MHD Simulations of Solar Coronal Dynamics: Effects of Parameter Variations on Local Energy Budget

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Motivation

- Joule heating has been identified as an important source of thermal energy in the solar corona (for instance, Peter et al., 2006; Gudiksen and Nordlund, 2005).
- The effectiveness of this process however, depends critically on the value of resistivity which enables current dissipation and the direct conversion of magnetic energy into thermal energy.
- The appropriate value of resistivity in the solar corona is still an open question.

Model

- Domain:

  x-[0,46.5]Mm

  y-[0,46.5]Mm

  z-[0,31]Mm

- Transition Region at 1.5Mm
  - defined through density (->Temperature)

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  x-[0,46.5]Mm

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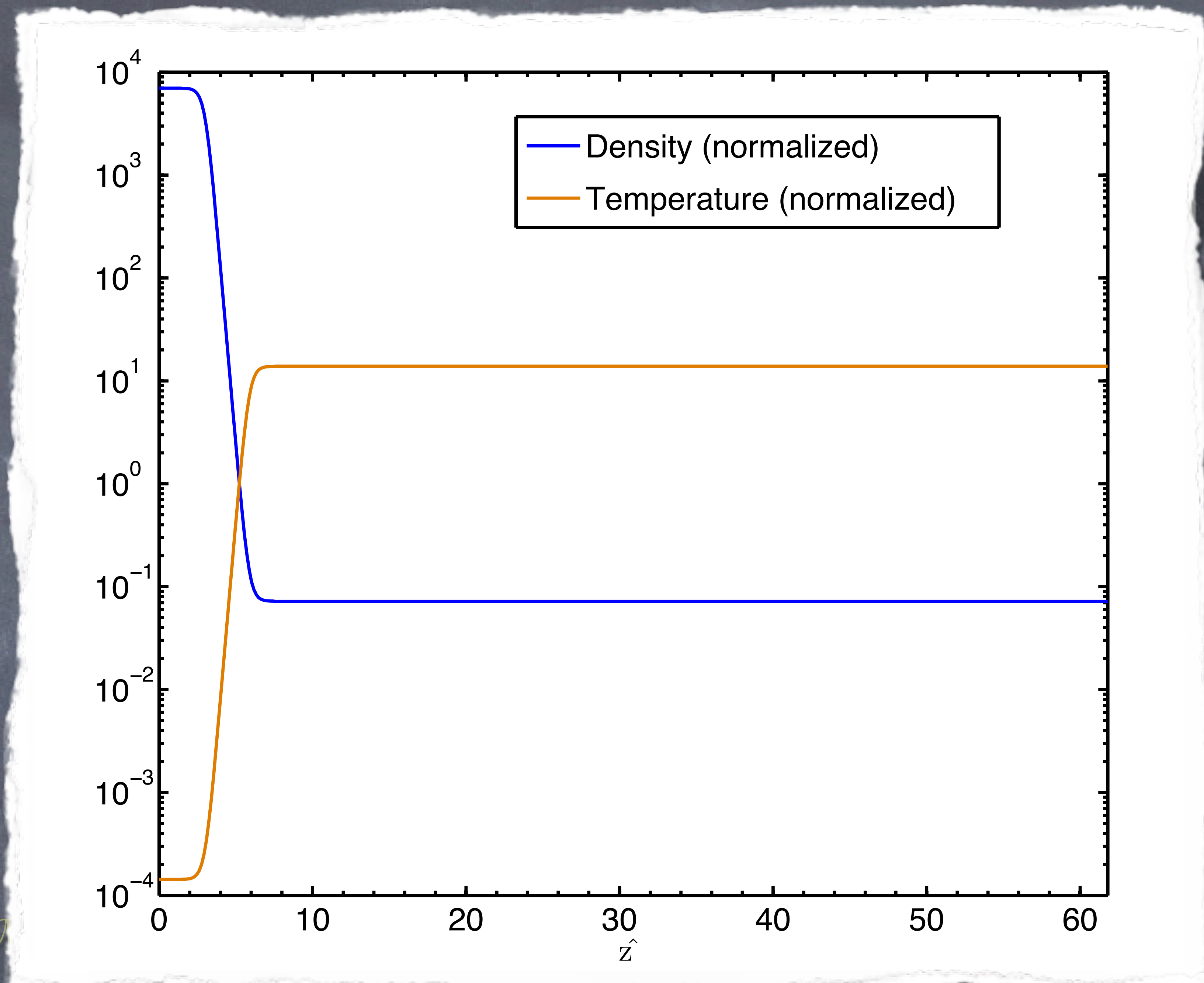
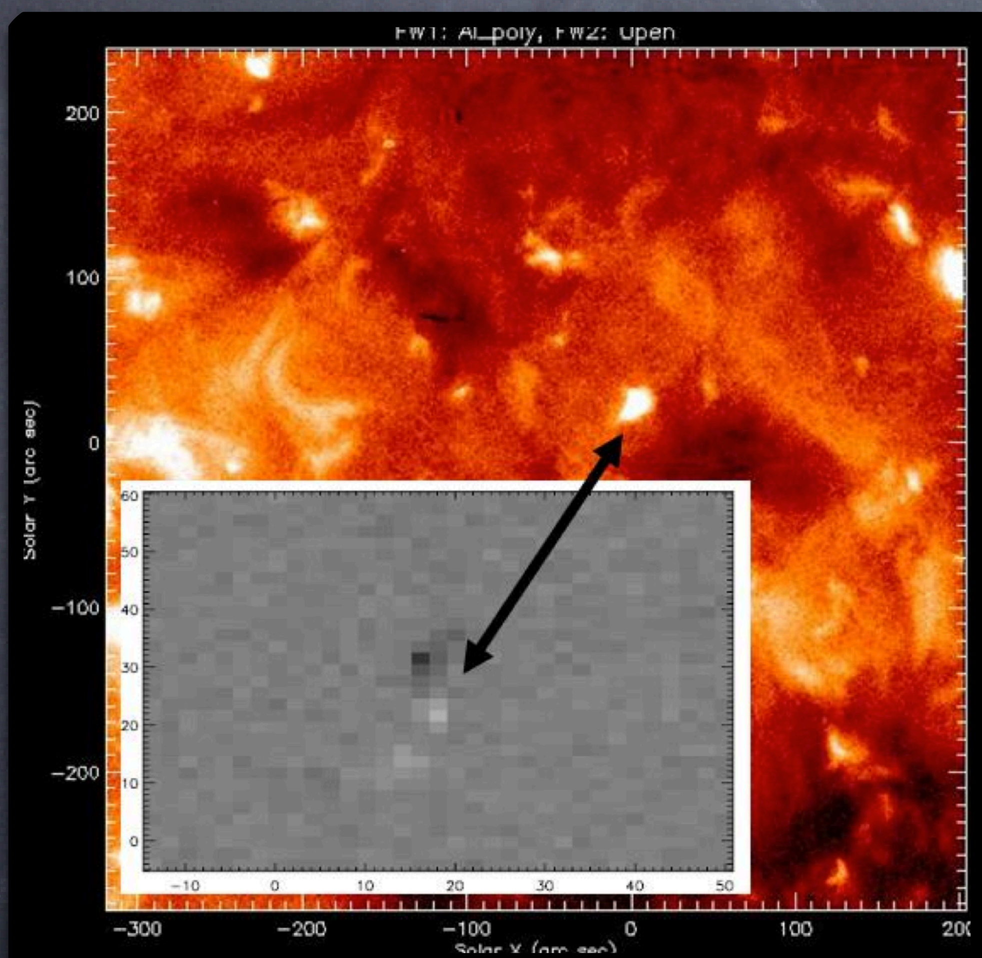


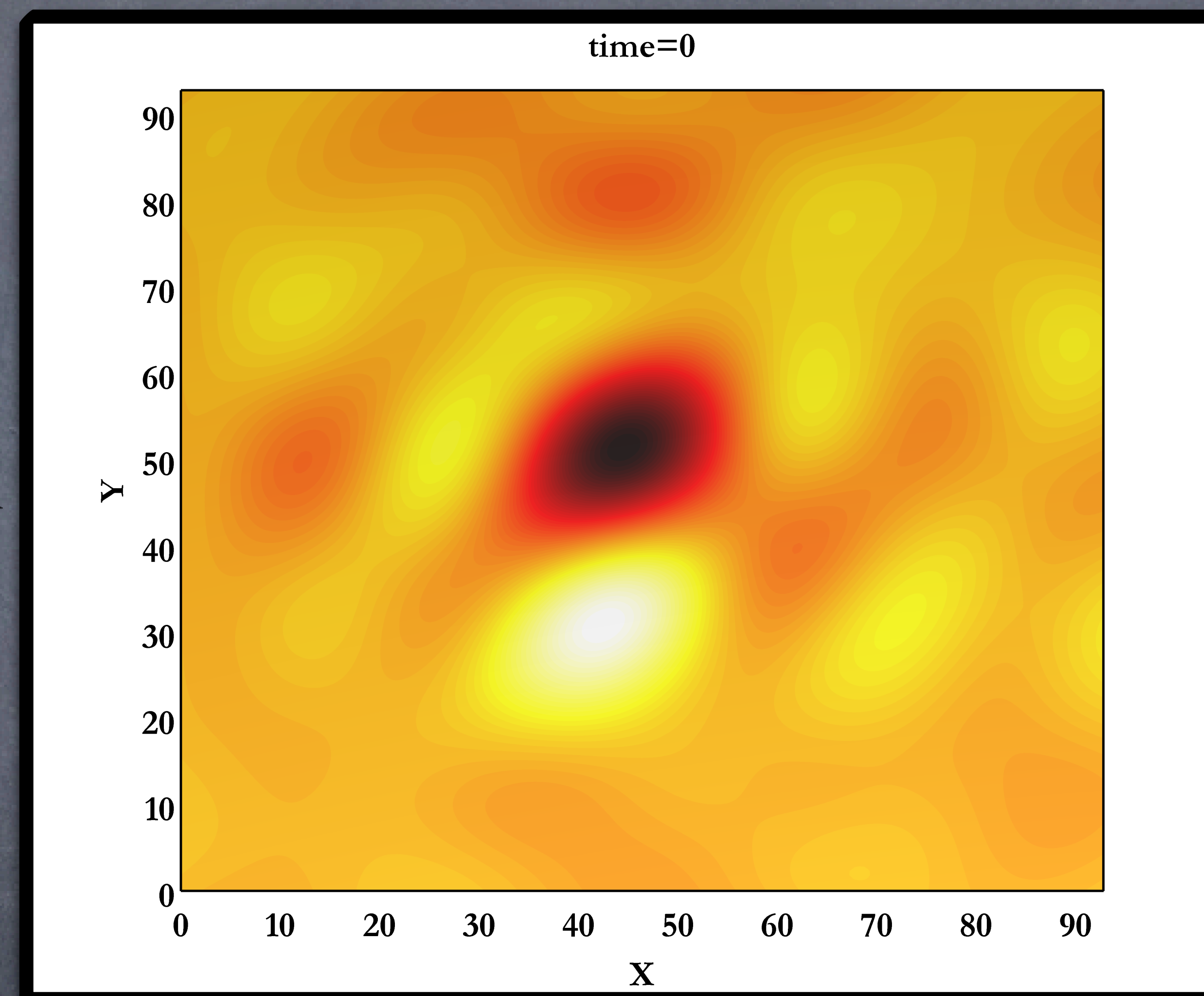
- Transition Region at 1.5Mm

  * defined through density (->Temperature)

Model (B-field)

XRT/Hinode observation of X-ray BP on Dec. 19, 2006





Javadi et al., 2011

B-field extrapolated from first 8 modes of Fourier filtered LOS observations

Model (B-field)

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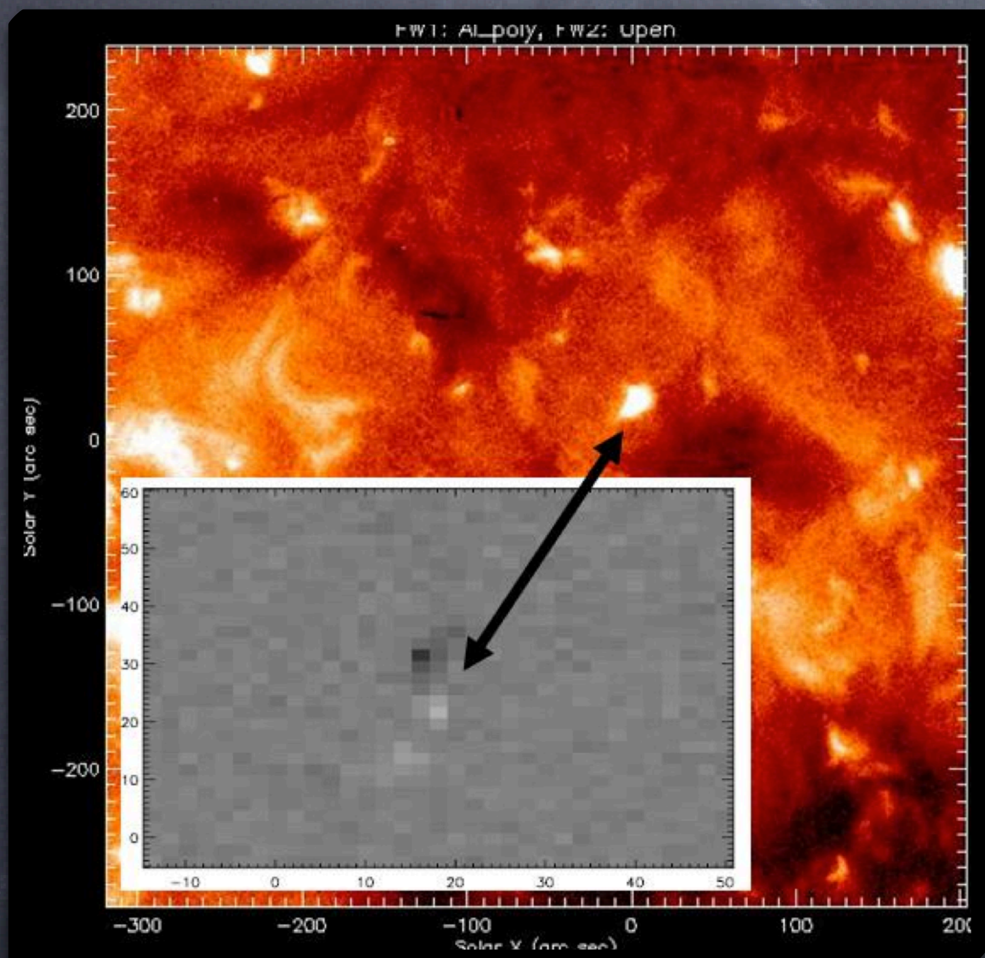
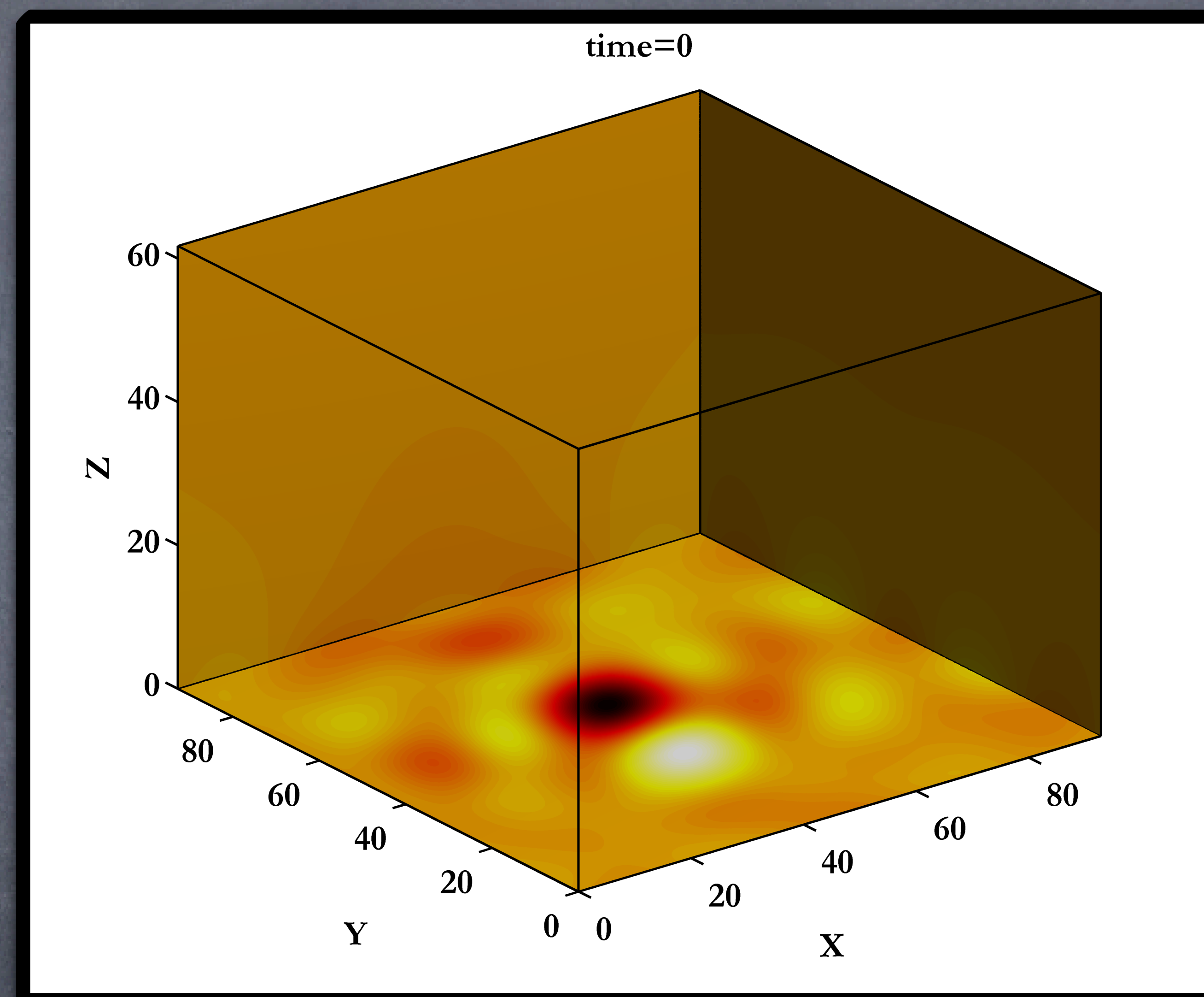
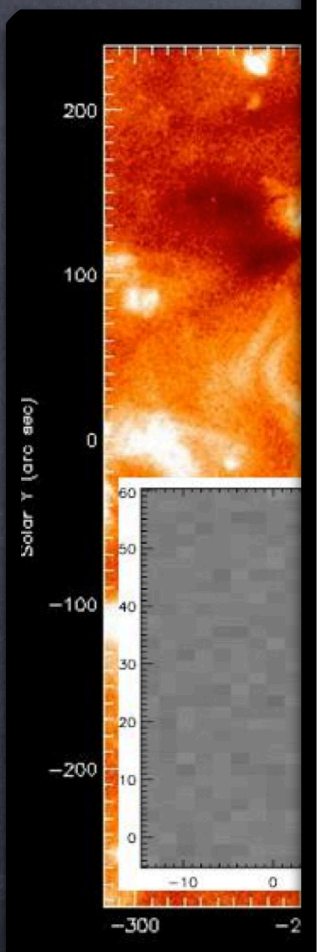


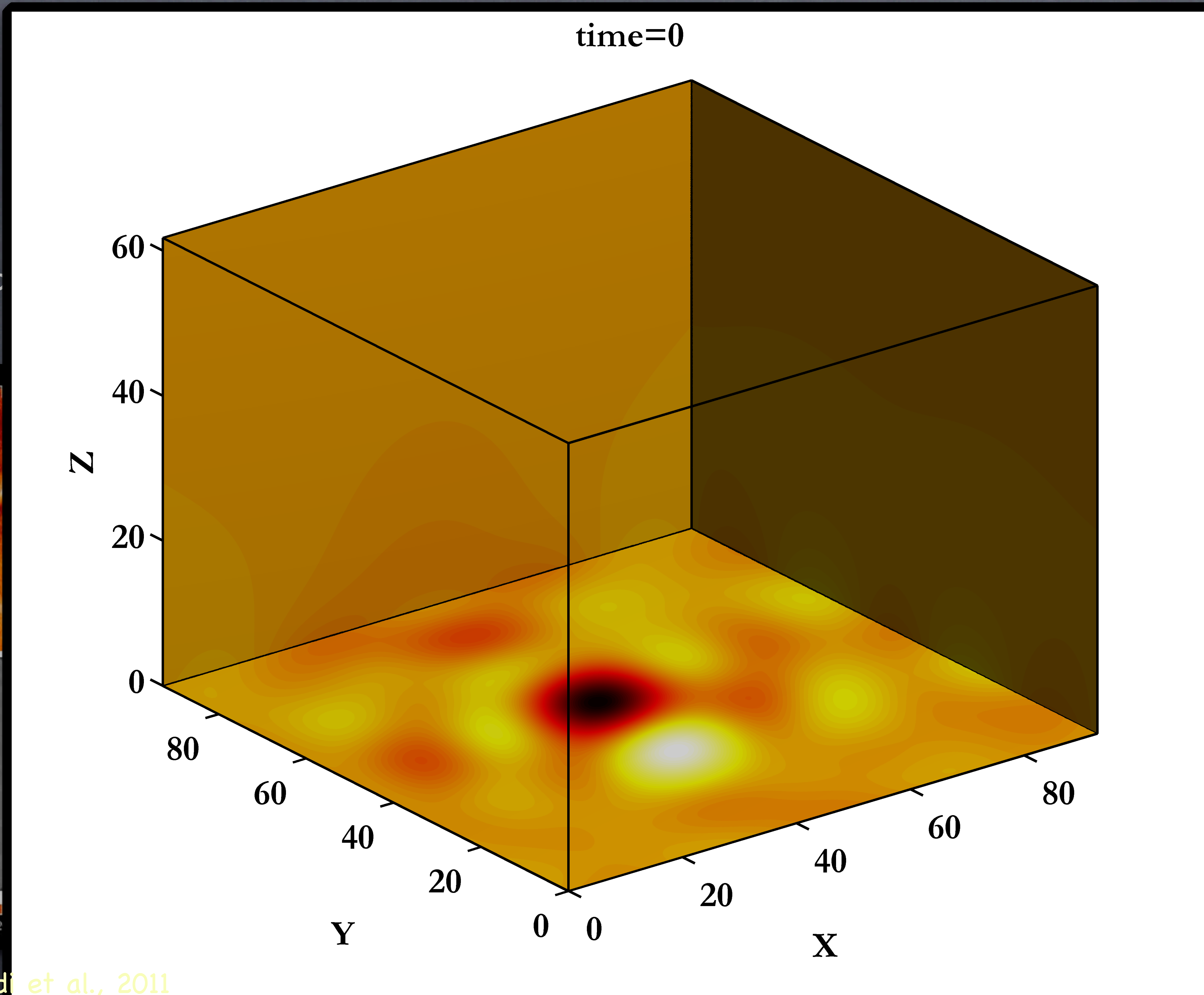


Javadi et al., 2011

B-field extrapolated from first 8 modes of Fourier filtered LOS observations

XRT/Hinode c





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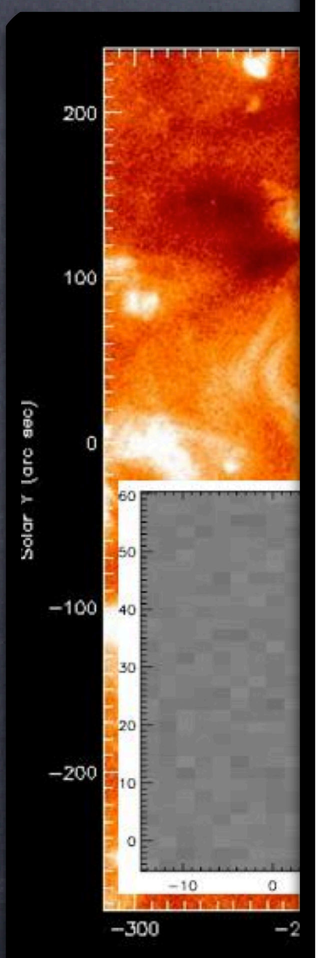
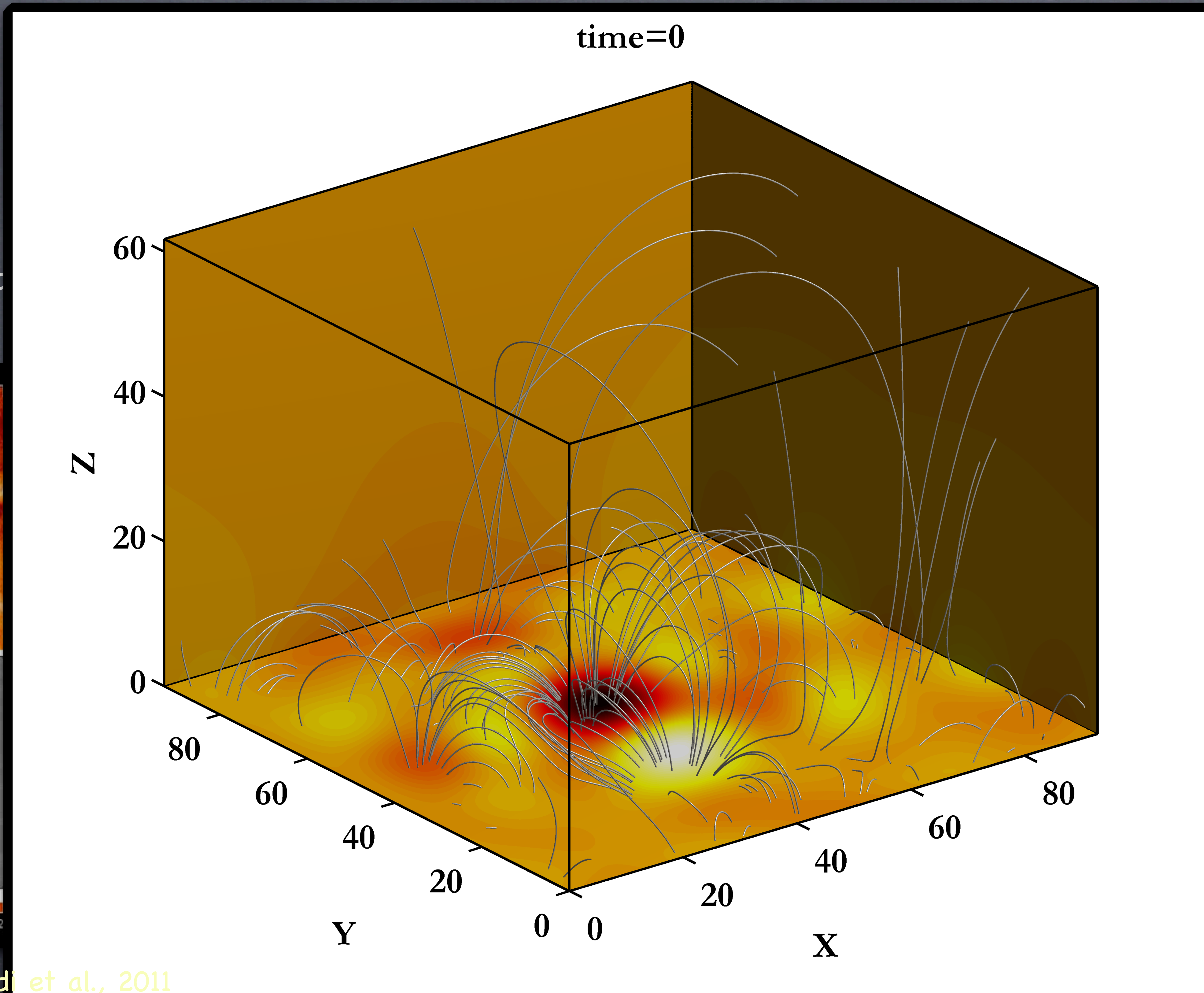
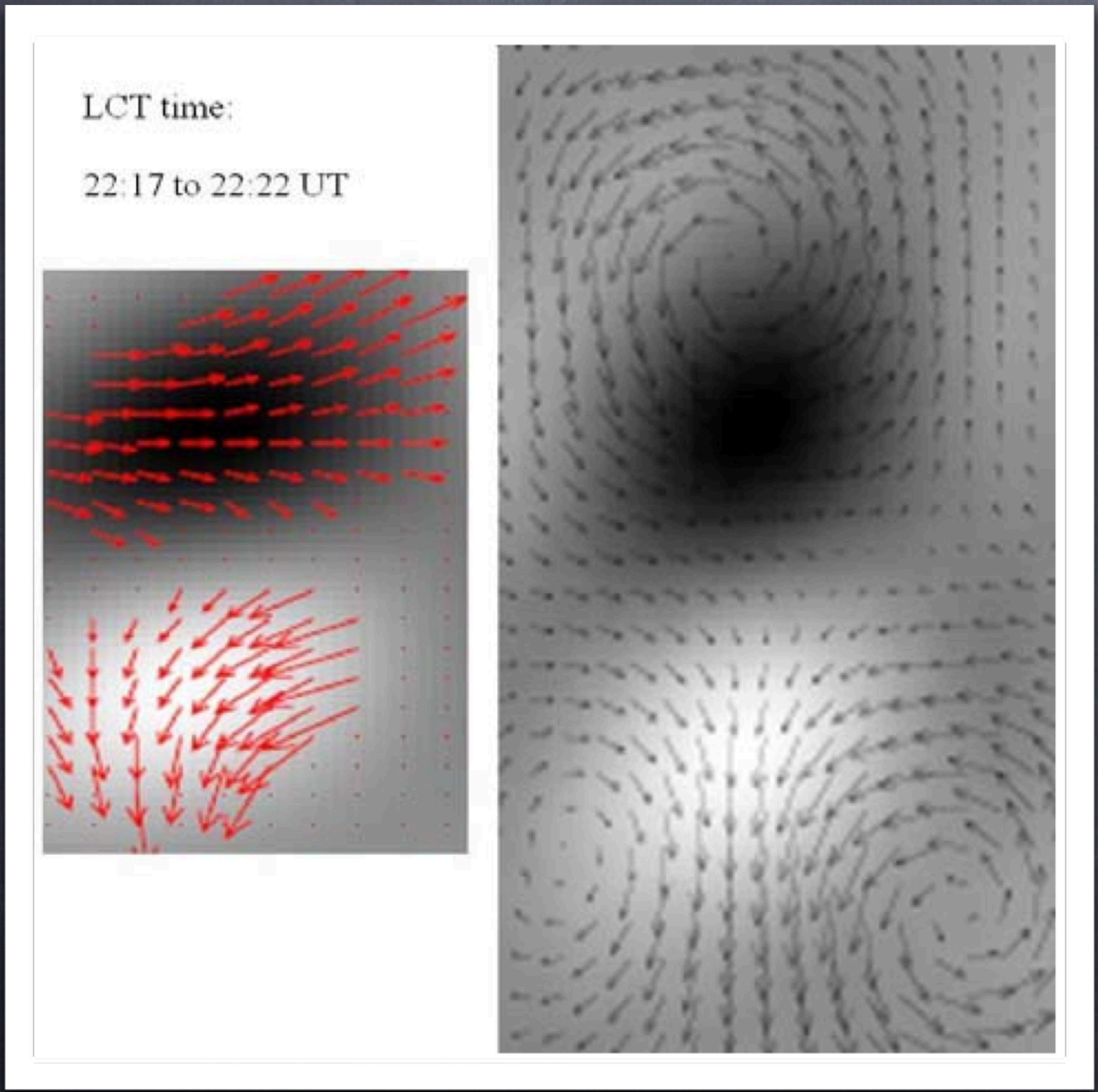




Javadi et al., 2011

B-field extrapolated from first 8 modes of Fourier filtered LOS observations

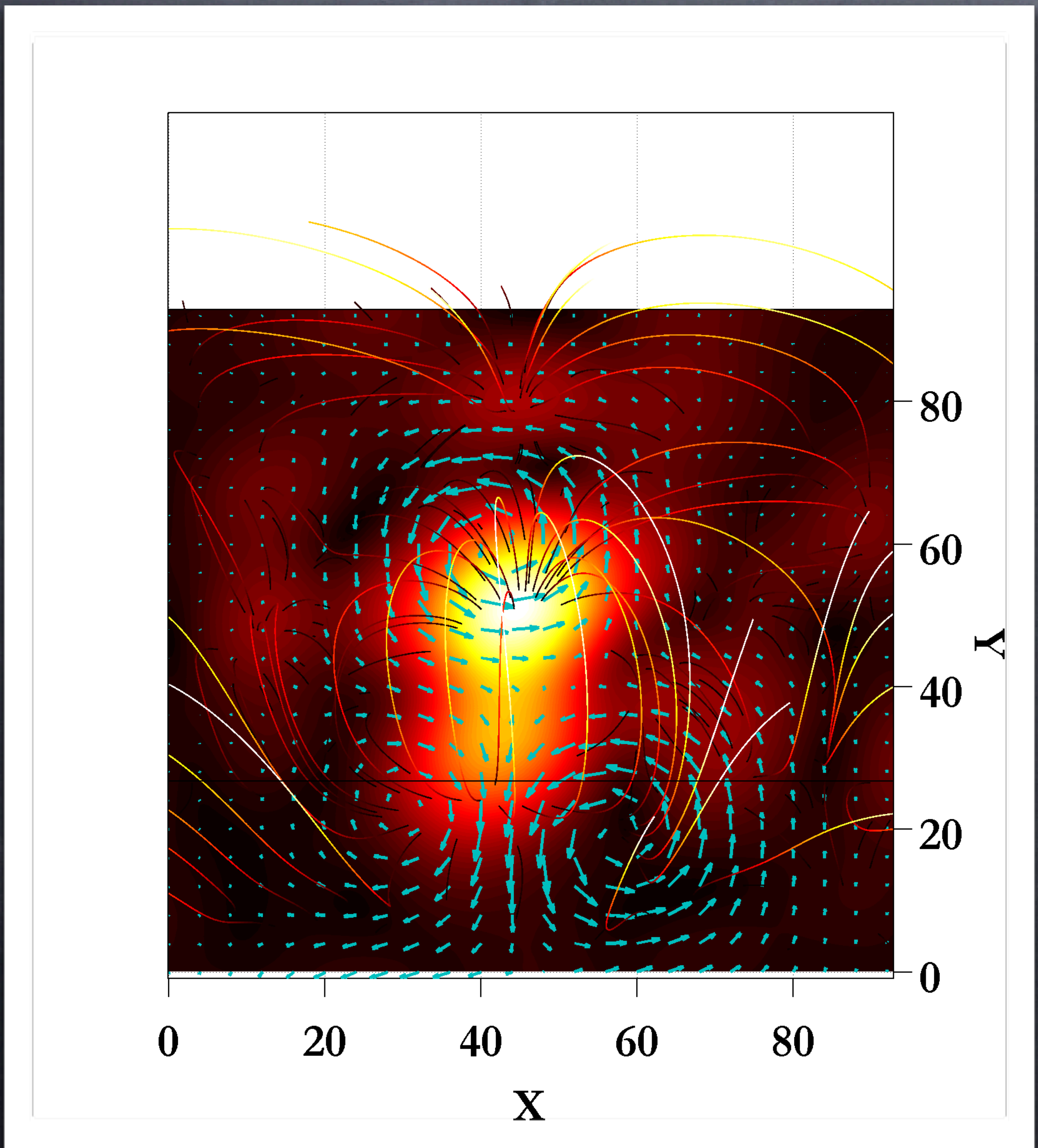
Model (velocity)



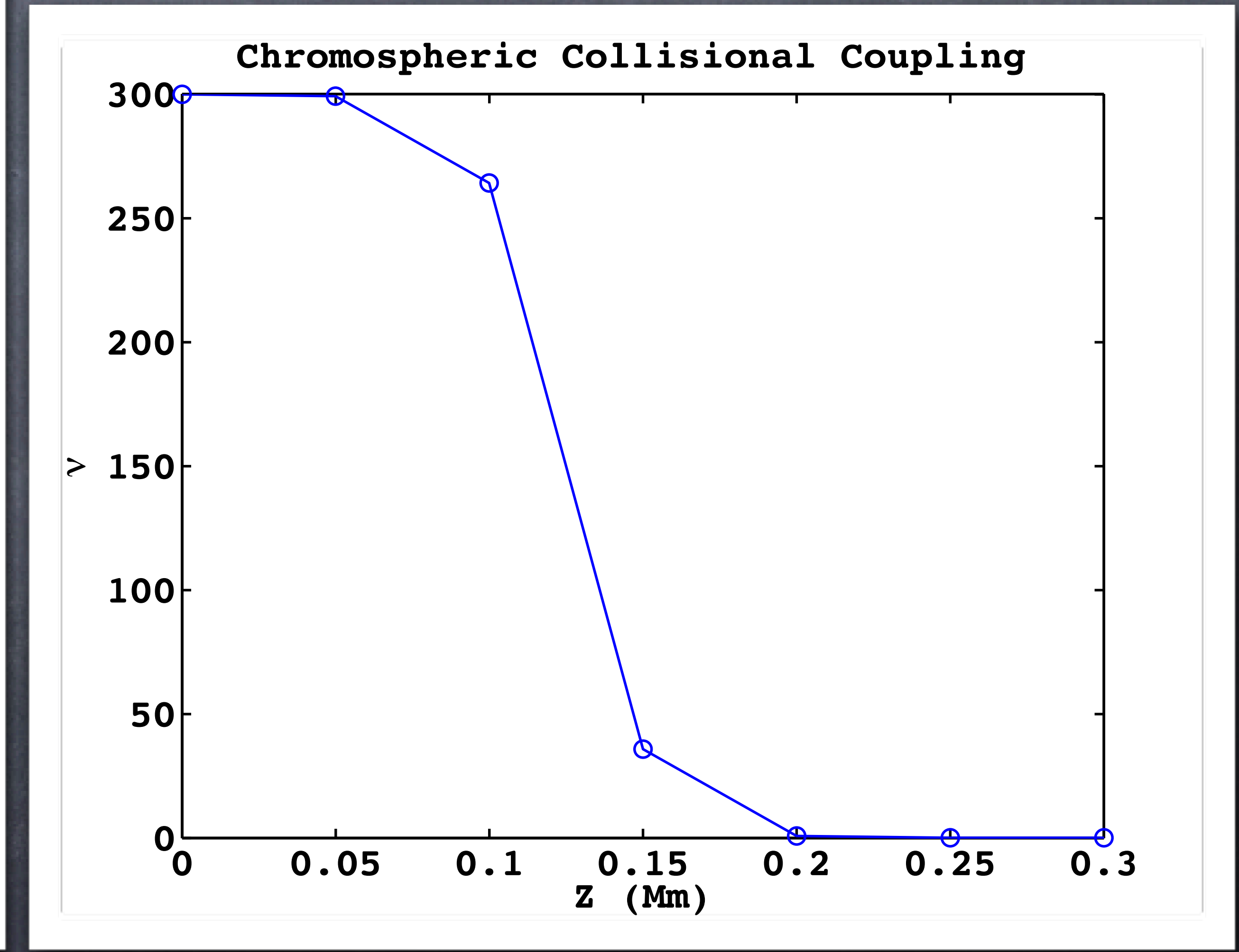
Javadi et al. (2011)

- Photospheric plasma motion is determined through local correlation-tracking of the Fourier filtered LOS B-field.
- Flow is approximated by the inclusion of incompressible flow vortices (no emergence) at the photospheric boundary.

Model (velocity cont.)



- Chromospheric plasma coupled to neutral motion near photospheric boundary through height-dep. "collisional" coupling term.



The Resistive MHD Equations (*normalized*):

$$\frac{\partial \rho}{\partial t} = -\boldsymbol{\nabla} \cdot \rho \boldsymbol{u}$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} = -\boldsymbol{\nabla} \cdot (\rho \boldsymbol{u}\boldsymbol{u}) - \boldsymbol{\nabla}(h^\gamma) + \boldsymbol{j} \times \boldsymbol{B} - \mu(\boldsymbol{u} - \boldsymbol{u}_0)$$

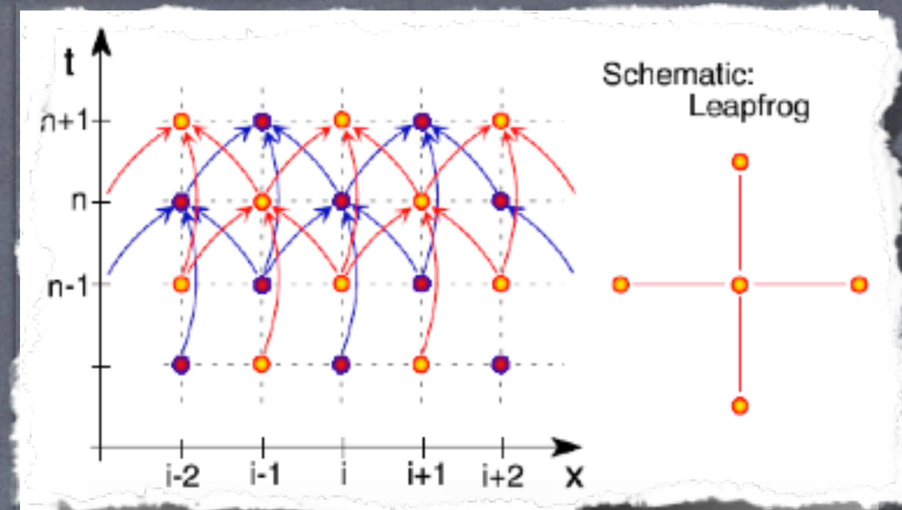
$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{u} \times \boldsymbol{B} - \eta \boldsymbol{j})$$

$$\frac{\partial h}{\partial t} = -\boldsymbol{\nabla} \cdot h\boldsymbol{u} - \frac{(1-\gamma)}{\gamma} h^{1-\gamma} \eta \boldsymbol{j}^2$$

where, $p = 2h^\gamma$ *(→conservative energy equation for ideal MHD)*

Numerics

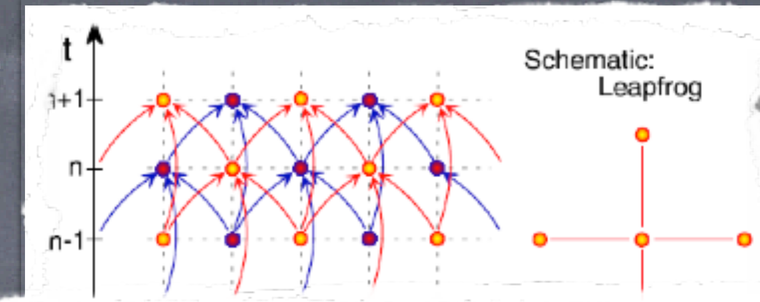
- Leapfrog / DuFort-Frankel
  - Non-uniform grid:
  - 2nd order --> explicit control over resistivity (not dep. on grid resolution)

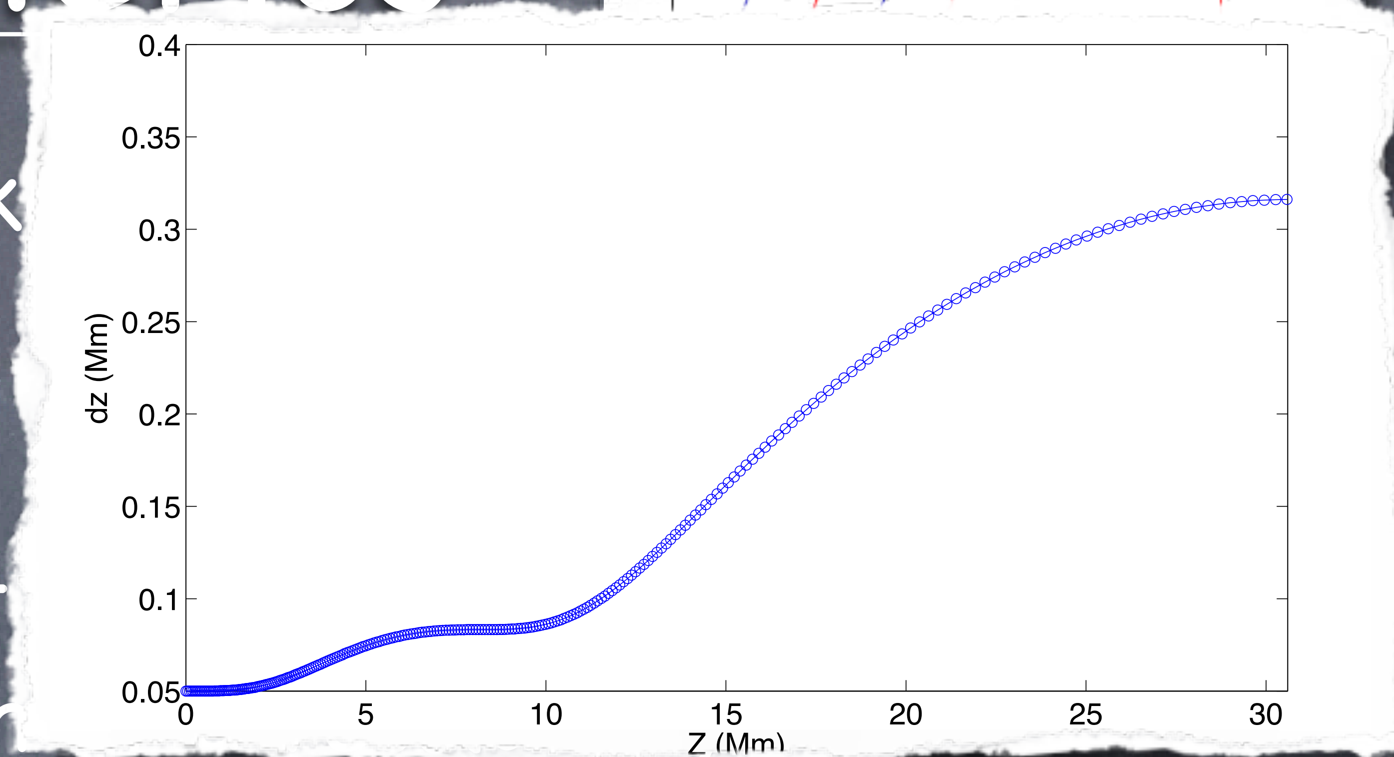


- Thorough OpenMP parallelization
- Normalization:

Plasma Parameter	Normalization Value
Density	$N_o = 2 \times 10^{15}\ \mathrm{m}^{-3}$
Length	$L_o = 500$ km
Magnetic Field	$B_o = 1 \times 10^{-4}$ T
Alfvén Speed	$v_A = 50$ km/s
Time	$\tau_o = 10.25$ s
Pressure	$P_o = 4 \times 10^{-3}$ Pa
Temperature	$T_o = 7.2 \times 10^4$ K

Numerics





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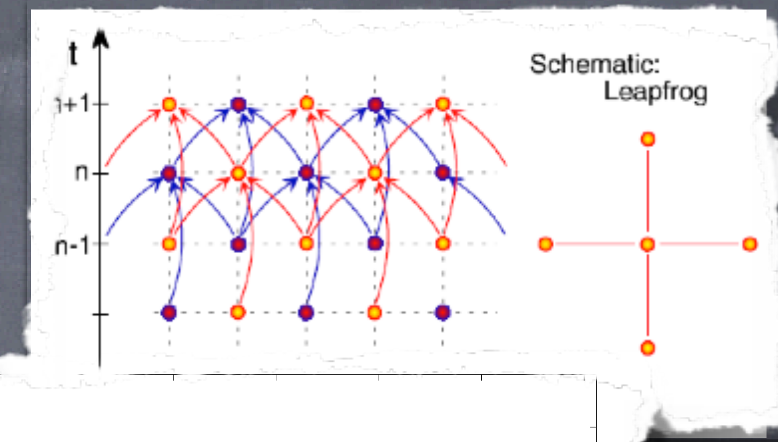

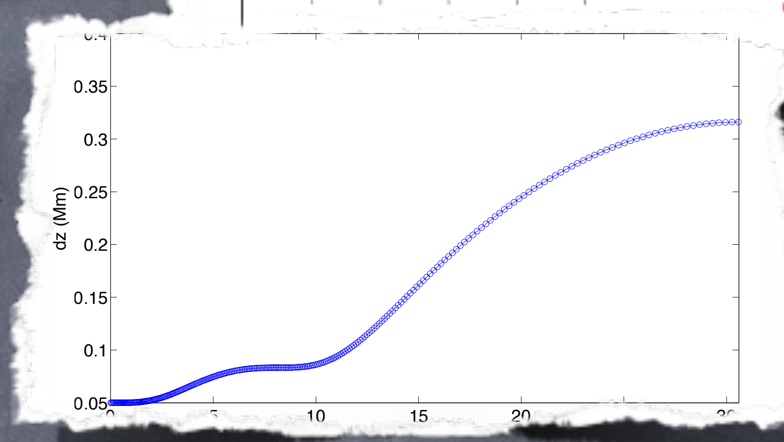

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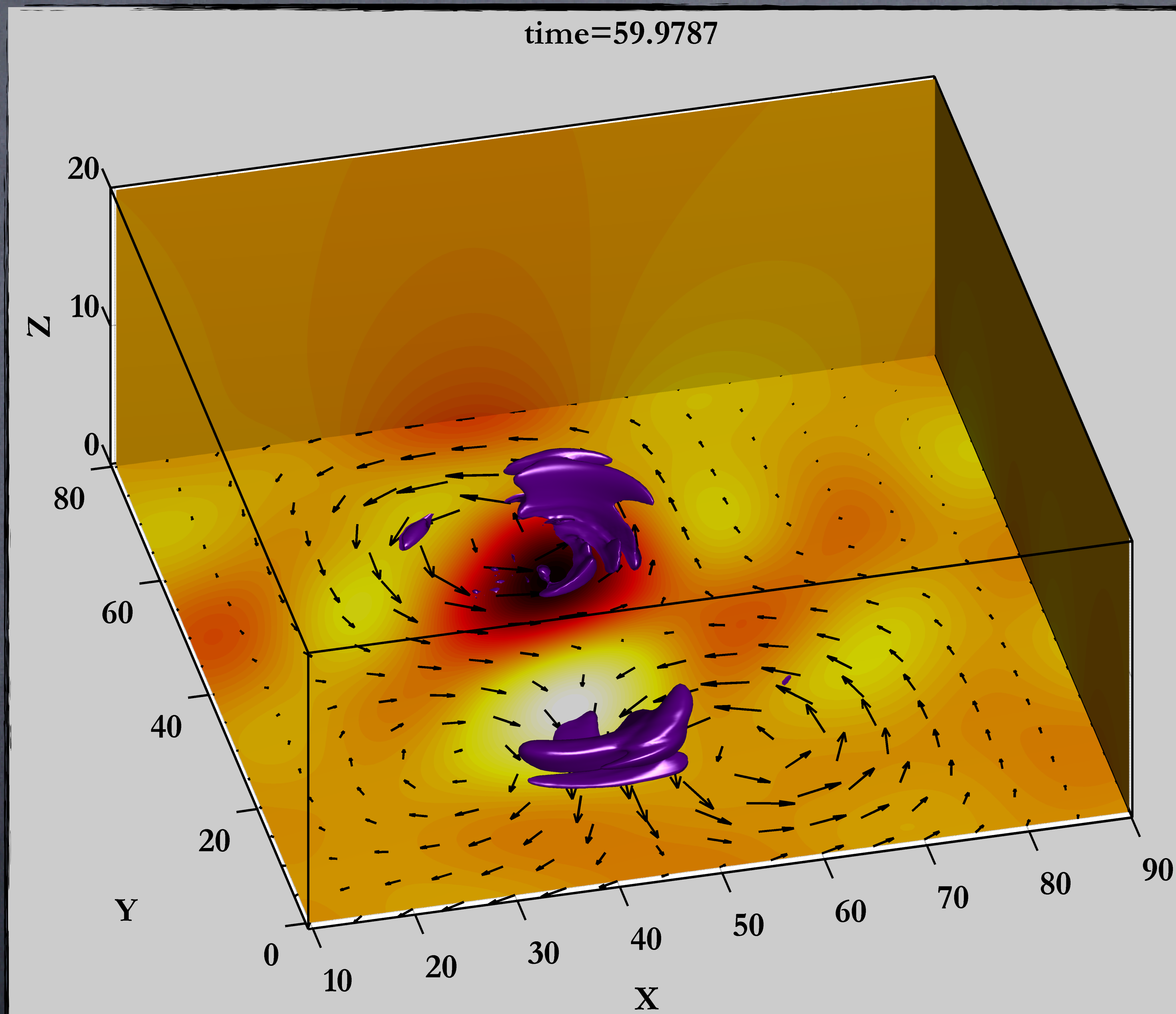
Resistivity

Parameter dep.:

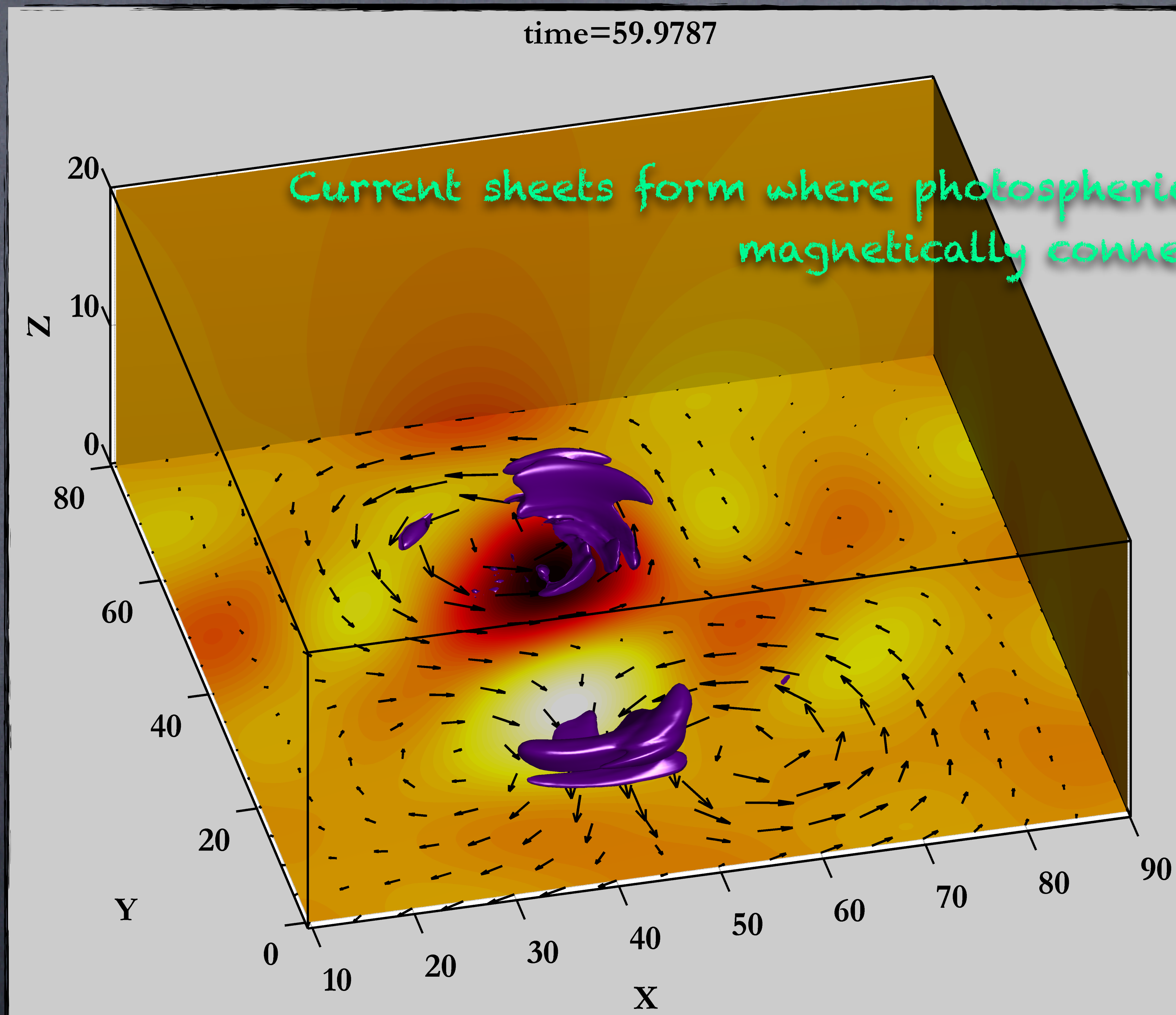
$$\eta^* = \eta_0 + \begin{cases} 0; & \text{if } |v_{cc}| < v_{crit} \\ \eta_{eff}\left(\frac{v_{cc}}{v_{crit}} - 1\right); & \text{if } |v_{cc}| \geq v_{crit} \end{cases}$$

where, $v_{cc} = \boldsymbol{j}/ne$, $\eta_{eff} = 300\ \Omega\text{m}$, and v_{crit} is taken as the electron thermal speed scaled to the MHD grid scale.

Current Sheet Formation



Current Sheet Formation



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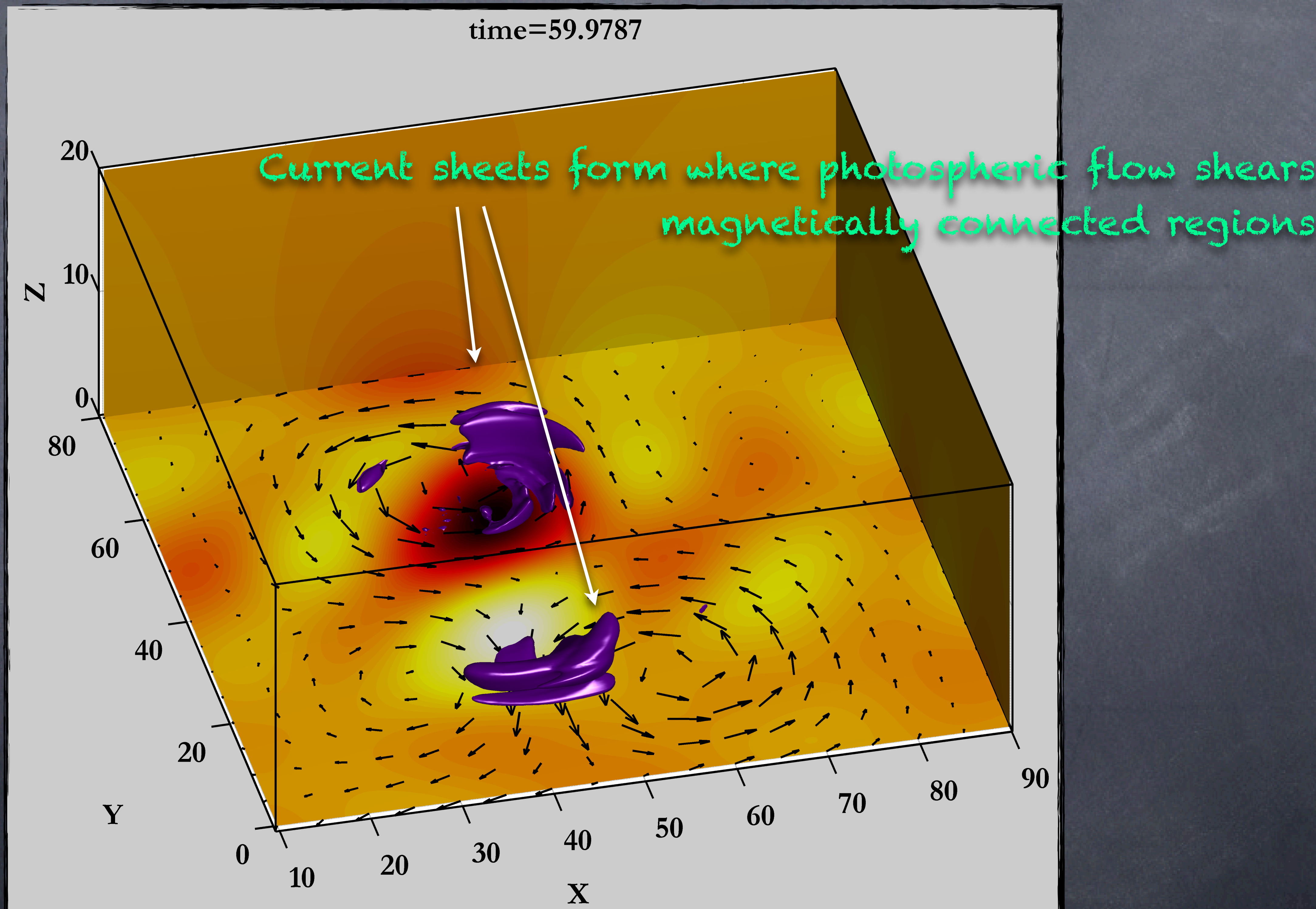

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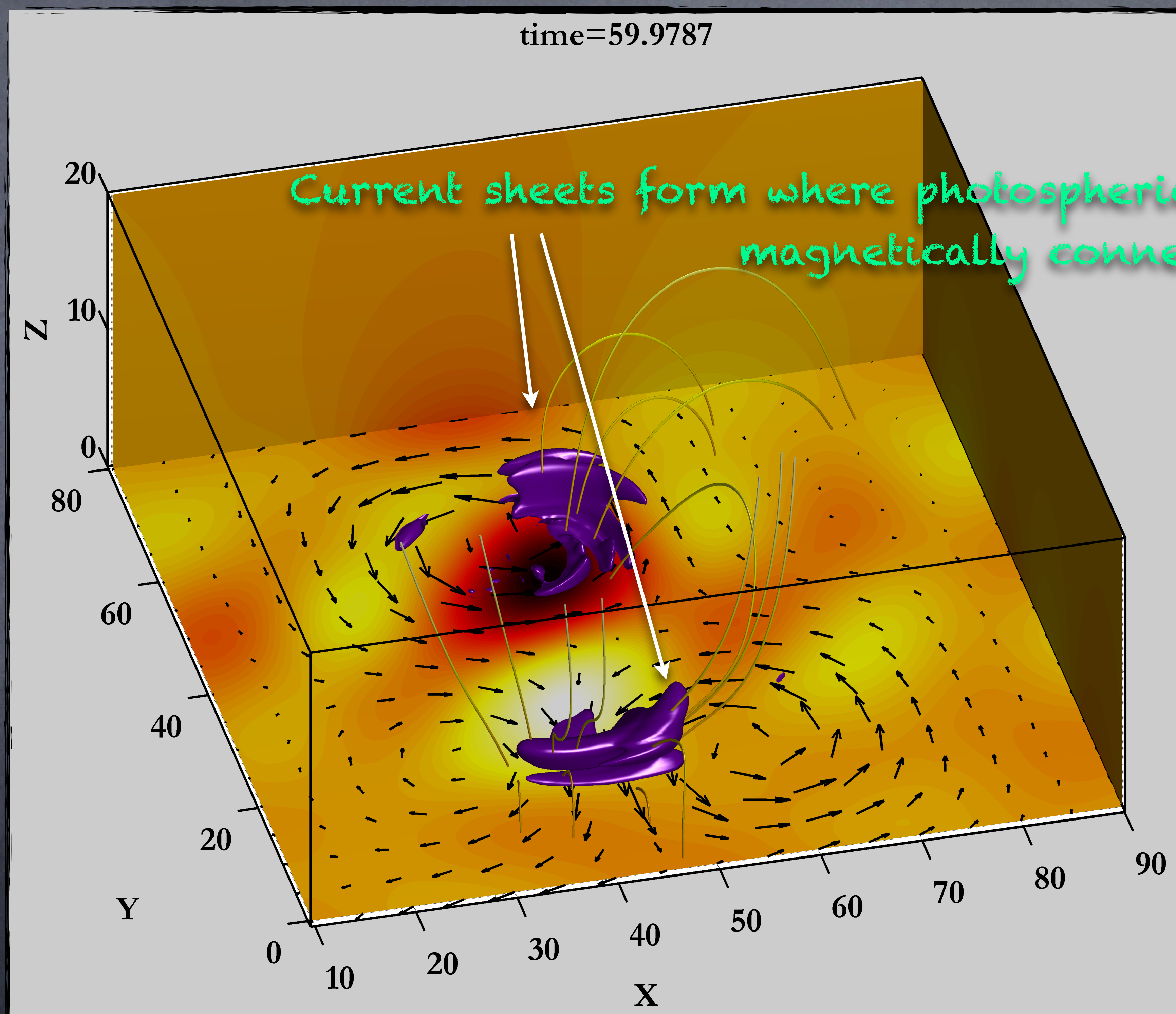
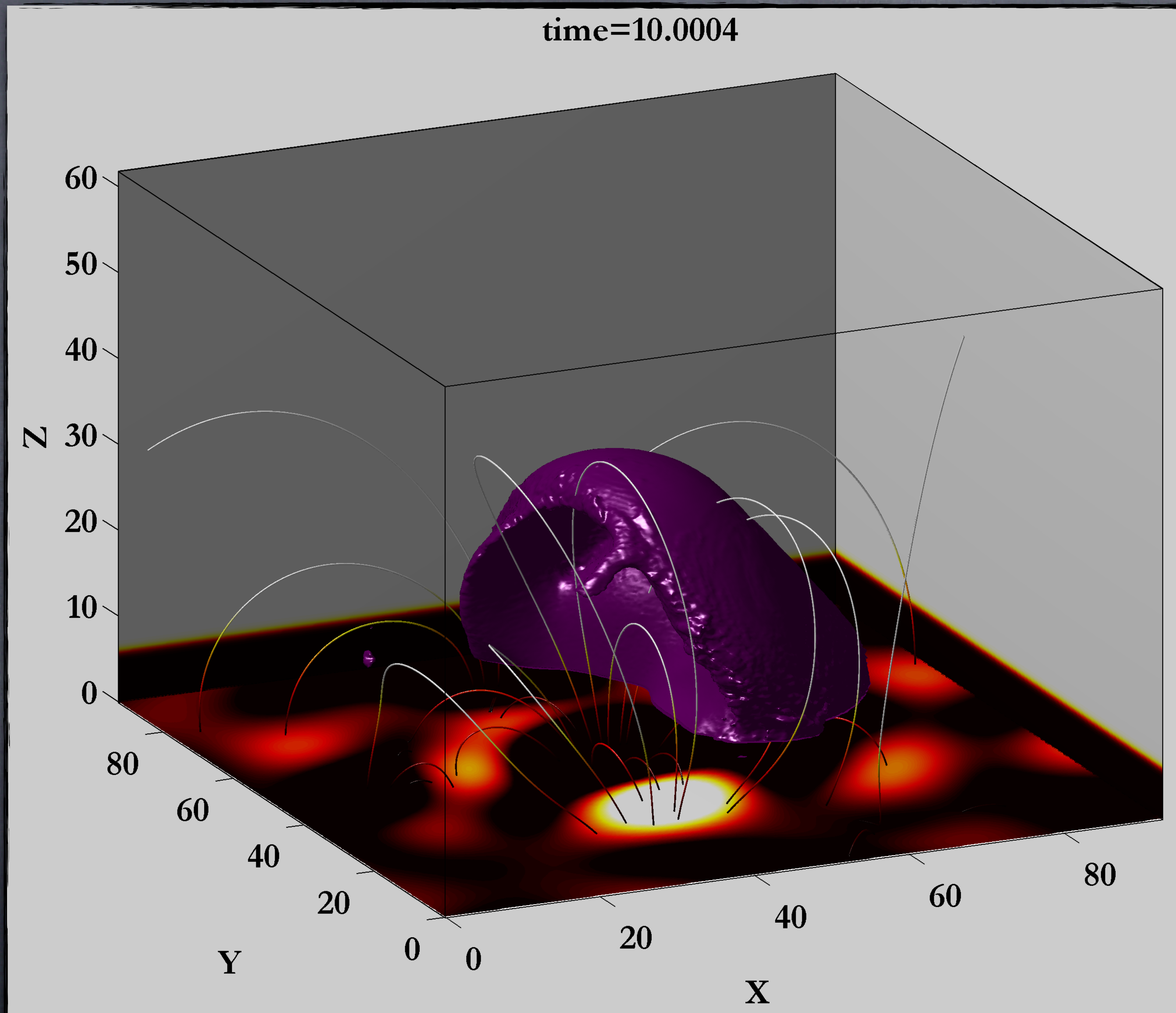
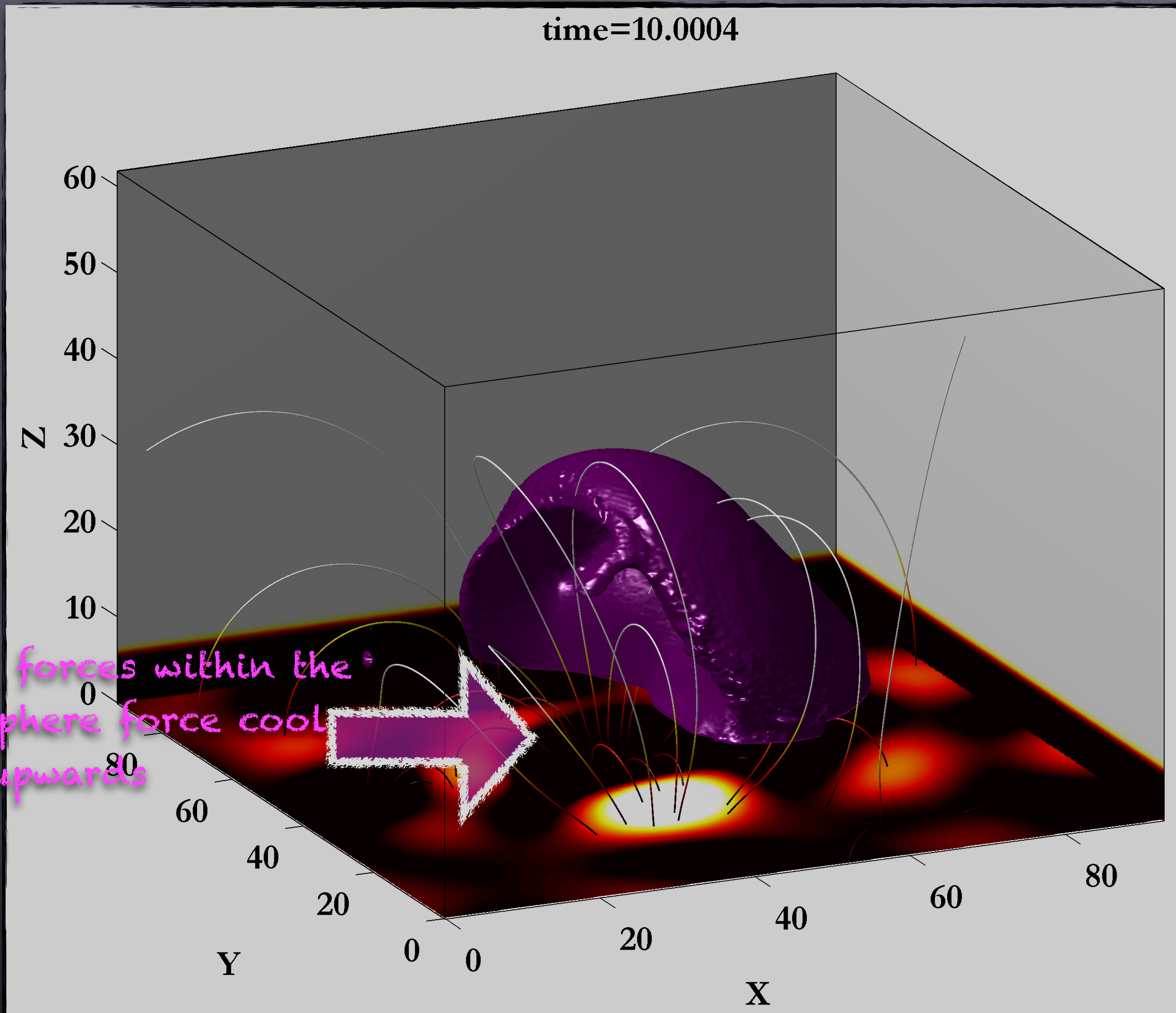
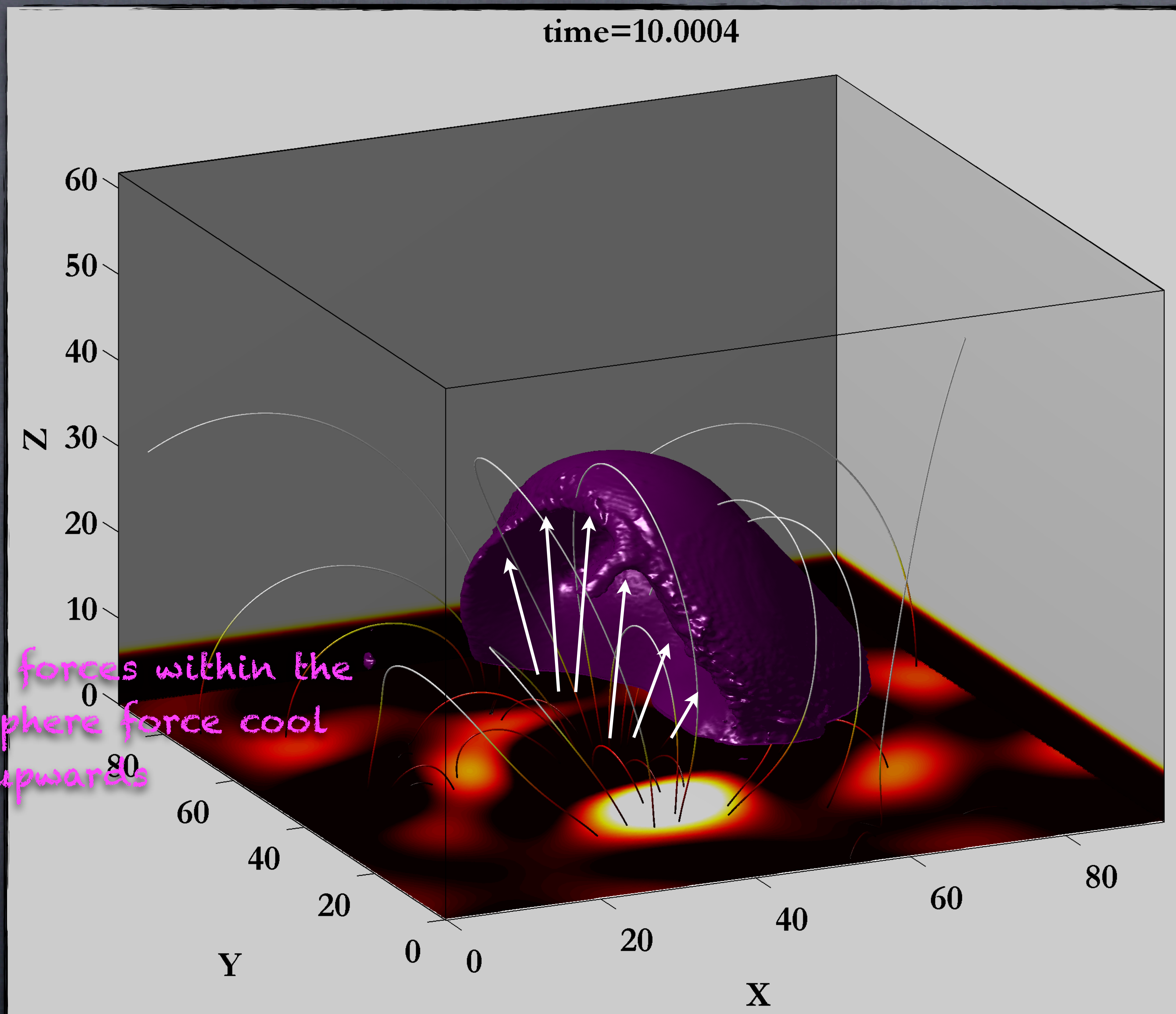



time=10.0004
Z
60
50
40
30
20
10
0
Y
80
60
40
20
0
X
0
20
40
60
80



Lorentz forces within the chromosphere force cool plasma upwards



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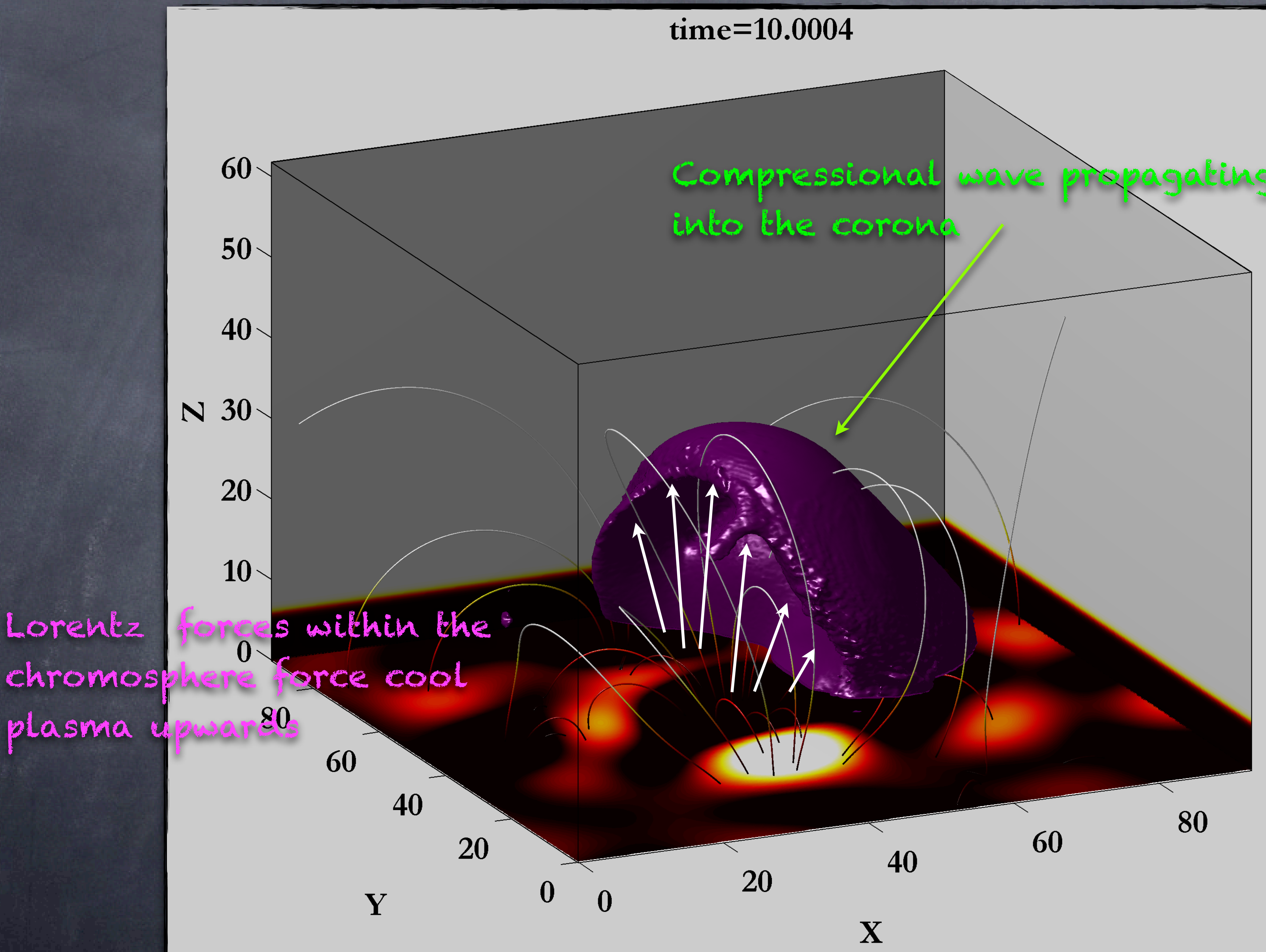

time=10.0004
Compressional wave propagating into the corona
Lorentz forces within the chromosphere force cool plasma upwards
Z
0
10
20
30
40
50
60
Y
0
20
40
60
80
X
0
20
40
60
80

Energy Conservation

$$\frac{d\varepsilon_{kin}}{dt} = -\frac{1}{2}\oint_{S_V} \rho u^2 \mathbf{u} \cdot d\mathbf{s} + \int_V \left(-\frac{1}{2}\mathbf{u} \cdot \nabla p + \mathbf{u} \cdot \mathbf{j} \times \mathbf{B}\right) d^3 v$$

$$\frac{d\varepsilon_{mag}}{dt} = \oint_{S_V} \left(-\mathbf{u}B^2 + (\mathbf{u} \cdot \mathbf{B})\,\mathbf{B} - \eta \mathbf{j} \times \mathbf{B}\right) \cdot d\mathbf{s} + \int_V \left(-\mathbf{u} \cdot \mathbf{j} \times \mathbf{B} - \eta \mathbf{j}^2\right) d^3 v$$

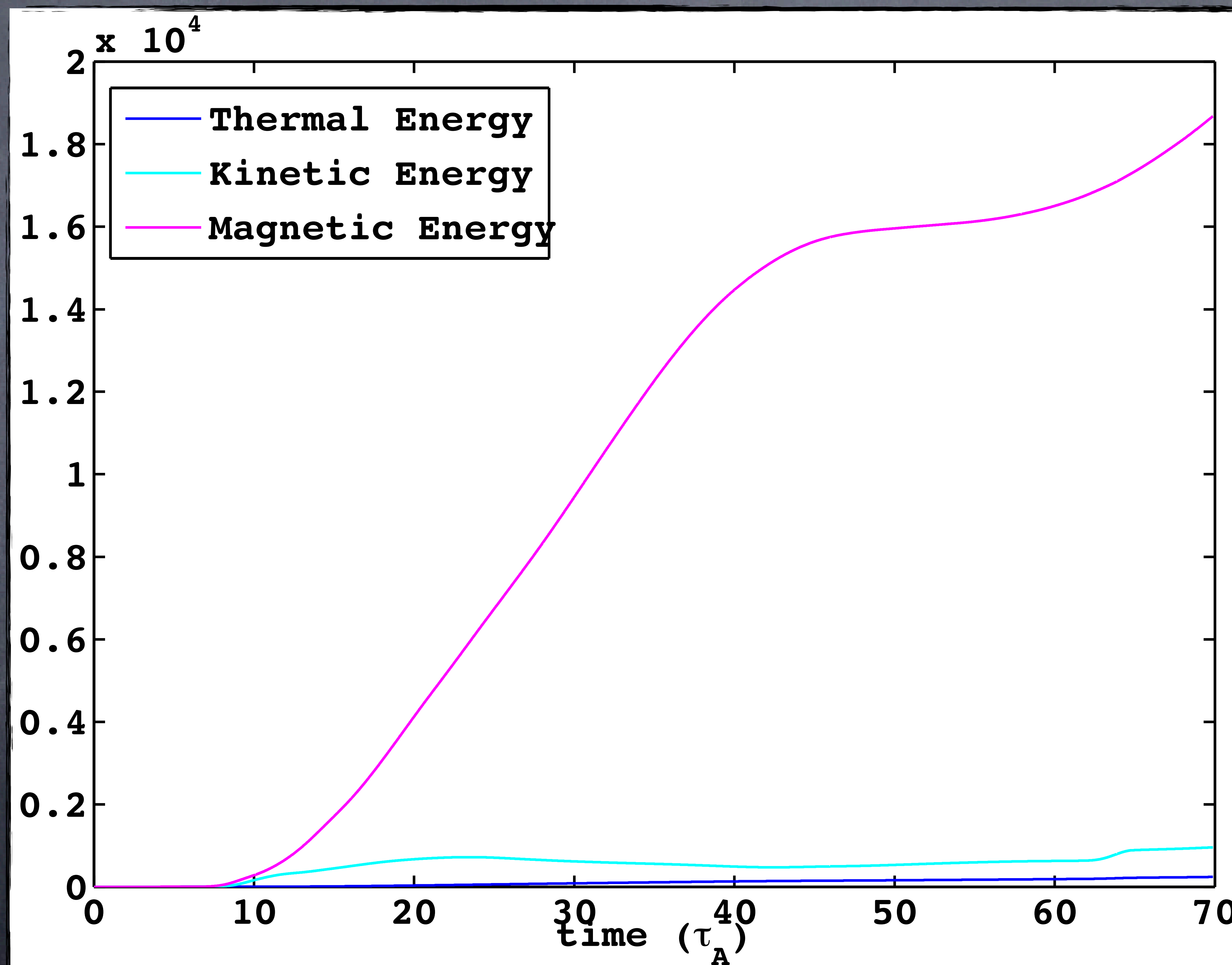
$$\frac{d\varepsilon_{th}}{dt} = -\frac{\gamma}{2\,(\gamma - 1)}\oint_{S_V} p\mathbf{u} \cdot d\mathbf{s} + \int_V \left(\frac{1}{2}\mathbf{u} \cdot \nabla p + \eta \mathbf{j}^2\right) d^3 v$$

Energy Conservation

$$\frac{d\varepsilon_{kin}}{dt} =$$

$$\frac{d\varepsilon_{mag}}{dt} = \quad \eta \mathbf{j}^2) \, d^3v$$

$$\frac{d\varepsilon_{th}}{dt} =$$



Energy Conservation

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$$\frac{d\varepsilon_{mag}}{dt} = \oint_{S_V} \left(-\mathbf{u}B^2 + (\mathbf{u}\cdot\mathbf{B})\,\mathbf{B} - \eta\mathbf{j}\times\mathbf{B}\right)\cdot d\mathbf{s} + \int_V \left(-\mathbf{u}\cdot\mathbf{j}\times\mathbf{B} - \eta\mathbf{j}^2\right) d^3v$$

$$\frac{d\varepsilon_{th}}{dt} = -\frac{\gamma}{2\,(\gamma-1)}\oint_{S_V} p\mathbf{u}\cdot d\mathbf{s} + \int_V \left(\frac{1}{2}\mathbf{u}\cdot\nabla p + \eta\mathbf{j}^2\right) d^3v$$

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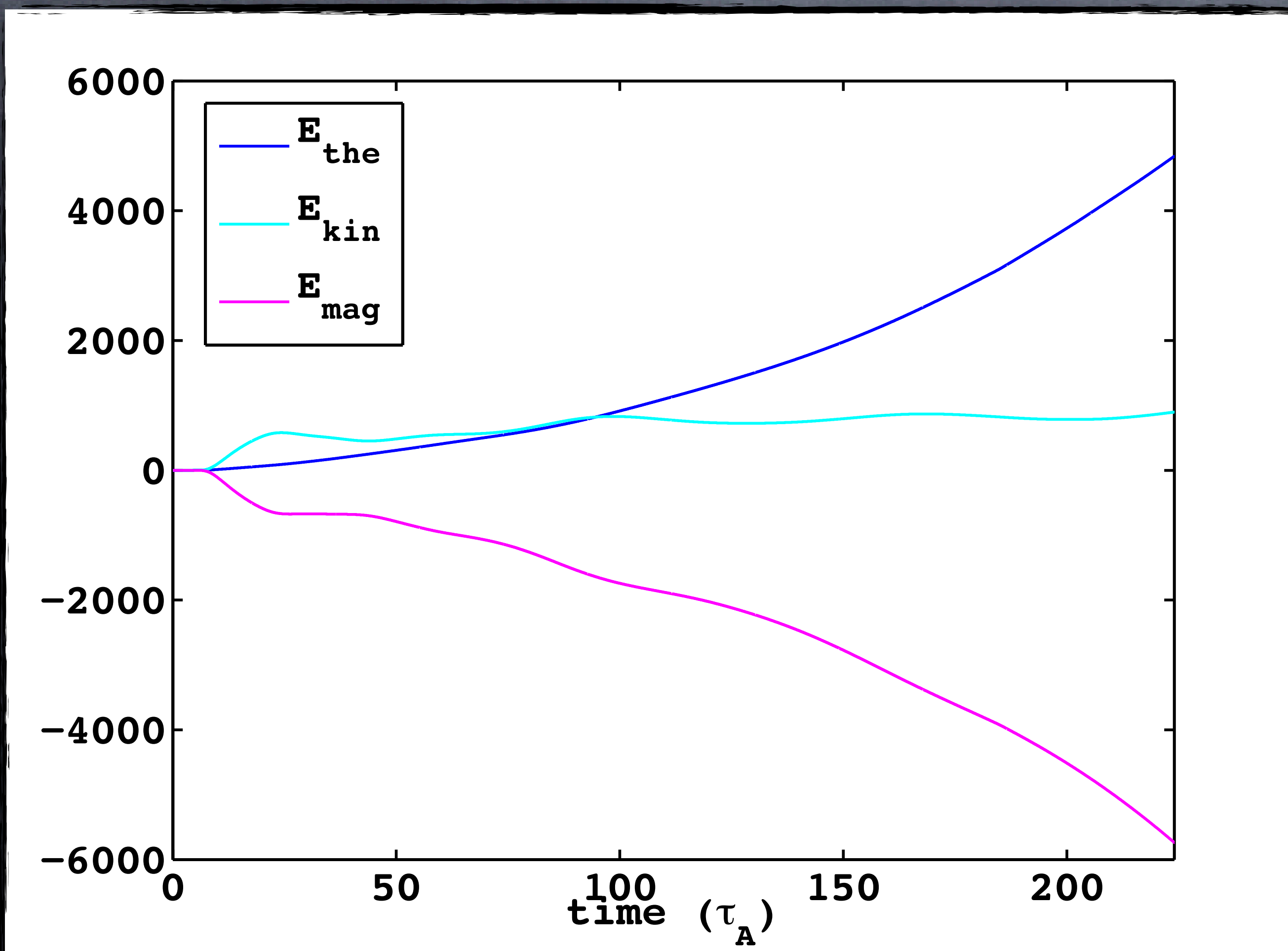
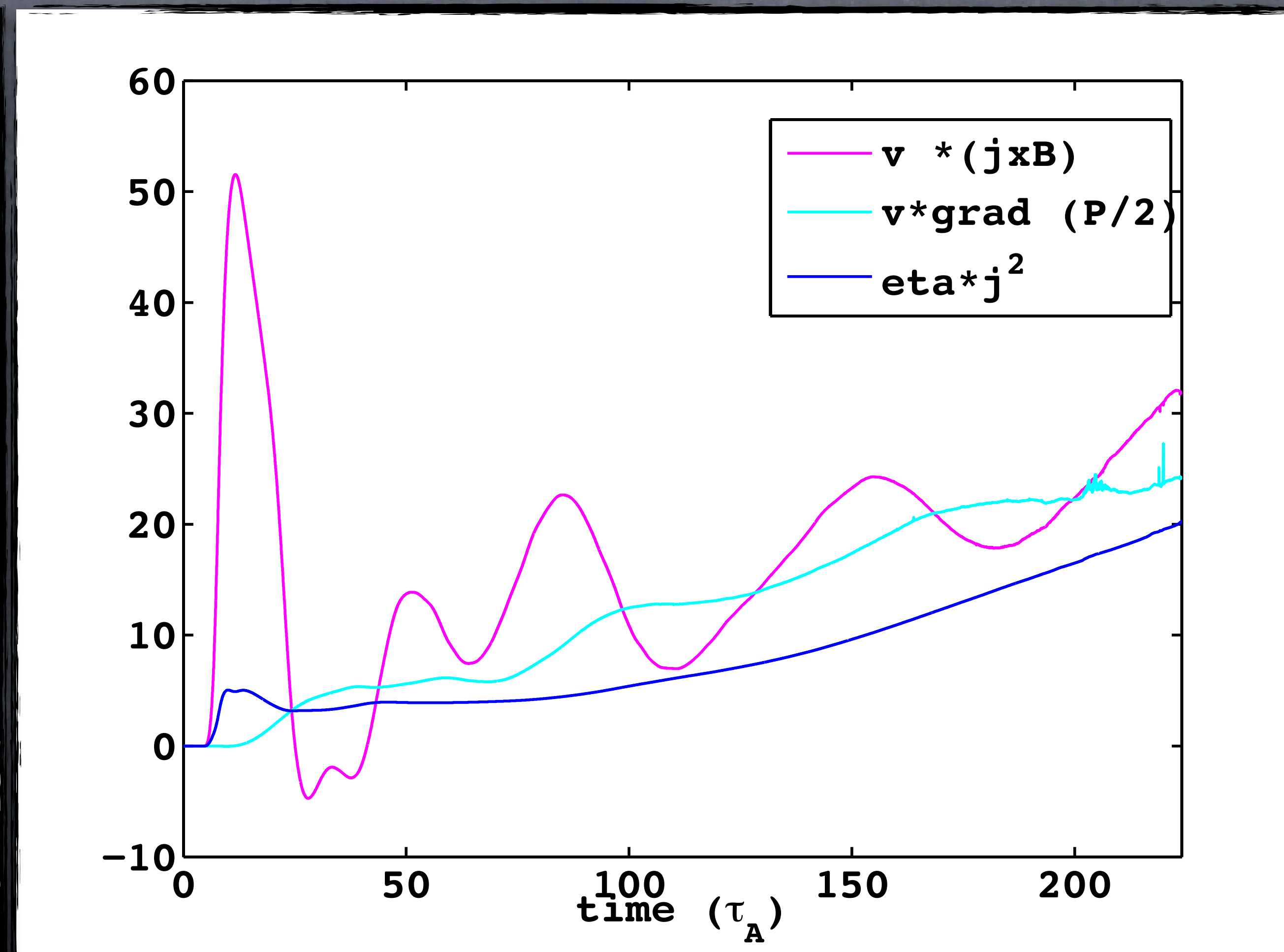
- Chosen BC's eliminate contribution from surface integrals (except through transition region)

Volumetric Energy Budget

Energies



Sources



Resistivity Models

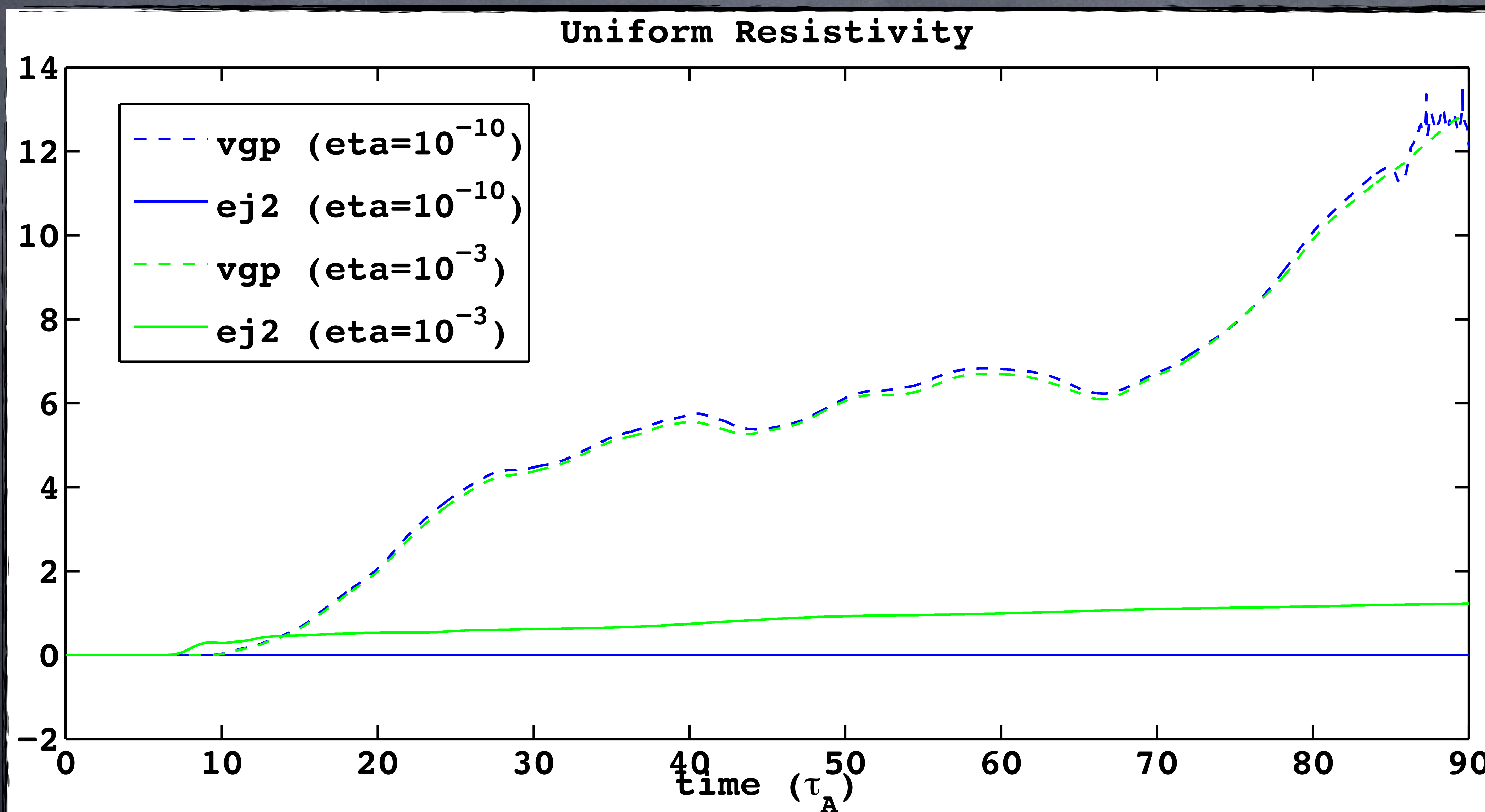
In order to investigate the role played by the resistivity in heating the corona we consider variations to the resistivity model including:

- Constant Uniform Resistivities

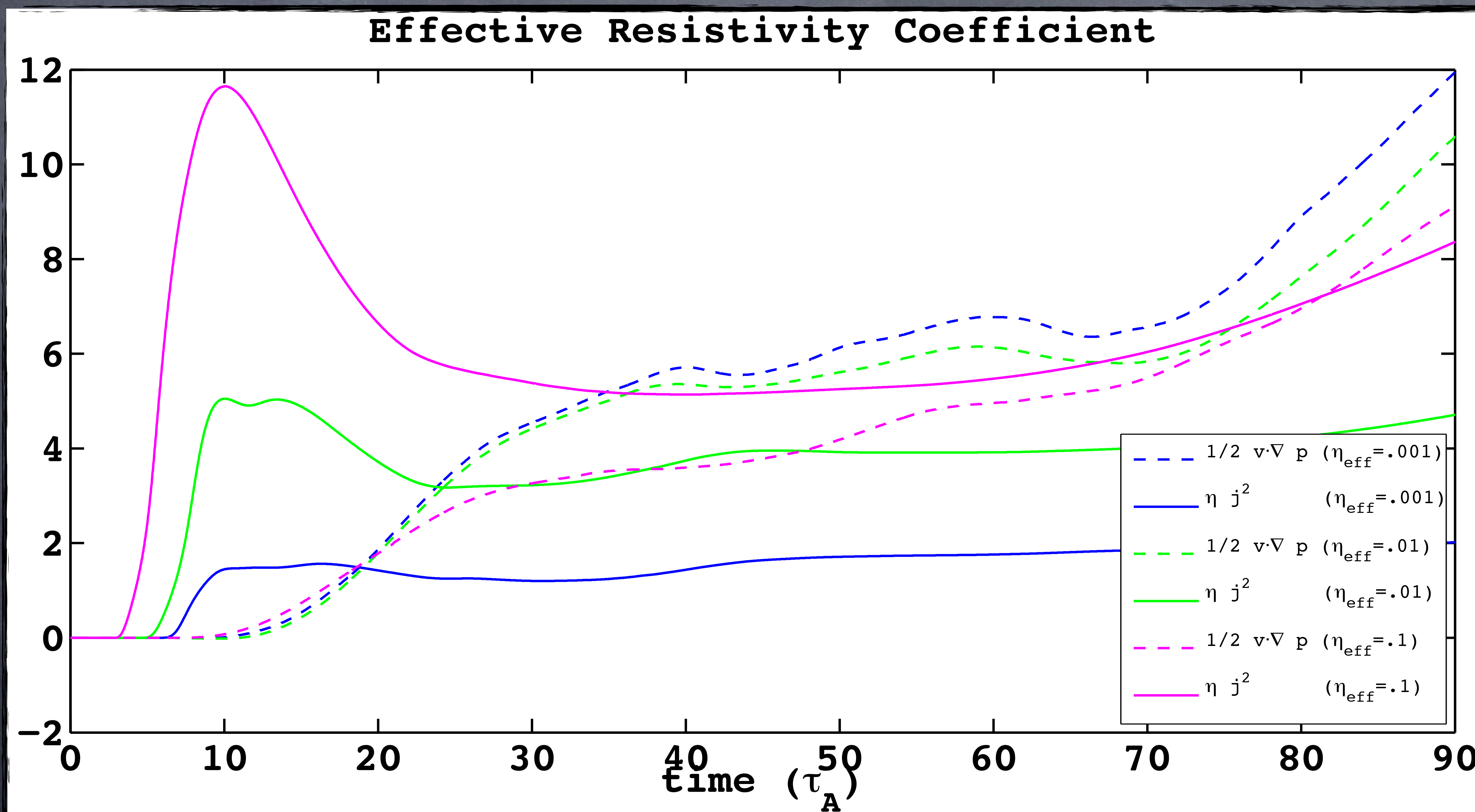
$$\eta^* = \eta_0 + \begin{cases} 0; & \text{if } |v_{cc}| < v_{crit} \\ \eta_{eff}\left(\frac{v_{cc}}{v_{crit}} - 1\right); & \text{if } |v_{cc}| \geq v_{crit} \end{cases}$$

- Variation of the Resistivity Coefficient (η_{eff})
- Variation of the Critical Value (v_{crit})
- Constant Uniform Critical Value (v_{crit})

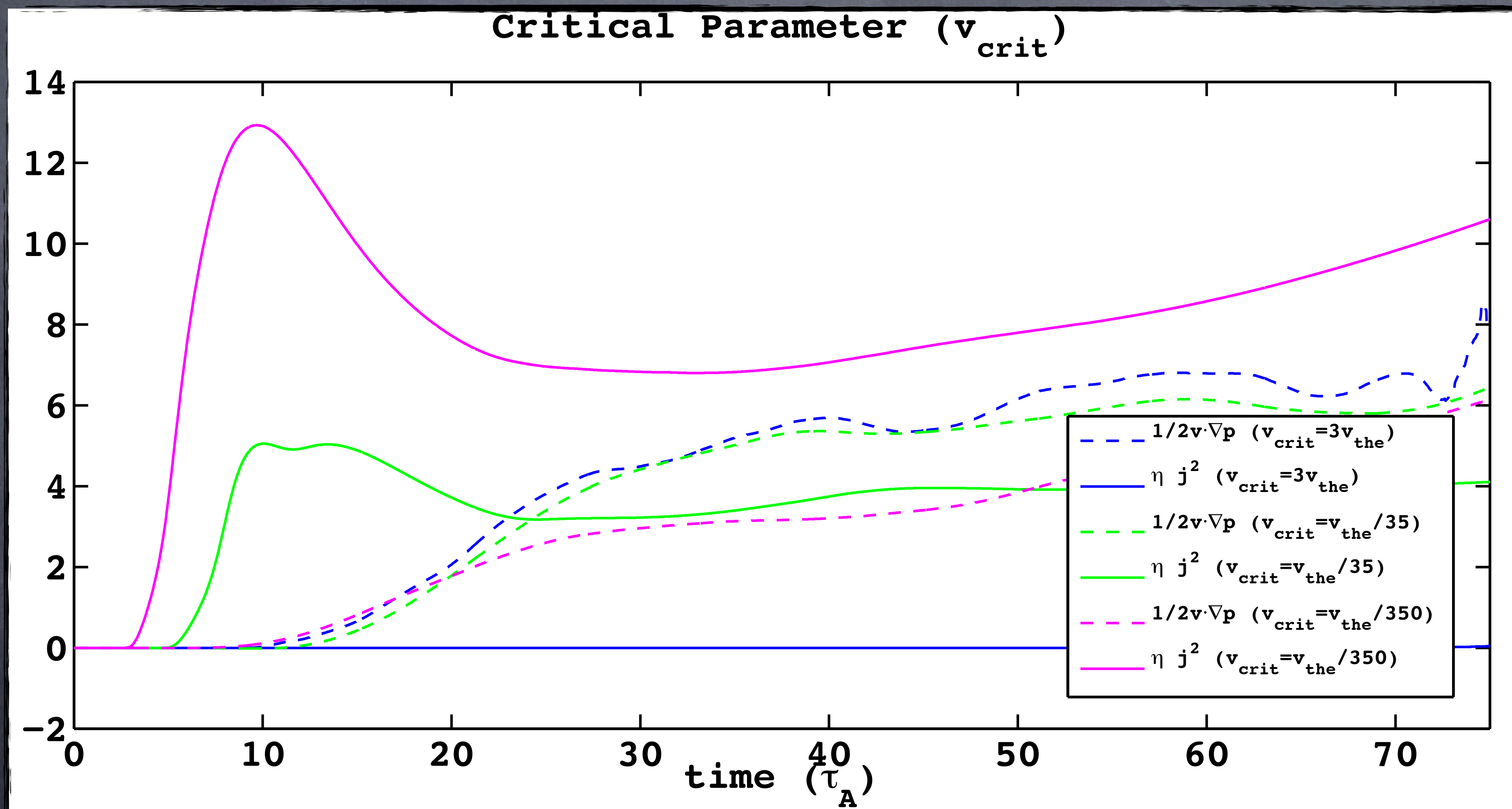
Constant Uniform Resistivity



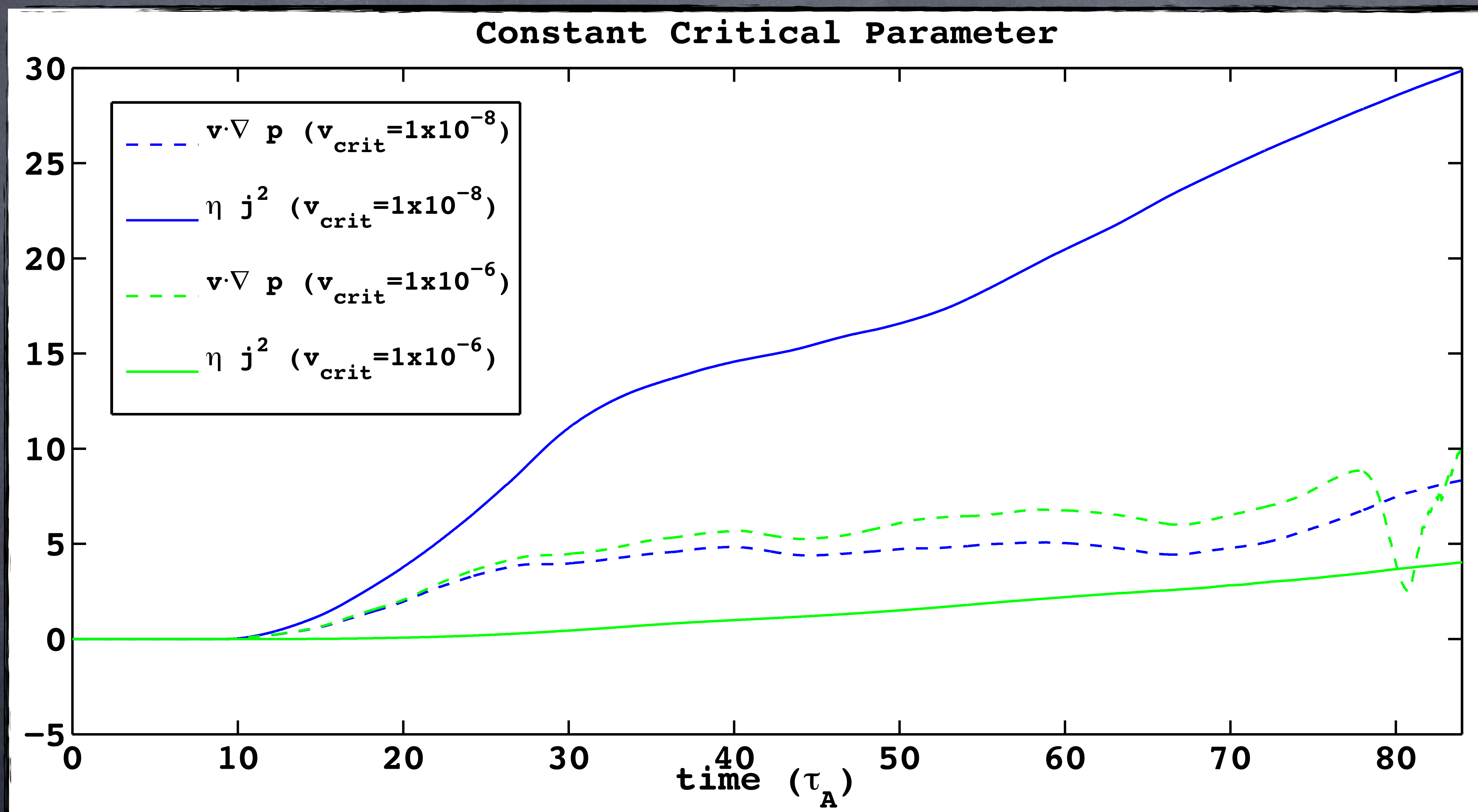
Variation of Resistivity Coefficient (η_{eff})



Variation of v_{crit}



Constant Uniform v_{crit}



Conclusions

- In agreement with Spangler 2009, we find the Spitzer resistivity too low to enable significant heating within the corona directly through current dissipation.
- Our results indicate a tendency for lower critical parameters to generate earlier onset and larger spatial extent of anomalous resistivity, thus leading to a more significant Joule dissipation and a greater increase in thermal energy within the corona. This is extends the findings of Roussev (2002) for the case of 2D reconnection to 3D.
- For most resistivity models considered herein, compression dominates Joule heating in driving coronal thermal energy increase. However, given a sufficiently large value of anomalous resistivity, the Joule heating may become the dominant source of heating (Büchner et al. (2006) have estimated the anomalous resistivity arising from non-linear ion acoustic instabilities to be as large as 6x10^4 Ohm-m).

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Roussev, I., Galsgaard, K., Judge, P.G., Physical consequences of the inclusion of anomalous resistivity in the dynamics of 2D magnetic reconnection, Astron. & Astrophys., 382, 639-649, 2002.

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