5th Summer School of the Hellenic Astronomical Society

Effects of Twist Parameter Variations on the Emergence of Magnetic Flux Tubes

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European Research Council
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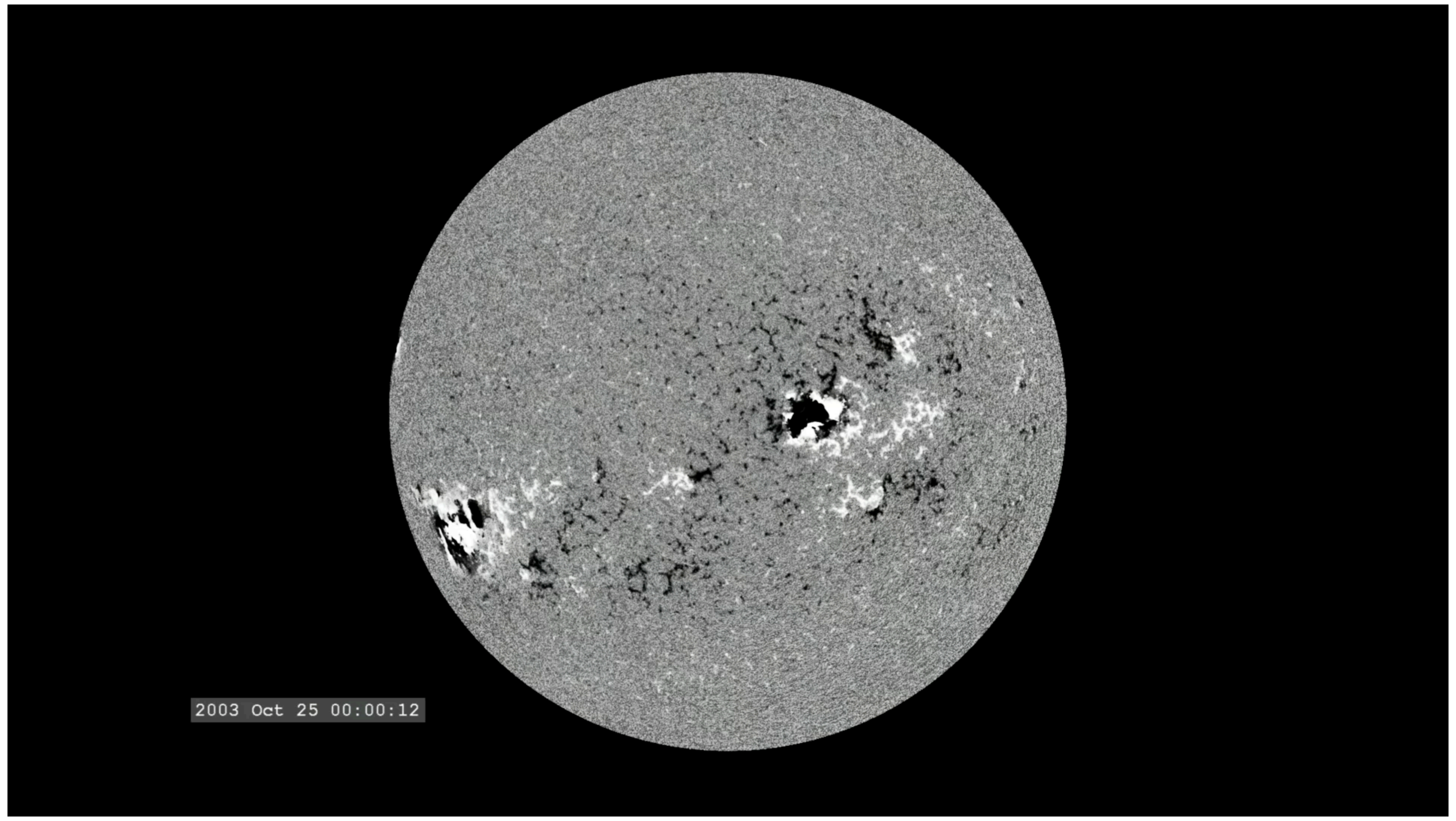
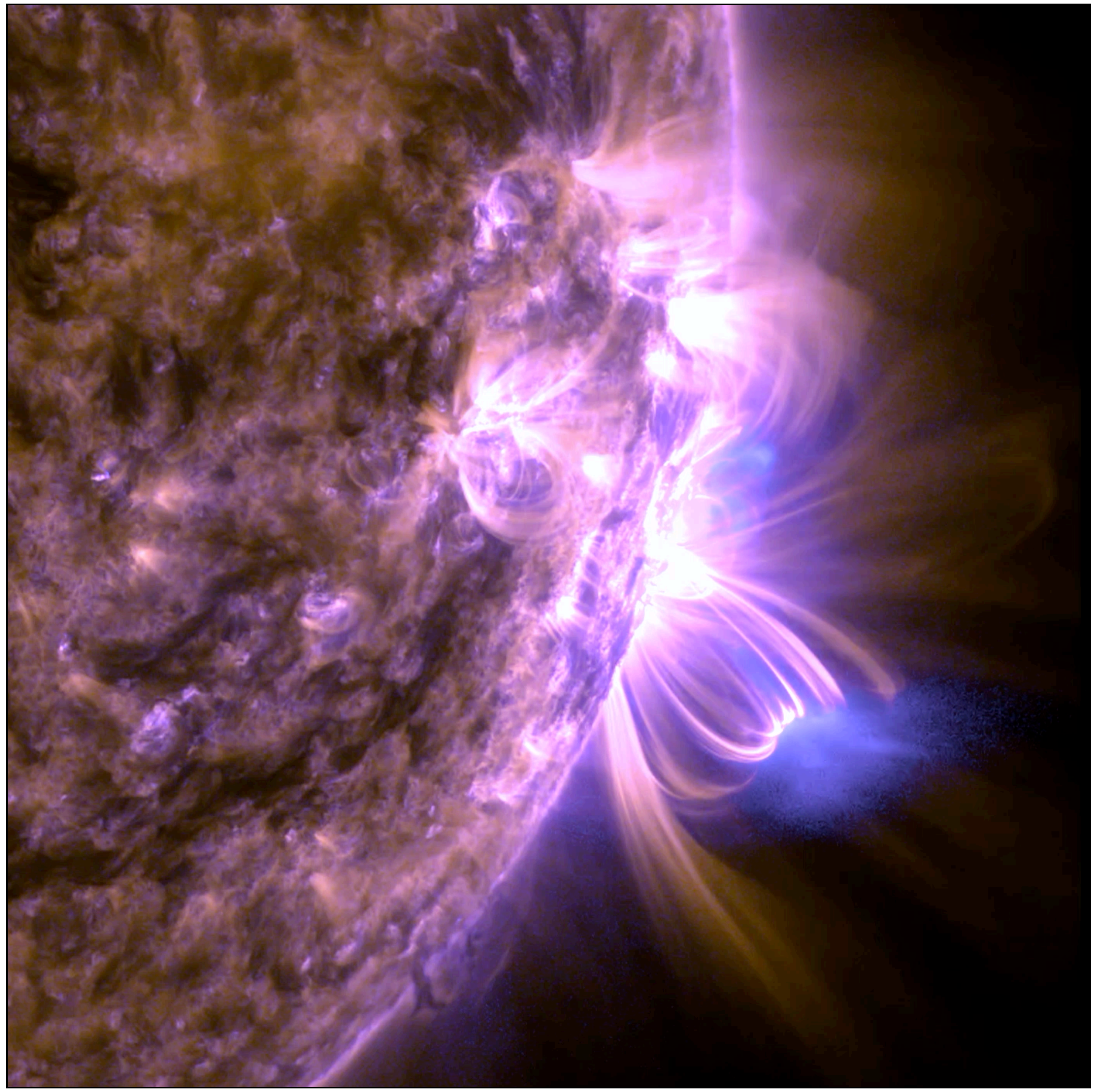
Why do we study flux emergence?

Flux emergence is connected to:

- **Formation of active regions**
- **Sunspots**
- **Solar flares**
- **CMEs**



NASA/Goddard Space Flight Center Scientific Visualization Studio

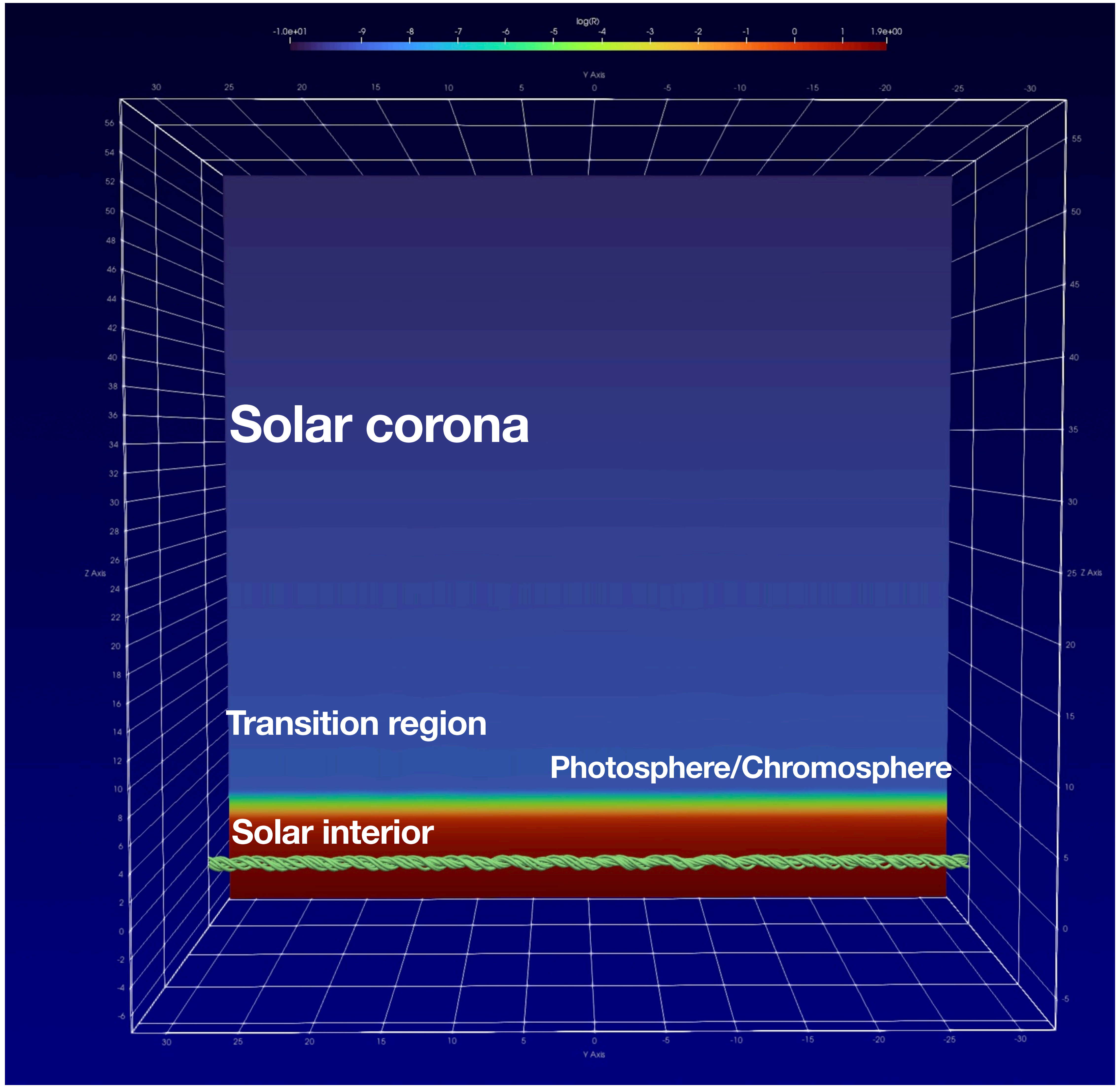


NASA's SDO captured images of the two solar flares on May 10 and May 11, 2024. The flares are classified as X5.8 and X1.5-class flares, respectively. The image shows a subset of extreme ultraviolet light that highlights the extremely hot material in flares created from a mixture of SDO's AIA 193, 171 and 131 channels.

3D resistive MHD Simulations of Magnetic Flux Emergence

LareXd solves 2D and 3D MHD equations using finite differencing in two main steps:

1. **Lagrangian Step**:tracks the movement of fluid elements (Lagrangian step) and then remapping or interpolating the data back onto a fixed grid (Eulerian step)
2. **Remap Step**: Variables are put back on the original grid. Gradient limiters preserve monotonicity, and shock viscosity helps resolve shocks.
3. The numerical grid is set to be a uniformly spaced $420 \times 420 \times 420$ box (Corresponds to $(x, y, z) = ([-31.5, 31.5], [-31.5, 31.5], [-5.4, 57.6])$ Mm.)
4. Customizable viscosity and resistivity, staggered grids to prevent checkerboard instability, and additional physics like partial ionization and thermal conductivity.



MHD Model

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Compressibility

Momentum Equation:

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

viscosity

Energy equation: $\rho\frac{D\epsilon}{Dt} + P\nabla\cdot\mathbf{v} = Q_{\mathbf{joule}} + Q_{\mathbf{viscous}}$

Faraday:

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

Resistivity terms included

Ampere's Law: $\mathbf{J} = \nabla\times\mathbf{B}\,/\,4\pi$

Ohm:

$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v}\times\mathbf{B})$

Fully ionized plasma

- **Compressibility**:
  - Accounts for density variations (important for shock waves)
  - Energy equation based on specific internal energy
- **Resistivity**:
  - Models magnetic diffusion and reconnection

EOS: $p = \rho RT/\mu$
Ideal gas

Initial conditions

- For the tube to be in hydrostatic equilibrium:

$$P_{out} = P_{in} + P_{mag}$$

- Density Deficit:

$$\frac{\Delta\rho}{\rho} = \frac{P_{in}}{P_{out}} exp \frac{-y^2}{\lambda^2}$$

- $\lambda = 0.9Mm$

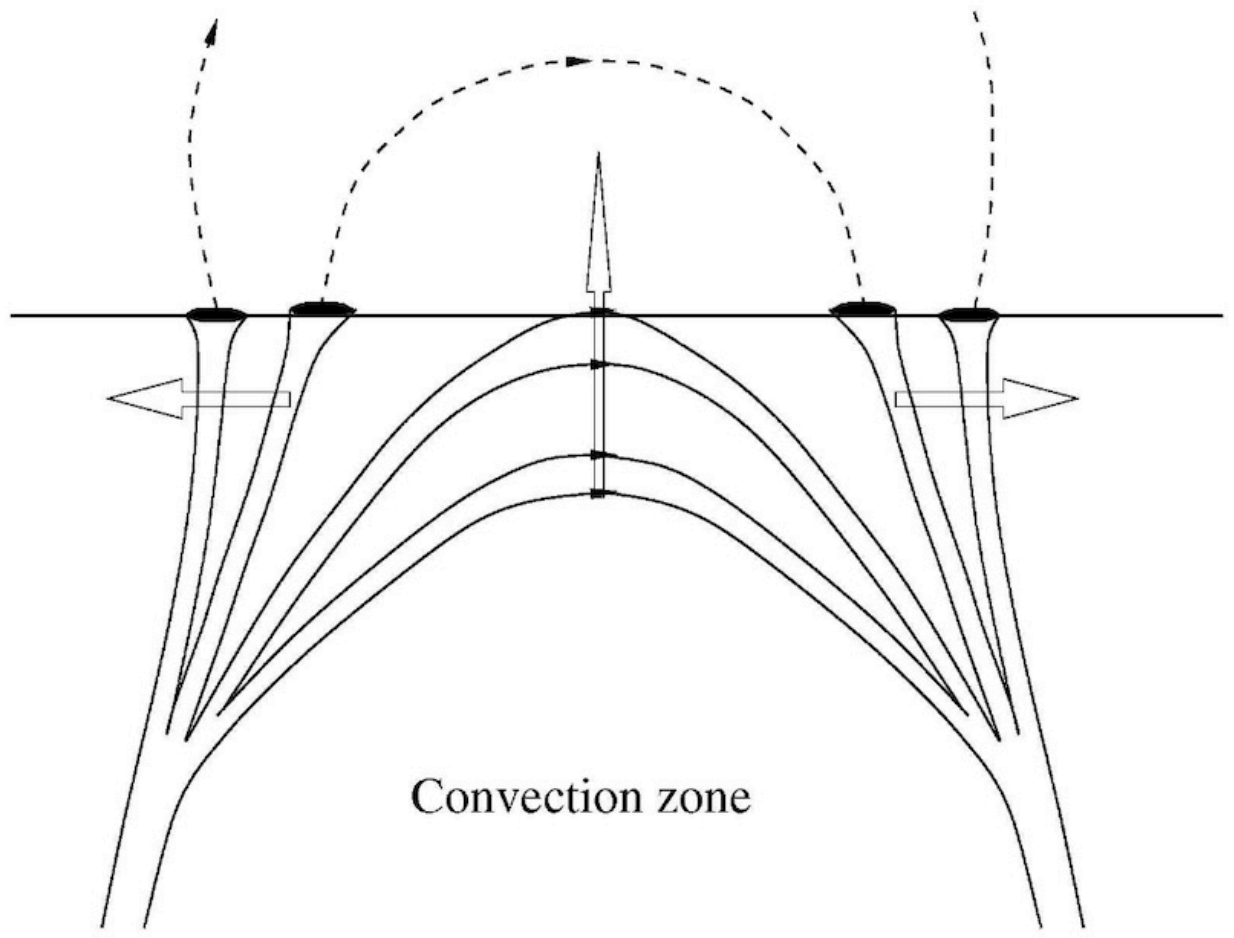
- Field of the flux tube:

$B_r = 0$

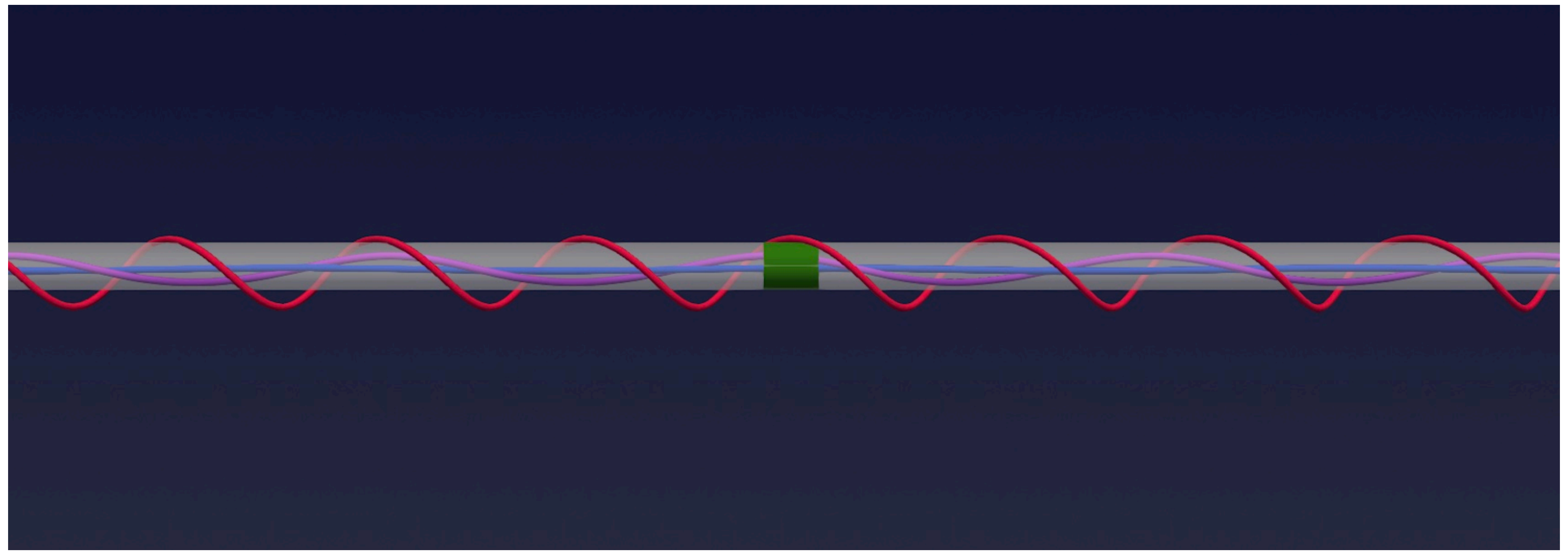
$B_\theta = arB_y$

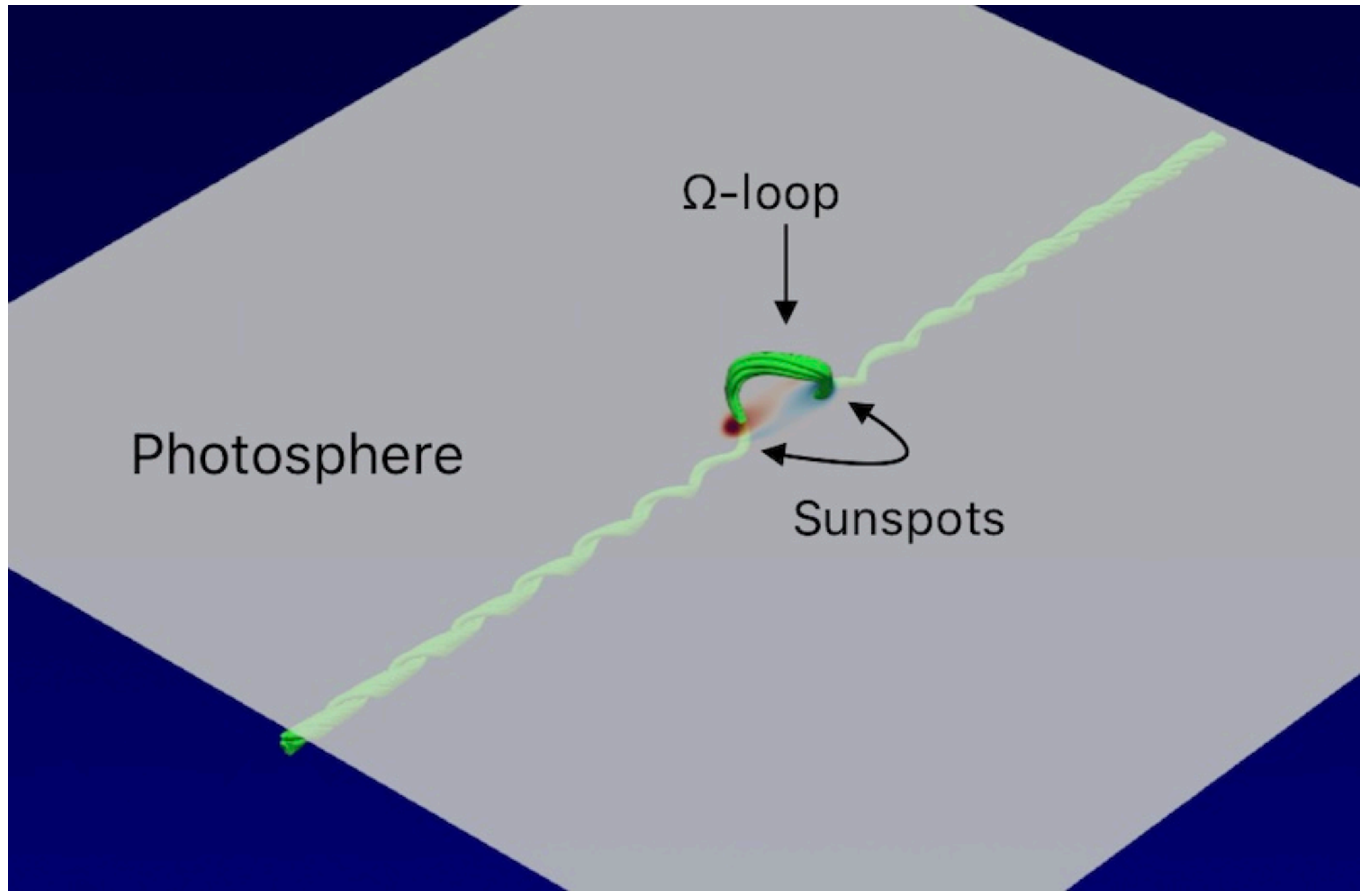
$B_y = B_0 exp(-\frac{r^2}{R^2})$

- $R = 0.45Mm$
- $r^2 = x^2 + z^2$



Zwaan (1985)





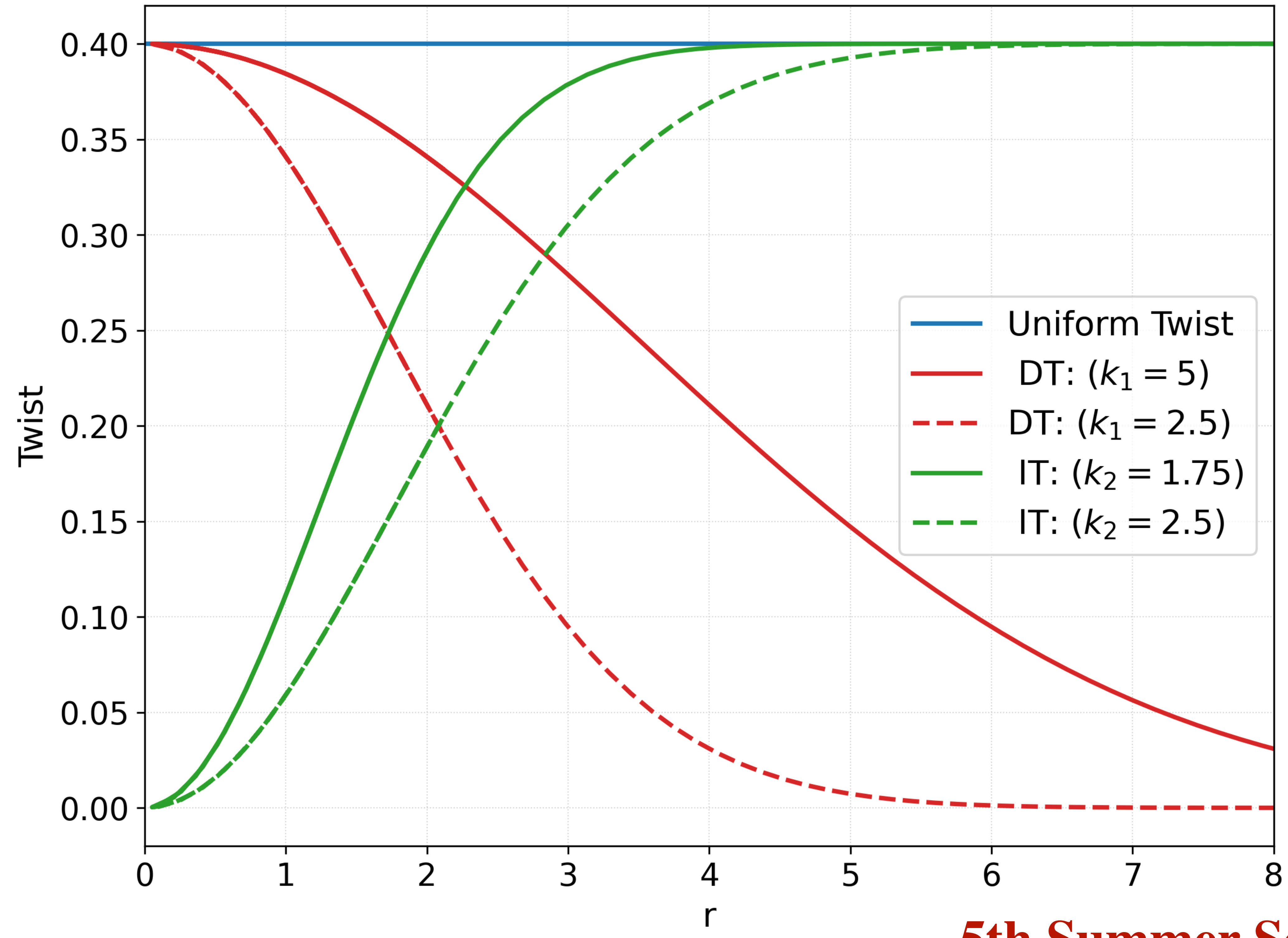
Twist profiles

- 3 experiments with different twist evolution

1. Constant twist: $a = 0.4$

2. Decreasing twist: $a_{DEC} = c exp(-r^2/k_1^2), k_1 =$ 5, 2.5

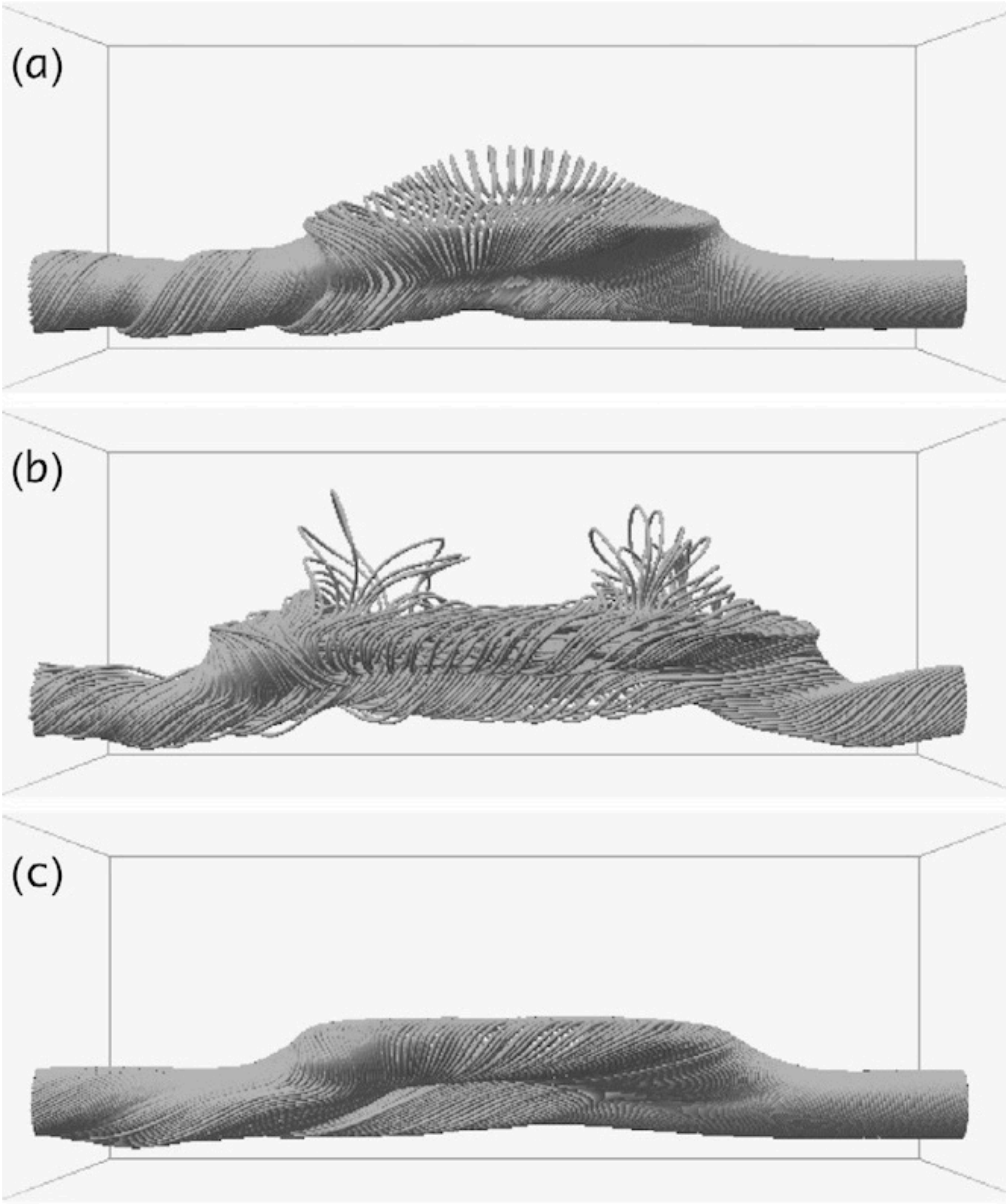
3. Increasing twist: $a_{INC} = c[1 - exp(-r^2/k_2^2)], k_2 =$ 1.75, 2.5



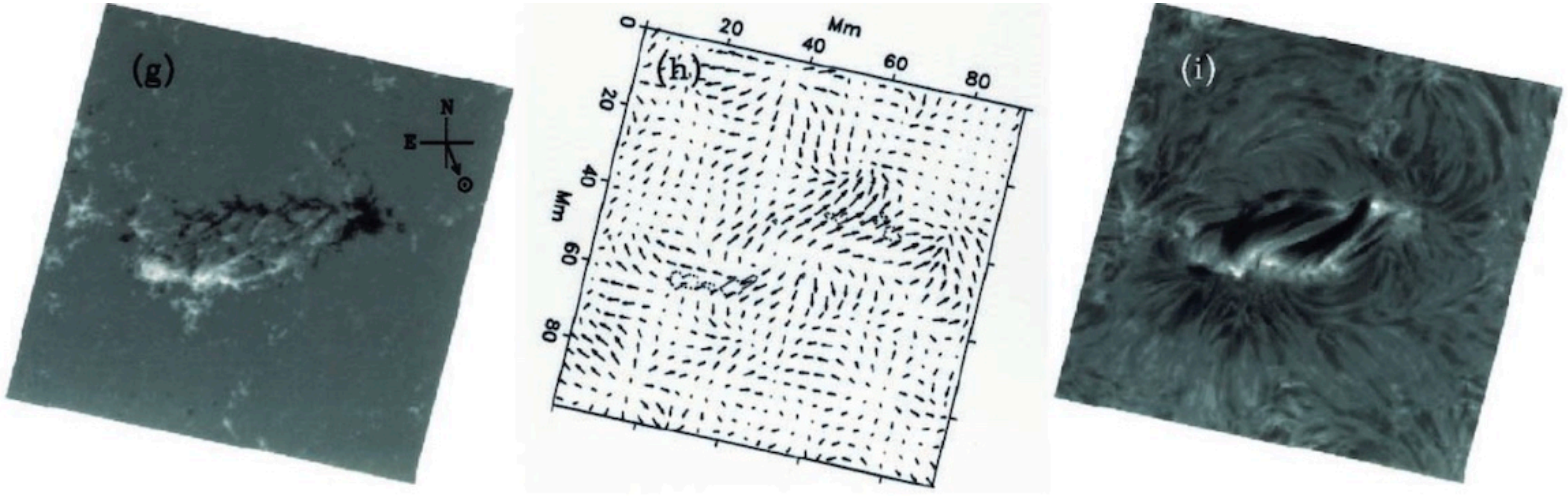
Why is twist important?

- Twist is the number of turns of the magnetic filed lines around the tubes axis per unit length.

- It plays a significant role in the evolution of the emergence procedure.



Murray et al. 2006



Strous et al. 1996

Experiments with no ambient field

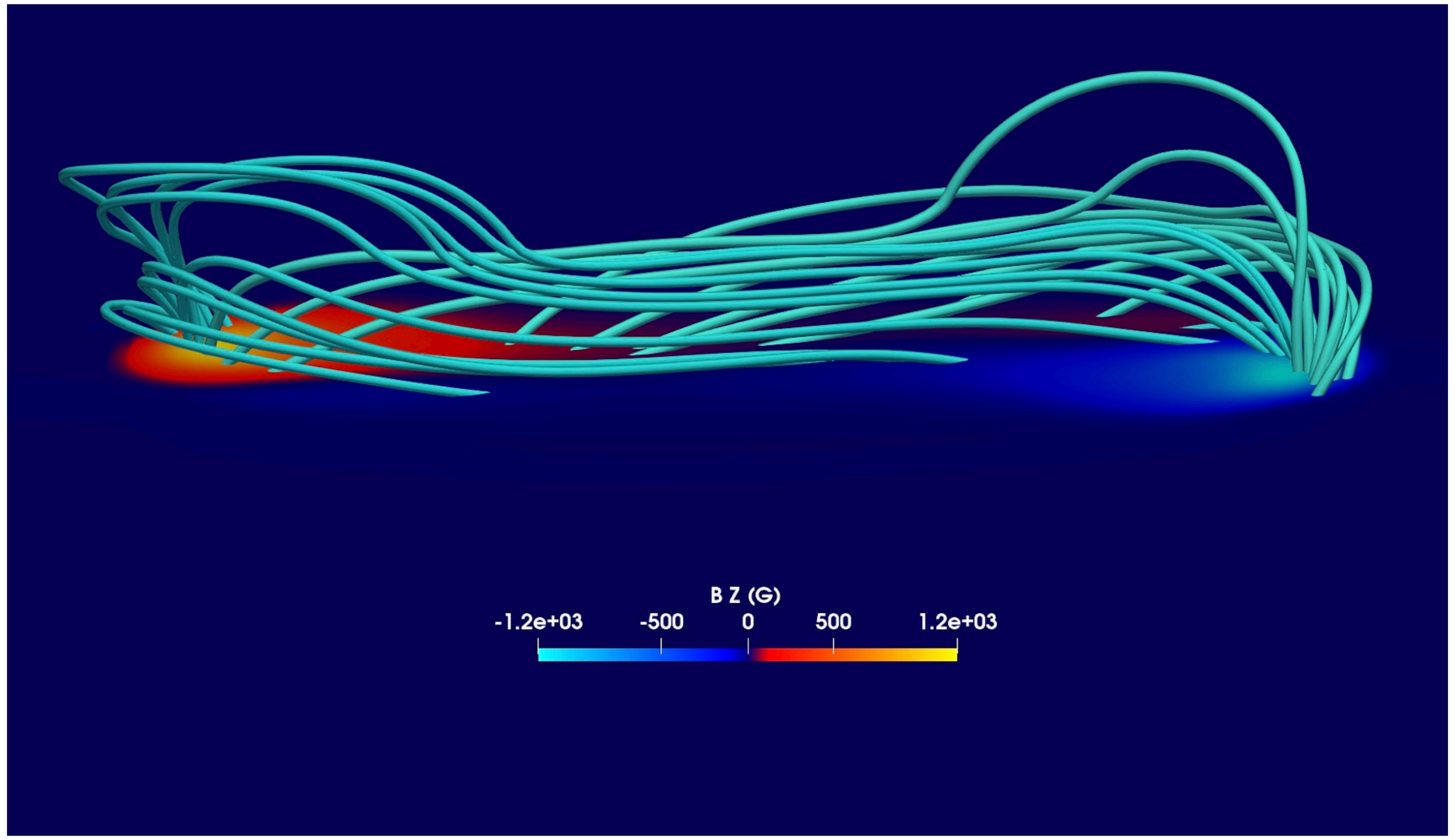
Experiments with no ambient field

Tubes with no distortion

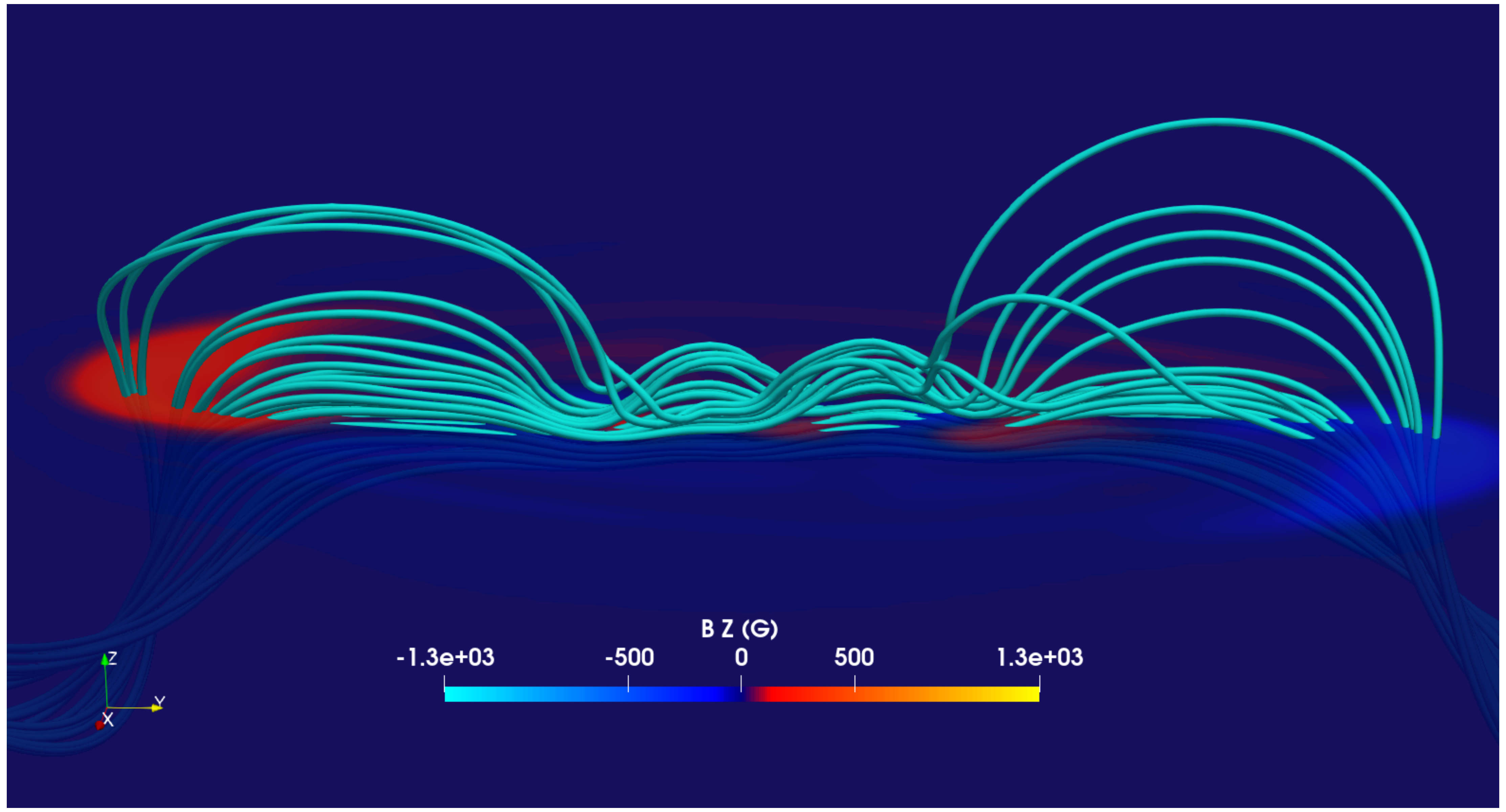
Tubes with distortion

Experiments with no ambient field

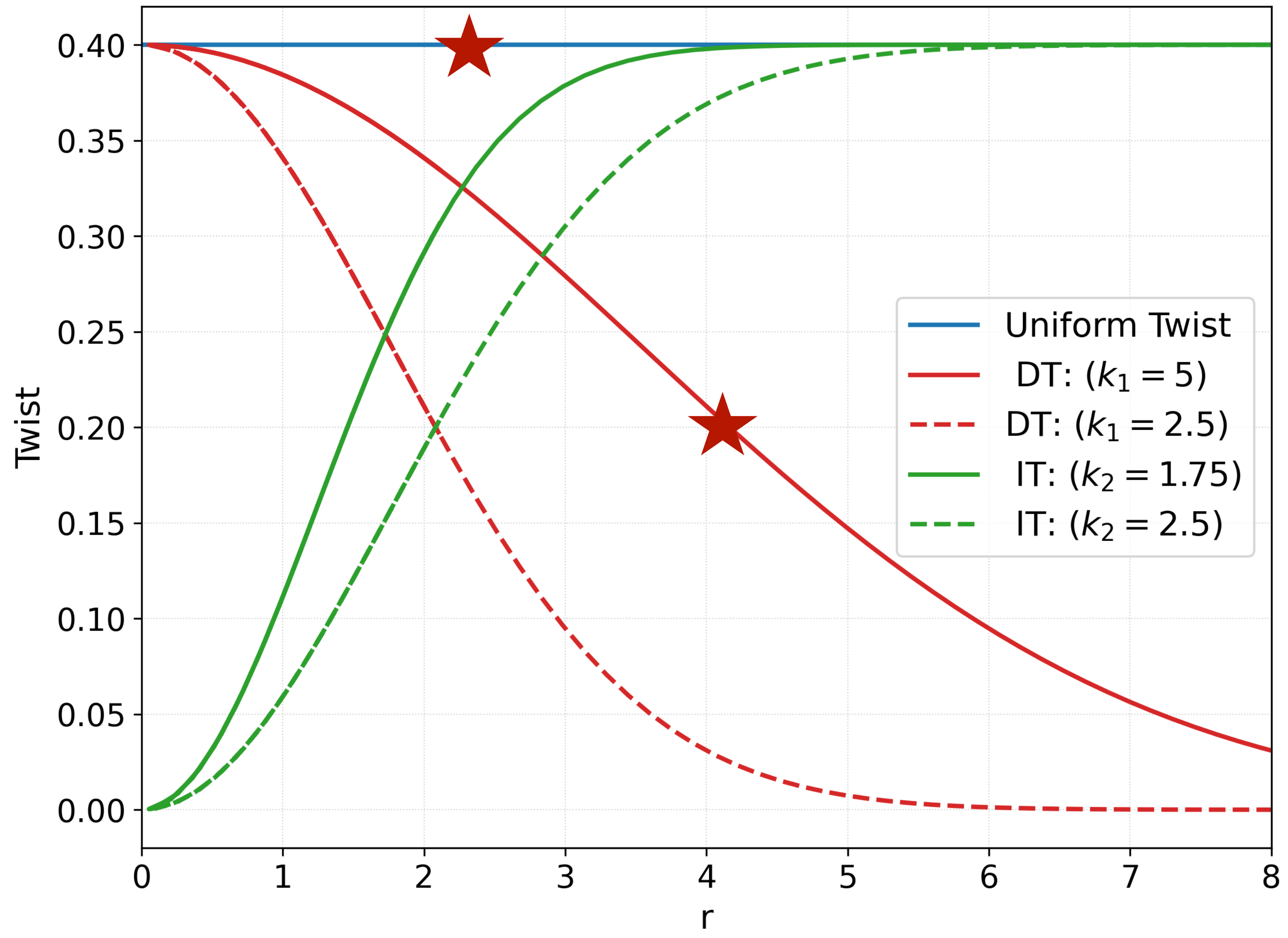
Tubes with no distortion



Tubes with distortion

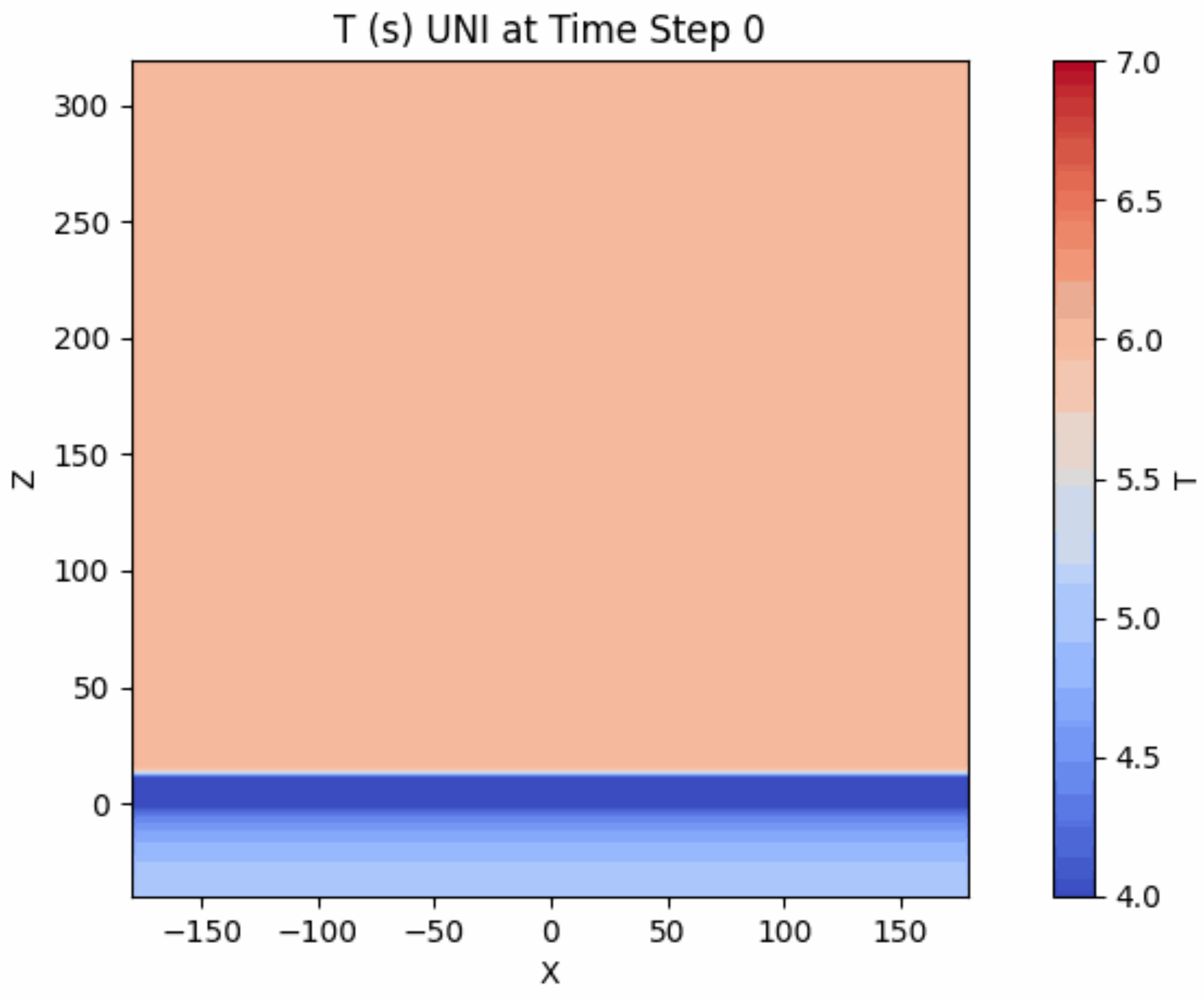


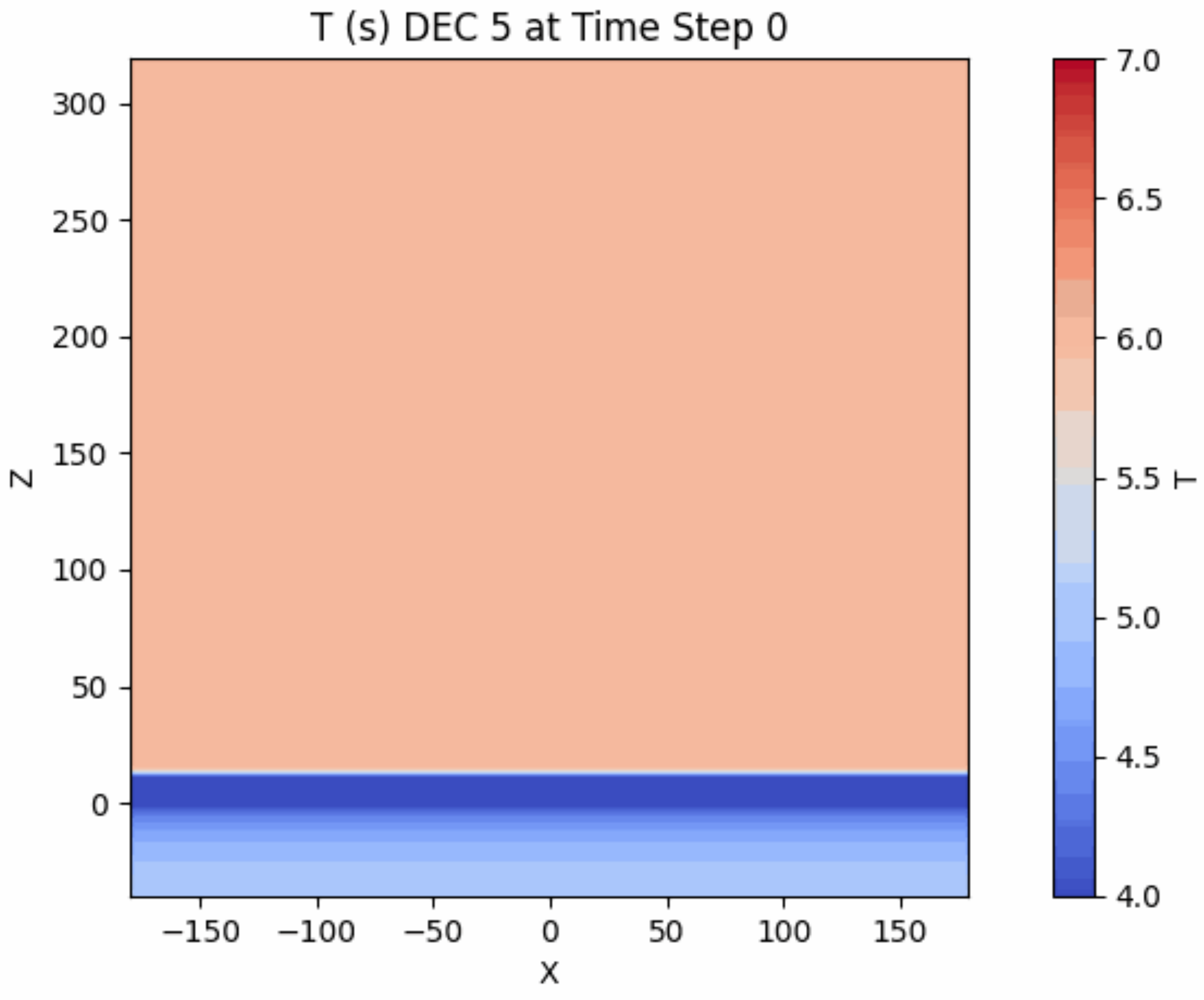
Tubes with no distortion



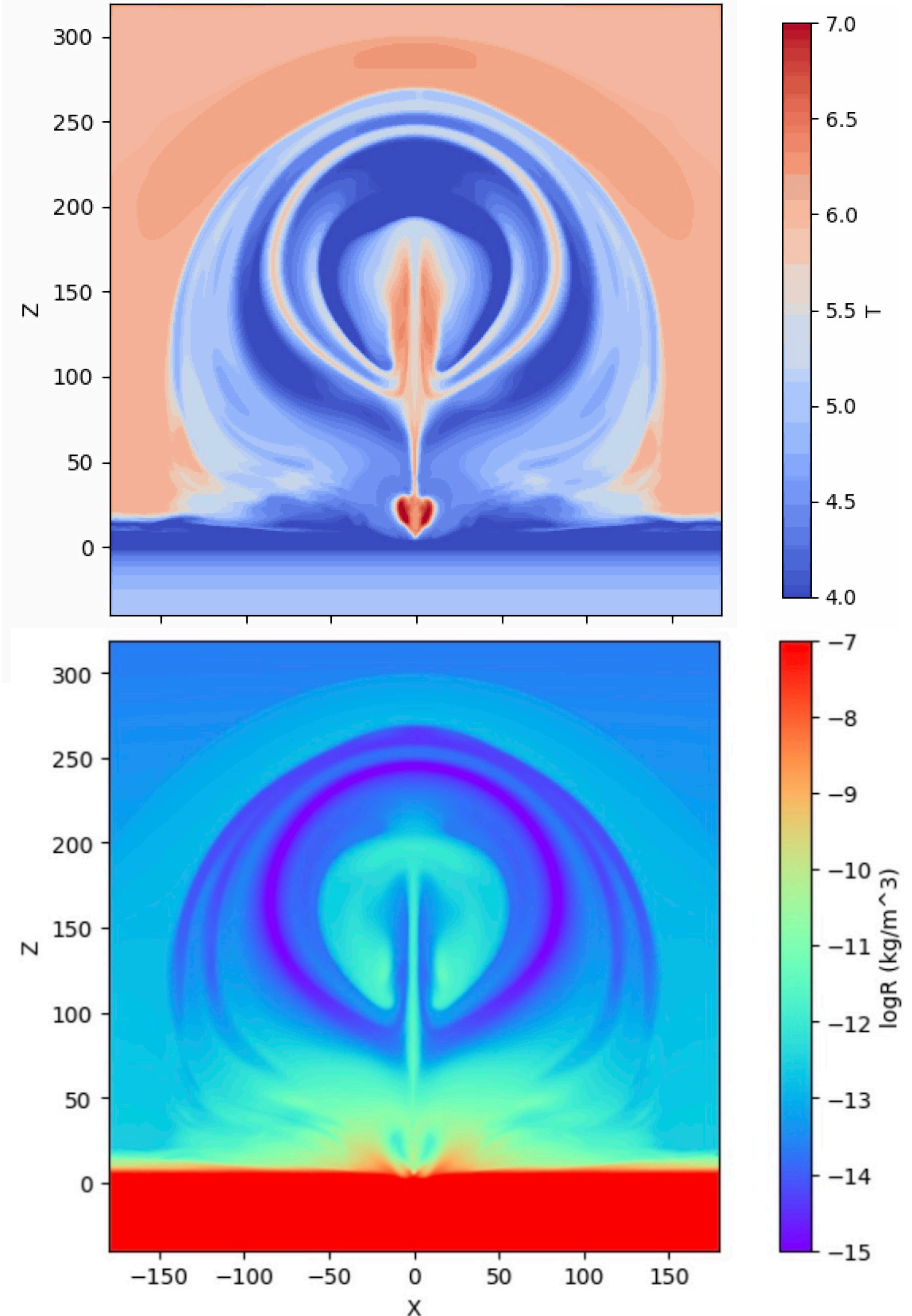
Tubes with distortion

Tubes with no distortion ★

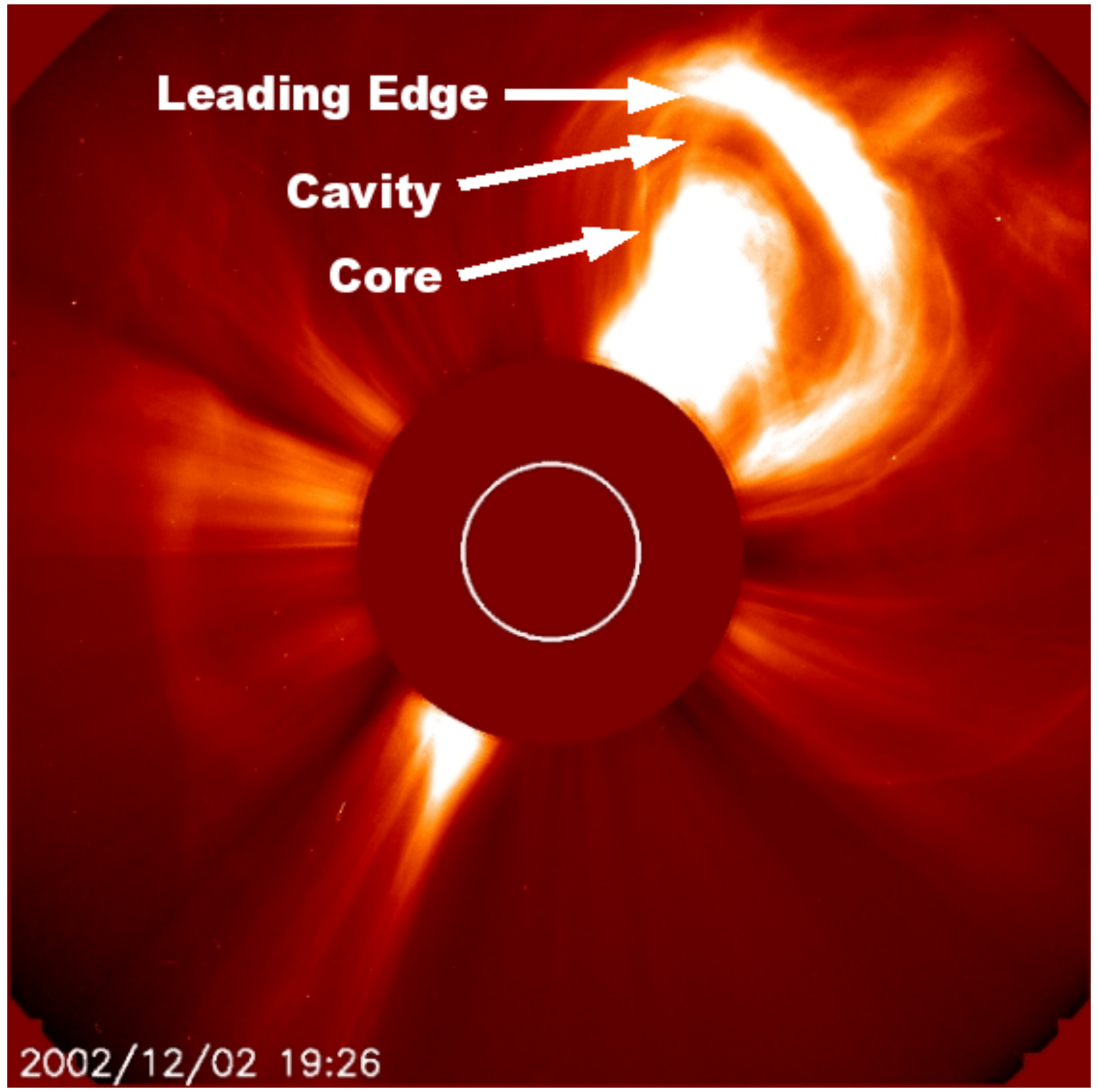




z=-12, B0=13

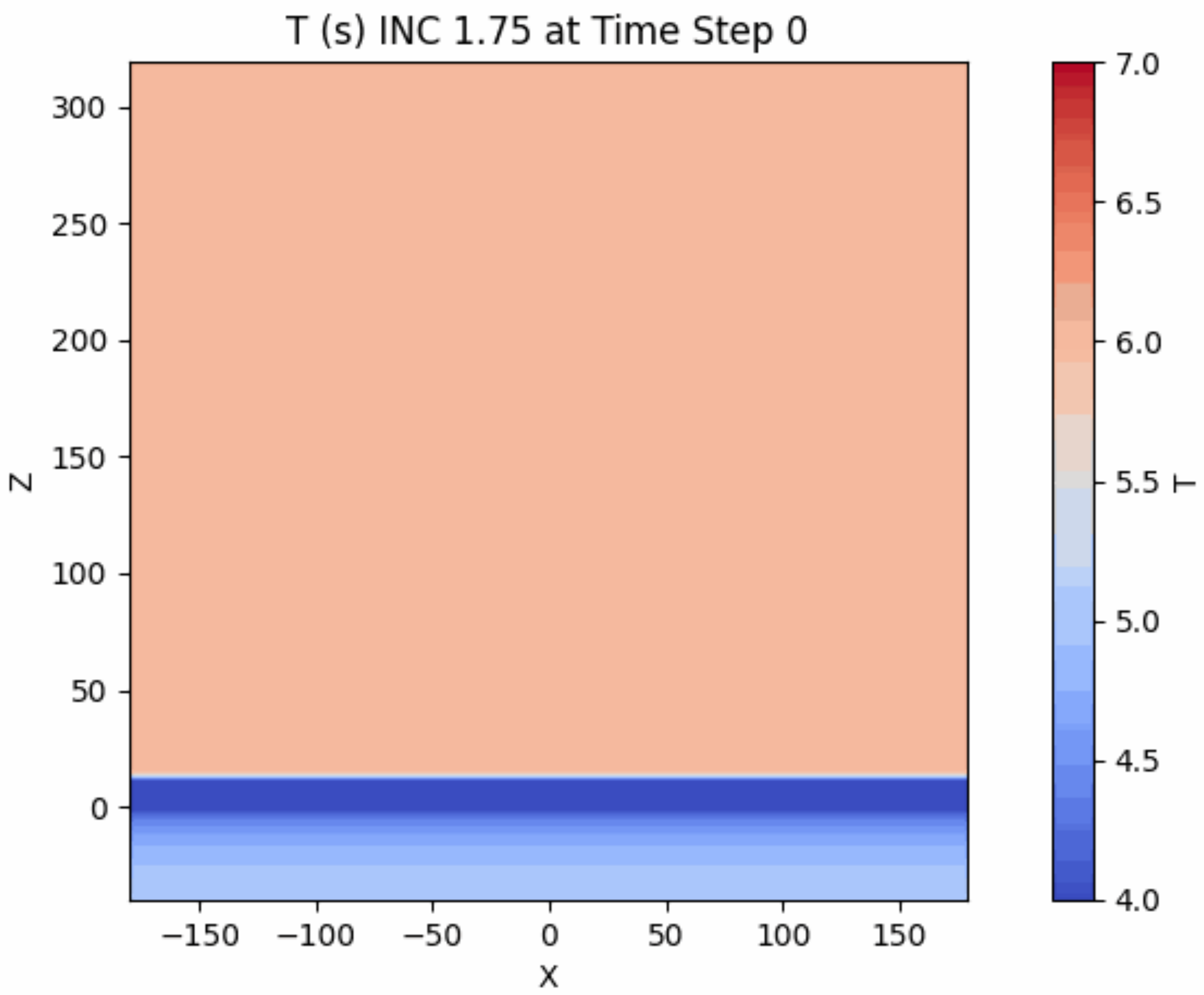


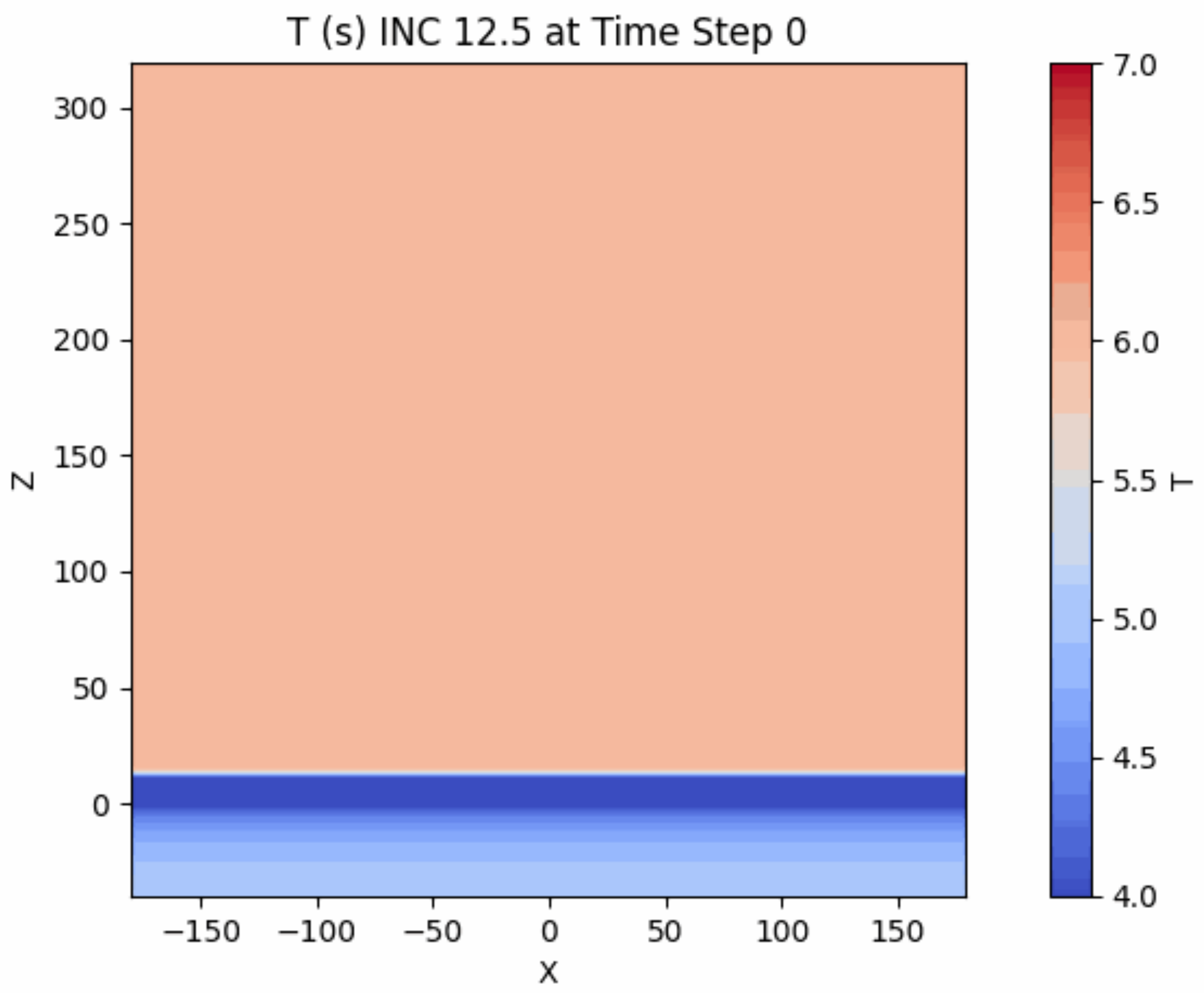
- The first eruption takes place in almost 70 minutes
- The emerging fields form a "bubble" shaped structure for the emerging hot and cold plasma
- We observe a hot, dense core of emerging plasma, surrounded by a cavity of cooler, less dense plasma, all of which rise above the envelope magnetic field.
- These layers are contained in the bright "front" of the erupting field i.e. a shell of dense coronal plasma.

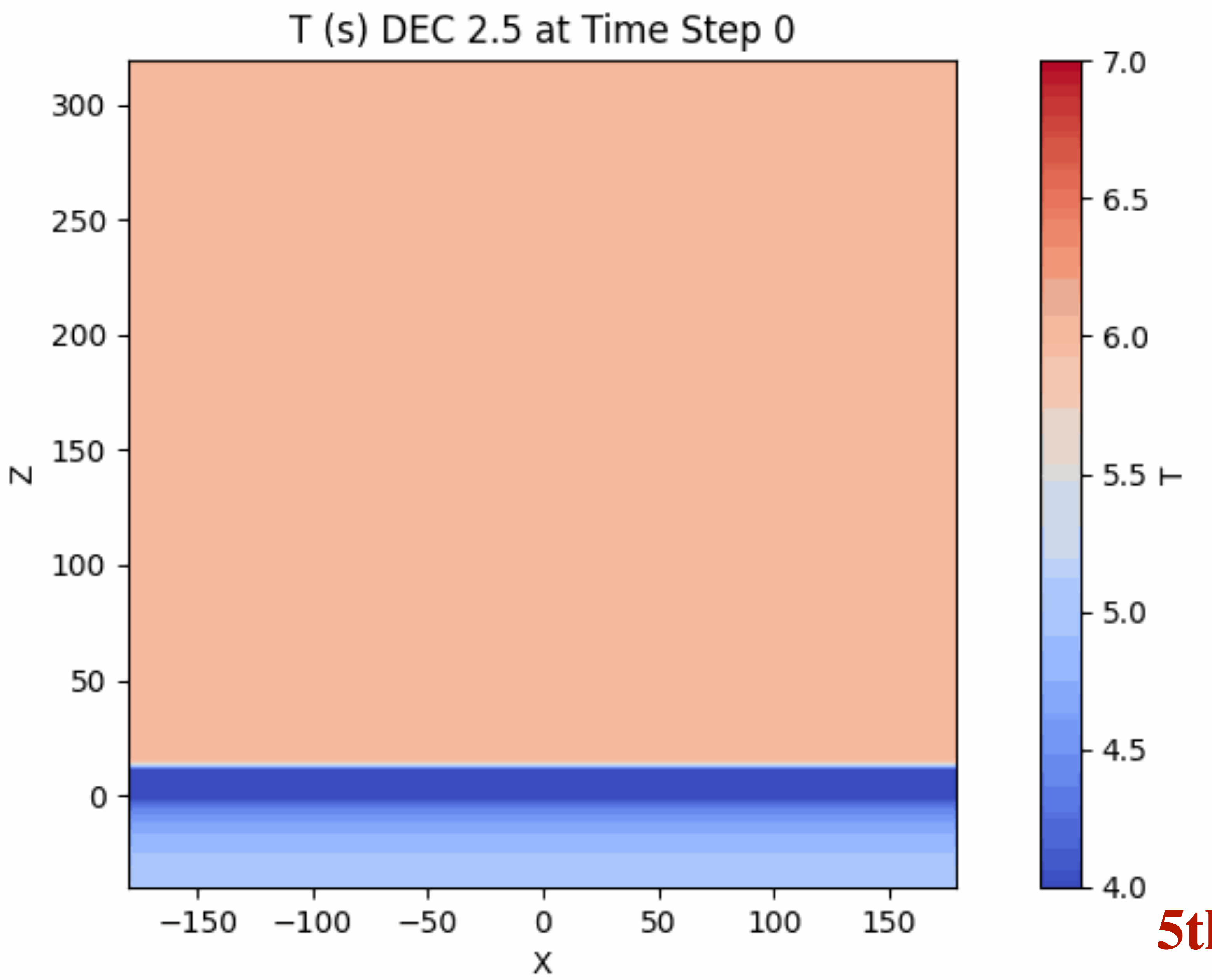


- **Colaninno et al. 2012**
- **SOHO-LASCO C2 on December 2, 2002.**

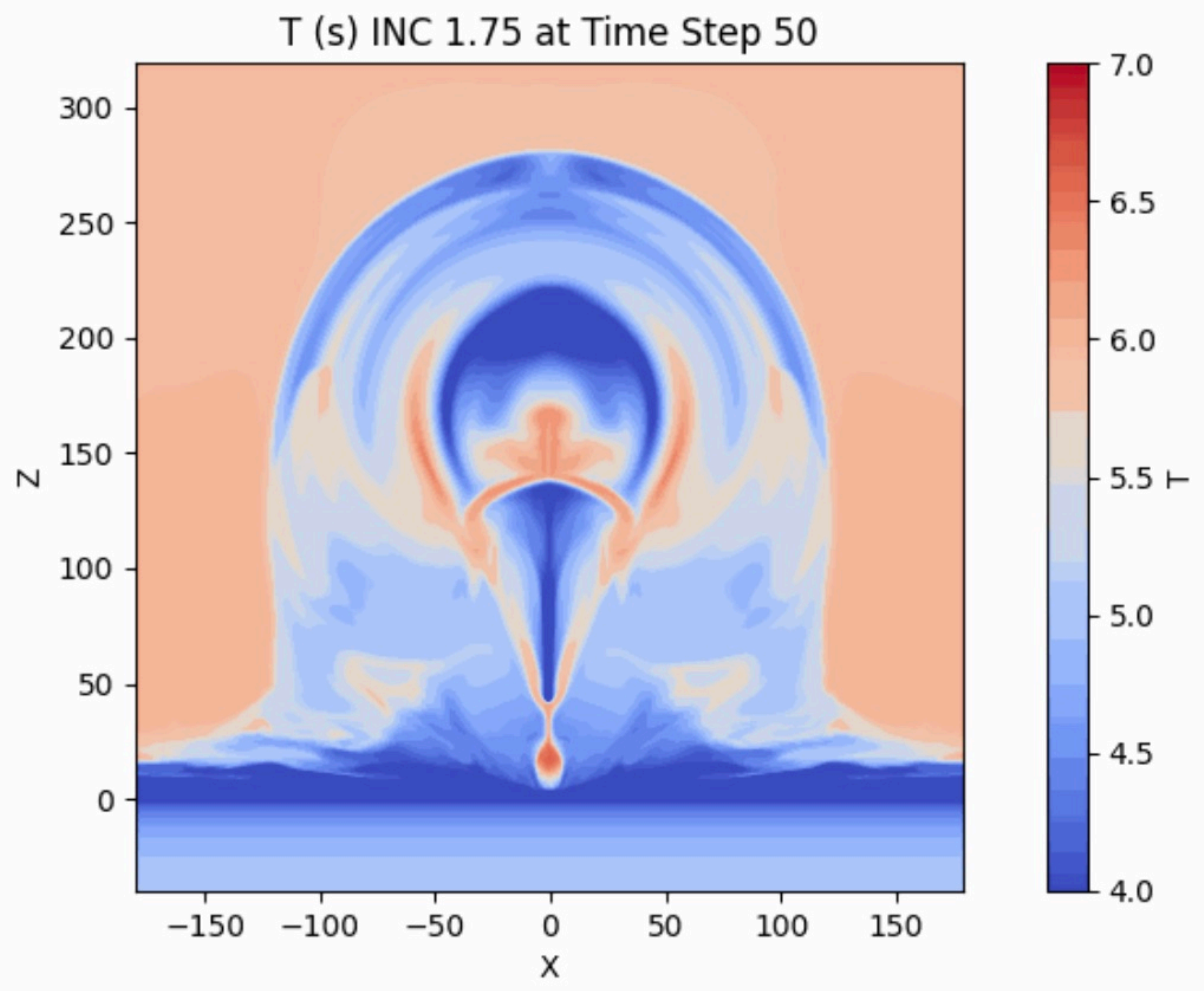
Tubes with distortion

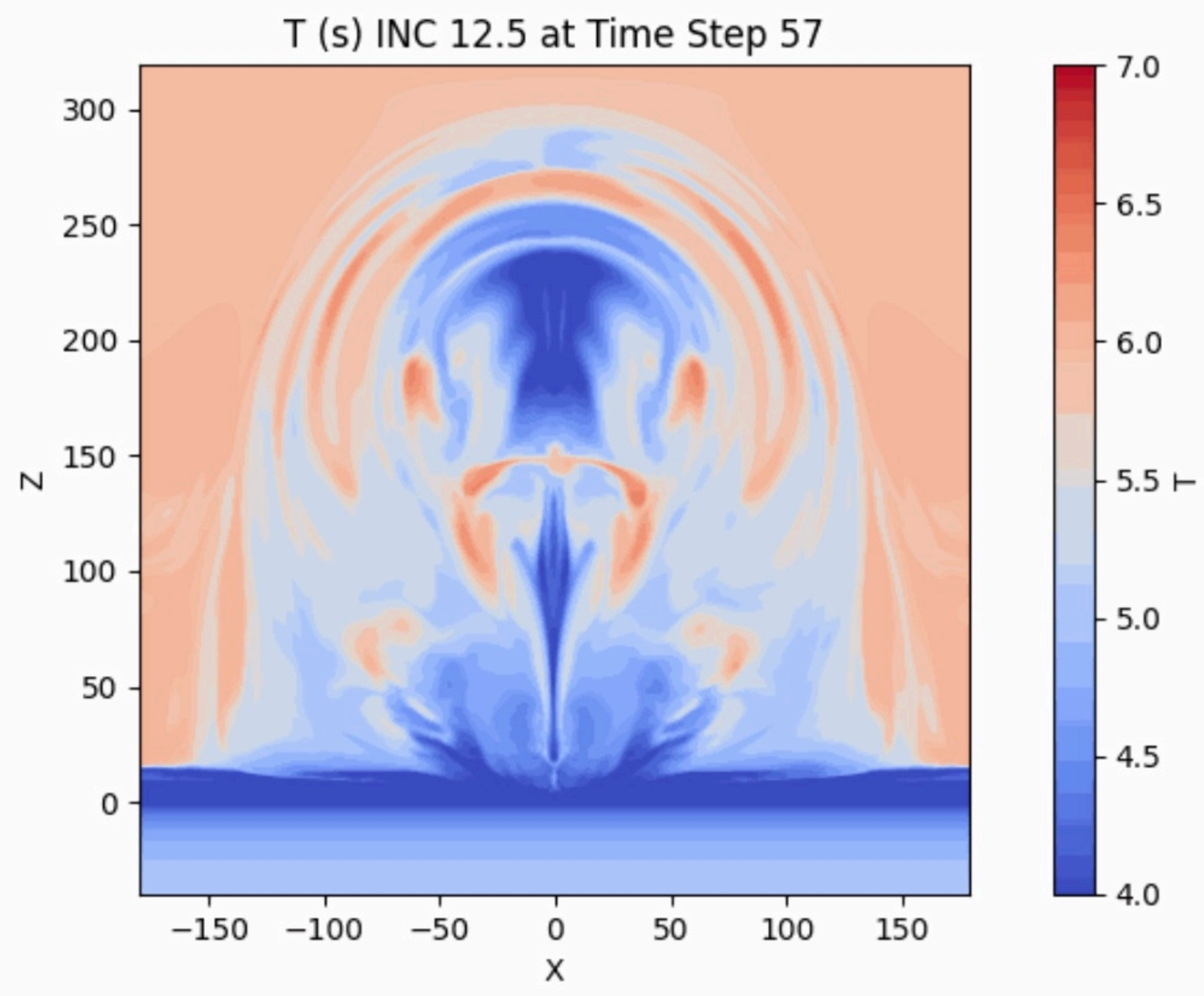


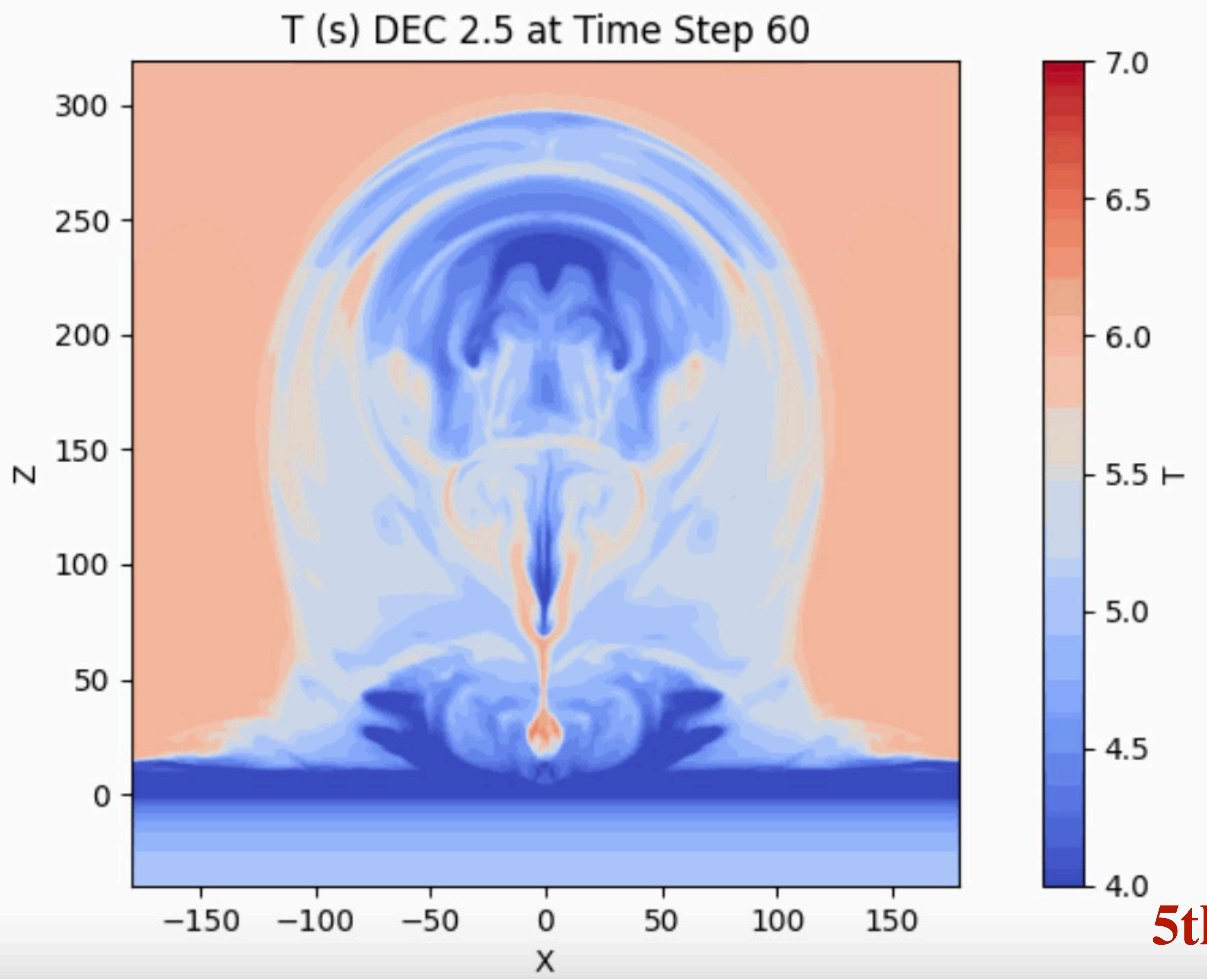




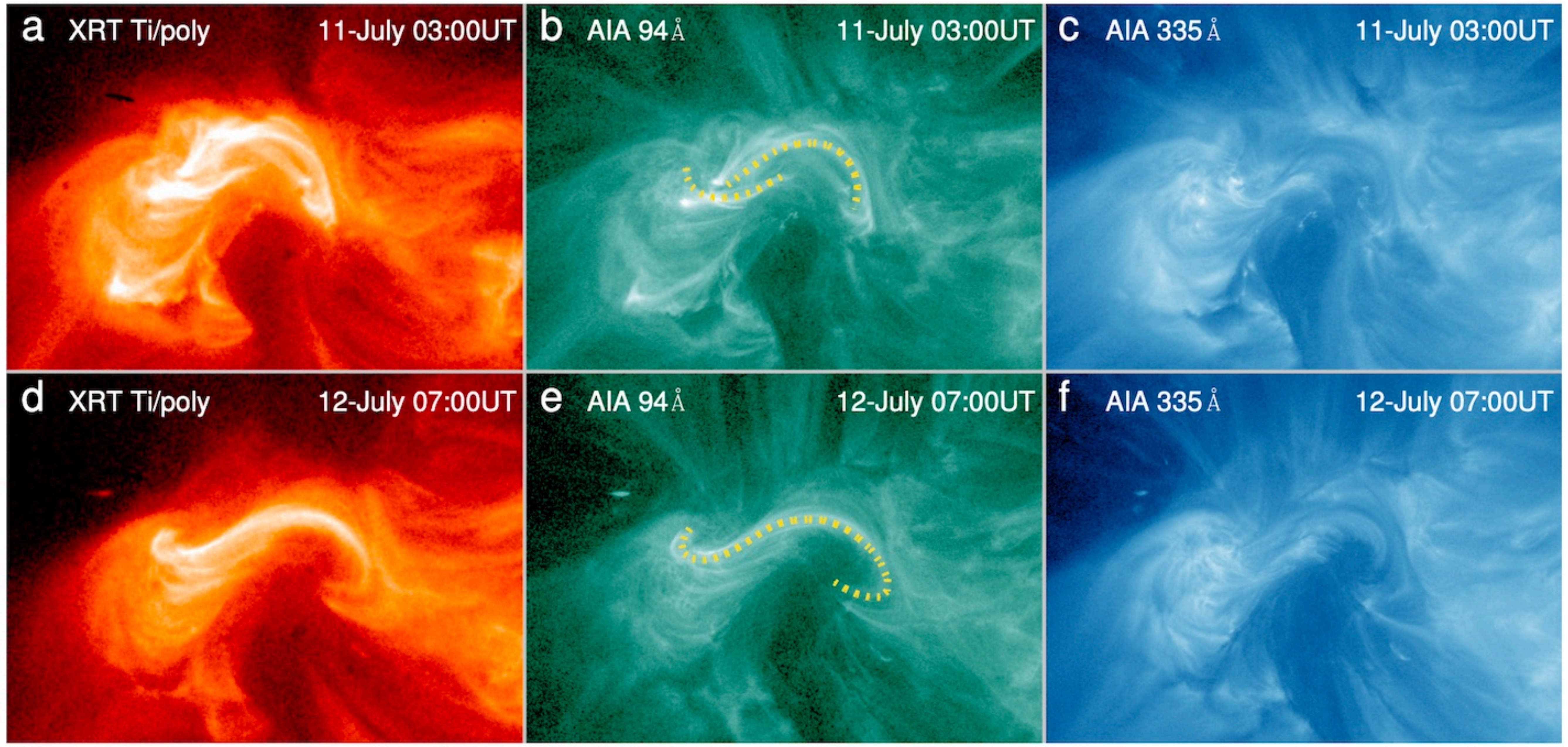
Tubes with distortion



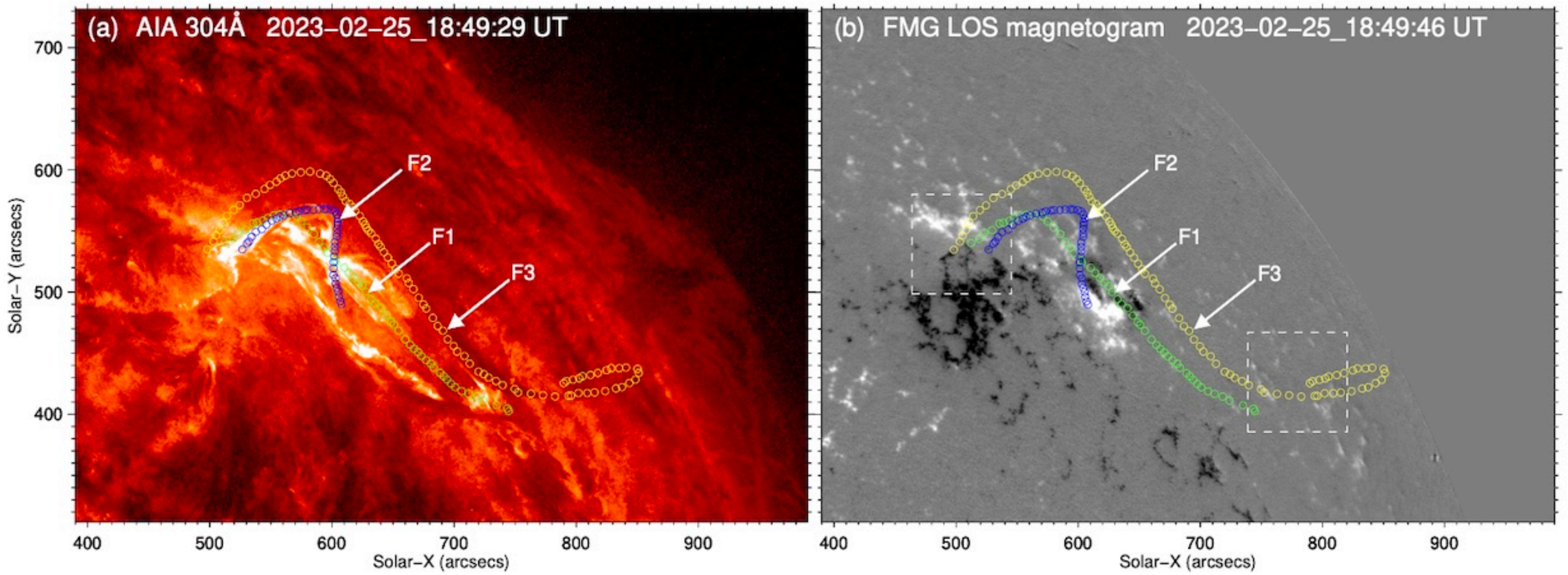




X Axis
Y Axis
Z Axis
7.0e+00
6.5
6
5.5
5
4.5
4
3.2e+00
logT (K)



- Cheng et al. (2014)
  - The eruption produced an X1.4 flare and a fast halo CME
  - AR 11520
  - SDO (AIA) / HINODE (XRT)



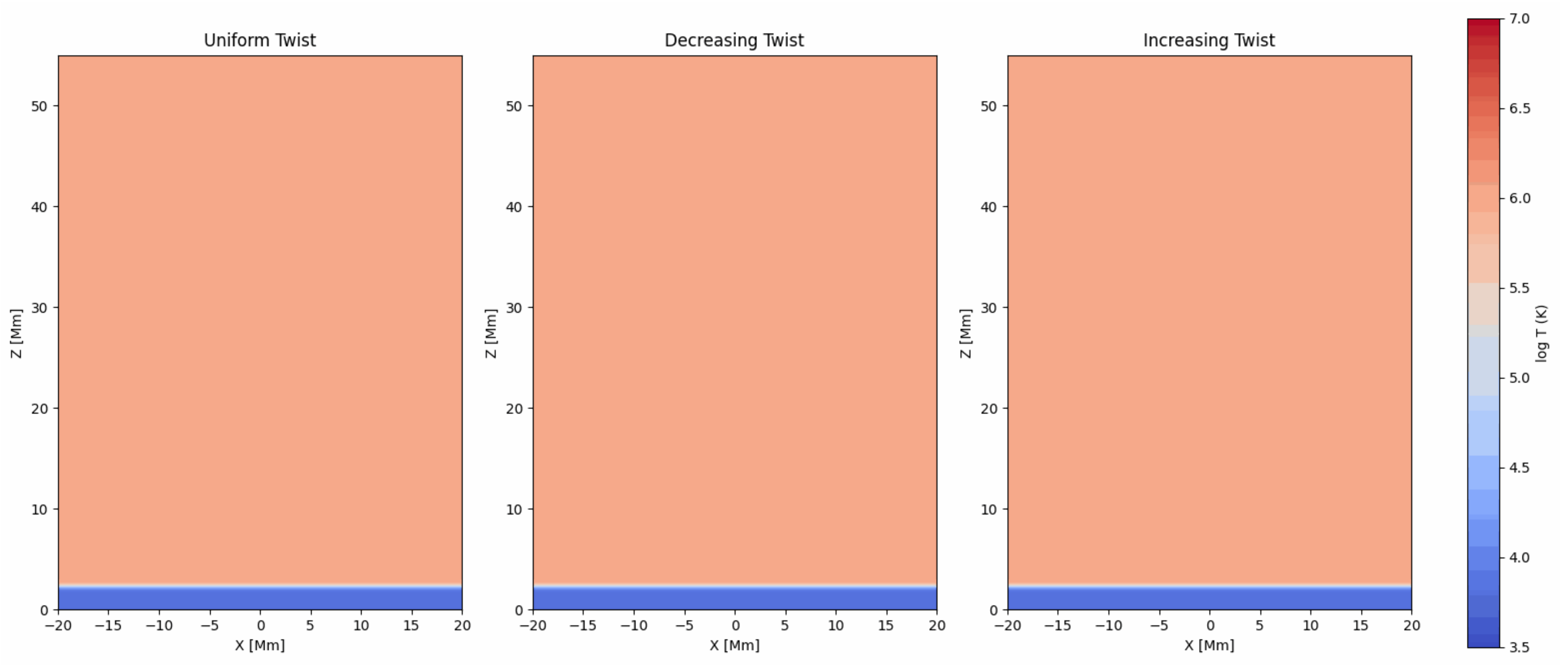
- Song et al. (2024)
  - SDO (AIA) /ASO (FMG)

Conclusions

- We conducted experiments with variable twist profiles.
- Some tubes undergo distortion while others don not.
- The eruption mechanism is different for the cases that undergo distortion.

Work in progress

- New experiments with different crucial parameters such as the initial magnetic field and twist.
- Investigate changes in scenarios with a magnetized solar atmosphere.
- New numerical simulations with kink unstable tubes.



Thank You!