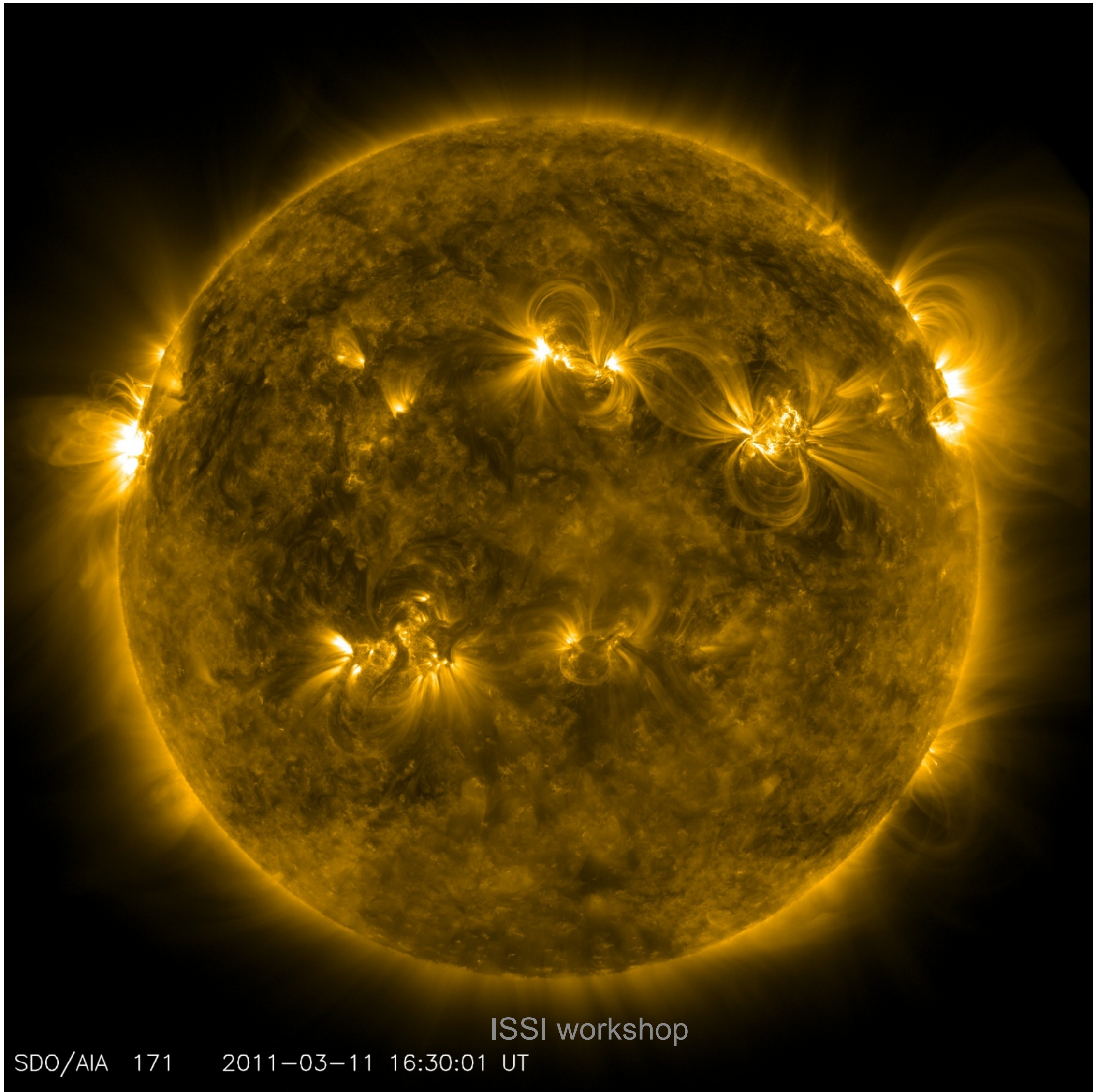
MHD modeling the heating of a twisted coronal loop

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
A. Hood – University of St. Andrews, UK
E. R. Priest – University of St. Andrews, UK

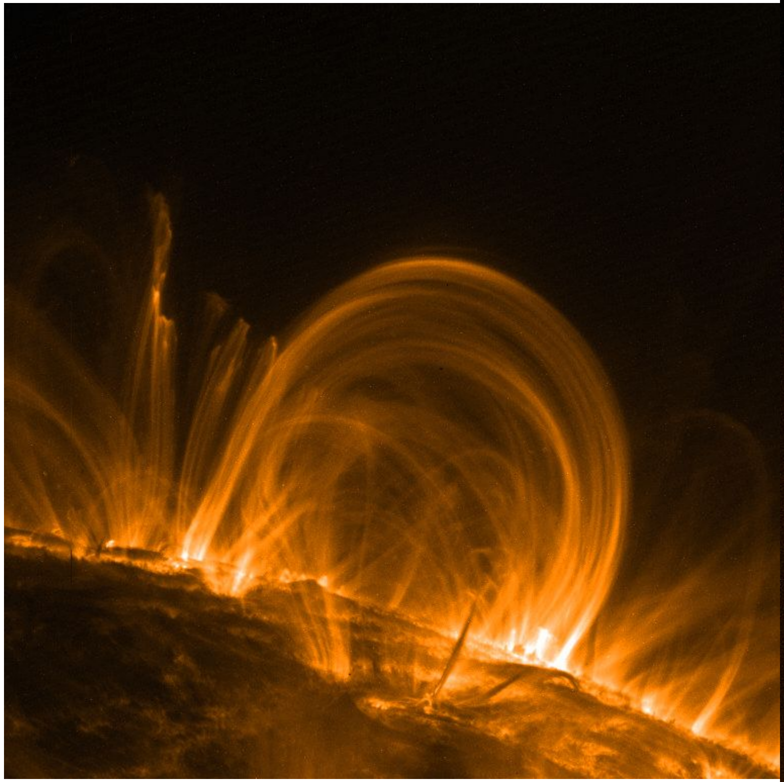
Outline

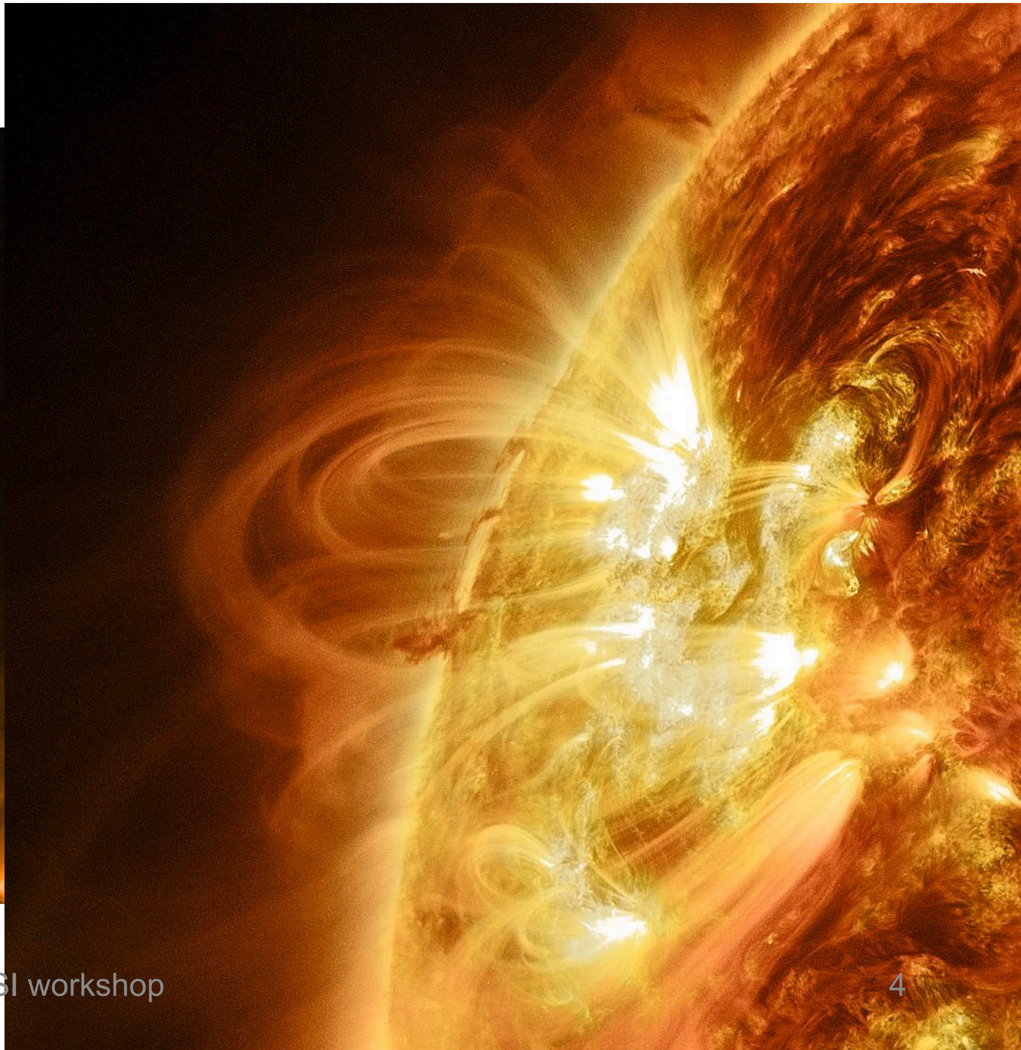
- Introduction: coronal loop issues
- Loop modeling
- 3D MHD loop modeling:
  – Uniform resistivity: monolithic loops
  – Switch-on resistivity: structured loops

Solar corona

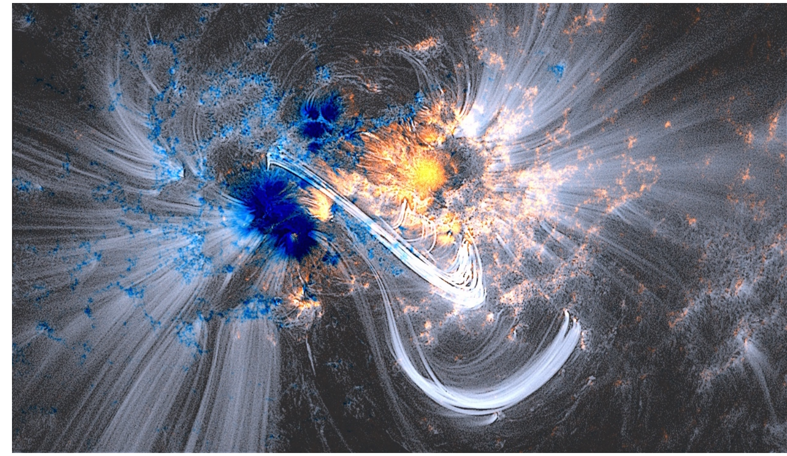


Coronal loops

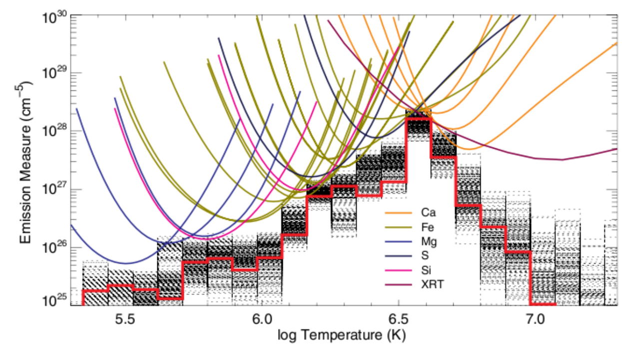




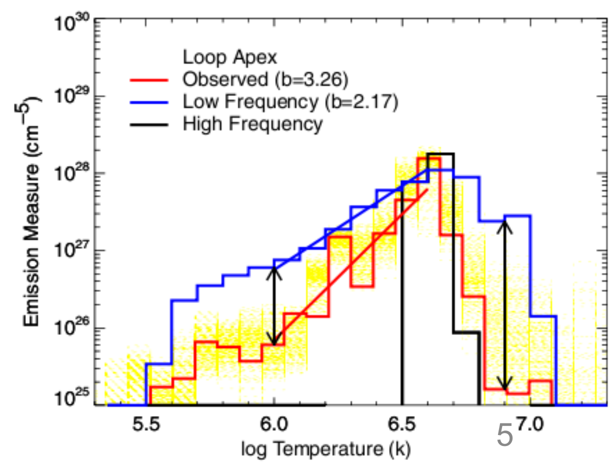
Coronal loops issues



- Out-of-equilibrium (e.g. overdensity)
- Multi-thermal structure
- Fine structure
- Flows
- Hot plasma (6-8 MK)
- Dynamic heating? Heating frequency?

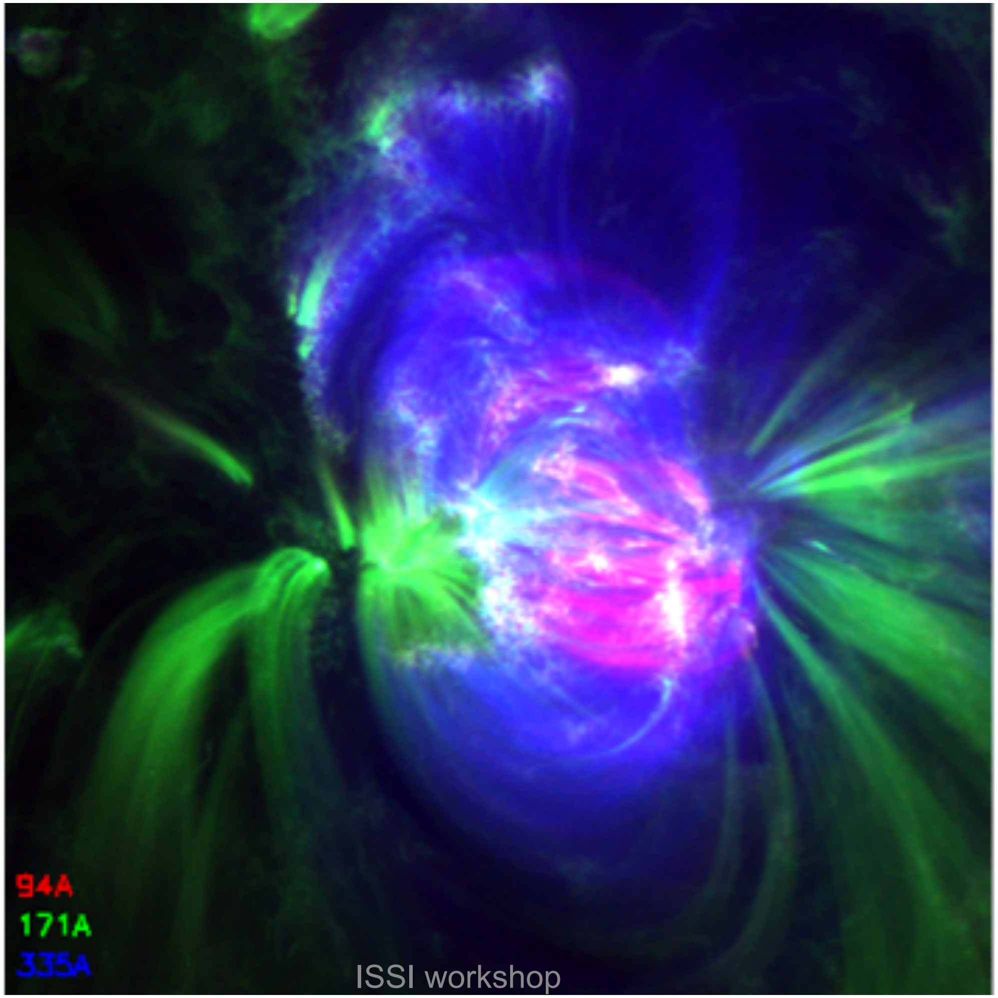


Warren et al 2011



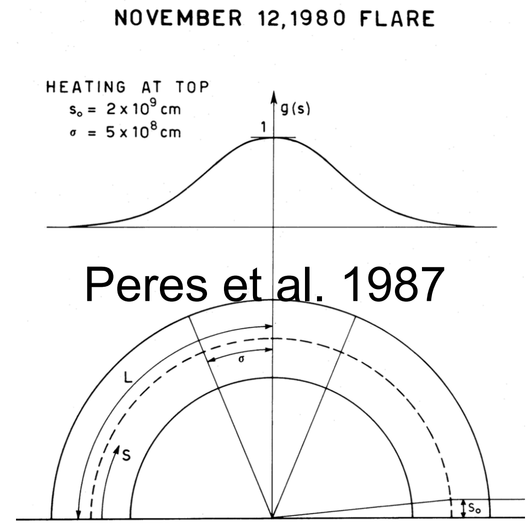
Dynamic heating? Very hot plasma (6-8 MK) in non-flaring active region cores

(pink, e.g. Reale+ 2011, Testa & Reale 2012, Petralia+ 2014)

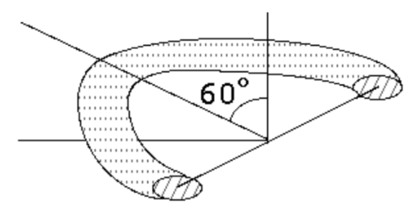


Loop modeling

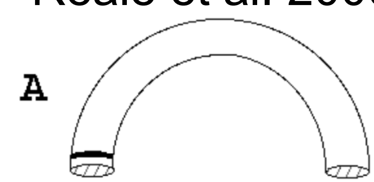
- Plasma confined in flux tubes moves and transports energy along the magnetic field lines
- Hydrodynamic modeling w/ empirical heating function
- Flares, loop ignition



Peres et al. 1987

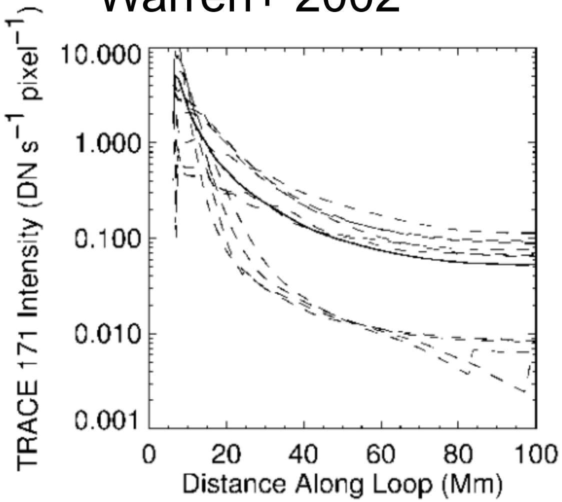


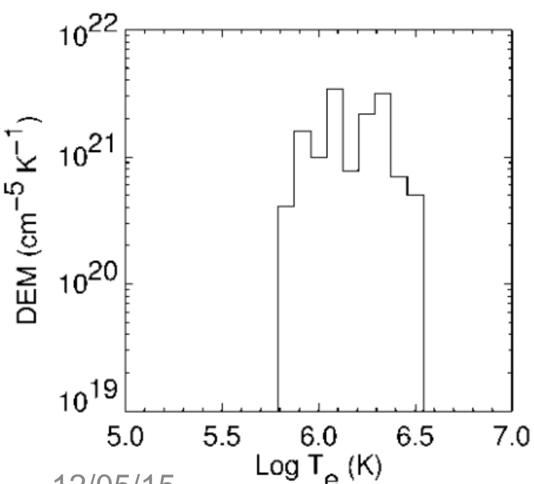
Reale et al. 2000



Next step:
Multi-strand loop modeling

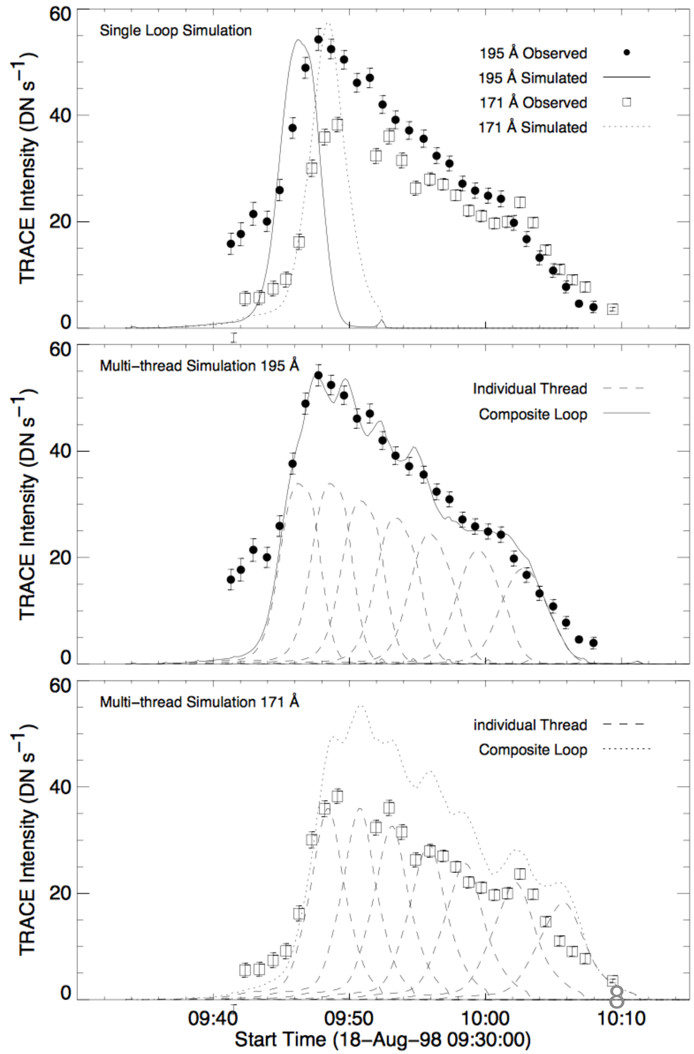
Warren+ 2002





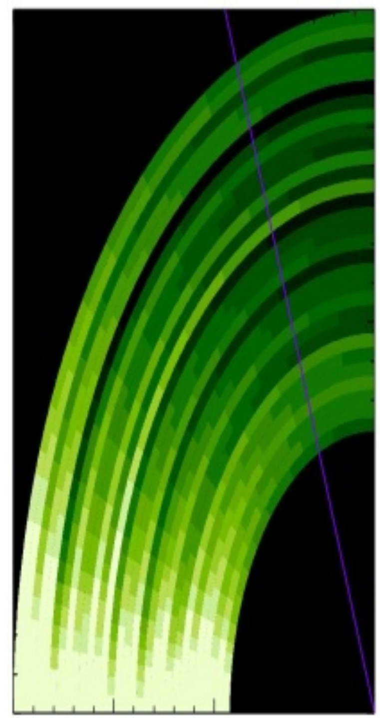
- Random combination of single loop outputs

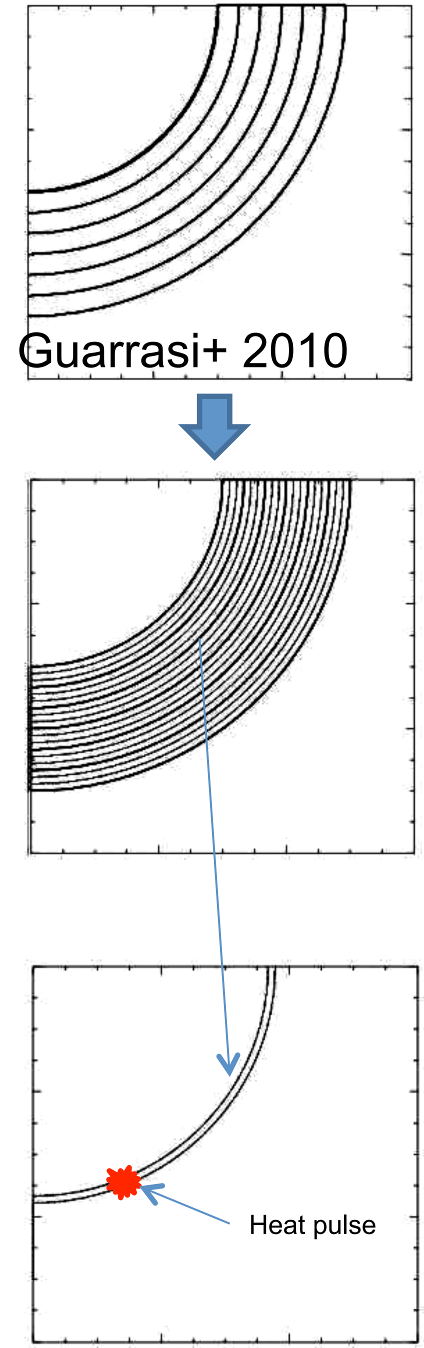
Warren+ 2003



Next step:
Multi-strand loop modeling

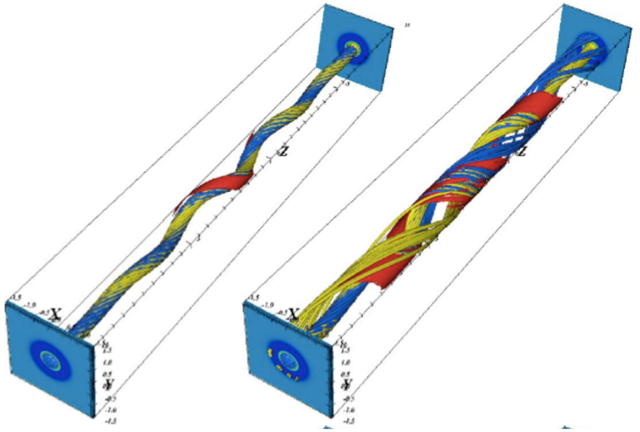
- Random combination of single strand evolution to reconstruct spatial aspect



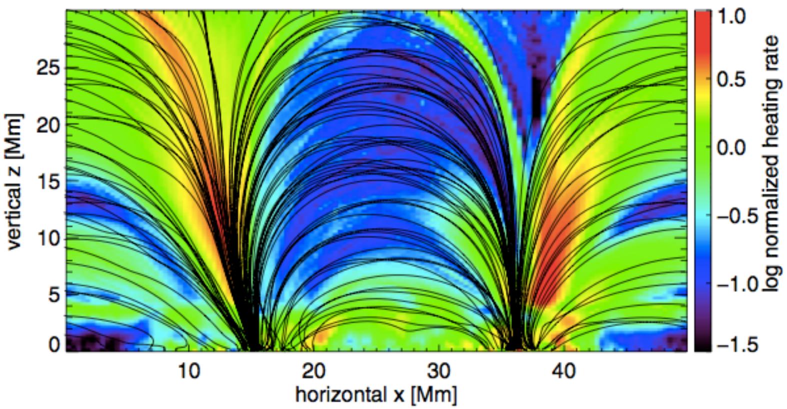


Toward self-consistent loop modeling

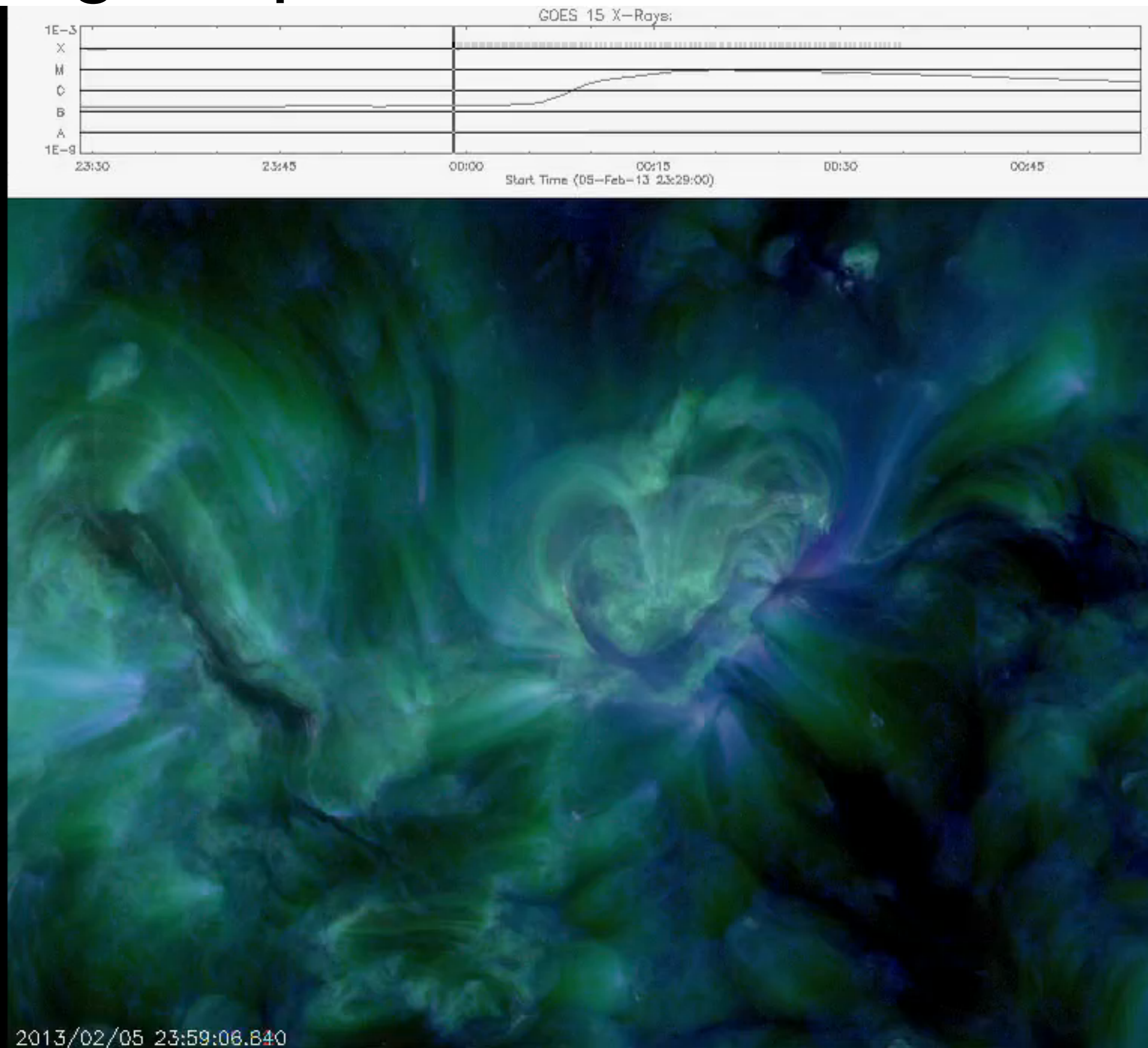
- 3D MHD numerical experiments
  - nonlinear phase of an ideal kink instability, where magnetic reconnection leads to relaxation to a state of minimum magnetic energy (e.g. Hood+ 2009).



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

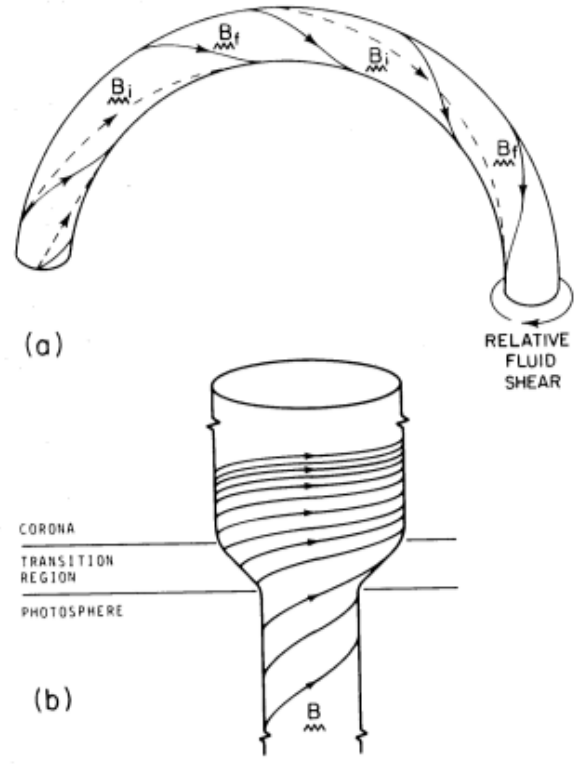


Twisting
(e.g. Depontieu+, Science, 2014)



MHD modeling of twisted coronal loops

- Progressive twisting of coronal loop field lines
- Driven by rotation of footpoints (Rosner+ 1978 Golub+ 1980)



Rosner, Golub, Coppi, Vaiana 1978

Rationale

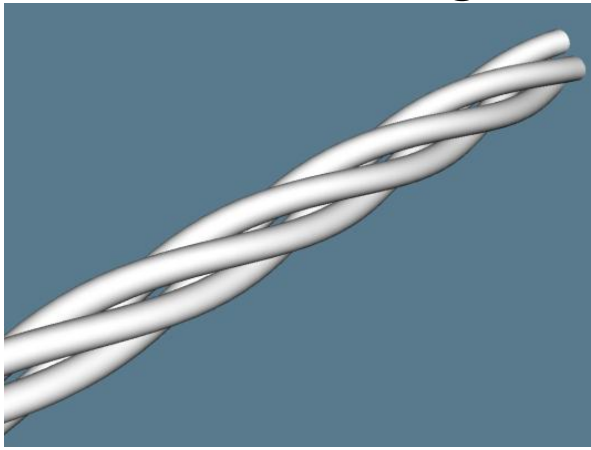
- Extension of hydrodynamic loop modeling to MHD loop modeling:
  - magnetic field to release energy, change of beta, non-uniform (expanding) field
  - Include chromosphere and TR
- Towards self-consistent modeling
- Keep it simple:
  - Magnetic twisting (not random braiding)
  - Simple resistivity
- Targets:
  - Typical loop structure
  - Dynamic heating
  - Fine structure

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)

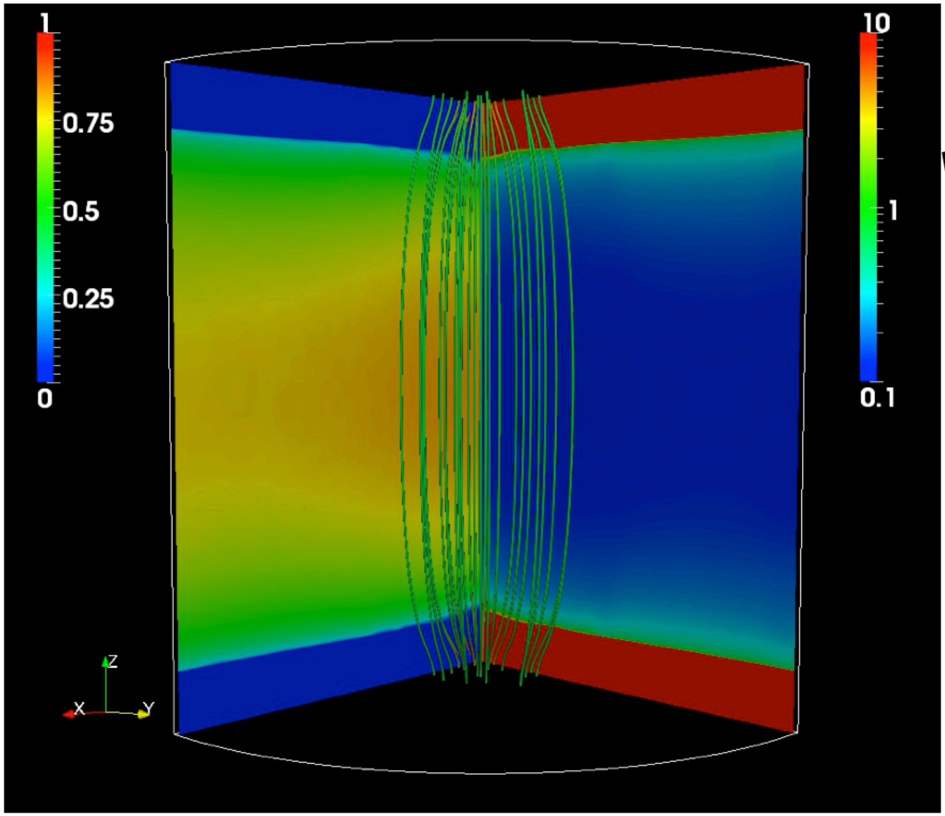


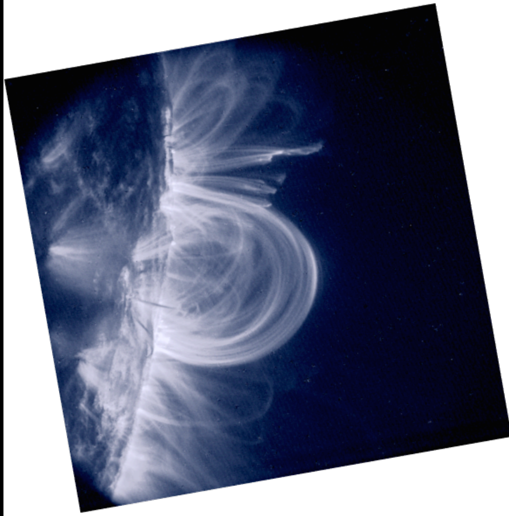
Numerical code: PLUTO 4 (Mignone+ 2007)

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

Project schedule: October 2012/April 2013+Fall 2013

Initial conditions





The 3D MHD model

Three-dimensional cylindrical coordinates: r, ϕ, z
One quarter domain: $0 < \phi < \pi/2$, $r_0 = 0.07\ 10^9$ cm
The equations:

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

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

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

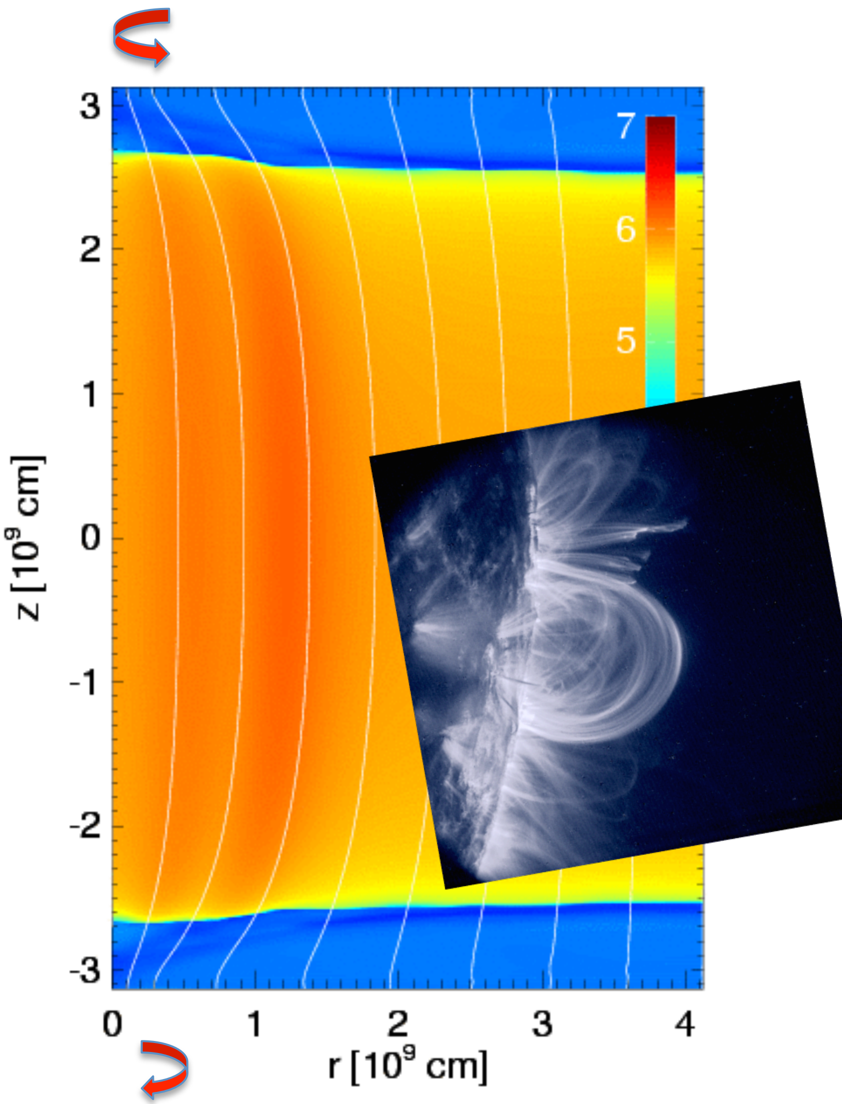
$$- \nabla \cdot [(\eta \cdot \boldsymbol{J}) \times \boldsymbol{B}] + \rho \boldsymbol{u} \cdot \boldsymbol{g} - \nabla \cdot \boldsymbol{F}_c - n_e n_H \Lambda(T)$$

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

where

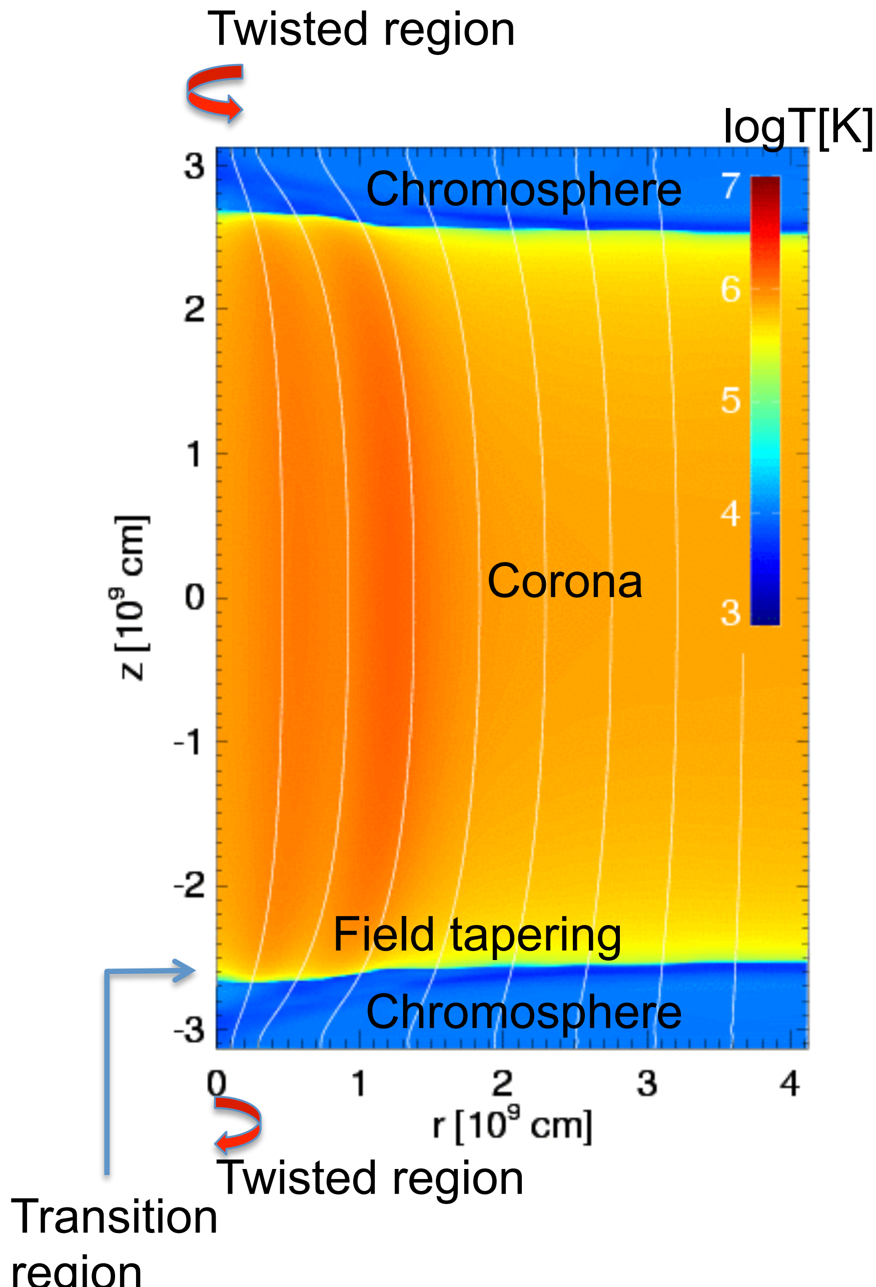
$$P_t = P + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2} \ , \qquad E = \epsilon + \frac{\boldsymbol{u} \cdot \boldsymbol{u}}{2} + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{2\rho} \ ,$$

$$\mathbf{F_c} = \frac{F_{sat}}{F_{sat} + |\mathbf{F_{class}}|} \mathbf{F_{class}}$$



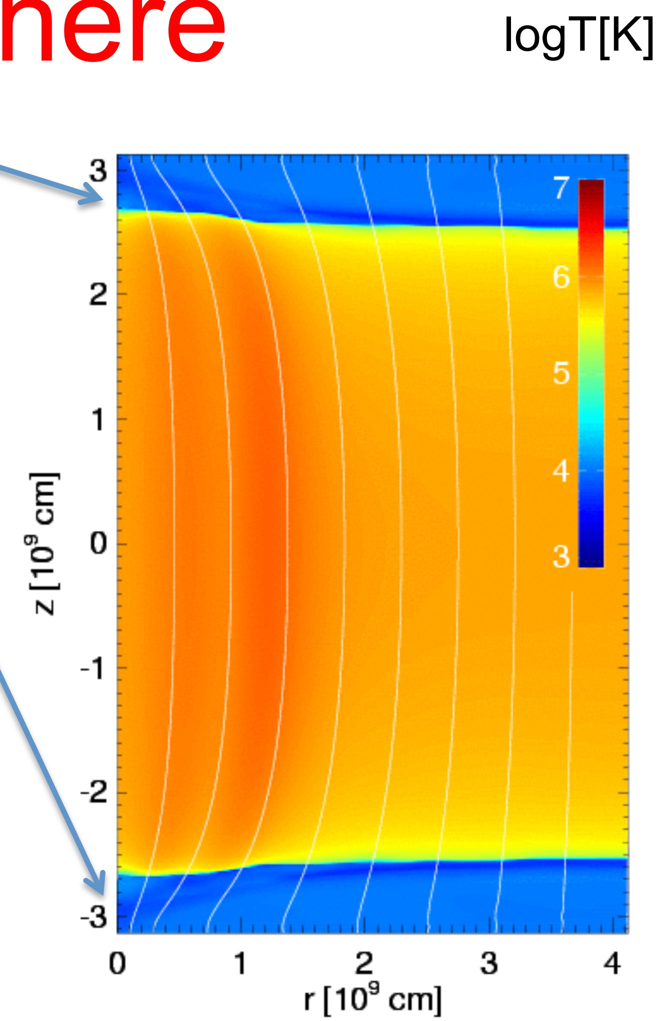
Initial atmosphere
(Guarrasi+ 2014)

- <u>Loop atmosphere:</u>
  - Hydrostatic: gravity of a curved loop
  - Tenuous and cool:
    - $2L = 5\ 10^9$ cm
    - $T_0 = 7\ 10^5$ K
    - $n_0 = 10^8\ cm^{-3}$
  - Background heating in the corona
- <u>Magnetic field:</u>
  - Loop expansion in the TR
  - B ~ 10 G in the corona (B~ 300 G in the chromosphere close to the central axis)
- Relaxed to equilibrium before twisting is switched on



The chromosphere

- Simplified:
  - Isothermal: $T = 10^4$ K
  - Gravitationally stratified
  - No heating, no radiative losses
- No resistivity at all times

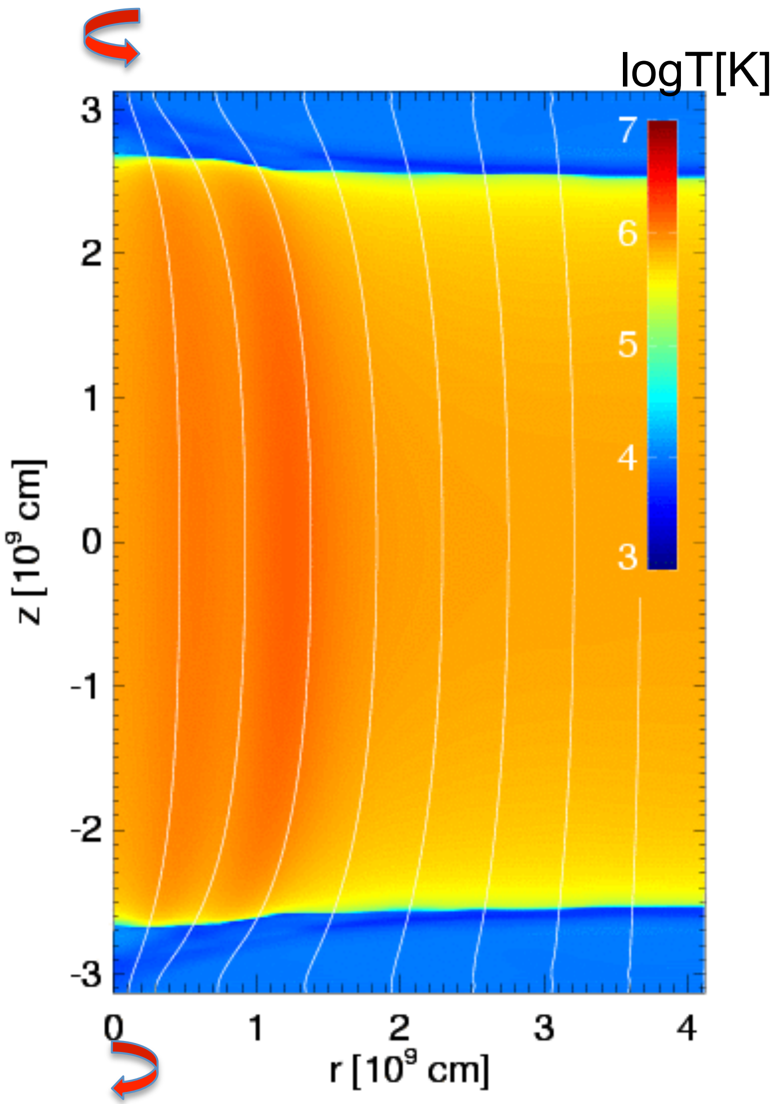


Two main simulations

- Uniform anomalous resistivity, smooth footpoint rotation
- Switch-on resistivity, perturbed footpoint rotation

Uniform anomalous resistivity

- <u>Anomalous resistivity</u> (Bingert & Peter 2011):
  - $\eta = 10^{13}$ cm^2/s
  - $R_m = v\,L/\eta \sim 1$ for $v \sim 10$ km/s, $L \sim 100$ km
  - Chromosphere: $\eta = 0$

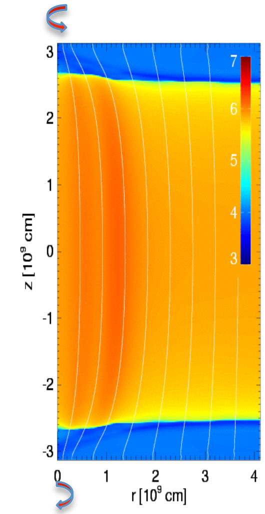


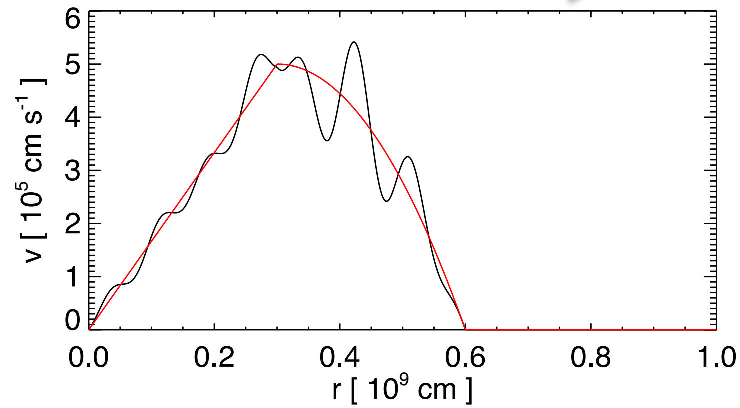
The smooth twisting (red line)

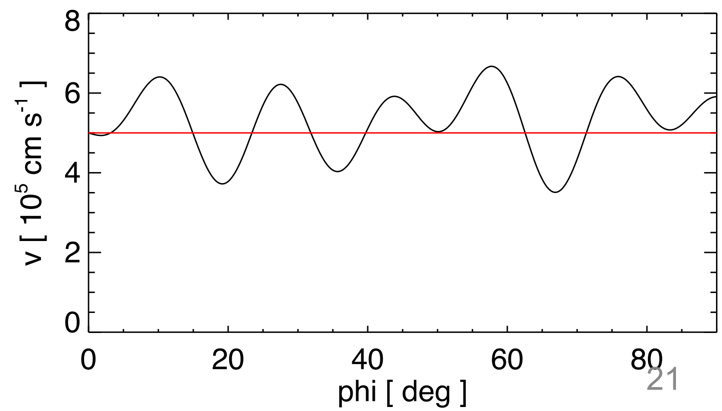
- <u>Footpoint rotation (z-boundaries):</u>
  - Profile: constant angular speed ω
  - Maximum: 5 km/s (both footpoints)
  - Radius: r = 3000 km
  - Linear reduction:
    ω ➔0: 3000 < r < 6000 km

  - B-field dragged by footpoint rotation ($\beta >> 1$): twisting!

  - The twisting begins at t=0





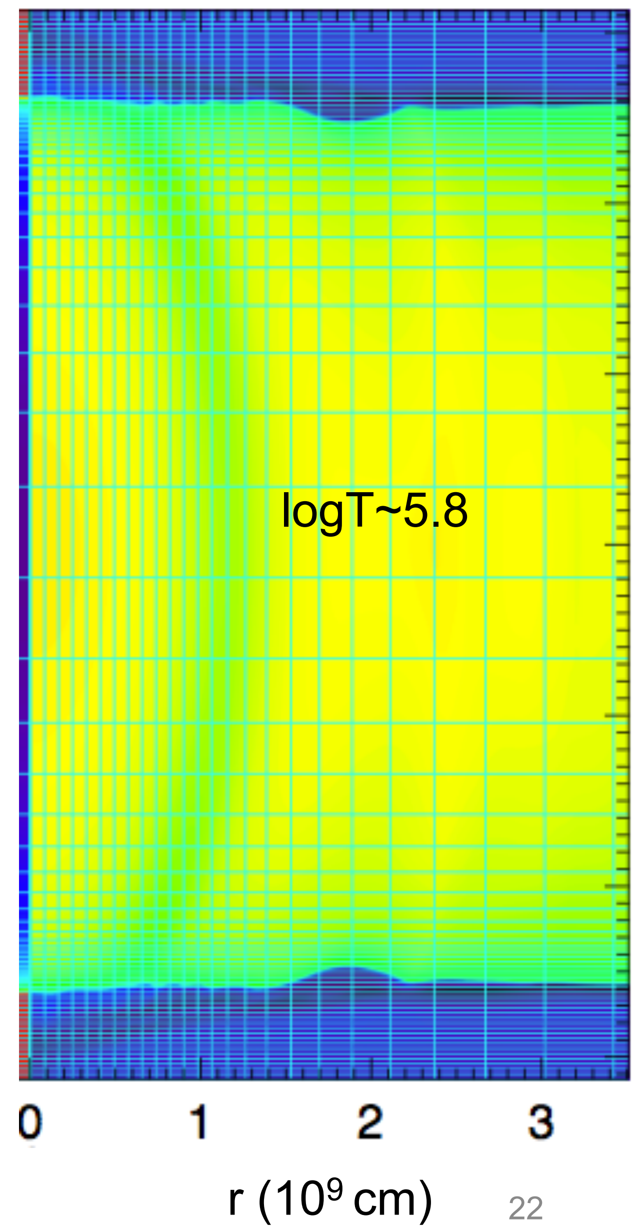


Uniform resistivity

- The domain is one quarter of the whole space: $0 < \phi < \pi/2$
- Non-uniform (fixed) grid: maximum resolution ~ 20 km (in TR)
- Box: $[r, \phi, z]$= [384, 256, 768] pts
- Time: t = 0 – 2600 s
- Twisting: ~2 π
- CPU time: 5 million hours

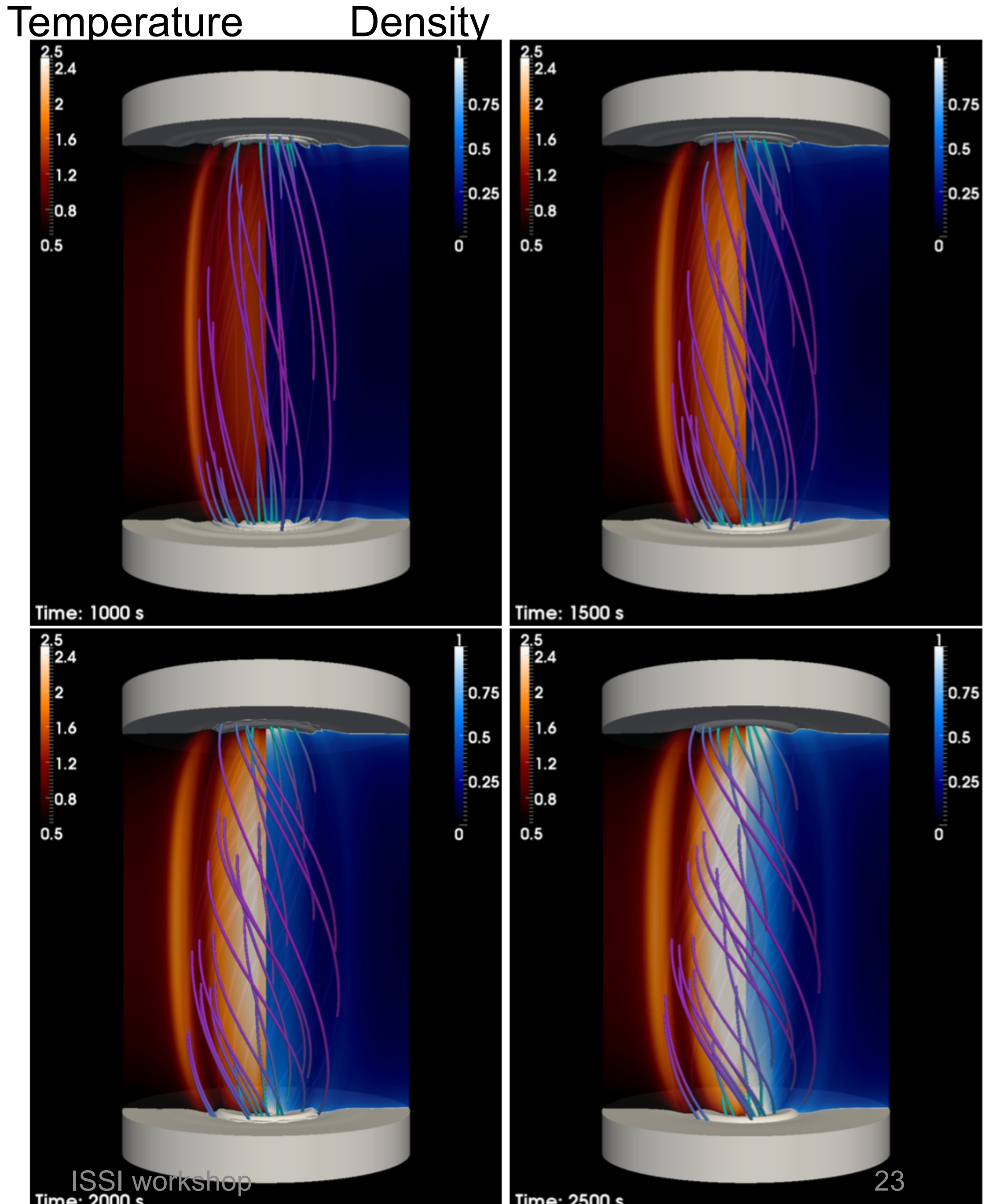
Grid resolution

Each box 10x10 grid points



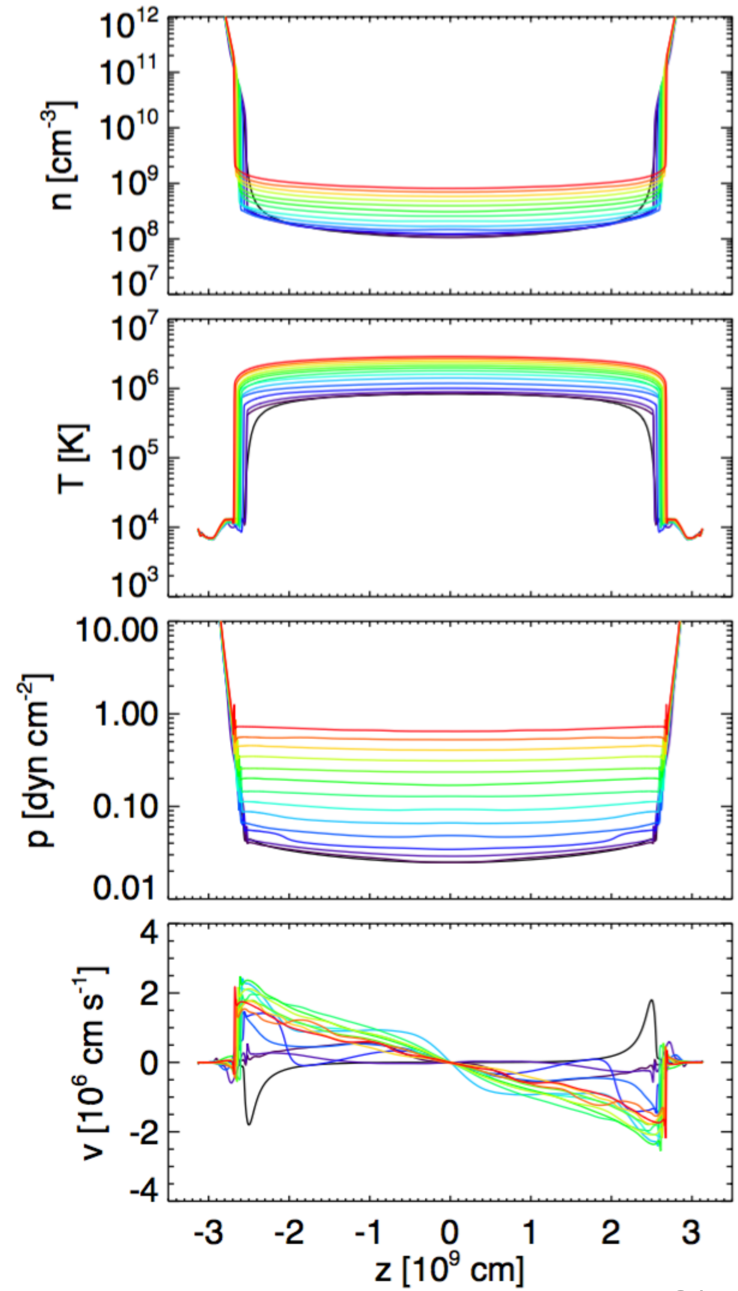
Basic modeling: uniform resistivity

- Cross-section+field lines
- Temperature rises uniformly
- Density from the chromosphere
- Uniform monolithic structure

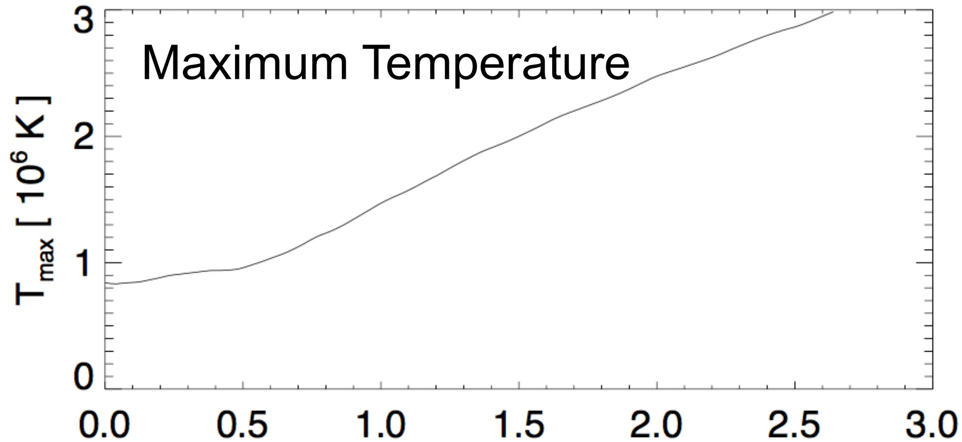


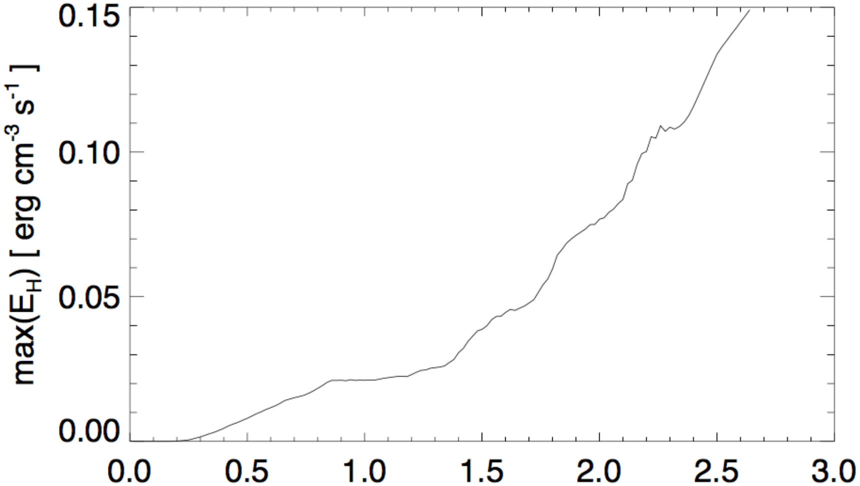
Uniform resistivity: Loop evolution along z

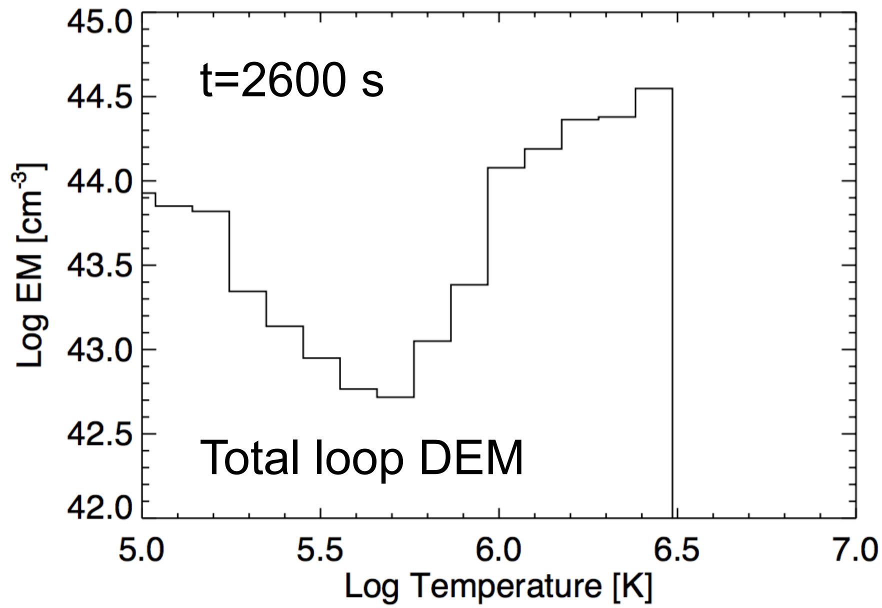
- Spaced every 200 s
- From blue (t=0) to red (t=1800 s)
- Gradual heating, gradual evolution
- Moderate evaporation speed

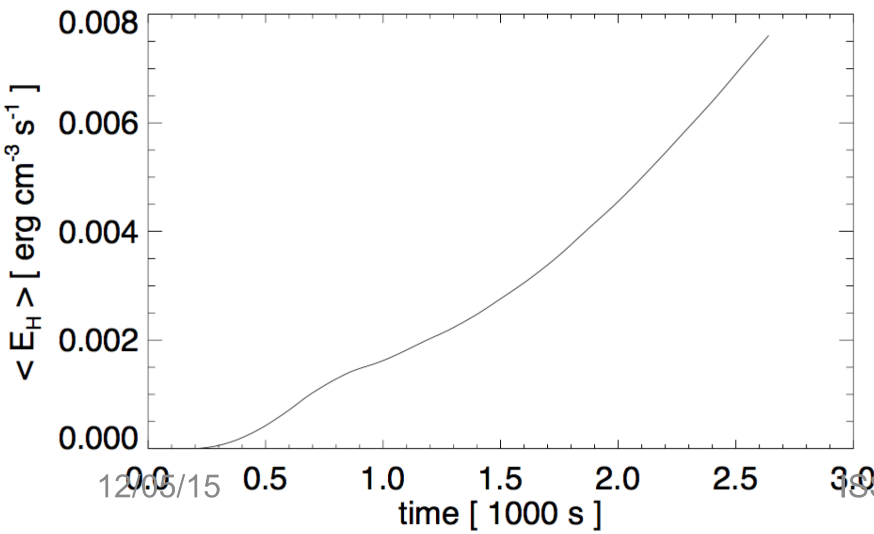


Uniform resistivity: Max T, DEM, Heating







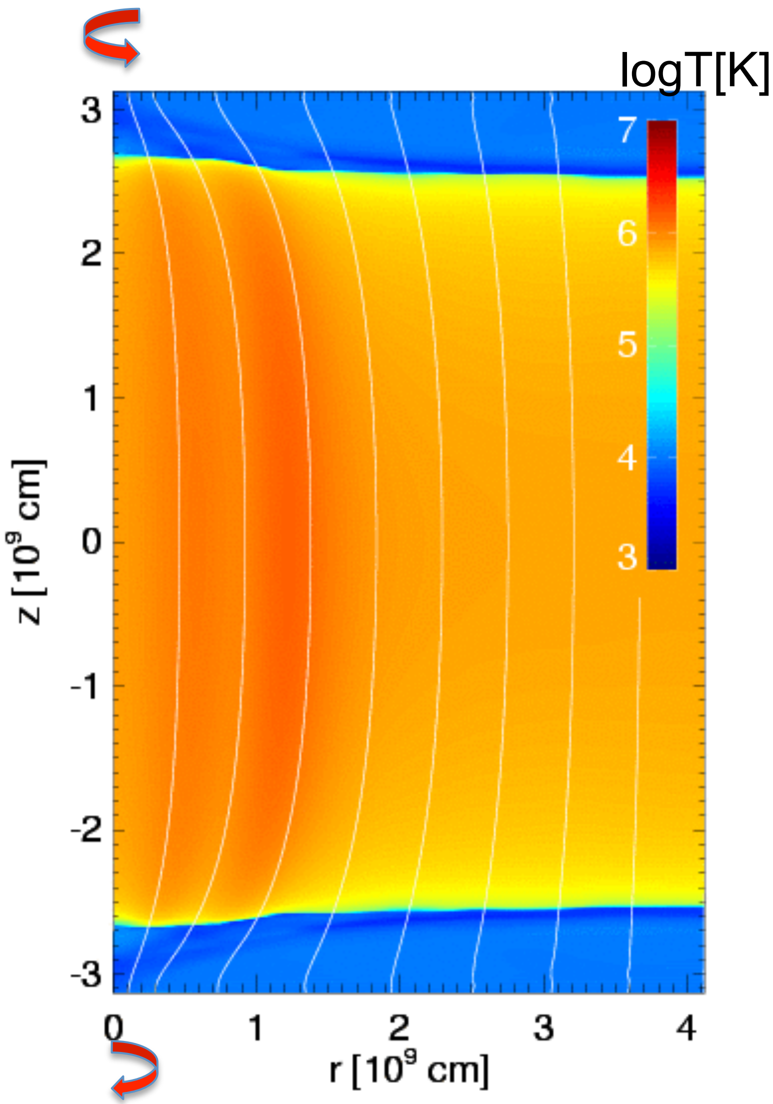


Uniform resistivity

- Loop heating
- Multi-thermal
- Slow flows
- No fine structure
- No hot plasma

Switch-on resistivity

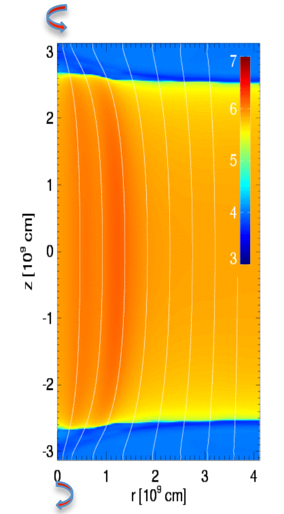
- "Switch-on" anomalous resistivity (Hood+ 2009, eq.7):
  - $\eta = 0$ for $J < J_{cr}$
  - $\eta = 10^{14}\ cm^2/s$ for $J > J_{cr}$
  - Threshold:
    - $J_{cr} = 75\ A/cm^2 = 3.16\ 10^{-8}\ esu\ cm^{-2}\ s^{-1}$ (from test simulations)
  - Minimum heating:
    - $H = \eta J_{cr}^2 \approx 10^{-2}\ erg\ cm^{-3}\ s^{-1}$
  - Chromosphere: $\eta = 0$

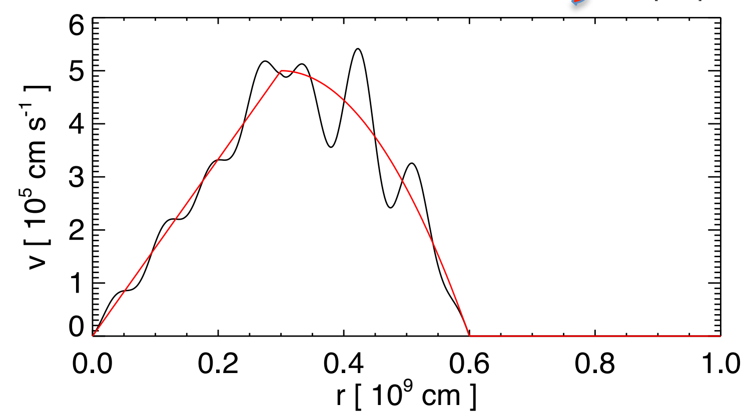


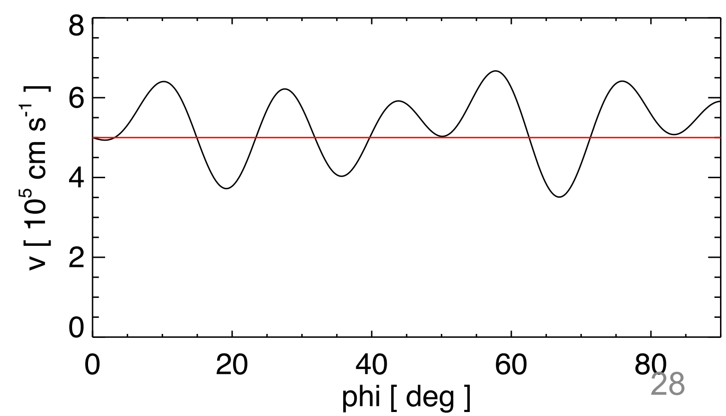
The perturbed twisting (black line)

- <u>Footpoint rotation (z-boundaries):</u>
  - Profile: constant angular speed ω
  - Maximum: 5 km/s (both footpoints)
  - Radius: r = 3000 km
  - Linear reduction:
    ω ➔0: 3000 < r < 6000 km

  - **RANDOMLY PERTURBED VELOCITY AT THE FOOTPOINTS**



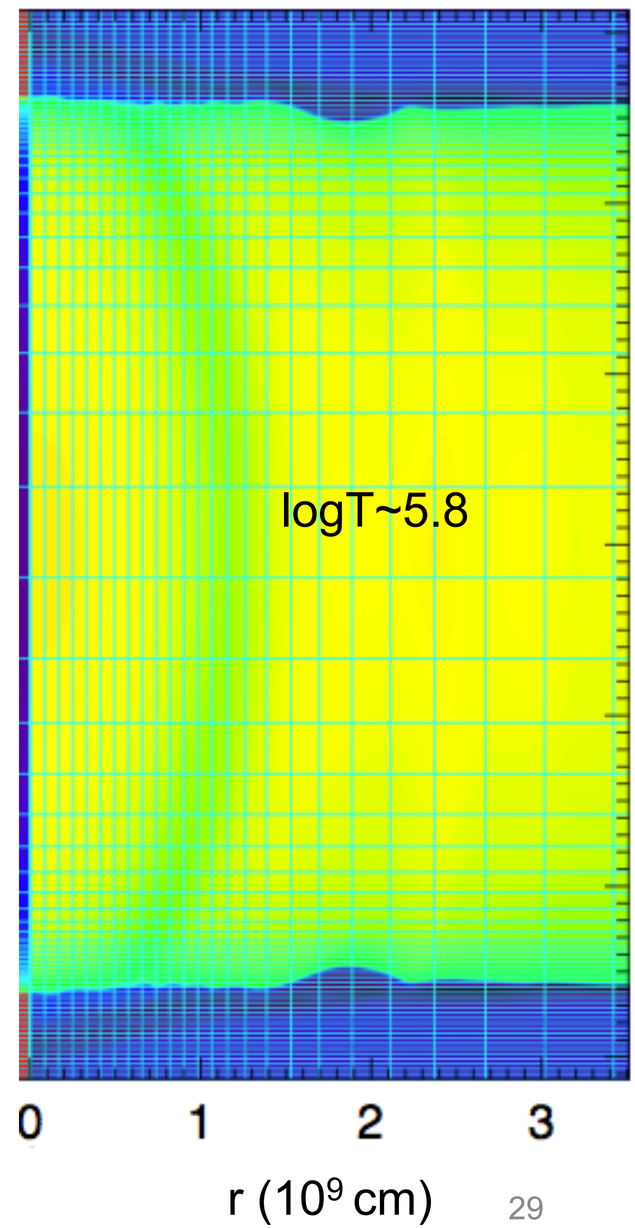




The main simulation

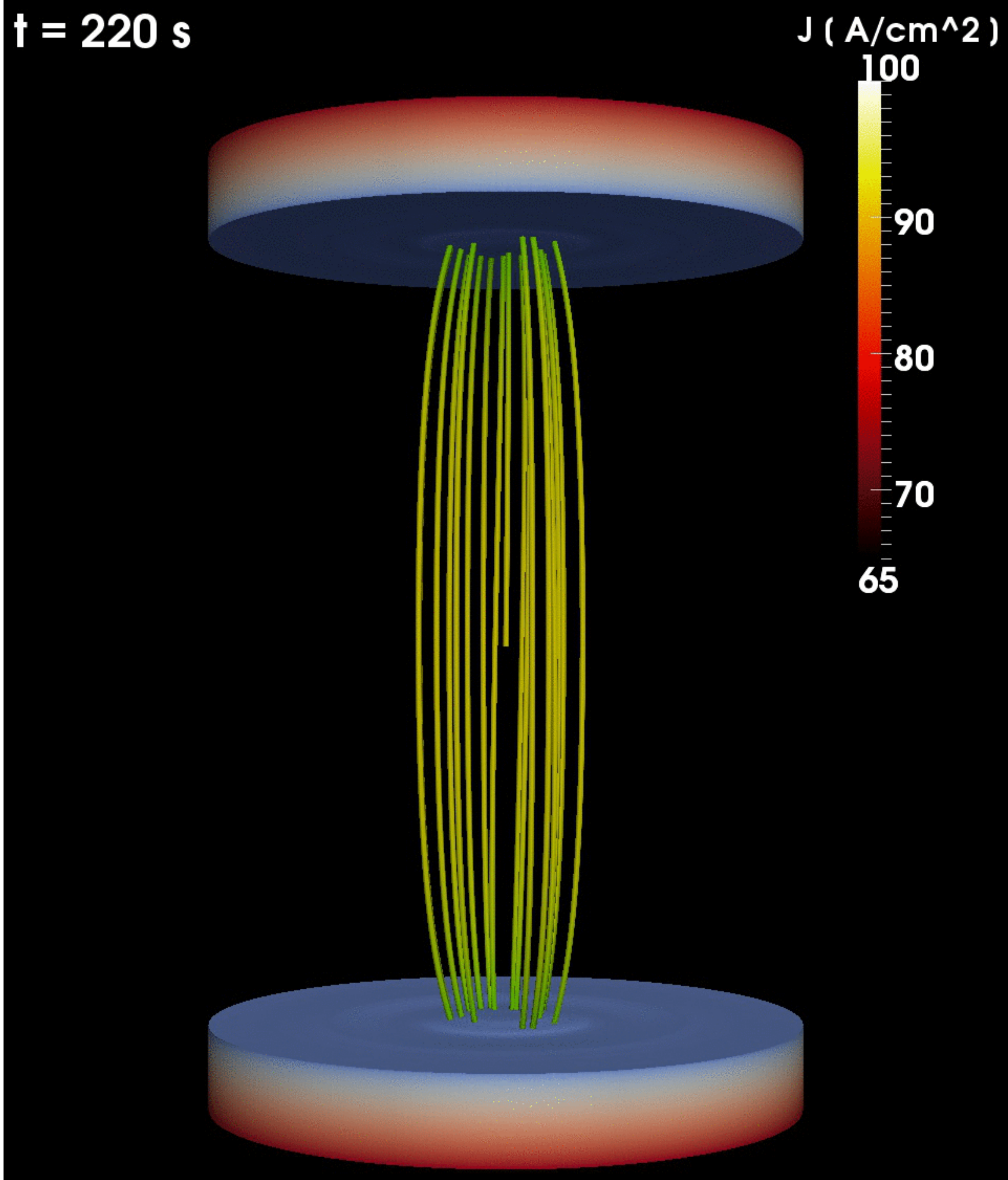
- Non-uniform (fixed) grid: maximum resolution ~ 20 km (in TR)
- Box: [r, ϕ, z]= [384, 256, 768] pts
- Time: t = 0 – 1870 s
- Twisting: ~1.5 π
- CPU time: 5 million hours, 32000 cores

Grid resolution
Each box 10x10 grid points



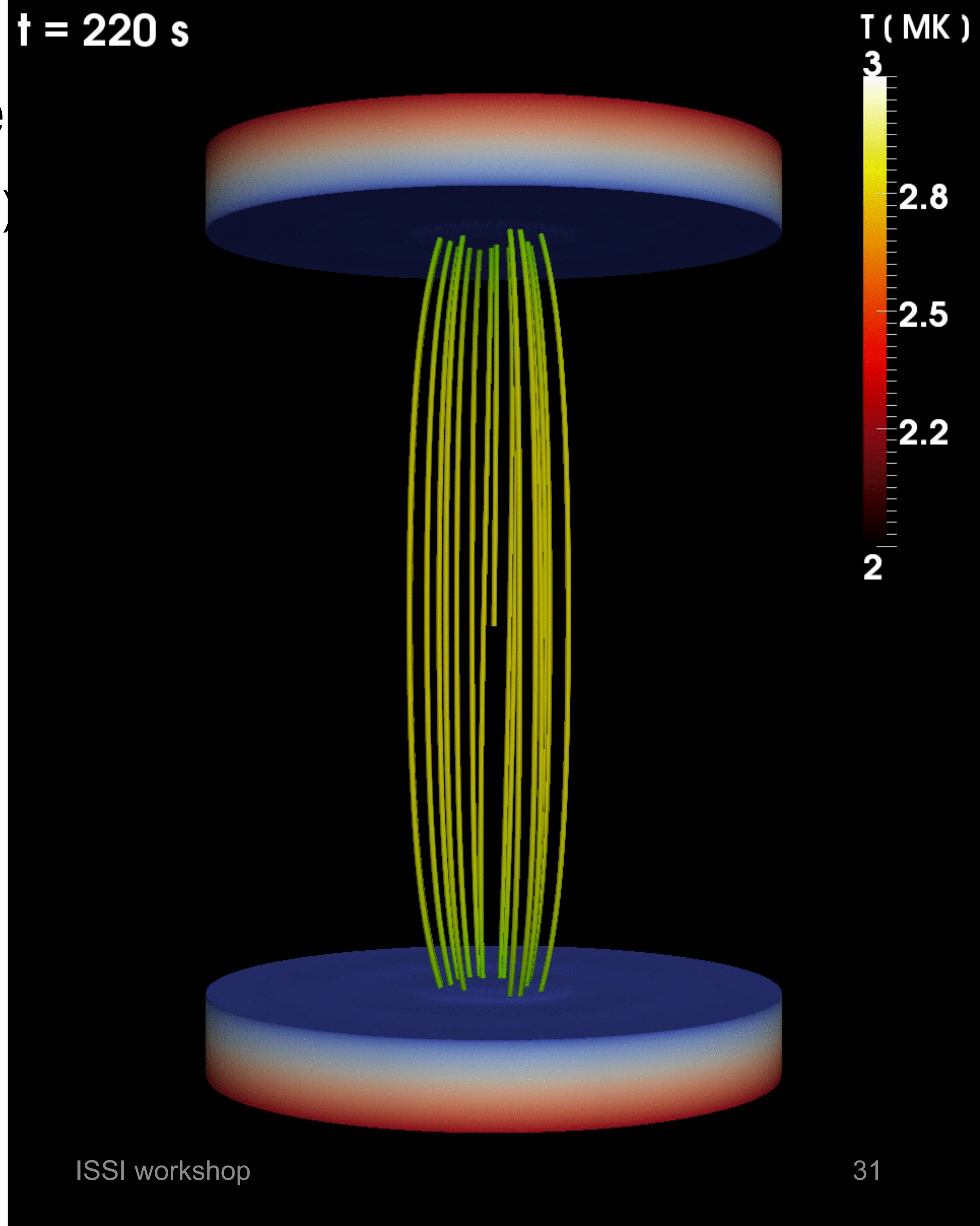
Current density
(+ field lines)

- Only above threshold shown, i.e. heating marker
- The blue surface is the boundary where the density is 10^9 cm^{-3}
- Most current sheets:
  - Close to axis
  - Close to footpoints
  - Lasting few frames: <1 min



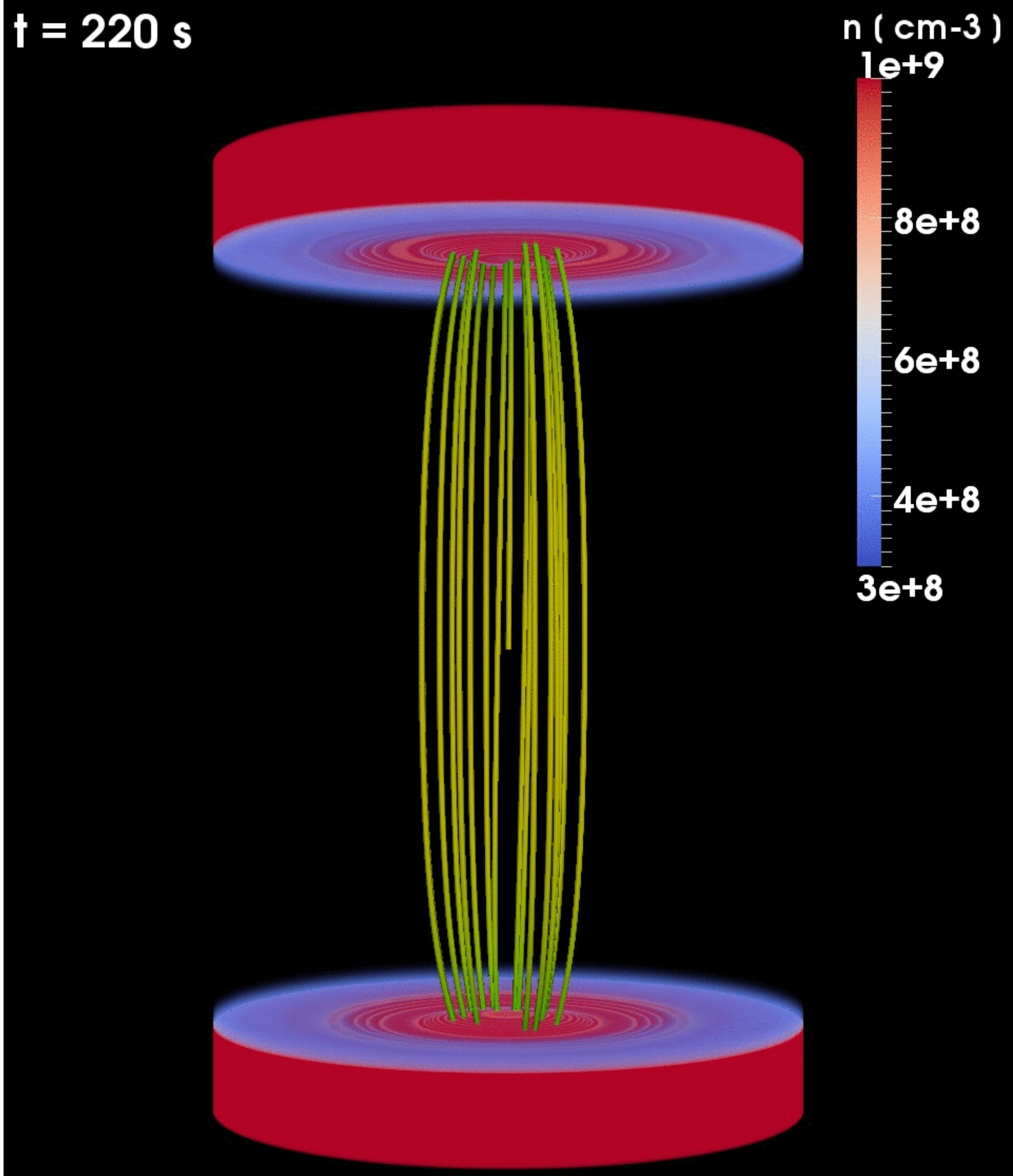
Temperature [MK] (+ field lines)

- Max T ~ 4 MK
- Fine structure



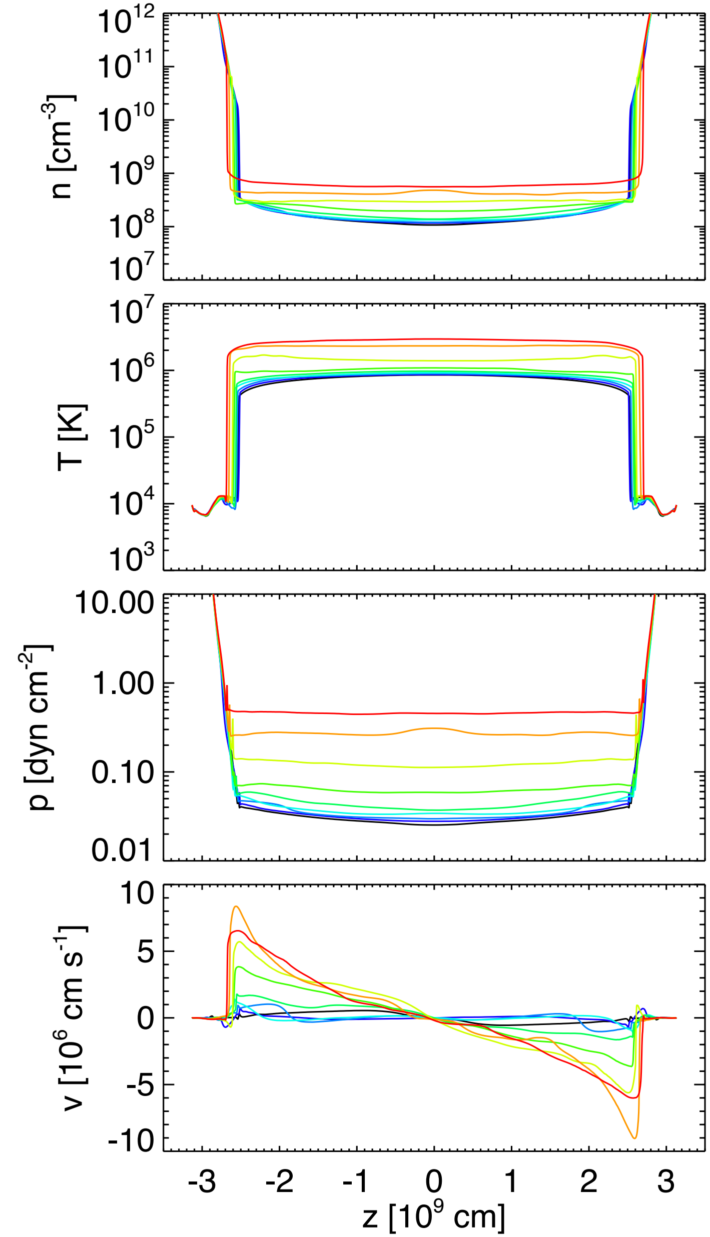
Density
(+ field lines)

- Units: 10^9 cm^{-3}
- Evaporation along field lines



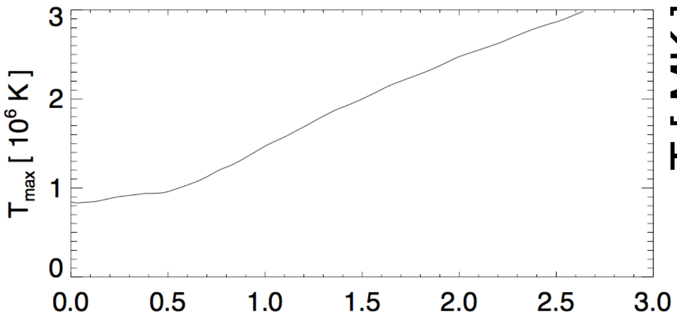
Loop evolution along z

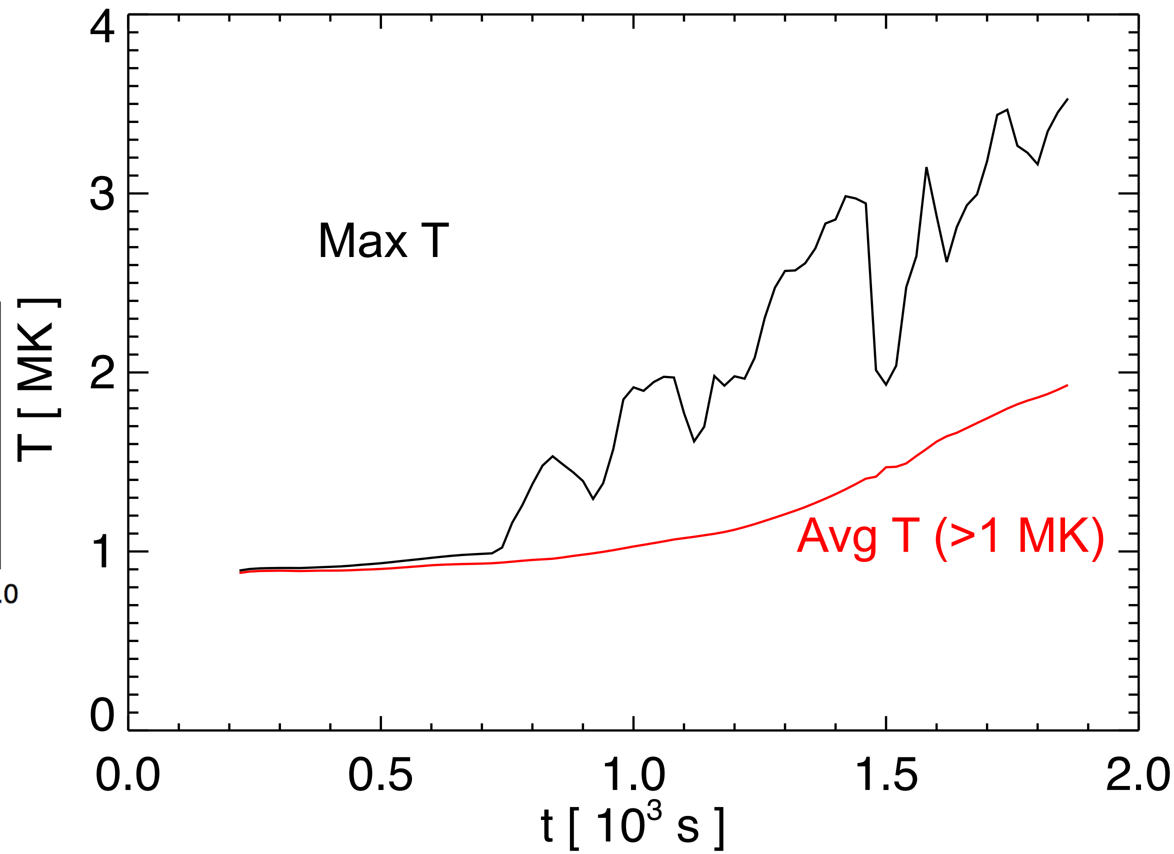
- Spaced every 200 s
- From blue (t=0) to red (t=1800 s)



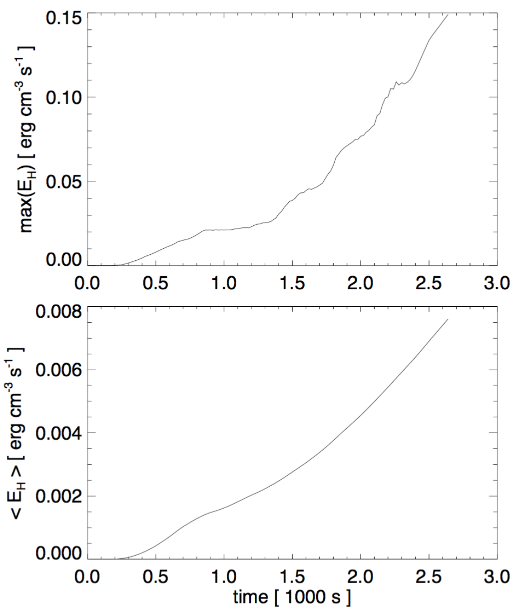
Temperature vs time

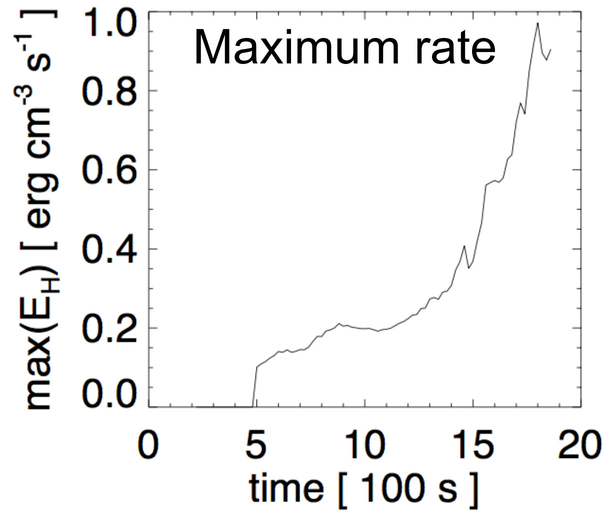
The maximum temperature shows a "turbulent" evolution

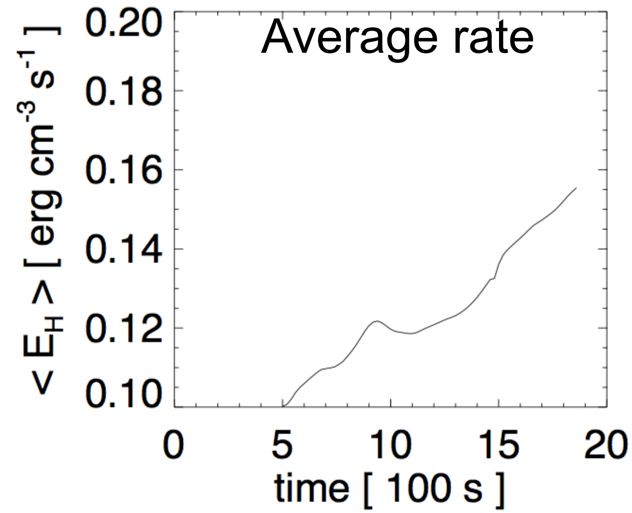


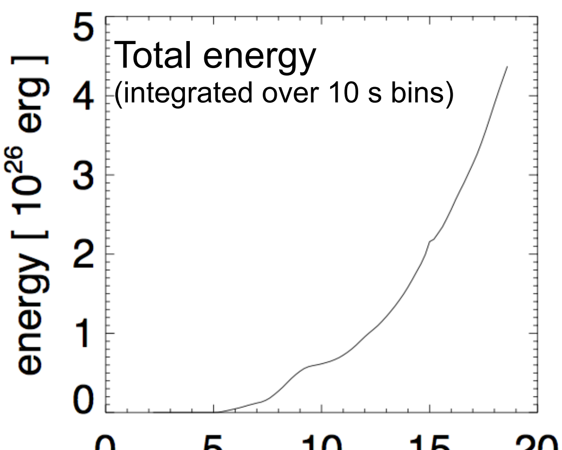


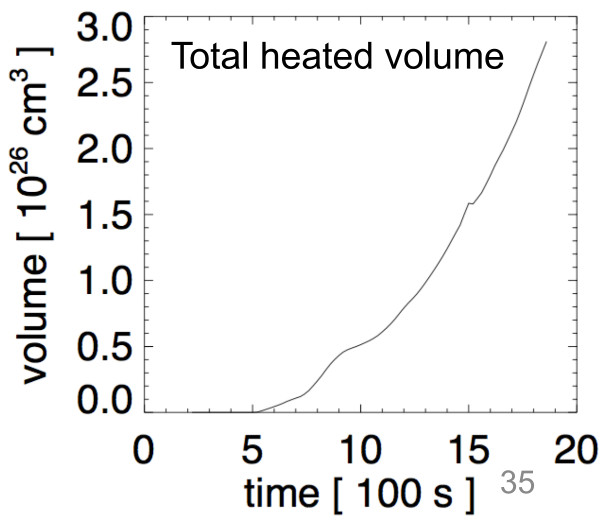
Heating rate vs time



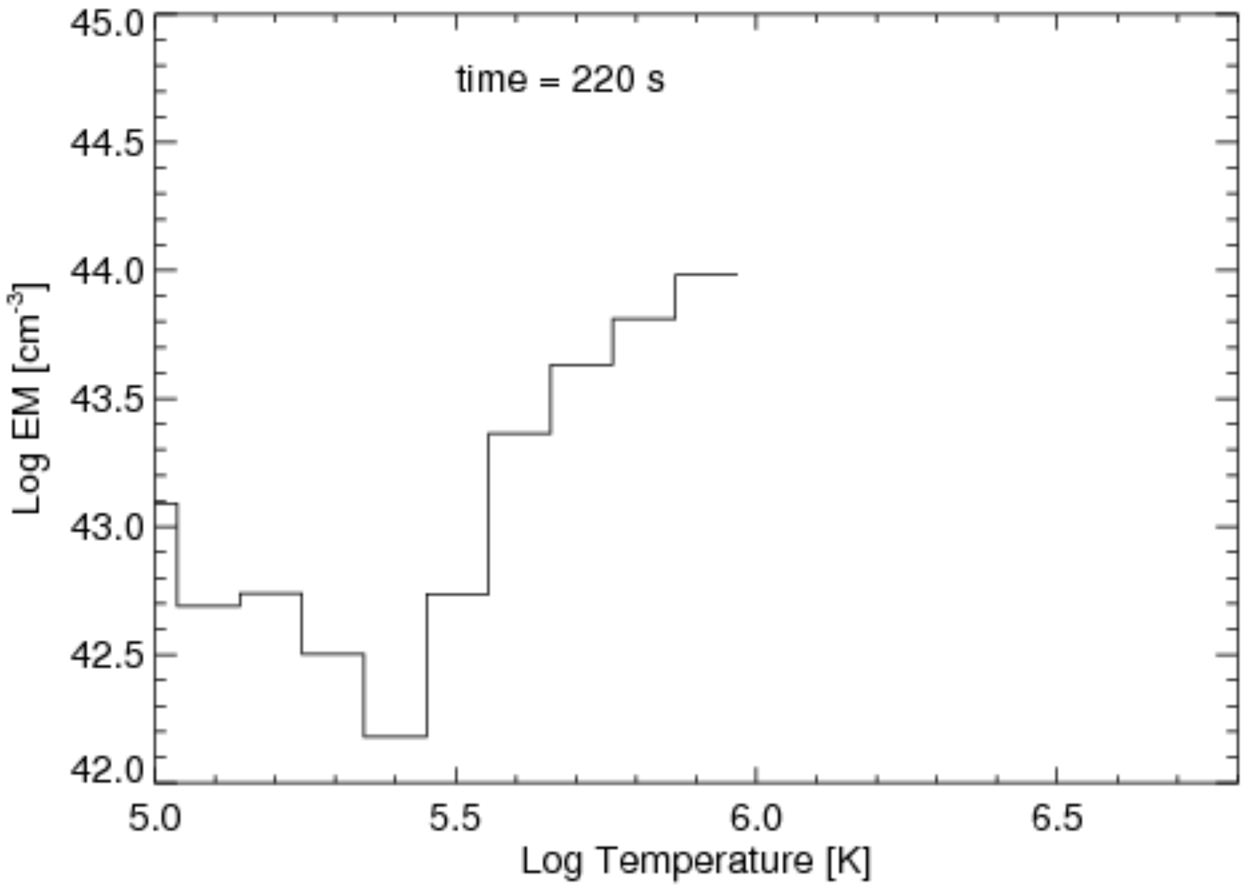








Total loop DEM



MHD loop modeling

Uniform resistivity

- Loop heating
- Multi-thermal
- Slow flows
- No fine structure
- No hot plasma

Switch-on resistivity

- Loop heating
- Multi-thermal
- Faster flows
- Fine structure
- Hot plasma
- Good as DEM/spectral diagnostics testing ground

Issues

- *Twisting and resistivity* -> typical loop evolution, including evaporation
- *Perturbed rotation* -> fine structure
- *Switch-on resistivity* -> hot component
- *Status* -> Paper I (uniform resistivity) to be submitted, Paper II in preparation
- *For diagnostics* -> density, temperature 3D map at t = 1800 s -> *you know the 3D truth, but not a trivial one*