Evolution of magnetized CMEs in the inner heliosphere

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Euhforia: long term goals

‘European heliospheric forecasting information asset’

Our long-term goal is to develop novel models to address the growing need for accurate space weather predictions :

- predict the magnetic structure of coronal mass ejections
- predict the properties of solar energetic particle (SEP) events
- provide tailored SW models

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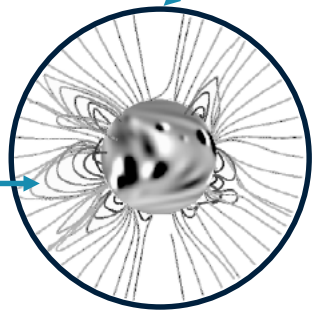
Solar wind modeling

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)

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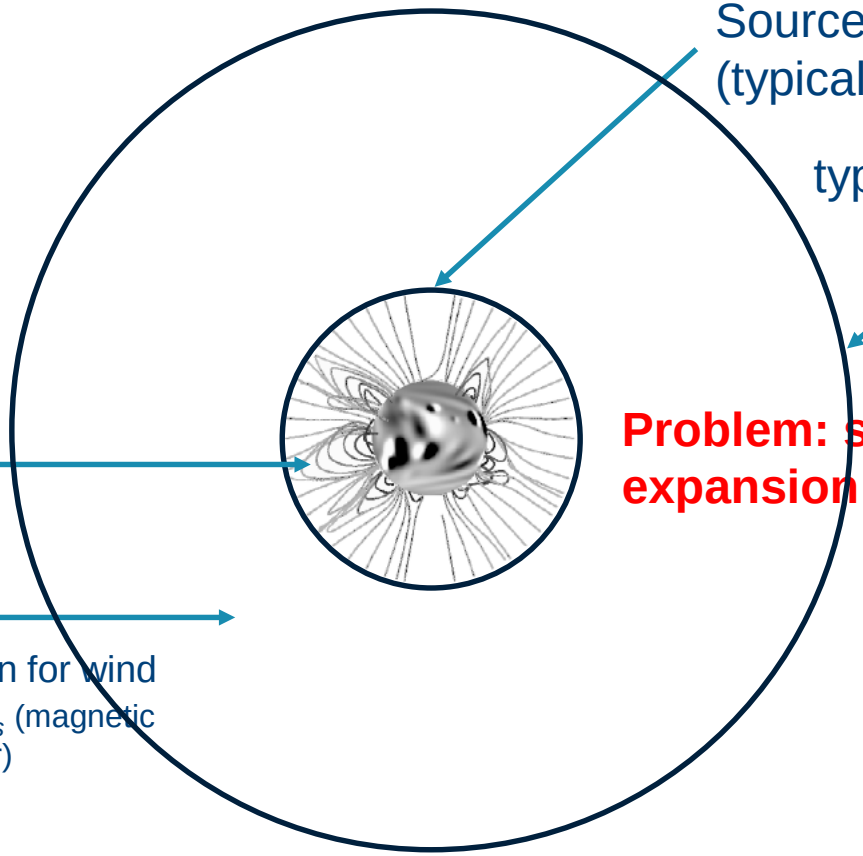

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typ. at about 21.5 Rs (0.1 AU)

Coronal model
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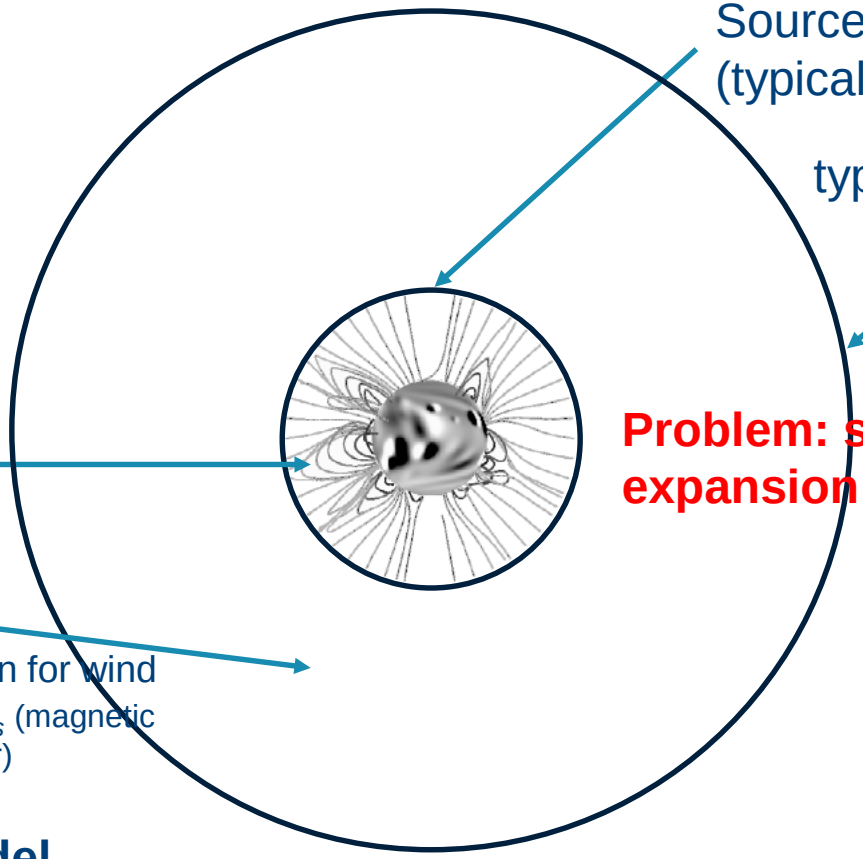
Problem: super-radial expansion of flux tubes

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



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

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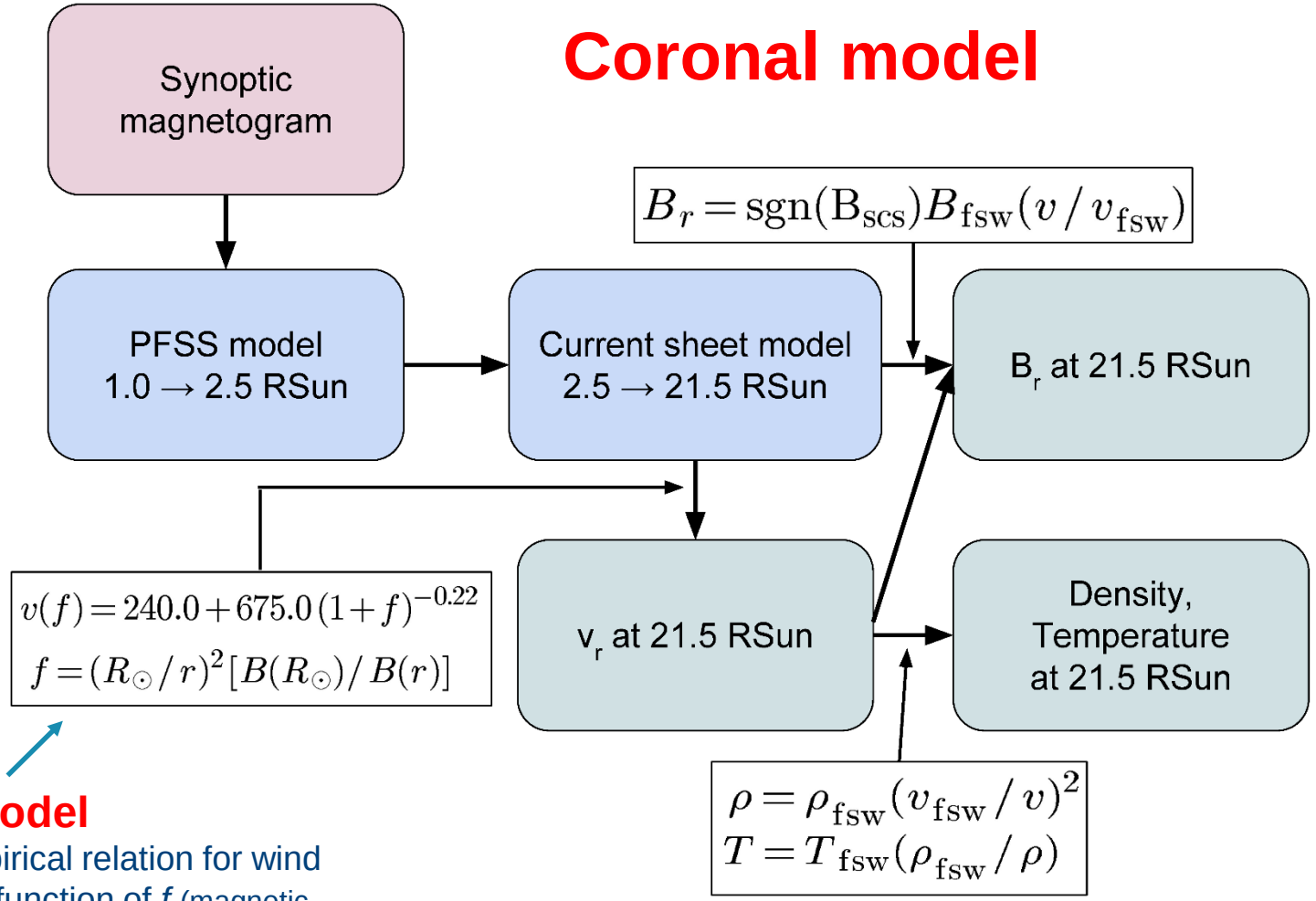
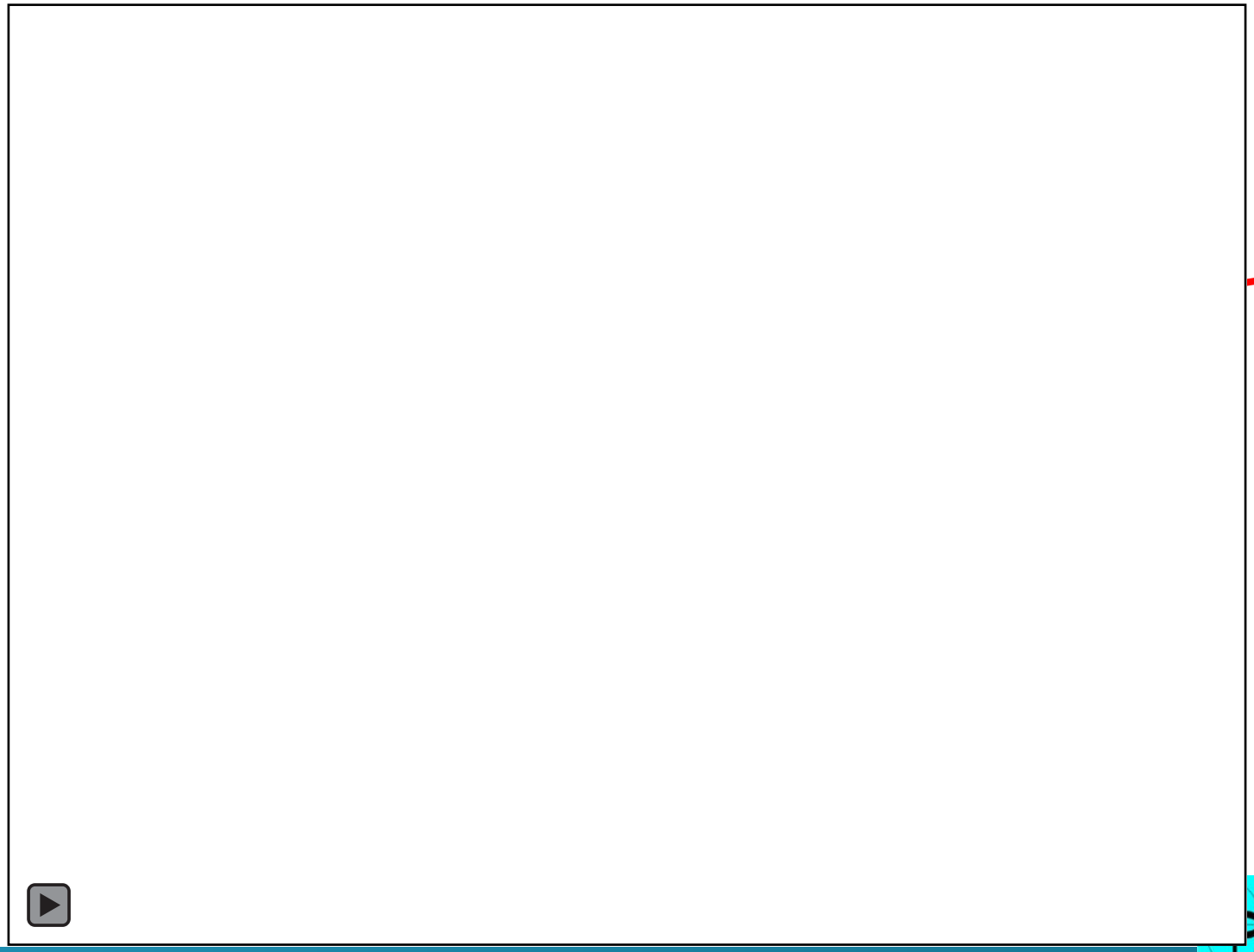


WSA model

Semi-empirical relation for wind speed as function of *f* (magnetic flux tube expansion factor)

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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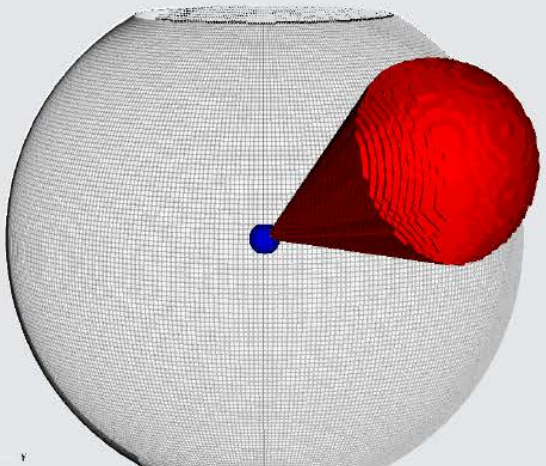
Heliosphere model with CMEs

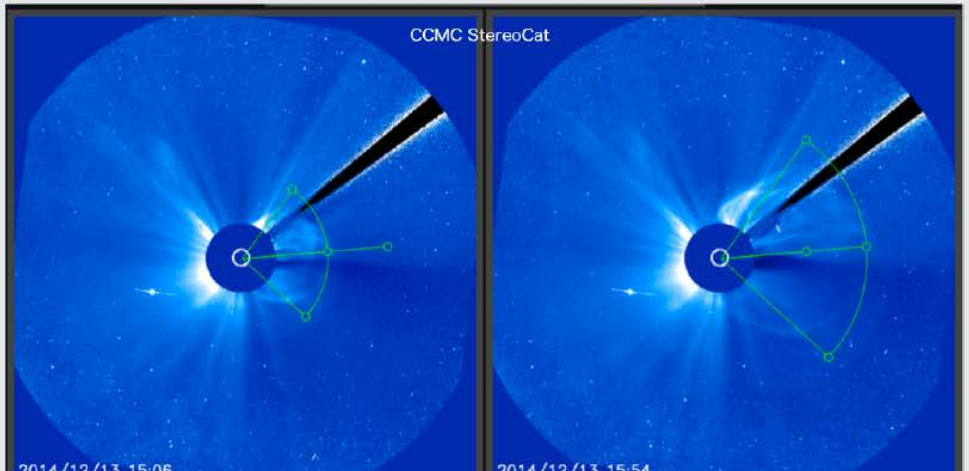
AIM: Compute time dependent evolution of MHD variables from 0.1 AU to 1 AU and beyond (up to a few AU)

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

Cone-model CMEs inserted at 21.5 AU as time-dependent boundary condition





Ballistic CME test
(same background wind)

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

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Euhforia: 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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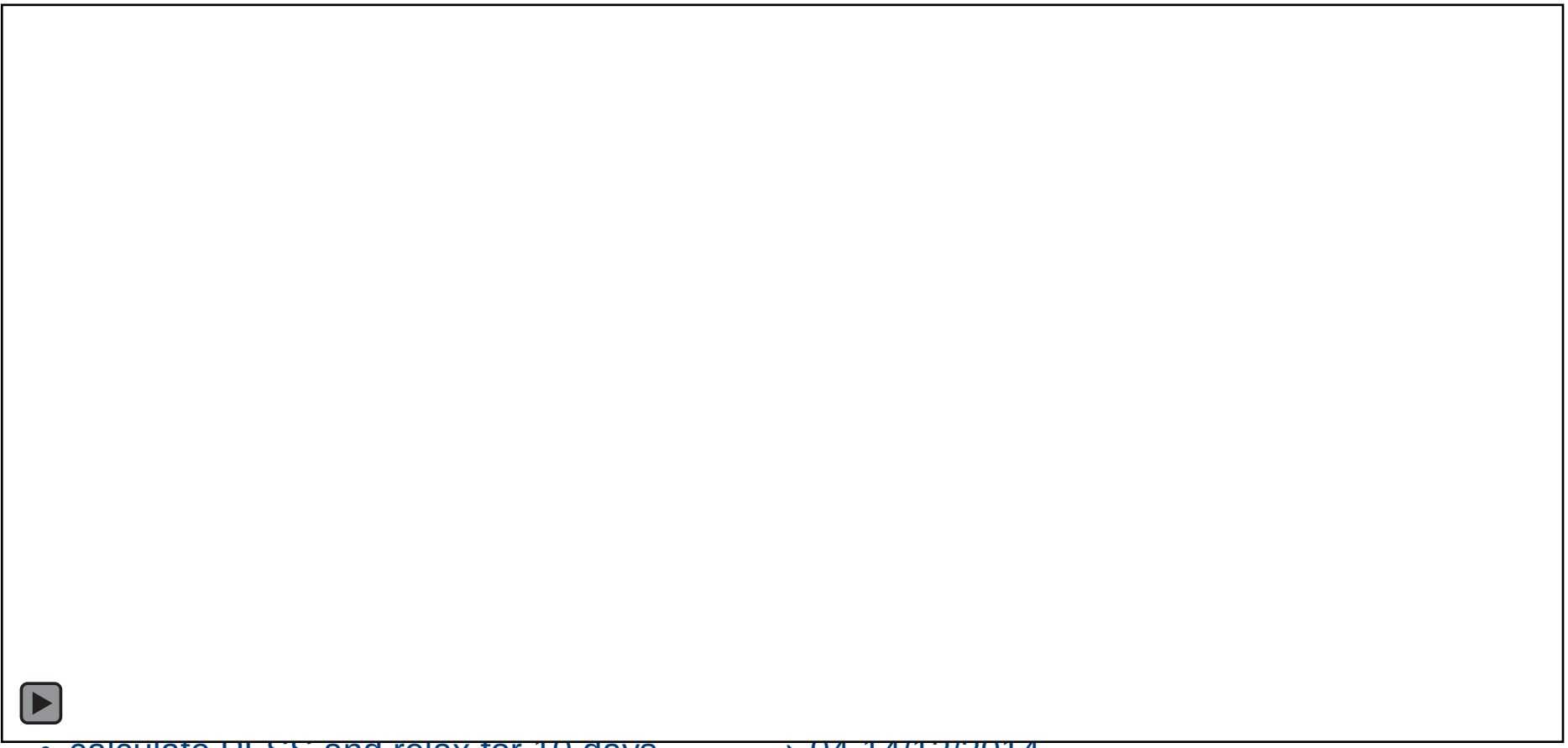
Three phases of simulation: V_r



- 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

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Euhforia: current status

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Status update

- **daily, semi real-time operations at ROB**
  - code is running more or less in an operational fashion

- **Validation (comparison with ENLIL & ACE) ongoing**
  - Same color table as ENLIL implemented (for easy comparison)
- **Synthetic ACE data & automatic comparison to in-situ observations at 1 AU now implemented**
- ***ADAPT maps can now be used* in addition to standard GONG maps**

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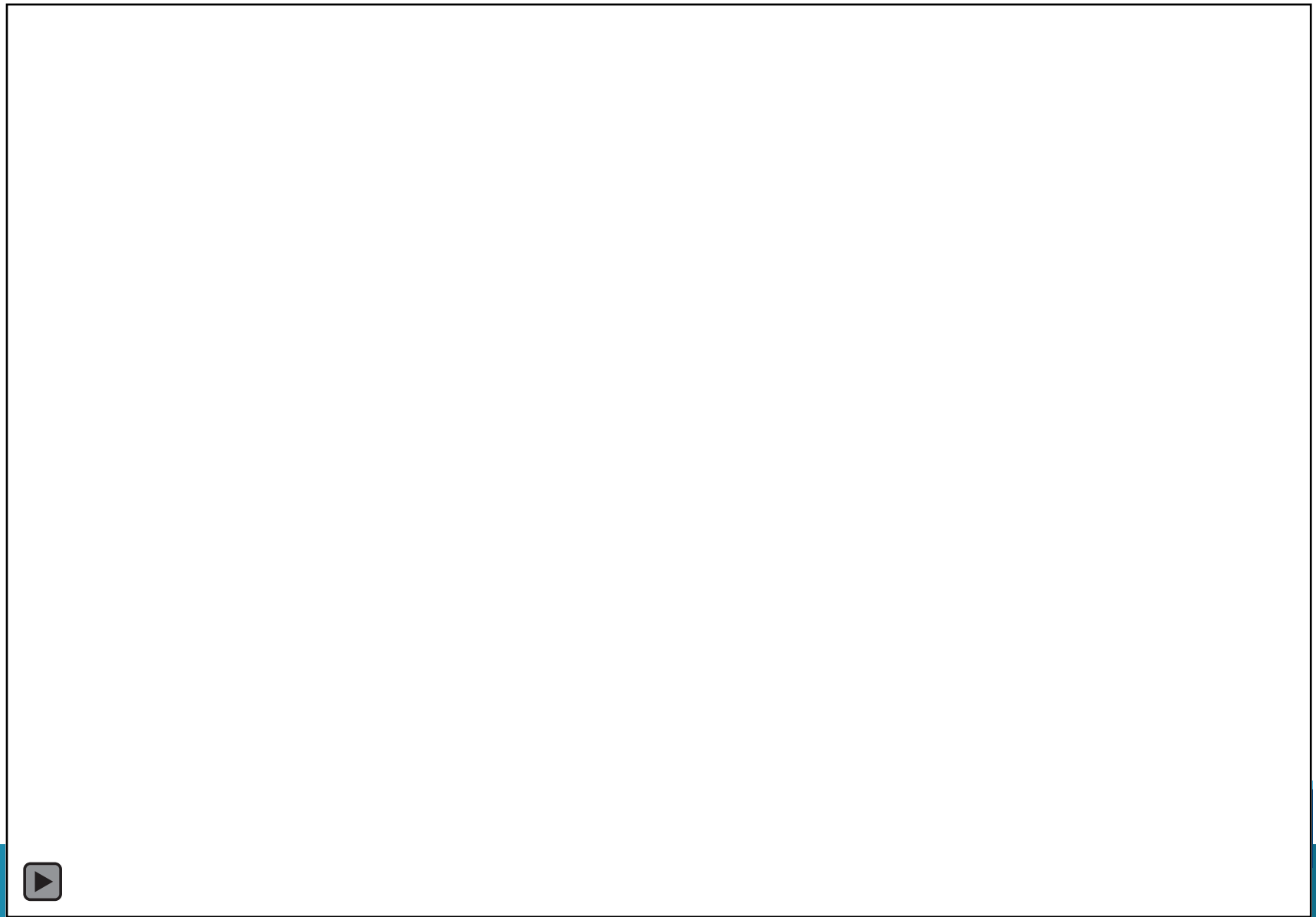
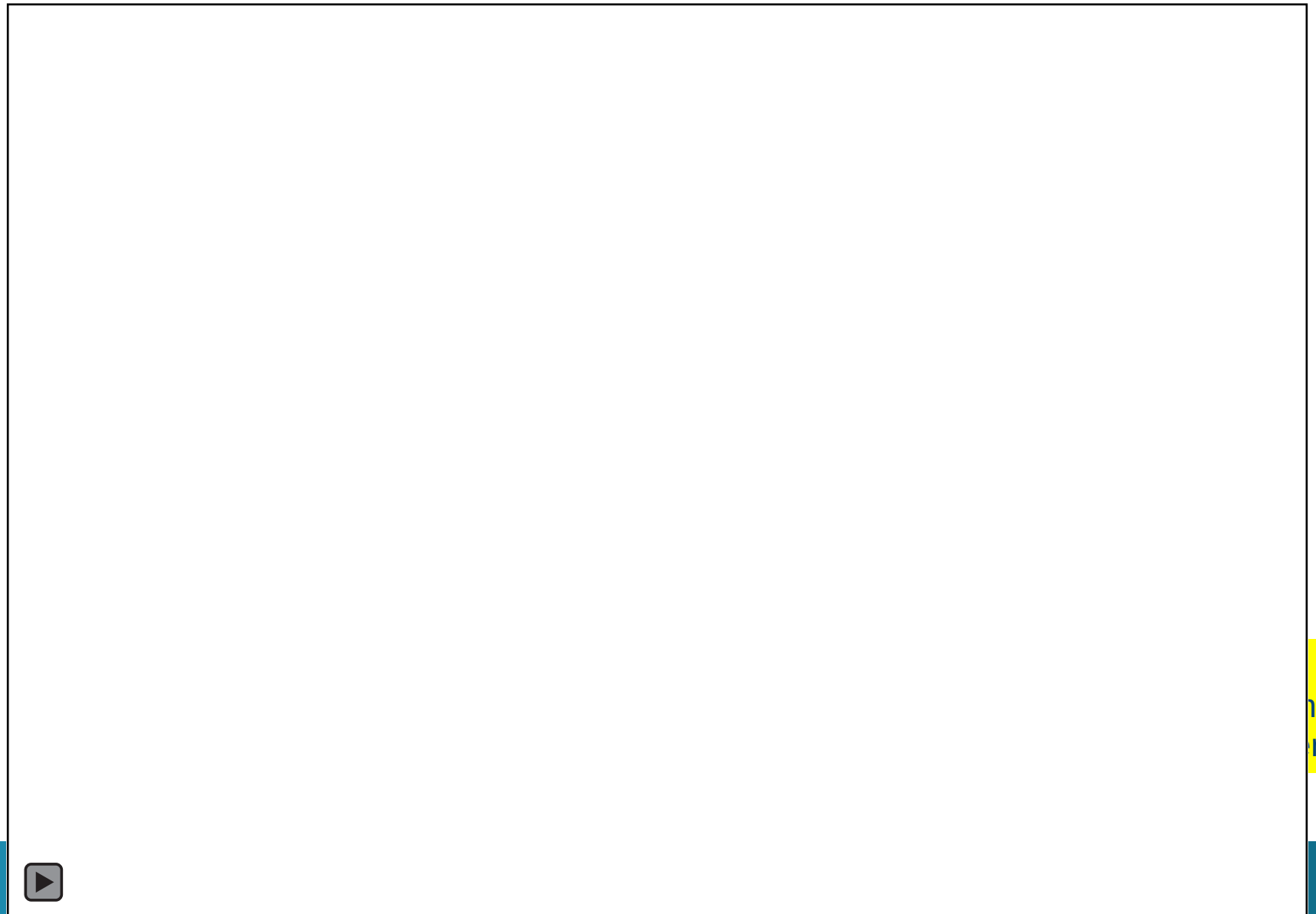
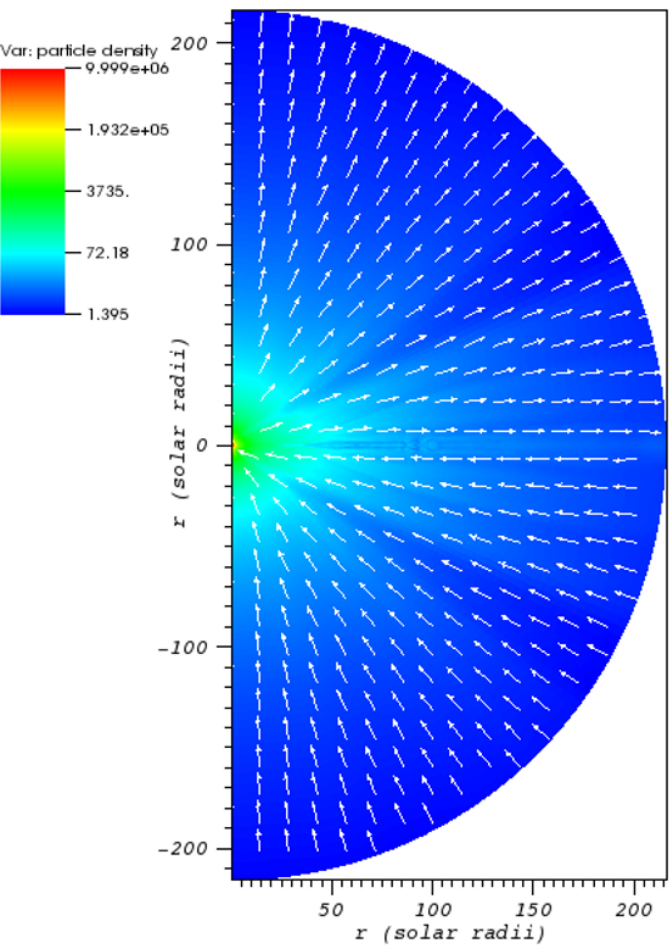
Improved plot: *radial velocity* V_r

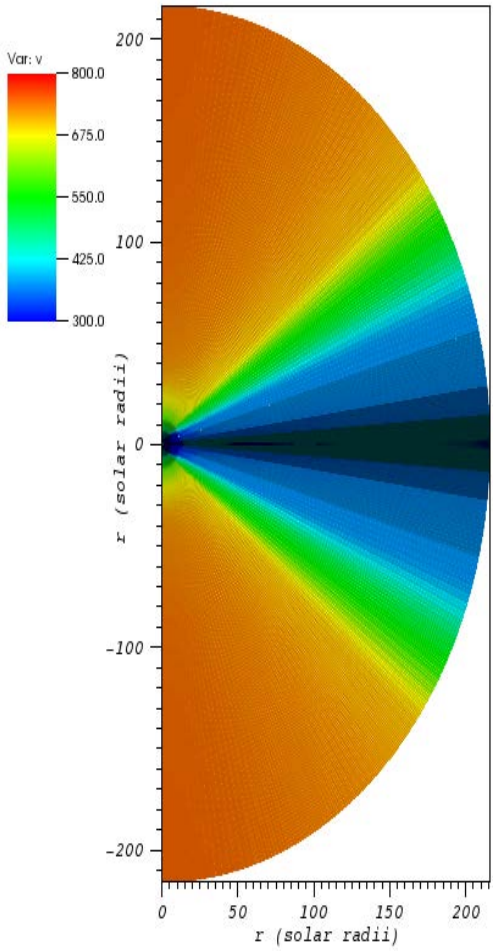


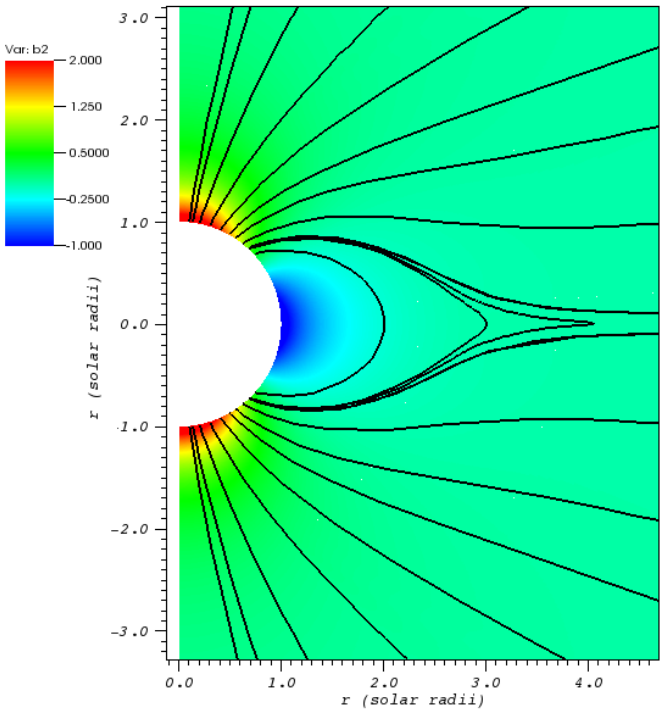
Improved plot: *numer density n*



New ultra-high resolution SW + FR CMEs







Back ground wind with 5 AMR levels

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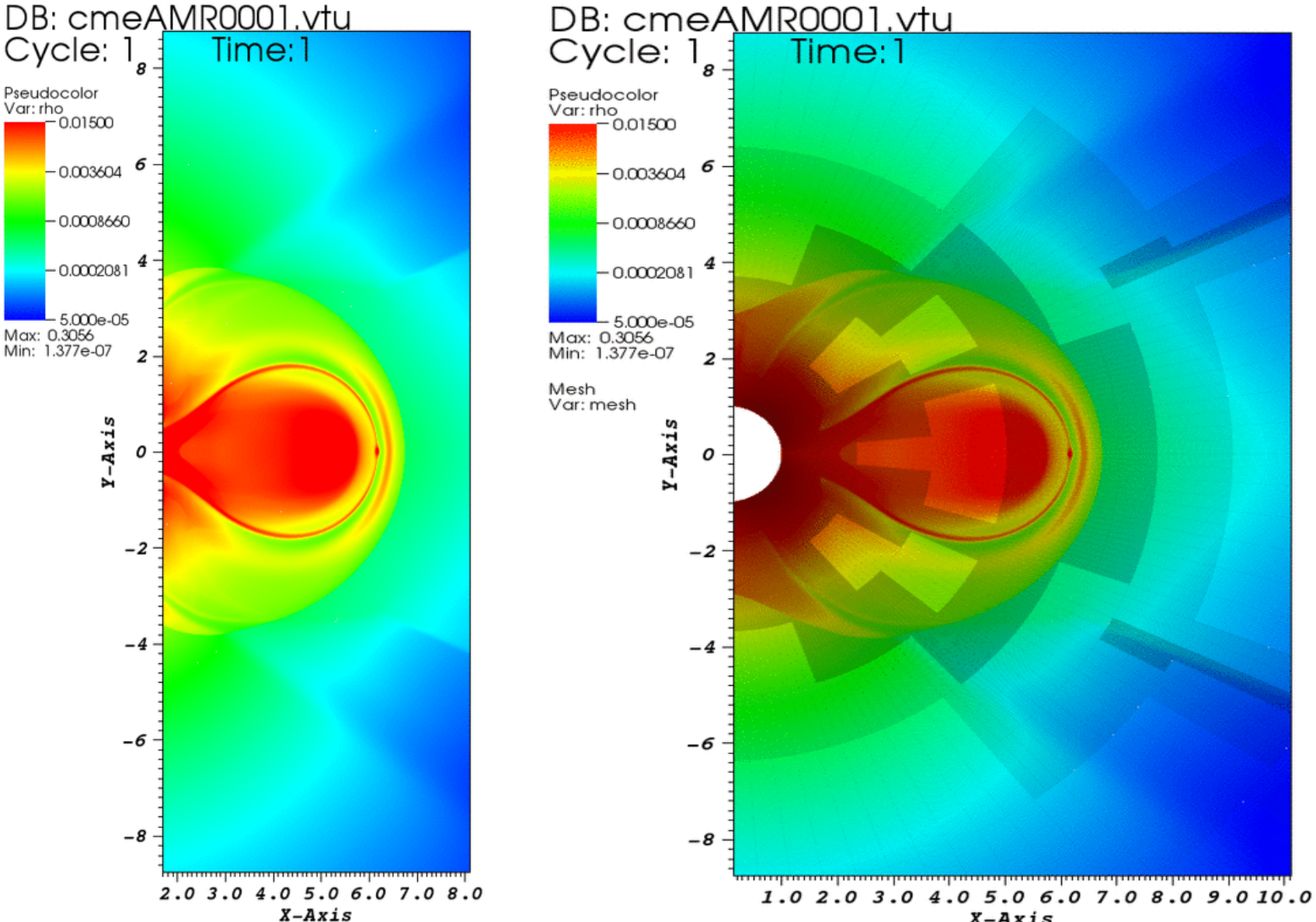
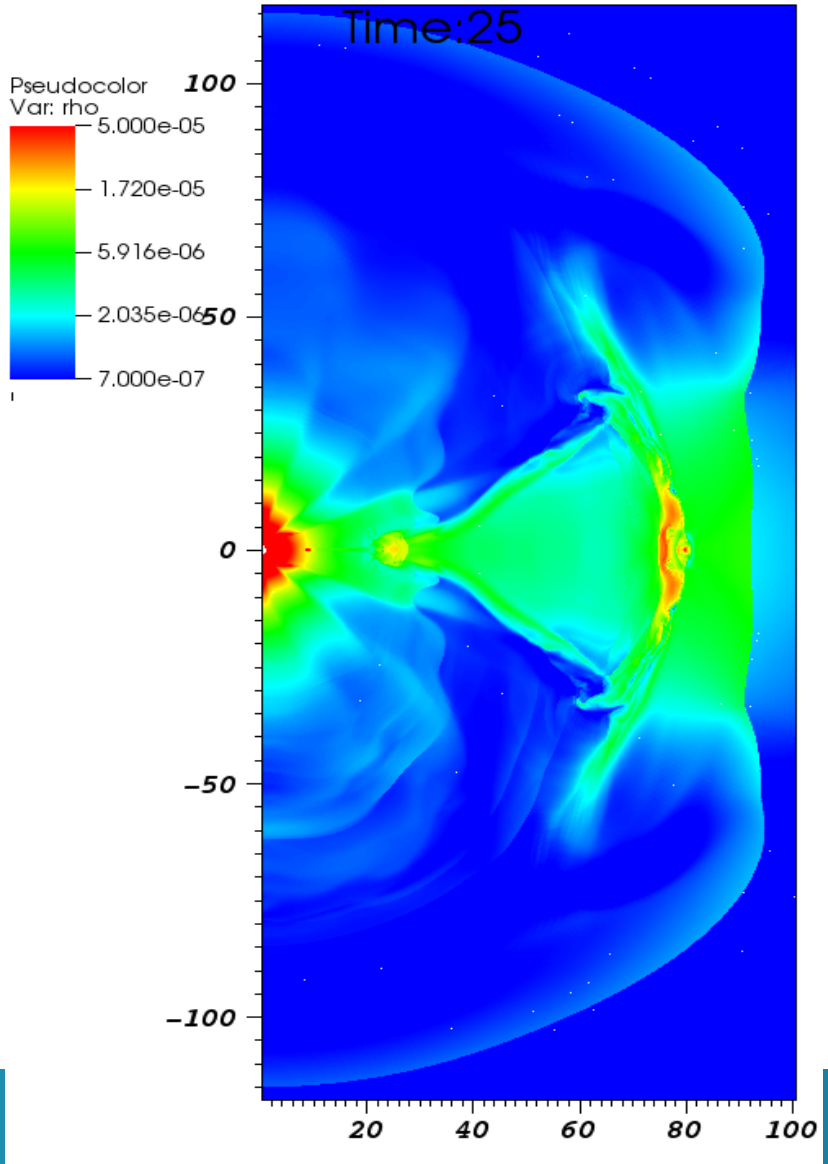
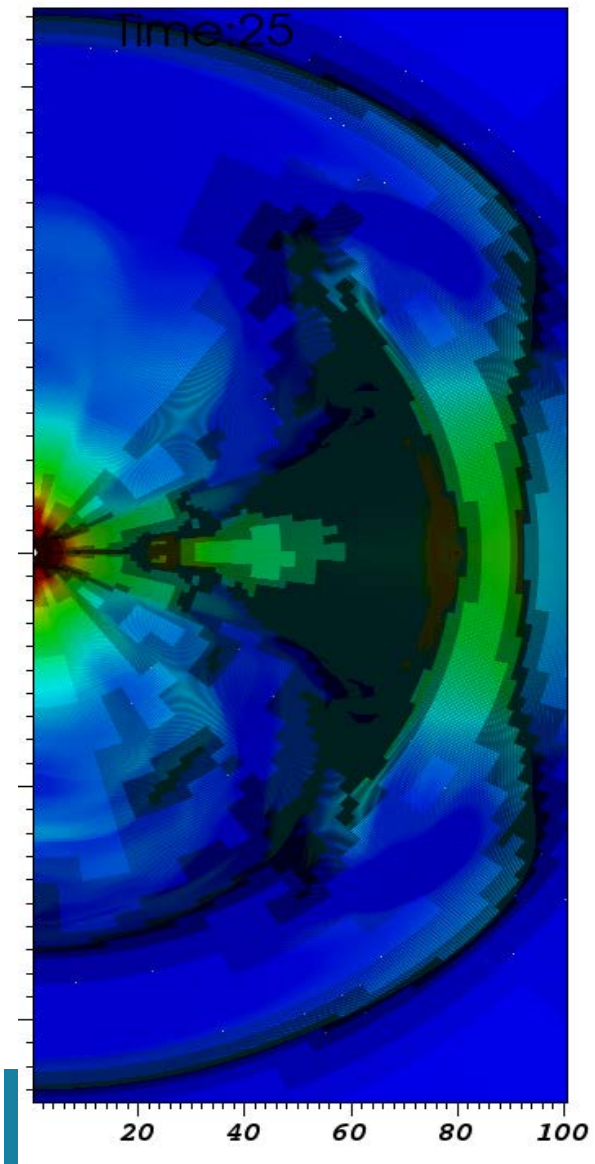
Scaled (zoomed) movie of density (with grid)



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.

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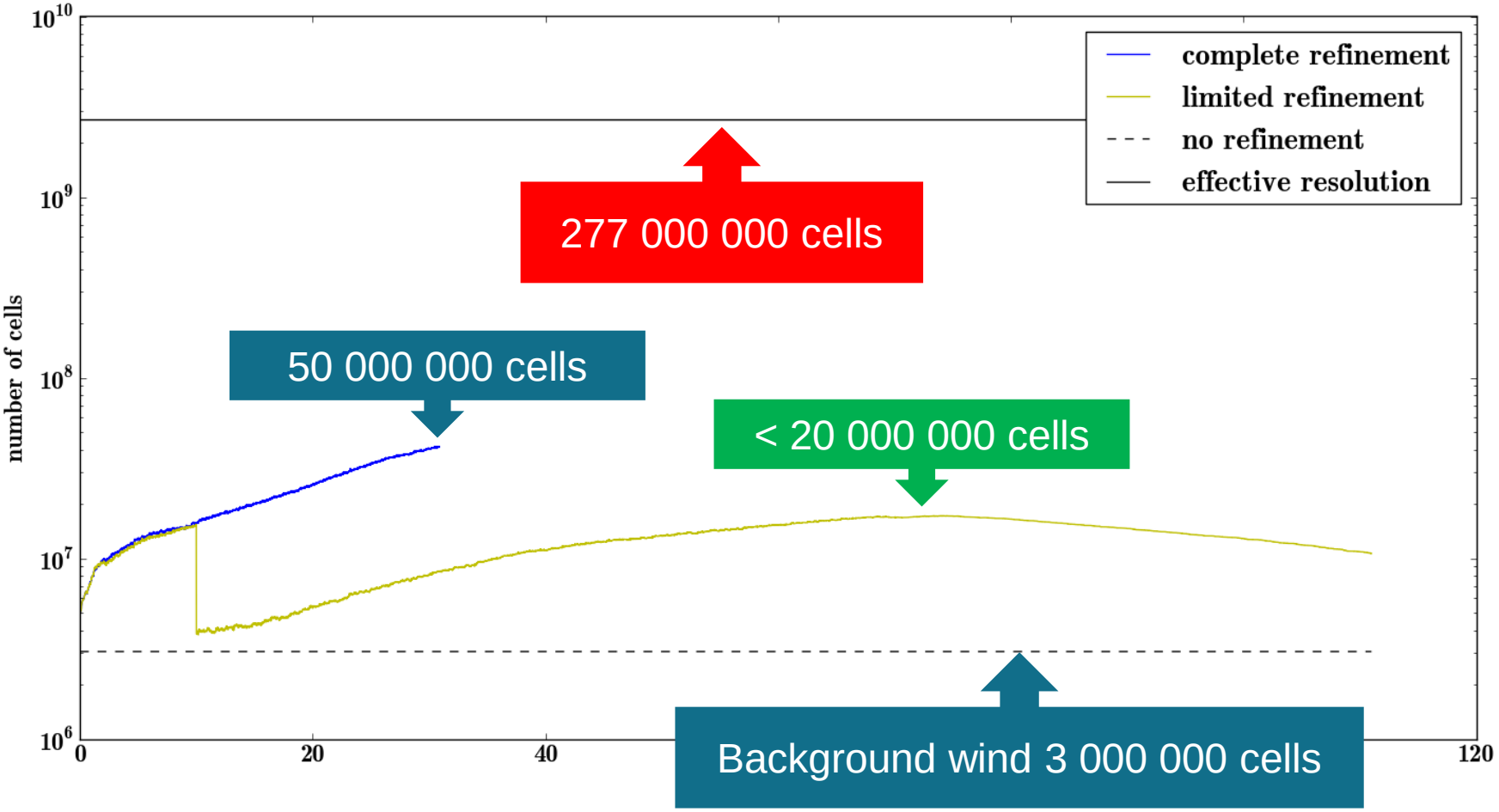
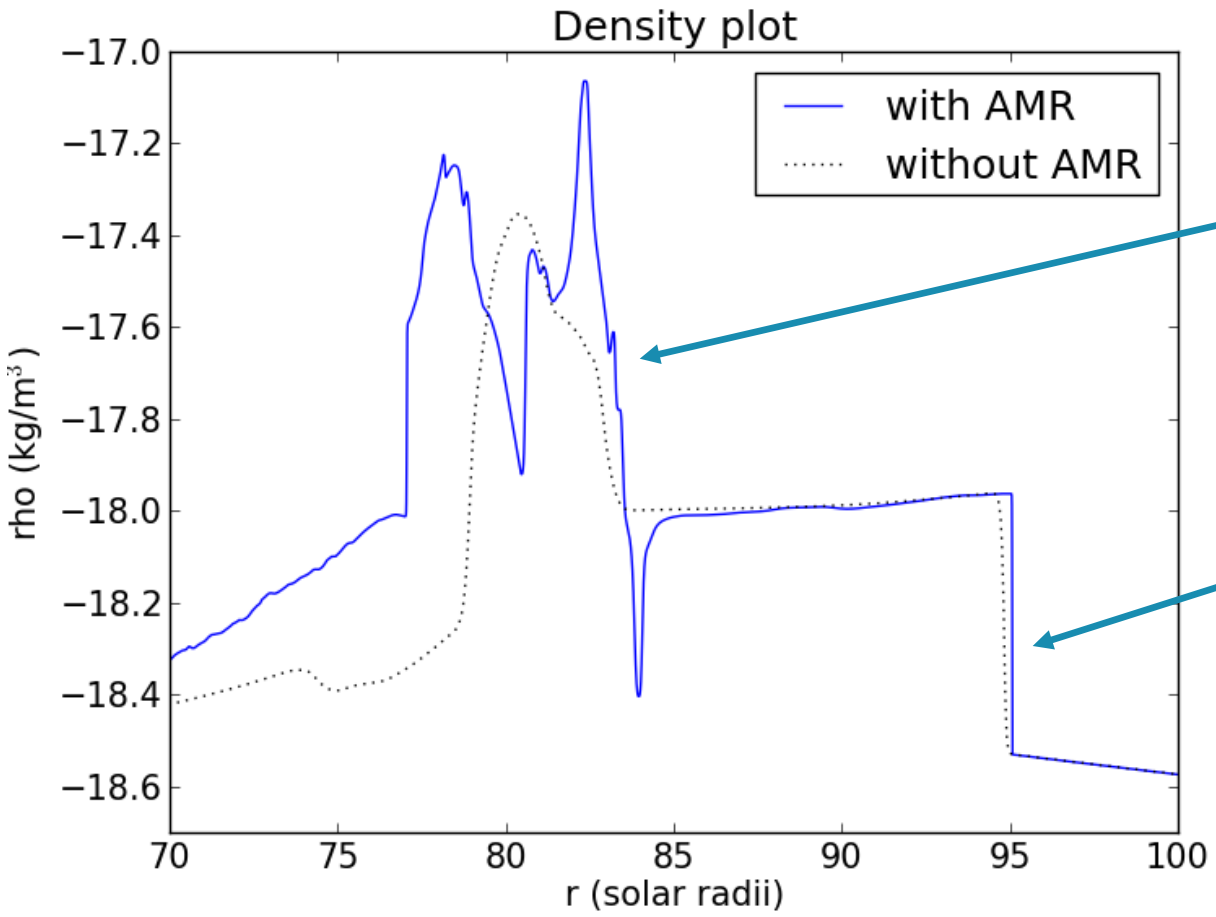
New ultra-high resolution results



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

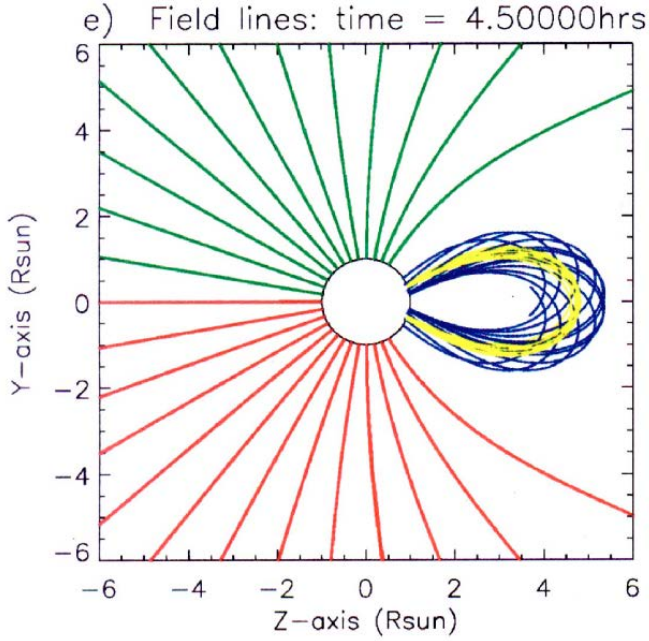
New ultra-high resolution results

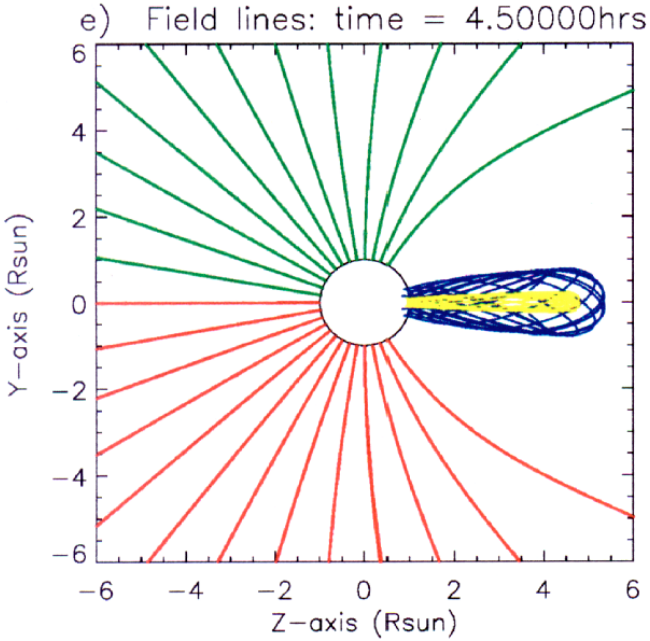


Close-up on the CME in the density profile. It is clear that the inner structure of the CME is much better captured when using AMR.

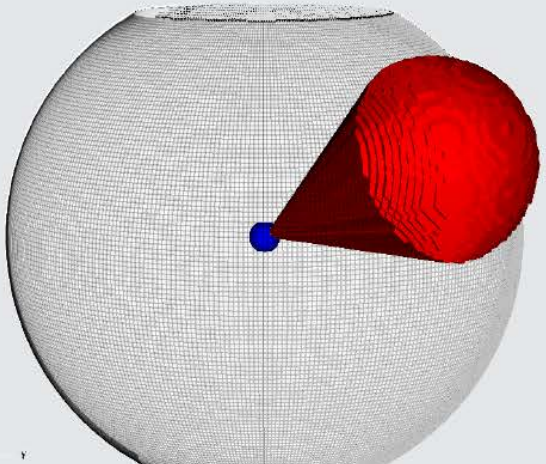
The height and position of the shock however remains practically the same.

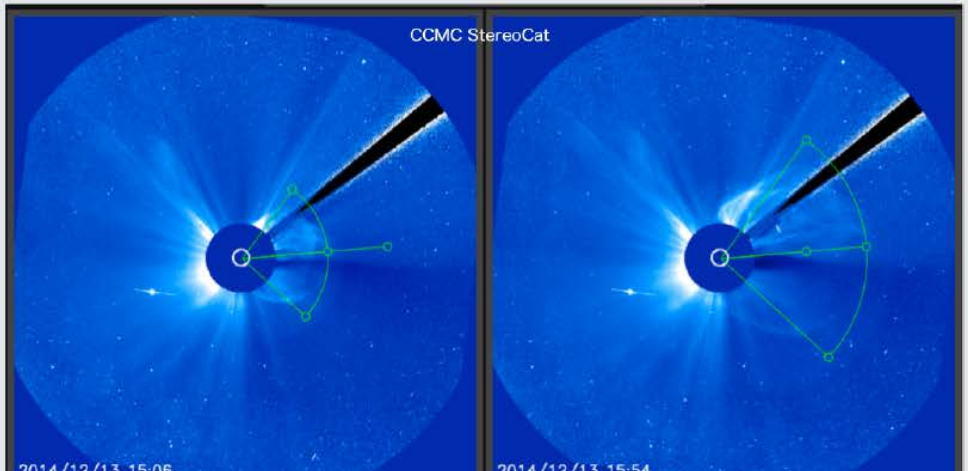
Building in Gibson & Low FR CME





Cone-model CMEs inserted at 21.5 AU as time-dependent boundary condition





Euhforia: current status

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Upcoming next

- **Further on-going model improvements**
  - **Update coronal model to MPI-AMRVAC, i.e. with AMR**
  - **Improve CME model (start from G&L magnetic flux rope)**
  - **including the possibility to launch flux rope CMEs (the parameters of the FR need to be given as input by the forecaster)**
- **Validation (comparison with ENLIL, ACE,…)**
- **Integration in SWE forecasting activities at ROB**
- **Visualisation improvements, integration with Helioviewer: TBD**
- **optimizations of the code**
- **Make code OPEN SOURCE**

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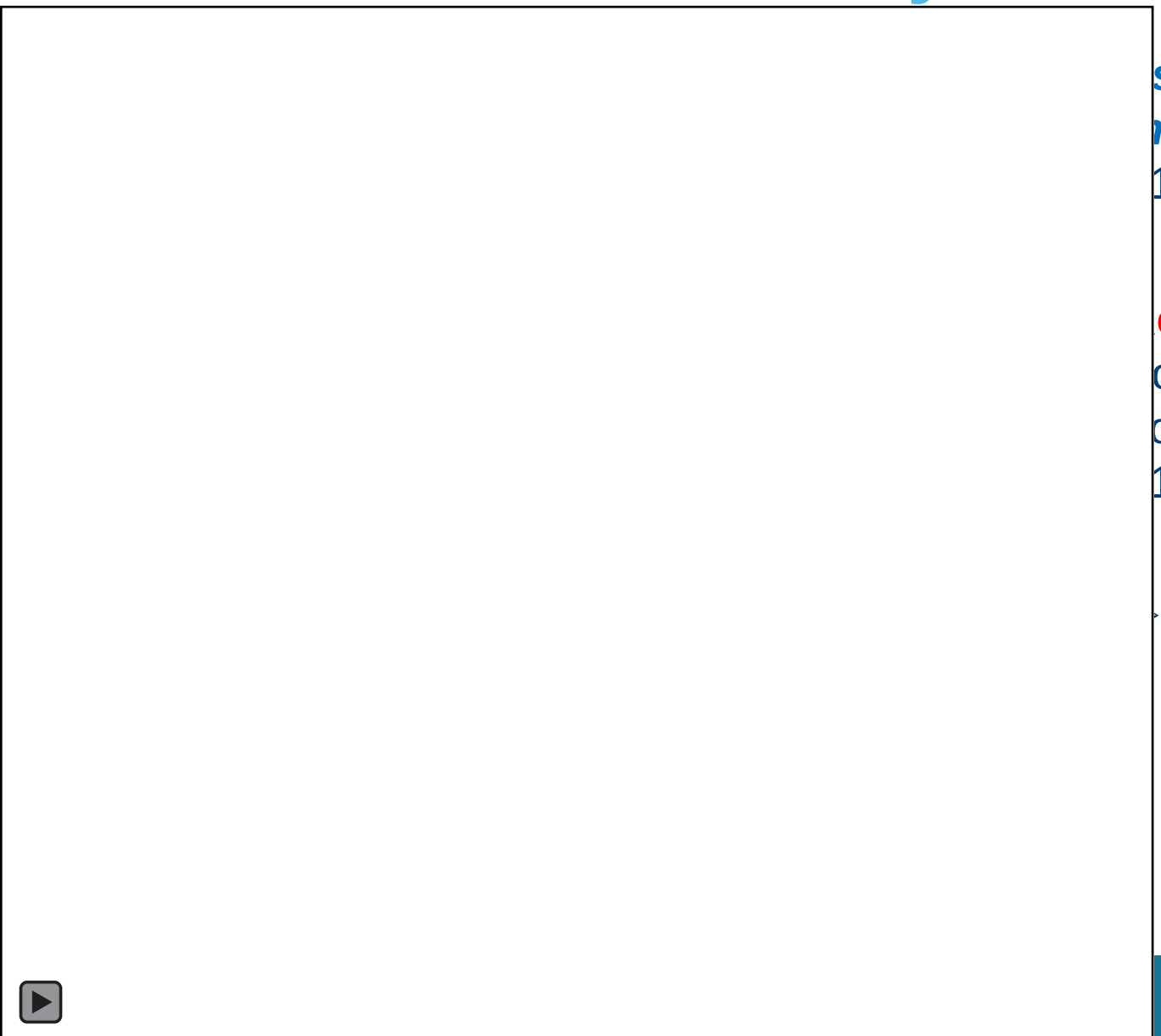
Euhforia: connectivity issue



sing the ADAPT
agnetogram for 2010-
1-01T00:00

ed curve = field line
om SolO (orbital
osition at 2020-
101T00:00)

- So the field line that connects to SolO is originating from the polar coronal hole in the south.

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Euhforia: connectivity issue

MOVIE

- **shows the wind using the ADAPT magnetogram for 2010-01-01T00:00**
- The red curve is the field line from **SolO** (orbital position at 2020-01-01T00:00) to the corona traced through the MHD,SCS,PFSS models:
  - The SCS, like PFSS, does not include rotation, that's why the field lines are **not curved** below 21.5 Rs.
  - Also, between the SCS and PFSS models the field **jumps**. This is a known feature of the combined model.
  - The white curves show other field lines, and the gray circles indicate r = 0.5, 1, 1.5 AU.
  - Once the view zooms closer to the corona, the open field regions are plotted on top of the radial magnetic field.

➢ **So the field line that connects to SolO is originating from the polar coronal hole in the south.**

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