Kinetic simulations of particle acceleration in astrophysical collisionless shocks

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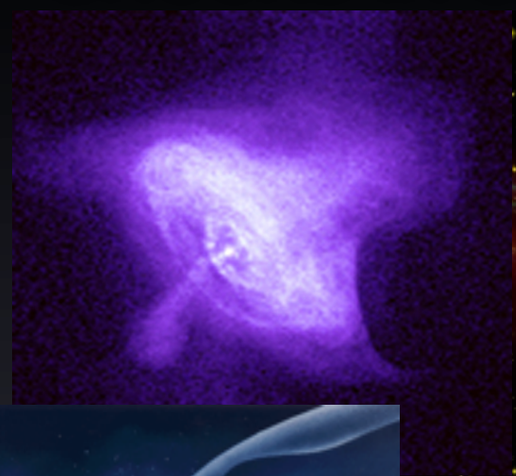
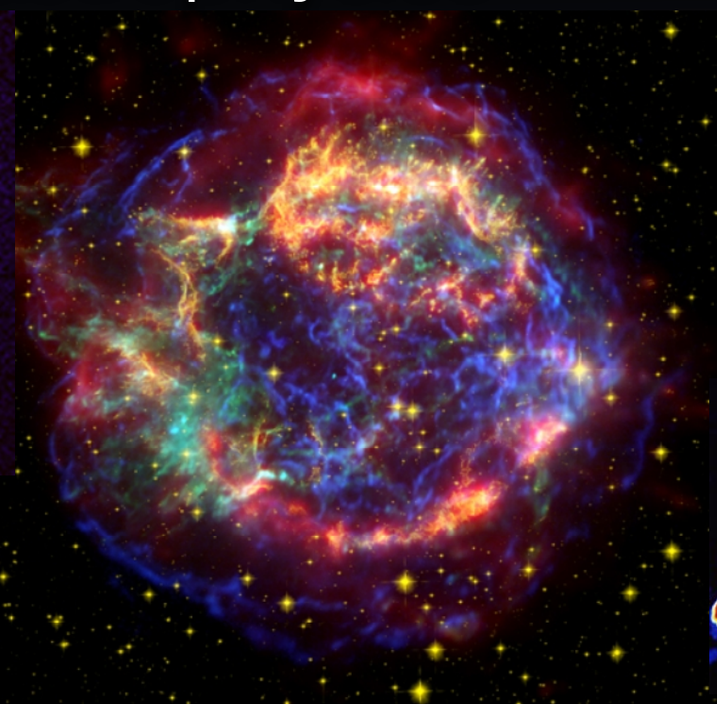
with help from R. Riquelme, L. Sironi, L. Gargate, J. Arons, U. Keshet, E. Waxman

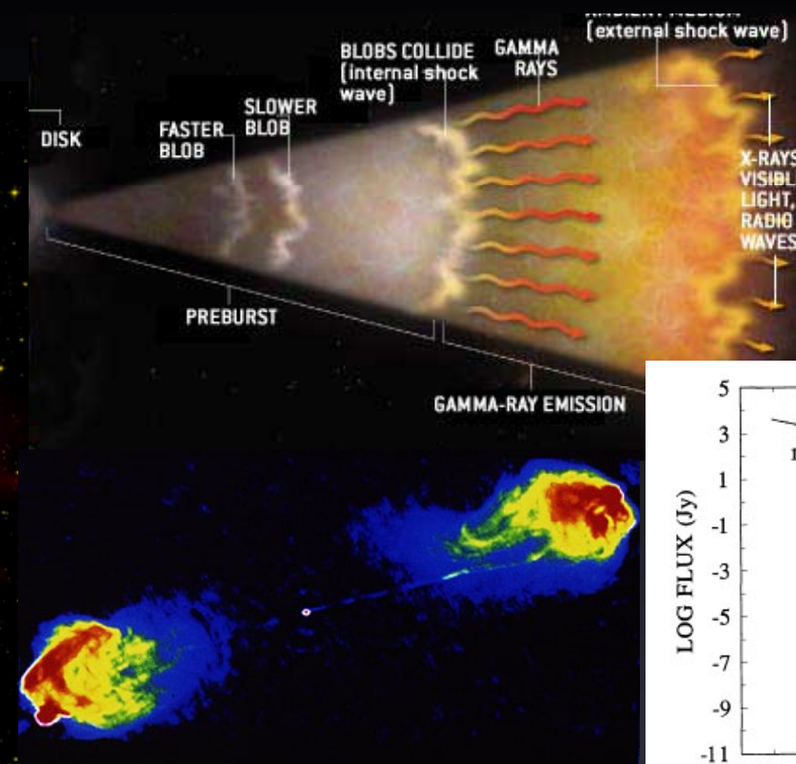
Outline

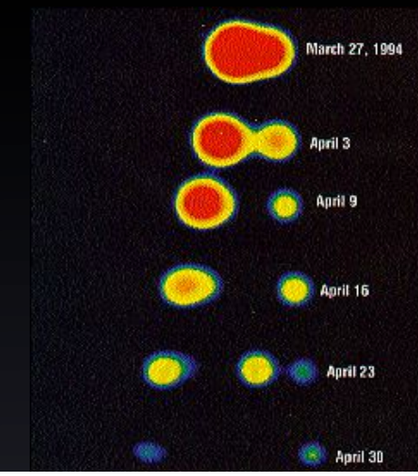
- Shocks as sites of particle acceleration
  - Diversity and similiarity of astrophysical shocks
- Shock structure: regimes of magnetization
- Acceleration properties of shocks
  - Relativistic vs non-relativistic shocks
- Field amplification and electron injection in nonrelativistic shocks
- Conclusions and applications

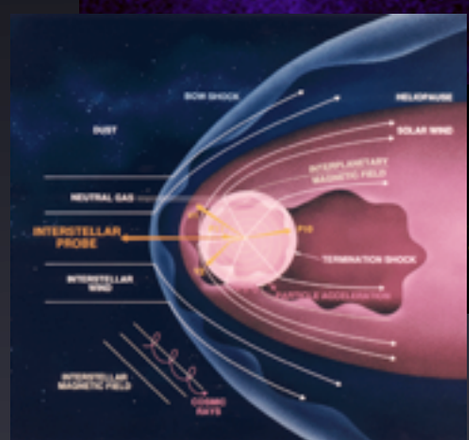
Shocks in astrophysics

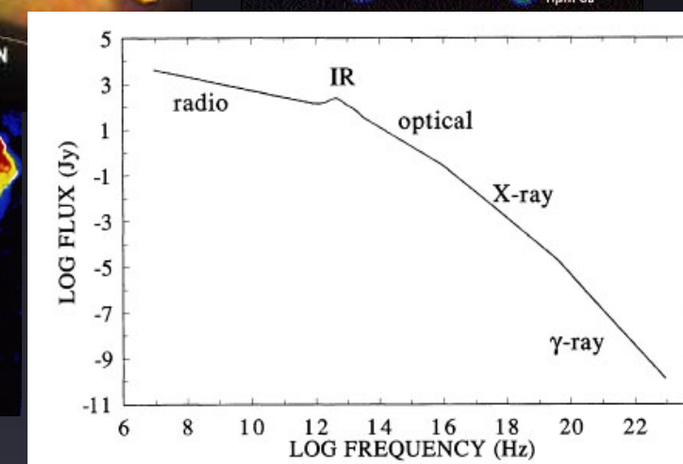










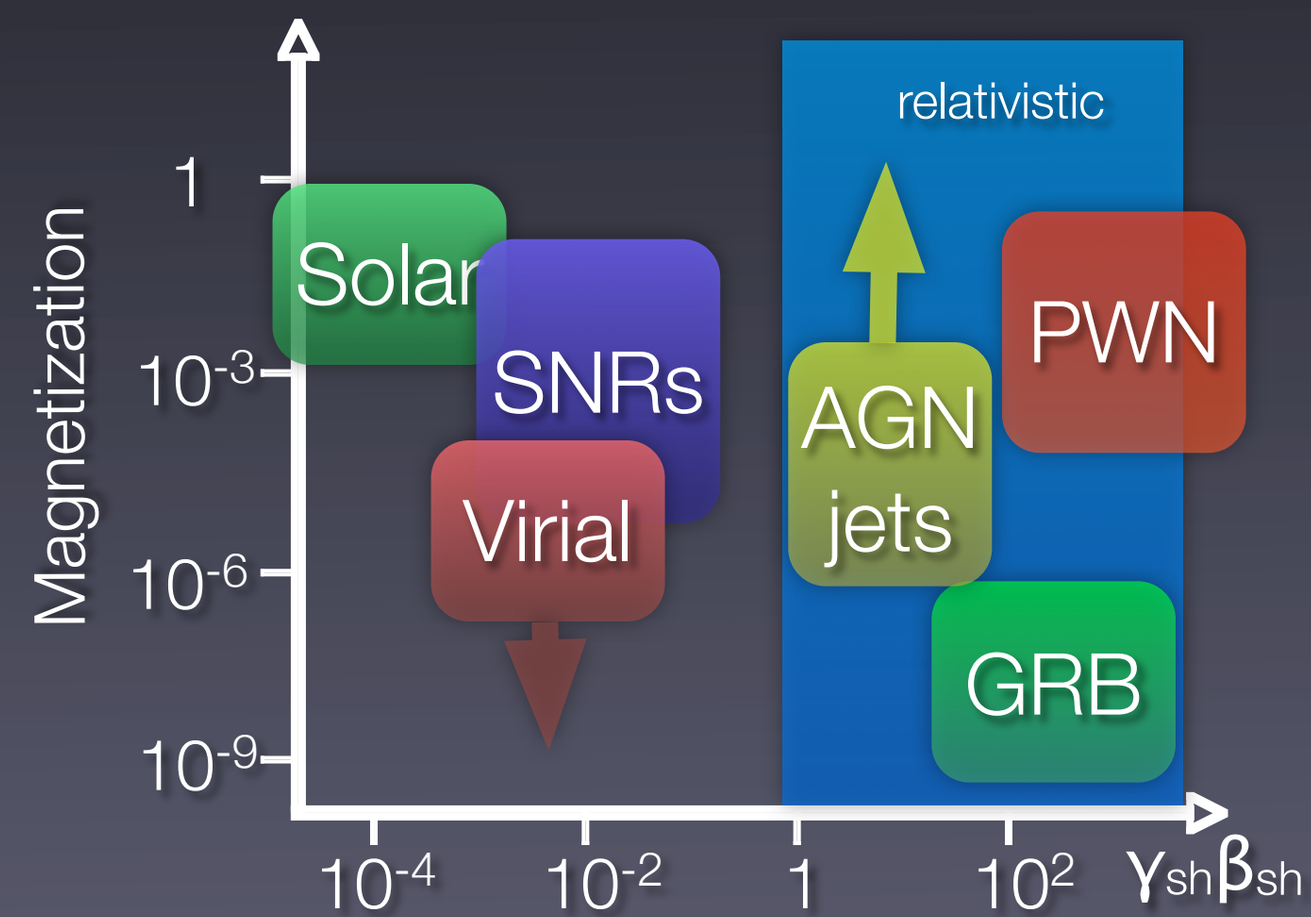


Astrophysical shocks are collisionless

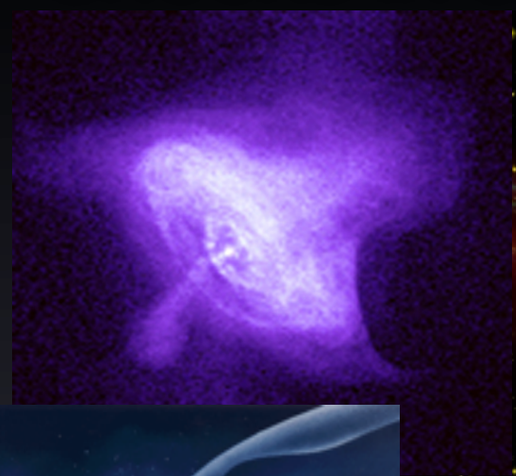
Shocks span a range of parameters: nonrelativistic to relativistic flows

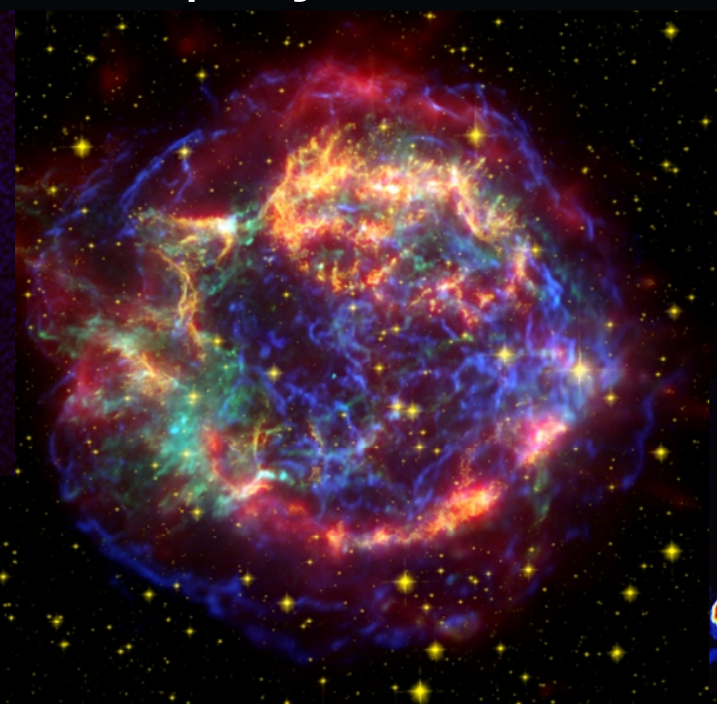
magnetization (magnetic/kinetic energy ratio)

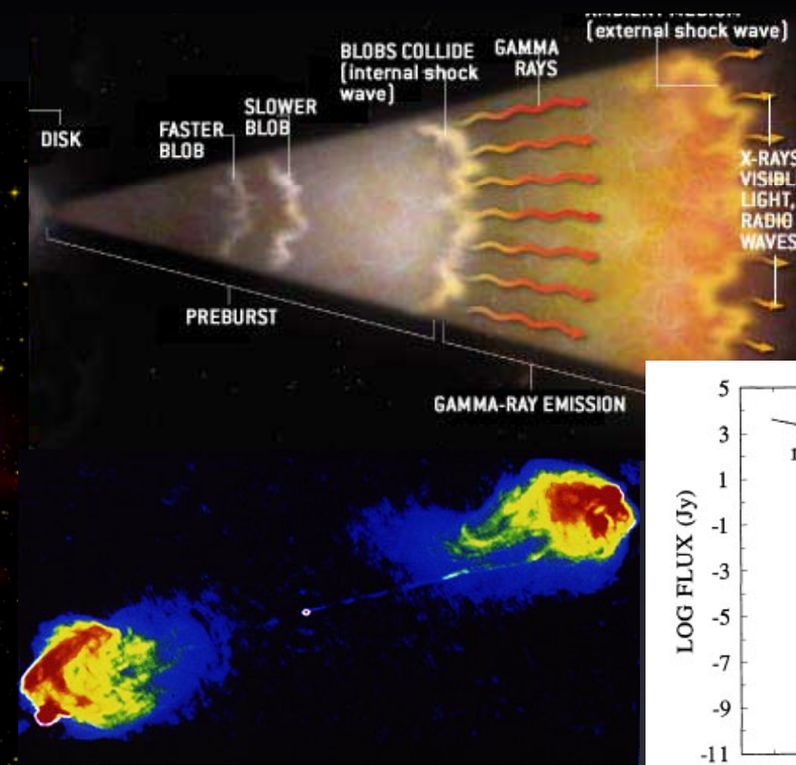
composition (pairs/e-ions/pairs + ions)

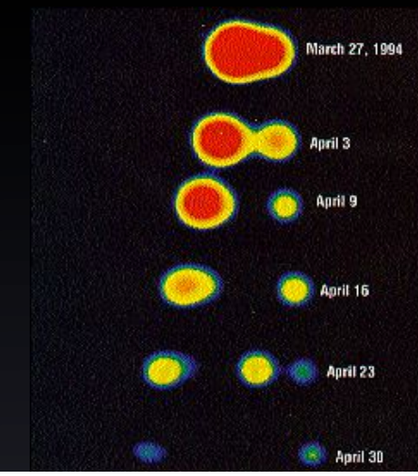


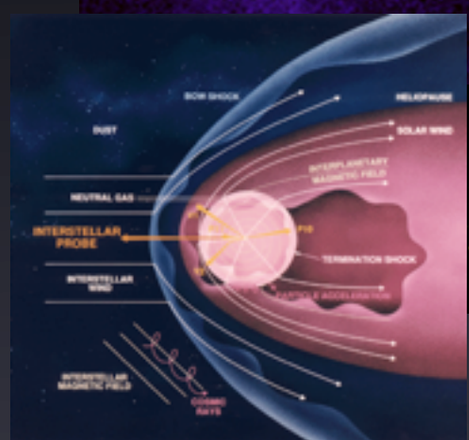
Shocks in astrophysics

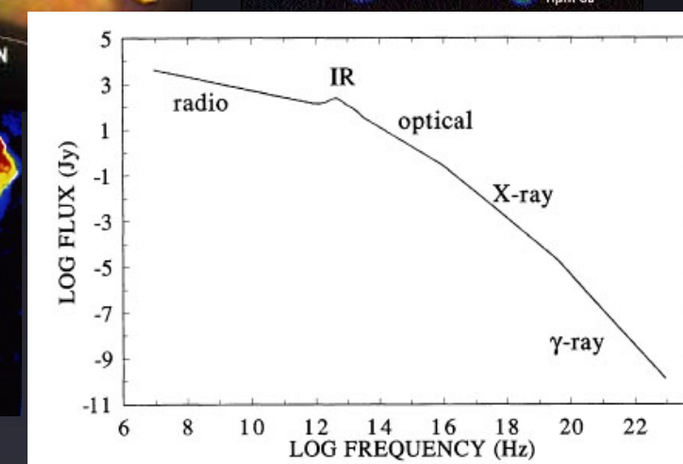






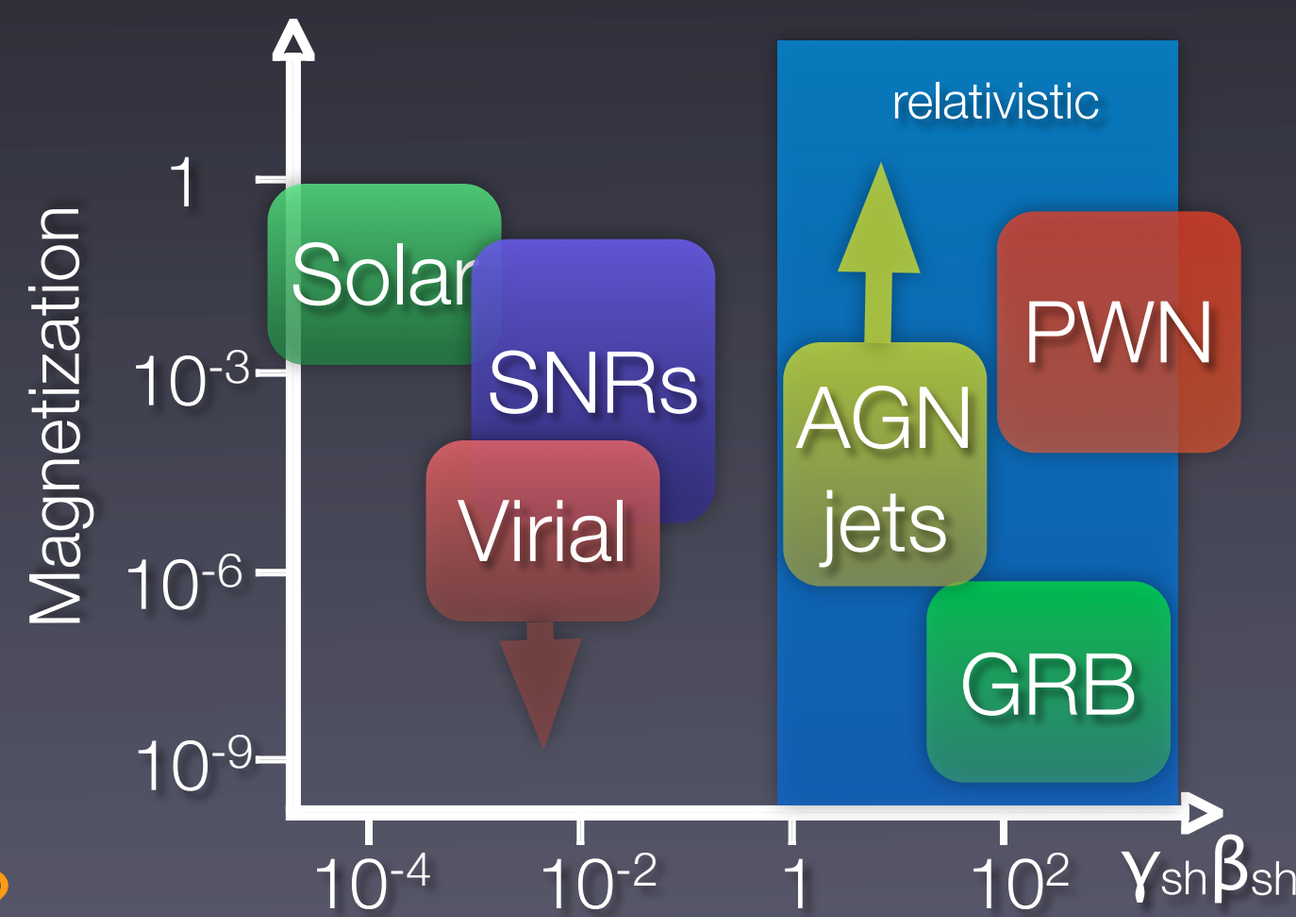






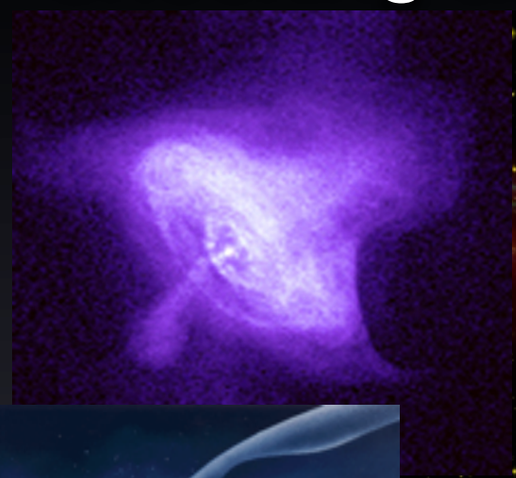
Astrophysical collisonless shocks can:

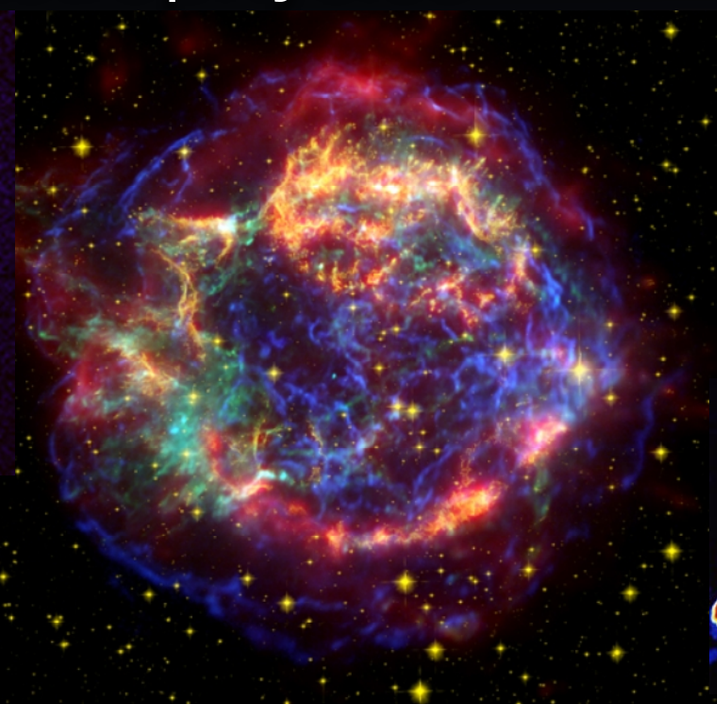
1. accelerate particles
2. amplify magnetic fields (or generate them from scratch)
3. exchange energy between electrons and ions

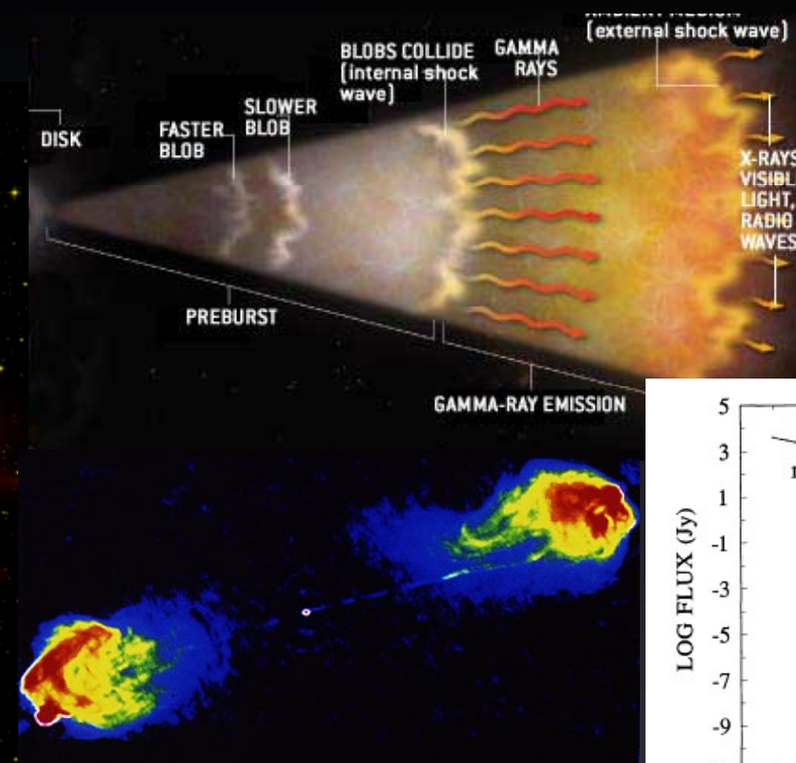


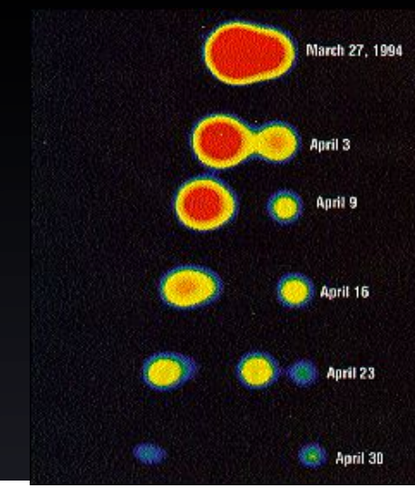
Is this all intrinsic to the shock?

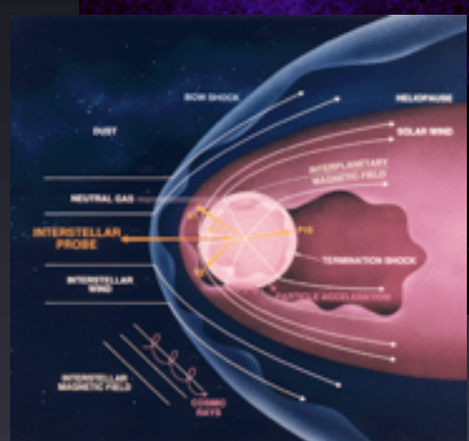
Shocking astrophysics

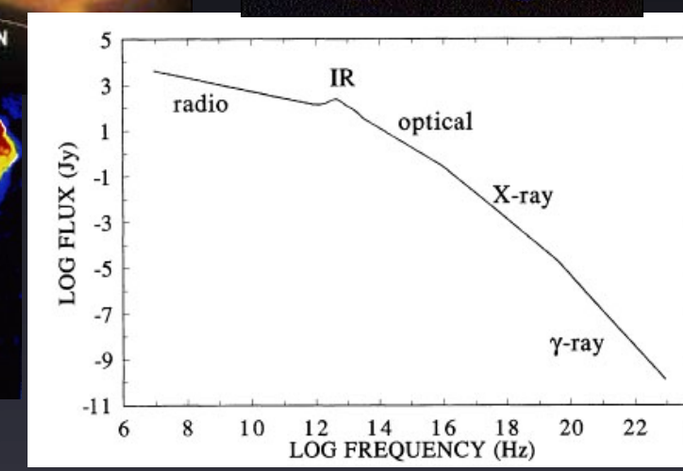












Open issues:

What is the structure of collisionless shocks? Do they exist? How do you collide without collisions?

Particle acceleration -- Fermi mechanism? Other? Efficiency?

Generation of magnetic fields? GRB/SNR shocks, primordial fields?

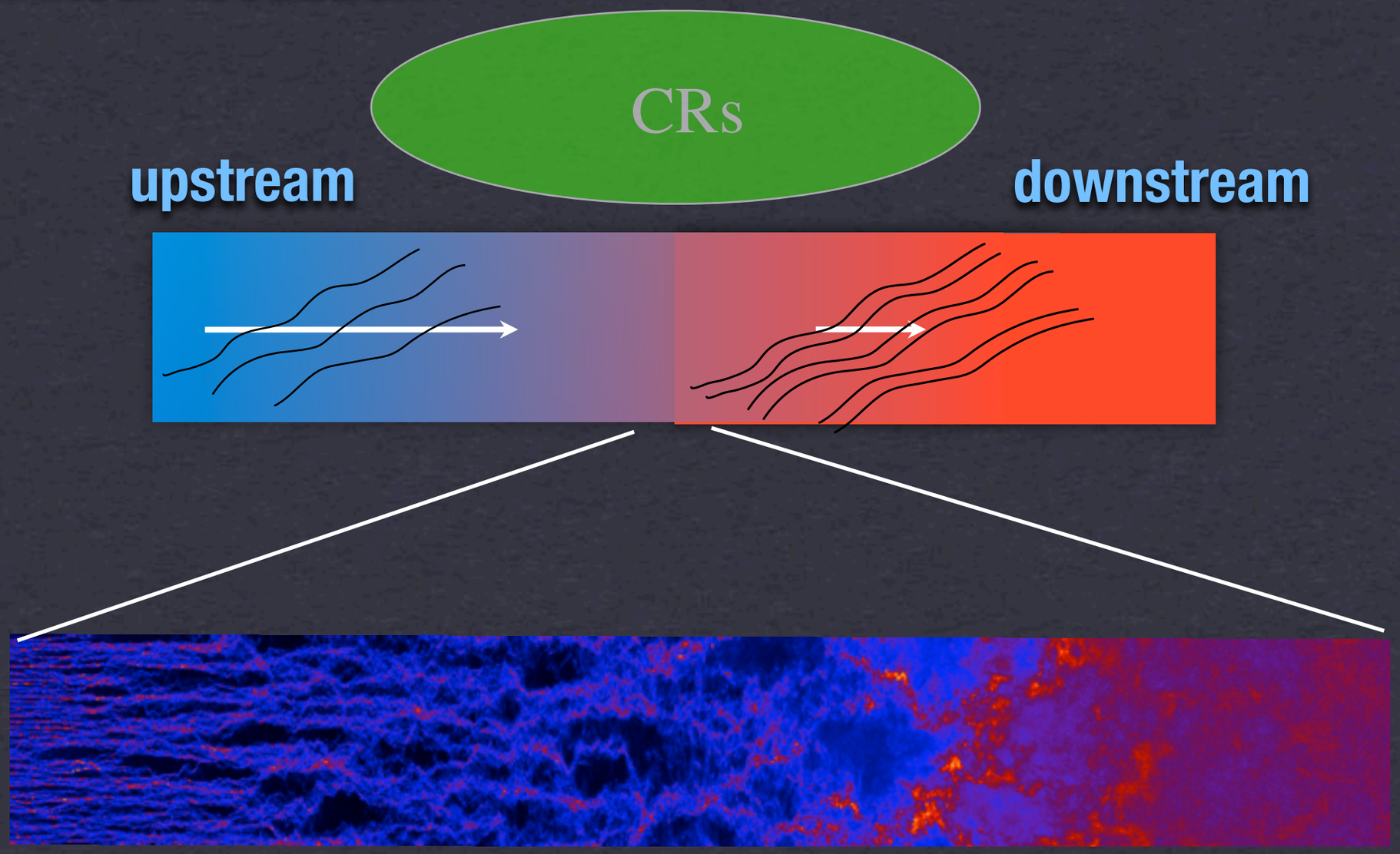
Equilibration between ions and electrons?

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

Need models of microphysics: plasma simulations

Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback



Collisionless shocks

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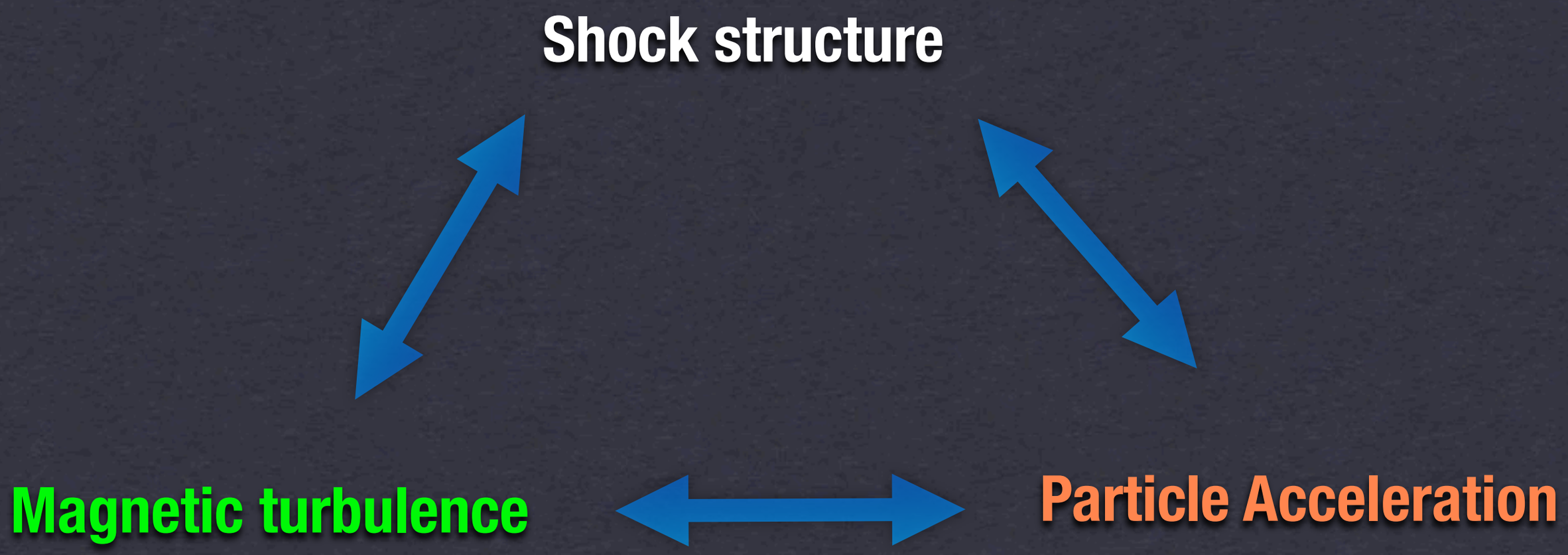
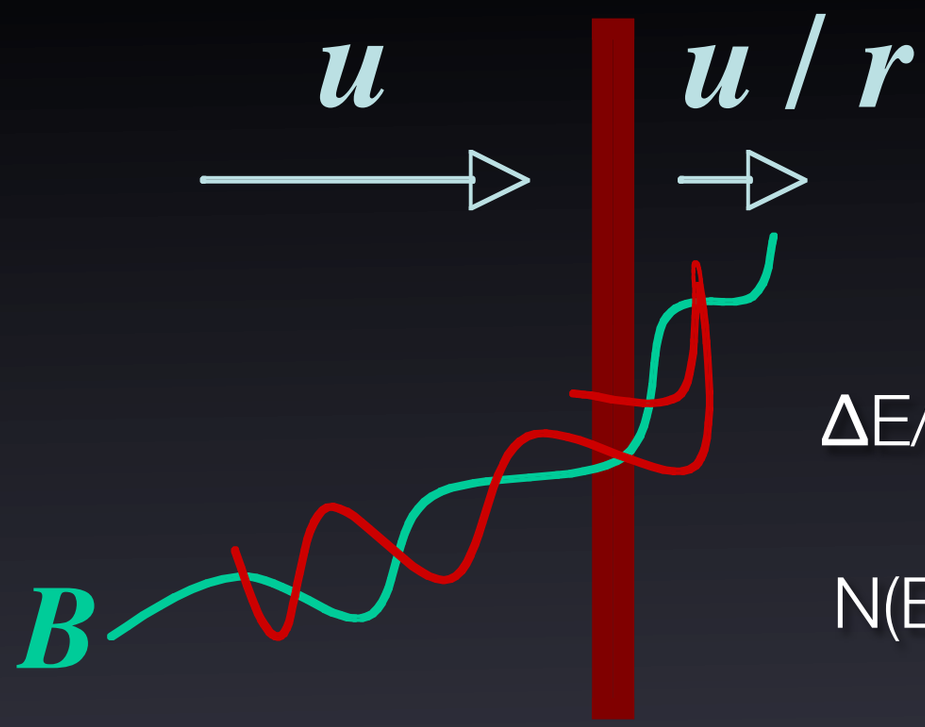
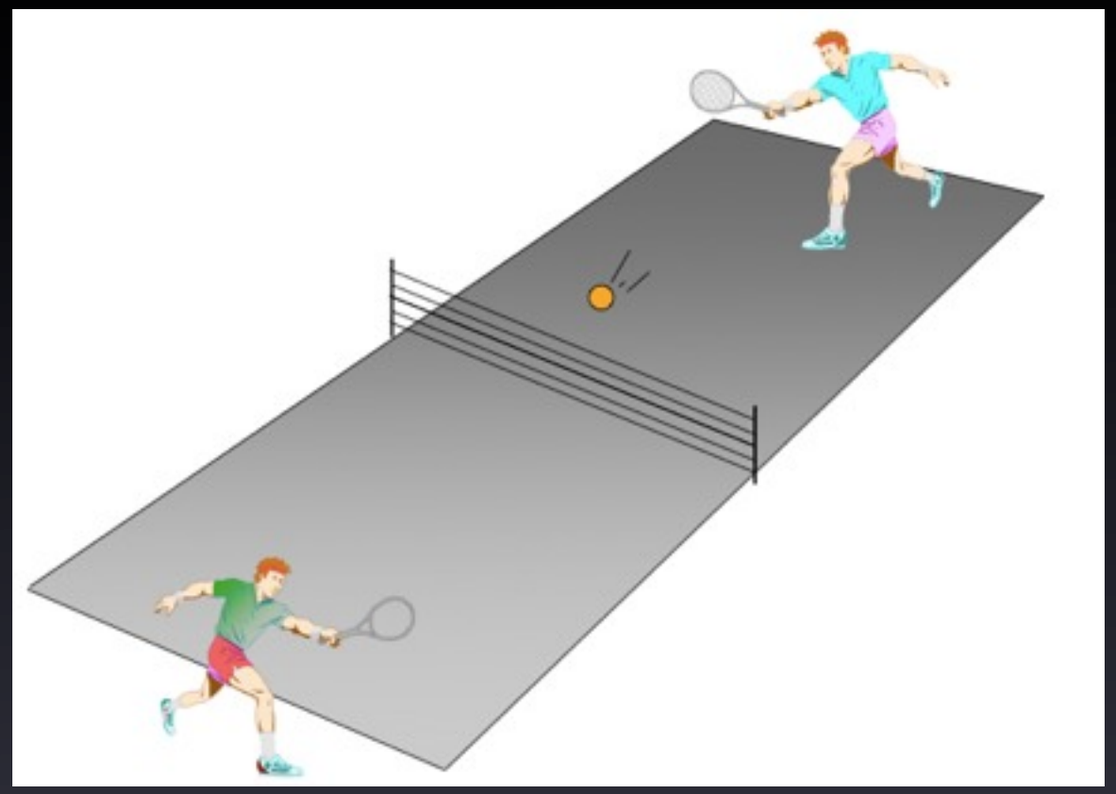


Particle acceleration:



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

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



Free energy: converging flows

Acceleration mechanisms:

- First order Fermi
  - Diffusive shock acceleration
  - Shock drift acceleration
  - Shock surfing acceleration
- Second order Fermi

Efficient scattering of particles is required. Monte Carlo simulations of rel. shocks show that this implies very high level of turbulence δB/B(Ostrowski et al). Is this realist

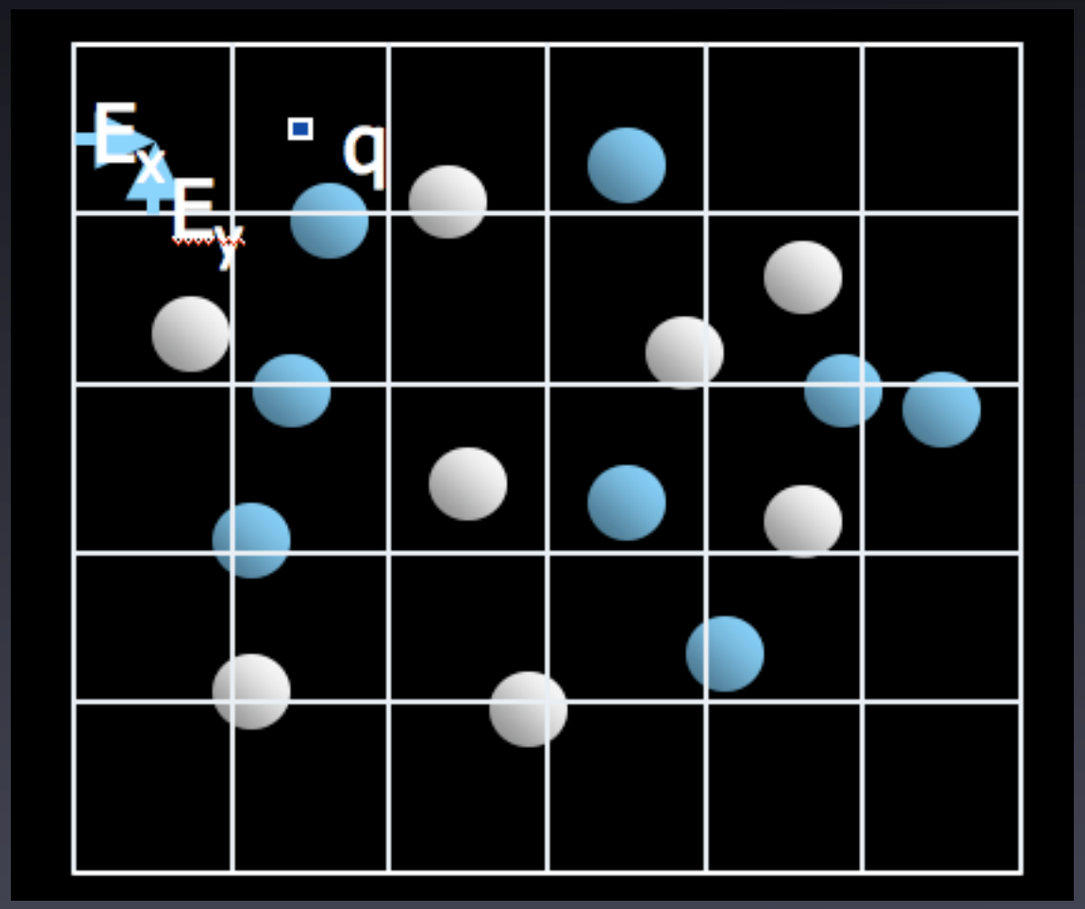
Requ
accel
shock
e

Needs
(waves) downstream.

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

Particle-in-Cell (PIC) method

Most fundamental way to treat plasma physics without (m)any approximations
price: have to resolve tiny and fast scales (plasma skin depth and plasma freq.)
to be interesting, simulations have to be large



PIC method (aka PM method):

- Collect currents at cell edges
- Solve fields on the mesh (Maxwell's eqs)
- Interpolate fields to particle positions
- Move particles under Lorentz force

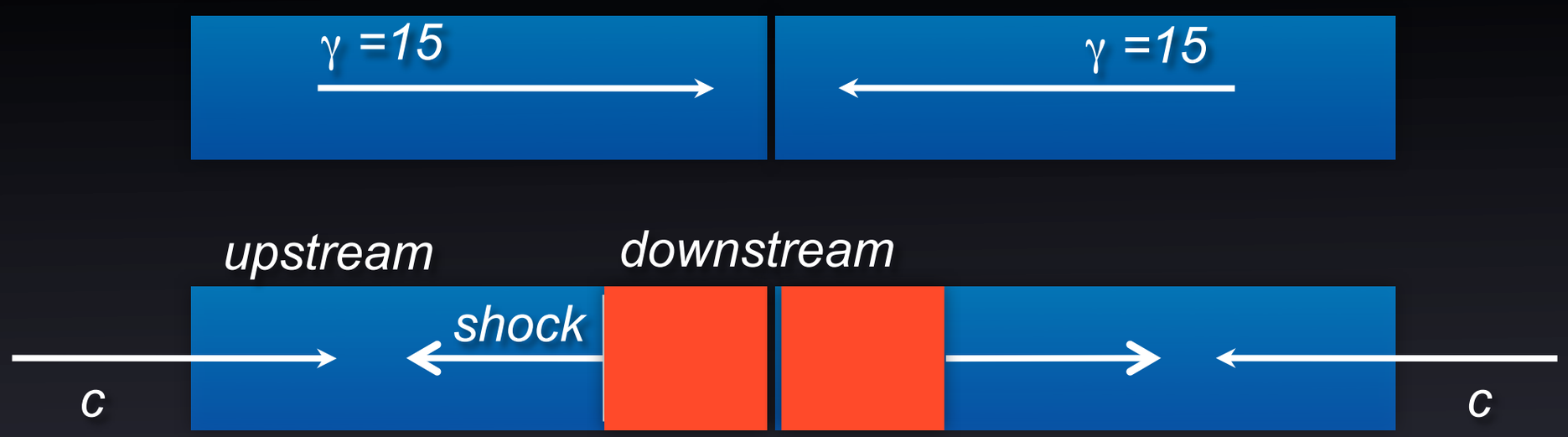
Commonly used in accelerator/plasma physics. Pioneered for relativistic shocks by Hoshino and Arons (1992)

Tools:

TRISTAN-MP **-- 3D parallel electromagnetic PIC code (mostly used in 2D) [Buneman 92, Spitkovsky 05]**

dHybrid **-- 3D parallel hybrid code, kinetic ions + fluid electrons[Gargate et al 07]**

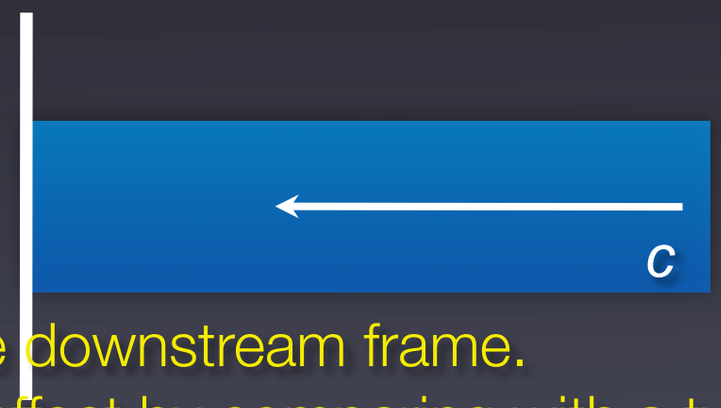
Problem setup



c/3 (3D) or c/2(2D) c/3(3D) or c/2(2D)

"Shock" is a jump in density & velocity

Use reflecting wall to initialize a shock



Simulation is in the downstream frame.

We verified that the wall plays no adverse effect by comparing with a two-shell collision.

Many groups are working on PIC simultaions:

Silva et al, Hoshino et al, Nishikawa et al, Nordlund et al.

All groups agree on main points, though run times and simulation sizes differ.

Key is running simulations long enough to see "steady" shocks

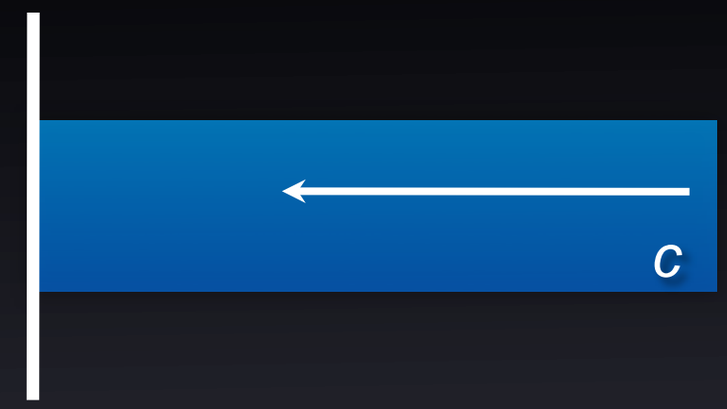
Largest runs go for ~10000 ω_p^{-1}; sizes up to 200^2x2000 skindepths; 4e10 particles

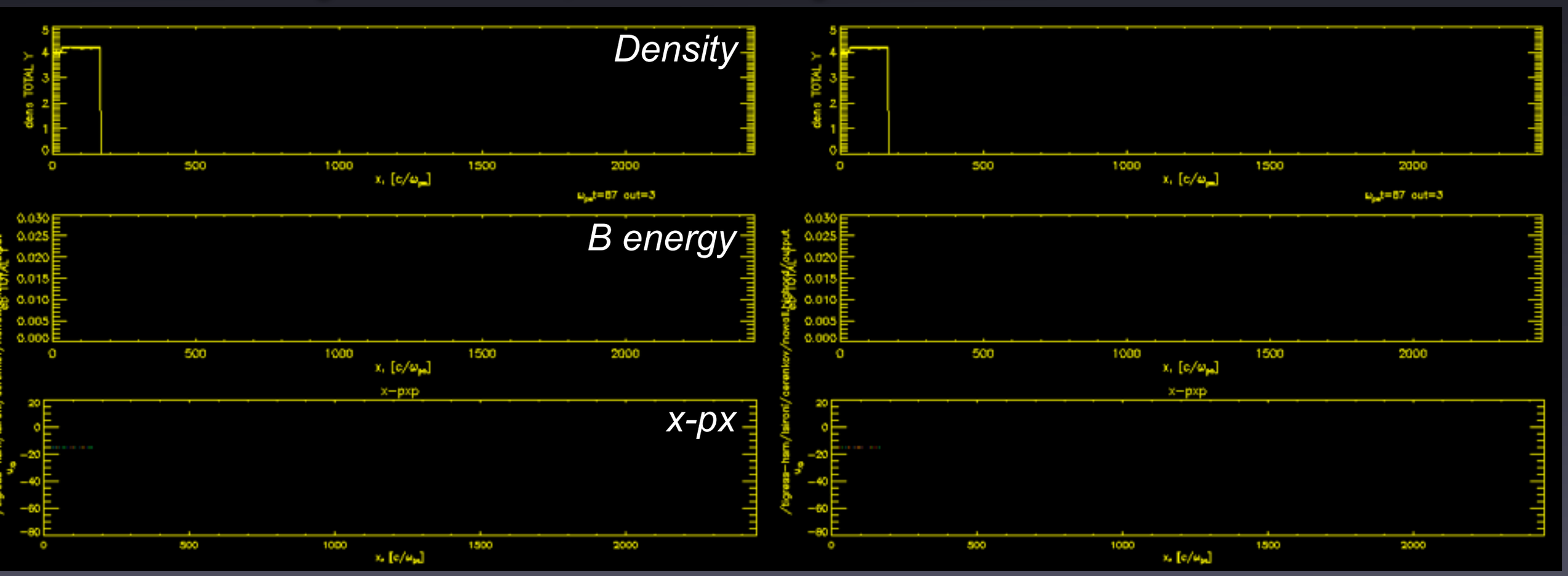
Relativistic numerical issues

Cold plasma needs to propagate relativistically through grid for large distances

Relativistic motion can lead to numerical Cerenkov instability. Very prominent for gamma>10.

Fixes include: high-order FDTD, current filtering





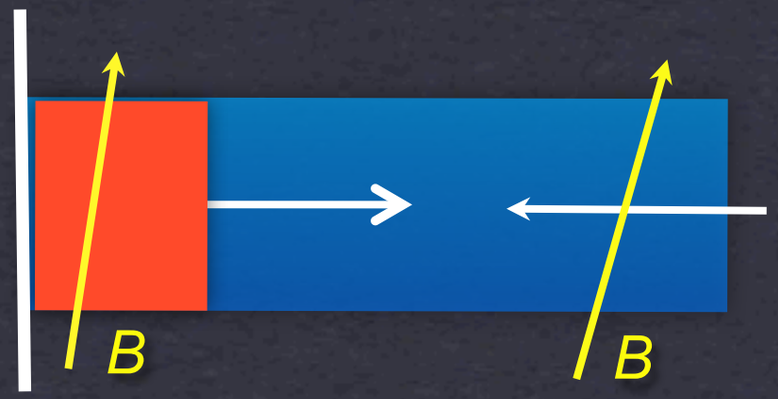
2-nd order FDTD

4-th order FDTD

Cerenkov instability can be controlled, though not completely eliminated

Survey of Collisionless Shocks

- We simulated relativistic and nonrelativistic shocks for a range of upstream B fields and flow compositions.



Main findings:

Dependence of shock mechanism on upstream magnetization

Ab-initio particle acceleration in relativistic shocks

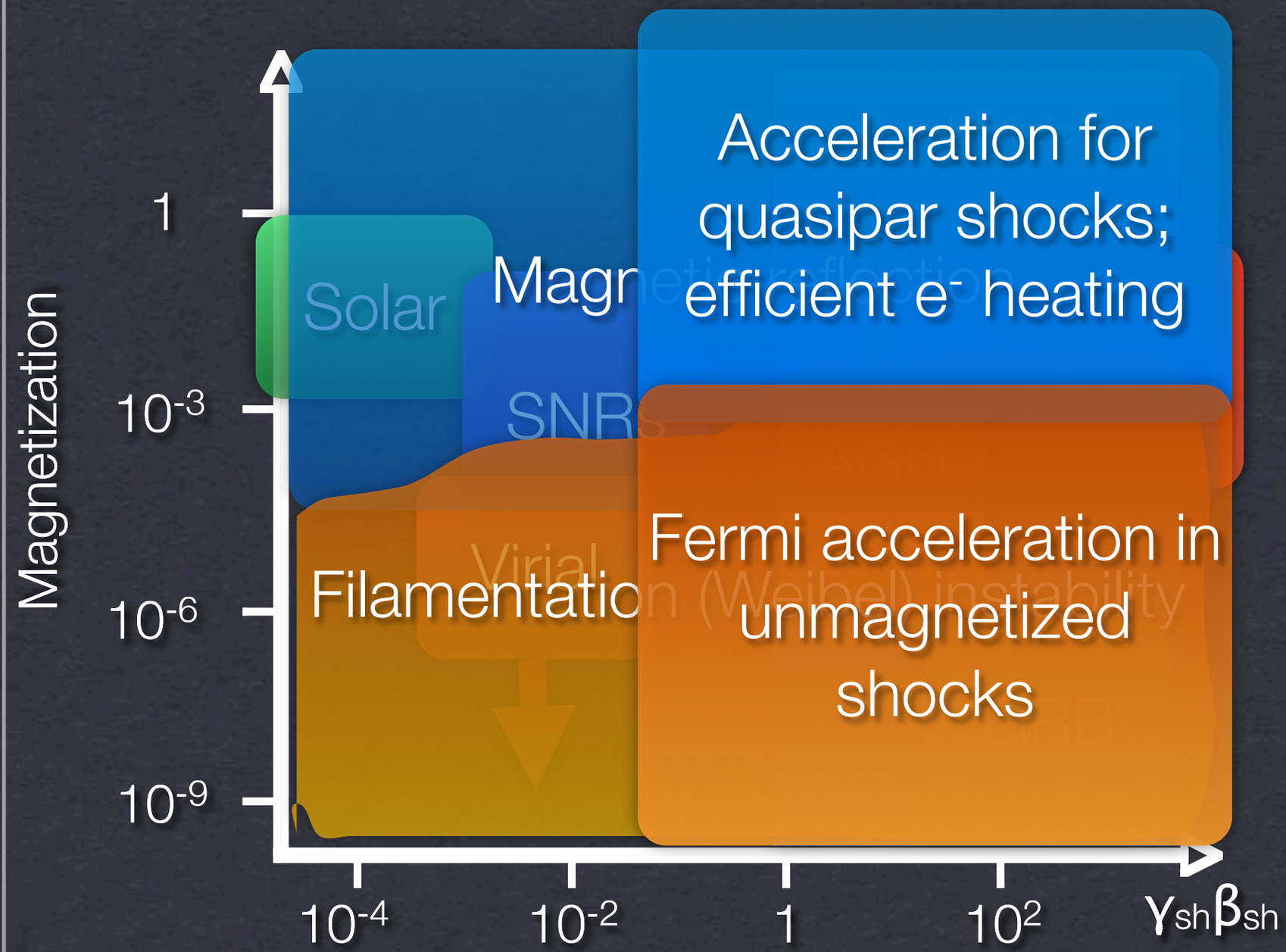
Shock structure and acceleration in non-relativistic shocks

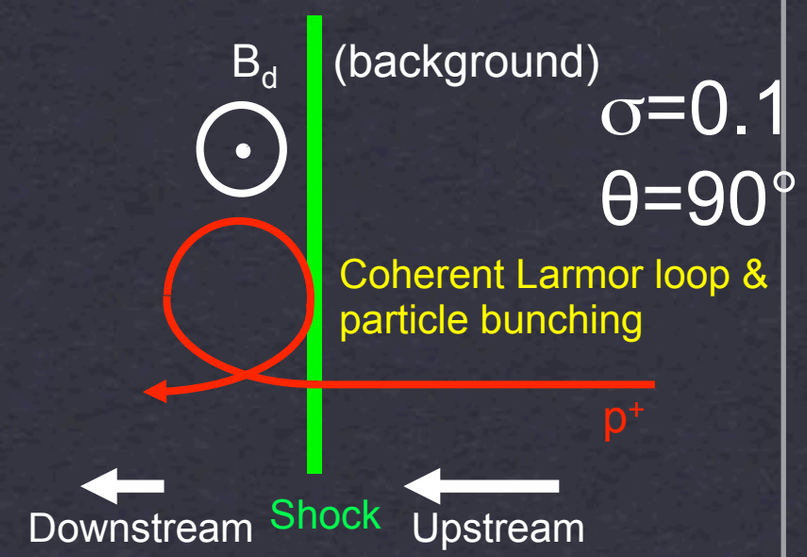
- Ion acceleration vs Mach # in quasiparallel shocks
- Electron acceleration in quasiperp shocks

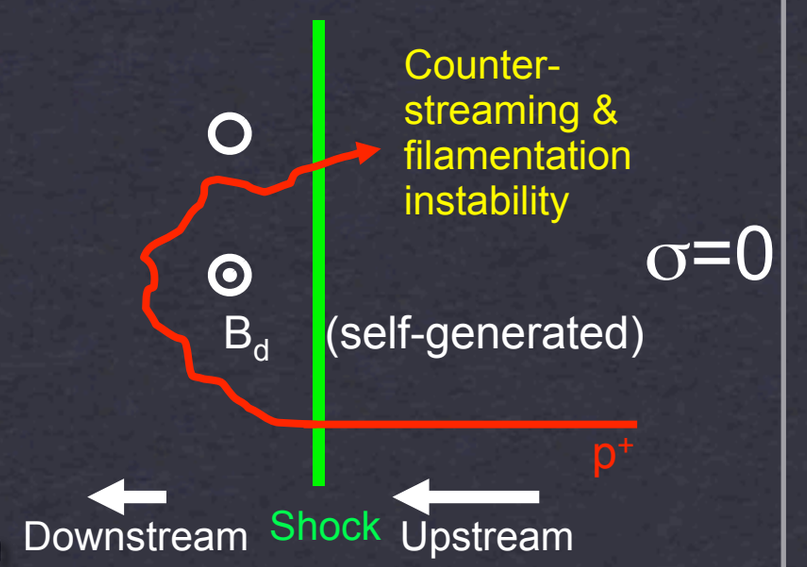
Field amplification and CR-induced instabilities

Parameter Space of shocks

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

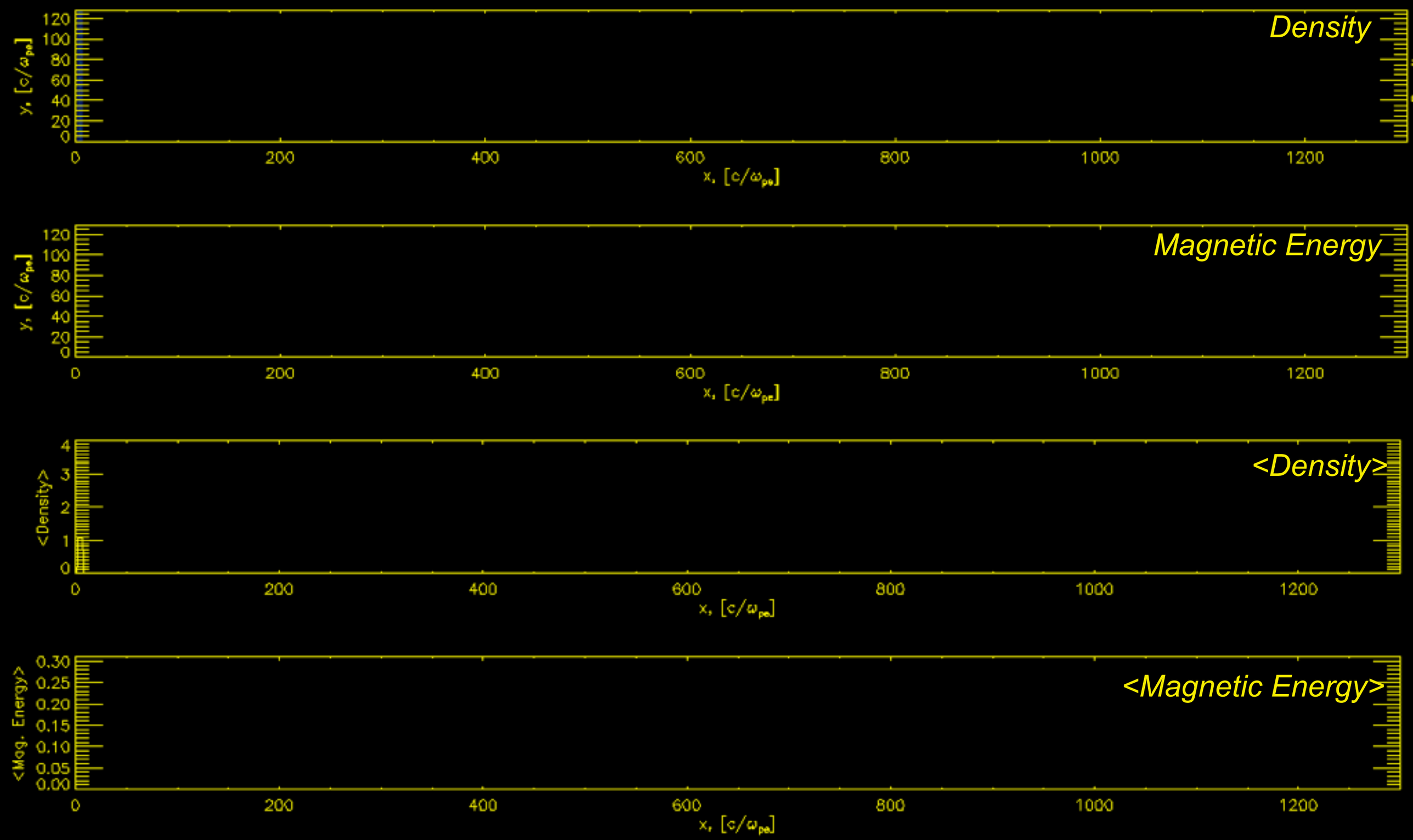






Collisionless shocks

Structure of an unmagnetized relativistic pair shock



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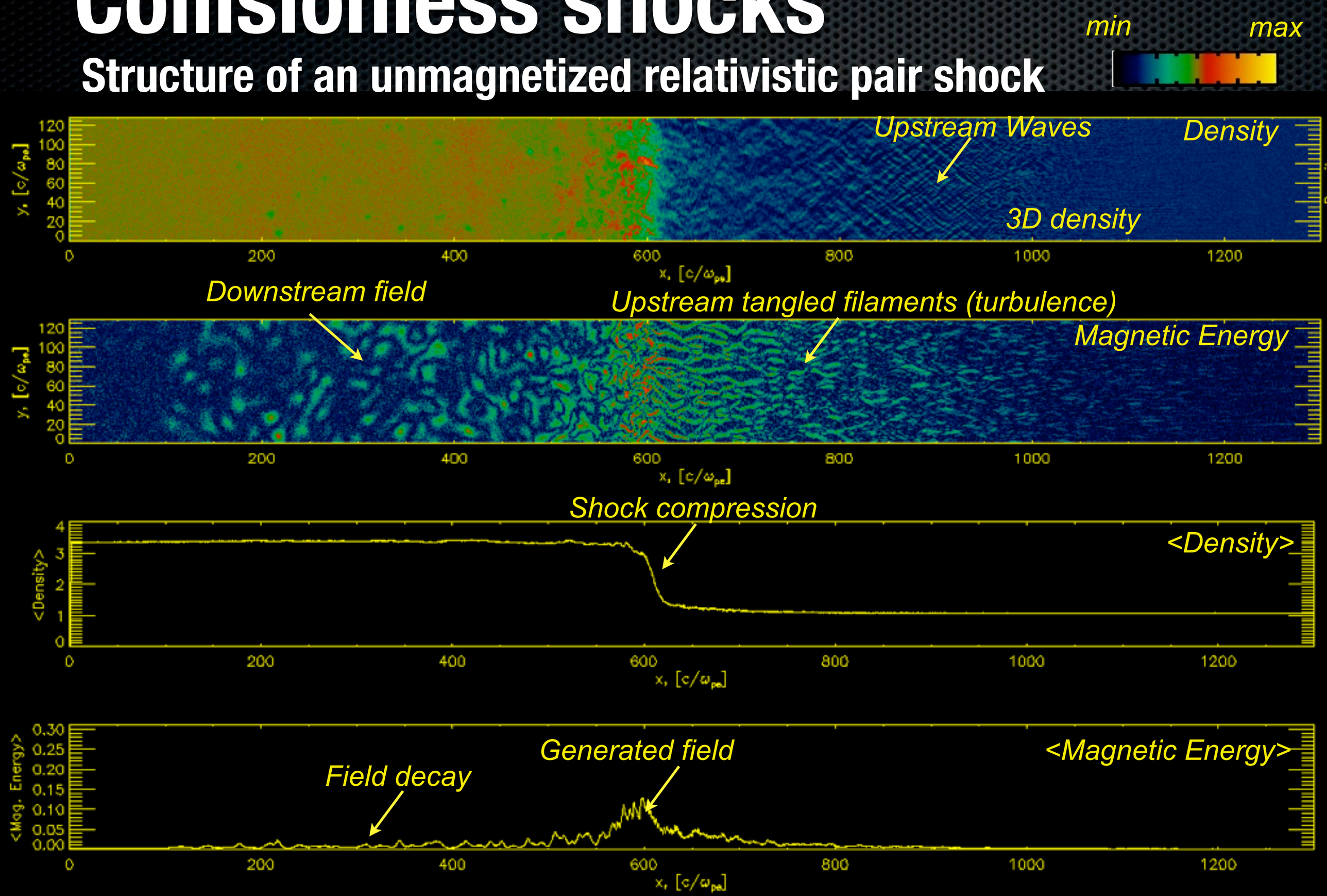

Collisionless shocks

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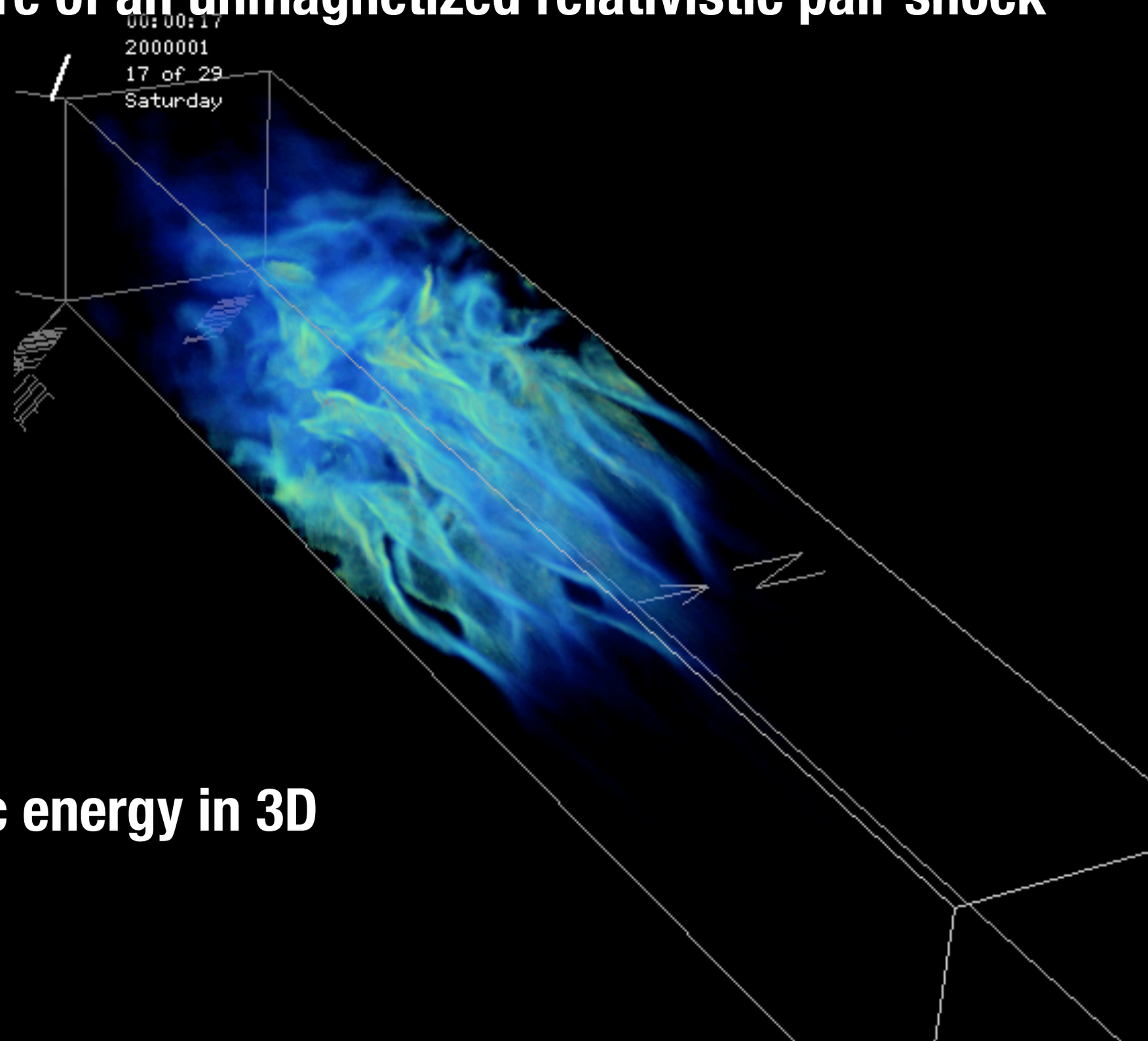
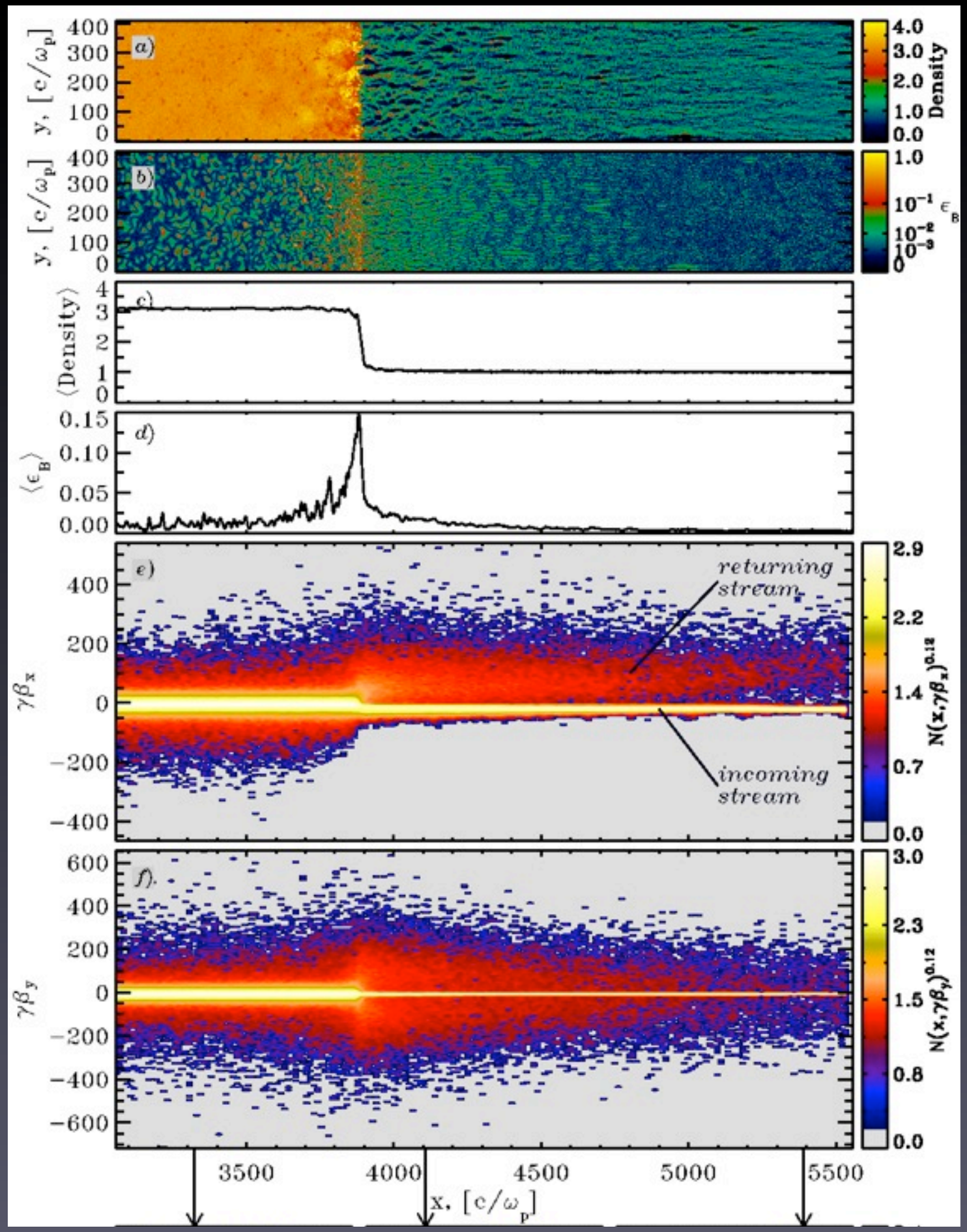


Magnetic energy in 3D



Unmagnetized pair shock:

shock is driven by returning particle precursor (CR!)

Steady counterstreaming leads to self-replicating shock structure

x- px momentum space

Long term 2D simulation

x- py momentum space

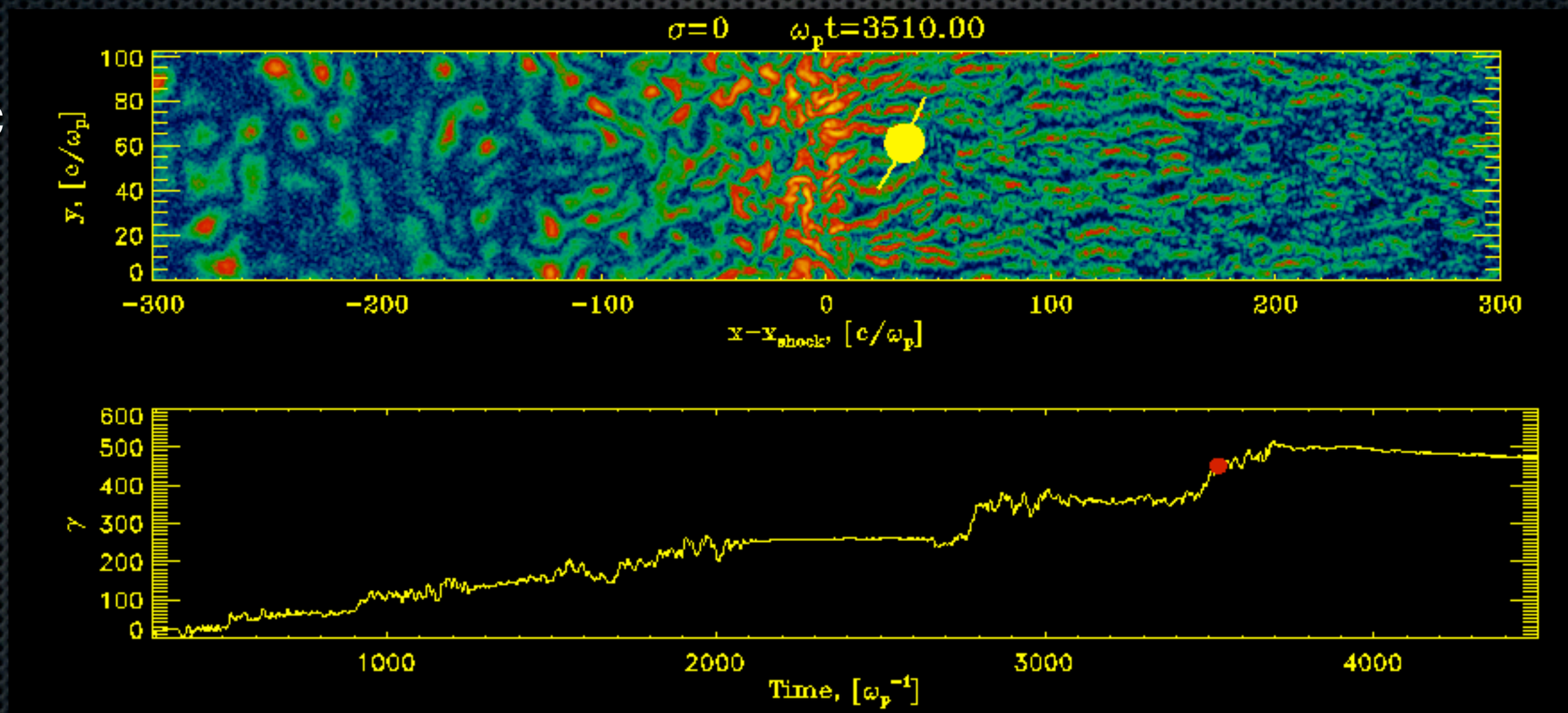
Shock structure for σ*=0 (AS '08)*

Particle acceleration

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

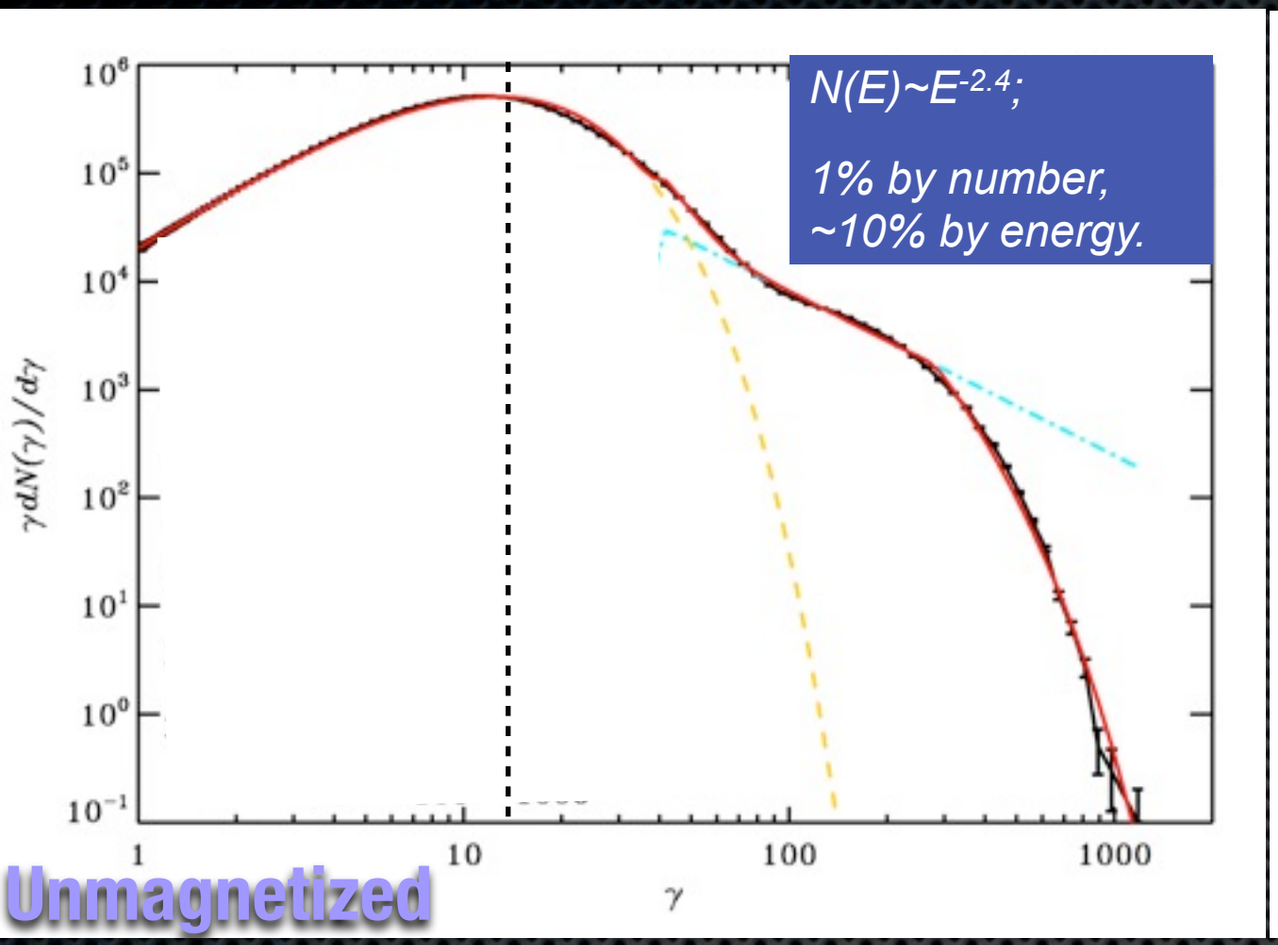
Magnetic filaments

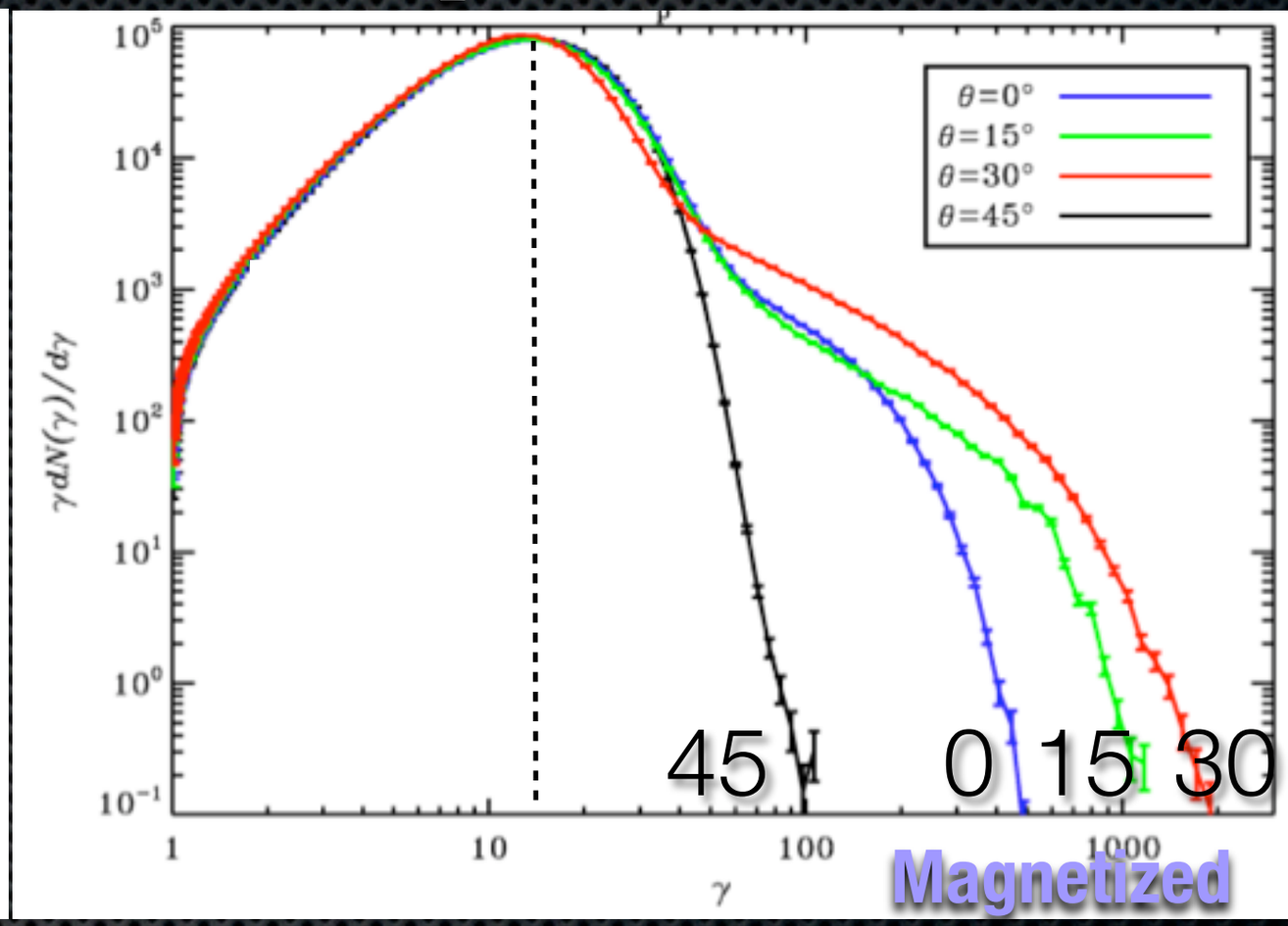
Particle energy

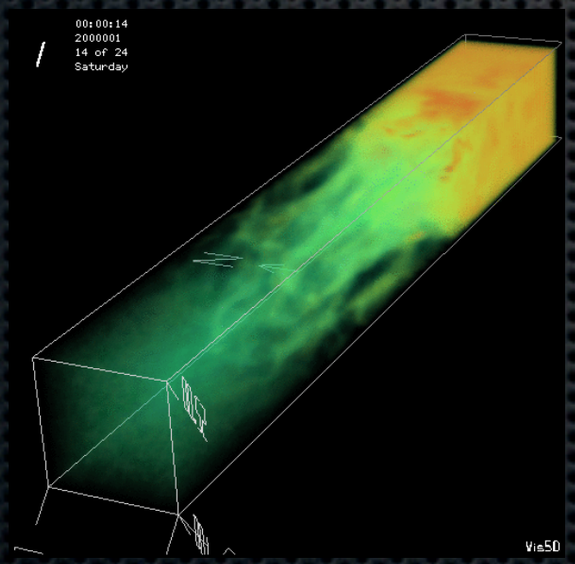


Particle acceleration: pairs

Sironi & AS 09

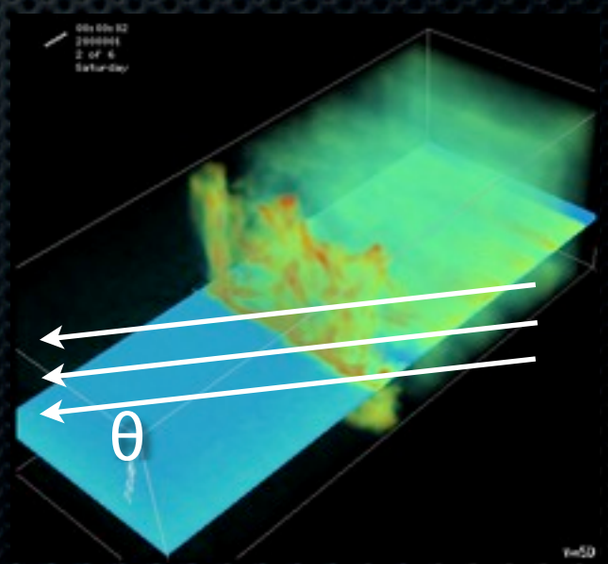




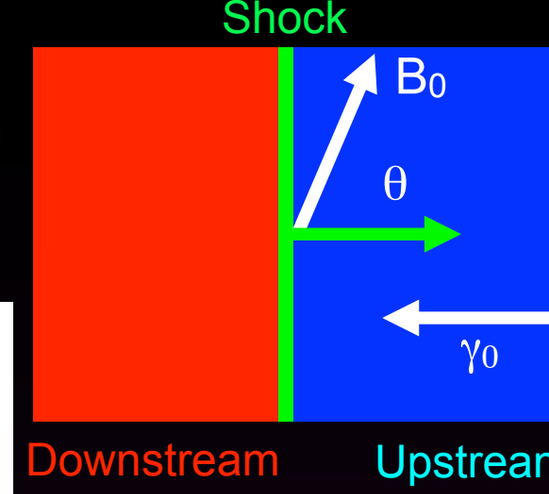


Conditions for acceleration in relativistic shocks:

low magnetization of the flow



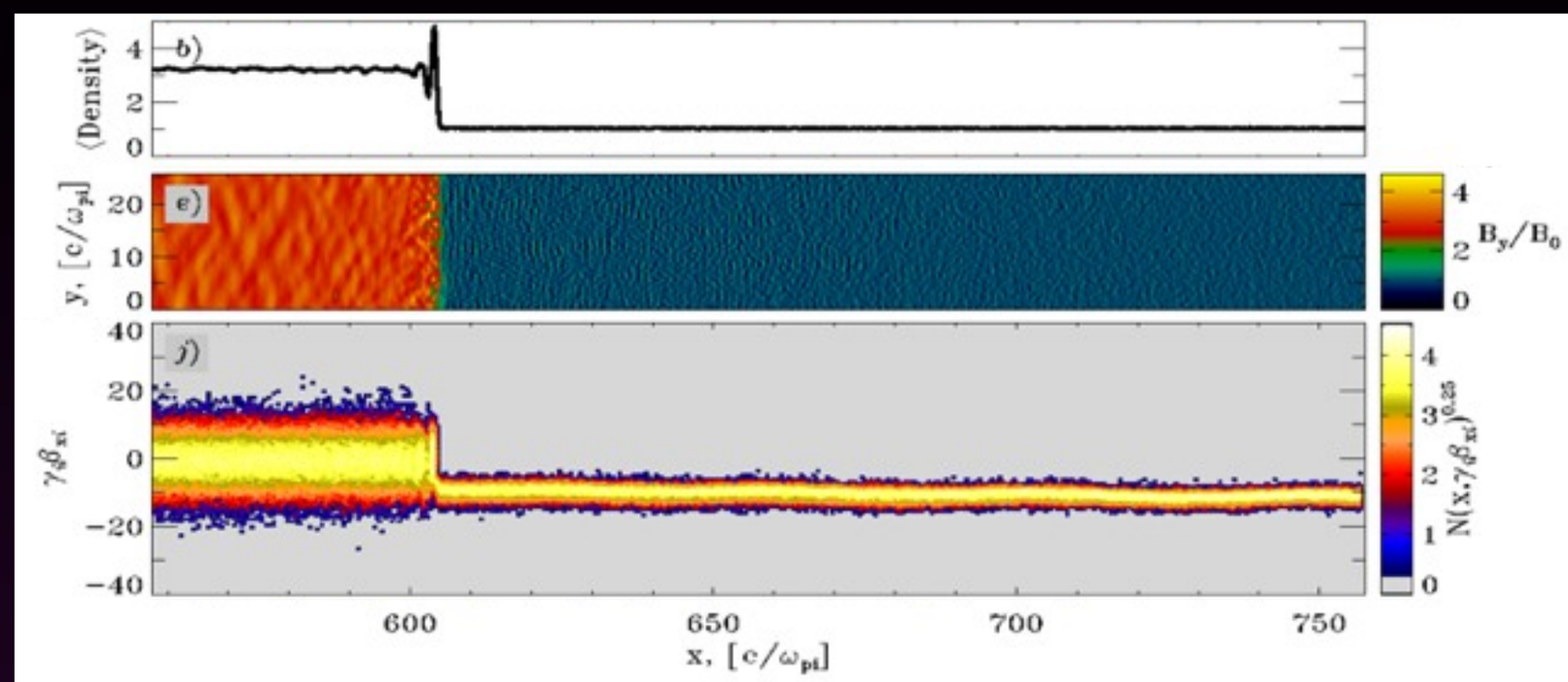
Perpendicular vs parallel shocks



- Quasi-perpendicular shocks: mediated by magnetic reflection

<Density>

σ=0.1
θ=75°
γ_0=15
e^--p^+



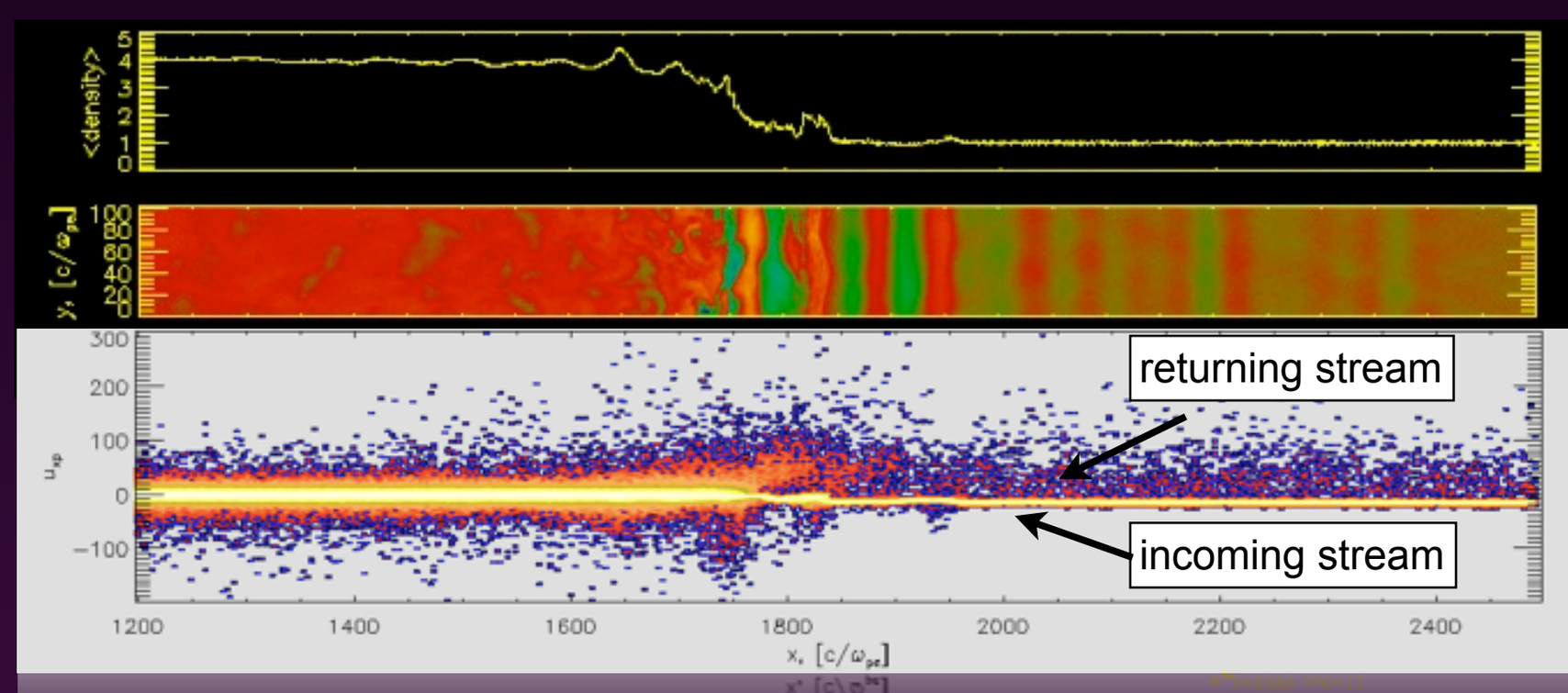
B_y

$\gamma\beta_x$

(LS and Spitkovsky 11)

- Quasi-parallel shocks: mediated by counter-streaming plasma instabilities

σ=0.1
θ=15°
γ_0=15
e^--p^+



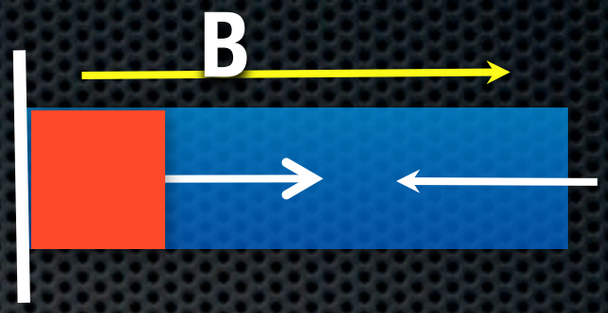
<Density>

B_y

$\gamma\beta_x$

(Sironi & AS 11)

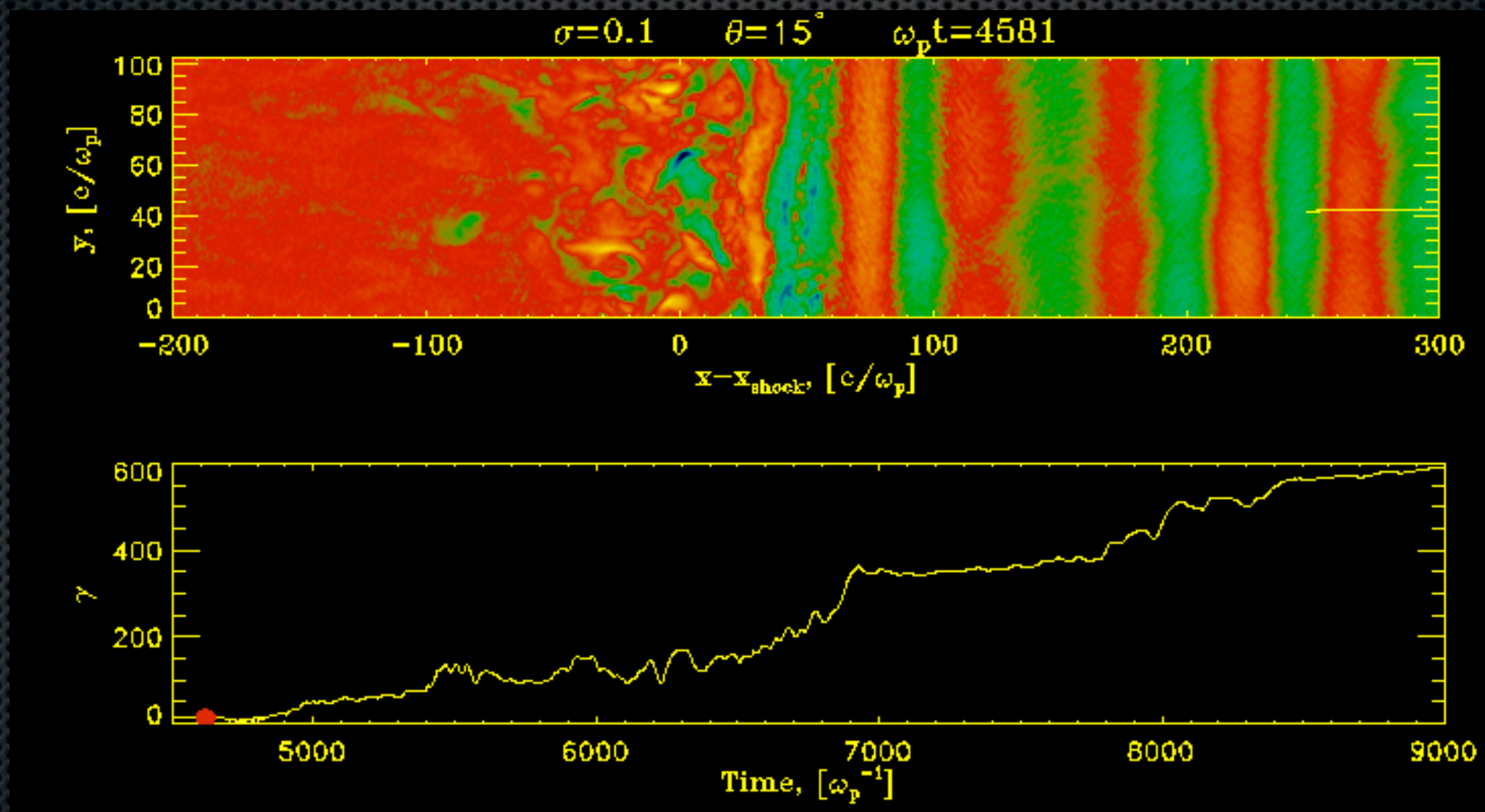
Particle acceleration



Magnetized shock (parallel, e-p): scattering on self-generated upstream waves

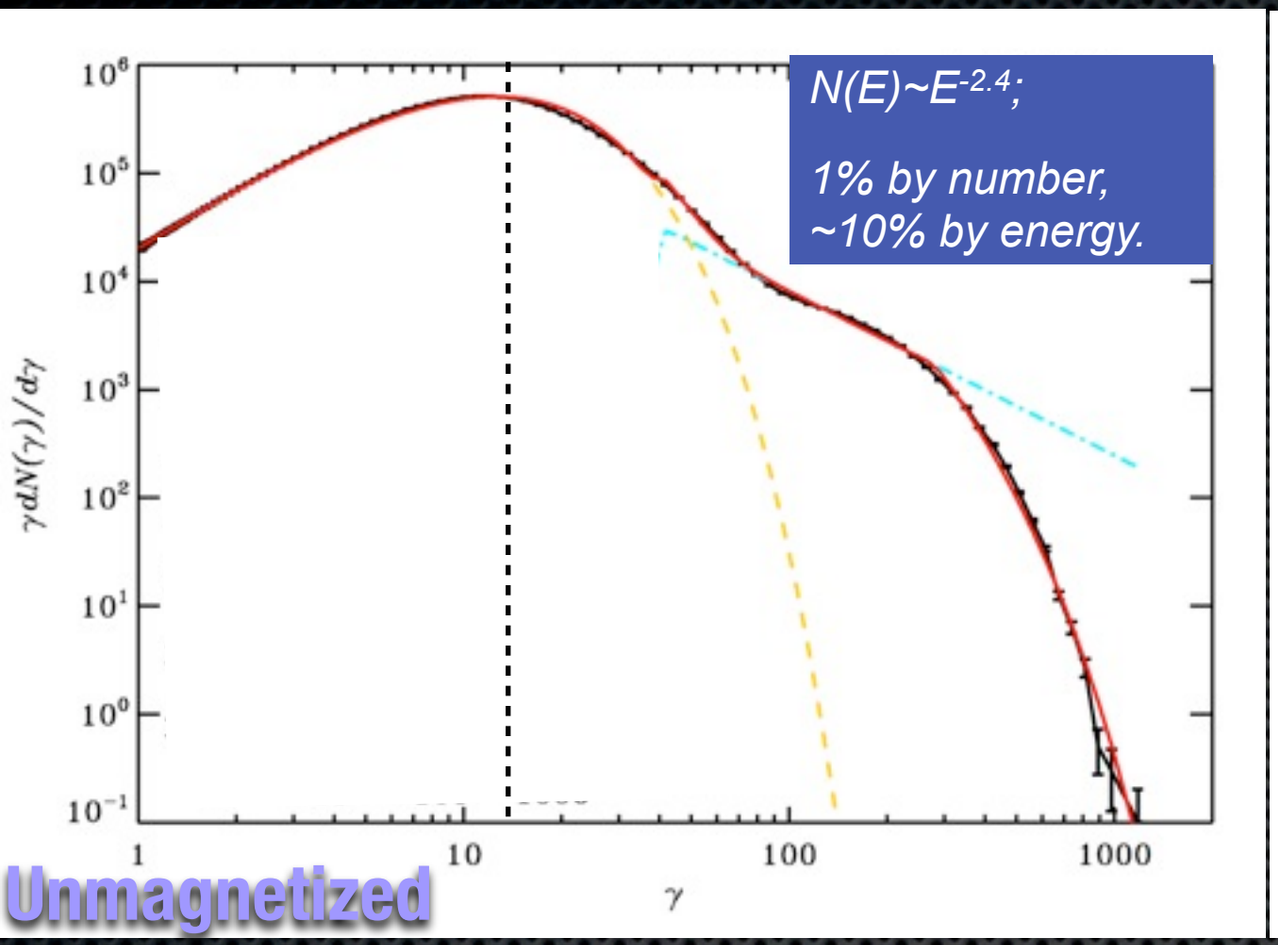
Magnetic energy

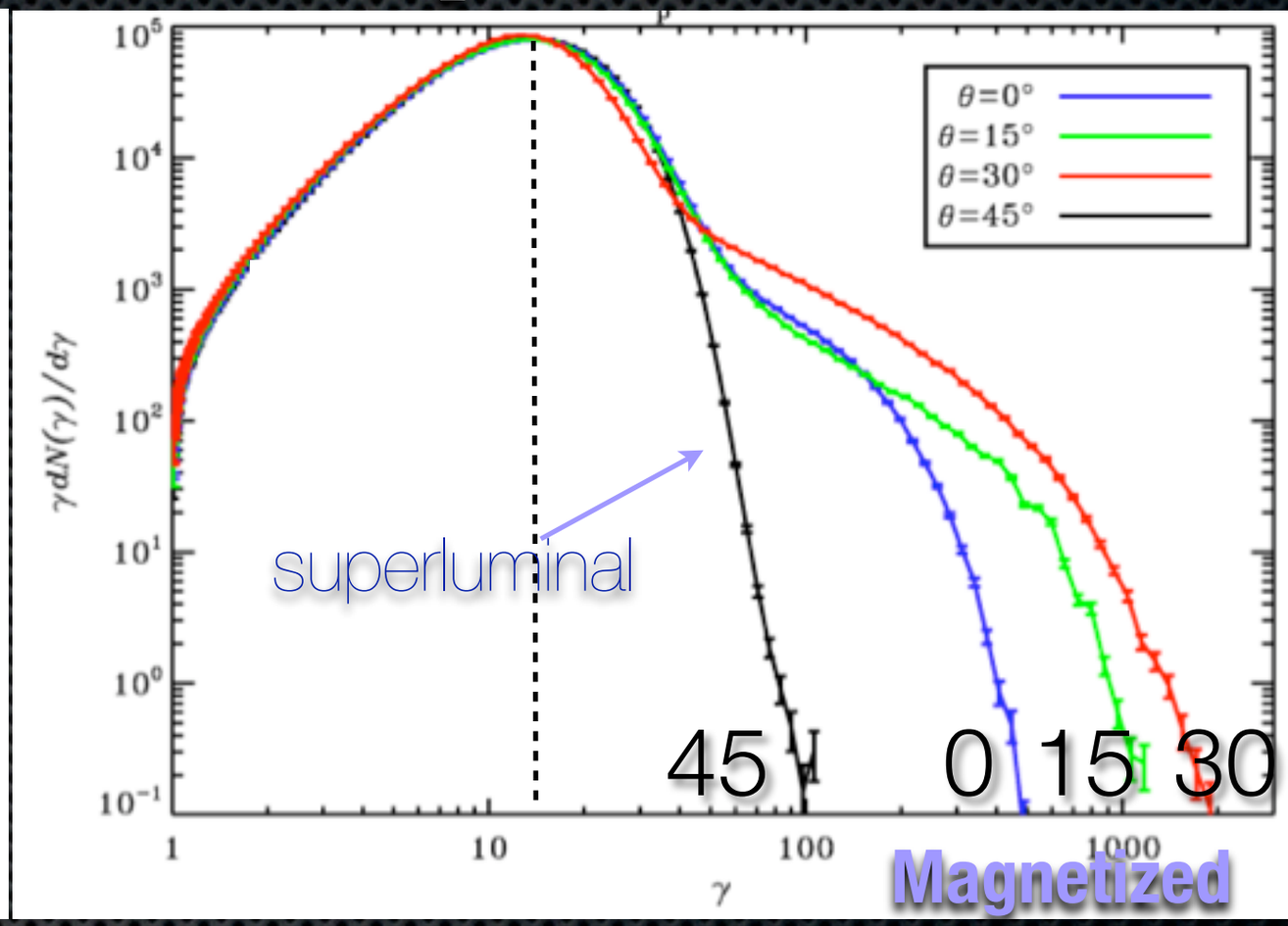
Particle energy

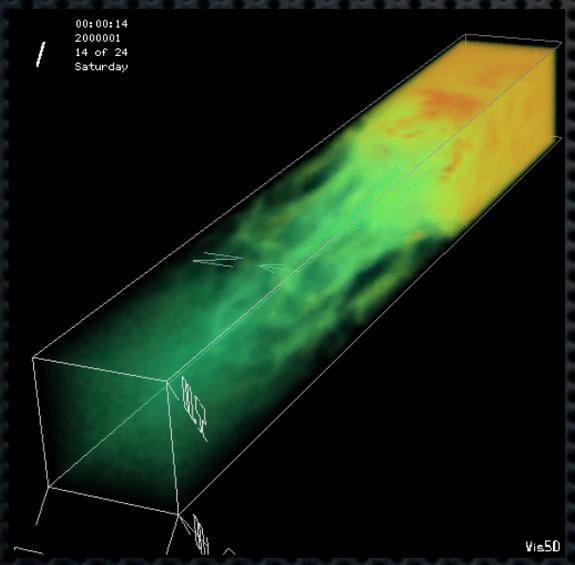


Particle acceleration: pairs

Sironi & AS 09

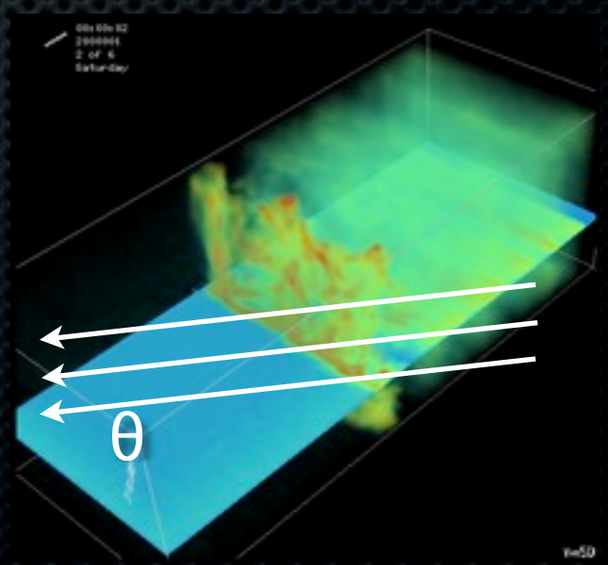




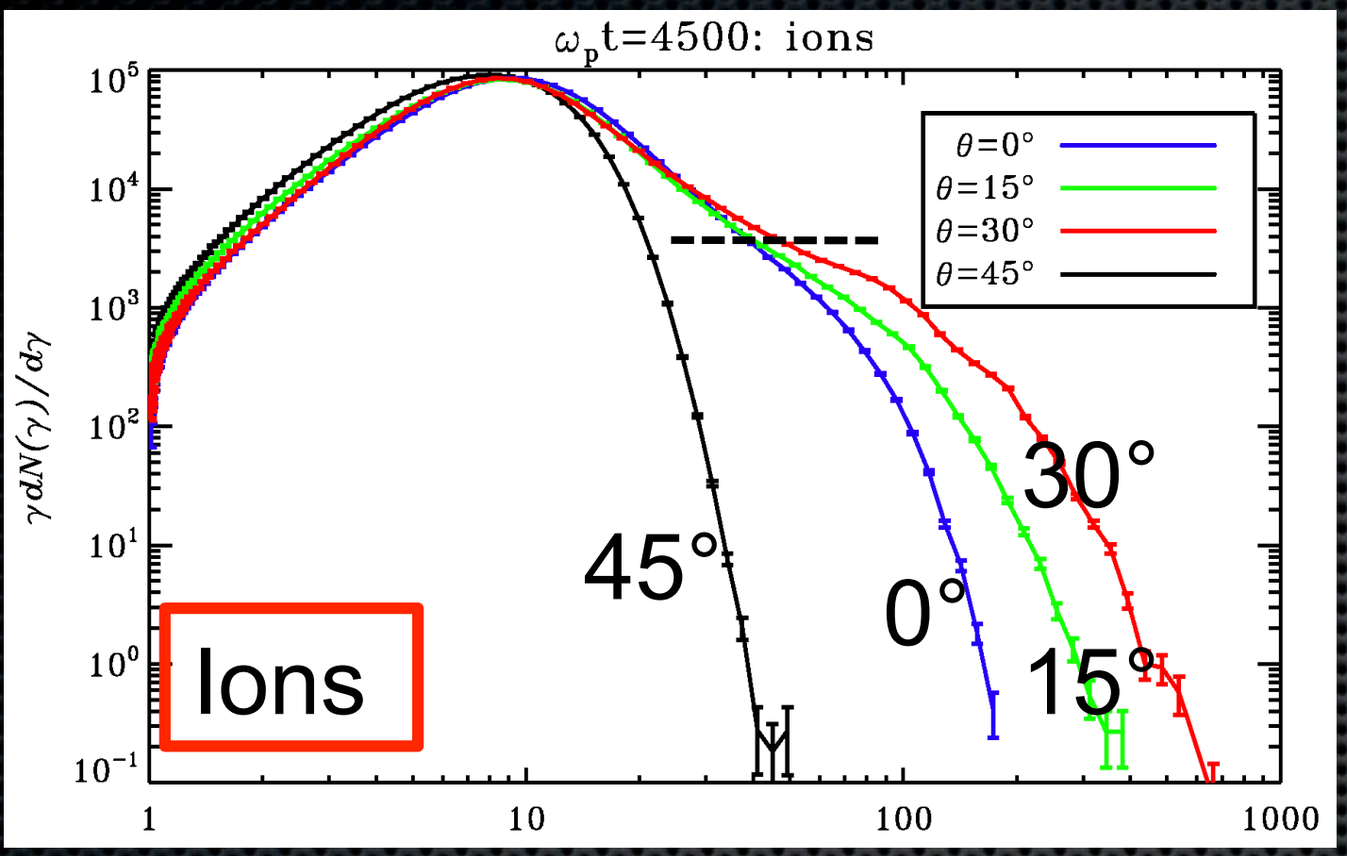


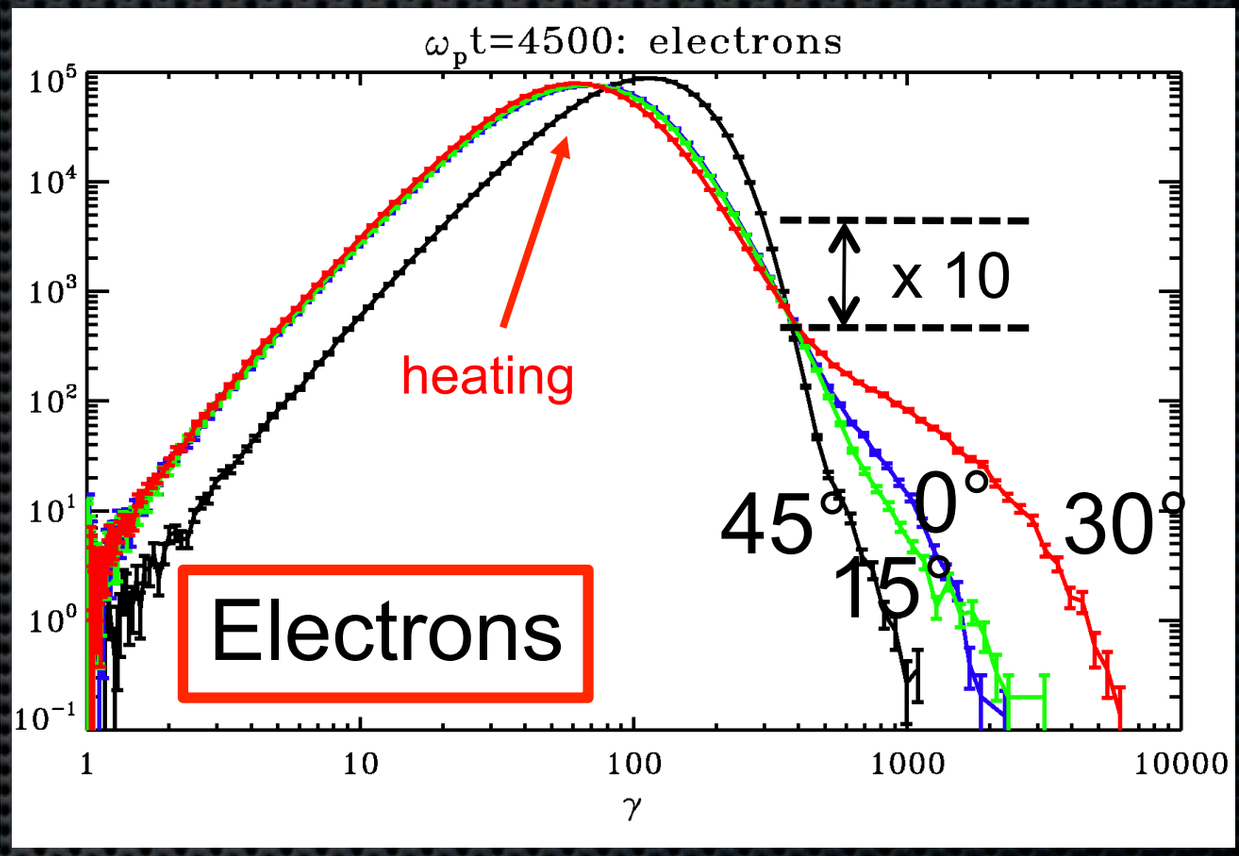
Conditions for acceleration in relativistic shocks:

low magnetization of the flow or quasi-parallel B field.



Particle acceleration: e-ions





Sironi & AS 10

Relativistic magnetized e-ion shocks:

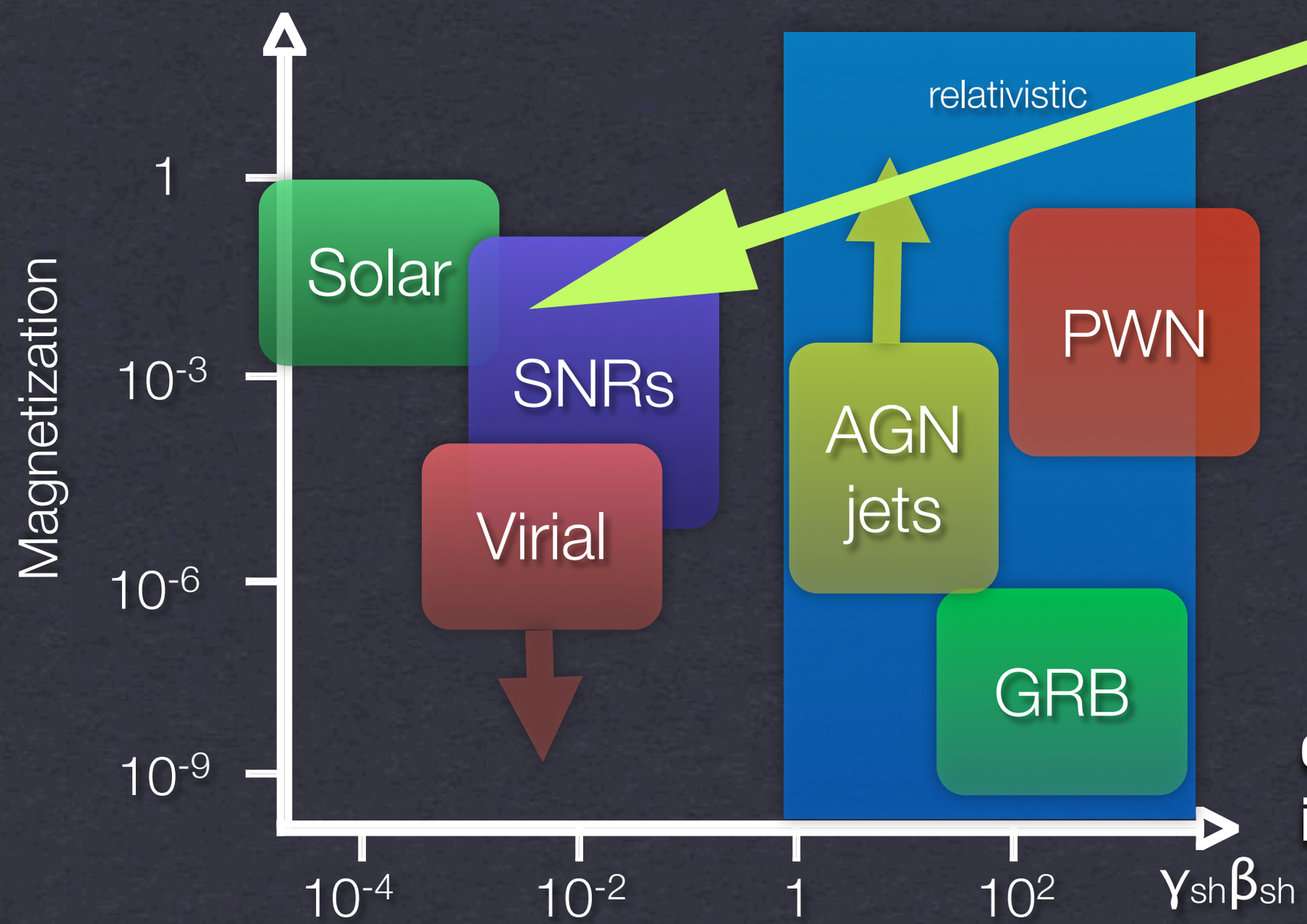
protons are accelerated for quasi-parallel configurations, up-to 30% of energy in the tail; 5% by number;

electron acceleration is 5-10 less efficient;

electrons are strongly heated by ions.

Parameter Space of shocks

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



Concentrate on nonrelativistic shocks:

1) PIC survey

2) Hybrid survey

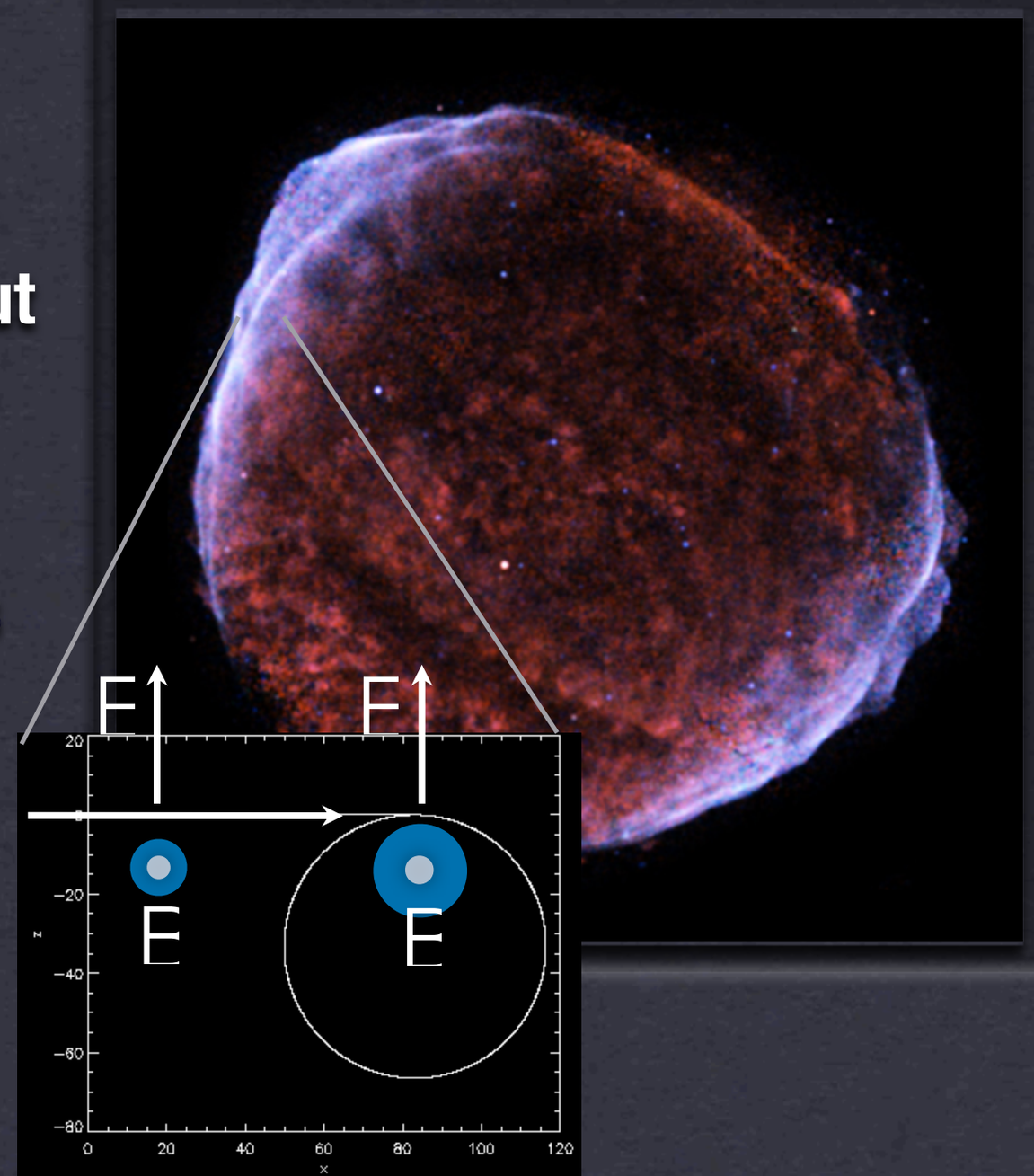
e and ions are different in non-relativistic case

Nonrelativistic shocks

We studied SNR shocks in e-ion plasma up to mass ratio 1600.

- Shock structure depends on magnetization (alfvenic Mach #)
- Ion acceleration is efficient in quasi-parallel shocks (<40% by energy), but electron acceleration is not efficient

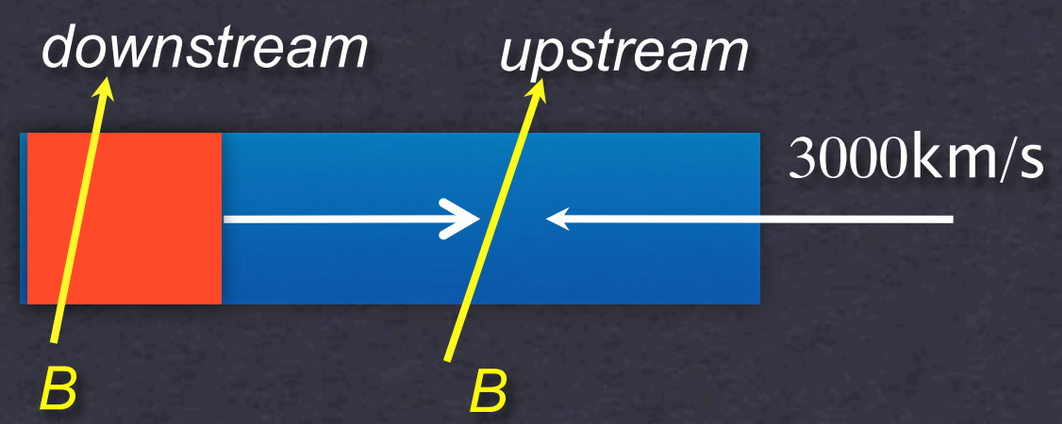
  Typically electron acceleration is suppressed because e Larmor radius is << ion Larmor radius. Need pre-acceleration of electrons
- Recently, we found a mechanism for electron injection into shock acceleration (Riquelme & AS, '11)



Numerical parameters: PIC

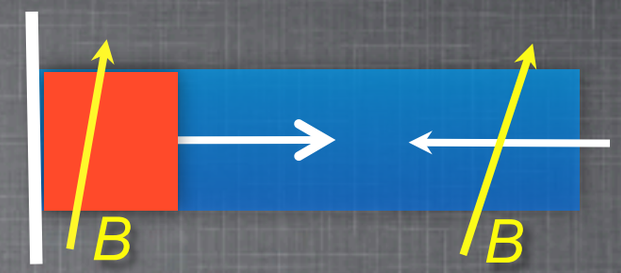
- Essentially two main types of shocks: quasi-parallel and quasi-perpendicular. Investigate inclinations of 75° and 0°. Mass ratio from 25 to 1600
- Speeds 3000 to 30000 km/s (0.01c - 0.1c)
- Alfvenic Machs from 3 to 140
  - For 1000km/s, B=25μG, Ma=18; for 3000km/s, Ma=54
- We are close to realistic parameters, albeit in 2.5D.

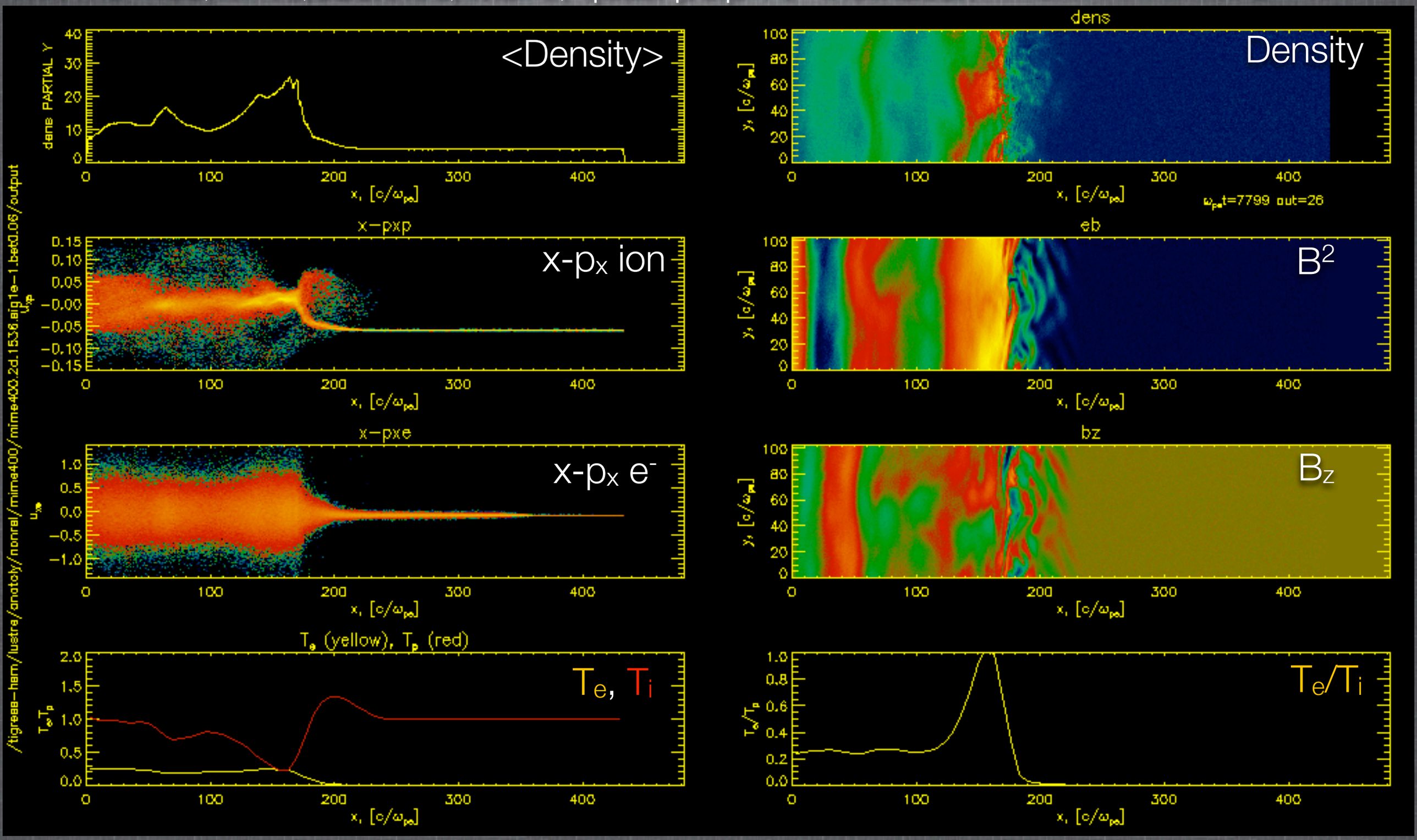
Typical resolutions: 10 cells per c/ompe
5-100 particles/cell
10000x1024 cells typical;
some 3D runs at 3000x512x128



Nonrelativistic shocks: shock structure

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

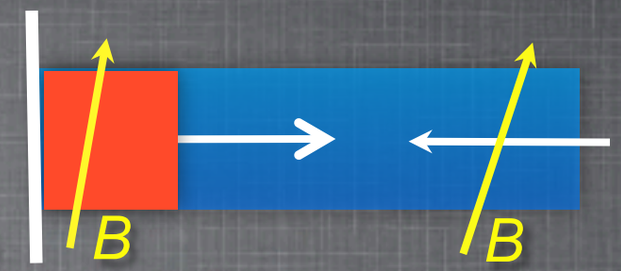


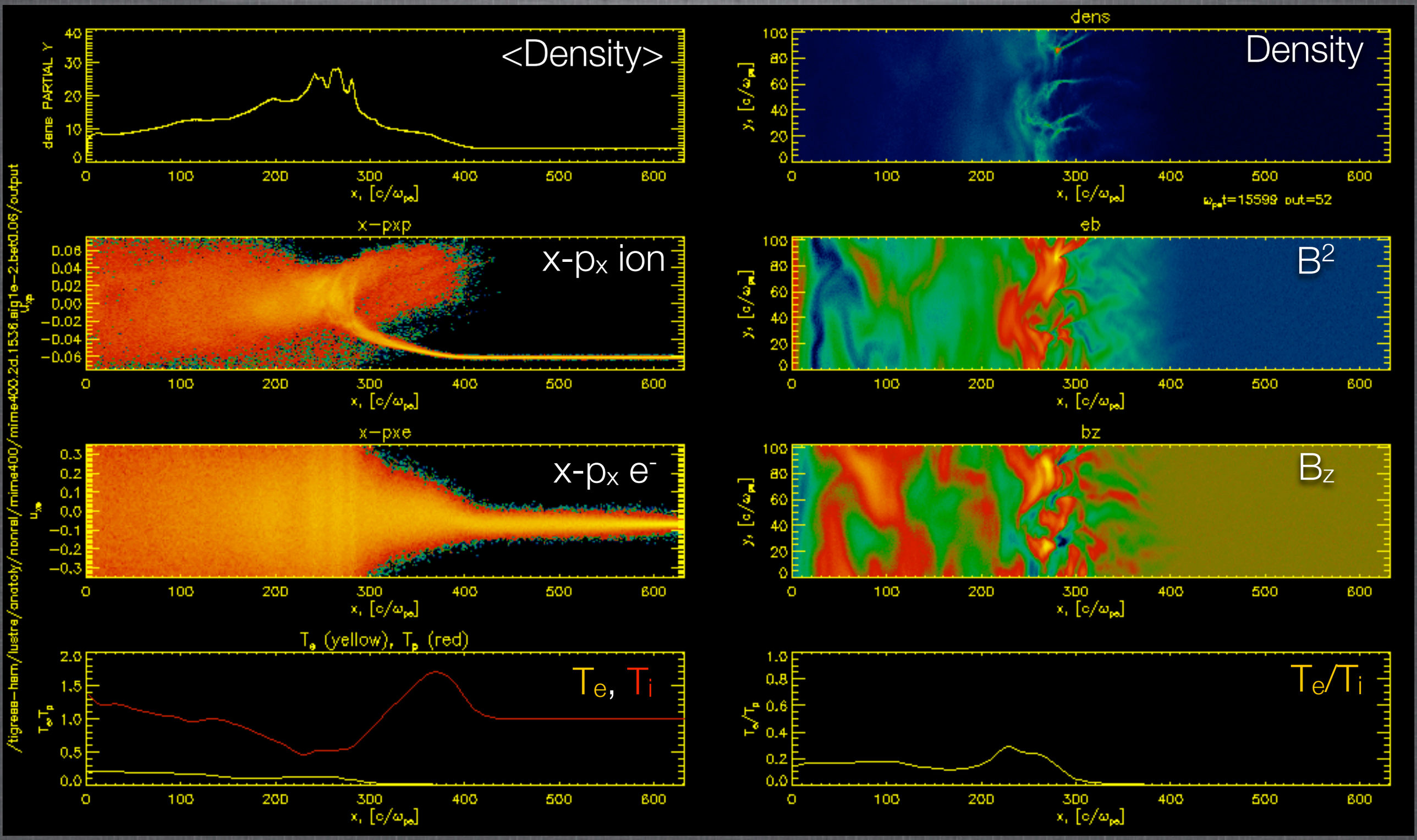


Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves.

Nonrelativistic shocks: shock structure

mi/me=400, v=18,000km/s, Ma=15 quasi-perp 75° inclination

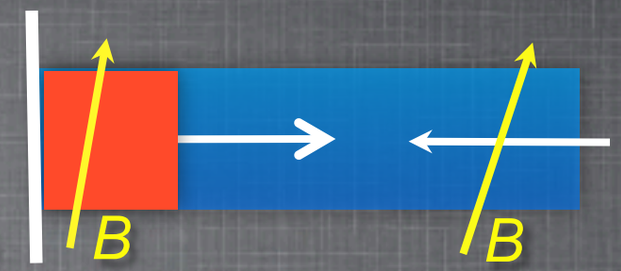


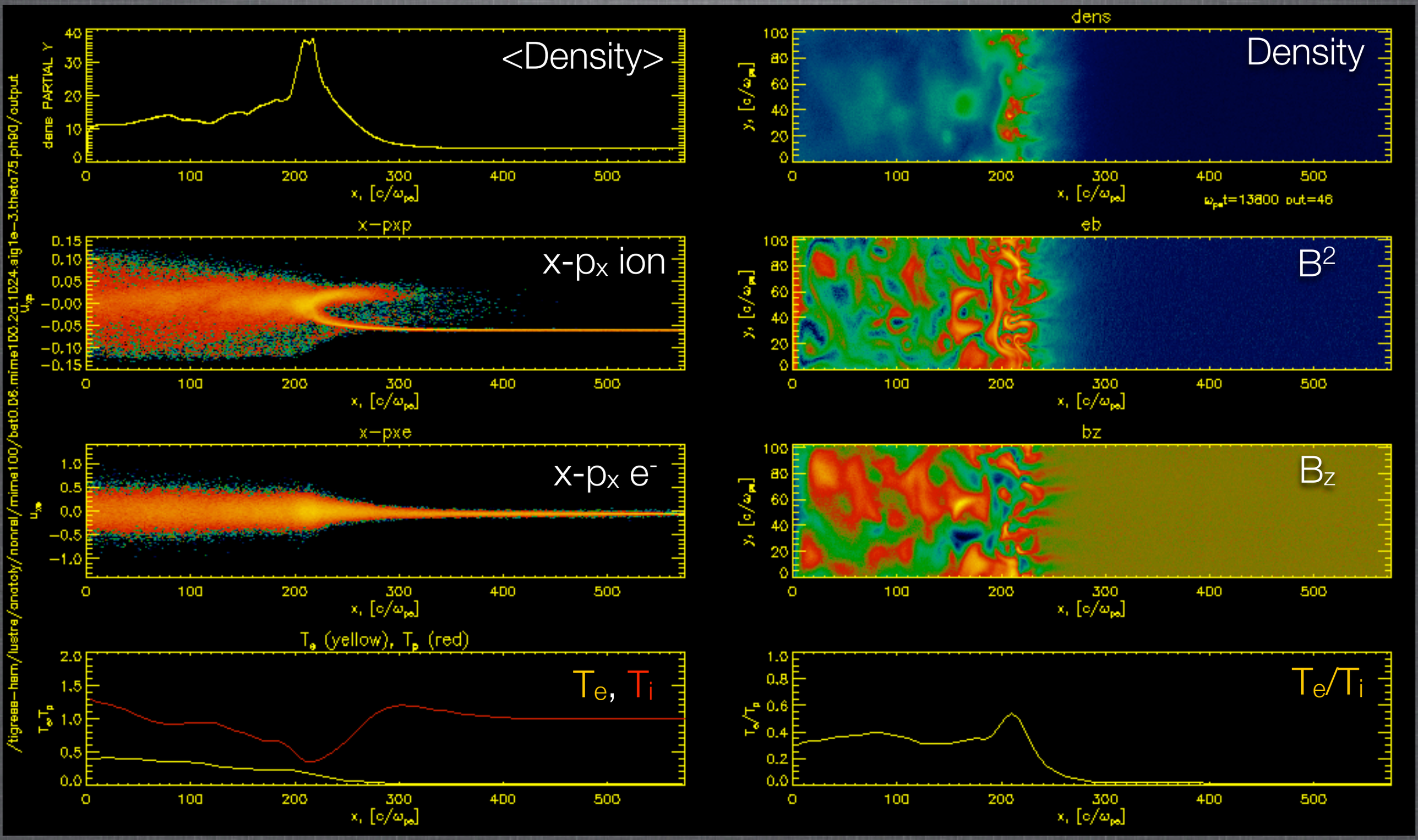


Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves, spectra.

Nonrelativistic shocks: shock structure

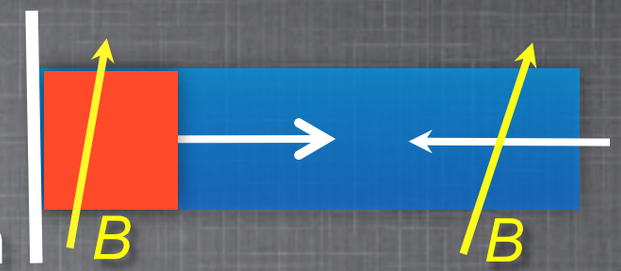
mi/me=100, v=18,000km/s, Ma=45 quasi-perp 75° inclination

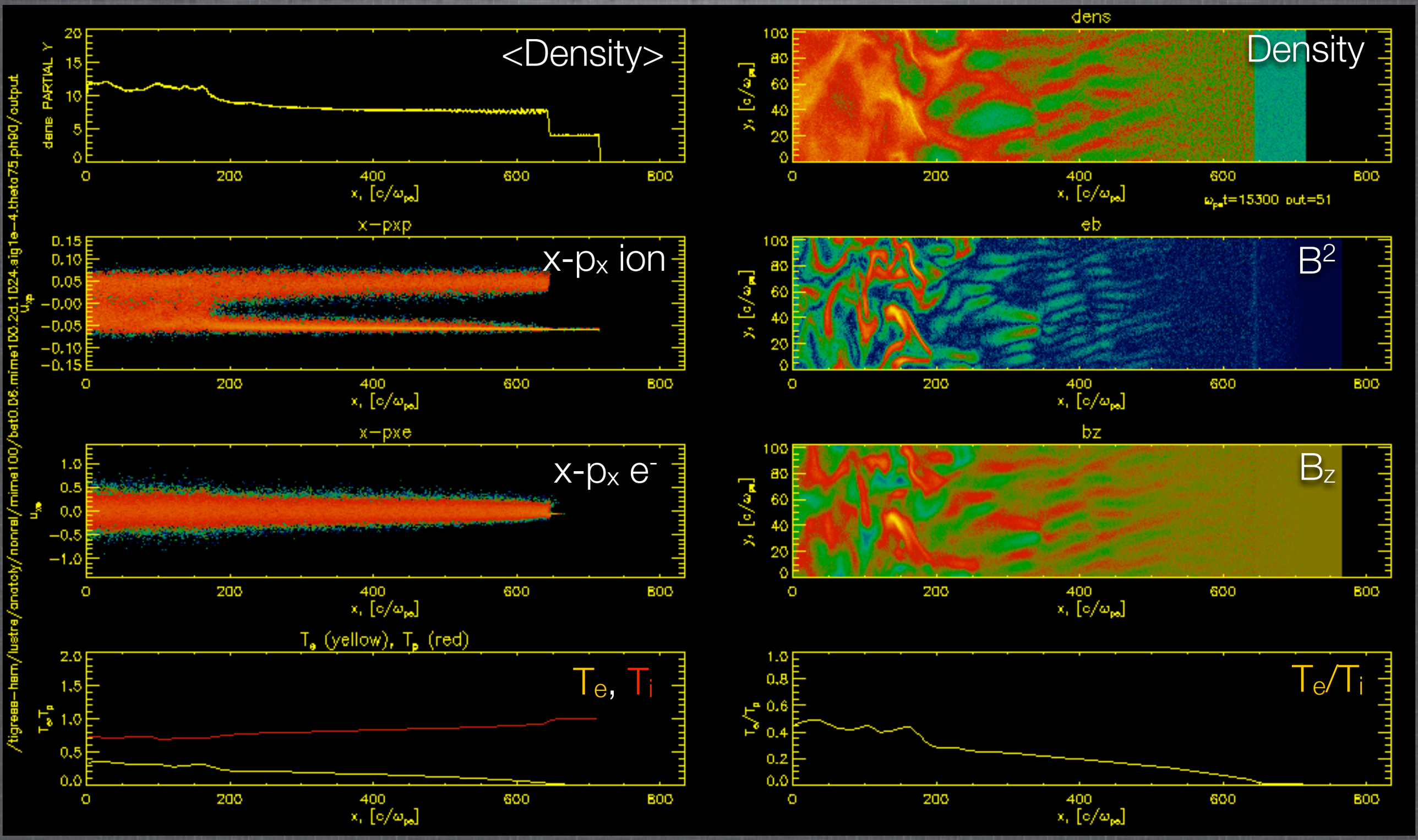




Nonrelativistic shocks: shock structure

mi/me=100, v=18,000km/s, Ma=140 quasi-perp 75° inclination

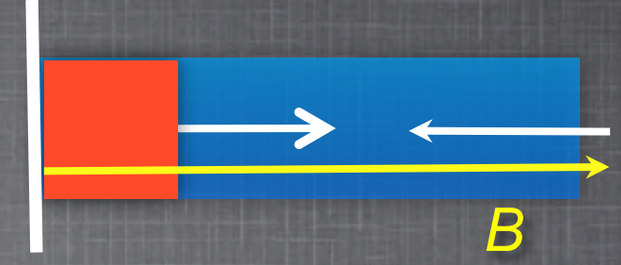


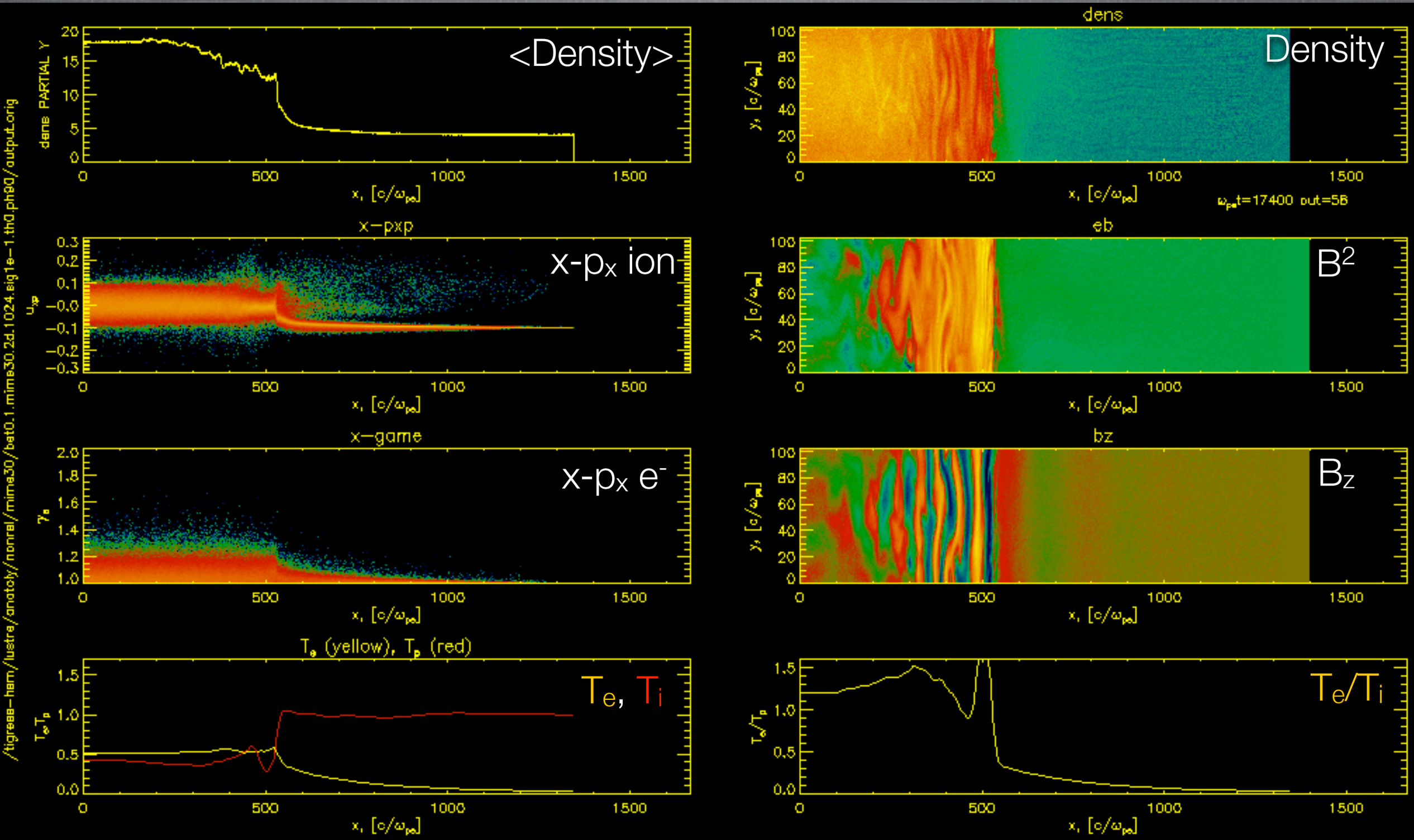


2D structure essential (cf. Shimado et al 2010), confirmed by other codes (e.g. Kato 2010)

Nonrelativistic shocks: quasiparallel shock

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



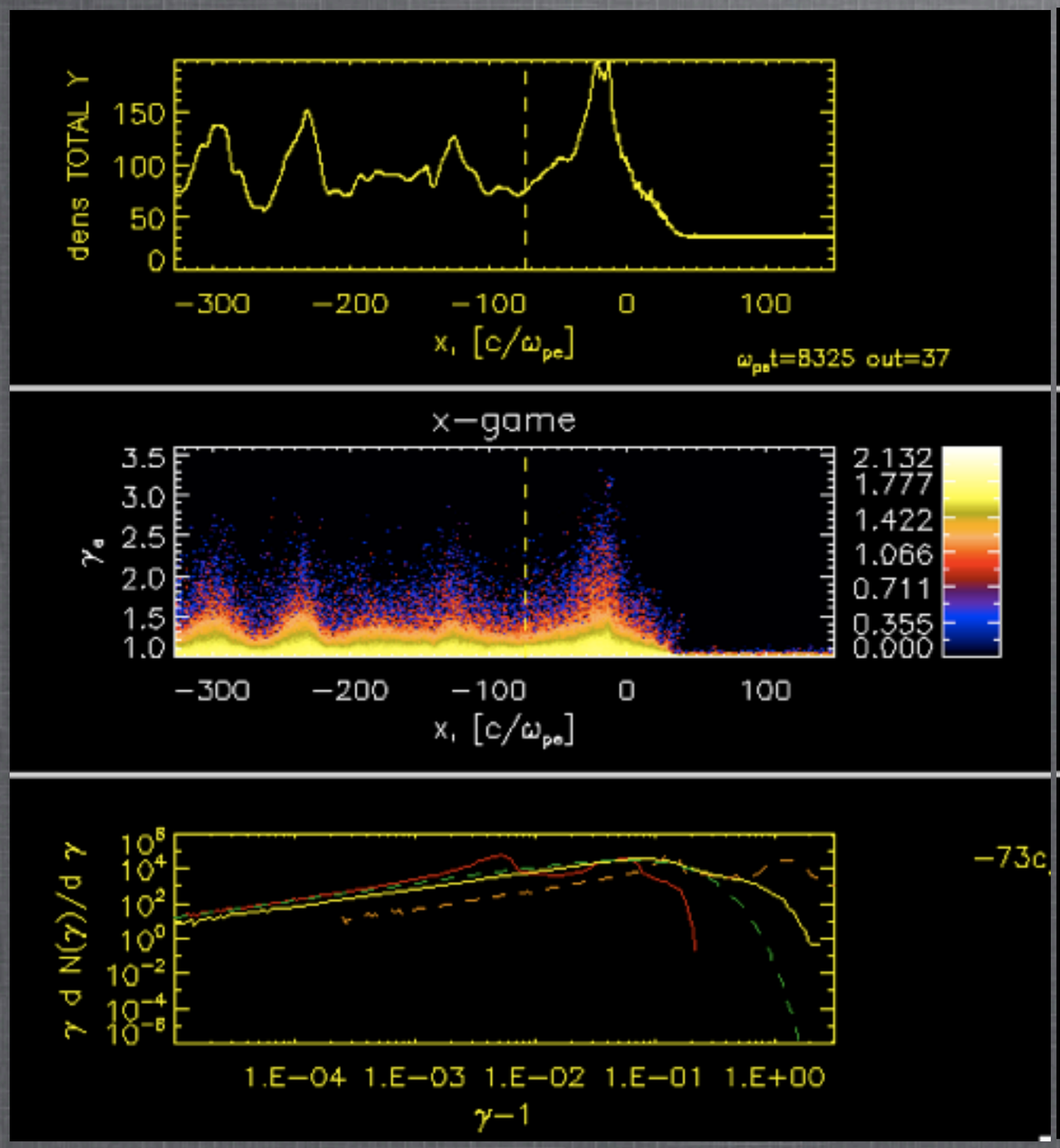


Circularly polarized waves in upstream and downstream. Field is reoriented.

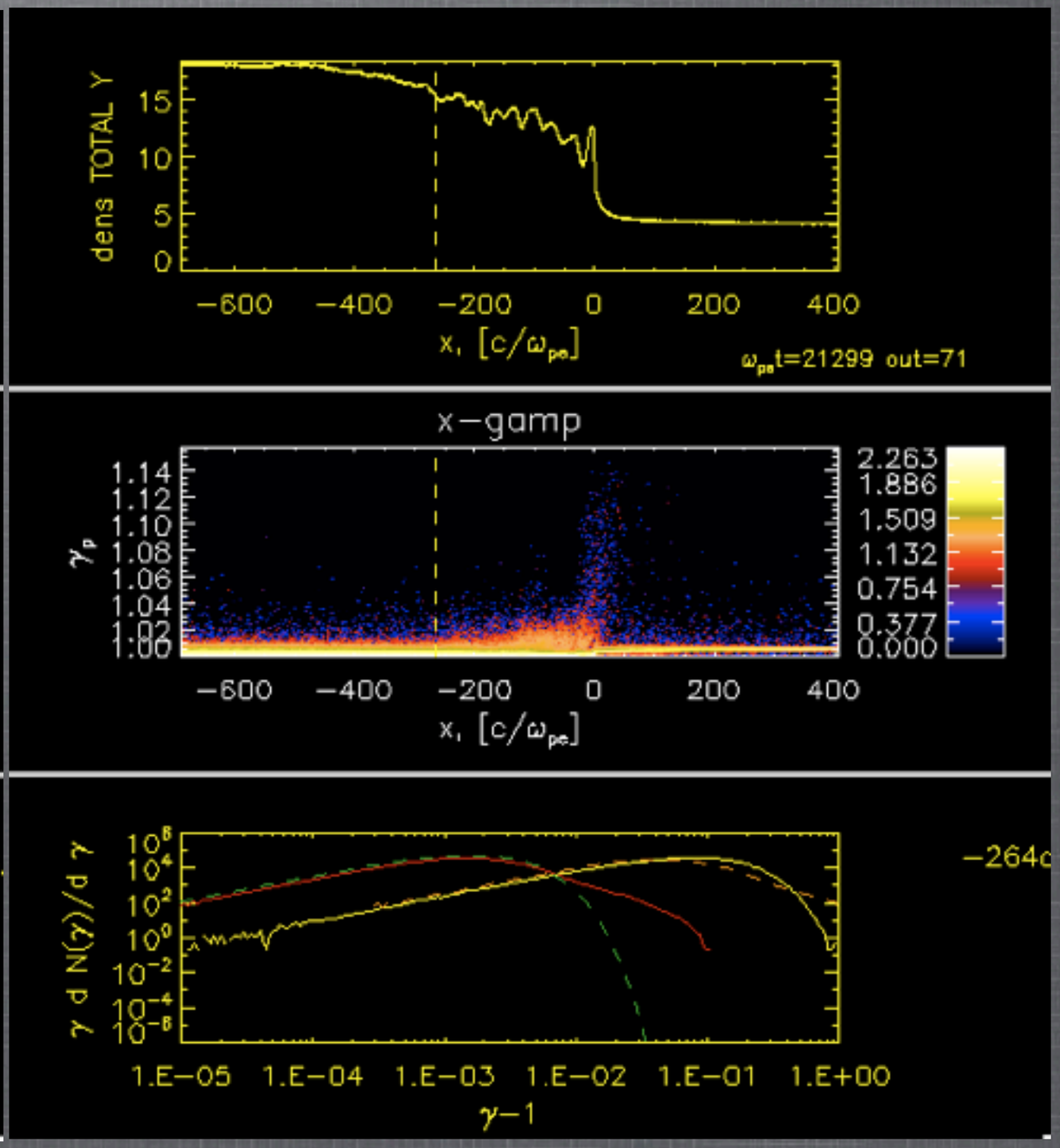
Nonrelativistic shocks: acceleration

Acceleration of electrons and ions occurs in different regimes!!!

Electrons are accelerated in quasi-perp shocks, ions in quasi-parallel shocks



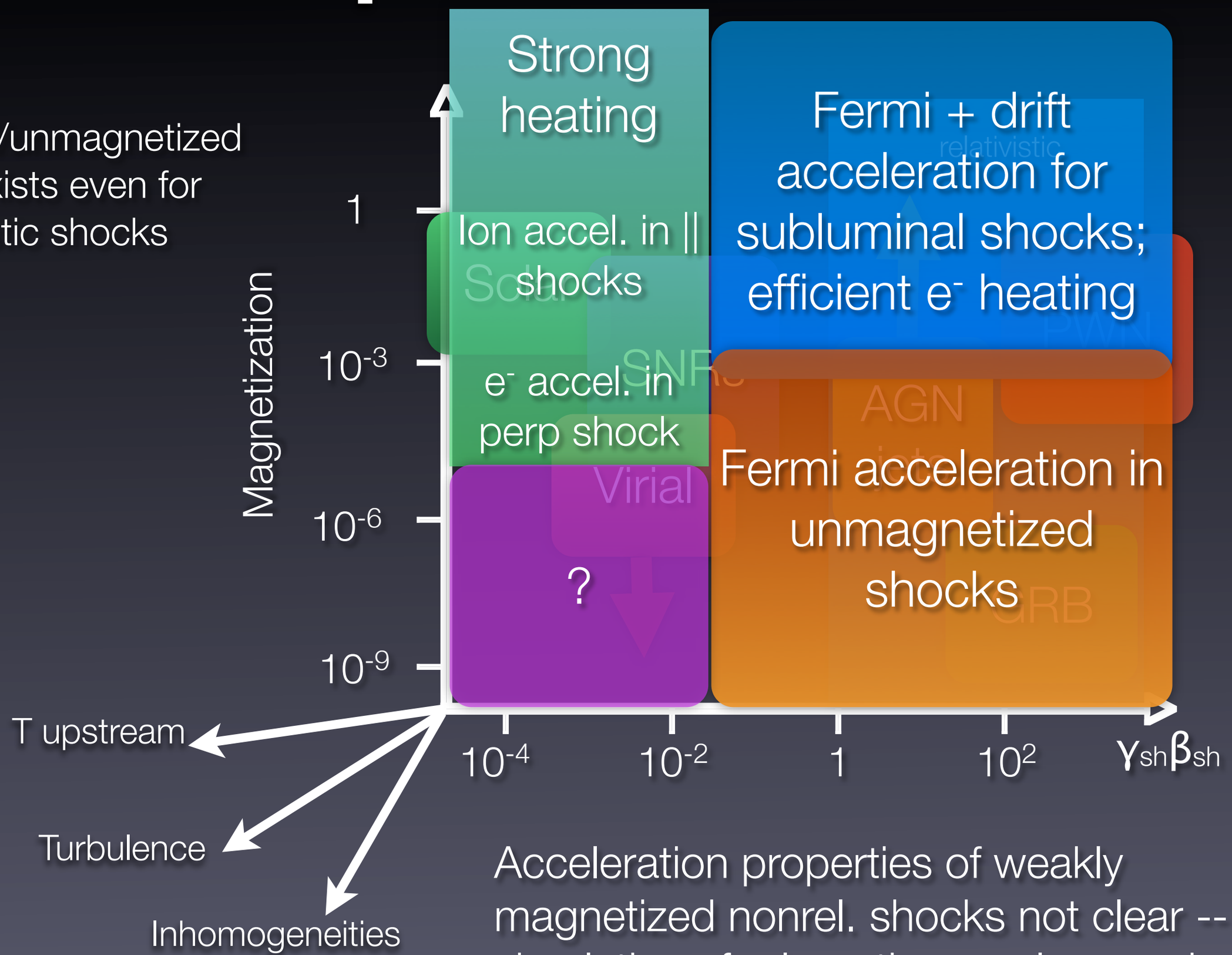
quasi-perpendicular shock



quasi-parallel shock

Parameter Space of shocks

Magnetized/unmagnetized transition exists even for non-relativistic shocks



Acceleration properties of weakly magnetized nonrel. shocks not clear -- simulations for long time scales needed

WHAT ACCELERATES ELECTRONS?

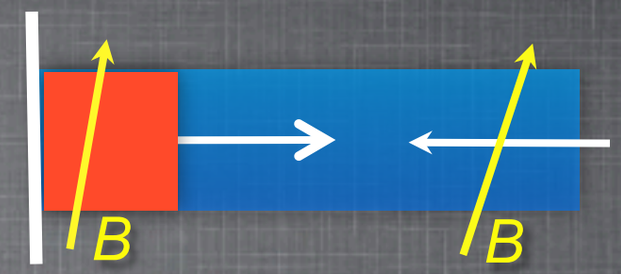
Electrons are notorious for being difficult to inject because of the disparity in the Larmor scales with ions.

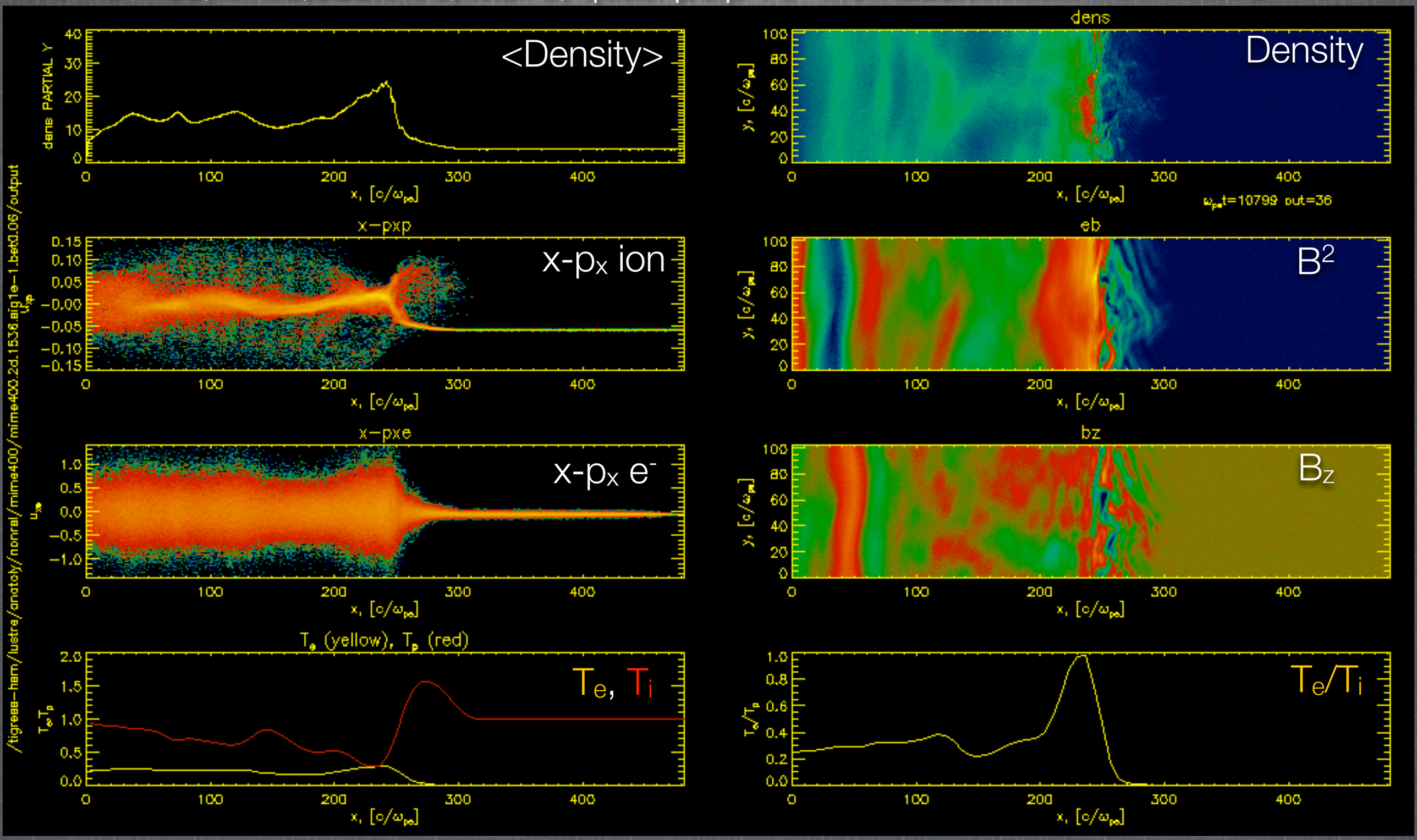
Shock is driven on ion scales, electrons need to be pre-accelerated to be injected. But how?

Recently, we found a mechanism for electron injection into shock acceleration (Riquelme & AS 2011)

Nonrelativistic shocks: shock structure

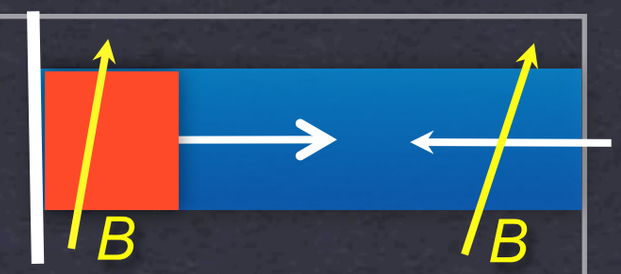
mi/me=400, v=18,000km/s, Ma=5, quasi-perp 75° inclination





Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves.

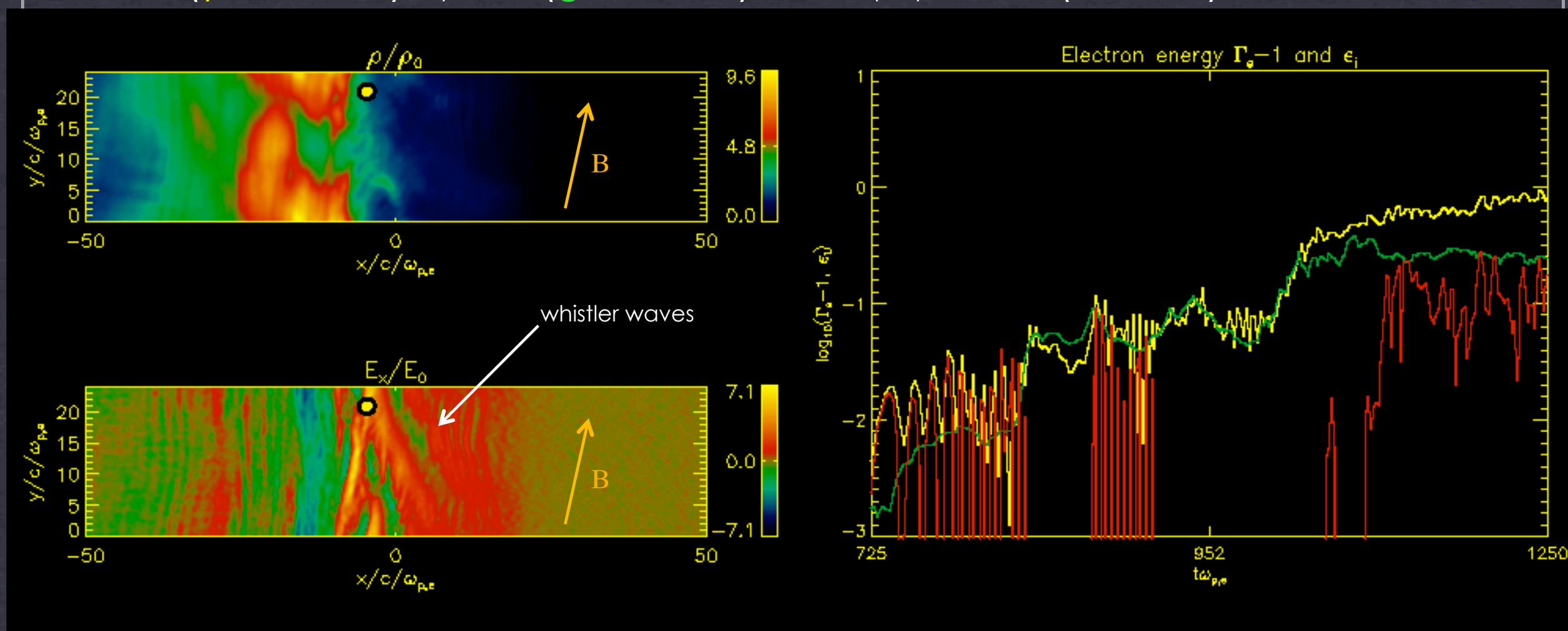
Electron acceleration



Whistler waves in the shock foot cause E || B.

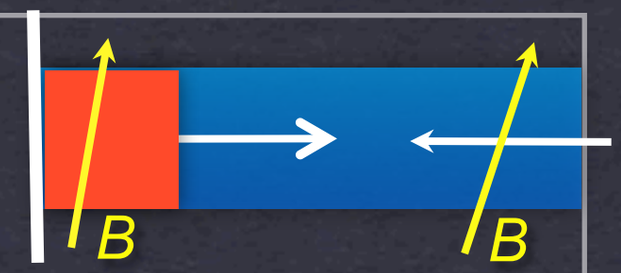
$$\epsilon_i \equiv \int \frac{e}{m_e c^2} v_i E_i dt$$

Γ_e-1 (yellow line), $\varepsilon_{parallel}$ (green line), and $\varepsilon_{perpendicular}$ (red line)



Electron moves along the magnetic field direction, preferentially along the y-direction. This allows a velocity along the x-direction of $\sim v_e \cos(\theta_{Bn})$. Thus, $\theta_{Bn} < 90^o$ is required.

Electron acceleration



Whistler waves in the shock foot cause E || B.

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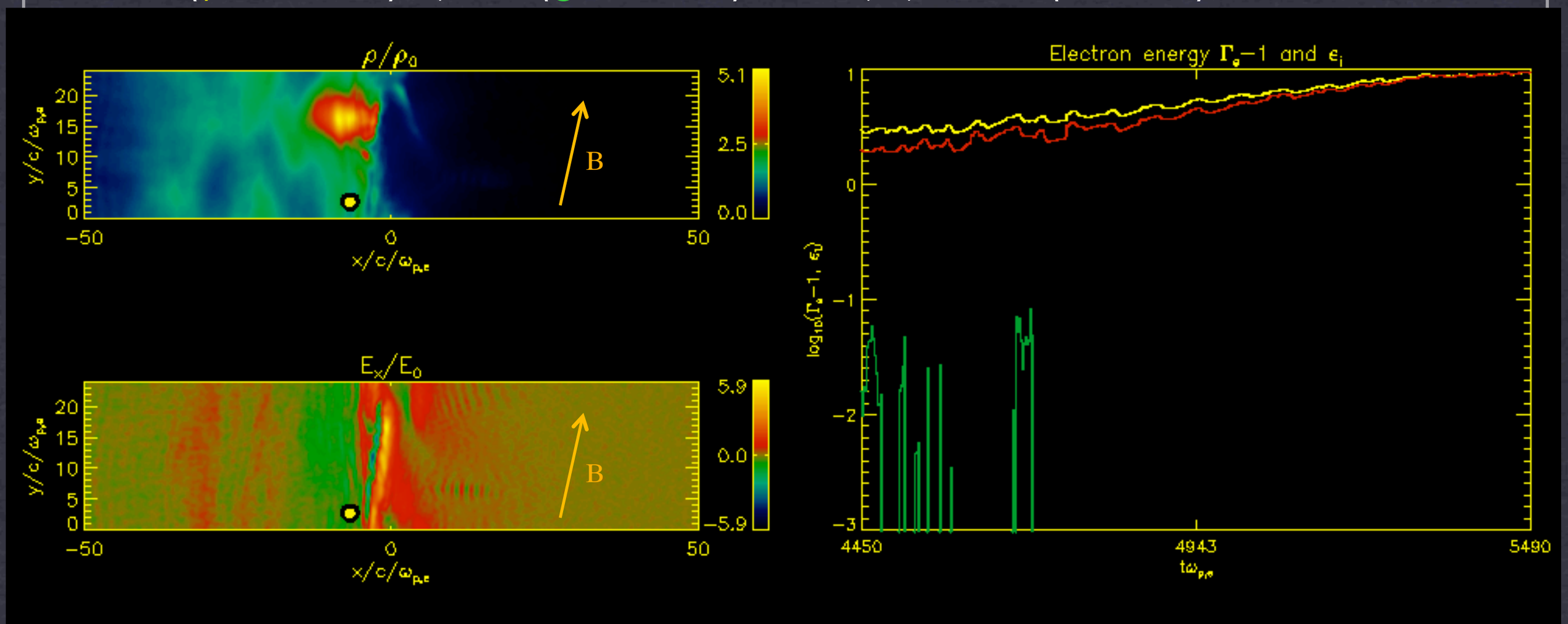
Γ_e-1 (yellow line), $\varepsilon_{parallel}$ (green line), and $\varepsilon_{perpendicular}$ (red line)



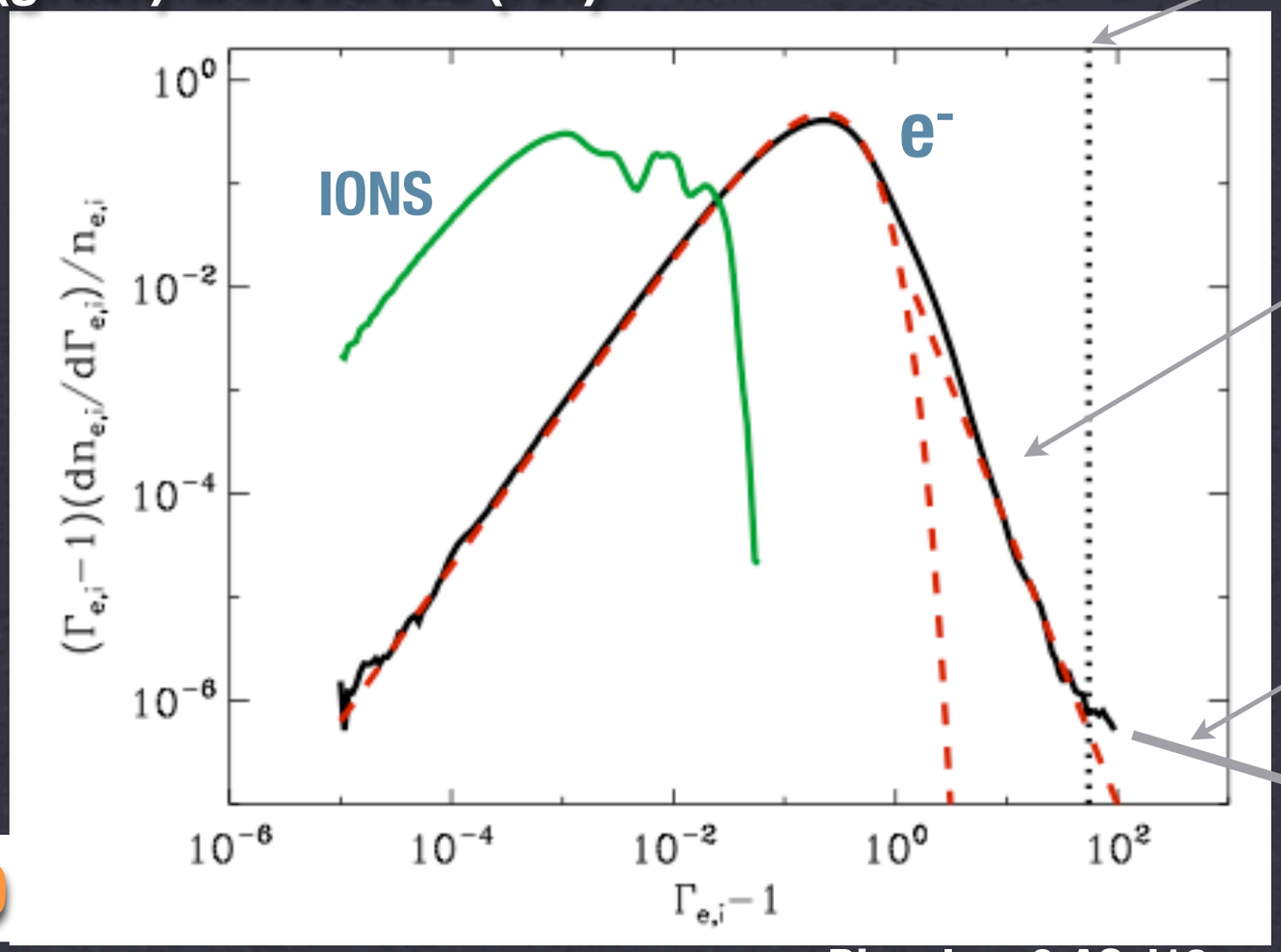
We observe pre-acceleration of electrons to energies comparable to ion energies (injection)

Parameter dependence

Spectrum of ions (green) & electrons (red)

Ma=7

mi/me=400



ion Larmor scale

pre-acceleration for injection

further DSA?

?

Riquelme & AS, '10

Electron injection needs:

Quasi-perpendicular shocks, $45° < \theta_{Bn} < 90°$

Lower Alfvenic Mach numbers (to create whistlers): $M_A < (m_i/m_e)^{1/2}$

What accelerates ions?

Ions: Hybrid shock survey

2D, field in-plane

Inclinations <75 deg

Machs 3,10,30,100

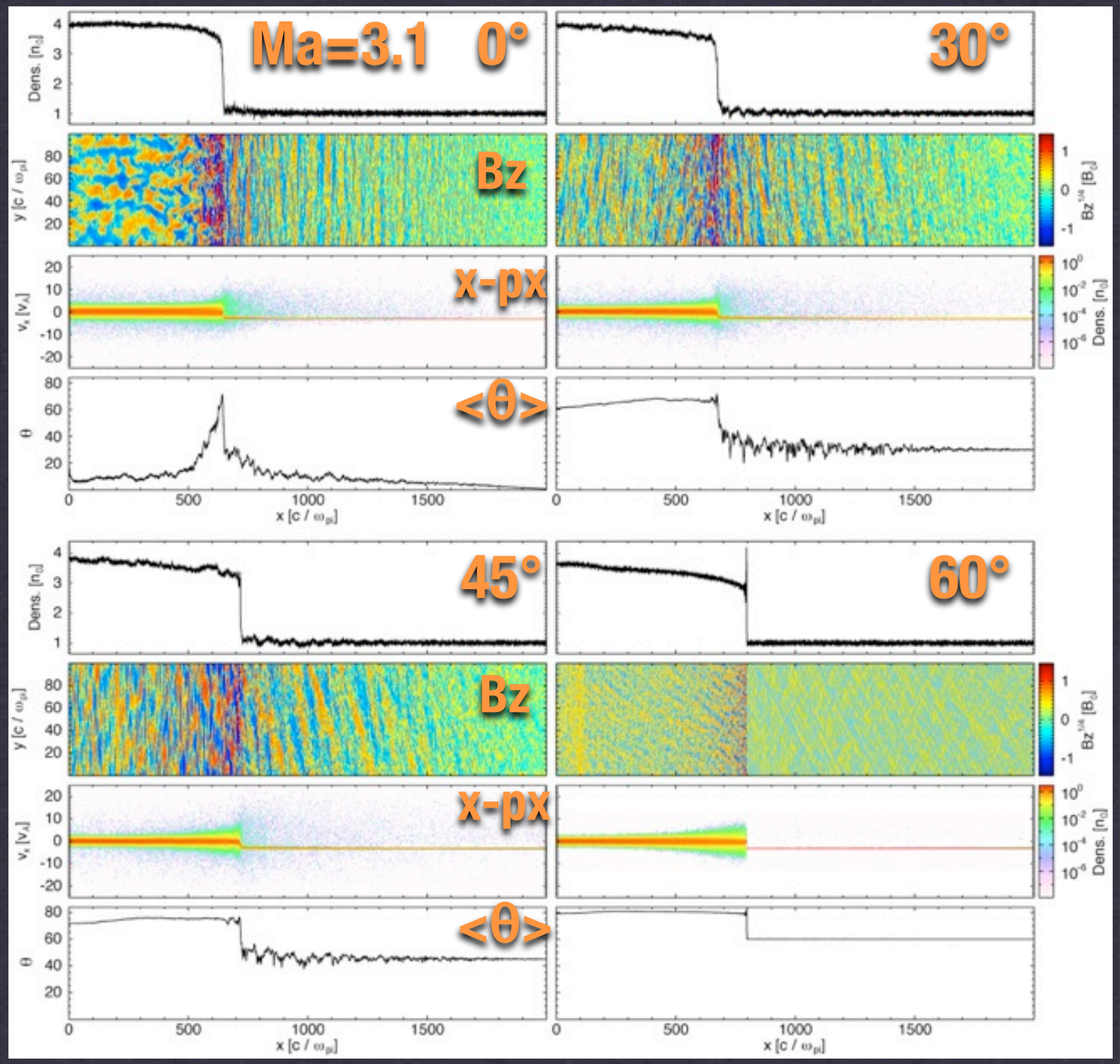
resolution 0.1 c/ompi

5-50 particles/cell

(Gargate+AS 2011)

At early time PIC and hybrid agree well.

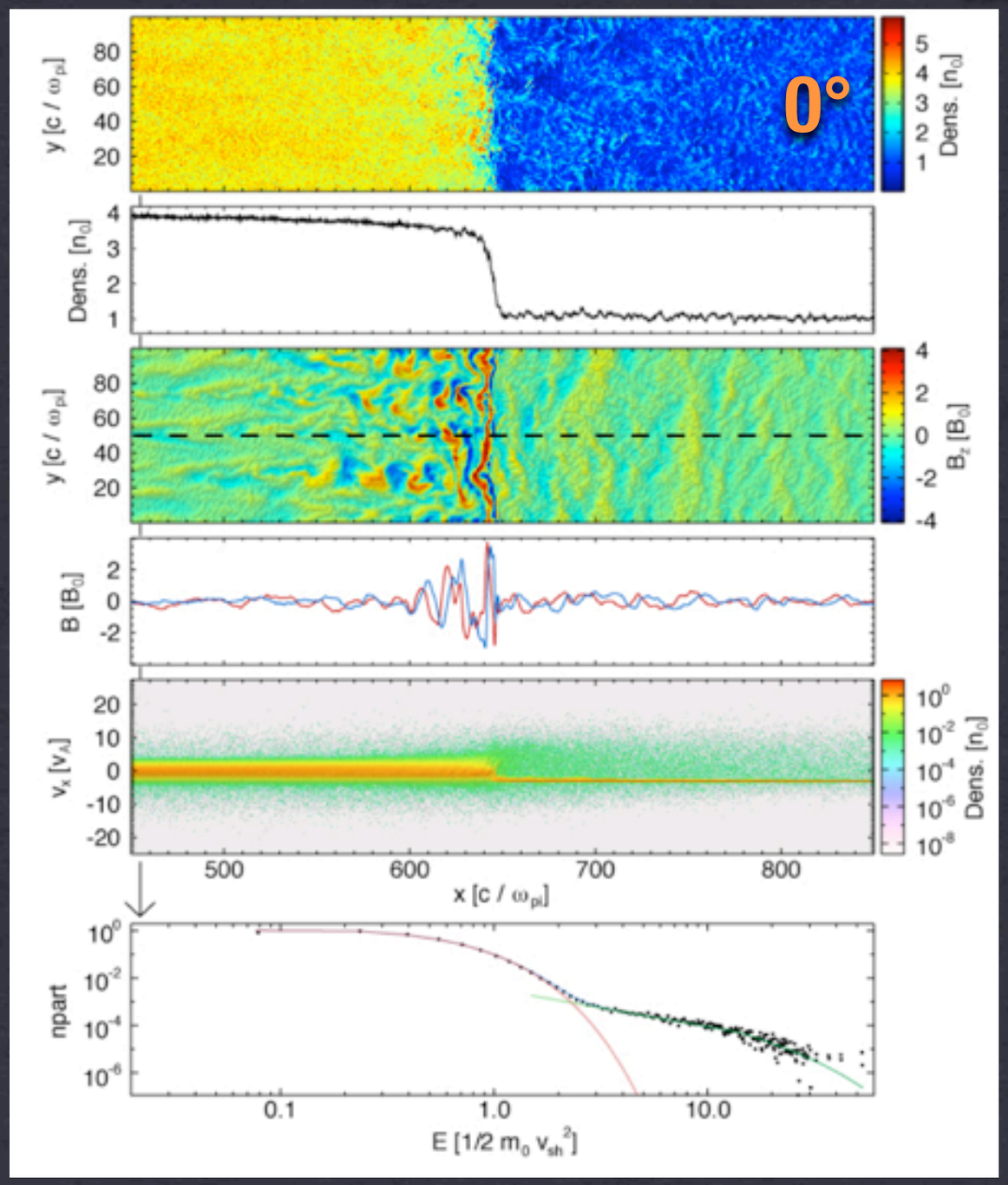
Quasi-parallel shocks work by reorienting the field

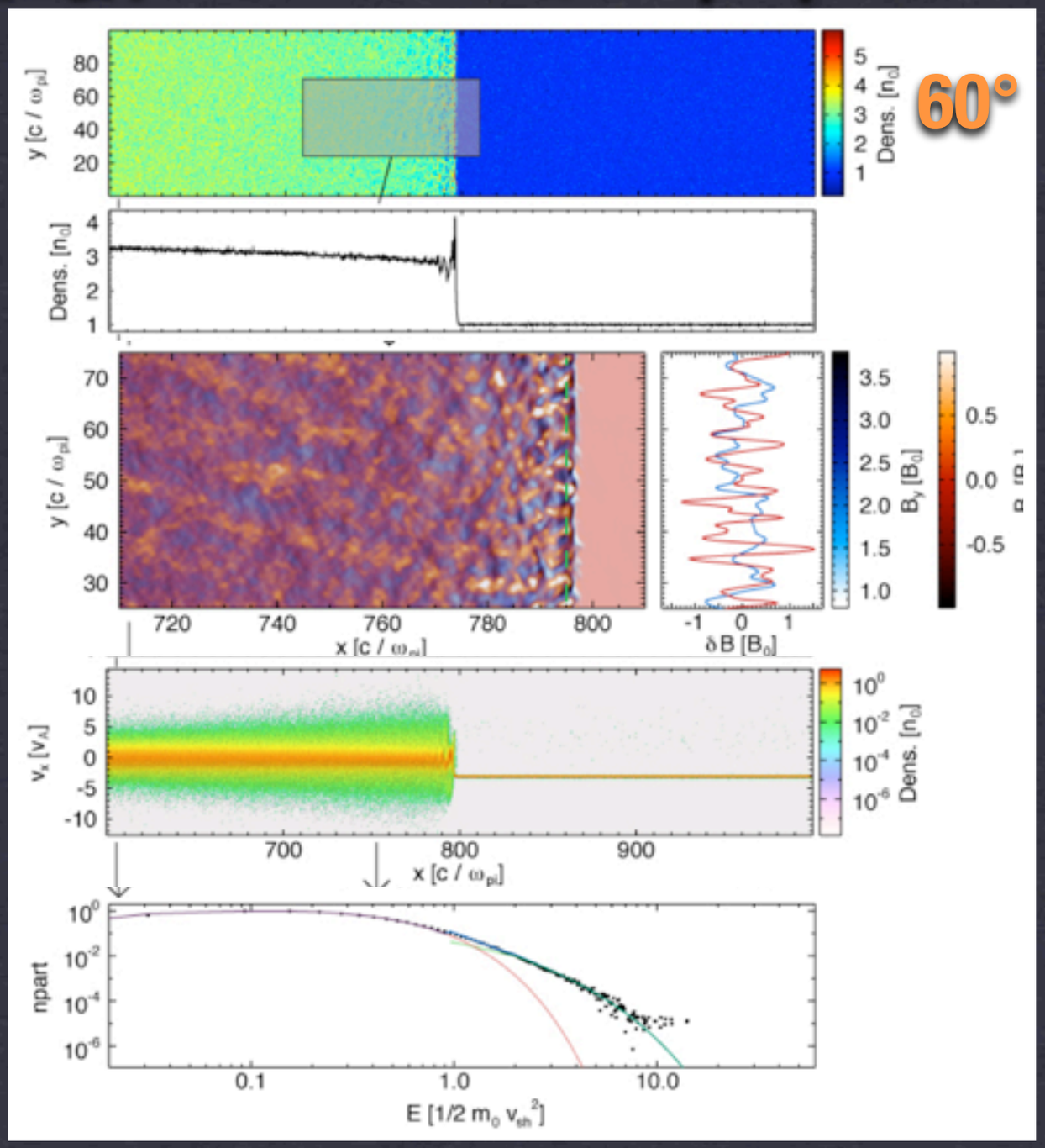


Hybrid shock survey

dHYBRID

Parallel shock **Ma=3.1** **Quasiperp shock**





Ion acceleration is most pronounced for quasi-parallel shock **Ma=3.1**

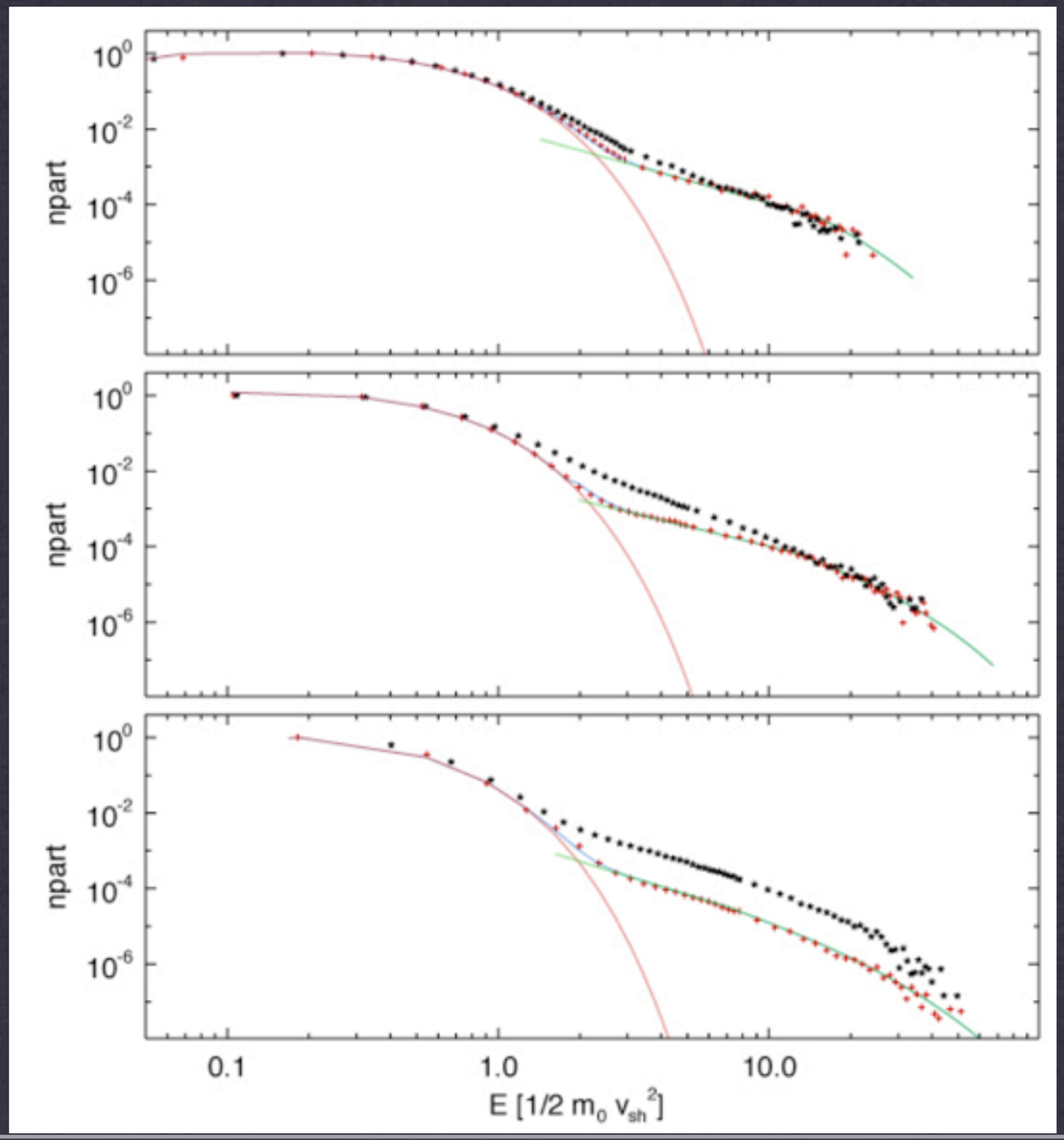
Hybrid shock survey

Slopes near n=2

$t=150\omega_{ci}^{-1}$

$t=300\omega_{ci}^{-1}$

parallel 0°



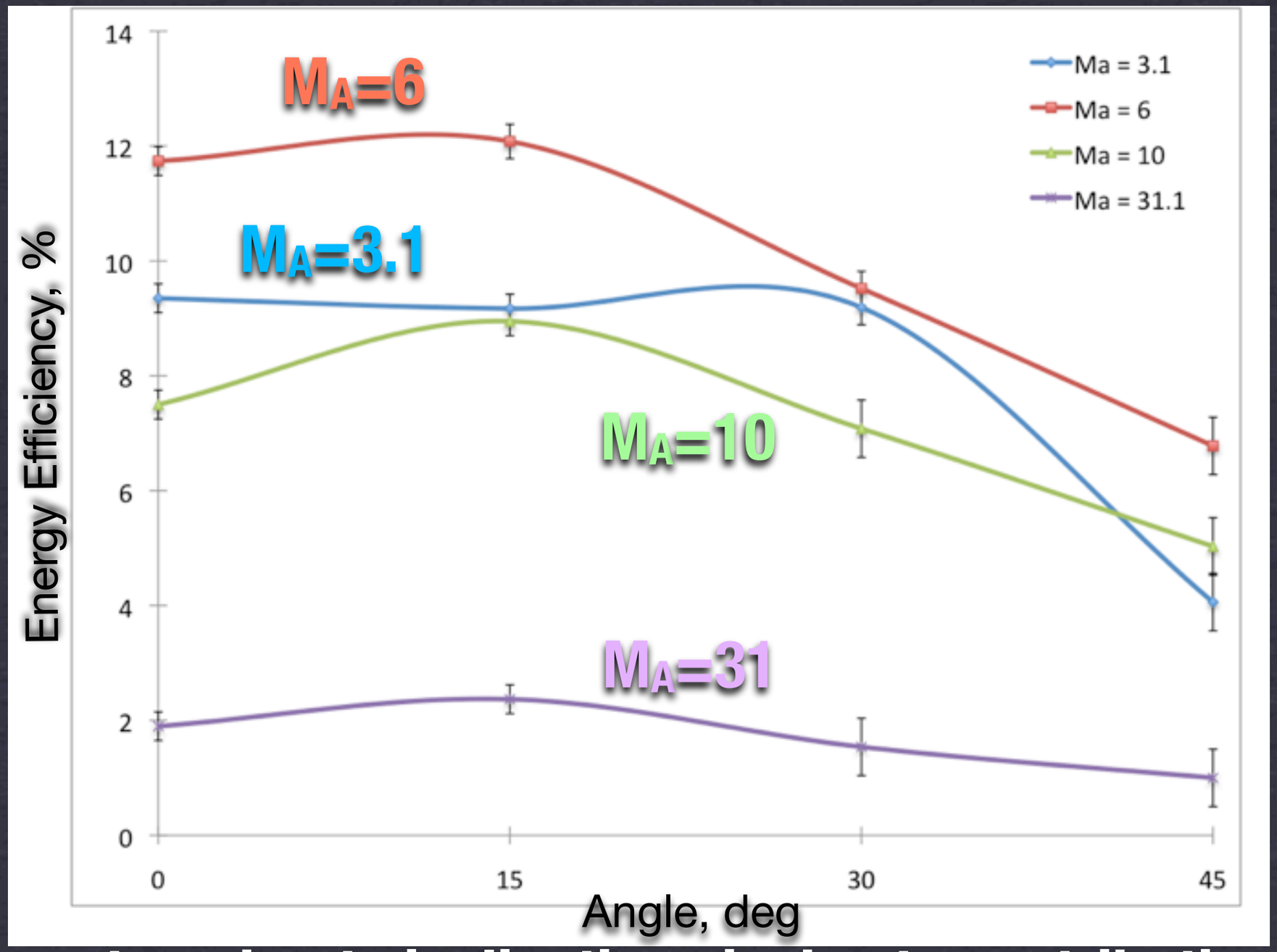
Ma=3.1

Ma=10

Ma=31

Acceleration Efficiency

Energy efficiency drops with increasing Mach number (>6) and angle

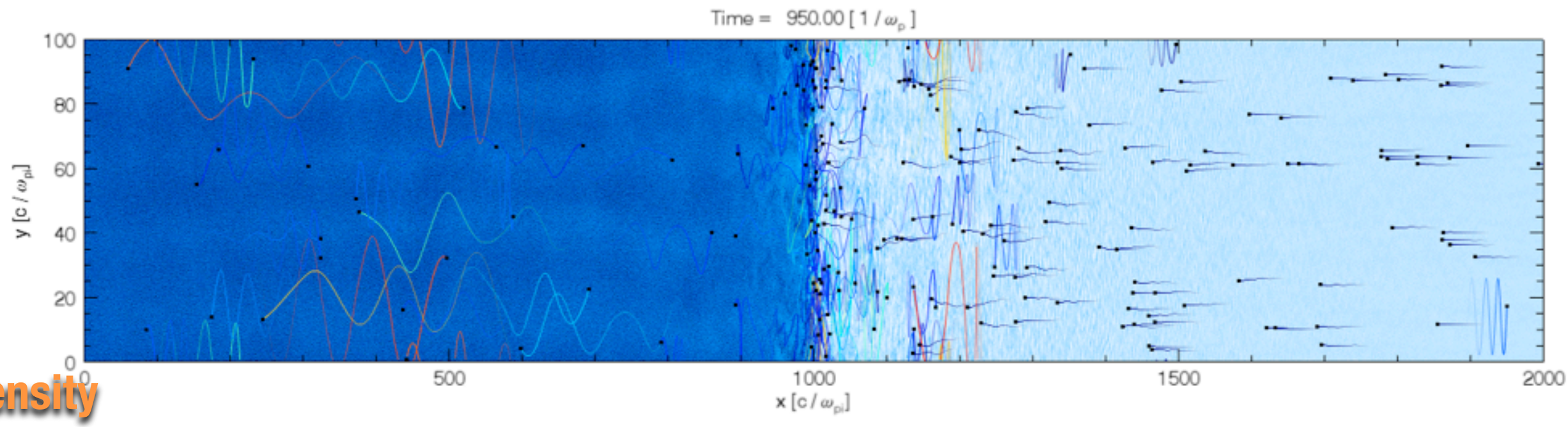


(Gargate+AS 2011)

Bump at moderate inclinations is due to contribution by SDA

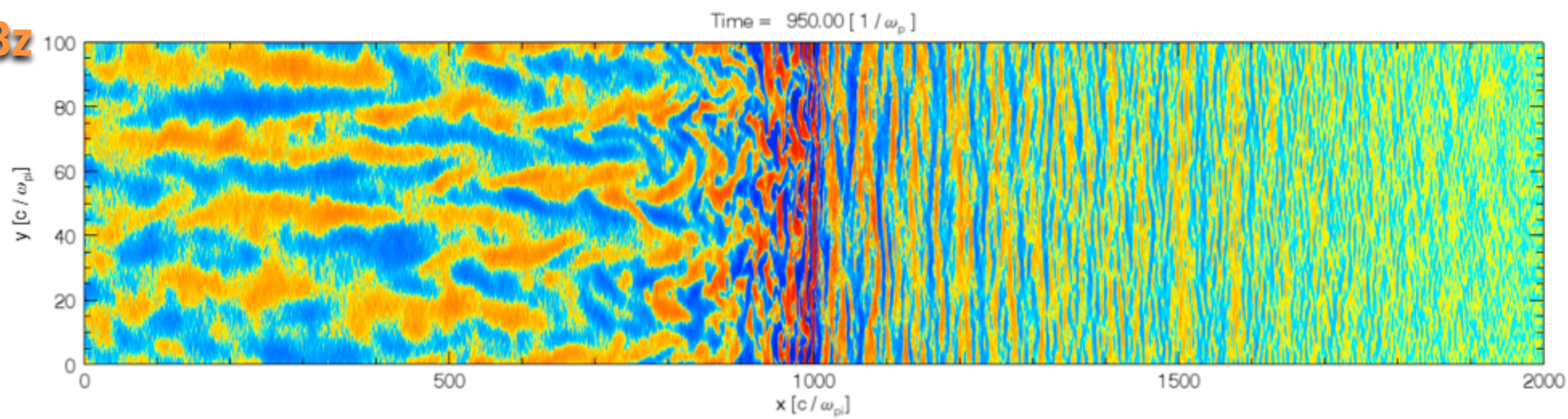
Acceleration Mechanism

Ma=3.1, parallel



density

Bz



Hybrid conclusions

Ion acceleration proceeds in quasi-parallel shocks with large efficiencies, decreasing at high Ma.

Escaping CRs drive generation of upstream waves (resonant for small M_A, non-resonant for large M_A). Look like CR current-driven Bell waves.

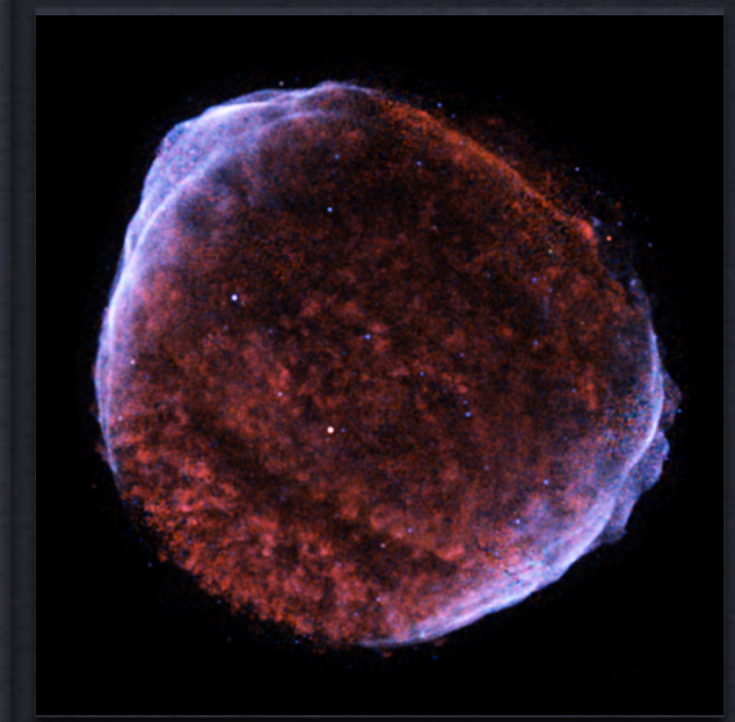
Injection does not happen by thermal leakage, mainly reflection from the shock.

Quasiparallel shocks work by reorienting the field

Note, that same shocks that accelerate ions do NOT accelerate electrons!!!

So, how does it all work out?

In SNRs, Alfvenic Mach number is expected to be high (>100). However, having nonthermal electrons requires highly amplified upstream B field to lower the effective $M_A < (m_i/m_e)^{1/2}$. Expect $M_A \sim 20$. Locally need quasi-perpendicular B field.



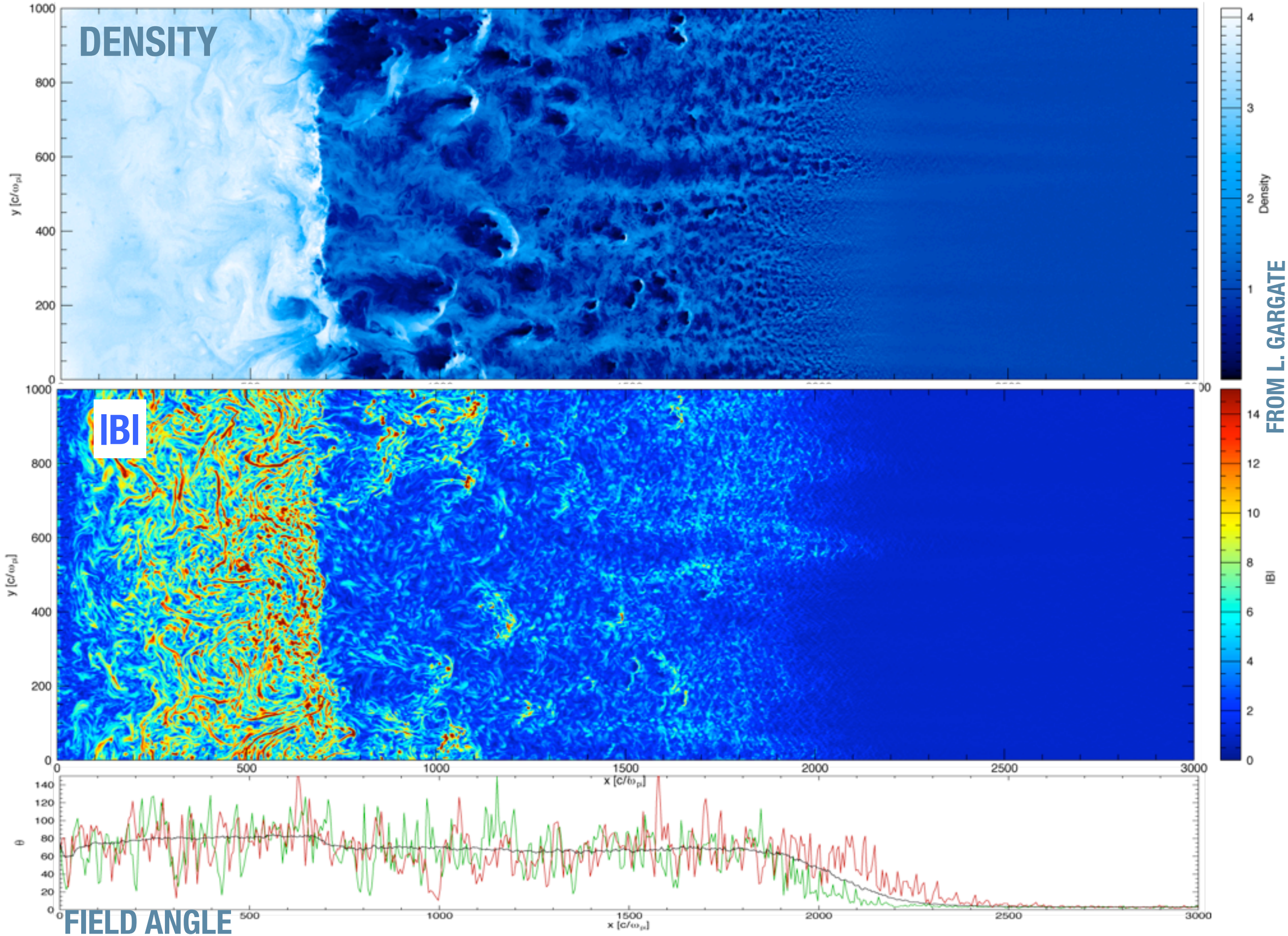
This amplification and field reorientation is likely caused by accelerated CRs escaping into the upstream (Bell's instability or firehose).The ions are better accelerated at quasi-parallel shocks.

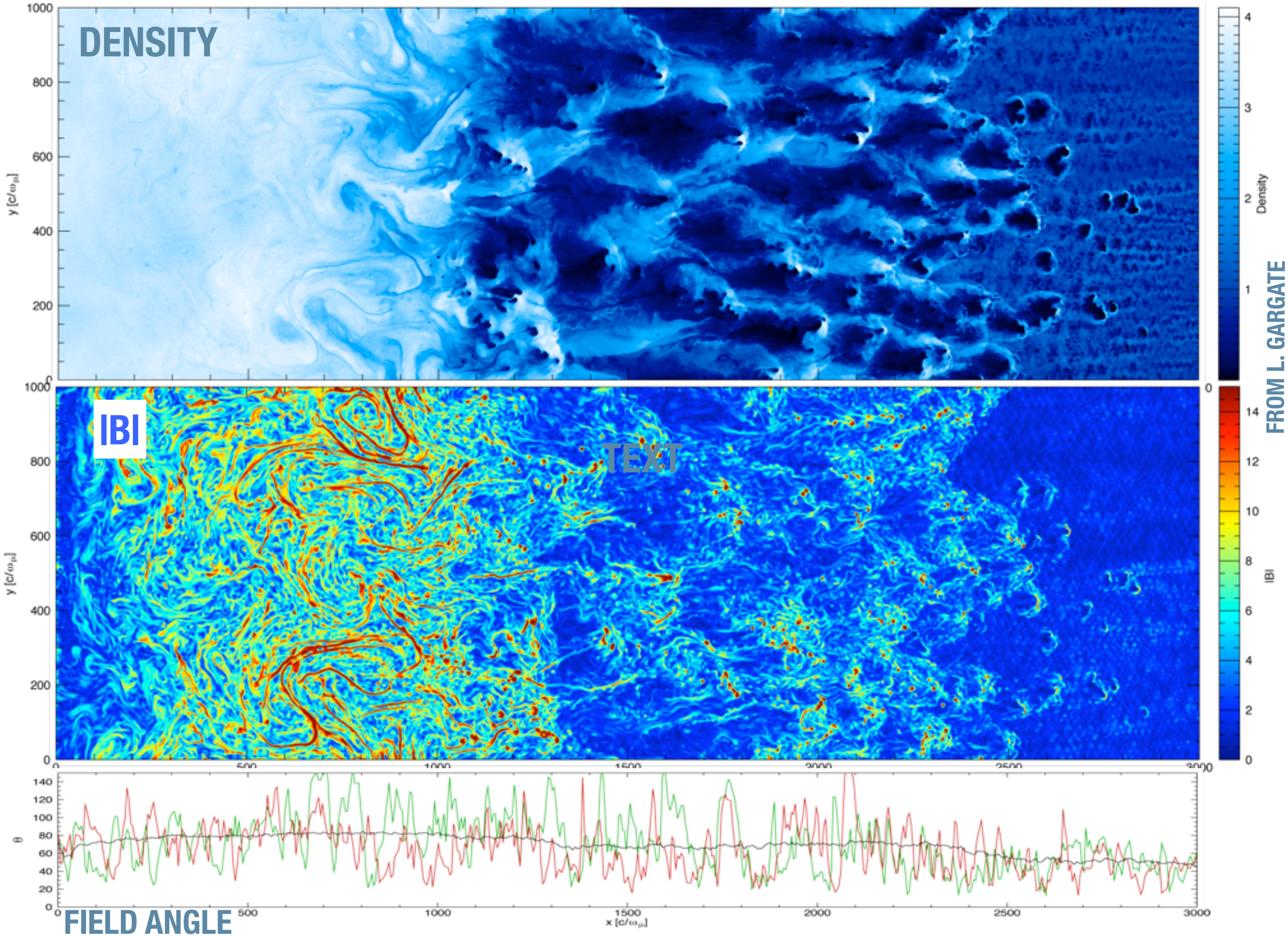
This favors large-scale radial B fields in young SNRs.

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

$$k_{max}\, c=2\pi J_{cr}/B_0$$

$$\gamma_{max}=k_{max} V_{Alfven,0}$$


DENSITY
Density
IBI
|B|
FIELD ANGLE
θ
y [c/ω_pi]
x [c/ω_pi]
FROM L. GARGATE


DENSITY
Density
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FIELD ANGLE
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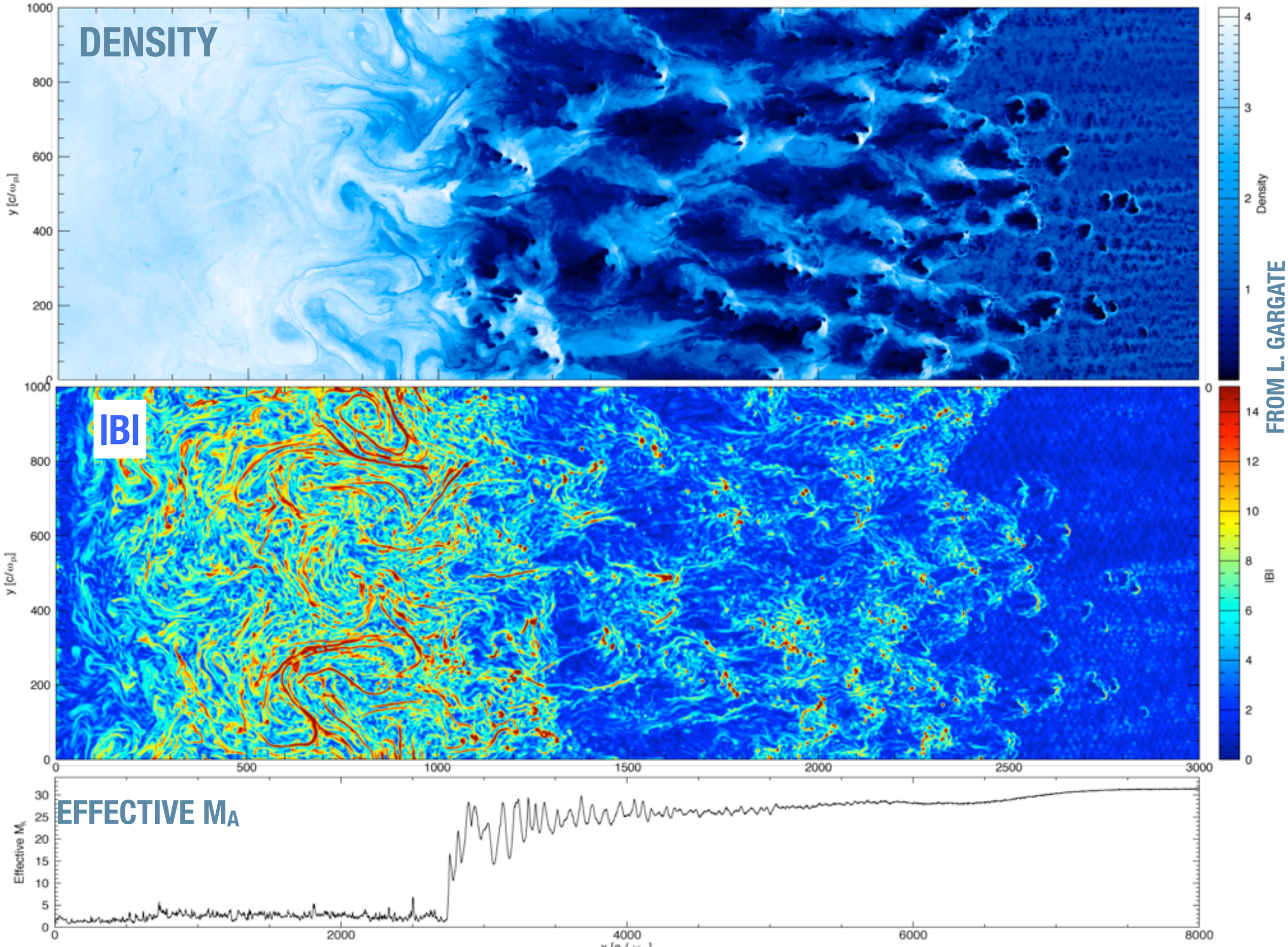
y [c/ω_pi]
x [c/ω_pi]
FROM L. GARGATE


DENSITY
Density
IBI
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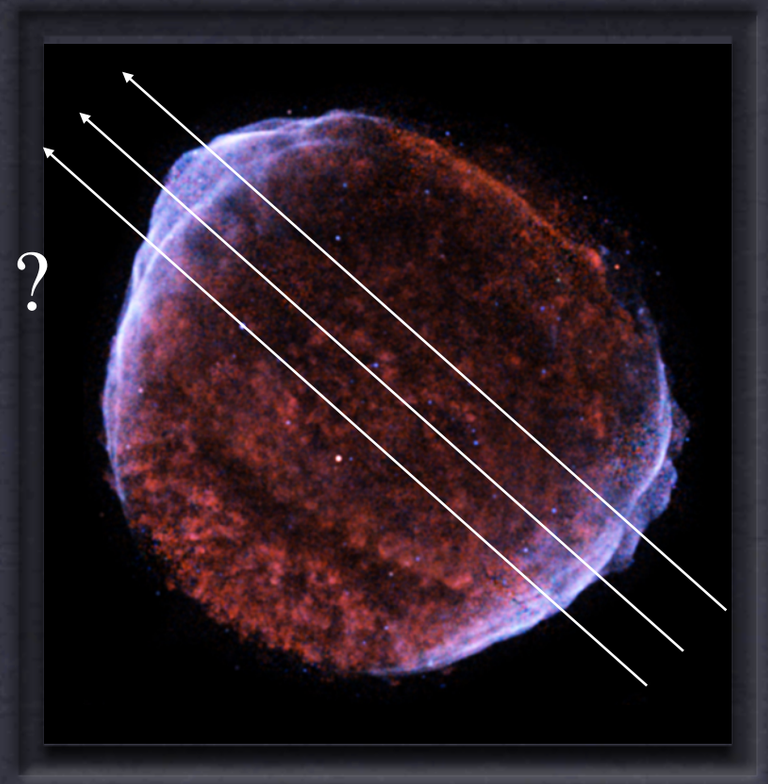
EFFECTIVE M_A
Effective M_A
y [c/ω_pi]
FROM L. GARGATE

SNR story

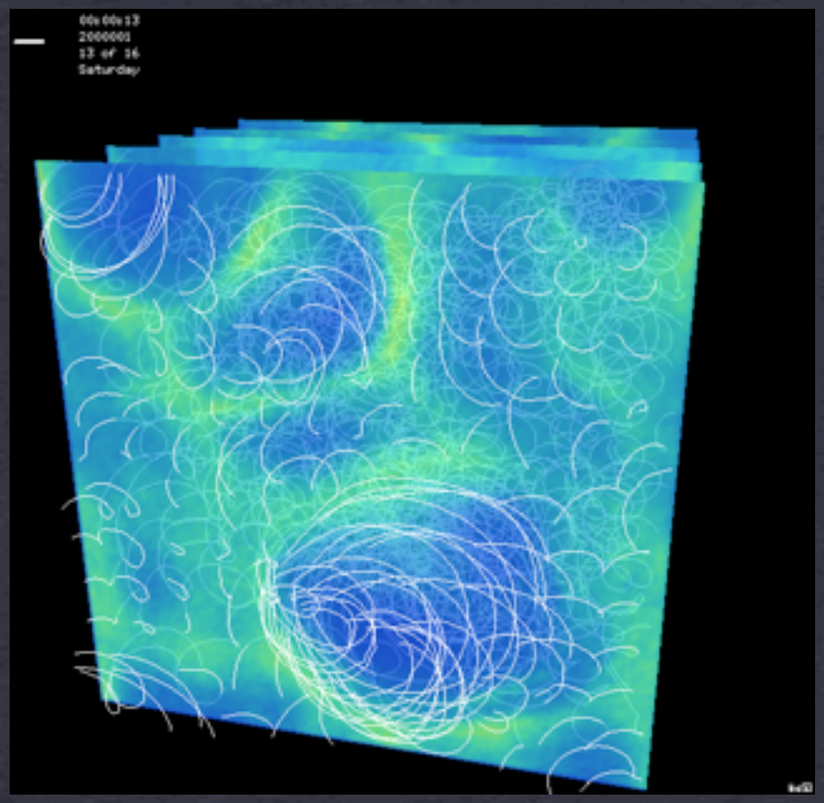


Nonthermally-emitting SNRs likely have large scale parallel magnetic field (radial). This leads to CR acceleration and field amplification to Ma < 40.

Local transverse field enters the shock, and causes electron injection.

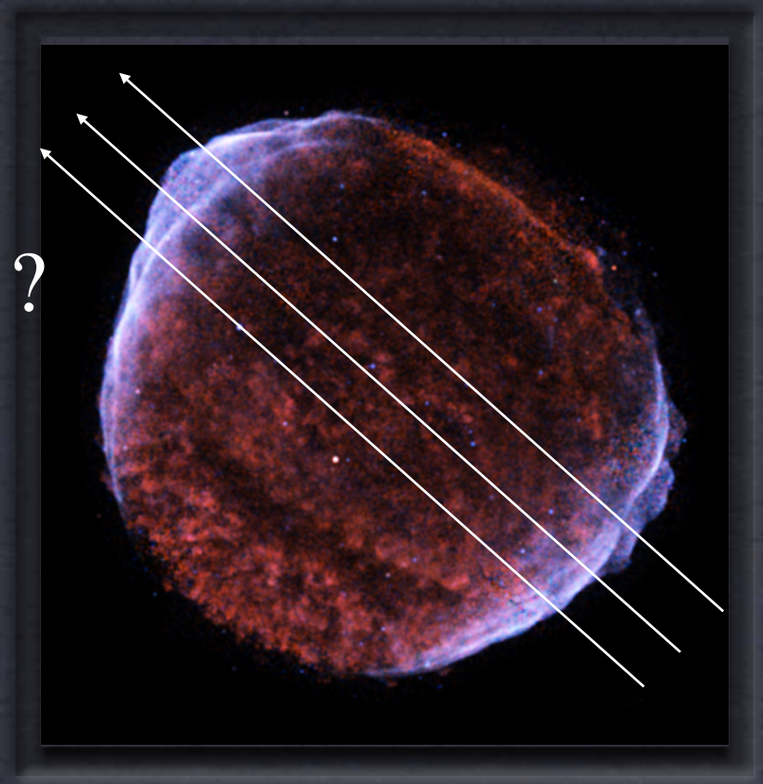
This favors large-scale radial B fields in young SNRs. Polarization in “polar caps” should be small -- field is random

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



Conclusions

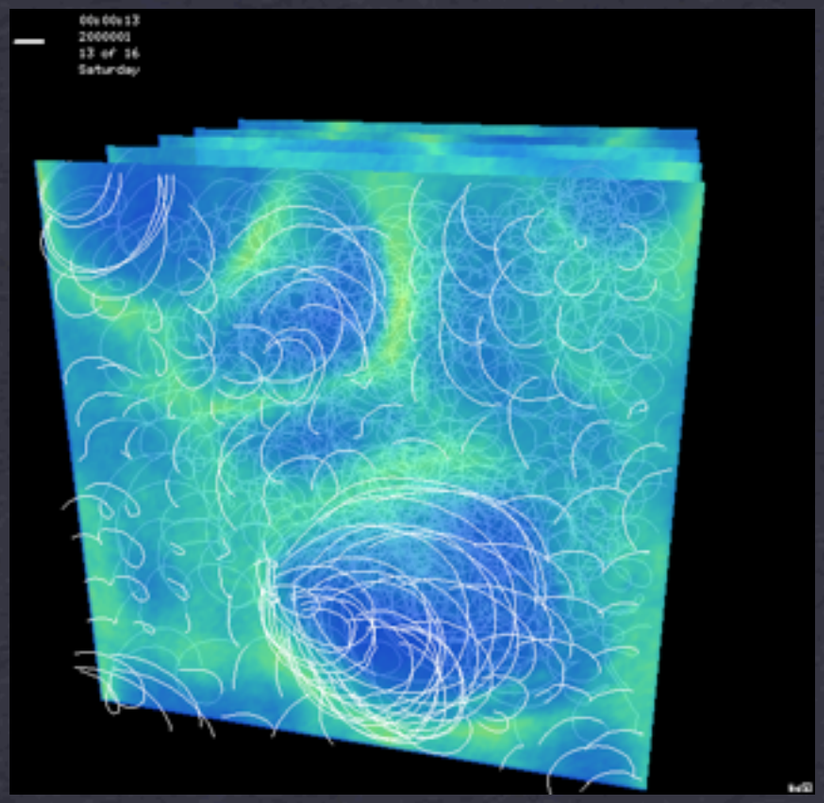
Kinetic simulations allow to calculate particle injection and acceleration from first principles, constraining injection fraction.



Magnetization (Mach #) of the shock controls the shock structure.

Relativistic shocks accelerate when weakly magnetized or quasi-parallel

Nonrelativistic shocks accelerate ions in quasi-par and electrons in quasi-perp. Can coexist if B fields are amplified by CRs.



Numerical challenges: multiscale simulations