Relativistic plasma astrophysics: theoretical perspective

Anatoly Spitkovsky (Princeton)

Relativistic plasma astrophysics: acceleration, reconnection and dissipation

Anatoly Spitkovsky (Princeton)

What is the most important question in your field?

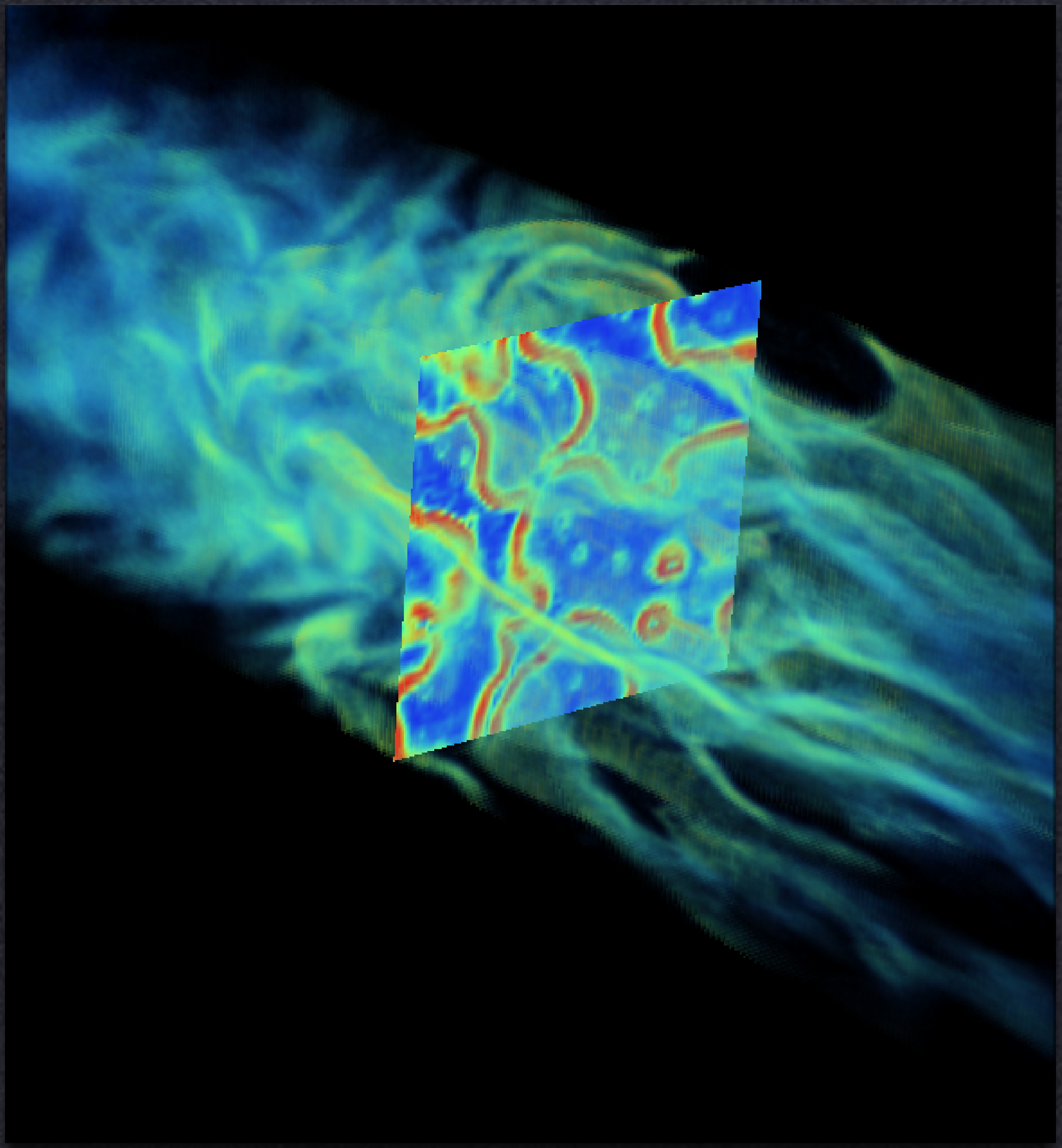
And why are you not working on it?

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...



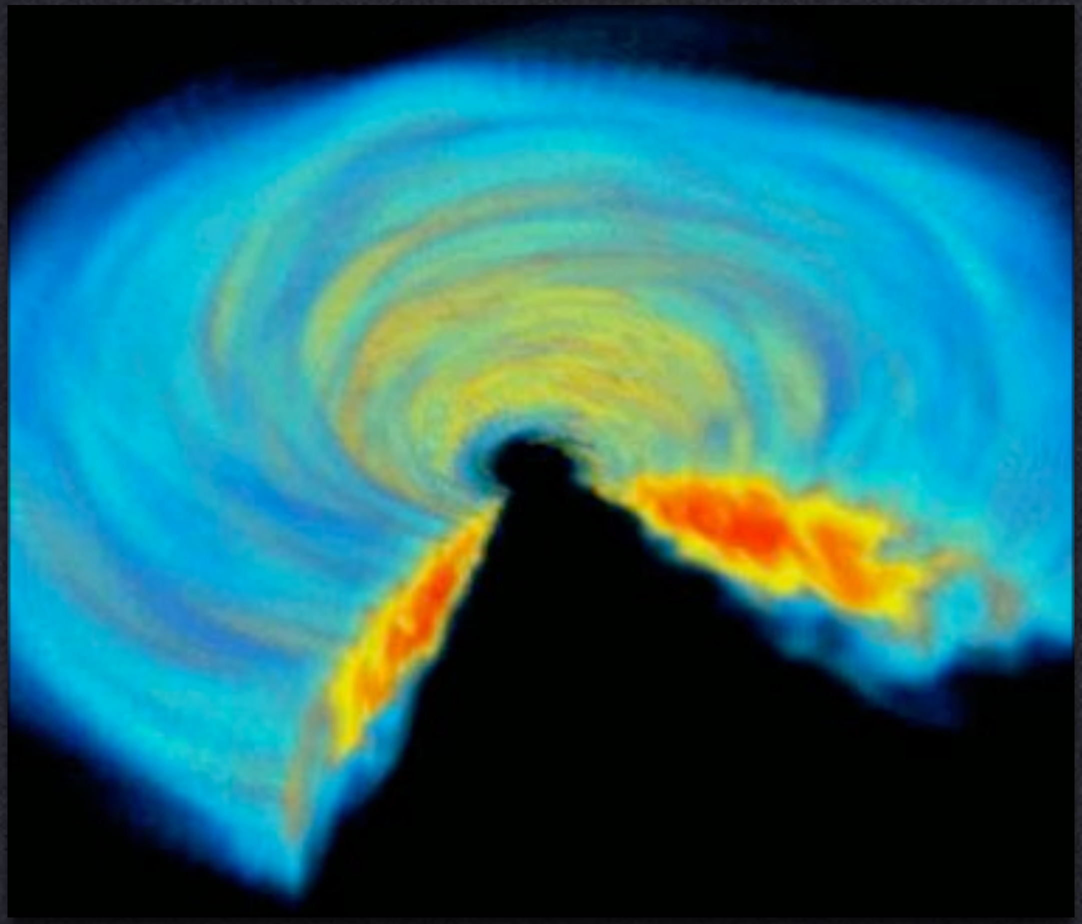
Plasma effects and HEA

- Accretion disks

  Origin of collisionless viscosity

  MRI: cascade termination, two-temperature flows, e-ion equilibration

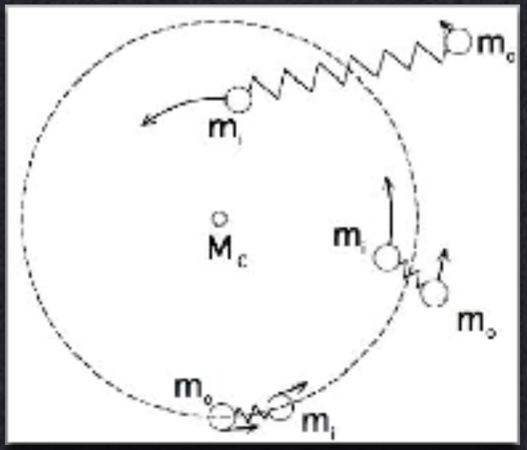
  Energization of disk coronae



- Clusters of galaxies:

  heat conduction and resistivity; transport in tangled fields

  Nonthermal pressure & CRs



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- Clusters of galaxies:
  - heat conduction and resistivity; transport in tangled fields
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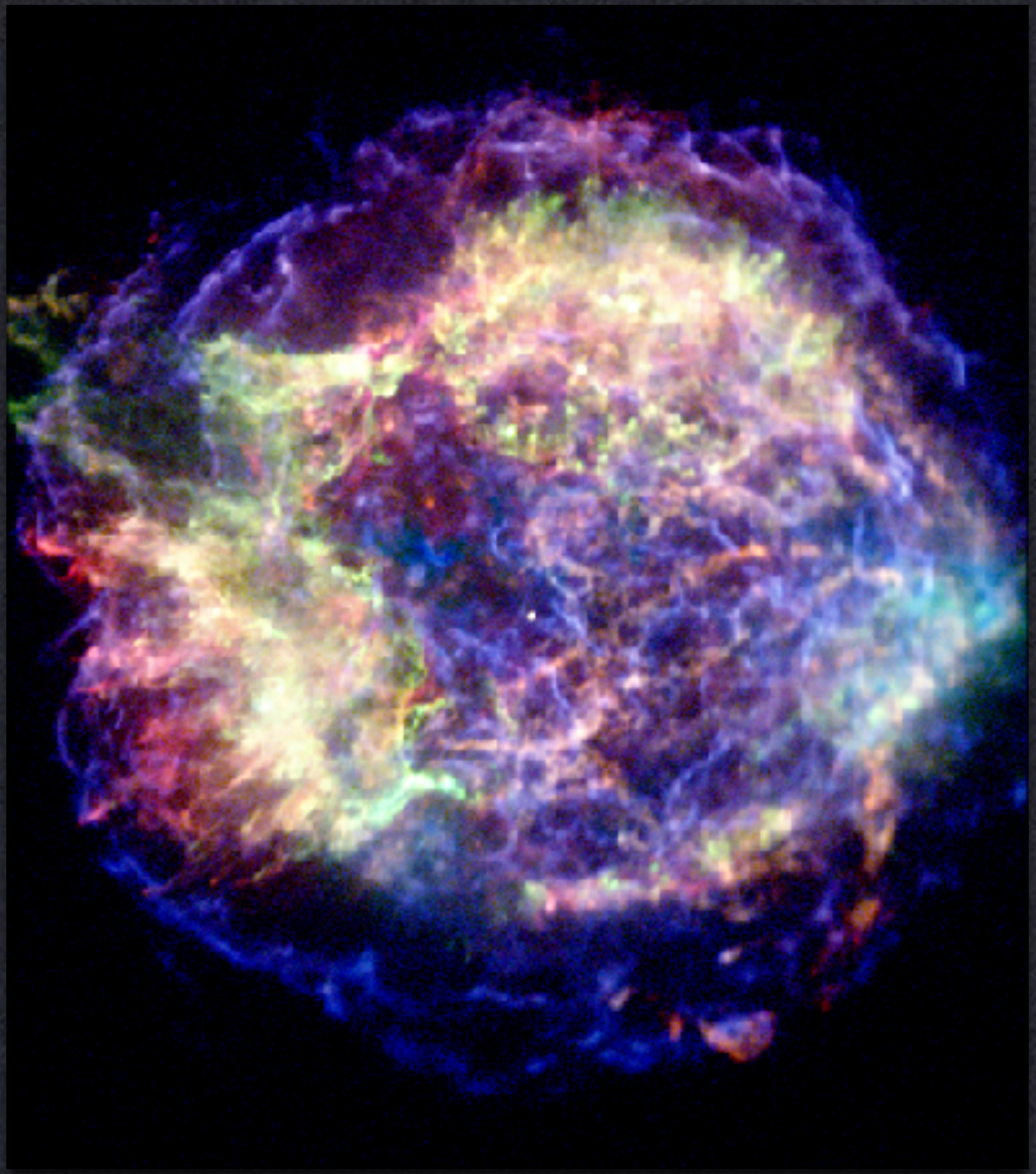
Plasma effects and HEA

- Supernova remnants
    - 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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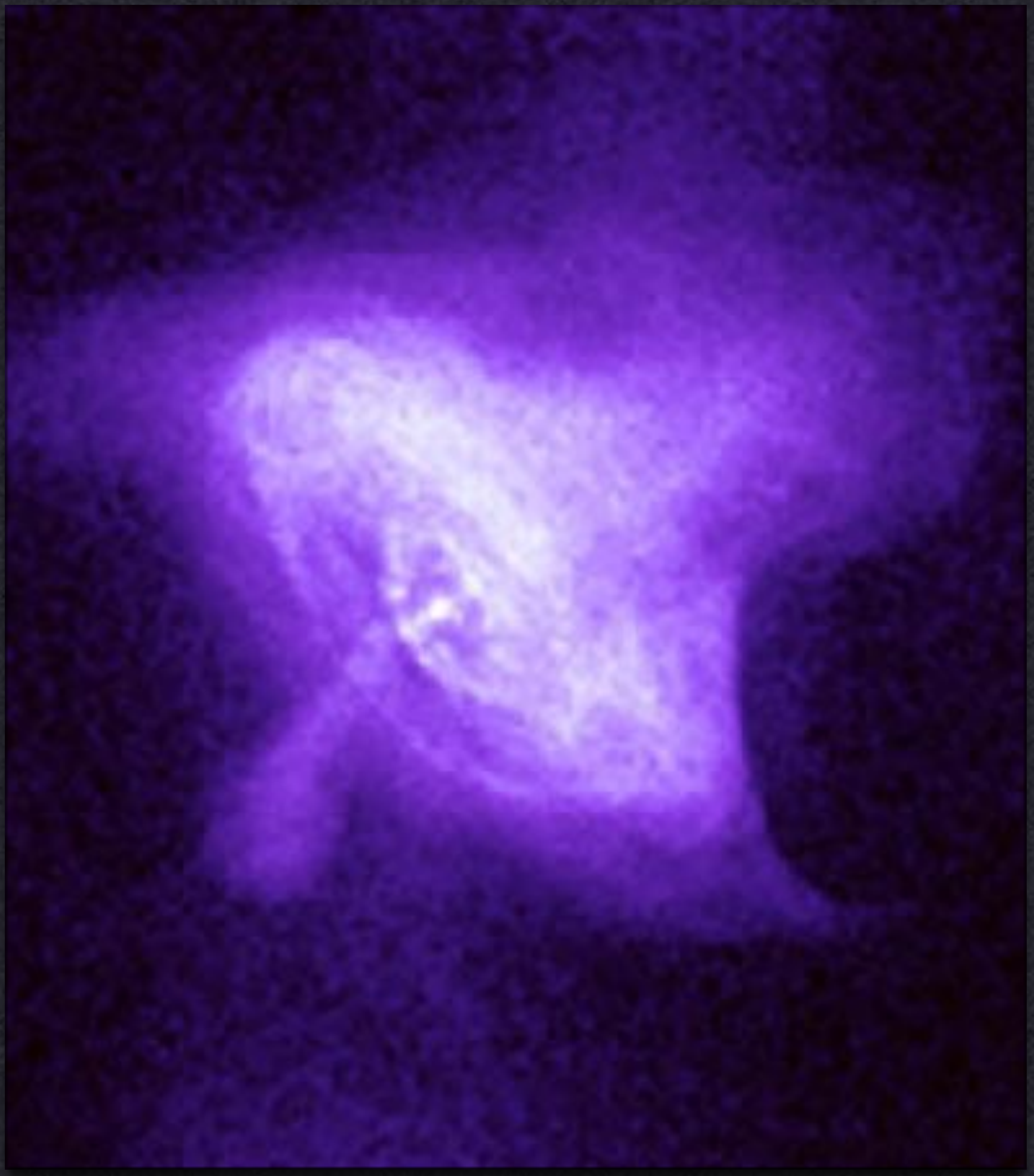
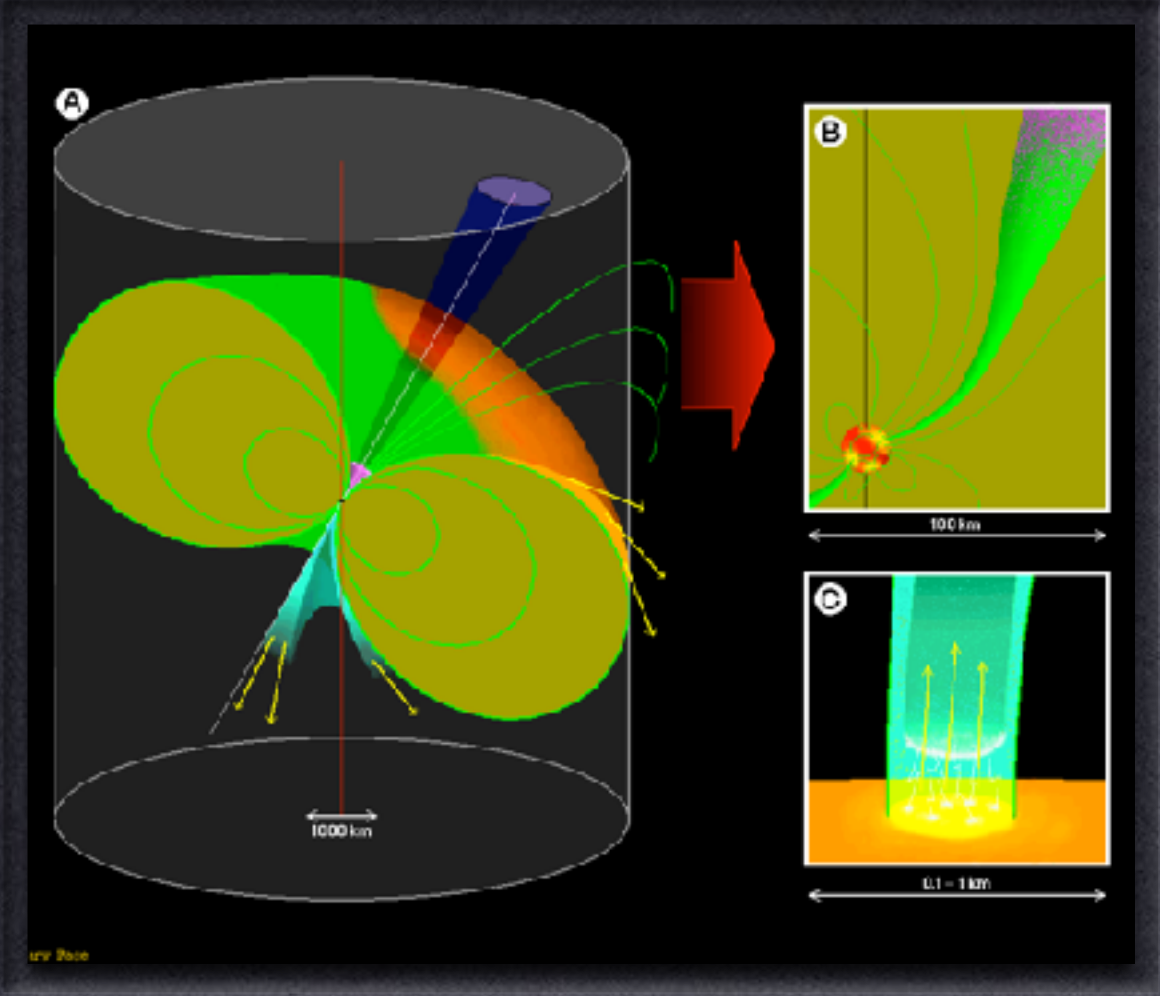


Plasma effects and HEA

- 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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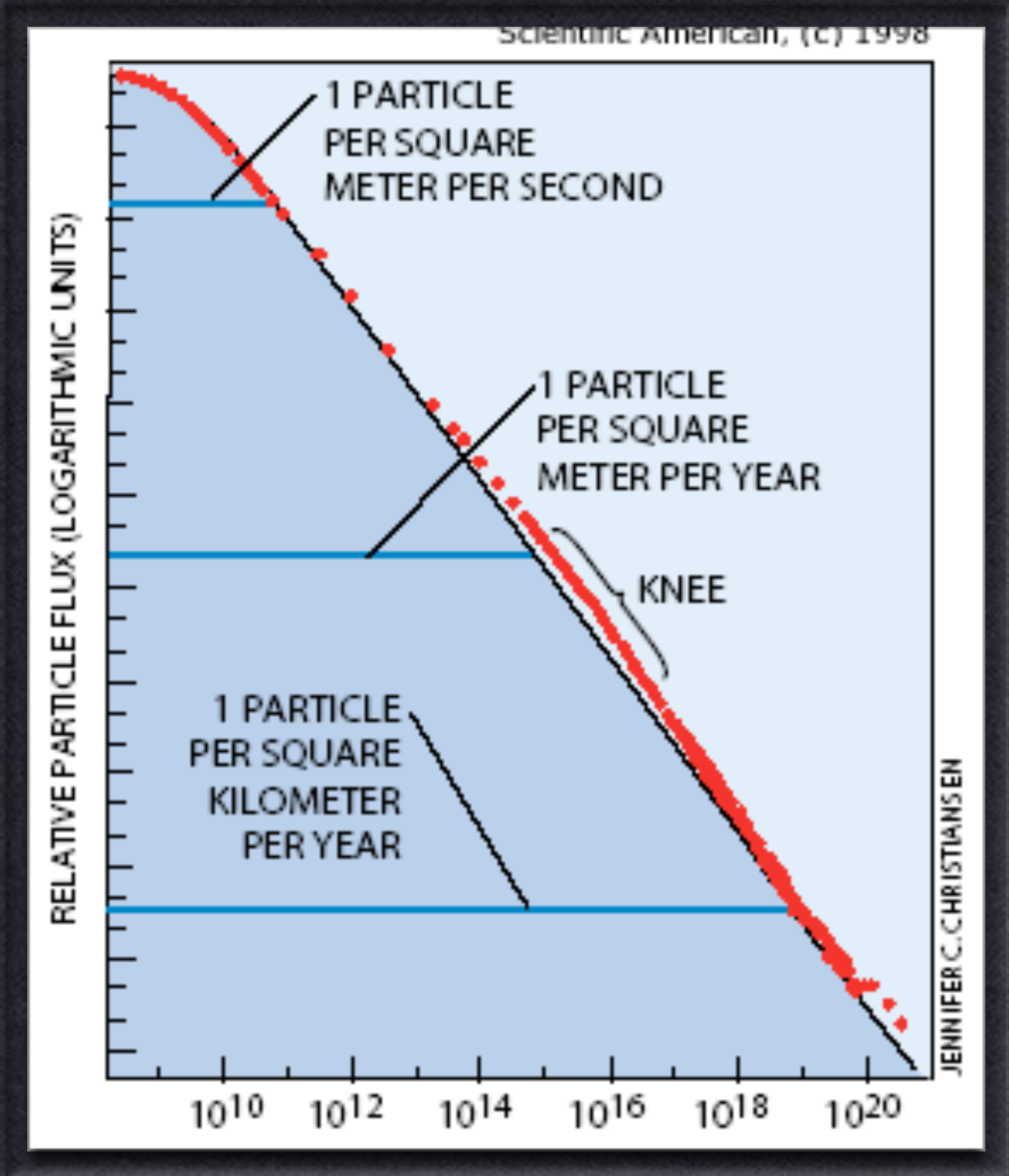
Plasma effects and HEA

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



Scientific American, (c) 1998

Goals (I):

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.

Goals (II):

determine how observable radiation is produced in unexpected classes of objects, e.g., coherent radiation, FRBs, PWN flares, NS mergers…

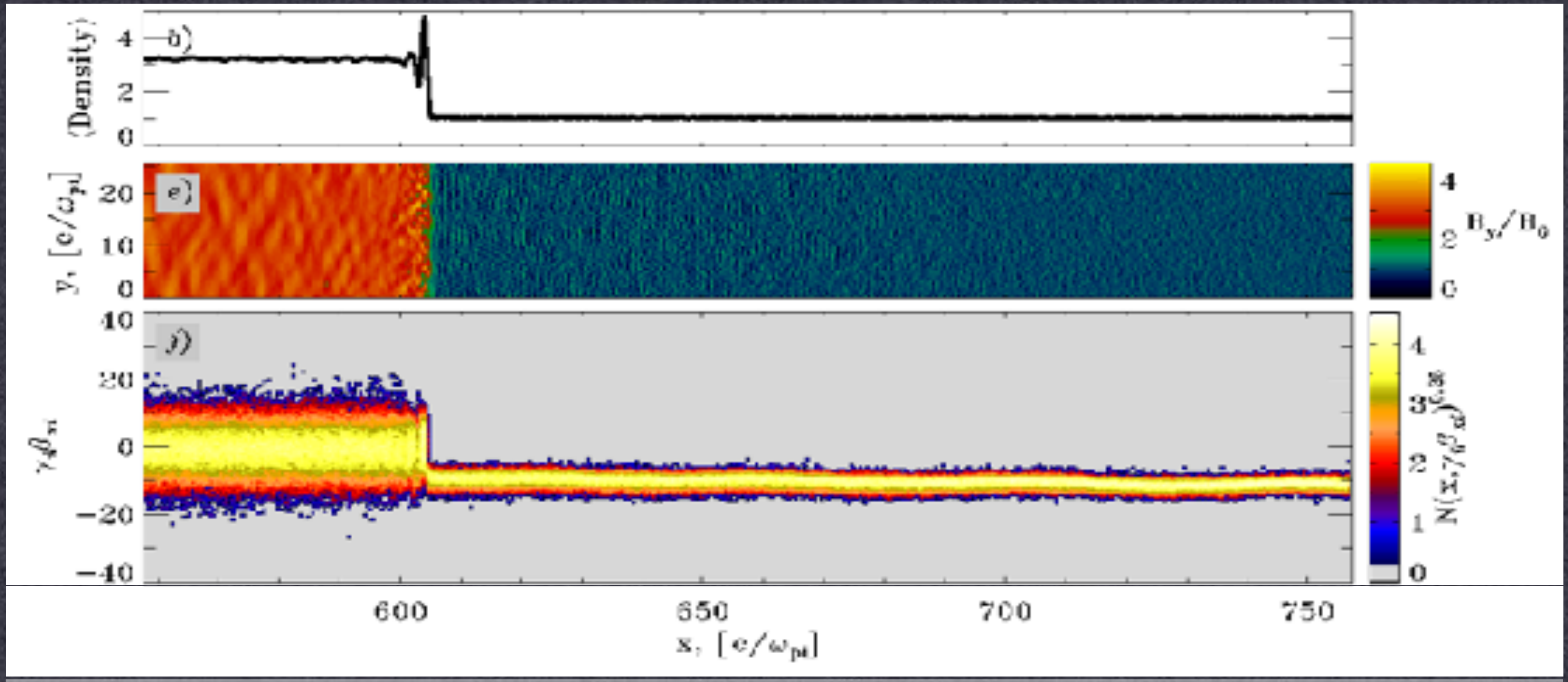
“Whence The Flux,” or “WTF” objects

Current developments and roadblocks:

- Acceleration: update on relativistic shocks
- Reconnection: update on pulsars and radiative effects
- New simulation techniques for future
- Coherent emission: FRBs

Relativistic shocks:

- GRB external shocks — low magnetization
- AGN jets, PWNe — intermediate magnetization
- Shock physics and acceleration controlled by magnetization
- Relativistic shocks die from superluminality



<Density>

$\sigma=0.1$

$\theta=75°$

$\gamma_0=15$

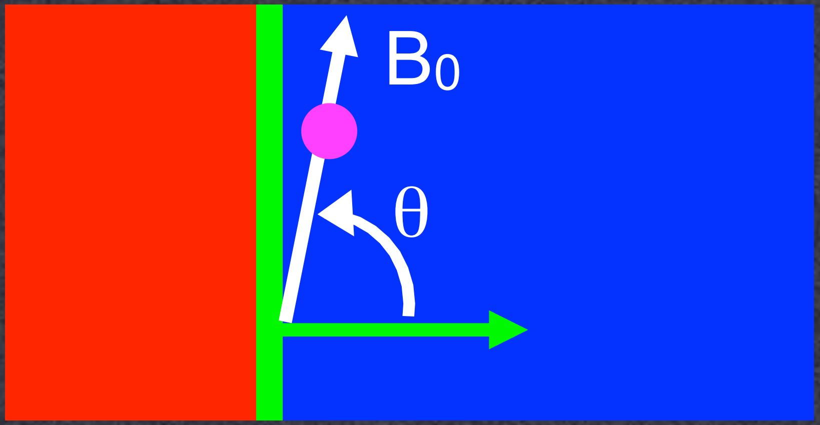
e^--p^+

B_y

$\gamma\beta_x$

(Sironi and AS 11)

Superluminal vs subluminal shocks

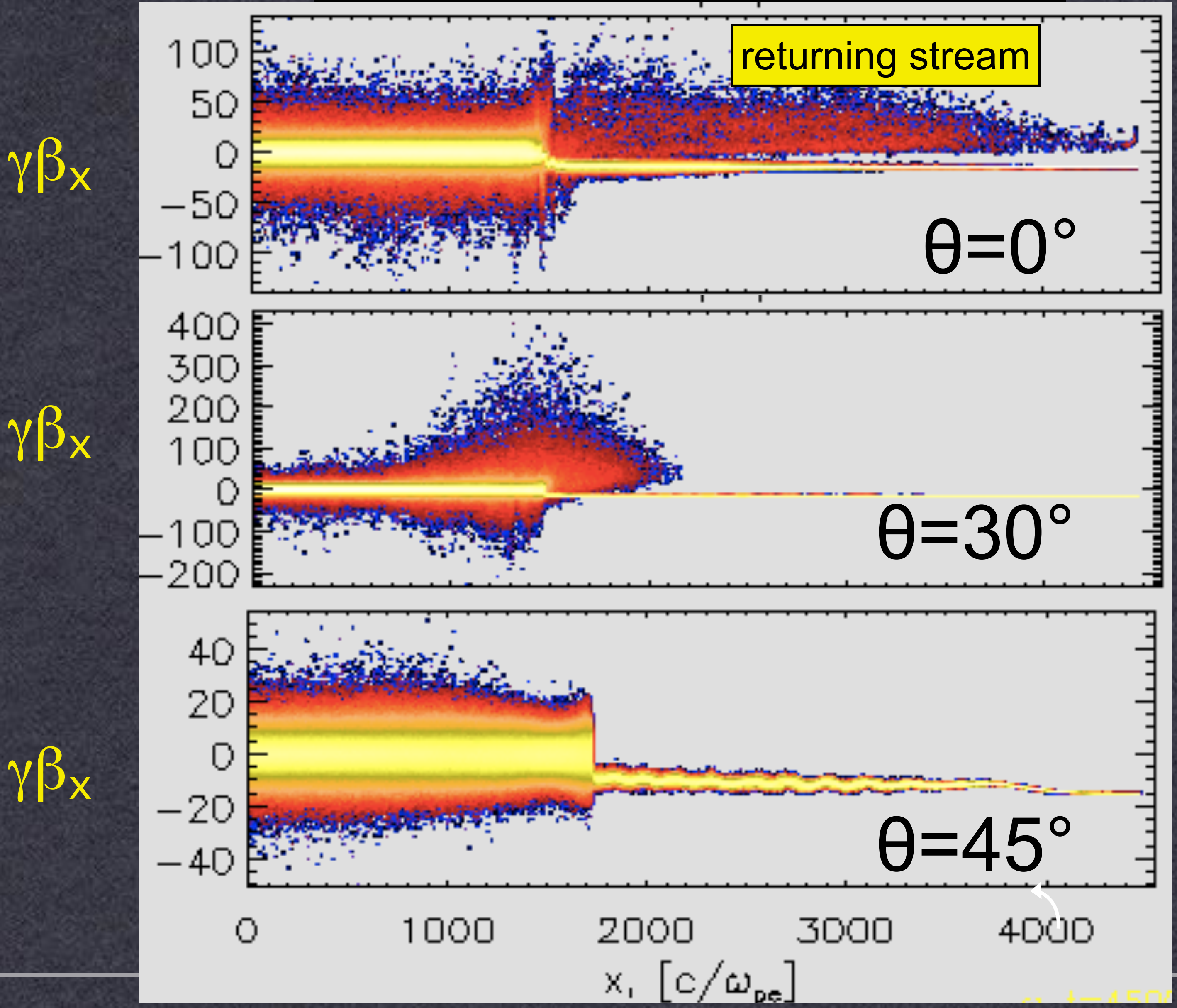


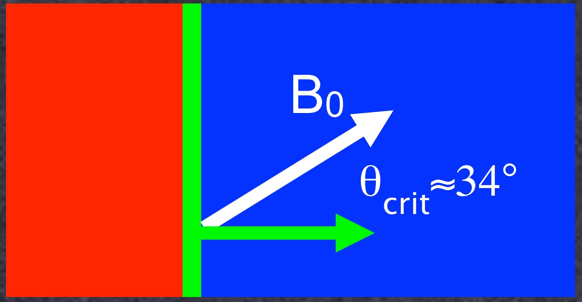
σ is large → particles slide along field lines

θ is large → particles cannot outrun the shock unless v>c (“superluminal” shock)

⇒ no returning particles in superluminal shocks

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





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

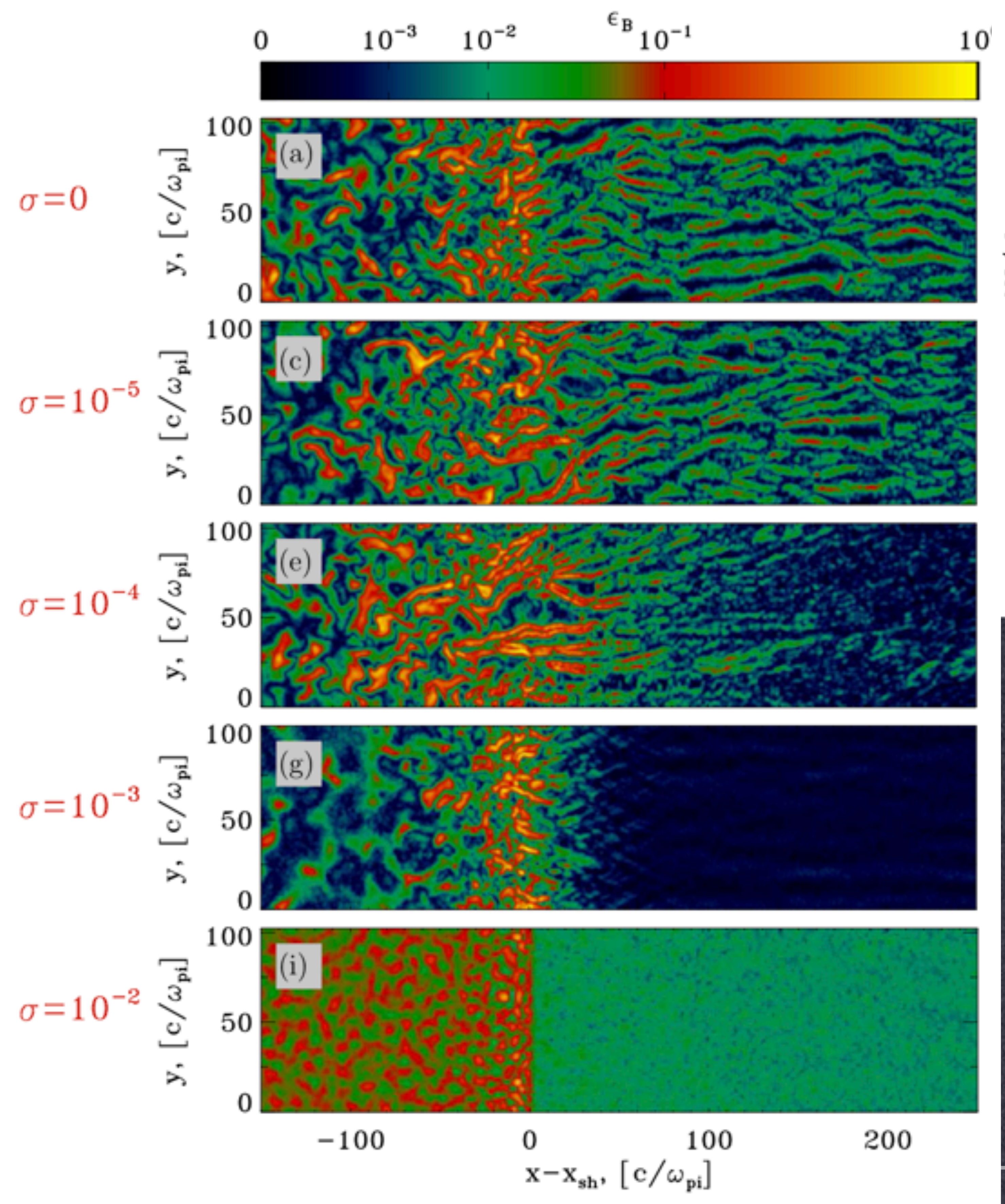
→ Fermi acceleration should be suppressed in superluminal shocks!

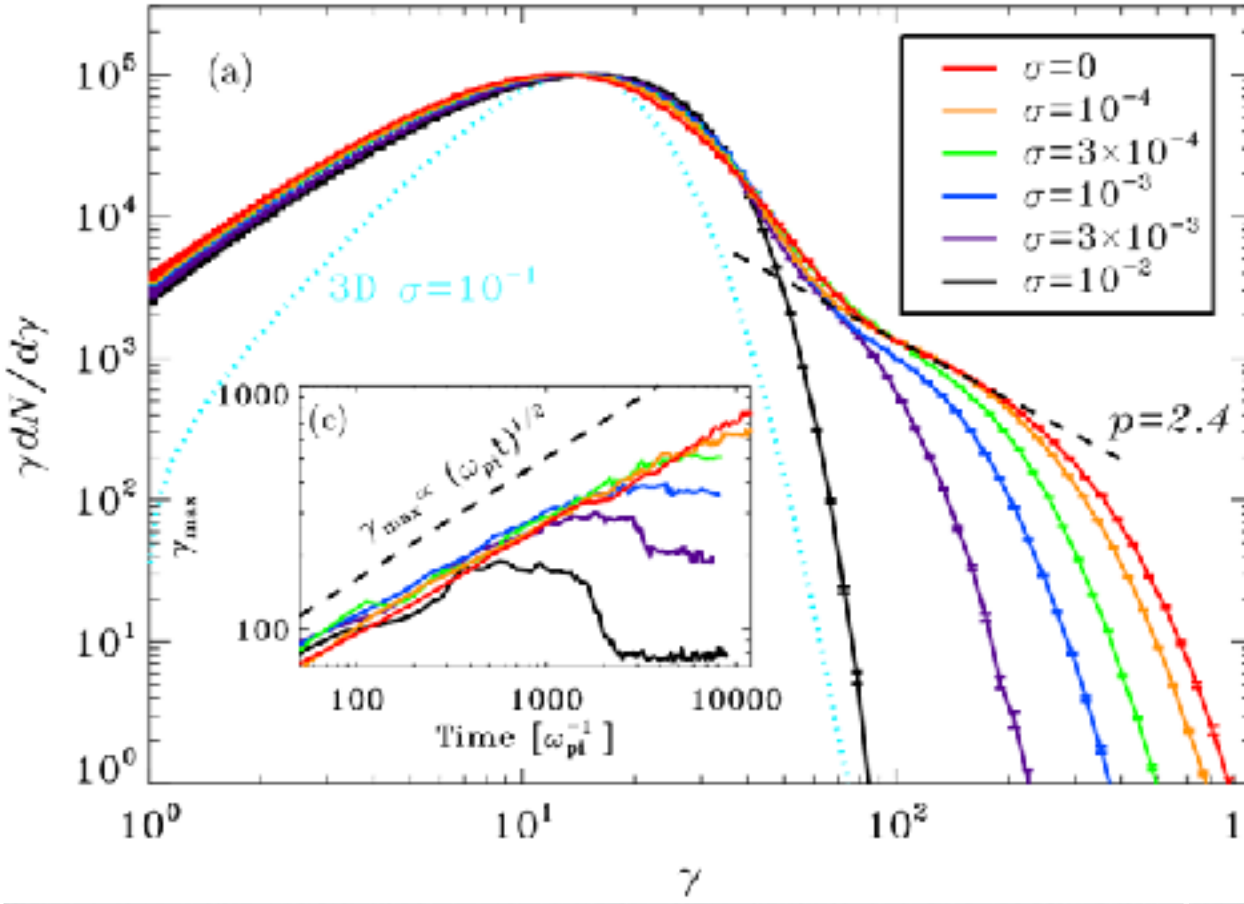
If $\sigma > 10^{-3}$, particle acceleration only for:

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

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

Precursor length controlled by B





Acceleration slows down to t^1/2

Seizes for sigma > 1e-2

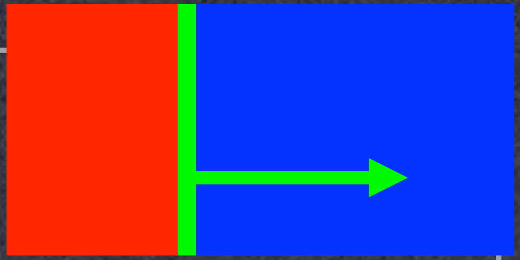
Maximum energy saturates

New ideas needed?

(Sironi et al 13

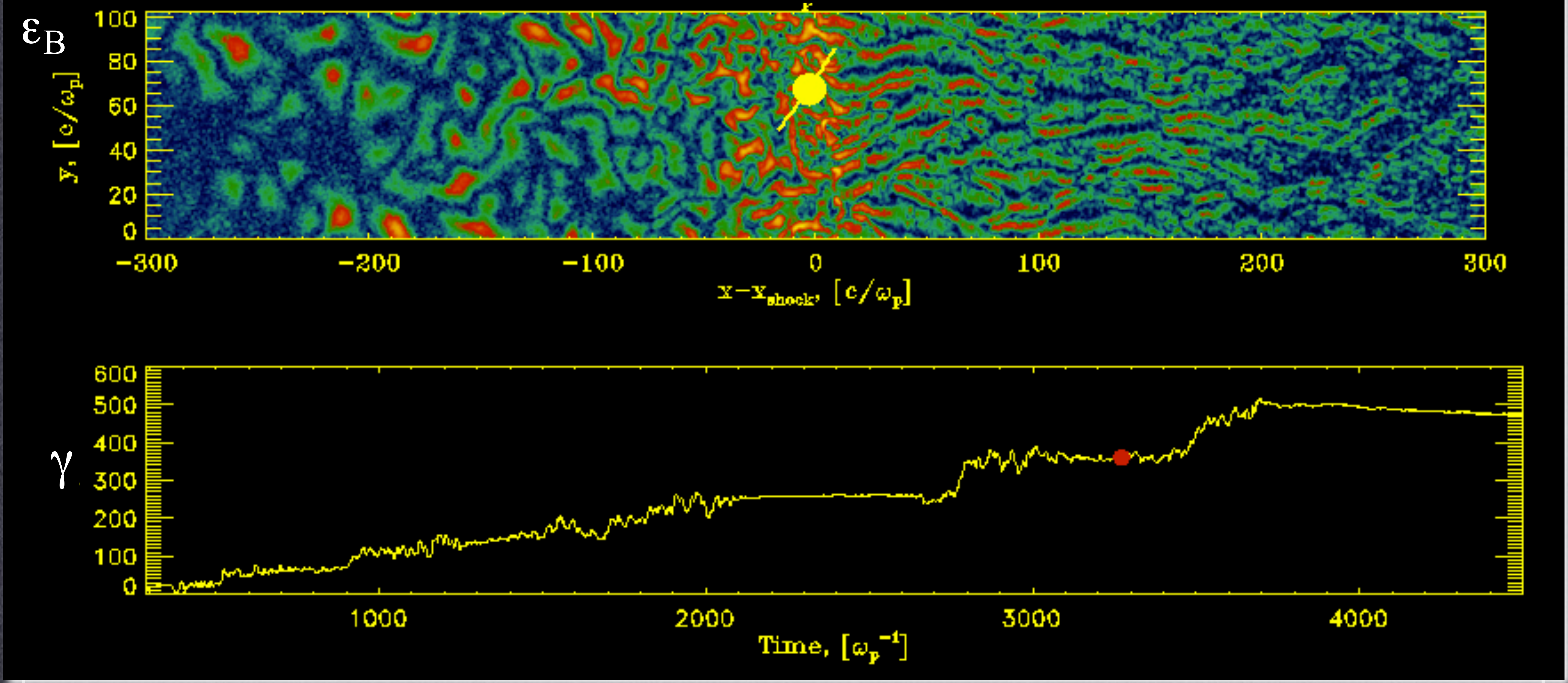
Plotnikov et al 17))

Low-σ shocks do accelerate!



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

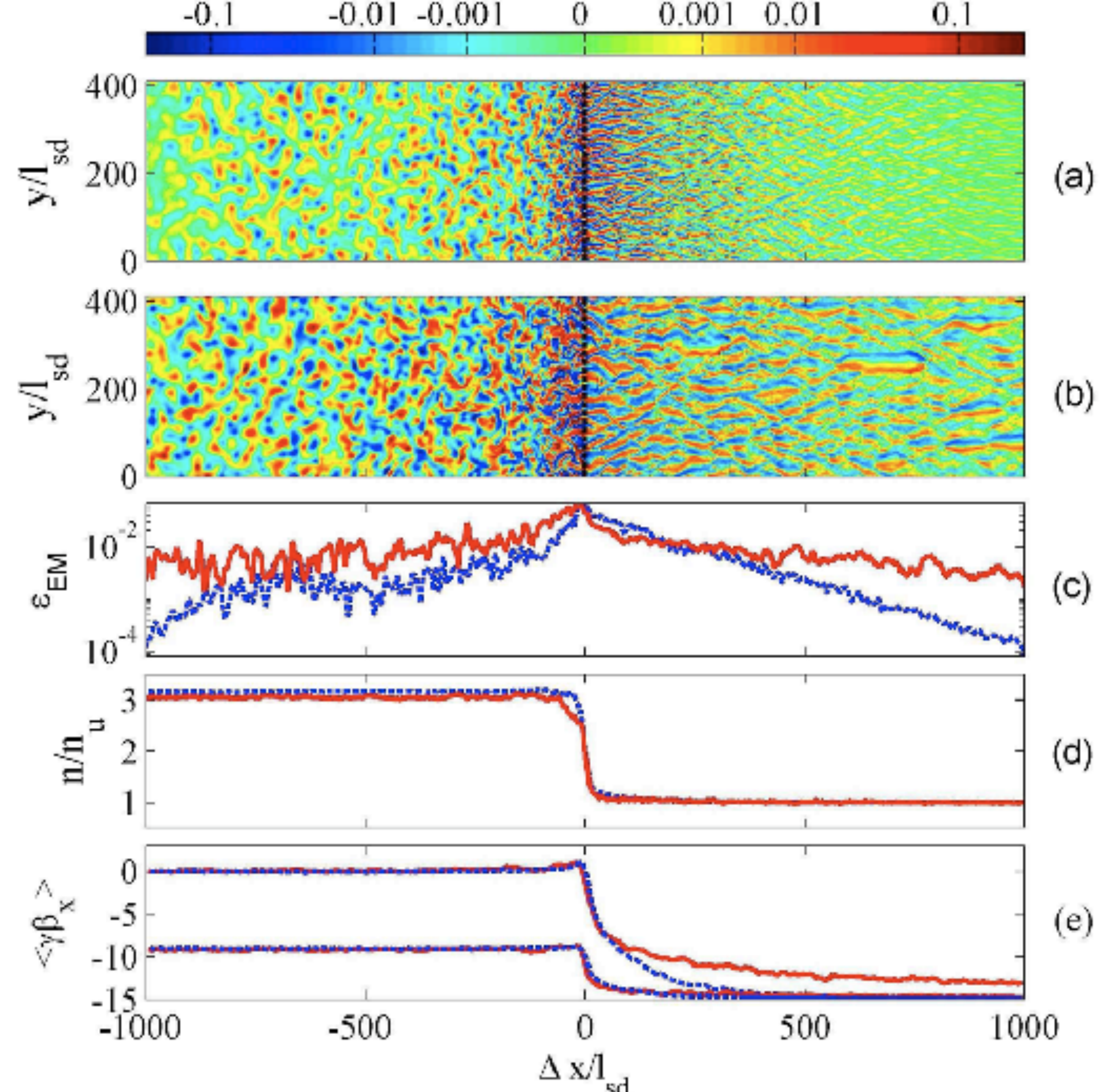
$\sigma=0$ $\gamma_0=15$ e⁻-e⁺ shock



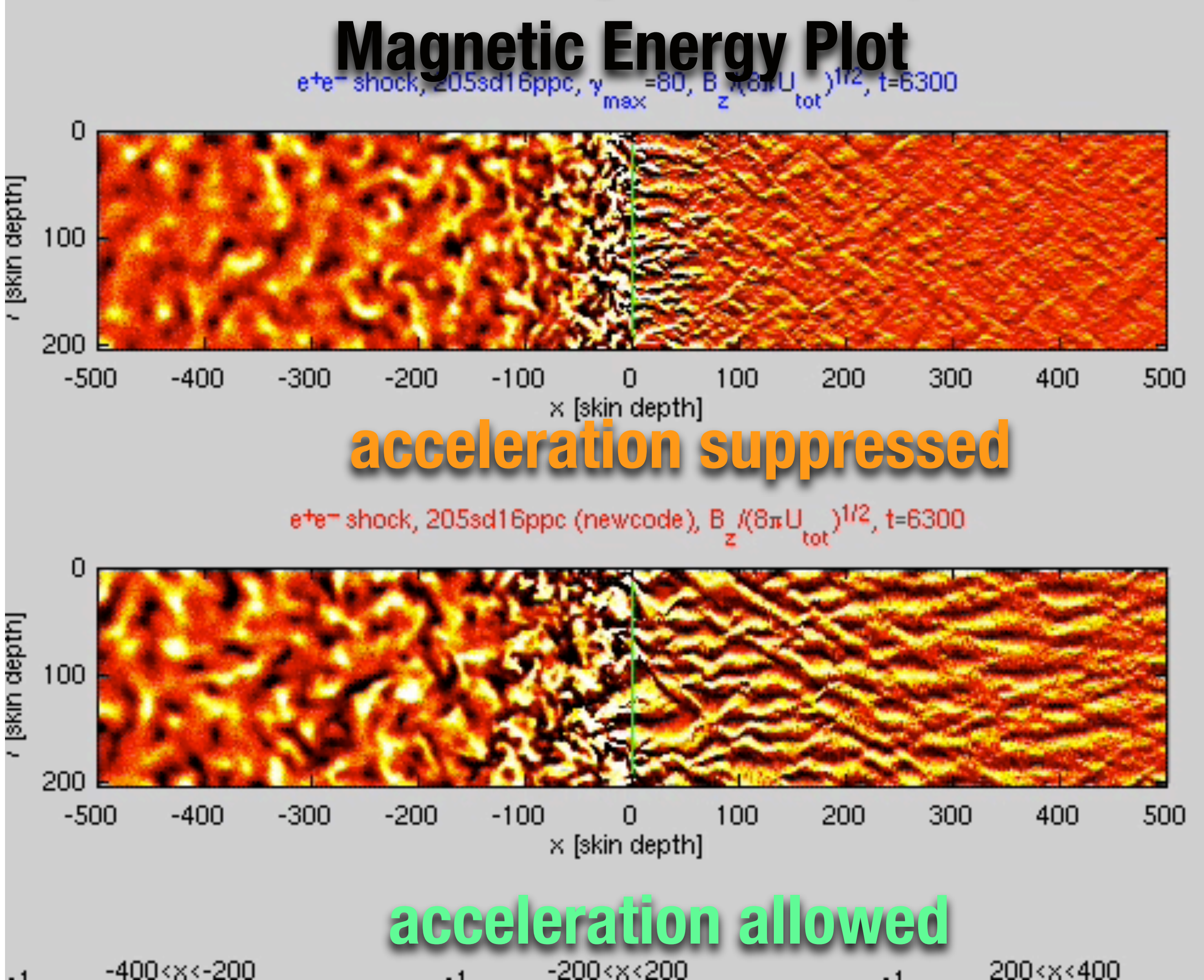
Field survival in long term

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)



1% downstream magnetization possible

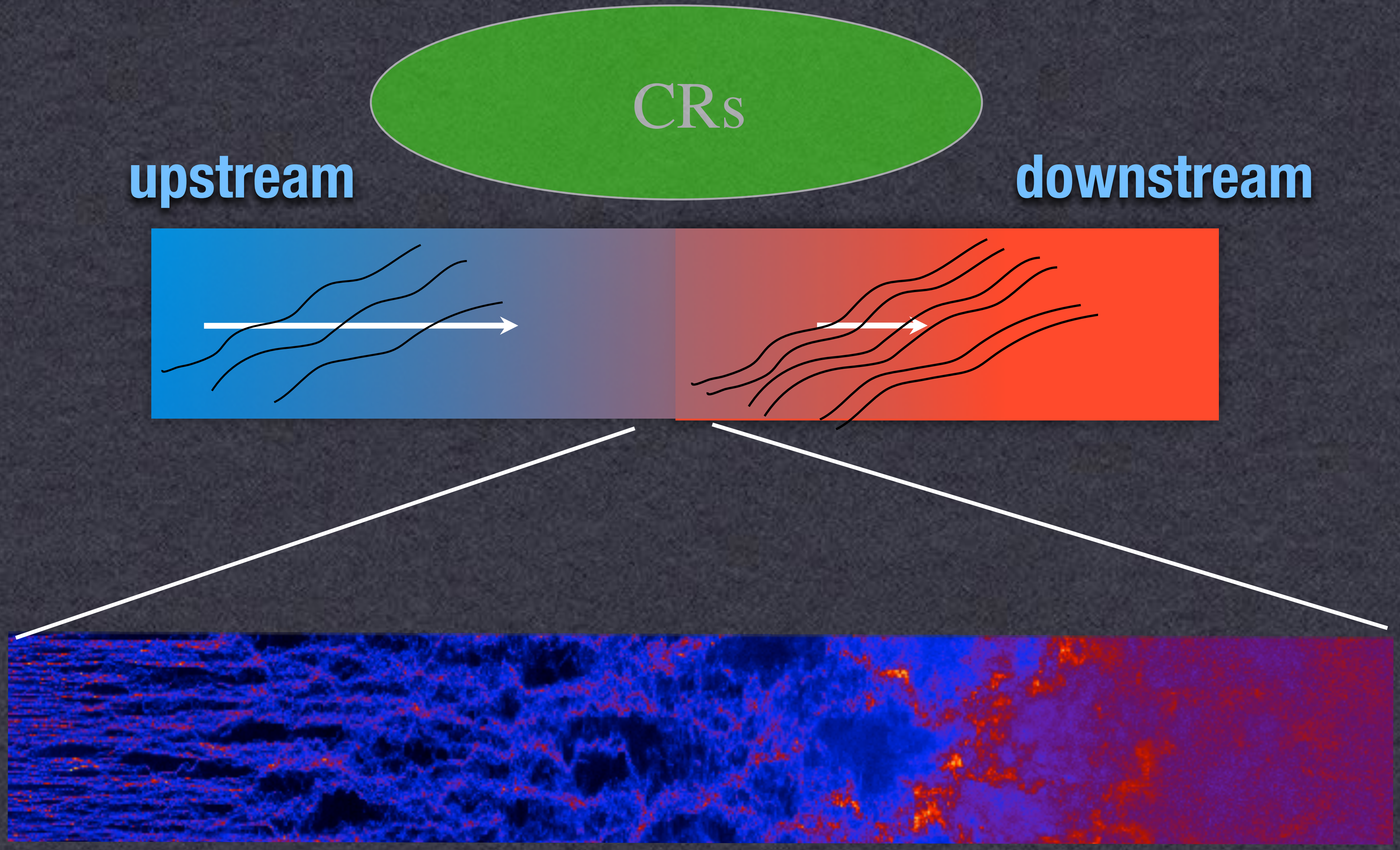

Magnetic Energy Plot

acceleration suppressed

acceleration allowed

Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback



CRs

upstream

downstream

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!

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:

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

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

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

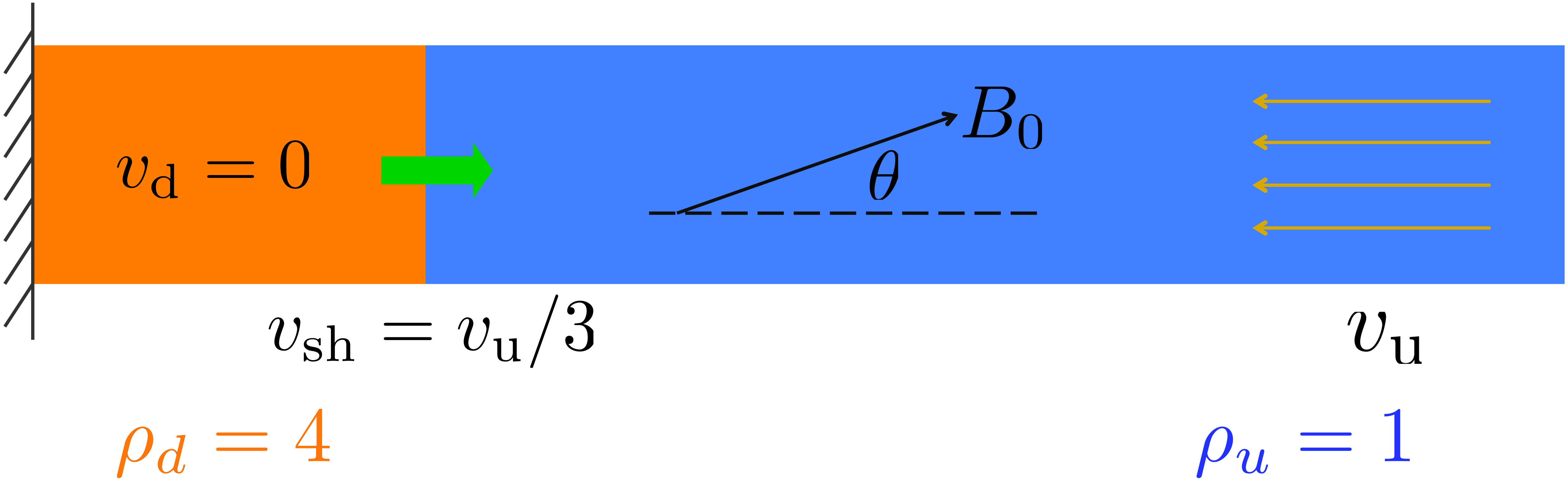
normal Hall term

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.

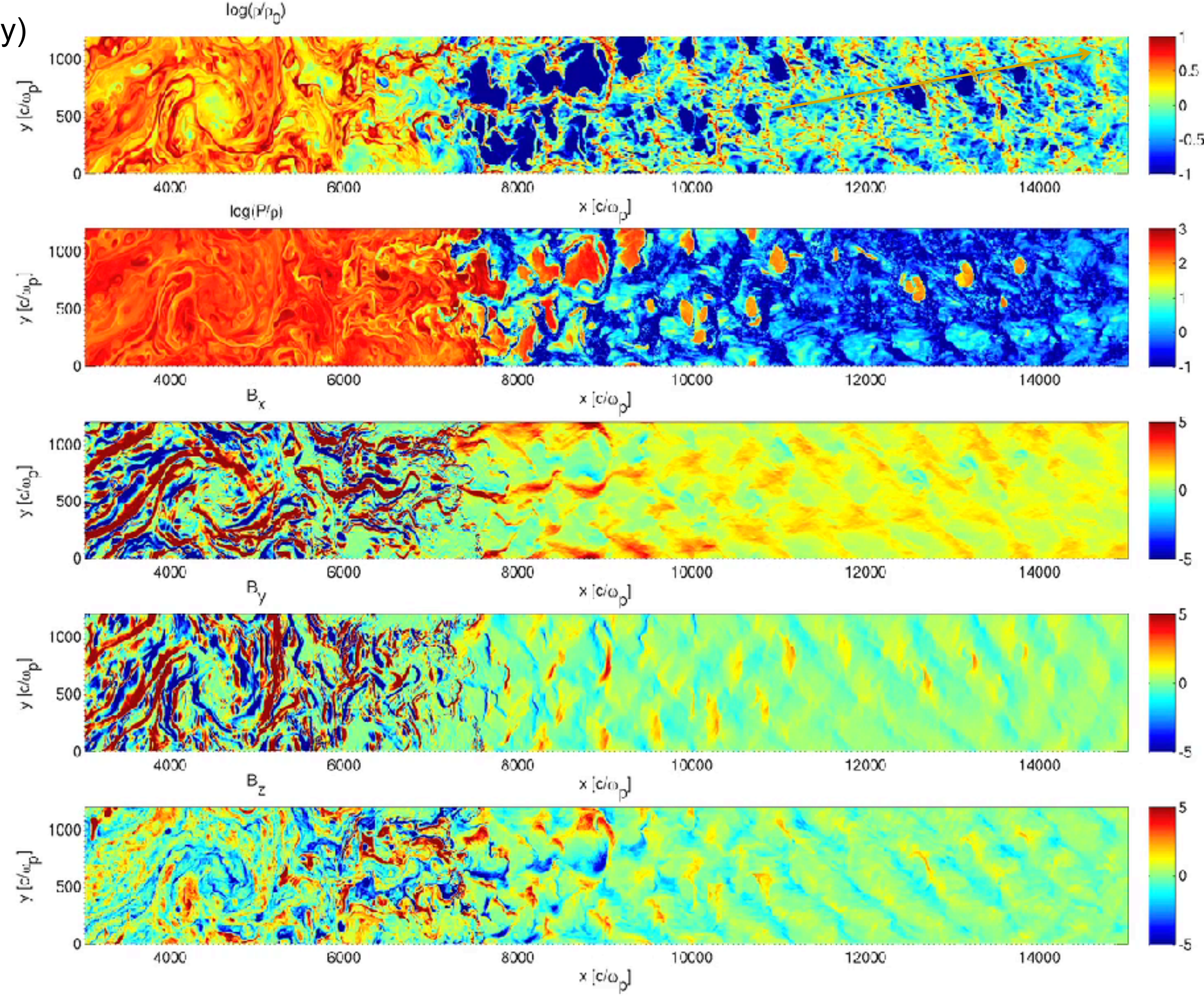
Log(Density)

Log(T)

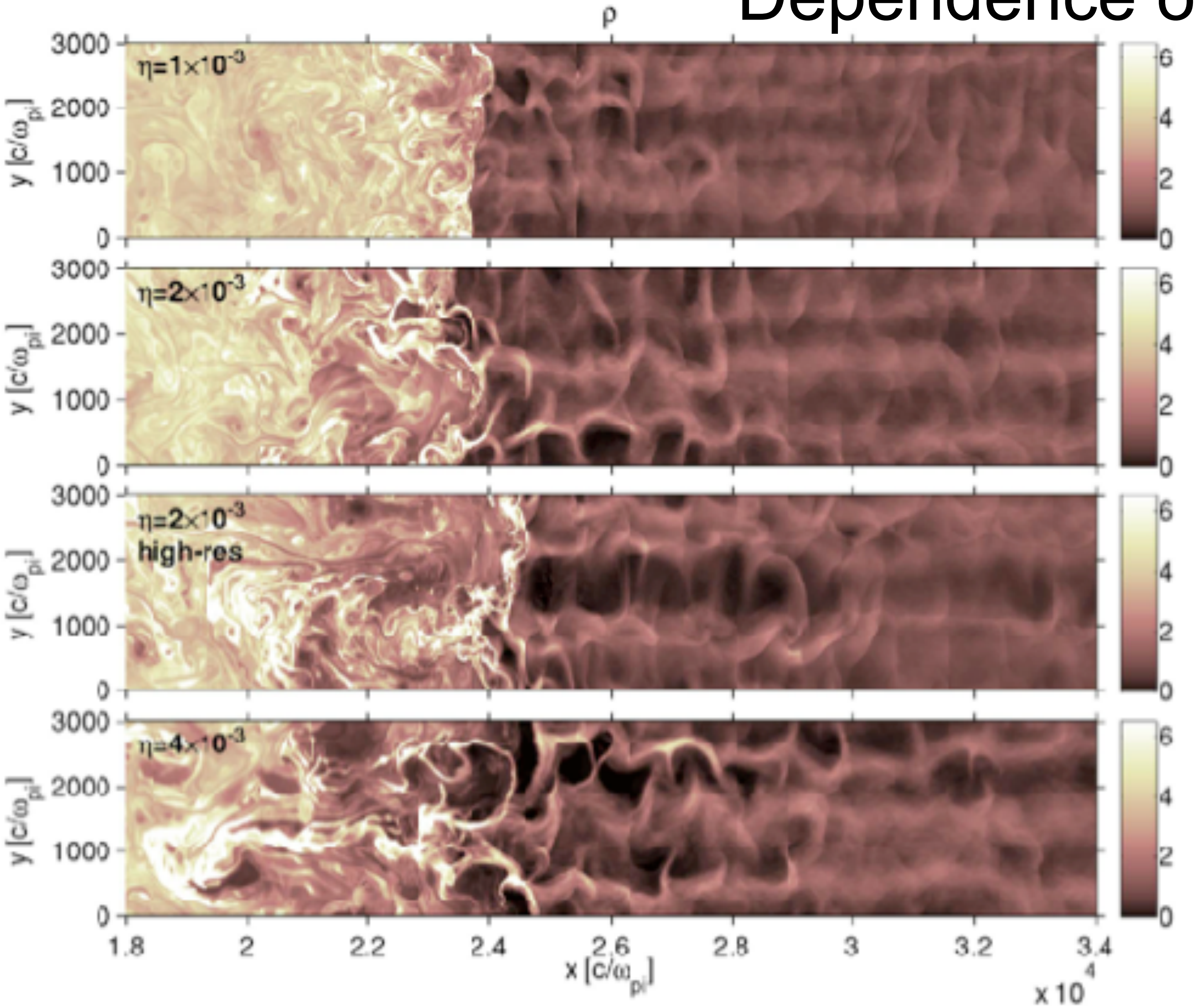
Bx field

By field

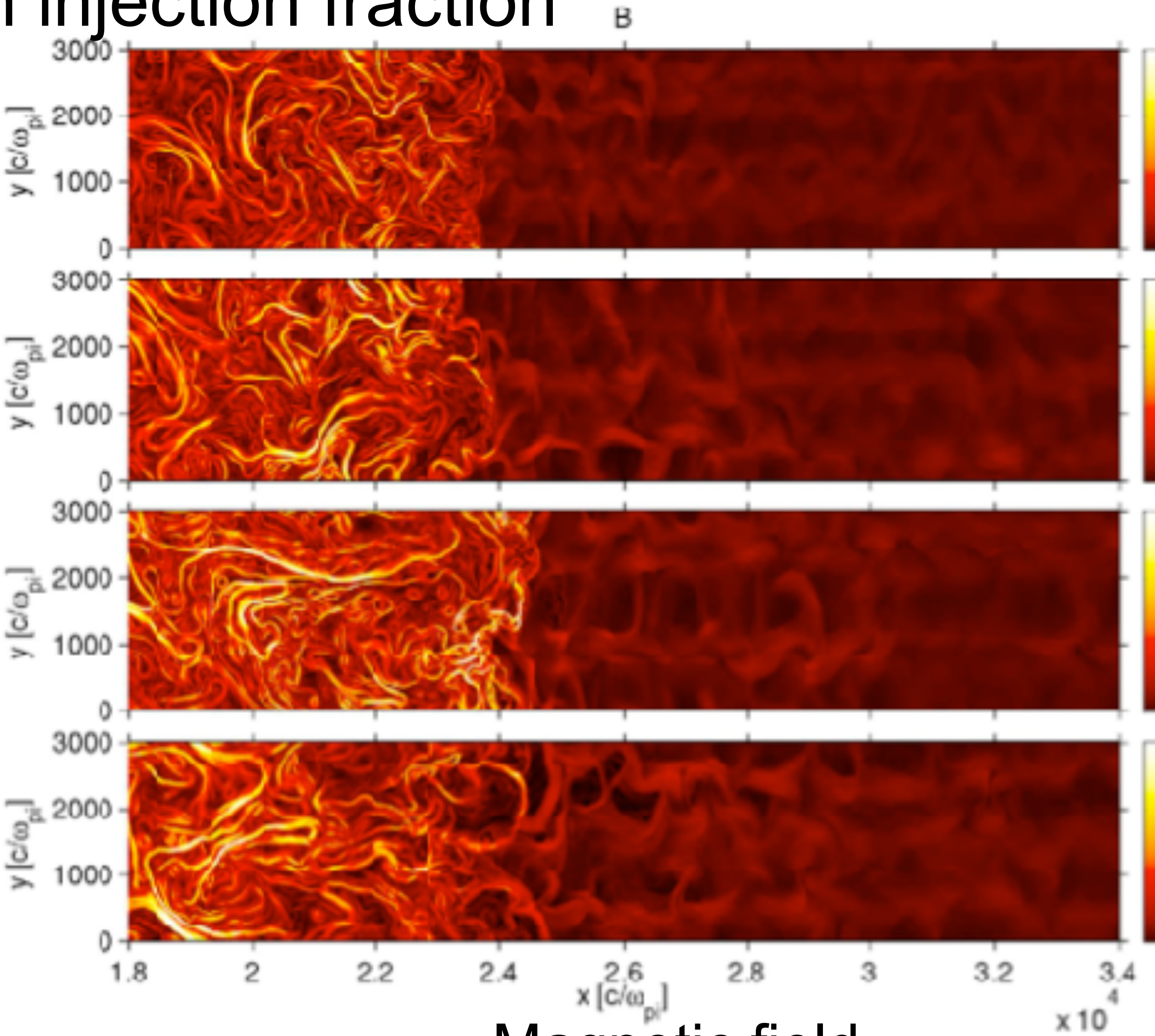
Bz field



Dependence on injection fraction

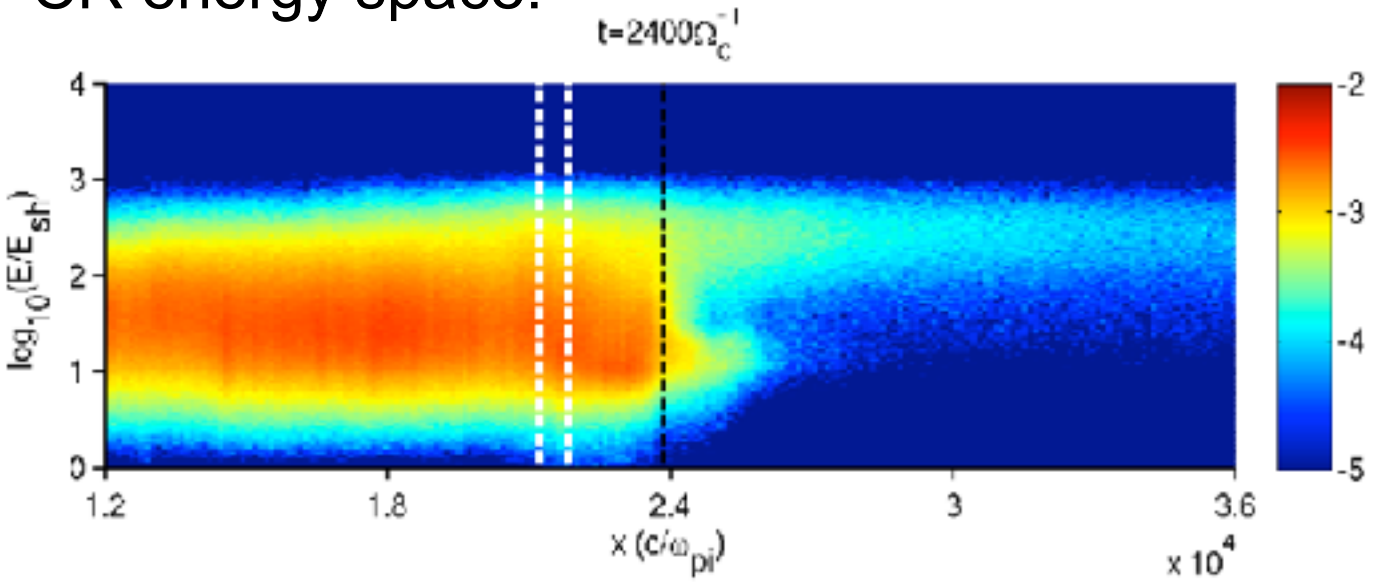


Density

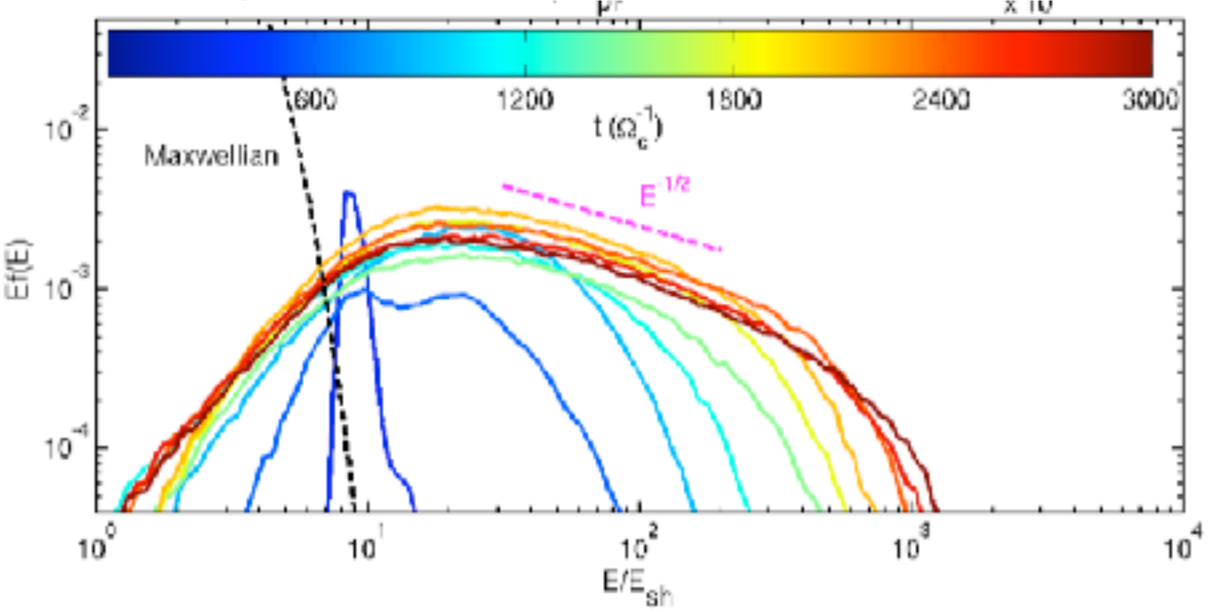


Magnetic field

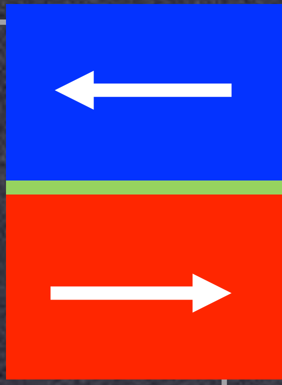
CR energy space:

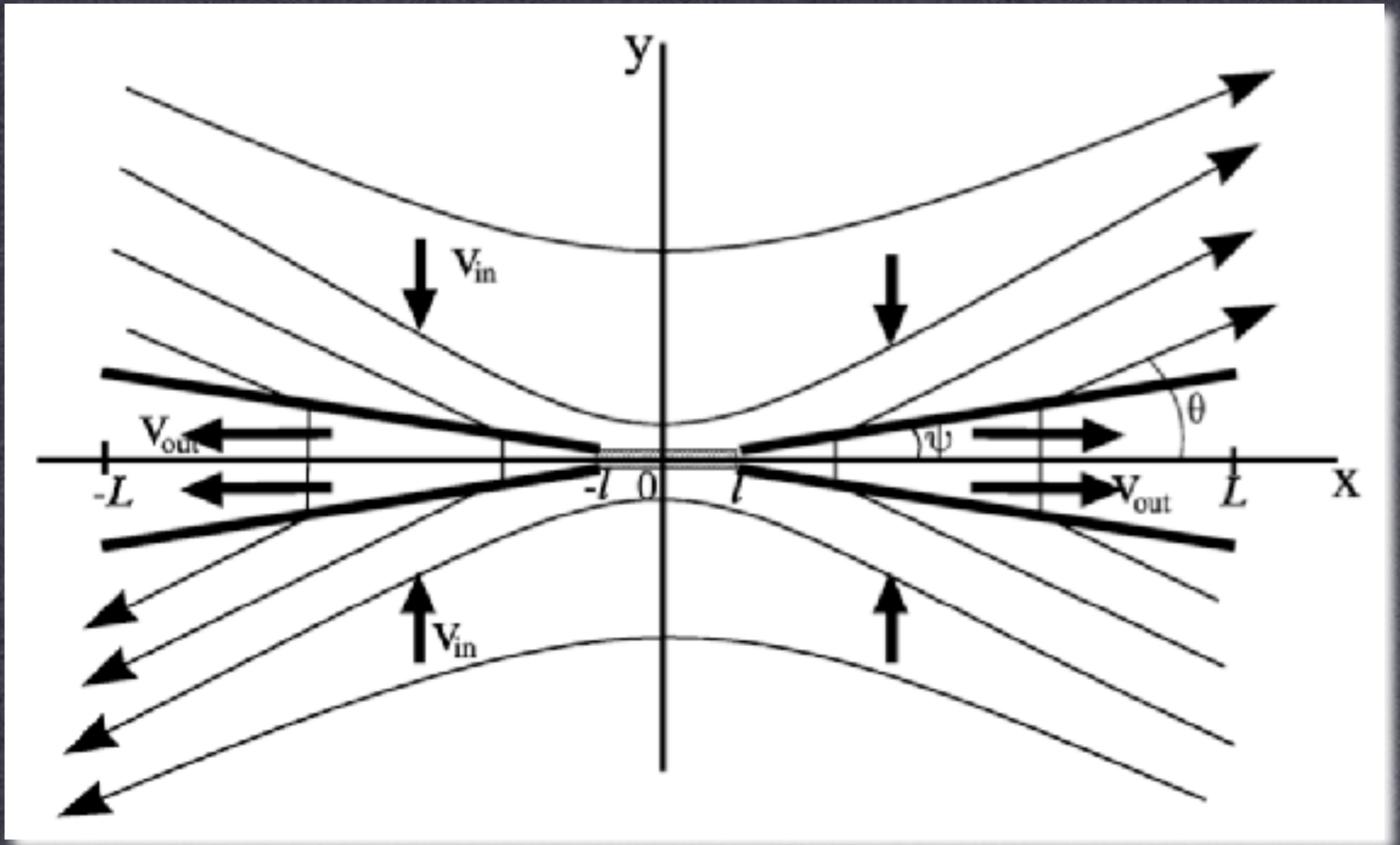


CR spectrum:



Relativistic reconnection:



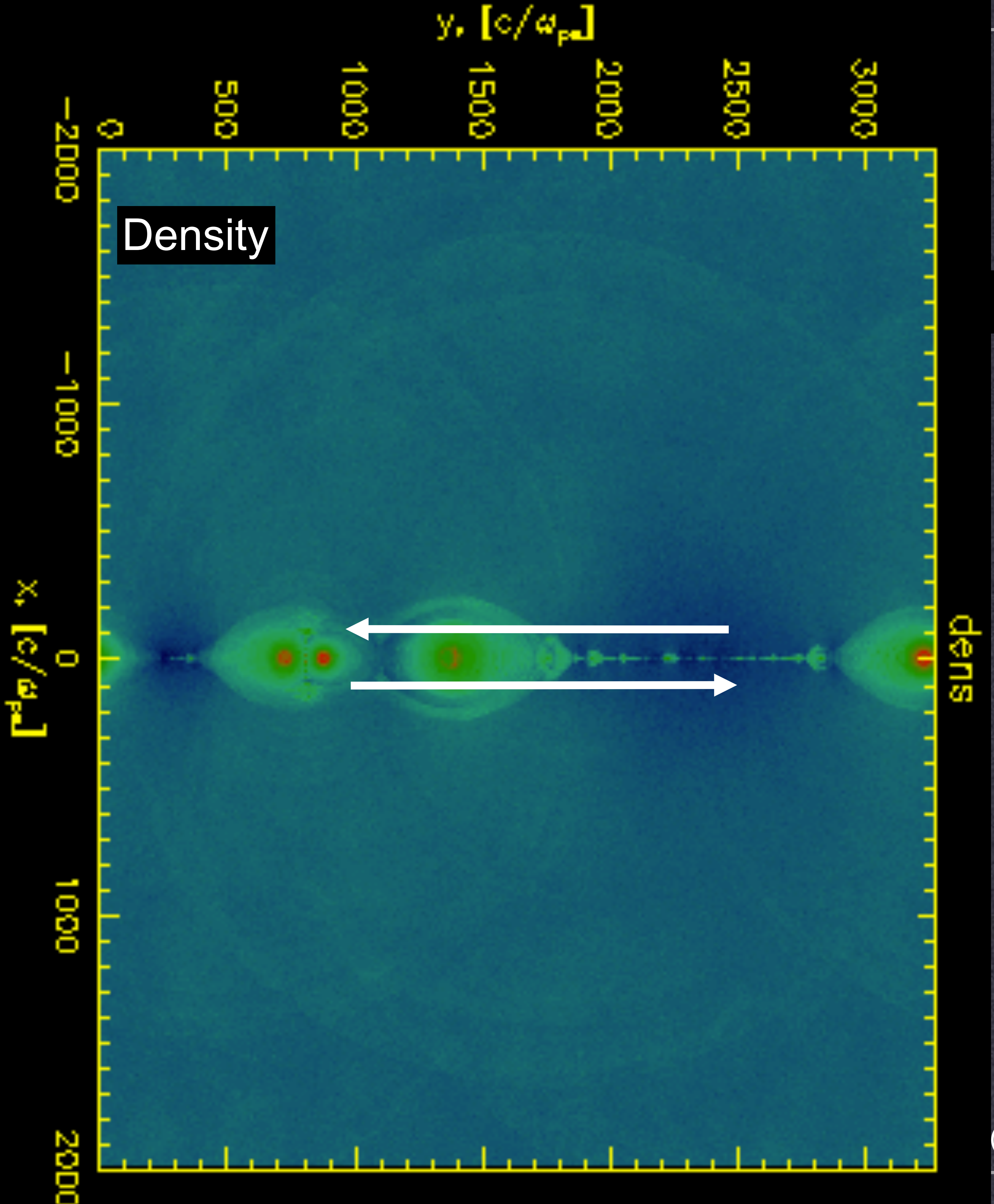


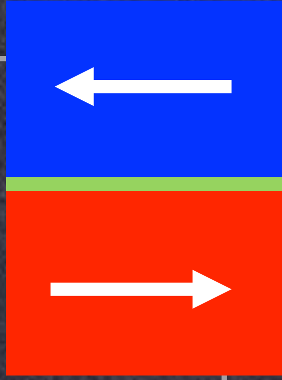
$$\sigma = \frac{B_0^2}{4\pi n_0 m_p c^2}$$

Relativistic magnetic reconnection: σ>>1

(Lyubarsky 05, Lyutikov & Uzdensky 03)

- **Does relativistic magnetic reconnection accelerate nonthermal particles?**
- **How fast is it?**
- **What is the mechanism? How reconnection works in a large system?**
- **Implications for AGNs, GRBs, pulsars**





σ=10 electron-positron

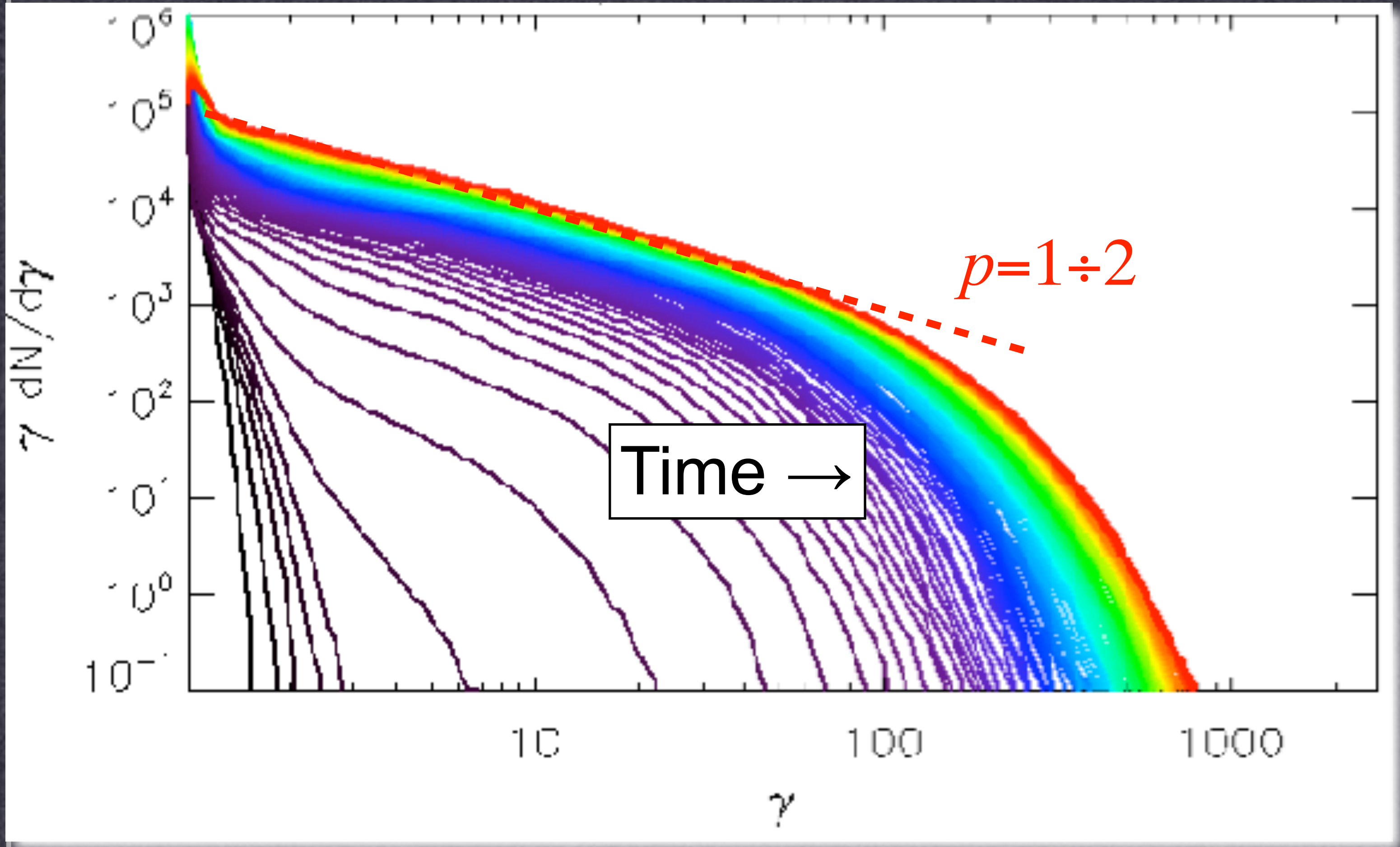
- Reconnection is a hierarchical process of island formation and merging.
- The field energy is transferred to the particles at the X-points, in between the magnetic islands.

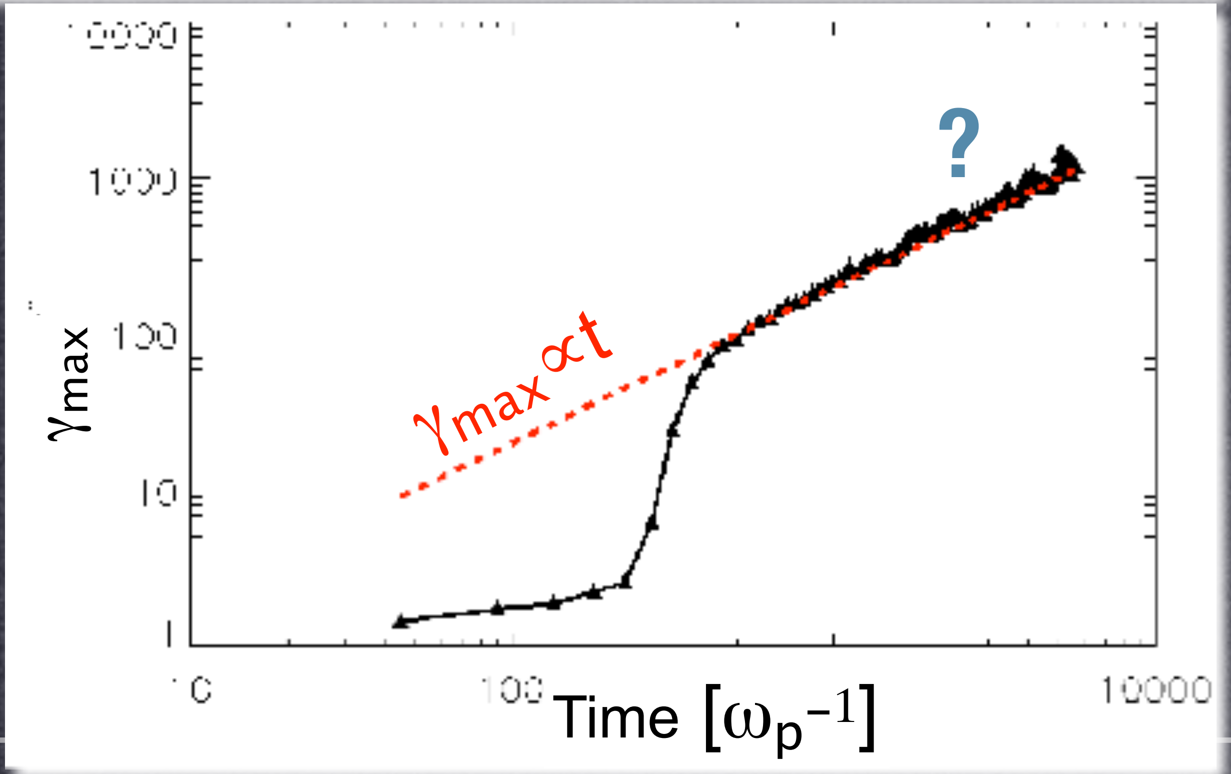
Does reconnection always happen? What about jet launching and propagation?

(Sironi et al) (Werner et al, Guo et al)

Formation of powerlaw

$\sigma=10$ electron-positron





Sironi & AS

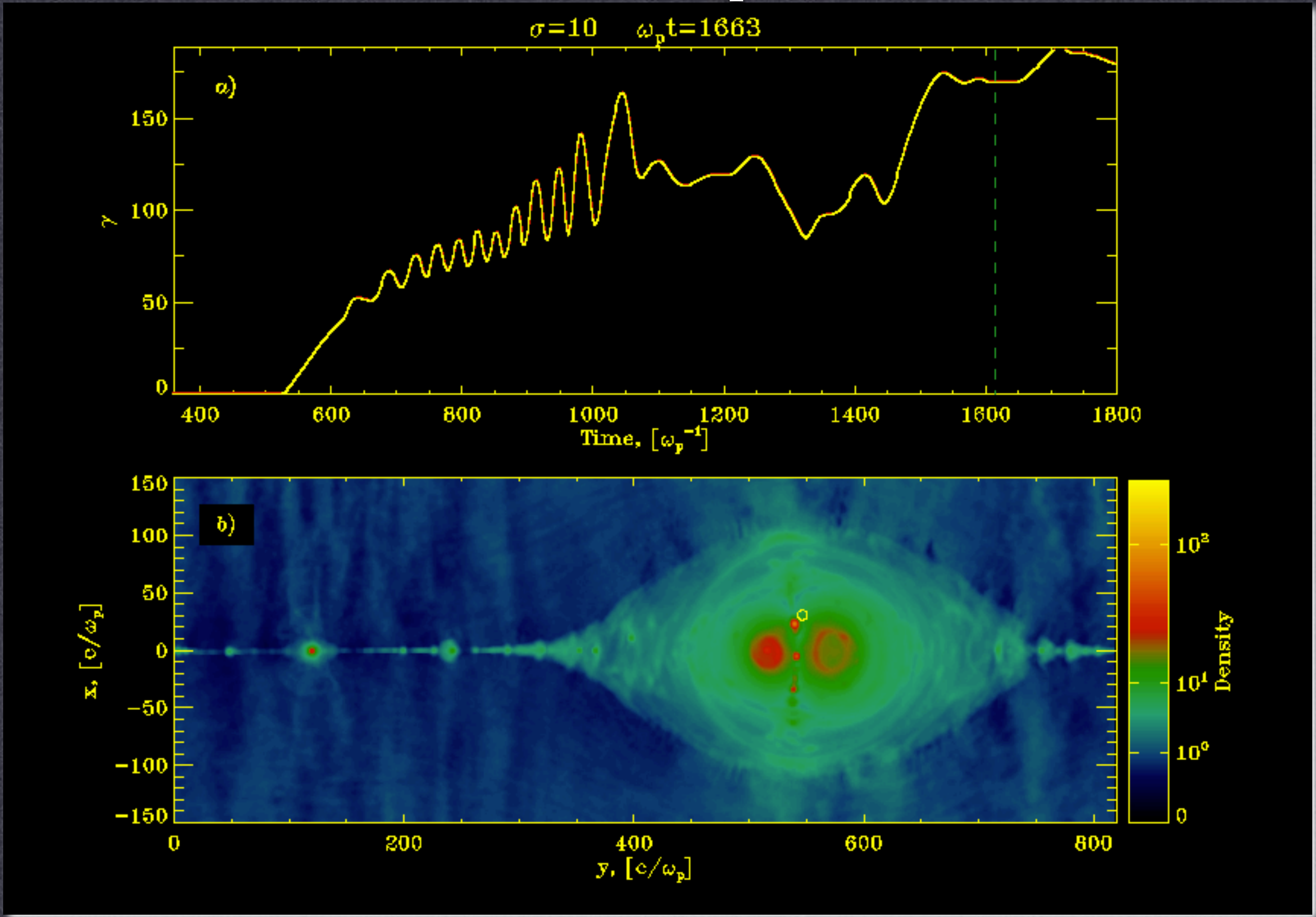
- At late times, the particle spectrum in the current sheet approaches a power-law tail $dn/d\gamma\propto\gamma^{-p}$ of slope $p\sim1\div2$, extending in time to higher and higher energies.

- The mean particle energy in the current sheet is $\sim\sigma/2$.

- The maximum energy grows as $\gamma_{max}\propto t$, with the coefficient dependent on the rec rate (may not hold at long term).

- Spectrum is robust

Acceleration process

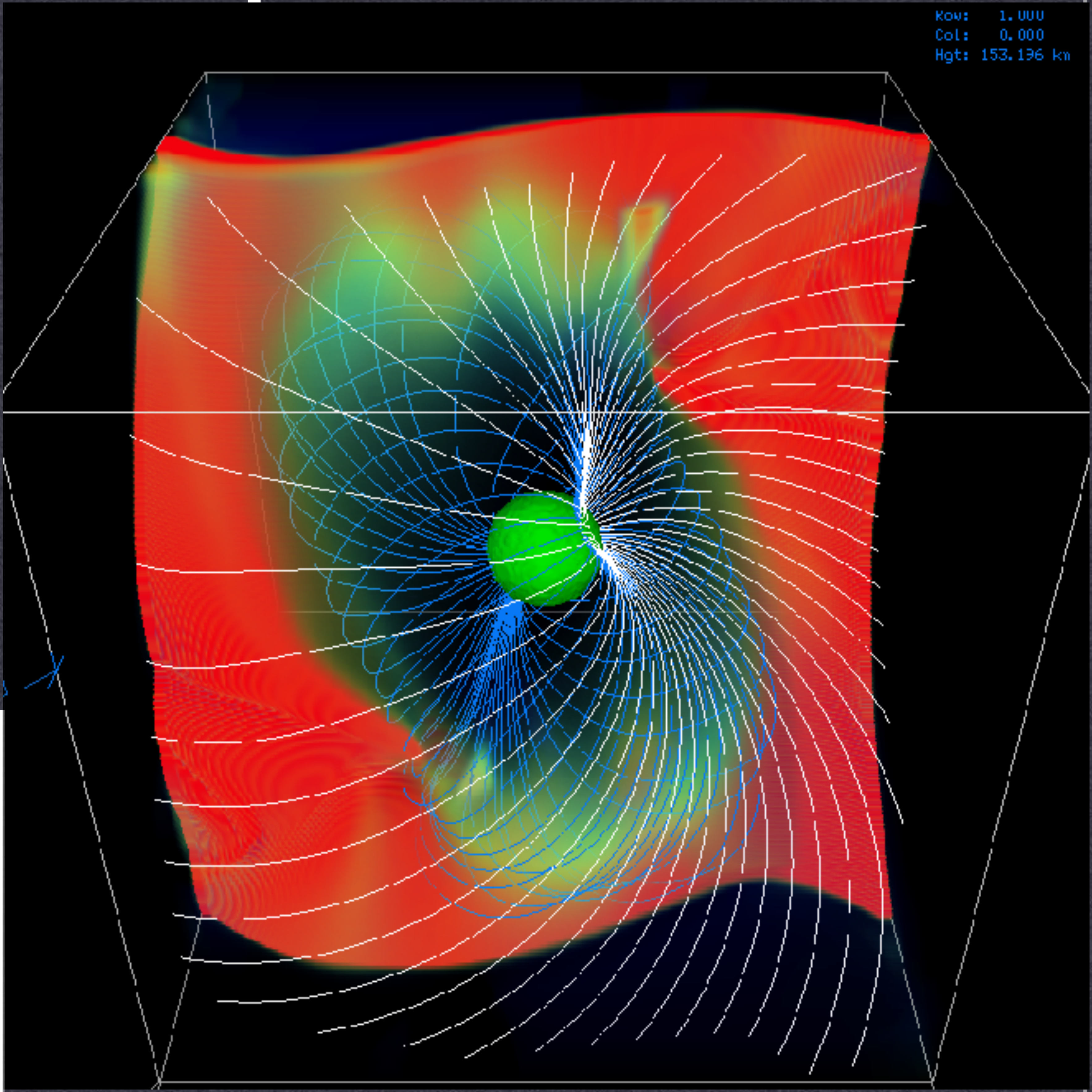


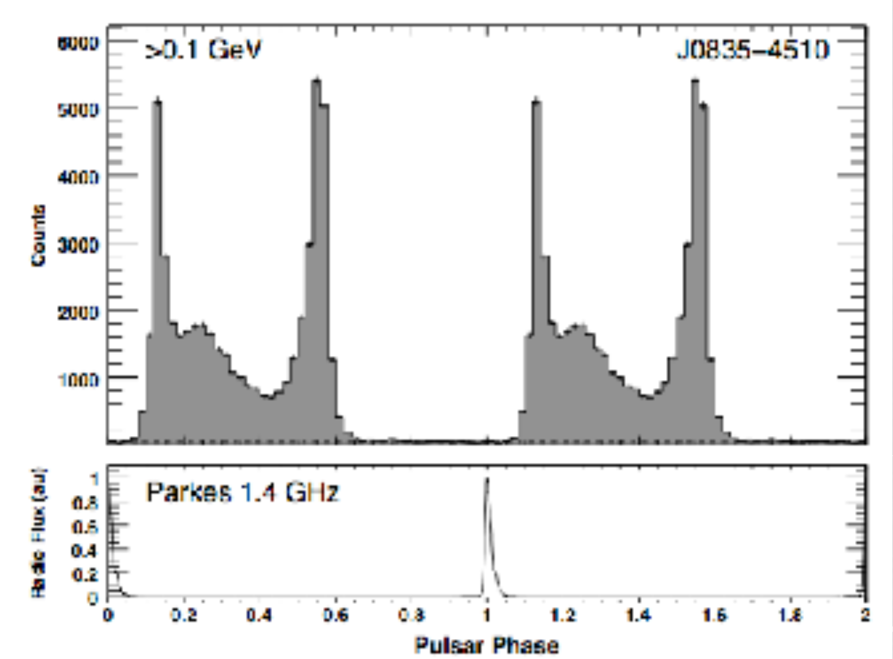
First kick: x-points; then Fermi acceleration in converging islands + antireconnection

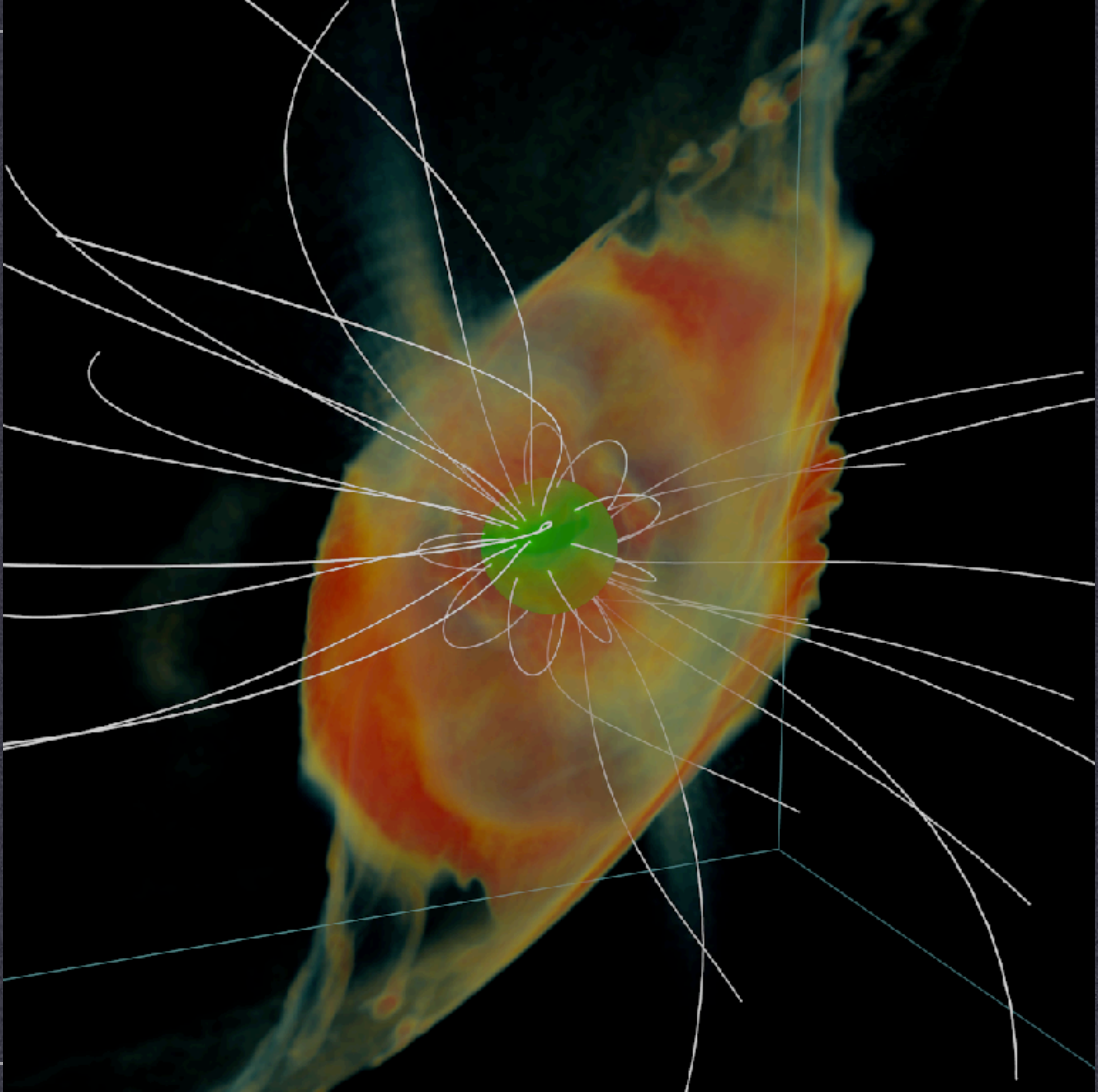
Reconnection in pulsar current sheets

Field lines that produce best force-free caustics seem to “hug” the current sheet at and beyond the LC.

Significant fraction of emission comes from beyond the light cylinder.



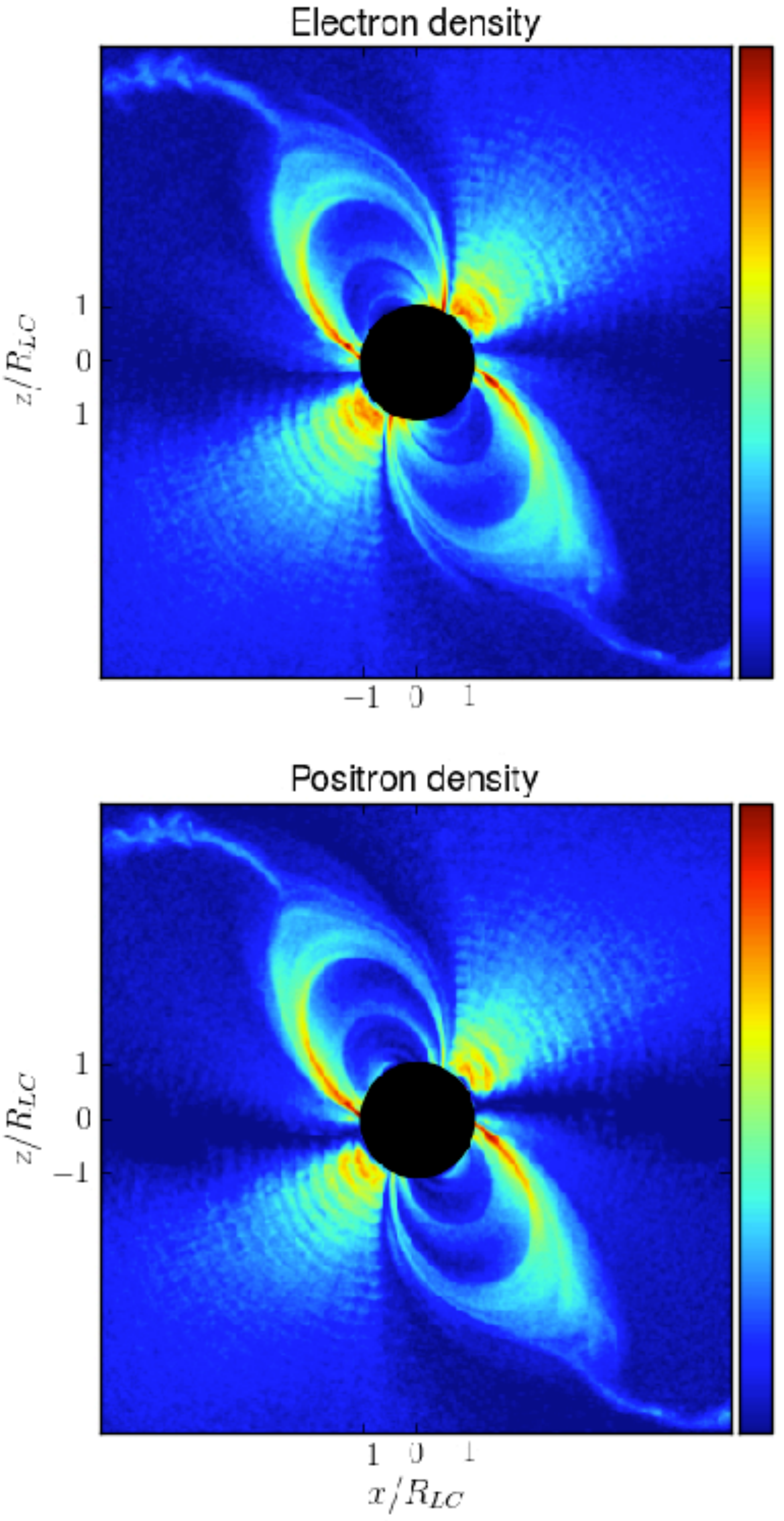




Current developments and roadblocks:

- Reconnection in pulsar current sheets occurs in the presence of pair production.
- This can modify the pair loading and effective magnetization. Whether a self-consistent solution exists needs to be understood (see poster by Hayk Hakobyan)
- Development of radiation-kinetic methods is needed (recently started), using particle photons.
- Analogous issues to radiation-MHD but inverted: high optical depth is difficult

Philippov, AS 2018



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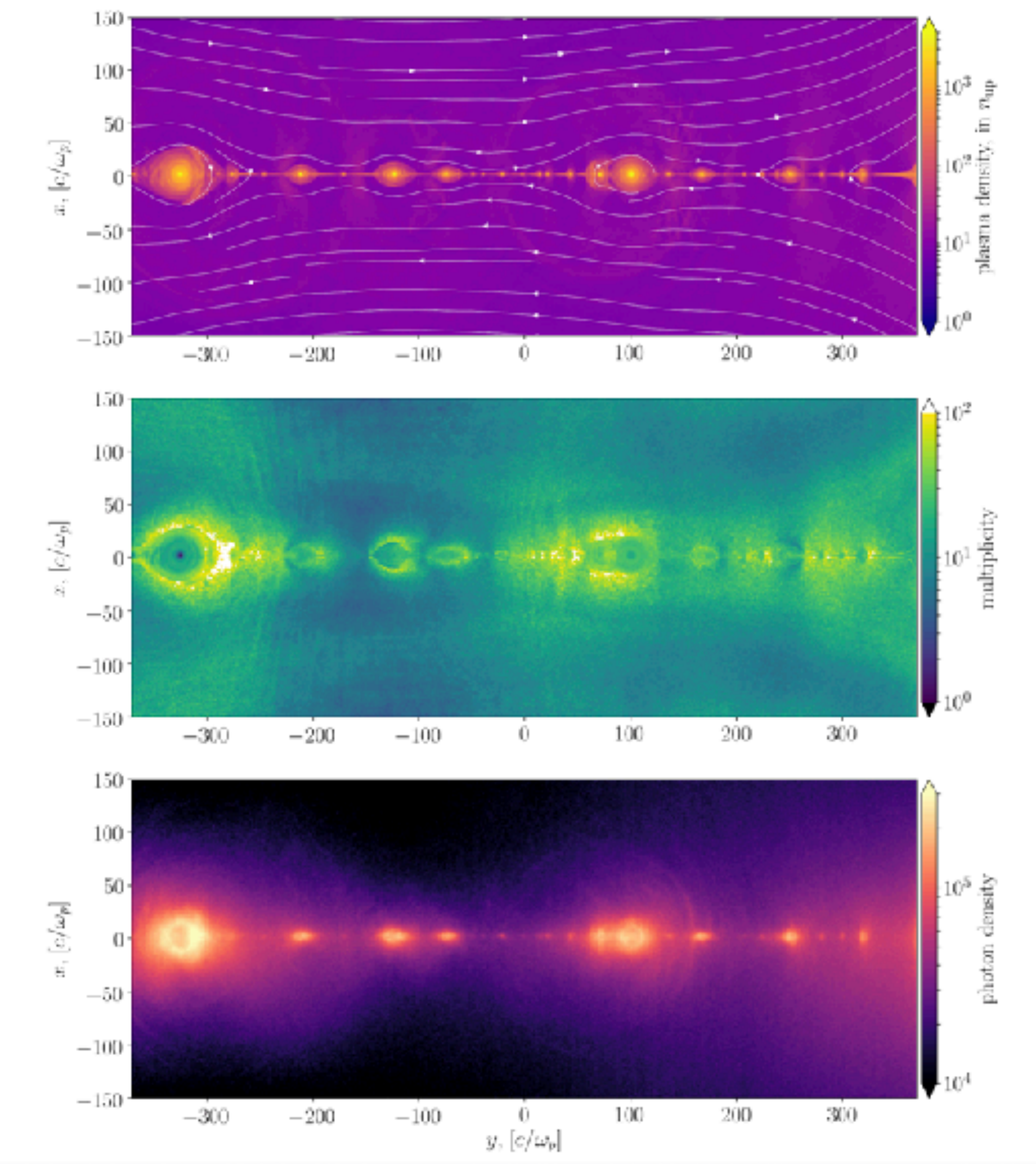
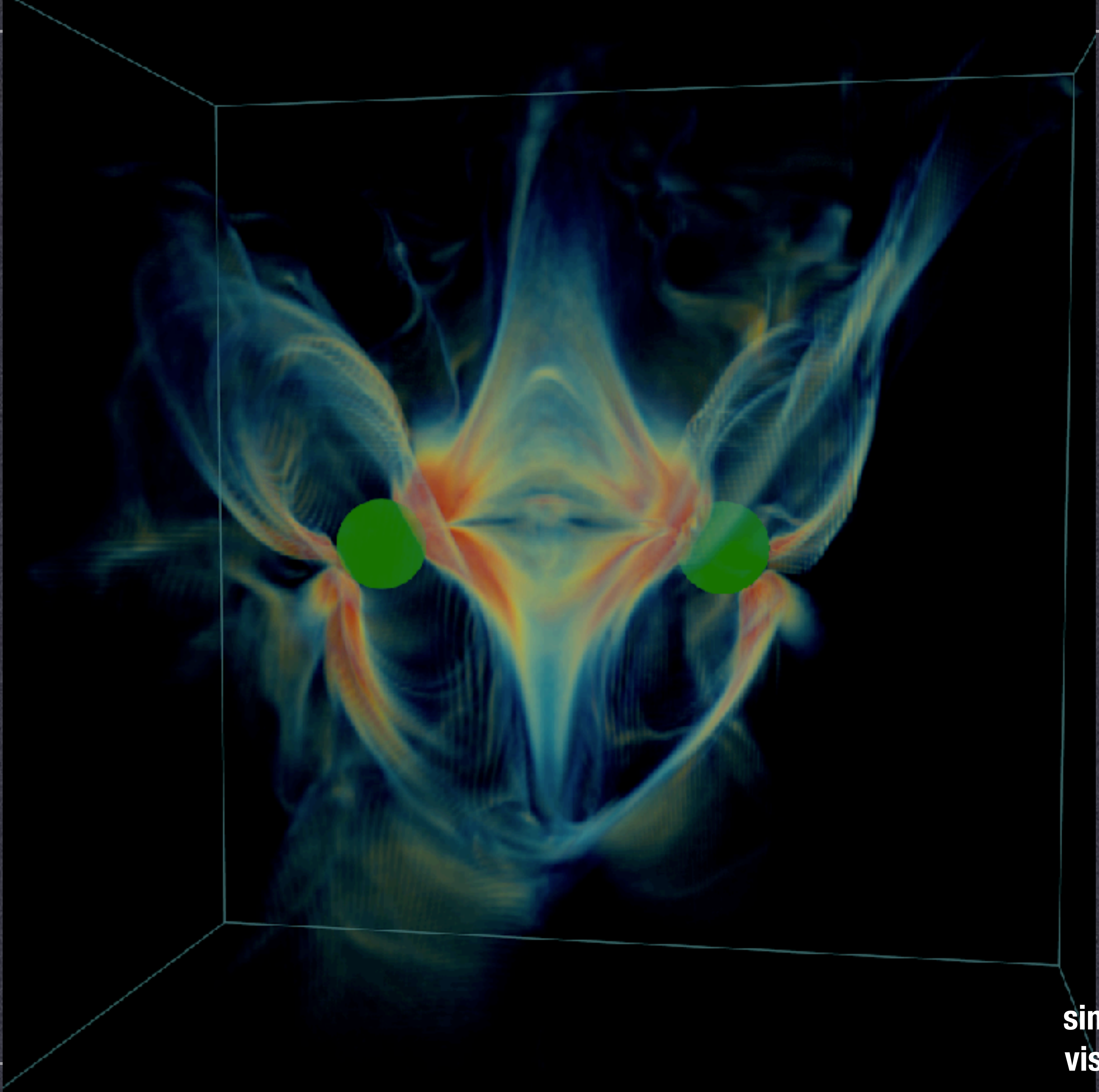


Hakobyan et al, in prep

Open questions in pulsars:

- Origin of broadband emission, including giant pulses
- Magnetospheric structure and spin down in middle-aged pulsars
- Structure and evolution of the striped current sheet: does it fall apart?
- Interaction of binary pulsars



sim: Philippov
vis: Hakobyan

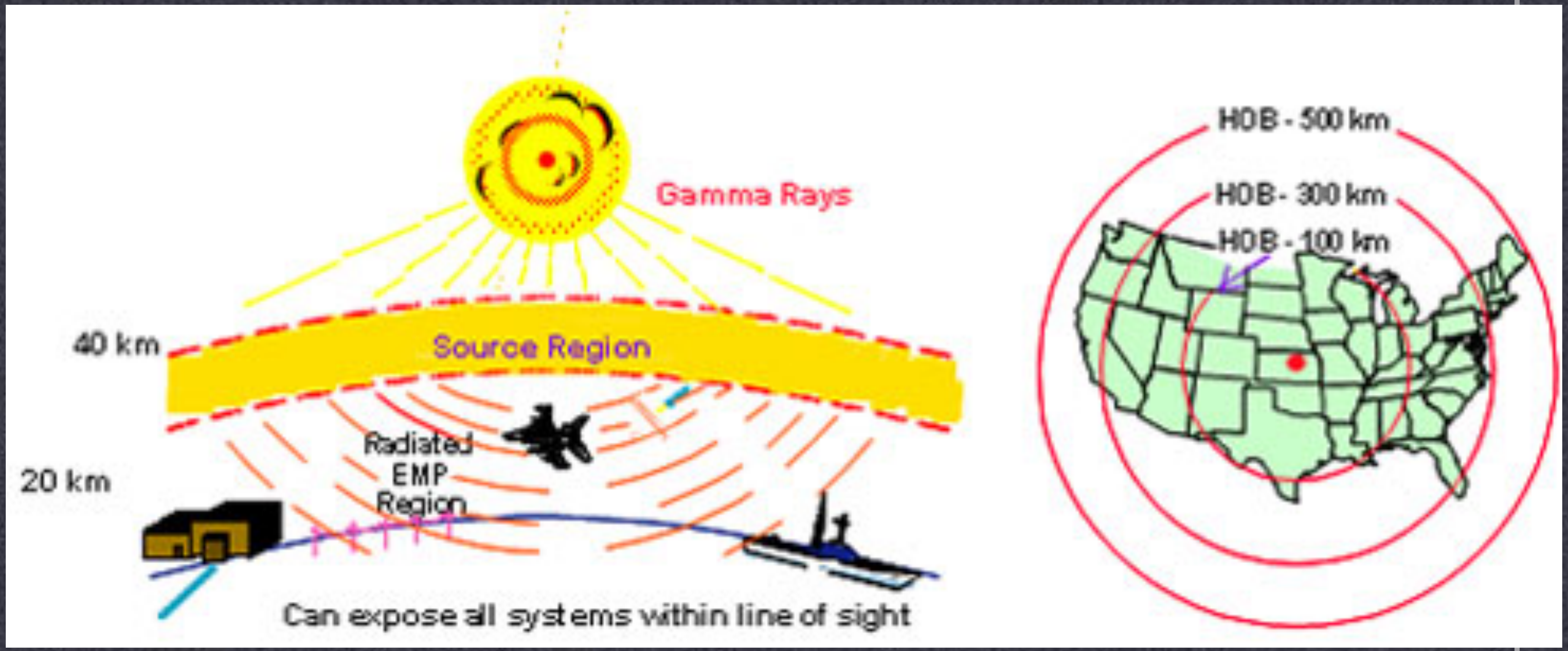
Generation of coherent emission in plasma:

- Traditionally, two paths:
  - antenna mechanism (bunches), or
  - instability (inverted population)

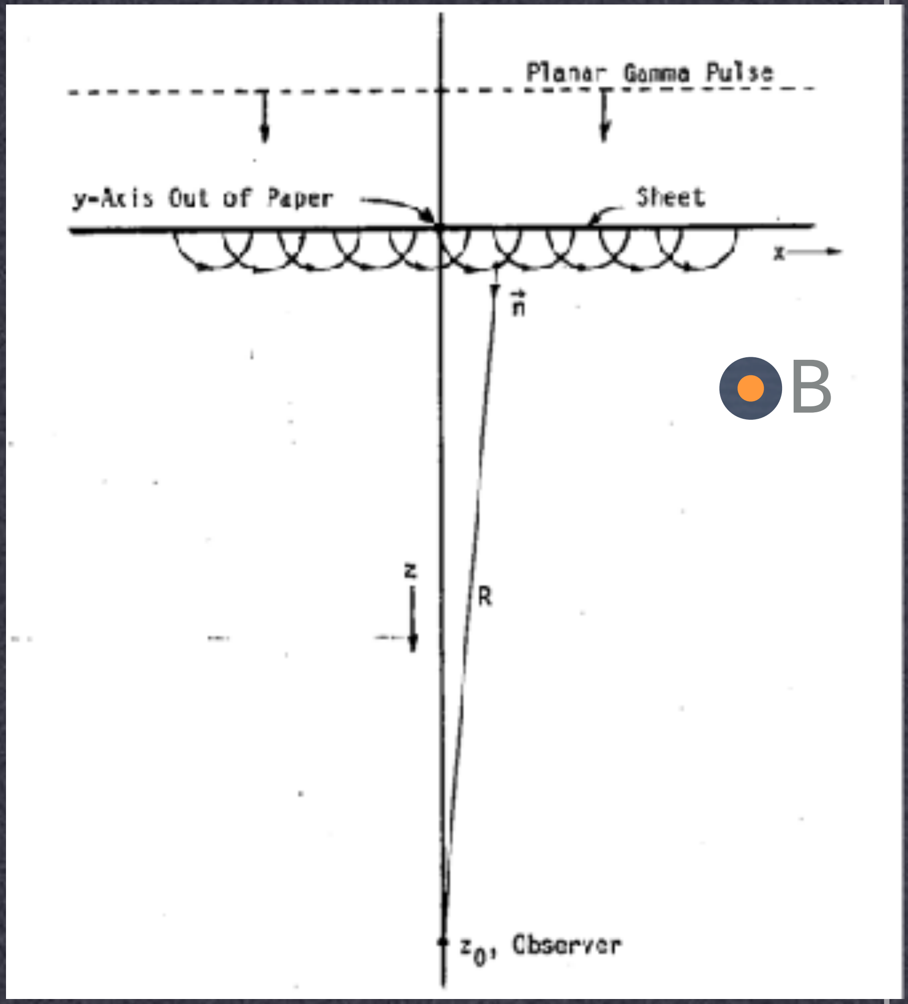
- Consider another possibility: “stimulated” emission

- Can we “squeeze" out a pulse of coherent radio emission from plasma? (AS & Philippov, in prep)
  - We have plenty of impulsive sources of energetic photons in astrophysics. Imagine a pulse of gamma-rays impinging on a blob of plasma. Assume Compton scattering is efficient at kicking electrons.
  - The front moves at c and kicks new electrons which will oscillate in the B field. Current source will be moving with the pulse

Nuclear electromagnetic pulse (EMP) analogy

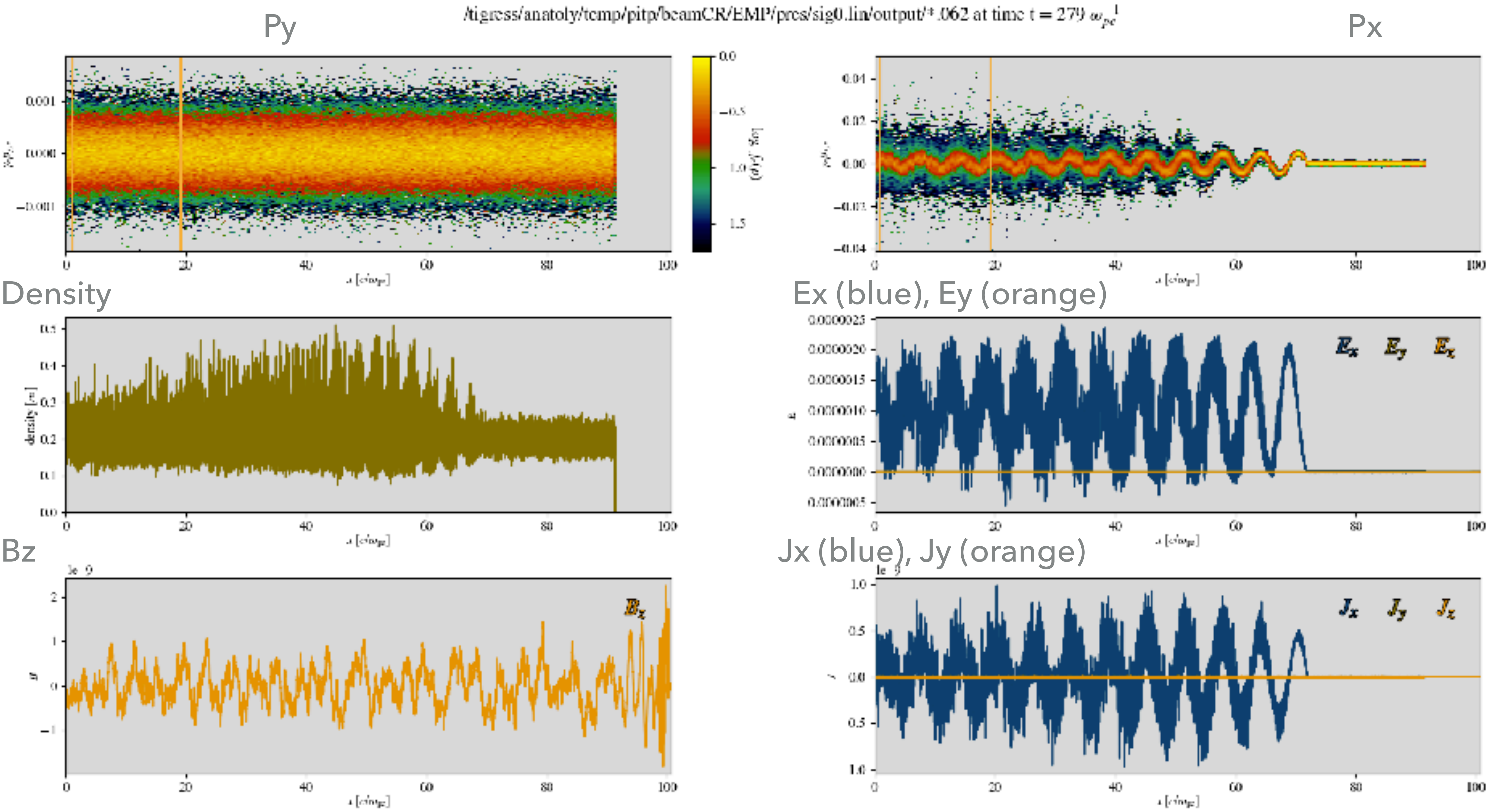


- High-altitude thermonuclear explosions can cause a devastating EMP over a wide area.
- Mechanism (Longmire 86): MeV gamma-rays from explosion Compton scatter electrons from the air.
- Electrons deflect in Earth’s B field, resulting in coherent transverse current pulse.
- Duration: microseconds. Spectrum: broad, around KHz-MHz



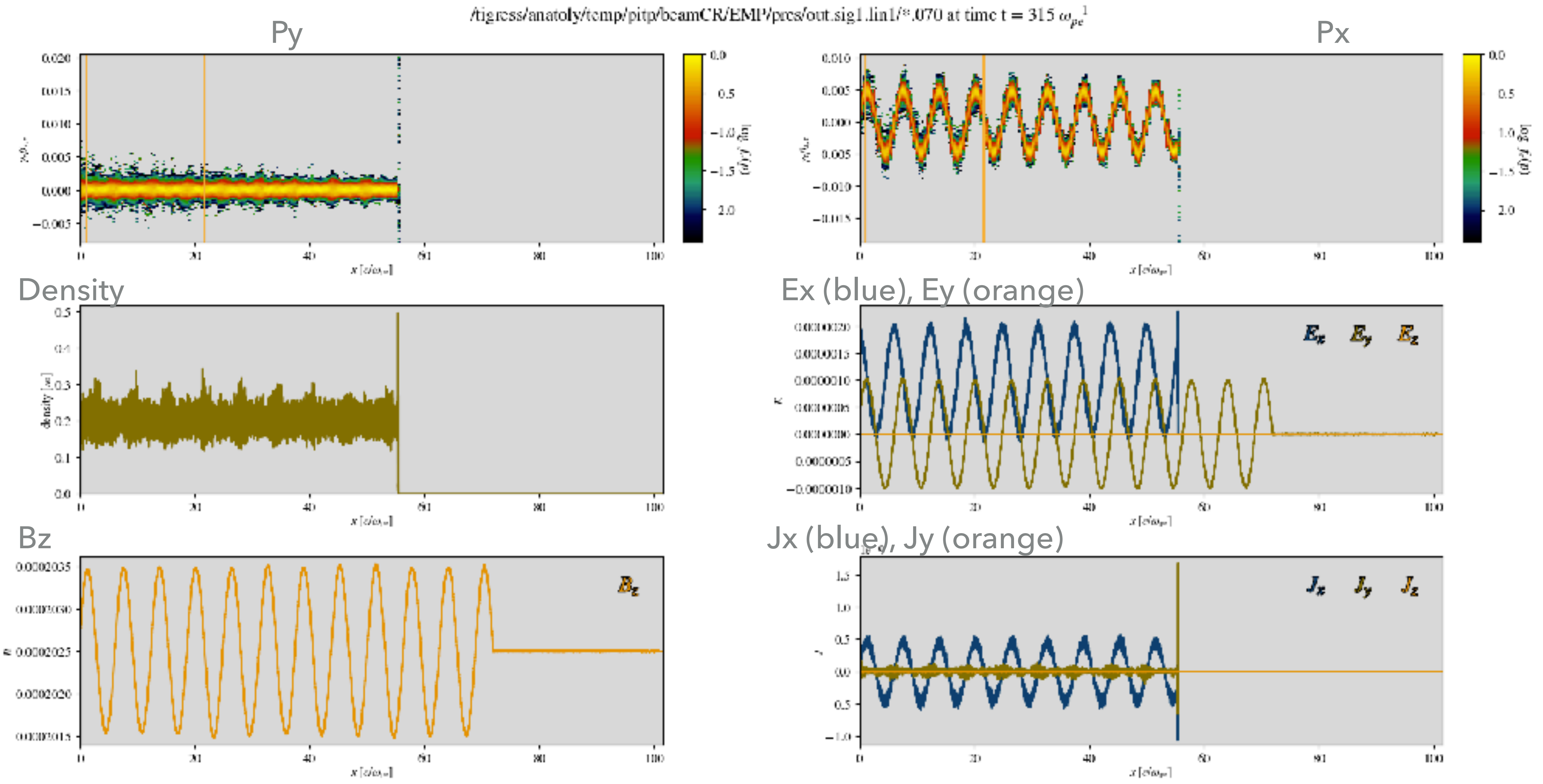
EMP WITH PLASMA

- Add plasma to the pulse to study back-reaction and propagation
- No B field – laser-plasma



EMP WITH PLASMA

- Add plasma to the pulse to study back-reaction and propagation
- sigma=1, linear F_rad (nonrelativistic velocity)



ELECTROMAGNETIC MODE

- Dispersion relation for magnetized plasma (k perp to B):

$$\begin{aligned} -i\omega m v_x &= -eE_x - e\left(\vec{v}\times\vec{B}_0\right)_x = -eE_x - ev_yB_0 \\ -i\omega m v_y &= -eE_y - e\left(\vec{v}\times\vec{B}_0\right)_y = -eE_y + ev_xB_0 \end{aligned}$$

$$\left(\frac{\omega^2}{c^2} - k^2\right)\vec{B}_1 = -i\mu_0\vec{k}\times\vec{j}$$

$$\begin{aligned} \vec{k}\times\vec{E} &= \omega\vec{B}_1 \\ kE_y &= \omega B_z \end{aligned}$$

$$\omega^2 = c^2k^2 + \omega_p^2\frac{(\omega^2-\omega_p^2)}{(\omega^2-\omega_H^2)}$$

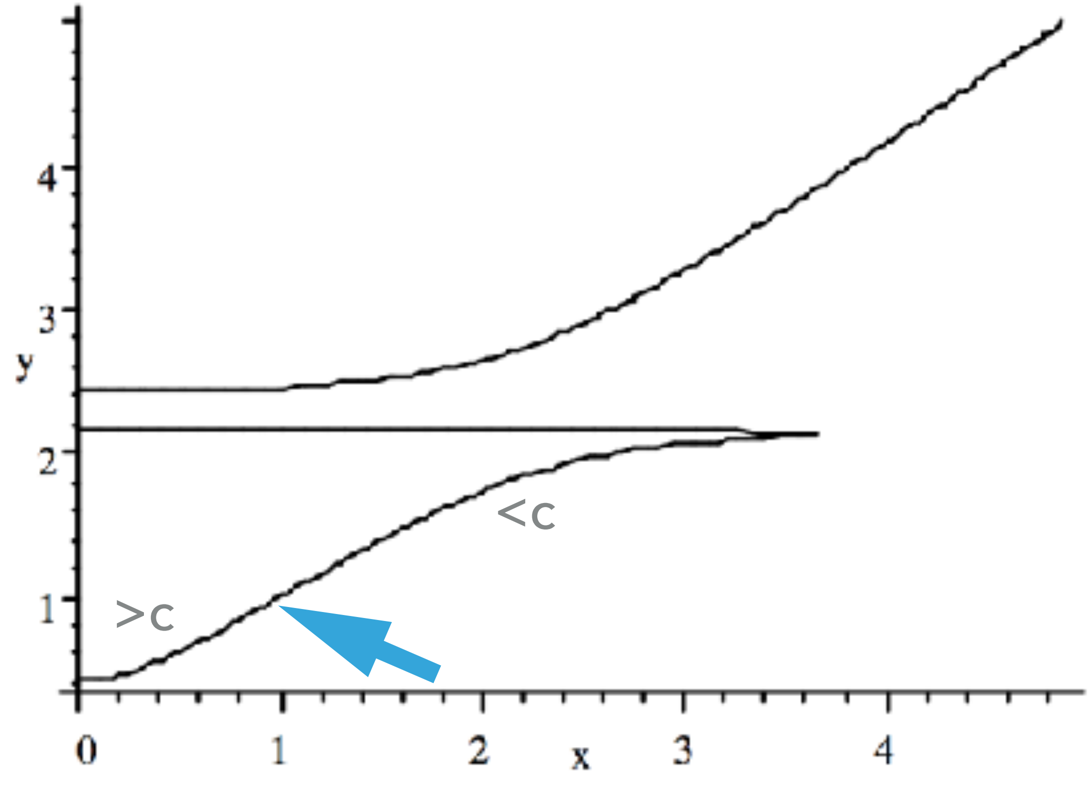
- Solution at omega_p: EM wave with phase speed = c.

- Phase speed of c is the speed of the triggering pulse

$$E_y = \sqrt{\sigma}E_x$$

$$\sigma = \frac{\omega_c^2}{\omega_p^2}$$

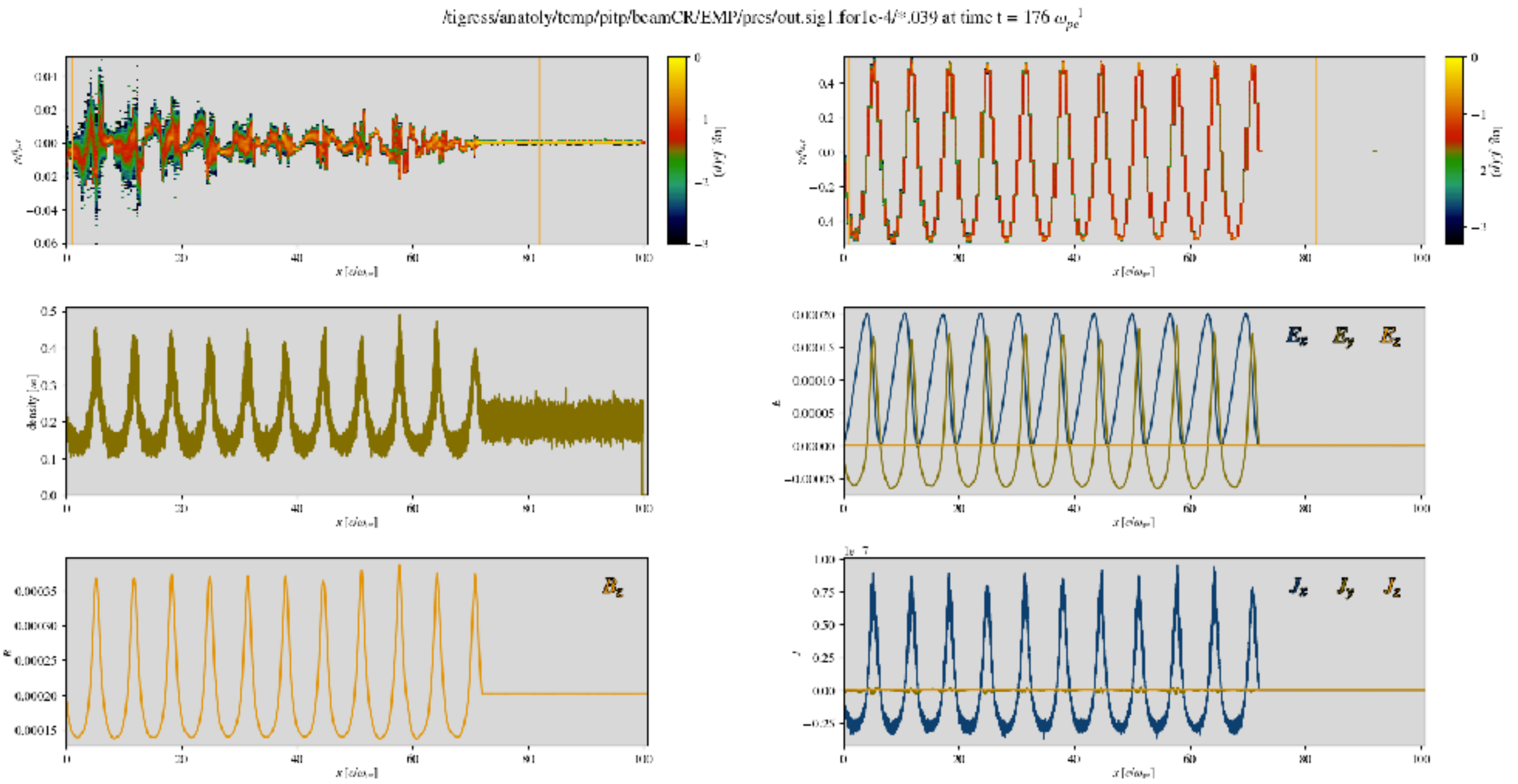
$$eE_x = F_{rad}$$



ω versus k for the X-mode

EMP WITH PLASMA

- Now add plasma to the pulse to study back-reaction
- B≠0, high magnetization, sigma=1, strong push (a=.5)



Frequencies

- EM wave at plasma frequency arises from Compton push and leaves the plasma
- Pulse length is determined by length of the plasma slab
- Amplitude is set by magnetization and radiation strength (particularly rise time of the radiation)
- At small magnetizations, for GHz modulation at plasma frequency, need 10^{10} cc plasma density, for stationary plasma.
- For strongly magnetized plasma, frequency is modulated by gyration as well, and also shows dispersion. This will pose constraints on magnetization of the scattering region.

Possible sites

- Need high density of plasma and a source of energetic photons
- GRB gamma rays colliding with dense clouds, or atmospheres?
- Magnetar flares impinging on magnetized plasma in the magnetosphere or nearby?
- Other ideas?

Conclusions:

- Multiscale physics is particularly challenging to study and rewarding to understand. Examples: shocks, CRs, reconnection
- Particle acceleration in relativistic shocks is still problematic
- Reconnection is likely to accelerate particles, but important to understand how it fits into global 3D picture
- Interplay between model and mechanism is showing the fun aspects of plasmas. Example: can coherent emission be squeezed out by Compton push of electrons?
- New tools are under development: full PIC variants, hybrid, MHD-PIC, 6D Vlasov codes, moment methods. First uses are happening. Next few years will be exciting!

Pre-anouncement:

KITP Santa Barbara program on

“Multi-scale processes in plasma astrophysics”

is in the final stages of consideration by KITP board.

Tentatively scheduled for Aug-Oct, 2019

Conference: Sep 9-12, 2019

Stay tuned!