Space weather applications using MHD

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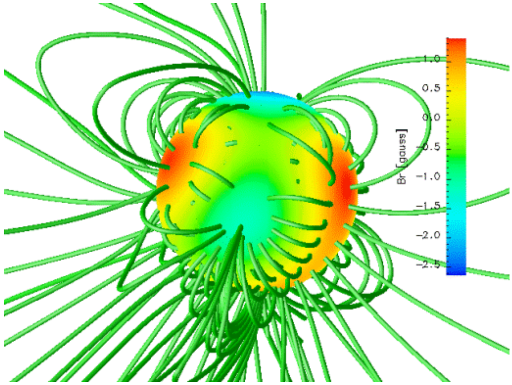
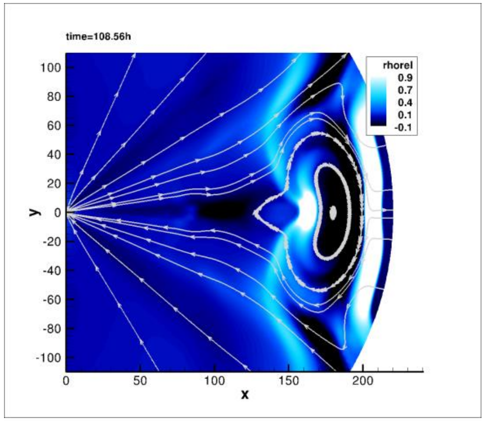
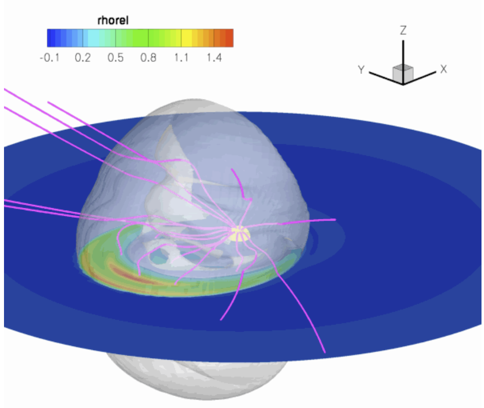
Outline

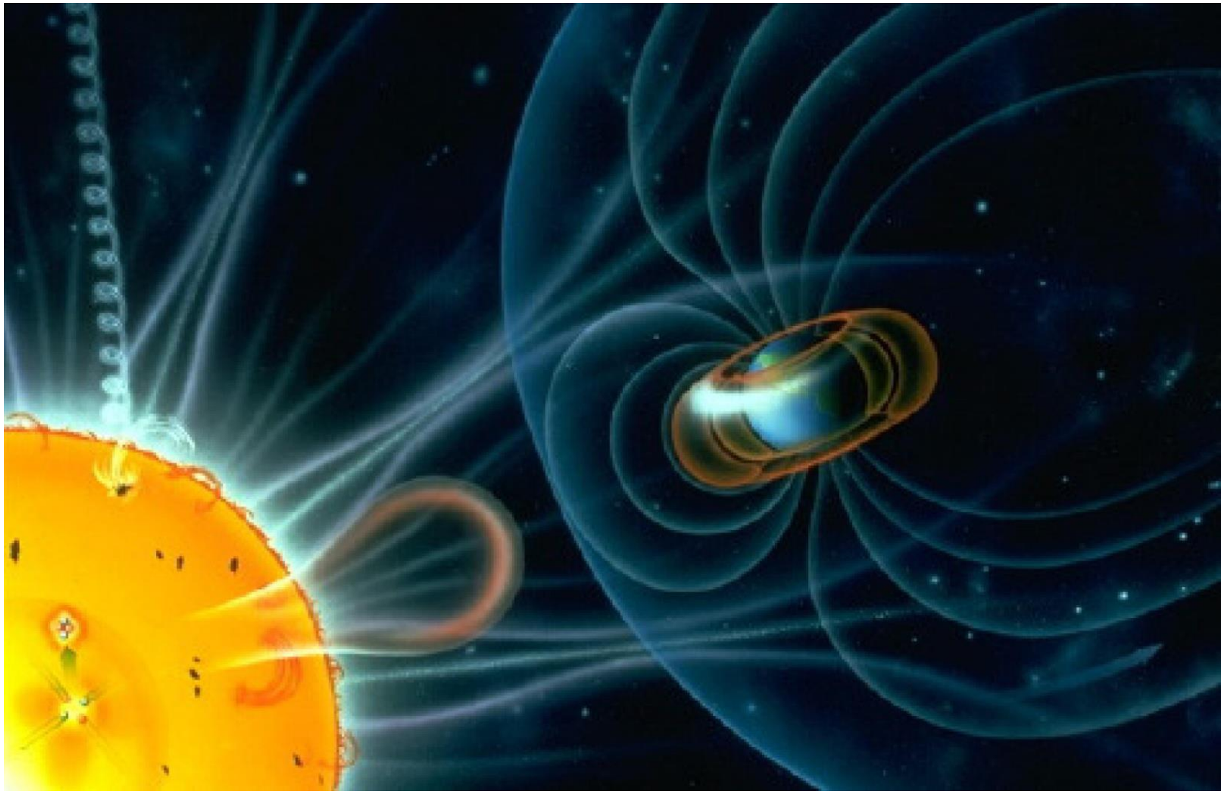
- **Motivation**
- **2.5D vs 3D models**
- **Self-consistent 2.5D break-out models**
  - **Symmetric shearing**
    - *Homologous CMEs*
  - **Asymmetric shearing & flux emergence**
    - *Parameter studies*
    - *Event studies: CME deflection*
    - *Event studies: sympathetic CMEs*
- ***Euhforia: 3D heliospheric model***
    - *Data-driven solar wind model*
    - *CME model(s)*
- ***Conclusions***







‘Space Weather’



cf. USA NSWP

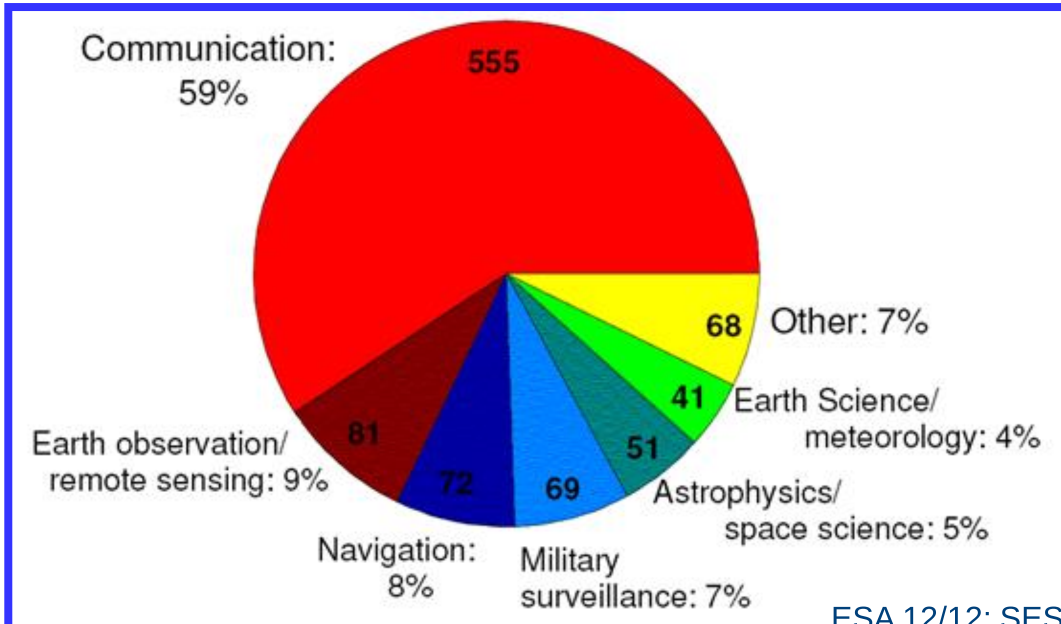
Strategic Plan:

“Space Weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.”

Damage to satellites

Courtesy: E. Daly

Total number of operating satellites: 1046			
LEO: 503	MEO: 73	Elliptical: 38	GEO: 432



- “replacement value of ~$B 170-230, and support-ing a ~$B 90/year industry”
- once in 100 yr (200 yr?) 1859 super-storm:
    - “potential economic loss of < $70 billion for lost revenue (~$44 billion) and satellite replacement for GEO satellites (~$24 billion);
    - 80 satellites (LEO, MEO, GEO) disabled;
    - Failure of many of [GNSS] satellite systems”

*Source: Forecasting the Impact of an 1859-calibre Superstorm on Satellite Resources: Odenwald, Green & Taylor, Advances in Space Research 2005

Space Weather has important eff...

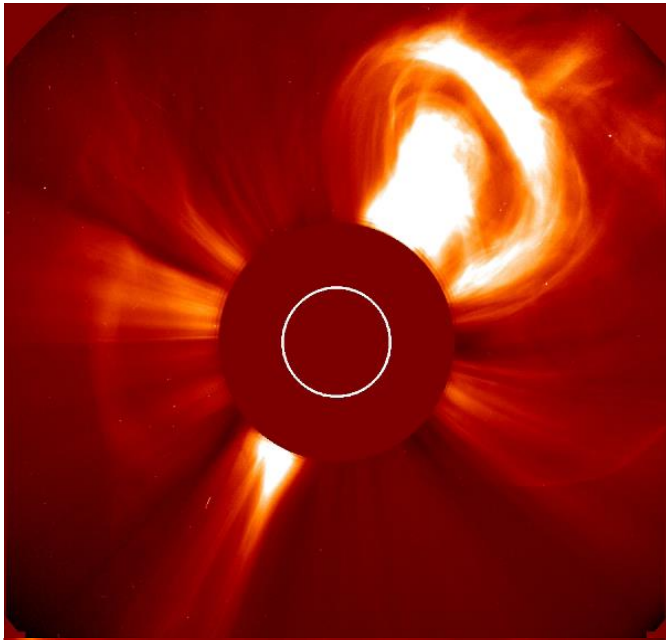
Effects of Space weather on Earth climate (change)?

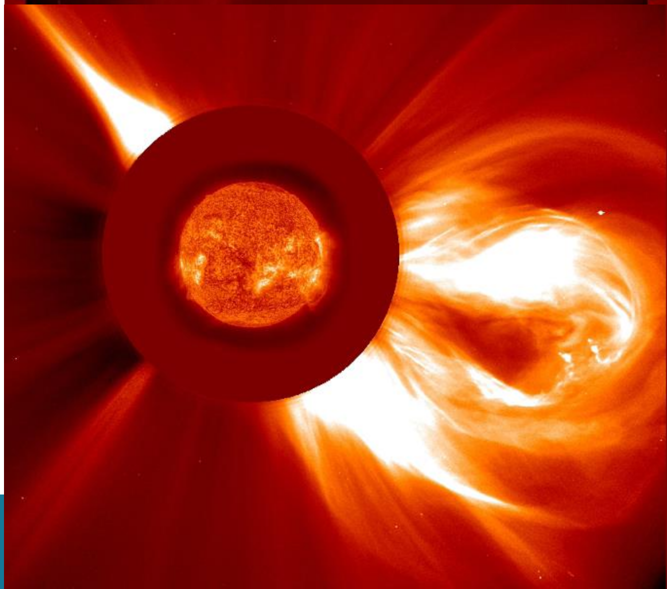
Estimate... ...mic losses: 10 b... ...year !
(estimates up to 1-2 ... first year after a severe storm like th... ...nov 2003*)

*cf. Severe Space Weather Events – Understanding Societal and Economic Impacts: A Workshop Report. The National Academies Press, 2008

Focus: KEY ROLE of CMEs

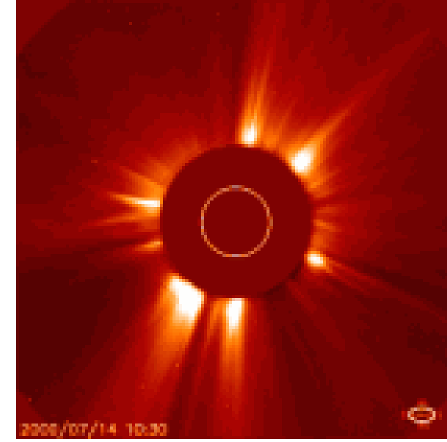
- **CMEs and solar flares are related**; ~75% of flares are associated with CMEs: they are both the result of a large-scale restructuring of the magnetic field
- CMEs interact with the solar wind and drive shock waves
- These shock waves accelerate charged particles
- CMEs cause geomagnetic storms when they arrive at Earth
- CMEs pose radiation threat in the inner solar system





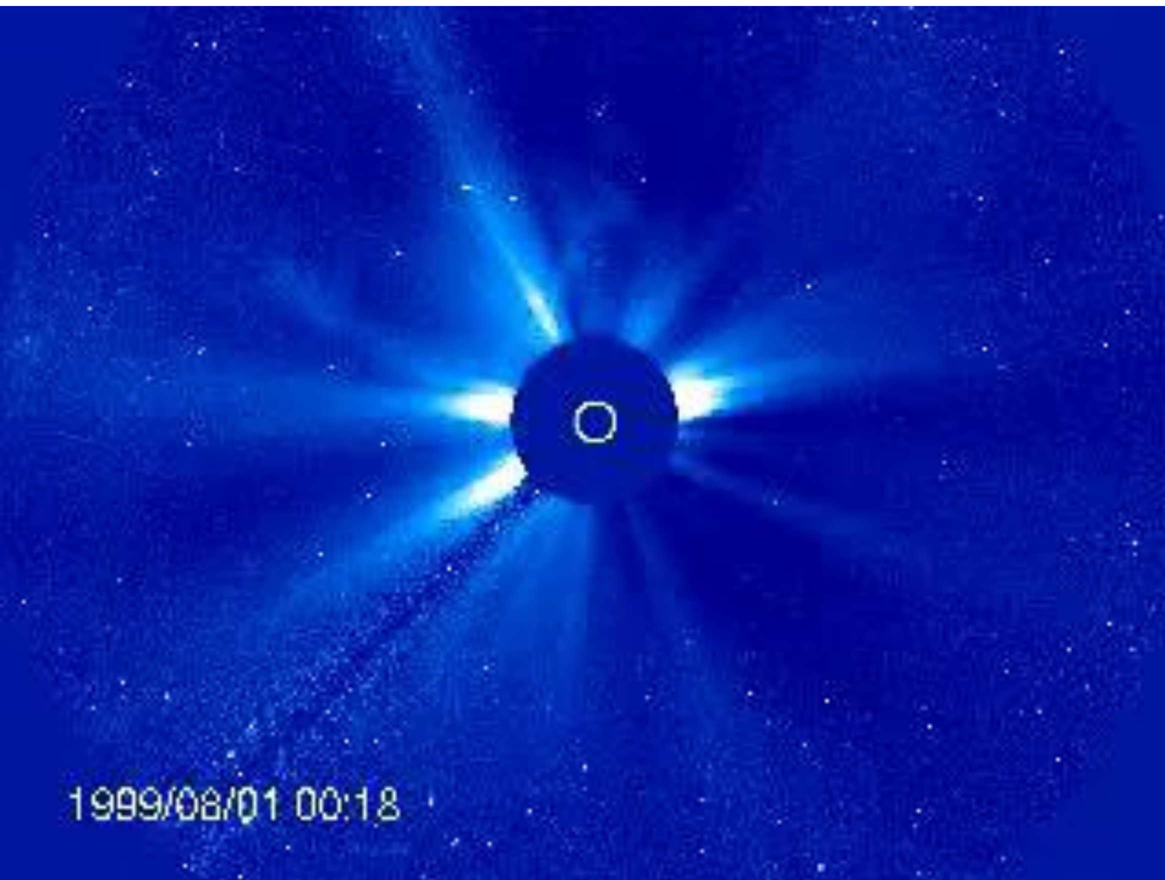
SoHO-Lasco C2

Solar flares and CMEs



When a CME is ejected in the direction of the Earth, we see a so-called 'halo event'

(about 10% of all the CMEs, more than 1 per week during solar maximum)



(halo) CMEs:

V_{cme} = 100 - 3000 km/s, typ. 450 km/s

Mass = 10^{13} - 10^{16} g

Bulk kinetic energy = 10^{27} - 10^{33} erg

(1st: OSO7 ('71) see Bruecker et al. '72)

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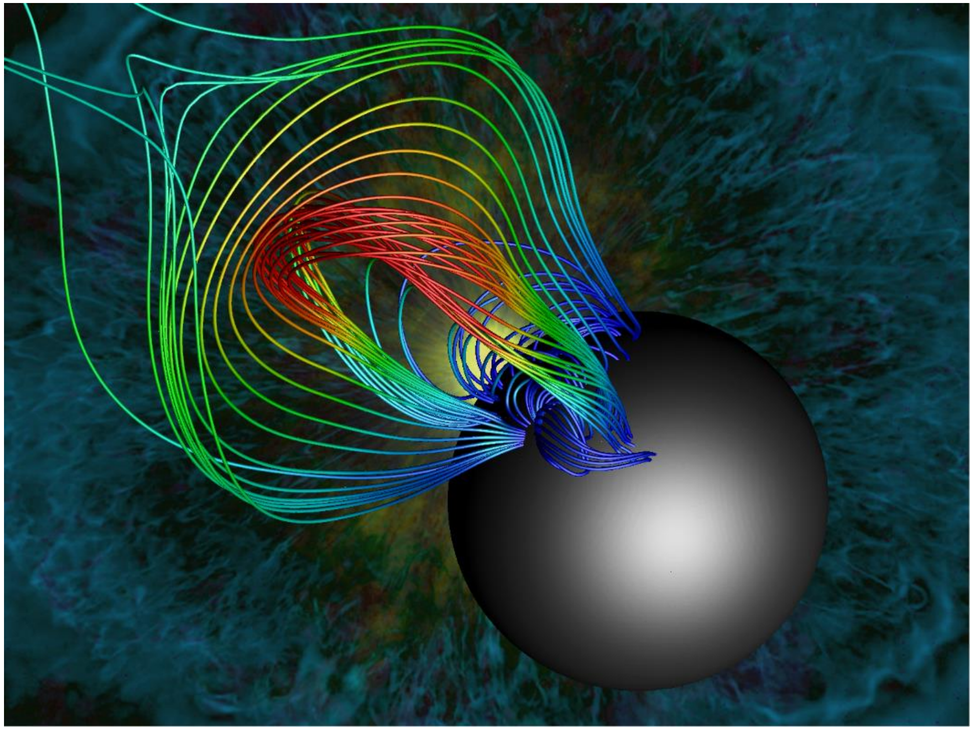
SoHO-Lasco C3

CME mysteries



Despite the plethora of CME observations, the ***exact trigger mechanism remains unknown***

Closed magnetic structures *seem to play a key role* in CME initiation

- **Power source**: energy stored in volumetric electric currents in the corona
- **Mechanism**: provided ***through the magnetic field*** by
  - *shearing motions / sunspot rotations*
  - *magnetic flux emergence/cancellation*
- **Cause of CMEs:** still under debate, but we have good general idea – *loss of equilibrium or stability of the coronal magnetic field*

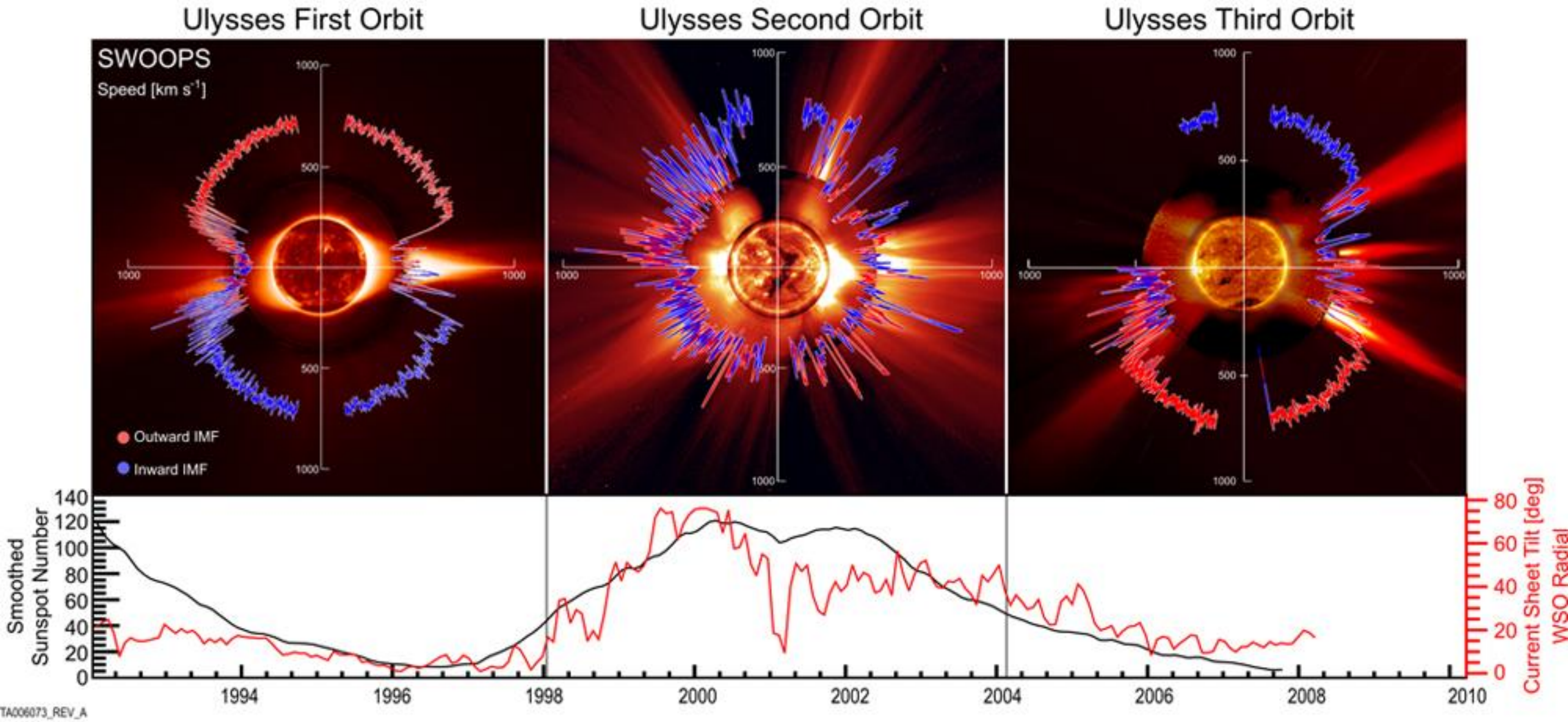
Numerical simulation models are complementary to observations and required to get physical insight in this phenomenon!

The background solar wind

- Continuous stream of high energetic particles flowing from the Sun.
- Finds its origin in the hot solar corona.
- **Two different components**:
  - **'FAST': V > 700 km/s (i.e. *2,5 million km/h*),** tenuous, almost uniform stream (from'coronal holes')
  - **'SLOW': 300 km/s (or *> 1 million km/h*), more dense and turbulent flow** (from tips and edges of streamers)

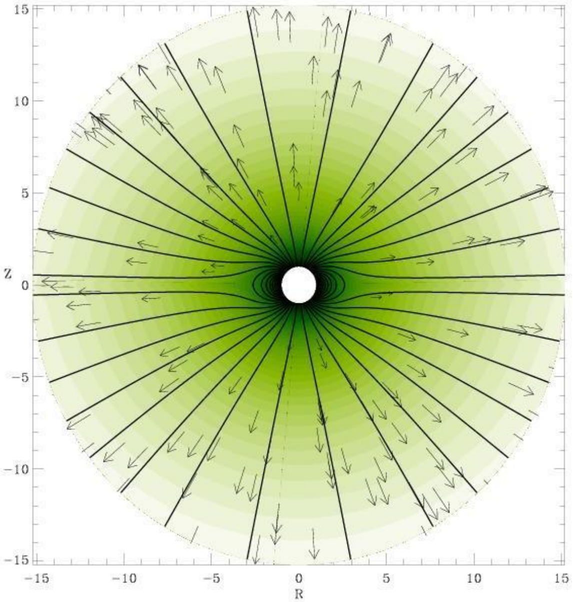
- Near the Earth: < V >= 400km/s, < n >= 10cm^{-3}
- Data from Ulysses, Helios, ACE, SOHO, Proba 2, Hinode, STEREO, SDO, etc.

The background solar wind



Ulysses (1992) provided data on the velocity of the solar wind (red and blue lines). Solar images from SOHO (ESA/NASA)

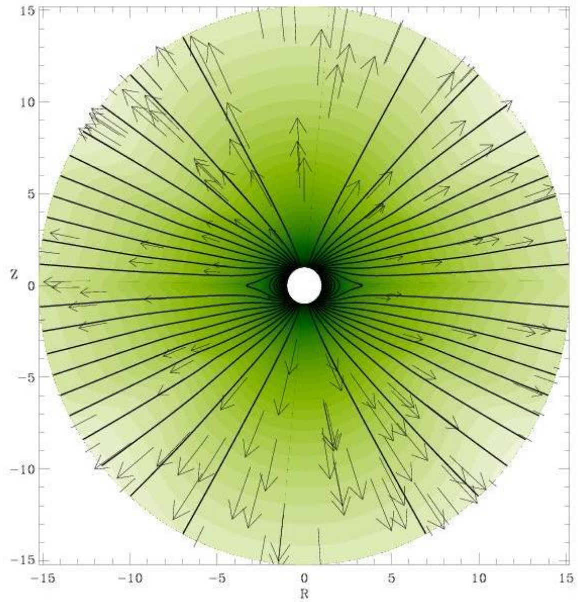
Solar wind simulations (2.5D)



Wind Model 1:

Polytropic Wind

Colour: density (logscale), black lines: magnetic field lines, arrows: velocity

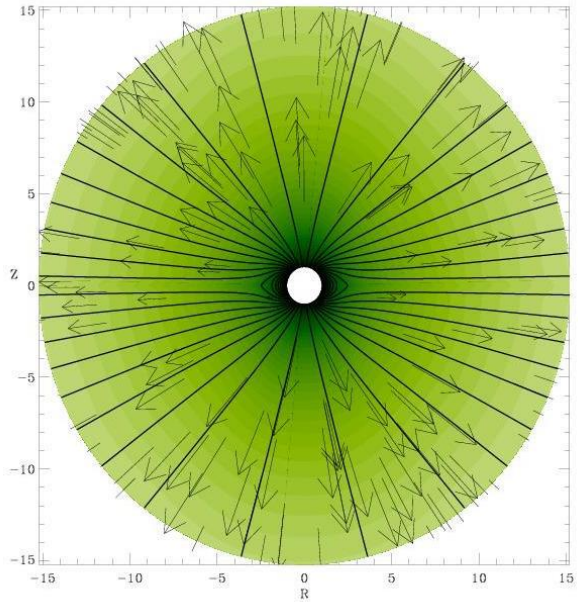


Wind Model 2:

MHD wind with extra heating/cooling source term:

$$Q = \rho q_0 e^{-\frac{(r-r_0)^2}{\sigma^2}} \left(T_0 - \gamma \frac{p}{\rho}\right)$$

(Groth et al. 2000)

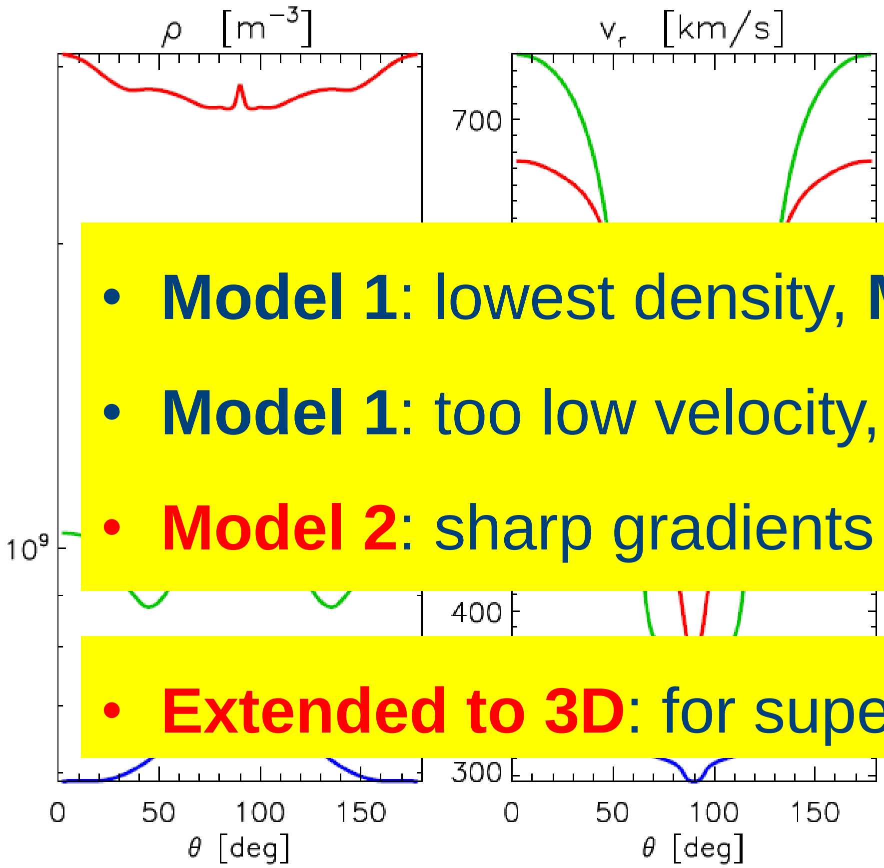


Wind Model 3:

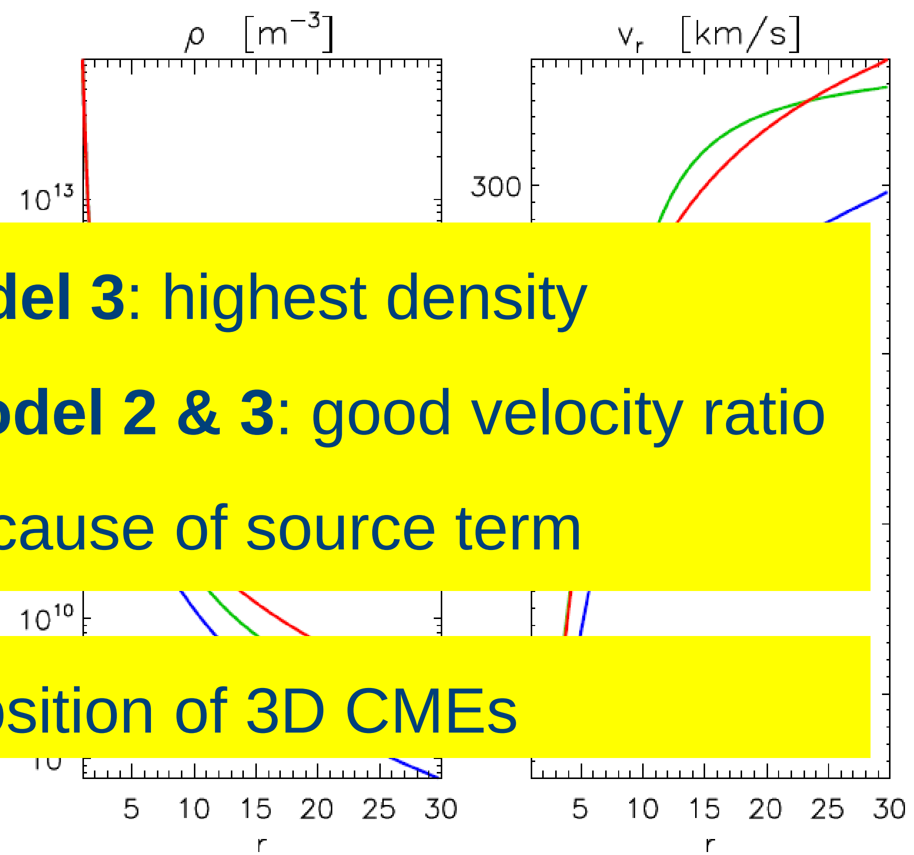
Polytropic Wind with Alfvén waves

Has additional pressure gradient due to effect of Alfvén waves.

Solar wind simulations (2.5D)



Profiles of density and velocity at $30R_\odot$. Blue: Model 1, green: Model 2, red: Model 3

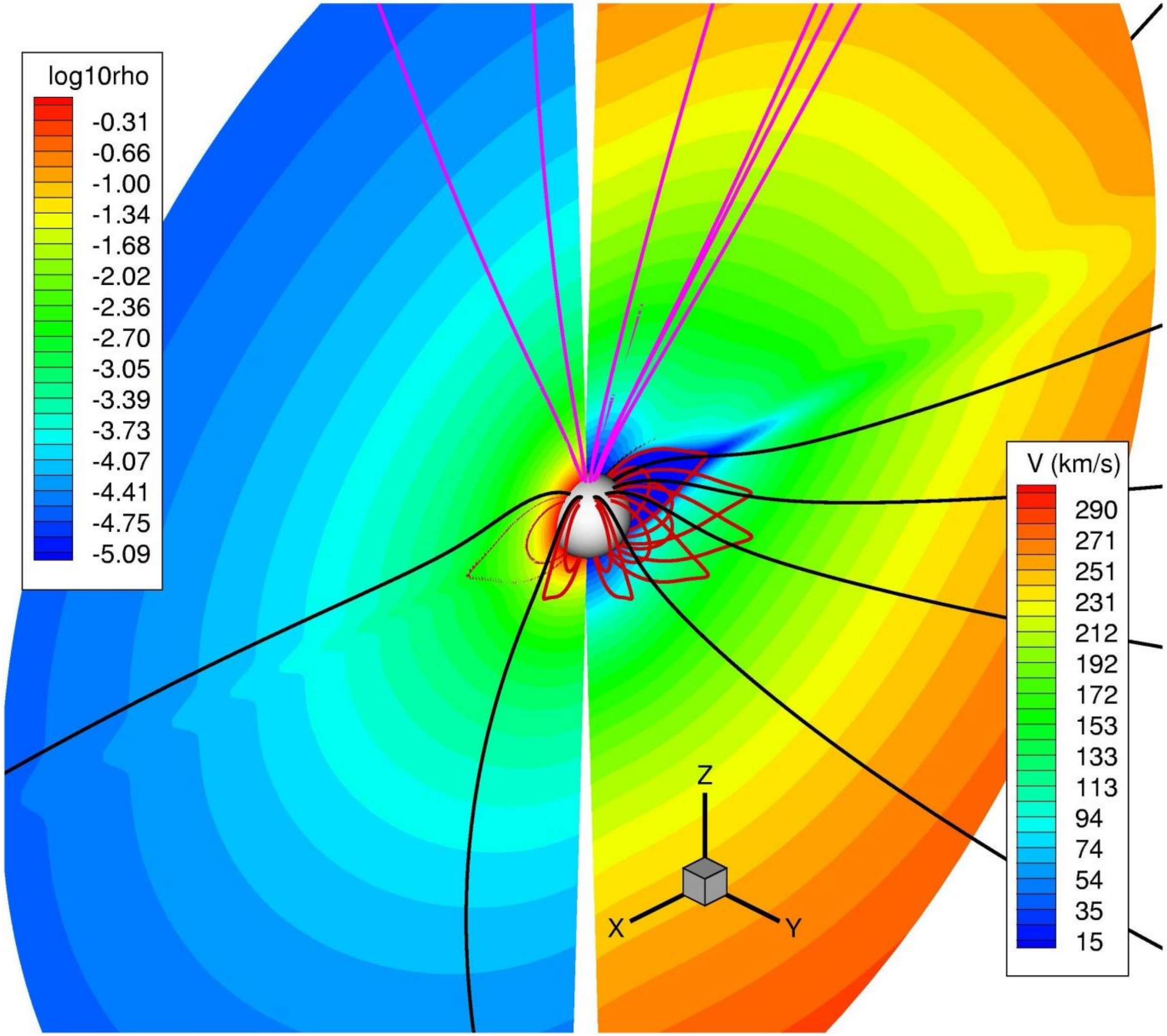


Profiles of density and velocity along the equator. Blue: Model 1, green: Model 2, red: Model 3

- **Model 1**: lowest density, **Model 3**: highest density
- **Model 1**: too low velocity, **Model 2 & 3**: good velocity ratio
- **Model 2**: sharp gradients because of source term

- **Extended to 3D**: for superposition of 3D CMEs

3D axi-symmetric wind

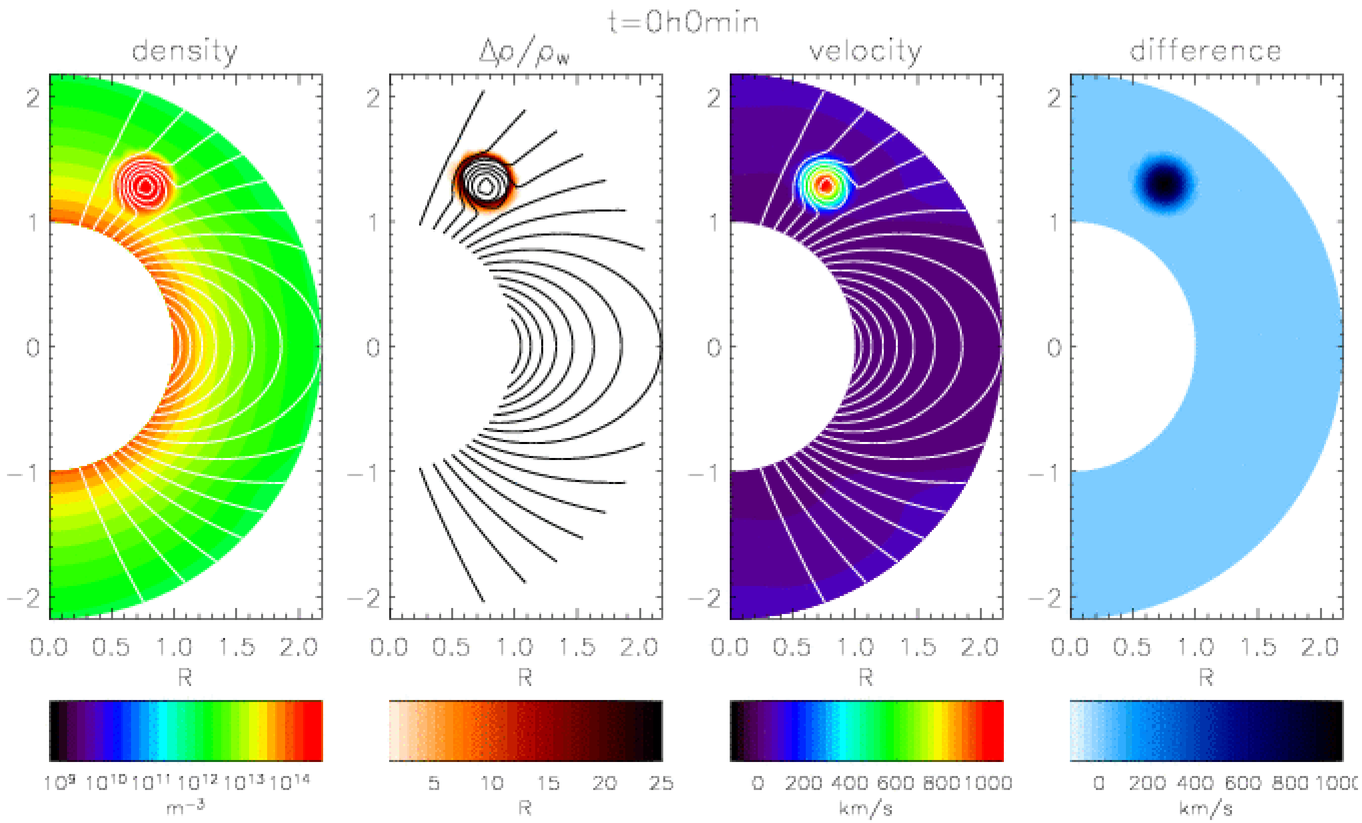


- used in combination with **3D CME** propagation models
- on structured grids $\rightarrow$ CPU demanding
- up to 30 R_S
- up to 1 AU takes 10 days on 440 CPUs *(without AMR)*

Motivation 2.5D models:

1) ± Same evolution
2) Less CPU power/time
3) Same data fits at 1AU

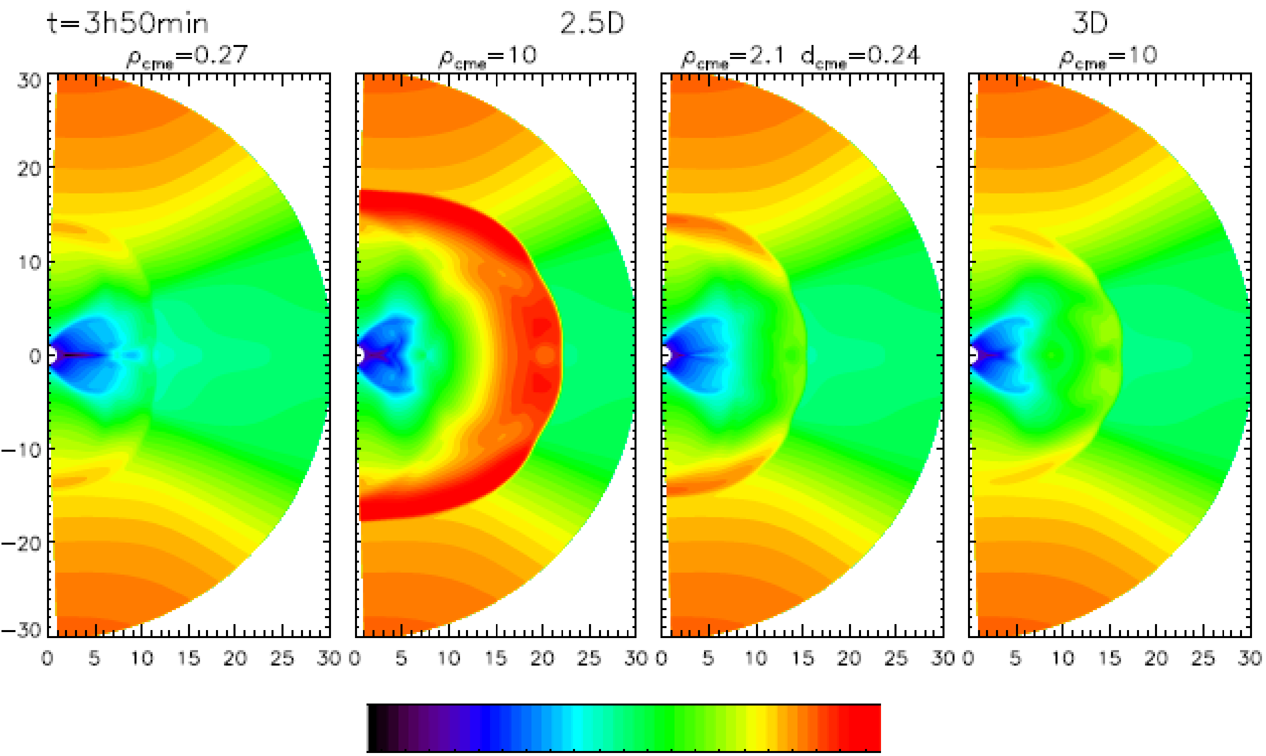
2.5D Flux-rope CME models



Initial setup with magnetized plasma blob, inverse polarity.
(from Chané et al 2005)

Remark: ENLIL uses such a 'ballistic' model (in 3D but without magnetic field!)

2.5D vs 3D CME simulations



Radial velocity contours in meridional plane at $t = 3$ hr 50 min for 3 different 2.5D CMEs (3 left panels, 640×91) and a 3D CME (right, $640 \times 91 \times 180$).

comparison 2.5D CME simulations vs 3D:

- *3D CME:* $\rho_{\rm cme} = 10$ *(*$=1.13 \times 10^{16}$ *g),* $v_{\rm cme} = \pm 1000$ *km/s*
- *2.5D 1: same mass as 3D CME*
- *2.5D 2: same* $\rho_{\rm cme}$ *as 3D CME*
- *2.5D 3: same momentum as 3D CME (when same width)* $\Rightarrow$ *evolution* $\approx$ *3D CME evolution*

"Magnetized plasma blob" model, Jacobs et al. (2007)

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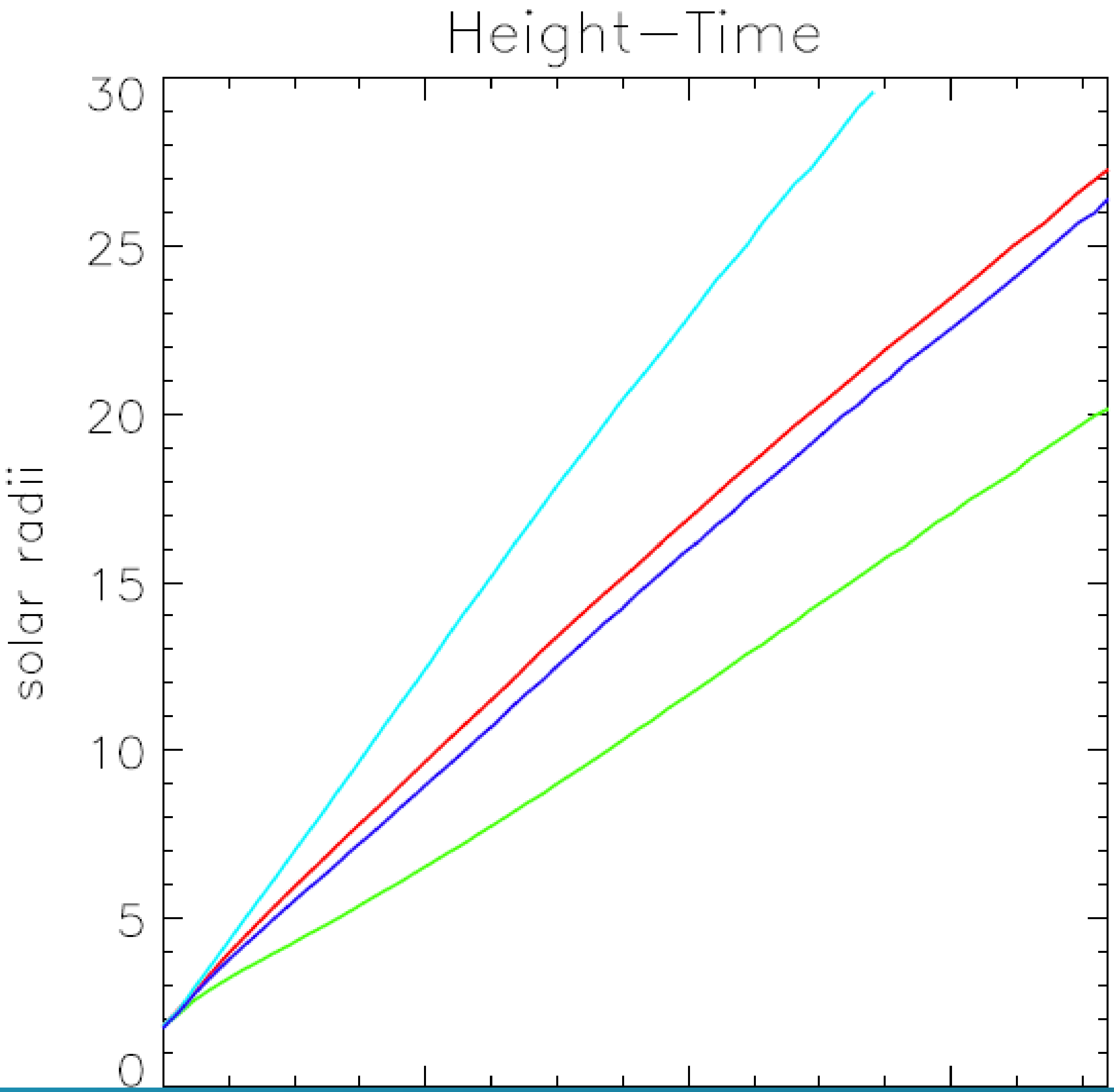
2.5D vs 3D CME simulations

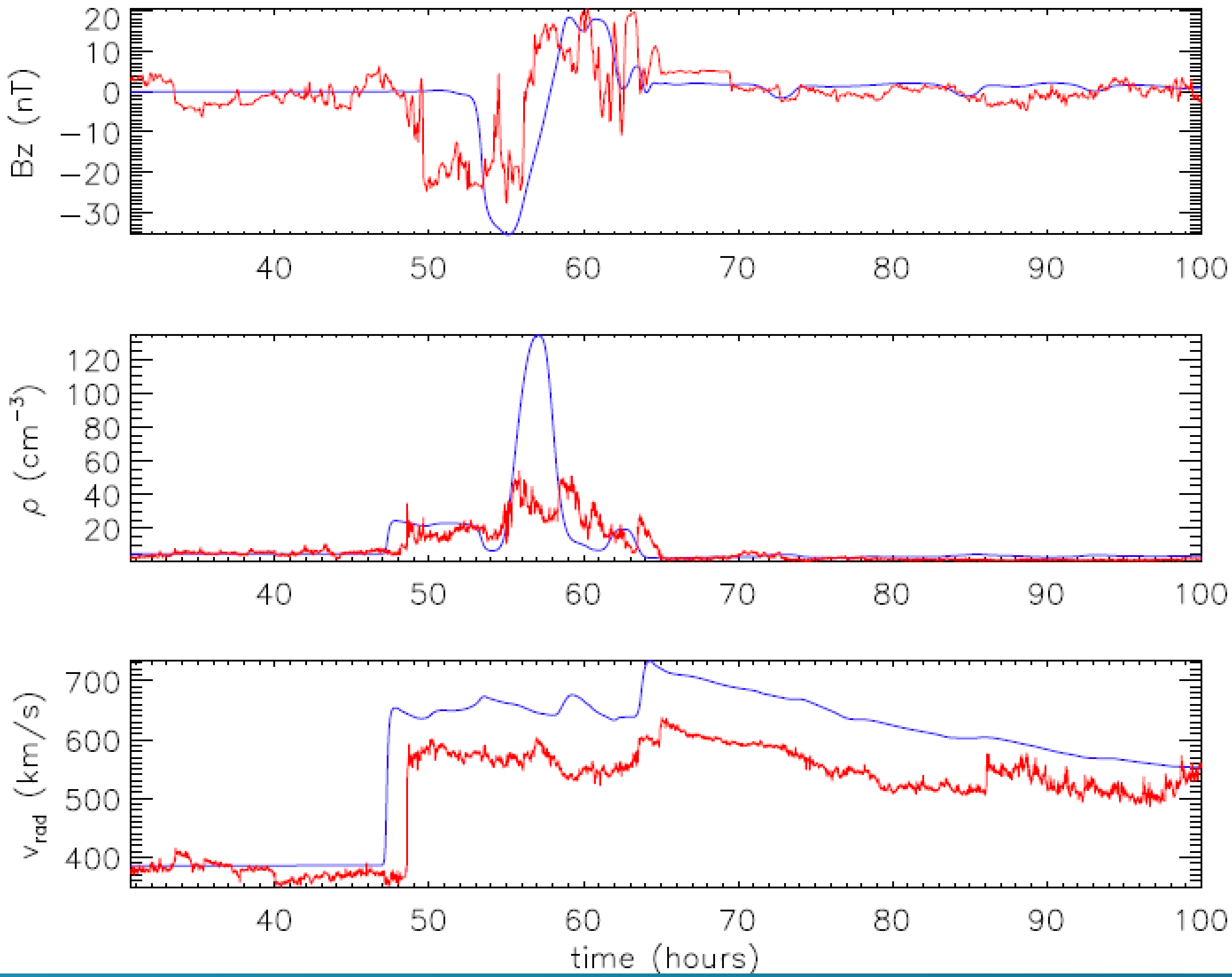


comparison 2.5D simulations vs 3D:

- *same* $\rho_{\rm cme}$ *as 3D CME*
- *same mass as 3D CME*
- *same momentum as 3D CME (when same width)*

$\Rightarrow$ *evolution* $\approx$ *3D evol.*

2.5D simulations fitting ACE data



Comparison between the in situ data obtained by the ACE spacecraft (red curves) and our best fitting simulation (blue curves).

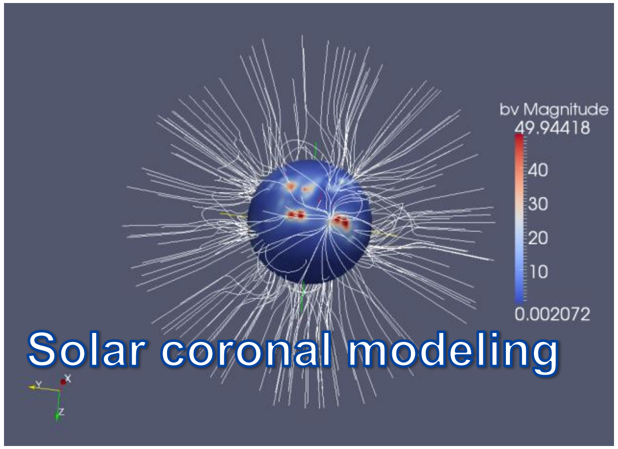
Best fit (with new wind model) for the April 4, 2000 Event.

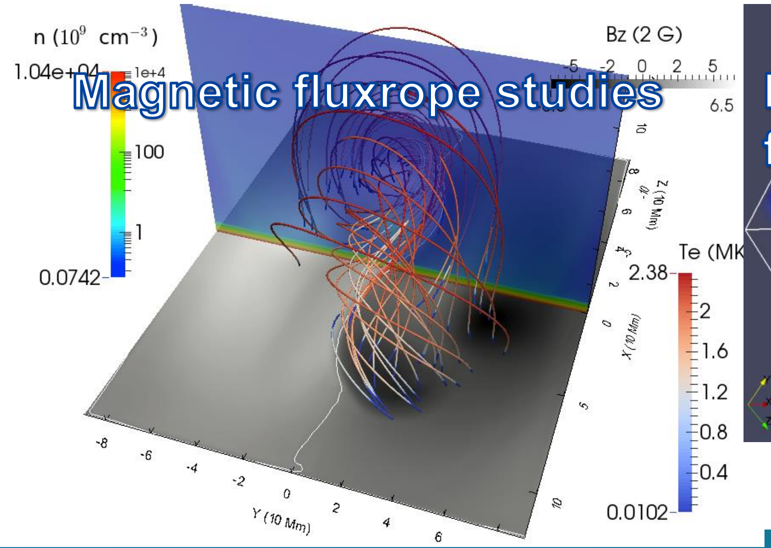
Chané et al. (2006)

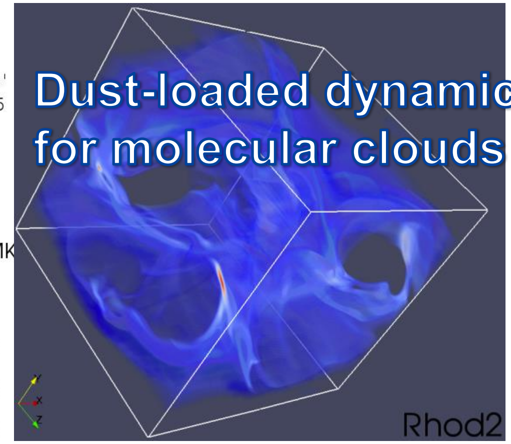
Numerical tool: MPI-AMRVAC

Based on VAC (Toth, 1994), further developed at CmPA, KU Leuven since 2006-2007 (by van der Holst and others)

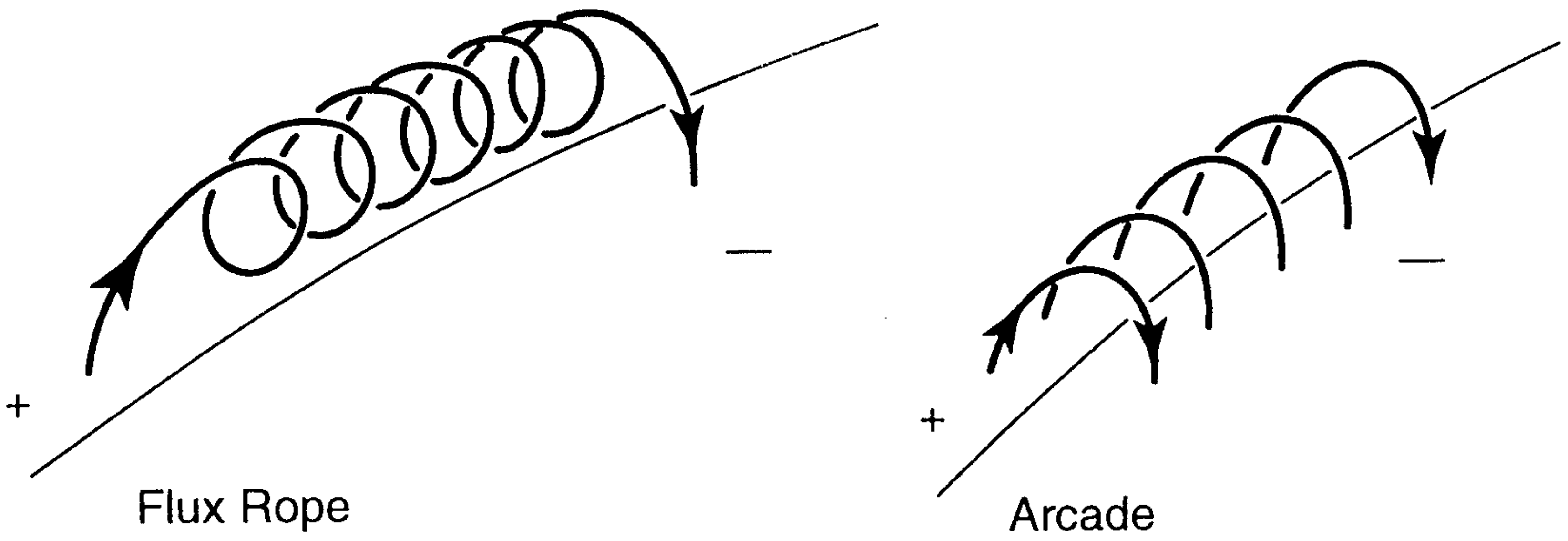
Any-D, block-grid-adaptive, massively parallel code for hydro to MHD multi-physics simulations, Newtonian to Relativistic regimes: fully open source development [gitorious.org, http://homes.esat.kuleuven.be/~keppens]





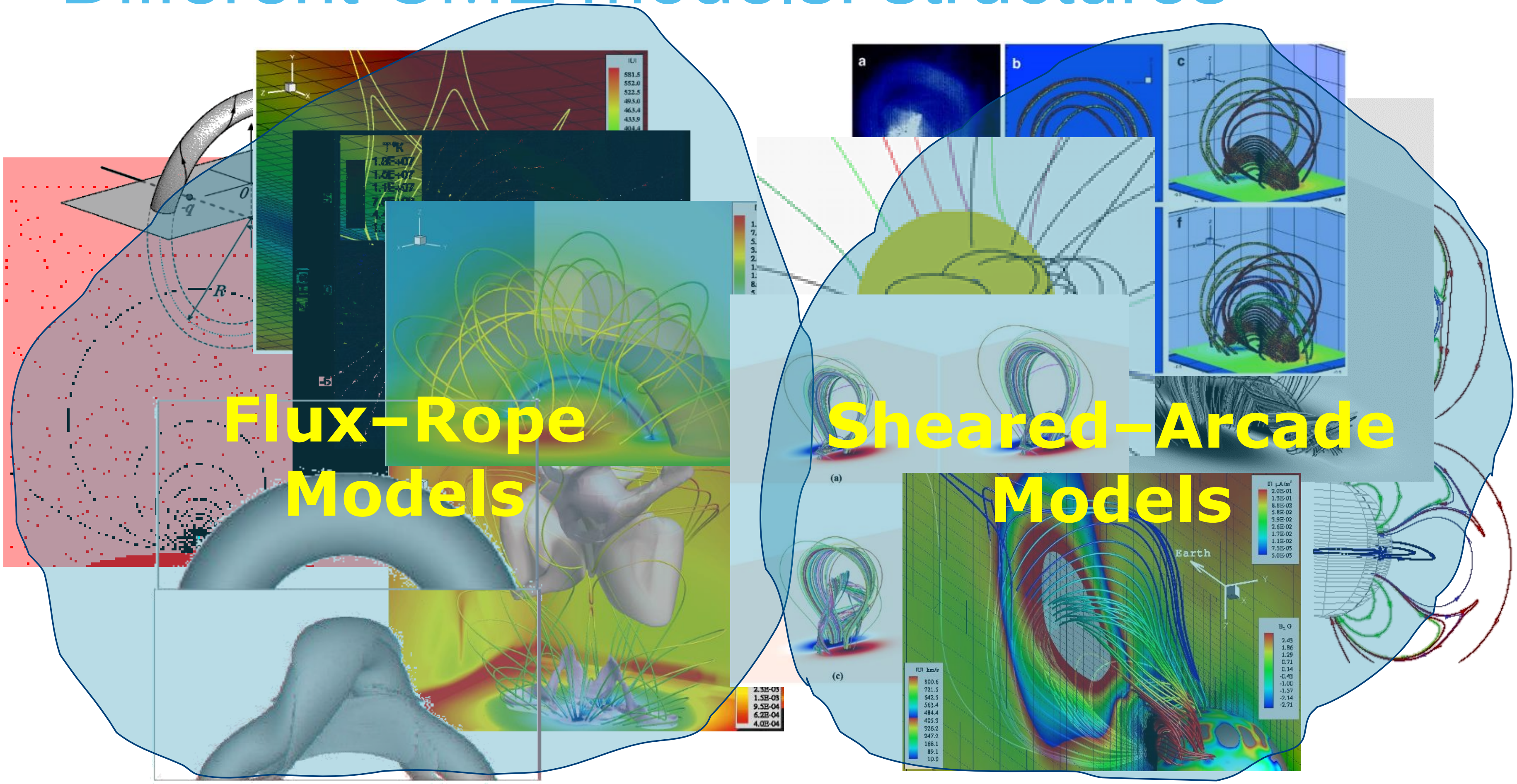


Different CME models: structures



Flux rope (left) and sheared arcade (right) magnetic topologies adopted by most CME models. Representative field lines are shown. *Courtesy: Klimchuk (2000)*

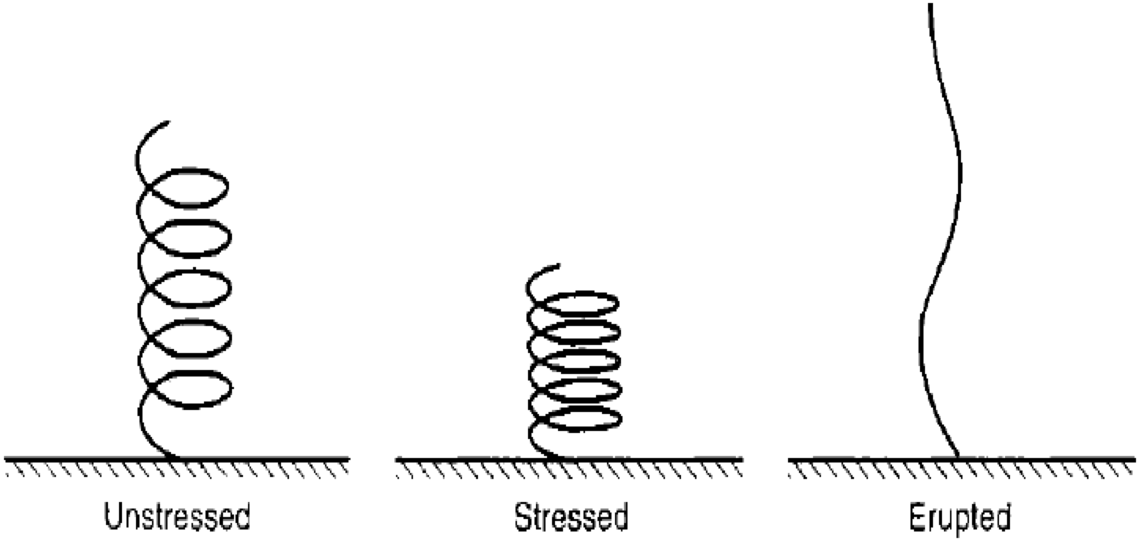
Different CME models: structures



Amari et al. (2000, 2003); Antiochos et al. (1999); Forbes & Isenberg (1991); Gibson & Low (1998); Kliem et al. (2004); Lin et al. (2001); Linker et al. (2001); Lynch et al. (2005); Manchester et al. (2003, 2004); Moore et al. (2001); Sturrock et al. (2001); Titov & Démoulin (1999); Tokman & Bellan (2002); and Roussev et al. (2003, 2004, 2007).

Courtesy: I. Roussev

Different CME models: energetics



$E_U < E_S < E_E$

Directly driven:

$E_U \rightarrow E_E$

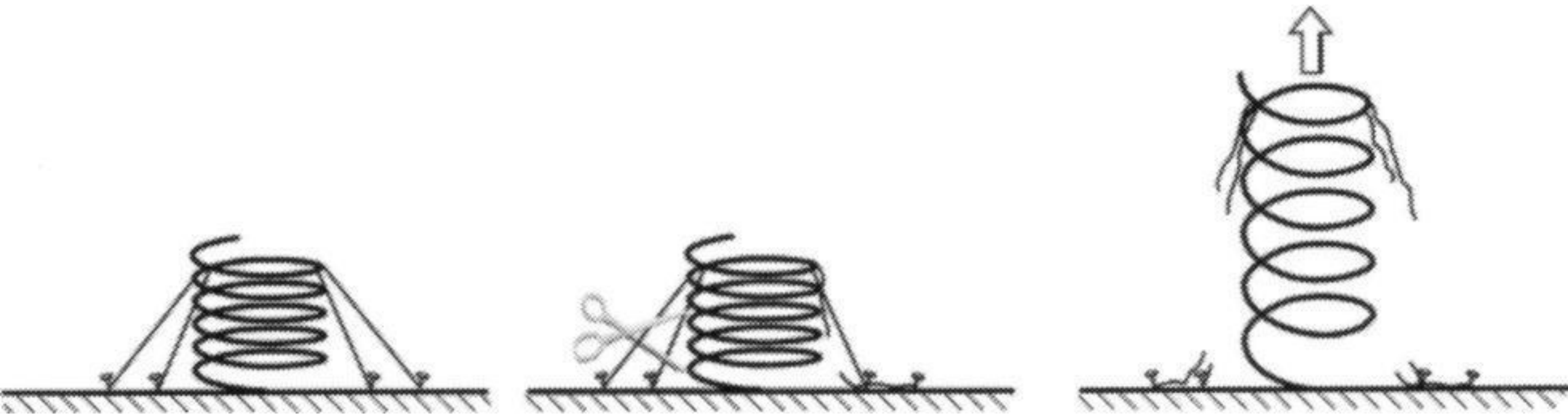
Storage/release:

$E_U \rightarrow E_S \rightarrow E_E$

Simple spring analogue to the solar corona. The three states represent the magnetic field when it is unstressed (potential), stressed (current-carrying), and erupted (also current-carrying). *Courtesy: Klimchuk (2000)*

Storage/release models

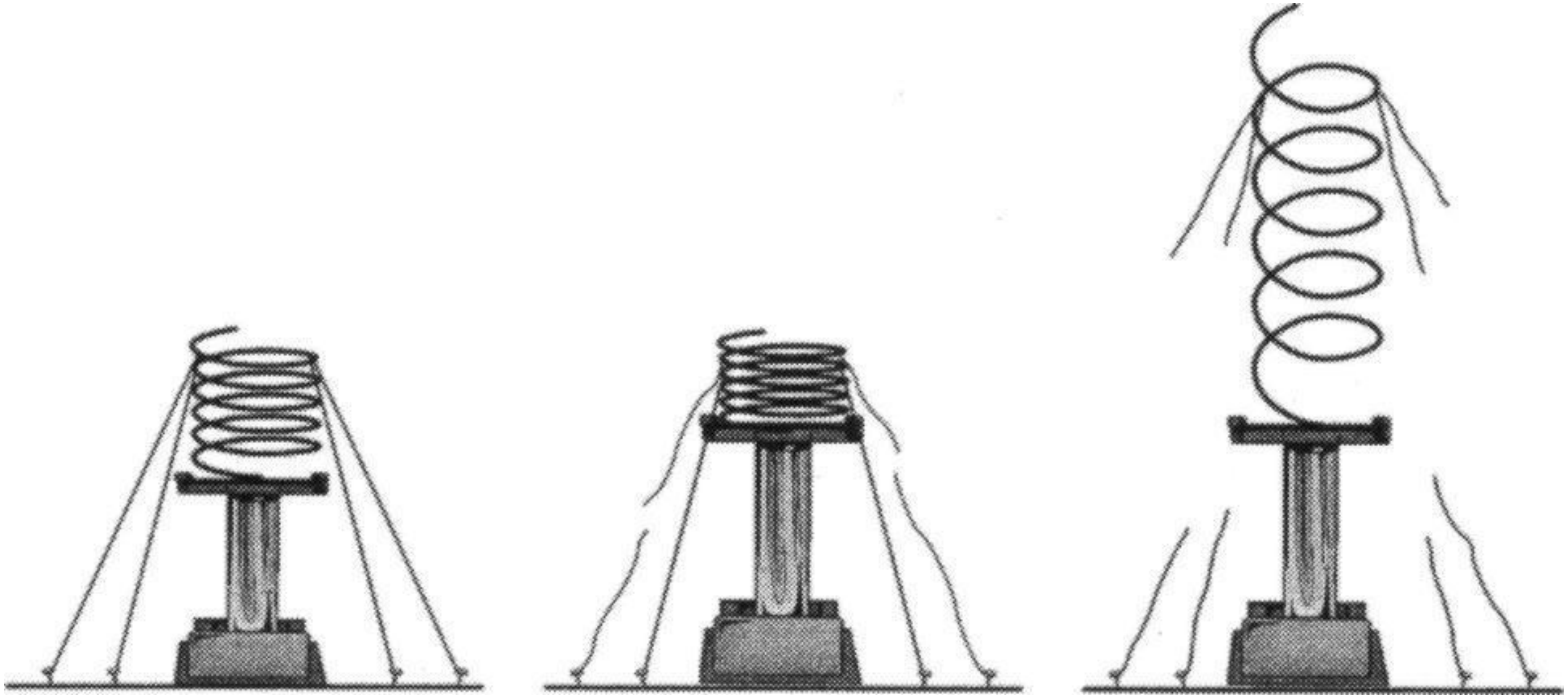
Tether release



Tether release model analogue. The spring is held in a compressed state by rope tethers. The tethers are slowly released, one by one, until the remaining tethers break from the additional strain. The spring explosively uncoils. *Courtesy: Klimchuk (2000)*

Storage/release models

Tether straining

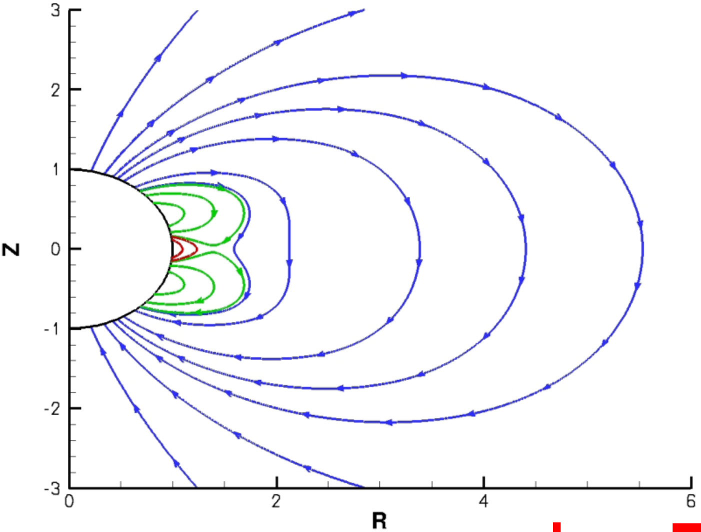


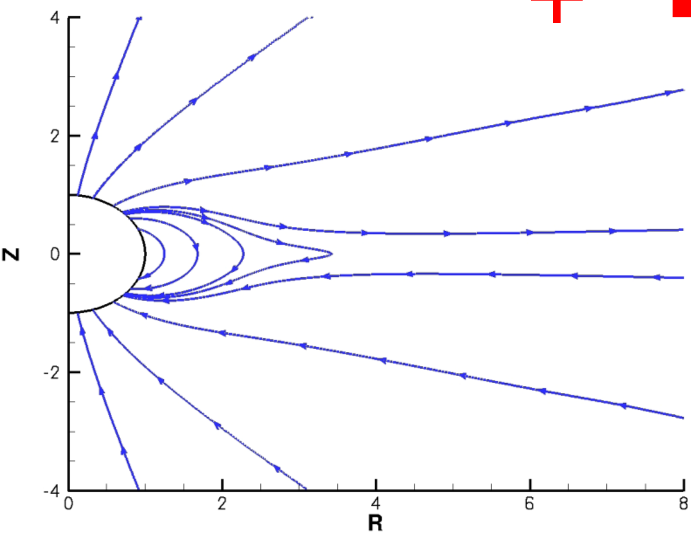
Tether straining model analogue. The bottom of the spring is slowly raised on a moveable platform while its top is held fixed by rope tethers attached to the ground. The strain on the tethers builds to the breaking point, and the spring explosively uncoils. *Courtesy: Klimchuk (2000)*

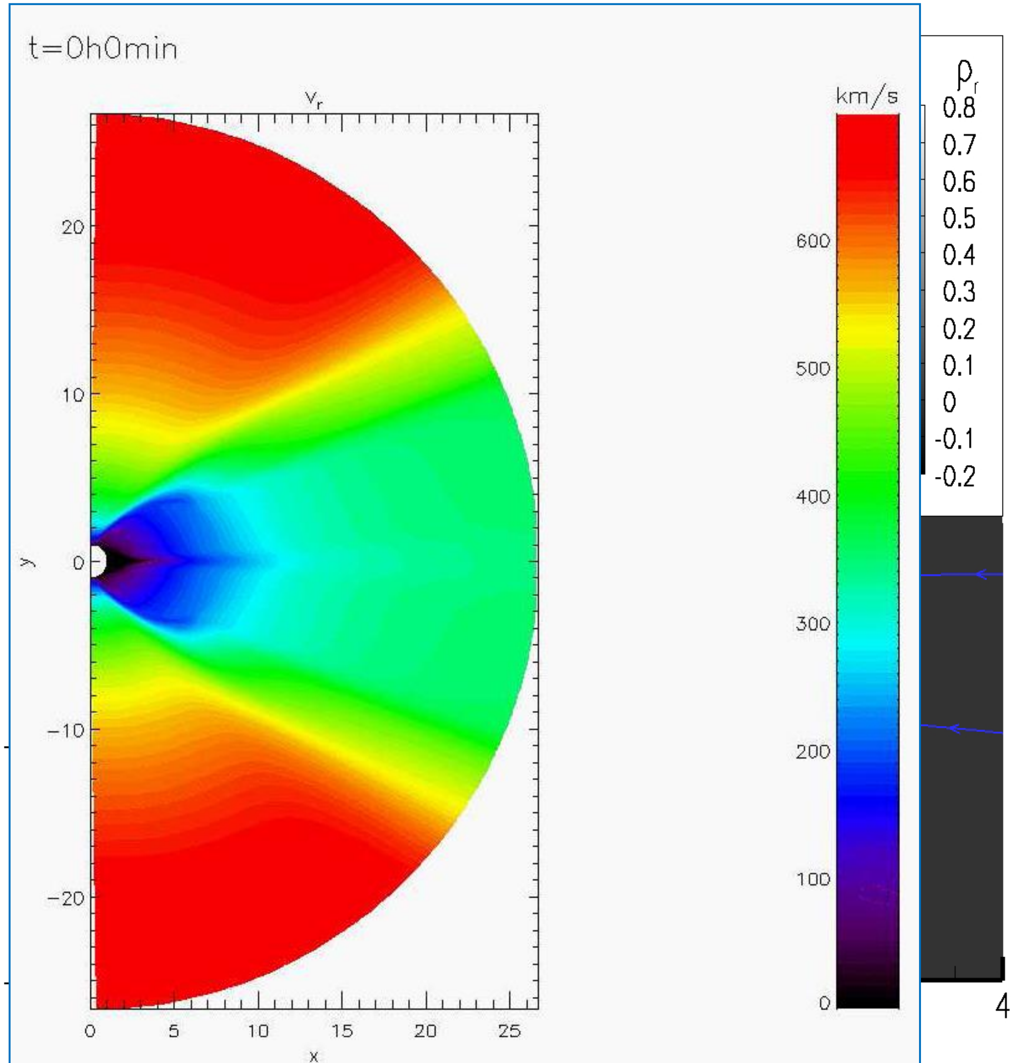
CME modeling (2.5D)

‘breakout’ CME, initial situation:

van der Holst et al. ApJ (2007)



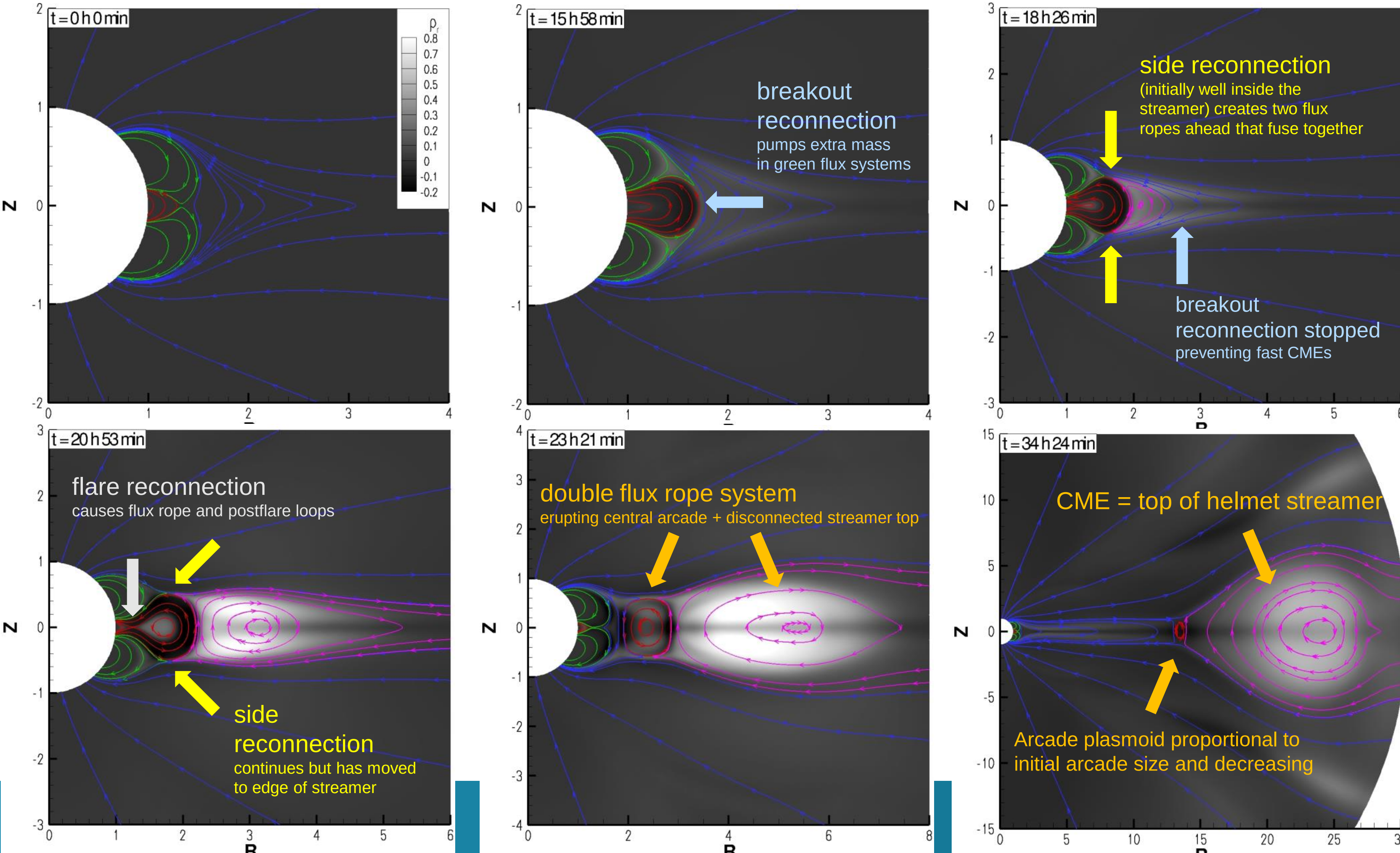




CME modeling (2.5D)

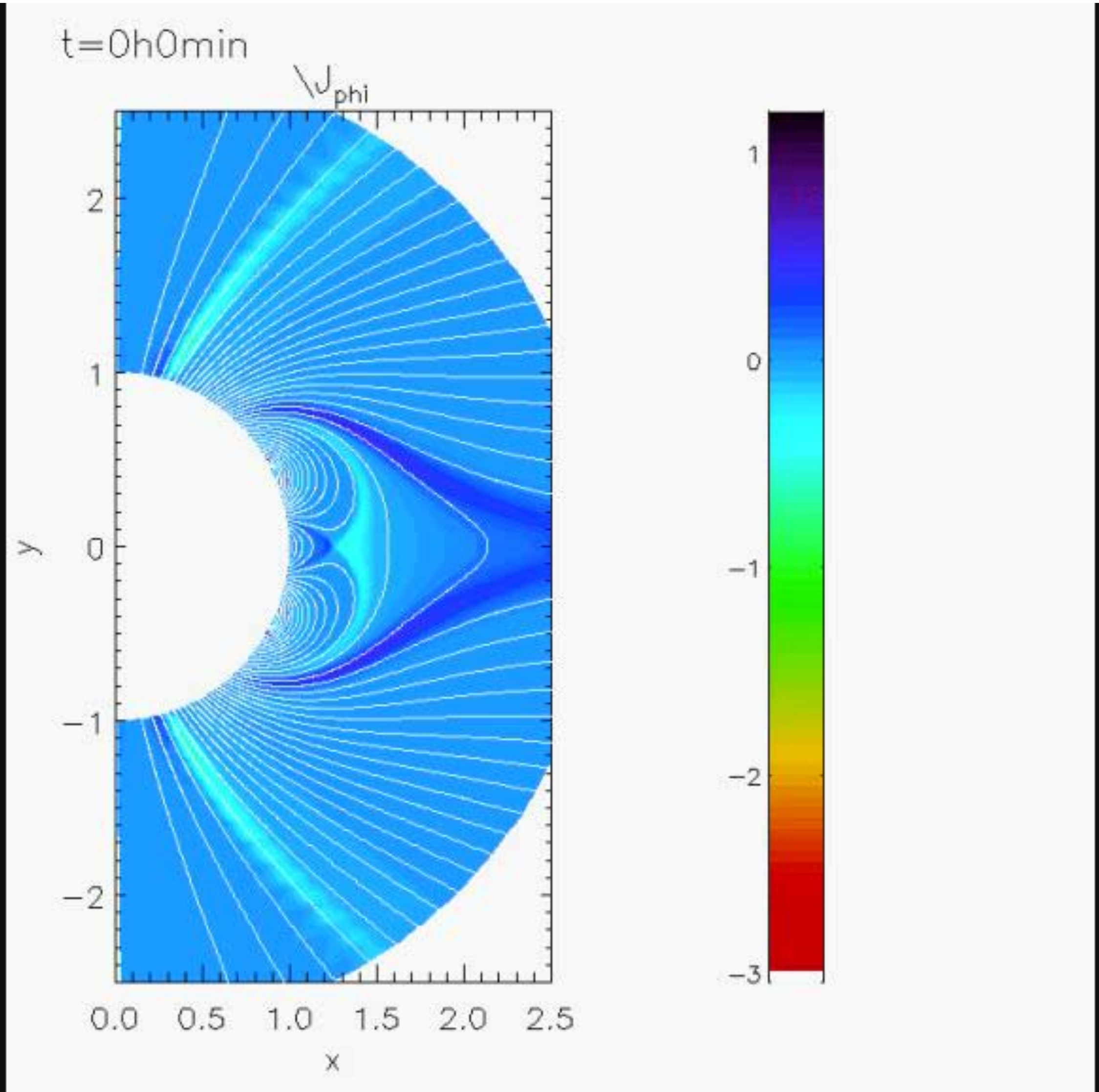
‘breakout’ CME, evolution:

van der Holst et al. ApJ (2007)



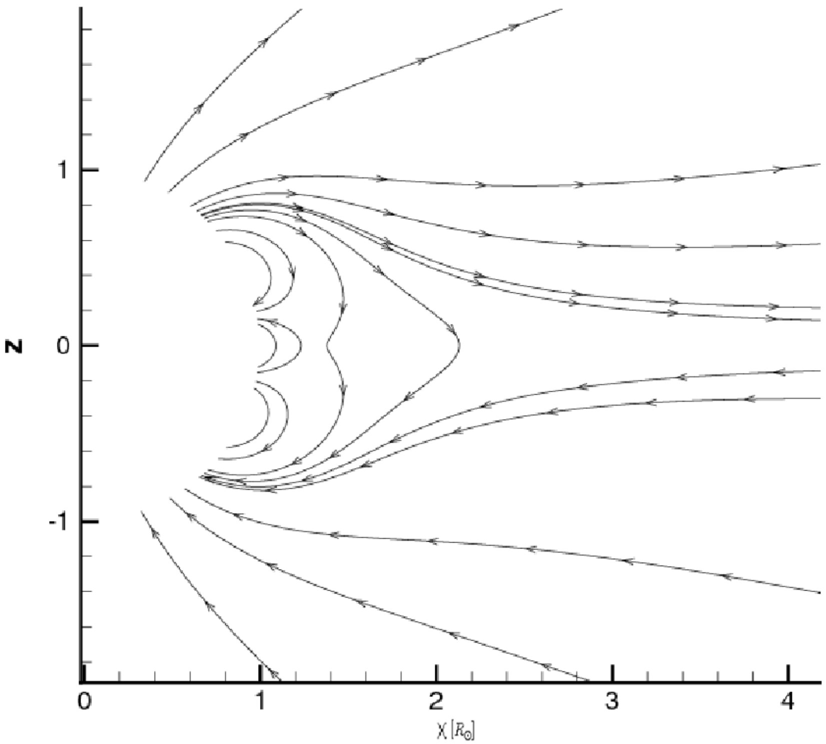
CME modeling (2.5D), symmetric driving

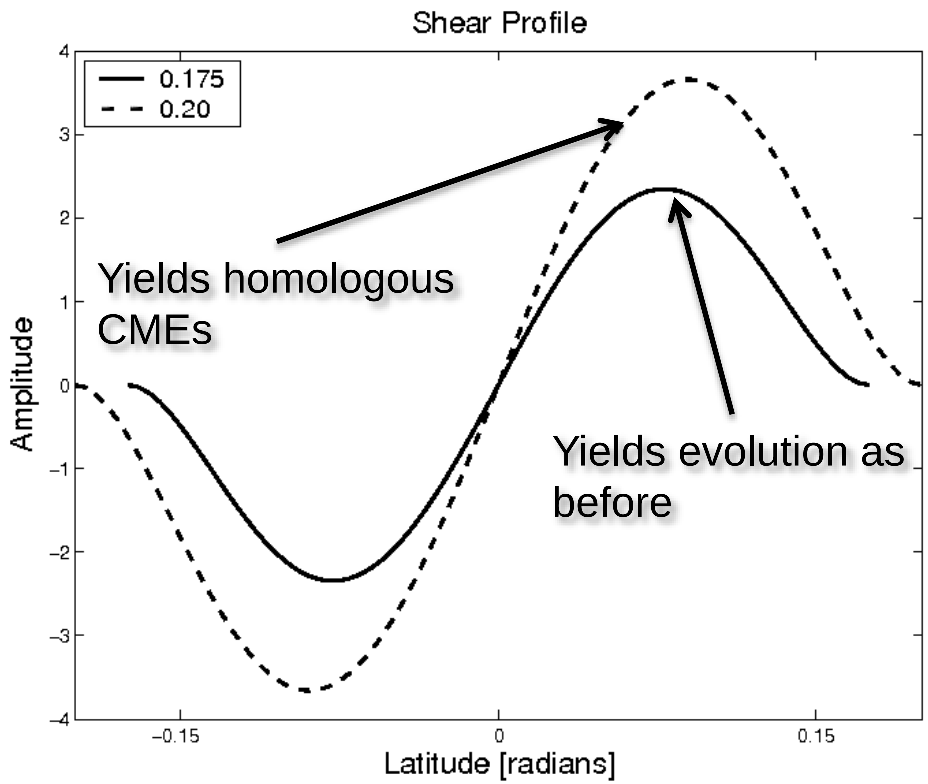
Mixed triggering *(Zuccarello et al., Ap.J. 2009)*



CME modeling (2.5D), 2.5D parameter study

Soenen et al. AA (2009)



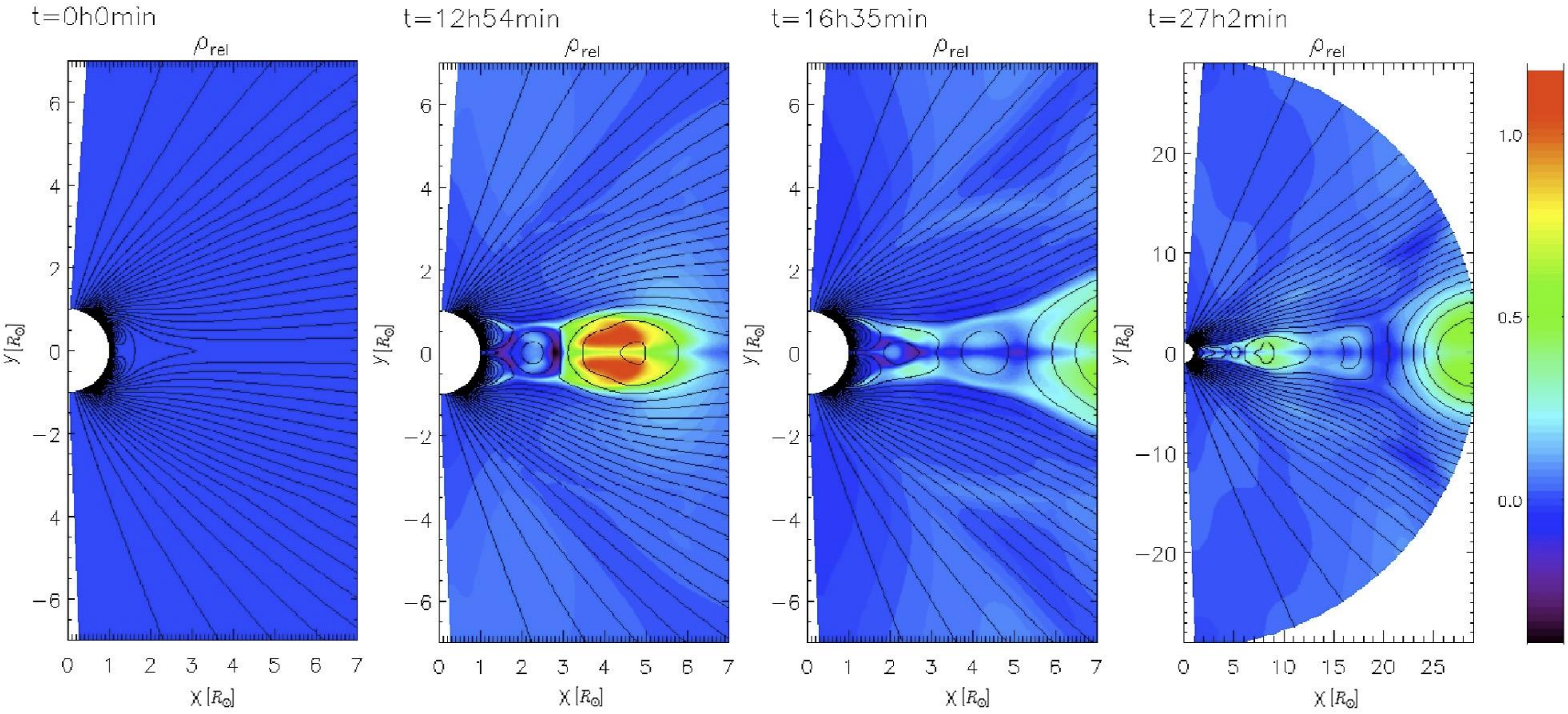


homologous CMEs

Left: initial magnetic field configuration. Right: shear velocity as a function of latitude

CME modeling (2.5D), parameter study

Soenen et al. AA (2009)



homologous CMEs

Snapshots for narrow shearing region: similar to van der Holst et al.(2007)

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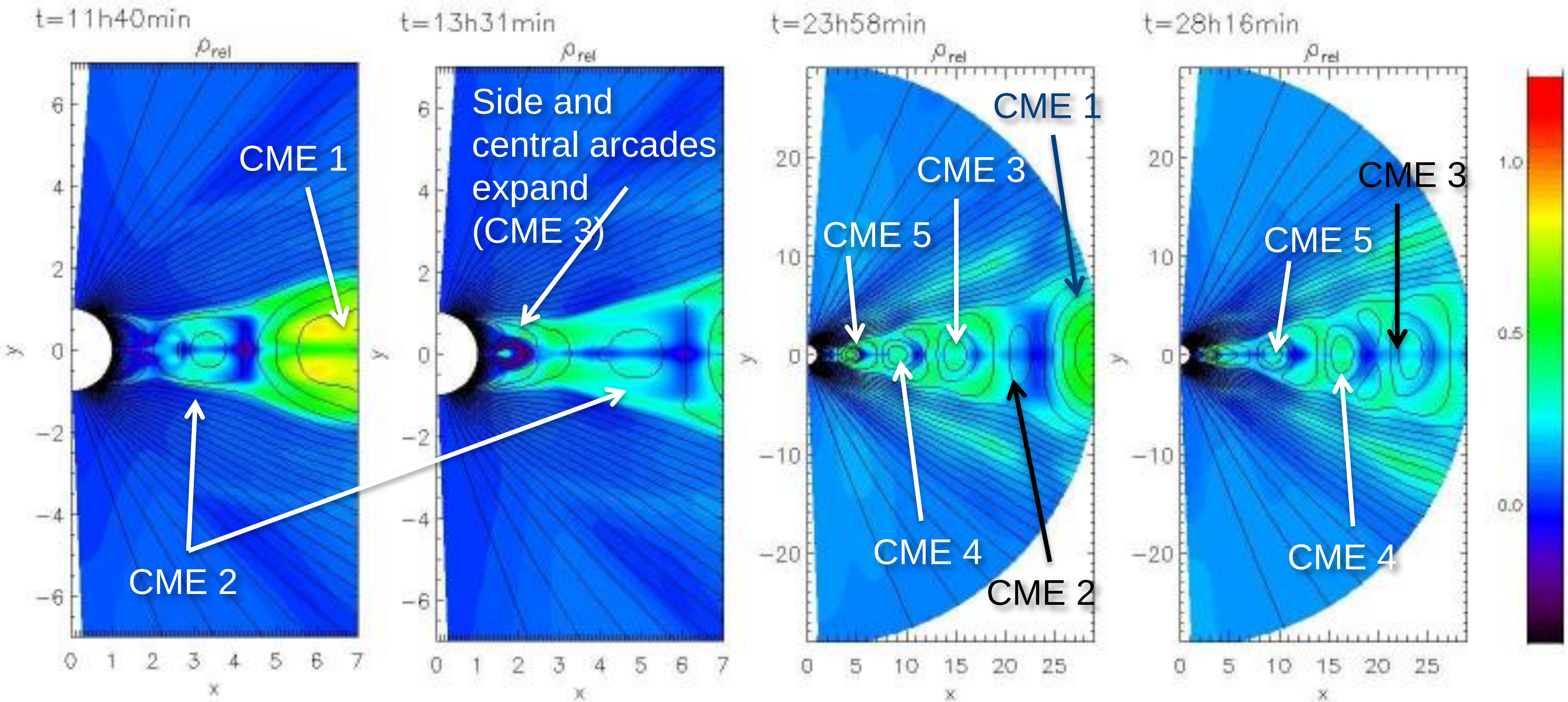
CME modeling (2.5D), parameter study

Soenen et al. AA (2009)



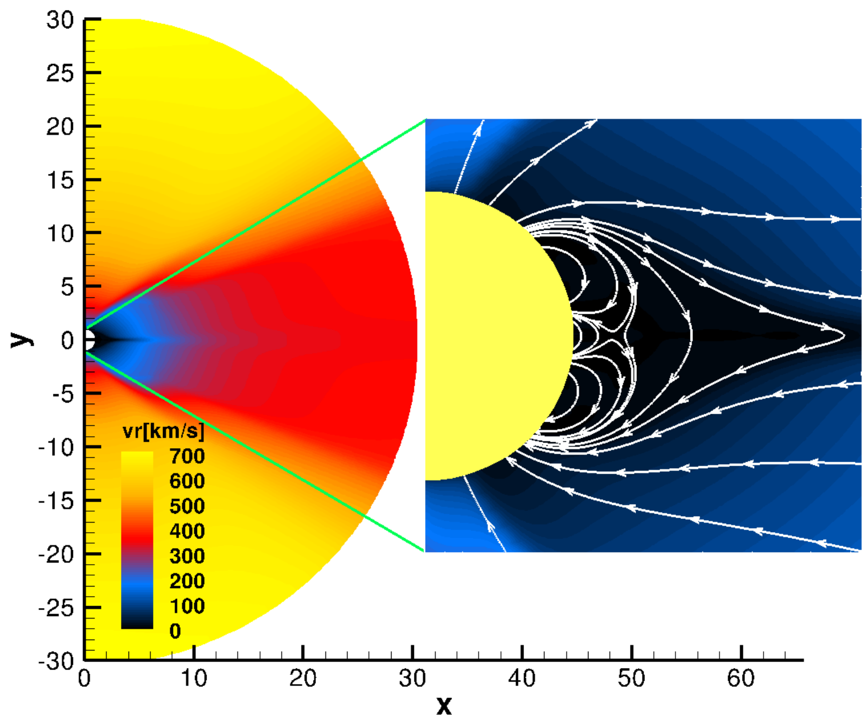
homologous CMEs

1) a weak overlying field; 2) two expanding side arcades that envelope and protect; 3) expanding central arcade due to **larger shearing region**.

Asymmetric driving (2.5D)

(Devriese et al., MSc thesis 2011)
(Zuccarello et al., PhD thesis 2012)

Left: The radial velocity profile of the background solar wind. Right: zoom of the left figure, showing the coronal magnetic field topology.



- The ideal MHD equations are solved in spherical coordinates and assuming axial symmetry.
- The coronal magnetic field consists out of a triple arcade structure centered around the equator, and embedded in a large-scale dipole field.

The CME model

- CME initiated by applying an additional azimuthal flow on the inner boundary, i.e. *shearing the magnetic foot points*.

$$v_\varphi = \begin{cases} v_0 \left[(\lambda-\lambda_0)^2 - \Delta\lambda^2\right]^2 \sin(\lambda-\lambda_0)\sin\left(\pi\frac{t-t_0}{\Delta t}\right) & \text{if} |\lambda-\lambda_0| < \Delta\lambda \\ 0 & \text{else} \end{cases}$$

in the **northern** arcade:

$\lambda = \pi/2-\theta \quad \lambda_0 = 26^\circ \quad \Delta\lambda = 8.5^\circ \quad \Delta t = 24h \quad v_\varphi^{max} = 16.95\text{kms}^{-1}$

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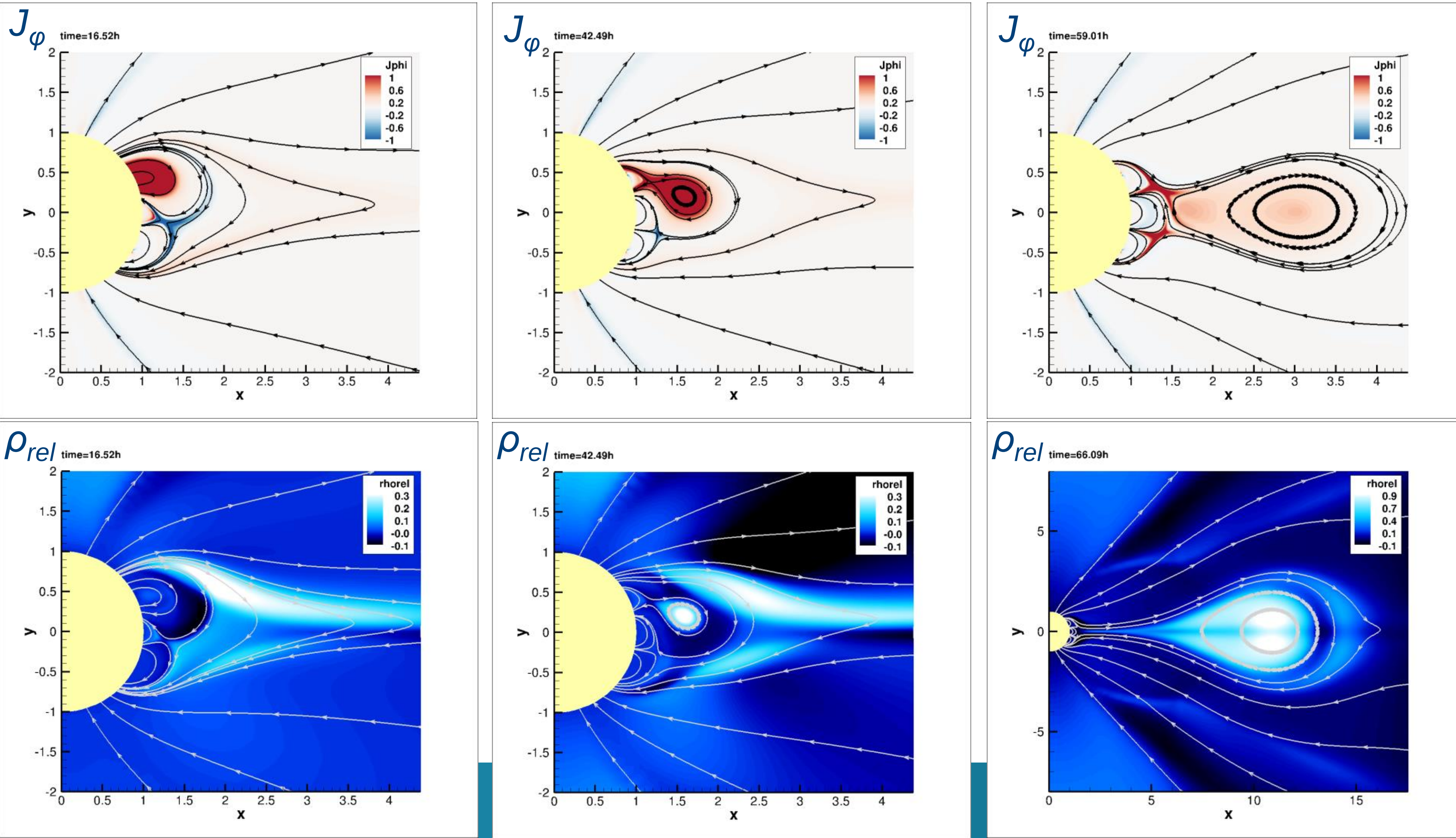
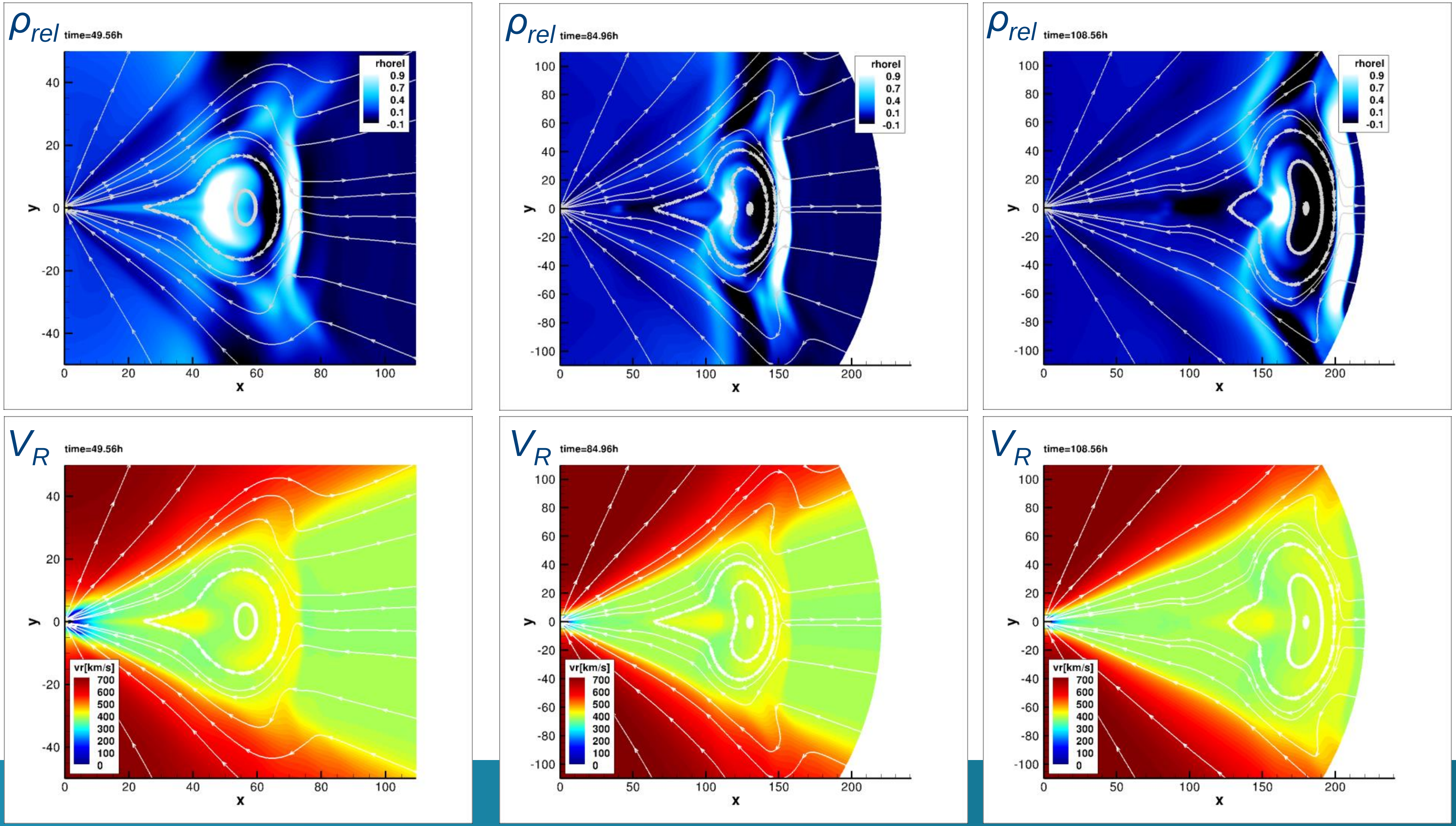
Asymmetric driving, 2.5D parameter study

Deflection of CME towards equator (cf. observations, *plots of* J_φ *and* ρ_{rel})

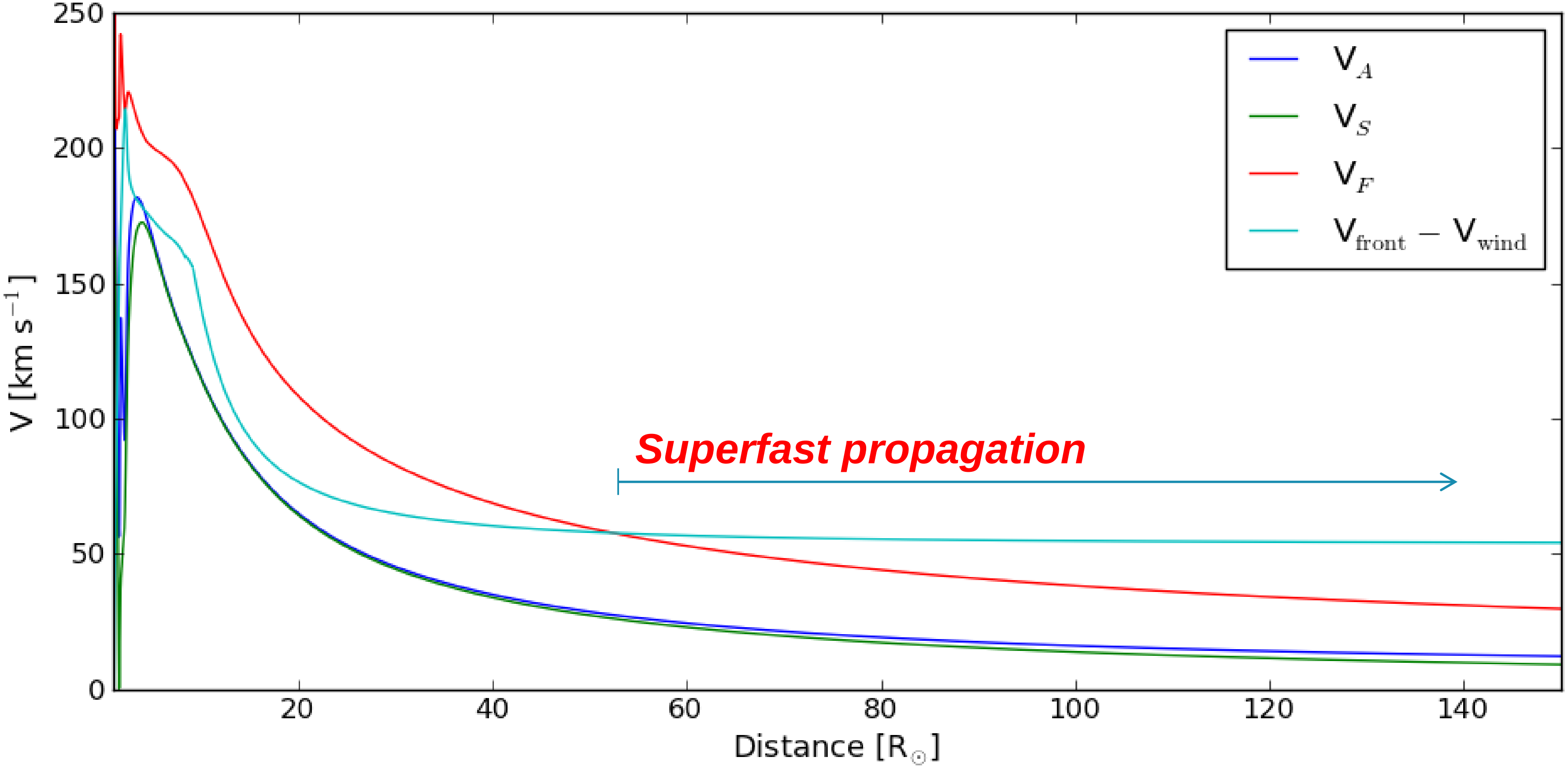


Asymmetric driving, 2.5D parameter study

IP CME evolution: erosion & deformation (cf. observations, *plots of* ρ_{rel} *&* V_R)

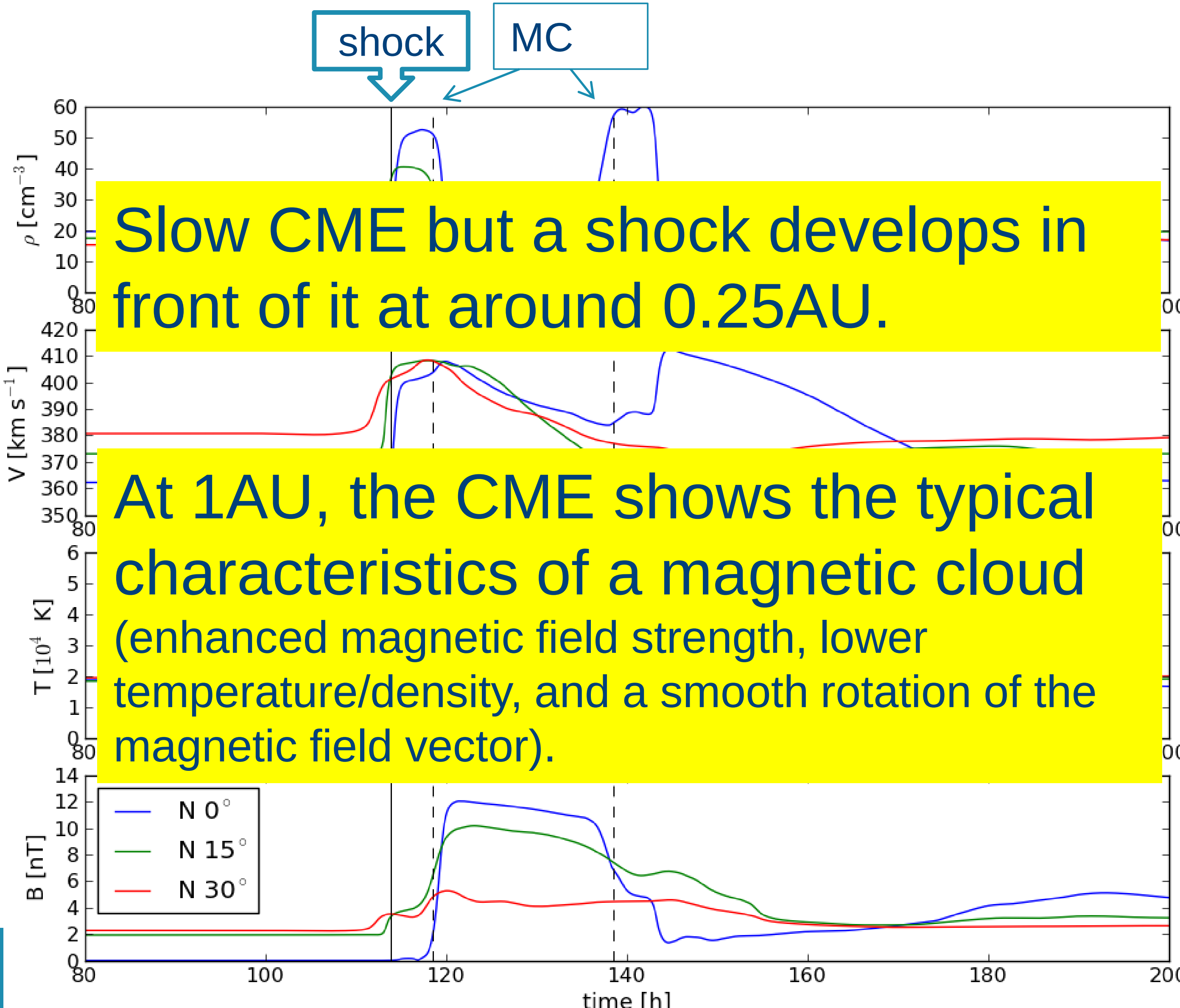


Asymmetric driving, 2.5D parameter study



Radial variation of 3 MHD wave velocities and the velocity of the front of the CME with respect to the background wind (cyan line).

Asymmetric driving, 2.5D parameter study

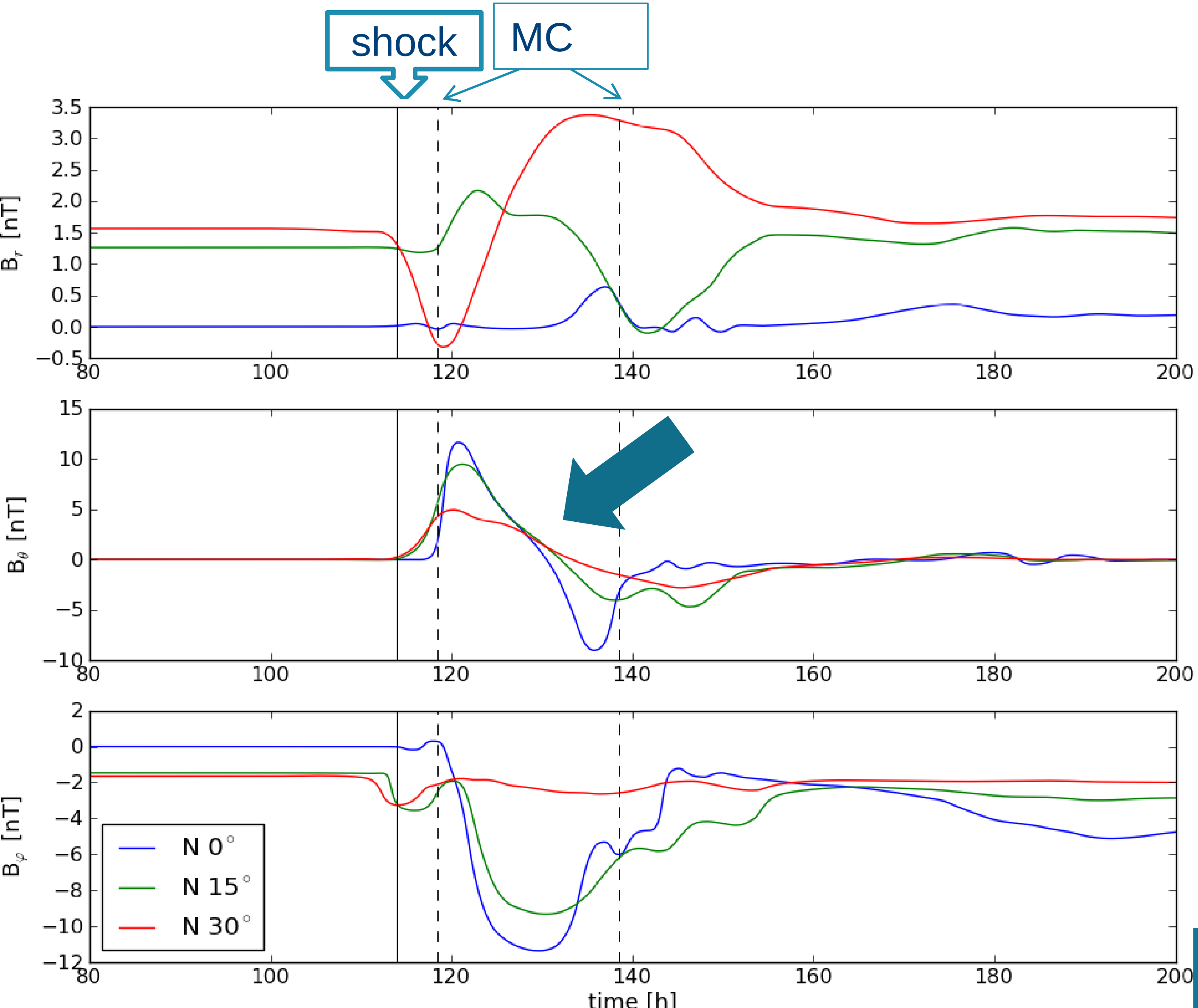


Slow CME but a shock develops in front of it at around 0.25AU.

At 1AU, the CME shows the typical characteristics of a magnetic cloud (enhanced magnetic field strength, lower temperature/density, and a smooth rotation of the magnetic field vector).

Evolution of density, radial velocity, temperature and magnetic field for a satellite in the equatorial plane (blue line), and above the equator 15º (green line) and 30º (red line) measured at 1 AU.

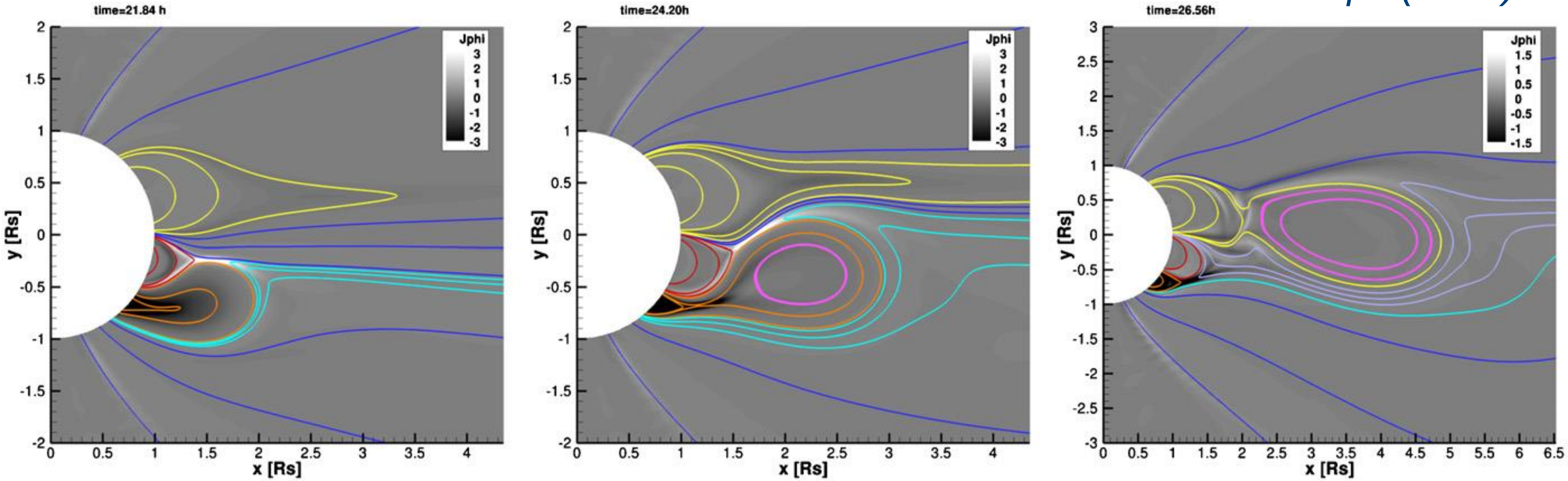
Asymmetric driving, 2.5D parameter study



Evolution of **magnetic field components** for a satellite in the equatorial plane (blue line), and above the equator 15º (green line) and 30º (red line) measured at 1 AU.

Case Study: CME deflection (1/2)

Zuccarello et al. ApJ (2012)



- We impose localized shearing motions along the polarity inversion line of the AR.
- The X-point is shifted northwards and interchange reconnection sets in.
- The southern arcade starts to rise and the prominence is formed.
- Southern arcade flux is transferred partially to central arcade and partially to open field.
- Reconnection at X-point results in a pressure imbalance → northward shift of the CME.
- The **newly formed open flux of the southern coronal hole** reconnects with the flux of the central arcade **definitely separating the flux rope from its formation location** and the flux rope gets absorbed in the northern helmet streamer.

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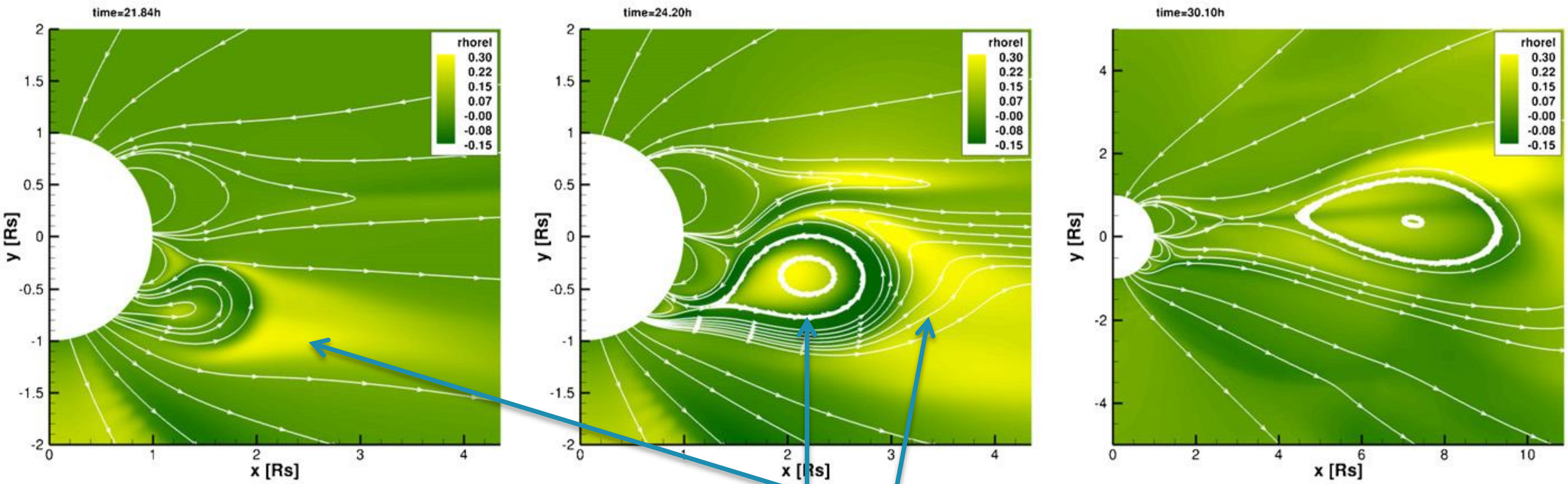
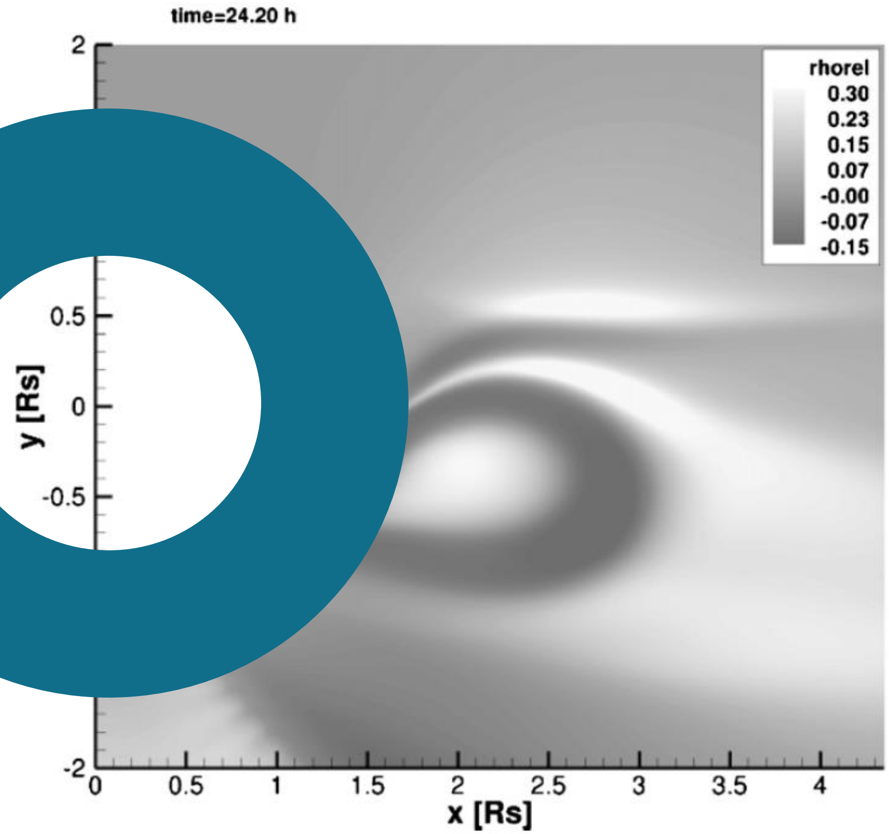
Case Study: CME deflection (2/2)

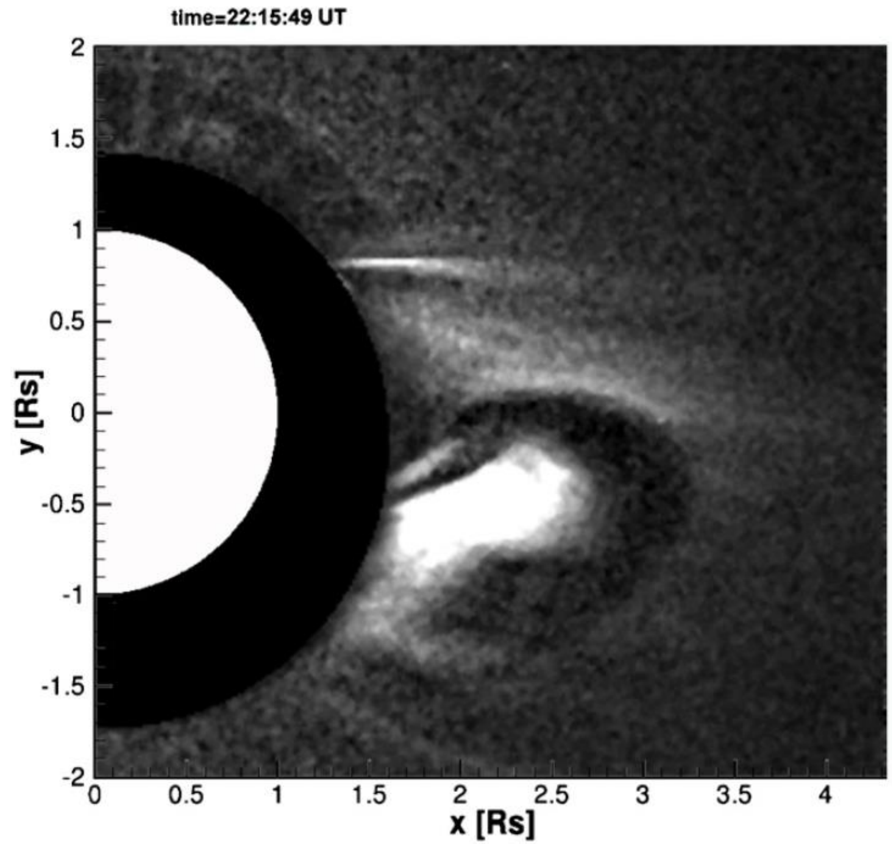
Zuccarello et al. ApJ (2012)



- As a consequence of the expansion, an increase in the relative density is observed at the leading edge of the expanding loops system, while a density depletion is observed behind it.
- An increase in the relative density in the central arcade due to reconnection corresponding to the loop brightening observed in EUV images.

Three-part structure





- When the flux rope is propagating within the COR1 FOV, the high-density core as well as the three-part structure are clearly visible.
- An increase in the relative density in the X-point is visible both in the observations and simulations.

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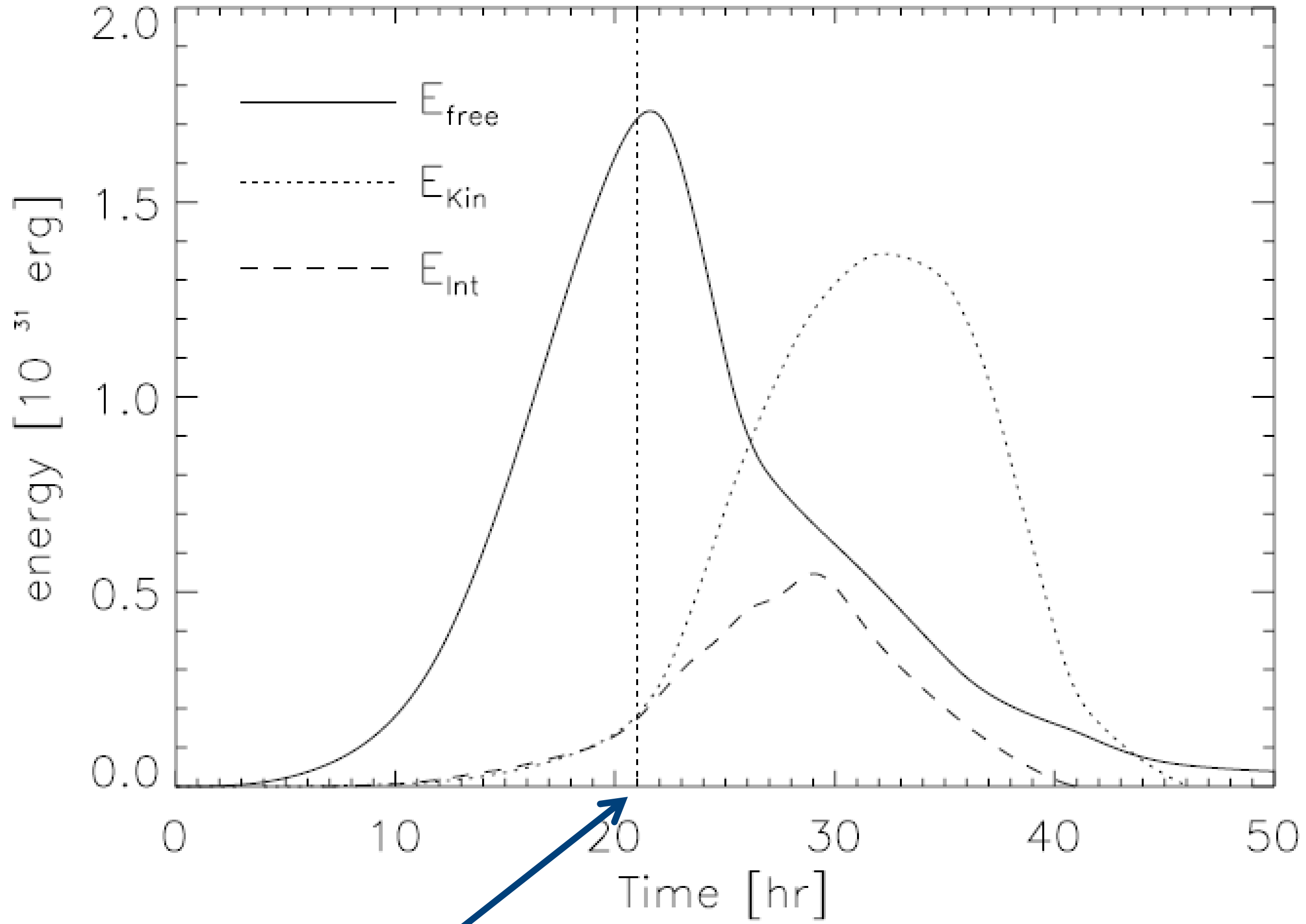
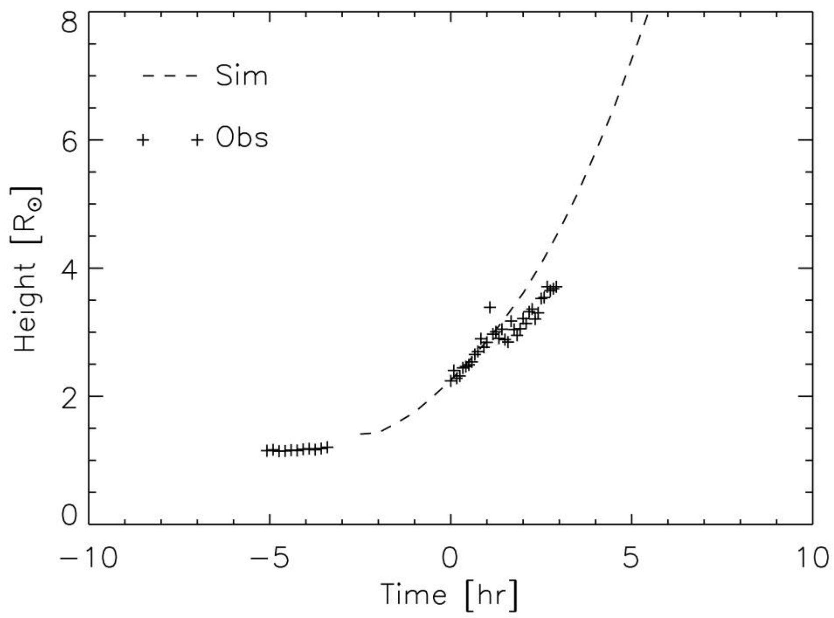
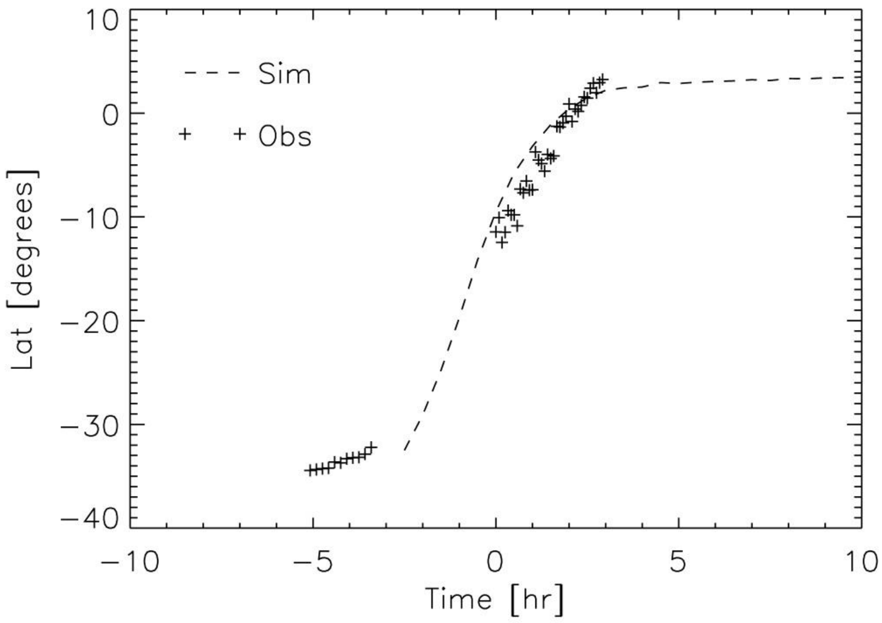
Energetics



Acceleration of flux rope

Radial & Latitudinal Evolution

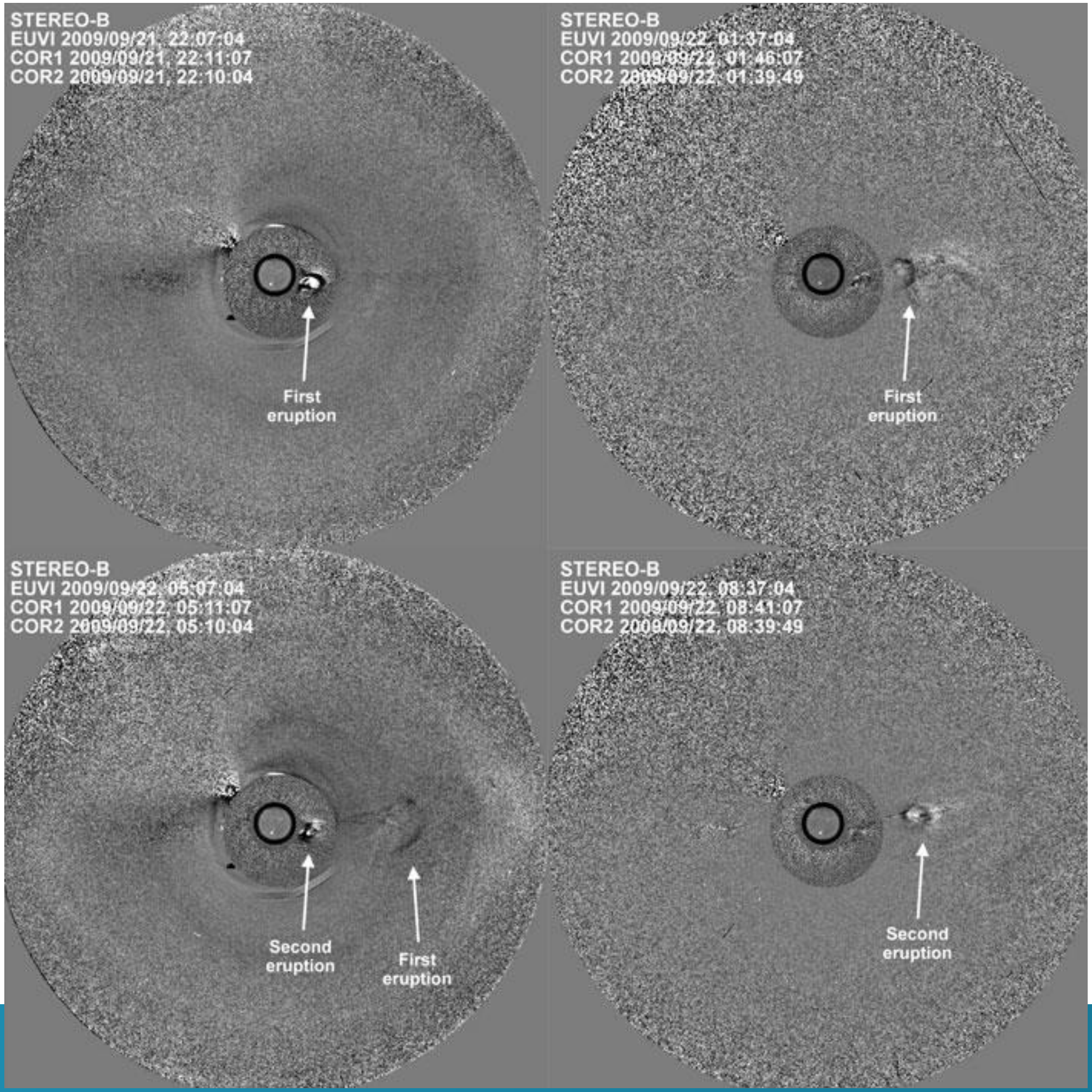




- Time zero is 20:00 UT on 2009 September 21, i.e. the time at which the CME was at $2.25R_0$.
- It takes about 6 hrs to reach an altitude of $4R_0$.
- The CME is deflected by ~20° within the first $2.25R_0$ and by ~16° within the COR1 FOV.

Case Study: sympathetic CMEs (1/3)

Two CMEs from the same location, suggesting they are homologous CMEs

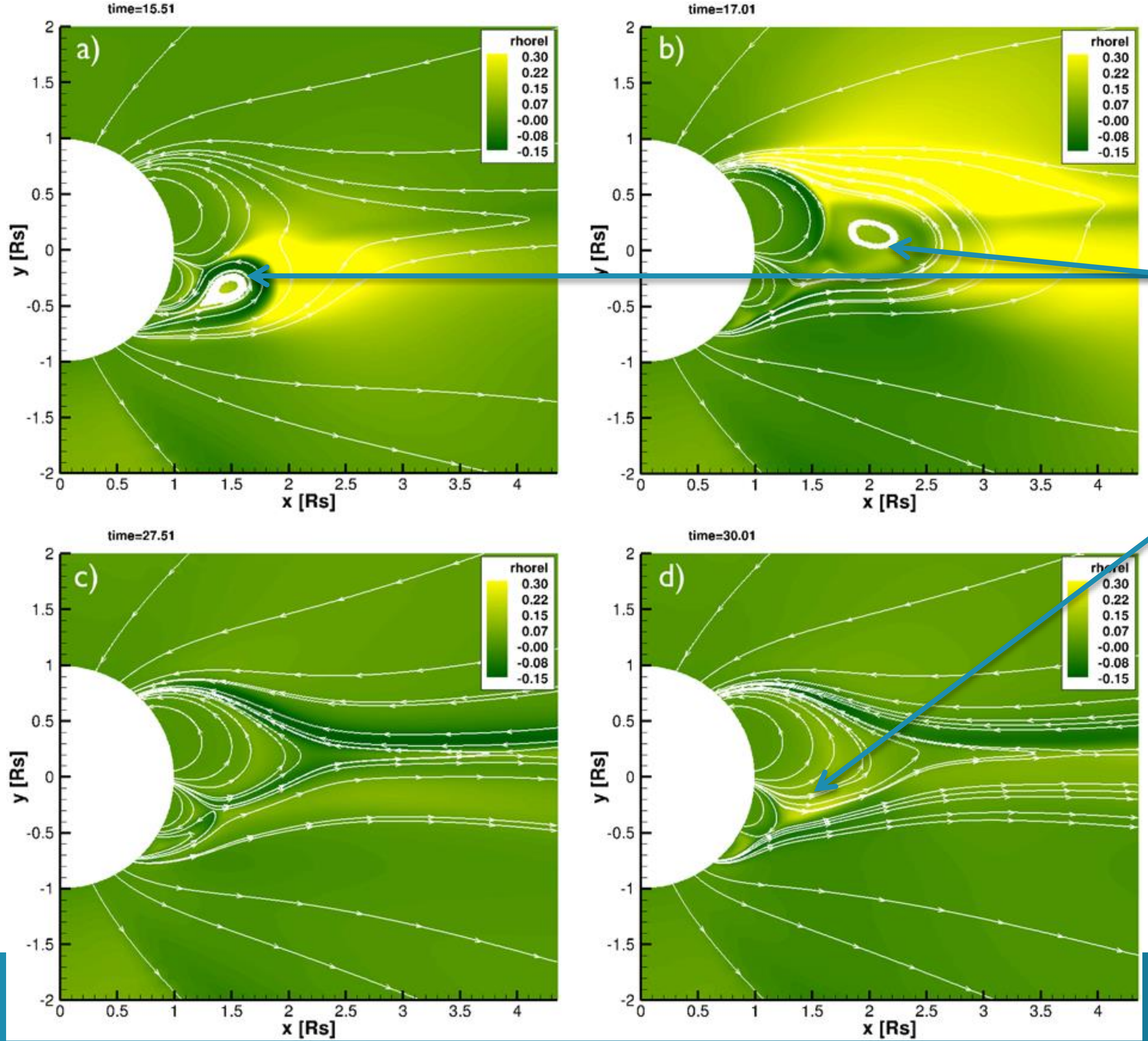


The **first and second eruptions** as seen by the COR1 and COR2 coronagraphs and the EUVI telescope onboard STEREO B; UT times are provided in each panel. Images shown here are **running differences**: typical cadences during the above observational period were 5 min and 15 min for COR1 and COR2, resp.

Zuccarello et al., 2012
Bemporad et al., 2012

Case Study: sympathetic CMEs (2/3)

… but detailed analysis learns they have two different initiation mechanisms:



4 snapshots of relative density

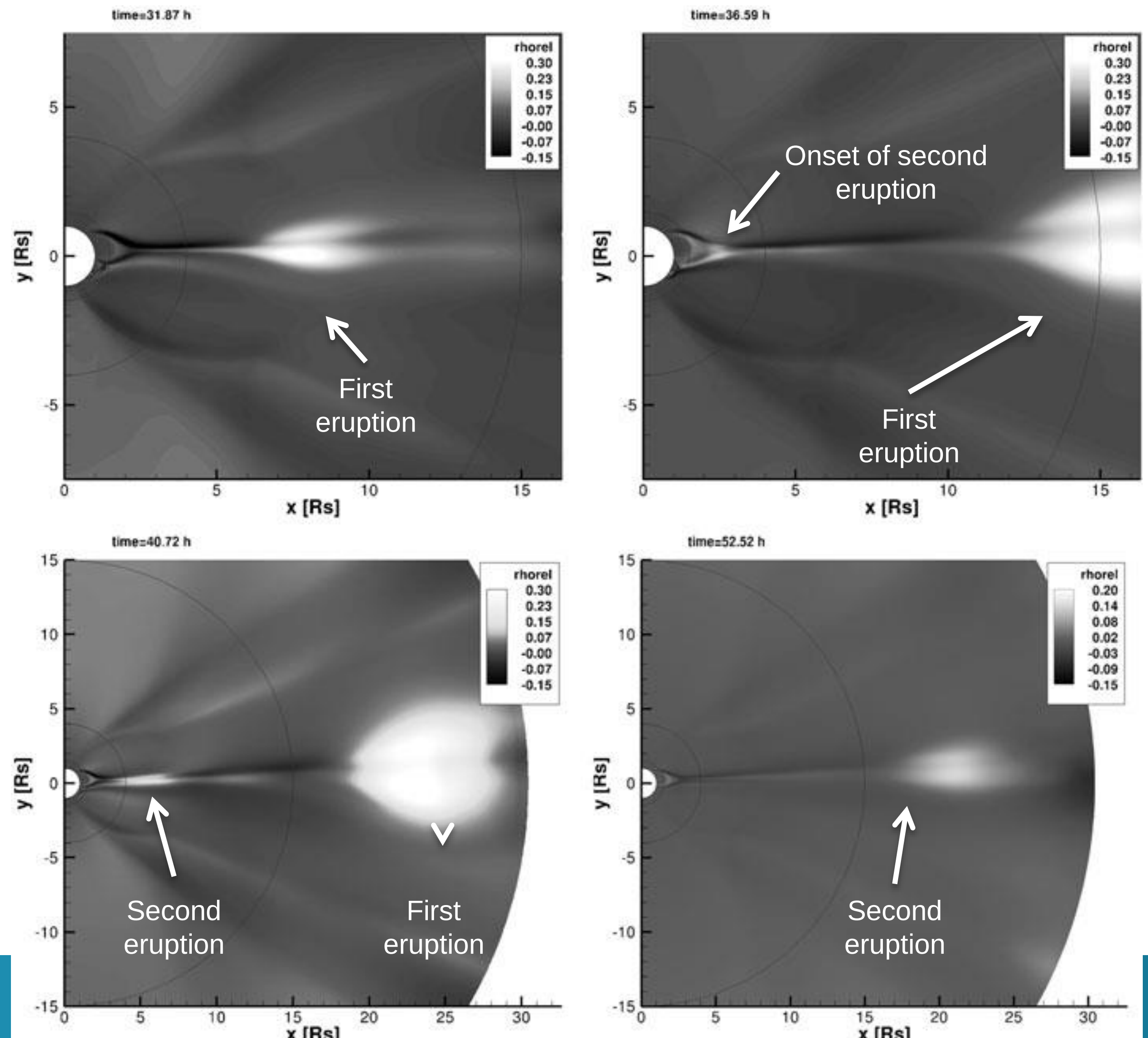
CME1: flux rope eruption (no helmet streamer detachment in this case)

CME2: triggered by the rearrangement of the overlying field

Zuccarello et al., 2012
Bemporad et al., 2012

Case Study: sympathetic CMEs (3/3)

The magnetic flux of CME2 is partially transferred to CME1



4 selected snapshots of the evolution of the relative density (relative to the steady-state background solar wind density) as both simulated CMEs are ploughing through the COR1 and COR2 FOVs

Zuccarello et al., 2012
Bemporad et al., 2012

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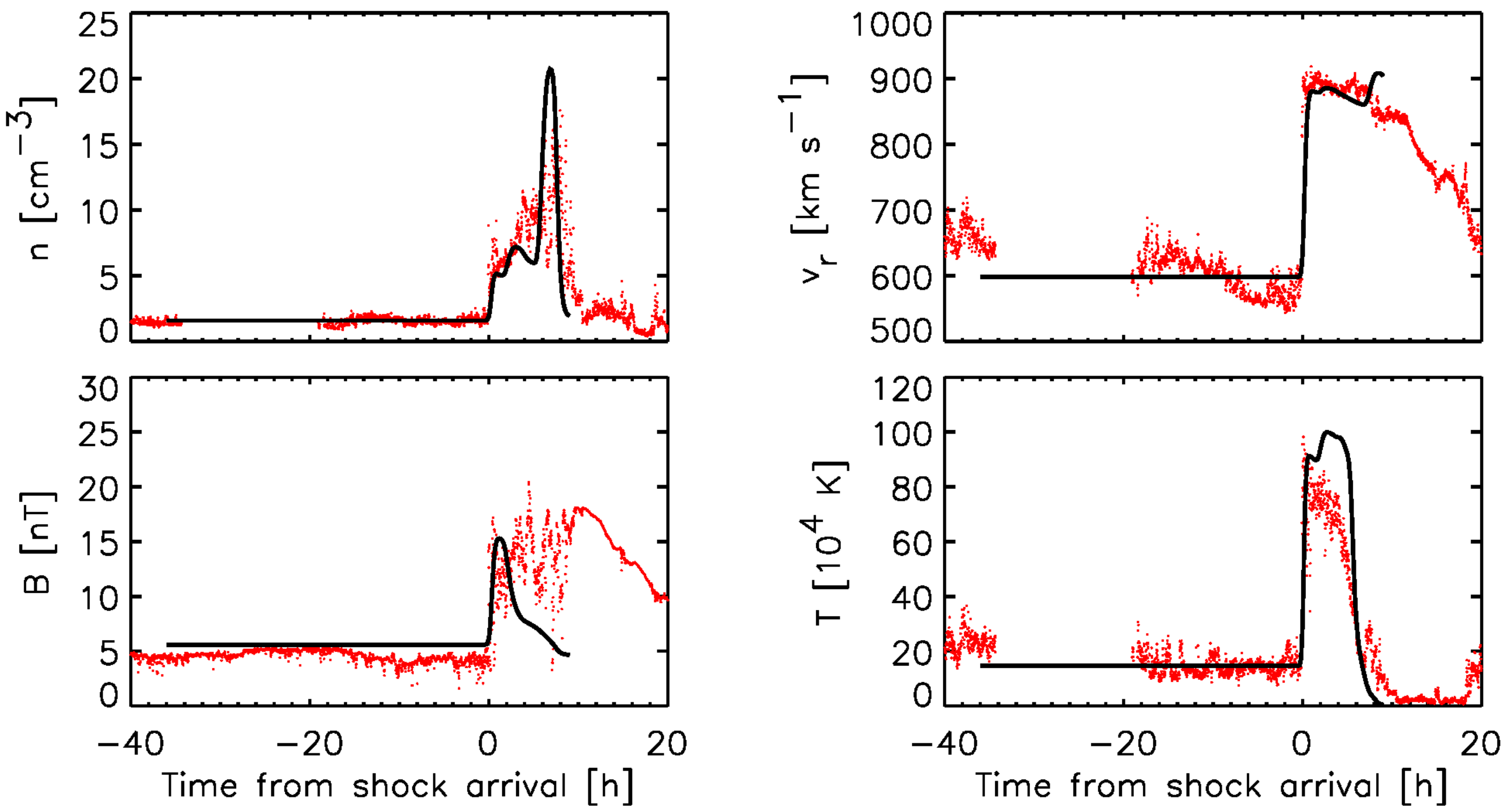
Linking MHD and particle simulations

- Combining a Sun-to-Earth MHD simulation of the propagation of a CME-driven shock and a simulation of the transport of particles along the interplanetary magnetic field (IMF) line connecting the shock front and the observer (cf. SOLPENCO)

2D CME Modelling



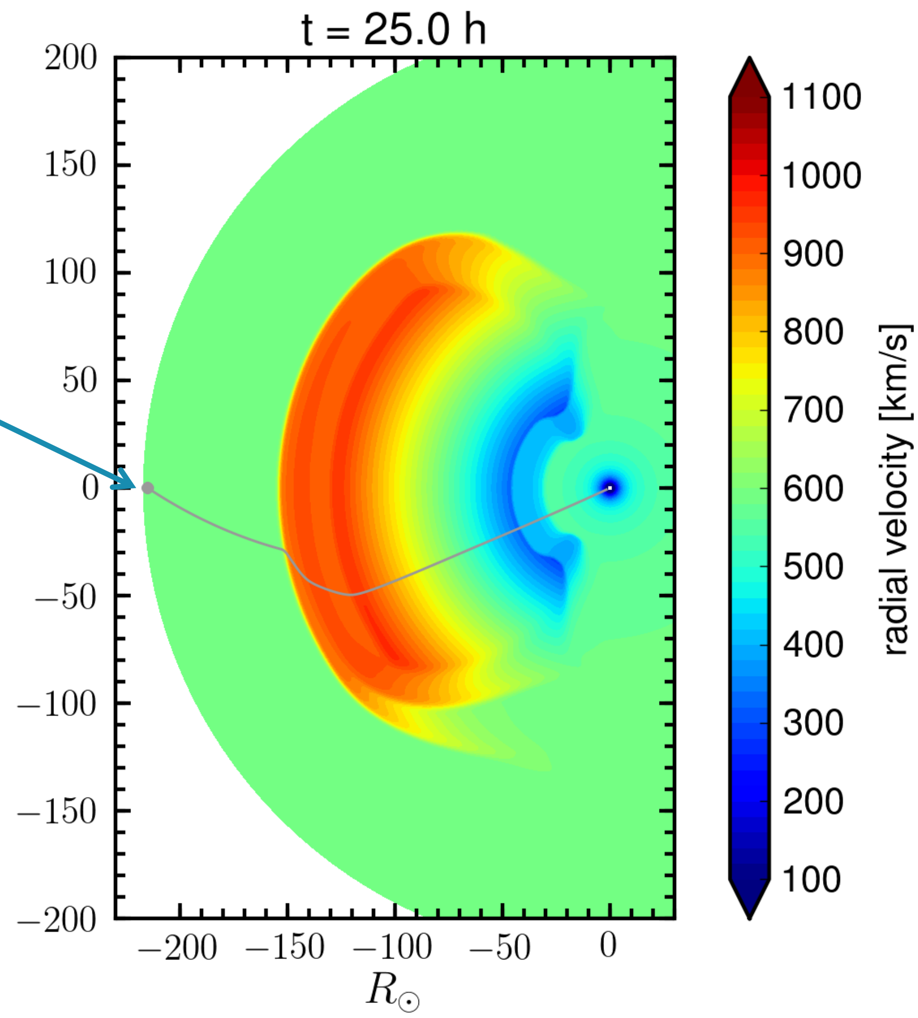
Pomoell et al. (2014)

Example: December 13, 2006 event

Black: model, Red: in-situ observations at 1 AU

Linking MHD and particle simulations

1) Magnetic field line passing through the *observer* is traced

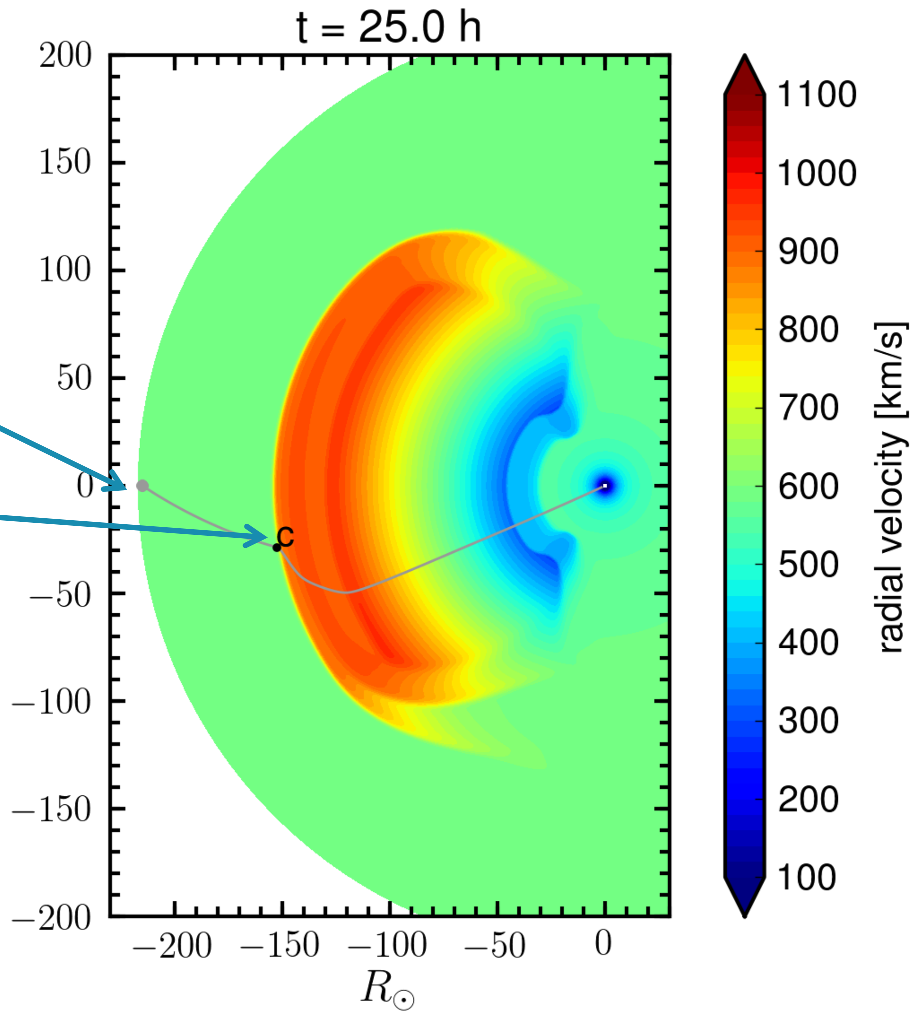


Pomoell et al. (2014)

Linking MHD and particle simulations

1) Magnetic field line passing through the *observer* is traced

2) The location where the field line connecting to the shock is located = *cobpoint*



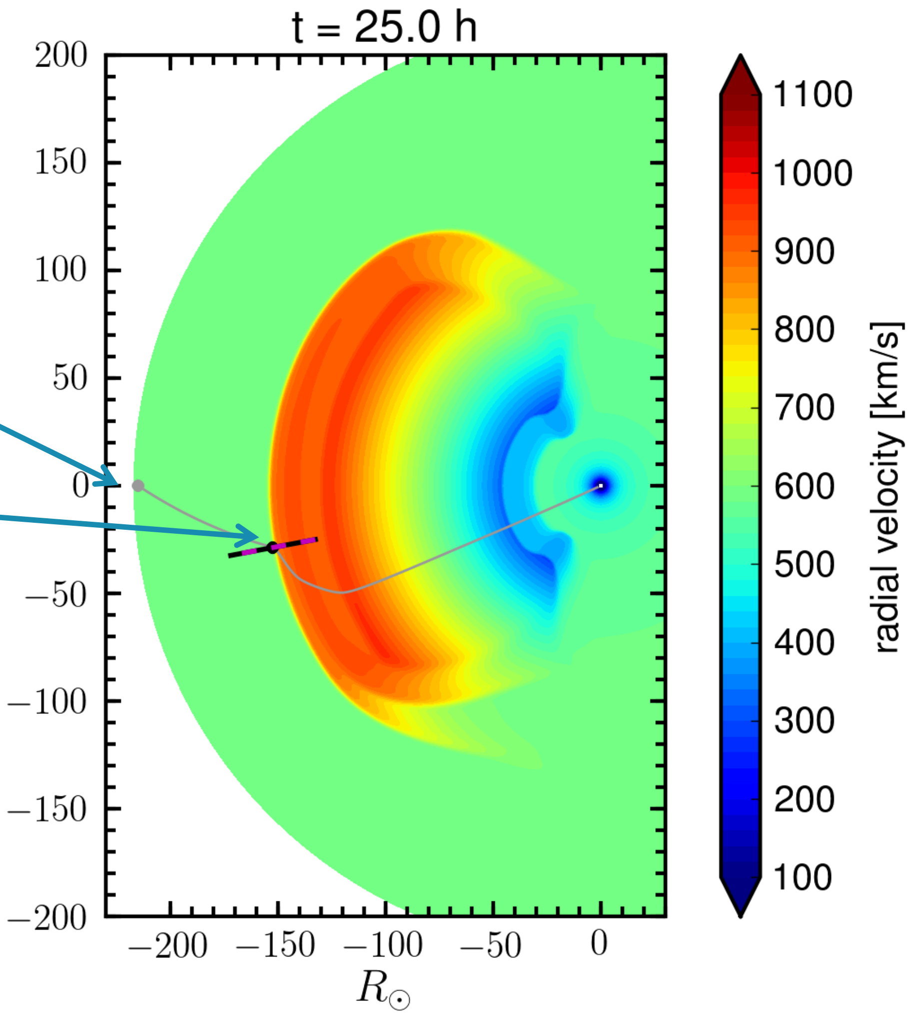
Pomoell et al. (2014)

Linking MHD and particle simulations

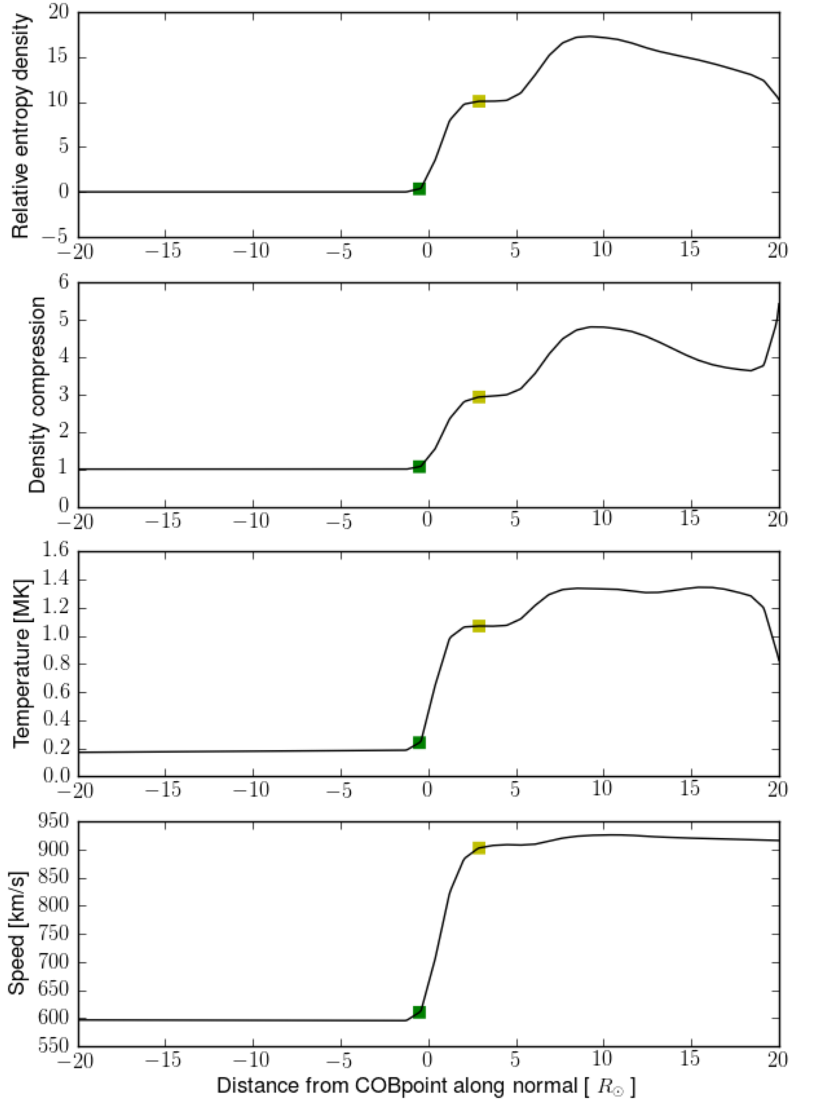
1) Magnetic field line passing through the *observer* is traced

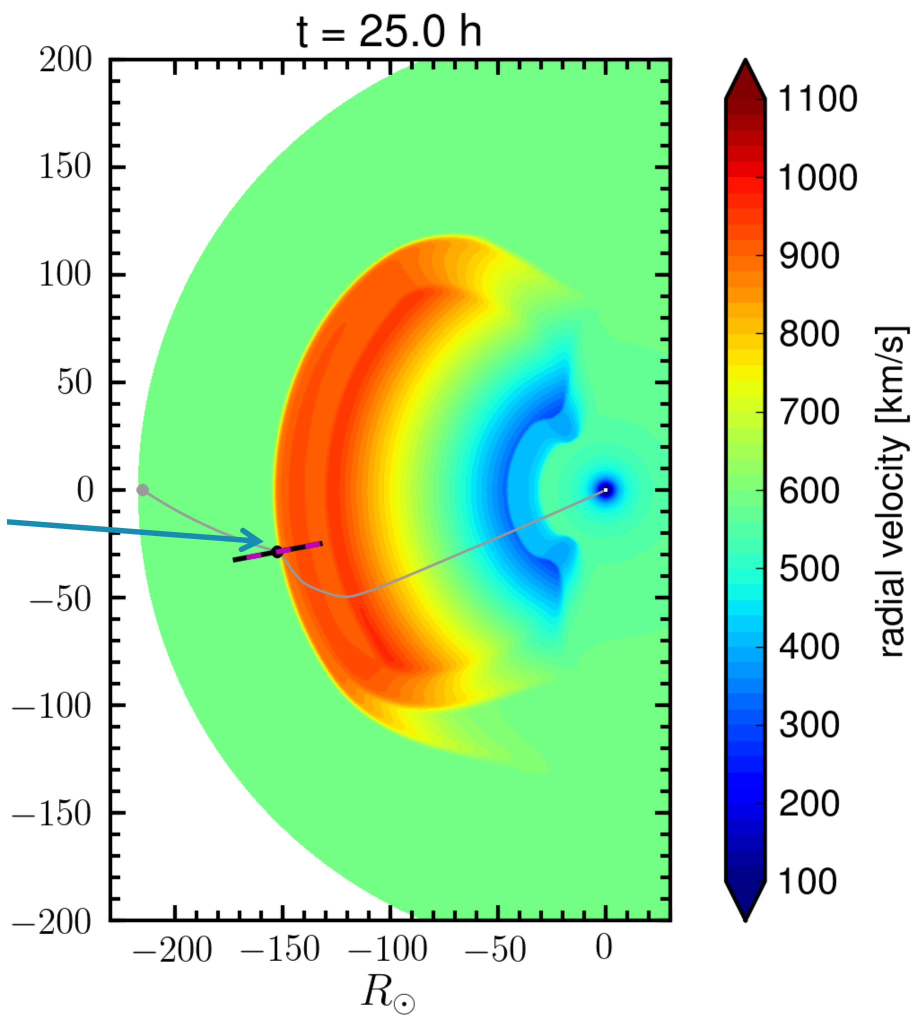
2) The location where the field line connecting to the shock is located = *cobpoint*

3) The parameters of the shock (e.g. shock normal) at the cobpoint are computed. These parameters as a function of time are then fed to the particle simulation



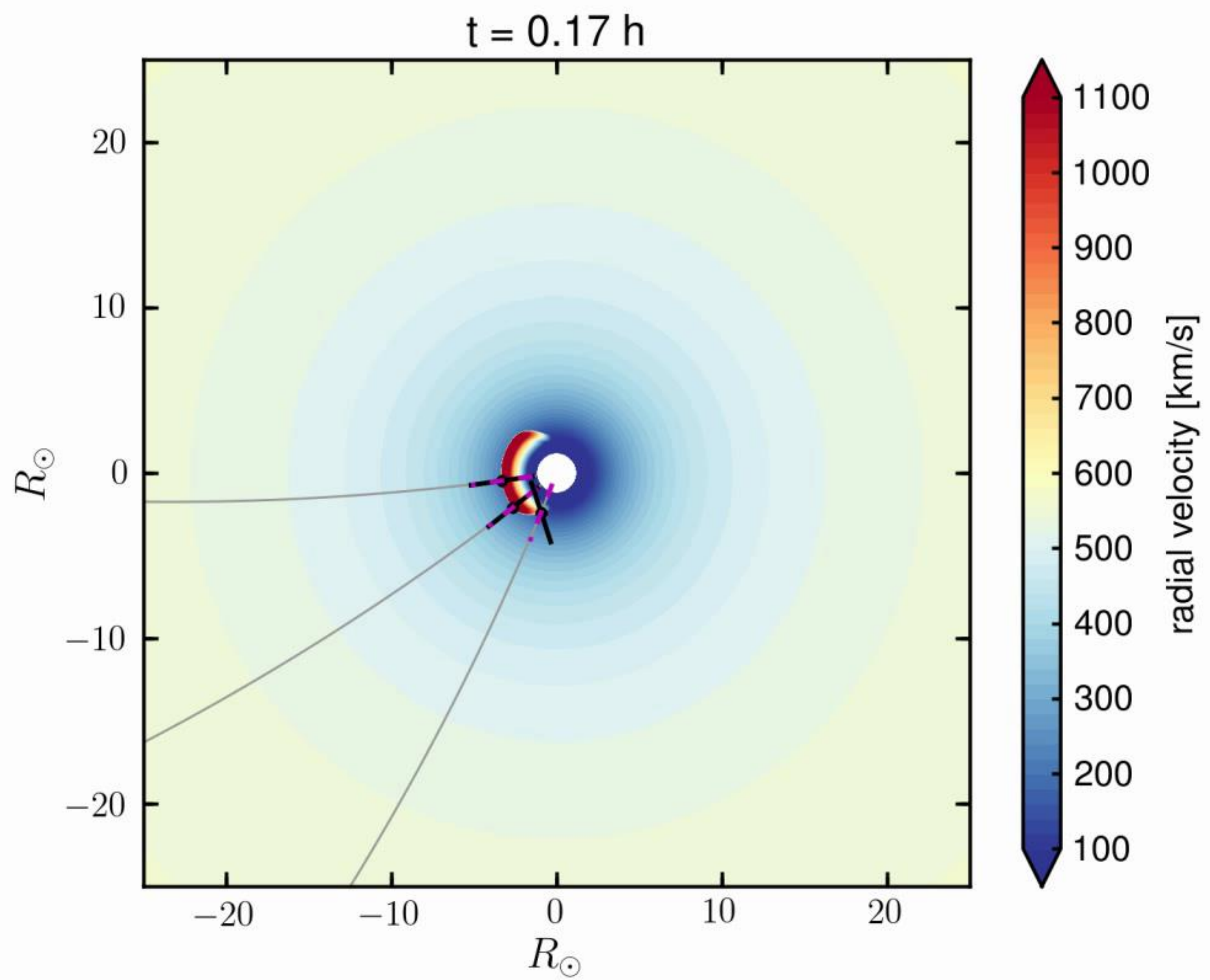
Linking MHD and particle simulations





MHD model of the December 13, 2006 event

Pomoell et al. (2014)

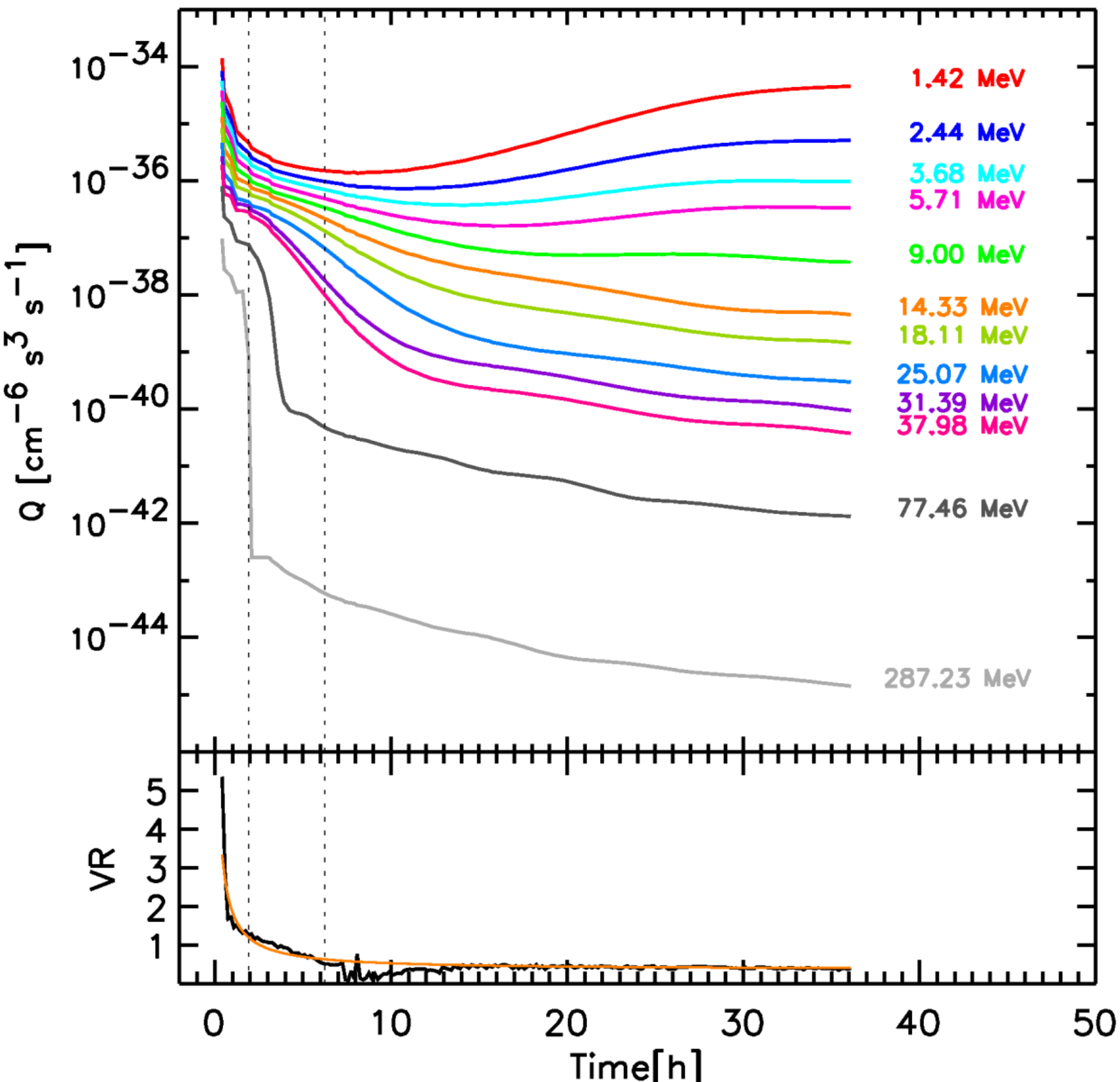


MHD model of the December 13, 2006 event

Top: Evolution of the injection rate of shock-accelerated protons at the cobpoint, Q, for a subset of modelled energy channels for the 2006 December 13 SEP event.

The bottom panel displays the evolution of the VR parameter.

Pomoell et al. (2014)



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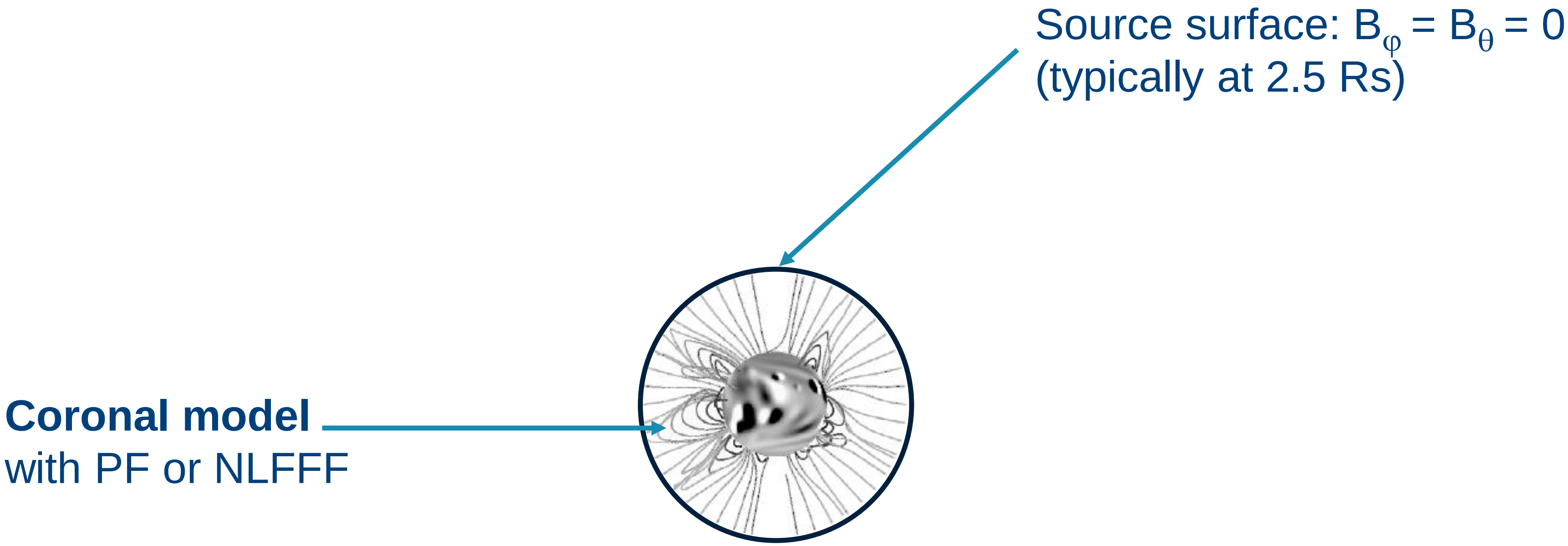
Heliosperic CME evolution model

- Data-driven solar wind with super posted CME evolution (cf. ENLIL)

Solar wind modeling

Taking coronal model as lower boundary condition



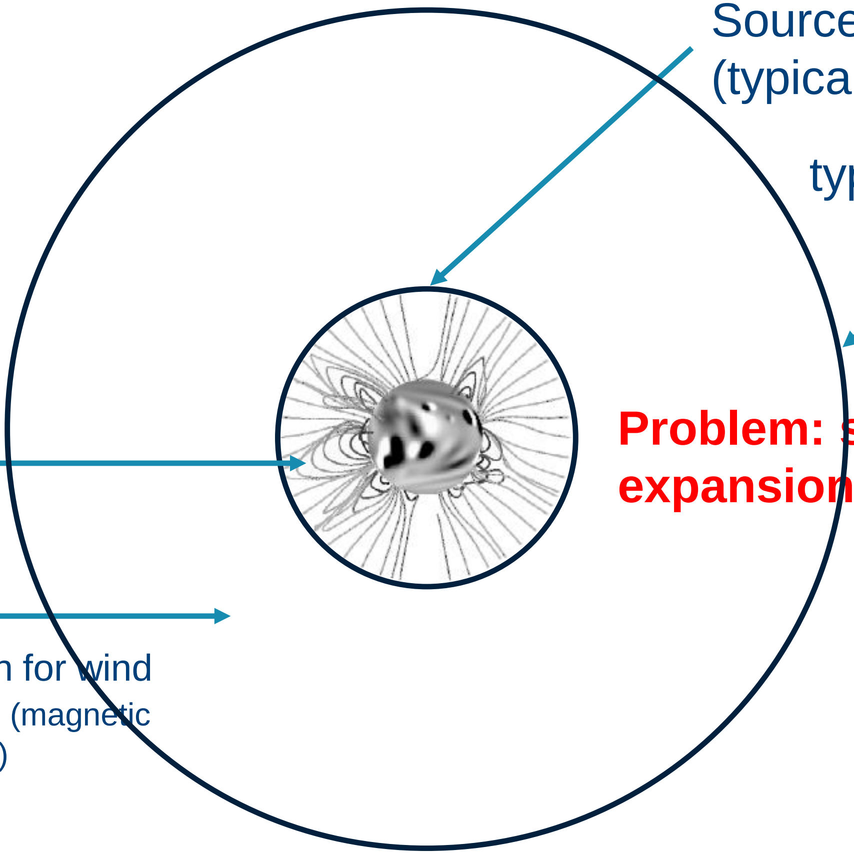
- Potential field source surface (PFSS) model (e.g. Wang & Sheeley; DeRosa & Schrijver,..)
- CORHEL/MAS model (Linker et al.)
- SWMF/S.C.-IH (van der Holst et al.)
- Nonlinear force-free field (NLFFF) models (Yeates & MacKay; Tadesse, Wiegelmann, et al.)
- AMR–CESE–MHD model (Feng et al. 2012)

Solar wind modeling

Taking coronal model as lower boundary condition

Source surface: $B_\varphi = B_\theta = 0$
(typically at 2.5 Rs)

typ. at about 21.5 Rs (0.1 AU)



Problem: super-radial expansion of flux tubes

Coronal model
with PF or NLFFF

WSA model
Semi-empirical relation for wind speed as function of f_s (magnetic flux tube expansion factor)

Solar wind modeling

Taking coronal model as lower boundary condition

Source surface: $B_\varphi = B_\theta = 0$
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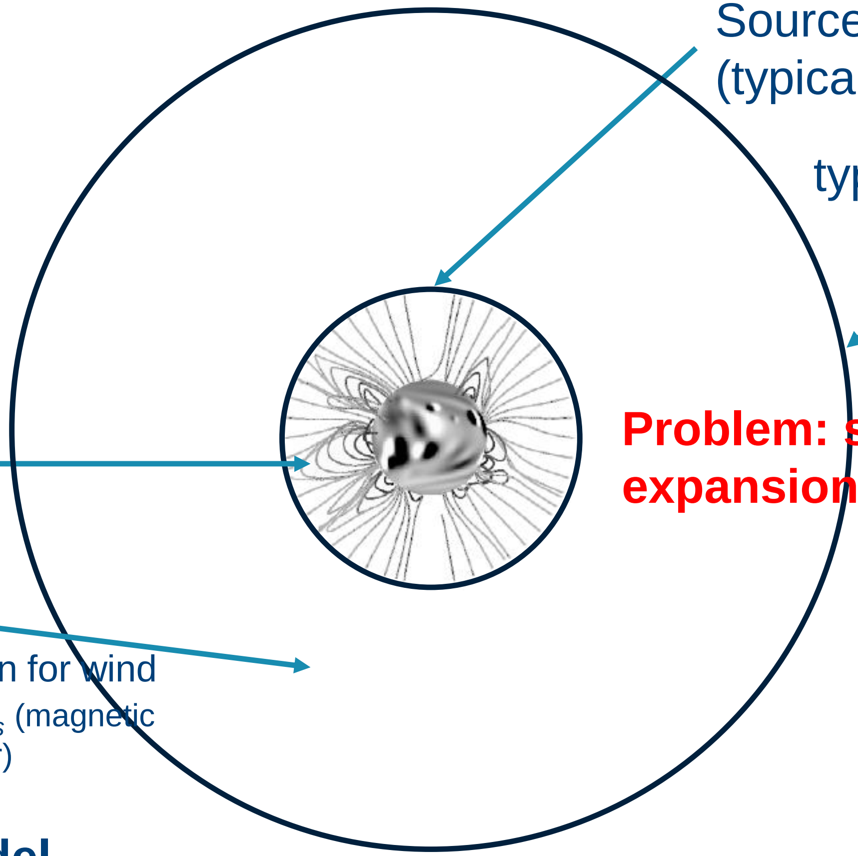

Coronal model
with PF or NLFFF

Problem: super-radial expansion of flux tubes

WSA model
Semi-empirical relation for wind speed as function of f_s (magnetic flux tube expansion factor)

MHD wind model
ENLIL, SWMF, **EUHFORIA**, …

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Coronal model

AIM: Produce plasma condition at r = 0.1 AU as input to MHD model

INPUT: GONG synoptic LOS magnetograms (updated every hour)

METHOD:

- **PFSS field extrapolation** using hybrid FFT (in azimuthal direction) and second order finite differences (in meridional plane)
- **Current sheet model** (Schatten) beyond the source surface
- Determination of CHs, distance to nearest CH, FT expansion factor etc., from the PFSS+CS model, i.e. various applications of field line tracing
- Based on parameters determined from the PFSS+CS model, use **semi-empirical formulas for the solar wind speed at r = 5 R_{Sun}**
- **Translate the speed at r = 5 R_{sun} to 0.1 AU**, other plasma variables set according to semi-empirical considerations

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Heliosphere model with CMEs

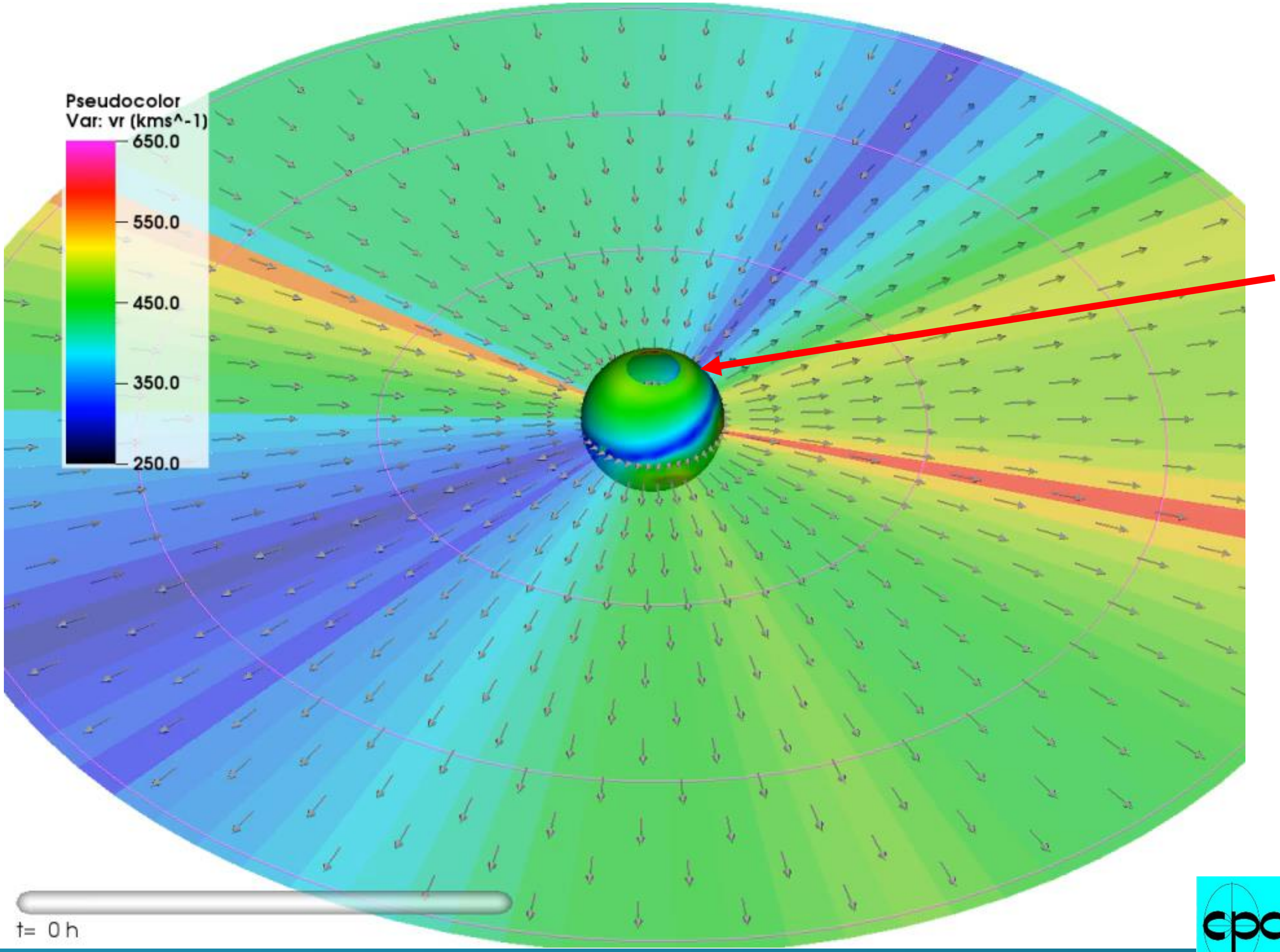
AIM: Compute time dependent evolution of MHD variables from 0.1 AU to 1 AU and beyond (up to a few AU)

INPUT: Plasma properties at 0.1 AU from coronal model, cone model CME parameters from fits to observations

METHOD:

- Second order finite volume MHD scheme
- Python matplotlib / VisIt for visualization

Very first test Euhforia



3D visualization of **MHD relaxation** in low resolution (same as ENLIL) 0.1 AU - 1 AU

Color = radial velocity (initially extended)
Arrows = magnetic field (initially radial)

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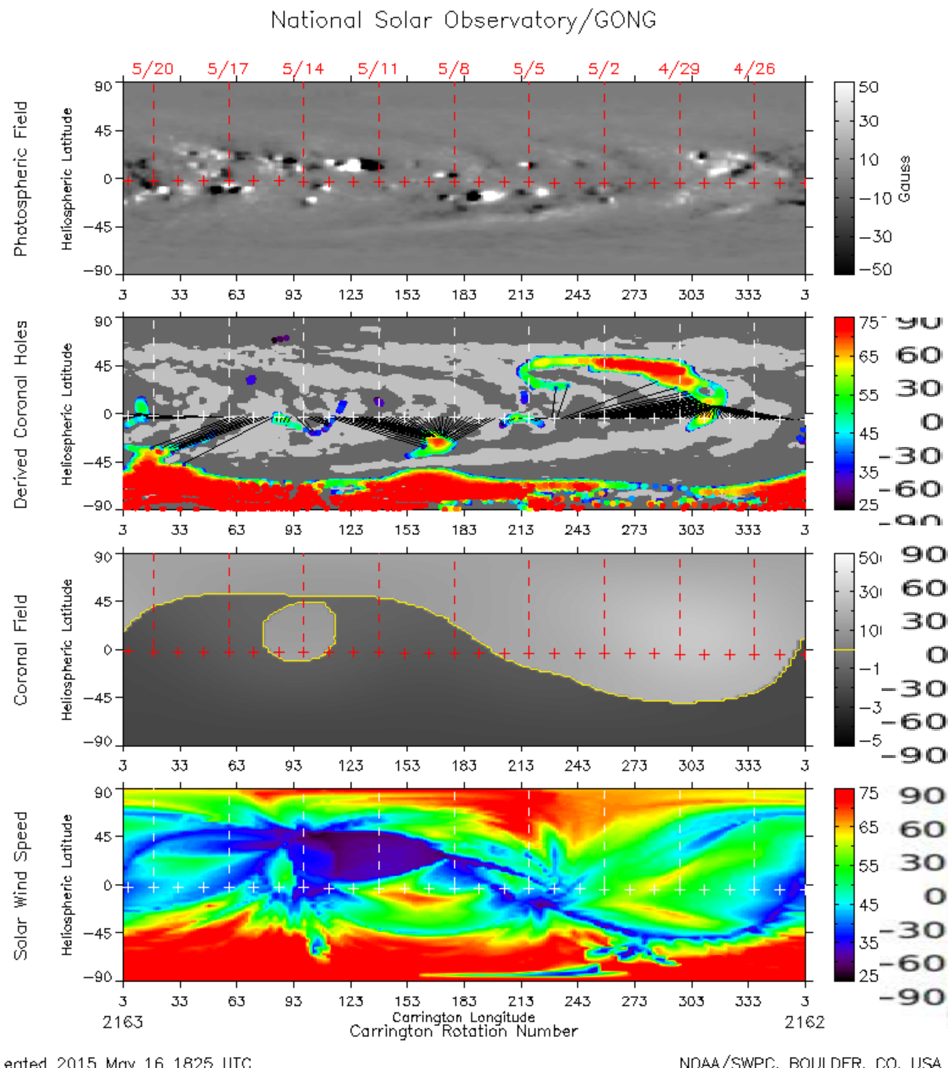
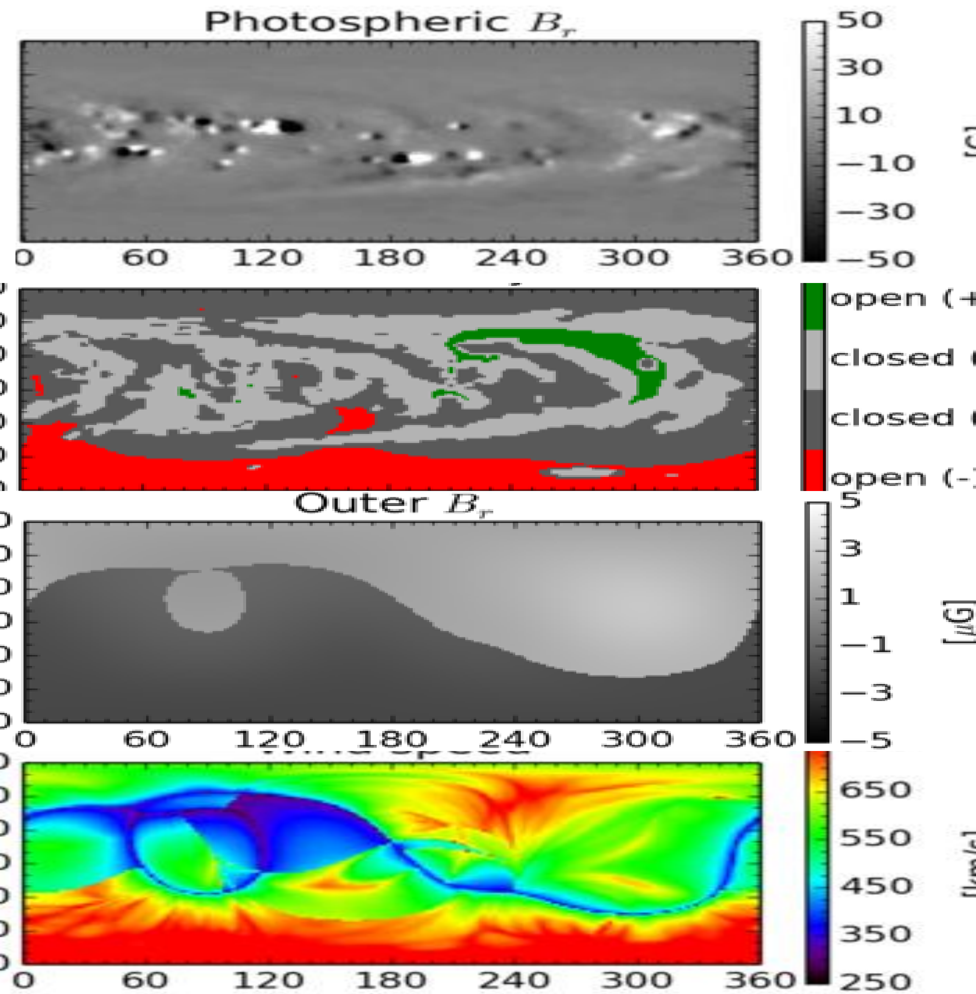
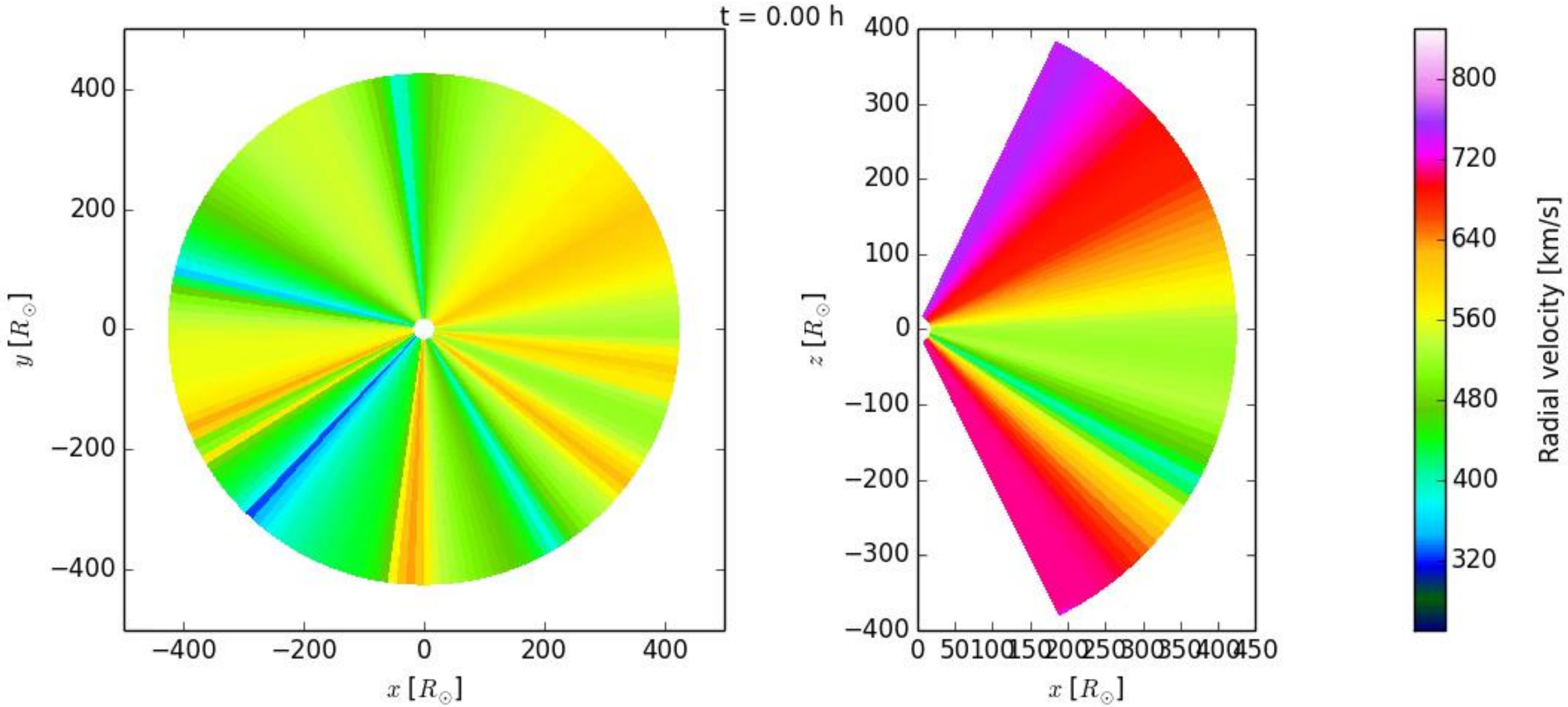
Comparison with WSA

Plot in WSA style (http://legacy-www.swpc.noaa.gov/ws/gong_all1.html





More conventional view for 2nd relaxation
(at double resolution)



More conventional movie of MHD relaxation
(ENLIL style, but twice ENLIL resolution)

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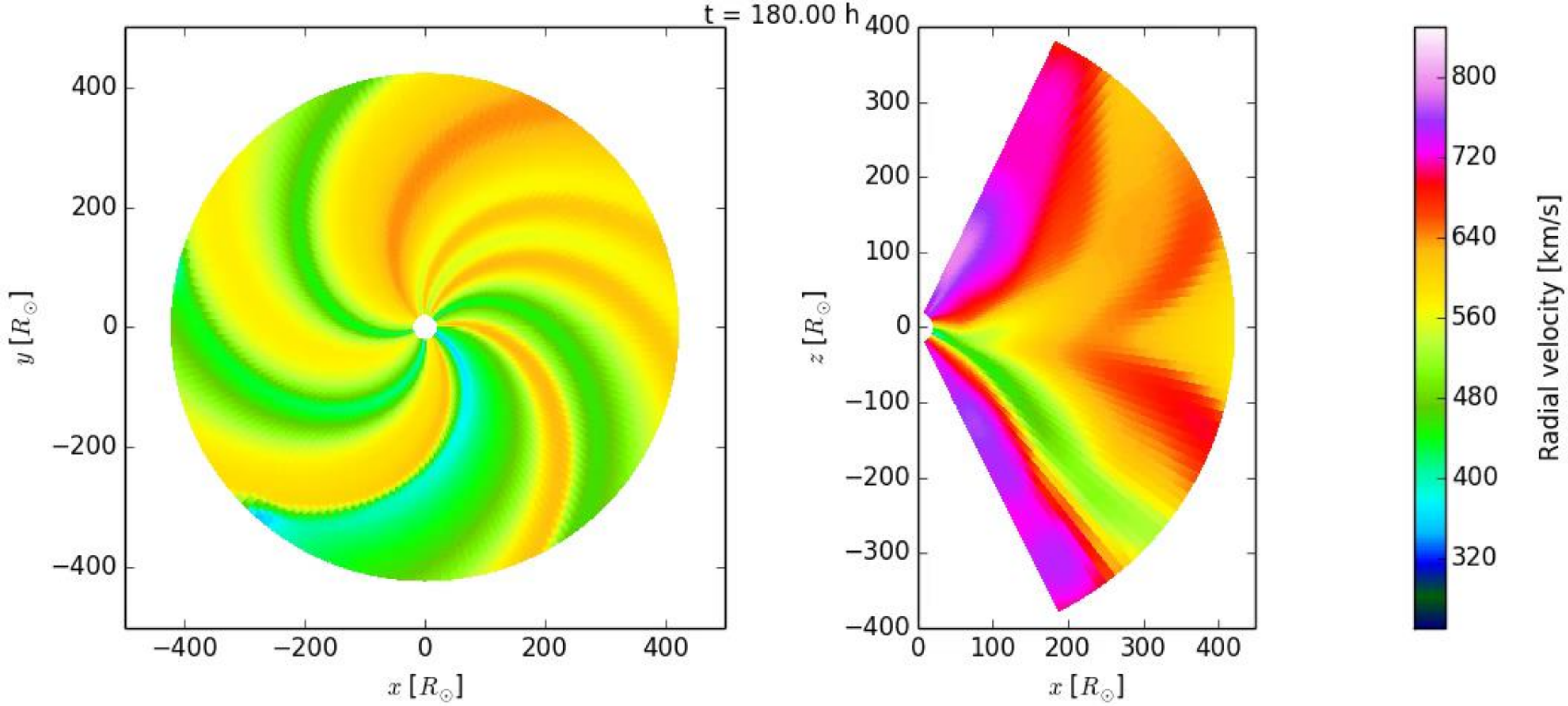
Ballistic CME test
(same background wind)



Superposition of a cone CME, introduced with a time-dependent BC at 0.1AU

Operational mode test

# CME event list					
# Time of CME at 21.5Rs	Lat [deg]	Lon [deg]	Width/2 [deg]	Speed [km/s]	flags
2012-12-19T01:00:00	-9.0	-60.0	45.0	8.500e+02	1
2014-12-17T04:28:00	-3.0	-34.0	17.0	1103.0	1
2014-12-17T08:39:00	30.0	5.0	29.0	603.0	1
2014-12-19T01:12:00	-9.0	-20.0	45.0	885.0	1
2014-12-19T02:28:00	-7.0	-90.0	14.0	544.0	1
2014-12-19T21:48:00	6.0	-83.0	22.0	337.0	1
2014-12-20T04:09:00	-43.0	23.0	25.0	964.0	1
2015-04-17T10:00:00	-9.0	-22.0	45.0	8.000e+02	1
2015-04-19T05:00:00	-19.2	22.0	50.0	9.000e+02	1

- Strong CME on 19/12/2014 at 1:12AM → **simulate this one!**
- Actually 6 CMEs (2 earlier and 3 later, the last one also strong)
- Use magnetogram of 19/12/2014 at 1:00AM (from GONG), and
  - calculate PFSS and relax for 10 days → 04-14/12/2014
  - Inject the CME *(and the CMEs before it)* → 14-19/12/2014
  - Predict the evolution of the CME*(s)* → starting from 19/12/2014, 1:12 AM

  → **Three phases are identified in next movie** *(normally only last two will be shown)*

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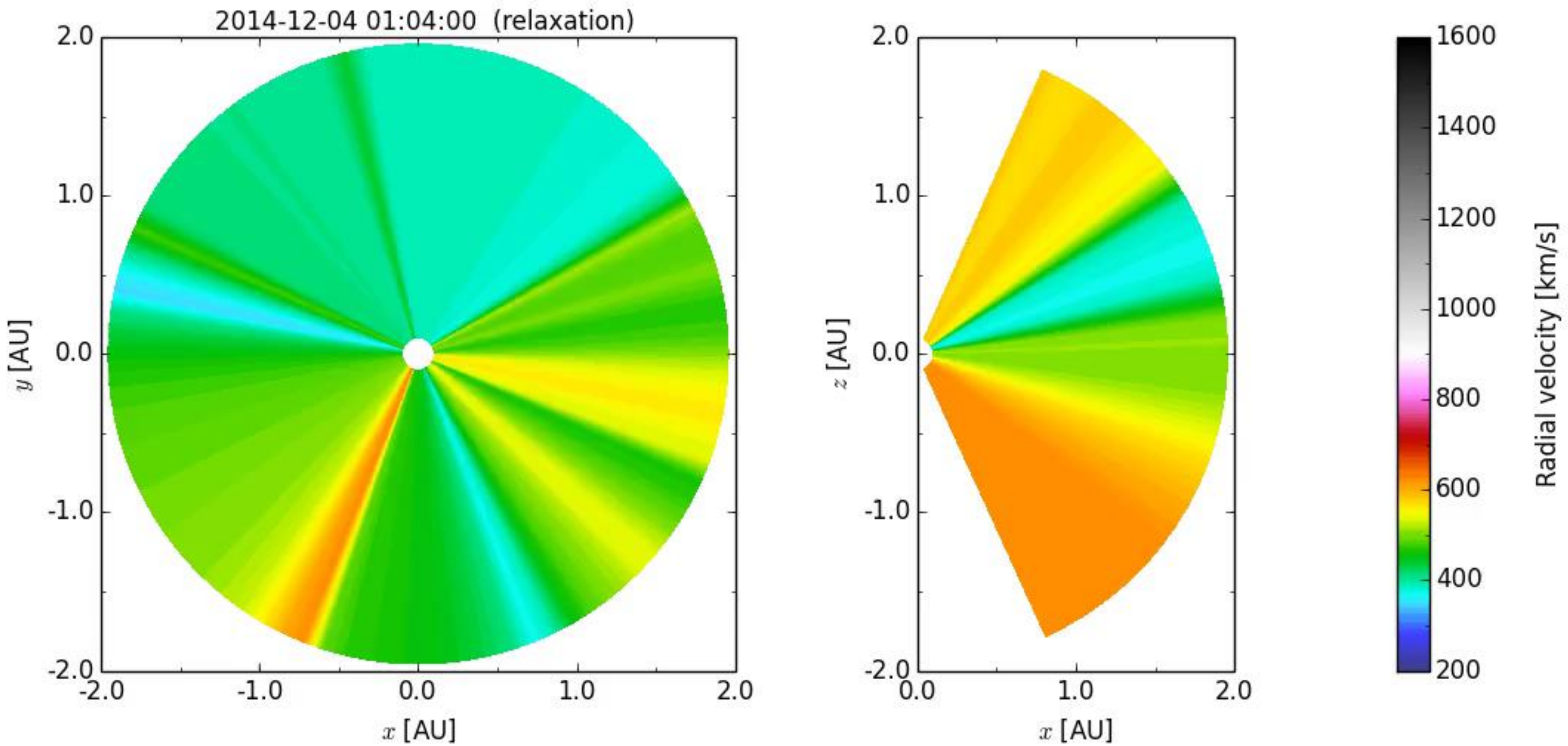
Three phases of simulation: V_r



- calculate PFSS and relax for 10 days → 04-14/12/2014
- Inject the CME *(and the CMEs before it)* → 14-19/12/2014
- Predict the evolution of the CME*(s)* → from 19/12/2014, 1:12 AM

Euhforia: current status

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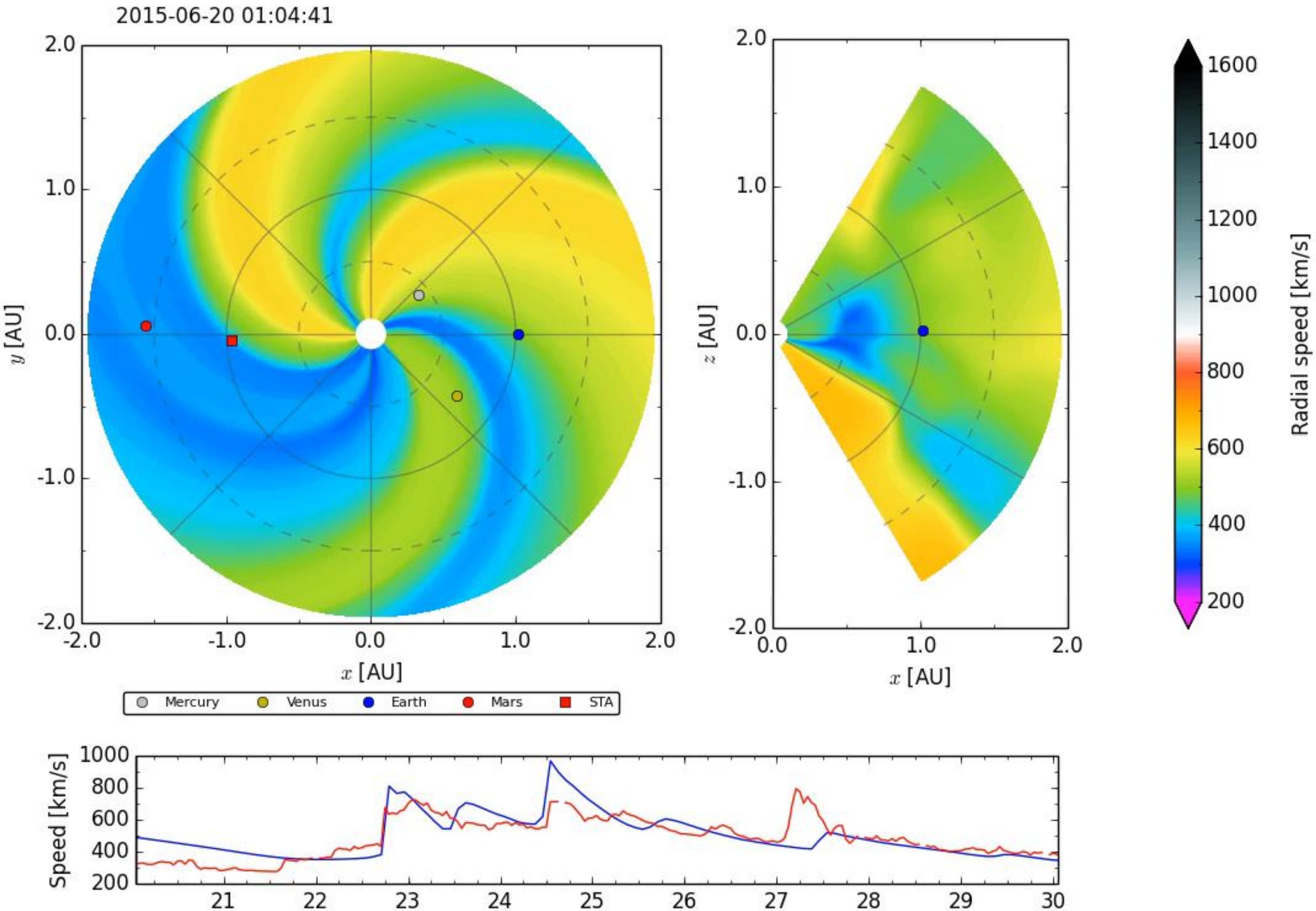
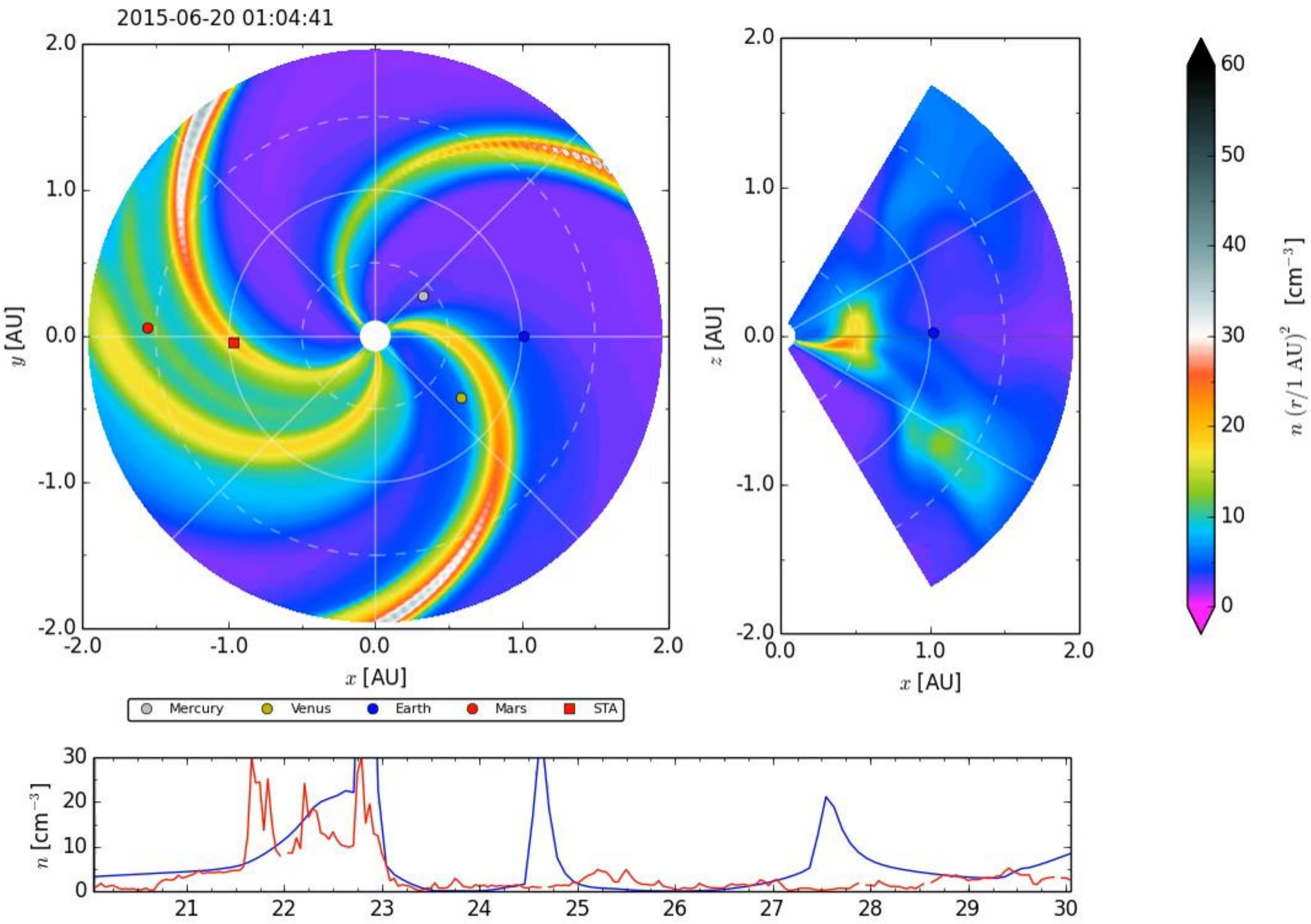
Current status

- **Code installed and results reproduced at ROB** → being integrated in forecast procedures
- **Validation (comparison with ENLIL) ongoing**
  - Same color table as ENLIL implemented (for easy comparison)
- **Synthetic ACE data & plots at 1 AU now implemented**

Improved plotting: *radial velocity* V_r

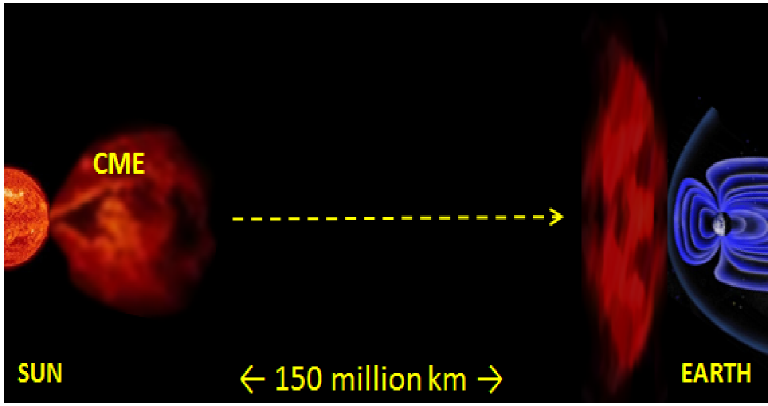


Improved plotting: *numer density n*



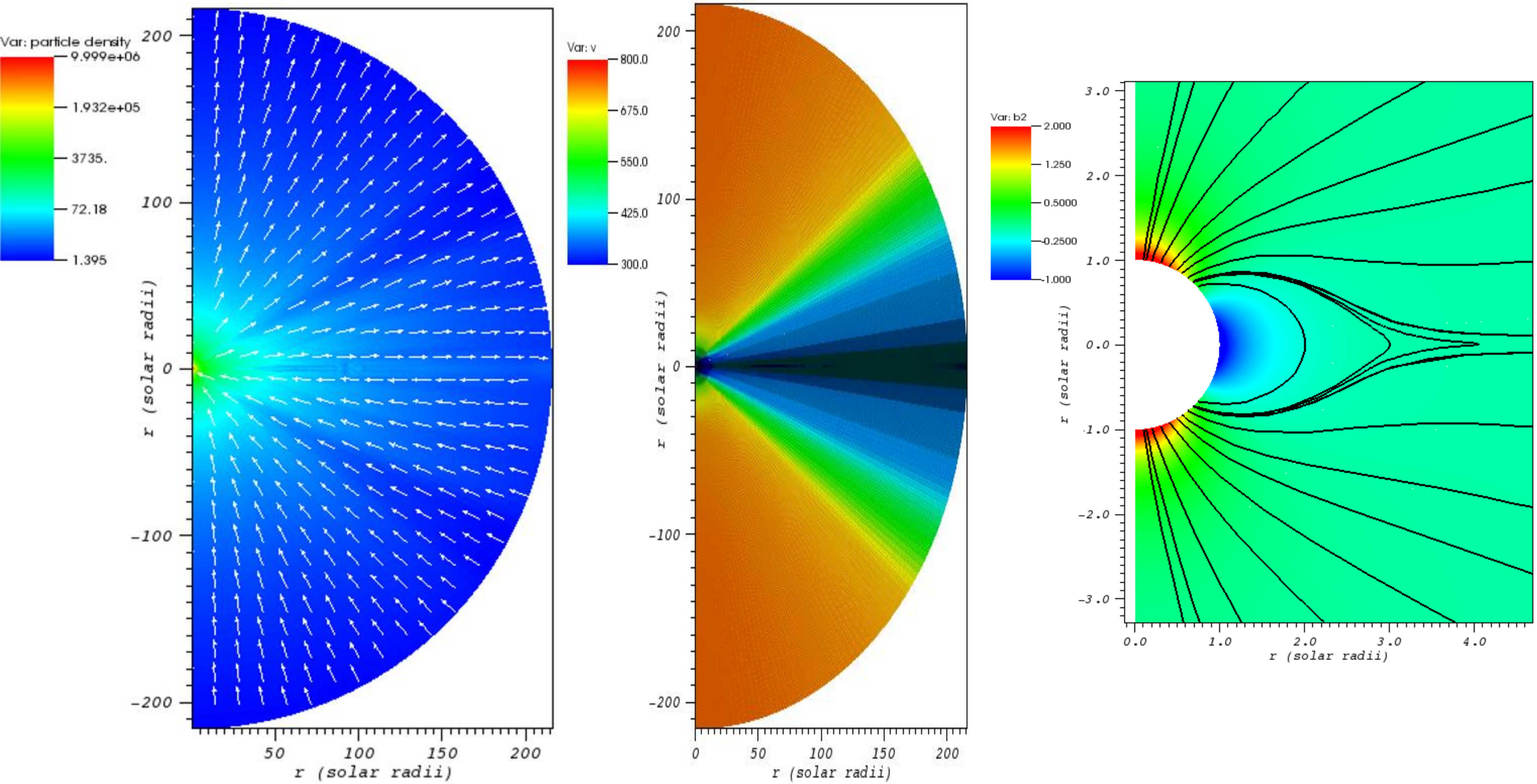
CME evolution mysteries

- **CMEs evolve considerably** during their long journey from the Sun to the Earth and this evolution **may significantly affect their ability to be geo-effective**



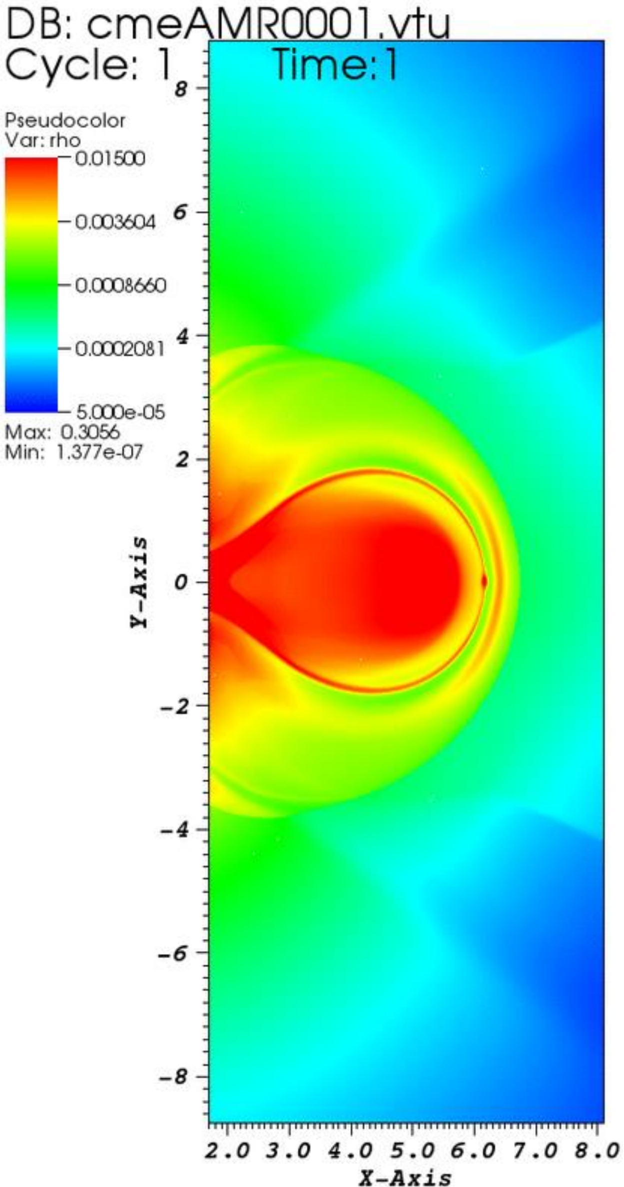
- we urgently need **to improve significantly our ability to estimate the magnetic structure of CMEs**
  - pursue a **data-driven approach** in order to model the complex time-dependent coronal dynamics
  - will enable more reliable CME evolution simulations, including **rotation** and **deflection** in corona (in both longitude and latitude) and the heliospheric effects of **erosion** (through MR), **deformation** (due to interaction with the ambient SW)
  - and enable to **distinguish the CME core** (IP magnetic cloud) **from the shock wave** it induces

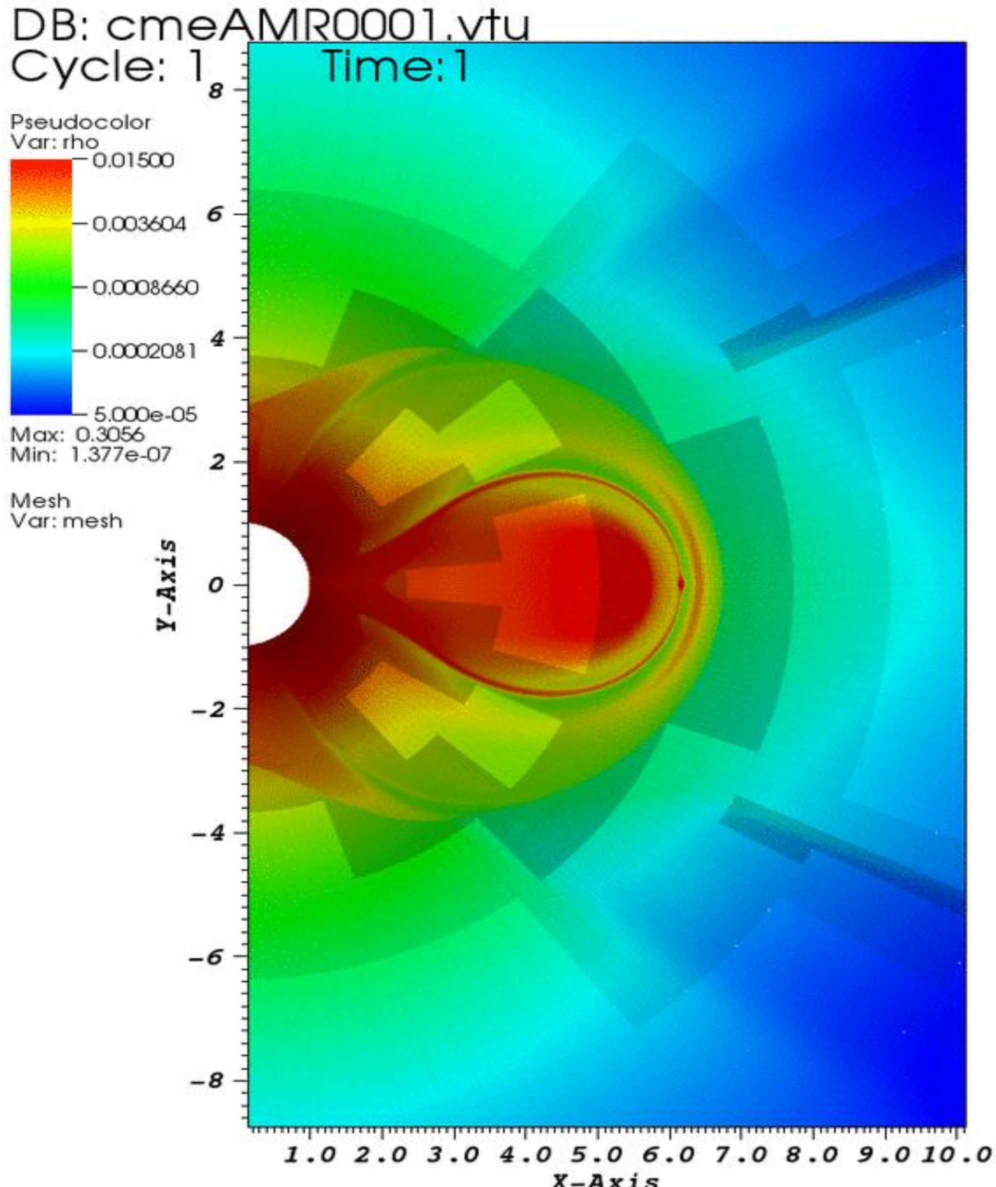
New ultra-high resolution results: SW



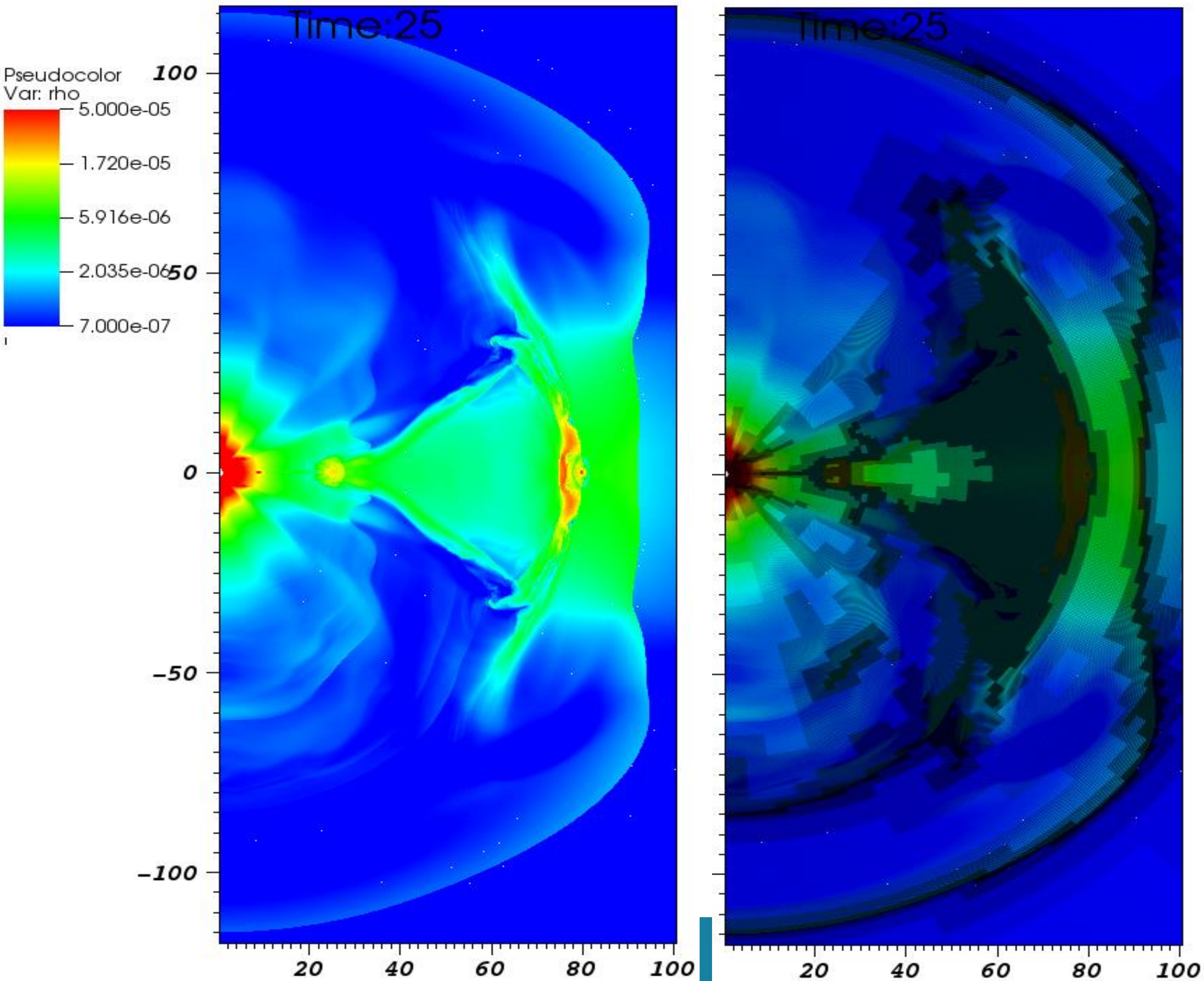
Back ground wind with 5 AMR levels

Scaled (zoomed) movie of density (with grid)





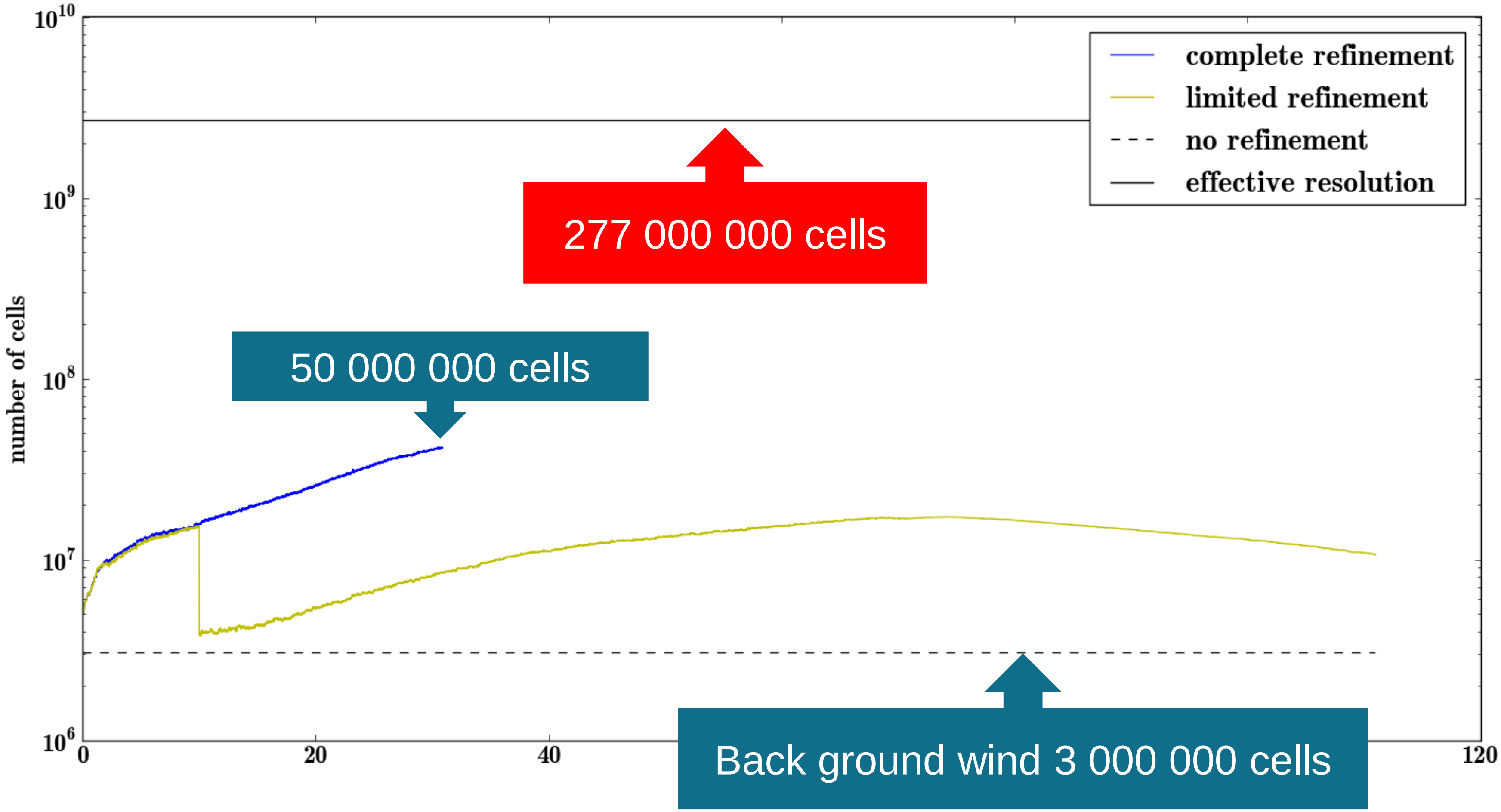
New ultra-high resolution results: CME



2D color plot of the density at 30h when the CME is ejected with
an initial velocity of 1000 km/s.

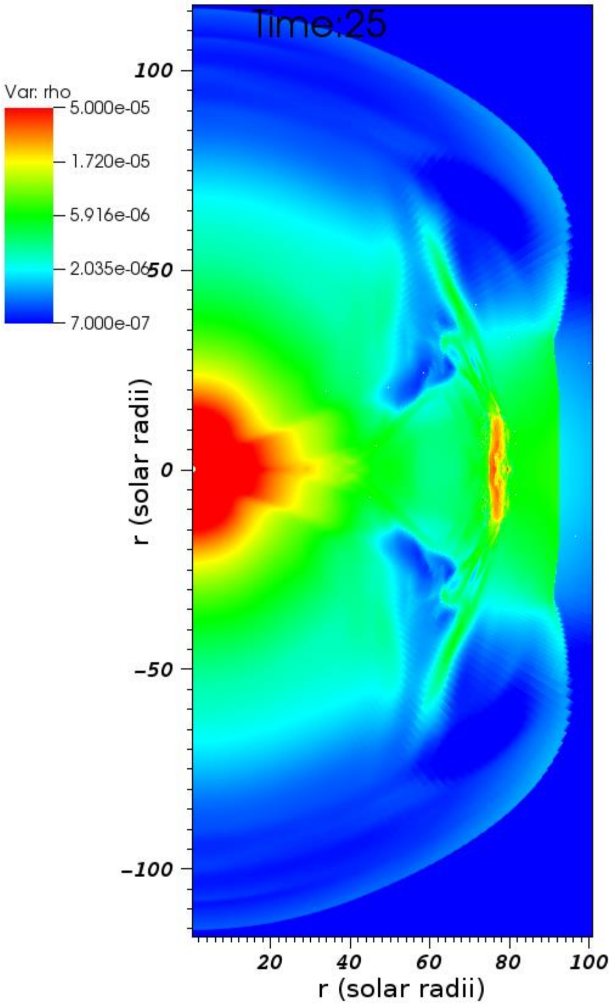
AMR has been applied on the whole grid (5 levels) according
to the gradient of the density.

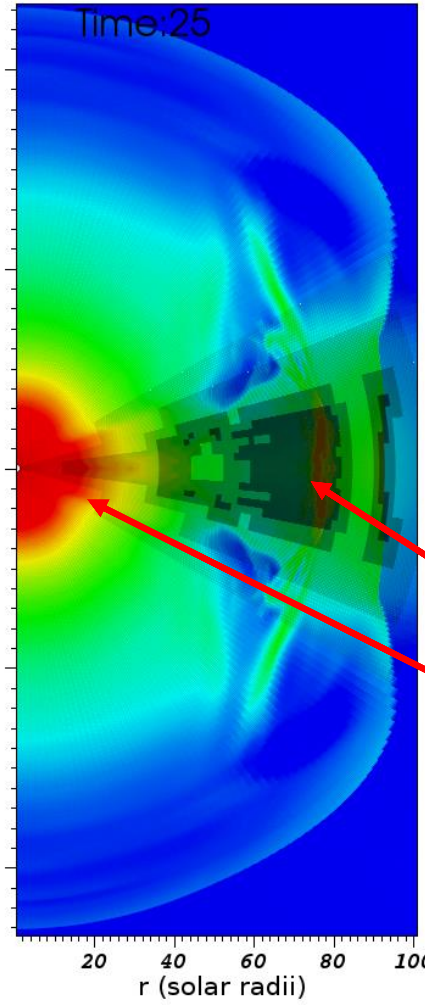
New ultra-high resolution results



Plot of the number of cells used in each simulation as a function of time.

Scaled (zoomed) movie of density (with grid)





2D color plot of the density at 25h when the CME is ejected with an initial velocity of 1000 km/s.

Fine tuning:
AMR still 5 levels but limited to part of the grid, only shock and IP MC are AMR resolved, i.e. no AMR close to Sun

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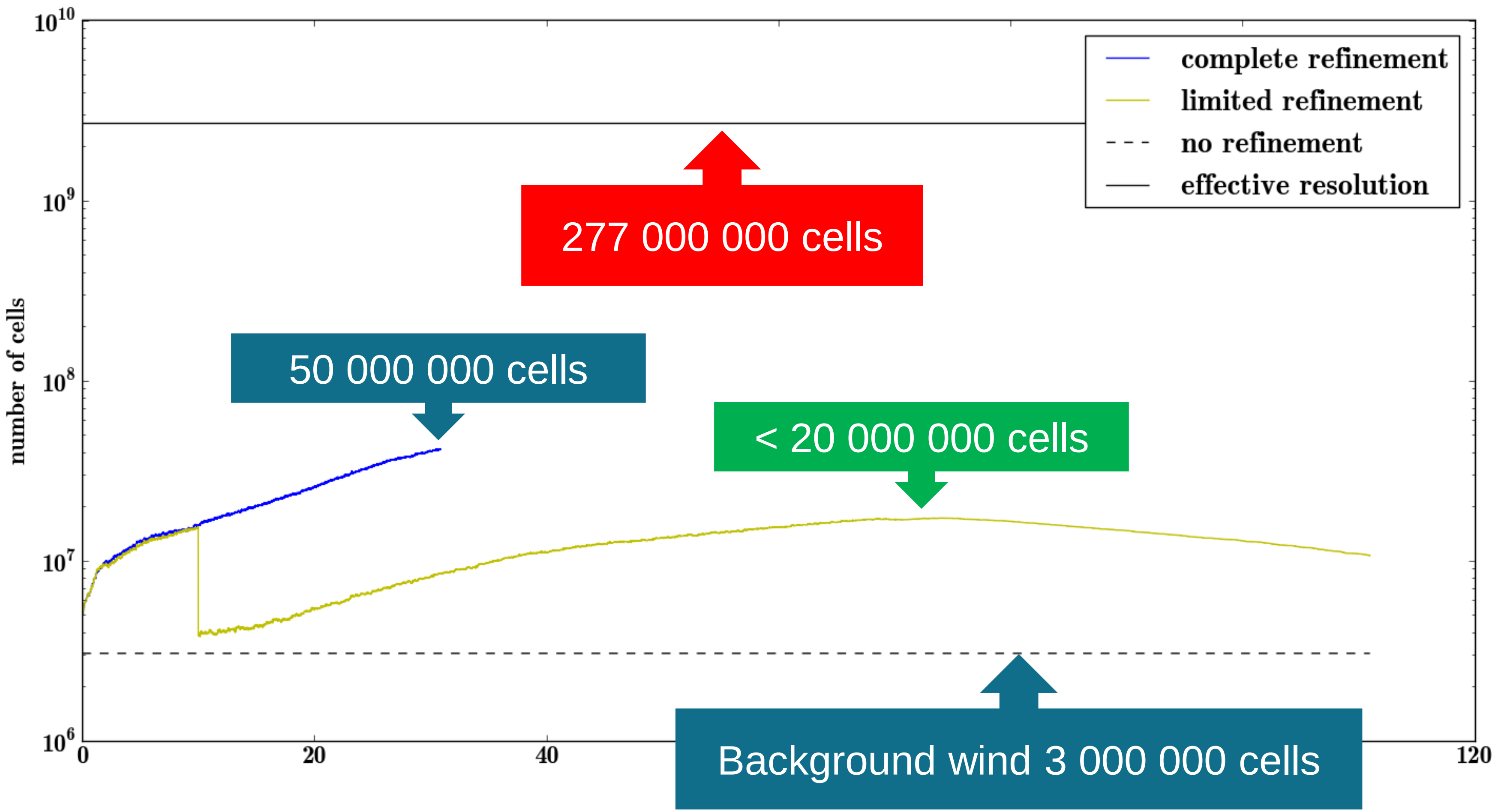
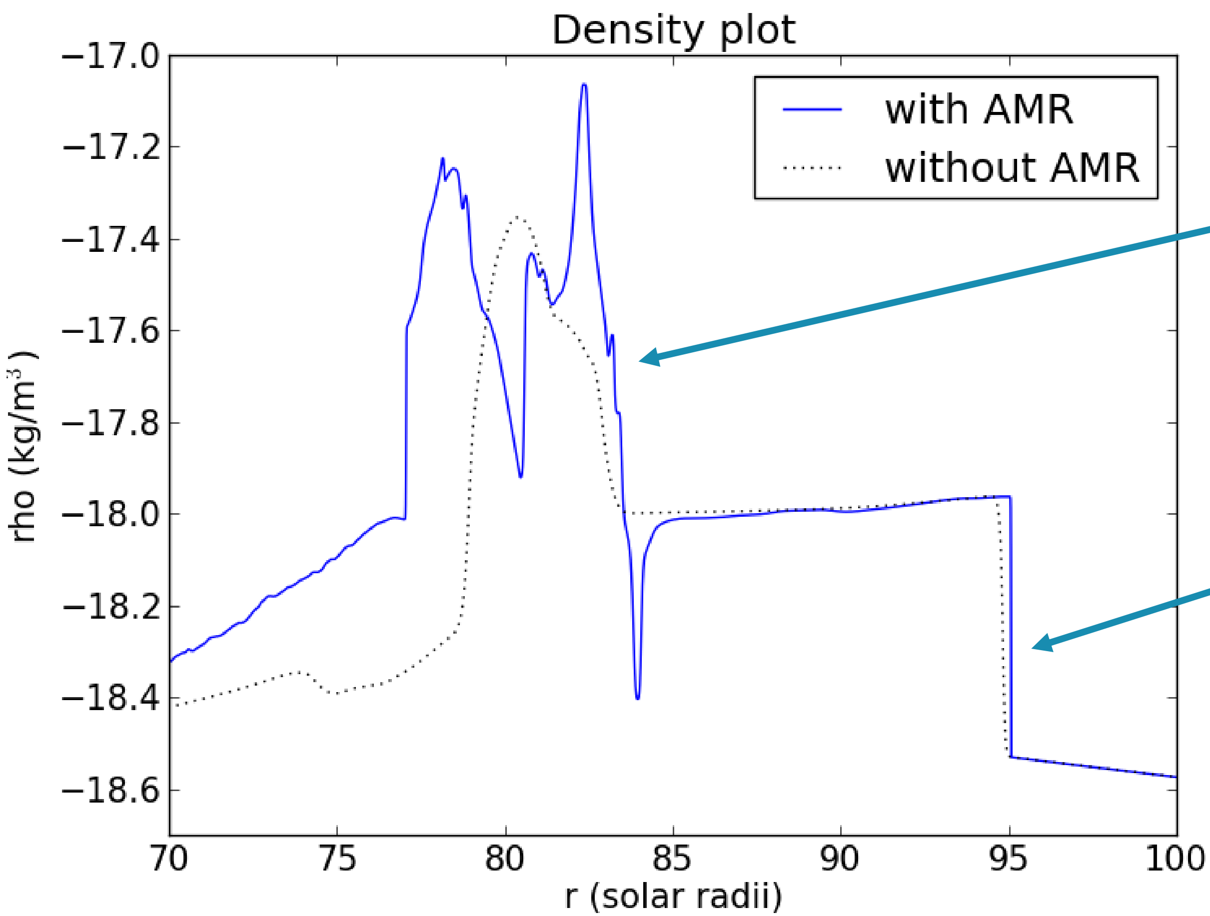
New ultra-high resolution results



Plot of the number of cells used in each simulation as a function of time.

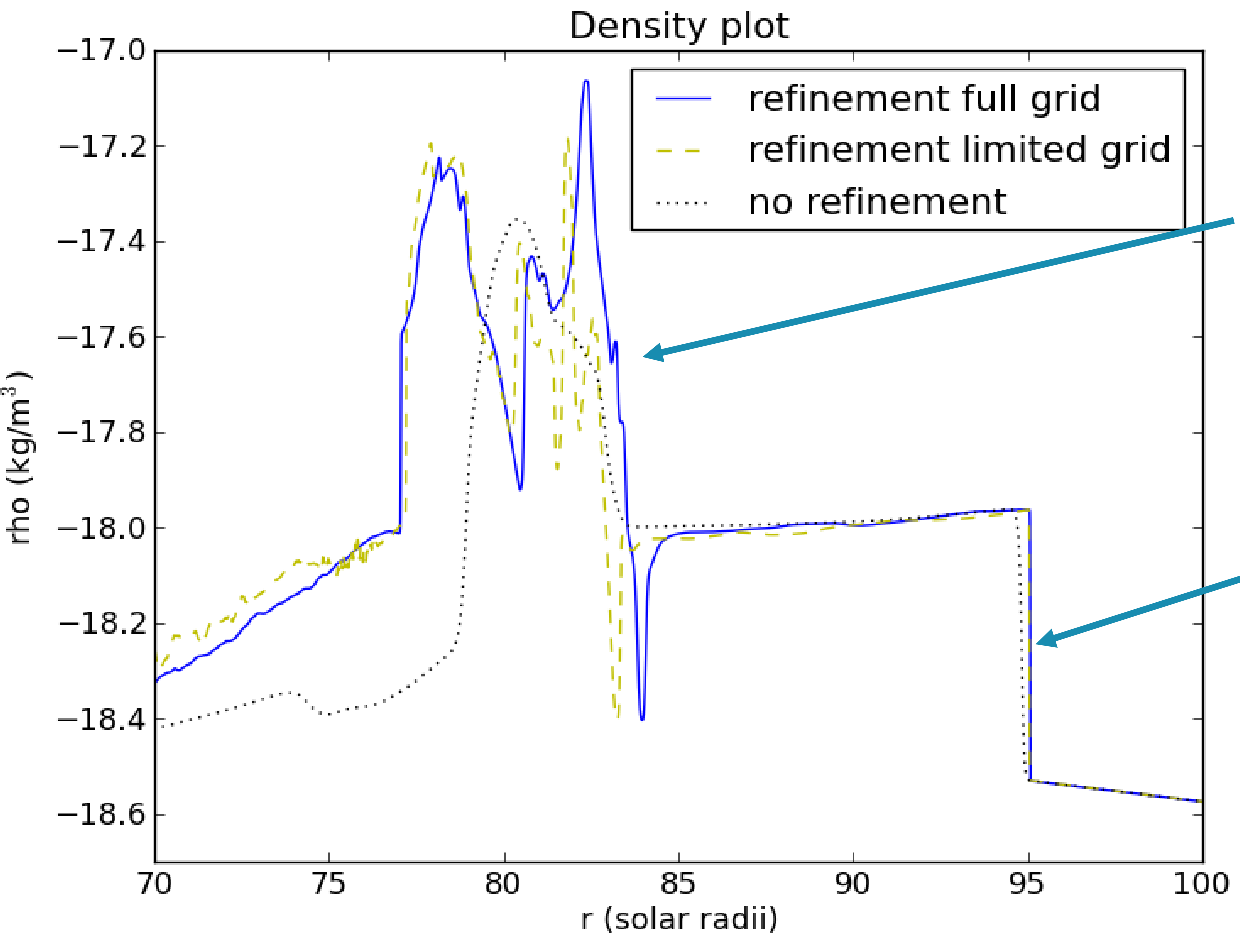
New ultra-high resolution results



Close-up on the CME in the density profile. It is clear that the inner structure of the CME is much better captured when using AMR.

The height and position of the shock however remains practically the same.

New ultra-high resolution results



Close-up on the CME in the density profile. It is clear that the inner structure of the CME is much better captured when using AMR.

The height and position of the shock however remains practically the same.

Blue: refinement over the full grid
Yellow: refinement only on a limited part of grid behind CME
Black: no AMR applied.

Euhforia: current status

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Current status

- CMEs added via BCs at 0.1 AU, testing
  - ENLIL „Ballistic” model (pressure/density pulse, **no magnetic field**)
  - **Magnetized CME models** tested (with AMR)

Next steps

- Calibrate the solar wind
- Historic test cases to compare with data and ENLIL
- Install magnetized *(flux-rope) CMEs*
- Improve coronal model *(magnetofrictional magnetic field)*
- Replace WSA part by *1D turbulence-based model along a field line*
- Update MHD part to *MPI-**AMR**VAC*
- Couple to SEP model and to GUMICS-4
- …

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Conclusions

- CMEs play a key role in Space weather
- CME simulations reveal the secrets of the Sun, ***supplementary to observations!***

- urgent need **to model the magnetic structure of CMEs**
  - Need more reliable CME evolution simulations, including **rotation** and **deflection** in corona (in both longitude and latitude) and the heliospheric effects of **erosion** (through MR), **deformation** (due to interaction with the ambient SW)
  - Need to **distinguish the CME core** (IP magnetic cloud) **from the shock wave** it induces

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Conclusions

There is still a lot of missing/neglected physics:

- **Photosphere is not in force-free state**, and so pressure gradients and cross-field currents may be important.
- We **lack detailed theory of magnetic reconnection in 3-D**; most models invoke MR, often caused by numerical diffusion.
- **Multi-fluid & partial ionization effects**: low temperatures in the low atmosphere pose the question of the (resistive) effects of partial ionization (ambipolar diffusion + Hall term in generalized Ohm's law, multi-fluid effects)

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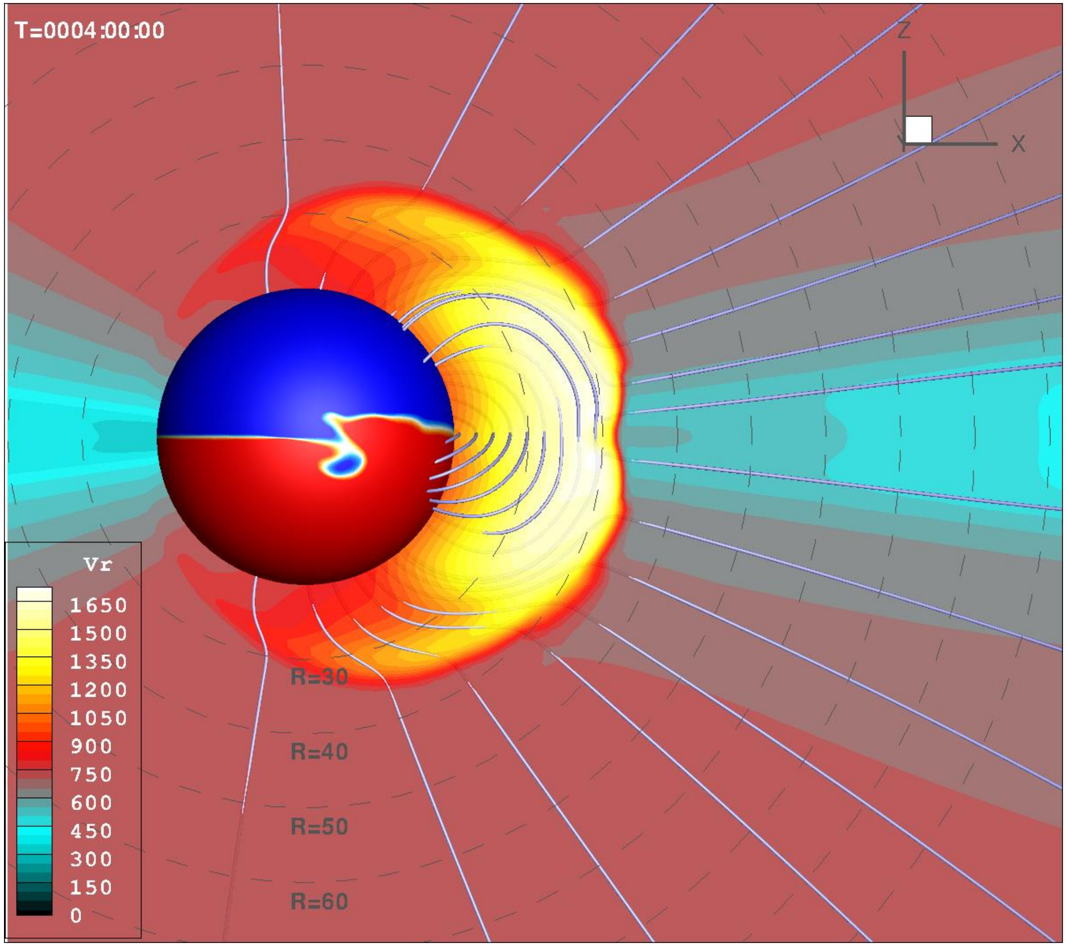
Thank you very much!



Questions?