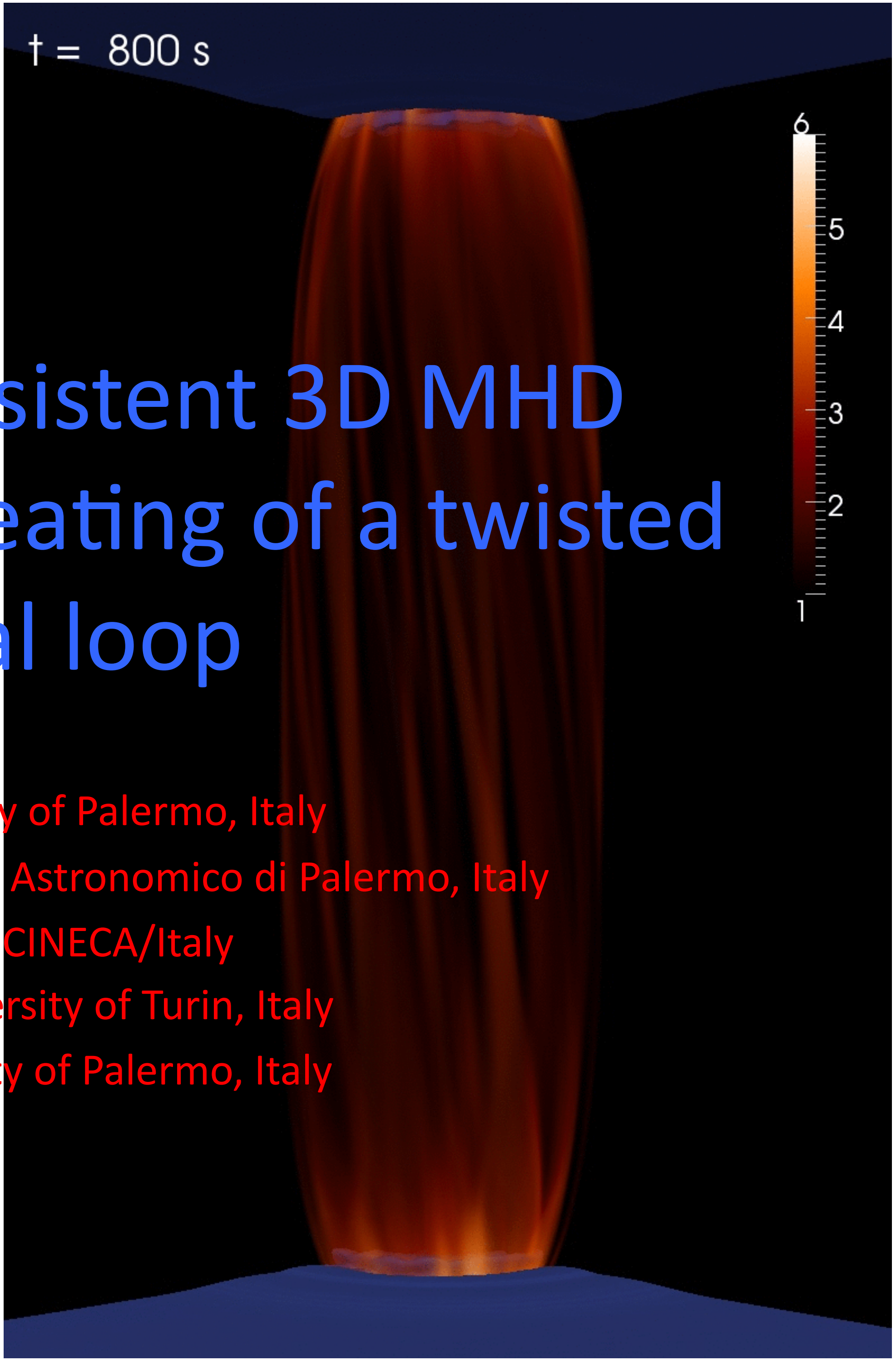
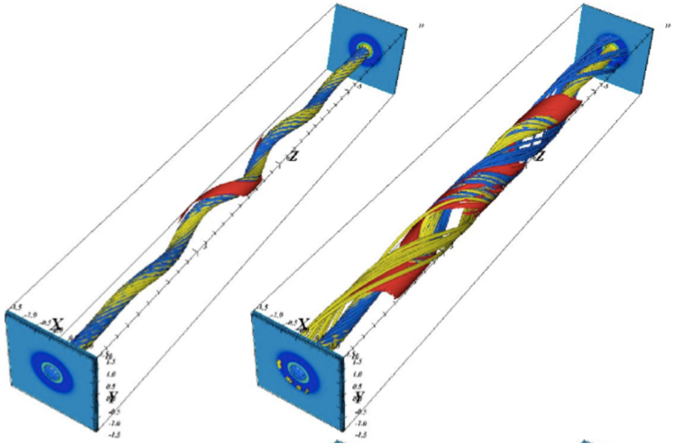


Toward self-consistent 3D MHD modeling of the heating of a twisted coronal loop

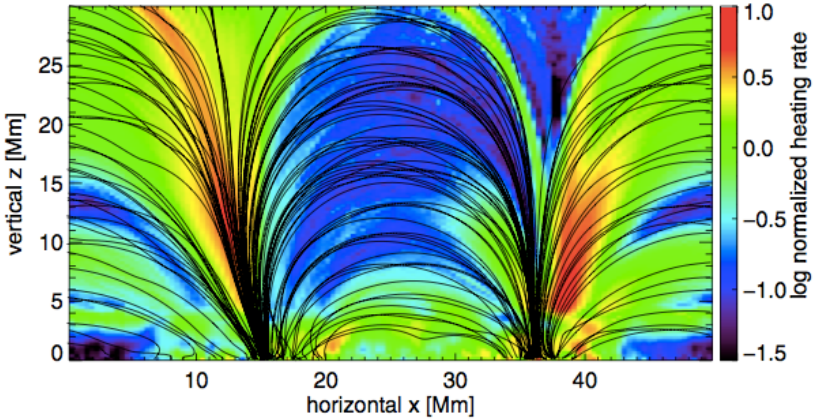
F. Reale – University of Palermo, Italy
S. Orlando – INAF/Osservatorio Astronomico di Palermo, Italy
M. Guarrasi – CINECA/Italy
A. Mignone – University of Turin, Italy
G. Peres – University of Palermo, Italy

3D MHD numerical experiments

- nonlinear phase of an ideal kink instability, where magnetic reconnection leads to relaxation to a state of minimum magnetic energy (e.g. Hood et al. 2009, Botha et al. 2011).



- self-consistent heating mechanism based on the braiding of magnetic field lines rooted in the convective photosphere (e.g. Bingert & Peter 2011).

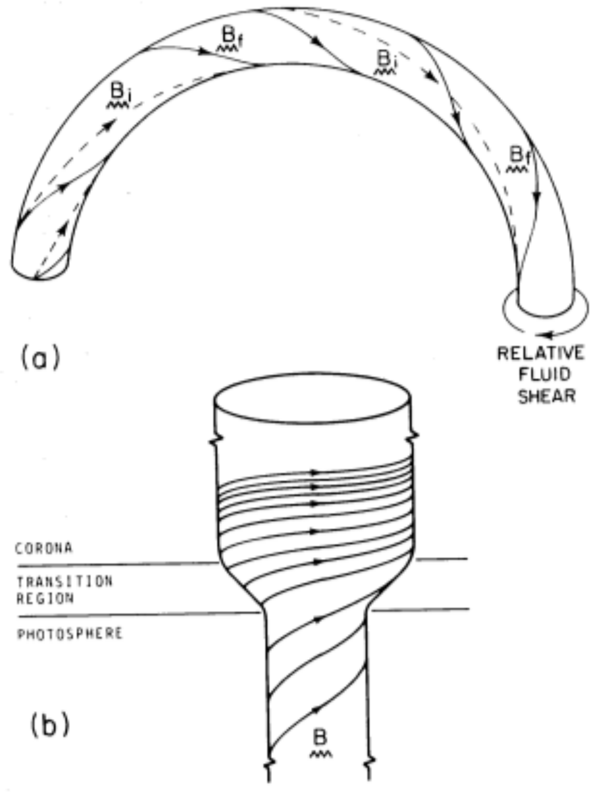


The concept

- 1D loop modeling: empirical heating function
- 3D MHD loop modeling: heating from reconnection of twisted magnetic field lines
- Evolution of loop modeling but …… keep it simple!

MHD modeling of twisted coronal loops

- Progressive twisting of coronal loop field lines
- Driven by rotation of footpoints (Rosner et al. 1978, Golub et al. 1980)
- New issues:
    - 3D MHD w/ th. cond.
    - High resolution
    - Chromosphere and Transition region



Rosner, Golub, Coppi, Vaiana 1978

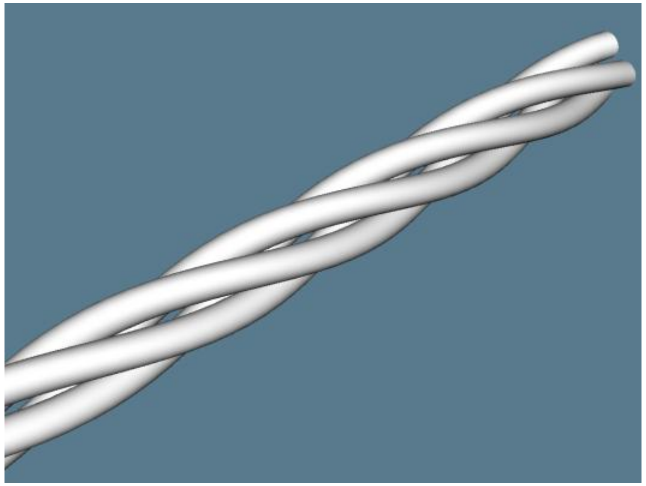
HPC PRACE project

(PRACE n°2011050755)
The way to heating the solar corona: finely-resolved twisting of magnetic loops

PI: **F. Reale**
Co-I: **S. Orlando, M. Miceli, M. Guarrasi**

Simulations: **3D MHD (resistivity; thermal cond.; radiative cooling; gravity)**

Numerical code: **PLUTO 4 (Mignone et al. 2007)**



Resources: **~ 31 Mhours on BlueGene/P FERMI/CINECA (storage ~ 10 TB)**

Project schedule: **October 2012/April 2013**

The 3D MHD model

Three-dimensional cylindrical coordinates

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

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u} - \boldsymbol{B}\boldsymbol{B} + \boldsymbol{I} P_t) = \rho \boldsymbol{g} \ ,$$

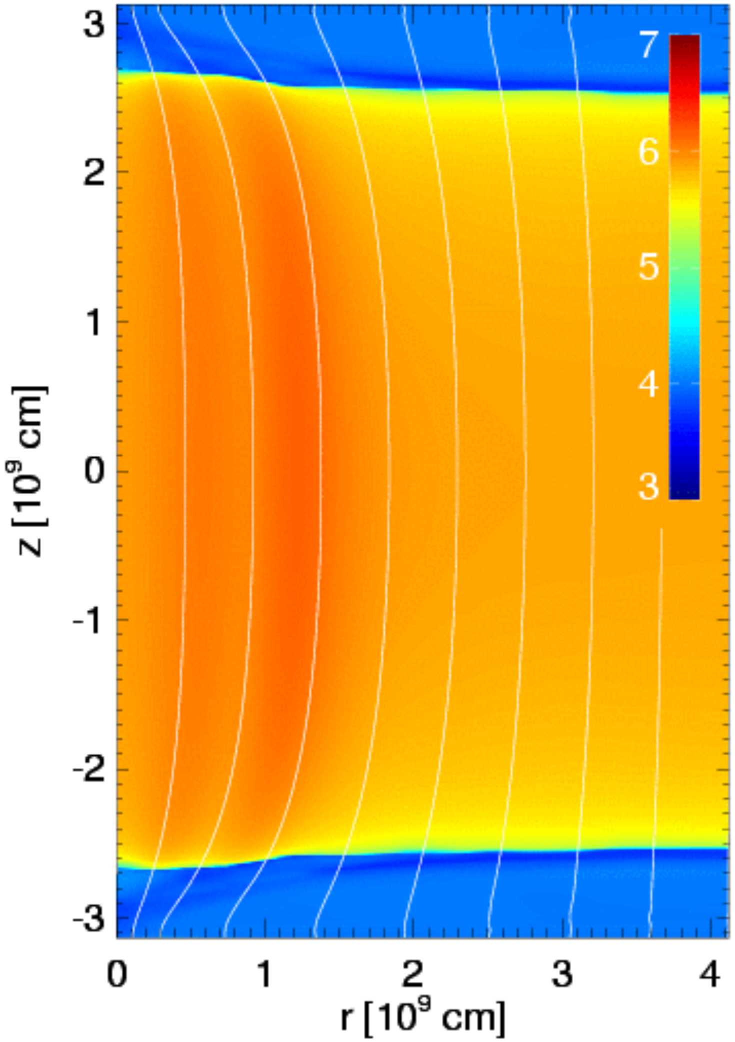
$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [\boldsymbol{u}(\rho E + P_t) - \boldsymbol{B}(\boldsymbol{u} \cdot \boldsymbol{B})] =$$

$$- \nabla \cdot [(\eta \cdot \boldsymbol{J}) \times \boldsymbol{B}] + \rho \boldsymbol{u} \cdot \boldsymbol{g} - \nabla \cdot \boldsymbol{F}_{\mathrm{c}} - n_{\mathrm{e}} n_{\mathrm{H}} \Lambda(T)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{u}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{u}) = -\nabla \times (\eta \cdot \boldsymbol{J}) \ ,$$

where

$$P_t = P + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2} \ , \qquad E = \epsilon + \frac{\boldsymbol{u} \cdot \boldsymbol{u}}{2} + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2\rho} \ ,$$



INITIAL LOOP

$2L = 5\ 10^9$ cm

$T_0 = 7\ 10^5$ K

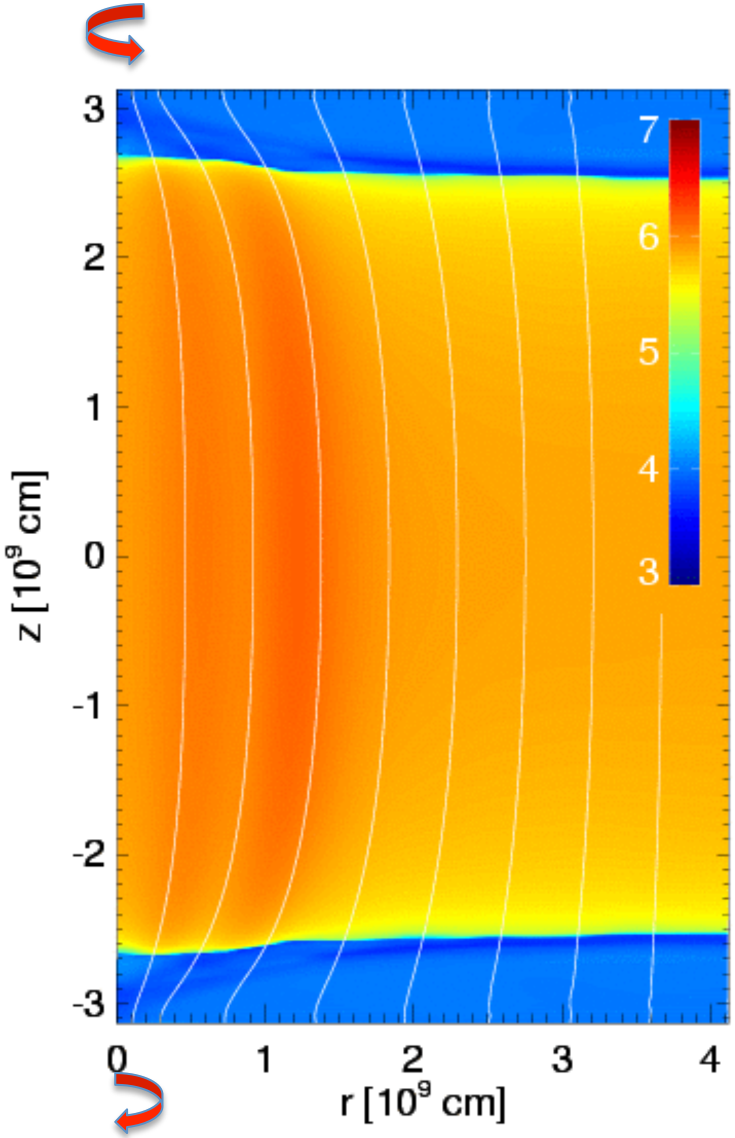
$n_0 = 1\ 10^8\ \mathrm{cm}^{-3}$

B ~ 10 G in the corona

Loop expansion

The twisting

- <u>Footpoint rotation (z-boundaries):</u>
  - Profile: constant angular speed
  - Maximum: 5 km/s (both footpoints)
  - Radius: r = 3000 km
  - Gradual reduction to 0: 3000 < r < 6000 km
  - B-field dragged by footpoint rotation(β >> 1): twisting!



The simulations

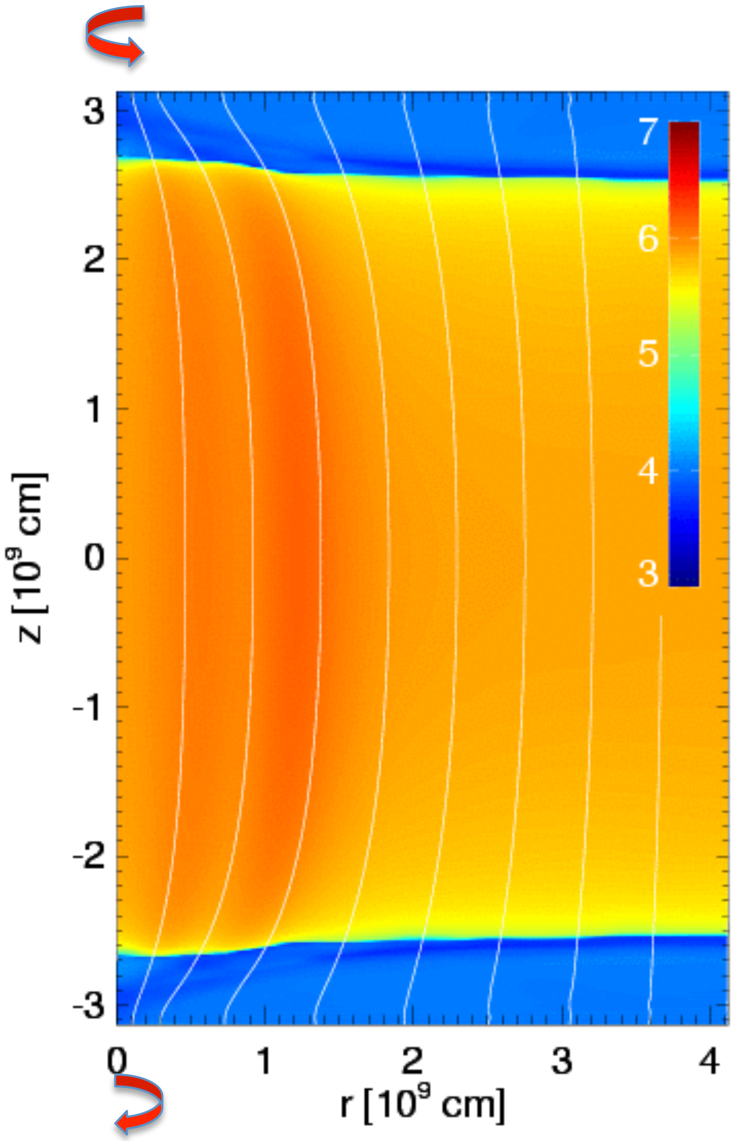
- Low/high resolution
- No resistivity: no heating
- Linear resistivity: distributed and gradual heating
- Turbulent resistivity…..

The final simulation

- “Turbulent” resistivity (Mackay & van Ballegooijen 2006, Yeates, Mackay & van Ballegooijen 2008):
  - $\eta = 0$ for $J<J_{cr}$
  - $\eta = 10^{14}\ \mathrm{cm}^2/\mathrm{s}$ for $J > J_{cr}$

  ($R_M \sim 1$)

  - Threshold: $J_{cr} = 3.16\ 10^{-8}$ esu $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (from test simulations)



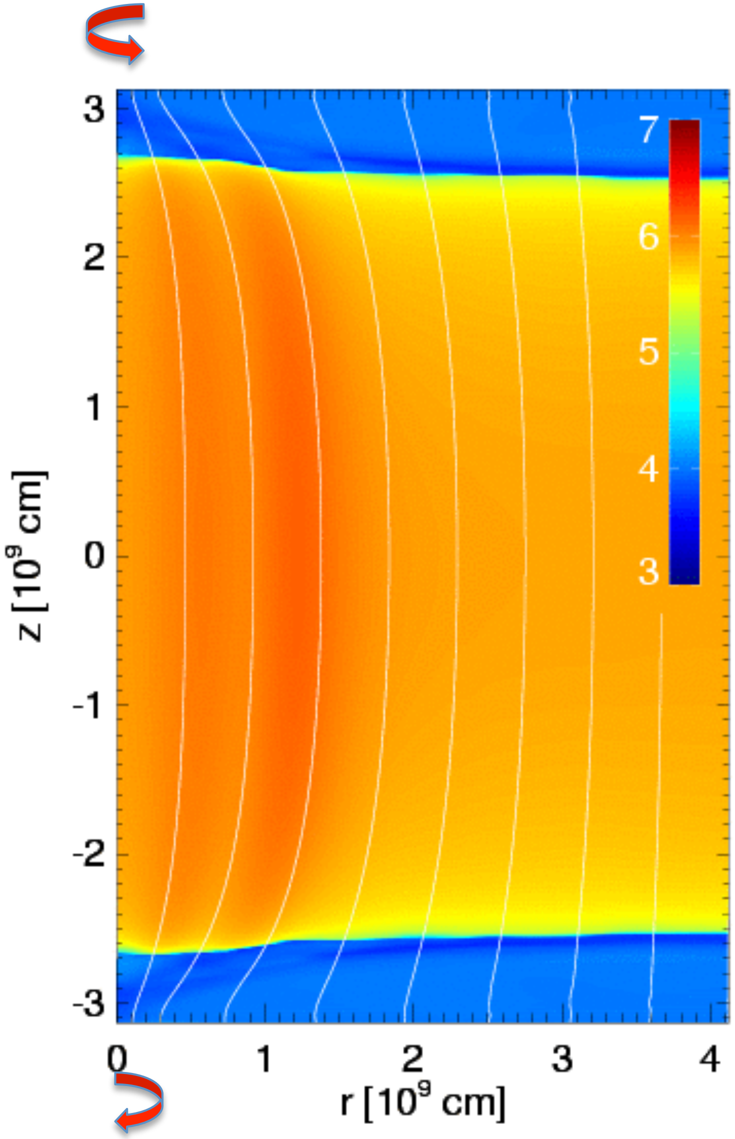
The final simulation (2)

- Non-uniform (fixed) grid/high resolution: maximum resolution ~ 20 km (in TR)

- Box: 384 x 256 x 768

- Time: t = 0 – 1540 s
- Twisting: ~1.5 π

- CPU time: 7 million hours, 16000/32000 cores

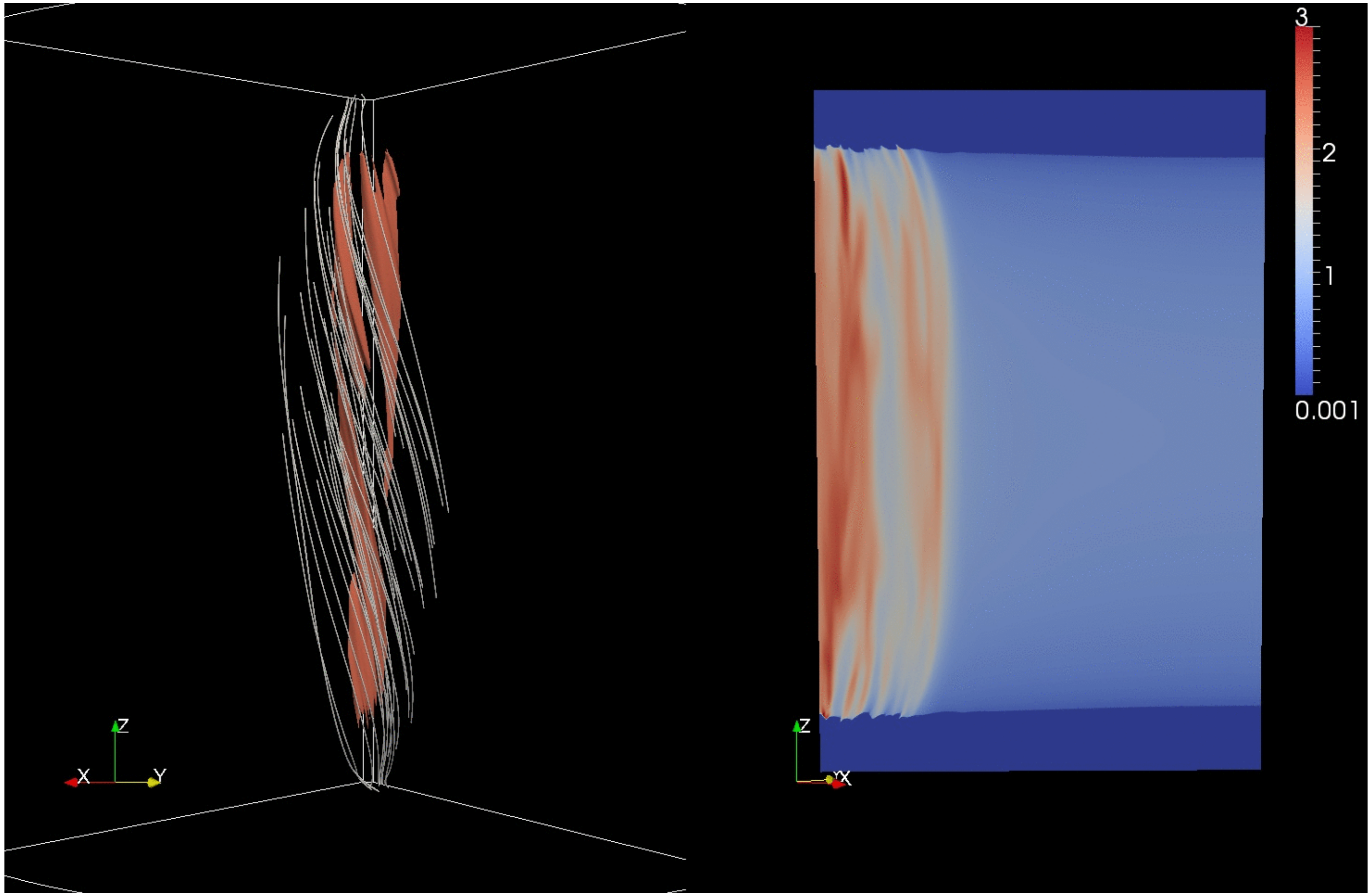


Twisting, reconnection and coronal heating

Last 10 min

Thermal conduction along magnetic field lines

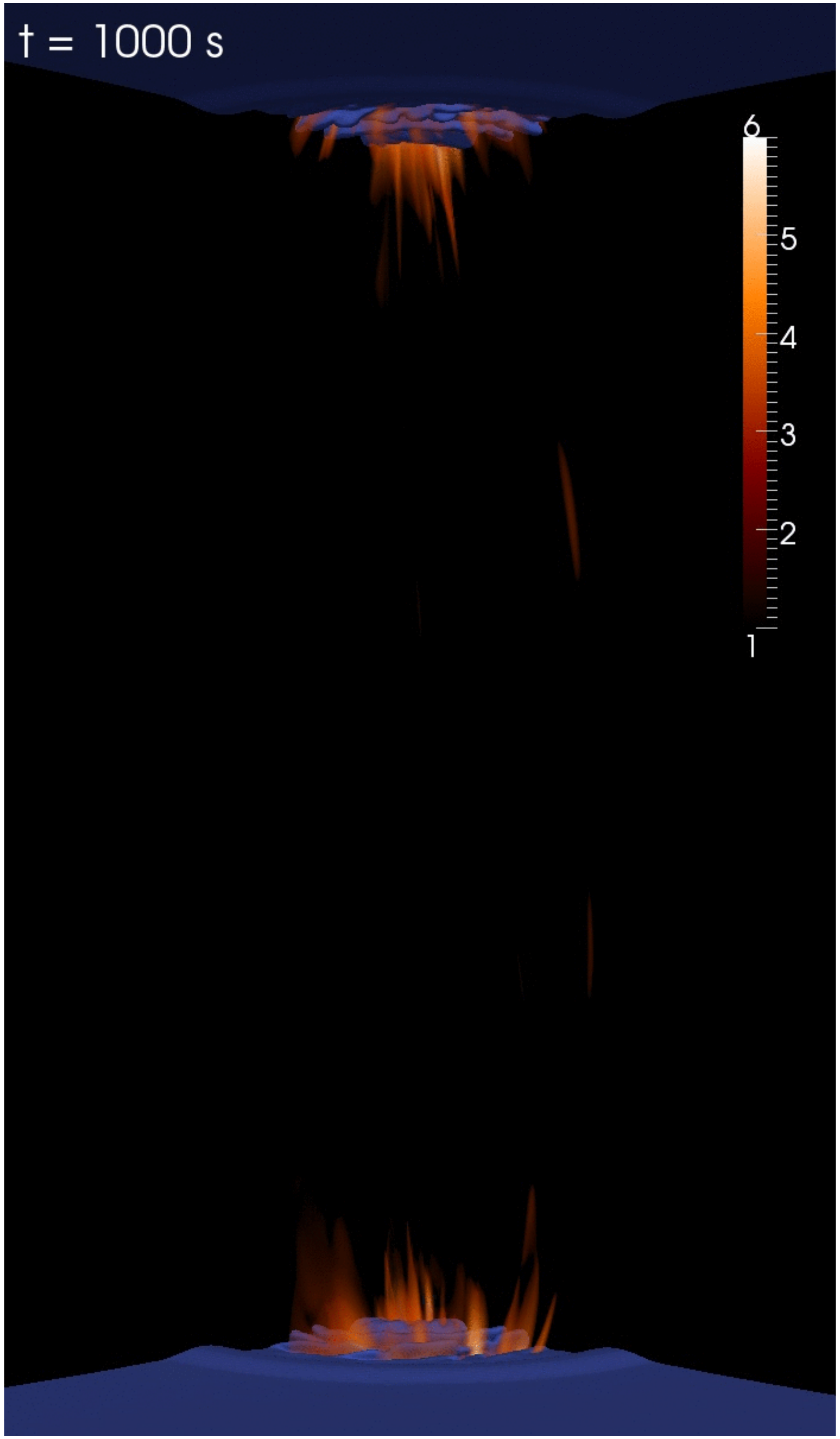
The corona heats to ~ 3 MK



Temperature [MK]

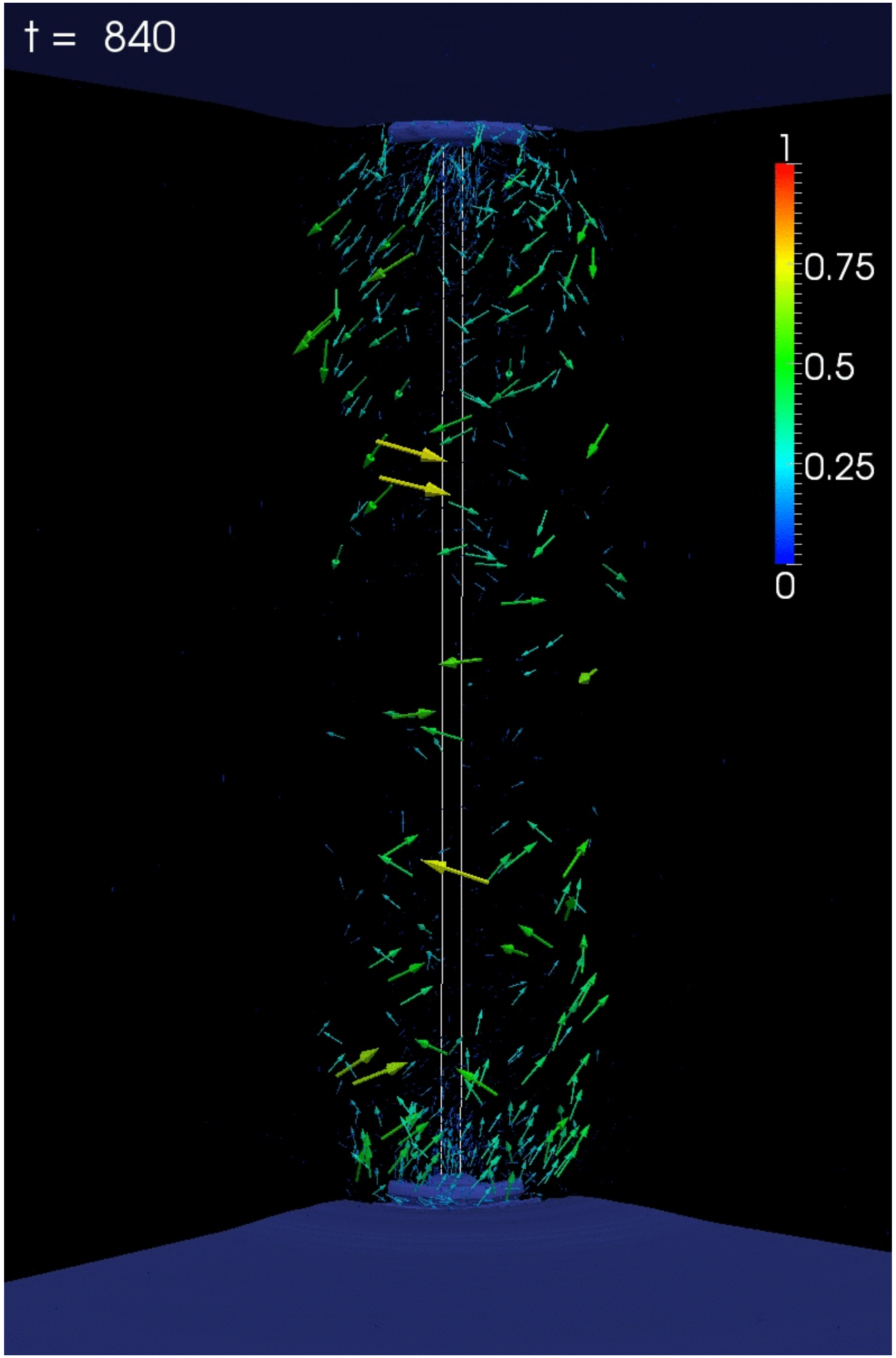
Current density

- Only above threshold shown, i.e. heating marker
- Close to axis
- Close to footpoints
- Lasting few frames: <1 min



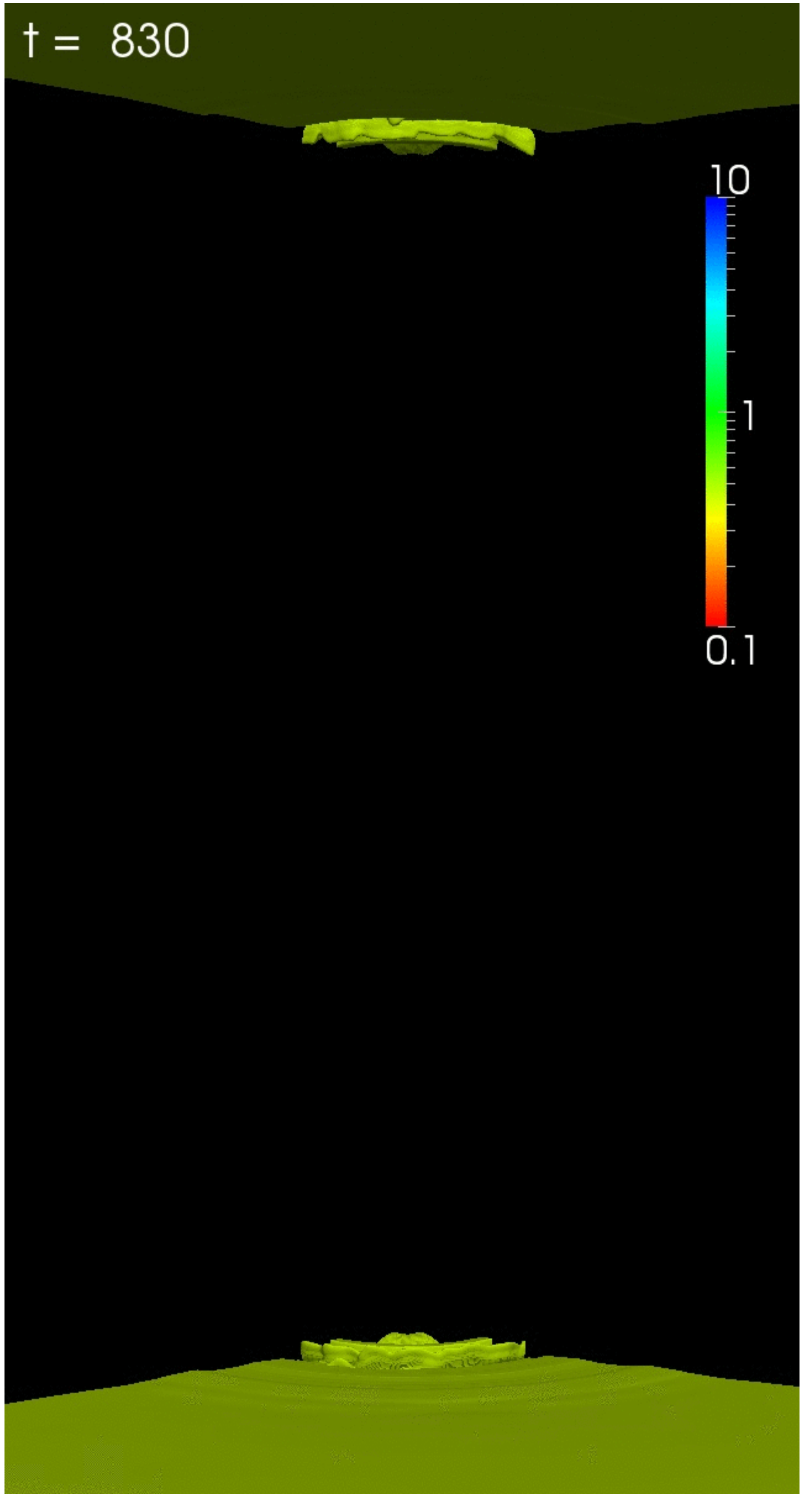
Evaporation: velocity

- Units: 100 km/s
- Maximum speed (at t=1540 s): 140 km/s
- “Red” arrows at the end….



Evaporation: density

- Units: 10^8 cm^{-3}
- Isosurface: 5 10^8 cm^{-3}
- Evaporation starts near the end, along field lines



Preliminary results

- Loop heated to realistic amount (~3 MK)
- Fine structuring naturally develops
- Finite width
- Heating in the low corona
- Heat pulses
- Evaporation correctly described

Next steps

- Explore details and structure along the field lines
- Derive observables
- Extend the simulation
- … and many others!

Sciencexpress Reports

Bright Hot Impacts by Erupted Fragments Falling Back on the Sun: A Template for Stellar Accretion

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Impacts of falling fragments observed after the eruption of a filament in a solar flare on 7 June 2011 are similar to those inferred for accretion flows on young stellar objects. As imaged in the ultraviolet (UV)–extreme UV range by the Atmospheric Imaging Assembly onboard the Solar Dynamics Observatory, many impacts of dark, dense matter display uncommonly intense, compact brightenings. High-resolution hydrodynamic simulations show that such bright spots, with plasma temperatures increasing from ~10^4 to ~10^6 kelvin, occur when high-density plasma ($>>10^{10}$ particles per cubic centimeter) hits the solar surface at several hundred kilometers per second, producing high-energy emission as in stellar accretion. The high-energy emission comes from the original fragment material and is heavily absorbed by optically thick plasma, possibly explaining the lower mass accretion rates inferred from x-rays relative to UV–optical–near infrared observations of young stars.

treme UV (XUV) narrowband channels of the Atmospheric Imaging Assembly (AIA) (*17*) on board the Solar Dynamics Observatory (SDO) (*18*), with high spatial resolution (~0.6 arc sec per pixel) and high cadence (12 s) (*19*) (see supplementary materials, section S1). During the flare, we clearly see, in all SDO/AIA XUV channels, that a dense dark filament is broken and violently ejected (movie S1). The cloud propagates outward at a speed of several hundred kilometers per second and fragments in all directions. The fastest fragments escape in the form of a typical coronal mass ejection (*20*), observed by the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph (*21*) white light telescope. Slower fragments fall back onto the solar surface. They are visible in all AIA XUV channels as dark, irregular, and moving strips on the brighter background corona. During their fall, the fragments change their morphology, stretching and dividing further (*19*), but they generally maintain a coherent structure and remain dark throughout their trajectory. When the fragments hit the solar surface, they drive intense brightenings in the impact region, visible in all AIA XUV and UV