Nonlinear fast wave propagation near a 2D magnetic X-point: Oscillatory Reconnection

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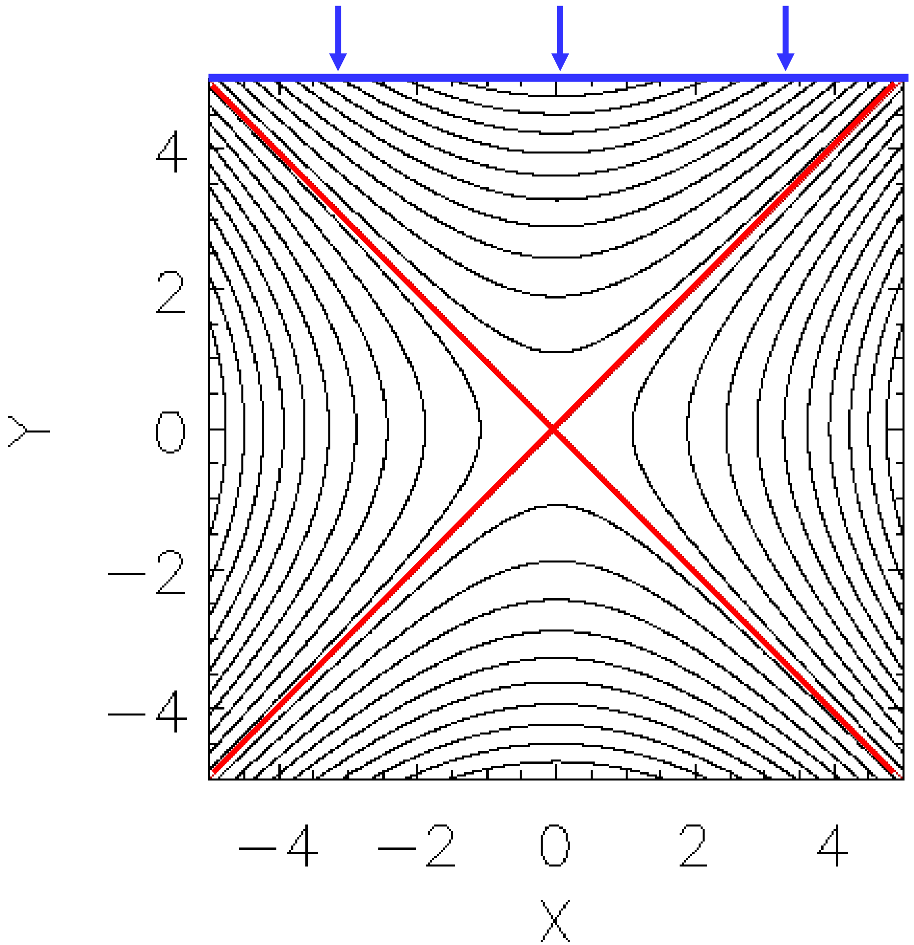
[linear] *McLaughlin & Hood (2004) A&A, **420**, 1129*
[nonlinear] *McLaughlin, De Moortel, Hood & Brady (2009) A&A, **493**, 227*

General Idea

- Consider wave propagation near to equilibrium magnetic field – simple 2D X-point.



$$\mathbf{B}_0 = \frac{B_0}{L}(y, x, 0)$$

MHD Equations

Solve with **LARE2D** code

$$\rho\left[\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\mathbf{v}\right]=-\nabla p+(\nabla\times\mathbf{B})\times\mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t}=\nabla\times(\mathbf{v}\times\mathbf{B})+\eta\nabla^2\mathbf{B}$$

$$\frac{\partial \rho}{\partial t}+(\mathbf{v}\cdot\nabla)\rho=-\rho\nabla\cdot\mathbf{v}$$

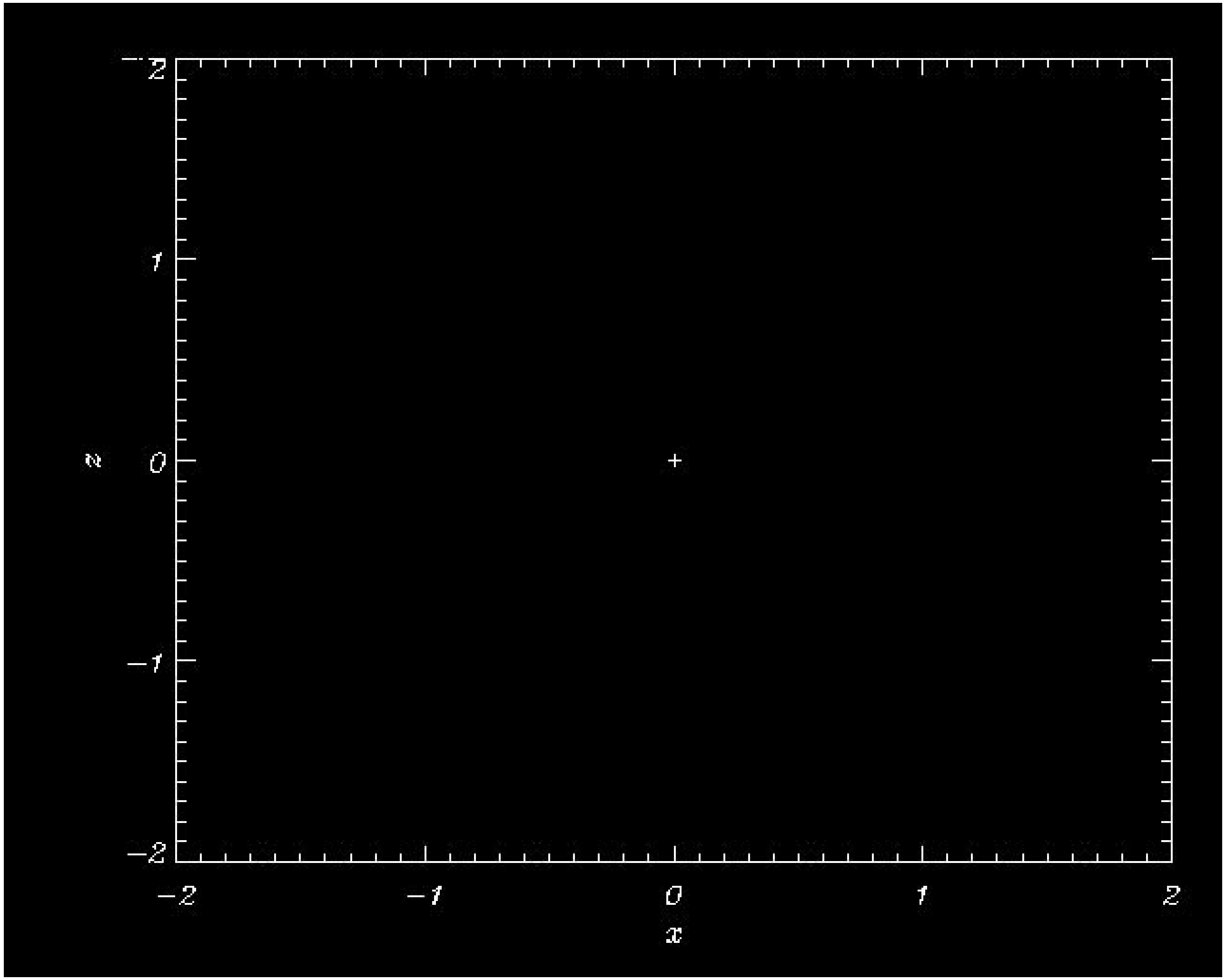
$$\frac{\partial \varepsilon}{\partial t}+(\mathbf{v}\cdot\nabla)\varepsilon=-\frac{P}{\rho}\nabla\cdot\mathbf{v}+\frac{\eta}{\rho}|\mathbf{j}|^2$$

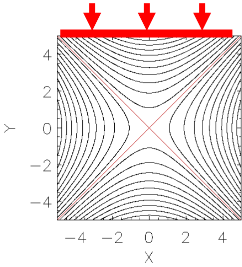
where $\varepsilon=\dfrac{P}{\rho(\gamma-1)}$

$$\gamma=5/3$$

$$\mathbf{B}_0=\nabla\times\mathbf{A}=\nabla A\times\hat{\mathbf{z}}$$

Linear, Cold Fast Wave (Numerical + WKB)





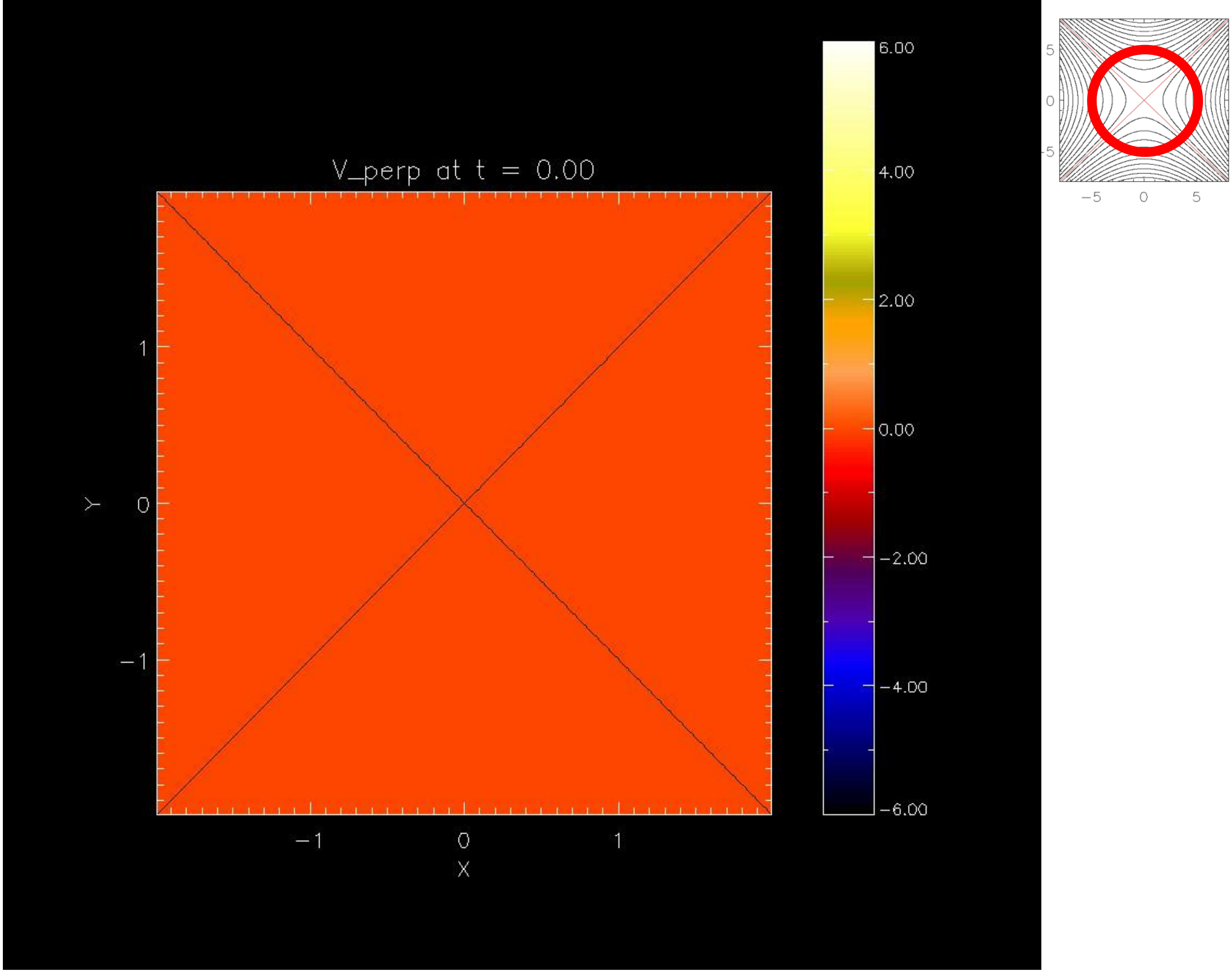
Extension to Nonlinear: Key questions

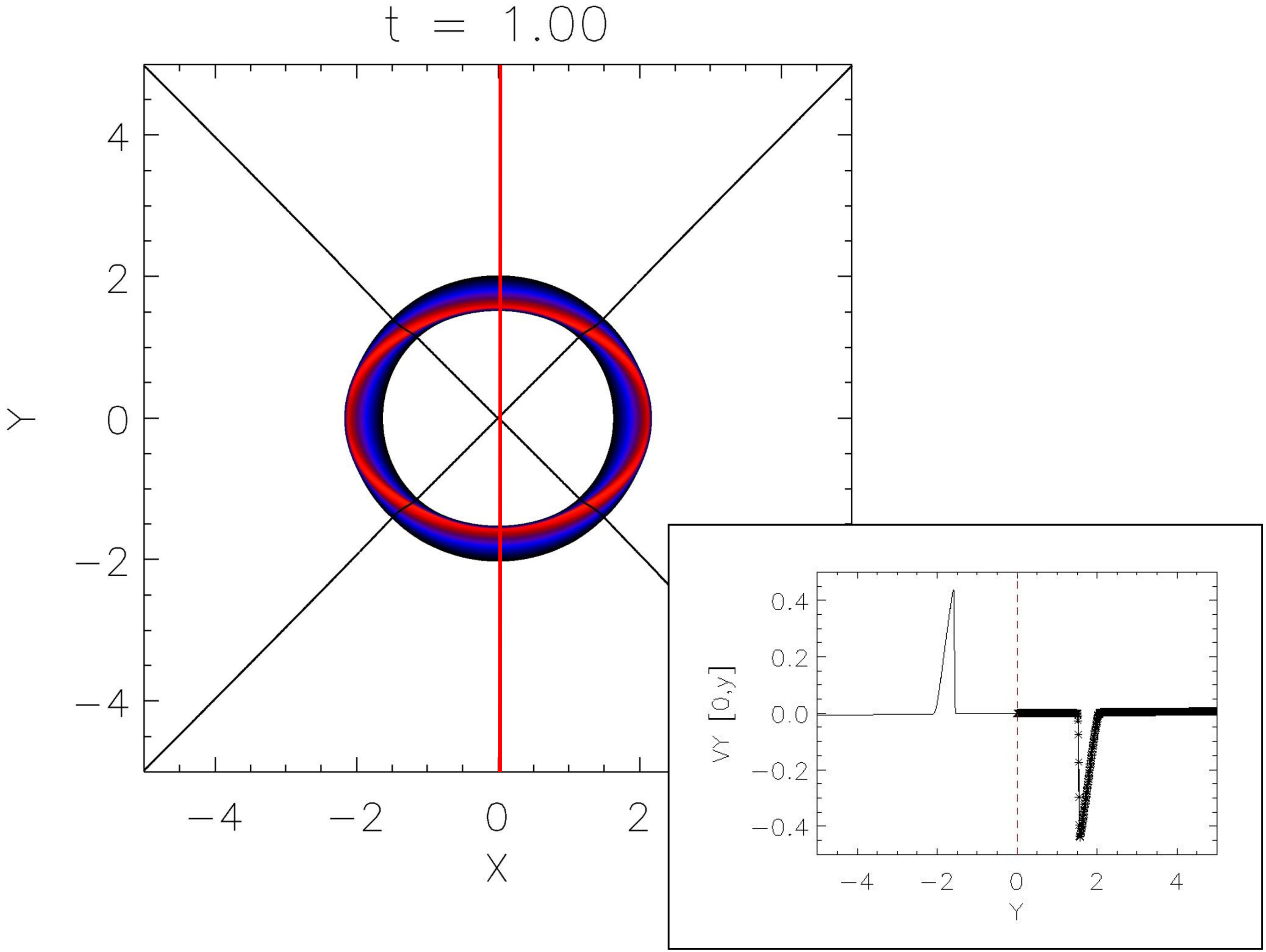
- *Now look at the properties and behaviour of nonlinear MHD waves in the neighbourhood of 2D null point.*

1) Does the fast wave now steepen to form shocks and can these now propagate across or escape the null?

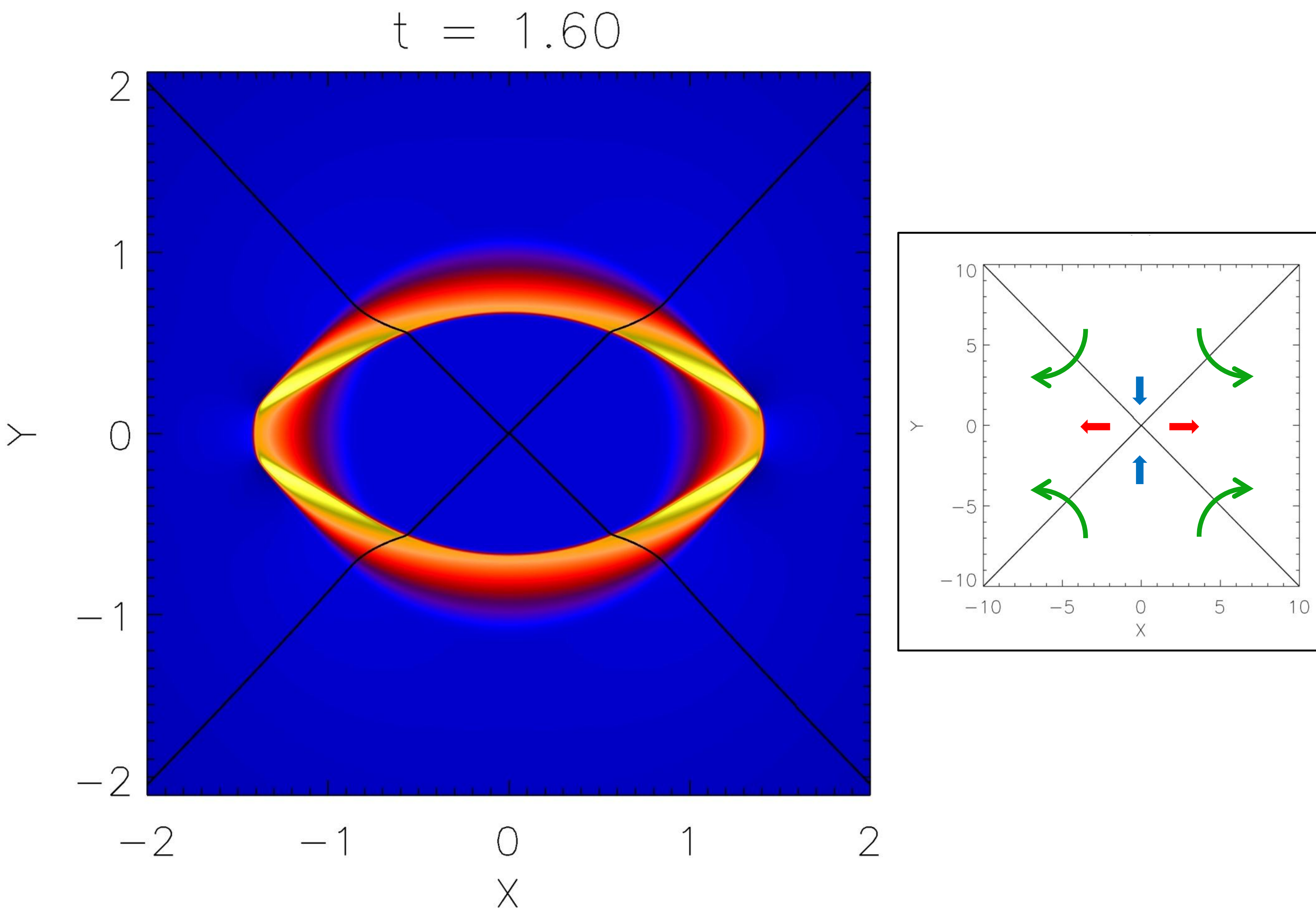
2) Can the refraction effect drag enough magnetic field into the null point to initiate X-point collapse or reconnection?

3) Has the rate of current density accumulation changed, and is the null still the preferential location of wave heating?

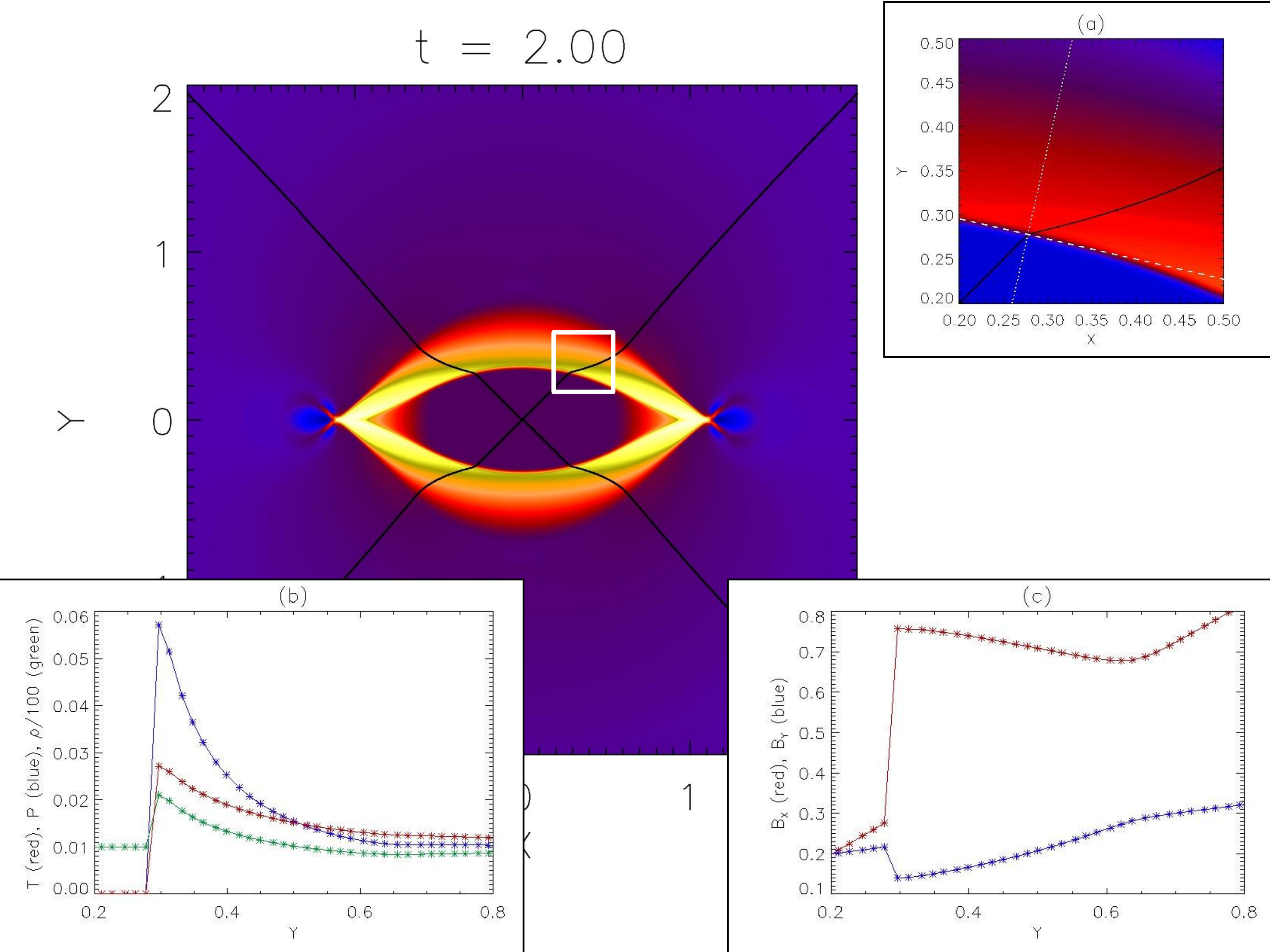

V_perp at t = 0.00
Y
X
1
0
−1
−1
0
1
6.00
4.00
2.00
0.00
−2.00
−4.00
−6.00
5
0
-5
−5
0
5

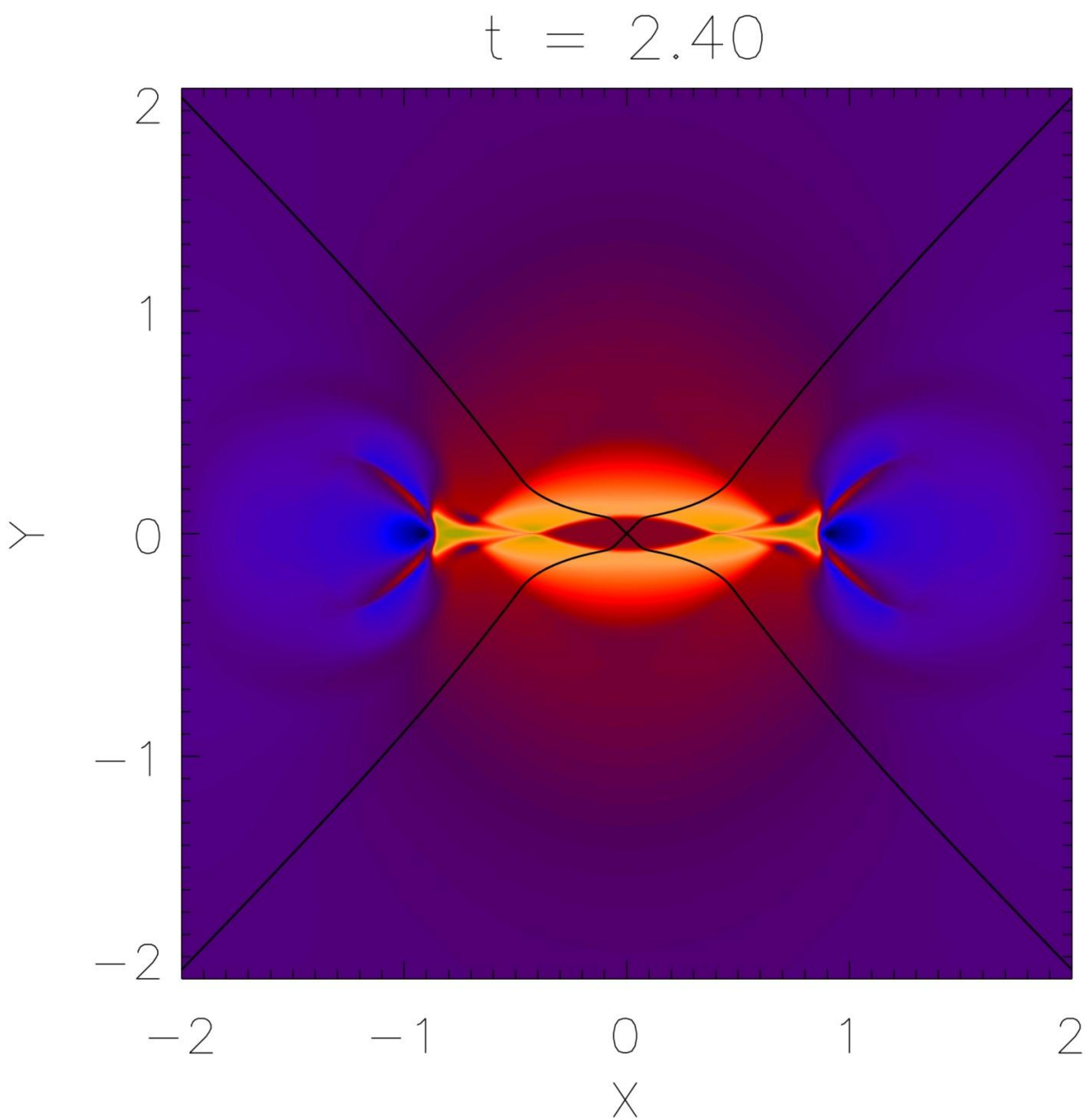


t = 1.00
Y
X
VY [0,y]
Y

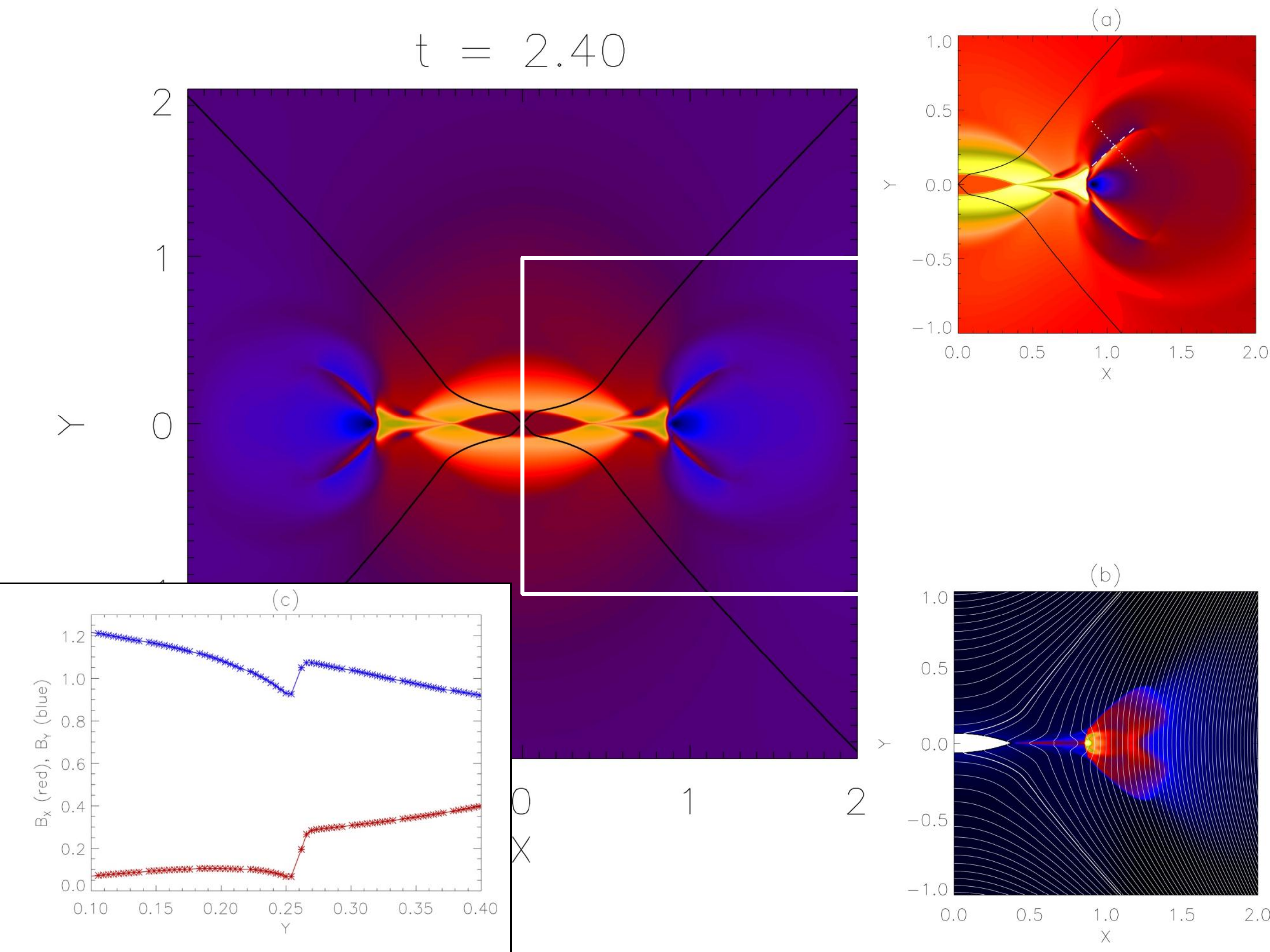


t = 1.60
2
1
0
−1
−2
Y
−2
−1
0
1
2
X
10
5
0
−5
−10
Y
−10
−5
0
5
10
X


t = 2.00
Y
X
(a)
(b)
T (red), P (blue), ρ/100 (green)
(c)
B_x (red), B_Y (blue)

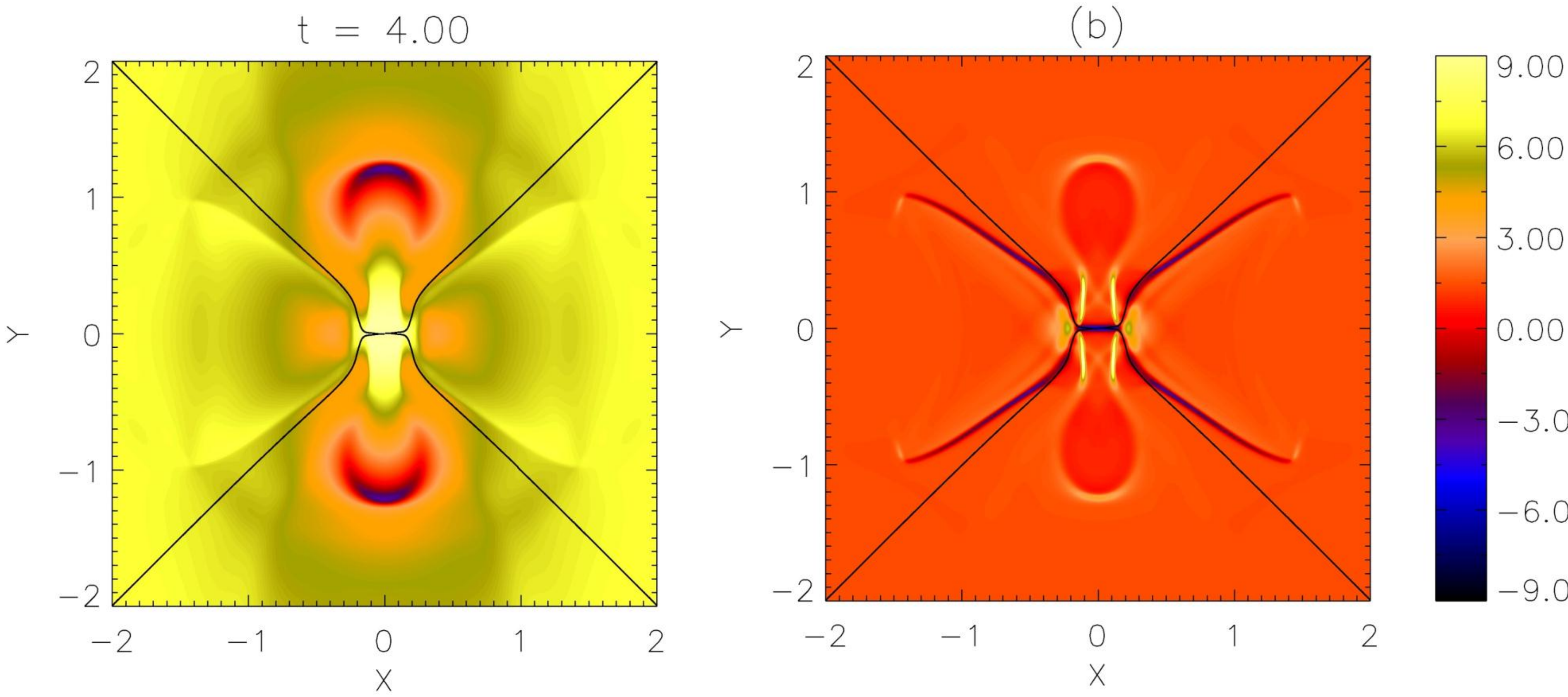


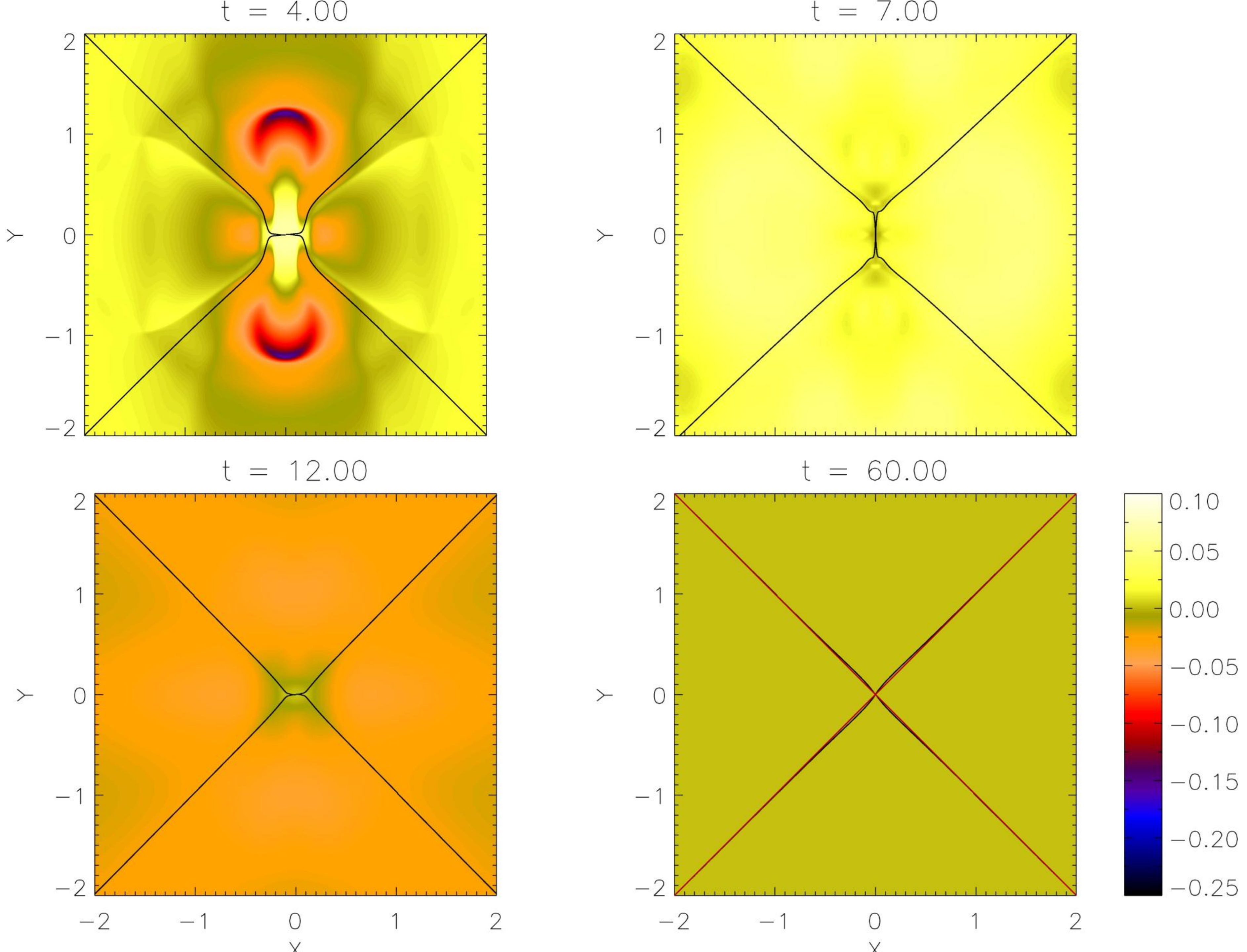
t = 2.40
Y
X
2
1
0
−1
−2
−2
−1
0
1
2



t = 2.40
Y
X
(a)
(b)
(c)
Bx (red), By (blue)

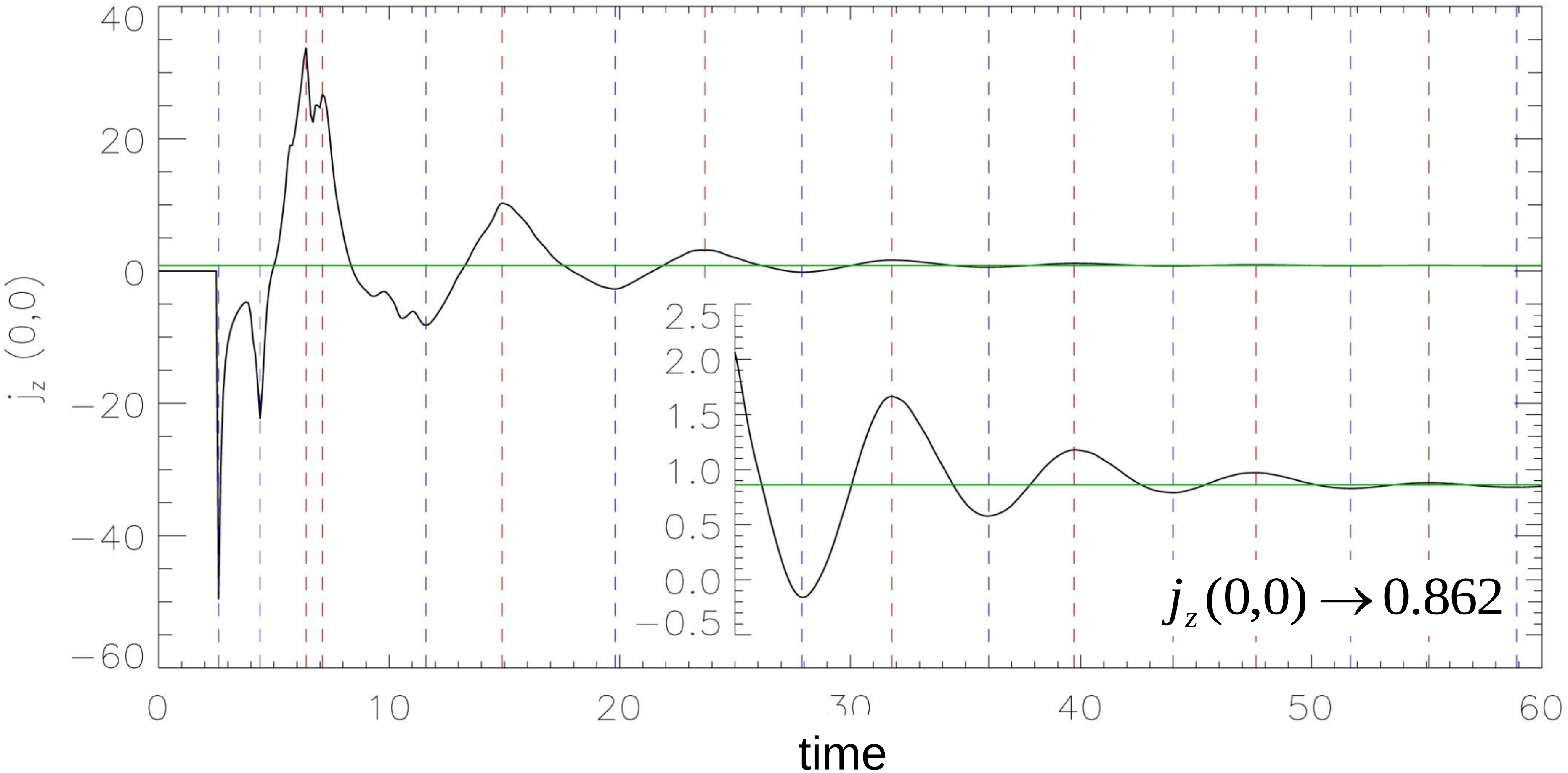
Build up of j_z





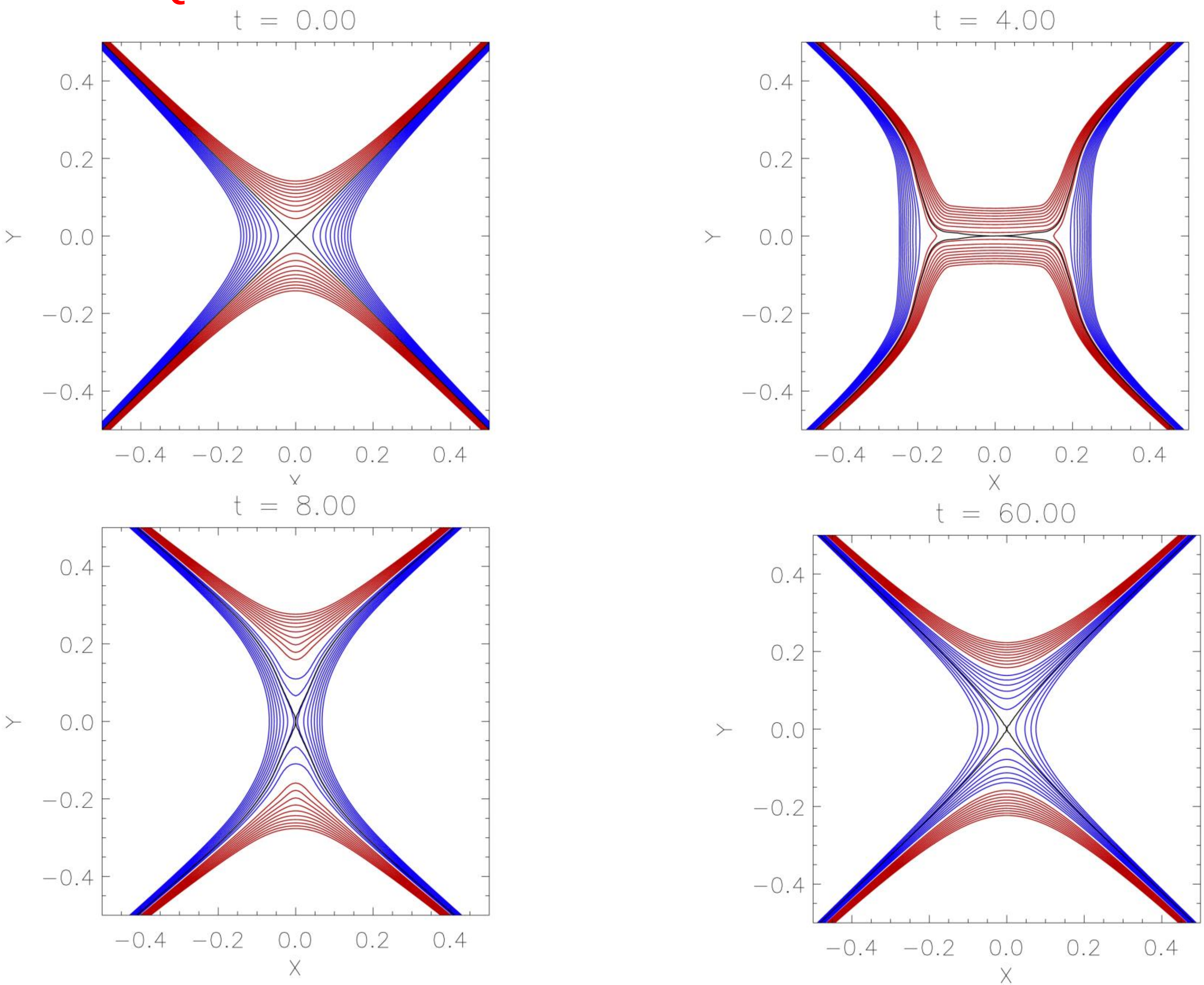
t = 4.00
t = 7.00
t = 12.00
t = 60.00
Y
X
−2
−1
0
1
2
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
−0.25

Evolution of j_z (0,0)



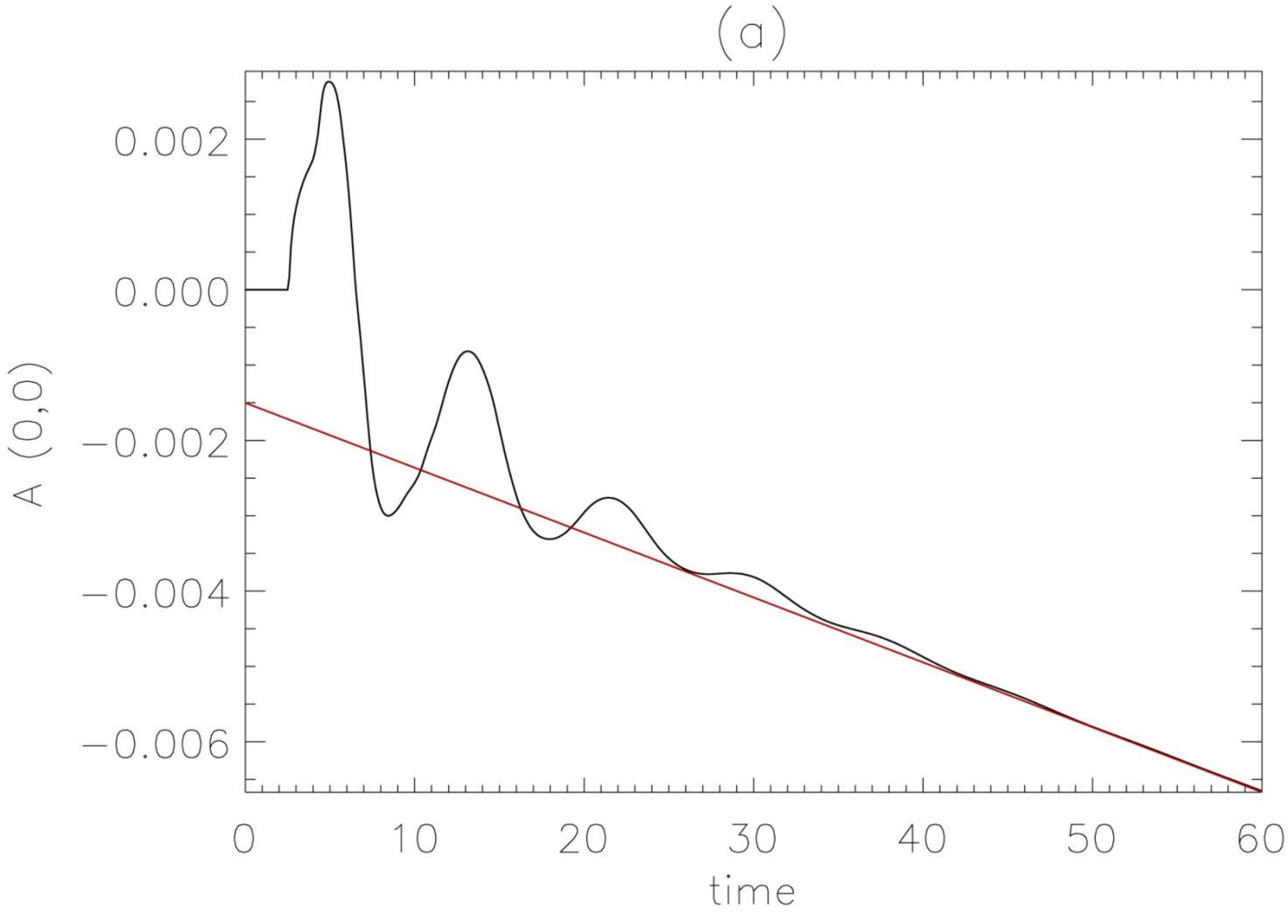
- It is clear we have oscillatory behaviour, but do we have reconnection?

Qualitative Evidence for Reconnection



Quantitative Evidence

Plot time evolution of $A_z\,(0,0)$
Changes in the vector potential at the origin indicate changes in connectivity.



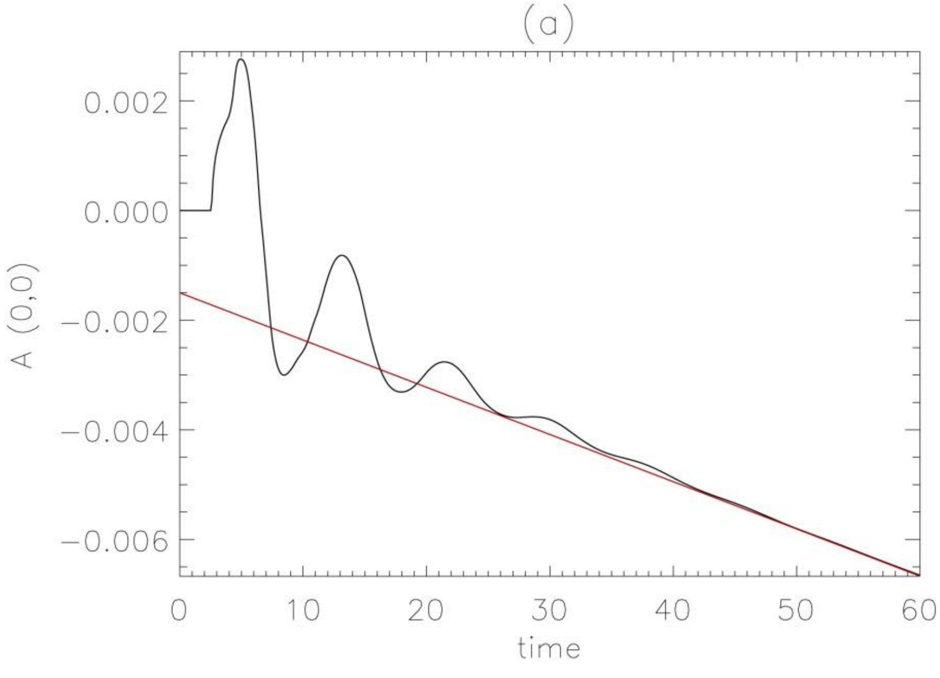
Quantitative Evidence

Before t=2.6, no change
After this, oscillates and displays clear downwards trend,
Tends to straight line: $A_z = -10^{-5}(8.615t + 148.434)$

This straight line is associated with the (final) current density remaining in the system: $\frac{\partial A_z}{\partial t} = \frac{1}{R_m}\nabla^2 A_z = -\frac{1}{R_m} j_z$

Hence, if our final state contains constant current density, then we expect A_z to change linearly in time.

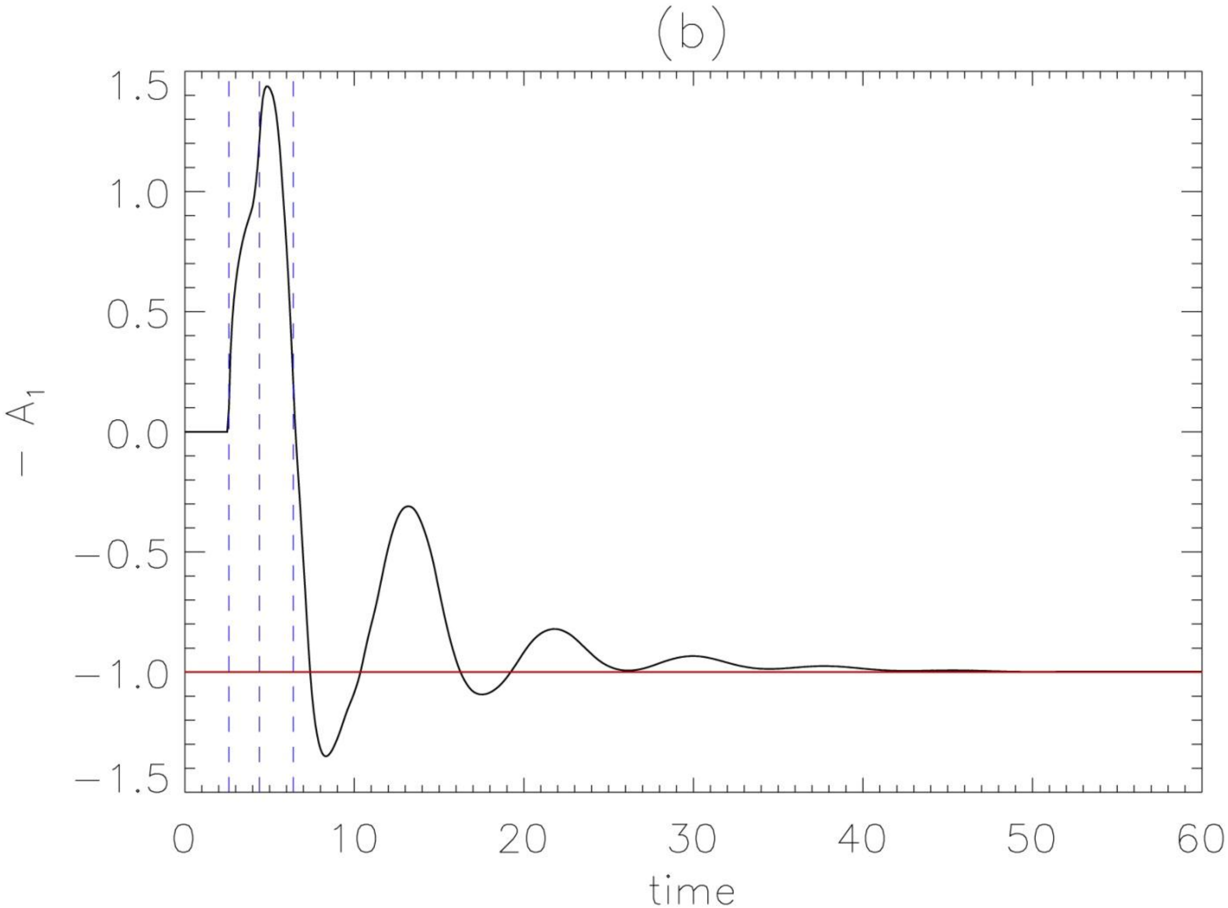
Integrating and comparing to the Straight line gives final current density of 0.8615, in agreement with current.



Quantitative Evidence

Remove straight line trend: $$A_1 = \frac{-10^5 A_z(0,0)}{8.615t + 148.434}$$

Can clearly see oscillatory nature of system



Conclusions

Investigated behaviour of nonlinear MHD fast waves in the neighbourhood of 2D null point.

1) Does the fast wave now steepen to form shocks and can these now propagate across or escape the null?

   Yes, nonlinear behaviour is completely different to linear case.
   Fast and slow shocks form and cross null.
   Shocks intersect & (asymmetrically) heat plasma via jets ($\beta \neq 0$).

2) Can the refraction effect drag enough magnetic field into the null point to initiate X-point collapse?

   Nonlinear wave deforms X-point. Oscillatory reconnection:
   * Cycle of horizontal and vertical current sheets.
   * Changes in vector potential at origin indicate changes in connectivity.

   Final state in force-balance, but non-potential.

3) Has the rate of current density accumulation changed, and is the null still the preferential location of wave heating?

   Current density now forms in many locations: current sheets, shock fronts.
   Neutral point no longer preferential location for heating.

– *[linear]* *McLaughlin & Hood (2004) A&A,* ***420****, 1129-1140*
– *[nonlinear]* *McLaughlin, De Moortel, Hood & Brady (2009) A&A,* ***493****, 227-240*