Summery and Discussion from the WG3 (Simulation Working Group)

Fang Shen and Dusan Odstrcil

Contributed by: Isabell Piantschitsch, Andrei Afanasev, Meng Jin and Camilla Scolini

Hvar, Croatia, 24 – 28, September 2018

1. Scientific Objective

(1) Provide global context for all CME events investigated by the ISEST team:

a. Make comparison among the popular numerical models, and the observations for these CME events;

b. Try to improve the numerical prediction ability

(2) Investigate processes of the CME initiation, heliospheric propagation, and CMEs interaction

(3) Develop tools to assist collaboration of numerical modelers, theoreticians, and observers

2. Presentations in WG3

(1) Invited talk by Dusan Odstricil:

“Near Real-Time Simulation of Heliospheric Space Weather”

(2) Contributions by:

a. Fang Shen:

” Three-dimensional MHD simulation of solar wind using a new boundary treatment: Comparison with in-situ data at Earth”

b. Isabell Piantschitsch

“Simulation of fast-mode MHD waves interacting with low density regions such as coronal holes”

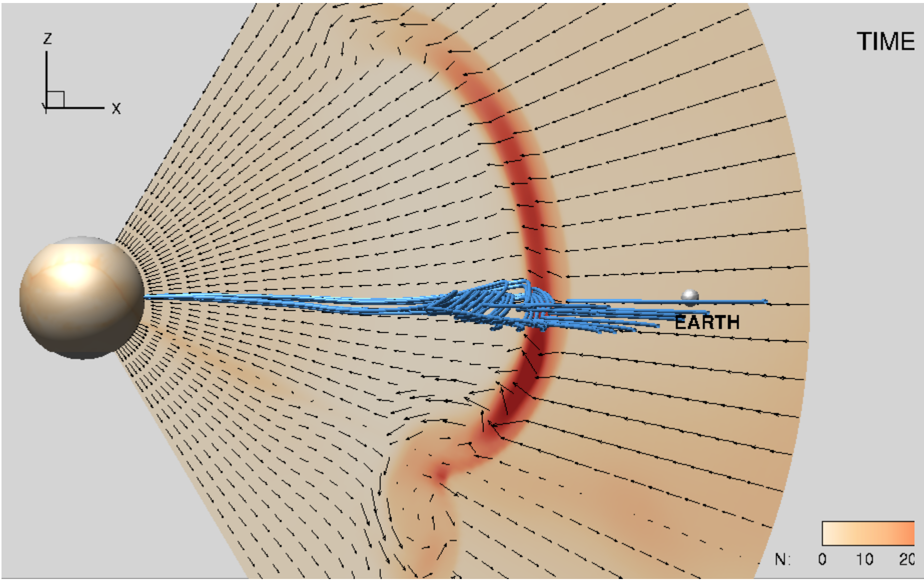
c. Andrei Afanasev

“Numerical simulations of coronal loop kink oscillations excited by different driver frequencies“

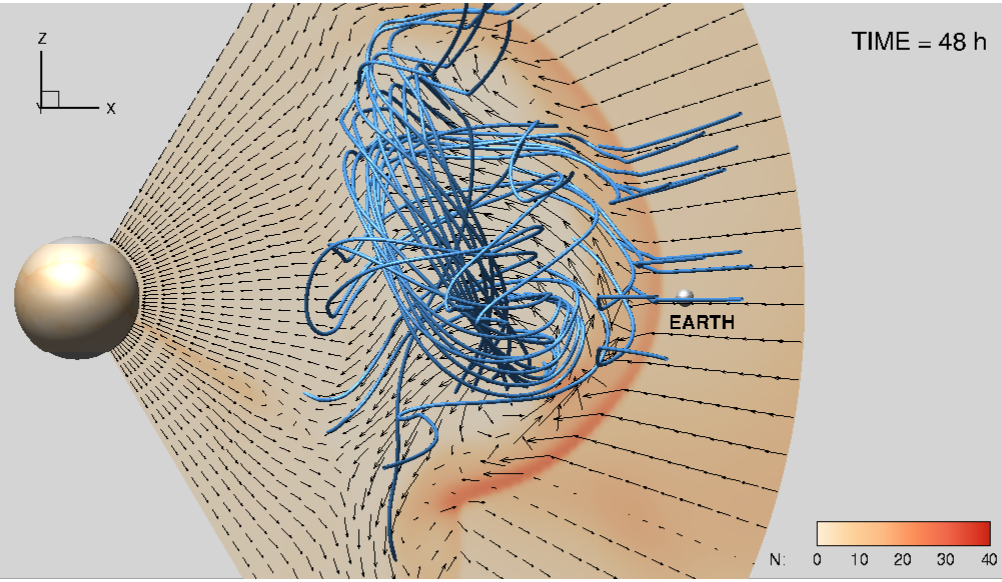
Near Real-Time Simulation of Heliospheric Space Weather

Density Structure — "Cone" vs "Spheromak"

Cone

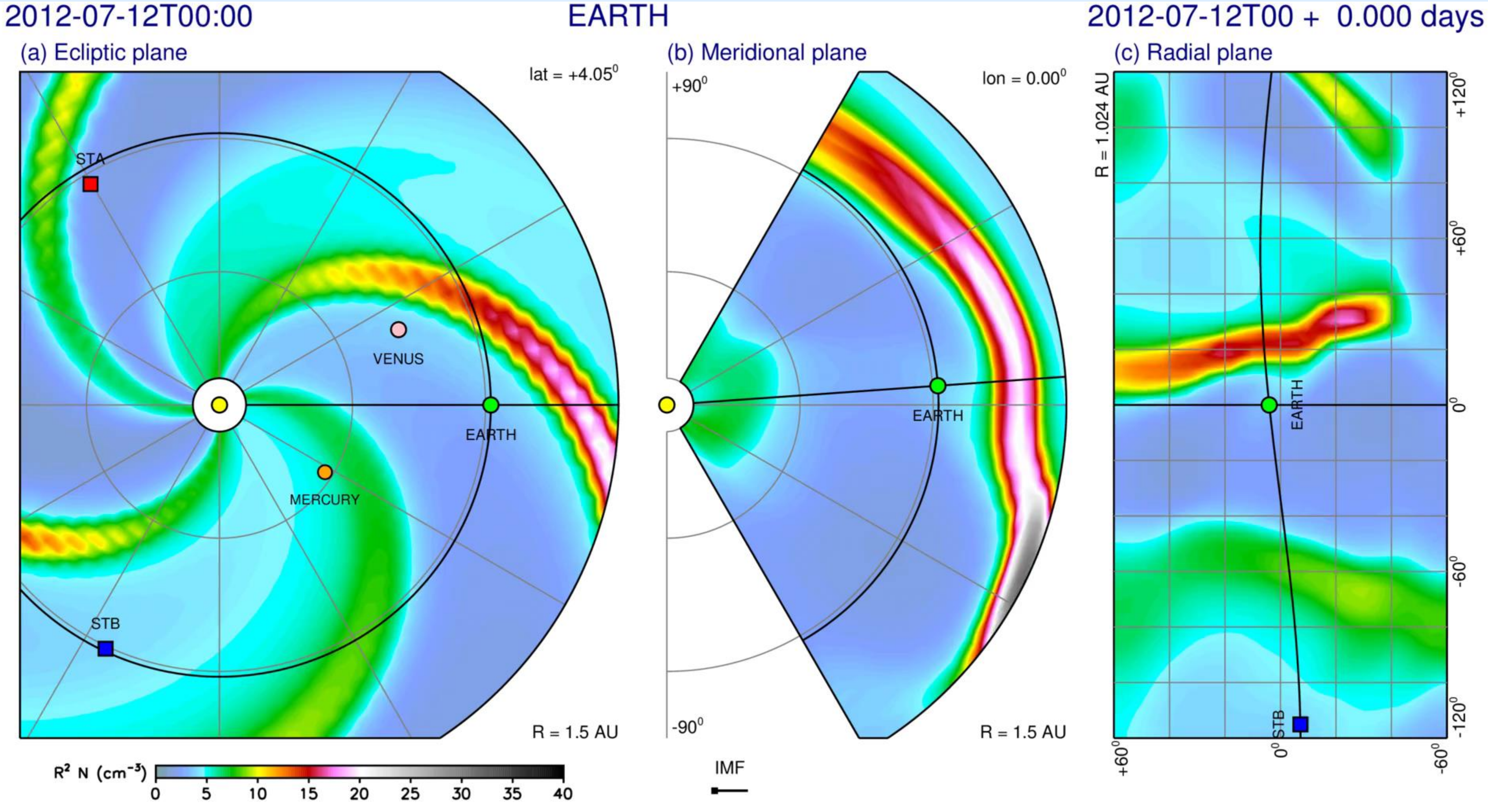


Spheromak



- "Cone" is launched with the initial density enhancement to crudely simulate CME expansion and initially overpressure hydrodynamic structures cannot resist to dynamic compression when interacting with background solar wind — large peaks and narrow extent of ejecta
- Spheromaks can provide more realistic density structures no need for the initial density enhancement

CME Event 2012-07-12 — bthe2e4

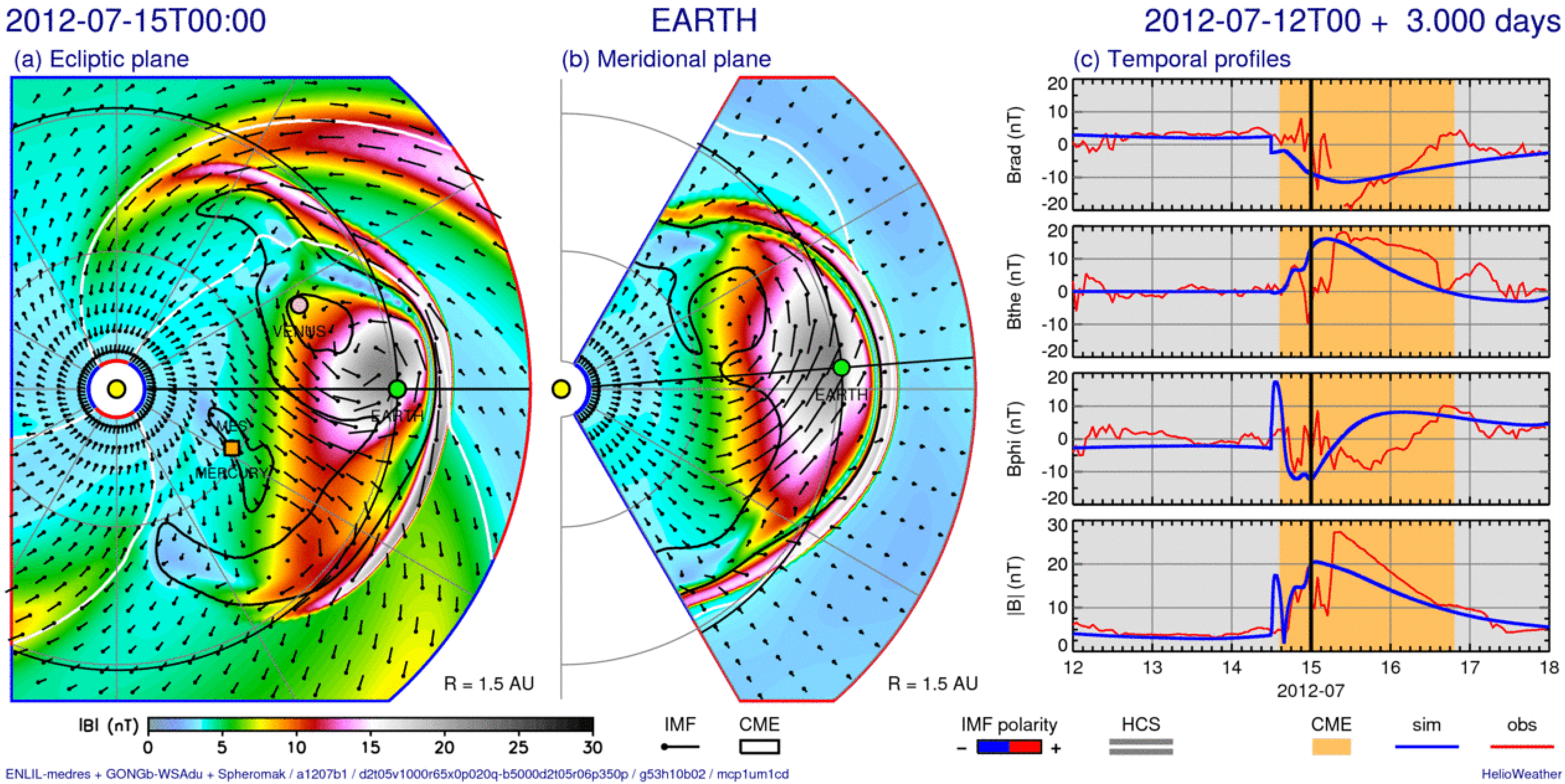


ENLIL-lowres + GONGb-WSAdu + Spheromak / a7b0 / d1v830r55n2q-bp3000d1p280 / g53h10b04z001 / mc1um1dz

HelioWeather

- ✦Strong magnetic field within a spheromak causes its expansion and this leads to a low-density cavity.
- ✦Such a cavity can be detected by heliospheric imagers before the ICME encounters Earth.
- ✦In case of well-observed strong events, this might be used for “mid-course” suggestions in ensemble modeling

CME Event 2012-07-12 — btot2e4



(see talk by Dusan Odstrcil)

Summary

- WSA-ENLIL-Cone “hybrid” modeling system:
  - routine, event-by-event, much faster than real time
  - operational version used at NOAA/SWPC, NASA/CCMC, UK/MetOffice, Korea/KSWC
  - research version is under continuous development
- Cone model enables:
  - predictions of ICME arrival times (ejecta and/or shock)
  - SEP alerts and predictions
  - synthetic white-light imaging (J-maps, mid-course correction)
- Launching of spheromaks is less realistic than launching of flux ropes but it enables:
  - operational predictions in the inner- and mid-heliosphere
  - utilization of existing tools
- Improvements over hydrodynamic cone model:
  - more realistic radial extent = duration of the event at Earth, planets and spacecraft
  - more realistic density structure (peaks, cavity) = comparison with remote imaging
  - estimate strength and duration of the Bz effect at Earth = geospace events
- Ongoing activities include calibration and ensemble modeling of the background solar wind with ADAPT, reducing the model-free parameters of the CME-like ejecta

Three-dimensional MHD simulation of solar wind using a new boundary treatment: Comparison with in-situ data at Earth

- New boundary Treatment

$$B_r = \mathrm{sign}\left(B^{\mathrm{PFSS}}\right) \times \frac{1}{\sqrt{2}} \mathrm{mean}\left(B^{1\mathrm{AU}}\right) \left(\frac{1\mathrm{AU}}{R_b}\right)^2$$

$$V_r = V_s + \frac{V_f}{(1+f_s)^{a_1}} \left[1 - 0.8 \exp\left(-\left(\frac{\theta_b}{a_2}\right)^{a_3}\right)\right]^{a_4}$$

$$N = N_0 \left(\frac{1\mathrm{AU}}{R_b}\right)^2 V_0 \left(\frac{1}{2} V_0^2 + \frac{GM_s}{R_s}\right) \left[V_r \left(\frac{1}{2} V_r^2 + \frac{GM_s}{R_s}\right)\right]^{-1}$$

$$T_p = \frac{1}{2} V_r^2 \times \left(\frac{1\mathrm{AU}}{R_b}\right)^{2(\gamma-1)}$$

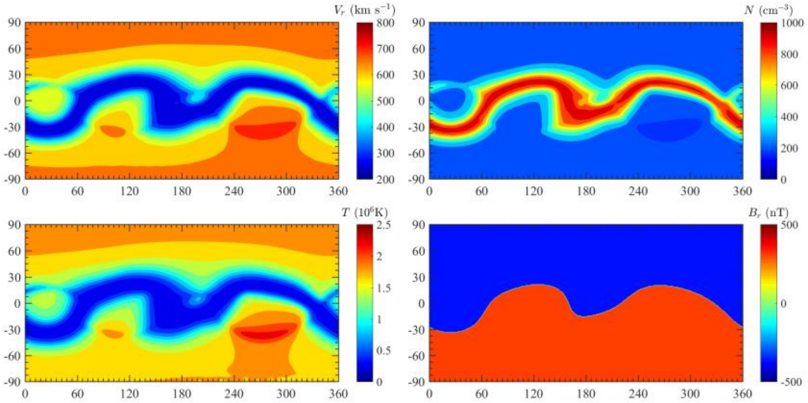
Ranges of free parameters at the lower boundary

Parameters	L_{max}	V_s(km·s^{-1})	a_2(°)	N_0(cm^{-3})	B_0(nT)
Minimum	6	250	2.0	1.3	2.6
Maximum	15	300	4.0	2.7	5.3

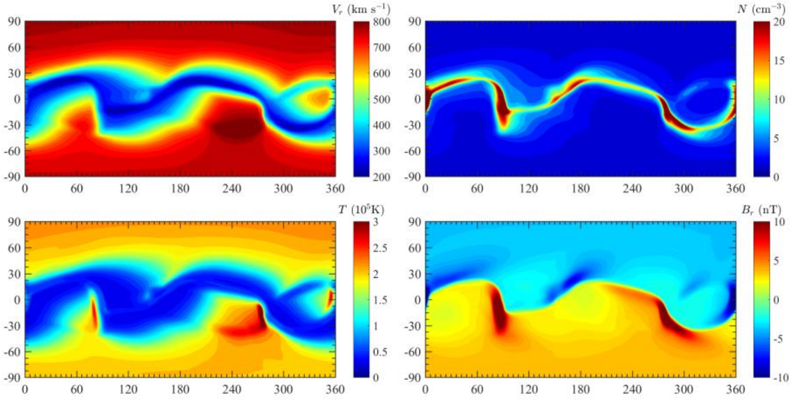
(see talk by Fang Shen)

Simulation Results——2007

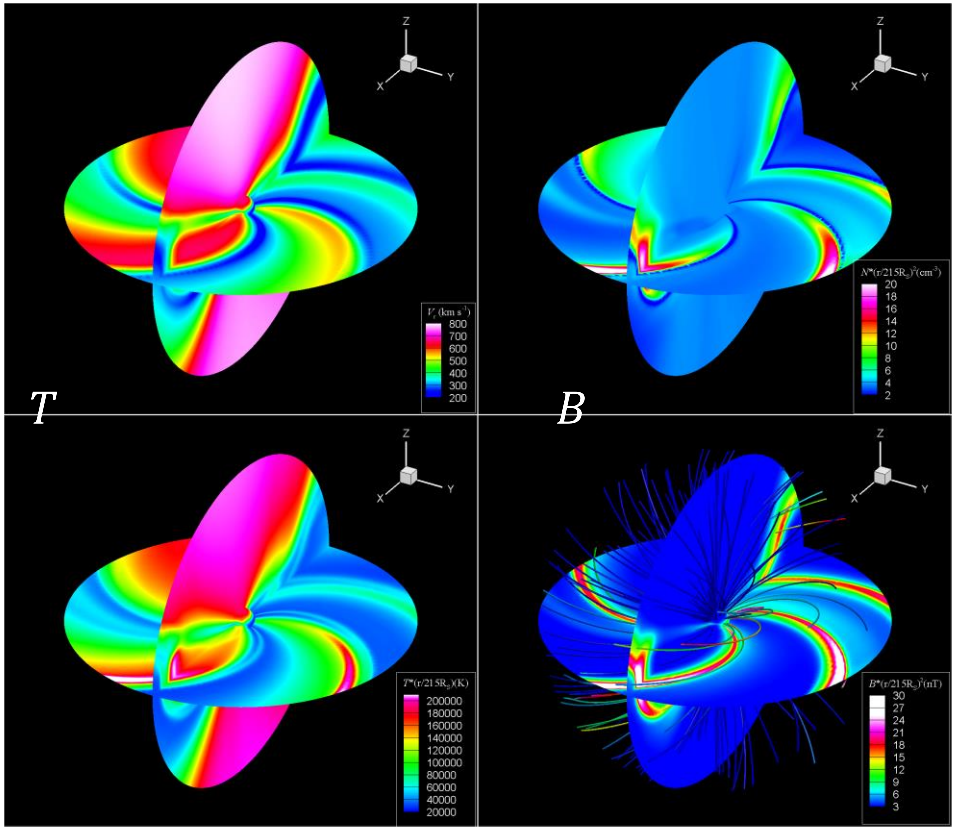
CR2053 (from 4 February 2007 to 4 March 2007)



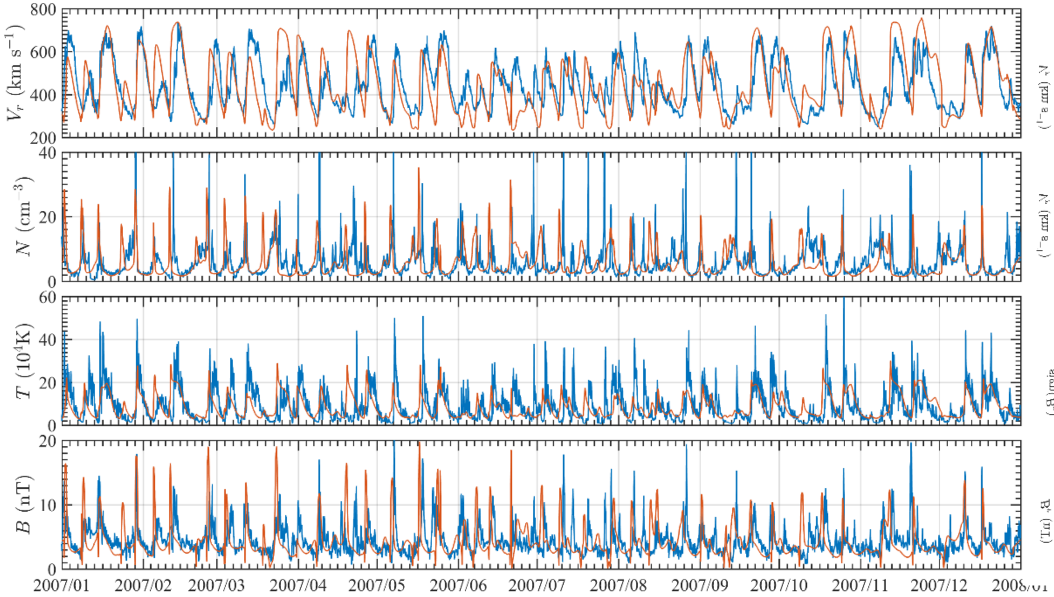
Distributions at the lower boundary



Distributions at 1AU



In the heliospheric equatorial and meridional plane


V_r (km s^{-1})
N (cm^{-3})
T (10^4K)
B (nT)
2007/01
2007/02
2007/03
2007/04
2007/05
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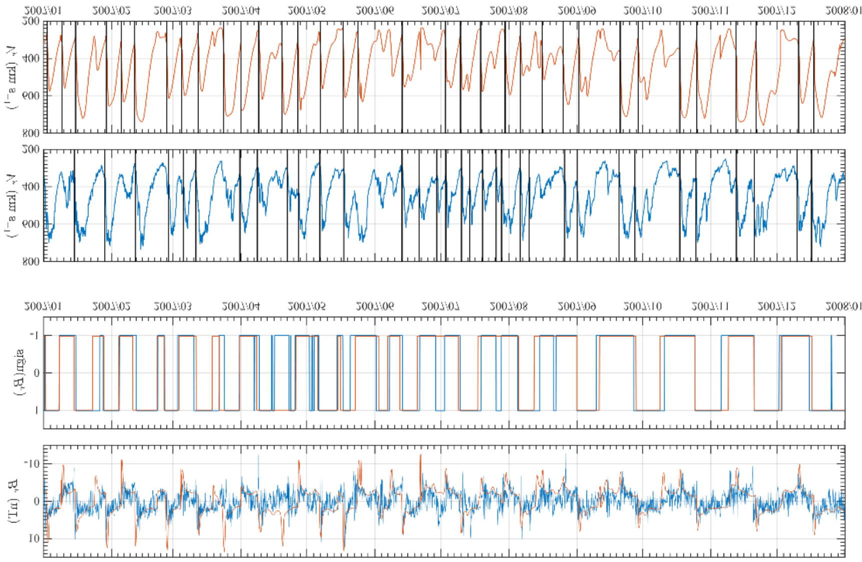
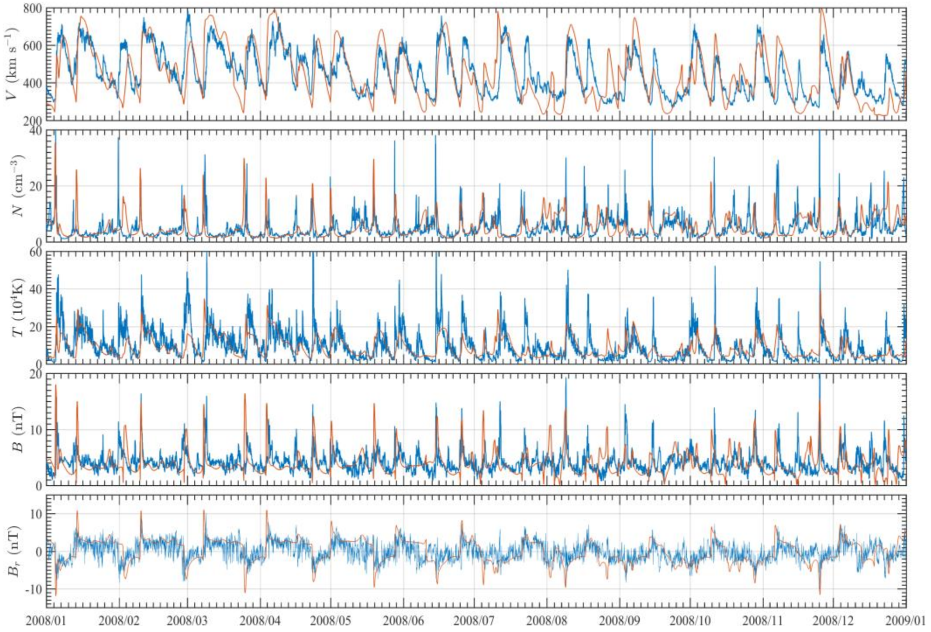
2007/11
2007/12
2008/01




V (km s^{-1})
N (cm^{-3})
T (10^4K)
B (nT)
B_r (nT)
2008/01
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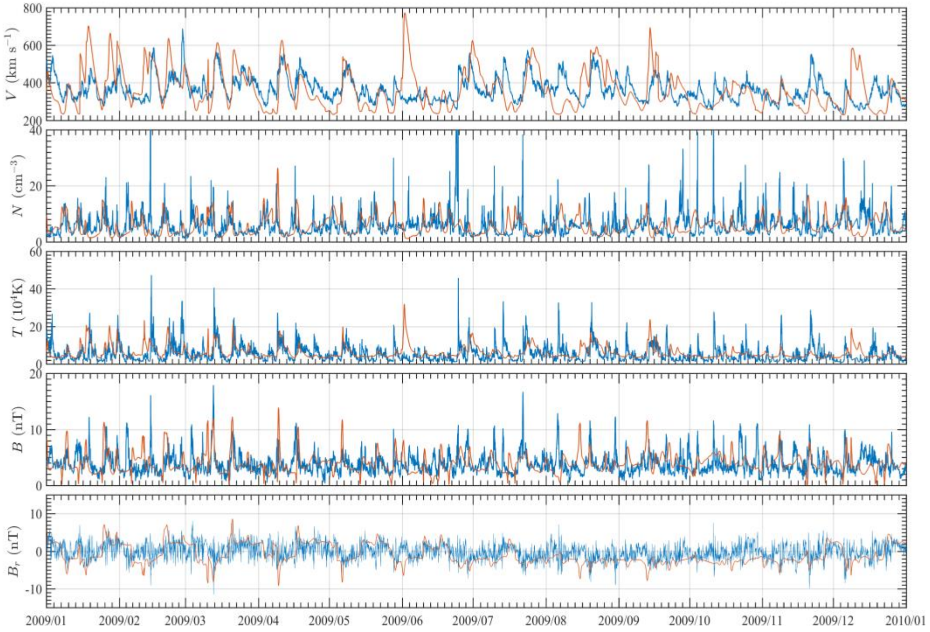
V (km s^{-1})
N (cm^{-3})
T (10^4K)
B (nT)
B_r (nT)
2009/01
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2009/05
2009/06
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2009/08
2009/09
2009/10
2009/11
2009/12
2010/01

Discussion and Summary

- In this work, we employ an improved 3D IN-TVD MHD model with a new boundary treatment to simulate the propagation and distribution of the solar wind into the heliosphere；
- In the boundary conditions, we reserve five free parameters, so as to simulate the solar wind for different phases of solar cycle, and to improve the prediction of solar wind parameters;
- Using the improved MHD model with the new lower boundary conditions, we simulated the background solar wind from 2007 to 2017. Our simulation could reproduce most of the characteristic solar wind structures, e.g., HSSs, sector boundary as well as the amplitudes of solar wind parameters near the Earth, including V, N, T, B and B_r ;
- In our model, the parameters for tuning freely are very few and the ranges are also relative small. Further, based on the simulation of past 11 years, these parameters can maintain unchanged for quite long time (several CRs to several years). Therefore the improved IN-TVD model with the new boundary treatment can be applied for prediction/forecast of solar wind parameters near the Earth .

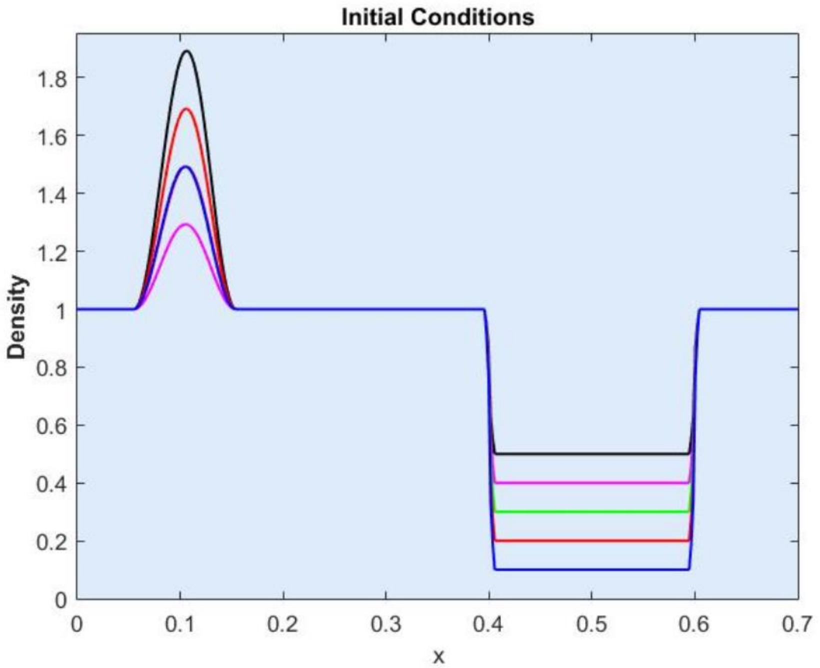
Simulation of fast-mode MHD waves interacting with low density regions such as coronal holes

Code Description

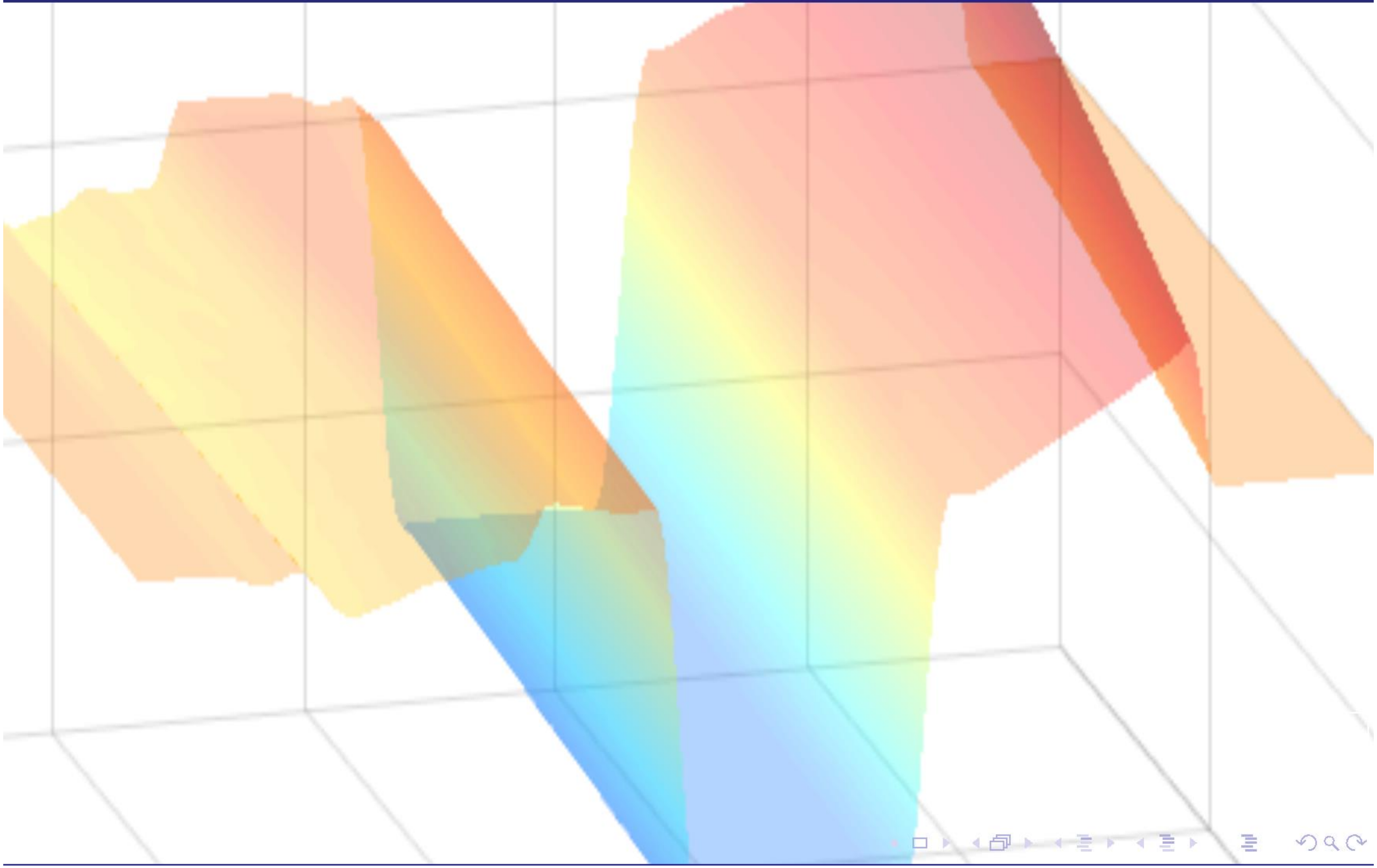
2.5D MHD Code

- TVDLF Method (first described by Toth & Odstrčil 1996)
- Fully explicit method
- standard MHD equations
- 2nd order accuracy in space and time
- transmissive boundary conditions

Initial Setup



(see talk by Isabell Piantschitsch)



Simulation of fast-mode MHD waves interacting with low density regions such as coronal holes

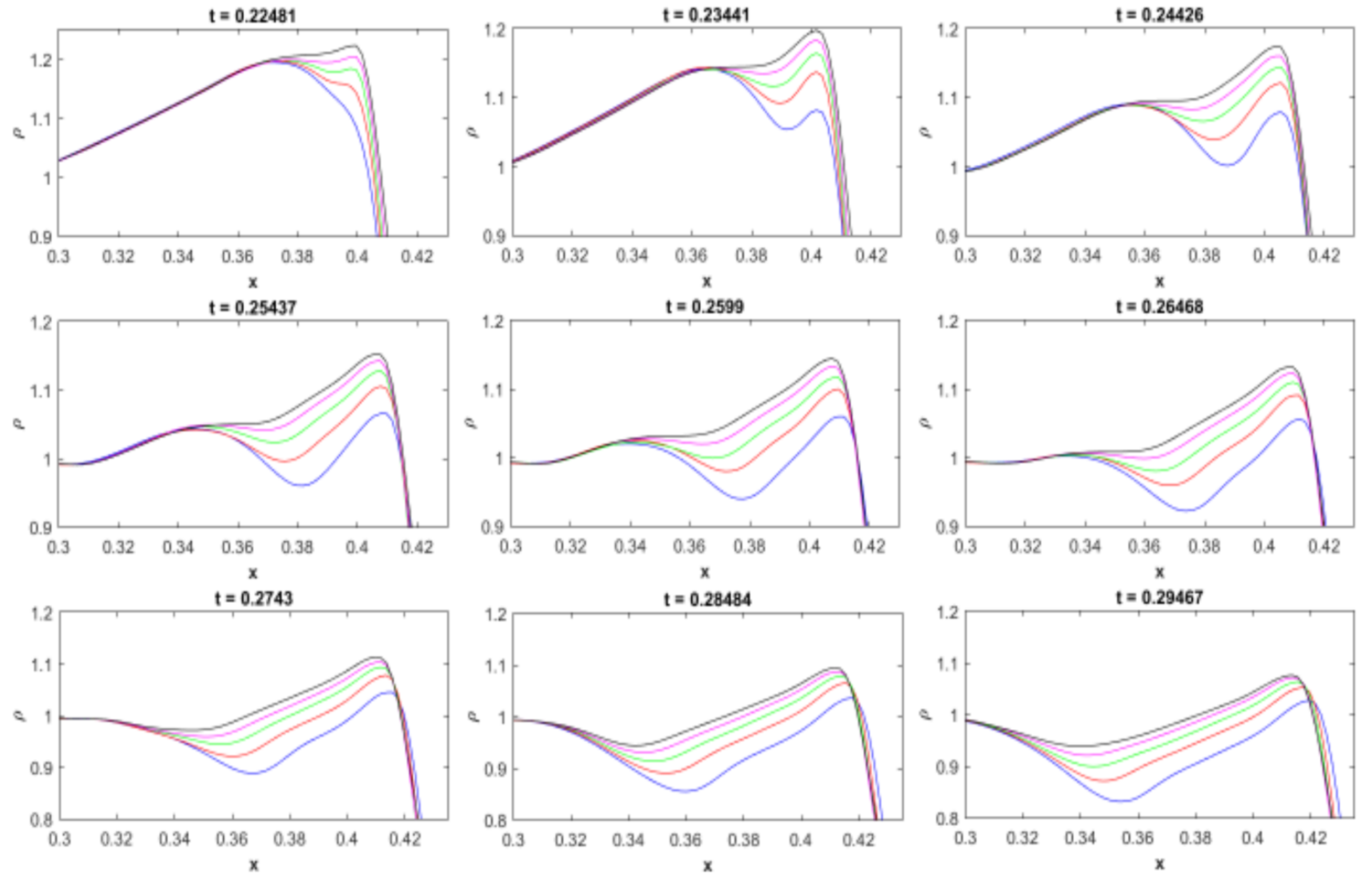
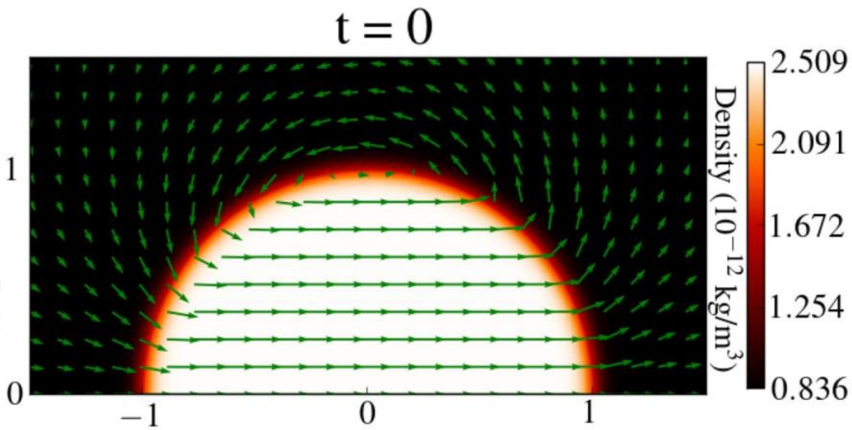


Figure: Morphology of 1st Stationary Feature (Taken from Piantschitsch et al. 2018a)

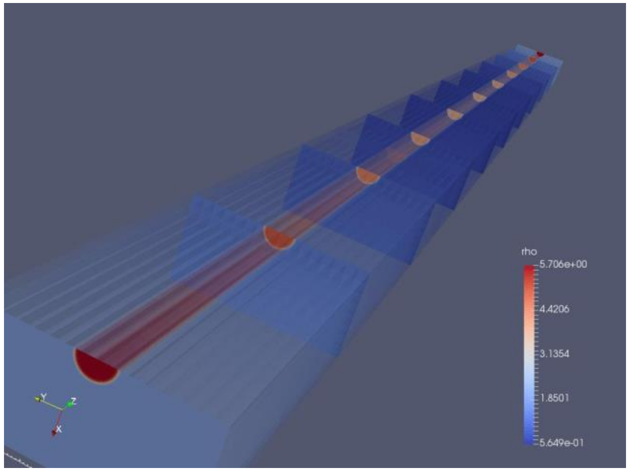
(also see talk by Isabell Piantschitsch)

Numerical simulations of coronal loop kink oscillations excited by different driver frequencies



Setup

- MPI-AMRVAC code
- Hotter and denser loop in straight magn
  - ✓ Hyperbolic tangent function for plasma de
- Gravitational stratification of the plasma
  - ✓ $g(z) = g_0 \mathrm{Cos}(\pi z/L)$
- Equilibrium with slightly reduced magnetic field strength inside the loop
  - ✓ Slow waves of several km/s amplitude propagate inside the box
- Boundary conditions
  - ✓ Open side boundaries (continuous boundary conditions), except for x=0 boundary, which takes into account the setup symmetry
  - ✓ Reflection of waves at one footpoint (*asymm* for *vel*, *cont* for *mag* , *strat_gh* for *p* and *rho*)
  - ✓ Continuous monoperiodic wave driver at the other loop footpoint with velocity amplitude of 5 km/s
- Uniform grid: 128x256x64 cells
- Box sizes: X: 0÷6 Mm, Y: -6÷6 Mm Z: 0÷200 Mm
- Resolution: 47 km/pix in xy-plane, 3.1 Mm/pix in z-direction
- Driver excites transverse motions in one footpoint only
- Period of driver: 92 – 421 s, fundamental mode (FM): 328 s
- Runtime: 2000 s; more than 6 FM periods
- Method: one-step TVD scheme + Woodward limiter

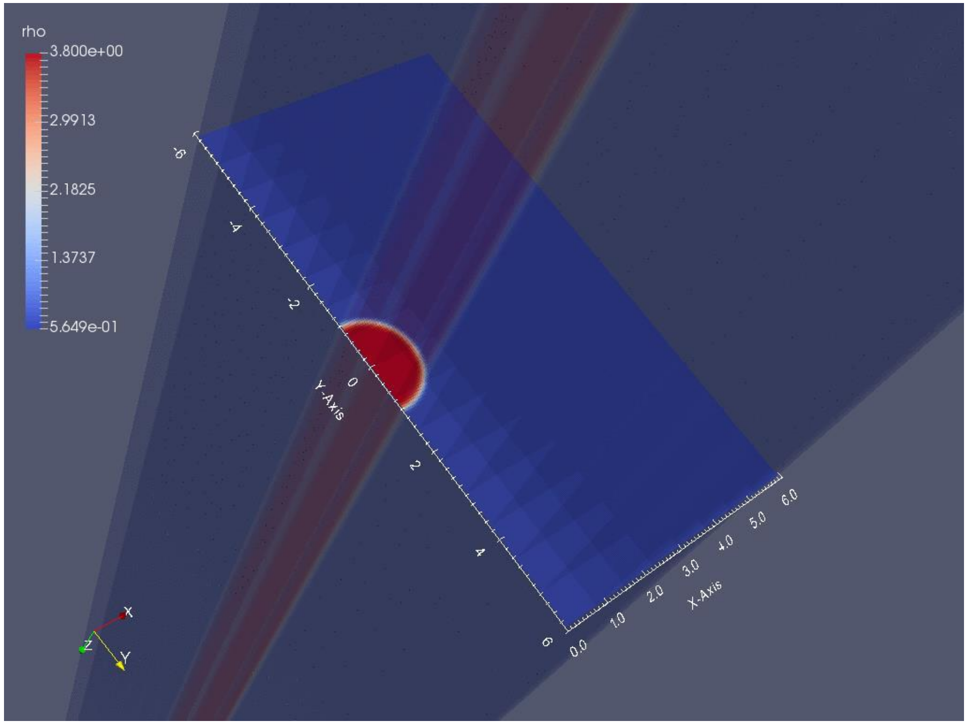


(see talk by Andrei Afanasev)

Numerical simulations of coronal loop kink oscillations excited by different driver frequencies

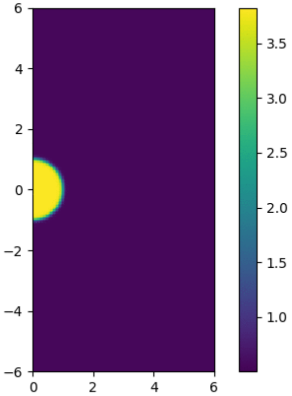
Driven standing kink oscillations

Fundamental mode

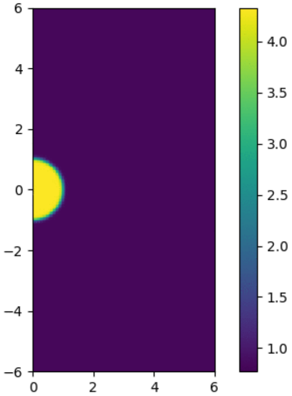


(see talk by Andrei Afanasev)

Kelvin-Helmholtz instability



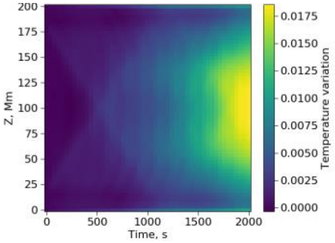
First harmonics;
anti-node is at 100 Mm



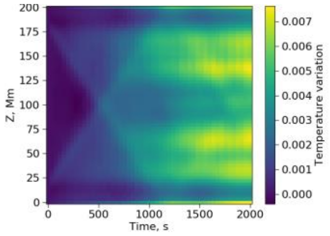
Second harmonics;
anti-nodes are at 50 and 150 Mm

Volume averaged temperature variation

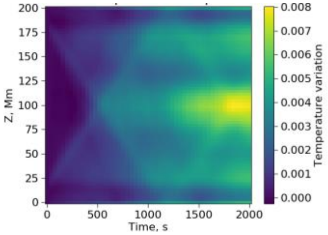
1st harmonics

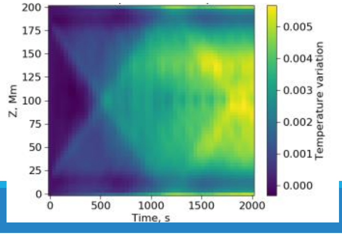


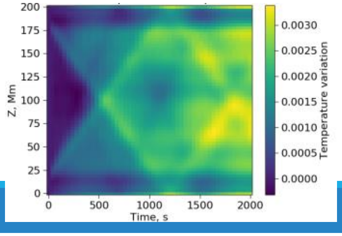
2nd harmonics



3rd harmonics







Summary

- We studied the excitation of a coronal loop by transverse motions and performed 3D numerical simulations of footpoint driven kink oscillations of a magnetic tube filled in with the denser, hotter, and gravitationally stratified plasma.
- We showed the response of a coronal loop to different monoperiodic external excitations. The maximum loop displacement is lower for higher frequencies because the energy of a driver is distributed to anti-nodes.
- In the cases of intermediate driver frequencies, KHI develops as well, which could explain the saturation in the kinetic energy density in those cases.
- For a hotter and denser stratified loop, the formation of hotter (than background plasma) KH turbulent layer at the loop boundary due to the coronal plasma mixing gives the enhancement in the volume averaged temperature at the positions of oscillation anti-nodes, or at those of the maximum loop displacement for non-eigenfrequency cases.

- **3. Presentations in WG4 but related to simulation**

(1) Meng Jin in WG4 (Invited talk):

“Sun-to-Earth Modeling of Coronal Mass Ejections with a Global MHD Model: Facilitating Physical Understanding and Space Weather Forecasting”

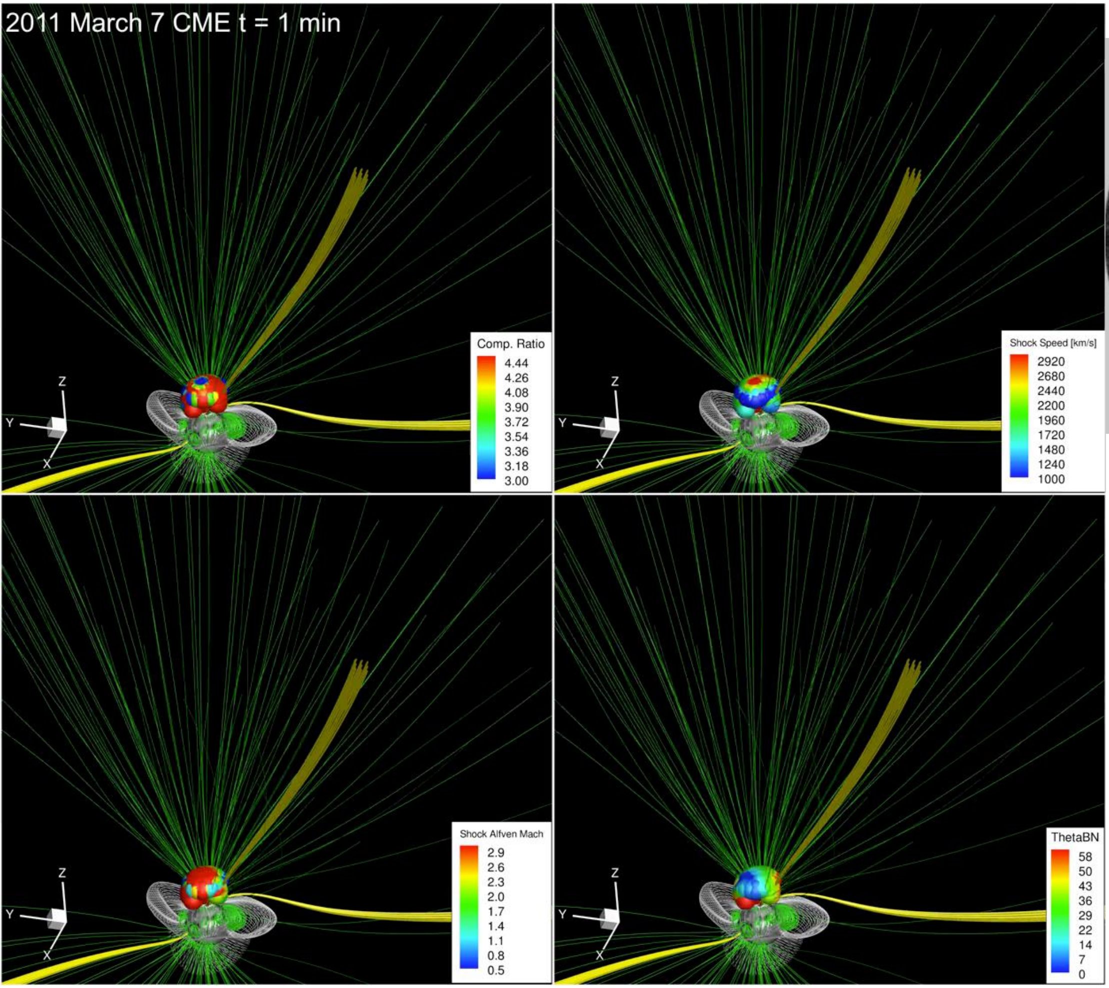
(2) Camilla Scolini in WG4 (Invited talk):

” Observation-based Sun-to-Earth simulations of geo-effective Coronal Mass Ejections with EUHFORIA”

Sun-to-Earth Modeling of Coronal Mass Ejections with a Global MHD Model: Facilitating Physical Understanding and Space Weather Forecasting

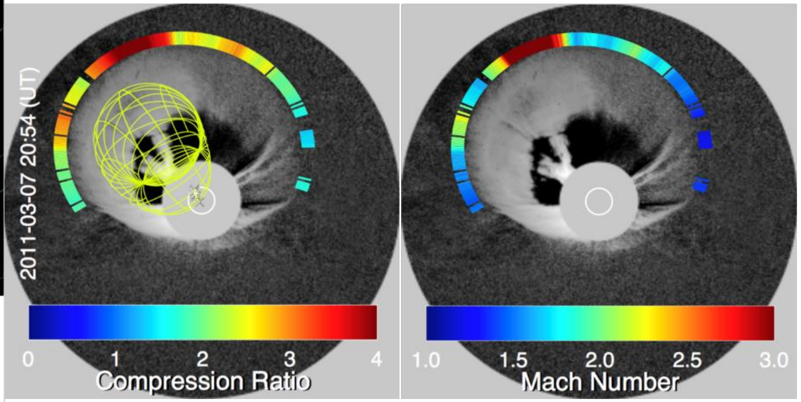
CME-driven Shocks (2011 March 7 Event)

Shock Evolution in the Simulation

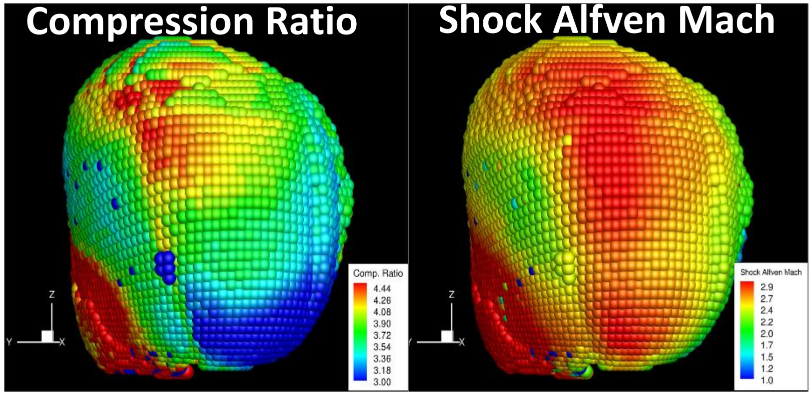


Shock Parameters from Observation

Kwon et al. 2018

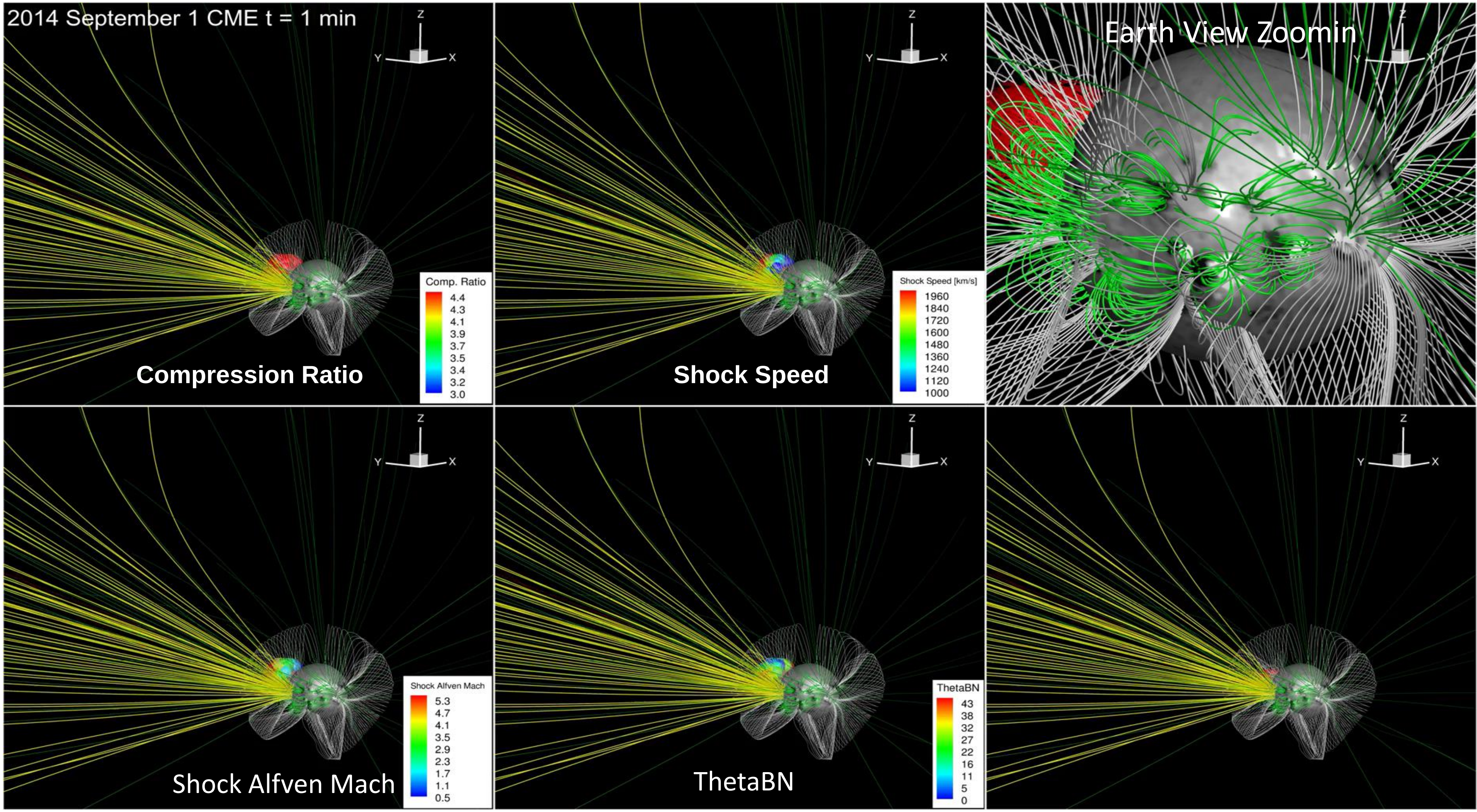


Shock Parameters from Simulation



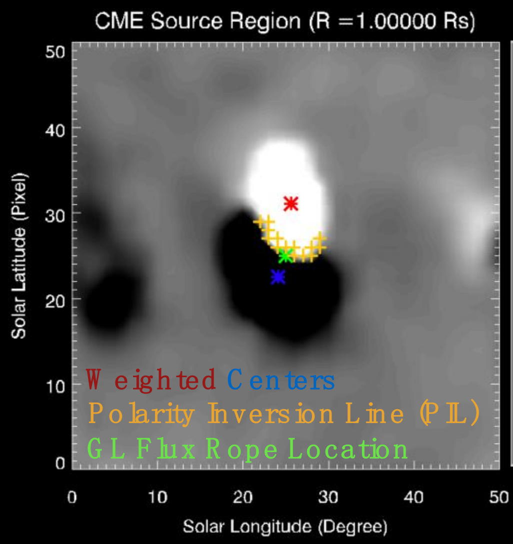
(see talk by Meng Jin)

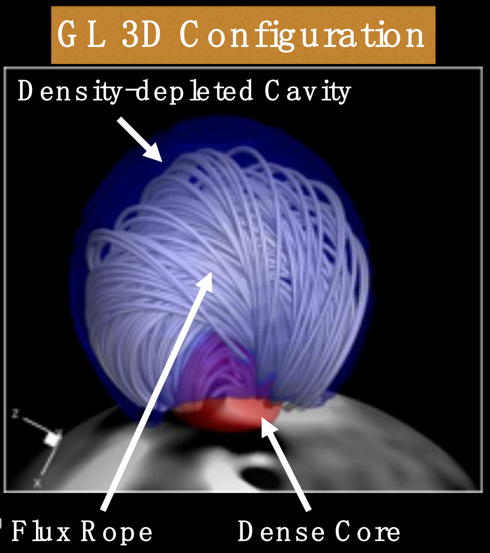
CME-driven Shock Evolution (2014 September 1)

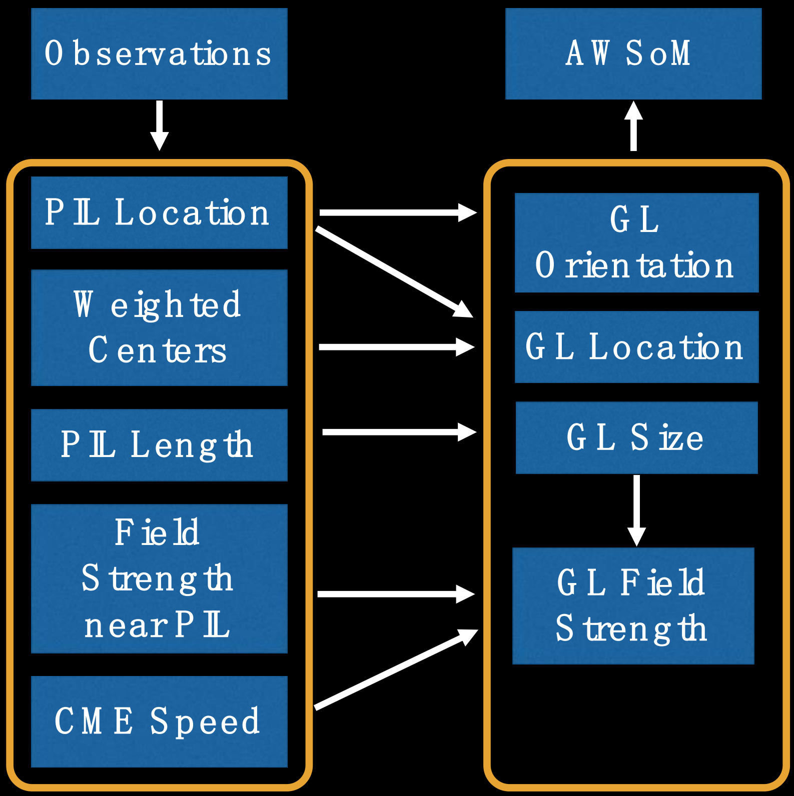


(see talk by Meng Jin)

EEGGL: Eruptive Event Generator (Gibson and Low)







Observations

PIL Location

Weighted Centers

PIL Length

Field Strength near PIL

CME Speed

GL Orientation

GL Location

GL Size

GL Field Strength

AWSoM

- EEGGL uses observational data to specify input parameters for the Gibson-Low flux rope model (Gibson & Low 1998) so that it may approximately reproduce observed CME events.

(Jin et al 2017b)

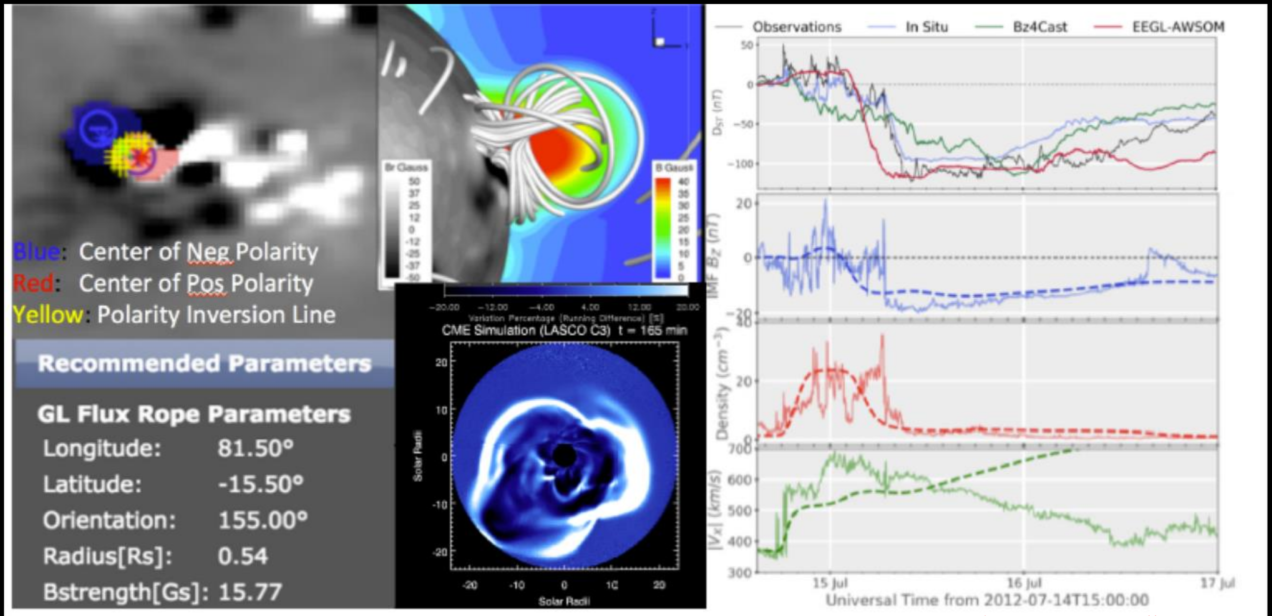
More information: https://ccmc.gsfc.nasa.gov/eeggl/

(see talk by Meng Jin)

Model Validation & Future Development

2012 July 12 Event Simulation using EEGGL

Extensive Events Run



Manchester & Welling 2018

- CME Simulations using EEGGL during Solar Cycle 23 and 24. A description about EEGGL

First C2 Appearance Date Time [UT]		Flare Class	Flare Location	Linear Speed [km/s]	White Light Comparison		Synthetic WL Movie	Remarks
1997/11/04	06:10:05	X2.1	S14W33	785	Observation	Simulation	Movie	NA
1997/11/06	12:10:41	X9.4	S18W63	1556	Observation	Simulation	Movie	NA
2000/07/14	10:54:07	X5.7	N22W07	1674	Observation	Simulation	Movie	Increased flux rope size
2000/11/08	23:06:05	M7.4	N10W77	1738	Observation	Simulation	Movie	Uncertain erupting PIL
2001/09/24	10:30:59	X2.6	S20E22	2402	Observation	Simulation	Movie	NA
2001/12/26	05:30:05	M7.1	N08W54	1446	Observation	Simulation	Movie	NA
2002/04/21	01:27:20	X1.5	N14W84	2393	Observation	Simulation	Movie	NA
2002/08/24	01:27:19	X3.1	S08W90	1913	Observation	Simulation	Movie	Increased flux rope size
2003/10/28	11:30:05	X17	S18E18	2459	Observation	Simulation	Movie	NA
2005/01/20	06:54:05	X7.1	N14W61	882	Observation	Simulation	Movie	NA
2006/12/06	18:29:00	X6.5	S06E63	2000	Observation	Simulation	Movie	No LASCO observation
2006/12/13	02:54:04	X3.4	S06W23	1774	Observation	Simulation	Movie	NA
2010/08/01	13:42:05	C3.2	N20E36	850	Observation	Simulation	Movie	NA
2011/02/15	02:24:05	X2.2	S18W15	669	Observation	Simulation	Movie	NA
2011/08/04	04:12:05	M6.0	N16W51	1315	Observation	Simulation	Movie	NA
2011/08/09	08:12:06	X6.9	N17W69	1610	Observation	Simulation	Movie	Increased flux rope size
2011/09/06	23:05:57	X2.1	N14W18	575	Observation	Simulation	Movie	NA
2011/10/22	10:24:05	M1.3	N25W77	1005	Observation	Simulation	Movie	Decreased flux rope size
2011/11/26	07:12:06	C1.2	N11W47	993	Observation	Simulation	Movie	Filament Eruption
2012/01/19	14:36:05	M2.6	N28E14	1120	Observation	Simulation	Movie	NA
2012/03/07	00:24:06	X5.4	N17E15	2684	Observation	Simulation	Movie	NA
2012/03/13	17:36:05	M7.9	N18W63	1884	Observation	Simulation	Movie	NA
2012/06/14	14:12:07	M1.9	S17W00	987	Observation	Simulation	Movie	NA
2012/07/12	16:48:05	X1.4	S17W08	885	Observation	Simulation	Movie	NA
2012/09/28	00:12:05	C3.0	N09W24	947	Observation	Simulation	Movie	NA
2013/03/15	07:12:05	M1.1	N09W05	1063	Observation	Simulation	Movie	NA
2013/04/11	07:24:06	M6.5	N10W01	861	Observation	Simulation	Movie	NA
2014/01/07	18:24:05	X1.2	S13W12	1830	Observation	Simulation	Movie	NA
2014/02/25	01:25:50	X4.9	S15E65	2147	Observation	Simulation	Movie	NA
2014/04/02	13:36:20	M6.6	N13E41	1471	Observation	Simulation	Movie	Increased flux rope size
2014/04/18	13:25:51	M7.3	S14W42	1203	Observation	Simulation	Movie	NA
2014/09/10	18:00:05	X1.6	N15E02	1267	Observation	Simulation	Movie	NA
2014/11/07	18:08:34	X1.6	N15E33	795	Observation	Simulation	Movie	NA
2015/03/15	01:48:05	C9.1	S17W38	719	Observation	Simulation	Movie	Decreased flux rope size
2015/04/04	23:36:05	--	S30E20	825	Observation	Simulation	Movie	Filament Eruption
2015/06/25	08:36:05	M7.9	N11W45	1627	Observation	Simulation	Movie	NA
2015/11/04	14:48:04	M3.7	N10W04	578	Observation	Simulation	Movie	CME speed is 955 km/s corrected for projection
2017/09/06	12:00:00	X9.3	S09W57	1800	Observation	Simulation	Movie	LASCO Catalog not available
2017/09/10	15:36:00	X8.2	S09W91	3000	Observation	Simulation	Movie	LASCO Catalog not available

- More validation studies are being conducted at the moment. The results will be used to improve the current EEGGL module.
- New development (e.g., autonomous source region identification) is on-going.

(see talk by Meng Jin)

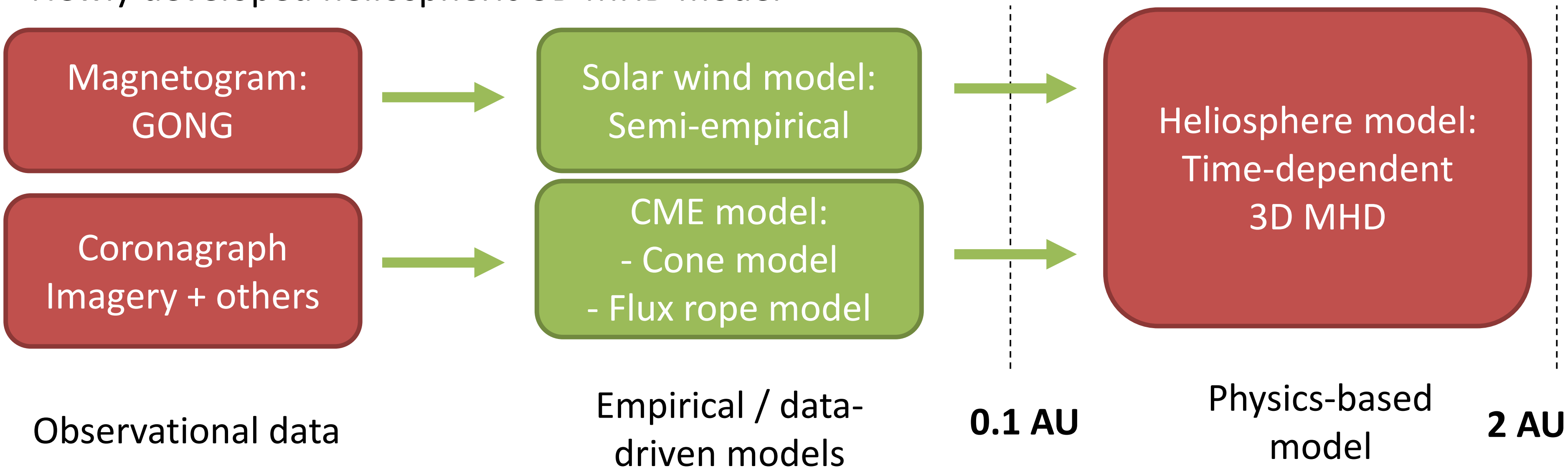
Summery

- The first-principles-based MHD global models play an important role in understanding the fundamental physical processes of CME propagation and interaction in the heliosphere. Although still very challenging, it shows promising potential to provide space weather forecast in the near future.
- **Data-driven Models**: The flux rope is self-consistently formed in the simulation driven by the electric or magnetic fields from observations (e.g., Cheung et al. 2012, Jiang et al. 2016).
- **More Observations**:
  - L5/polar mission (more coverage of surface magnetic field)
  - Sub-L1 constellation mission (better understanding of flux rope magnetic field)
  - coronal magnetic field/plasma measurements (erupting flux rope structure)
- **How these "missing data" influence our modeling capability needs to be understand.**

Observation-based Sun-to-Earth simulations of geo-effective Coronal Mass Ejections with EUHFORIA

EUHFORIA: Introduction

Newly developed heliospheric 3D MHD model



Magnetogram:
GONG

Coronagraph
Imagery + others

Solar wind model:
Semi-empirical

CME model:
- Cone model
- Flux rope model

Heliosphere model:
Time-dependent
3D MHD

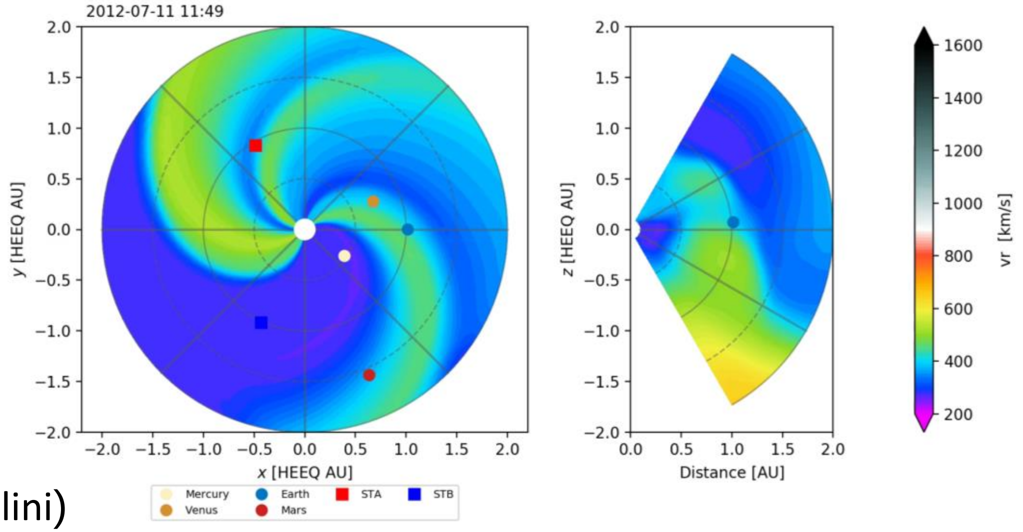
Observational data

Empirical / data-driven models

0.1 AU

Physics-based model

2 AU

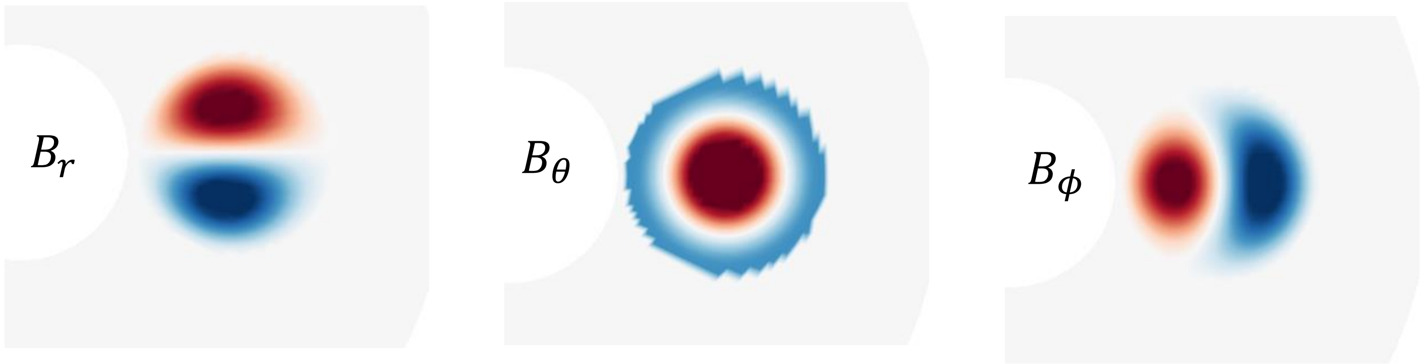


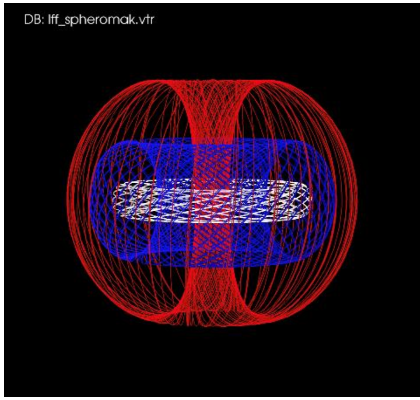
(see talk by Camilla Scolini)

Pomoell & Poedts 2018

EUHFORIA: Spheromak CME

Flux rope modeled as Linear Force Free Spheromak





CME
kinematics
Cone model

- Start time of CME
- Propagation velocity of CME
- Latitude of centre of CME source region
- Longitude of centre of CME source region
- Half-width of CME
- Density of CME
- Temperature of CME
- Title angle of the CME
- Helicity of the CME
- Total toroidal flux

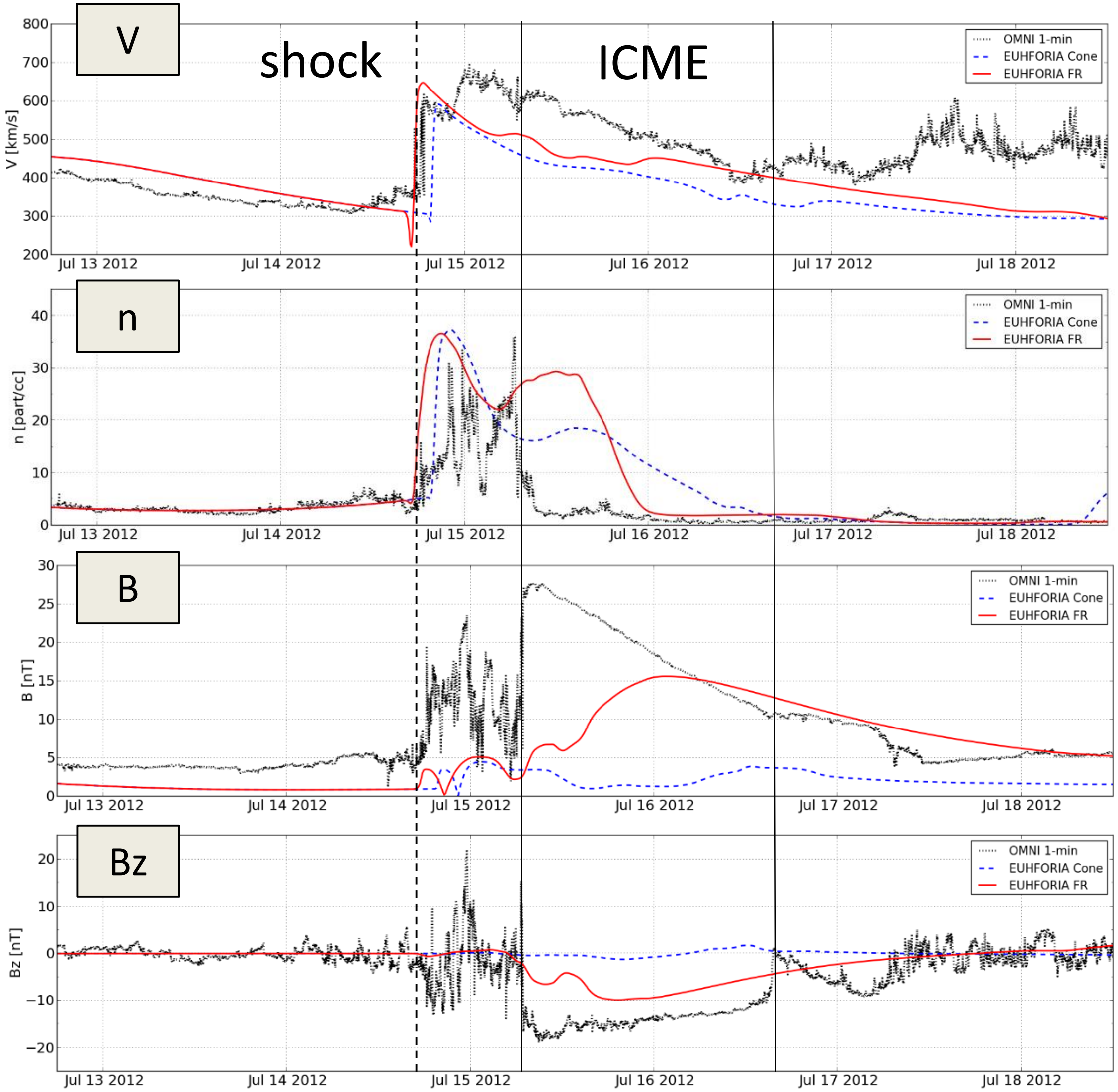
Flux rope
parameters

(see talk by Camilla Scolini)

July 12 2012 CME

ISEST WG4 Event 1

Spheromak vs cone model: predictions @ L1



CME simulated using observation-based parameters

- **CME arrival time** and **peak density/speed** well reproduced by both models

→ Magnetospheric compression

- **IMF rotations**: well reproduced with spheromak
- Min **Bz prediction** improved by **+40%** using spheromak compared to cone

→ Dayside reconnection & geomagnetic activity

(see talk by Camilla Scolini)

3. Conclusion---Future

❂ Simulations have really reached the point where very different simulations are used for different goals:

- ❖ Real-time forecasting: ENLIL, EUHFORIA
- ❖ Providing environment for analyses of real events: ENLIL, EUHFORIA, SWMF, AWSOM, H3DMHD, CESE, COIN……
- ❖ Understanding causes of eruption: complex initiation mechanism, as much realistic physics as possible
- ❖ CME-CME interaction: Most advanced domain where people are using simulations + data analysis (remote + in-situ) to learn new things.

❂ Future: individual progress can be expected: *e.g.,* KU LEUVEN, STELab, NSSC, Michigan, IRAP-CDPP, LMSAL…

Next Year, 2nd China-Europe Solar Physics Meeting, the same location, in 6-10 May…..

3. Conclusion---Future

- For coordinated work, 1-2 event(s) should be chosen - in coordination with other WGs (1 isolated, 1 multiple? ISEST-simulation campaign events).
- What is importance of solar initiation? What are the key model-input parameters for CME simulation? Direction? Speed? How to determine orientation at 0.1 AU?
- What are forecasting-performances of different empirical, analytical, and numerical models?
- How well models reproduce heliospheric kinematics of ICMEs?
- What can be done regarding the geomagnetic-activity forecasting?
- At the Parker Solar Probe and Solar Orbiter era, what aspect can be expected to improve further? E.g., Short-time forecast? Testing theories on the structure and heating processes of the solar corona? (See the talk by R. F. Pinto and P. Hess)

……

Thanks