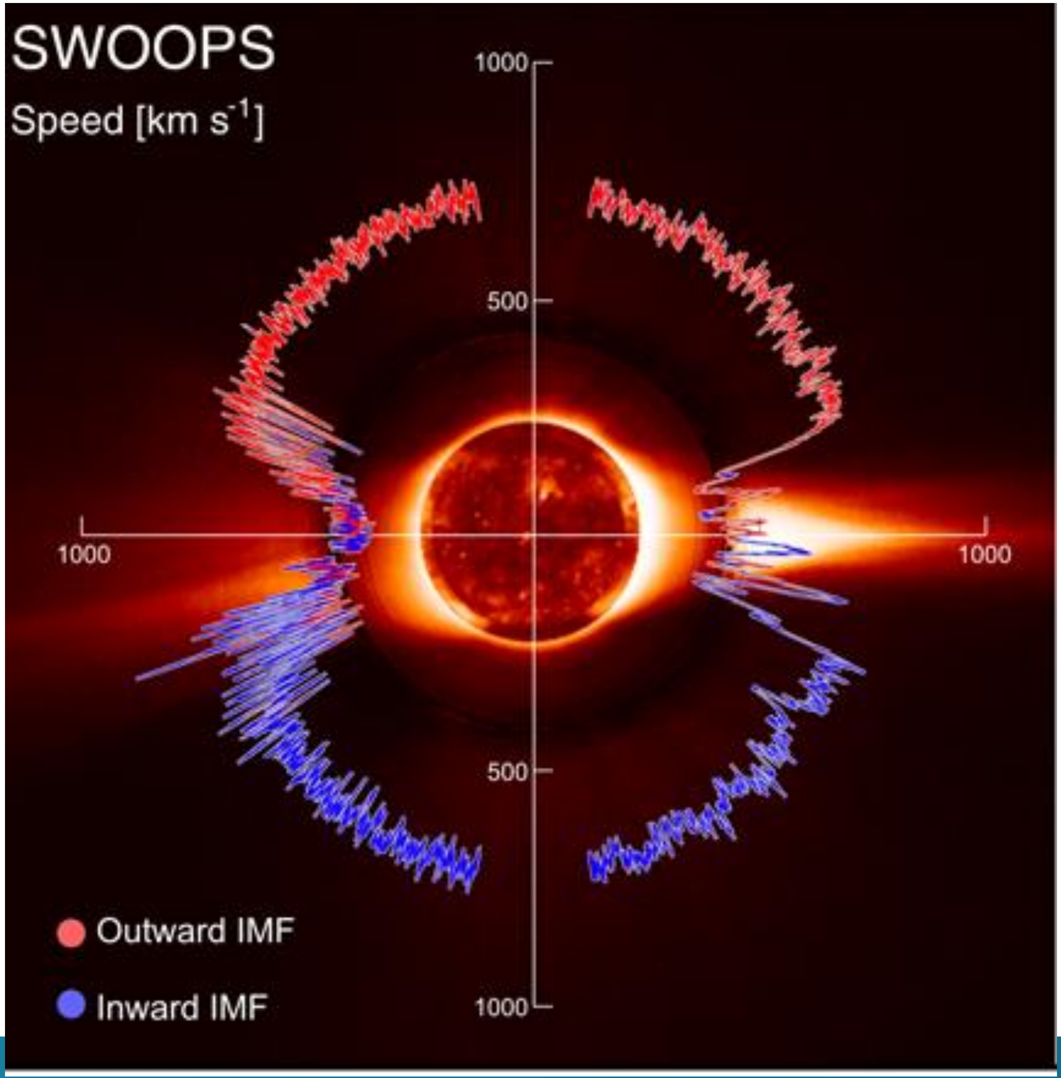
Initiation and evolution of CMEs in the inner heliosphere

S. Poedts, J. Pomoell, E. Chané
Centre for mathematical Plasma Astrophysics
Dept. Mathematics KU Leuven

HELCATS workshop, MPS Goettingen, Germany, 21/5/2015

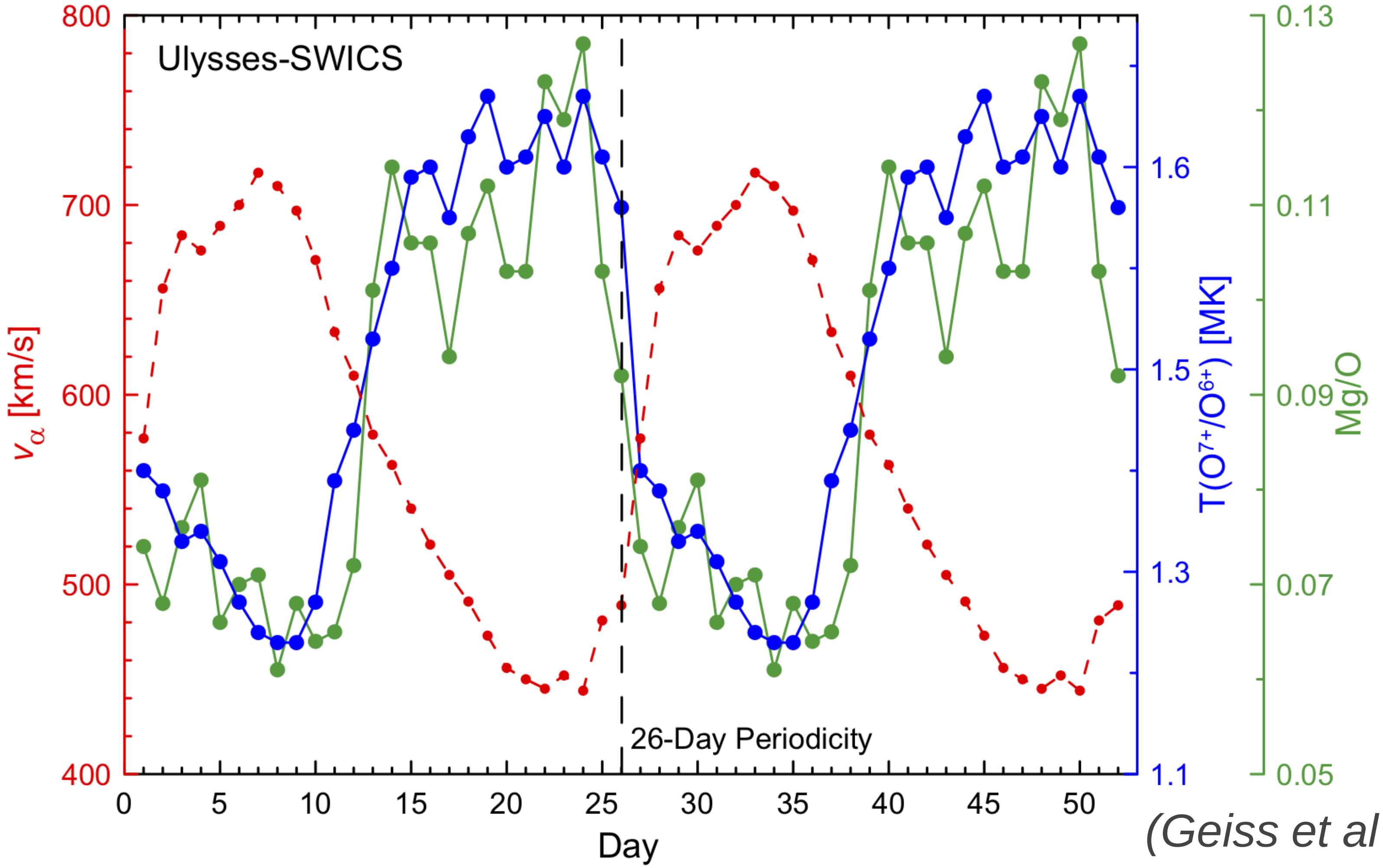
The solar wind

- Wind divides into two distinct types:
  steady fast > 500 km/s
  variable slow < 500 km/s
- Slow wind is concentrated along stalks (ecliptic)
- Large angular extent compared to bright stalk



(McComas et al 2008)

Measurements in Heliosphere



(Geiss et al 1995)

Element abundances and freeze-in T of solar winds

Properties of the two winds

Composition:

- Fast ~ photospheric FIP and T ~ 1 MK
- Slow ~ coronal FIP and T ~ 1.3 MK

Spatial:

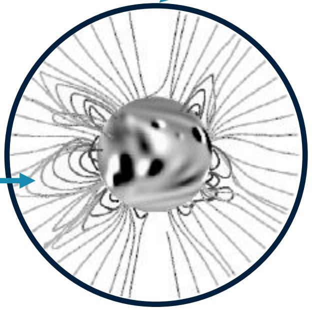
- Fast wind extends to poles, originates from non-transient (> 1 day) coronal holes (approx. quasi-steady wind of Parker)
- Slow wind surrounds heliospheric current sheet (HCS)
  - Similar to closed-field plasma
  - But can extend ~ 30° from HCS
  - Solar source long-standing problem in Heliophysics

Solar wind modeling

Taking coronal model as lower boundary condition

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

Coronal model
with PF or NLFFF

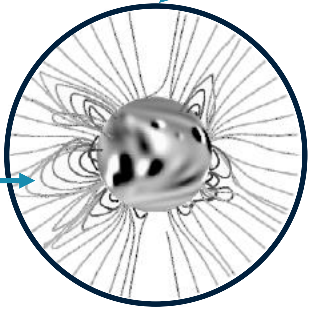


- Potential field source surface (PFSS) model (e.g. Wang & Sheeley; DeRosa & Schrijver,..)
- CORHEL/MAS model (Linker et al.)
- SWMF/S.C.-IH (van der Holst et al.)
- Nonlinear force-free field (NLFFF) models (Yeates & MacKay; Tadesse, Wiegelmann, et al.)
- AMR–CESE–MHD model (Feng et al. 2012)

Solar wind modeling

Taking coronal model as lower boundary condition

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



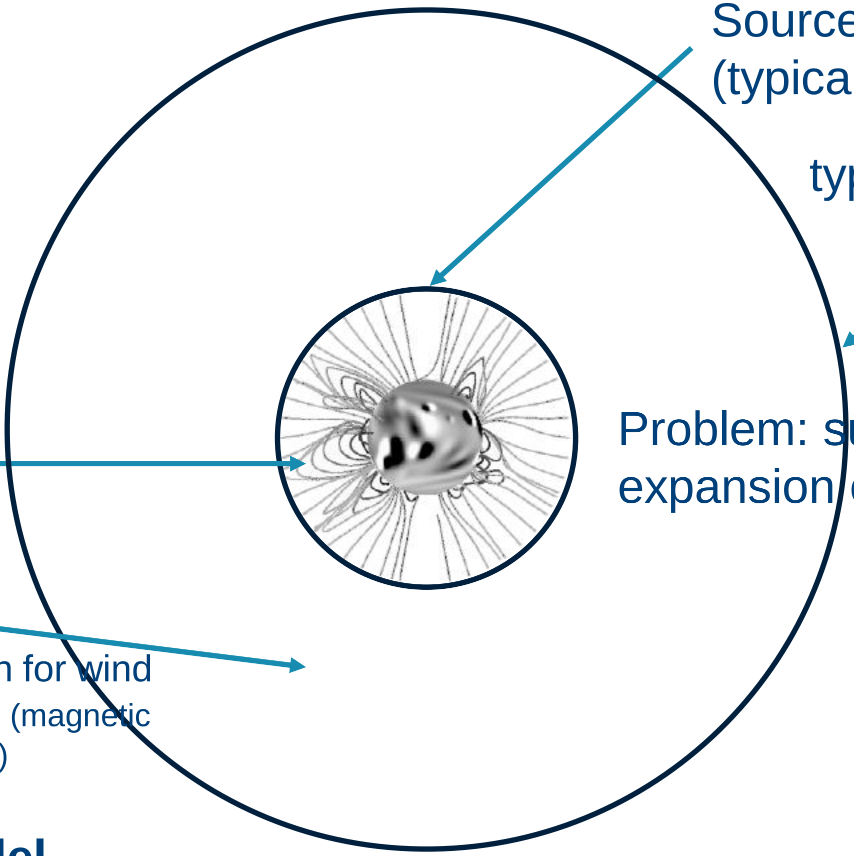
Coronal model
with PF or NLFFF

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)

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)

MHD wind model
ENLIL, SWMF, **Euhforia**, etc.

Euhforia

'European heliospheric forecasting information asset'

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

cpa KU LEUVEN

Euhforia

‘European heliospheric forecasting information asset’

Heliosphere model with CMEs

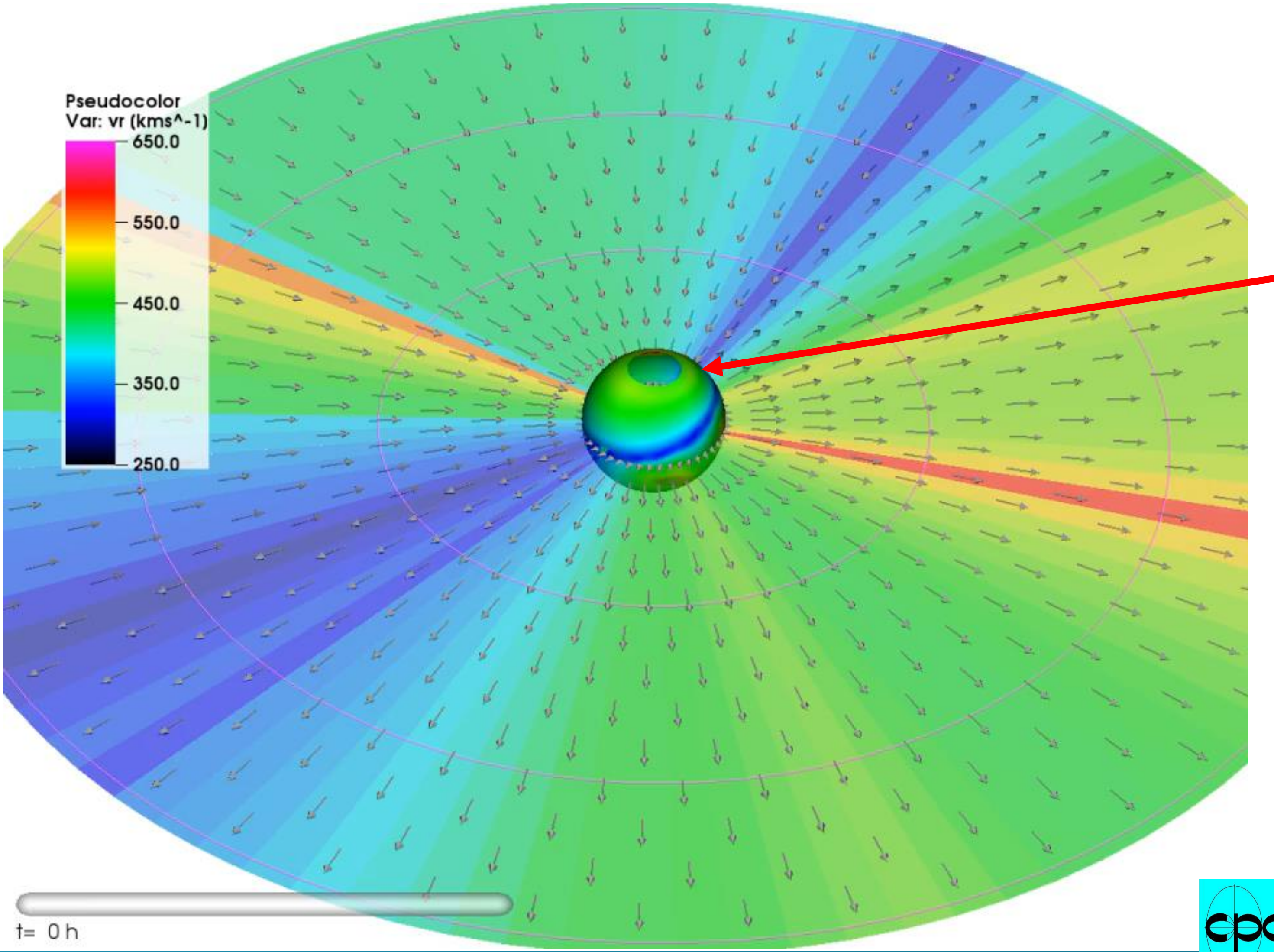
AIM: Compute time dependent evolution of MHD variables from 0.1 AU to 1 AU and beyond (up to a few AU)

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
- Current sheet model (Schatten) beyond the source surface
- Python matplotlib / VisIt for visualization

Very first test Euhforia

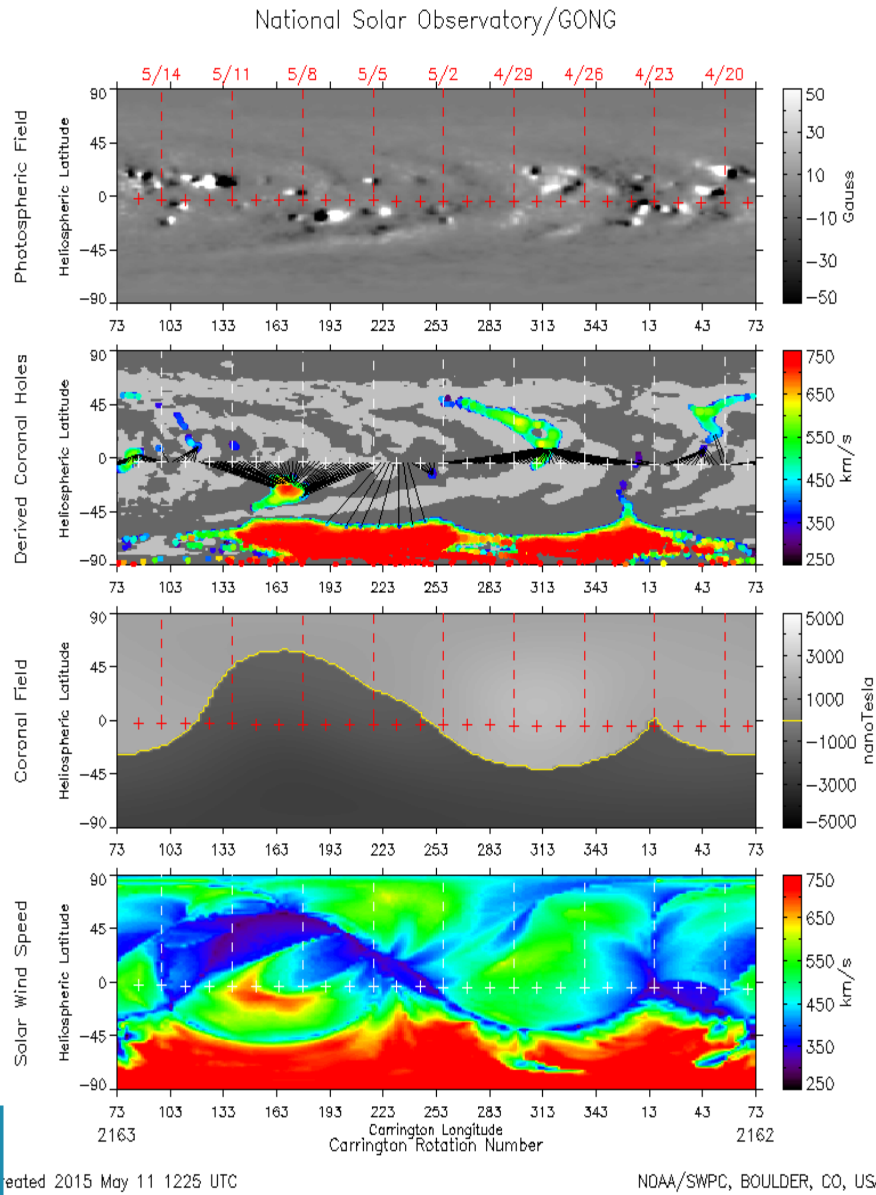


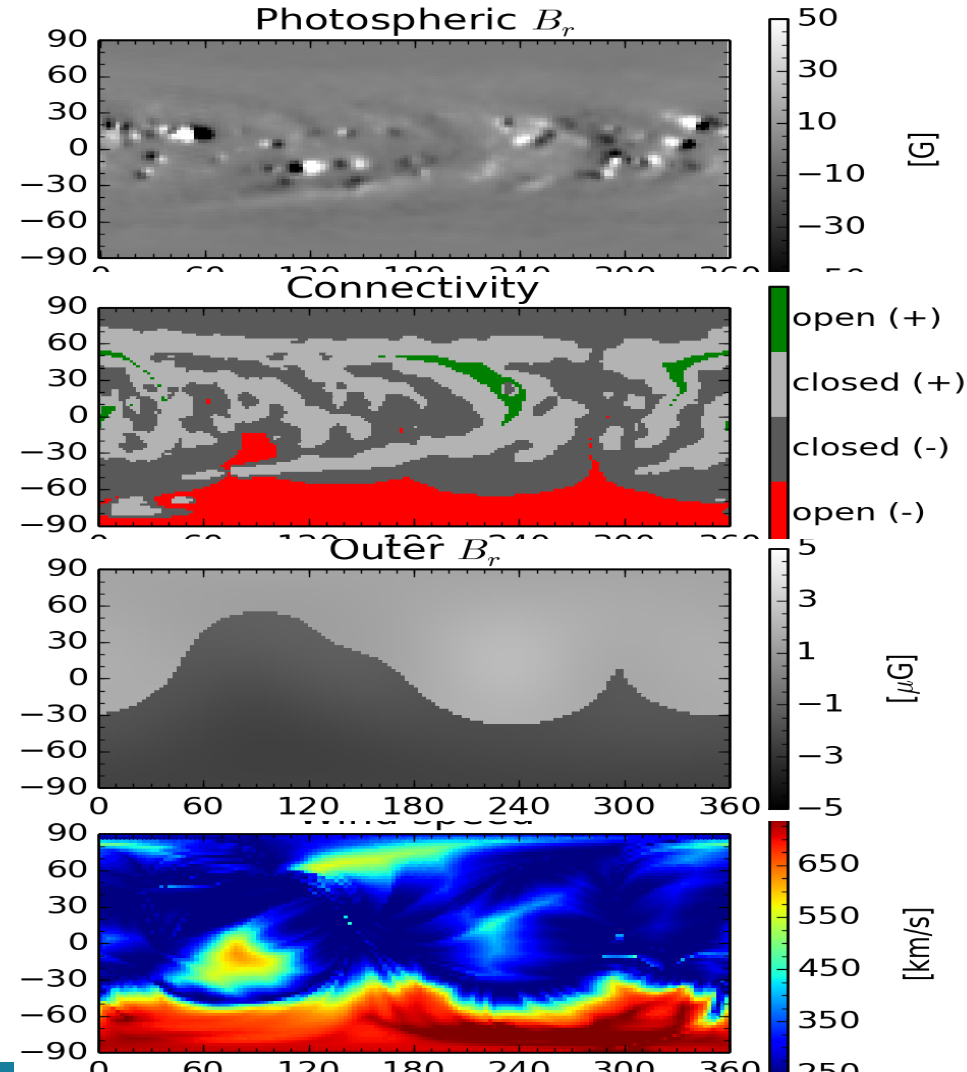
3D visualization of **MHD relaxation** in low resolution (same as ENLIL) 0.1 AU - 1 AU

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

Comparison with WSA

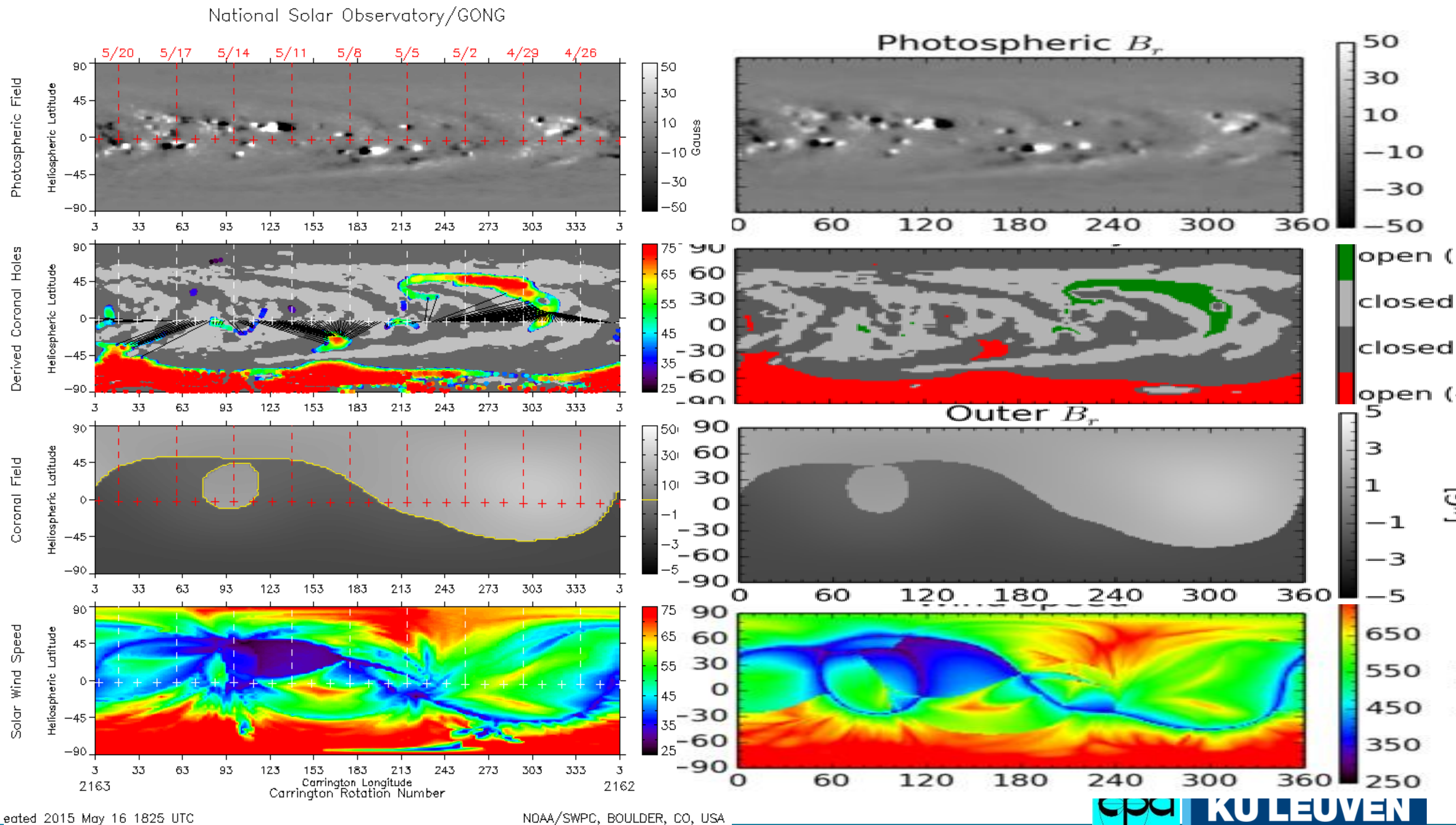
Plot in WSA style (http://legacy-www.swpc.noaa.gov/ws/gong_all1.html)



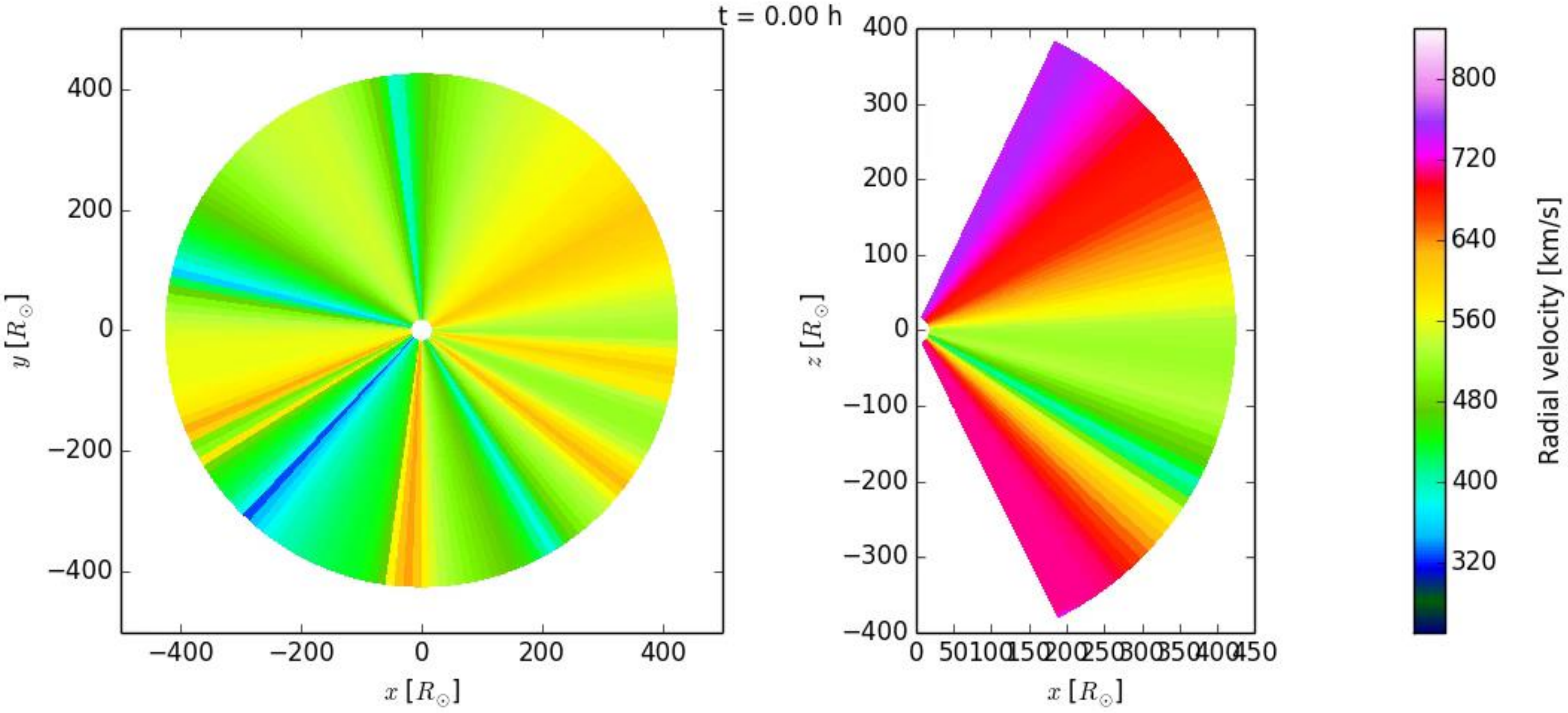


Comparison with WSA

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

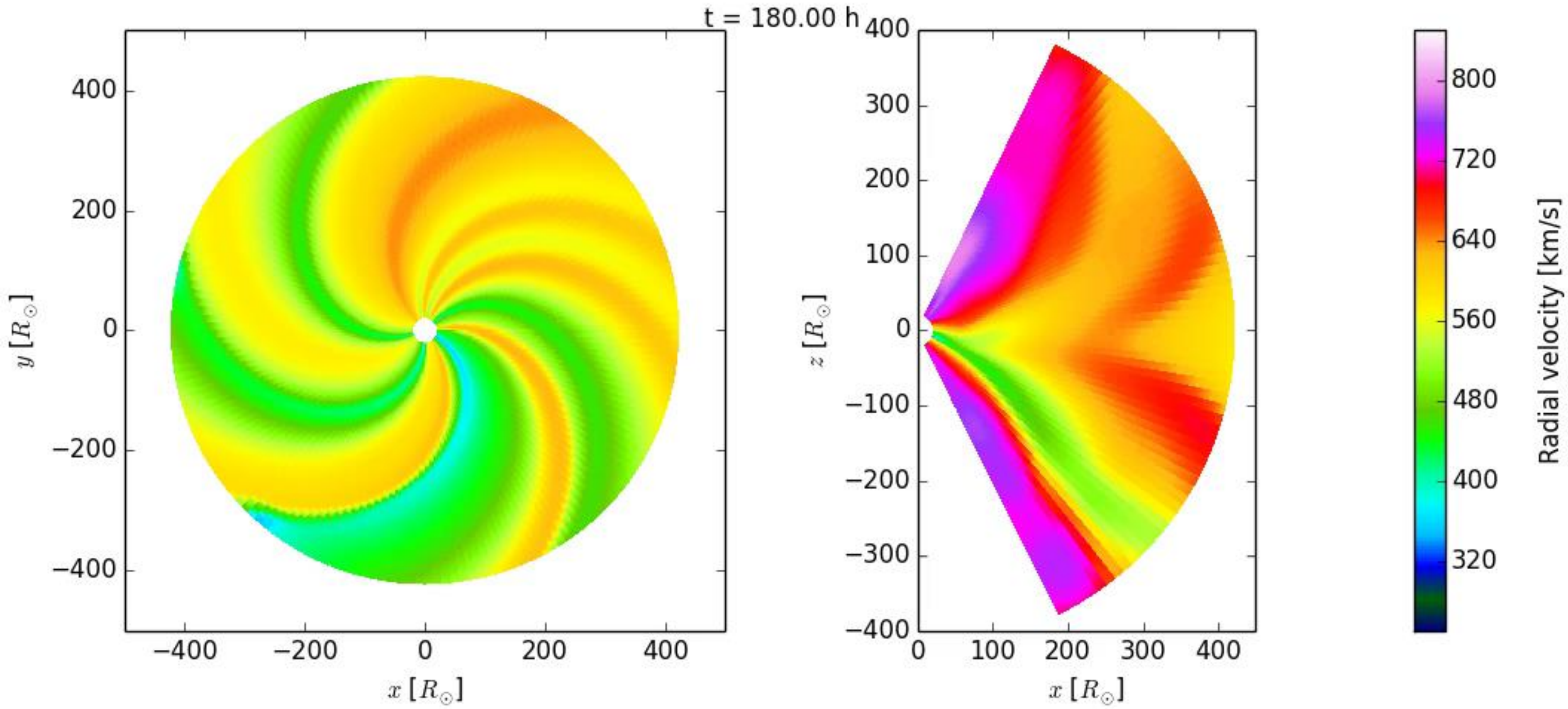


More conventional view for 2nd relaxation
(at double resolution)



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

Ballistic CME test
(same background wind)



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

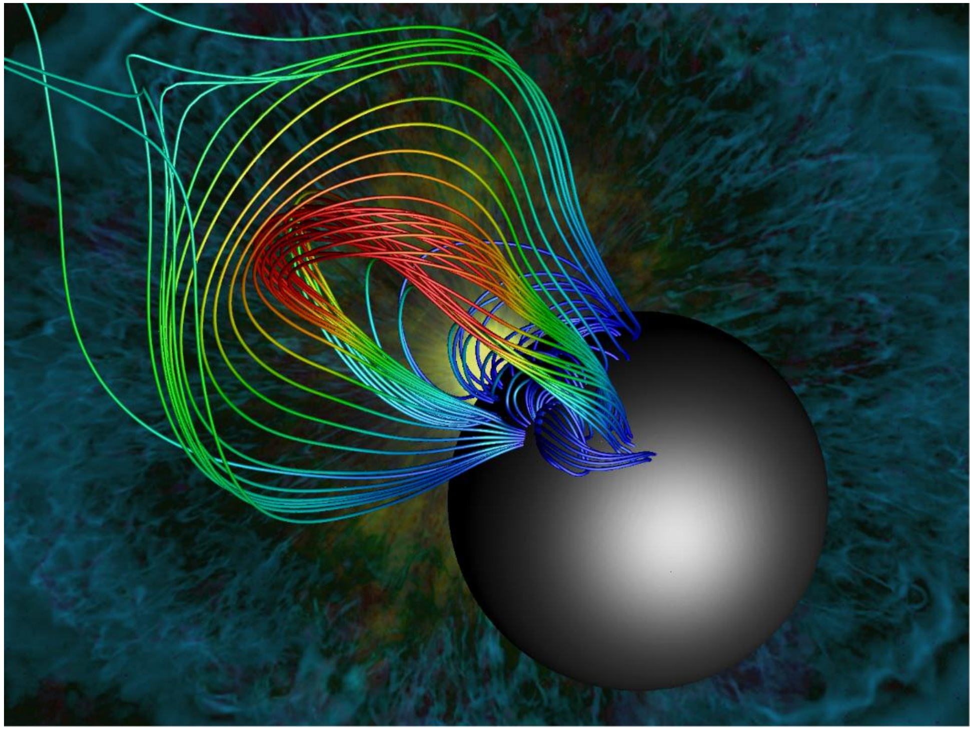
Euhforia: current status

‘European heliospheric forecasting information asset’

Current status

- We can produce physically meaningful SW solutions
- Installed at ThinKing (KU Leuven cluster)
- Being installed at ROB on their new cluster
- MHD part (0.1 AU – 1 AU) takes most of the CPU time (but needs to be ran once or twice a day at most)
- CMEs added via BCs at 0.1 AU, testing
  - ENLIL „Ballistic” model (pressure/density pulse, no magnetic field)
  - Magnetized CME models tested (with AMR)
- Checking possibility to use interplanetary scintillation data as boundary conditions at 0.1AU instead of WSA

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

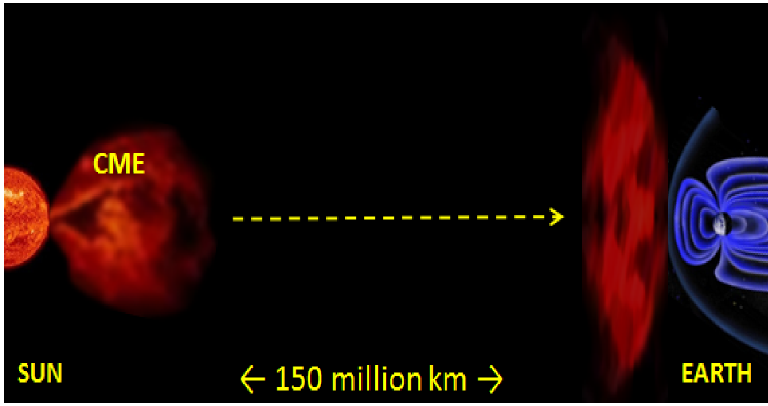
- **Power source**: energy stored in volumetric electric currents in the corona
- **Mechanism**: provided ***through the magnetic field*** by
  - *shearing motions / sunspot rotations*
  - *magnetic flux emergence/cancellation*
- **Cause of CMEs:** still under debate, but we have good general idea –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

cpa KU LEUVEN

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**

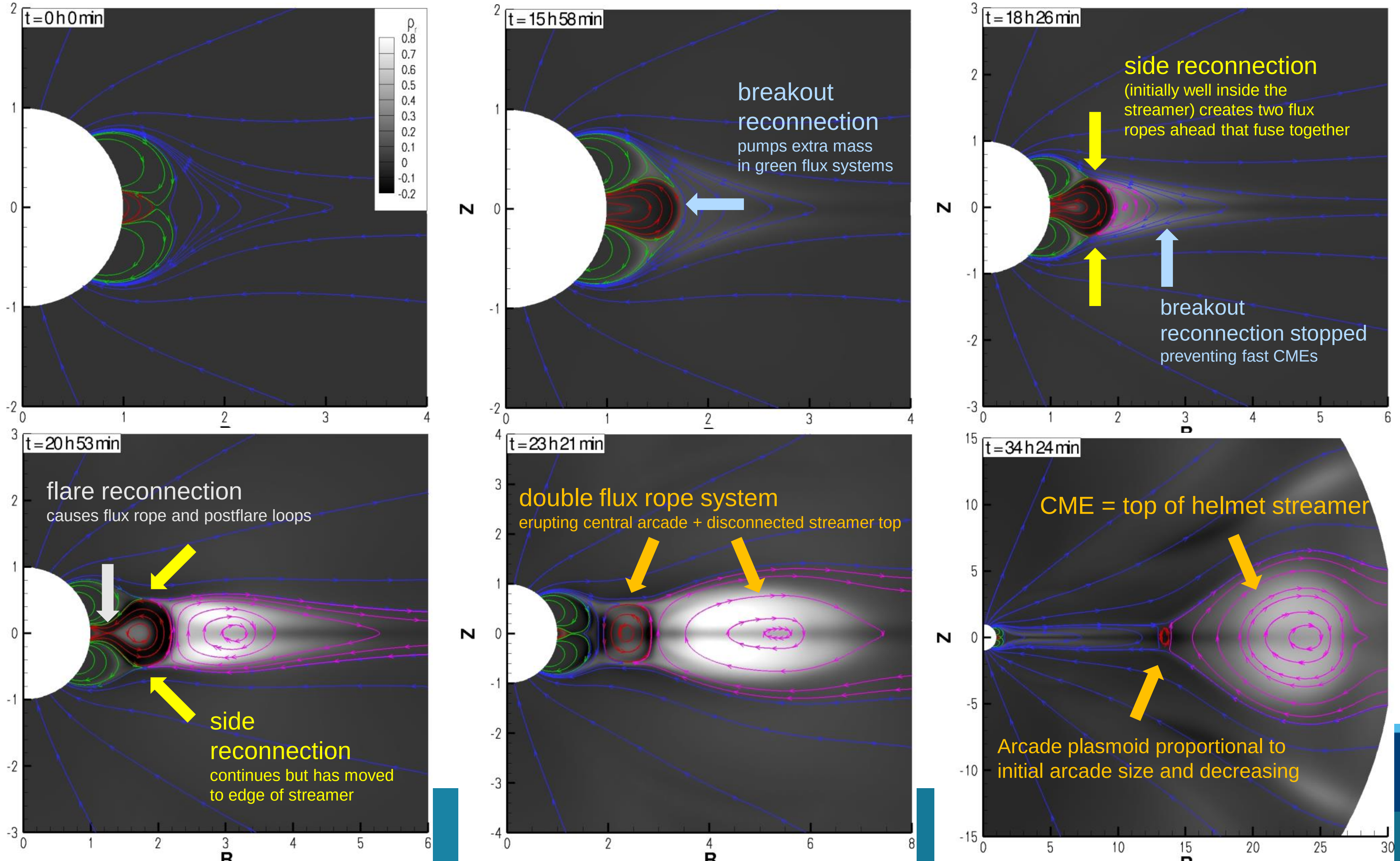


- we urgently need **to improve significantly our ability to estimate the magnetic structure of CMEs**
  - pursue a **data-driven approach** in order to model the complex time-dependent coronal dynamics
  - will enable more reliable CME evolution simulations, including **rotation** and **deflection** 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

CME modeling (2.5D)

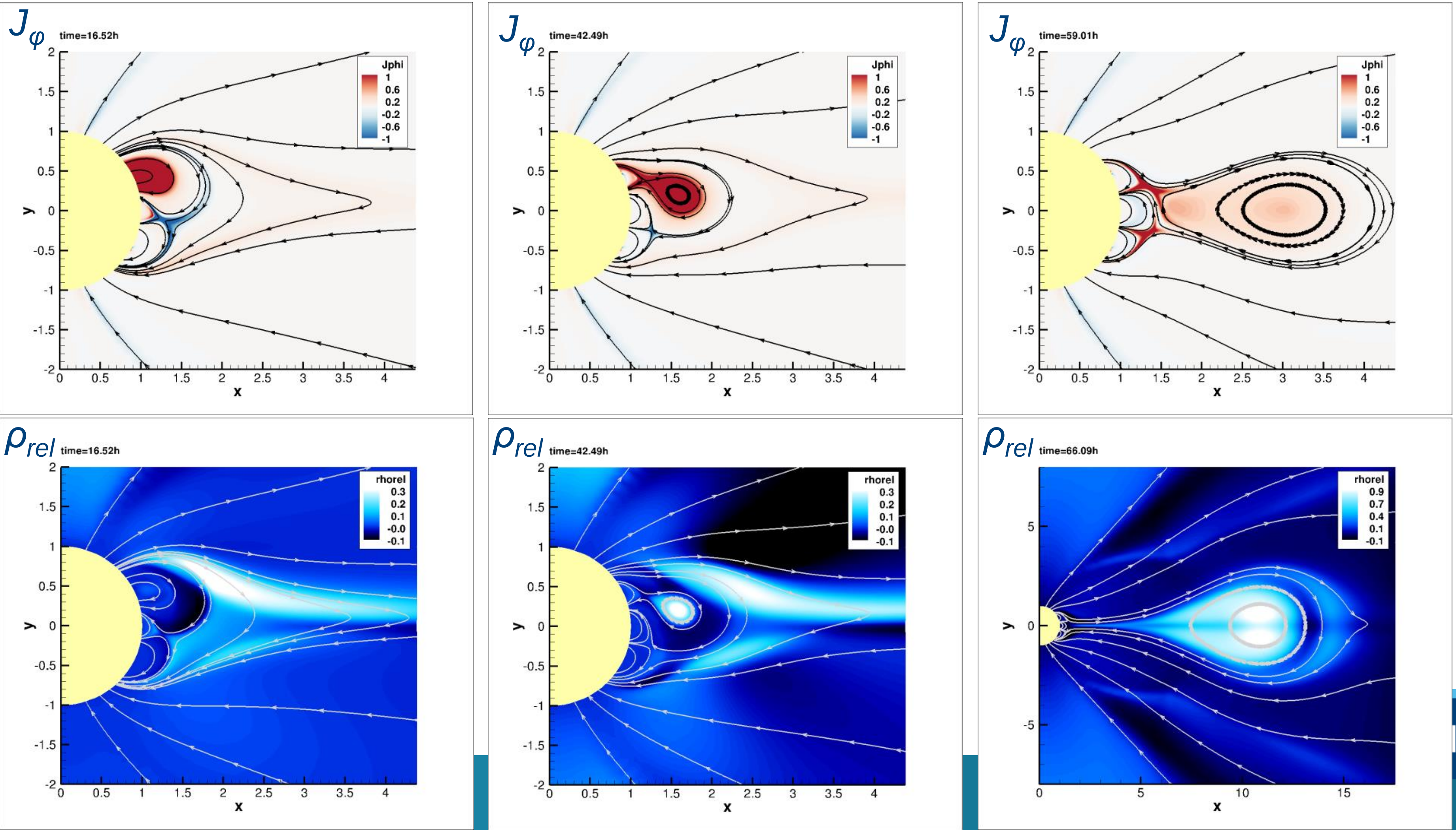
‘breakout’ CME, evolution:

van der Holst et al. ApJ (2007)

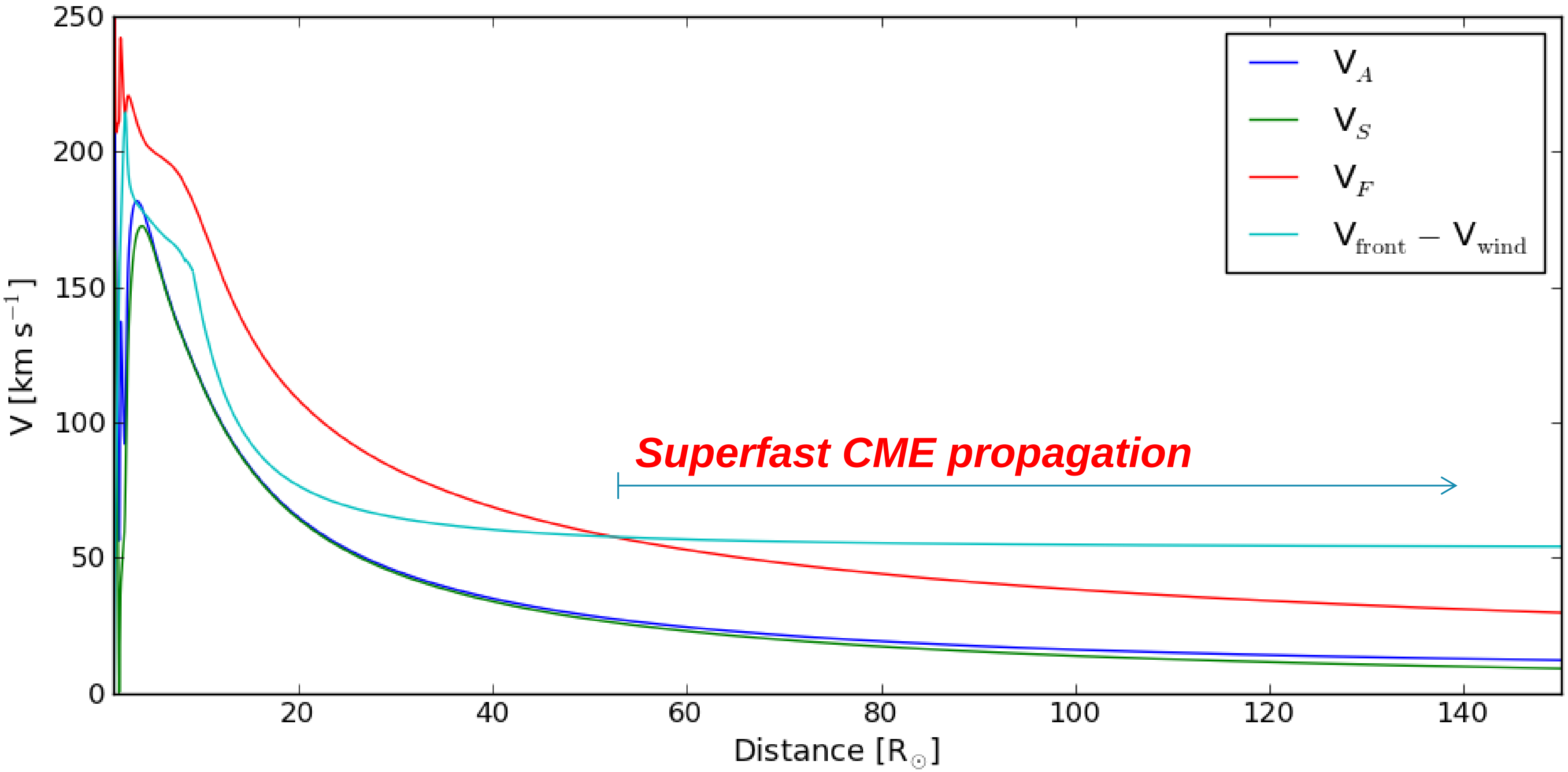


Asymmetric driving, 2.5D parameter study

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

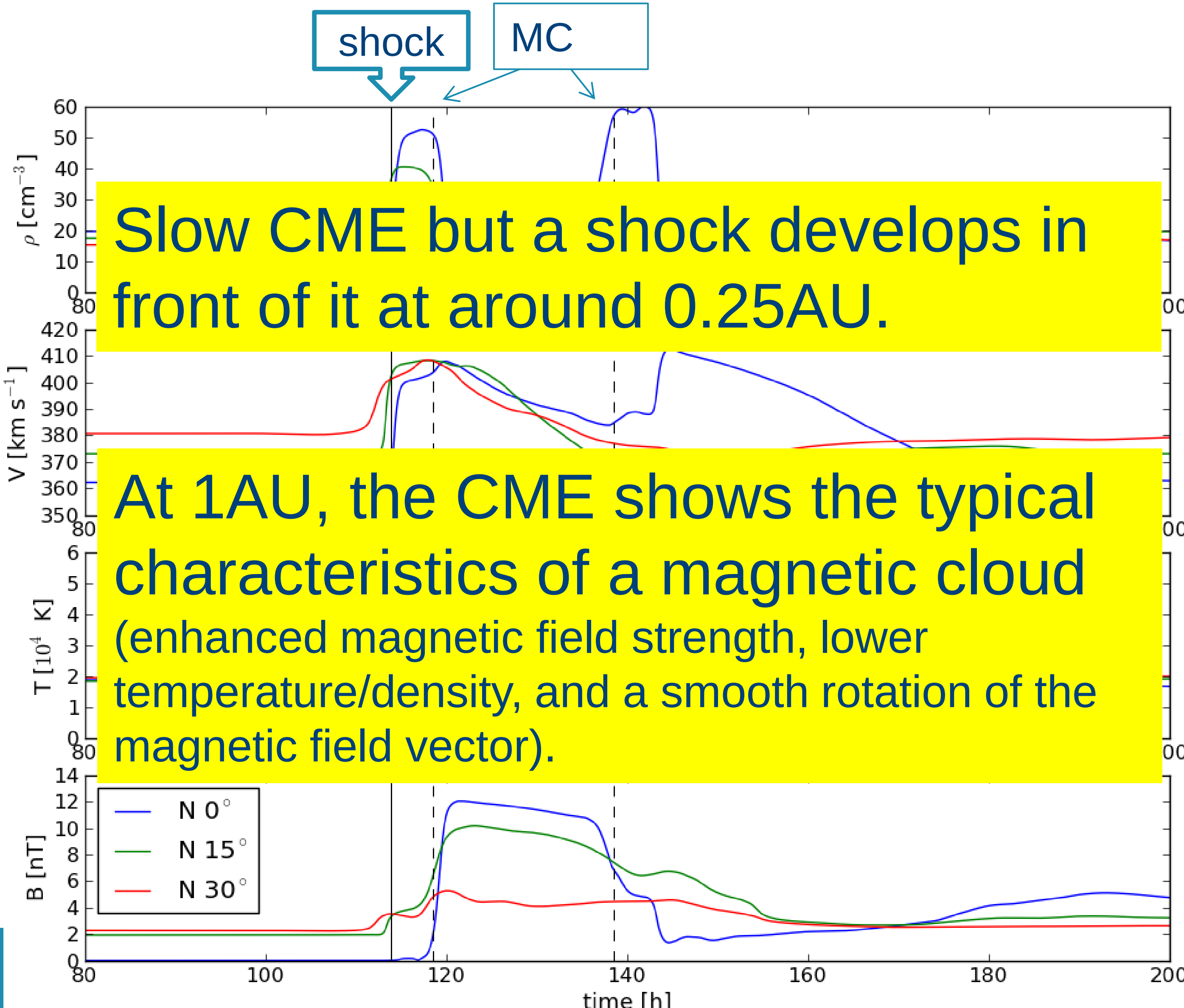


Asymmetric driving, 2.5D parameter study



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



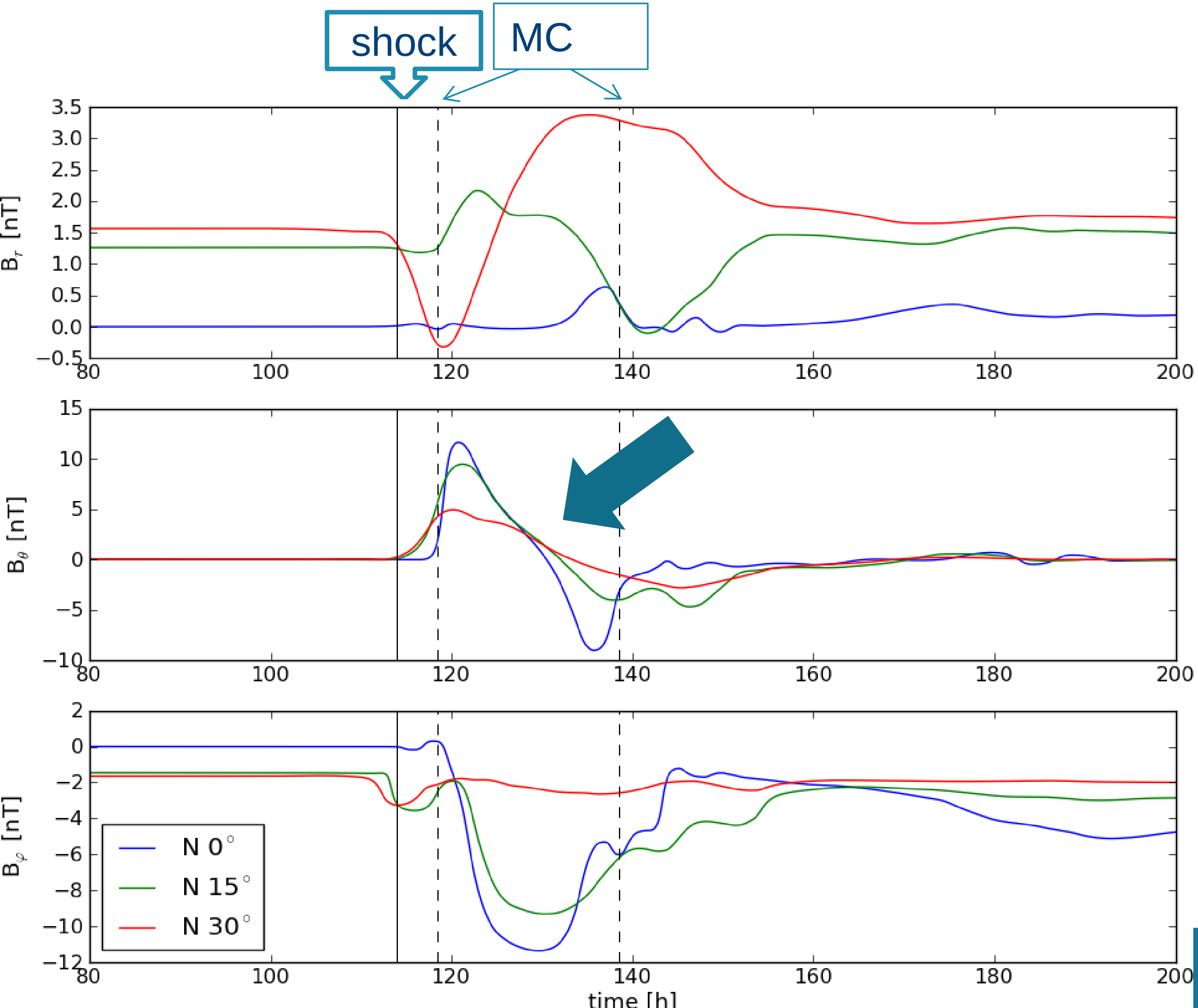
Slow CME but a shock develops in front of it at around 0.25AU.

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 (or .3 AU)

cpa KU LEUVEN

Asymmetric driving, 2.5D parameter study

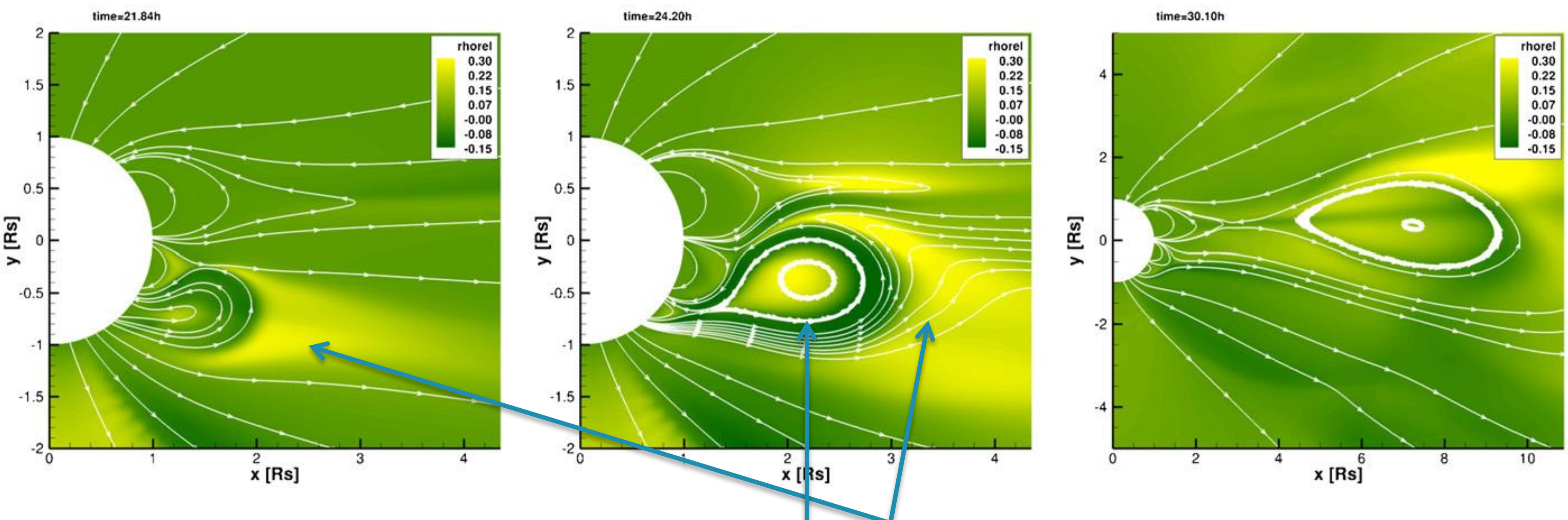


Evolution of **magnetic field components** for a satellite in the equatorial plane (blue line), and above the equator 15º (green line) and 30º (red line) measured at 1 AU (or .3 AU)

KU LEUVEN

Case Study: CME deflection

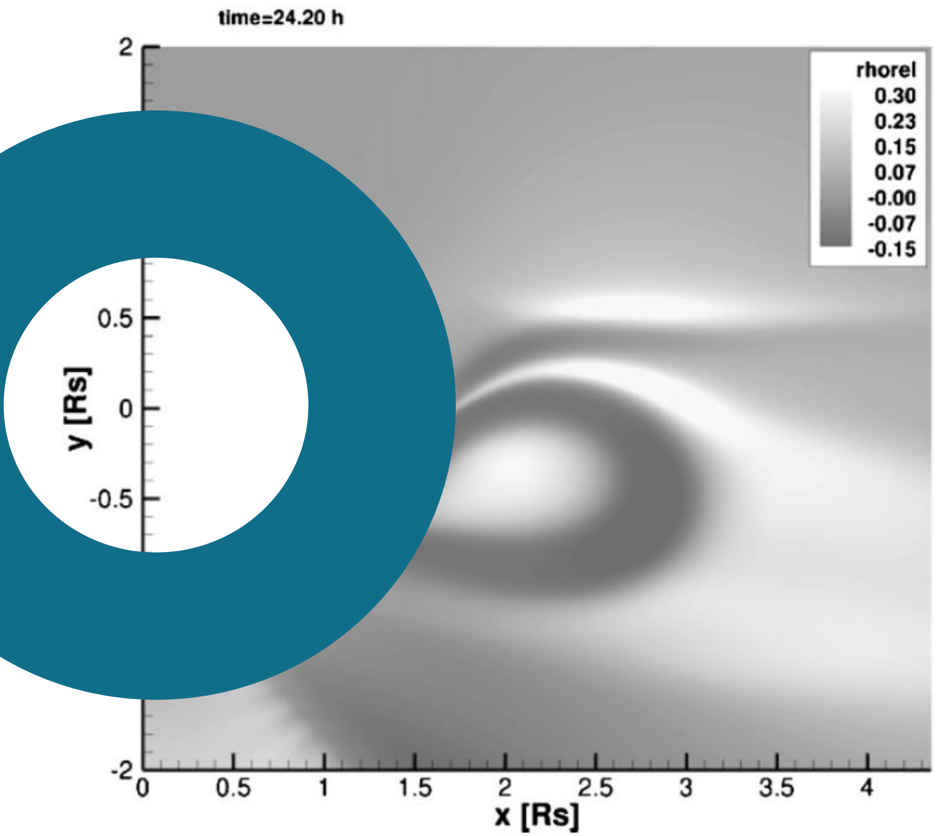
Zuccarello et al. ApJ (2012)

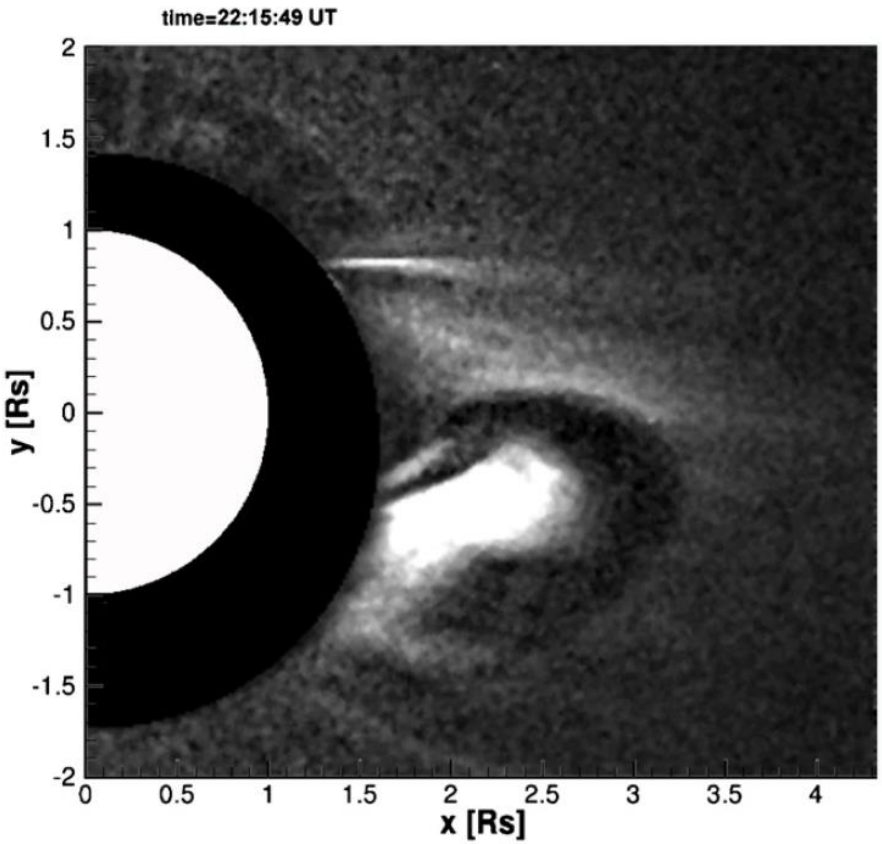


- As a consequence of the expansion, an increase in the relative density is observed at the leading edge of the expanding loops system, while a density depletion is observed behind it.
- An increase in the relative density in the central arcade due to reconnection corresponding to the loop brightening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

KU LEUVEN

Three-part structure

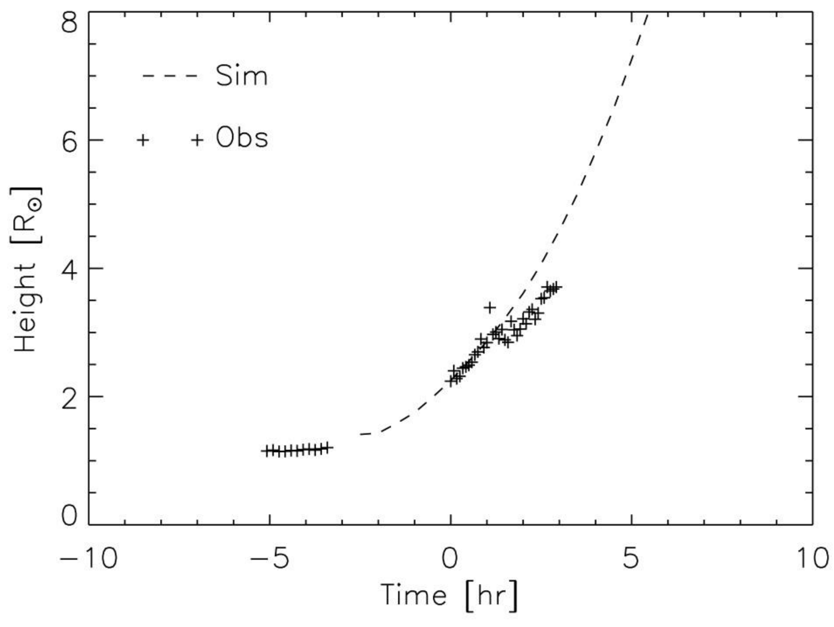


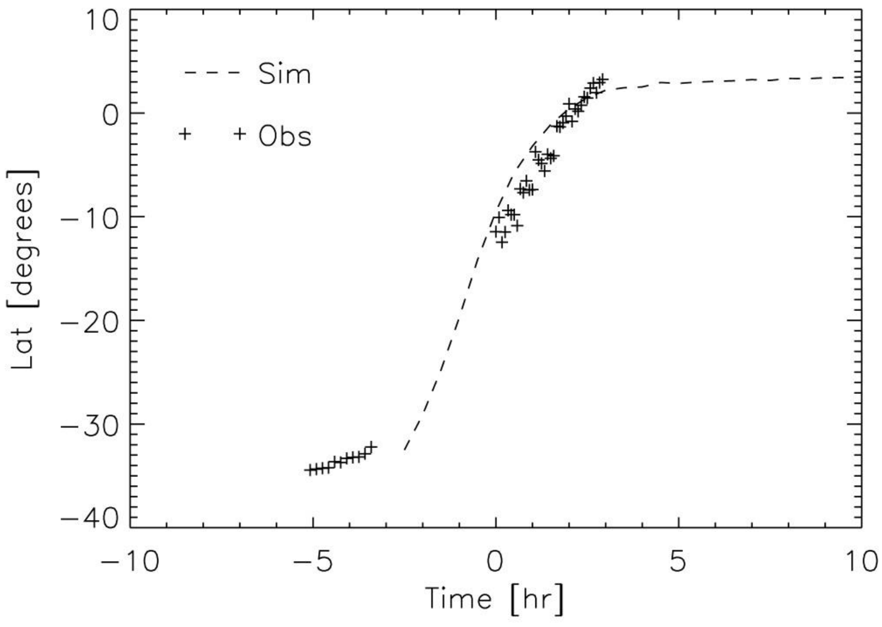


- When the flux rope is propagating within the COR1 FOV, the high-density core as well as the three-part structure are clearly visible.
- An increase in the relative density in the X-point is visible both in the observations and simulations.

cpa KU LEUVEN

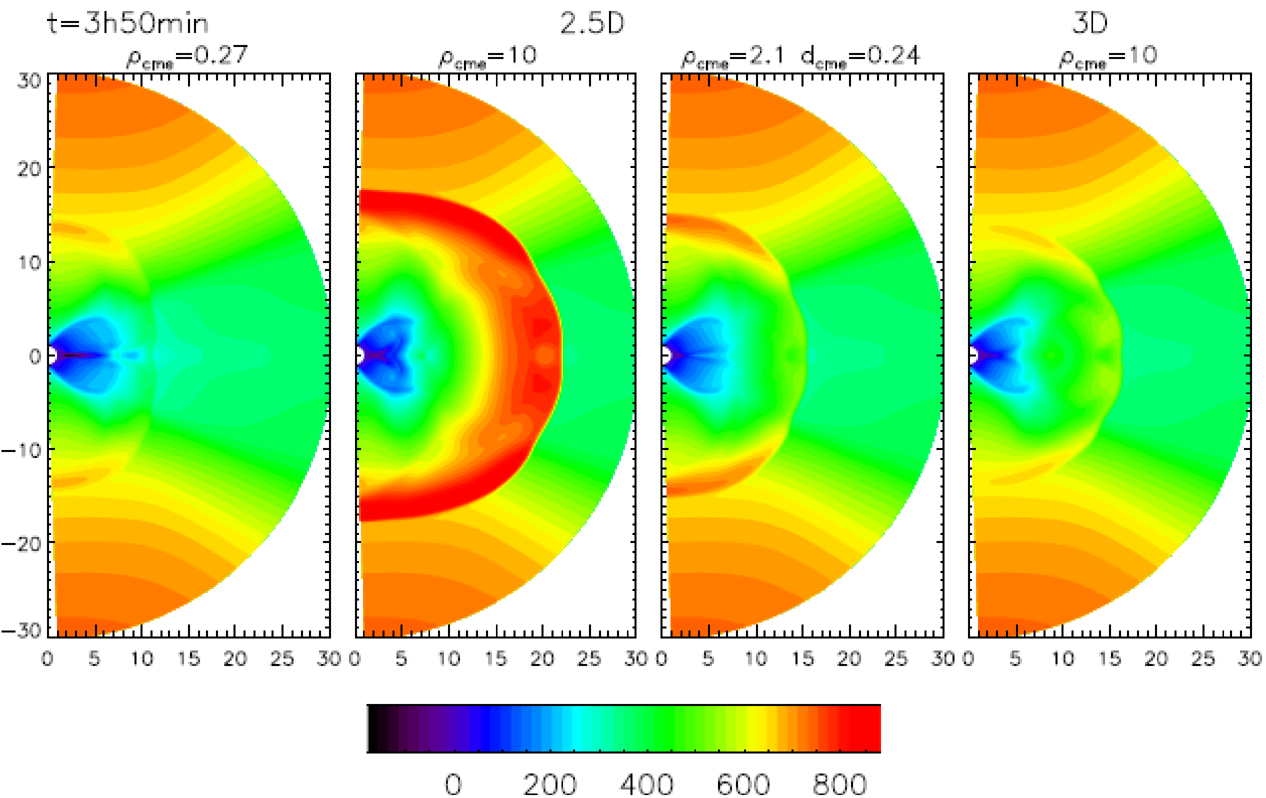
Radial & Latitudinal Evolution





- 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.

2.5D vs 3D CME simulations



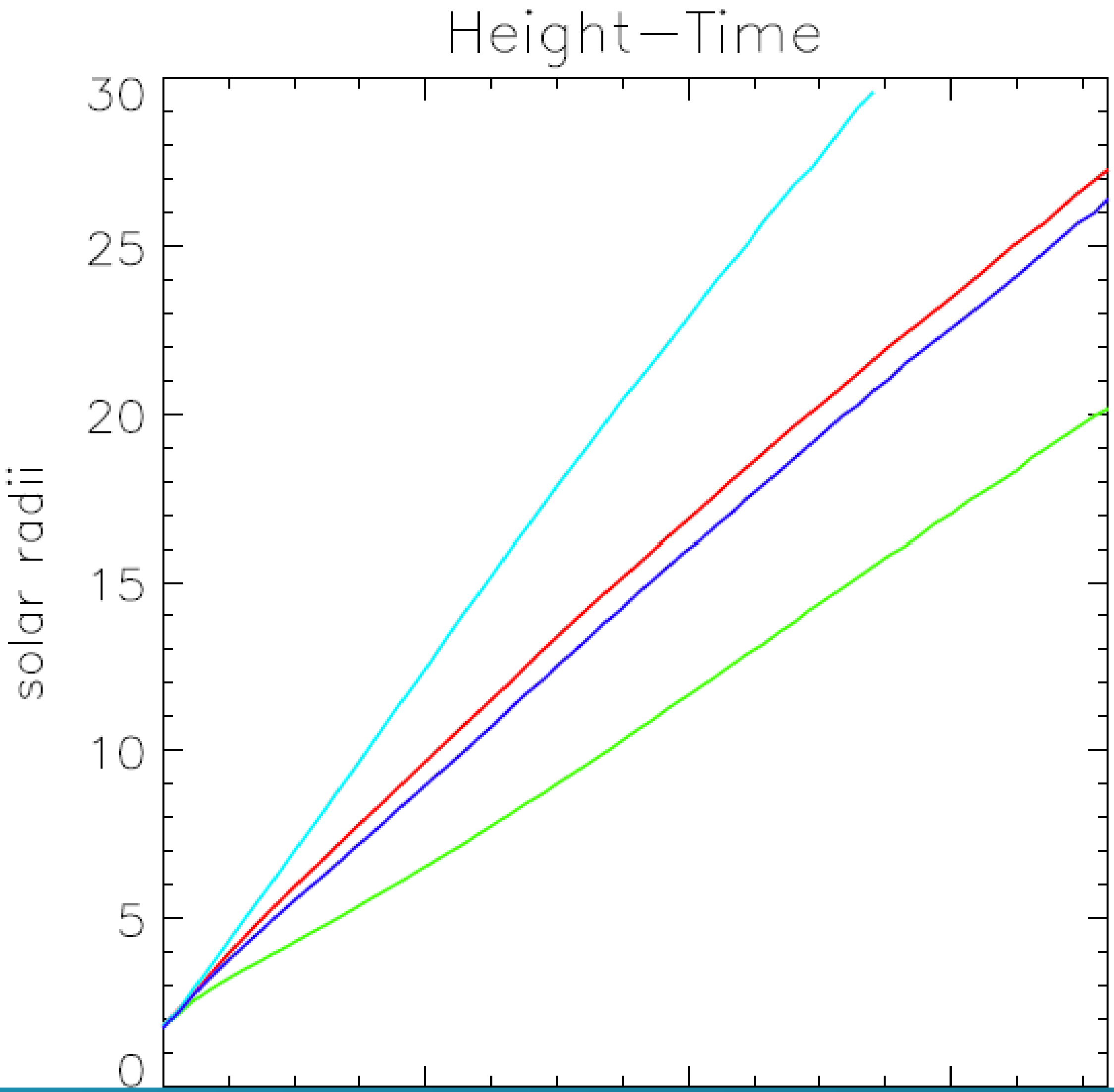
Radial velocity contours in meridional plane at $t = 3$ hr 50 min for 3 different 2.5D CMEs (3 left panels, 640×91) and a 3D CME (right, $640 \times 91 \times 180$).

comparison 2.5D CME simulations vs 3D:

- *3D CME:* $\rho_{\rm cme} = 10$ (=1.13×10^{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*

Jacobs et al. (2007)

2.5D vs 3D CME simulations

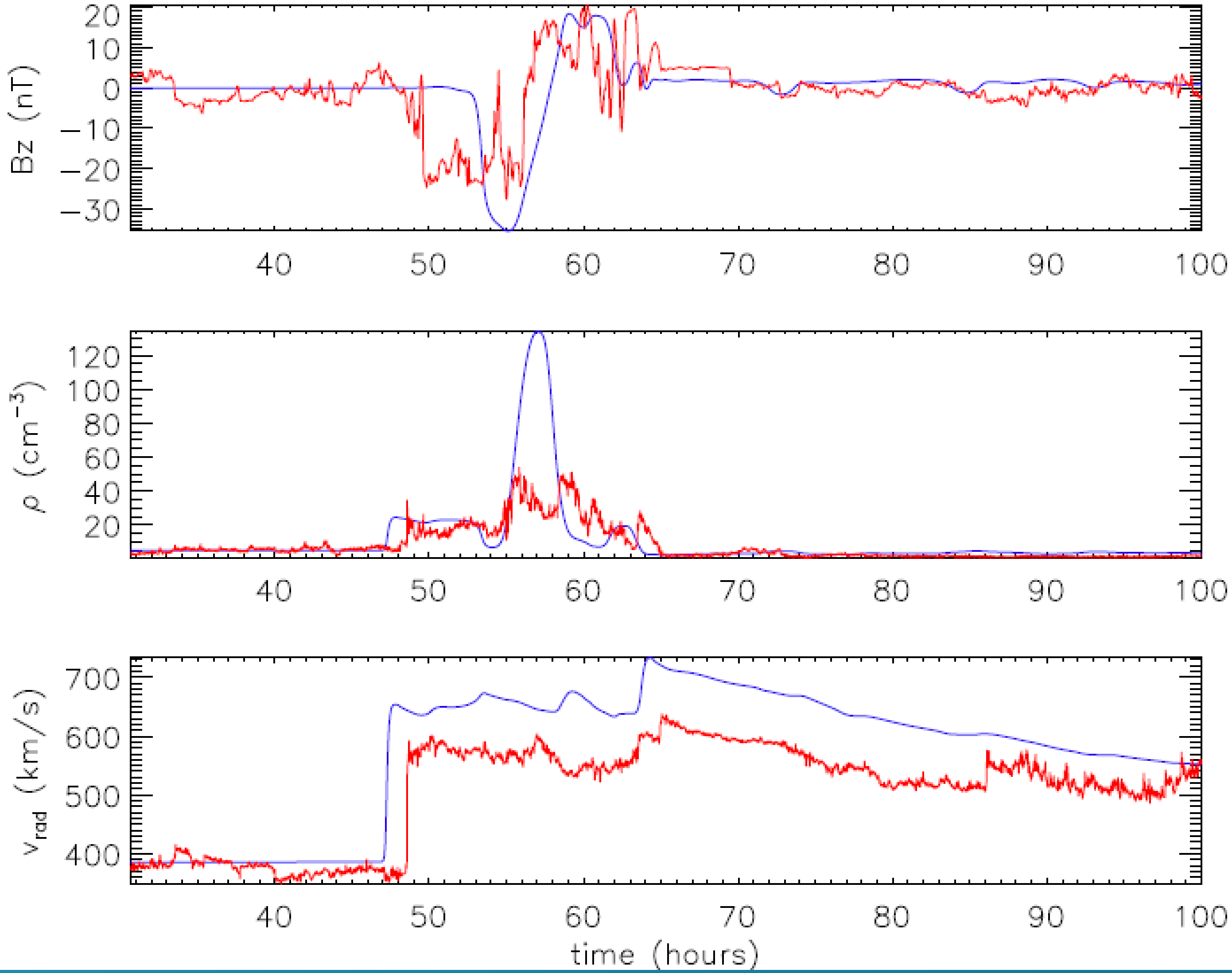


comparison 2.5D simulations vs 3D:

- *same* ρ_{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



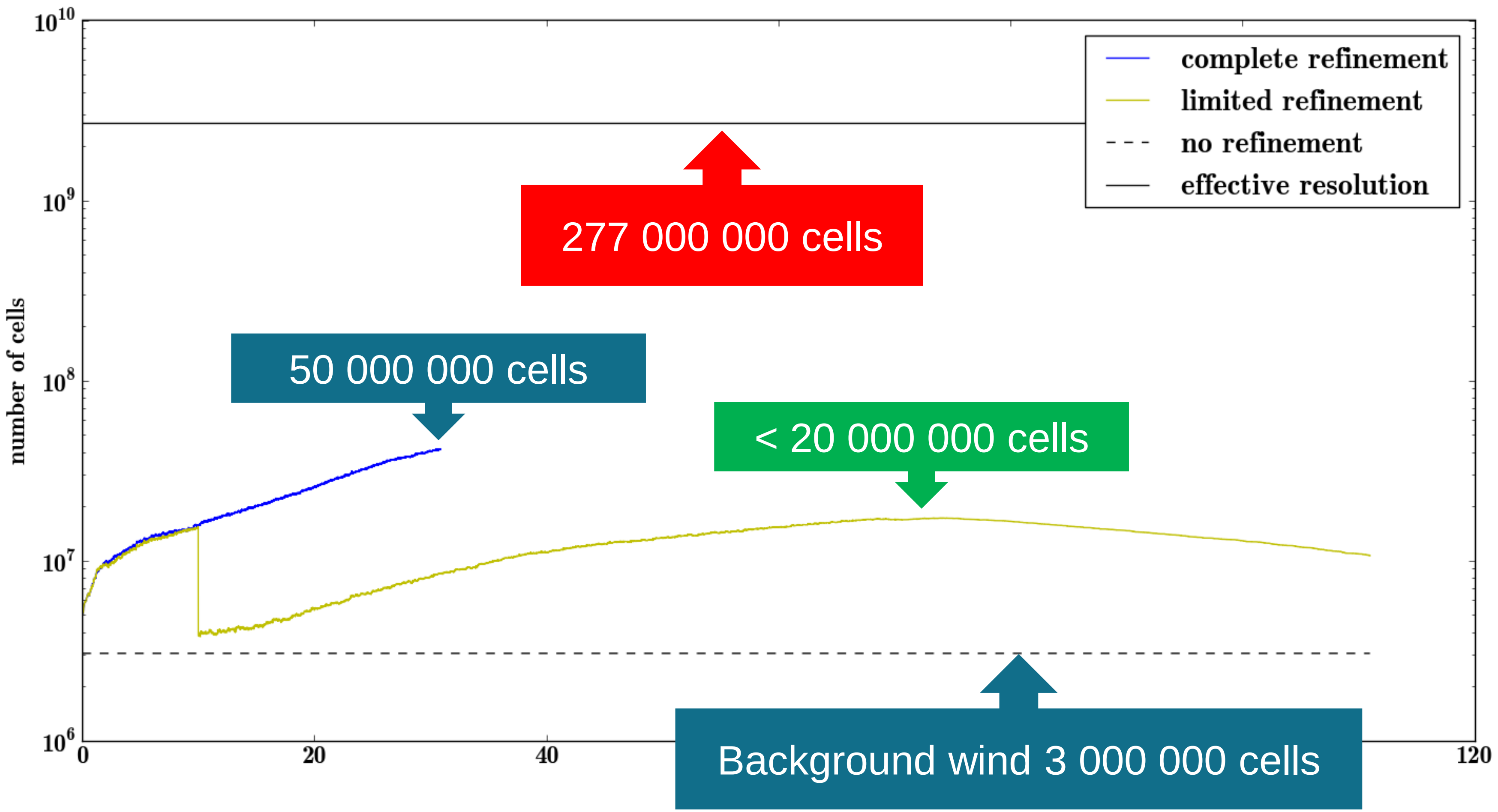
Comparison between the in situ data obtained by the ACE spacecraft (red curves) and our best fitting simulation (blue curves).

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

Chané et al. (2006)

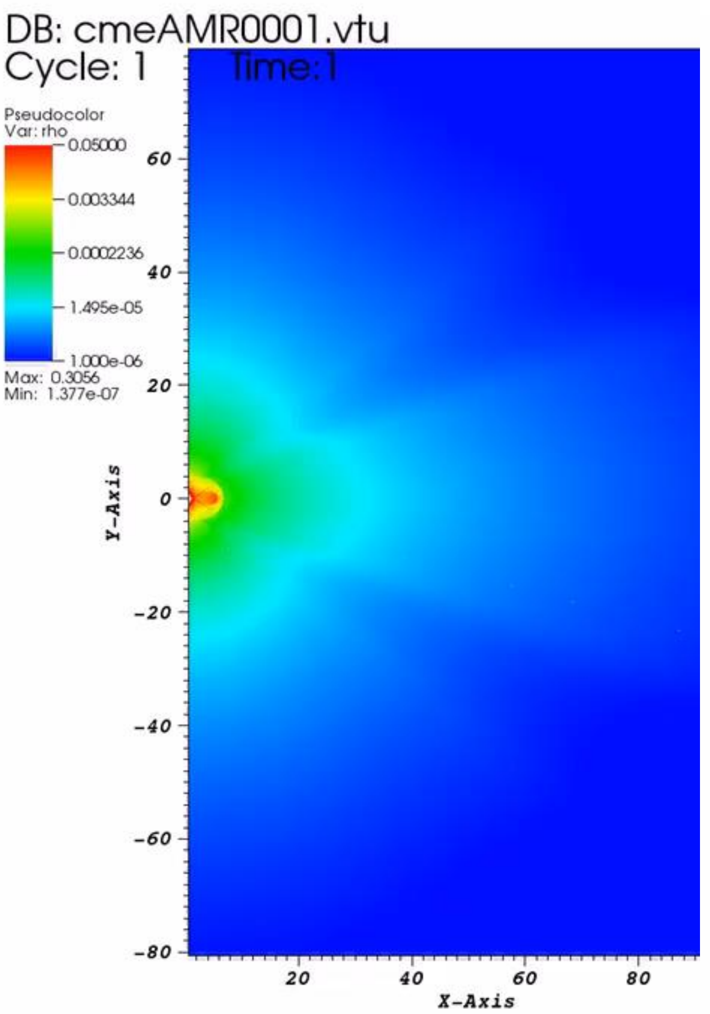
KU LEUVEN

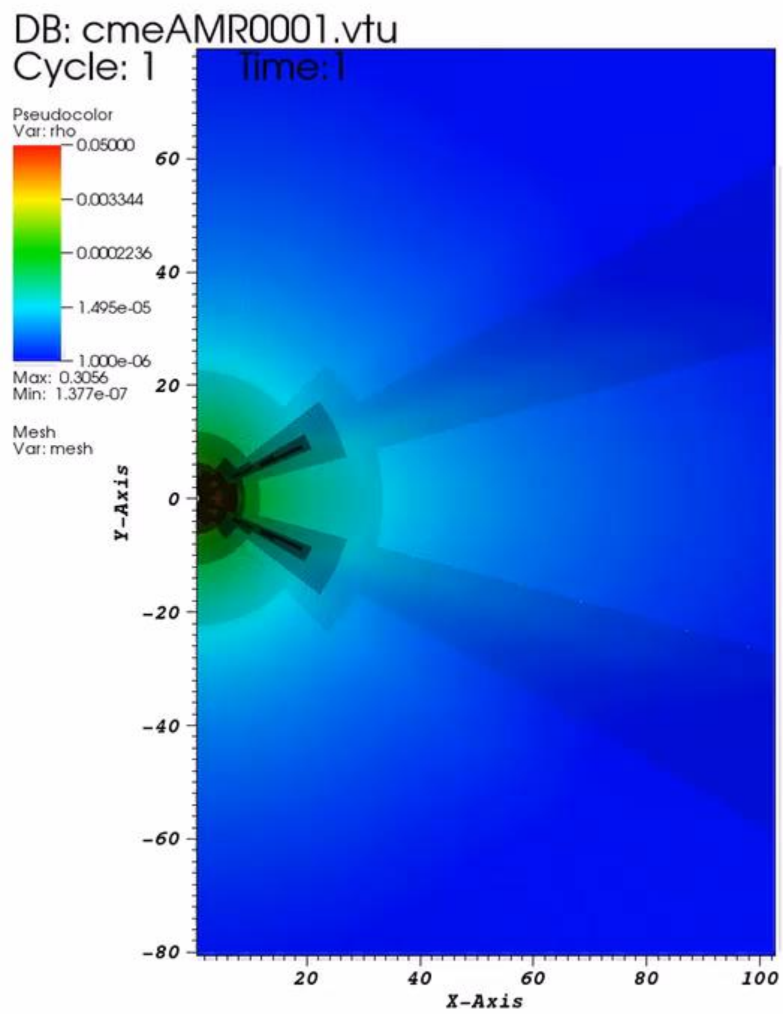
New ultra-high resolution results



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

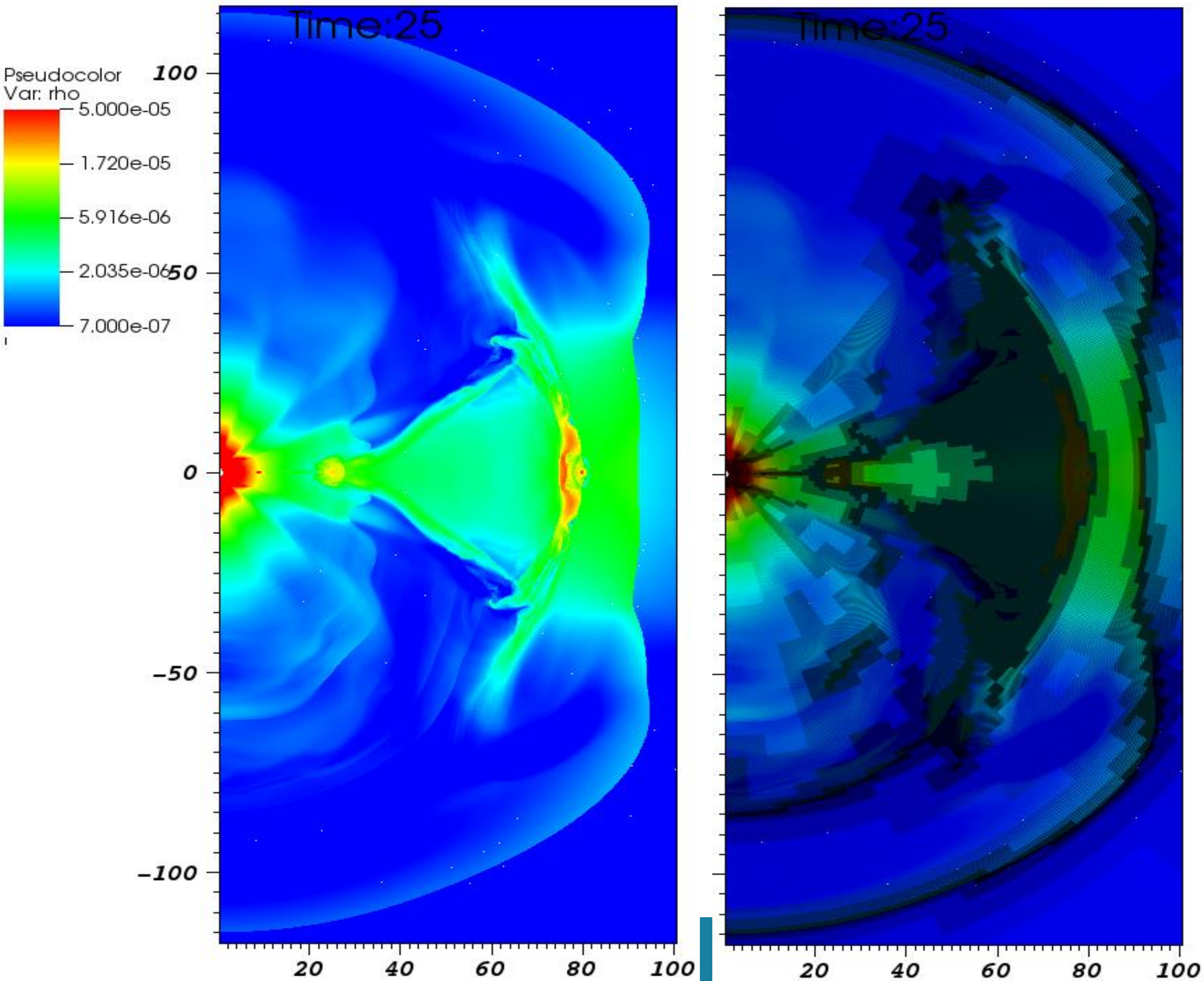
New ultra-high resolution results





user: skralan
Mon May 4 10:04:52 2015

New ultra-high resolution results

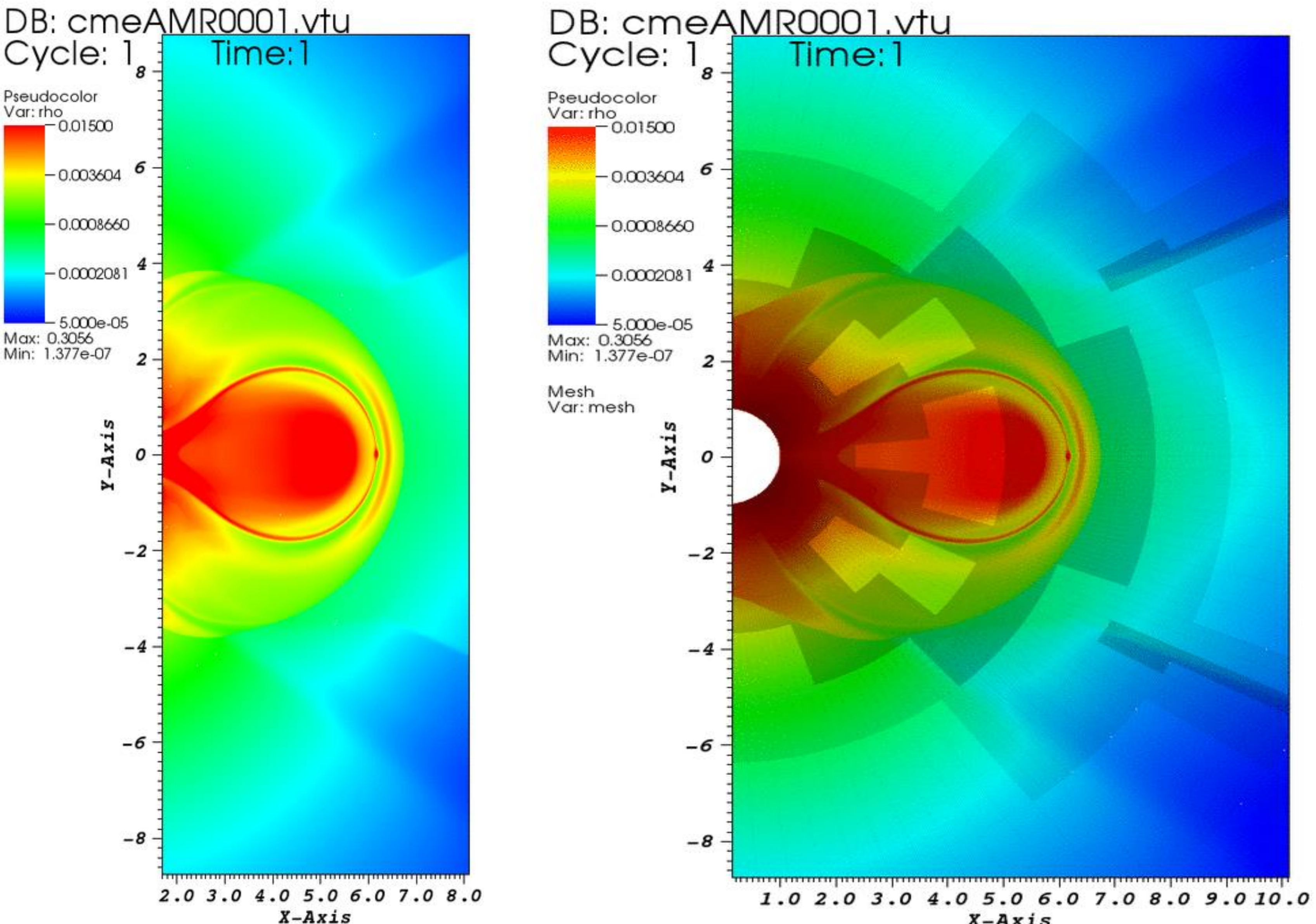


2D color plot of the density at 30h when the CME is ejected with
an initial velocity of 1000 km/s.

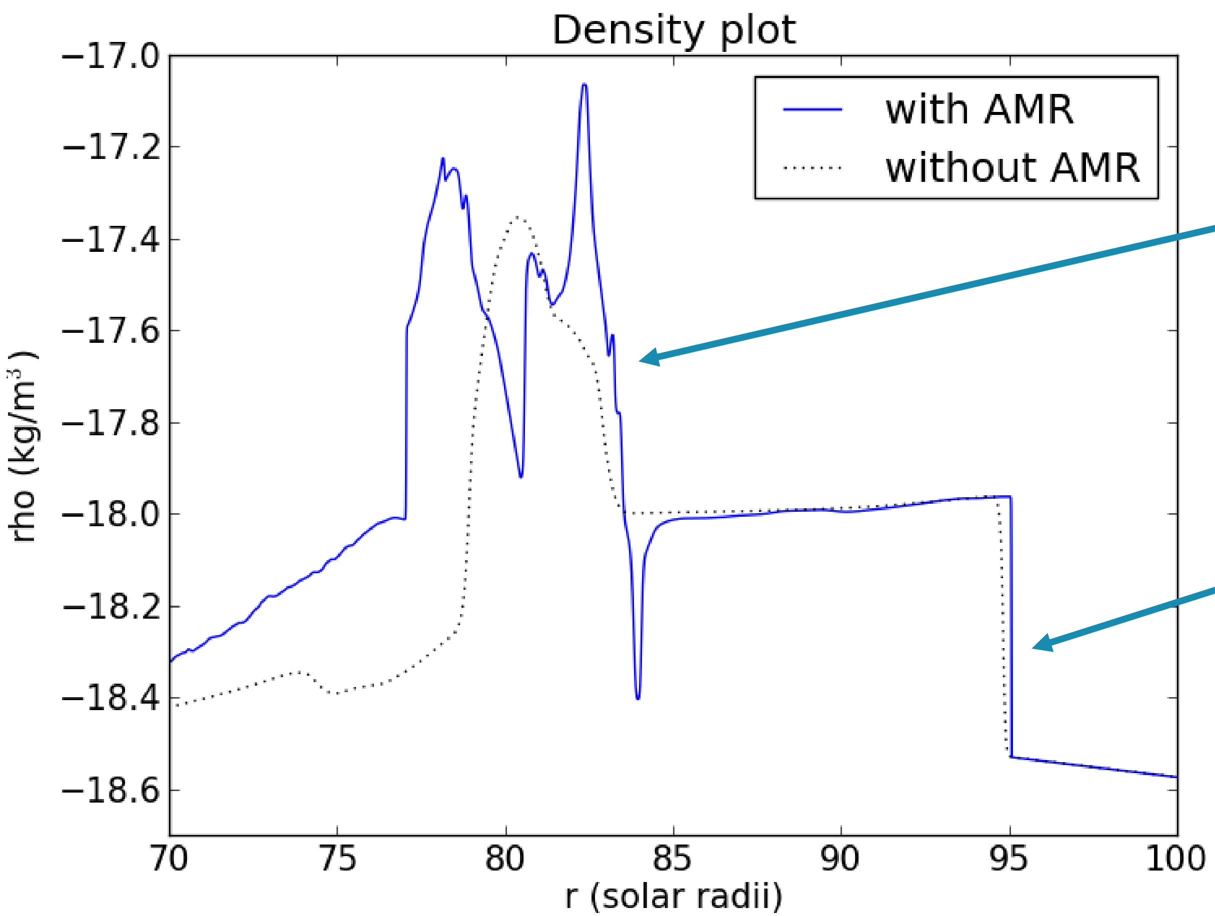
AMR was first applied on the whole grid according
to a gradient in the density.
Fine tuning: only shock and IP MC are AMR resolved.

cpa KU LEUVEN

Scaled (zoomed) movie of density (with grid)



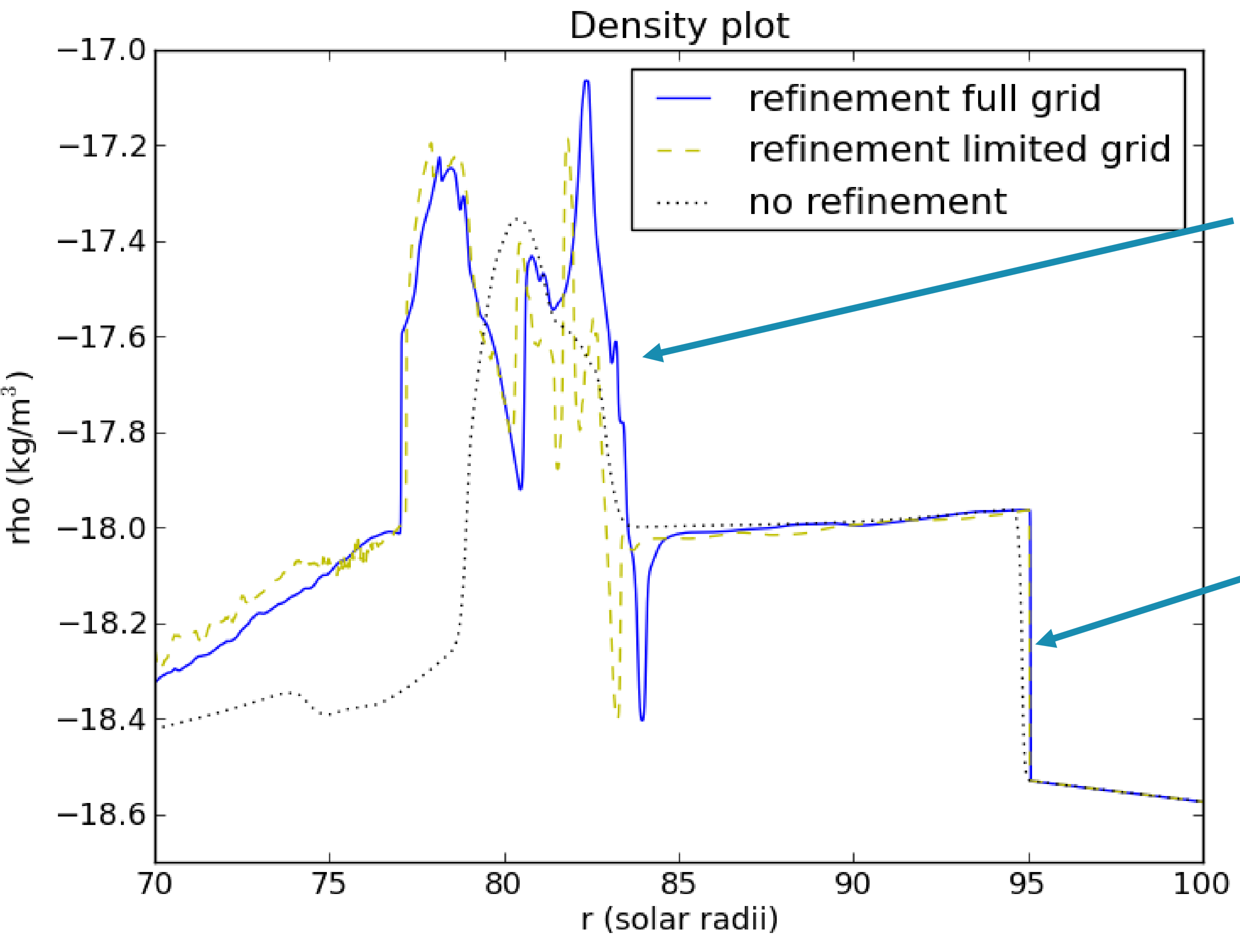
New ultra-high resolution results



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.

Conclusions

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

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)

cpa KU LEUVEN

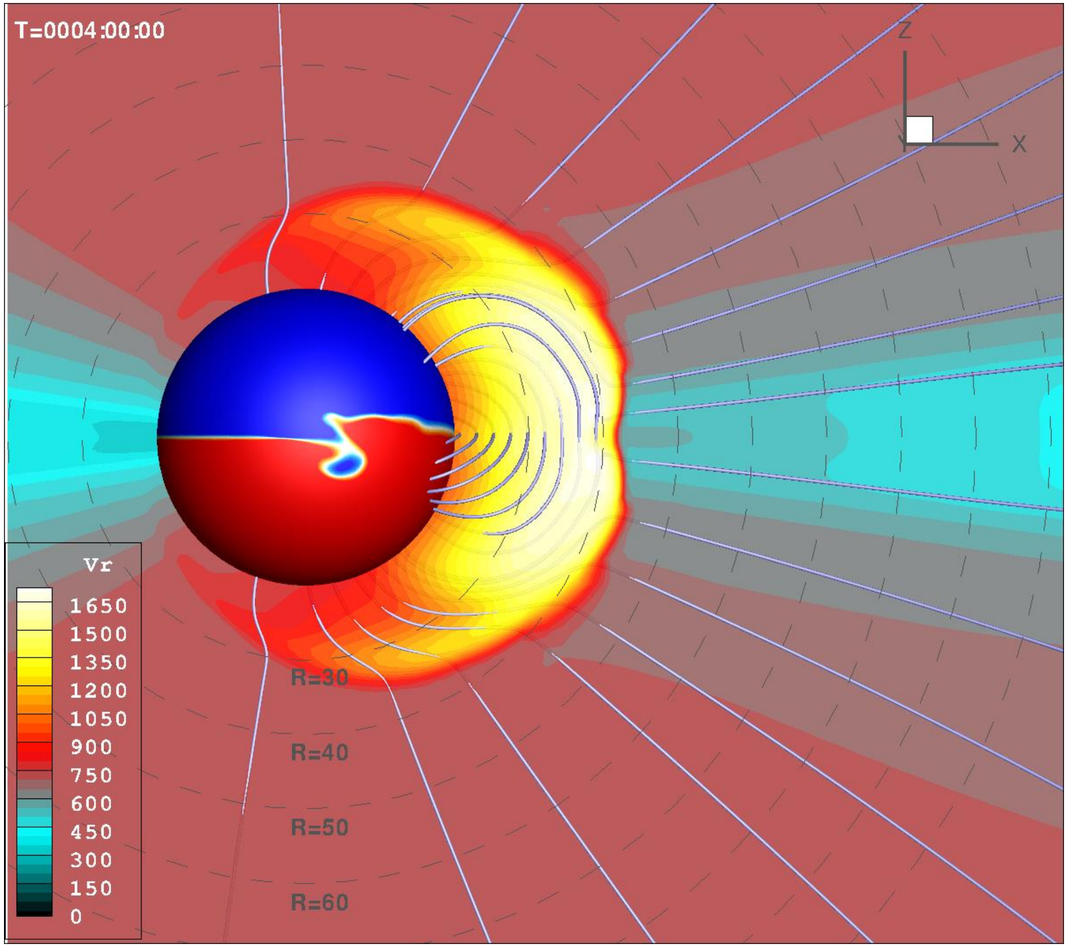
Conclusions / recommendations

- 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

- **Triggering mechanism(s): for magnetic coupling to chromosphere & photosphere**
  - **Take into account partial ionization effects**
  - **Take into account multi-fluid effects** (i.e. not only ambipolar diffusion)

CPA KU LEUVEN

Thank you very much!



Questions?

- How do you know so much?
- I asked them.
McCoy and Spock (Star Trek)

cpa KU LEUVEN

cpa KU LEUVEN