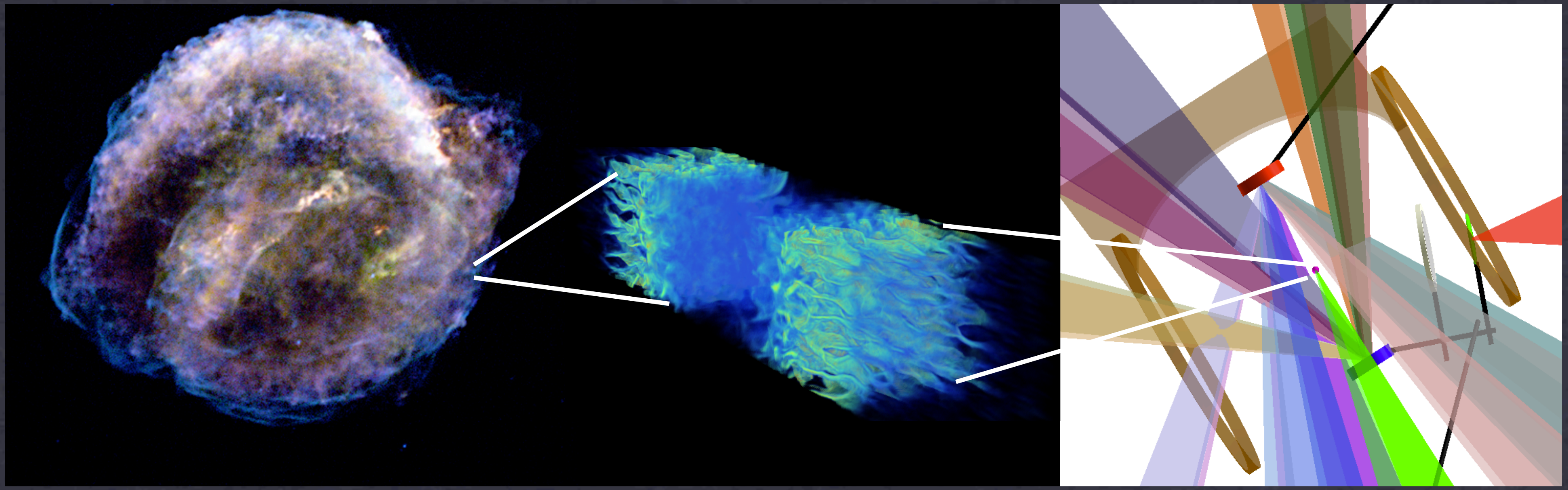
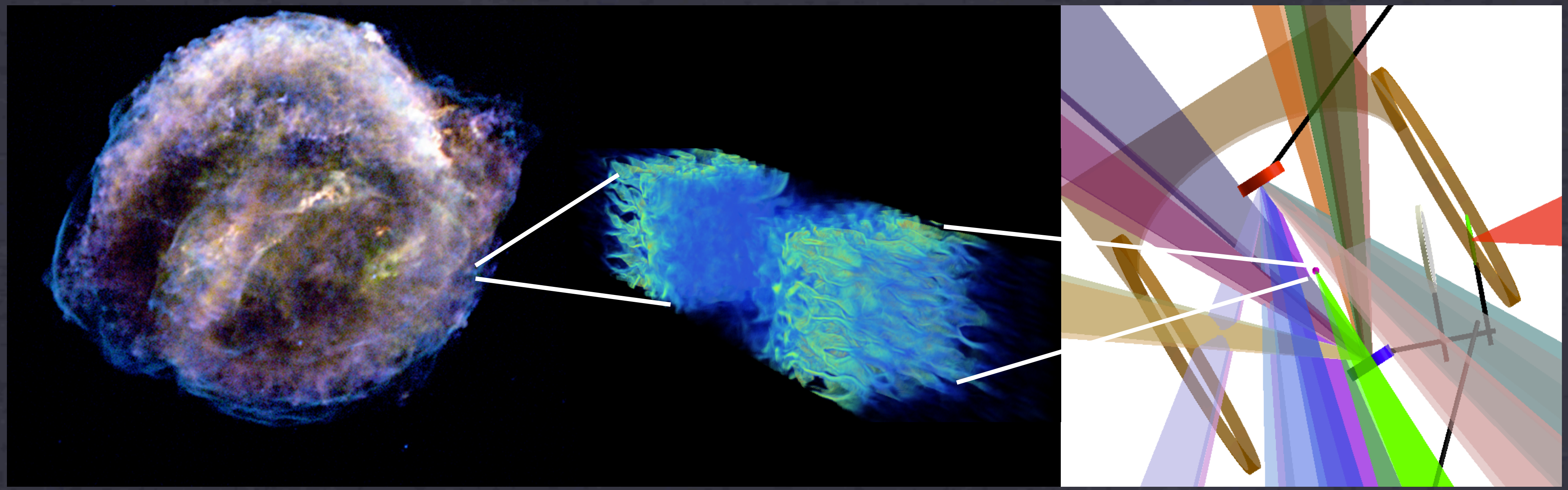


Universe ⟷ microphysics ⟷ experiments

Collisionless shock experiments with laser-ablated plasmas: status and prospects

Anatoly Spitkovsky (Princeton)

Colliding beam experiments on Omega: MagShock

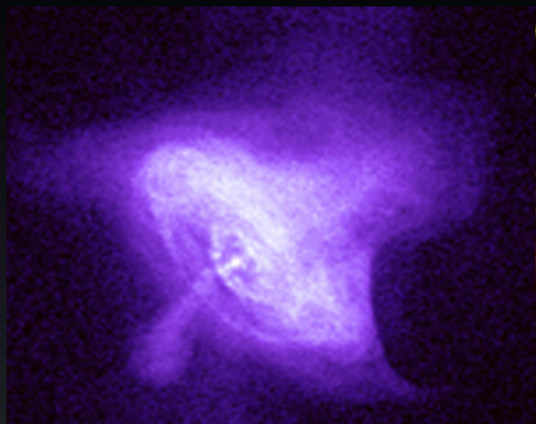


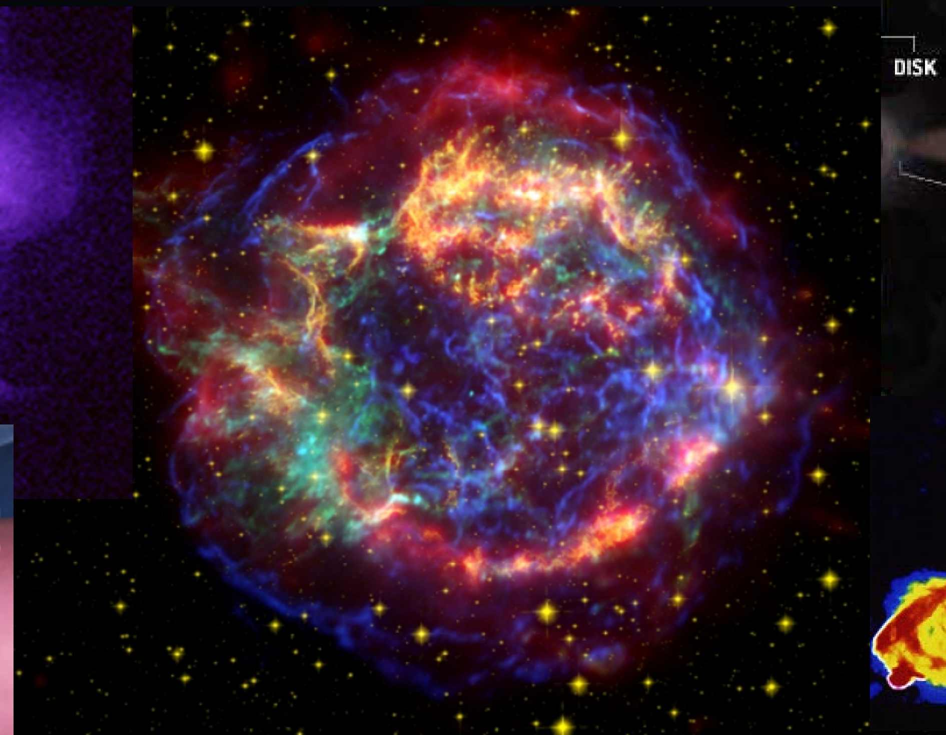
ACSEL collaboration (Astrophysical Collisionless Shock Experiments with Lasers)

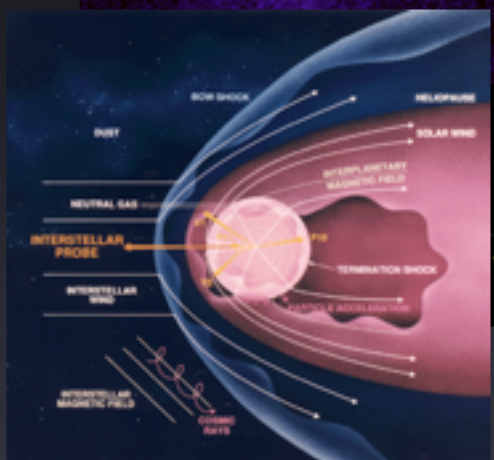
Princeton University (USA):	A. Spitkovsky, D. Caprioli
LLNL (USA):	C. Huntington, H.-S. Park, C. Plechaty, S. Ross, B. Remington, D. Ryutov, N. Kugland
LLE, Univ. of Rochester (USA):	G. Fiksel, P.-Y. Chang, D. Froula, J. Knauer
Osaka University (Japan):	Y. Sakawa, H. Takabe, Y. Kuramitsu, T. Morita
Oxford University (UK):	G. Gregori, J. Meinecke, A. Bell
LULI (France):	M. Koenig, A. Ravasio, A. Pelka, T. Vinci, C. Riconda, R. Yurchak
ETH Zurich (Switzerland):	F. Miniati
York University (UK):	N. Woolsey
Rice University (USA):	E. Liang, M. Levy
University of Michigan (USA):	R. P. Drake, M. Grosskopf, C. Kuranz, E. Rutter

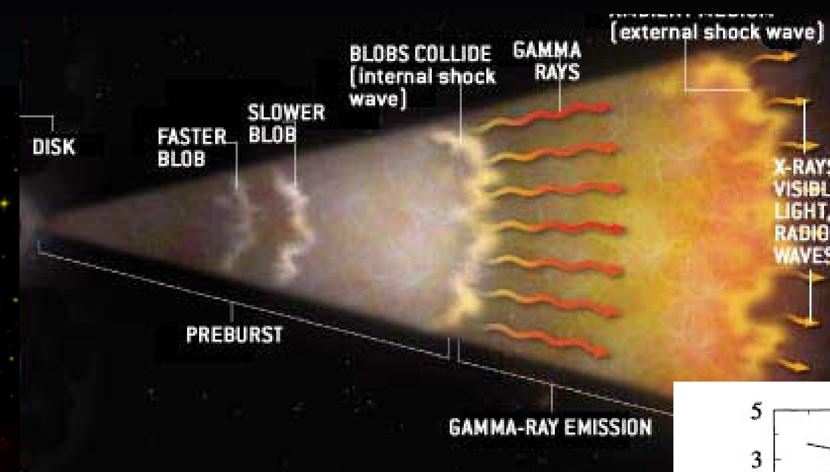
Goal: create a platform for shock studies on HED laser facilities (scaling to NIF)

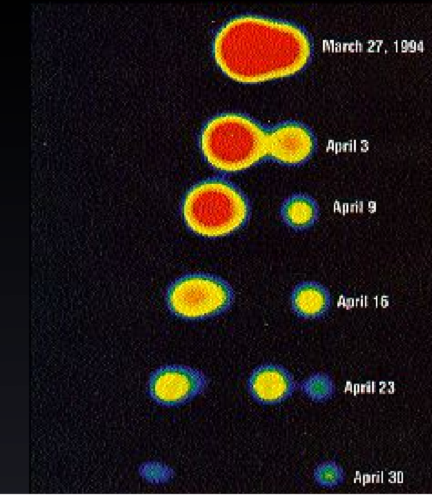
Shocks in astrophysics

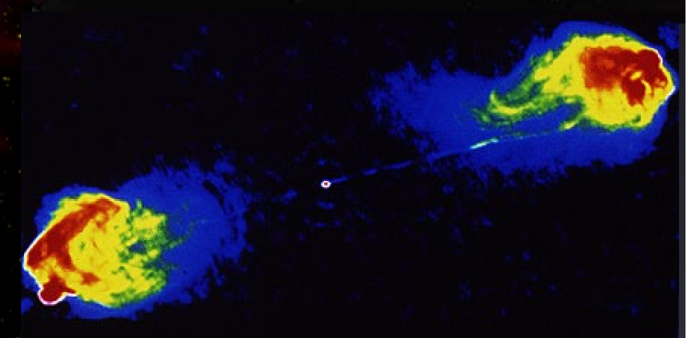


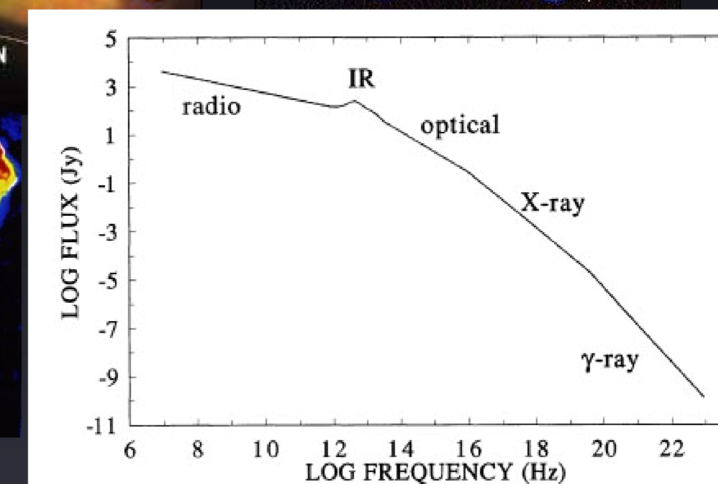












Astrophysical shocks are collisionless

Shocks span a range of parameters:
nonrelativistic to relativistic flows

magnetization (magnetic/kinetic energy ratio)

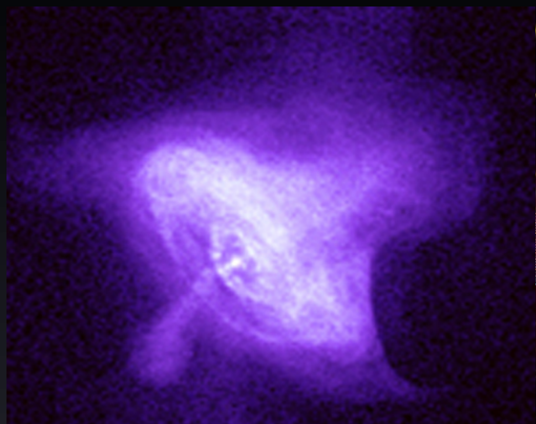
composition (pairs/e-ions/pairs + ions)

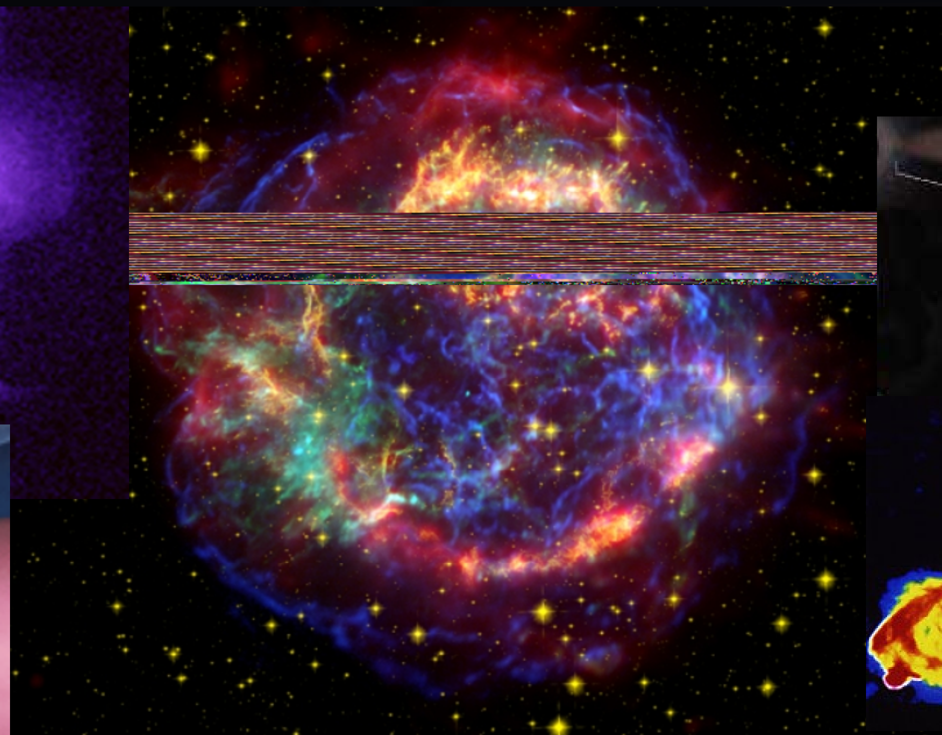
Astrophysical collisonless shocks can:

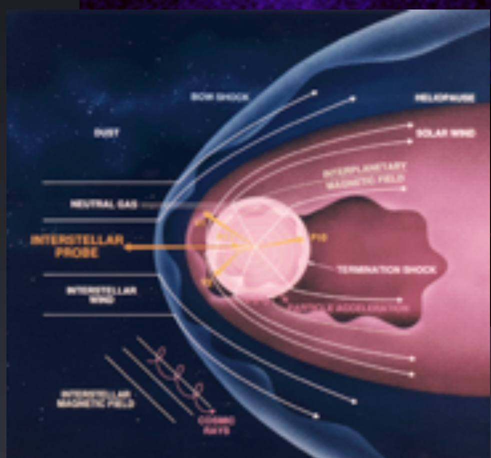
1. accelerate particles
2. amplify magnetic fields (or generate them from scratch)
3. exchange energy between electrons and ions

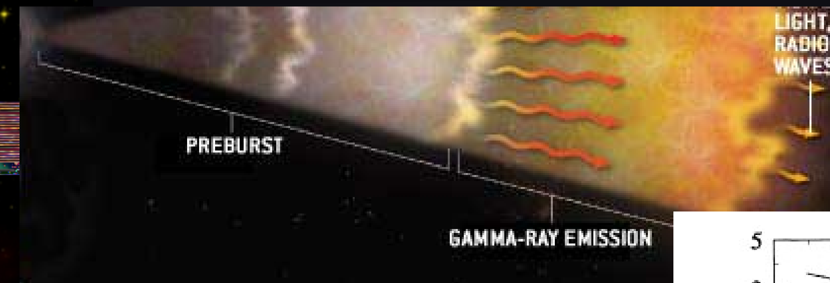
Is this all intrinsic to the shock?

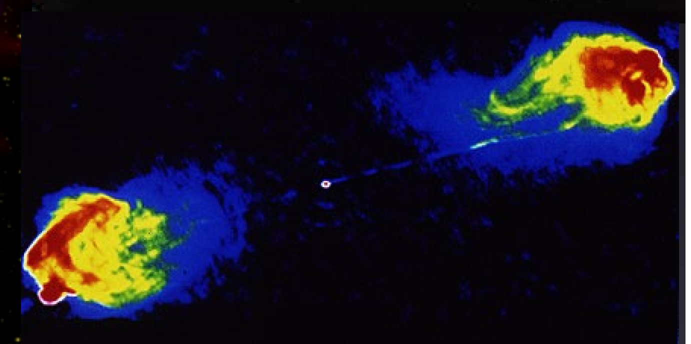
Shocks in astrophysics

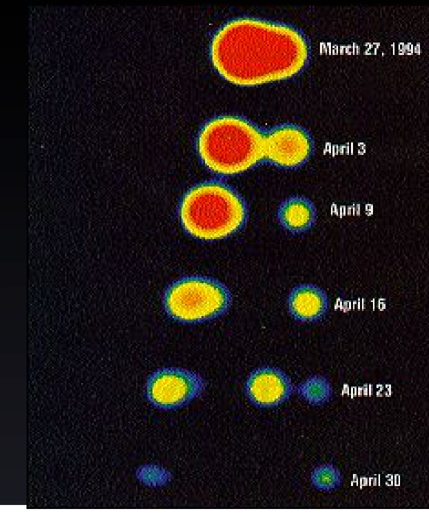


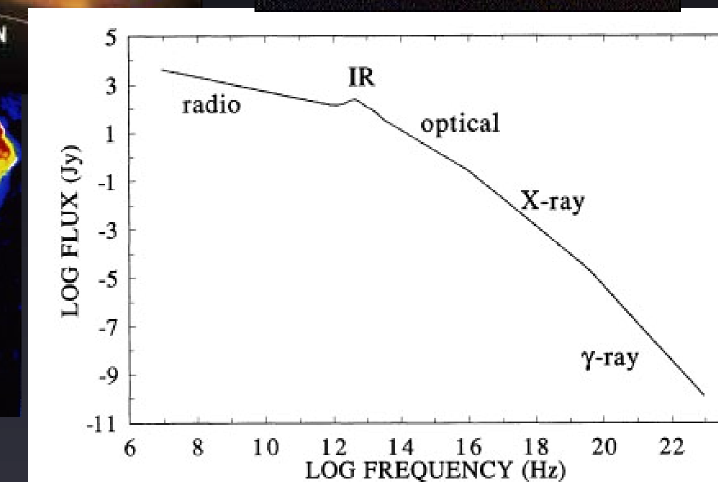












Open issues:

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

Particle acceleration -- Fermi mechanism? Other? Efficiency?

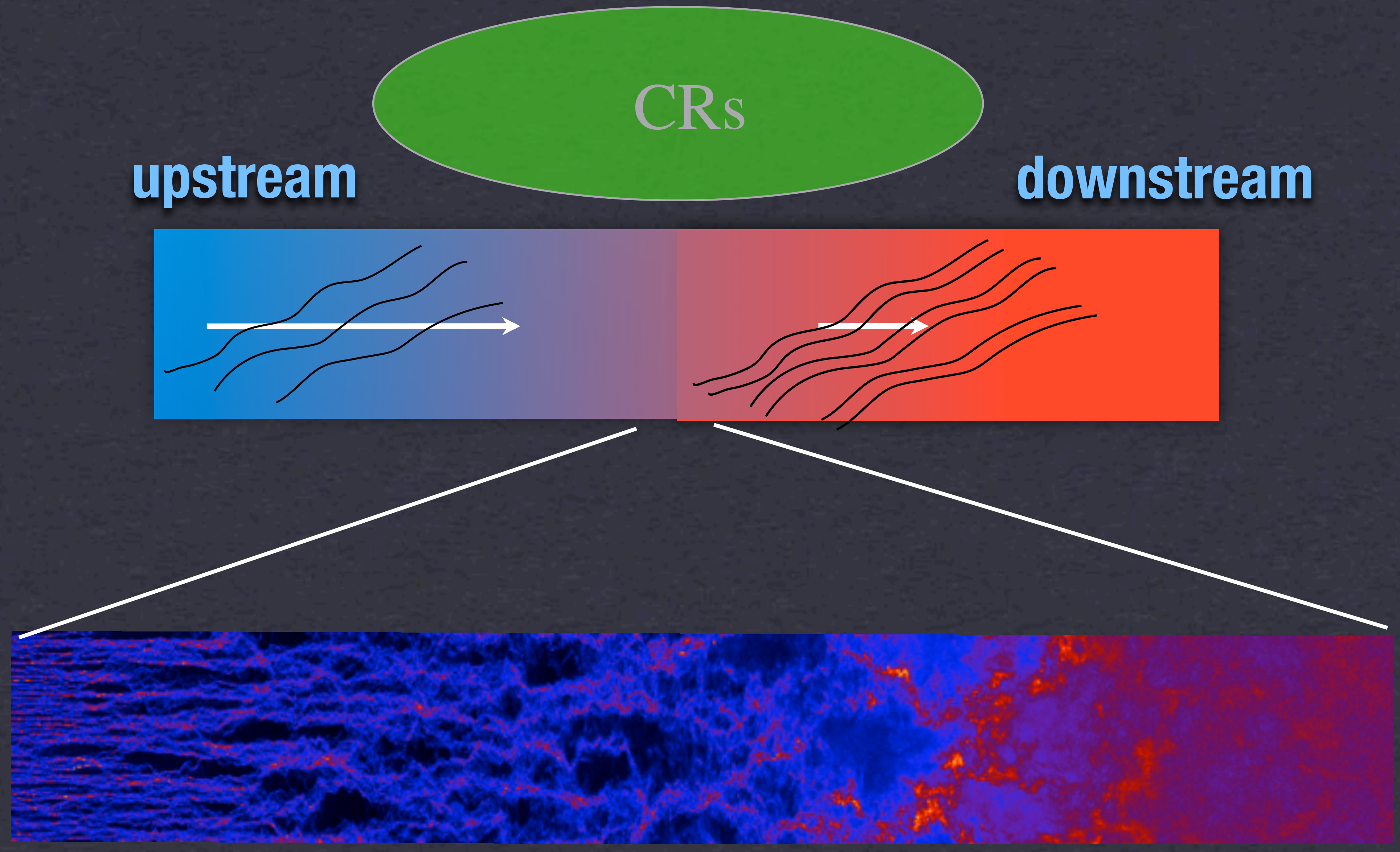
Generation of magnetic fields? GRB/SNR shocks, primordial fields?

Equilibration between ions and electrons?

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

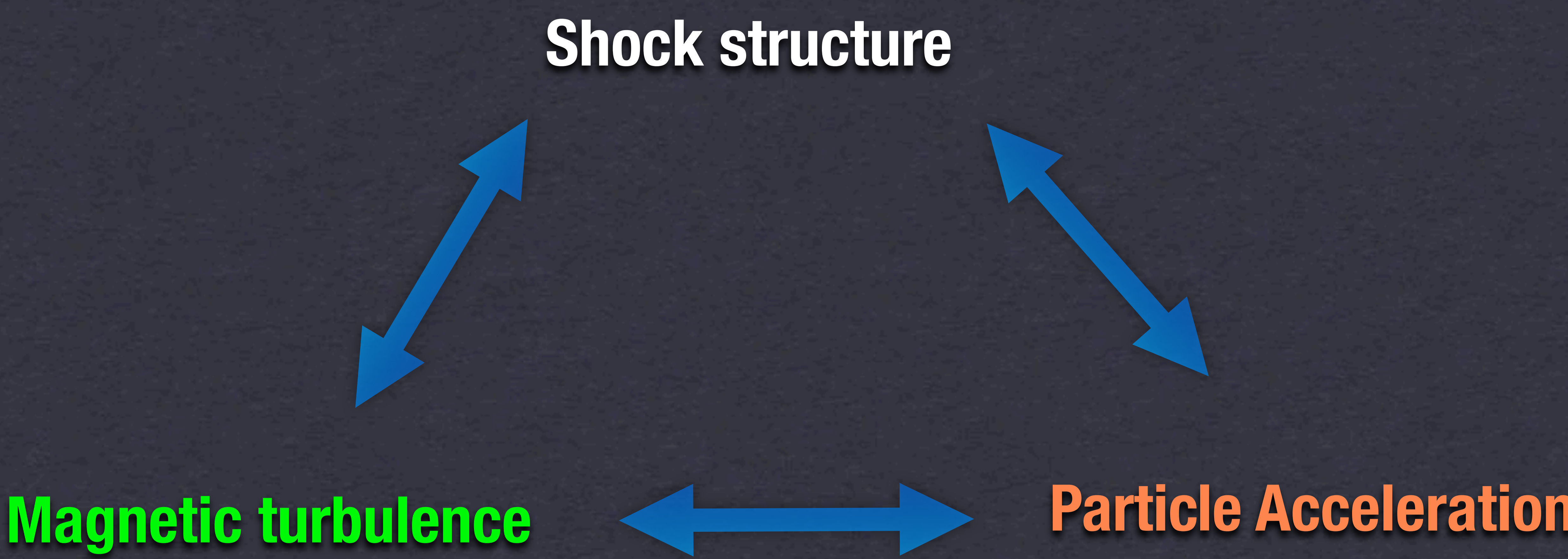
Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback



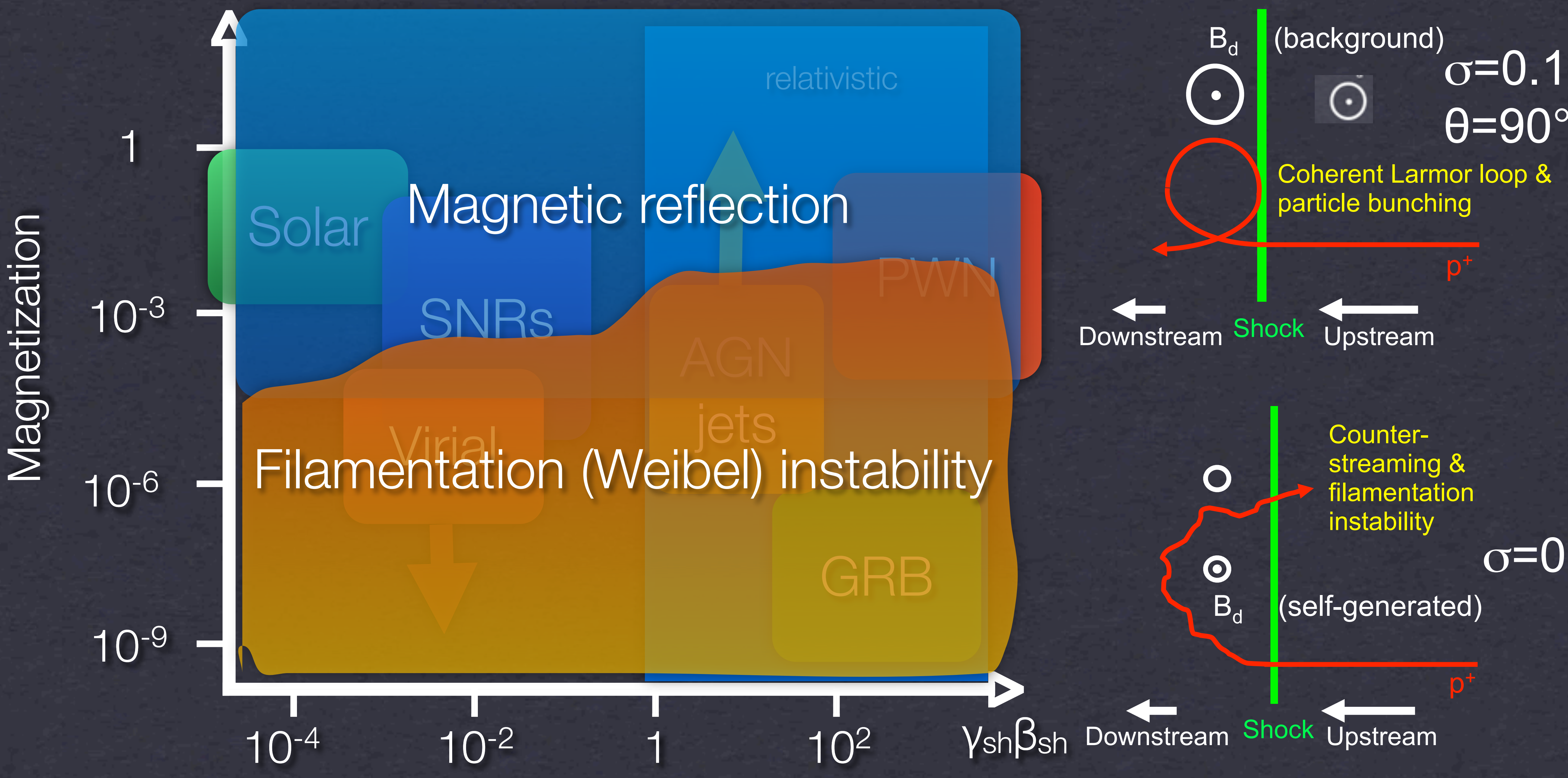
Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback

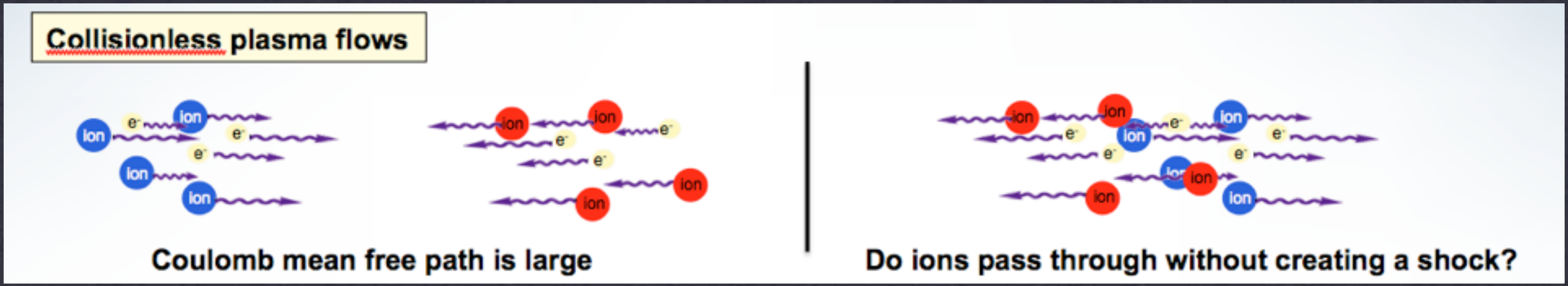


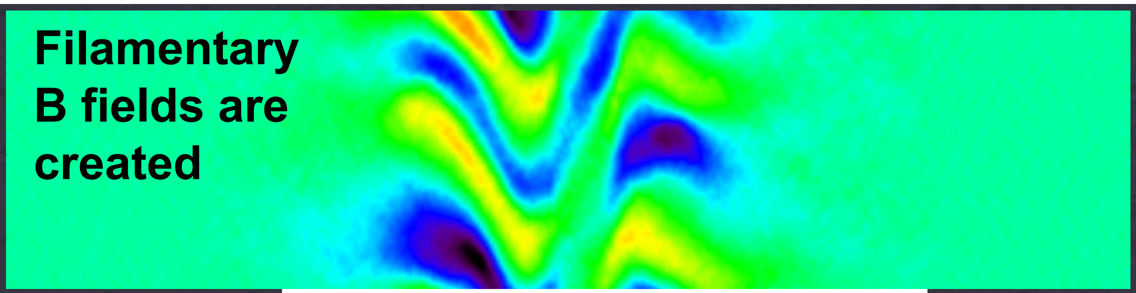
Parameter Space of shocks

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



How collisionless shocks work

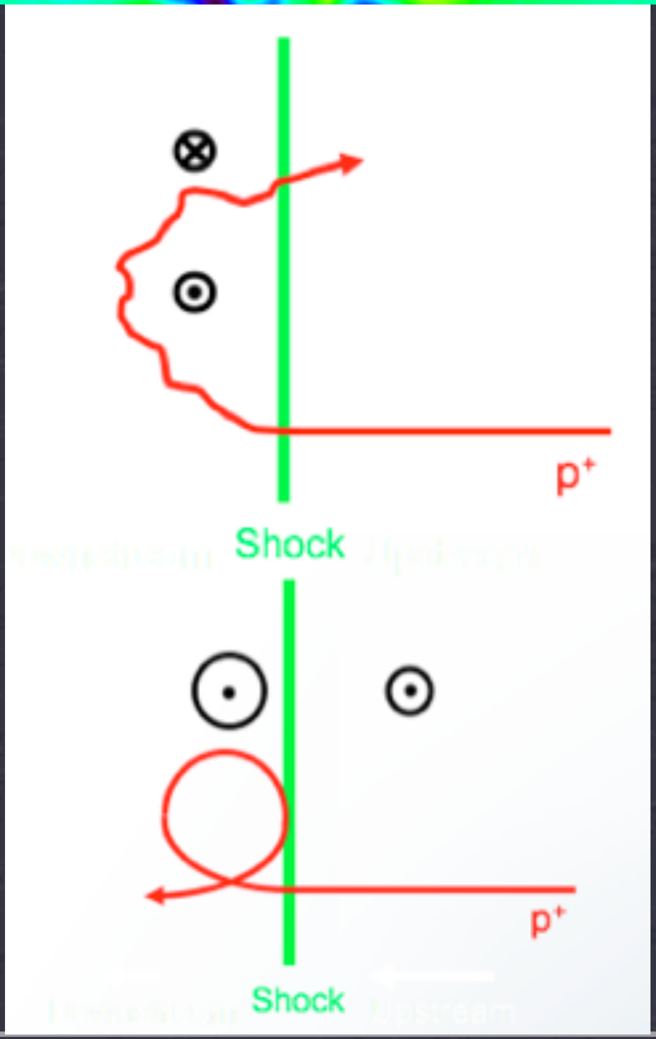




Two main mechanisms for creating collisionless shocks:

1) For low initial B field, particles are deflected by self-generated magnetic fields (filamentation/Weibel instability)

2) For large initial B field, particles are deflected by compressed pre-existing fields



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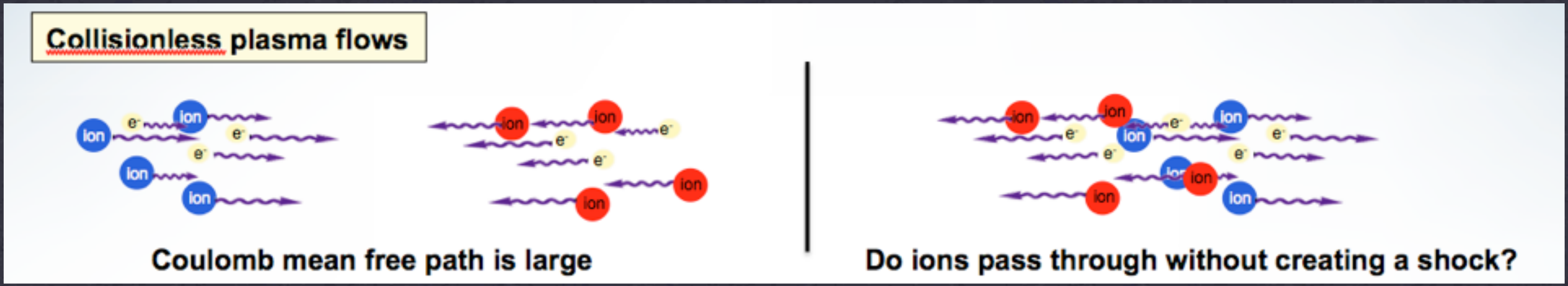

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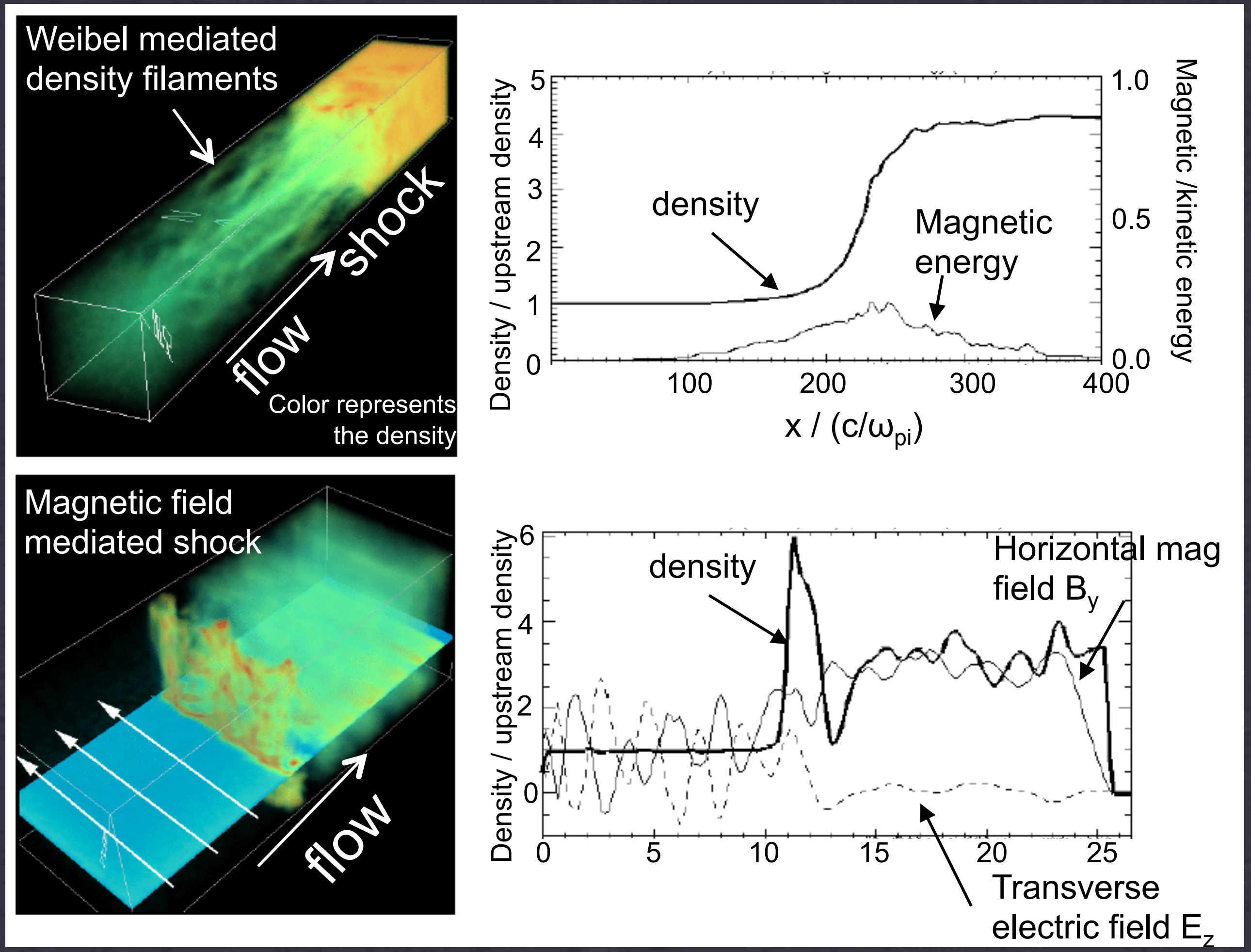
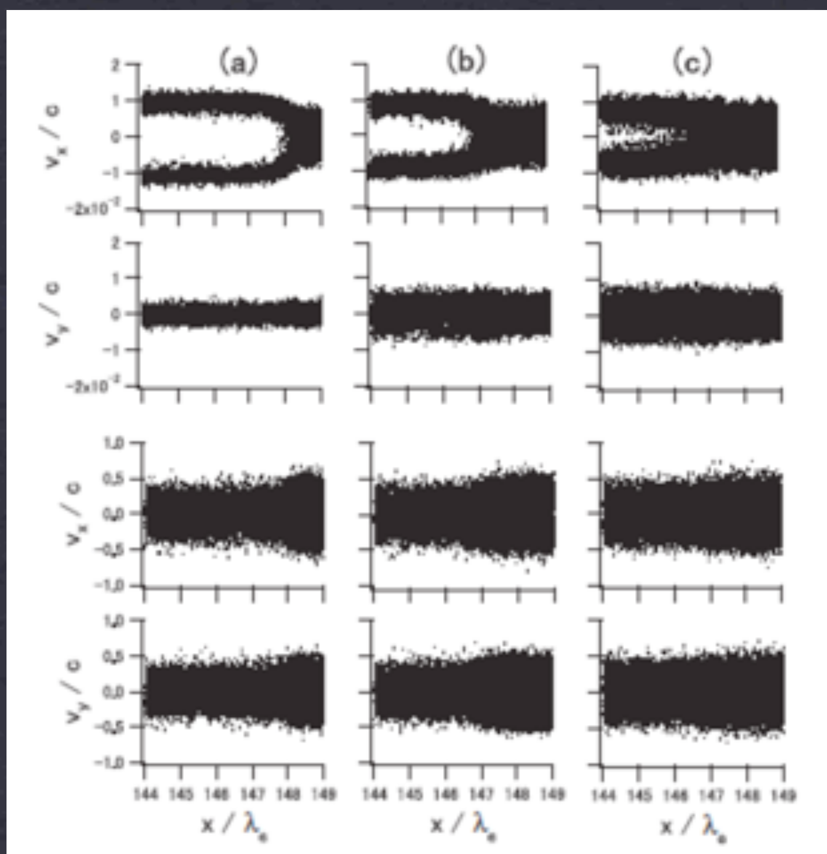
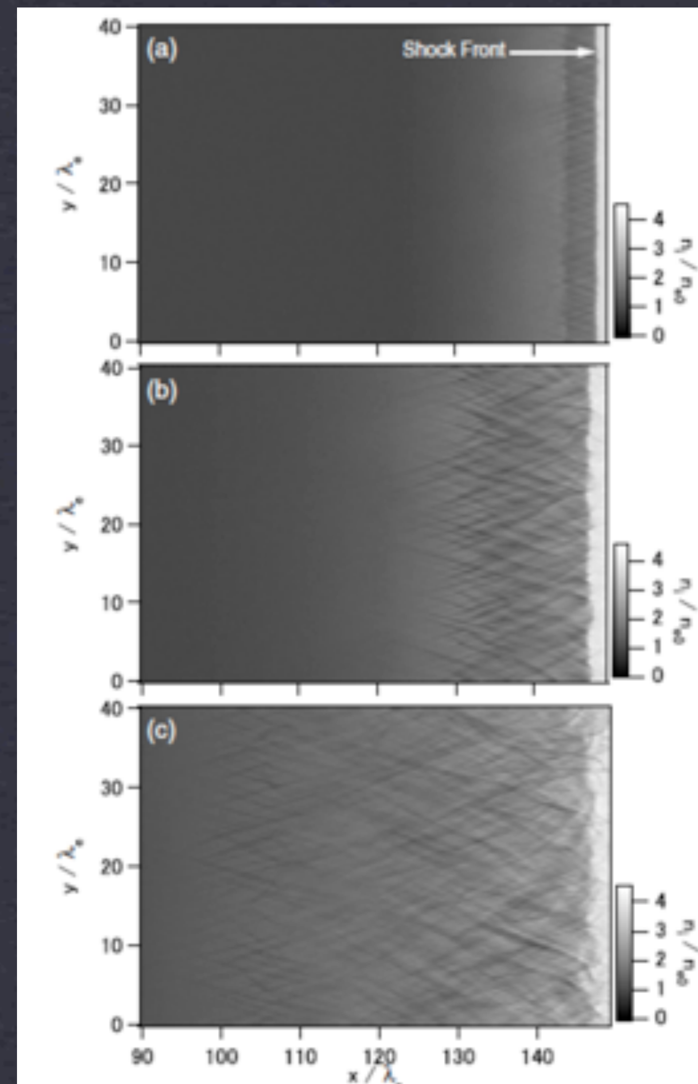
Spitkovsky (2005)

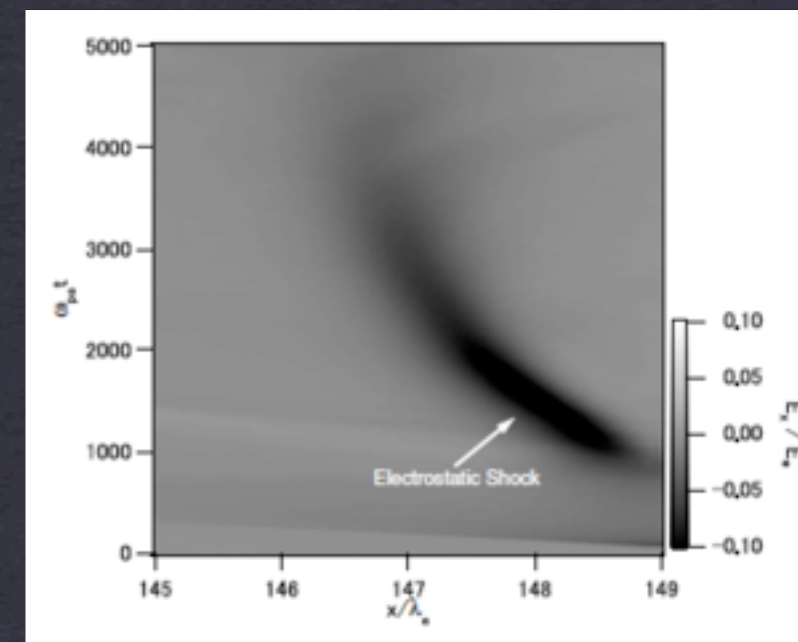


A note about electrostatic shocks

Another mechanism for shocks: electrostatic shocks; Reflection from electric potential.







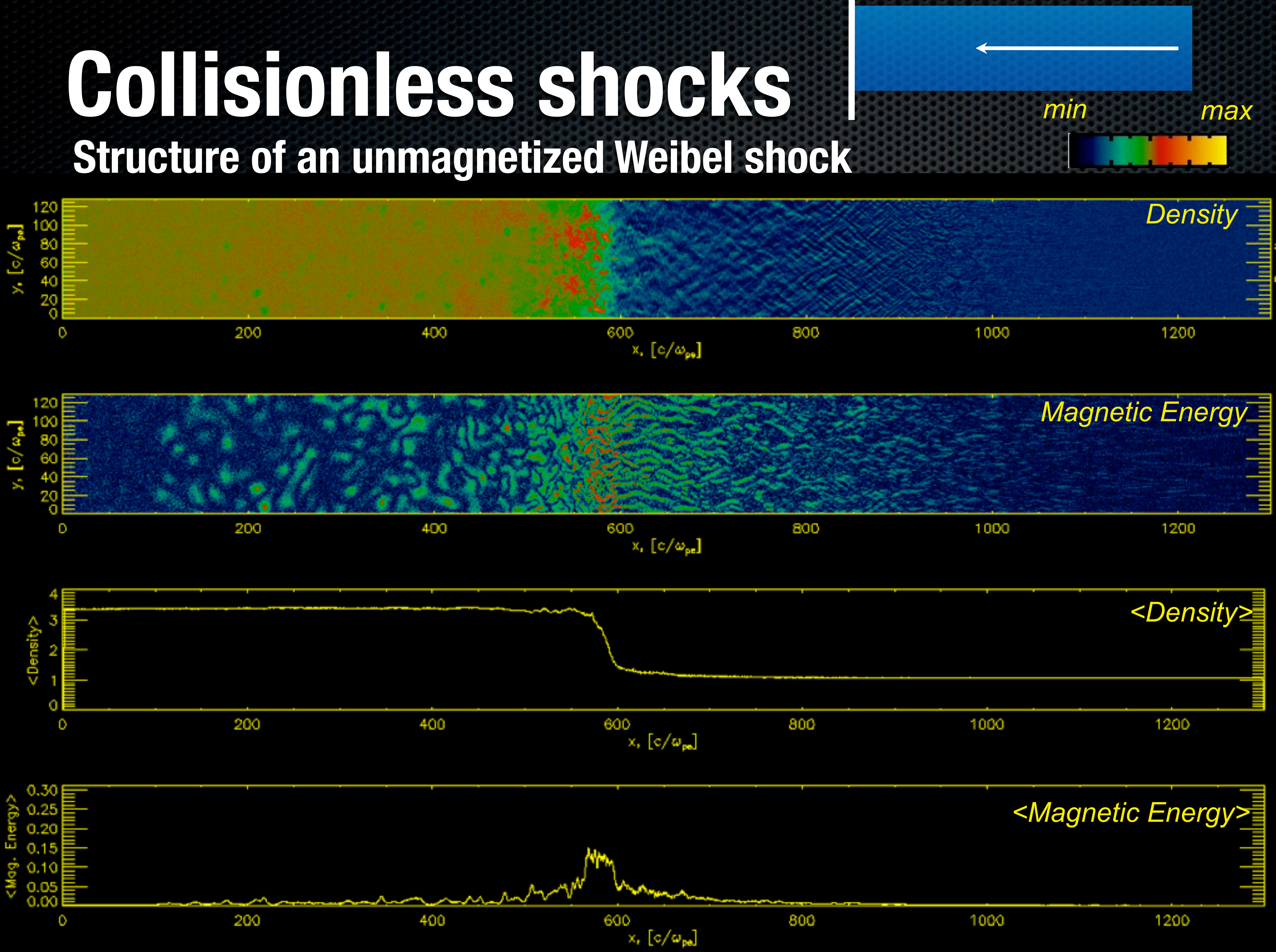
Generally exist for low effective Mach numbers: M < 2.6

Require Te>>Ti. Typically are transient (Kato & Takabe 10)

Unlikely to be important in astrophysical shocks; frequently claimed in experiments (e.g., Kuramitsu et al 2011)

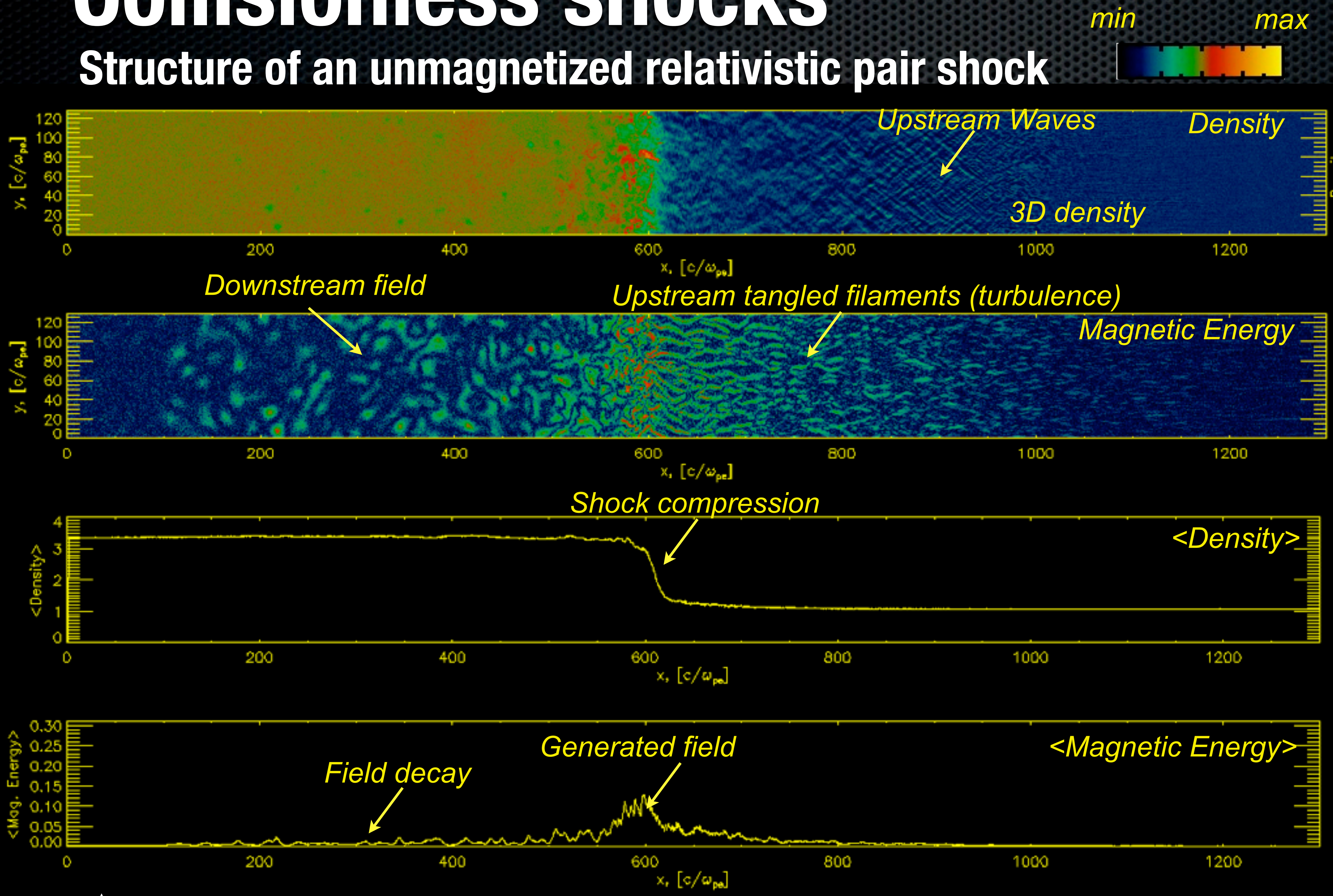
Collisionless shocks

Structure of an unmagnetized Weibel shock



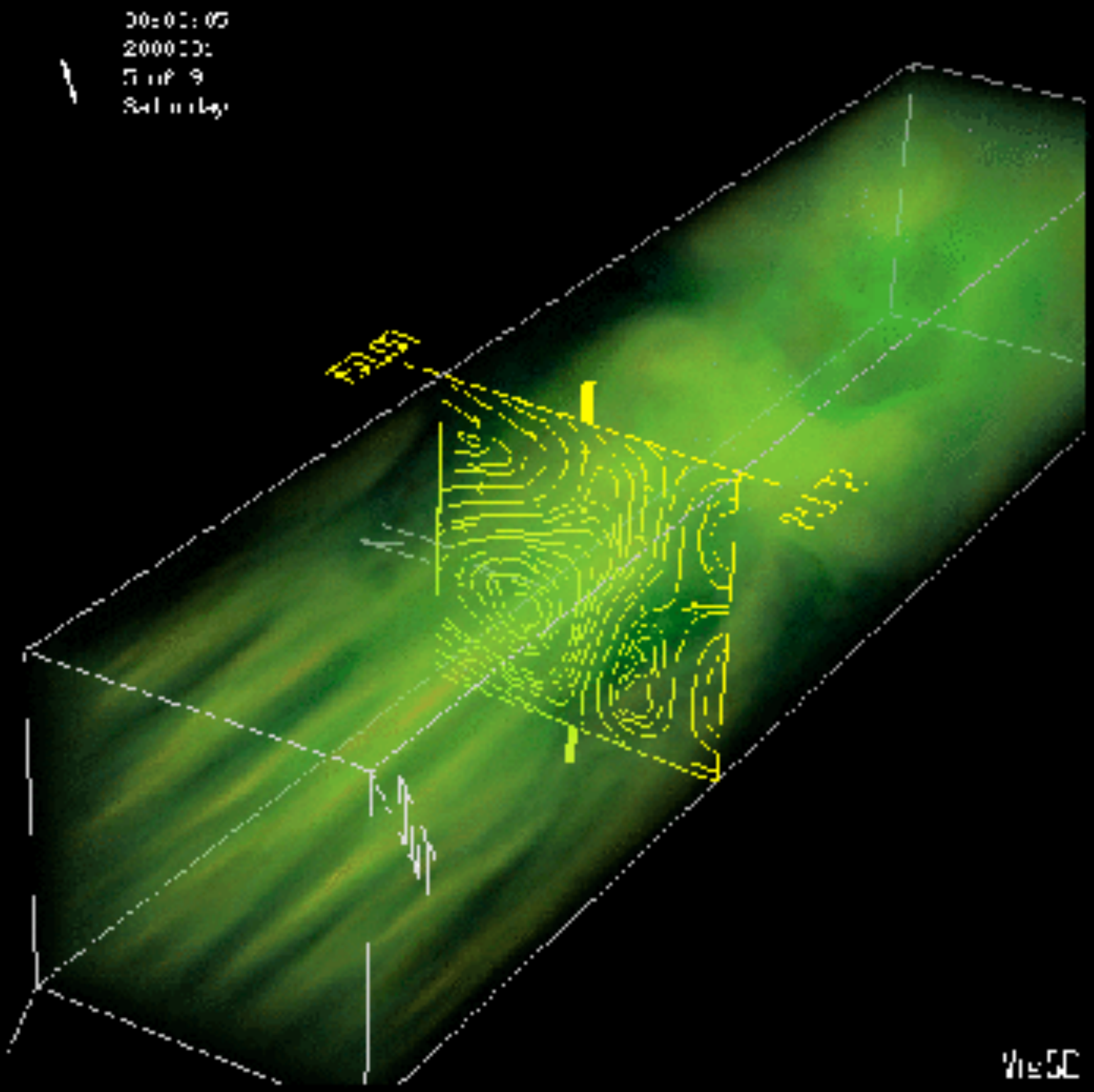
Collisionless shocks

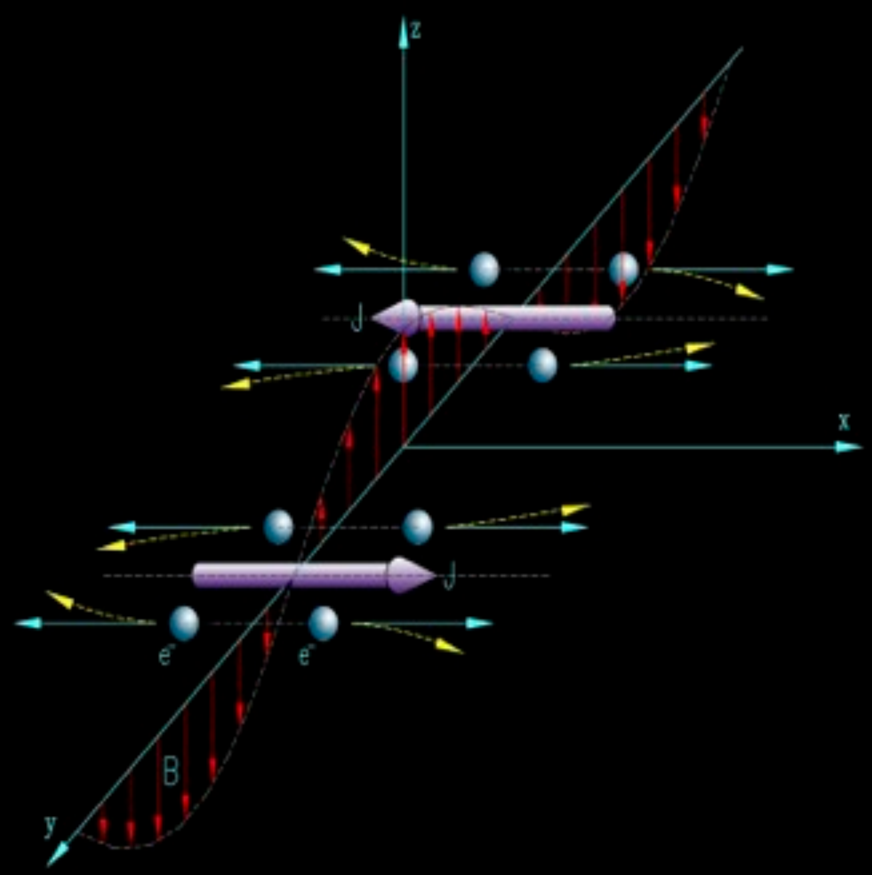
Structure of an unmagnetized relativistic pair shock



Weibel instability

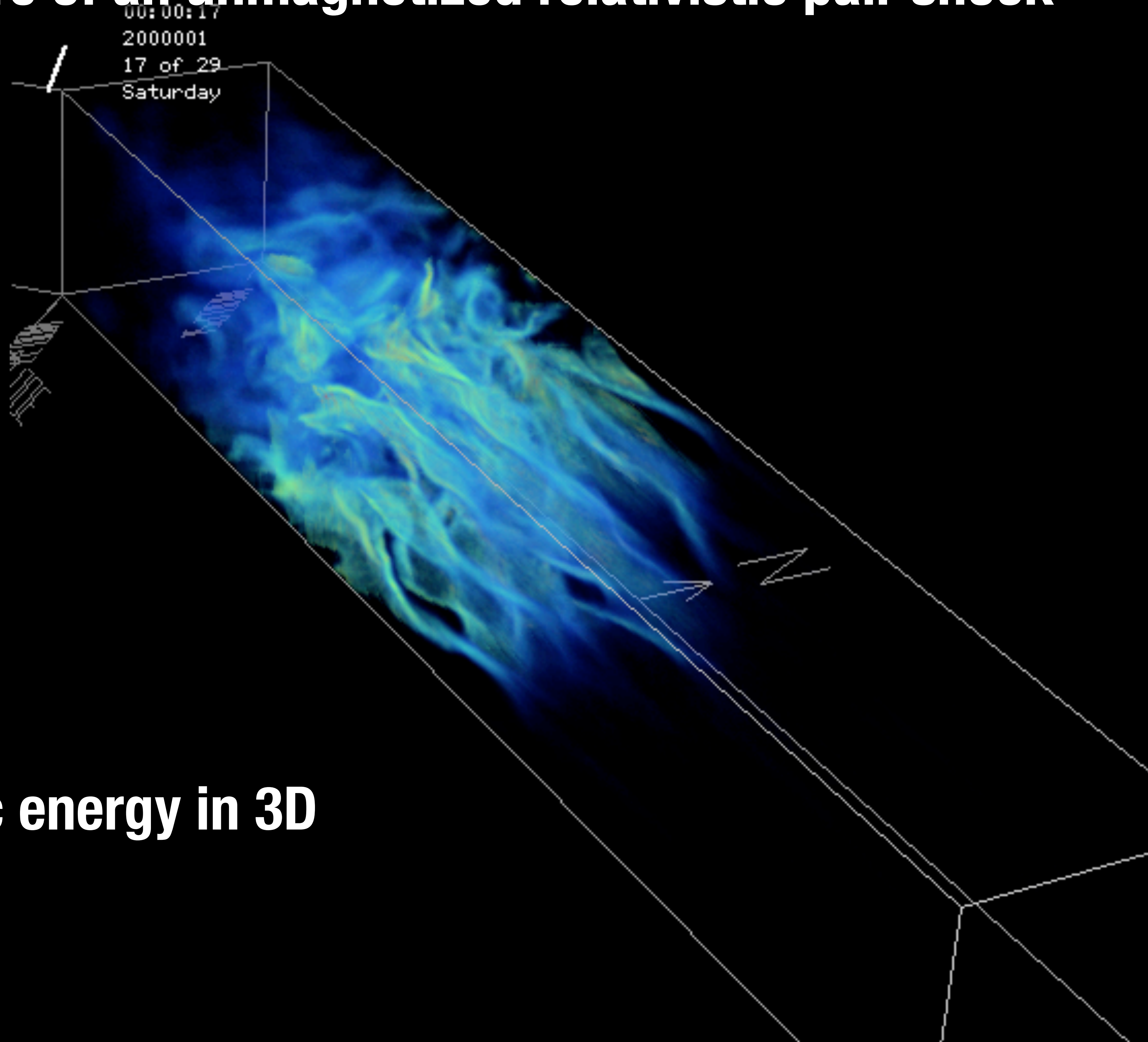
growth of field from skin-depth scale by current filament mergers





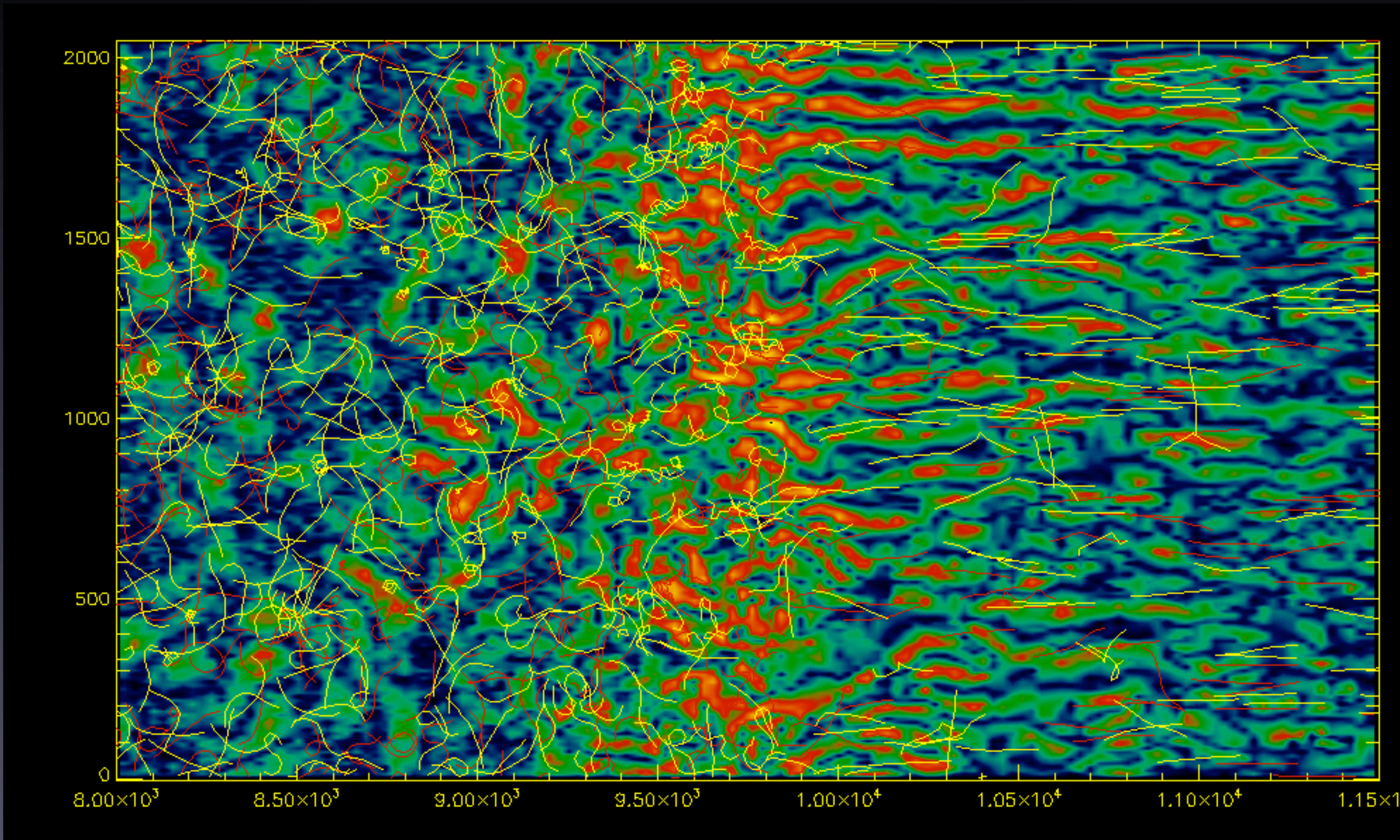
Collisionless shocks

Structure of an unmagnetized relativistic pair shock:

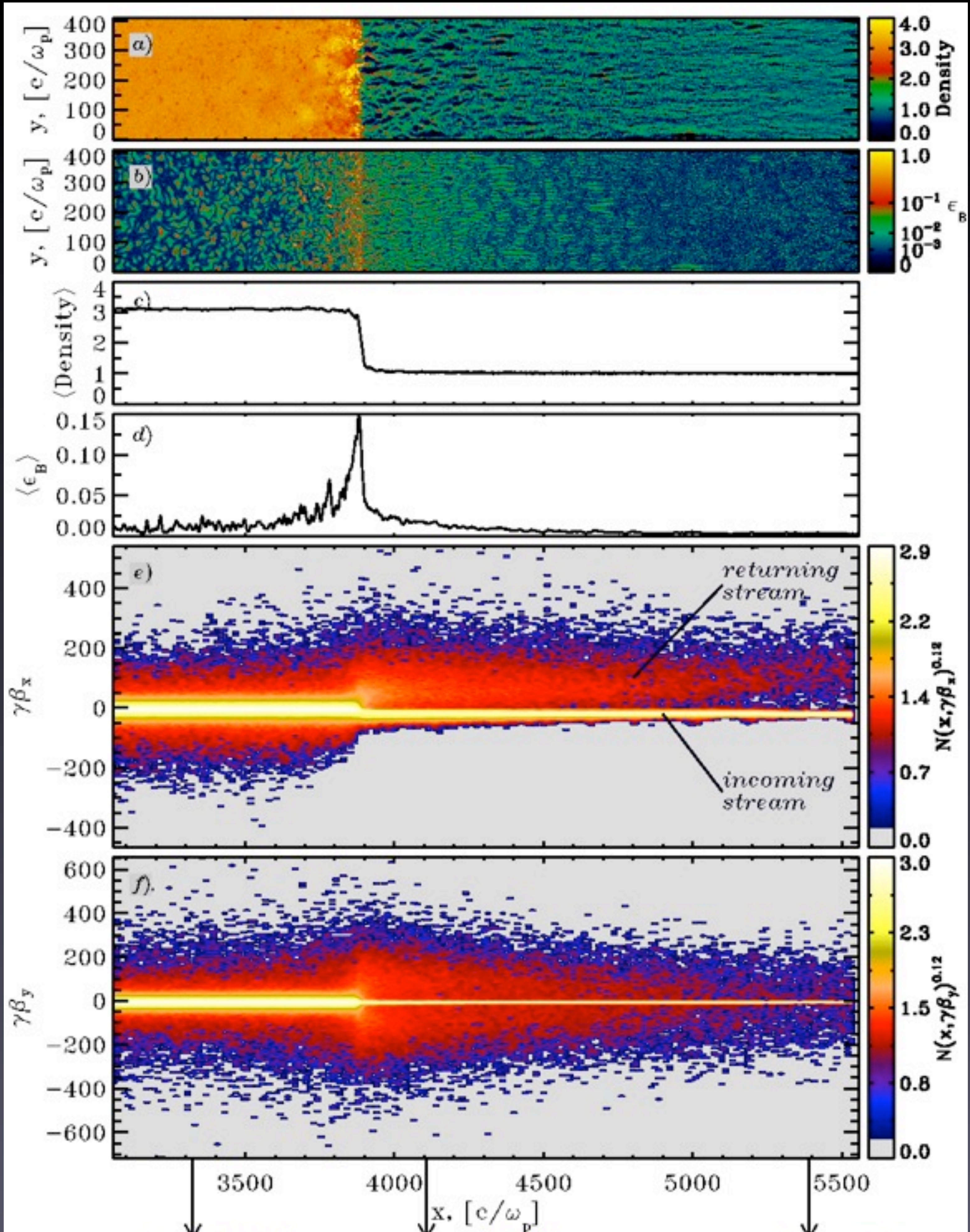


Magnetic energy in 3D

Unmagnetized pair shock: particle trajectories



color: magnetic energy density



Unmagnetized pair shock:

shock is driven by returning particle precursor (CR!)

Steady counterstreaming leads to self-replicating shock structure

x- px momentum space

Long term 2D simulation

x- py momentum space

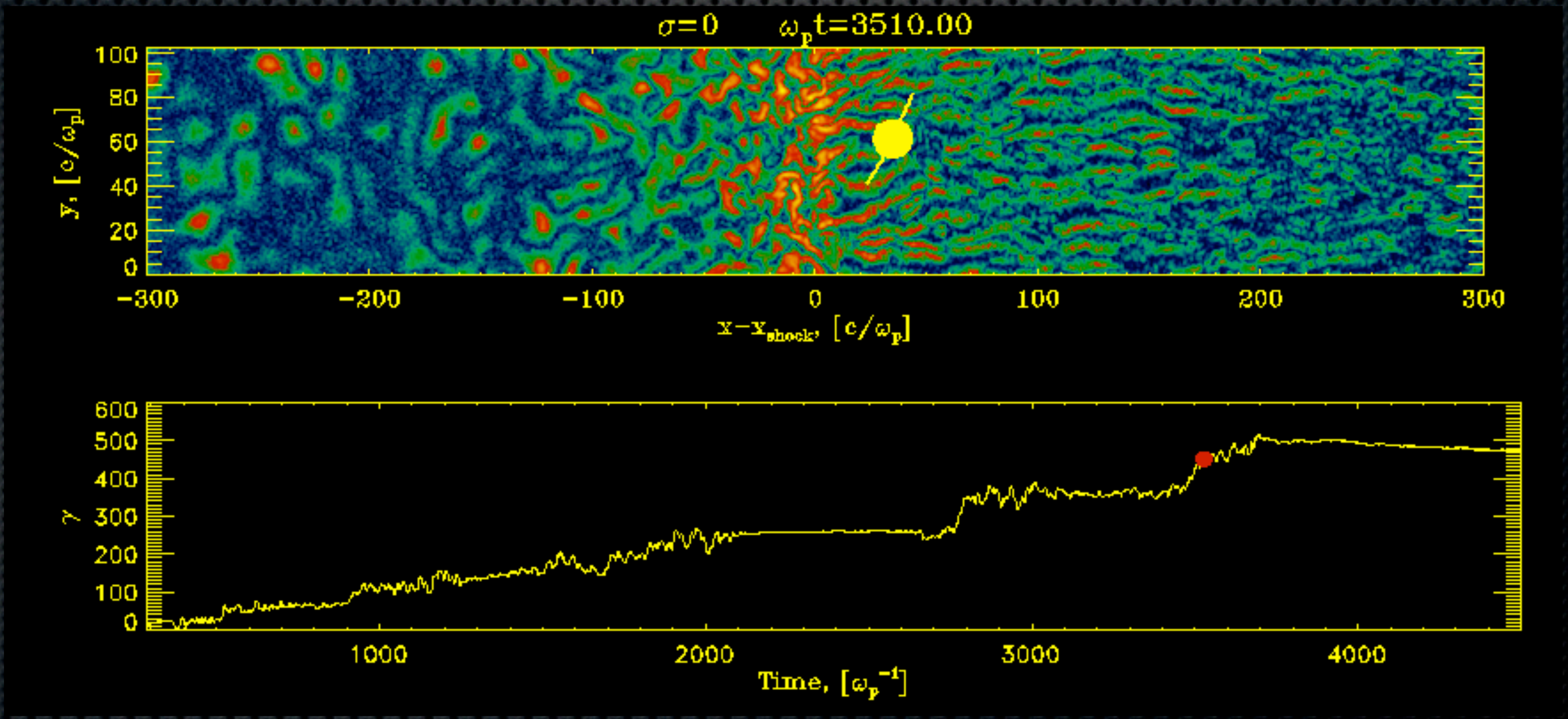
Shock structure for σ=0 (AS '08)

Particle acceleration

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

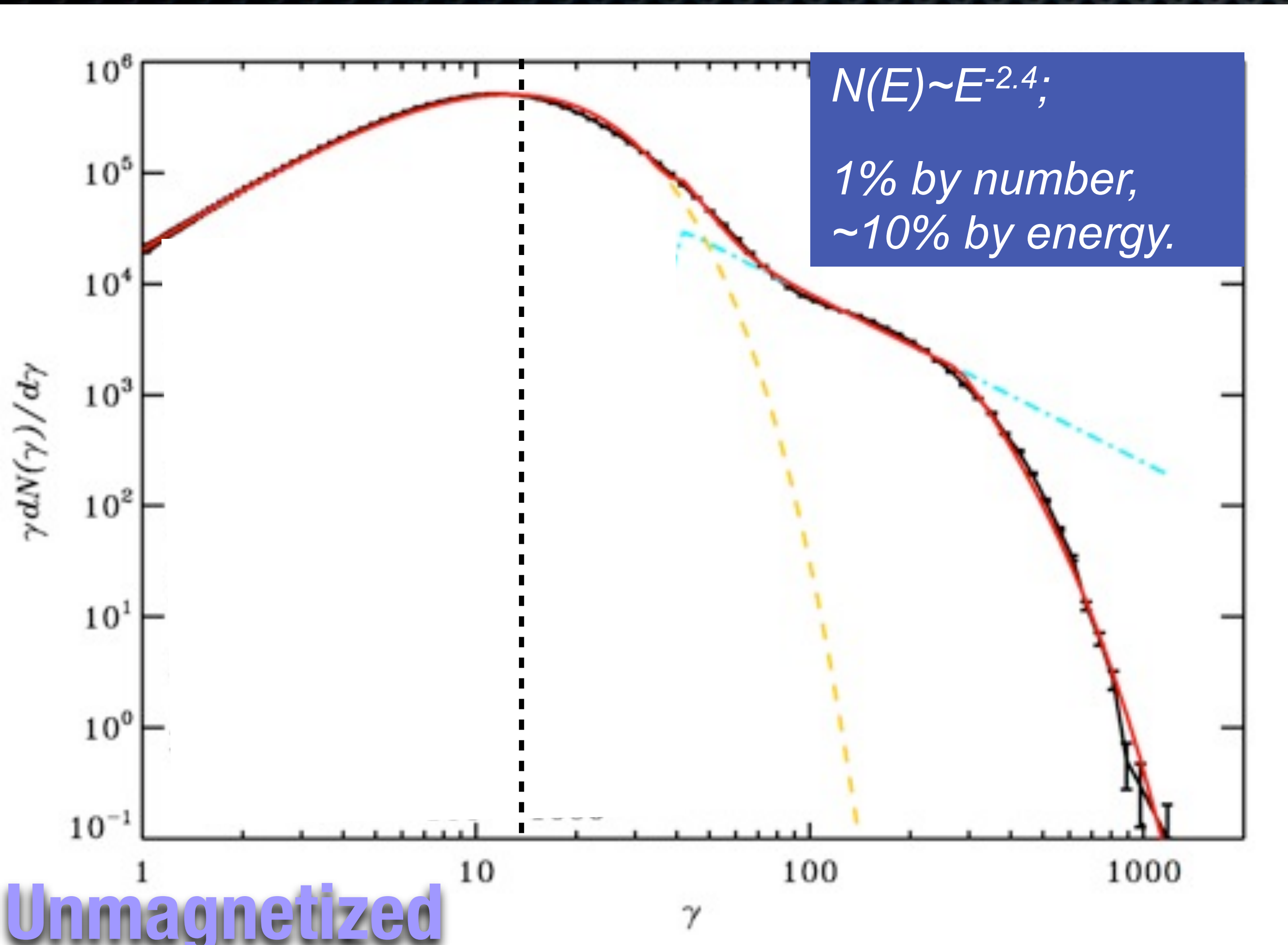
Magnetic filaments

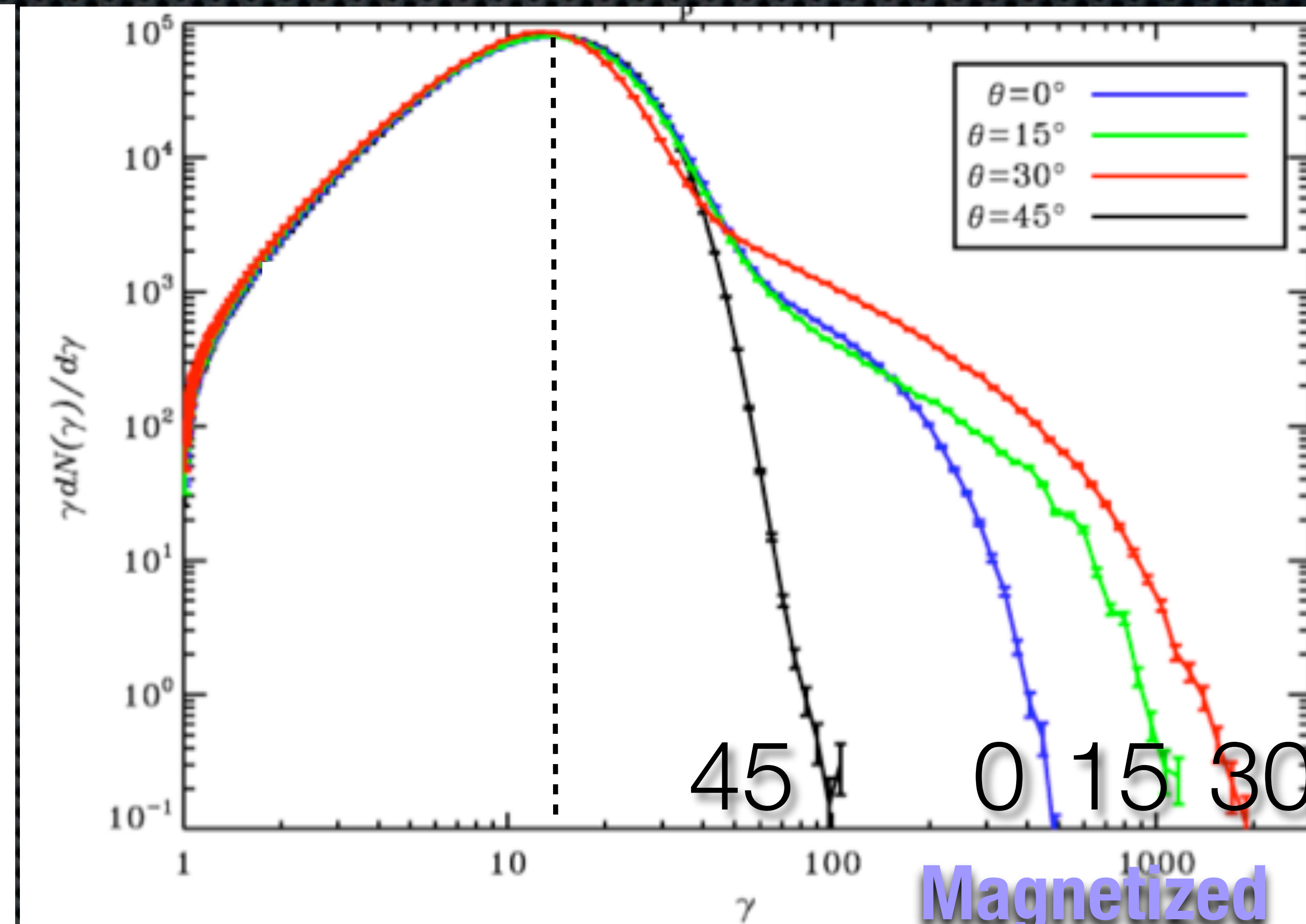
Particle energy

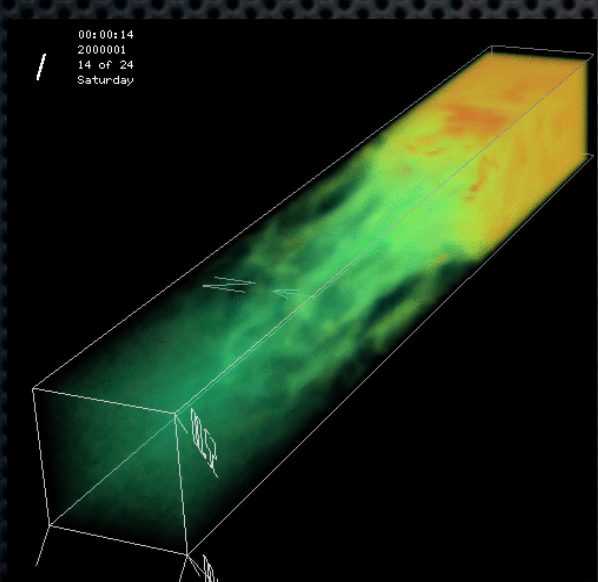


Particle acceleration: rel. shocks

Sironi & AS 09

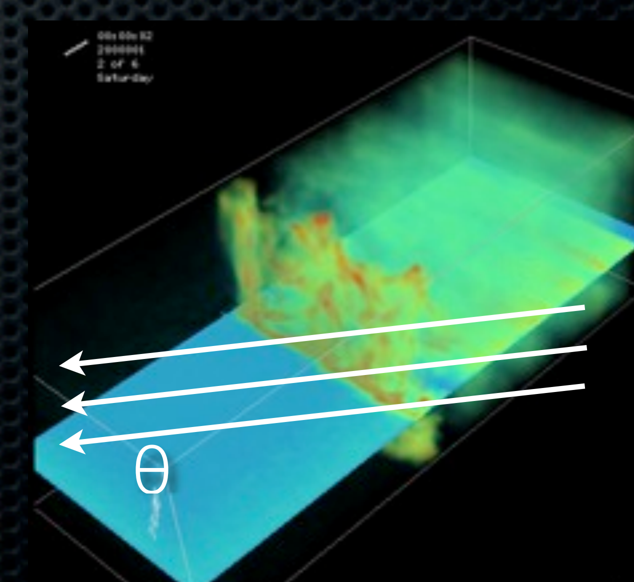






Conditions for acceleration in relativistic shocks:

low magnetization of the flow or quasiparallel magnetic field



Parameter Space of shocks

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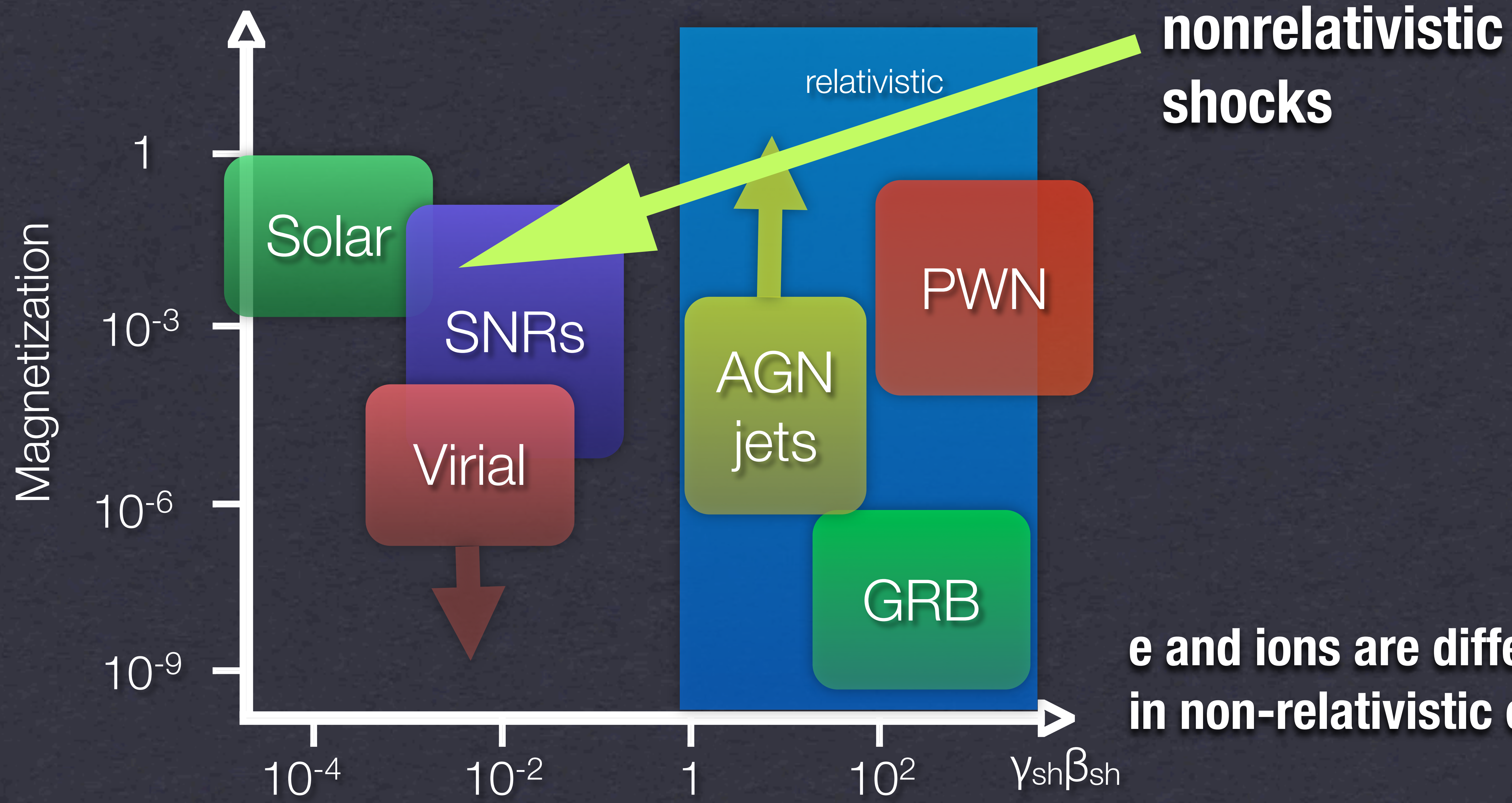


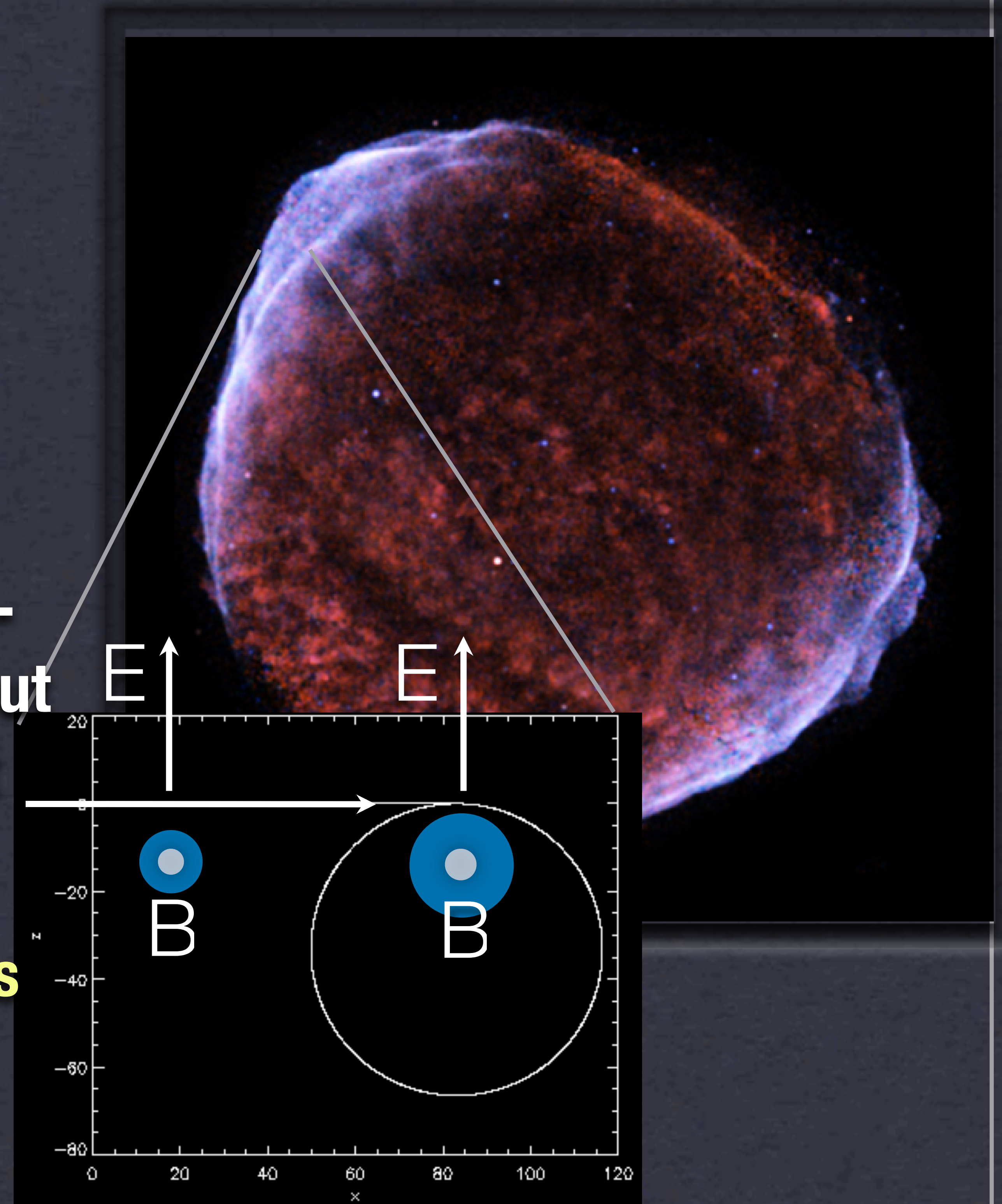
e and ions are different in non-relativistic case

Nonrelativistic shocks

Application: supernova remnants. Mach numbers in 100s.

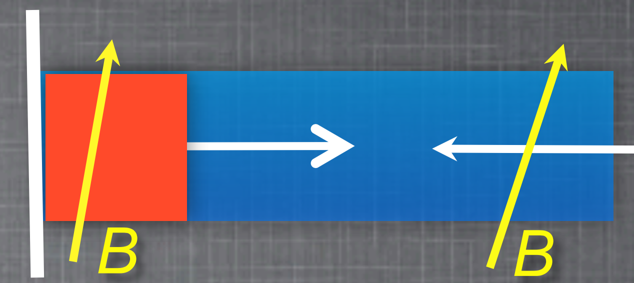
- Shock structure depends on magnetization (alfvenic Mach #)
- Formal Alfvenic Mach # in SNR is in 100s, unless there is field amplification.
- Ion acceleration is efficient in quasi-parallel shocks (<40% by energy), but electron acceleration is not efficient

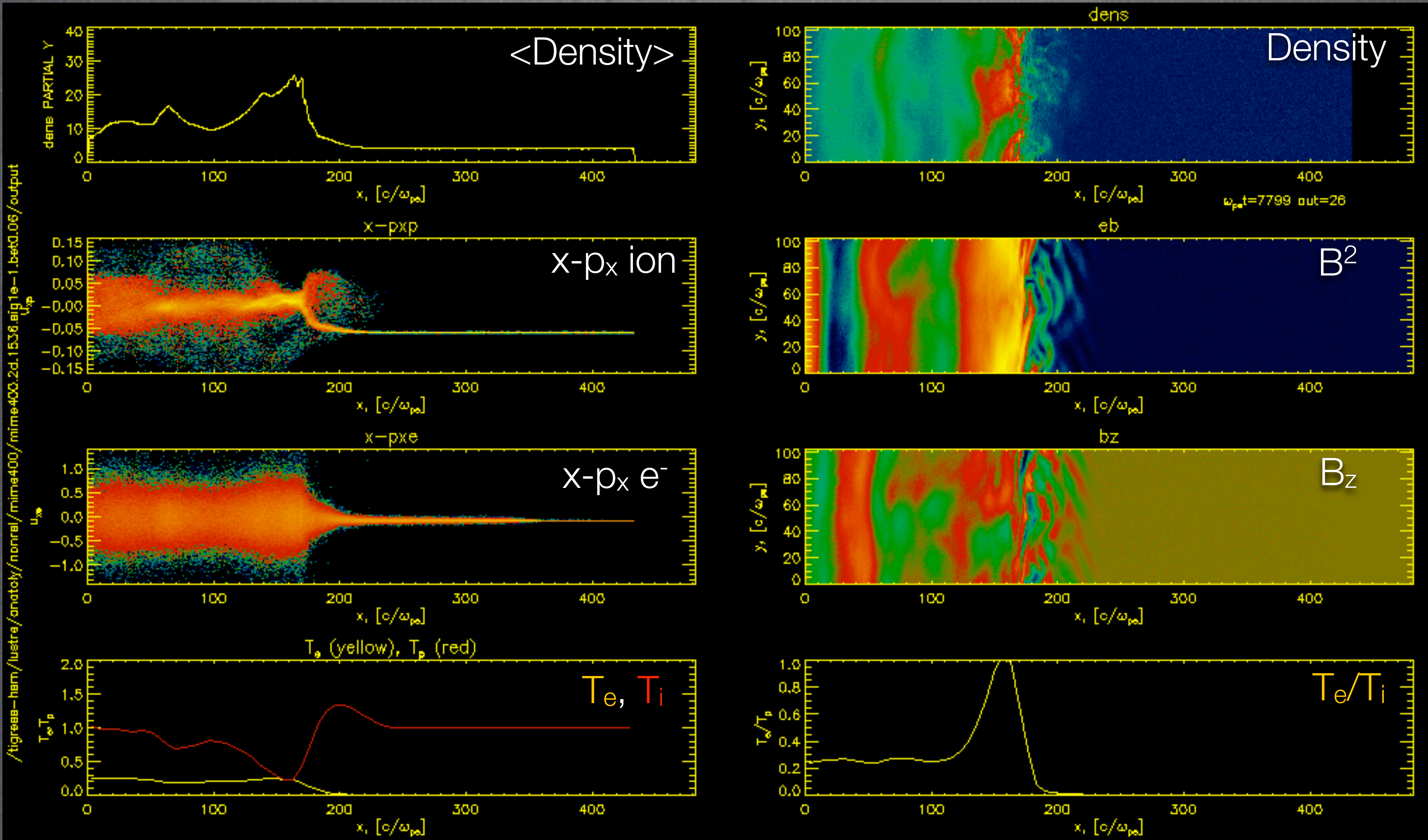
Typically electron acceleration is suppressed because e Larmor radius is << ion Larmor radius. Need pre-acceleration of electrons.



Nonrelativistic shocks: shock structure

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

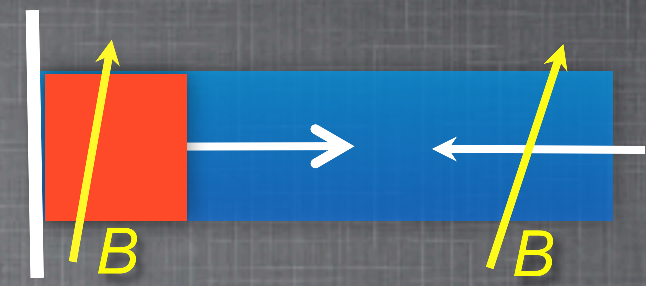


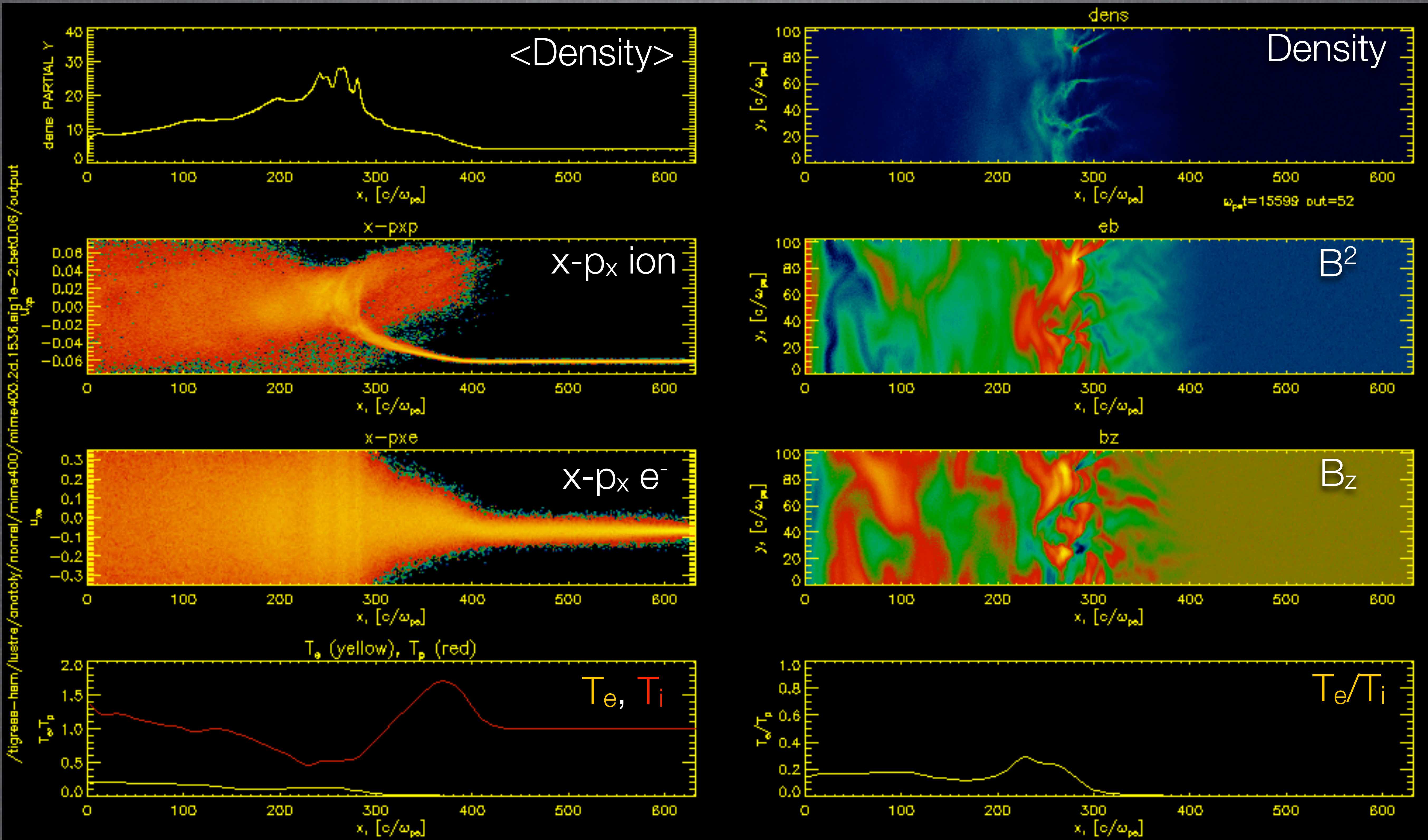


Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves.

Nonrelativistic shocks: shock structure

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

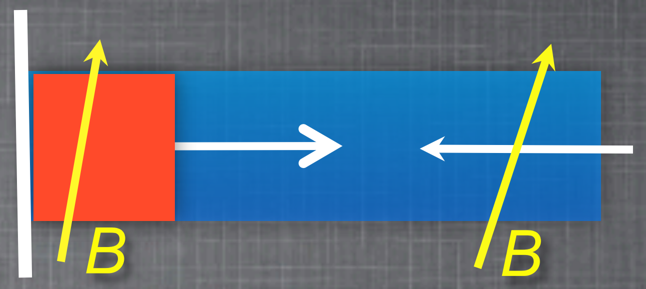


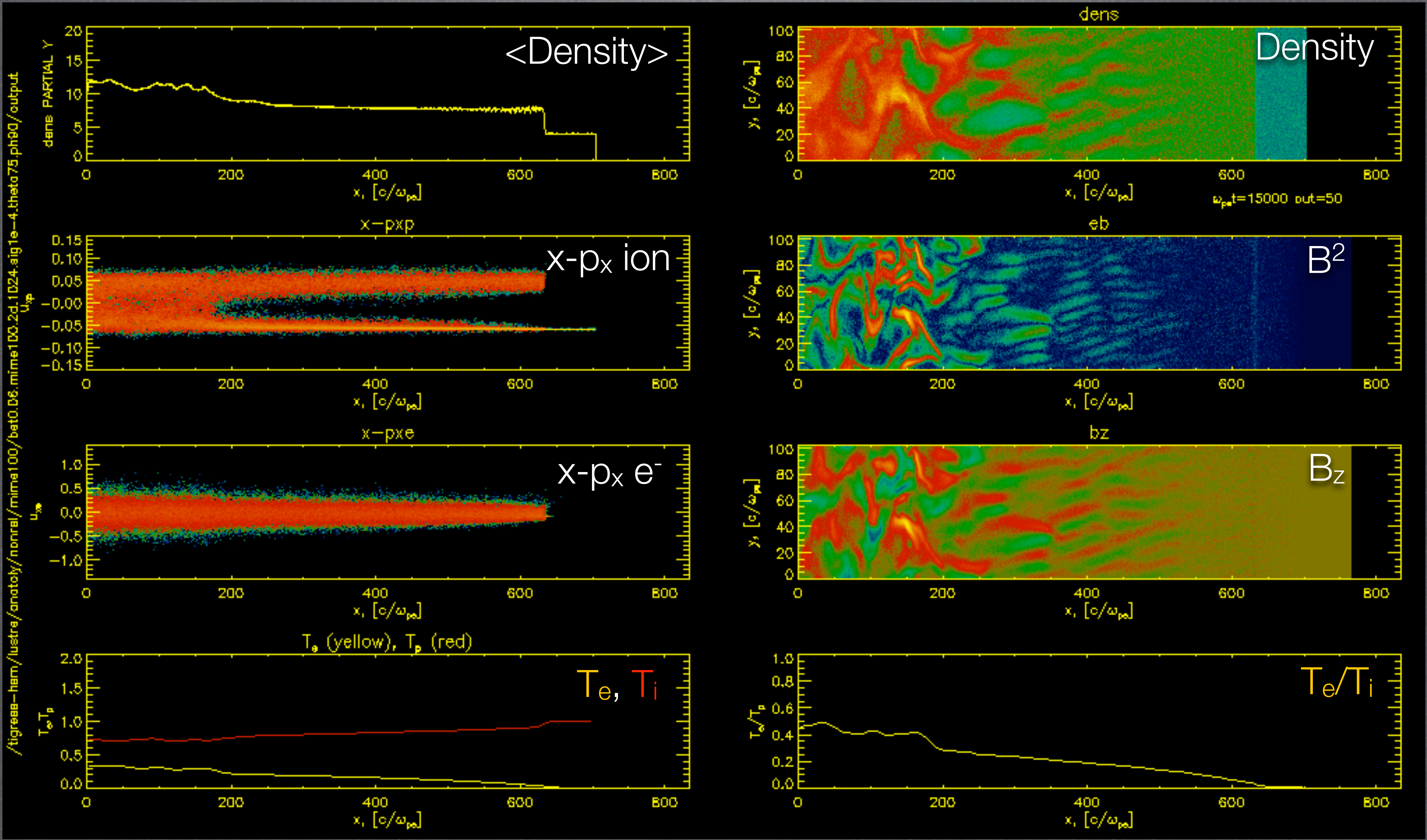


Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves, spectra.

Nonrelativistic shocks: shock structure

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

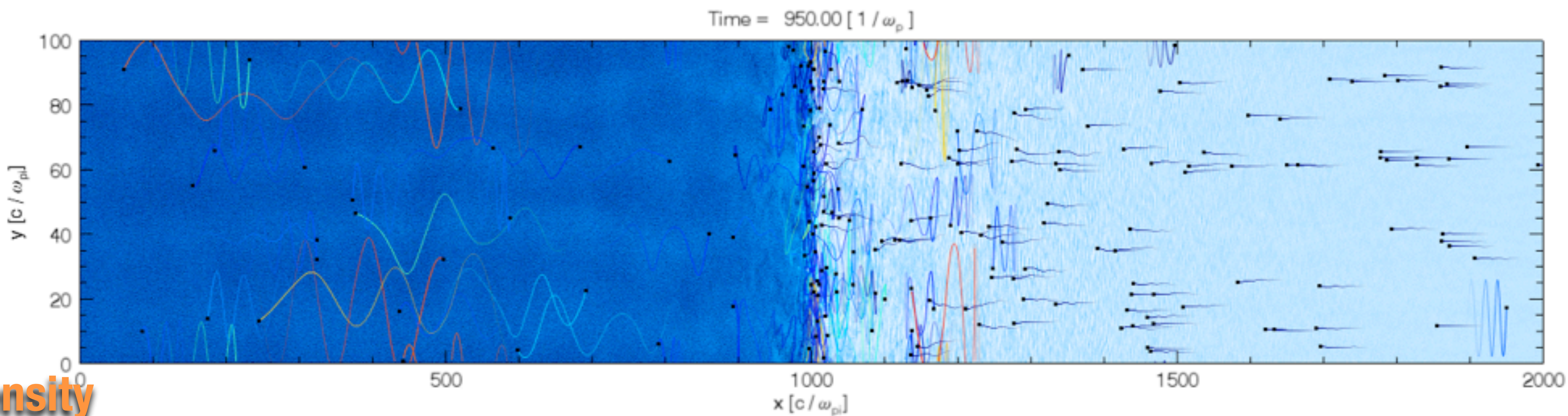




2D structure essential (cf. Shimado et al 2010), confirmed by other codes (e.g. Kato 2010)

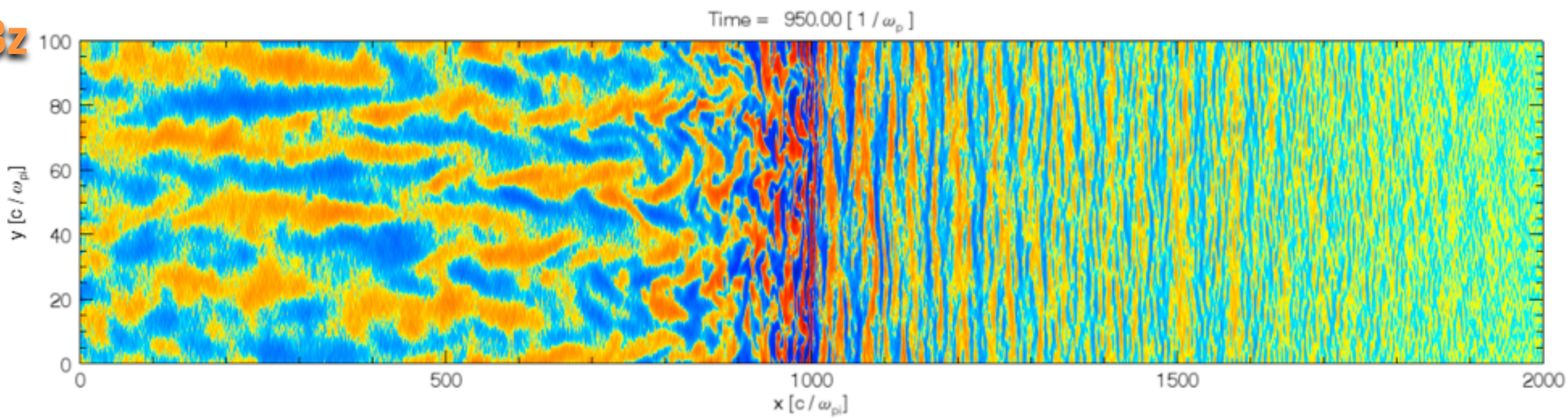
Acceleration Mechanism dHYBRID

Ma=3.1, parallel



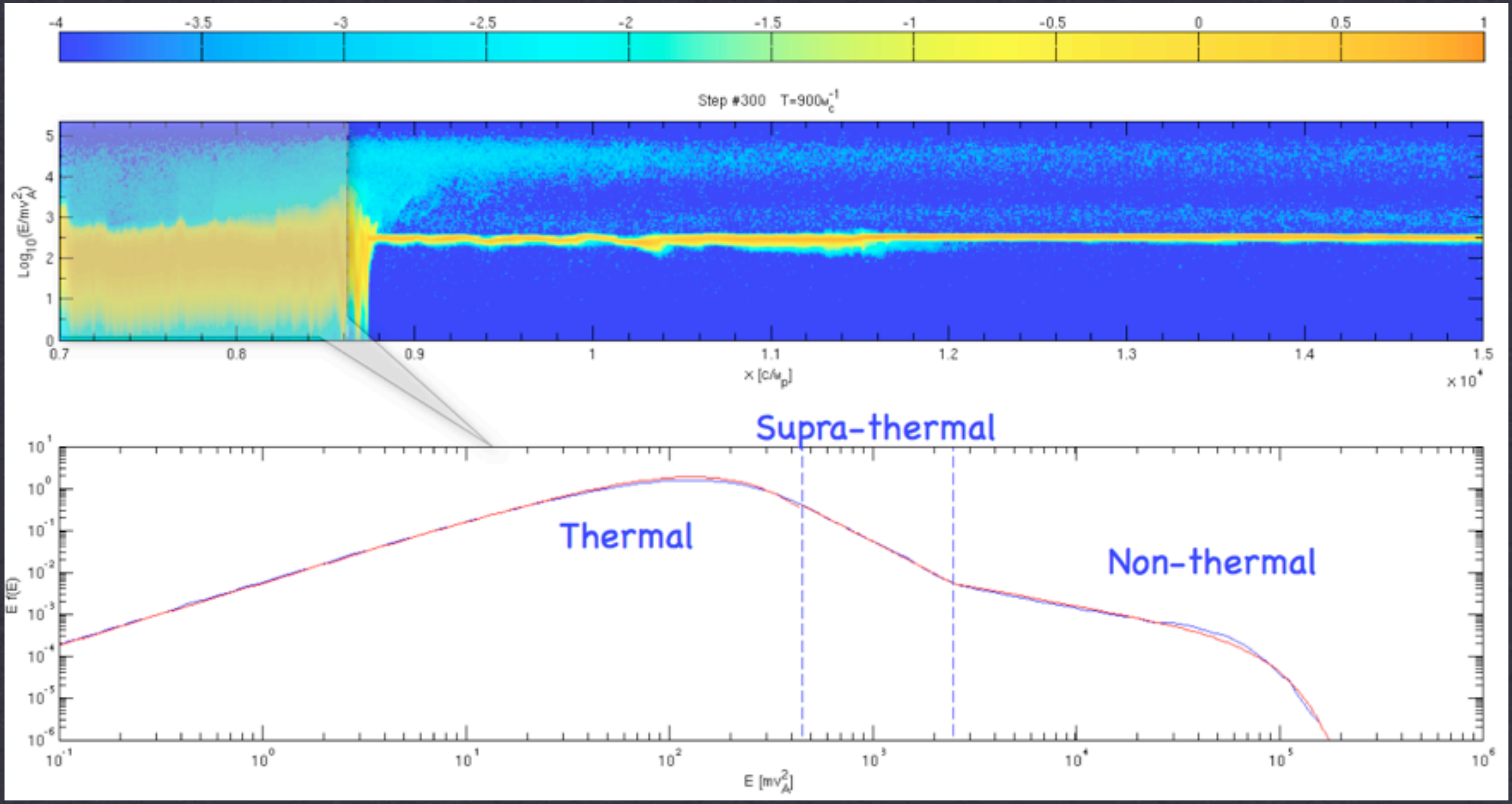
density

Bz



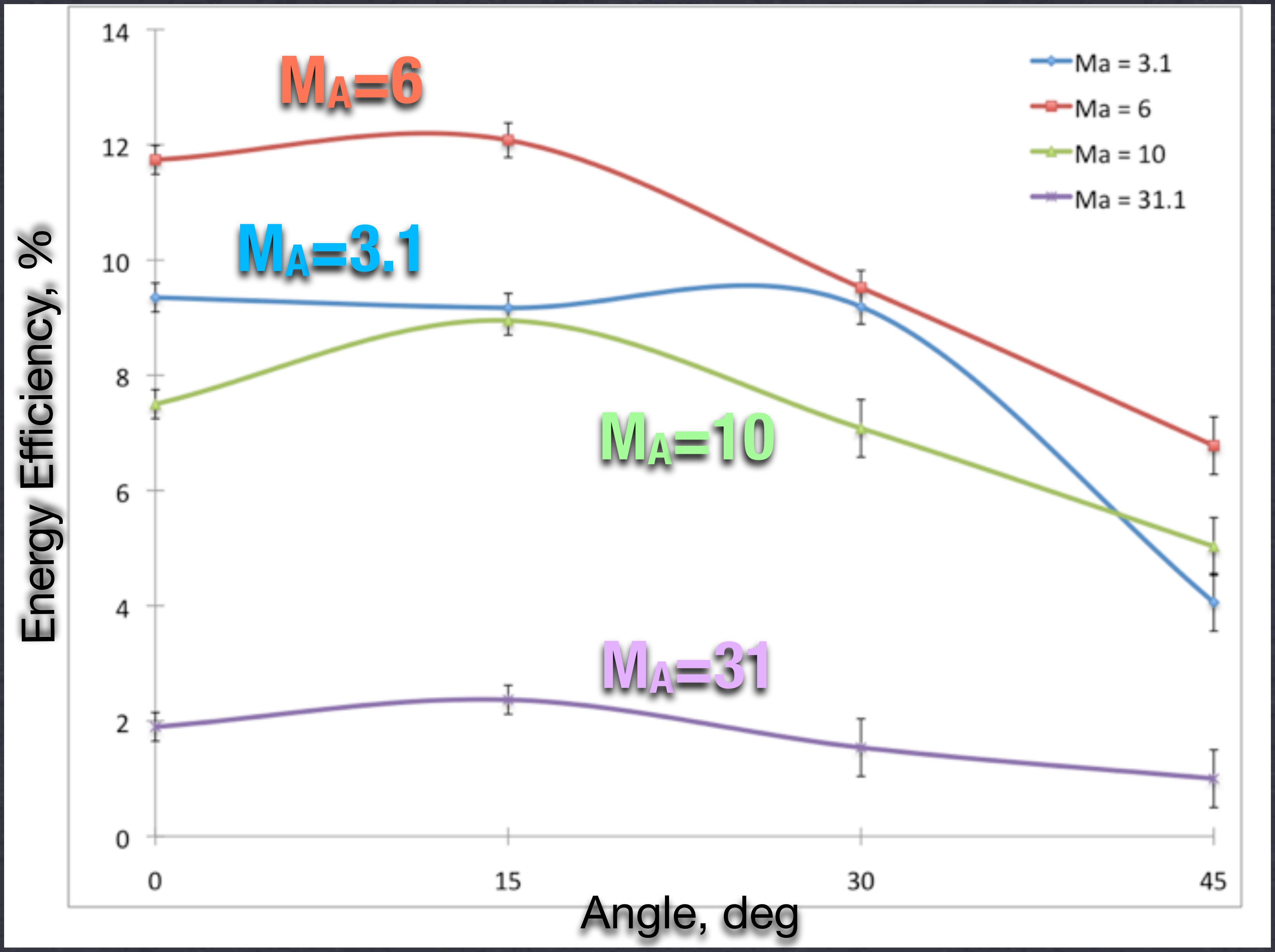
Ion acceleration in nonrel shocks

- **Injection physics: what determines the number of injected particles?**
- Most injection happens at the shock



Acceleration Efficiency

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

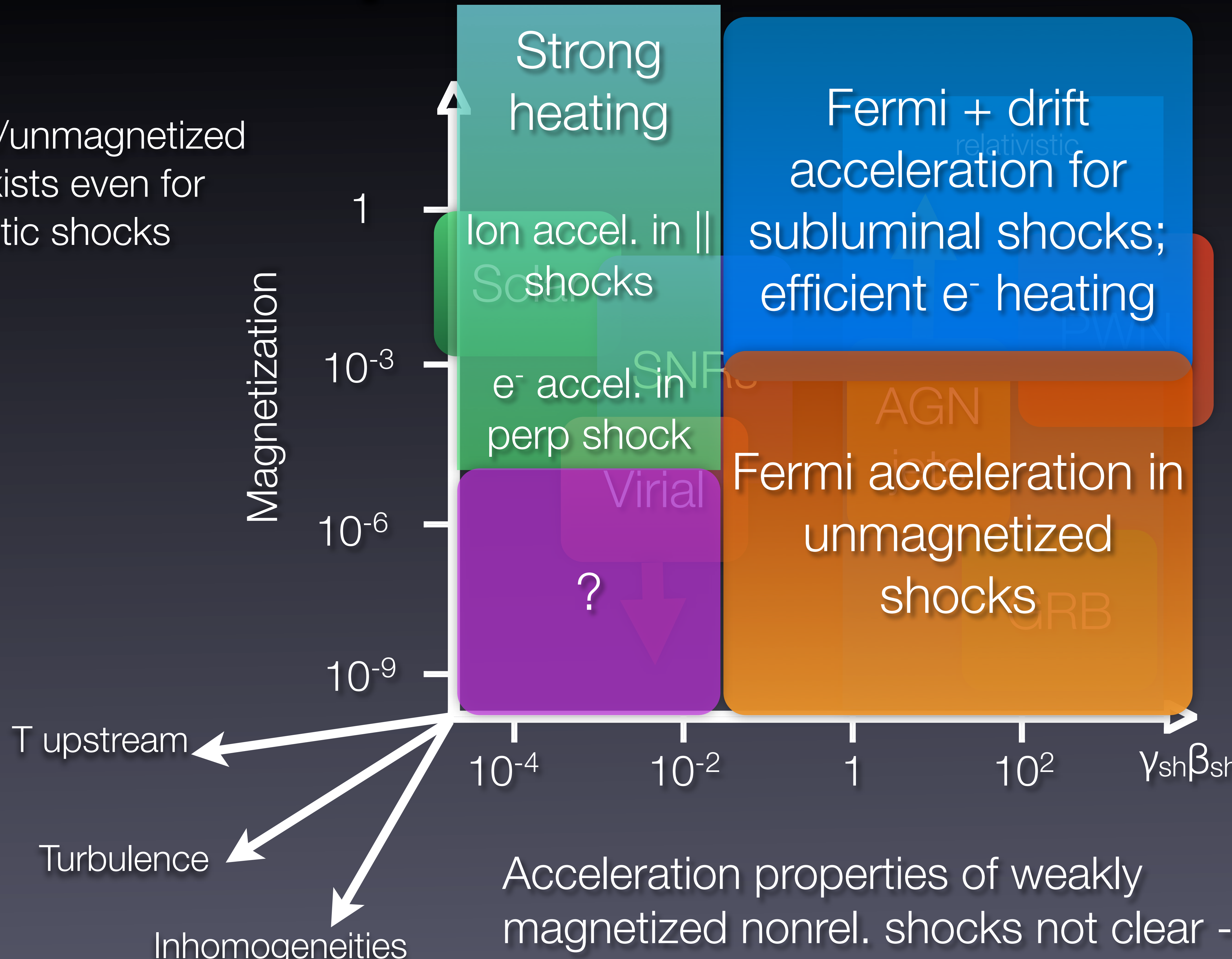


(Gargate+AS 2011)

Bump at moderate inclinations is due to contribution by SDA

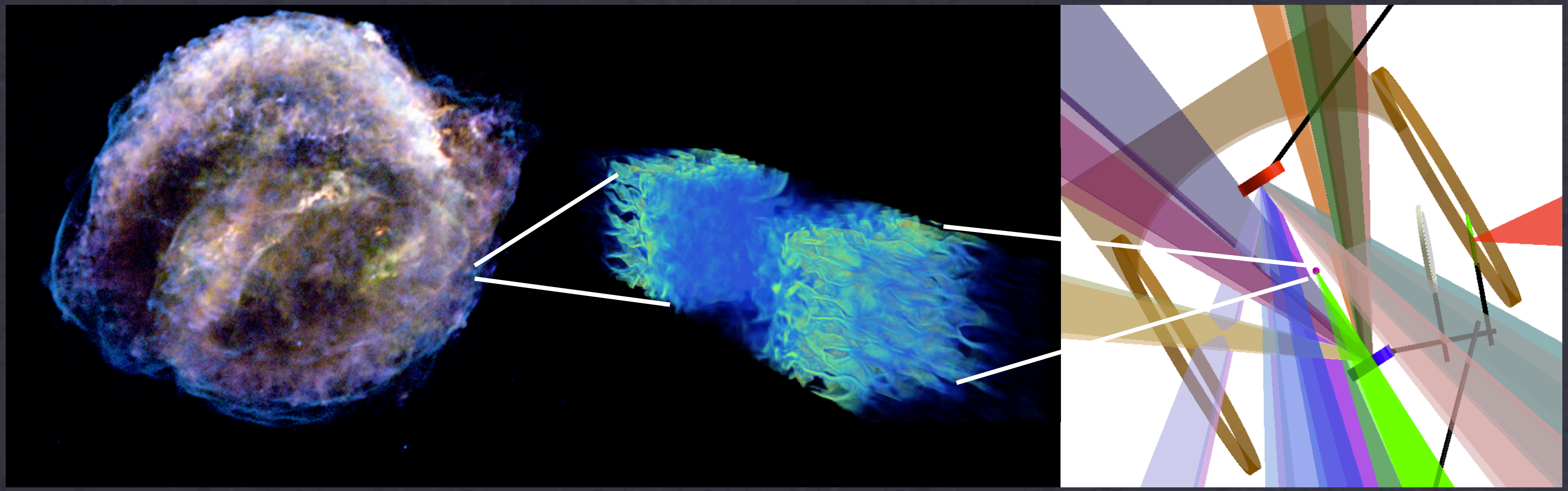
Parameter Space of shocks

Magnetized/unmagnetized transition exists even for non-relativistic shocks



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

What do we want to learn about shocks from experiments?



Universe ⟷ microphysics ⟷ experiments

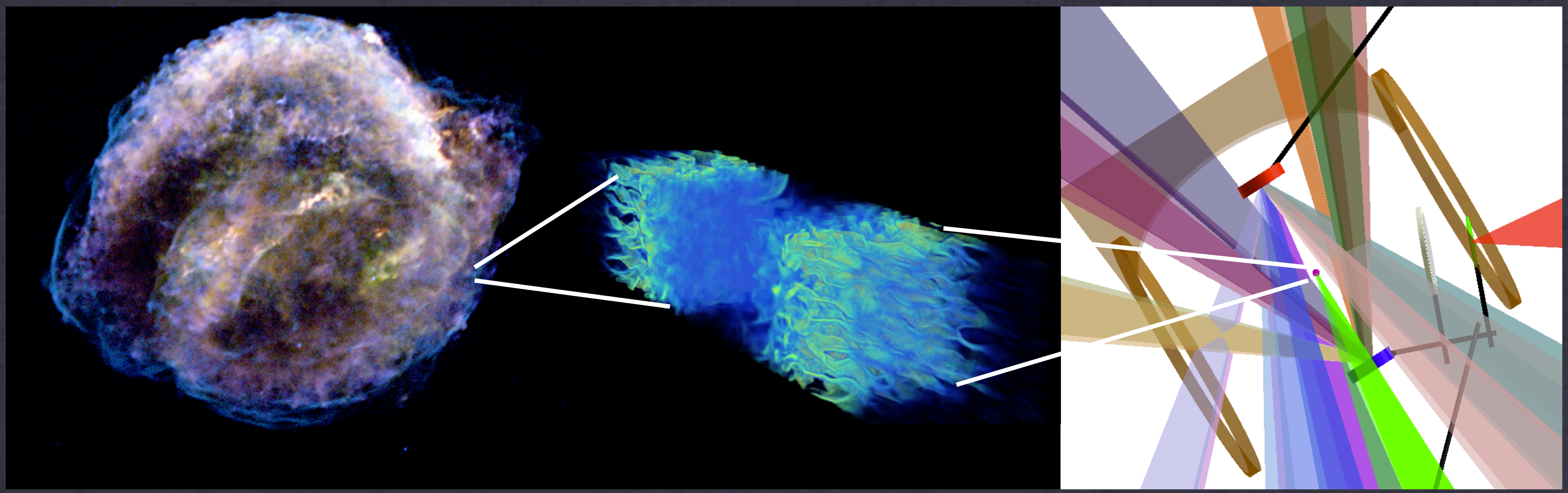
Shock mediation regimes: unmagnetized vs magnetized

Mechanisms of particle injection at shocks (full DSA is unlikely)

Efficiency of electron heating and energy exchange at shocks

Mechanisms of magnetic field amplification and turbulence excitation

What do we need experiments to satisfy?



Universe ⟷ microphysics ⟷ experiments

Collisinless conditions (forces us to go to high velocities)

Sufficient longitudinal and transverse size to form shocks

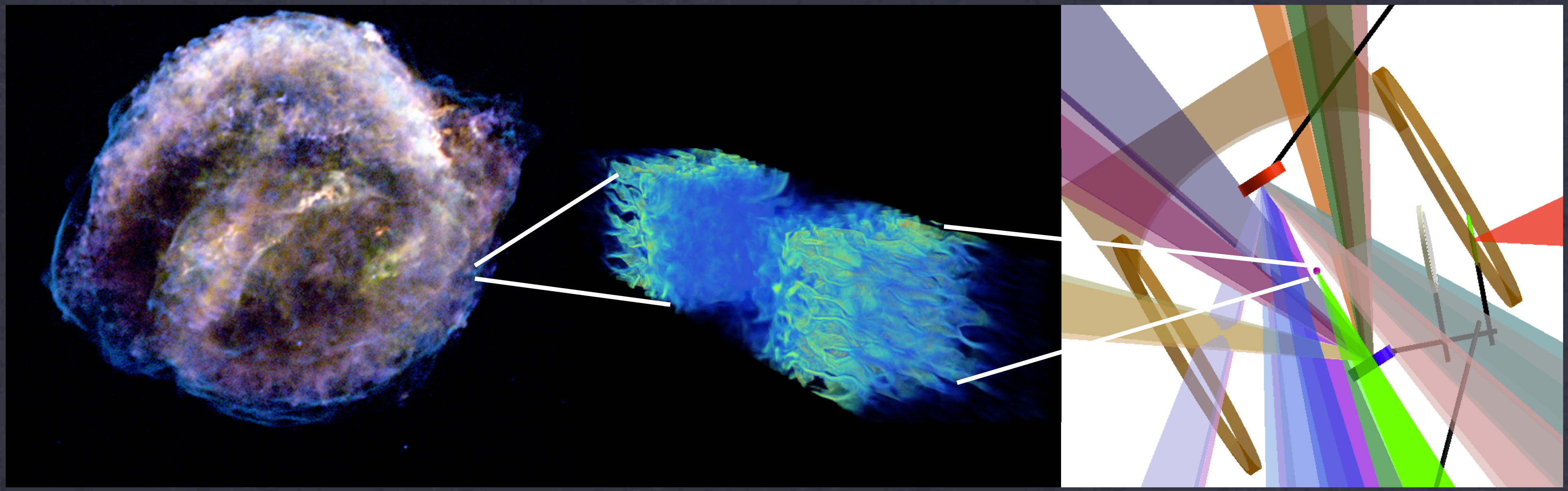
(length > 100 ion skin depths; width > several skin depths)

Ability to dial magnetization and field geometry

Availability of particle and field diagnostics

Dimensionless astro parameters can be reproduced in the lab

Possible experiments



Universe ⟷ microphysics ⟷ experiments

Several classes of experiments include:

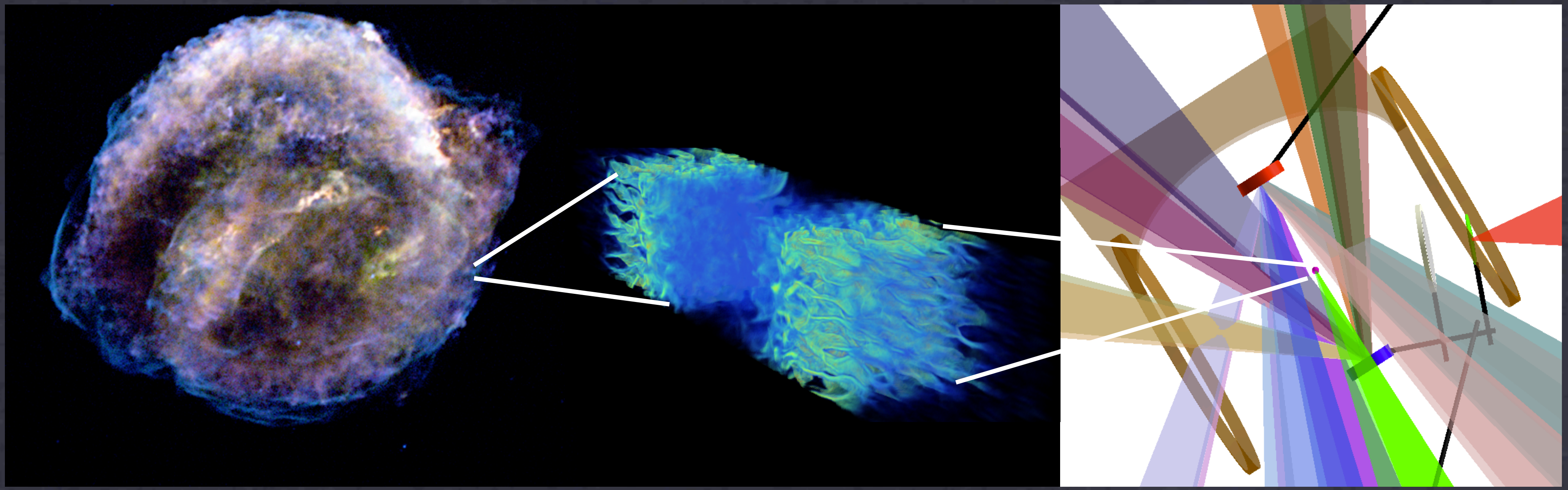
Collision of two high speed beams (ablation or guns)

Explosion of a solid driver in plasma

Launch compression through near solid target

Get around collisionality through high velocities (bulk or thermal)

Colliding beam experiments on Omega Laser



ACSEL collaboration (Astrophysical Collisionless Shock Experiments with Lasers)

Princeton University (USA):	A. Spitkovsky, L. Gargate
LLNL (USA):	H.-S. Park, N. Kugland, S. Ross, D. Ryutov, B. Remington, C. Sorce, C. Plechaty, S. Pollaine
LLE, Univ. of Rochester (USA):	G. Fiksel, D. Froula, J. Knauer
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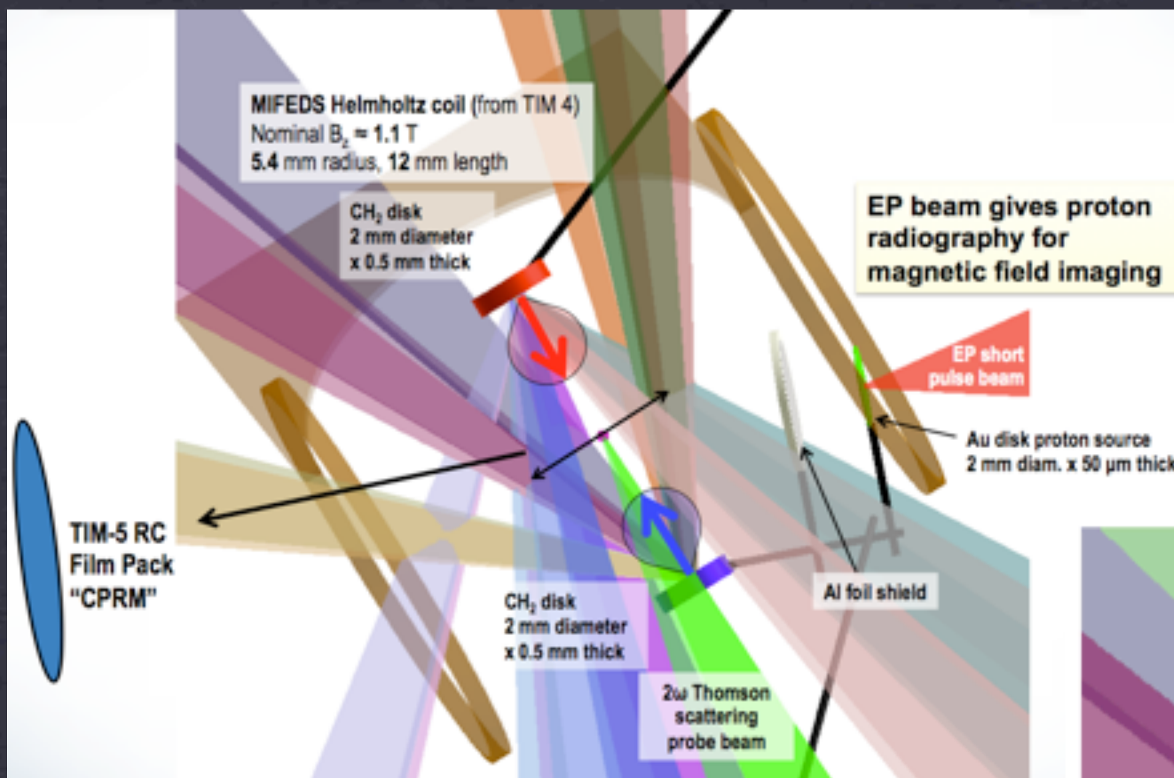
Goal: create a platform for shock studies on HED laser facilities (scaling to NIF)

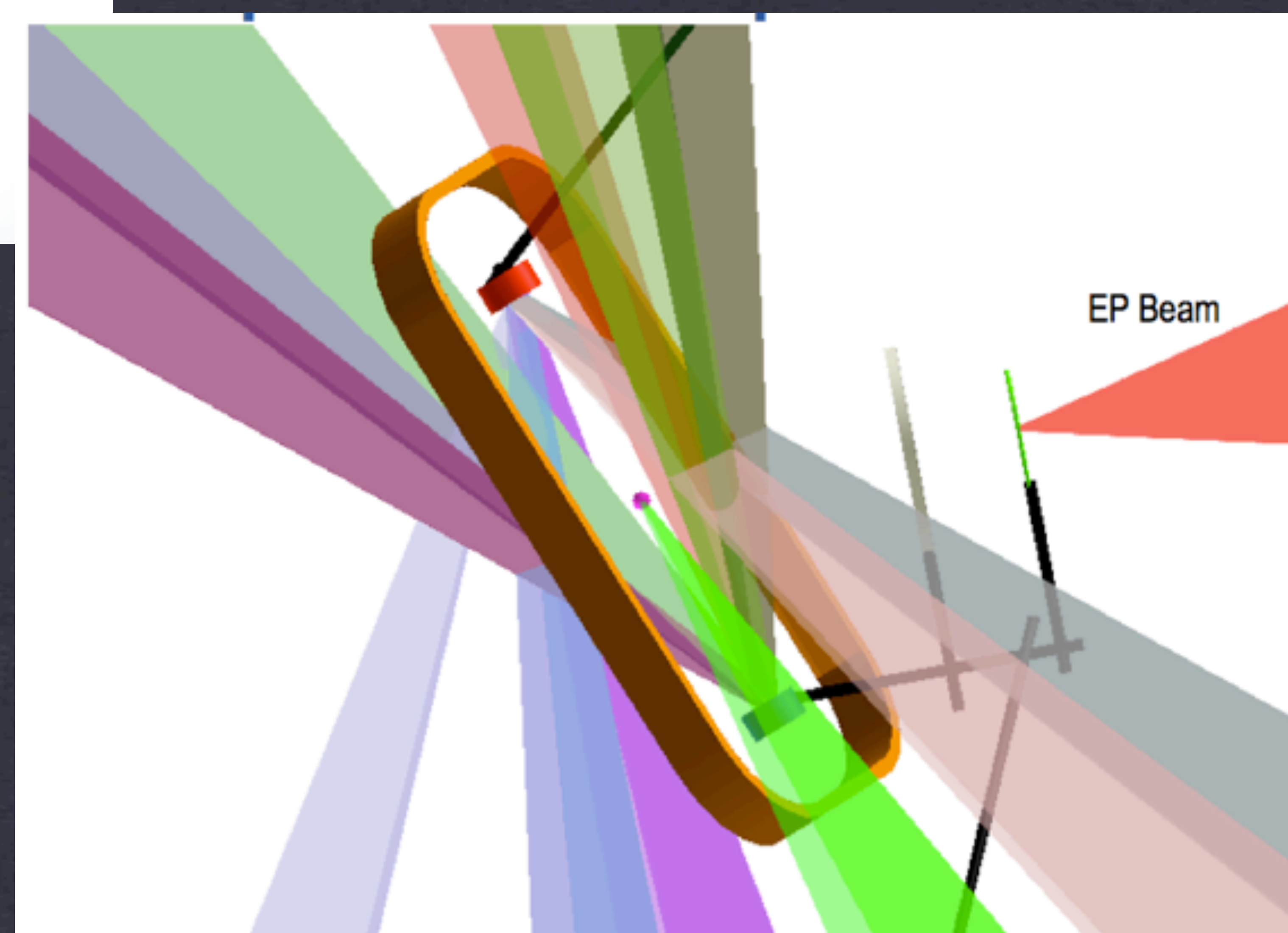
Colliding beam experiments on Omega Laser

ACSEL collaboration (Astrophysical Collisionless Shock Experiments with Lasers)



We study the shock formation mechanism as a function of external fields. Want to observe filamentary and reflection shocks.

MagShock 11a



MagShock 12a

NLUF grant
DE-NA0000868

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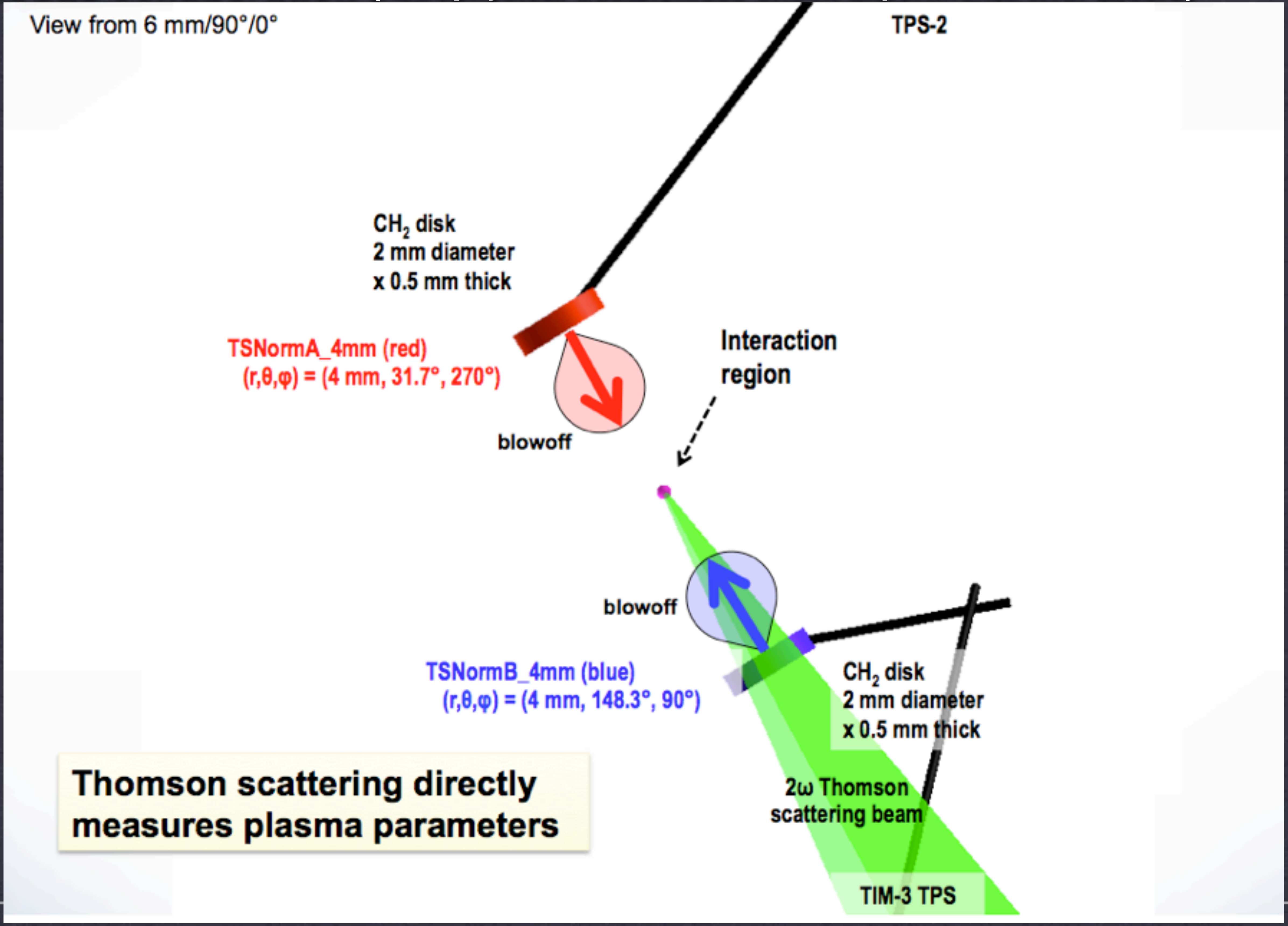

Thomson scattering directly measures plasma parameters

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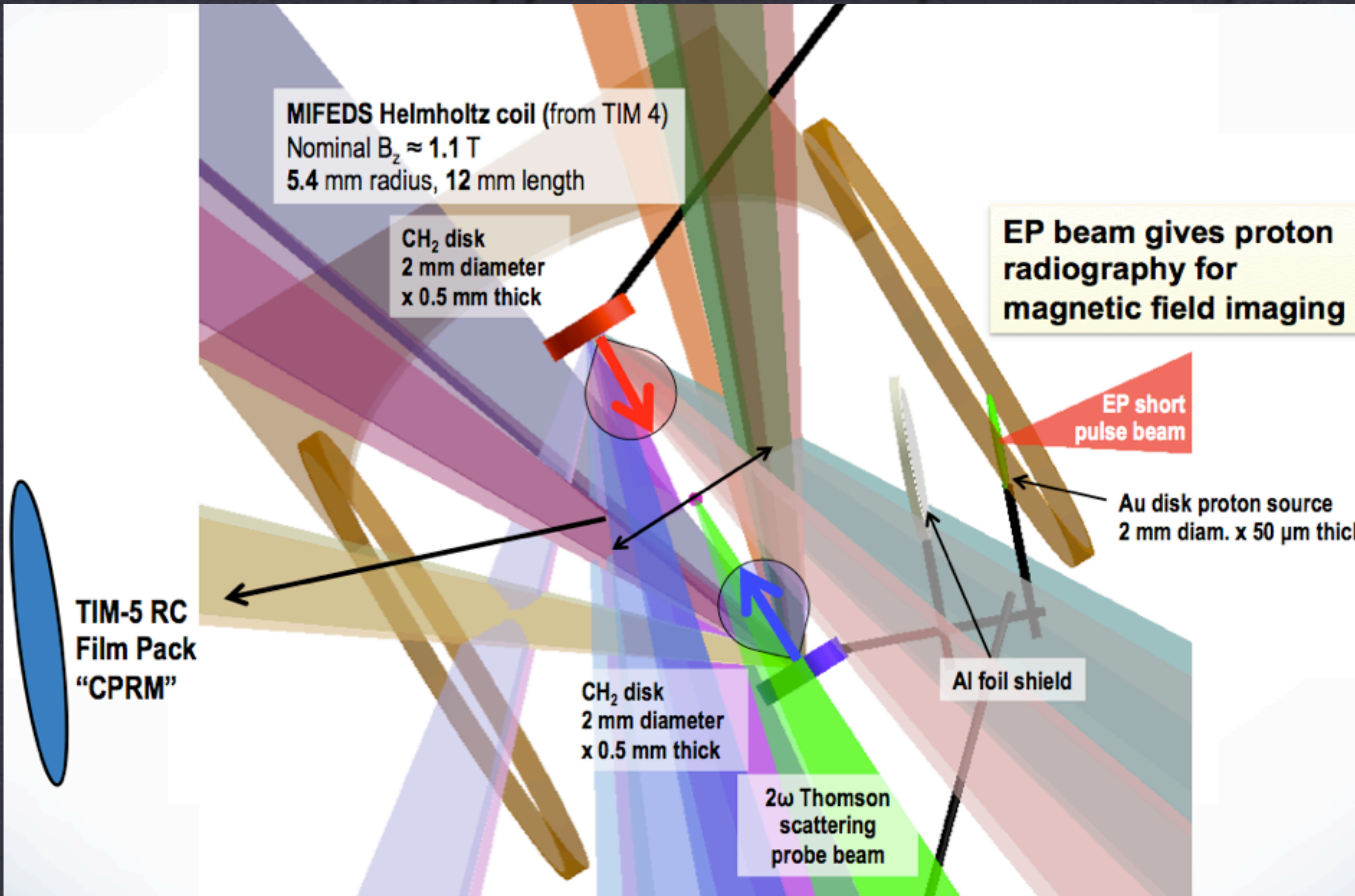

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Expected conditions: 10^{15} W/cm^2, 1ns pulse

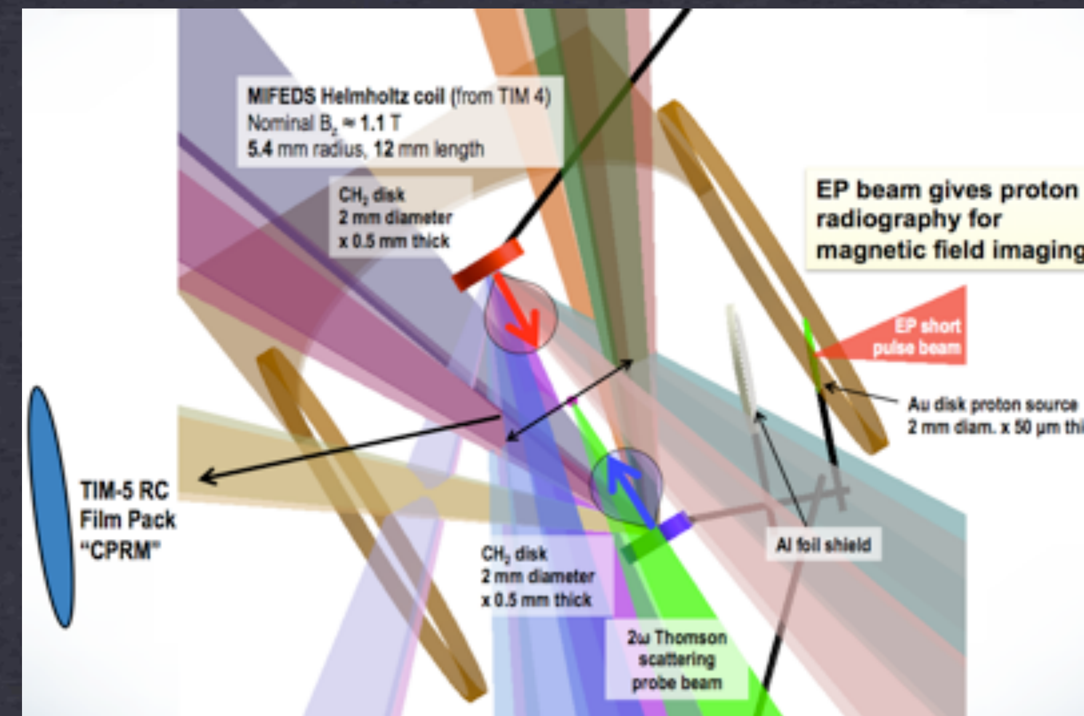
1000-2000 km/s ablation flow of CH_2

10^{18} - 10^{19}cc plasma densities

Target separation 8mm; mfp > 4cm

External field: 1-10 T (depending on config)

Interaction region parameters:



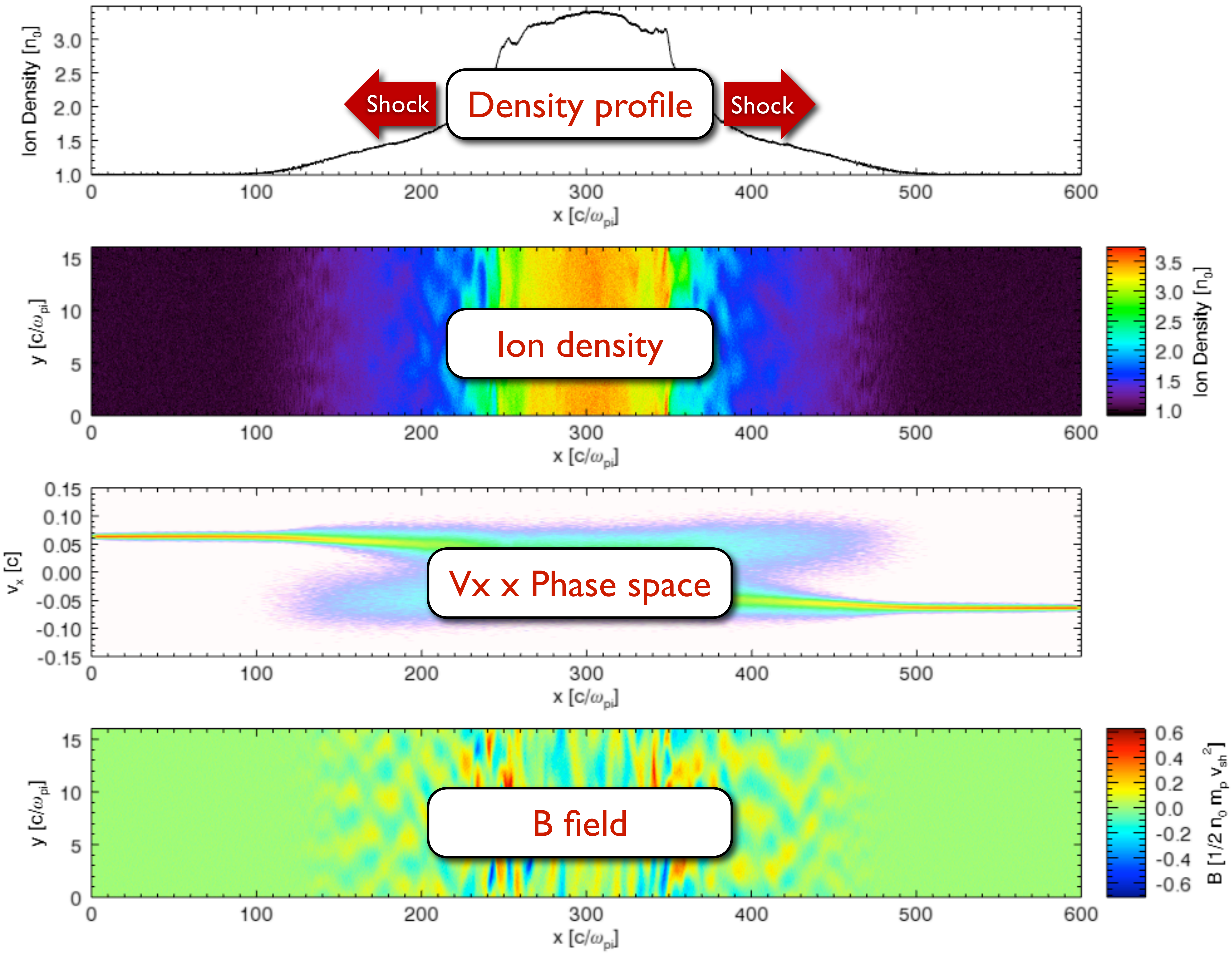
$$\sigma \equiv \frac{B^2/4\pi}{n m_i v^2/2} = \frac{2}{M_A^2} = \left(\frac{\omega_{ci}}{\omega_{pi}}\right)^2 \left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_{pi}}{R_{Li}}\right]^2$$

$$\sigma = 10^{-} \ldots \left(\frac{B}{\ldots}\right)^2 \left(\frac{10^{18}\mathrm{cm}^{-3}}{\ldots}\right) \left(\frac{1000\mathrm{km/s}}{\ldots}\right)^2 \left(\frac{m}{\ldots}\right)$$

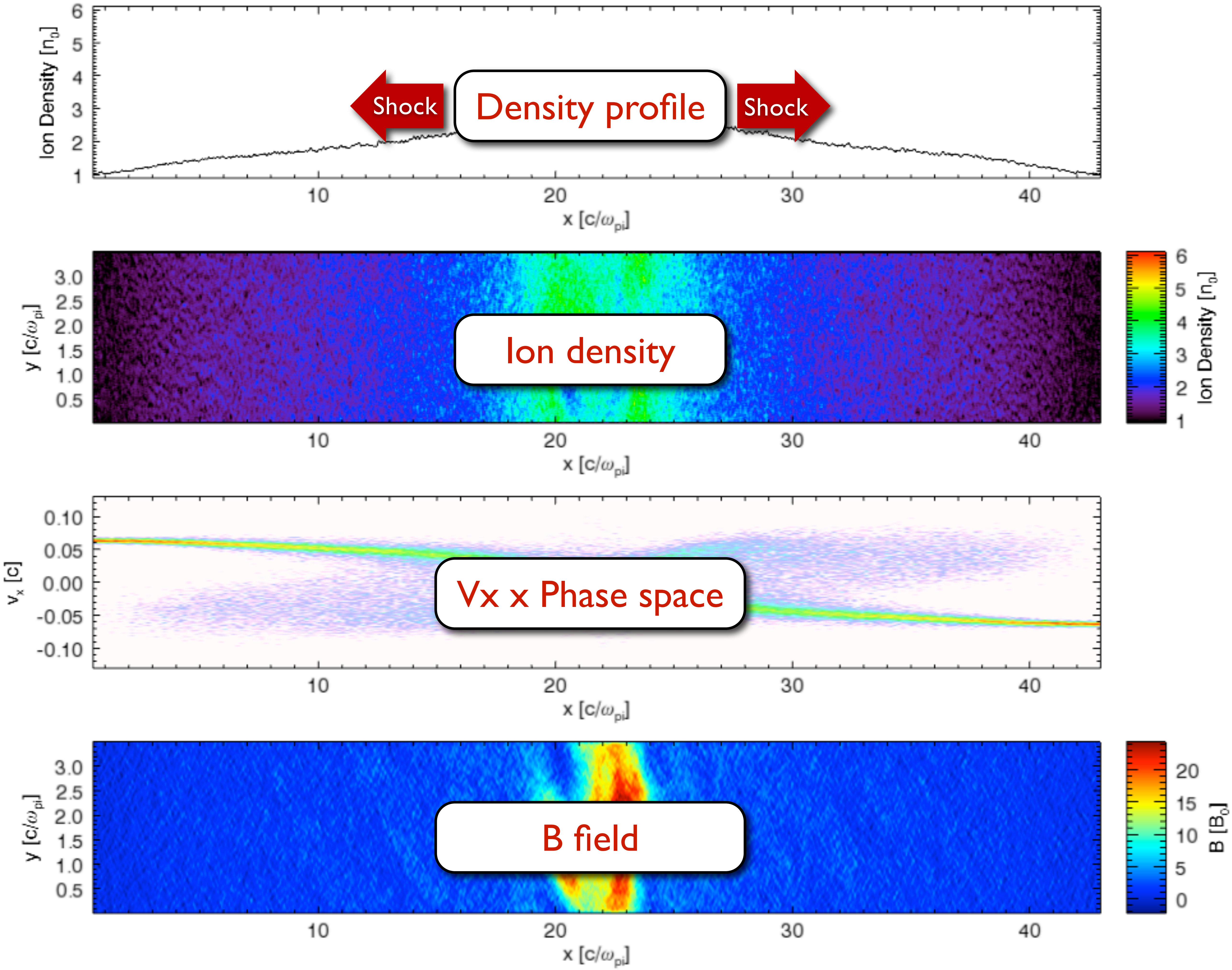
We modeled the experiment with particle-in-cell simulations

$$c/\omega_{pi} = \ldots n)^{1/2}$$

$$R_{Li} = 1\mathrm{cm}\left(\frac{A}{Z}\right)\left(\frac{v}{1000\mathrm{km/s}}\right)\left(\frac{1T}{B}\right)$$

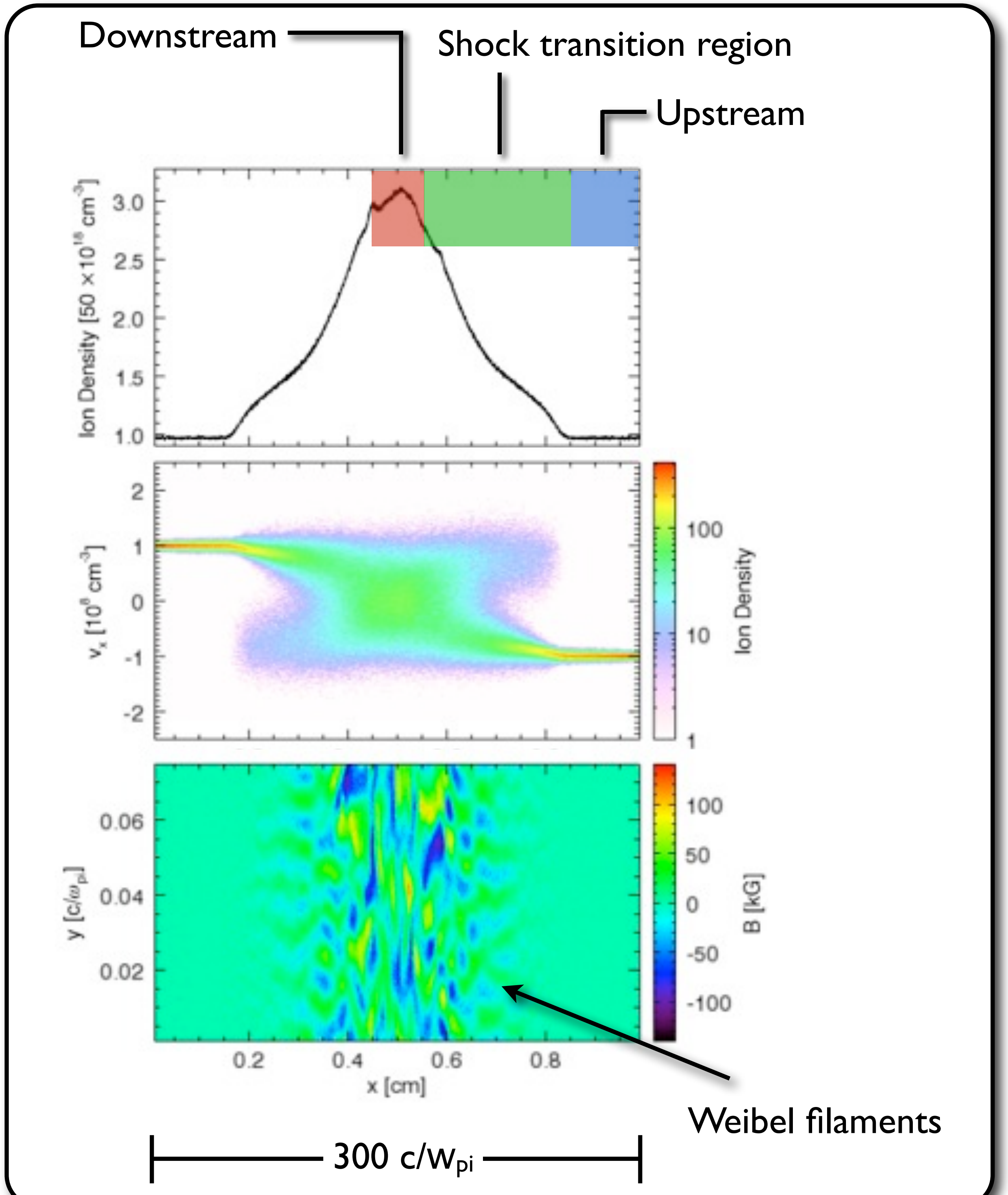


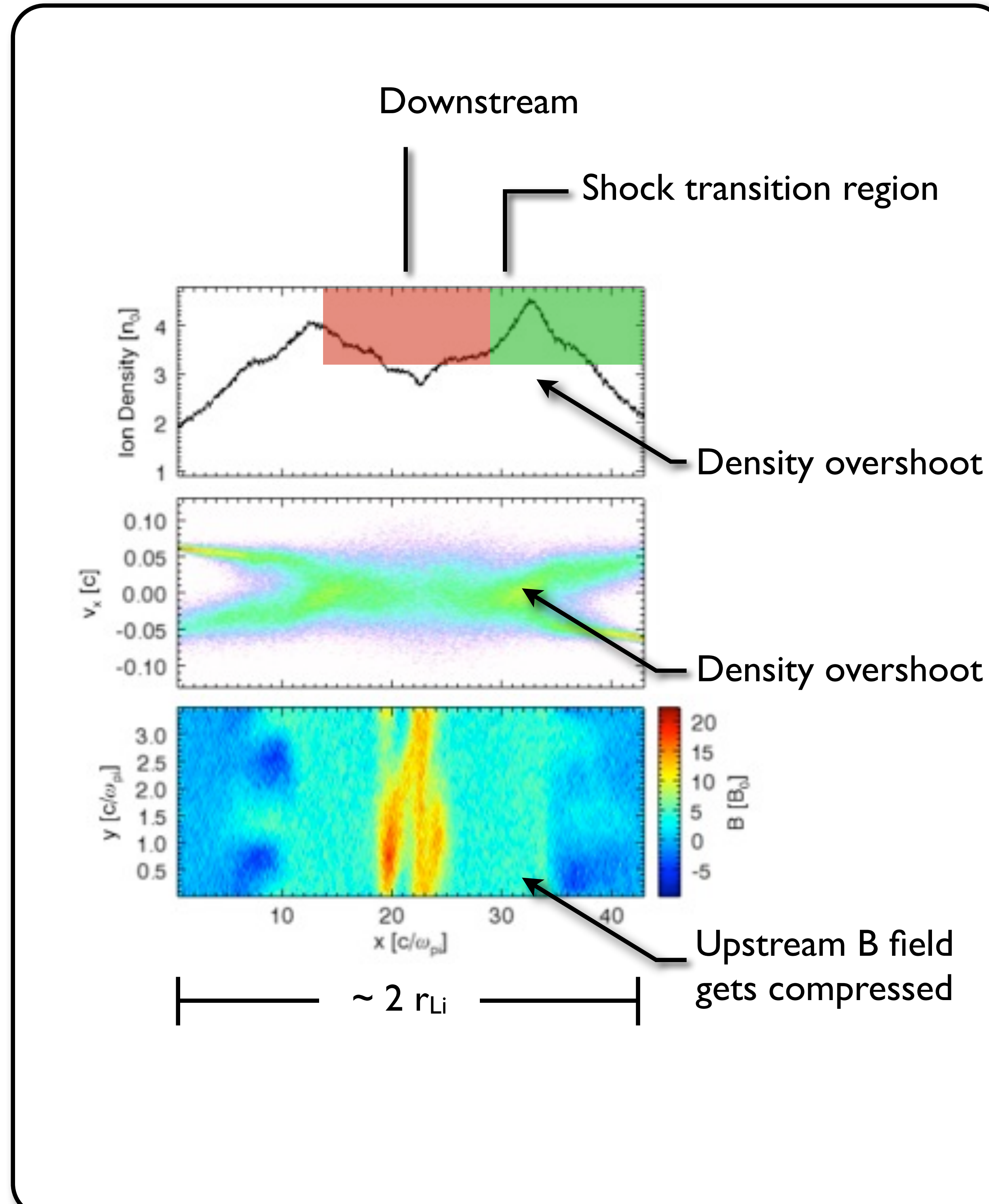
Density profile
Shock
Shock
Ion Density [n_0]
x [c/ω_{pi}]
Ion density
y [c/ω_{pi}]
Vx x Phase space
v_x [c]
B field
B [$1/2\, n_0 m_p v_{sh}^2$]



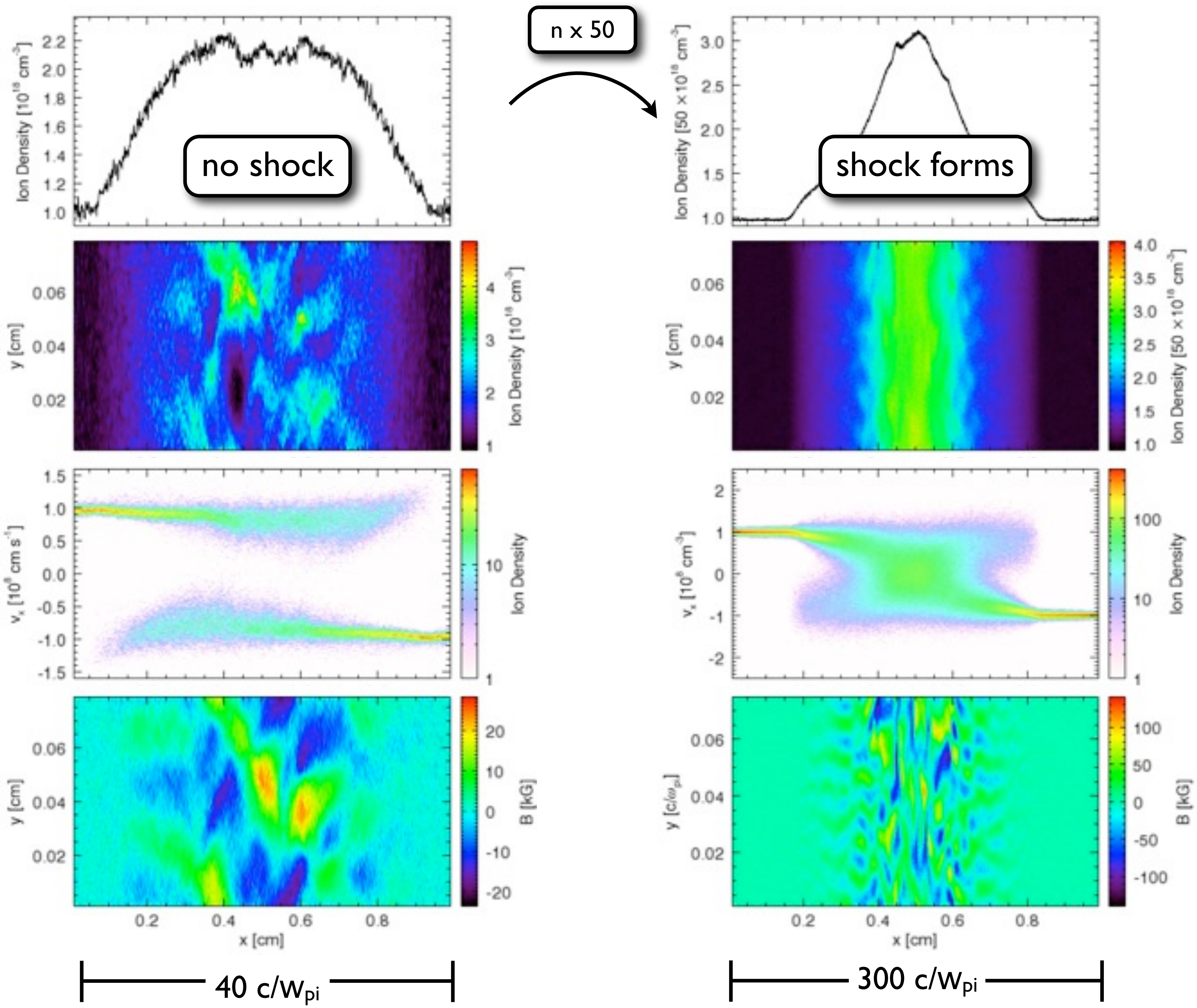
Density profile
Shock
Shock
Ion Density [n0]
x [c/ωpi]
Ion density
y [c/ωpi]
Ion Density [n0]
Vx x Phase space
vx [c]
B field
B [B0]

Components of shock structure





Shock formation time: ion-scale phenomena determines shock behavior



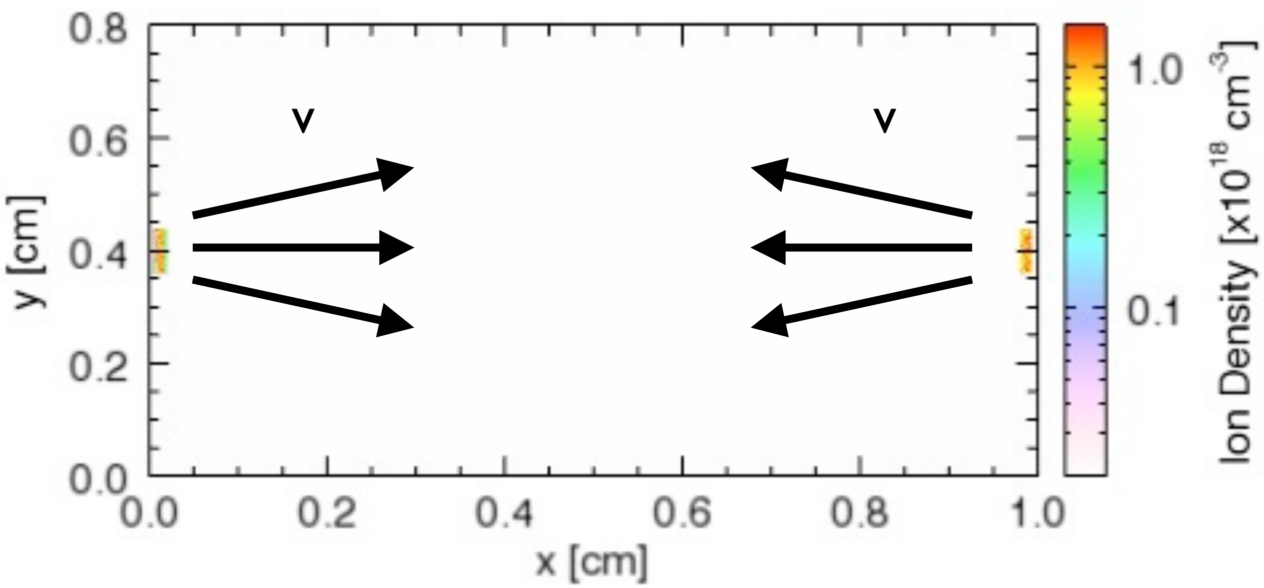
- Sonic Mach number is ~ 10
- Increasing n by 50 increases Lx by $50^{1/2}$ ~ 7
- Shock "formation length" is independent of beam velocity

Shock will form due to the Weibel instability if the beams interact over ~ 300 c/w_{pi}

(regardless of physical velocity or density)

How to get shocks in the lab: basic conditions (magnetized vs unmagnetized)

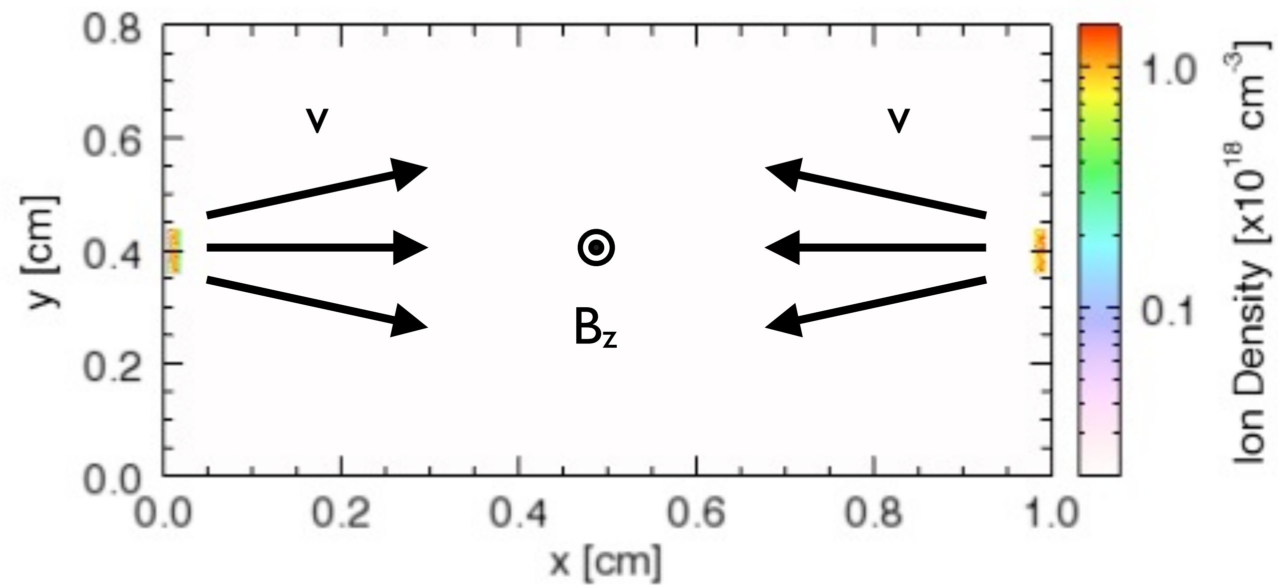
Unmagnetized



Make sure the beams are allowed to interact over a long enough distance (c/w_{pi})

In practical terms, for a given interaction distance, increase density

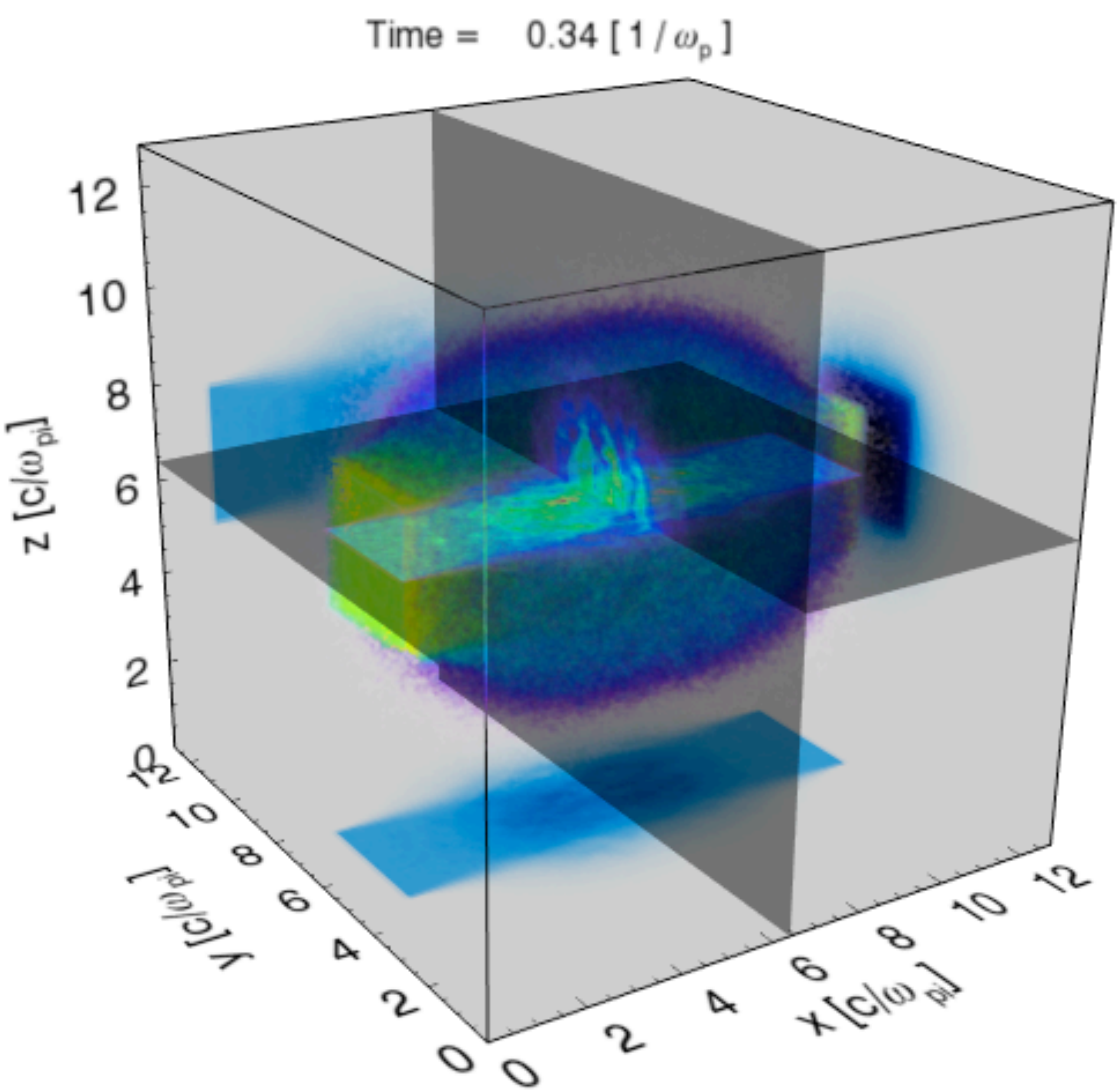
Magnetized



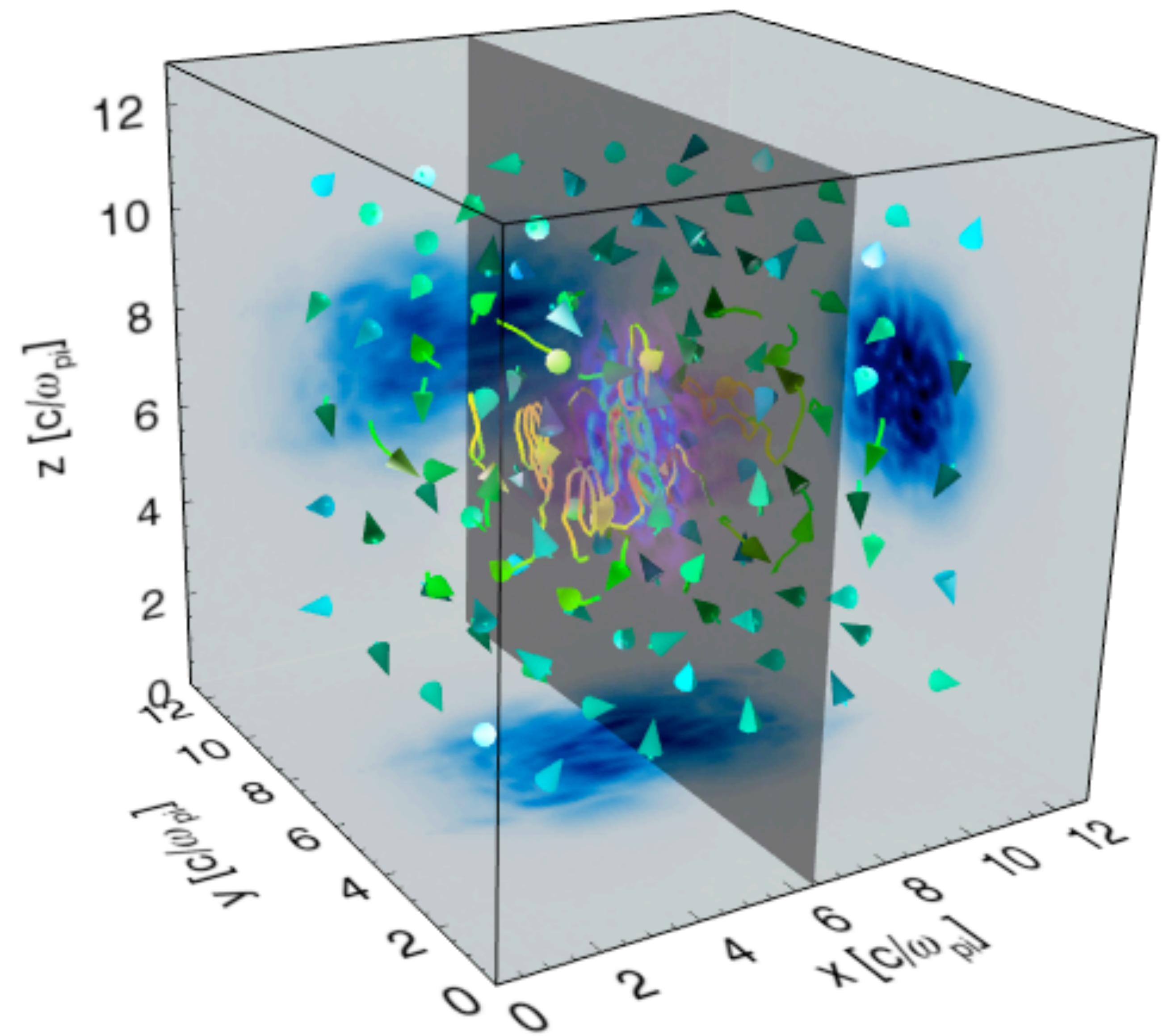
Make sure r_{Li} < interaction region ($Lx > 5\ r_{Li}$)
Make sure $s < 1$ (but not too low)

In practical terms, for a given B field, decrease density or velocity of the flow

Unmagnetized interaction with finite transverse size beam

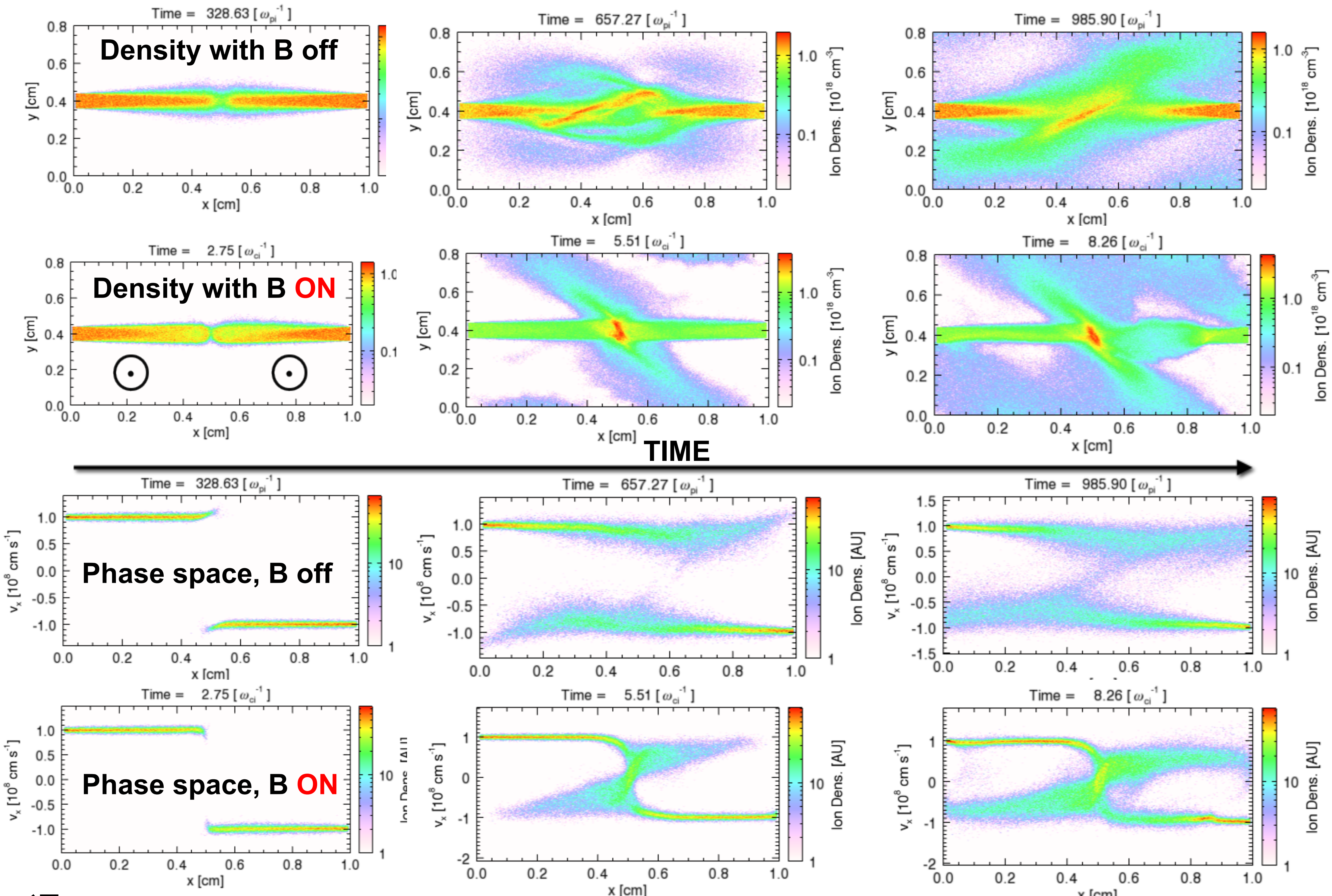


Density (ions)



B field (projections and vector field)

Simulations of plasma collision with and without B field



B=6T

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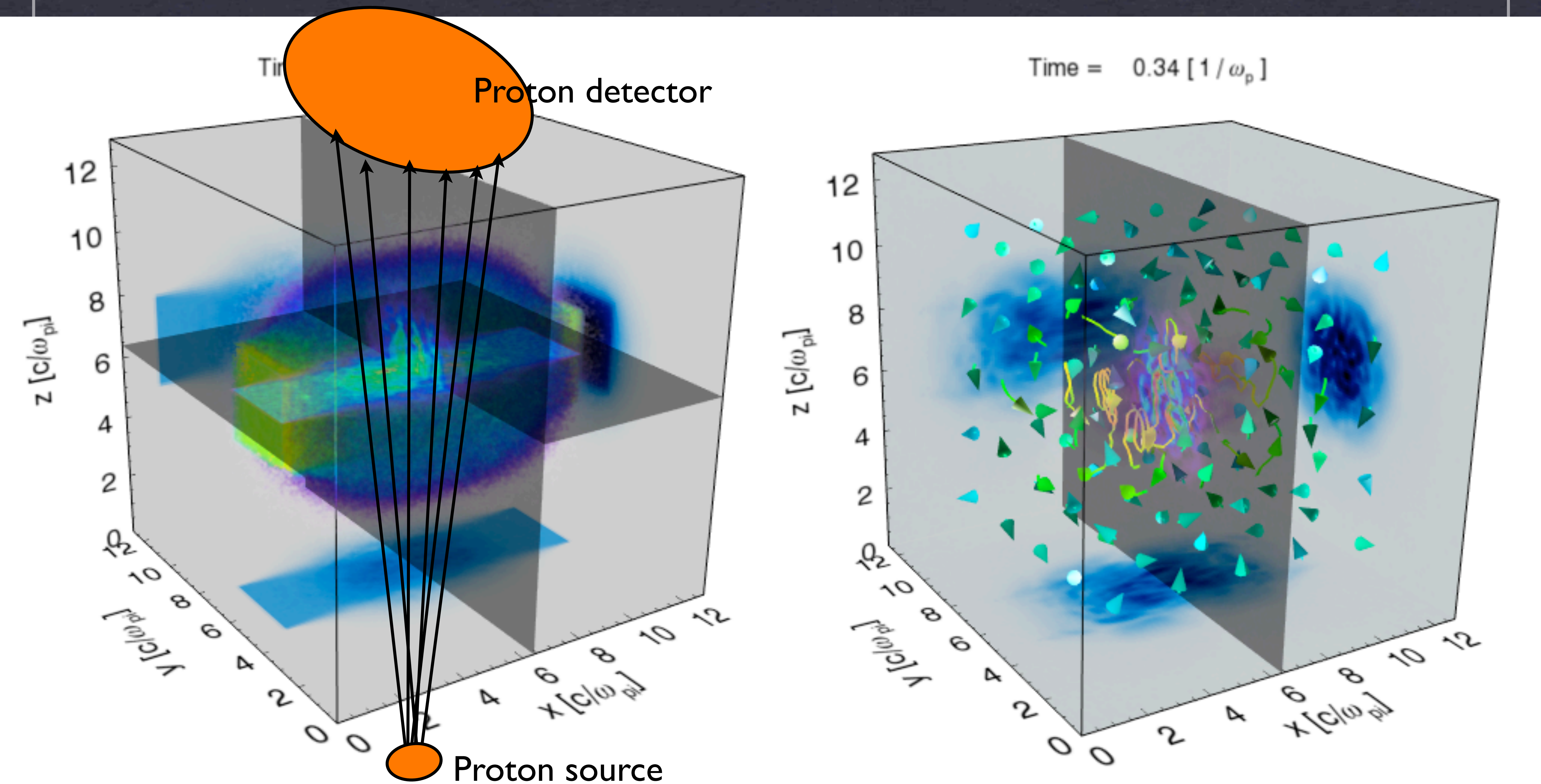
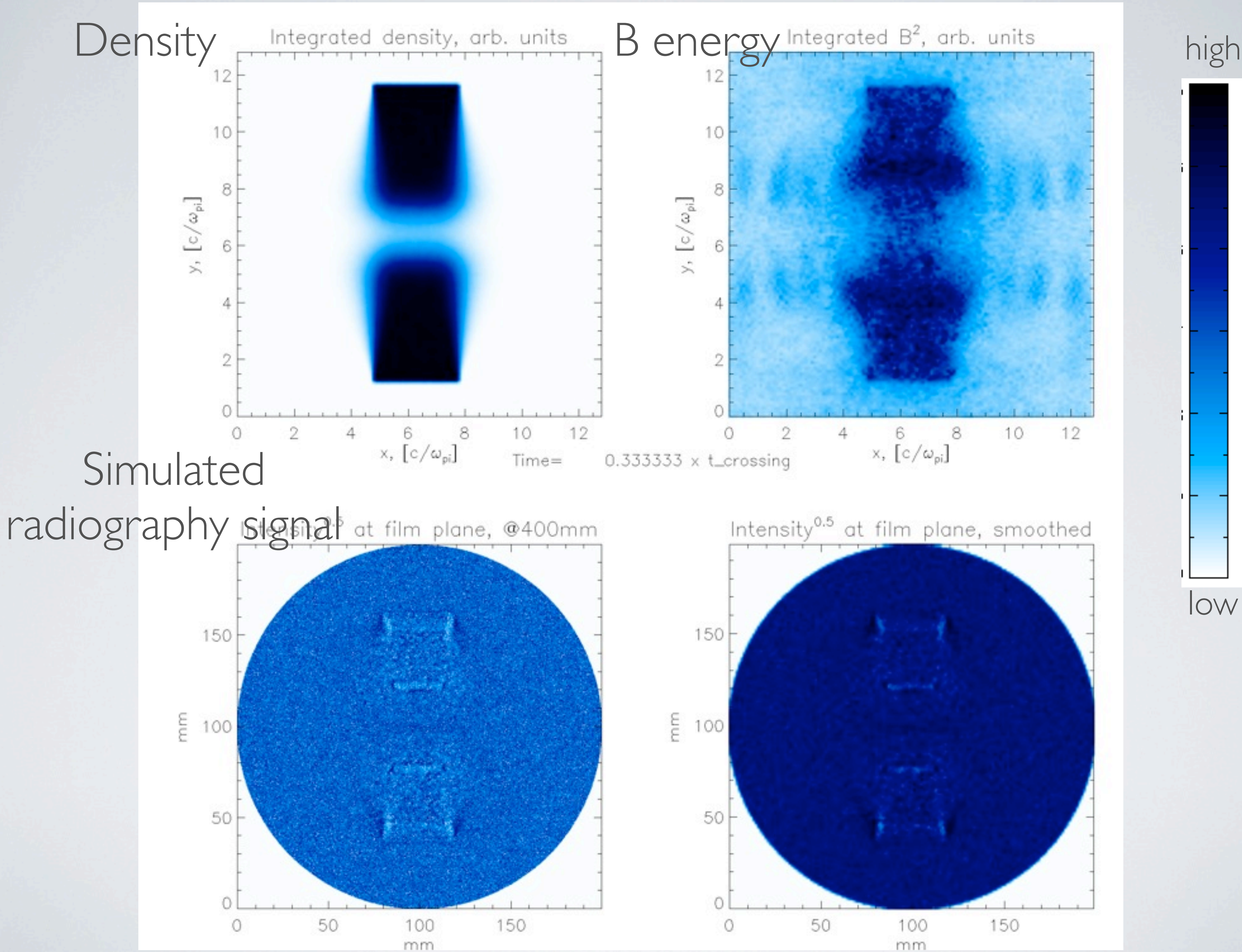
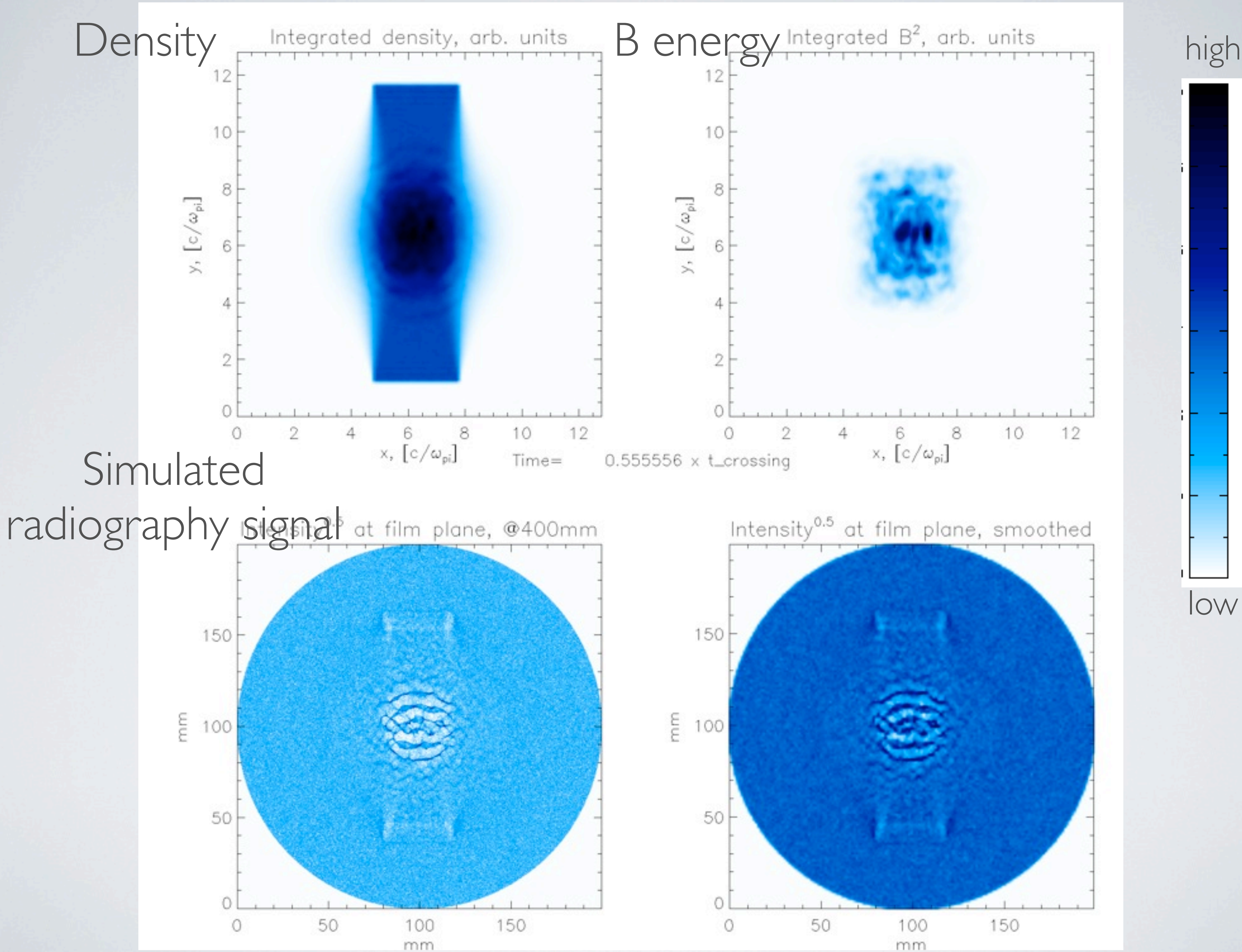
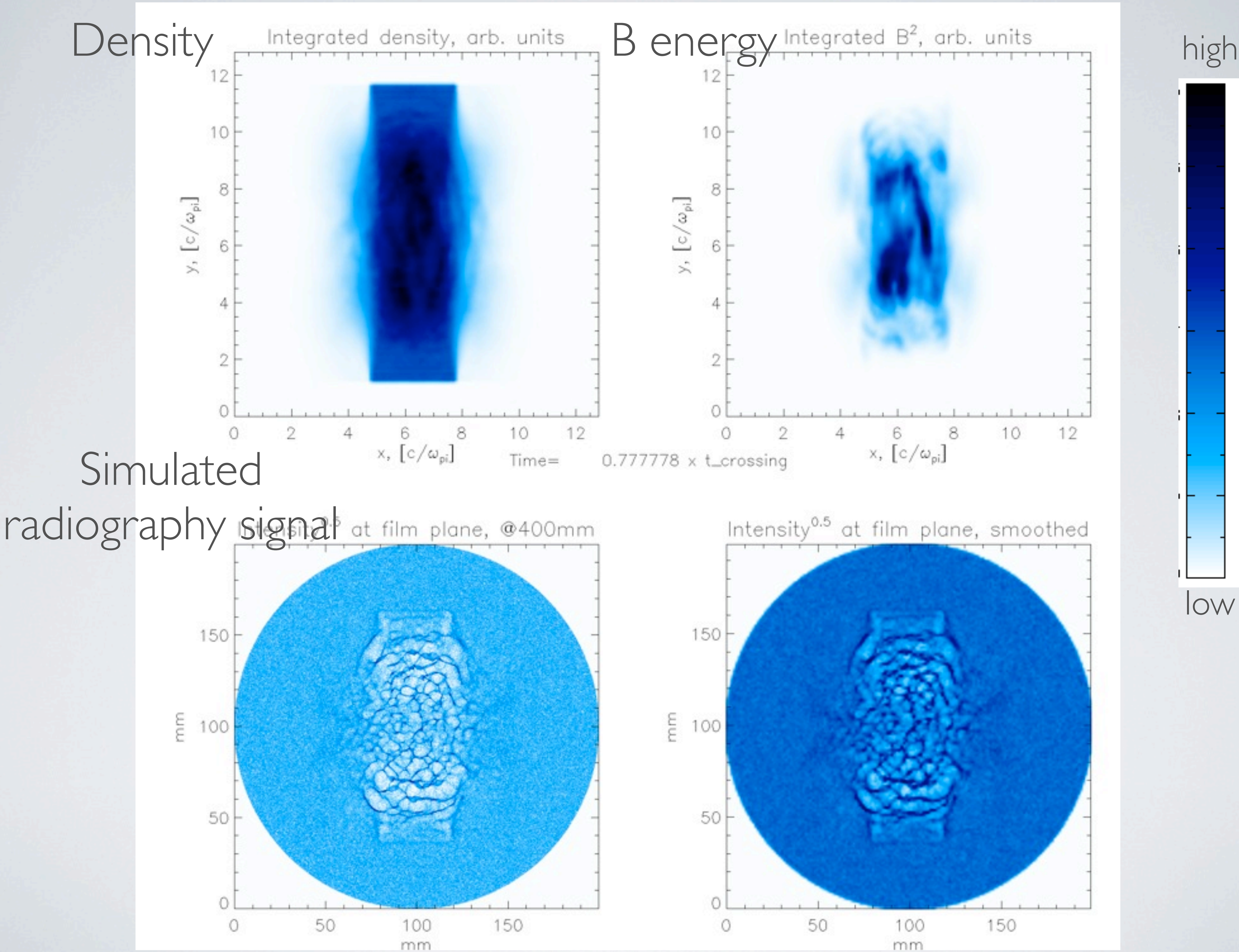
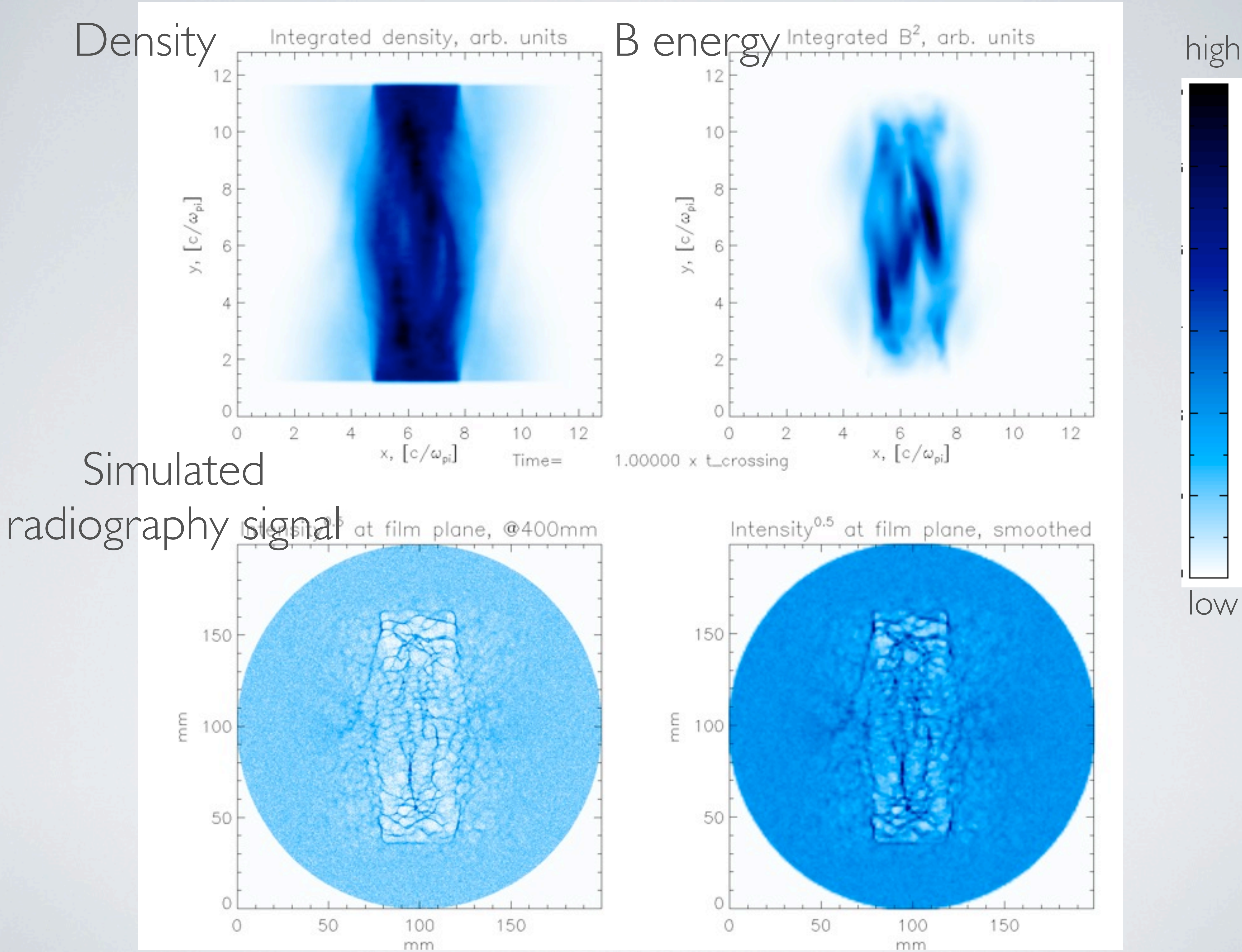


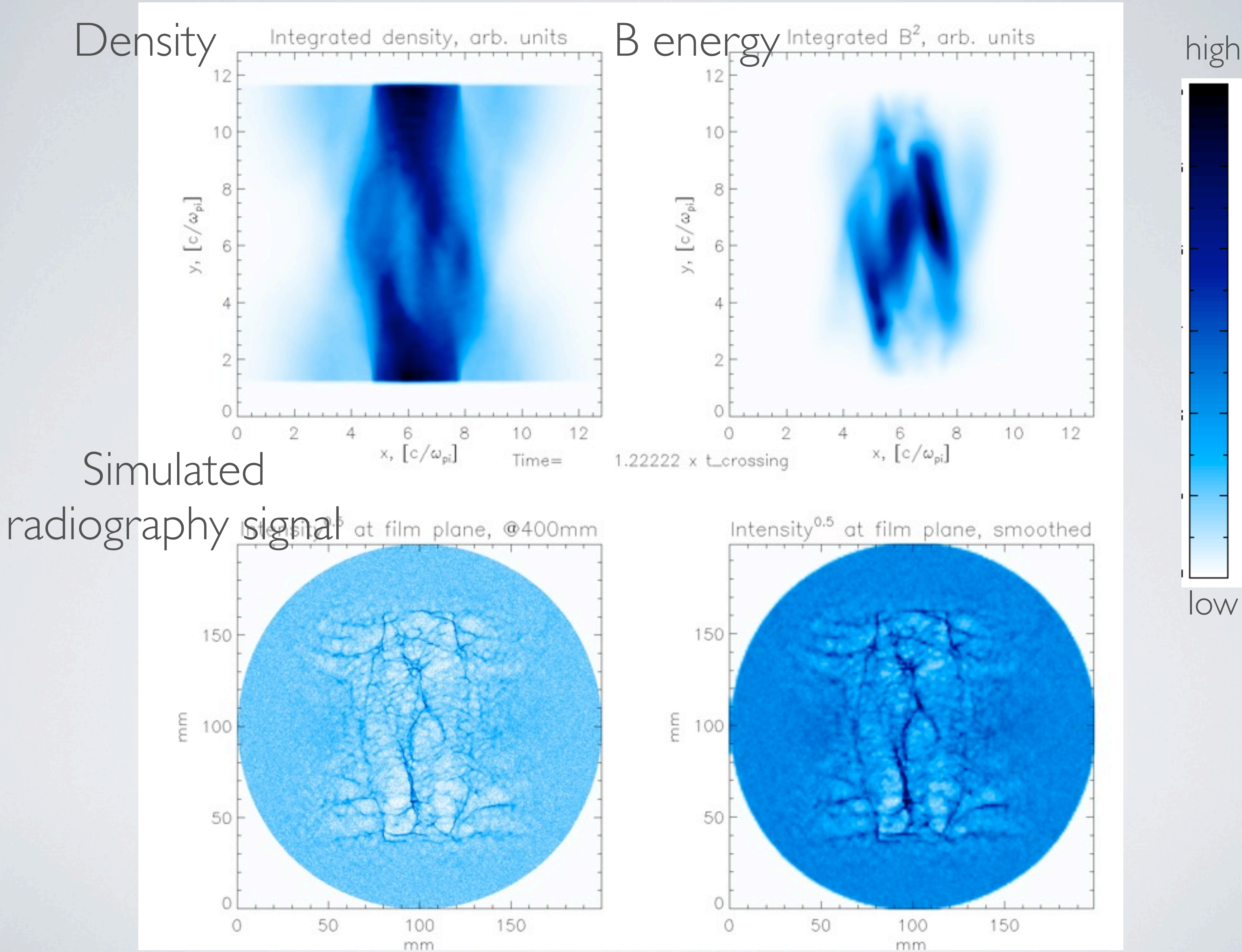
Proton radiography diagnostics

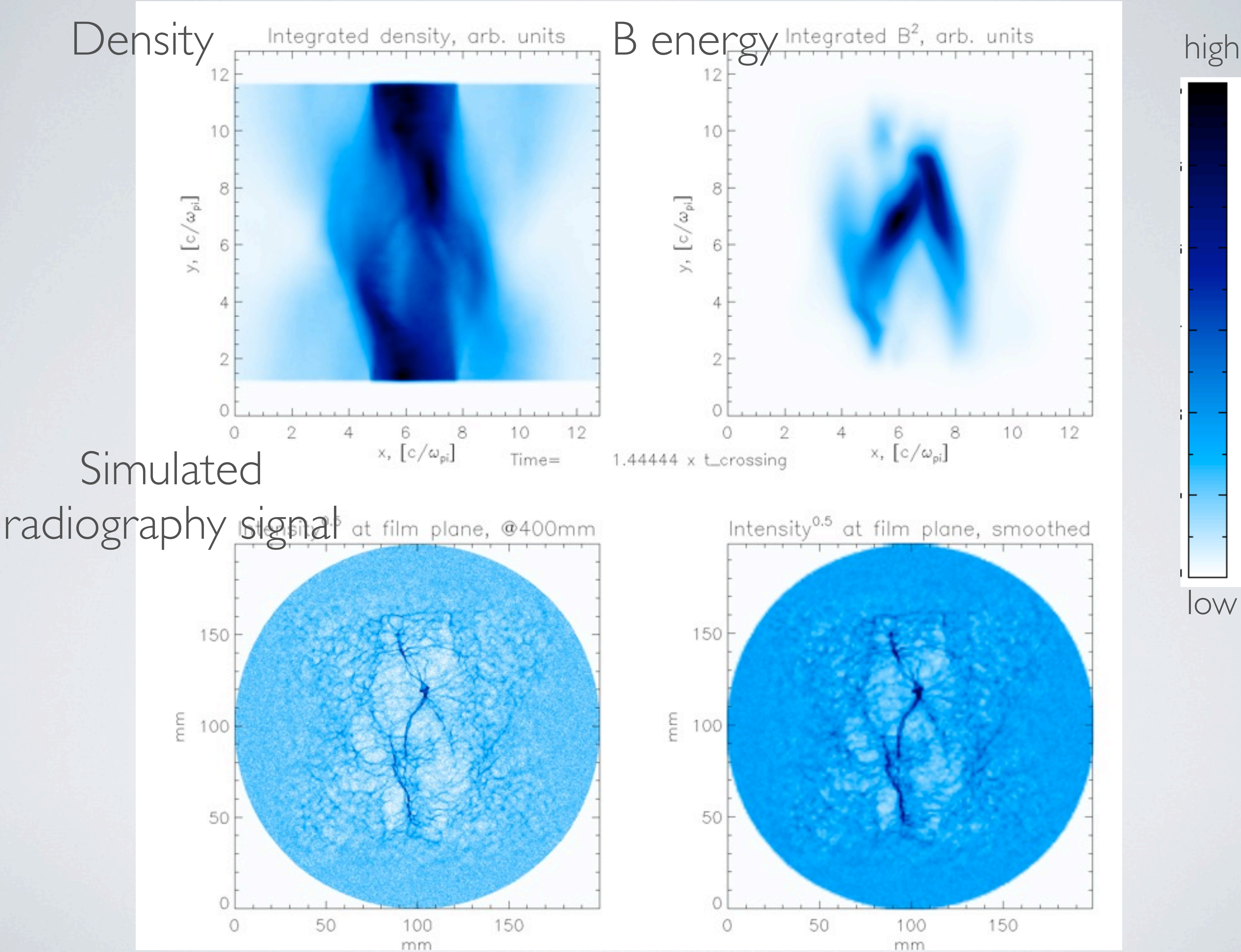

Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ω_pi]
x, [c/ω_pi]
Time= 0.333333 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm


Density
Integrated density, arb. units
B energy
Integrated B^2, arb. units
high
low
y, $[c/\omega_{pi}]$
x, $[c/\omega_{pi}]$
Time= 0.555556 x t_crossing
Simulated radiography signal
Intensity$^{0.5}$ at film plane, @400mm
Intensity$^{0.5}$ at film plane, smoothed
mm


Density
Integrated density, arb. units
B energy
Integrated B^2, arb. units
y, [c/ω_{pi}]
x, [c/ω_{pi}]
Time= 0.777778 x t_crossing
Simulated radiography signal
Intensity$^{0.5}$ at film plane, @400mm
Intensity$^{0.5}$ at film plane, smoothed
mm
high
low

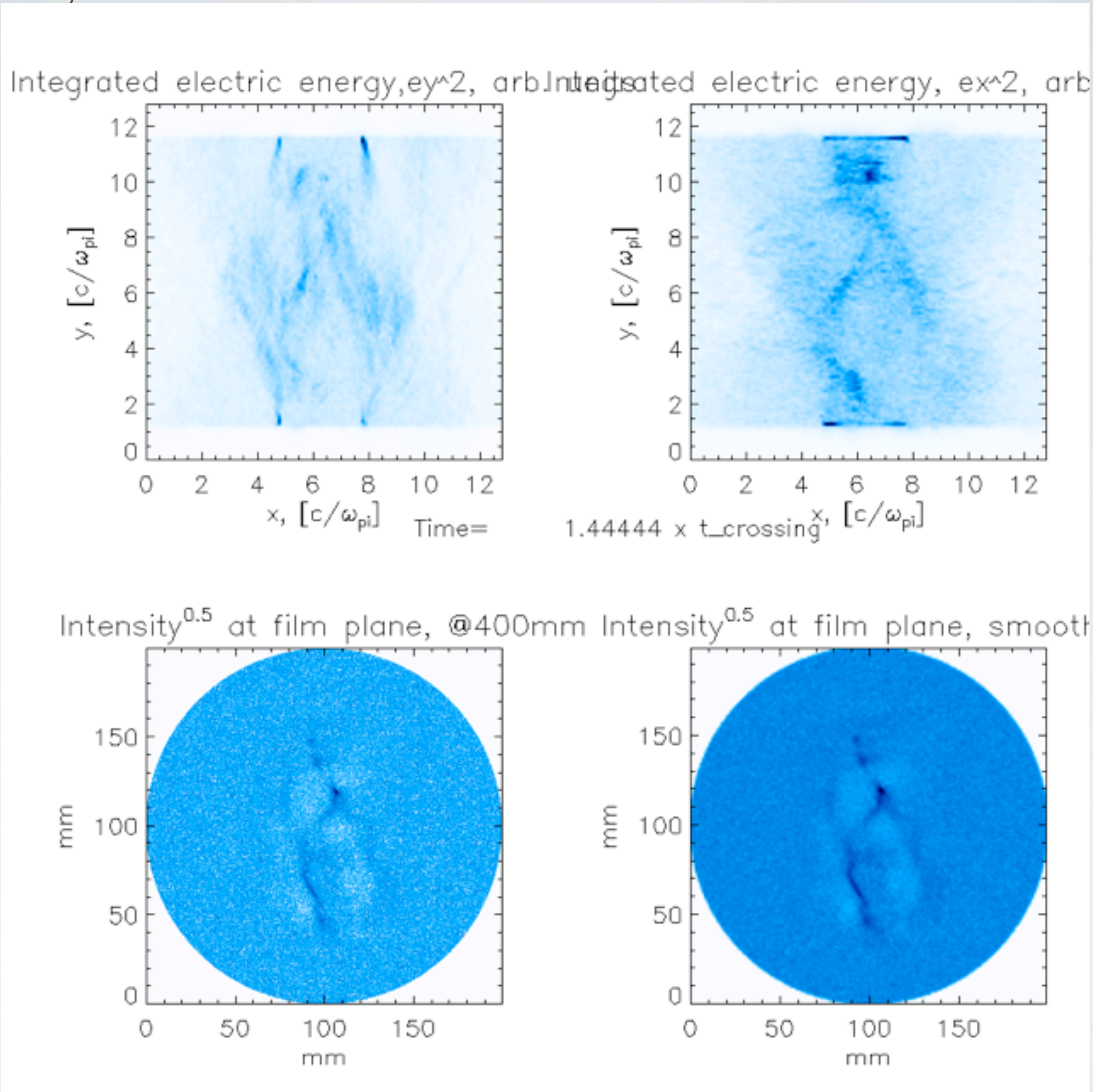

Density
Integrated density, arb. units
B energy
Integrated B^2, arb. units
high
low
y, [c/ω_{pi}]
x, [c/ω_{pi}]
Time= 1.00000 x t_crossing
Simulated radiography signal
Intensity$^{0.5}$ at film plane, @400mm
Intensity$^{0.5}$ at film plane, smoothed
mm


Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ω_pi]
x, [c/ω_pi]
Time= 1.22222 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm



Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ω_pi]
x, [c/ω_pi]
Time= 1.44444 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm

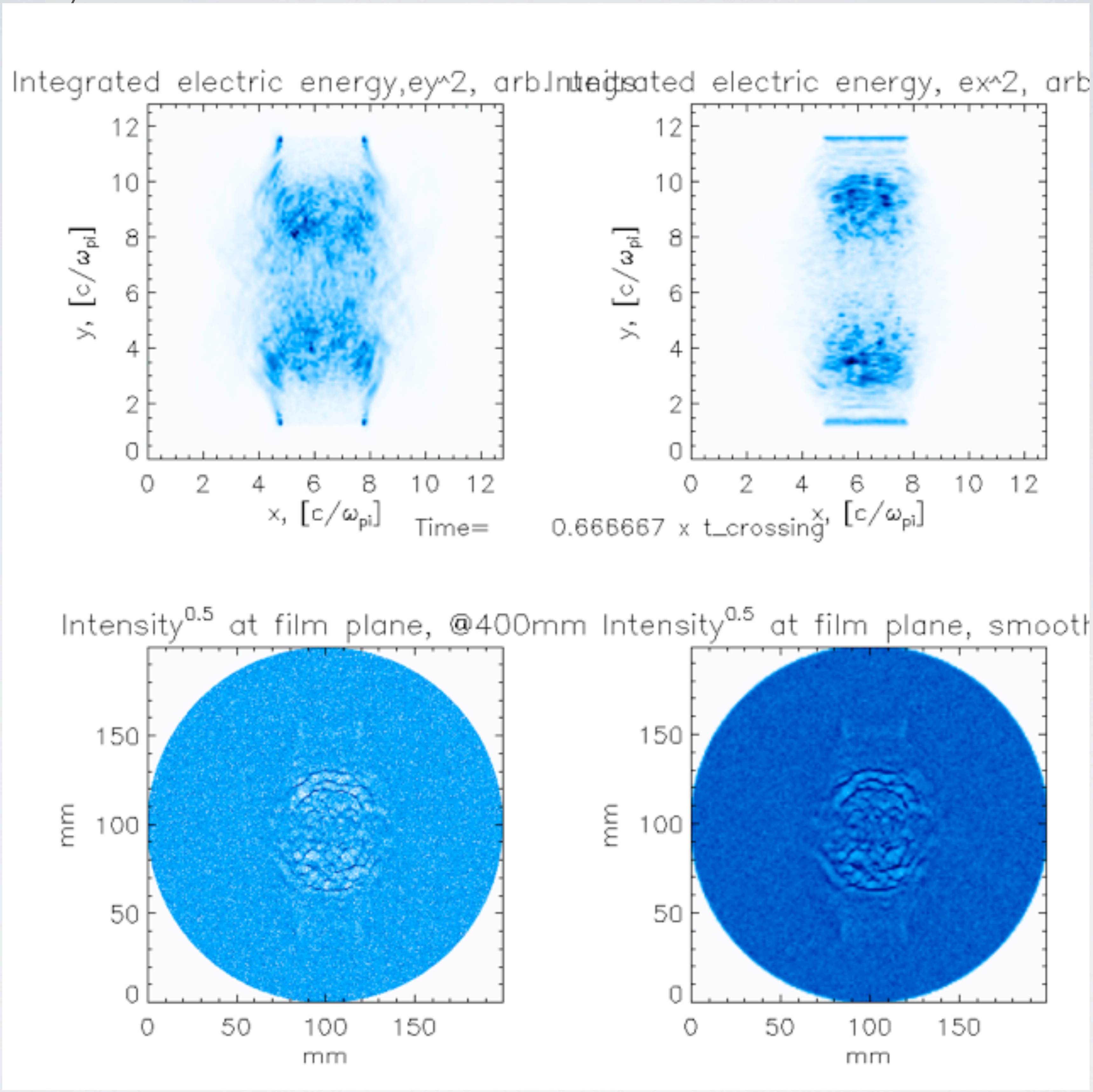
Early time -- bubbles. late time filaments. How come?



Only B field

Bubbles are due to E field, filaments due mainly to B field.

Early time -- bubbles. late time filaments. How come?



Only E field

Bubbles are due to E field, filaments due mainly to B field.

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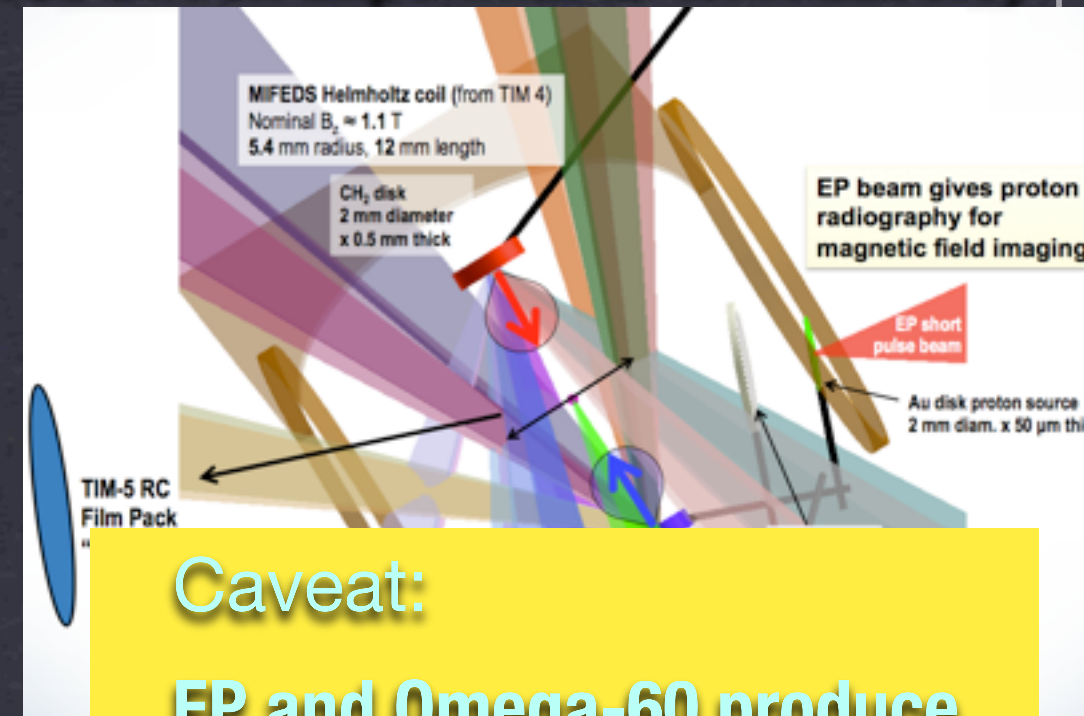
Experimental efforts: ColShocks (PI H.-S. Park, LBS) & MagShock (PI: AS, NLUF)

3 kinds of experiments at LLE

1) Omega only shots -- good for characterizing flows with Thomson scattering, with and without B field.

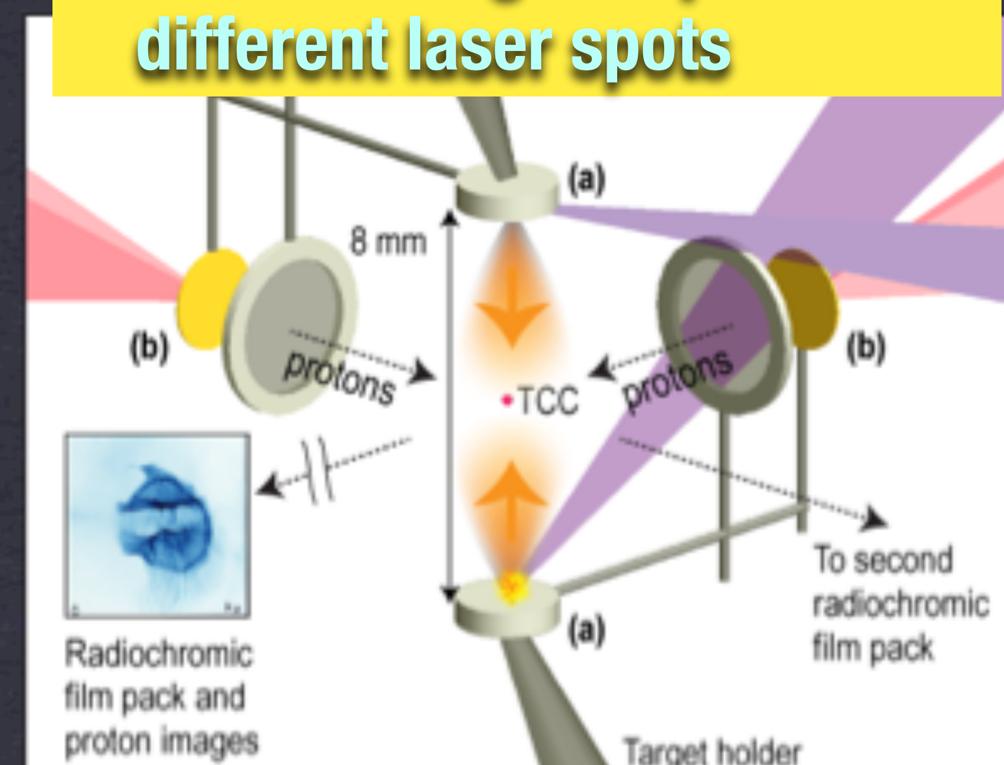
2) Omega/EP shots -- colliding flows with proton radiography (from two directions). No Thomson scattering; with and without B field (MIFEDS fielded at EP in FY2013)

3) Joint Omega+EP shots: colliding flows with proton radiography (one axis), B field, and Thomson. (Few shots available -- not all configurations/time sequences explored)



Caveat:

EP and Omega-60 produce different laser spots



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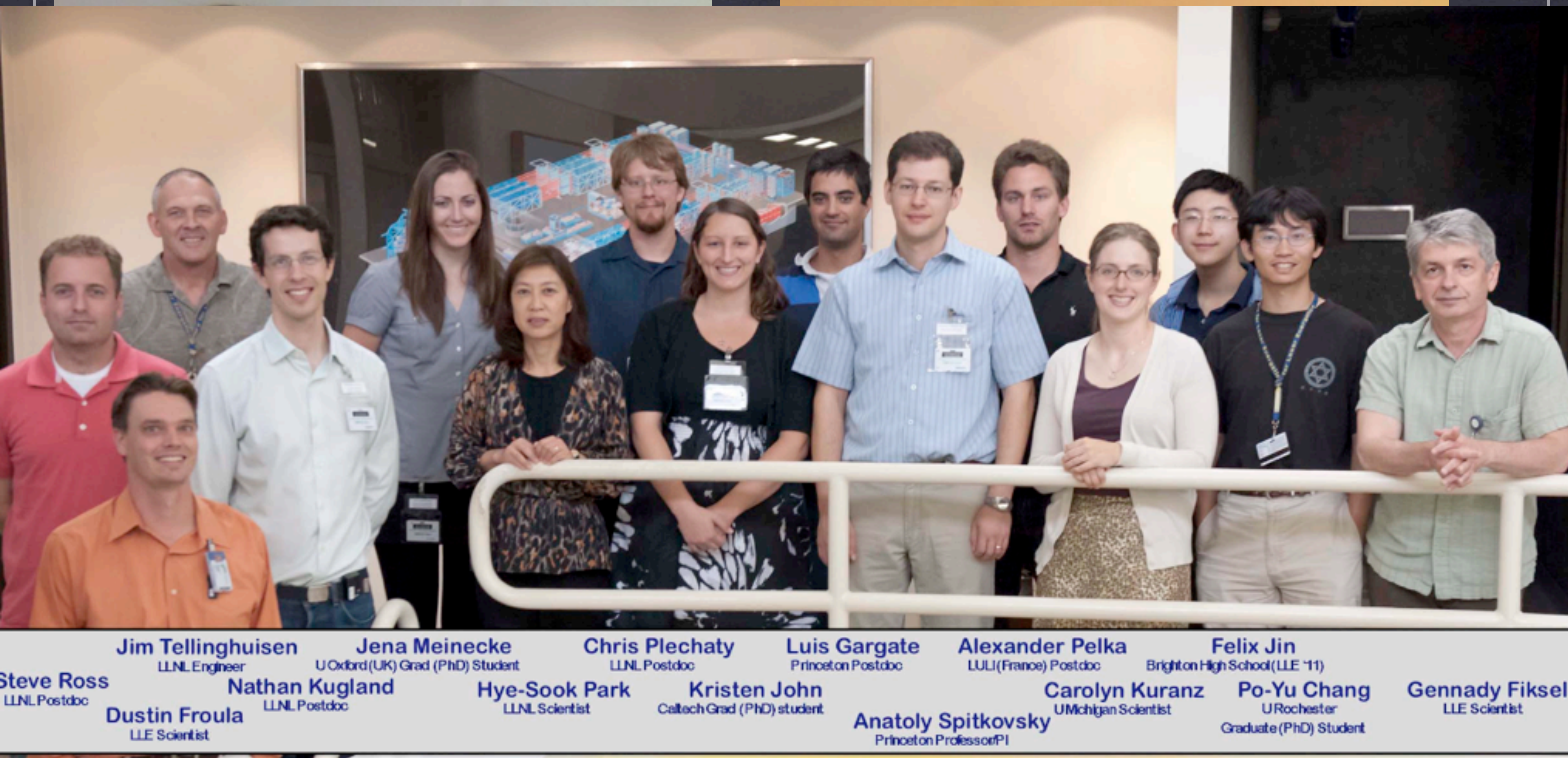

Colliding beam experiments on Omega Laser

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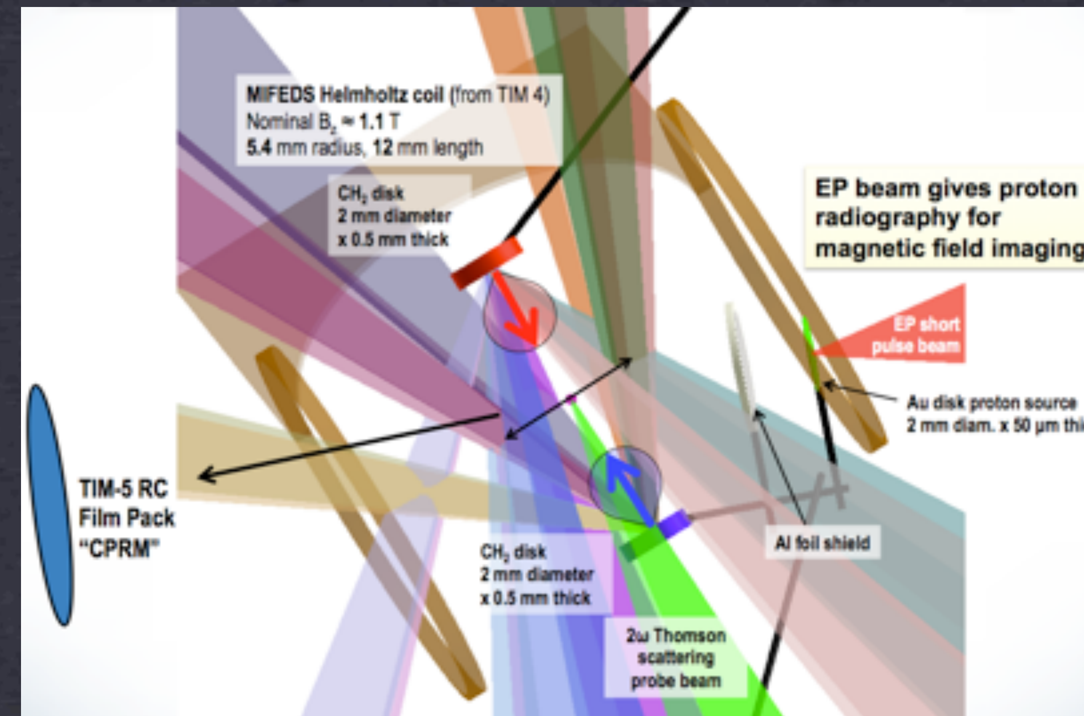
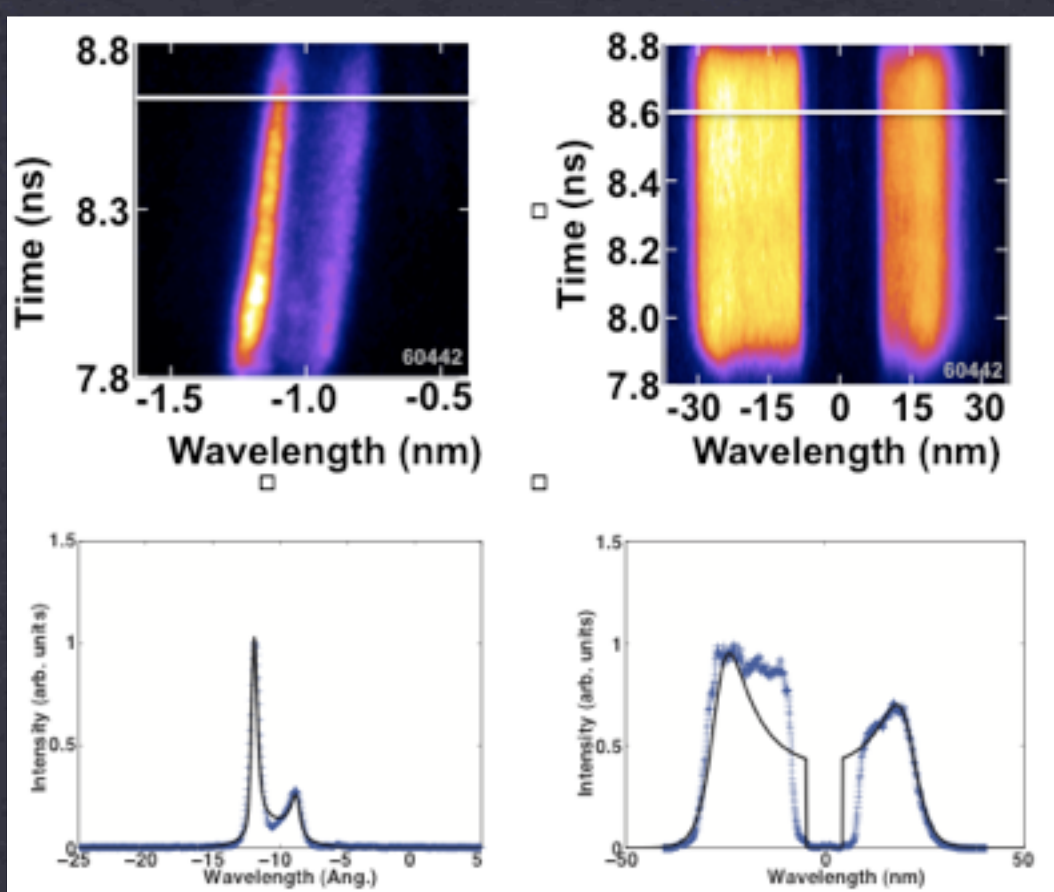
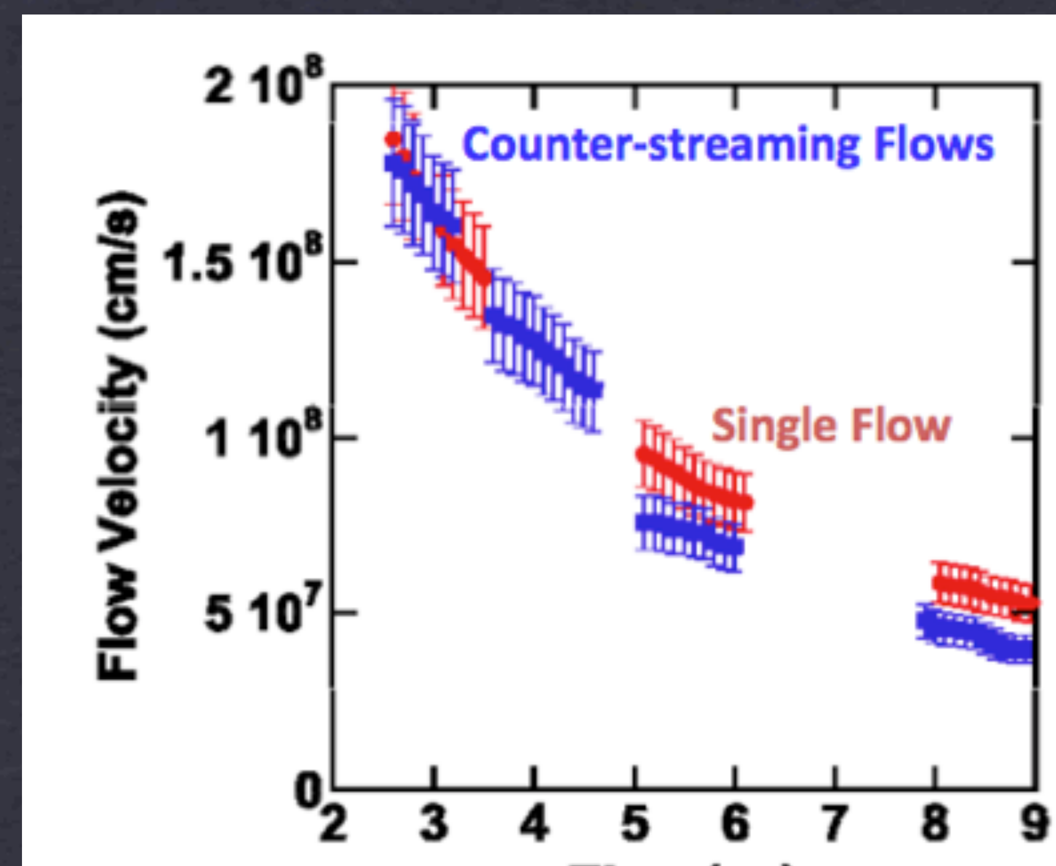
Experimental status:

Several successful campaigns at Omega and EP to test the setup and field the diagnostics.



Thomson scattering operational, giving plasma conditions in single vs double foil run

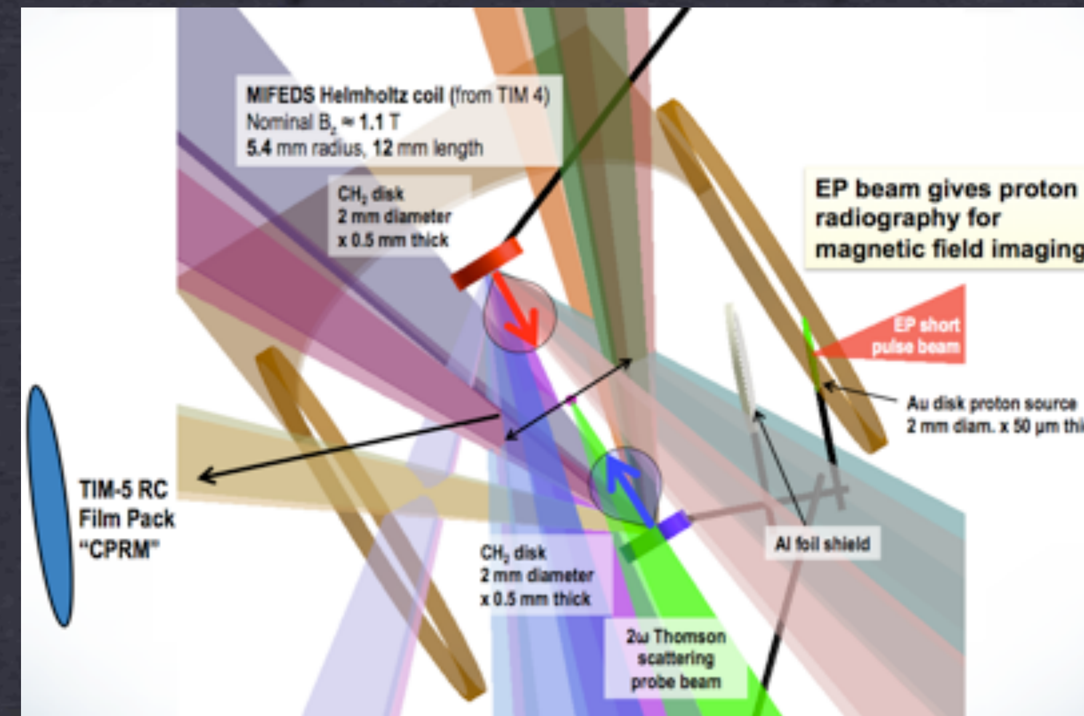




Ross et al (2012)

Colliding beam experiments on Omega Laser

ACSEL collaboration (Astrophysical Collisionless Shock Experiments with Lasers)



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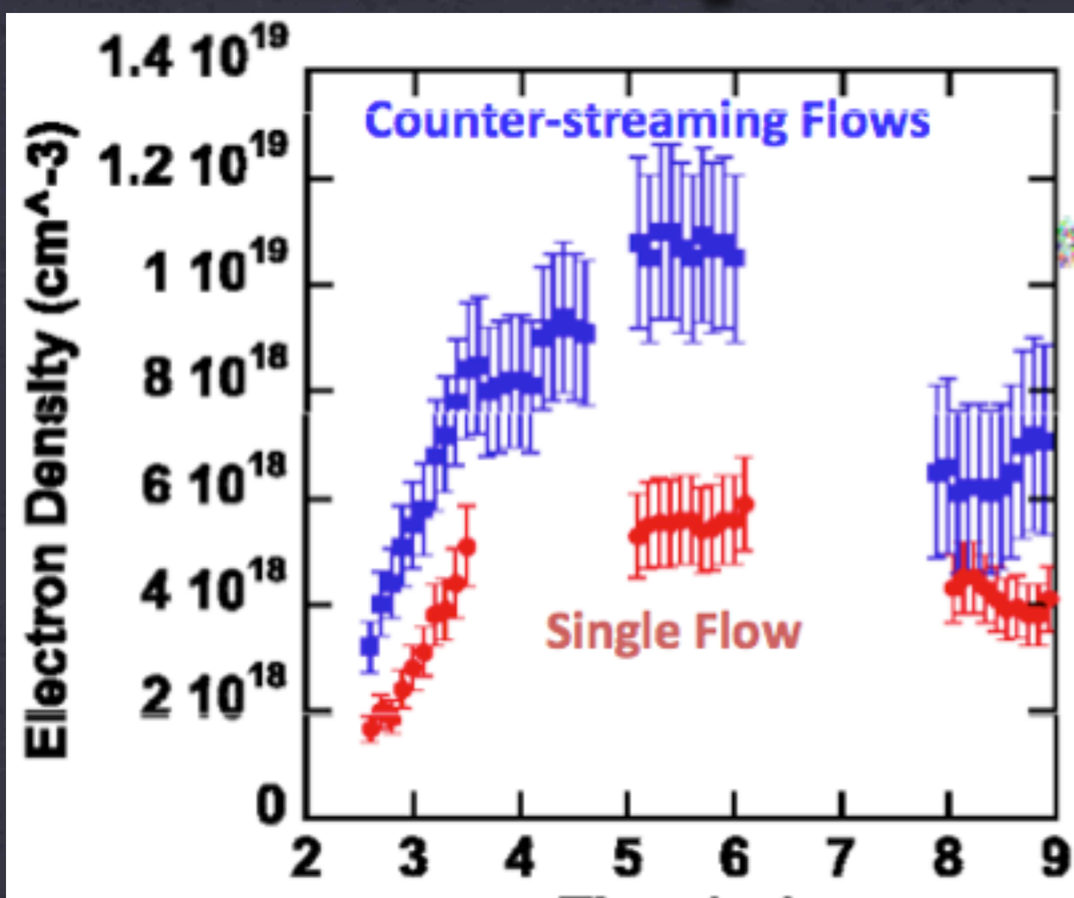
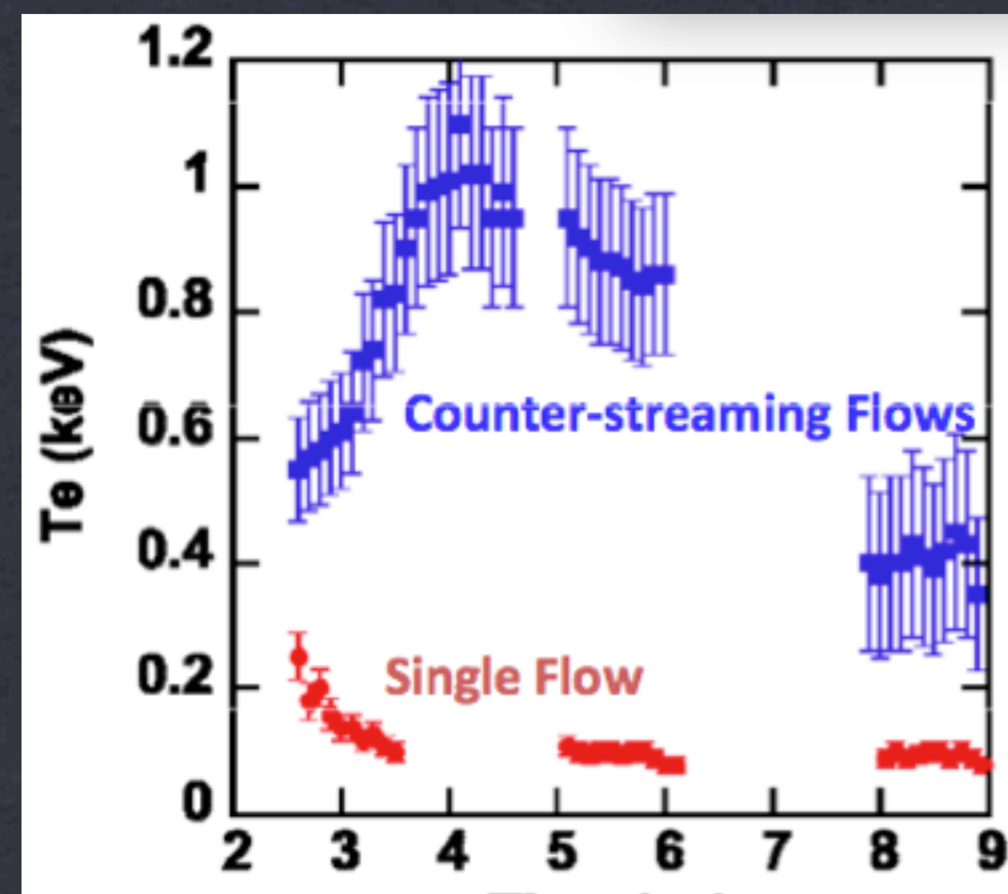


Ross et al (2012)

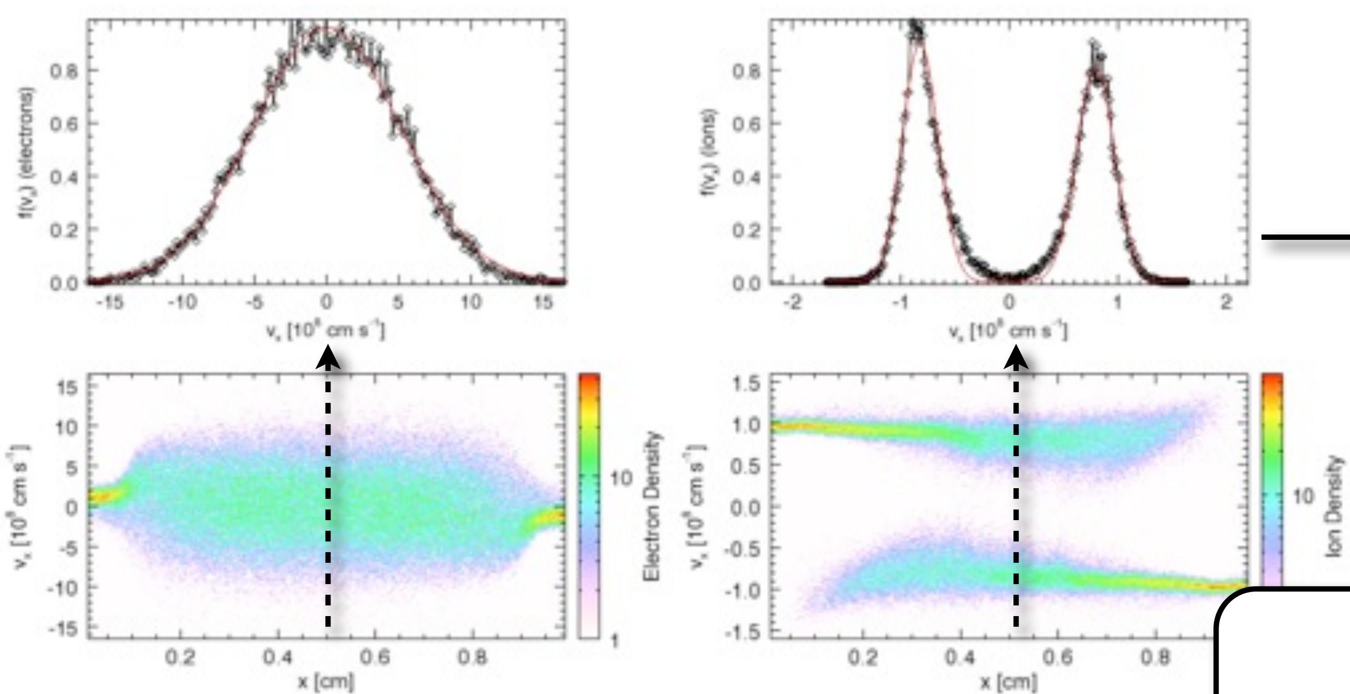


Ross et al (2012)

Plasma distribution functions and temperature from simulations

Electrons
T ~ 150 eV

Ions
T_I ~ 285 eV / T_2 ~ 330 eV

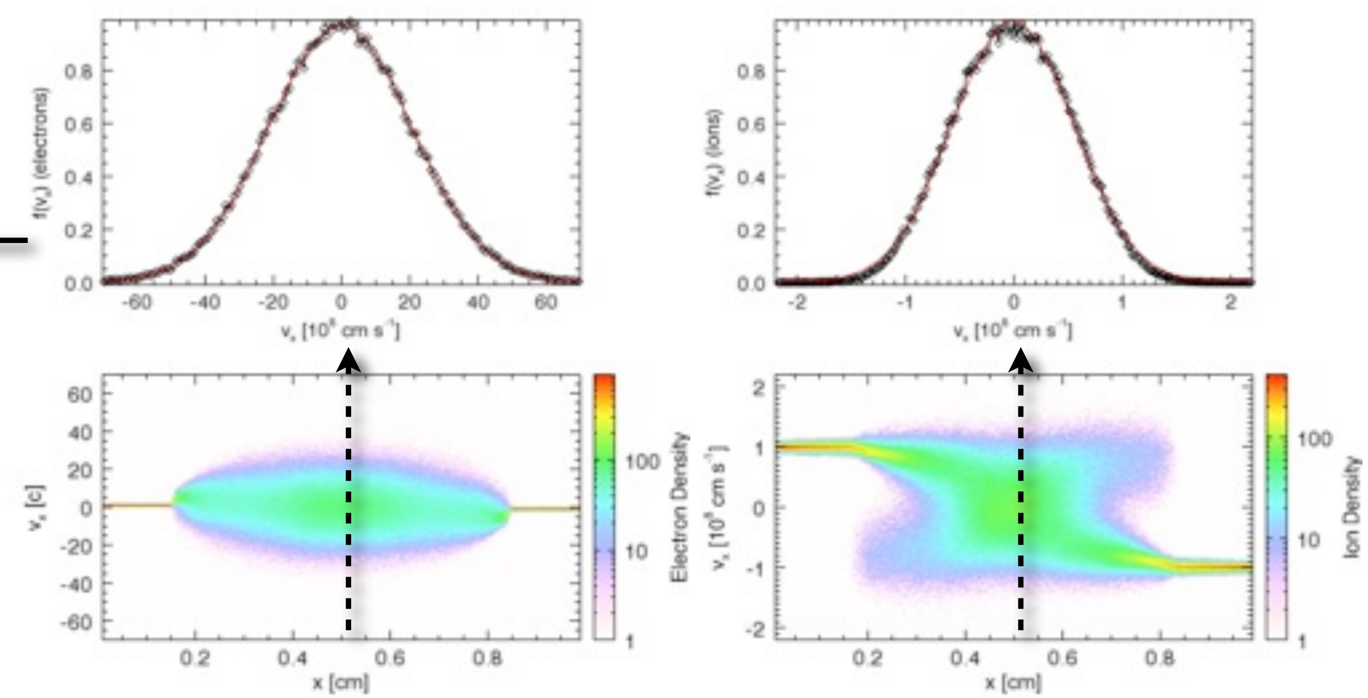


Unmagnetized
$n \sim 10^{18}$ cm^{-3}

Synthetic Thomson scattering diagnostic

Electrons
T ~ 2500 eV

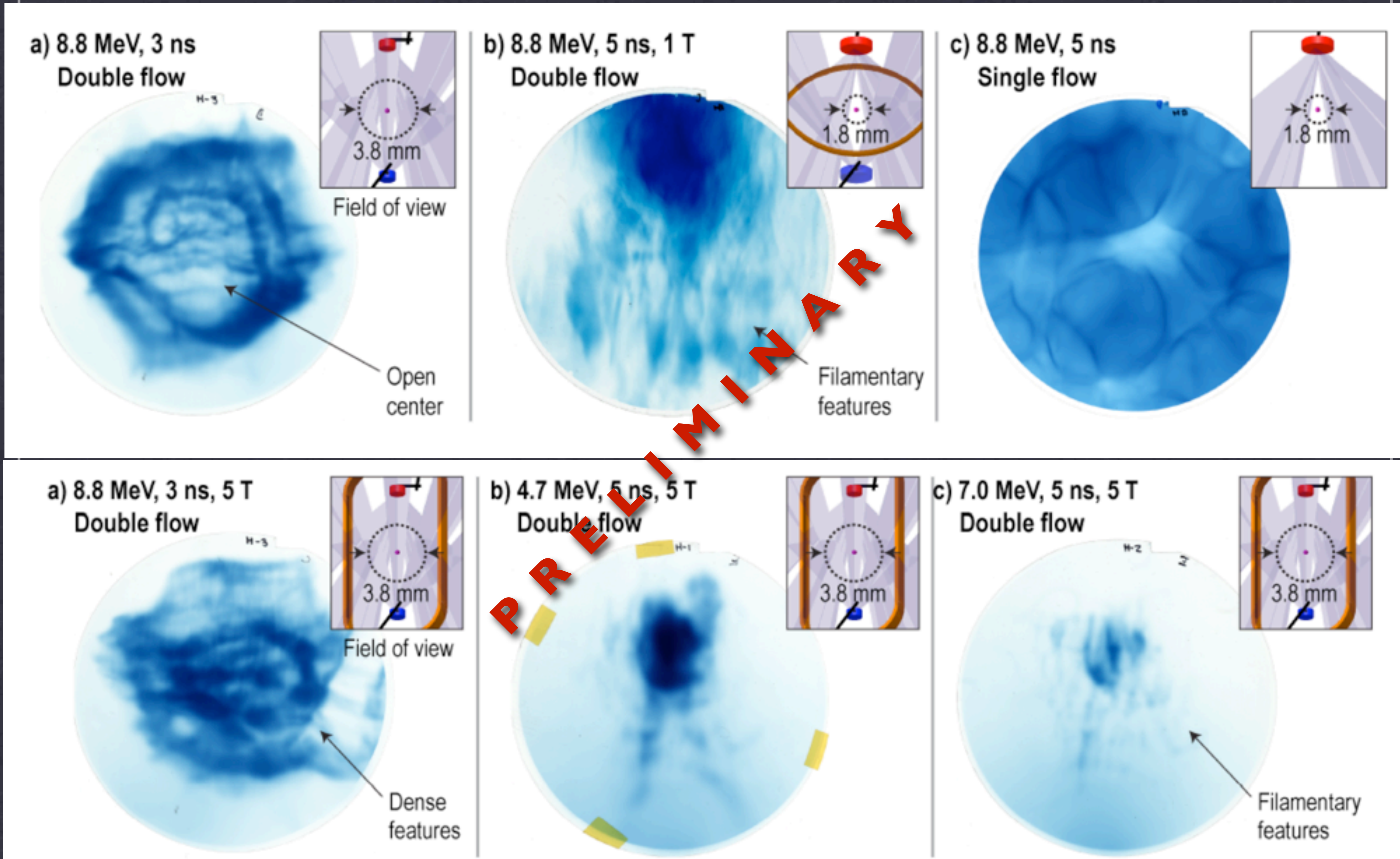
Ions
T_I ~ 3240 eV



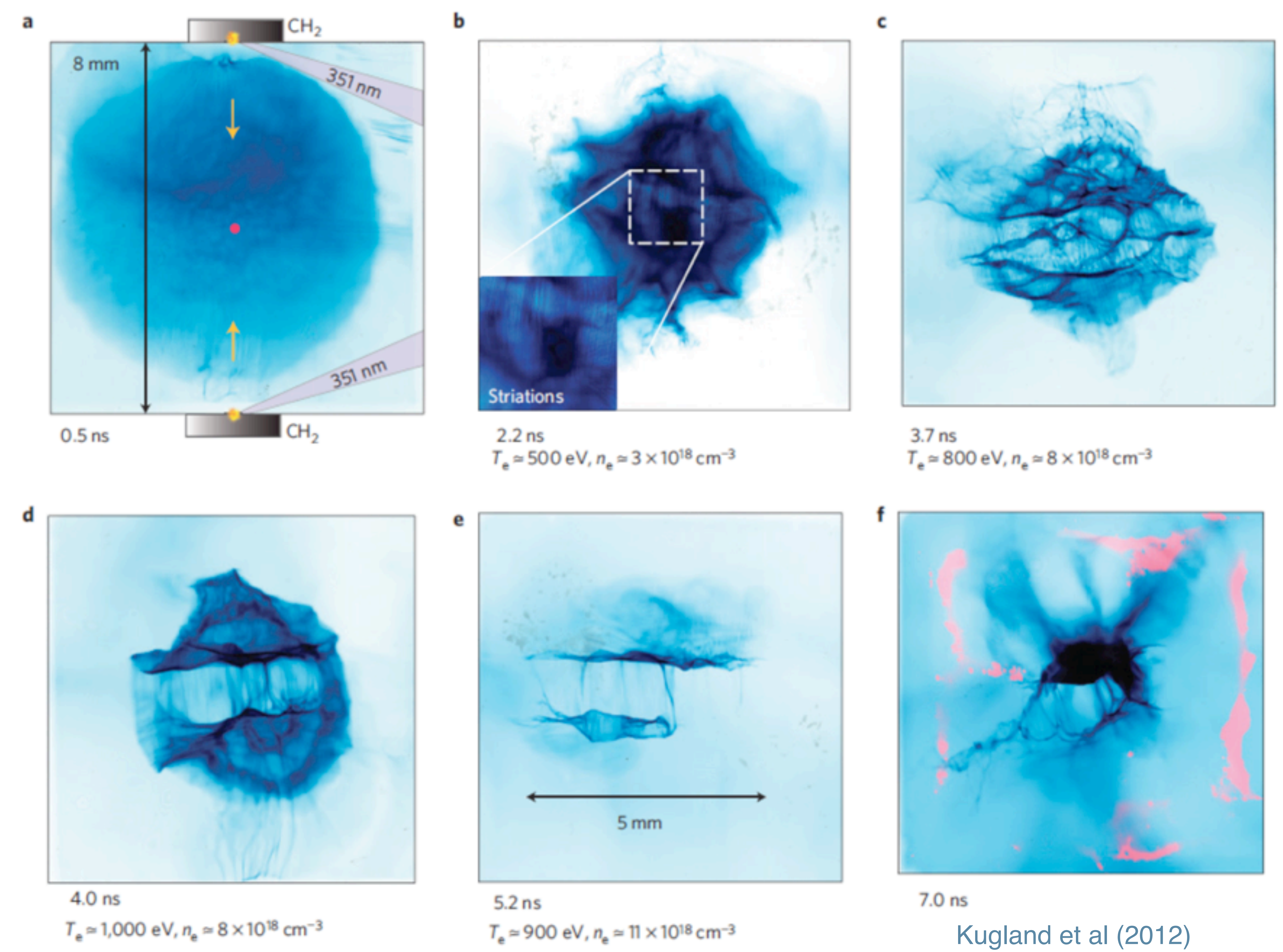
Synthetic Thomson scattering diagnostic

Unmagnetized
$n \sim 5 \times 10^{19}$ cm^{-3}

Experimental results: Joint Shots



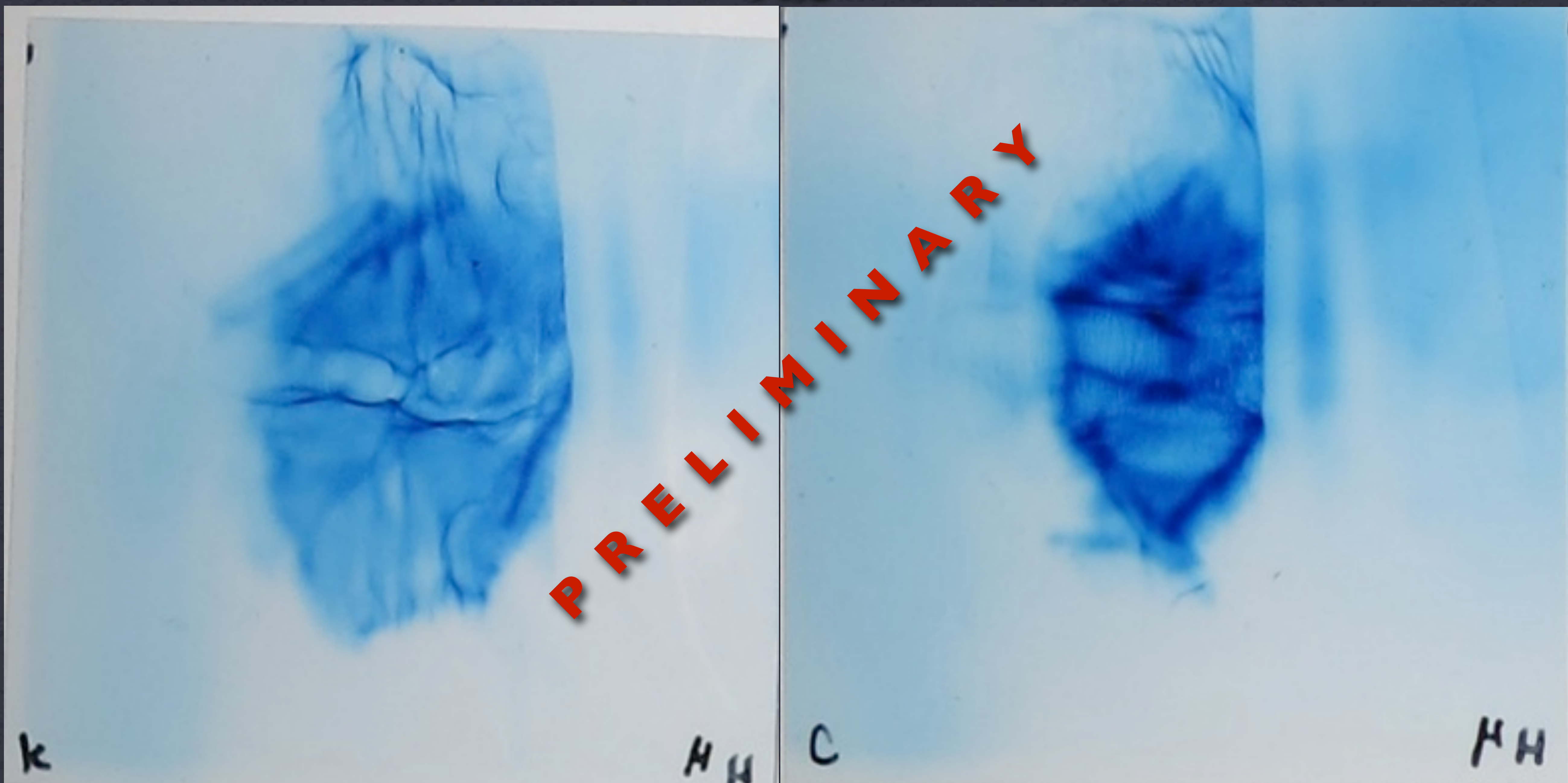
Experimental results: EP Shots   Planar structures emerging



Kugland et al (2012)

Experimental results: EP Shots with MIFEDS

4 ns



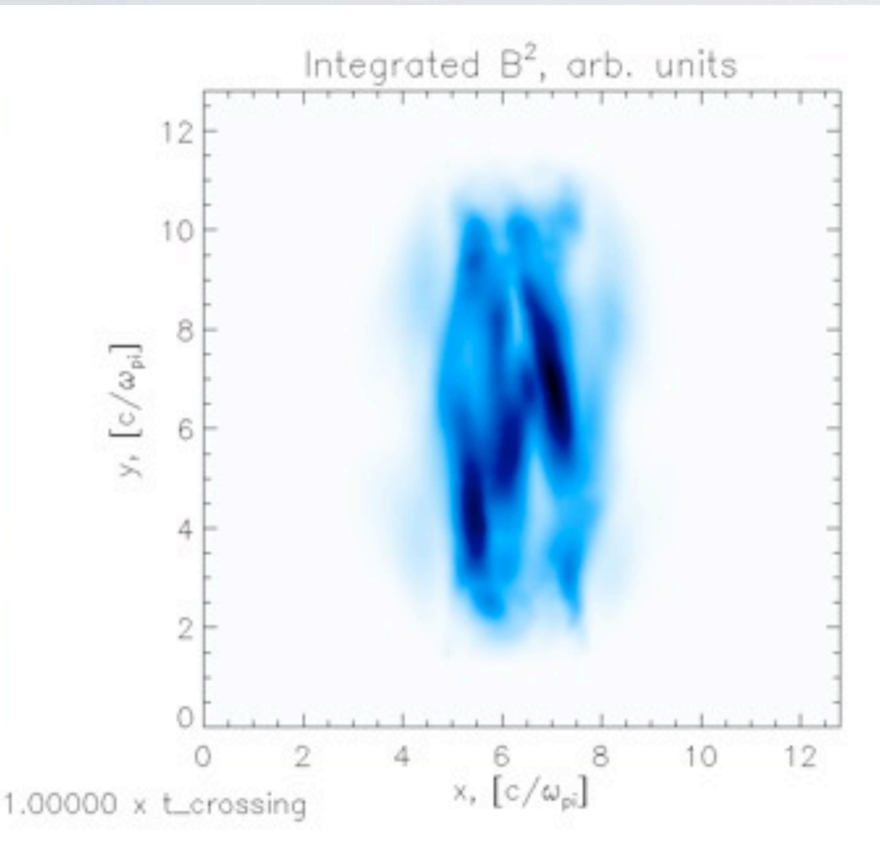
B=0

B=10 T

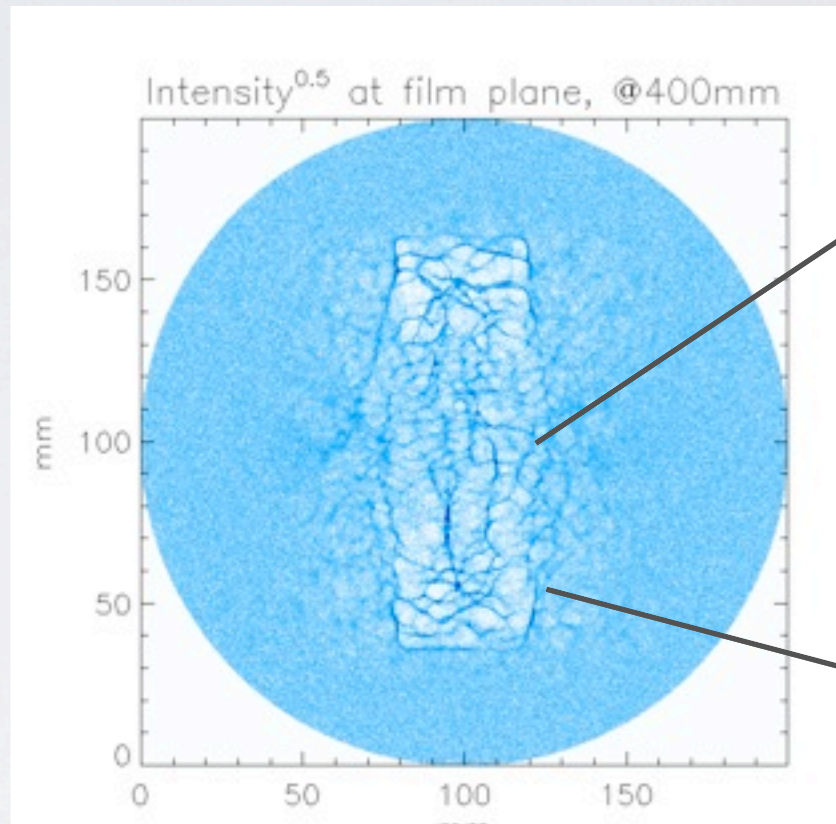
“Butterfly” pattern persisting

Possible interpretations of the data

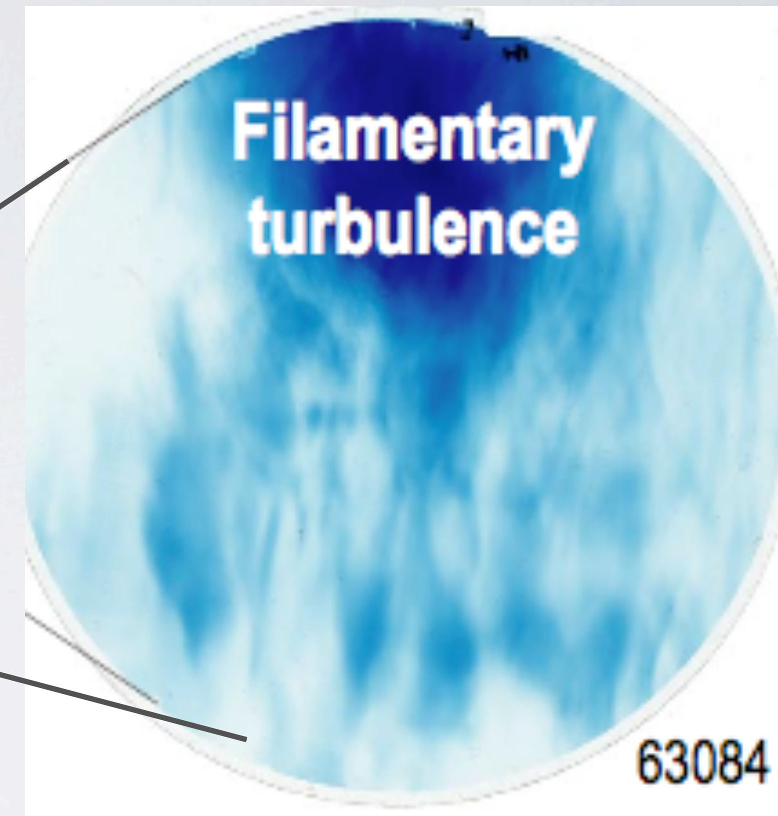
At late times, the Weibel instability creates filamentary magnetic fields, and this is reflected in filaments in proton signal. We confirmed that these filaments are mainly due to self-generated magnetic fields.



Simulation
B field energy



Simulated
proton signal



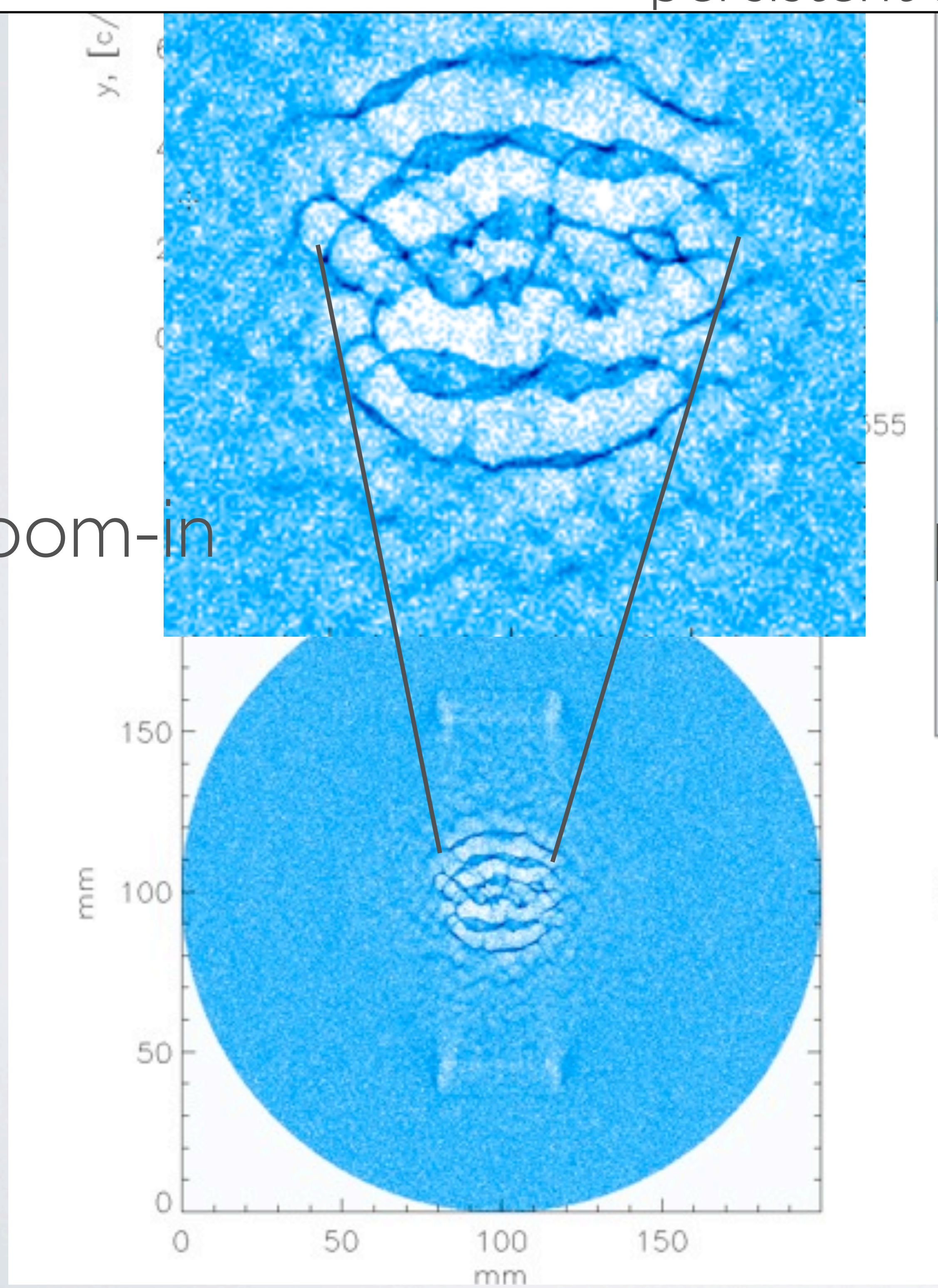
Proton imaging
data, joint shots

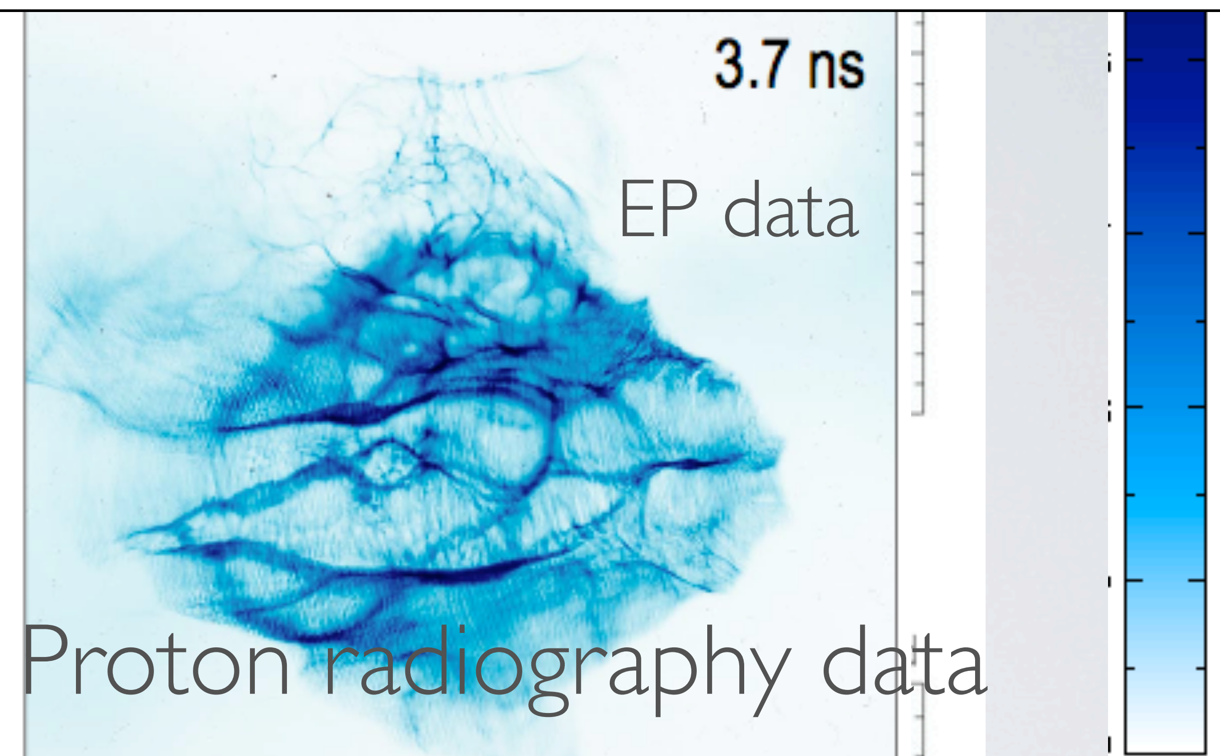
We have tentative evidence for filamentation appearing in joint shots. We do not understand why we do not see same filamentation in EP shots. This modeling is currently underway.

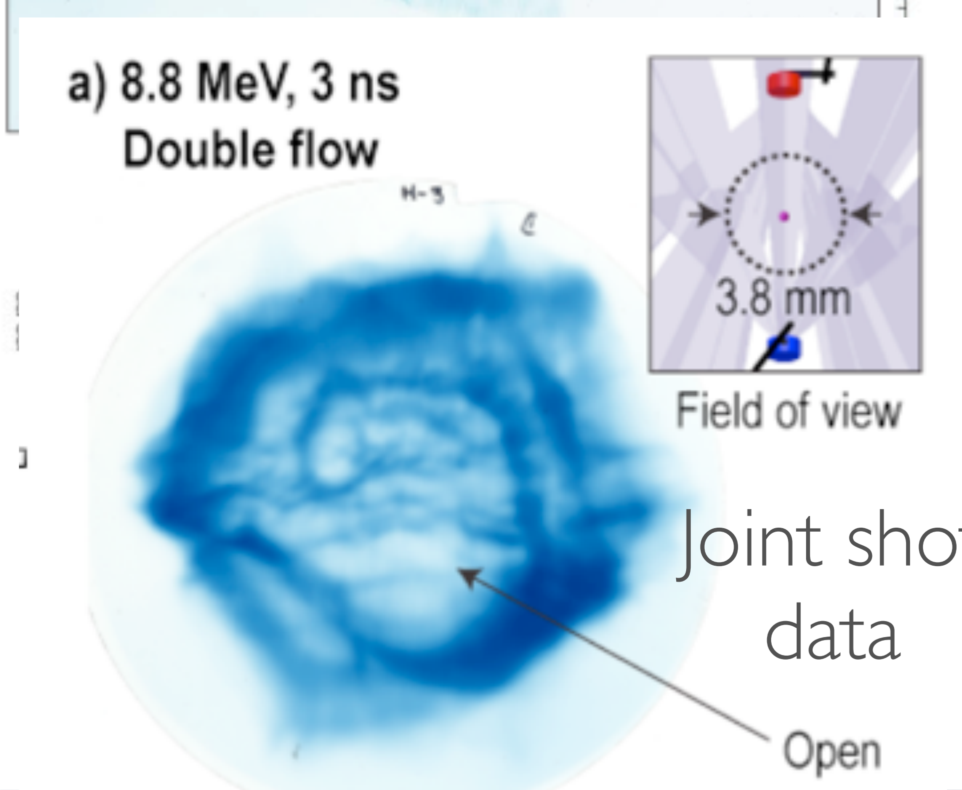
Possible interpretations of the data

1) At early times horizontal structures could be due to electrostatic transient fields; This is consistend with early times in Joint shots.

2) Advected fields from Biermann battery at late times could cause persistent structures







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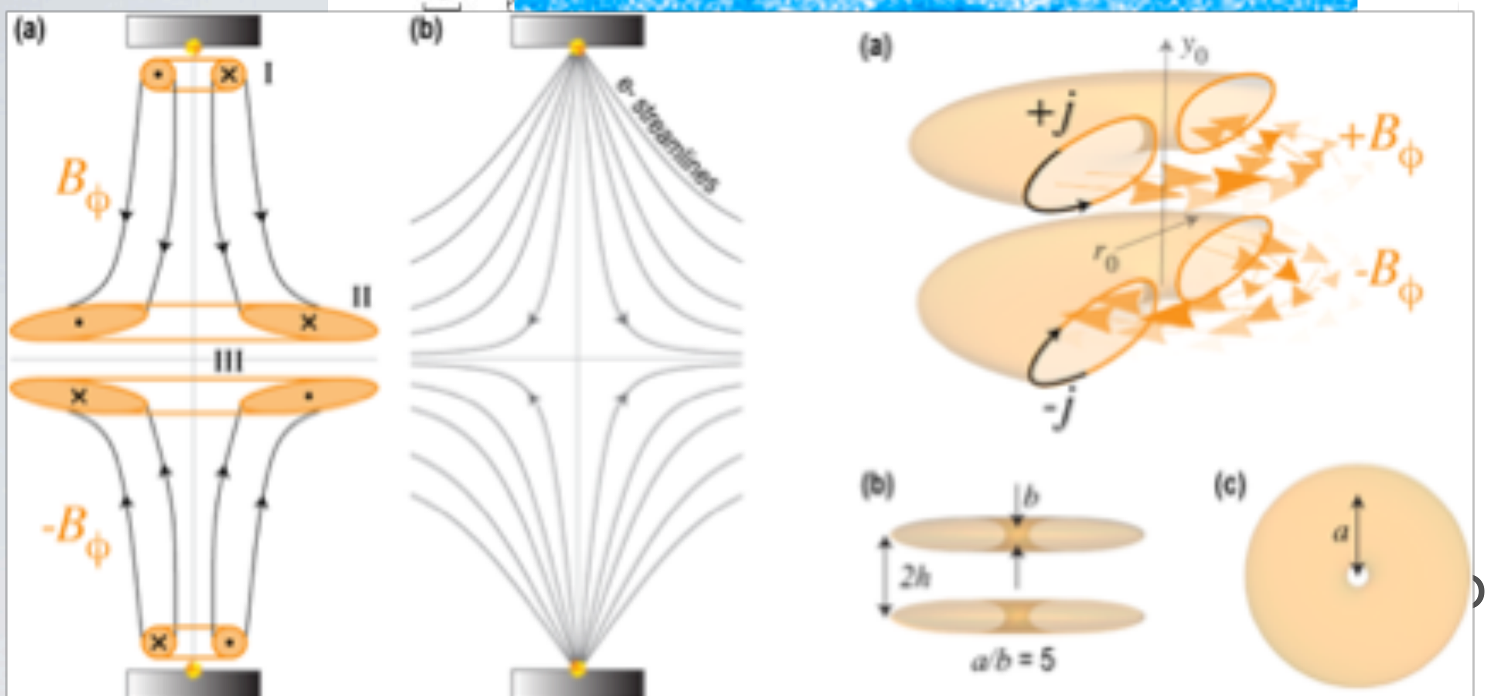
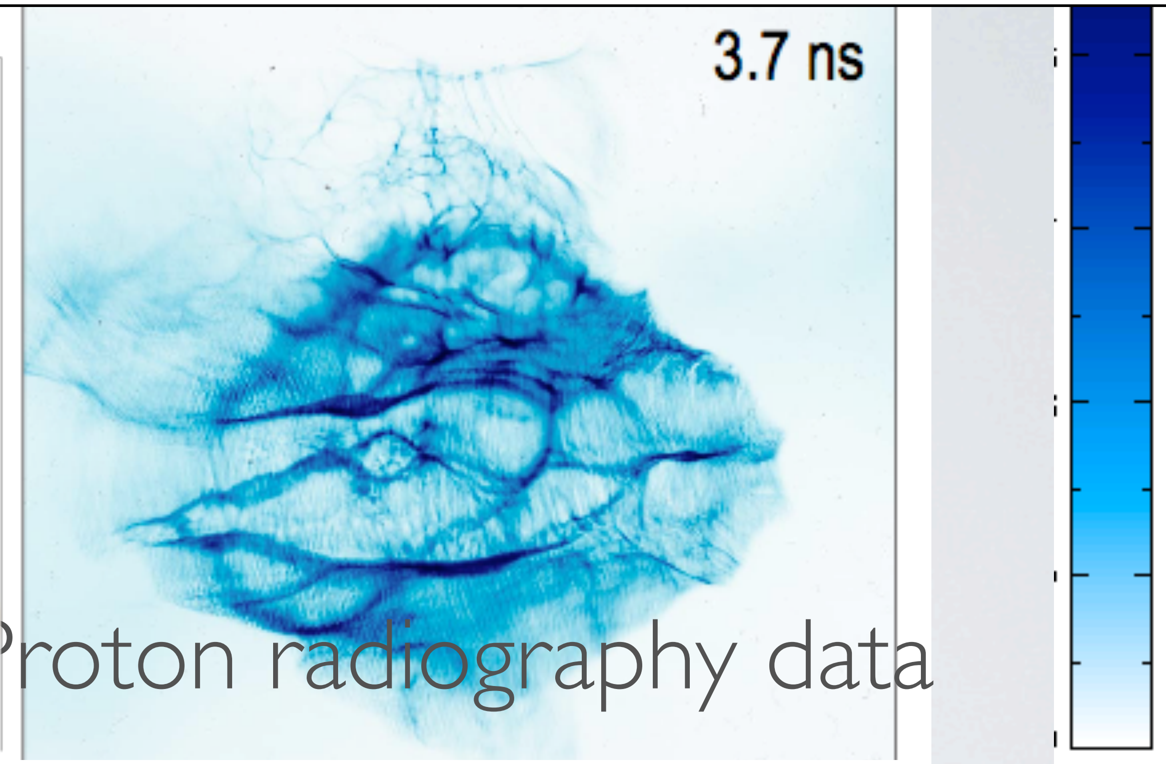
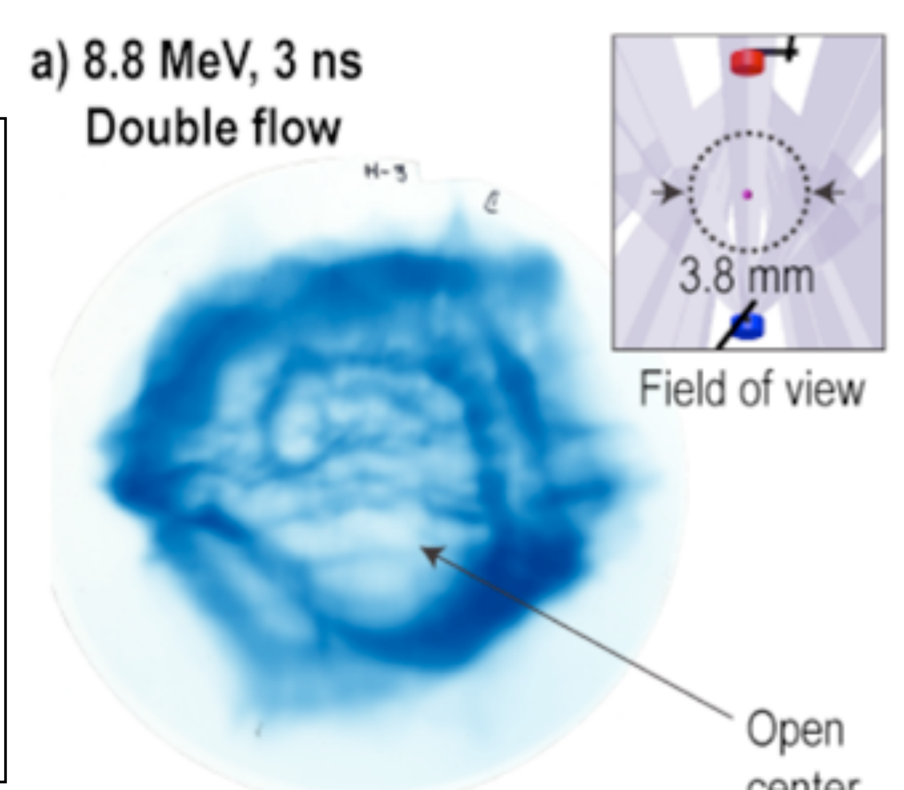


Ryutov 2013



Proton radiography data



Persistent features are observed only on EP shots -- could it be because the laser is creating stronger Biermann fields on EP? Spot size is smaller than on Omega, and no phase plates are used

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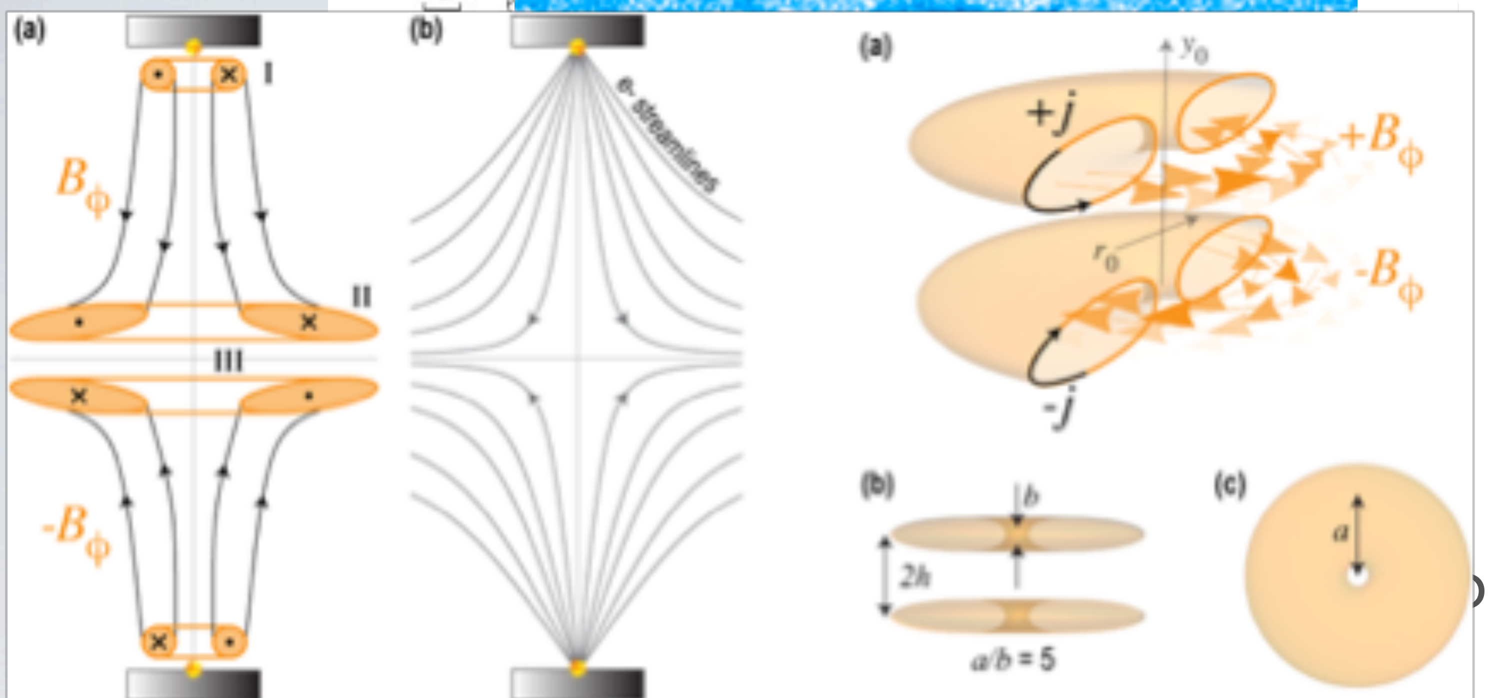

Ryutov 2013

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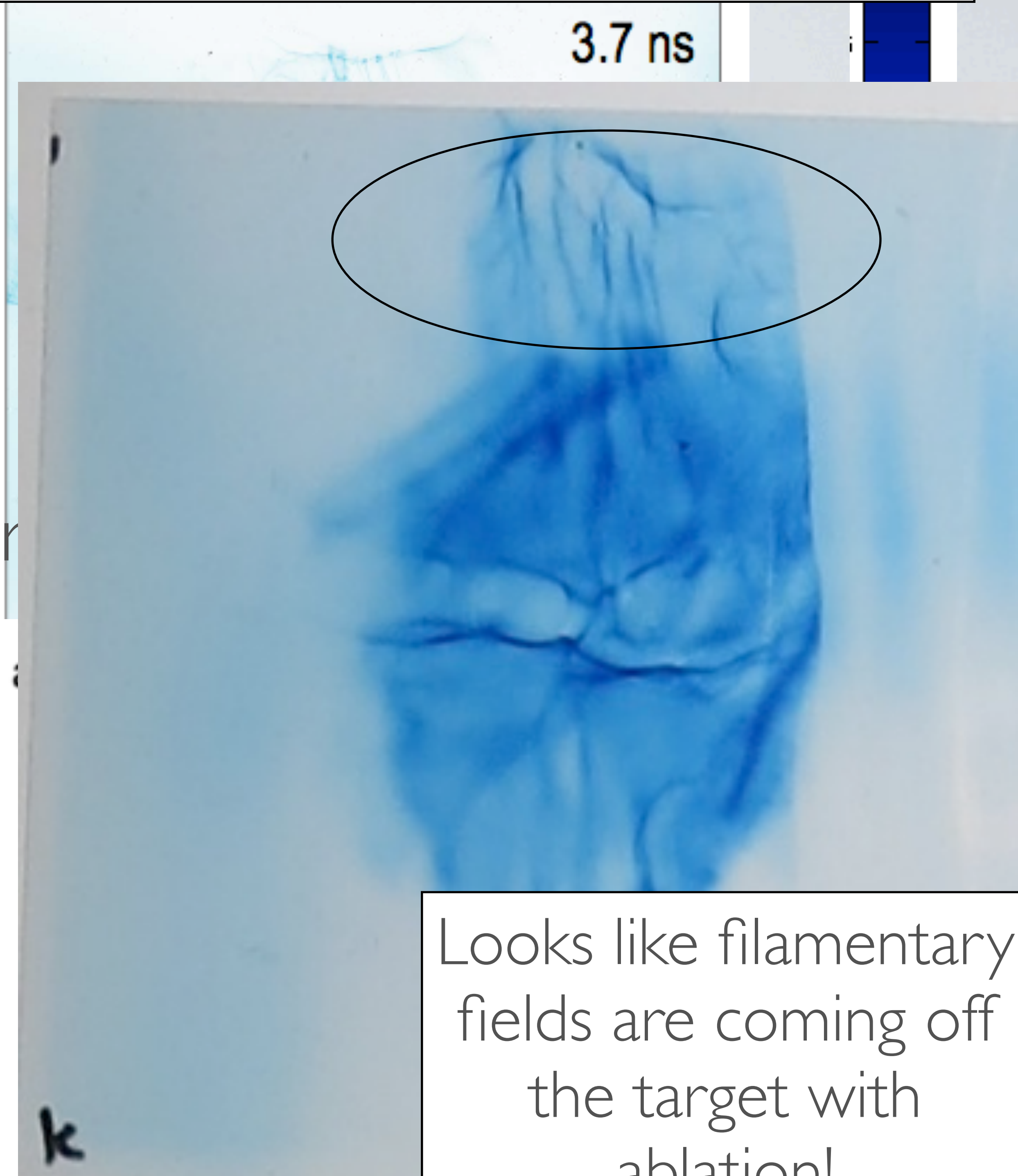

Looks like filamentary fields are coming off the target with ablation!

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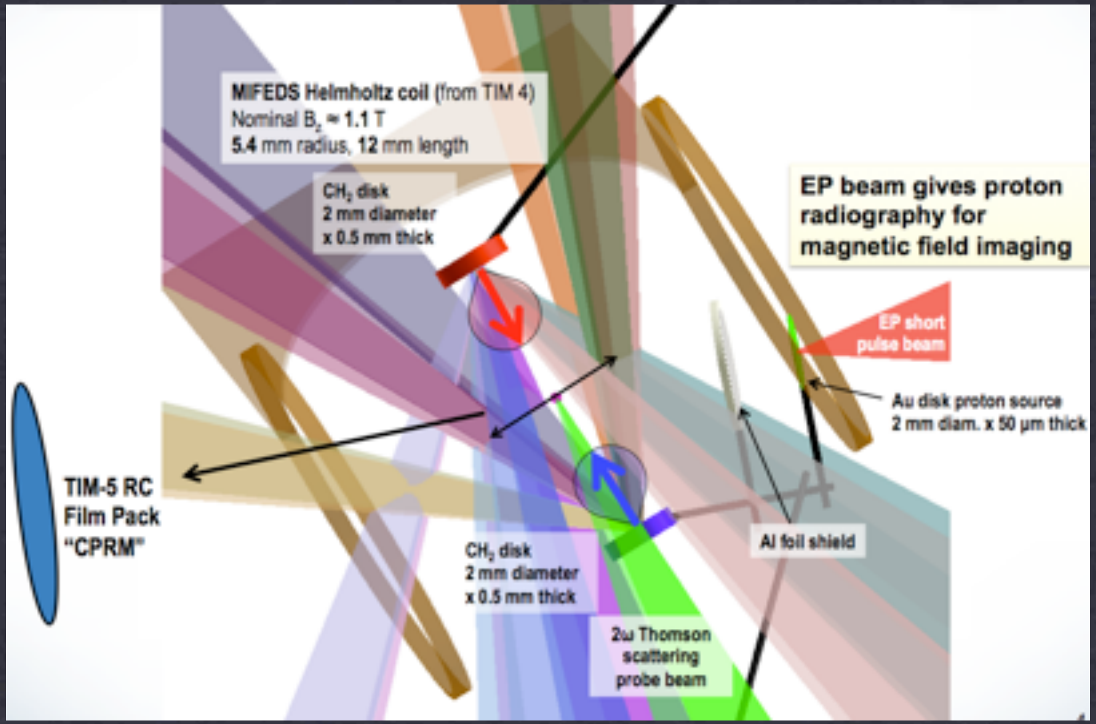

Current efforts:

Understanding Thomson and radiography signals using simulated diagnostics.

Magnetic effects: 1-5T field is too weak to show significant difference in Thomson diagnostics. Most likely the interaction was still filamentation. Working to increase the field at the interaction region. Thomson with 10T will come in May

Magnetic field penetration into the beam is not confirmed. It is possible that the field is excluded from the ablated plasma. Magnetic field along the flow is still possible in that case.

Need magnetic diagnostics in plasma.

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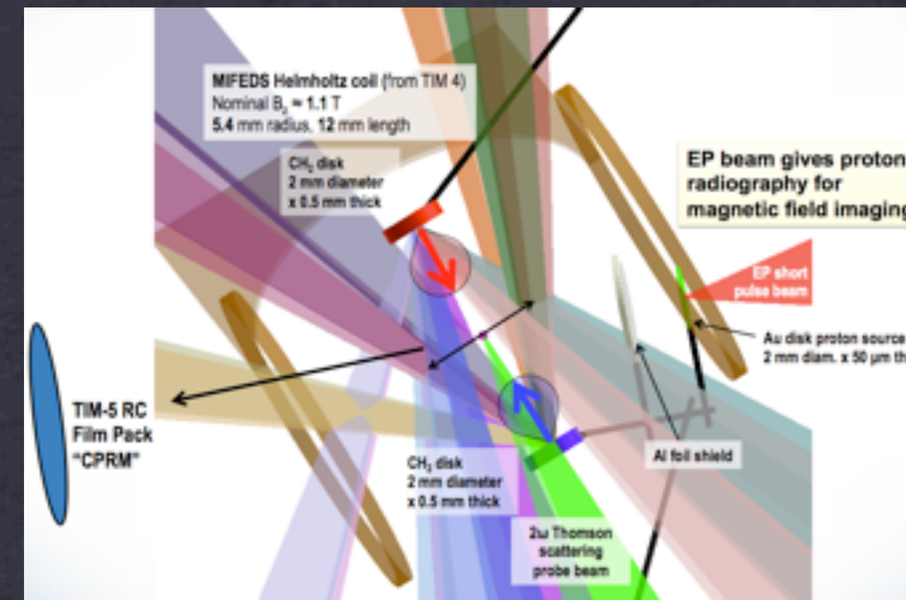
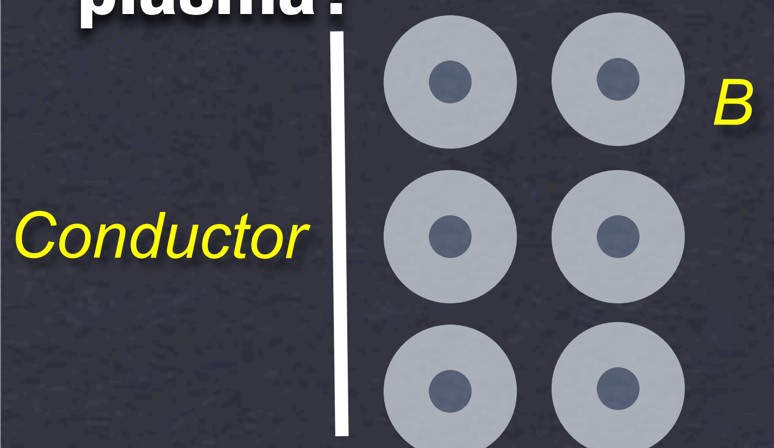
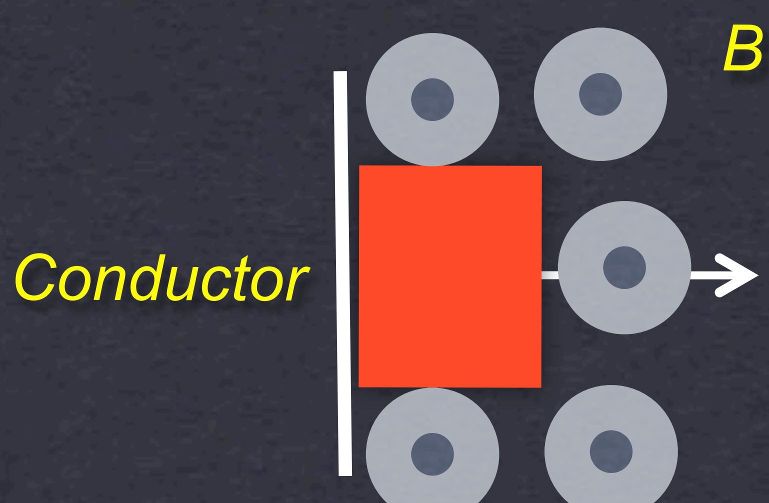


If plasma comes off a conductor, it will exclude the field. Ablation front into a plastic will ionize it and cause the available flux to be confined to the small ablated thickness. Does B field get in plasma?



What about Biermann (self-generated) fields?

Work in progress



Pre-plasma idea may be interesting.

In FY14 will also try parallel fields.

Conclusions

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

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

We need to confirm these theoretical/simulation ideas with data. Astrophysical data is typically ambiguous, so more controlled experiments are crucial.

Several laser experiments are currently being done, and collisionless conditions relevant for astrophysical scaling are now accessible at HED laser facilities.

Preliminary evidence suggests Weibel filamentation is observed at late times. NIF conditions will provide enough experimental length to see the shock form.

Interesting synergy with reconnection experiments -- you should see the development of shocks!