https://esa-vswmc.eu

VSWMC & recent coronal modeling developments

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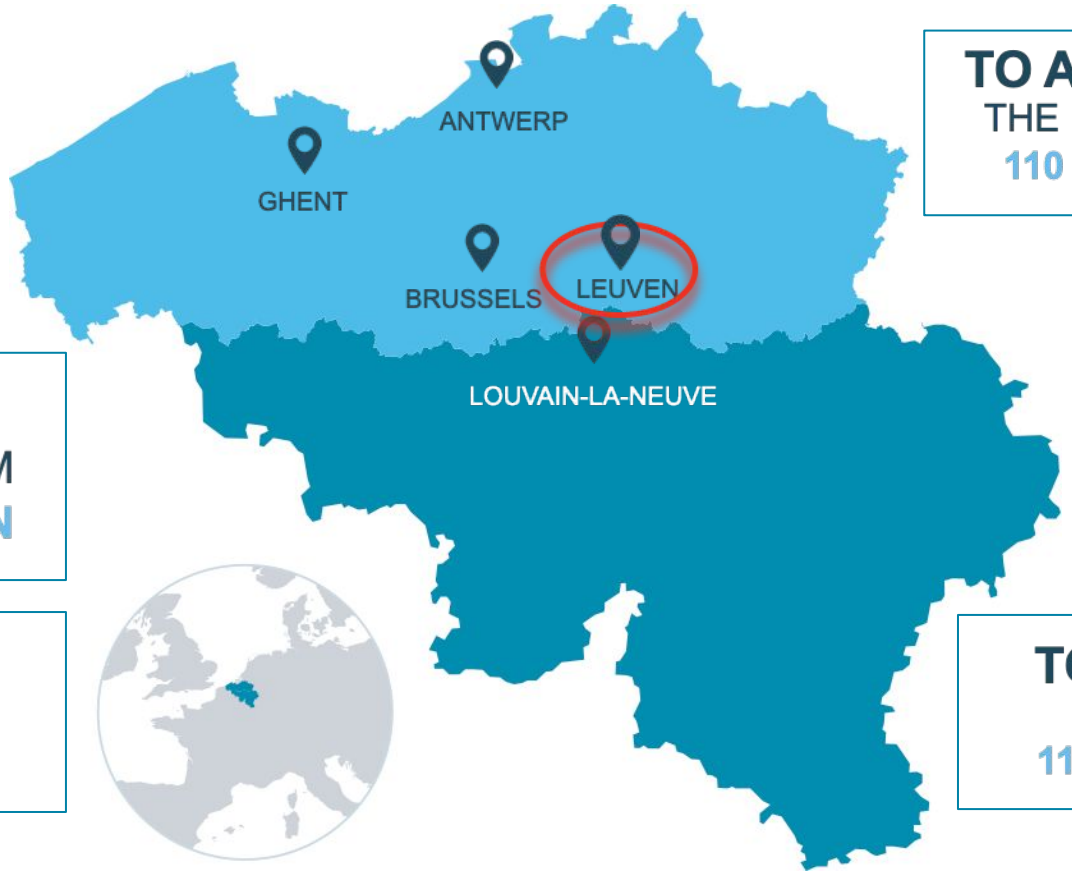
ISWI, Baku, 31 Oct - 4 Nov 2022

Leuven

- A “stone’s throw away” from Brussels
- Around 100k inhabitants (mostly university)
- Over 60k students

[Leuven municipality, 2022]

Leuven



TO AMSTERDAM
THE NETHERLANDS
110 MIN BY TRAIN

TO LONDON
UNITED KINGDOM
120 MIN BY TRAIN

TO PARIS
FRANCE
90 MIN BY TRAIN

TO COLOGNE
GERMANY
110 MIN BY TRAIN

The space weather

- Studies the time-varying conditions in the solar system, with special focus on the surroundings of the Earth
- The Earth interacts with the space weather through the magnetosphere, ionosphere, thermosphere and exosphere

- **Solar wind:** the stream of particles leaving the Sun, filling the solar system (heliosphere)
  - generally “low” energy particles (0.5 - 10 keV)
  - slow and fast wind: 300 – 750+ km/s

- **Coronal mass ejections** (CME): significant release of Solar plasma and magnetic field

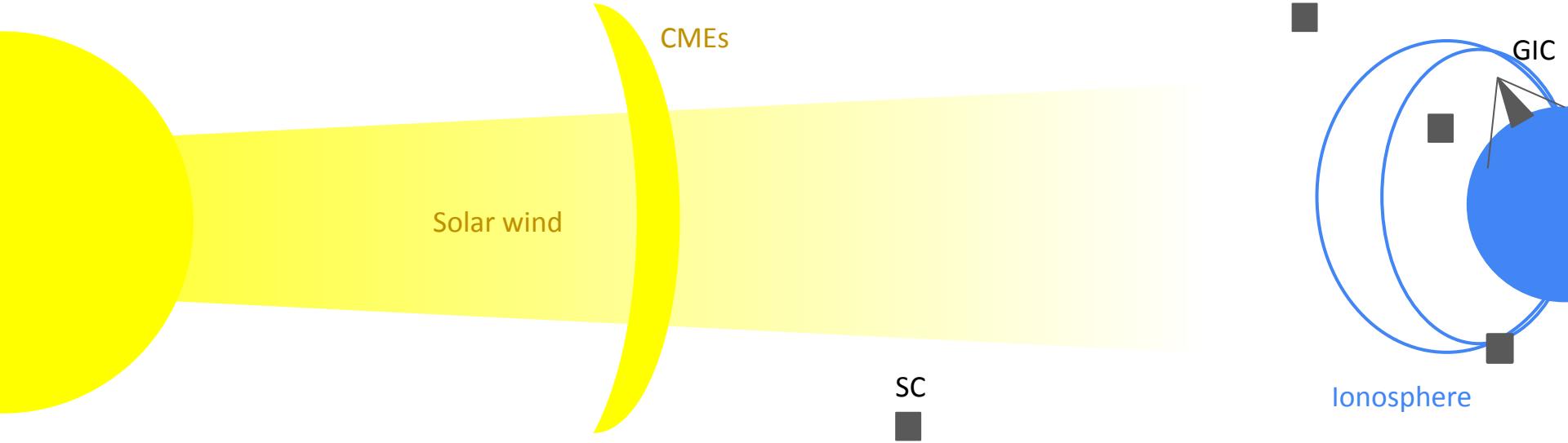
Space weather forecasting

- **ESA Space Weather services**
  - network to provide 39 services to 8 service domains:
    - spacecraft design
    - spacecraft operations
    - human space flight
    - launch operations
    - trans-ionospheric radio link
    - space surveillance & tracking
    - non-space system operation
    - general data services

[esa.int]

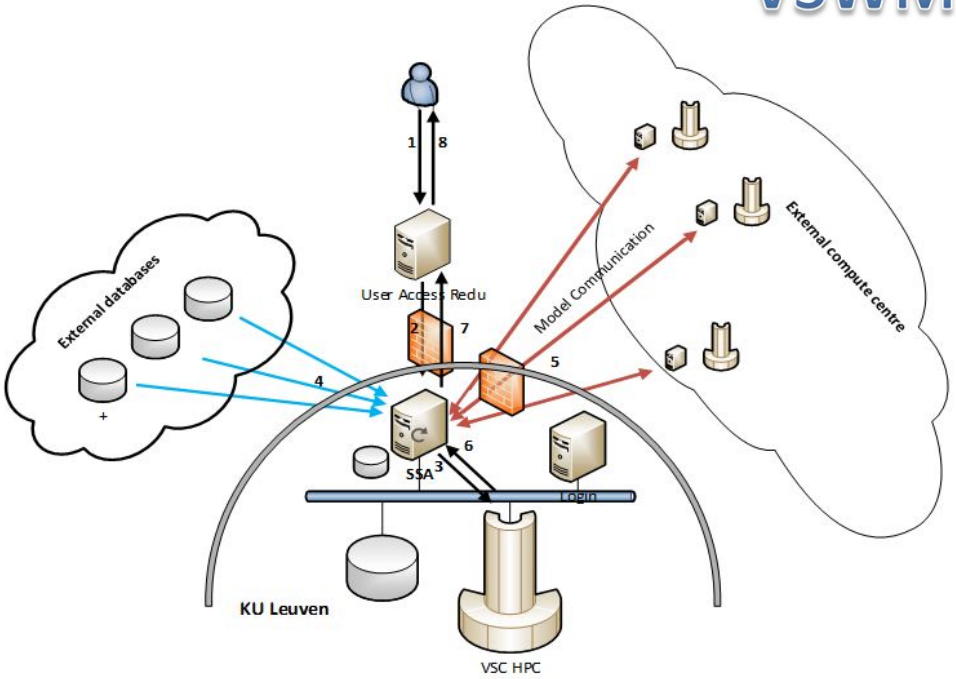
Virtual SWE Modelling Centre

Solar surface → corona → heliosphere (SEU, TID) → ionosphere (RF link) → ground currents (GIC)



Virtual SWE Modelling Centre

- Within general data services: **The Virtual Space Weather Modelling Centre:**
  - interactive end-to-end space weather simulations, with interfaces for forecasters
  - to access, couple, verify, validate and run space weather models
  - to visualise and compare model outputs
  - geographically or locally distributed



CURRENT SPACE WEATHER

SPACE WEATHER AT ESA

SERVICE DOMAINS

EXPERT SERVICE CENTRES

- ESC Solar Weather
- ESC Heliospheric Weather
- ESC Space Radiation
- ESC Ionospheric Weather
- ESC Geomagnetic Conditions

OTHER RESOURCES

CONTACT

REQUEST FOR REGISTRATION

Expert Service Centres / ESC Heliospheric Weather / kul-cmpa-federated /

Federated products from the Centre for mathematical Plasma-Astrophysics (KUL)

Virtual Space Weather Modelling Centre

HISTORY NEW RUN

Welcome to the VSWMC

The Virtual Space Weather Modelling Centre (VSWMC) is a full scale, open end-to-end (meaning from the Sun to the Earth) space weather modelling, enabling to combine (*couple*) various space weather models in an integrated tool, with the models located either locally or geographically distributed. Hence, the VSWMC brings together models for different components of the space weather in an integrated environment that enables to run them and to couple them.

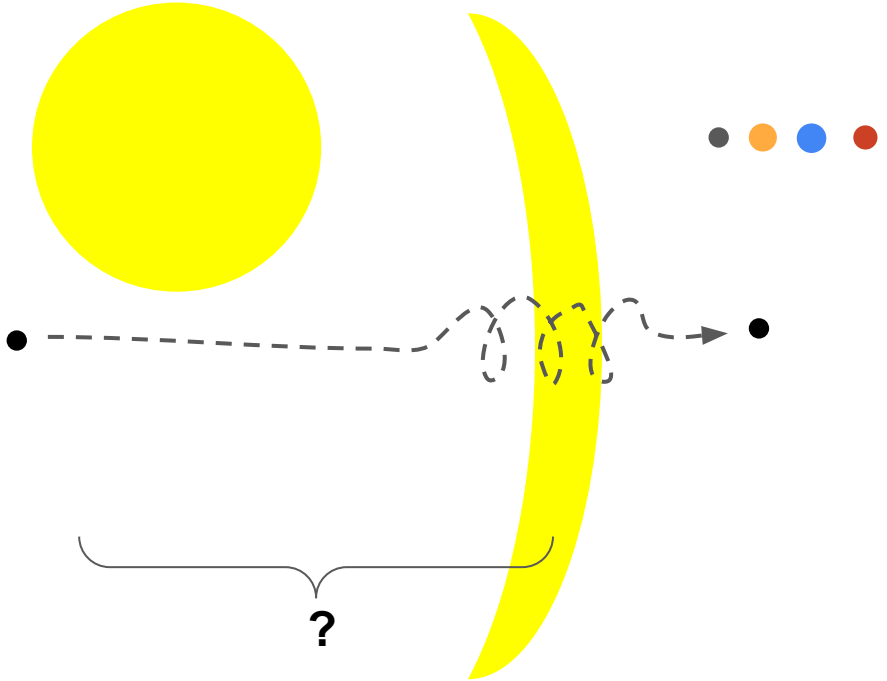
About VSWMC Full-size

VSWMC models

- **Dst Index**: simple empirical model to determine the Dst index from the solar wind parameters at L1
- **EUHFORIA Corona**: the semi-empirical WSA-SCS based coronal model of EUHFORIA
- **EUHFORIA Heliosphere**: the heliospheric wind and CME evolution model of EUHFORIA
- **EUHFORIA Visualization**: provides the standard pictures and movies output of EUHFORIA
- **GUMICS-4**: an Earth magnetosphere model
- **Kp Index**: simple empirical model to determine the Kp index from the solar wind parameters at L1
- **Magnetopause Stand-Off Distance**: simple empirical model to determine the stand-off distance of the magnetopause from solar wind parameters at L1
- **ODI**: model to get data out of the ODI database
- **Wind-Predict**: polytropic MHD global coronal model
- **CTIP**: Coupled Thermosphere Ionosphere Plasmasphere Model
- **MULTI-VP**: global coronal model
- **BPiM**: 3D dynamic model of the plasmasphere
- **NARMAX (SNRB and SNGI)**: electron fluxes at geostationary orbit covering the GOES 15 energy channels >800keV and >2MeV (SNRB) and geomagnetic indices Kp and Dst (SNGI)
- **SPARX**: SEP time-flux profiles
- **Gorgon-Space**: = alternative magnetosphere model
- **MCM**: temp., density, and composition of the thermosphere
- **DTM**: temp., density, and composition of the thermosphere

KU Leuven projects

- Heliospheric forecasting:
  - *EUHFORIA, EUHFORIA + MULTI-VP*
  - *Icarus (MPI-AMRVAC)*
- Particle modelling: *PARADISE*
- Coronal MHD CFD:
  - Global coronal modelling *(COCONUT)*
  - Local multifluid modelling



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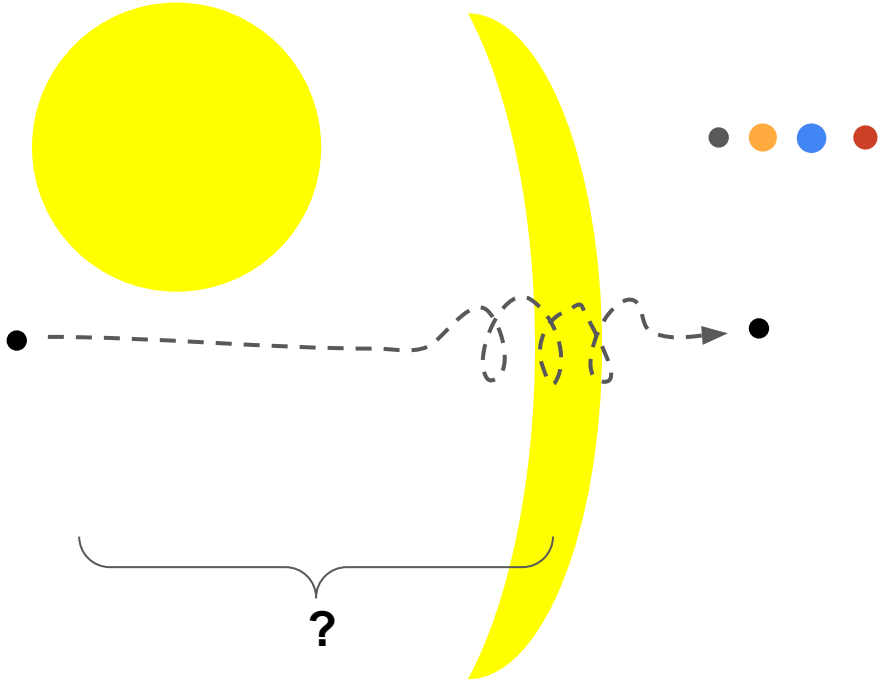
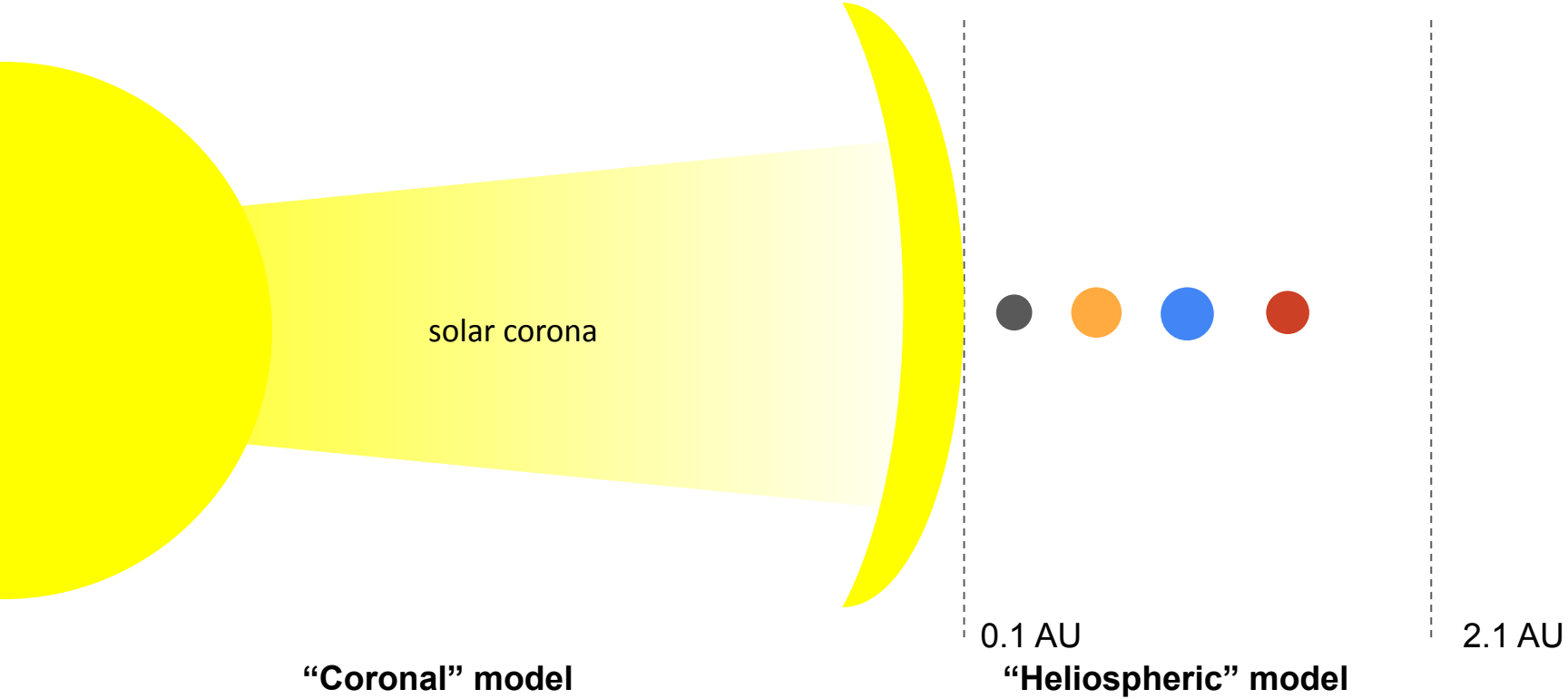


EUHFORIA (Poedts & Pomoell 2018)



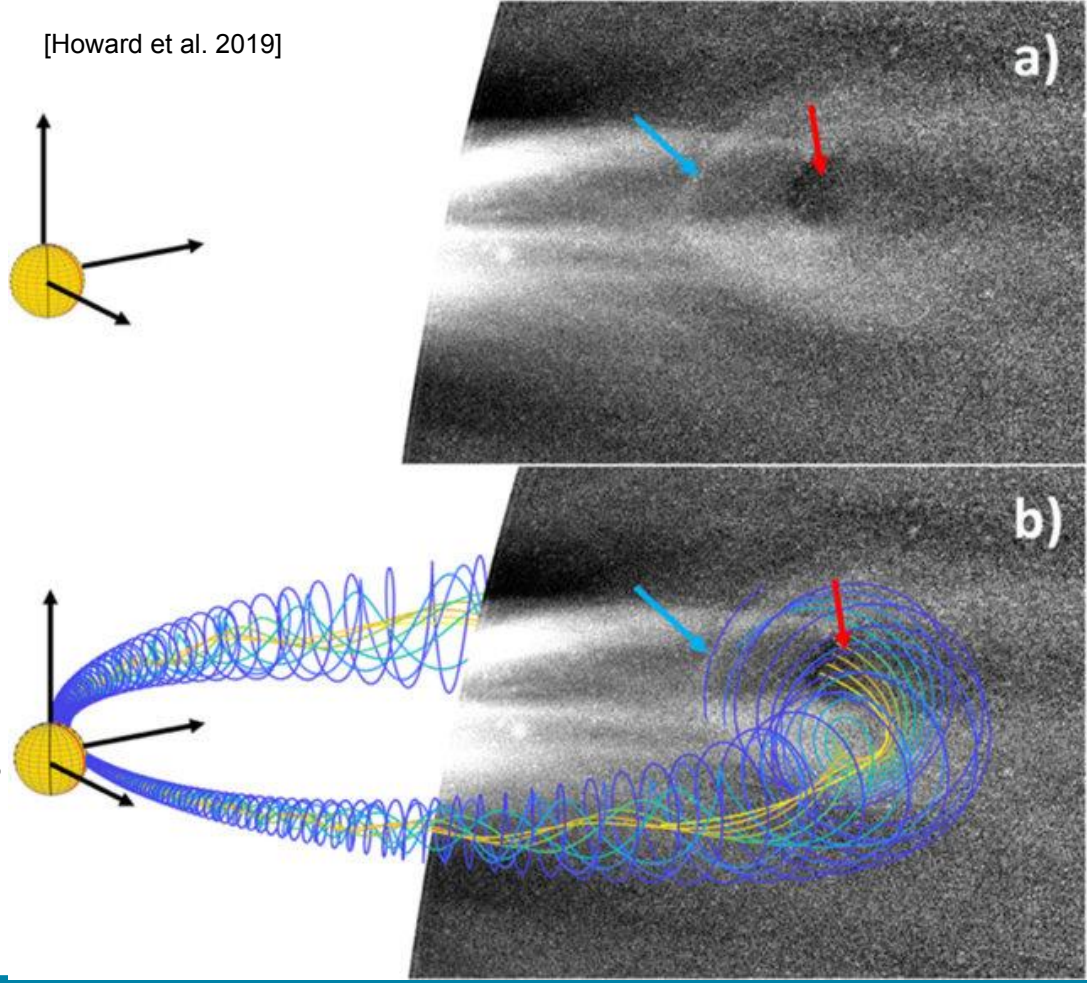
EUHFORIA

- Compute:
  - Background solar wind
  - CMEs as 3D flux ropes: bundles of helical B-field lines that wind about a common axis

Science:

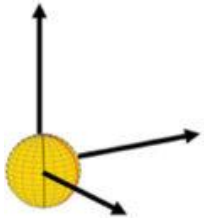
- Characterise the evolution of CMEs
- Improve modelling of these flux ropes based on observations
- Analyse CME-CME evolutions

[Howard et al. 2019]



[Howard et al. 2019]

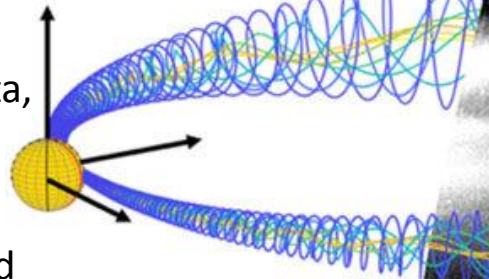
EUHFORIA: CMEs

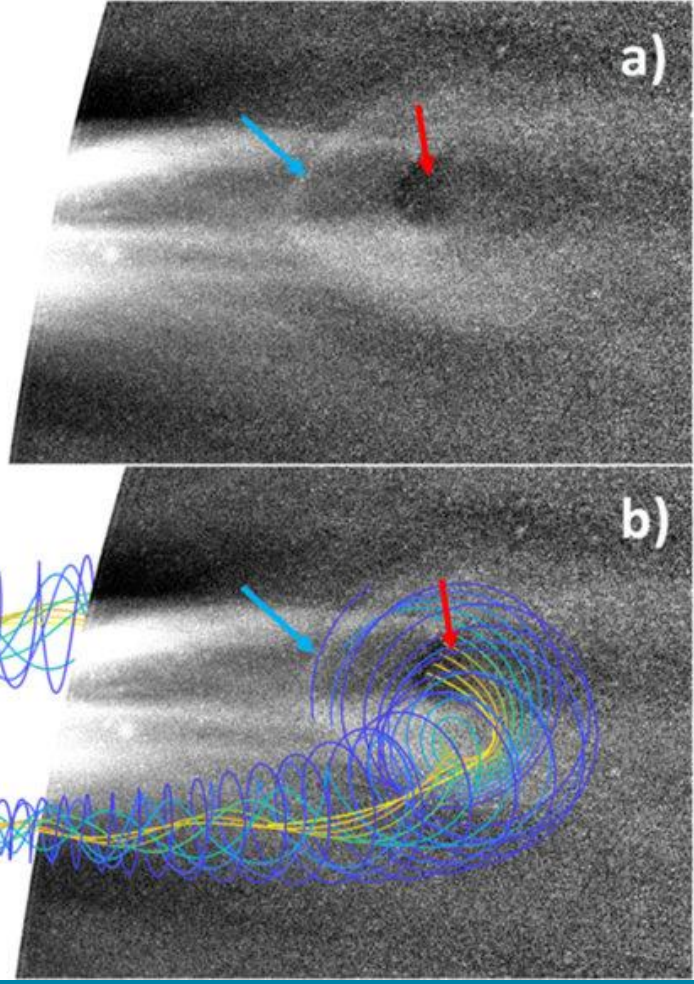


Applications:

- Space weather forecasts (“European ENLIL”): Time of arrival/ Geo-effectiveness

- Support for space missions (e.g. PSP, SolO):
  - choice of observational targets, interpretation of low-latency data, prioritisation of data for downlink, link between remote-sensing observations and in-situ measurements





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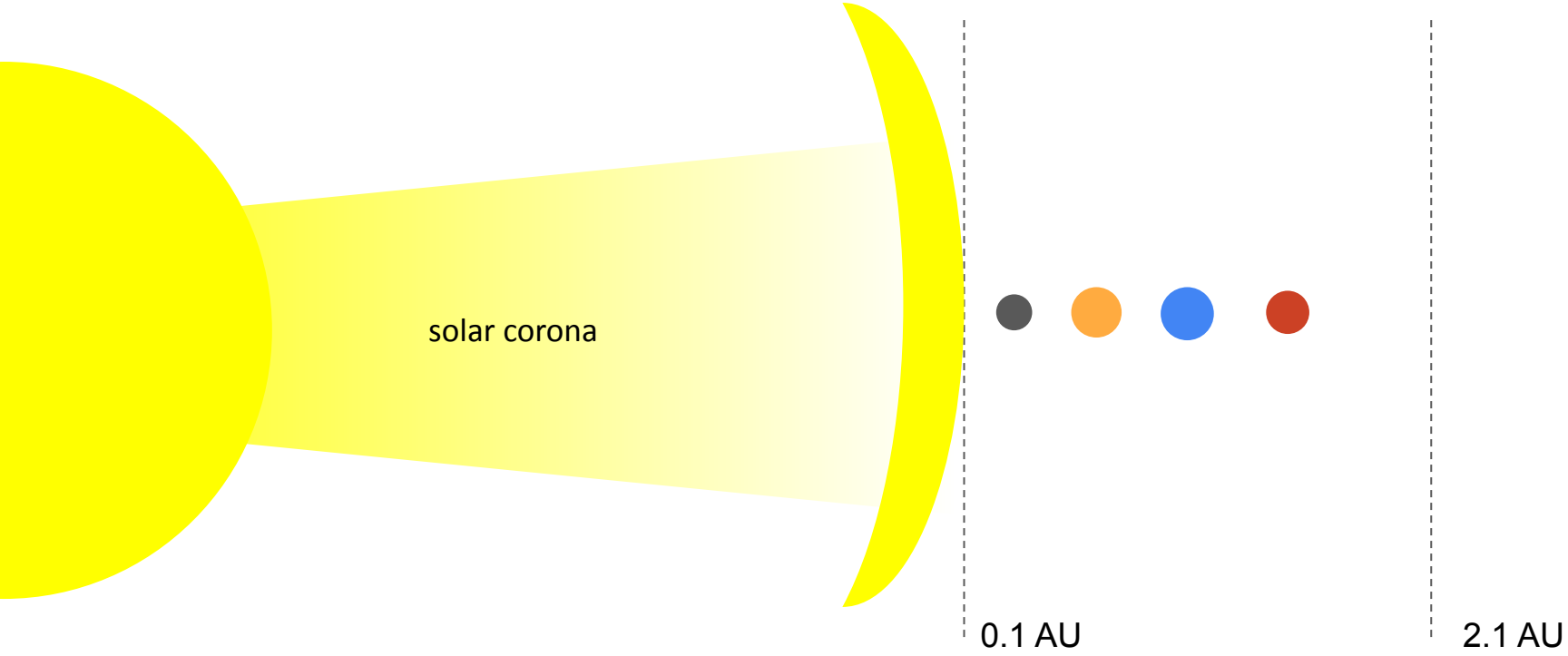

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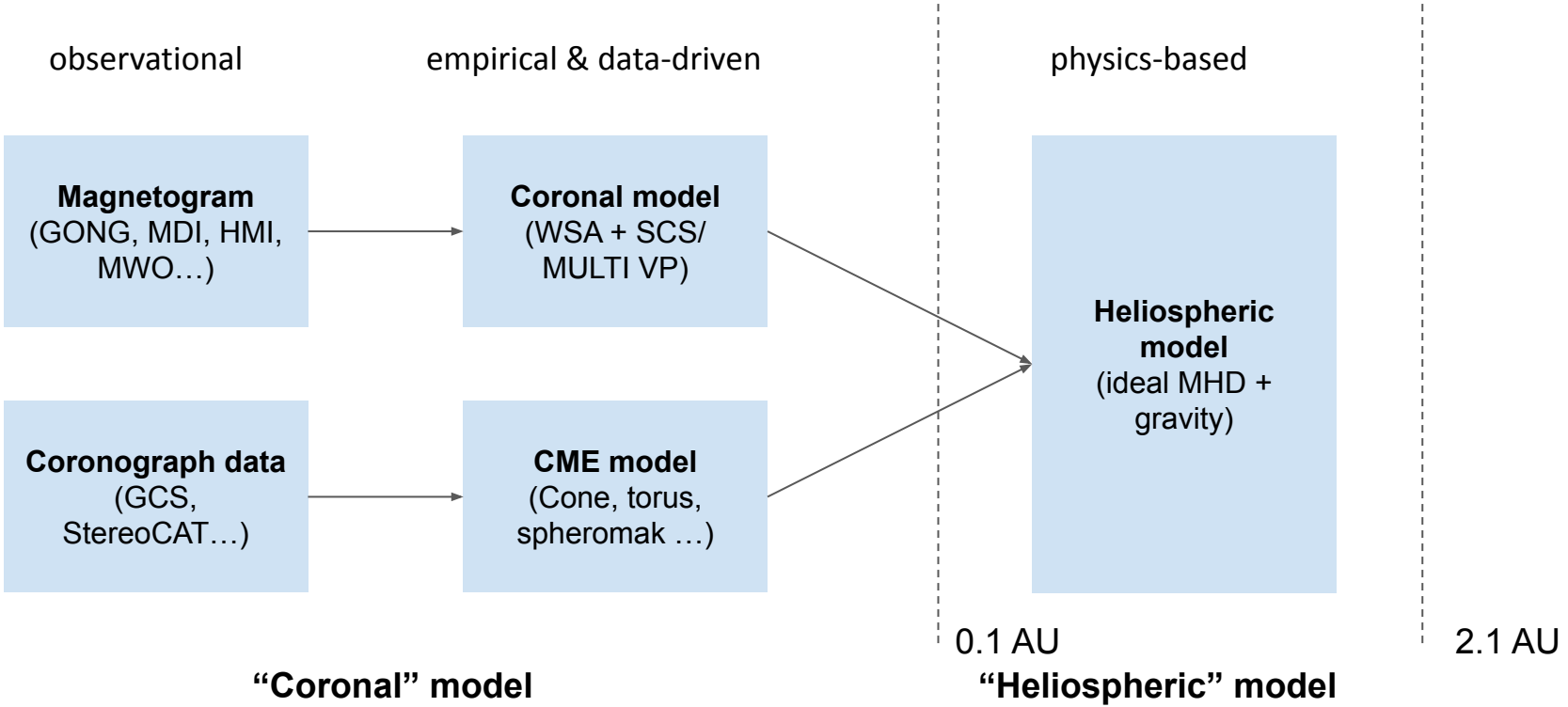

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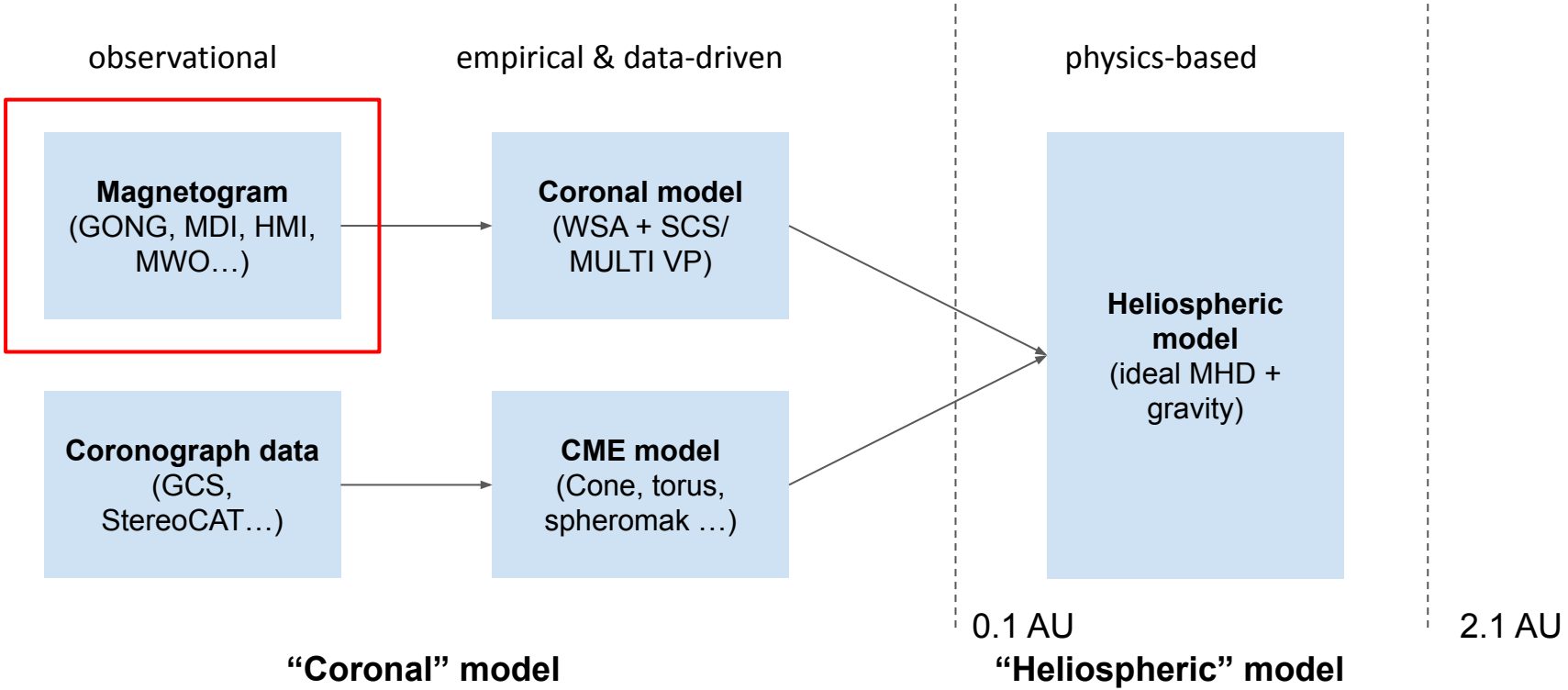
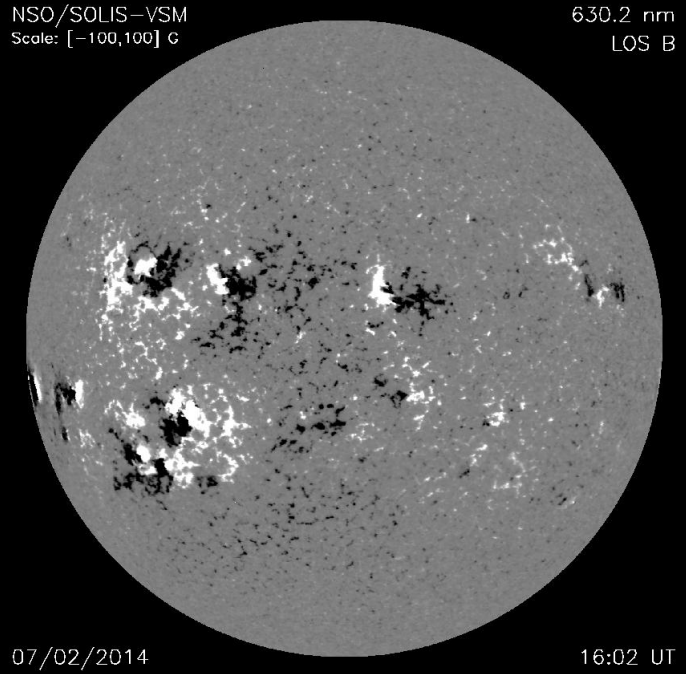
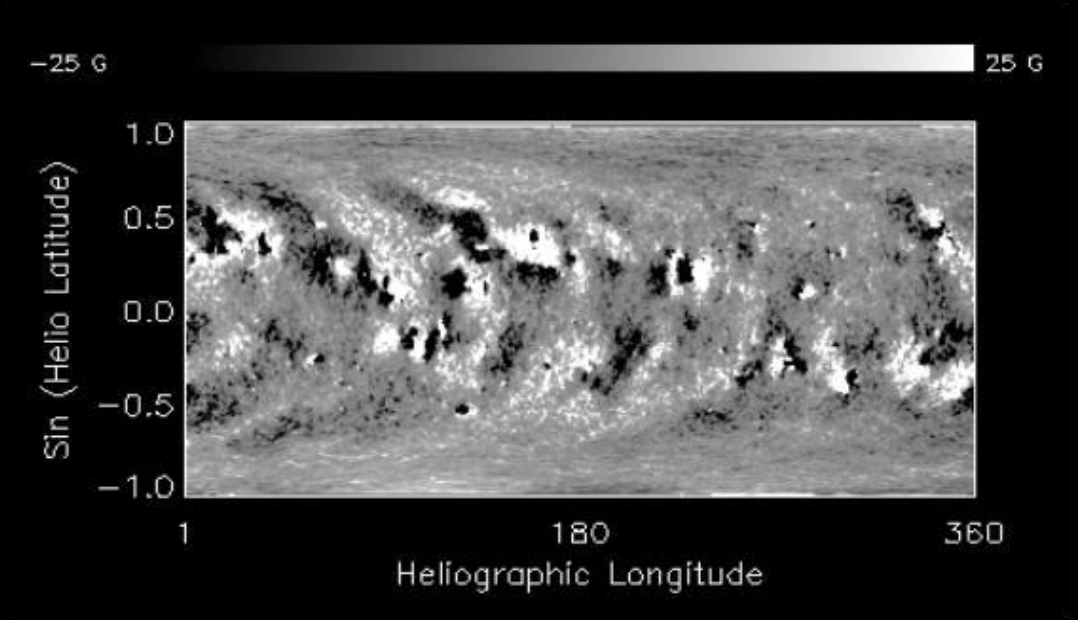


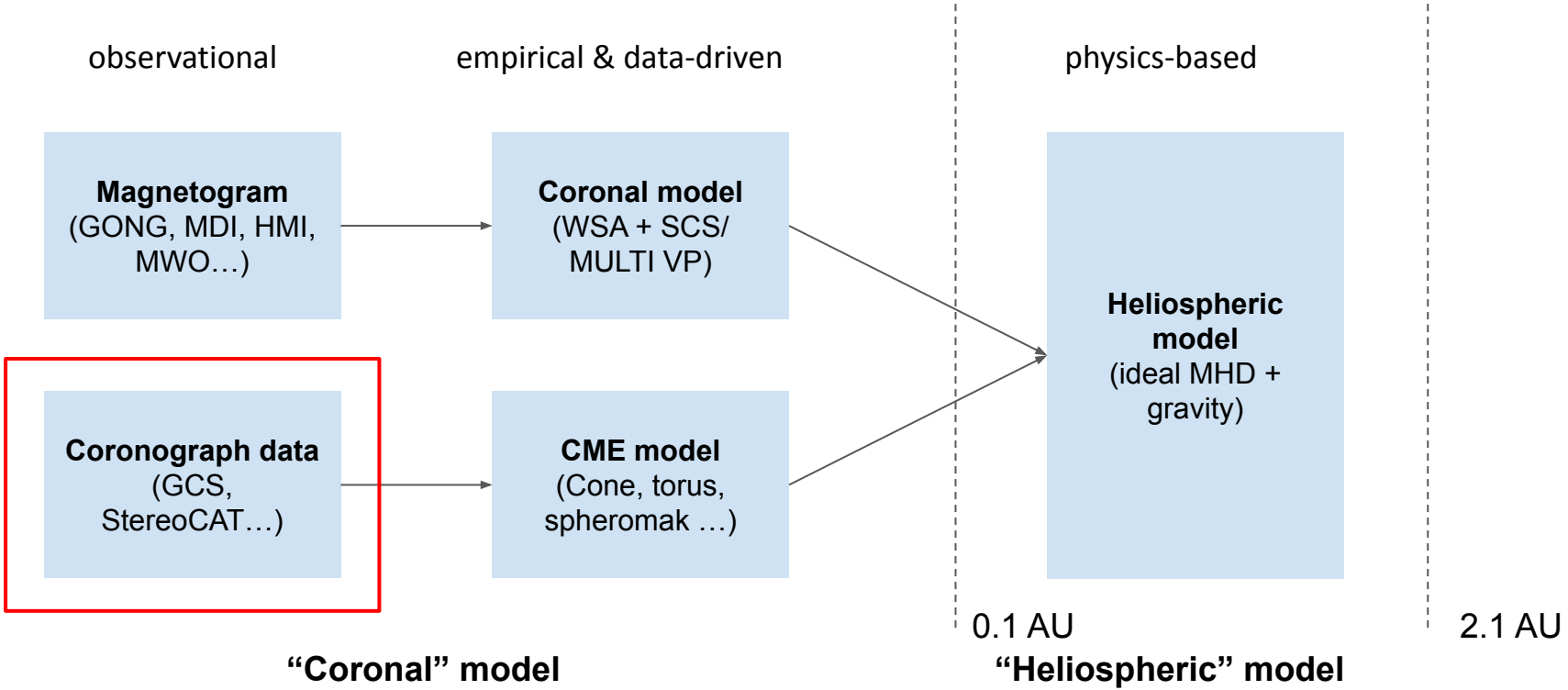
EUHFORIA: GONG magnetograms



[Jin et al. 2016]

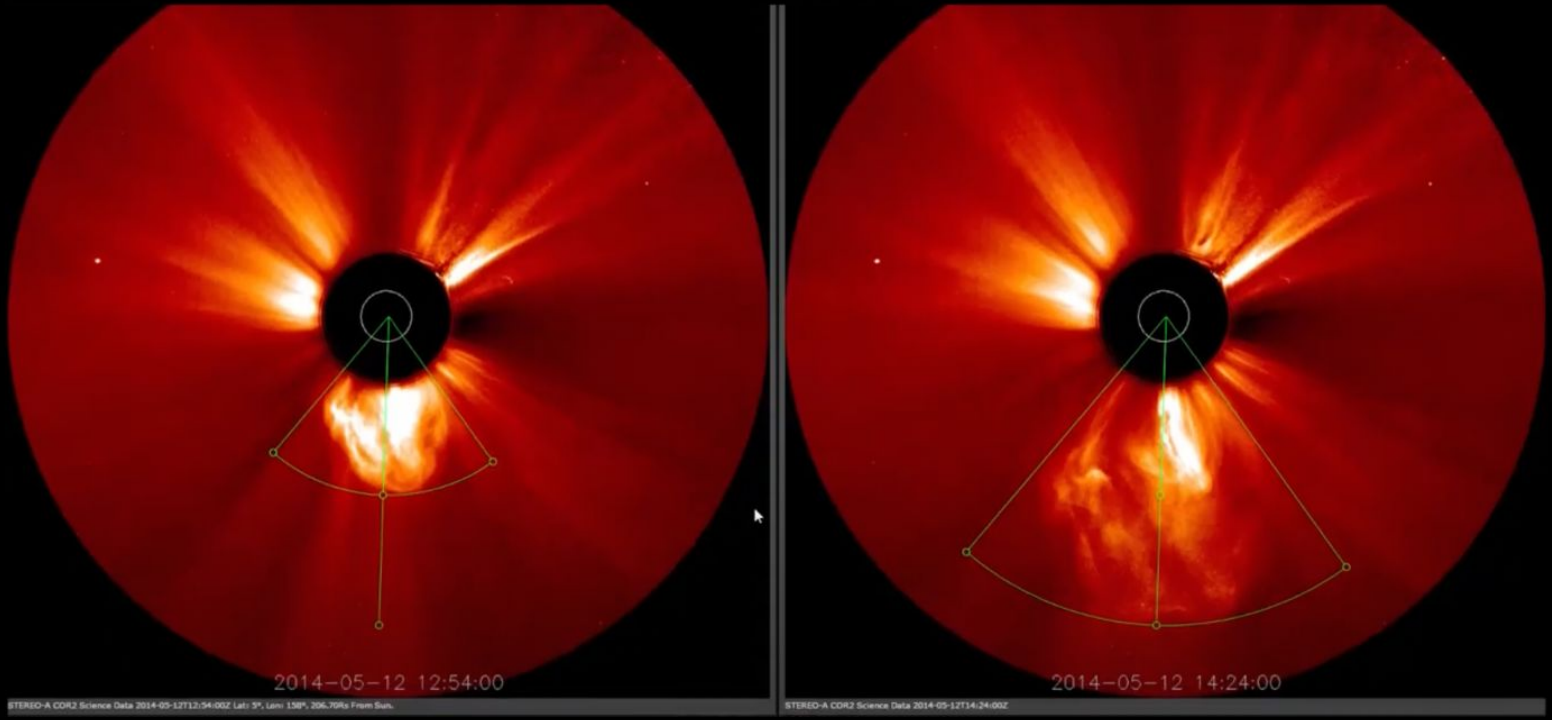


EUHFORIA (Poedts & Pomoell 2018)



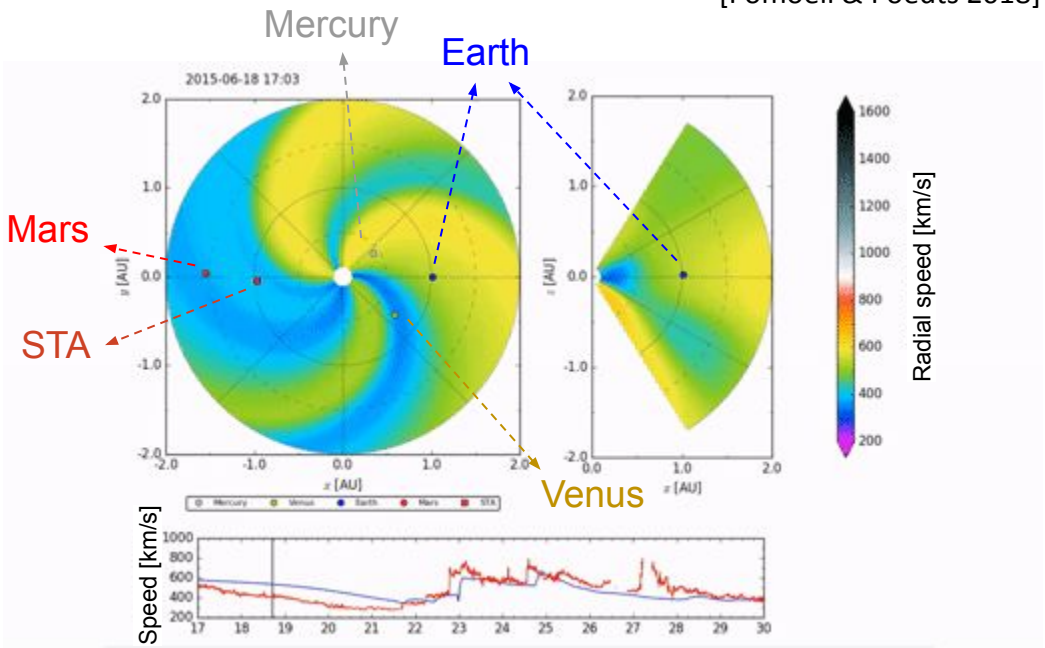
EUHFORIA: StereoCAT / GCS

[NASA, STEREO-A-COR2]



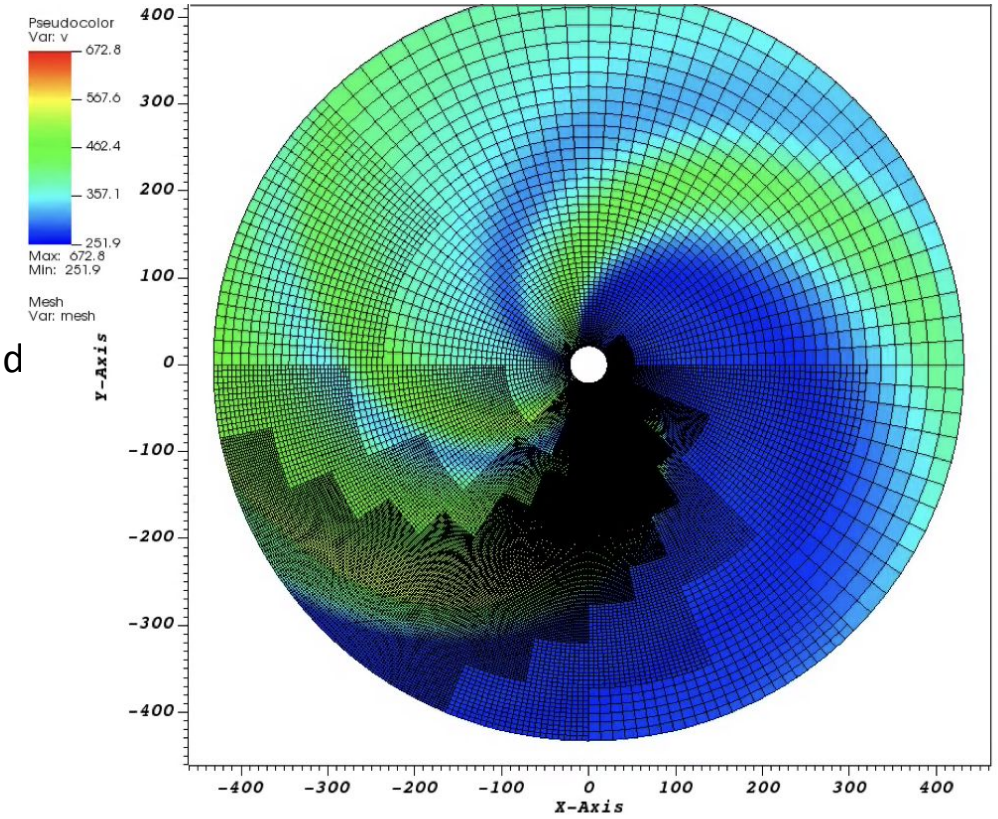
EUHFORIA: Preview

[Pomoell & Poedts 2018]



Icarus (Verbeke et al. 2022)

- Implemented into MPI-AMRVAC: parallelized adaptive mesh refinement framework (Xia et al. 2018)
- Traces the shock and locally refines the grid for better performance
- Email: tinatin.baratashvili@kuleuven.be



KU Leuven projects

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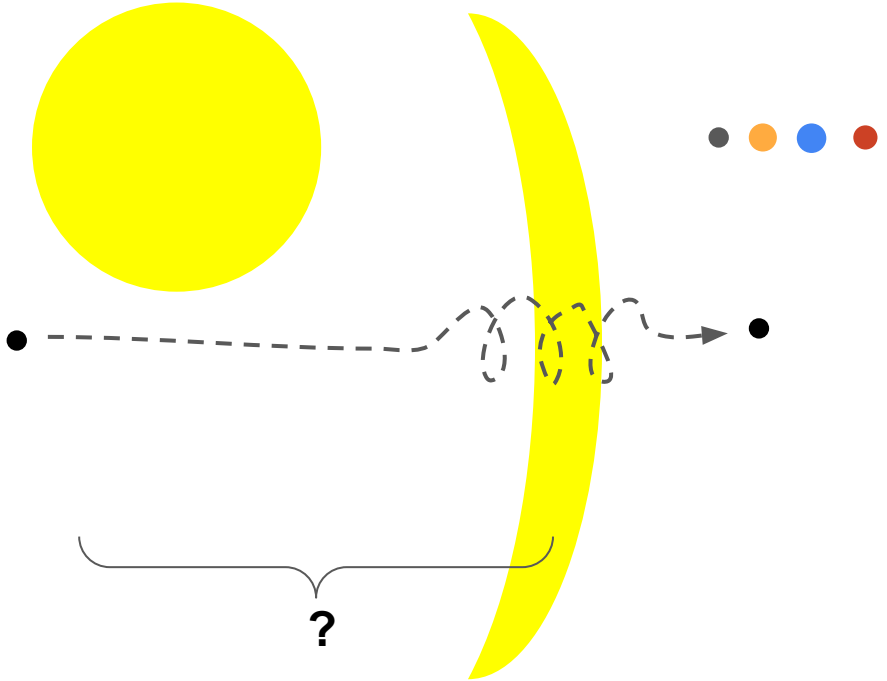
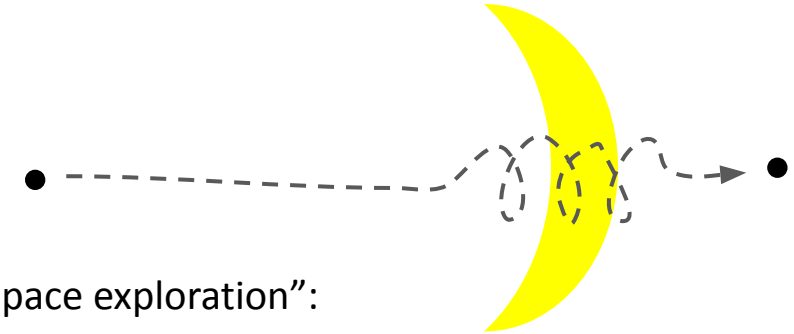


Paradise (Wijsen et al. 2020)

- Electronic damage → mostly high energy particles:
  SEP = solar energetic particles



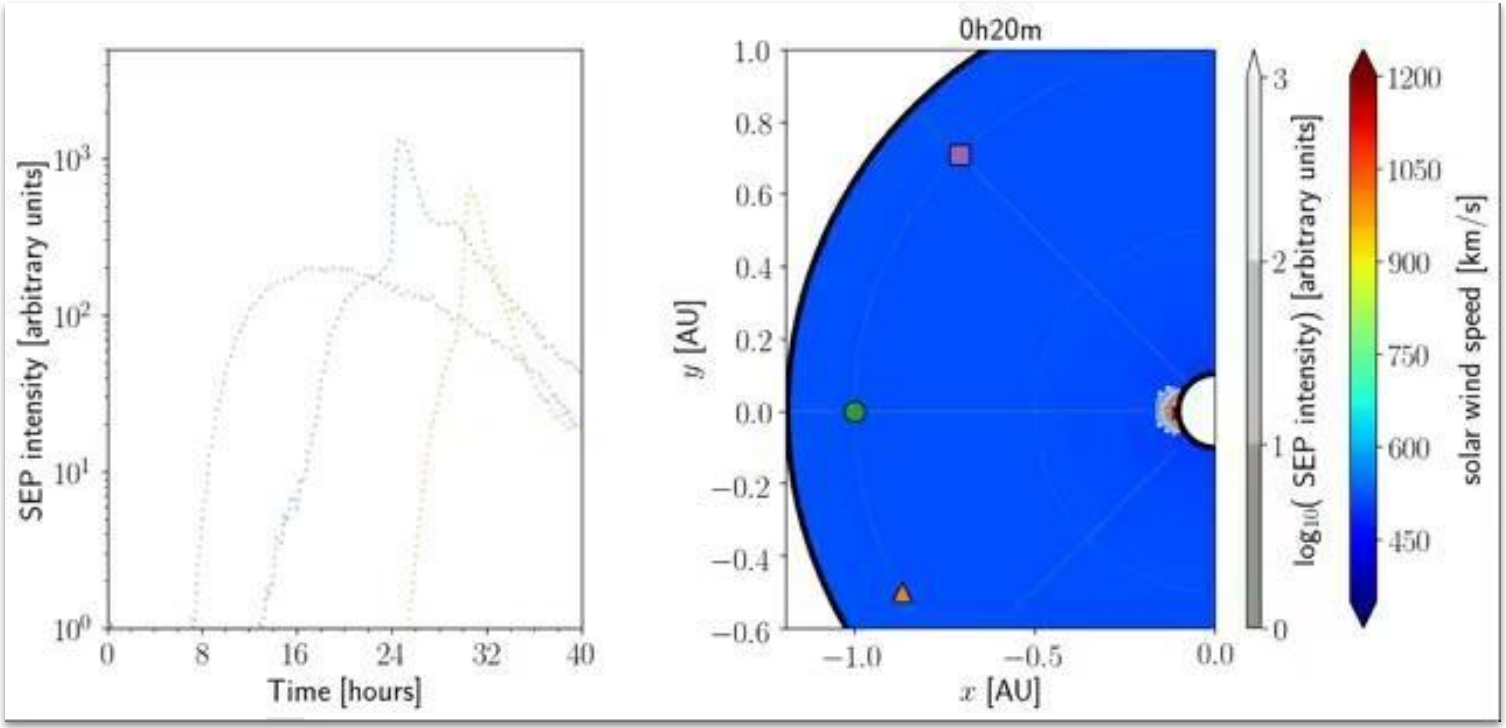
- “Particle radiation asset directed at interplanetary space exploration”:
  - A new model of SEPs propagating & accelerated via the solar wind

- Based on Vlasov equation (FTE)

- To be coupled with EUHFORIA (and COCONUT) in a new project

- Email: nicolas.wijsen@kuleuven.be

Paradise (Wijsen et al. 2020)



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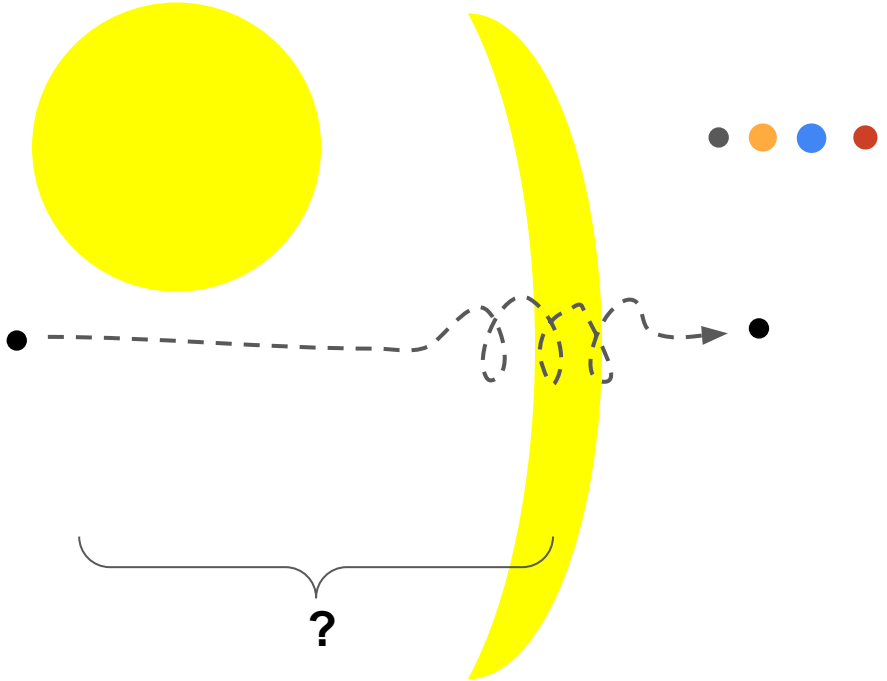
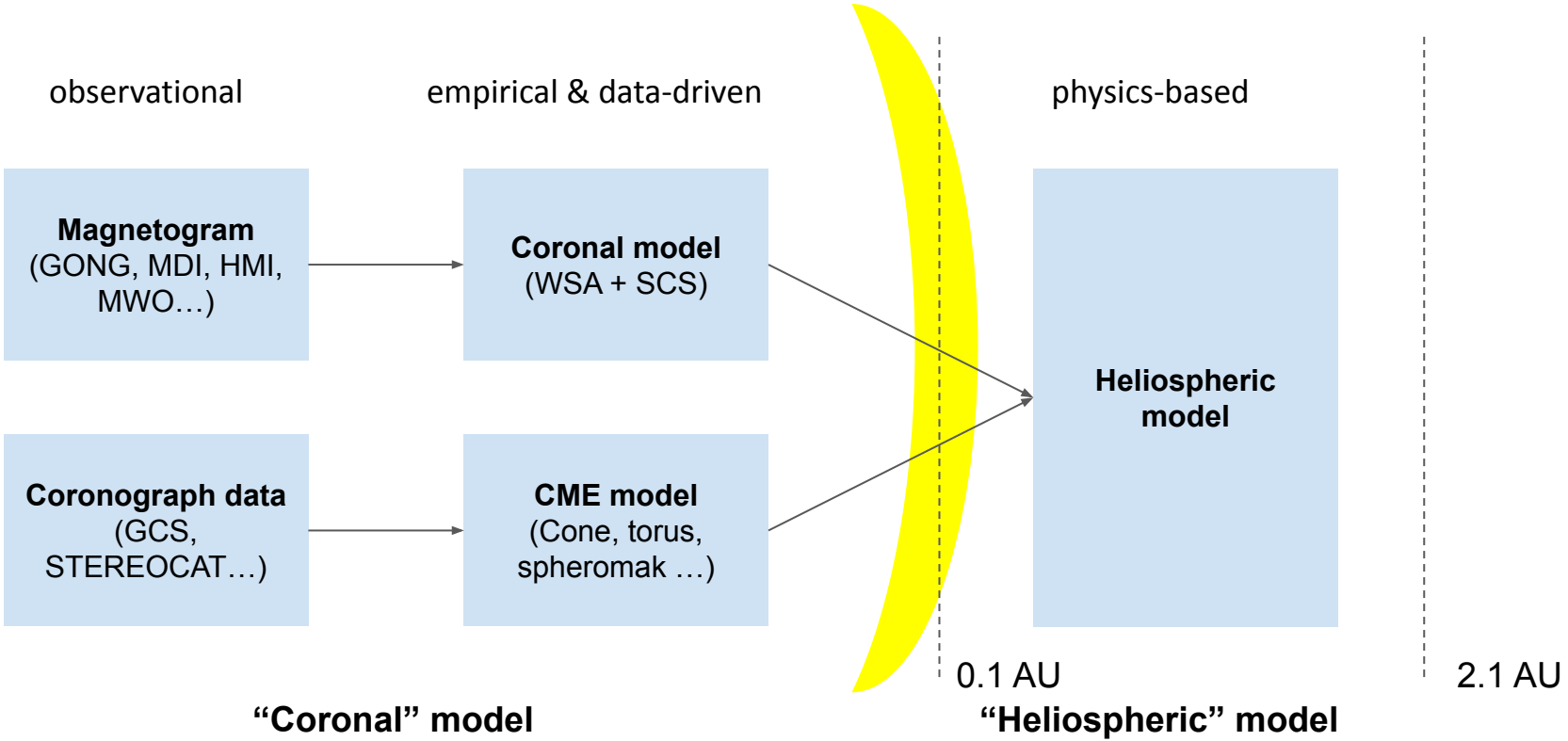
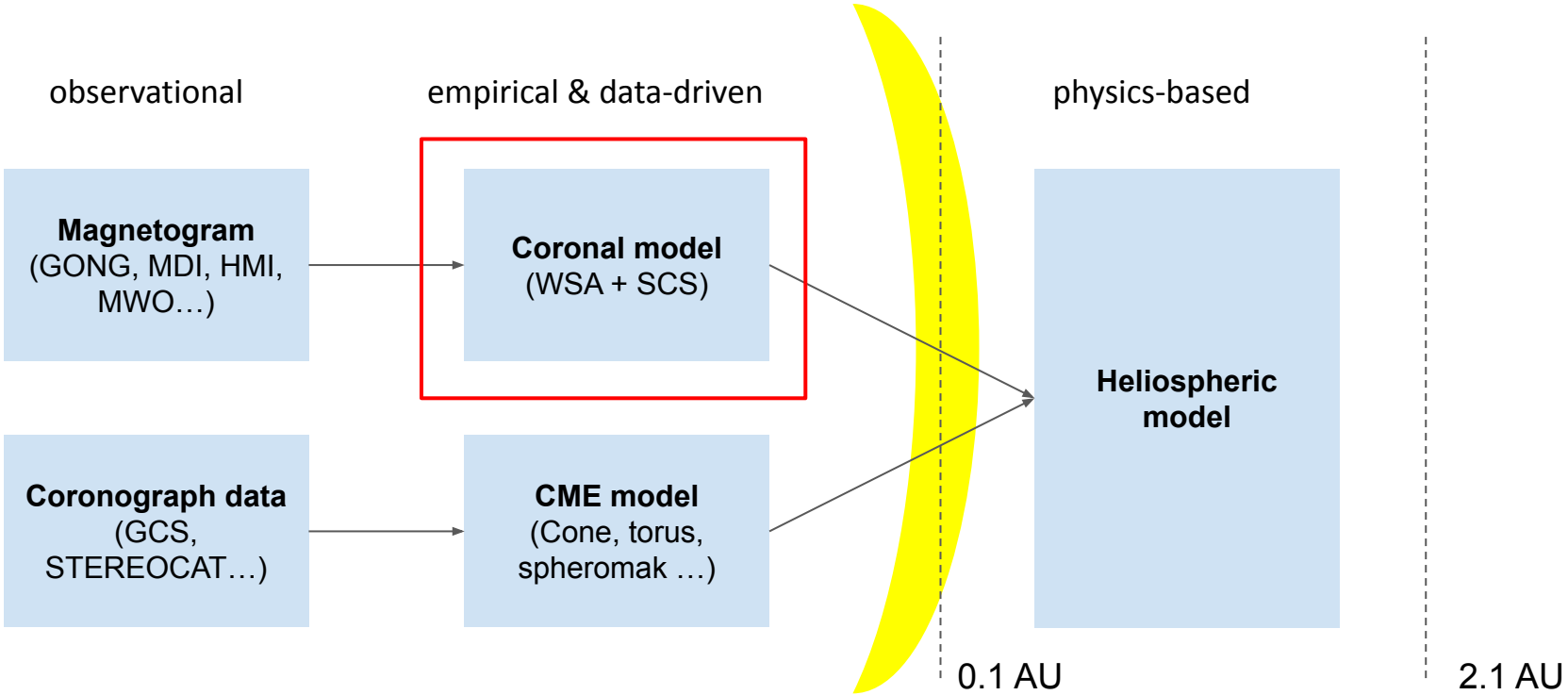


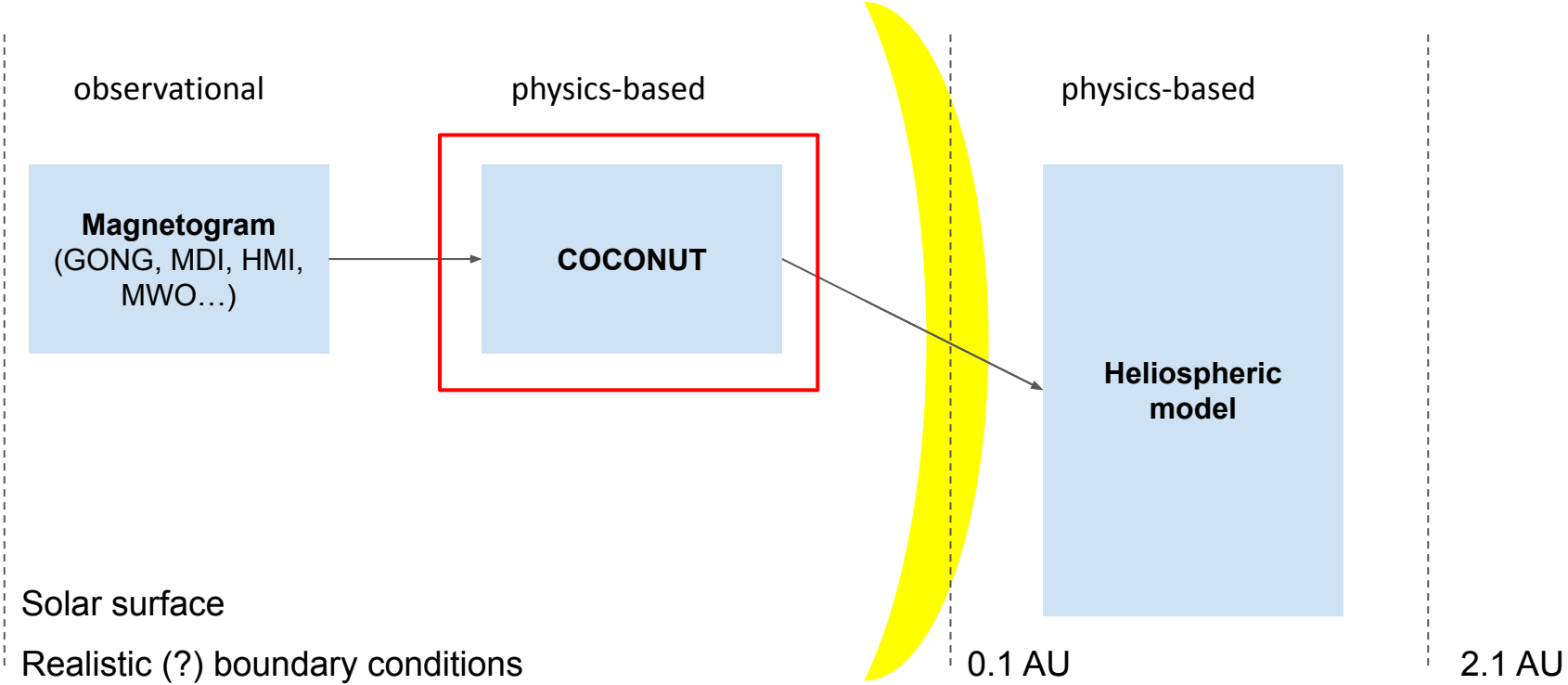
Back to EUHFORIA…



Back to EUHFORIA…



The need for a better coronal model

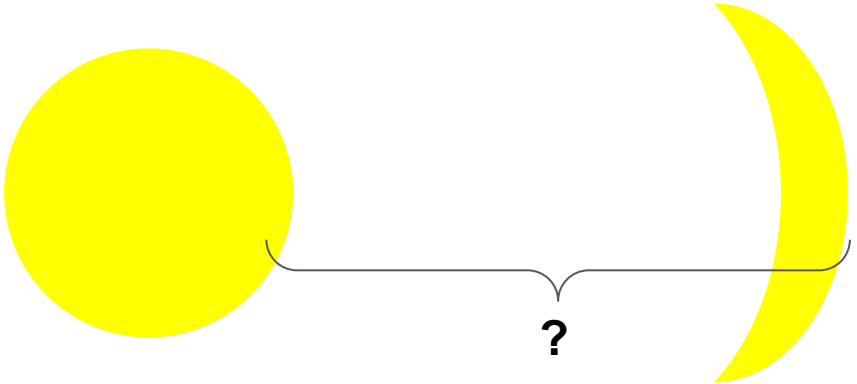


https://github.com/andrealani/COOLFluiD

COOLFluiD CFD framework (Lani 2002)

- C++ based multiphysics platform for fluid dynamics simulations

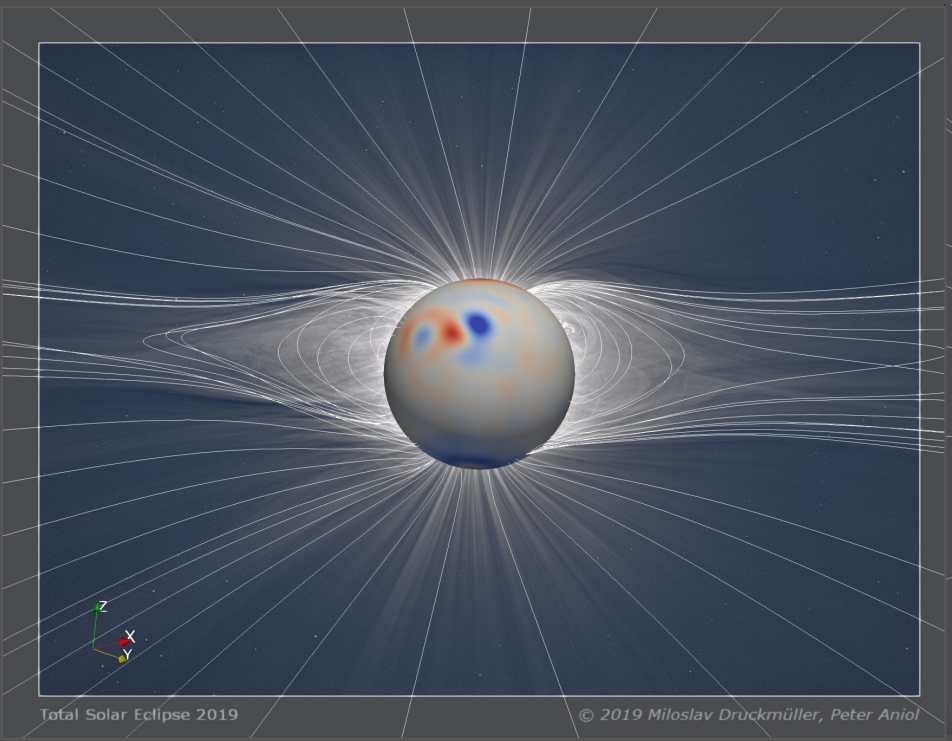
- Heavily parallelized

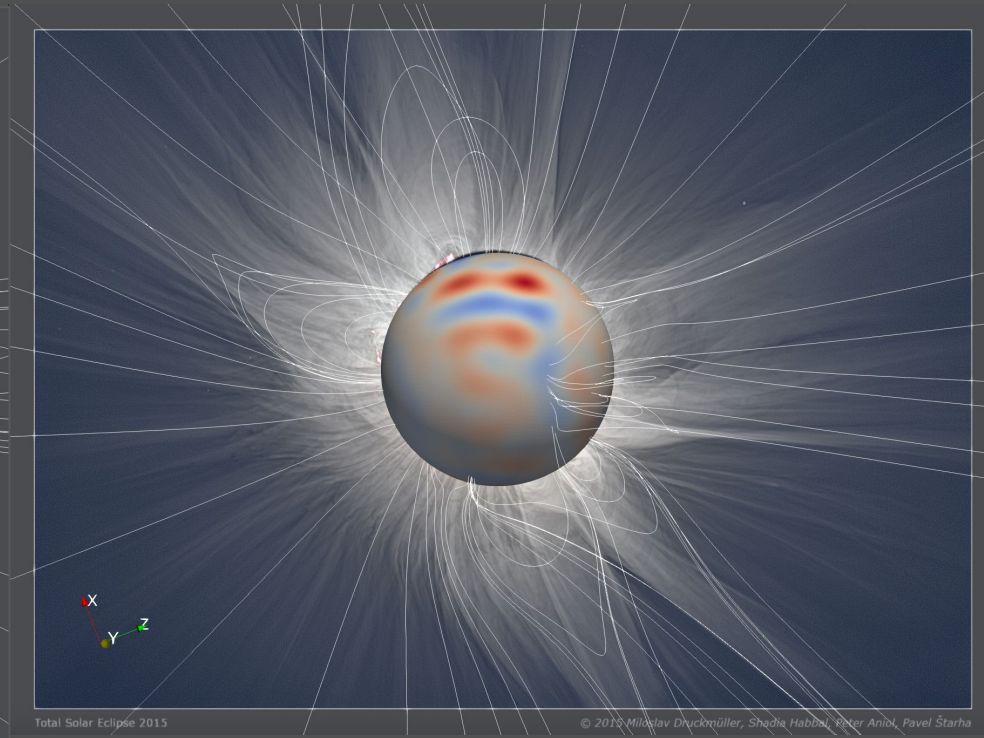


- Different than most state-of-art solvers:
  - Unstructured grid
  - Implicit scheme ⟶ CFL of up to several thousands
    ⟶ realistic convergence for space weather forecasts (convergence within a few hours)
    ⟶ realistic convergence for computationally very heavy problems (3D, multiple fluids…)

COCONUT: current state (results)

[Kuzma et al., submitted]





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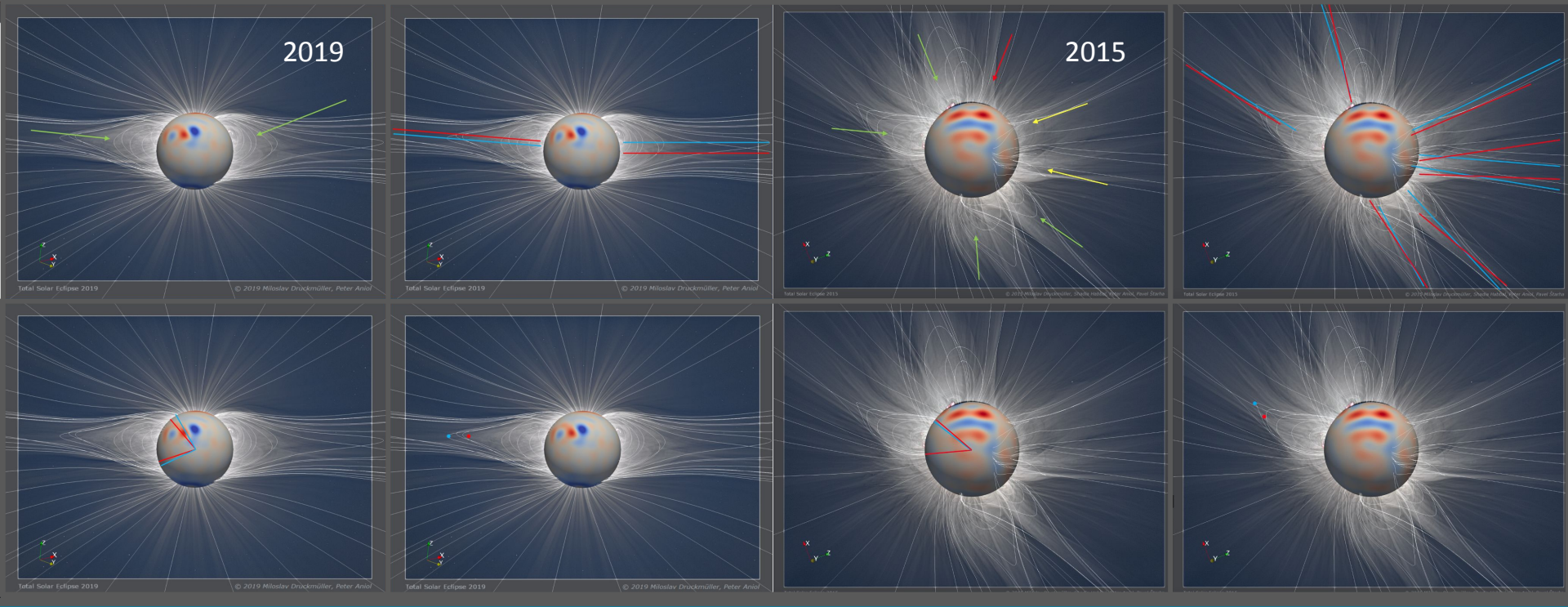

COCONUT: current state (performance)

- up to 35x speedup for data-driven simulations compared to state-of-art

Code	Case	Number of elements	Number of processors	Highest CFL	Iterations	Time (minutes)
COCONUT	Dipole	332 800	84	5000	137	5.6
Wind-Predict	Dipole	320 000	84	0.3	80445	15.0
COCONUT	Quadrupole	332 800	84	300	290	11.9
Wind-Predict	Quadrupole	320 000	84	0.3	94310	17.0
COCONUT	GONG ($\ell_{max} = 15$)	$1.9\ 10^6$	196	2000	1397	87.5
Wind-Predict	GONG ($\ell_{max} = 15$)	$2.0\ 10^6$	196	0.3	163768	960
COCONUT	GONG ($\ell_{max} = 30$)	$1.9\ 10^6$	196	2000	1528	86.8
Wind-Predict	GONG ($\ell_{max} = 30$)	$2.0\ 10^6$	196	0.3	607988	3040

[Perri & Leitner et al., 2022]

COCONUT: future steps?

- Adding more realistic physics:
  - source terms: heating, radiation, conduction
  - multifluid formulation
  - flux rope insertion

- Further improving performance & reliability:
  - grid refinement techniques & AMR
  - flux reconstruction

- Coupling to other VSWMC software:
  - PARADISE (particle acceleration)
  - EUHFORIA & ICARUS
  - magnetic connectivity studies

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- The entire platform is **open source** on github ⟶ collaboration
- All published papers are **open access**
- Documentation can be provided on request (in preparation)

We look forward to collaborating with you!

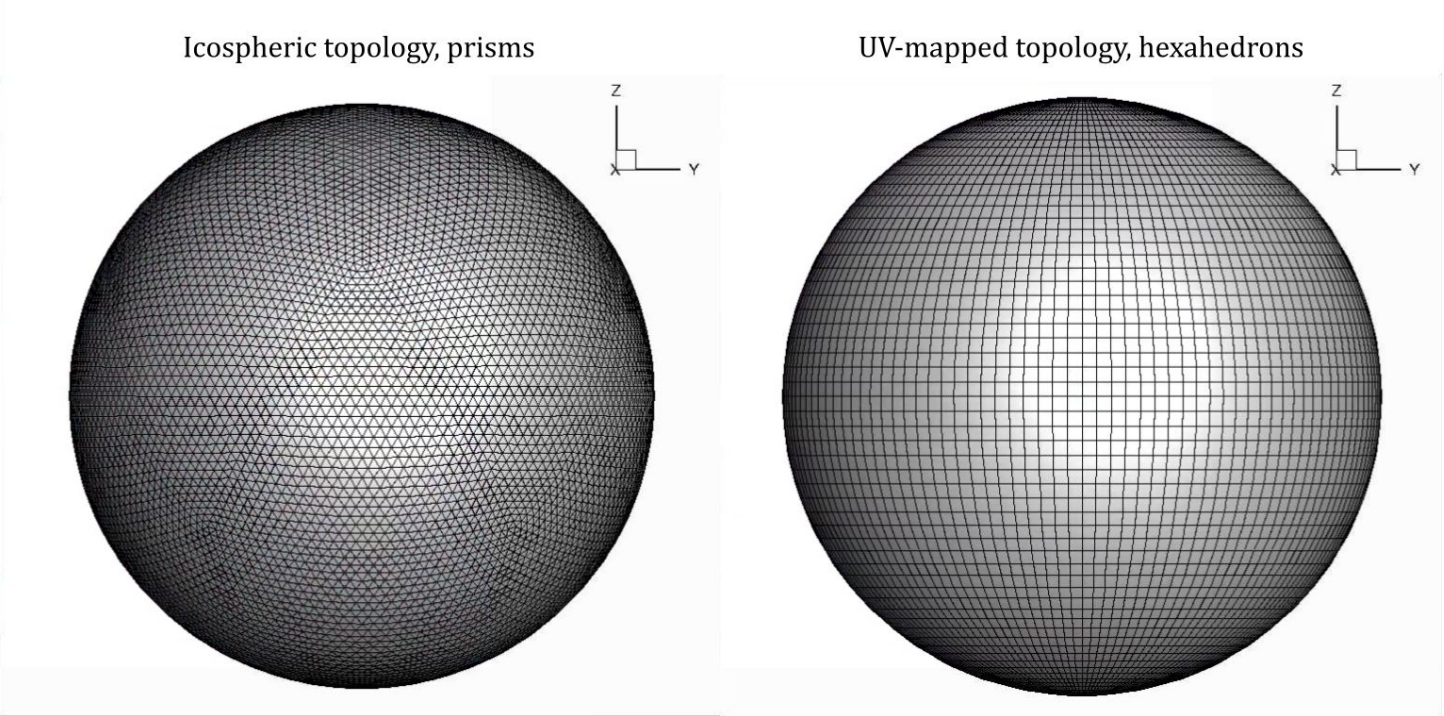
Thank you for your attention!

michaela.brchnelova@kuleuven.be

KU LEUVEN euhforia esa

Backup slides

COCONUT grid - surface & radial (Brchnelova et al. 2022)



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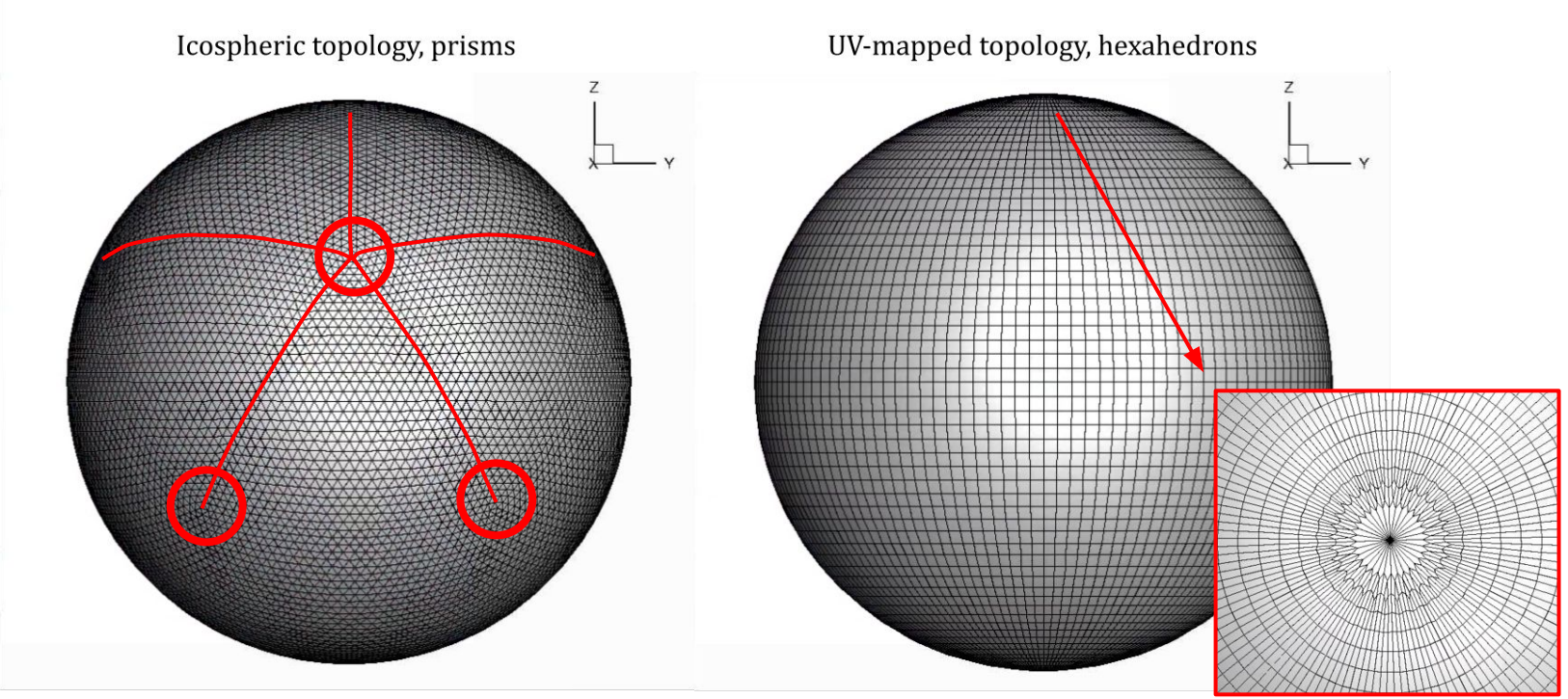
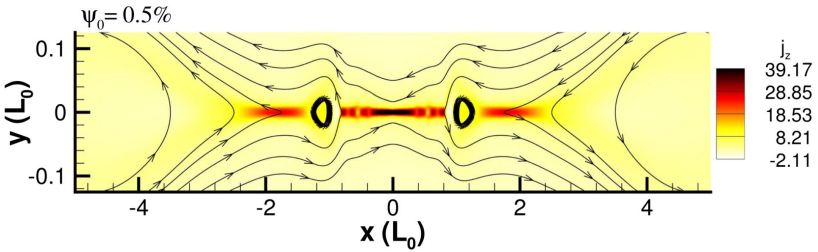
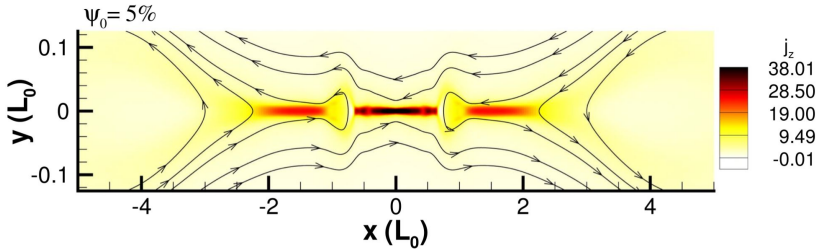
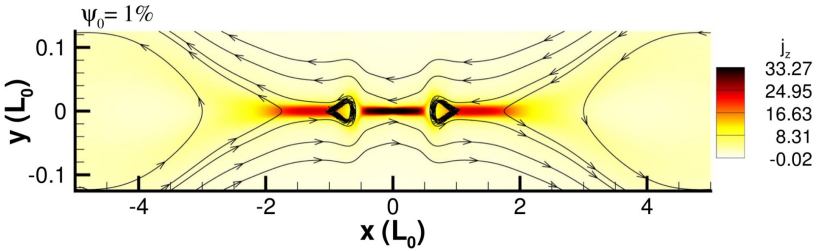


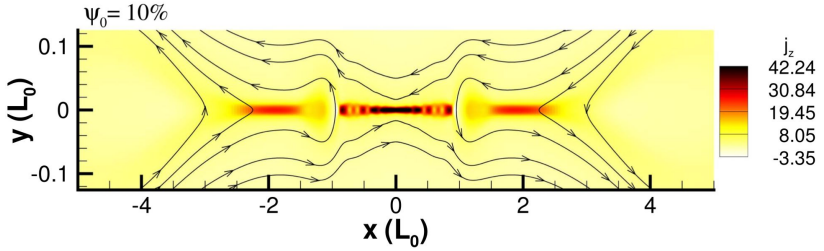
Multifluid magnetic reconnection (Laguna et al. 2012)

- psi0 is the initial ionization fraction, shown for model 1



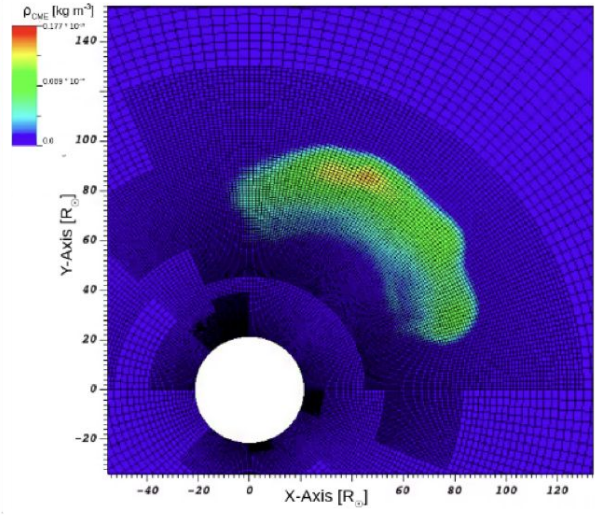




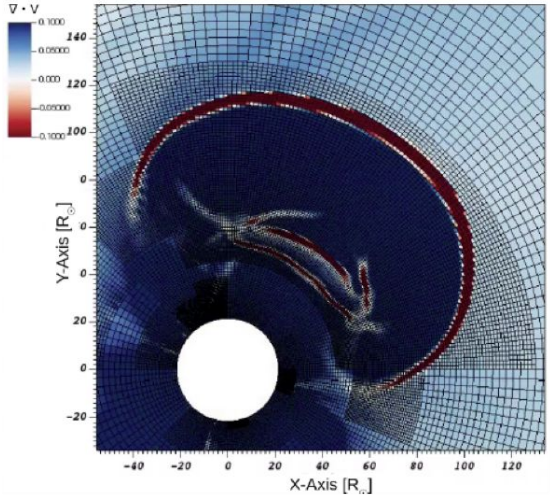


Combining AMR criteria (Verbeke et al. 2022)

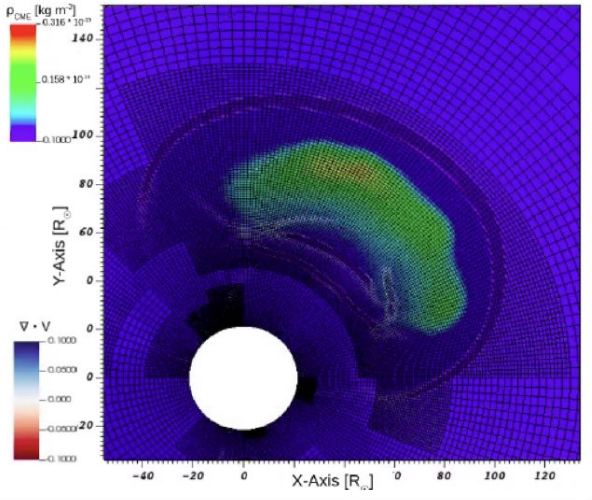
- the criteria can be combined:



tracing rho



div(V)



tracing rho + div(V)

The Virtual Space Weather Modelling Centre (VSWMC)

- Dst & kappa indices:
  - semi-empirical models (based on O'Brien & McPherron, 2000, Newell et al., 2008)
- Heliospheric models:
  - *AMRVAC Solar Wind* & CME (2.5D) (Hosteaux et al., 2018, 2019; Xia et al., 2018)
  - *EUHFORIA* (Pomoell & Poedts, 2018; Scolini et al., 2018)
- Magnetospheric models:
  - *GUMICS-4* (Janhunen et al., 2012; Lakka et al., 2019)
  - *COOLFluiD unsteady* (Lani et al., 2013; Yalim & Poedts, 2014)
- Thermosphere & Ionosphere:
  - *CTIP* (Fuller-Rowell & Rees, 1980; Millward et al., 1996).