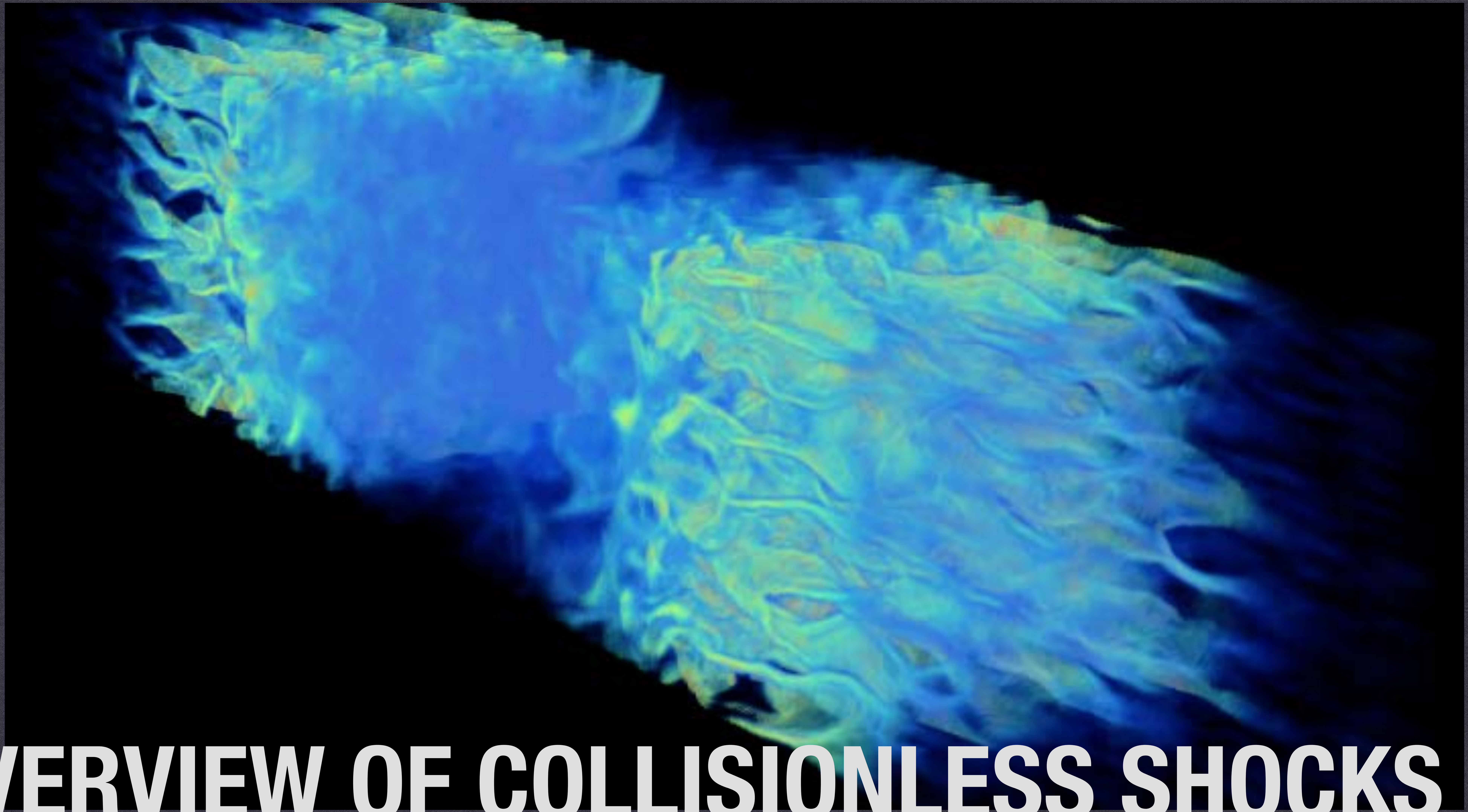


# OVERVIEW OF COLLISIONLESS SHOCKS

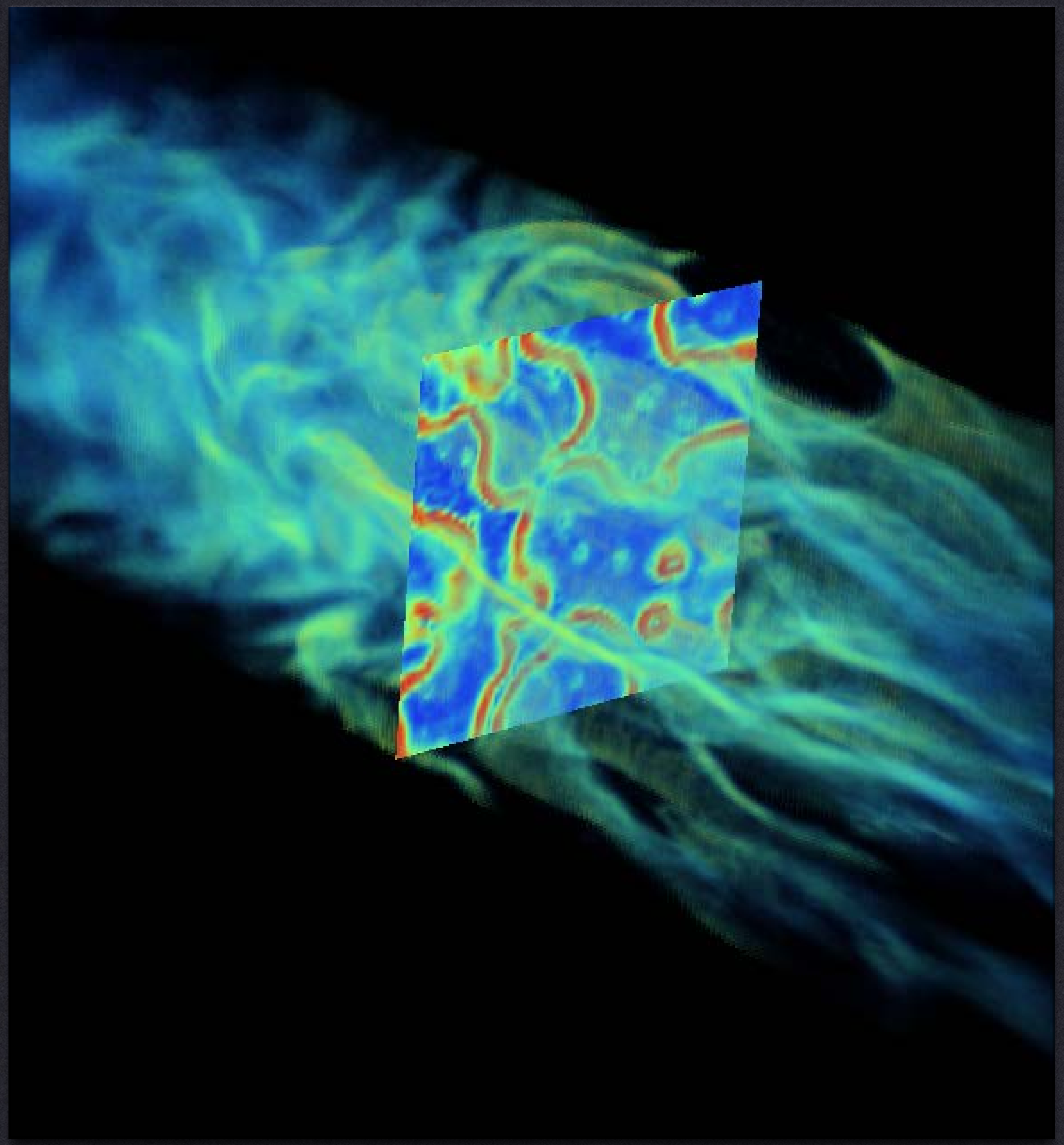
ANATOLY SPITKOVSKY (PRINCETON)

# What is plasma astrophysics?

- Most astrophysical processes involve plasmas
- Plasma scales << astro scales

  frequency = $10^4$ (n/1cc)$^{1/2}$ Hz;  spatial scale = $10^5$ (n/1cc)$^{-1/2}$ cm

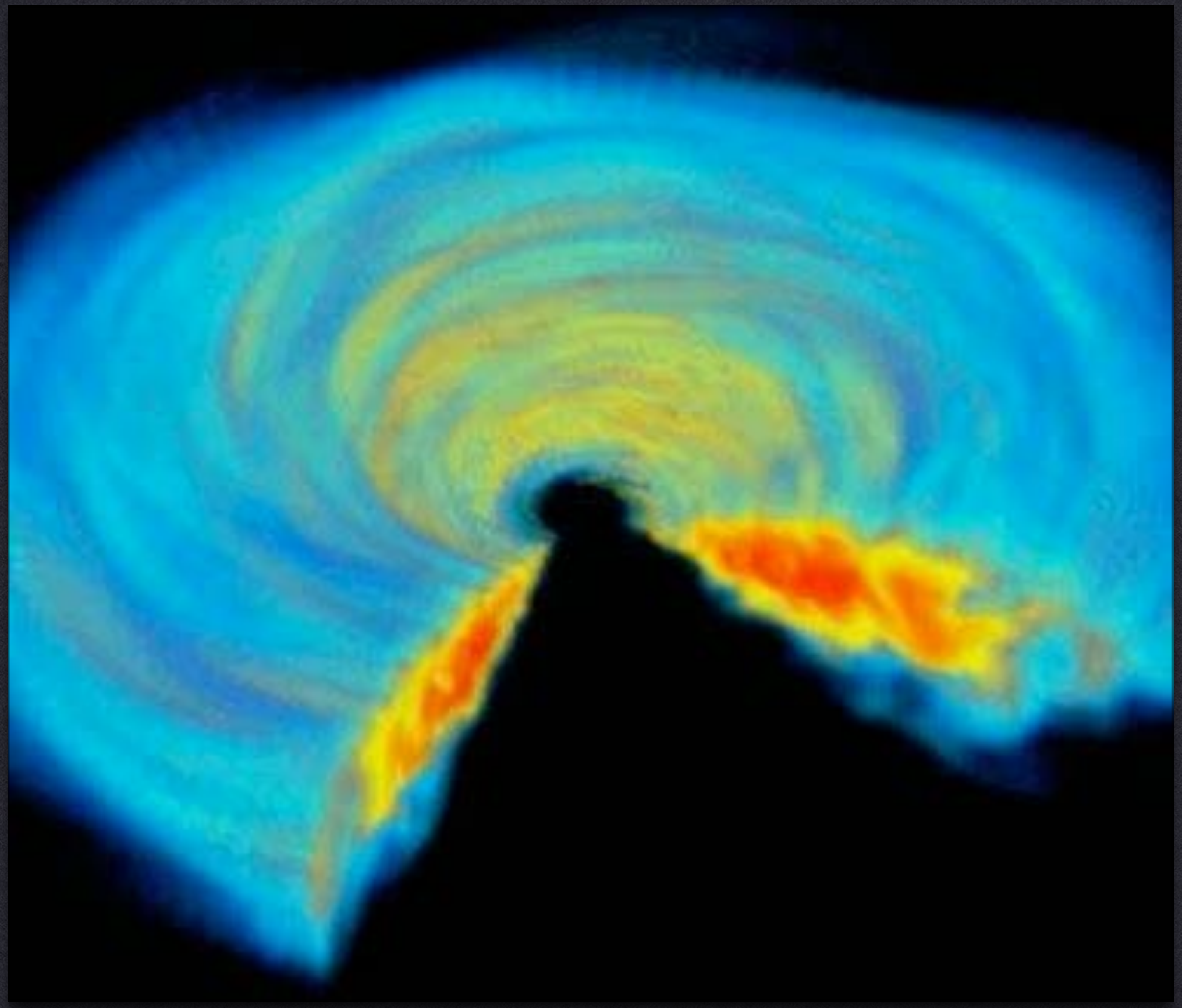
- Most interesting: when microscopic physics affects macroscopic observables
- Most disturbing: these effects typically are either badly parameterized or ignored...

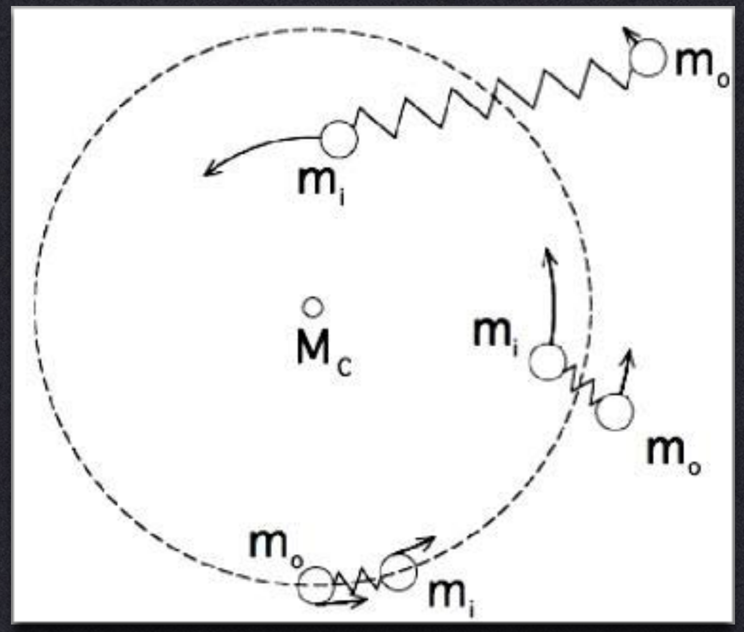


# Plasma effects and HEA

high-energy astrophysics

- Accretion disks
  - Origin of collisionless viscosity
  - MRI: cascade termination, two-temperature flows, e-ion equilibration
  - Energization of disk coronae
- Clusters of galaxies:
  - heat conduction and resistivity; transport in tangled fields
  - Nonthermal pressure & CRs





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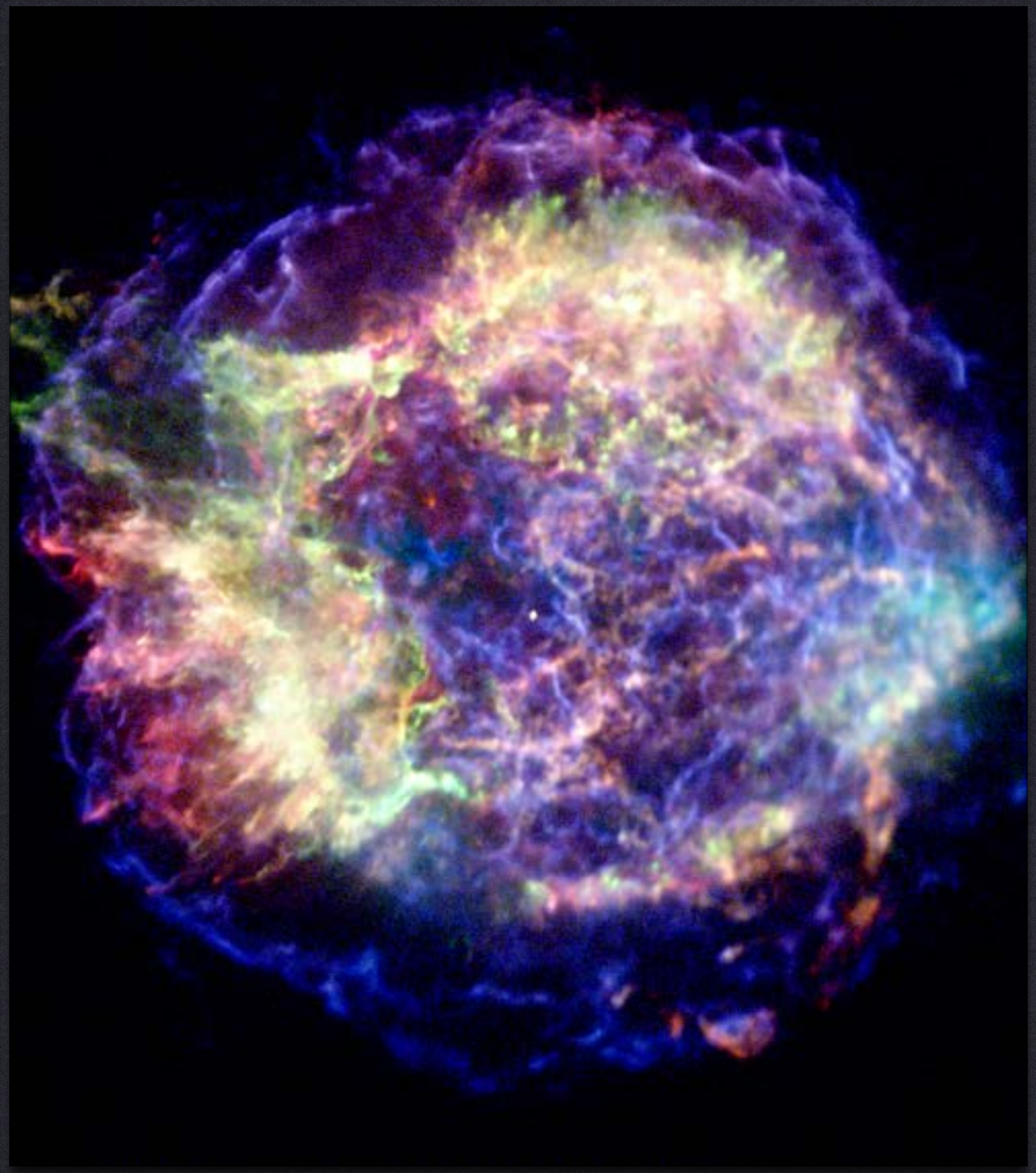
# Plasma effects and HEA

high-energy astrophysics

- Supernova remnants: shocks
  - CRs & magnetic field amplification
  - Electron-ion equilibration
- Nonthermal Sources (SNRs, PWNe, GRBs, jets, clusters)
  - Particle injection and acceleration
  - Physics of collisionless shocks
  - Magnetic field generation
  - Non-shock acceleration possibilities?



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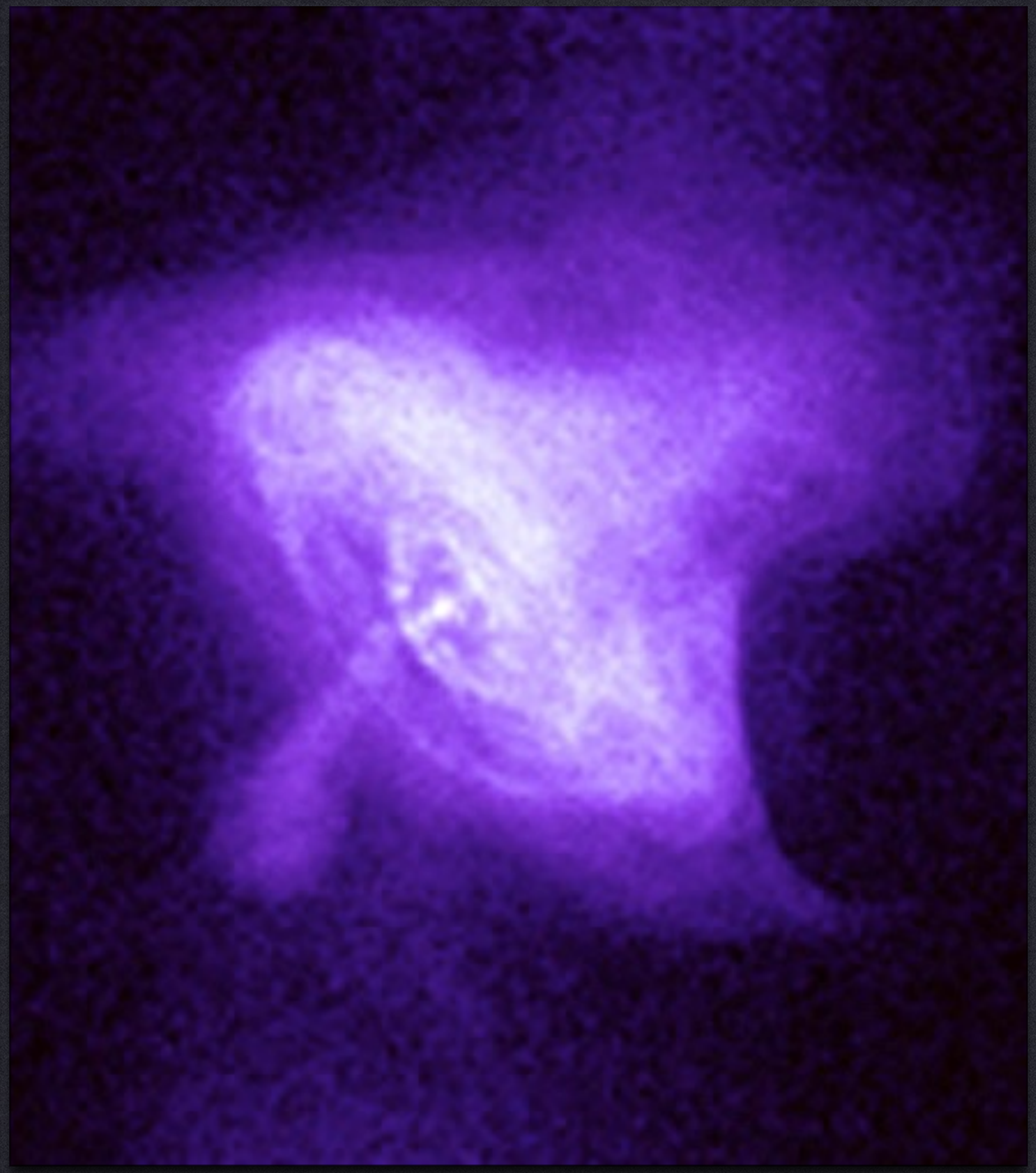
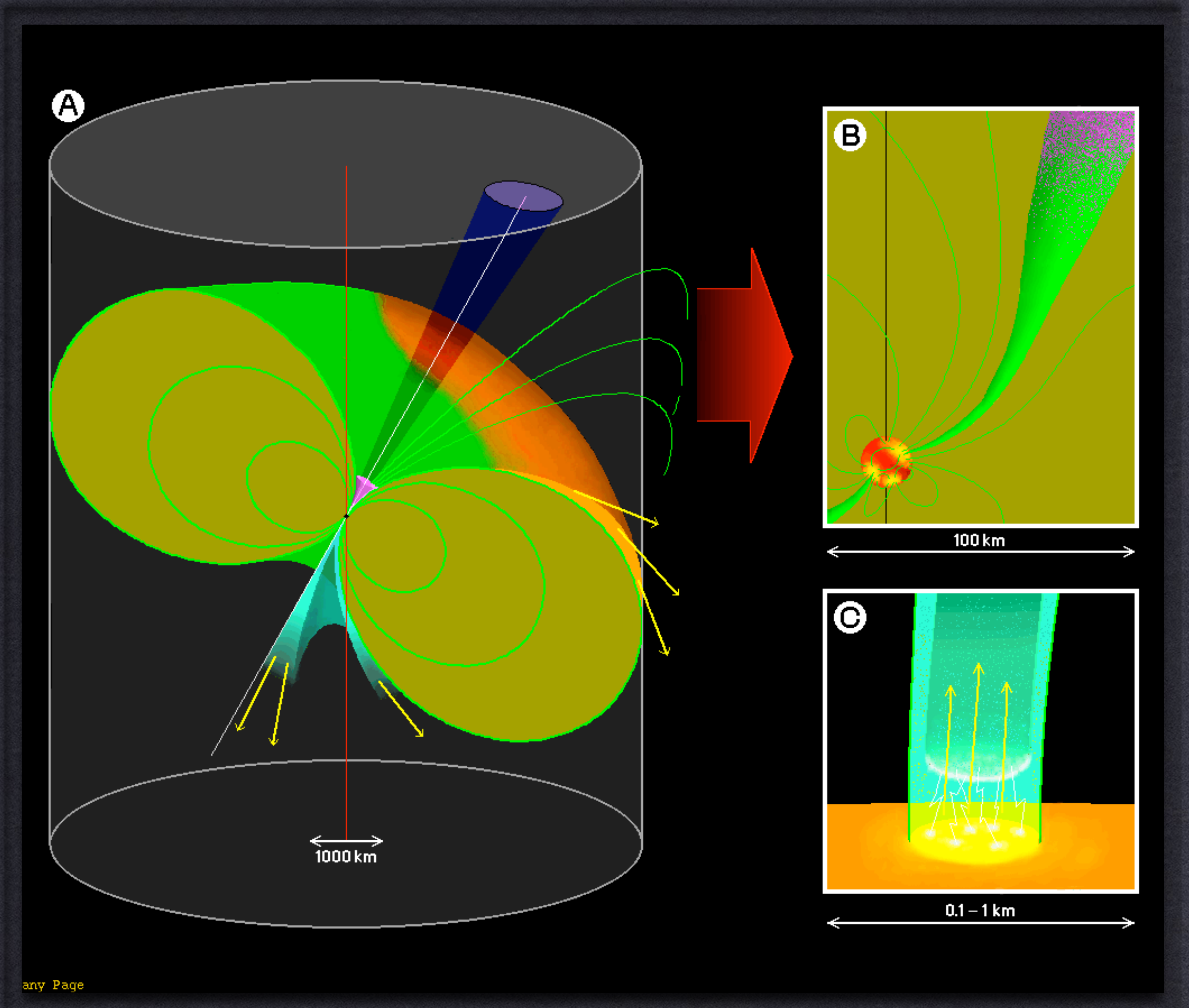


# Plasma effects and HEA

high-energy astrophysics

- Neutron star magnetospheres
  - Plasma creation and acceleration
  - Physics of strong currents
  - Importance of rel. reconnection
  - Origin of radiation
- Relativistic jets and winds
  - Collimation + acceleration
  - Conversion of magnetic to kinetic energy, dissipation.



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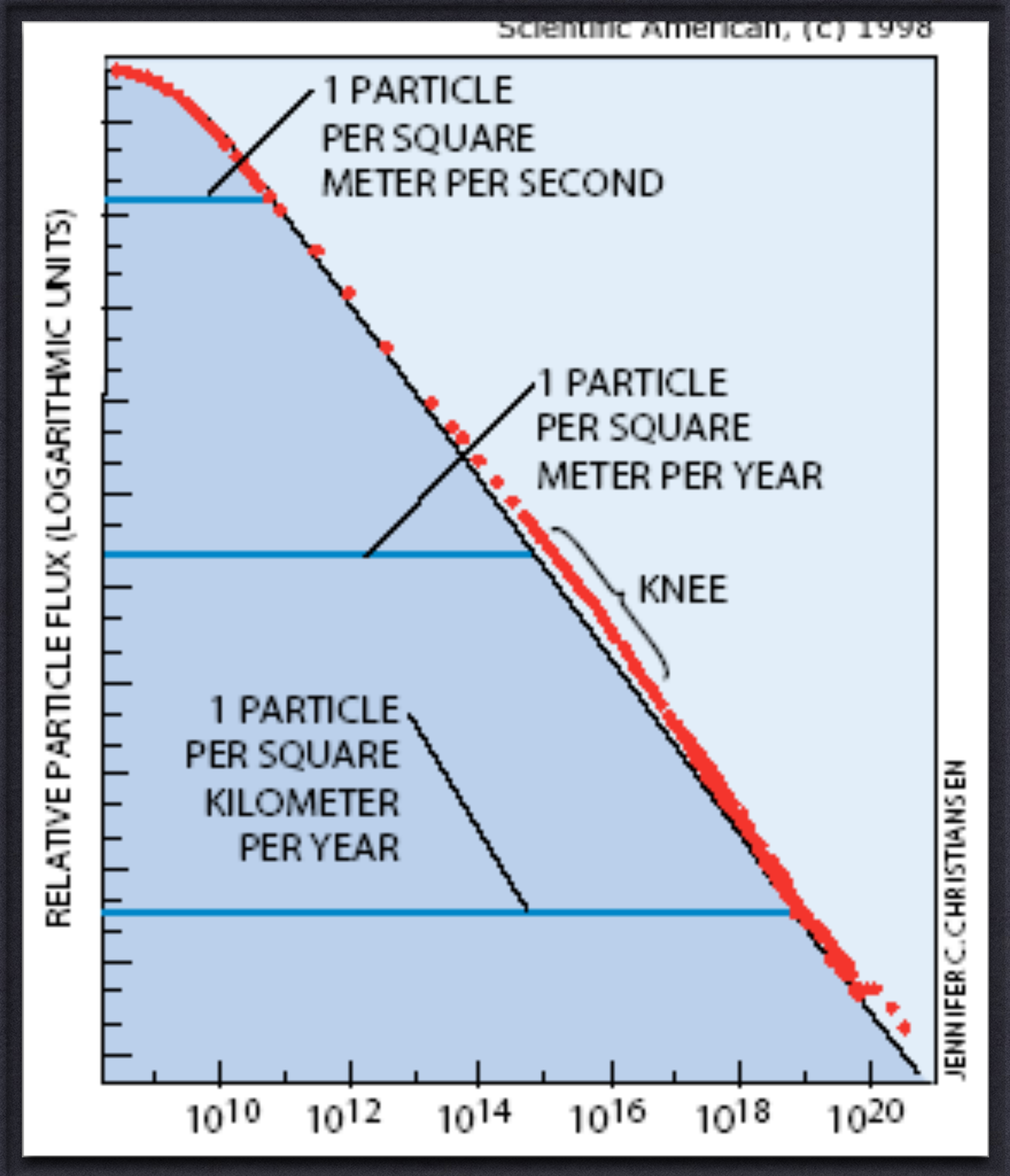
# Plasma effects and HEA

high-energy astrophysics

- Cosmic rays
    - Sources of galactic and extra-galactic CRs
    - Influence of CRs on galaxies
    - CR transport



## Goals:

model astrophysical systems with microphysical parameterizations determined from plasma simulations;

constrain astrophysical scenarios based on realistic plasma physics, and determine plasma conditions based on astrophysical observables.

# Outline

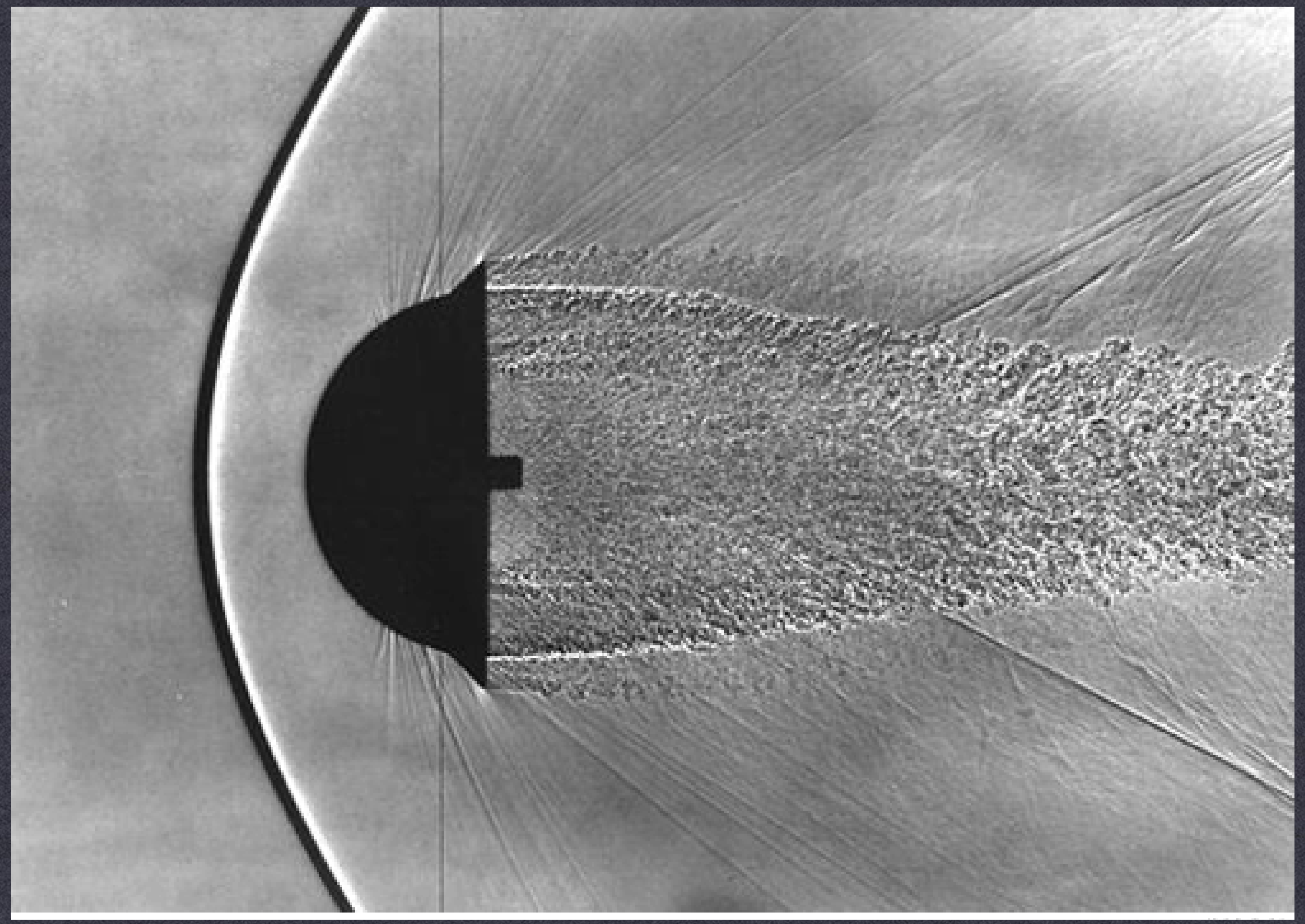
- Collisionless shocks and particle acceleration
  - Observational background
  - Shocks as multi-scale systems
  - Physics of particle acceleration
  - Numerical survey of collisionless shocks with PIC simulations: from relativistic to non-relativistic shocks
  - Implications for astrophysical observations
  - CR transport (if have time)
- Earthly connections (laboratory experiments)

# The physics of collisionless shocks

Shock: sudden change in density, temperature, pressure that decelerates supersonic flow

Thickness ~mean free path
in air: mean free path ~micron

On Earth, most shocks are mediated by collisions



Astro: Mean free path to Coulomb collisions in enormous: 100pc in supernova remnants, ~Mpc in galaxy clusters
*Mean free path > scales of interest*

(and GR

shocks must be mediated without direct collision, but through interaction with collective fields

*collisionless shocks*

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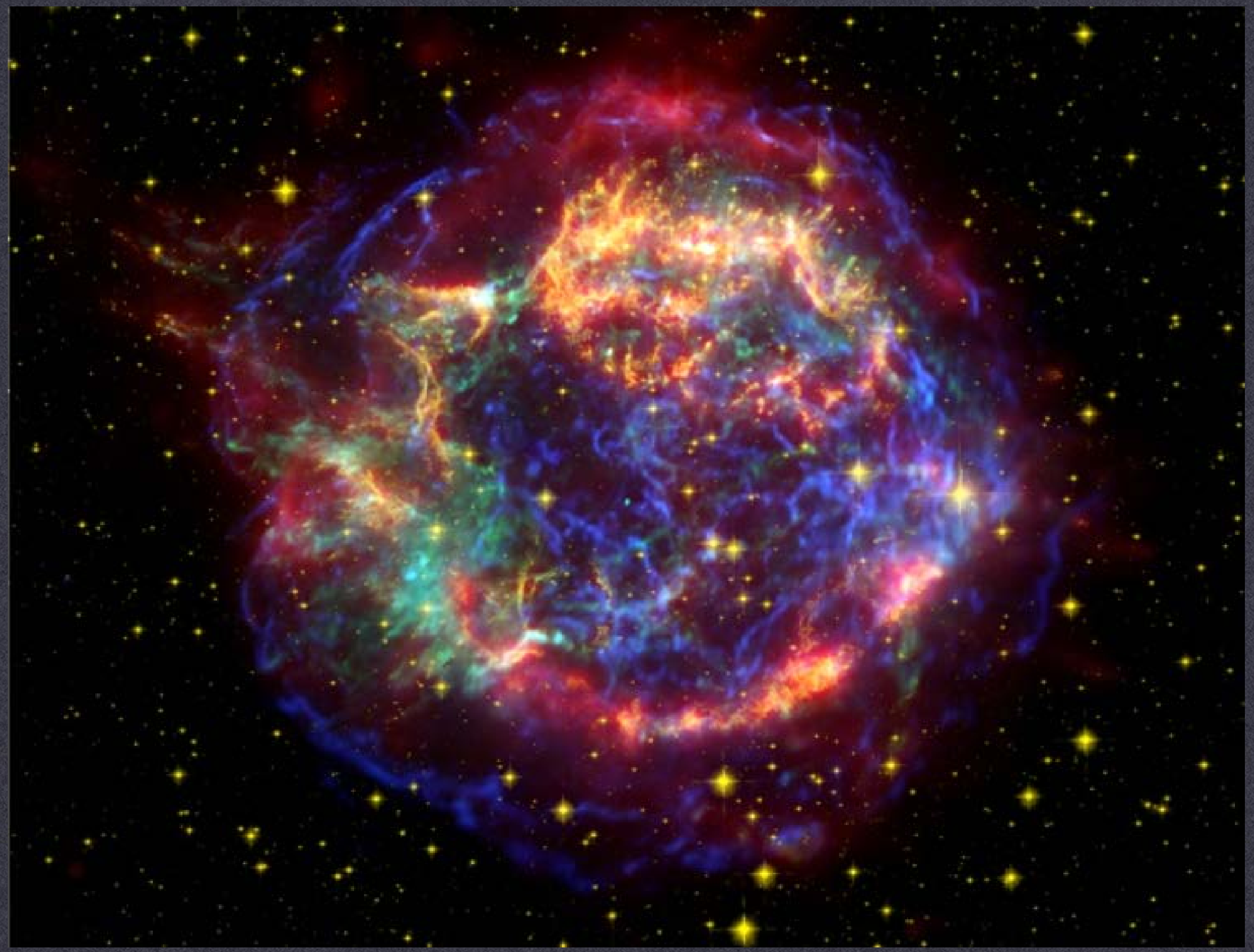

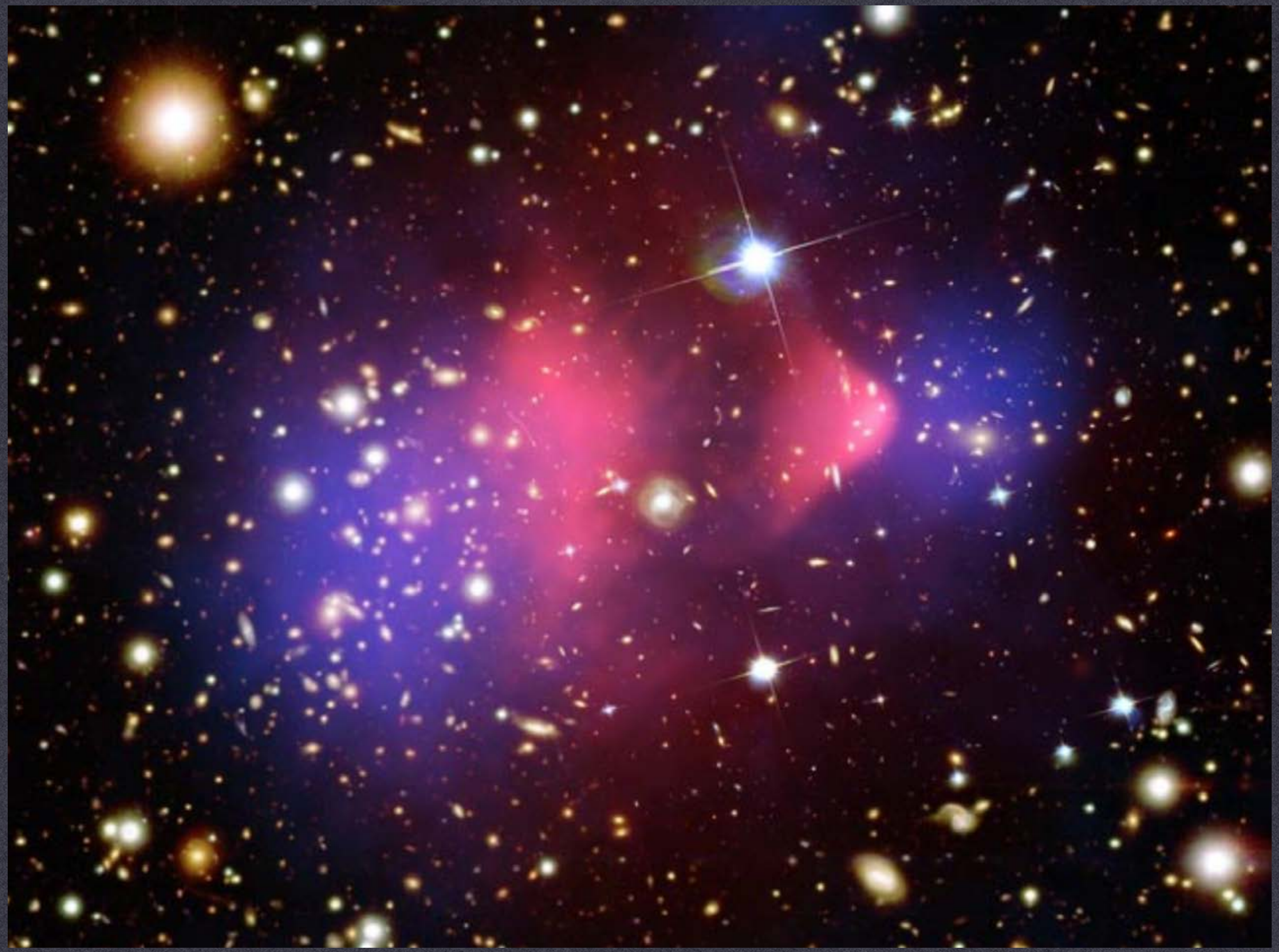

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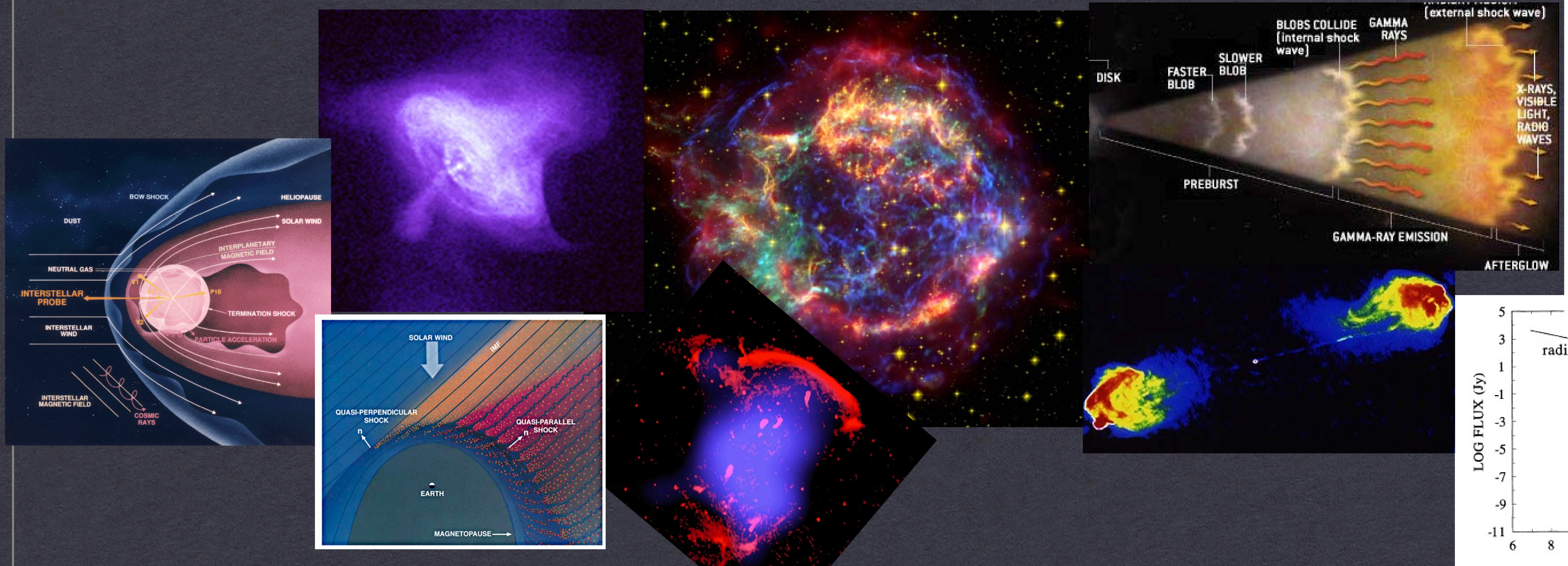
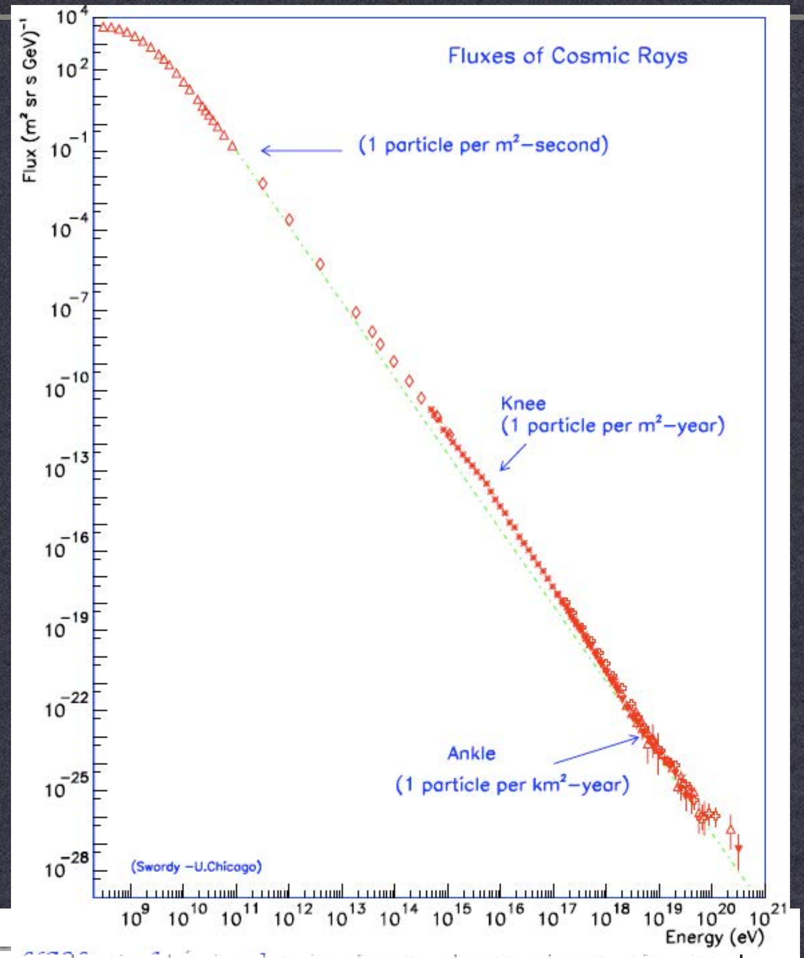
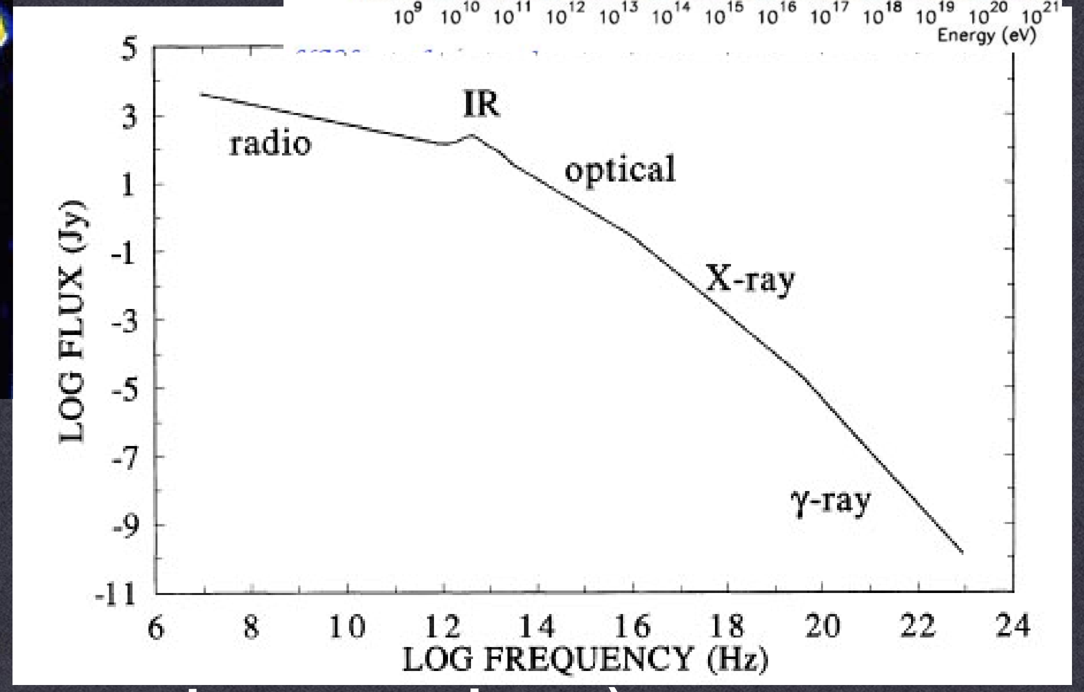
# Shocks & power-laws in astrophysics




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

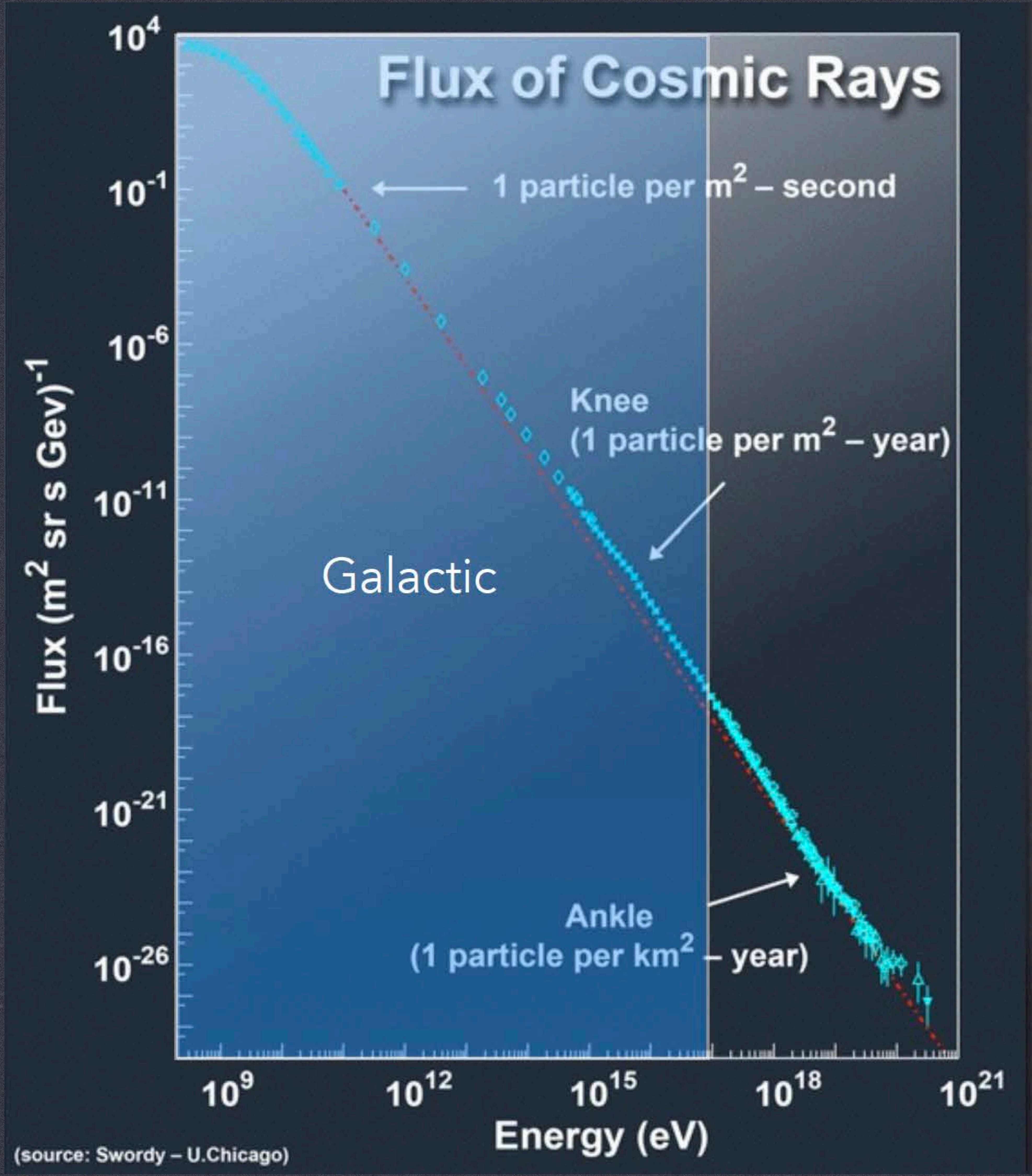
1) accelerate particles to power-laws
2) amplify magnetic fields
3) exchange energy between electrons and ions

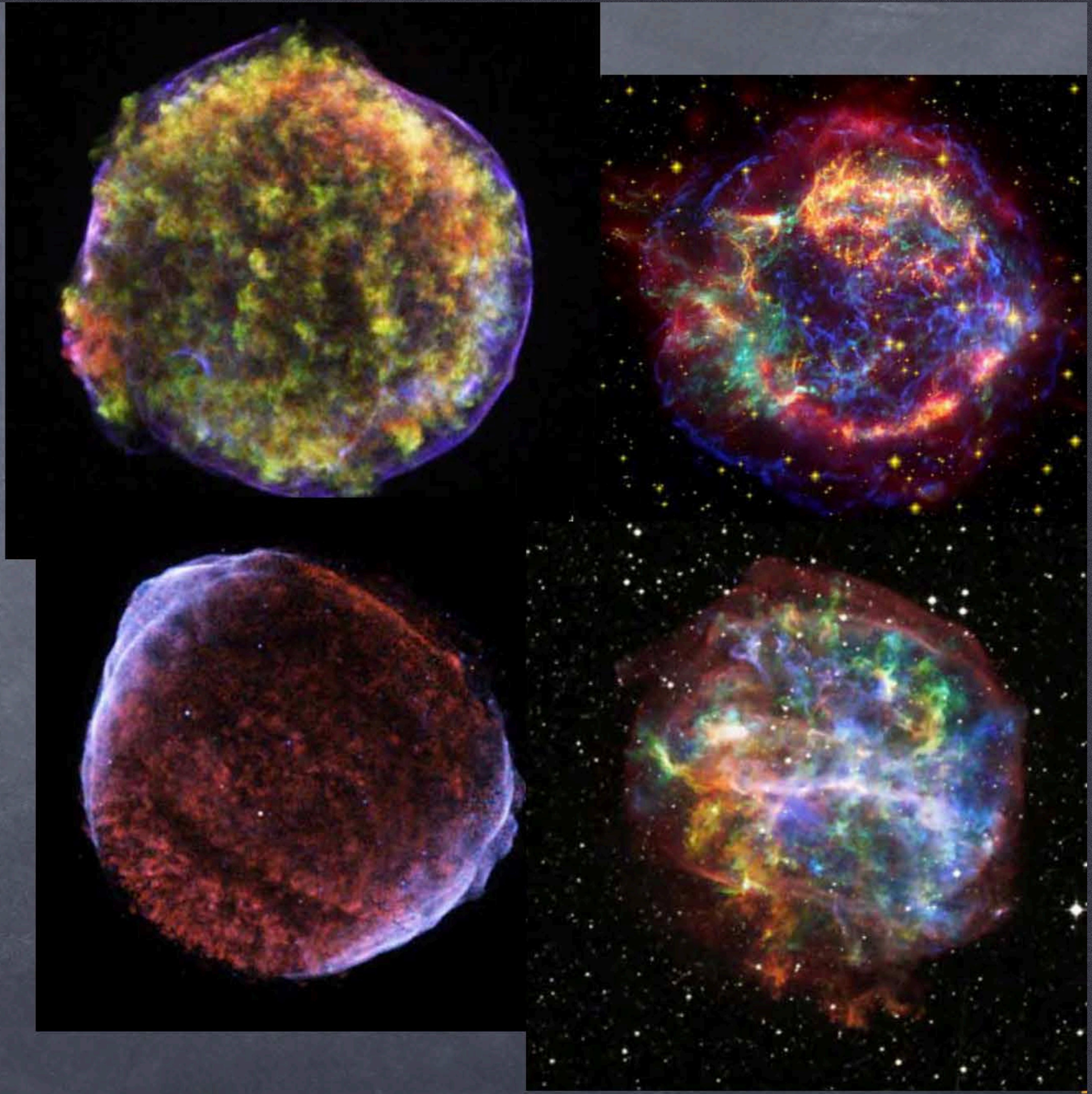
How do they do this? Mechanisms, efficiencies, conditions?…

# Example: 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 (10-30% 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)

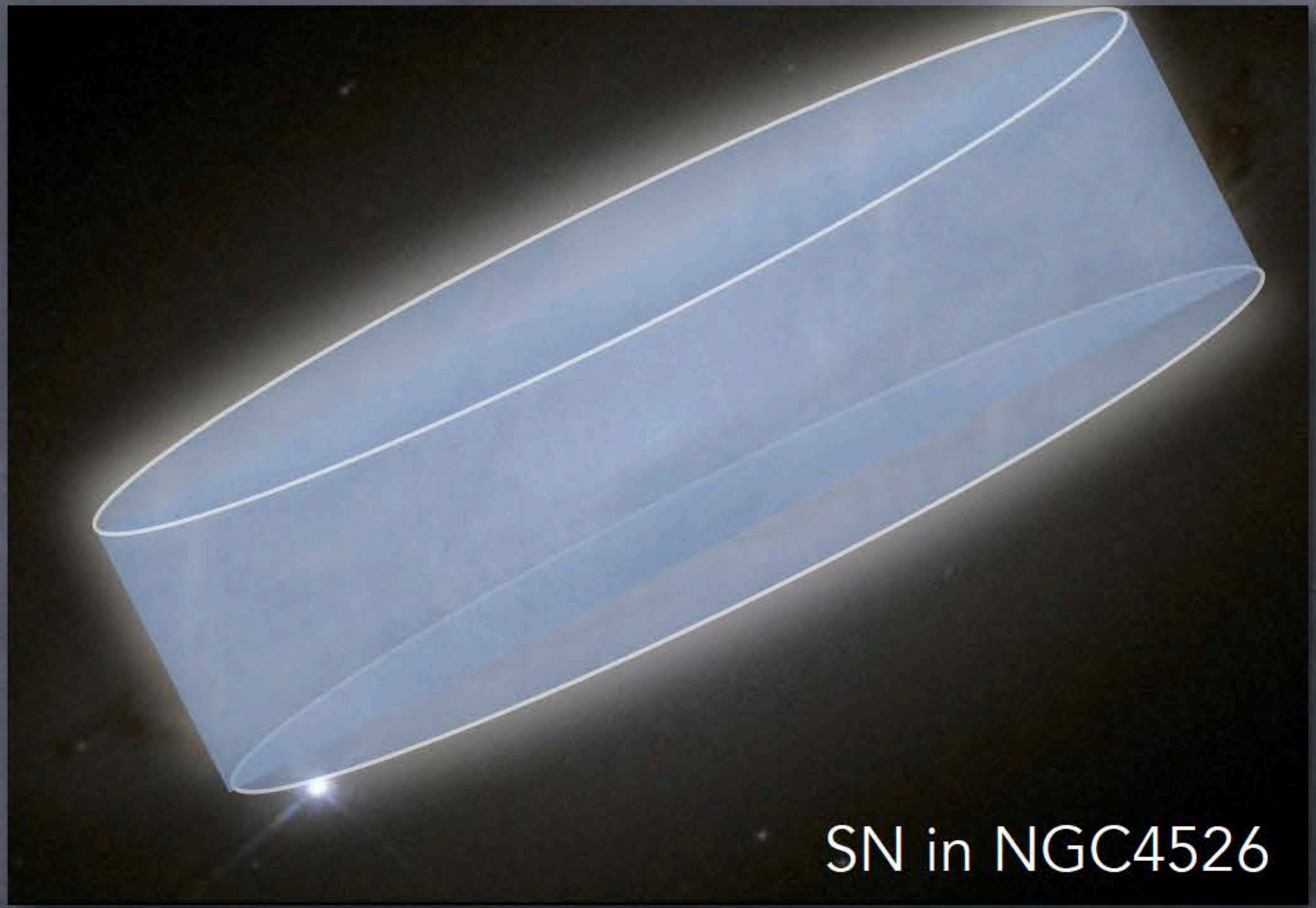
# *SNR Paradigm* for Galactic Cosmic Rays



# SNR paradigm: energetics

- Baade-Zwicky (1934) energetic argument, updated




$$\varepsilon_{CR} = 0.5 eV cm^{-3}$$

$$V_{conf} = \pi R^2 h = 2 \times 10^{67}\ cm^3$$

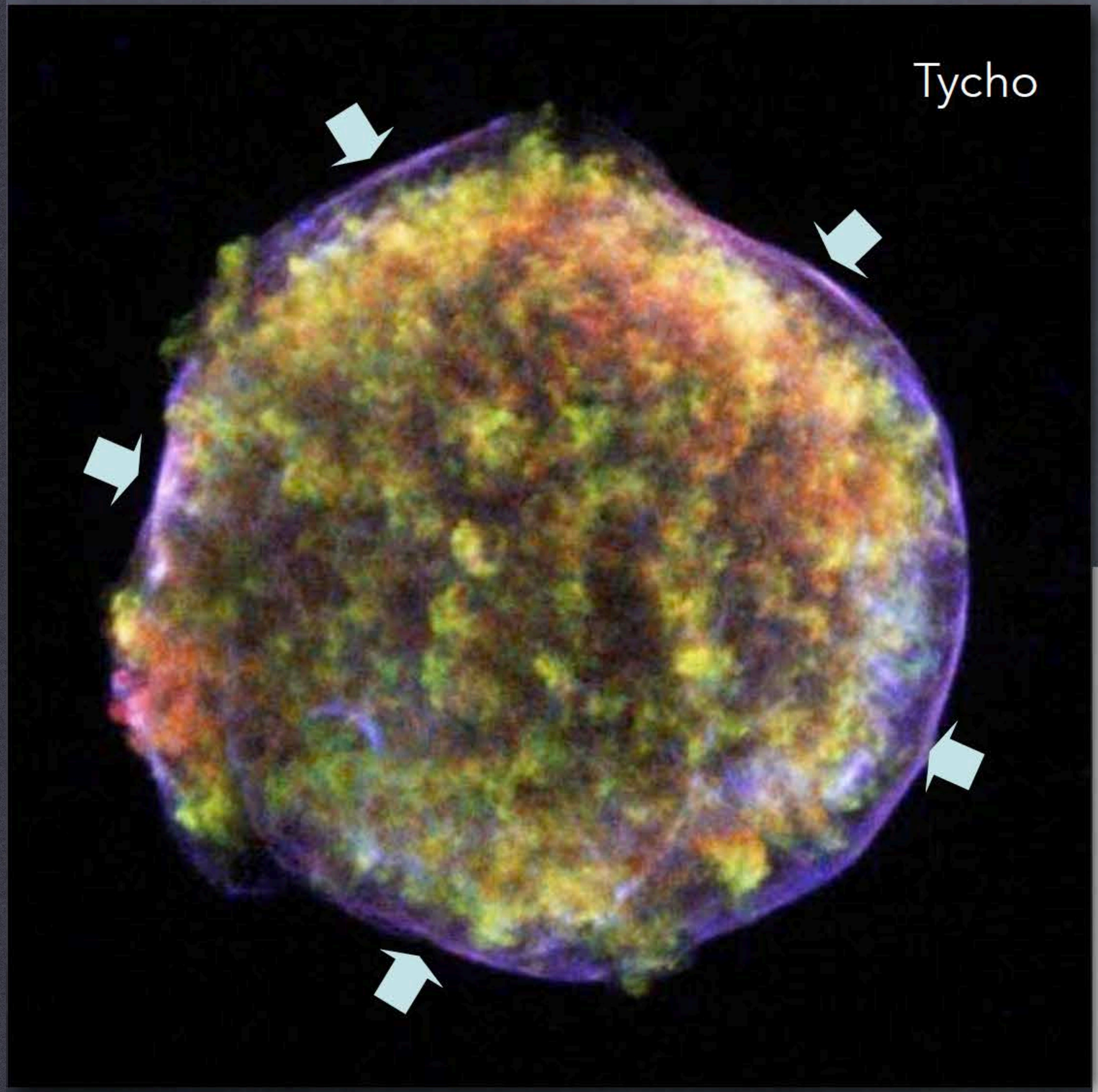
$$W_{CR} = \varepsilon_{CR} V_{conf} \approx 2 \times 10^{55}\ erg$$

$$L_{CR} \approx \frac{W_{CR}}{\tau_{conf}} \approx 5 \times 10^{40}\ erg\ s^{-1}$$

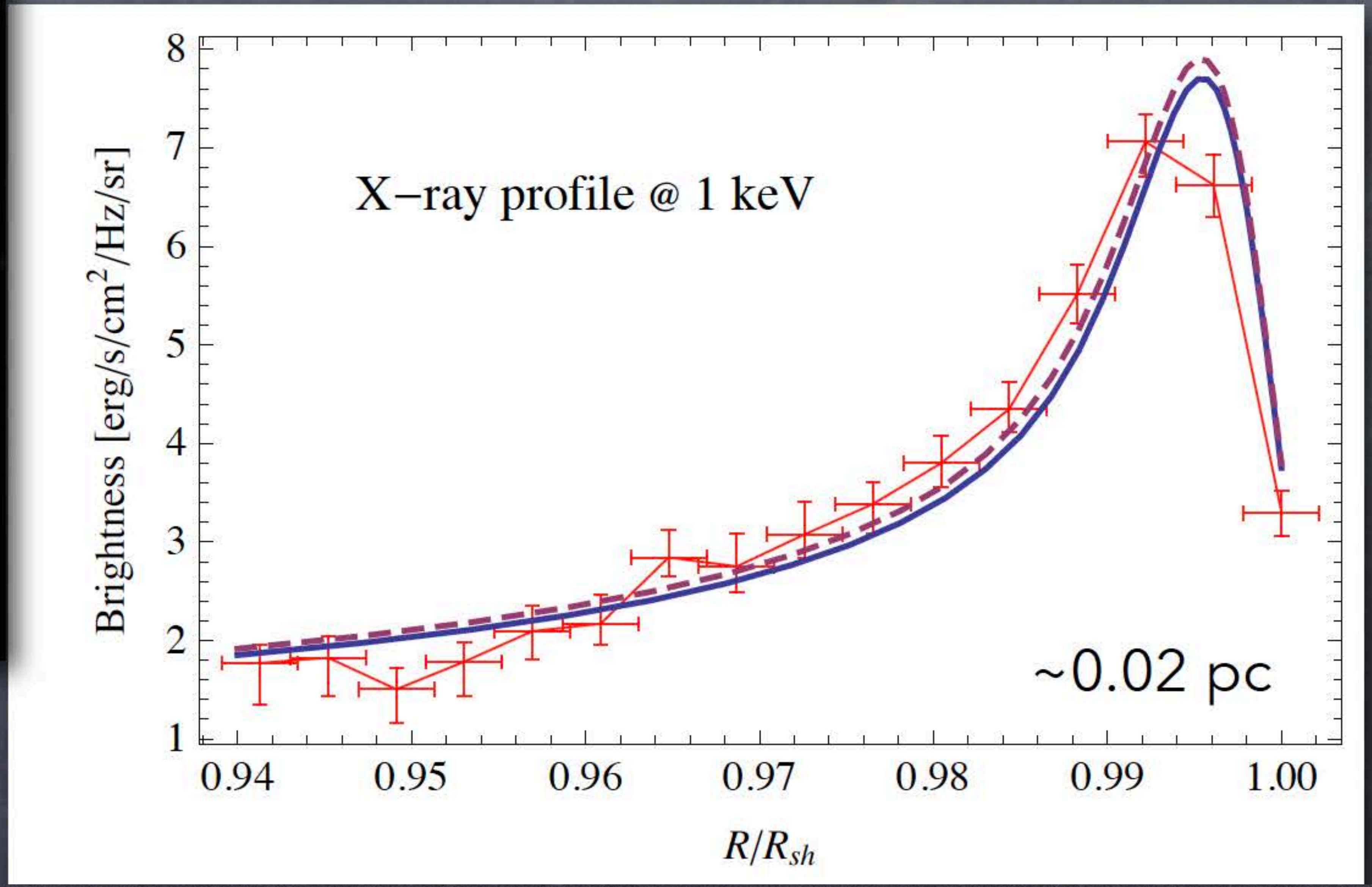
$$L_{SN} = R_{SN} E_{kin} \approx 3 \times 10^{41}\ erg\ s^{-1}$$

~10% of SN ejecta kinetic energy converted into CRs can account for the energetics

# Evidence of magnetic field amplification



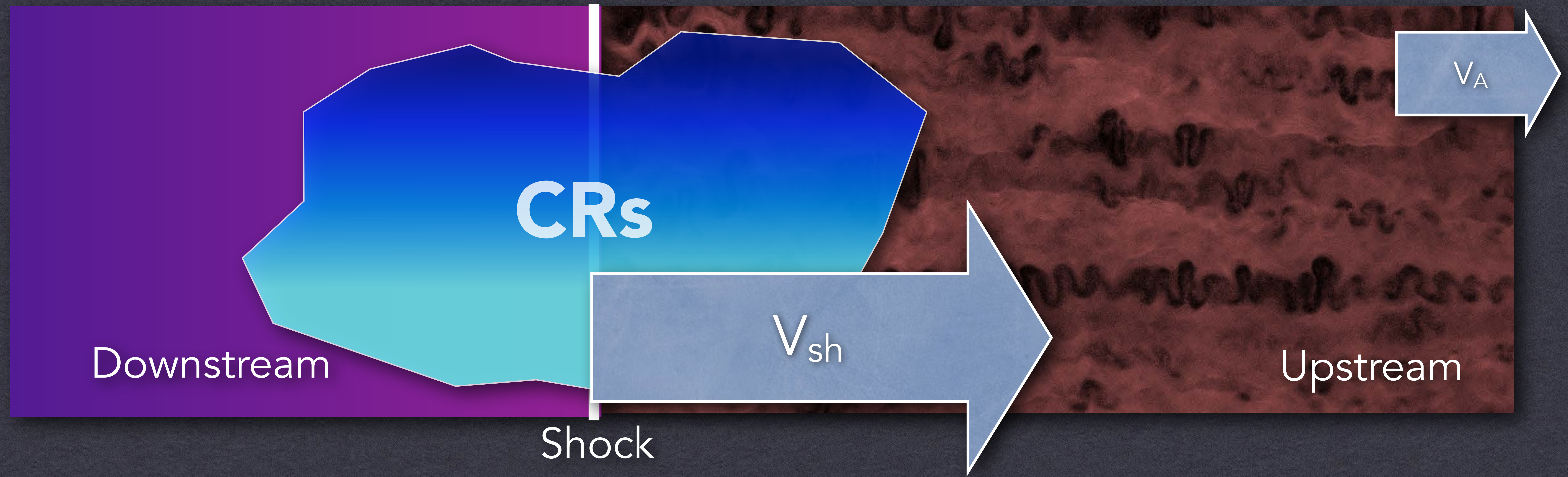

- Narrow (non-thermal) X-ray rims due to synchrotron losses of multi-TeV electrons...
- ...in fields as large as B∼100-500μG




Völk et al, 2005...;
Warren et al, 2005;
Uchiyama et al. 2007;
Cassam-Chenaï et al. 2008;
Morlino & Caprioli 2012;
Slane et al. 2014;
Ressler et al. 2014;

# SNR paradigm: maximum energy

- The magnetic field can be amplified by CR-driven instabilities
- The coupling between CRs and waves enhances $V_A \propto B$




$$\boxed{v_A = \frac{B}{\sqrt{4\pi\rho}}}$$

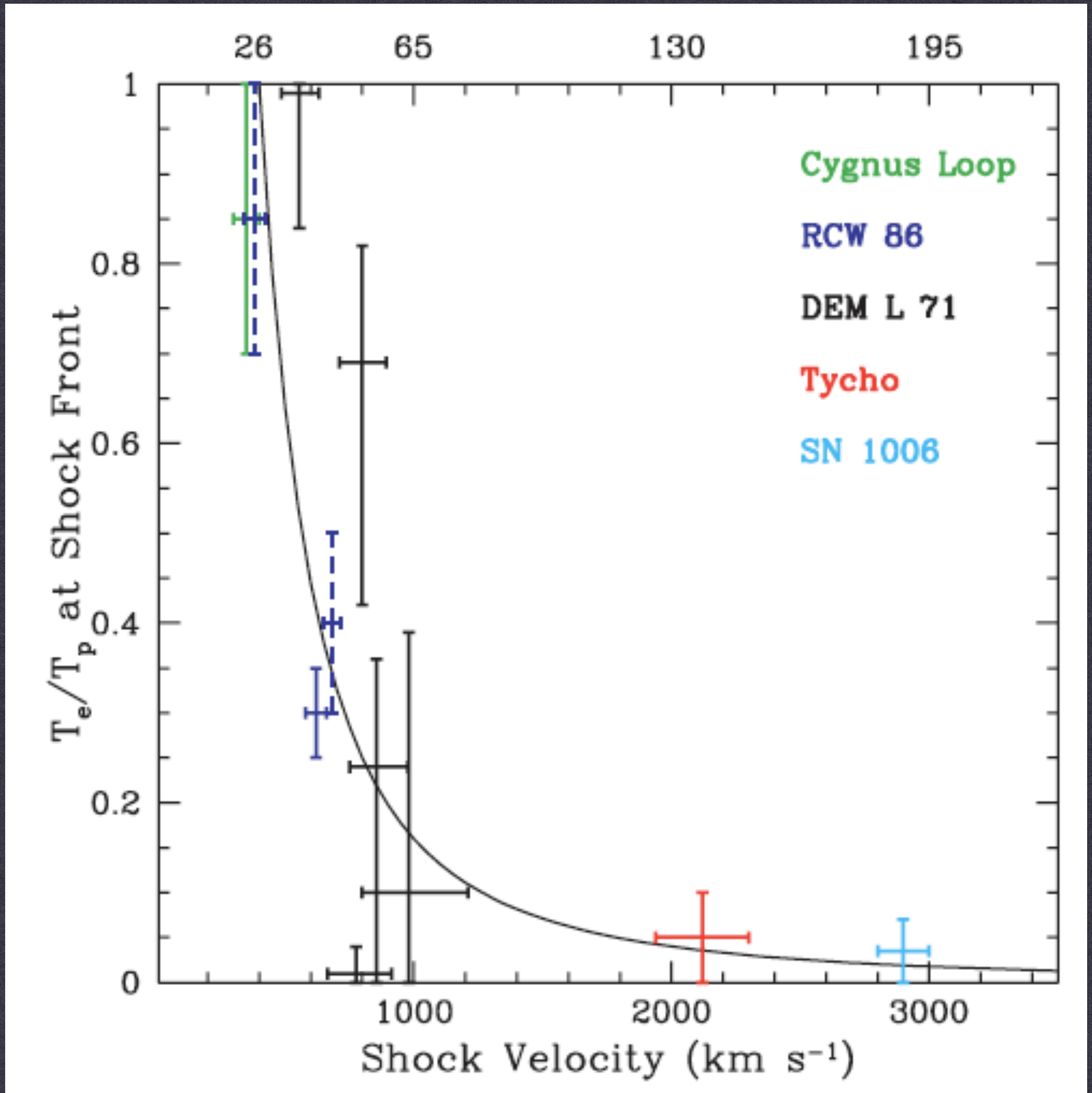
- Maximum energy achievable in a SNR: $\boxed{T_{acc} \propto \frac{D(E)}{V_{sh}^2} = T_{age}}$

$V_{sh} \sim 5\text{x}10^8$ cm/s

$T_{SNR} \sim 10^3$ yr

  - With Galactic diffusion: $E_{max} \sim$ GeV!
  - With Bohm diffusion $D_B(E)=cr_L(E)/3$ in the Galactic B, $E_{max} \sim$ 100 TeV $<E_{knee}$
  - B needs to be amplified by a factor of >10 (both UPS and DOWNS) to explain the knee!

# Shock diagnostics:

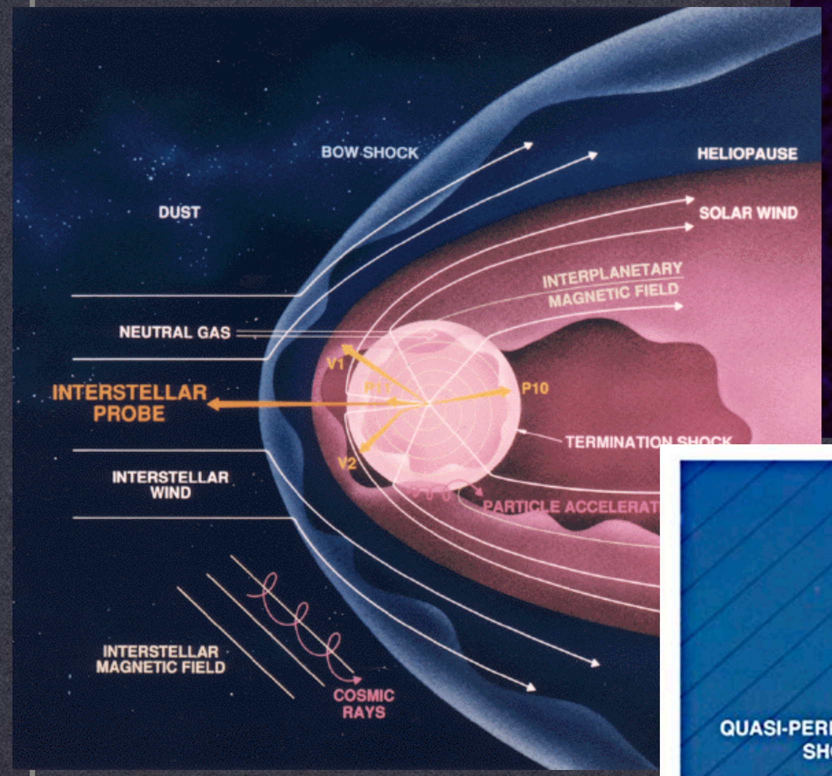


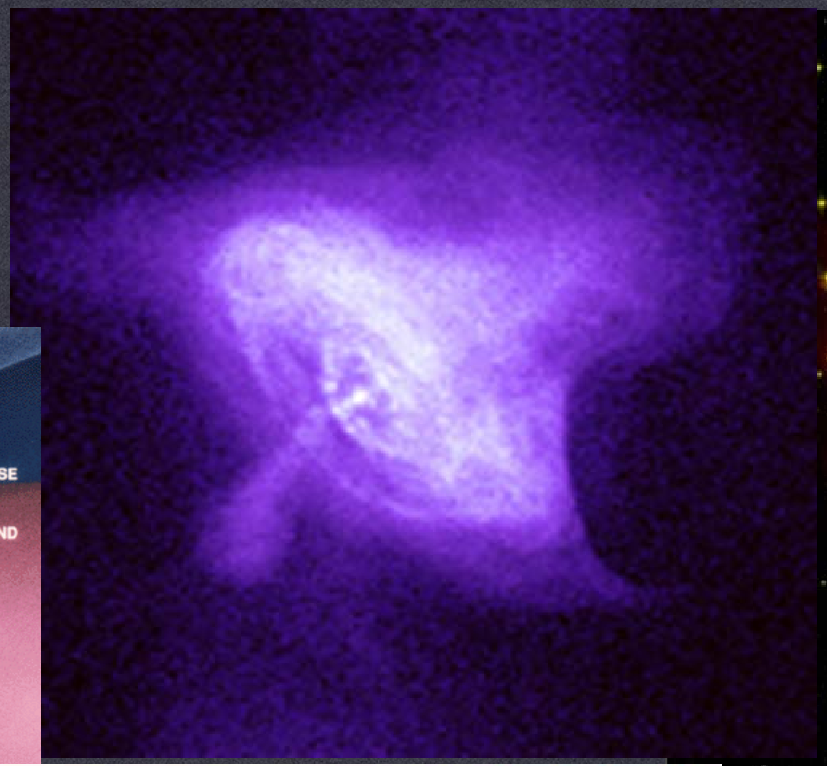

Ghavamian, Laming & Rakowski (2007)

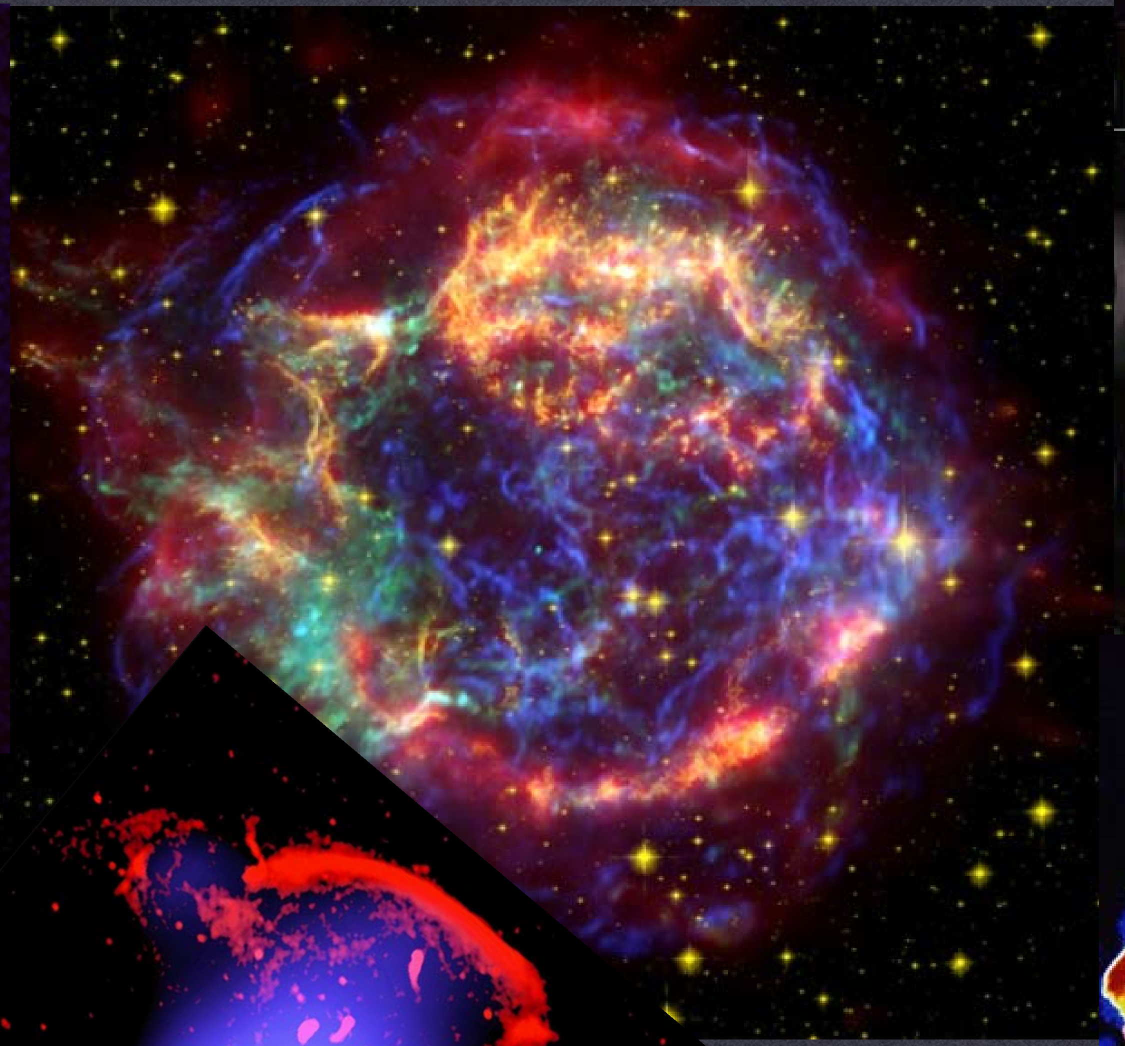
*also work by Heng and van Adelsberg (2008)*

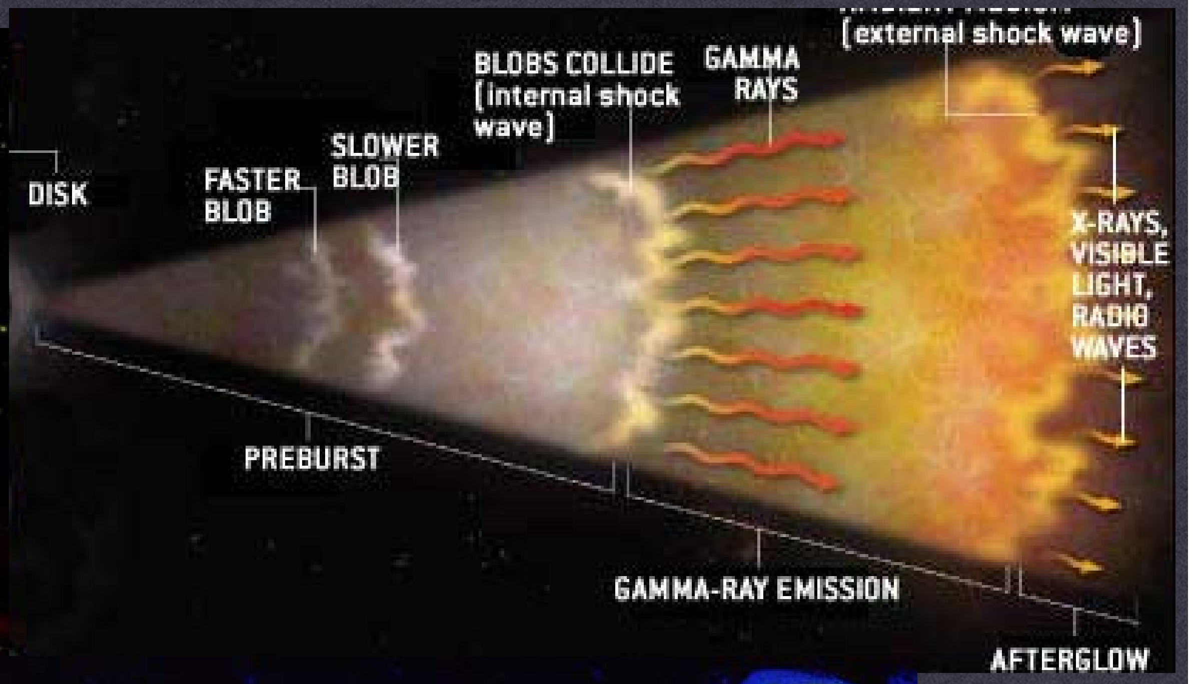
- In SNRs magnetic field of up to 100 μG is inferred from fitting IC and synchrotron together, and from year-scale variability. Much more than expected from compression of ISM field (e.g. Vink & Laming 2003, Uchiyama et al 2007).
- In SNRs partition of energy between electrons and ions can be studied with Balmer lines (narrow and broad components from charge-exchange) [Ghavamian et al 07]. Surprising result -- constant electron energy independent of velocity!
- Field amplification is required for relativistic shocks in GRBs to give any synchrotron emission ($\varepsilon_B$~1%) in GRB afterglows.
- Significant energy transfer to electrons in relativistic e-ion shocks ($\varepsilon_e$~10%) in GRBs

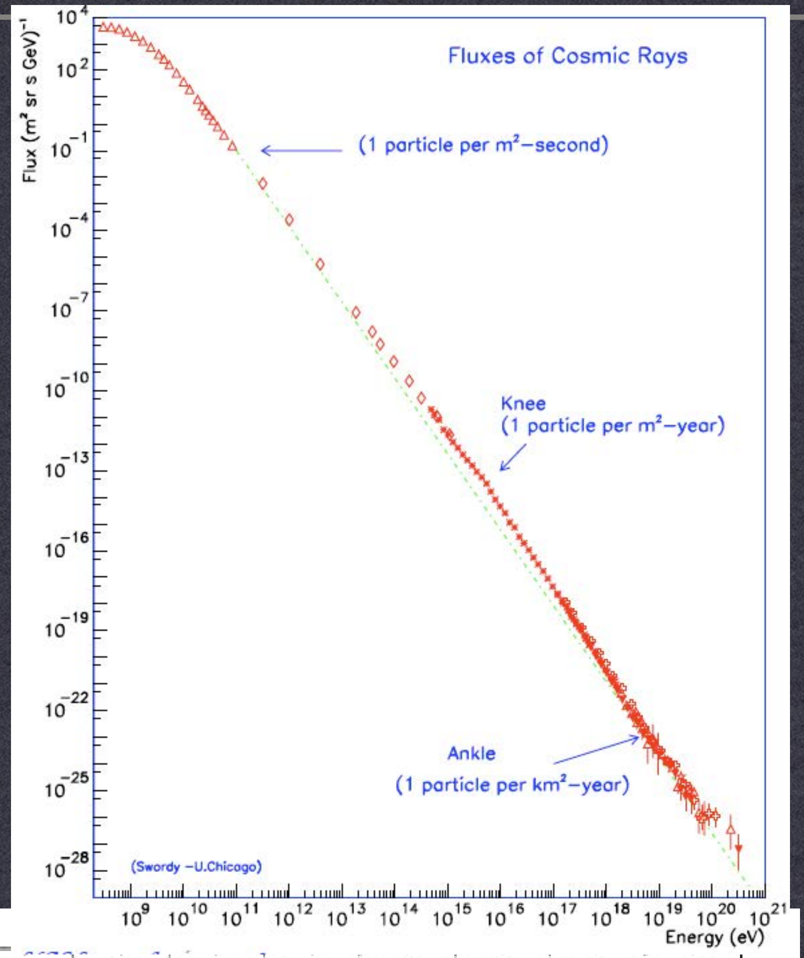
# Shocks & power-laws in astrophysics

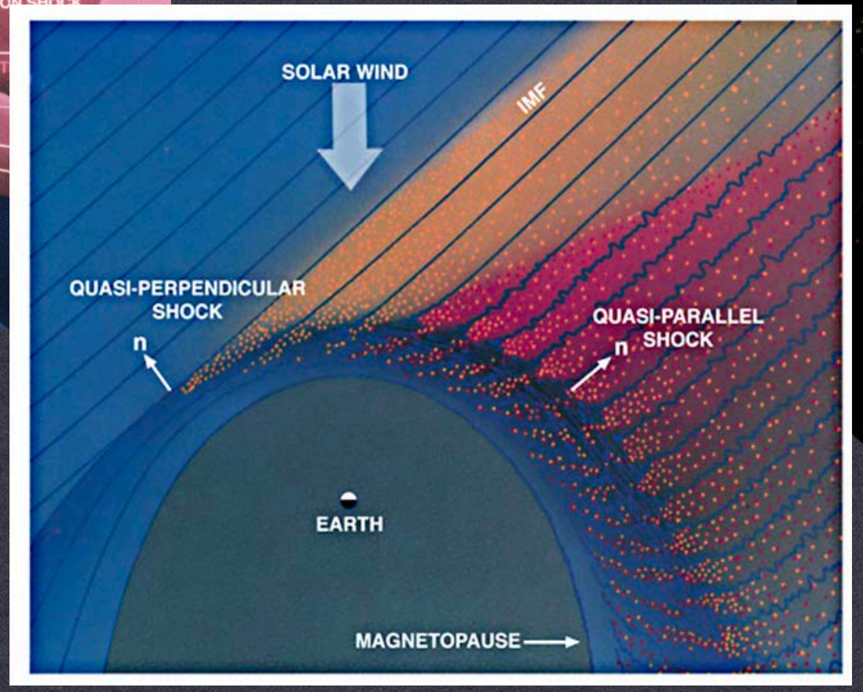


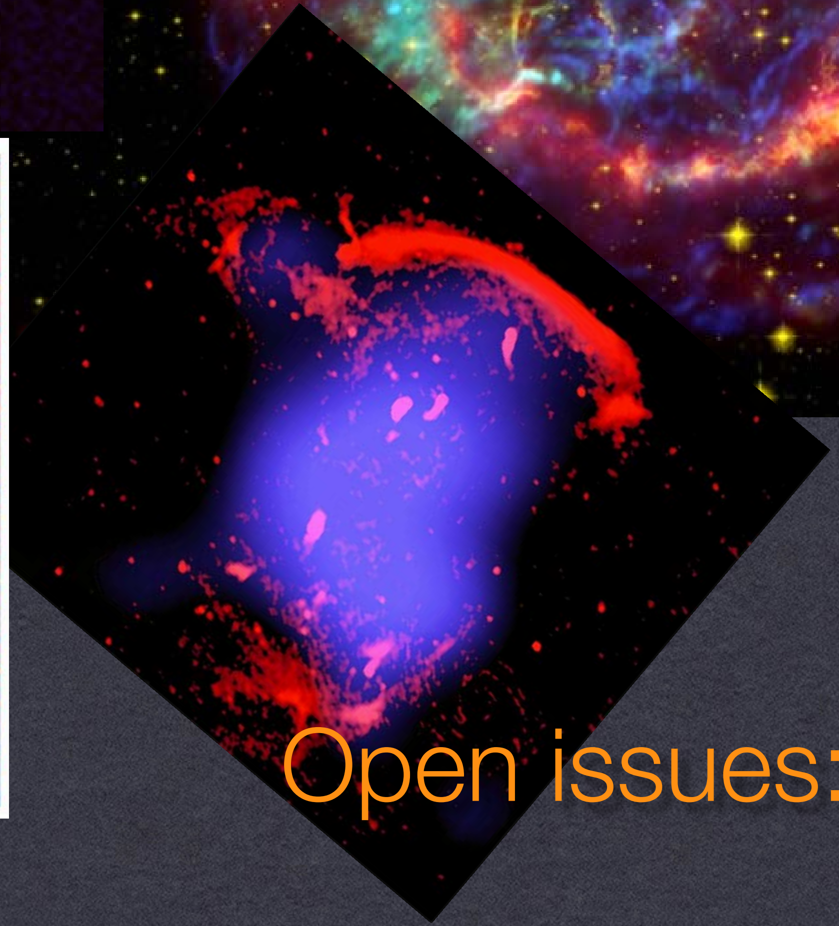



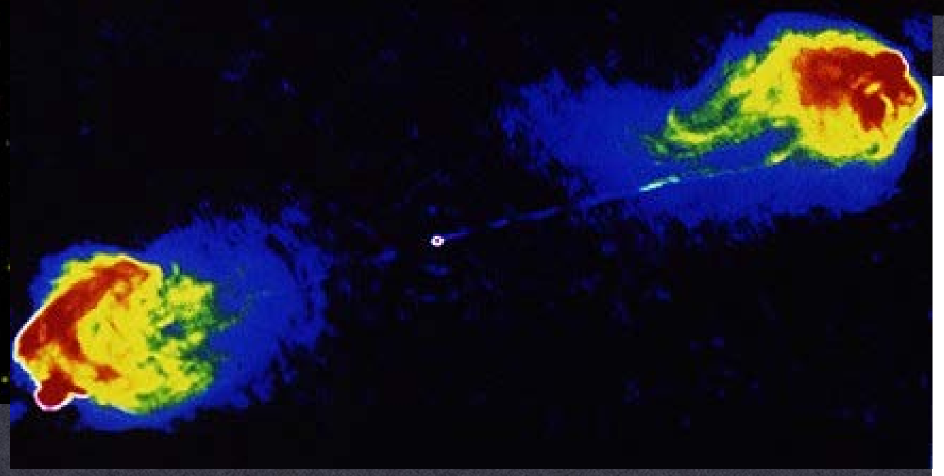


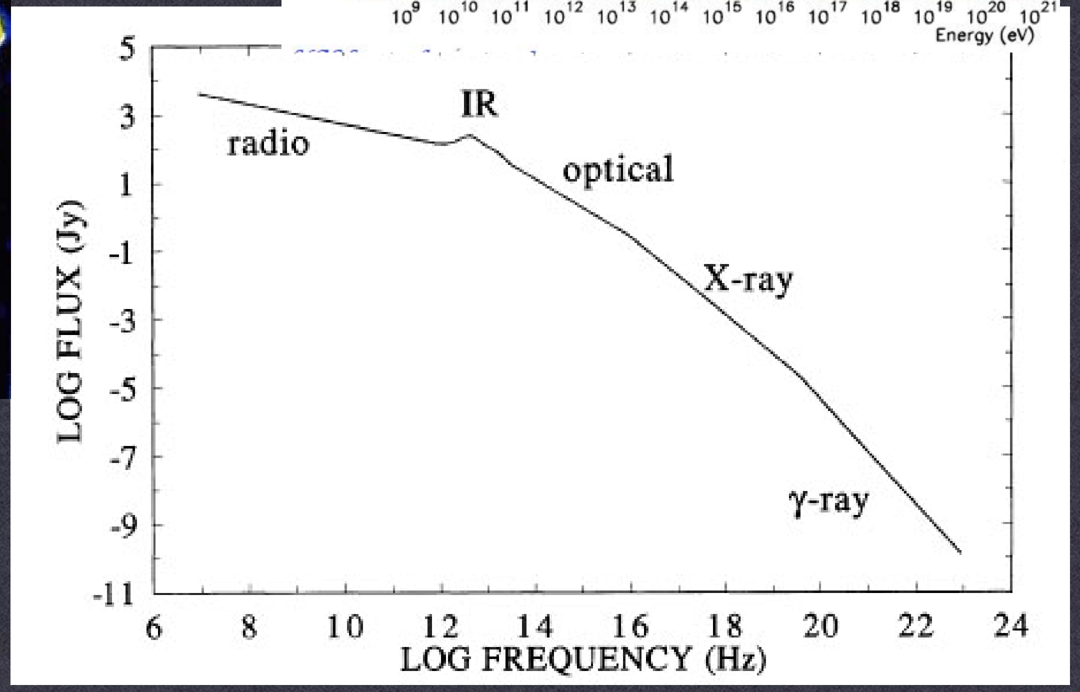







Open issues:

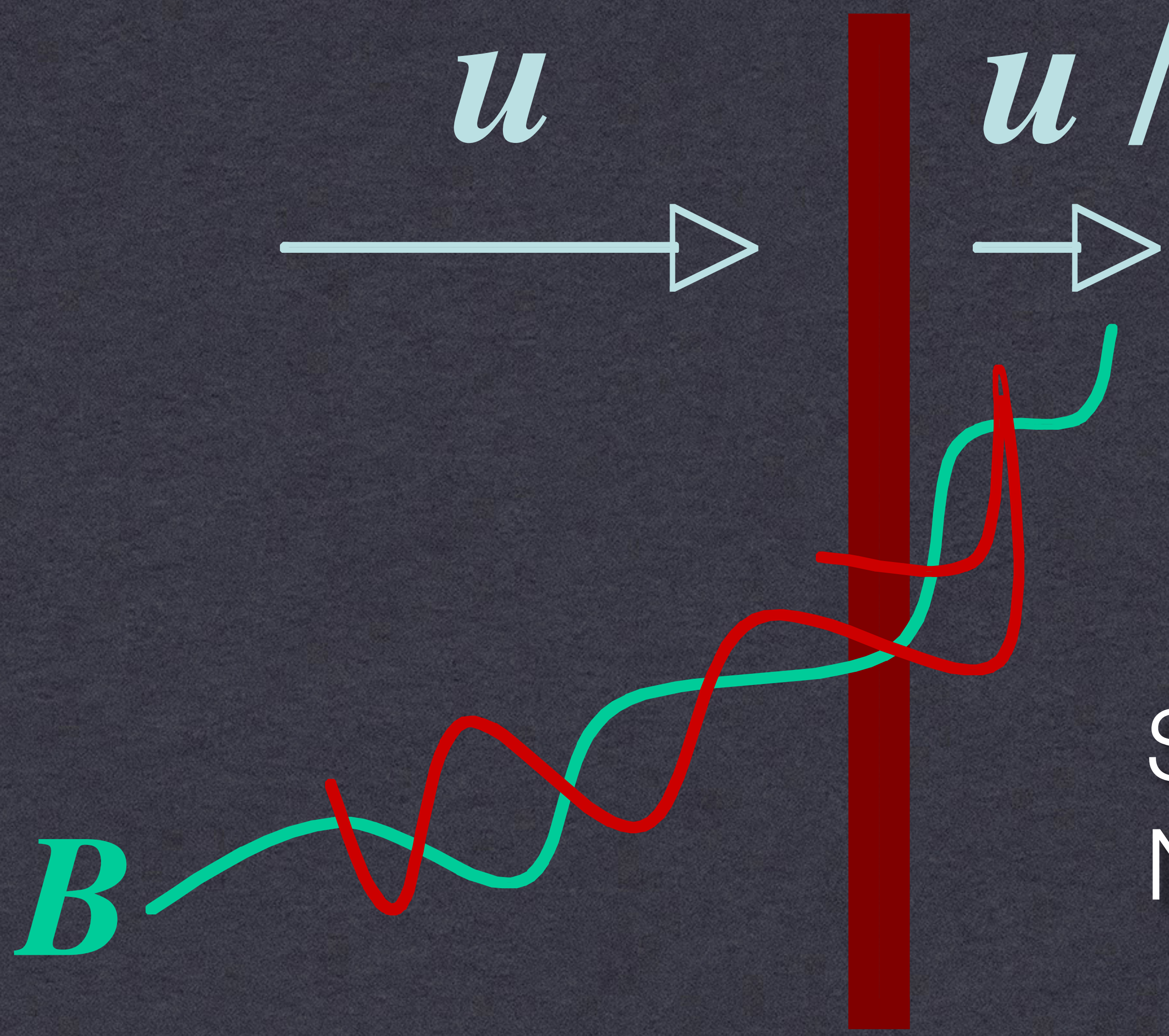
What is the structure of collisionless shocks? Do they exist?
Are there different regimes?

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

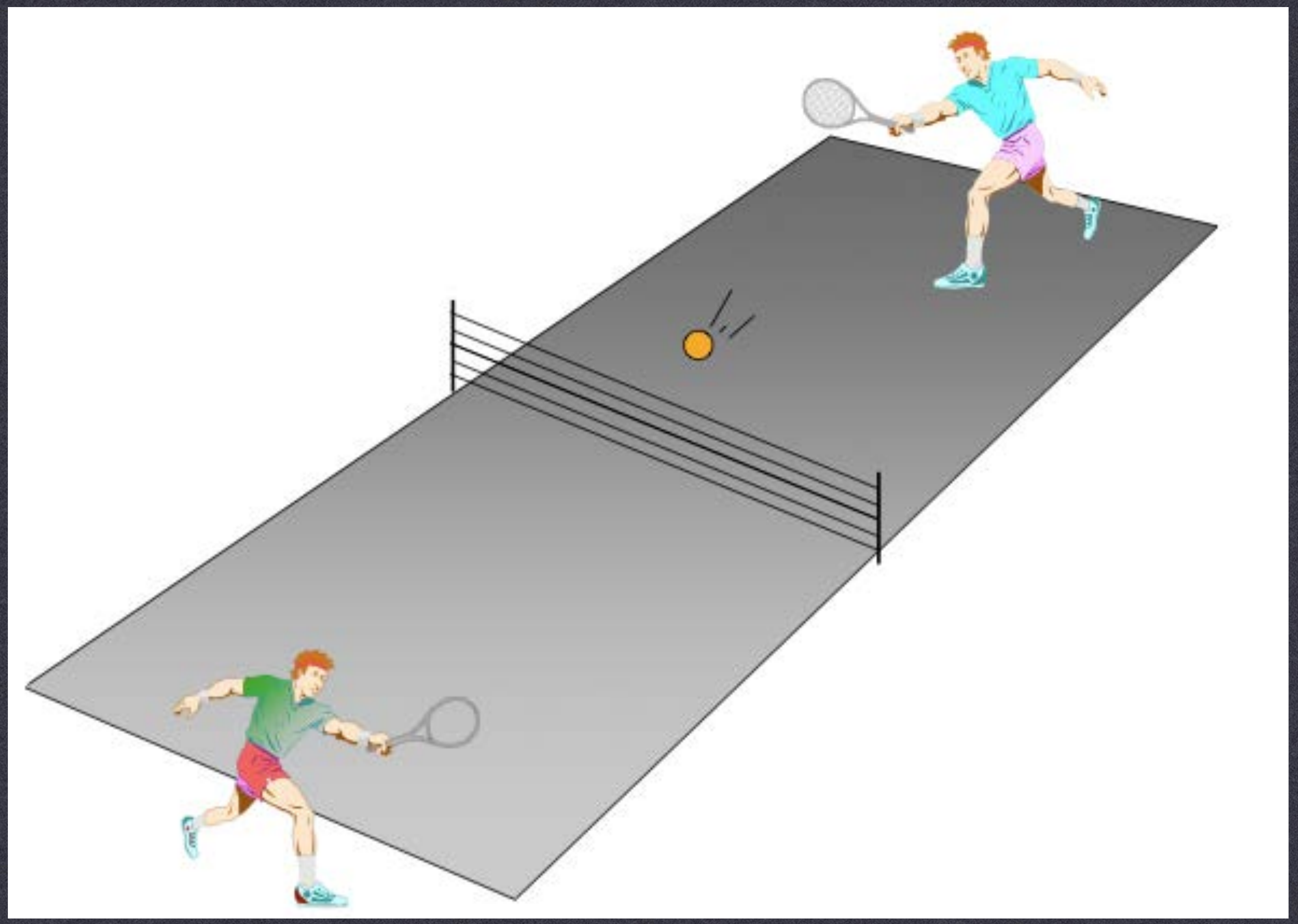
# Particle acceleration:



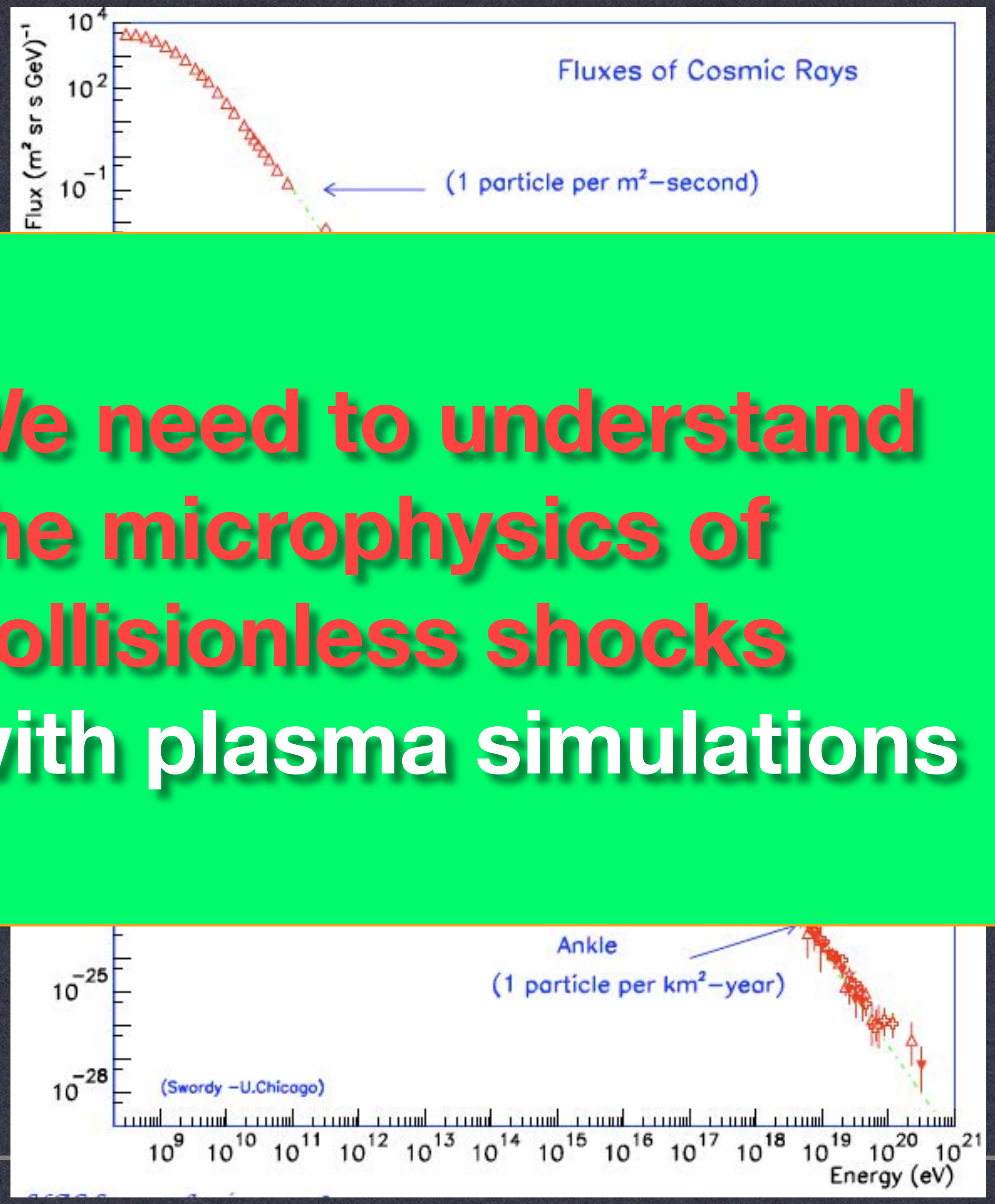

$\Delta E/E \sim v_{shock}/c$

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

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



*Free energy: converging flows*



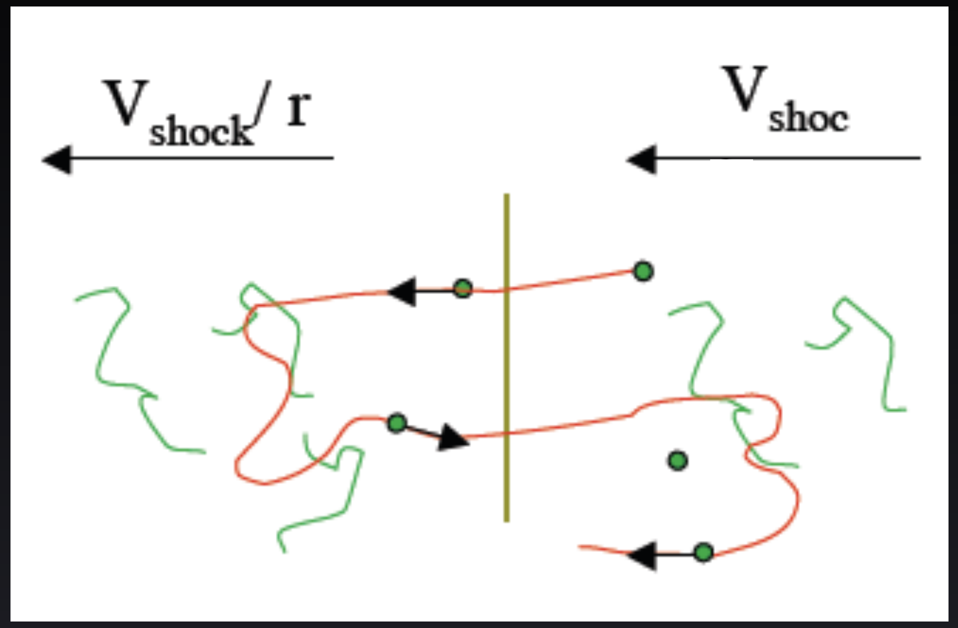

**We need to understand the microphysics of collisionless shocks with plasma simulations**

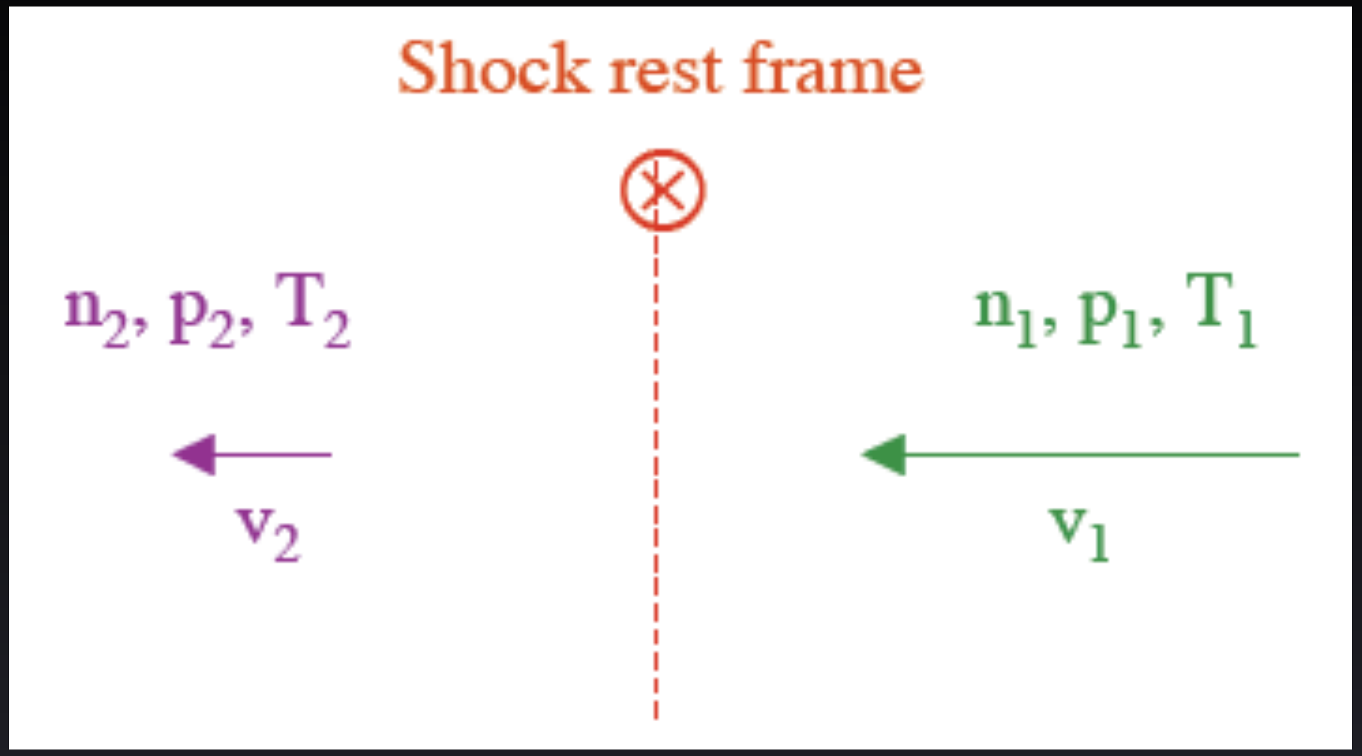
- Original idea -- Fermi (1949) -- scattering off moving clouds. Too slow (second order in v/c) to explain CR spectrum, because clouds both approach *and* recede.

- In shocks, acceleration is first order in v/c, because flows are always converging (Blandford & Ostriker 78,Bell 78, Krymsky 77)

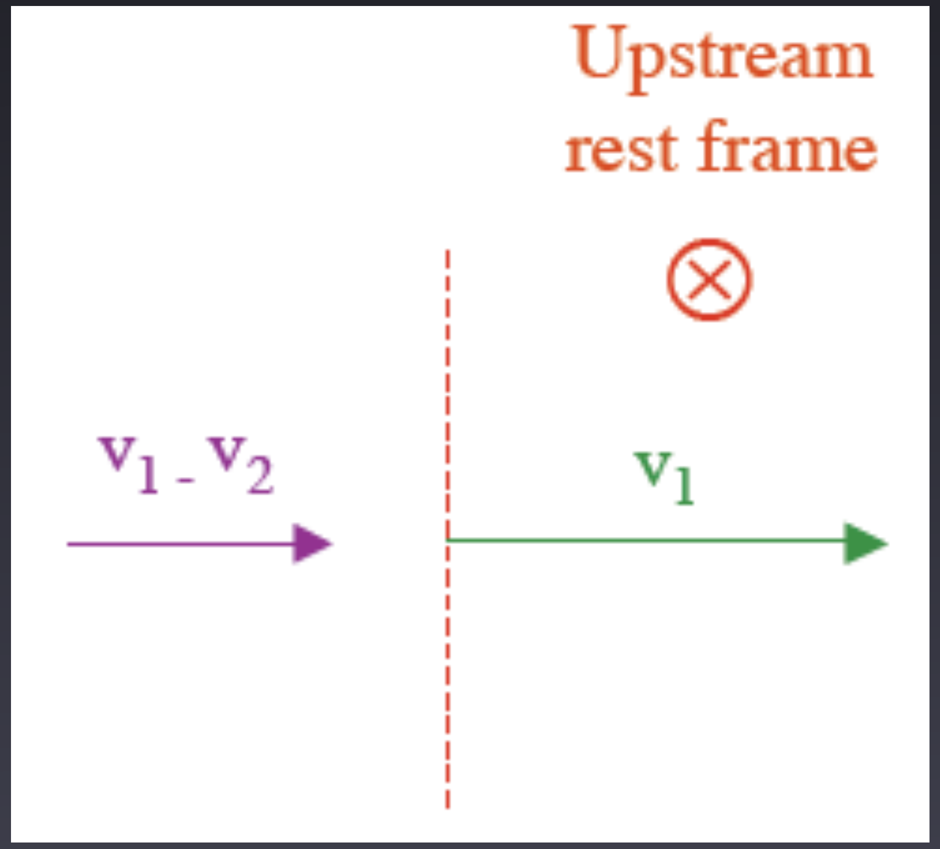
- Efficient scattering of particles is required. Particles diffuse around the shock. Monte Carlo simulations show that this implies very high level of turbulence. Is this realistic? Are there specific conditions?

# Particle acceleration:




From upstream, the downstream is approaching



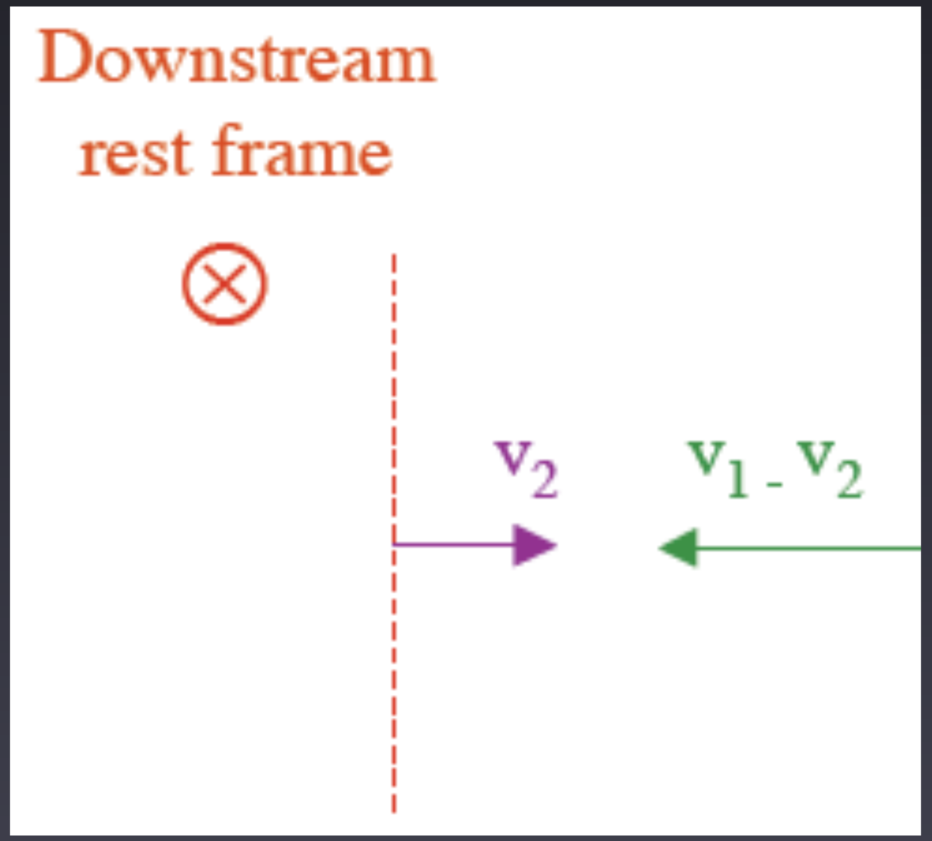

$$E' = E + p_x \Delta v$$

$$p_x = E/c$$

$$\frac{\Delta E}{E} = \frac{\Delta v}{c}$$ for head-on kick

Either crossing results in energy gain first order in velocity of the shock

From downstream, the upstream is approaching




How does this lead to power law?

$$E_{new} = E_{old}\beta \quad E = E_0\beta^j \qquad N = N_0 P^j \qquad \frac{\log(N/N_0)}{\log(E/E_0)} = \frac{\log P}{\log \beta}$$

$$\frac{N(>E)}{N_0} = \left(\frac{E}{E_0}\right)^{\log P/\log\beta} \qquad n(E) = E^{(\log P/\log\beta)-1} = E^k$$

k=(r+2)/(r-1), where r Is compression ratio

For strong shock k=-2, $n(p)=p^{-4}$

## See lecture notes by Achterberg 2003

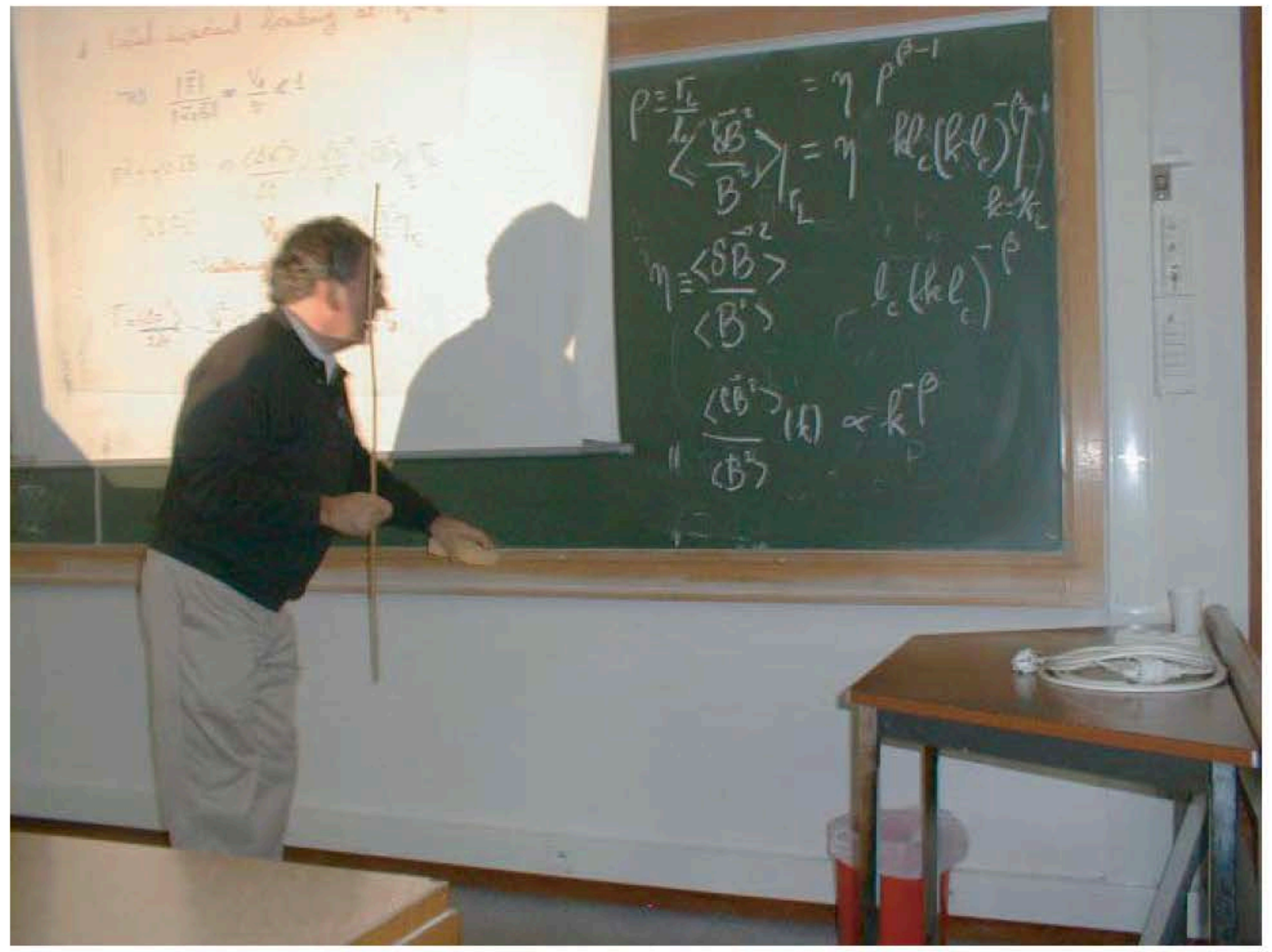
COURSE 7

**COSMIC RAYS AND PARTICLE ACCELERATION AT ASTROPHYSICAL SHOCKS**

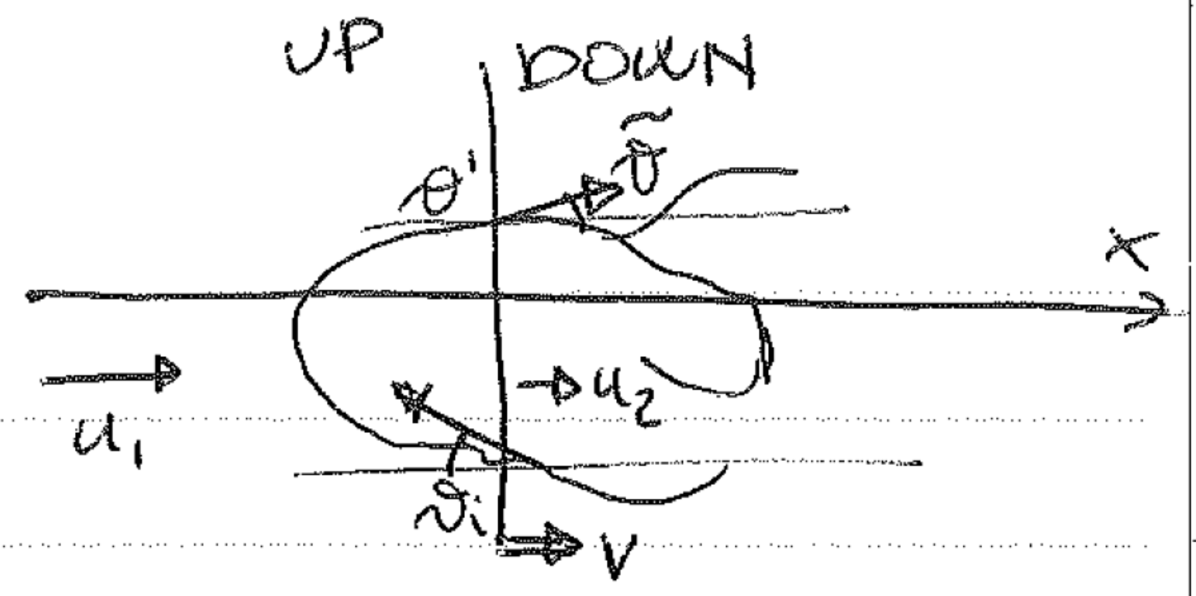
A. ACHTERBERG

*Sterrenkundig Instituut, Utrecht University, & Center for High Energy Astrophysics, Amsterdam, The Netherlands*

*Guy Pelletier presenting the course prepared by Abraham Achterberg*



# SHOCK ACCELERATION




Consider a TEST-PARTICLE in the DS FRAME, with velocity $\beta \gg u_1, u_2$.

Hp Let us assume that there is TURBULENCE to scatter the part. in pitch angle $\vartheta$.

Let the flight cosine be $\mu = \cos\vartheta$

and be $V = u_1 - u_2$ the relative velocity between UP/DS

$\boxed{DS_i}$ $E = E_i$ $p_{x_i} = \beta \mu_i E_i$ $pc = \beta E$ $p_{x_i} = p\mu_i$

$\boxed{DS_i \to US}$ $E' = \Gamma E_i (1 + \beta_v \beta \mu_i)$ $\Gamma = \gamma_V$

The part. is isotropized by turbulence, and may re-encounter the shock with a different $\vartheta = \vartheta'$ and with $\beta = \beta'$

$\hookrightarrow$ $E'_f = E'_i$ & $p'_{xf} = E'_f \beta' \mu'$

Back in the DS.

$\boxed{DS_f}$ $\boxed{E_f = \Gamma^2 E_i (1 + \beta_v \beta \mu_i)(1 - \beta_v \beta' \mu')}$ $[\beta^*_{-v} = -\beta_v$

Back in the DS.

DS f

$$\boxed{E_f = \Gamma^2 E_i (1+\beta_v \beta \mu_i)(1-\beta_v \beta' \mu')}$$

$[\beta_{-v}^* = -\beta_v$

Now, I have to also convert $\mu'$ into $\mu_f^*$

$$\mu_f = -\frac{\beta_v - \mu'\beta}{1-\mu'\beta_v} \qquad \mu' = \frac{\mu_f + \beta_v}{\beta + \mu_f \beta_v}$$

$[\beta, \beta' \sim 1$

Finally:

$$\frac{E_f}{E_i} = \Gamma^2 (1+\beta_v \mu_i)\left[1 - \beta_v \frac{\mu_f + \beta_v}{\beta + \mu_f \beta_v}\right]$$

$$= \Gamma^2 (1+\beta_v \mu_i) \frac{1-\beta_v^2}{1+\mu_f \beta_v} = \frac{1+\beta_v \mu_i}{1+\beta_v \mu_f}$$

$$\boxed{\frac{E_{final}}{E_{init}} \simeq (1+\beta_v \mu_i)(1-\beta_v \mu_f)} \qquad \text{for } \beta_v \ll 1$$

AVERAGE OVER $\mu_i, \mu_f$

DS

We want to calculate the flux of particle in direction $\mu$: $\phi \propto n v_x \propto \mu$; therefore

$$\left\langle \frac{E_f}{E_i} \right\rangle_{\mu_f} = \frac{\int d\mu_f \mu_f (1+\beta_v \mu_i)(1-\mu_f \beta_v)}{\int d\mu_f \mu_f}$$

$P(\mu) \propto \mu$

# Limits of integration

**ups->dwnstr**

For the part to enter ~~upstream~~ downstream:

$$\mu_f + u_2 \geq 0 \quad \Rightarrow \quad \boxed{-u_2 \leq \mu_f \leq 1}$$

**dwnstr->ups**

For the part to enter upstream:

$$\mu_i + u_2 \leq 0 \quad \Rightarrow \quad \boxed{-1 \leq \mu_i \leq -u_2}$$

Performing the average:

$\beta_V \equiv V$

$$\left\langle \frac{E_f}{E_i} \right\rangle_{\mu_f} = \frac{1+V\mu_i}{\frac{1}{2}(1-u_2^2)} \int_{-u_2}^{1} d\mu_f (1-\mu_f V)\mu_f$$

$$= \frac{1+V\mu_i}{\frac{1}{2}(1-u_2^2)} \left\{ \frac{1}{2}(1-u_2^2) - \frac{V}{3}(1-u_2^3) \right\}$$

$$\left[ \int_{-u_2}^{1} d\mu\,\mu = \frac{1}{2}(1-u_2^2) \right]$$

$$\left[ \int_{-u_2}^{1} d\mu\,\mu^2 = \frac{1+u_2^3}{3} \right]$$

$$\left\langle \frac{E_f}{E_i} \right\rangle_{\mu_f,\mu_i} = \left\{ 1 - \frac{2}{3}V\left(\frac{1+u_2^3}{1-u_2^2}\right) \right\} \frac{1}{\frac{u_2^2-1}{2}} \int_{-1}^{-u_2} d\mu_i\, \mu_i (1+V\mu_i)$$

$$\left[ \int_{-1}^{-u_2} d\mu\,\mu = \frac{u_2^2-1}{2} \right]$$

$$= \left[ 1 - \frac{2}{3}V\left(\frac{1+u_2^3}{1-u_2^2}\right) \right] \left[ 1 + \frac{2}{3}V\left(\frac{1-u_2^3}{u_2^2-1}\right) \right] \simeq$$

$$\left[ \int_{-1}^{-u_2} d\mu\,\mu^2 = \frac{1-u_2^3}{3} \right]$$

$$\simeq 1 + \frac{2}{3}V\left(\frac{1+u_2^3}{u_2^2-1}\right) - \frac{2}{3}V\left(\frac{1-u_2^3}{1-u_2^2}\right) + O(V^2) \simeq 1 + \frac{4}{3}V$$

$$\boxed{\left\langle \frac{\Delta E}{E} \right\rangle_{\mu_i,\mu_f} = \frac{4}{3}(u_1-u_2)}$$

# BELL'S APPROACH

Let's start with $N_0$ particles with energy $E_0$

Be: – G: the energy gain per step: $E_K = G^K E_0$

– P: the probability of staying in the accelerator

After K cycles: $N_K = P^K N_0$ [G, P indep of E

Since:

$$\frac{N_K}{N_0} = P^K \quad \log\left(\frac{N_K}{N_0}\right) = K \log P$$

$$\frac{E_K}{E_0} = G^K \quad \log\left(\frac{E_K}{E_0}\right) = K \log G \quad \Rightarrow$$

$$\log\left(\frac{N_K}{N_0}\right) = \frac{\log P}{\log G} \log\left(\frac{E_K}{E_0}\right) \Rightarrow \cancel{\log\left(\frac{N_K}{N_0}\right)} \quad \boxed{\frac{N_K}{N_0} = \left(\frac{E_K}{E_0}\right)^{-\alpha}, \quad \alpha = -\frac{\log P}{\log G}}$$

## RETURN PROBABILITY

The ret. prob. P is the ratio of FLUXES of particles returning to the shock to entering part

$$P = \frac{|J_{ret}|}{J_{in}} = \frac{-\int d\mu(\mu+u_2)\Big|_{\mu+u_2\leq 0}}{\int d\mu(\mu+u_2)\Big|_{\mu+u_2\geq 0}} = \frac{-\int_{-1}^{-u_2}}{\int_{-u_2}^{1}} \qquad \left[\int d\mu\,(\mu+u_2) = \frac{\mu^2}{2}+\mu u_2\Big|_{min}^{max}\right]$$

$$= \frac{-\left|\mu u_2 + \frac{\mu^2}{2}\right|_{-1}^{-u_2}}{\mu u_2 + \frac{\mu^2}{2}\Big|_{-u_2}^{1}} = \frac{-\left|-u_2^2 + \frac{u_2^2}{2} + u_2 - \frac{1}{2}\right|}{u_2 + \frac{1}{2} + u_2^2 - \frac{u_2^2}{2}} = \frac{-\left|-u_2^2+2u_2-1\right|}{u_2^2+2u_2+1} = \left(\frac{1-u_2}{1+u_2}\right)^2$$

$$\boxed{P \simeq 1 - 4u_2} \quad \text{for} \quad u_2 \ll 1 \qquad \left[r = \frac{u_1}{u_2}\right]$$

FIRST ORDER FERMI @ SHOCKS

$$\alpha = -\frac{\log P}{\log G} = -\frac{\log(1-4u_2)}{\log\left(1+\frac{4}{3}(u_1-u_2)\right)} \simeq \frac{4u_2}{\frac{4}{3}(u_1-u_2)} = \frac{3u_2}{u_1-u_2} = \frac{3}{r-1}$$

$$\frac{N_k}{N_0} = \left(\frac{E_k}{E_0}\right)^{-\frac{3}{r-1}} \Rightarrow N(>E_0) = N_0\left(\frac{E}{E_0}\right)^{-\frac{3}{r-1}} \Rightarrow \boxed{\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\alpha-1} \propto \left(\frac{E}{E_0}\right)^{-\frac{r+2}{r-1}}}$$

# DSA - KINETIC DERIVATION

VLASOV: For a collisionless plasma the Boltzmann eq. reduces to (cons # particle in phase space)

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\vec{\nabla}_x f + \dot{\vec{p}}\cdot\vec{\nabla}_p f = 0 \qquad \dot{\vec{p}} = q\left[\vec{E} + \frac{\vec{v}}{c}\times\vec{B}\right]$$

Hp: The fluid has scattering centers (Alfvén waves) with $v_A \ll u$, which scatter the part in pitch-angle, but don't change their energy [they do it $O\left(\frac{v_A}{c}\right)^2$.

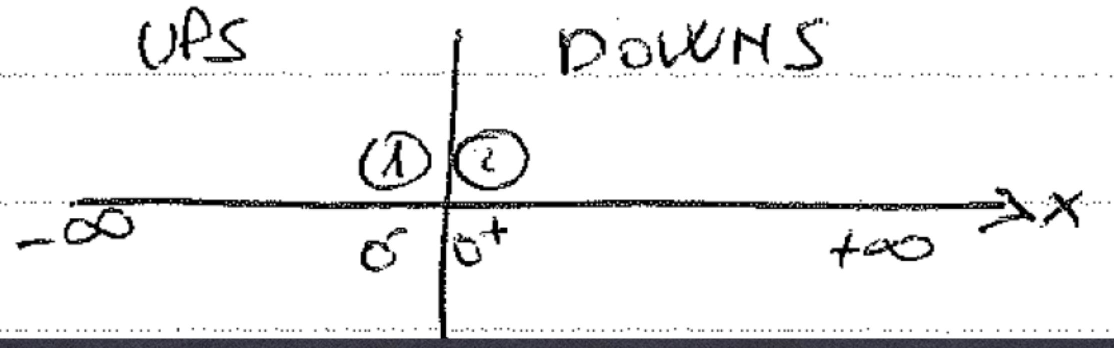
1 ↳ $f$ is isotropic in the wave frame

2 ↳ The first-order anisotropic flux is $\phi = -D\,\frac{\partial f}{\partial x}$ [$O\left(\frac{u}{c}\right)$ small pitch-angle scattering

PARKER:

$$\underbrace{\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x}}_{\text{ADVECTION}} = \underbrace{\frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right]}_{\text{DIFFUSION}} + \underbrace{\frac{p}{3}\frac{du}{dx}\frac{\partial f}{\partial p}}_{\text{AD. CHANGE}} + \underbrace{Q(p,x)}_{\text{INJECTION}}$$

Consider a shock and $\frac{\partial f}{\partial t} = 0$

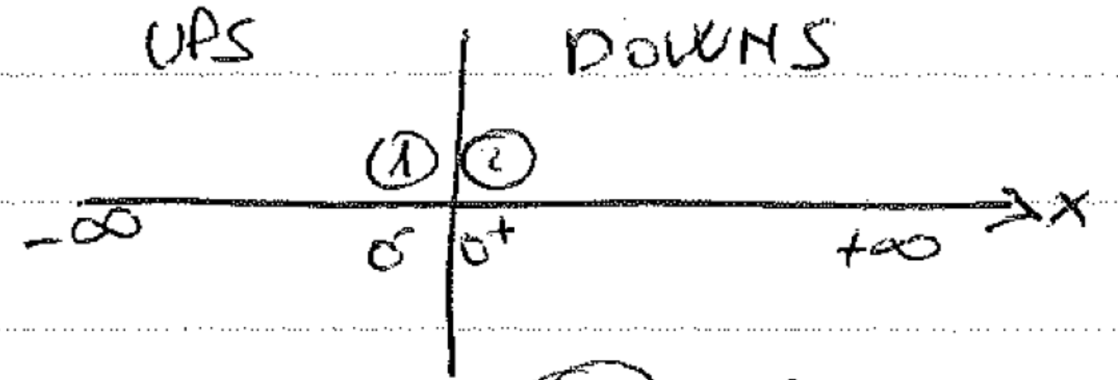



$$\frac{du}{dx} = (u_2 - u_1)\,\delta(x)$$

PARKER: $$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] + \frac{p}{3}\frac{du}{dx}\frac{\partial f}{\partial p} + Q(p,x)$$

ADVECTION DIFFUSION AD. CHANGE INJECTION

Consider a shock and $\frac{\partial f}{\partial t} = 0$




$$\frac{du}{dx} = (u_2 - u_1)\,\delta(x)$$

B/C: ① $f_{0^-} = f_{0^+}$ ② $f_{-\infty} = 0$ ③ $\left.\frac{\partial f}{\partial x}\right|_{-\infty} = 0$ ④ $\frac{\partial D}{\partial x} = 0$

$\int_{0^-}^{0^+}$: $$0 = \cancel{D\left.\frac{\partial f}{\partial x}\right|_2} - D\left.\frac{\partial f}{\partial x}\right|_1 + \frac{p}{3}(u_2-u_1)\frac{\partial f}{\partial p}$$

$\int_{-\infty}^{0^-}$: $$\int u\frac{\partial f}{\partial x} = uf\Big|_{-\infty}^{0^-} - \cancel{\int f\frac{du}{dx}} = D\left.\frac{\partial f}{\partial x}\right|_{0^-} - \cancel{D\left.\frac{\partial f}{\partial x}\right|_{-\infty}}$$

$$u_1 f_0 = D\left.\frac{\partial f}{\partial x}\right|_{0^-}$$

$$\Rightarrow u_1 f_0 = \frac{p}{3}(u_2-u_1)\frac{\partial f}{\partial p} \qquad \frac{df}{f} = \frac{3u_1}{u_2-u_1}\frac{dp}{p} \Rightarrow \boxed{f \propto p^{-\frac{3u_1}{u_1-u_2}} \propto p^{-\frac{3n}{n-1}}}$$

SEEDS: If $f(x=-\infty) = f_\infty(p)$ $$f_0(p) = q\,p^{-q}\int_0^p dp'\, p'^{\,q-1} f_\infty(p') + A_0\, p^{-q}$$

$$f(x,p) = f_0(p)\exp\left[\frac{ux}{D}\right]$$

# ACCELERATION TIME:

We saw that particles diffuse on a scale $\frac{D}{u}$ upstream; they have an average $\langle v \rangle = \frac{c}{3}$, so it takes

$$\tau_{up} = \frac{D}{u}\left(\frac{c}{3}\right)^{-1} \simeq \frac{3}{c}\frac{D}{u}$$

to come back from upstream. The time for a total UP+DOWN cycle is:

$$\tau_{cy} \simeq \frac{3}{c}\left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right)$$

The average energy gain is $\left\langle \frac{\Delta E}{E} \right\rangle \overset{\beta \approx 1}{\simeq} \left\langle \frac{\Delta p}{p} \right\rangle = \frac{4(u_1 - u_2)}{3c}$ and the acceleration time scale is

$$T_{ACC} \simeq \frac{p}{\dot{p}} \simeq \frac{p \Delta t}{\Delta p} \simeq \frac{\cancel{3}\, 9/4}{u_1 - u_2}\left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right)$$

The average energy gain is $\left\langle \frac{\Delta E}{E} \right\rangle \overset{\beta \sim 1}{=} \left\langle \frac{\Delta p}{p} \right\rangle = \frac{4(u_1 - u_2)}{3c}$
and the acceleration time scale is

$$T_{ACC} \simeq \frac{p}{\dot{p}} \simeq \frac{p \Delta t}{\Delta p} \simeq \frac{\cancel{4}\,1/4}{u_1 - u_2} \left( \frac{D_1}{u_1} + \frac{D_2}{u_2} \right)$$

A more refined calculation (Drury '83) gives:

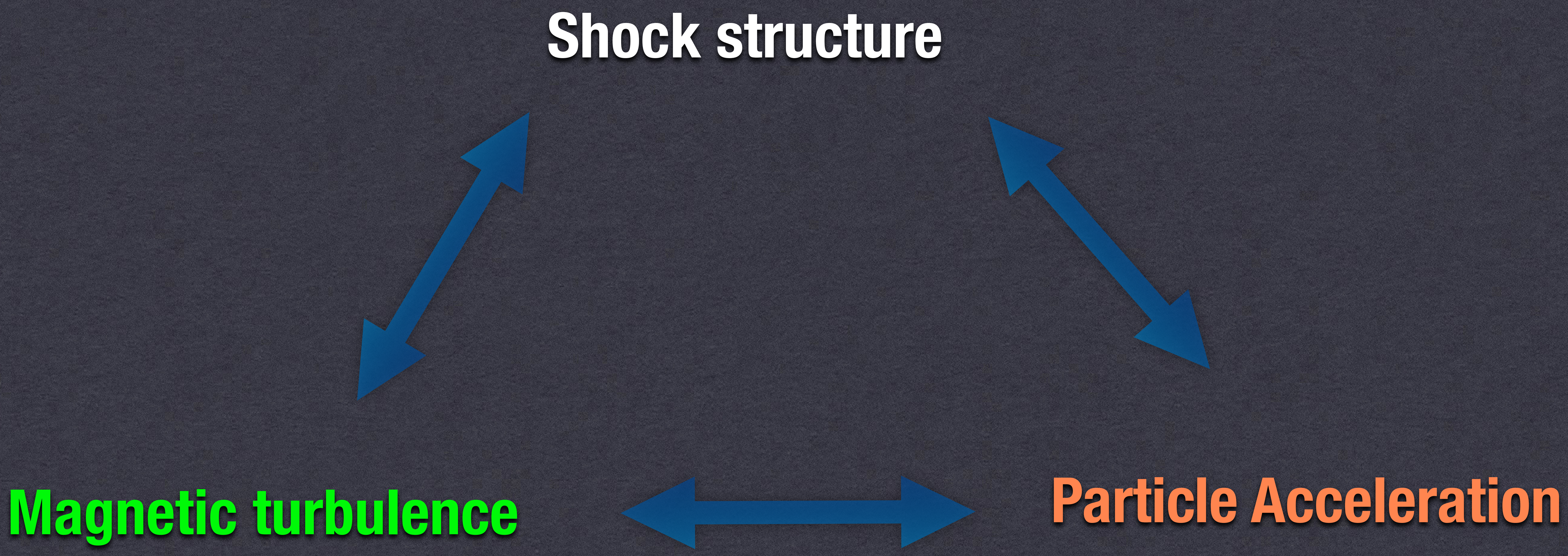
$$\tau_{ACC} = \frac{3}{u_1 - u_2} \left( \frac{D_1}{u_1} + \frac{D_2}{u_2} \right) \quad \text{if } D_i \propto \frac{1}{B_i}$$

Since $B_2 \sim r B_1$ and $u_1 = r u_2 \Rightarrow \frac{D_1}{u_1} \simeq \frac{D_2}{u_2}$

$$\boxed{\tau_{ACC} \simeq \frac{6 \cdot r}{r-1} \frac{D}{V_{sh}^2}}$$

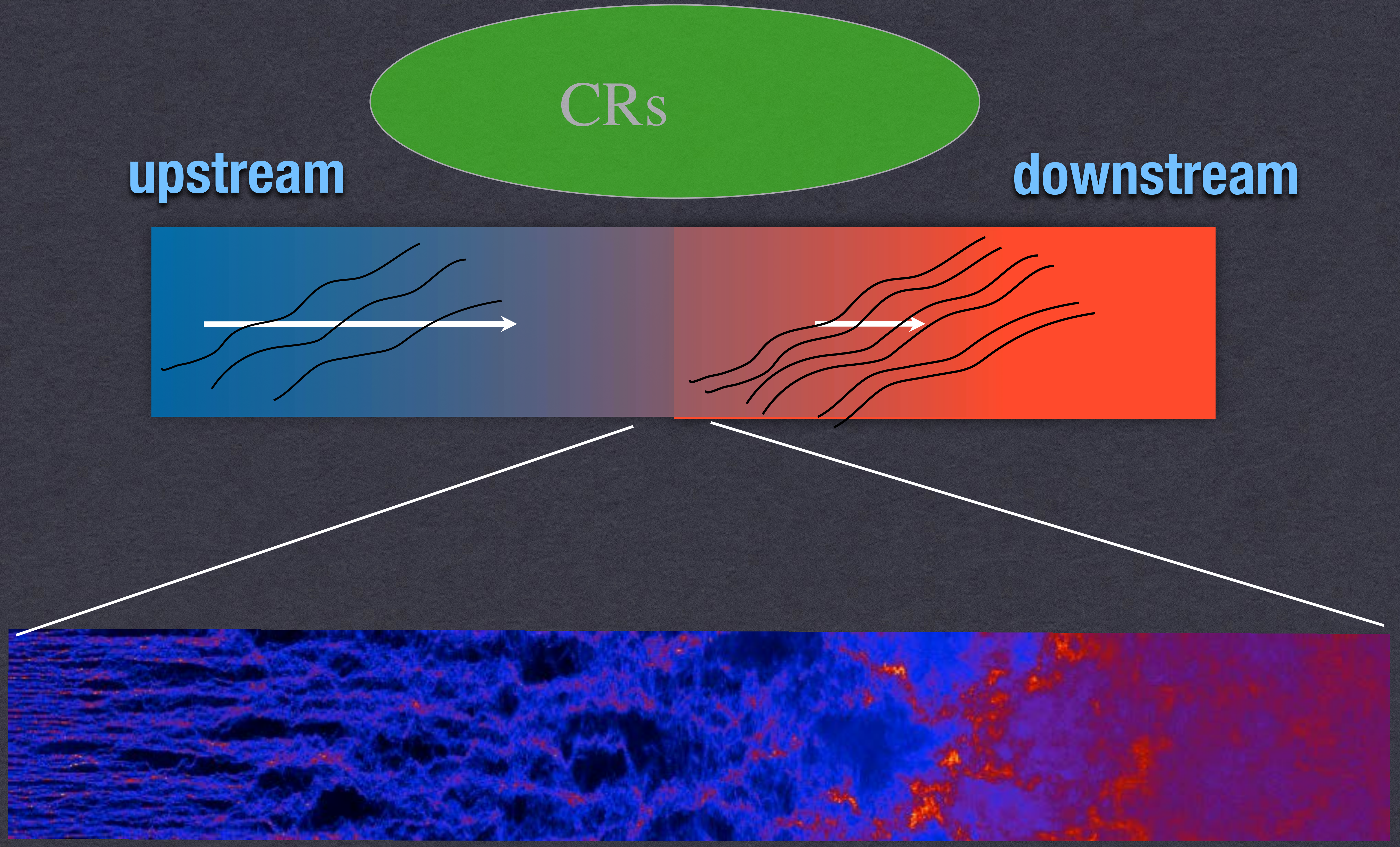
# Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback



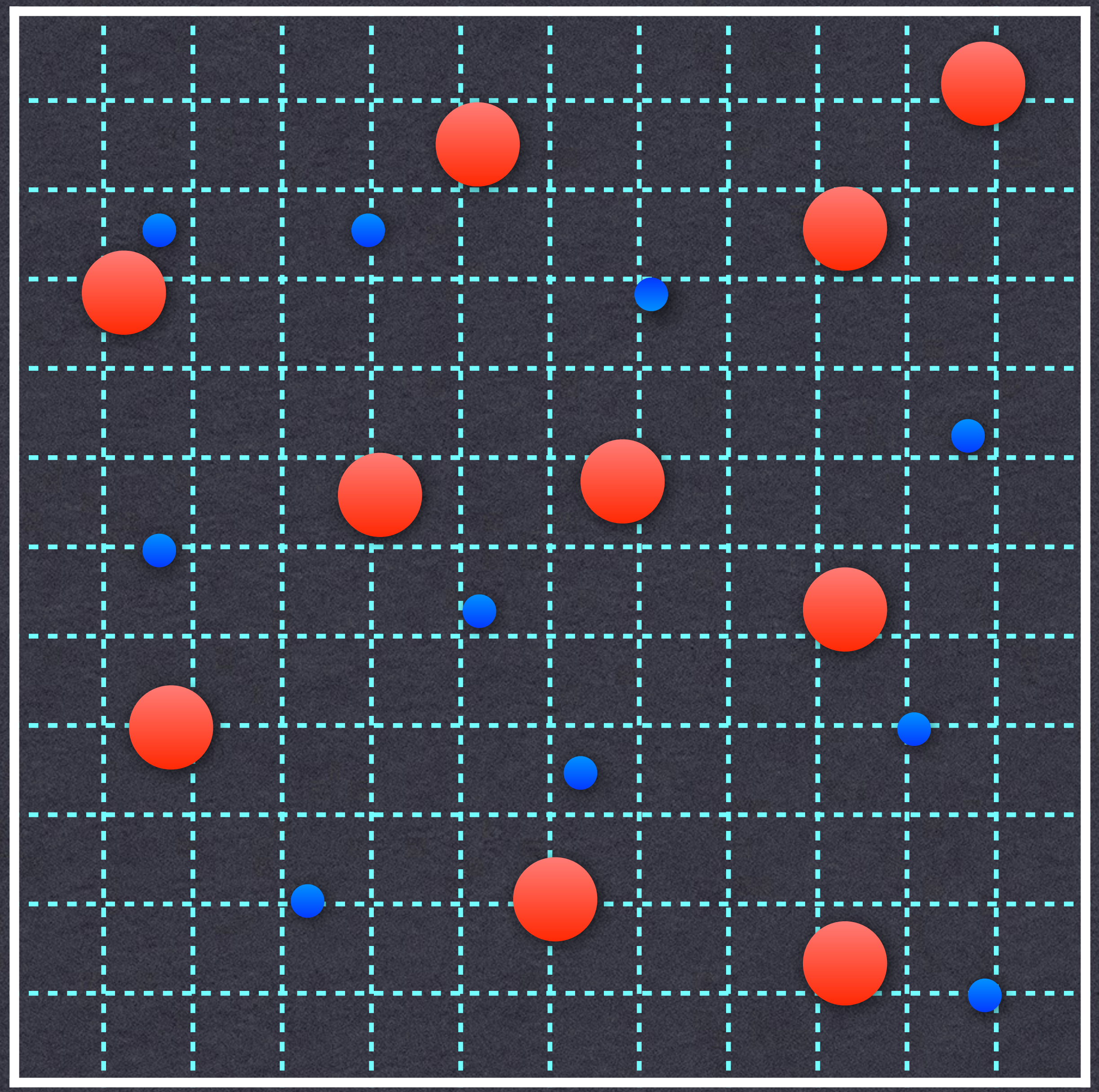
# Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback

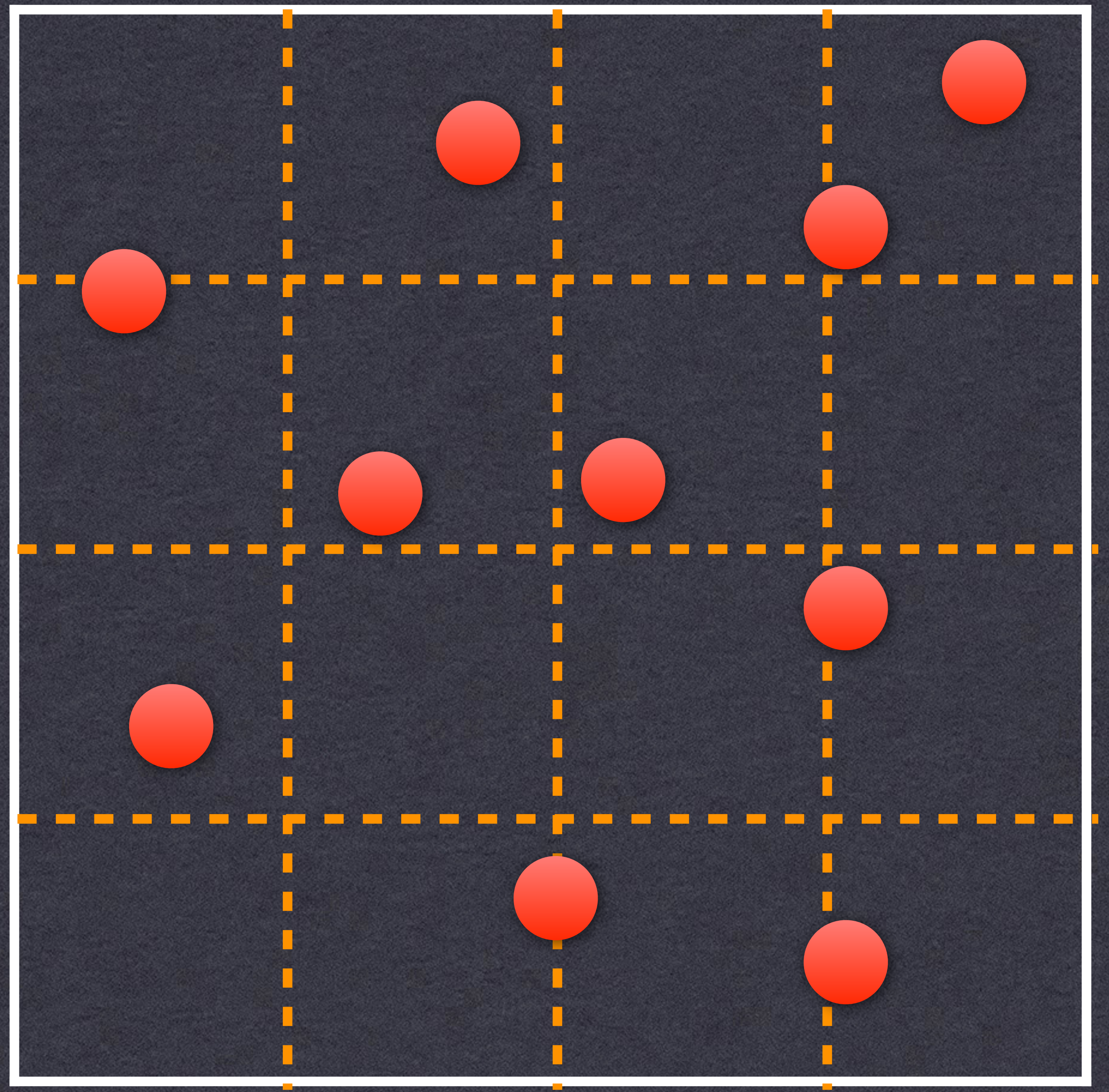


# Collisionless shocks from first principles

- **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!

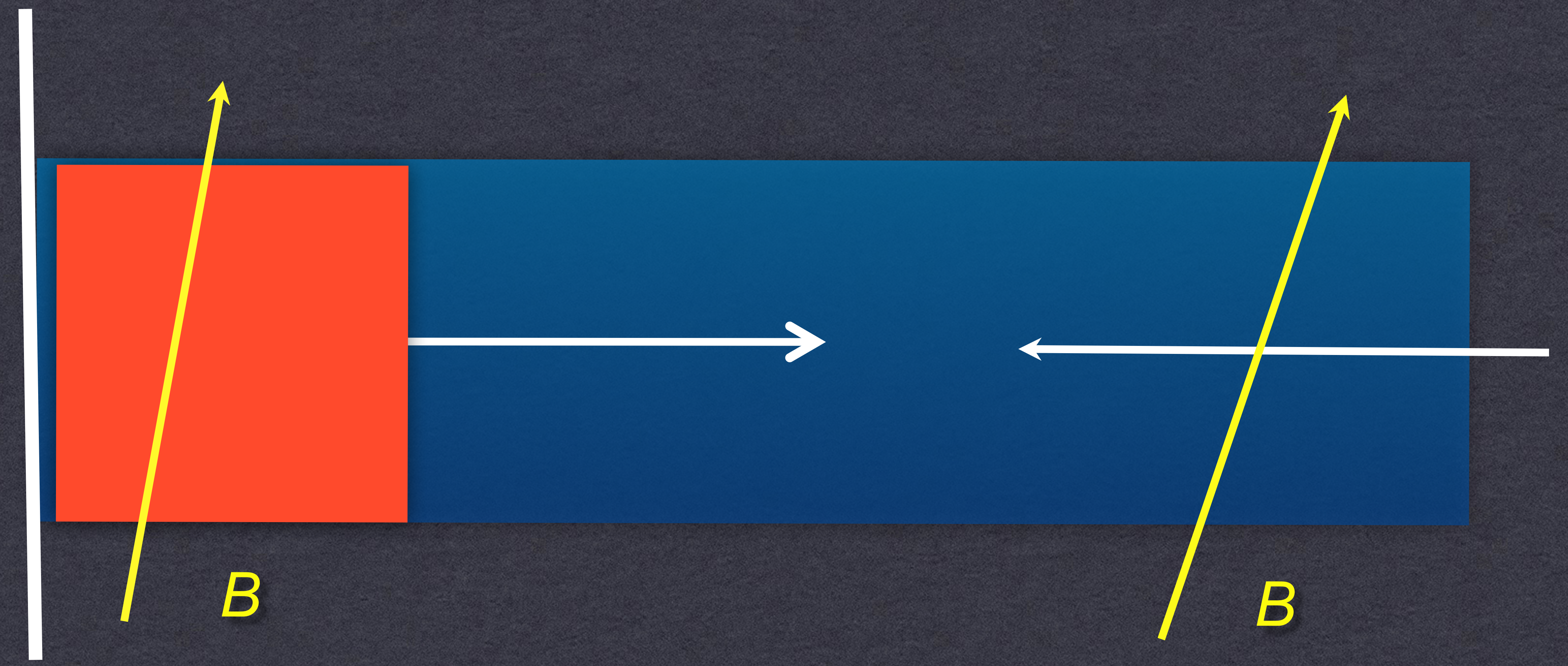


- **Hybrid approach**: dHybrid code
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, DC & Spitkovsky 2013, 2014)
  - massless electrons for more macroscopic time/length scales



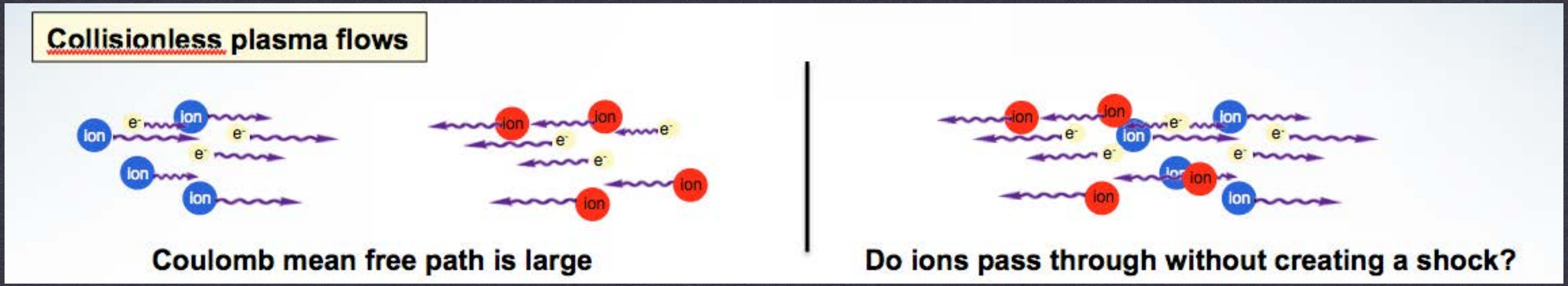
# Survey of Collisionless Shocks

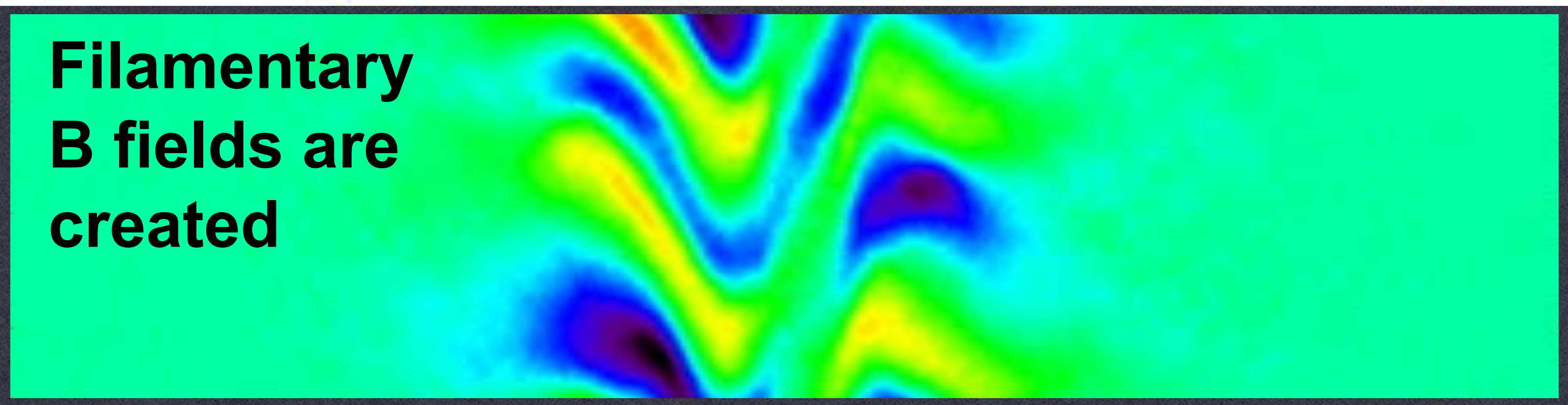
We simulated relativistic and nonrelativistic shocks for a range of upstream B fields and flow compositions, ignoring pre-existing turbulence.




Study: physics of shock transition, presence of particle acceleration (ions and electron), and field amplification by accelerated particles as a function of flow parameters, such as field strength (magnetization), field orientation (parallel vs perpendicular shocks), and shock speed and flow composition

# How collisionless shocks work

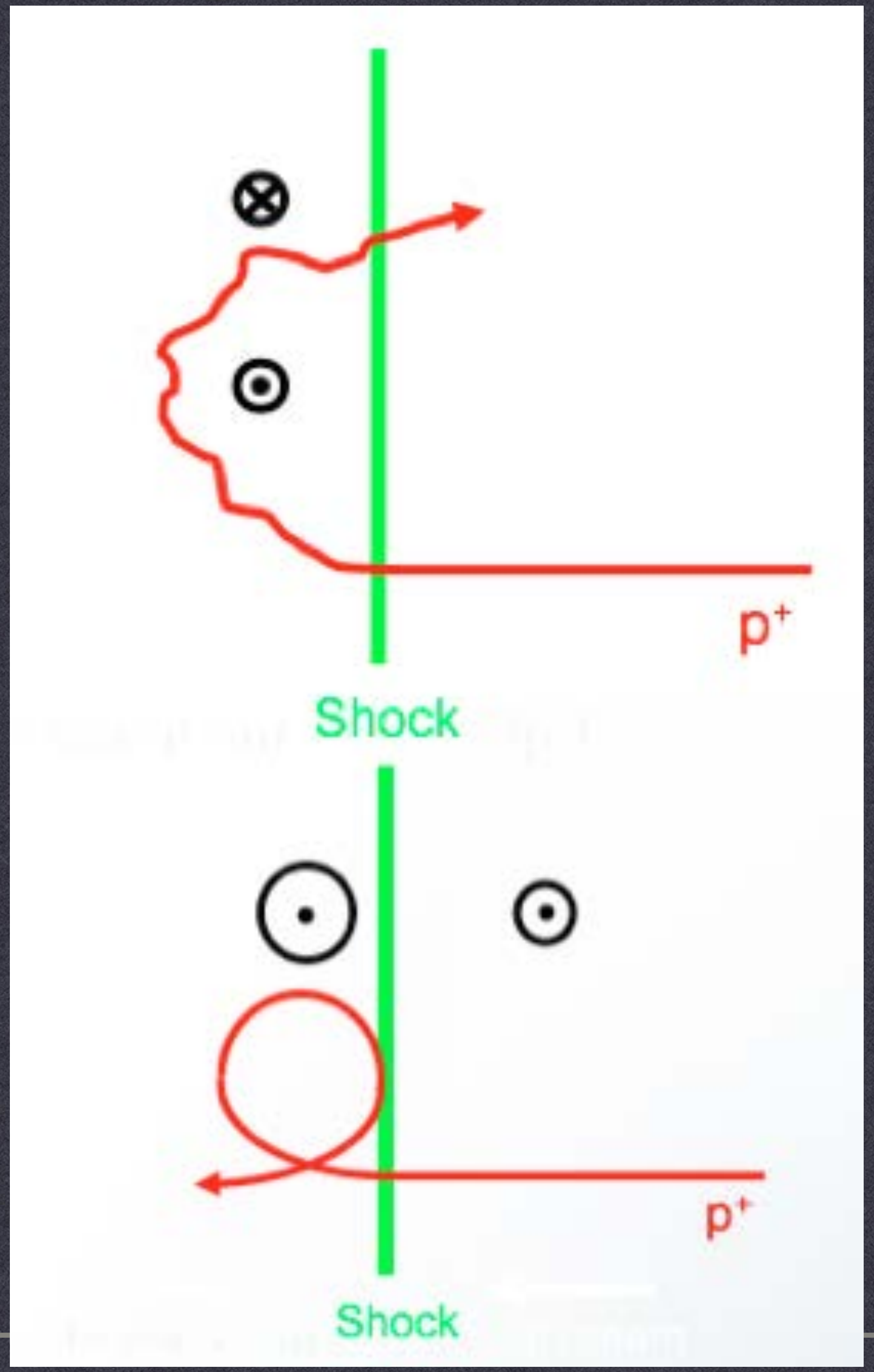



Two main mechanisms for creating collisionless shocks:

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

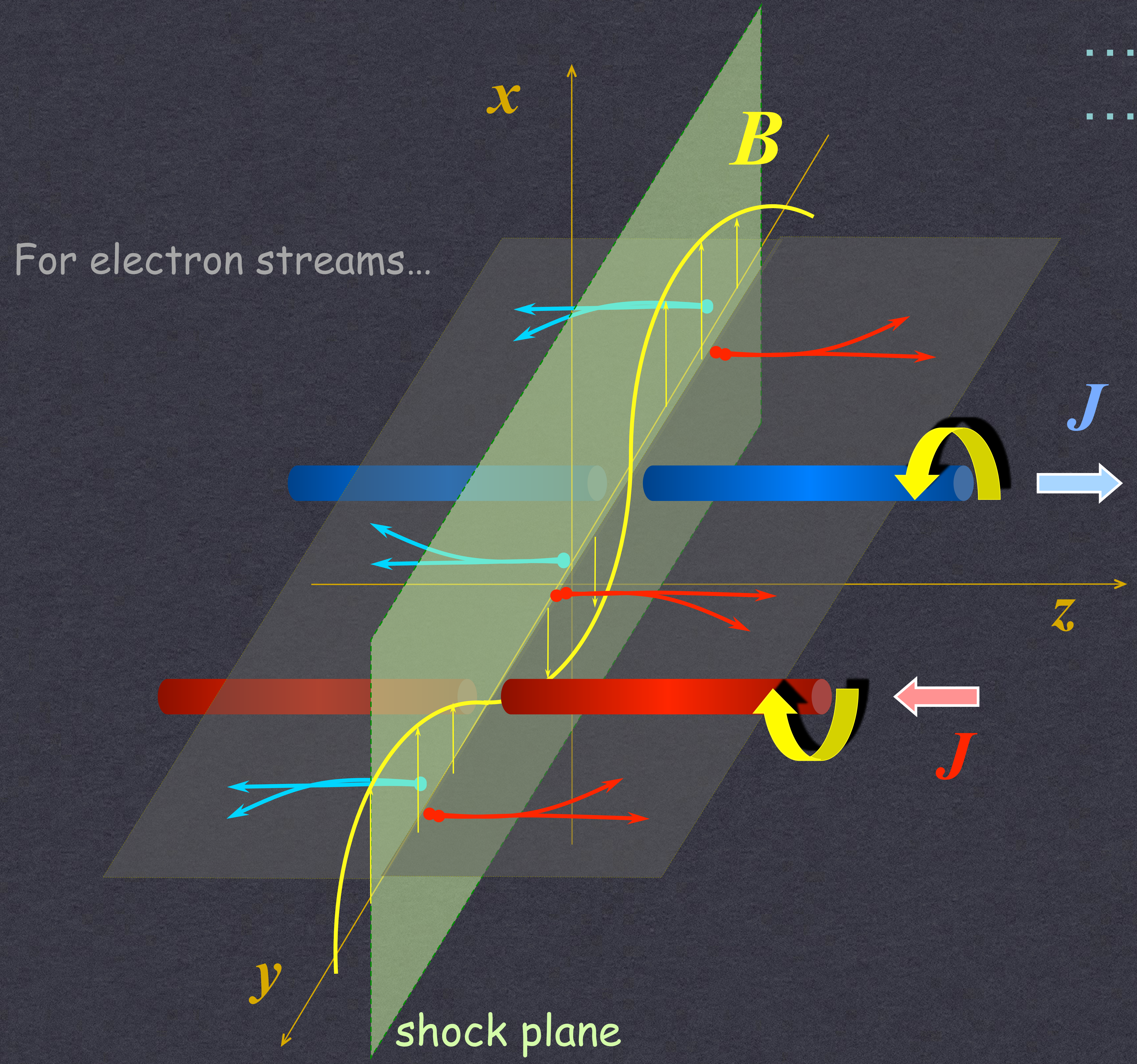
2) For large initial B field, particles are deflected by compressed pre-existing fields; Alfvenic Mach # < 100



# Weibel instability

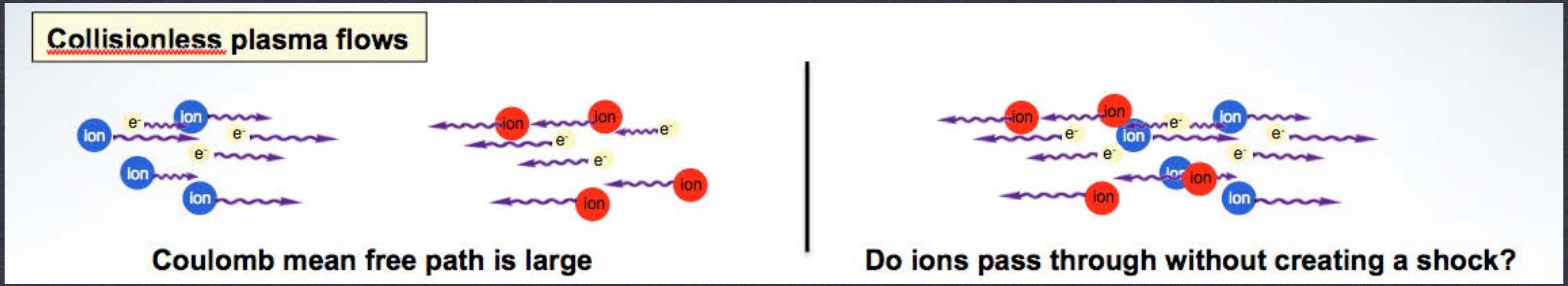
(Weibel 1956, Medvedev & Loeb, 1999, ApJ)

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




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

# How collisionless shocks work

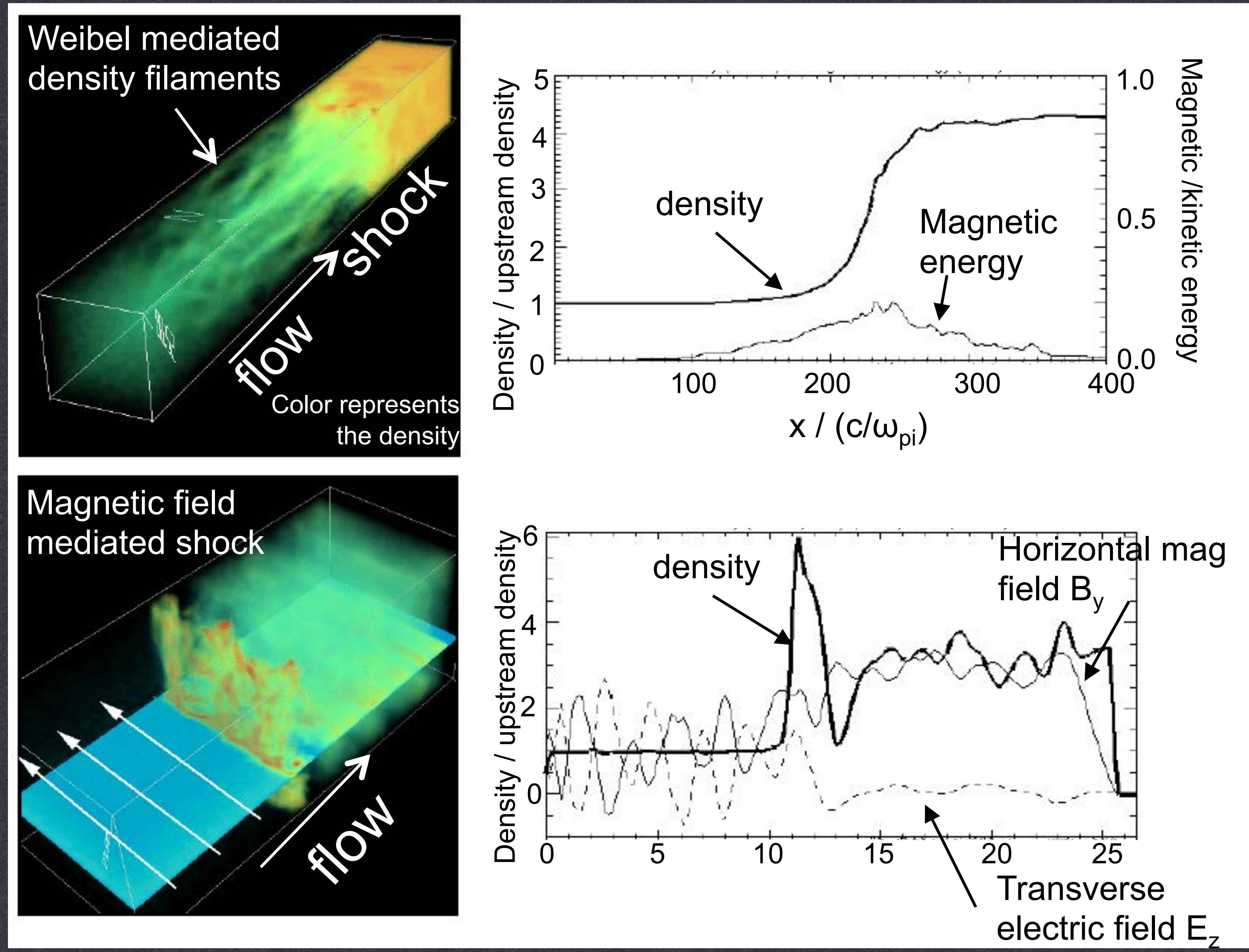



**Two main mechanisms for creating collisionless shocks:**

**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**

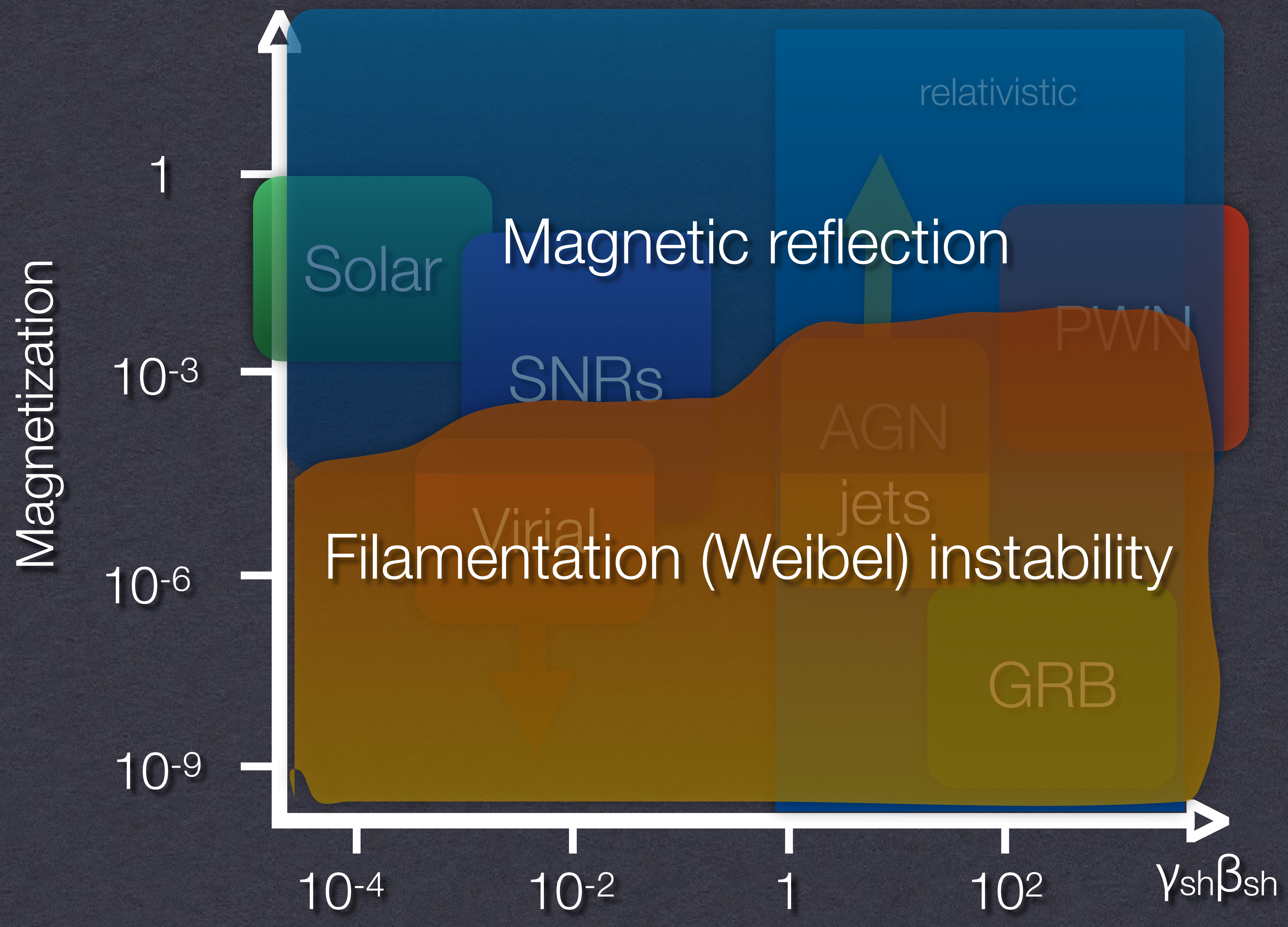
Spitkovsky (2005)

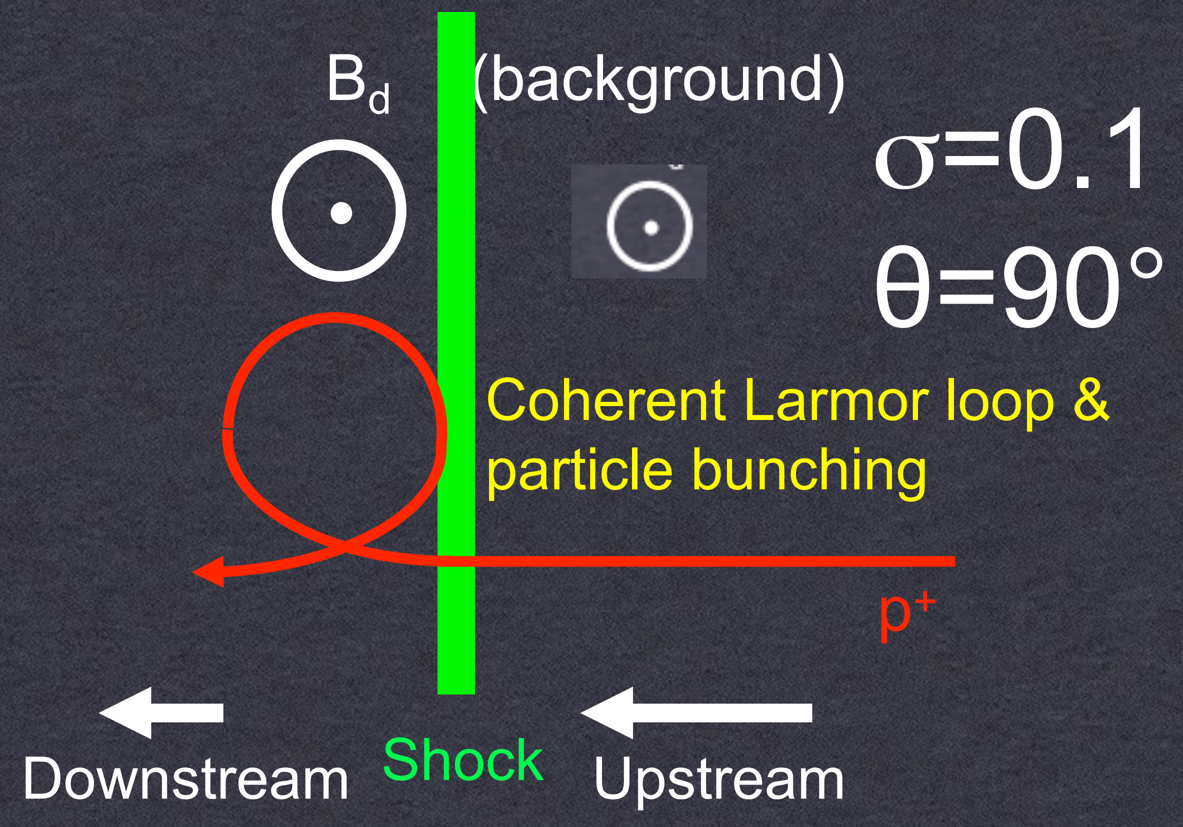


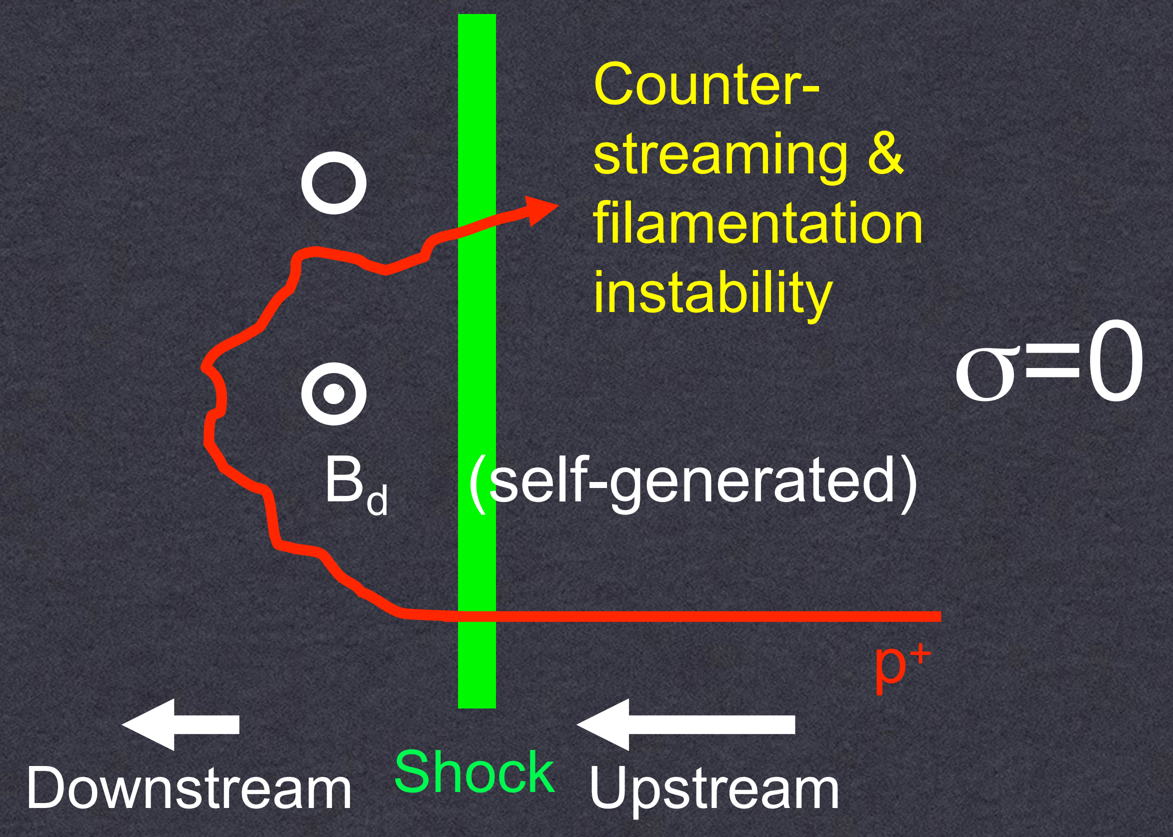
# Parameter Space of shocks

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

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

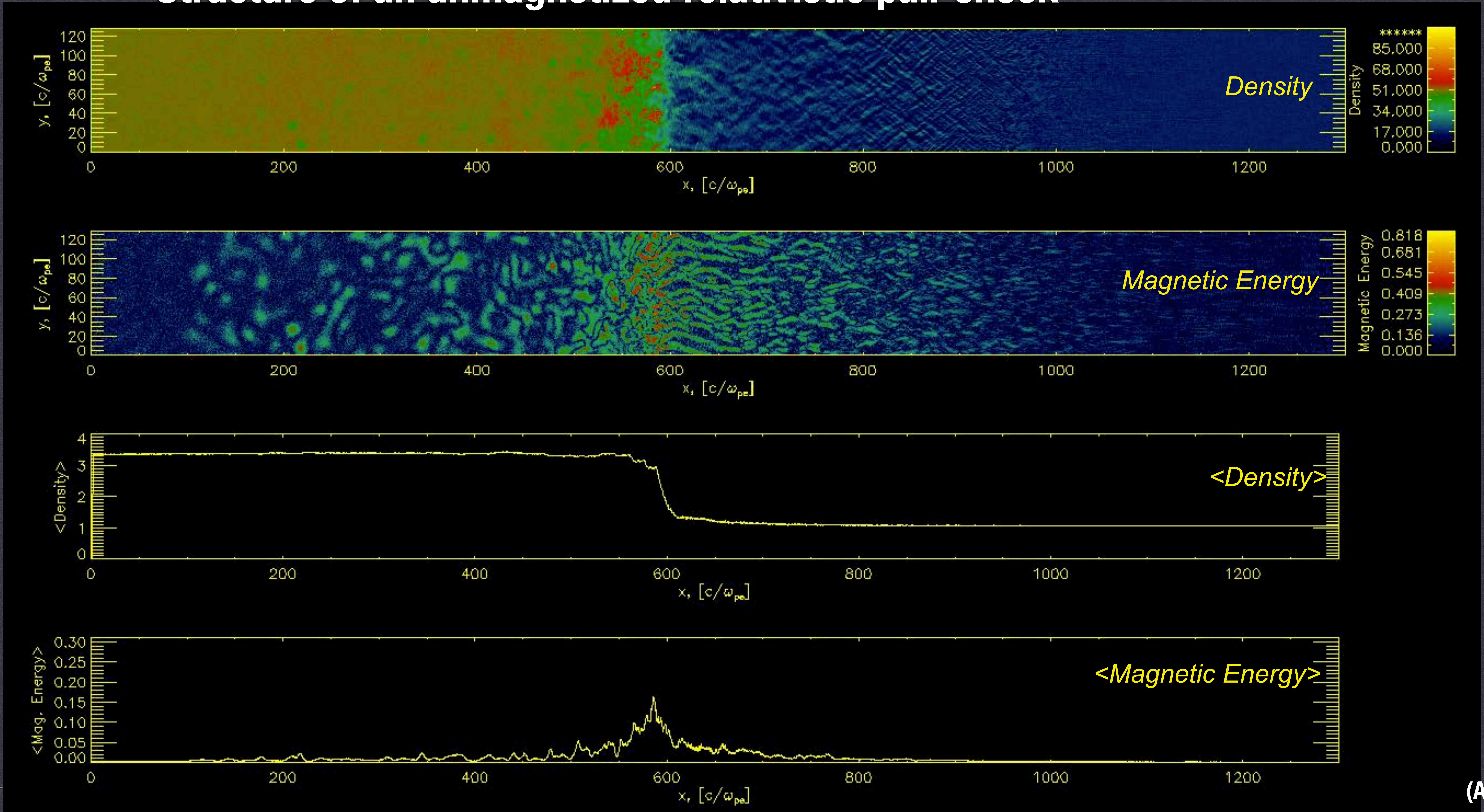


# Collisionless shocks

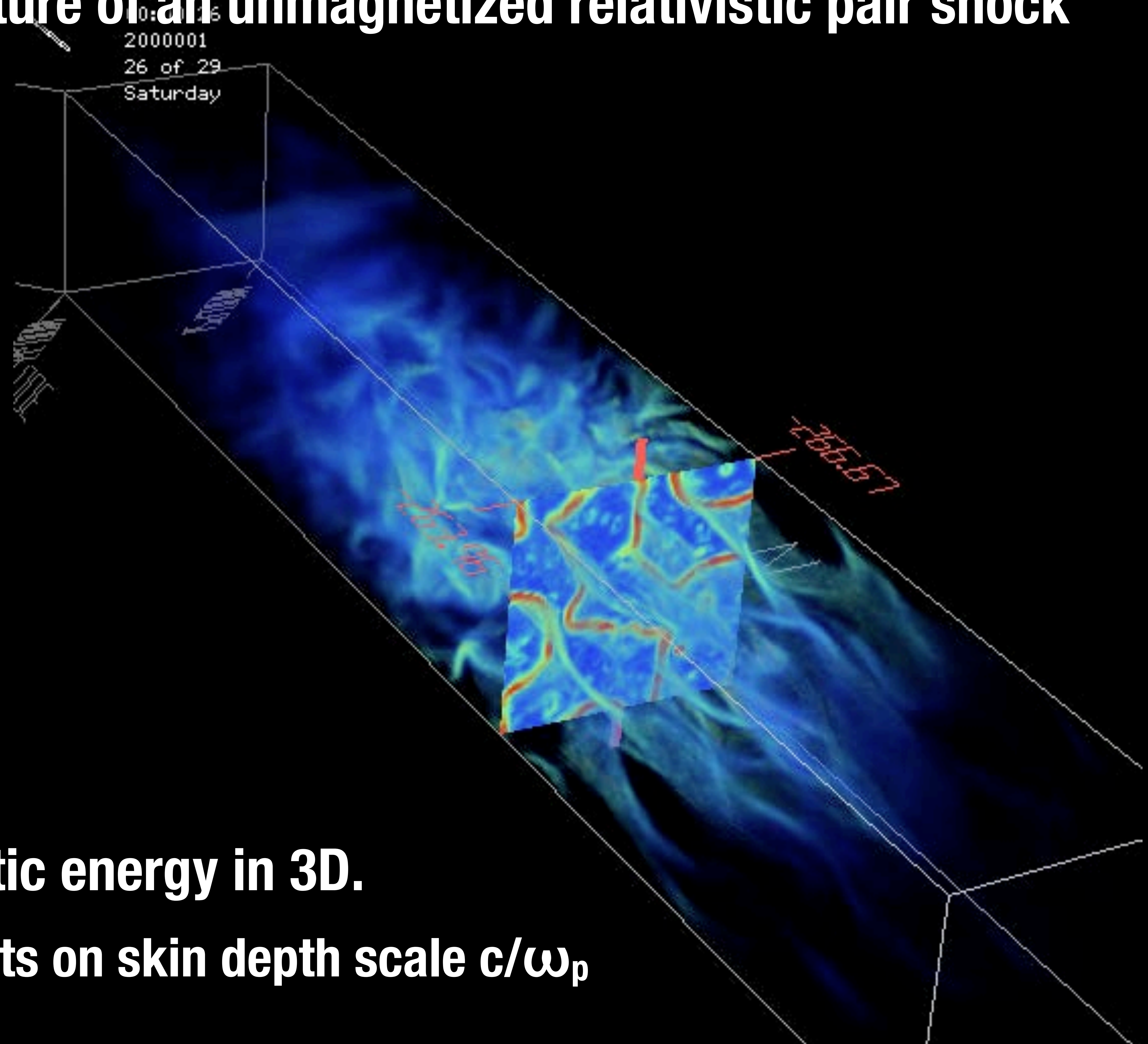
## Structure of an unmagnetized relativistic pair shock




(AS 2008)

# Collisionless shocks

## Structure of an unmagnetized relativistic pair shock

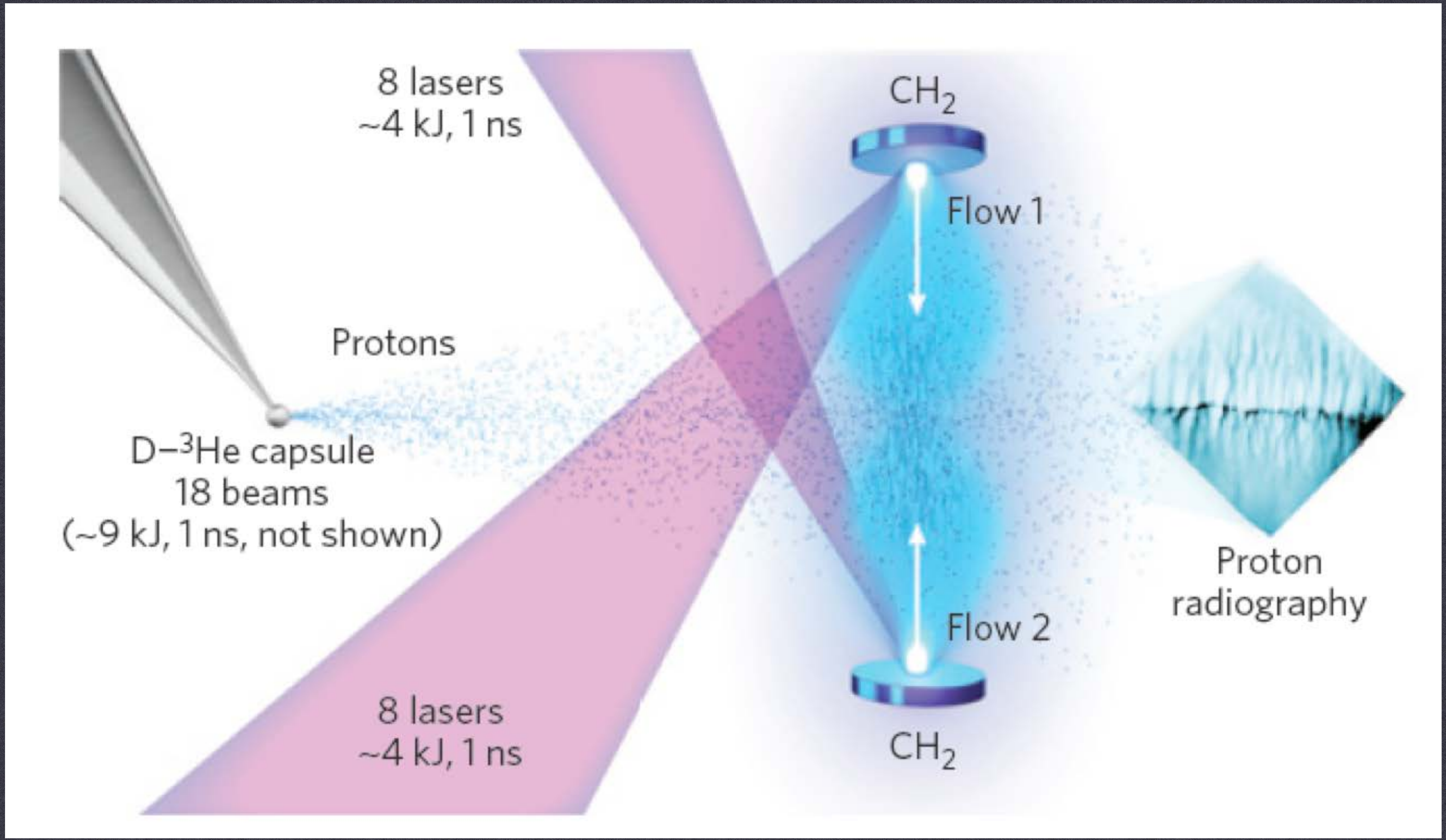



**Magnetic energy in 3D.**

**Filaments on skin depth scale $c/\omega_p$**

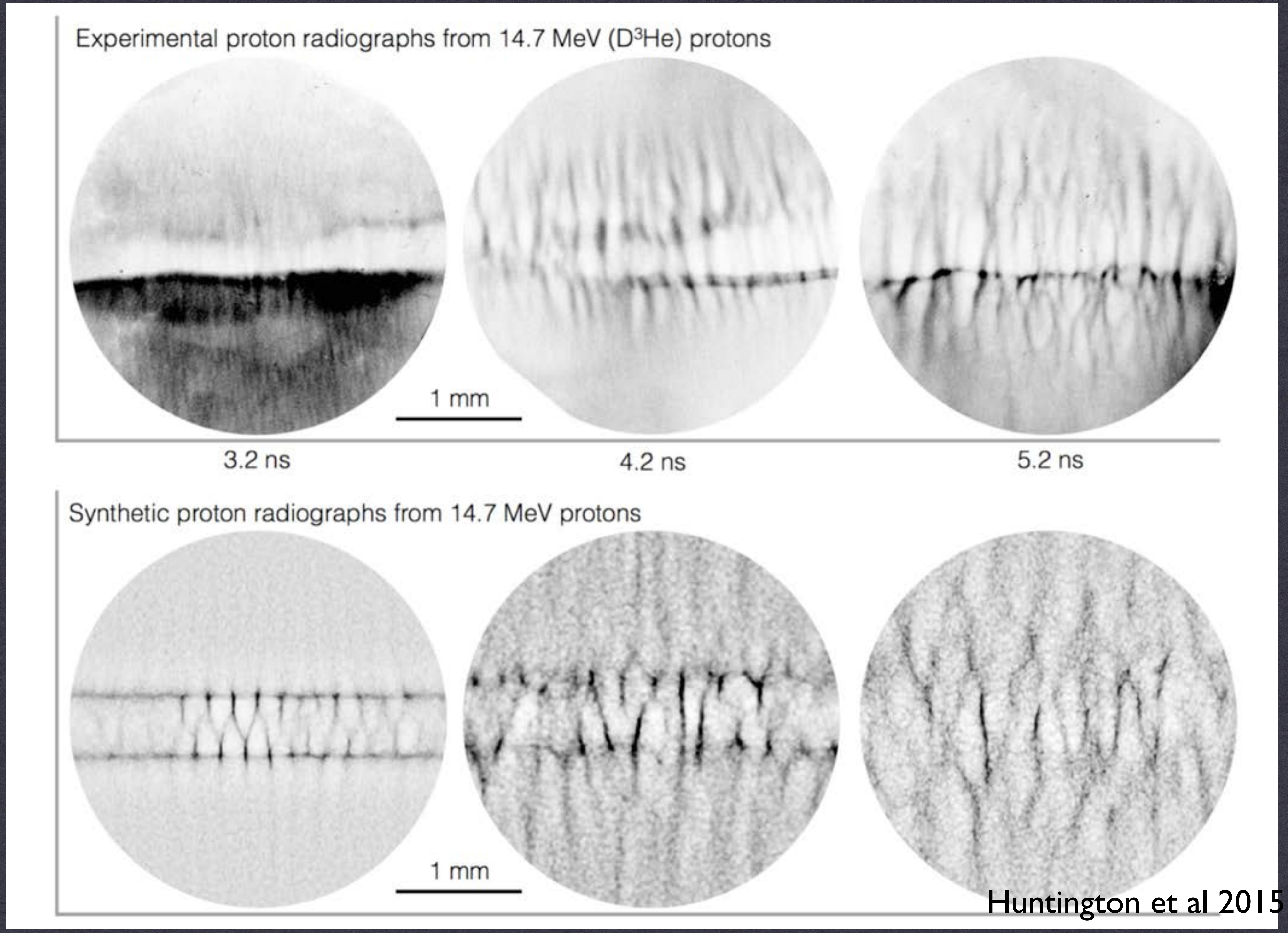
# Aside: does this actually happen?
# Shock formation experiments on Omega Laser

**ACSEL collaboration (Astrophysical Collisionless Shock Experiments with Lasers) Princeton, Livermore, Oxford, Ecole Politechnique, Osaka**

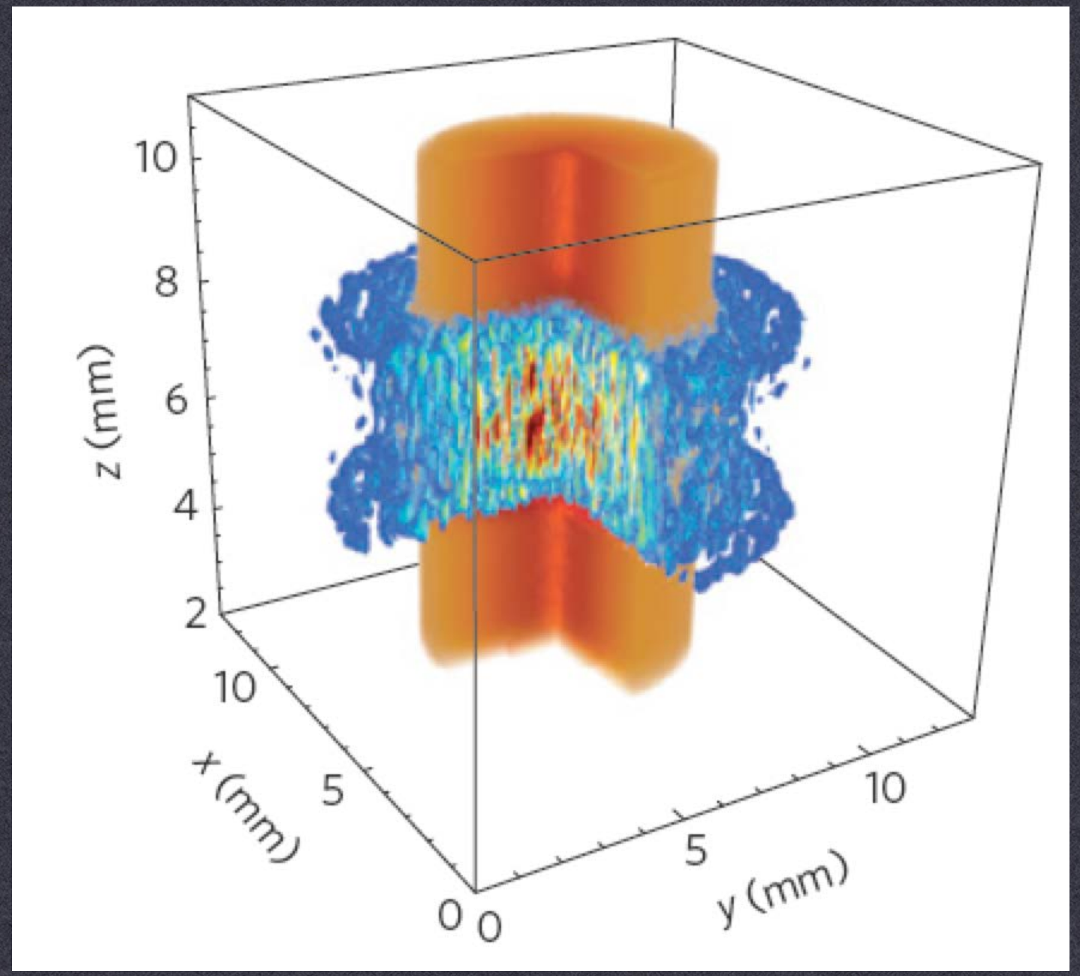



**Huntington et al 2015, Nature Physics**

# Proton radiography of colliding flows




Experiment

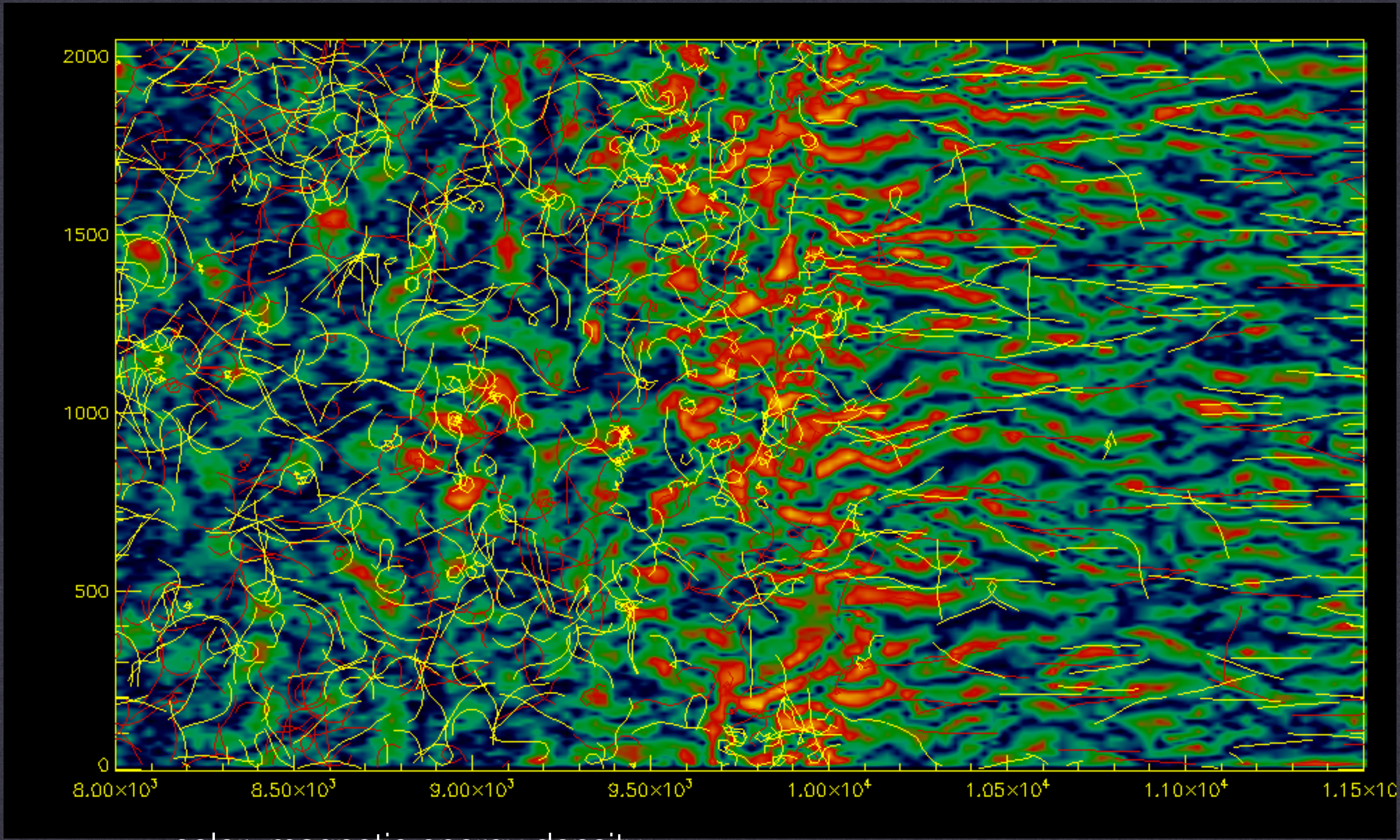



Simulation

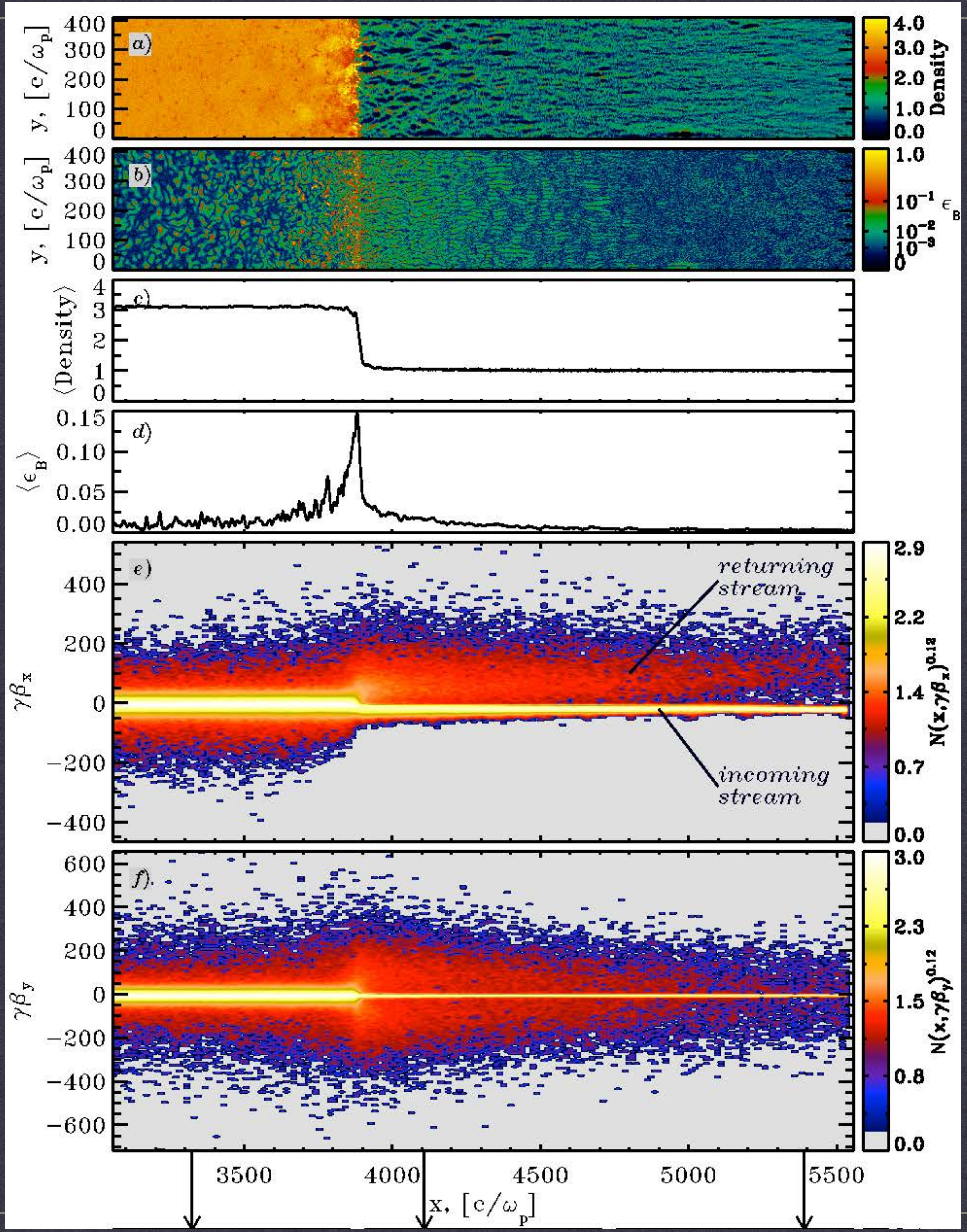
**Weibel filamentation is observed in the lab!**
**Current work: magnetized shocks**

**cf: Fox et al 2014**

# Unmagnetized pair shock: particle trajectories




color: magnetic energy density




*Density*

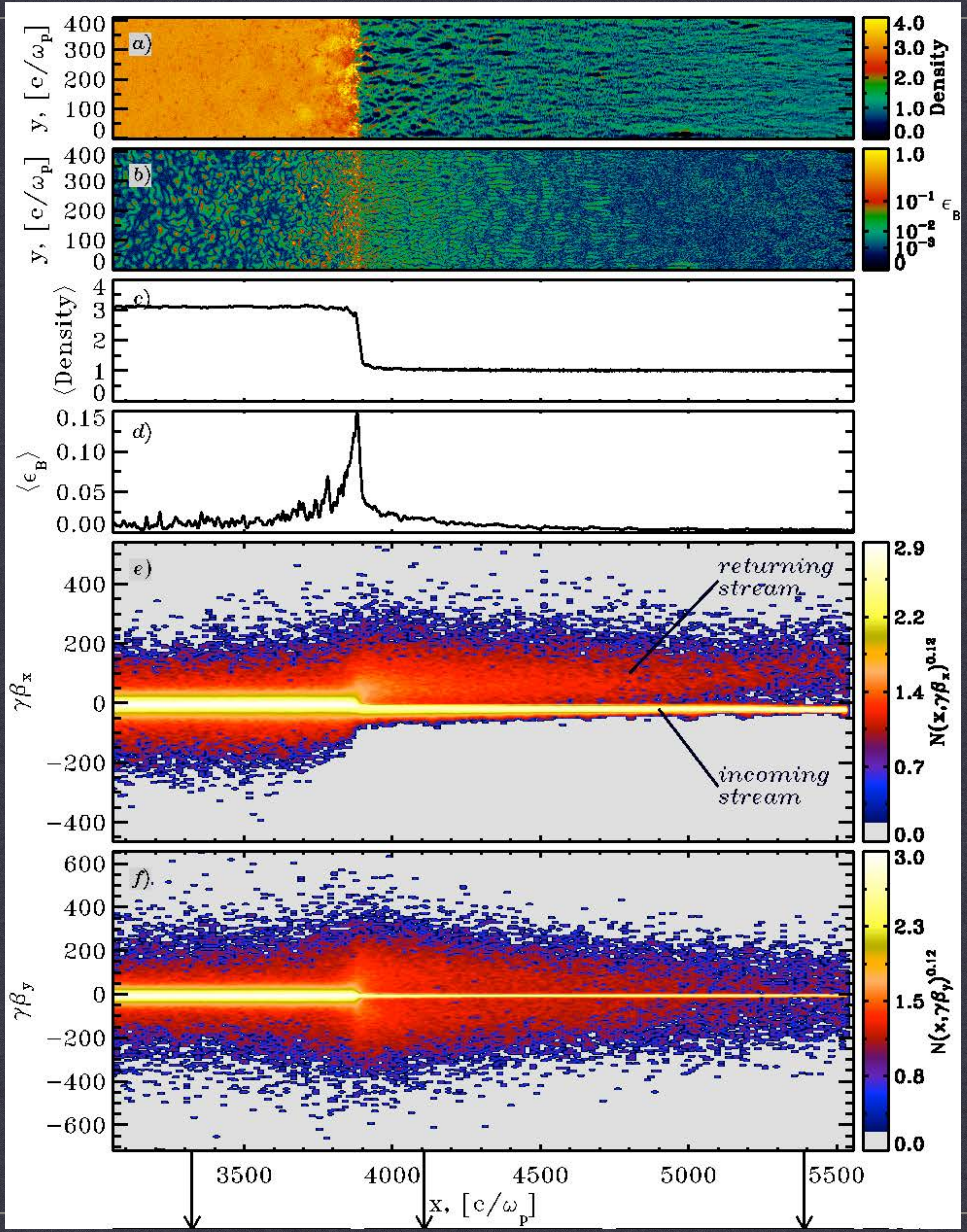
Shock formation from counterstreaming

shock is driven by returning particle precursor

*x- px momentum space*

*x- py momentum space*

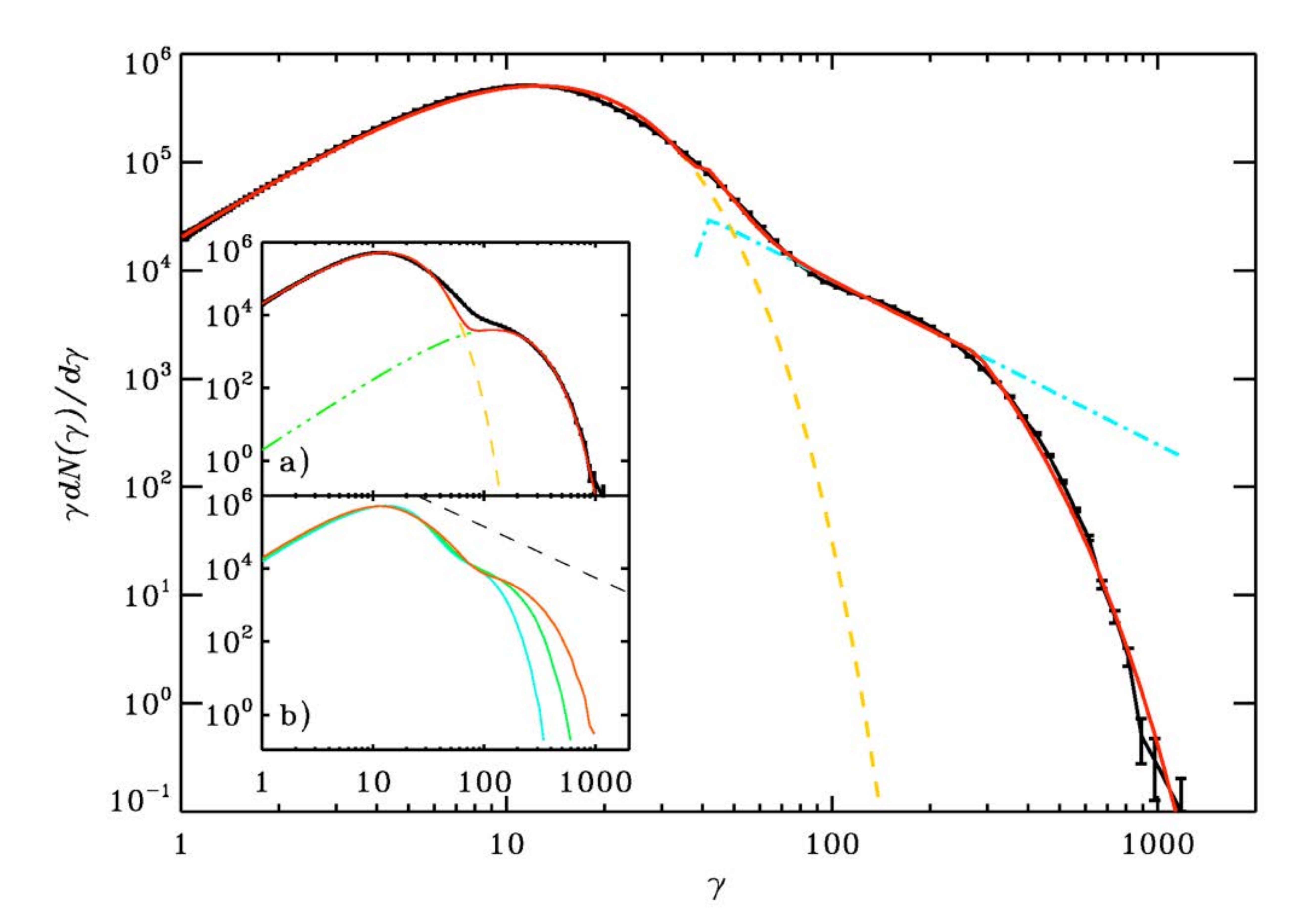
*Shock structure for $\sigma$=0 (AS '08)*



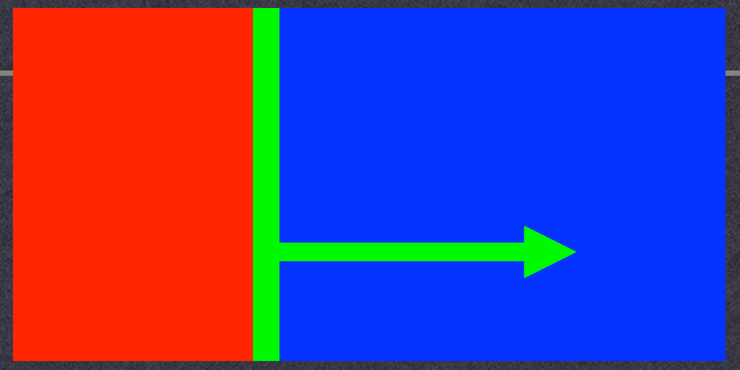
## downstream spectrum: development of nonthermal tail

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

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

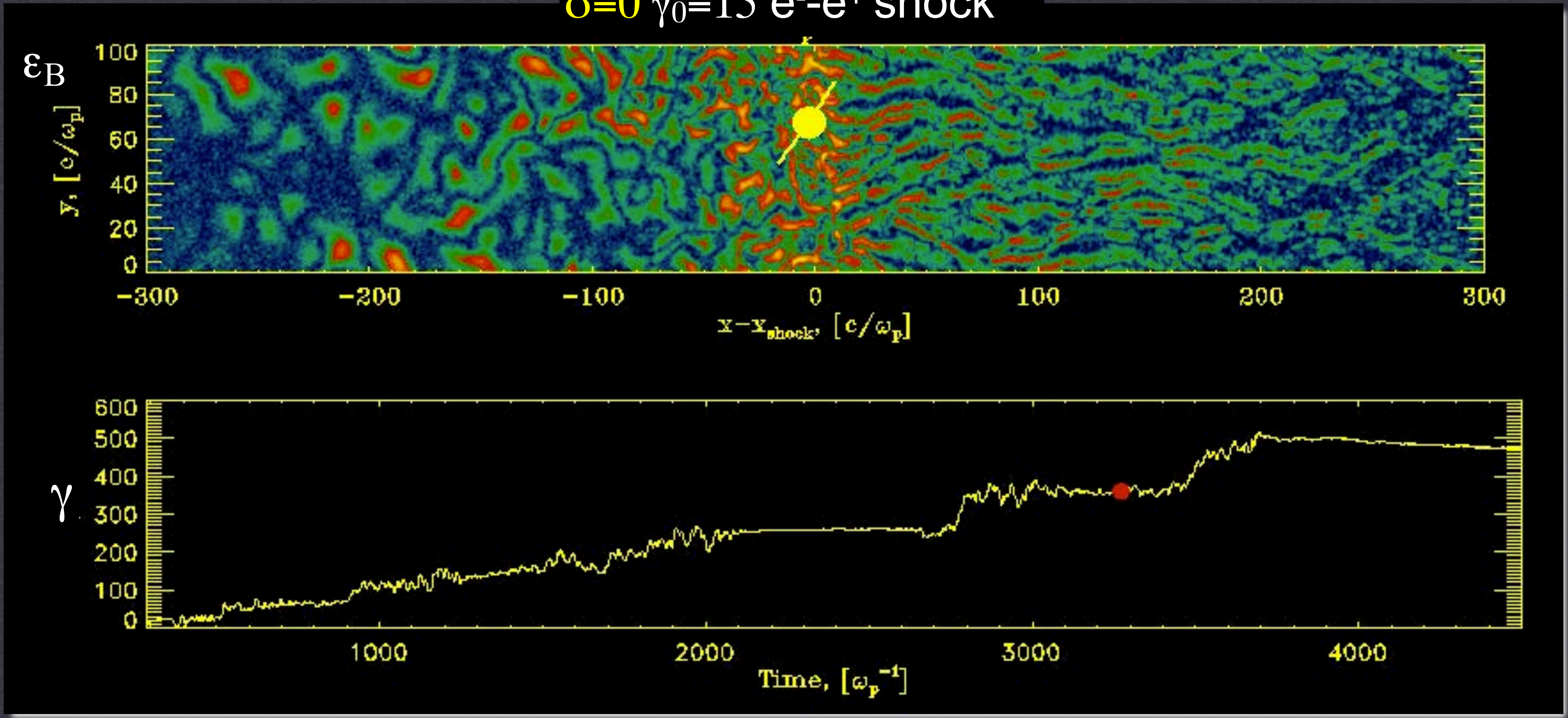


# Low-$\sigma$ shocks do accelerate!



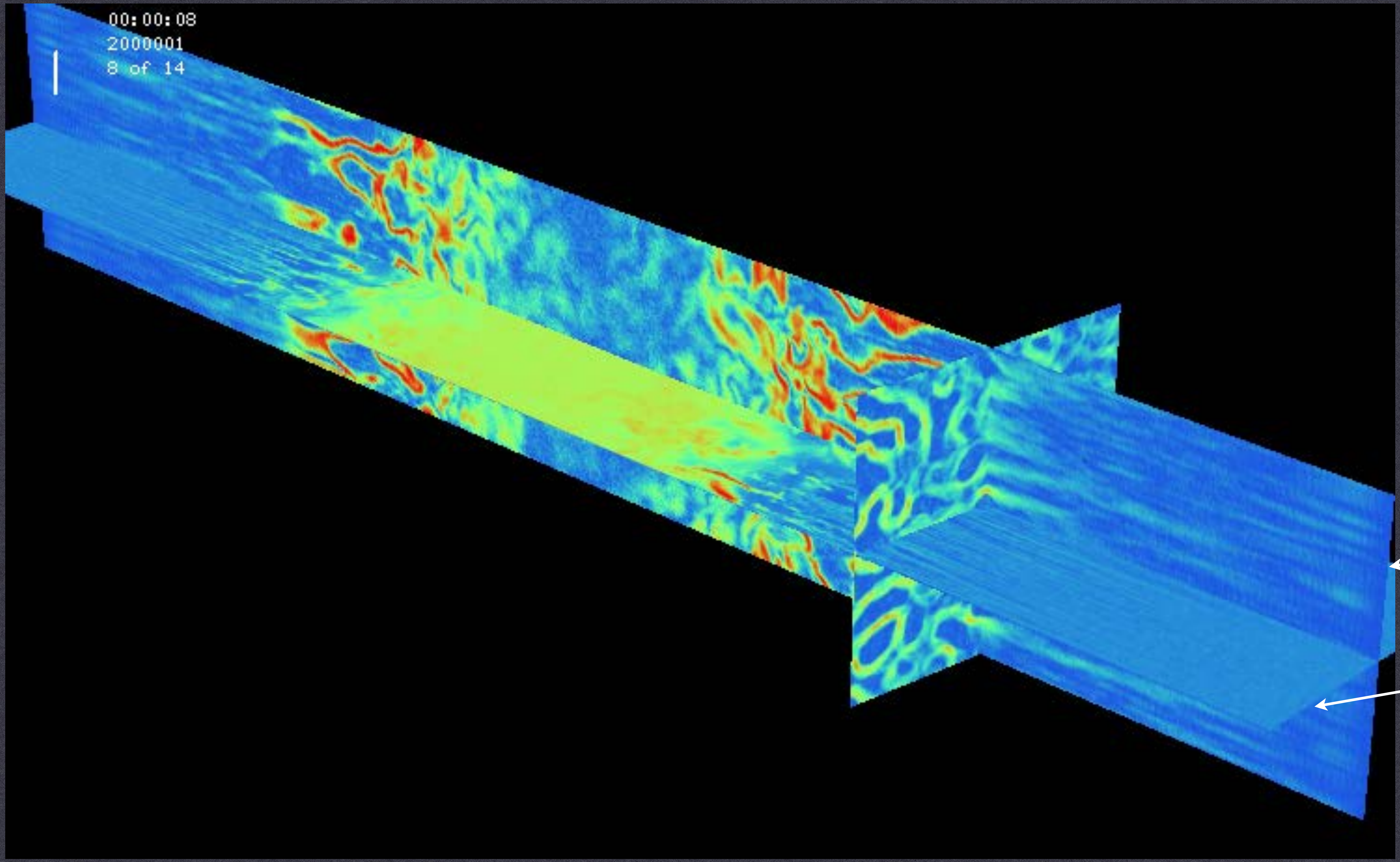
Fermi process from first principles: particles scatter off magnetic turbulence produced self-consistently as part of the shock evolution

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



# Transition between magnetized and unmagnetized shocks:

$\sigma=0$

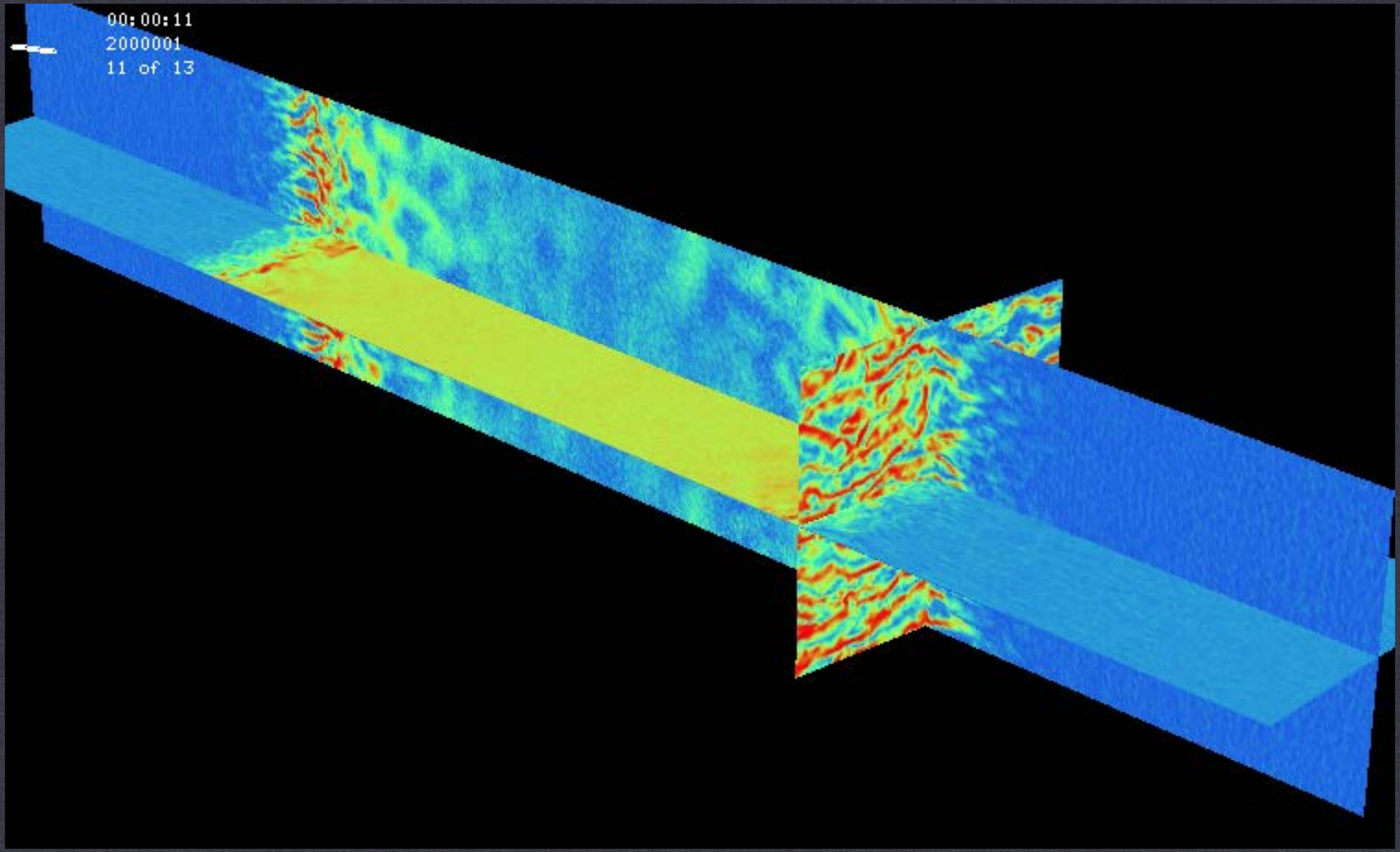



Magnetic energy

Density

# Transition between magnetized and unmagnetized shocks:

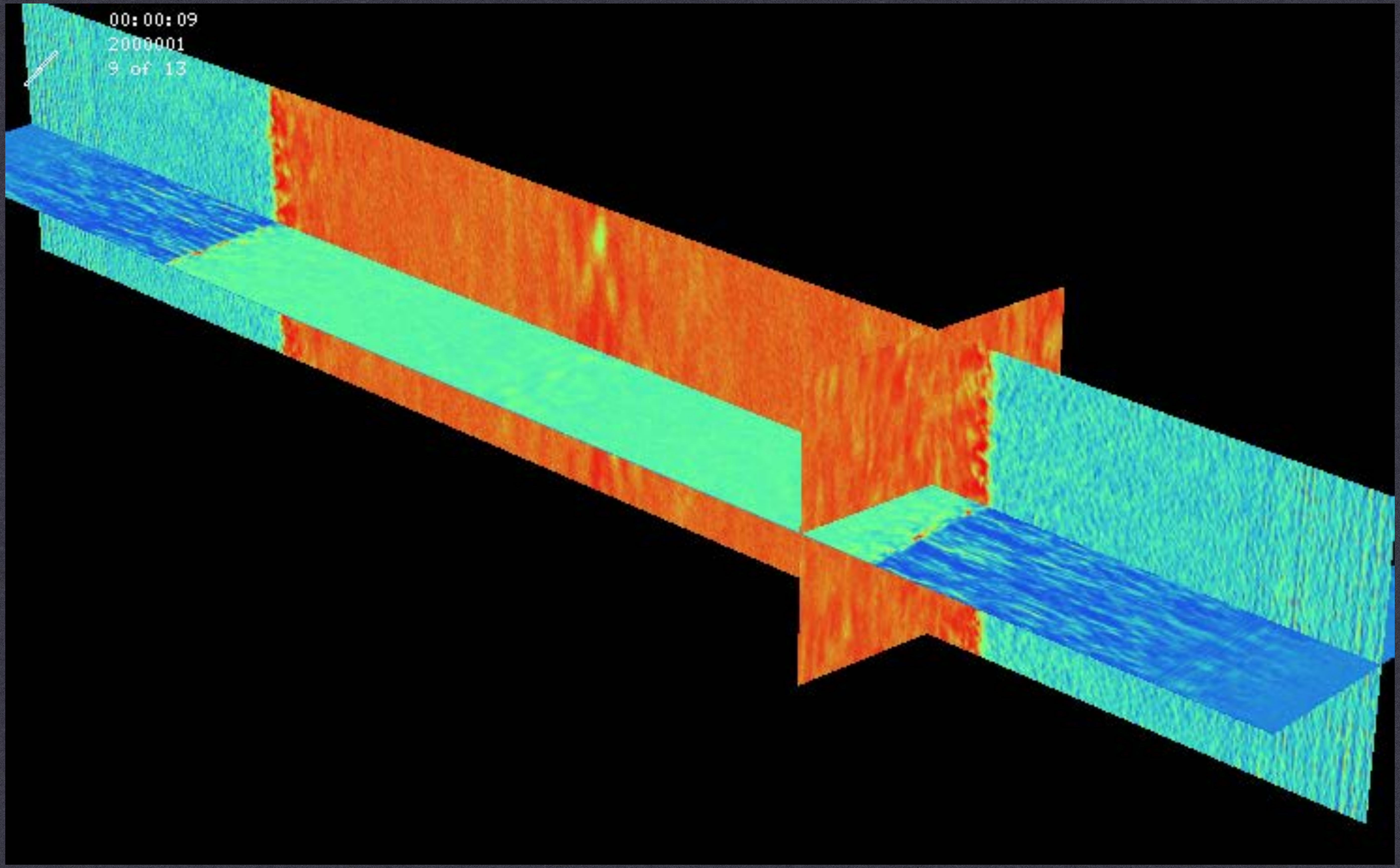
$\sigma=10^{-3}$




B field

# Transition between magnetized and unmagnetized shocks:

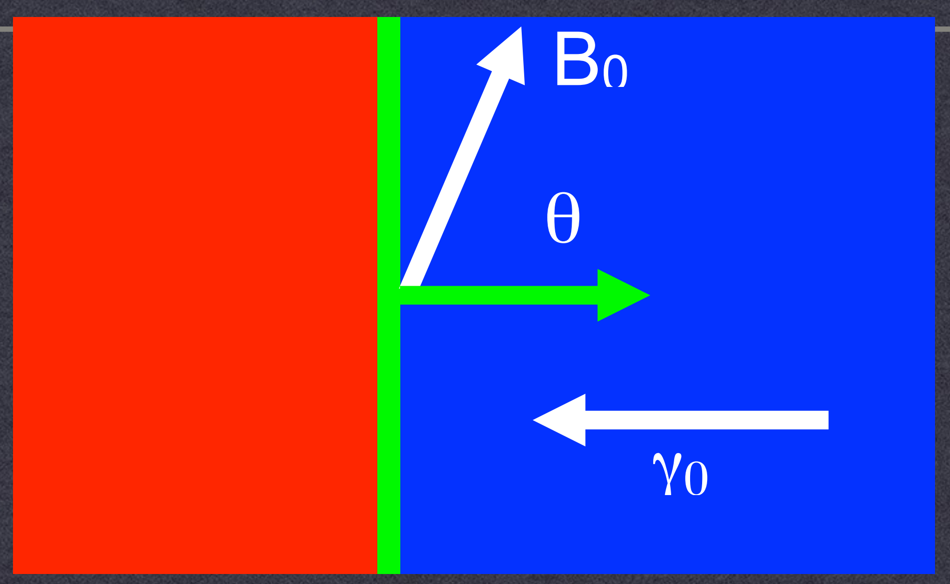
$\sigma=10^{-1}$




B field

Acceleration: $\sigma<10^{-3}$ produce power laws, $\sigma>10^{-3}$ just thermalize

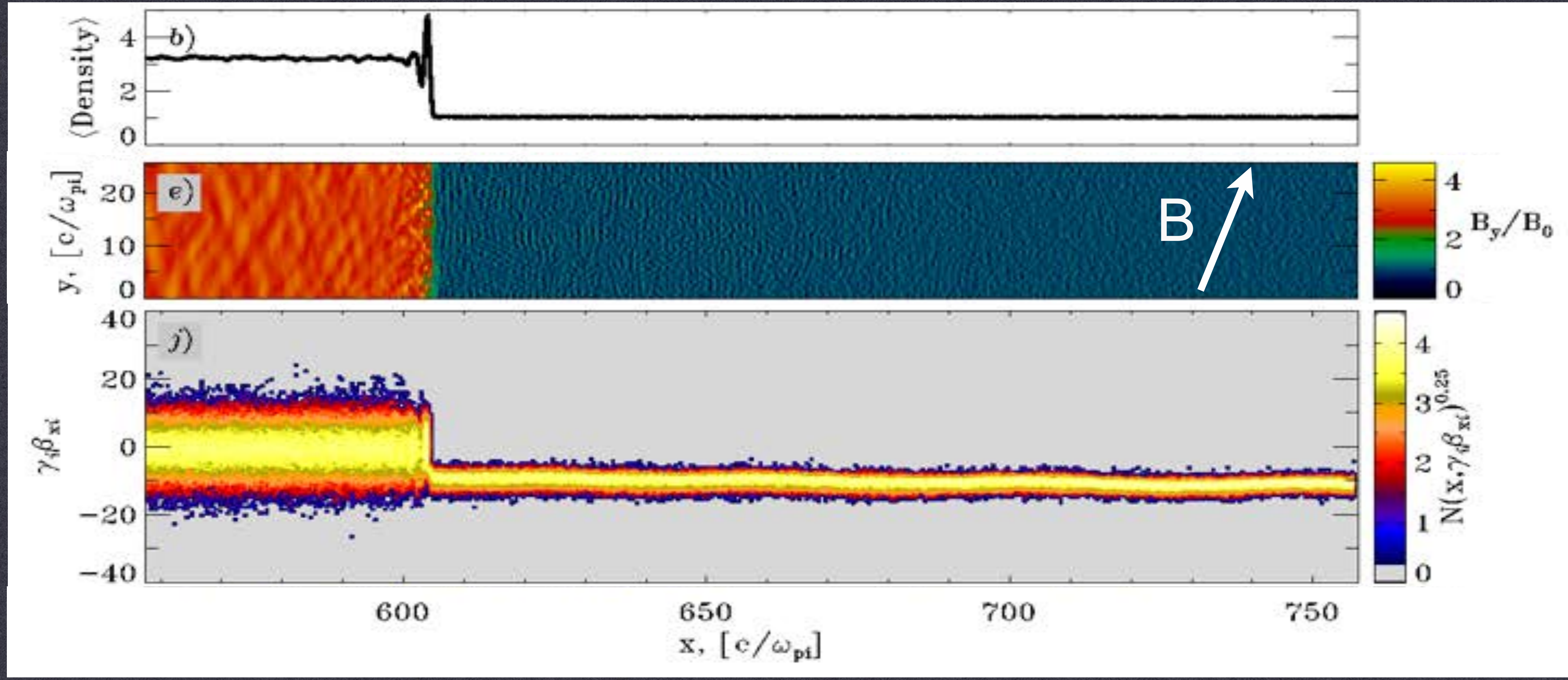
# Perpendicular vs parallel shocks




- Quasi-perpendicular shocks: mediated by magnetic reflection

<Density>

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



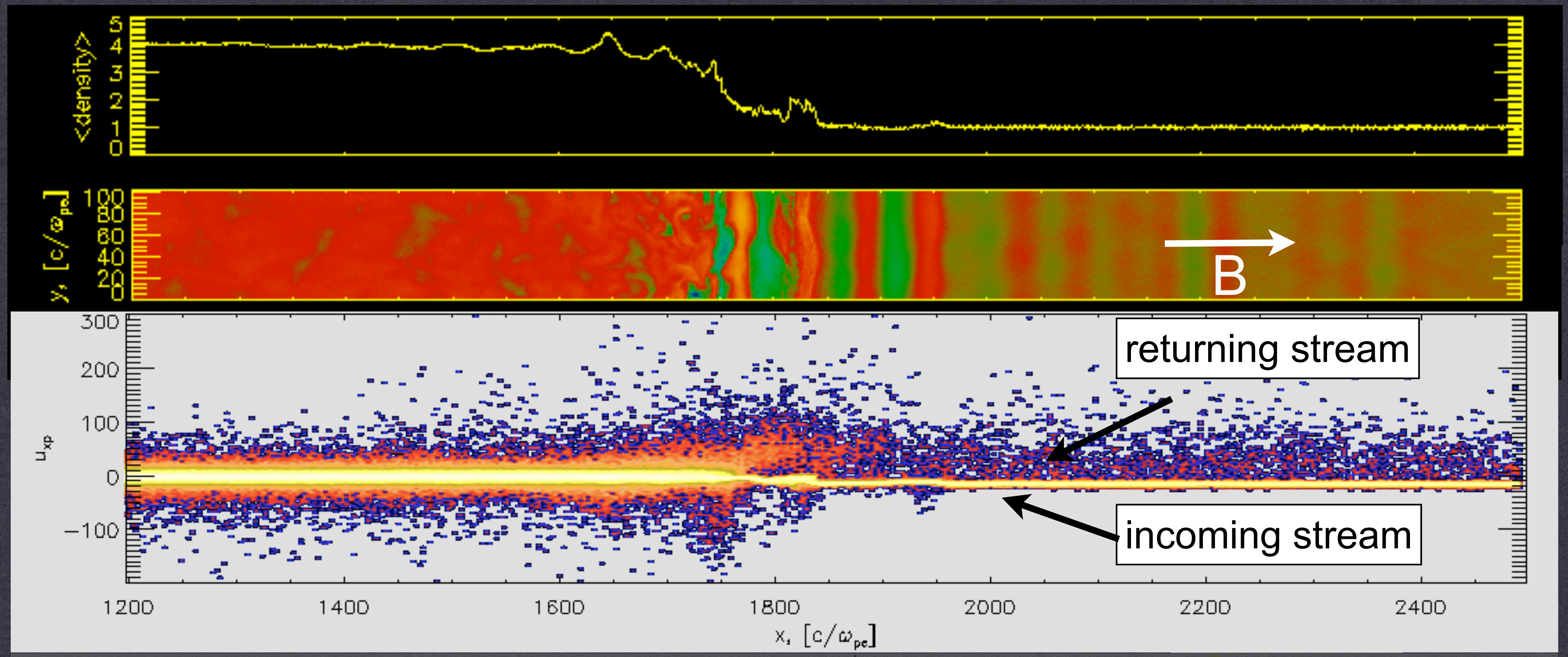

$B_y$

$\gamma\beta_x$

(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)

# SHOCK ACCELERATION

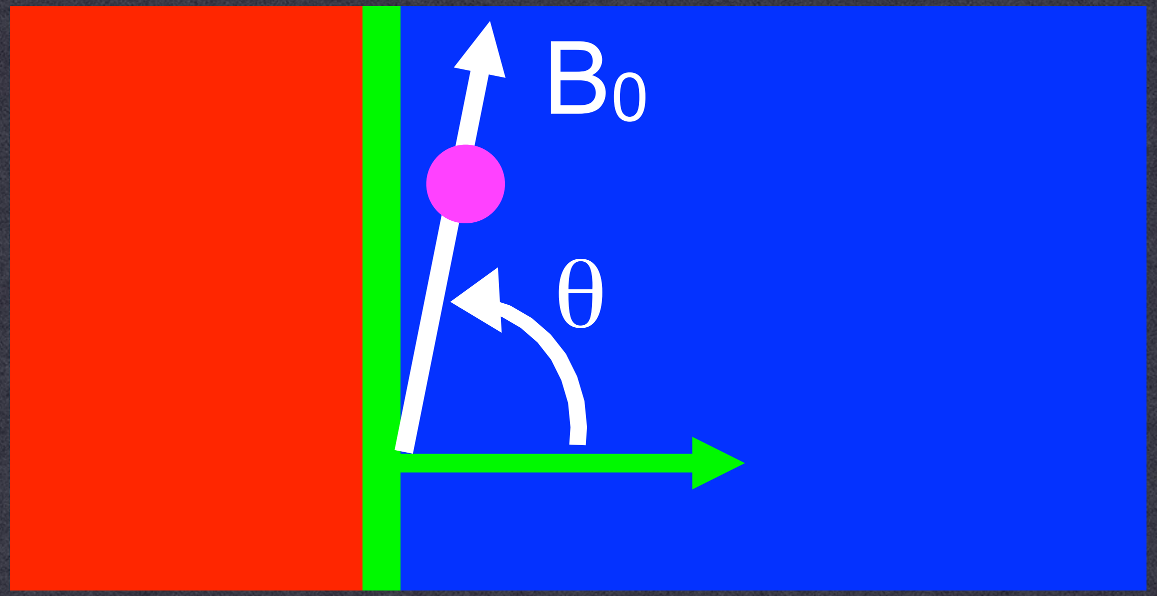
**Two crucial ingredients:**

**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)**

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

# Superluminal vs subluminal shocks



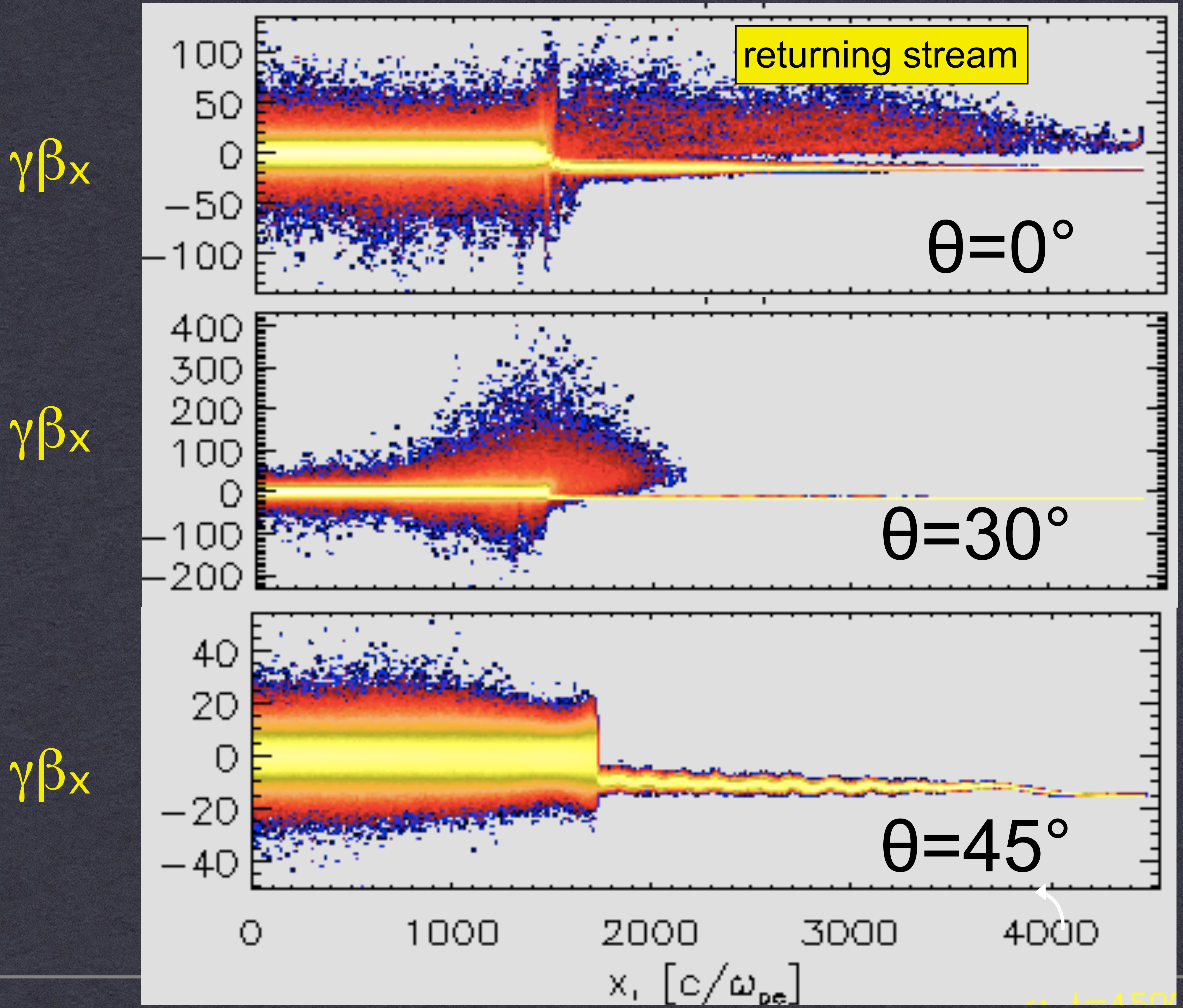

$\sigma$ is large → particles slide along field lines

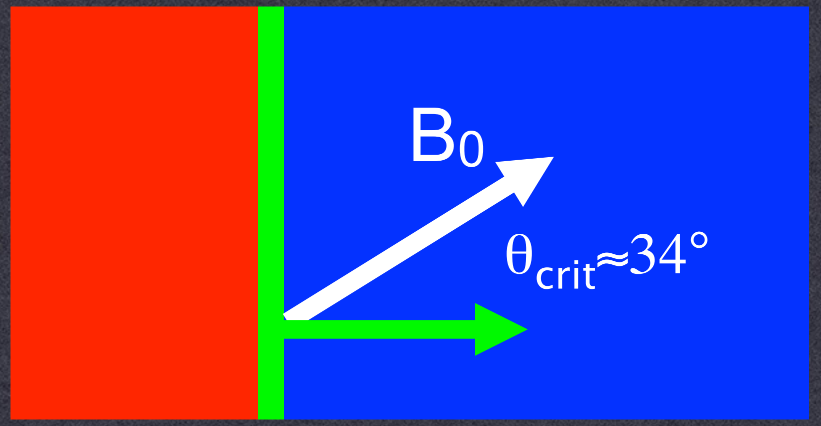
$\theta$ is large → particles cannot outrun the shock

unless v>c ("superluminal" shock)

⇒ no returning particles in superluminal shocks

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




Subluminal / superluminal boundary at $\theta\sim 34°$

→ Fermi acceleration should be suppressed in superluminal shocks!

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

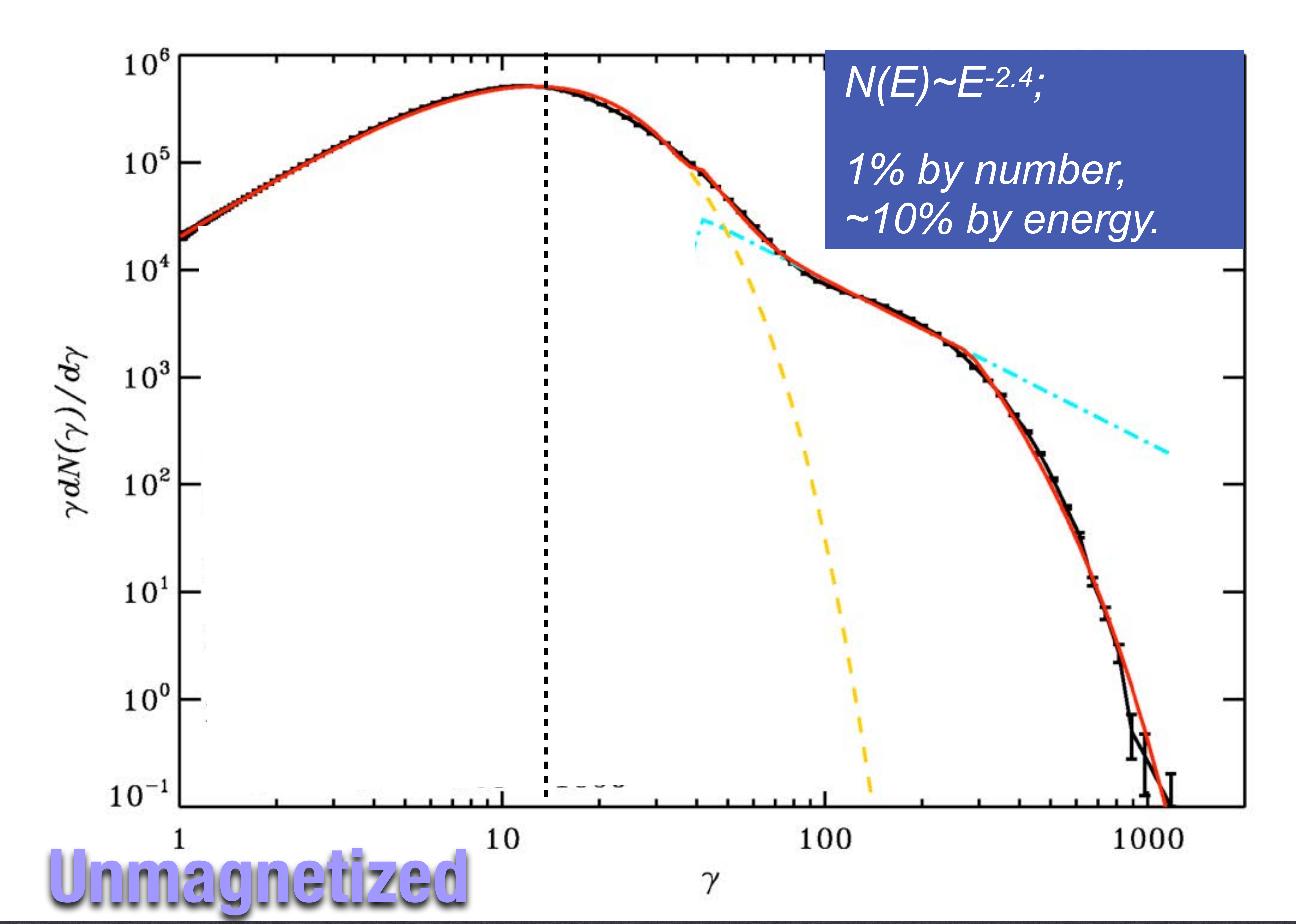
$\theta<\theta_{crit}\approx 34°$ (downstream frame)

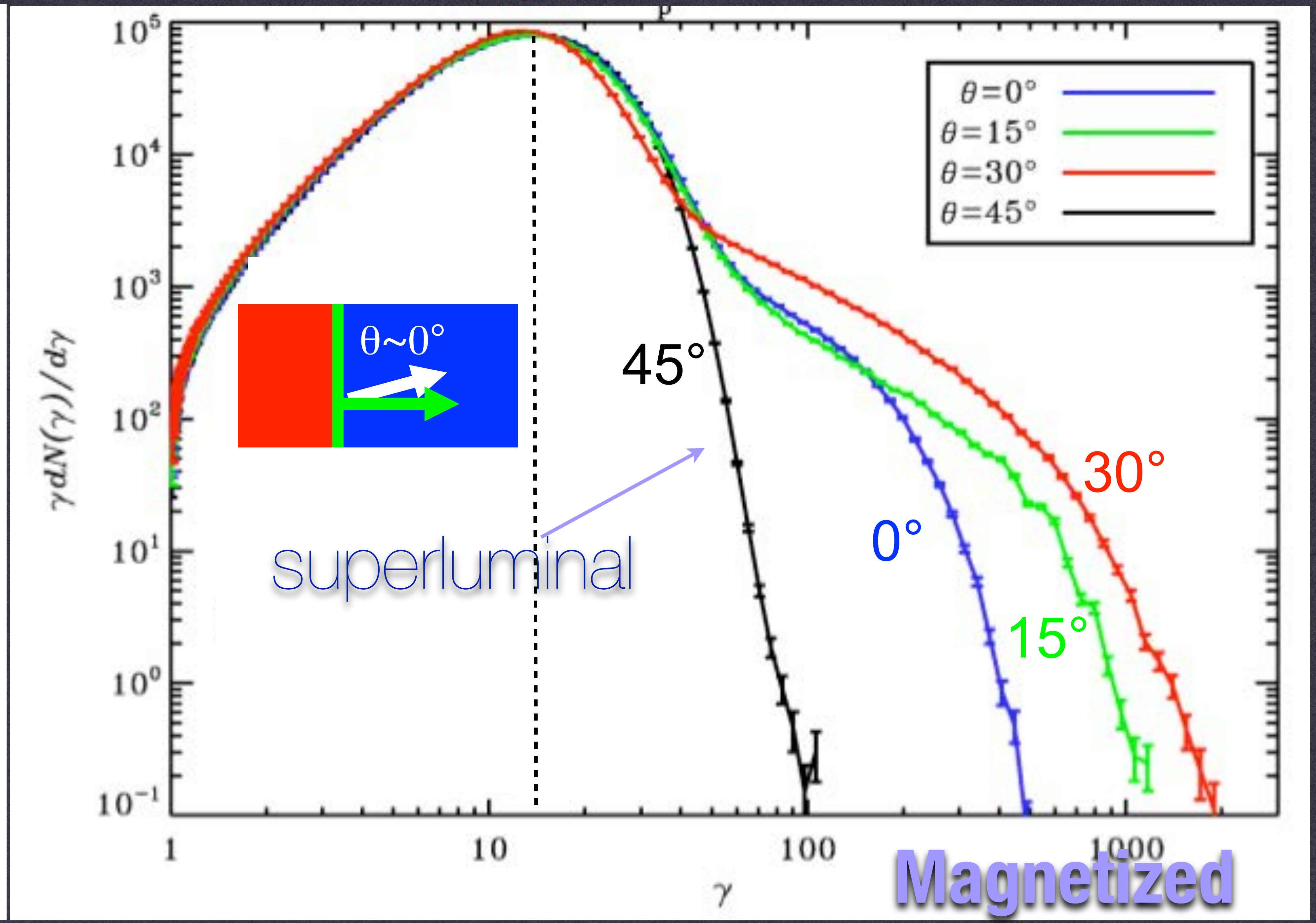
$\theta'<34°/\gamma_0<<1$ (upstream frame)

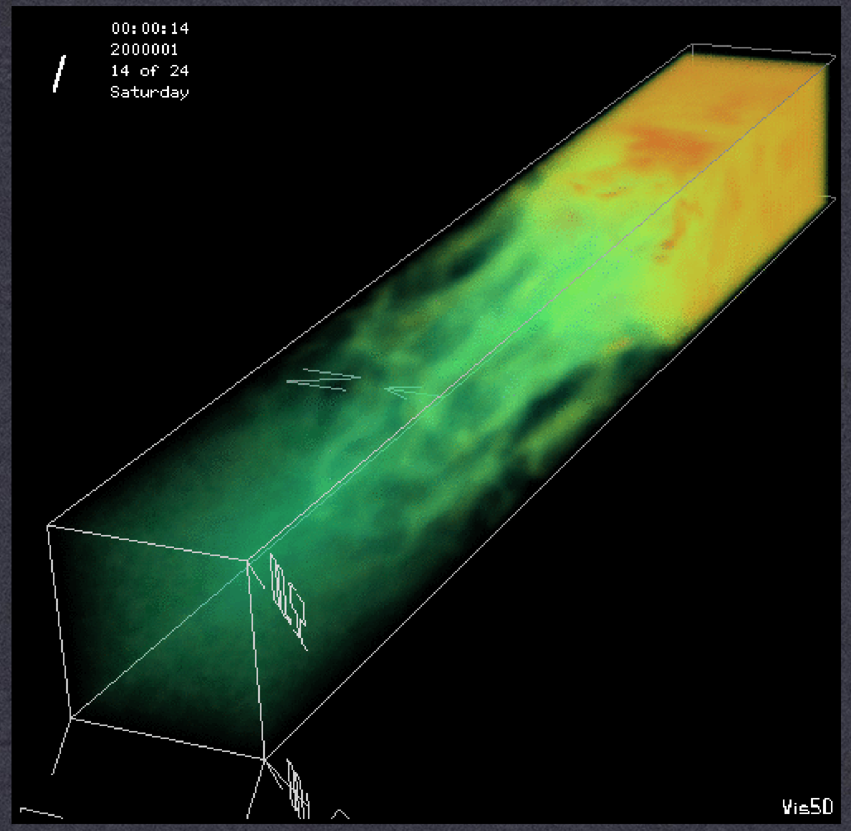
Easy to kill!

# PARTICLE ACCELERATION

Sironi & AS 09



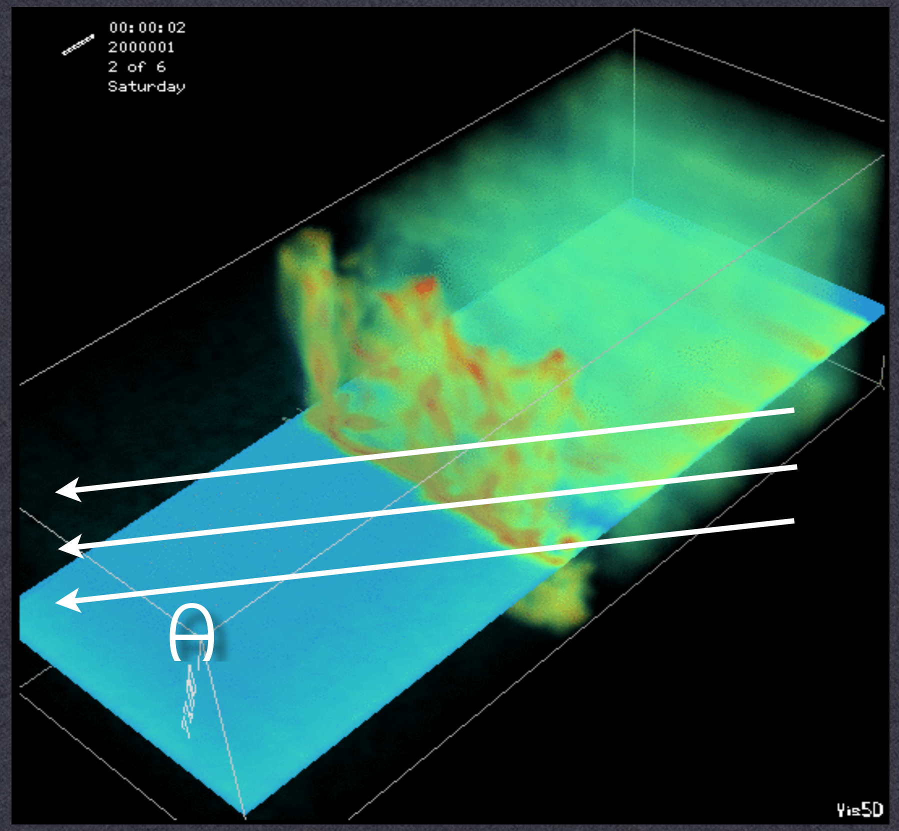



**Conditions for acceleration in relativistic shocks:**

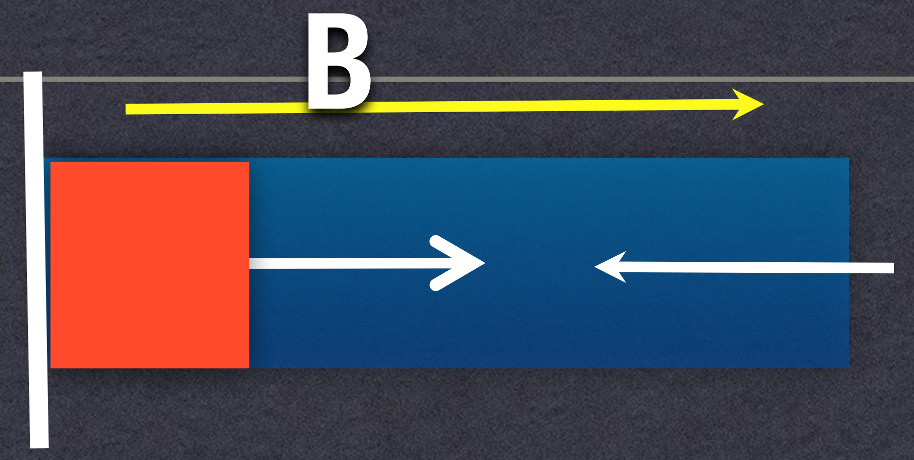
**low magnetization of the flow**

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

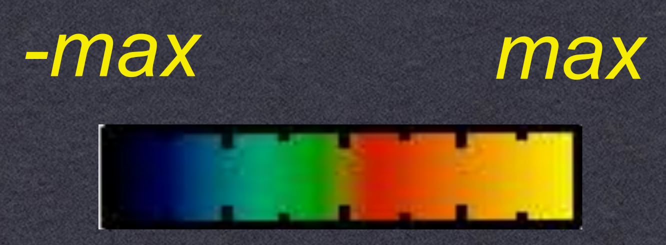
**electrons & ions behave similarly**



# PARTICLE ACCELERATION

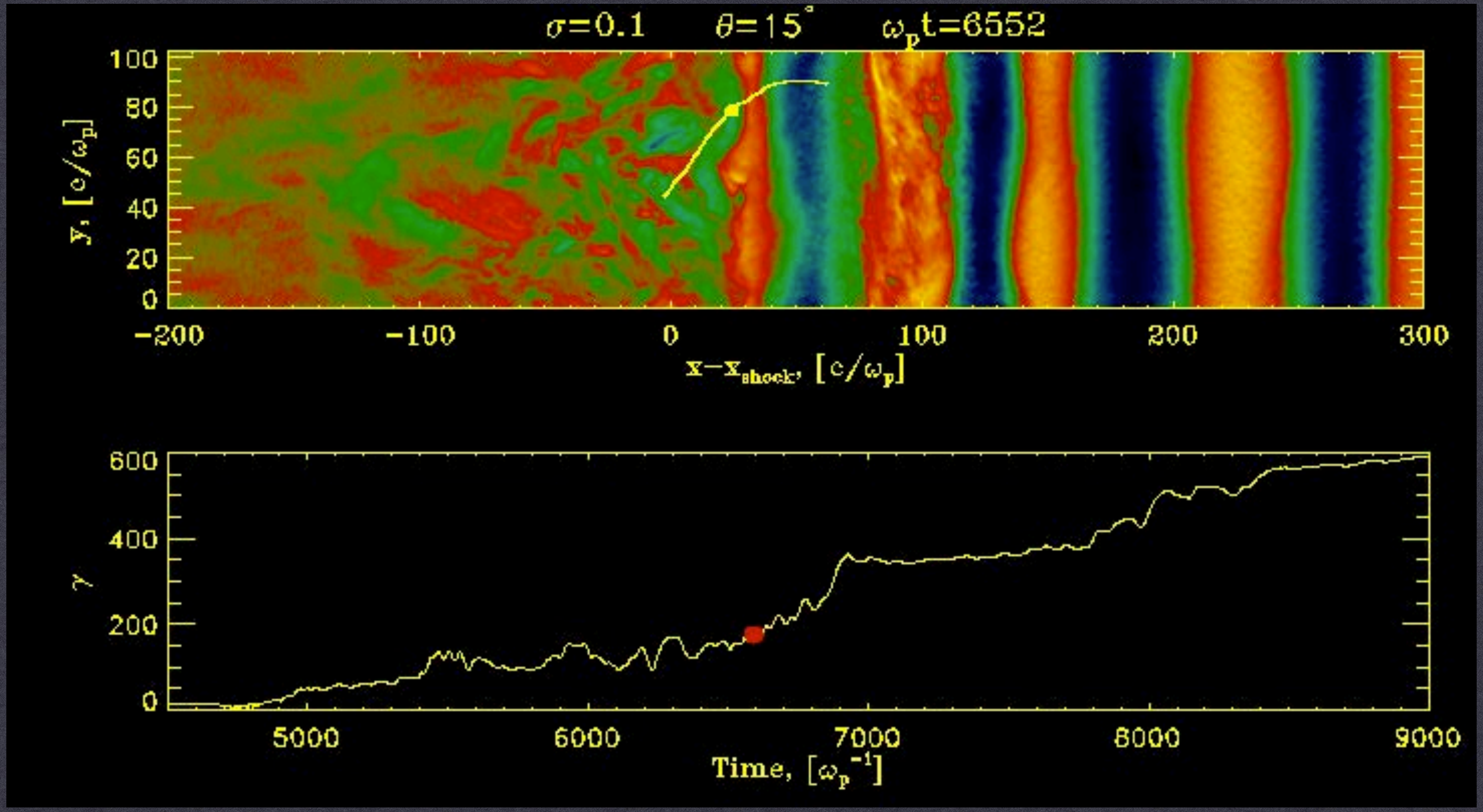



Magnetized shock (parallel, e-p): scattering on self-generated upstream waves



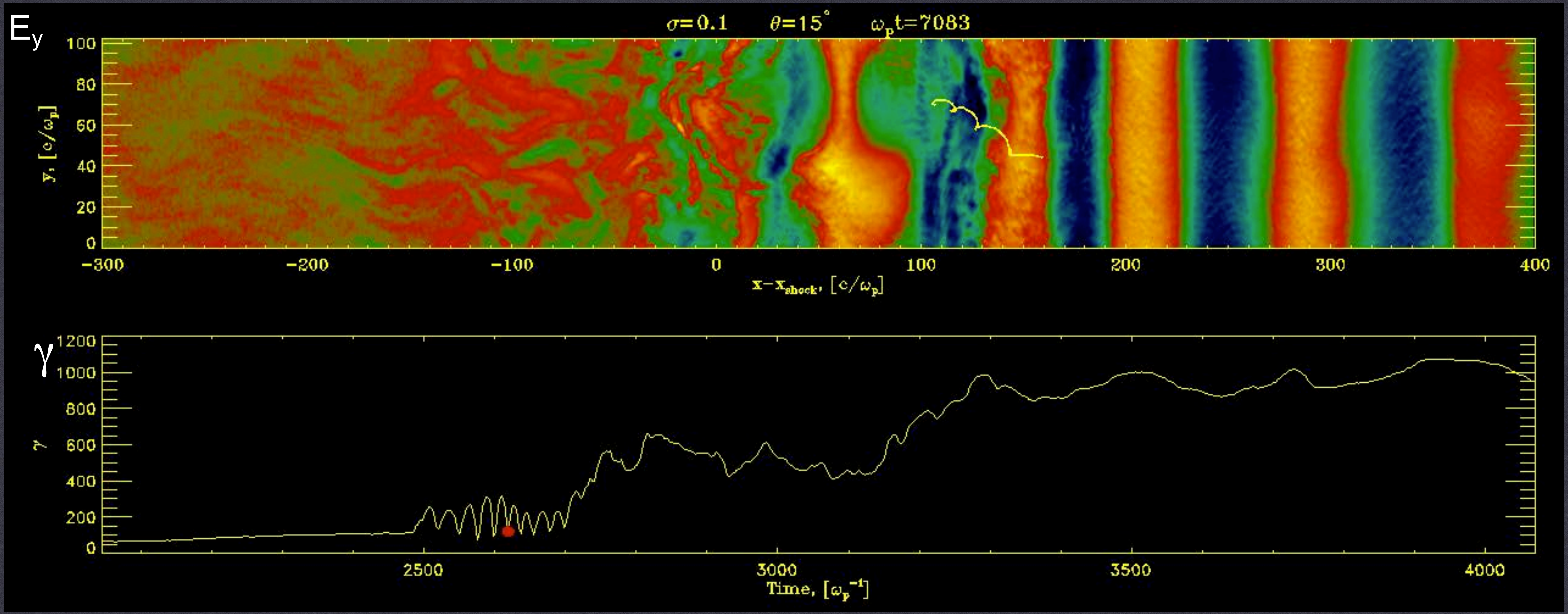

Transverse Magnetic Field

Particle energy



# Electron acceleration

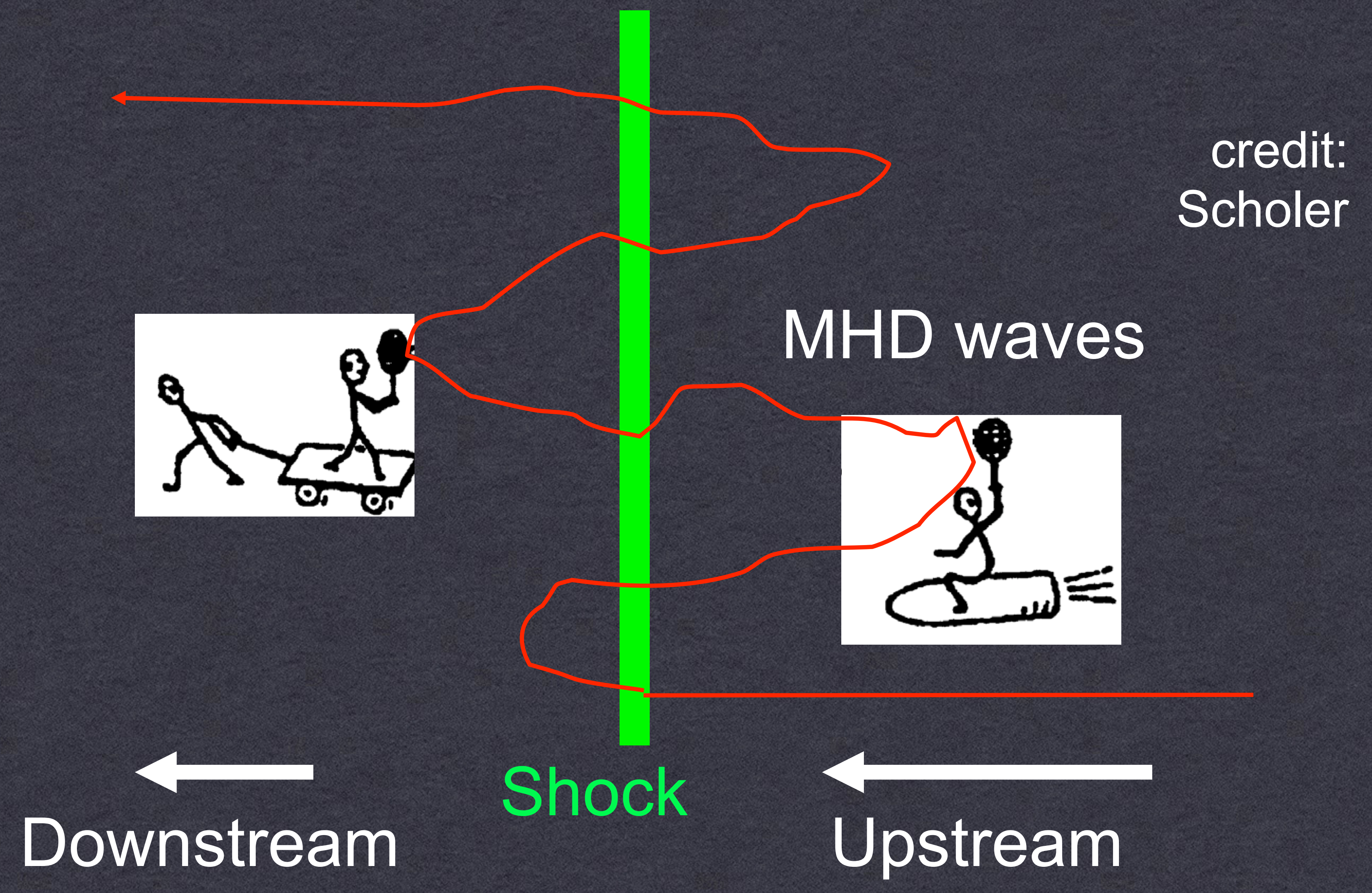
σ=0.1 θ=15° e⁻-p⁺ shock: ELECTRONS are more strongly tied to the magnetic field lines and get quickly advected downstream



# Acceleration process in subluminal shocks

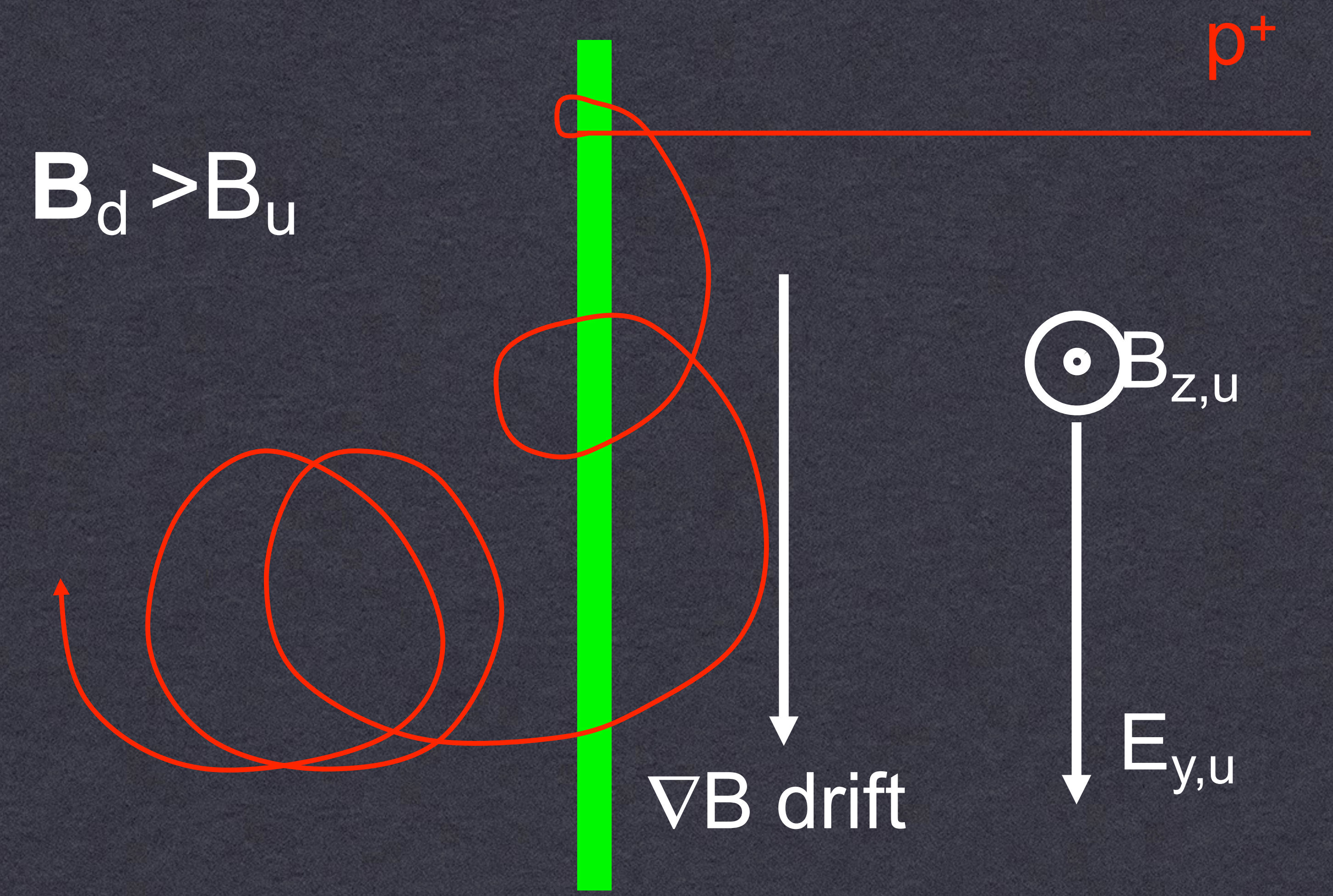
- Diffusive Shock Acceleration (DSA) or Fermi acceleration:

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



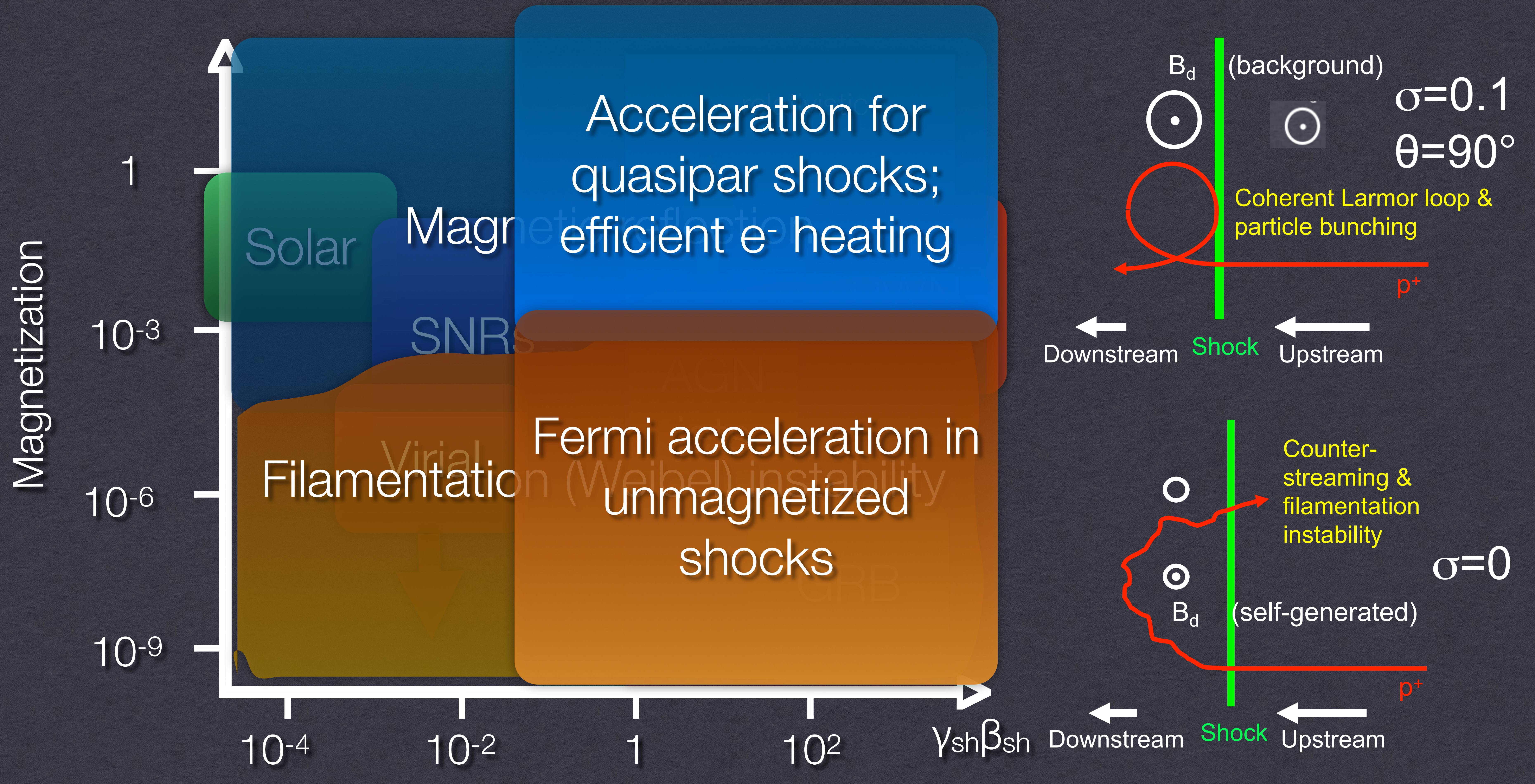

- Shock-drift acceleration (SDA): oblique shocks only!

Shock-reflected particles are accelerated by the background electric field while drifting along the shock surface

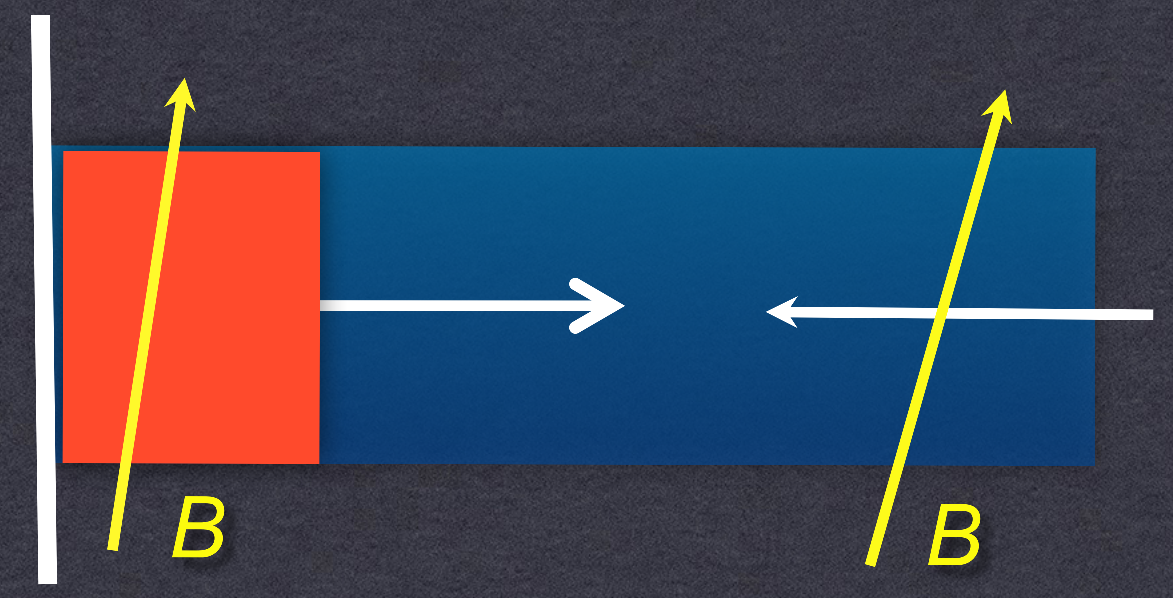


# Parameter Space of shocks

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



# Relativistic shocks



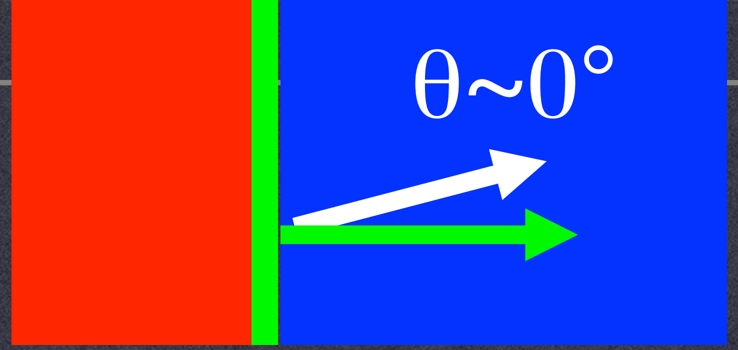

What are we missing?

Simulations are converged on the early evolution, not much dependence on mass ratio or shock gamma-factor for gamma>5.

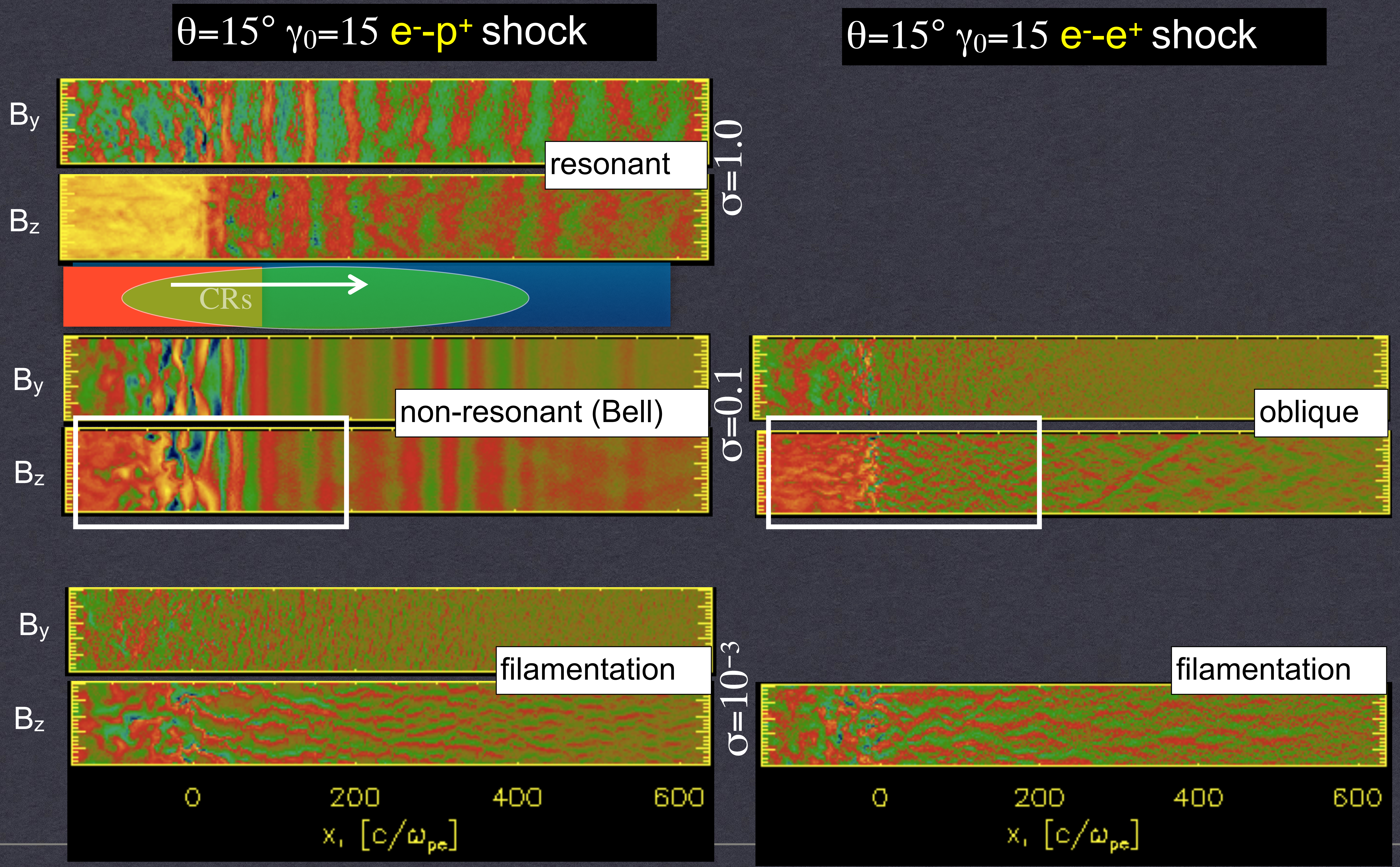
However, we cannot rule out dramatic long term shock evolution effects.

Consider wave generation and field amplification in the long term.

# Electron-positron vs electron-ion

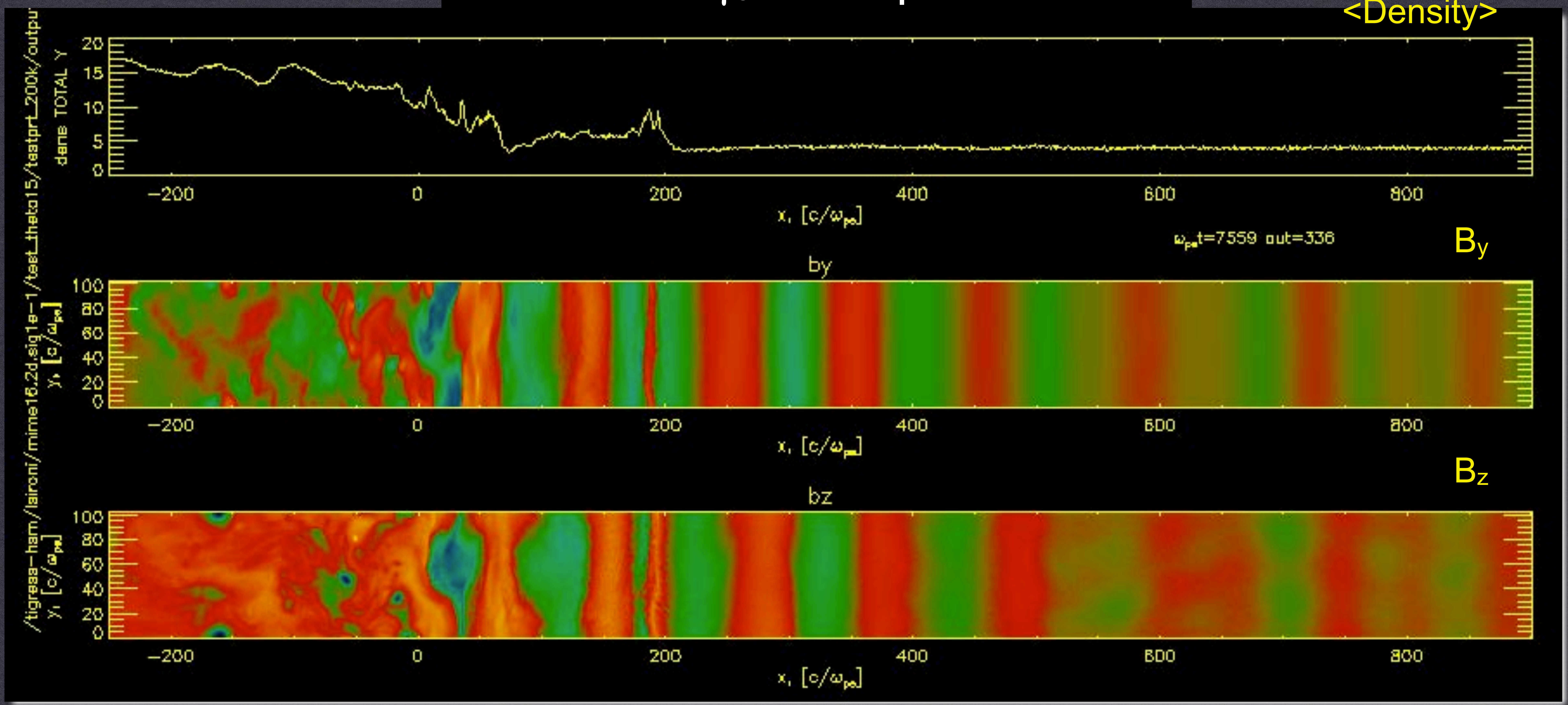



Similar spectra, but different microphysical instabilities for particle scattering



# Long-term evolution of dominant instability

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




(Sironi & AS 11)

- Dominant mode changes from electron filamentation to Bell's nonresonant instability: transverse box is now too small!
- Shock reformation (and SLAMS) seen in the density profile at late times

# Field survival long term: still unclear

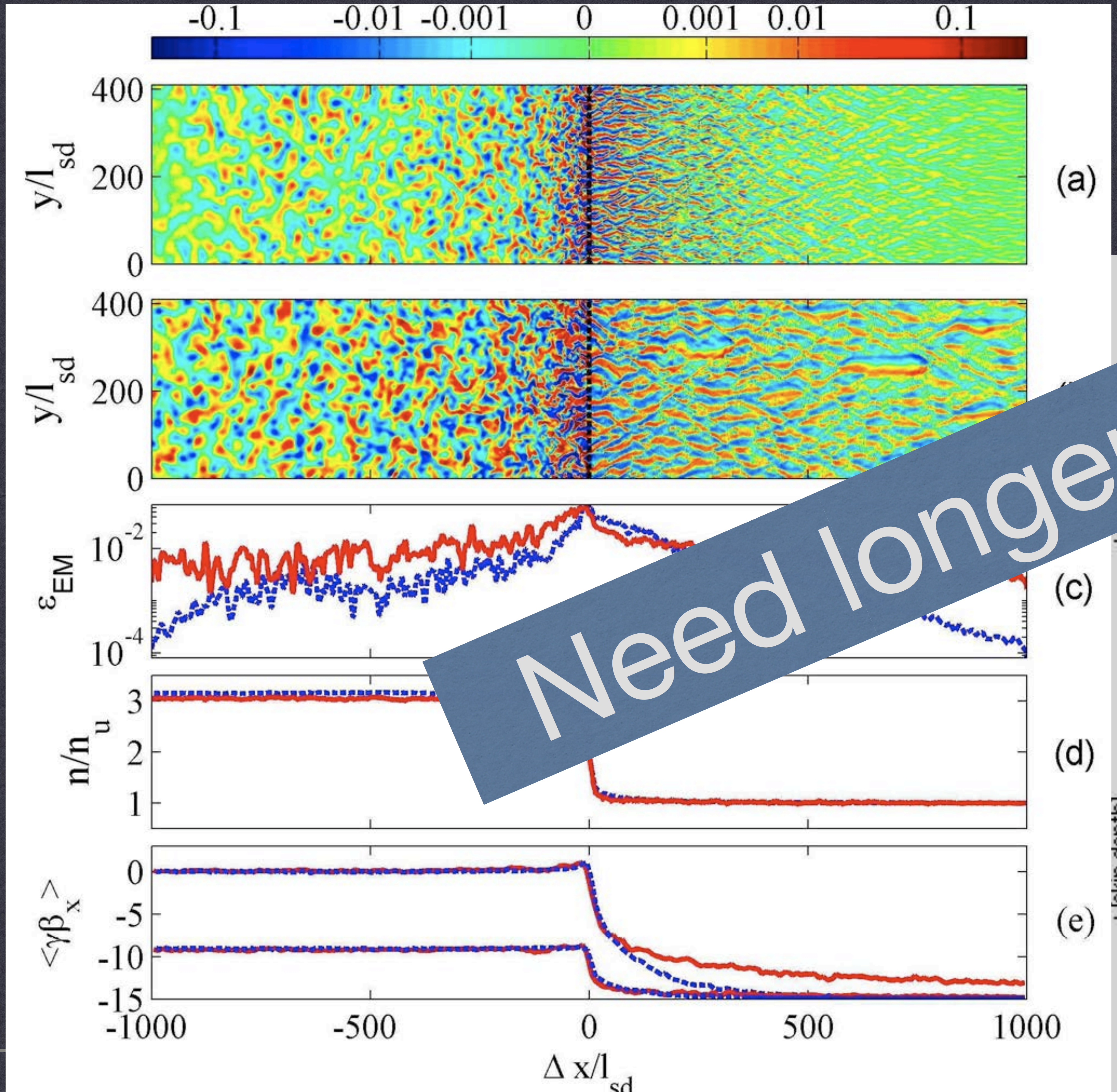
**In unmagnetized shocks field is created on plasma scale and then decays. Need to make it on larger scale. Accelerated particles feedback?**

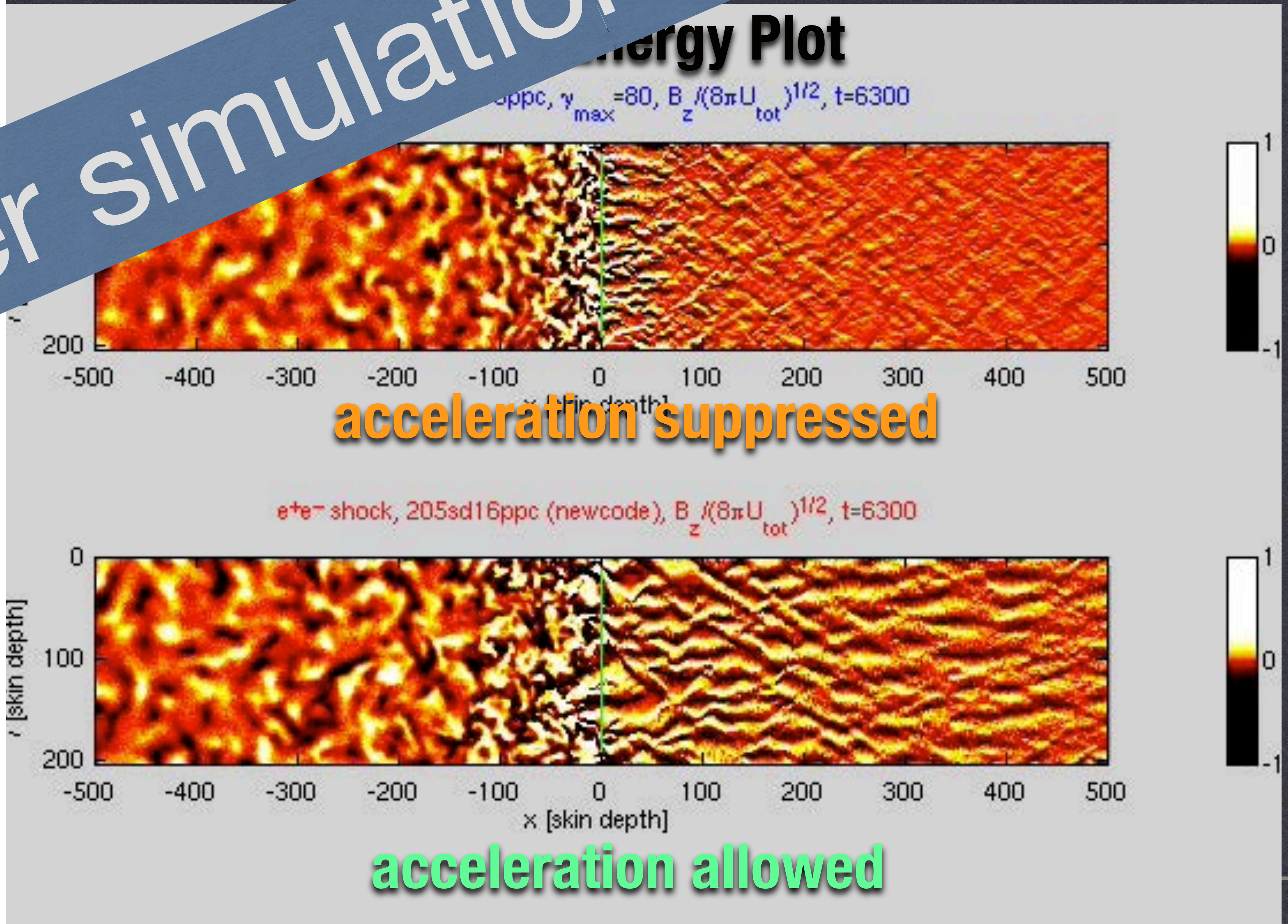
*(Keshet, Katz, A.S., Waxman 2009)*

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

**1% downstrea… possible**

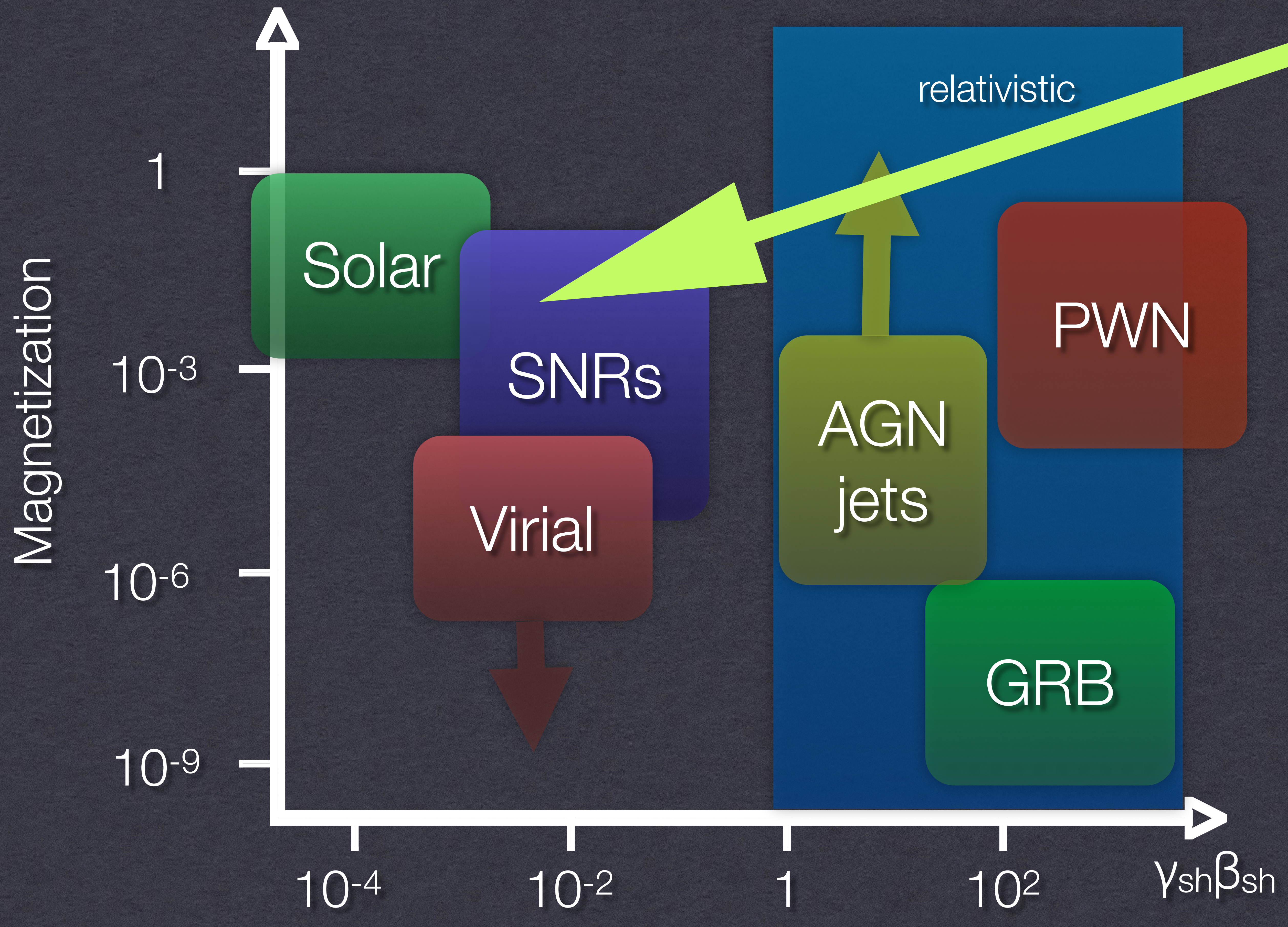
Need longer simulations!



# 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)**

# Parameter Space of shocks

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

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

In ISM: beta ~ 1, $M_s$=$M_A$, $c_s$~$v_A$~10 km/s
SNRs: v=1000-15000 km/s, $M_s$=$M_A$=100-1500; With B amplification $M_A$ can decrease to 10-30.

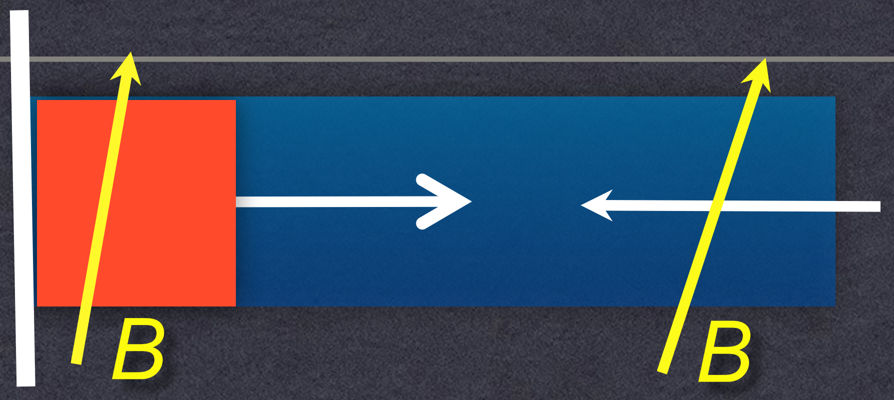
In galaxy clusters: beta ~ 100, $M_s$ = $M_A$/10
Relics: v=1000 km/s, $M_s$= few, $M_A$ = 10-20

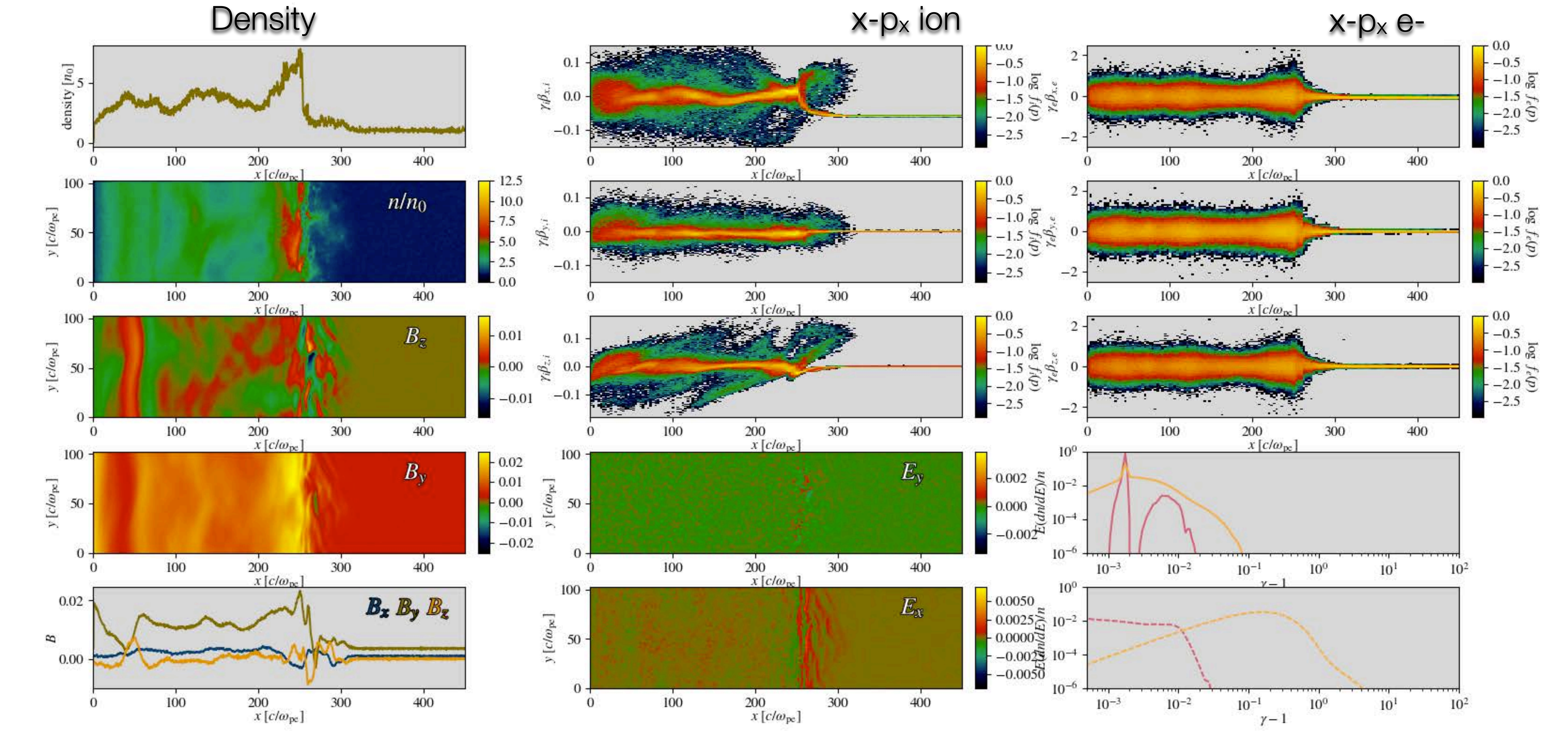
Virial shock: v=1000 km/s, $M_s$~$M_A$~100, similar to SNR

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

# Nonrelativistic shocks: shock structure

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

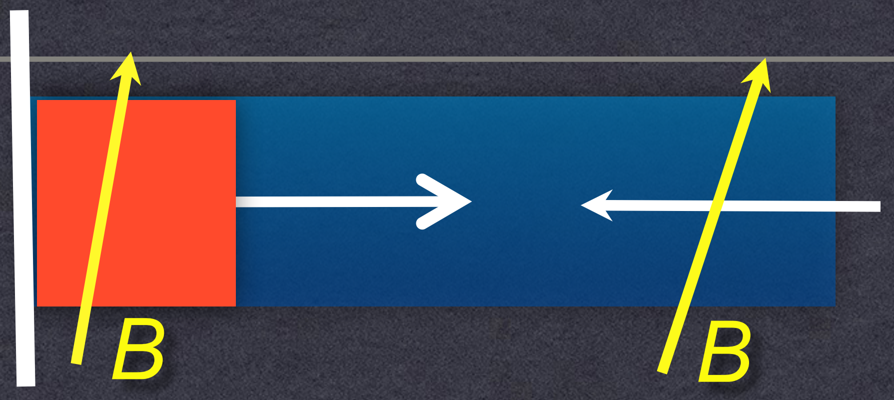


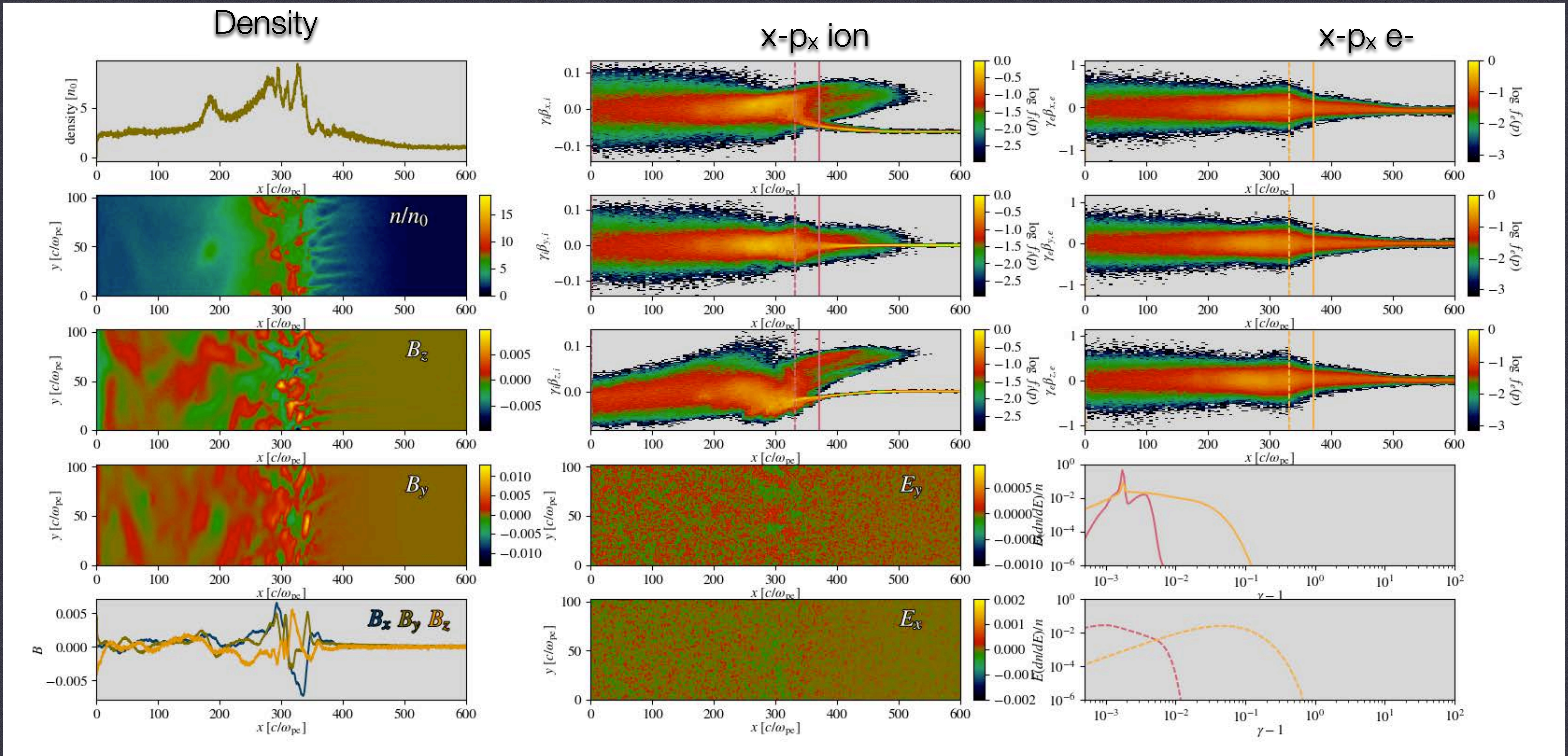




PIC simulation: Shock foot, ramp, overshoot, returning ions, electron heating, whistlers

# Nonrelativistic shocks: shock structure

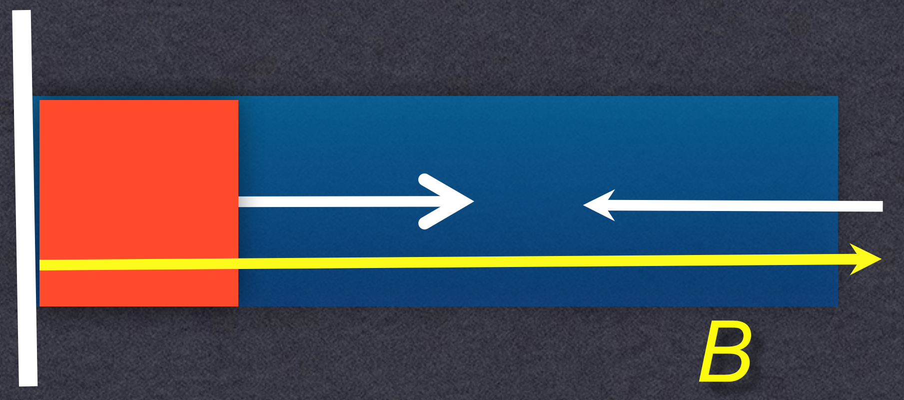
mi/me=100, v=18,000km/s, $M_A$=45 quasi-perp 75° inclination

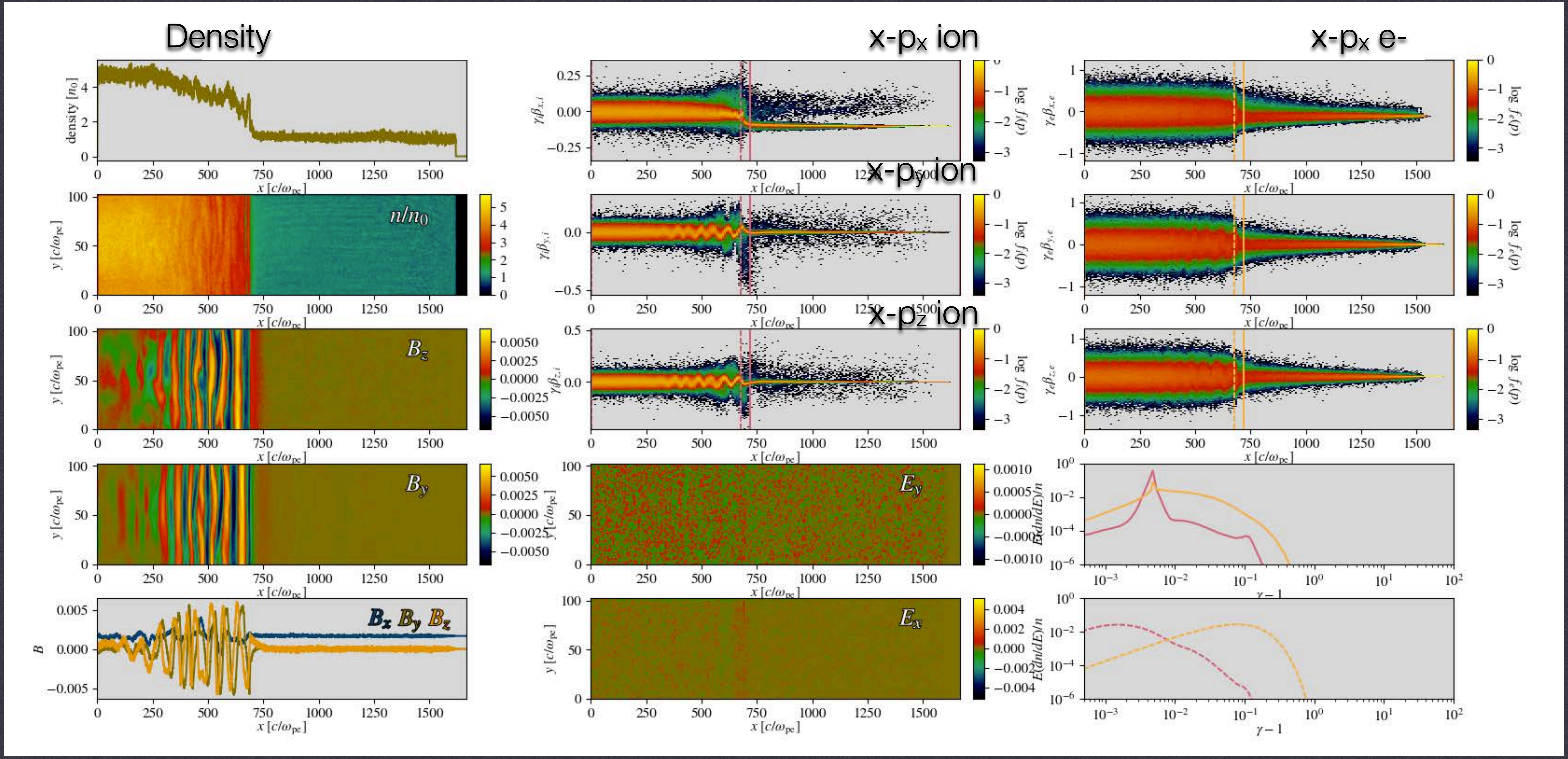


# Nonrelativistic shocks: quasiparallel shock

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

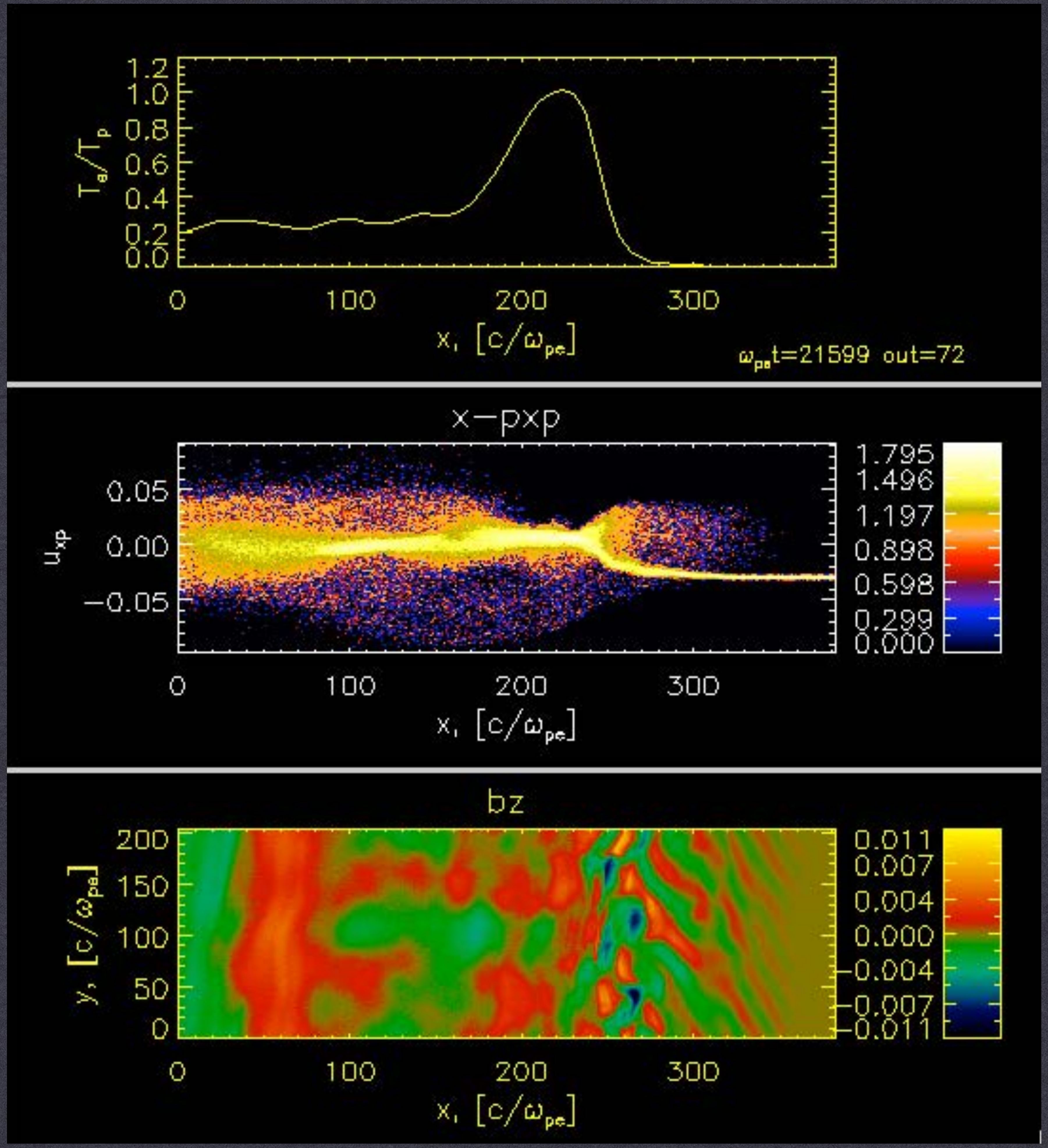


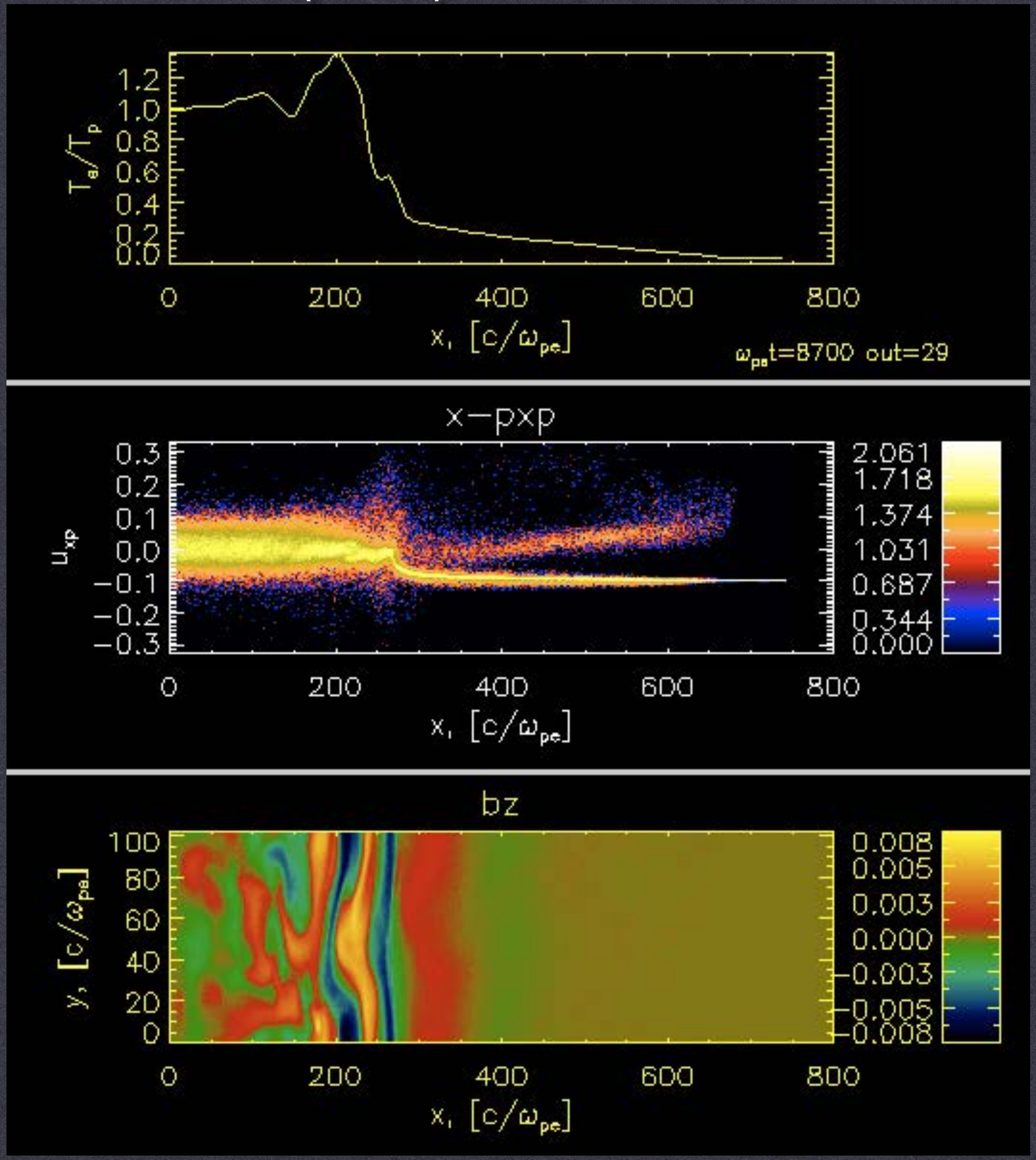
# Nonrelativistic shocks: heating

Heating varies between 20% of equipartition for perp shocks, to 50% in parallel

quasi-perpendicular shock



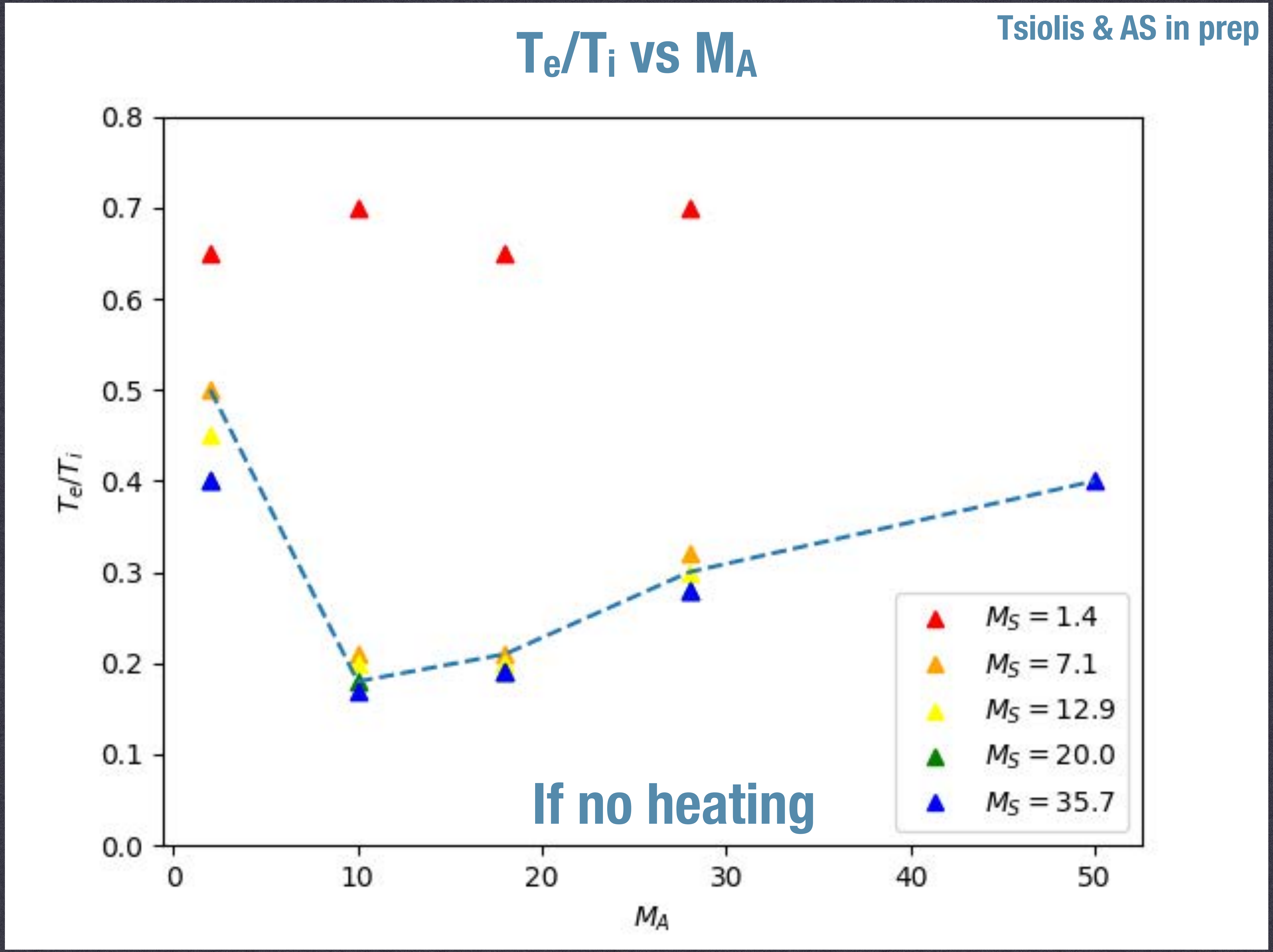

quasi-parallel shock




Not much dependence on mass ratio, speed, magnetization, etc.

# Nonrelativistic shocks: electron heating

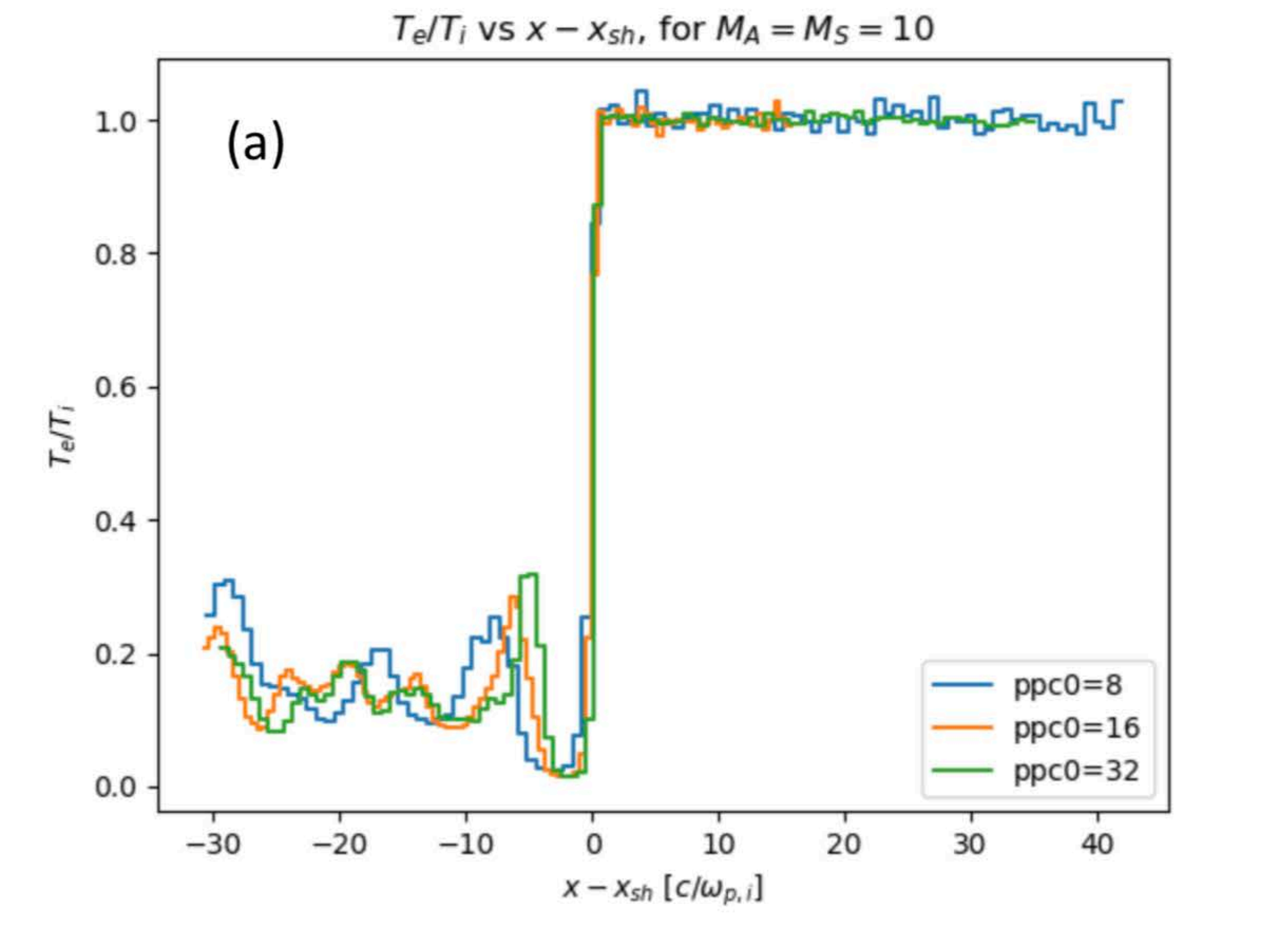
Expect: $T_e/T_i \sim m_e/m_i$… In simulations, heating varies between 10% of equipartition for perp shocks, to 50% in parallel shocks



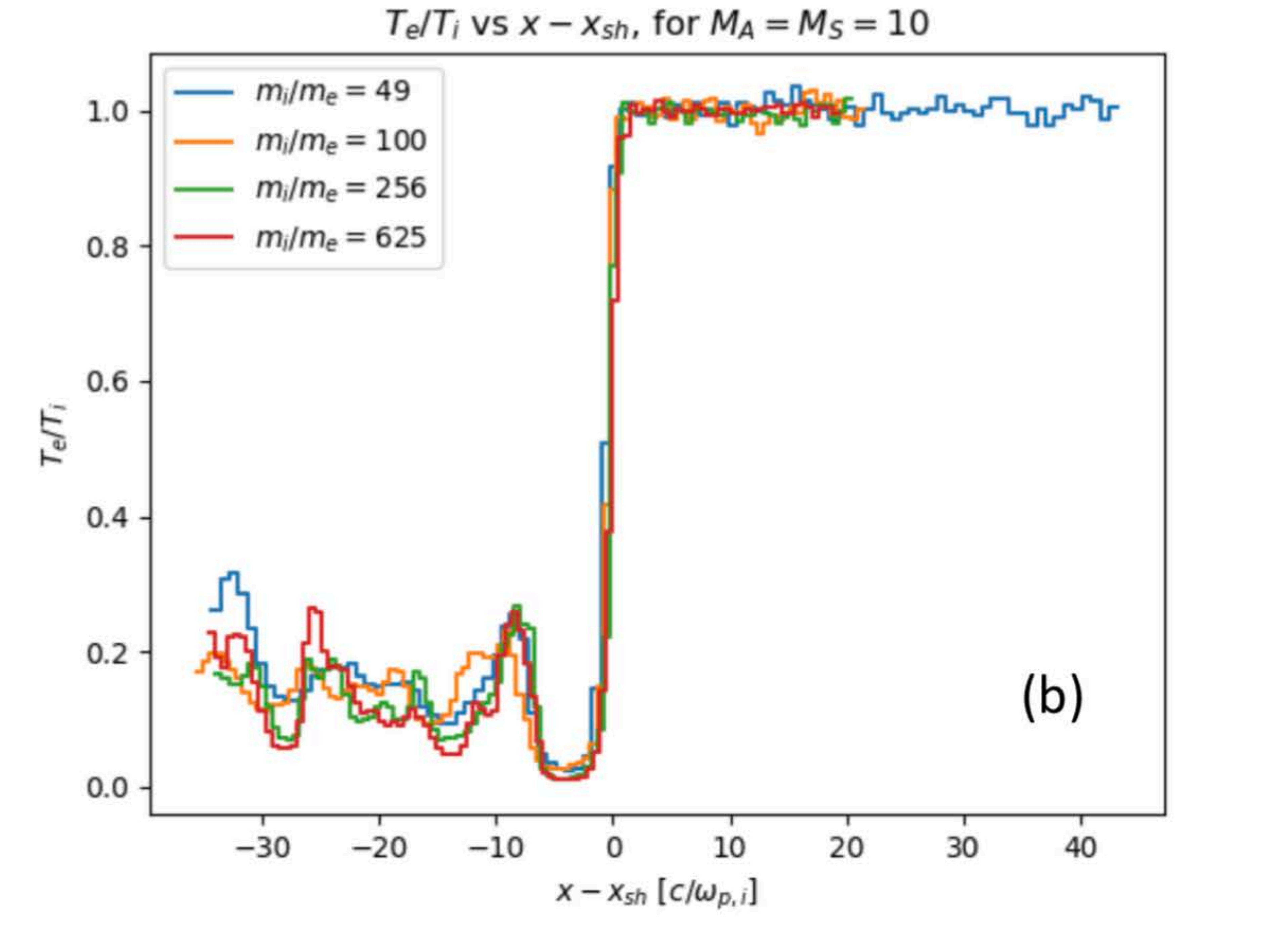

Not much dependence on mass ratio, speed, etc.

# Convergence:

With particle number:

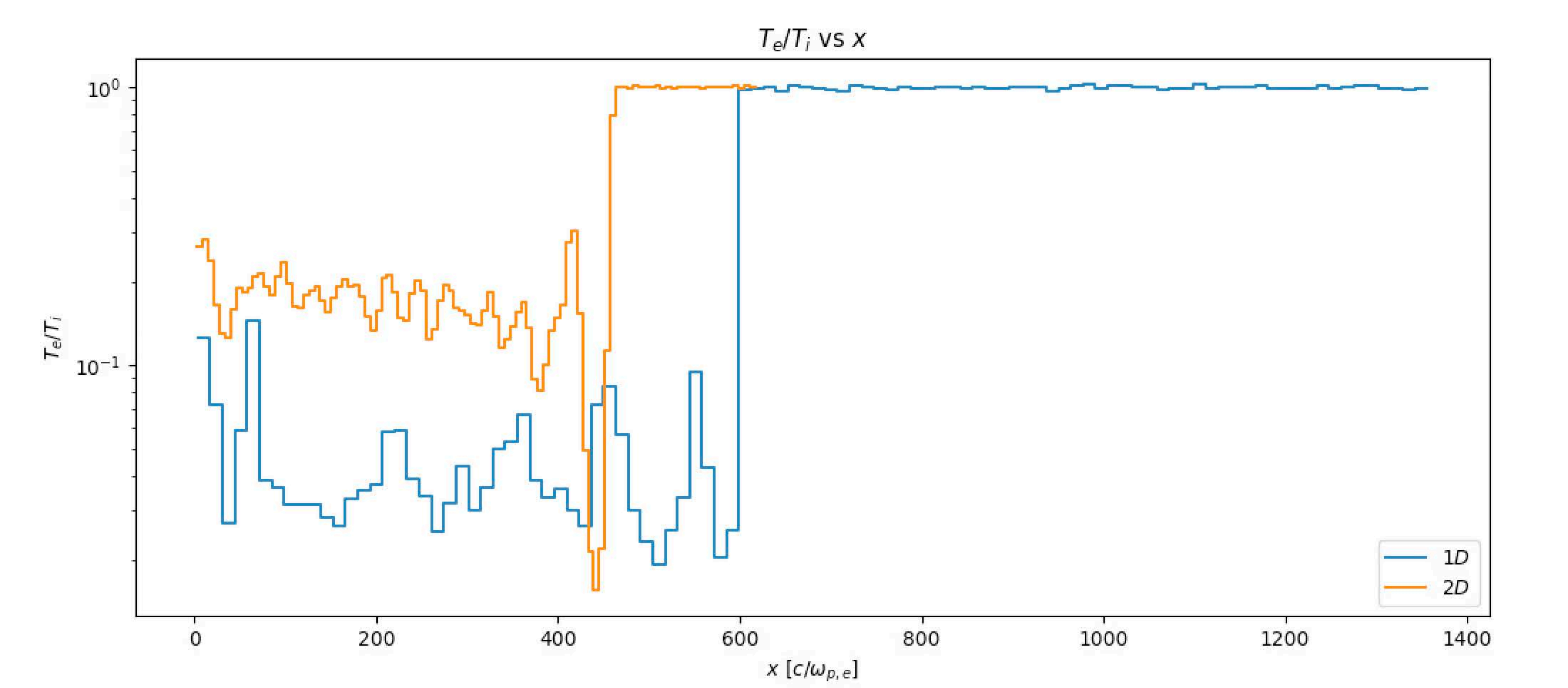



With mass ratio:



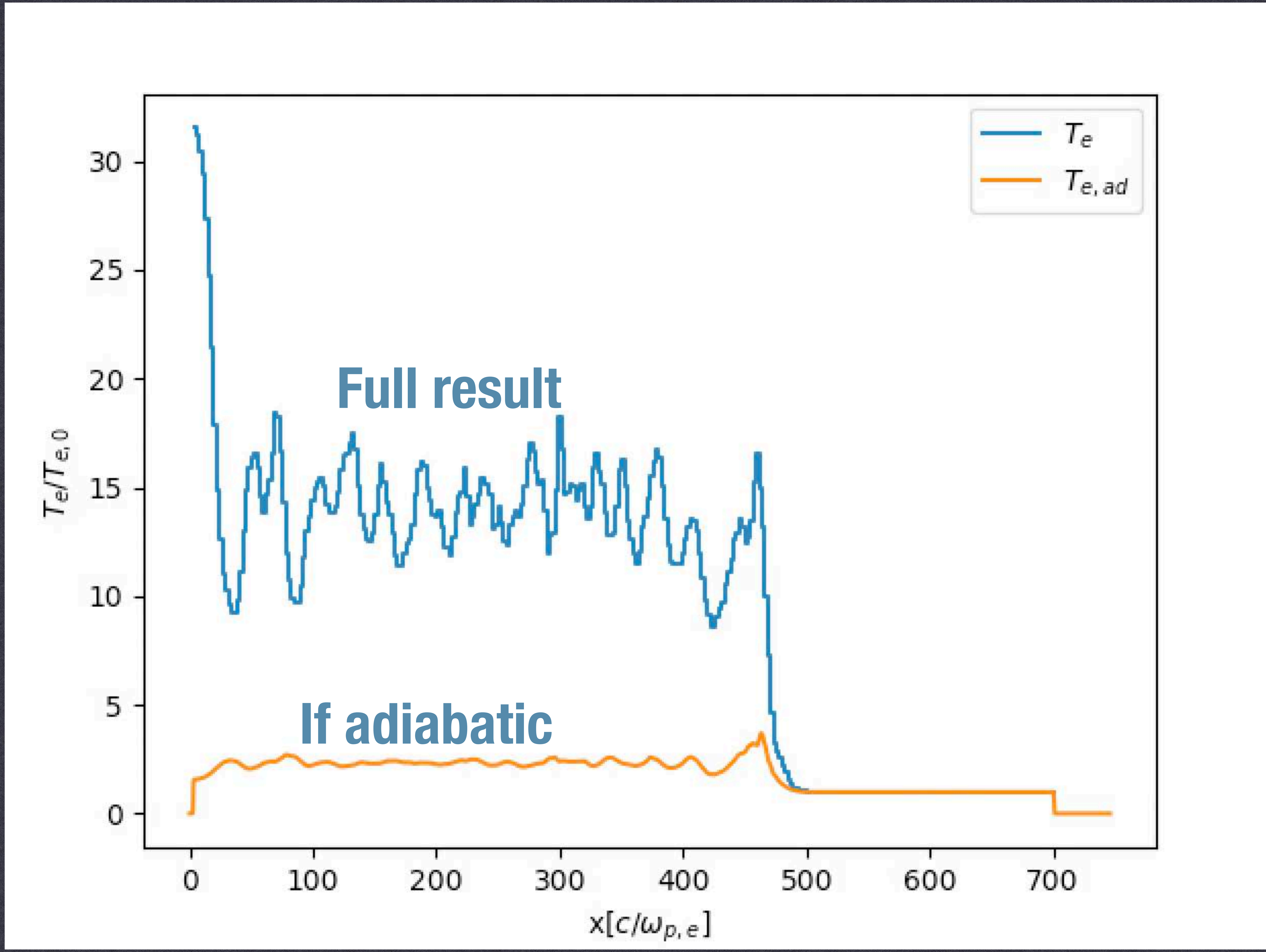
Convergence:

Dimensionality:

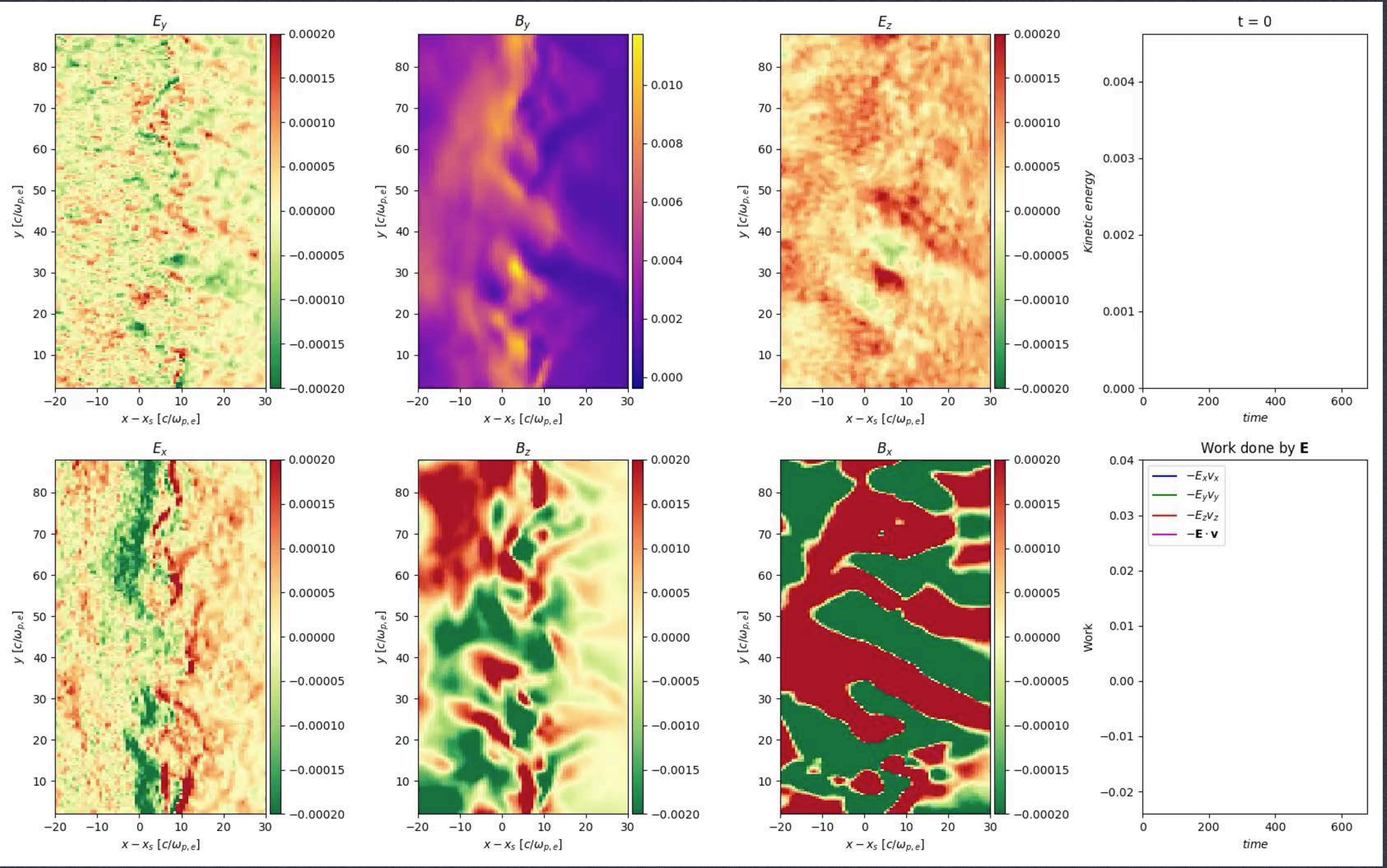



Being in 2D is important!

Is it heating?



# Mechanism? Interaction with time-variable E fields in corrugated shock structure



# SHOCK ACCELERATION

**Two crucial ingredients:**

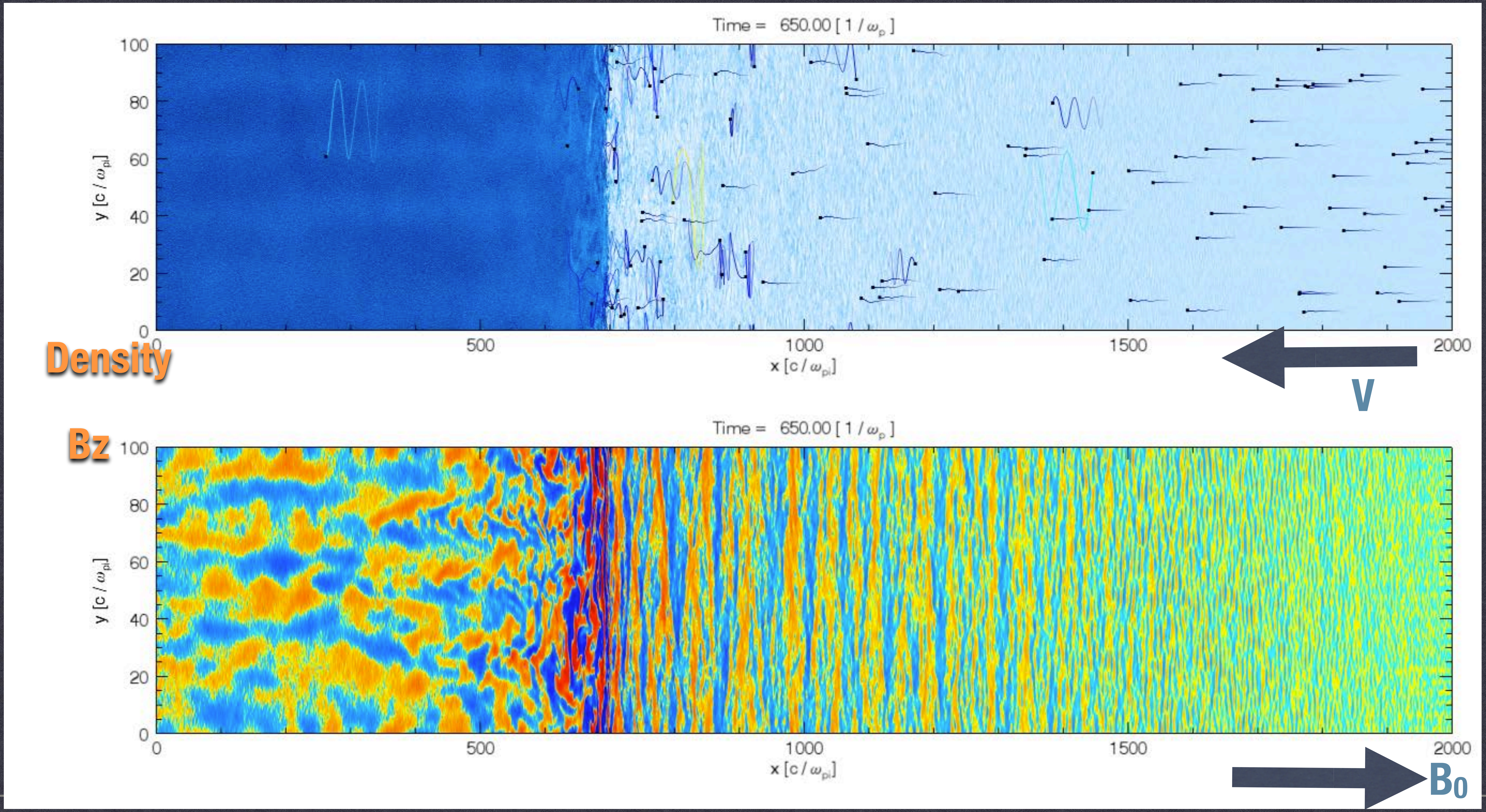
**1) ability of a shock to reflect particles back into the upstream (injection)**

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

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

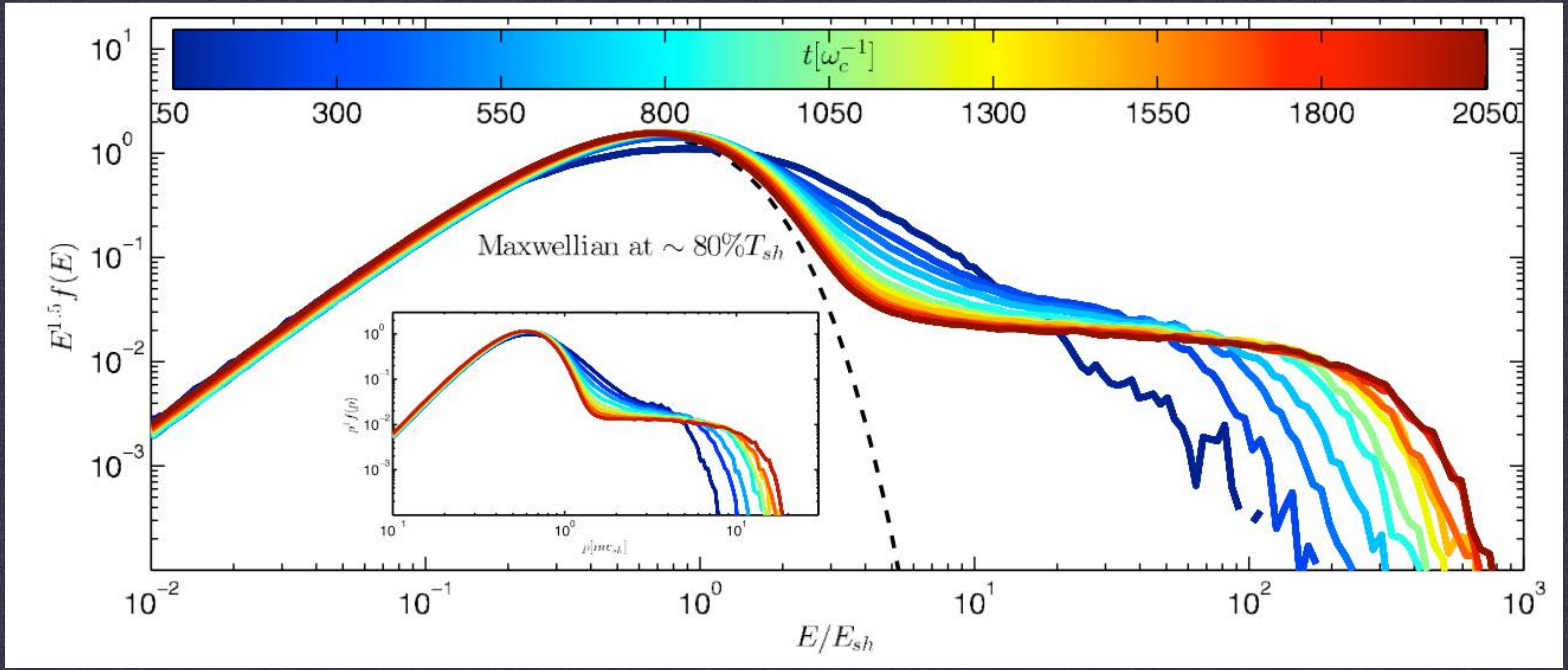
# Quasiparallel shocks: proton and electron accelerators;

Mach 10 nonrelativistic hybrid simulation of proton acceleration



# Proton spectrum

**Long term evolution: Diffusive Shock Acceleration spectrum recovered**




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

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

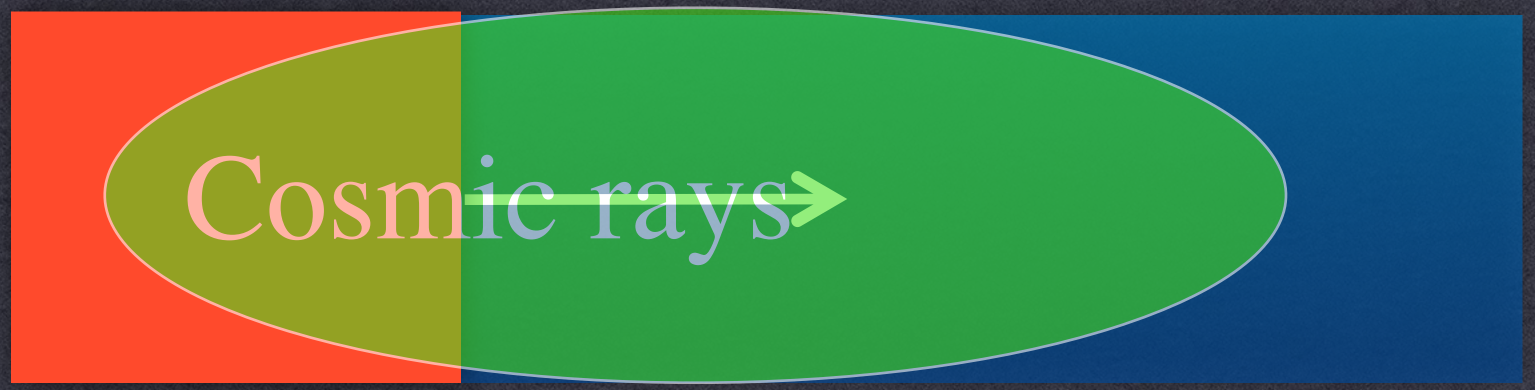
CR backreaction is affecting downstream temperature

Caprioli & AS 2014a

# Field amplification

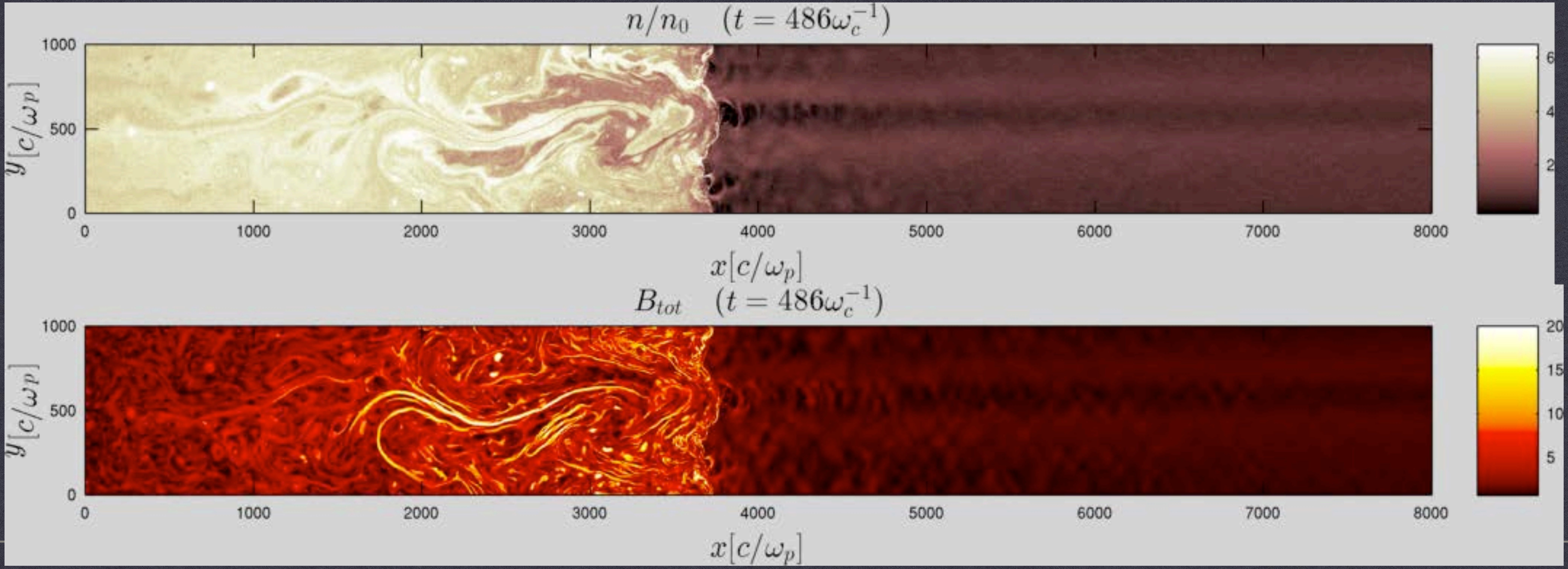
We see evidence of CR effect on upstream.

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




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

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



# B field amplification

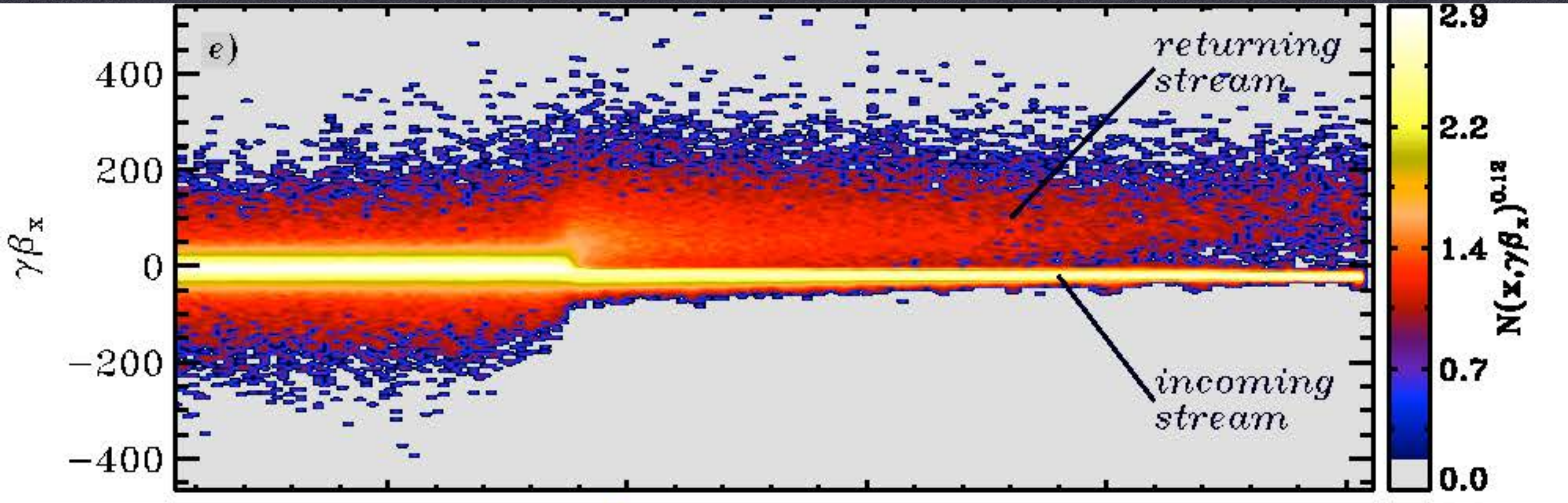
*CR accelerating shocks can cause a current of protons to propagate through the upstream. Bell (04, 05) found an MHD instability of CRs flying through magnetized plasma.*

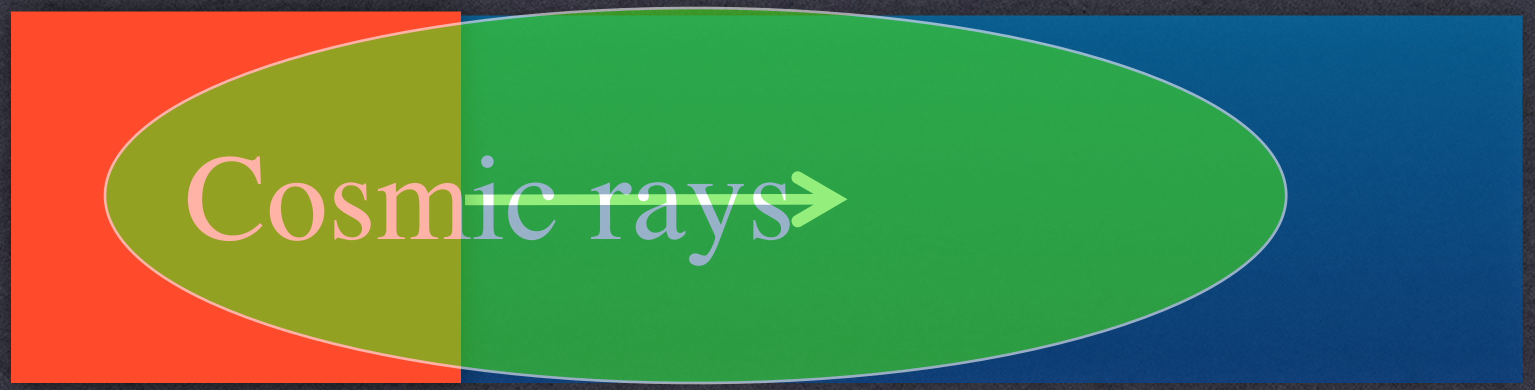
*The interaction is nonresonant at wavelength << Larmor radius of CRs.*

*We simulated this instability with PIC in 2D and 3D (Riquelme and A.S. 08)*

*Saturation is due to CR deflection; for SNR conditions expect ~10-40x field increase.*

*Bell's nonresonant CR instability*




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

$p_{xi}$

# B field amplification

*Bell's nonresonant CR instability*

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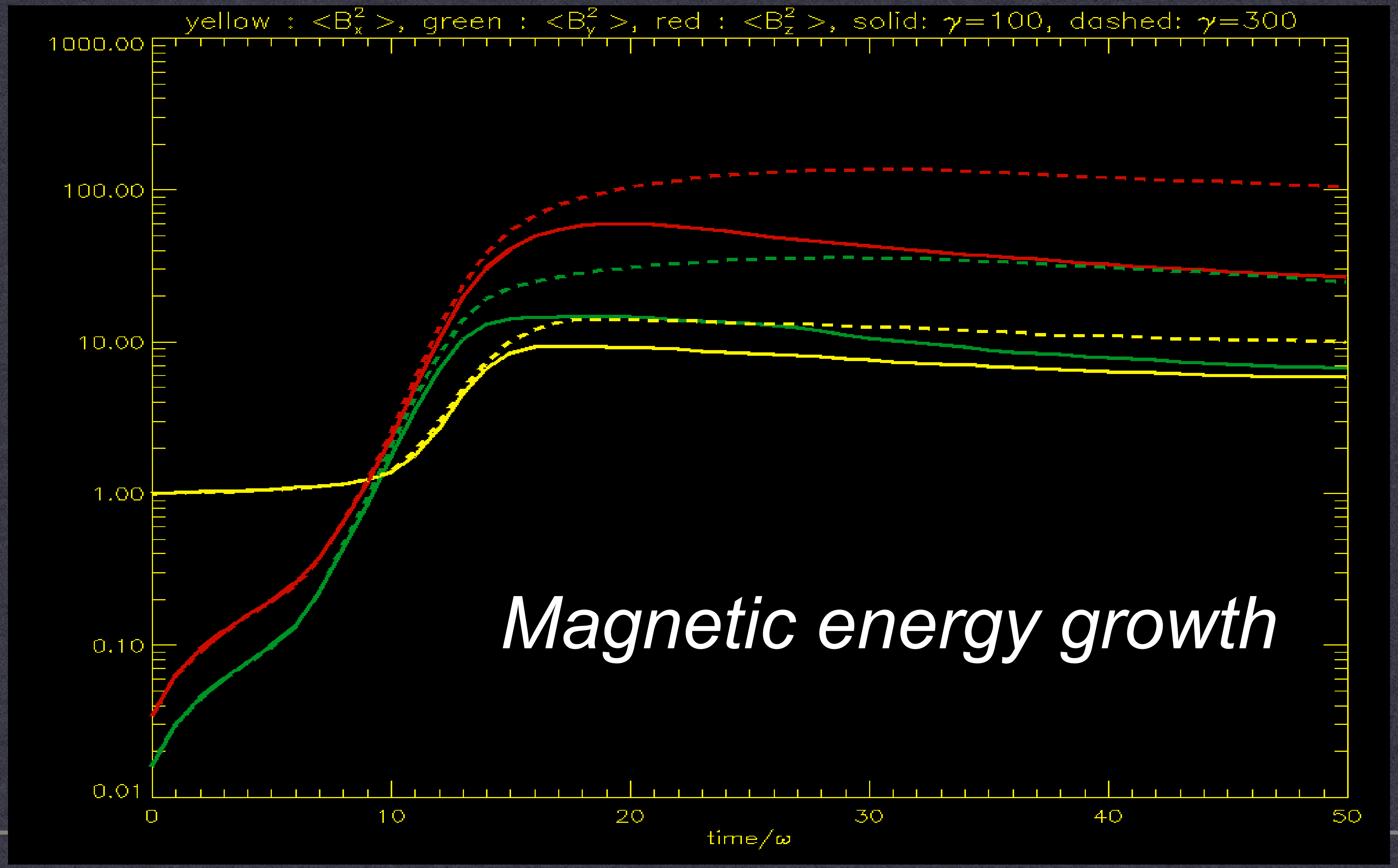
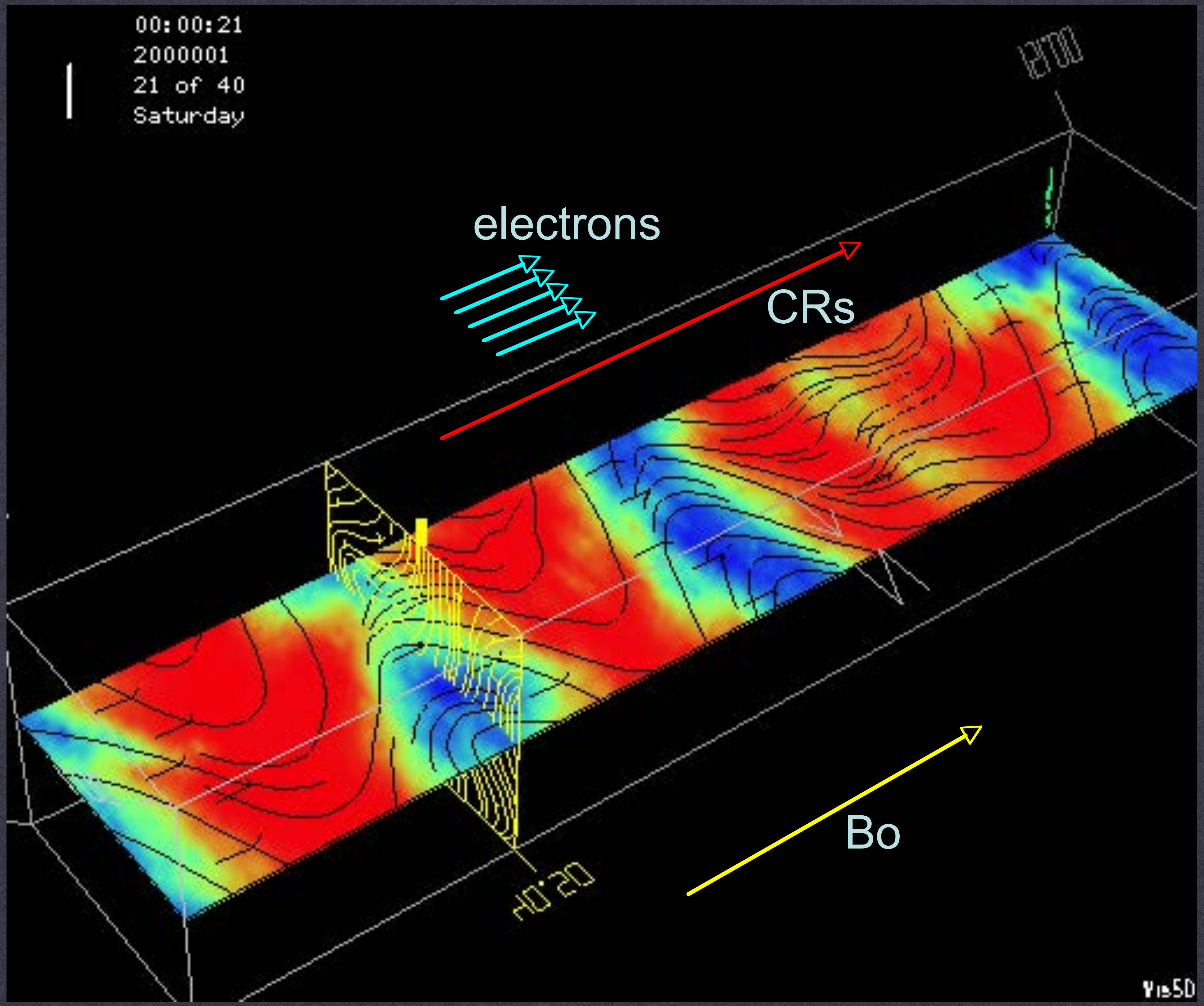



$$k_{max}\, c = 2\pi J_{cr}/B_0$$

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

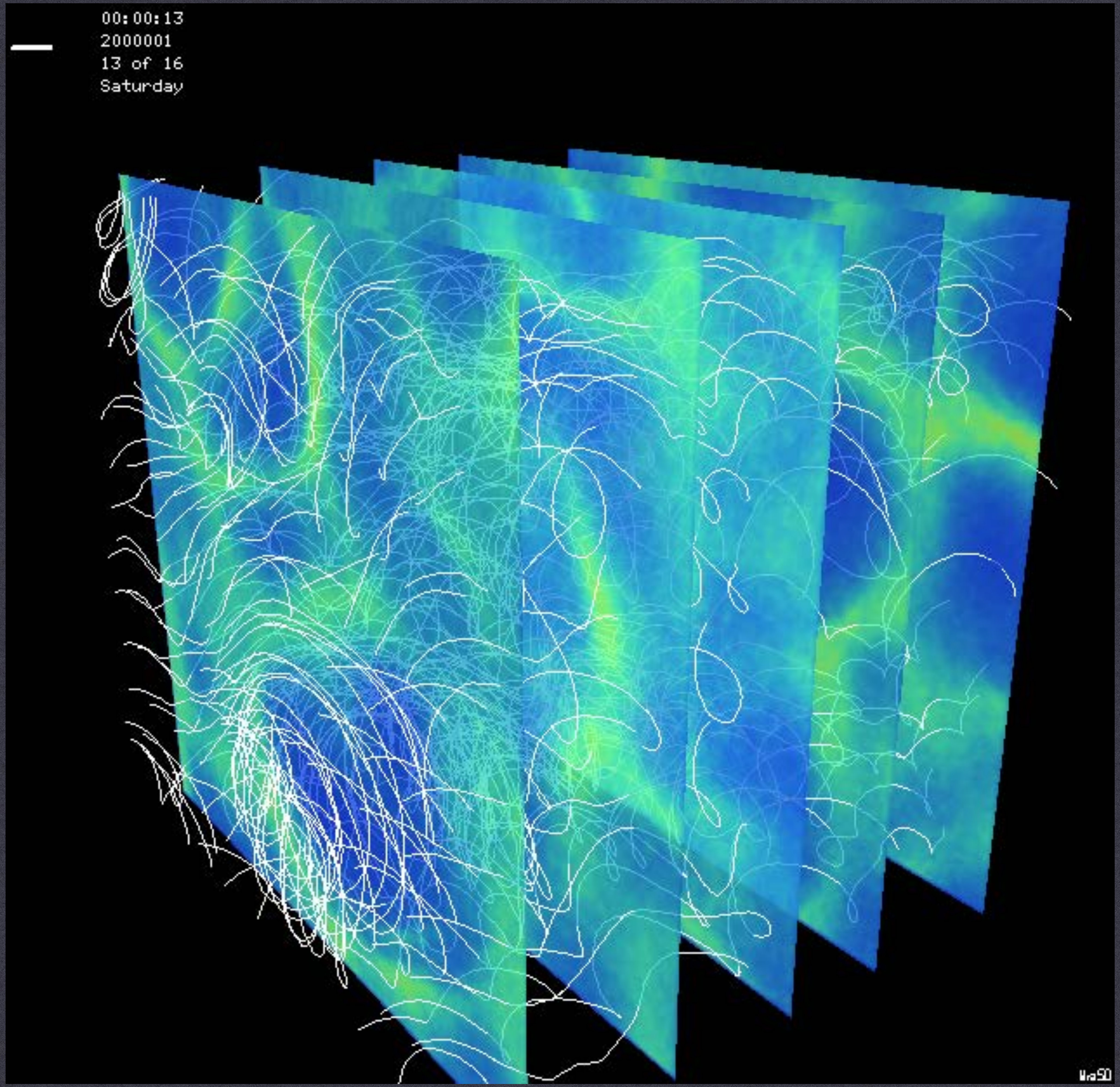
*Need magnetized plasma: $\omega_{ci} >> \gamma_{max}$*

$p_{xi}$

# B field amplification: 3D runs

*Bell's nonresonant CR instability*

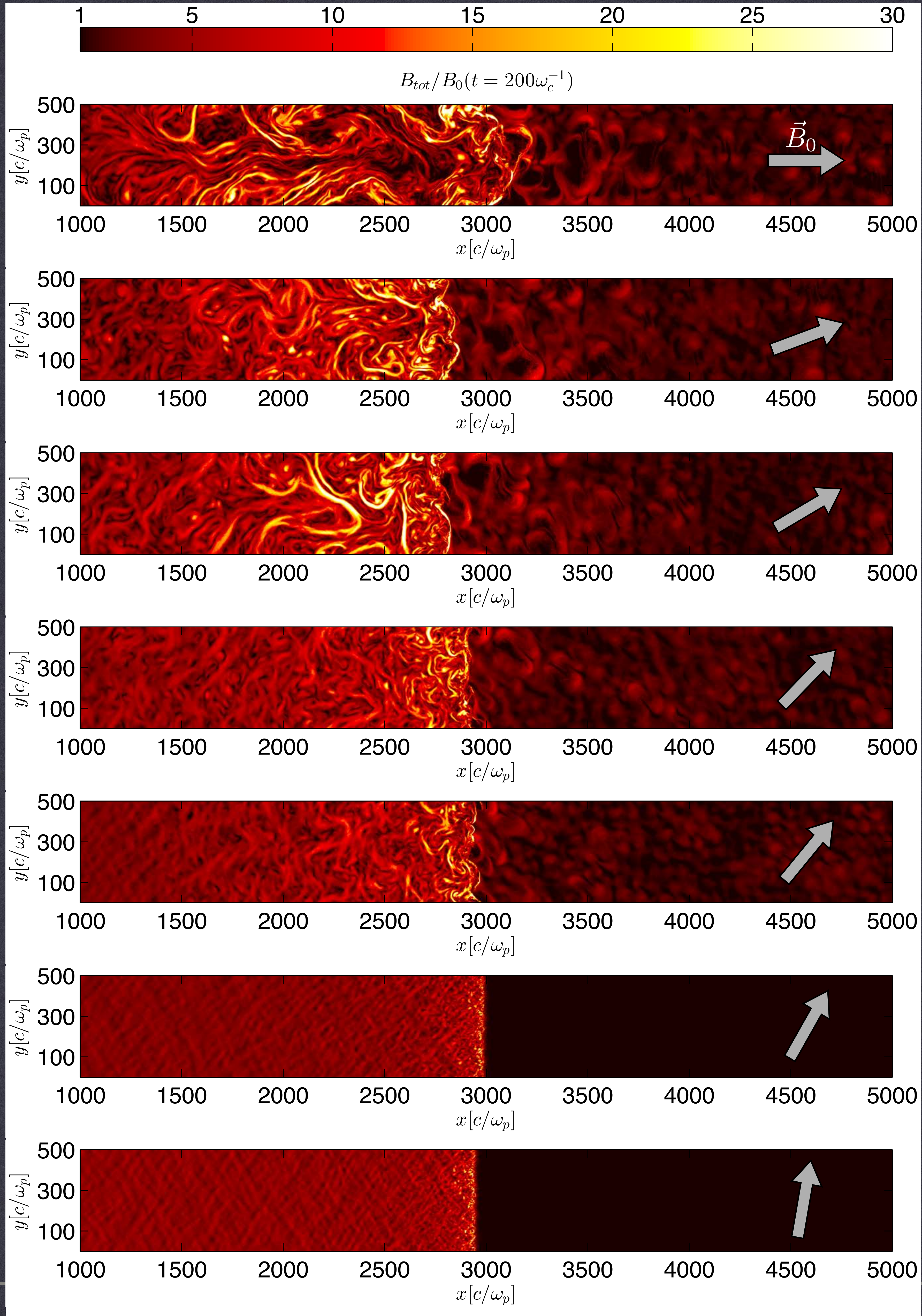
*(Riquelme and A.S. 2009)*

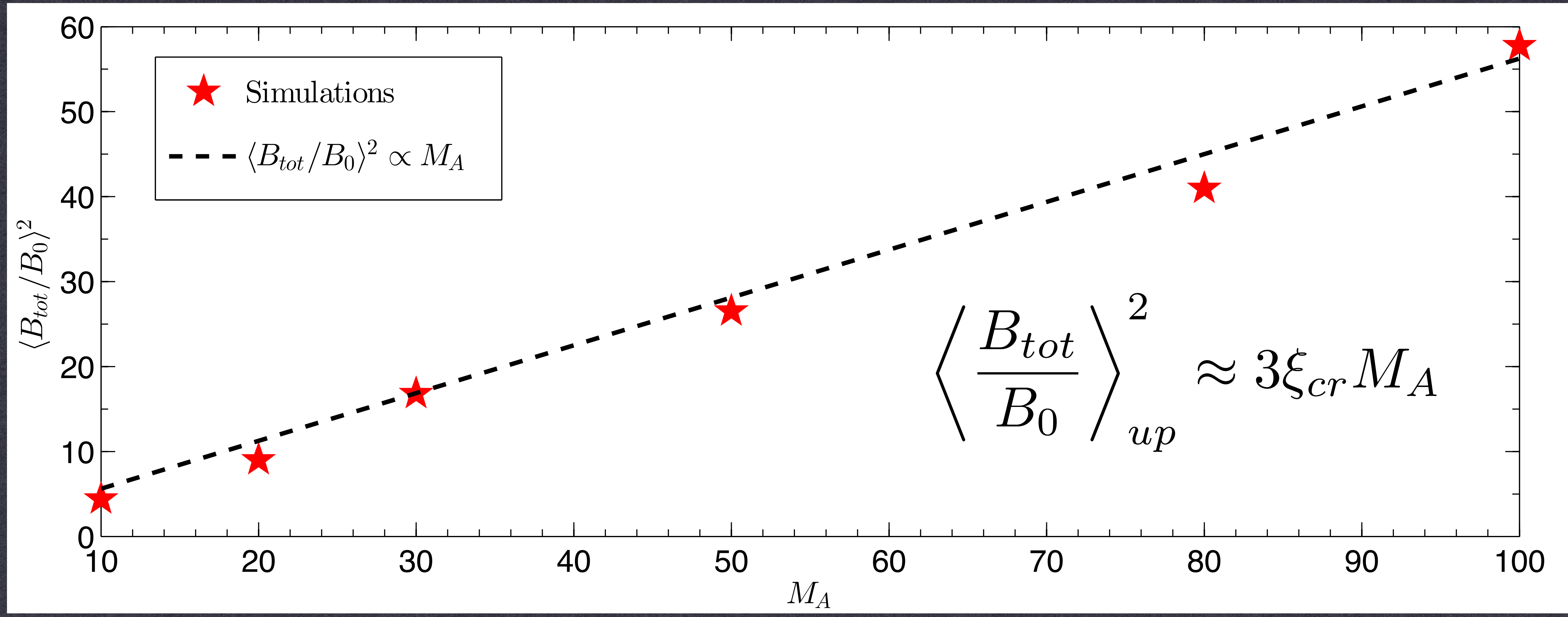



*Field amplification of ~10 in SNRs can be due to Bell's instability*

$p_{xi}$

# Dependence of field amplification on inclination and Mach #

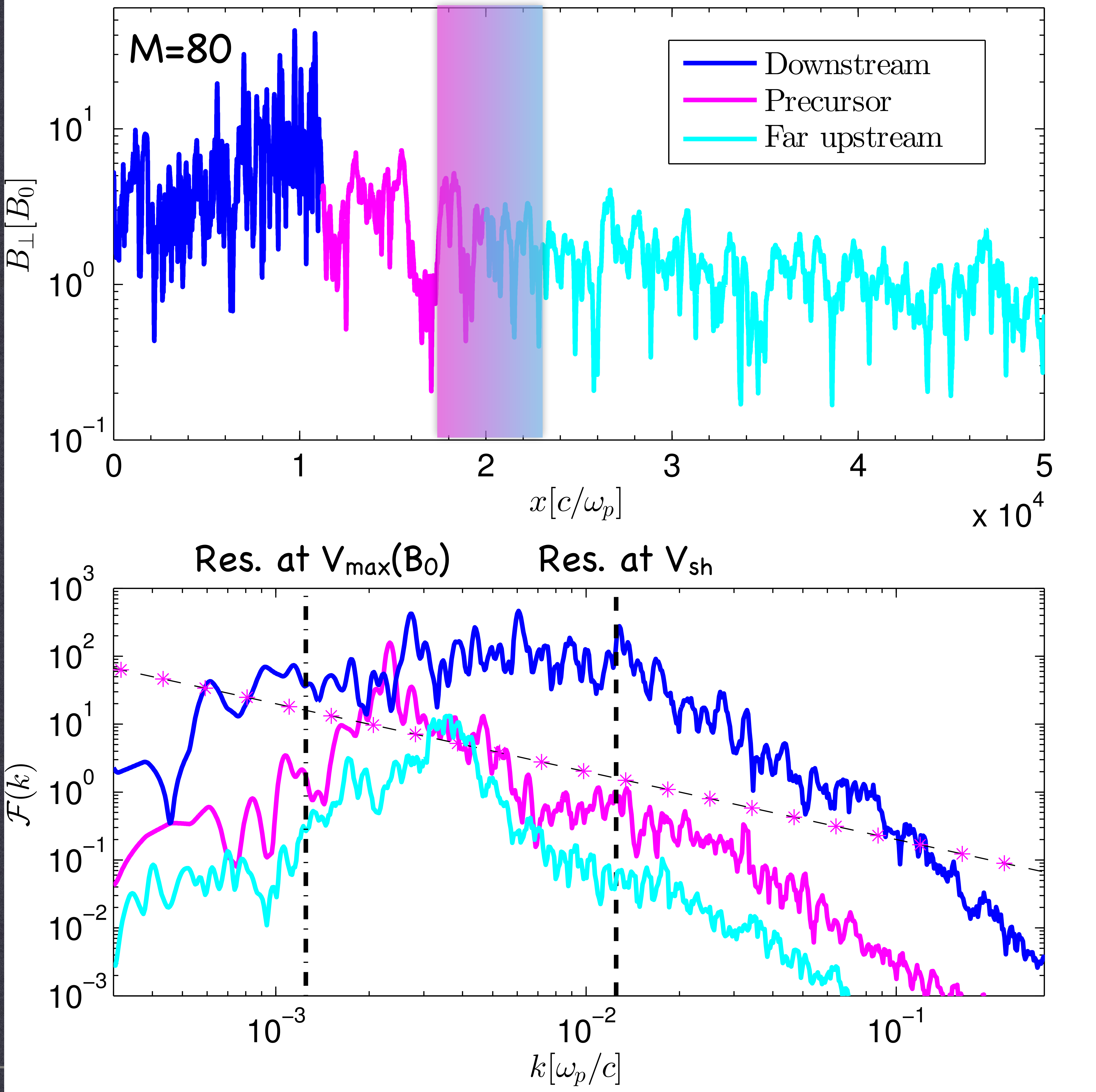



**More B amplification for stronger (higher $M_A$) shocks**

- Different flavors of CR-driven streaming instabilities
  (Amato & Blasi 2009; Caprioli & AS 2014b)
  - For $M_A$<30, resonant (cyclotron)
  - For $M_A$>30, non-resonant (Bell's): strongly non-linear!
- Bohm-like diffusion in the self-generated B
  (Reville & Bell 2013; Caprioli & AS 2014c)

# Magnetic field spectrum, high $M_A$




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

**Free escape boundary**

- Precursor: diffusion + resonant

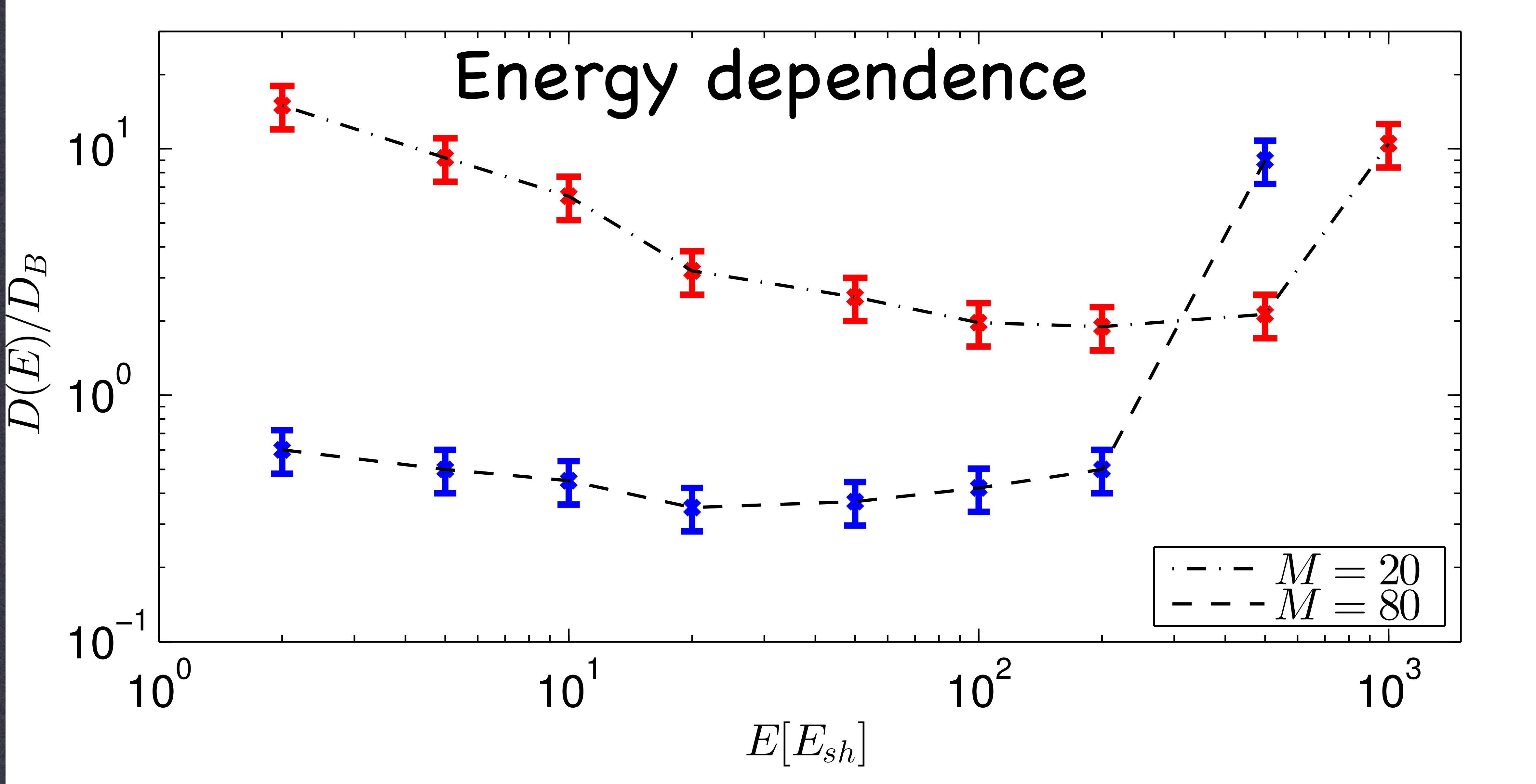
Caprioli & AS, 2014b

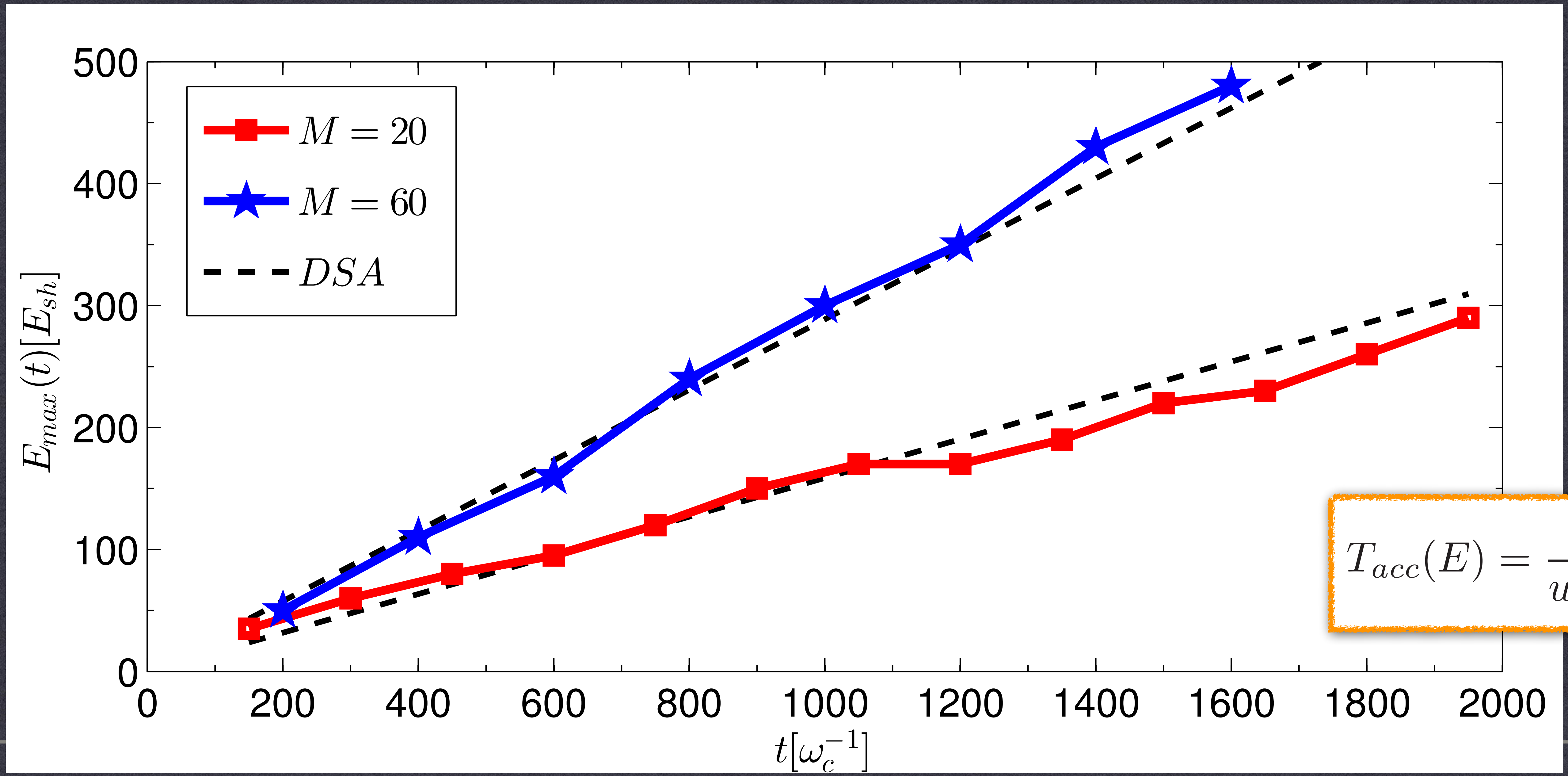
# Diffusion coefficient

- 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



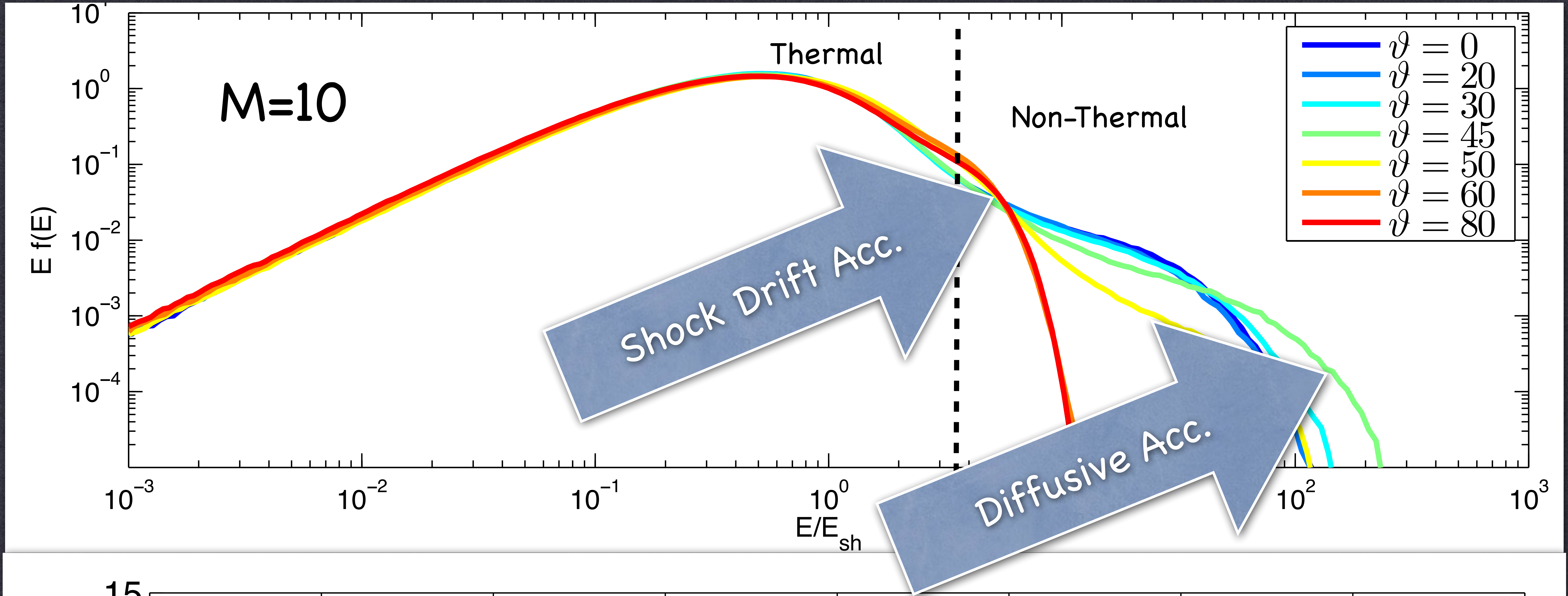



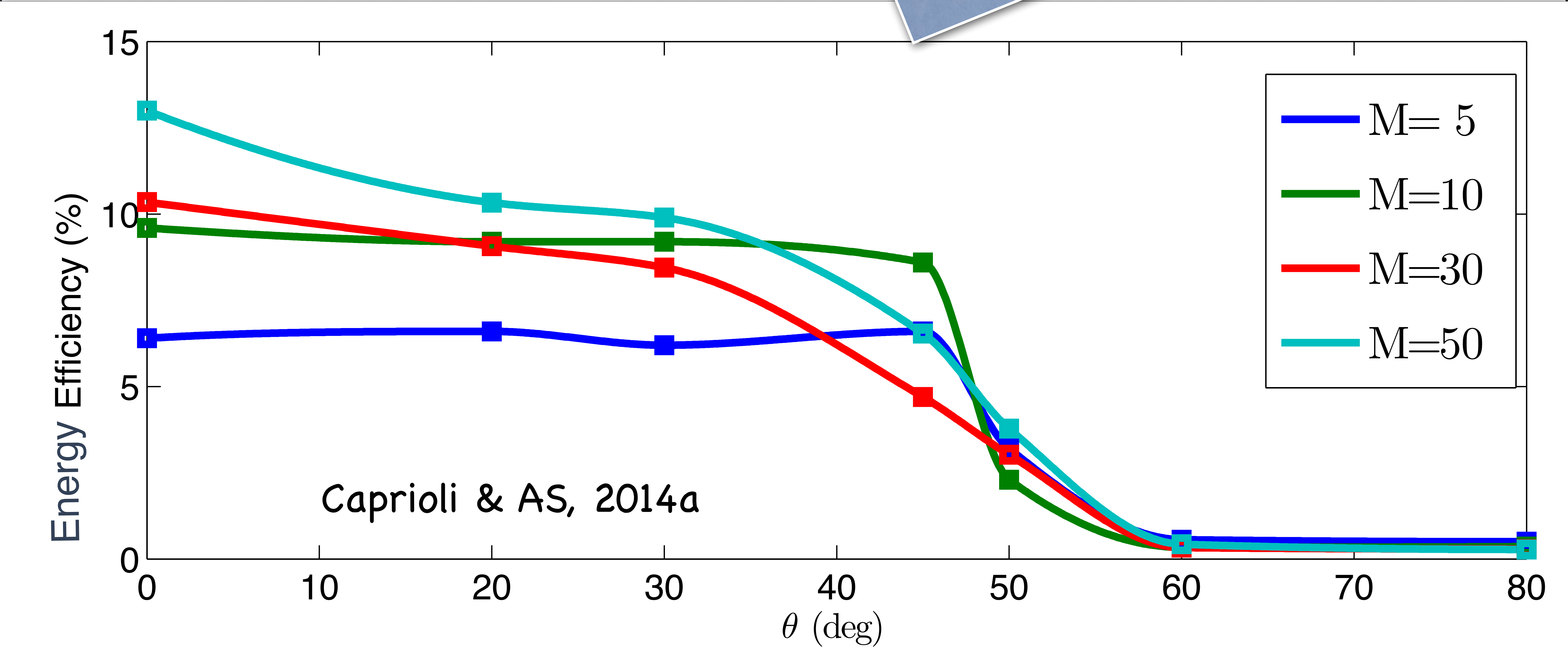

- Evolution of $E_{max}(t)$ according to DSA (e.g., Drury 1983)

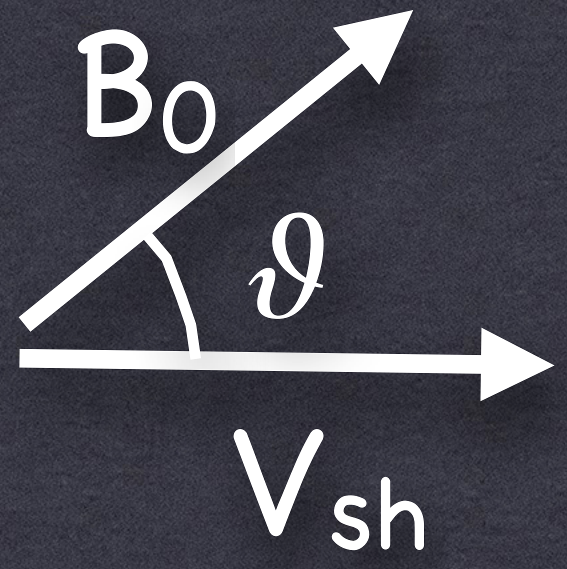
$$T_{acc}(E) = \frac{3}{u_1 - u_2}\left[\frac{D_1(E)}{u_1} + \frac{D_2(E)}{u_2}\right] \simeq \frac{3r^3}{r^2 - 1}\frac{D(E)}{v_{sh}^2}.$$

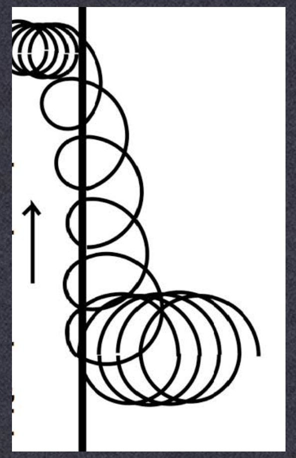
Caprioli & AS, 2014c

# ACCELERATION IN PARALLEL VS OBLIQUE SHOCKS



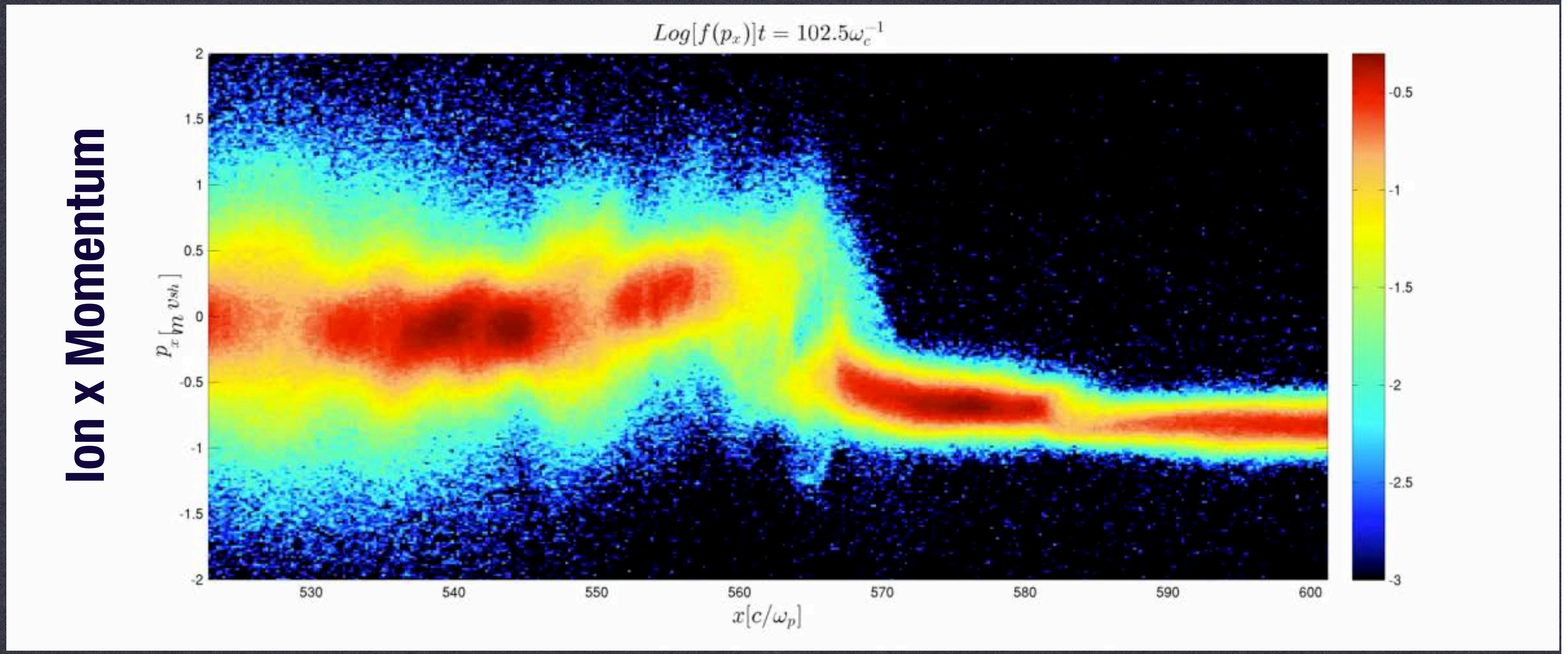



**About 1% accelerated protons by number, what is causing that?**

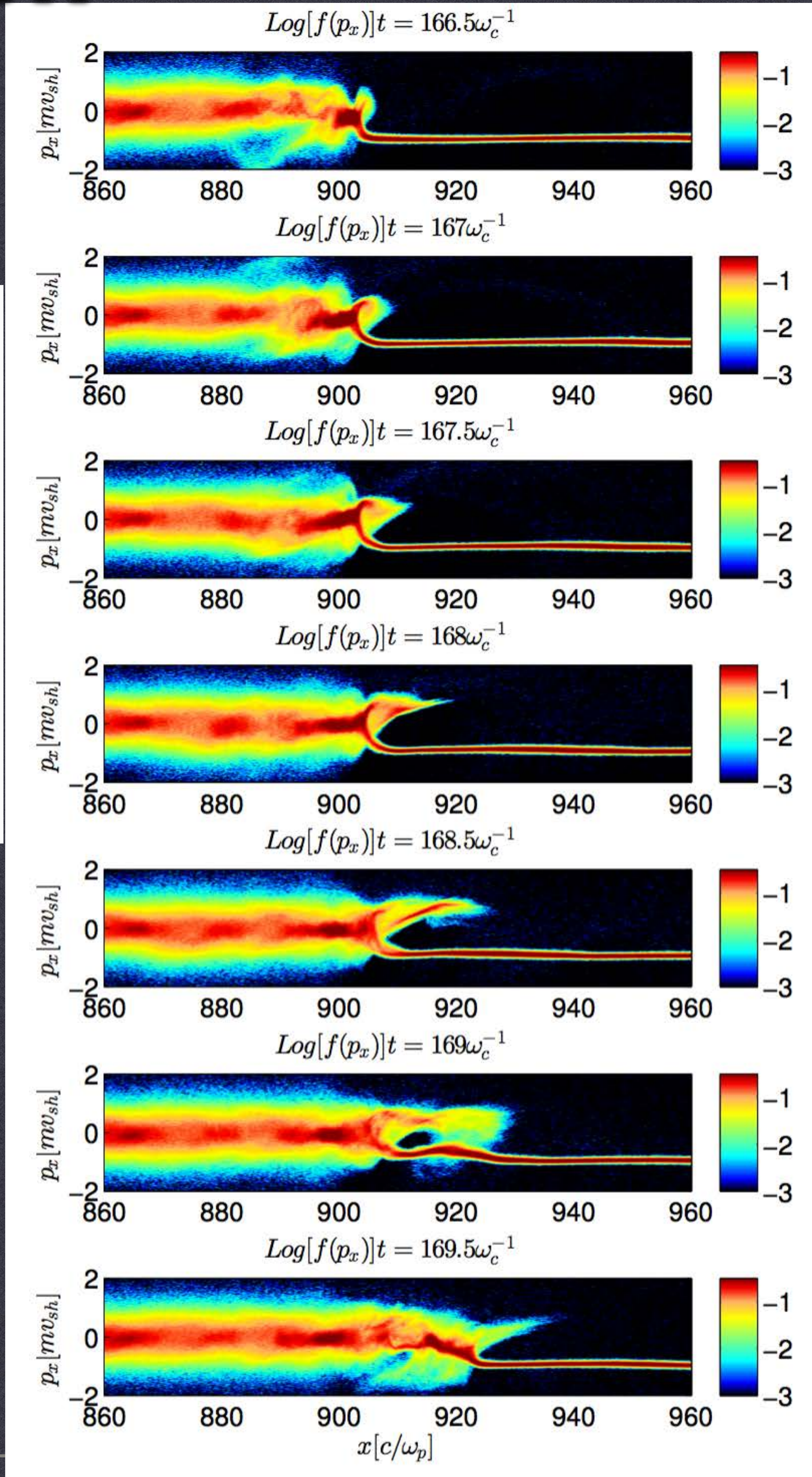
# Shock structure & injection

Quasiparallel shocks look like intermittent, reforming quasiperpendicular shocks



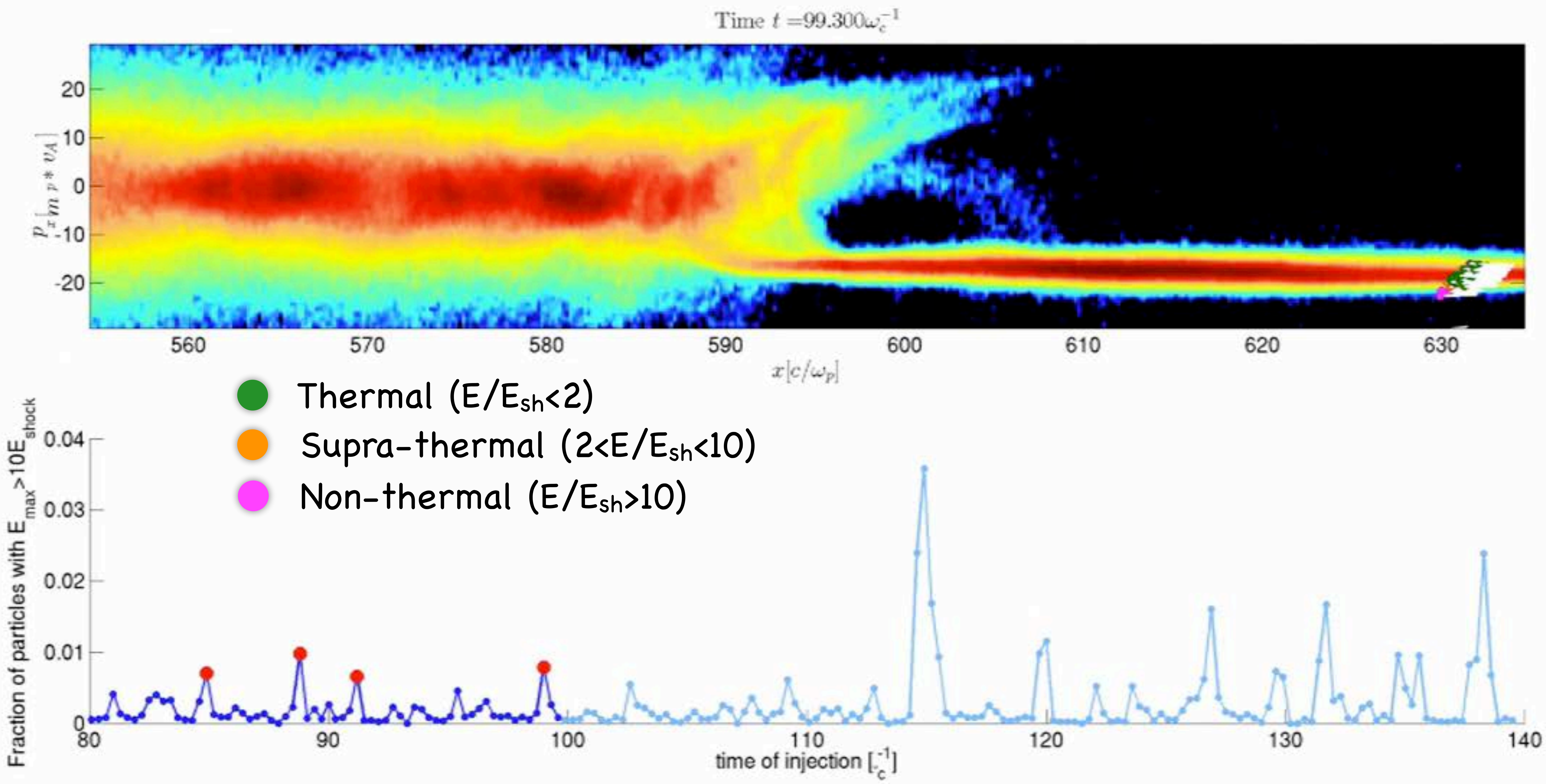

Injection of ions happens on first crossing due to specular reflection from reforming magnetic and electric barrier and shock-drift acceleration.

Multiple cycles in a time-dependent shock structure result in injection into DSA; no “thermal leakage” from downstream (Pop, Caprioli, AS 15).



# Injection mechanism: importance of timing

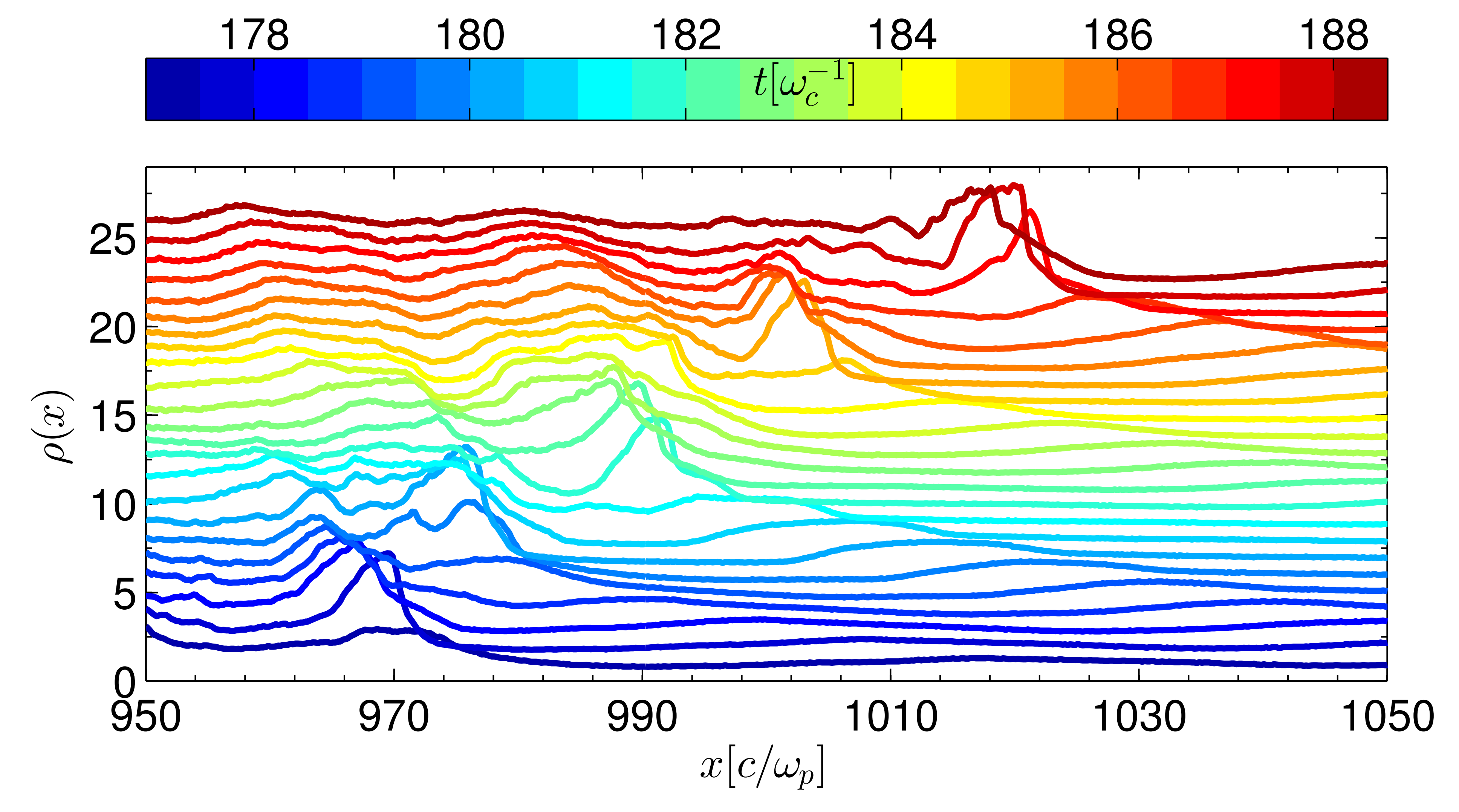
Caprioli, Pop & AS 2015



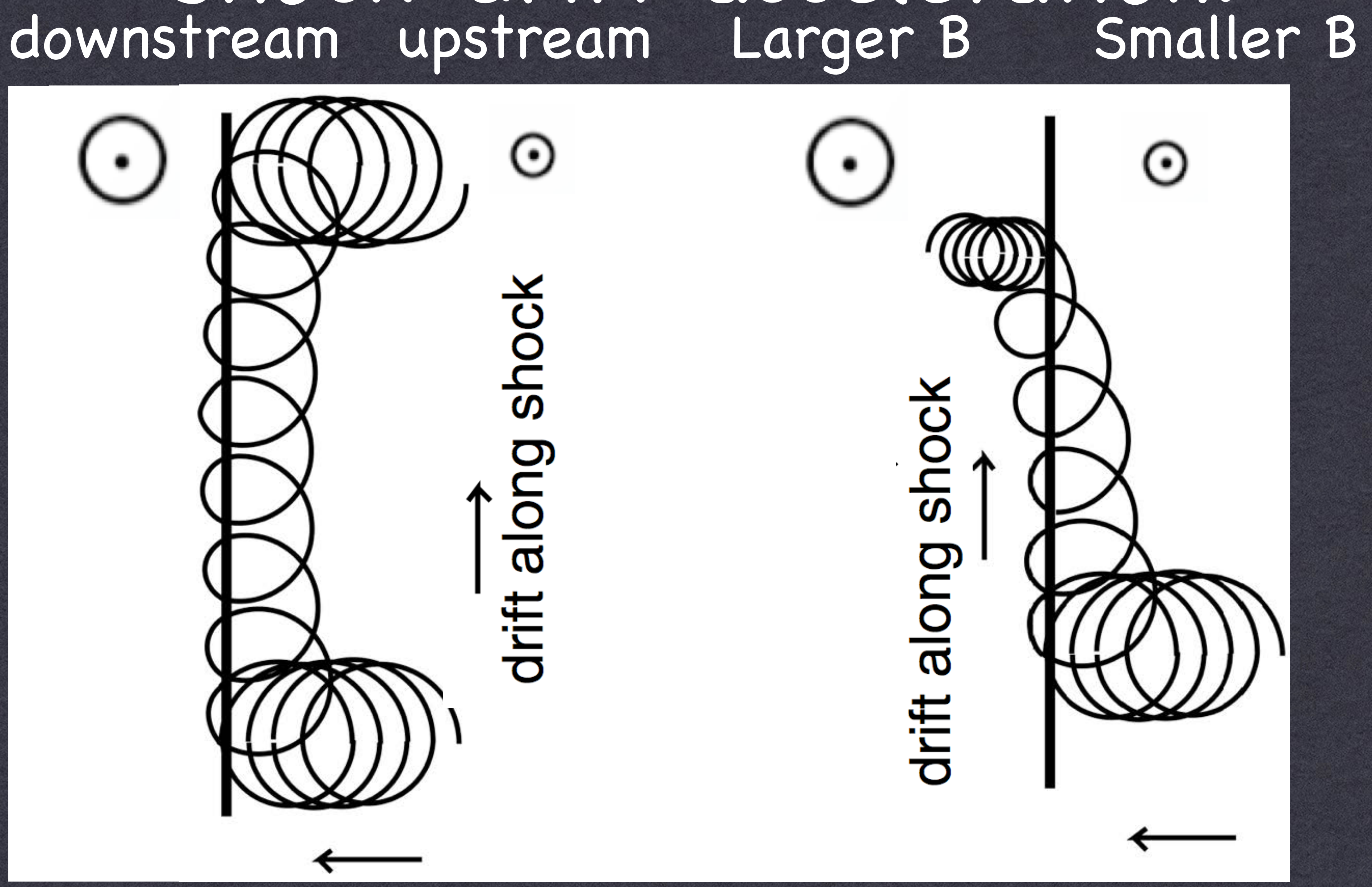
Caprioli, Pop & AS 2015

# Ion injection: theory

- 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



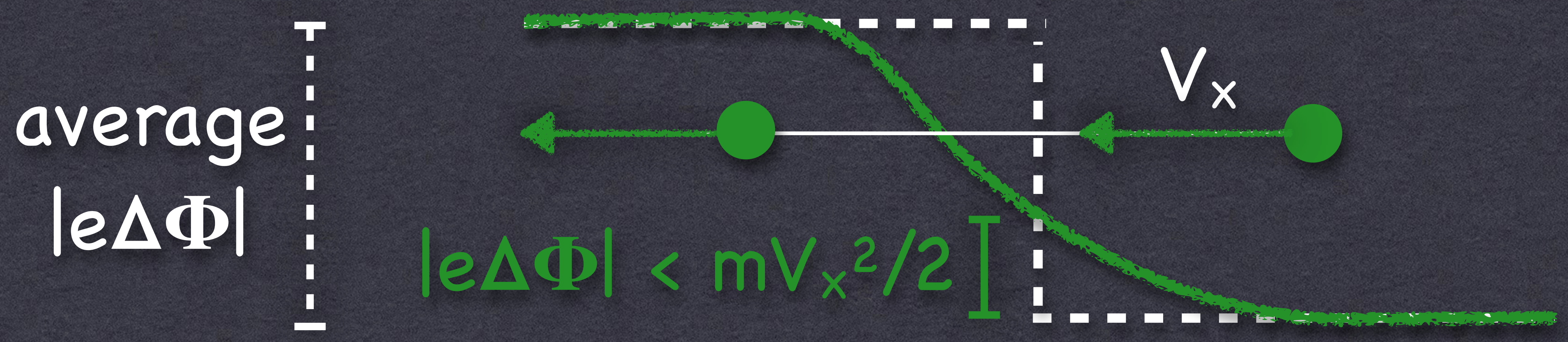

Shock-drift acceleration:




Path of incoming particle

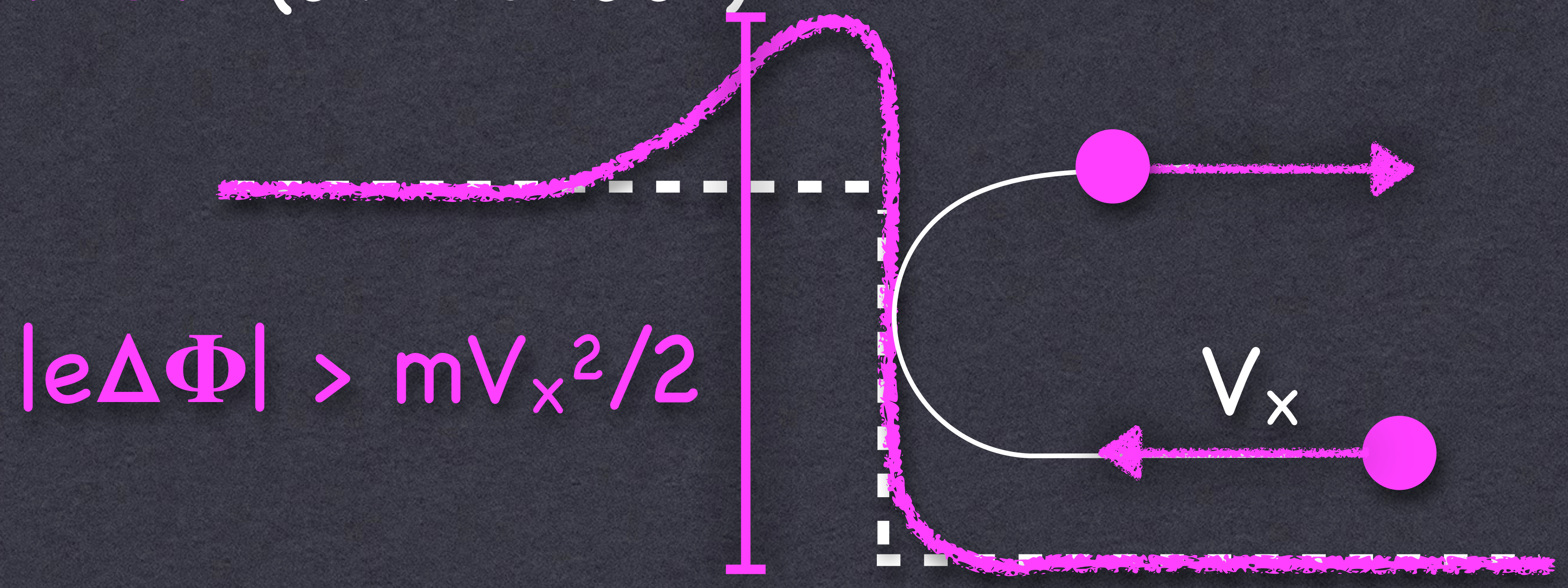
# Encounter with the shock barrier

- 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 $\vartheta$
- 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 $\vartheta=45^{\circ}$, $E_{inj}\sim 10E_0$, which requires N~3 -> $\eta\sim 1\%$

# Encounter with the shock barrier

- Low barrier (shock reforming)

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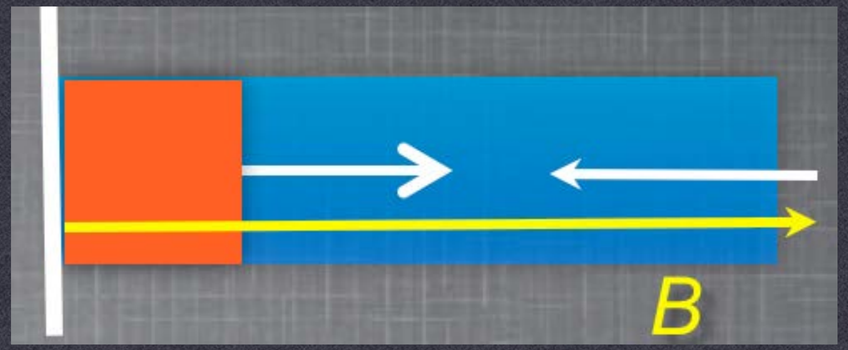
- High

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; need to expand it to relativistic case

- To c
- Part
- Afte
- For $\vartheta=45^{\circ}$, $E_{inj}$~$10E_0$, which requires N~3 -> η~1%

# Quasiparallel shocks: electron acceleration



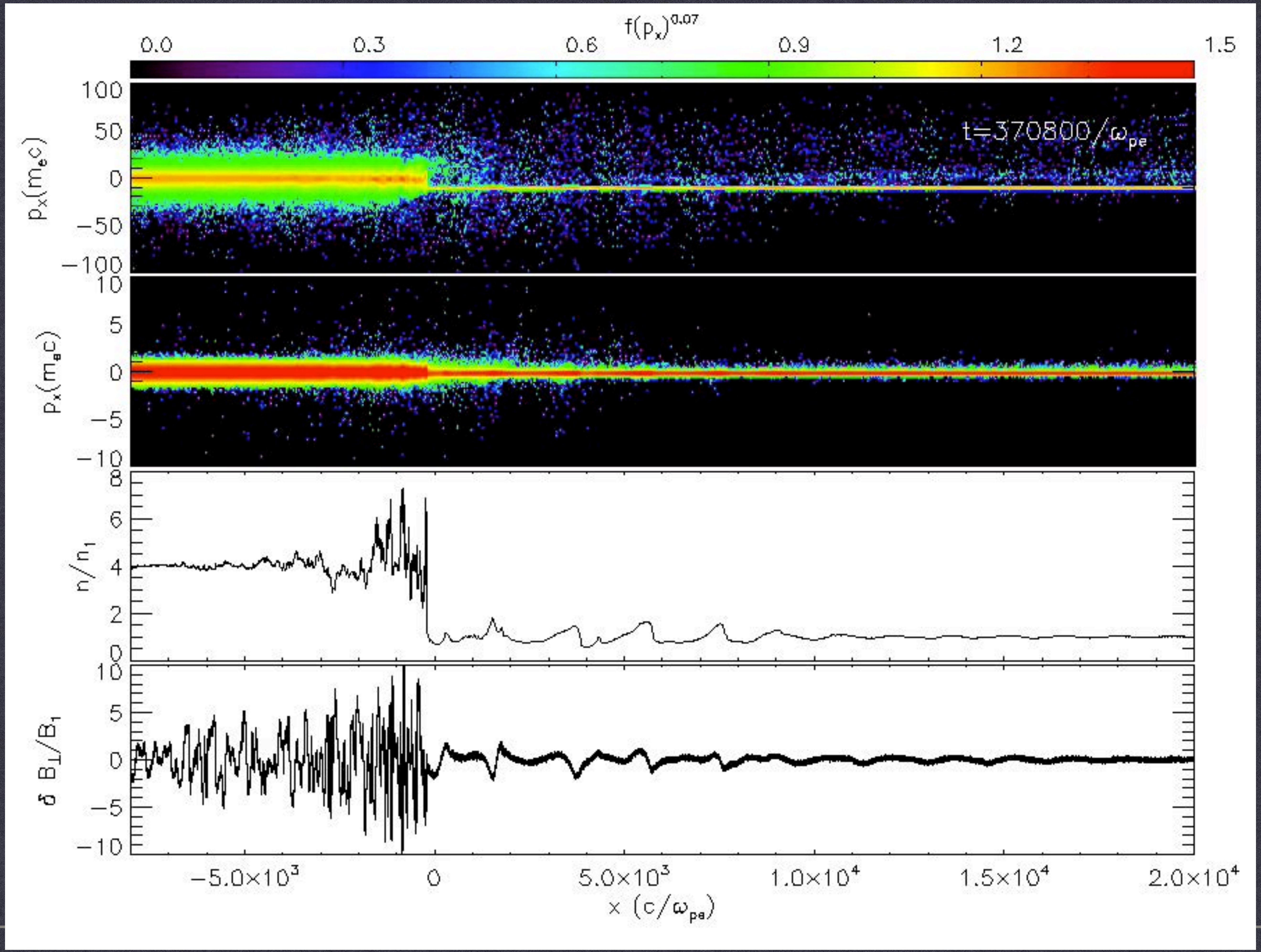

Recent evidence of electron acceleration in quasi parallel shocks.
PIC simulation of quasiparallel shock. Very long simulation in 1D.
Alfven Mach = Sonic Mach = 20; mi/me=100-400;
Ion-driven Bell waves drive electron acceleration: correct polarization

Ion phase space

Electron phase space

Density

Transverse Magnetic field



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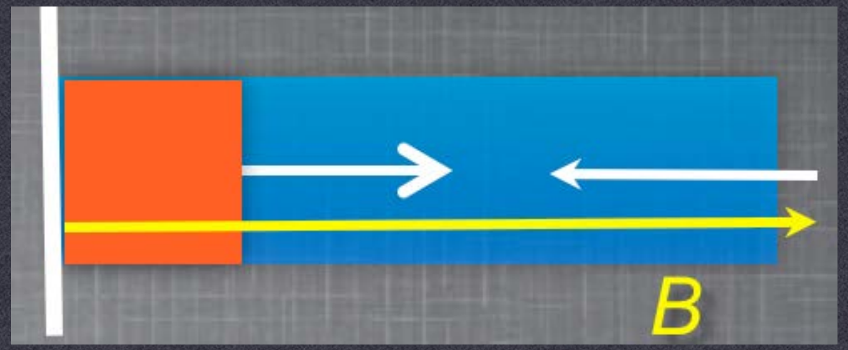
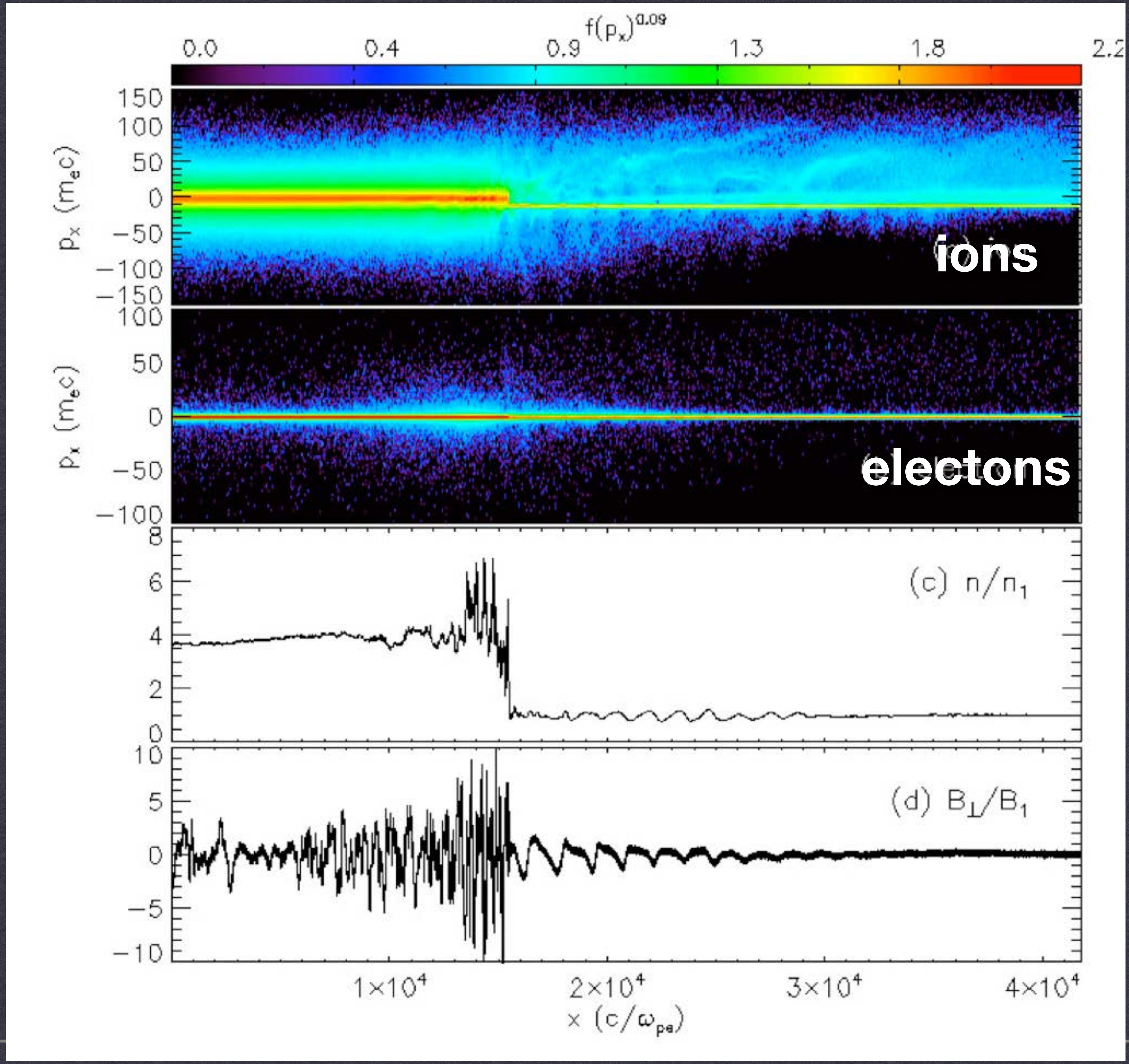
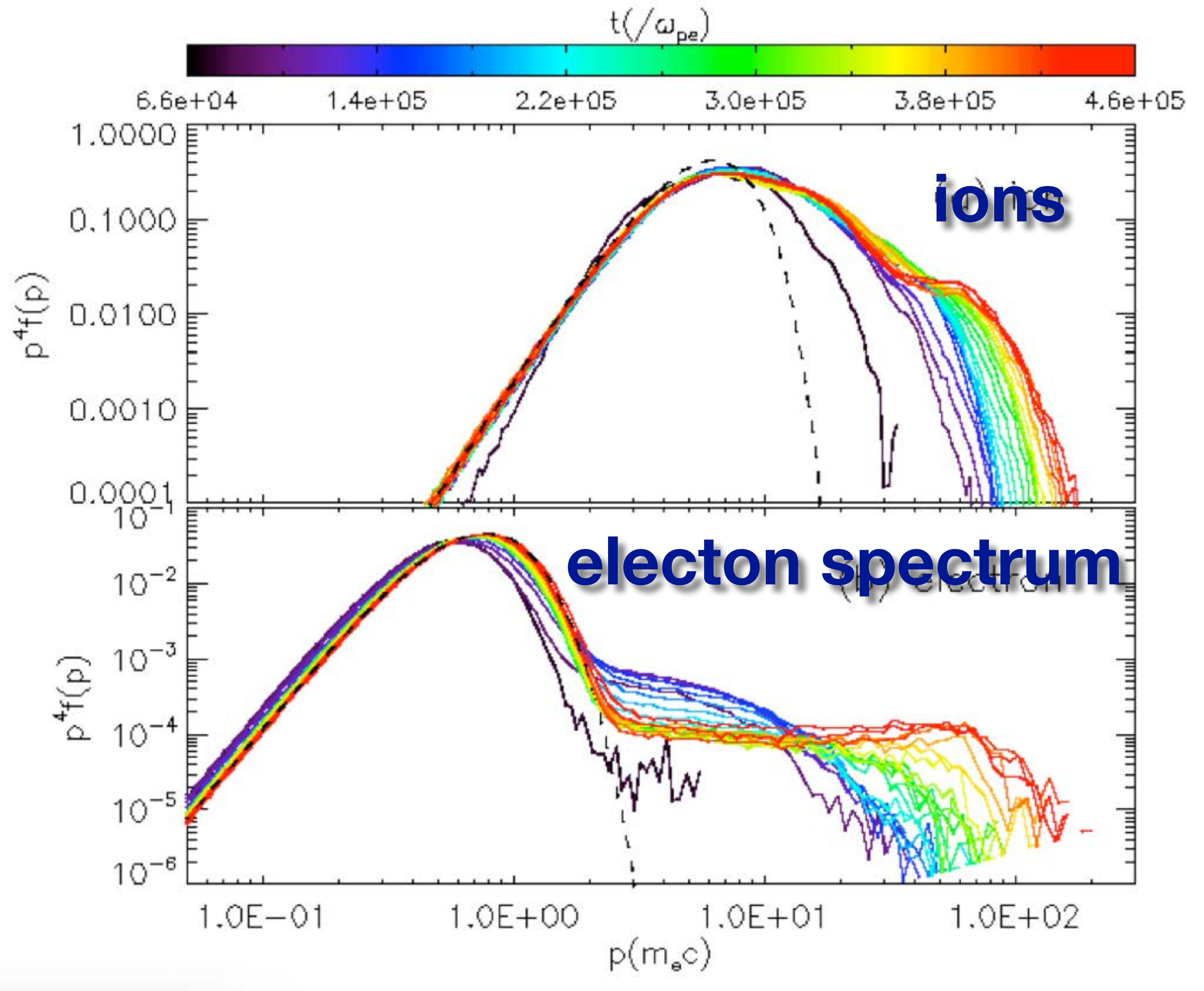


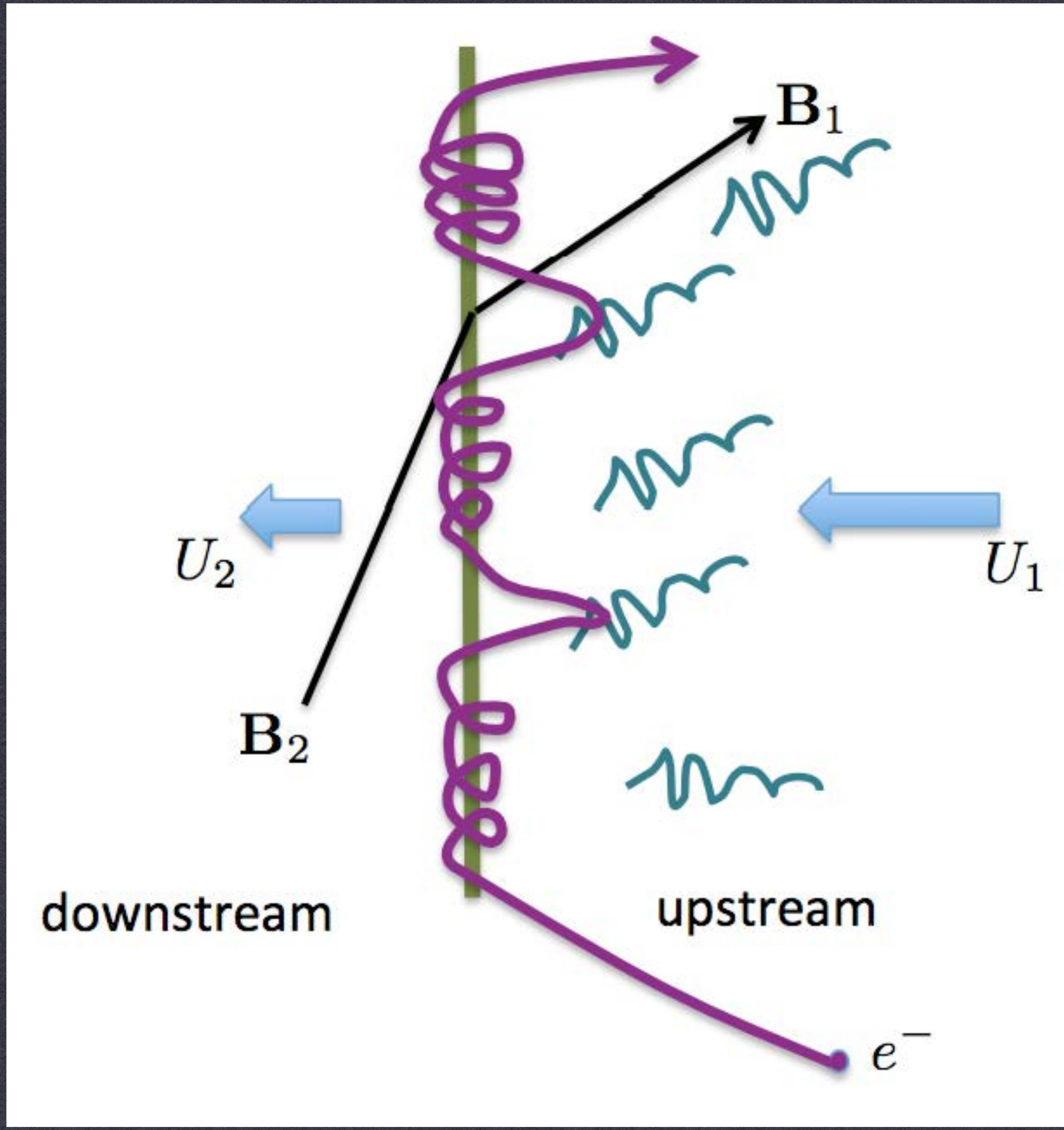




DSA spectrum recovered in _both_ electrons and ions. Electron-proton ratio obtained: $\mathbf{K_{ep}=10^{-3}\ \text{-}10^{-2}}$

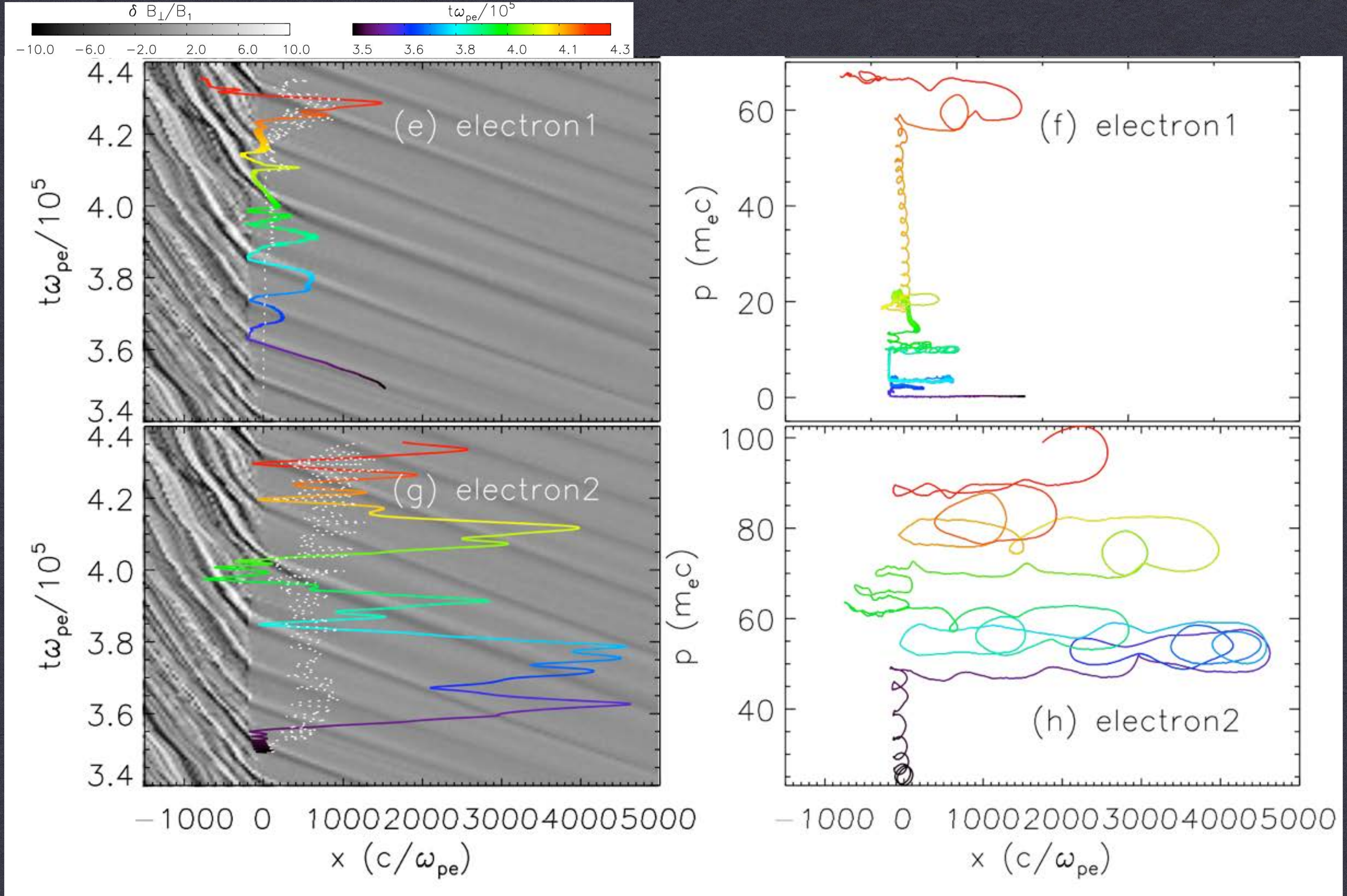
*Park, Caprioli, AS (2015)*

# 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+ diffusion in upstream



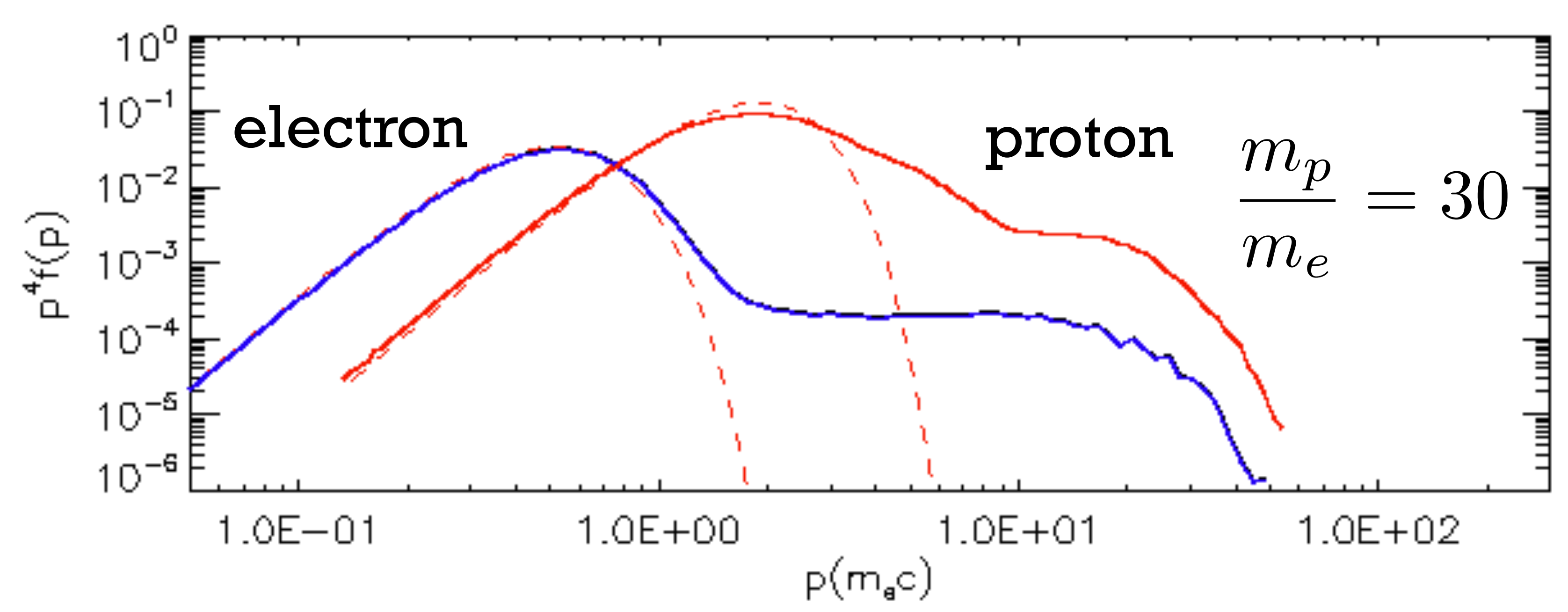

Shock-drift

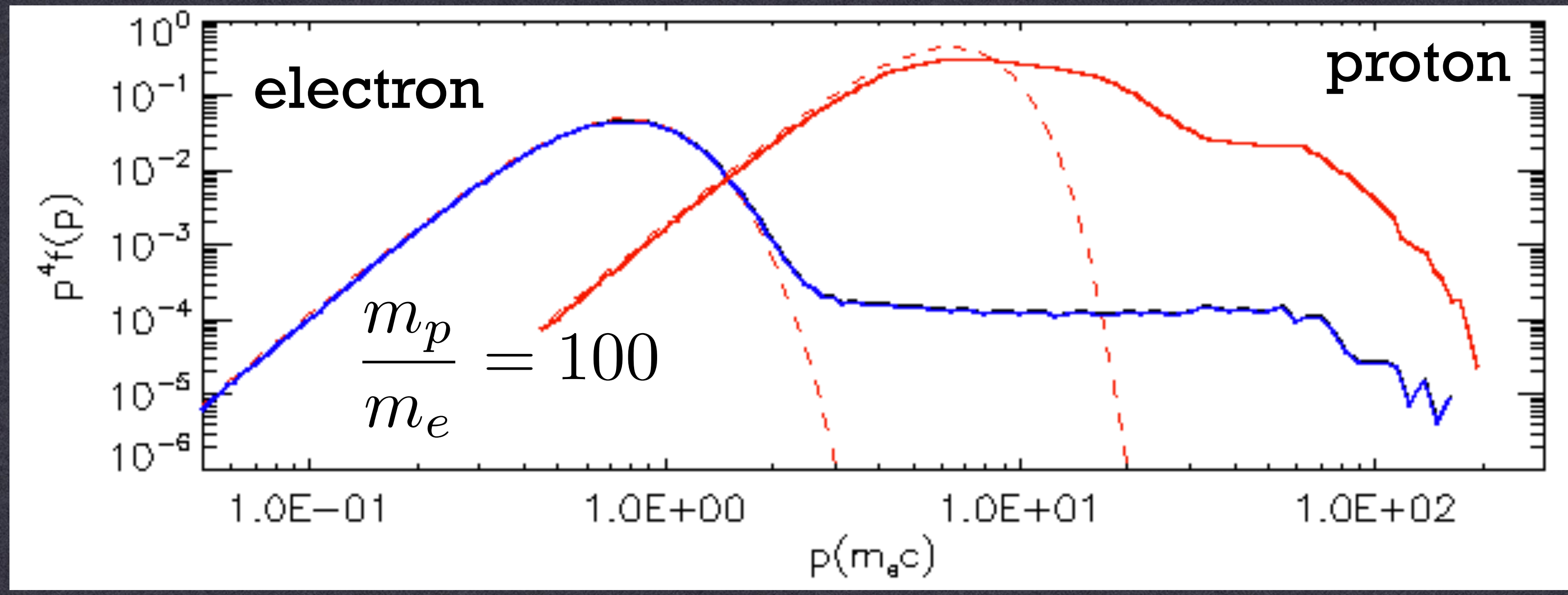
Diffusive

Electron track from PIC simulation.

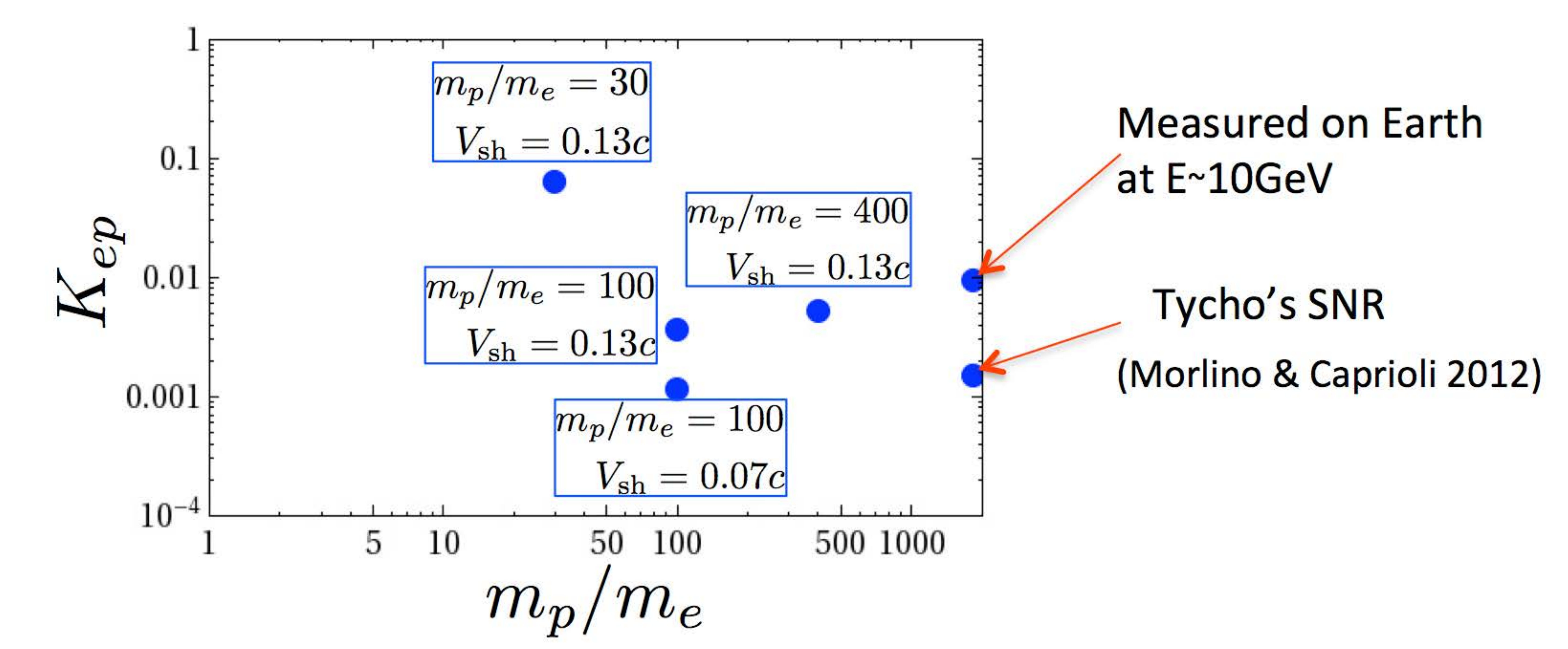
# Electron-proton ratio $K_{ep}$:

*Park, Caprioli, AS (2015)*

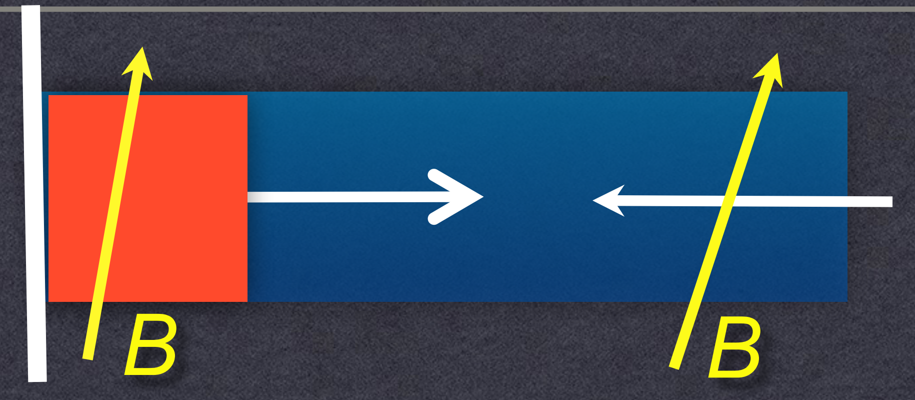


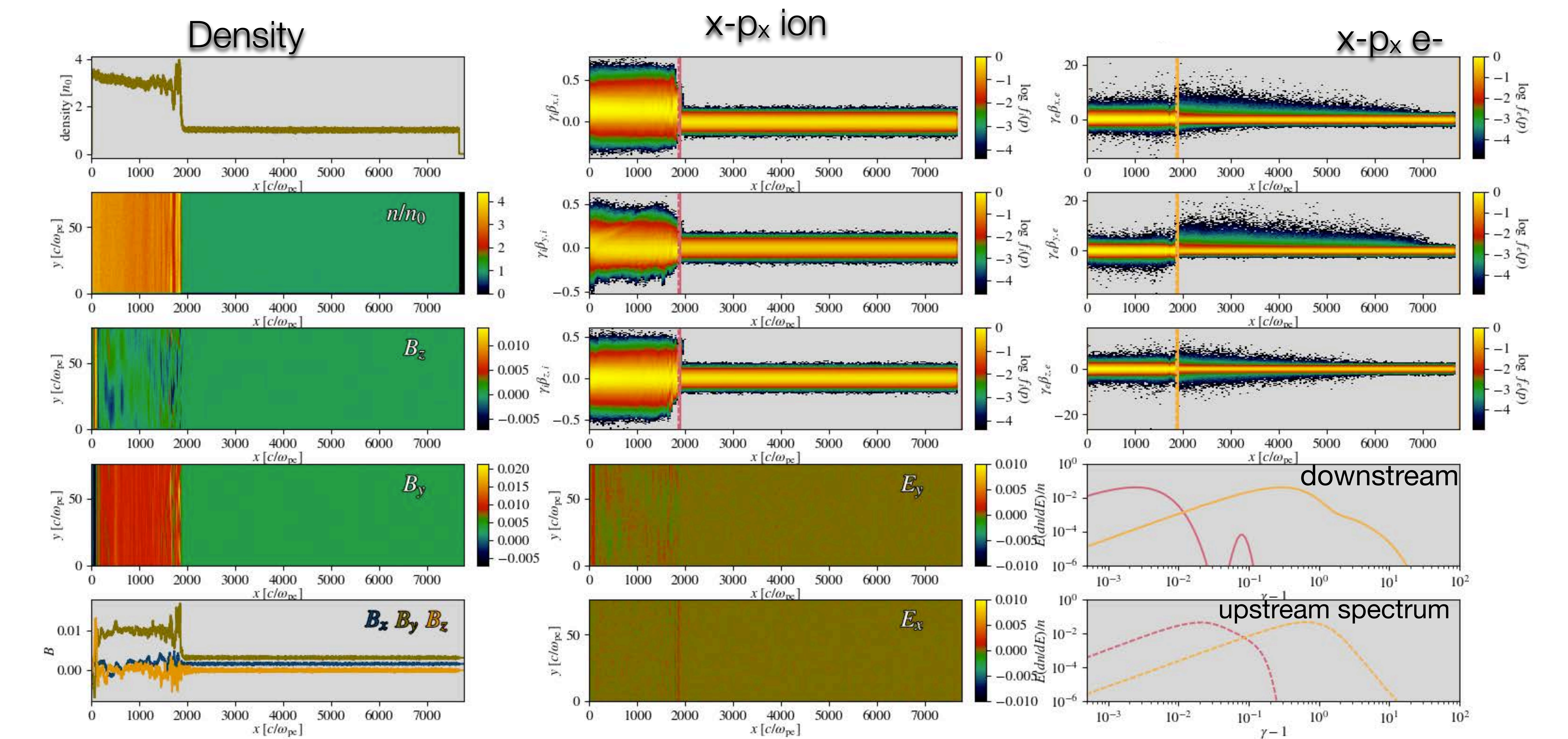

$$K_{\rm ep} \equiv \frac{f_e(p)}{f_p(p)} = \text{const for } p > p_{\rm inj} \quad K_{\rm ep} \approx 3.8 \times 10^{-3} \text{ for } \frac{m_p}{m_e} = 100$$



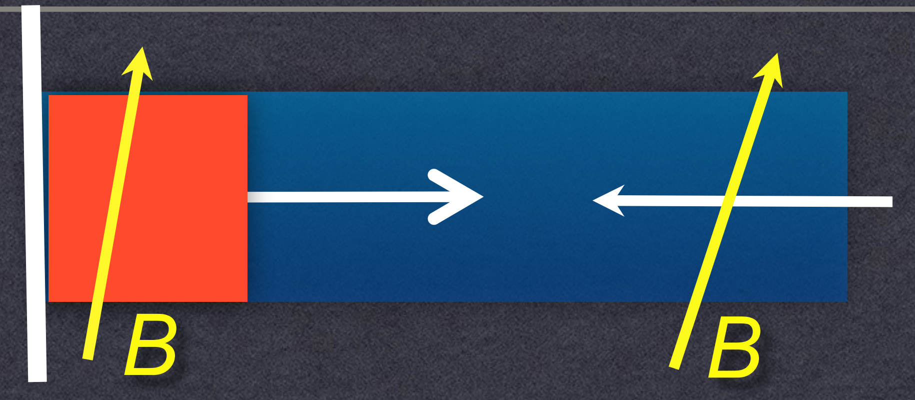
# Quasiperpendicular shocks: electron acceleration




**Low sonic Mach # = 2; 63 degrees shock inclination, mi/me=100, $M_A$=12. Reflected electrons and electron-driven waves upstream. Growth of nonthermal tail in electrons. First obtained by Guo, Sironi, Narayan (2014); also see Kang et al (2019)**



# Quasiperpendicular shocks: electron acceleration

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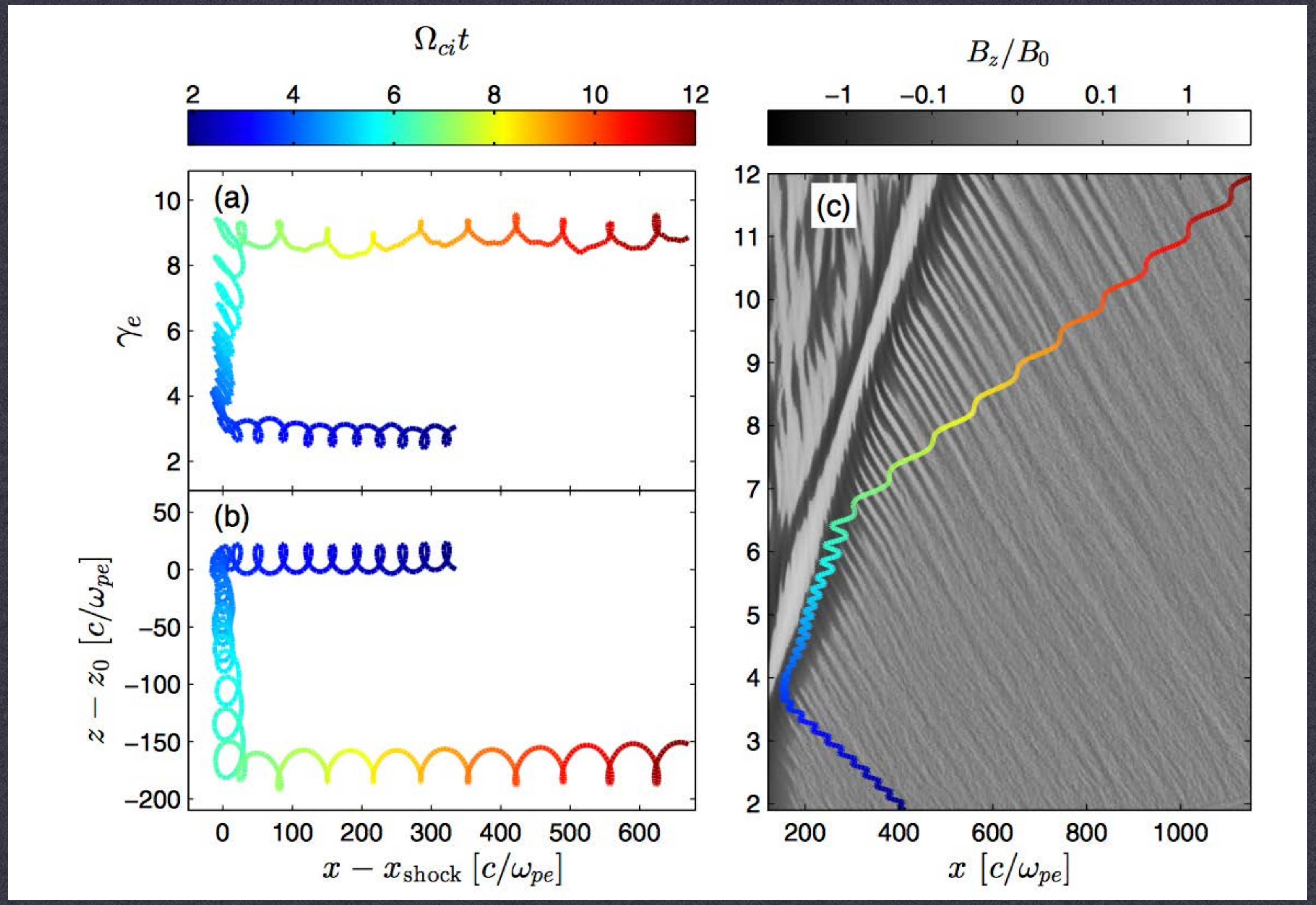
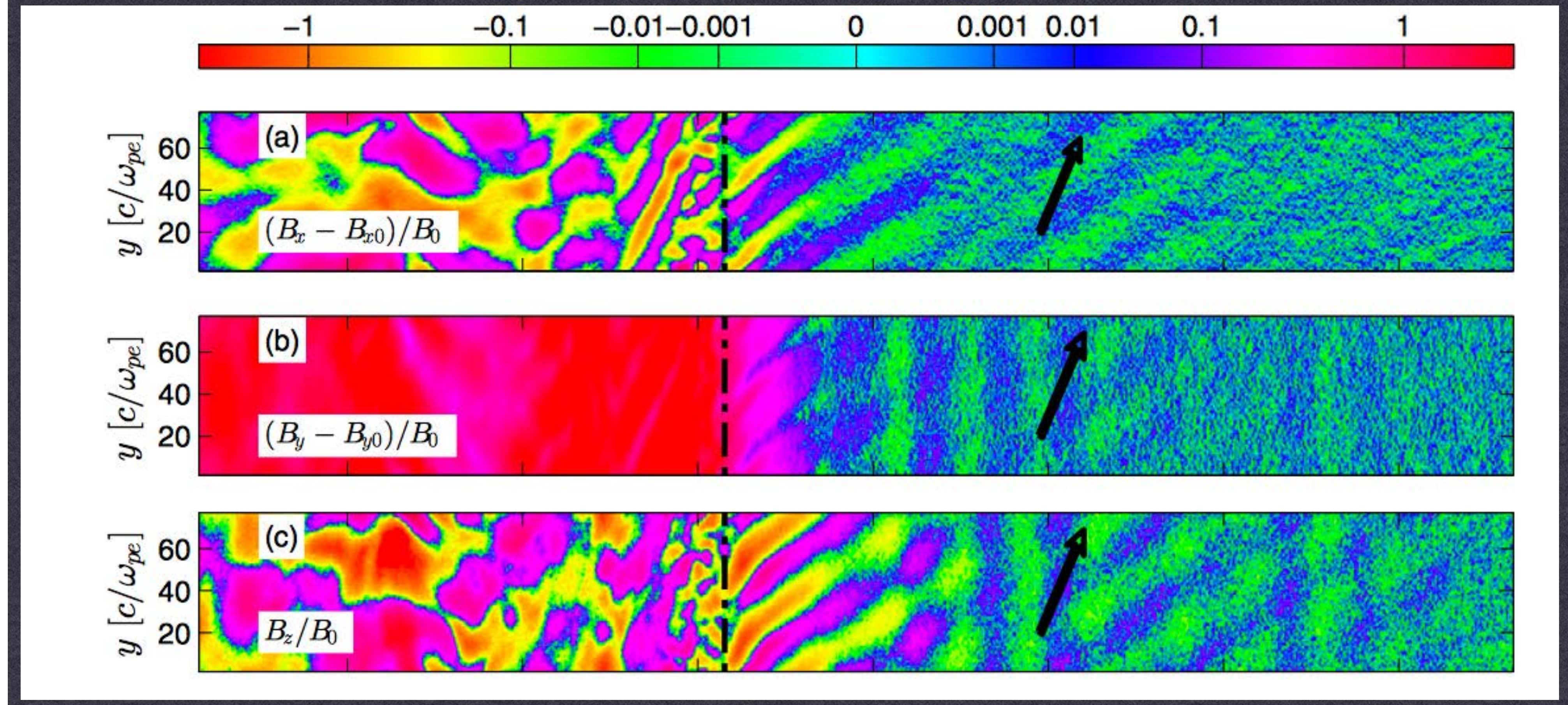
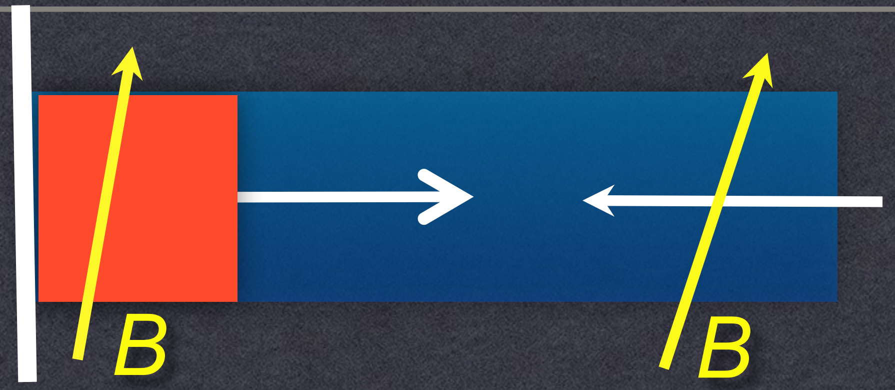


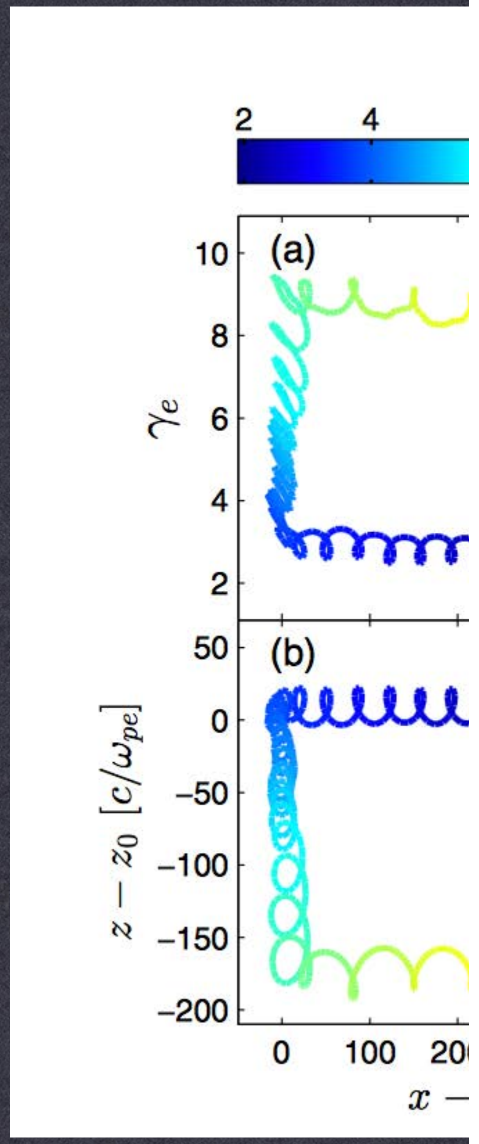



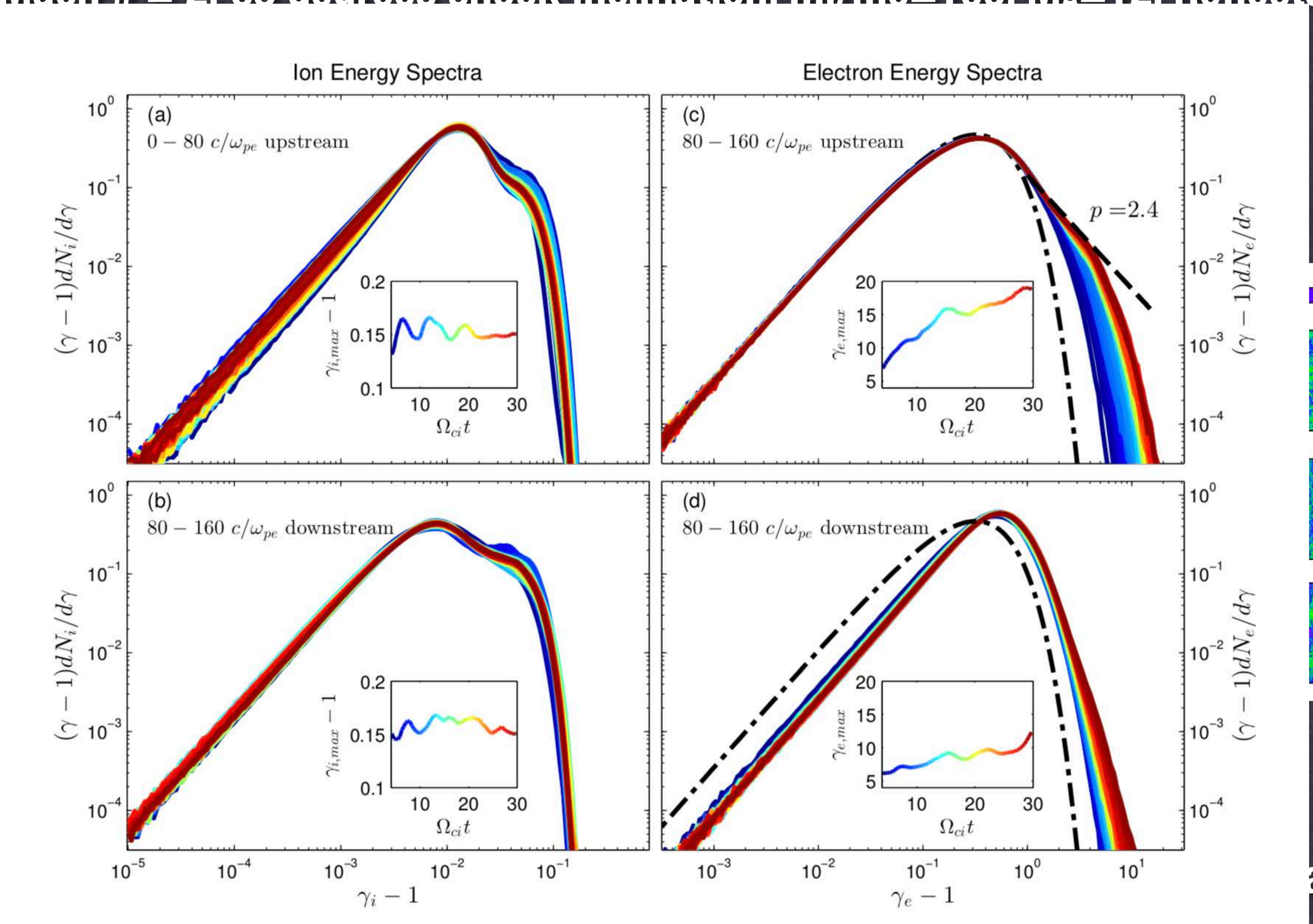

Hot electrons can mirror from the shock and enter shock drift cycle. As they leave towards the upstream they drive waves (electron firehose(?) or non-resonant streaming waves). These waves eventually bring the particles back. NB: no nonthermal ions!

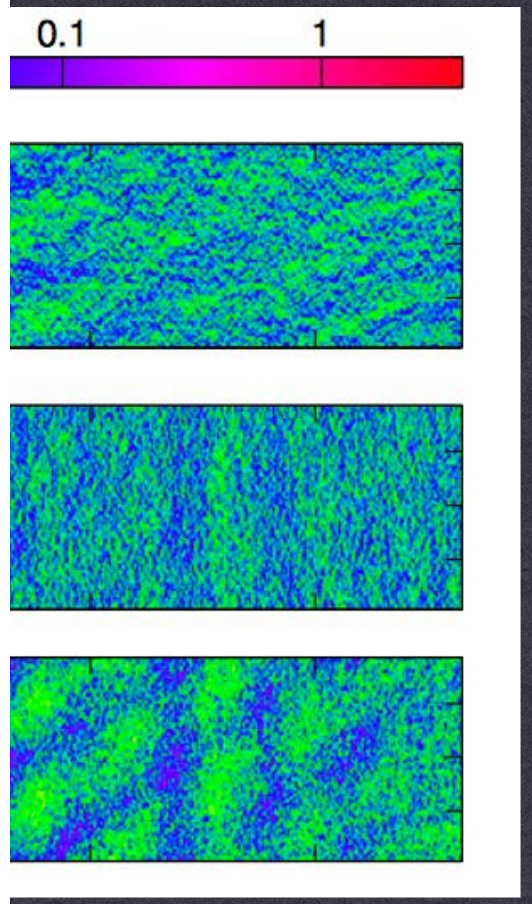
# Quasiperpendicular shocks: electron acceleration




**Low sonic Mach # = 2; 63 degrees shock inclination, mi/me=100, $M_A$=12. Reflected electrons a**
**First obtain**



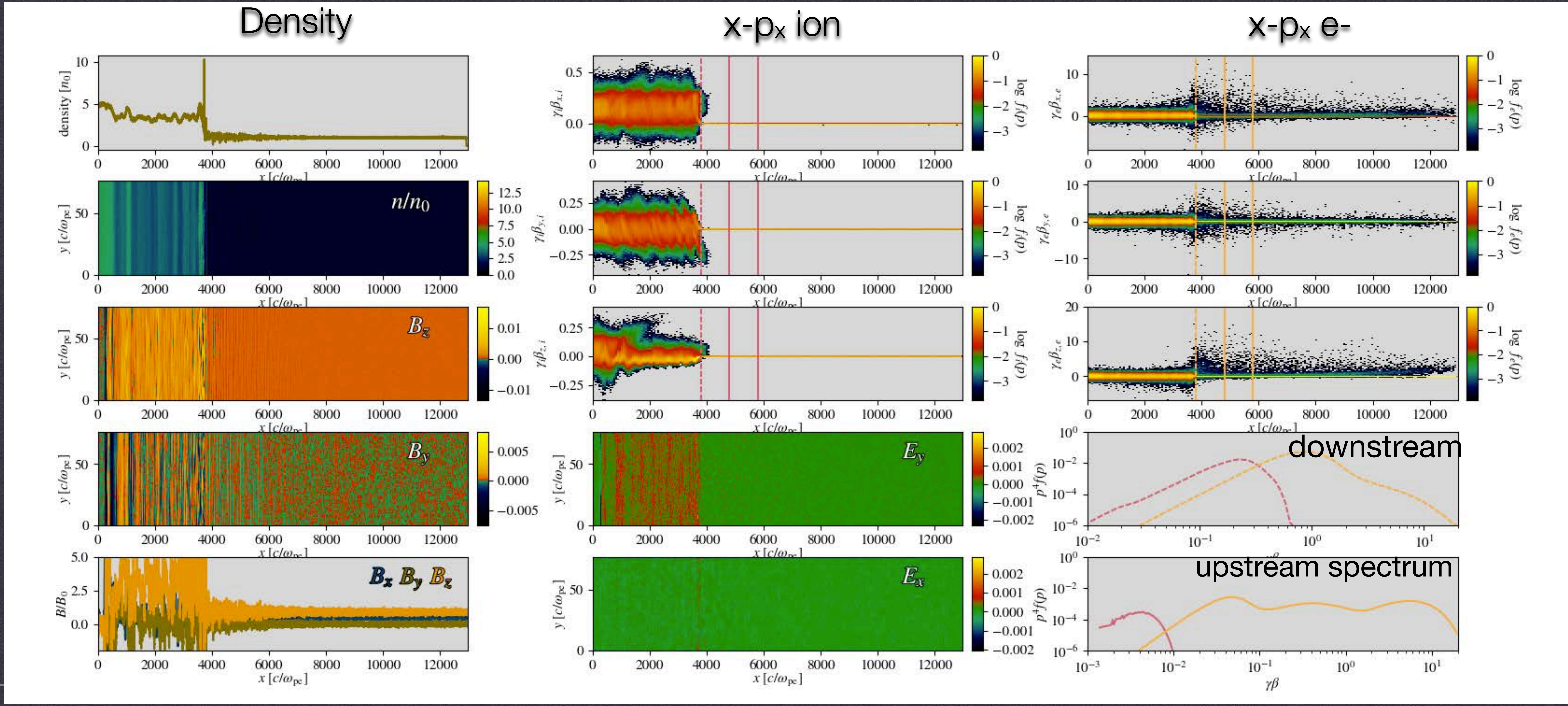



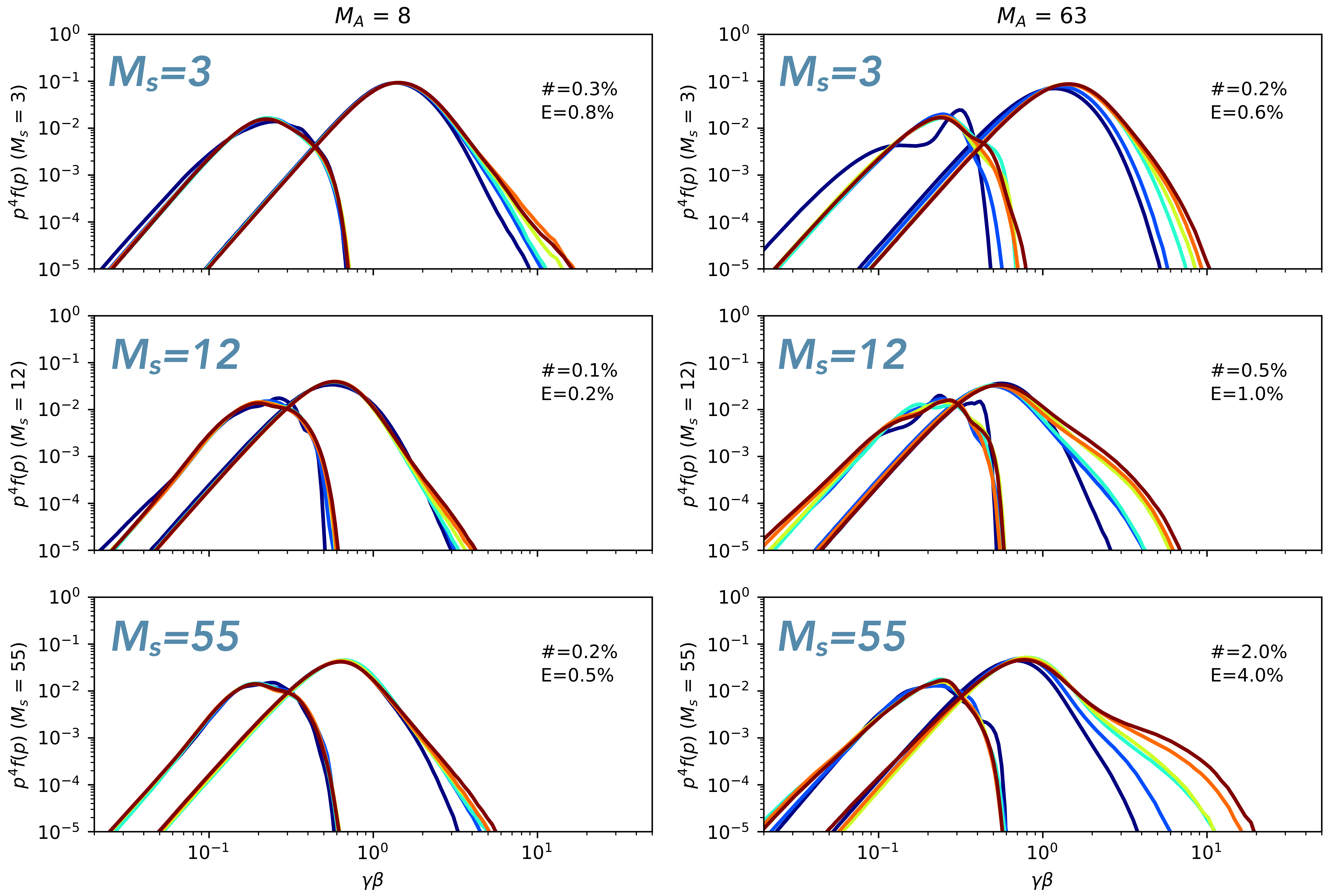

**Hot electron … towards the upstrear … aves).**
**These waves eventually bring the particles back. NB: no nonthermal ions!**

# Quasiperpendicular shocks: electron acceleration

**We tried it at higher Mach numbers: Sonic Mach # = Alfvenic = 50; 63 degrees shock inclination, mi/me=100. (Xu, Caprioli, AS in prep). Acceleration proceeds even with cold upstream. Electrons are pre-heated before the shock by ion ring instabilities.**

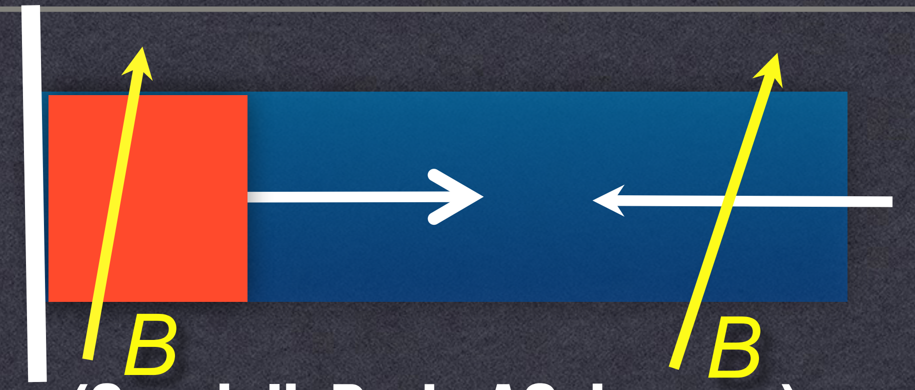


# Downstream spectra for a range of $M_A$ and $M_s$

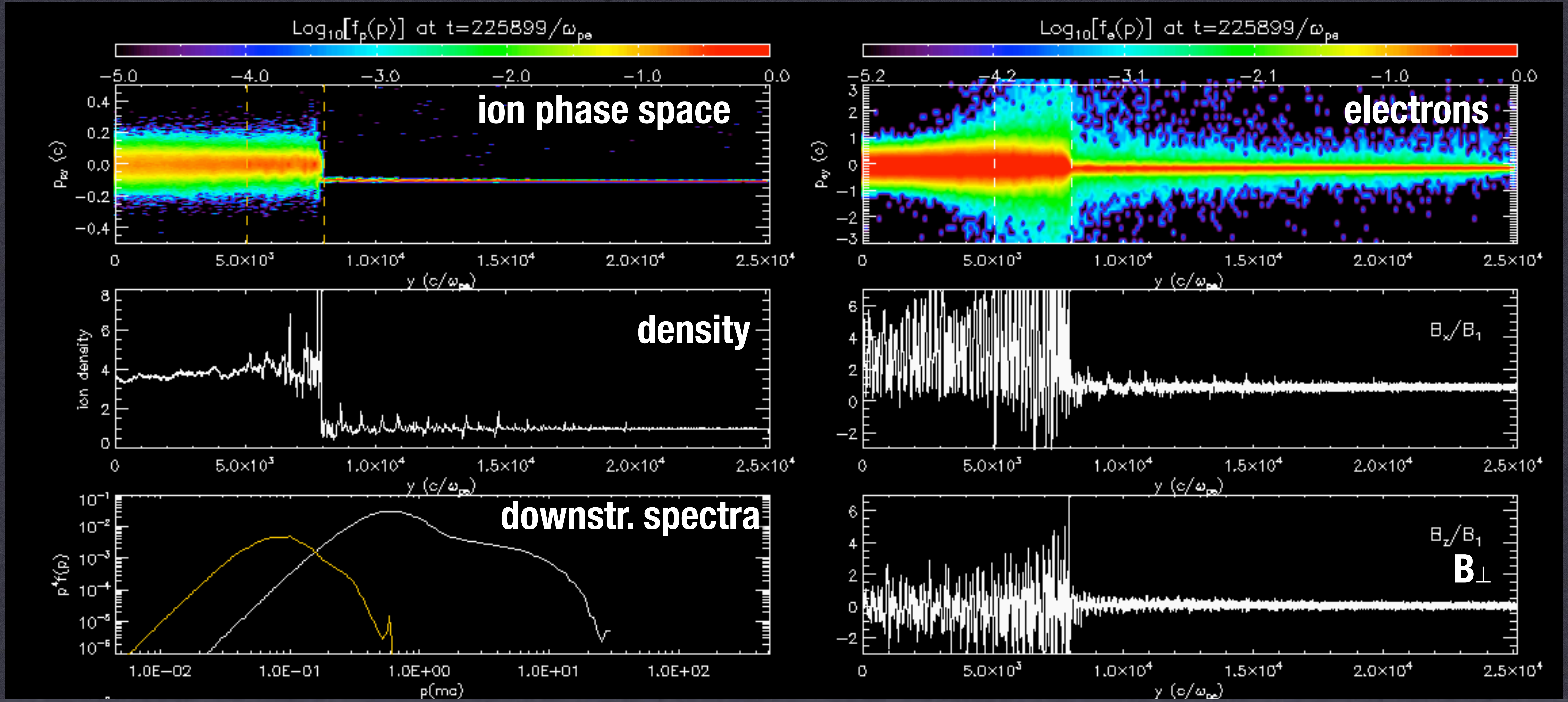


# Extreme acceleration in 1D

**Higher sonic Mach: 60 degrees shock inclination, mi/me=100, $M_A=M_s=20$; electron-driven waves upstream**



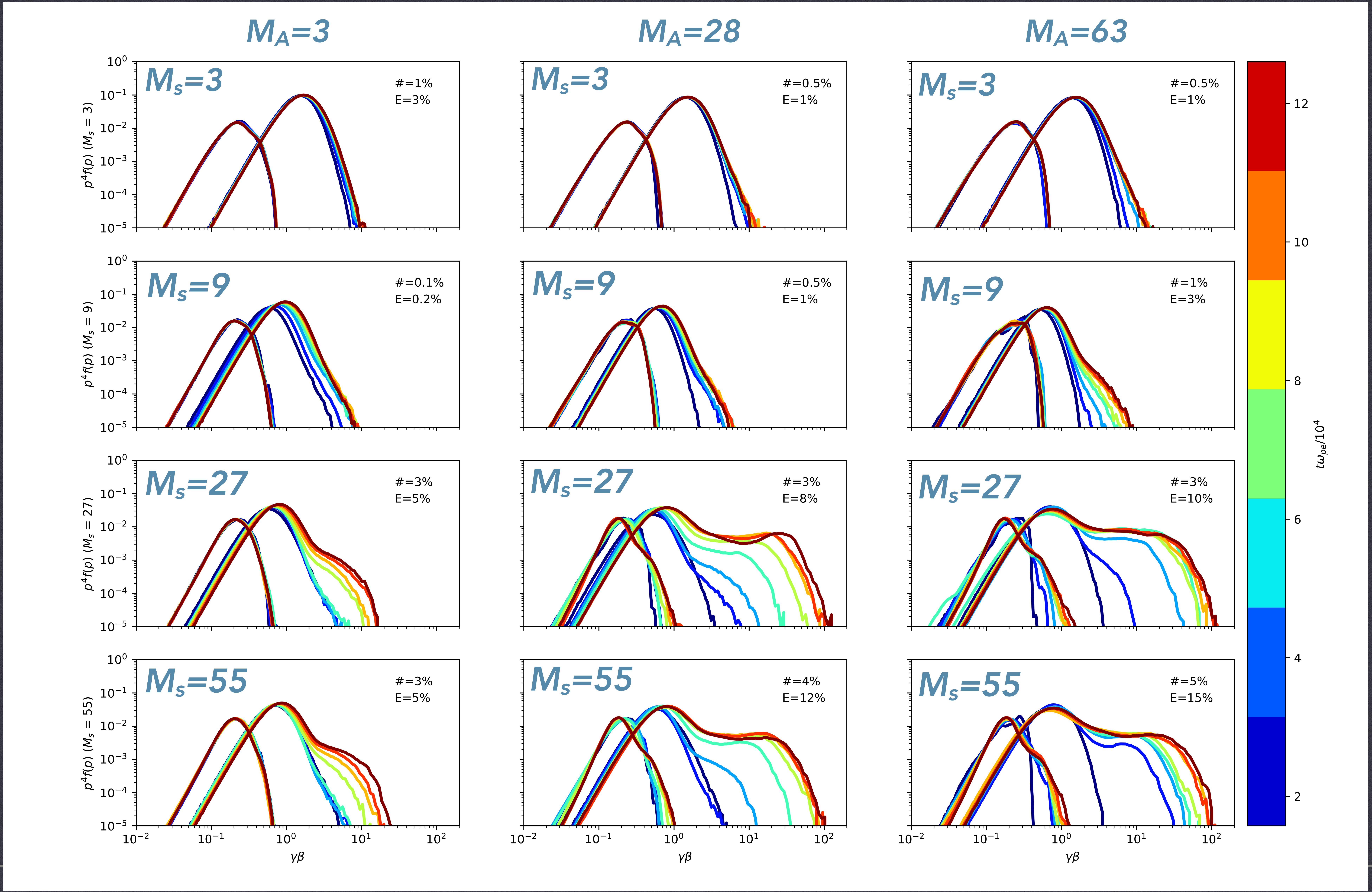

(Caprioli, Park, AS, in prep)



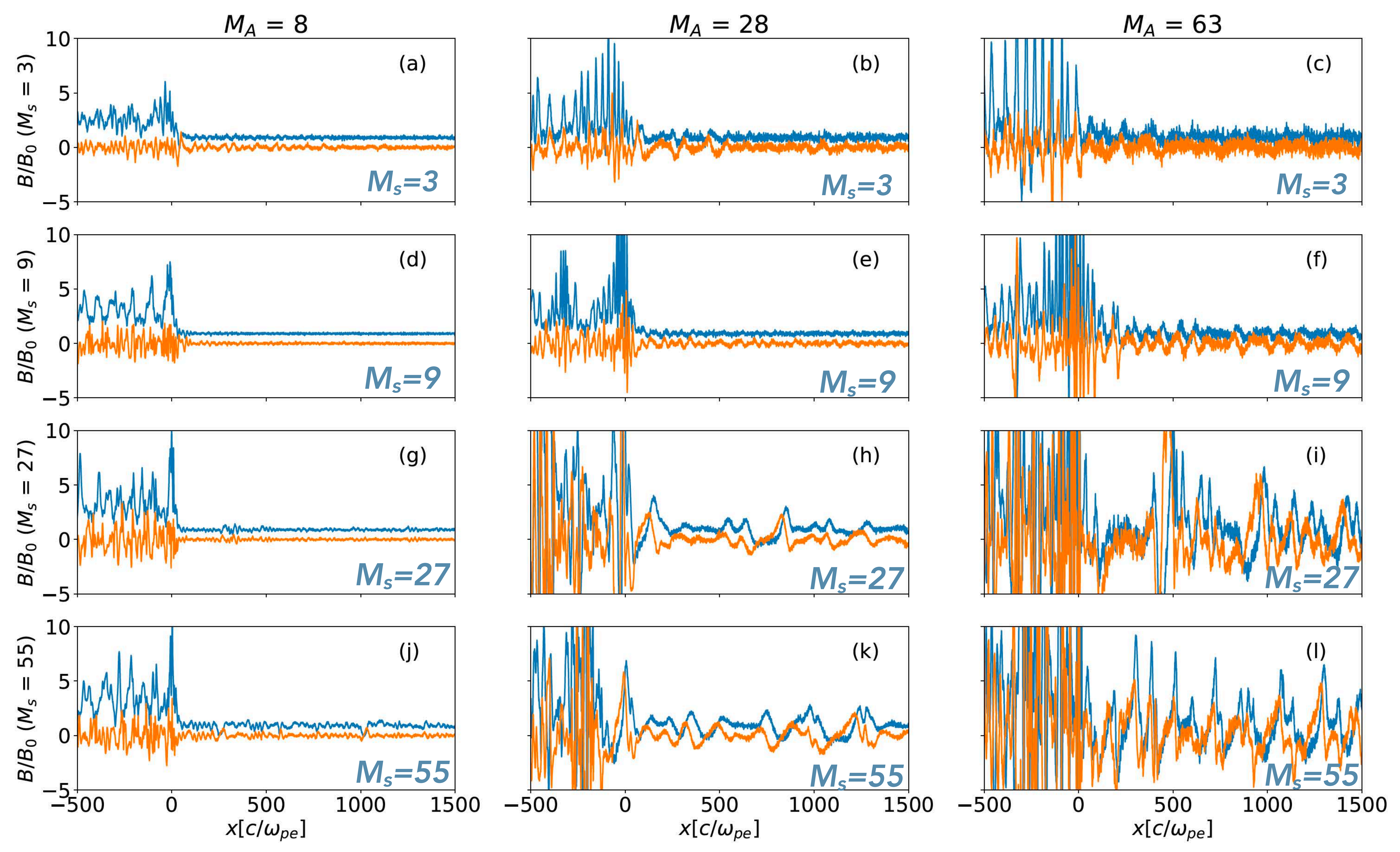

Ions are not injected or accelerated into DSA, while electrons drive their own Bell-type waves. Electrons are reflected from shock due to magnetic mirroring.

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

# 1D simulations: Downstream spectra for a range of $M_A$ and $M_s$



# Electron-driven upstream waves

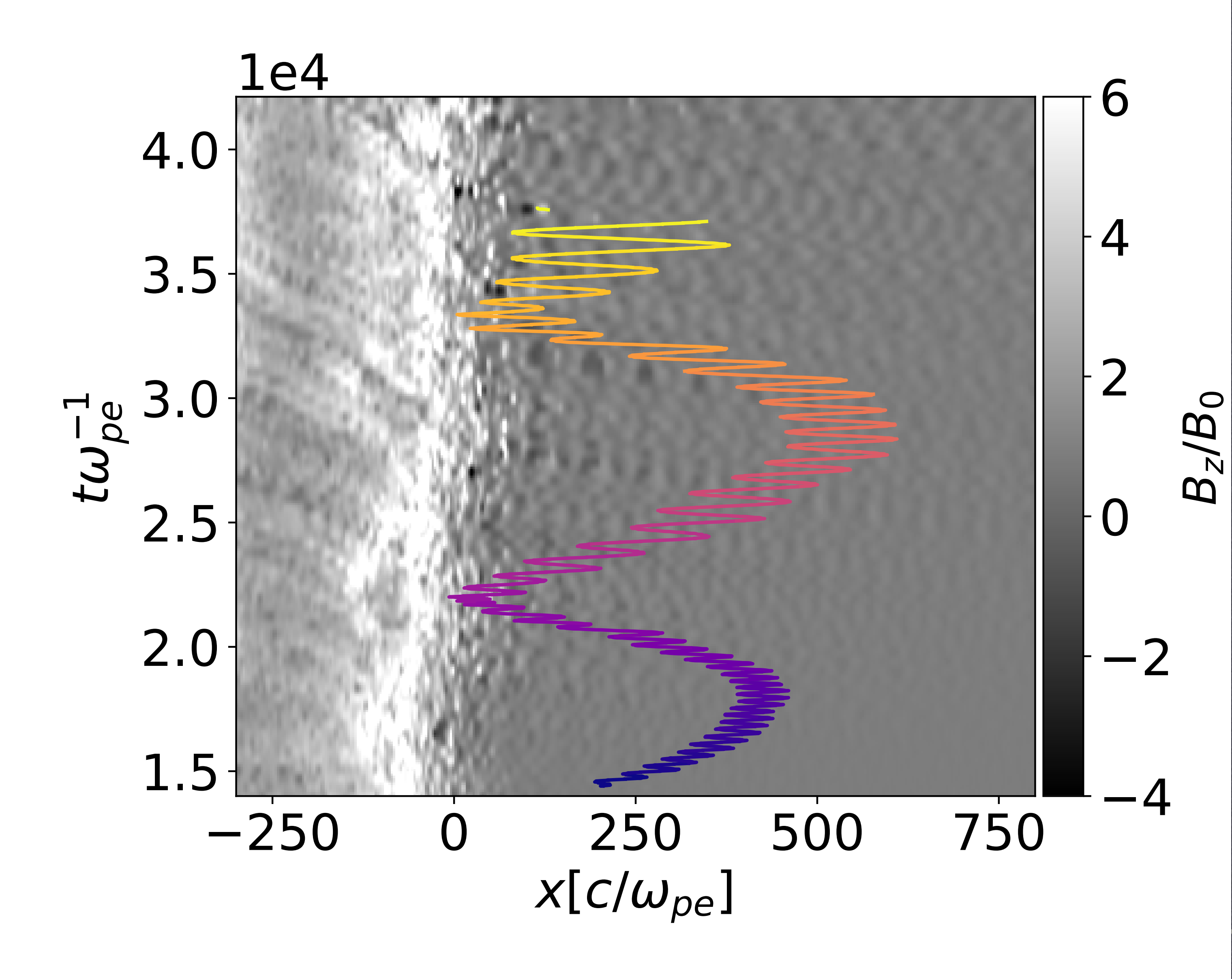


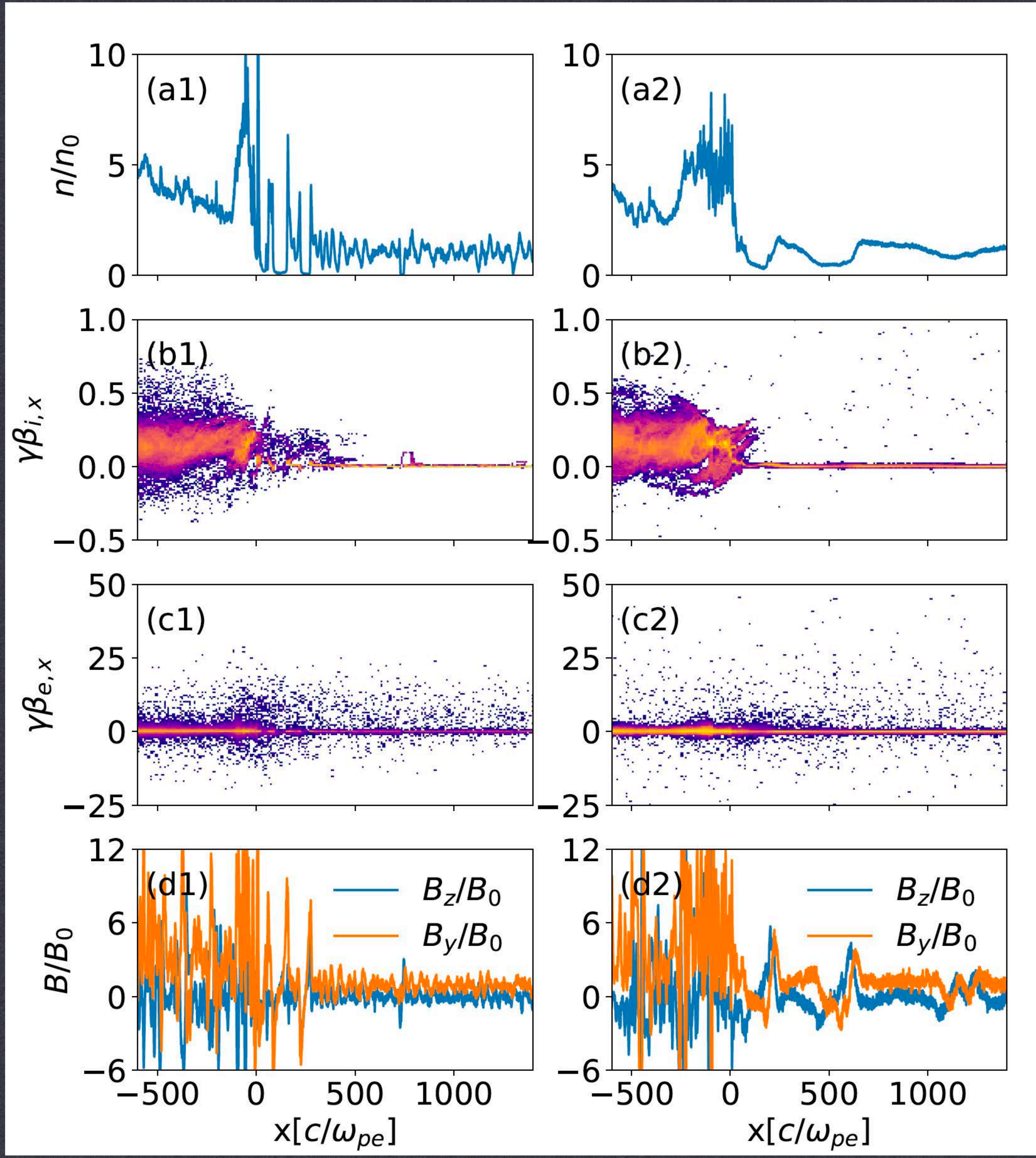
# Electron-driven waves

Upstream waves are circularly polarized and are non-resonant with electrons in high Mach number case.

Bell-type instability driven by returning electron current.

Different from electron-firehose invoked by Guo et al for low Mach number shocks.



# Electron acceleration in quasi-perp shocks

Electrons seem to be reflected at most Ma, up to 10% by number. In general low Ma is not conducive to electron reflection unless Ms is small (electrons are hot).

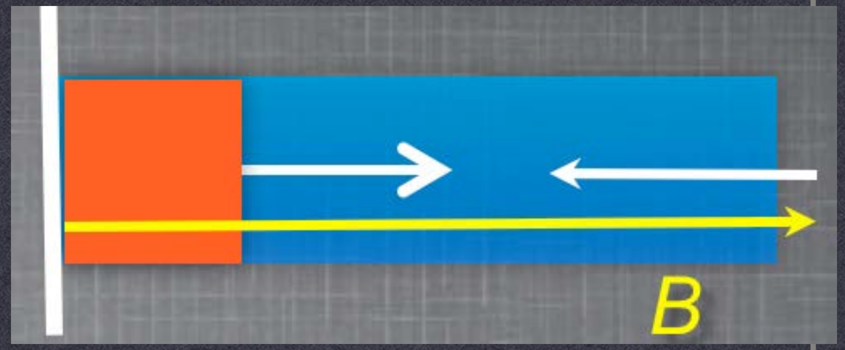
For low Ma and high Ms, the shock becomes filamentary and does not reflect well (quasi-parallel regions).

At high Ma and high Ms, ion loop is more unstable and causes pre-heating of electrons, making it conducive to injection.

To be understood: evolution of upstream turbulence (fraction returning to the shock in DSA is smaller in 2D). Downstream spectra are still steep in 2D ($E^{-3}$), but more like DSA in 1D high Mach.

Also, the role of 3D, and in-plane vs out-of-plane B field not clear.

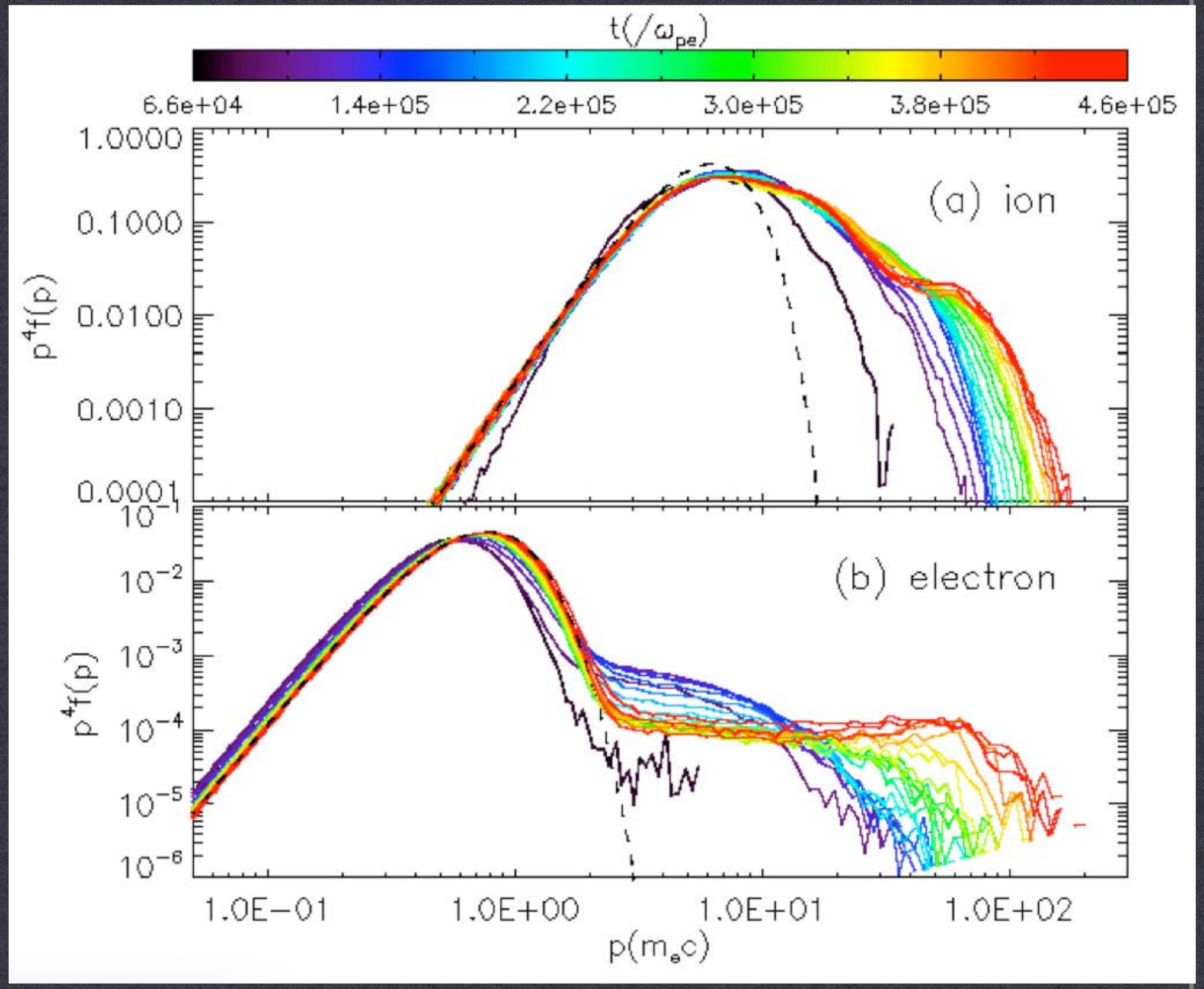
# Shock acceleration: emerging picture




Acceleration in laminar field:

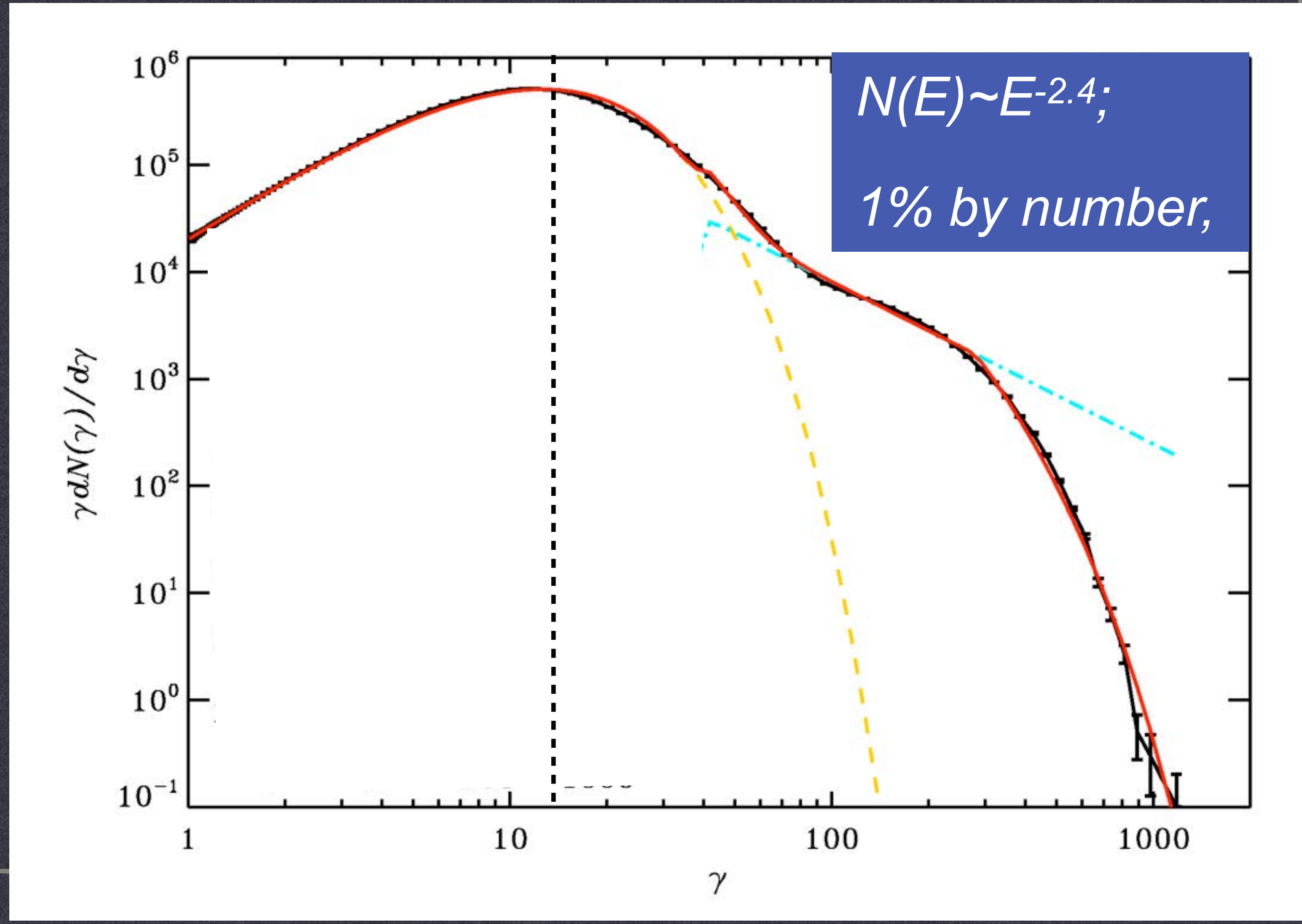
quasi-parallel -- accelerate both ions and electrons
(Caprioli & AS, 2014abc; Park, Caprioli, AS 2015)

quasi-perpendicular -- accelerate mostly electrons
(Guo, Sironi & Narayan 2014; Caprioli, Park, AS in prep)

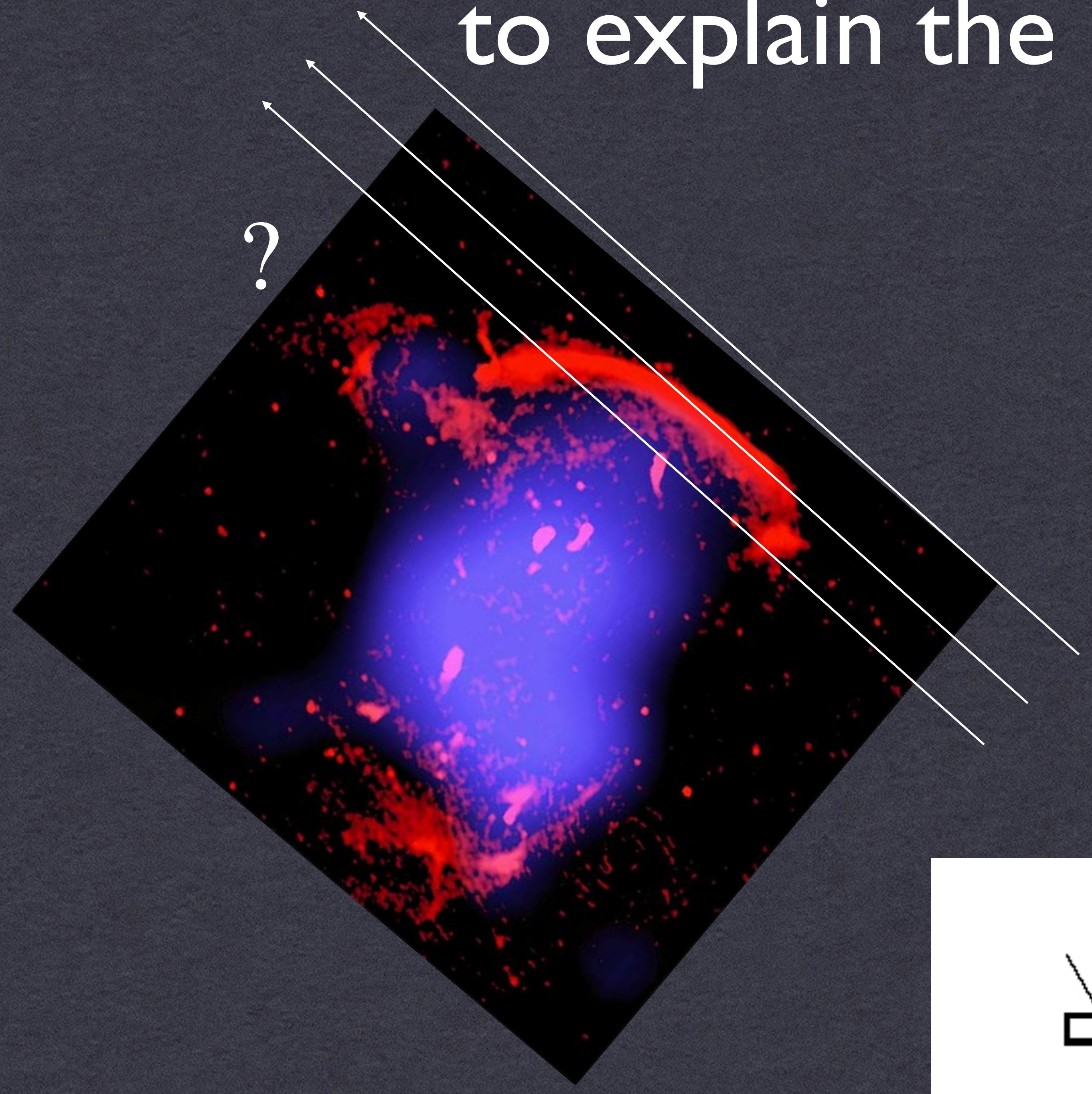


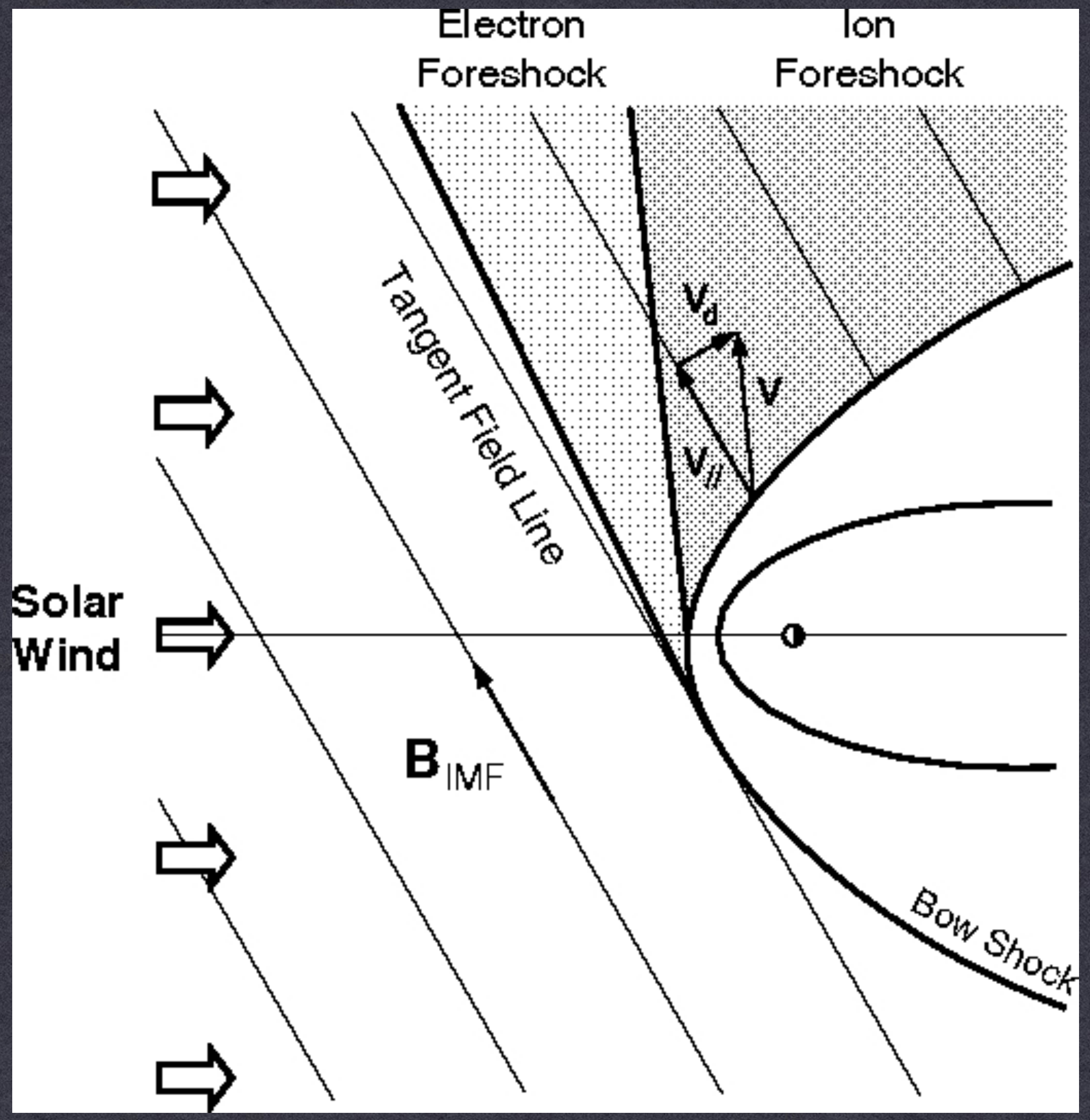

Relativistic shocks as in GRBs:

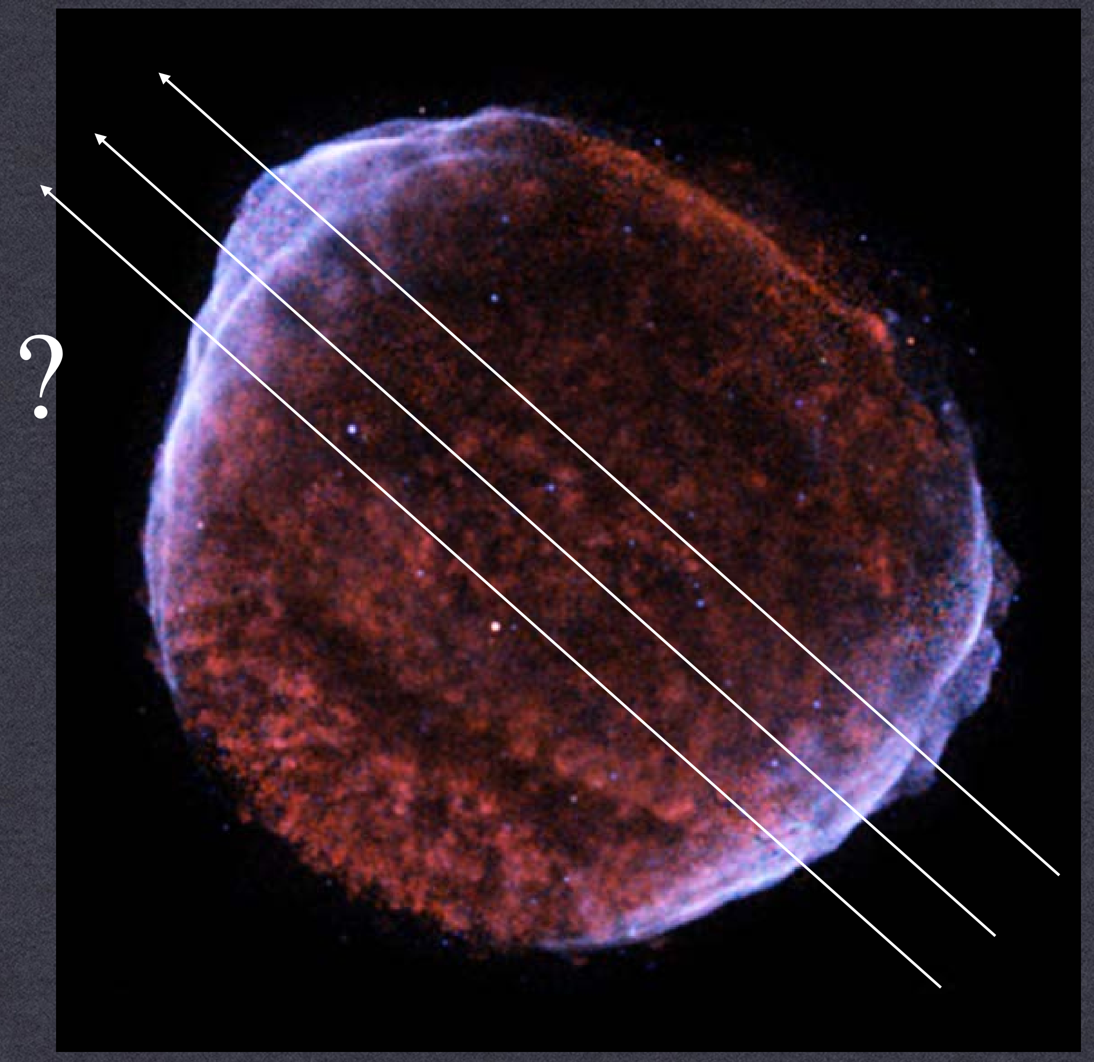
Effectively weak magnetization of ISM is conducive to acceleration via Weibel shocks, or in the presence of favorably inclined field — Bell shocks.
Both predict -2 power laws, but could be different acceleration rates (linear vs sqrt in time)



# Injection of e- without CRs at quasi-perp shock can help to explain the lack of gamma-ray signal in clusters.




Magnetosphere preferentially reflects electrons in a range of oblique angles

SNR morphology in external field explained by quasirallel and quasiperp regions.

# Conclusions

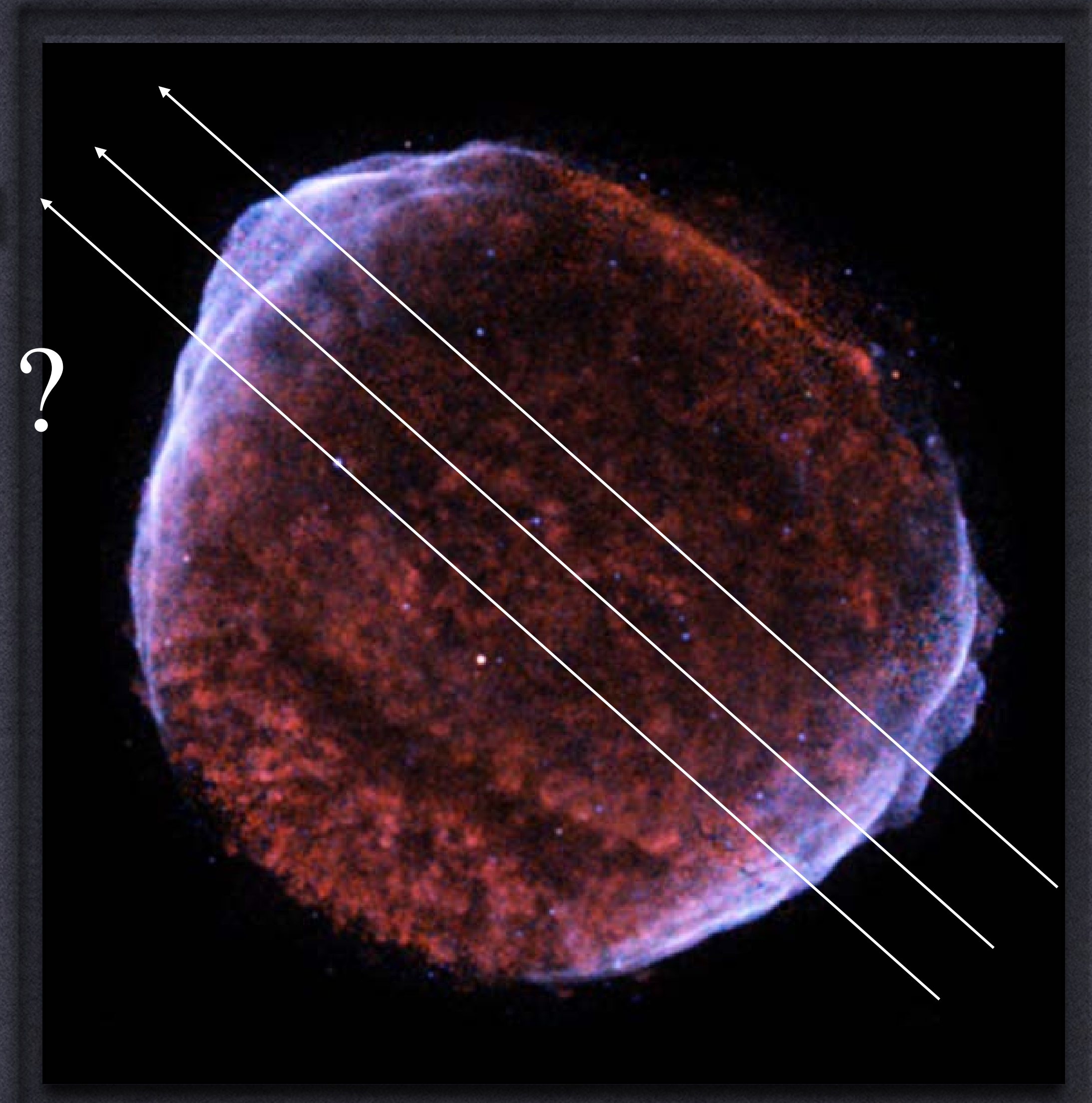
Kinetic simulations allow to calculate particle injection and acceleration from first principles, constraining injection fraction

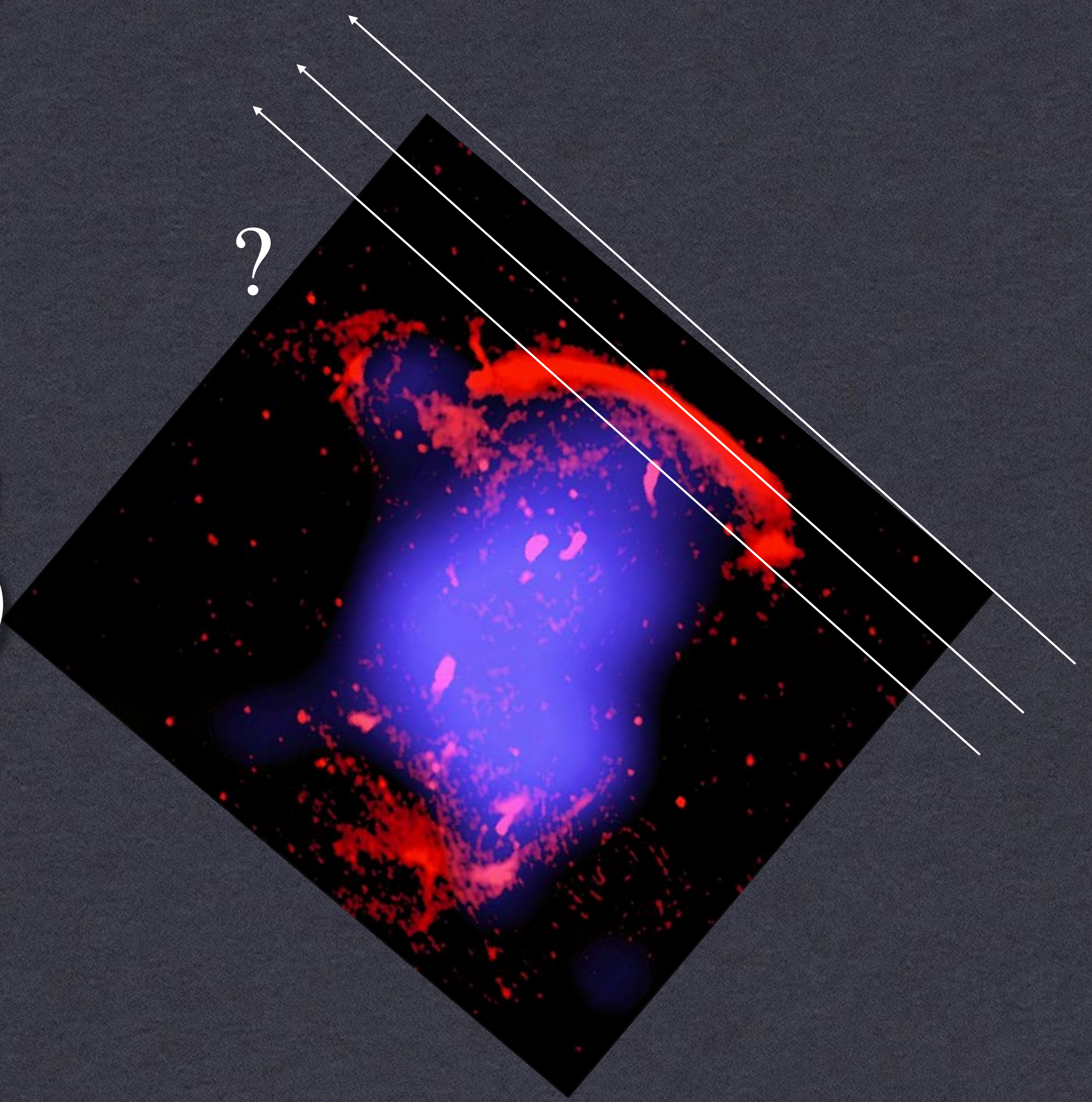
Magnetization (Mach #) of the shock and B inclination control the shock structure

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

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

Long-term evolution & 3D effects need to be explored more, new “hybrid” ideas to come



# Roadblocks:

- Multiscale problem — need to resolve the shock and large upstream;
- Numerical instabilities in relativistic advection in PIC: numerical Cherenkov; prevents evolution for longer than 10k plasma times;
- Relativistic contraction prevents using upstream frame;
- New ideas for simulating relativistic shocks with CR feedback are needed!

New ideas: 

# MHD-PIC: MHD with CR particles

Full equations for the CR particles:

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

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

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

Full equations for the gas:

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

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

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

Bai et al 2015; van Marle et al 2017; Mignone et al 2018

# The Athena MHD code

Higher-order Godunov schemes with unsplit integrators, PPM reconstruc-tion and constrained transport.

(Stone et al. 2008)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathbf{P}^*) = 0,$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = 0,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

where:

$$P^* = P + B^2/2$$

$$E = \frac{P}{\gamma - 1} + \frac{1}{2}\rho v^2 + \frac{B^2}{2}$$

- Mass, momentum, magnetic flux and energy conserved to machine precision
- 90% efficiency on up to $10^5$ processors
- Rigorous convergence test against analytical solutions.

# CR-induced Hall Effect

Electrons are force-free: $$\boldsymbol{E} + \frac{\boldsymbol{v}_e}{c} \times \boldsymbol{B} = 0$$

Decomposition of current density:

$$\frac{c}{4\pi} \nabla \times \boldsymbol{B} = \boldsymbol{J}_{\rm tot} = n_i q_i \boldsymbol{v}_i - n_e e \boldsymbol{v}_e + n_{\rm CR} q_{\rm CR} \boldsymbol{u}_{\rm CR}$$

$$e n_e = q_i n_i + q_{\rm CR} n_{\rm CR}$$

Generalized Ohm's law:

$$\boldsymbol{E} = -\frac{\boldsymbol{v}_i}{c} \times \boldsymbol{B} + \frac{1}{e n_e c} \boldsymbol{J}_{\rm tot} \times \boldsymbol{B} - \frac{q_{\rm CR} n_{\rm CR}}{e n_e} \frac{(\boldsymbol{u}_{\rm CR} - \boldsymbol{v}_i)}{c} \times \boldsymbol{B}$$

inductive term

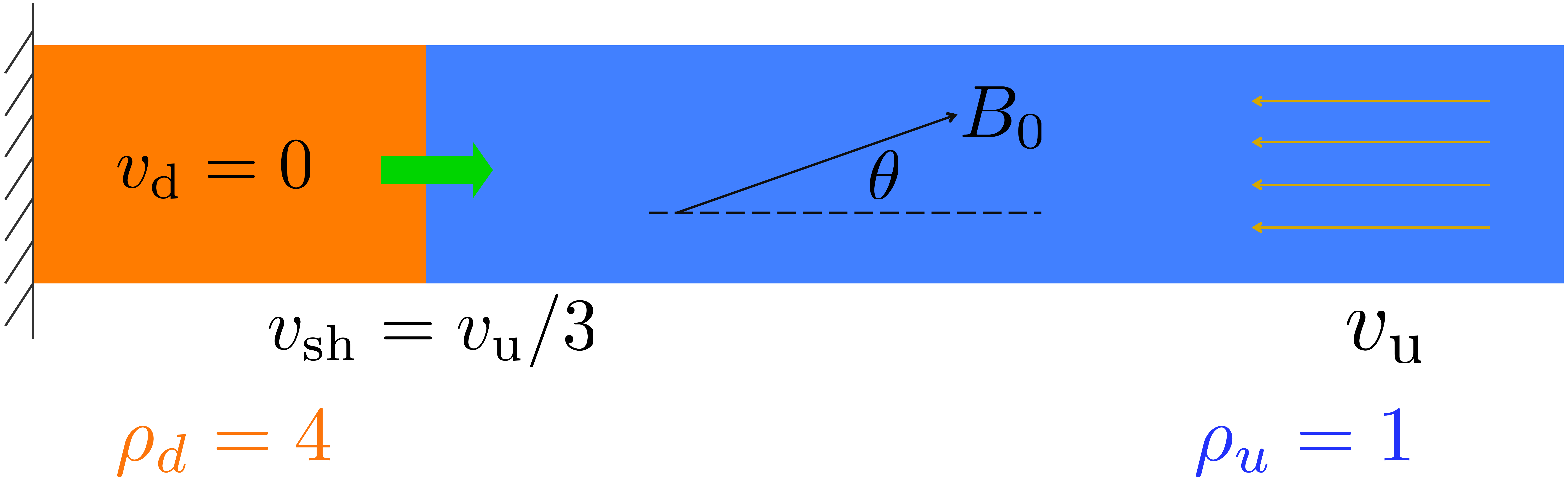
normal Hall term

CR-induced Hall term

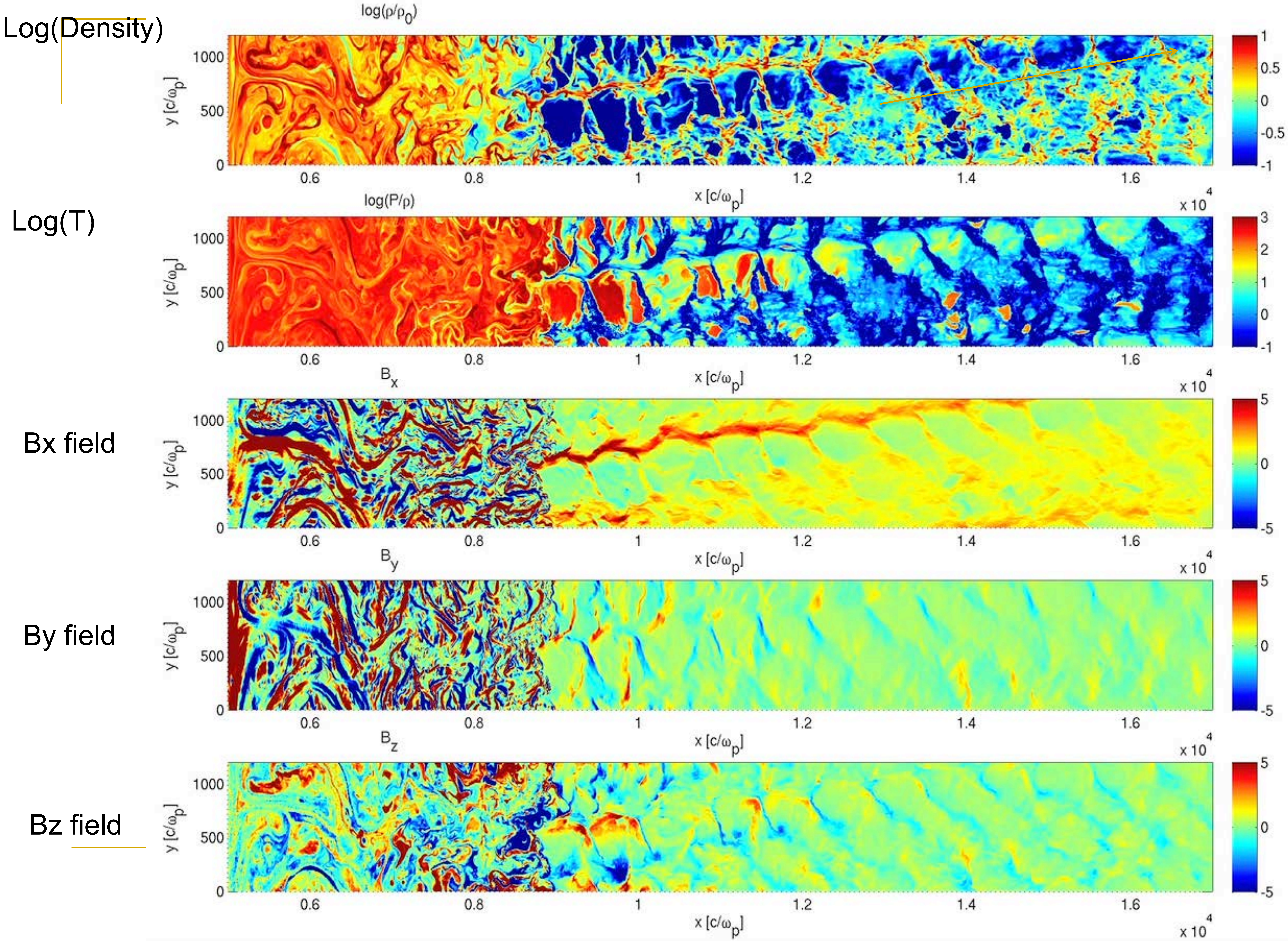
Important on scales < ion skin depth

scale independent

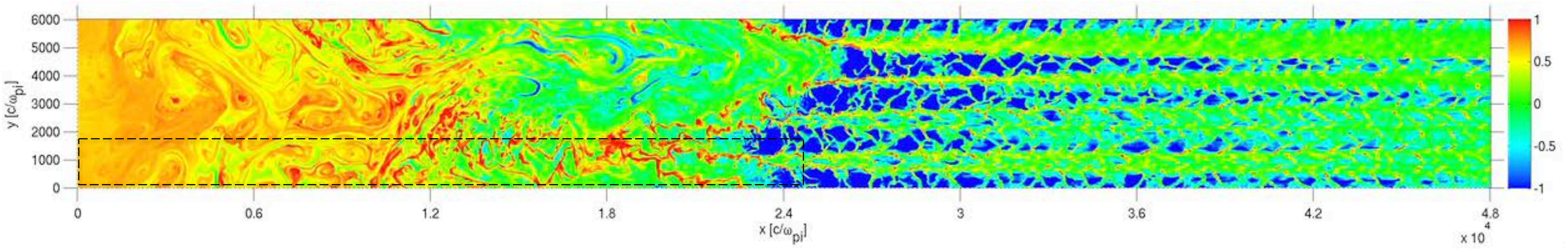
# Setting up the shock problem




- Inject CR particles at the shock with some efficiency η.
- They are injected at energy of 10 Eshock isotropically.
- Escaping CRs drive upstream waves, and acceleration ensues.

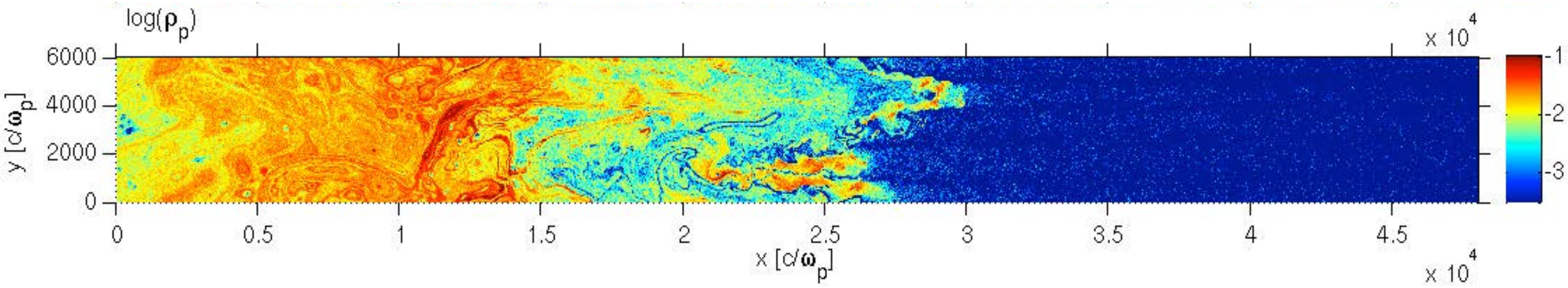

Log(Density)
log(ρ/ρ0)
Log(T)
log(P/ρ)
Bx field
Bx
By field
By
Bz field
Bz
y [c/ωp]
x [c/ωp]
x 10^4
0.6
0.8
1
1.2
1.4
1.6
0
500
1000

# With much larger box size

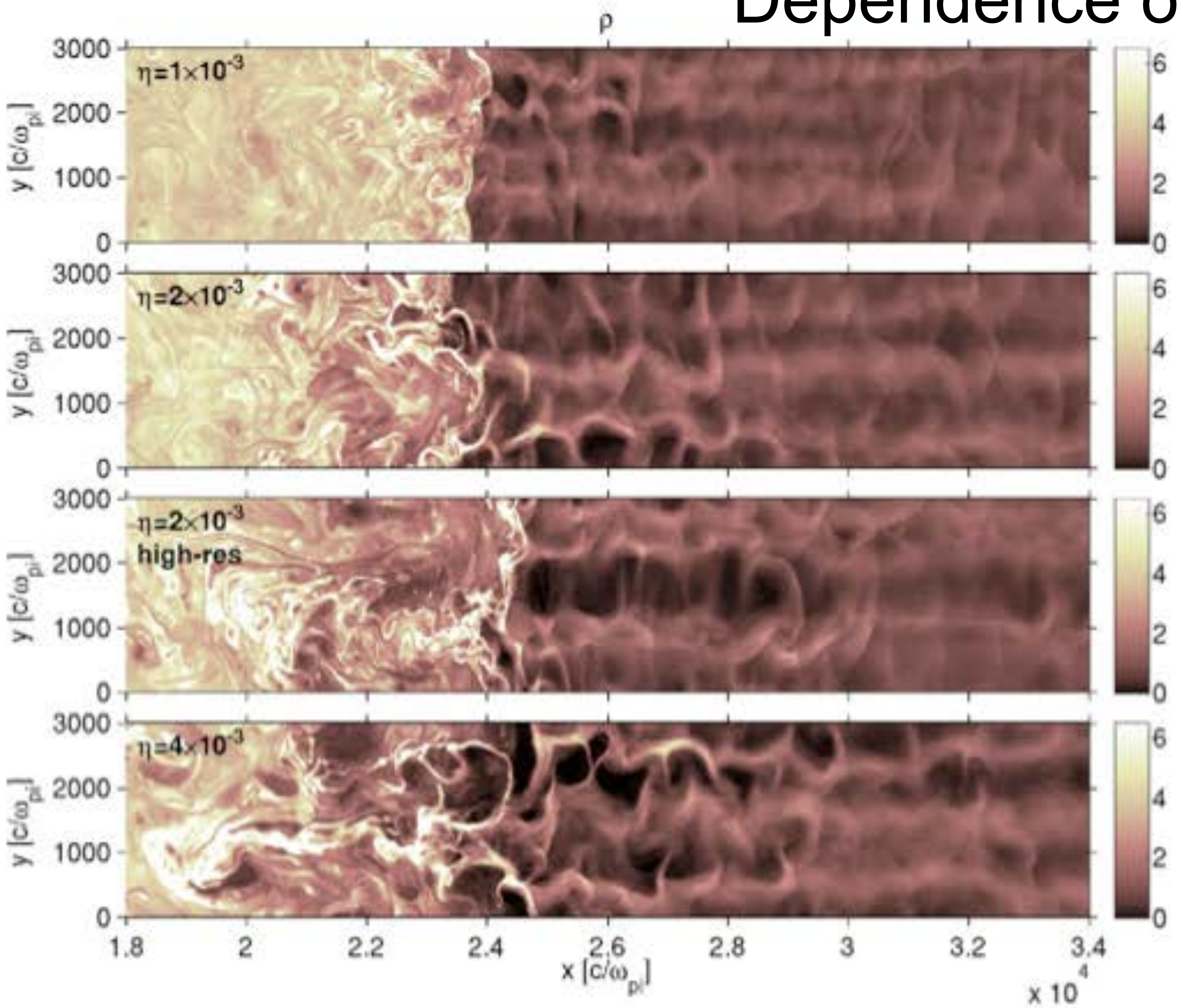



Shock precursor is even thicker than the downstream region.

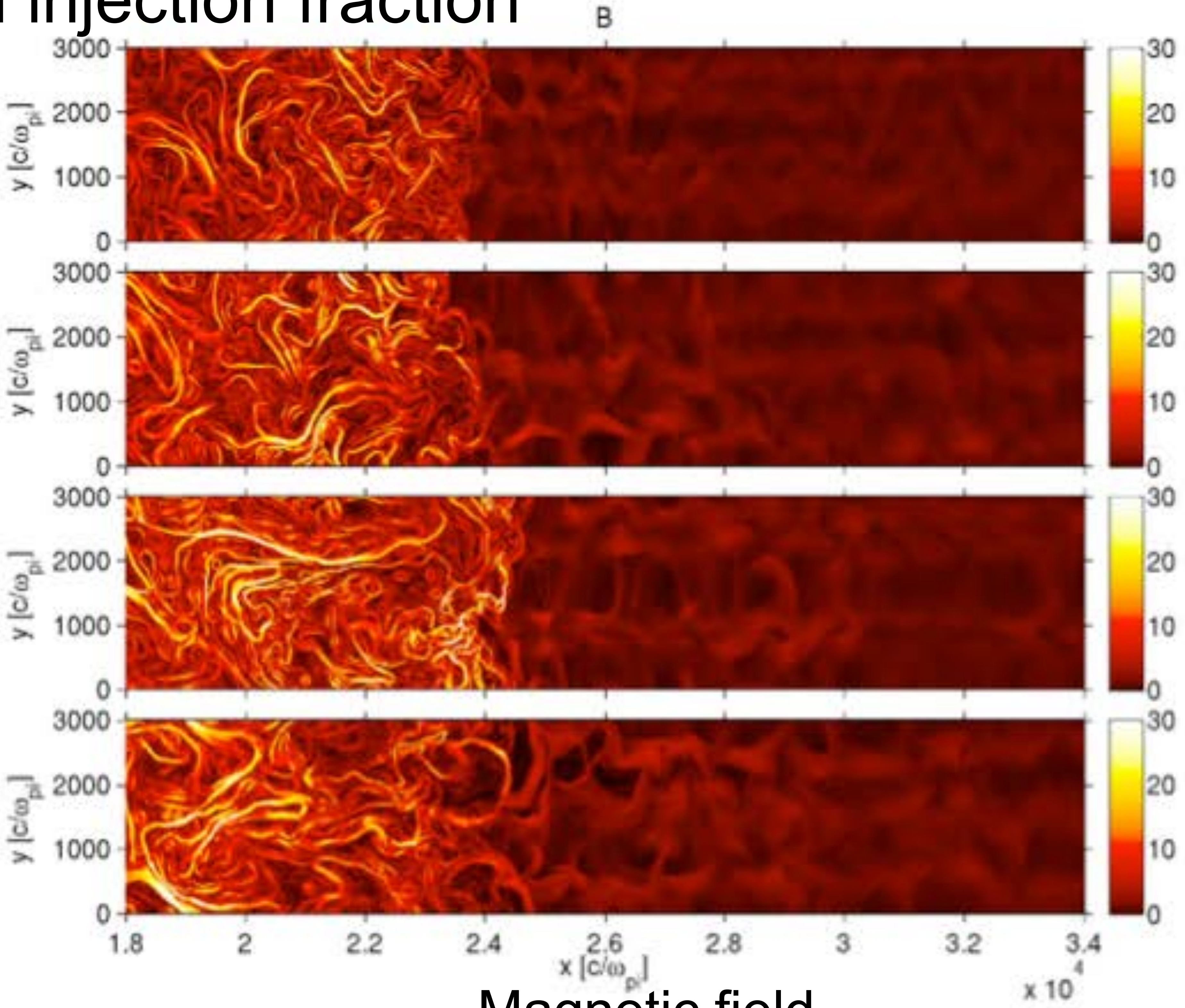
Large-scale features @ shock precursor: comparable to the transverse box size.



# Dependence on injection fraction

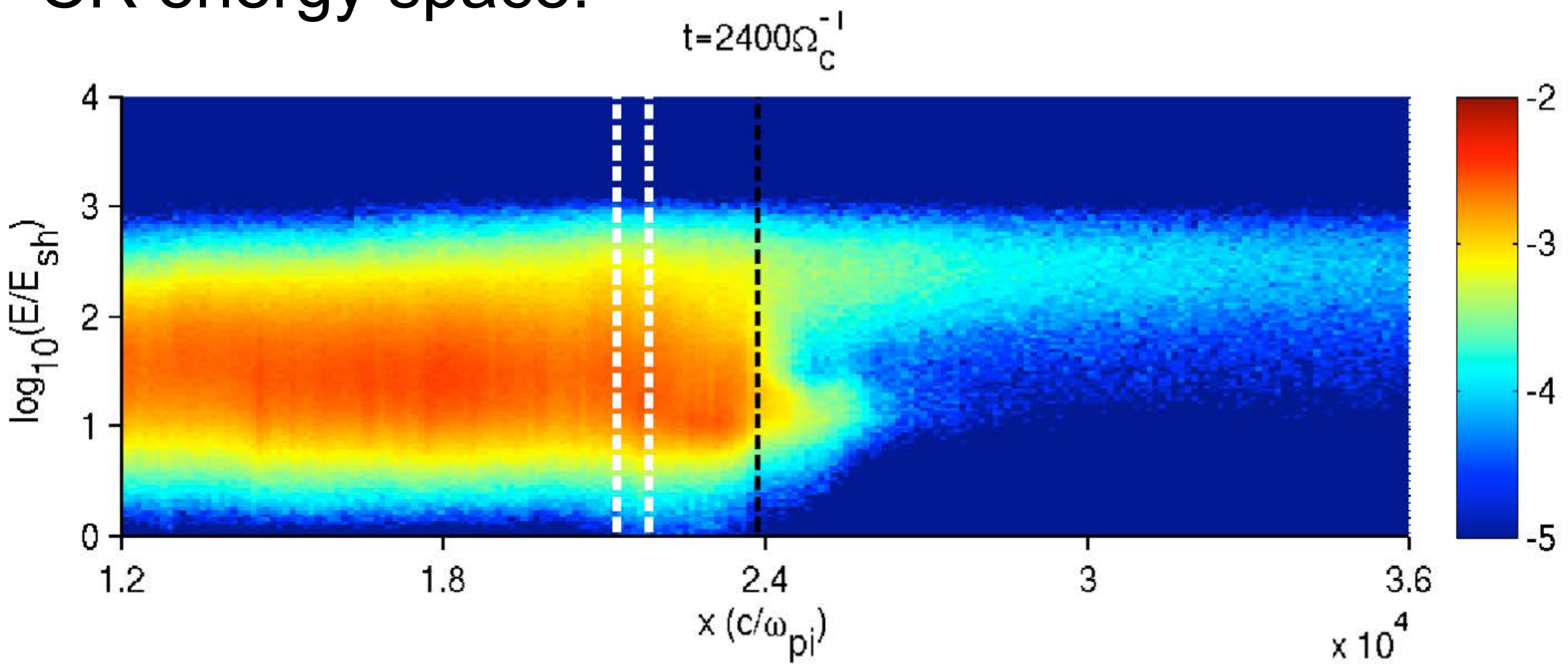



Density

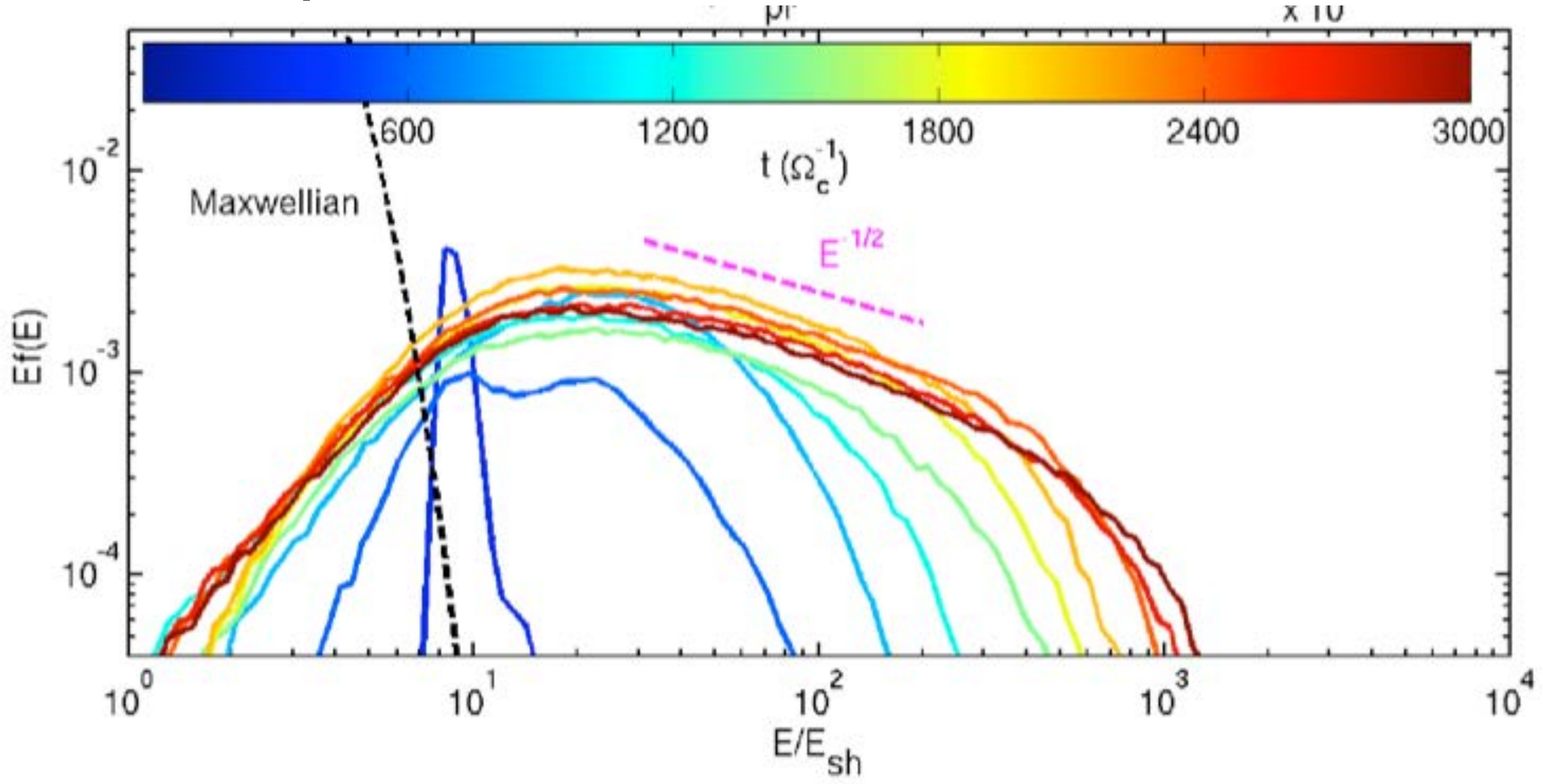



Magnetic field

CR energy space:

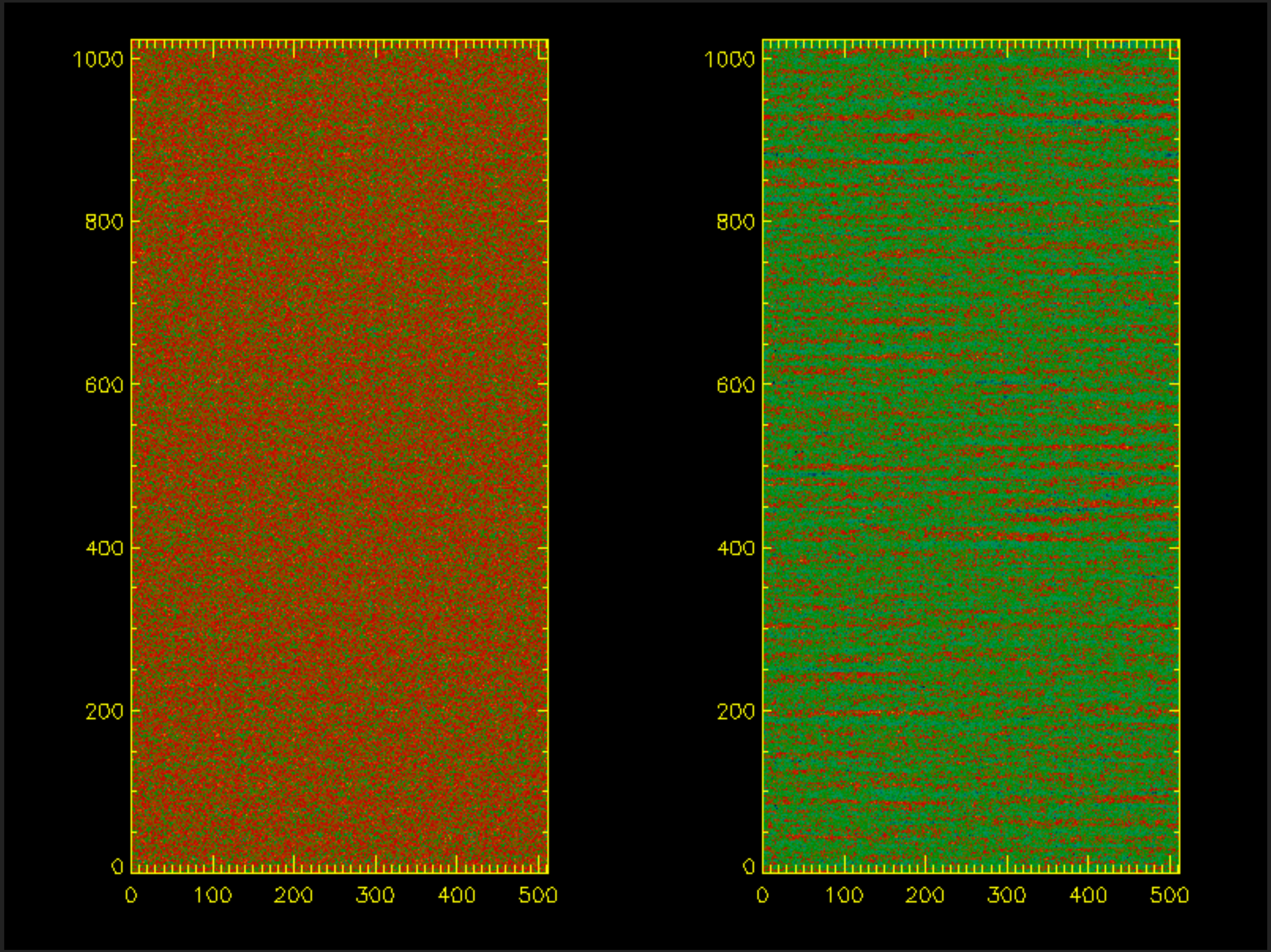



CR spectrum:

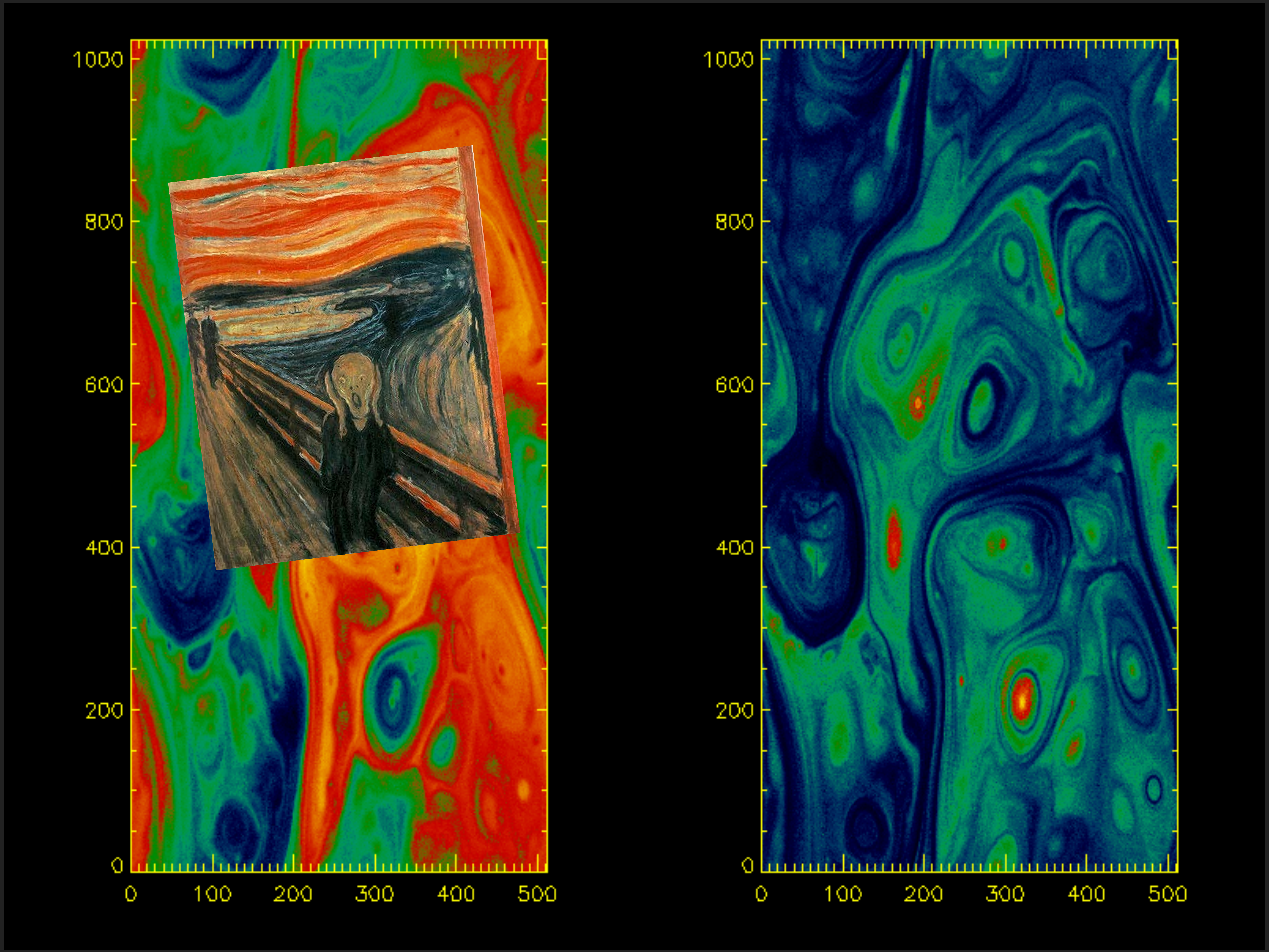


# Extra Material

# CR DRIVEN INSTABILITIES



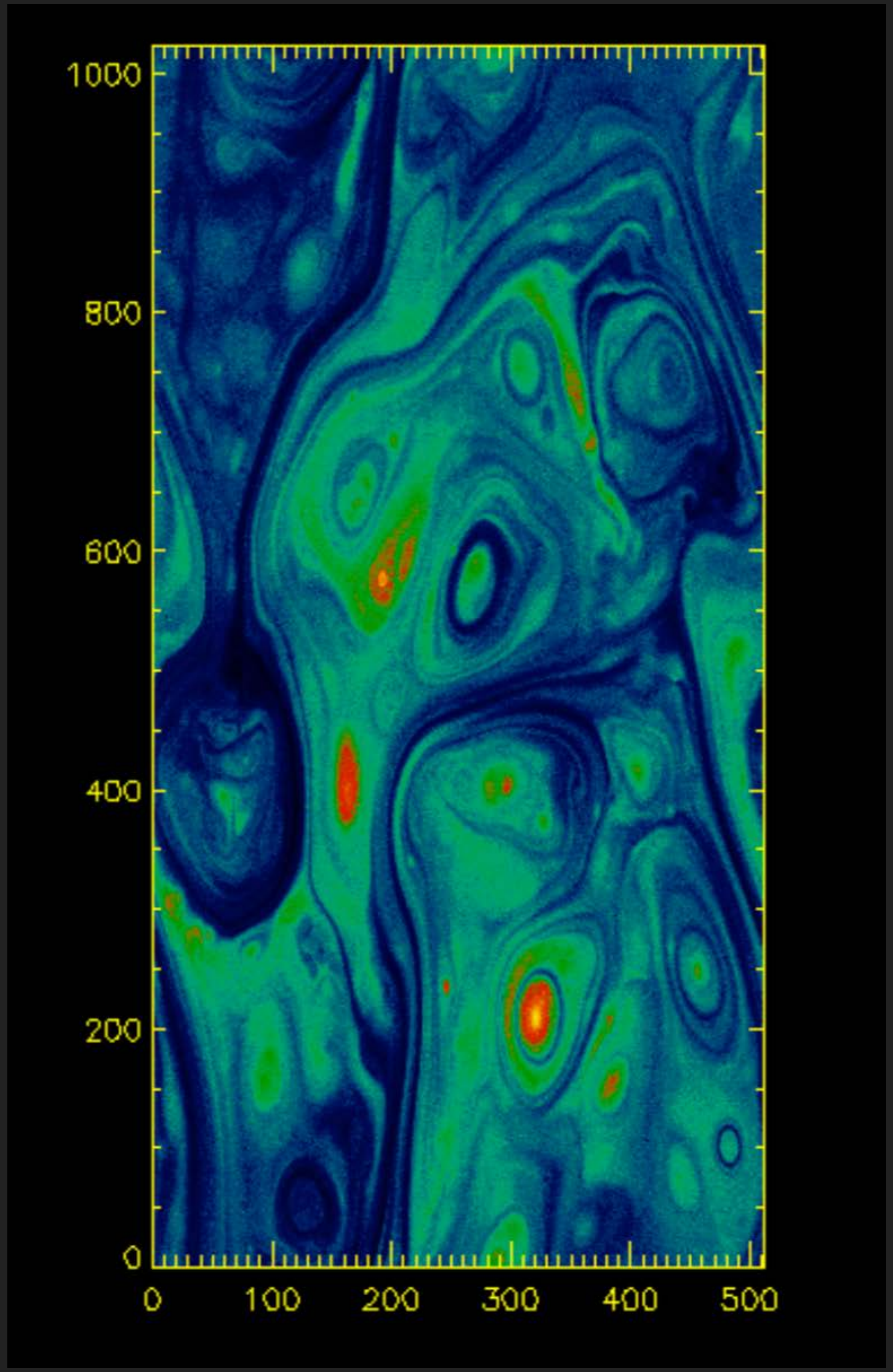
# CR DRIVEN INSTABILITIES



# COSMIC RAYS AND YOU

- CRs are important component of our galaxy (MW)
  - CR energy density comparable to other galactic components -> potentially dynamically important
  - CR trapping time >> light crossing time, Isotropy -> interaction with other component of MW

- Interest:
  - Galactic winds (e.g. Girichidis+ 2016, Ruszkowski+ 2016)
  - Star formation quenching (e.g. Ruszkowski+ 2016)
  - Structure/magnitude of galactic B-field
  - Feedback on shock structure in SNRs



# Cosmic Ray Treatment Matters

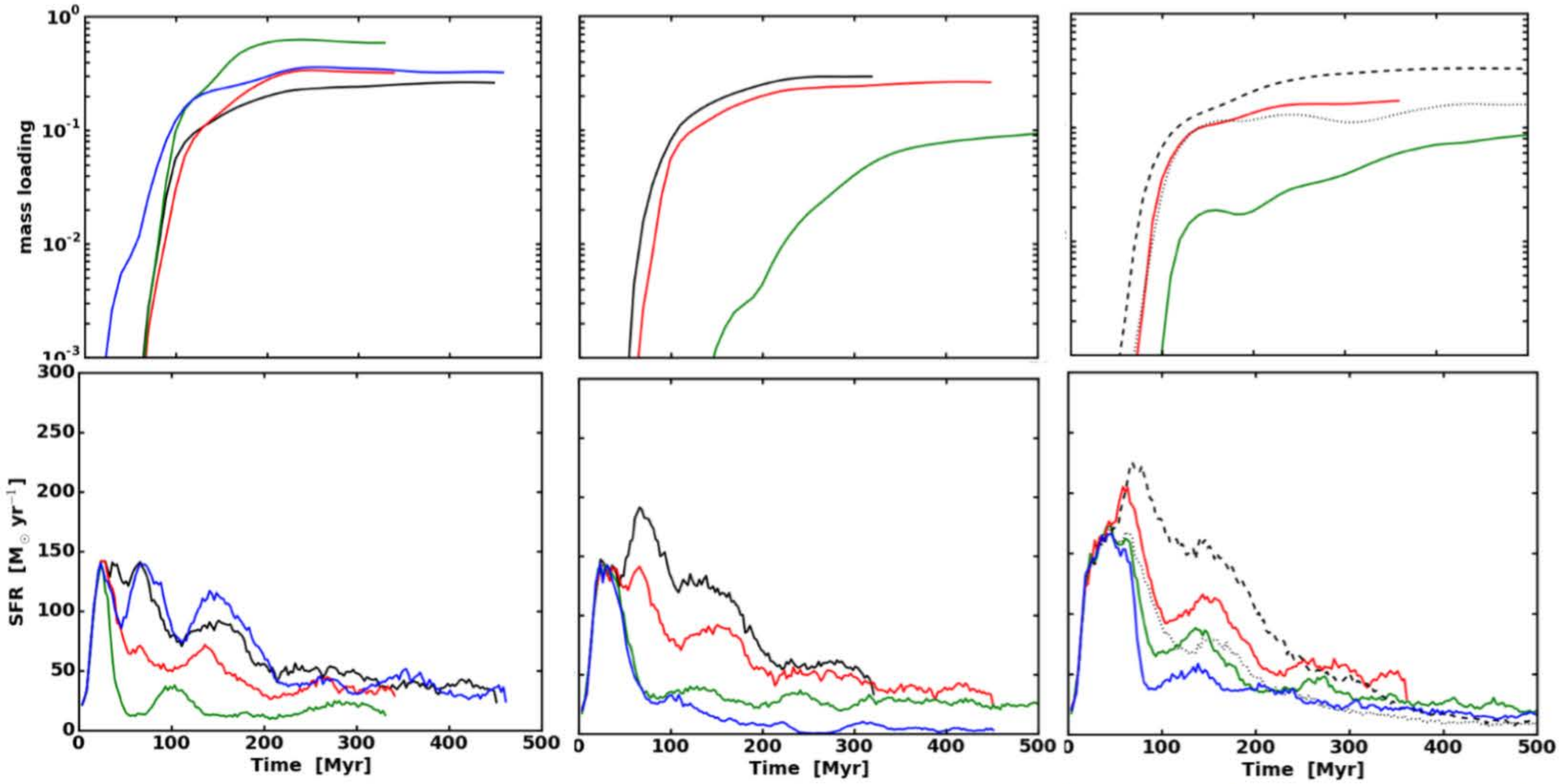



**Figure 4.** Galactic wind mass loading (top row) and star formation (bottom row). *Left* column (all cases for $f = 4$, SN feedback efficiency of $100M_{\odot}$/SN): $f_{\rm cr} = 0.1$ (black); $f_{\rm cr} = 0.15$ (red); $f_{\rm cr} = 0.3$ (green); $f_{\rm cr} = 0.15$, $B_0 = 3\mu$G (blue); *Middle* column (all cases for $f_{\rm cr} = 0.1$, SN feedback efficiency of $100M_{\odot}$/SN): $f = 8$ (black), $f = 4$ (red), $f = 1$ (green), $f = 0$ (blue); *Right* column (all cases for $f_{\rm cr} = 0.1$, SN feedback efficiency of $185M_{\odot}$/SN): $f = 3$ (red), $f = 1$ (green), $f = 0$ (blue), $\kappa_{||} = 10^{28}{\rm cm}^2{\rm s}^{-1}$ (no streaming; dashed), $\kappa_{||} = 3\times10^{27}{\rm cm}^2{\rm s}^{-1}$ (no streaming; dotted). Note that the mass loading curves in the no-streaming cases ($f = 0$ cases) in the middle and right columns are not shown due to the absence of the wind.

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# Treatment of CR propagation determines feedback in galactic wind

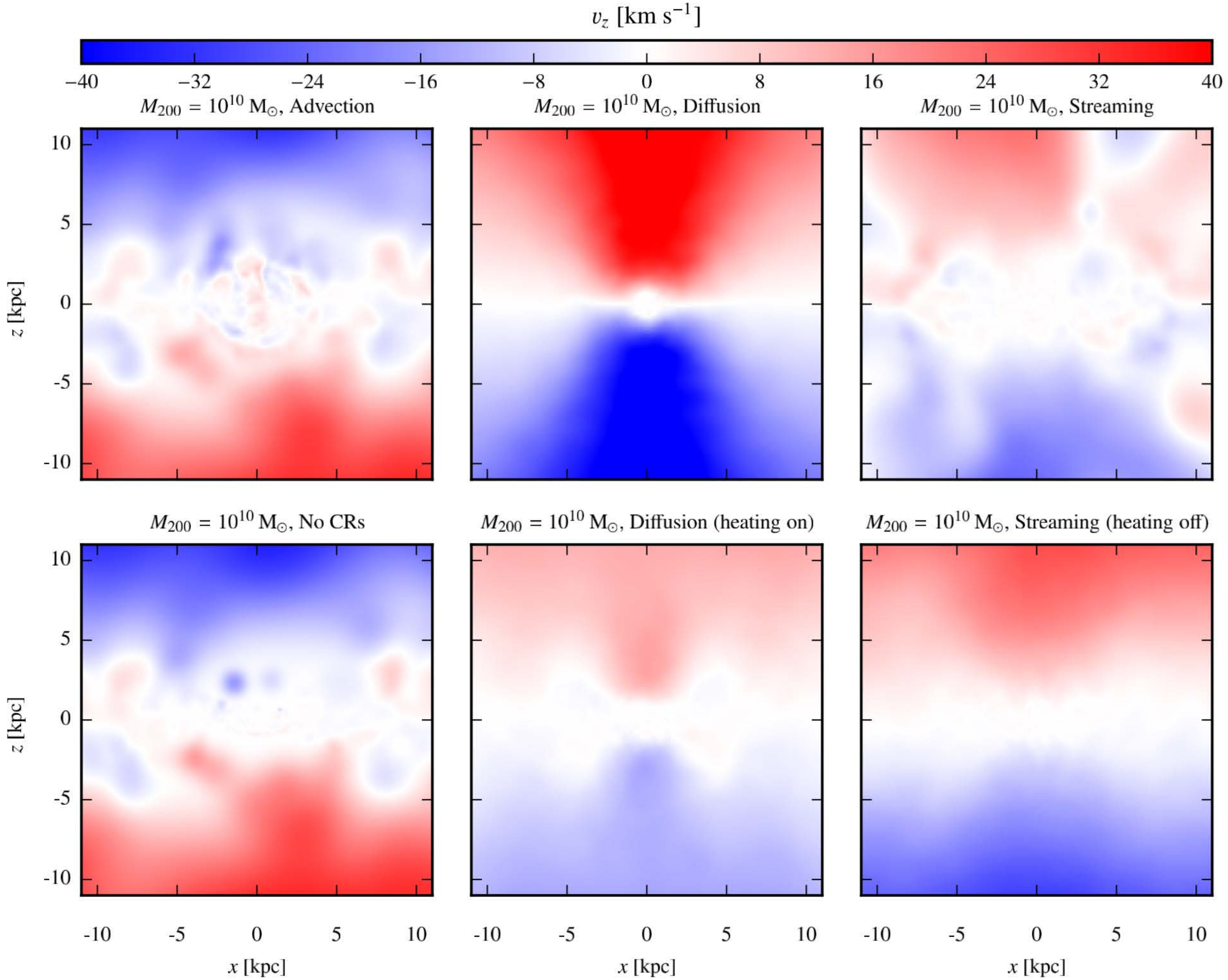


**Figure 3.** Edge-on slices of vertical velocity $v_z$ through the centre of the $10^{10}$ M$_\odot$ halo. Shown are the six different simulation models after 1 Gyr. Only models with active CR transport (i.e., streaming or diffusion) drive outflows from the disk (middle and right-hand panels). The outflow in the pure diffusion model is much stronger than in the streaming model due to the CR energy loss as a result of the Alfvén wave cooling term, $\boldsymbol{v}_\mathrm{A} \cdot \boldsymbol{\nabla} P_\mathrm{c}$. Artificially suppressing this term (bottom right panel) results in a stronger and faster outflow. Only models without the Alfvén wave cooling term show vertical velocities that exceed the virial velocity $v_{200} = \sqrt{GM_{200}/R_{200}} = 35$ kpc substantially.

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$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \quad (1)$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} \boldsymbol{v}^{\mathrm{T}} + P) = -\rho \nabla \Phi, \quad (2)$$

$$\frac{\partial \varepsilon_{\mathrm{g}}}{\partial t} + \nabla \cdot (\boldsymbol{v} \varepsilon_{\mathrm{g}}) = -P_{\mathrm{g}} \nabla \cdot \boldsymbol{v} + |\boldsymbol{v}_{\mathrm{A}} \cdot \nabla P_{\mathrm{c}}| + \Gamma_{\mathrm{g}} + \Lambda_{\mathrm{g}}, \quad (3)$$

$$\frac{\partial \varepsilon_{\mathrm{c}}}{\partial t} + \nabla \cdot \boldsymbol{F}_{\mathrm{c}} = -P_{\mathrm{c}} \nabla \cdot \boldsymbol{v} - |\boldsymbol{v}_{\mathrm{A}} \cdot \nabla P_{\mathrm{c}}| + \Gamma_{\mathrm{c}} + \Lambda_{\mathrm{c}}, \quad (4)$$

$$\boldsymbol{F}_{\mathrm{c}} = \boldsymbol{v} \varepsilon_{\mathrm{c}} + \boldsymbol{v}_{\mathrm{s}} (\varepsilon_{\mathrm{c}} + P_{\mathrm{c}}) - \kappa \nabla \varepsilon_{\mathrm{c}},$$

$$\nabla^2 \Phi = 4\pi G (\rho + \rho_{\mathrm{dm}} + \rho_*). \quad (5)$$

Weiner, Pfrommer, Oh 2017

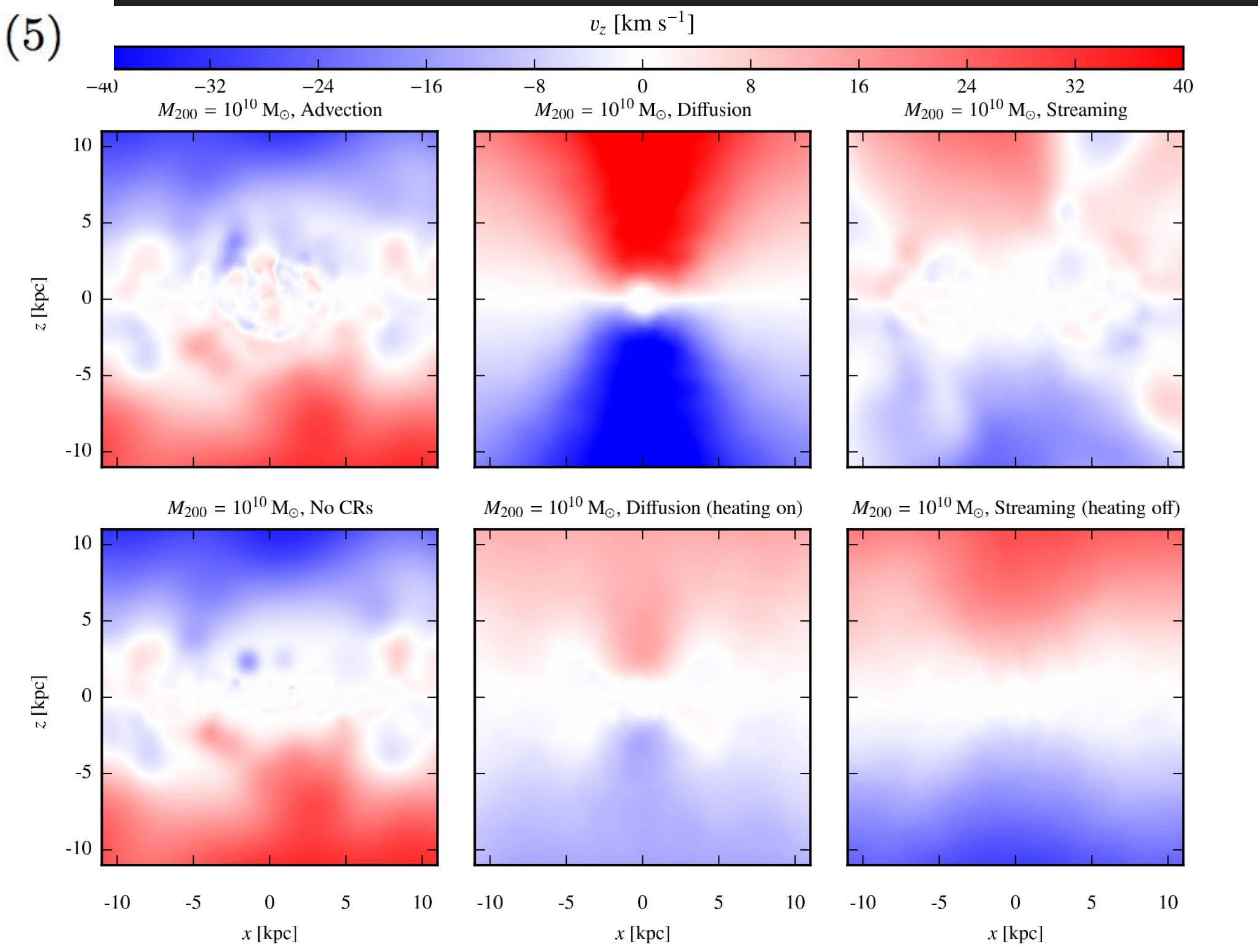
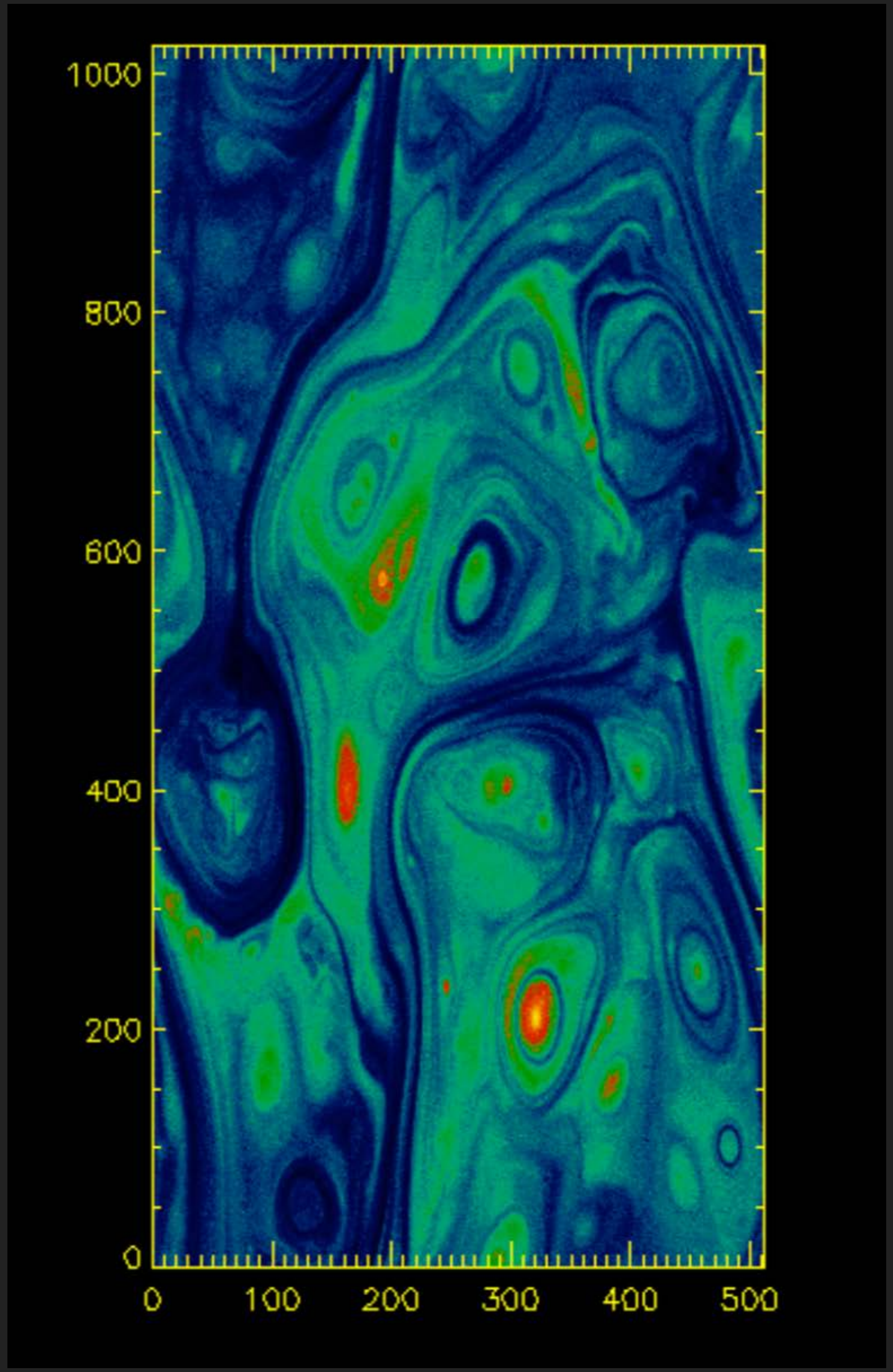



**Figure 3.** Edge-on slices of vertical velocity $v_z$ through the centre of the $10^{10}$ M$_\odot$ halo. Shown are the six different simulation models after 1 Gyr. Only models with active CR transport (i.e., streaming or diffusion) drive outflows from the disk (middle and right-hand panels). The outflow in the pure diffusion model is much stronger than in the streaming model due to the CR energy loss as a result of the Alfvén wave cooling term, $\boldsymbol{v}_{\mathrm{A}} \cdot \nabla P_{\mathrm{c}}$. Artificially suppressing this term (bottom right panel) results in a stronger and faster outflow. Only models without the Alfvén wave cooling term show vertical velocities that exceed the virial velocity $v_{200} = \sqrt{GM_{200}/R_{200}} = 35$ kpc substantially.

Diffusion with no streaming results in stronger wind; heating by CRs

# COSMIC RAYS AND US

- Use kinetic PIC code to study CR streaming
- Get CR diffusion coefficients
- Resonant Saturation
- CR streaming: does $v_{CR}$-> $v_A$?
- Damping?

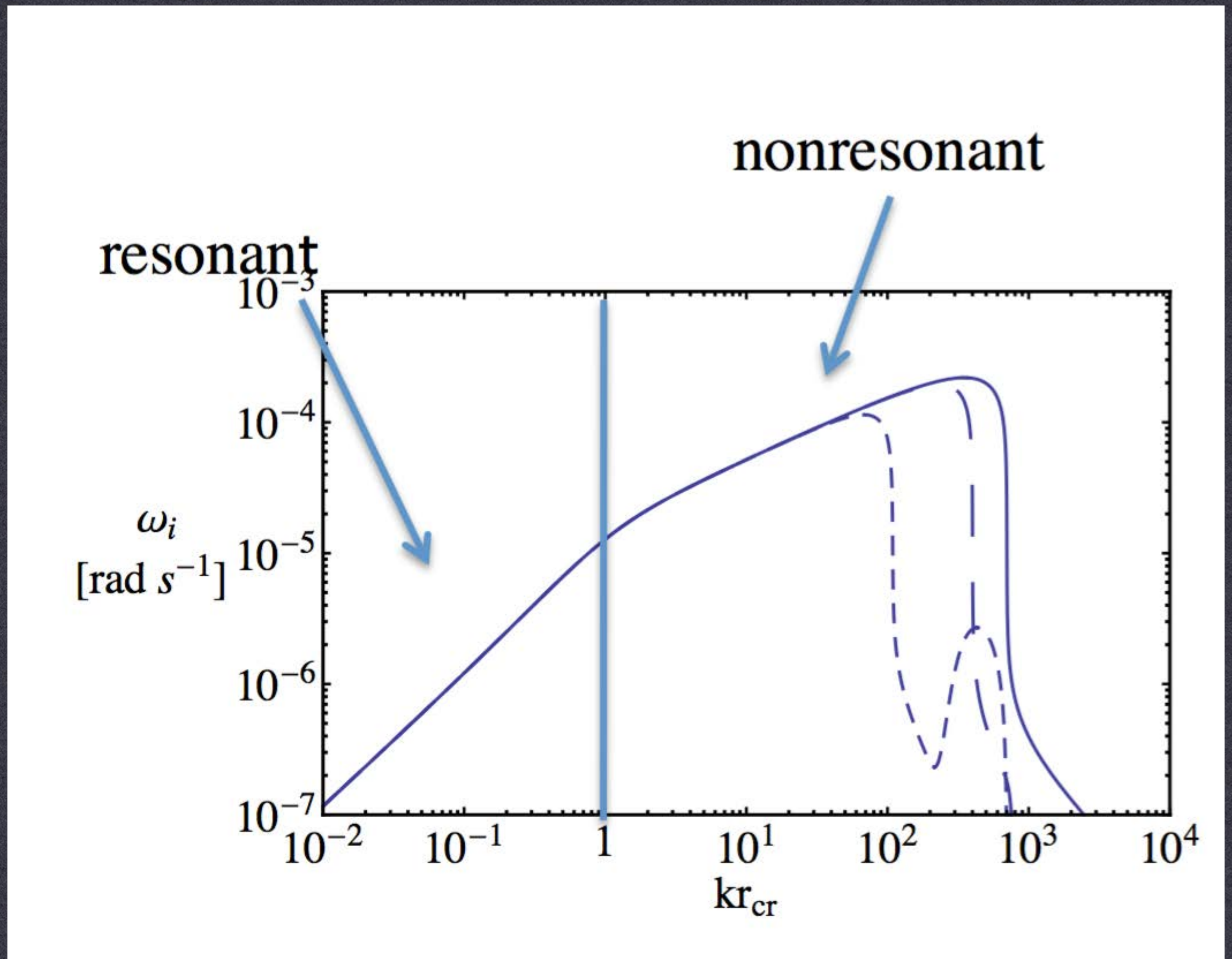


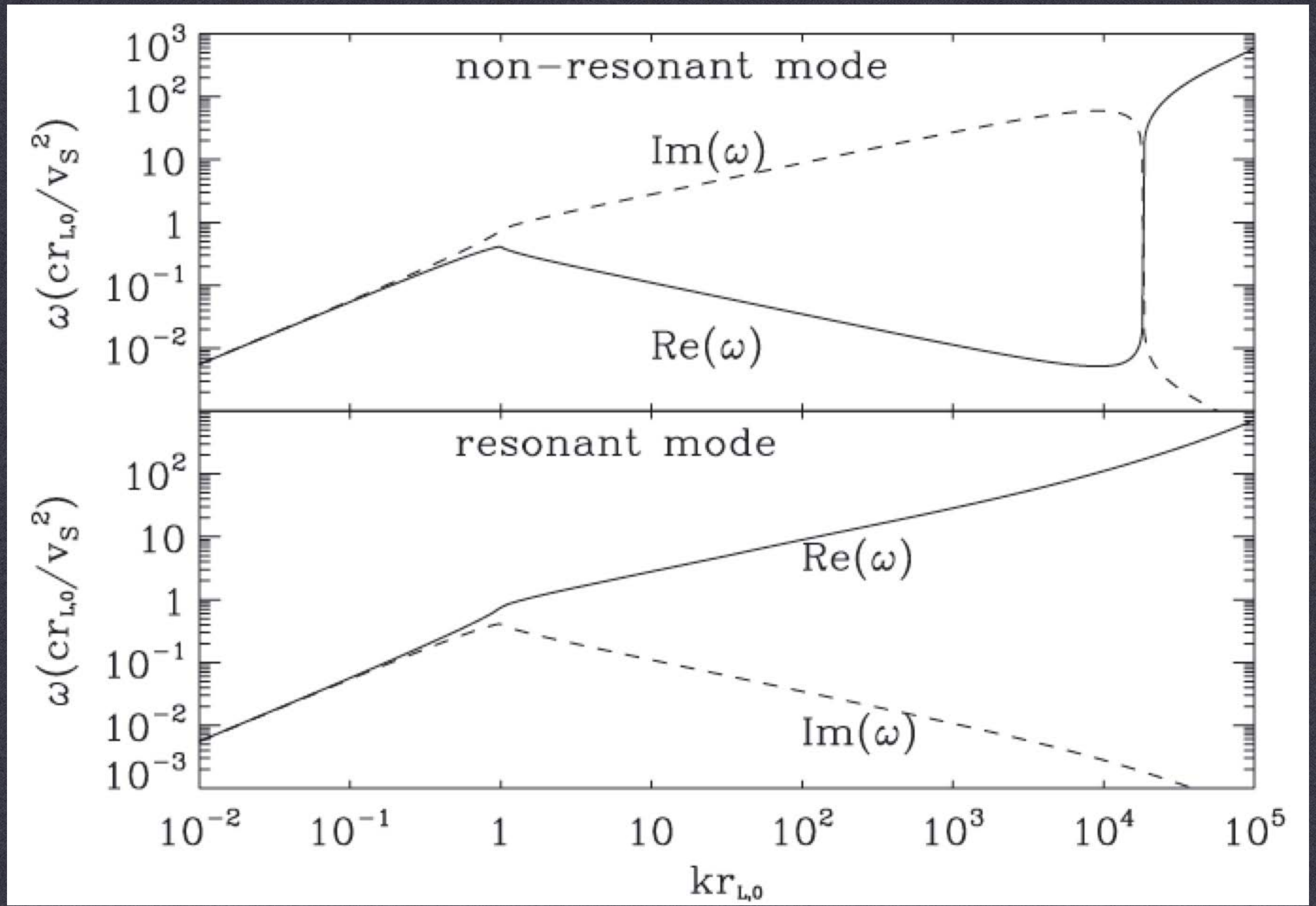
# COSMIC RAYS AND PLASMAS

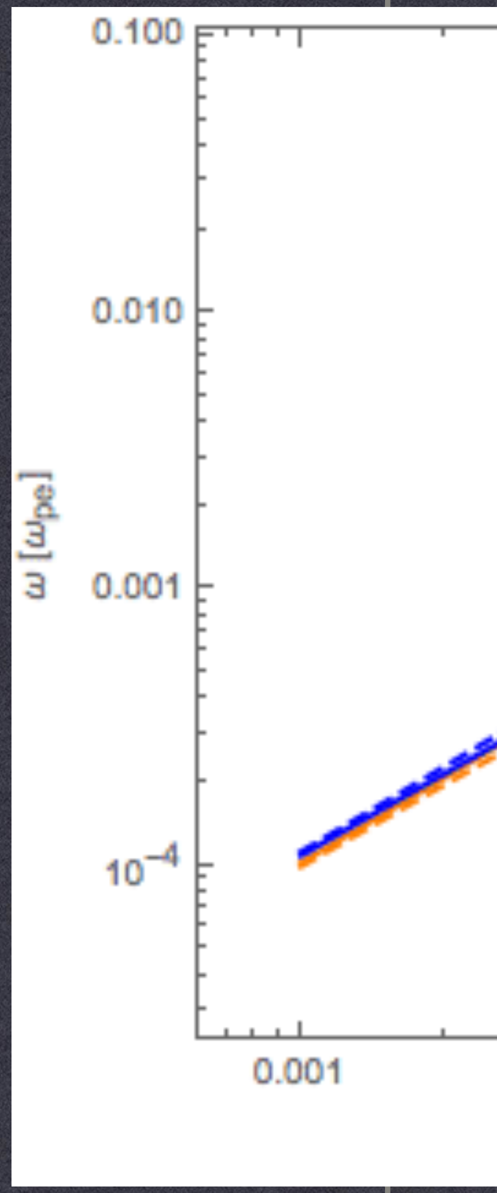
- Comparison to analytic results (Amato & Blasi 2008)
- Dispersion relation depends on $J_{CR}r_g/B_0$

$$\frac{\sigma}{v_A^2} = \frac{N_{CR}}{n_i}\frac{p_0}{m_i c}\frac{v_S c}{v_A^2} = \frac{4\pi}{c} J \frac{r_{L,0}}{B_0}$$

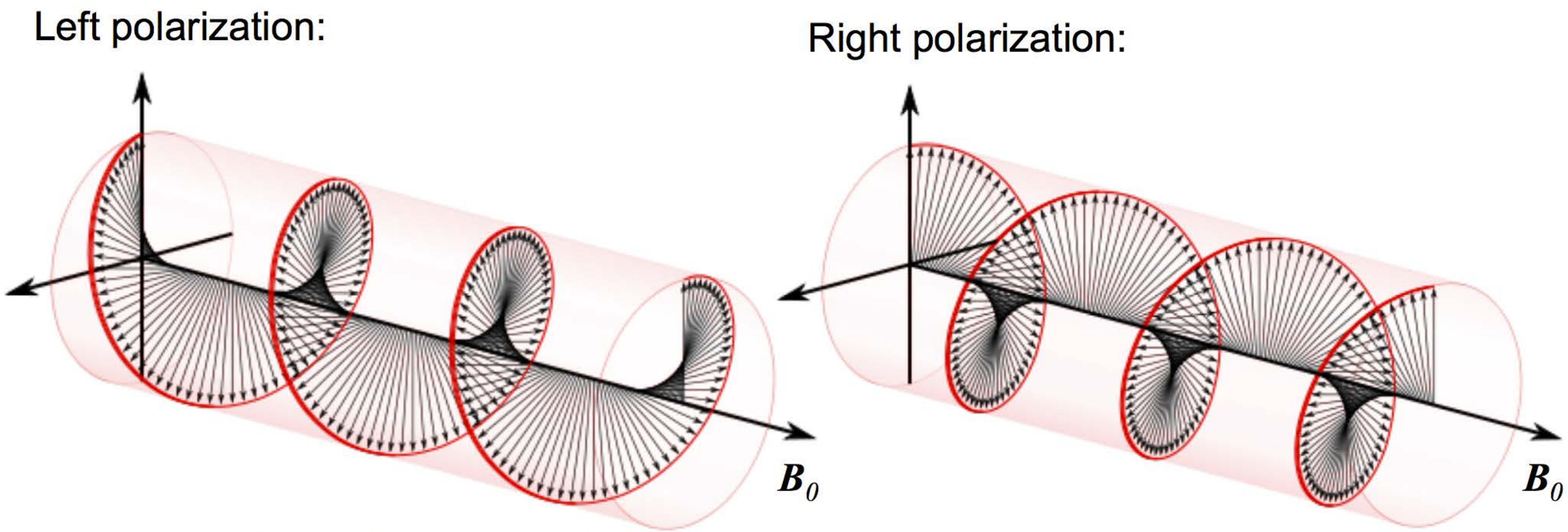
  – $J_{CR}r_g/B_0 \gg 1$: Current Driven -> $\gamma_{max} \sim (\pi/\rho c^2)^{1/2} J_{CR}$ ; $k_{max} = 2\pi J_{cr}/B_0 c$
  – $J_{CR}r_g/B_0 \ll 1$: Gyroresonance -> $k_{max} \sim 1/r_g$



# Resonant interactions with Alfvén waves




Resonant with backward-traveling ions.

Resonant with forward-traveling ions.

Gyro resonance: $\omega - kv_z = \pm\Omega$

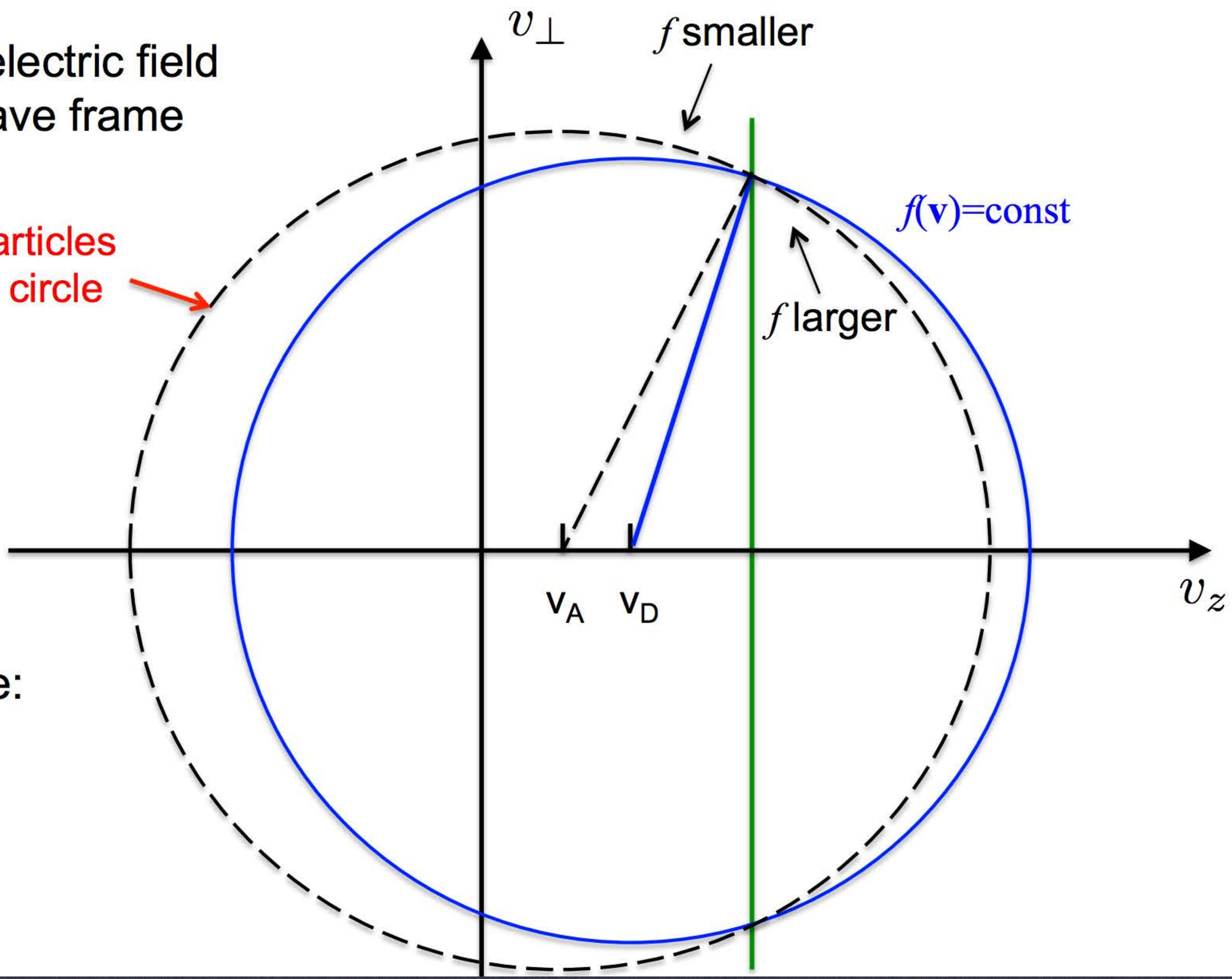
In general, $\omega \ll \Omega$: $v_z = \pm\Omega/k$

from X. Bai

# CR streaming instability: basic physics

Alfven wave: electric field vanishes in wave frame

Individual CR particles move along this circle




Gyro resonance:

$v_z = \Omega / k$

# Gyroresonant Streaming Instability

$$\Gamma_{cr} = \frac{\pi^2 q^2}{2} \frac{v_A^2}{c^2} \sum_{\pm} \int \underbrace{\delta(\omega - kv\mu \pm \omega_c)}_{\text{resonance condition}} v(1-\mu^2) \left[ \underbrace{\frac{\partial f}{\partial p}}_{\text{damping}} + \left( \frac{kv}{\omega} - \mu \right) \underbrace{\frac{1}{p}\frac{\partial f}{\partial \mu}}_{\text{excitation by anisotropy}} \right] p^2 dp d\mu,$$

Simple approximation to the growth rate:

$$\Gamma_{cr} \sim C\omega_{ci} \frac{n_{cr}(> p_1)}{n_i} \left( \frac{v_D}{v_A} - 1 \right),$$

$$p_1 \equiv \frac{m\omega_c}{k}$$

Minimum cosmic ray momentum that can resonate with a given k.

# Basic properties

When CR drift velocity $v_D$ exceeds $v_A$:

- Forward-traveling CRs resonantly excite (right) polarized, forward-propagating Alfven waves.
- Backward-traveling CRs resonantly excite (left) polarized, forward propagating Alfven waves.
- Backward-propagating Alfven waves are suppressed.

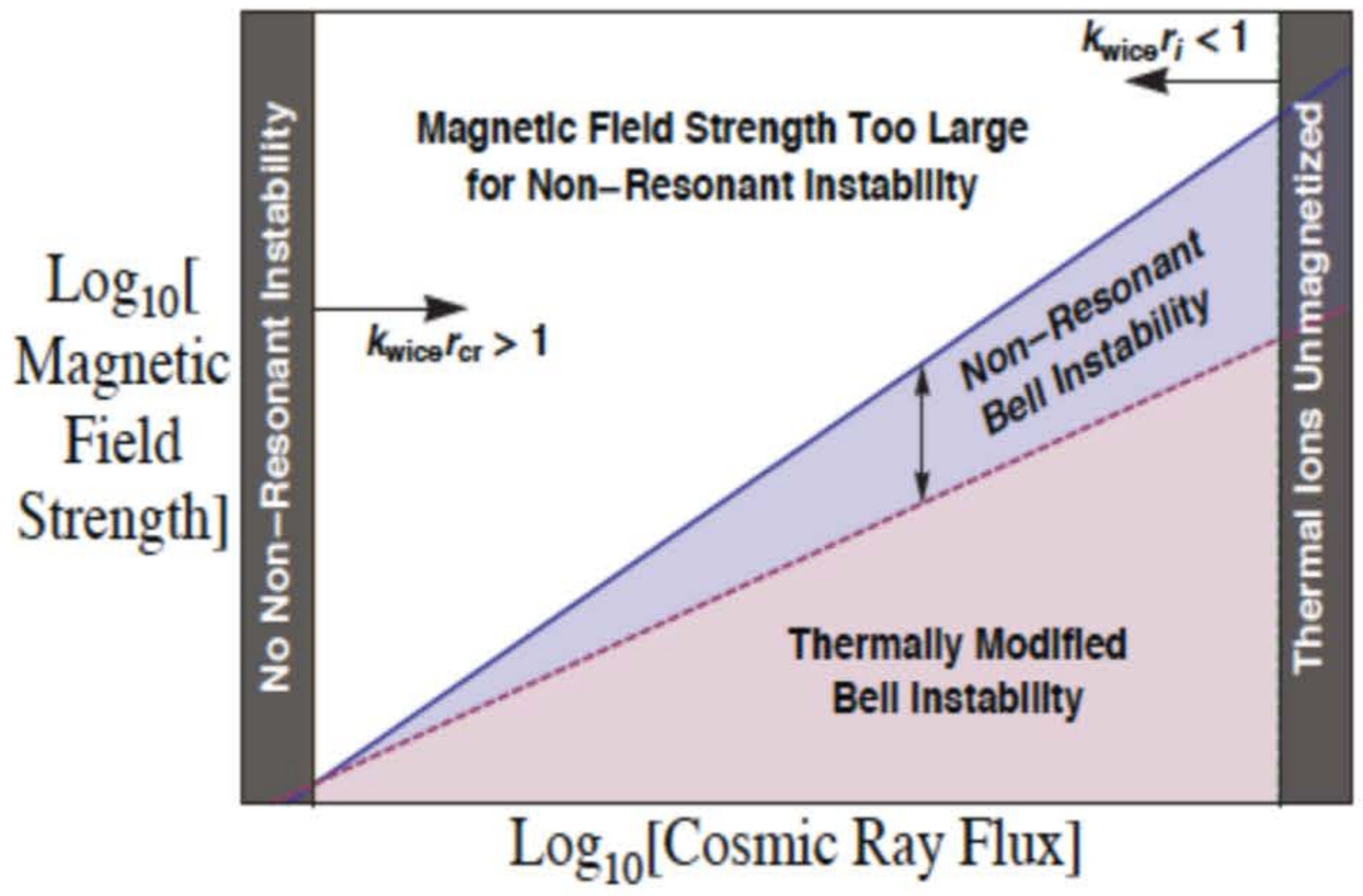
Characteristic growth rate:

$$\Gamma(k) \approx \Omega_c \frac{N_{\rm CR}(p > p_{\rm res}(k))}{n_i} \frac{v_D - v_A}{v_A}$$

More generally, when CR anisotropy exceeds ~$v_A/c$, certain Alfven modes become resonantly unstable.

# Nonresonant Instabilities

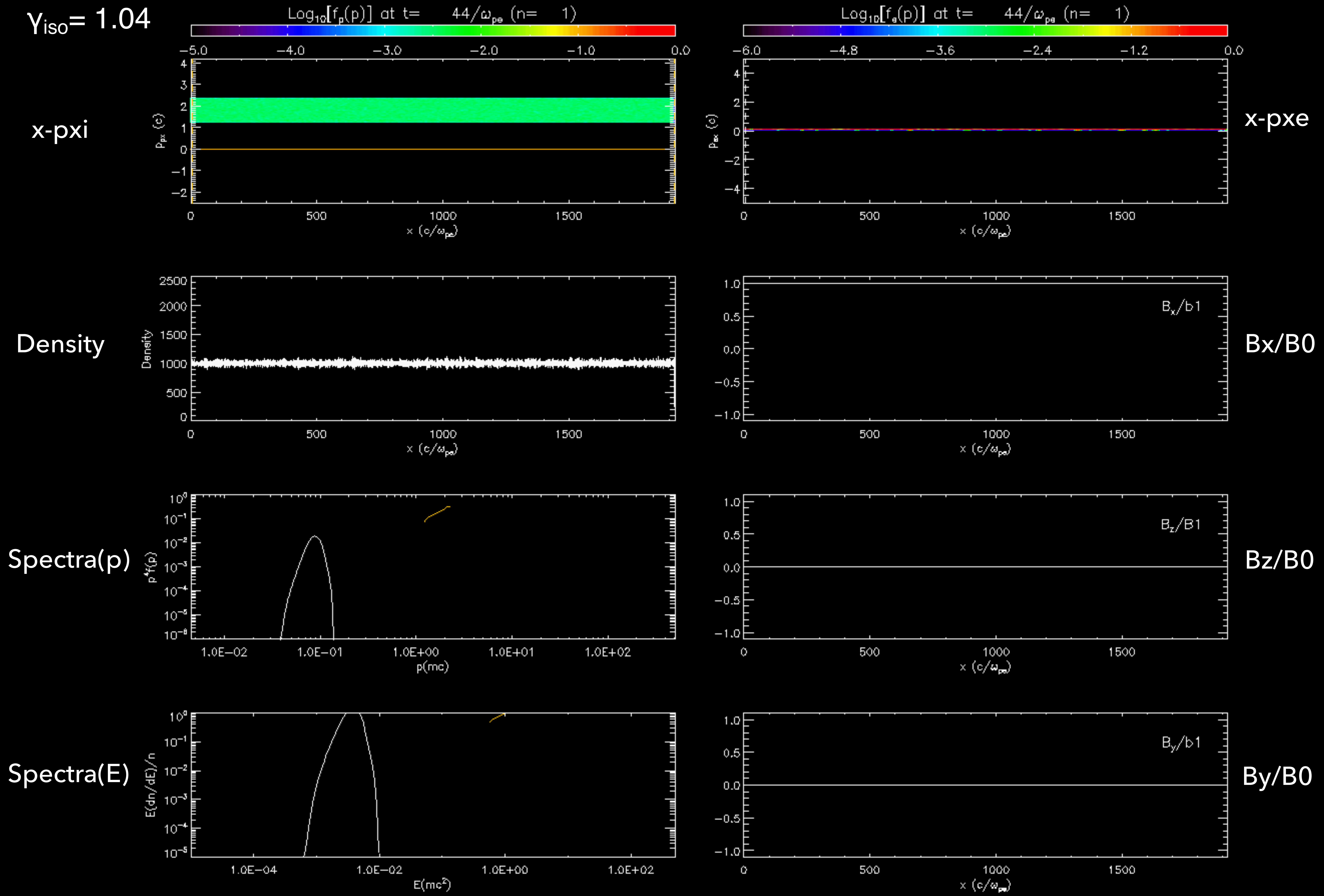
- When $U_{cr}/U_B > c/v_D$ there is a nonresonant instability driven by the electron current that compensates the cosmic ray current *(keep the nonresonant cosmic rays in the dispersion relation)*.
- Conditions are met at shocks, and possibly in young galaxies.




EVERETT & ZWEIBEL 10

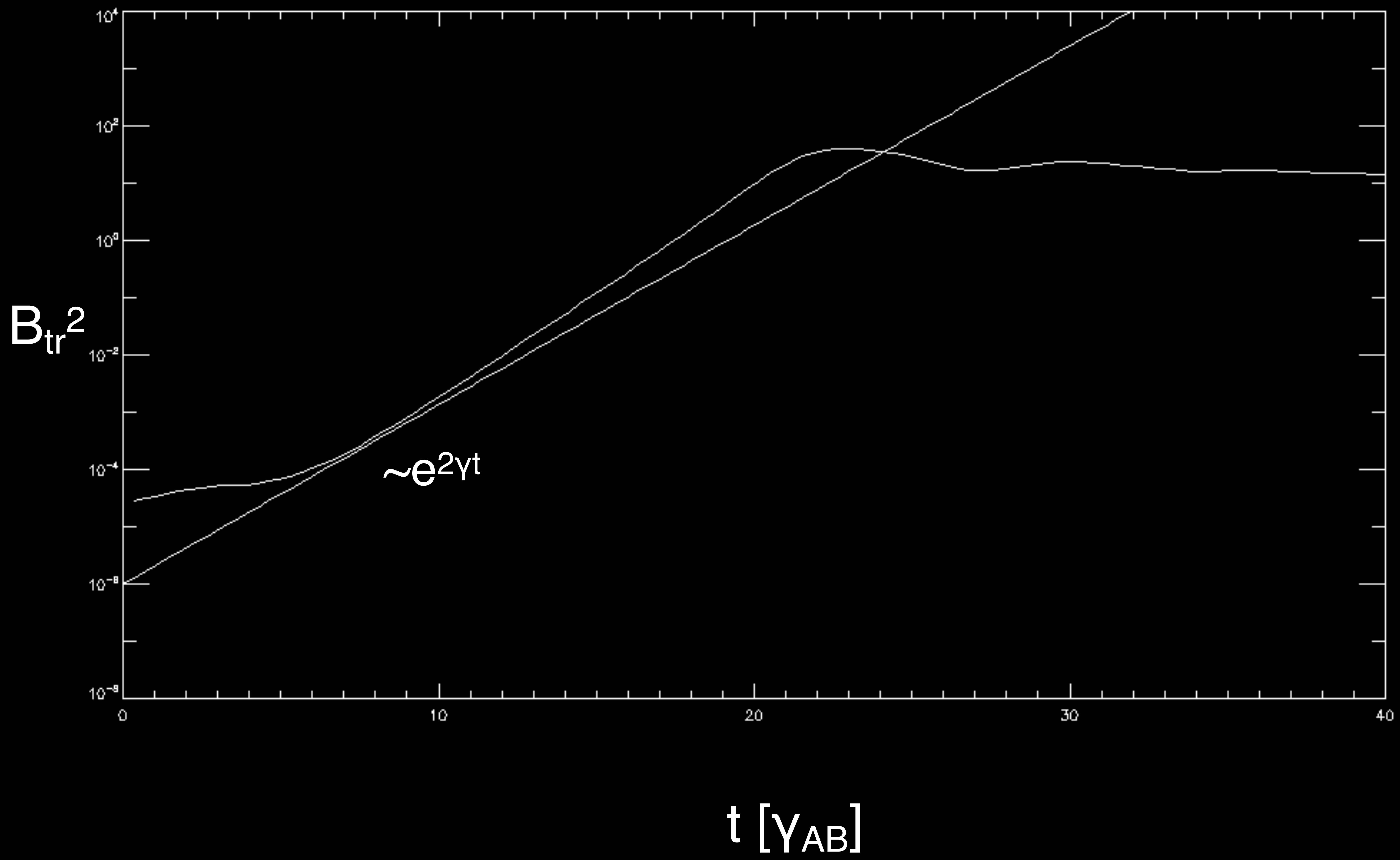
# PIC simulation:Resonant Instability

$v_A \sim .2c$
$\gamma_{dr} = 2$
$\gamma_{iso} = 1.04$



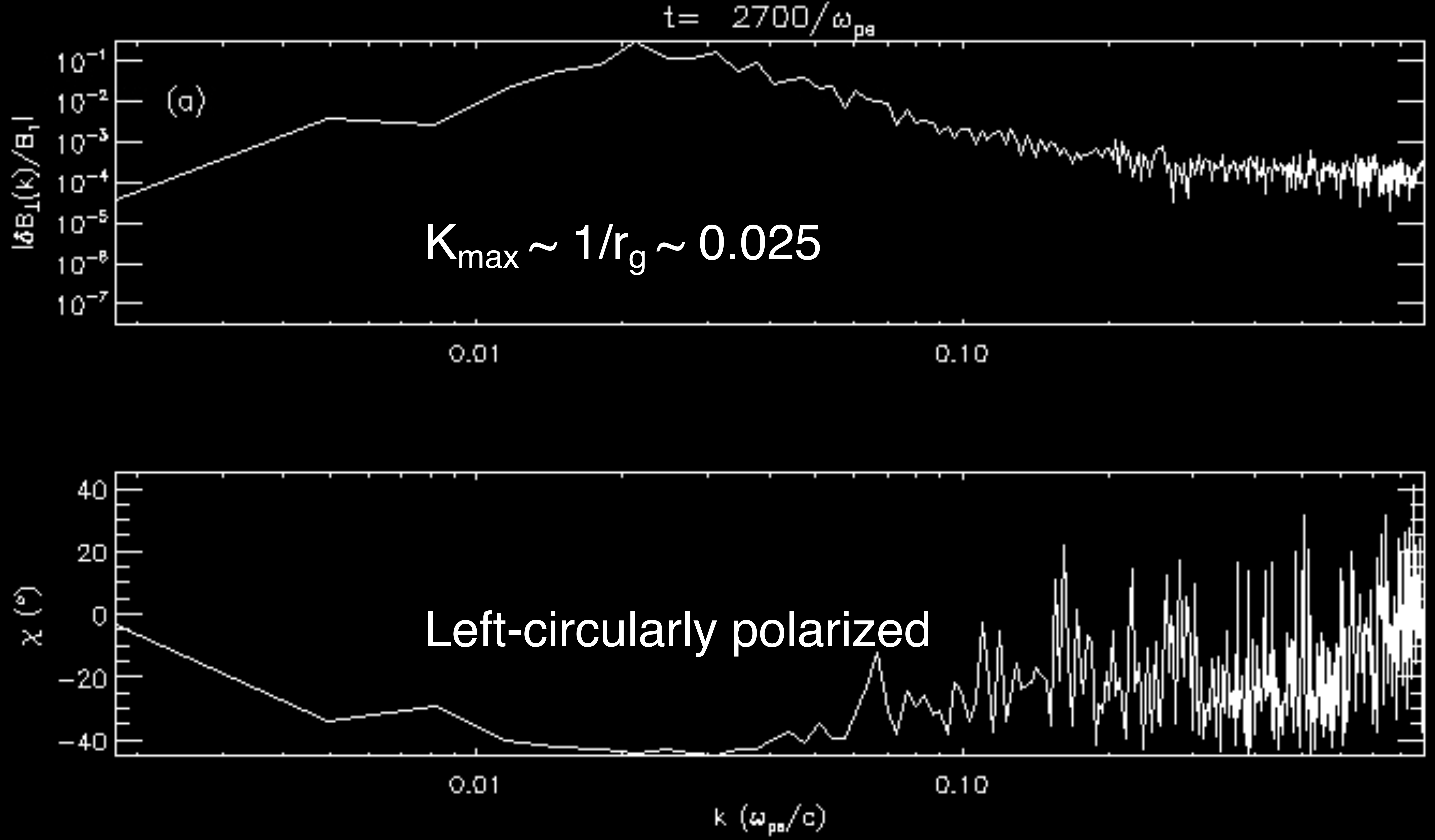
$v_A \sim .2c$
$\gamma_{dr} = 2$
$\gamma_{iso} = 1.04$

# Resonant Instability



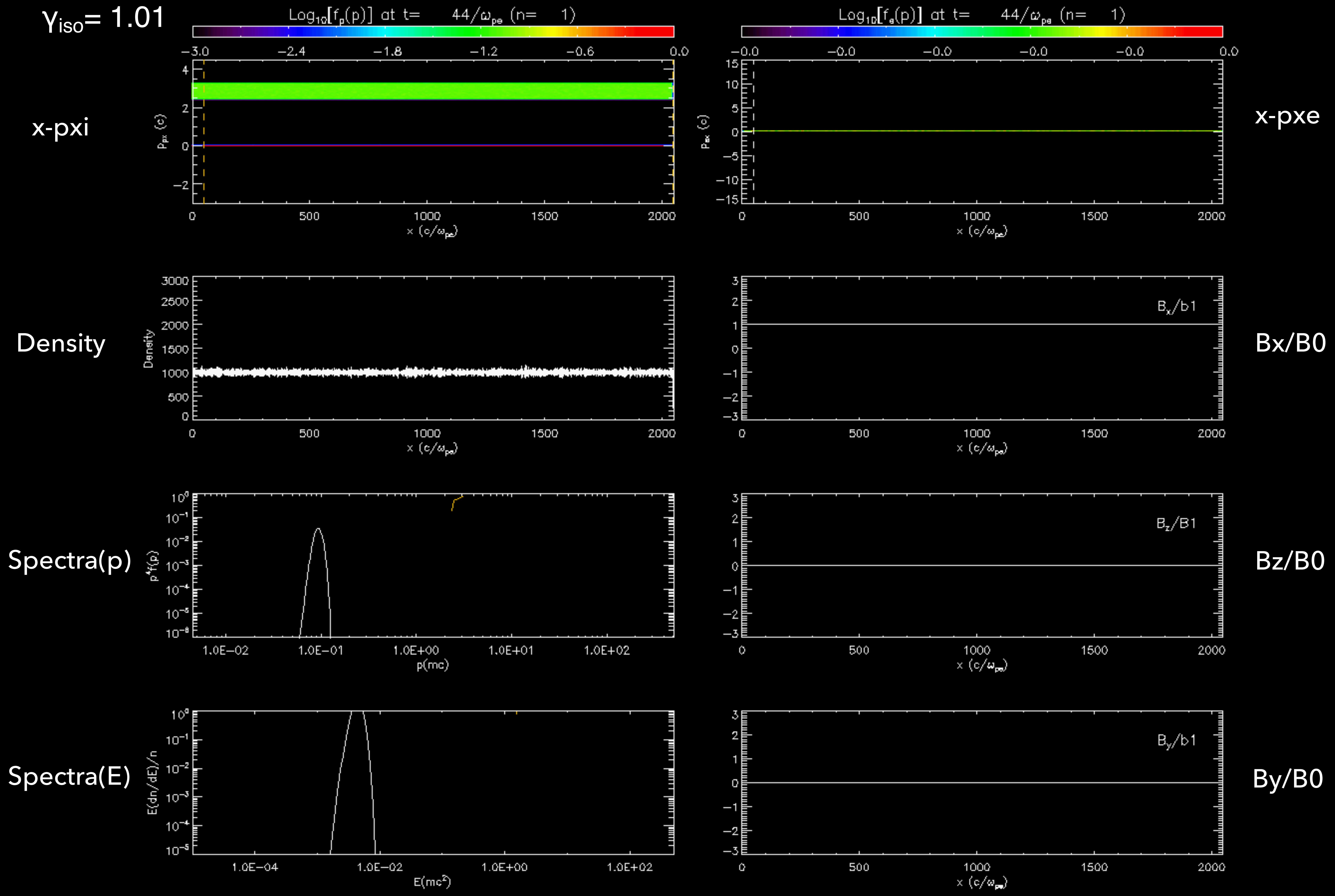
$v_A \sim .2c$
$\gamma_{dr} = 2$
$\gamma_{iso} = 1.04$

# Resonant Instability



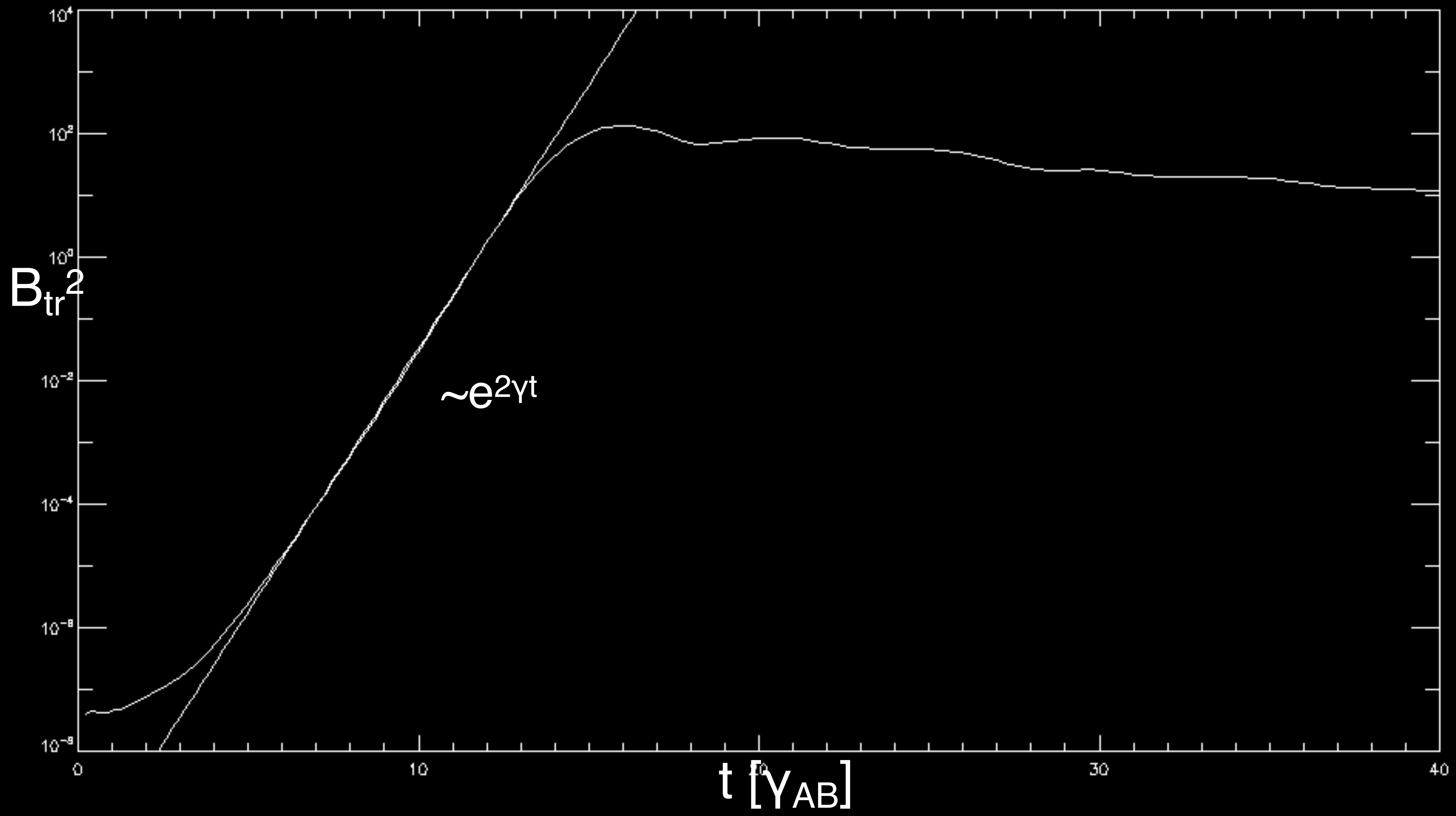
# PIC simulation: nonresonant Instability

$v_A \sim .14c$
$\gamma_{dr} = 3$
$\gamma_{iso} = 1.01$



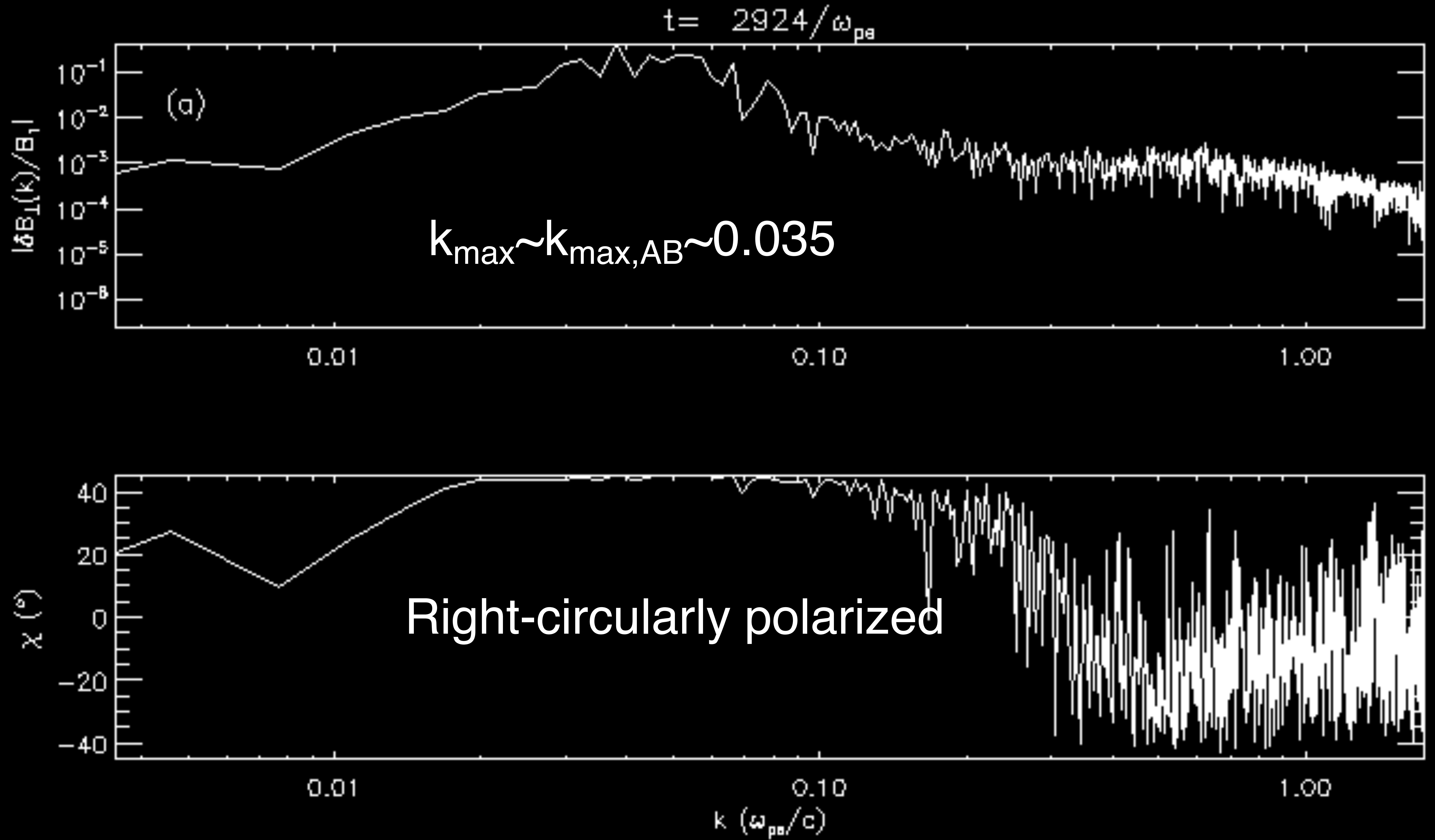
# Nonresonant Instability

$v_A \sim .14c$
$\gamma_{dr} = 3$
$\gamma_{iso} = 1.01$



$v_A \sim .14c$
$\gamma_{dr} = 3$
$\gamma_{iso} = 1.01$

# Nonresonant Instability

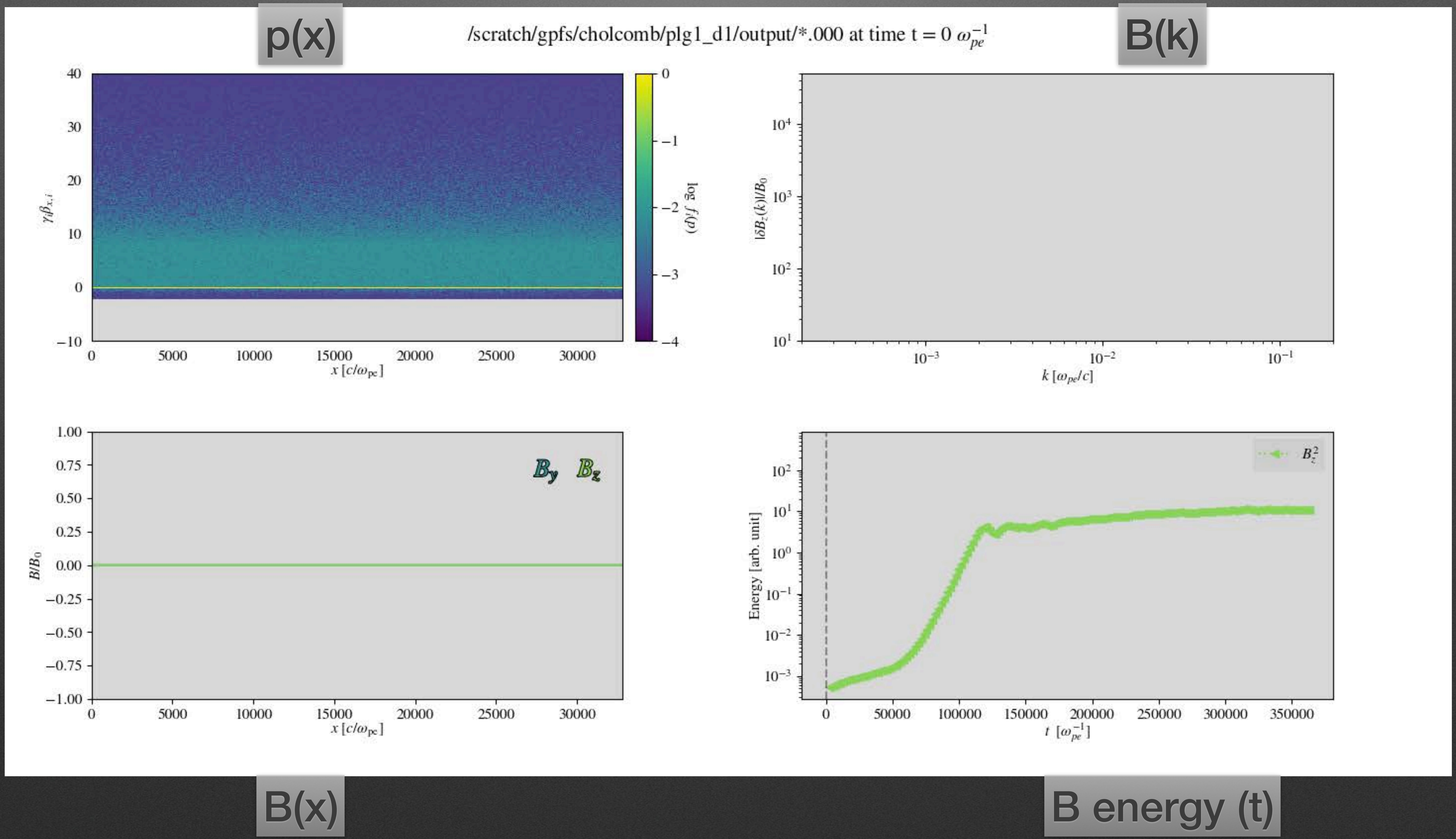



$k_{max} \sim k_{max,AB} \sim 0.035$

Right-circularly polarized

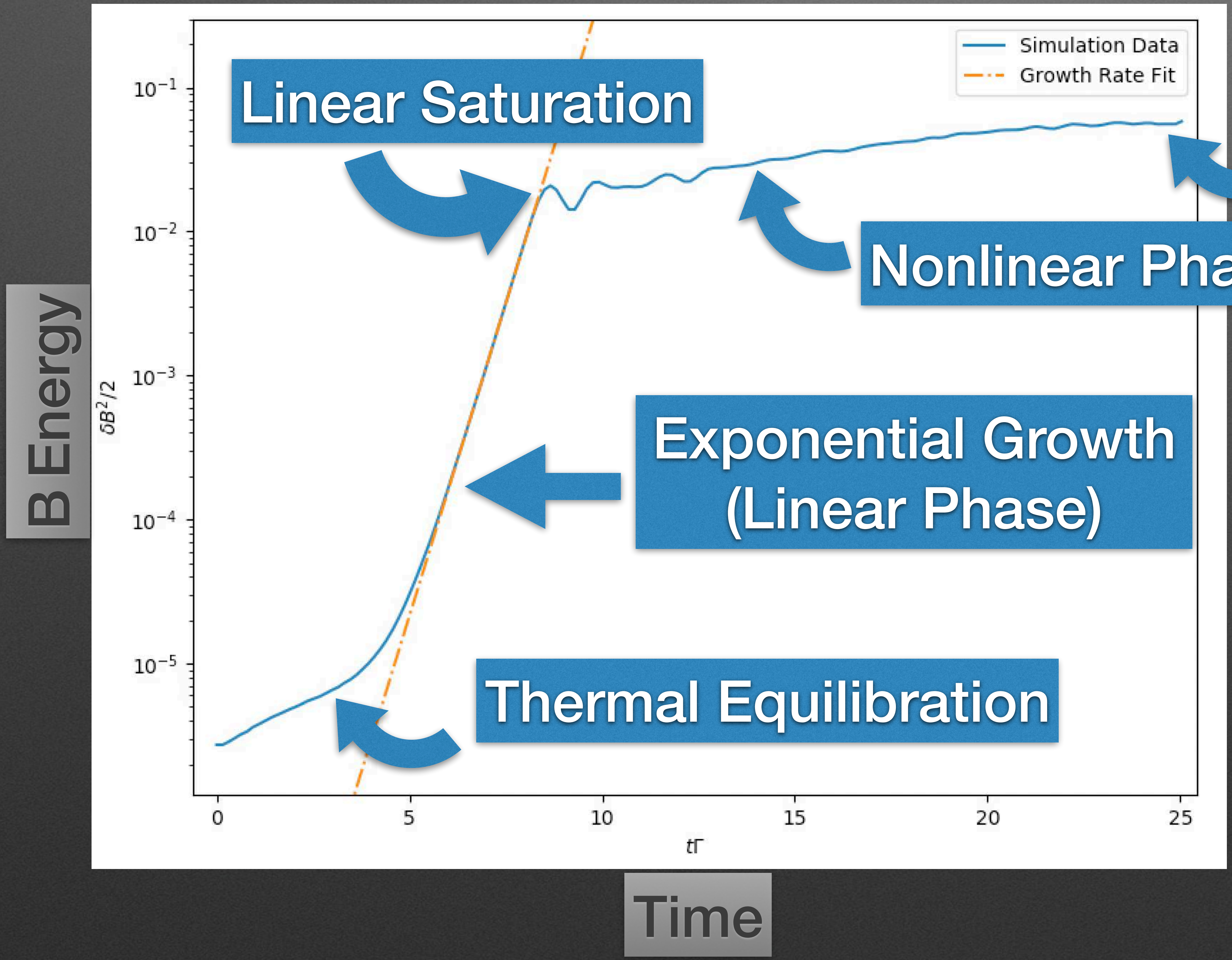
# Power-Law CR Distribution

$n_{cr} = 2*10^{-3}\ n_i$
$v_D/v_A = .8c/.1c$
$\gamma = [2, 10]$



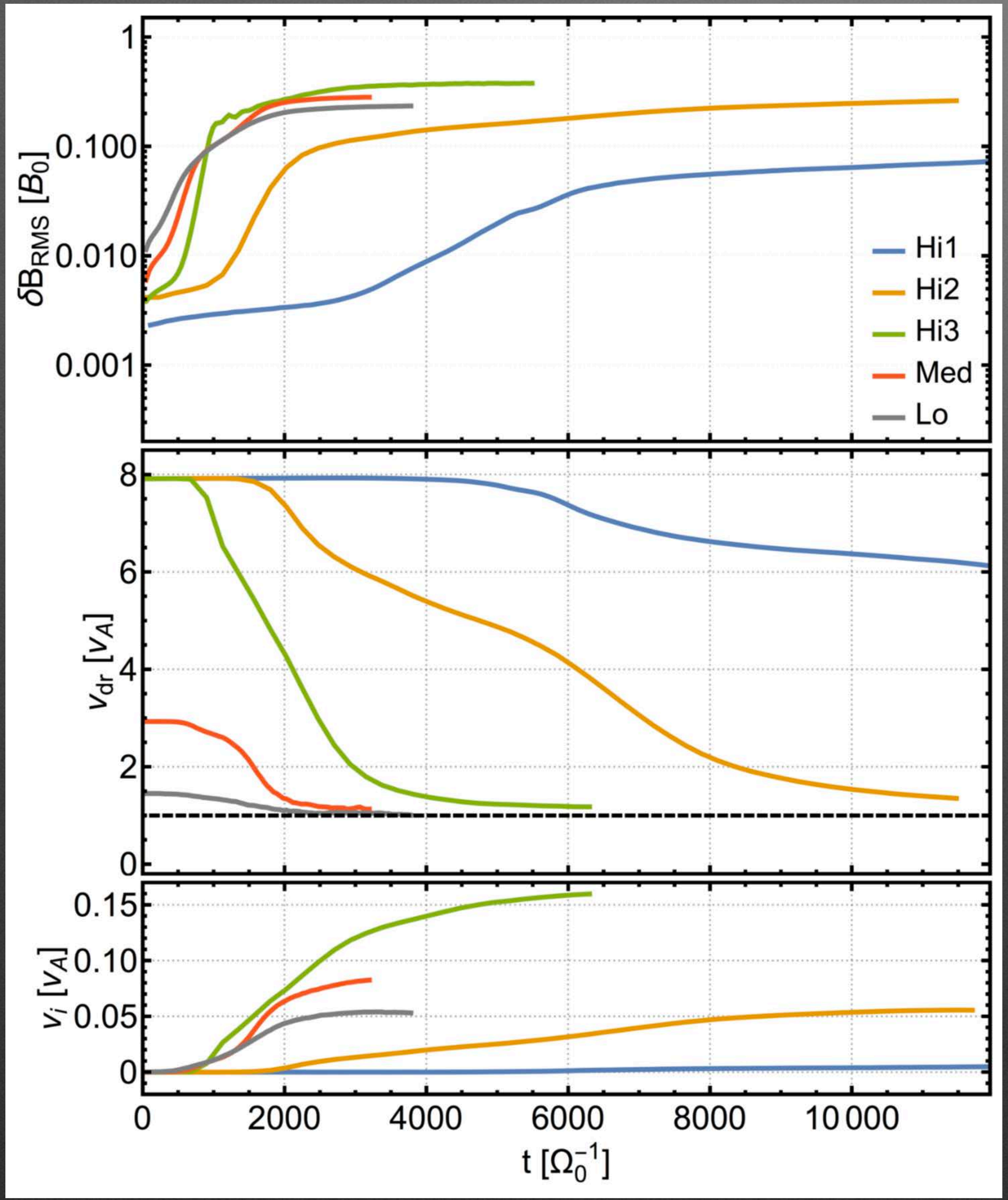
# Growth Rate

$n_{cr} = 2*10^{-3}\ n_i$
$v_D/v_A = .8c/.1c$
$\gamma = [2, 10]$




Measured growth rate adequately matches expectation

# Streaming Speeds



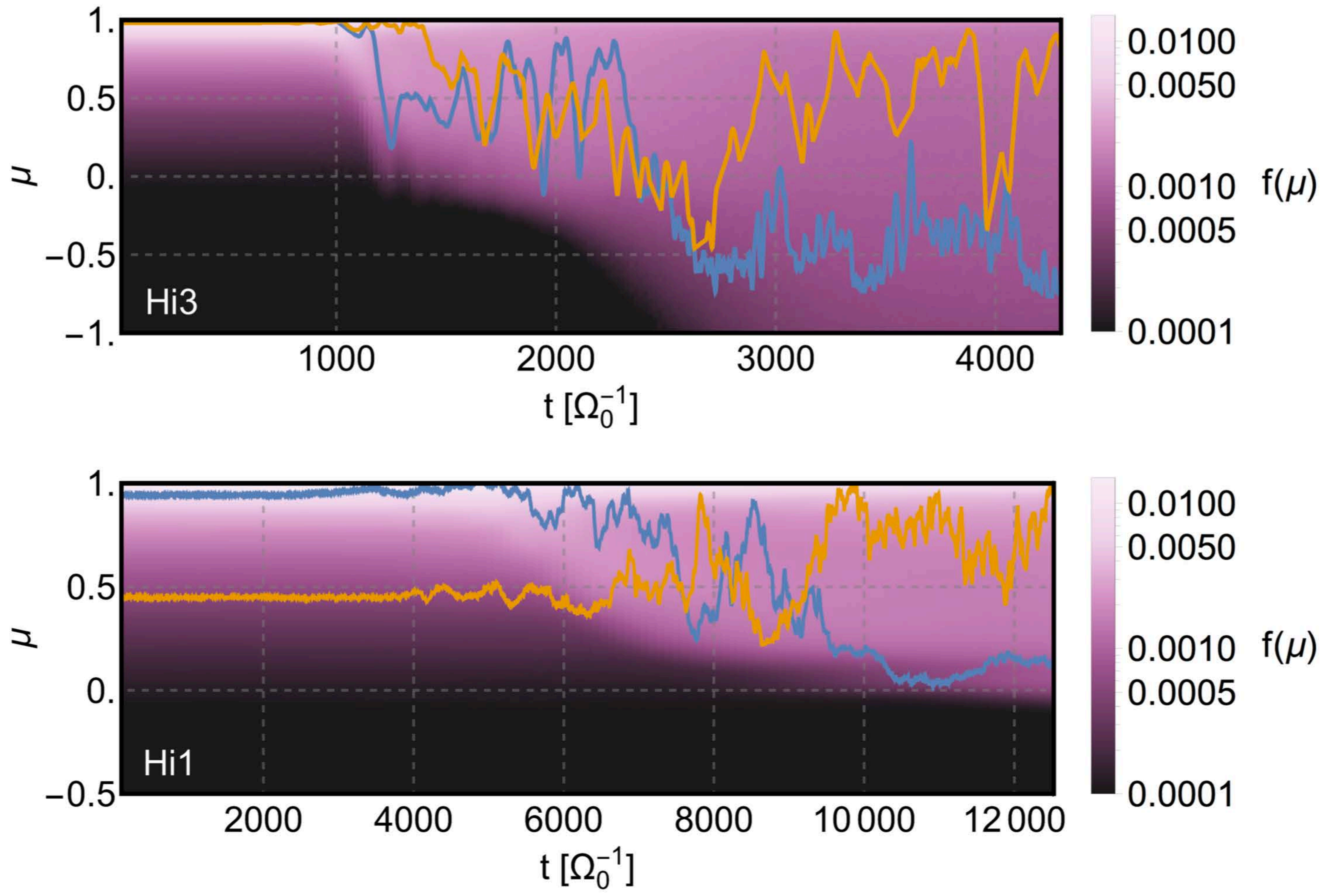

CR drift speed evolution depends on wave spectrum

Large amplitude waves quickly reduce $v_{dr}$ ➡ $v_A$

Small-amplitude right-handed waves result in protracted decay phase of $v_{dr}$
as CRs slowly cascade to smaller μ

Waves drive bulk motion in the background plasma —
CR-driven wind

# Power-Law Distribution Evolution

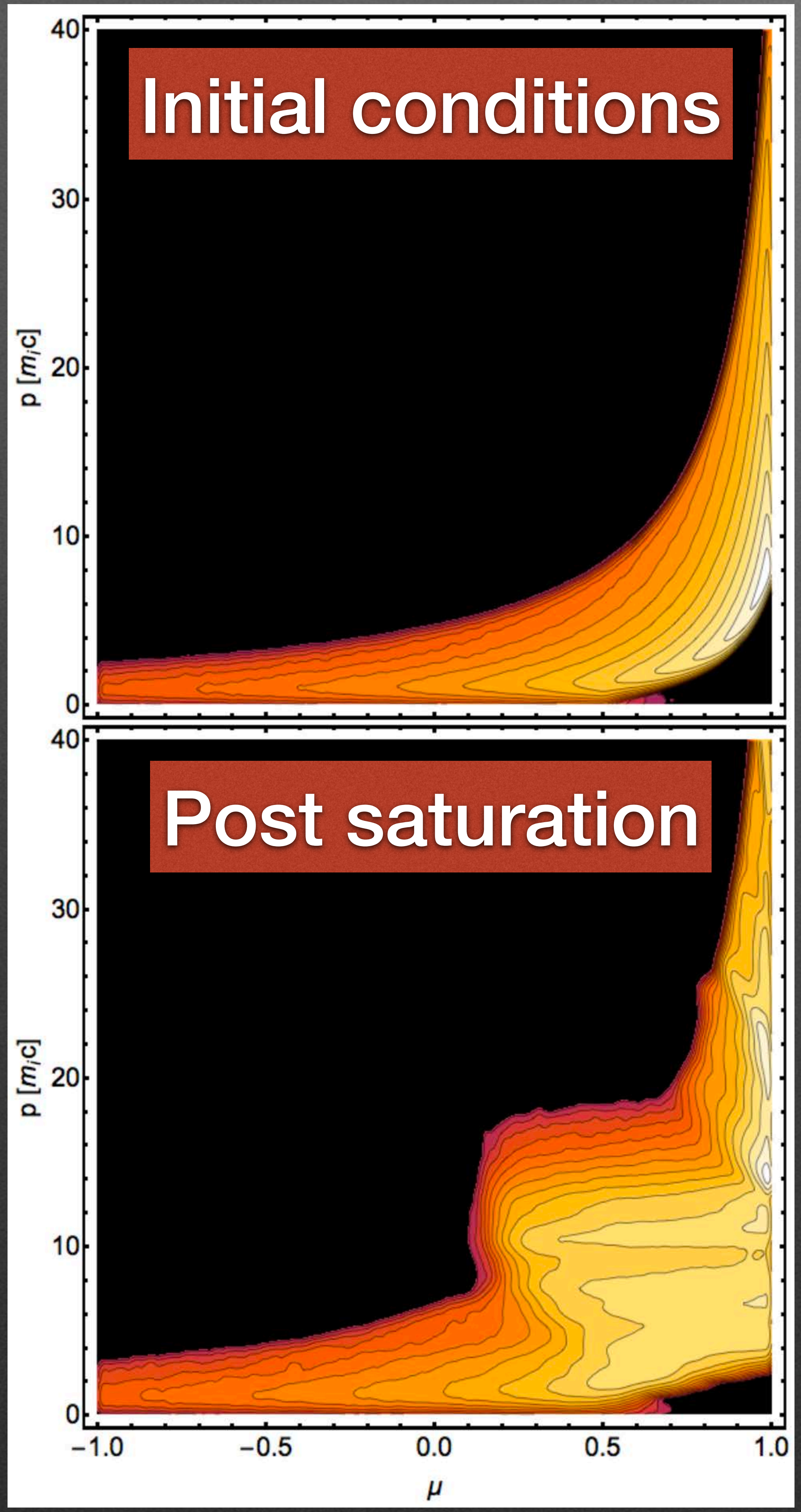



High CR Density
dB/B ~ 0.3

Low CR Density
dB/B ~ 0.1

Isotropy is not achieved unless left-handed modes are generated

# Saturation Mechanism




$$\Gamma^{\pm}_{\mathrm{cr}}(k) = \frac{\pi^2 q^2}{2}\frac{v_A^2}{c^2}\sum_{\pm}\iint \delta\left(\omega - k\mu v \pm \Omega(p)\right)\boxed{\left(\frac{\partial f}{\partial p} + \left(\frac{kv}{\omega} - \mu\right)\frac{1}{p}\frac{\partial f}{\partial \mu}\right)} v p^2 (1-\mu^2)\, dp\, d\mu$$

Instability is quenched when gradients are flattened

# Instabilities saturate by getting rid of anisotropy

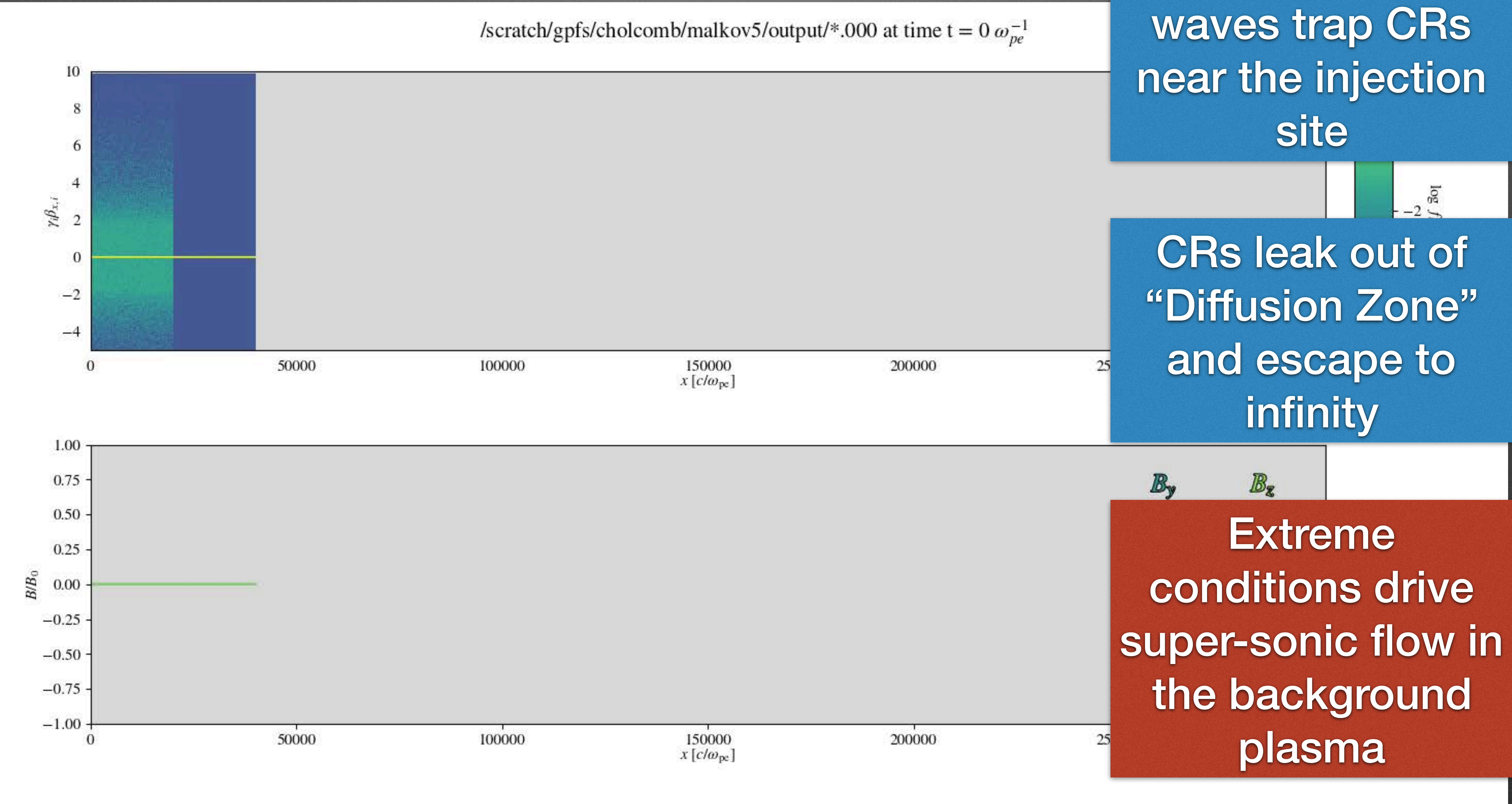
If waves are strong —> can slow down first, v_drift->v_a

If waves are weak —> can flatten the distribution first, and if drift is large, no waves of polarization needed to turn particles around are present — may get large drift.

This may be important near sources with large anisotropy, e.g. SNRs

# CR Cloud Simulations

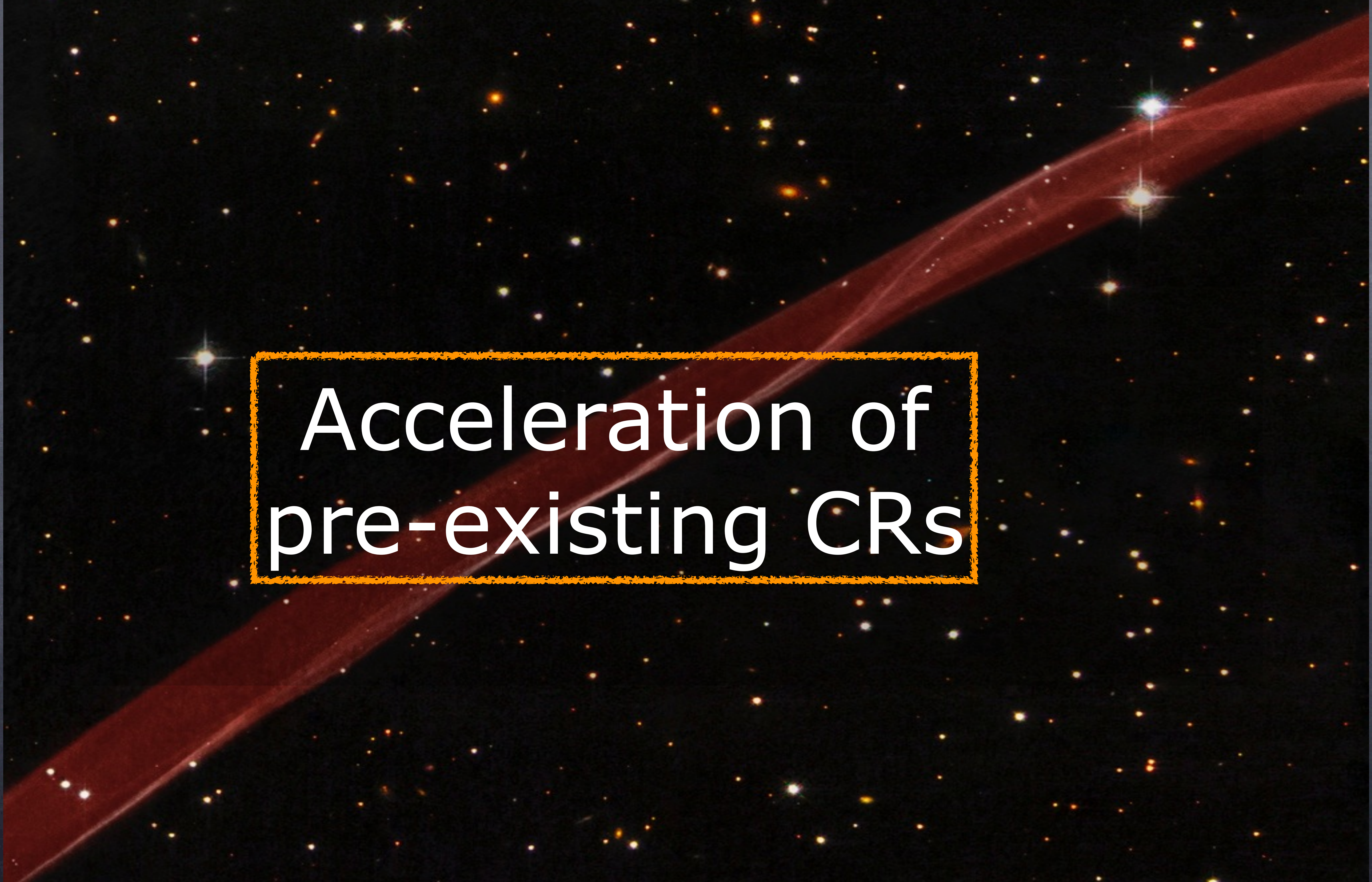
High CR Density




Large amplitude waves trap CRs near the injection site

CRs leak out of “Diffusion Zone” and escape to infinity

Extreme conditions drive super-sonic flow in the background plasma

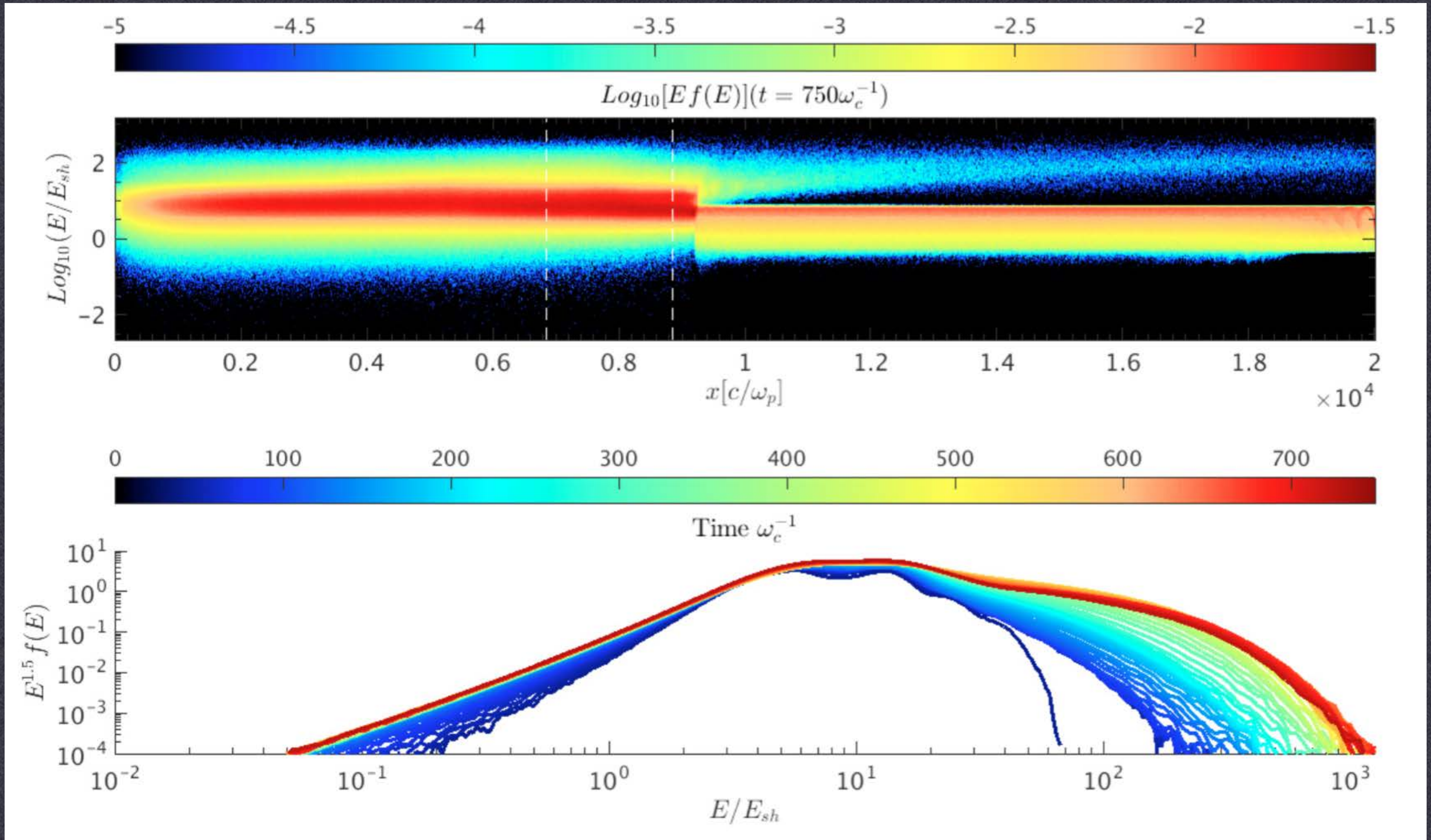


# Acceleration of pre-existing CRs

# Re-acceleration of pre-existing CRs

Add hot "CR" particles to upstream flow (Caprioli, Zhang, AS 2018).

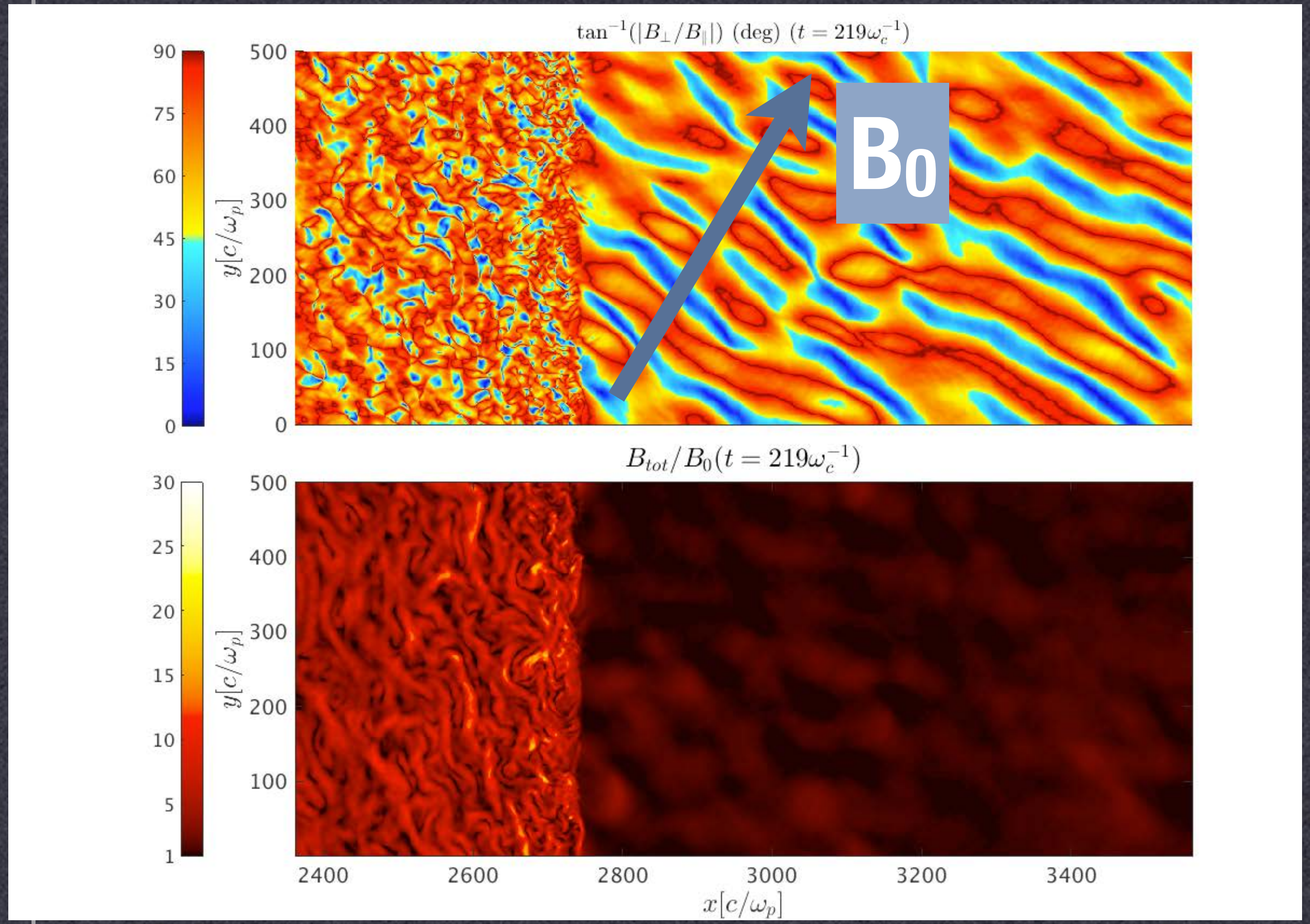
Quasi-perp shock: CRs have large Larmor radii and can recross the shock, accelerate, and be injected into diffusive acceleration process



# Turbulence driven by reaccelerated CRs

Escaping CRs drive turbulence

**field inclination**

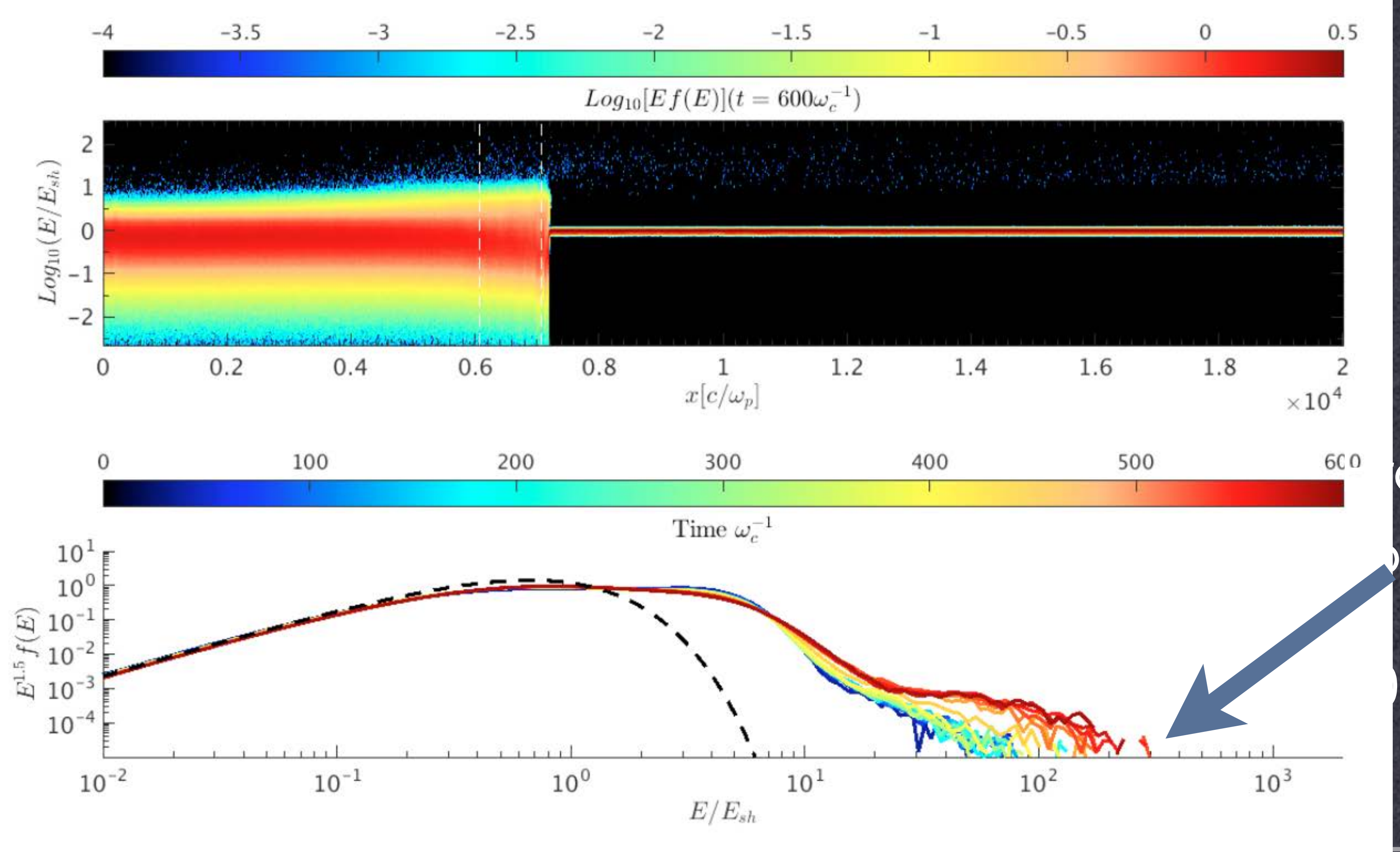



Orientation of the field at the shock changes to regions of quasi-parallel, and efficiency of H acceleration increases.

Pre-existing CRs improve local efficiency of the shock!

Growth time in SNR ~10yrs << age.

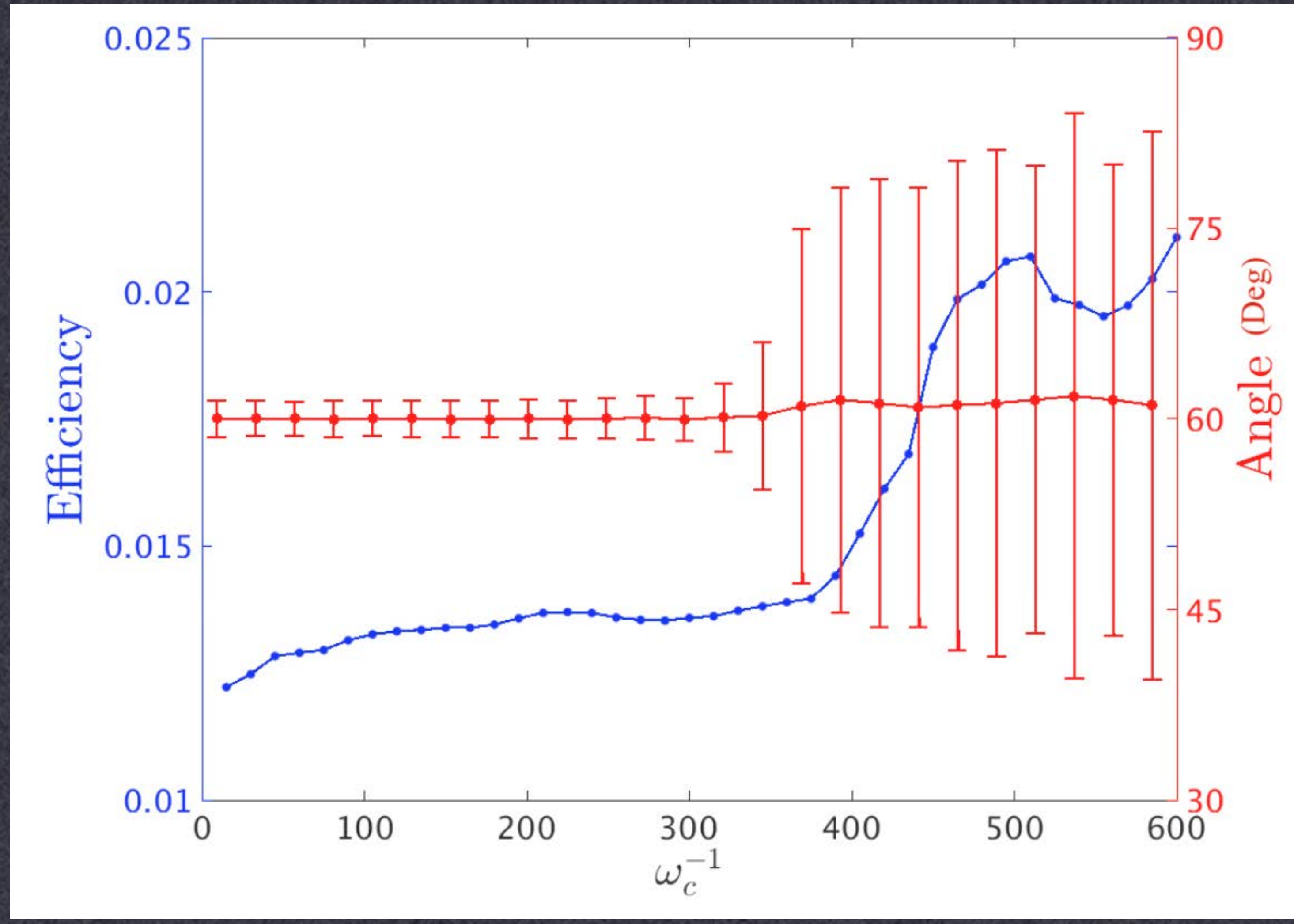
$n_{cr}$=2e-3



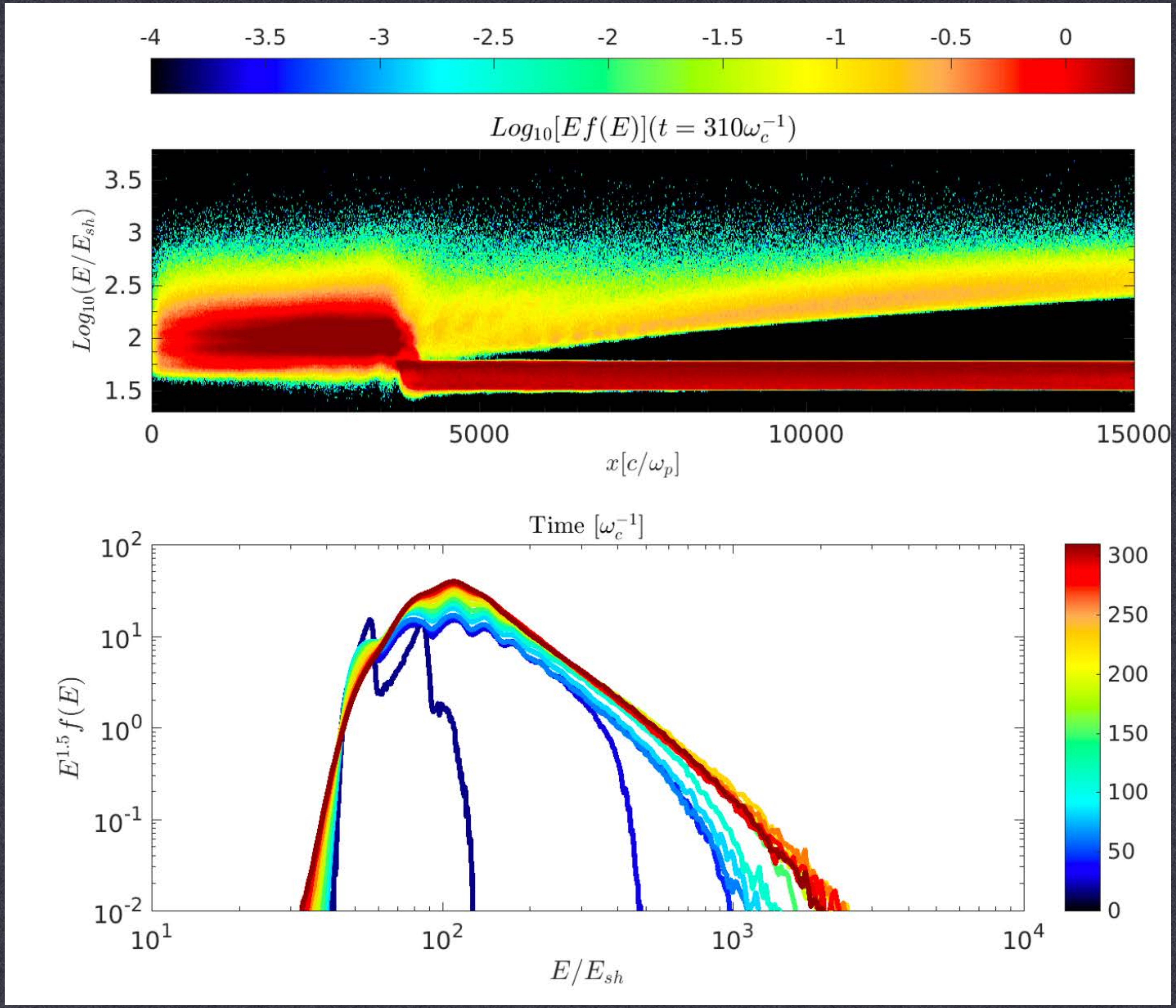

oton

ectrum

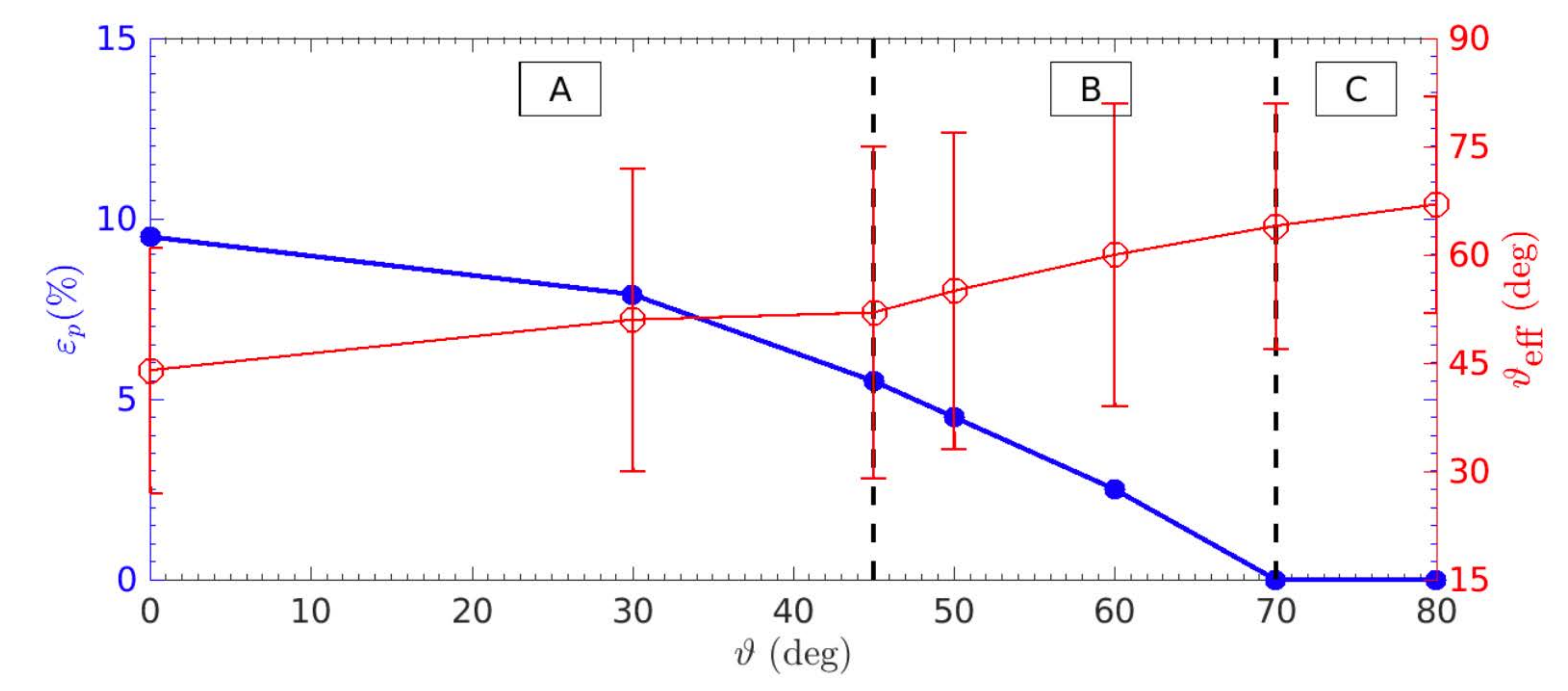
° shock



# Reacceleration of CRs in oblique shocks: spectrum is steeper, $E^{-4}$



# Efficiency of acceleration of protons in presence of CRs




Efficiency of reacceleration of CRs: