MODELLING OF CORONAL RAIN

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MPI-AMRVAC

http://homes.esat.kuleuven.be/~keppens/Contents.html

MPI-parallelized Adaptive Mesh Refinement Versatile Advection Code

Conservation laws, with shock-dominated problems

Dimensional independent notation (based on the Loop Annotation Syntax, or LASY)

WHAT WE DON'T KNOW

- Link to coronal heating?
  - **Footpoint** heating?
- **Morphology of magnetic field structure?**

THE MODEL WE USE

2.5D **thermodynamic** MHD model (AMRVAC)

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

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + p_{tot}\mathbf{I} - \frac{\mathbf{B}\mathbf{B}}{\mu_0} \right) = \rho \mathbf{g}, \tag{2}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left(E\mathbf{v} + p_{tot}\mathbf{v} - \frac{\mathbf{v} \cdot \mathbf{B}}{\mu_0}\mathbf{B} \right) = \rho \mathbf{g} \cdot \mathbf{v} + \nabla \cdot (\vec{\kappa} \cdot \nabla T) - Q + H, \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = 0, \tag{4}$$

THE MODEL WE USE

Linear force-free magnetic field (B_0=12 G, theta=30 degree)

$$B_x = -B_0 \cos\left(\frac{\pi x}{L_0}\right) \sin\theta_0 \exp\left(-\frac{\pi y \sin\theta_0}{L_0}\right),$$

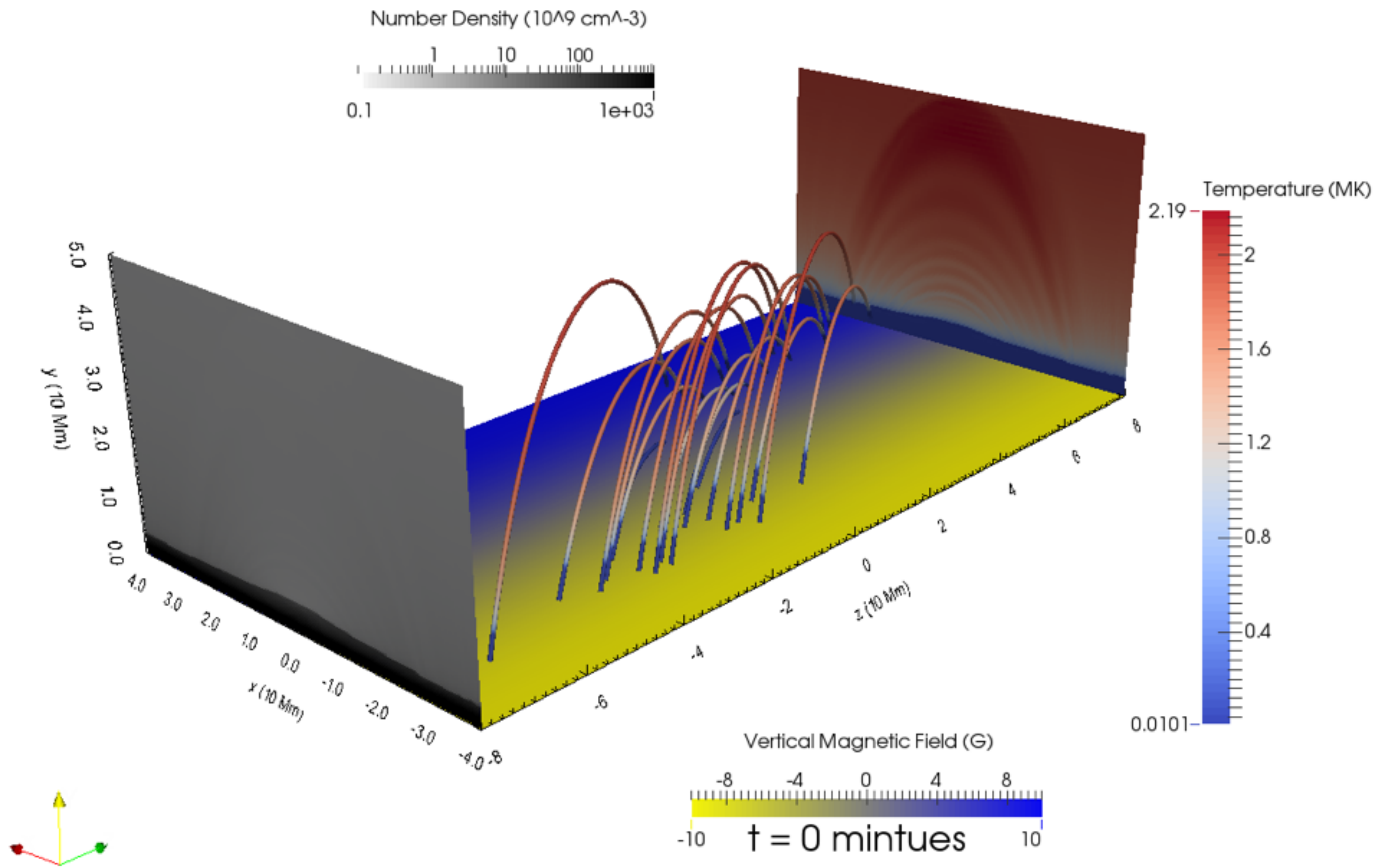
$$B_y = B_0 \sin\left(\frac{\pi x}{L_0}\right) \exp\left(-\frac{\pi y \sin\theta_0}{L_0}\right),$$

$$B_z = -B_0 \cos\left(\frac{\pi x}{L_0}\right) \cos\theta_0 \exp\left(-\frac{\pi y \sin\theta_0}{L_0}\right). \qquad (1)$$

THE MODEL WE USE

A **background** heating decaying exponentially with height, c0=10^-4 erg cm^-3 s^-1and, lambda=50 Mm

$$H_0 = c_0 \exp\left(-\frac{y}{\lambda_0}\right)$$


Number Density (10^9 cm^-3)
1 10 100
0.1 1e+03
Temperature (MK)
2.19
2
1.6
1.2
0.8
0.4
0.0101
y (10 Mm)
5.0 4.0 3.0 2.0 1.0 0.0
x (10 Mm)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
z (10 Mm)
-8 -6 -4 -2 0 2 4 6 8
Vertical Magnetic Field (G)
-8 -4 0 4 8
-10 10
t = 0 mintues

THE MODEL WE USE

Extra heating is localized near the chromopheres

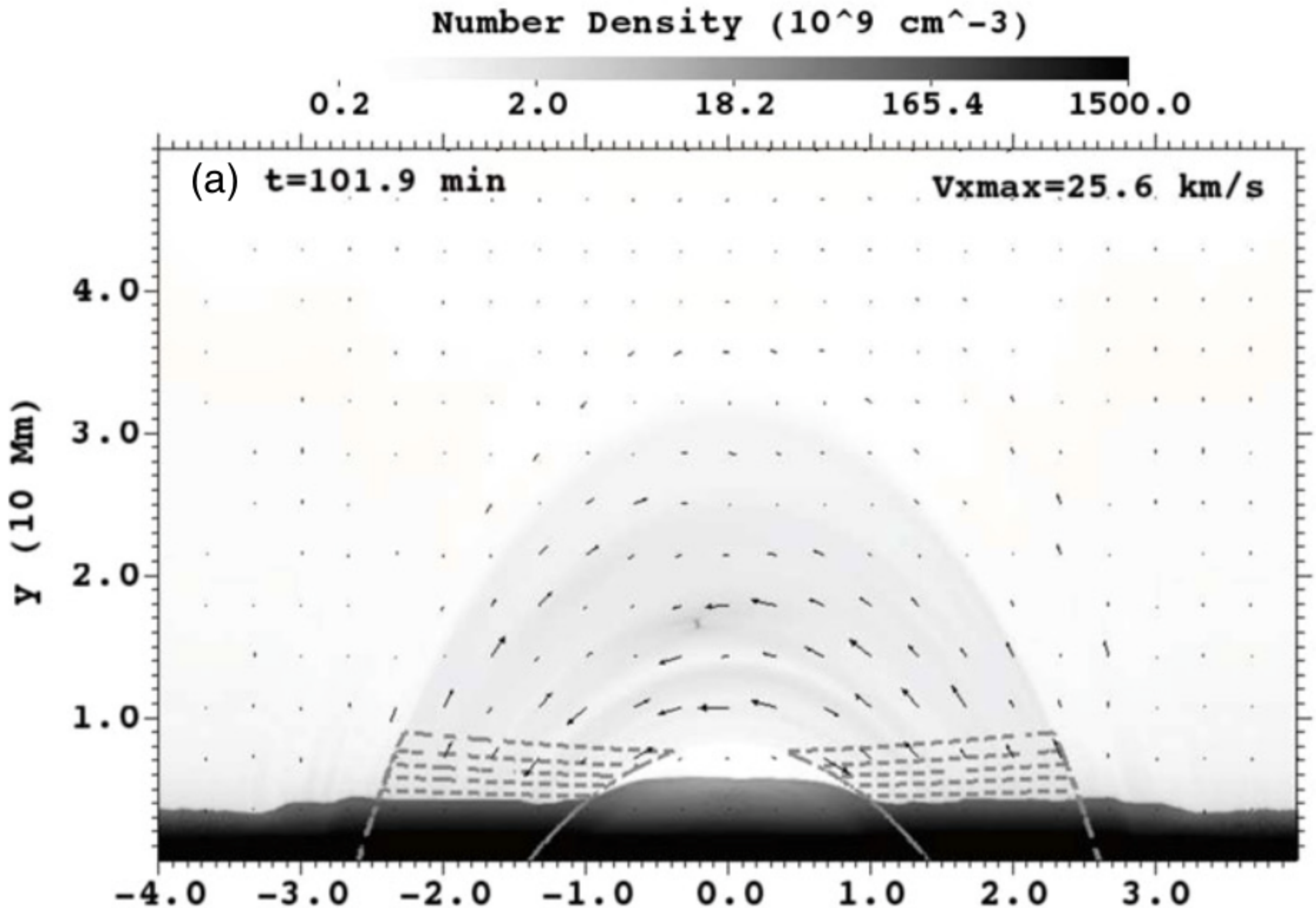
C1=10^-2 erg cm^-3 s^-1 and yc=0.3 Mm

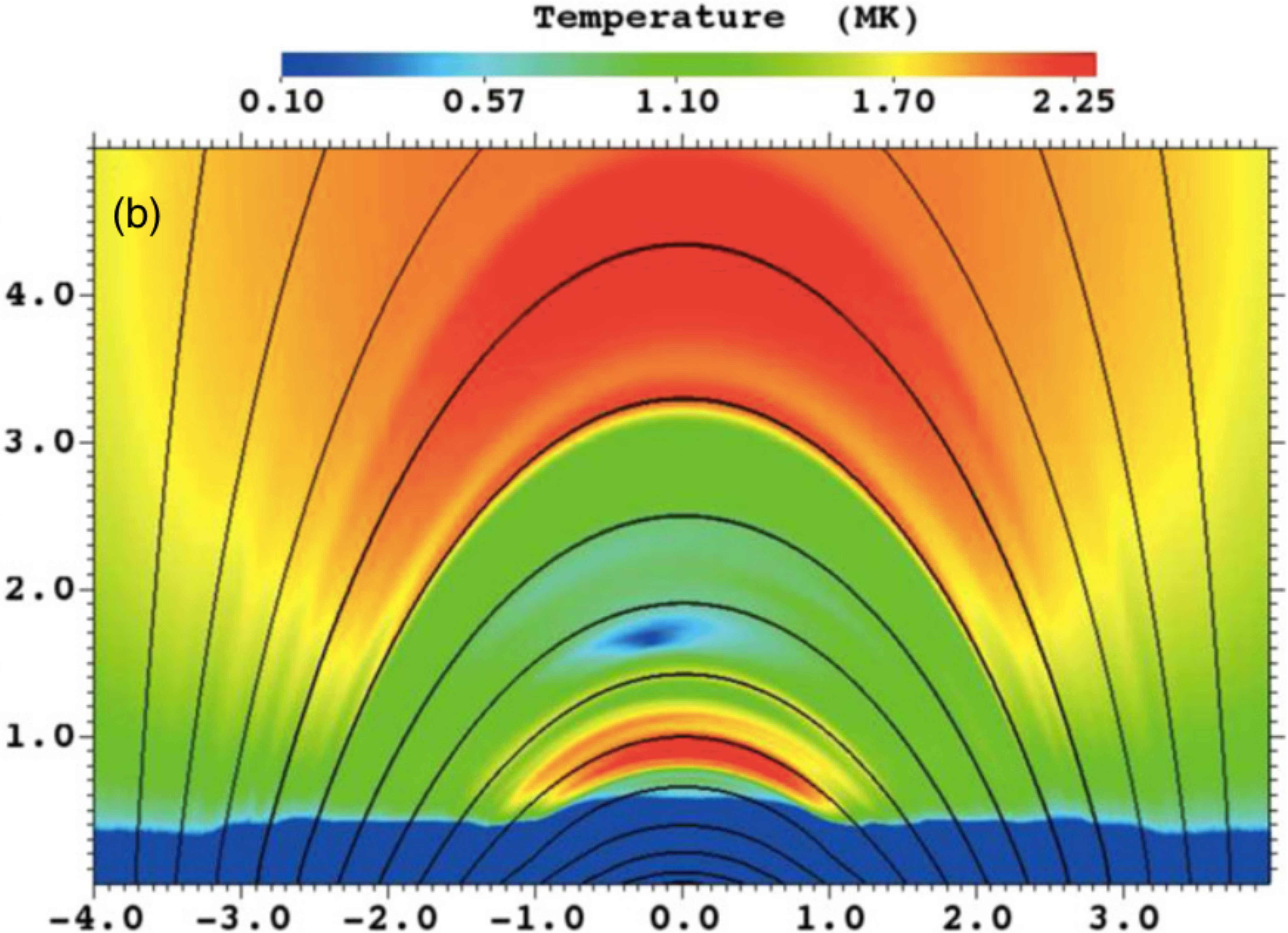
x1=26 Mm, x2=14 Mm, a=0.8 Mm^2, b=1.2 Mm^2

$$H_1 = \begin{cases} c_1 & \text{if} \quad y < y_c \quad \text{and} \quad A(x_1,0) < A(x,y) < A(x_2,0) \\ c_1 \exp(-(y-y_c)^2/\lambda^2) & \text{if} \quad y \geq y_c \quad \text{and} \quad A(x_1,0) < A(x,y) < A(x_2,0) \end{cases}$$

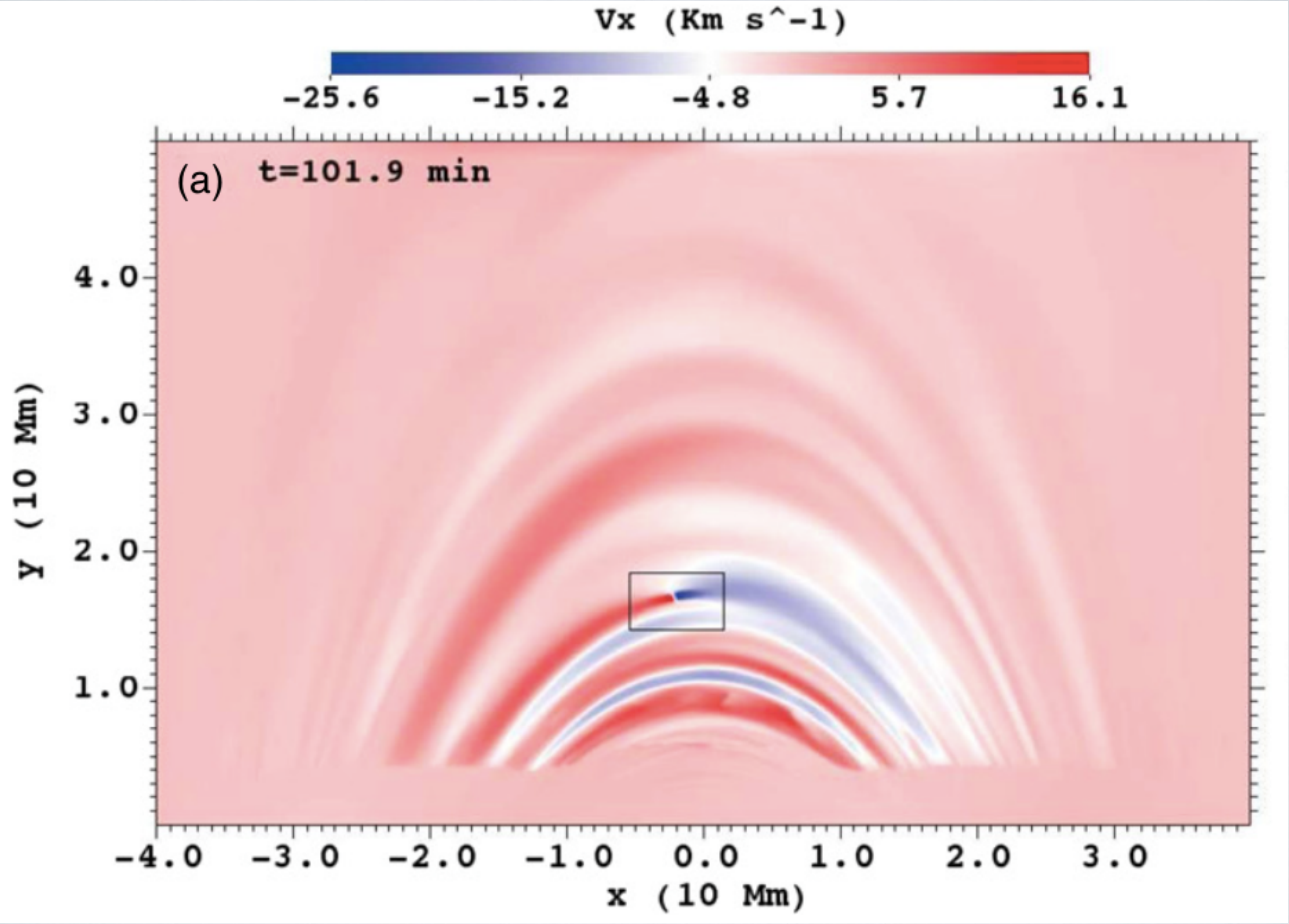
$$A(x,y) = \frac{B_0 L_0}{\pi} \cos\left(\frac{\pi x}{L_0}\right) \exp\left(-\frac{\pi y \sin\theta_0}{L_0}\right) ,$$

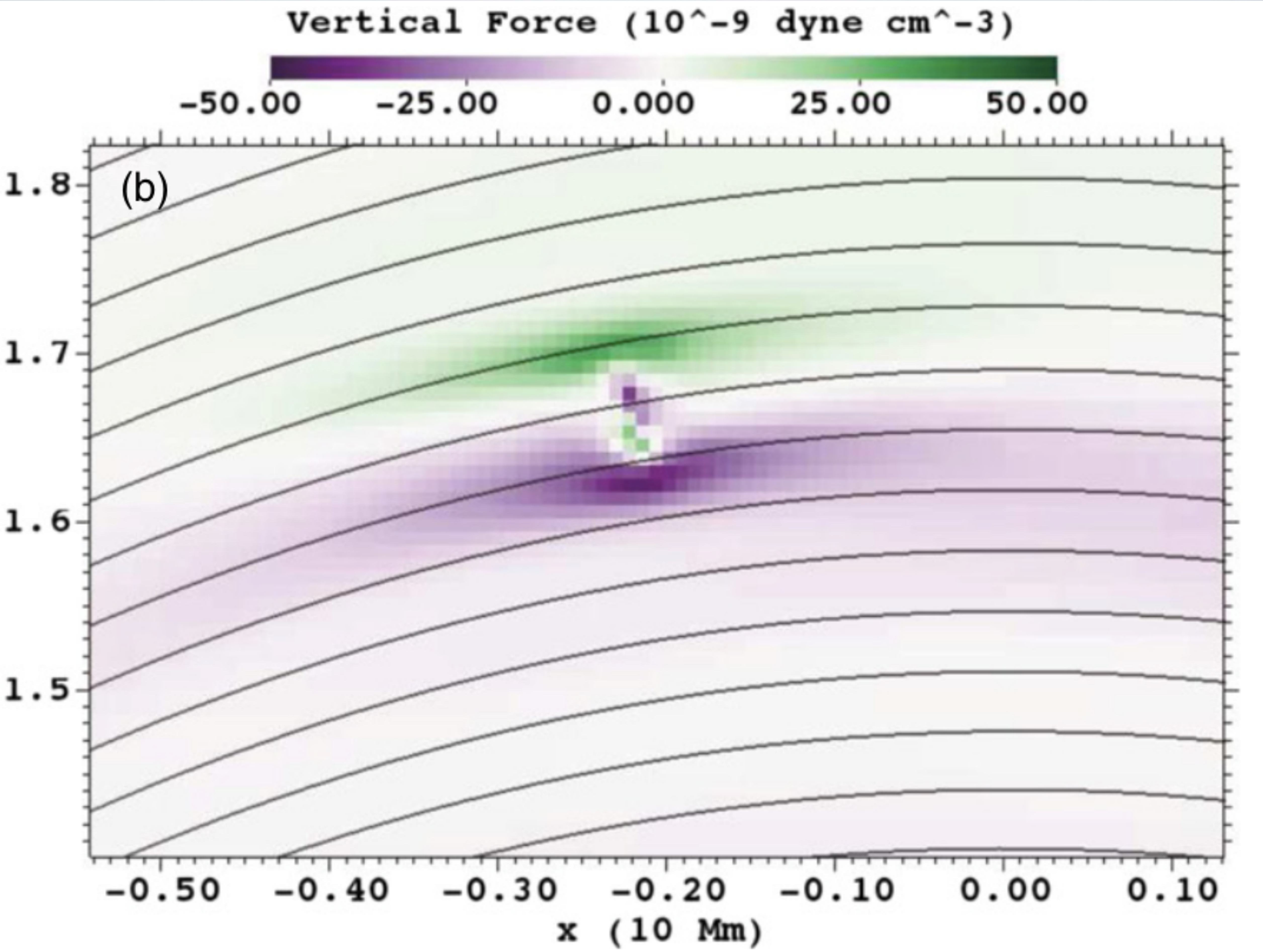
$$\lambda^2 = \frac{a\,(A(x,y) - A(x_2,0))}{A(x_2,0) - A(x_1,0)} + b \quad (\mathrm{Mm}^2) ,$$


Number Density (10^9 cm^-3)
0.2
2.0
18.2
165.4
1500.0
(a) t=101.9 min
Vxmax=25.6 km/s
y (10 Mm)
4.0
3.0
2.0
1.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0



Temperature (MK)
0.10
0.57
1.10
1.70
2.25
(b)
4.0
3.0
2.0
1.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0

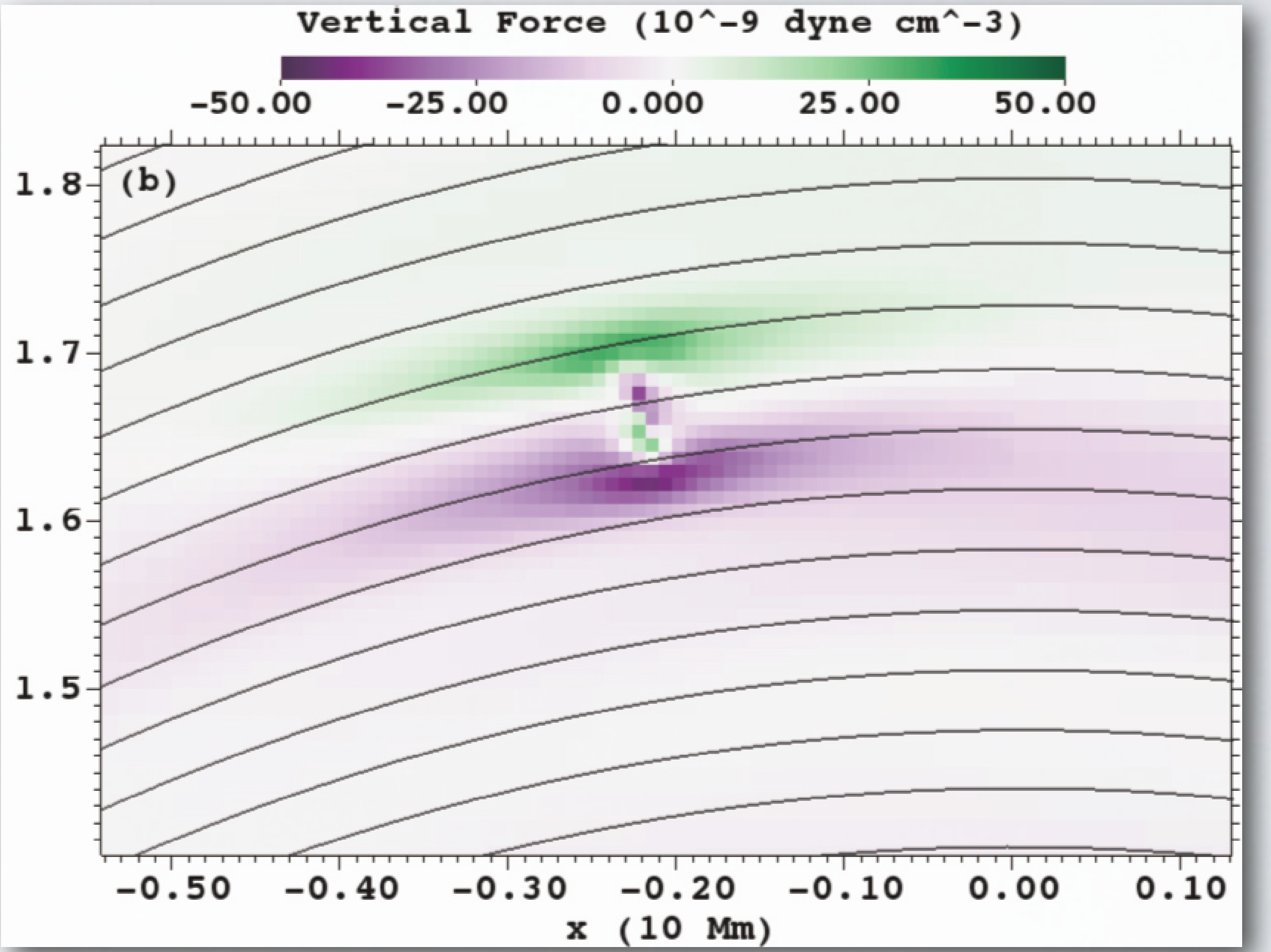

Vx (Km s^-1)
-25.6
-15.2
-4.8
5.7
16.1
(a)
t=101.9 min
4.0
3.0
2.0
1.0
y (10 Mm)
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
x (10 Mm)



Vertical Force (10^-9 dyne cm^-3)
-50.00
-25.00
0.000
25.00
50.00
(b)
1.8
1.7
1.6
1.5
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
0.10
x (10 Mm)

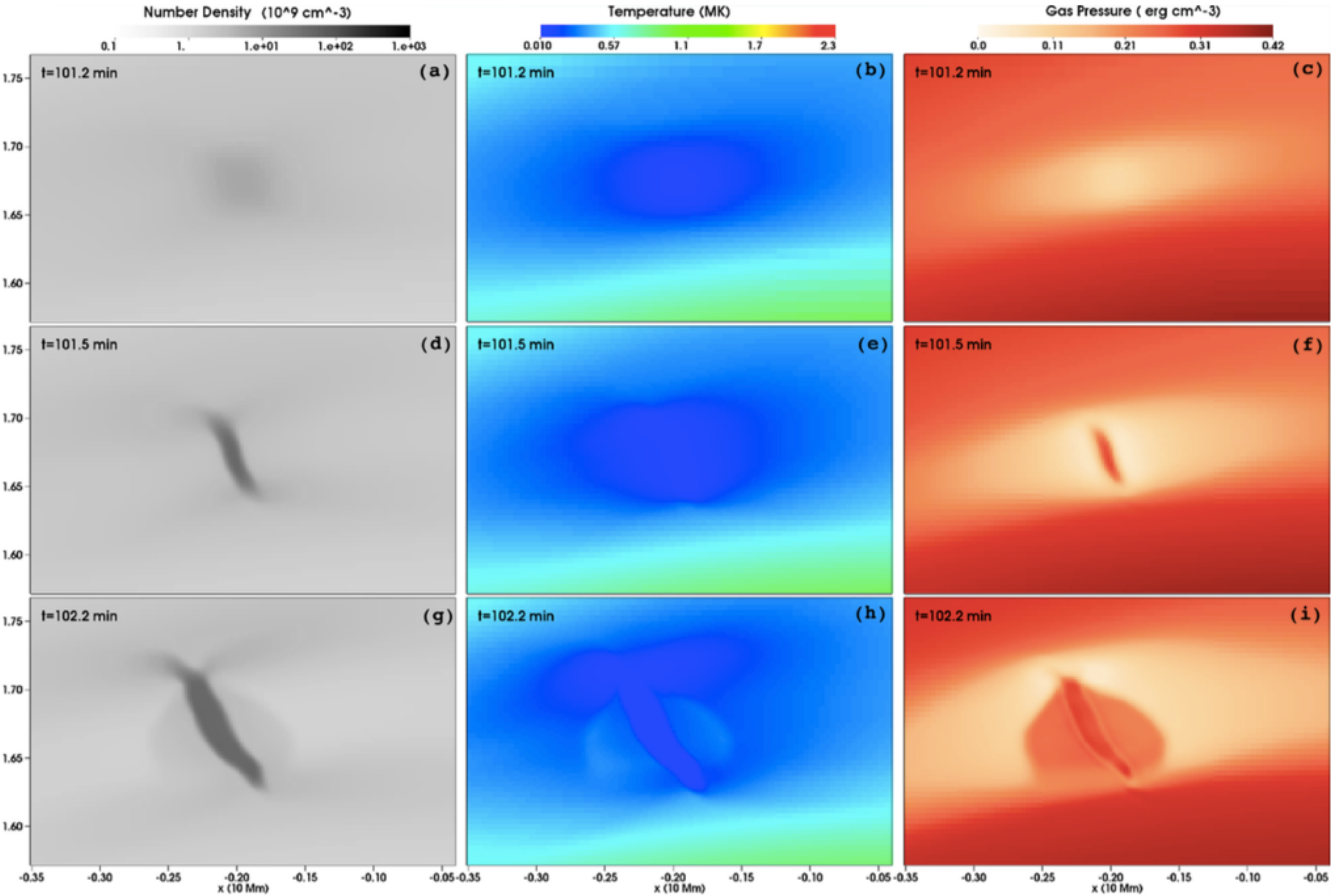
MULTIDIMENSIONAL EFFECT

- The perturbed force field over 1 Mm in width
- Dominant about equal pressure and Lorentz force
- Induces field variation on neighbouring field lines
- Similar condensation arise on both ends of this one

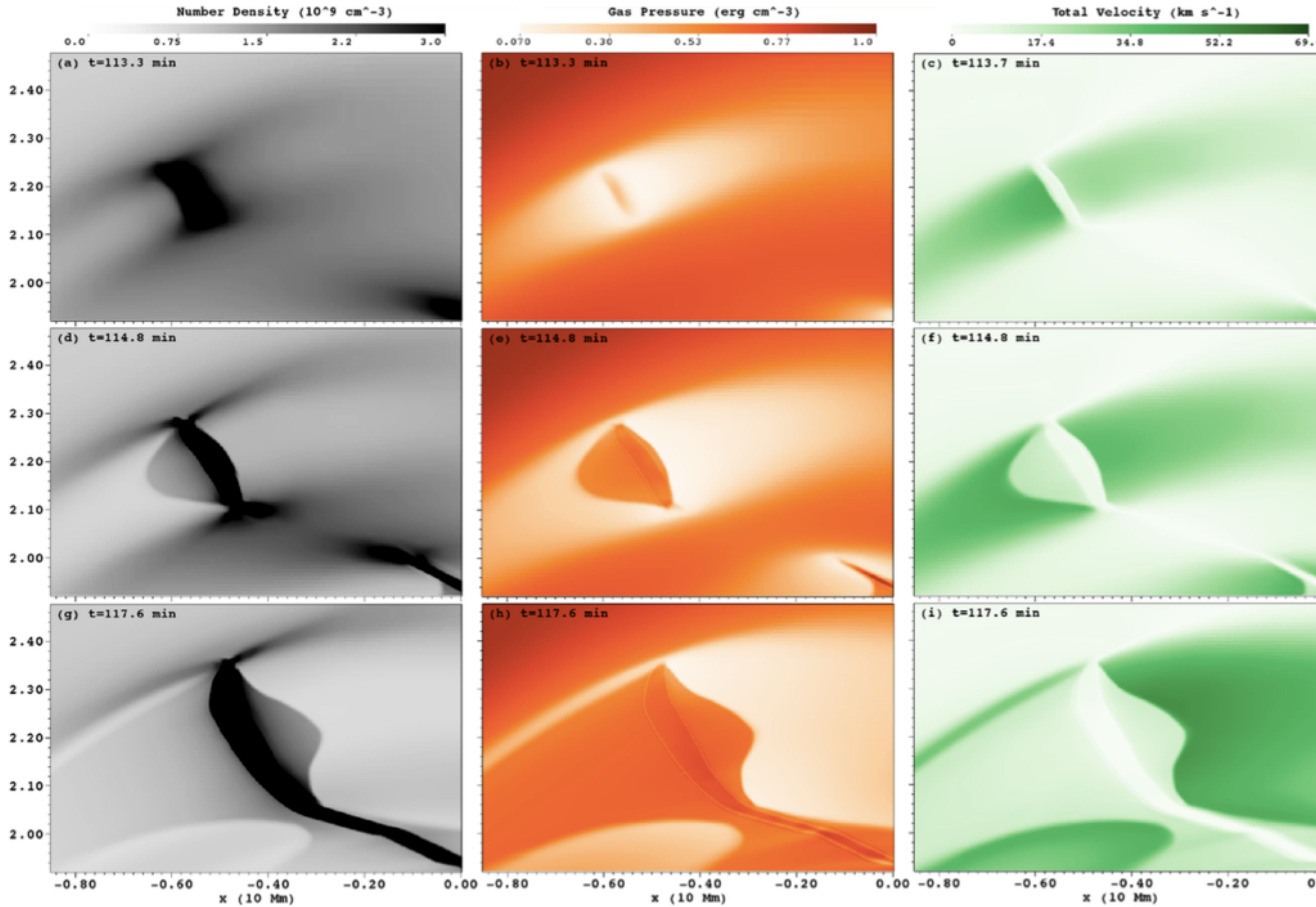


The signed vertical total force with gravity, Lorenz force and pressure gradient in a zoomed view on the first blob forming.

Number Density (10^9 cm^-3)
1
10
100
1000
1e+4
0.254
2e+04
Time: 99.3
y (10 Mm)
5.0
4.0
3.0
2.0
1.0
0.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
x (10 Mm)

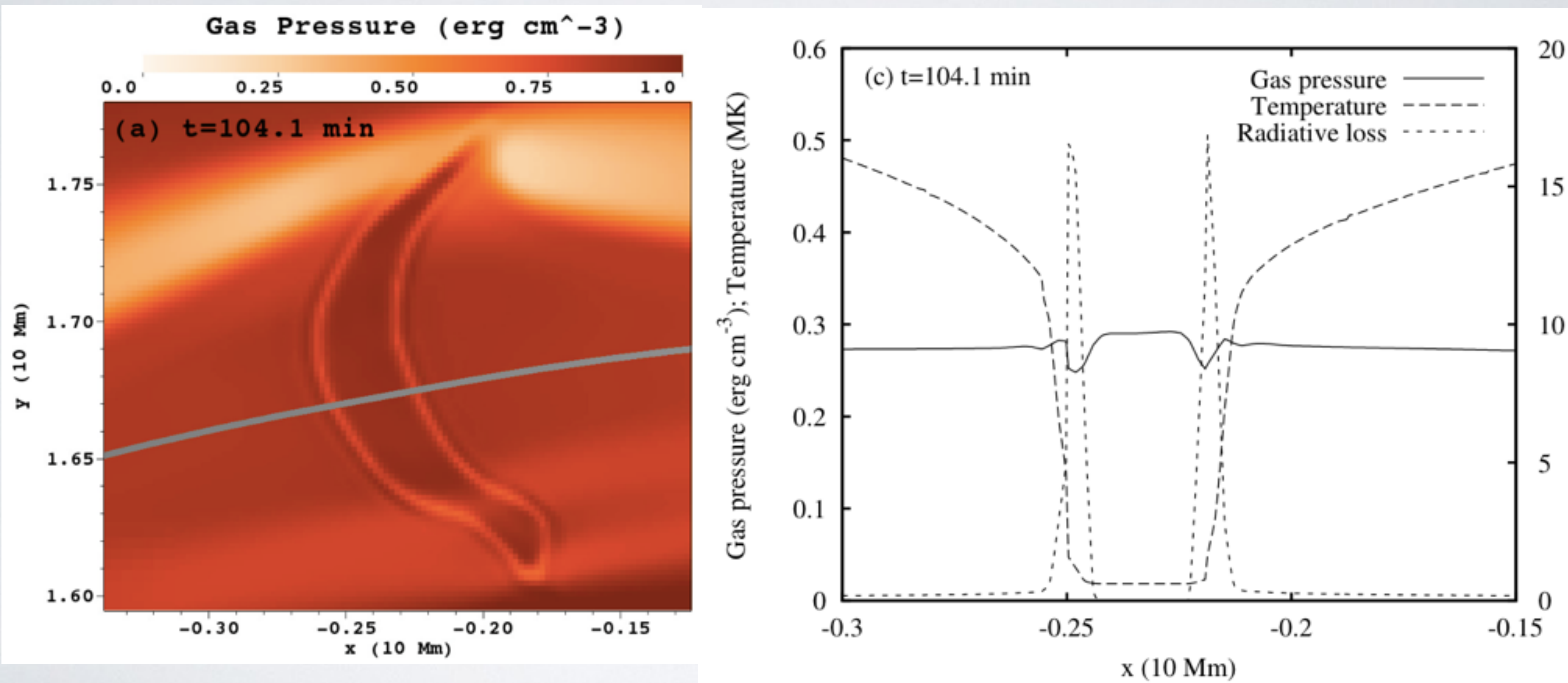


Number Density (10^9 cm^-3)
0.1
1.
1.e+01
1.e+02
1.e+03
Temperature (MK)
0.010
0.57
1.1
1.7
2.3
Gas Pressure (erg cm^-3)
0.0
0.11
0.21
0.31
0.42
t=101.2 min
(a)
(b)
(c)
t=101.5 min
(d)
(e)
(f)
t=102.2 min
(g)
(h)
(i)
1.75
1.70
1.65
1.60
-0.35
-0.30
-0.25
-0.20
-0.15
-0.10
-0.05
x (10 Mm)

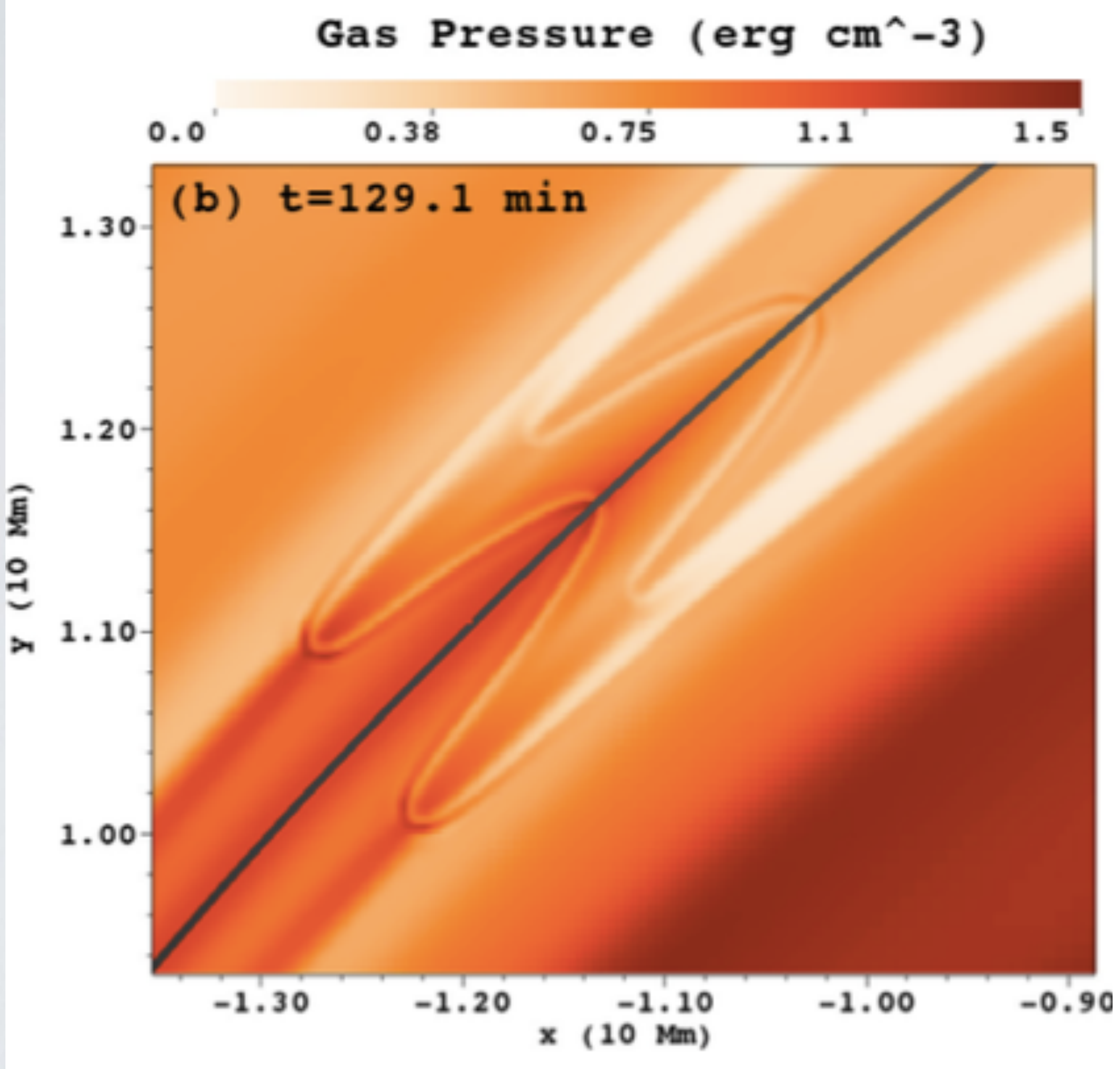


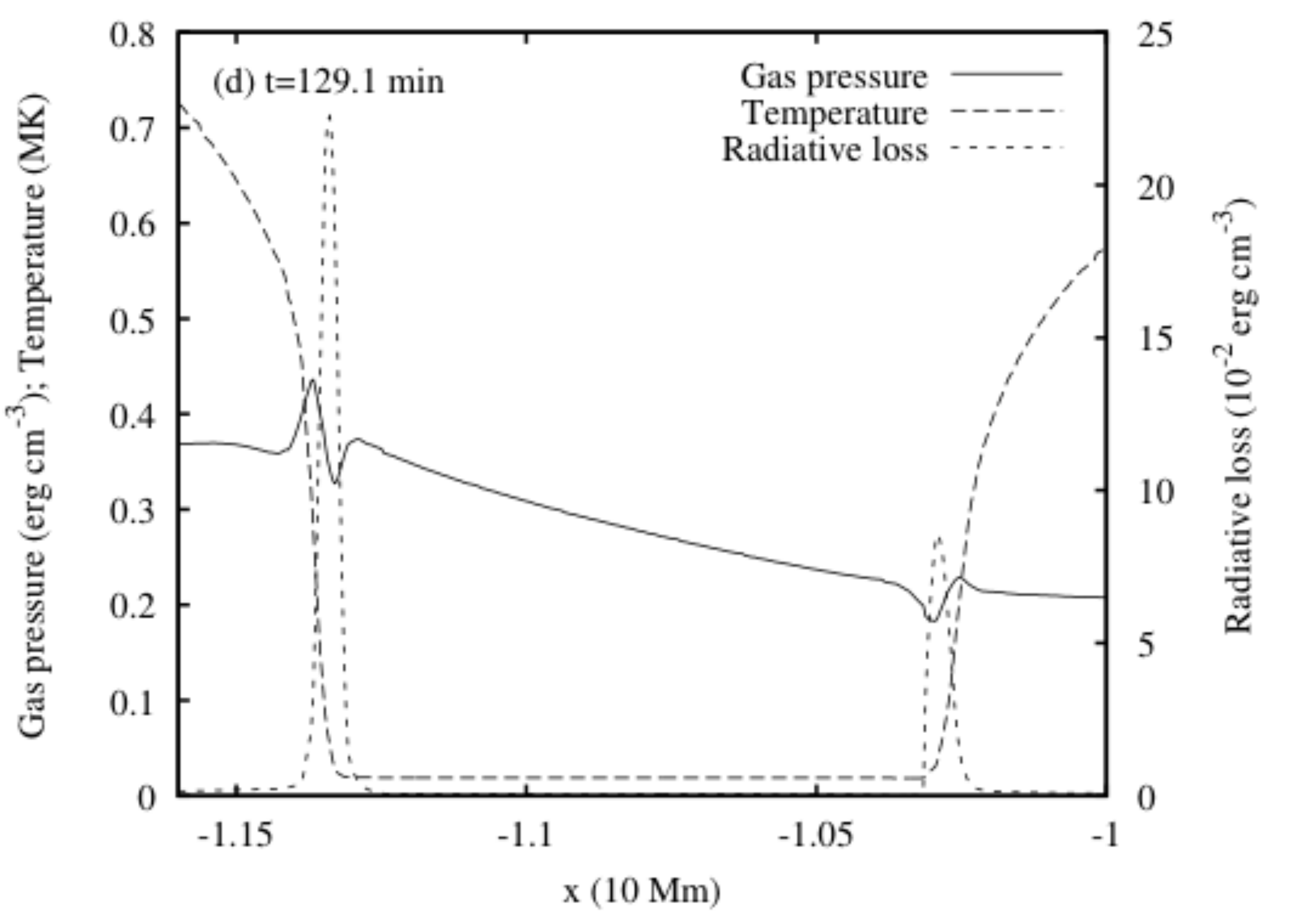
Number Density (10^9 cm^-3)
0.0
0.75
1.5
2.2
3.0
Gas Pressure (erg cm^-3)
0.070
0.30
0.53
0.77
1.0
Total Velocity (km s^-1)
0
17.4
34.8
52.2
(a) t=113.3 min
(b) t=113.3 min
(c) t=113.7 min
(d) t=114.8 min
(e) t=114.8 min
(f) t=114.8 min
(g) t=117.6 min
(h) t=117.6 min
(i) t=117.6 min
2.40
2.30
2.20
2.10
2.00
-0.80
-0.60
-0.40
-0.20
0.00
x (10 Mm)

Prominence-Corona-Transition-Region

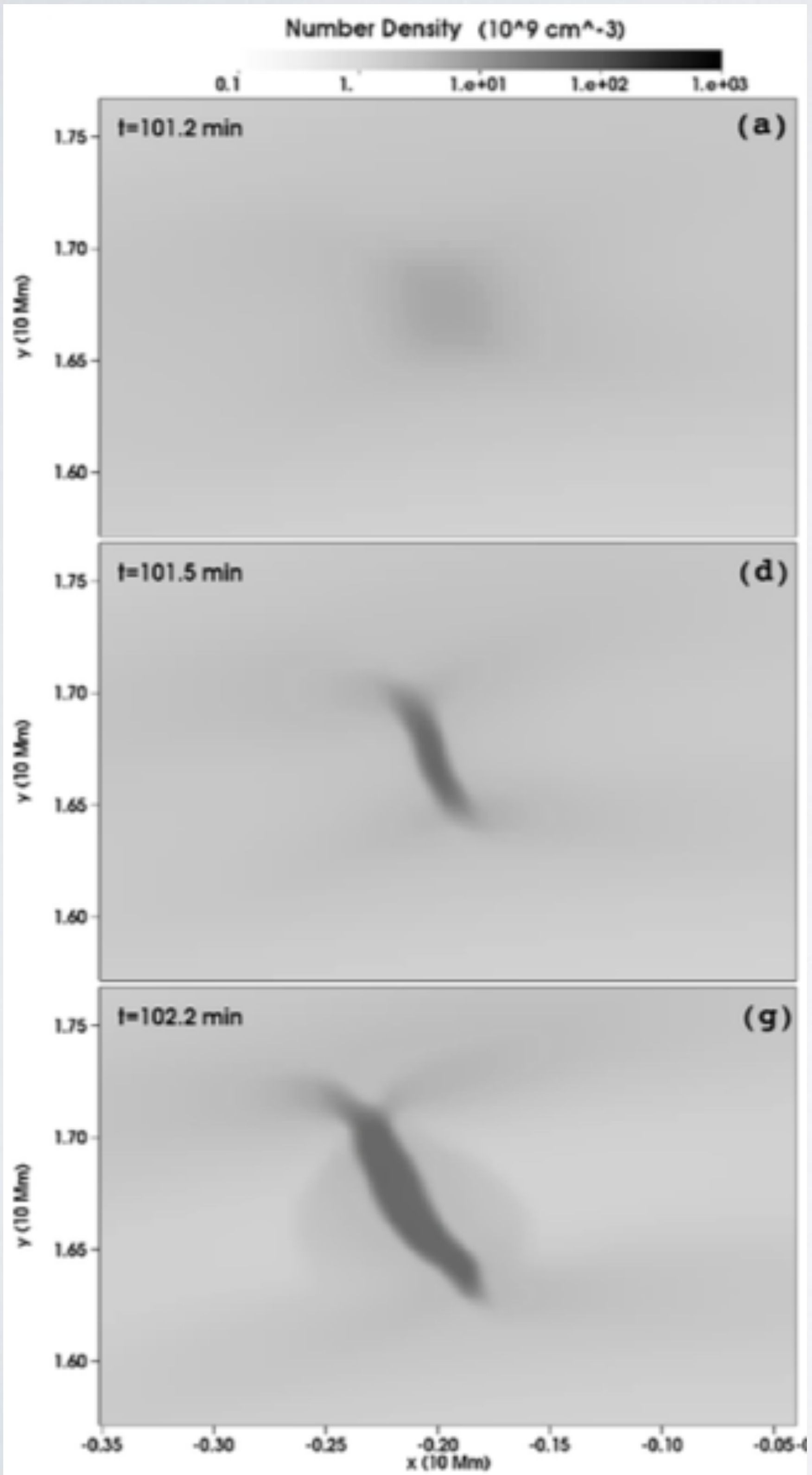


Prominence-Corona-Transition-Region

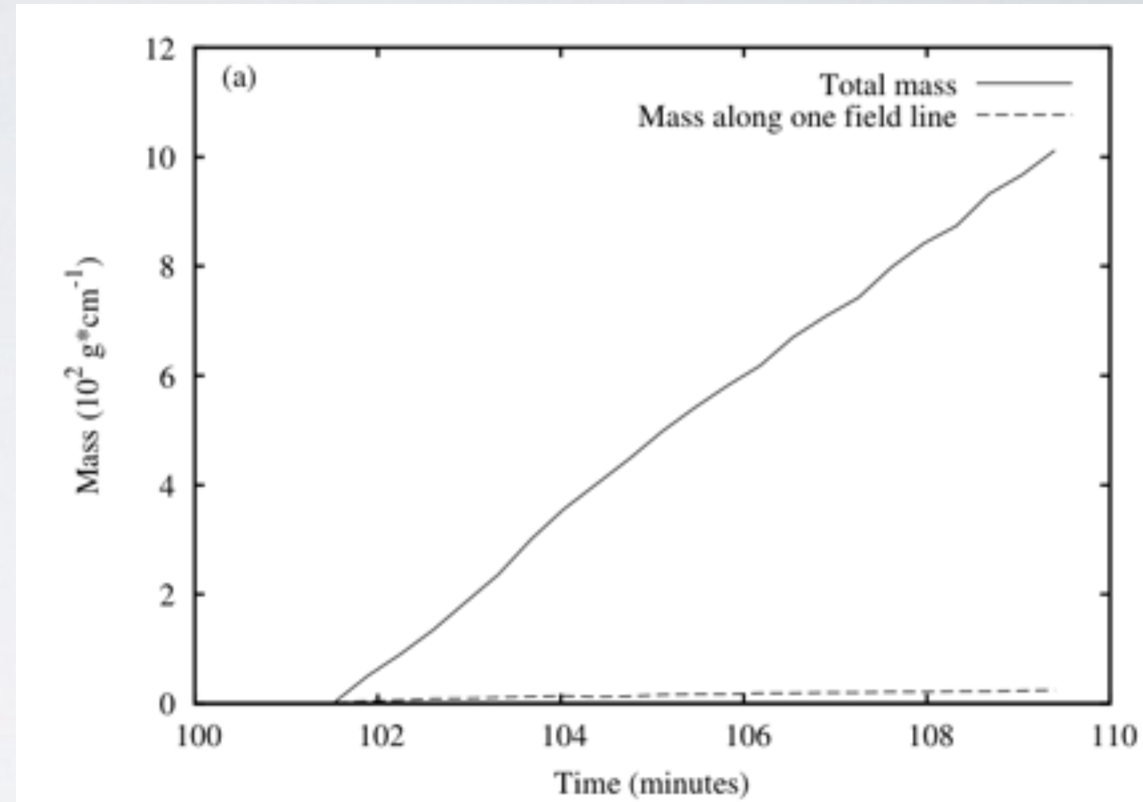




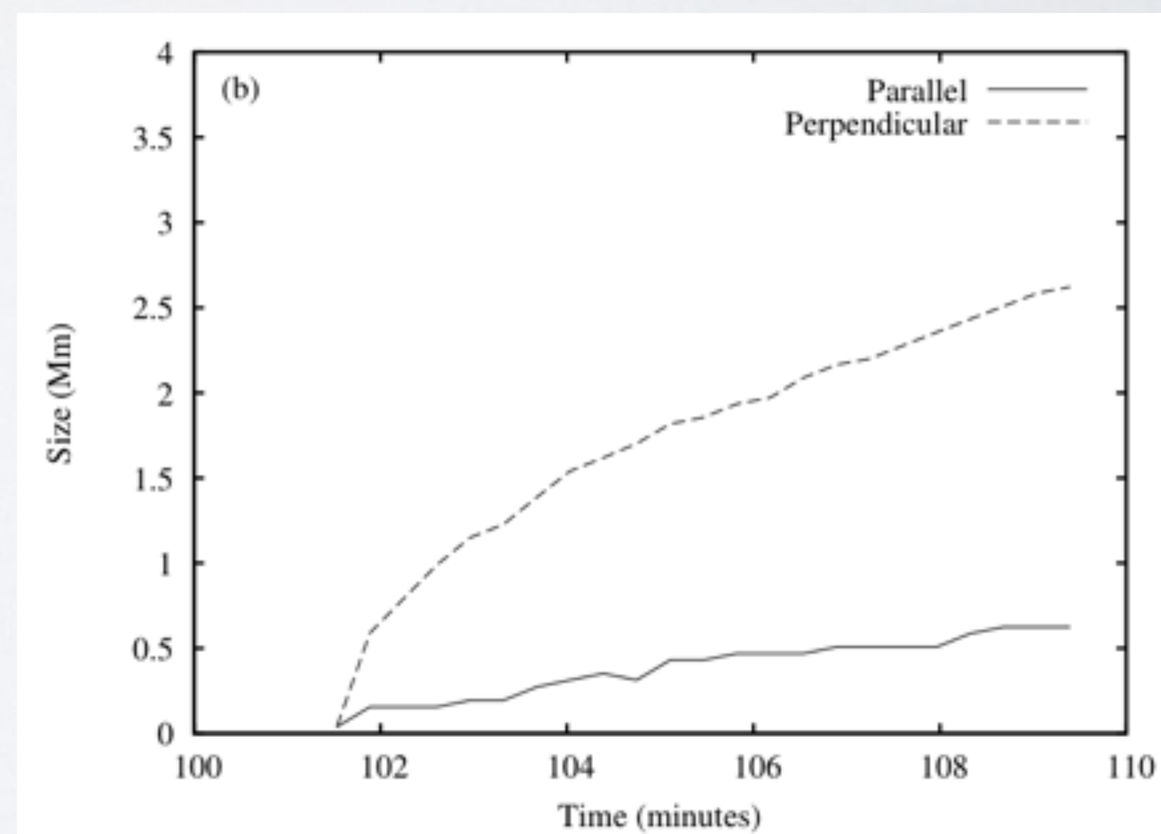
CONDENSATION RATE



- Mass

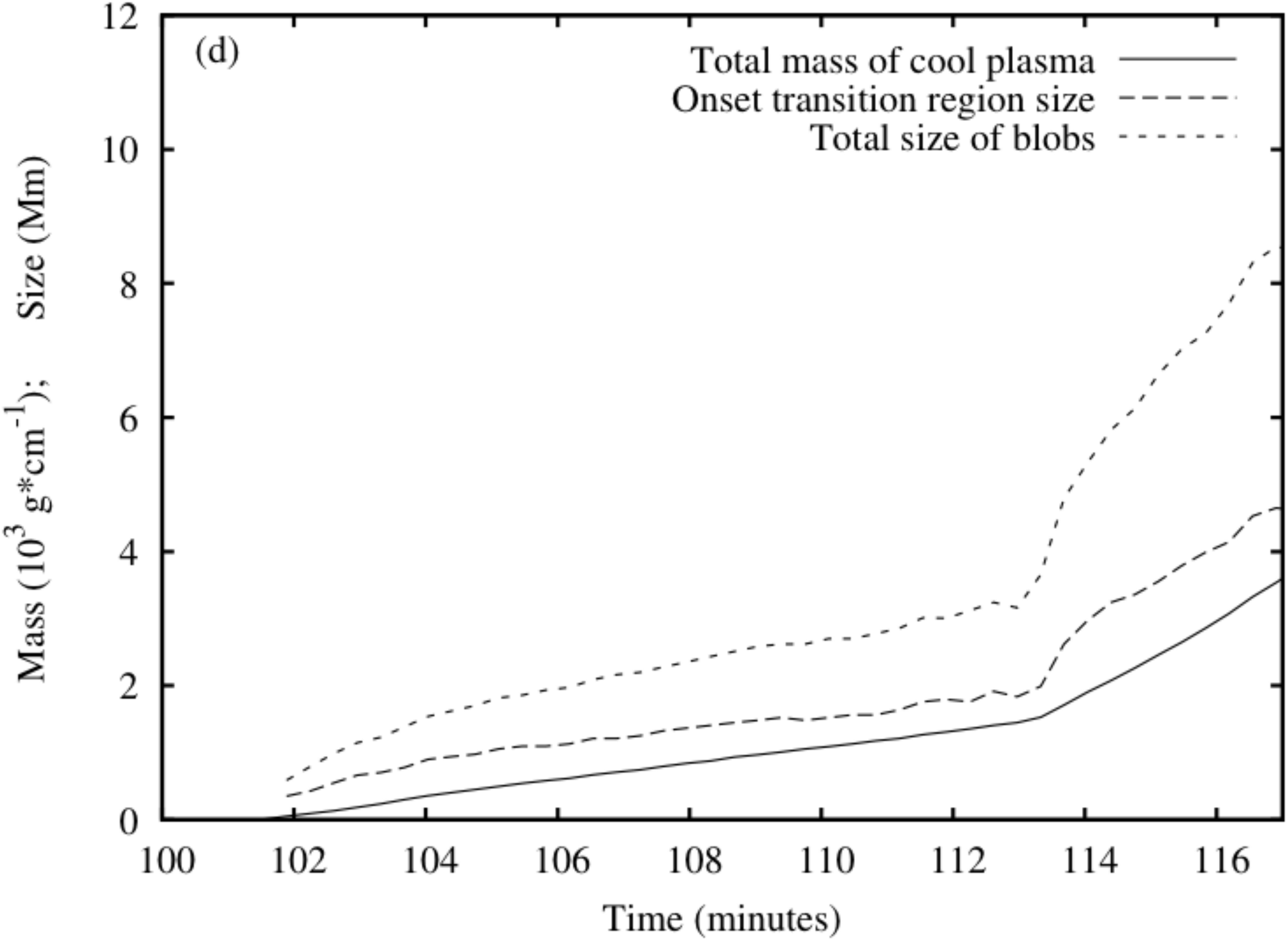


- Size

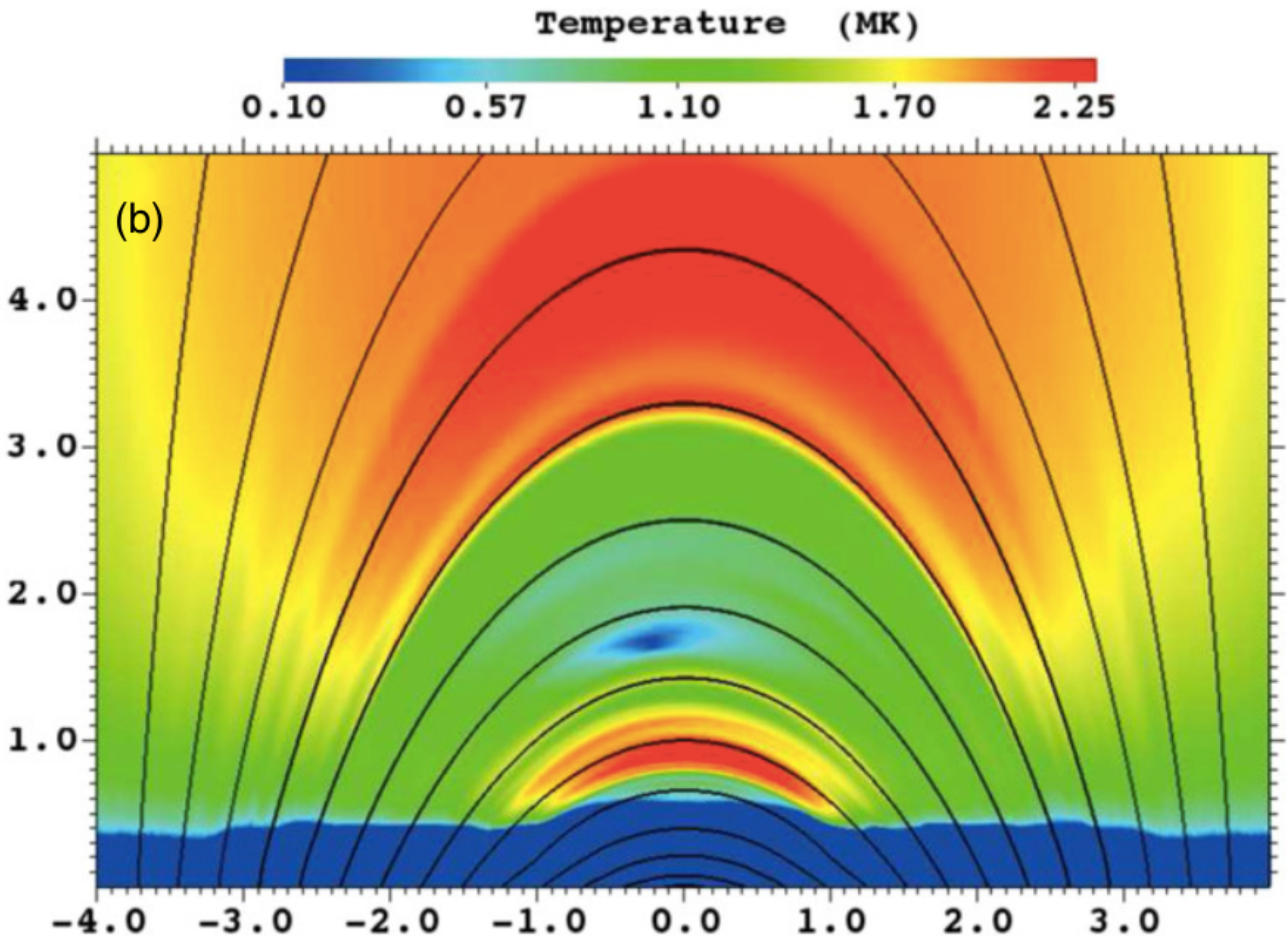


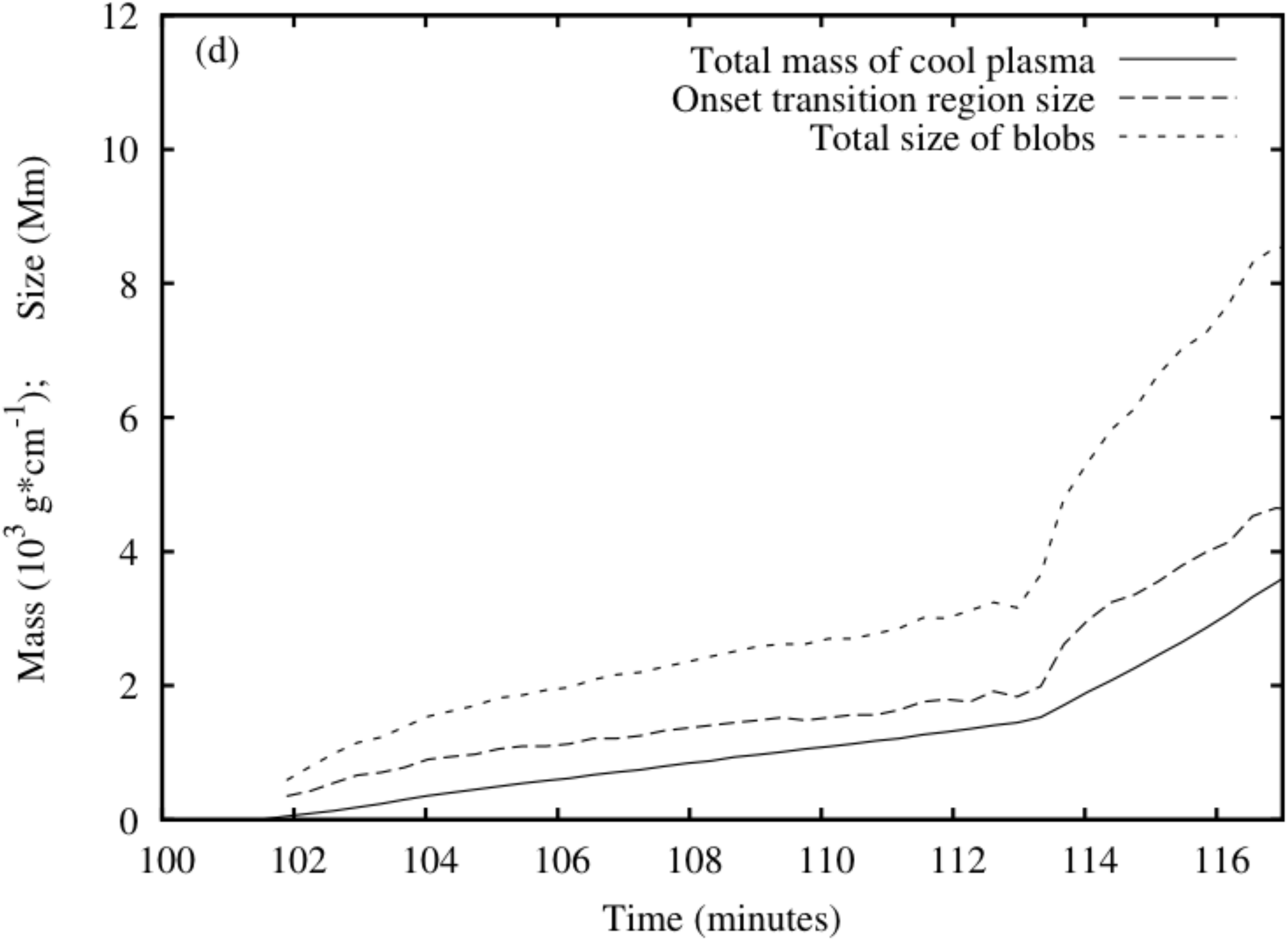
CONDENSATION RATE

Faster growth in size in the **perpendicular** direction !

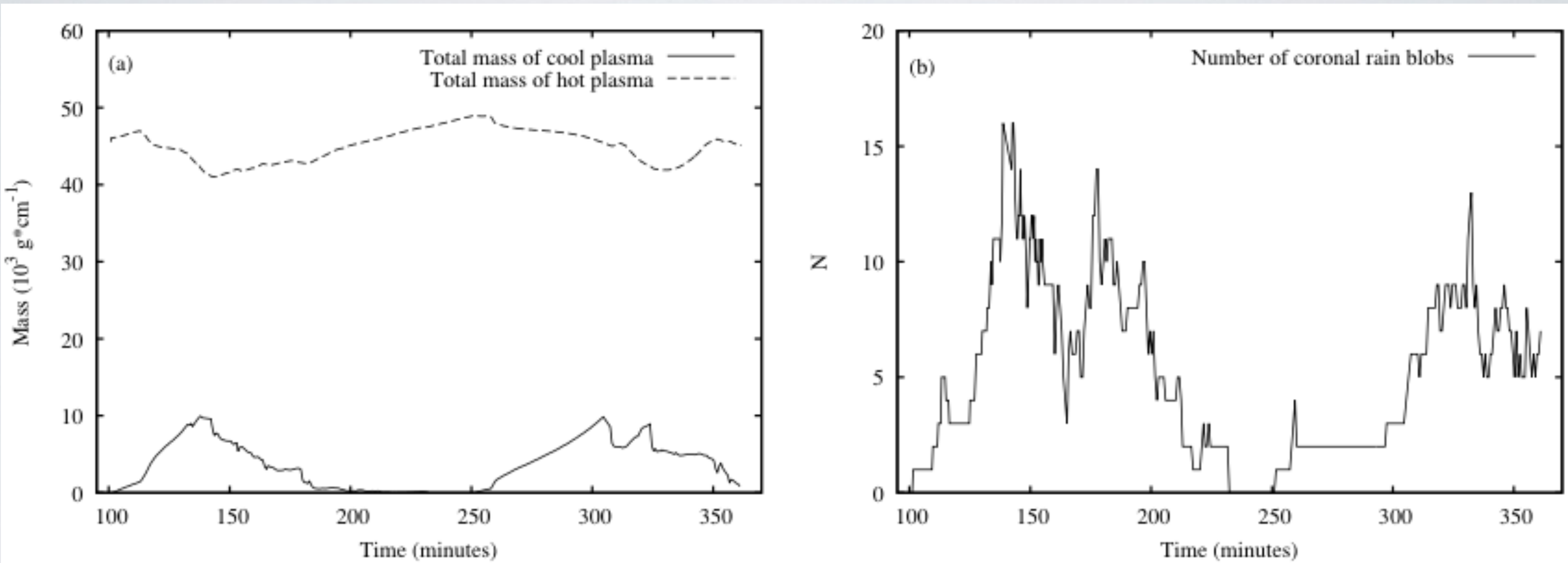


(d)
Total mass of cool plasma
Onset transition region size
Total size of blobs
Mass (10^3 g*cm^-1); Size (Mm)
Time (minutes)
0
2
4
6
8
10
12
100
102
104
106
108
110
112
114
116


Temperature (MK)
0.10
0.57
1.10
1.70
2.25
(b)
4.0
3.0
2.0
1.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0


(d)
Total mass of cool plasma
Onset transition region size
Total size of blobs
Mass (10^3 g*cm^{-1}); Size (Mm)
Time (minutes)
0
2
4
6
8
10
12
100
102
104
106
108
110
112
114
116

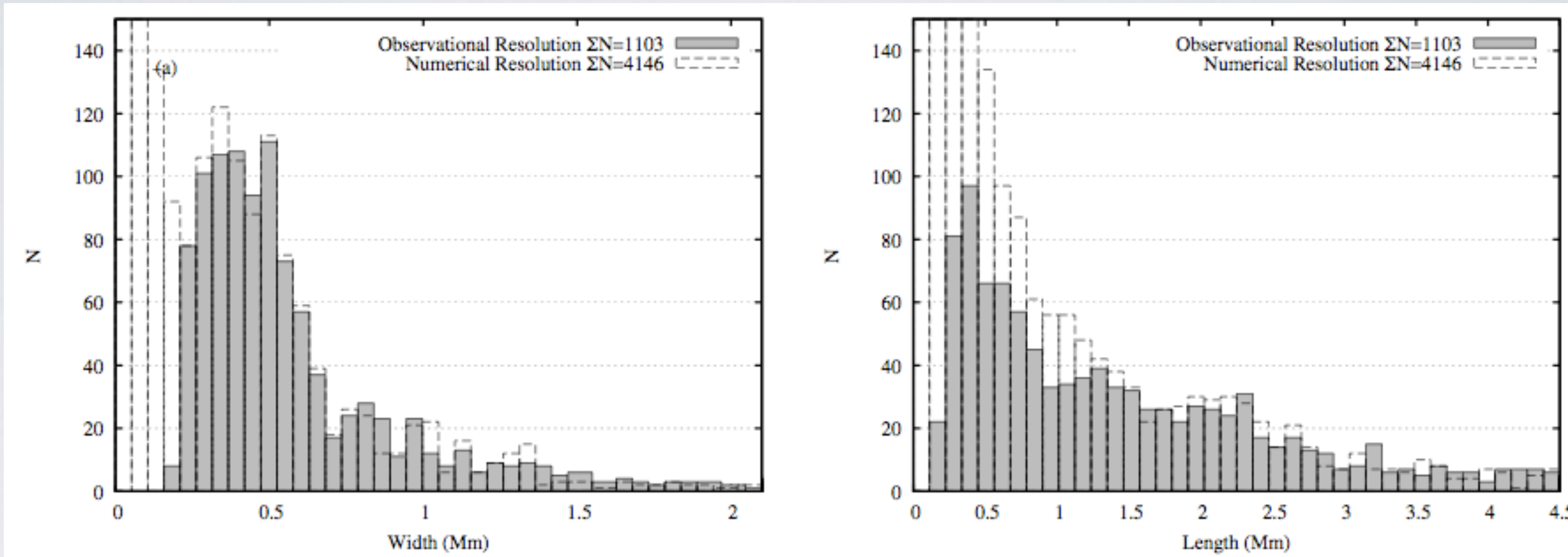
LIMIT CYCLES OF RAIN

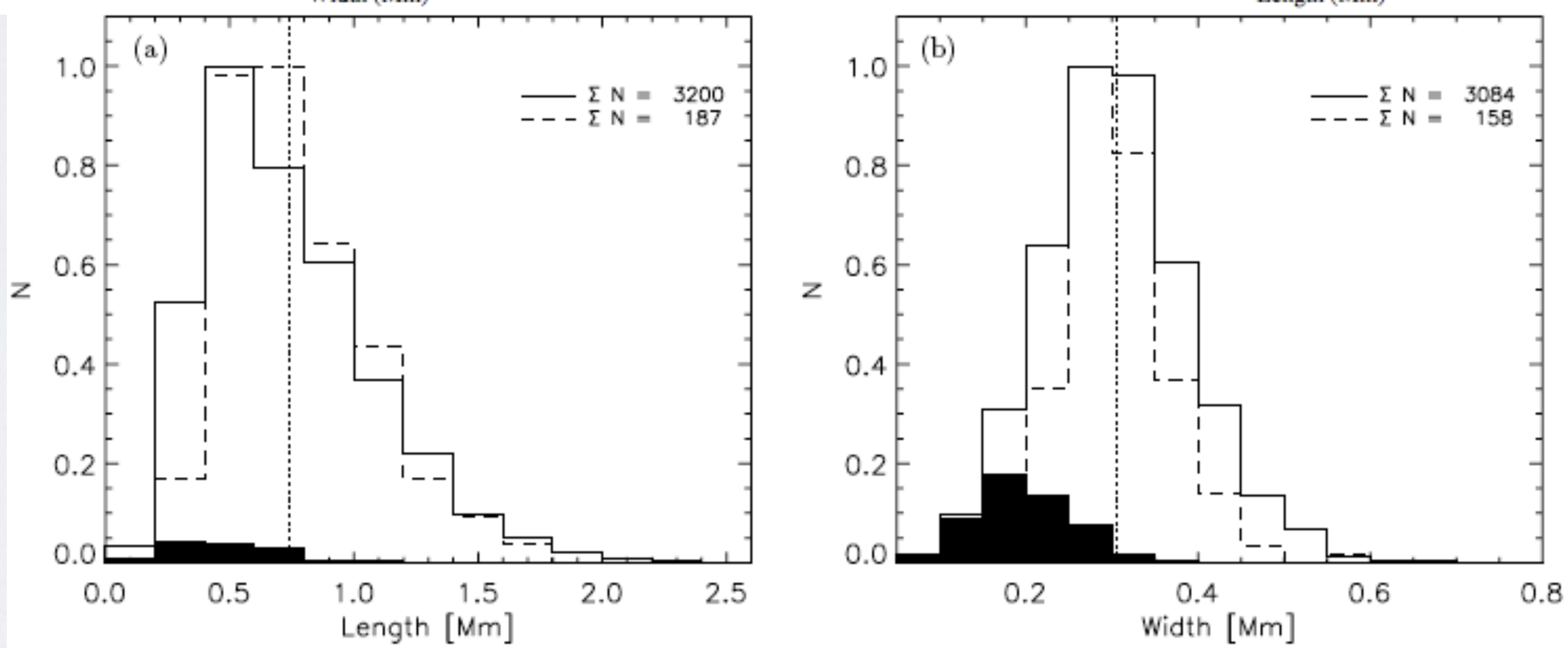


Temporal evolution of mass (left) and number (right)of blobs

Interpreted as 'limit cycles of loop evolution' by Mueller et .al (2003)

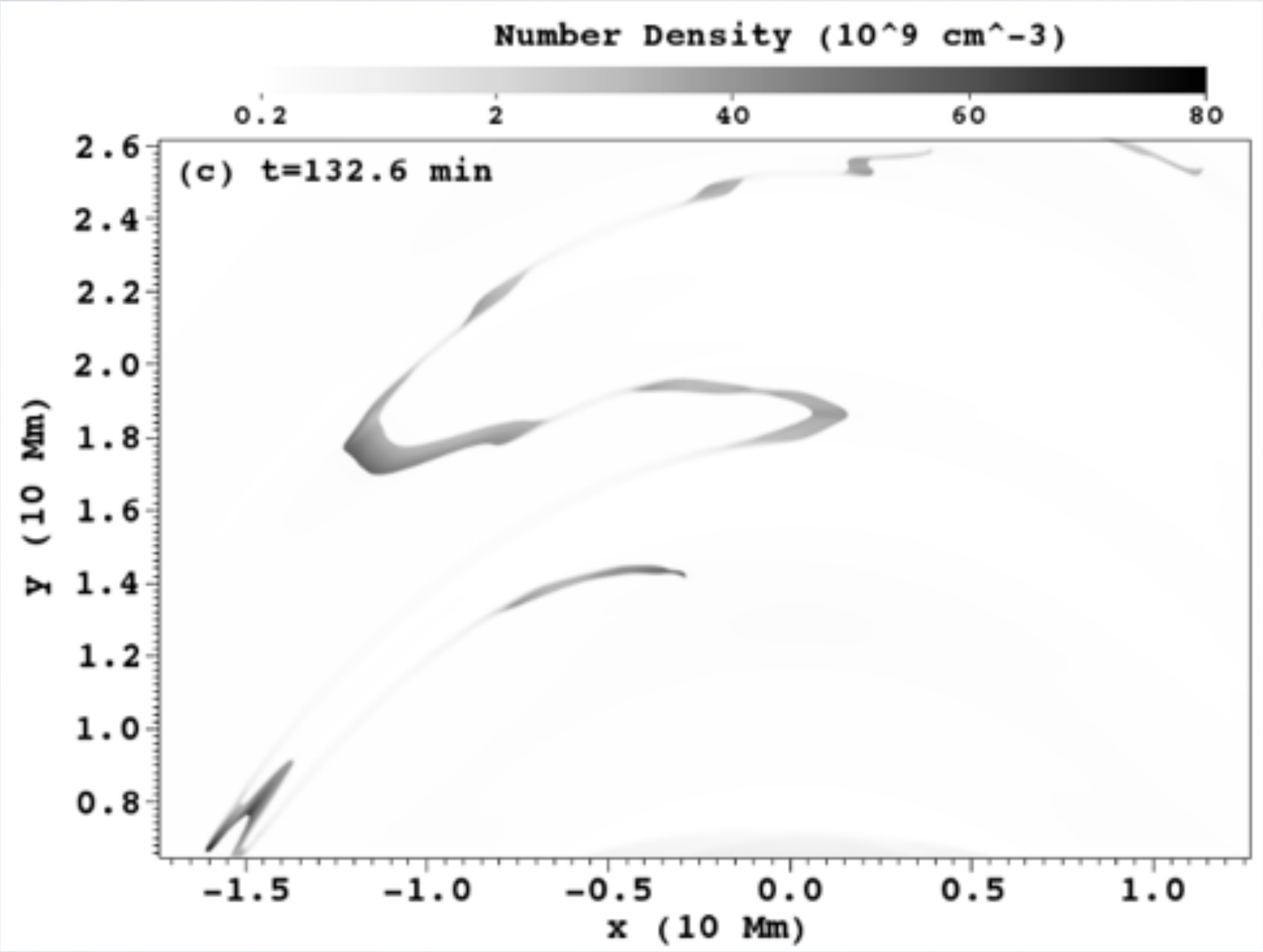
BLOB SIZE



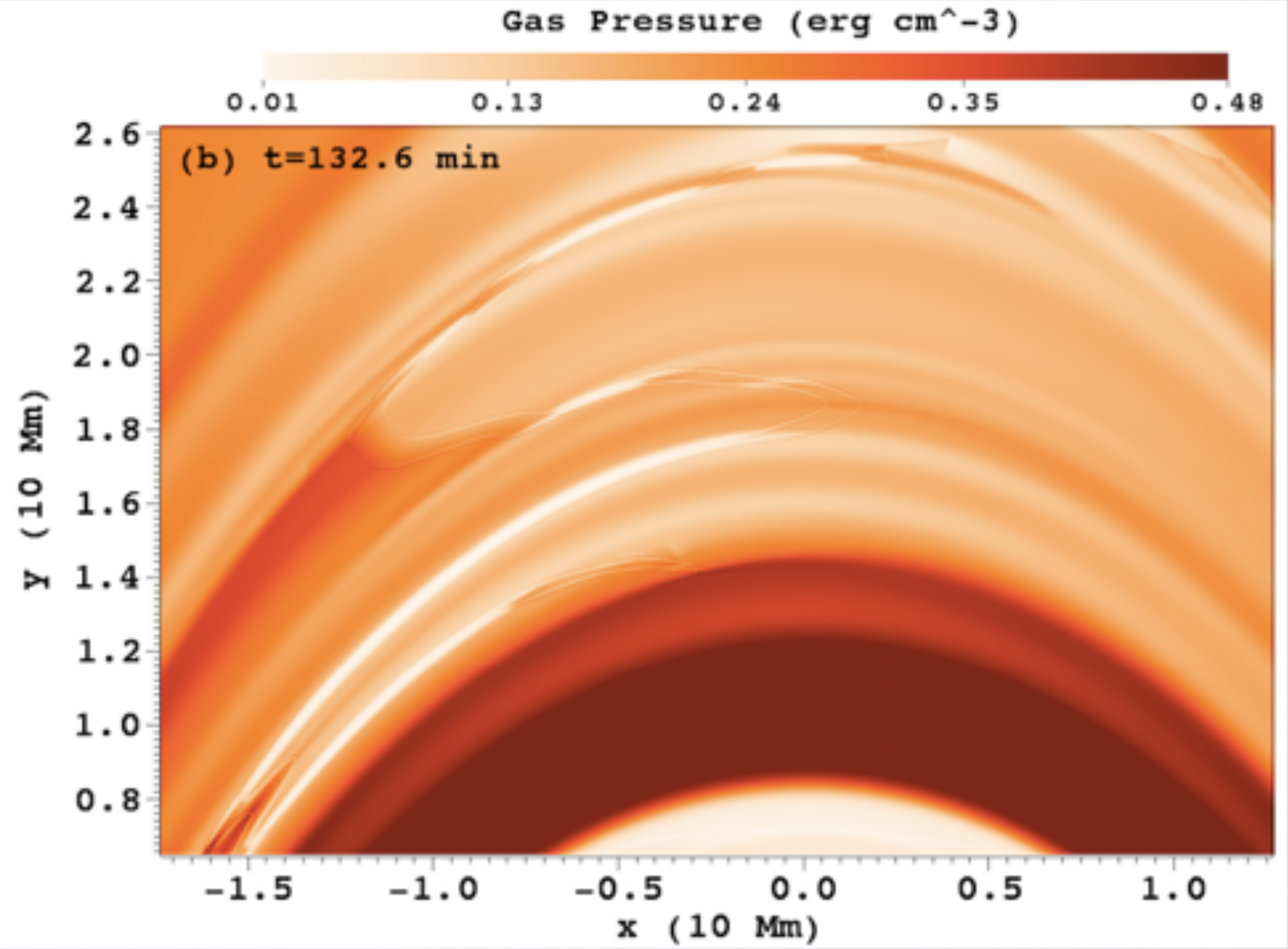


Width and Length of blobs from simulations (top), compared with observational results (bottom) by Antolin et al. 2012

SHEAR FLOWS

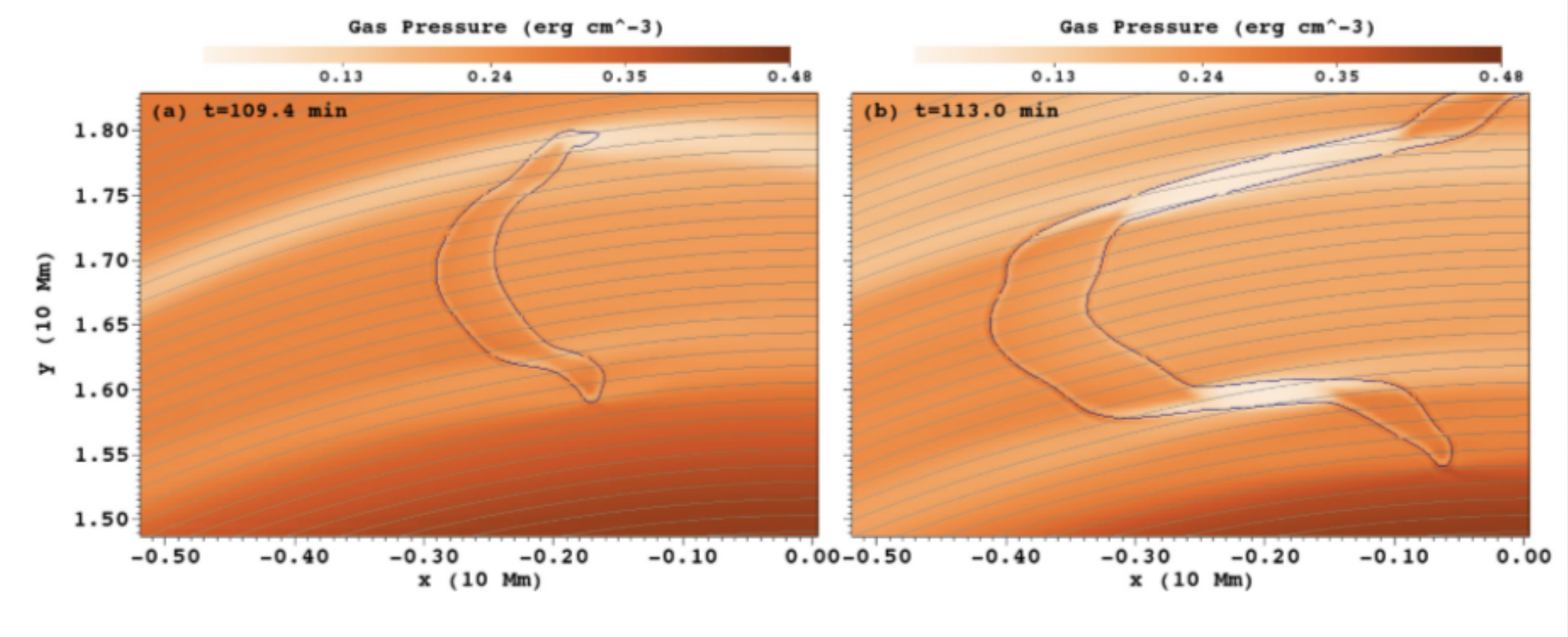


Number Density (10^9 cm^-3)
0.2
2
40
60
80
(c) t=132.6 min
y (10 Mm)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
-1.5
-1.0
-0.5
0.0
0.5
1.0
x (10 Mm)



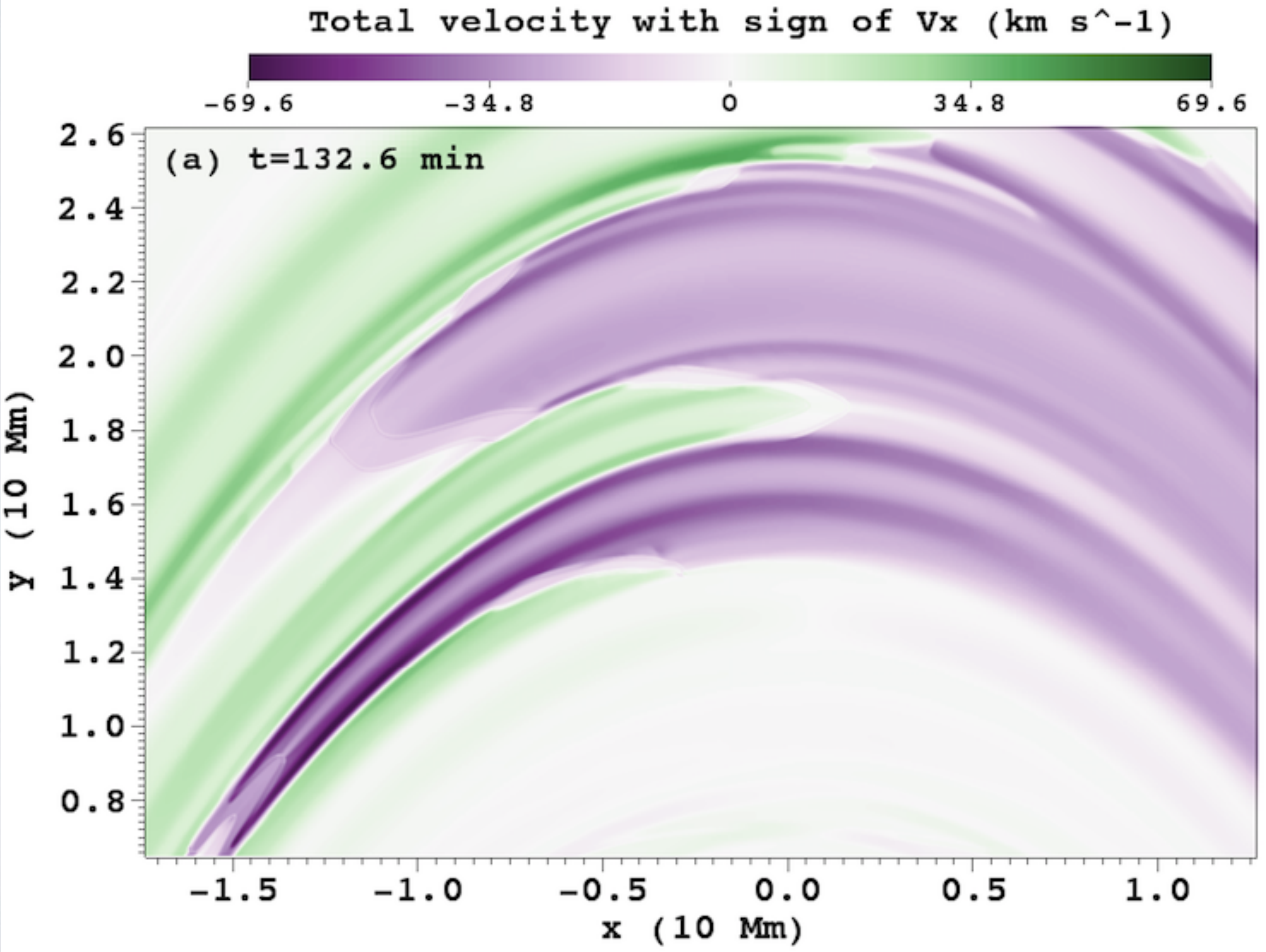
Gas Pressure (erg cm^-3)
0.01
0.13
0.24
0.35
0.48
(b) t=132.6 min
y (10 Mm)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
-1.5
-1.0
-0.5
0.0
0.5
1.0
x (10 Mm)

SHEAR FLOWS

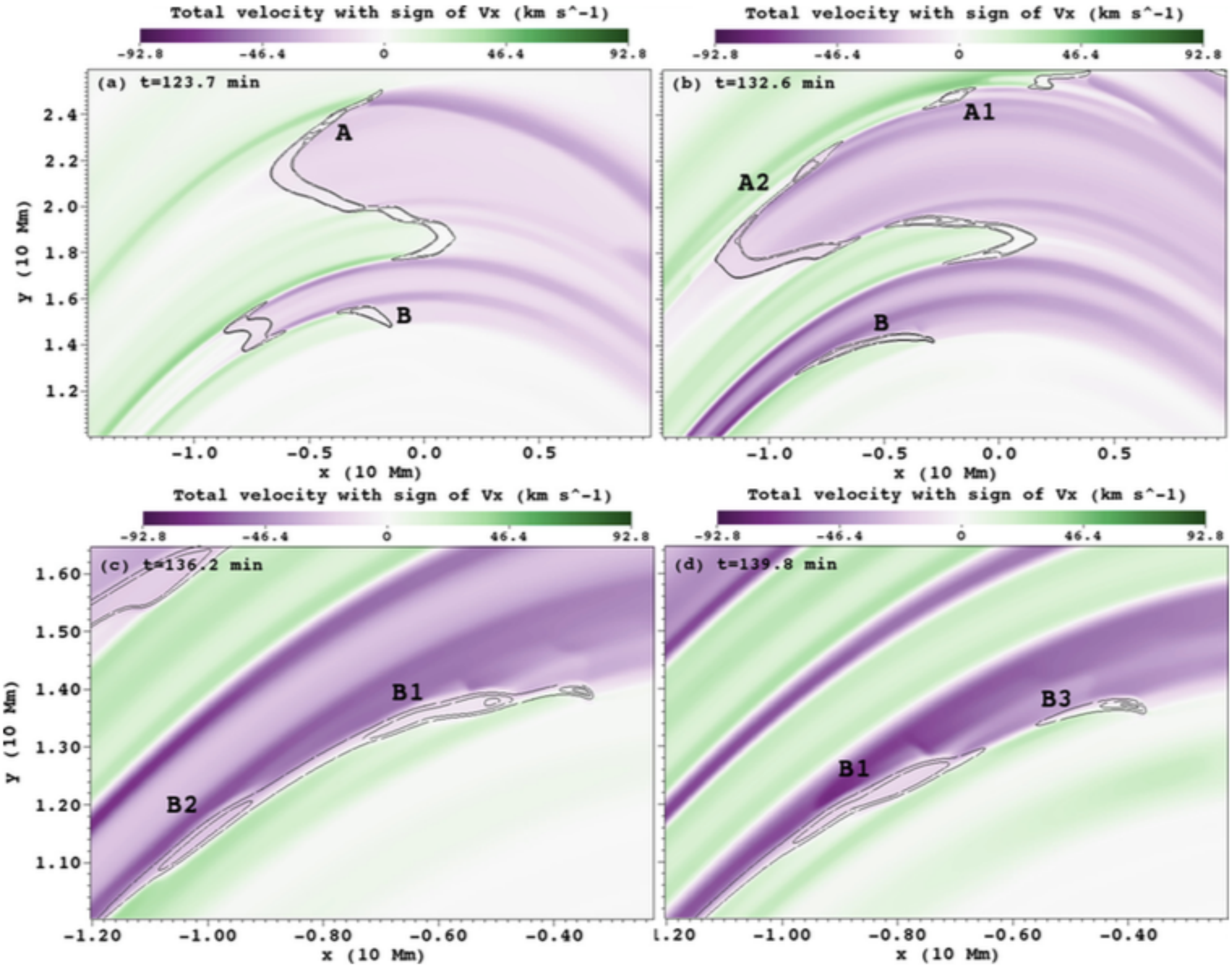


Gas Pressure (erg cm^-3)
0.13
0.24
0.35
0.48
(a) t=109.4 min
1.80
1.75
1.70
1.65
1.60
1.55
1.50
y (10 Mm)
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
x (10 Mm)
Gas Pressure (erg cm^-3)
0.13
0.24
0.35
0.48
(b) t=113.0 min
-0.50
-0.40
-0.30
-0.20
-0.10
0.00
x (10 Mm)

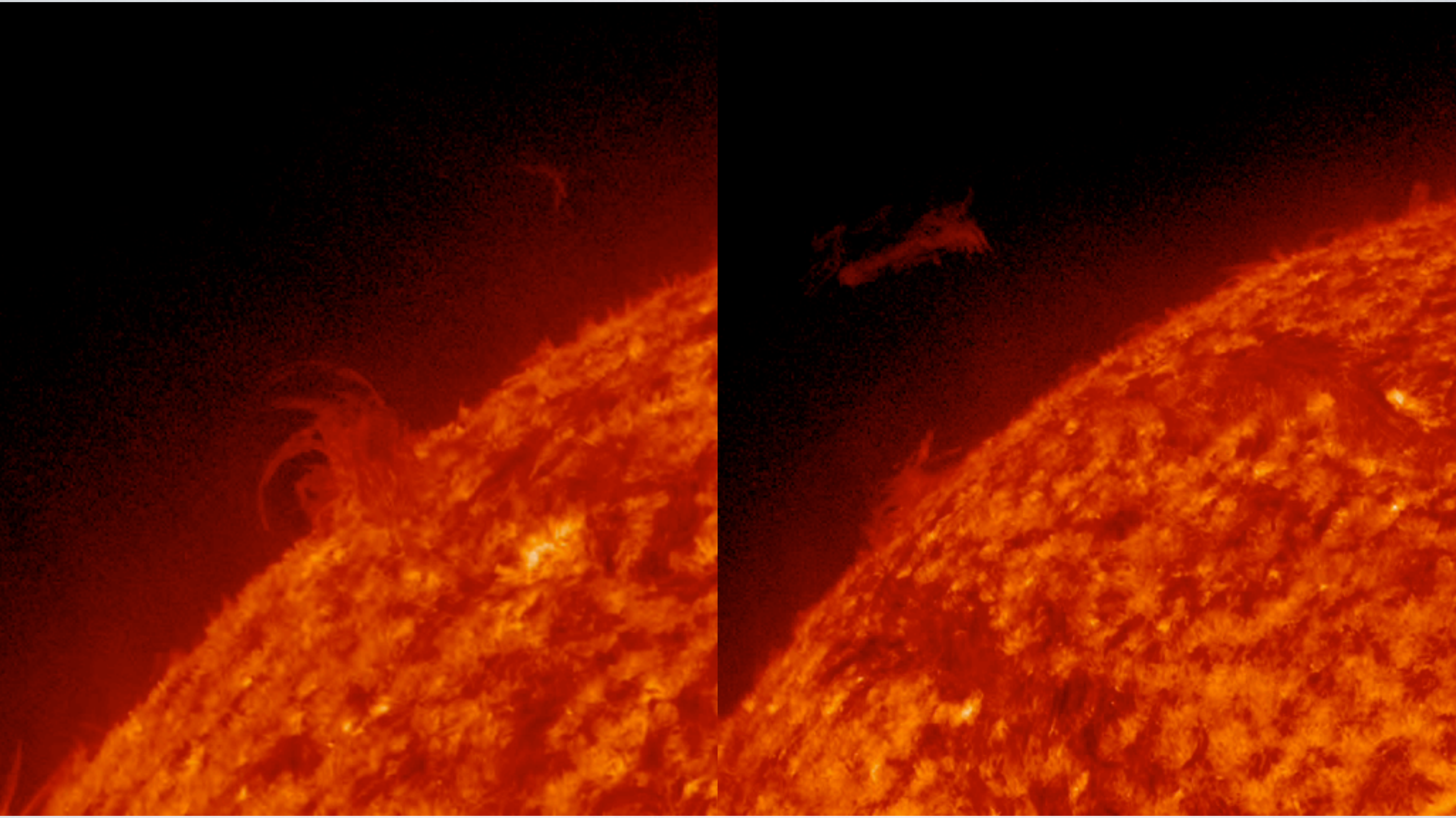
SHEAR FLOWS

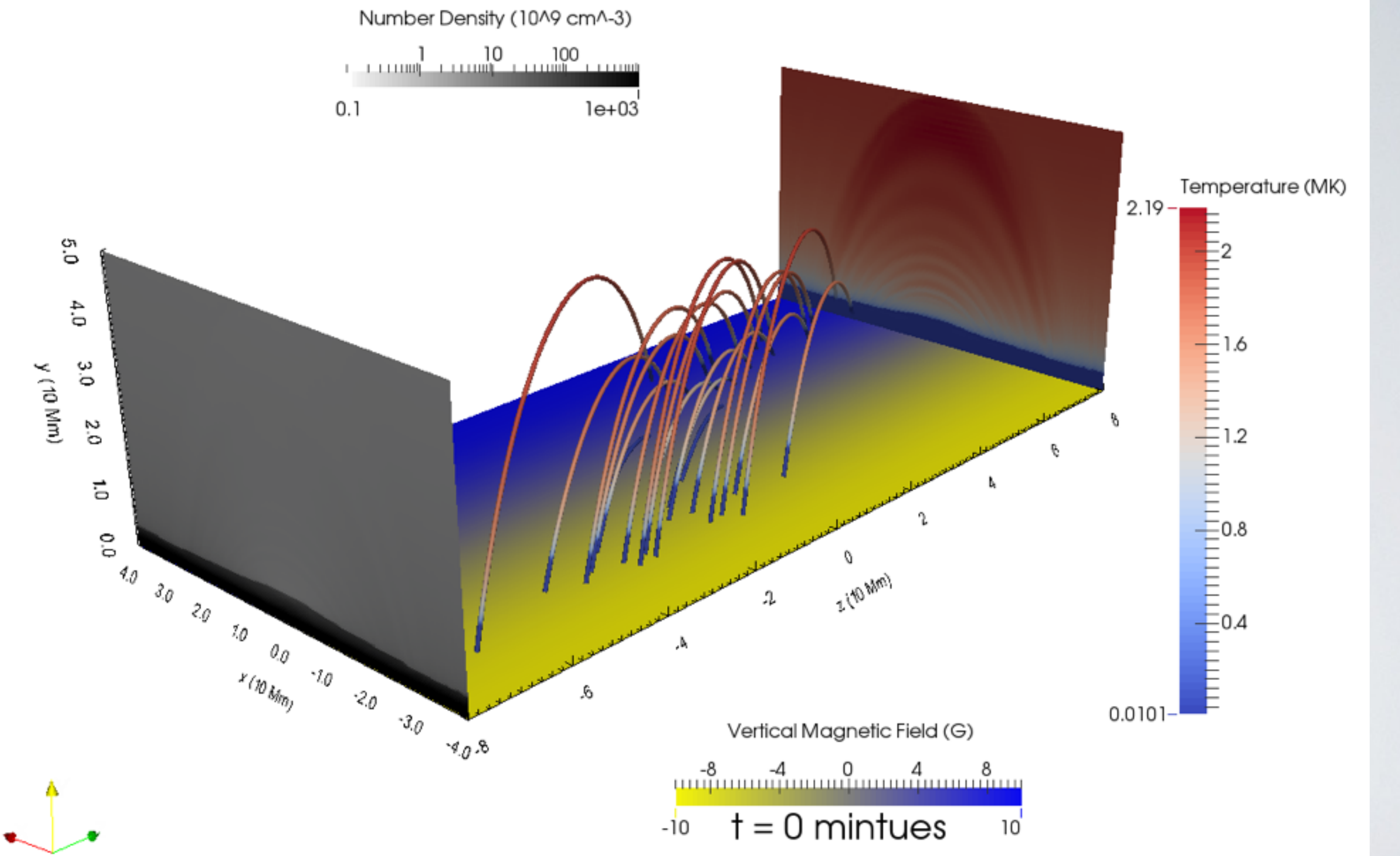


Total velocity with sign of Vx (km s^-1)
-69.6
-34.8
0
34.8
69.6
(a) t=132.6 min
y (10 Mm)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
-1.5
-1.0
-0.5
0.0
0.5
1.0
x (10 Mm)


Total velocity with sign of Vx (km s^-1)
-92.8
-46.4
0
46.4
92.8
(a) t=123.7 min
A
B
y (10 Mm)
x (10 Mm)
(b) t=132.6 min
A1
A2
B
(c) t=136.2 min
B1
B2
(d) t=139.8 min
B3
B1

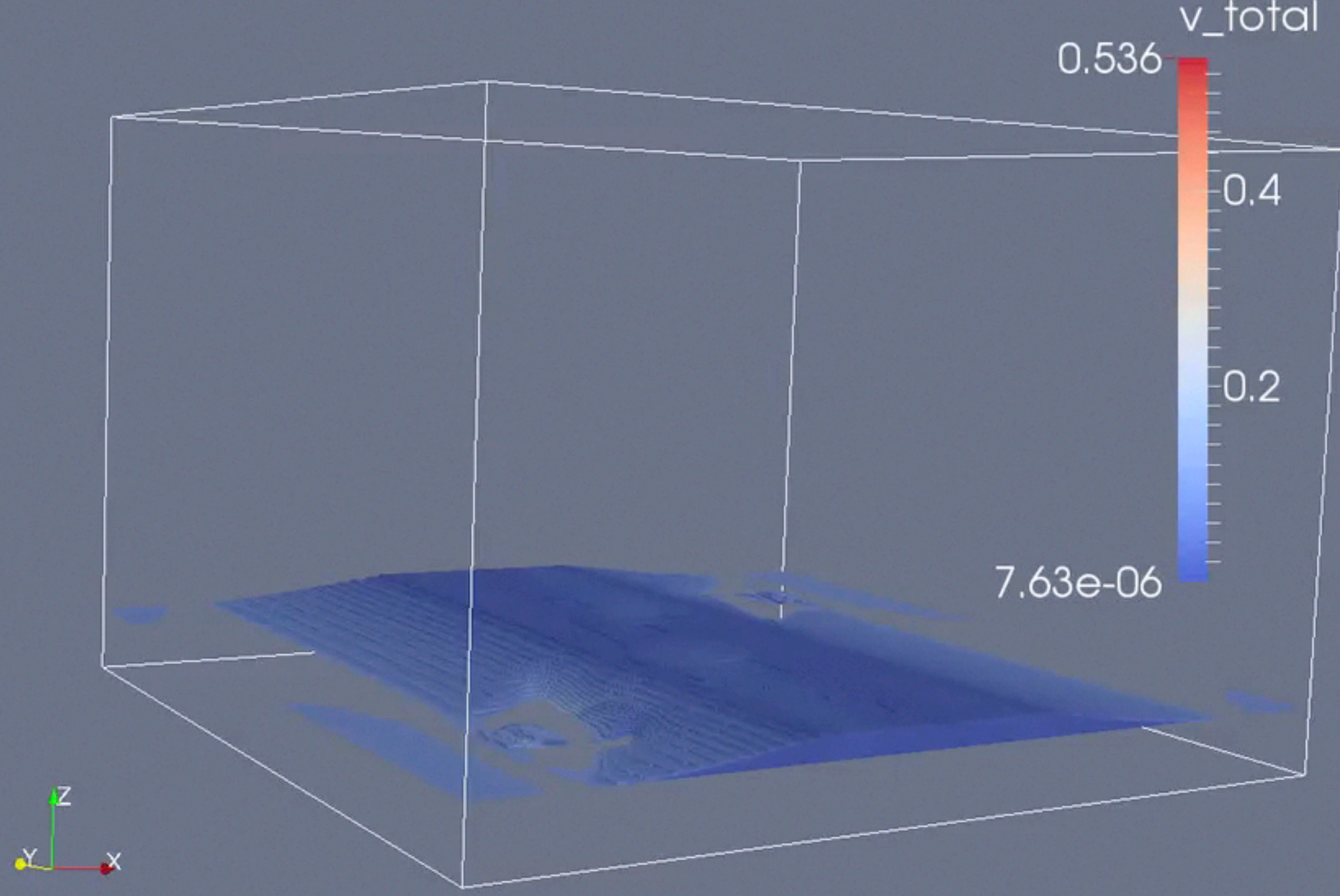
CONCLUSION





Number Density (10^9 cm^-3)
1
10
100
0.1
1e+03
Temperature (MK)
2.19
2
1.6
1.2
0.8
0.4
0.0101
y (10 Mm)
5.0
4.0
3.0
2.0
1.0
0.0
x (10 Mm)
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
z (10 Mm)
-8
-6
-4
-2
0
2
4
6
8
Vertical Magnetic Field (G)
-8
-4
0
4
8
-10
10
t = 0 mintues

Density colored with total velocity



3D Prominece Formation with a Coronal Cavity

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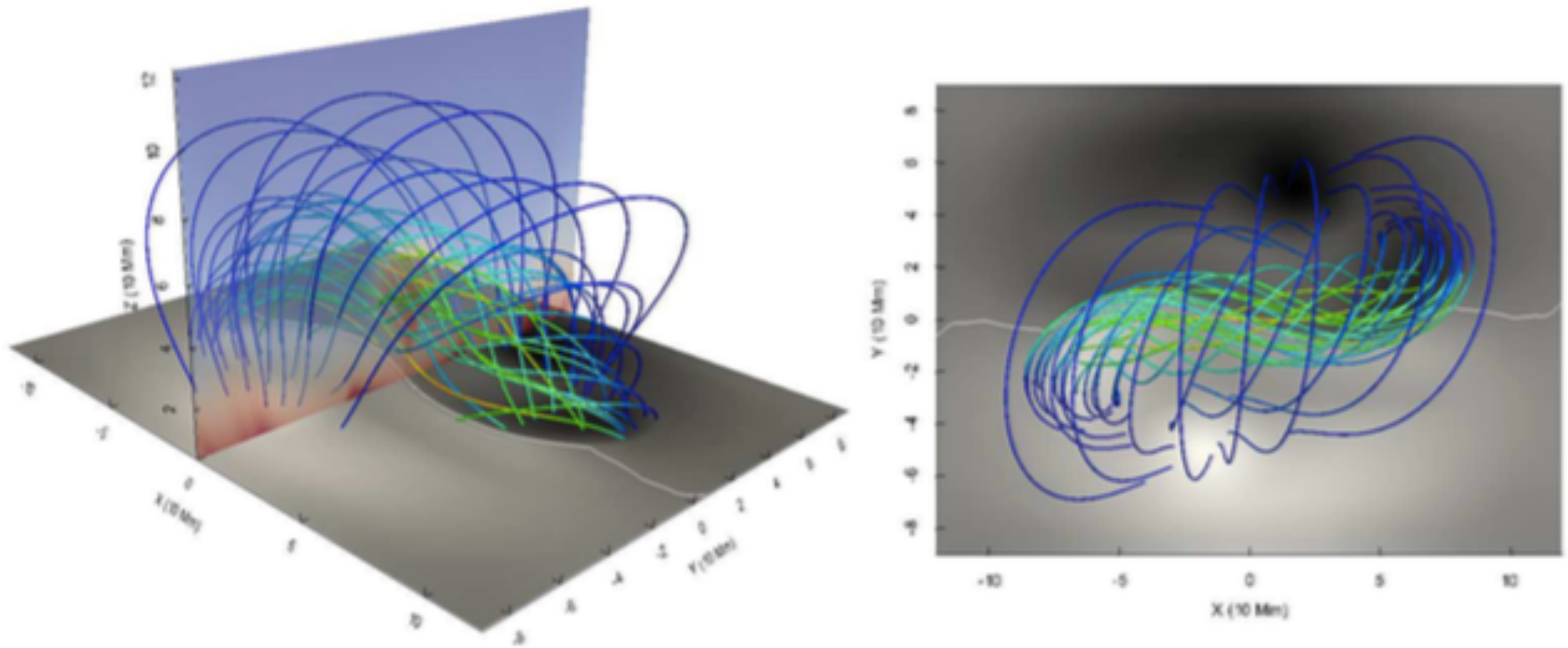
[2]National Astronomical Observatory of Japan
[3]Department of Applied Mathematics, University of Leeds

Nanjing, June 27, 2014

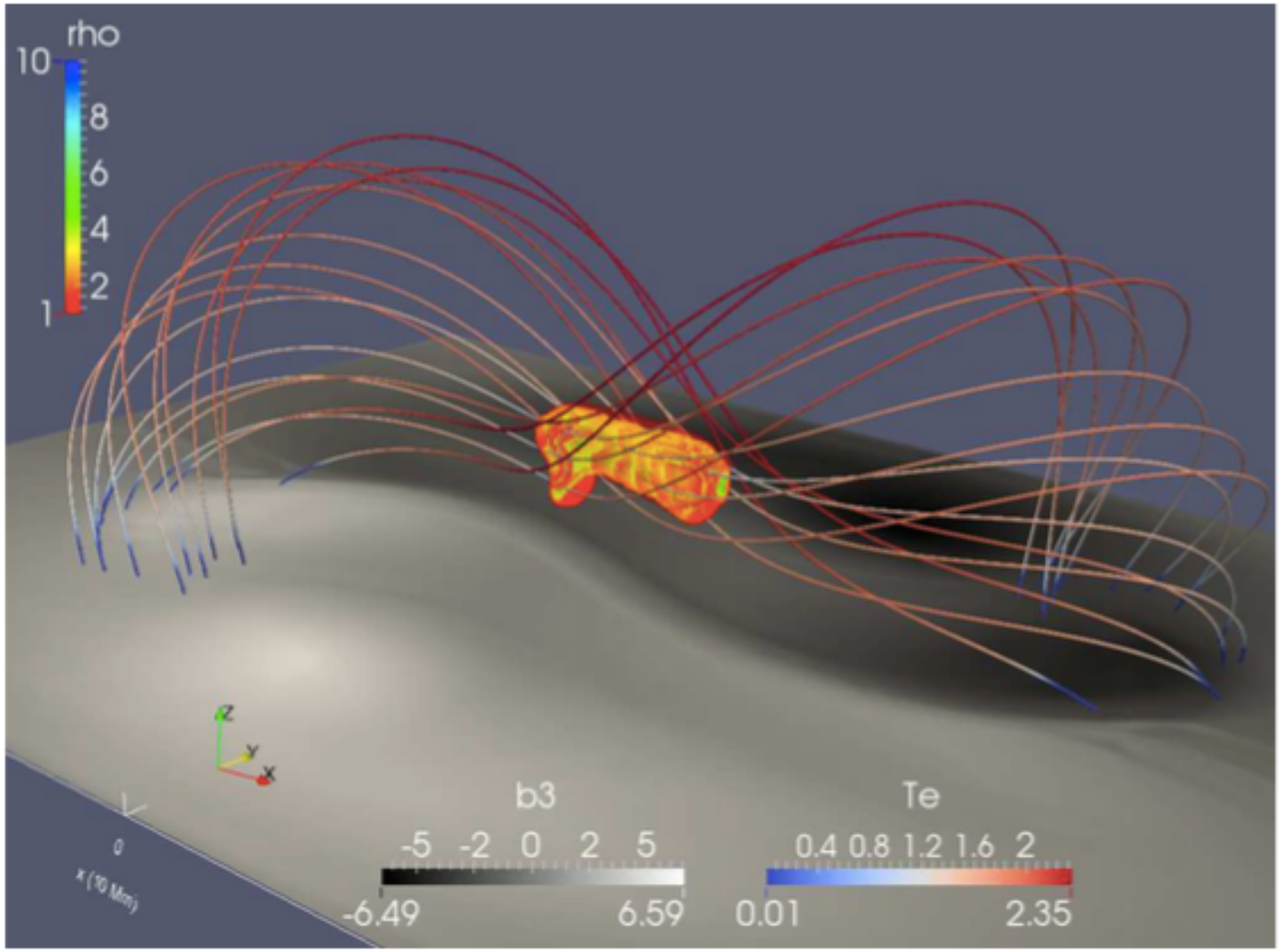
Initial conditions



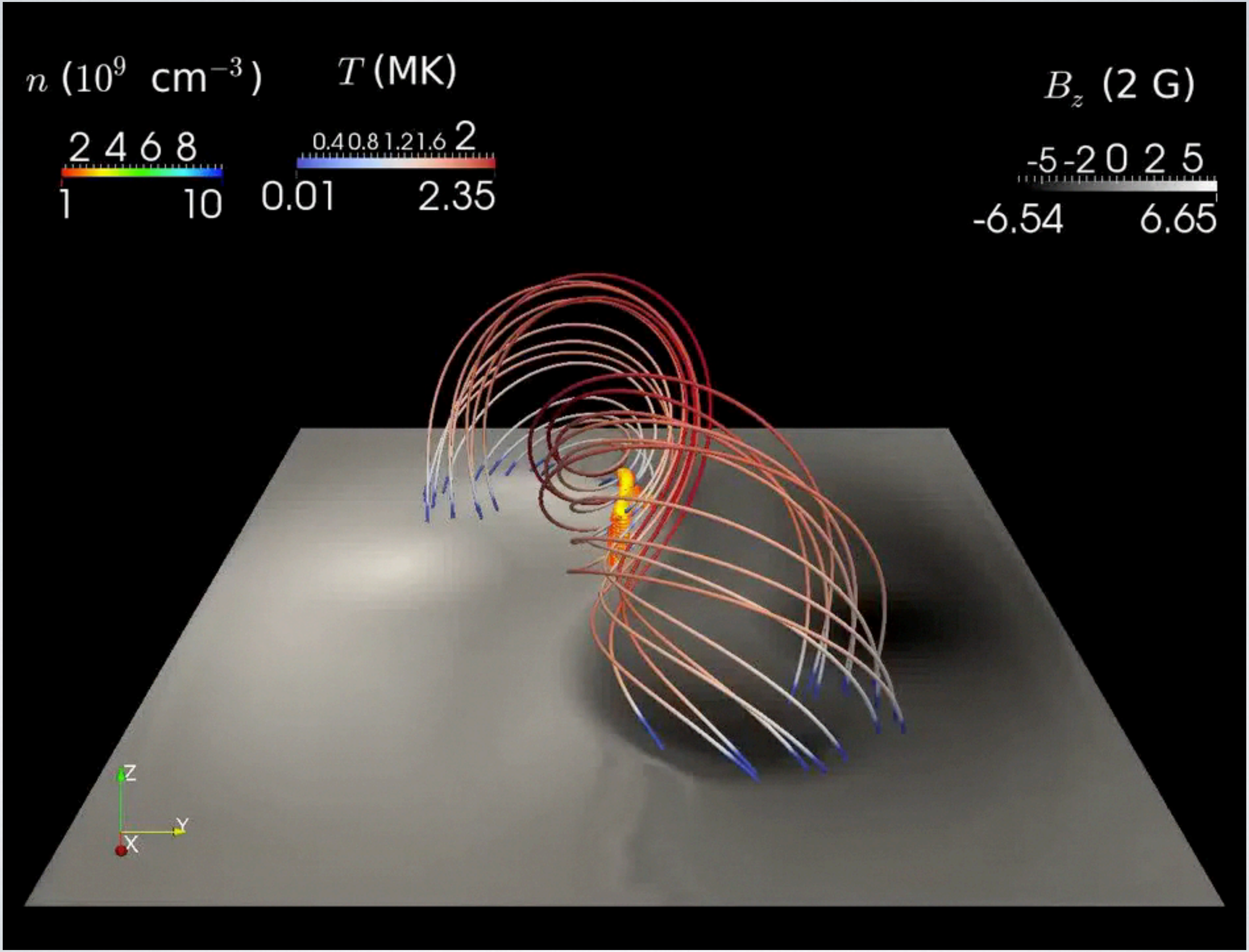
- restart from the isothermal flux rope with the additional variable of total energy
- Cartesian 3D box, horizontal axes x (-120,120) Mm and y (-90,90) Mm, vertical axis z (3, 123) Mm
- create a chromosphere: rewrite temperature $T(z)$ (10000 K) and density $\rho(z)$ according to hydrostatic stratification in the bottom layer with thickness of 4 Mm

First 3D prominence formation

Time: 115 mins; Density threshold for condensation: 3×10^{9} cm^{-3}

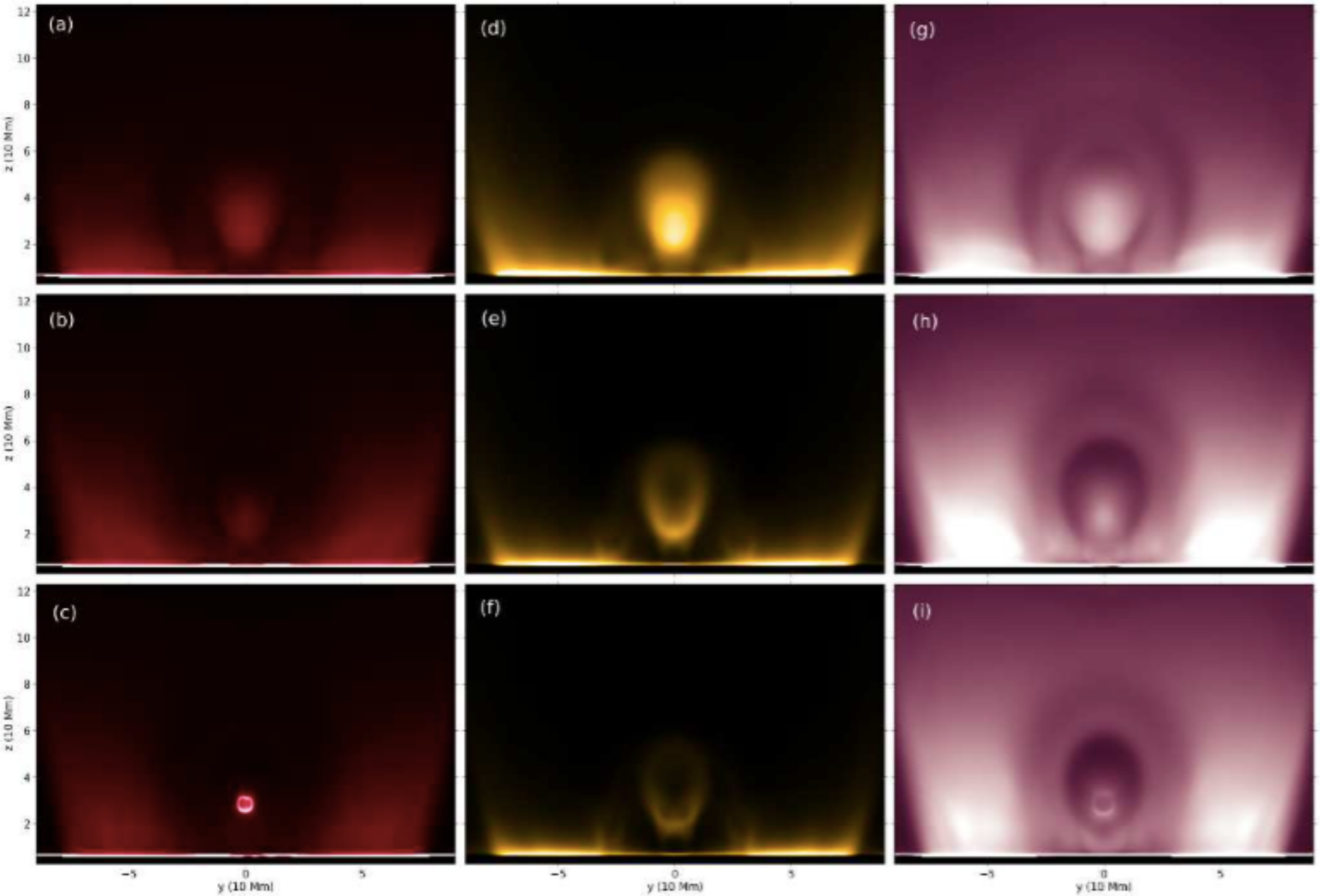


size: 30 Mm length, 16 Mm tall, 4.5 Mm thick, extends to 26 Mm height

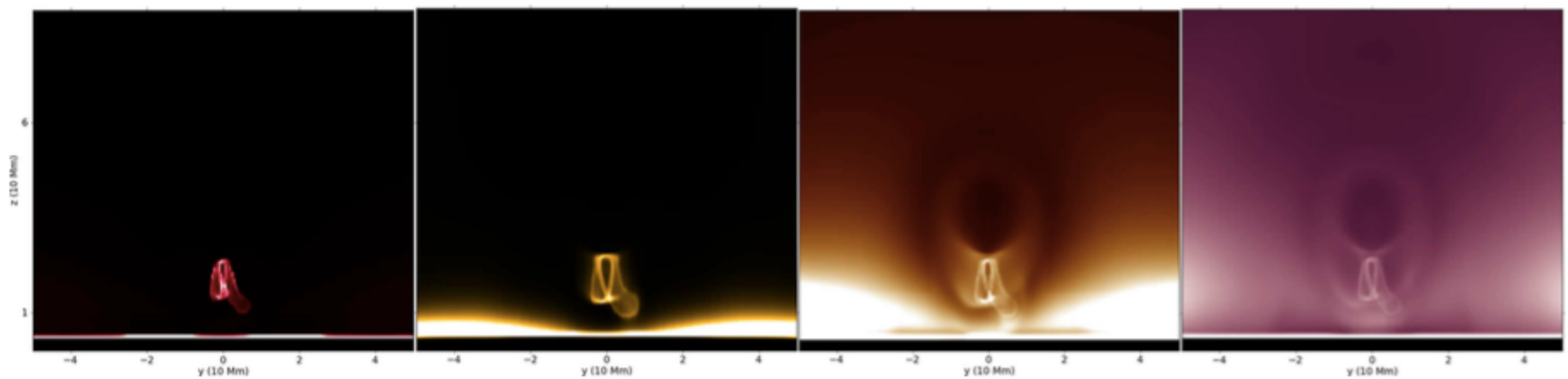


n (10^9 cm^{-3})
2 4 6 8
1 10
T (MK)
0.4 0.8 1.2 1.6 2
0.01 2.35
B_z (2 G)
-5 -2 0 2 5
-6.54 6.65
Z
Y
X

Dynamic condensation in AIA synthetic views

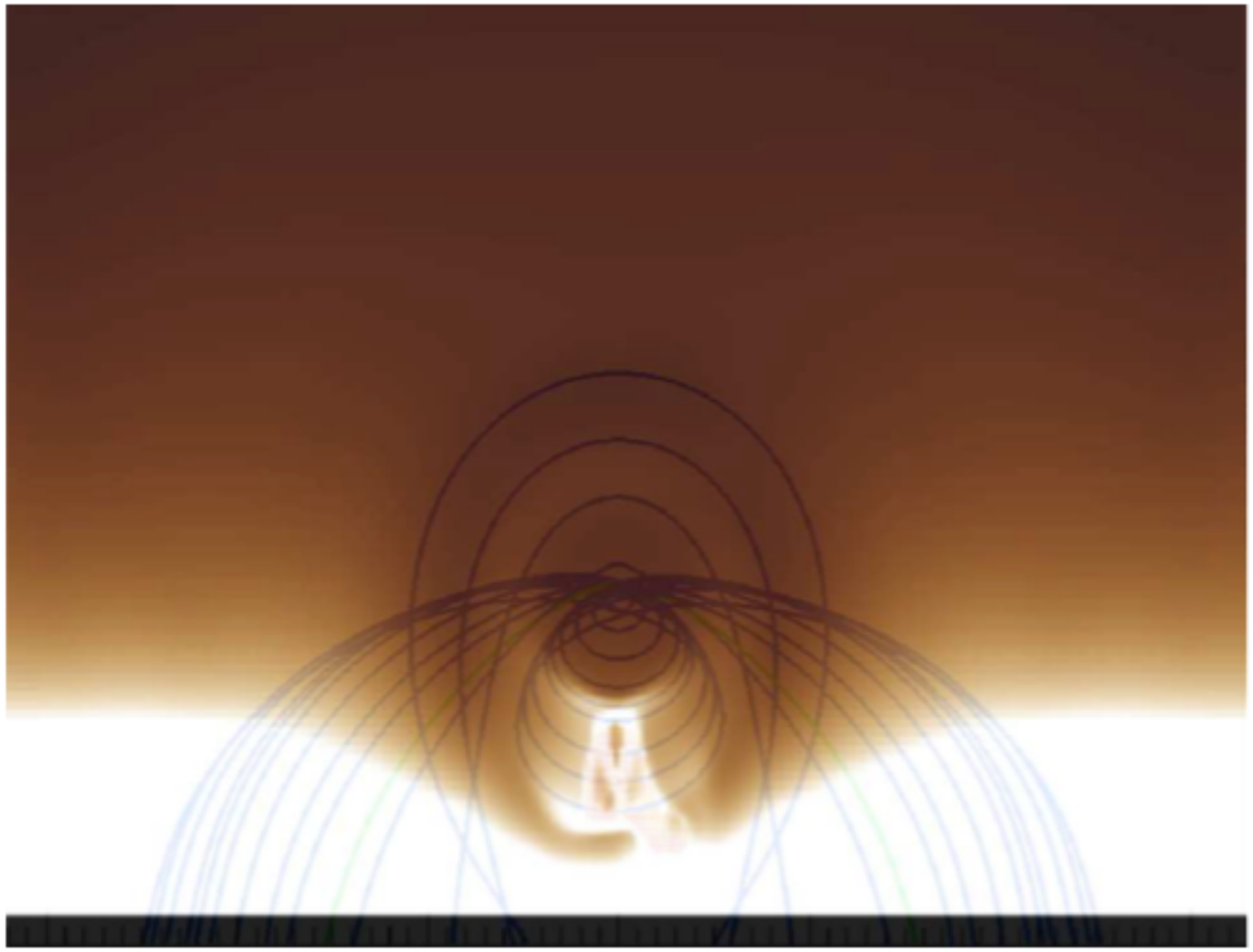


AIA synthetic views of the prominence and cavity



- The PCTR is bright all four EUV bands
- Protruding tail ('barb') extends to lower altitude
- "horns" extend from the top of the prominence to the upper cavity in 193 and 211 bands
- density depletion in the cavity (20–30 %), 2 MK temperature

Magnetic topology of cavity



- prominence-loaded field lines maintain denser coronal plasma than prominence-free field lines
- magnetic structure changes smoothly from the prominence to the cavity

THANK YOU FOR ATTENTION

Governing Equations of Radiative Hydrodynamics

- 1D radiative hydrodynamic equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial s}(\rho v) = 0, \tag{1}$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial s}(\rho v^2 + p) = \rho g_{\parallel}, \tag{2}$$

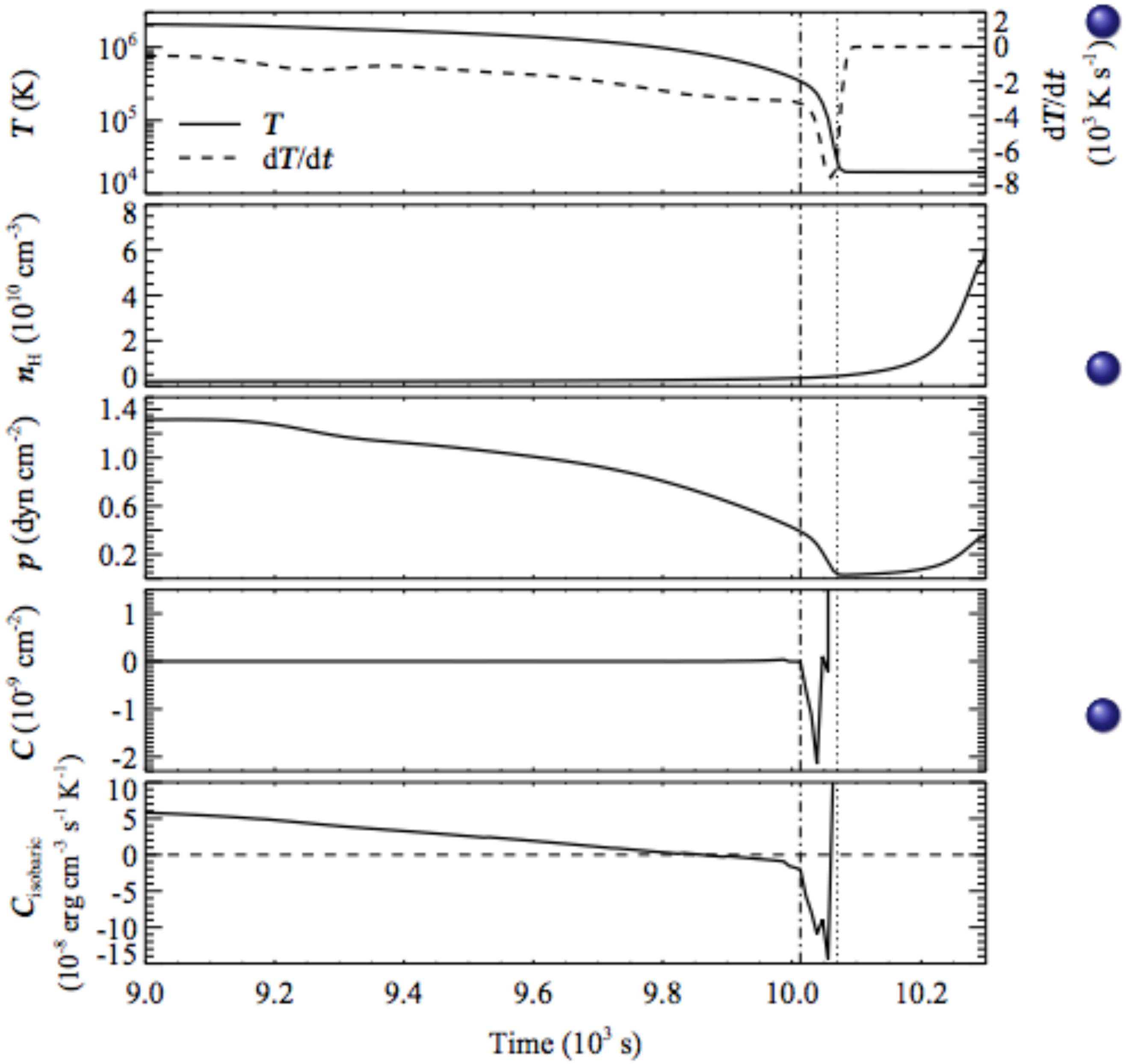
$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial s}(Ev + pv) = \rho g_{\parallel} v + H - R + \frac{\partial}{\partial s}\left(\kappa \frac{\partial T}{\partial s}\right). \tag{3}$$

$$\tag{4}$$

- $E = \rho v^2/2 + p/(\gamma - 1)$, $p = 2.3 n_{\mathrm{H}} k_{\mathrm{B}} T$, $R = n_{\mathrm{H}} n_{\mathrm{e}} \Lambda(T)$, $\gamma = 5/3$, $\kappa = 10^{-6} T^{5/2}$

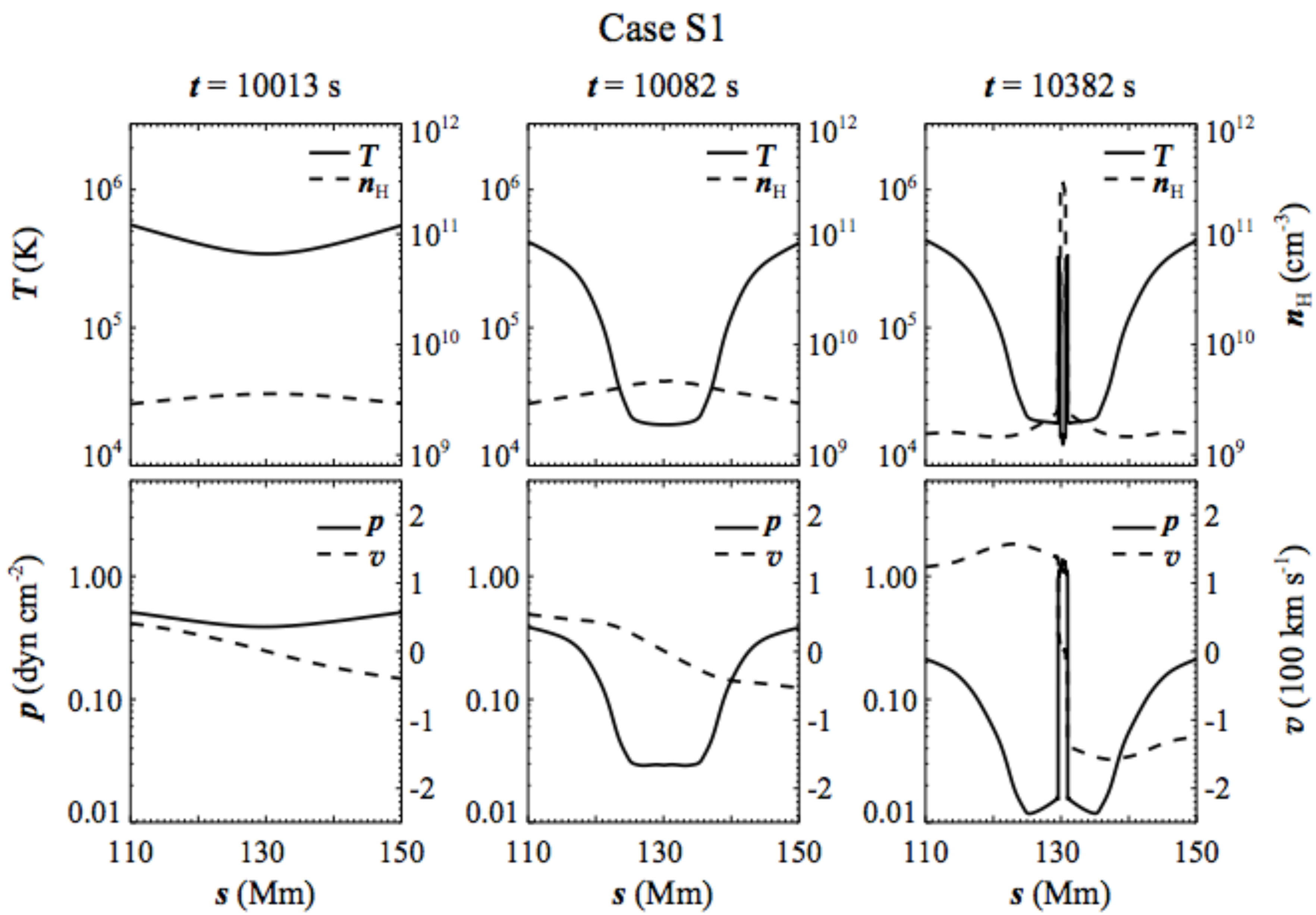
Evidence of thermal instability

Evolution of loop center in case S1

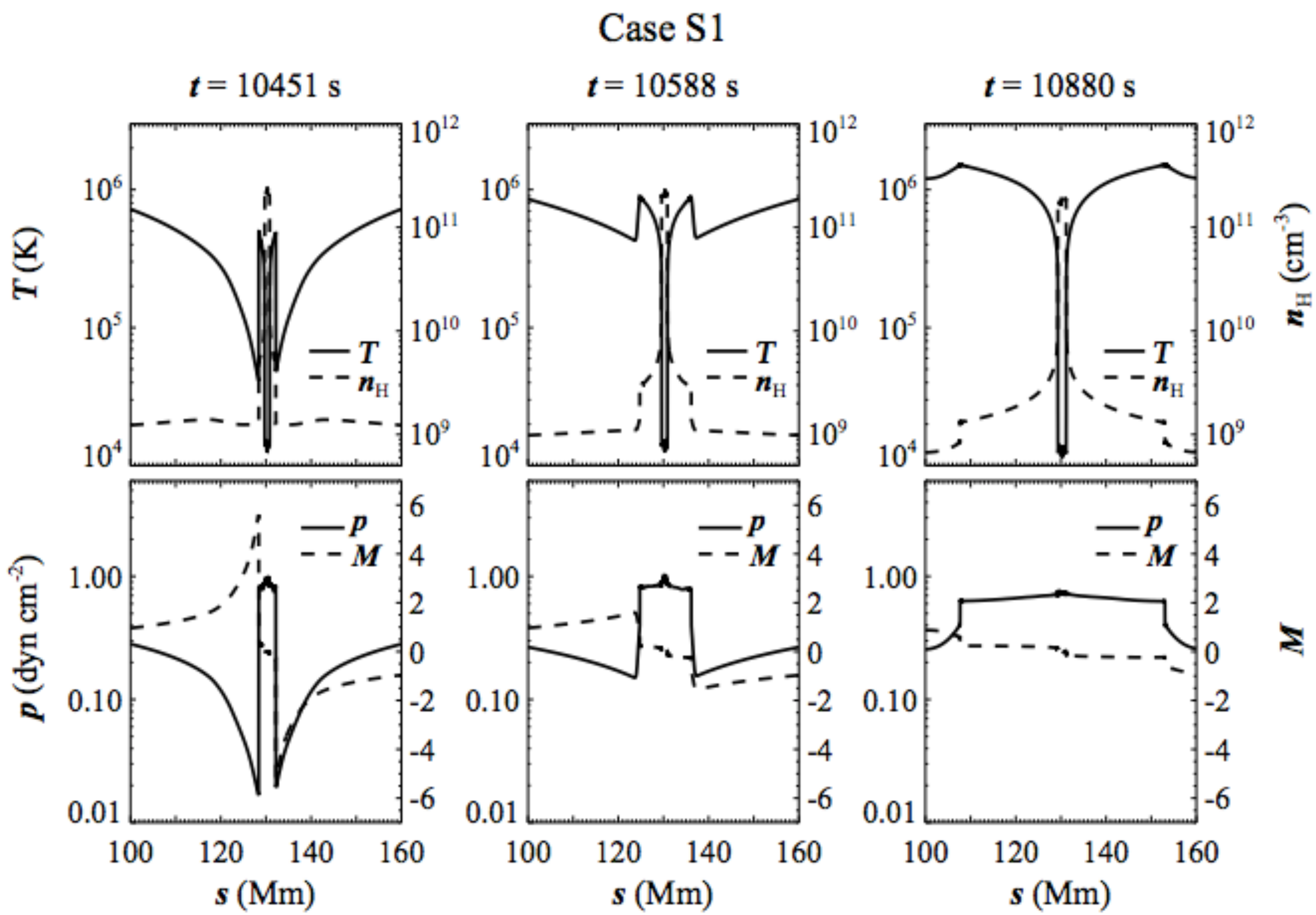


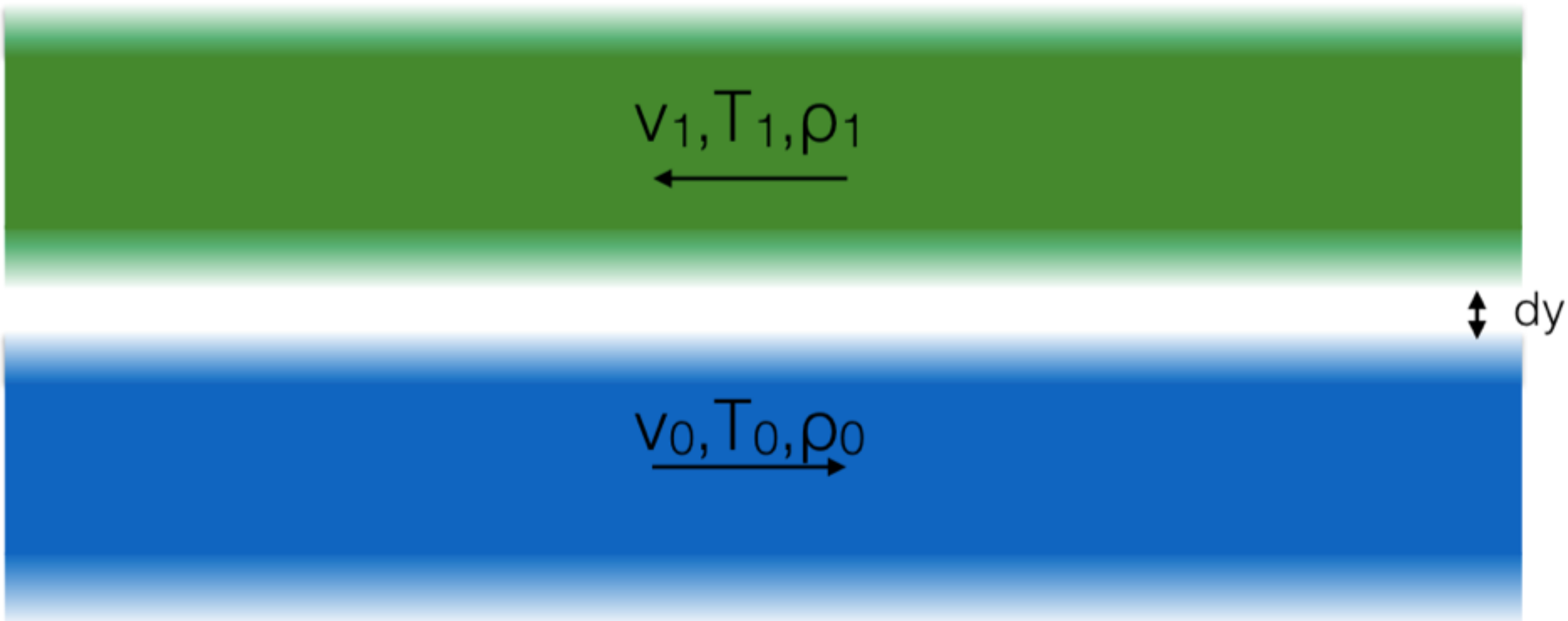
- isochoric thermal instability criterion (Parker 1953):
  $$C \equiv k^2\kappa - \frac{\partial H}{\partial T} + \frac{\partial R}{\partial T} < 0$$
- The criterion turns to significantly negative when catastrophic cooling.
- Isobaric criterion (Field 1965) is not appropriate.

Details of the Condensation



Propagating Shocks





$dy << 1,\ \rho_0/\rho_1 \sim 1, v_0 \sim v_1$