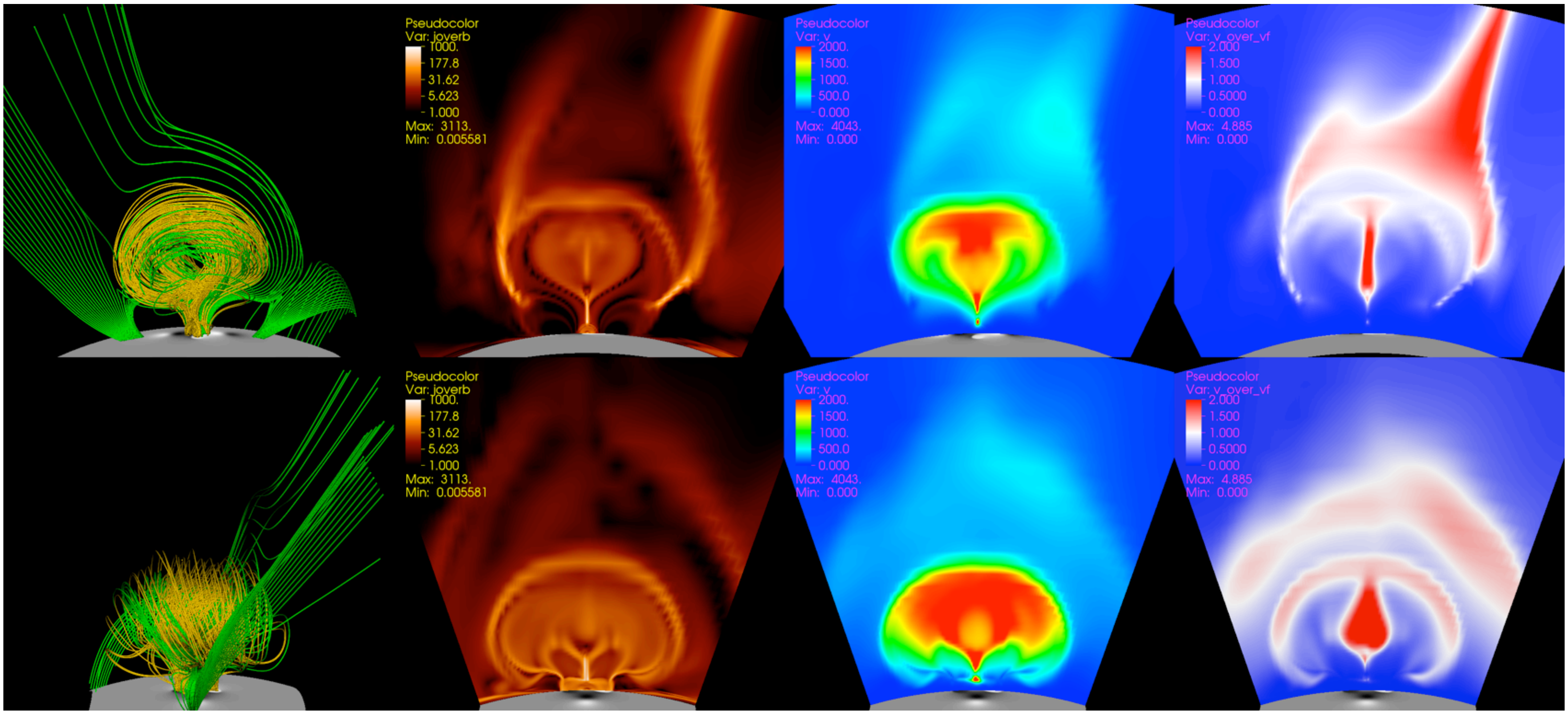
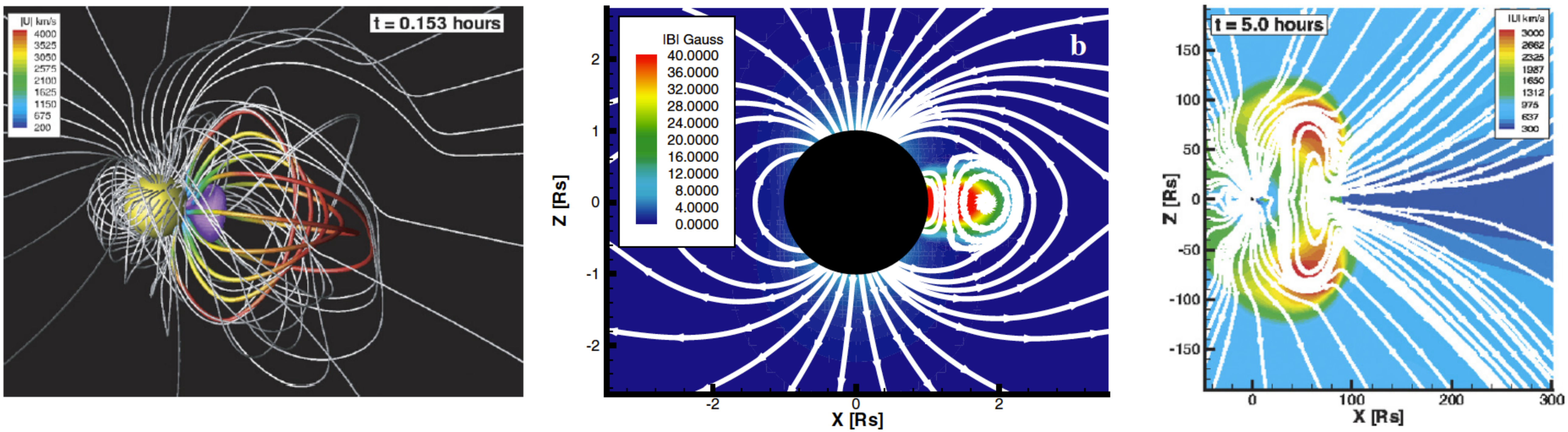
Modeling fast CMEs --- progress report PSI

"From Sun to Ice" team meeting, 2012 May 17/18, Boulder



T. Török, C. Downs, Z. Mikić, V.S. Titov, J.A. Linker, R. Lionello, P. Riley

Simulation of “extremely fast” CME



Manchester et al. (2006)

- insert flux rope with 40.000 G (!) into ambient corona (out of equilibrium)
- okay to qualitatively study evolution of very fast CME “further out”, but:
- does not tell us much about what makes CMEs fast

What makes CMEs fast ?

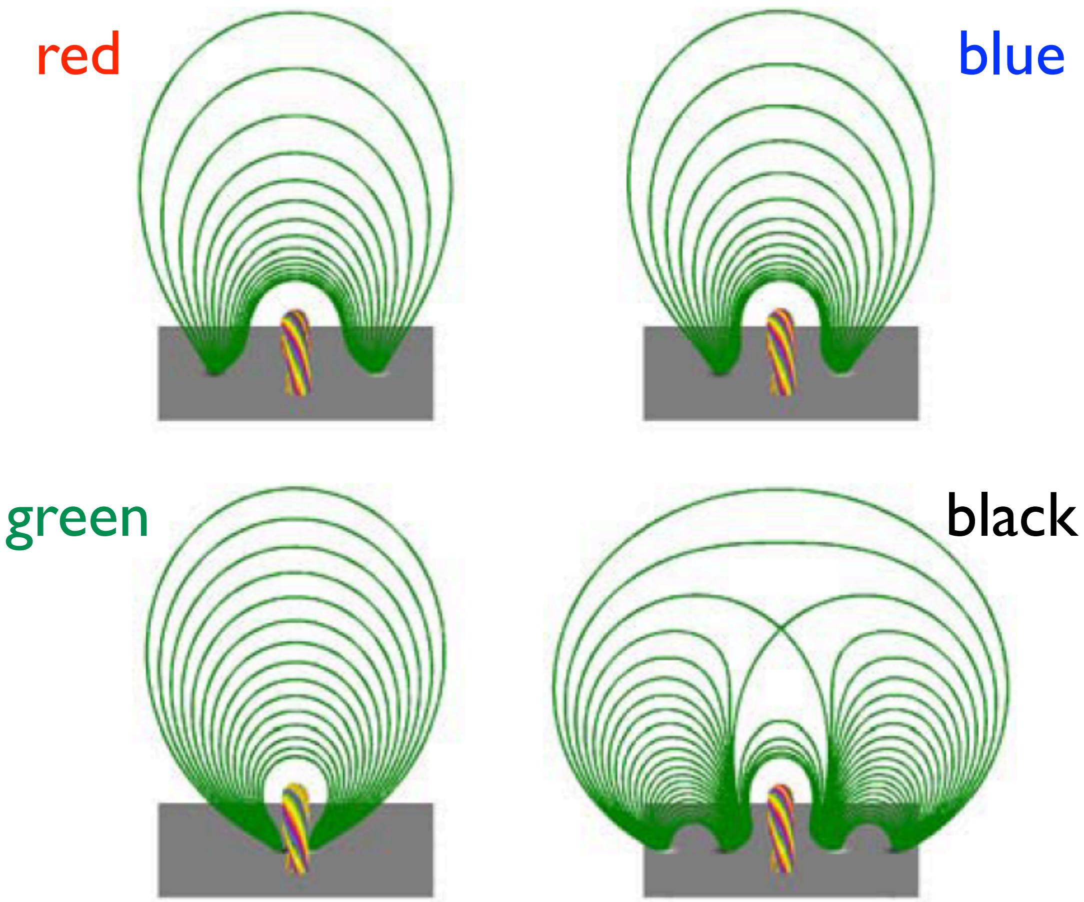
Apparently many (partly related) parameters, e.g.:

- size, complexity, and strength of source region
- available free magnetic energy
- length and number of PILs
- ambient field topology (open vs. closed)
- others ...

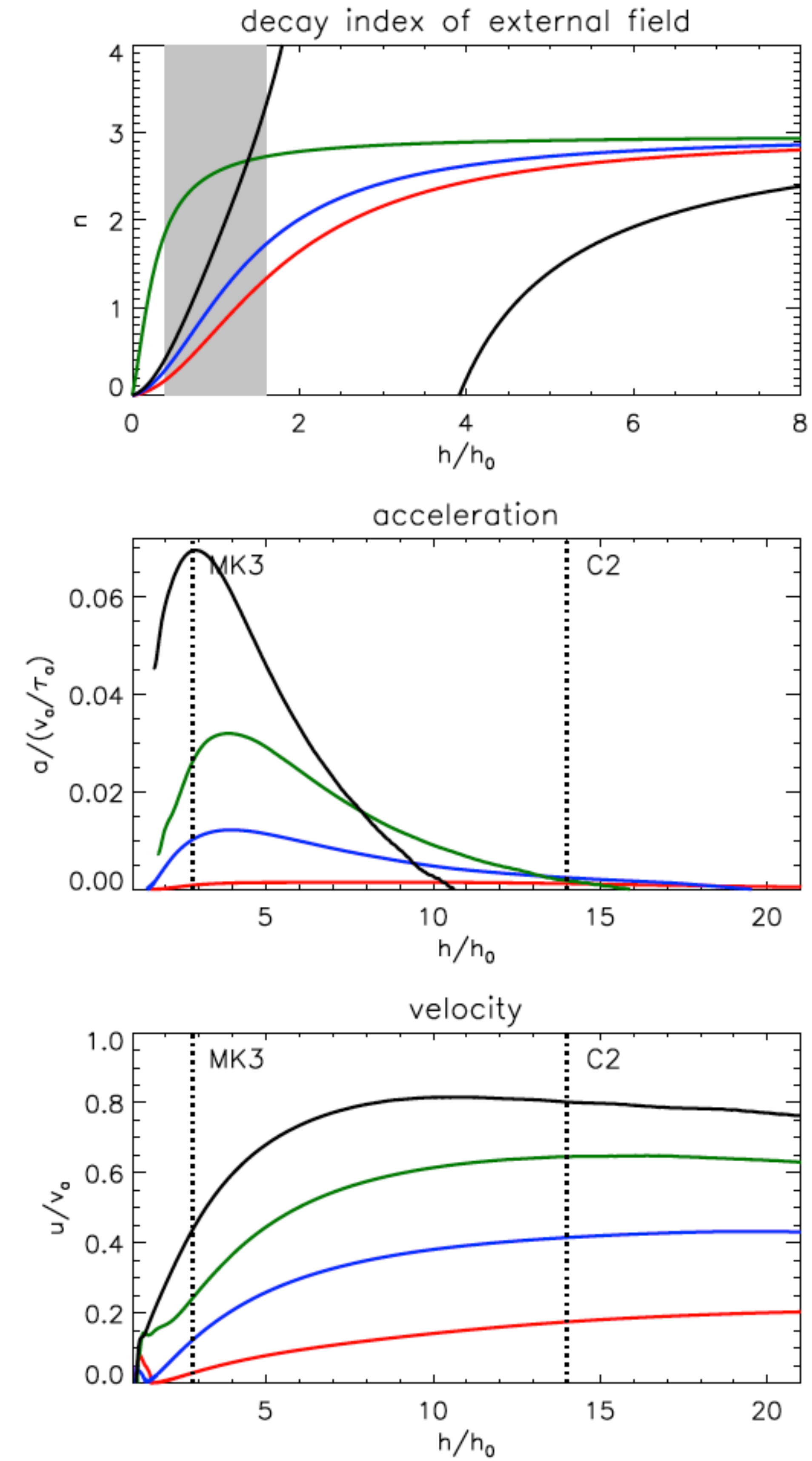
We focus (for now) on two parameters:

- gradient of overlying field (decay index)
- compactness of erupting structure

1.) Influence of overlying field gradient for CME speed

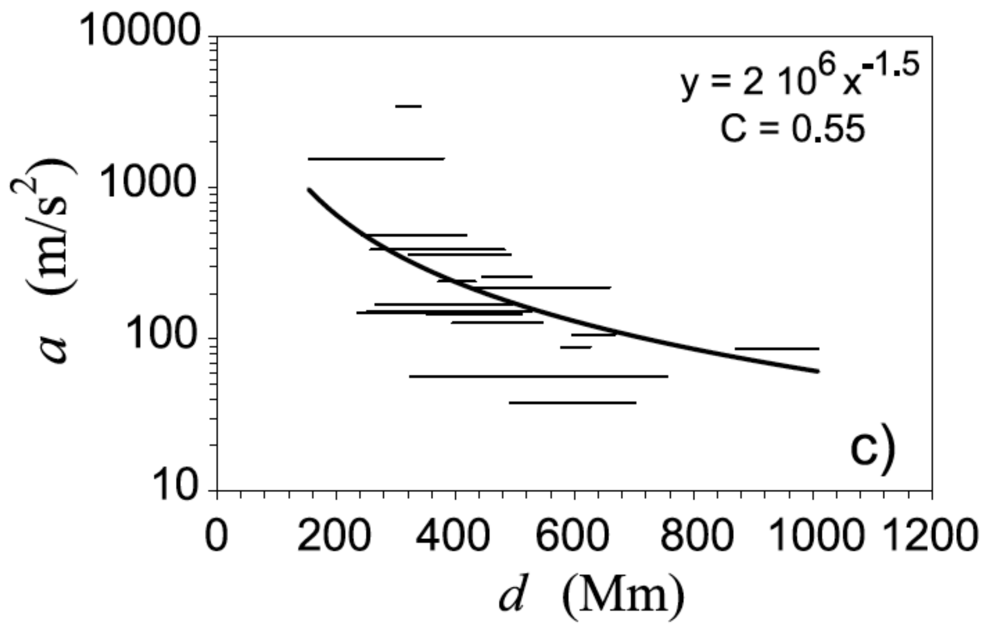


Török & Kliem (2007)

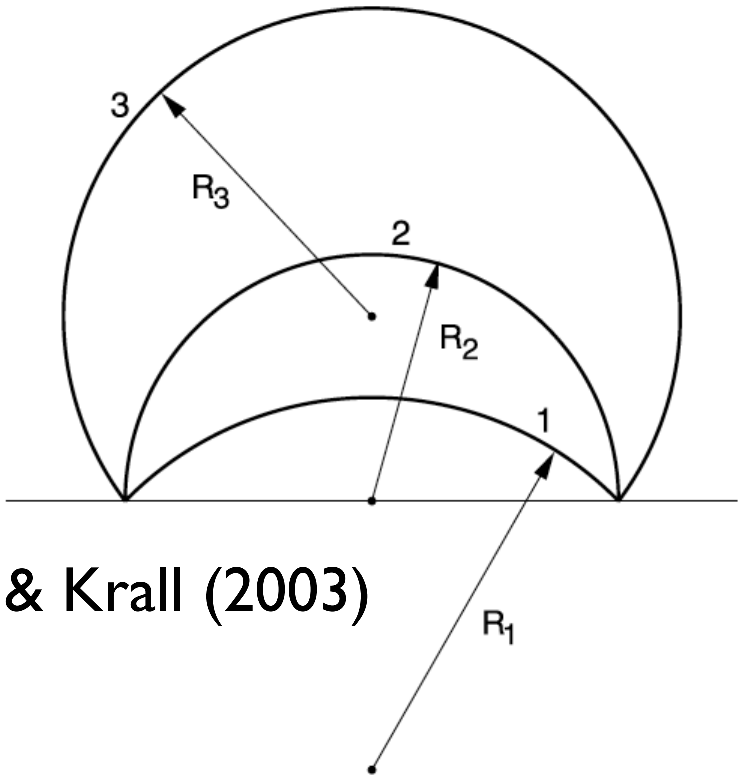


strong decay of external field → fast CME

2.) Role of compactness of source region



Vršnak et al. (2007)



Chen & Krall (2003)

- prominences typically erupt when they have reached an almost semi-circular shape
- compact flux rope → eruption starts at lower height (stronger fields)

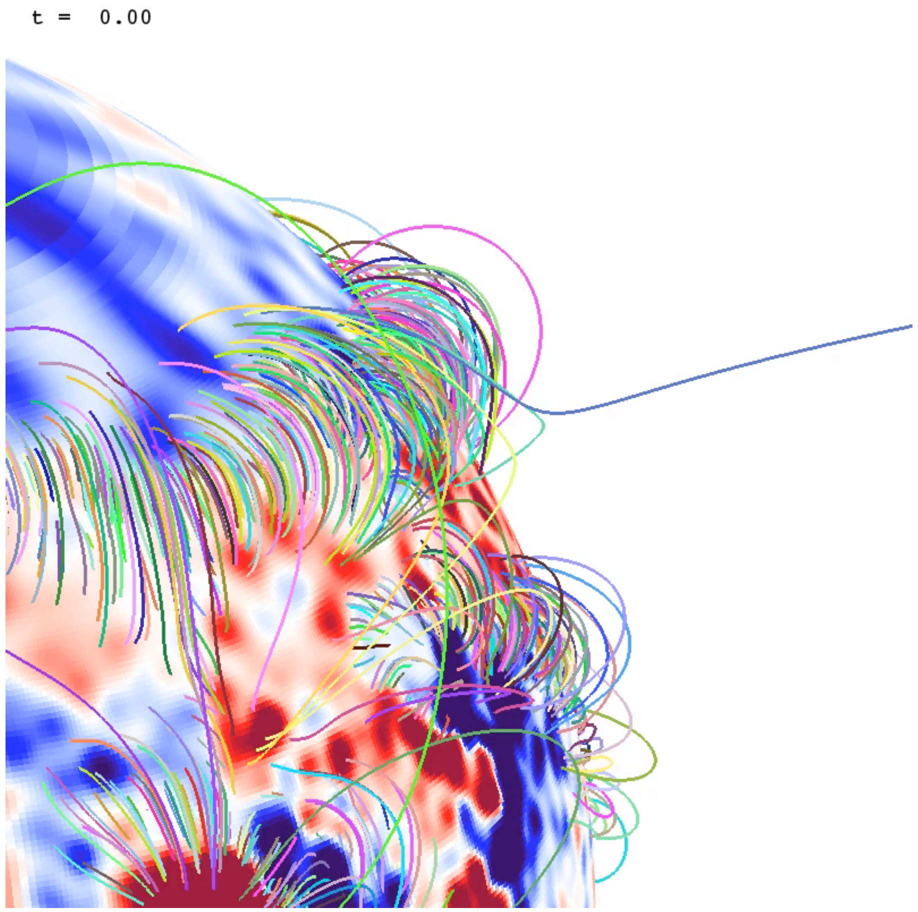
  → hoop force larger

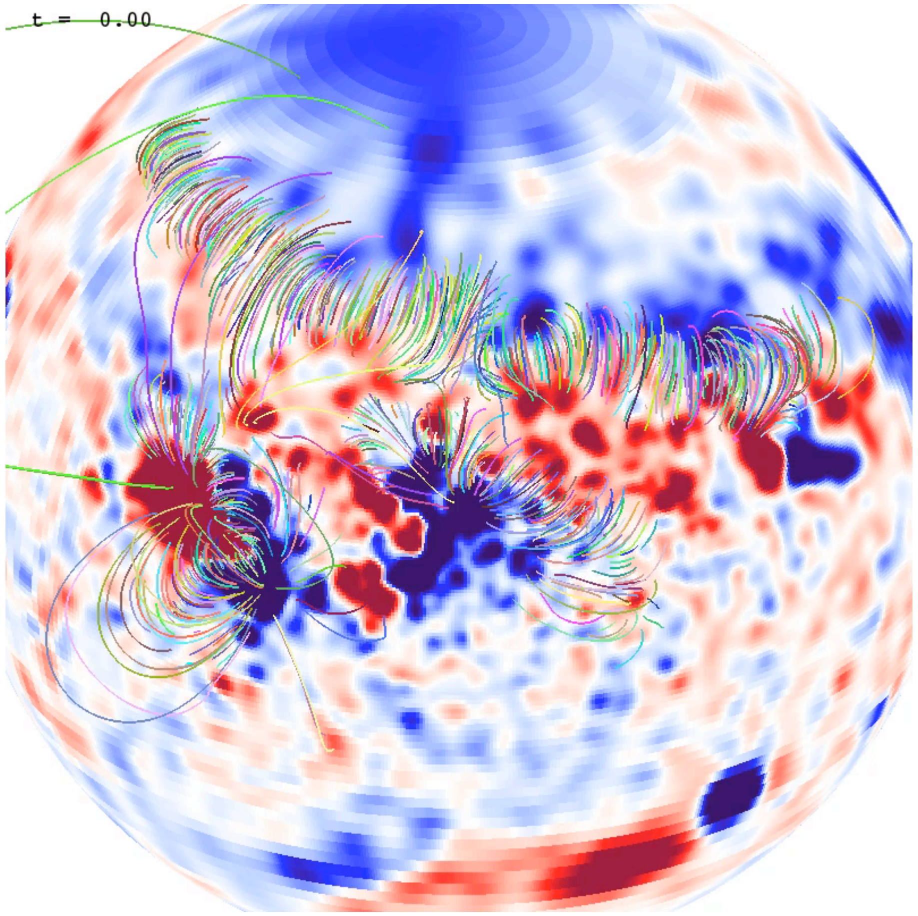
  → reconnection stronger

compact source region → fast CME

Recipe: create AR with strong decay index & produce compact flux rope

PSI eruption simulations





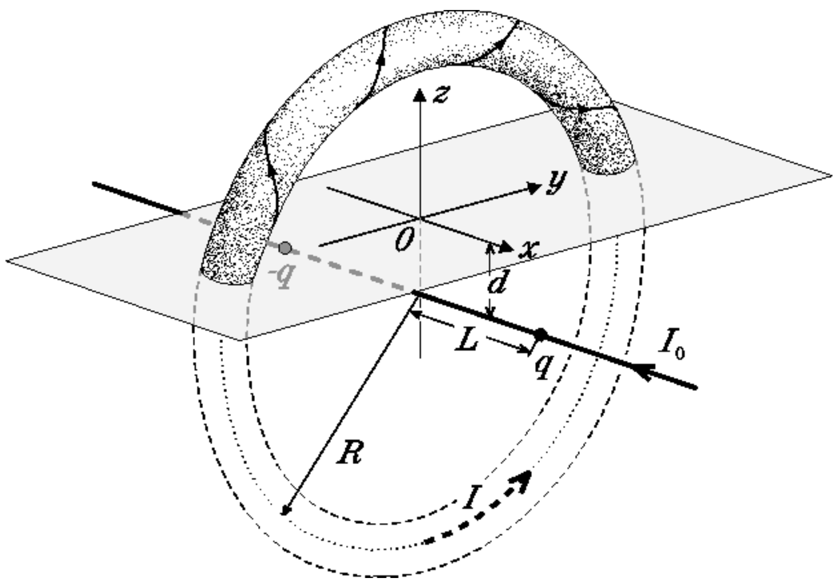
advantages:

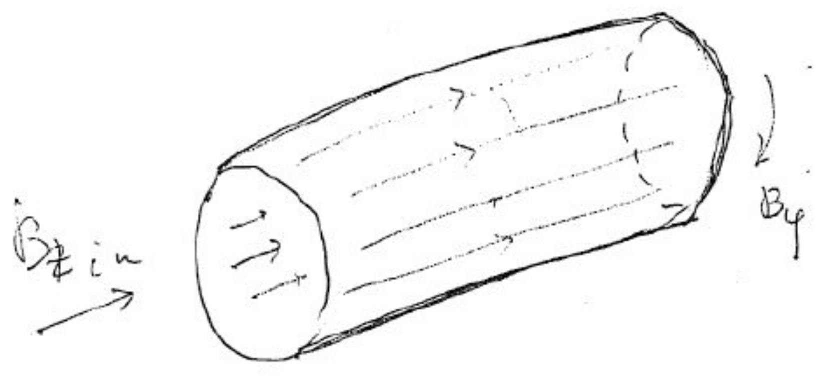
- flexible (can handle, e.g., long and strongly curved PILs)
- relatively self-consistent
- preserves magnetogram

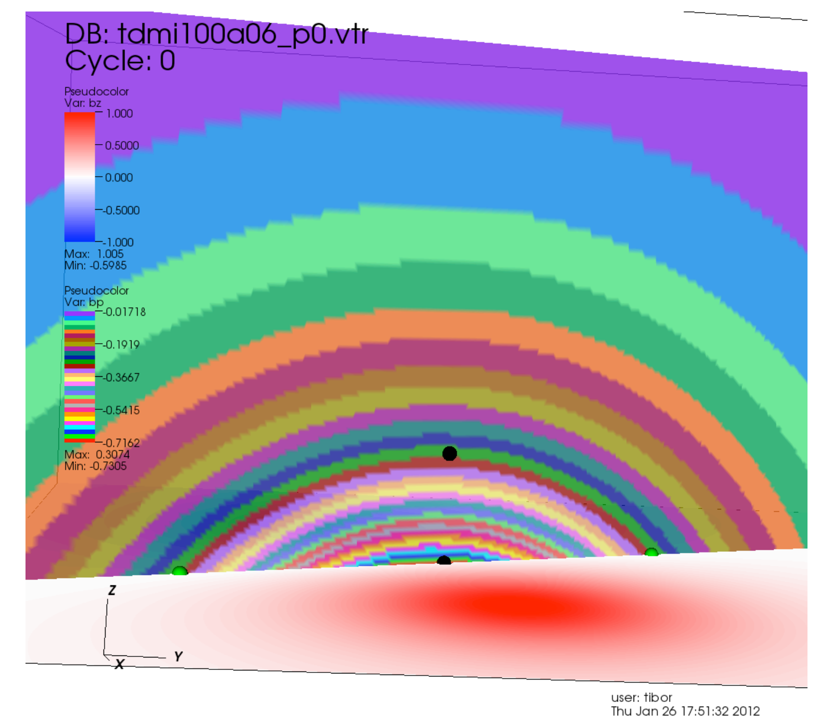
disadvantages:

- relatively time-consuming
- not well suited to explore parameter space

New model: modified TD equilibrium







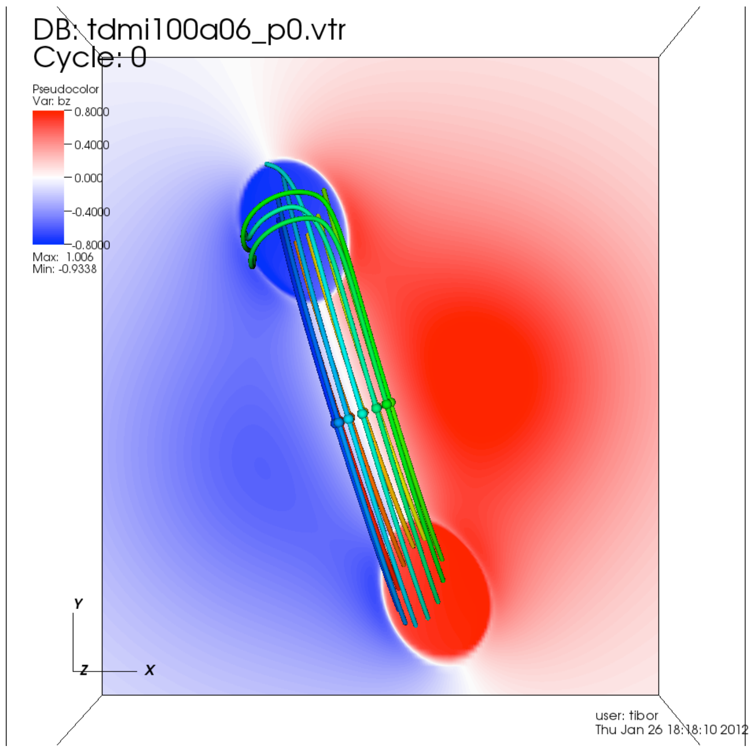
- “flux rope” with surface current & axial field inside

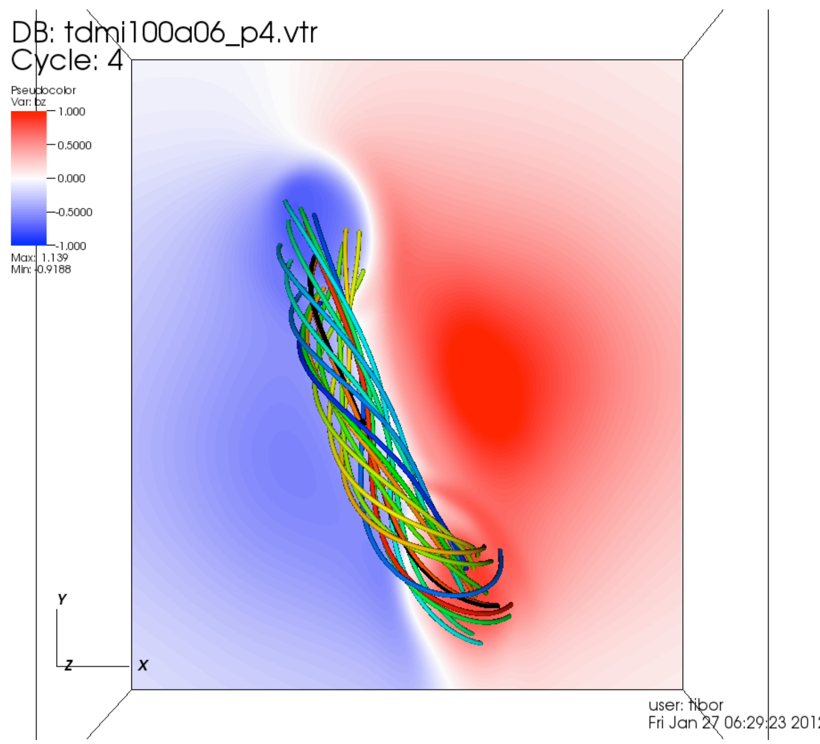
→ insert rope (in equilibrium) along contours of stabilizing ambient field

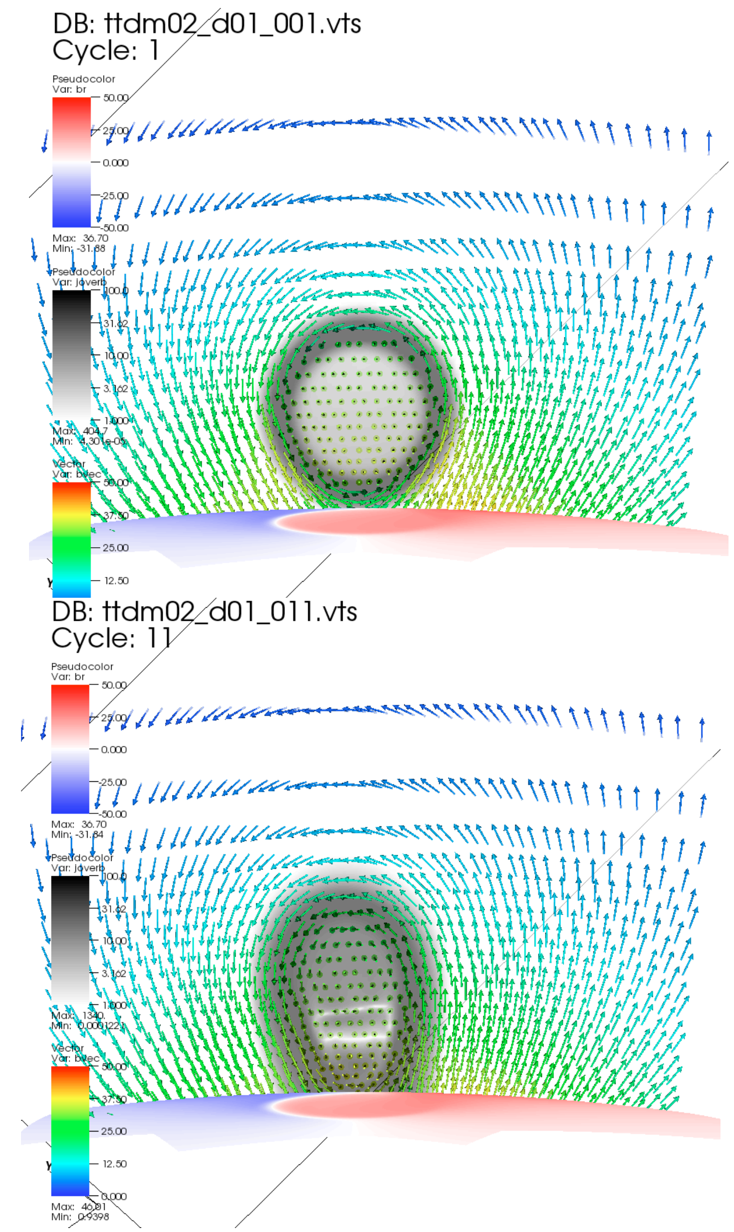
advantages:
- pre-eruptive coronal flux ropes can be produced “quickly”
- allows to estimate stability properties from analytical solution

disadvantages:
- not well suited for long, curved PILs
- changes magnetogram after insertion

Numerical relaxation



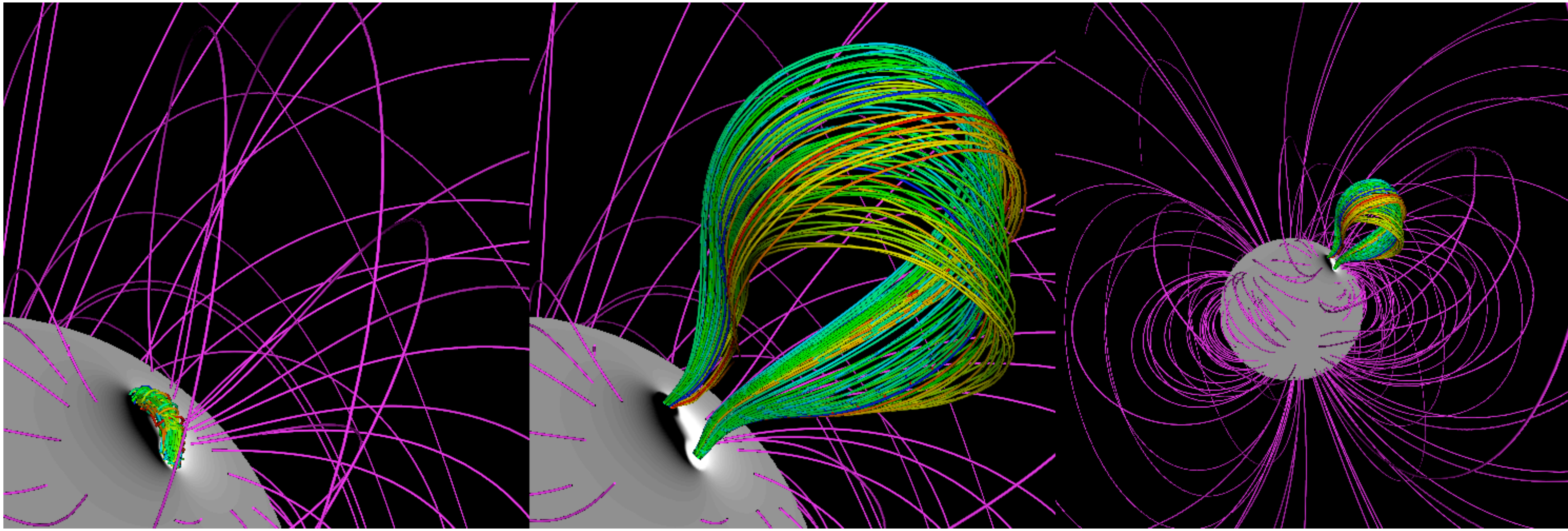




- stable flux rope forms during relaxation

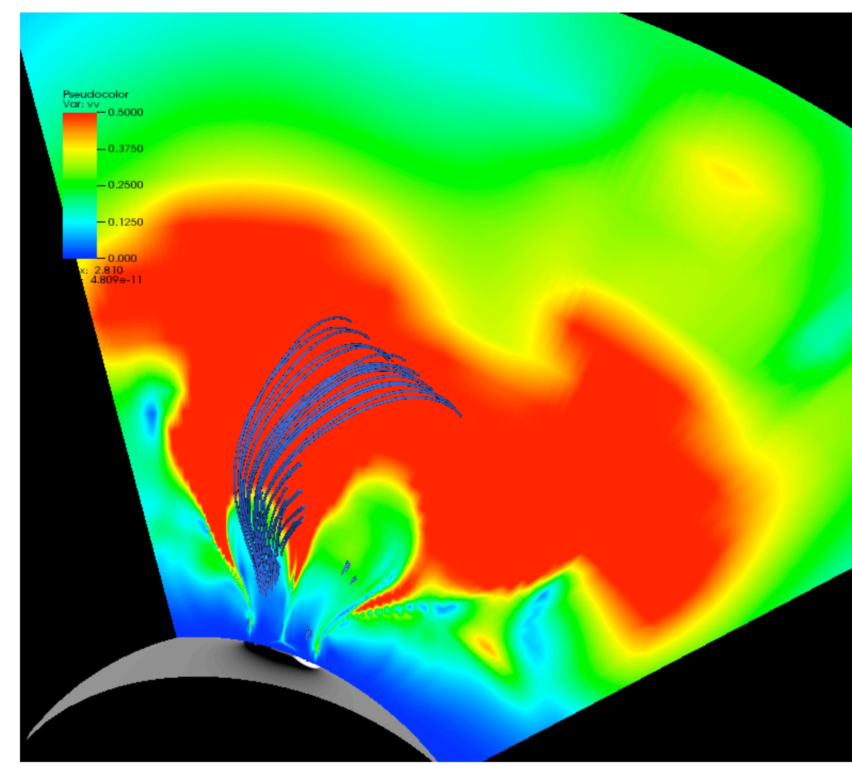
- problem: resulting equilibrium current different → needs to be obtained by "try and error"

Eruption

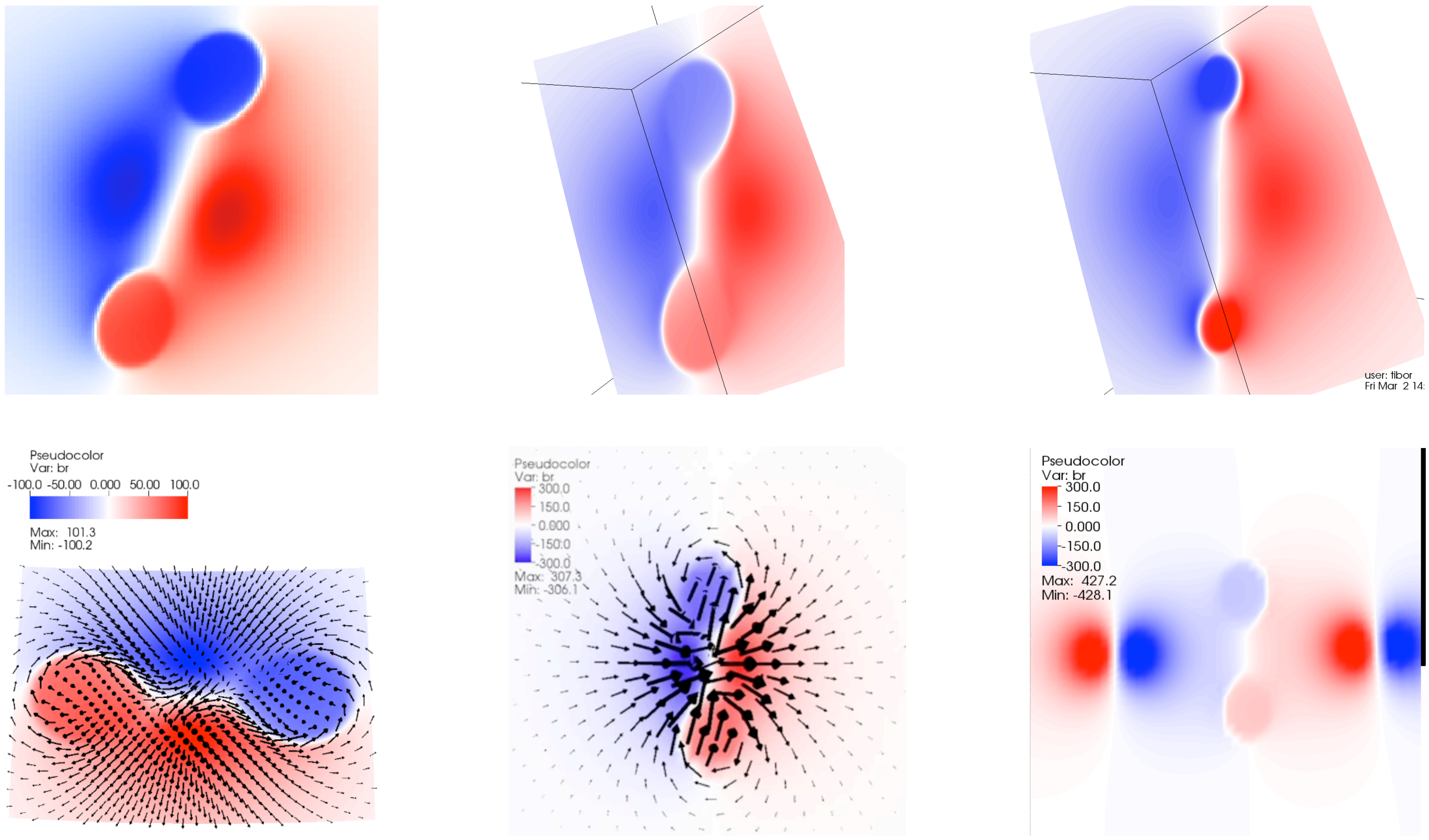


trigger eruption by either:

- produce stable rope + apply converging flows
- use (slightly) supercritical flux rope current

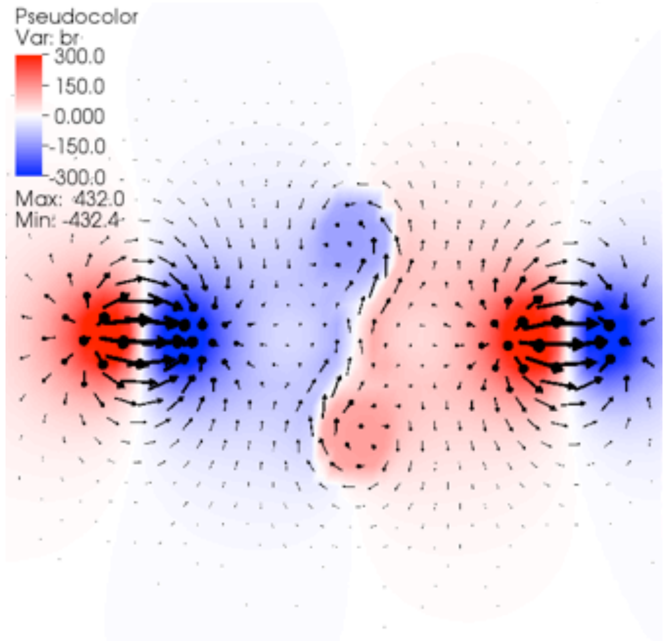


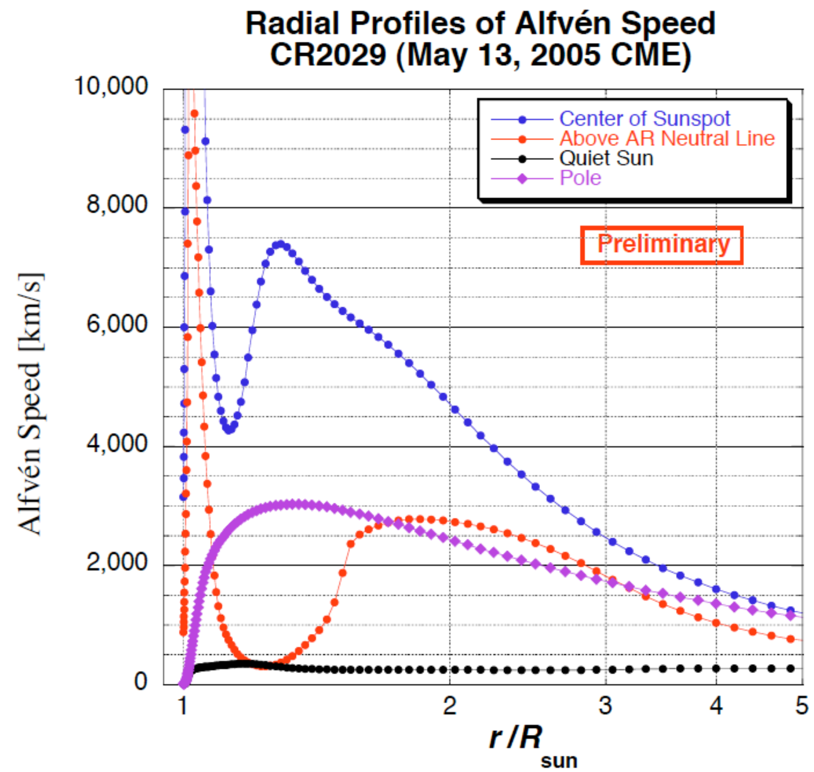
Explore different configurations (zero beta)

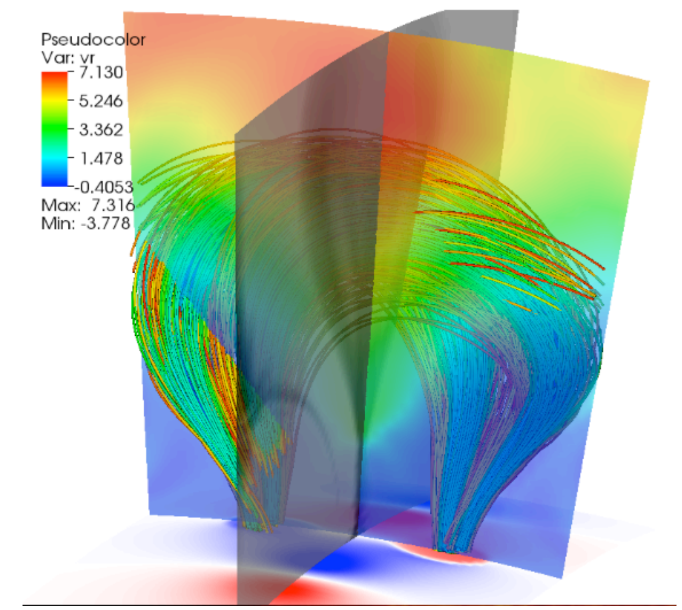


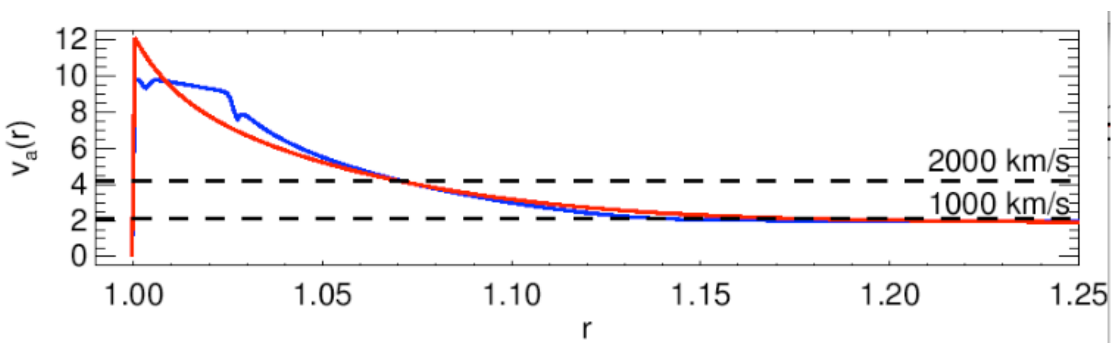
- study different ARs with different complexity, flux & decay index
- vary flux rope parameters (size, thickness, strength)

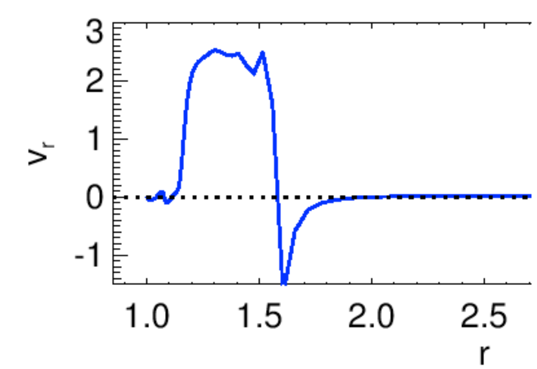
Problem: CME speed very sensitive to chosen density



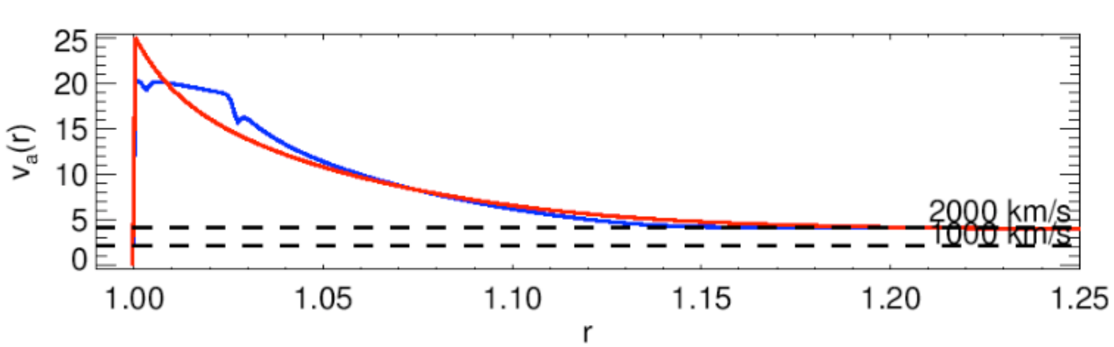


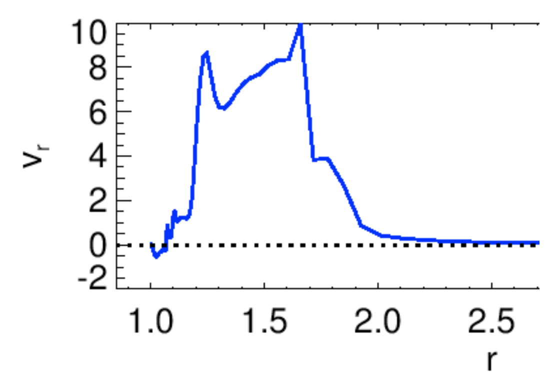






v_r ≈ 1300 km/s

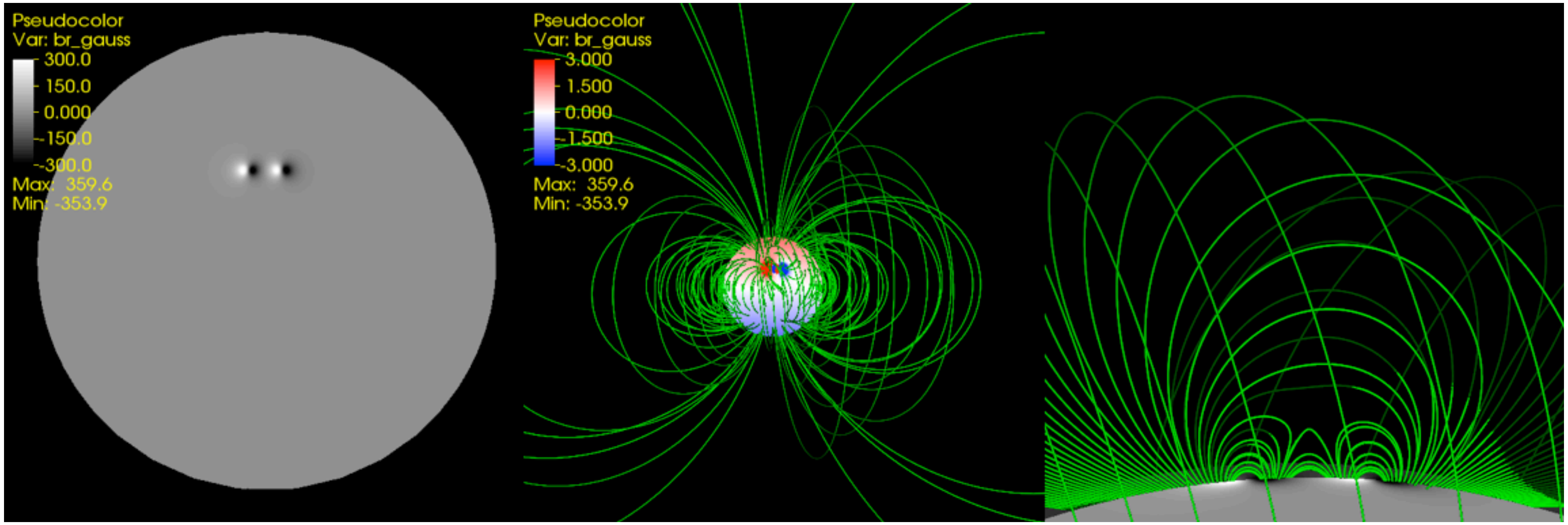




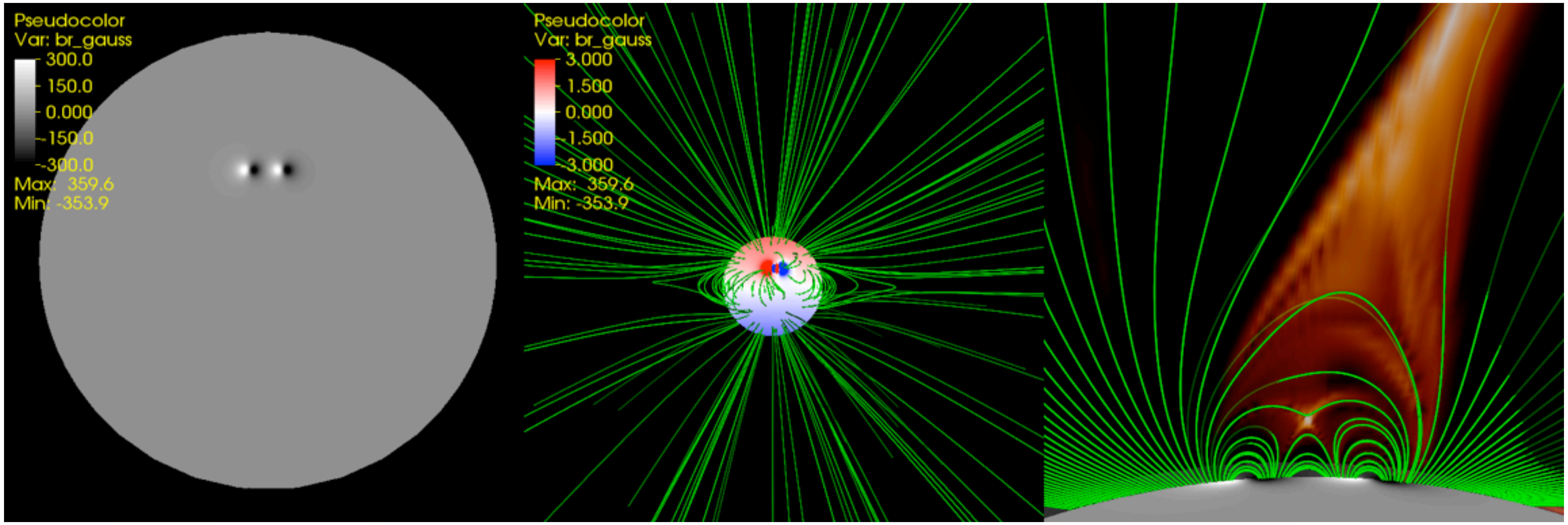
v_r ≈ 4000 km/s

same magnetic configuration gets about three times faster !

Thermodynamic simulation: initial field & solar wind relaxation

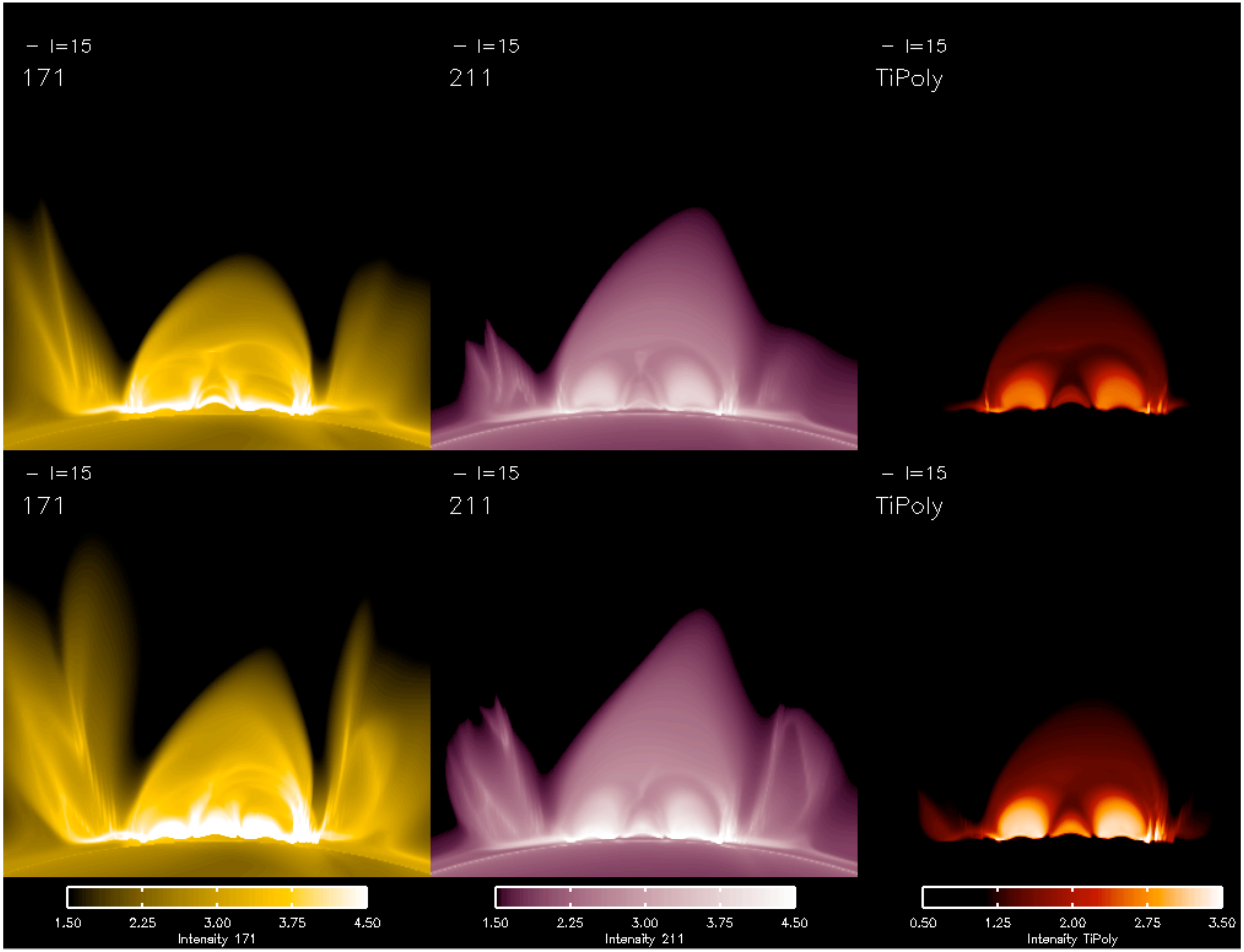


global dipole + quadrupolar active region (large decay index + relatively compact)



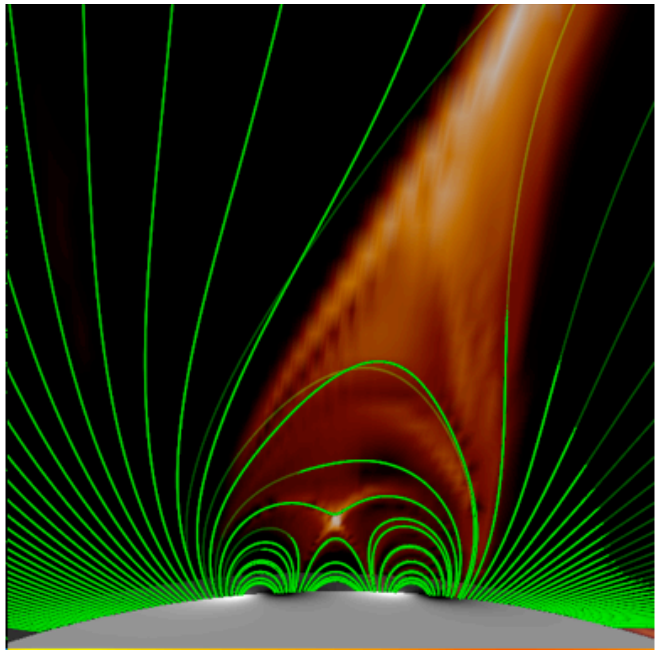
relaxation: coronal field opens up + streamer forms above active region

Testing different heating parameters

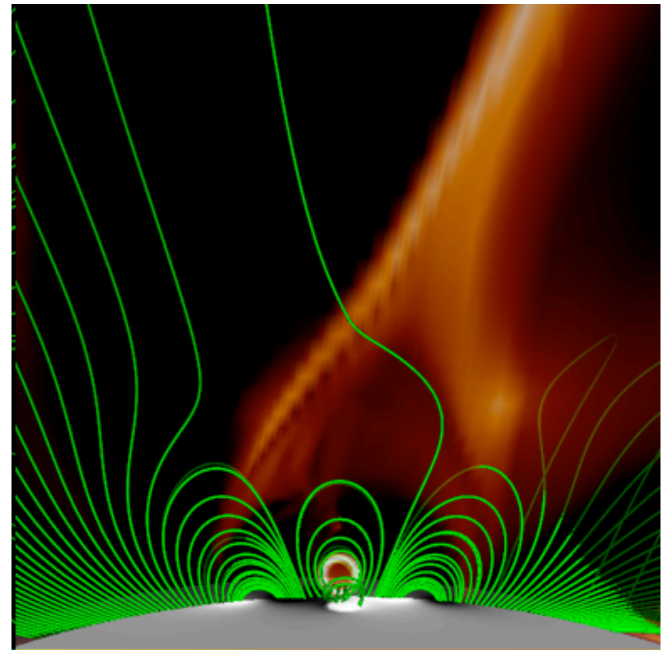


→ insert flux rope into this configuration

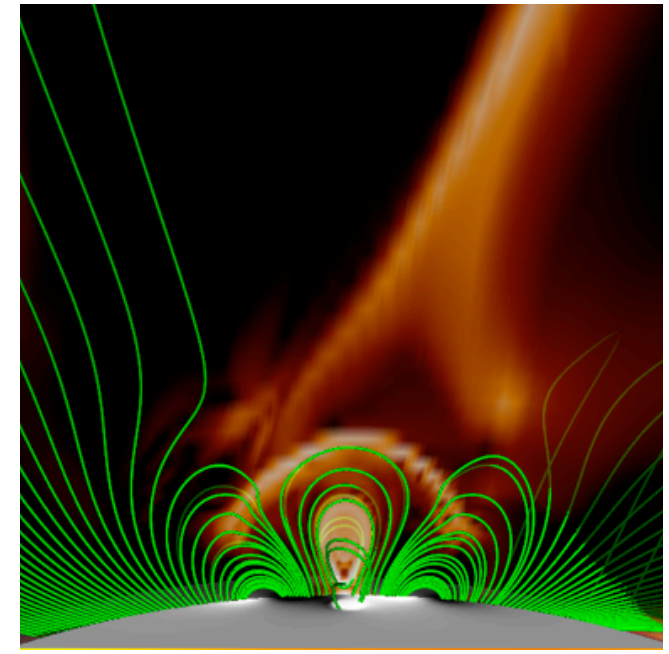
Insert flux rope



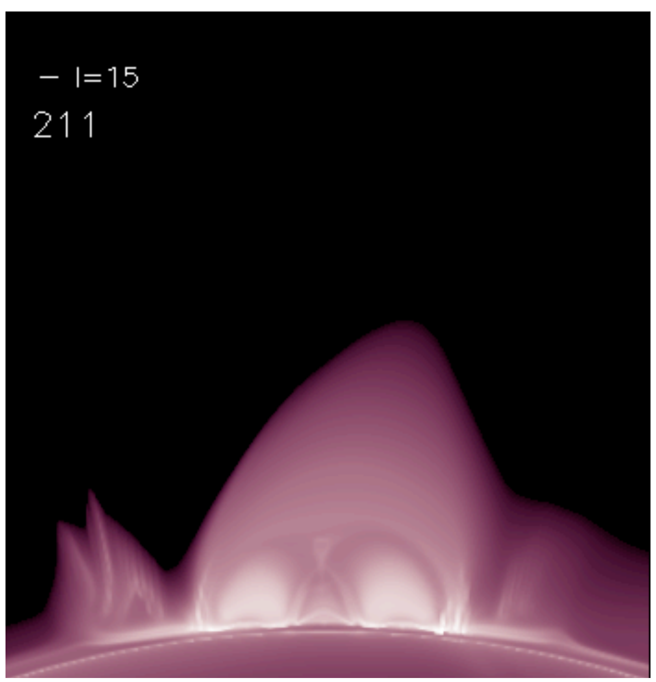
steady state

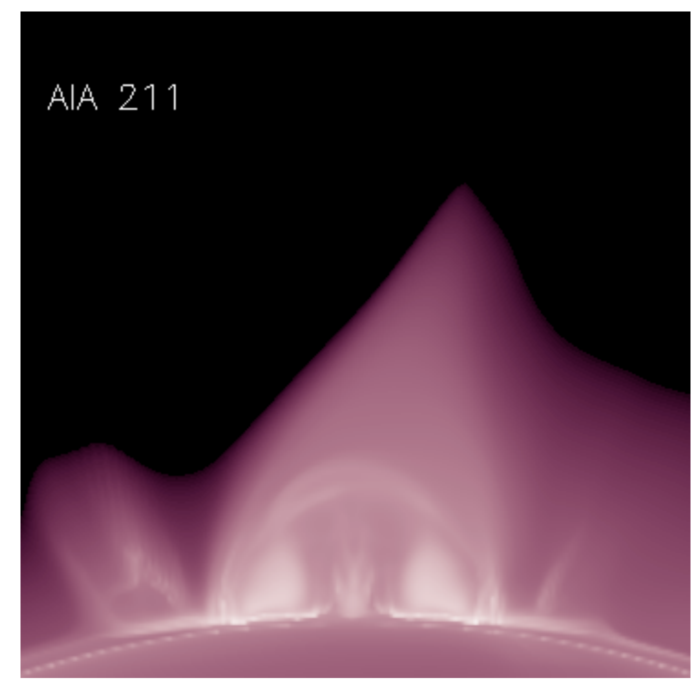


rope inserted



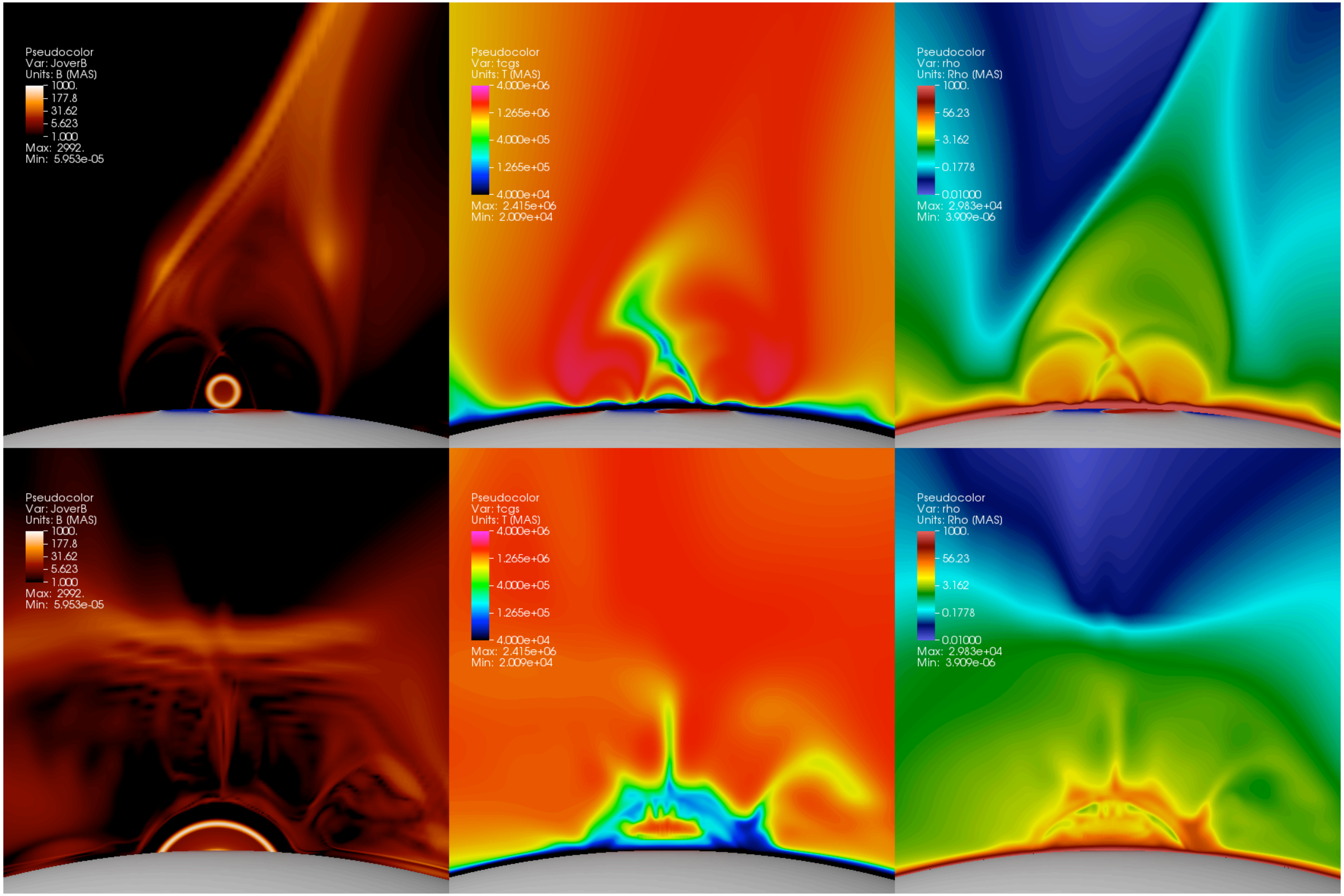
wave triggered





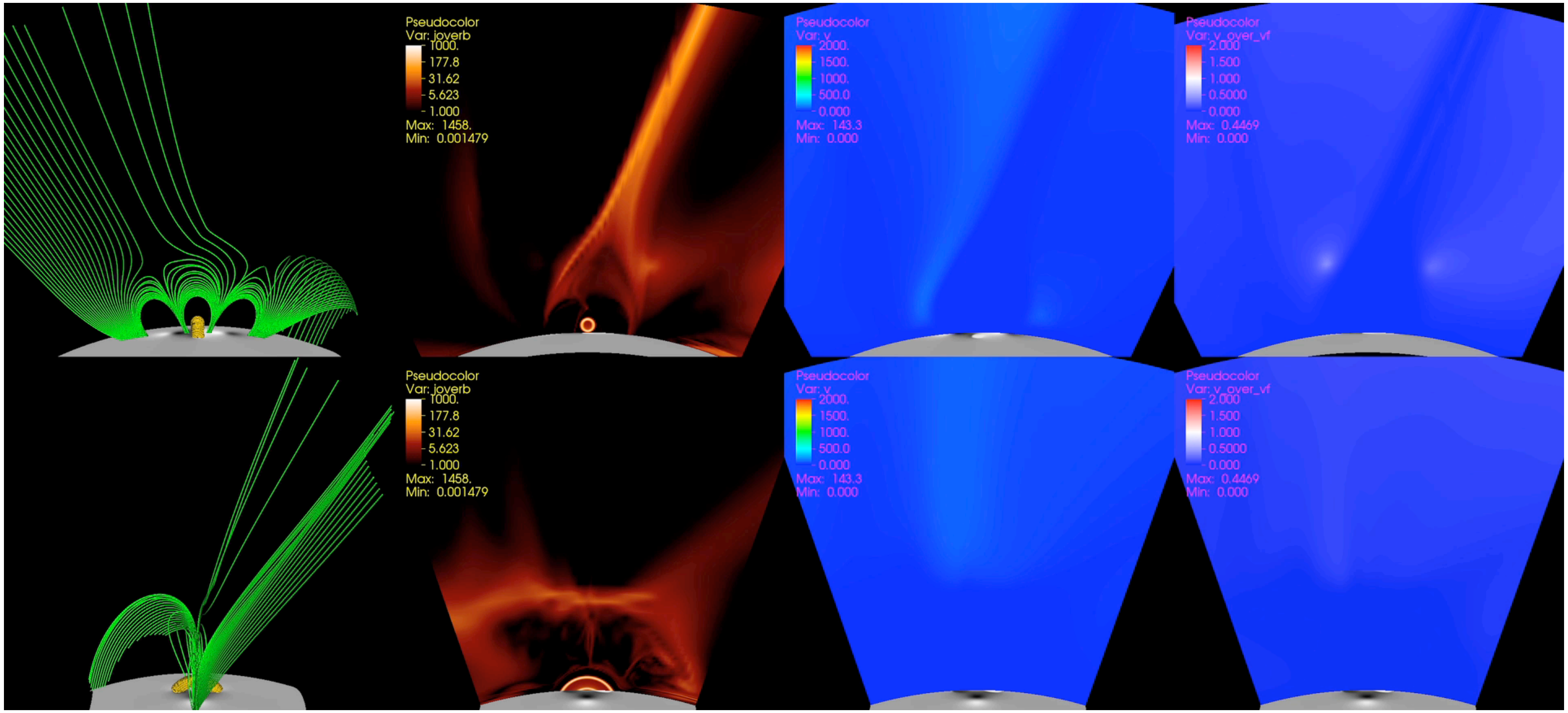
- presently: simple superposition of corona and rope
- problem: perturbation triggers fast (1000 km/s) wave

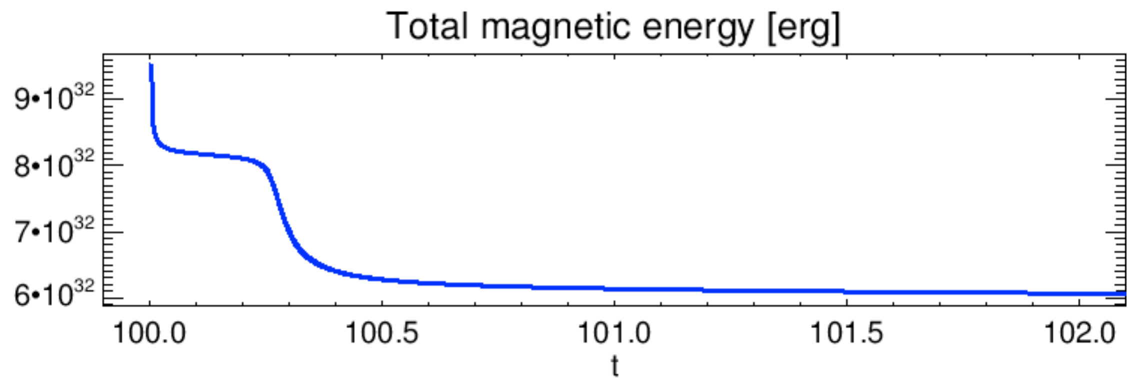
Relaxation after flux rope insertion; flux rope current I = 1.6 * I_eq

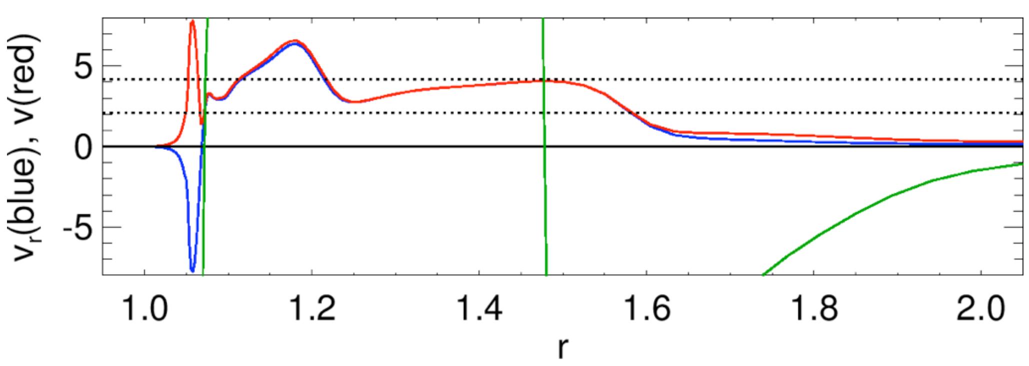


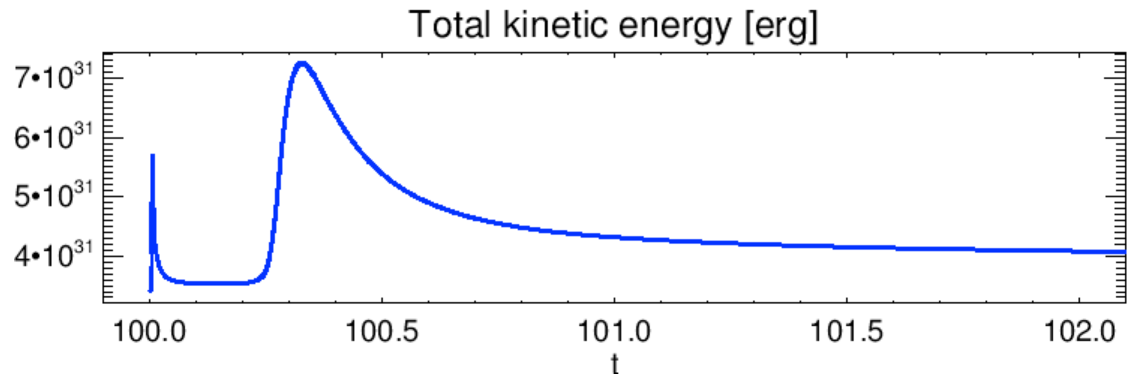
- (apparently) stable flux rope + "prominence" formation (condensation ?)
- problem: imposing converging flows (so far) leads to numerical instabilities

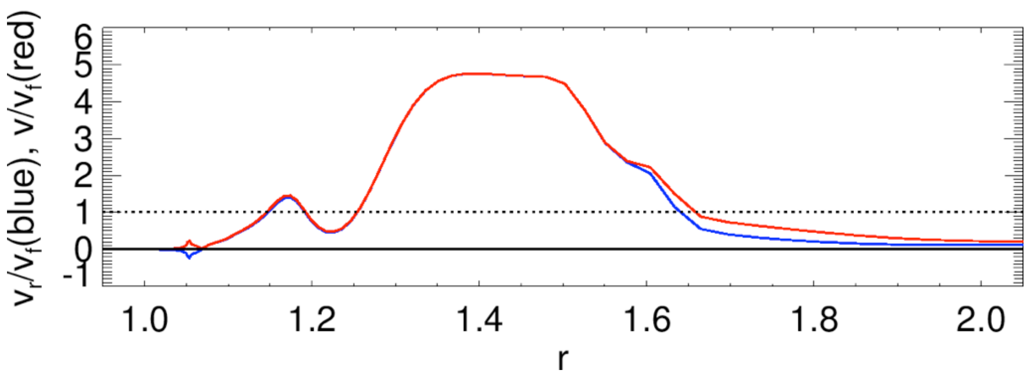
Supercritical current: I = 2.2 * I_eq



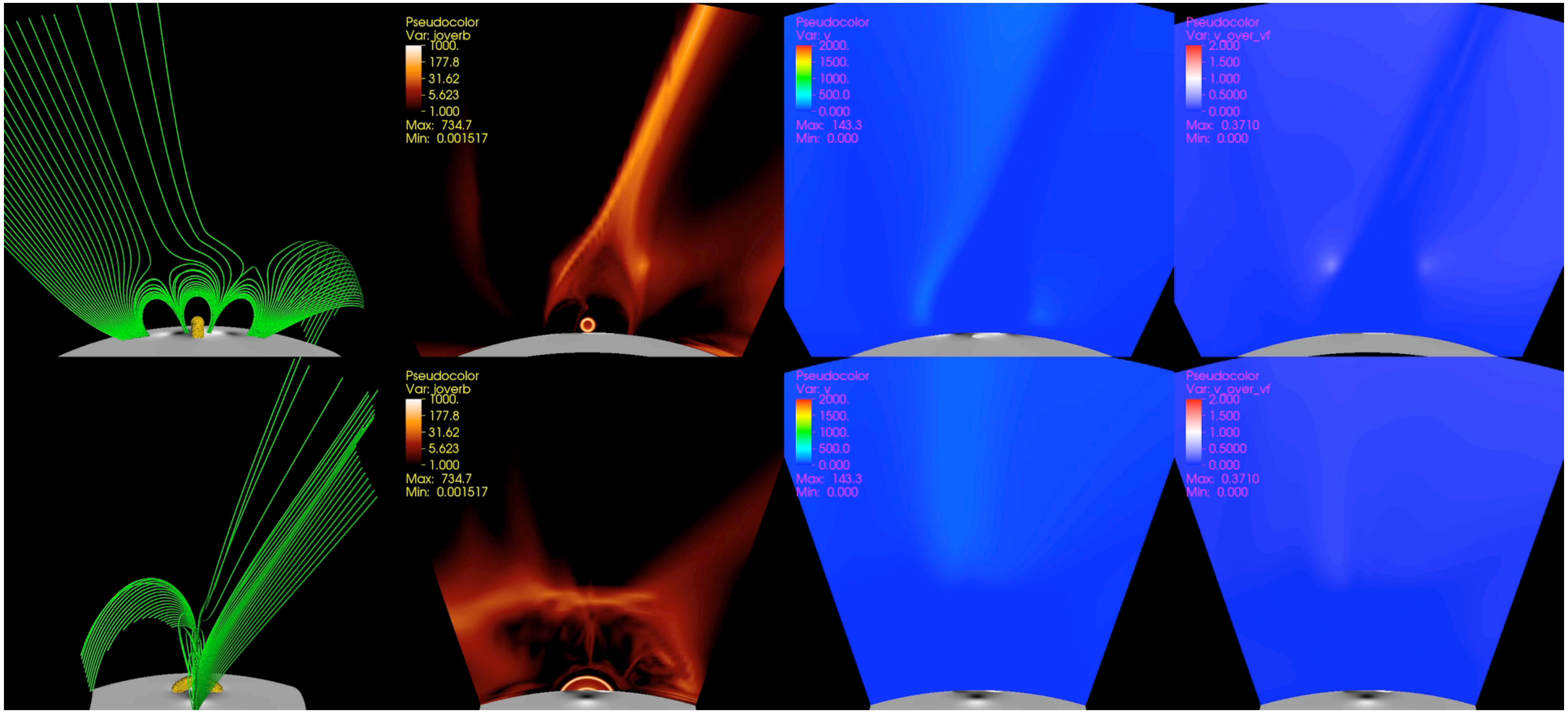


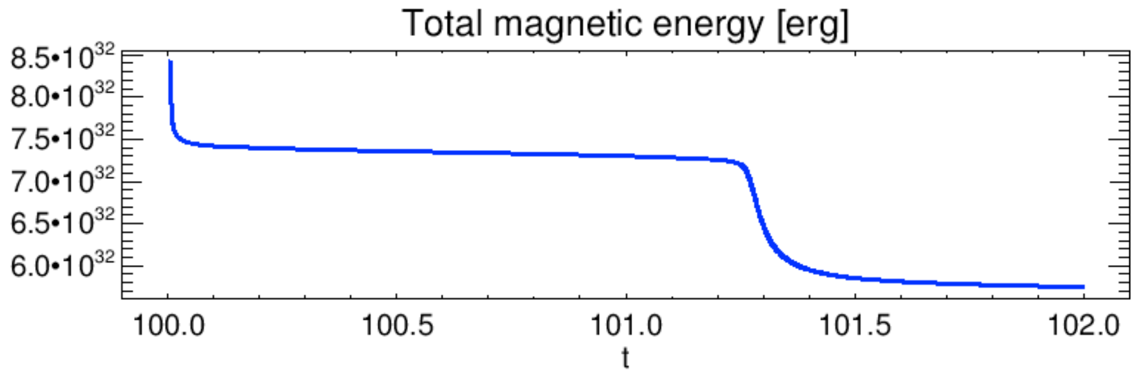


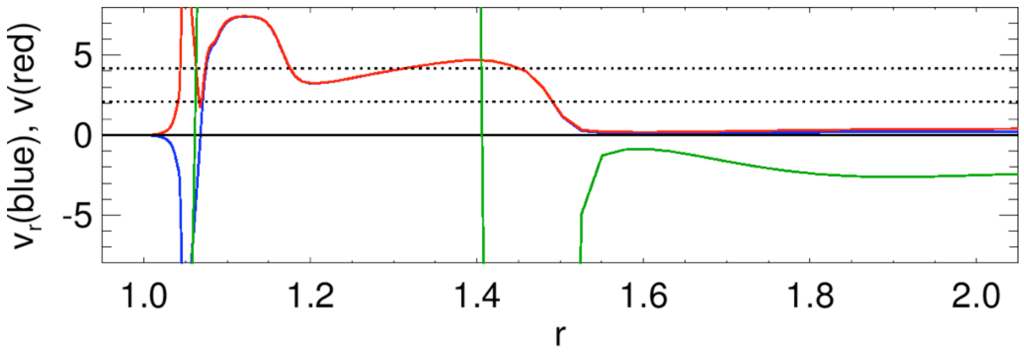


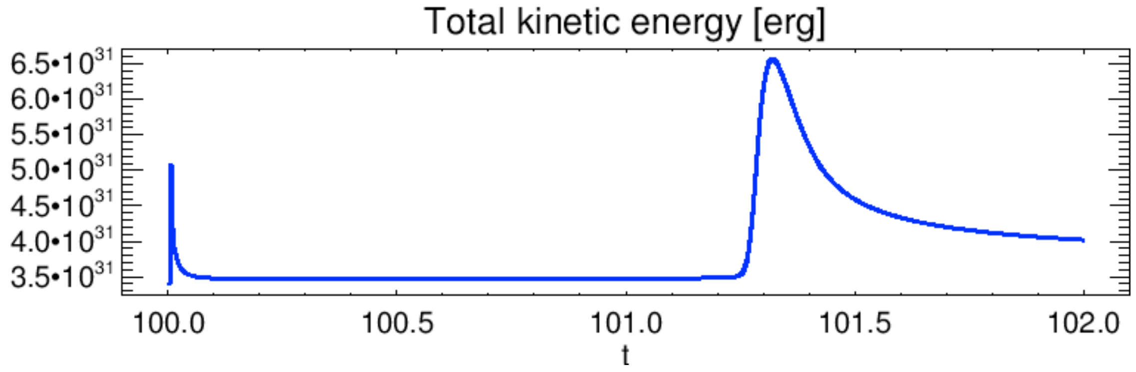


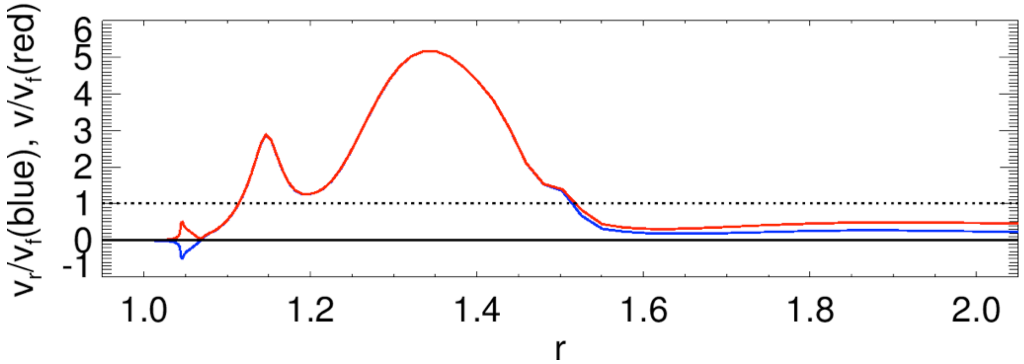
Smaller supercritical current: I = 2.0 * I_eq (eruption onset delayed !)



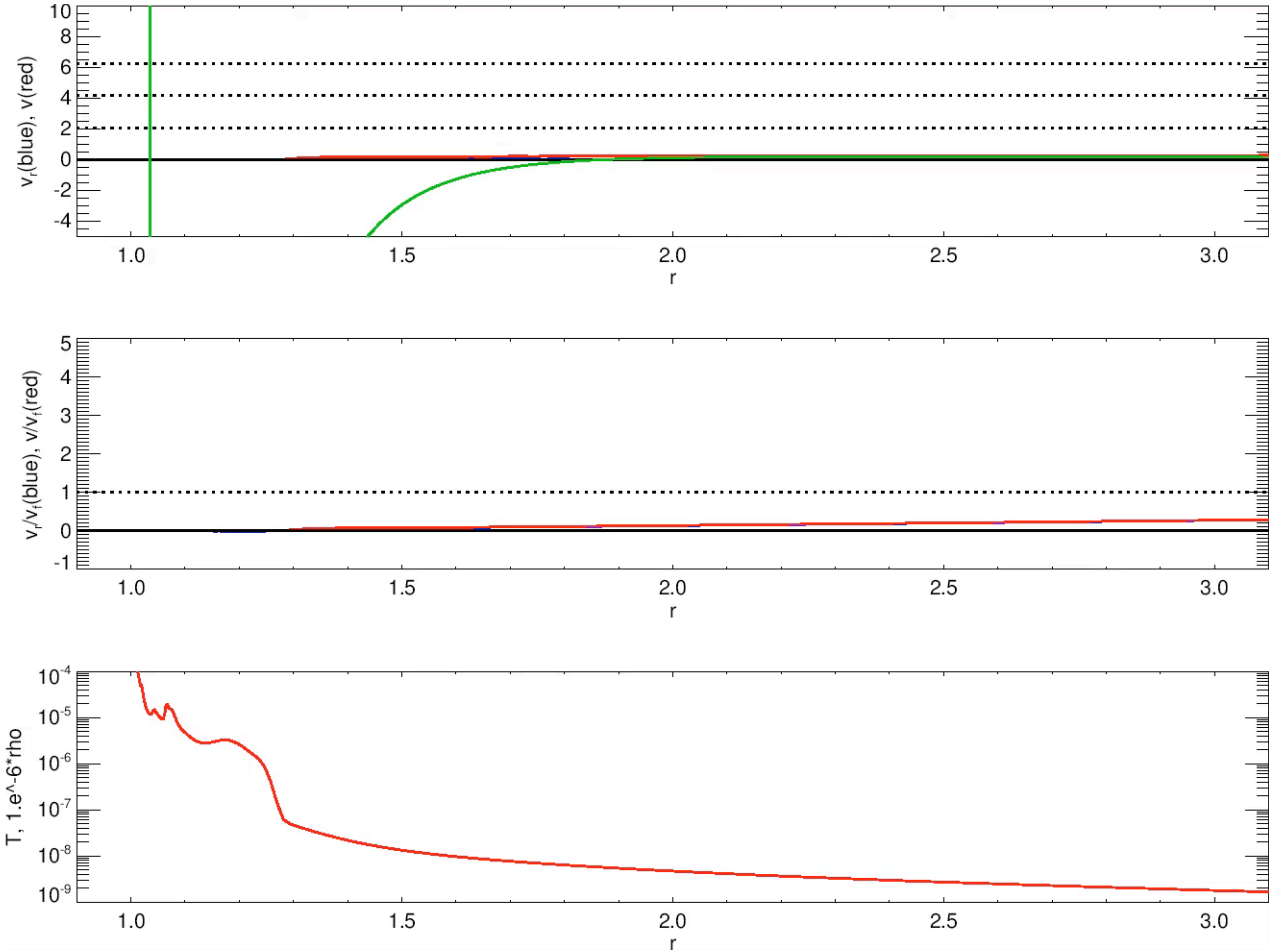




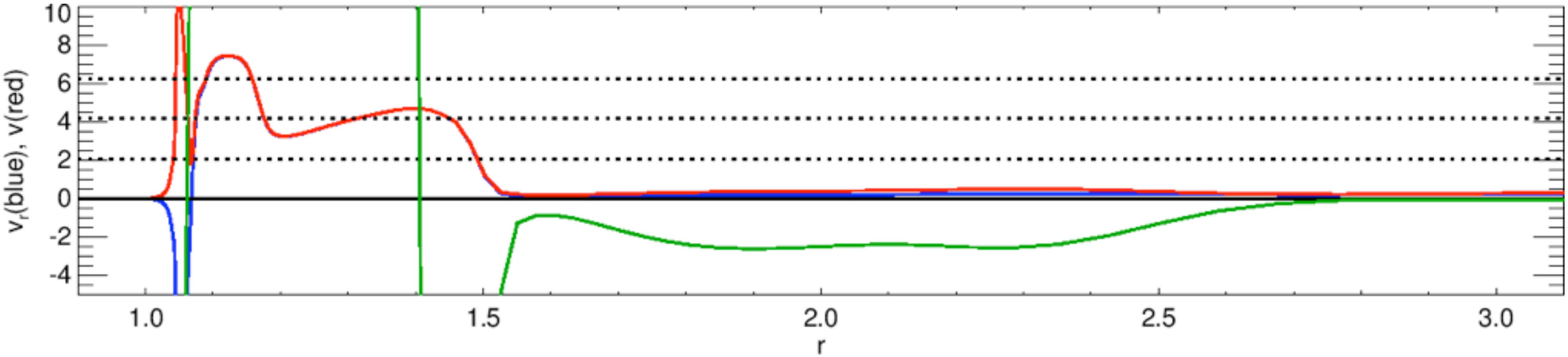


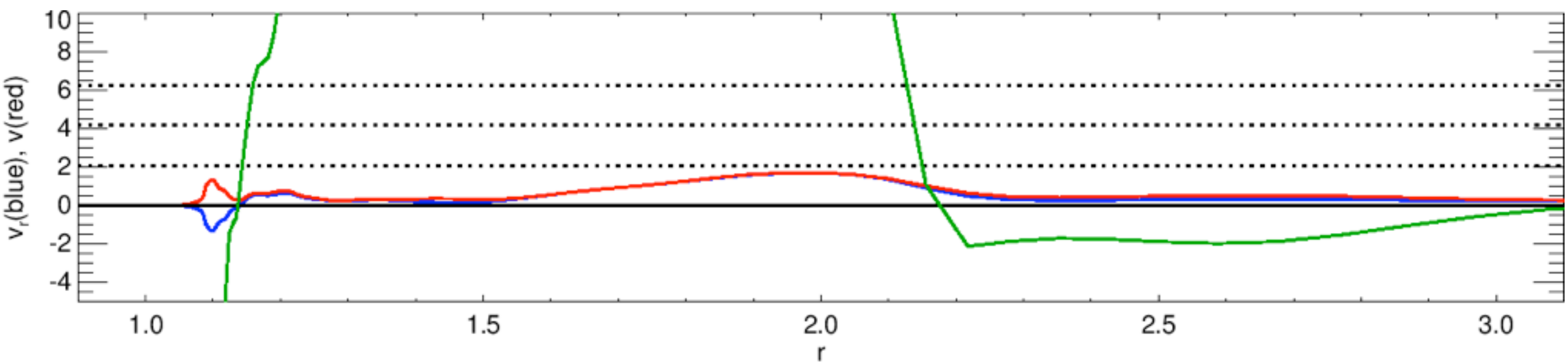


Speed and density (l = 2.0 * l_eq)



Deceleration (I = 2.0 * I_eq)

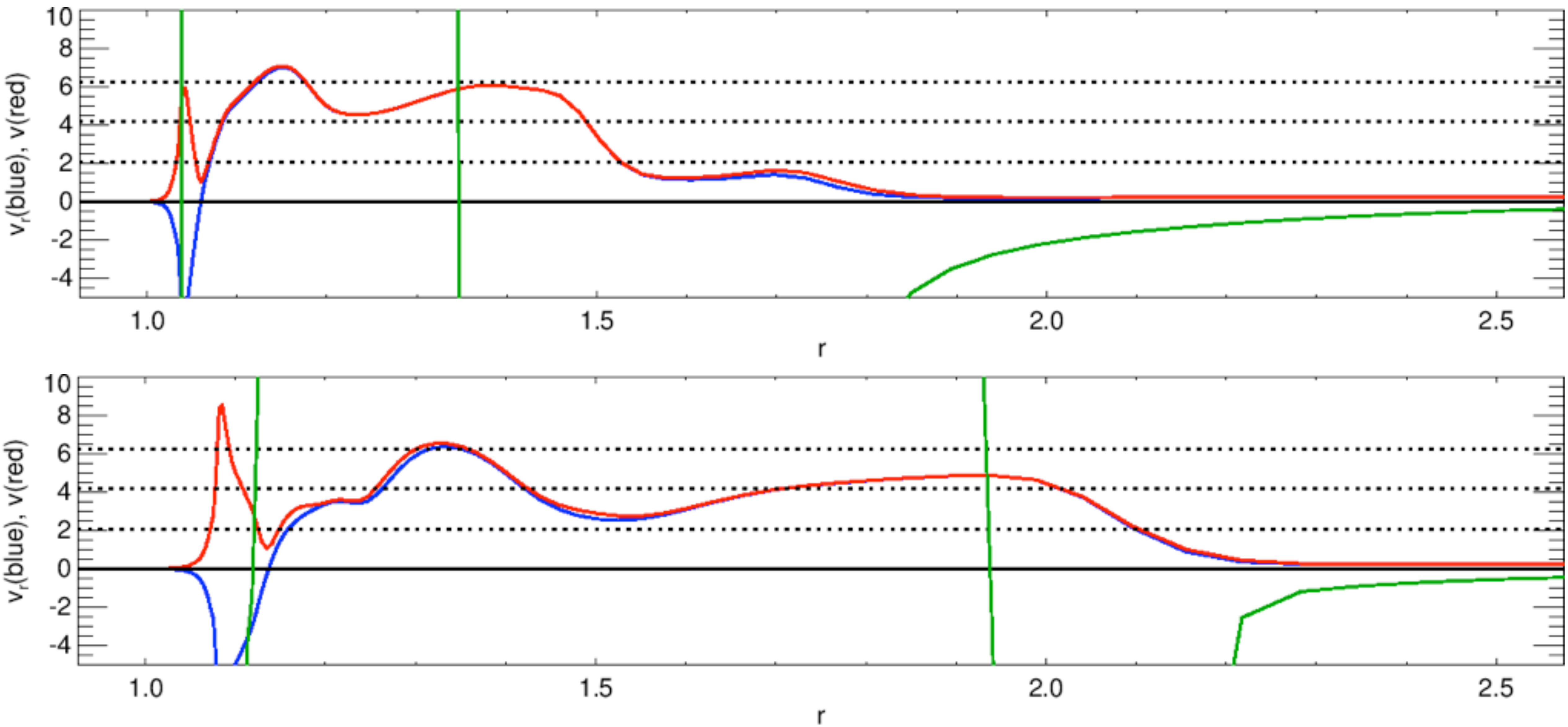




CME core at 1.4 R_sun: v > 2000 km/s

CME core at 2.0 R_sun: v < 1000 km/s

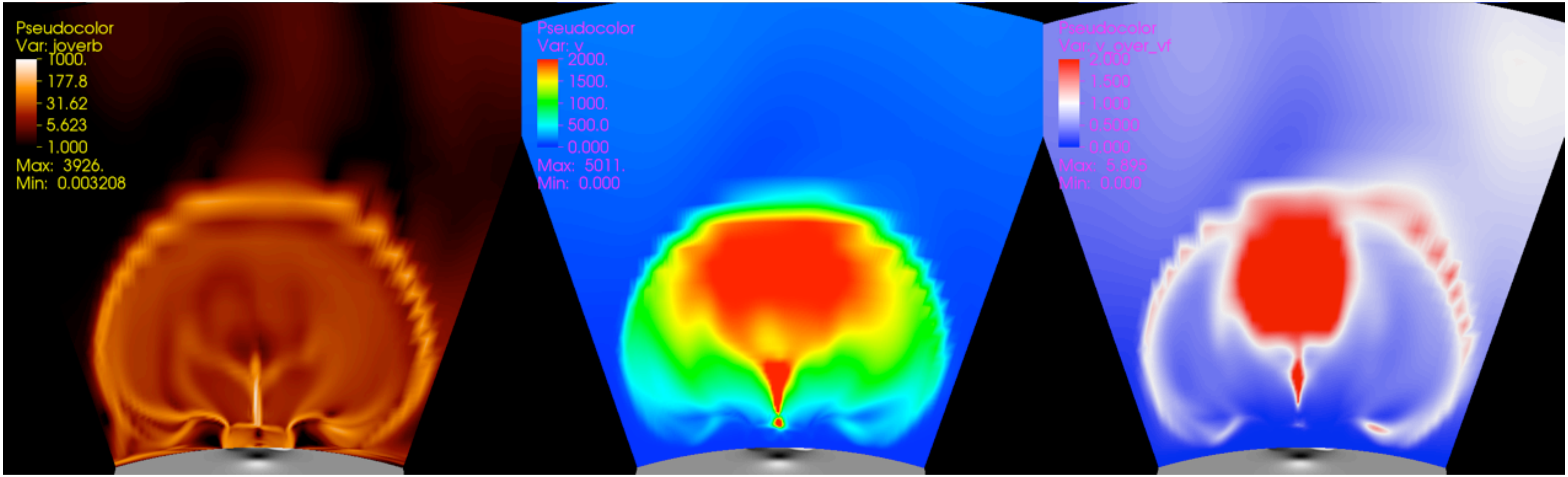
More compact rope (located lower down & supercritical I = 4.6 * I_eq)



CME core at 1.4 R_sun: v = 3000 km/s

CME core at 2.0 R_sun: v = 2000 km/s

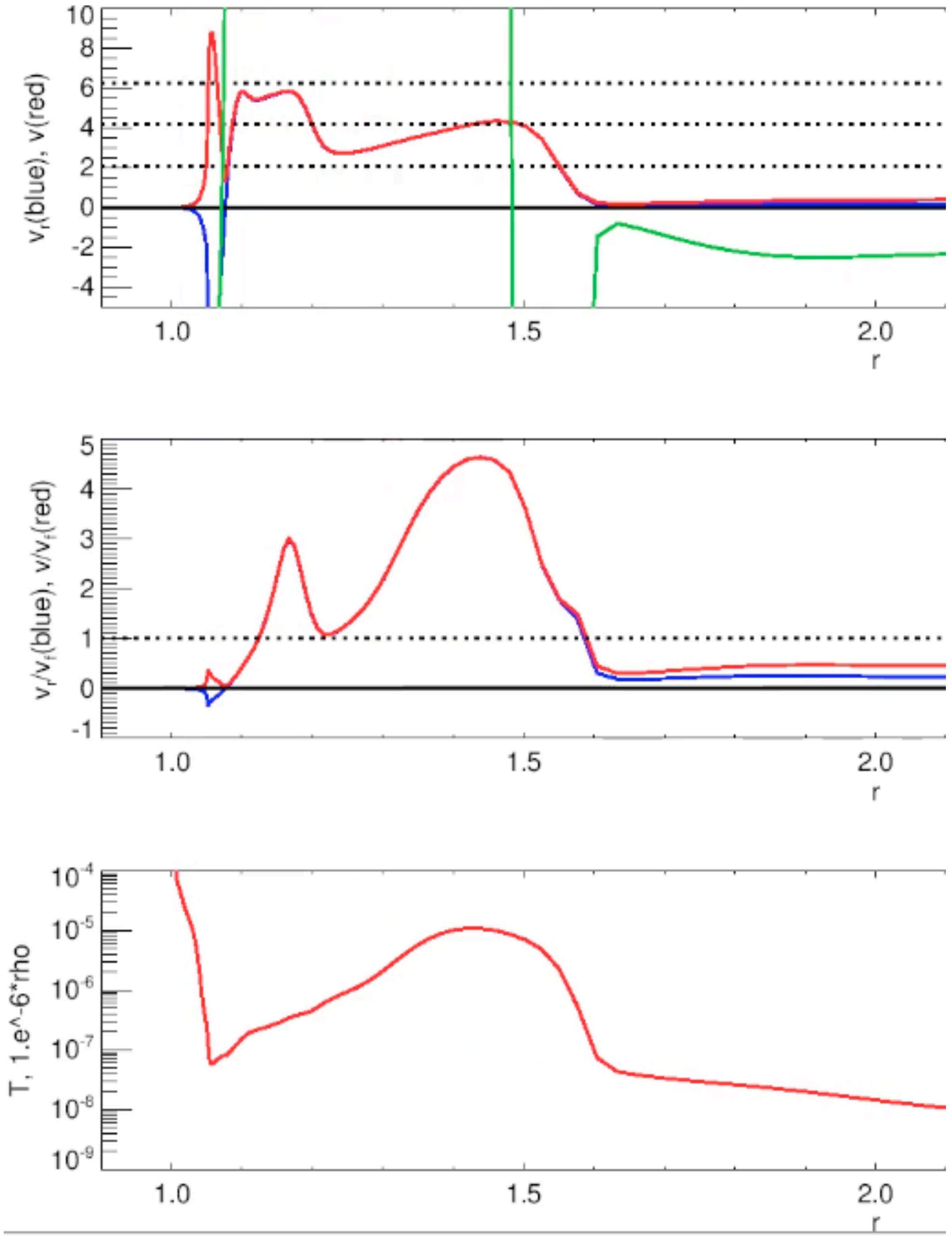
Summary: I = 2.0 * I_eq



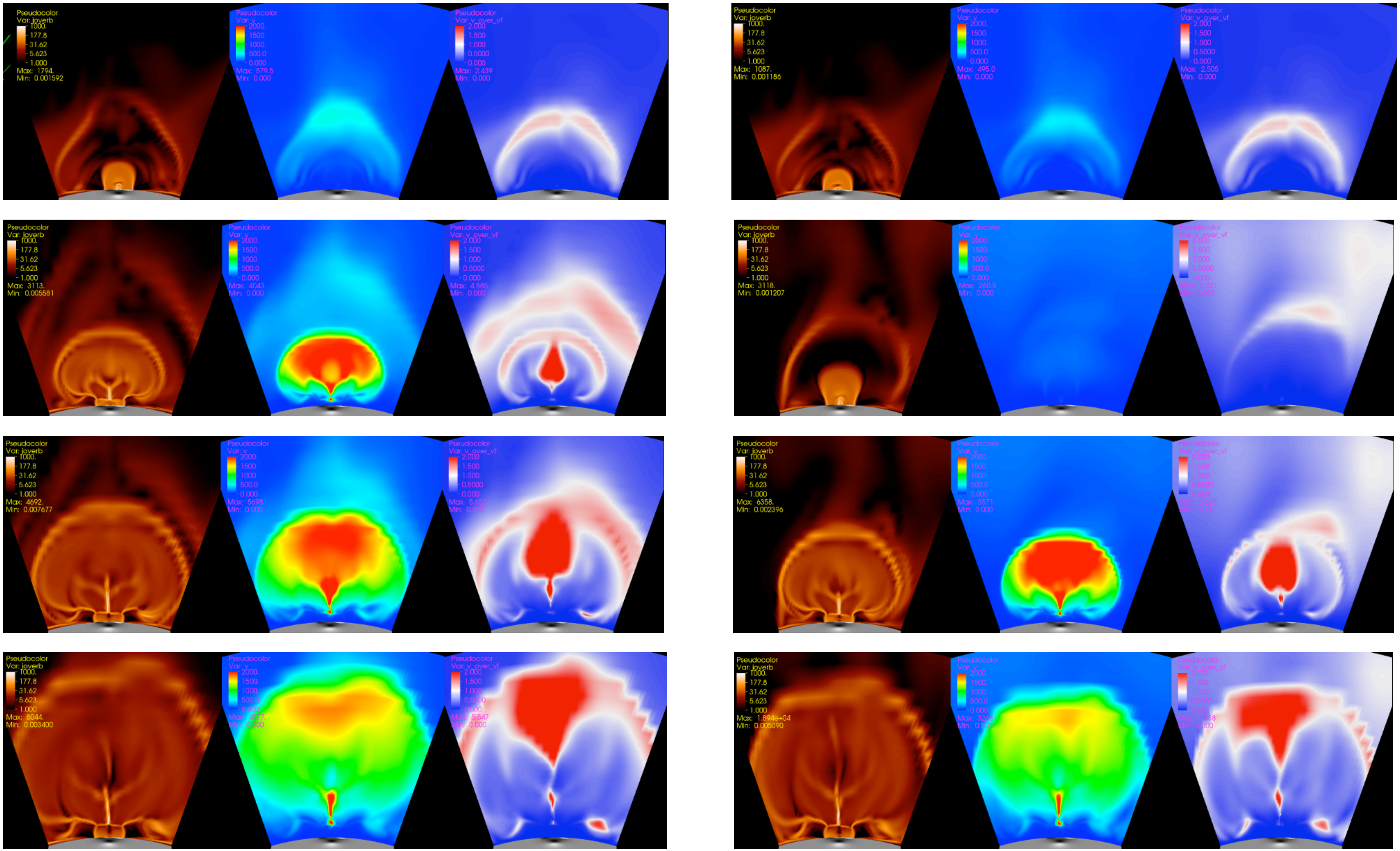
- max. CME speed > 2000 km/s → produces shock (but CME slows down)
- magnetic energy release ≈ 1.6 * 10^32 ergs
- B_max ≈ 600 G
- AR flux ≈ 2 * 10^22 Mx

(still relatively small numbers compared to largest observed events)

Problem: shock not well resolved



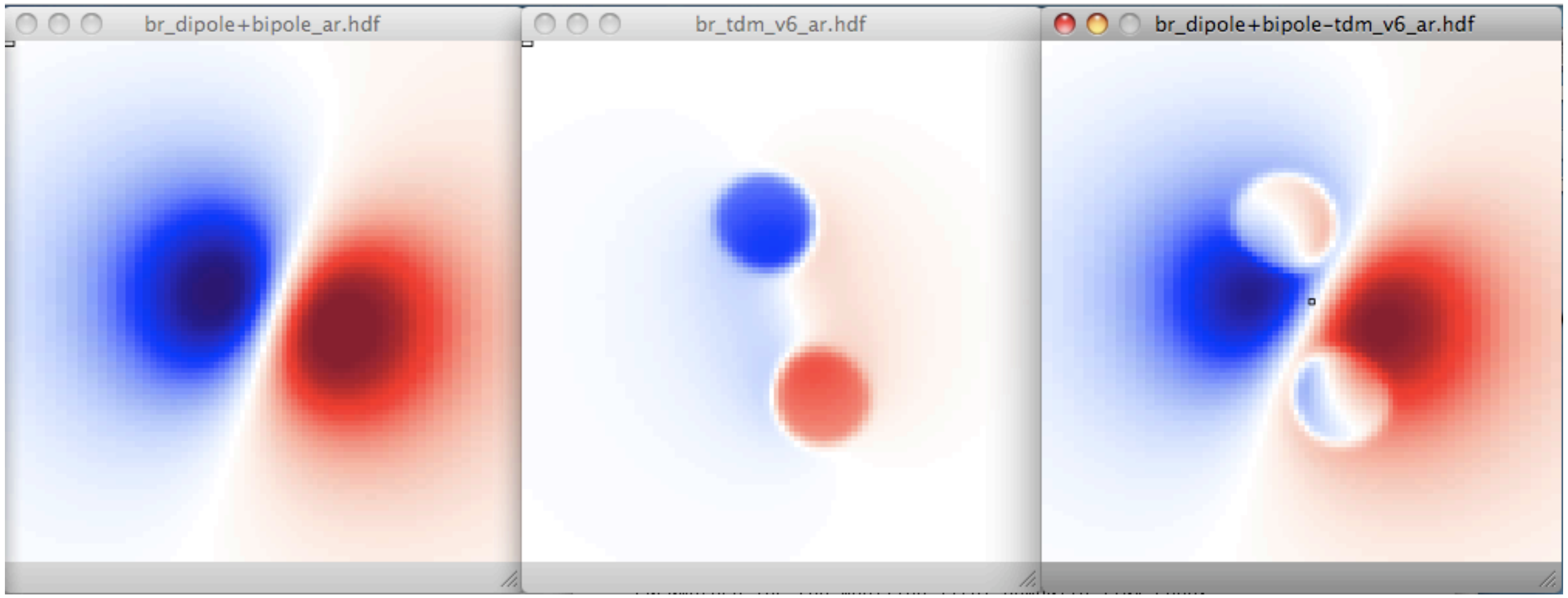
Problem: perturbation (wave) after flux rope insertion

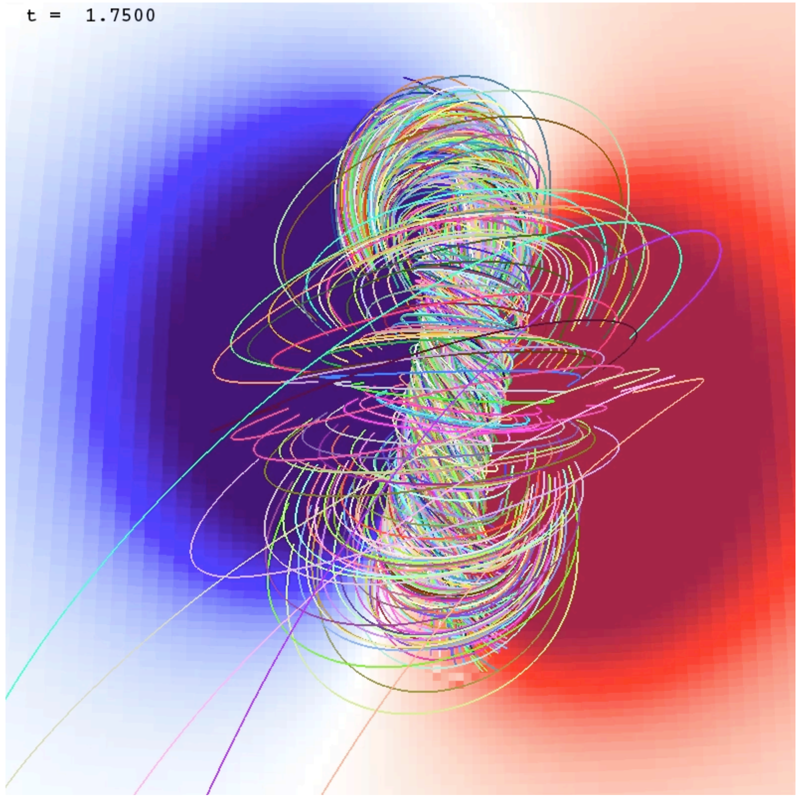


I = 2.2 * I_eq

I = 2.0 * I_eq

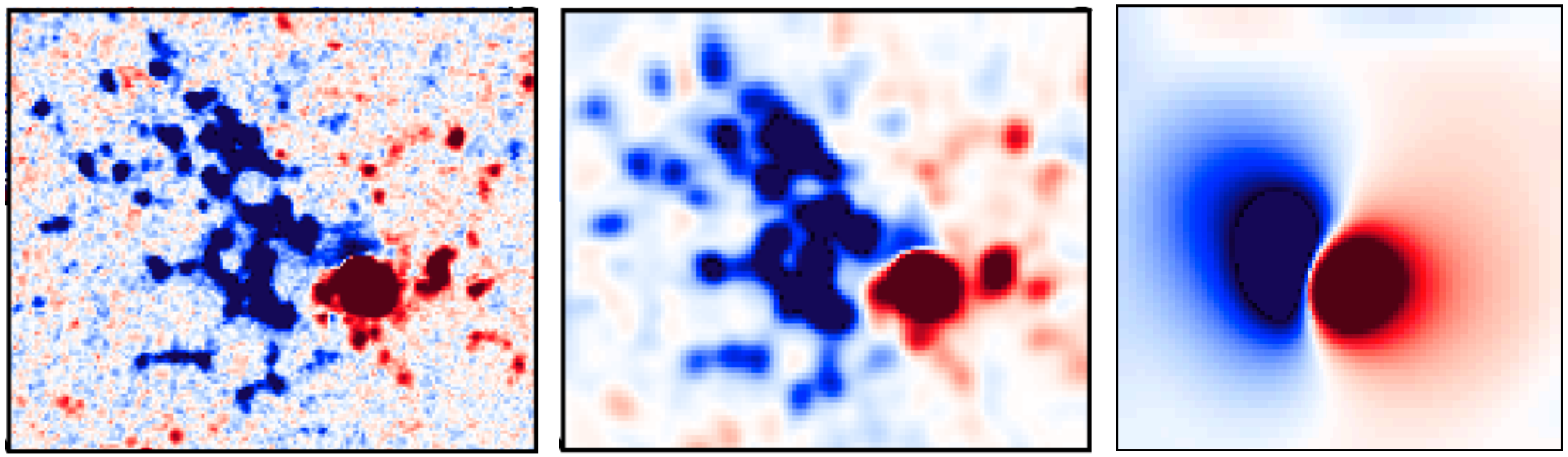
Problem: preserving original magnetogram



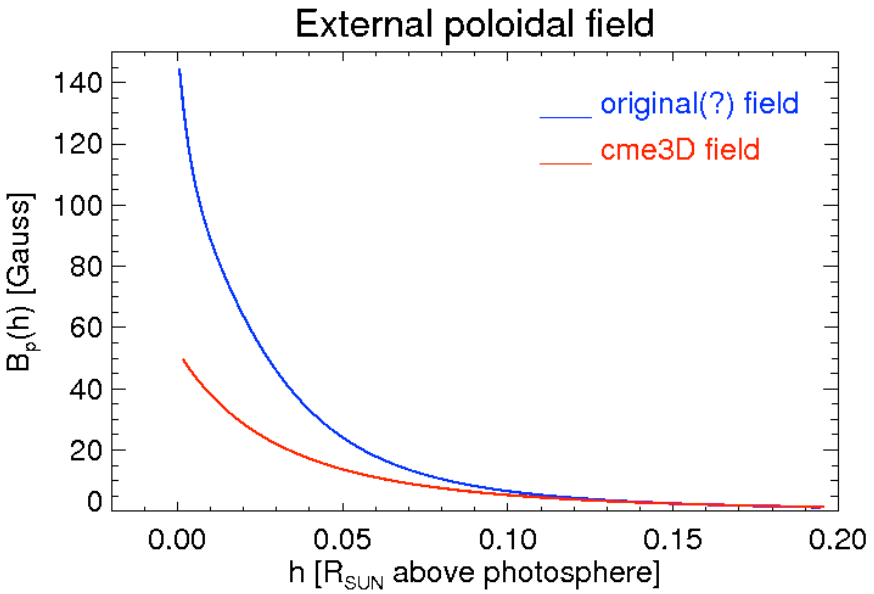


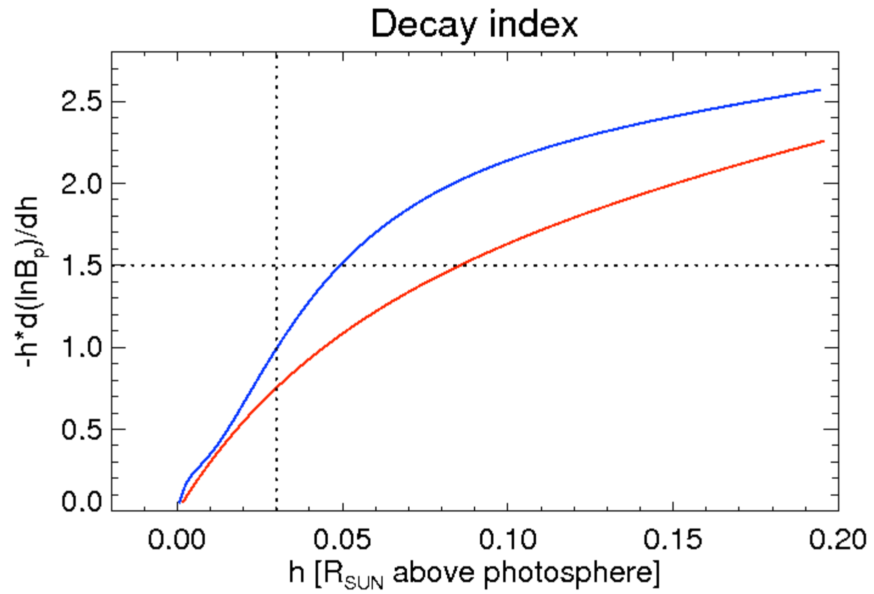
- simple superpositon of flux rope and coronal field changes magnetogram
- modeling real events requires to preserve magnetogram
- we have started to work on this (using a method similar to van Ballegooijen's)

Problem: proper modeling of overlying field decay



May 12, 1997





- simplification (smoothing) of magnetogram typically decreases decay index

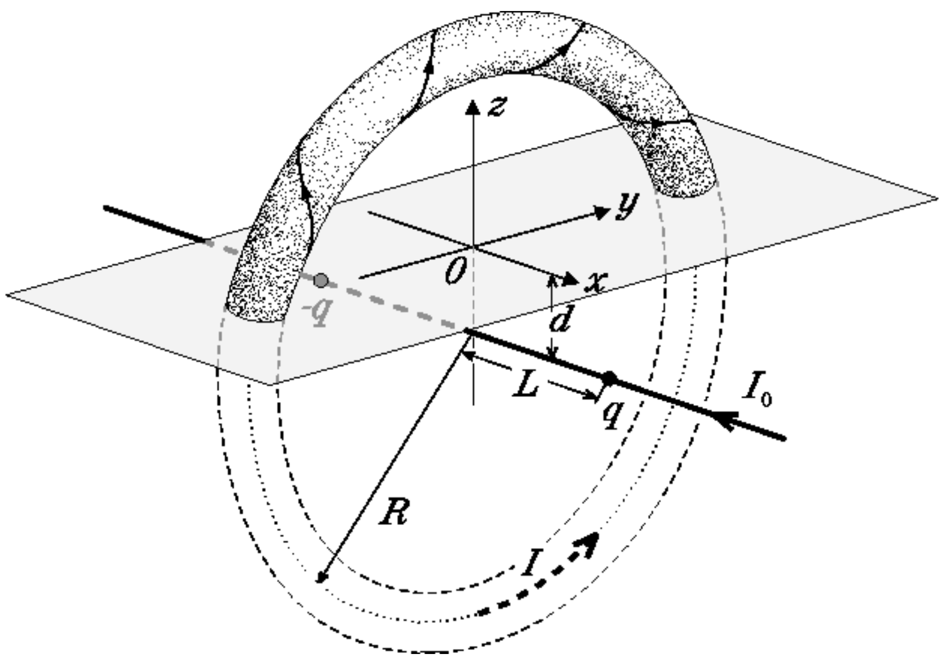
→ simulated eruption will be too slow !

Next steps

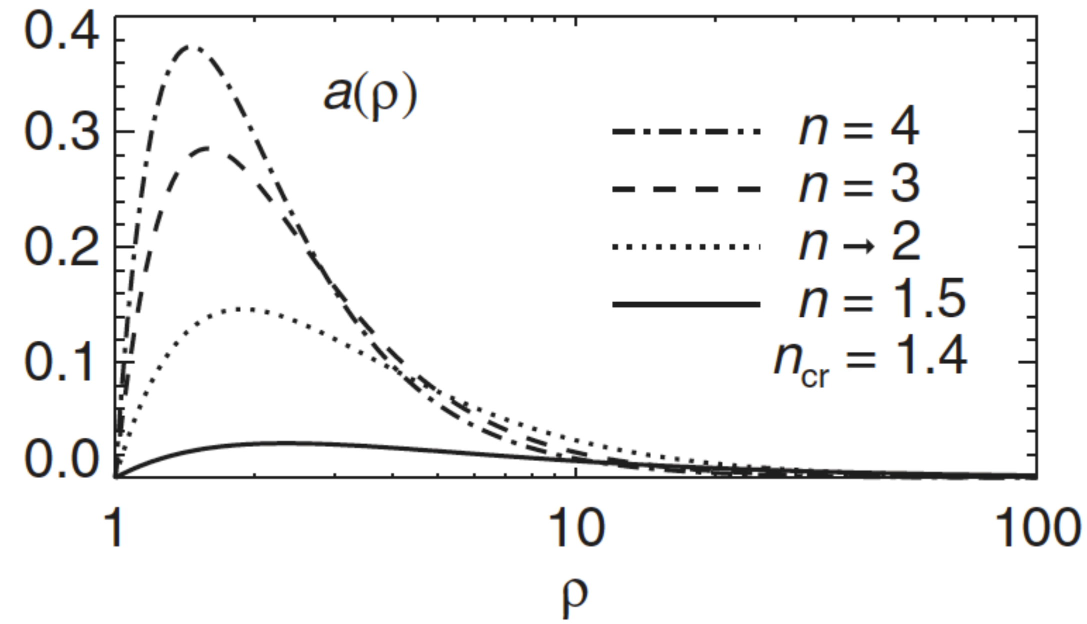
- better grid resolution (numerics easier; shock & CME propagation better resolved)
- start eruption from fully relaxed flux rope (converging flows)
- use stronger AR fields → faster eruption & less deceleration ?
- improve flux rope insertion → avoid initial perturbation & magnetogram changes
- study influence of decay index & compactness using different configurations
- use observed magnetogram & model real event

Backup slides

Torus instability



Titov & Démoulin (1999)



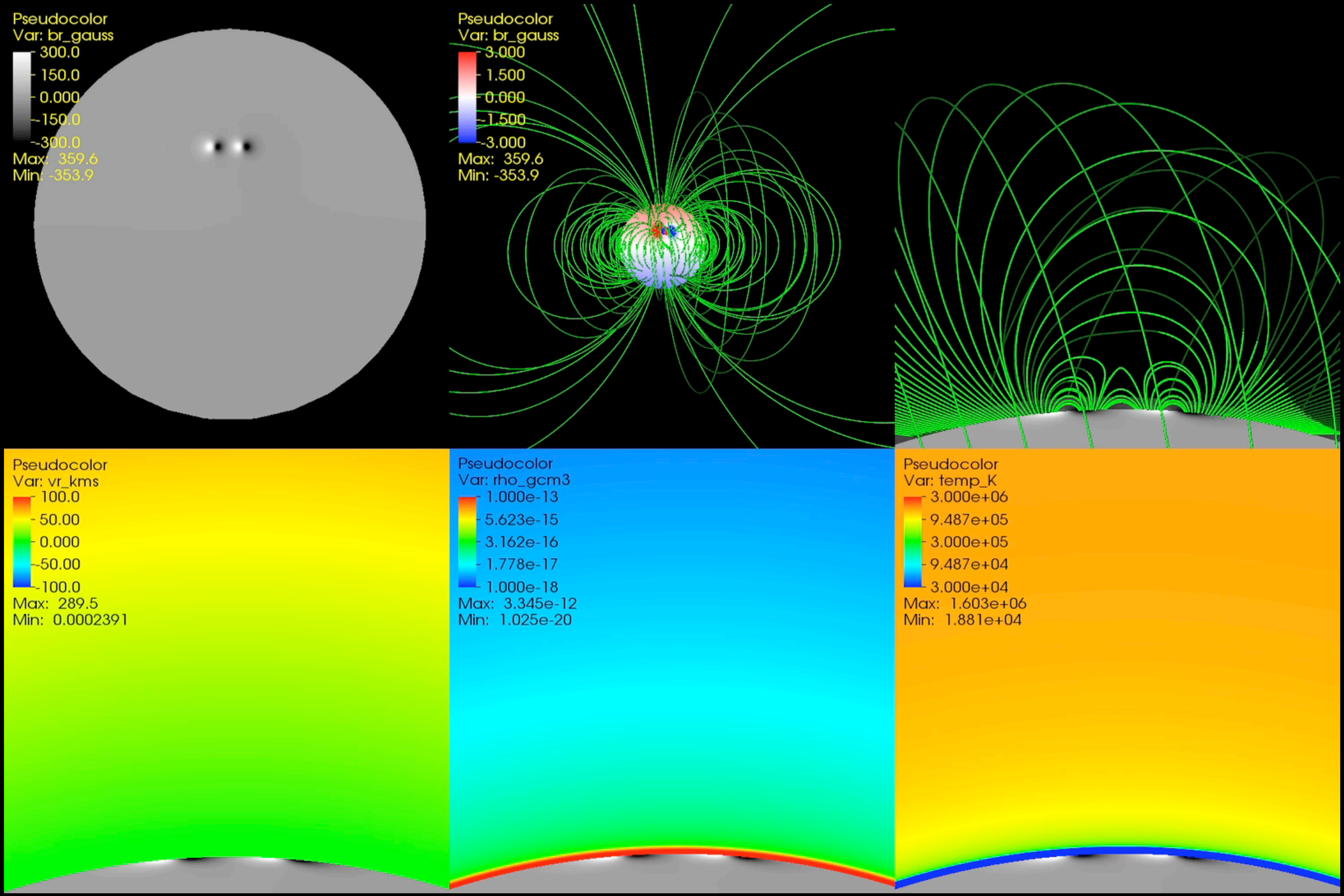
Kliem & Török (2006)

- ideal MHD instability; occurs if overlying field drops sufficiently fast with height

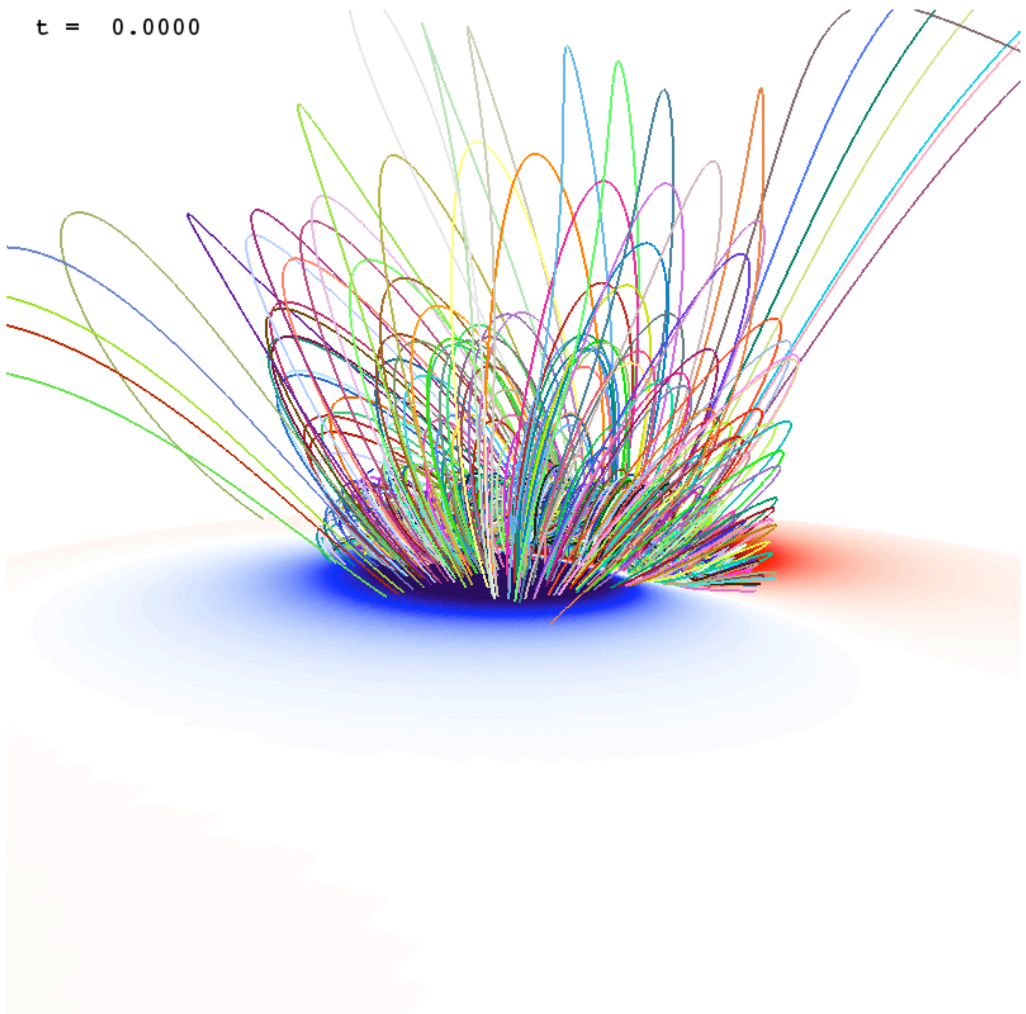
- acceleration profile depends on decay index $n = -h\, d(\ln B)/dh$ of overlying field:

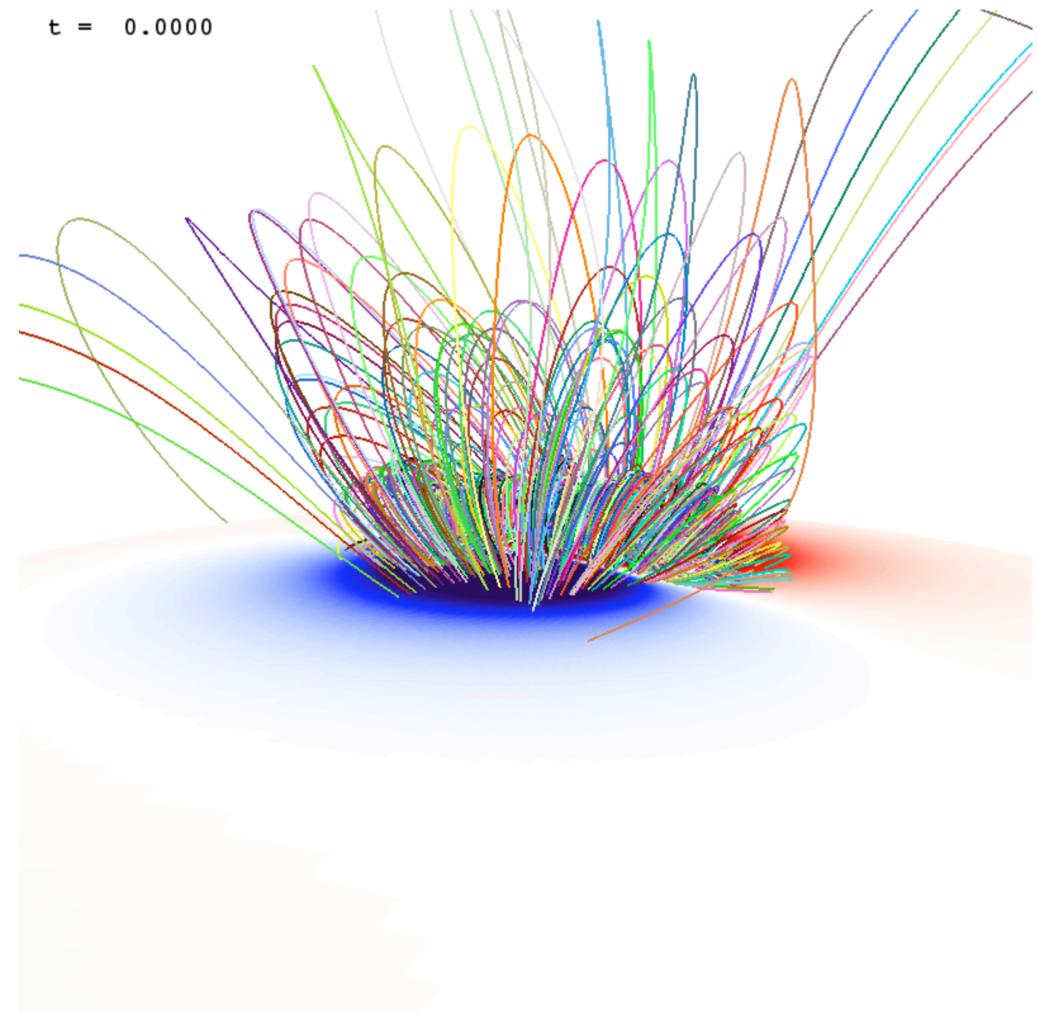
  $n \approx 1.5$ (quiet Sun): weak & long-lasting acceleration (gradual)

  $n > 2$ (active regions): strong & short acceleration (impulsive)


Pseudocolor
Var: br_gauss
300.0
150.0
0.000
-150.0
-300.0
Max: 359.6
Min: -353.9
Pseudocolor
Var: br_gauss
3.000
1.500
0.000
-1.500
-3.000
Max: 359.6
Min: -353.9
Pseudocolor
Var: vr_kms
100.0
50.00
0.000
-50.00
-100.0
Max: 289.5
Min: 0.0002391
Pseudocolor
Var: rho_gcm3
1.000e-13
5.623e-15
3.162e-16
1.778e-17
1.000e-18
Max: 3.345e-12
Min: 1.025e-20
Pseudocolor
Var: temp_K
3.000e+06
9.487e+05
3.000e+05
9.487e+04
3.000e+04
Max: 1.603e+06
Min: 1.881e+04

Problem: asymmetry of ambient field





- configuration very sensitive to asymmetries of ambient field
- needs to be improved ...