Modeling of Coronal Rain

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What we know about coronal rain

Observation:

•Flows, not waves
•Cool plasma (~ 10^4 K)
•Rapidly produced in the corona (timescale of minutes)
•Falls down to the chromospheres along loop-like paths
•Seems to elongate as it falls
•Falling speeds are lower than free fall
(Schrijver et al. 2001; De Groof et al. 2004, 2005; O'Shea et al. 2007; Antolin et al. 2010, 2011, 2012)

First reported:
Kawaguchi (1970)
Leroy (1972)

1D Simulations:

•Thermodynamic evolution in individual field lines (Goldsmith 1971; Antiochos & Klimchuk 1991; Antiochos et al. 1999).
•Catastrophic coolingŦ sets in locally, rapid formation of condensations
(Karpen et al. 2001; Mueller et al. 2003, 2004, 2005; De Groof et al. 2005; Antolin et al. 2010; Xia et al. 2011)

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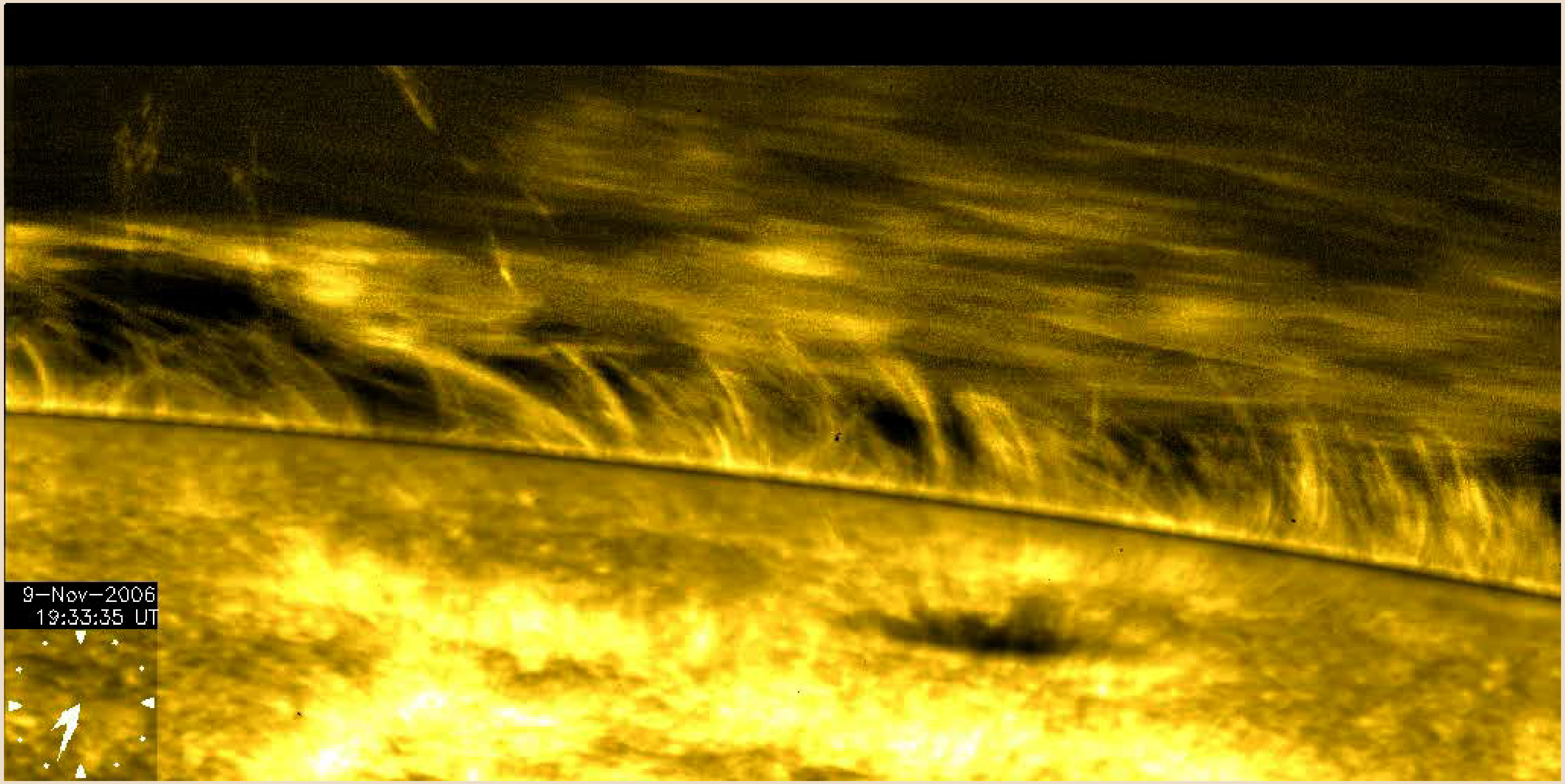
Open questions

- Is it a common active region phenomenon?
  (Klimchuk et al. 2010; Kamio et al. 2011; Antolin et al. 2011, 2012)
- Link to coronal heating? (Antolin et al. 2010)
  - Footpoint heating or coronal heating
- Morphology of magnetic field structure

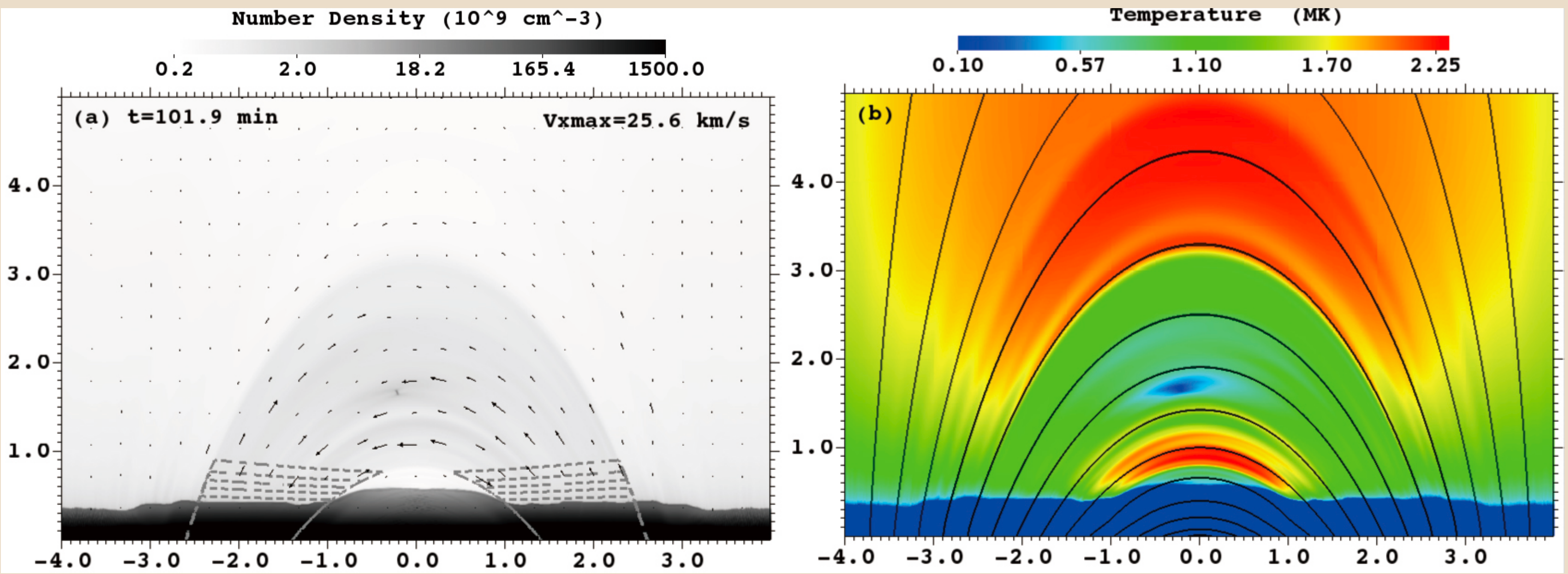


Model

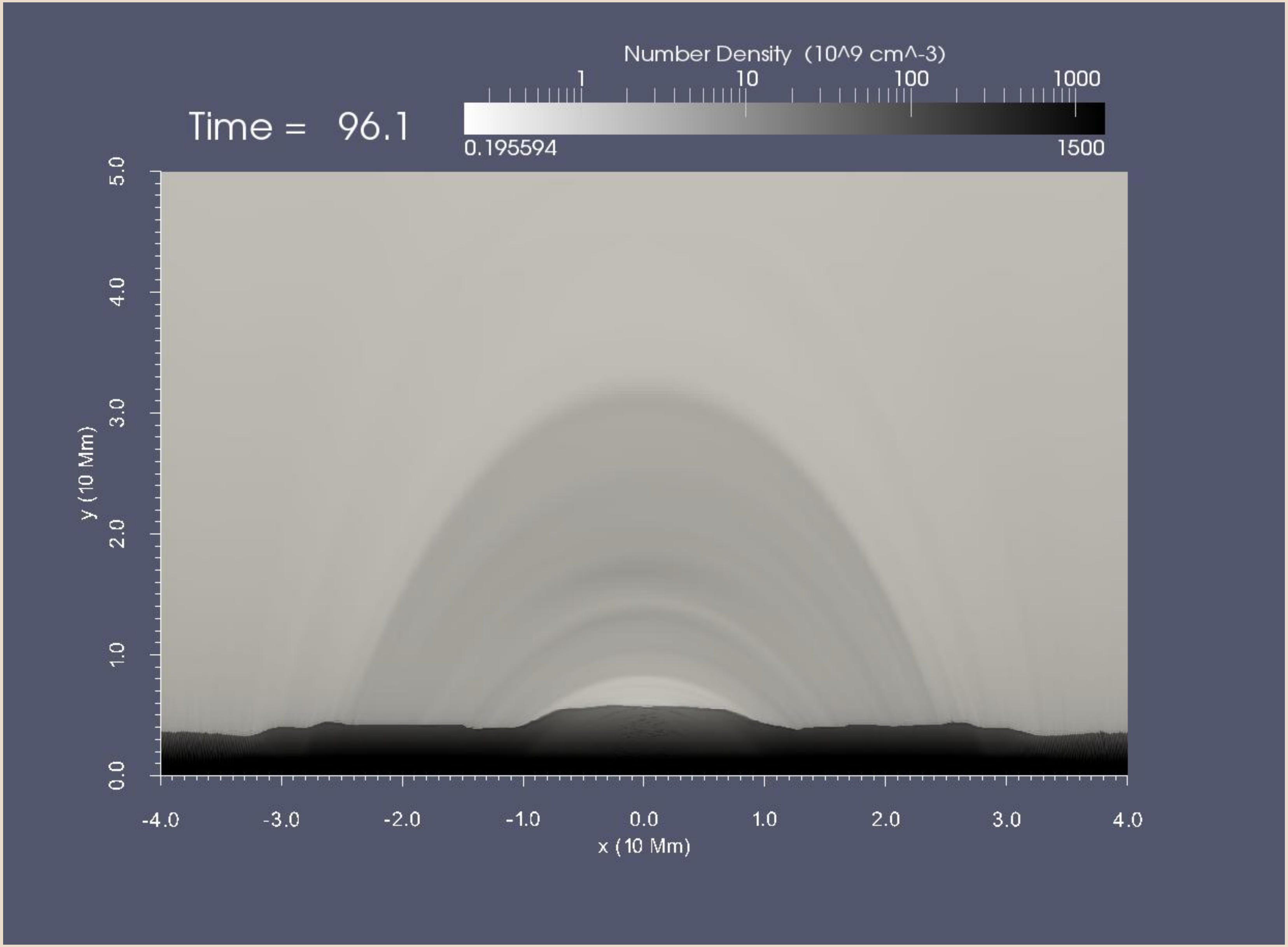
- A 2.5D MHD model (AMRVAC, Keppens et al. 2012)
- A linear force-free magnetic field (B0=12 G, theta=30 d)

- A background heating rate decaying exponentially with height
  - Relaxation to get a state (with max V < 5km/s)

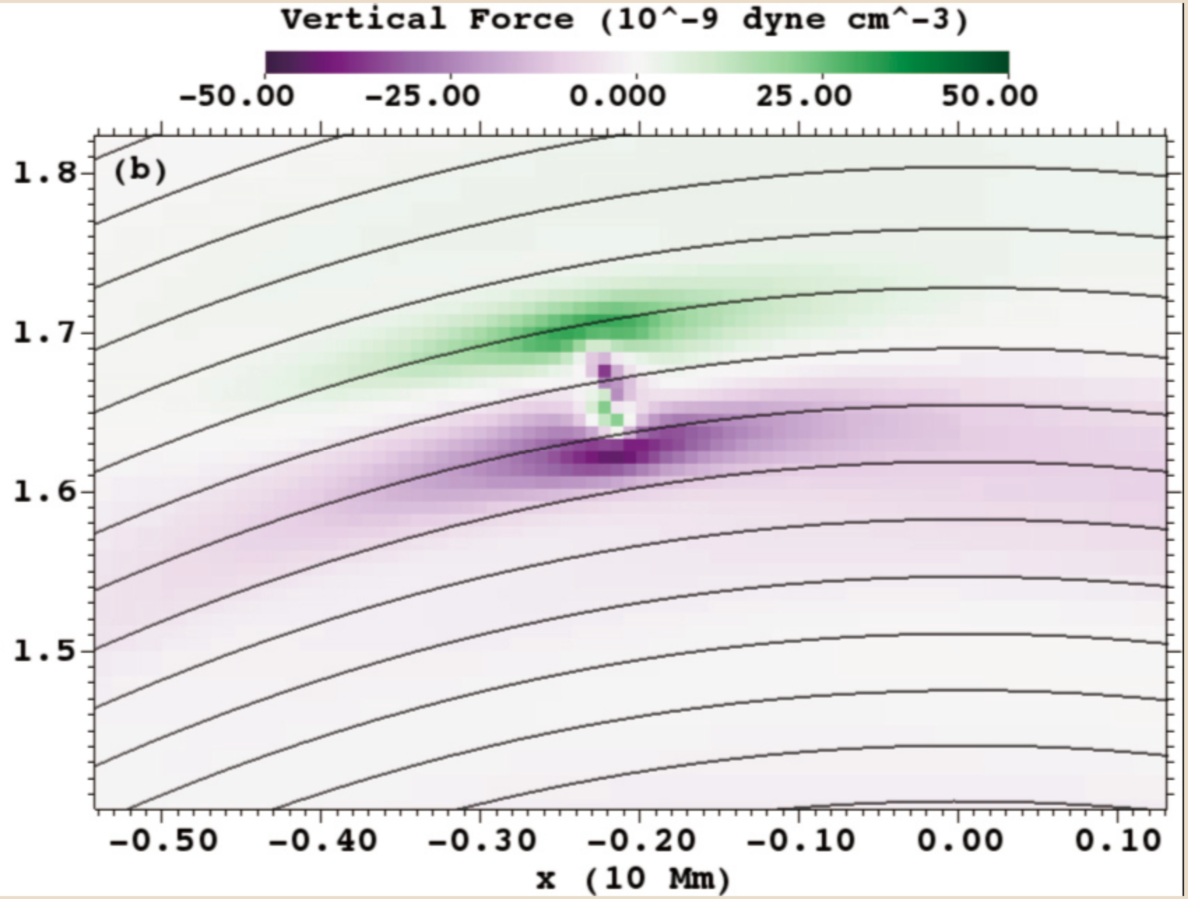
- Extra heating is localized near the chromospheres



Result: movie



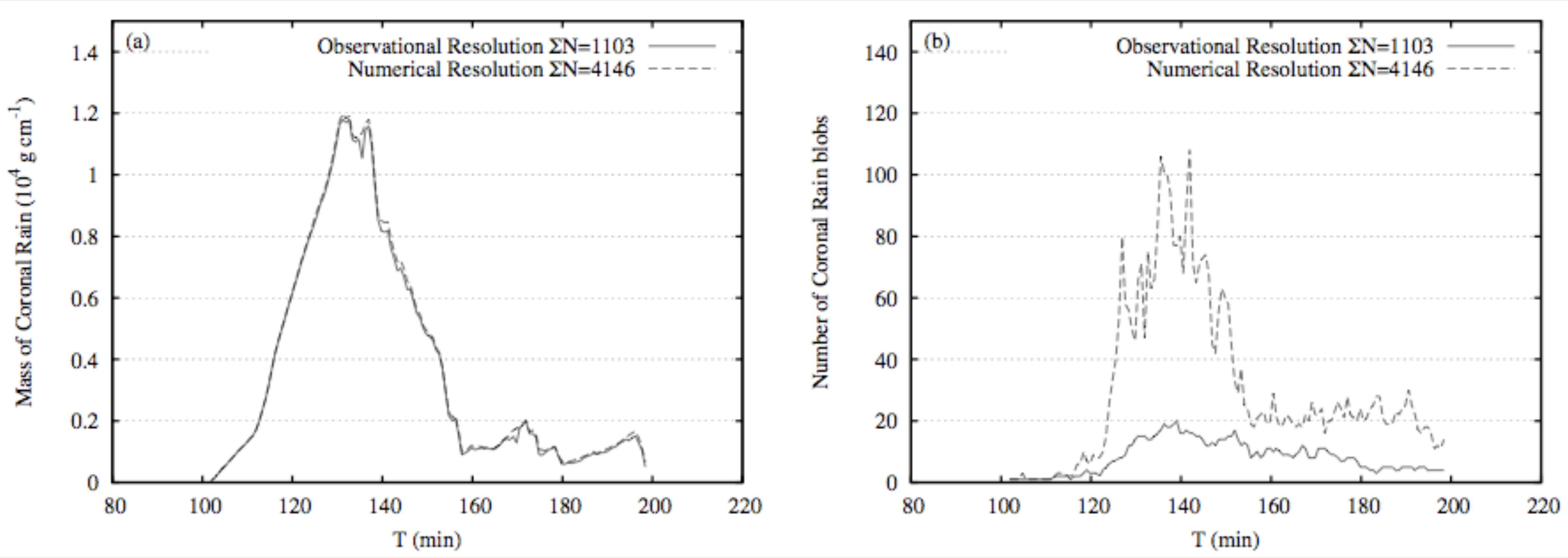
Multi-D Effect



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

- The perturbed force field over 1 Mm in width
- Dominant about equal pressure and Lorentz force contributions
- Induces field variations on neighboring fieldlines
- Similar condensation processes continuously arise on both ends of the first one.

Statistics

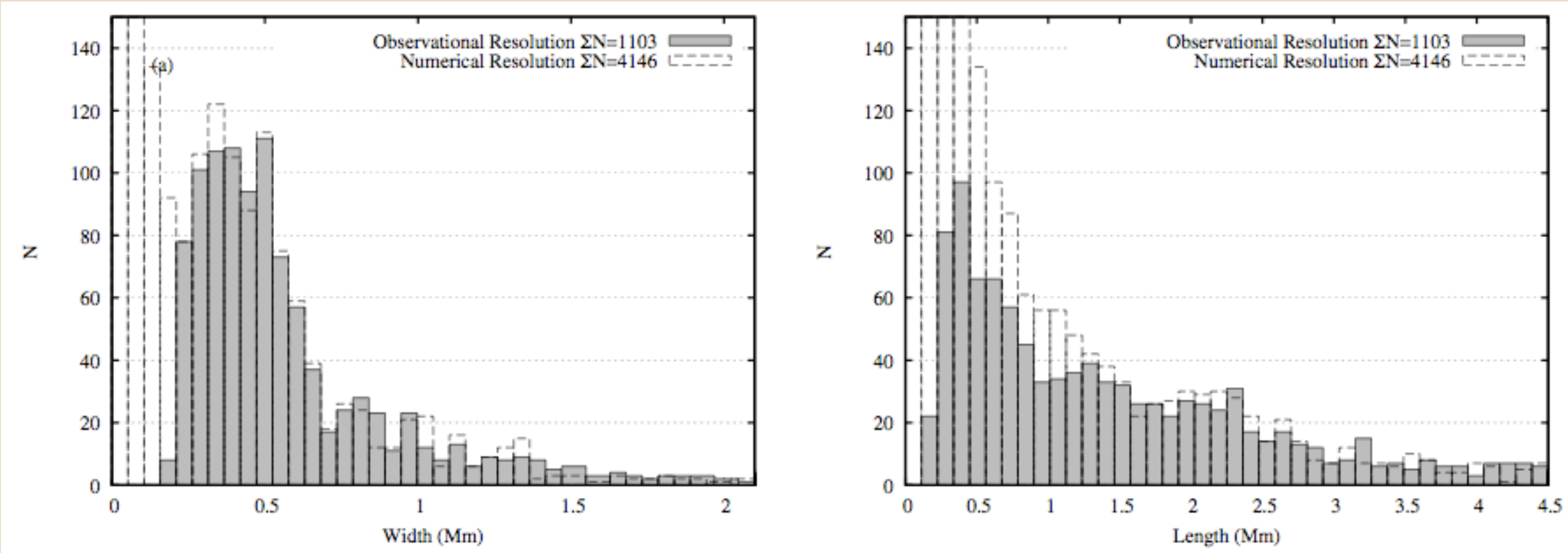


(Total mass) (Number of blobs)

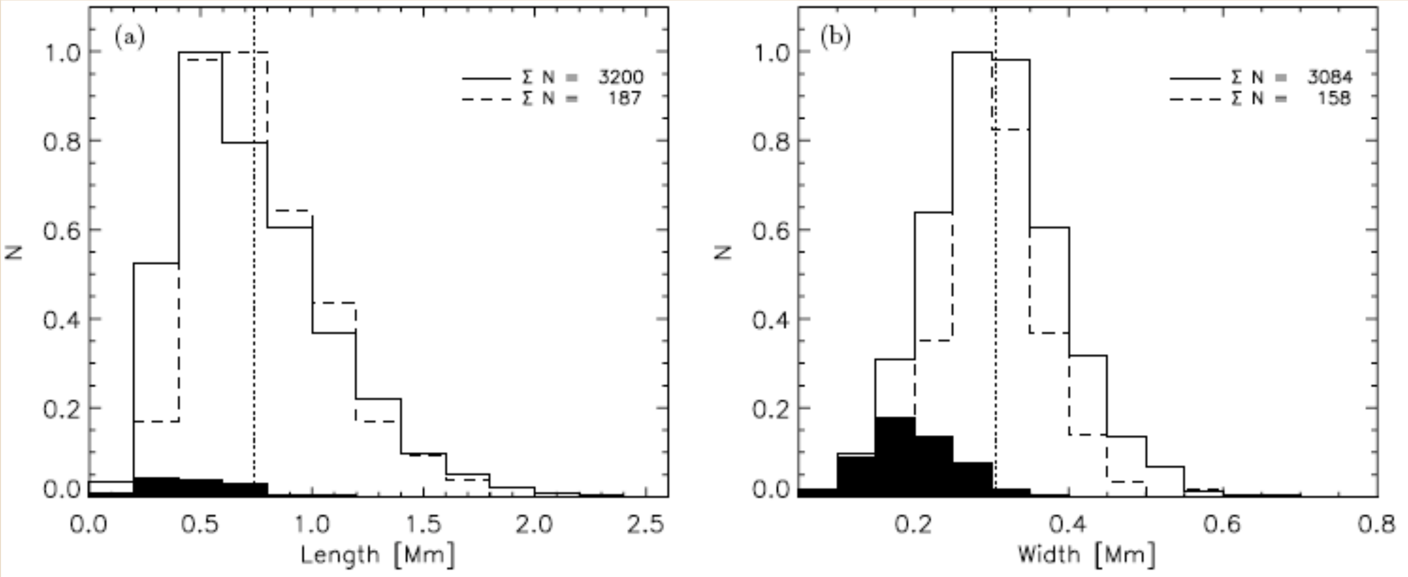
1. Form a zigzag rope
2. Display a spectacular of fragmenting, forming plasma blobs, loose balance slide down along magnetic lines.
3. After about 160 minutes, due to the depletion of plasma in loops, the subsequent phase seems less vigorous. (Antolin et al. 2010; Antolin & Rouppe van der Voort 2012)

- Interpreted as 'limit cycles of loop evolution' by Mueller et al. (2003).
- Many small blobs are unresolved by recent observational instruments (in prepare)

Statistics



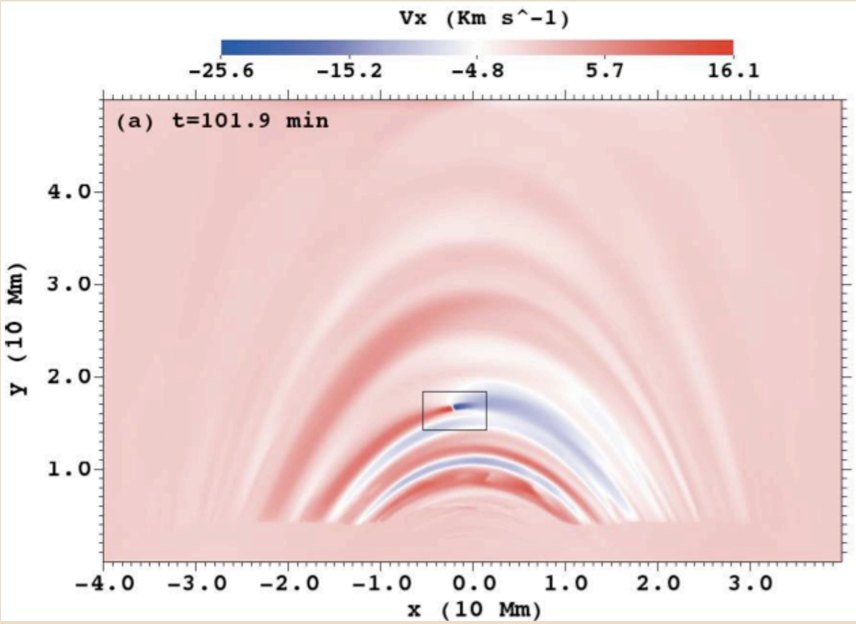
(left) and (right) show the distribution function of width and length (numerical and observational resolution



Normalized histograms for the lengths (left) and widths (right) of the condensations. The solid and dashed lines correspond to off-limb and on-disk blobs, respectively.

Antolin et al. 2012

V-shape blobs



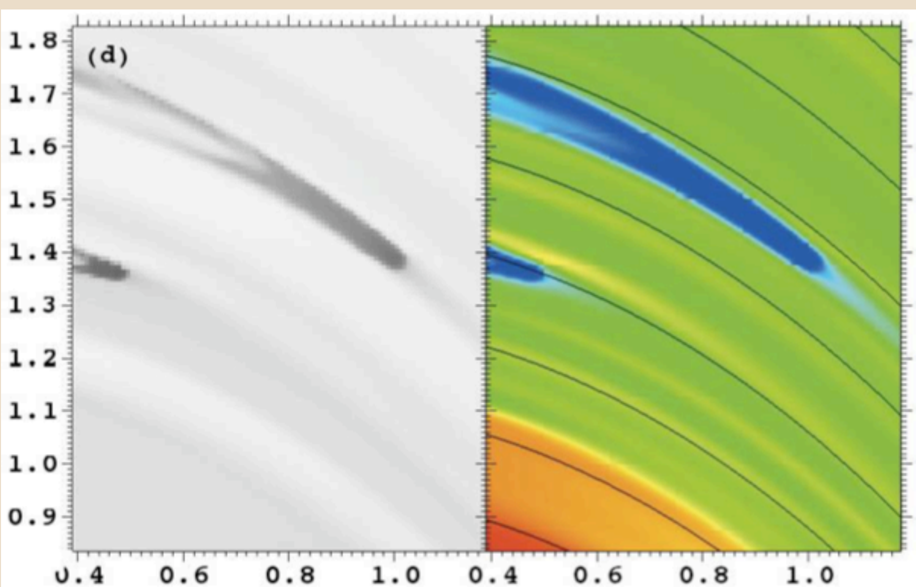
The x-velocity component

Low P causes Fast inflows

P gradient against G

Inflows fade away, begin to slide

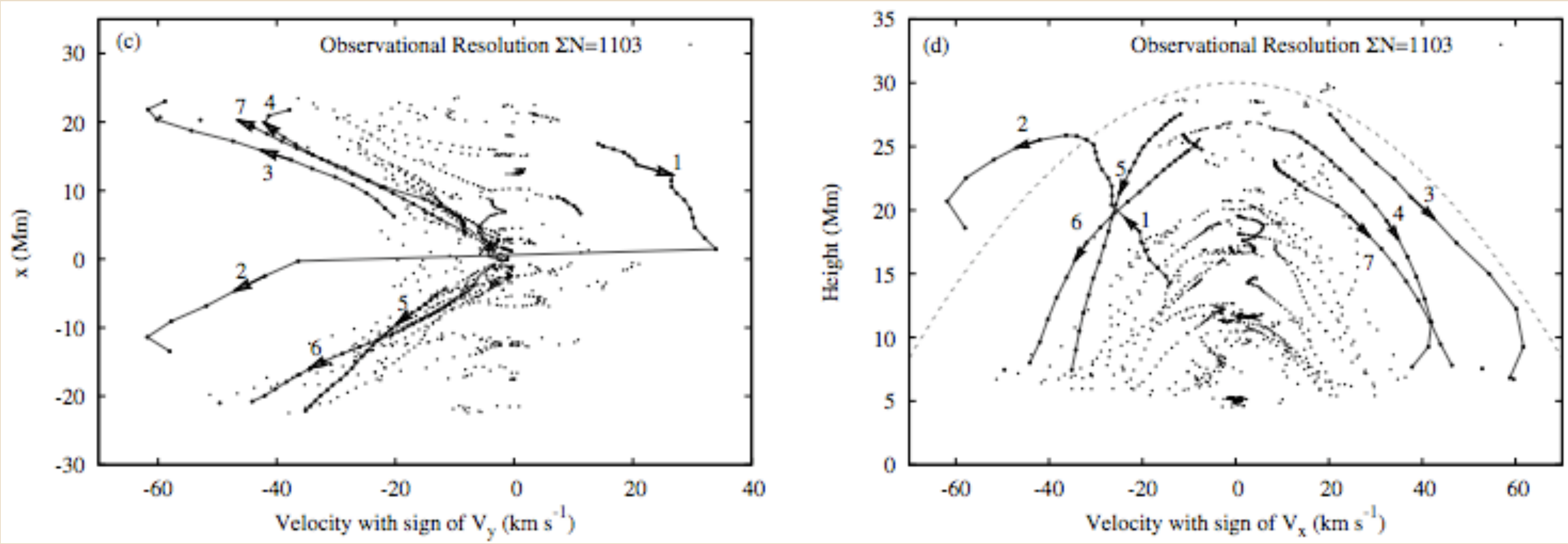
Form a V shape blob



Thermal structure of blobs, with a layer of TR temperature (strong radiative loss)

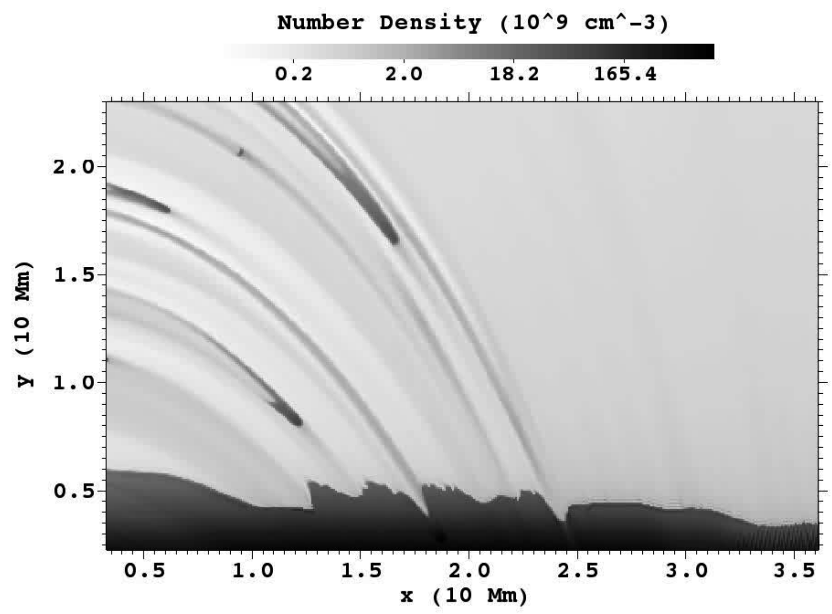
Number Density (left) and Temperature (right)

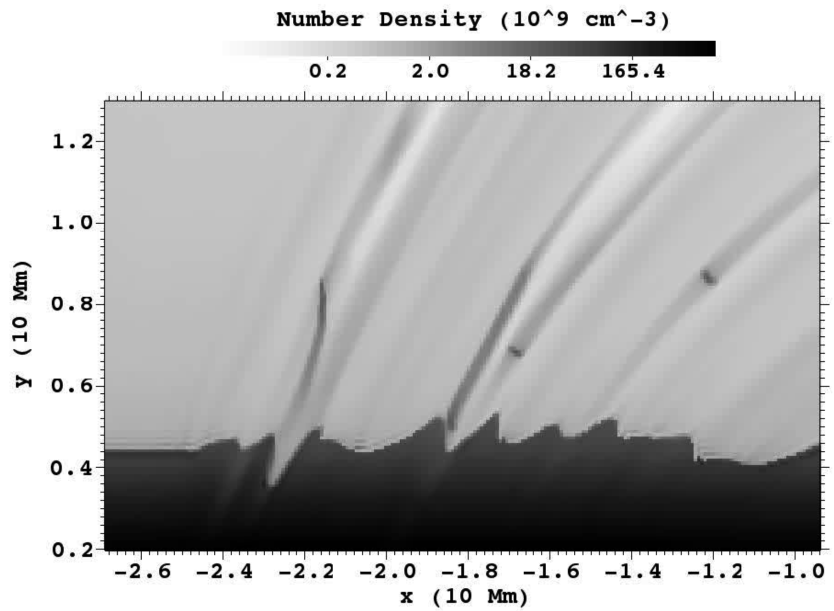
Dynamics



(left) scatter plot of projected velocity with sign of Vy versus x-axis value; (right) scatter plot of projected velocity with sign of Vx versus height of blobs. Solid curves connecting points show the trace of several blobs

Dynamics





Blobs merge and rise

Bobs destruction and rise

Conclusion

- First time in a realistic multi-dimensional magnetic configuration
- Multi-dimensional effect between loops
- Enough statistics to quantify blob widths, lengths as average 400 km, 800 km, and the velocity distribution from small value to 65 km s^-1 (confirmed by observations)
- The deformation of blobs into V -shapes
- A variety of dynamics (blobs which evaporate in situ, or get siphoned over the apex of the background arcade)
- For future, we are planning to do 3D simulation, more realistic !!!

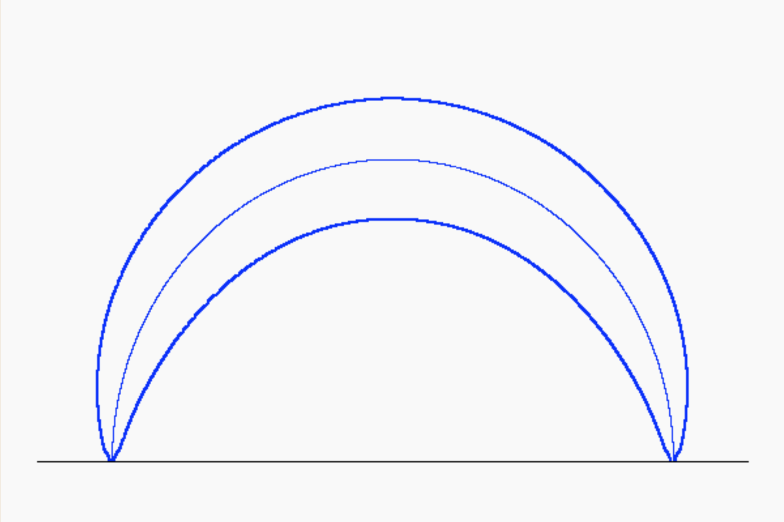
Thermal instability

Thermal instability (Field 1965):

“Catastrophic cooling”---A coronal loop subject to footpoint heating can be thermally unstable ((Antiochos et al. 1999, 2000, Müller et al. 2003, 2004)

- Temperature ↗ Density ↗
- Radiation losses ↗
- Temperature ↘
- Thermal instability
- Local pressure drop:
- Catastrophic cooling
- Condensation & evacuation

(Antolin 2012)



Model

$$H_1 = \begin{cases} C_1 & \text{if} \quad y < y_c \quad \text{and} \quad A_1(2.6) < A(x,y) < A_1(1.4) \\ C_1 \exp(-(y-y_c)^2/\lambda^2) & \text{if} \quad y \geq y_c \quad \text{and} \quad A_1(2.6) < A(x,y) < A_1(1.4) \end{cases} \tag{3}$$

$$A_1(x) = \frac{B_0 L_0}{\pi} \cos\left(\frac{\pi x}{L_0}\right), A(x,y) = A_1(x) \exp\left(-\frac{\pi y \sin\theta_0}{L_0}\right),$$

$$\lambda^2 = \frac{8\,(A(x,y) - A_1(1.4))}{A_1(2.6) - A_1(1.4)} + 12 \quad (\mathrm{Mm}^2),$$

where $C_1 = 10^{-2}$ erg cm^{-3} s^{-1}, y_c=3 Mm and $\theta_0 = 30°$.