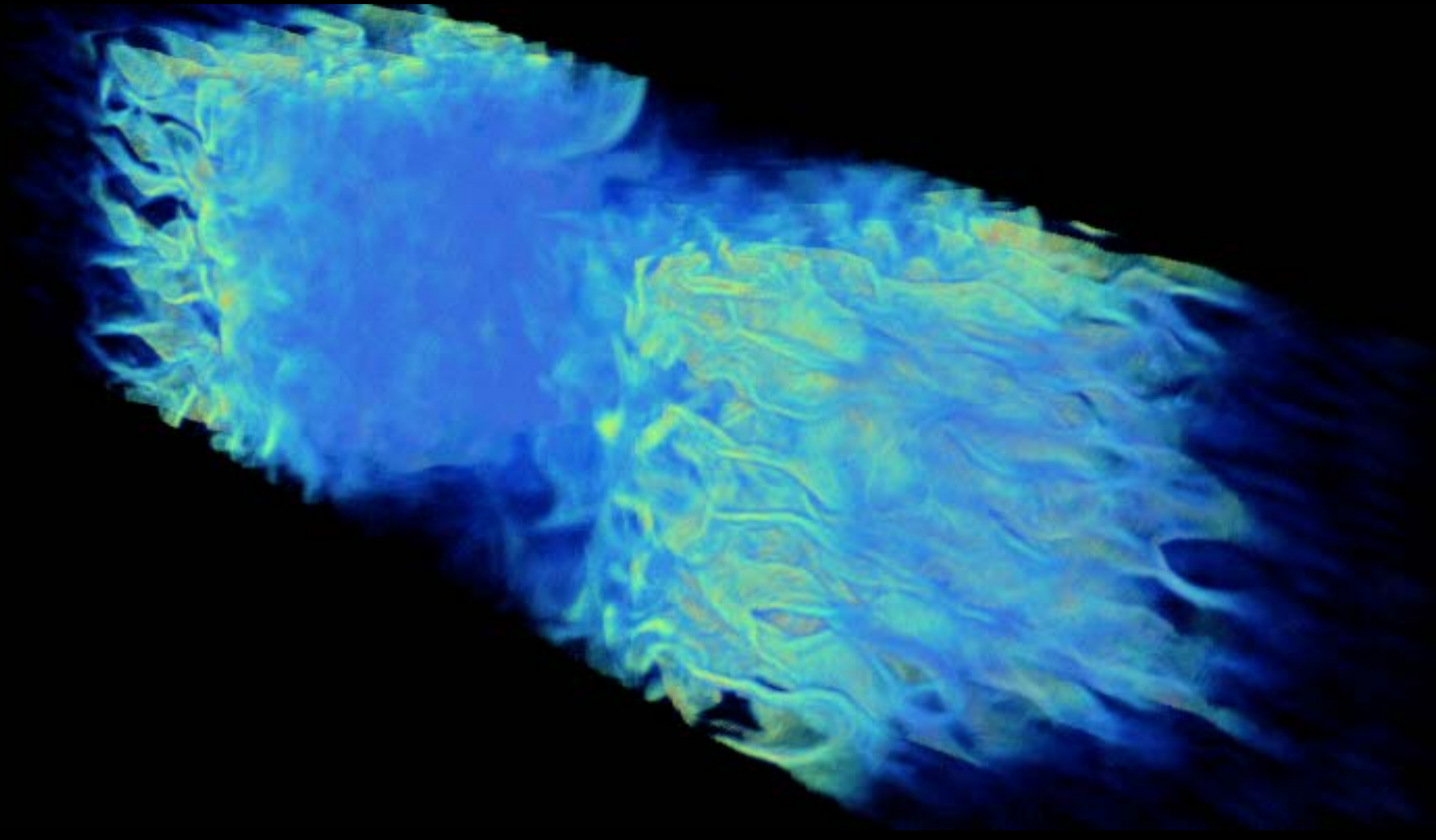
Kinetic Simulations of Astrophysical Plasmas III: Applications

Anatoly Spitkovsky (Princeton)



Acceleration, reconnection and dissipation: adventures in plasma astrophysics

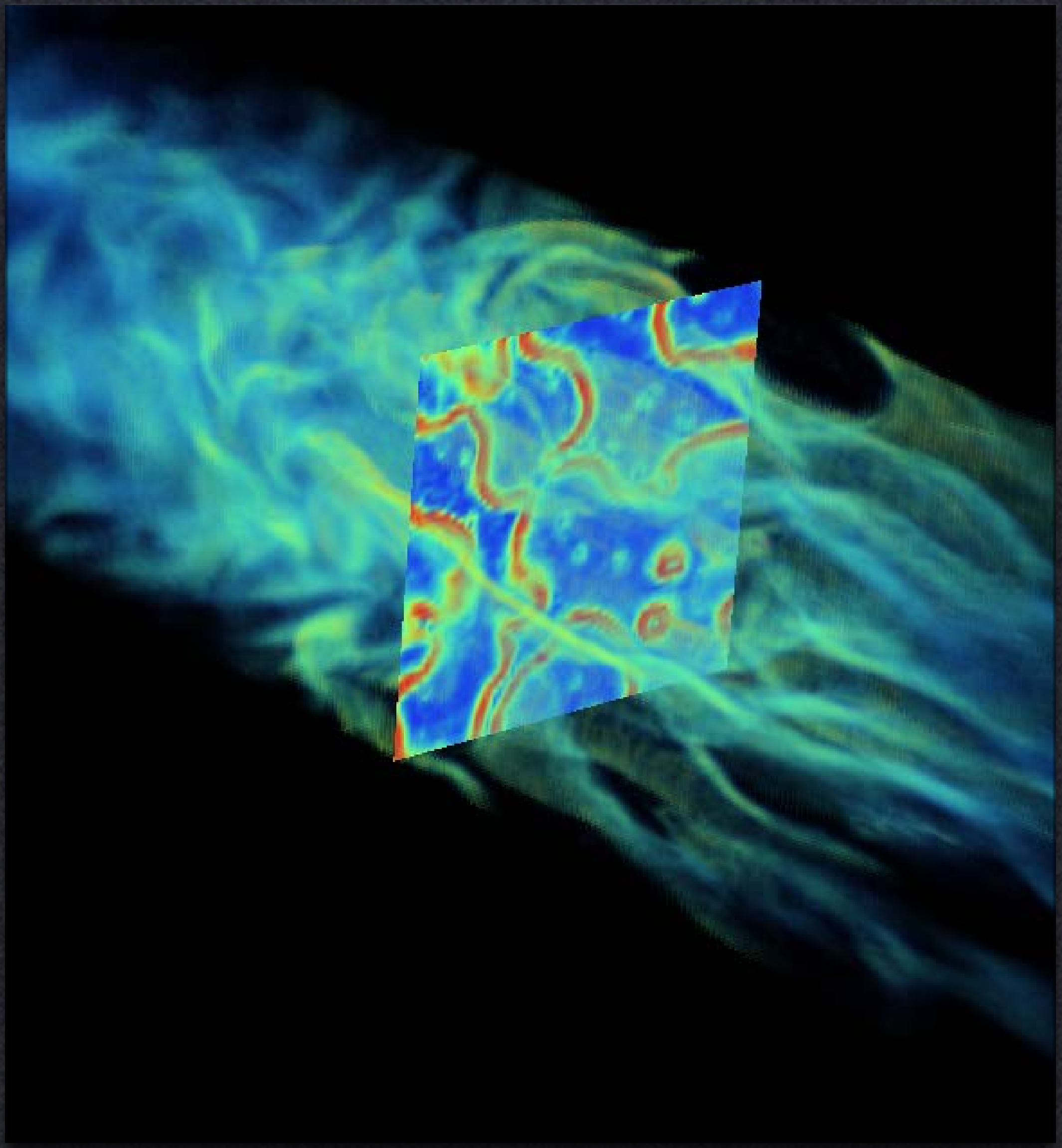
Anatoly Spitkovsky (Princeton)

What is plasma astrophysics?

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

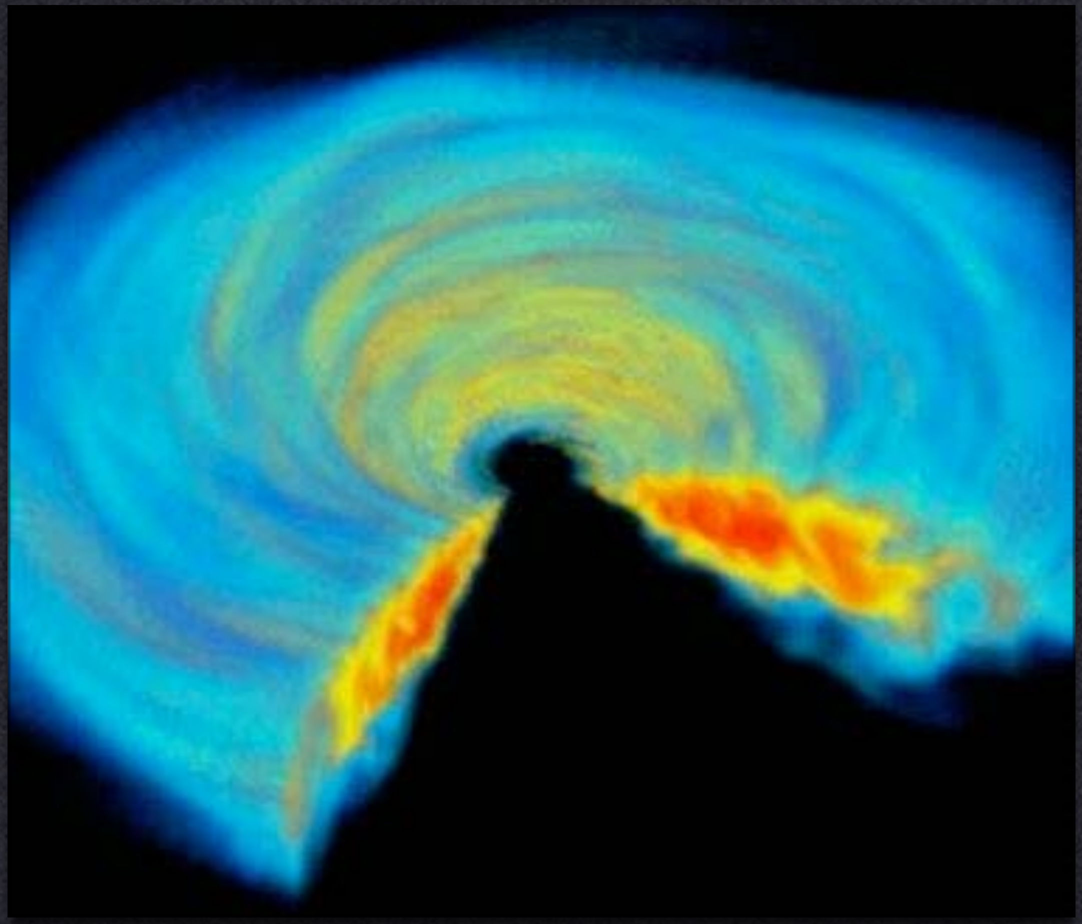
  frequency = 10^4 (n/1cc)$^{1/2}$ Hz;
  spatial scale = 10^5 (n/1cc)$^{-1/2}$ cm

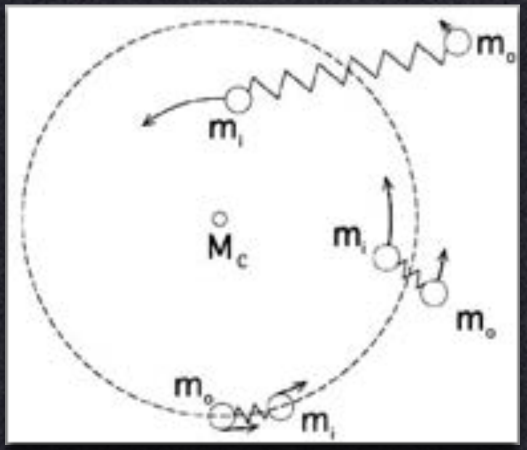
- Most interesting: when microscopic physics affects macroscopic observables
- Most disturbing: these effects typically are either badly parameterized or ignored...



Plasma effects and HEA

- 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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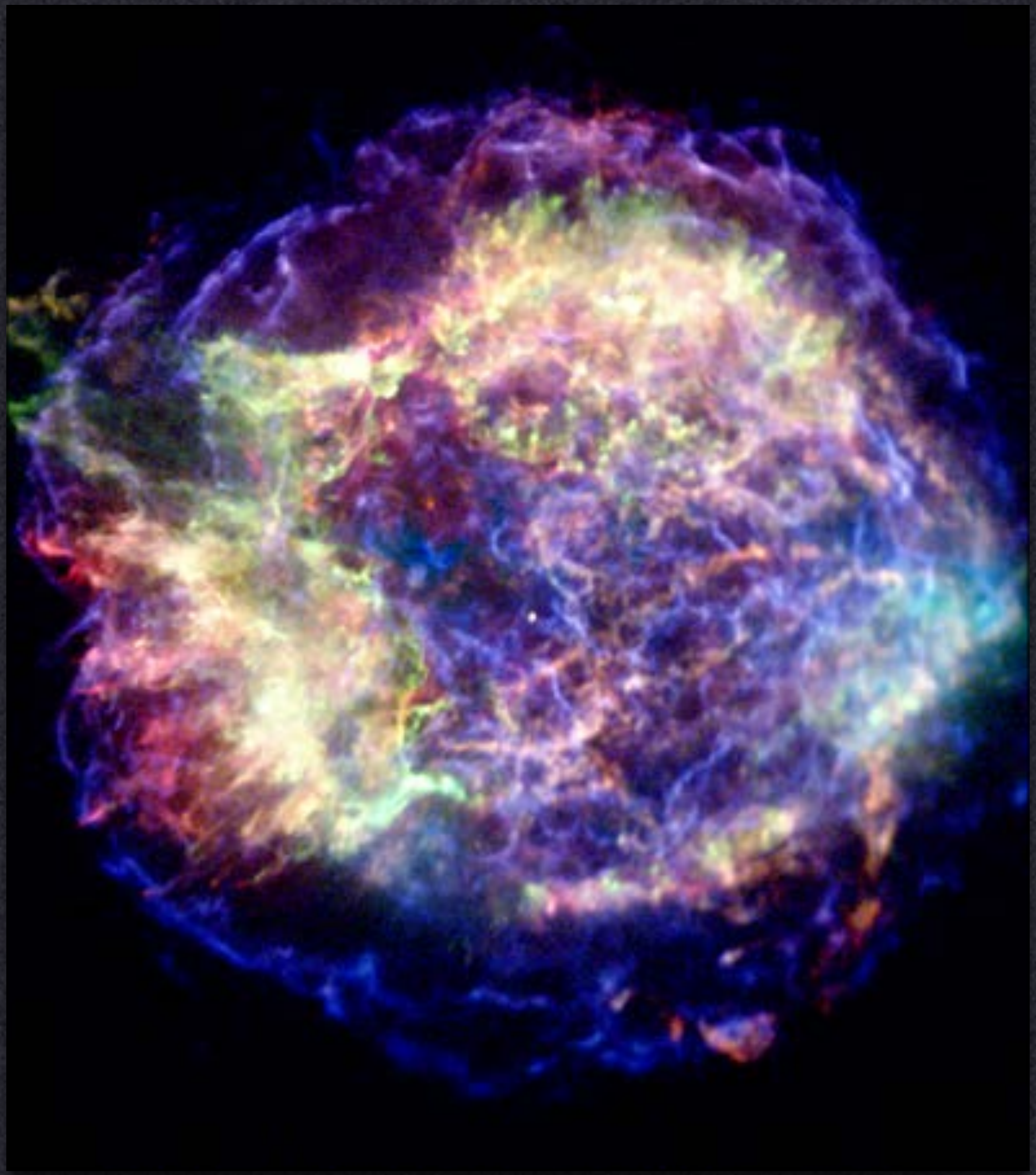
Plasma effects and HEA

- 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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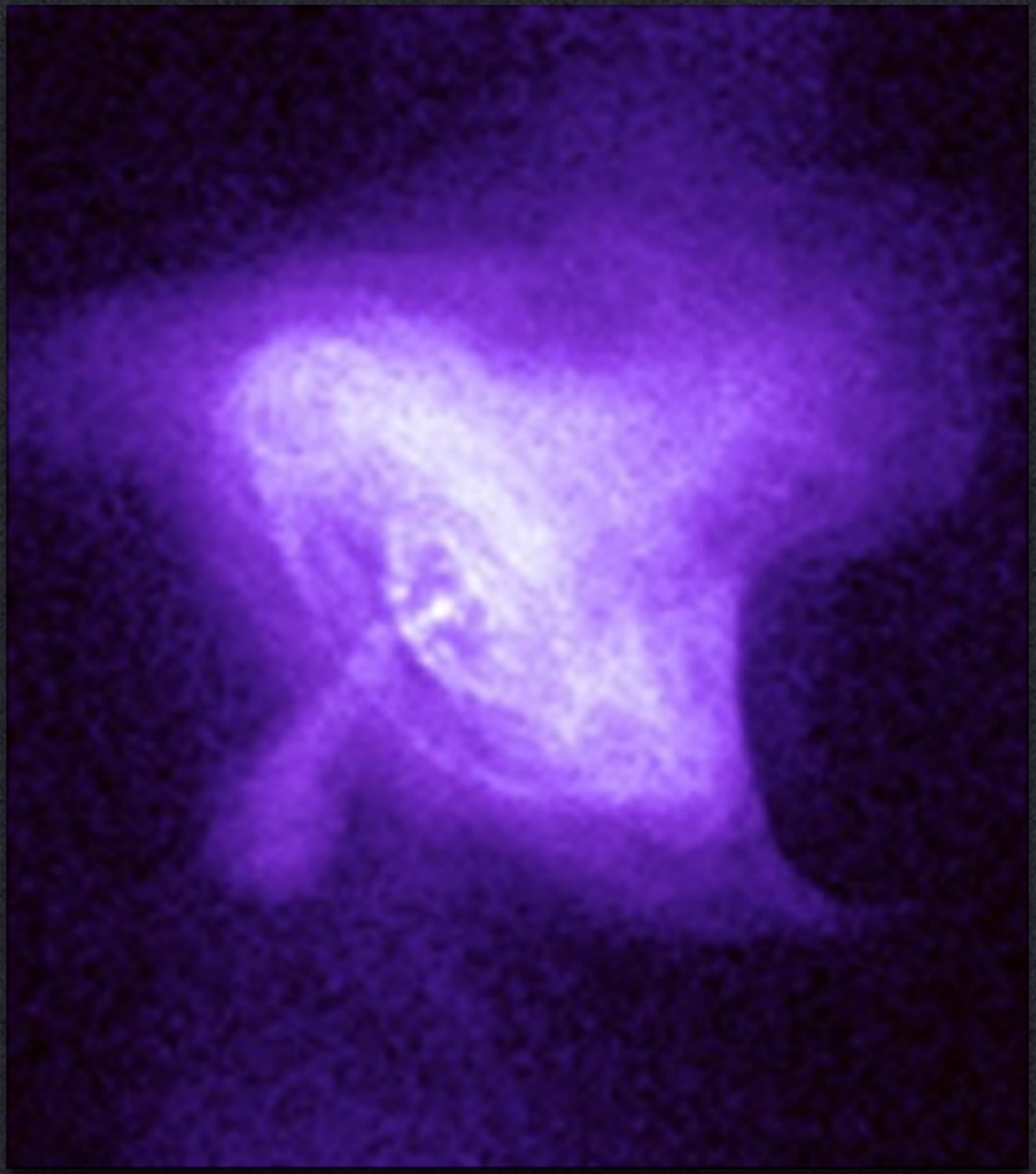
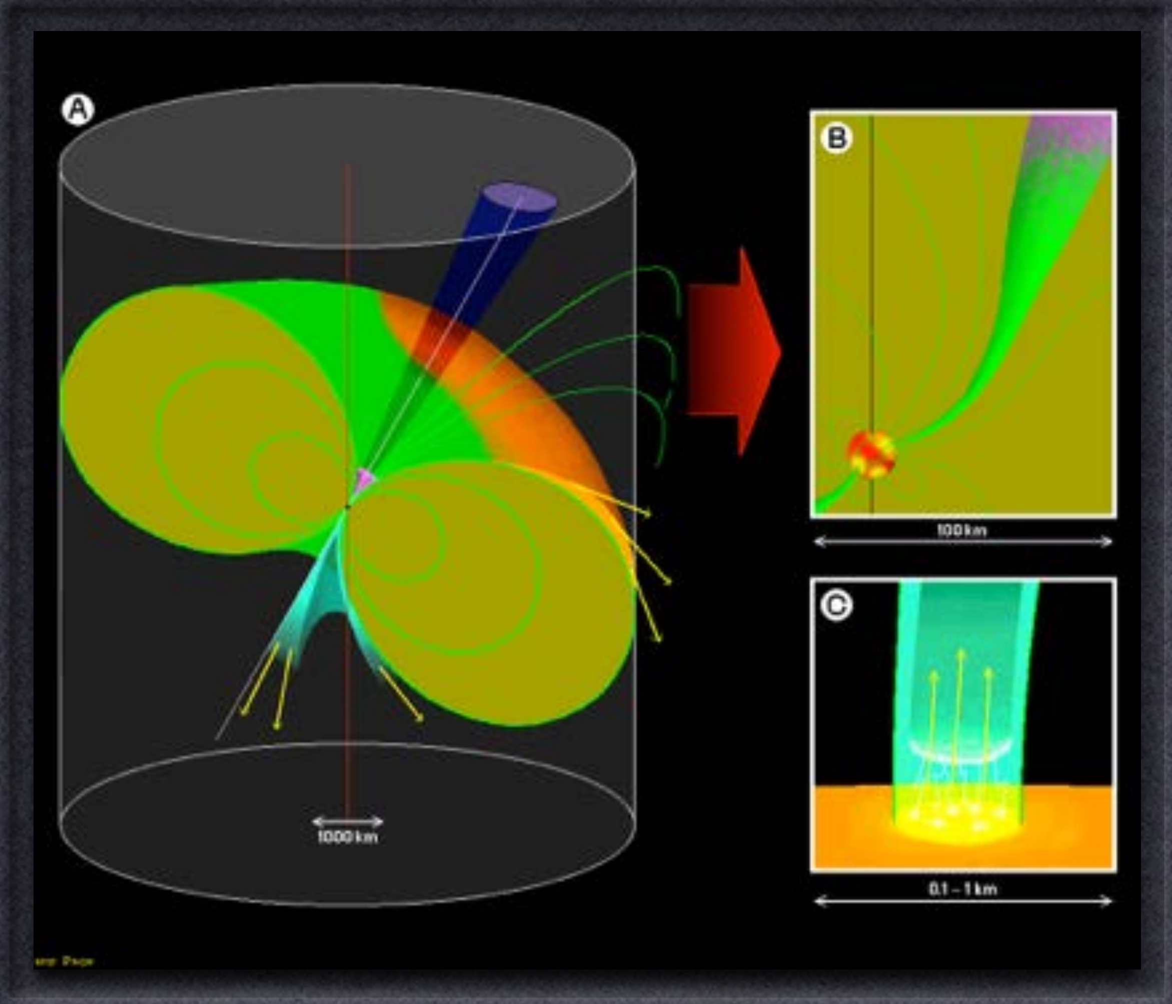


Plasma effects and HEA

- 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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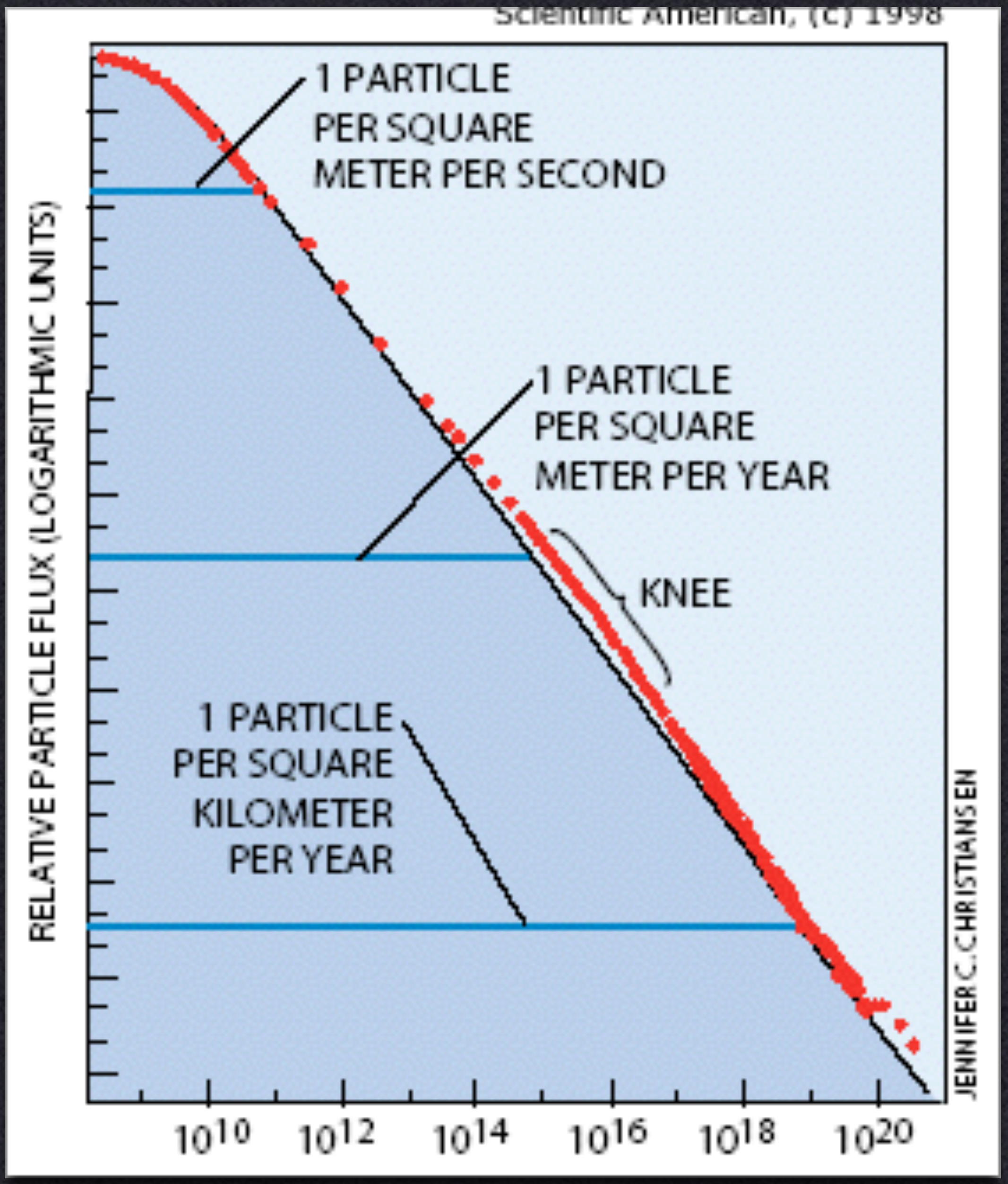
Plasma effects and HEA

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



Goals:

model astrophysical systems with microphysical parameterizations determined from plasma simulations;

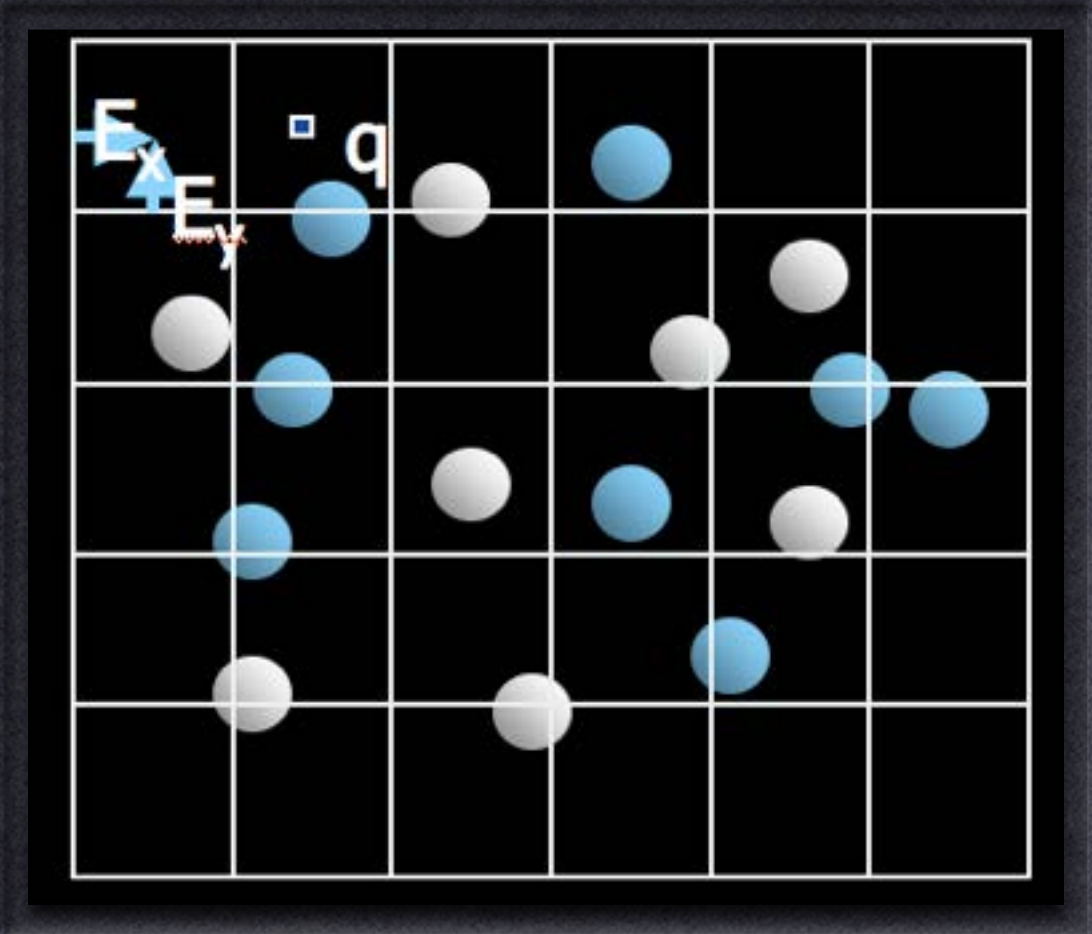
constrain astrophysical scenarios based on realistic plasma physics, and determine plasma conditions based on astrophysical observables.

Outline

- Plasmas in high-energy astrophysics
  - Collisionless shocks and particle acceleration
  - Relativistic magnetospheres
  - Heating and acceleration in relativistic reconnection
- Earthly connections (laboratory experiments)

Tools

- Ab-initio plasma simulations (Particle-In-Cell): Tristan-MP
    - 3D, relativistic EM PIC code, massively parallel
- Hybrid code: dHybrid
    - Kinetic ions, fluid e, 3D
- MHD, RMHD, force-free codes
    - Pencil, Athena, HARM, FFcode



Collisionless shocks

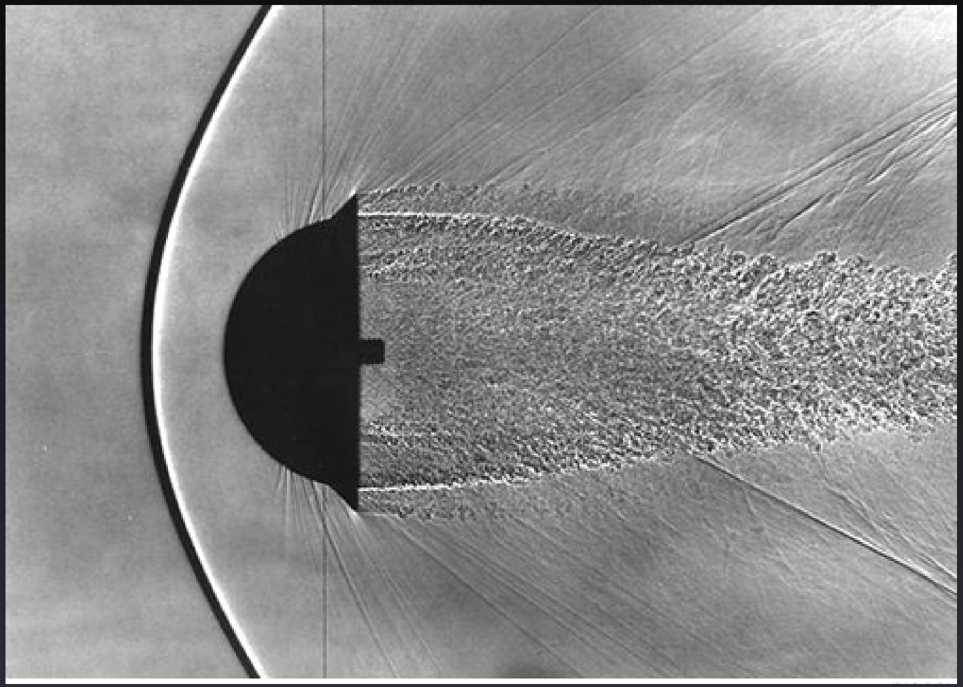
with L. Sironi, D. Caprioli, M. Riquelme, J. Park, L. Gargate

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



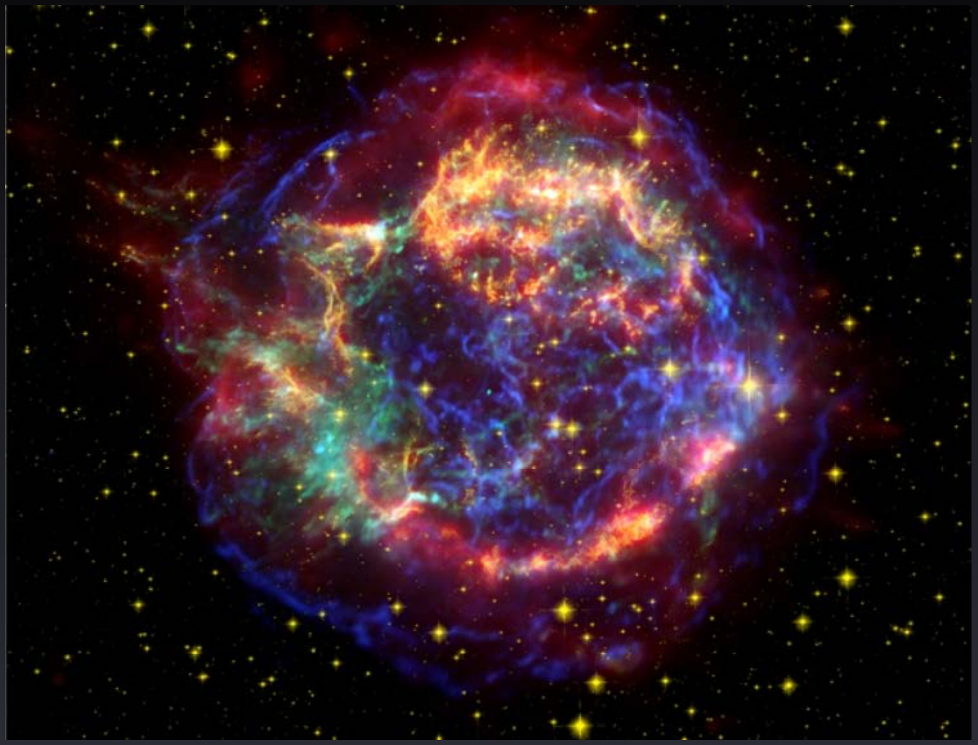
Astro: Mean free path to Coulomb collisions in enormous: 100pc in supernova remnants, ~Mpc in galaxy clusters

Mean free path > scales of interest

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

collisionless shocks

The physics of collisionless shocks



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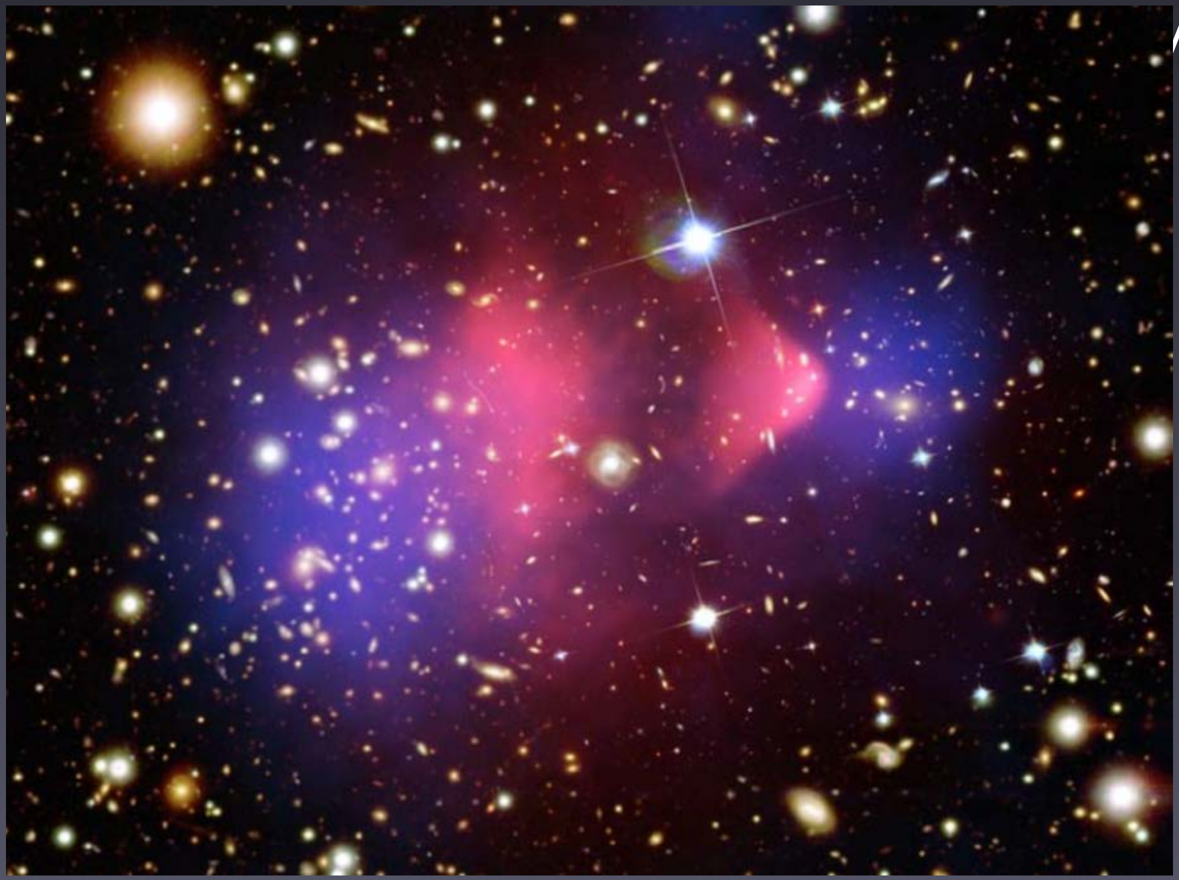

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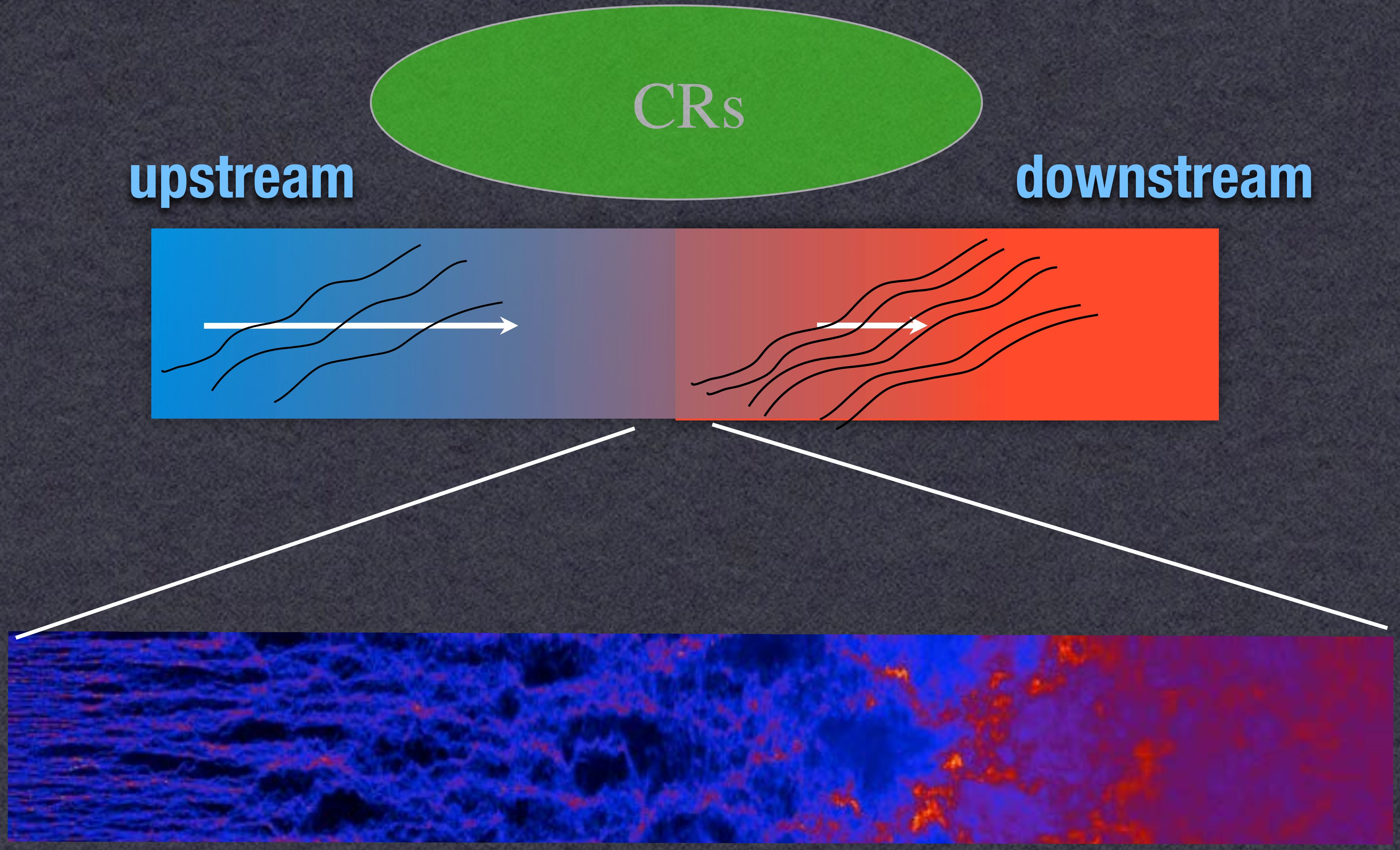
collisionless shocks

Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback



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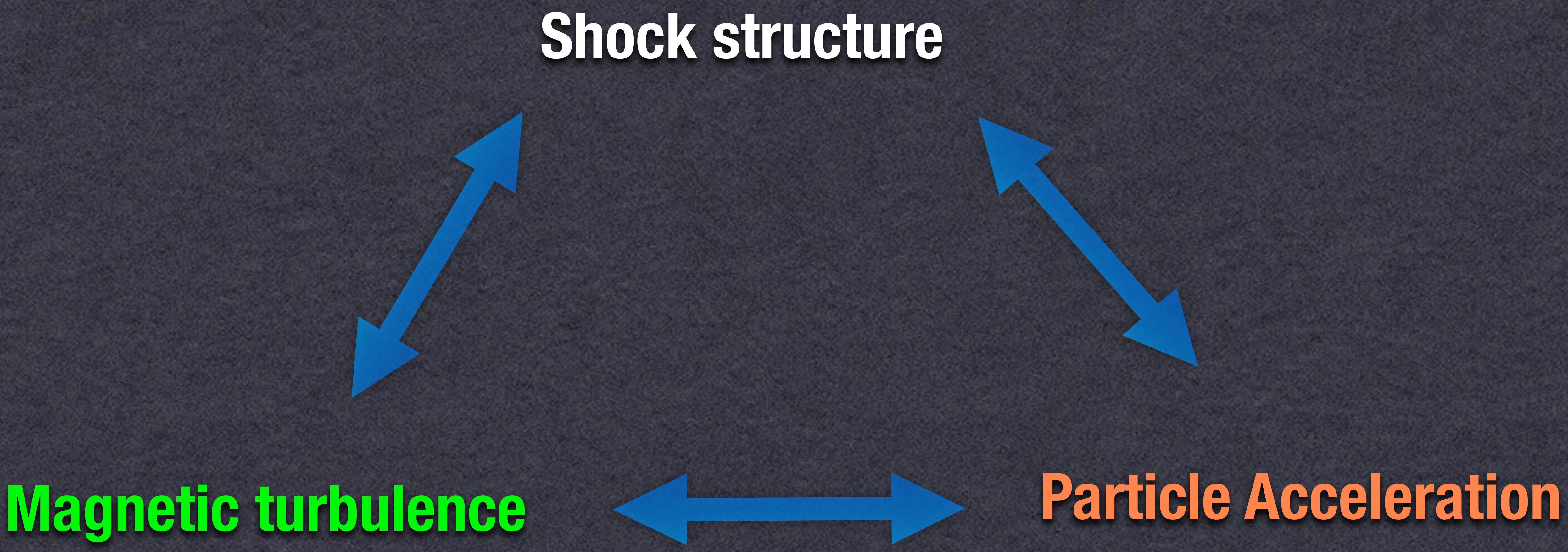
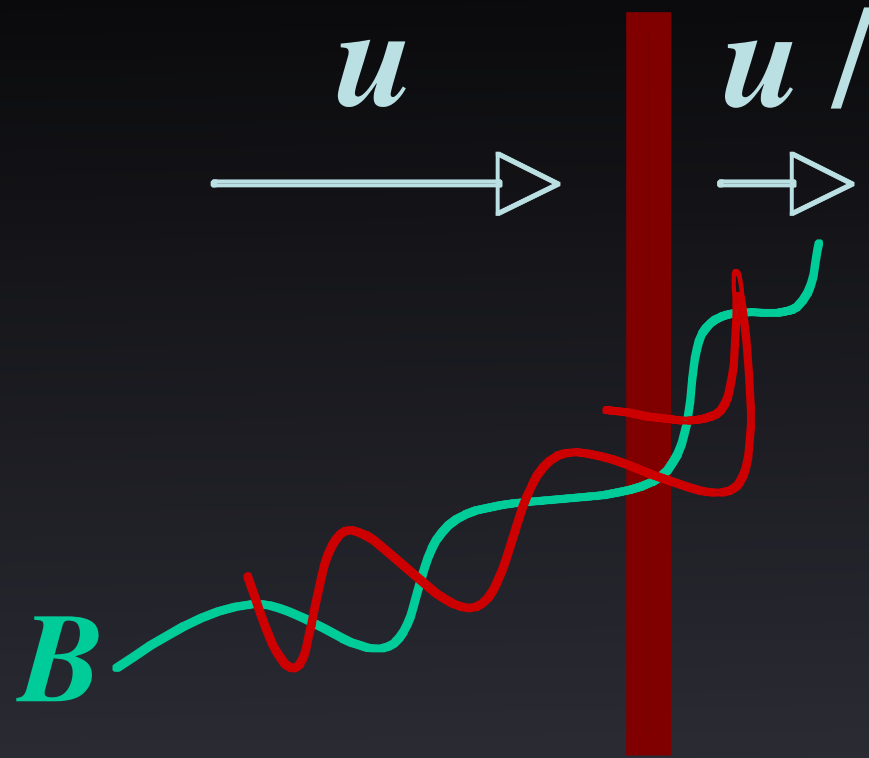


Shock structure

Magnetic turbulence

Particle Acceleration

Particle acceleration:



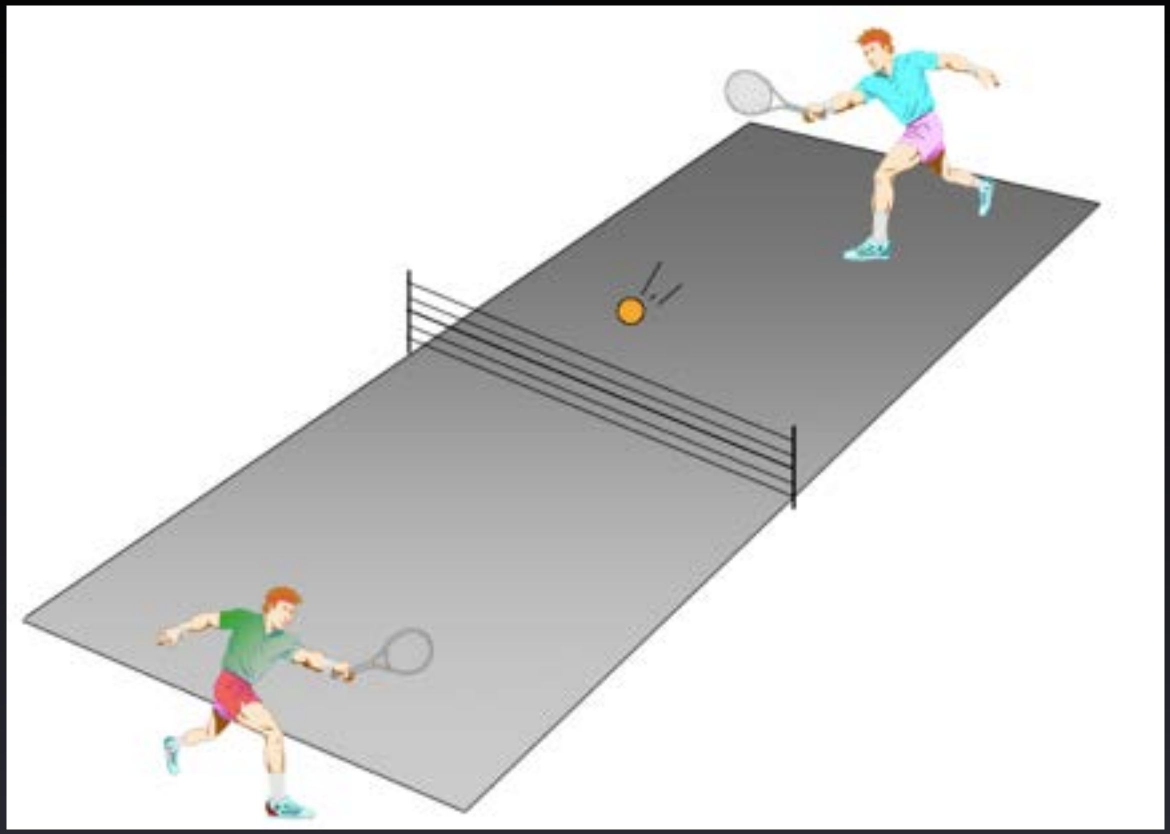
$\Delta E/E \sim v_{shock}/c$

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

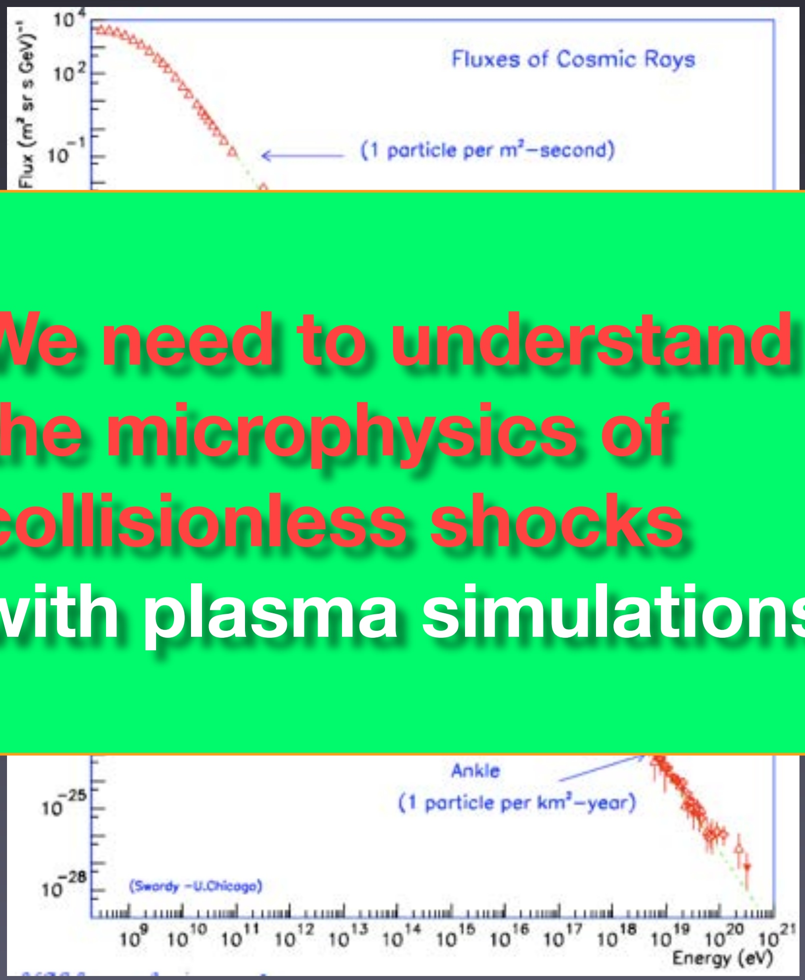
- Original idea -- Fermi (1949) -- scattering off moving clouds. Too slow (second order in v/c) to explain CR spectrum, because clouds both approach *and* recede.

- 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?

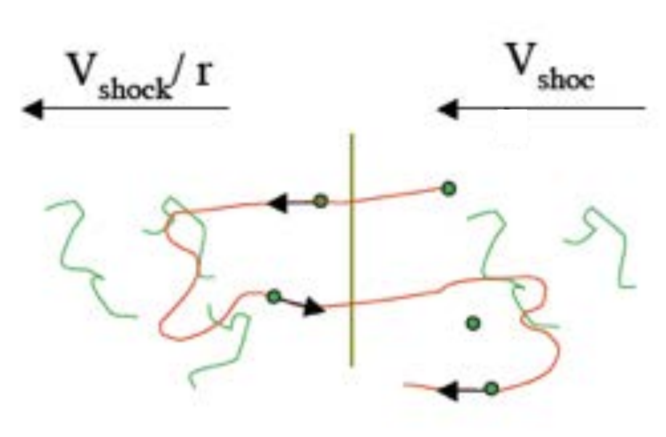


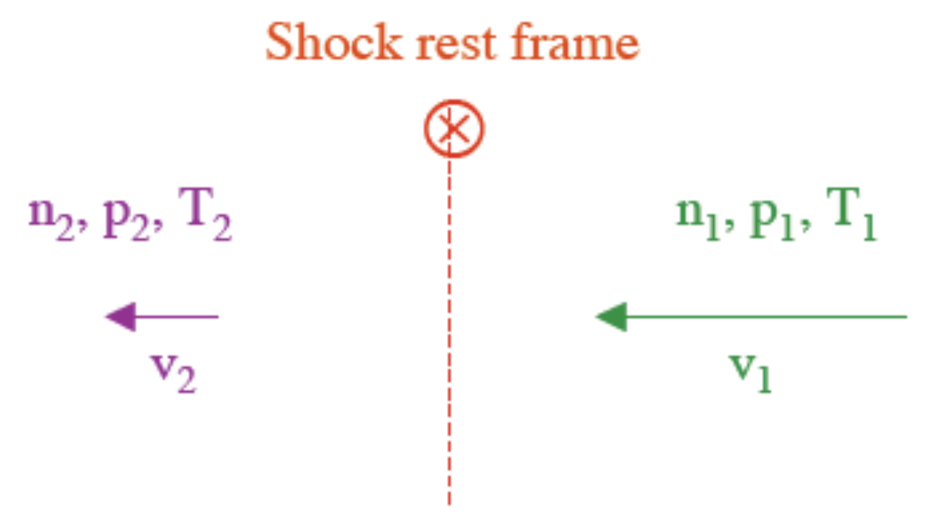
Free energy: converging flows



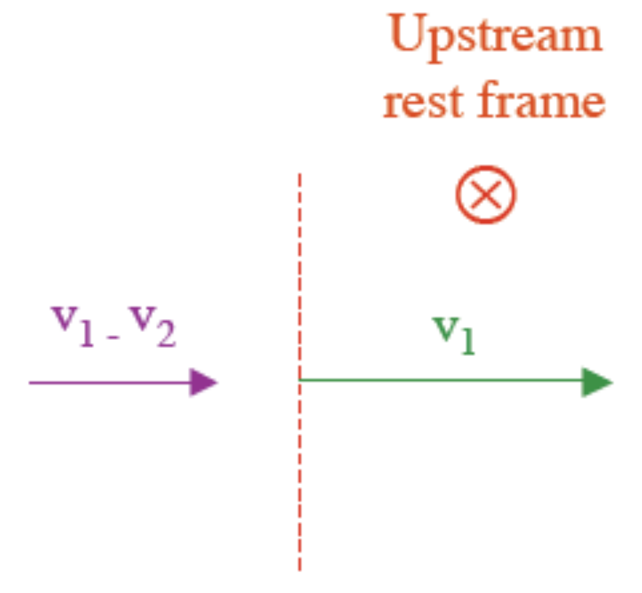
We need to understand the microphysics of collisionless shocks with plasma simulations

Particle acceleration:





From upstream, the downstream is approaching



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

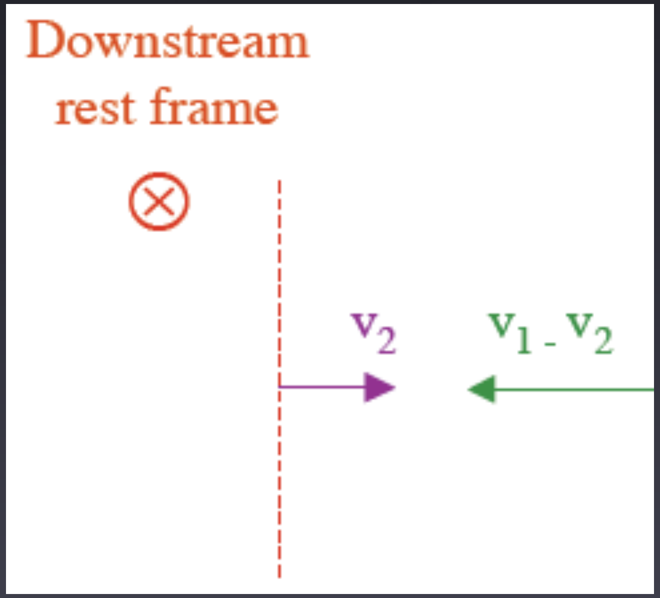
$$p_x = E/c$$

$$\frac{\Delta E}{E} = \frac{\Delta v}{c}$$

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?

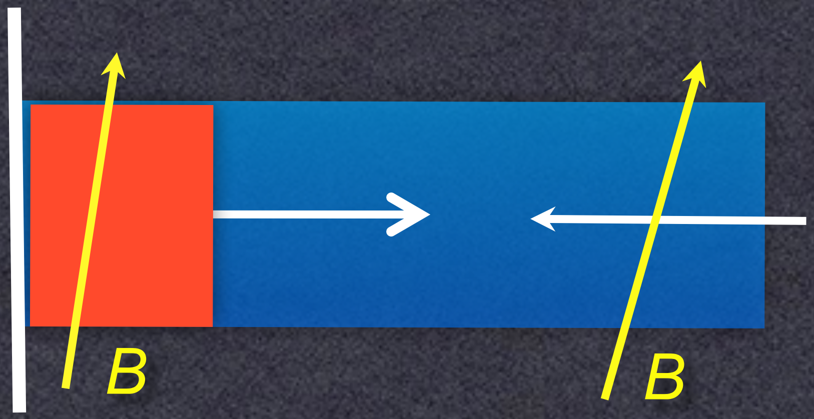
$$E_{new} = E_{old}\beta \quad E = E_0 \beta^j \quad N = N_0 P^j \quad \frac{\log(N/N_0)}{\log(E/E_0)} = \frac{\log P}{\log \beta}$$

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

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

Survey of Collisionless Shocks

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



Main findings:

Dependence of shock mechanism on upstream magnetization

Ab-initio particle acceleration in relativistic shocks

Shock structure and acceleration in non-relativistic shocks

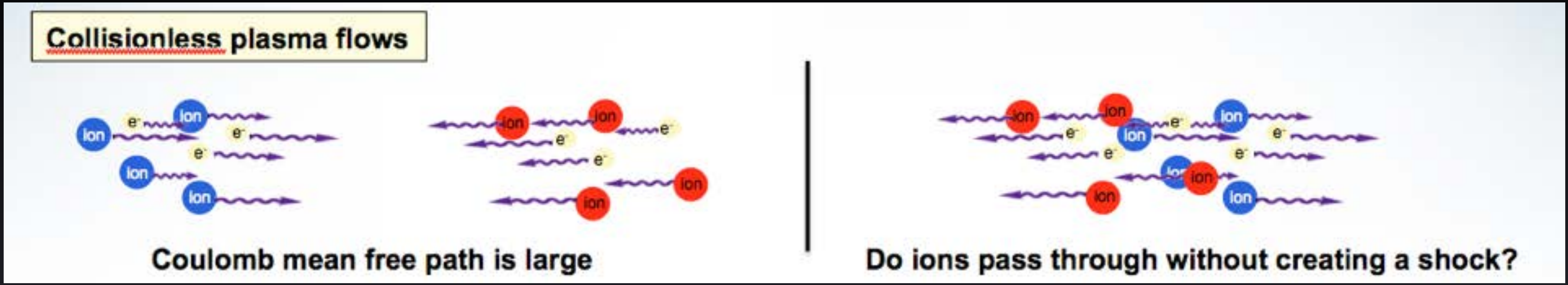
    Ion acceleration vs Mach # in quasipar shocks; DSA; D coeff.

    Evidence for simultaneous e-ion acceleration in parall. shks

    Electron acceleration in quasiperpendicular shocks

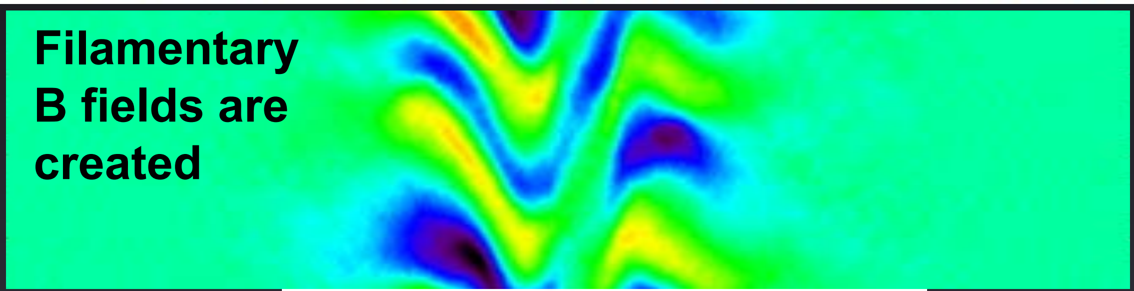
Field amplification and CR-induced instabilities

How collisionless shocks work



Coulomb mean free path is large

Do ions pass through without creating a shock?

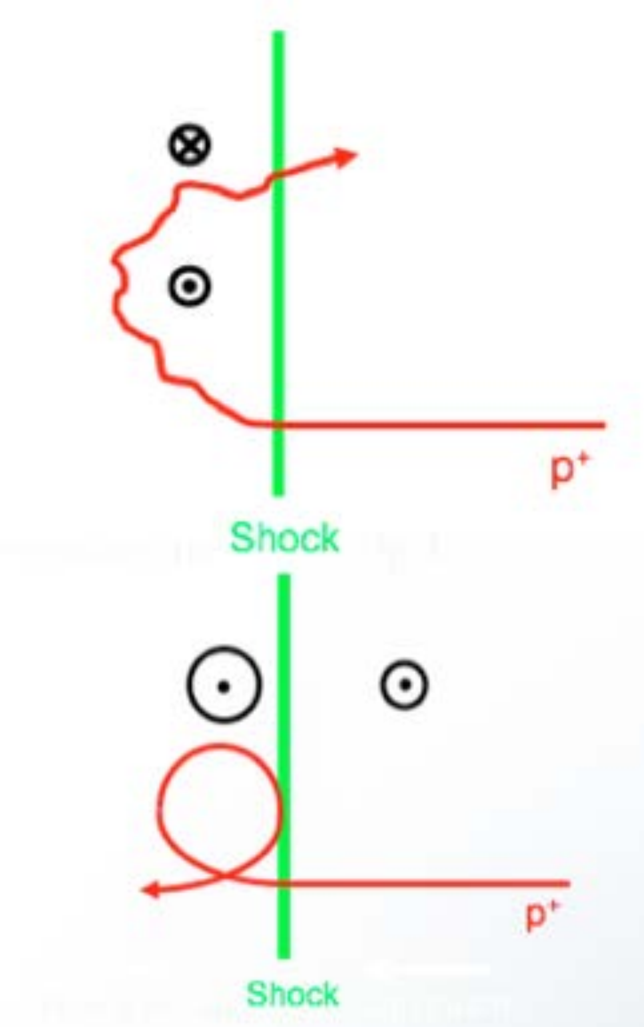


Filamentary B fields are created

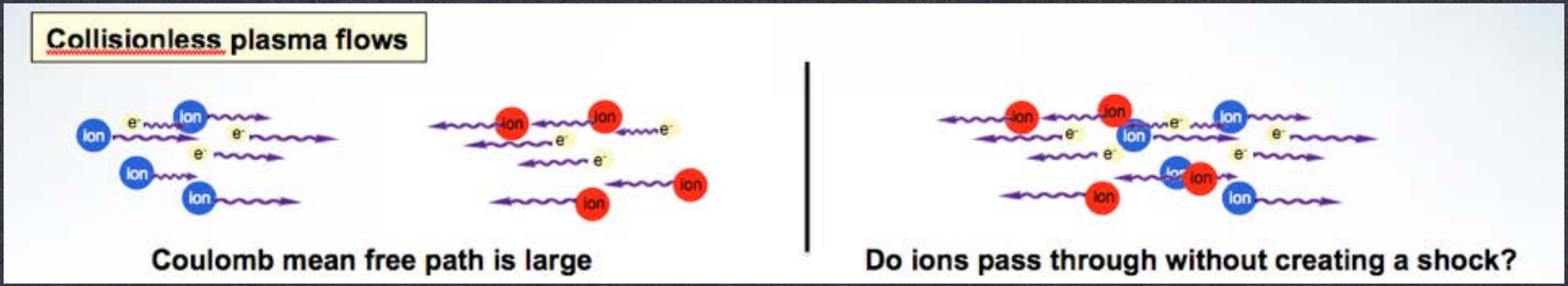
Two main mechanisms for creating collisionless shocks:

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



How collisionless shocks work



Collisionless plasma flows

Coulomb mean free path is large

Do ions pass through without creating a shock?

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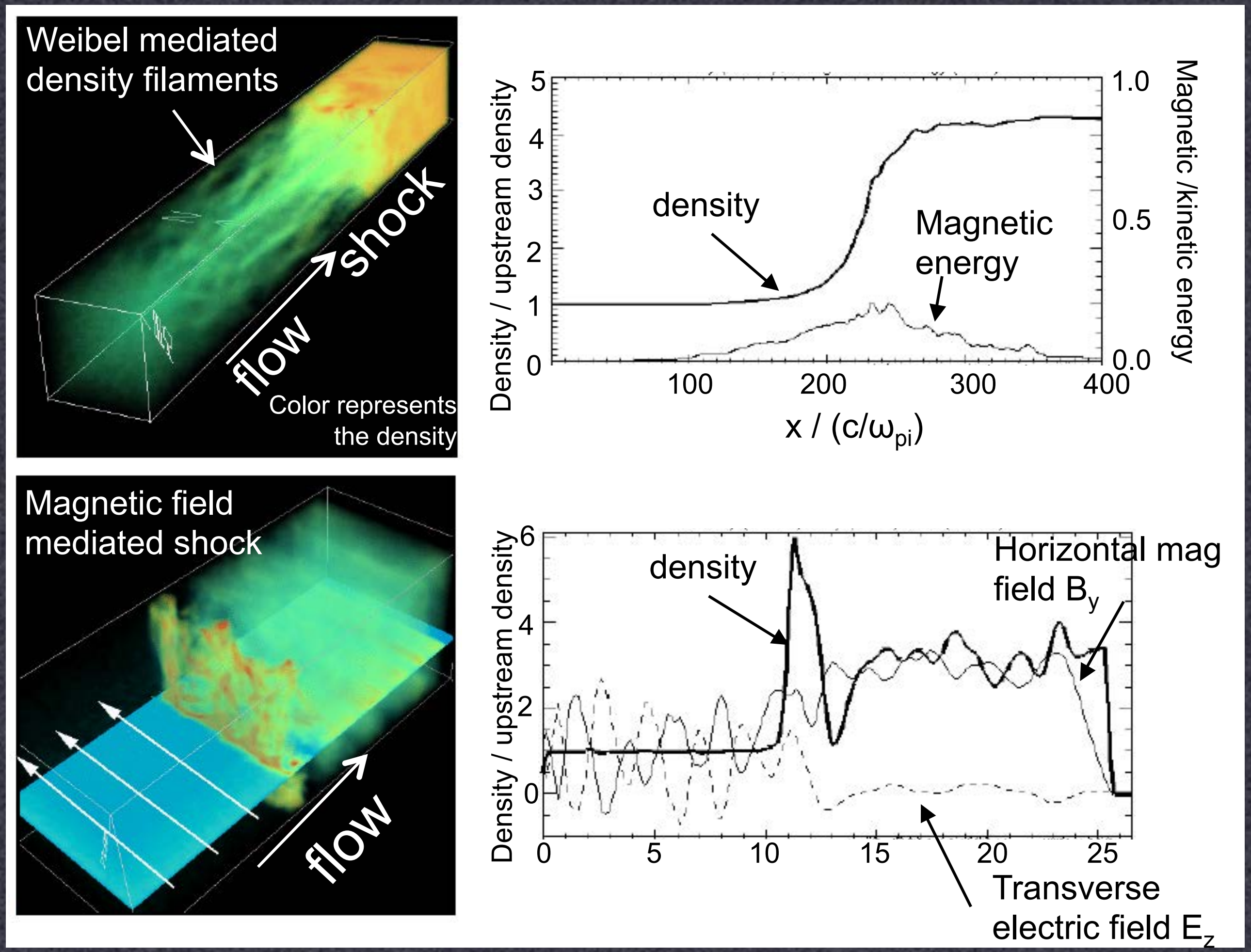
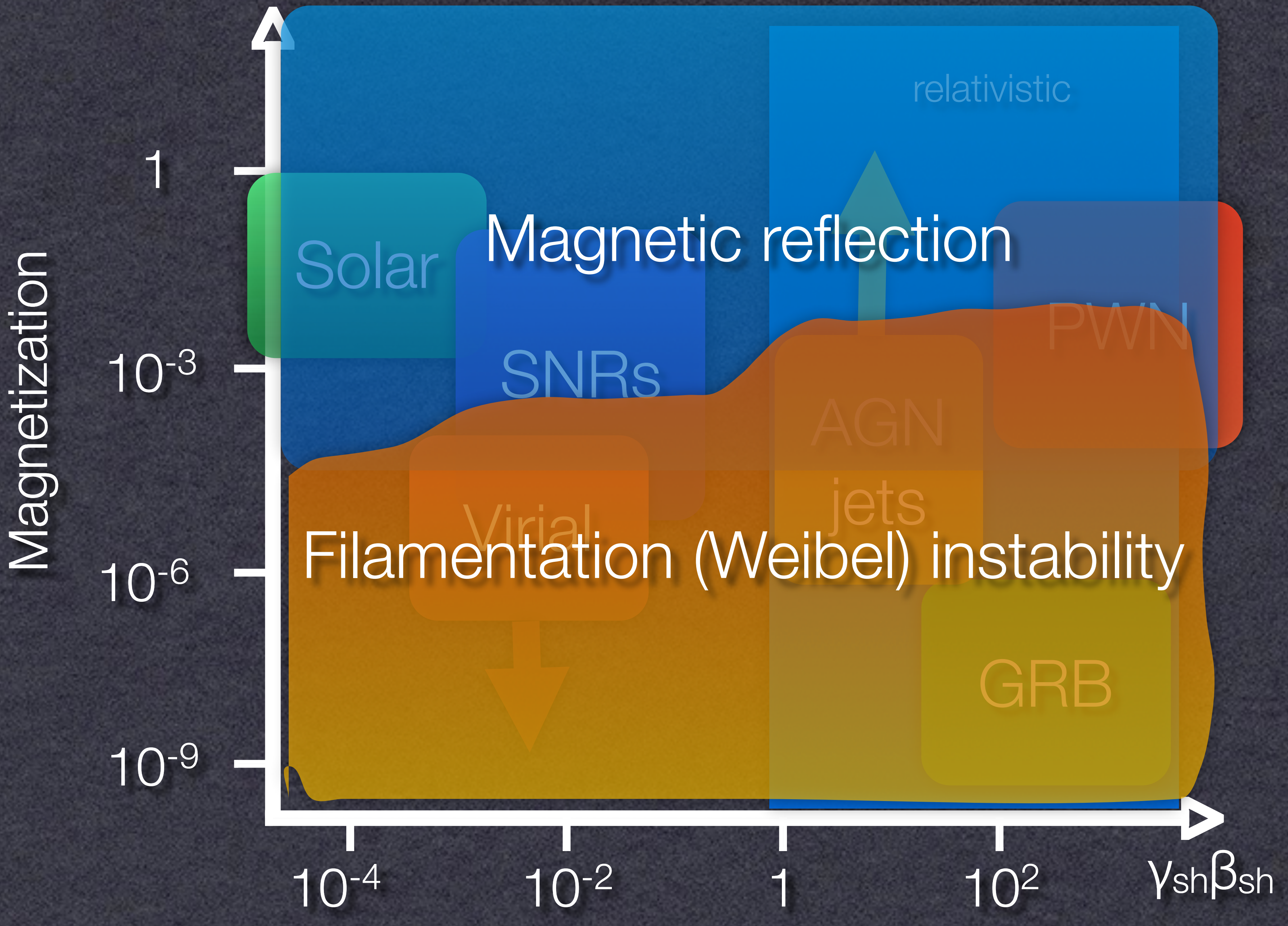
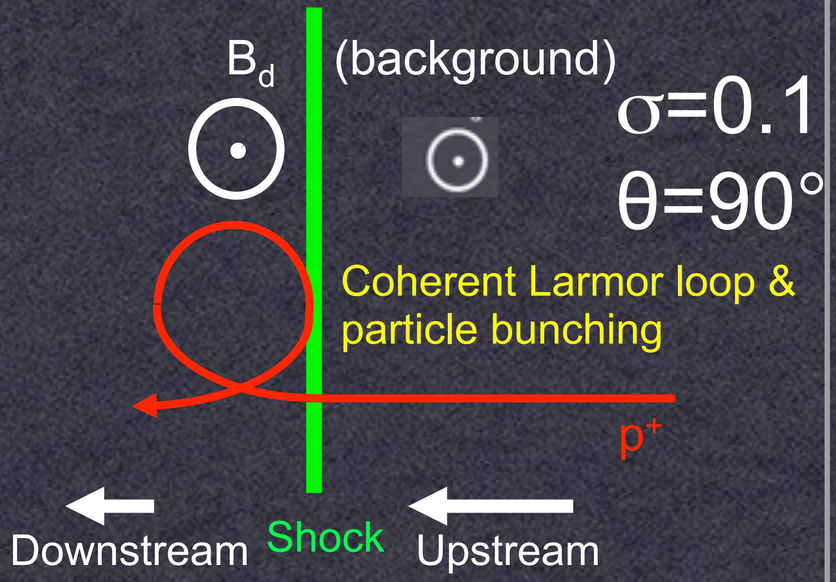
Spitkovsky (2005)

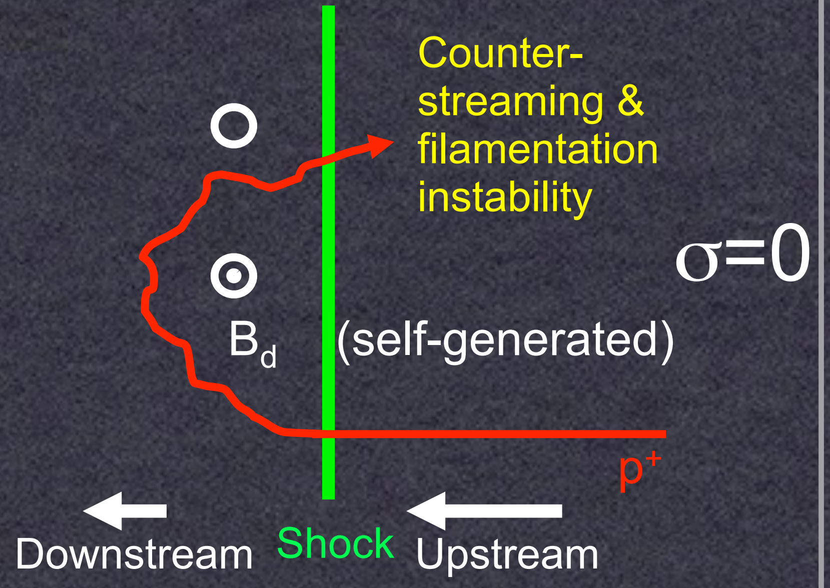


Parameter Space of shocks

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

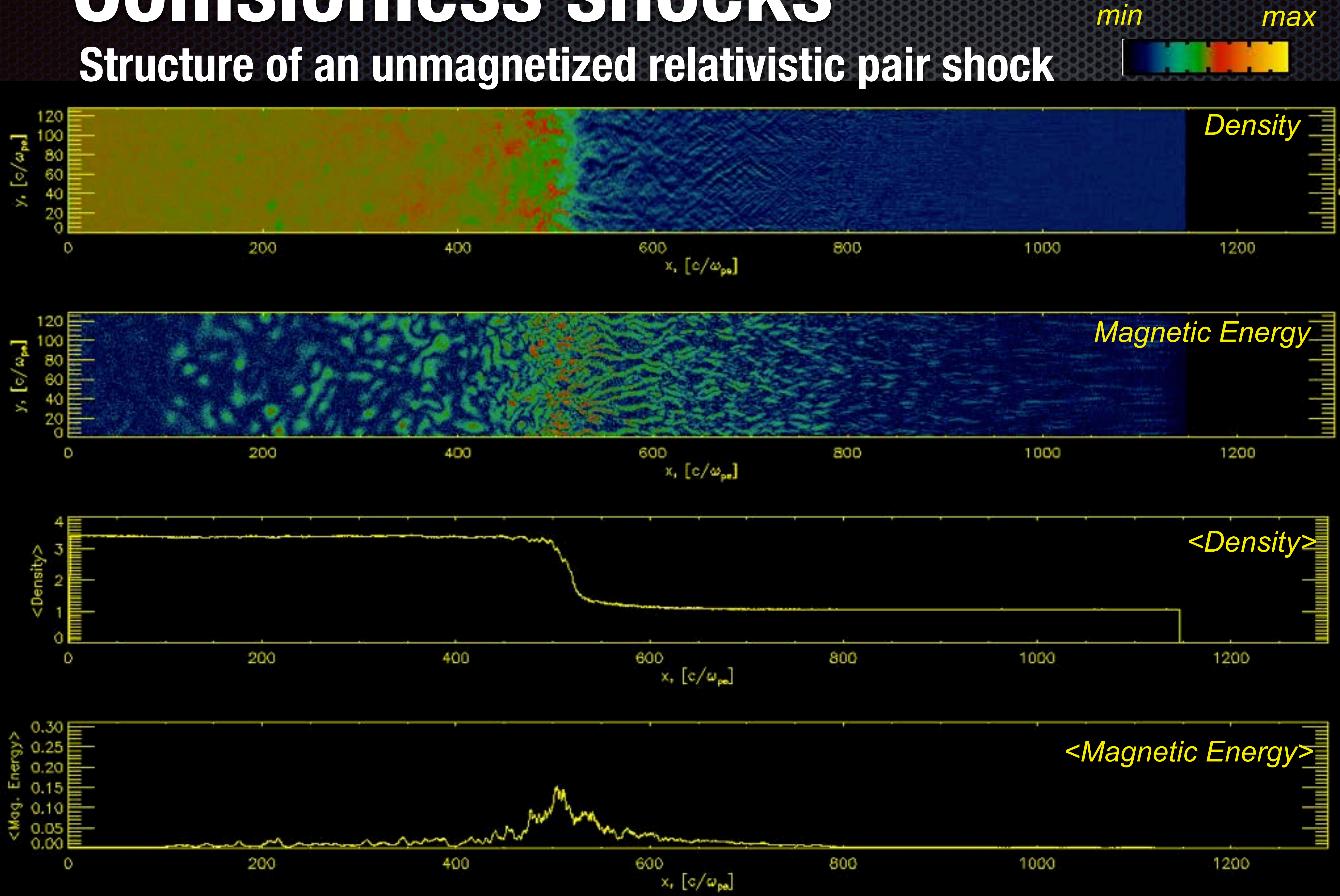






Collisionless shocks

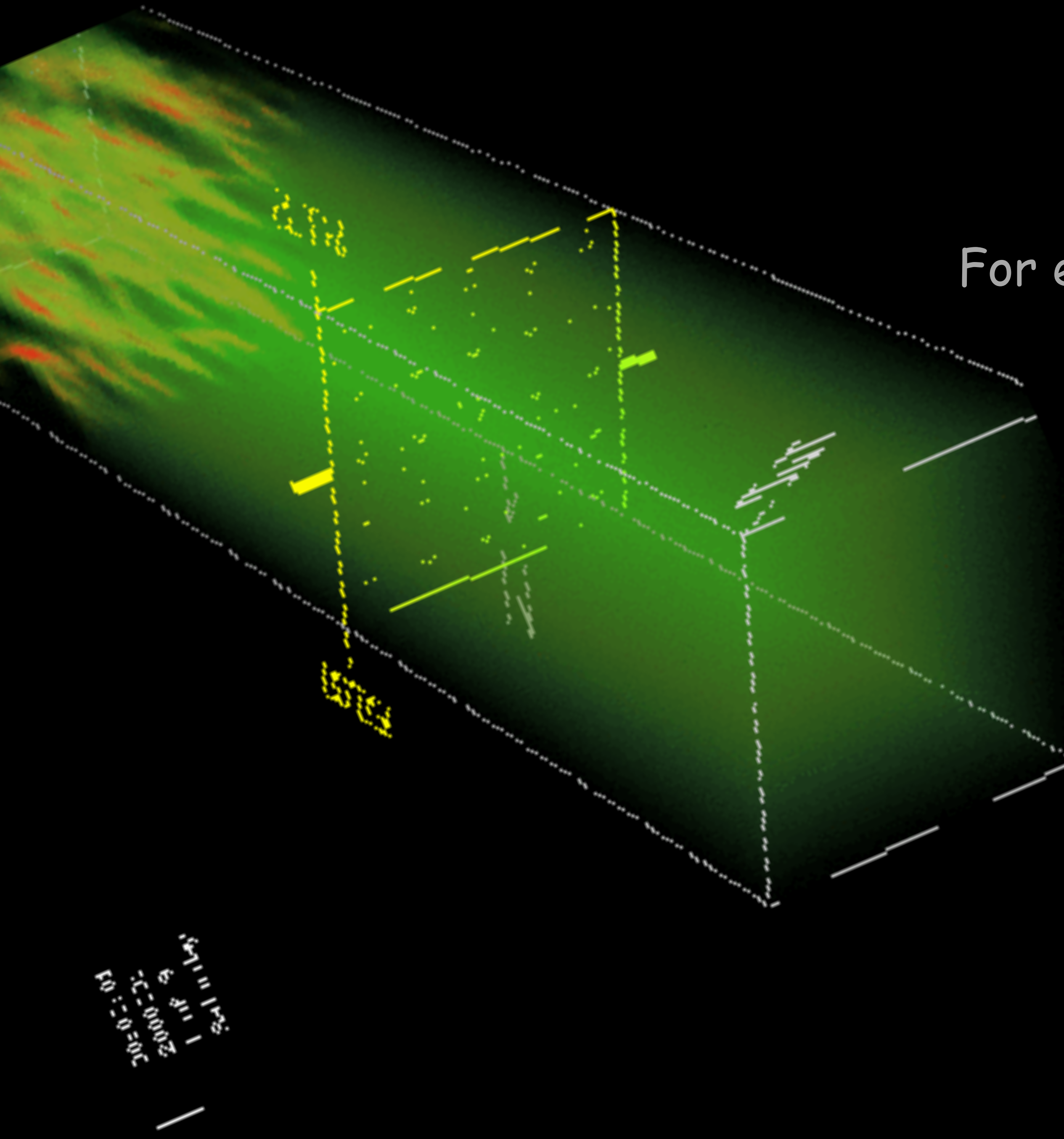
Structure of an unmagnetized relativistic pair shock



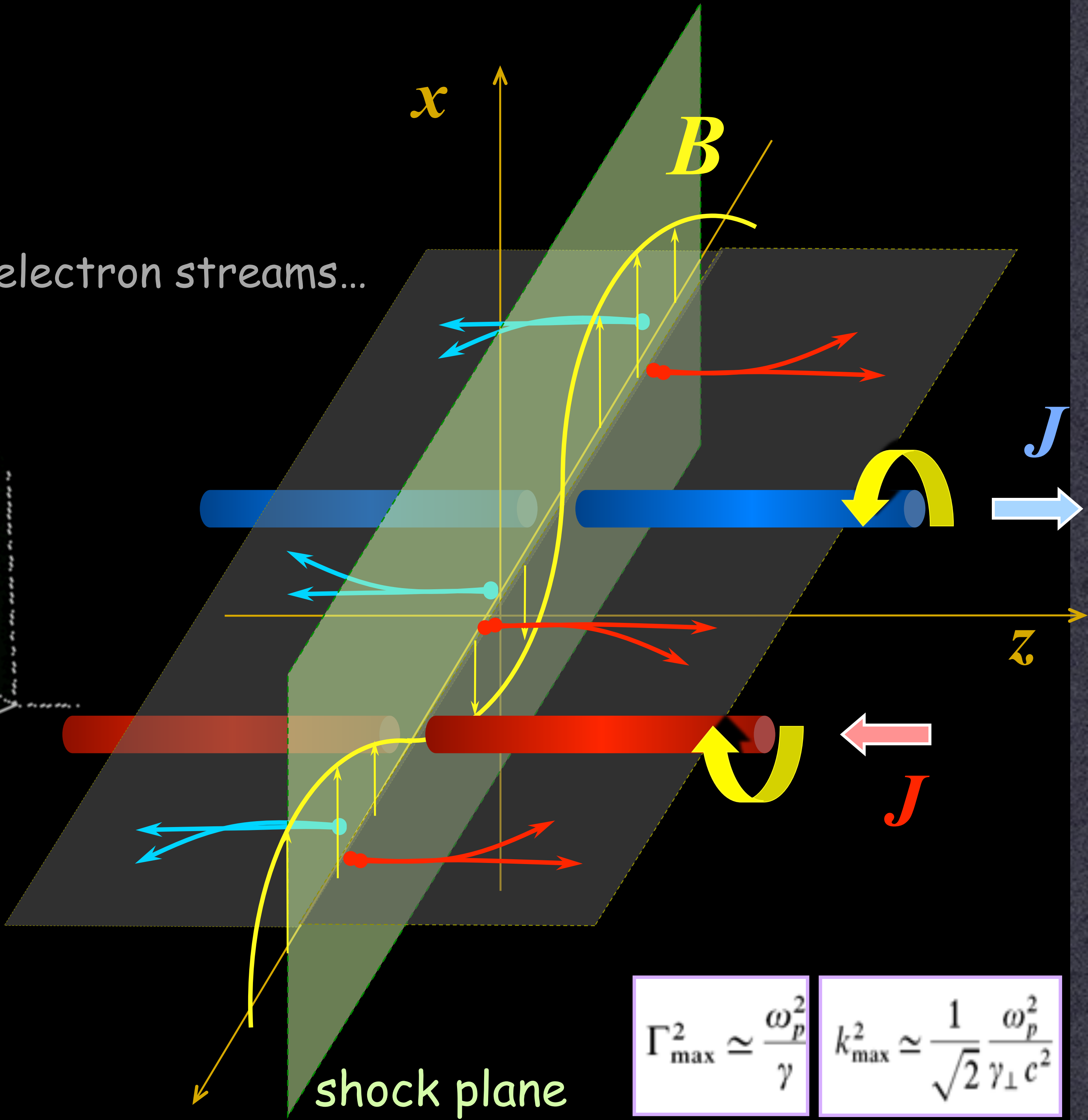
Weibel instability

growth of field from skin-depth scale by current filament mergers

(Medbedev & Loeb, 1999, ApJ)



For electron streams...



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

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

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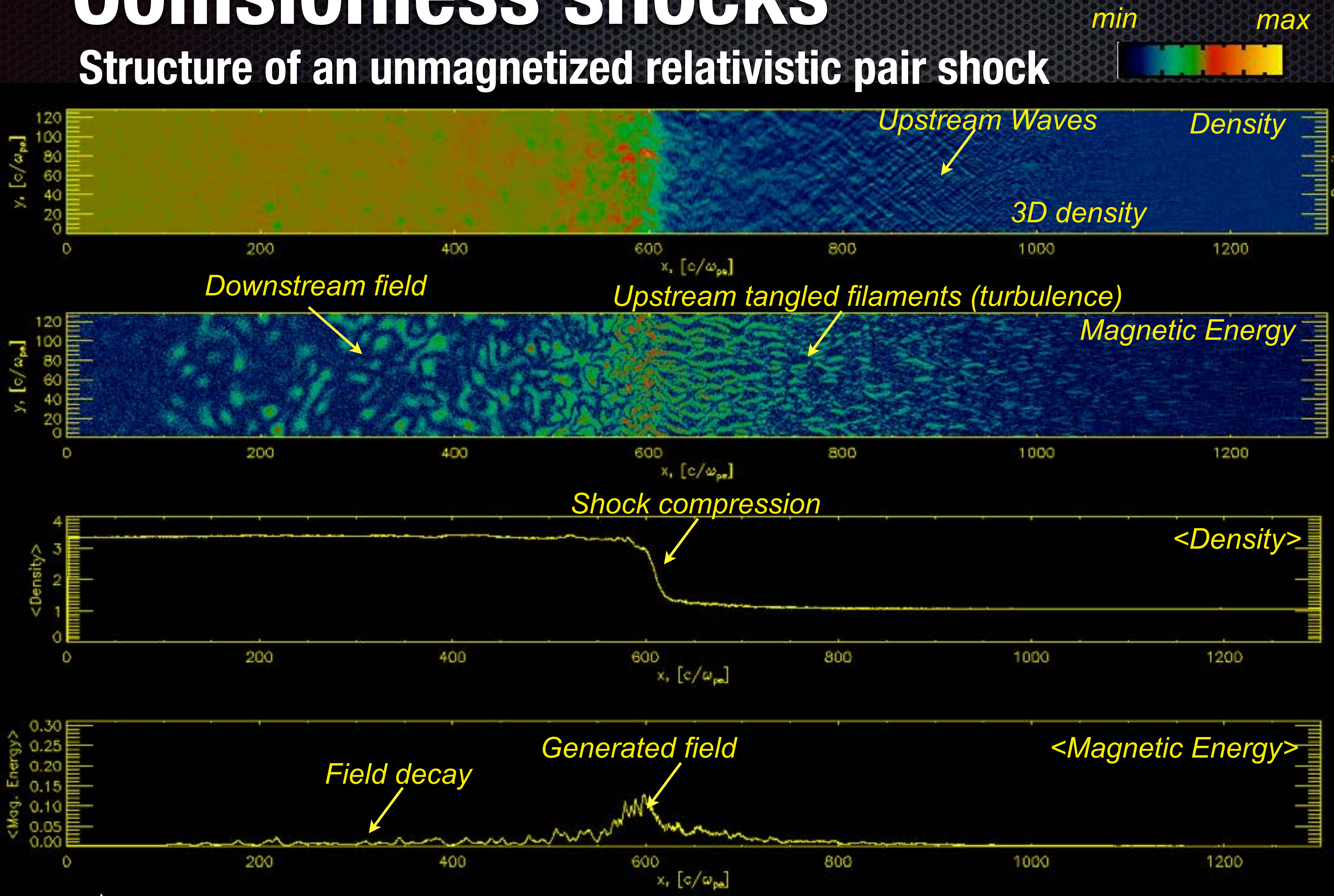


Upstream Waves

Density

3D density

Downstream field

Upstream tangled filaments (turbulence)

Magnetic Energy

Shock compression

<Density>

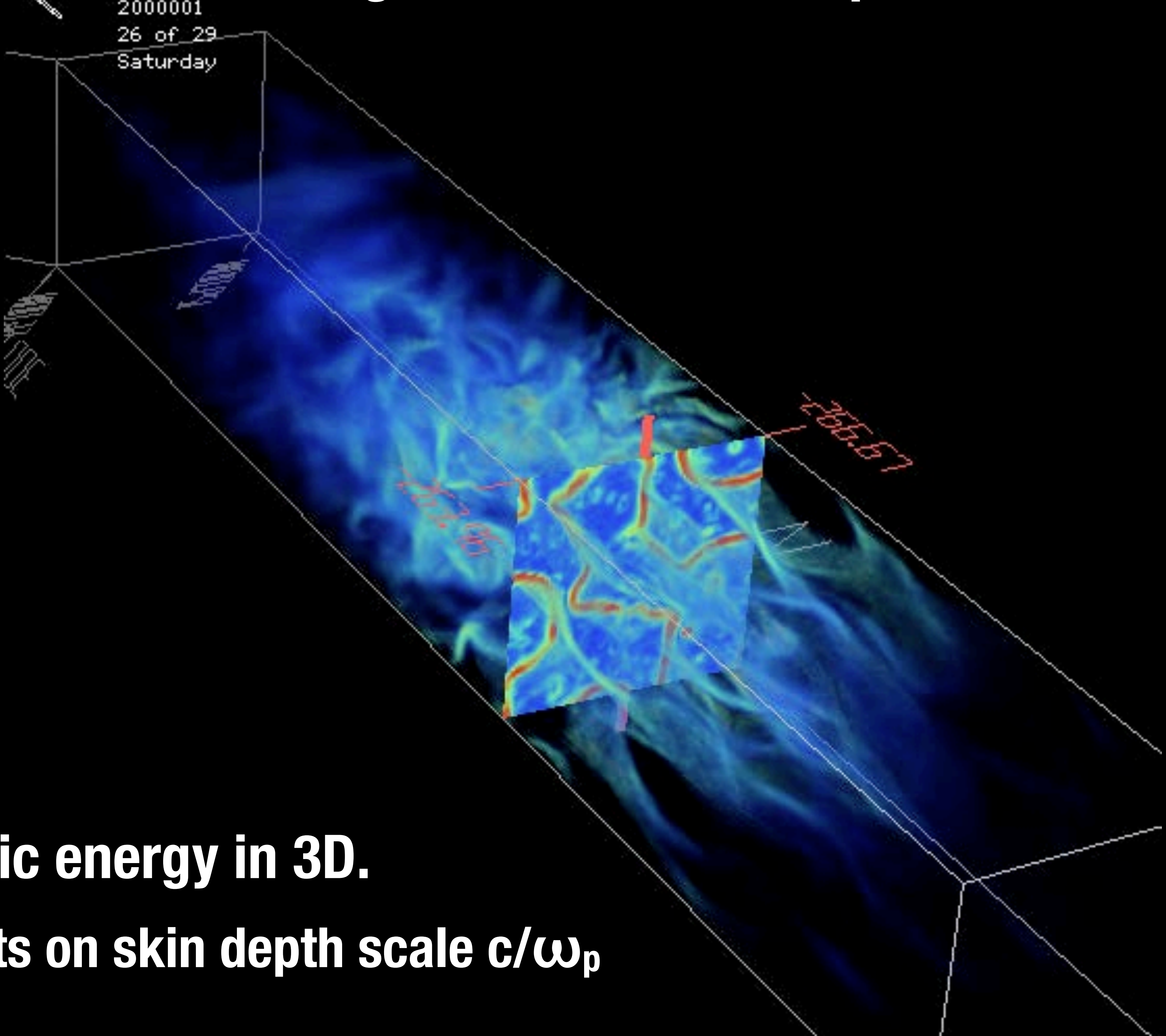
Generated field

Field decay

<Magnetic Energy>

Collisionless shocks

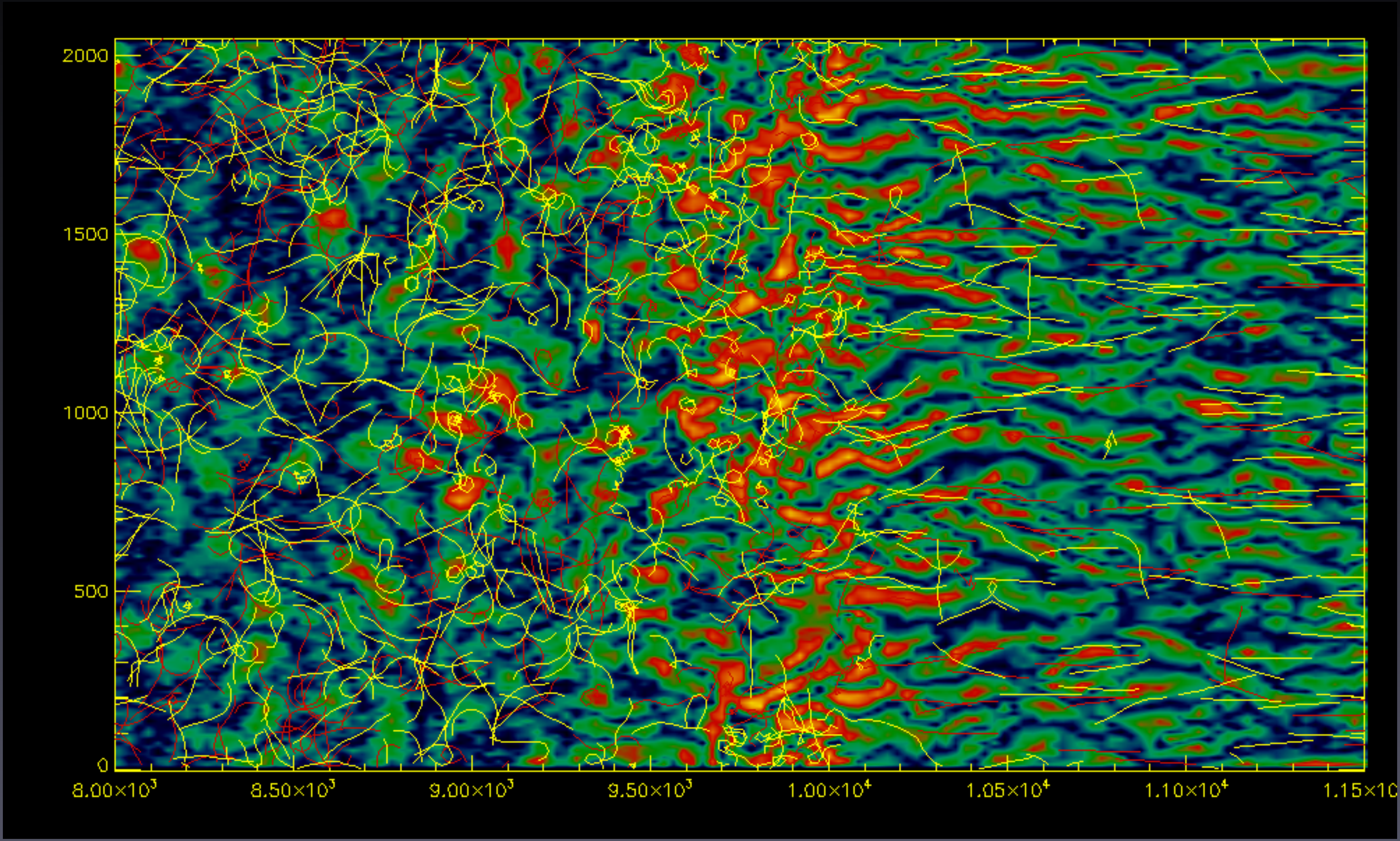
Structure of an unmagnetized relativistic pair shock



Magnetic energy in 3D.

Filaments on skin depth scale c/ω_p

Unmagnetized pair shock: particle trajectories

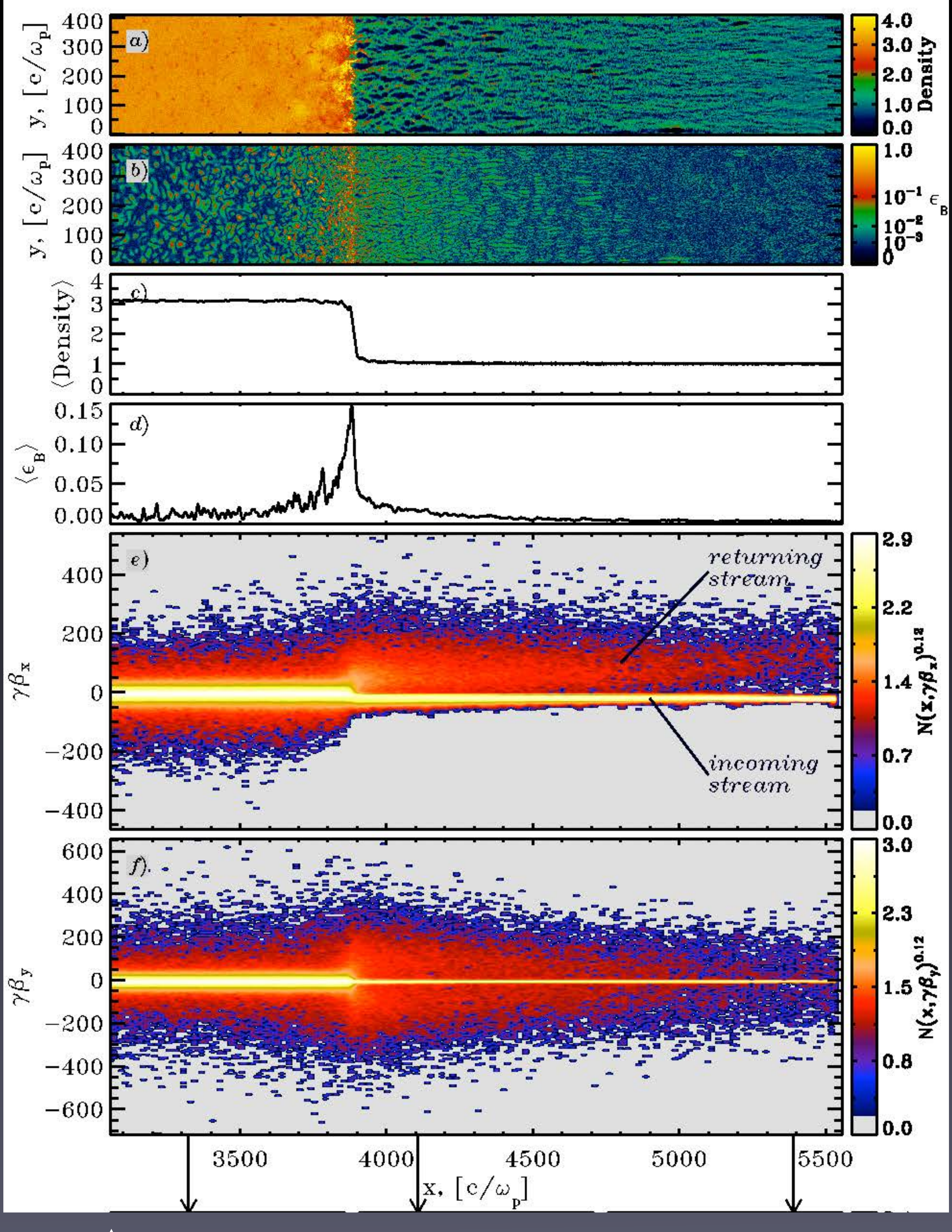


color: magnetic energy density

Unmagnetized shock:

shock is driven by returning particle precursor (CR!)

Steady counterstreaming leads to self-replicating shock structure



x- px momentum space

x- py momentum space

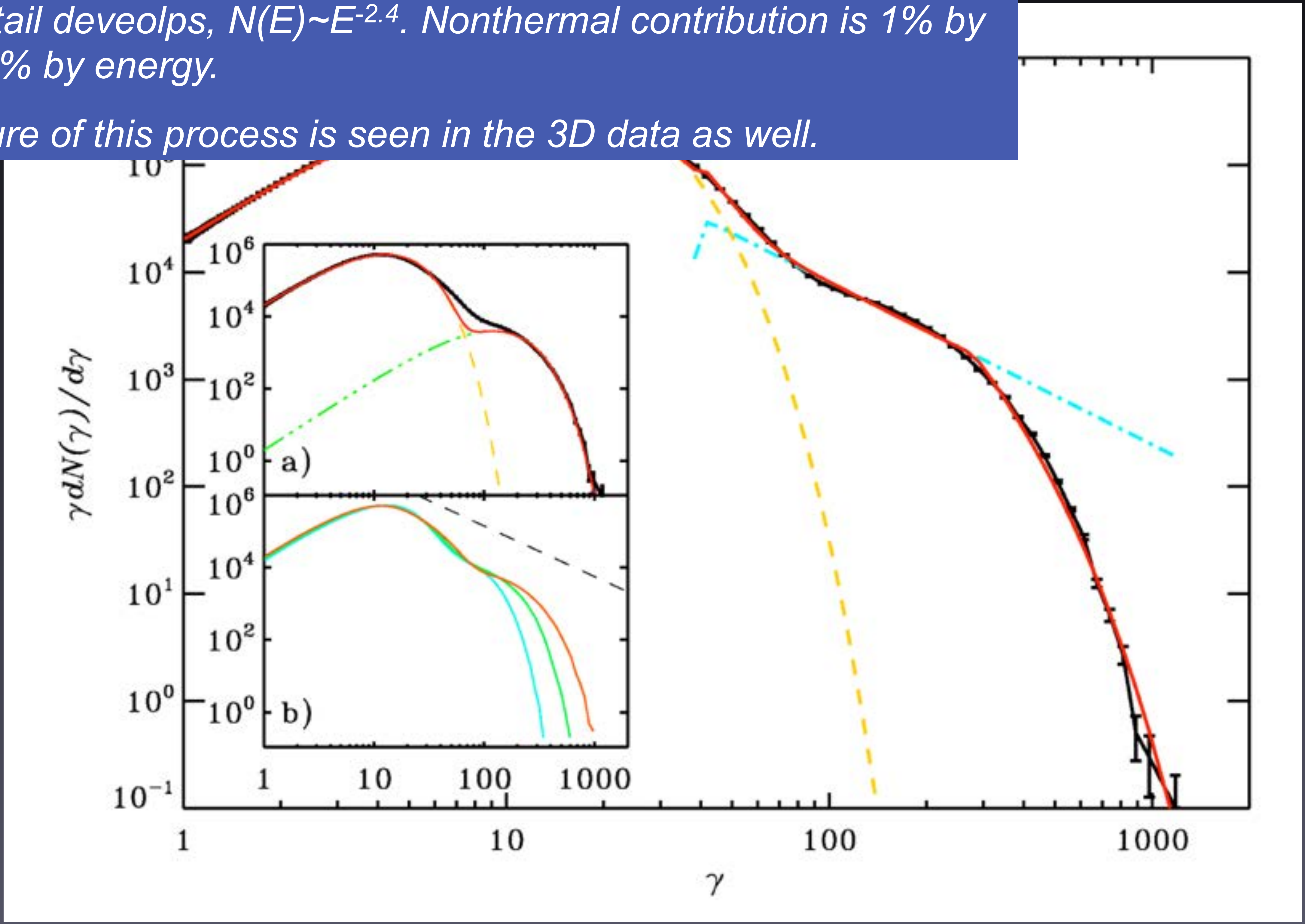
Shock structure for $\sigma=0$ (AS '08)

Unmagnetized pair shock:

downstream spectrum: development of nonthermal tail!

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

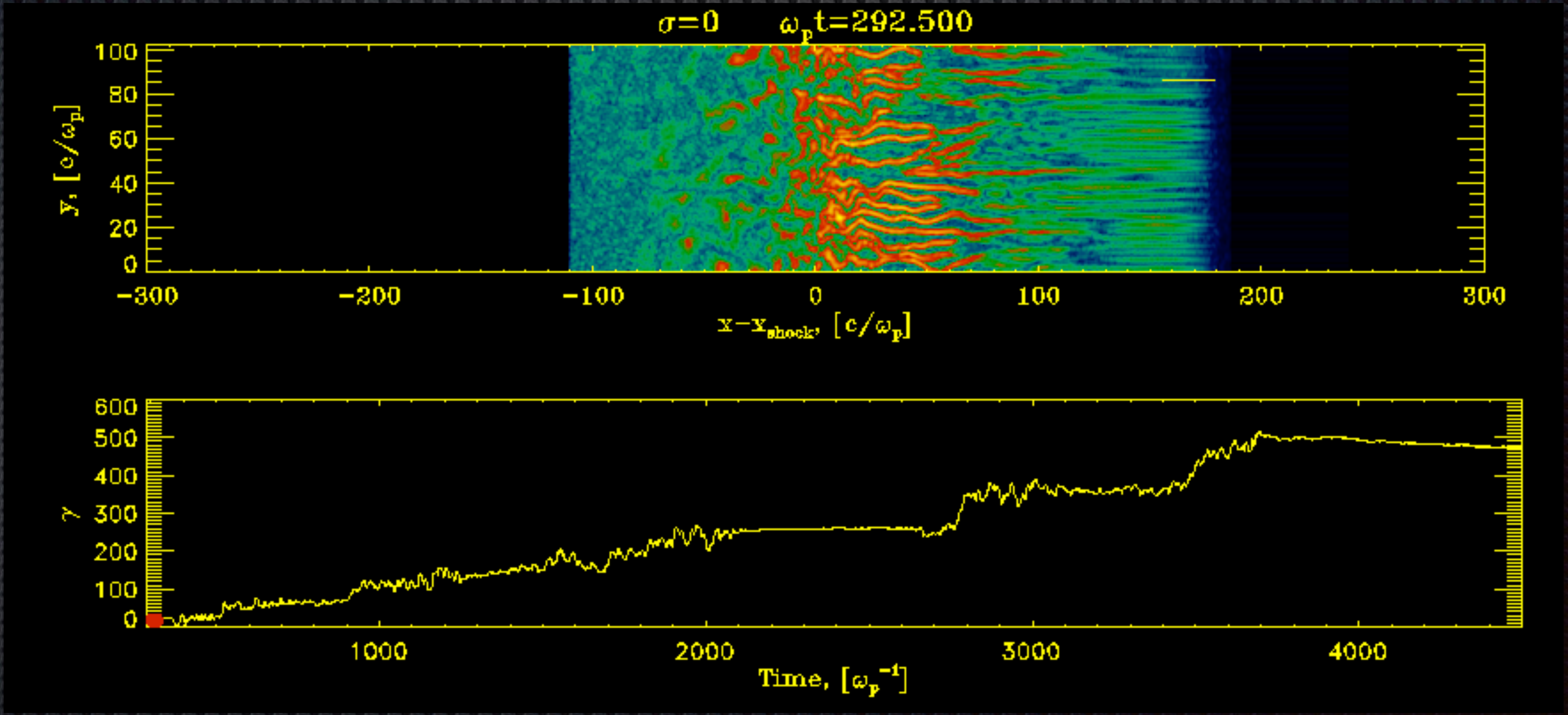
Early signature of this process is seen in the 3D data as well.



A.S. (2008)

Particle acceleration

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

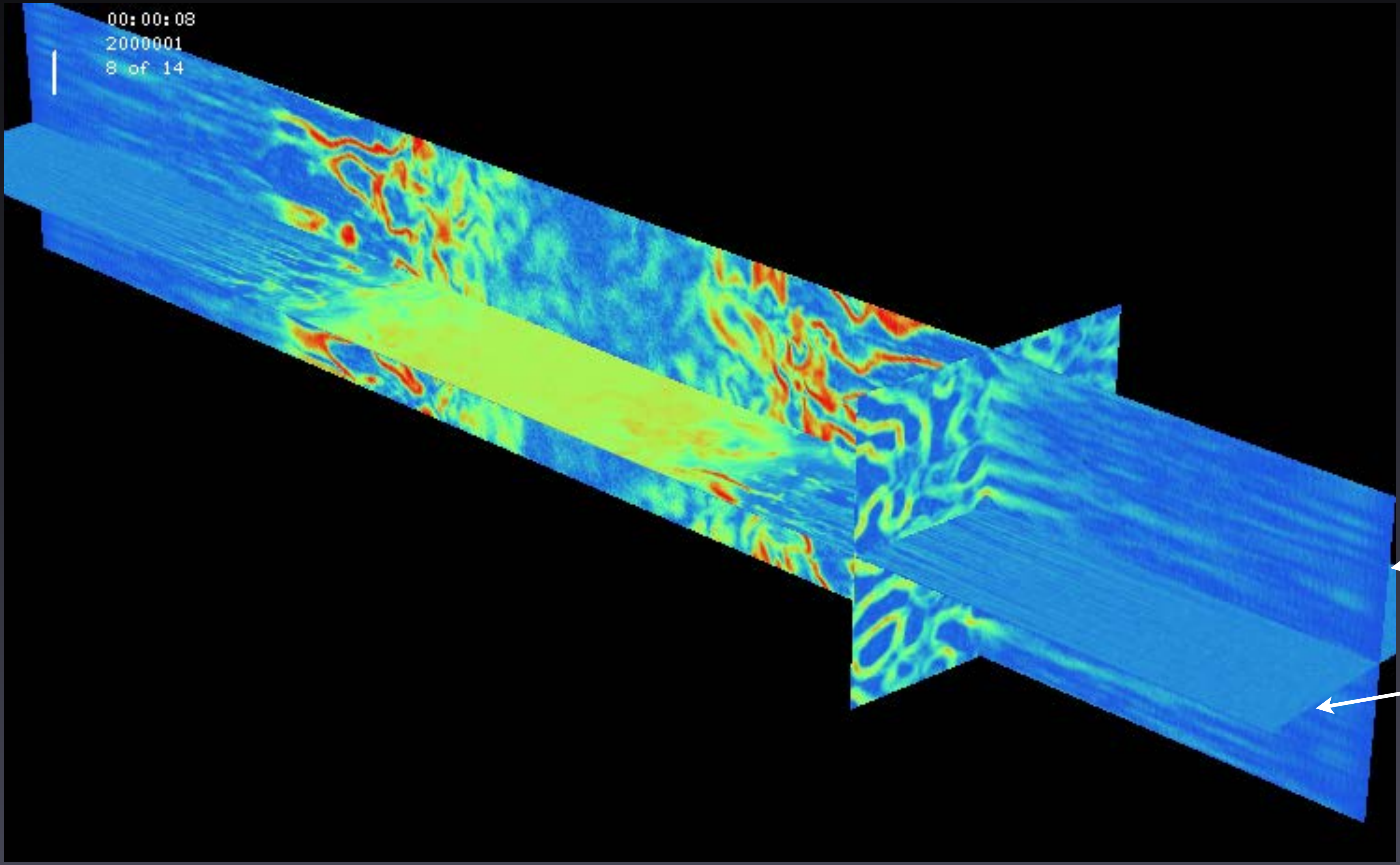


Magnetic filaments

Particle energy

Transition between magnetized and unmagnetized shocks:

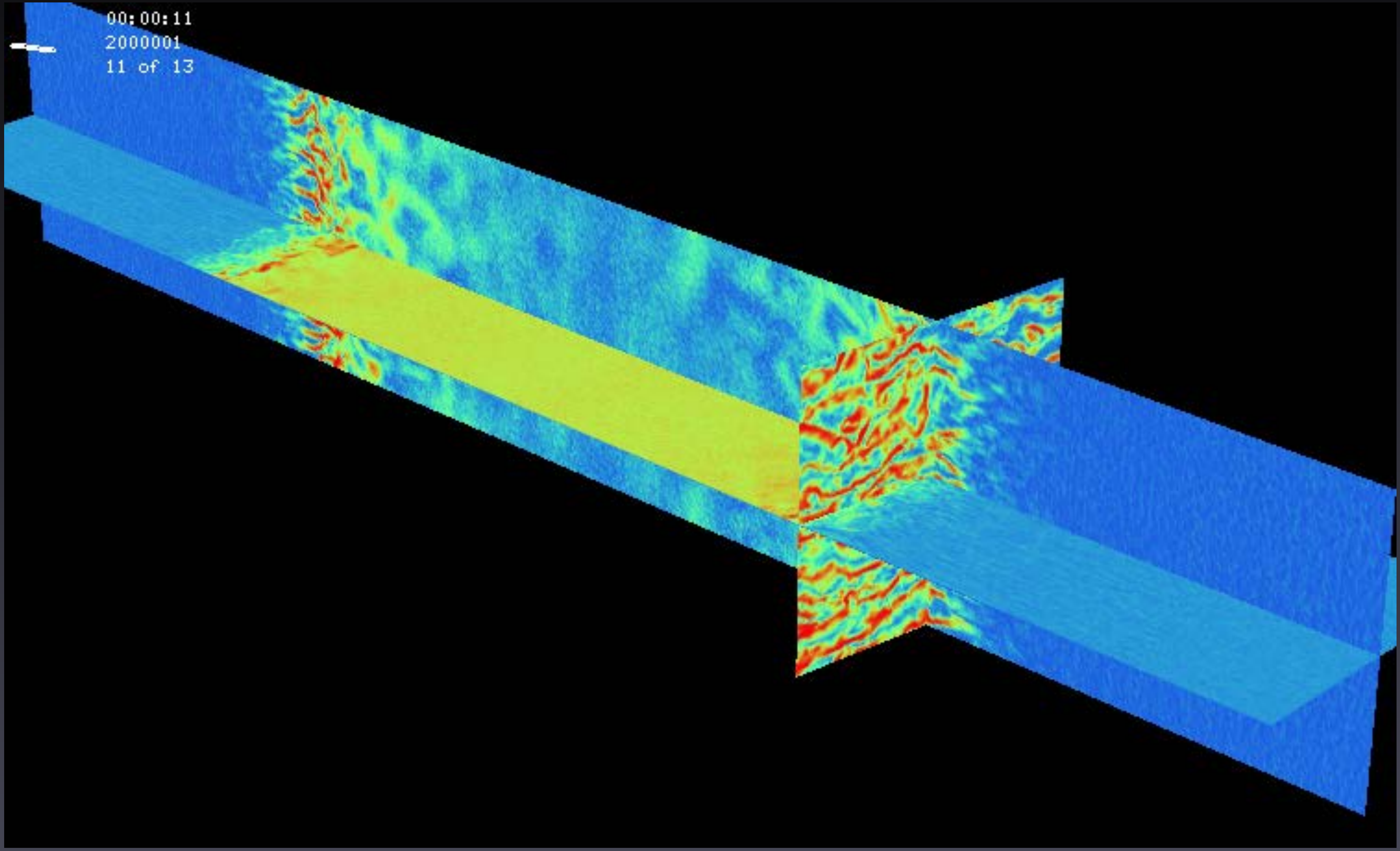
$\sigma=0$



Magnetic energy

Density

Transition between magnetized and unmagnetized shocks:

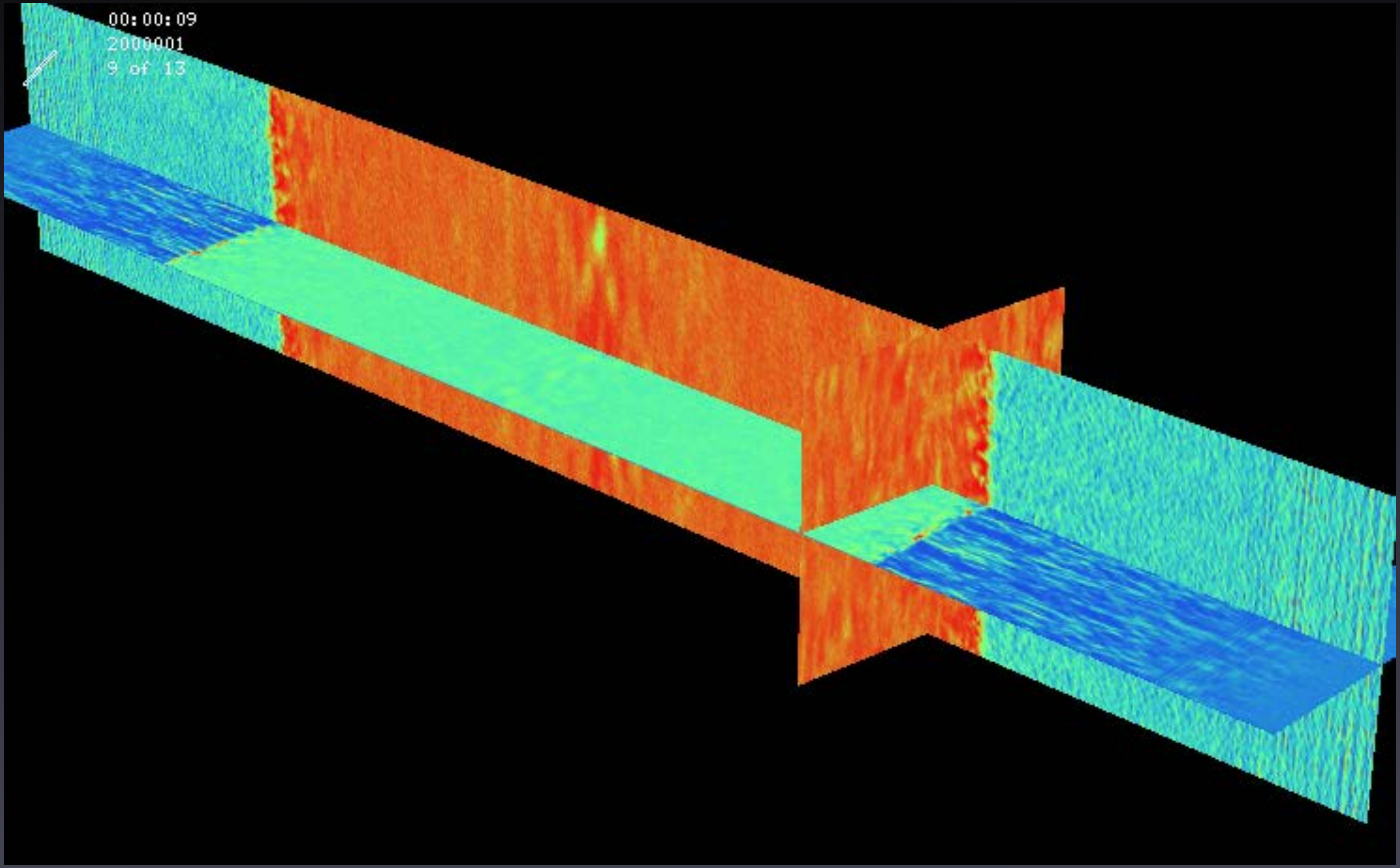


$\sigma=10^{-3}$

B field

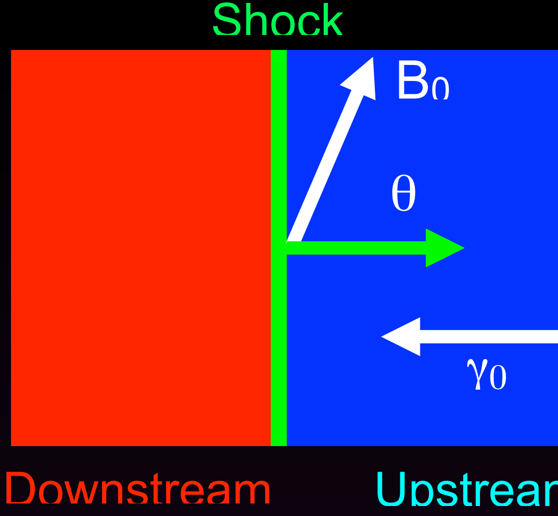
Transition between magnetized and unmagnetized shocks:

$\sigma=10^{-1}$



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

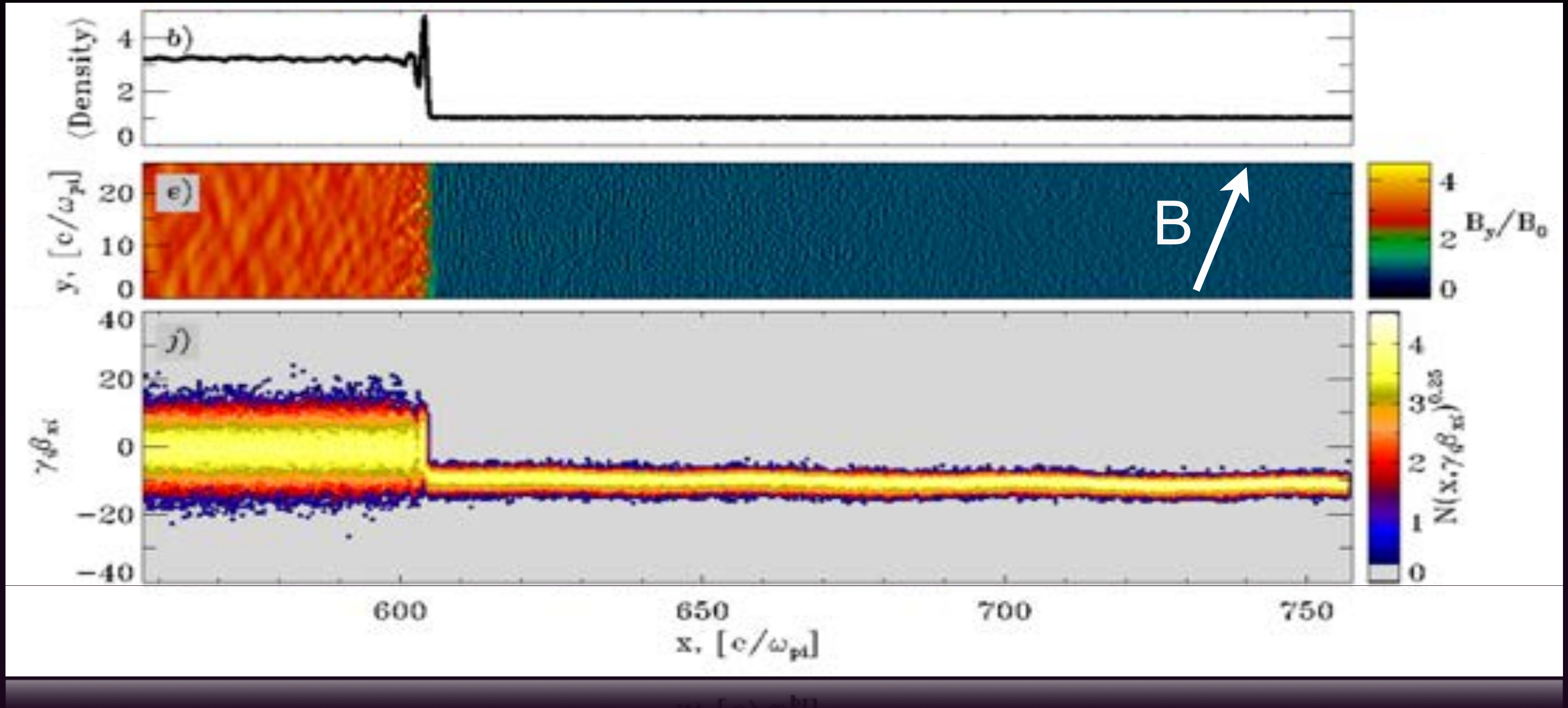
Perpendicular vs parallel shocks



- Quasi-perpendicular shocks: mediated by magnetic reflection

<Density>

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



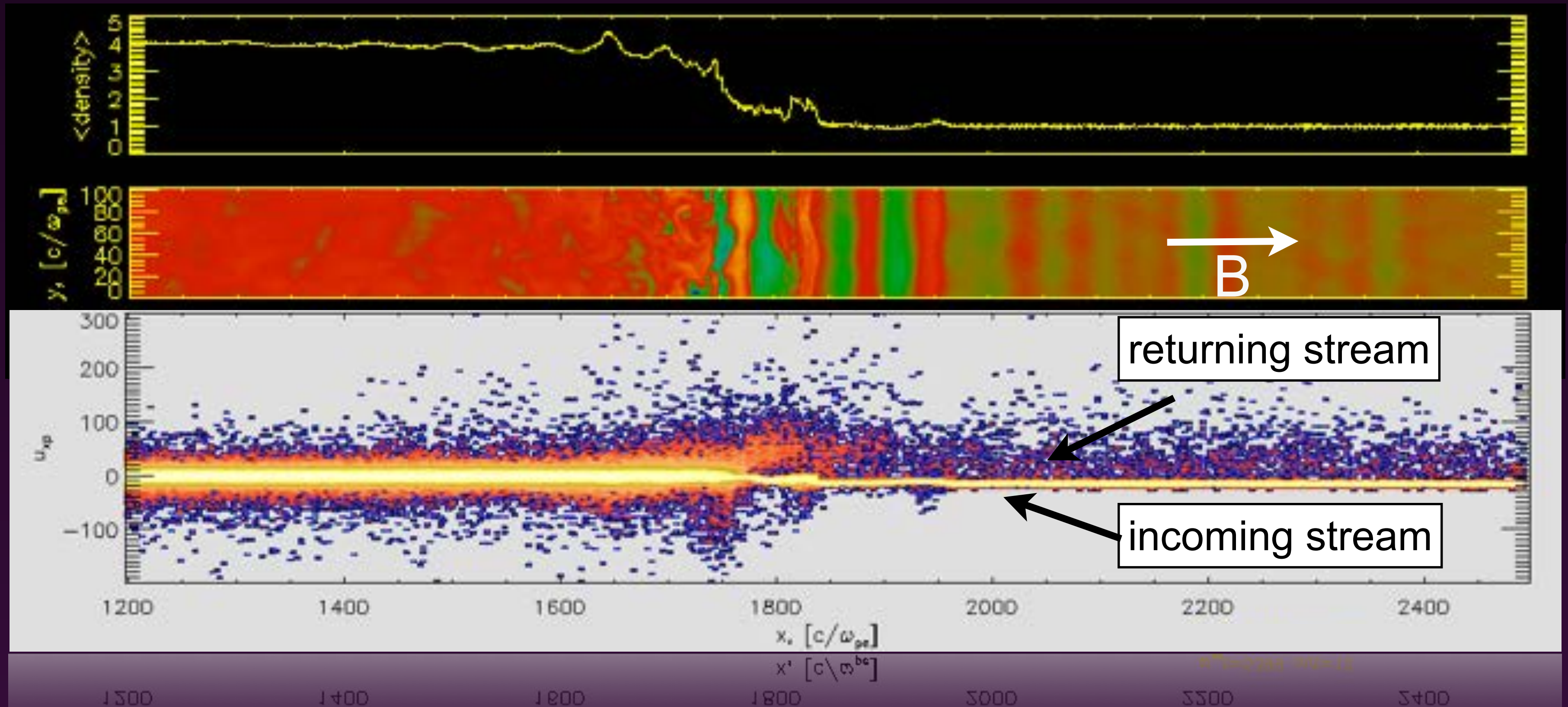
B_y

$\gamma\beta_x$

(Sironi and AS 11)

- Quasi-parallel shocks: instabilities amplify transverse field component

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



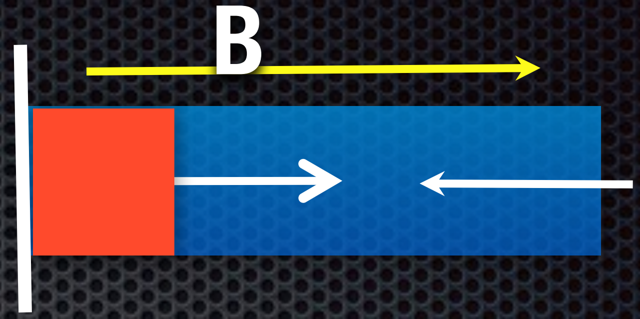
<Density>

B_y

$\gamma\beta_x$

(Sironi & AS 11)

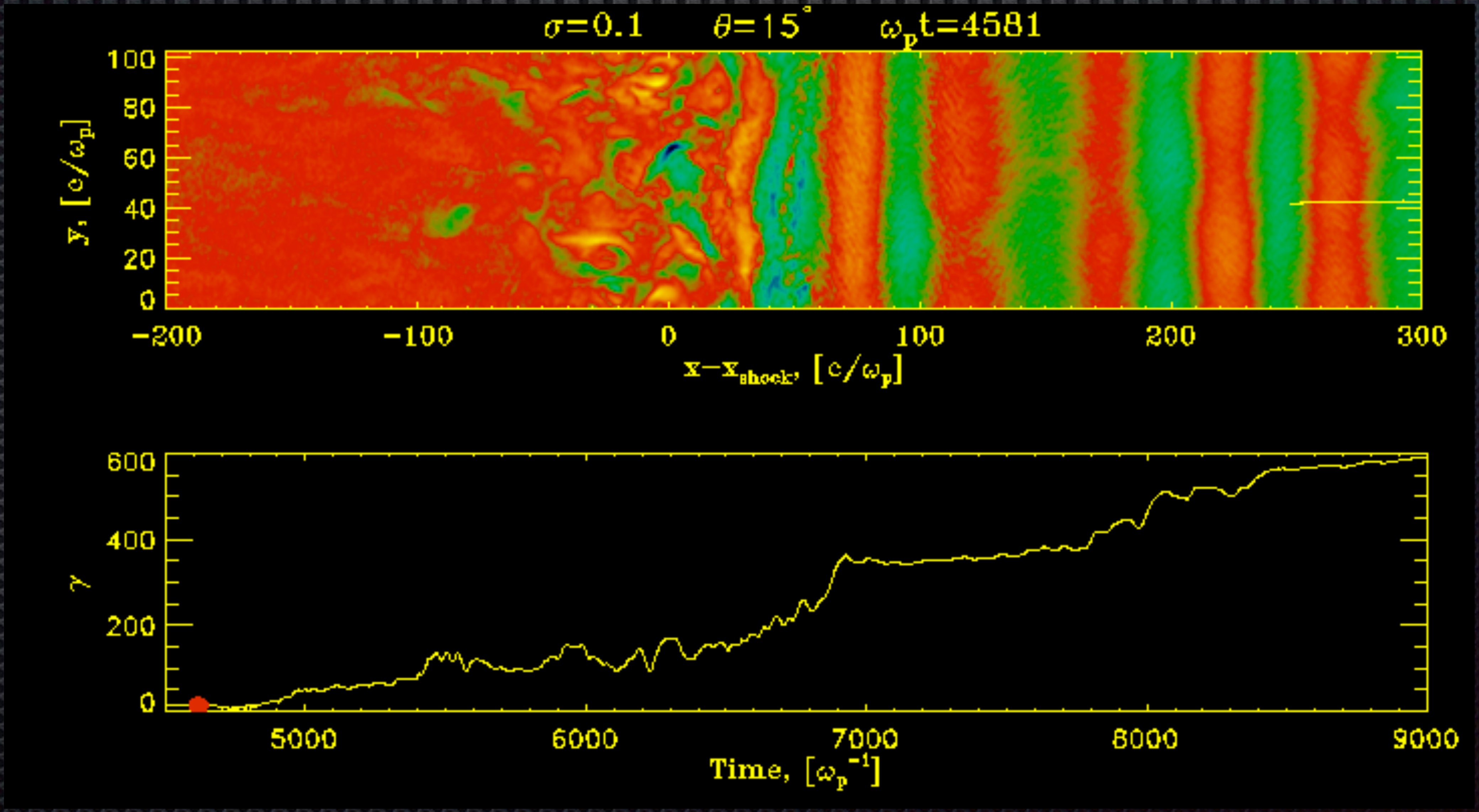
Particle acceleration



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

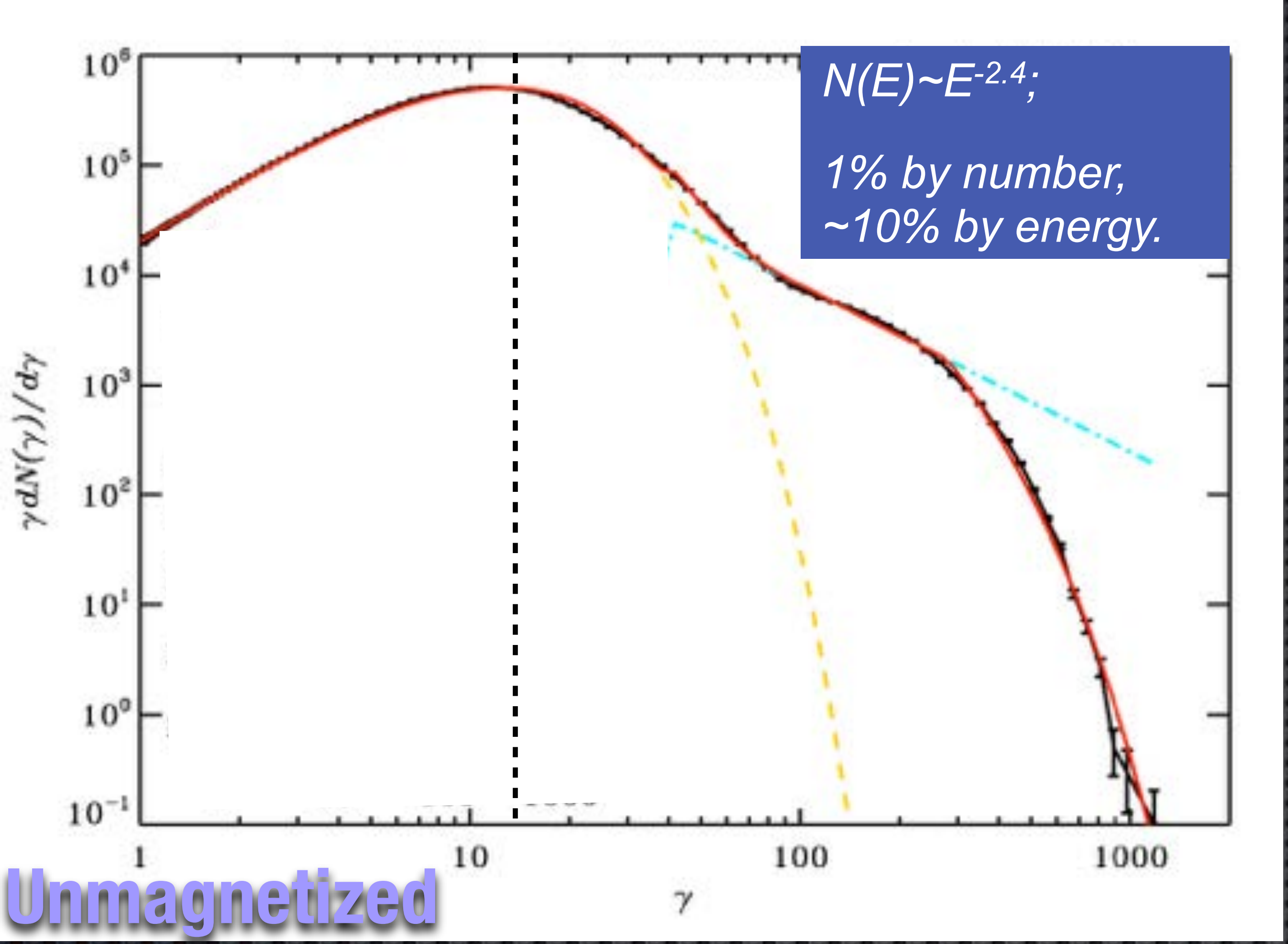
Magnetic energy

Particle energy



Particle acceleration: pairs

Sironi & AS 09



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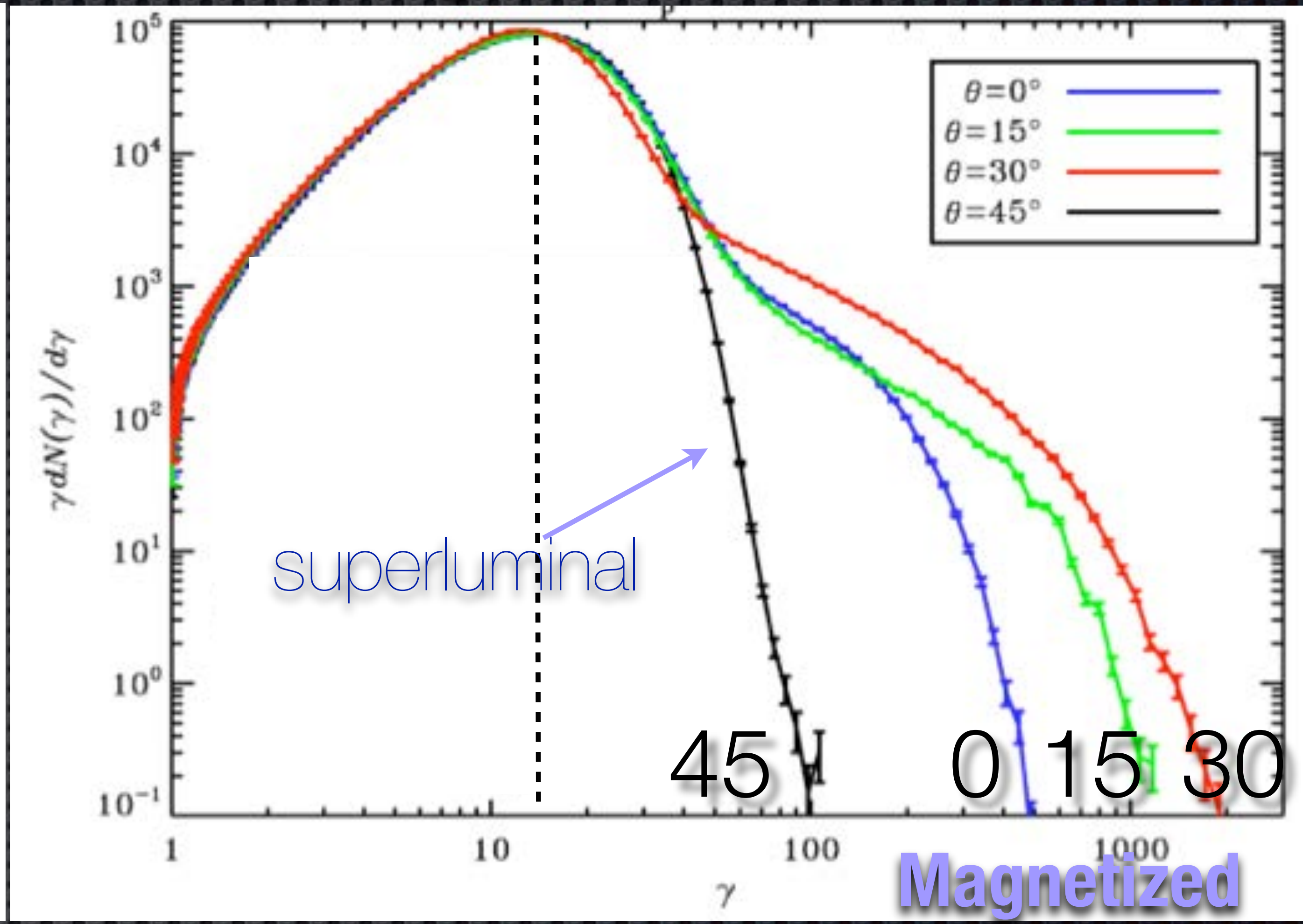
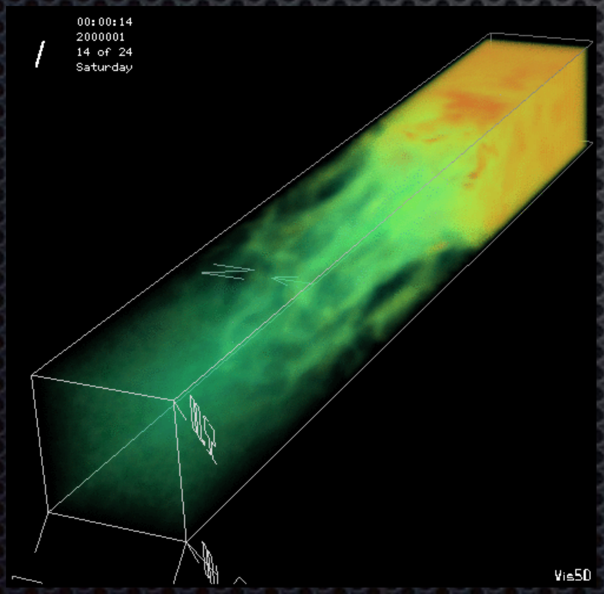
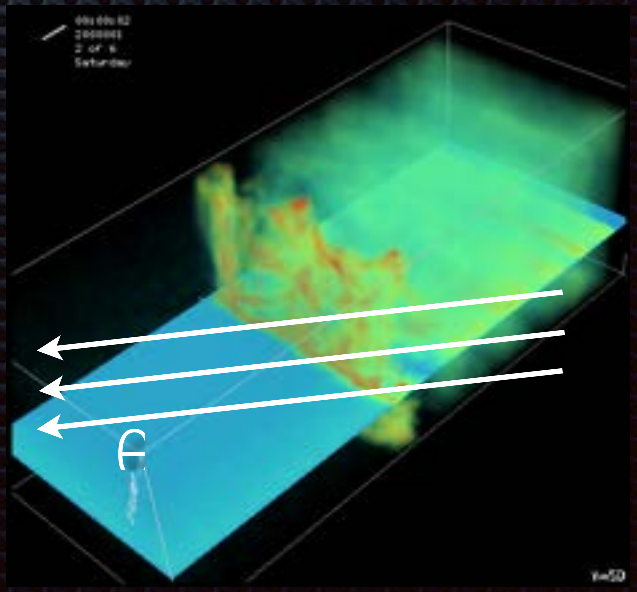


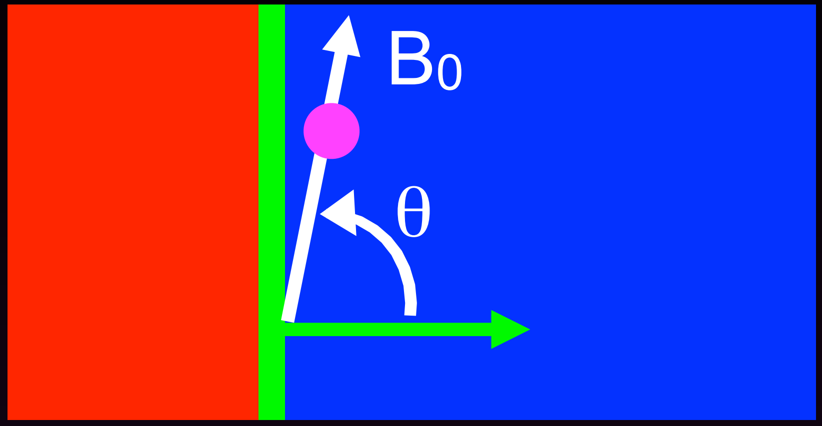


Conditions for acceleration in relativistic shocks:

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



Superluminal vs subluminal shocks



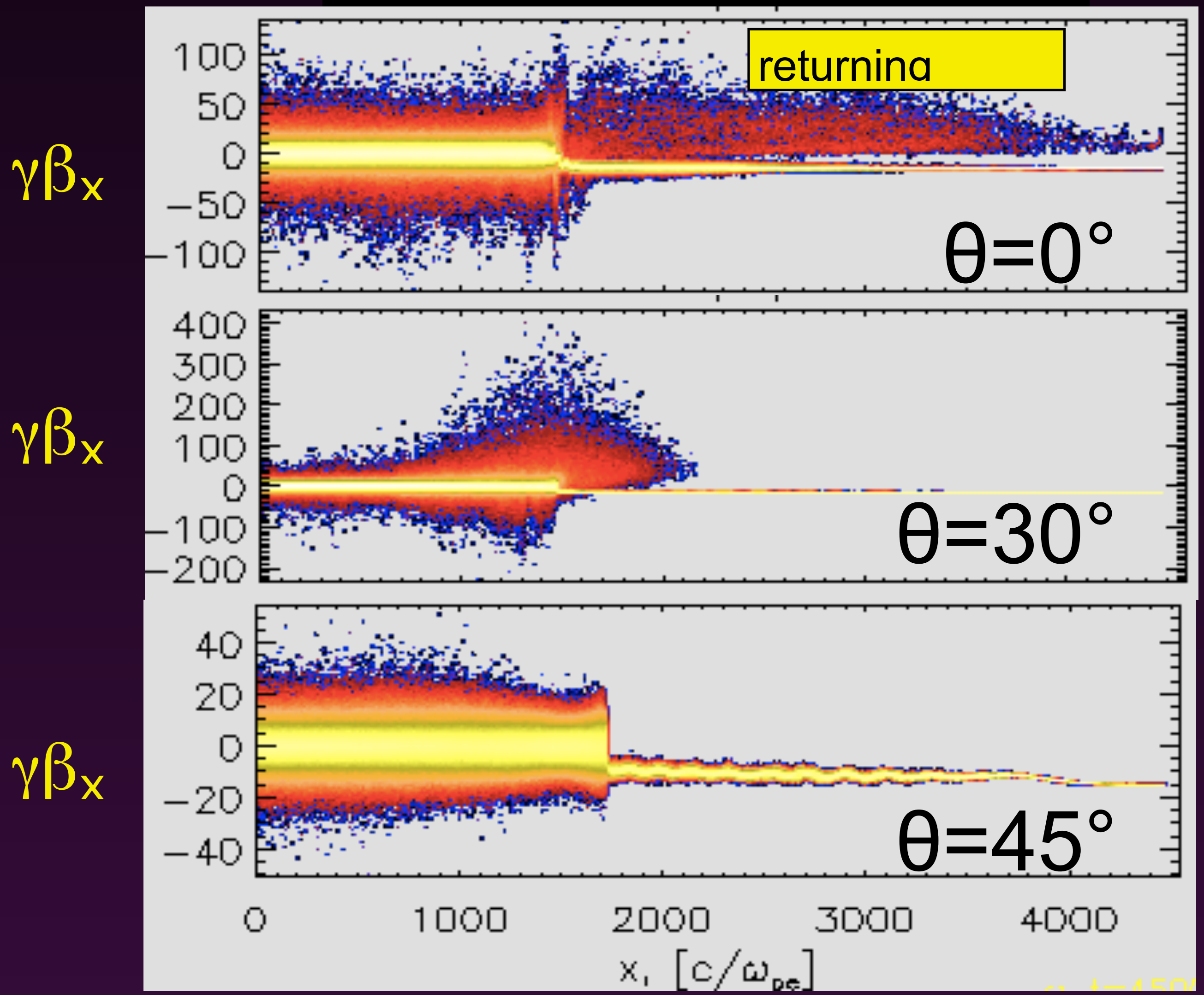
σ is large → particles slide along field lines

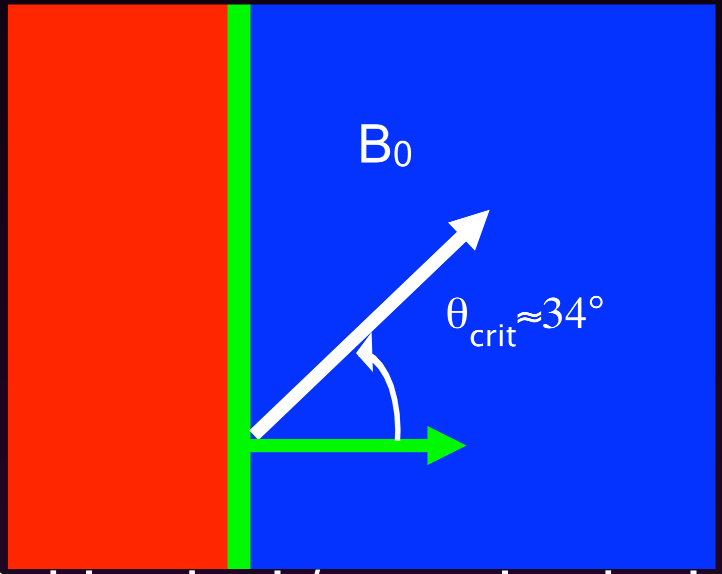
θ is large → particles cannot outrun the shock

unless v>c (“superluminal” shock)

⇒ no returning particles in superluminal shocks

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





Subluminal / superluminal boundary at $\theta \sim 34^\circ$

→ Fermi acceleration should be suppressed

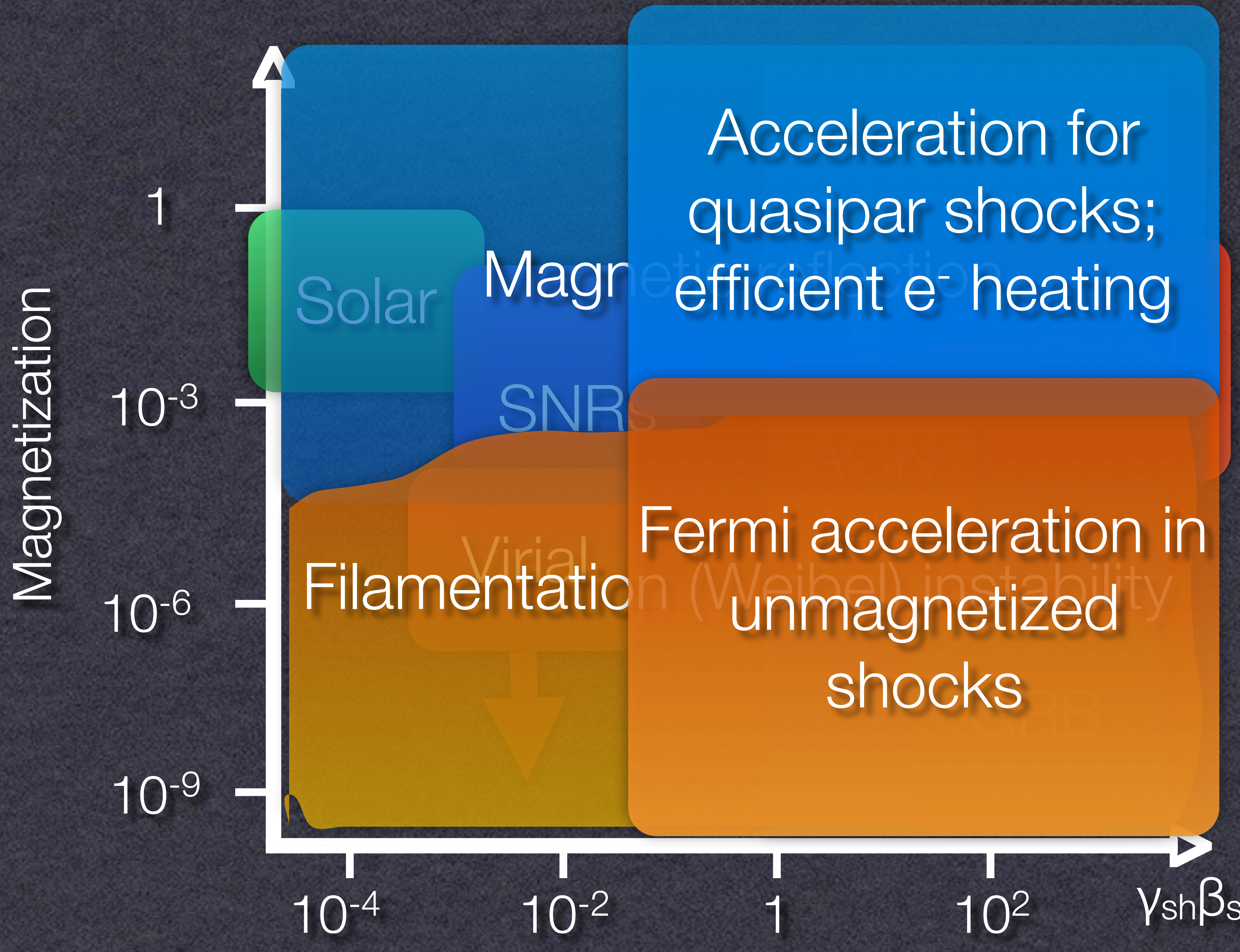
If $\sigma > 10^{-3}$, particle acceleration only for:

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

$\theta' < 34^\circ/\gamma_0 \ll 1$ (upstream frame)

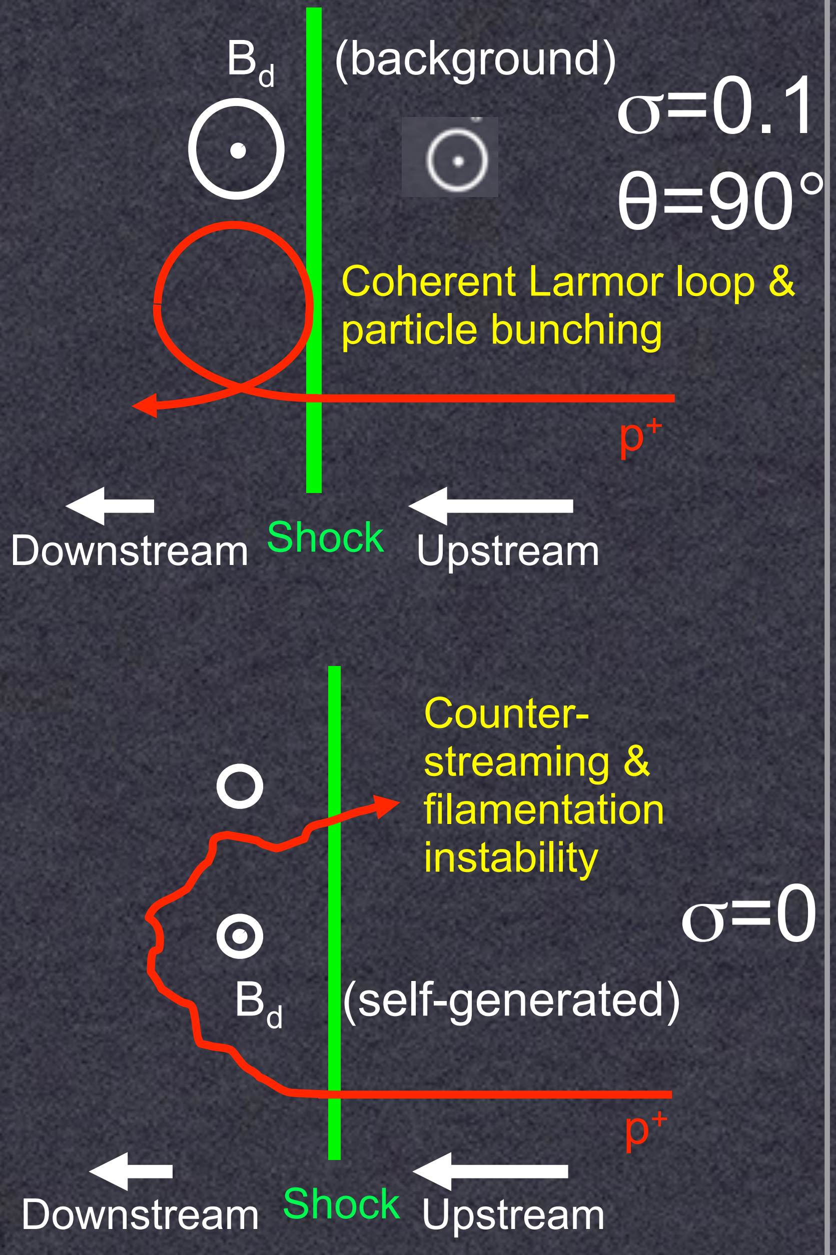
Parameter space of shocks

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



Acceleration for quasipar shocks; efficient e$^-$ heating

Fermi acceleration in unmagnetized shocks



Astrophysical implications

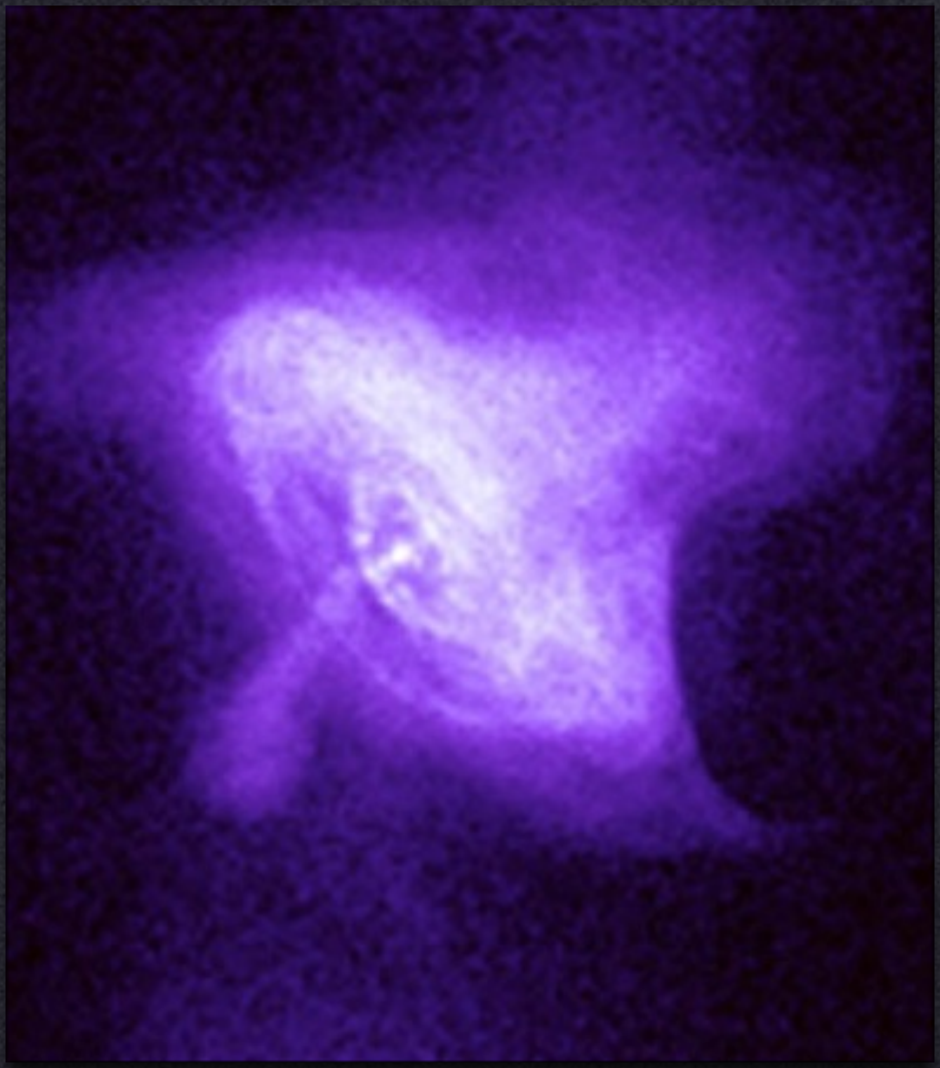
- Pulsar Wind Nebulae

  Toroidal magnetic geometry will accelerate particles if field is weak at the shock

  Implies efficient magnetic dissipation in the wind

  Low equatorial magnetization -- consistent with PWN morphology

  Alternative: magnetic dissipation at the shock (reconnection)



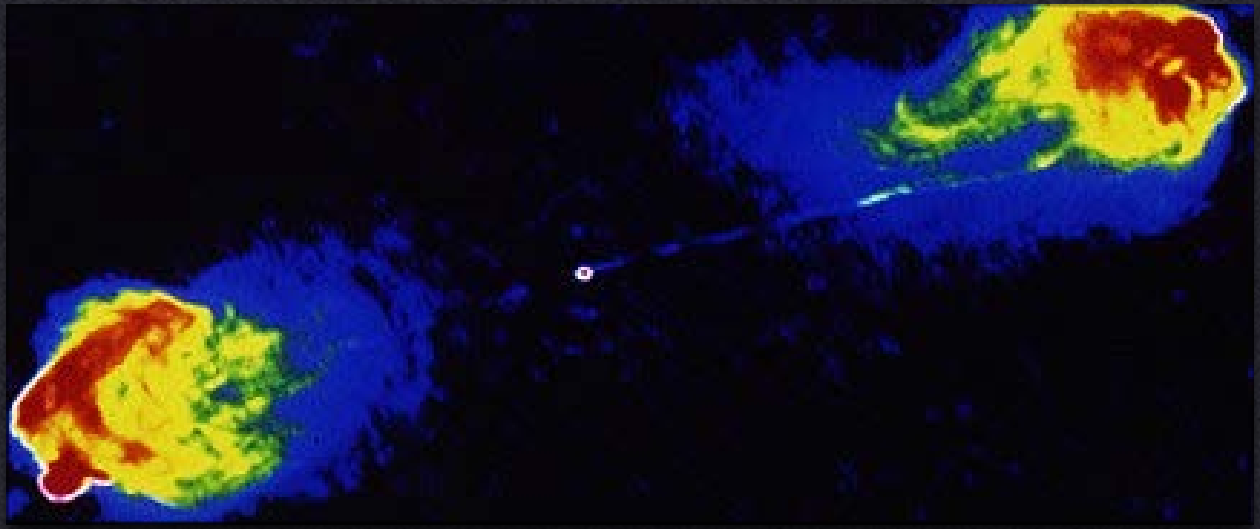
Astrophysical implications

- AGN Jets

  High magnetization toroidal field configuration is disfavored

  Either magnetic field is dissipated in the process of acceleration,

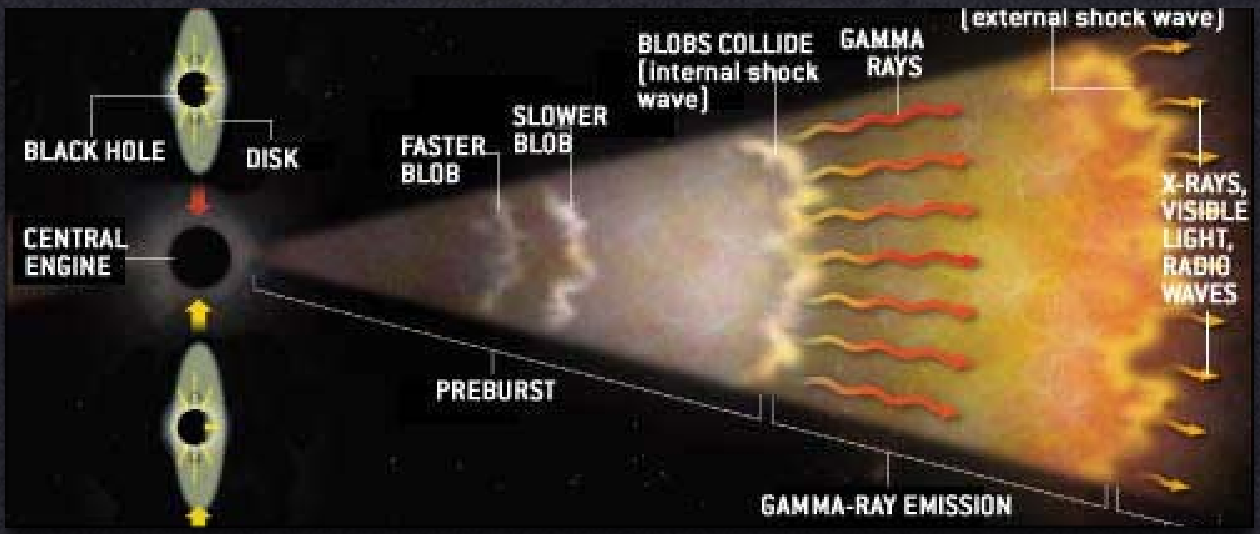
  or field is reoriented to lie along the flow (sheath vs spine flows?)



- GRB jets

  Low magnetization external shocks can work; Field survival?

  Efficient electron heating explains high energy fraction in electrons



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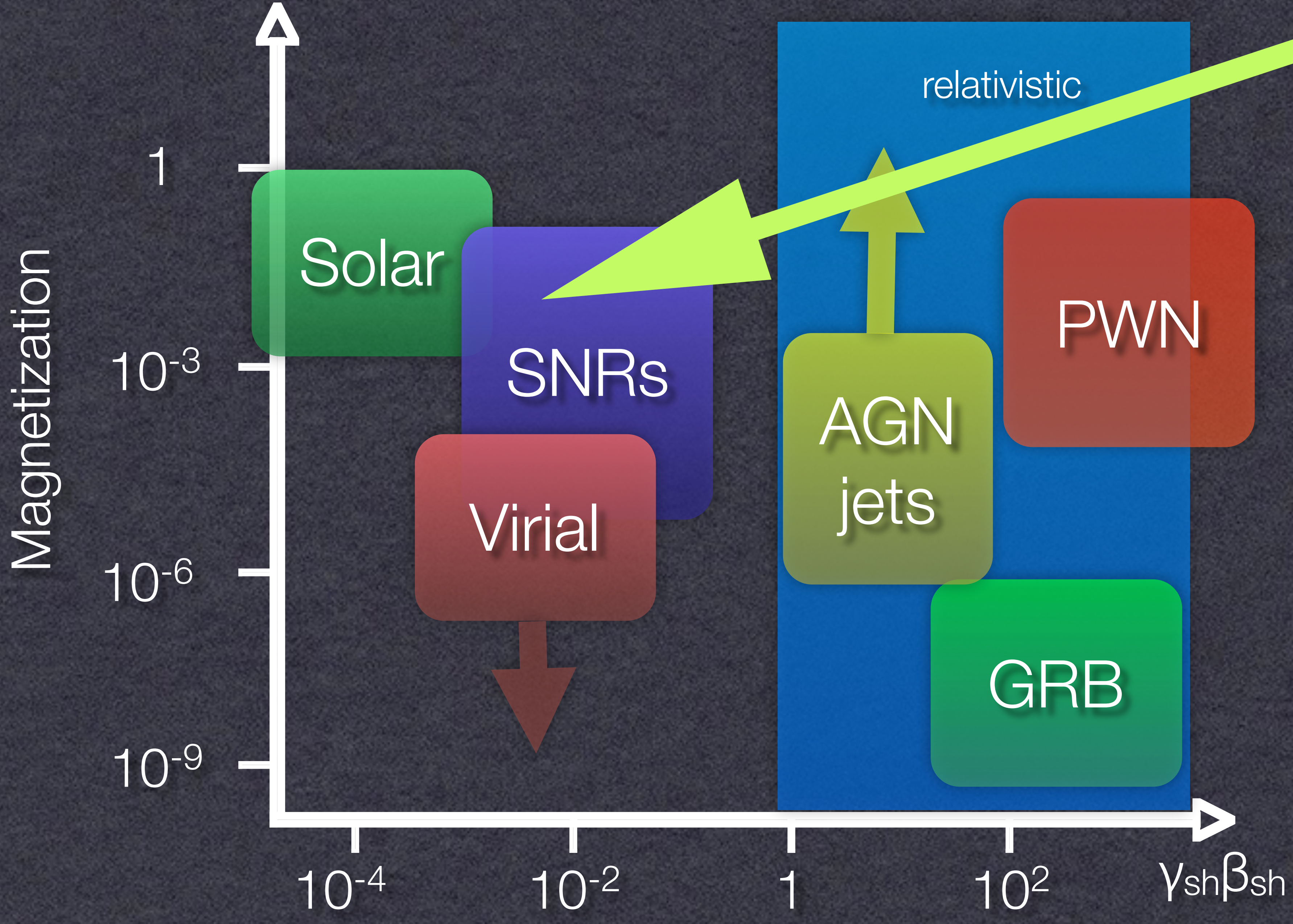
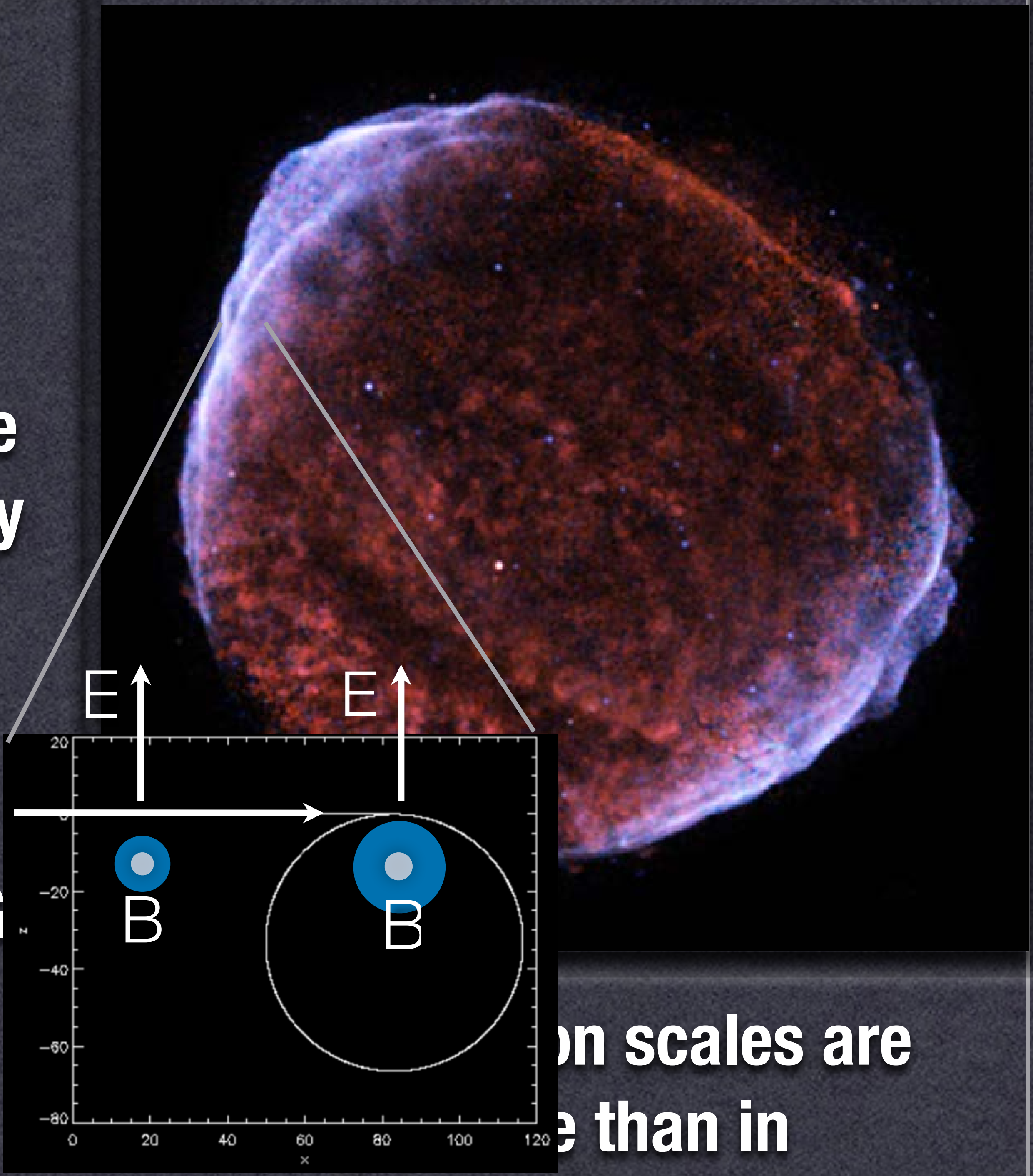


nonrelativistic shocks

e and ions are different in non-relativistic case

Nonrelativistic shocks

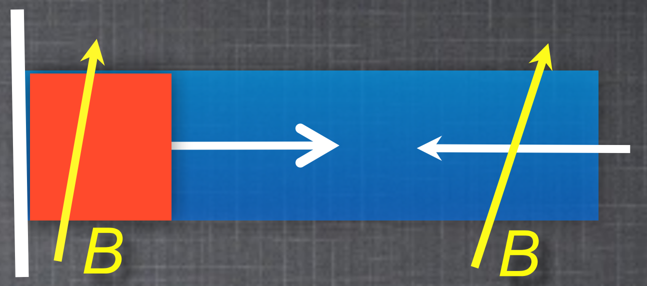
- Thin synchrotron-emitting rims observed in supernove remnants (SNRs)
- Electrons are accelerated to 100 TeV energies
- Cosmic Ray protons are inferred to be accelerated efficiently too (10-40% by energy, up to 10^{16}(?) eV)
- Magnetic field is inferred to be amplified by more than compression at the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

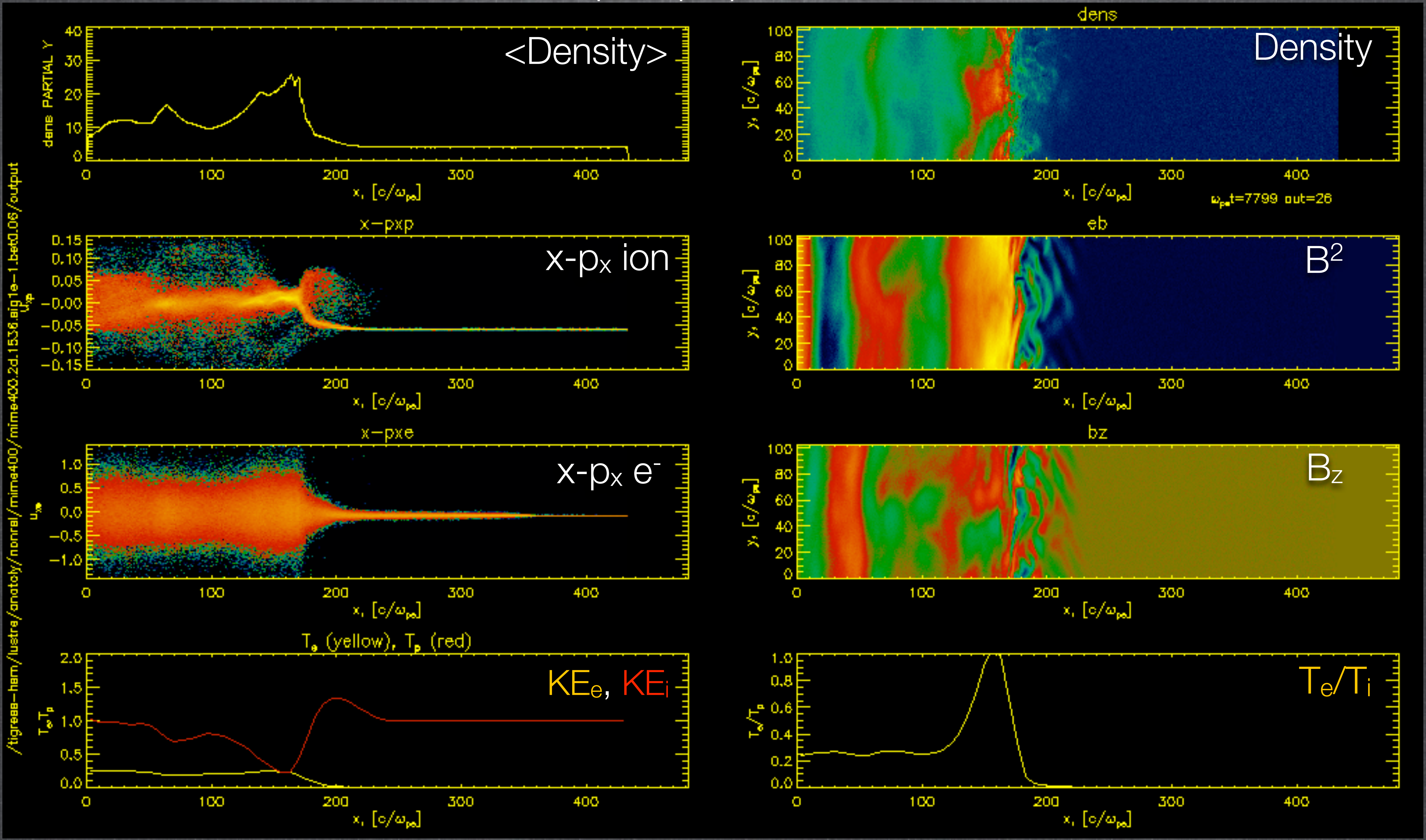


on scales are
e than in
relativistic shocks

Nonrelativistic shocks: shock structure

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

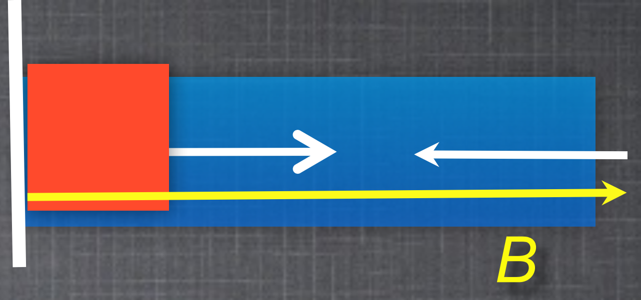


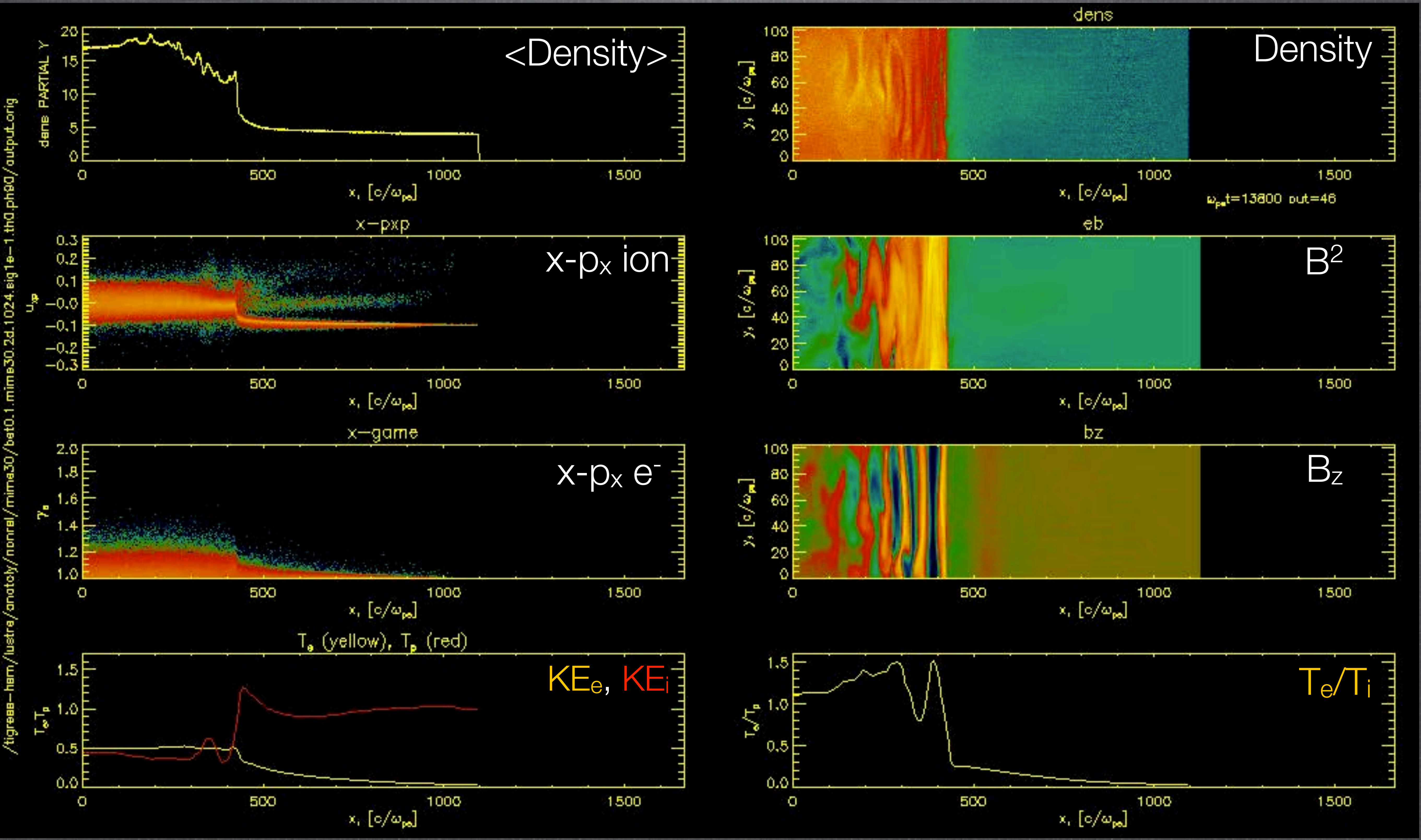


PIC simulation: Shock foot, ramp, overshoot, returning ions, electron heating, whistlers

Nonrelativistic shocks: quasiparallel shock

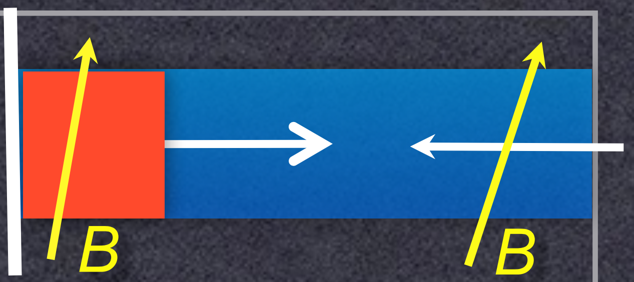
mi/me=30, v=30,000km/s, Ma=5 parallel 0° inclination





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

Electron acceleration

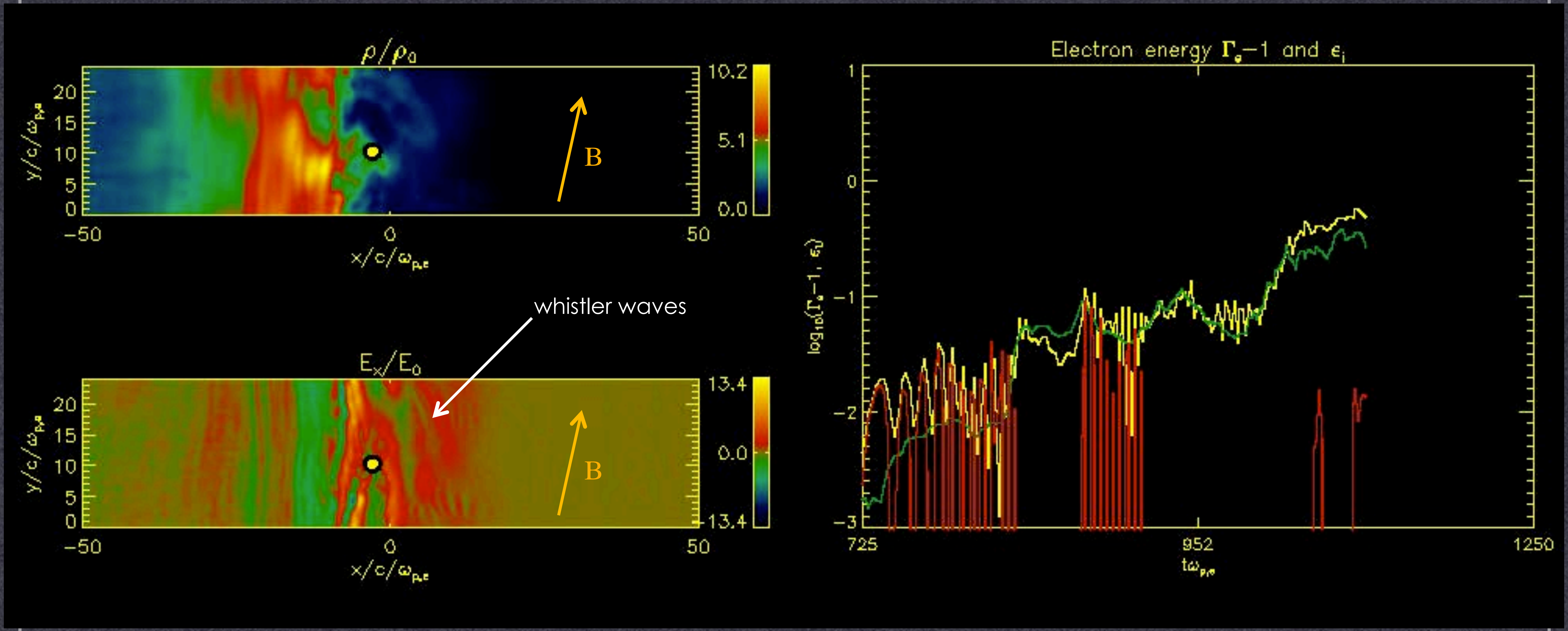


Quasi-perpendicular shock

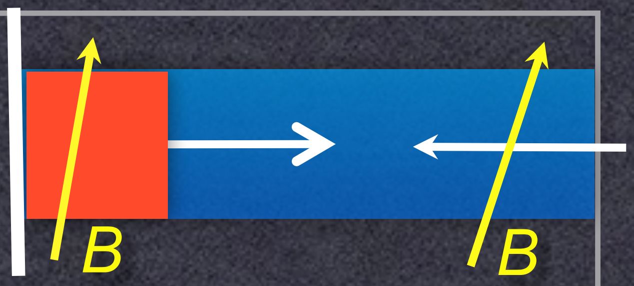
Whistler waves in the shock foot cause E ll B.

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

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



Electron acceleration



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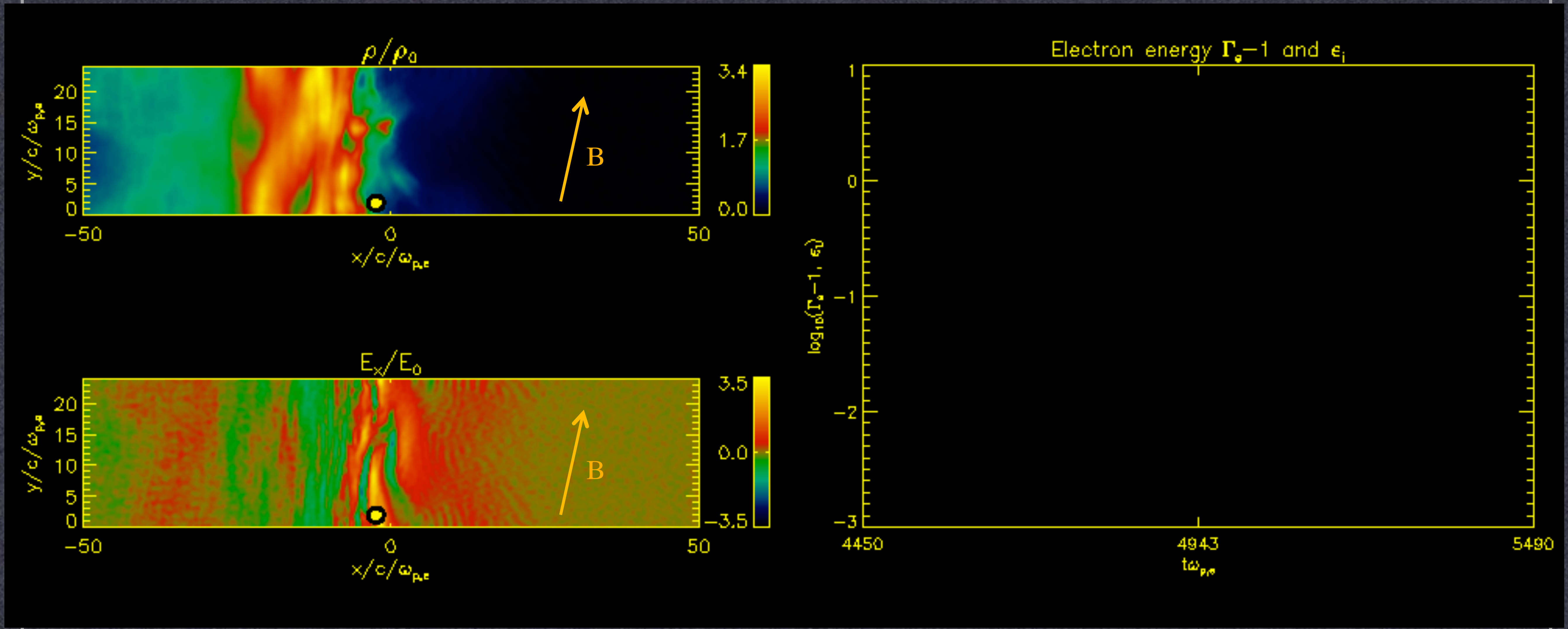


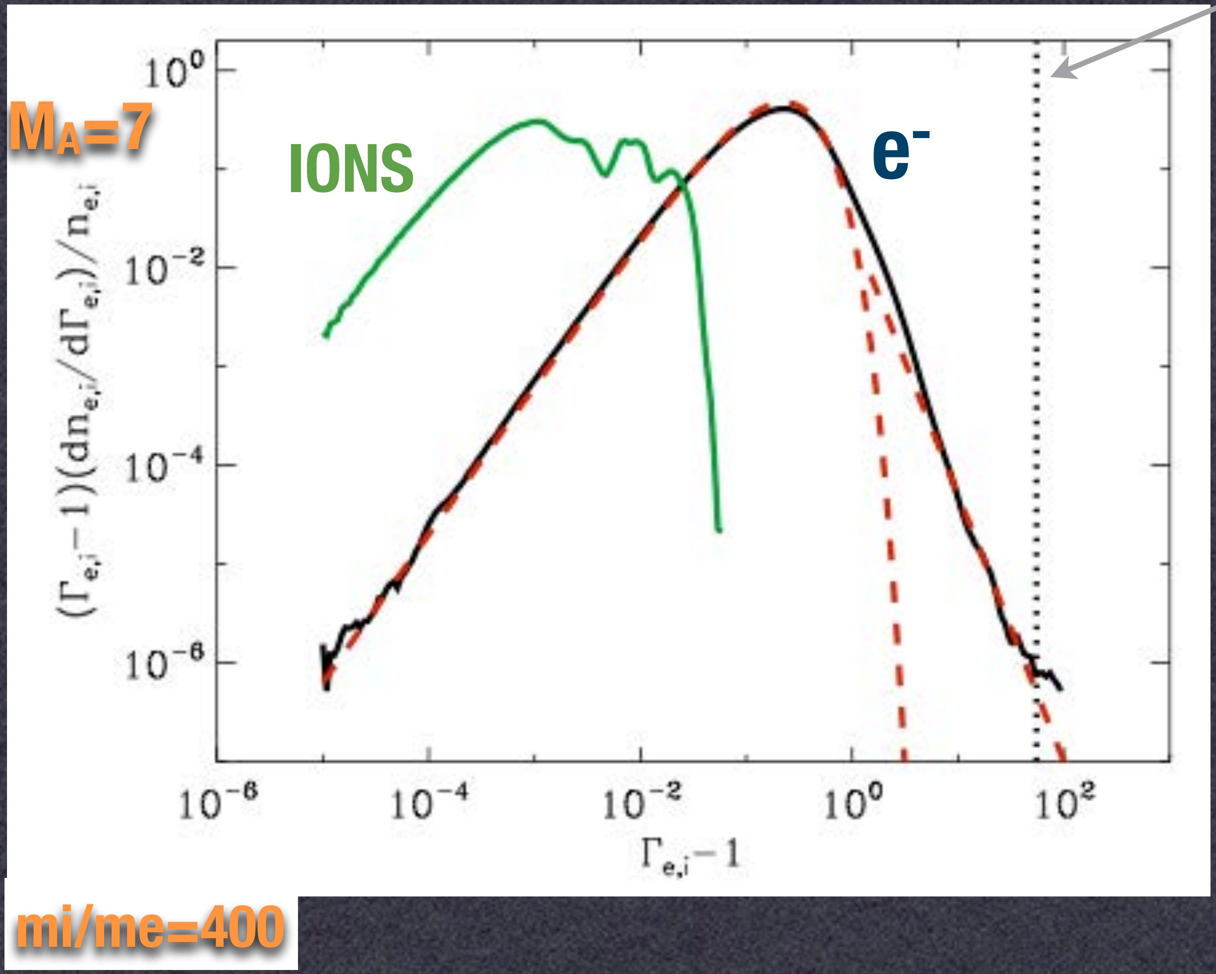
We observe pre-acceleration of electrons to energies comparable to ion energies (injection)

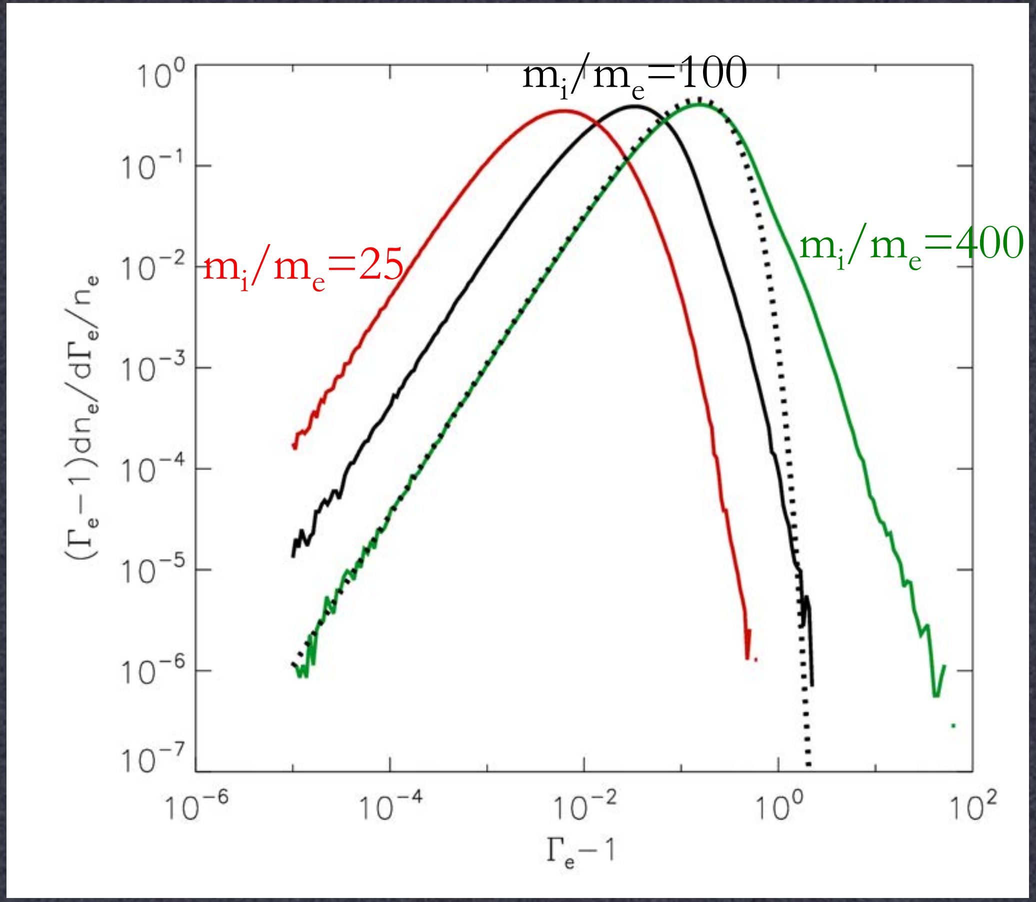
Parameter dependence

Spectrum of ions (green) & electrons (red)

Mass ratio

ion Larmor scale





Riquelme & AS, ’11

Electron injection needs:

long-term evolution still unclear

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

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

Shock acceleration

Two crucial ingredients:

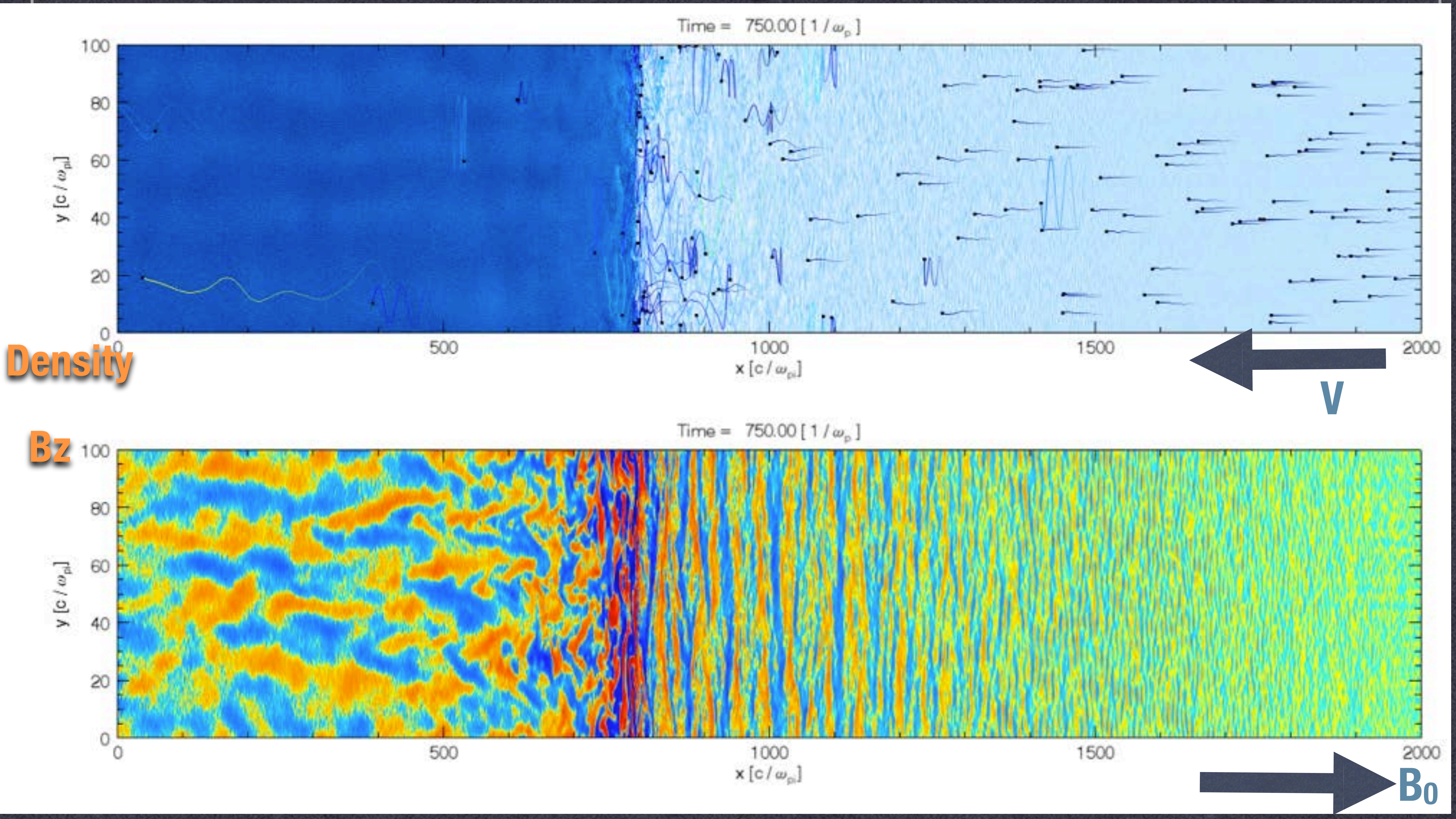
1) ability of a shock to reflect particles back into the upstream (injection)

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

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

Ion acceleration

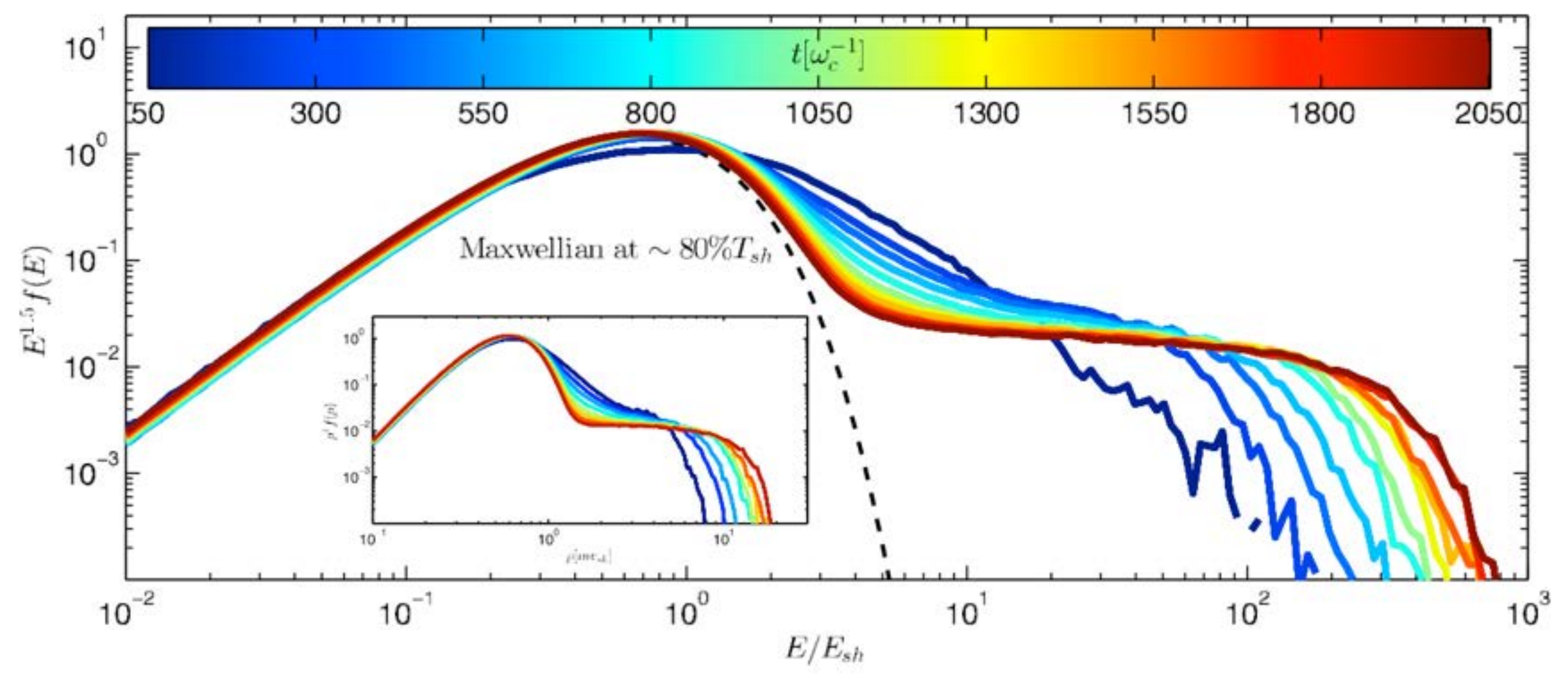
M_A=3, parallel shock; hybrid simulation. Quasi-parallel shocks accelerate ions and produce self-generated waves in the upstream.



Ion spectrum

dHYBRID

Long term evolution: Diffusive Shock Acceleration spectrum recovered



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

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

CR backreaction is affecting downstream temperature

Caprioli & Spitkovsky 2014

B field amplification

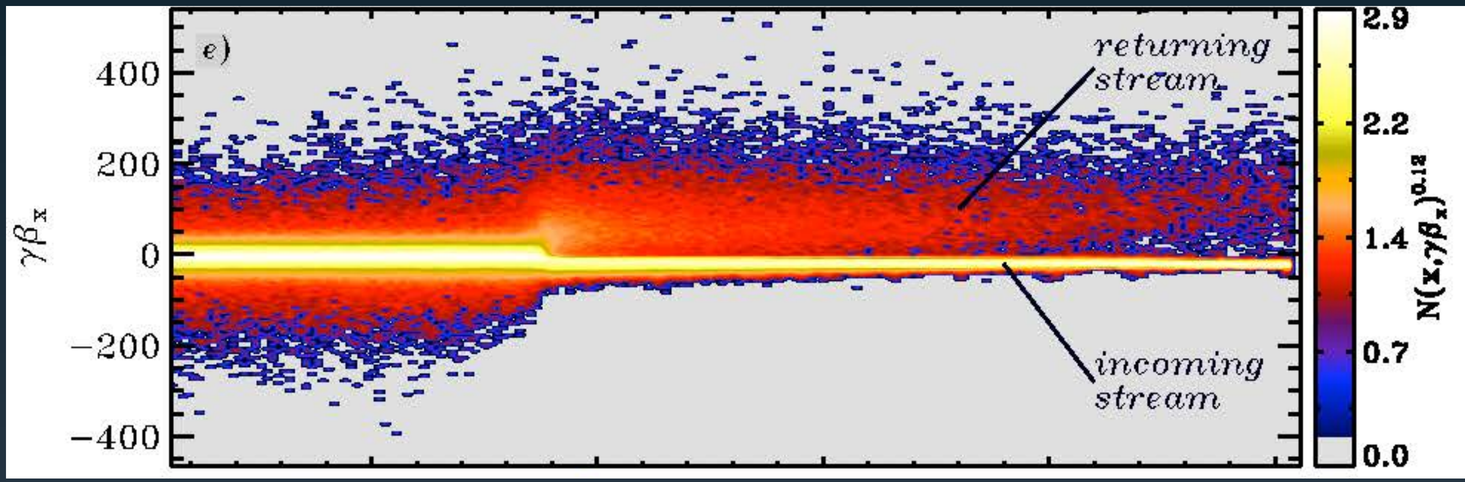
CR accelerating shocks can cause a current of protons to propagate through the upstream. Bell (04, 05) found an MHD instability of CRs flying through magnetized plasma.

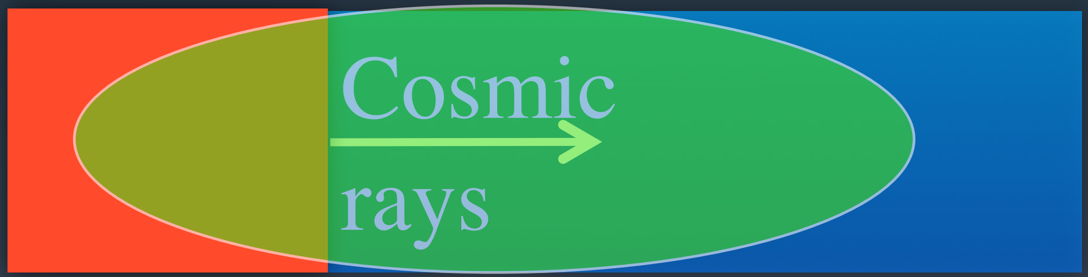
The interaction is nonresonant at wavelength << Larmor radius of CRs.

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 rays

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

B field amplification

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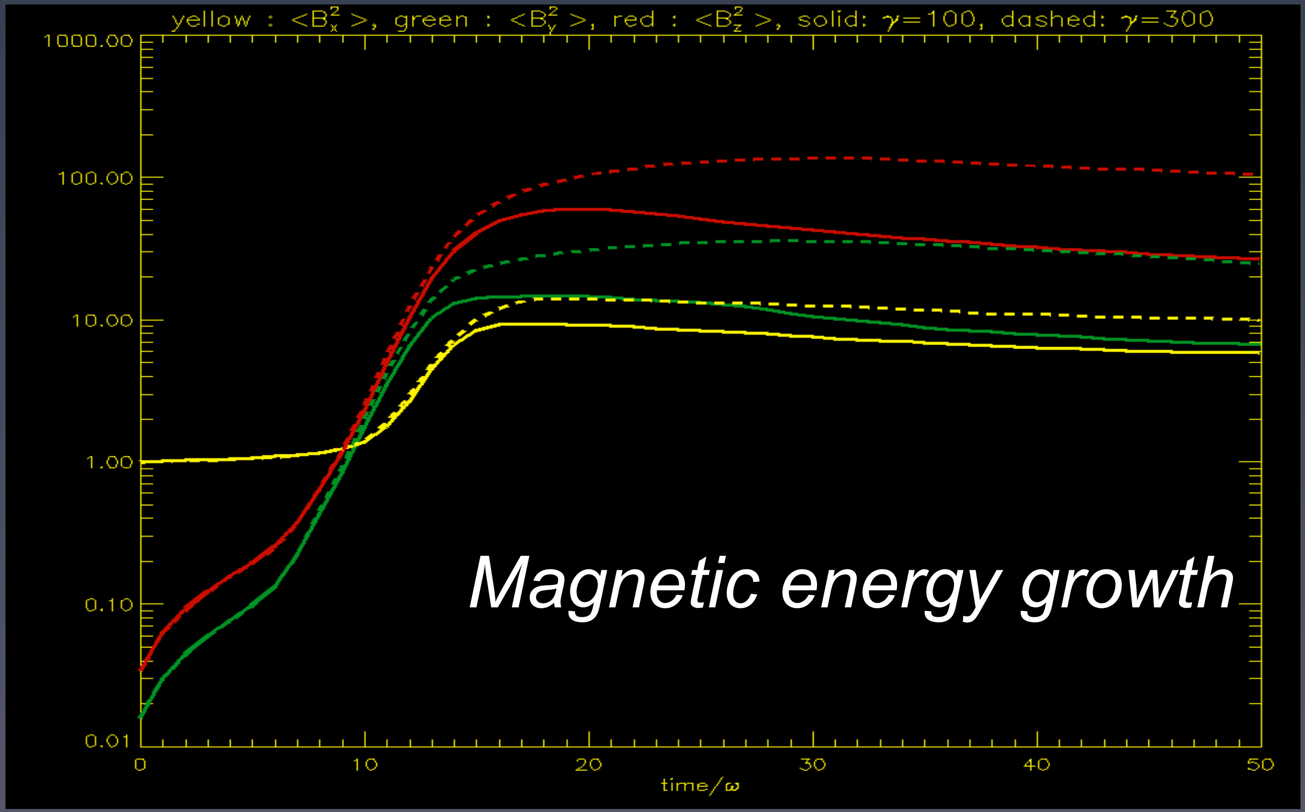
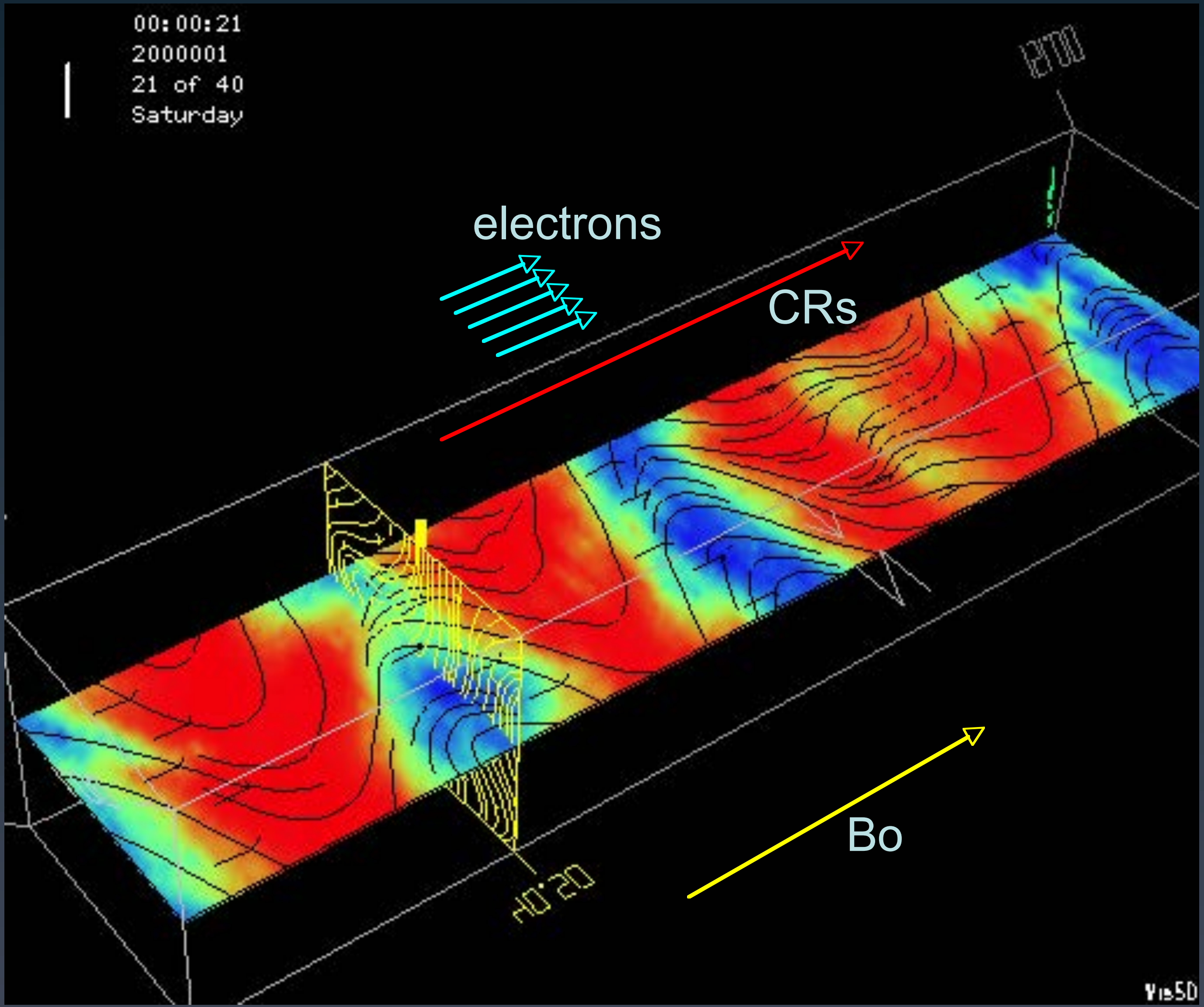


Magnetic energy growth

Bell's nonresonant CR instability



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

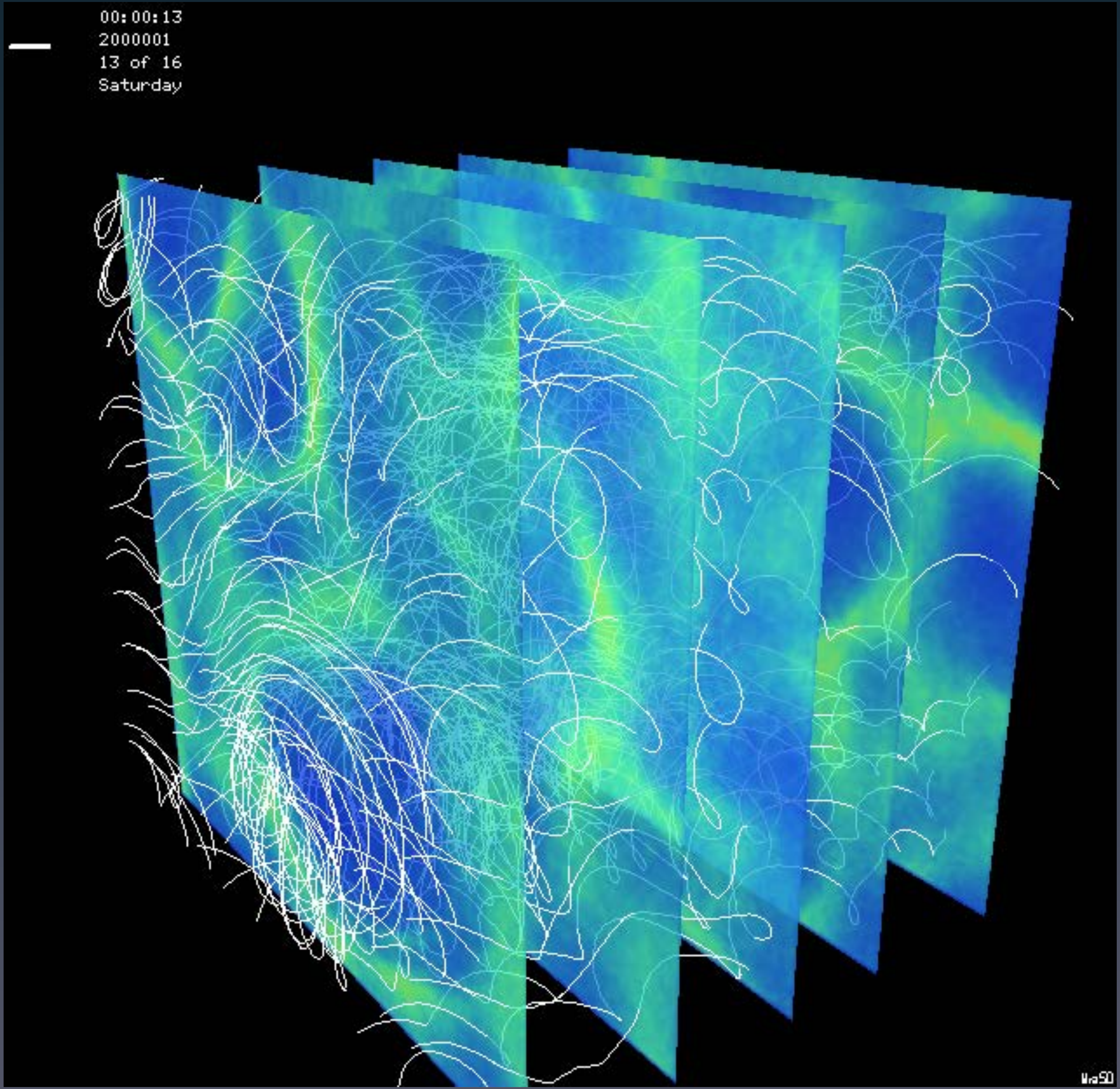
$$\gamma_{max} = k_{max} V_{Alfven,0}$$

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

B field amplification: 3D runs

Bell's nonresonant CR instability

(Riquelme and A.S. arXiv:0810.4565)

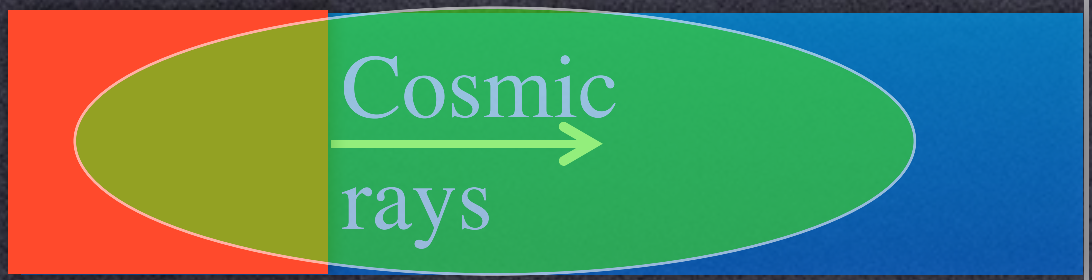


Field amplification of ~10 in SNRs can be due to Bell's instability

Field amplification

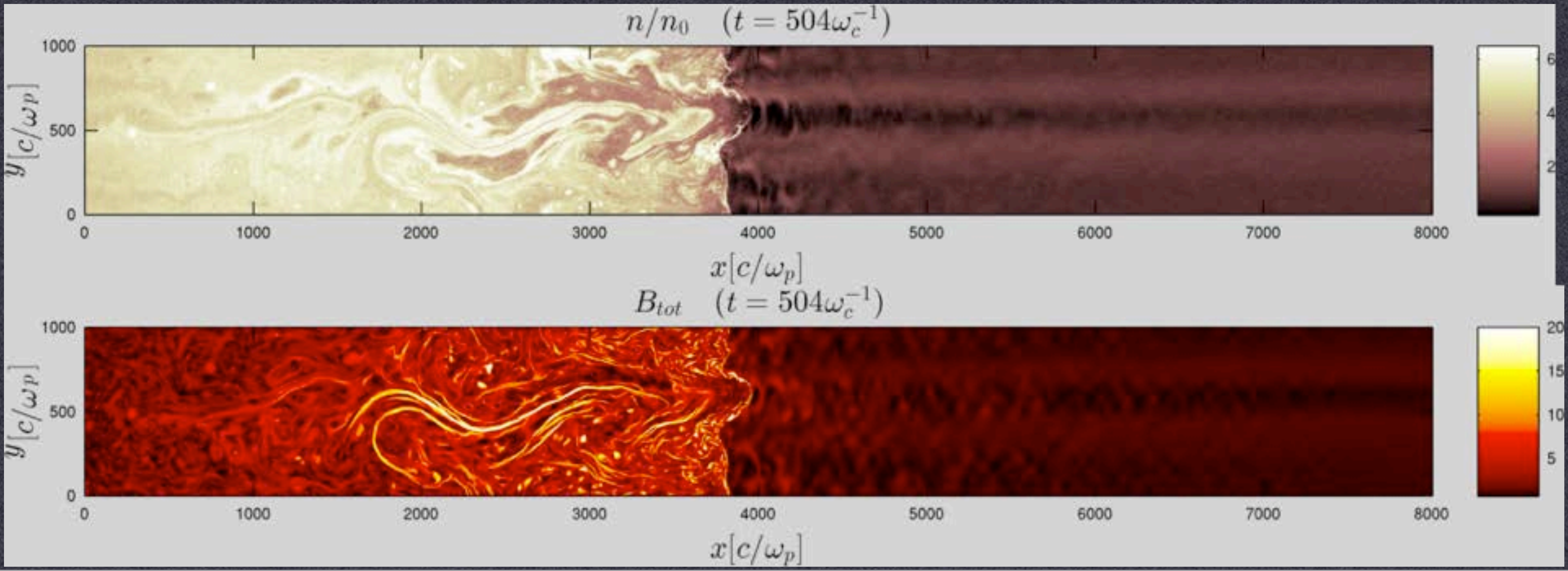
We see evidence of CR effect on upstream.

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

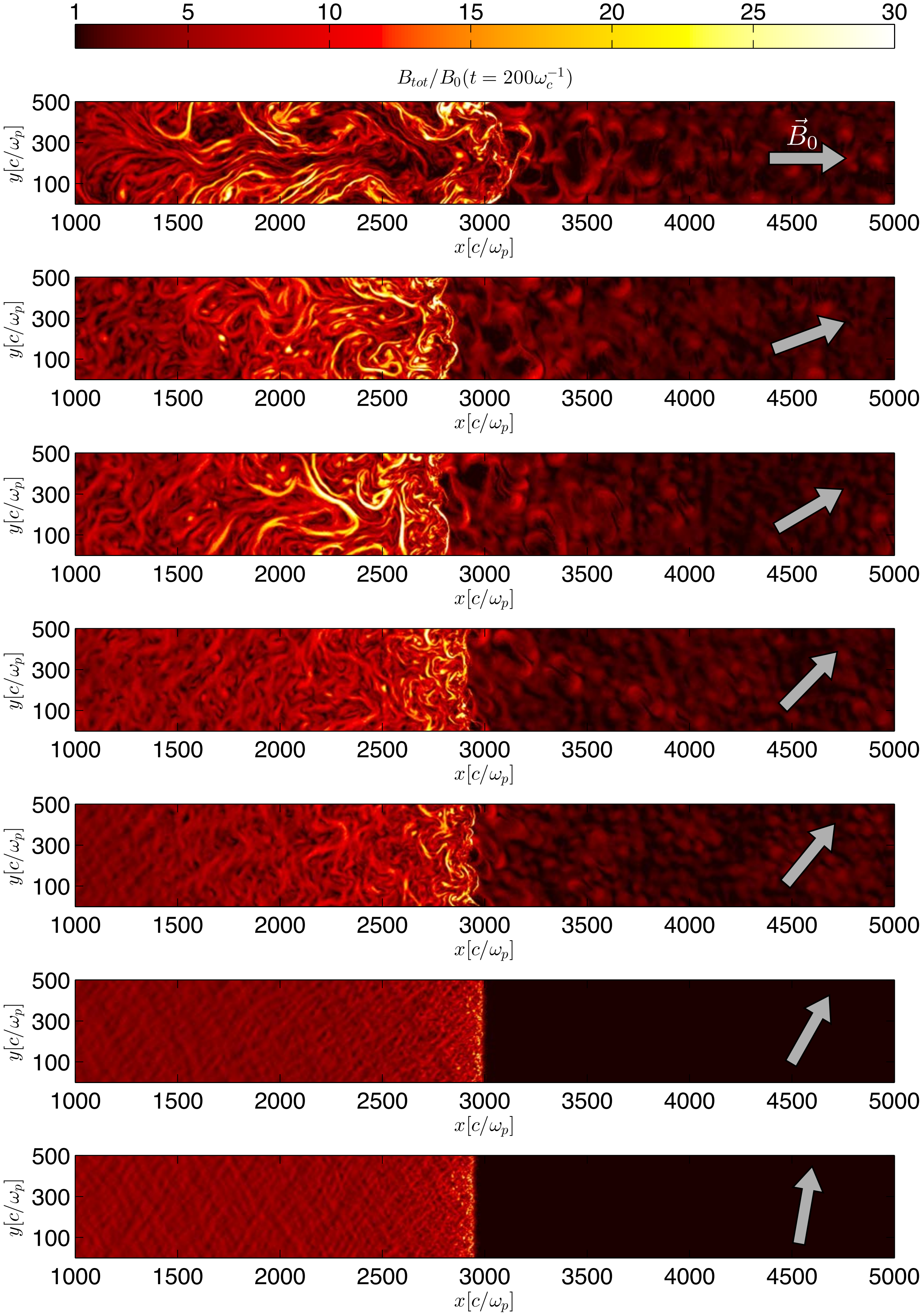


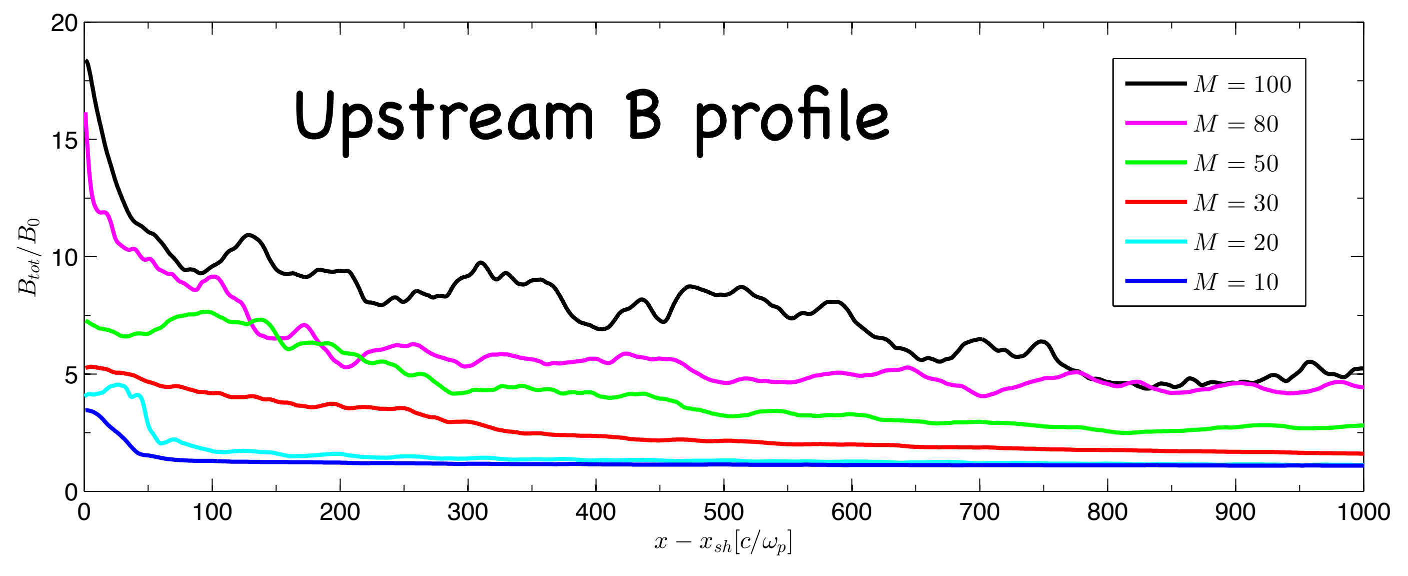
Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

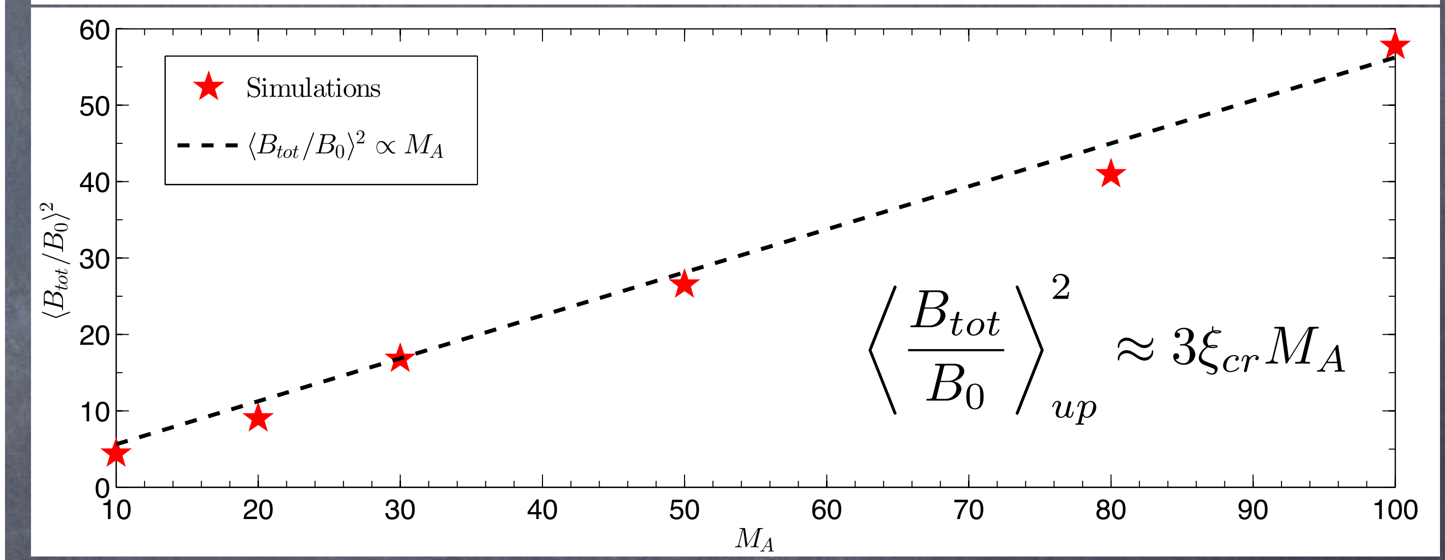
Combination of nonresonant (Bell), resonant, and firehose instabilities + CR filamentation



Dependence of field amplif. on inclination and M



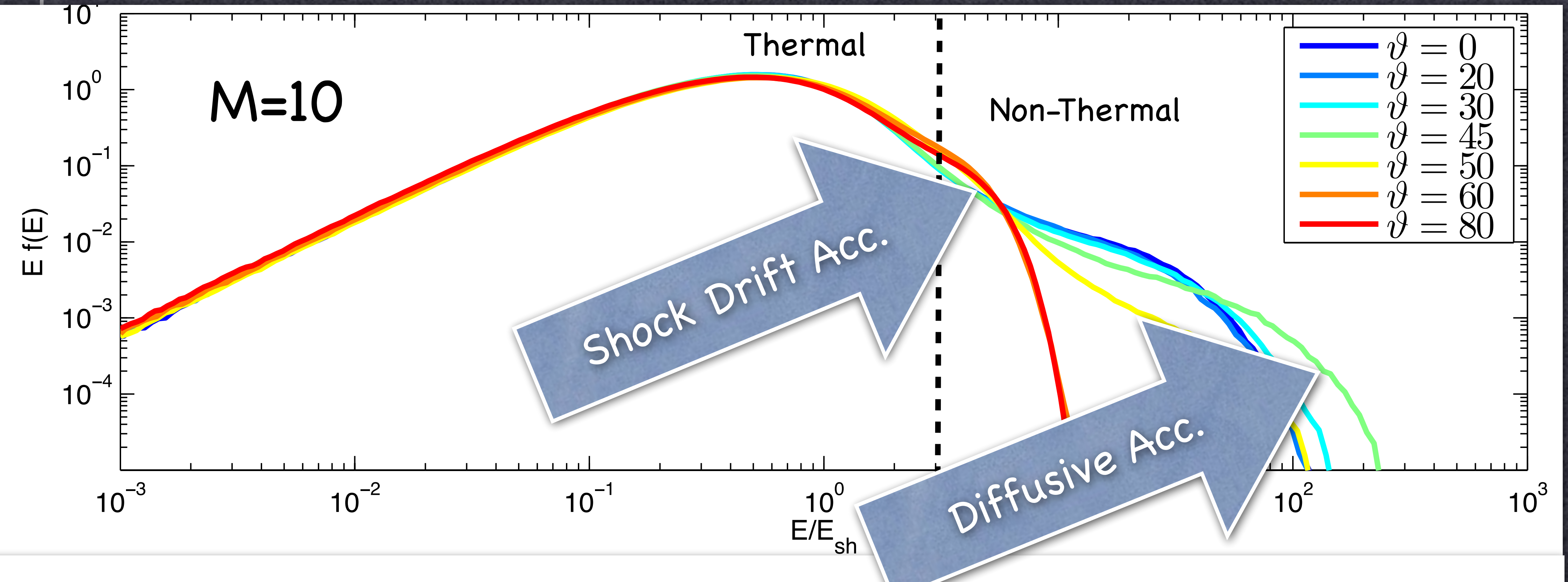


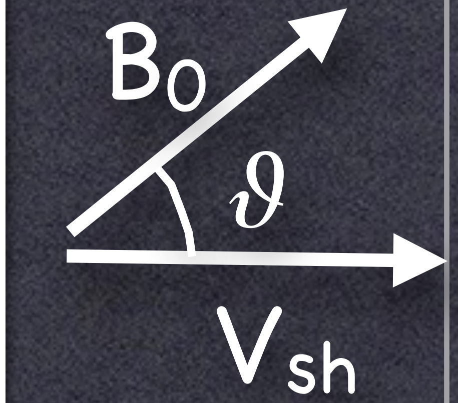


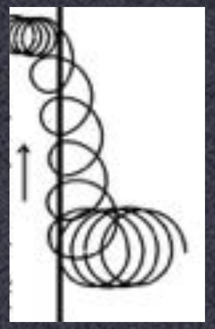
- In agreement with the prediction of resonant streaming instability

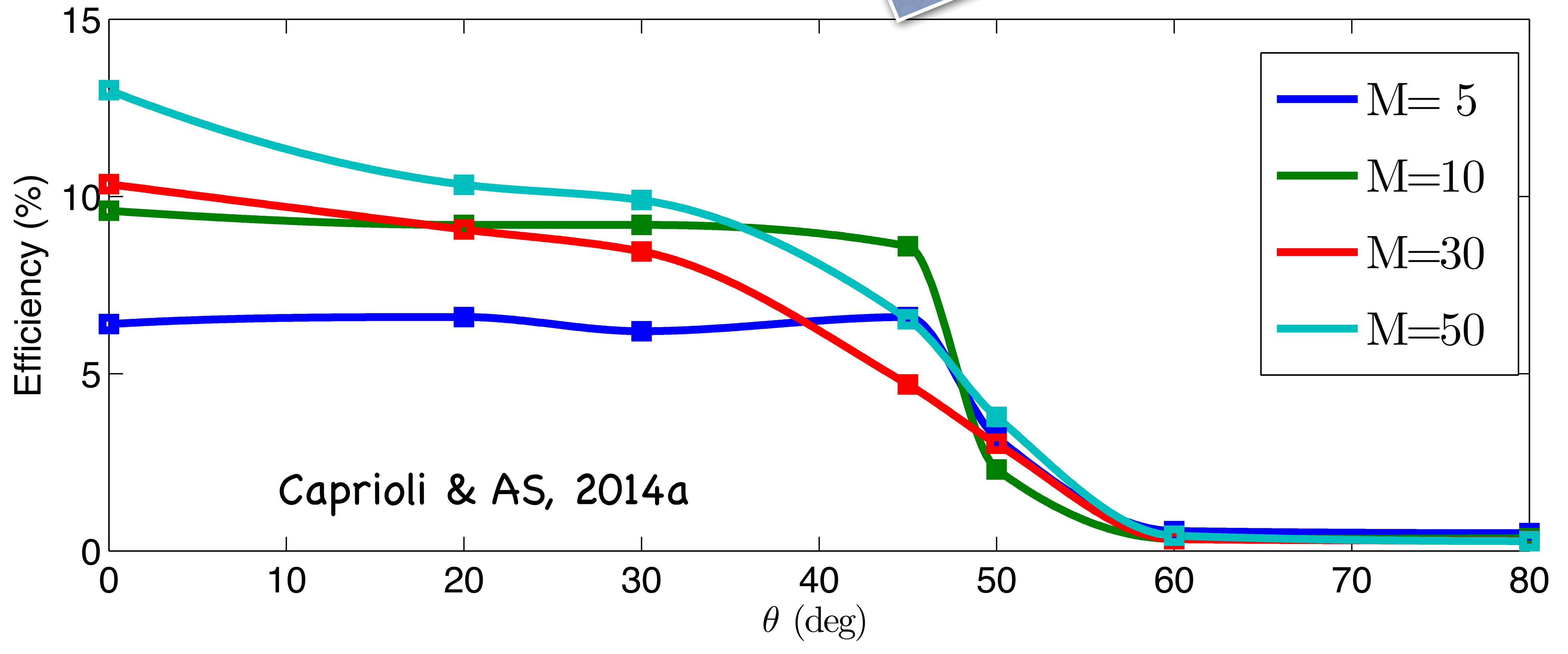
More B-field amplification for stronger shocks!

Acceleration in parallel vs oblique shocks









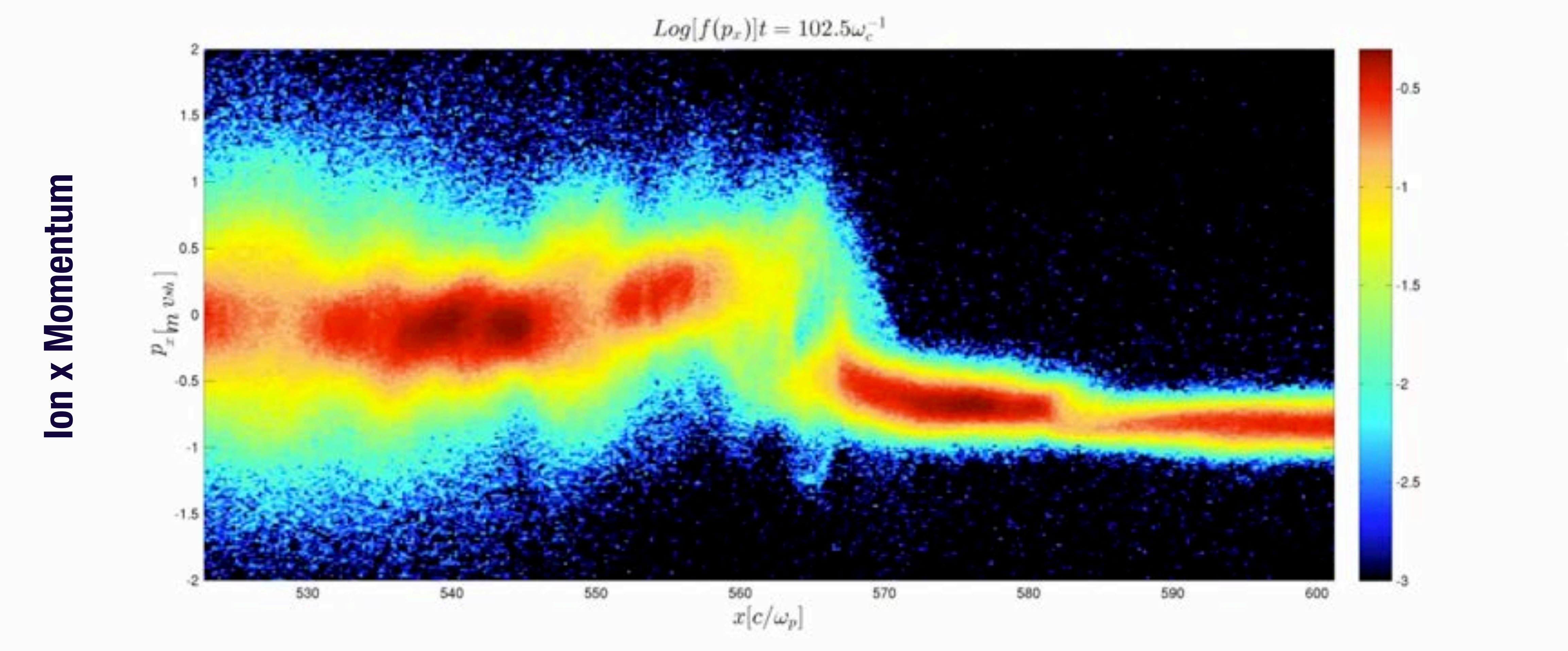
Caprioli & AS, 2014a

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

Shock structure & injection

dHYBRID

Quasiparallel shocks look like intermittent quasiperp shocks

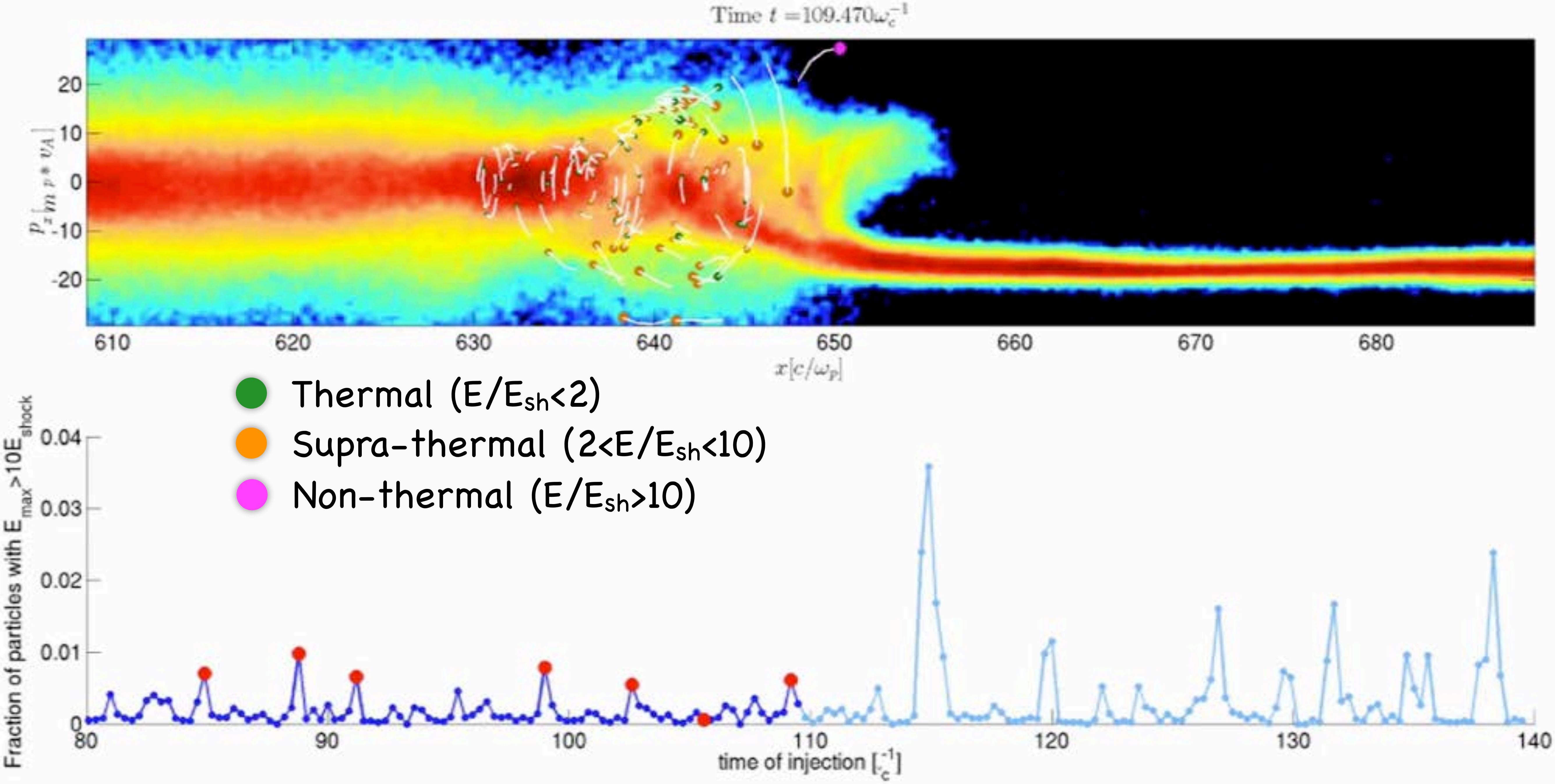


Injection of ions happens on first crossing due to specular reflection from reforming magnetic and electric barrier and shock-drift acceleration.

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

Injection mechanism: importance of timing

Caprioli, Pop & AS 2015

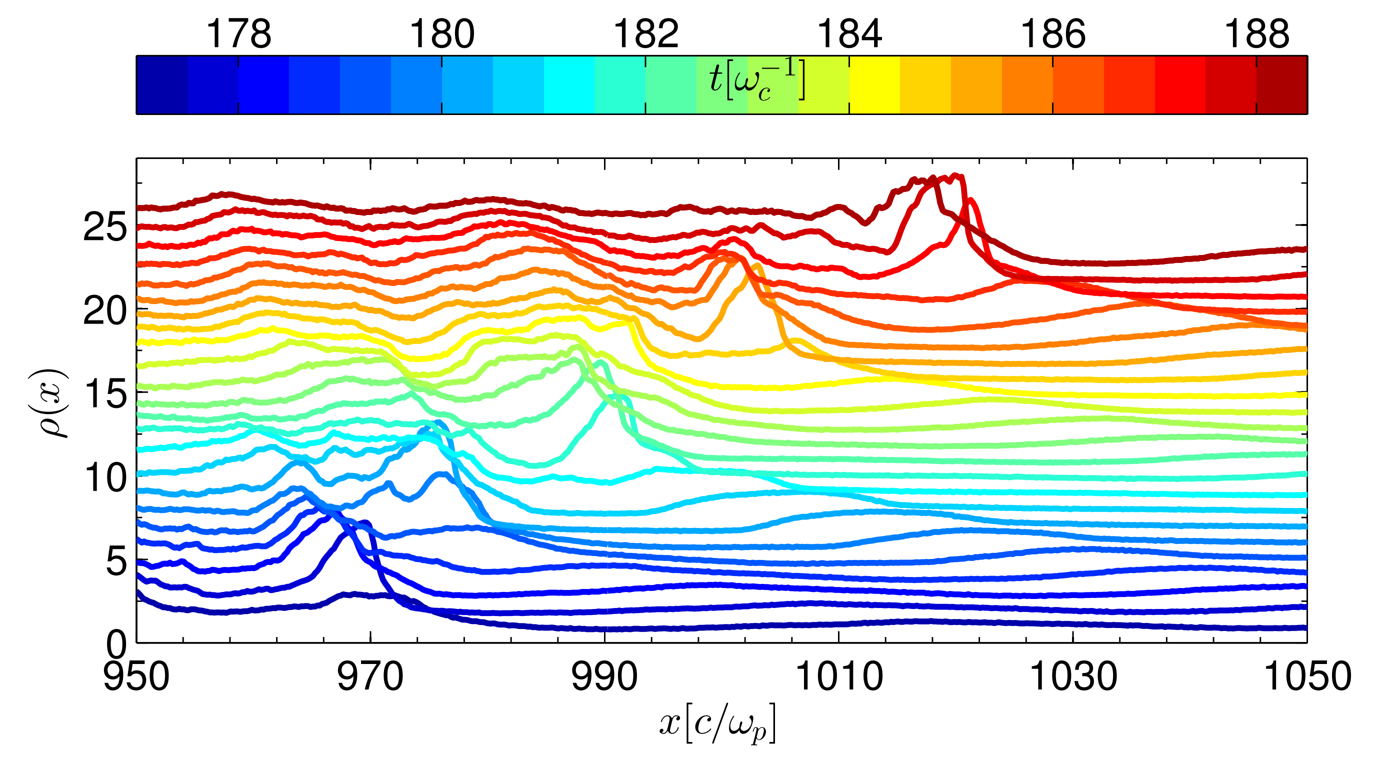


- ● Thermal ($E/E_{sh}<2$)
- ● Supra-thermal ($2<E/E_{sh}<10$)
- ● Non-thermal ($E/E_{sh}>10$)

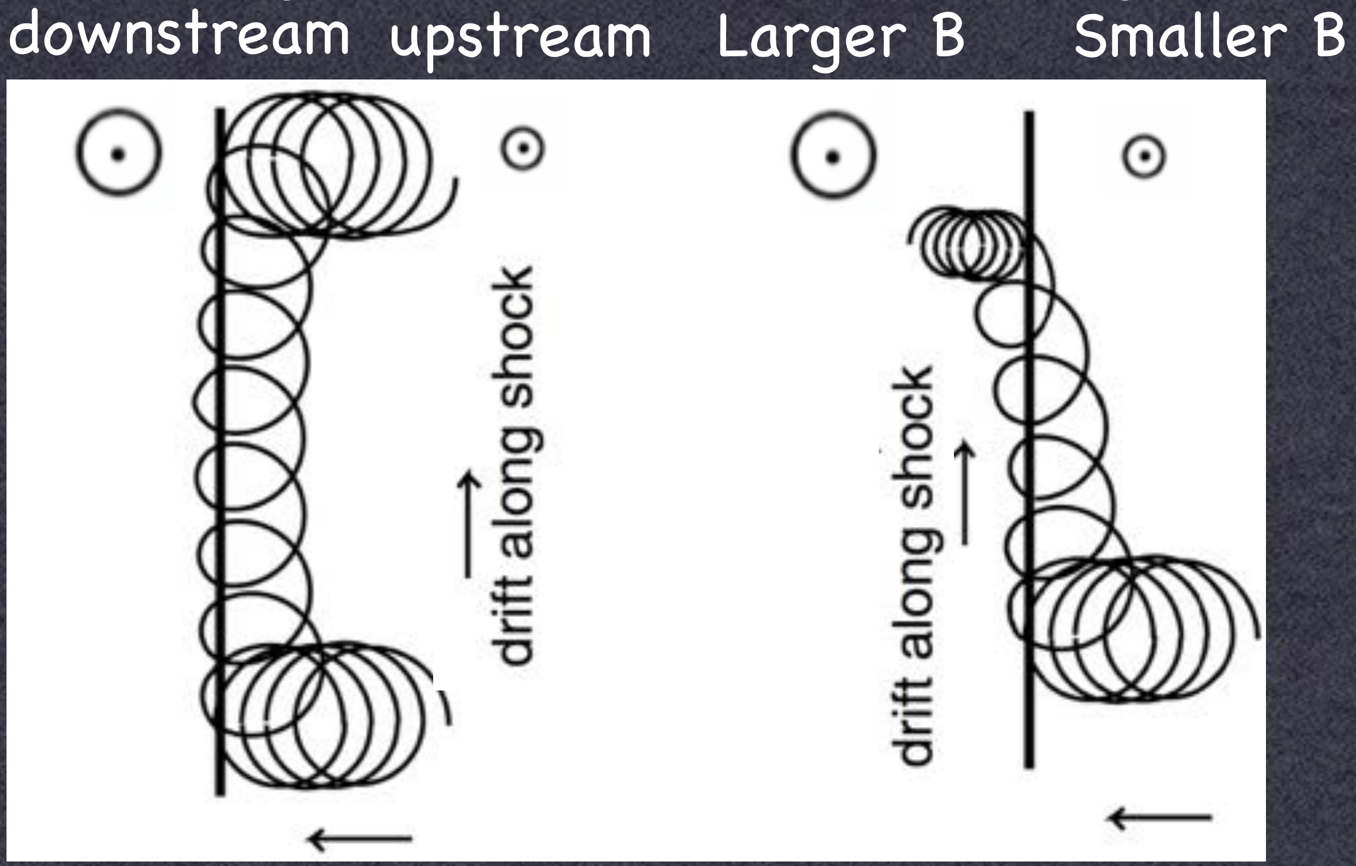
Ion injection: theory

Caprioli, Pop & AS 2015

- Reflection off the shock potential barrier (stationary in the downstream frame)
- For reflection into upstream, particle needs certain minimal energy for given shock inclination;
- Particles first gain energy via shock-drift acceleration (SDA)
- Several cycles are required for higher shock obliquities
- Each cycle is "leaky", not everyone comes back for more
- Higher obliquities less likely to get injected



Shock-drift acceleration:



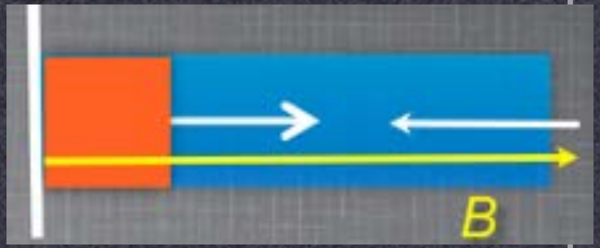
Path of incoming particle

What accelerates electrons?

results of full PIC simulations simulations

Park, Caprioli & AS, PRL, 2015

Electron acceleration at parallel shocks



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

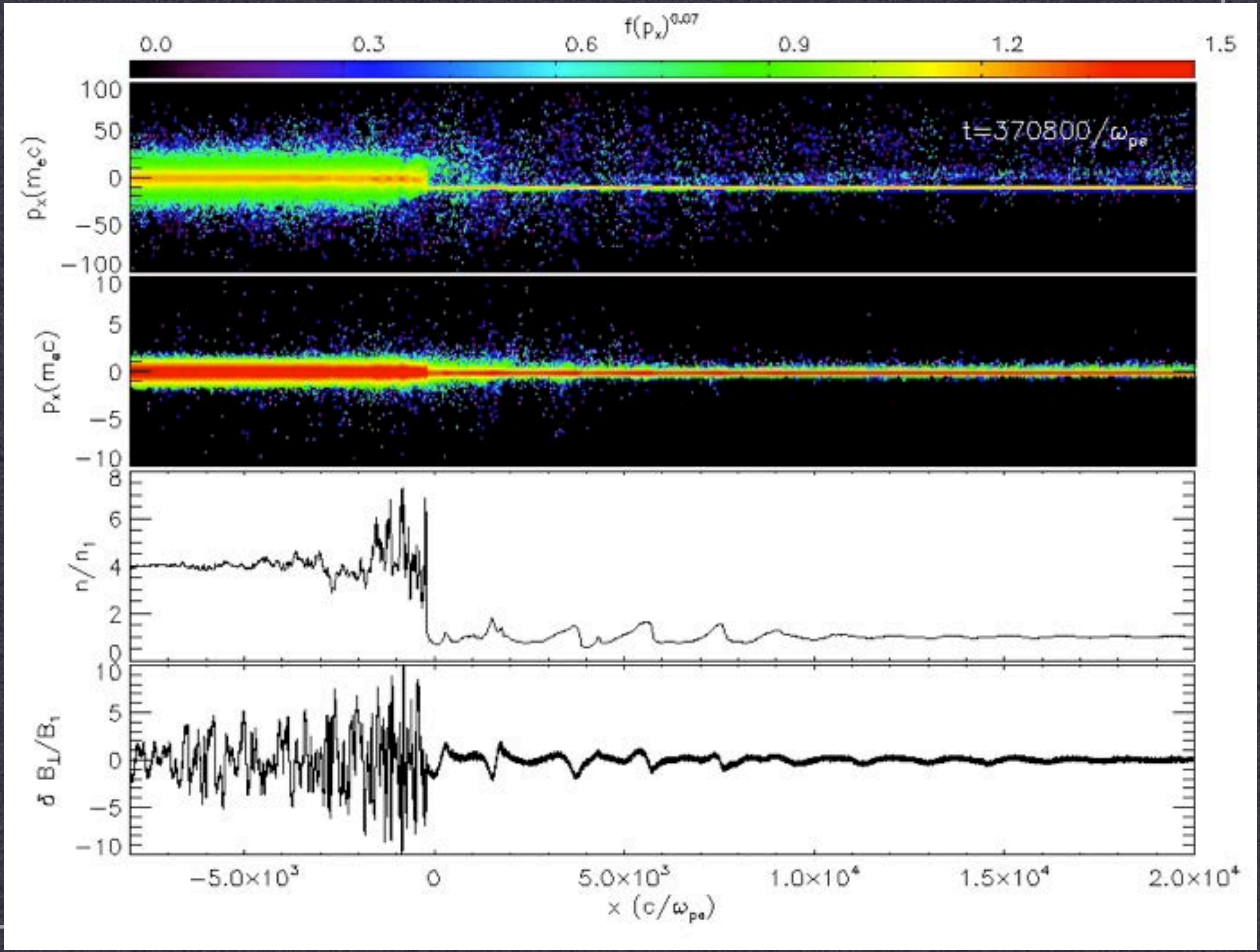
Ion-driven Bell waves drive electron acceleration: correct polarization

Ion phase space

Electron phase space

Density

Transverse Magnetic field



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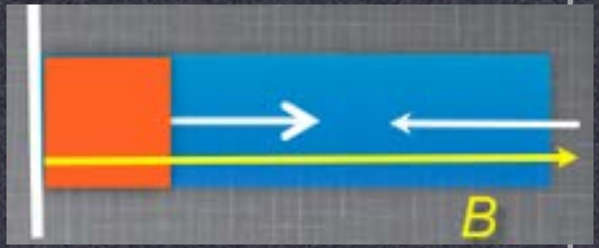
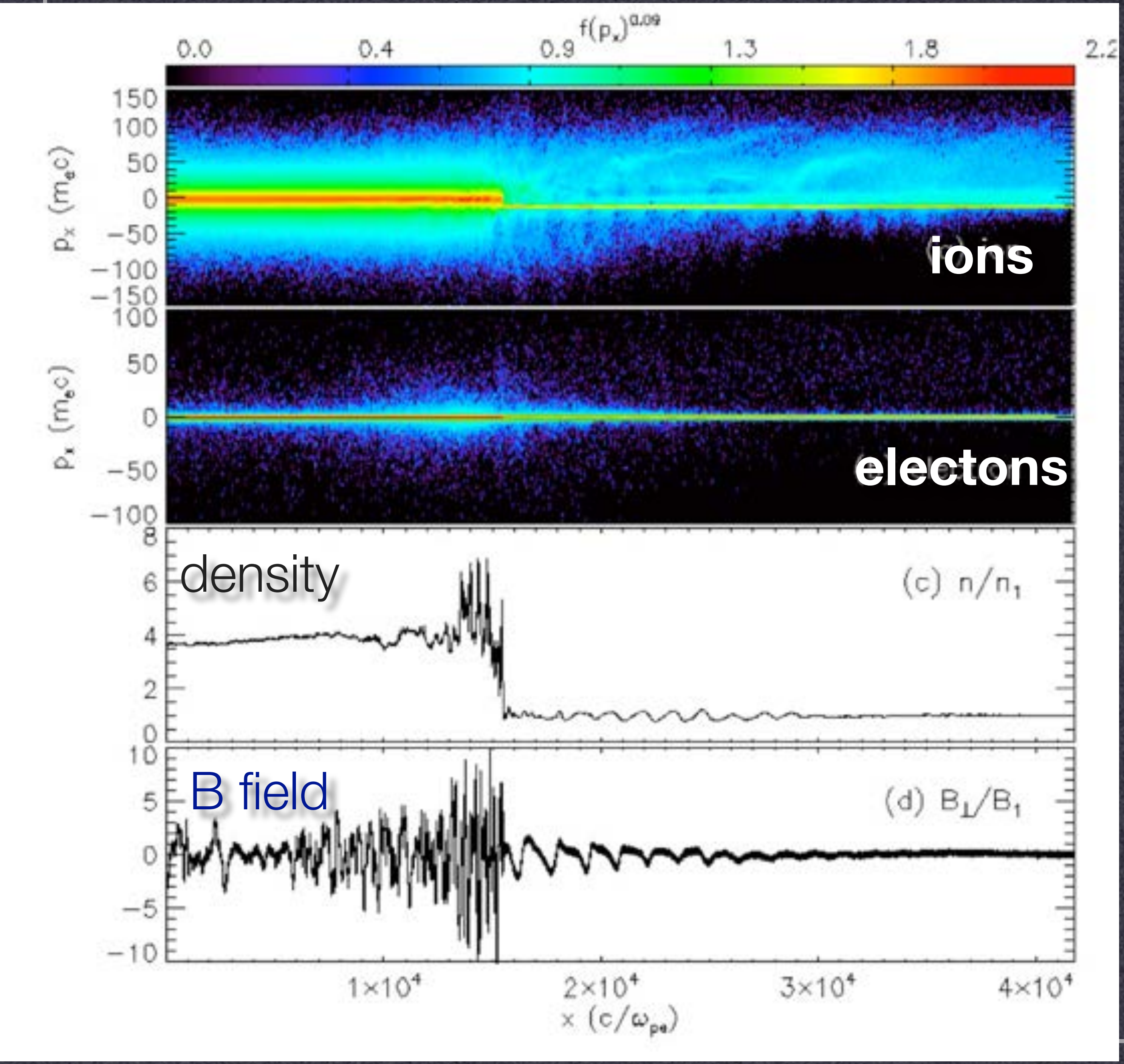
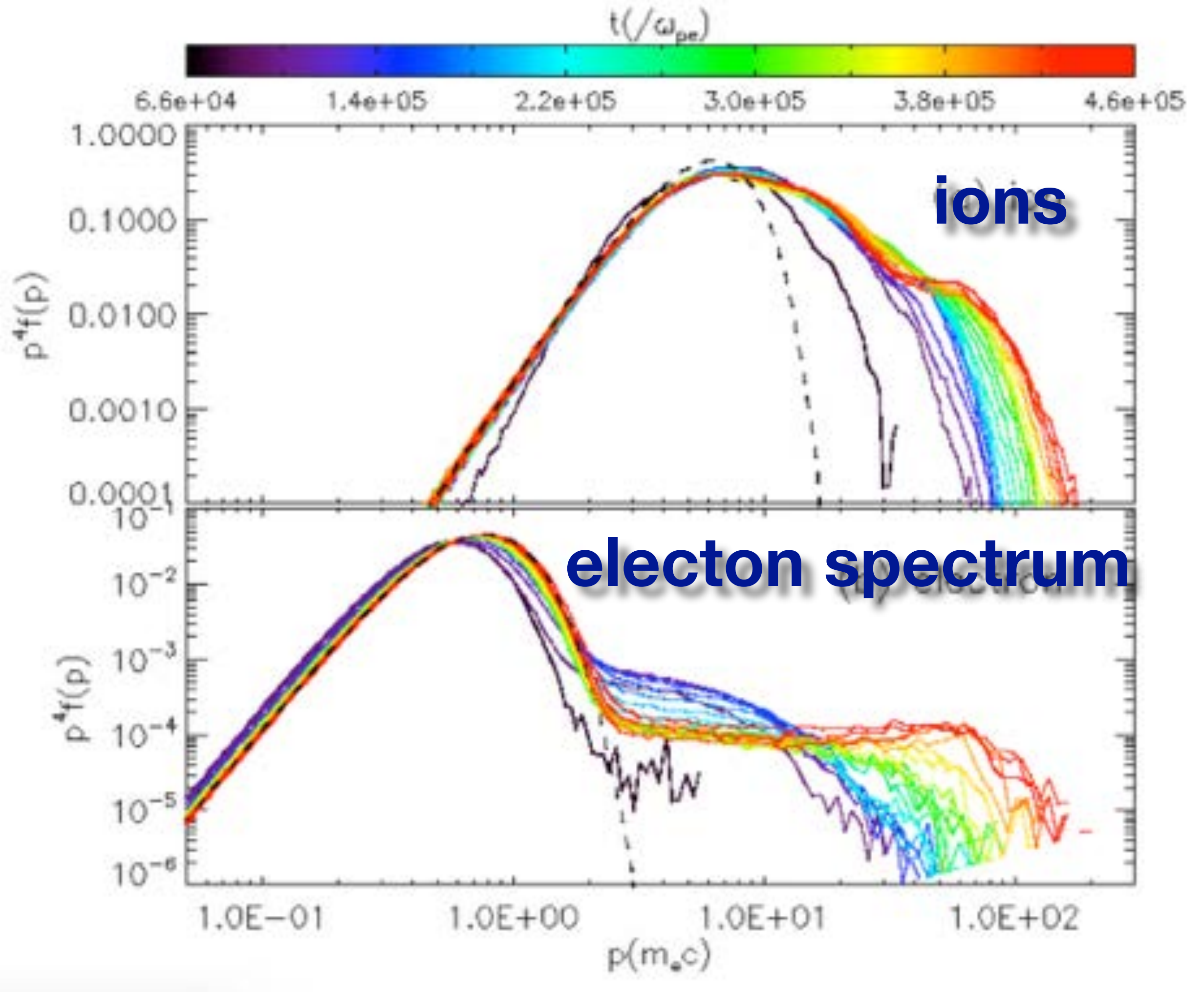


Ion-driven Bell waves drive electron acceleration: correct polarization



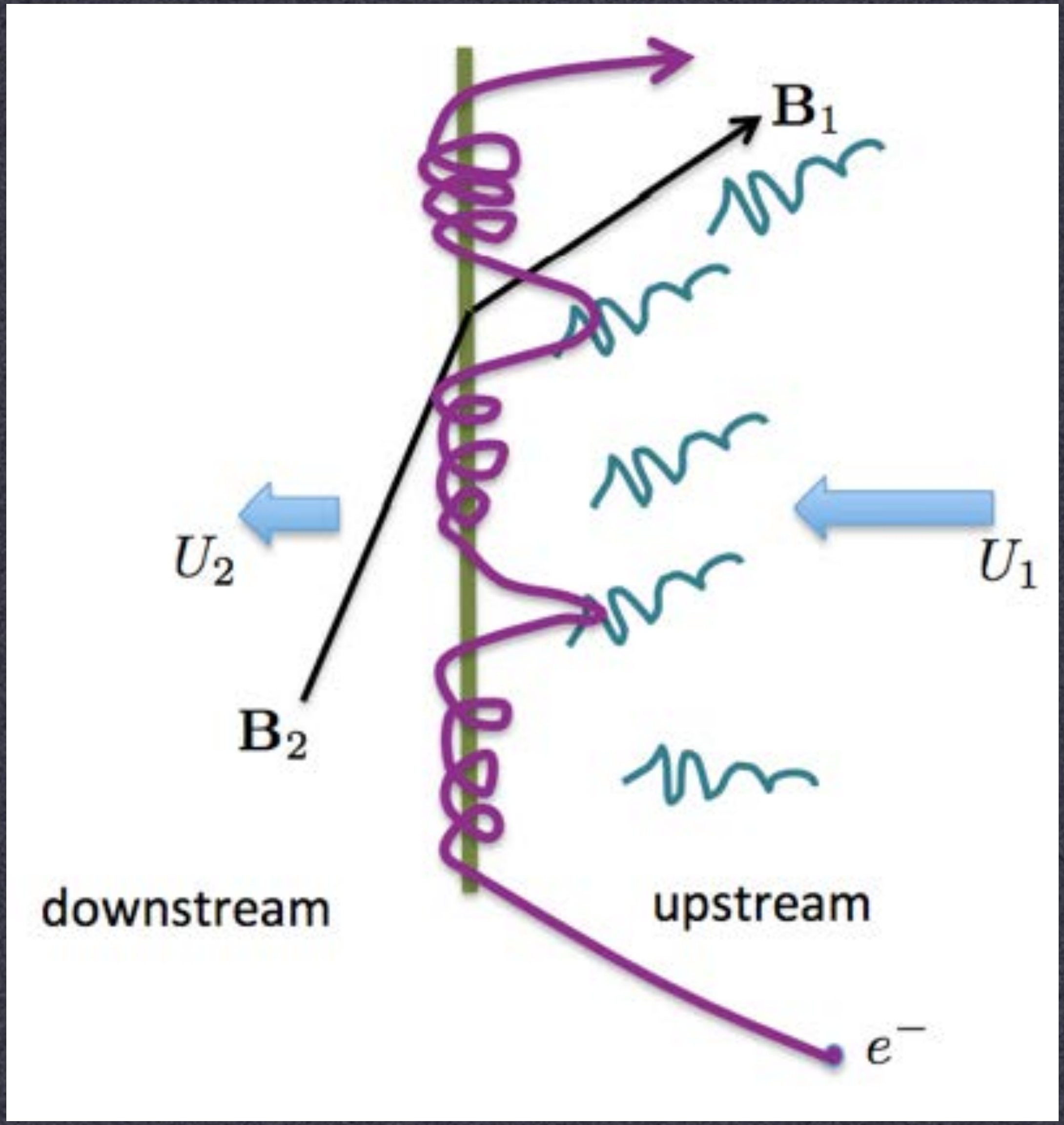


DSA spectrum recovered in _both_ electrons and ions
Electron-proton ratio can be measured!

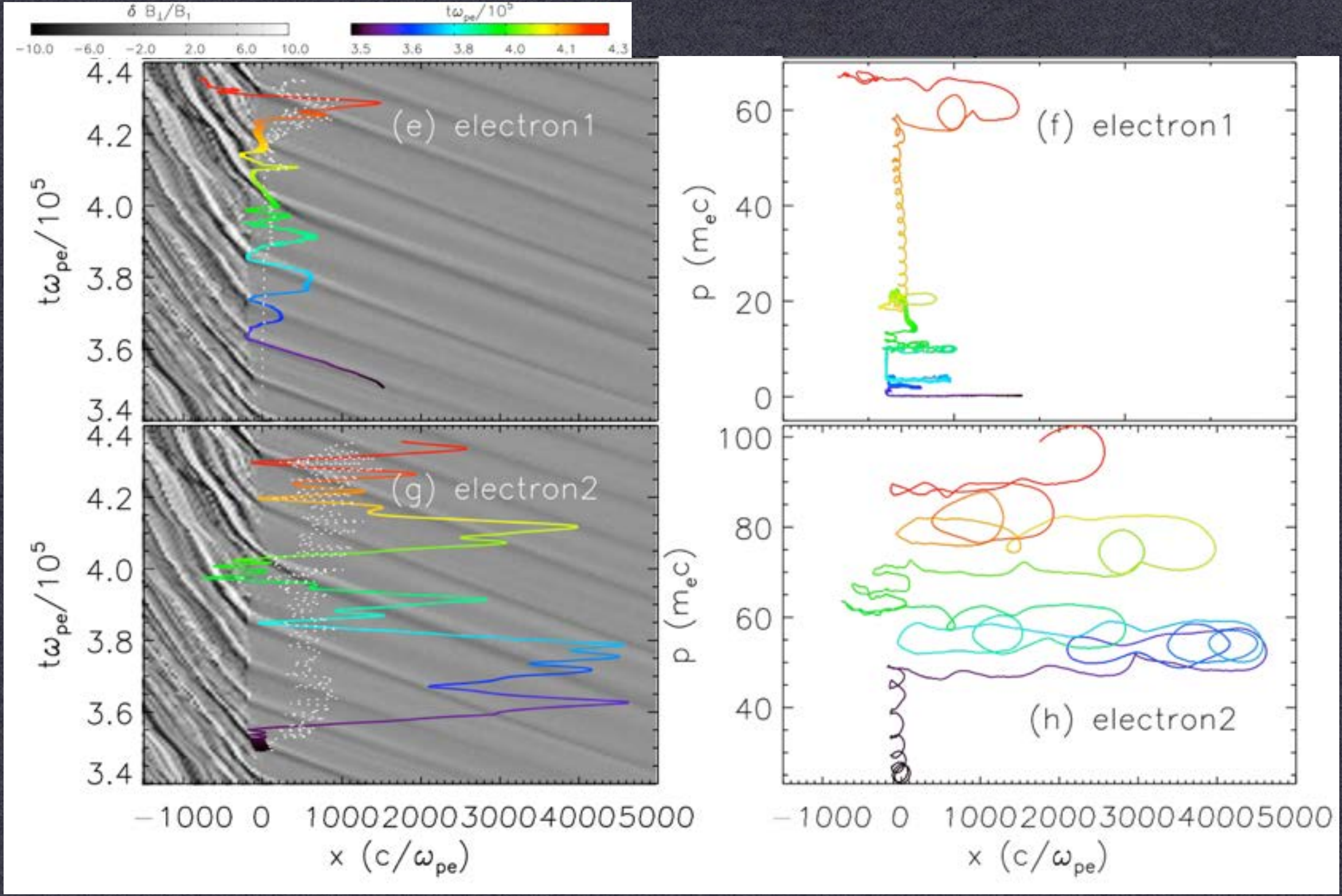
Park, Caprioli, AS (2015)

Electron acceleration at parallel shocks

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



Electron acceleration mechanism: shock drift cycles

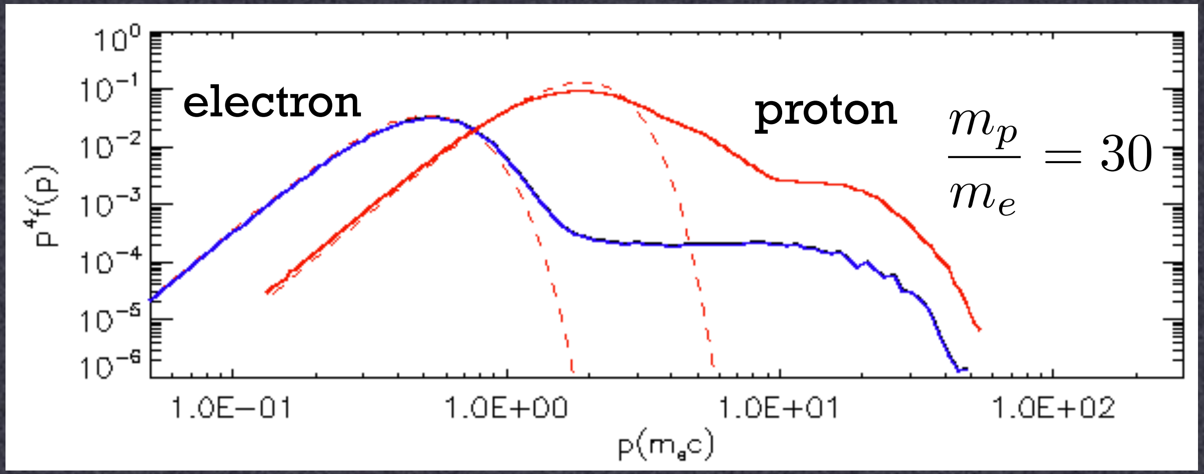


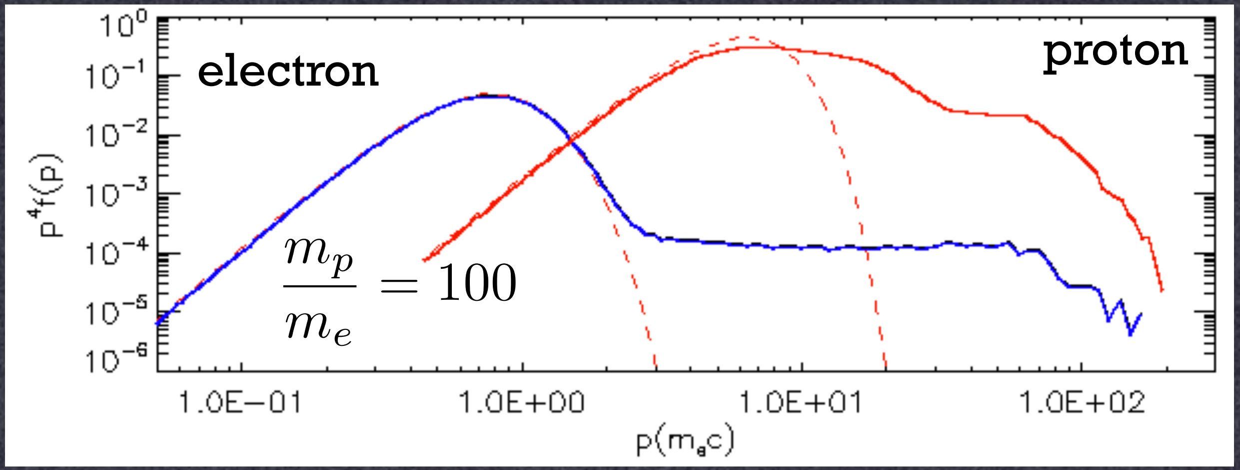
Shock-drift

Diffusive

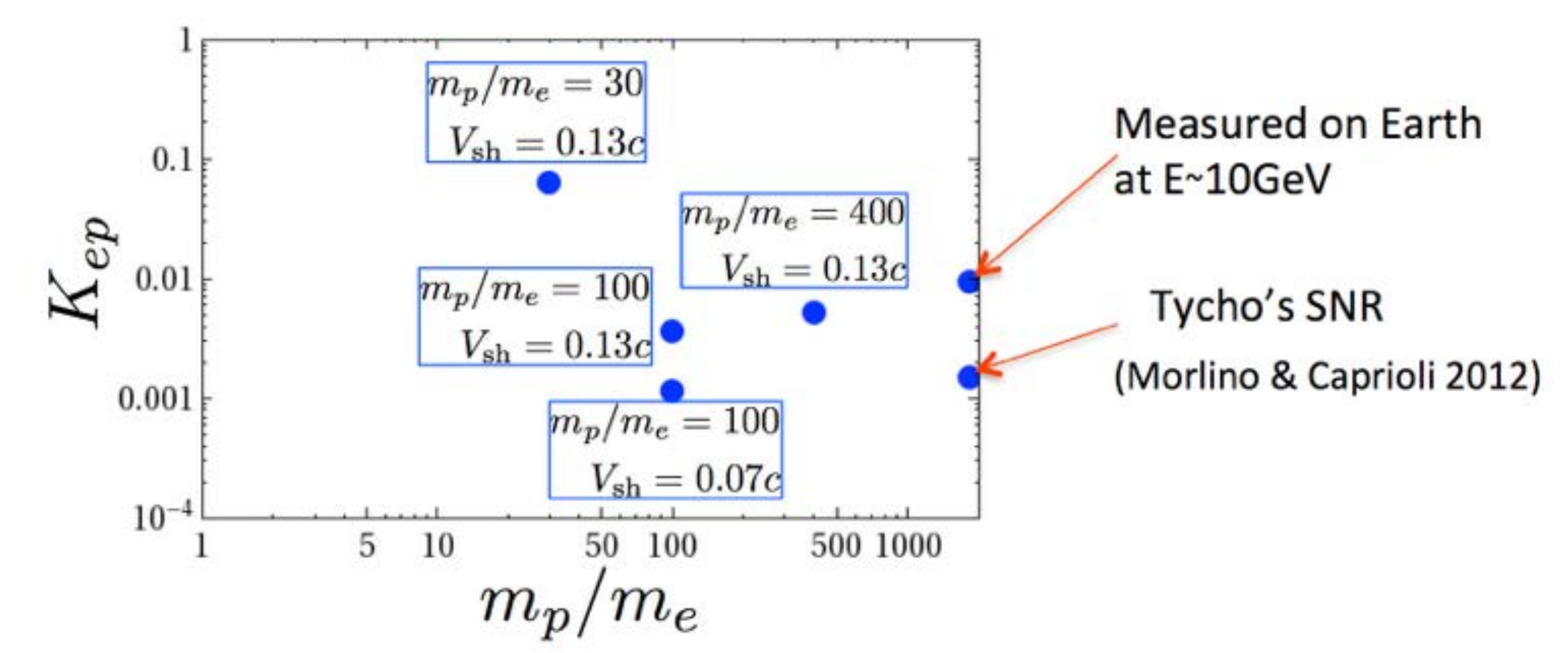
Electron track from PIC simulation.

Electron-proton ratio K_{ep}:





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



Measured on Earth at E~10GeV

Tycho's SNR

(Morlino & Caprioli 2012)

Shock acceleration: emerging picture

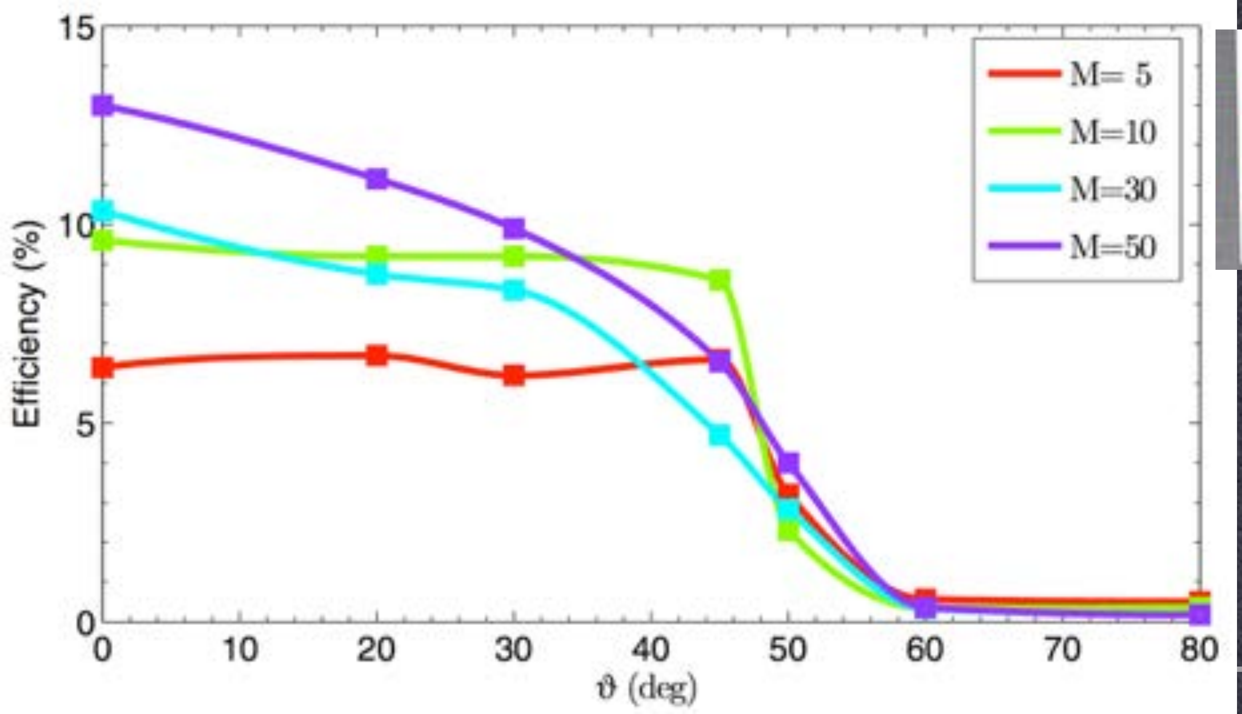
Acceleration in laminar field:

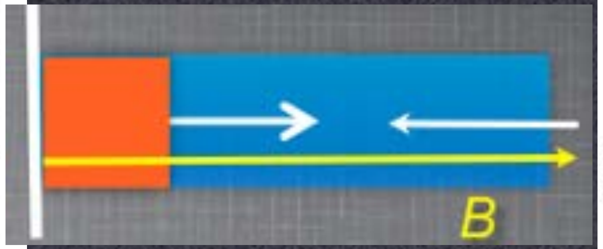
quasi-parallel -- accelerate both ions and electrons

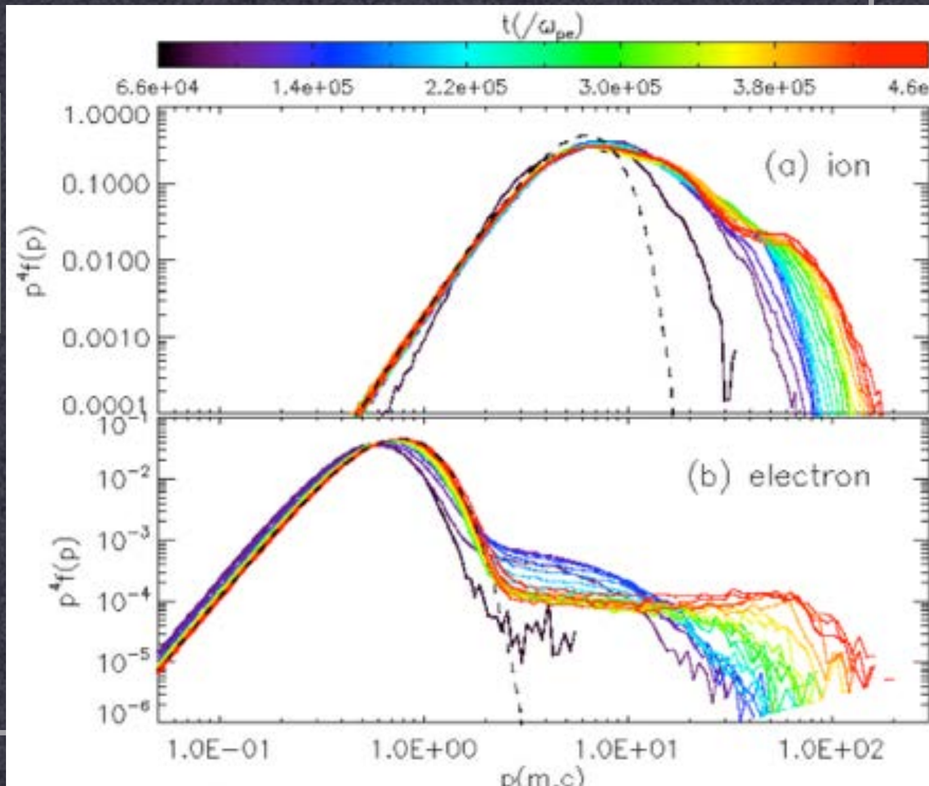
(Caprioli & AS, 2014abc; Park, Caprioli, AS 2015)

quasi-perpendicular -- accelerate mostly electrons

(Guo, Sironi & Narayan 2014; Caprioli, Park, AS in prep)







Shock acceleration: emerging picture

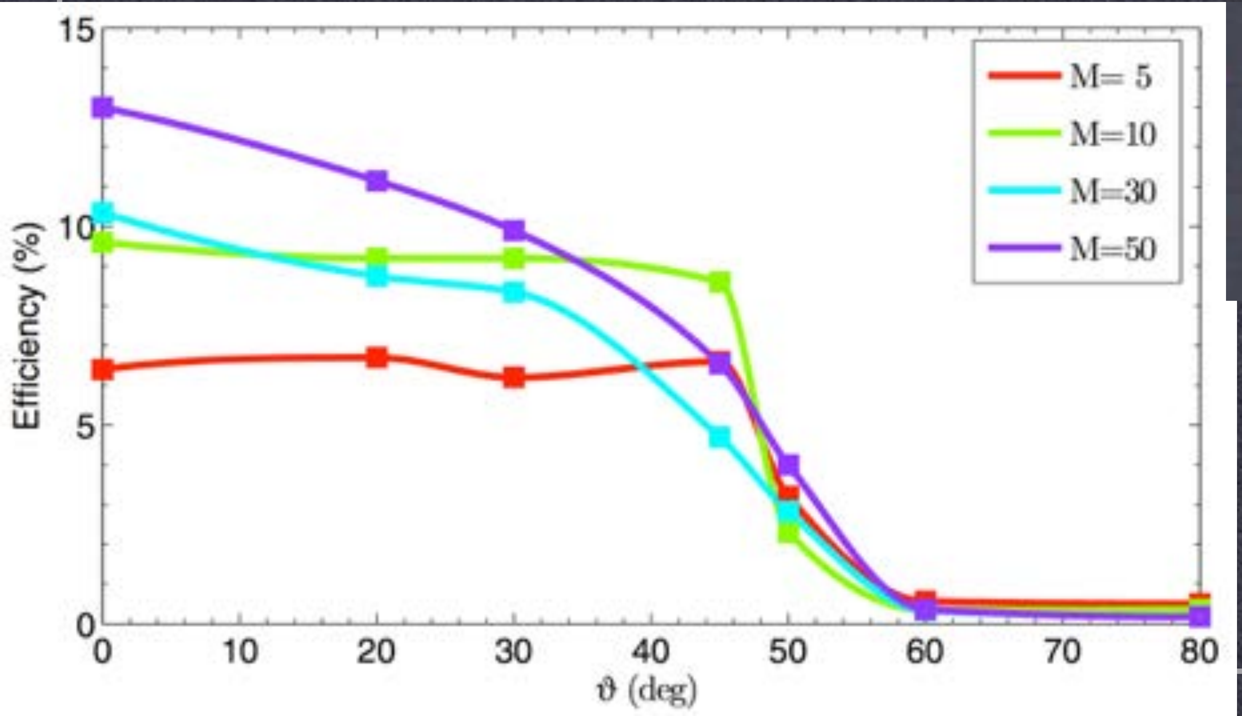
Acceleration in laminar field:

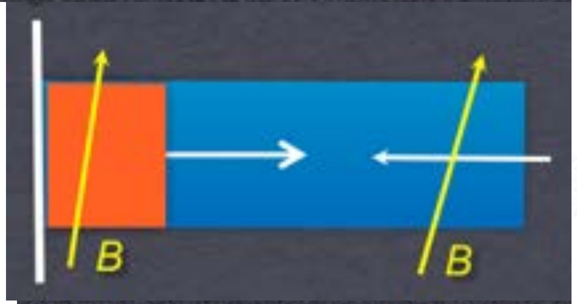
quasi-parallel -- accelerate both ions and electrons

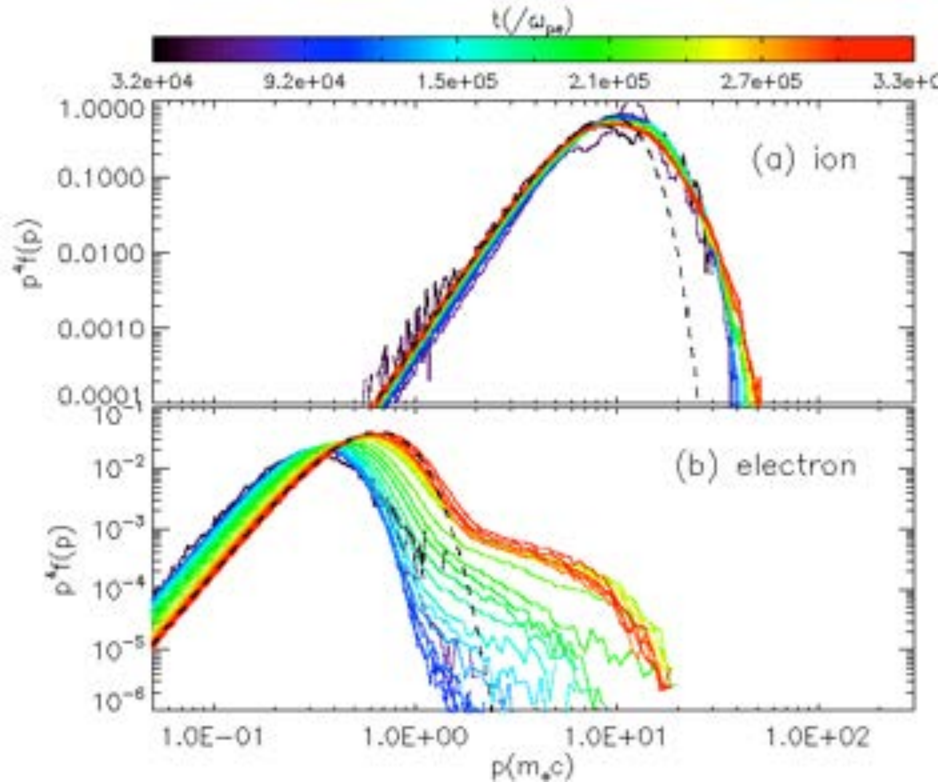
(Caprioli & AS, 2014abc; Park, Caprioli, AS 2015)

quasi-perpendicular -- accelerate mostly electrons

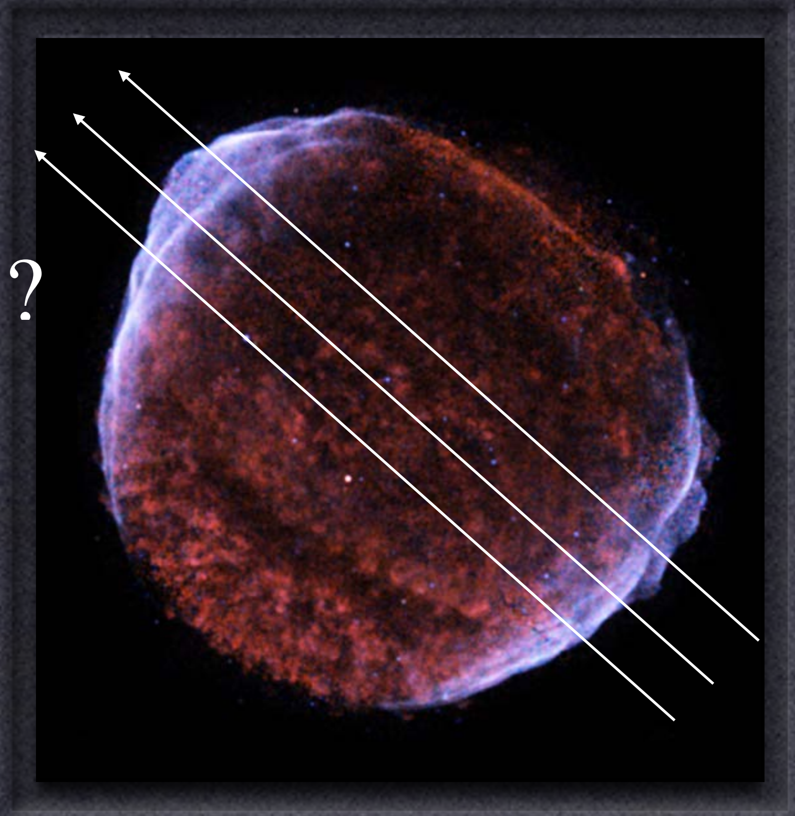
(Guo, Sironi & Narayan 2014; Caprioli, Park, AS in prep)







SNR story



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

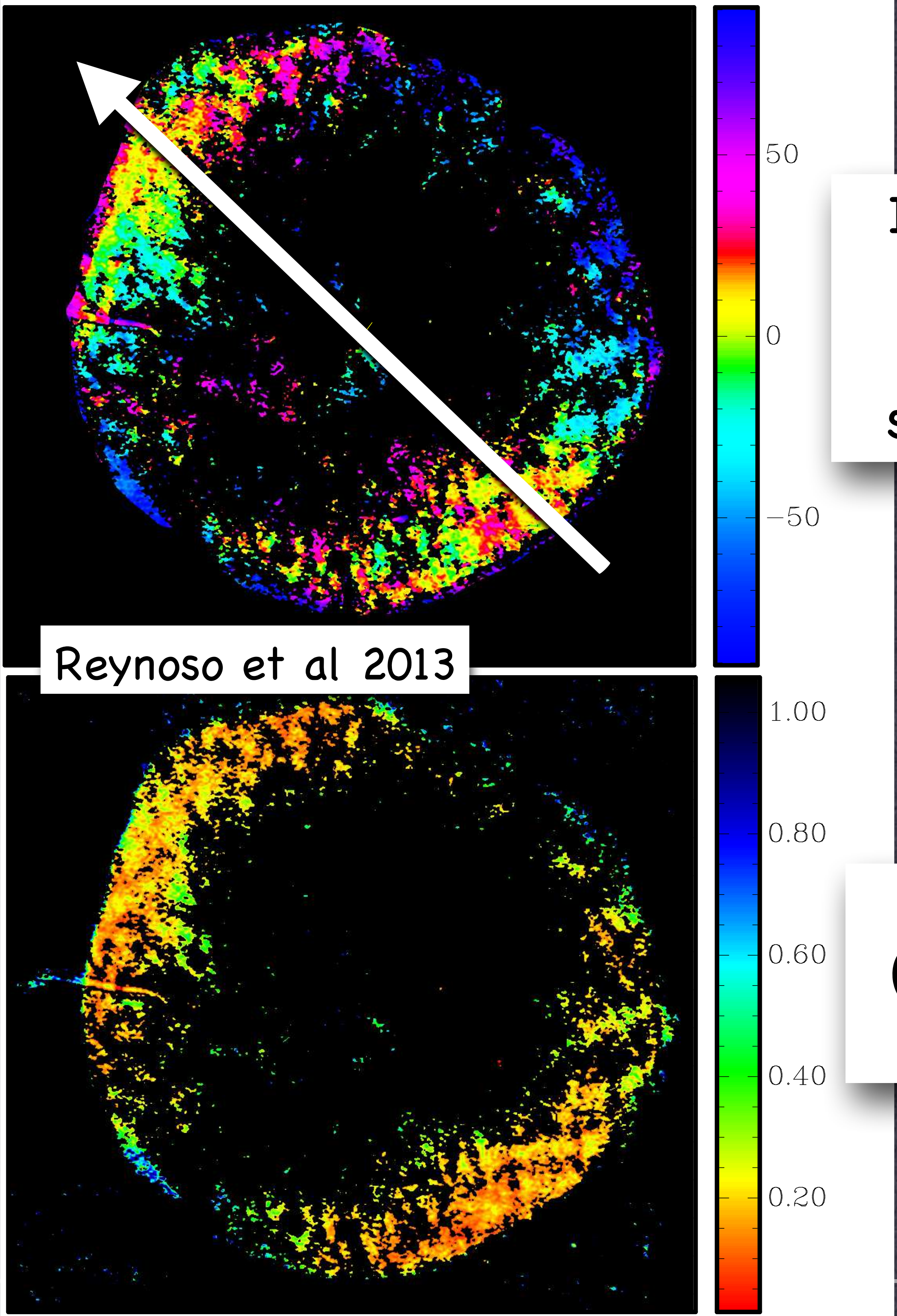
Locally-transverse field enters the shock, and causes electron injection and DSA.

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

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

SN1006: a parallel accelerator

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



Reynoso et al 2013

Inclination of the B field wrt to the shock normal

Polarization
(low=turbulent
high=ordered)

Magnetic field amplification and particle acceleration where the shock is parallel

Shocking astrophysics

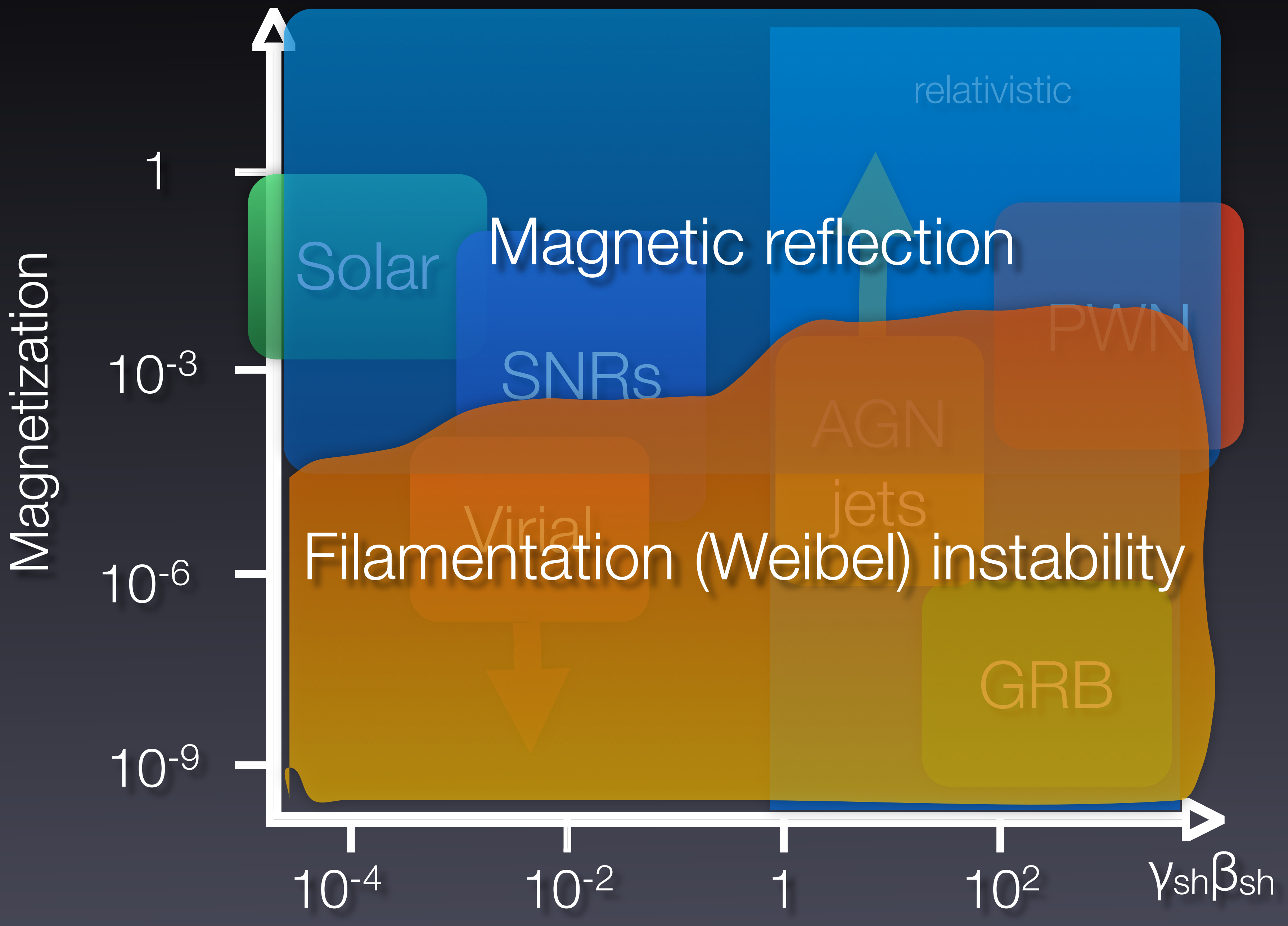
Open issues:

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

Particle acceleration -- Fermi mechanism? Other? Efficiency?

Equilibration between ions and electrons?

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



Shocking astrophysics

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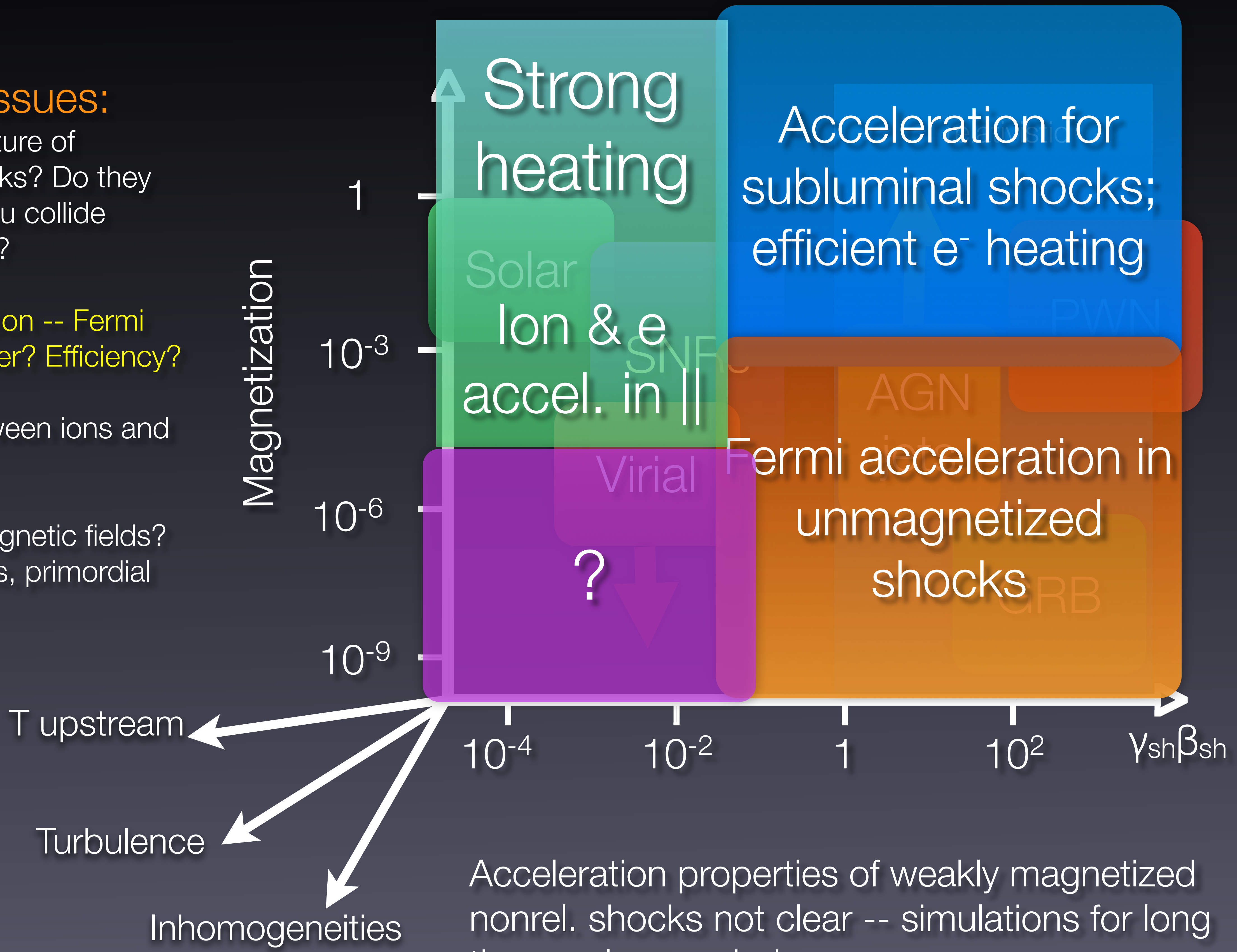


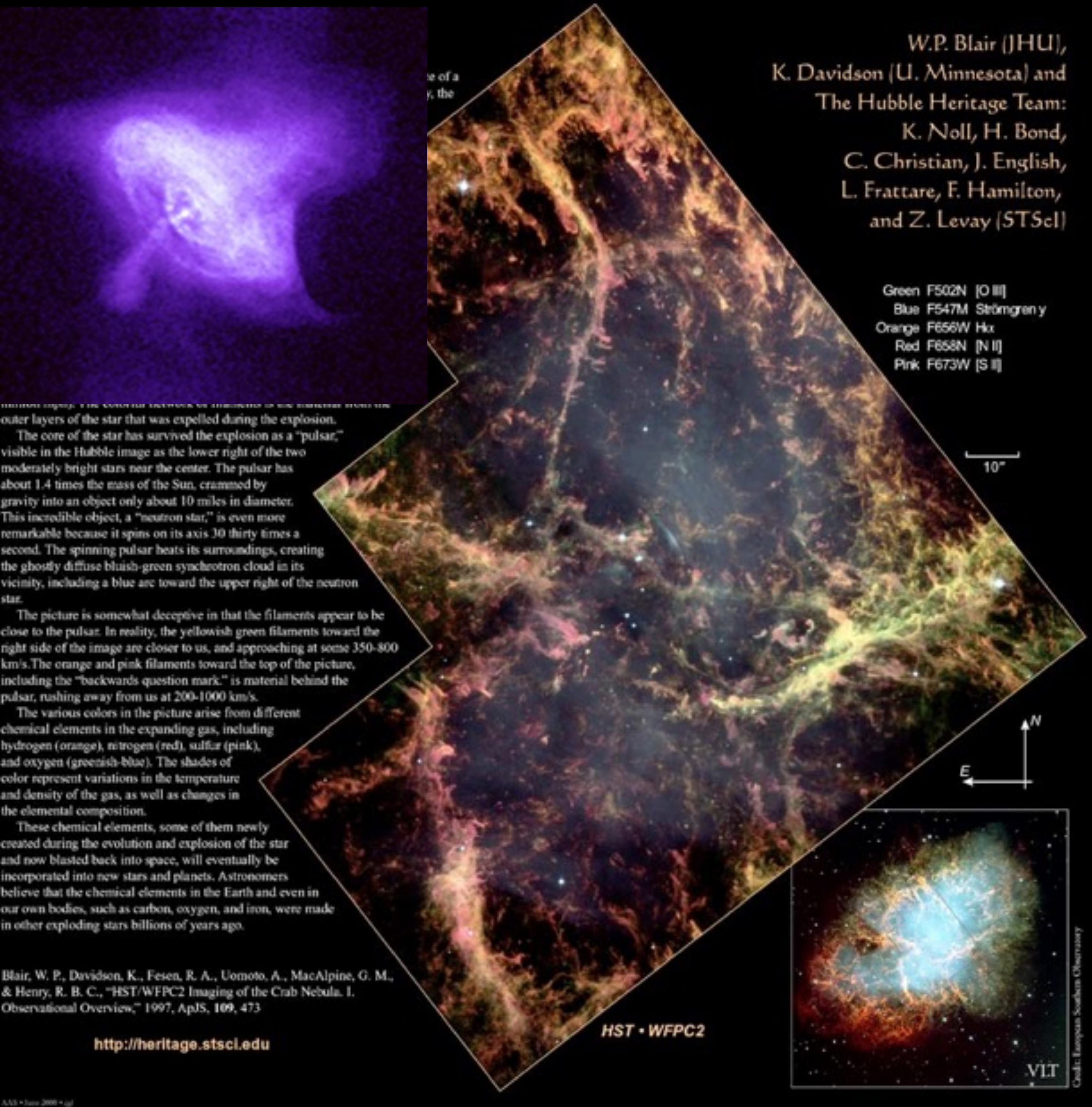
Acceleration properties of weakly magnetized nonrel. shocks not clear -- simulations for long time scales needed

Relativistic magnetospheres

with X. Bai, M. Belyaev, J. Li, A. Philippov, A. Tchekhovskoy

Pulsars

- ***Pulsars are neutron stars, born in supernova explosions***



W.P. Blair (JHU),
K. Davidson (U. Minnesota) and
The Hubble Heritage Team:
K. Noll, H. Bond,
C. Christian, J. English,
L. Frattare, F. Hamilton,
and Z. Levay (STScI)

outer layers of the star that was expelled during the explosion.

The core of the star has survived the explosion as a "pulsar," visible in the Hubble image as the lower right of the two moderately bright stars near the center. The pulsar has about 1.4 times the mass of the Sun, crammed by gravity into an object only about 10 miles in diameter. This incredible object, a "neutron star," is even more remarkable because it spins on its axis 30 thirty times a second. The spinning pulsar heats its surroundings, creating the ghostly diffuse bluish-green synchrotron cloud in its vicinity, including a blue arc toward the upper right of the neutron star.

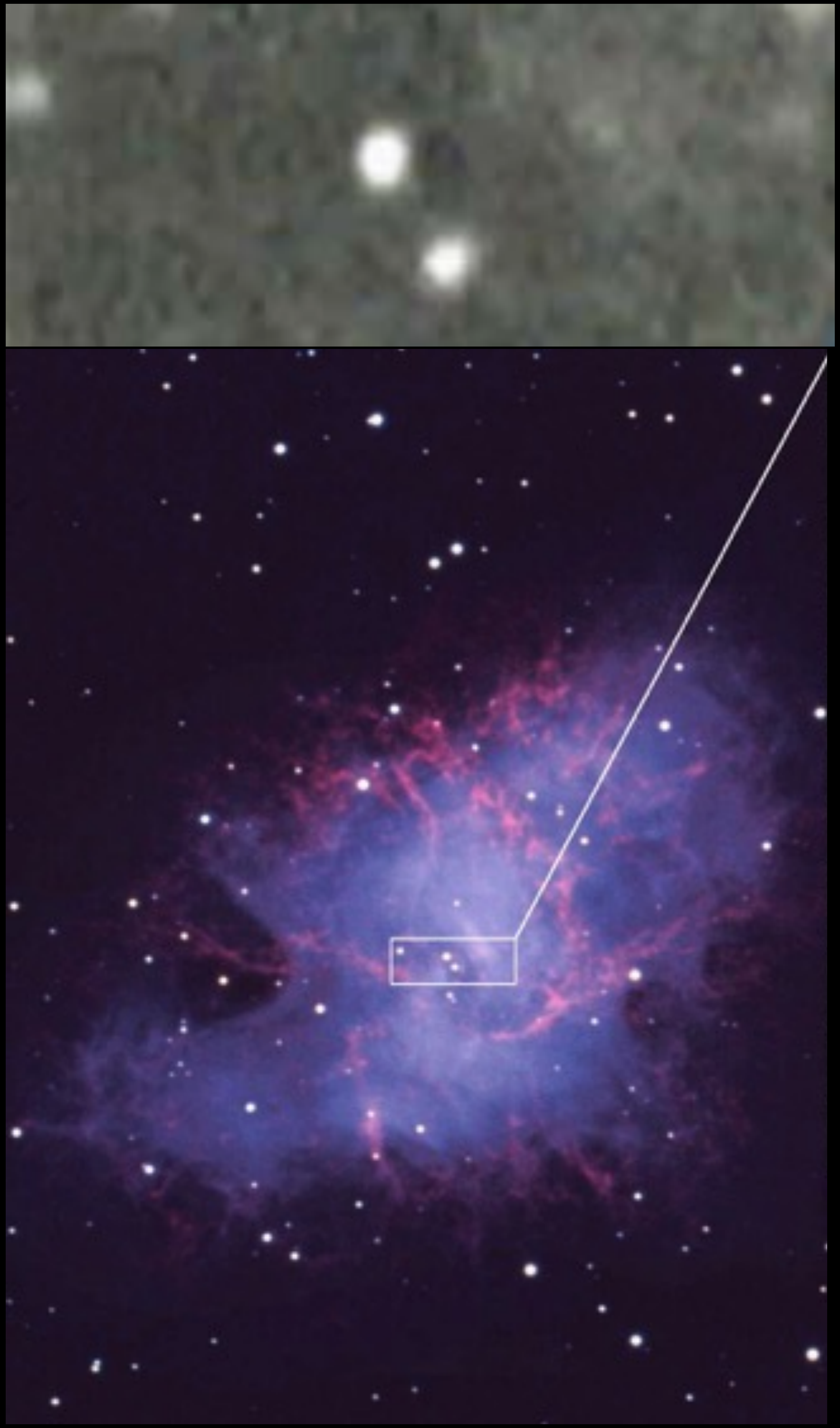
The picture is somewhat deceptive in that the filaments appear to be close to the pulsar. In reality, the yellowish green filaments toward the right side of the image are closer to us, and approaching at some 350-800 km/s. The orange and pink filaments toward the top of the picture, including the "backwards question mark," is material behind the pulsar, rushing away from us at 200-1000 km/s.

The various colors in the picture arise from different chemical elements in the expanding gas, including hydrogen (orange), nitrogen (red), sulfur (pink), and oxygen (greenish-blue). The shades of color represent variations in the temperature and density of the gas, as well as changes in the elemental composition.

These chemical elements, some of them newly created during the evolution and explosion of the star and now blasted back into space, will eventually be incorporated into new stars and planets. Astronomers believe that the chemical elements in the Earth and even in our own bodies, such as carbon, oxygen, and iron, were made in other exploding stars billions of years ago.

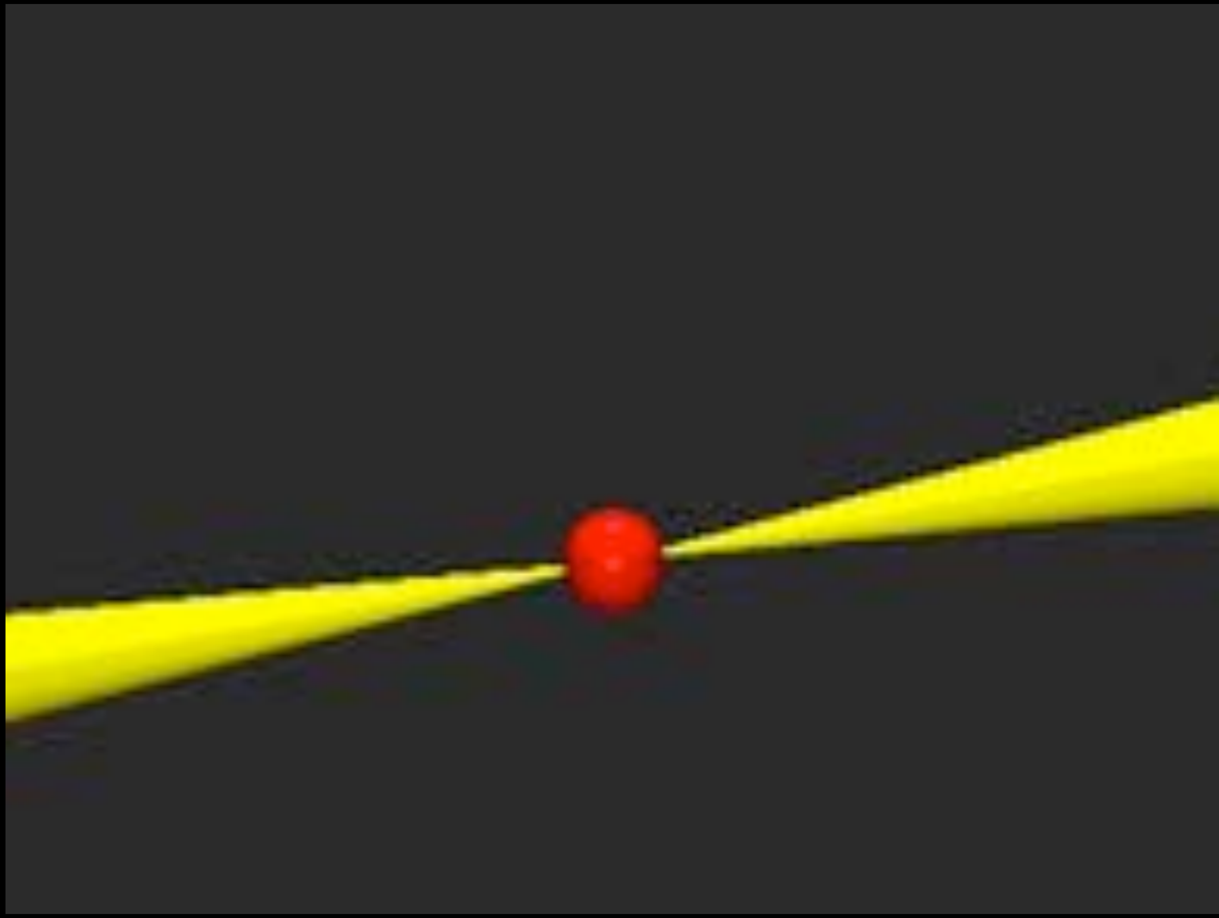
Blair, W. P., Davidson, K., Fesen, R. A., Uomoto, A., MacAlpine, G. M., & Henry, R. B. C., "HST/WFPC2 Imaging of the Crab Nebula. I. Observational Overview," 1997, ApJS, **109**, 473

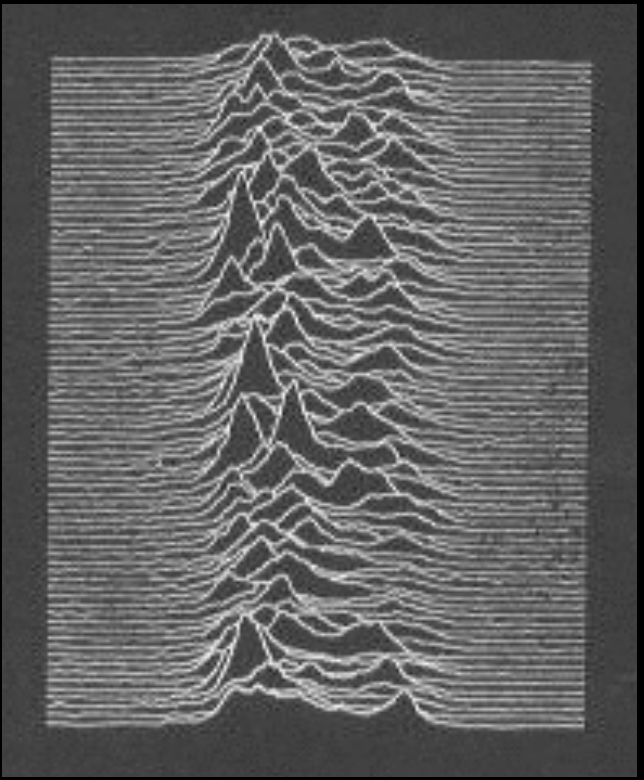
http://heritage.stsci.edu

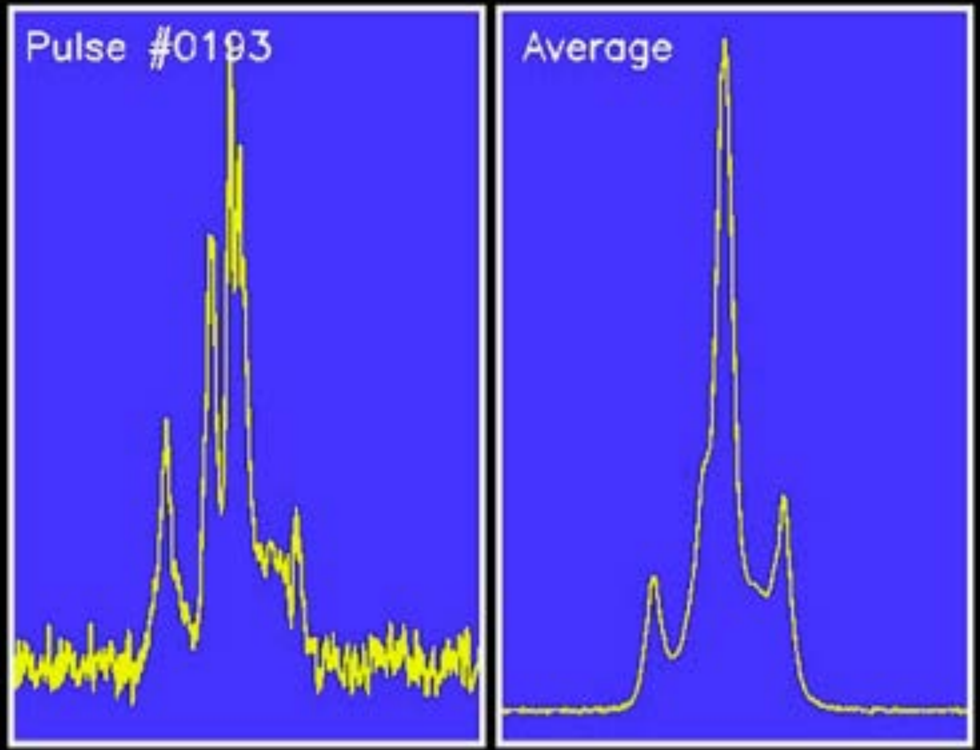


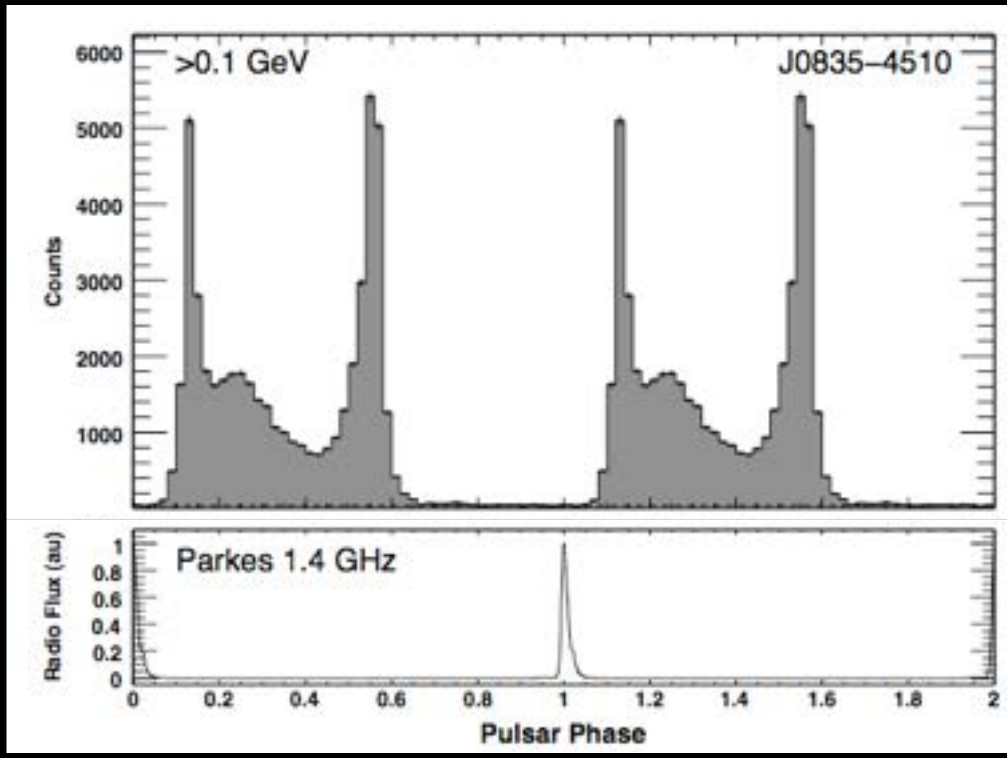
Pulsars: cosmic lighthouses

- *Neutron Star -- 10km in radius, 1.4 Solar Mass*
- *Central densities -- density of nuclei*
- *Gravity is 100 billion times Earth gravity*
- *Pulsars emit from radio to gamma ray*
- *Spin periods -- from 1.5 ms (700 Hz!) to 8 sec*
- *Individual pulses quite different, but average profile is very stable (geometry)*
- *Sweeping dipole magnetic field*
- *Pulsars spin down -- inferred B field 10^{12}G*

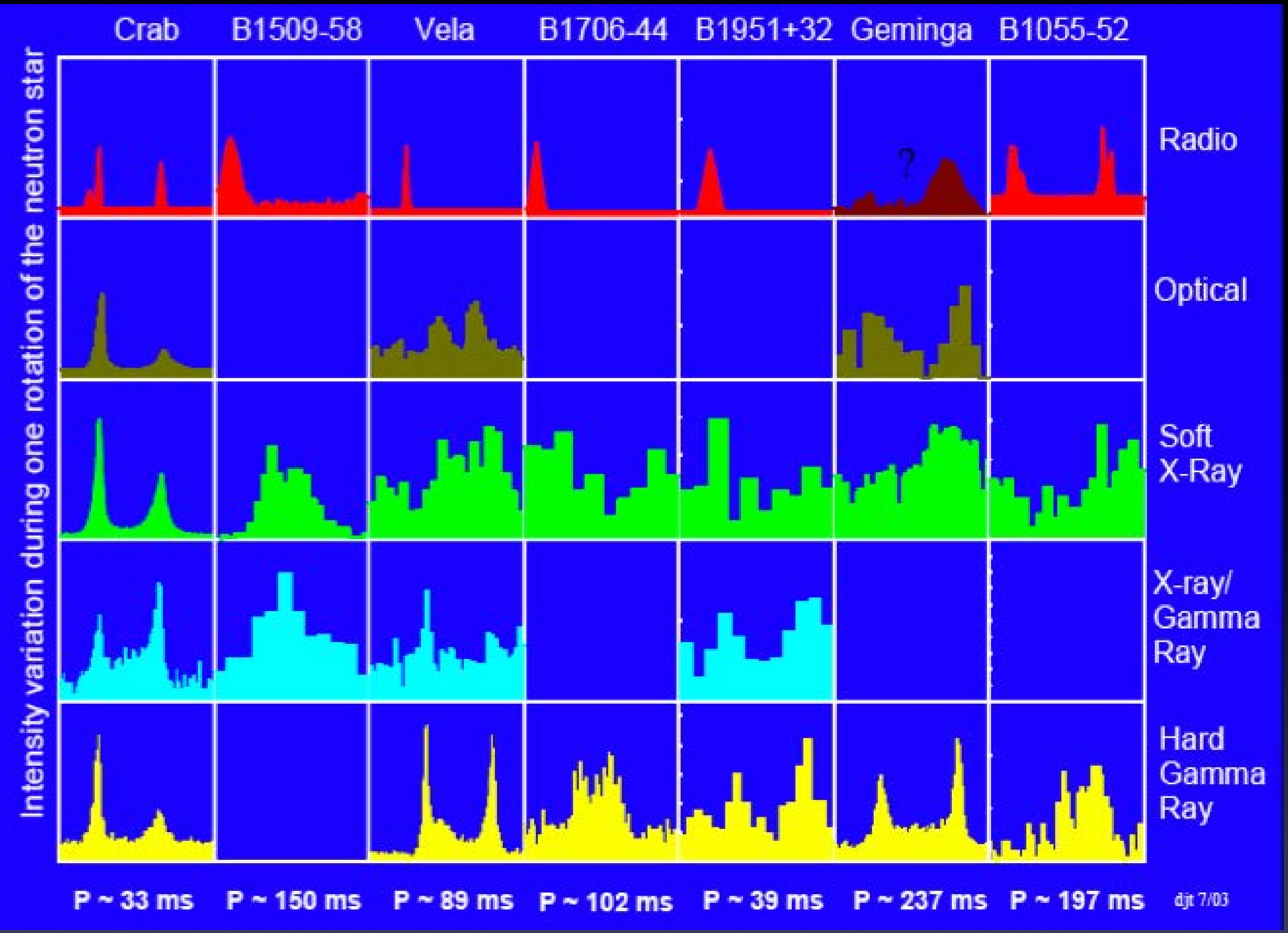


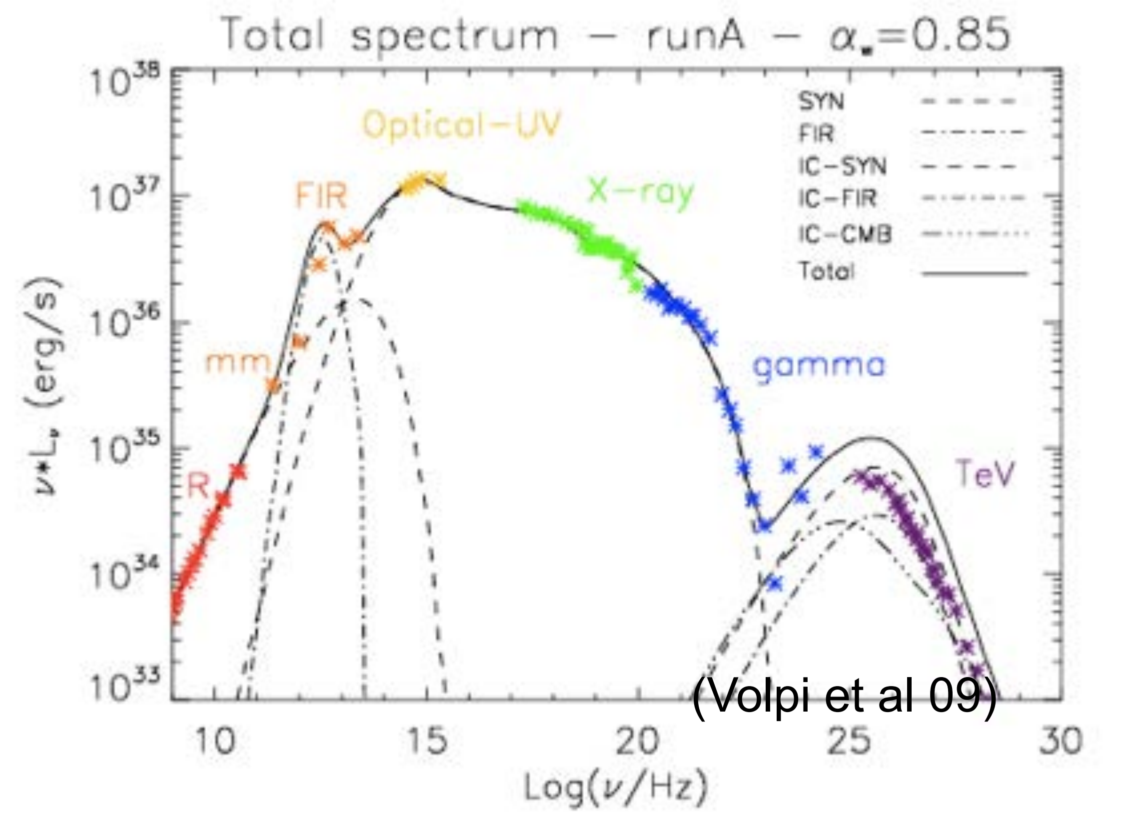




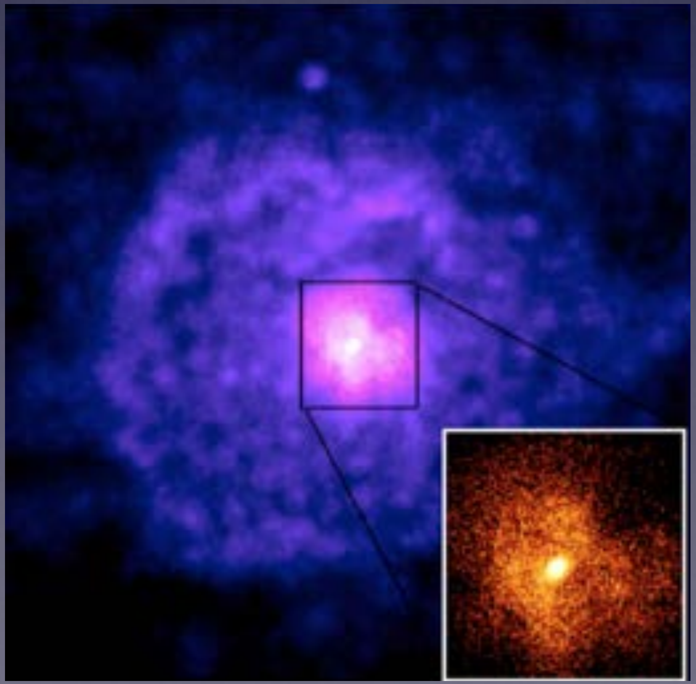


- Broadband pulsed emission, now > 100 GeV (Veritas).
- PWNe: radio-TeV. 10^{40} pairs/sec. Also, flares!

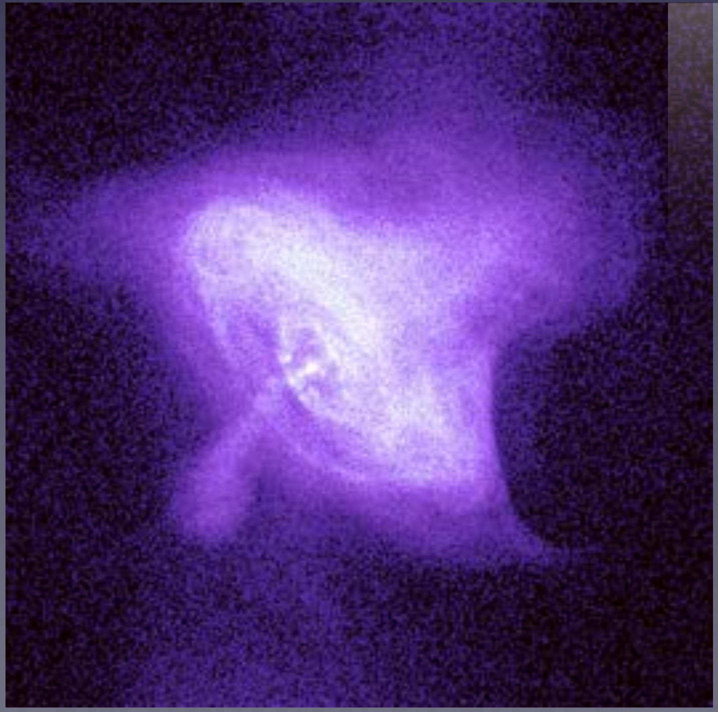




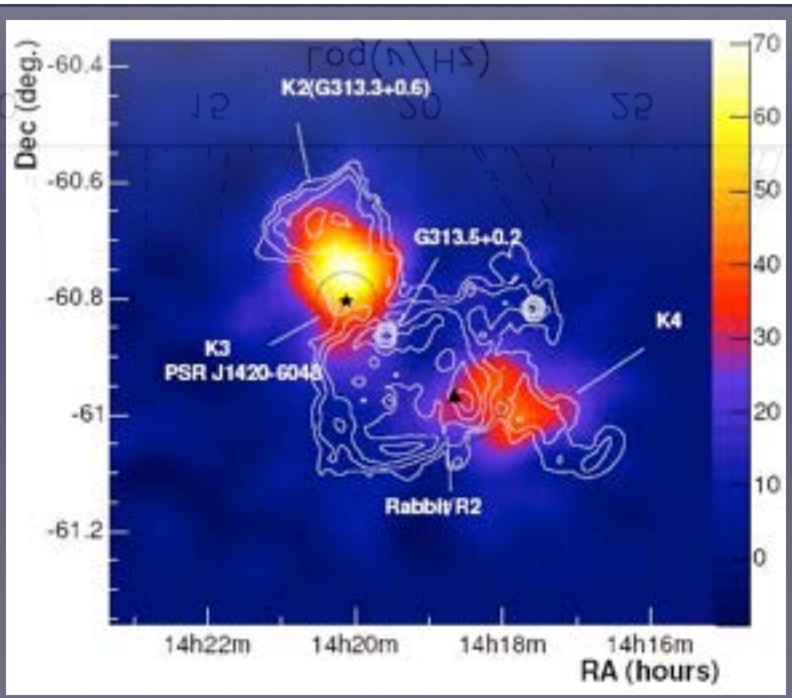
(Volpi et al 09)



G21.9 (Safi-Harb et al 2004)



Crab (Weisskopf et al 2000)



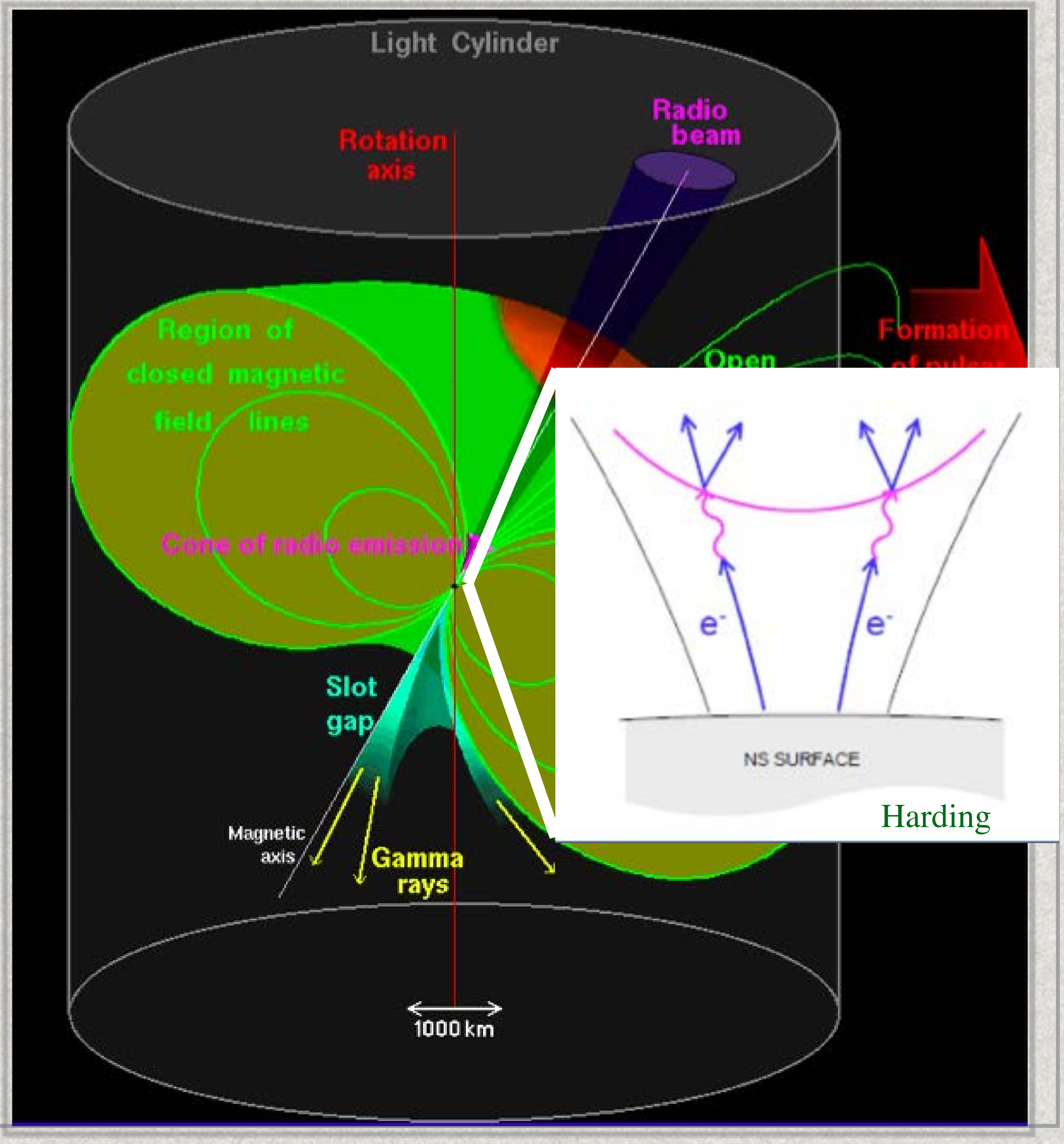
HESS J1420 (Aharonian et al 2006)

Open questions:

- What is the structure of pulsar magnetosphere and how do pulsars spin down?
- What are the properties of the wind near pulsar? In the nebula?
- What causes pulsed emission?
- How are observed spectra generated? (how particles are accelerated?)

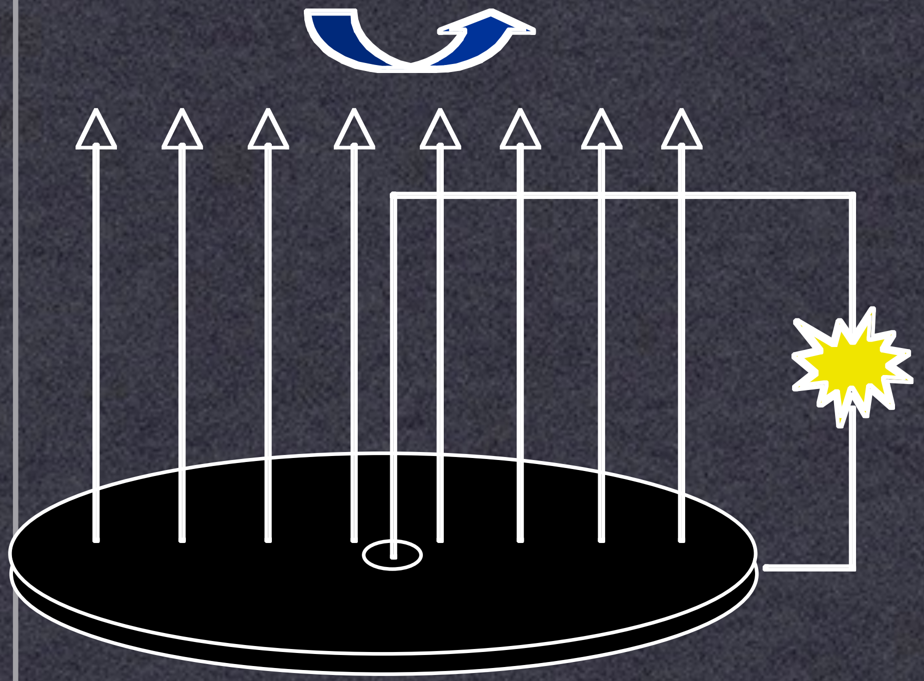
Magnetospheric cartoon

- Open & closed (corotating) zones.
- Light cylinder
- Sweepback
- Plasma is born in discharges
- Minimal (Goldreich-Julian) charge density



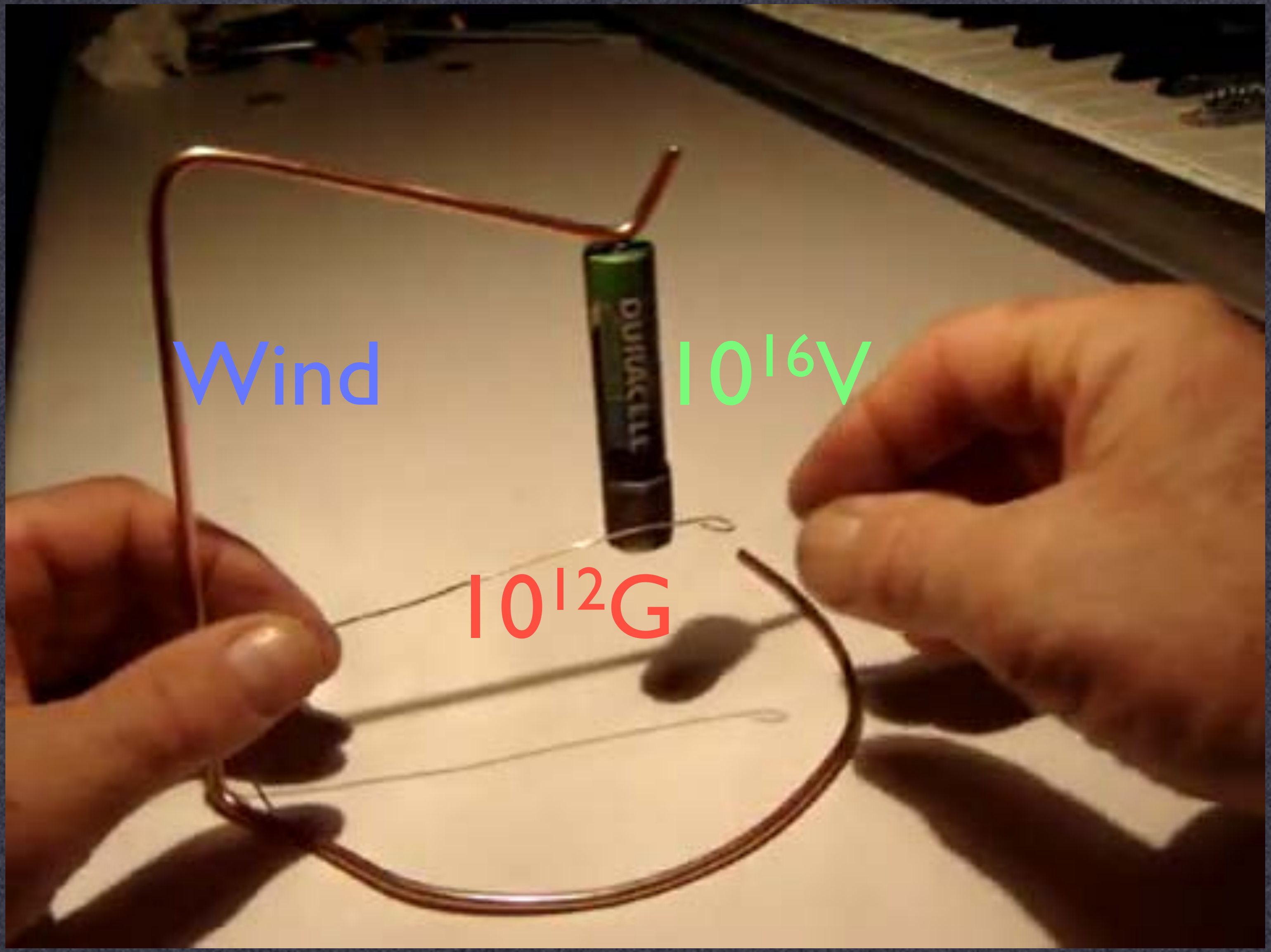
Harding

Pulsar physics: unipolar induction



Faraday disk

$$\phi_0 = \Omega B a^2 / c$$

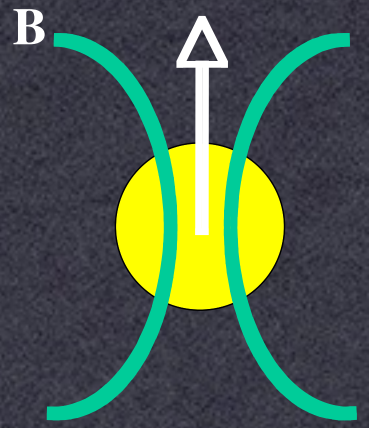


Pulsar “in reverse”

Rule of thumb: $V \sim \Omega\Phi;\ \ P \sim V^2 / Z_0 = I\,V$

Crab: B ~ 10^{12} G, Ω ~ 200 rad s^{-1}, R ~ 10 km

Voltage ~ 3 x 10^{16} V; I ~ 3 x 10^{14} A; Power ~ 10^{38}erg/s



And yet it spins down...

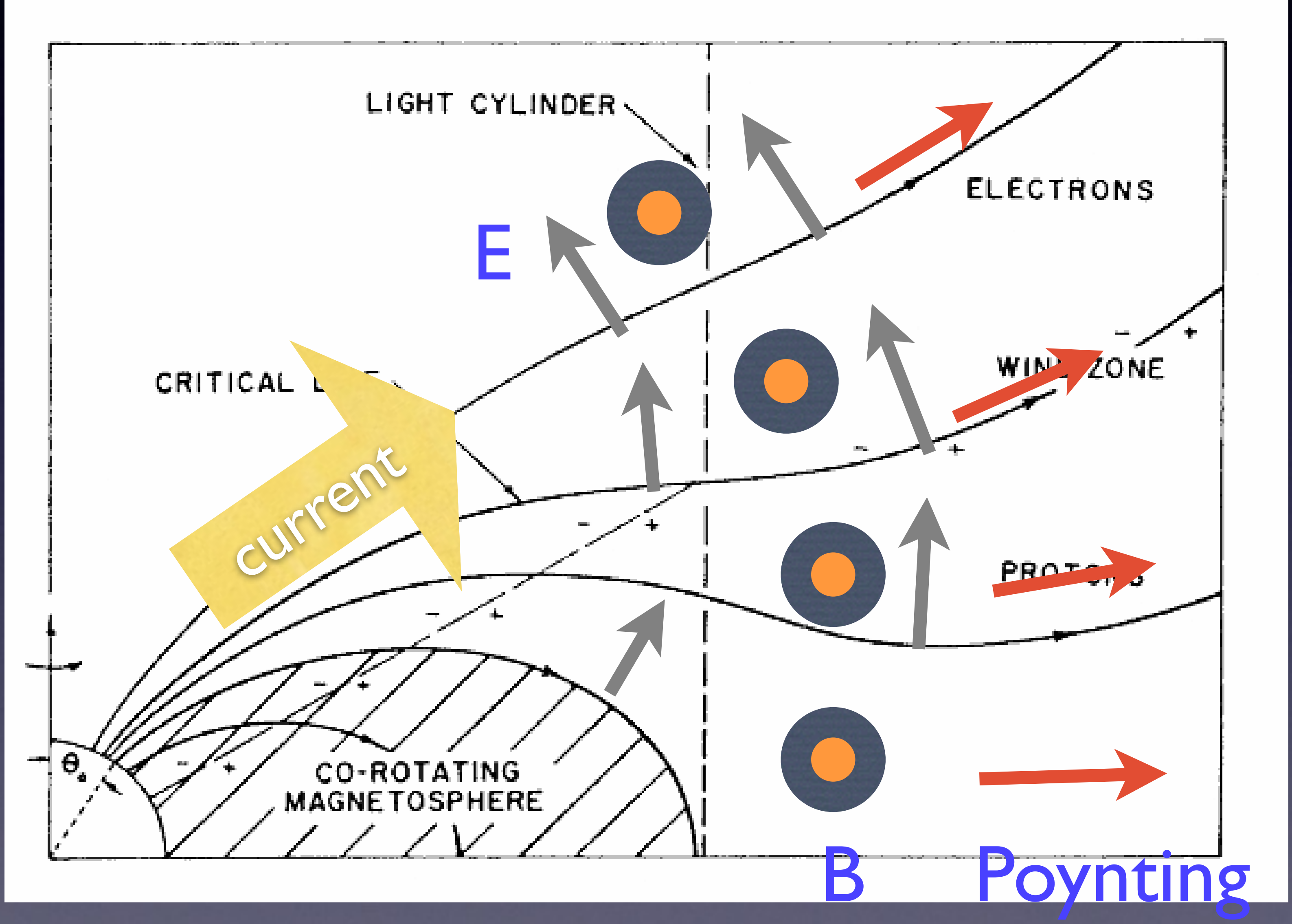
$$j_{GJ} = \rho_{GJ} c = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi}$$

$$\frac{1}{4\pi}\nabla\cdot\vec{E} = \rho_{GJ} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}$$

$$\rho_{GJ} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}$$

- Corotation electric field
- Sweepback of B field due to poloidal current
- ExB -> Poynting flux

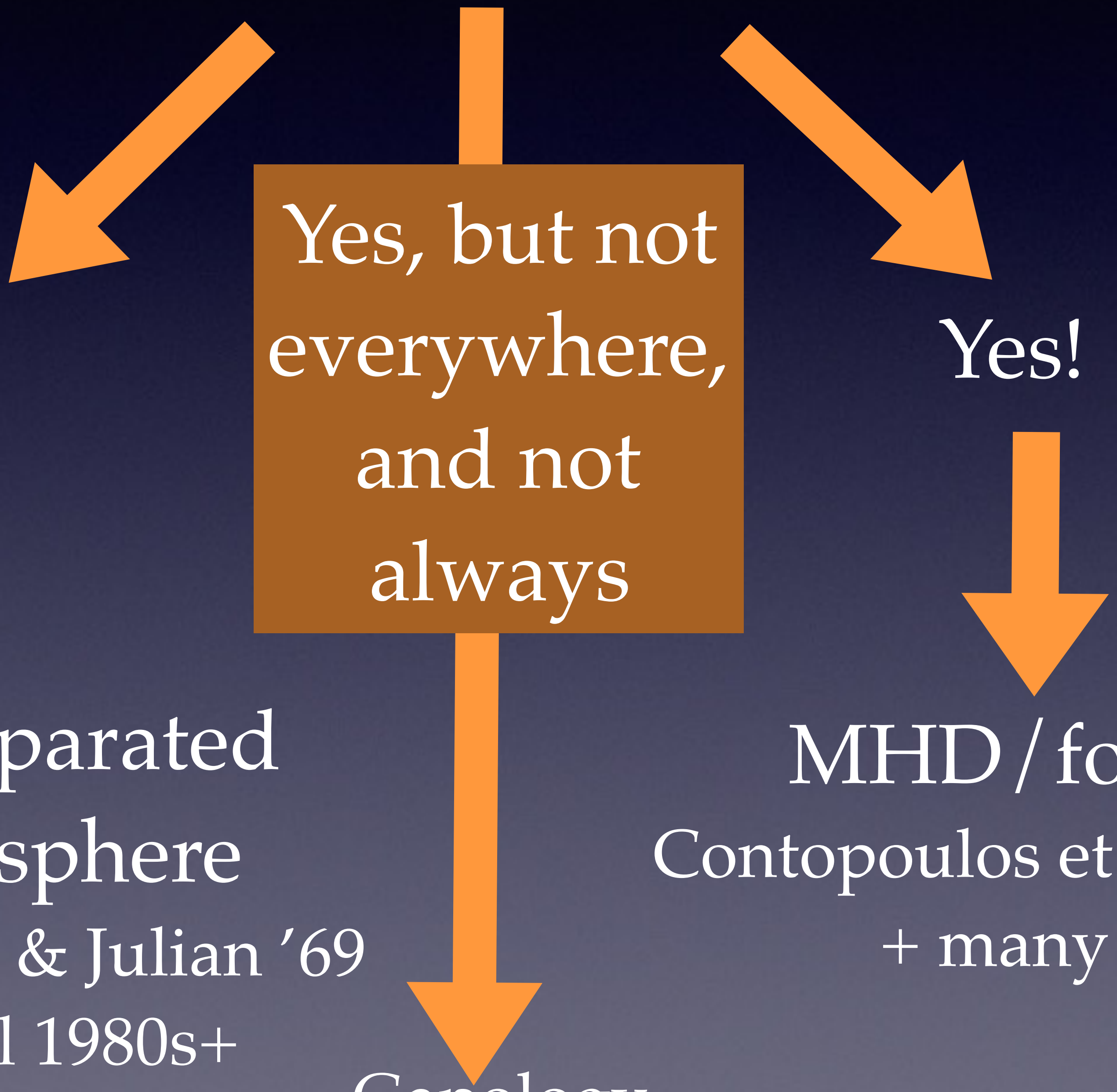
- Electromagnetic energy loss



Goldreich & Julian 1969

MODELING: TWO PATHS

Is there dense ($n \gg n_{GJ}$) plasma in the magnetosphere?



No!

Charge separated magnetosphere

as in Golderich & Julian ’69

Michel et al 1980s+

Yes, but not everywhere, and not always

Gapology

(Ruderman et al, Cheng et al, Romani, Harding)

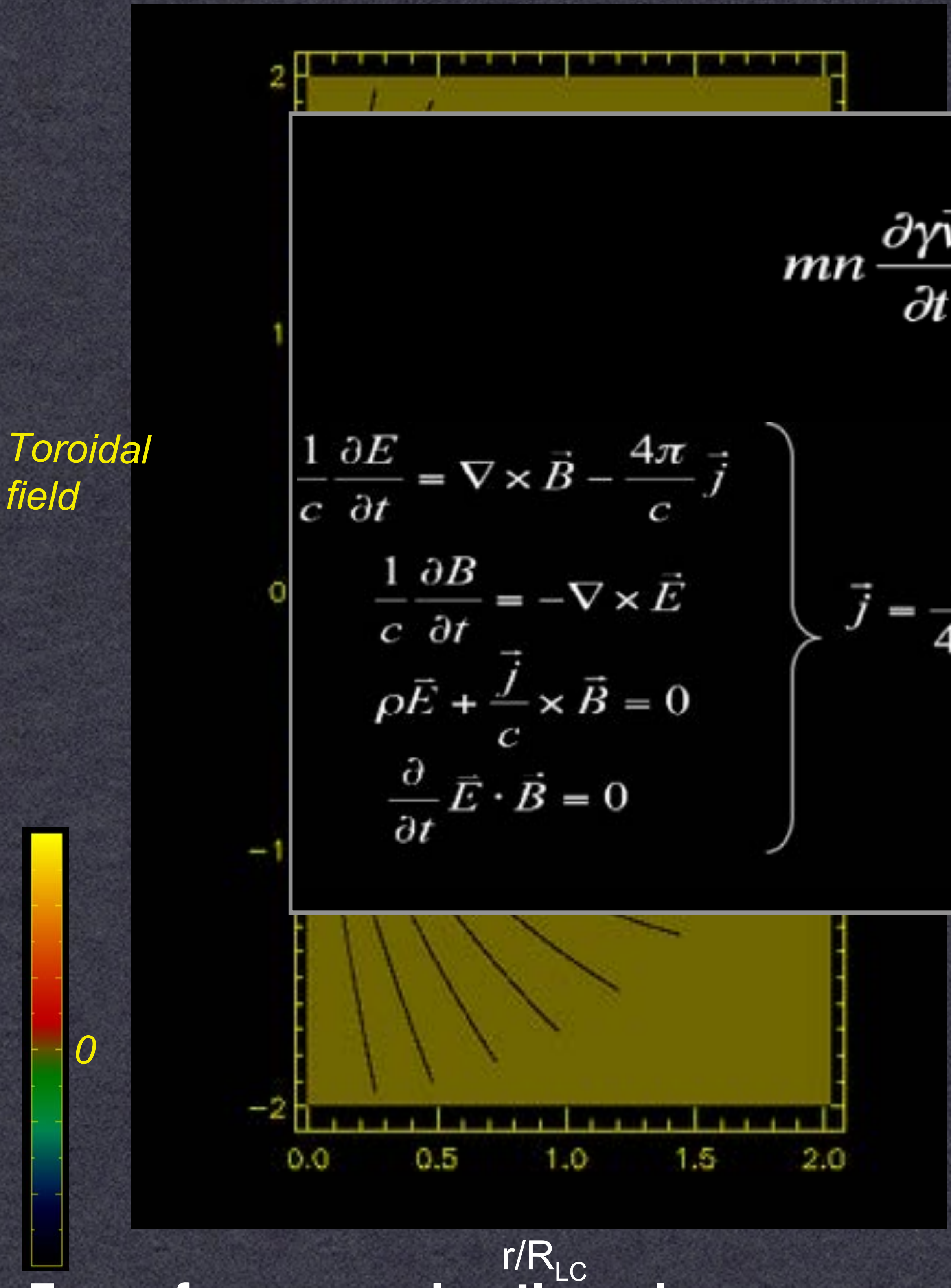
Yes!

MHD / force-free

Contopoulos et al 1999, AS 06

+ many others

Aligned rotator: plasma magnetosphere



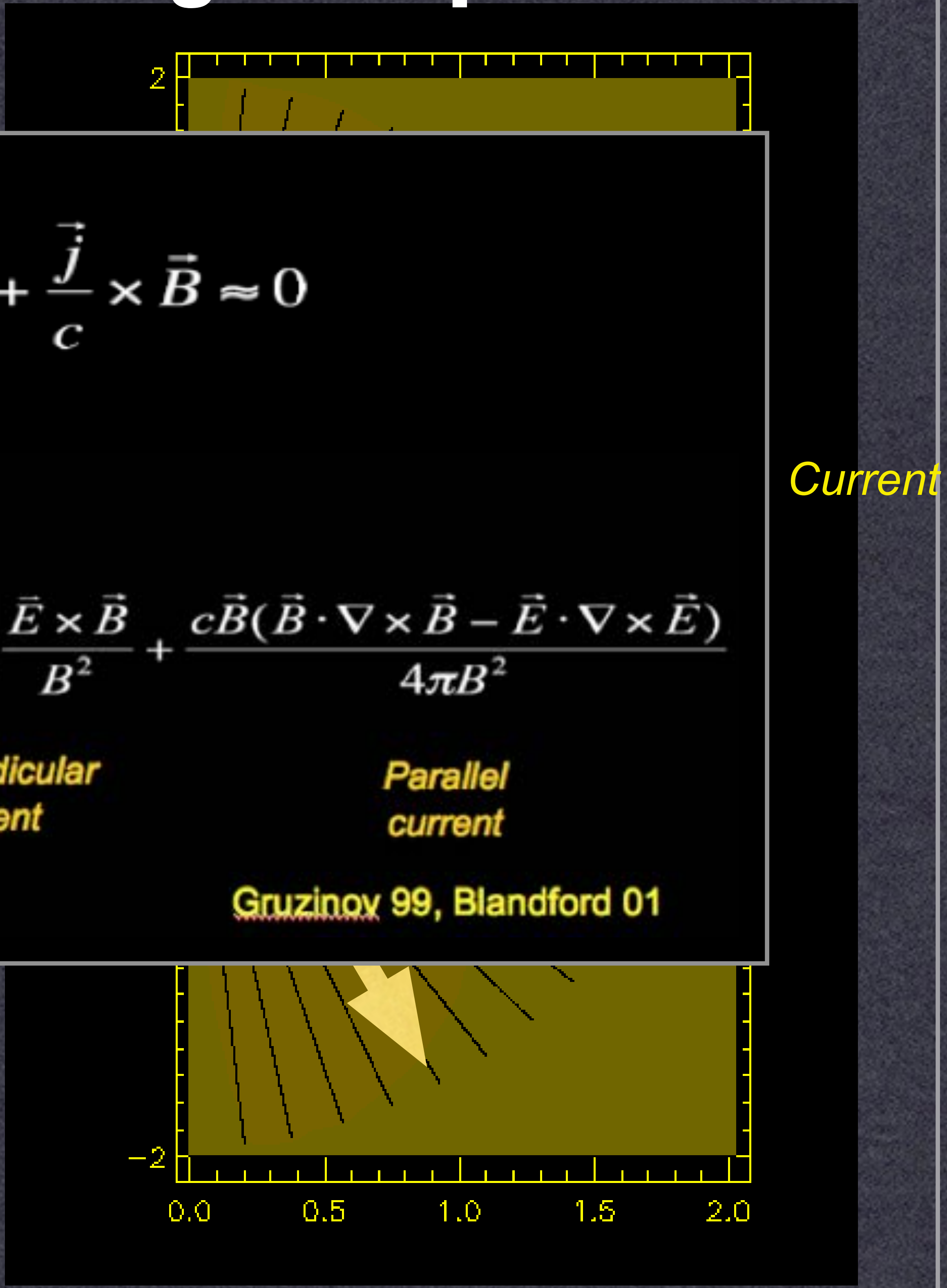
$$mn\frac{\partial\gamma\vec{v}}{\partial t} = \rho\vec{E} + \frac{\vec{j}}{c}\times\vec{B} \approx 0$$

$$\left.\begin{aligned} \frac{1}{c}\frac{\partial E}{\partial t} &= \nabla\times\vec{B} - \frac{4\pi}{c}\vec{j} \\ \frac{1}{c}\frac{\partial B}{\partial t} &= -\nabla\times\vec{E} \\ \rho\vec{E} + \frac{\vec{j}}{c}\times\vec{B} &= 0 \\ \frac{\partial}{\partial t}\vec{E}\cdot\vec{B} &= 0 \end{aligned}\right\} \vec{j} = \frac{c}{4\pi}(\nabla\cdot\vec{E})\frac{\vec{E}\times\vec{B}}{B^2} + \frac{c\vec{B}(\vec{B}\cdot\nabla\times\vec{B} - \vec{E}\cdot\nabla\times\vec{E})}{4\pi B^2}$$

Perpendicular current

Parallel current

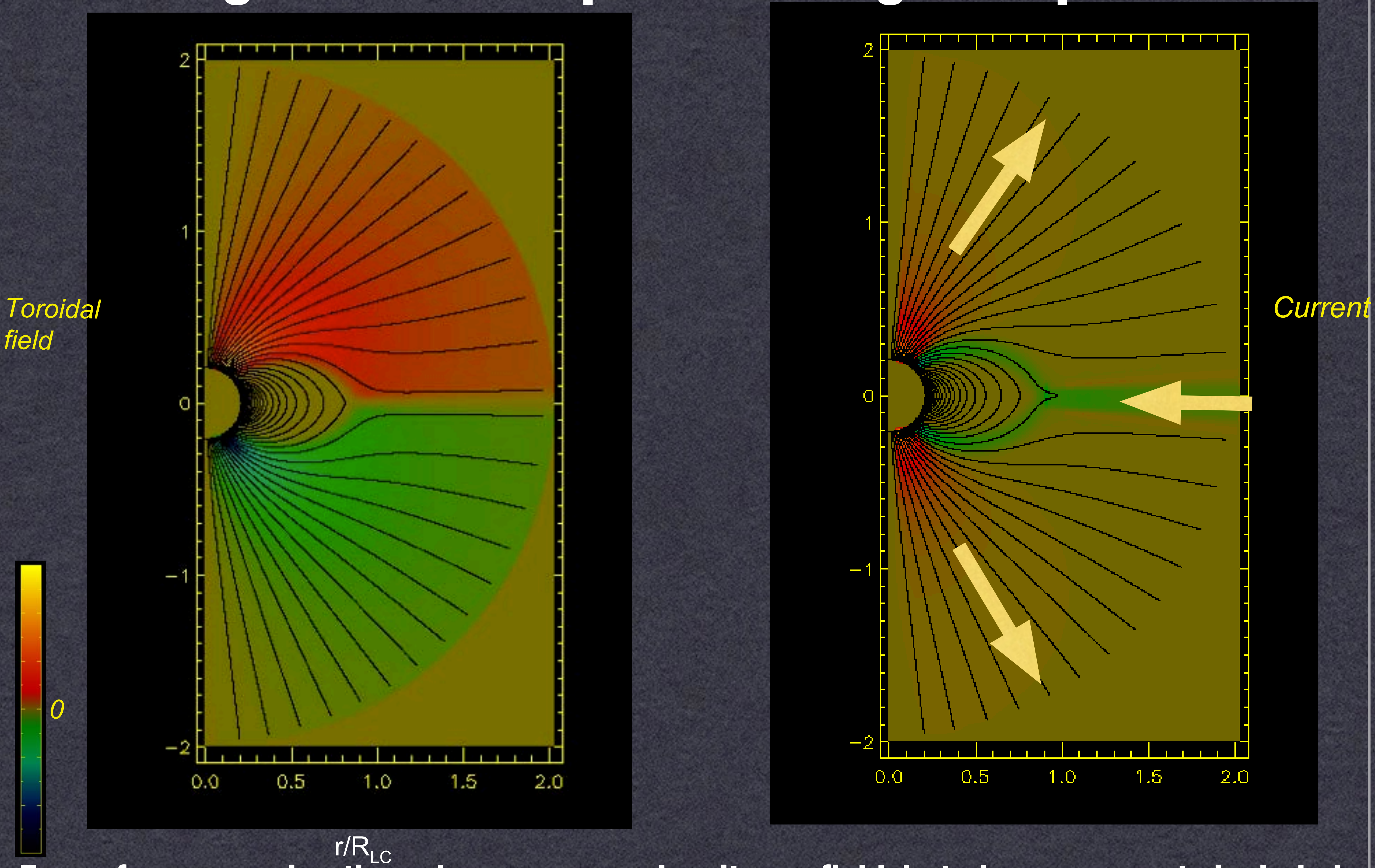
Gruzinov 99, Blandford 01



Force-free approximation: plasma energy density << field, but plasma currents included.

Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point

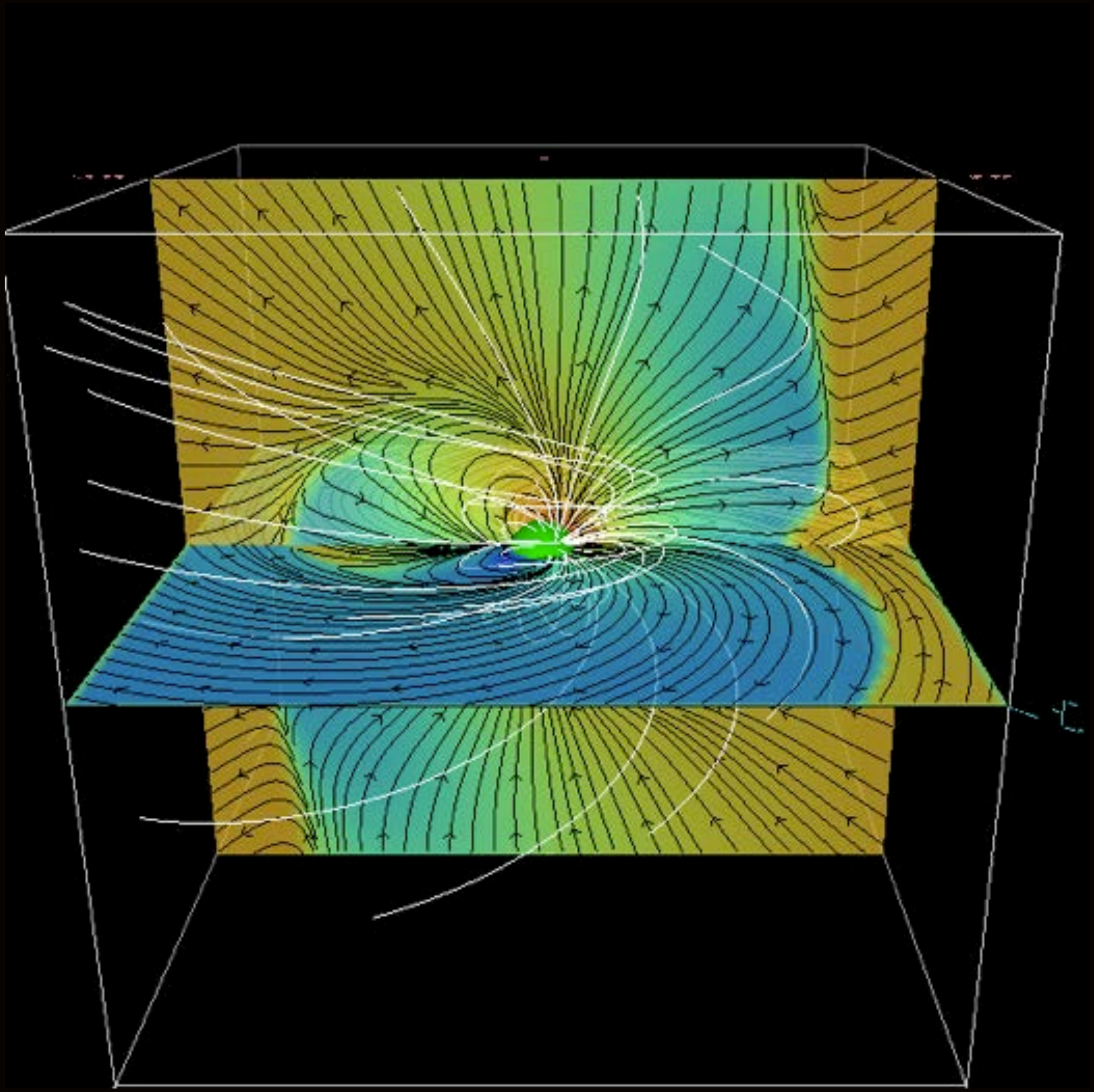
Aligned rotator: plasma magnetosphere



Force-free approximation: plasma energy density << field, but plasma currents included.

Properties: current sheet, split-monpolar asymptotics; closed-open lines; Y-point

Oblique rotator: force-free



AS ’06; recently in RMHD: Tchekhovskoy, AS, Li 2013

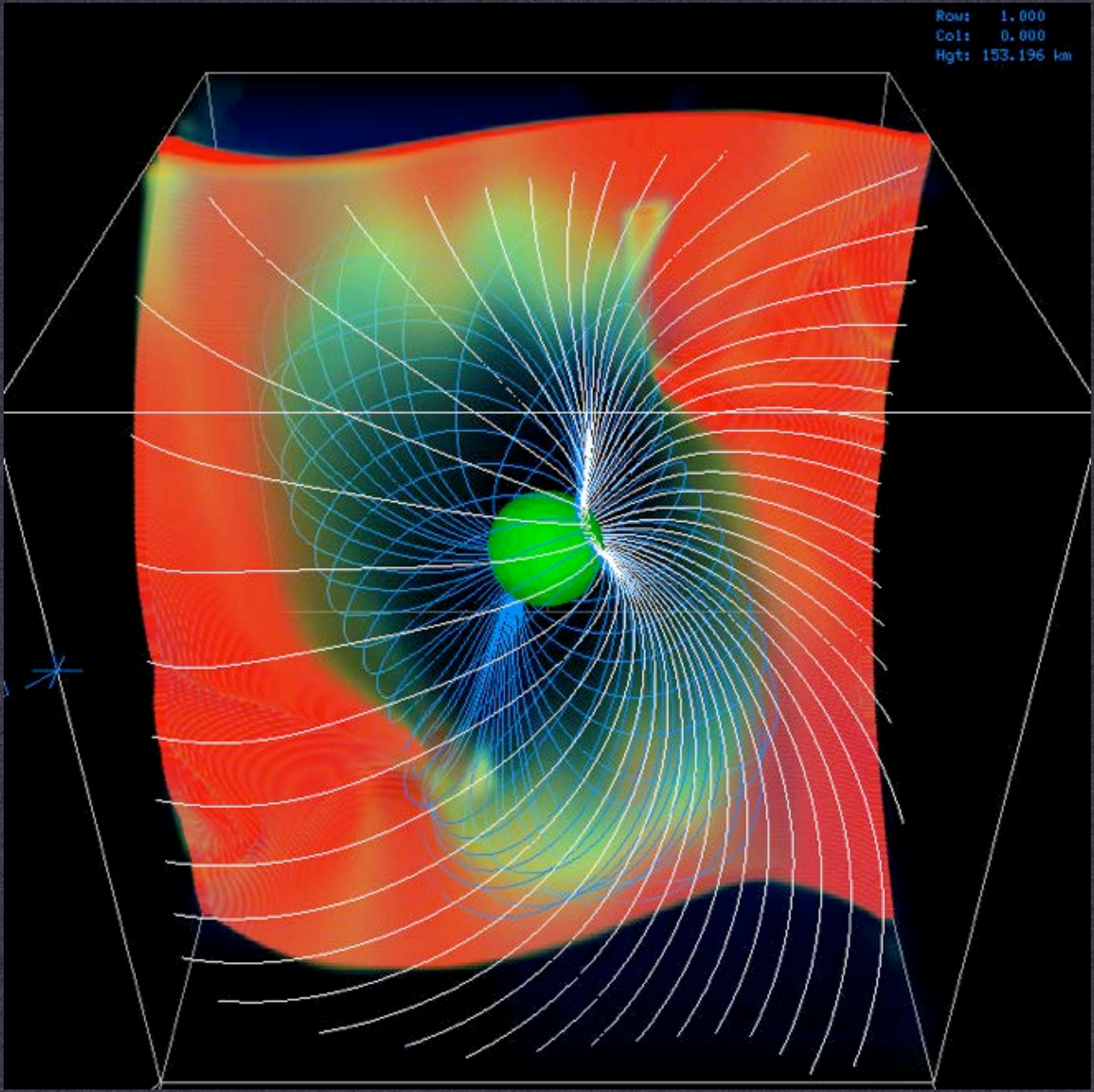
Current sheet emission results in double peaked pulses

Color -> current

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.

Best place to put a resistor in the circuit!



Abundant plasma models

Pros:

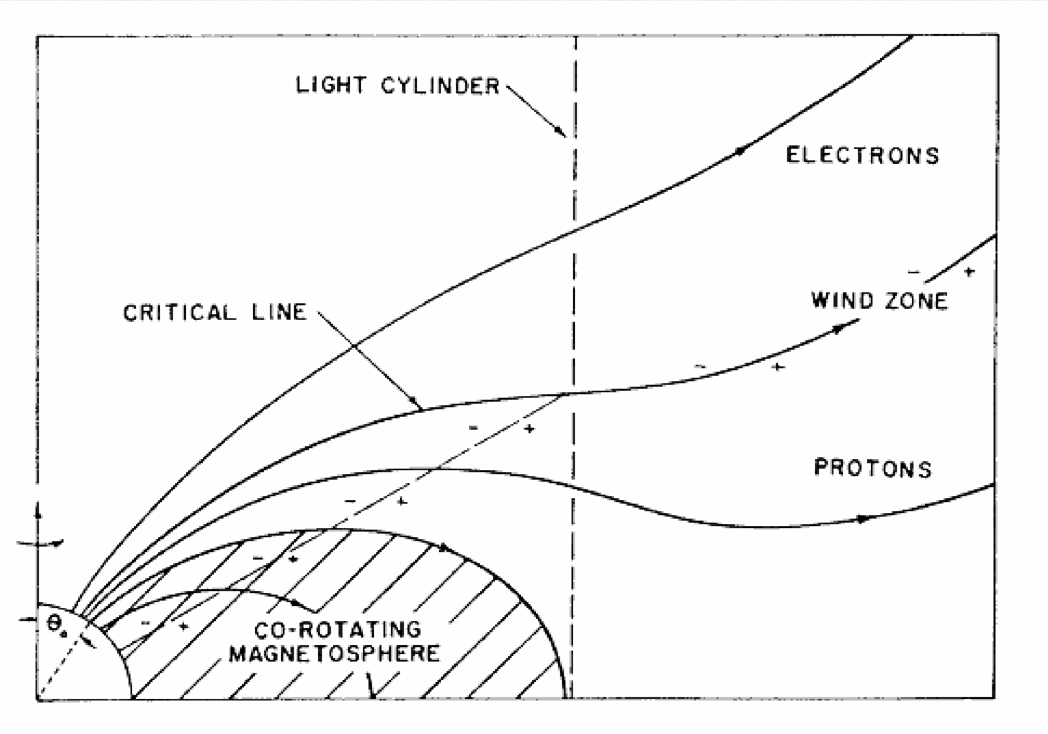
- Allow us to compute global structure of the magnetosphere
- Spin-down power
- Geometry of emission

Cons:

- No acceleration; dissipation is artificial
- No radiation
- Are these solutions unique?

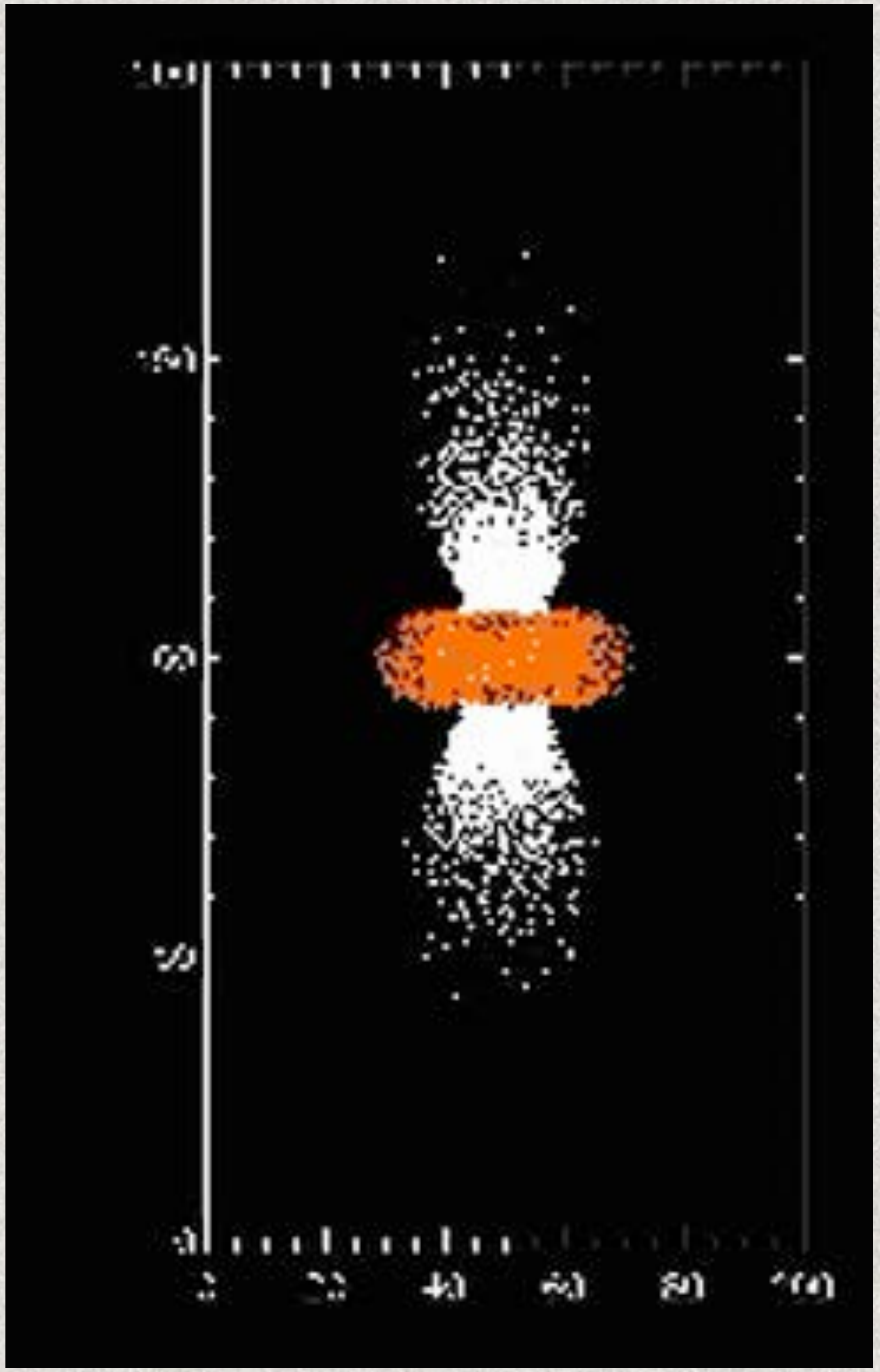
Charge-separated models

Is this the right cartoon?



Free escape from the surface, plasma density ~ GJ.

Use particle-in-cell simulations



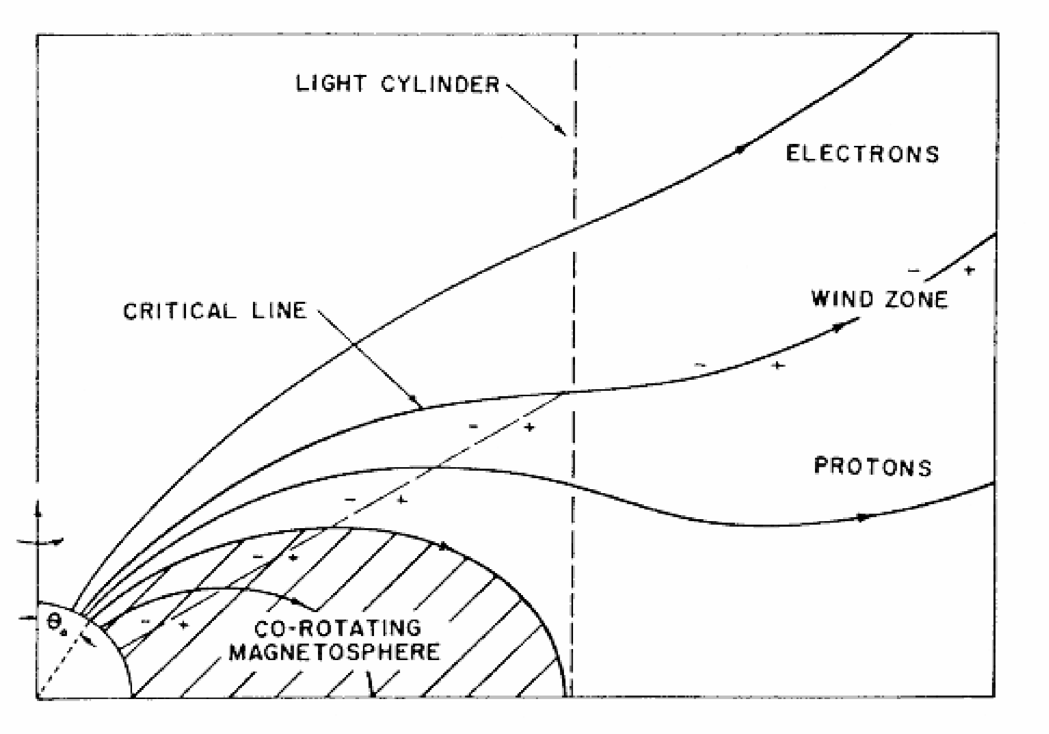
AS & Arons 02;
Michel et al 84, 01;
Philippov & AS '14

Disk+dome electrospheres

No spin-down

Are these the dead pulsars after pair production ends?

Charge-separated models



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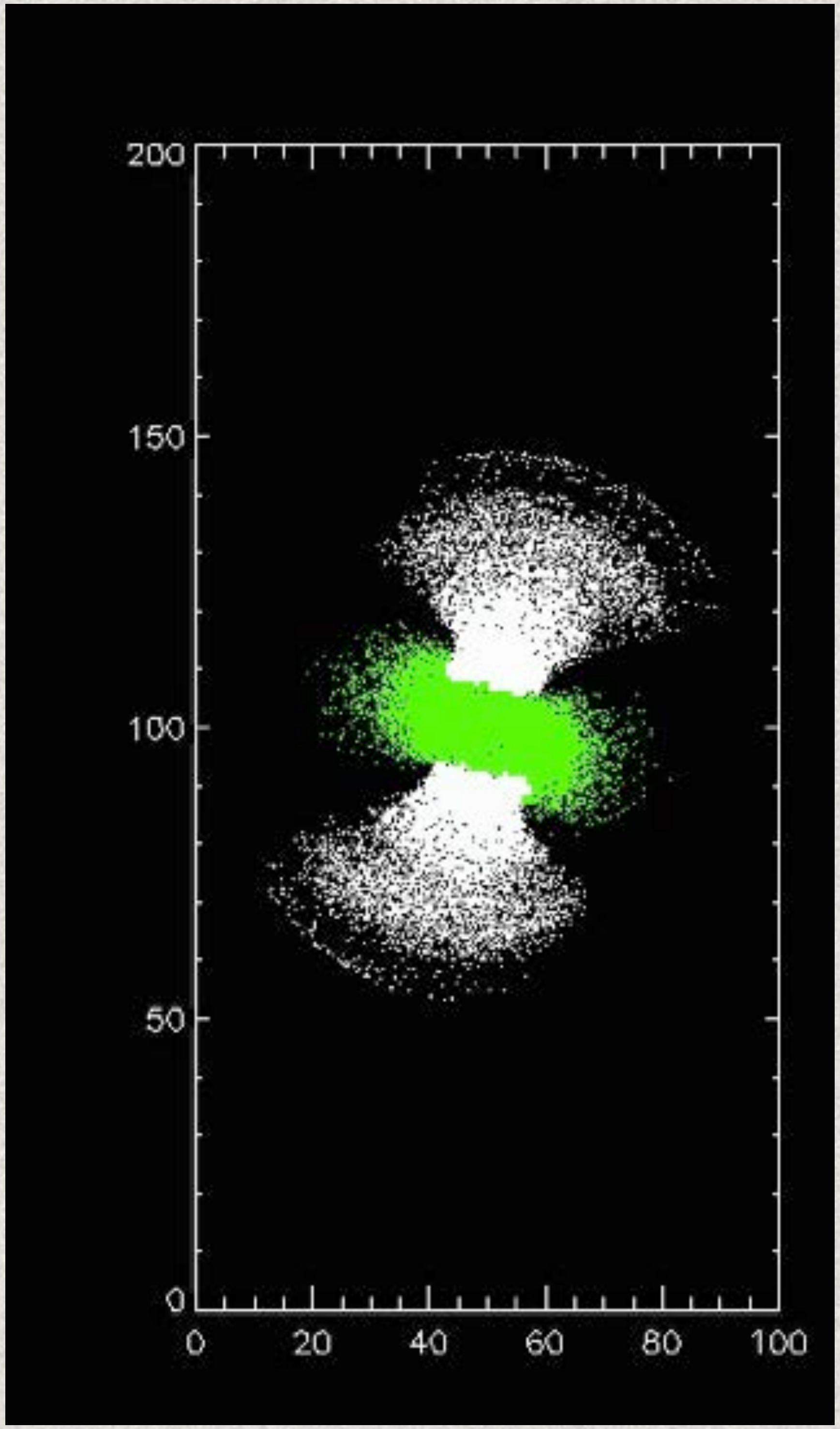

AS & Arons 02;
Michel et al 84, 01;
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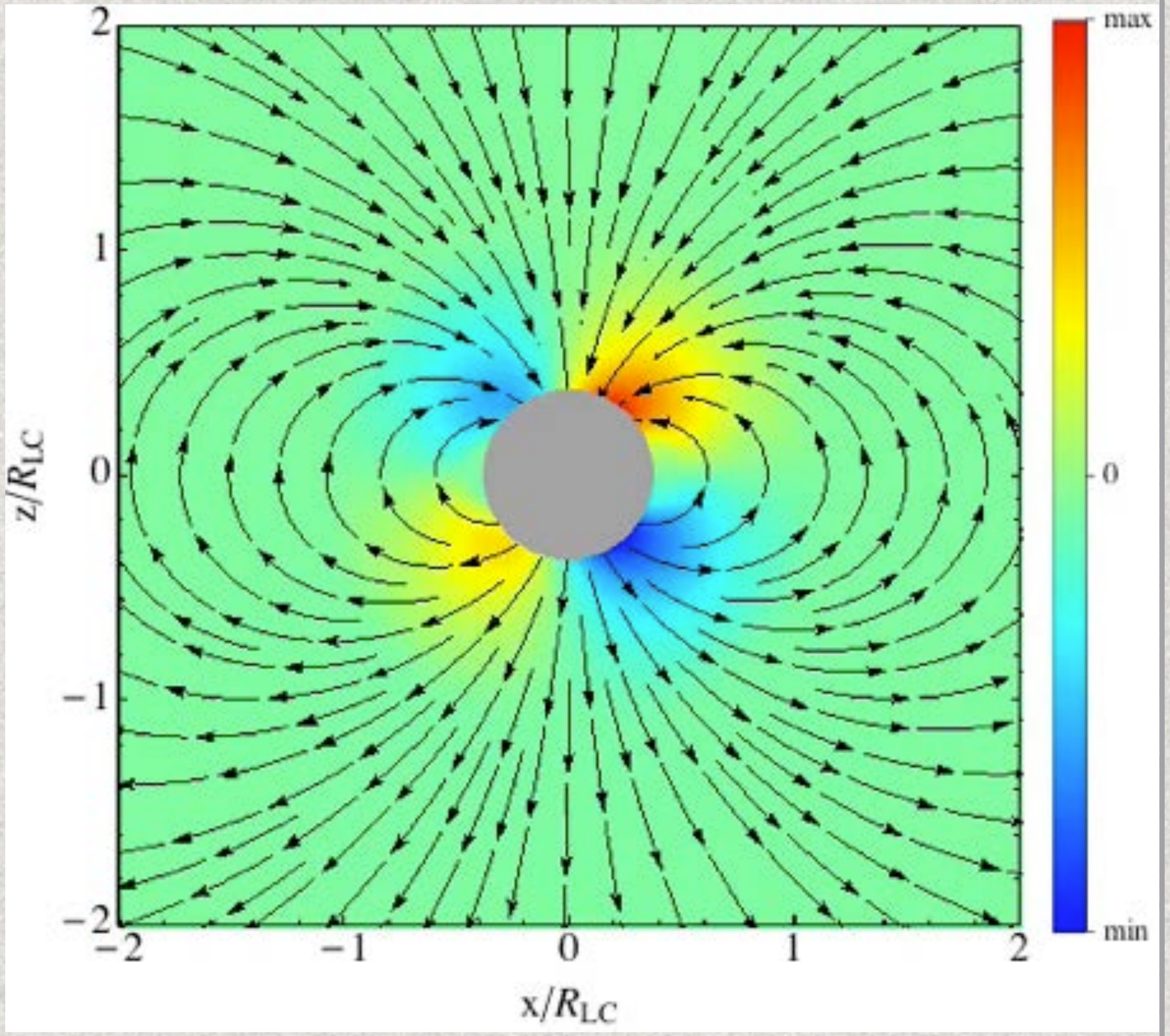
No spin-down

Are these the dead pulsars after pair production ends?

Abundant plasma solution w/PIC

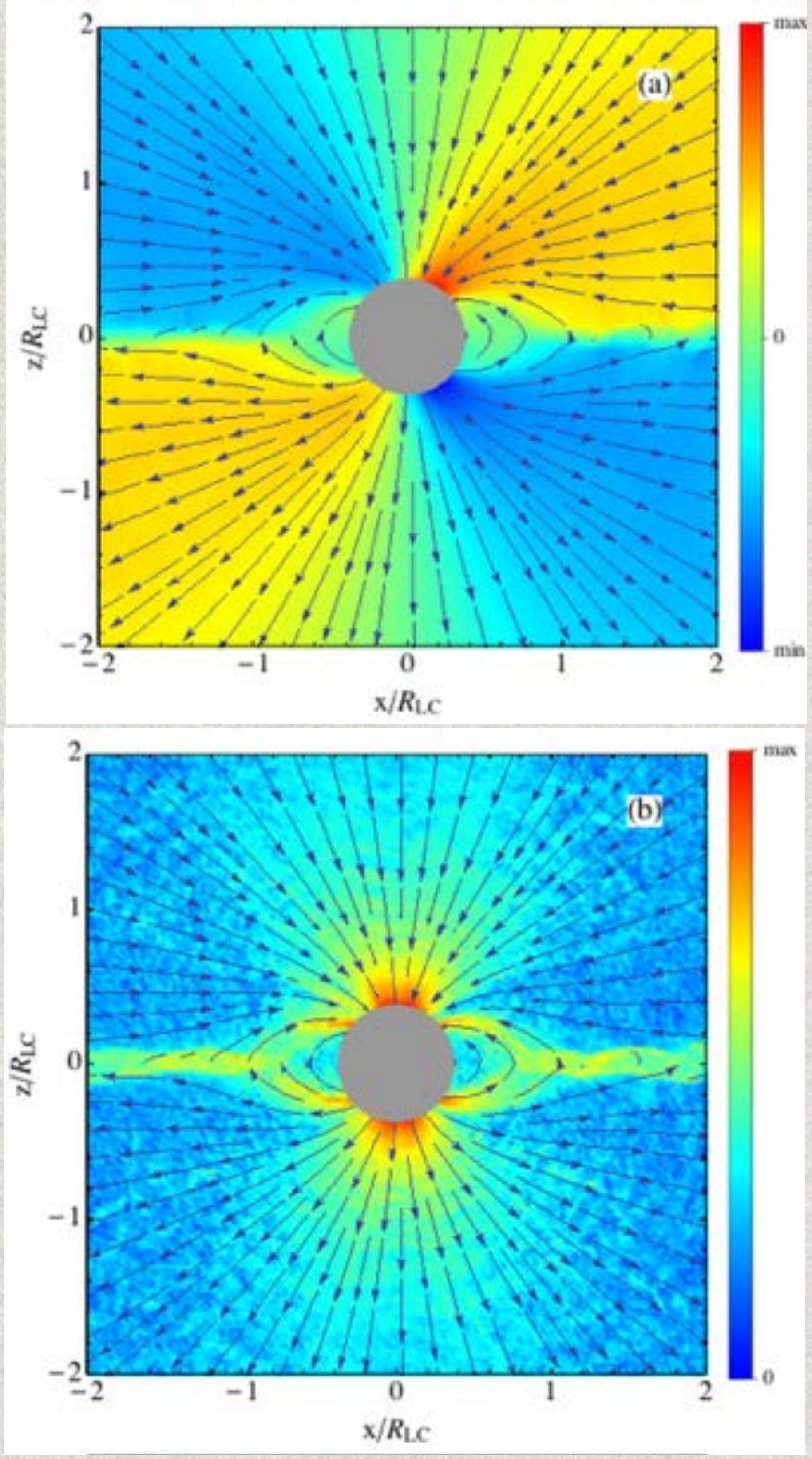
Philippov + AS 2014

- BC on the star: space-charge limited flow, particle escape, good spherical conductor (challenge on Cartesian grid).
- We used “plasma sphere” BC.
- Dump plasma throughout magnetosphere: faking abundant pair formation throughout LC



Abundant plasma solution w/PIC

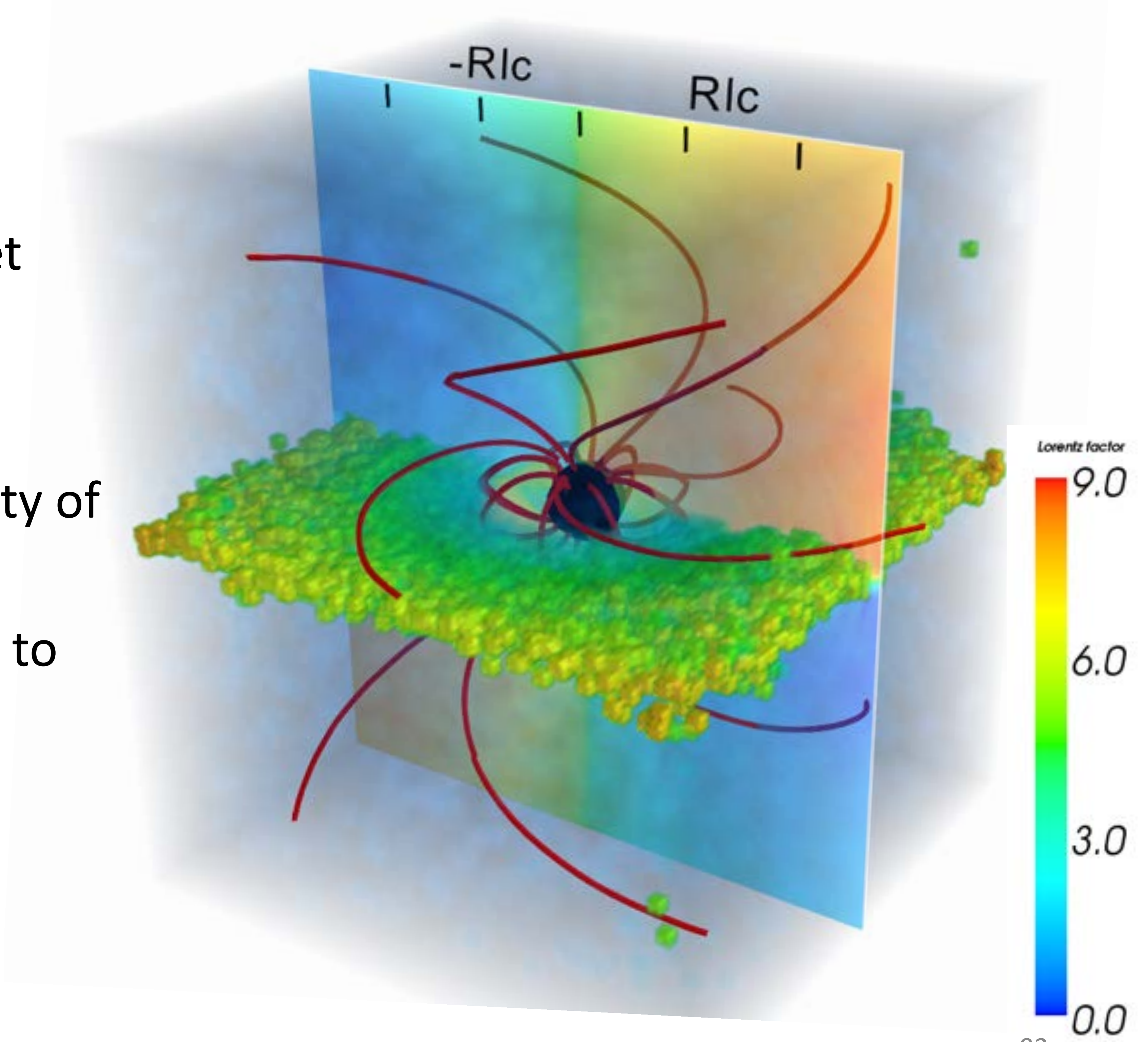
- Abundant pair plasma with PIC reproduces force-free
- Small dissipation (~10% in current sheet)
- Particle acceleration mainly in the sheet
- Drift-kink instability of the sheet



Philippov + AS 2014

Volumetric pair supply in the aligned magnetosphere

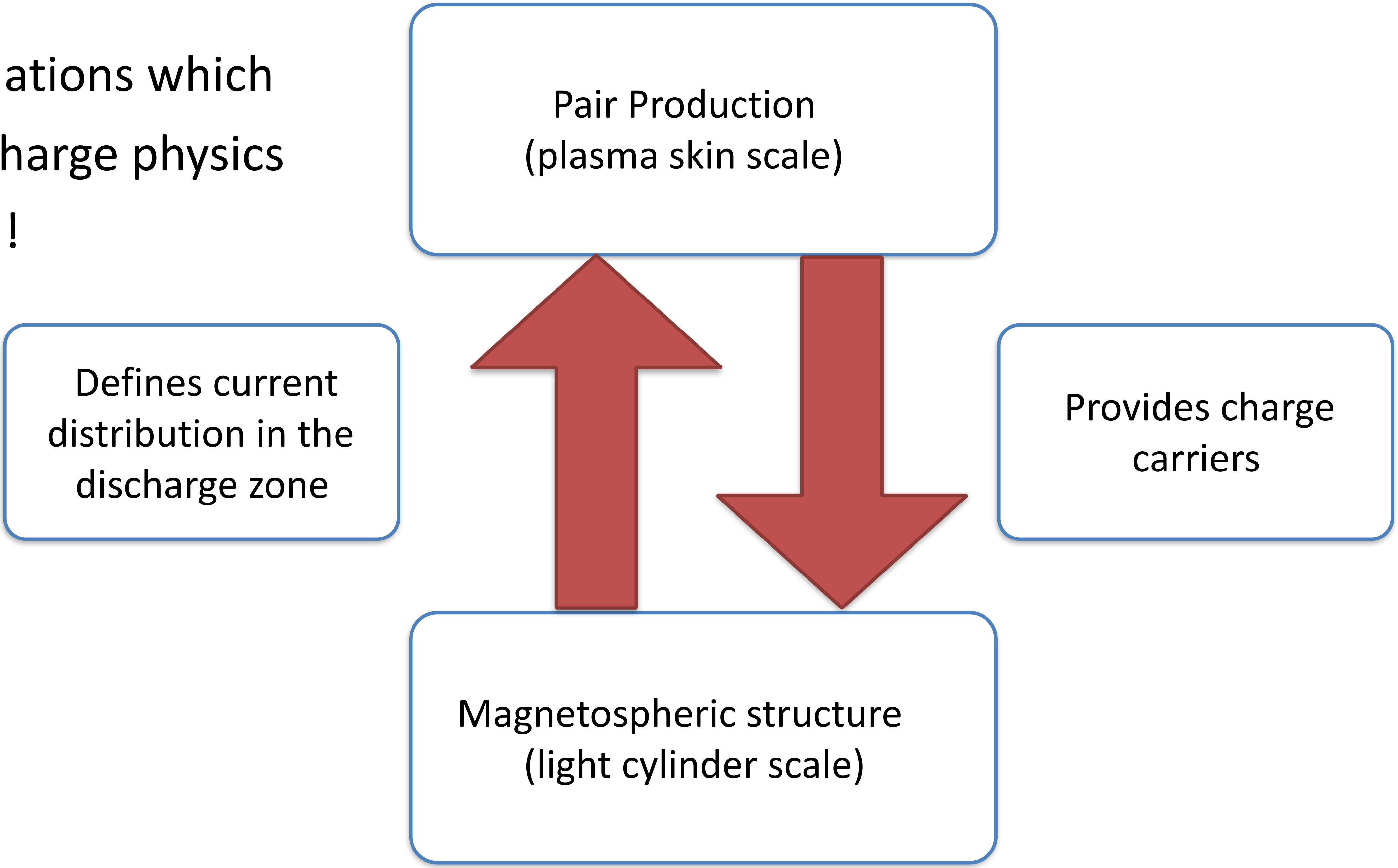
- Approaches force-free
- Self-consistent current sheet
- 10% of Poynting flux is dissipated within $2R_{LC}$.
- Observed drift-kink instability of the current sheet.
- Particles are accelerated up to energies limited by magnetization.



Philippov & Spitkovsky, ApJ, 2014

Magnetosphere is a self-regulated system

Global simulations which capture discharge physics are required!



Pair Production
(plasma skin scale)

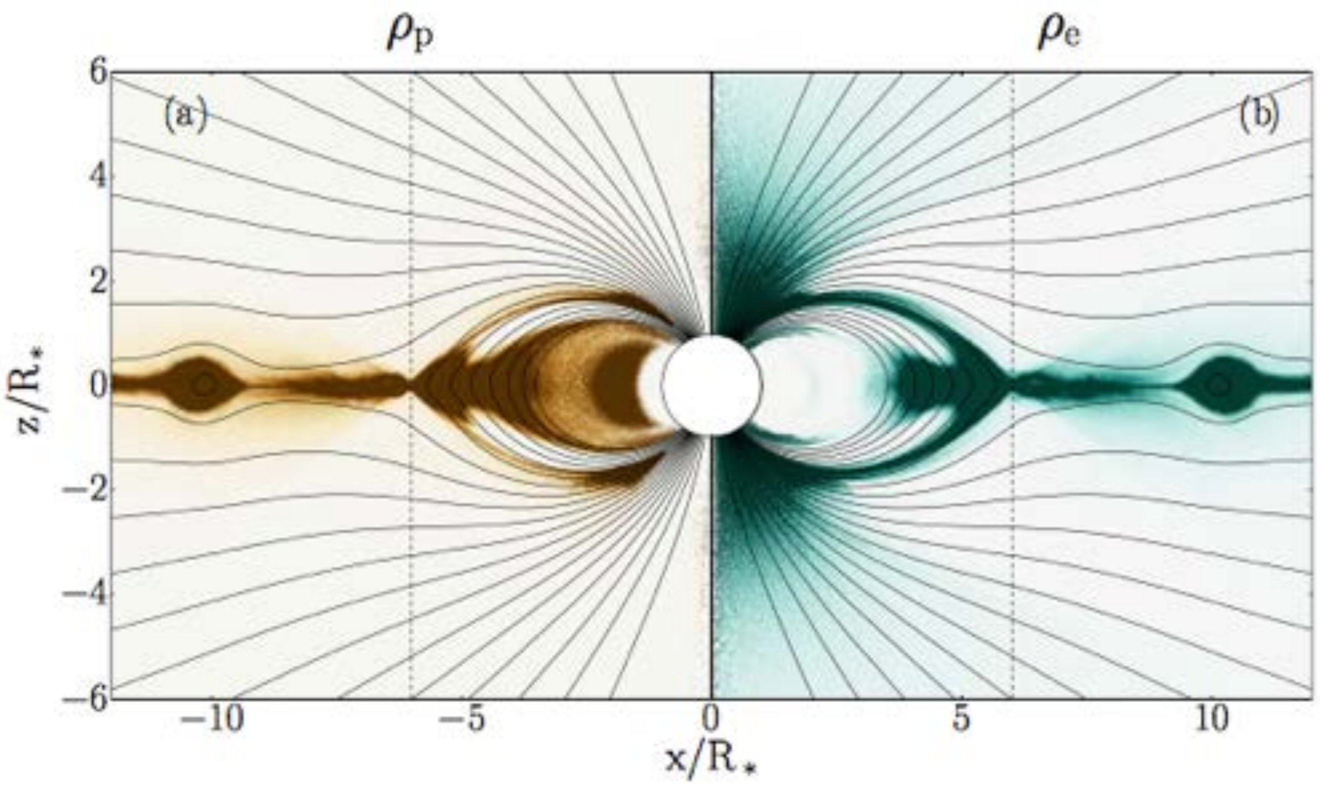
Defines current distribution in the discharge zone

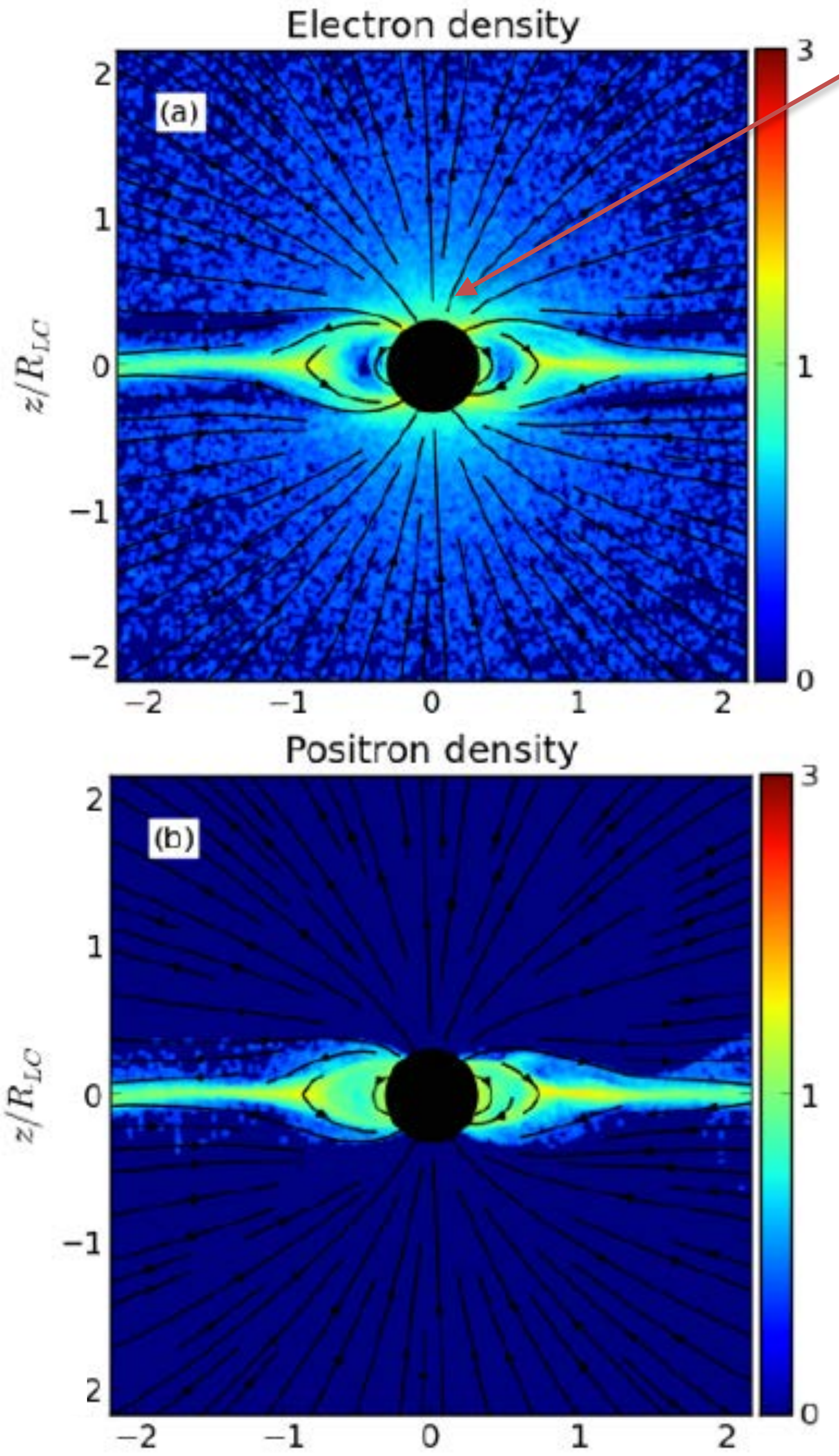
Provides charge carriers

Magnetospheric structure
(light cylinder scale)

Aligned pulsar with pair production: no dense solutions!

Approaches force-free like solution,
but no pair production in the polar region,
where the space-charge limited flow does not
lead to particle acceleration.



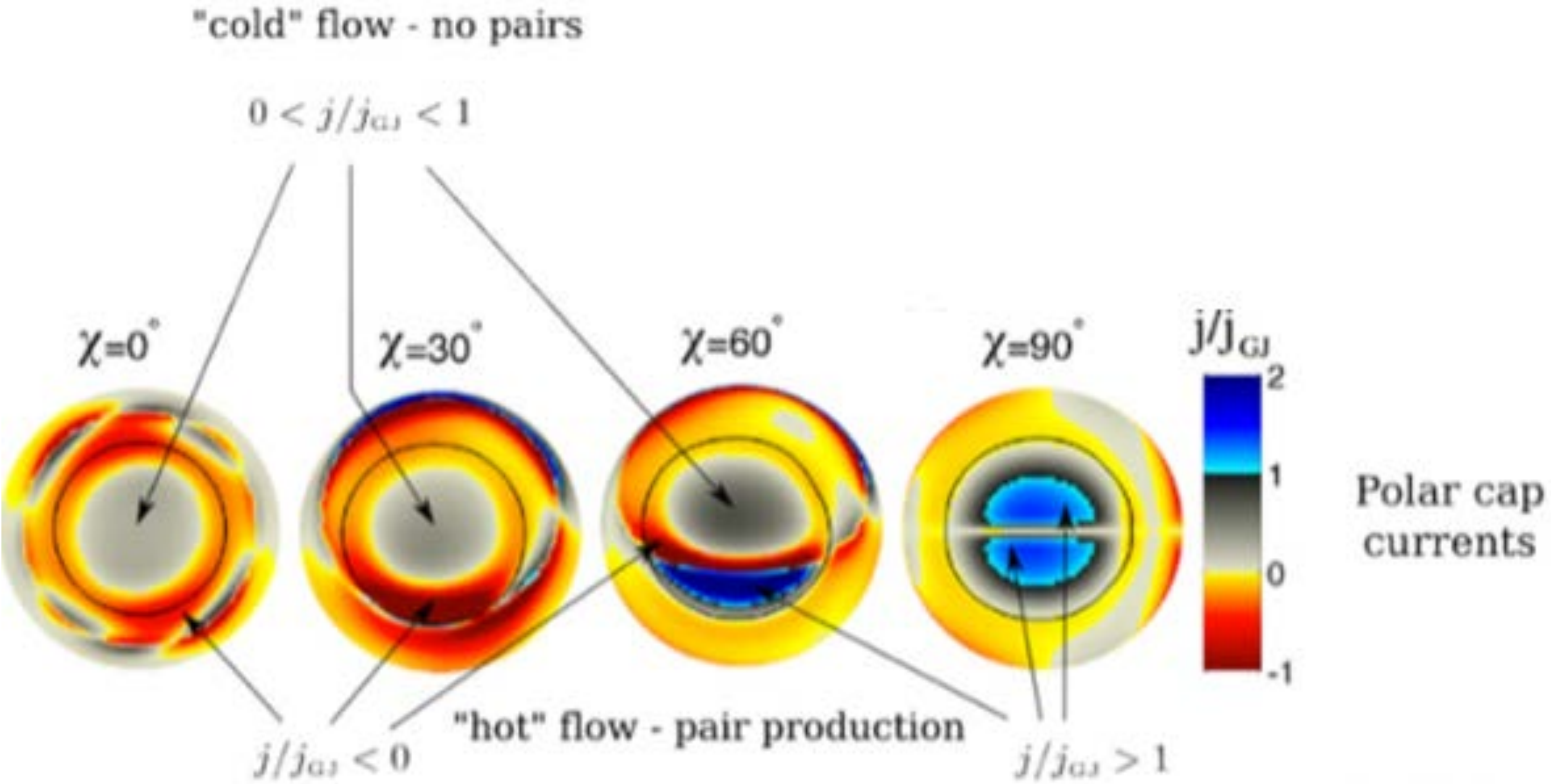


$j<j_{GJ}$

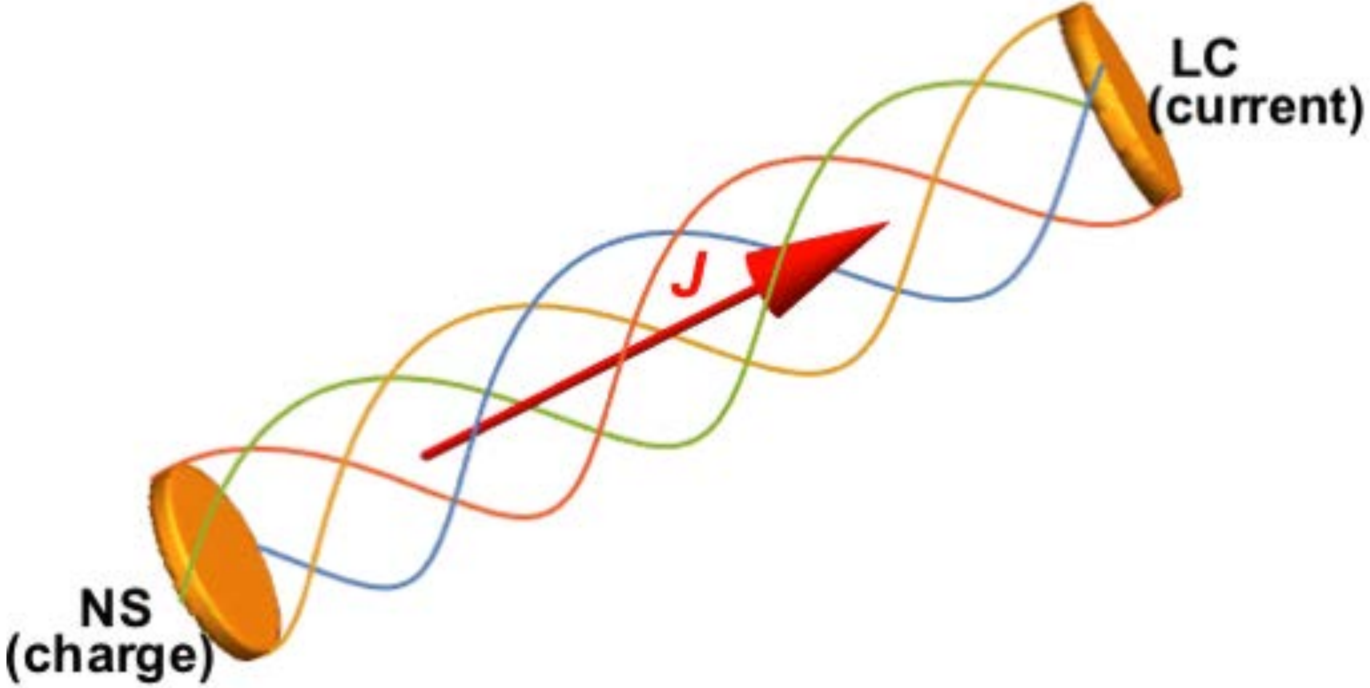
Chen, Beloborodov, ApJ, 2014
Philippov et al., ApJ, 2015a

Why is acceleration weak?

- Need to sustain both charge and current density. Key quantity is $j/c\rho_{GJ}$
- If j<charge density*c, charges are advected with non-relativistic velocity
- Current is set by twist of the field lines at LC



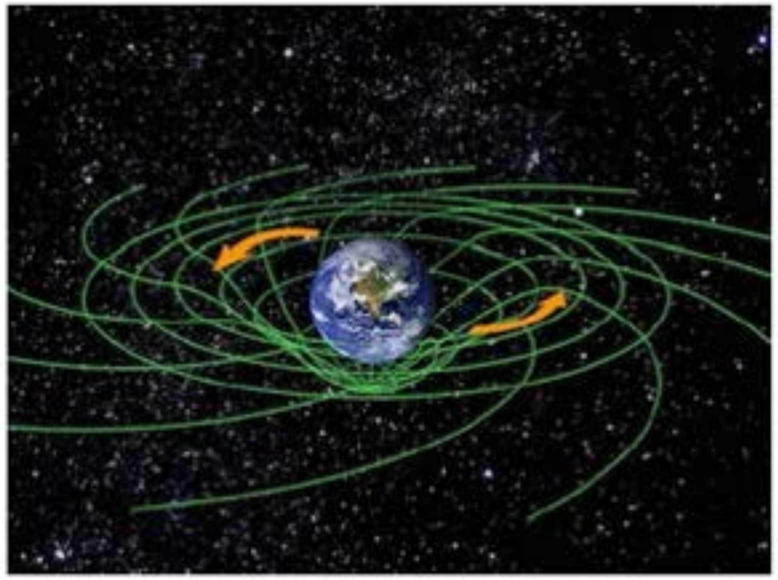
Timokhin & Arons, MNRAS, 2013



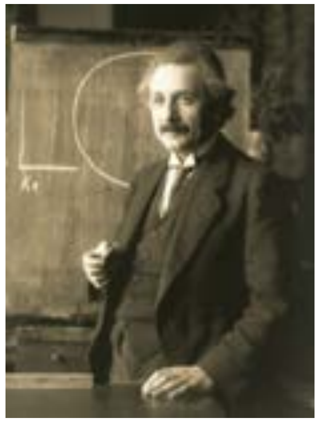
When realistic currents set by global magnetosphere are included in the simulation of polar cap discharge, we find that abundant pair production may not happen for aligned and most oblique pulsars! Is this really possible?

Prof. Einstein saves the day (1915-2015)!

Problem:
High multiplicity solutions possible only for high inclinations, but radio is observed from pulsars of all obliquities.



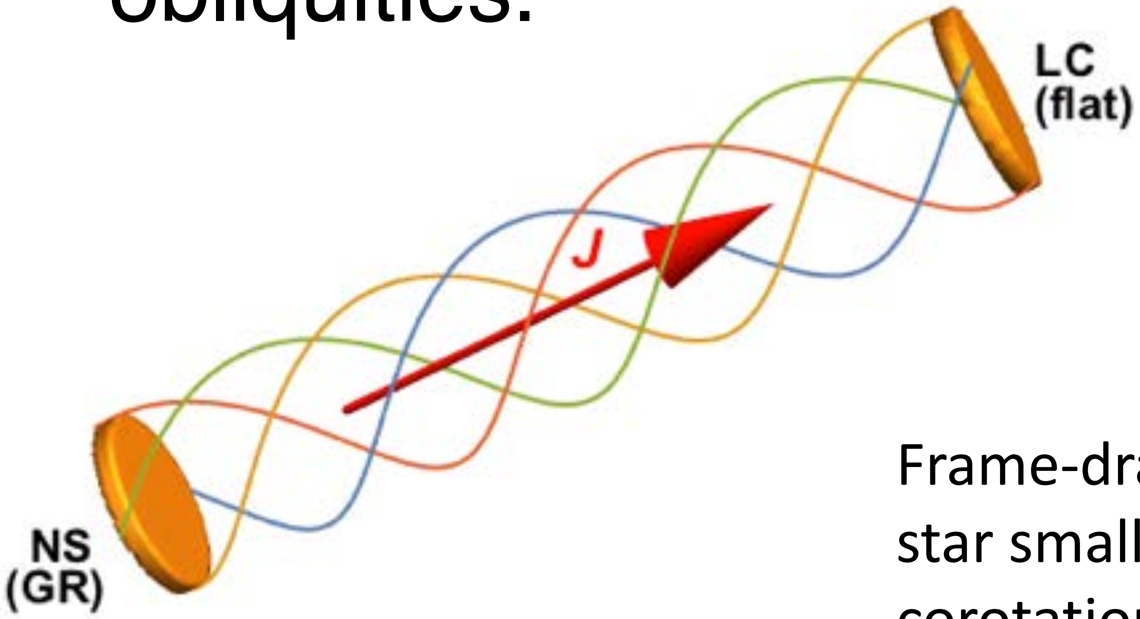
Lense-Thirring frame dragging



$$\omega_{LT} = \frac{2}{5}\Omega_* \frac{r_s}{R_*} \qquad \vec{g_0} = \vec{\beta} = \frac{1}{c}\vec{\omega}_{LT} \times \vec{r}$$

$$\nabla \times \left(\alpha\vec{E} + \boxed{\frac{\vec{\beta}}{c} \times \vec{B}}\right) = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t},$$

$$\nabla \times \left(\alpha\vec{B} - \frac{\vec{\beta}}{c} \times \vec{E}\right) = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \alpha\vec{j} - \rho\vec{\beta}.$$



Frame-dragging makes effective rotation frequency of the star smaller close to the star (this lowers the necessary corotation charge), but the rotation is still the same far from the star (this keeps the current the same).

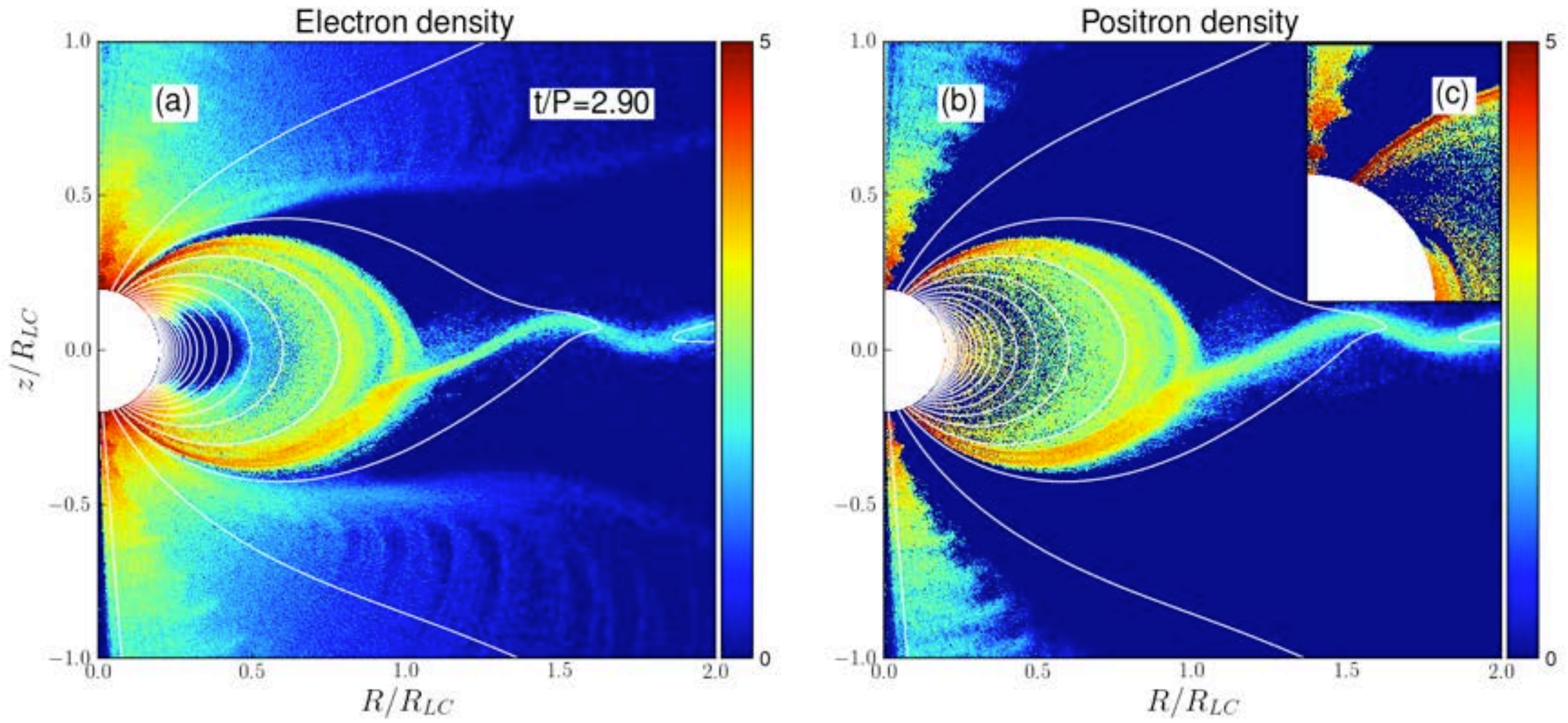
$$\frac{J_{\hat{r}}}{\rho_{GJ}c} \approx \left(\frac{J_{\hat{r}}}{\rho_{GJ}c}\right)_{\text{flat}} \frac{1}{1 - \omega_{LT}/\Omega_*}$$

Beskin 1990, Muslimov & Tsygan 1992

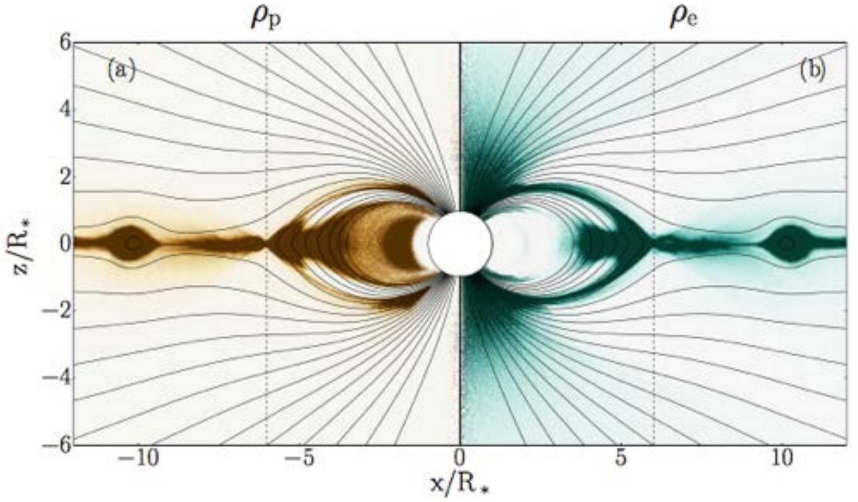
$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = \alpha q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) + \xcancel{\alpha m\gamma\vec{g} + \alpha H\vec{p}} \qquad \frac{\mathrm{d}x^i}{\mathrm{d}t} = \alpha v^i - \beta^i$$

Philippov et al. (2015b)

GR aligned rotator



Philippov et al., 2015 ApJ



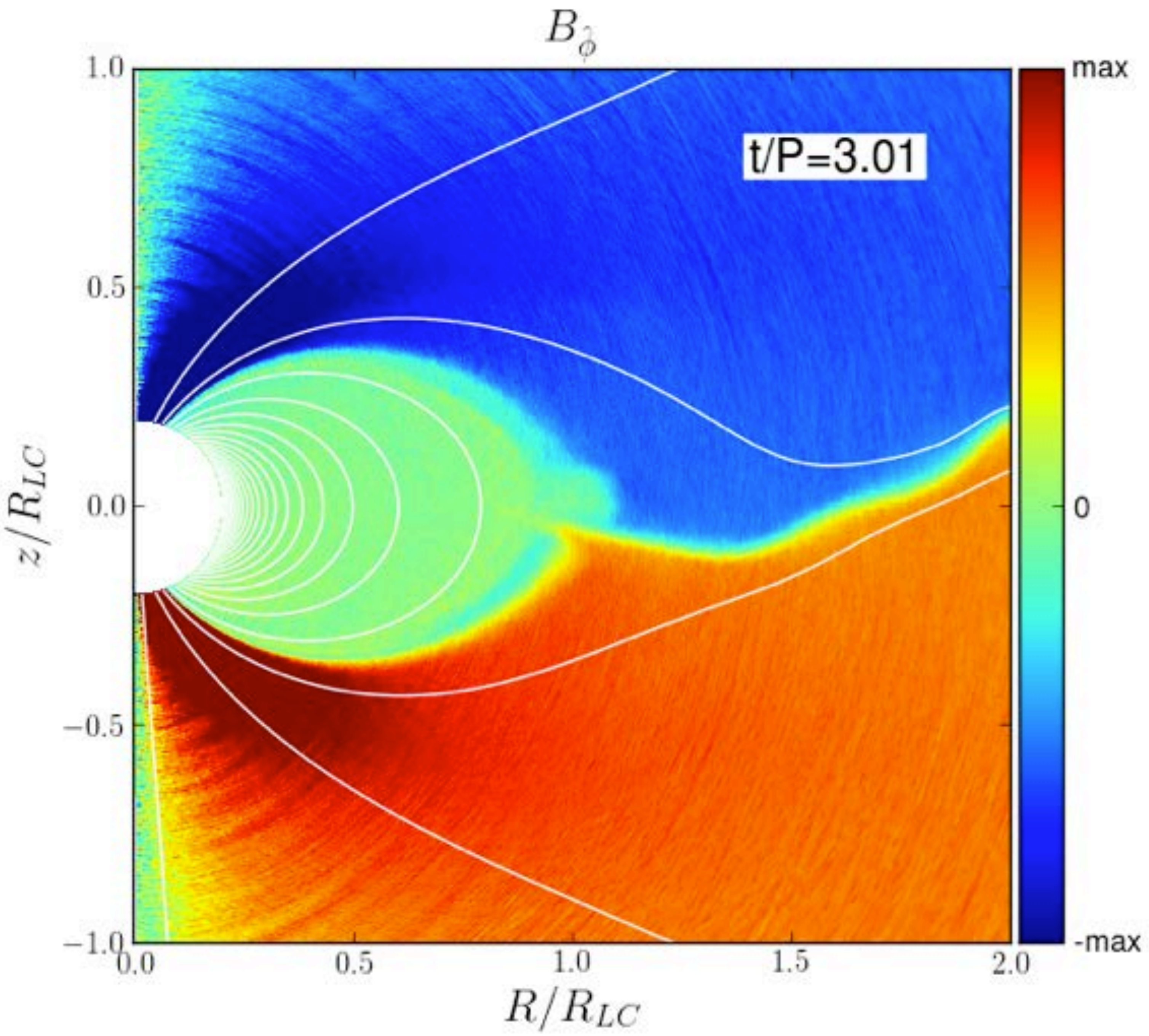
Chen & Beloborodov, ApJ, 2014

Flat space solution, no pair production

Feedback from the current sheet on polar cap pair production - implications for the radio variability?

Implications for radio emission

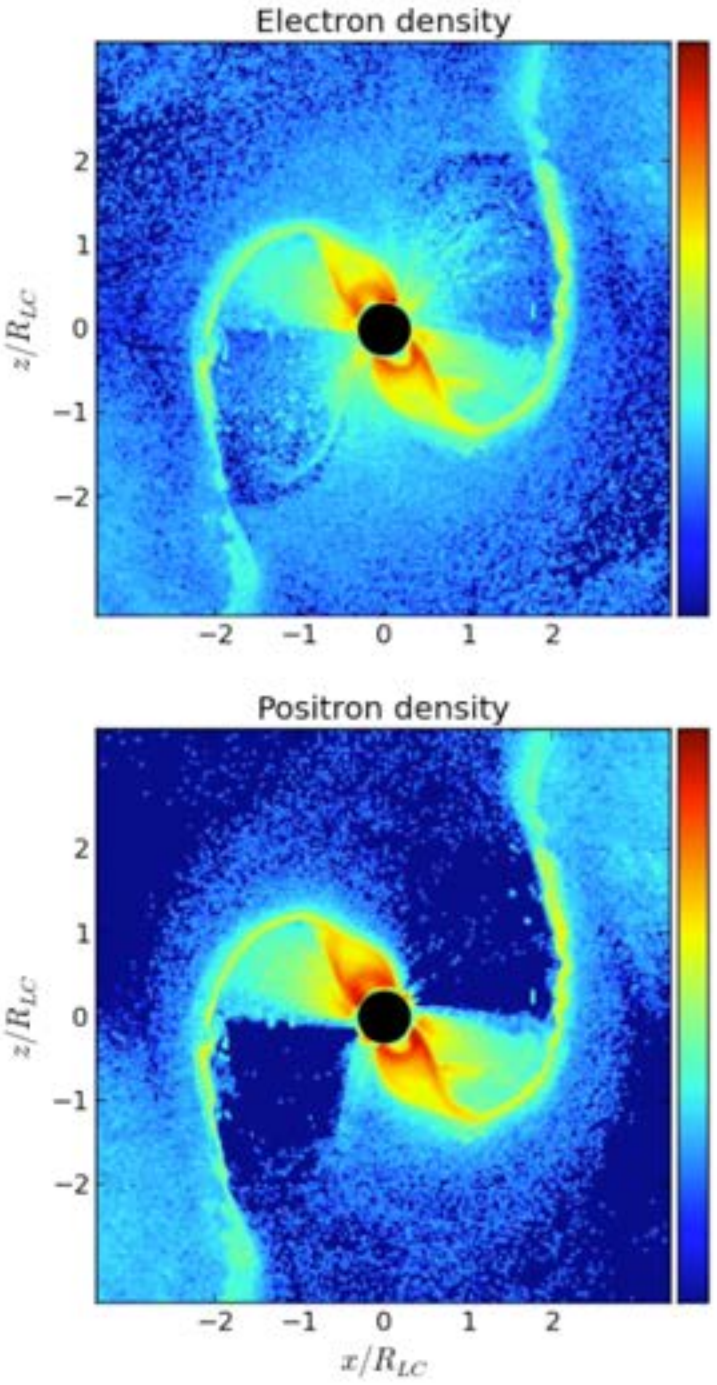
- Non-stationary discharge drives waves in the open field zone.
- Waves are generated in the process of electric field screening by plasma clouds. They are driven by collective plasma motions, thus, coherent (see also Beloborodov 2008, Timokhin & Arons 2013)



Flat space vs GR: oblique models

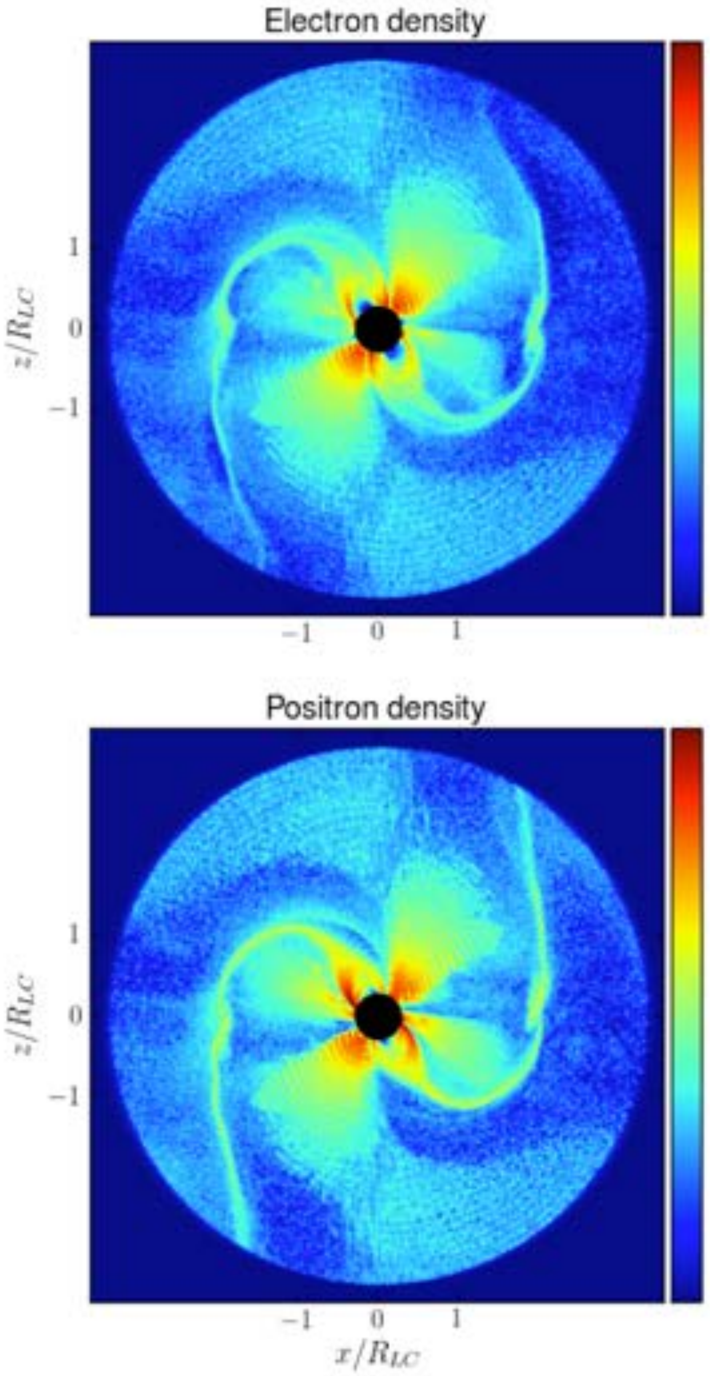
GR helps to establish polar pair cascade for inclined rotators!

GR, radiative cooling, extraction of ions and photon propagation is included now!



Philippov et al., ApJ, 2015

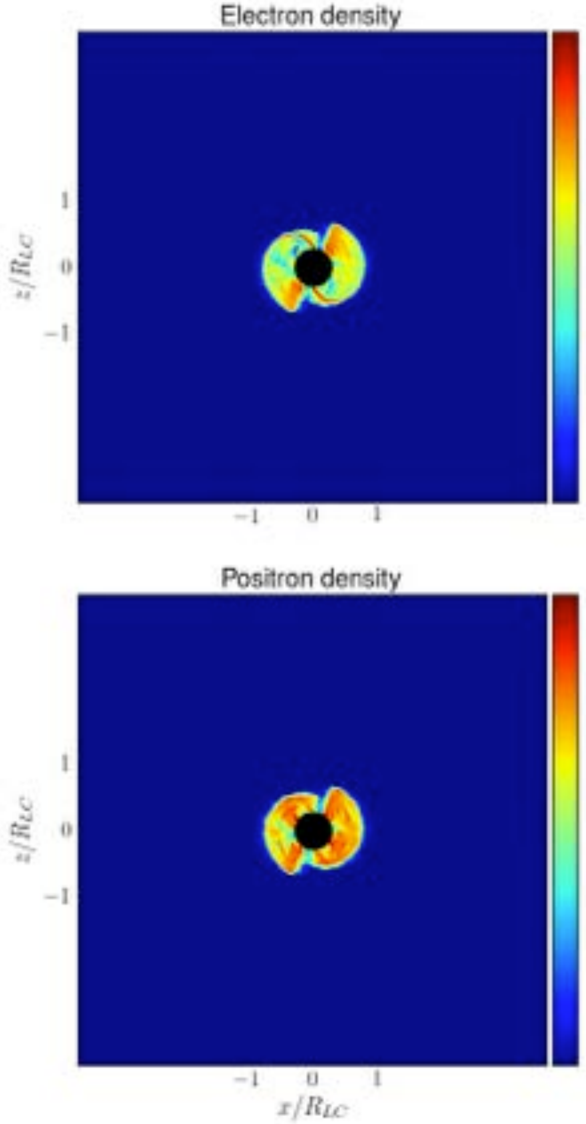
flat space



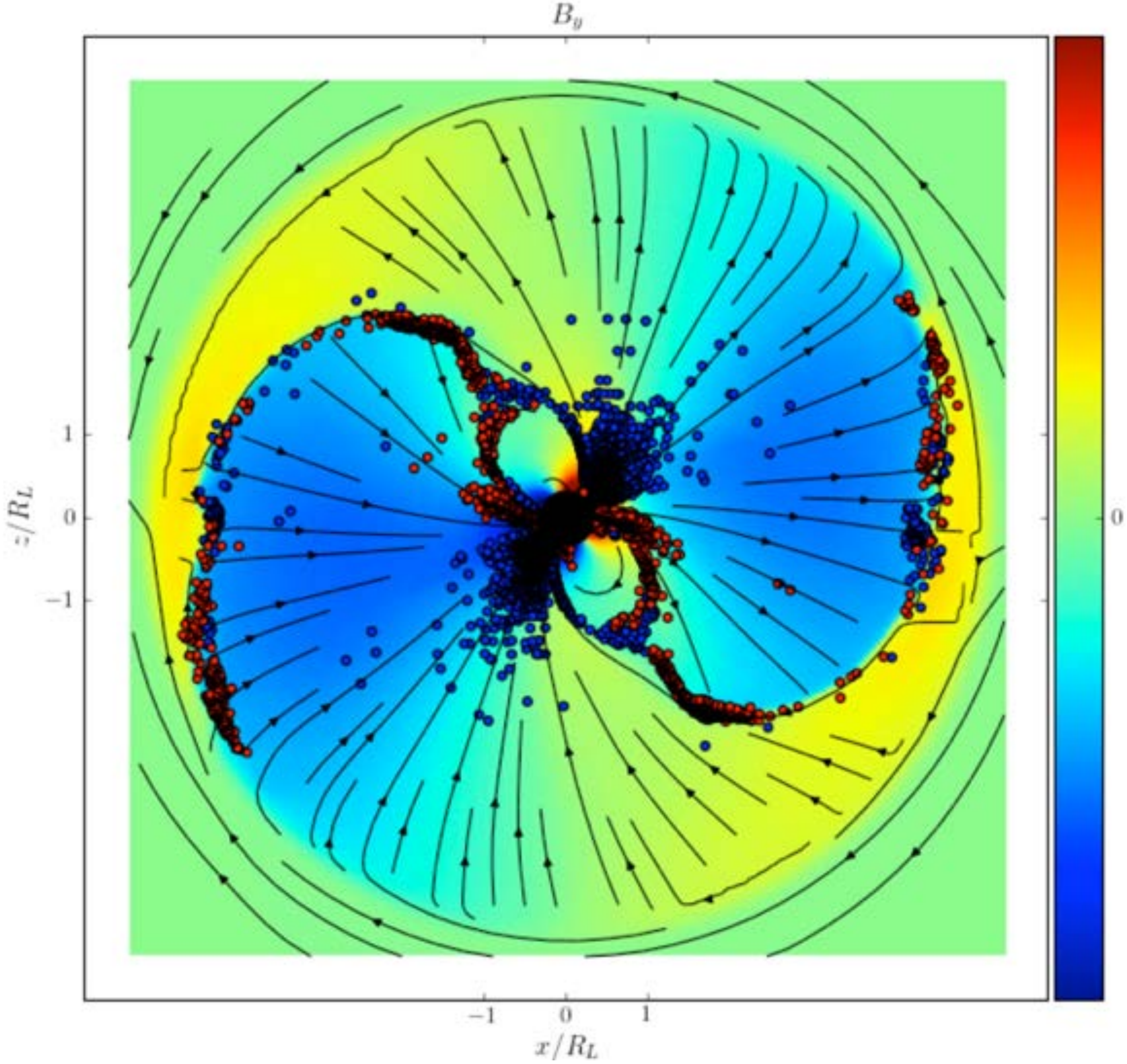
Philippov & AS, in preparation

$$\text{photon mfp}(r = R_{LC}) < R_{LC}$$

GR



GR oblique models: where pair formation happens?



Highlights polar cap, return current layers and the current sheet. Pairs injected into the vacuum gap above the current sheet do not launch an avalanche.

Philippov & Spitkovsky, in preparation

PIC simulation of magnetospheres II

- Core - EM PIC codes TRISTAN-MP (Spitkovsky 2008) and Zeltron (Cerutti et. al., 2014).
- Conducting BC at the stellar surface, "absorbing layer" BC at the outer edge. Provide free escape of particles (both electrons and ions) from the surface.
- Radiative cooling is implemented for particle motion. To get correct cooling rates, need to resolve Larmor gyrations in time.

$$\mathbf{g} = \frac{2}{3} r_e^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E}) \mathbf{E} \right] - \frac{2}{3} r_e^2 \gamma^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot \mathbf{E})^2 \right] \boldsymbol{\beta}$$

- Pair creation with the threshold based on particle energy. Recently added tracking of photons and the pair formation threshold based on photon energy.
- Effects of GR: simulations in slowly rotating metric.
- Scales approached:

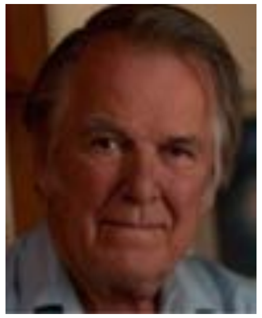
$$R_*/(c/\omega_p) \approx 30 - 40 \gg 1 \qquad R_{LC}/R_* = 3 - 5$$

$$\Phi_{PC} = \mu \Omega^2 / c^2 \approx 500 \gg \gamma_{\text{threshold}} = 40$$

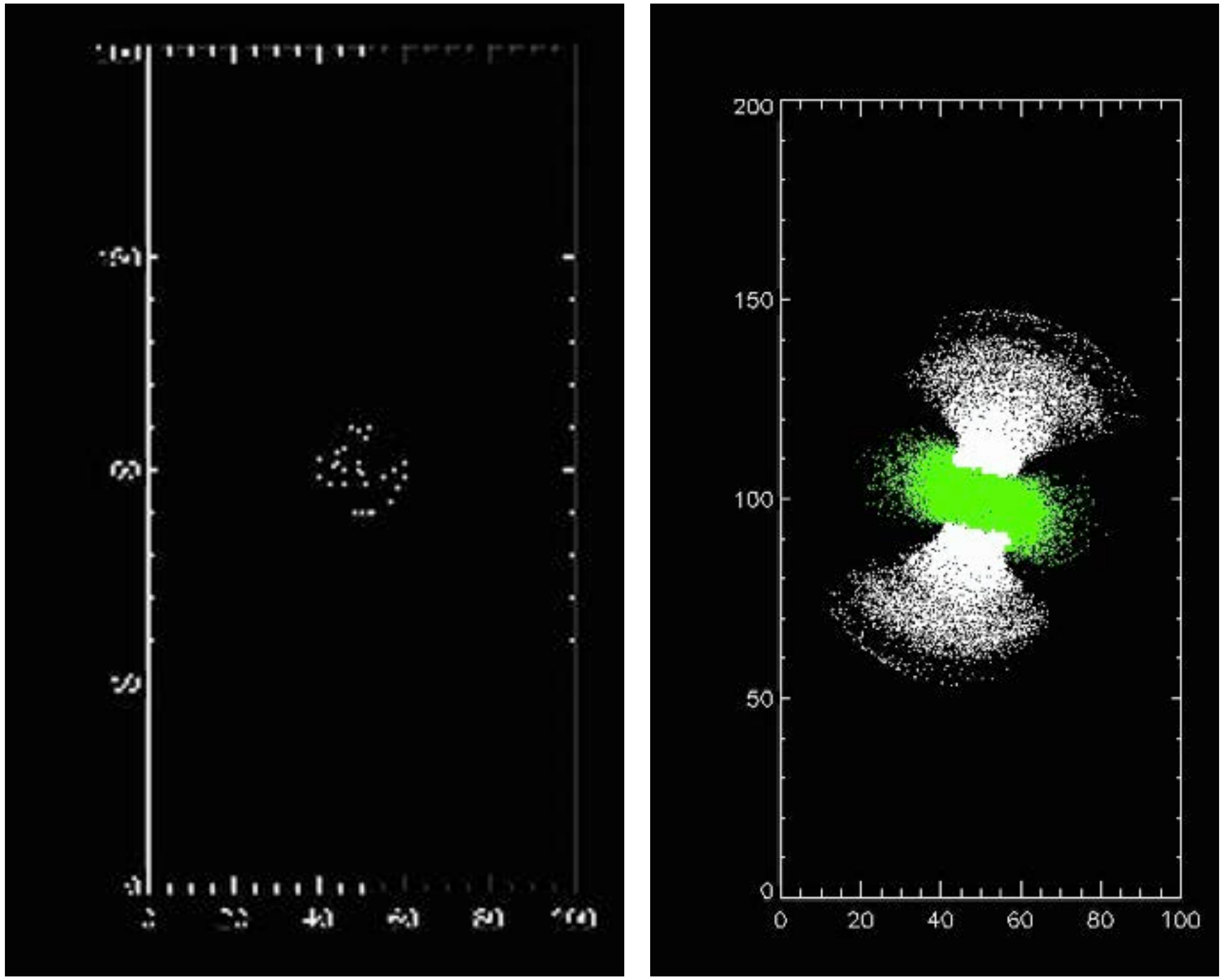
Jump-starting the pulsar: regimes of plasma supply

- Availability of plasma supply and whether magnetosphere is filled with plasma can determine the properties of spin-down and radiation. We tried:
  - Free particle escape from the surface without pair production.
  - Free escape with pair production: aligned and oblique rotators.
  - Modifications of pair supply in GR.

Electrostatically trapped solution


C. Michel

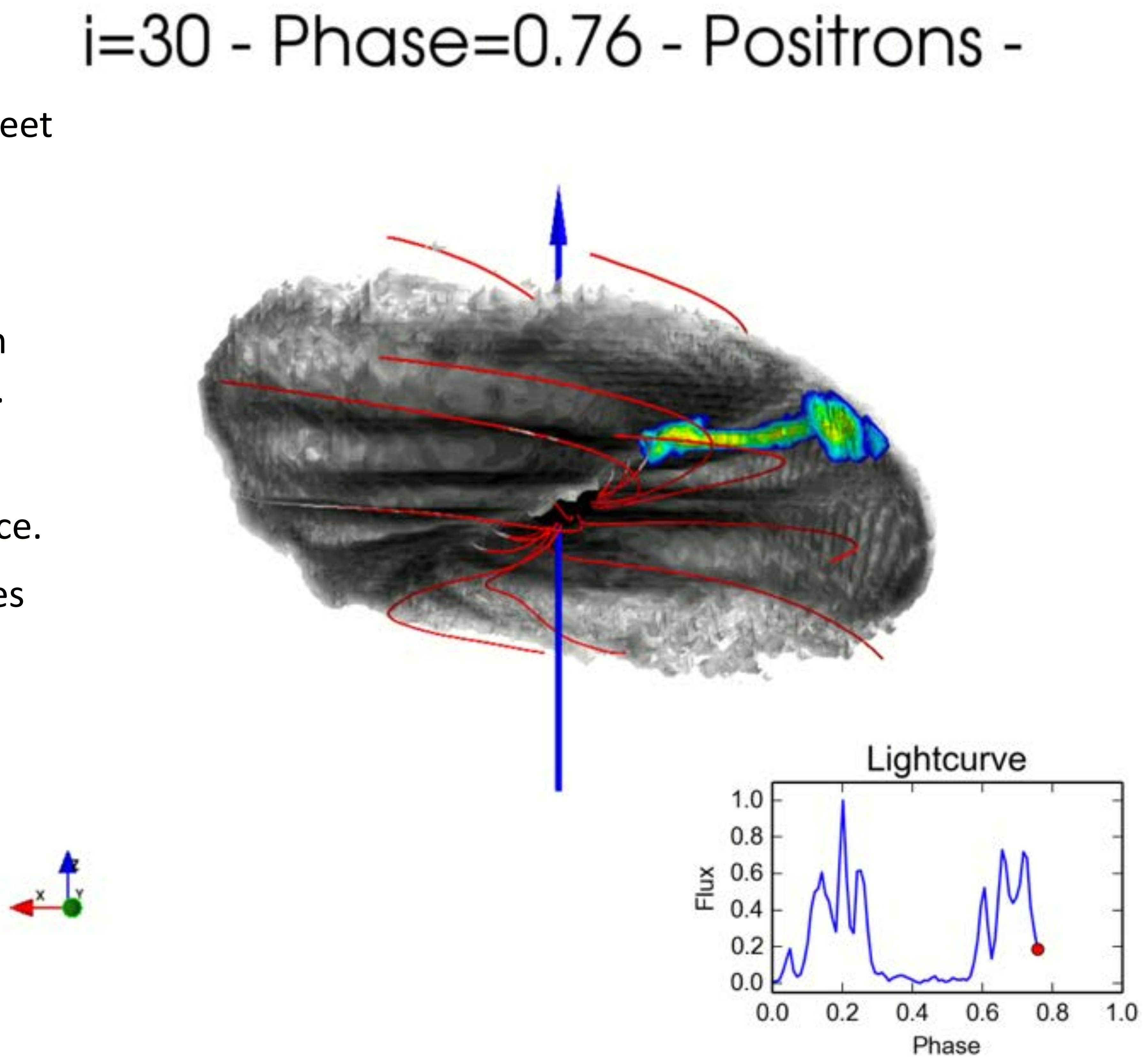
- Only free escape from the surface
- Disk-dome solution
- Almost no outflow and spin-down



Kraus-Polstorff & Michel, 1985; Spitkovsky & Arons, 2002; Petri et al., 2002; Philippov & Spitkovsky, 2014

Gamma-ray modeling

- Simulations prefer current sheet as a particle accelerator. Particles radiate synchrotron radiation.
- We apply radiative cooling on particles and collect photons.
- Observe caustic emission.
- Neutral injection at the surface.
- Predict gamma-ray efficiencies 1-20% depending on the inclination angle. Higher inclinations are much less dissipative.



Cerutti, Philippov & Spitkovsky

MNRAS 2016

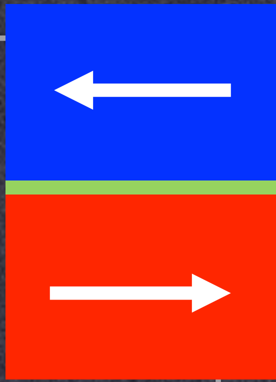
Pulsars:

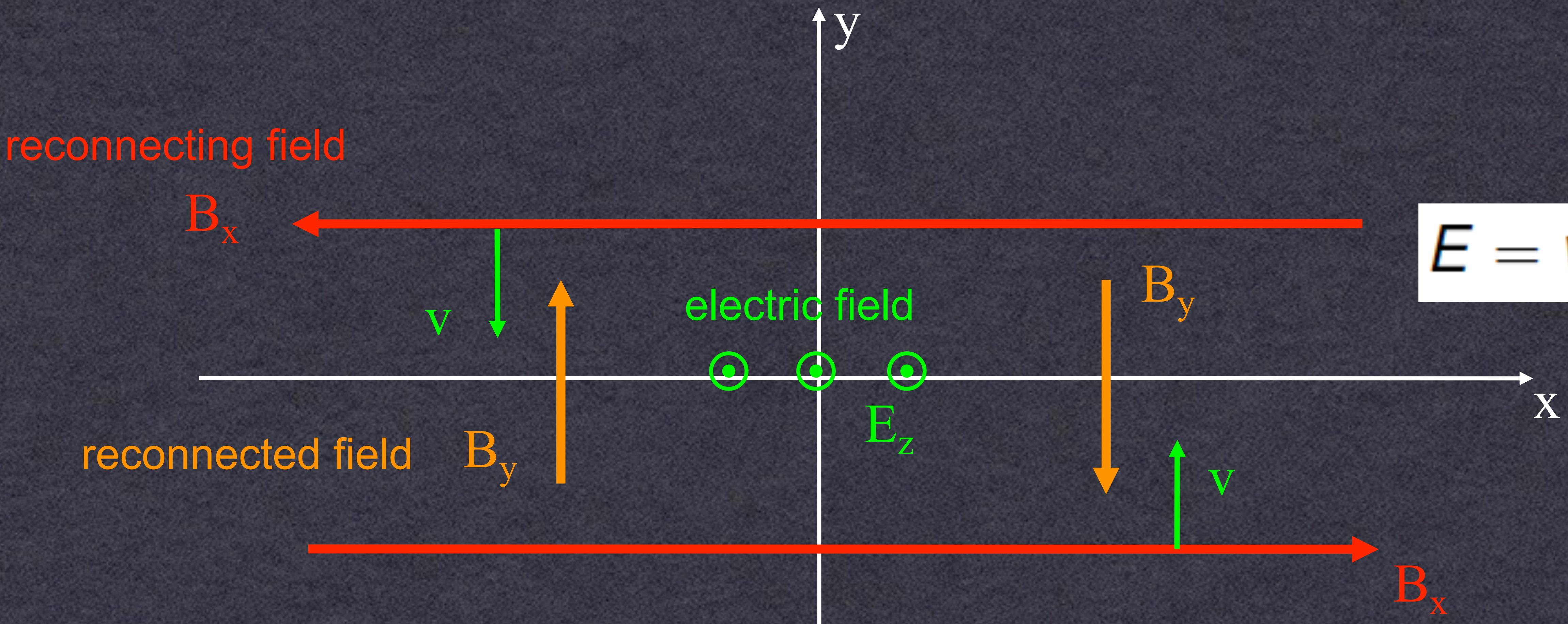
- Origin of pulsar emission has been a puzzle since 1967 - full kinetic simulations are finally addressing this from first principles.
- In flat space, self-consistent kinetic models show that pair cascade does not operate in the polar region for small obliquities, works for >40 degrees.
- General relativity effects are essential in producing discharges in low obliquity pulsars.
- Current sheet is an effective particle accelerator. Particles in the sheet emit powerful gamma-rays mainly via synchrotron mechanism.
- Radio emission is likely caused by the non-stationary discharge at the polar cap.

Relativistic reconnection

with Lorenzo Sironi

Magnetic reconnection





y

reconnecting field

B_x

v

electric field

B_y

x

E_z

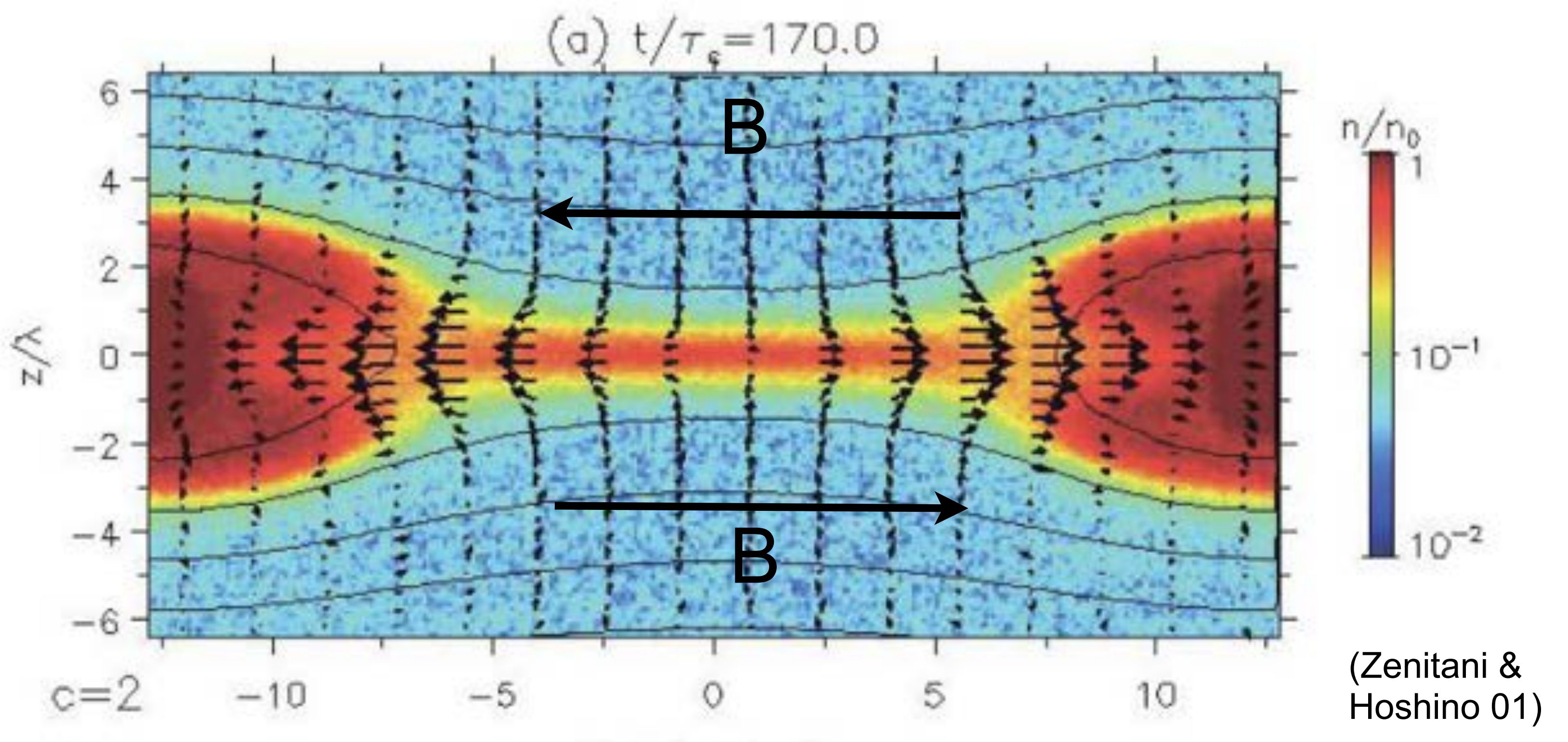
reconnected field

B_y

v

B_x

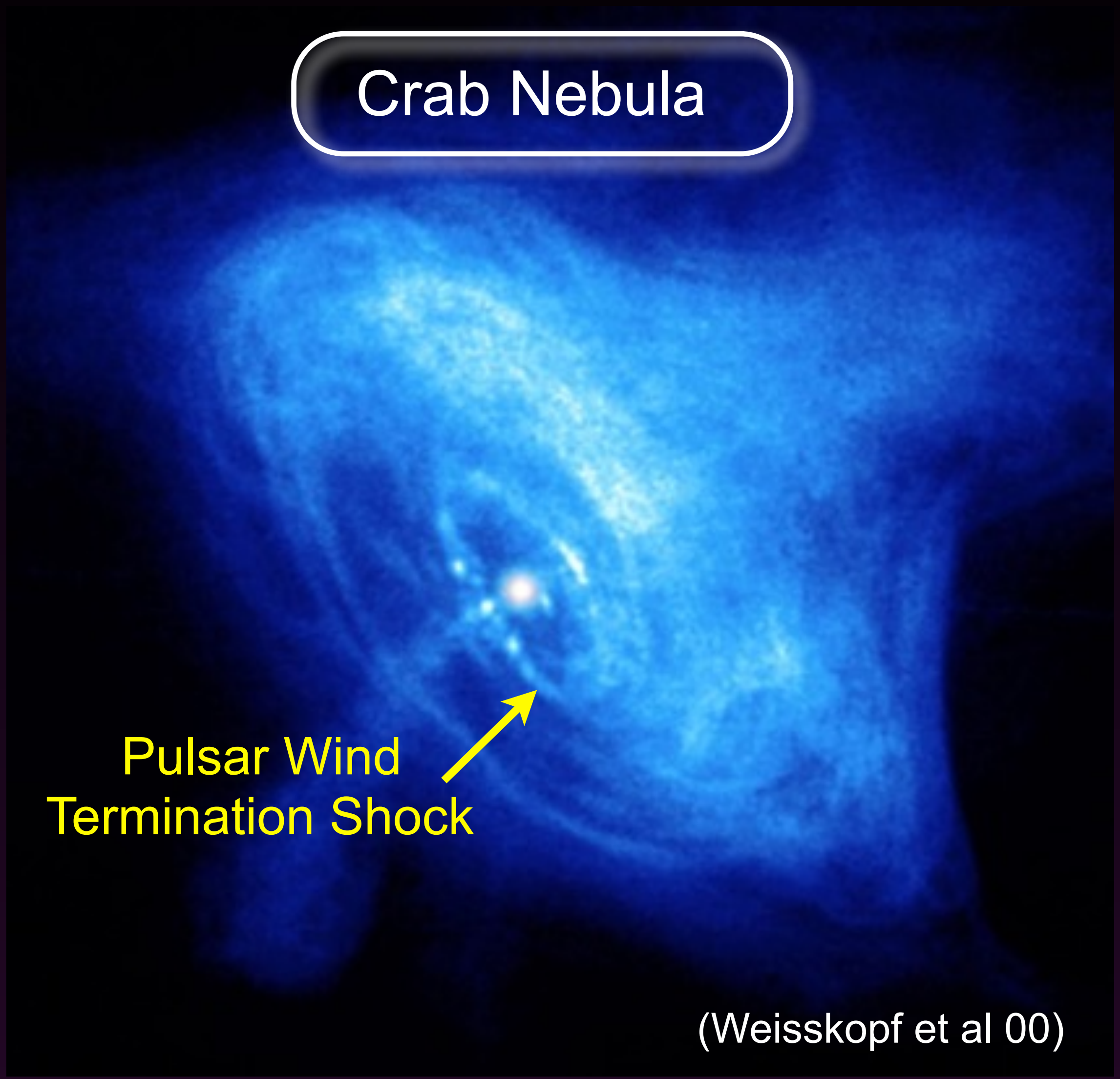
$$E = v \wedge B$$



(Zenitani & Hoshino 01)

Dissipation in relativistic outflows

Crab Nebula

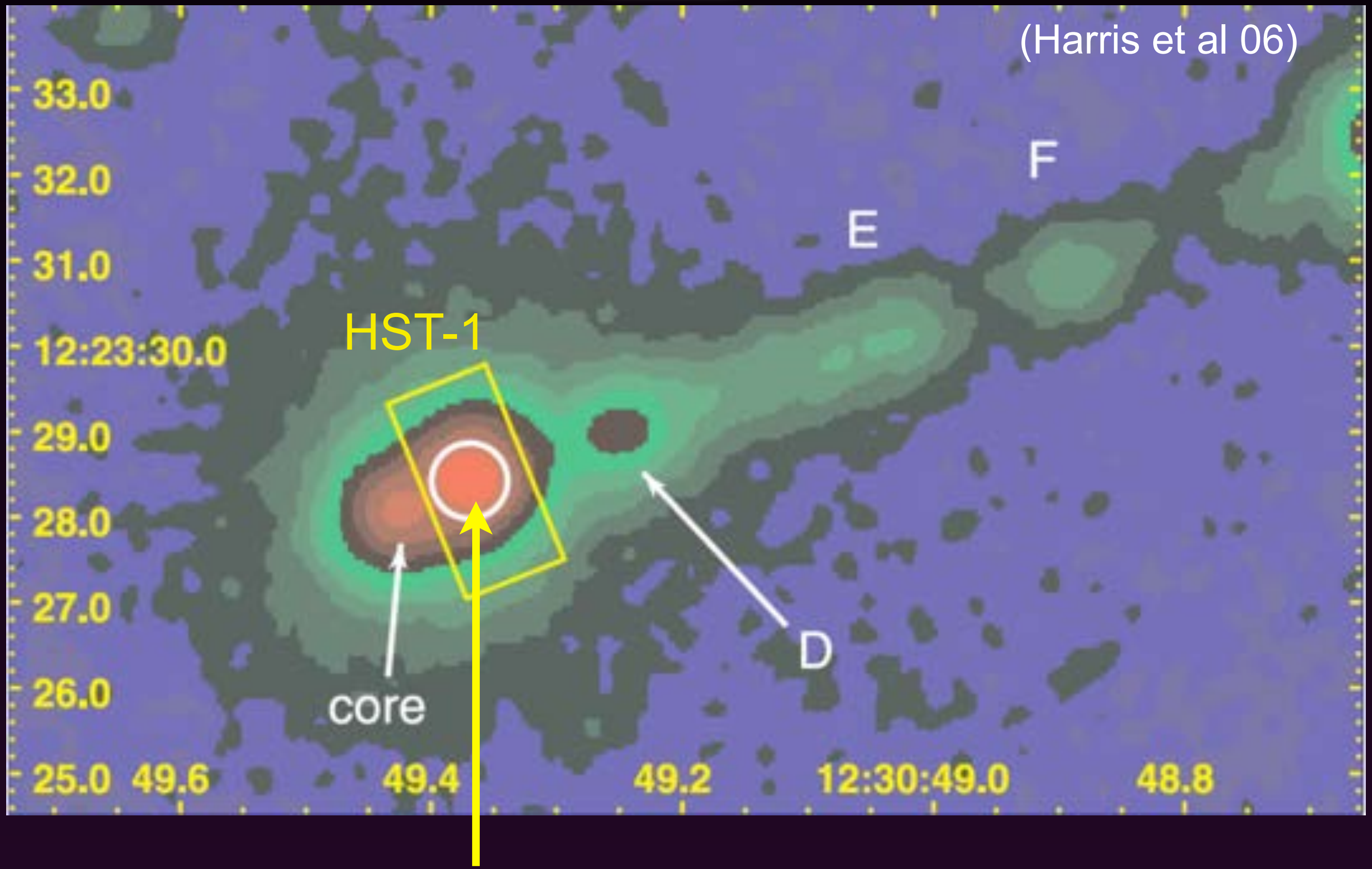


Pulsar Wind Termination Shock

(Weisskopf et al 00)

Shocks or Reconnection?

M87



(Harris et al 06)

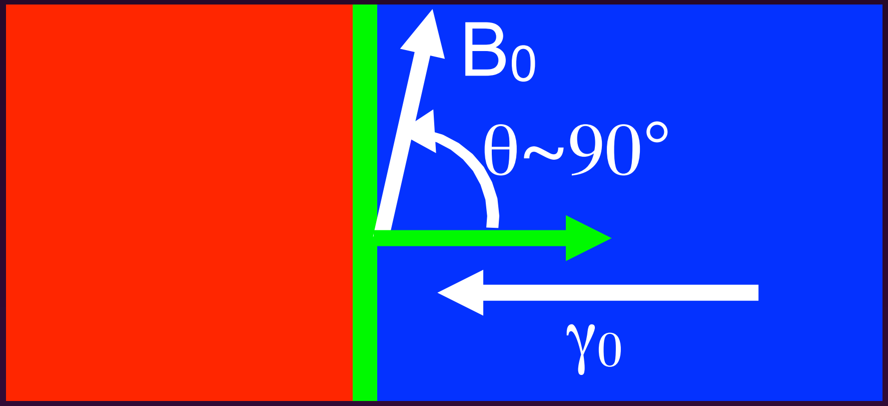
Internal Dissipation: Shocks or Reconnection?

Relativistic outflows: $\gamma_0 \gg 1$

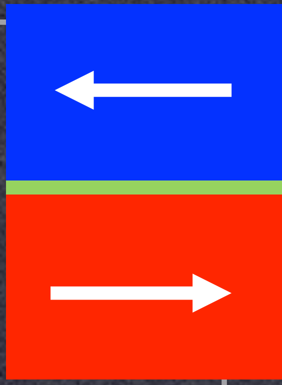
Magnetized: $\sigma = 0.01 - 0.1$

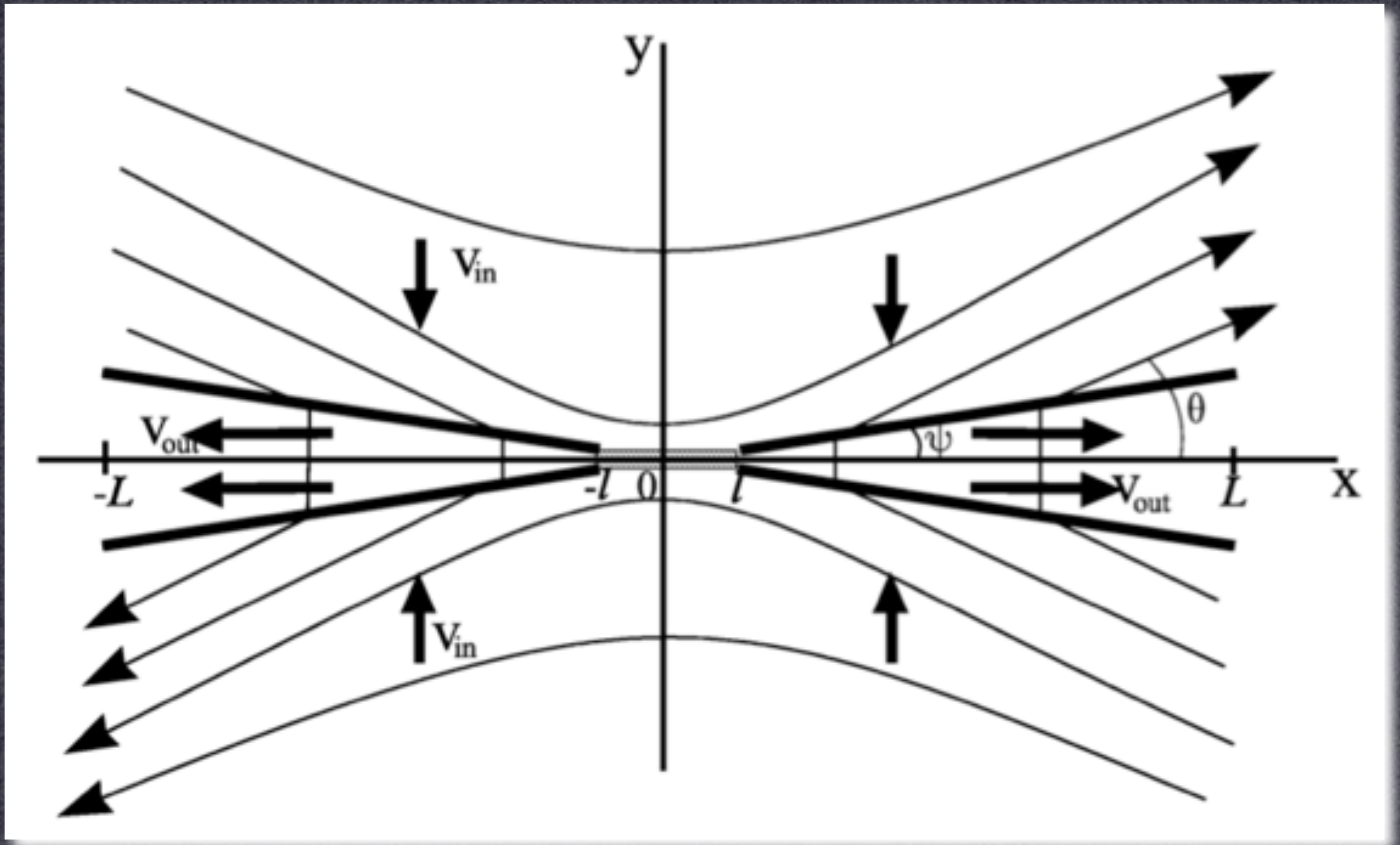
If shocks, then the field is ⊥ to the shock normal

$$\sigma = \frac{B_0^2}{4\pi\gamma_0 n_0 m_p c^2}$$



Open questions:





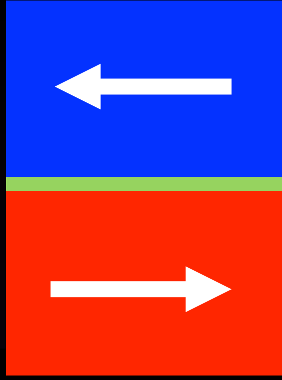
$$\sigma = \frac{B_0^2}{4\pi n_0 m_p c^2}$$

Relativistic magnetic reconnection: σ>>1

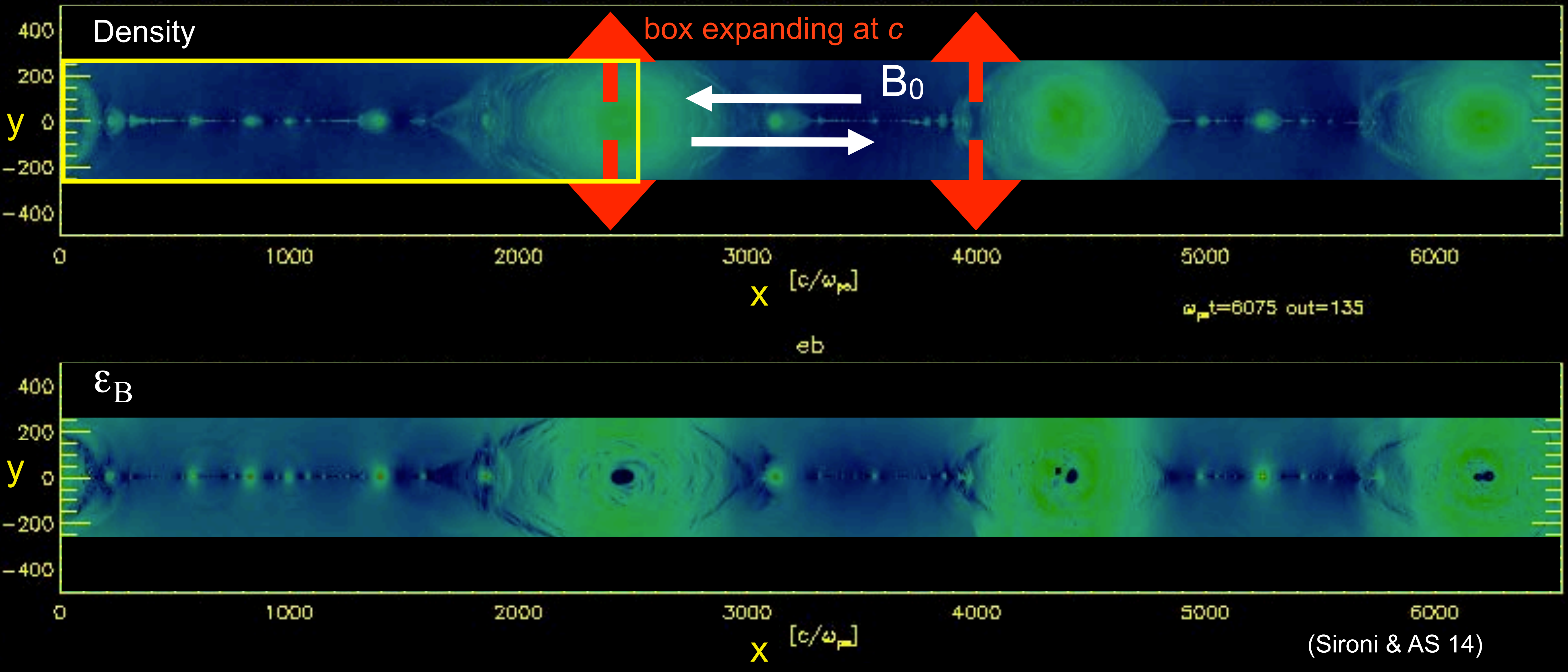
(Lyubarsky 05, Lyutikov & Uzdensky 03)

- **Does relativistic magnetic reconnection accelerate nonthermal particles?**
- **How fast is it?**
- **What is the mechanism? How reconnection works in a large system?**

Hierarchical reconnection



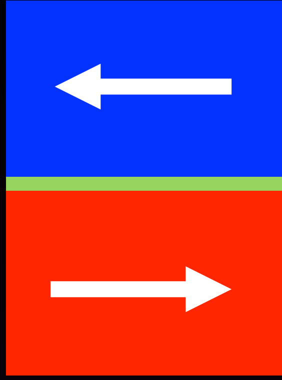
$\sigma=10$ electron-positron



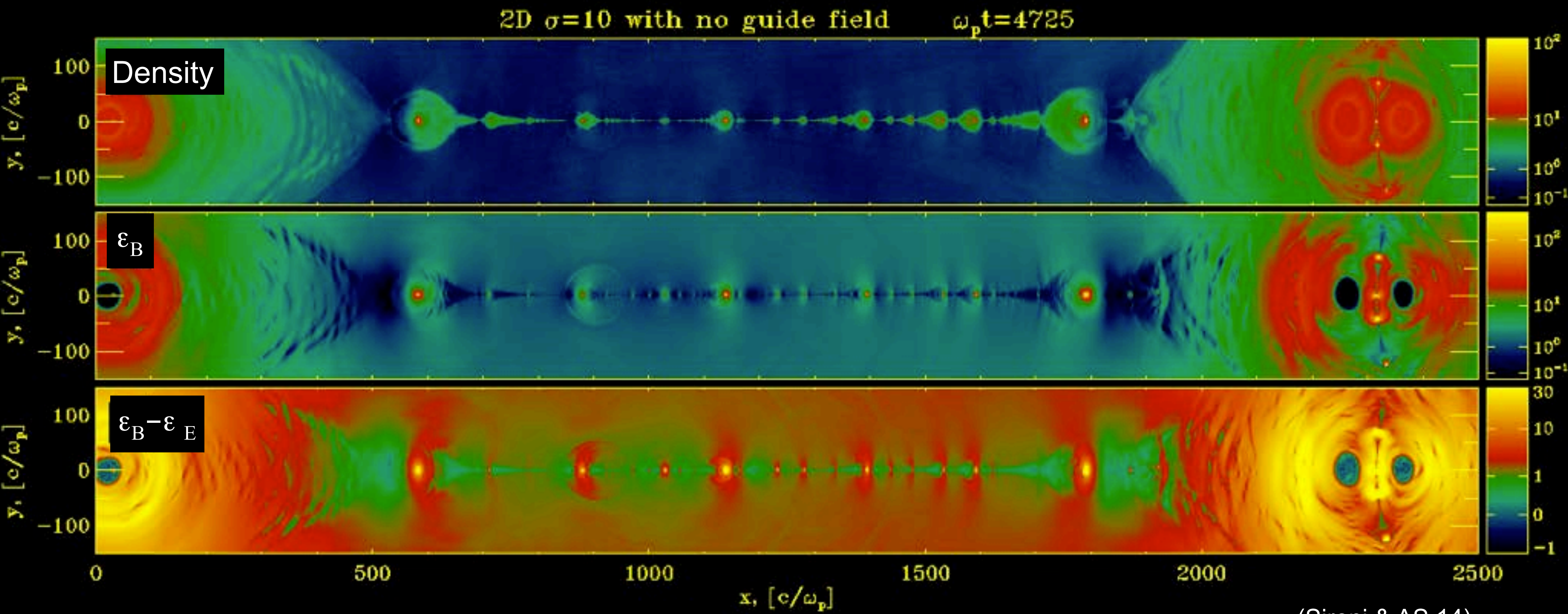
(Sironi & AS 14)

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

Hierarchical reconnection



$\sigma=10$ electron-positron

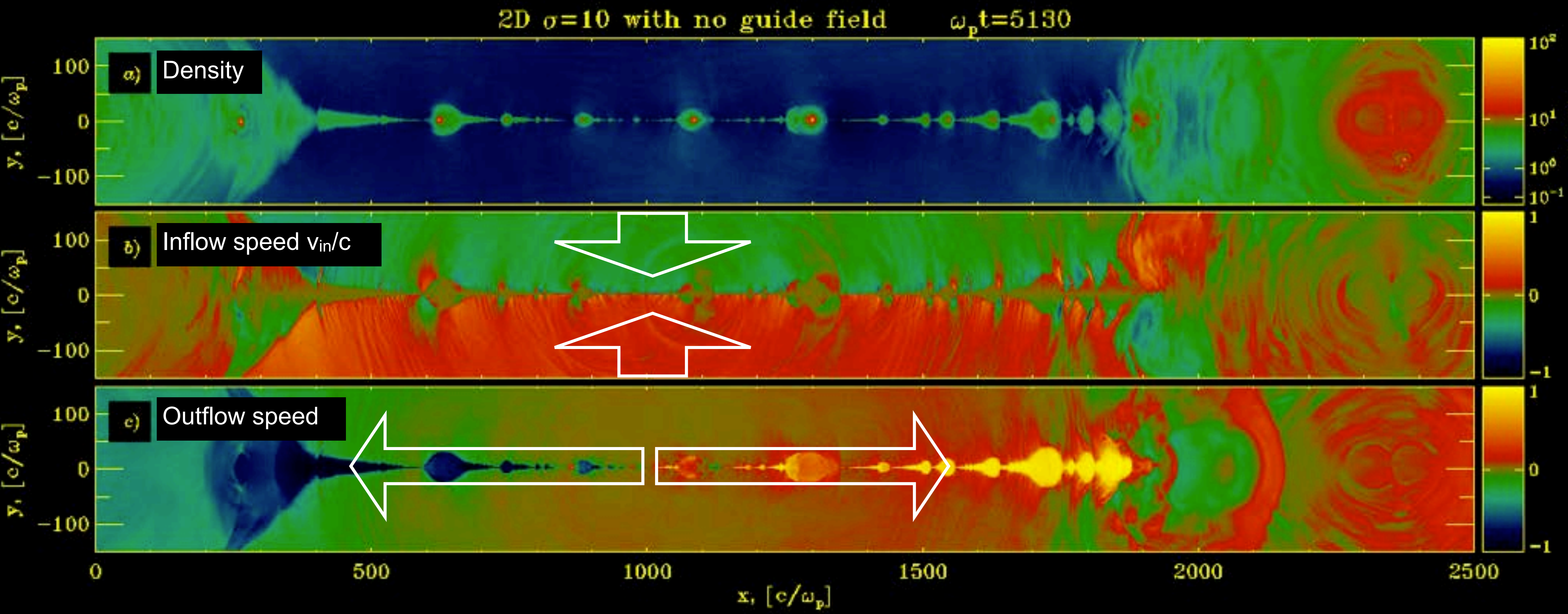


(Sironi & AS 14)

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

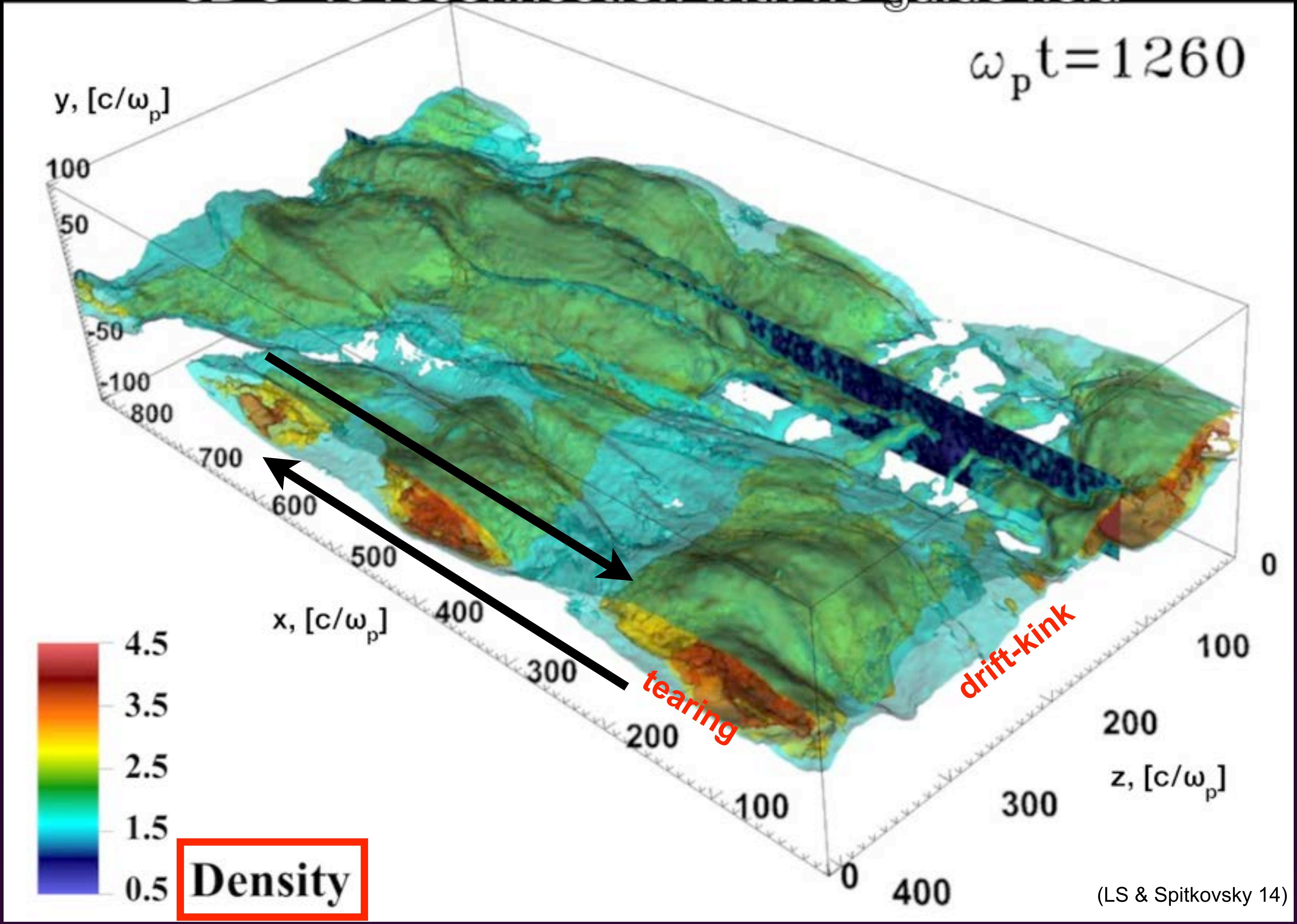
Inflows and outflows

σ=10 electron-positron



- Inflow into the X-line is non-relativistic, v_{in} ~ 0.1 c (so, the reconnection rate *r* ~ 0.1).
- Outflow into the islands is ultra-relativistic, at the Alfven speed $v_A = c\sqrt{\dfrac{\sigma}{1+\sigma}}$

3D σ=10 reconnection with no guide field

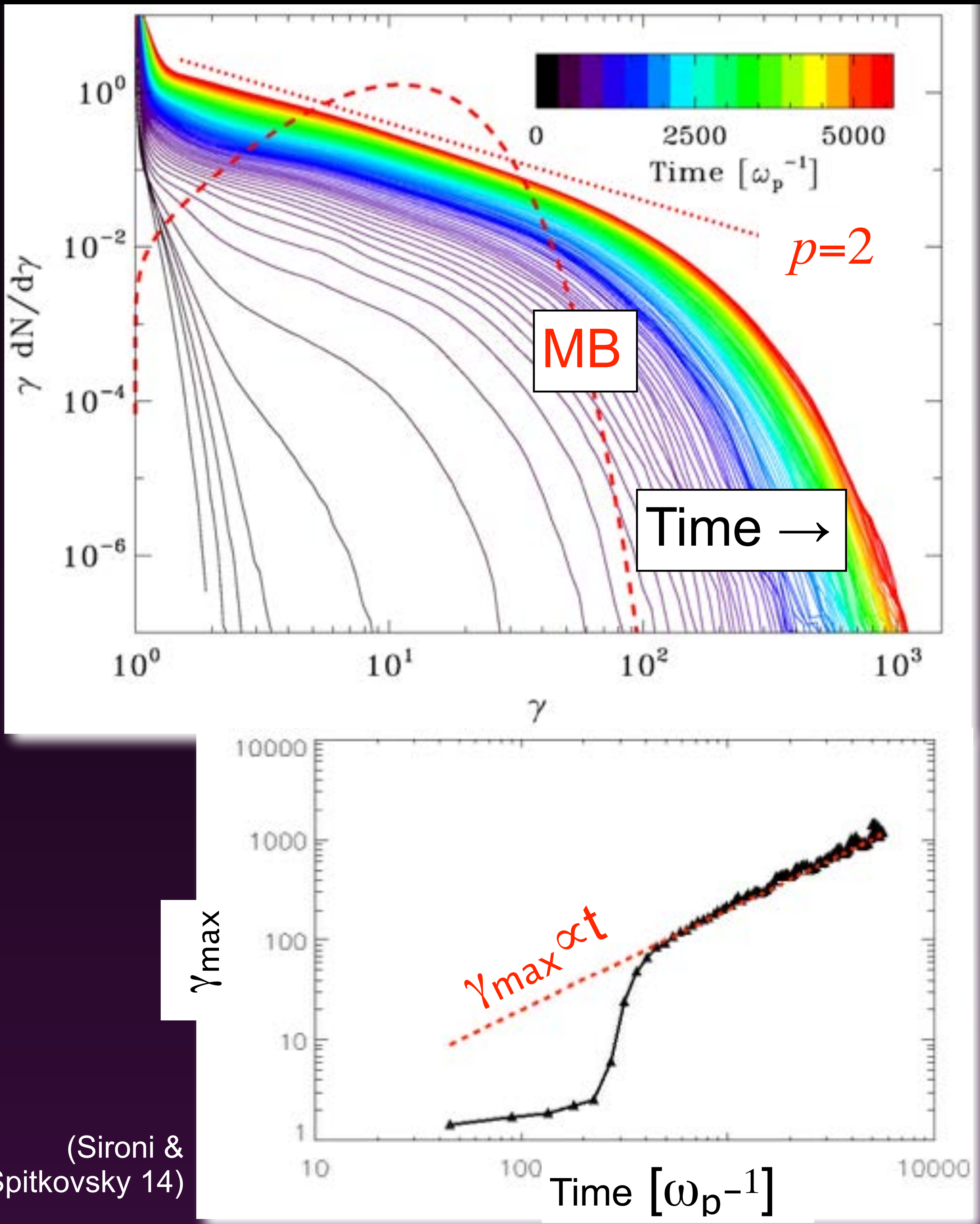


(LS & Spitkovsky 14)

- In 3D, the in-plane tearing mode and the out-of-plane drift-kink mode coexist.
- The drift-kink mode is the fastest to grow, but the physics at late times is governed by the tearing mode, as in 2D.

The particle energy spectrum

$\sigma=10$ electron-positron



(Sironi & Spitkovsky 14)

- At late times, the particle spectrum in the current sheet approaches a power law $dn/d\gamma \propto \gamma^{-p}$ of slope $p\sim2$.

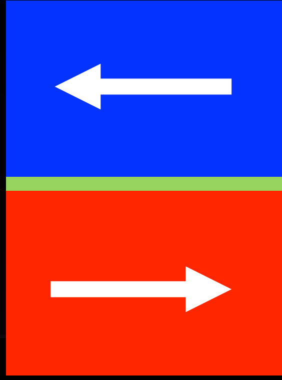
- The normalization increases, as more and more particles enter the current sheet.

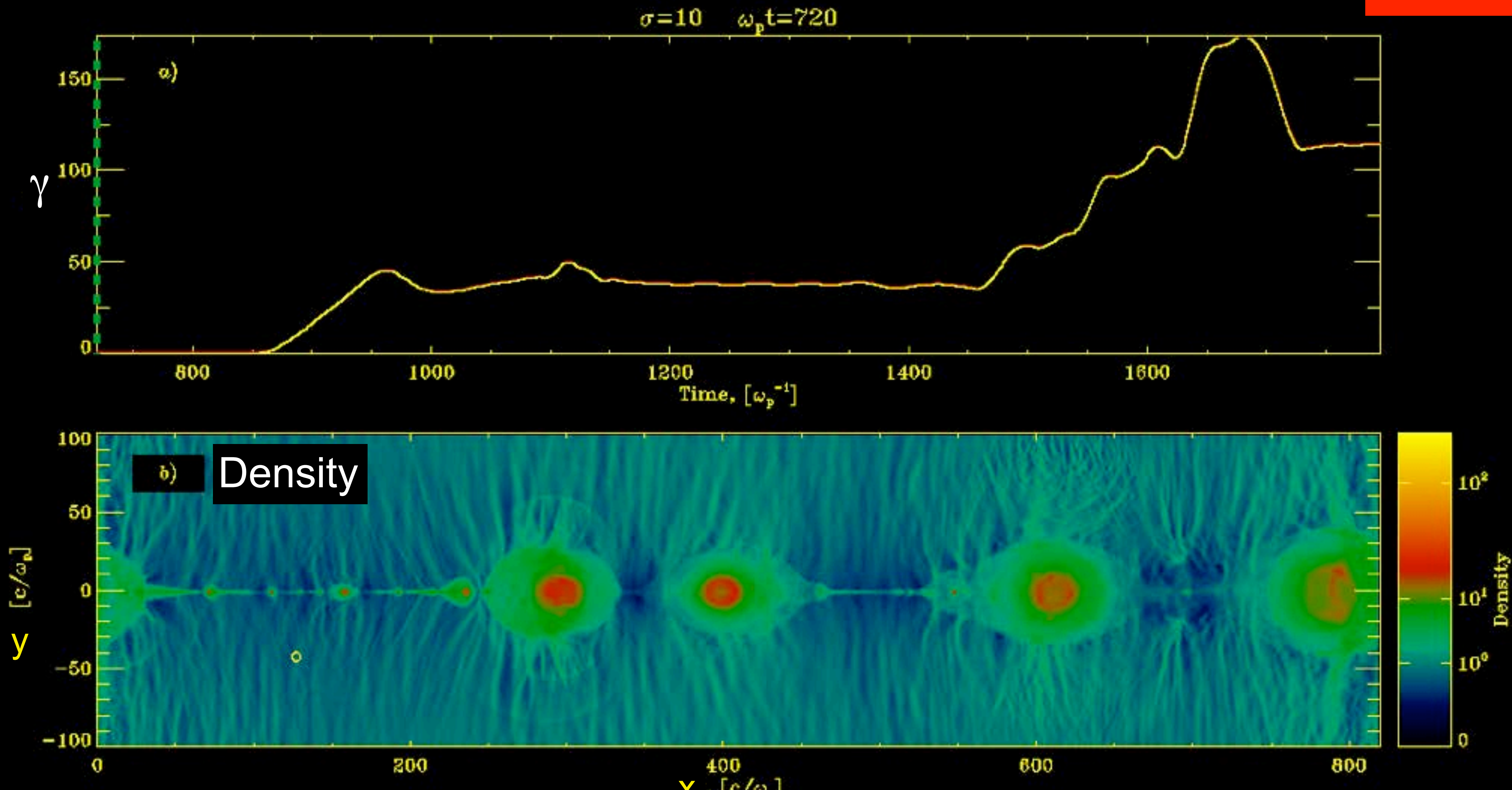
- The mean particle energy in the current sheet is $\sim\sigma/2$

→ energy equipartition

- The max energy grows as $\gamma_{max}\propto t$ (compare to $\gamma_{max}\propto t^{1/2}$ in shocks).

The highest energy particles

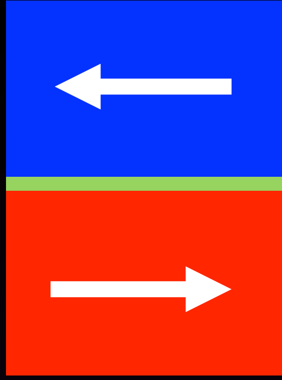


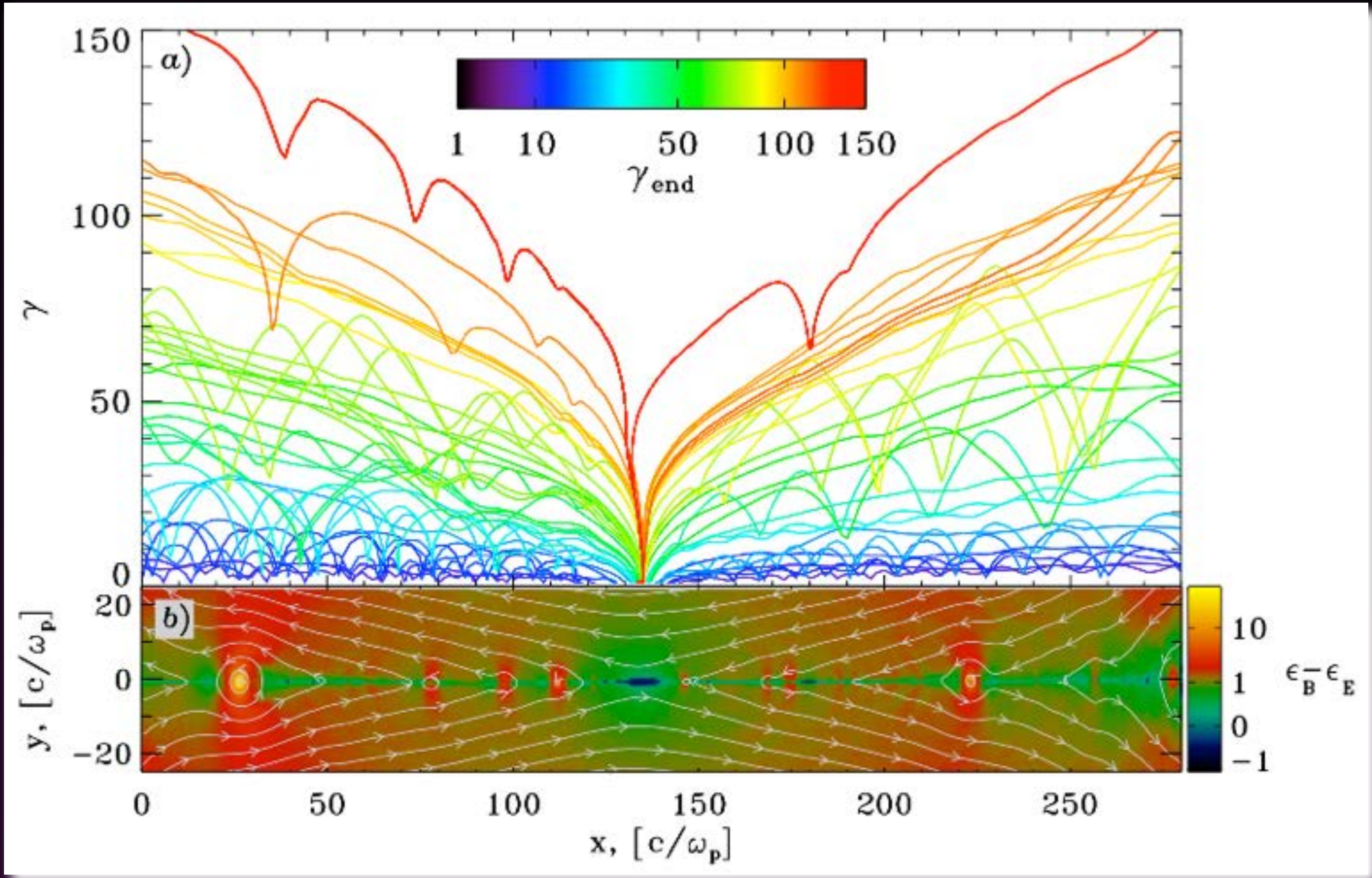


(LS & Spitkovsky 14)

Two acceleration phases: 1) at the X-point; 2) in between merging islands

(1) Acceleration at X-points



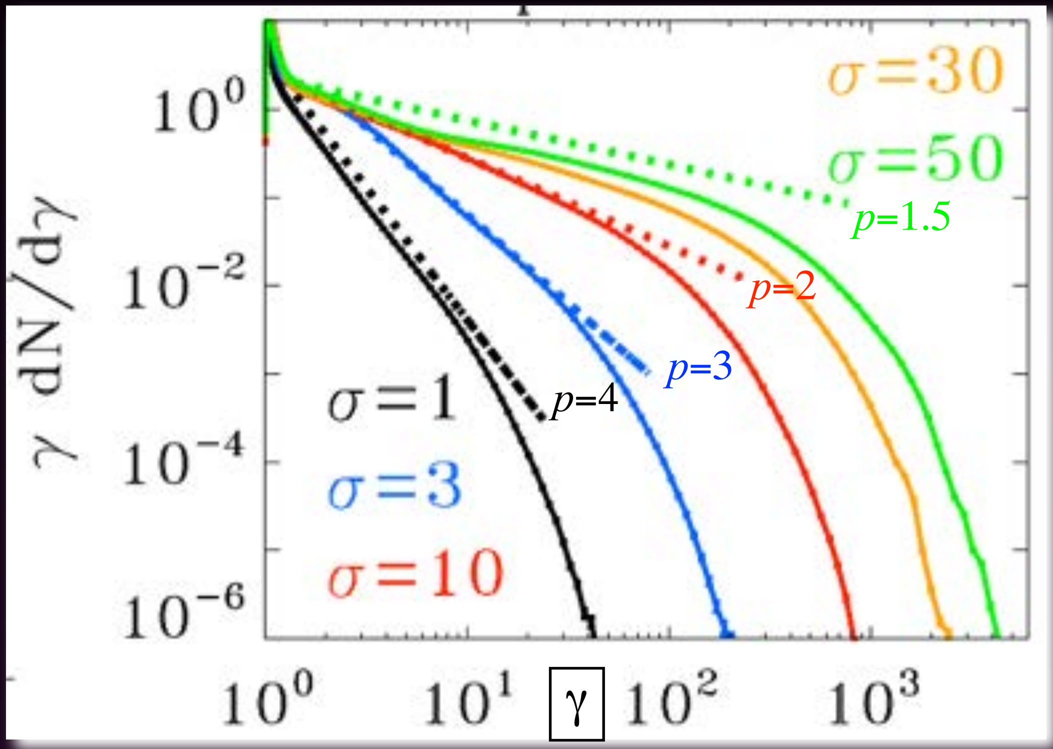


(LS & Spitkovsky 14)

- In cold plasmas, the particles are tied to field lines and they go through X-points.
- The particles are accelerated by the reconnection electric field at the X-points, and then advected into the nearest magnetic island.
- The energy gain can vary, depending on where the particles interact with the sheet.

Reconnection conclusions

- Relativistic reconnection is fast (0.1c inflows)
- Can generate robust nonthermal spectra, flatter than shock-acceleration; also, broad “multi-temperature” distributions.
- Acceleration mechanism is X-point boost and subsequent island merger.
- Can occur in many scenarios, e.g., striped winds in pulsars, GRB jets, etc.
- Complements shock acceleration nicely as another nonthermal generation process.

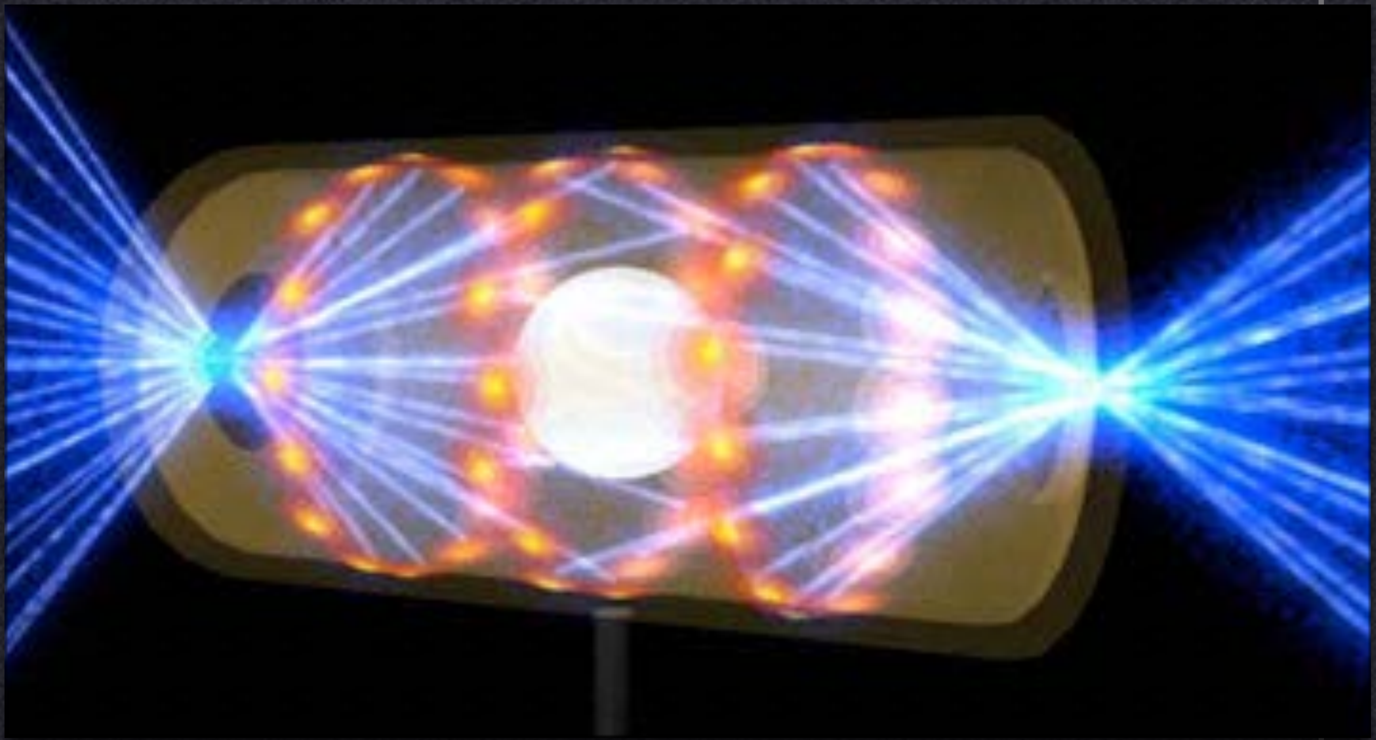


(LS & Spitkovsky 14, confirmed by Guo et al. 14, Werner et al. 14)

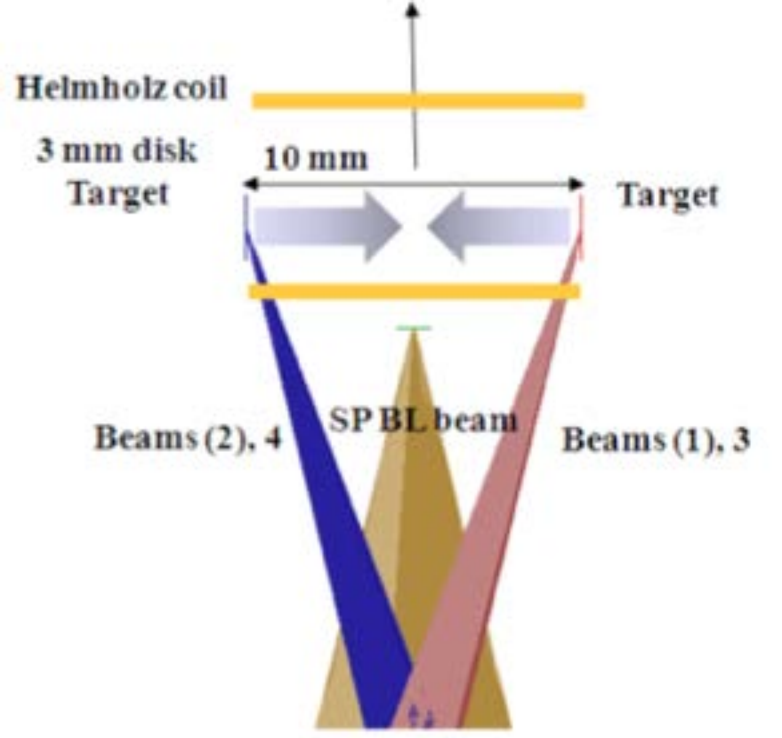
Relativistic reconnection produces extended non-thermal tails of accelerated particles, whose power-law slope is harder than *p*=2 for high magnetizations (σ>10)

Earthly connections: laboratory astrophysics

Plasma astrophysics in the lab

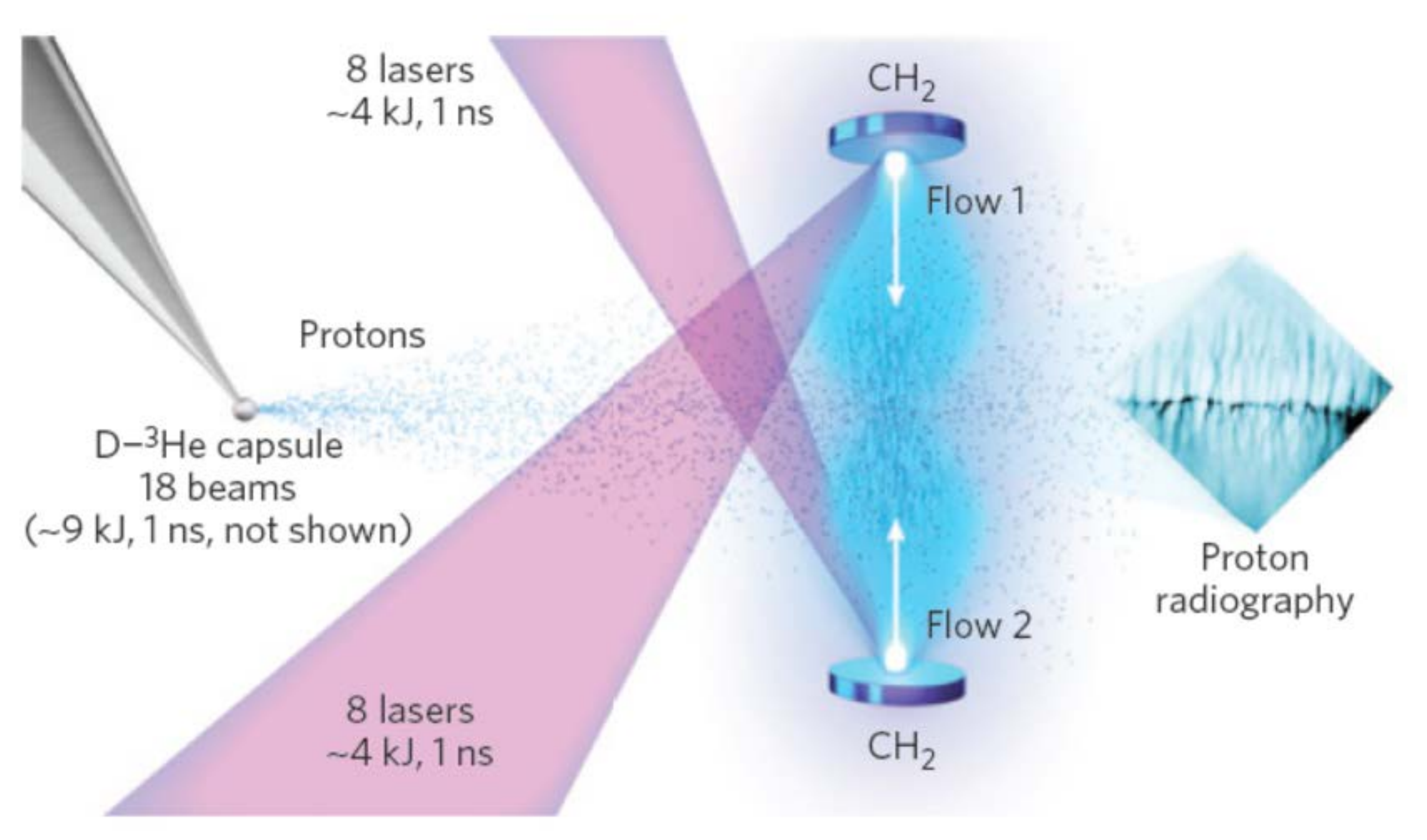


- Astrophysically relevant microscopic conditions can be obtained in the laboratory
  - Low collisinality
  - High speeds
  - Large energy densities and fields
- Laser-plasma experiments can achieve interesting conditions to test microphysics
  - Current & planned experiments: Omega EP (Rochester), NIF (LLNL)
- Other experiments: UCLA, LANL



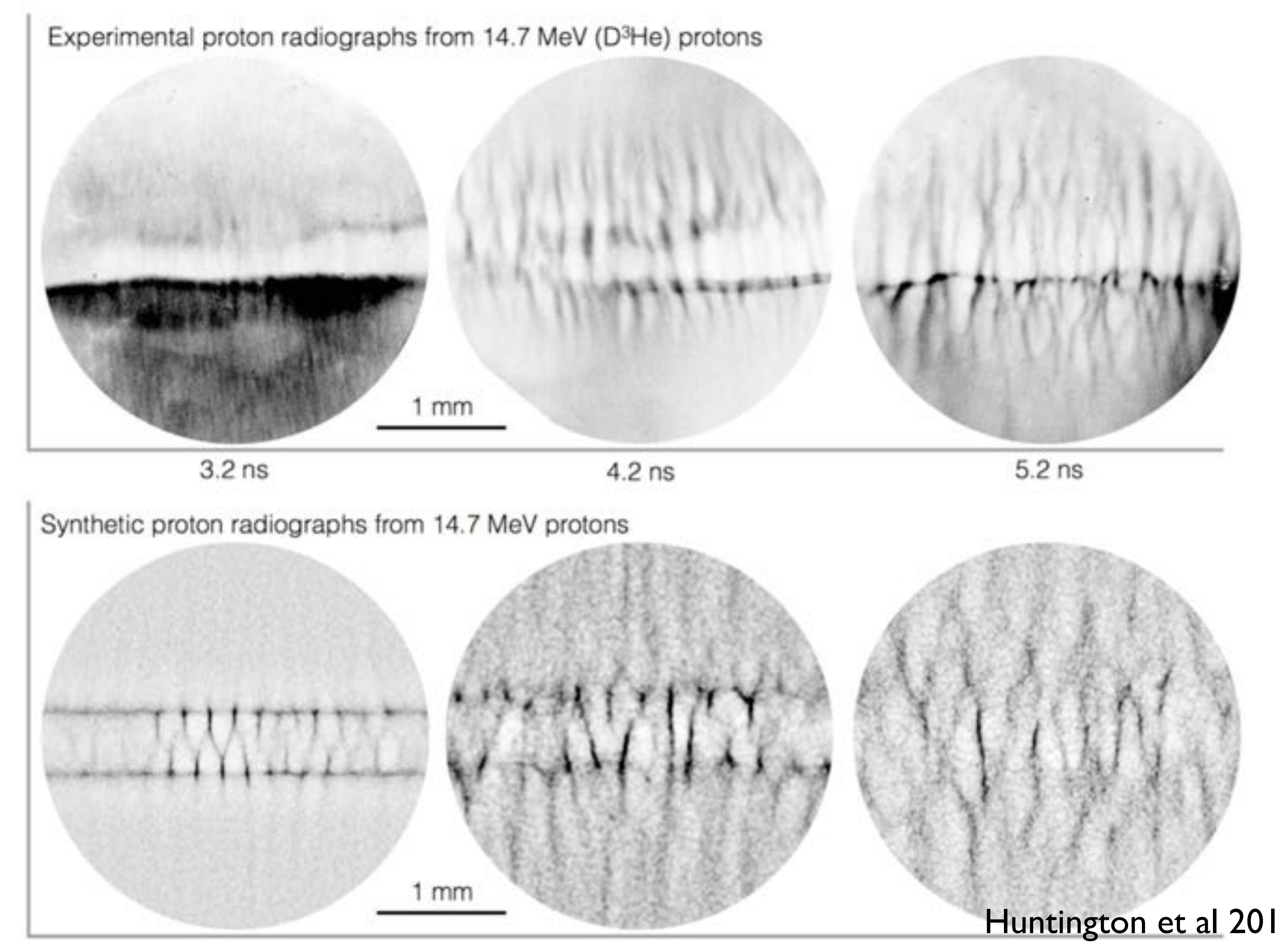
Does this actually happen?
Shock formation experiments on Omega Laser

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



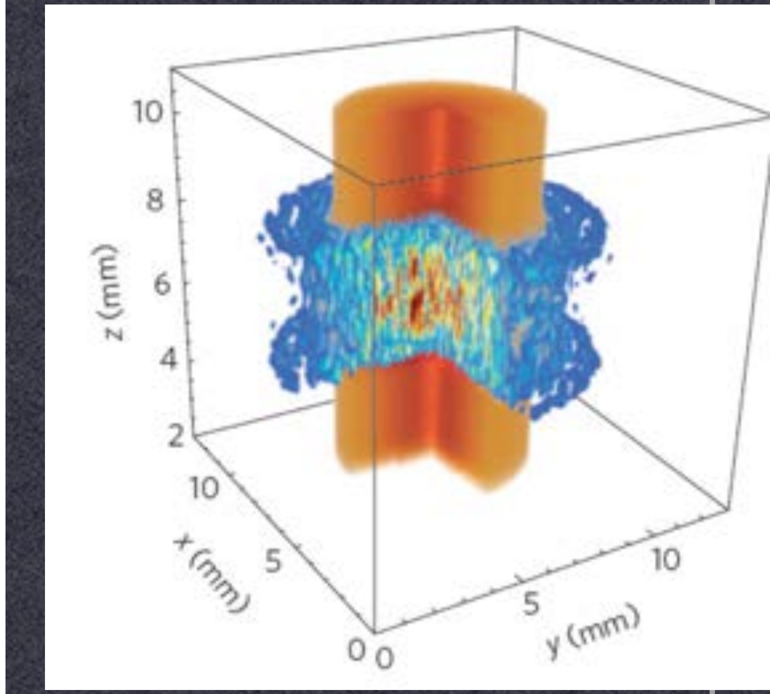
Huntington et al 2015, Nature Physics

Proton radiography of colliding flows



Huntington et al 2015

Experiment

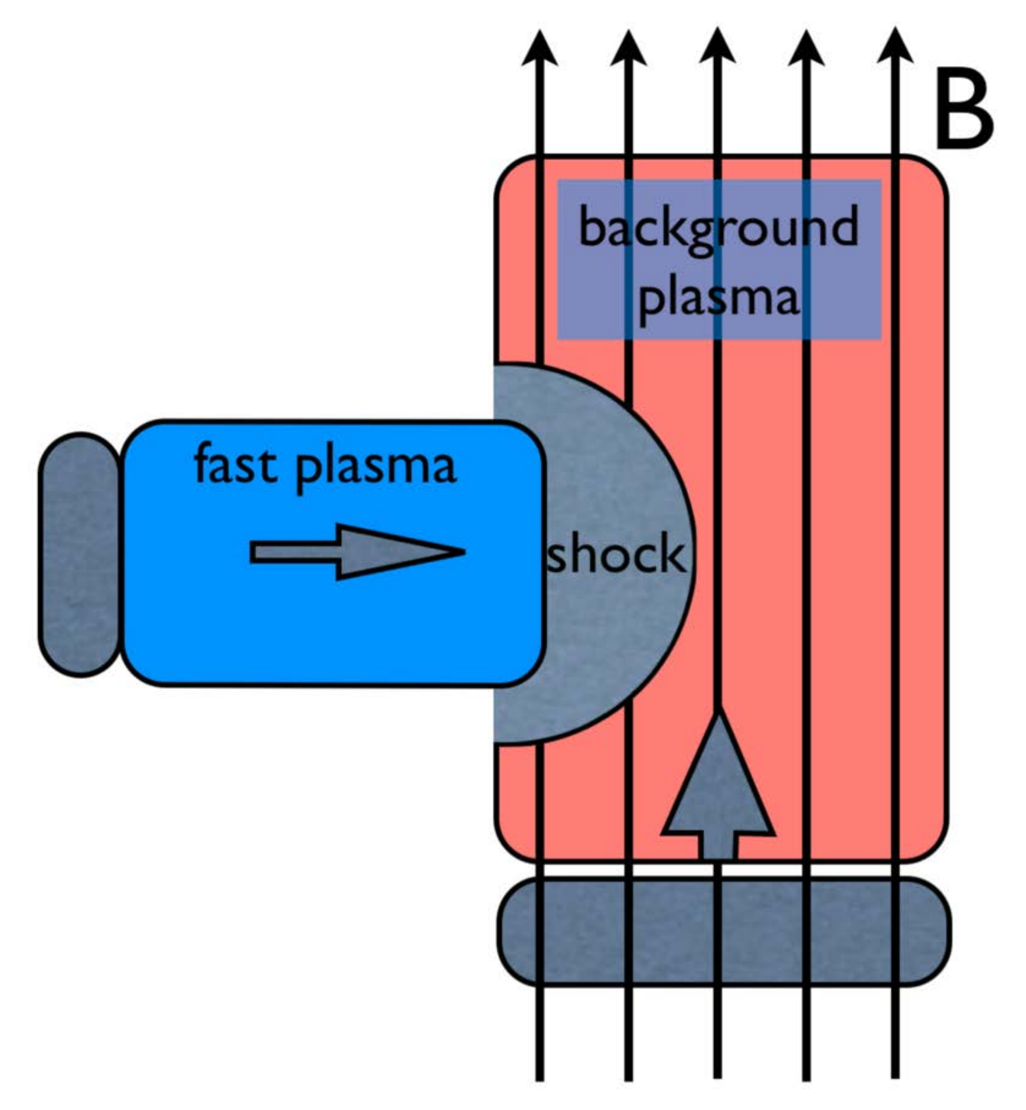


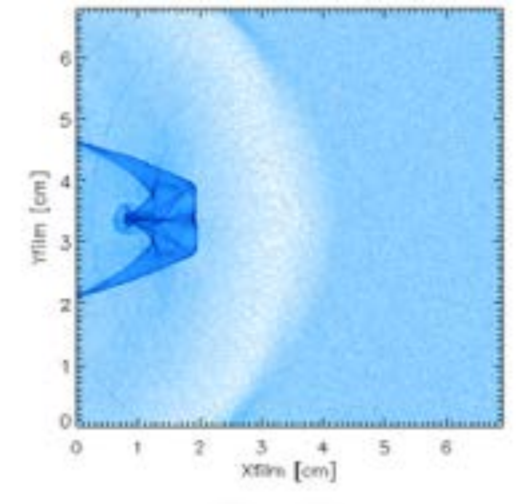
Simulation

Weibel filamentation is observed in the lab!

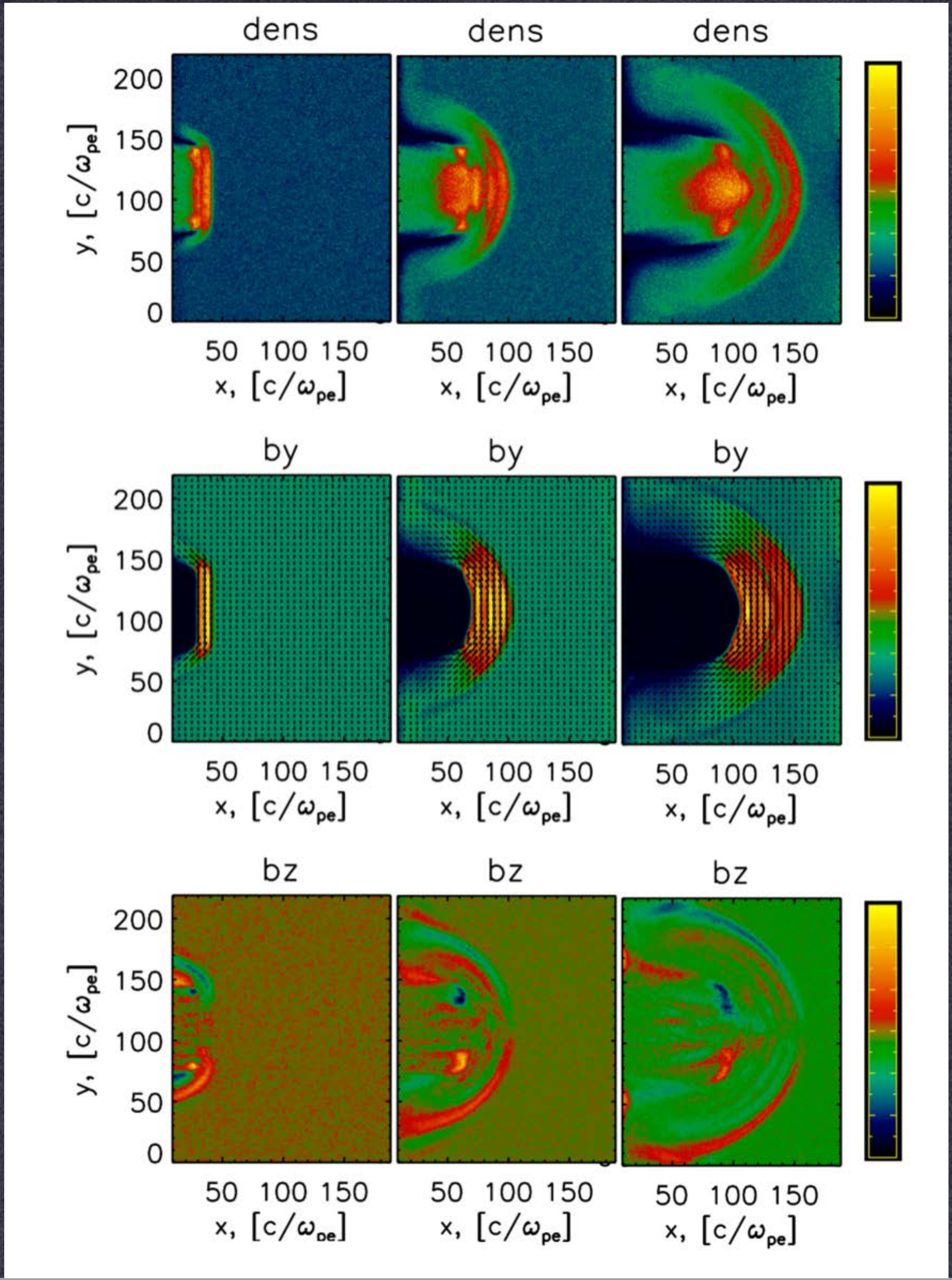
Huntington et al 2015, Nature Physics

Towards magnetized shocks



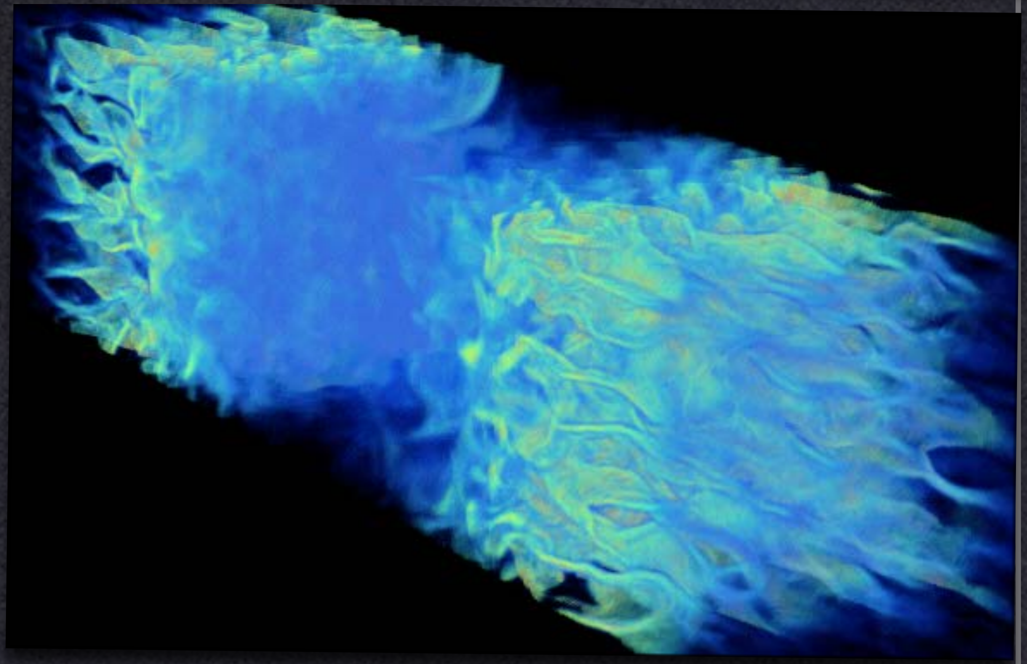


proton image



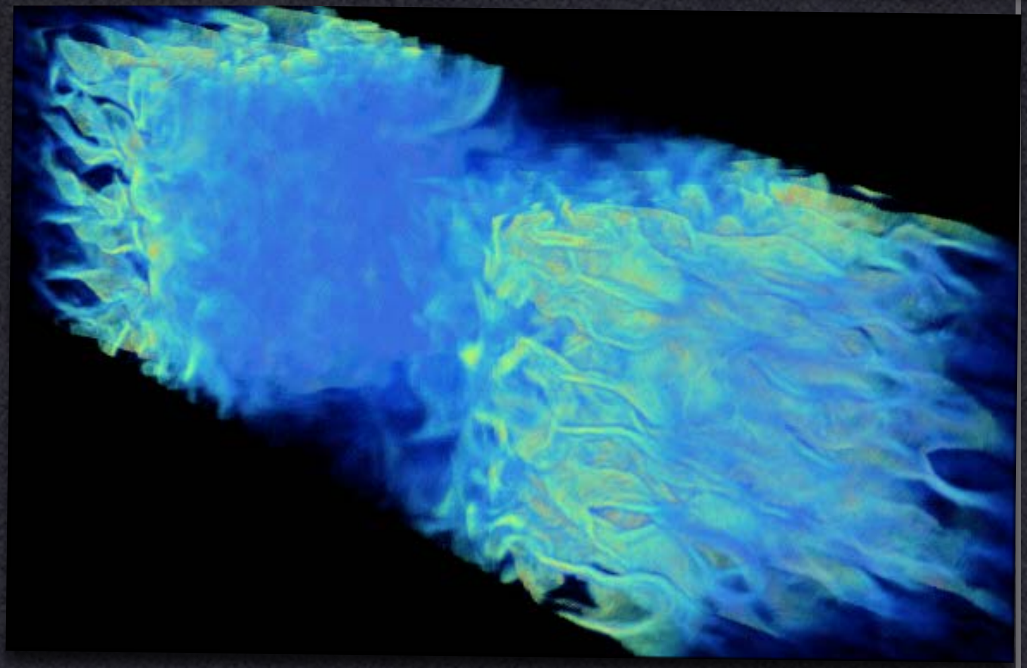
Conclusions and outlook

- Plasma astrophysics is an emerging field that has the potential to answer many long-standing questions in astrophysics.
- Some results:
  - Particle acceleration and shocks from first principles; self-consistent injection process efficiency
  - Importance of relativistic reconnection for pulsars
  - Reconnection accelerates particles
  - Shock (and reconnection) physics can be studied in the lab



Conclusions and outlook

- Plasma astrophysics is an emerging field that has the potential to answer many long-standing questions in astrophysics.
- Open questions:
  - How the microphysics of reconnection, acceleration, and heating work
  - How to connect the scales in a convincing astrophysical way



Conclusions and outlook

Combination of high-performance computing and analytic theory with code verification by laboratory experiments will lead to significant advances in our understanding of cosmic plasmas.