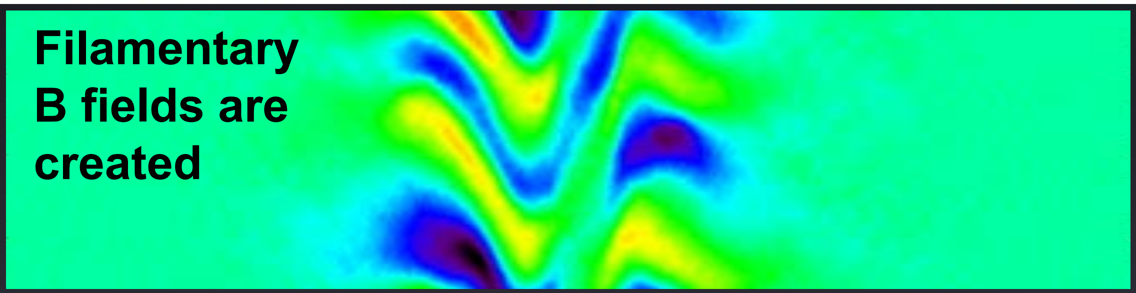
Shock structure and acceleration in non-relativistic shocks

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

FIeld amplification and CR-induced instabilities

How collisionless shocks work

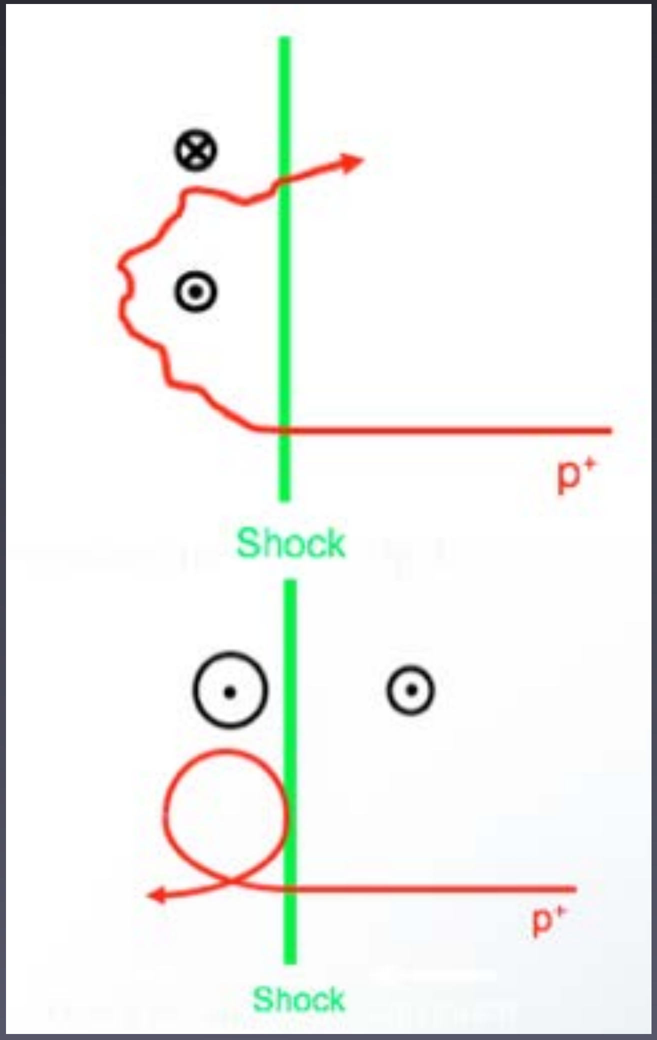




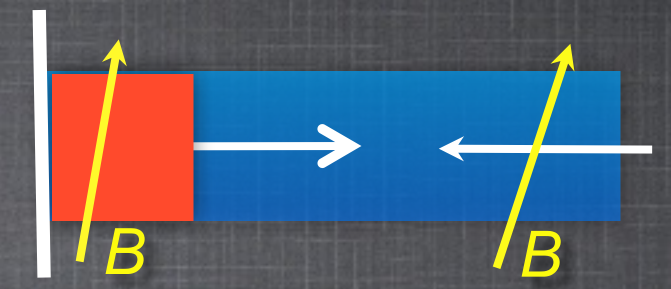
Two main mechanisms for creating collisionless shocks:

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

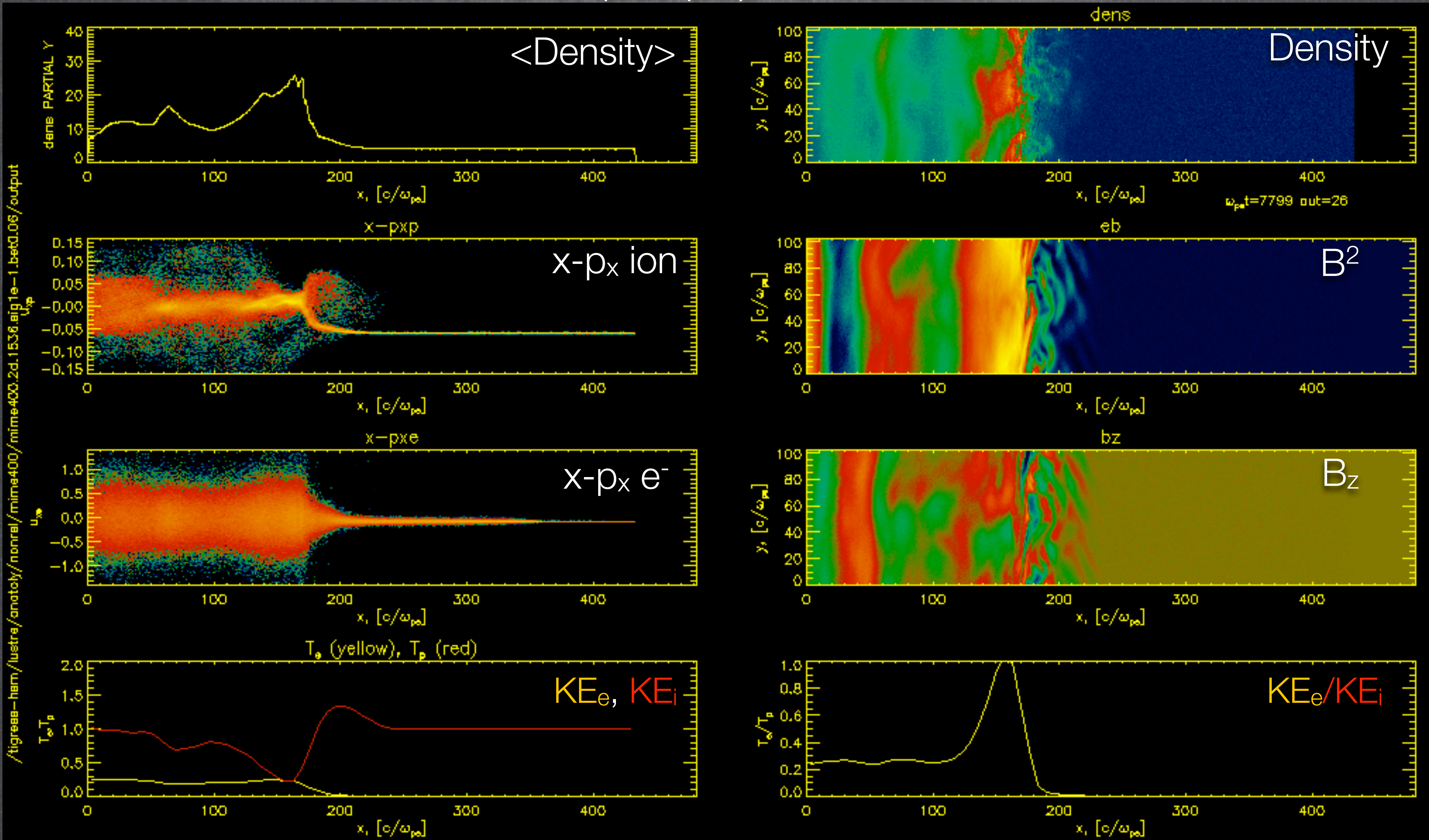
2) For large initial B field, particles are deflected by compressed pre-existing fields; Alfvenic Mach # < 100



Nonrelativistic shocks: shock structure



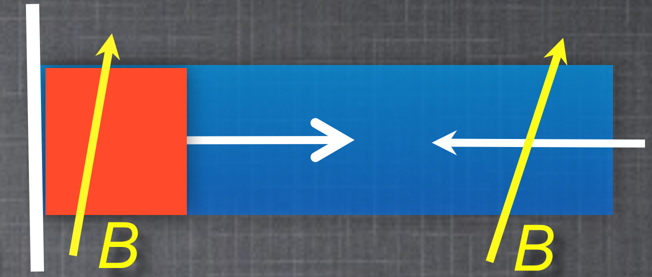
mi/me=400, v=18,000km/s, Ma=5, quasi-perp 75° inclination

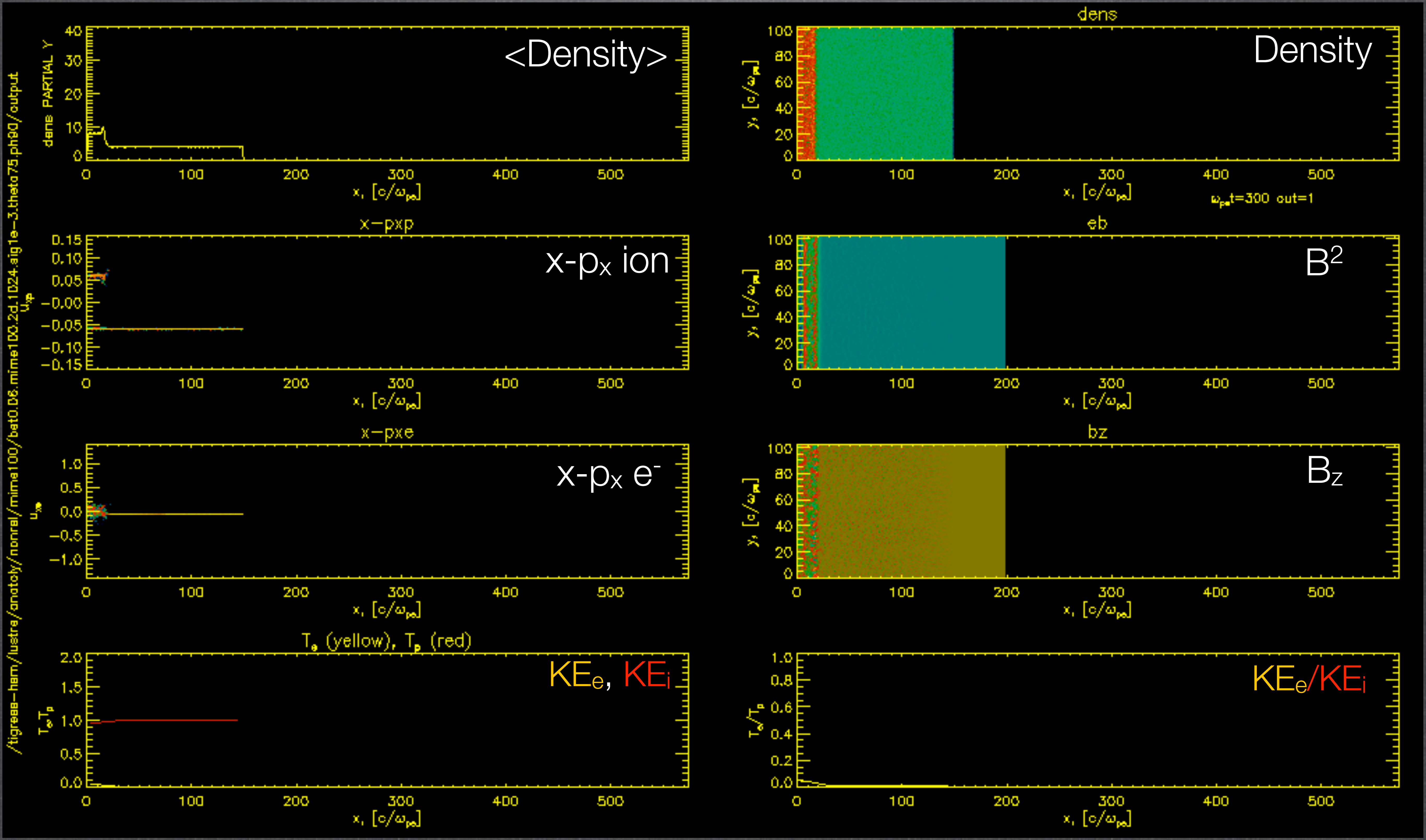


PIC simulation: Shock foot, ramp, overshoot, returning ions, electron heating, whistlers

Nonrelativistic shocks: shock structure

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

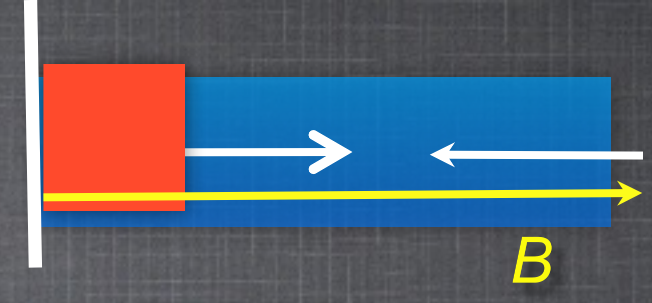


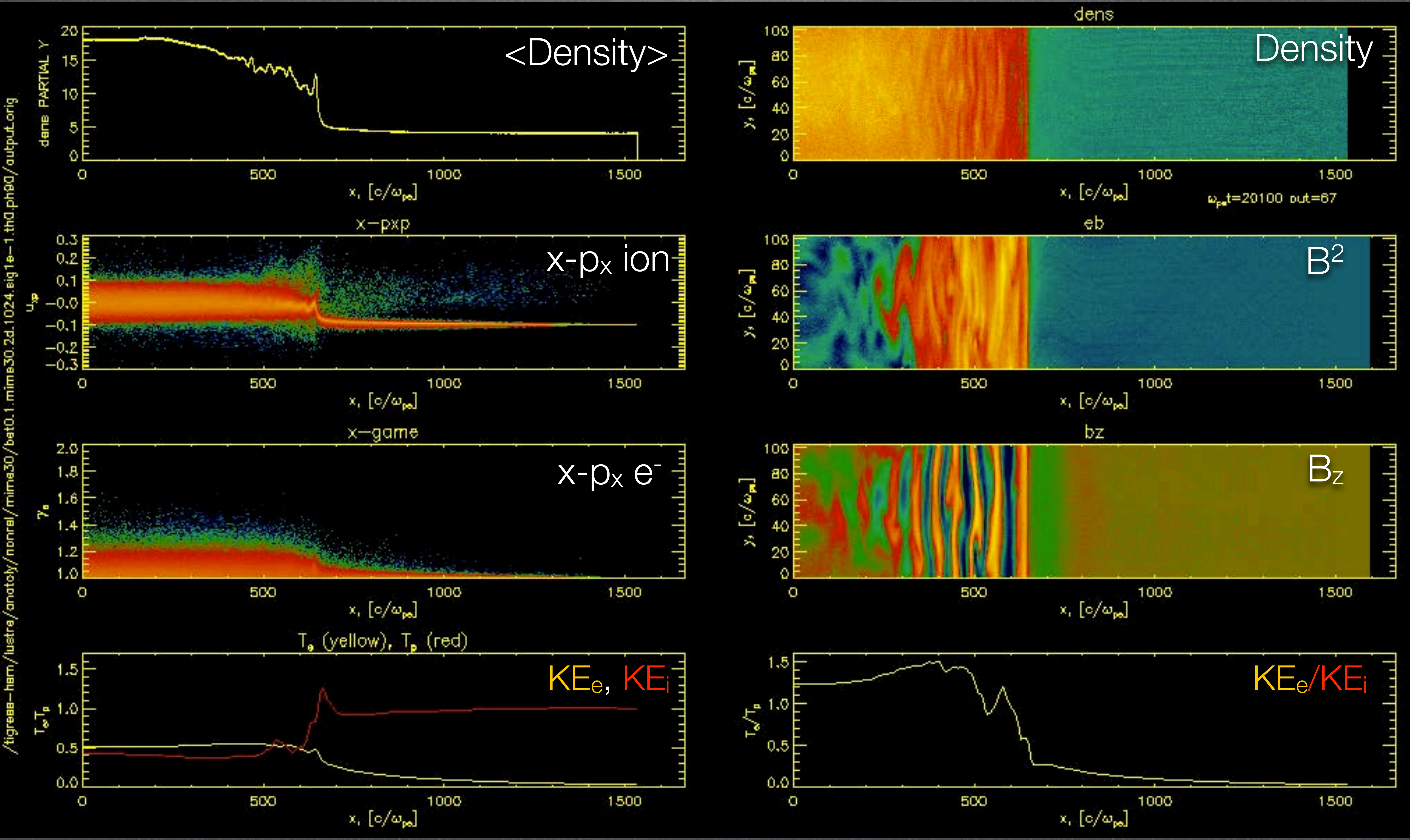


PIC simulation: Initial weibel filamentation eventually succumbs to magnetic reflection

Nonrelativistic shocks: quasiparallel shock

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

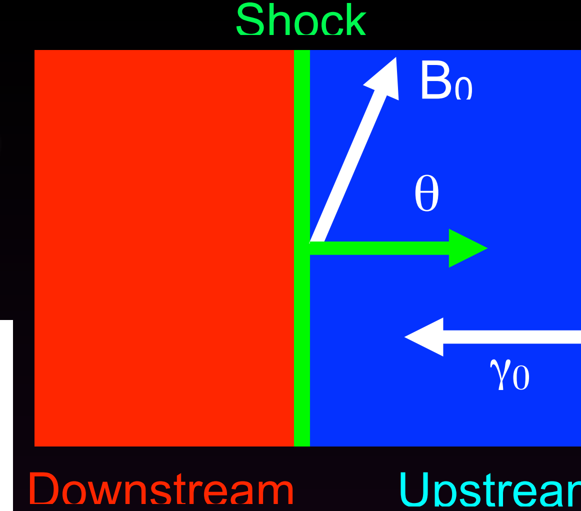




PIC simulation: returning ions, reorientation of B field, rotating B perp; shock reformations

Perpendicular vs parallel shocks

• Quasi-perpendicular shocks: mediated by magnetic reflection



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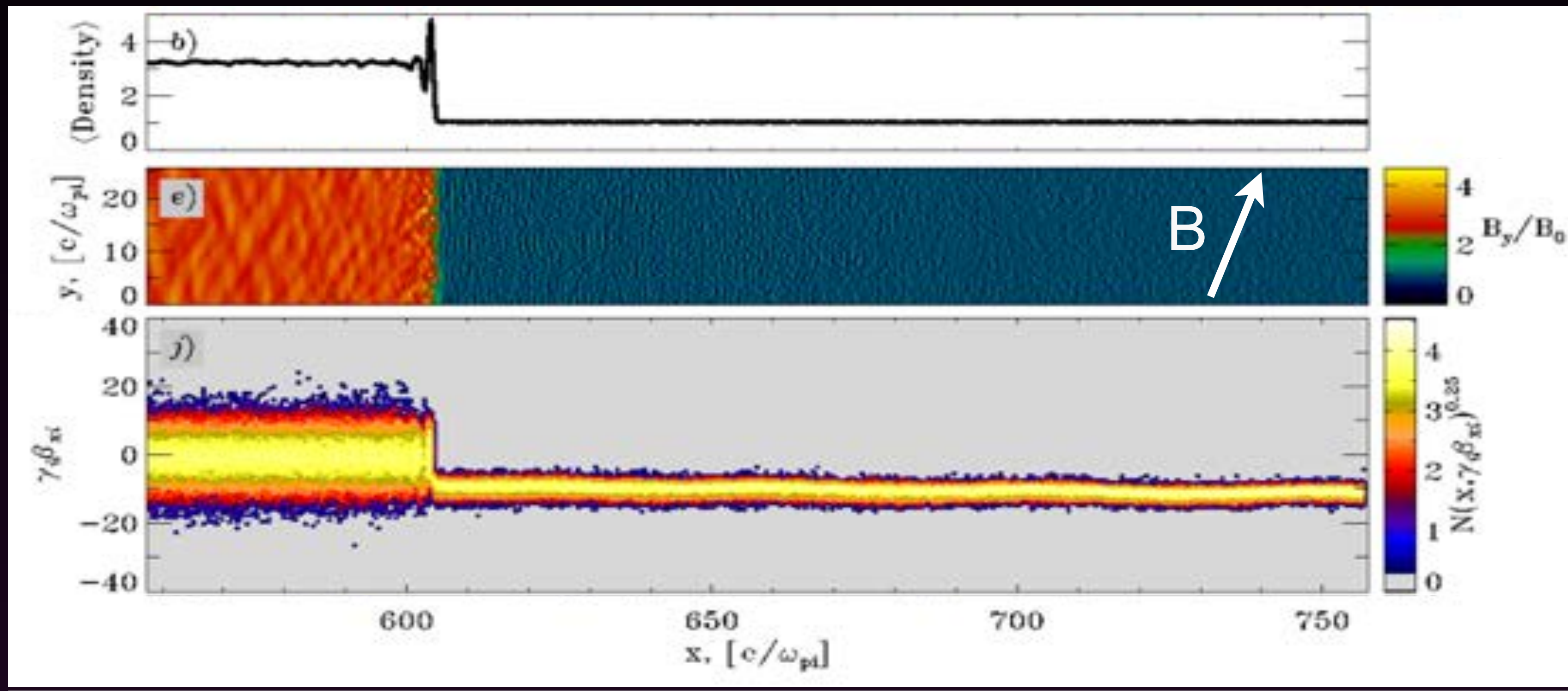
Mach 5
$\theta=75°$
relativist.
e^--p^+



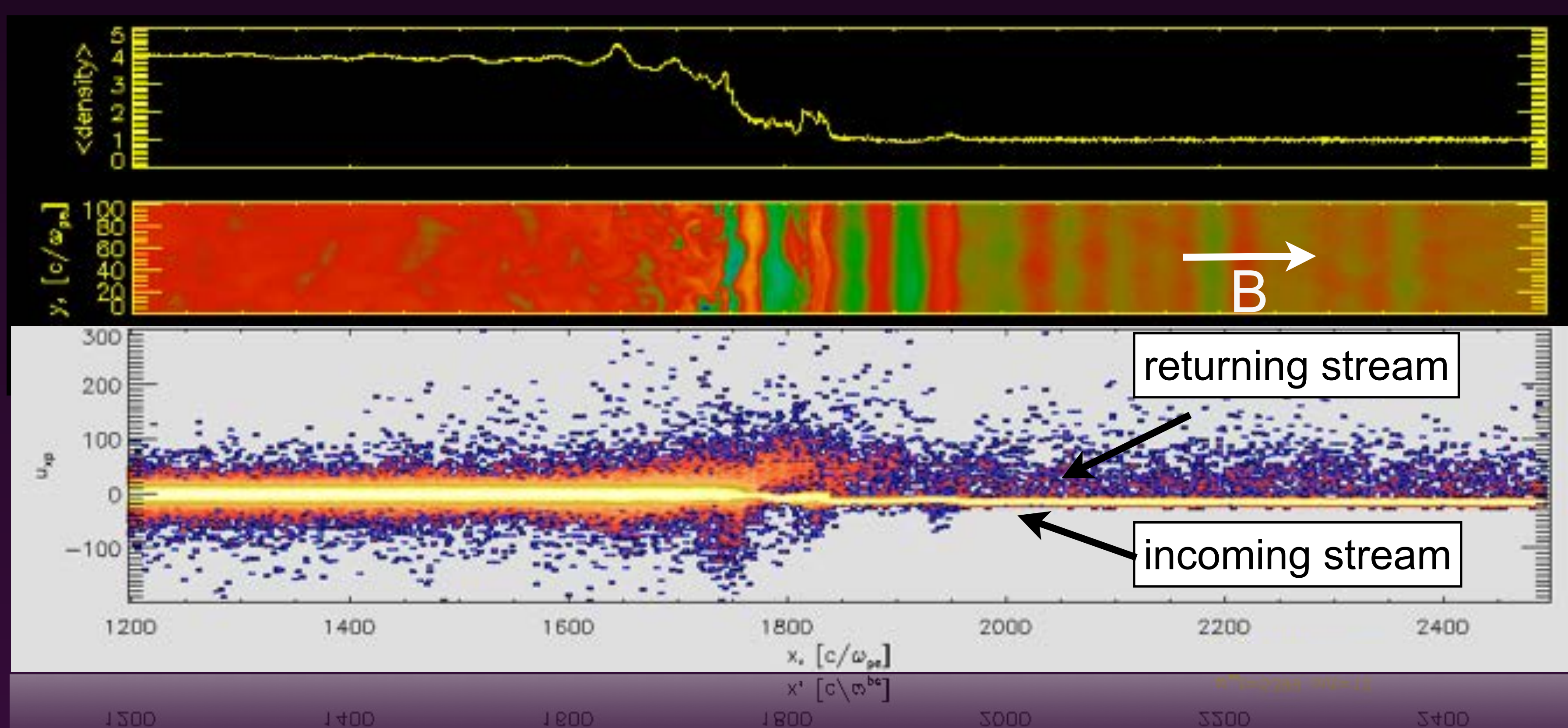
B_y

$\gamma\beta_x$

(Sironi and AS 11)

• Quasi-parallel shocks: instabilities amplify transverse field component

Mach 5
$\theta=15°$
relativist.
e^--p^+



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B_y

$\gamma\beta_x$

(Sironi & AS 11)

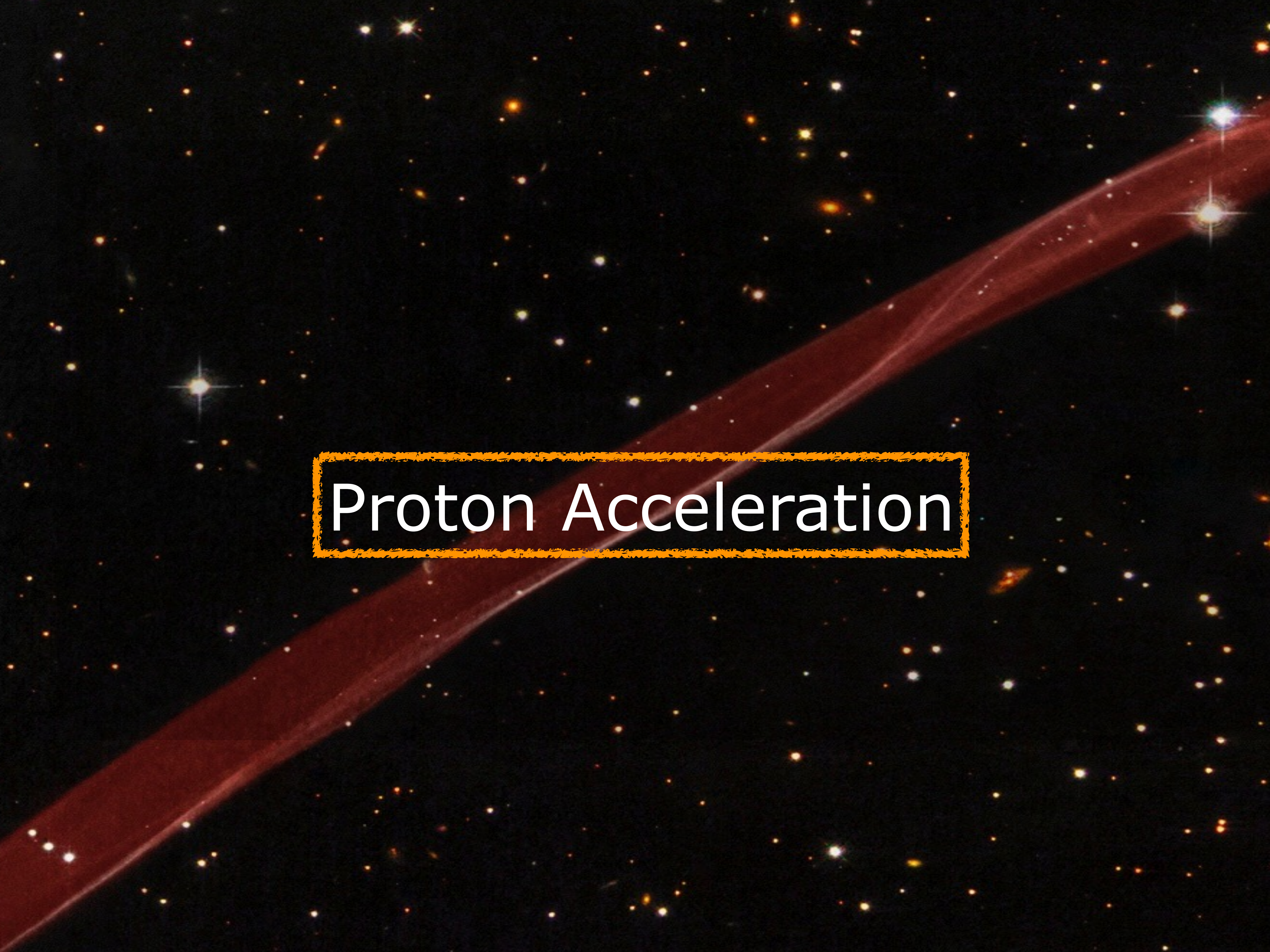
Shock acceleration

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)

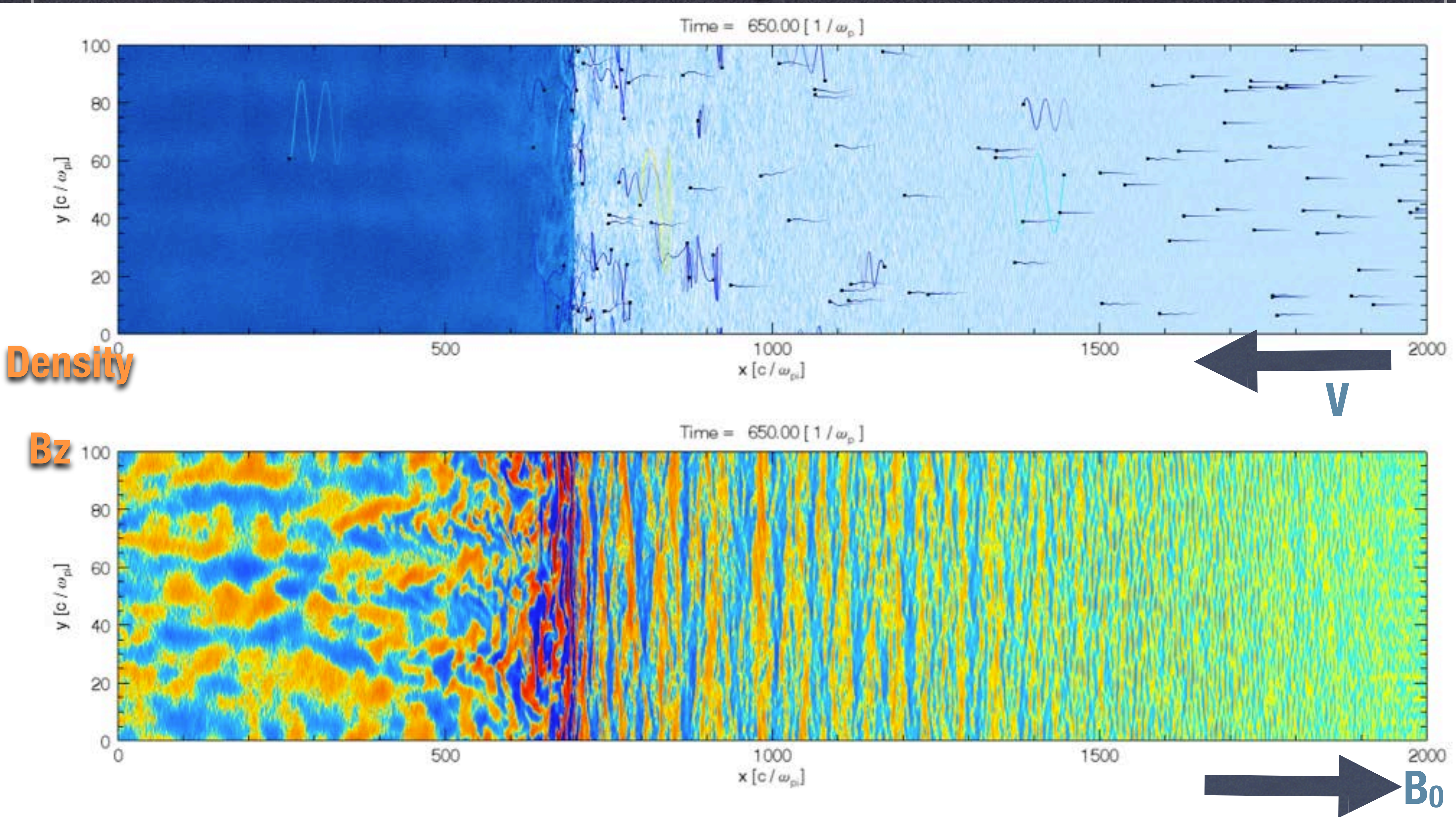
Generically, parallel shocks are good for ion and electron acceleration, while perpendicular shocks mainly accelerate electrons. *There are many sub-regimes, not fully mapped yet.*



Proton Acceleration

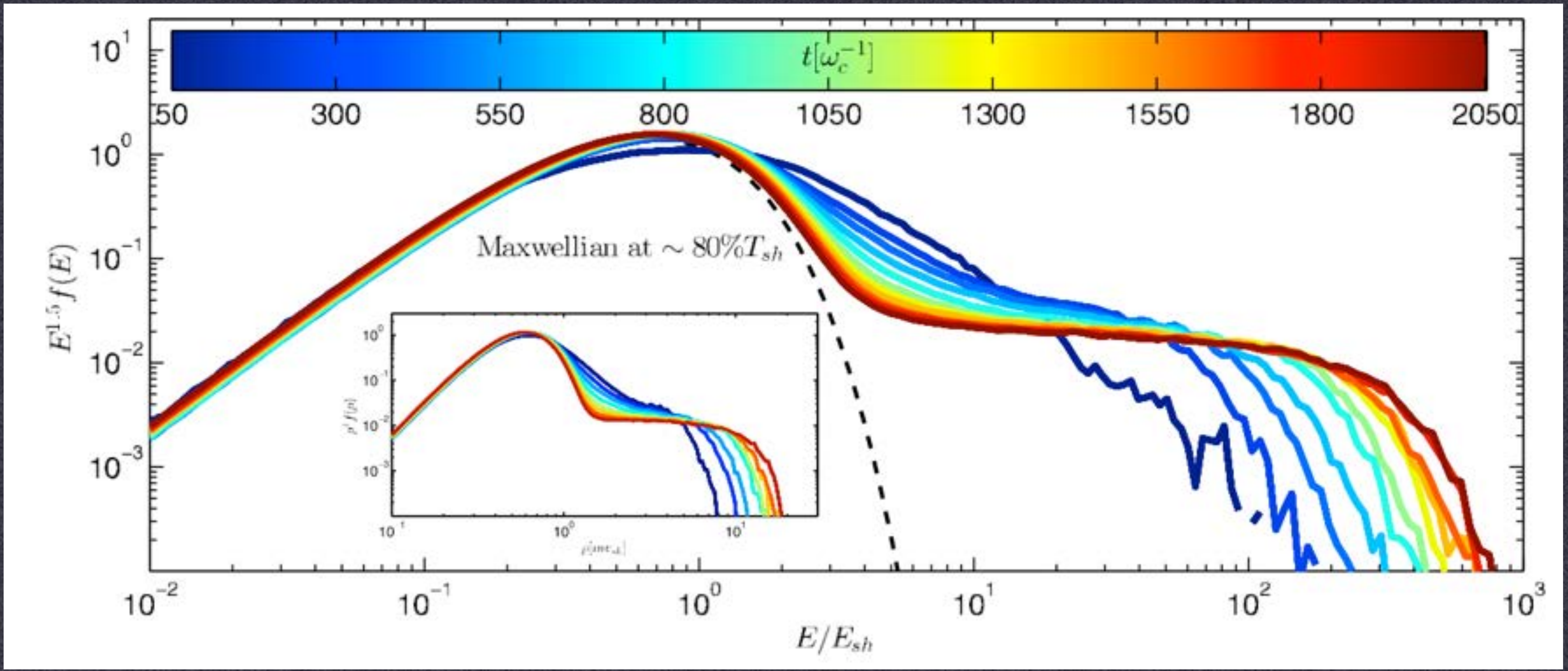
Proton acceleration

M_A=5, parallel shock; hybrid simulation. Quasi-parallel shocks accelerate ions and produce self-generated waves in the upstream.



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)

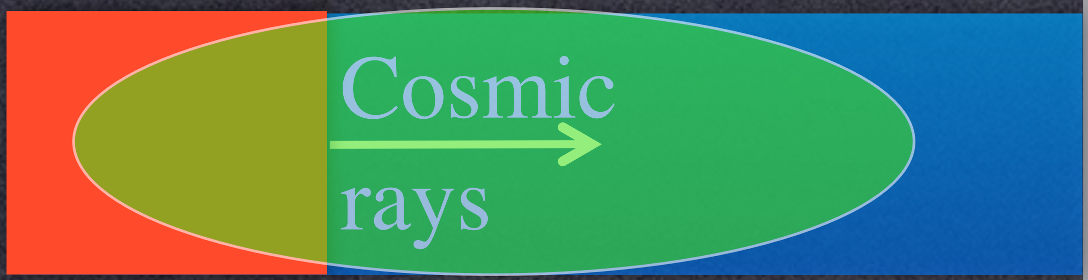
CR backreaction is affecting downstream temperature

Caprioli & Spitkovsky 2014a

Field amplification

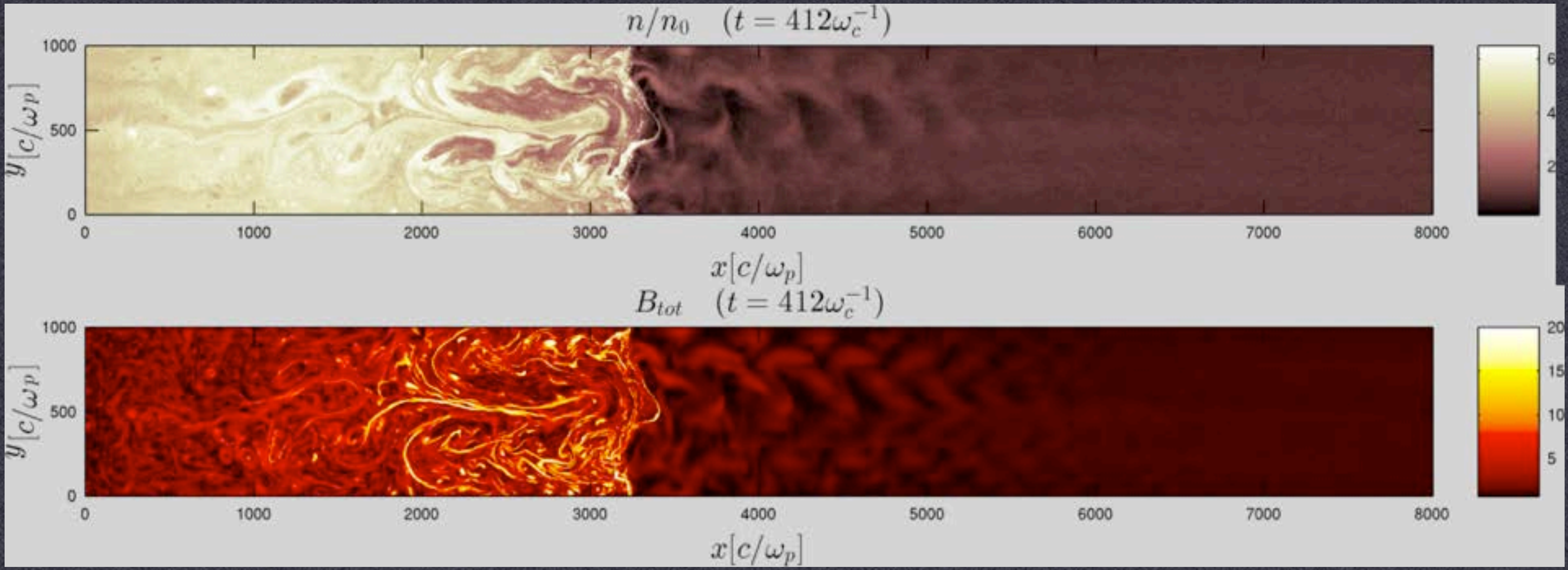
We see evidence of CR effect on upstream.

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

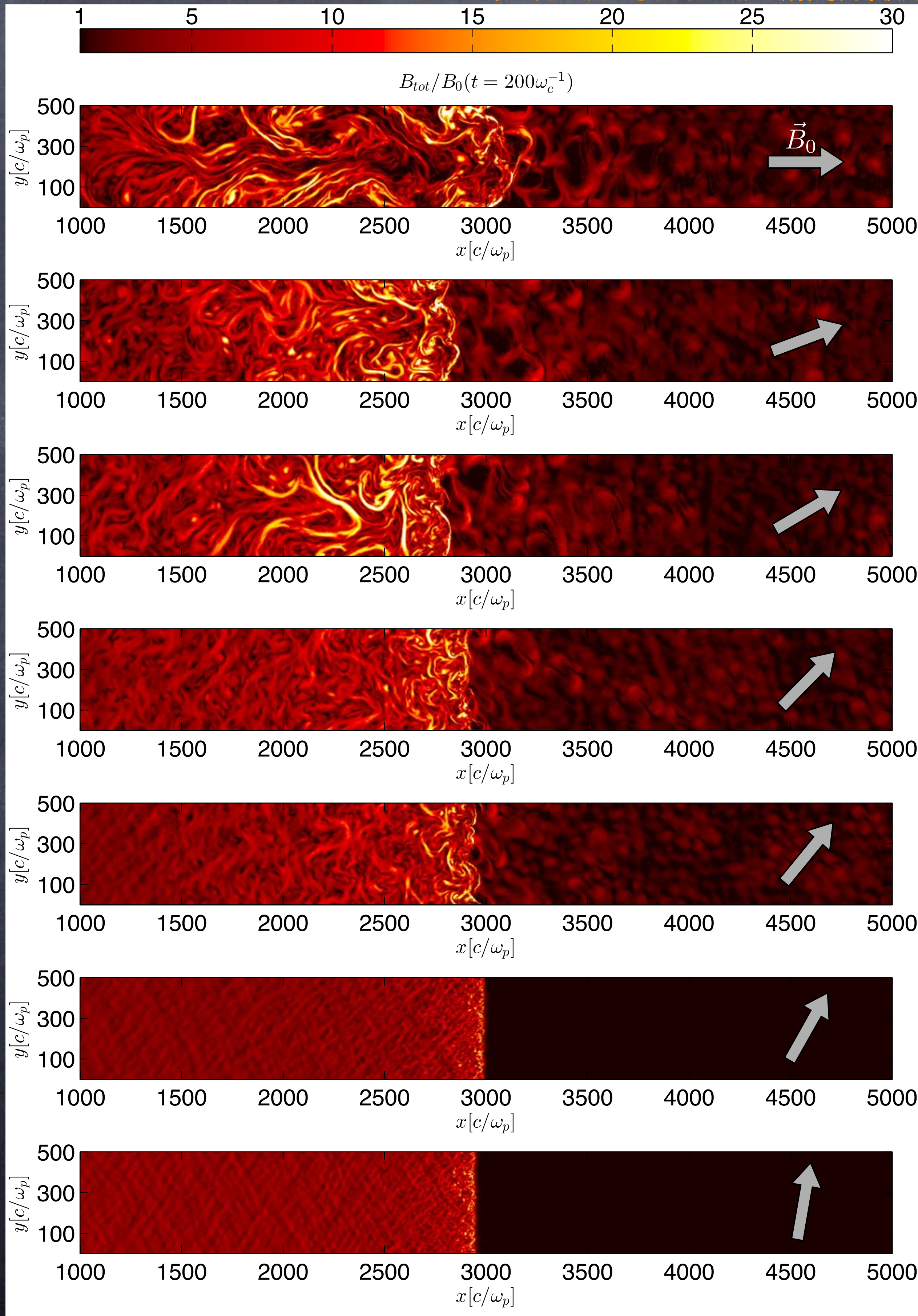


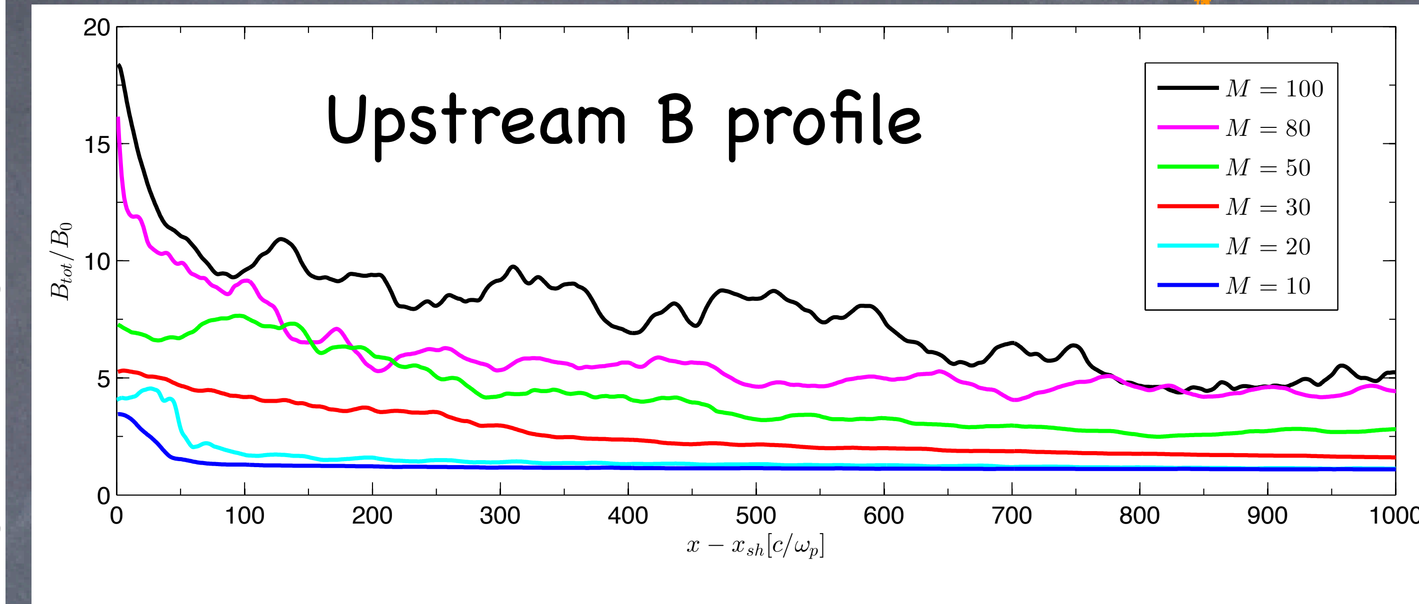
Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

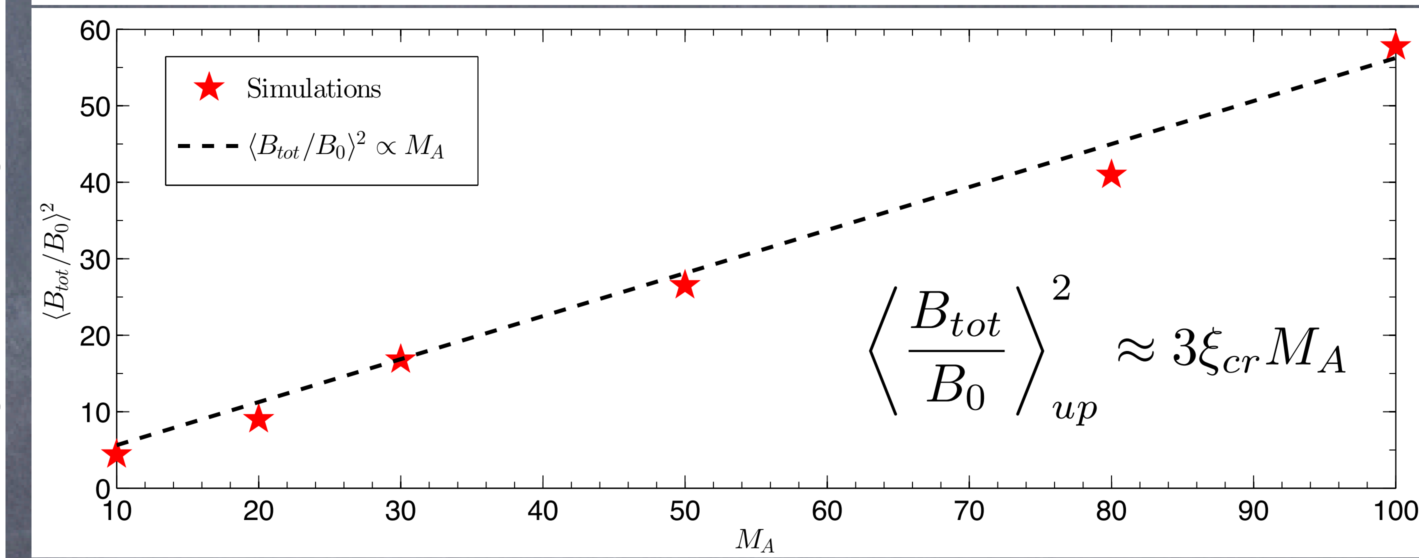
Combination of nonresonant (Bell), resonant, and firehose instabilities + CR filamentation



Dependence of field amplif. on inclination and M



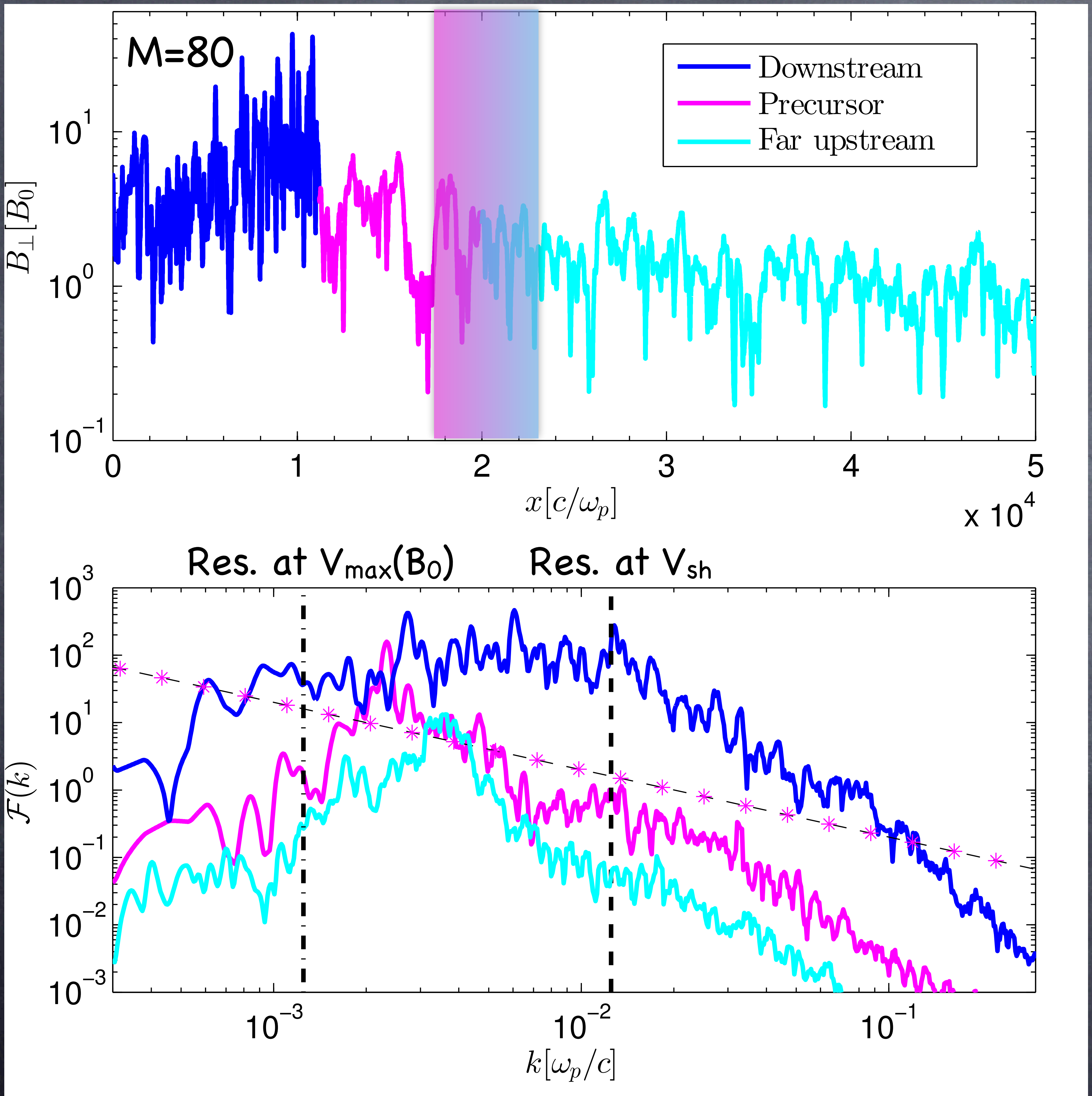




- In agreement with the prediction of resonant streaming instability

More B-field amplification for stronger shocks!

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

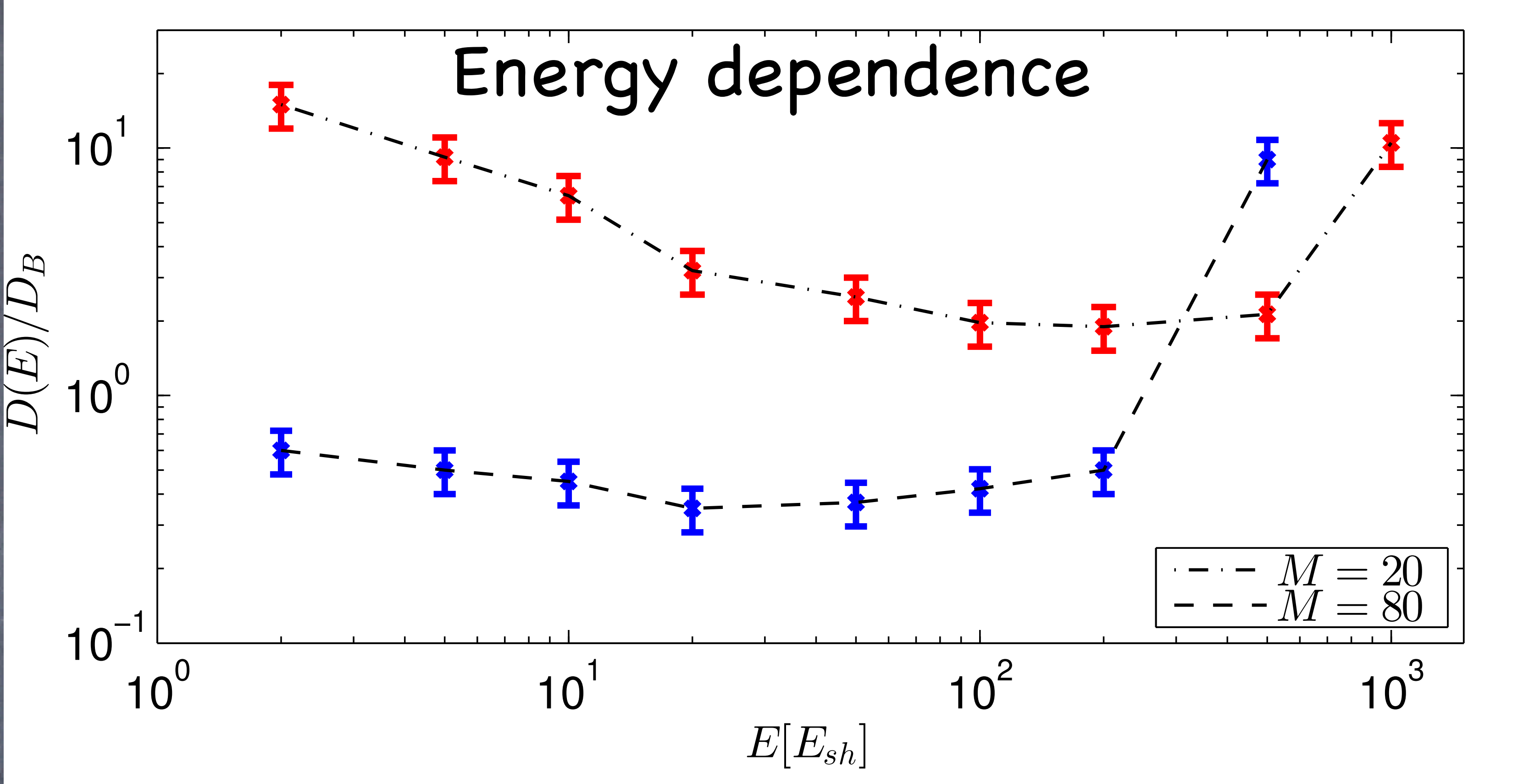
Caprioli & AS, 2014b

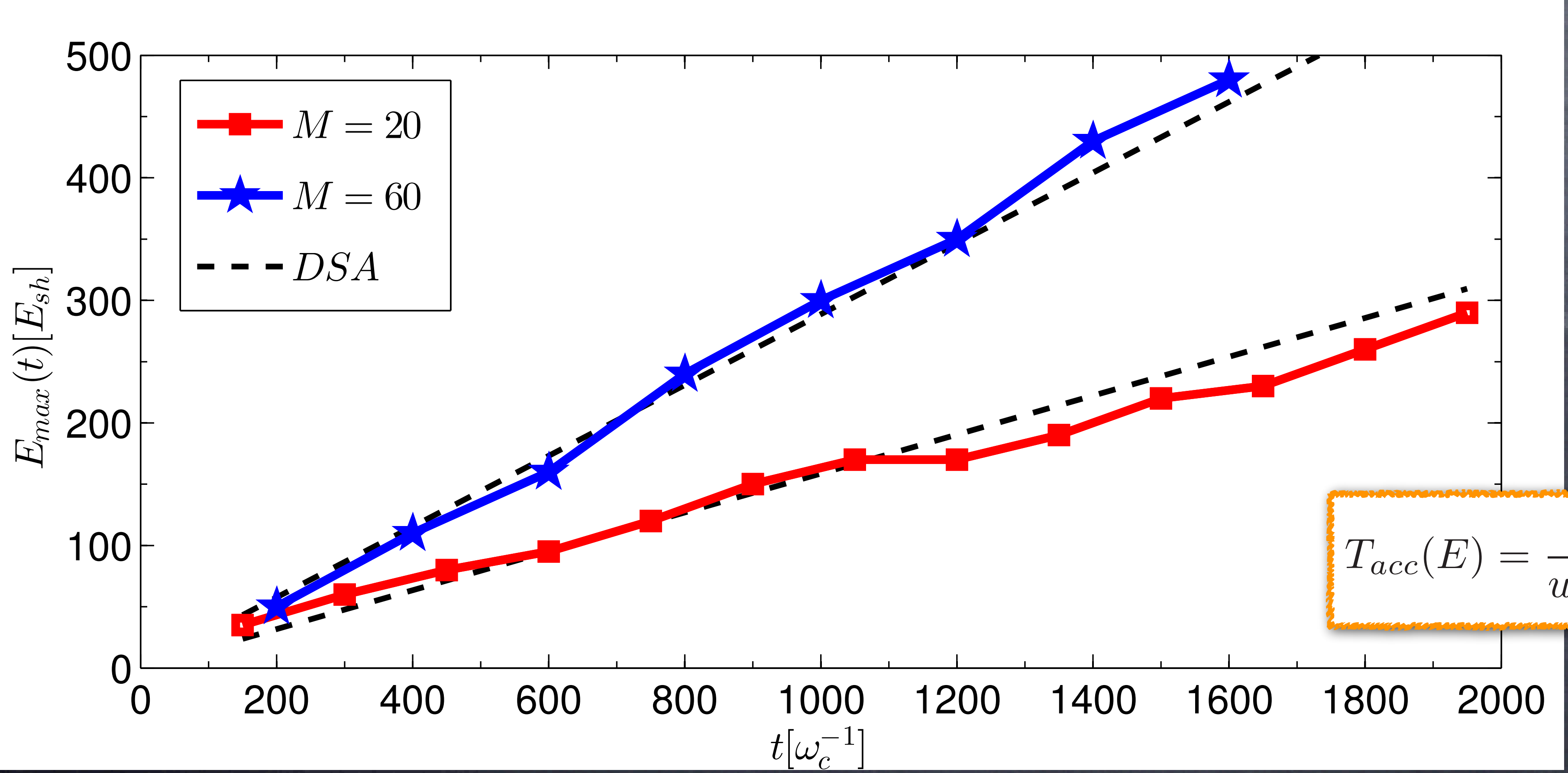
Diffusion coefficient

- Directly measurable in simulations:

$$D(E) \equiv \lim_{t\to\infty} D(E,t) = \lim_{t\to\infty} \sum_{n=1}^{N} \frac{|x_n(t) - x_n(0)|^2}{2tN}.$$

Bohm diffusion in the amplified B



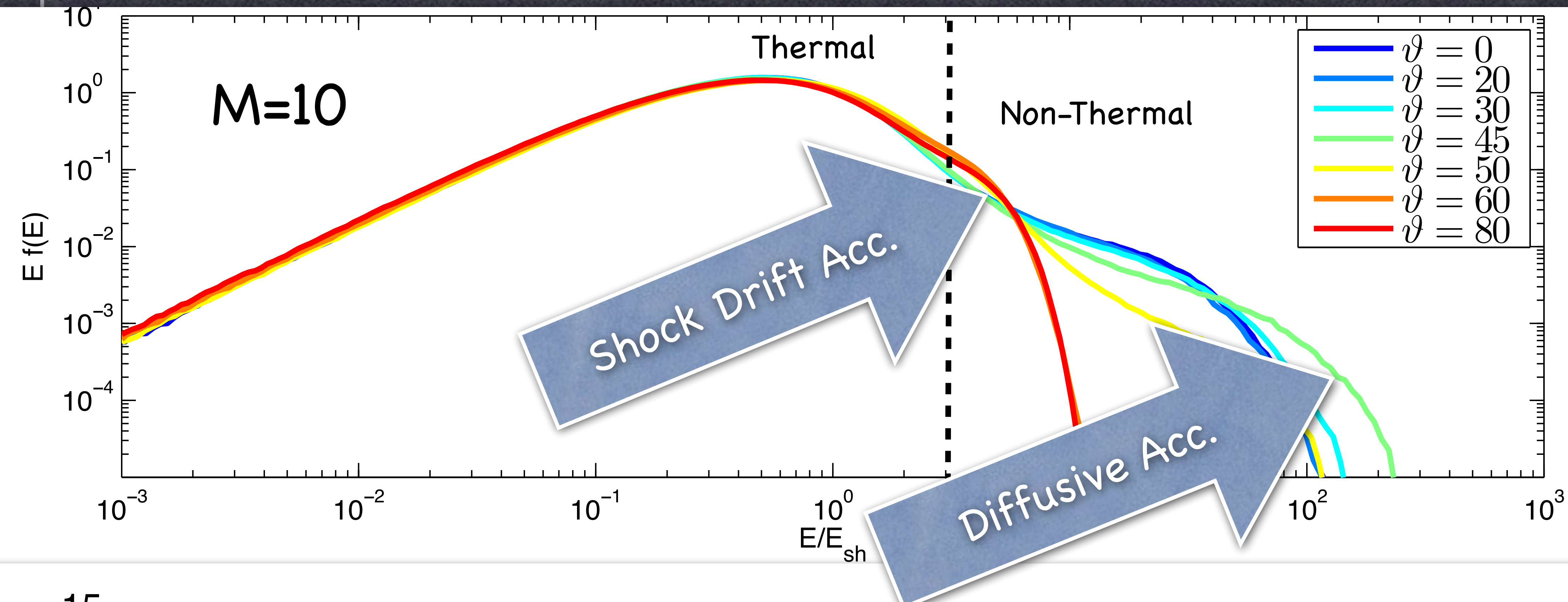


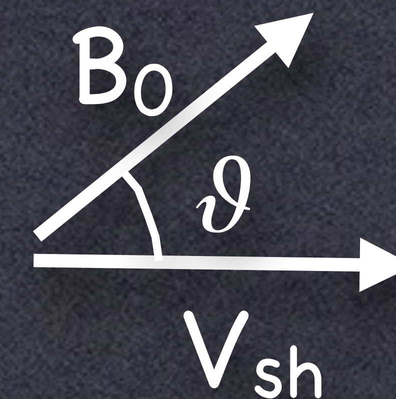
- Evolution of E_{max}(t) according to DSA (e.g., Drury 1983)

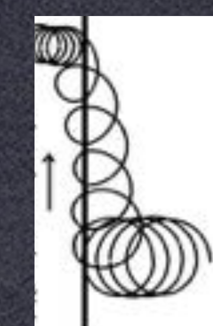
$$T_{acc}(E) = \frac{3}{u_1 - u_2}\left[\frac{D_1(E)}{u_1} + \frac{D_2(E)}{u_2}\right] \simeq \frac{3r^3}{r^2-1}\frac{D(E)}{v_{sh}^2}.$$

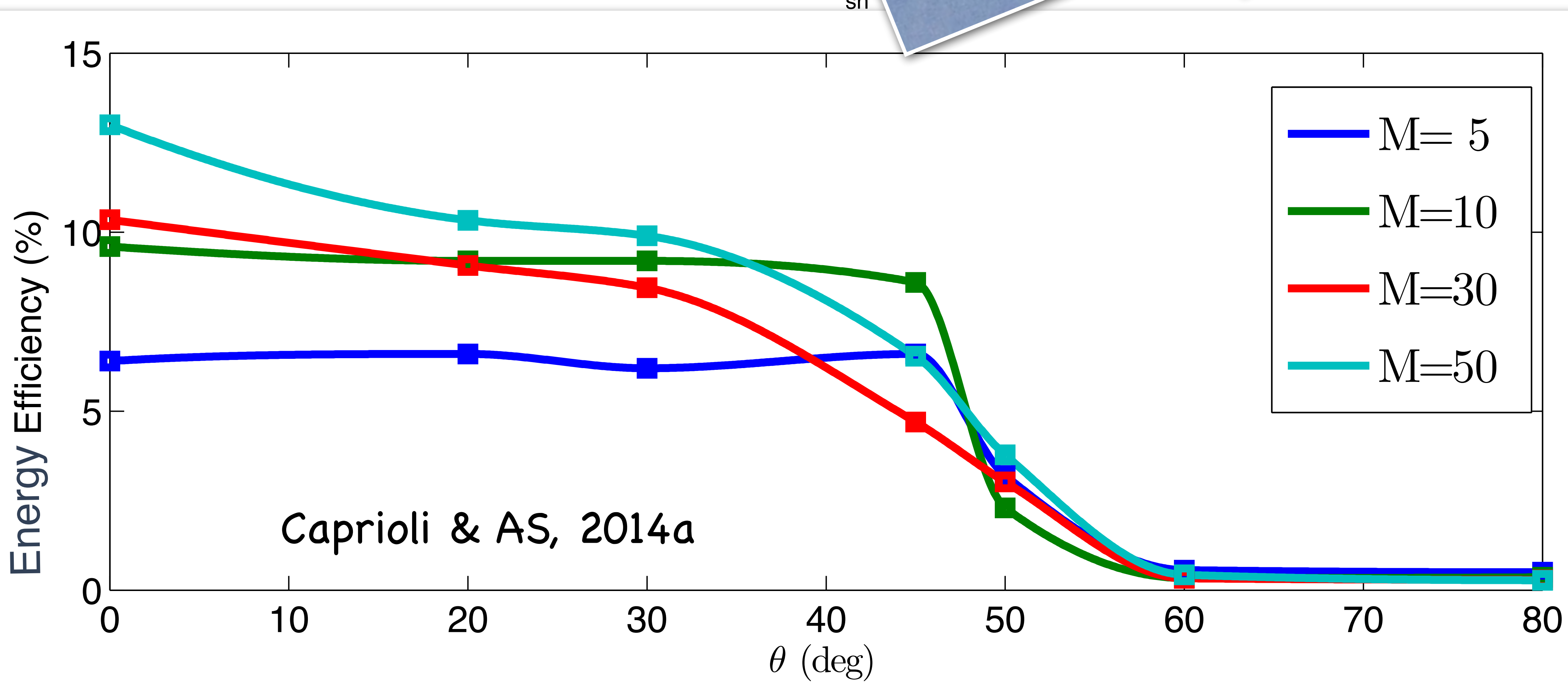
Caprioli & AS, 2014c

Acceleration in parallel vs oblique shocks







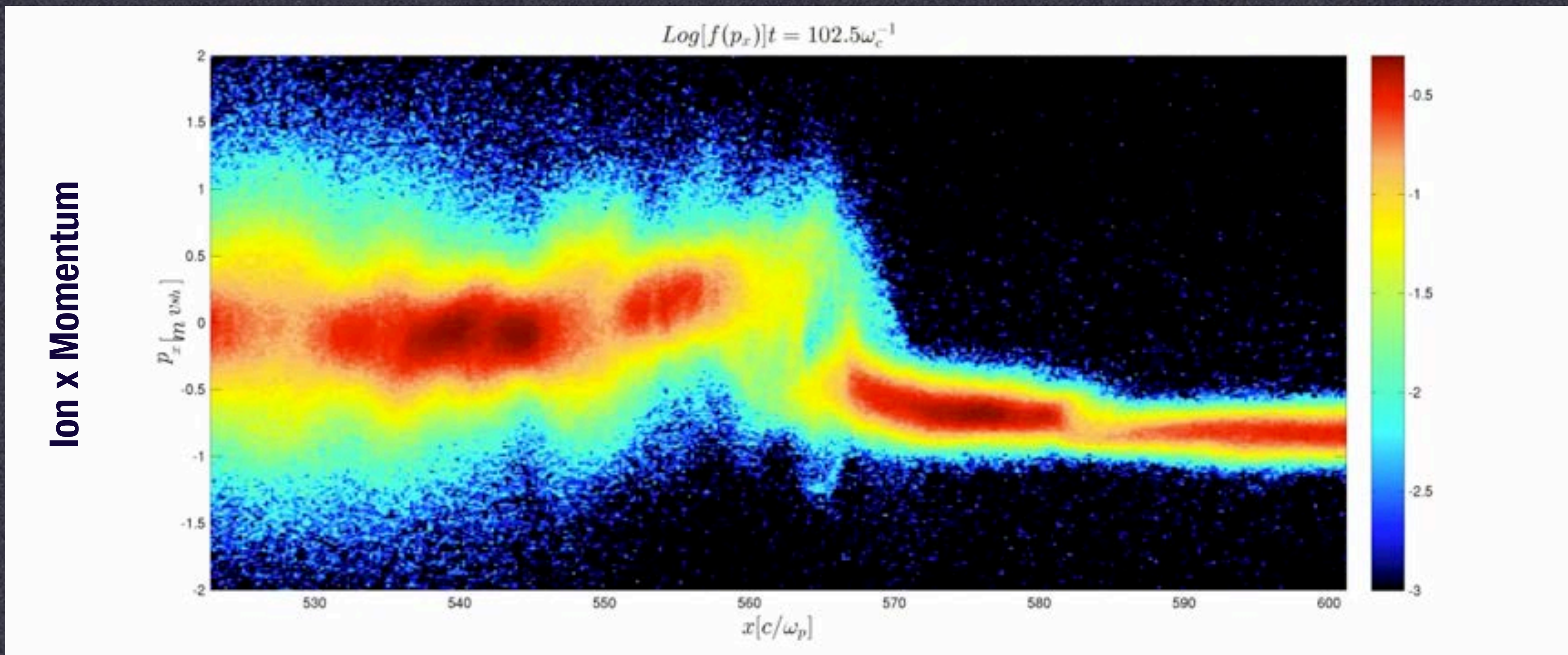


About 1% accelerated protons by number, what is causing that?

Shock structure & injection

dHYBRID

Quasiparallel shocks look like intermittent quasiperp shocks

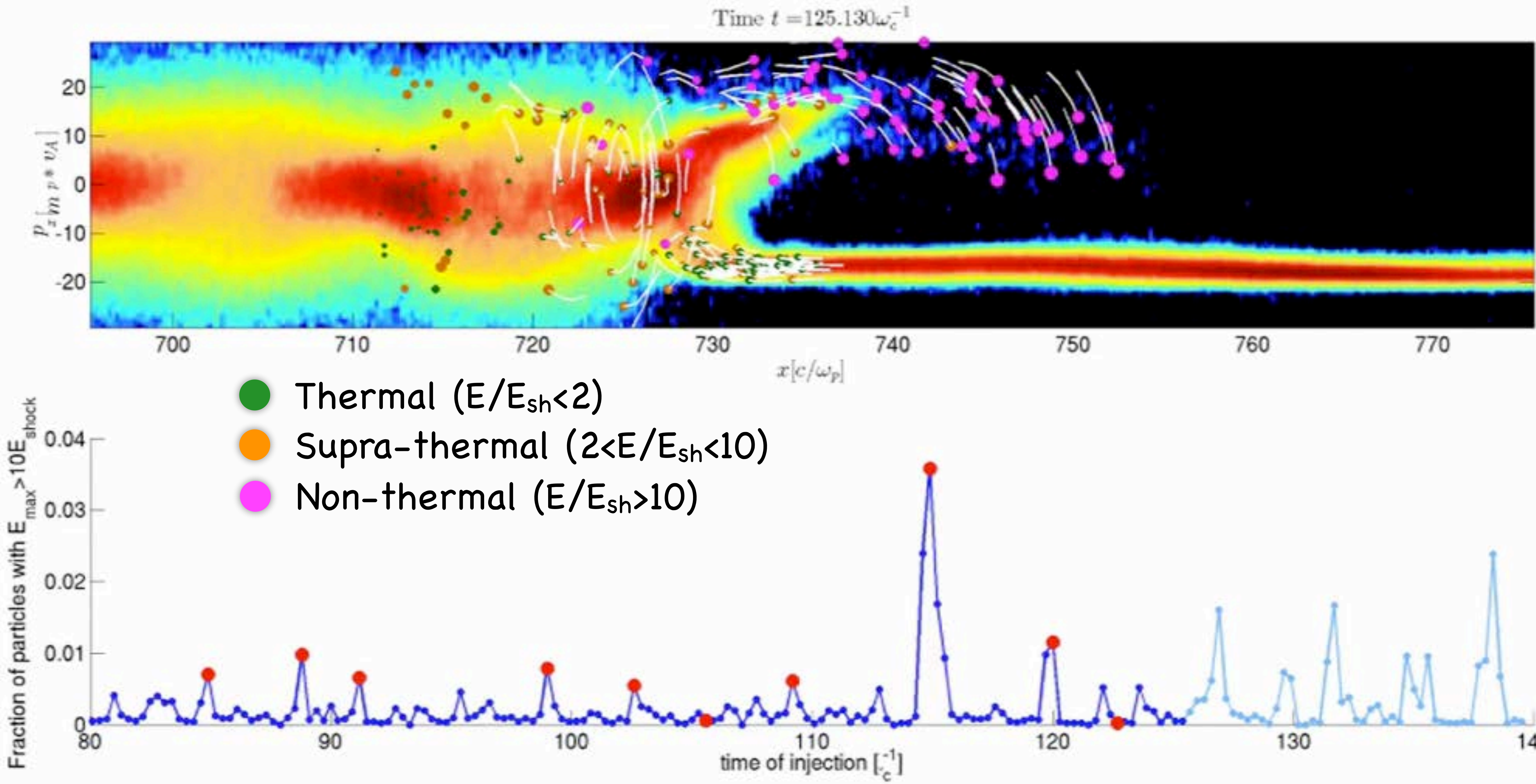


Injection of ions happens on first crossing due to specular reflection from reforming magnetic and electric barrier and shock-drift acceleration.

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

Injection mechanism: importance of timing

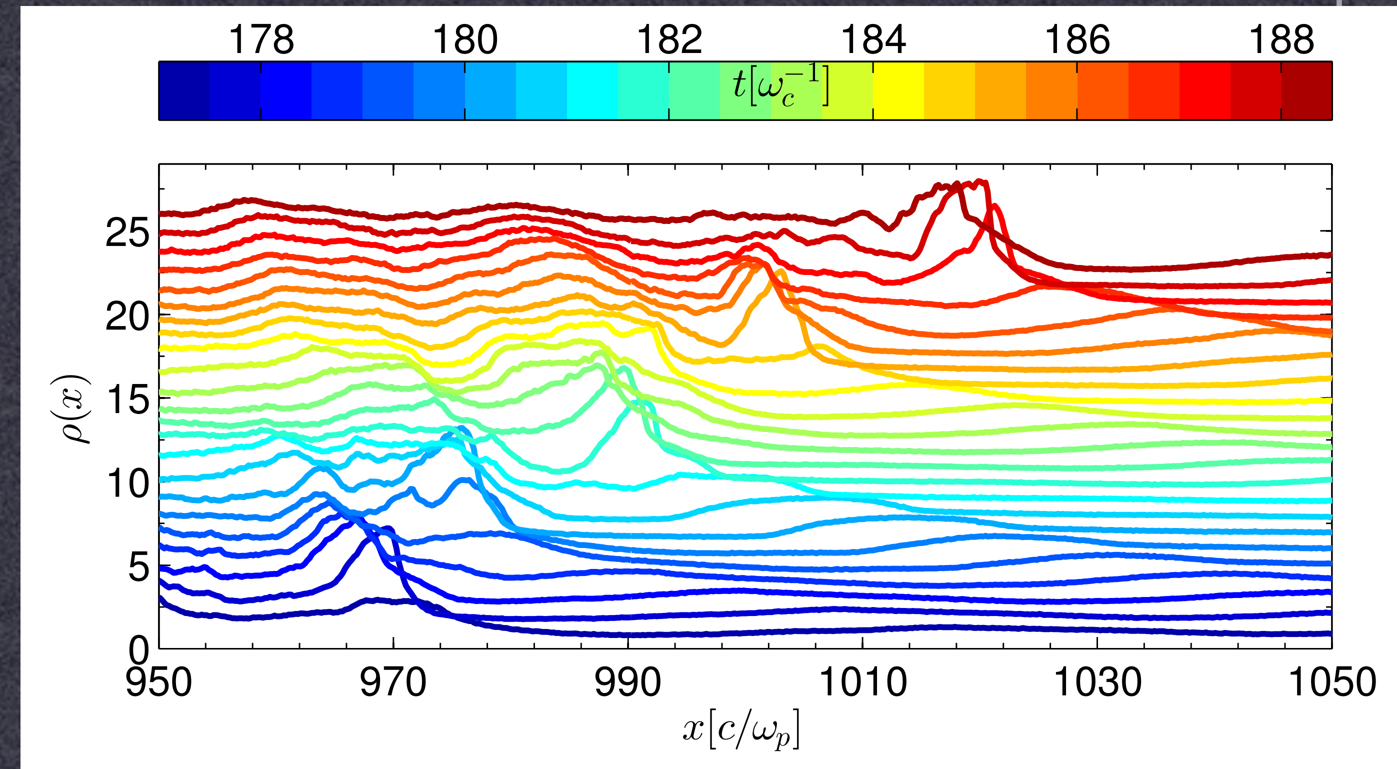
Caprioli, Pop & AS 2015



Proton injection: theory

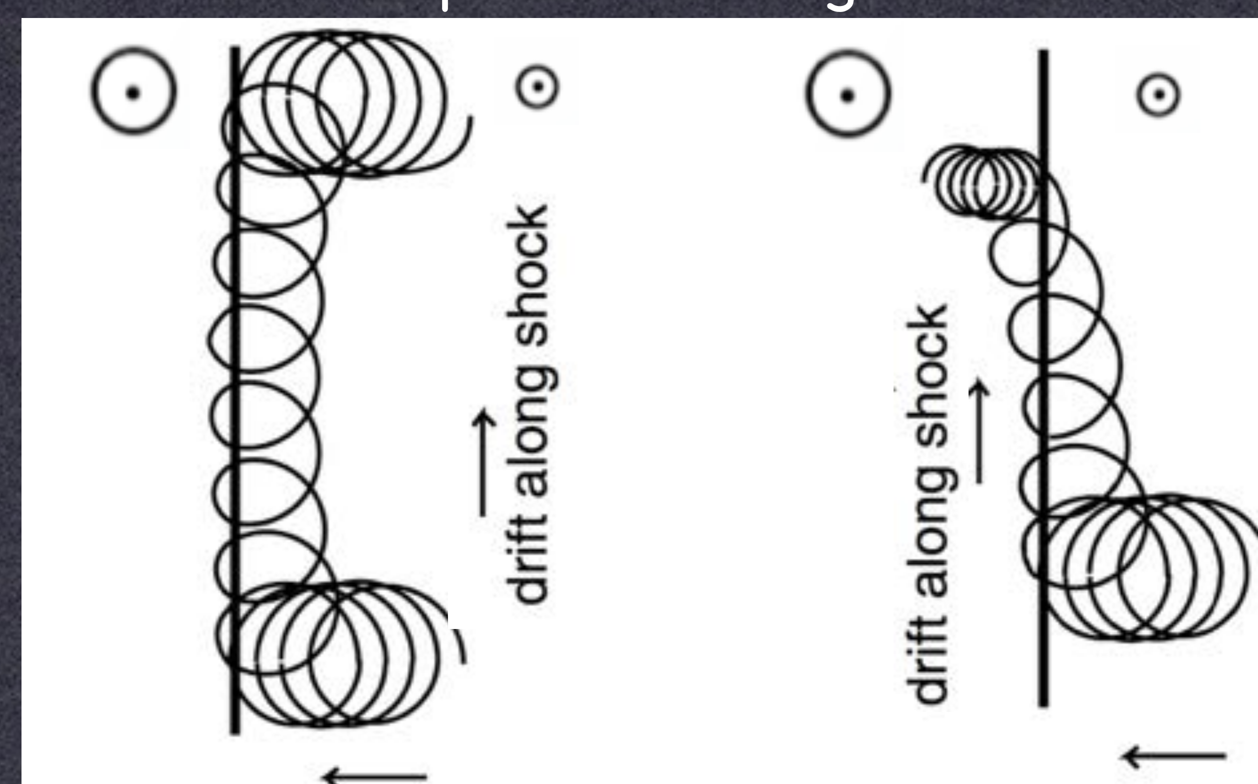
Caprioli, Pop & AS 2015

- 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
- Each cycle is "leaky", not everyone comes back for more
- Higher obliquities less likely to get injected



Shock-drift acceleration:

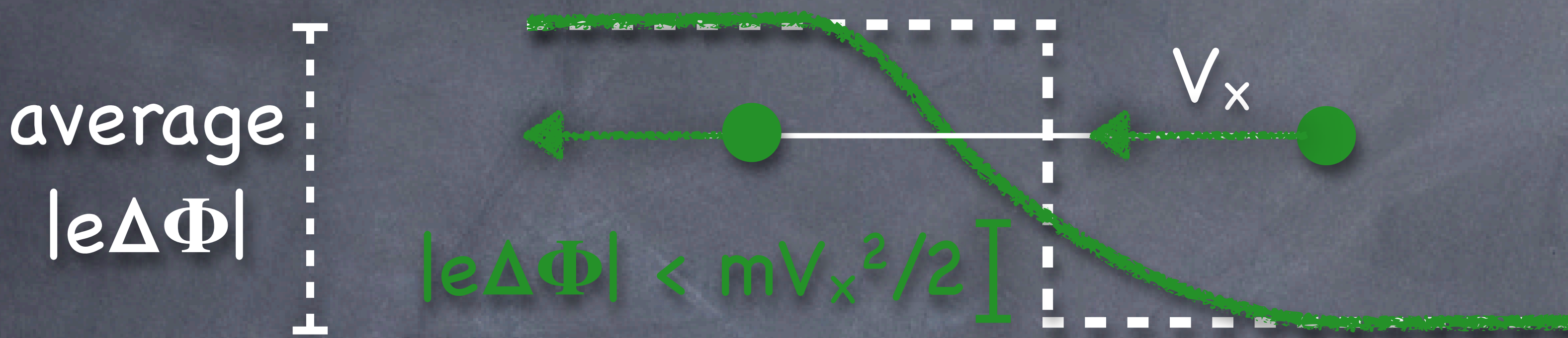
downstream upstream Larger B Smaller B



Path of incoming particle

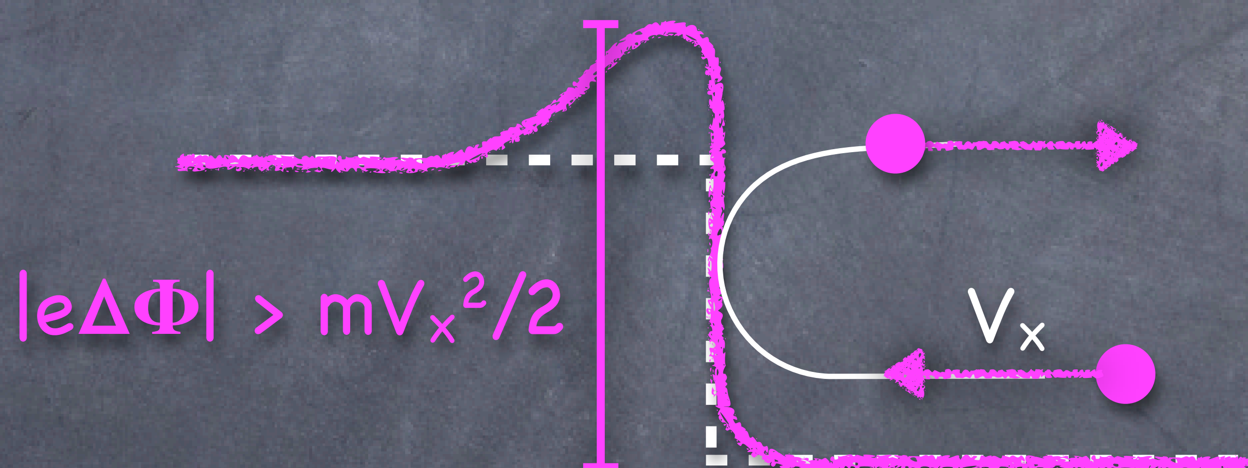
Encounter with the shock barrier

- Low barrier (shock reforming)



Particles are advected downstream, and thermalized

- High barrier (overshoot)



Particles are reflected upstream, and energized via Shock Drift Acc.

- To overrun the shock, proton need a minimum E_{inj}, increasing with ϑ
- Particle fate determined by barrier duty cycle (~25%) and shock inclination
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For ϑ=45°, $E_{inj} \sim 10 E_0$, which requires N~3 -> $\eta \sim 1\%$

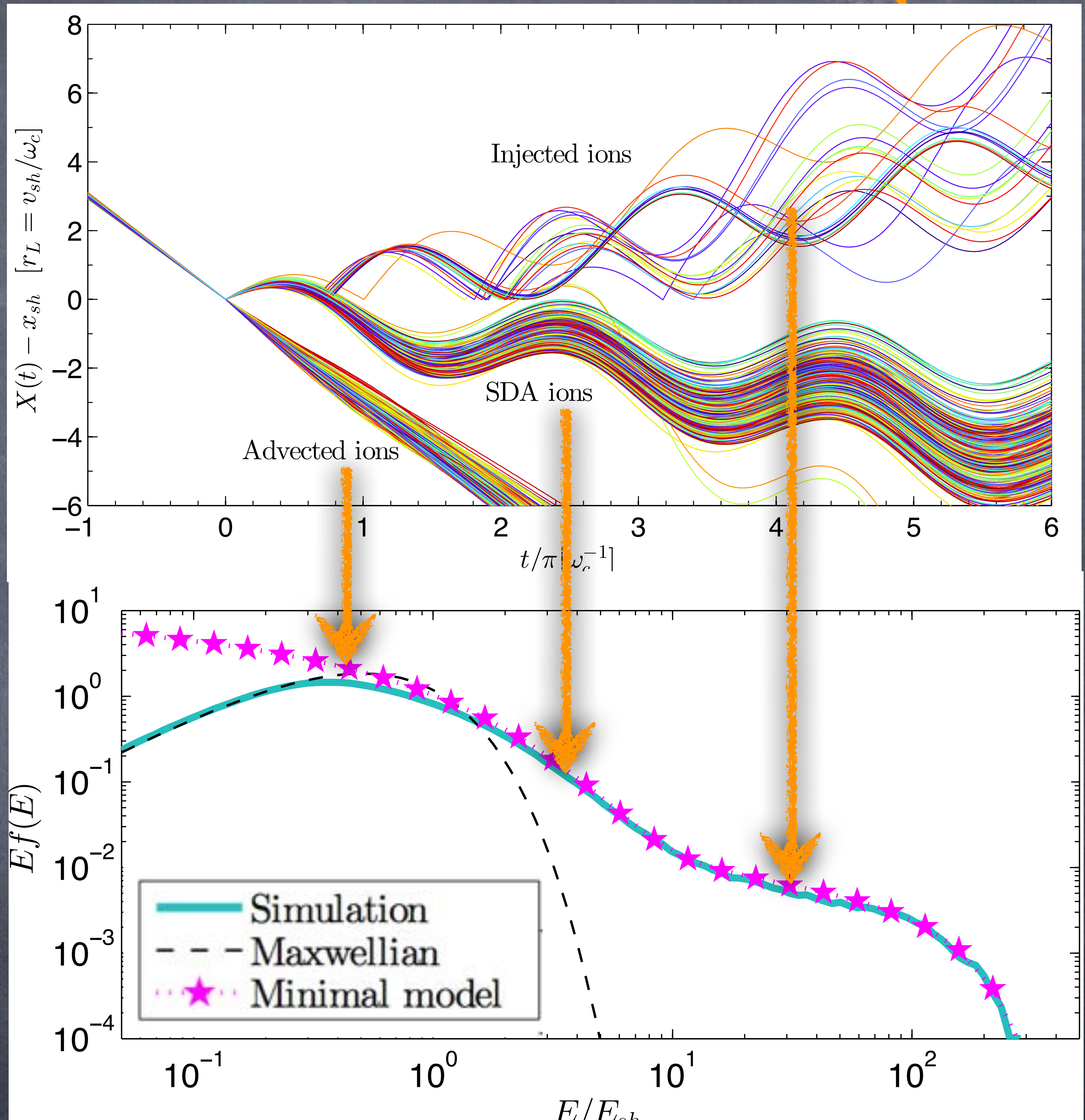
Minimal Model for Ion Injection

- 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



$p_{\rm inj} \approx 2.3 m_p V_{\rm sh} = 30 m_e c$

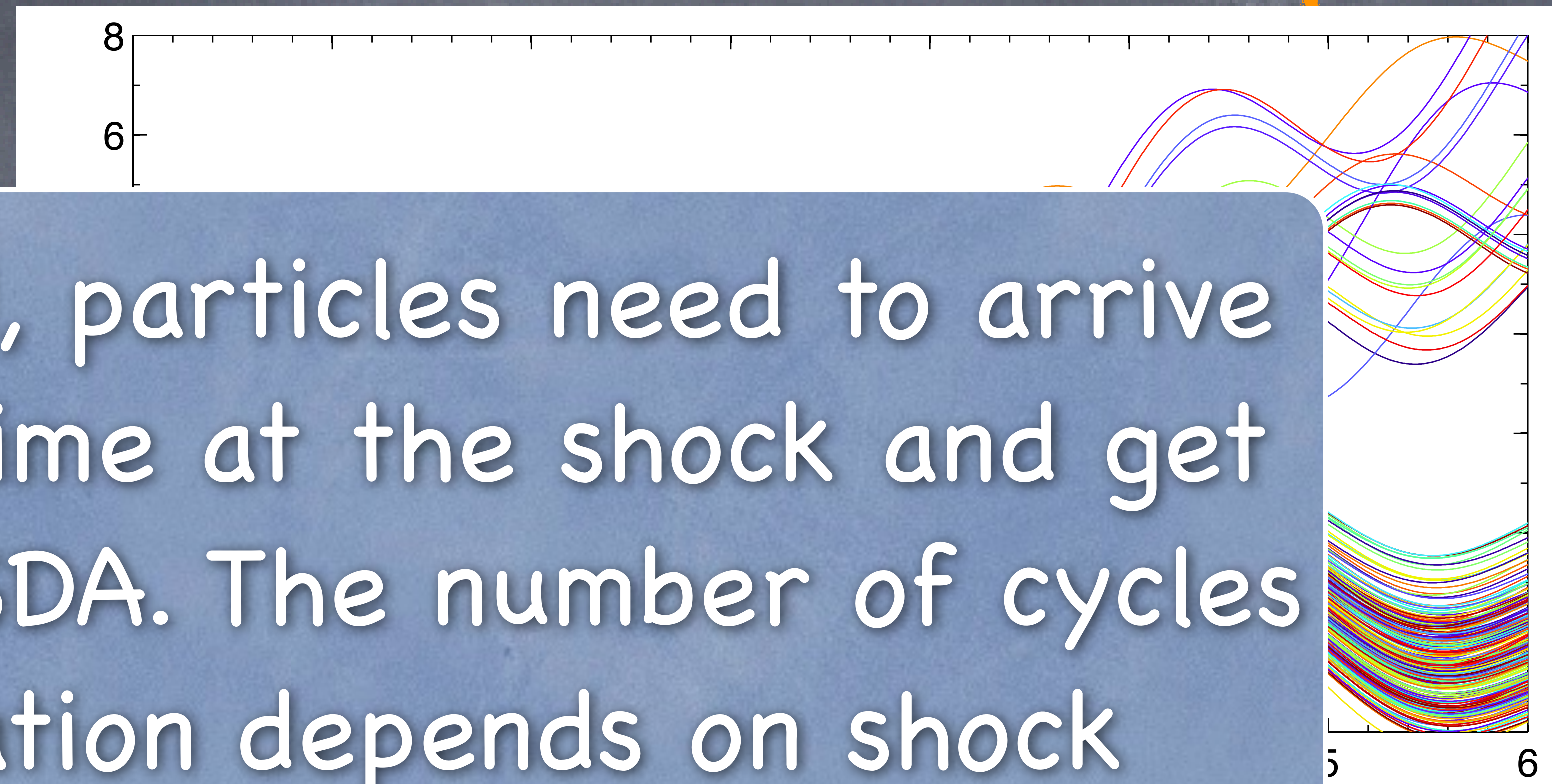
Caprioli, Pop & Spitkovsky, 2015

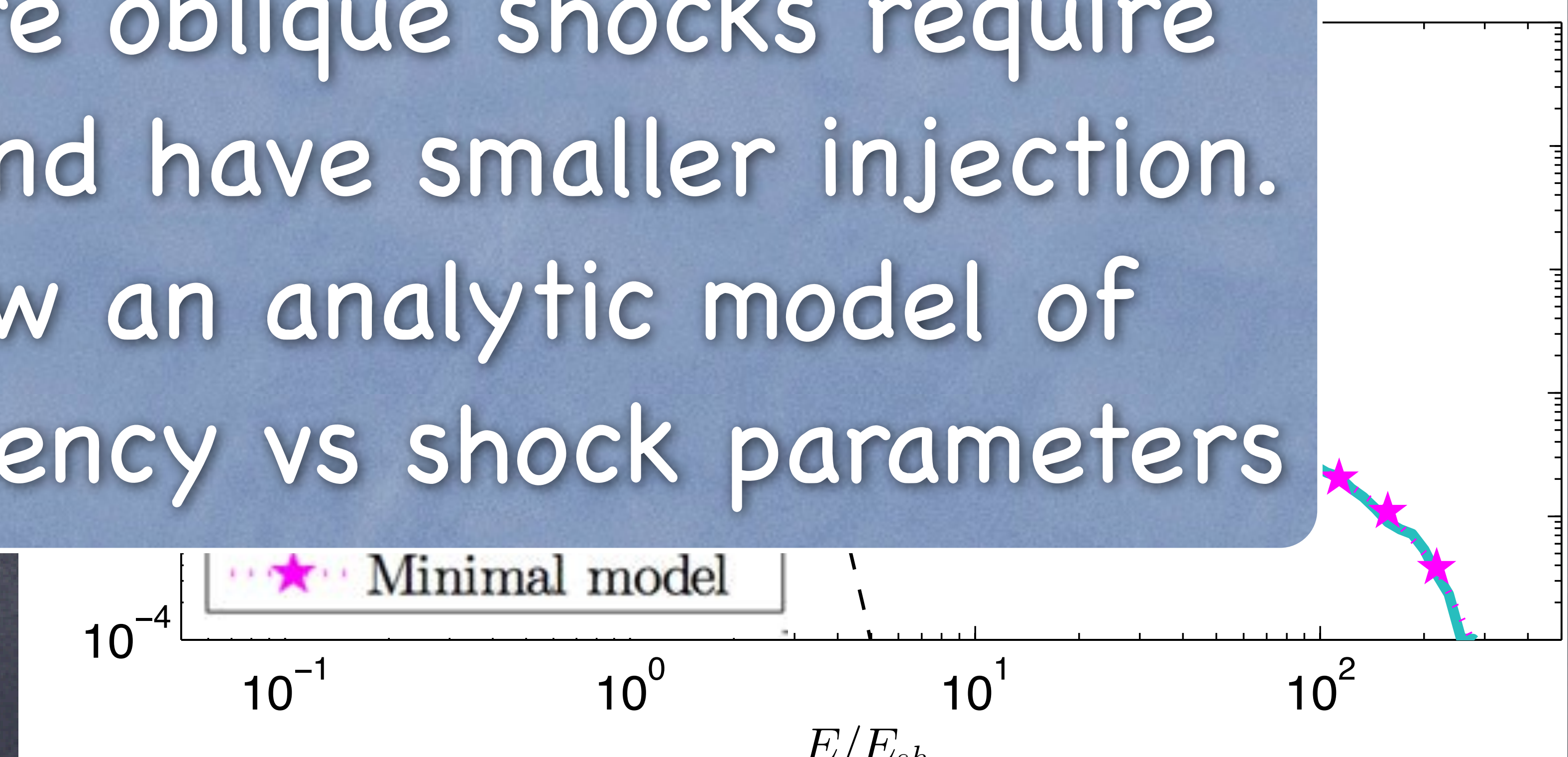
Minimal Model for Ion Injection

- Time-varying potential barrier
  - High...
    -> R...
    -> S...
  - Low-...
- Spectru...

$f(E) \propto$ ...

- P=proba...
- ε =fractional energy gain/cycle



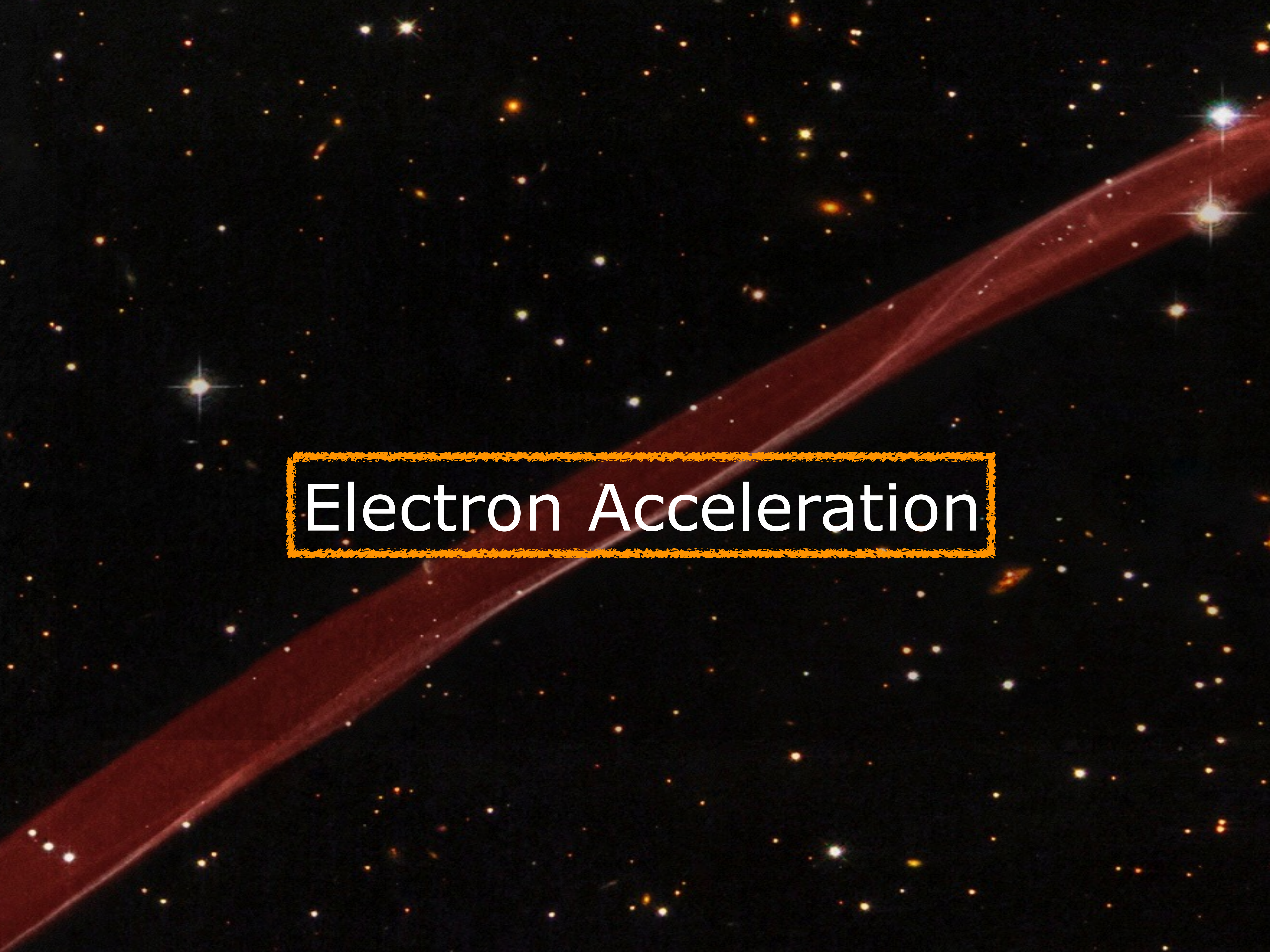


$p_{\rm inj} \approx 2.3 m_p V_{\rm sh} = 30 m_e c$

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 efficiency vs shock parameters

Caprioli, Pop & Spitkovsky, 2015

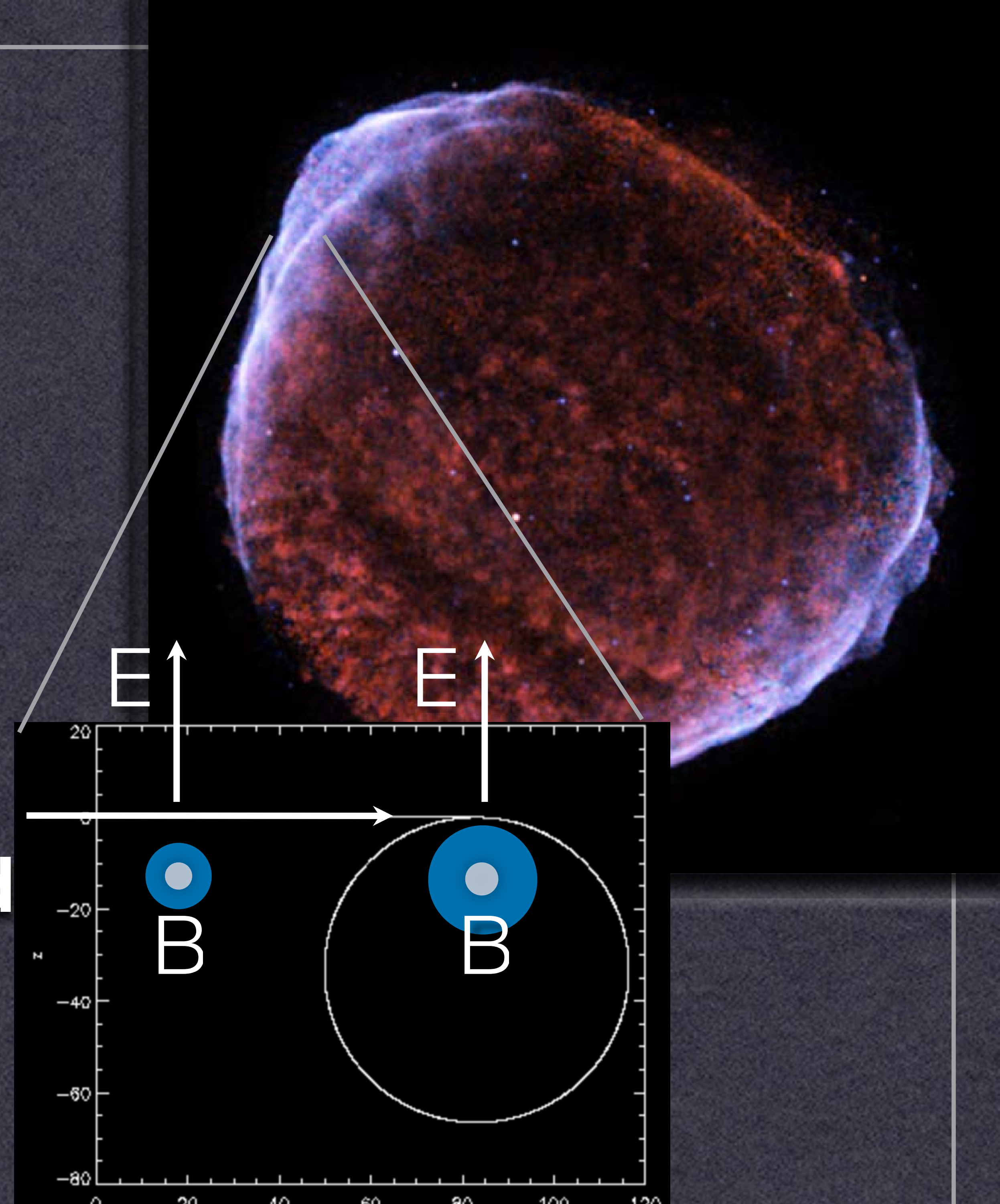
Electron Acceleration



WHAT ACCELERATES ELECTRONS?

Electrons are notorious for being difficult to inject because of the disparity in the Larmor scales with ions.

Shock is driven on ion scales, electrons need to be pre-accelerated to be injected. But how?

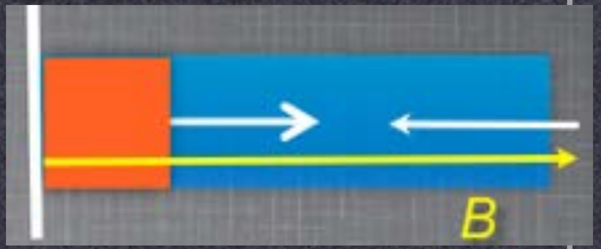


Typically electron acceleration is suppressed because e Larmor radius is << ion Larmor radius. Need pre-acceleration of electrons.

This means trapping at the shock, and turbulence upstream. Is it self-generated?

Electron acceleration at parallel shocks

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



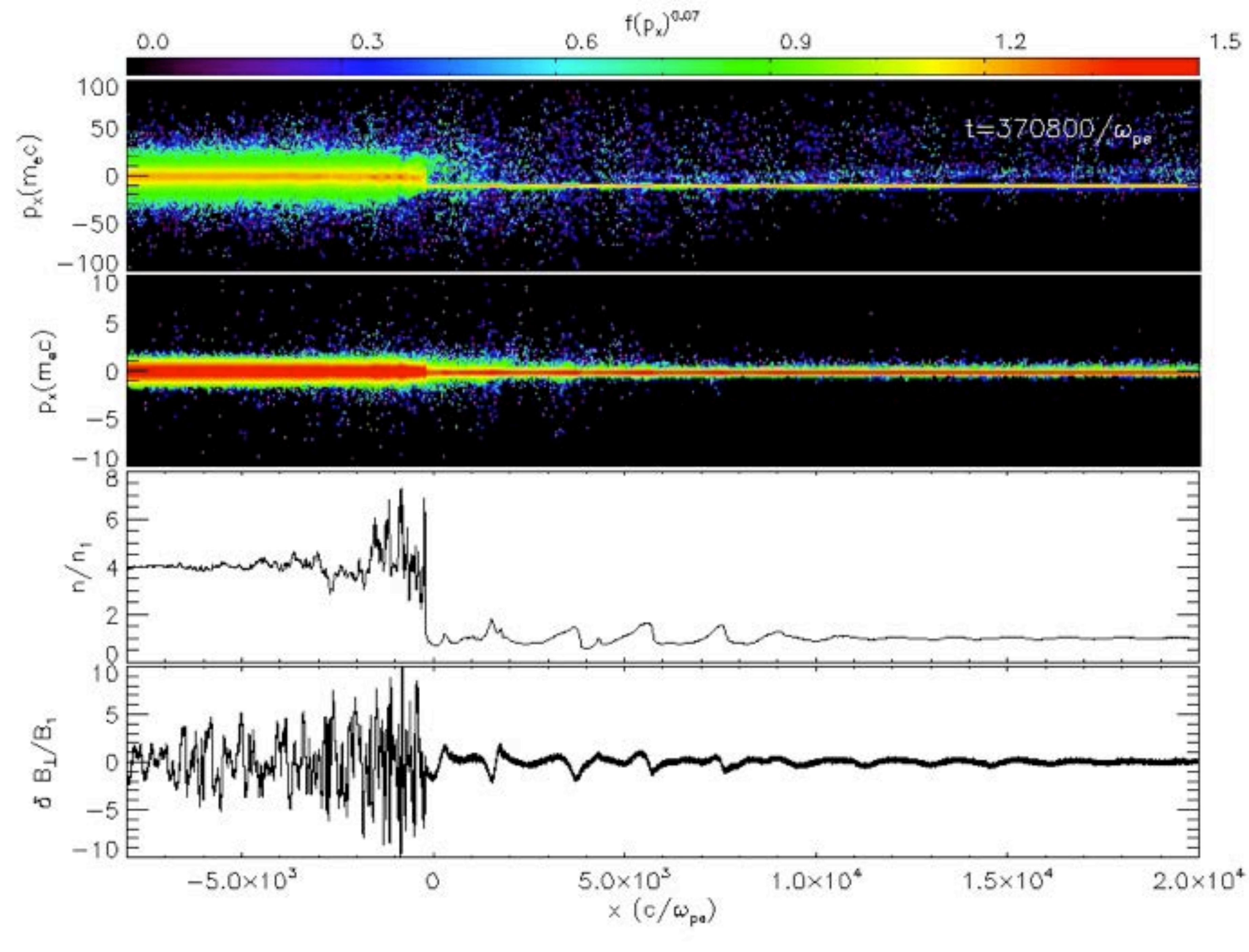
Ion-driven Bell waves drive electron acceleration: correct polarization

Ion phase space

Electron phase space

Density

Transverse Magnetic field



Electron acceleration at parallel shocks

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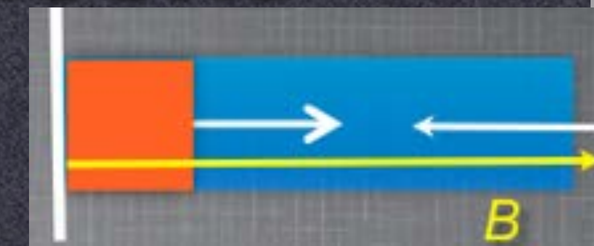

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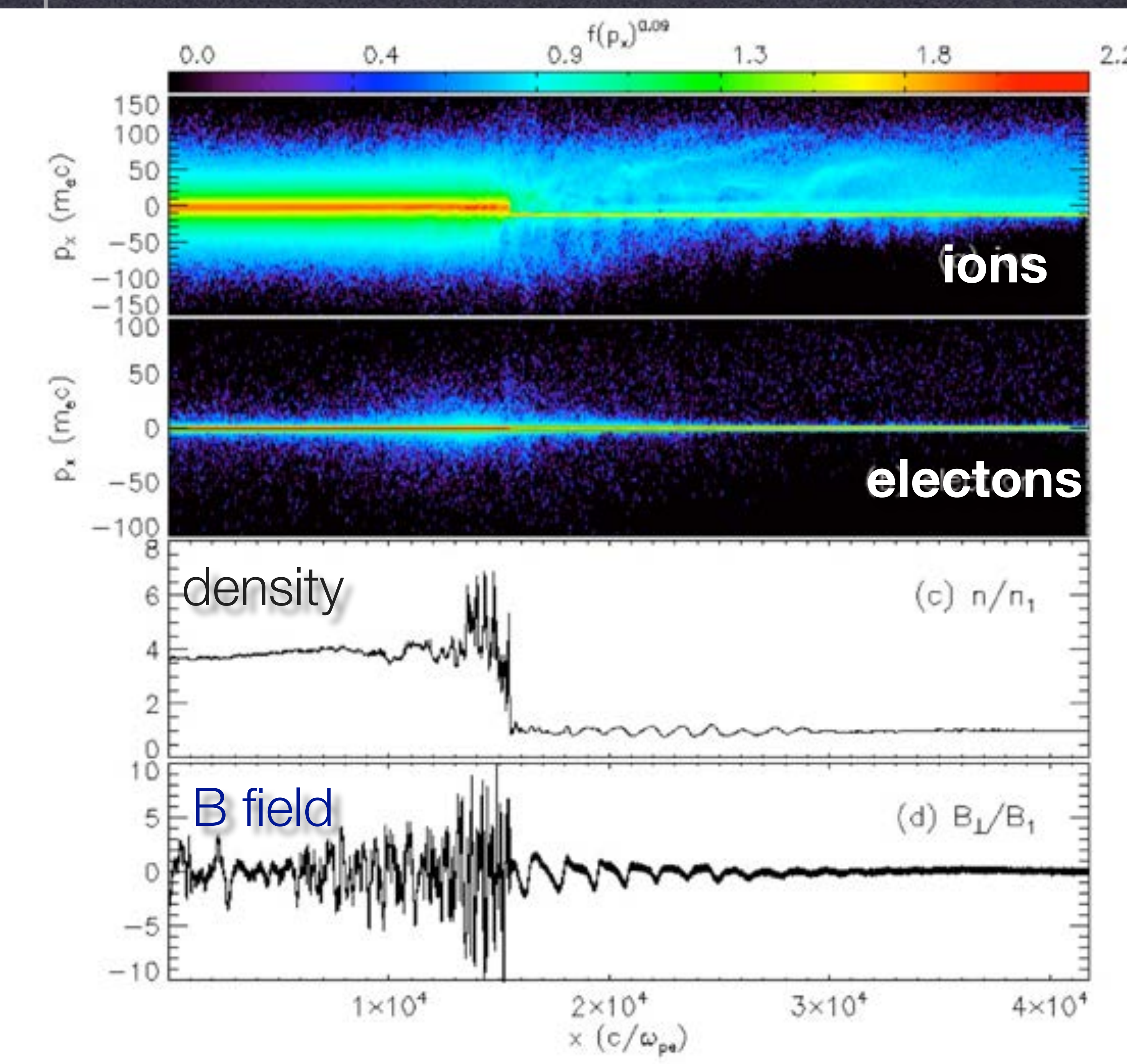
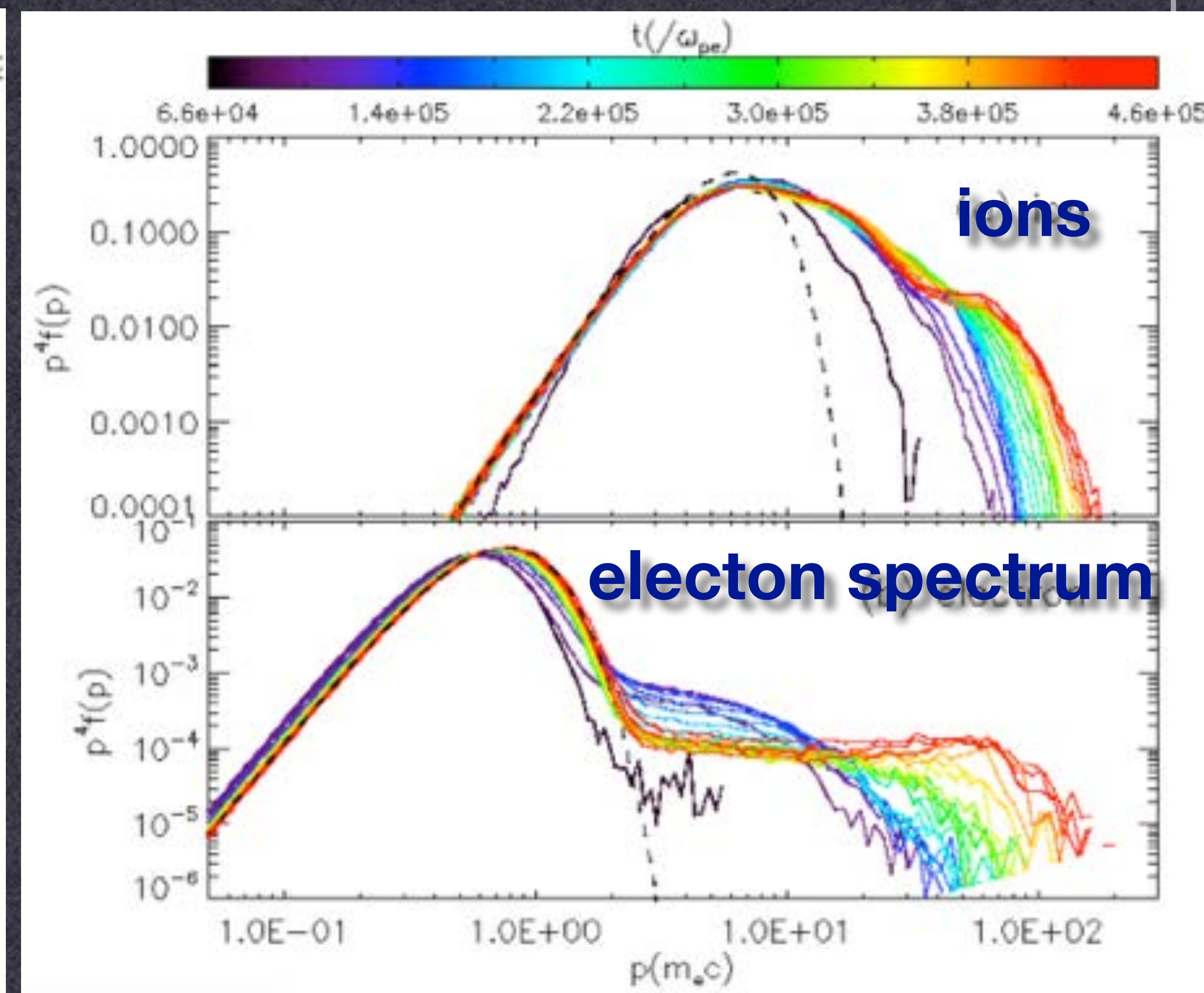


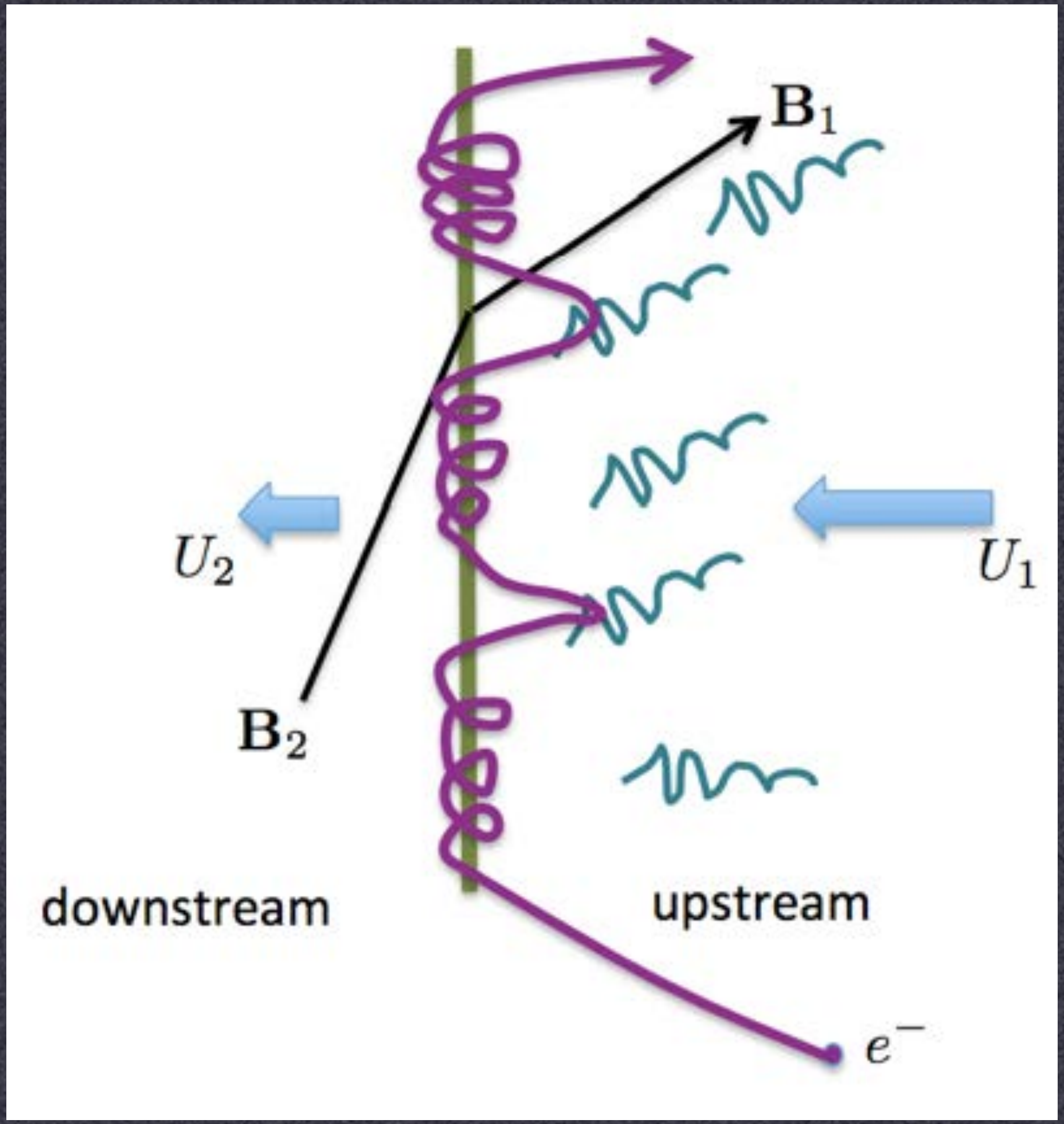


DSA spectrum recovered in _both_ electrons and ions
Electron-proton ratio can be measured!

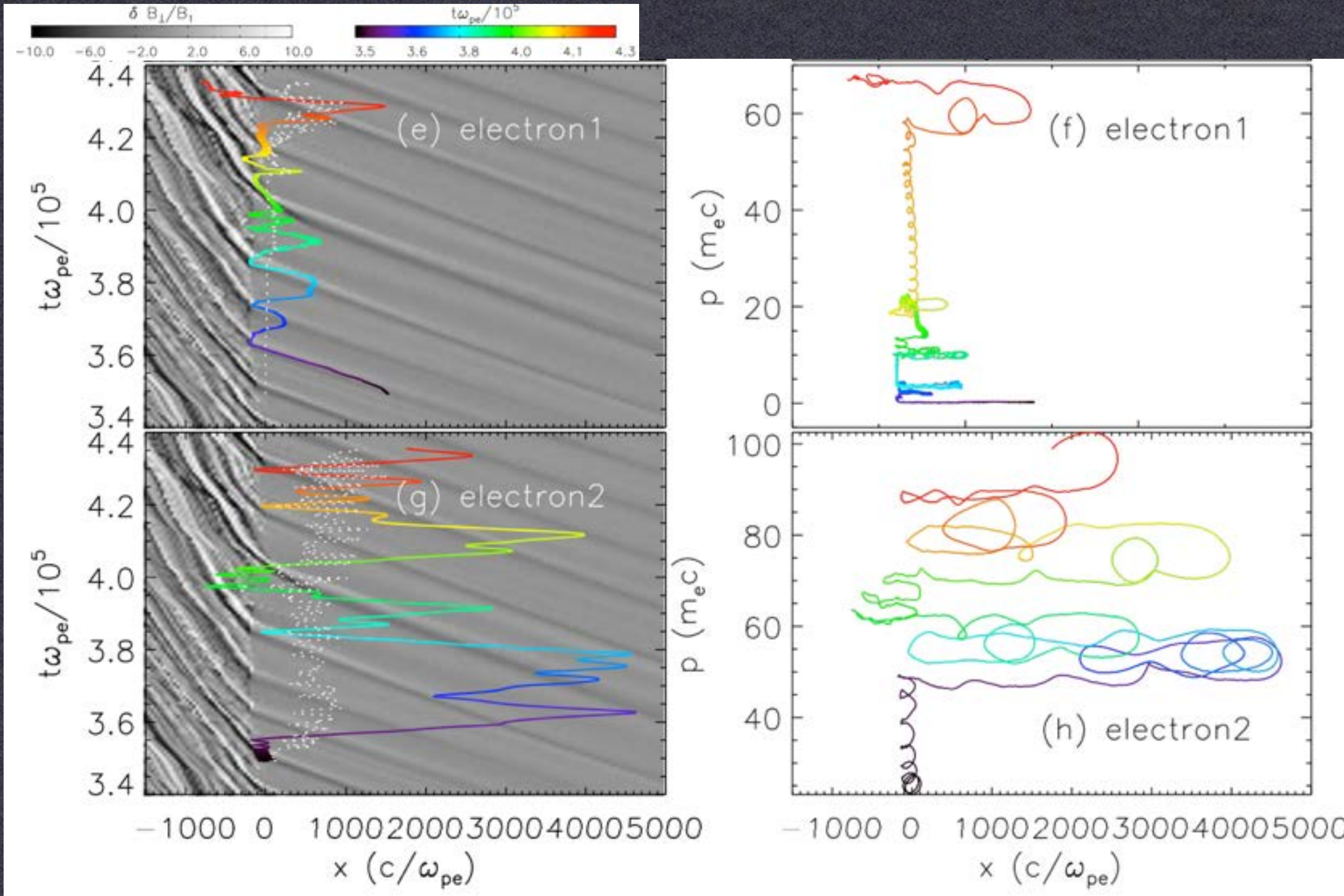
Park, Caprioli, AS (2015)

Electron acceleration at parallel shocks

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



Electron acceleration mechanism: shock drift cycles



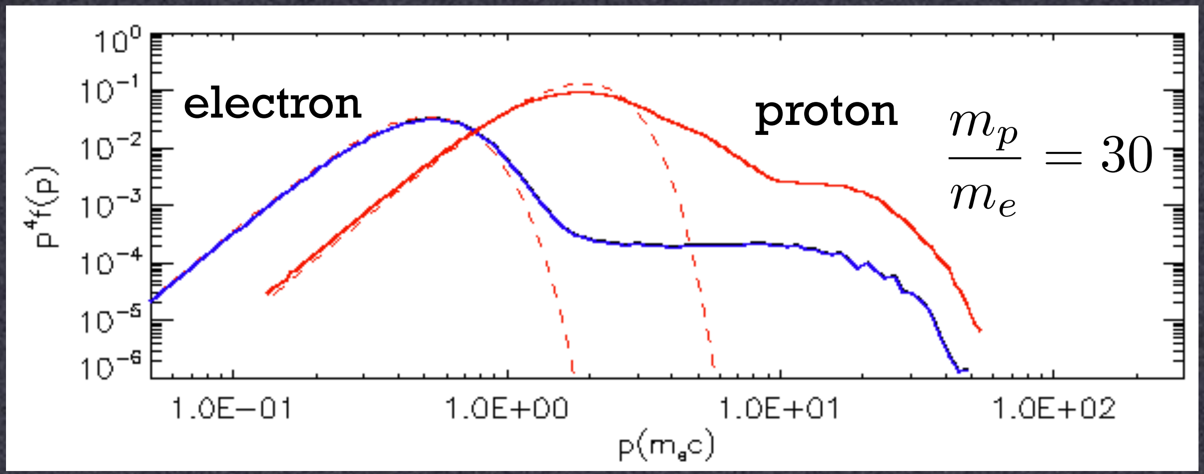
Shock-drift

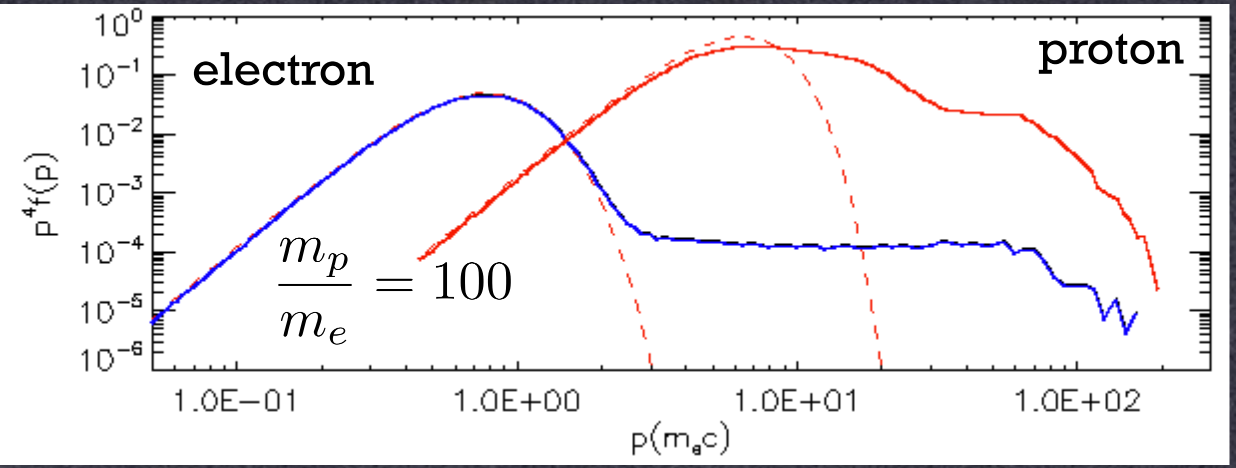
Diffusive

Electron track from PIC simulation

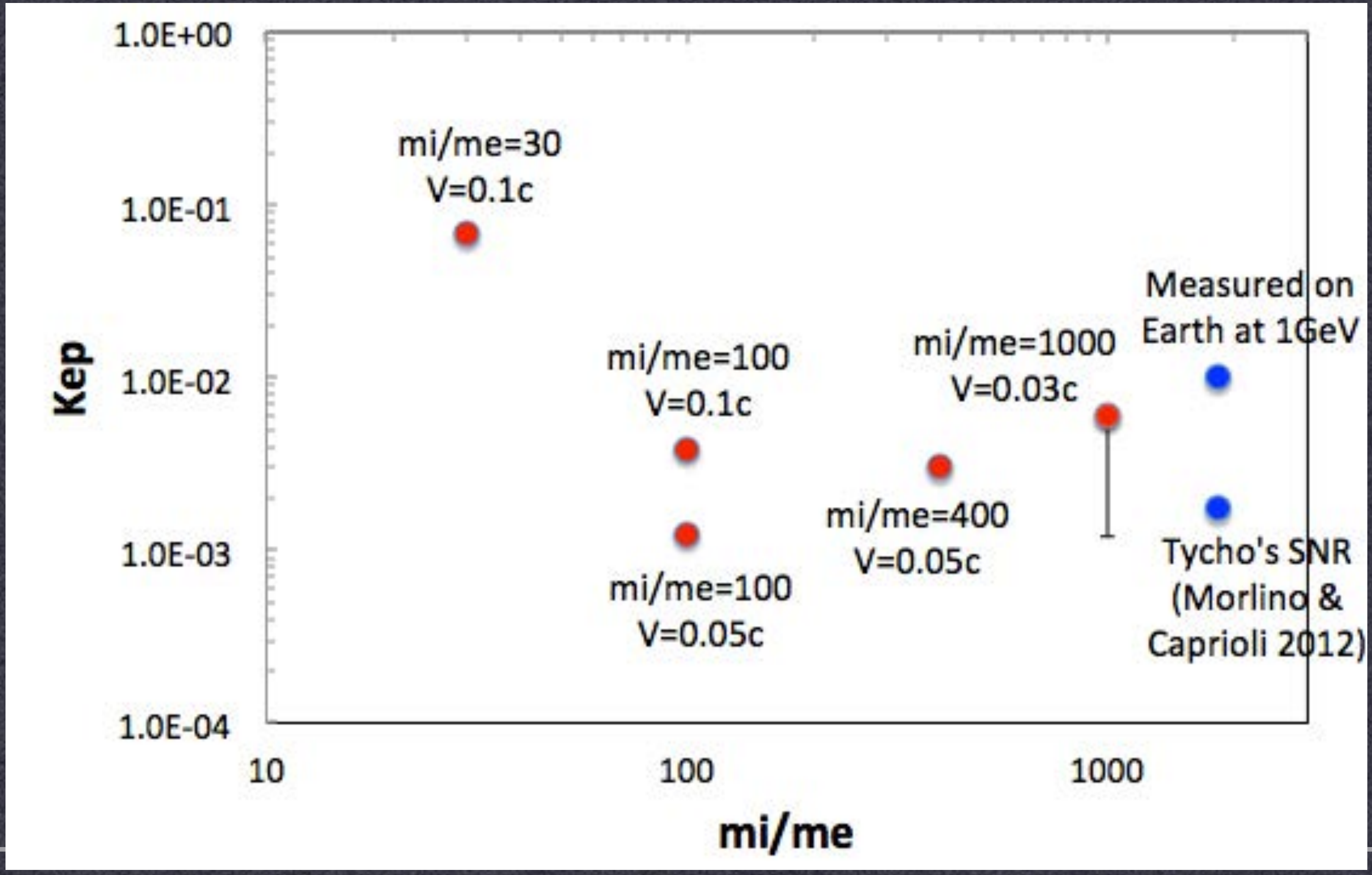
Electron-proton ratio K_{ep}:

Park, Caprioli, AS (2015)



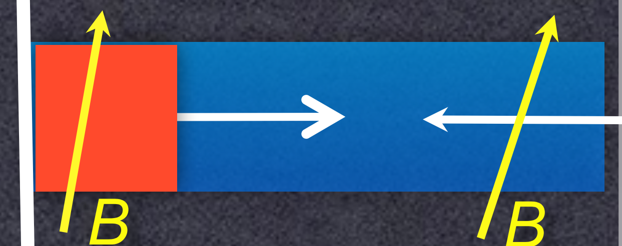


$$K_{\rm ep} \equiv \frac{f_e(p)}{f_p(p)} = \text{const for } p > p_{\rm inj} \quad K_{\rm ep} \approx 3.8 \times 10^{-3} \text{ for } \frac{m_p}{m_e} = 100$$

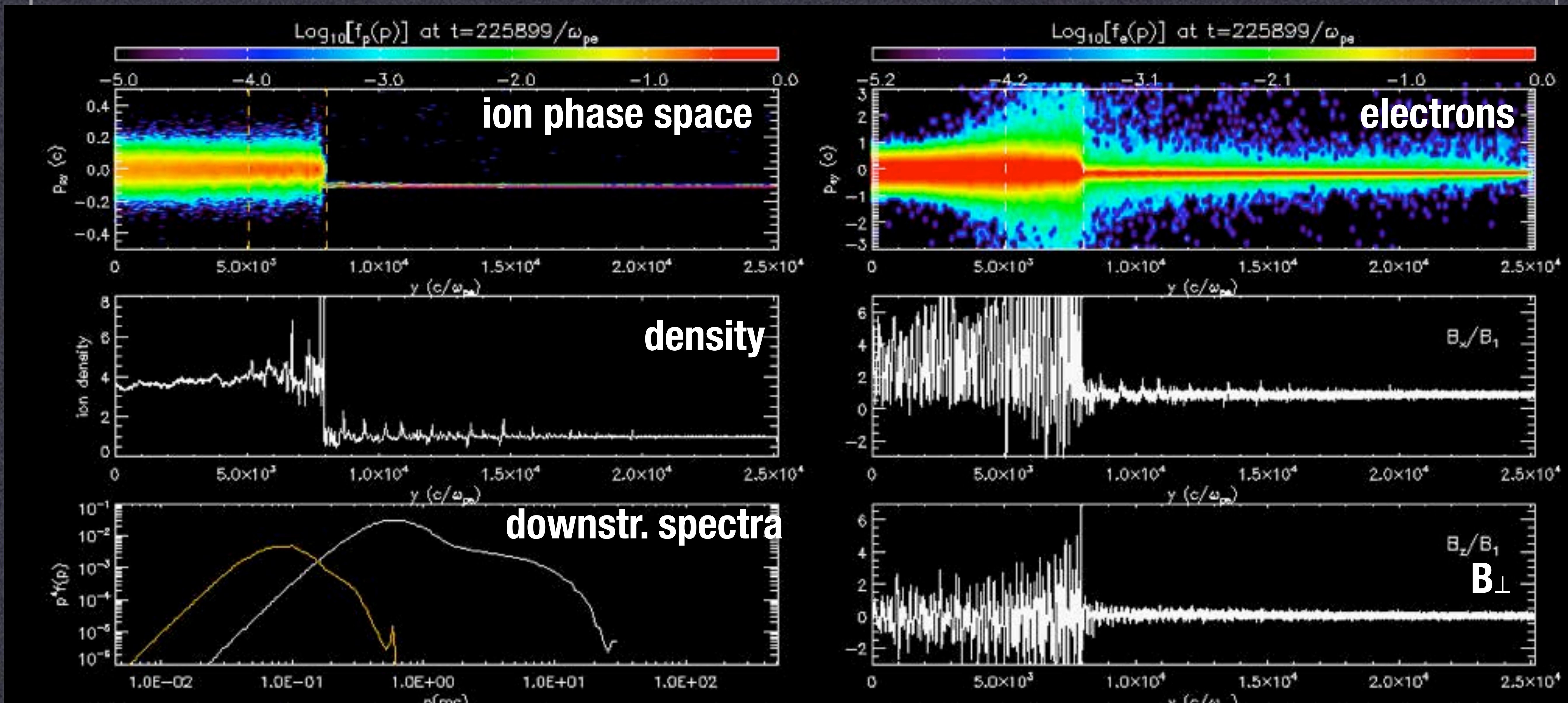


Electron acceleration at ⊥-shocks

60 degrees shock inclination, mi/me=100, M_A=20;
electron-driven waves upstream, v/c=0.1



(Caprioli, Park, AS, in prep)

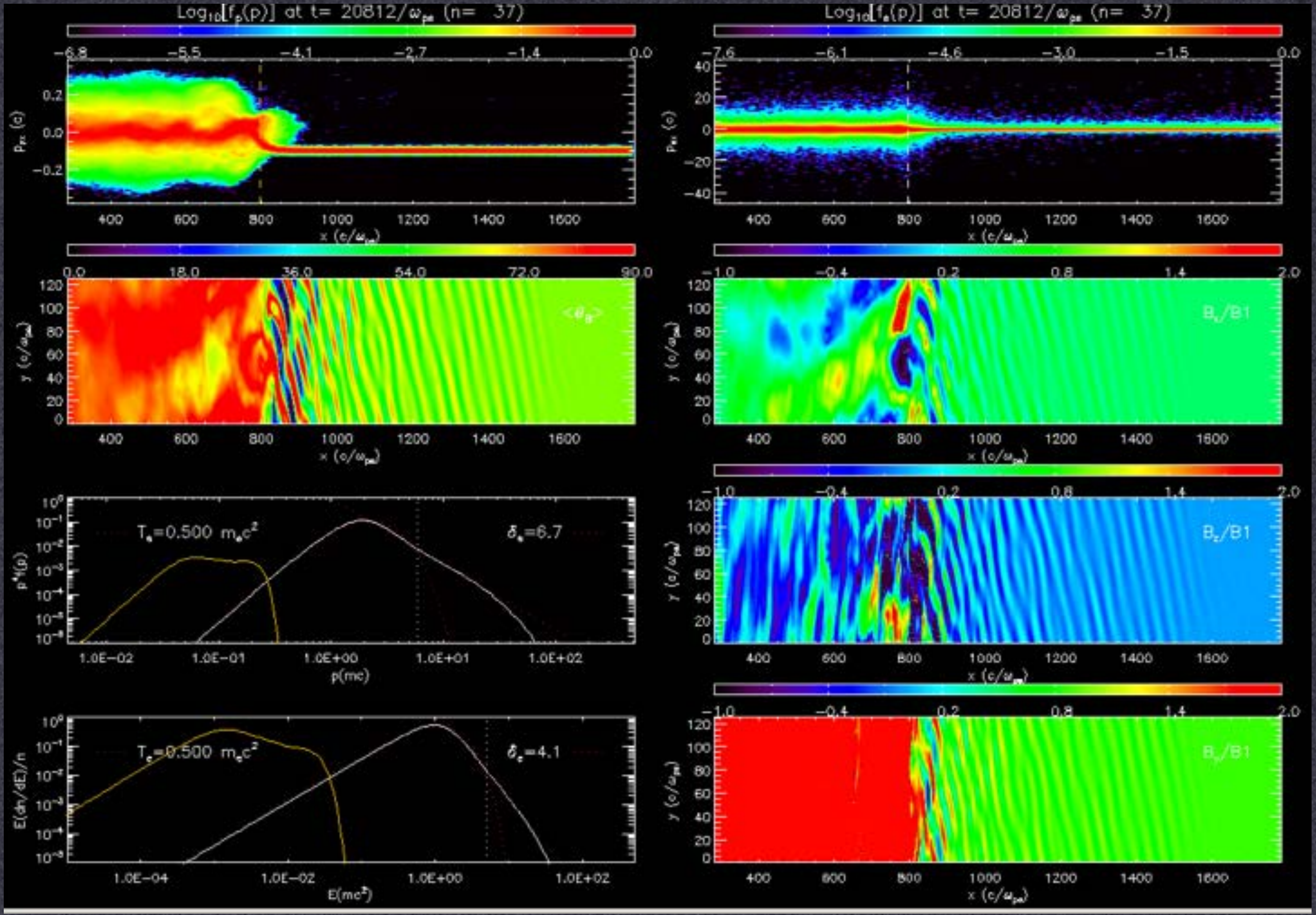


Ions are not injected or accelerated into DSA, while electrons drive their own Bell-type waves. Electrons are reflected from shock due to magnetic mirroring.

Recover DSA electron spectrum, 0.1-4% in energy, <1% by number. Work in Progress…

Electron acceleration at ⊥-shocks: 2D

60 degrees shock inclination, mi/me=1000, M_A=7, v/c=0.1; electron-driven waves upstream



Low-M shocks; Whistler waves in the shock foot for $M_A < m_i/m_e$;

Electron DSA! Large-amplitude Electron-driven modes in the upstream

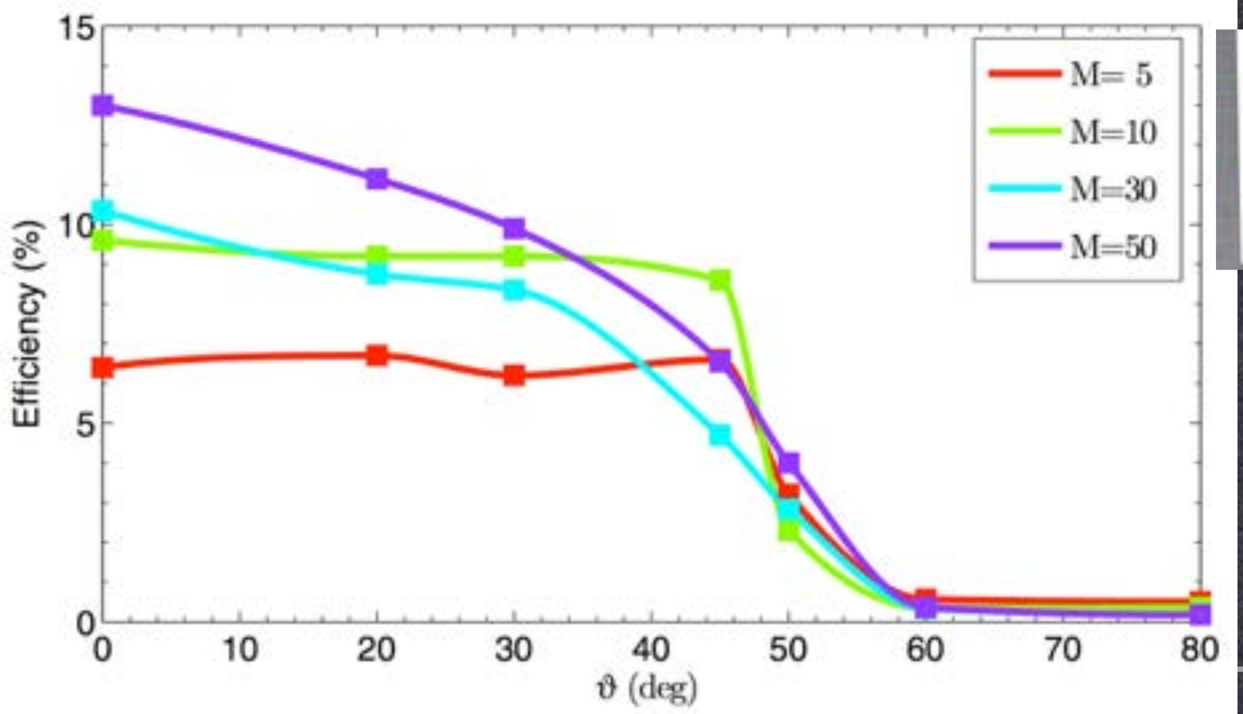
Oblique firehose? (Guo 2014) Or whistlers? Work in Progress…

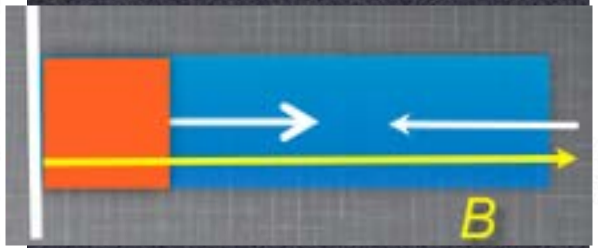
Shock acceleration: emerging picture

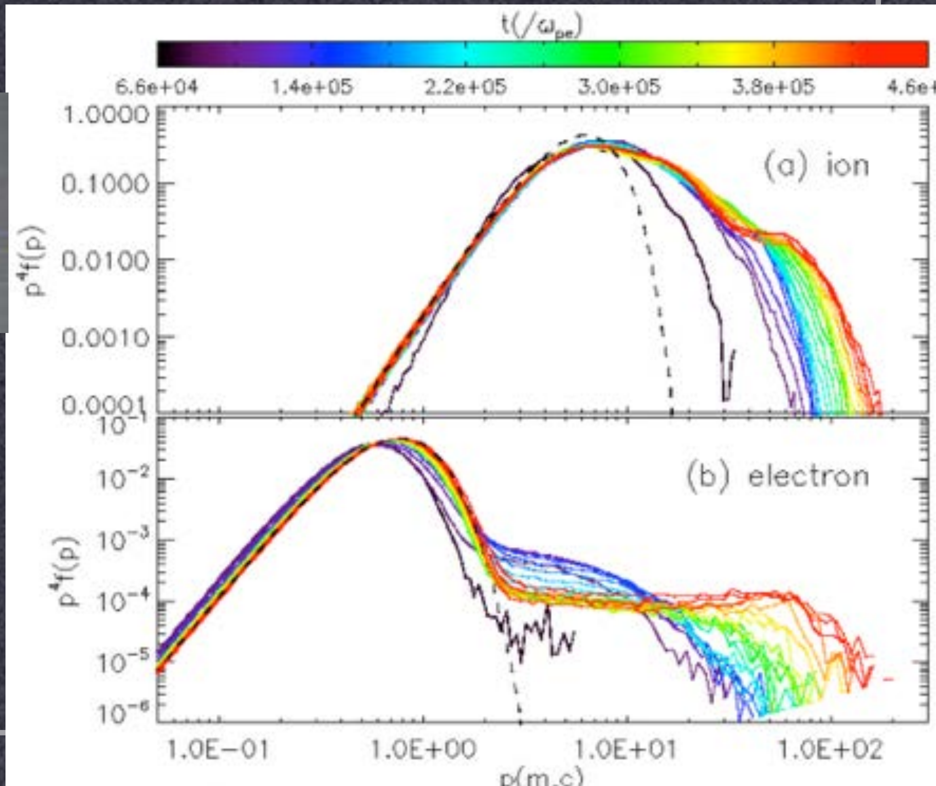
Acceleration in laminar field:

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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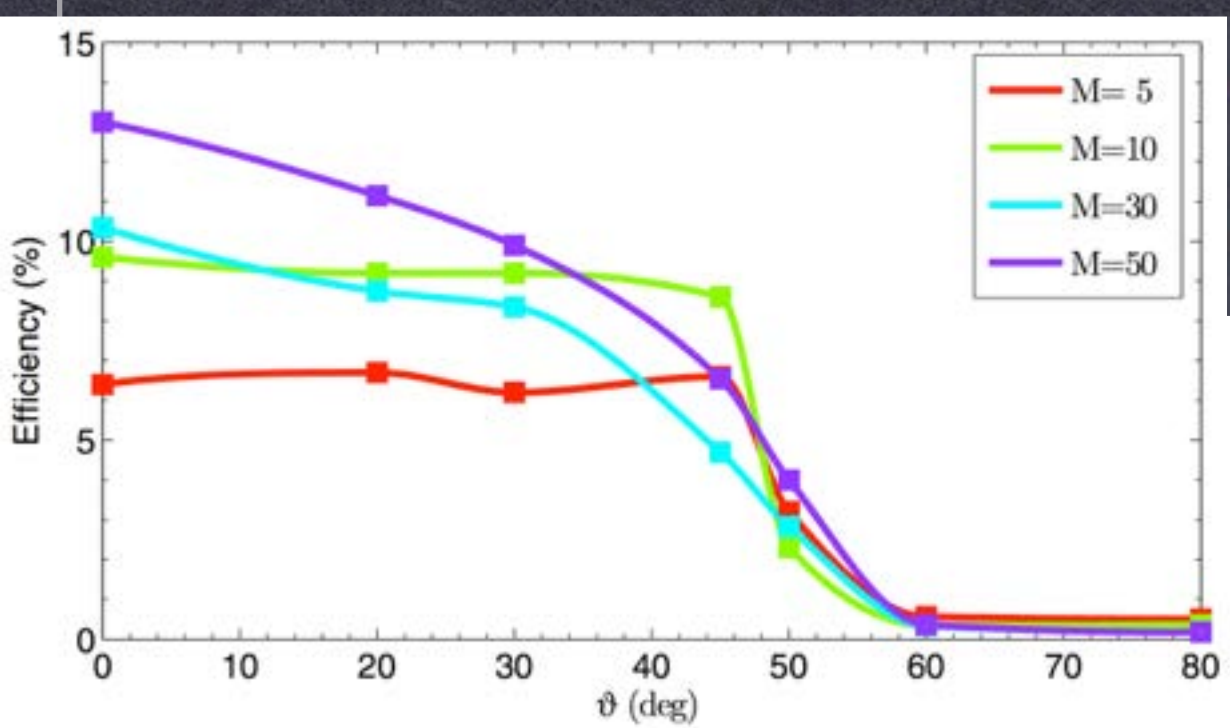
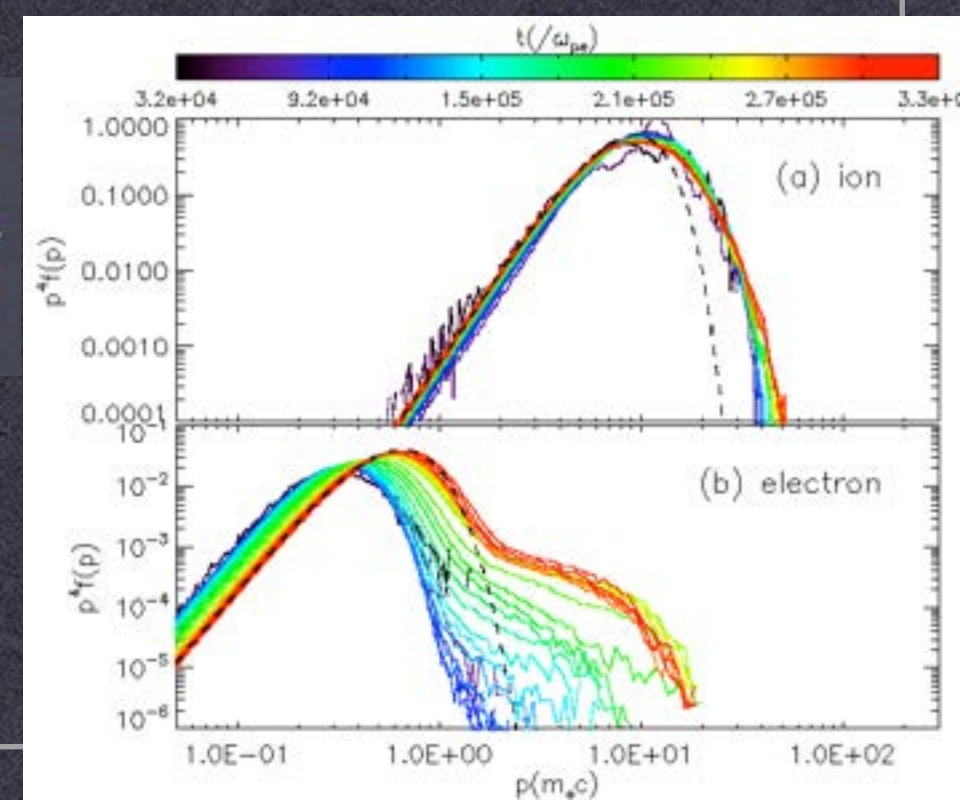
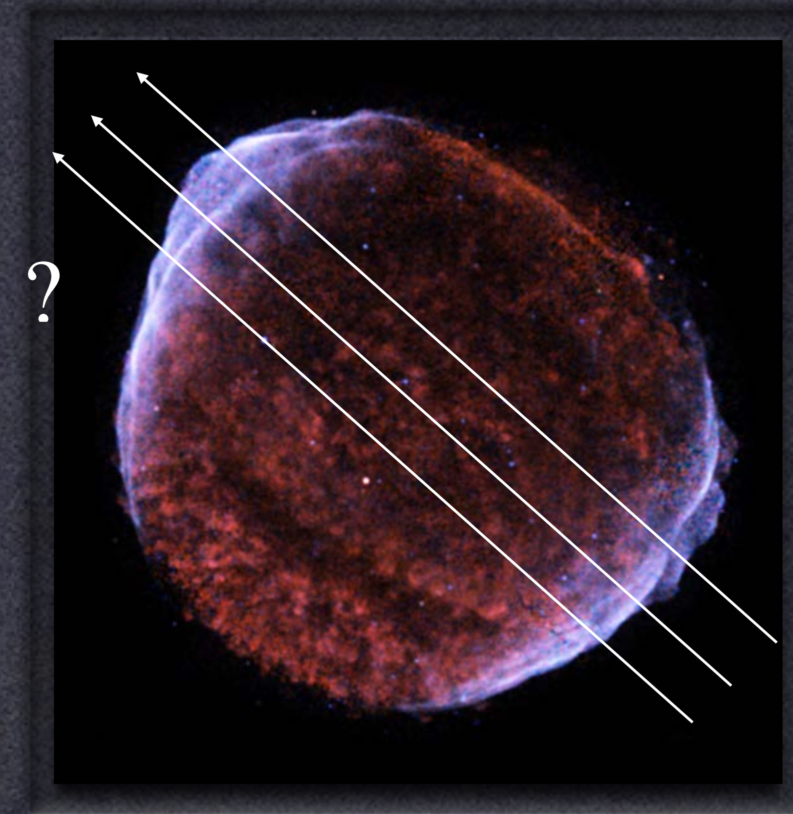




Young SNR story



Nonthermally-emitting SNRs likely have large scale parallel magnetic field (radial). This leads to CR acceleration and field amplification.

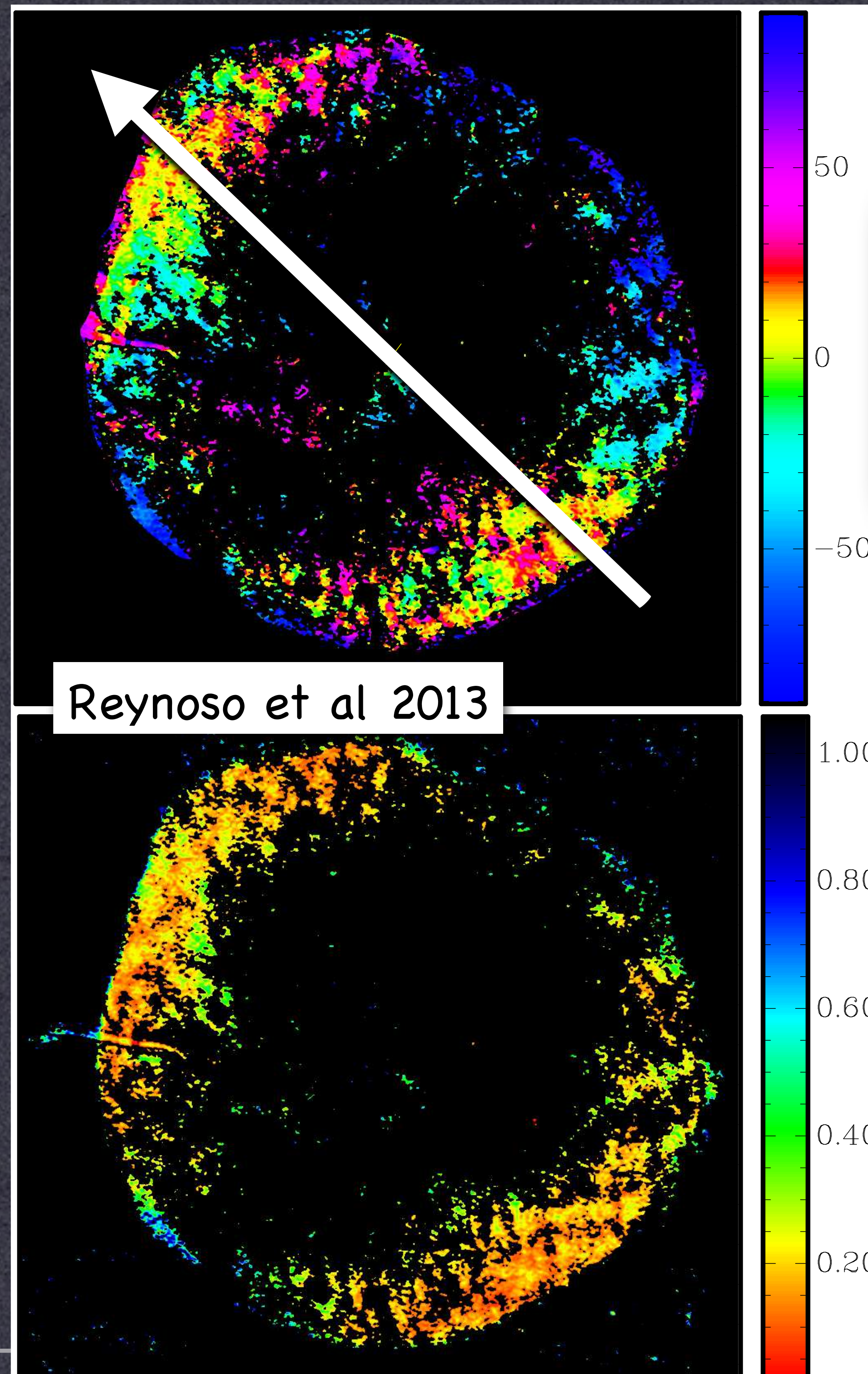
At the shock field is turned transverse by CR turbulence — scatters and accelerates electrons.

This favors large-scale radial B fields in young SNRs. Polarization in "polar caps" should be small -- field is random

Ab-initio plasma results allow to put constraints on the large-scale picture!

SN1006: a parallel accelerator

X-ray emission (red=thermal white=synchrotron)



Reynoso et al 2013

Inclination of the B field wrt to the shock normal

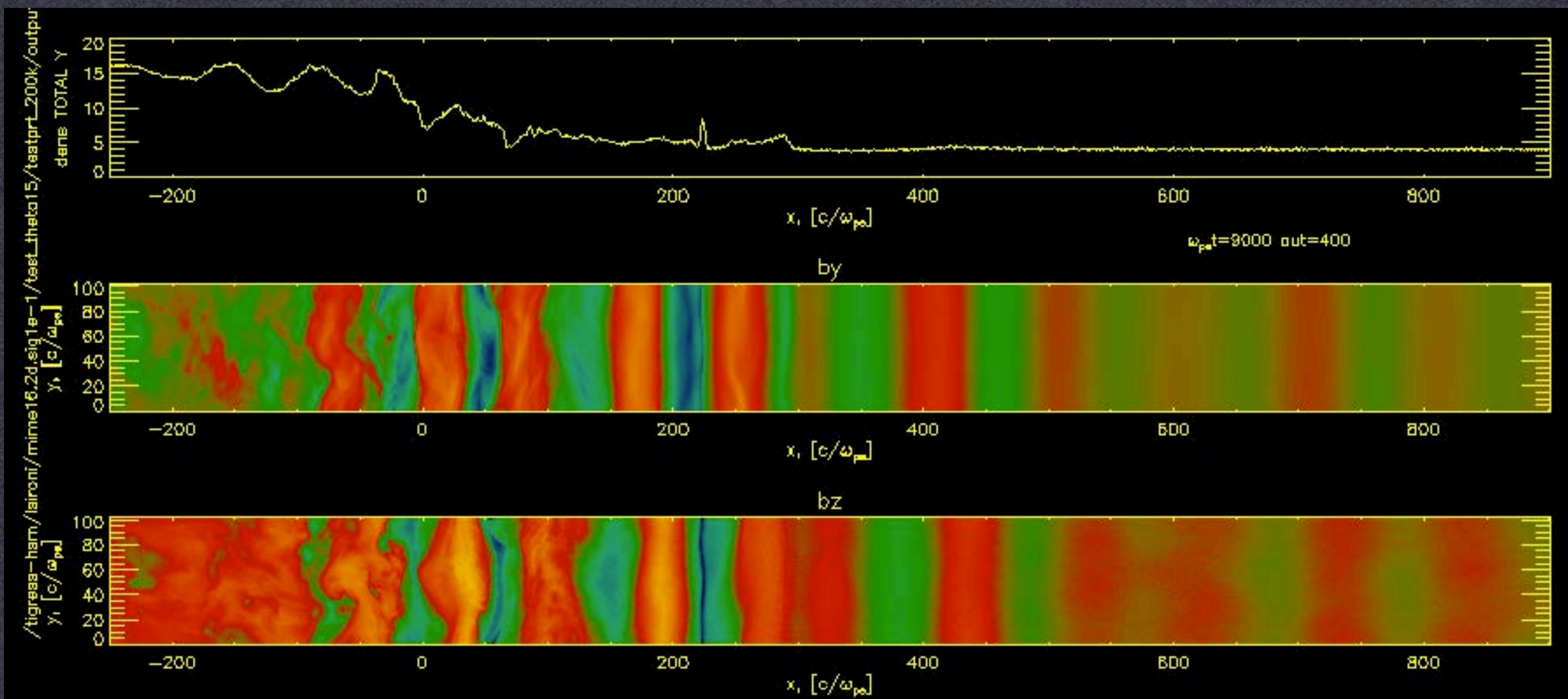
Polarization (low=turbulent high=ordered)

Magnetic field amplification and particle acceleration where the shock is parallel

A note about young SNR shocks:

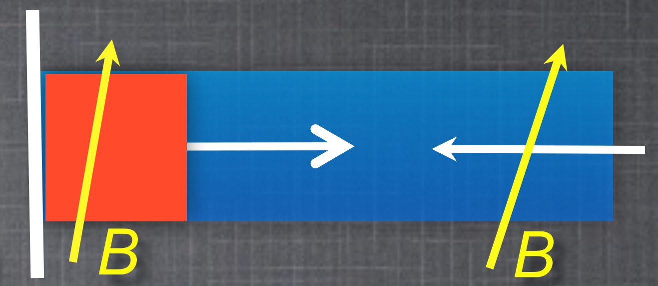
Technically these are very high Alfven Mach # shocks (>100). The field is initially weak, so Weibel instabilities could be important. However, we believe that long term field will get amplified and our simulations at moderate M_A represent well what happens.

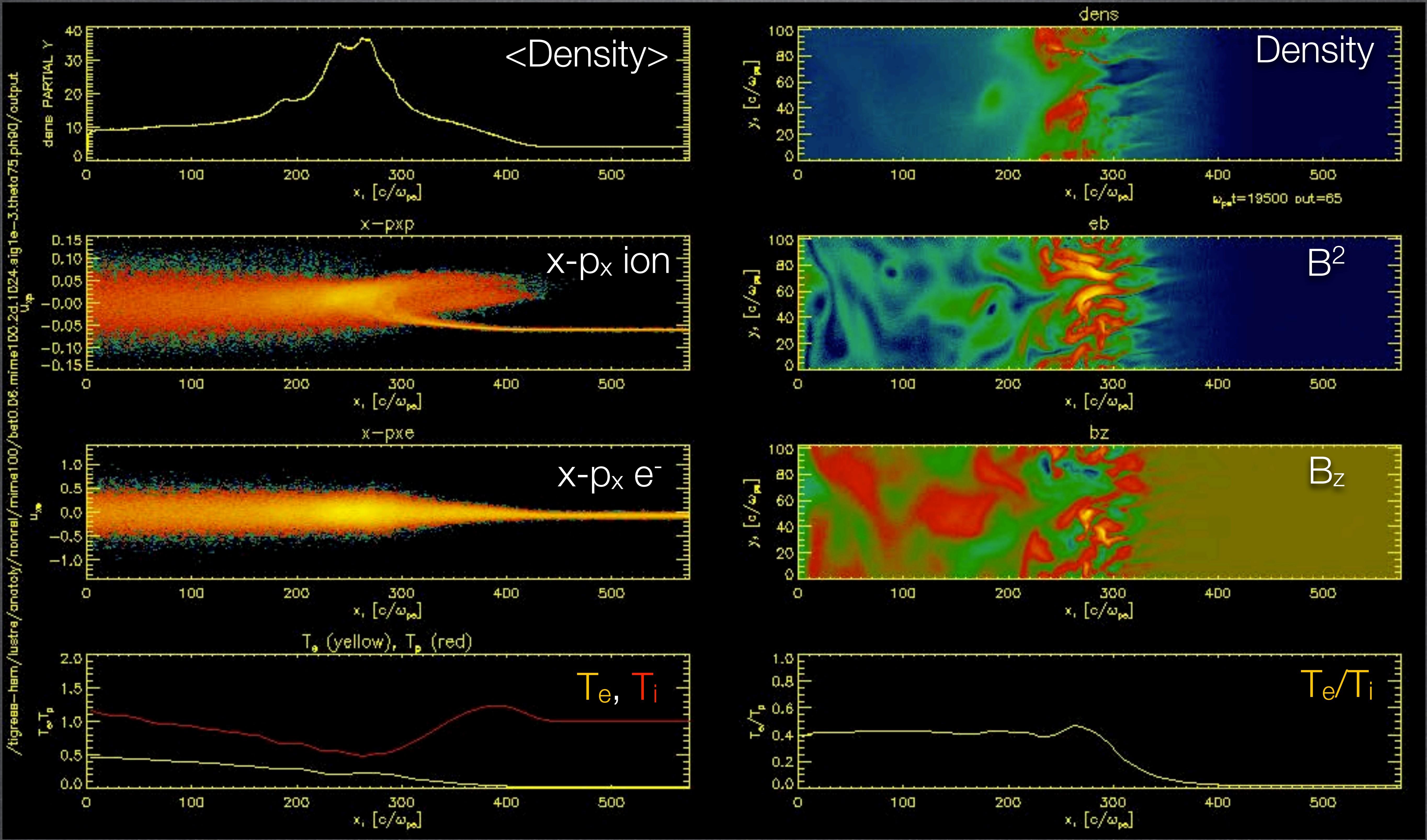
How Weibel filamentation gets overwhelmed by Bell:



Nonrelativistic shocks: shock structure

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





Temperature equilibration?

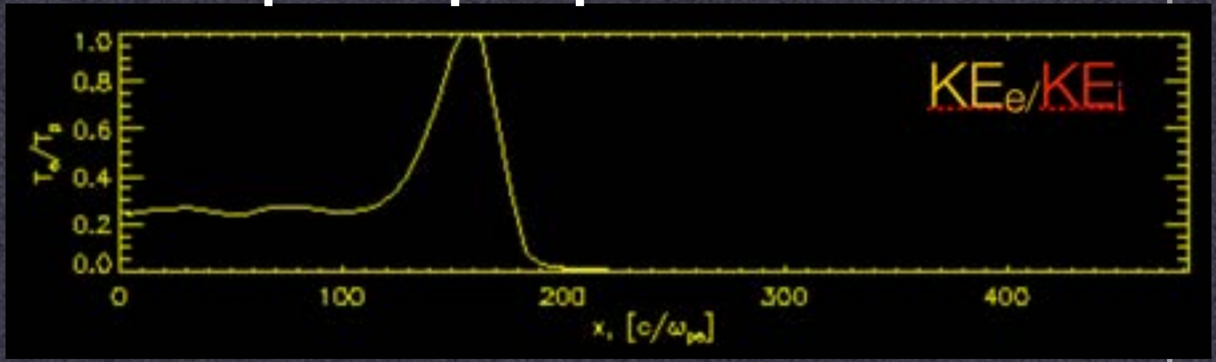
In full PIC simulations we see very efficient energy exchange between ions and electrons:

Te/Ti~0.1-0.3 for quasi-perp shocks
Te/Ti ~0.5-1 for quasi-parallel shocks

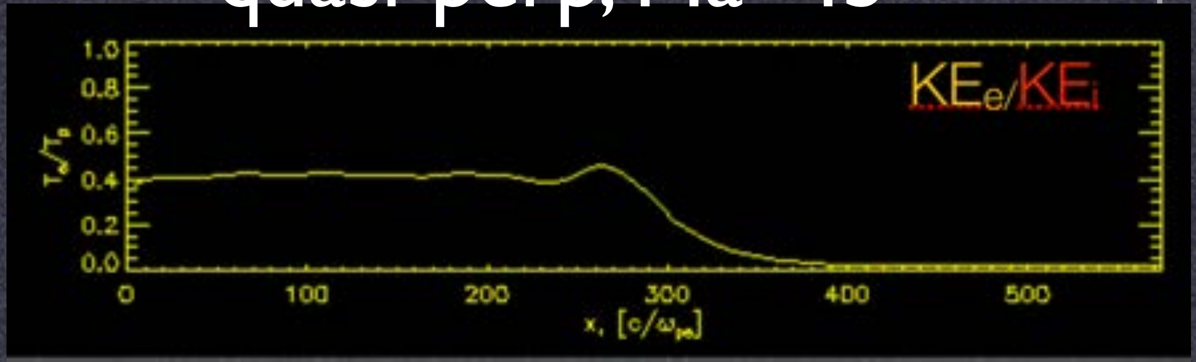
Physics: shock transition instabilities and upstream electron pre-heating in ion-driven turbulence

How does this mesh with observations?

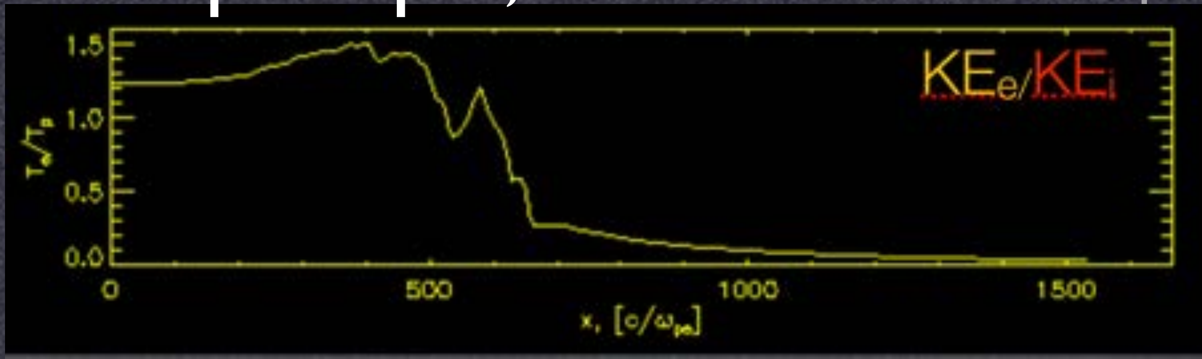
quasi-perp, Ma=10



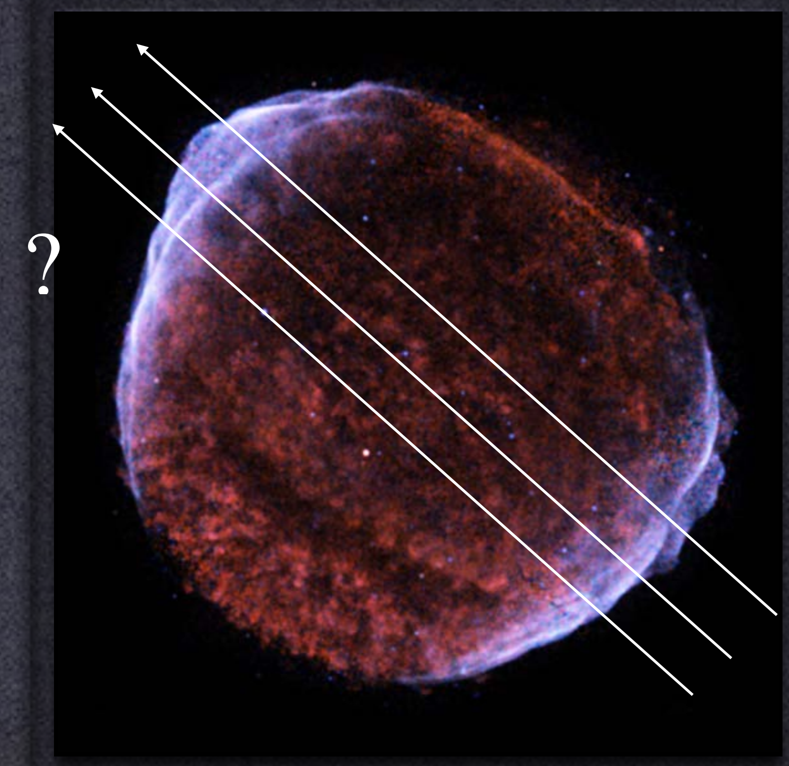
quasi-perp, Ma=45



quasi-par, Ma=10



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

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; $K_{ep} \sim 10^{-3}$; p^{-4} spectrum

Electrons are accelerated in quasi-perp shocks, energy several percent, number <1%. Fewer ions are accelerated at oblique shocks.

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