Heliospheric and solar coronal modelling

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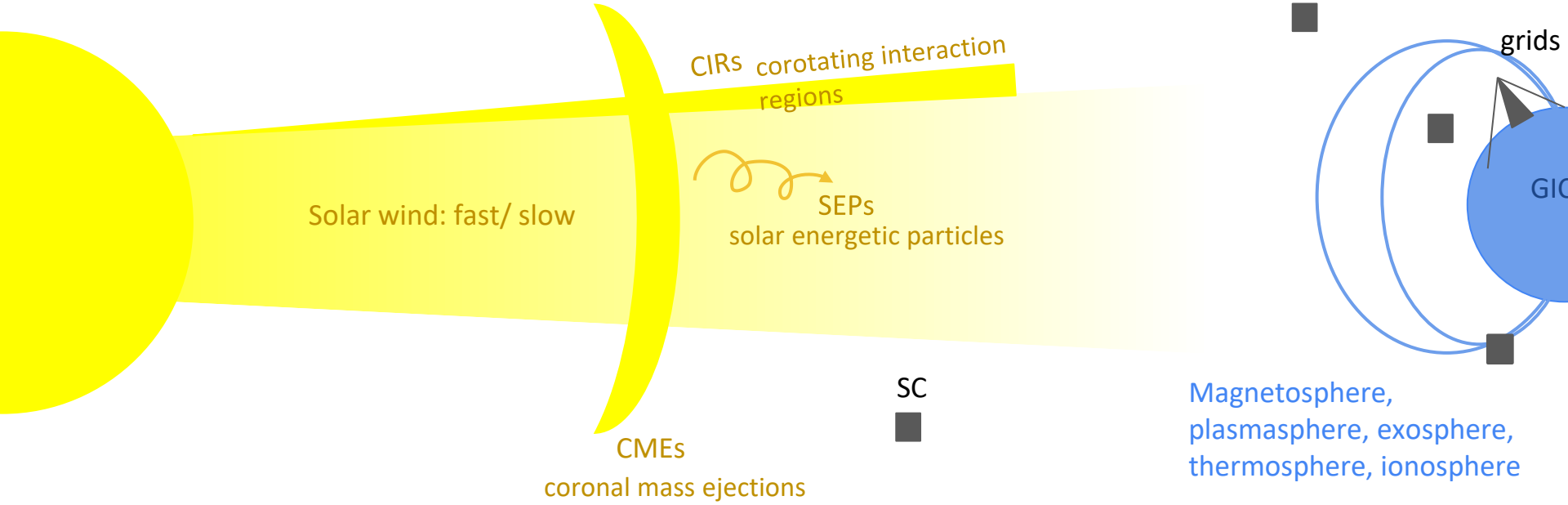
PITHIA-NRF, KU Leuven, 5 to 9 February 2024

Space weather modelling toolchains (e.g., VSWMC)

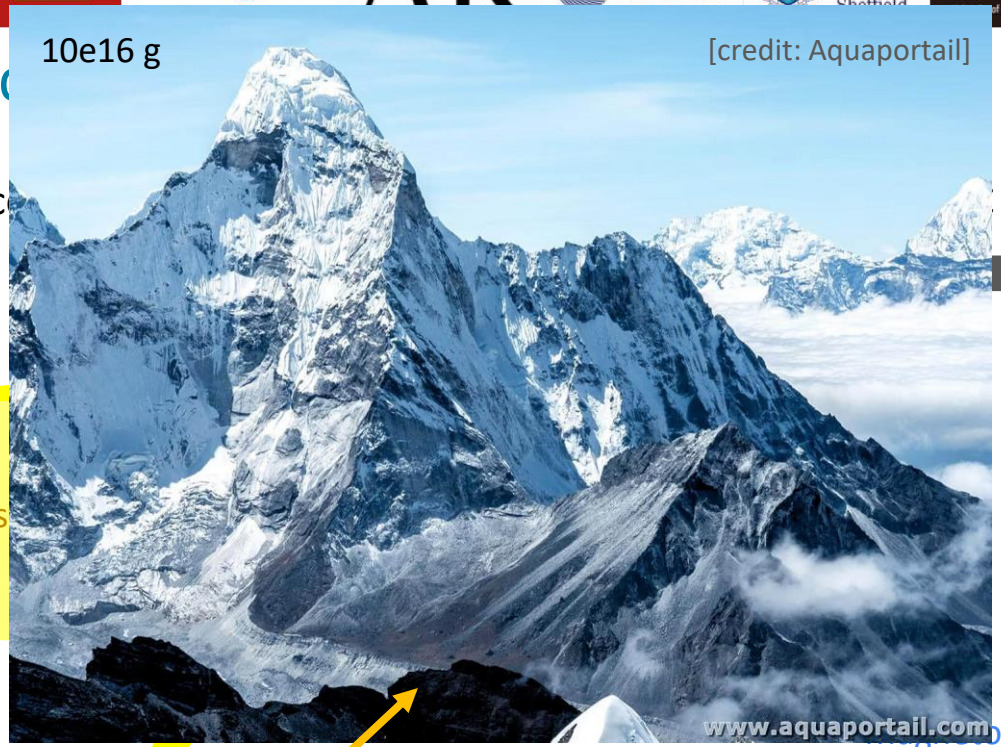
Solar surface → corona → heliosphere → magnetosphere → TI(M)E → GIC



Space weather mod

Solar surface → c

Solar wind: fas



CMEs
coronal mass ejections

grids

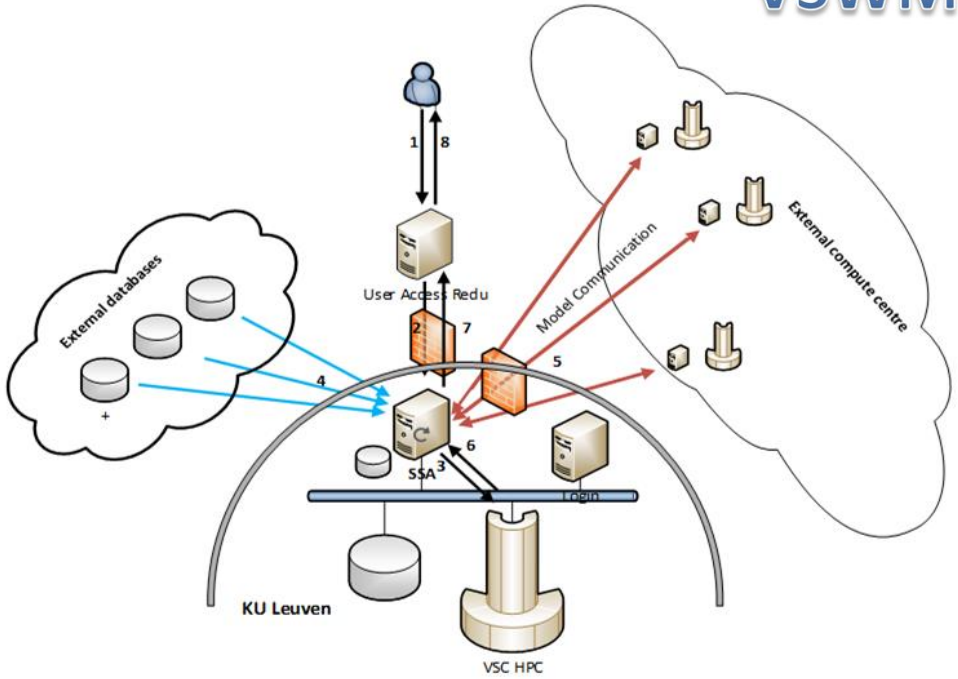
GIC

magnetosphere,
plasmasphere, exosphere,
thermosphere, ionosphere

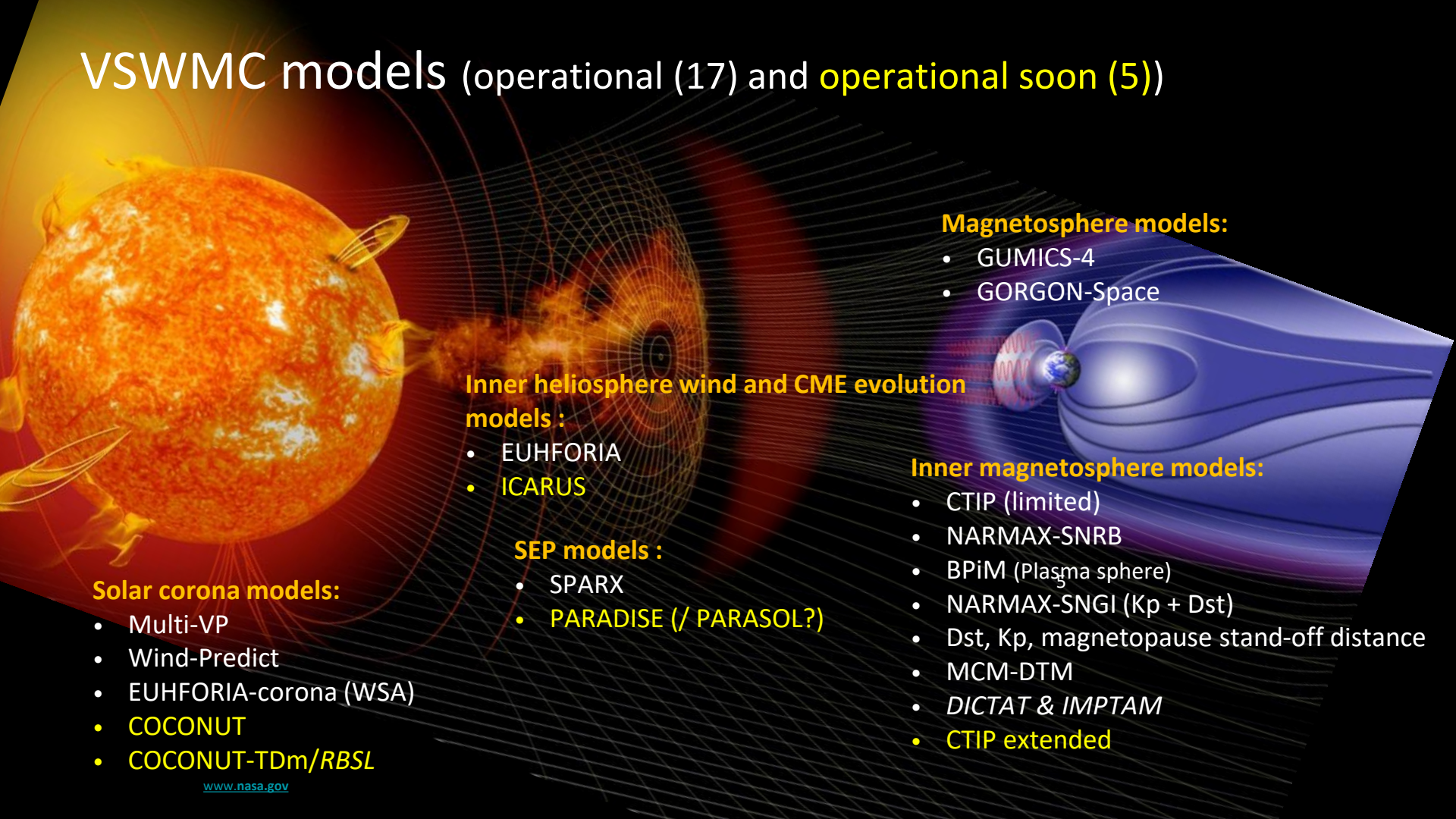
Virtual SWE Modelling Centre

VSWMC

- 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



VSWMC models (operational (17) and operational soon (5))



Solar corona models:
- Multi-VP
- Wind-Predict
- EUHFORIA-corona (WSA)
- COCONUT
- COCONUT-TDm/*RBSL*

Inner heliosphere wind and CME evolution models :
- EUHFORIA
- ICARUS

SEP models :
- SPARX
- PARADISE (/ PARASOL?)

Magnetosphere models:
- GUMICS-4
- GORGON-Space

Inner magnetosphere models:
- CTIP (limited)
- NARMAX-SNRB
- BPiM (Plasma sphere)
- NARMAX-SNGI (Kp + Dst)
- Dst, Kp, magnetopause stand-off distance
- MCM-DTM
- *DICTAT & IMPTAM*
- CTIP extended

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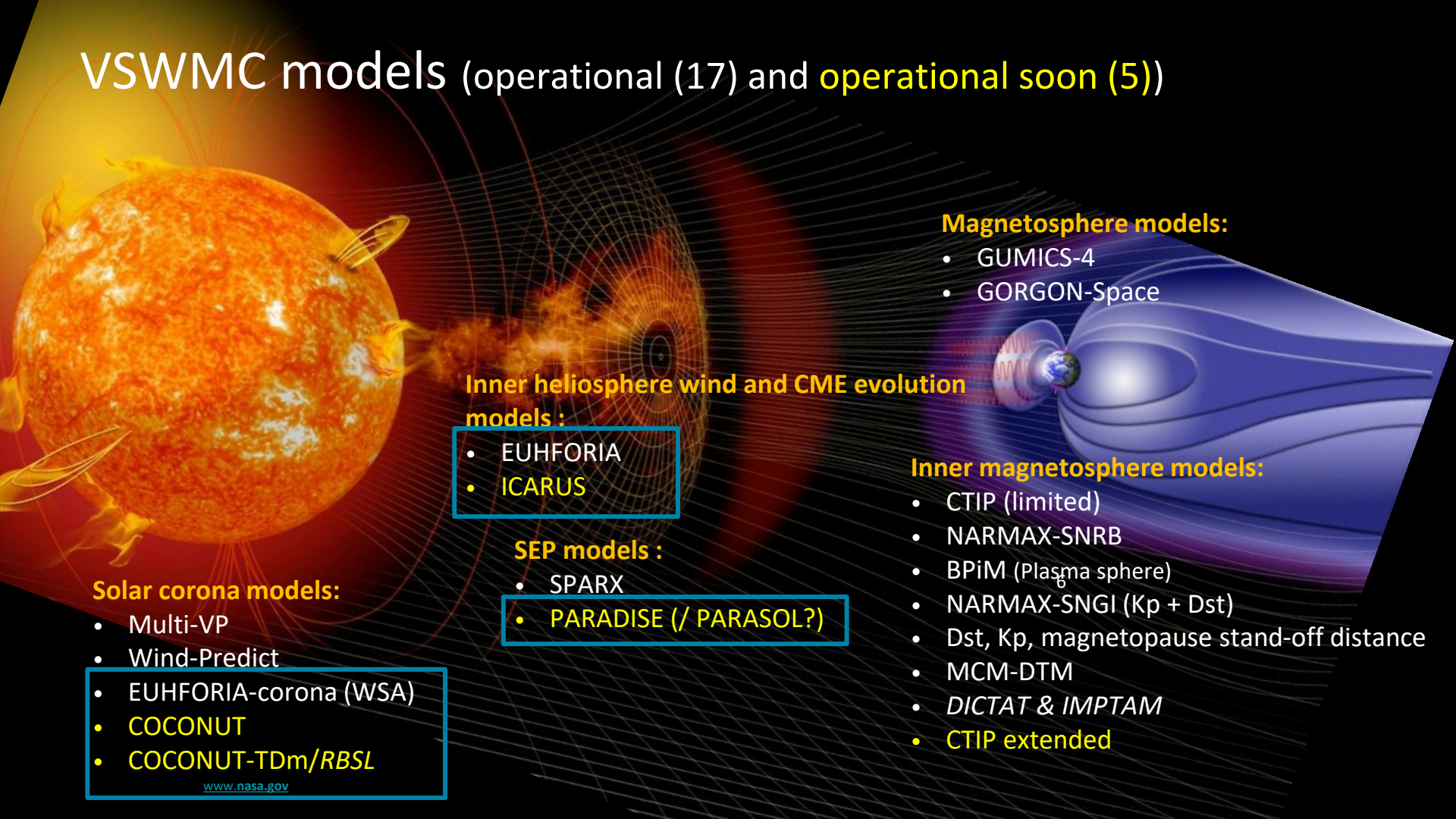

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EUHFORIA in the e-Science Centre

PITHIA-NRF
e-Science Centre

HOME SEARCH & BROWSE Login

Home / Browse Metadata / Data Collection-related Metadata / Data Collections / EUHFORIA: EUropean Heliospheric FORecasting Information Asset

EUHFORIA: EUropean Heliospheric FORecasting Information Asset

EUHFORIA (EUropean Heliospheric FORecasting Information Asset) consists of two main parts: a semi-empirical coronal model, the purpose of which is to determine the plasma environment of the solar wind at the location of the inner boundary of the heliospheric module, and the heliospheric model, which provides the dynamics of the background solar wind with superposed CMEs into the inner heliosphere by numerical evolution of the MHD equations. EUHFORIA runs at the Virtual Space Weather Modeling Center (VSWMC) on the ESA Space Weather Network (ESA-SWE) website (https://swe.ssa.esa.int). VSWMC is an interactive modeling system developed for space weather research from the Sun to the Earth. It allows users to run different tools stand-alone or in combination with models that are locally or geographically dispersed.

Identifier Properties

Local ID	DataCollection_EUHFORIA
Namespace	kul
Version	2
Created	Tuesday 28th Feb. 2023, 01:30:00
Last Modified	Monday 24th April 2023, 18:56:00

Interact

Interaction Method	Description	Data Format	Link
Direct Link to Data Collection	The ESA-SWE website requires an account to run. Once received, go to the VSWMC webpage and select: "NEW RUN". From the list of model chains that appear, you can choose those that contain EUHFORIA, or separately the coronal and heliospheric EUHFORIA models. Also, the	image/png (click the link to show information on this ontology term)	Open Latest VSWMC ESA-SWE Landing Page in new tab

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 /

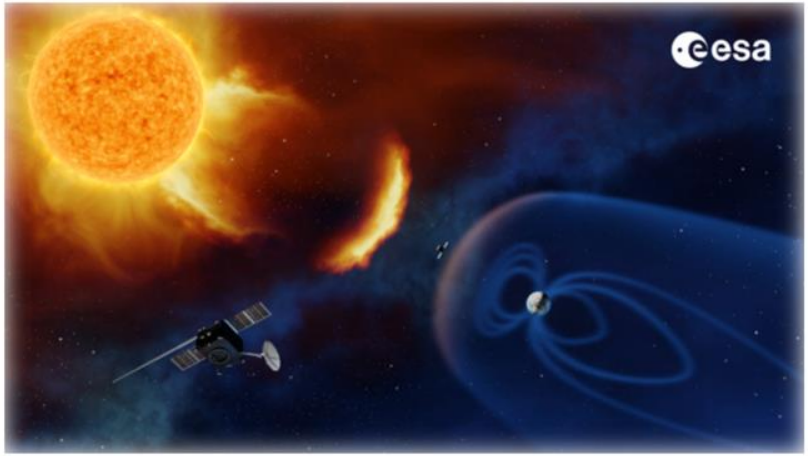
Federated products from the Centre for mathematical Plasma-Astrophysics (KUL)

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

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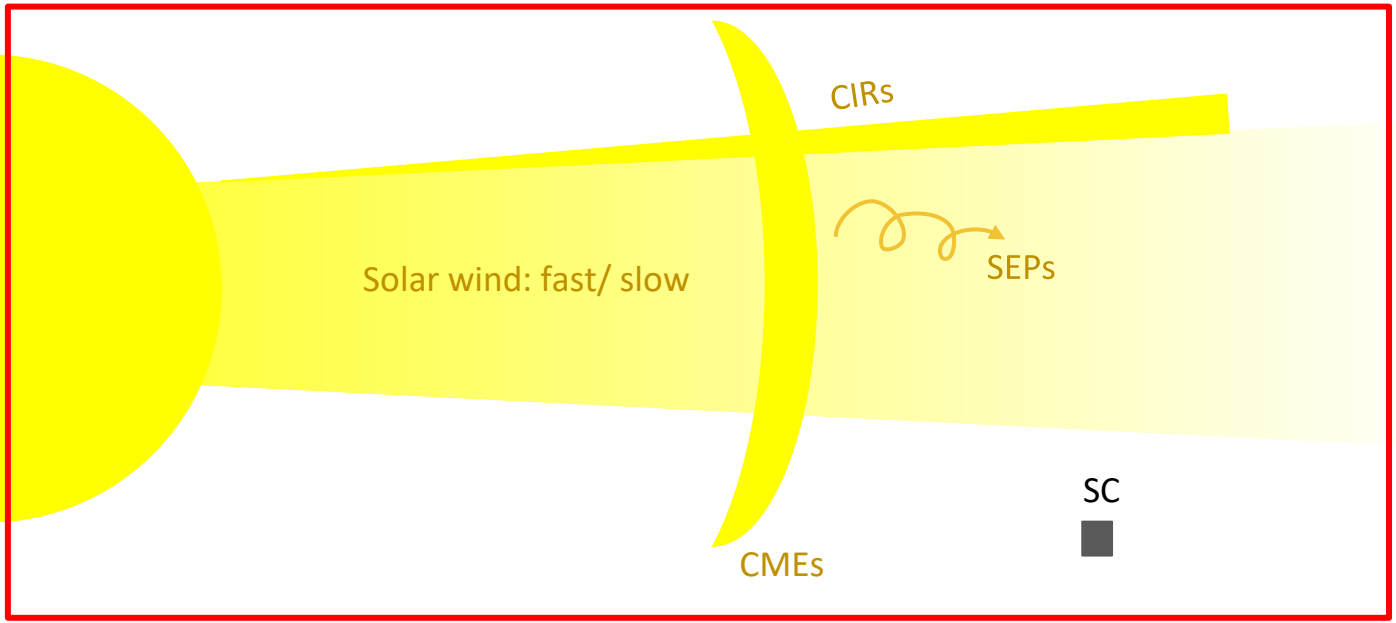
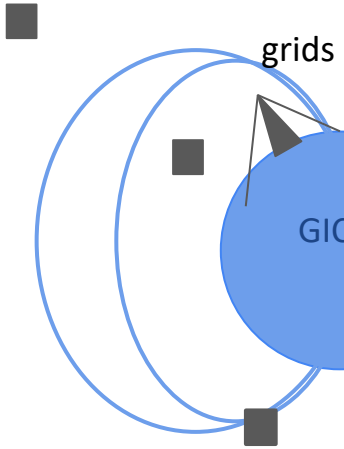
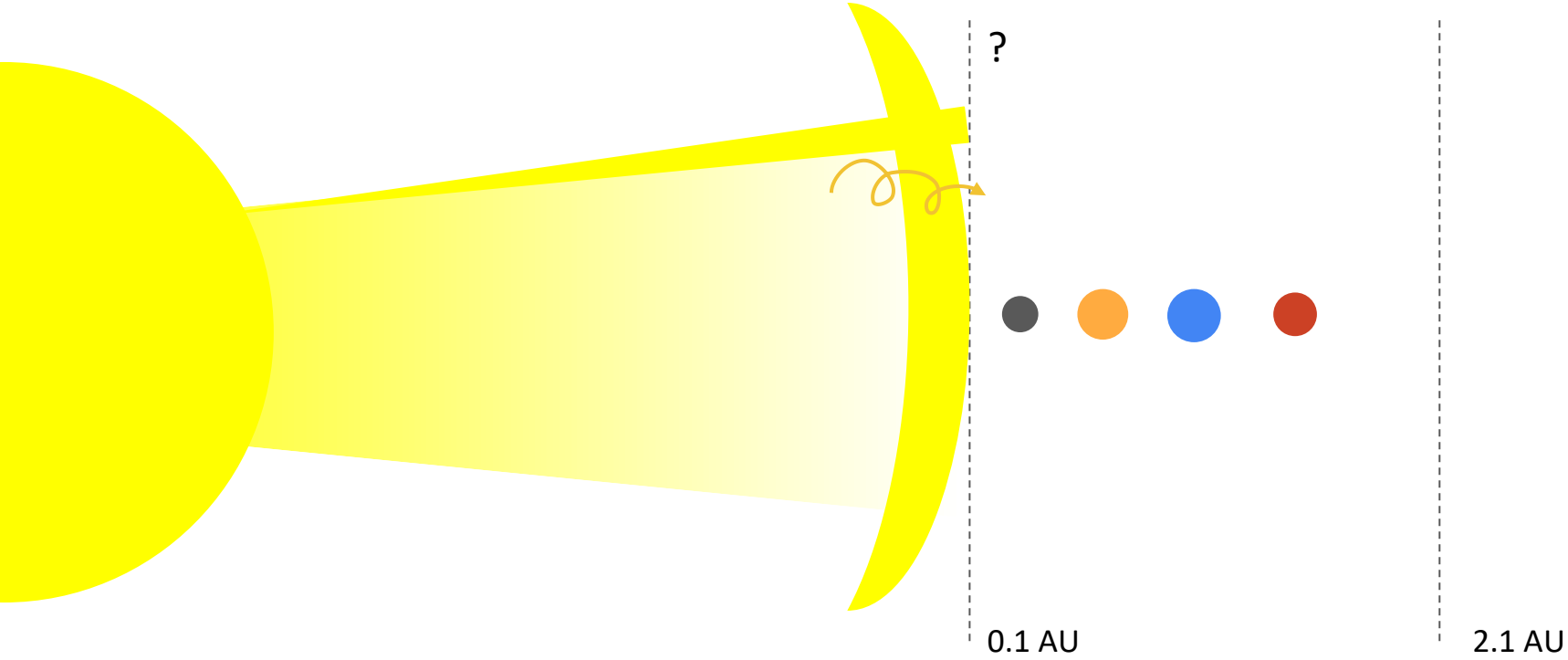




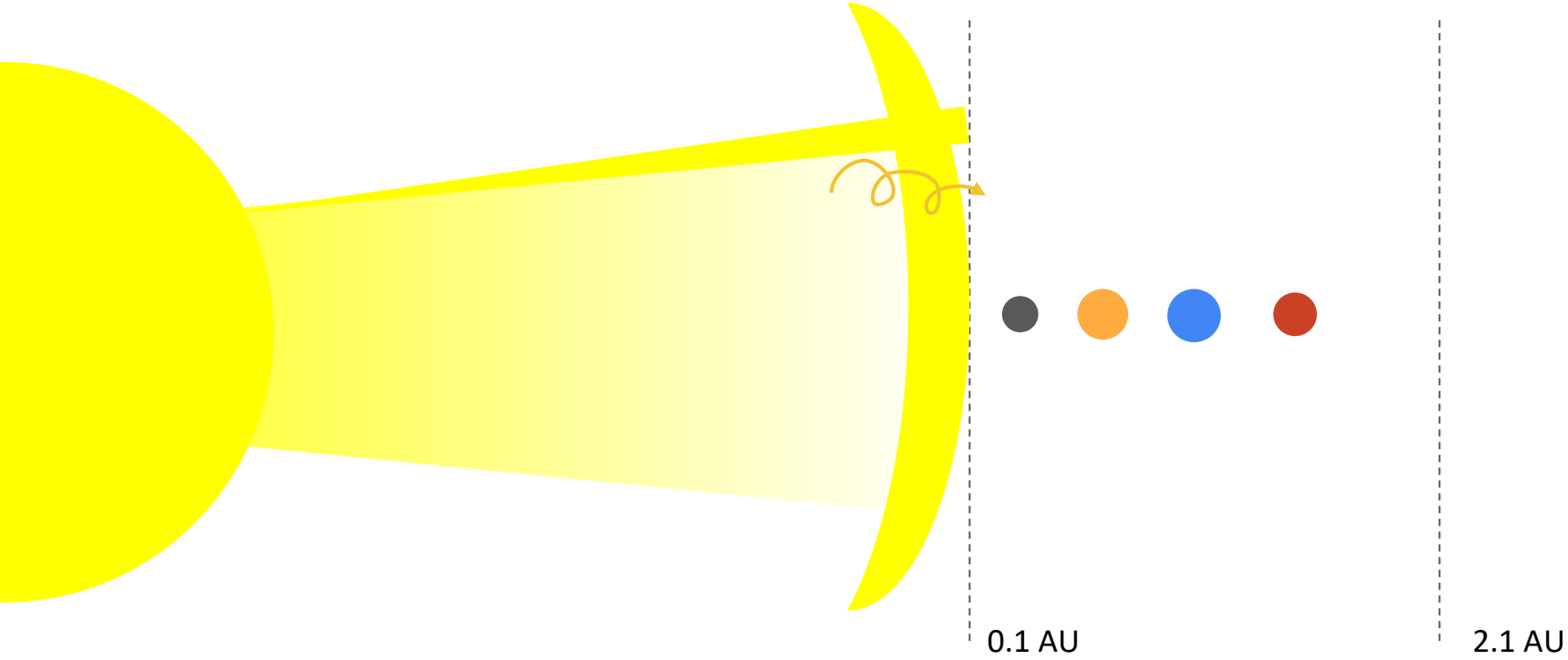
Magnetosphere, plasmasphere, exosphere, thermosphere, ionosphere

Domain division



Domain division

Parker solar wind (SW):
- supersonic from 2-3 R_S
- super-Alfvénic from 14 - 17 R_S



“Coronal” model

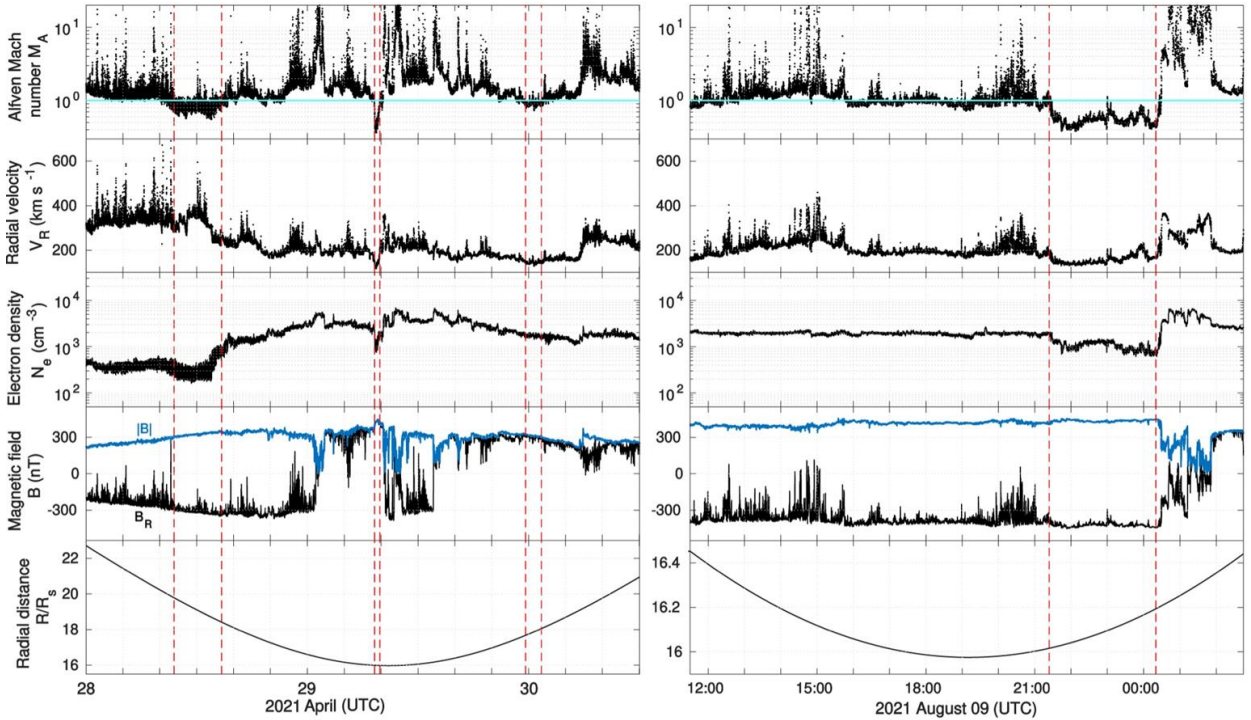
“Heliospheric” model

Domain division

[Bandyopadhyay et al., 2022]

- is the SW always supersonic & super-Alfvénic at 21.5 R_S or 0.1 AU? Perhaps not.

- in such conditions, the models might be physically unsuitable



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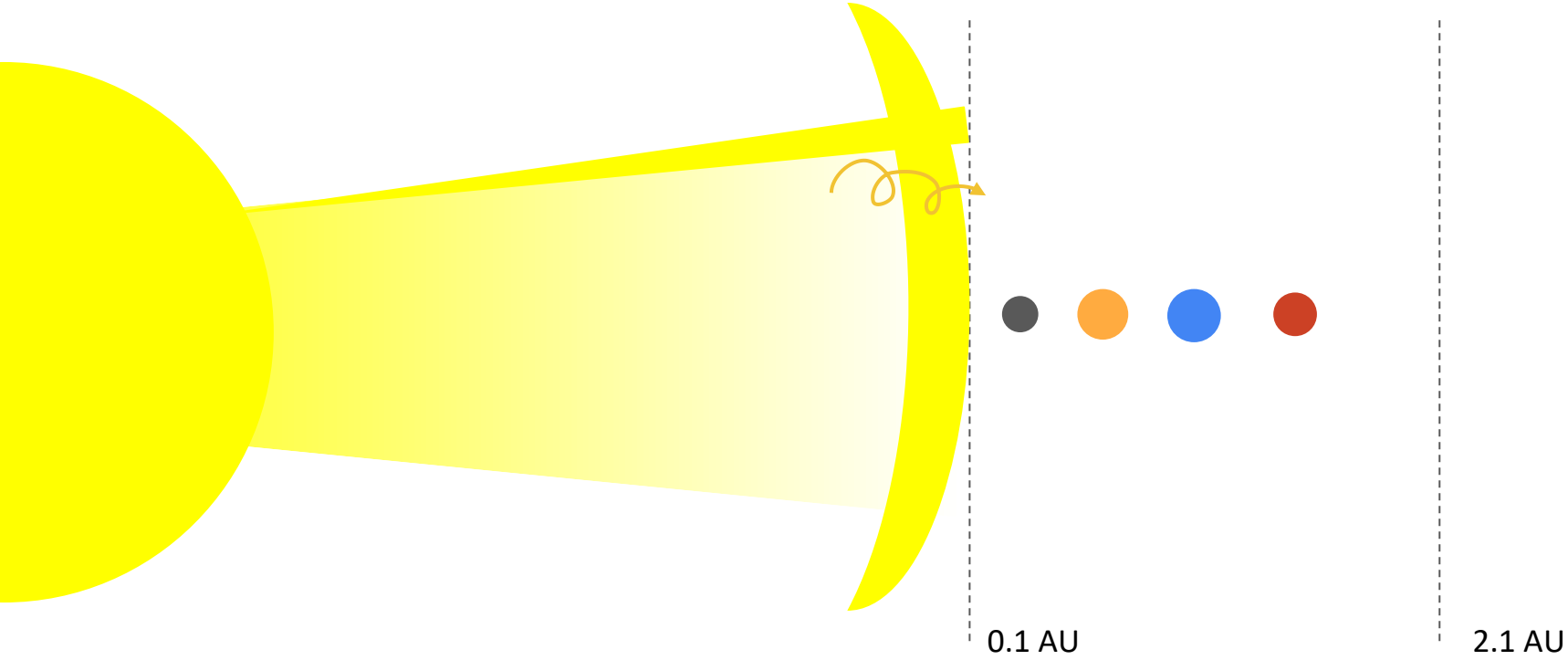
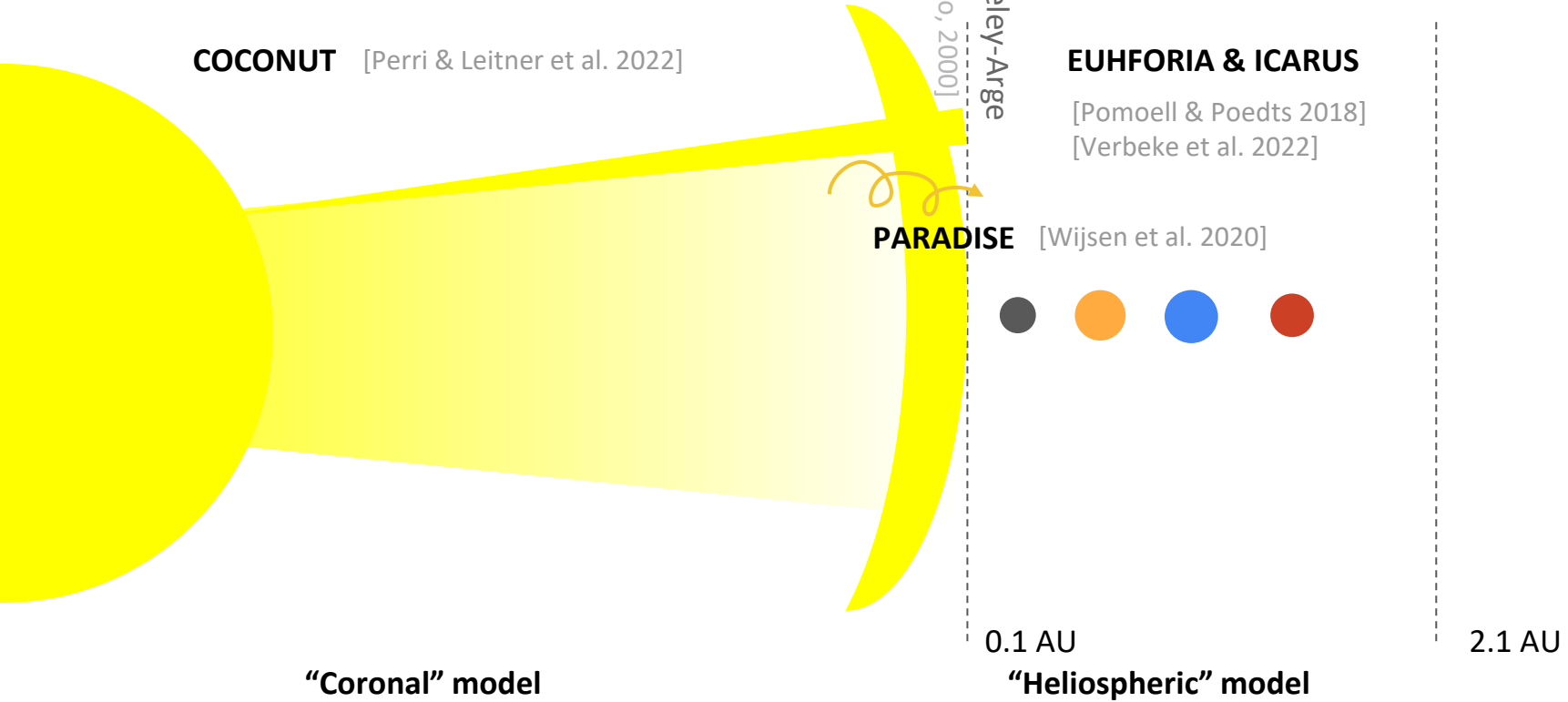


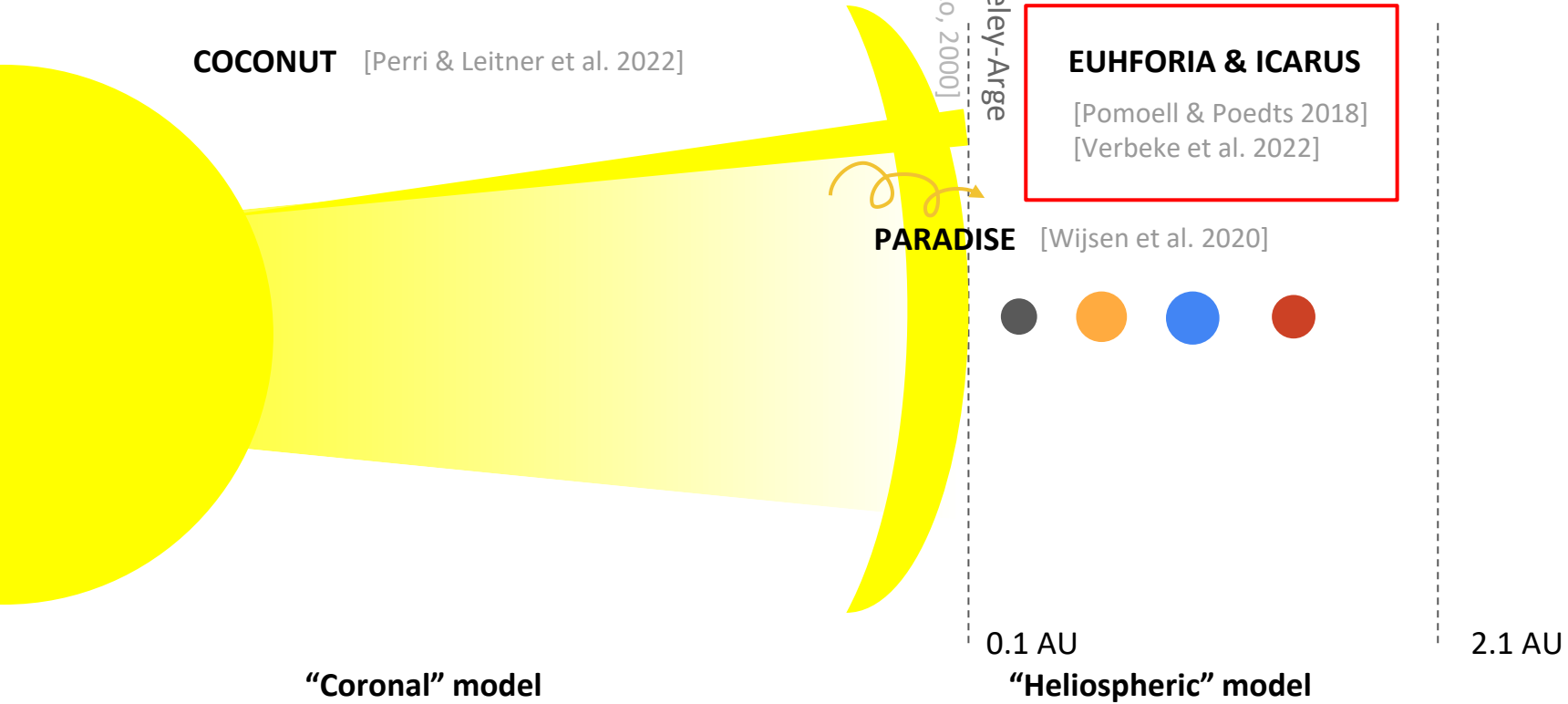
“Coronal” model

“Heliospheric” model

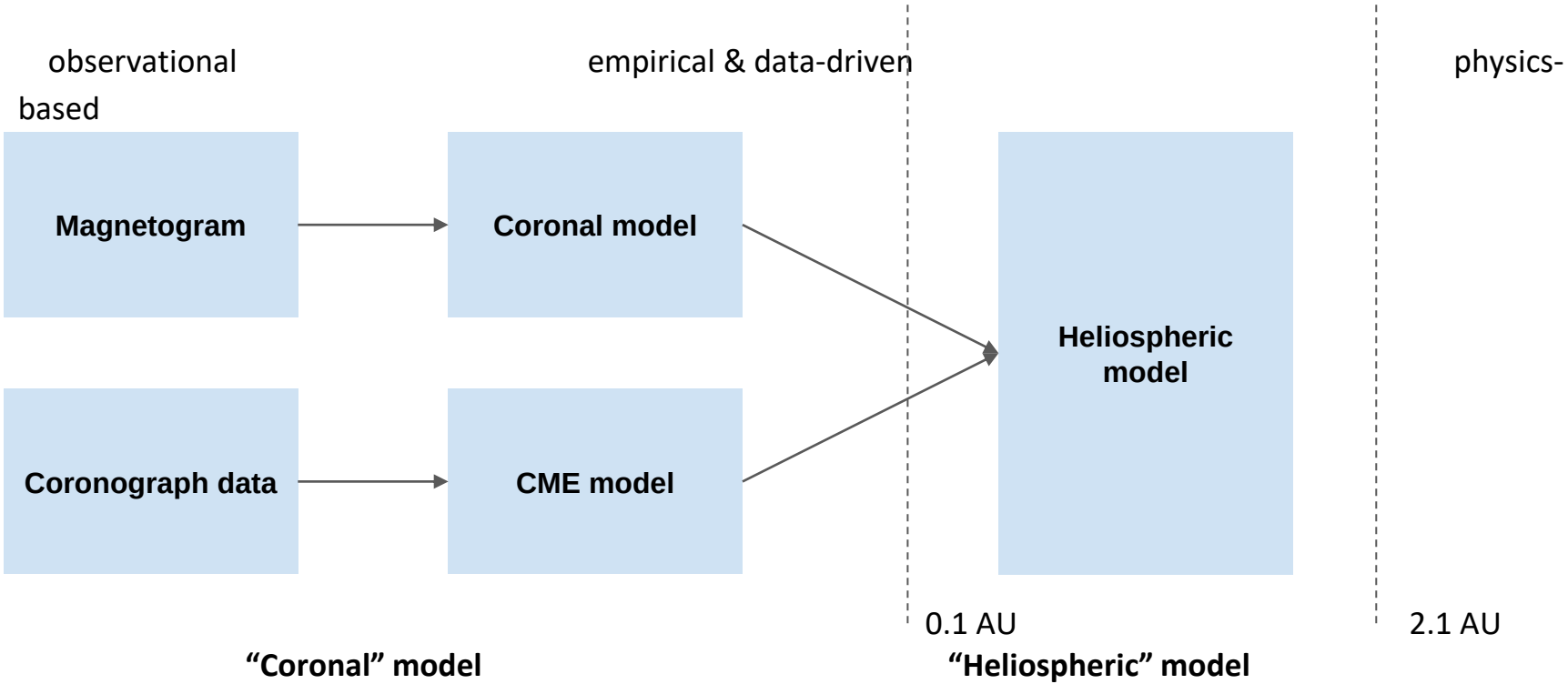
KU Leuven tools



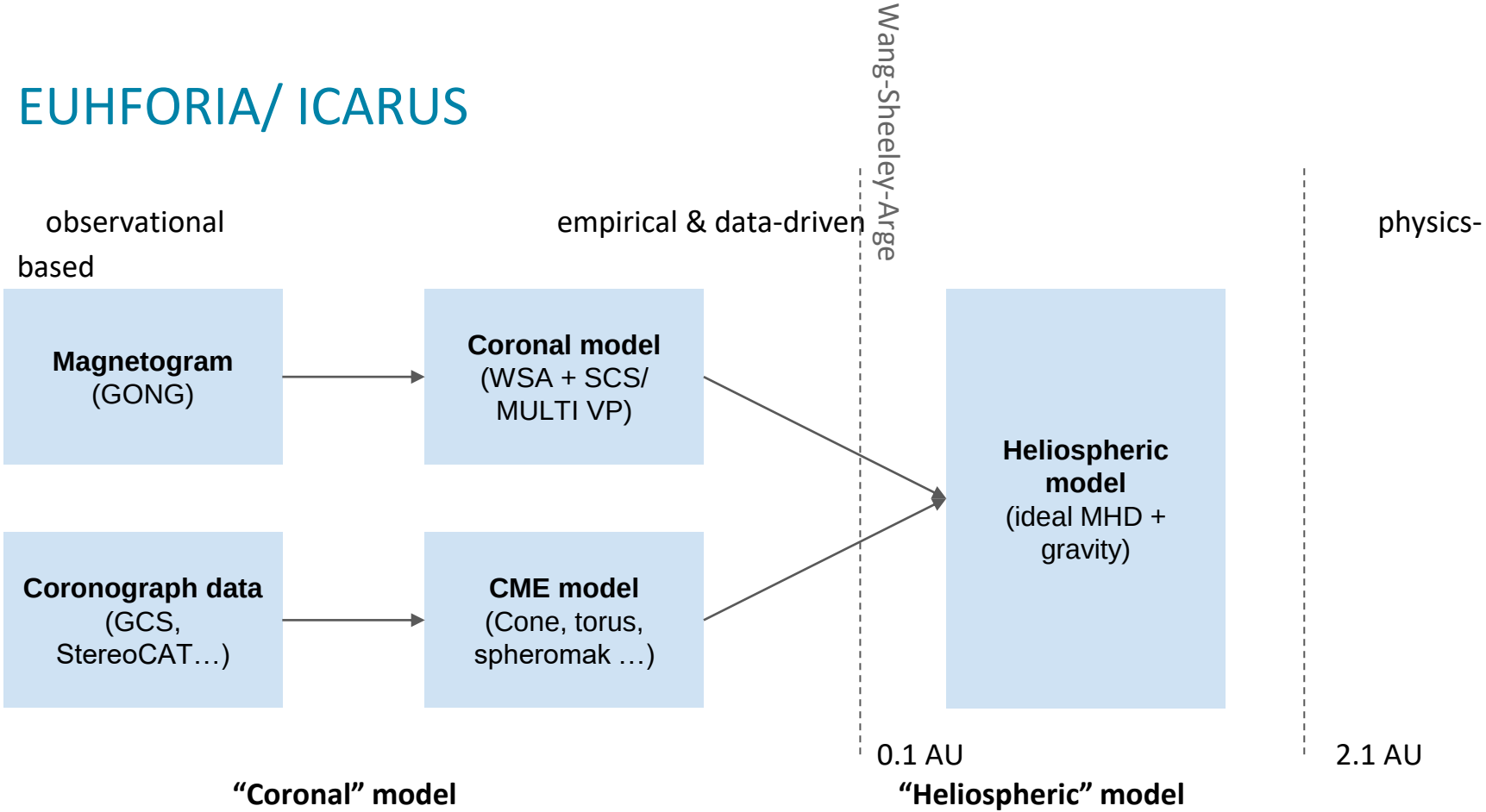
KU Leuven tools



System level



EUHFORIA/ ICARUS



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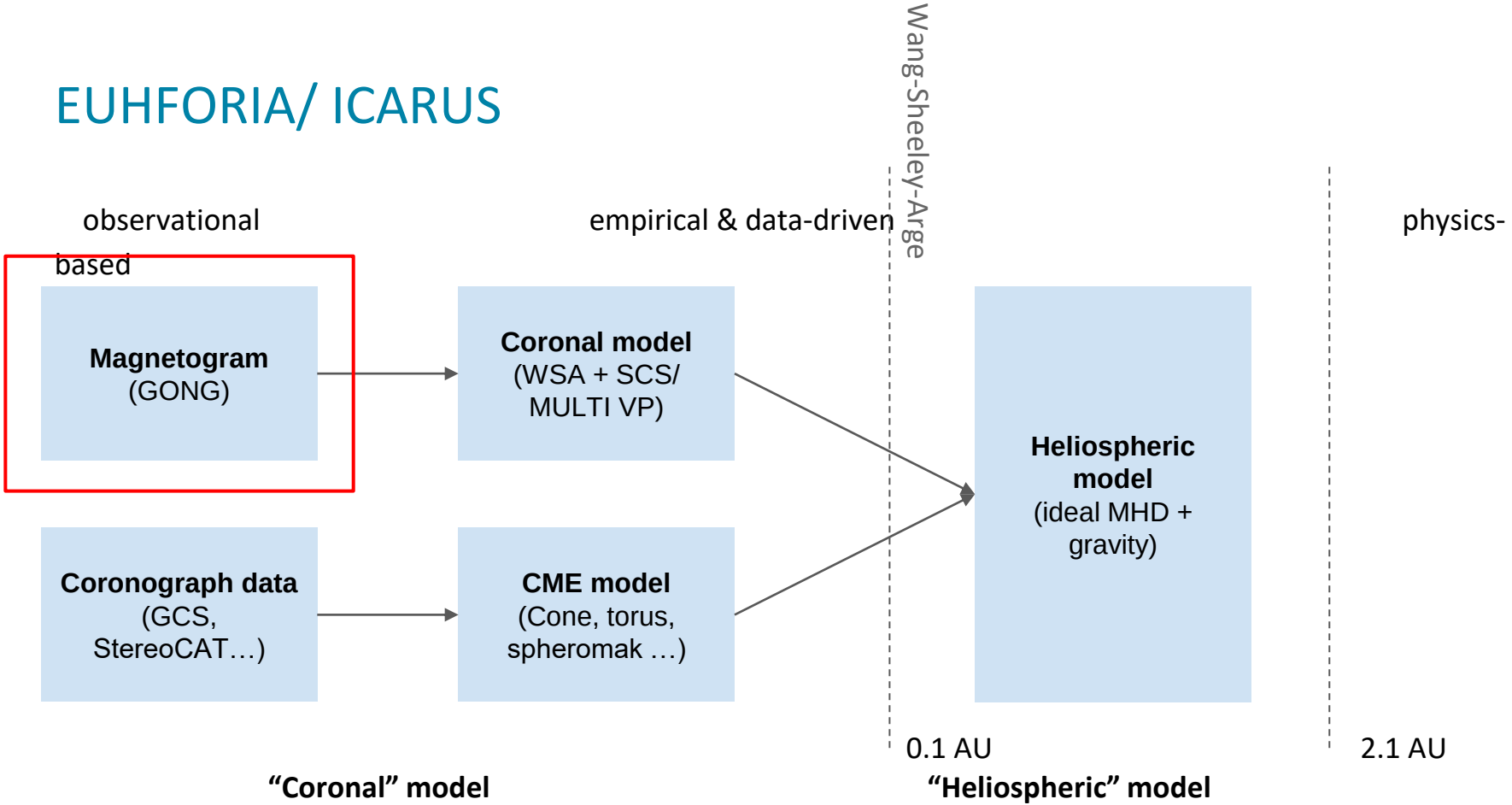
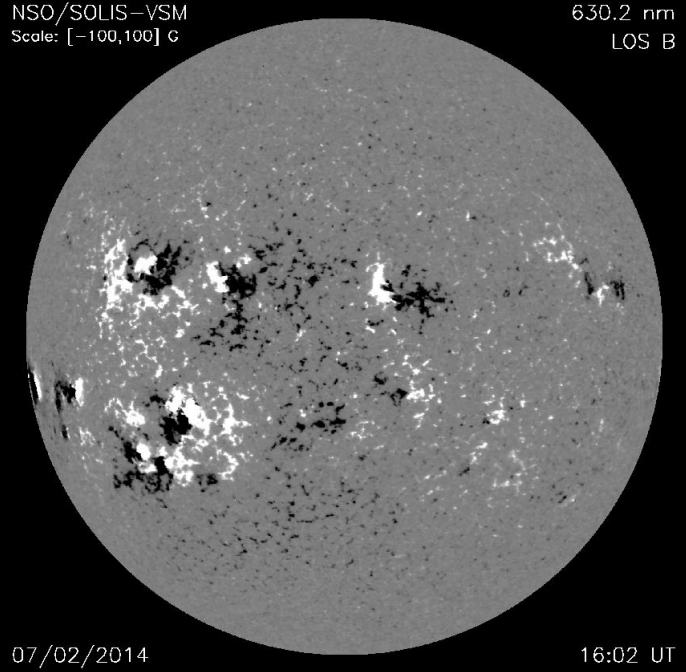
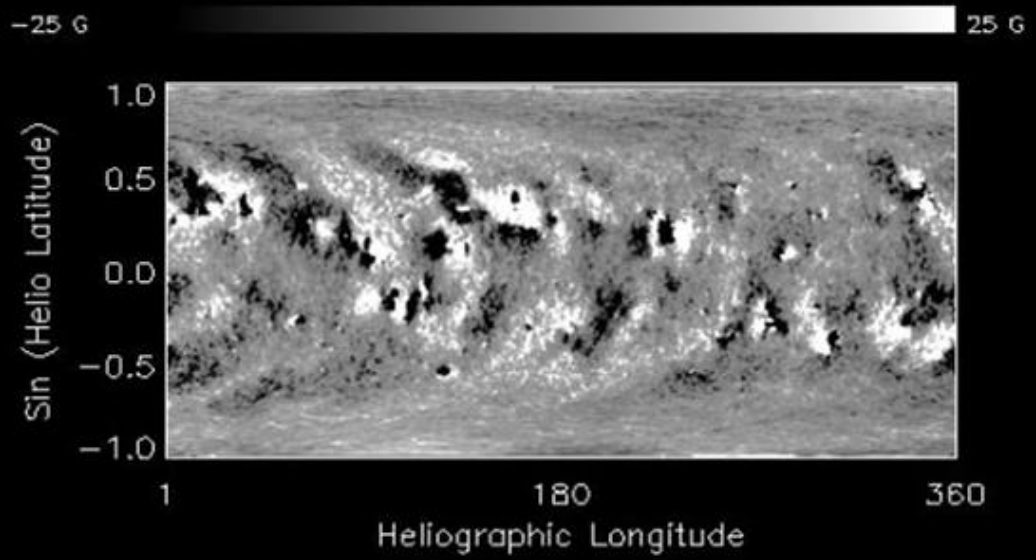


EUHFORIA/ ICARUS: GONG magnetograms



[Jin et al. 2016]



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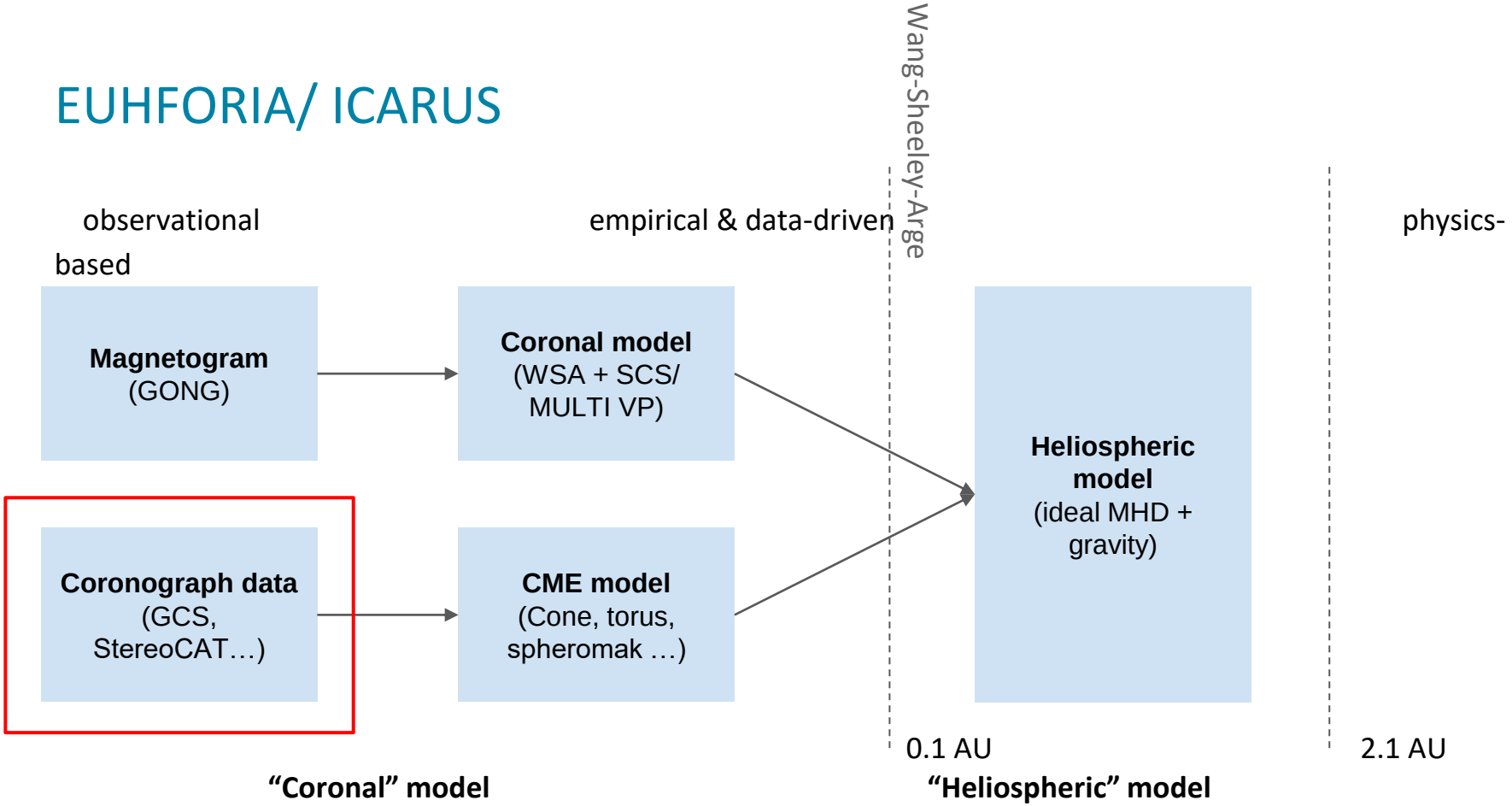
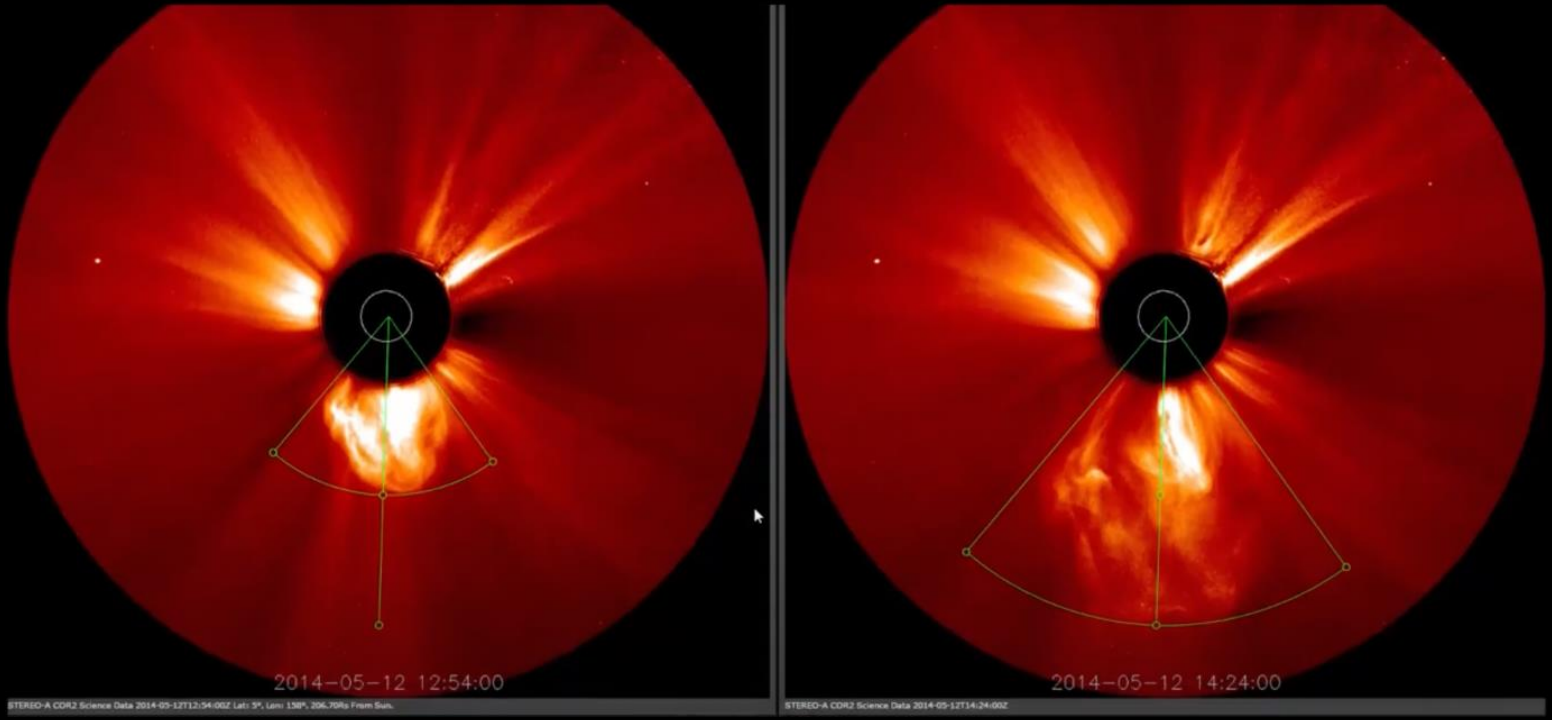


EUHFORIA/ ICARUS: StereoCAT / GCS

[NASA, STEREO-A-COR2]



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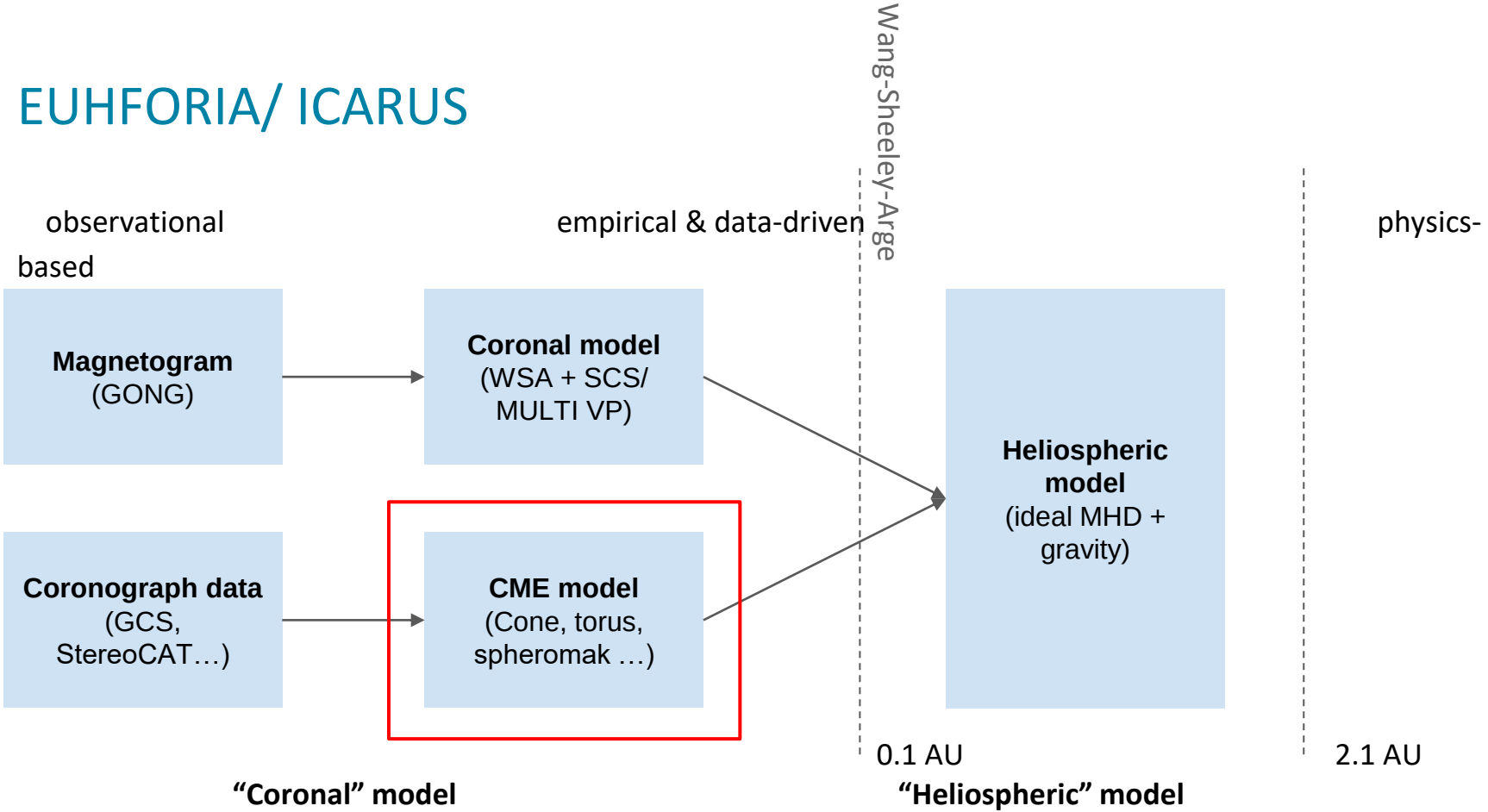
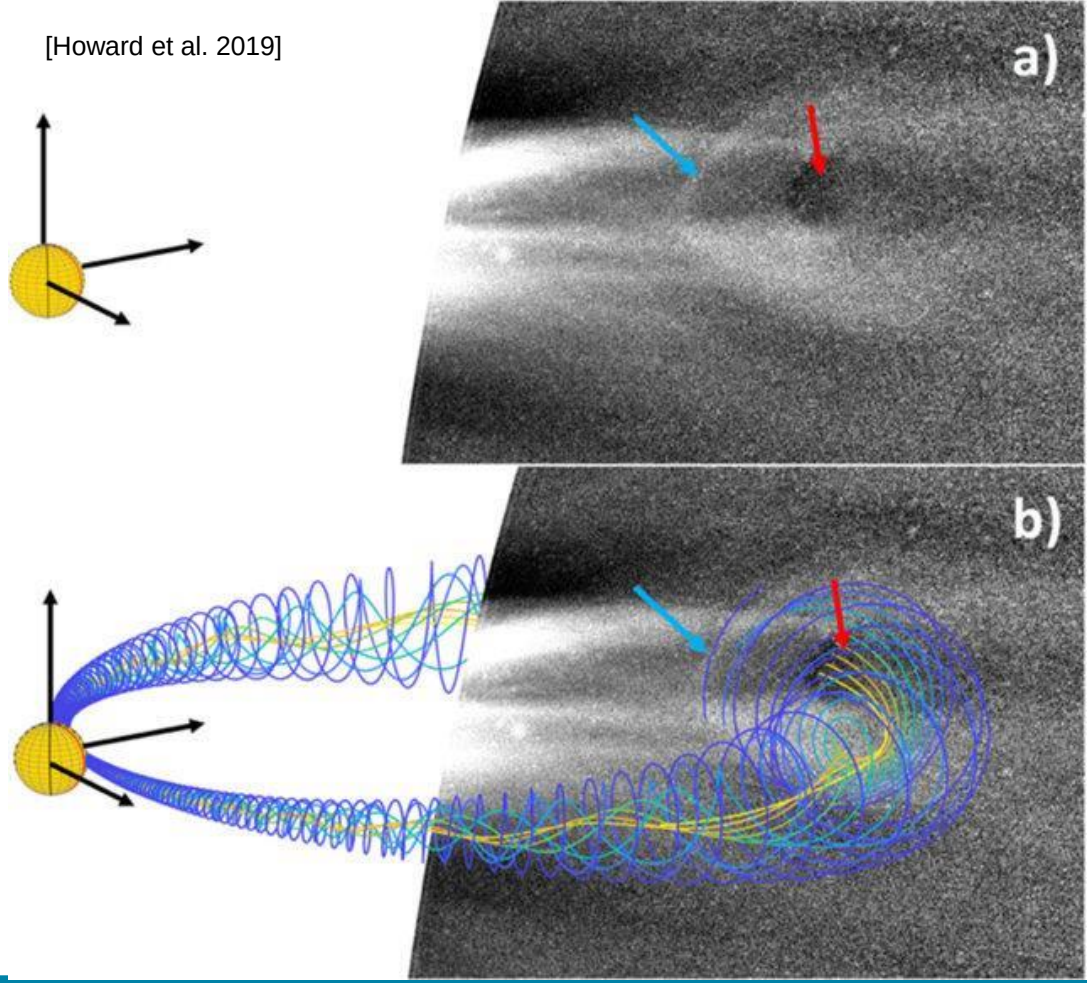


EUHFORIA/ ICARUS

- CMEs are modelled as 3D flux ropes: bundles of helical B-field lines that wind about a common axis
- The precise geometry and magnetic field profile depends on the assumed model:
  - cone
  - torus
  - spheromak
  - Fri3D

[Howard et al. 2019]



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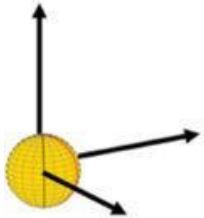
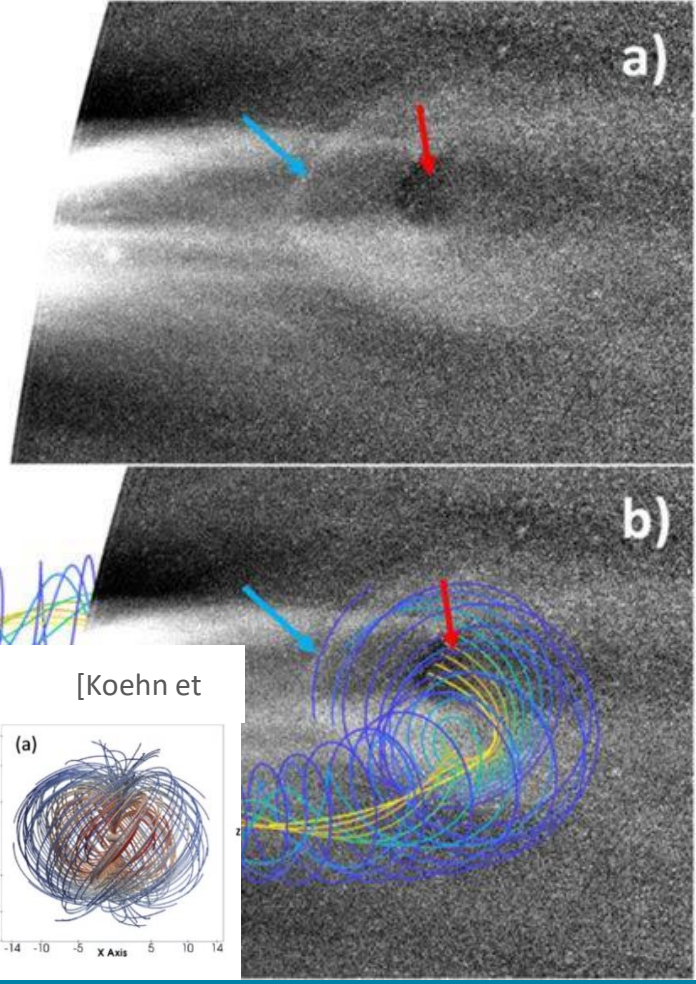
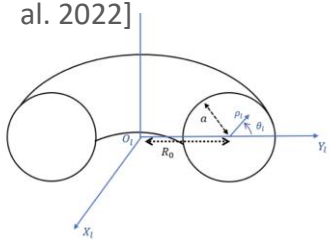
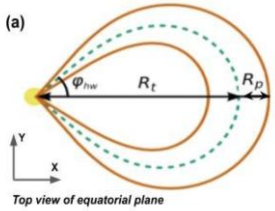




[Linan et al. 2024]
al. 2022]

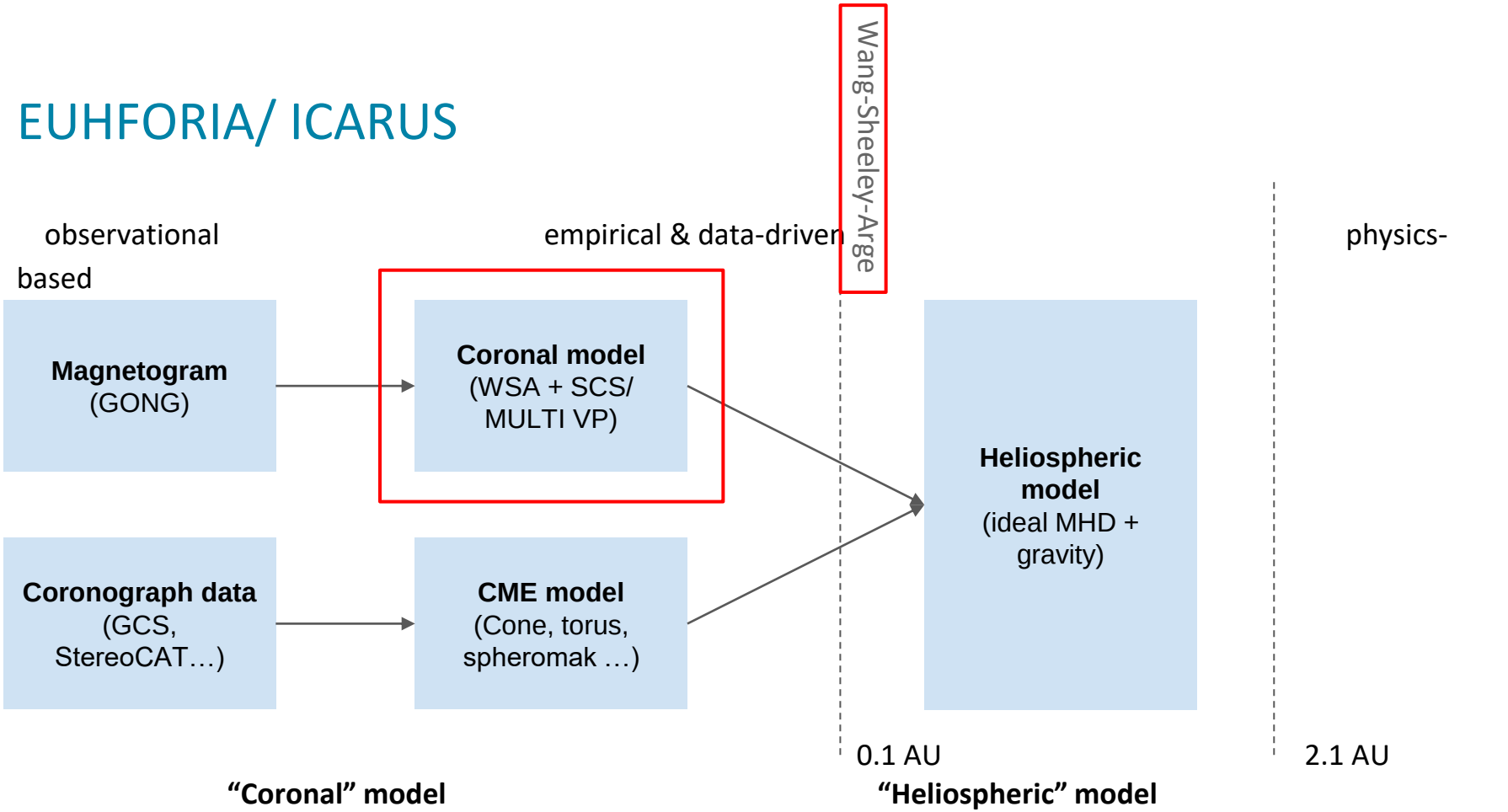


[Maharana et al. 2022]



[Koehn et

EUHFORIA/ ICARUS



The Wang-Sheeley-Arge model [Arge & Pizzo 2000, Arge et al. 2003, Arge et al. 2004]

[Samara et al. 2021]

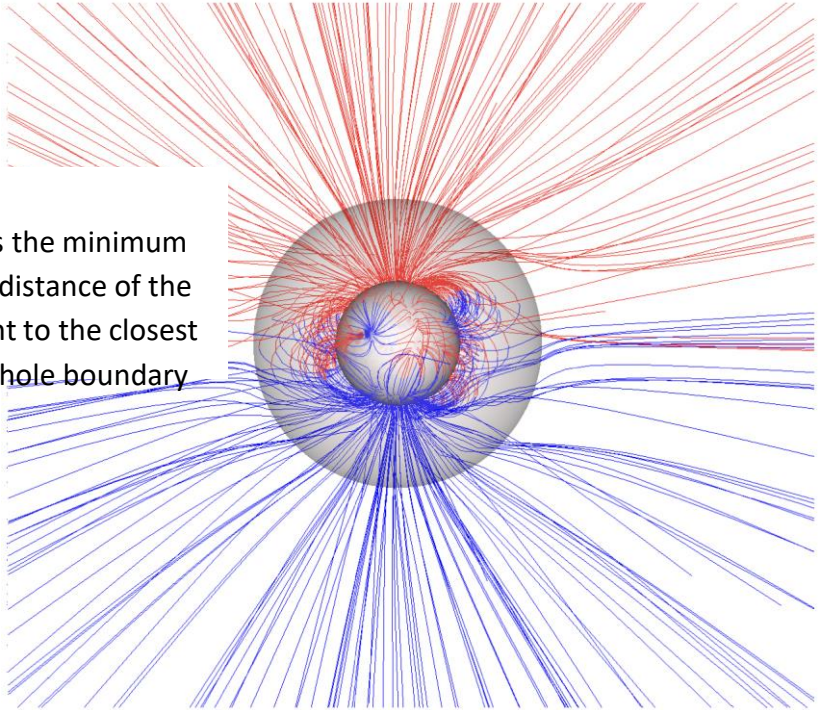
- PFSS up to 2.6 R_S, Shatten current sheet from 2.3 R_S
- field line tracing to determine the expansion factor: [Pomoell & Poedts 2018]

$$f = \left(\frac{R_\odot}{R_b}\right)^2 \frac{B_r(R_\odot, \theta, \phi)}{B_b(R_b, \theta_b, \phi_b)}$$

- then the (radial) SW speed is:

$$v_r(f, d) = 240 + \frac{675}{(1+f)^{0.222}} \left[1 - 0.8 \exp\left(-\left(\frac{d}{0.02}\right)^{1.25}\right)\right]^3$$

here d is the minimum angular distance of the footpoint to the closest coronal hole boundary



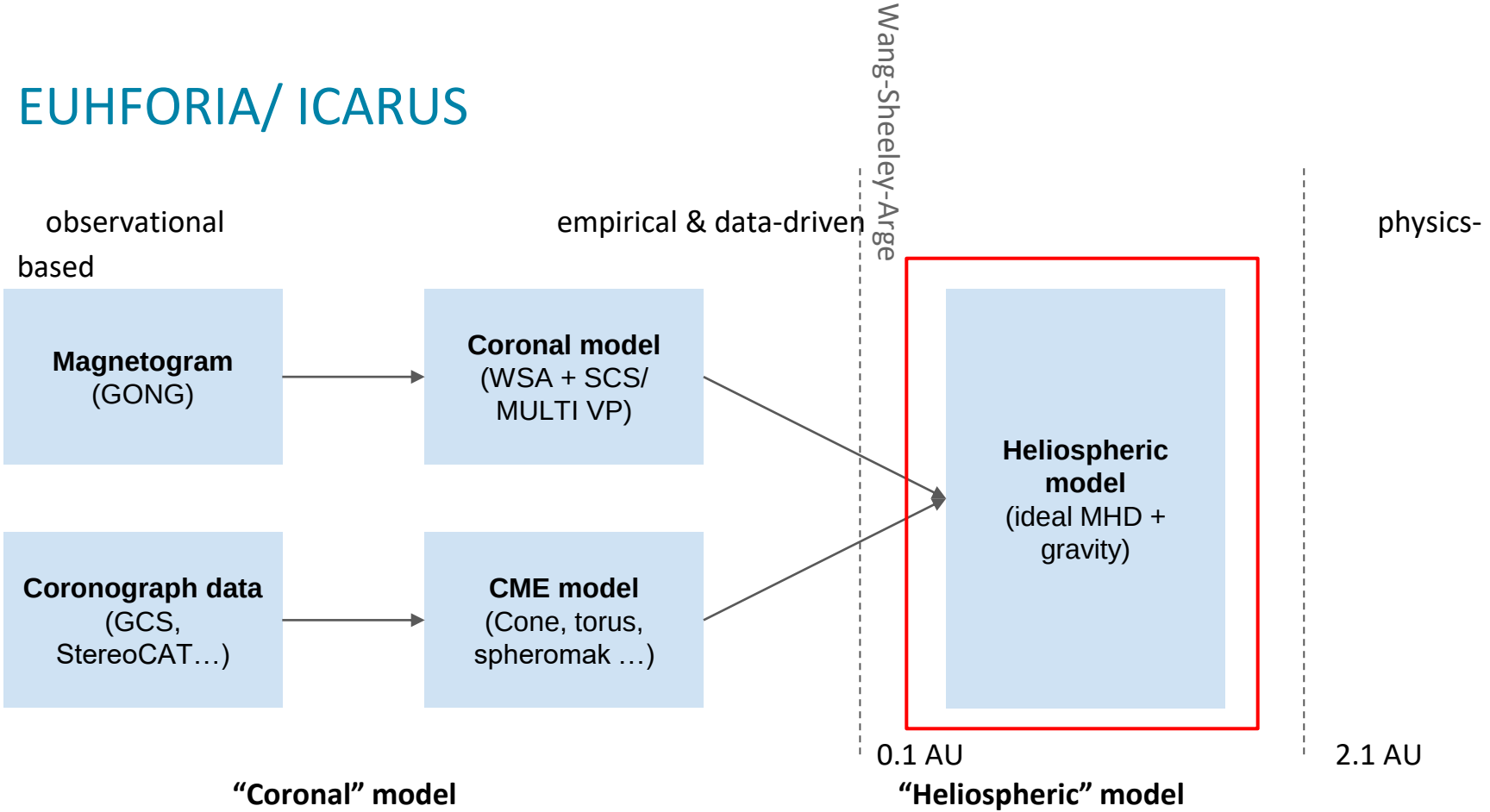
- from which we determine ($B_\theta = 0$):

$$B_r = \mathrm{sgn}(B_{corona}) B_{fsw}(v_r/v_{fsw}) \quad T = T_{fsw}(\rho_{fsw}/\rho) \quad n = n_{fsw}(v_{fsw}/v_r)^2$$

- with:

$$B_{fsw} = 300\,\mathrm{nT} \quad v_{fsw} = 675\,\mathrm{km\,s^{-1}} \quad T_{fsw} = 0.8\,\mathrm{MK} \quad n_{fsw} = 300\,\mathrm{cm^{-3}}$$

EUHFORIA/ ICARUS



EUHFORIA/ ICARUS ideal MHD

[Pomoell & Poedts 2018]

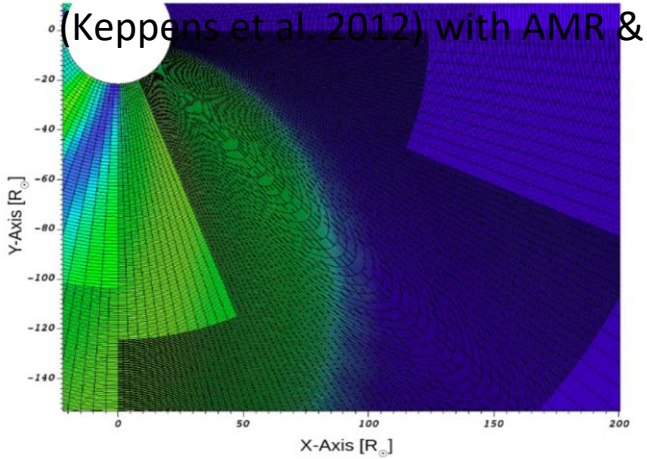
- in the rest of the heliospheric domain (0.1 - 2.1AU):
  ideal MHD + gravity
- ICARUS: EUHFORIA, but based on MPI-AMRVAC (Keppens et al. 2012) with AMR & grid stretching

$$\frac{\partial \rho}{\partial t} = -\nabla\cdot(\rho \mathbf{v}),$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} = -\nabla\cdot\left[\rho \mathbf{v}\mathbf{v} + \left(P + \frac{B^2}{2\mu_0}\right)\mathcal{I} - \frac{1}{\mu_0}\mathbf{B}\mathbf{B}\right] + \rho \mathbf{g},$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}),$$

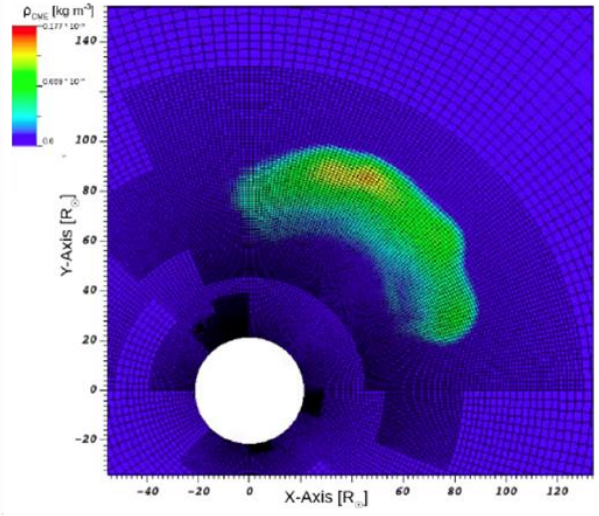
$$\frac{\partial E}{\partial t} = -\nabla\cdot\left[\left(E + P - \frac{B^2}{2\mu_0}\right)\mathbf{v} + \frac{1}{\mu_0}\mathbf{B} \times (\mathbf{v} \times \mathbf{B})\right] + \rho \mathbf{v}\cdot\mathbf{g},$$



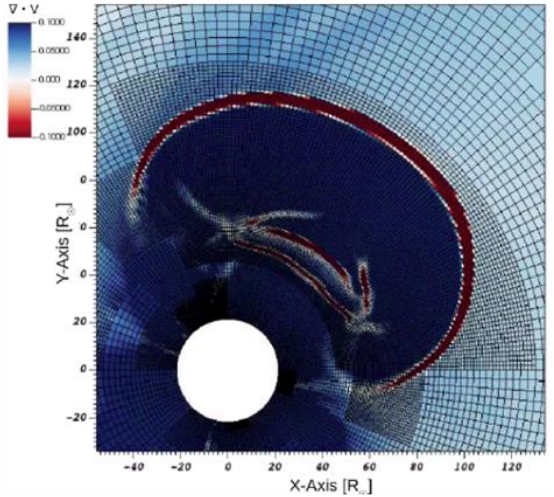
[Verbeke et al. 2022]

ICARUS: a variety of AMR criteria (Verbeke et al. 2022)

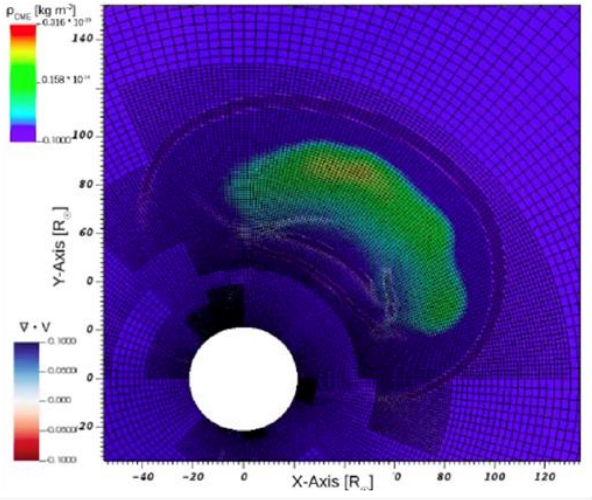
- the criteria can be combined:



tracing ρ

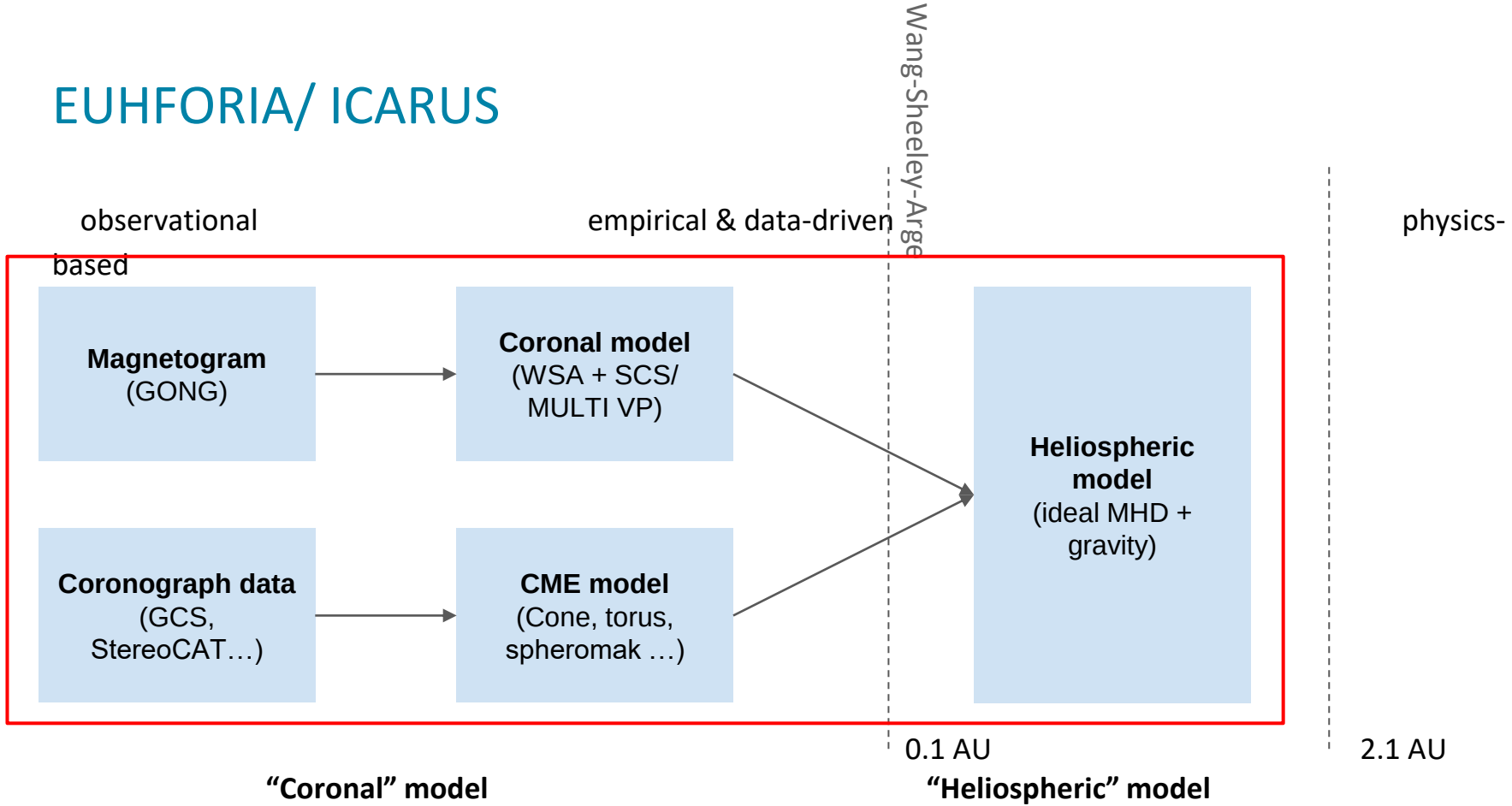


tracing ρ + div(V)

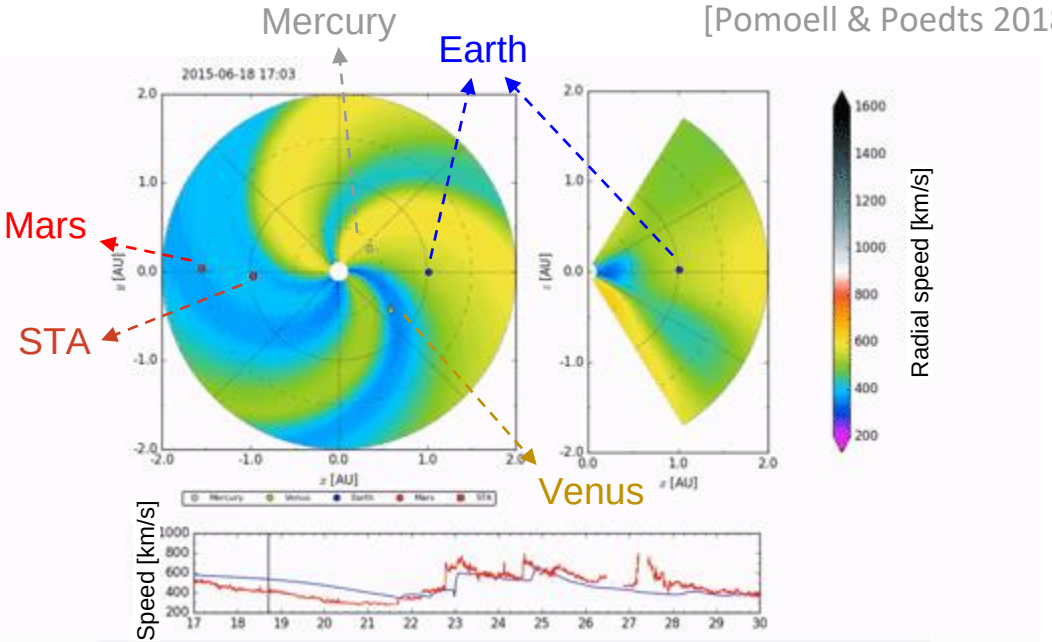


div(V)

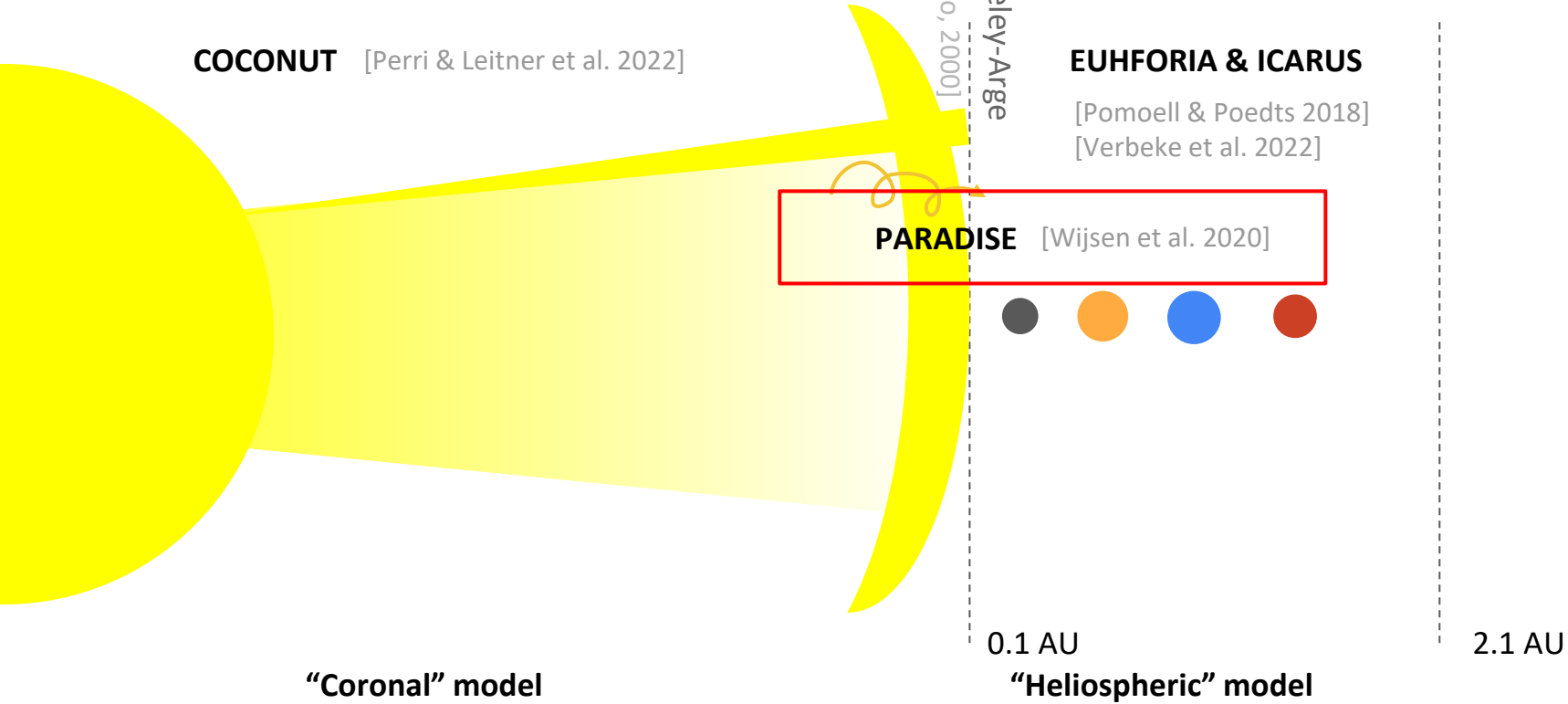
EUHFORIA/ ICARUS



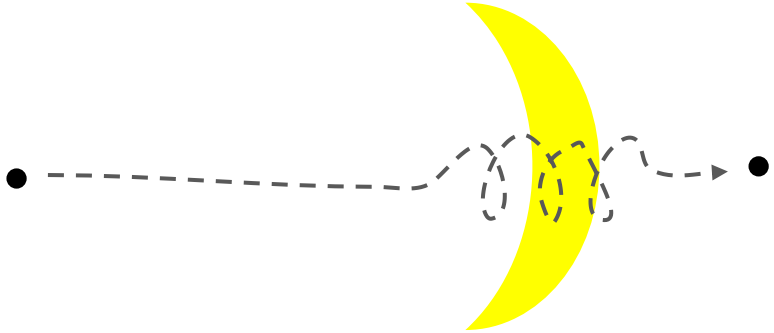
EUHFORIA (Pomoell & Poedts 2018): Preview



KU Leuven tools



Paradise (Wijsen et al. 2020)



- computes directional particle $j(\mathbf{x}, p, \mu, t)$, where p is the momentum magnitude and μ the momentum pitch angle cosine, via the so-called Focus Transport Equation (FTE)

- uses the background field from MHD (ICARUS/ EUHFORIA/ COCONUT) and does not couple back (it is assumed that the effect of SEP on the background plasma is negligible)

spatial cross-field diffusion tensor

pitch-angle diffusion coefficient

$$\frac{\partial j}{\partial t} + \frac{\partial}{\partial \mathbf{x}} \cdot \left[\left(\frac{d\mathbf{x}}{dt} + \frac{\partial}{\partial \mathbf{x}} \cdot \boldsymbol{\kappa}_\perp \right) j \right] + \frac{\partial}{\partial \mu} \left[\left(\frac{d\mu}{dt} + \frac{\partial D_{\mu\mu}}{\partial \mu} \right) j \right] + \frac{\partial}{\partial p} \left(\frac{dp}{dt} j \right) = \frac{\partial^2}{\partial \mu^2} \left[D_{\mu\mu} j \right] + \frac{\partial}{\partial \mathbf{x}} \cdot \left[\frac{\partial}{\partial \mathbf{x}} \cdot (\boldsymbol{\kappa}_\perp j) \right],$$

solar wind velocity

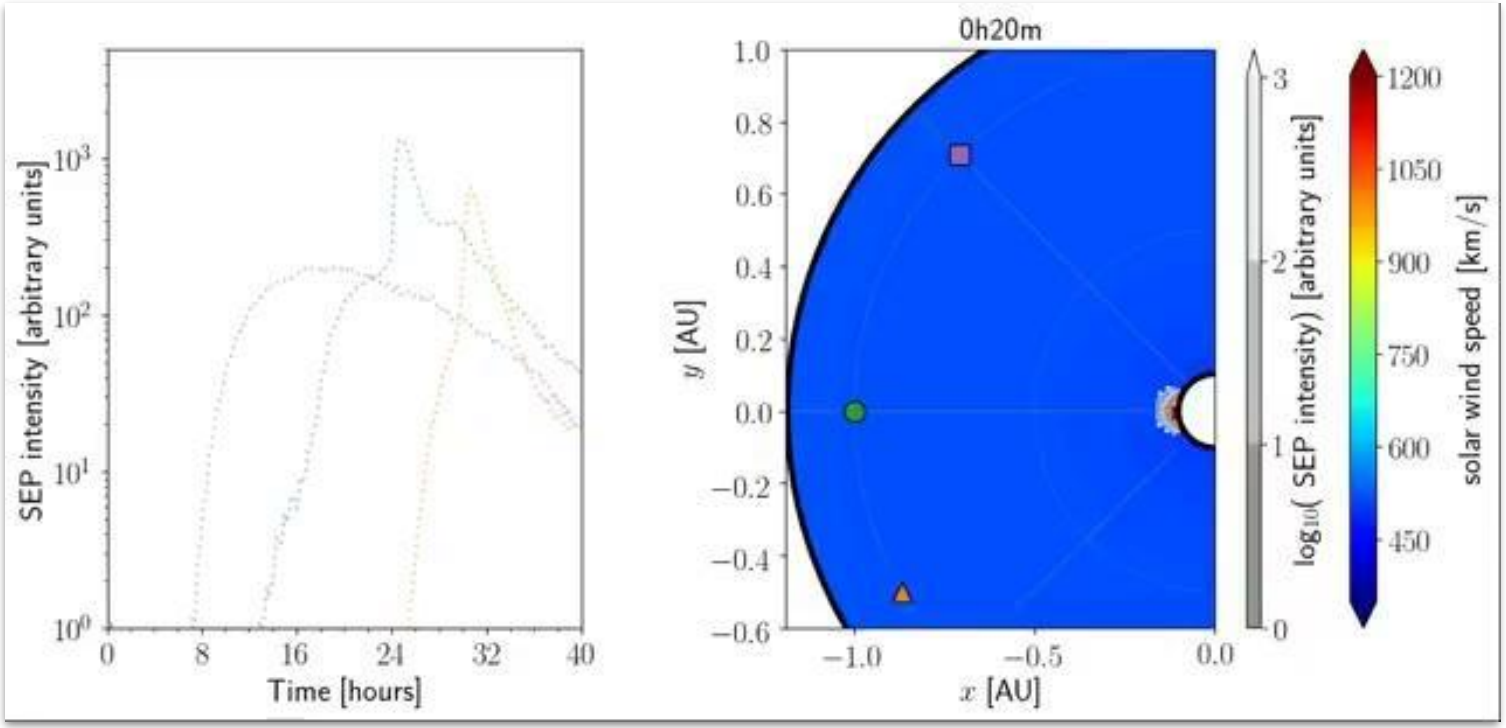
drift velocity

$$\frac{d\mathbf{x}}{dt} = \mathbf{V}_{\mathrm{sw}} + \mu v \mathbf{b} + \mathbf{V}_d$$

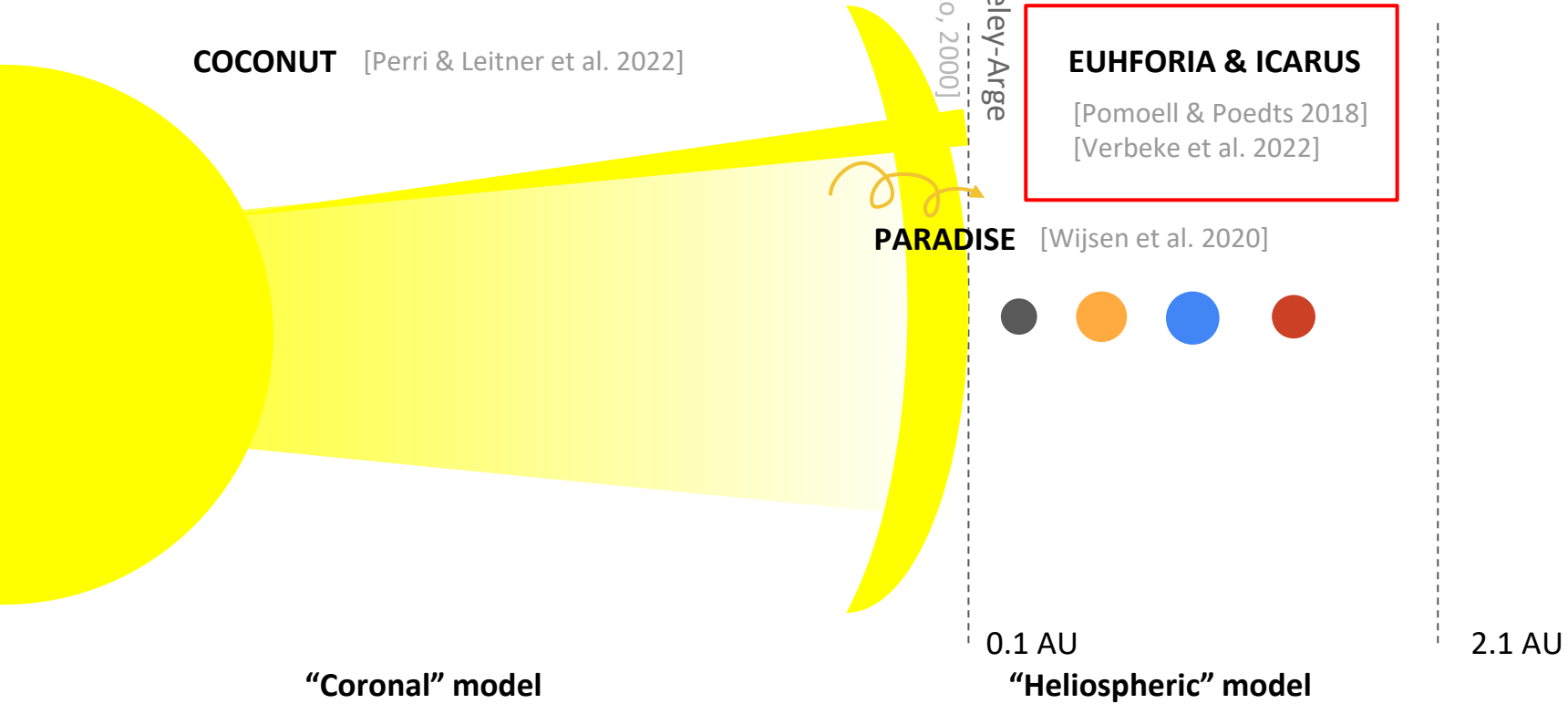
$$\frac{d\mu}{dt} = \frac{1-\mu^2}{2} \left(v \nabla \cdot \mathbf{b} + \mu \nabla \cdot \mathbf{V}_{\mathrm{sw}} - 3\mu \mathbf{b}\mathbf{b} : \nabla \mathbf{V}_{\mathrm{sw}} - \frac{2}{v} \mathbf{b} \cdot \frac{d\mathbf{V}_{\mathrm{sw}}}{dt} \right)$$

$$\frac{dp}{dt} = \left(\frac{1-3\mu^2}{2} (\mathbf{b}\mathbf{b} : \nabla \mathbf{V}_{\mathrm{sw}}) - \frac{1-\mu^2}{2} \nabla \cdot \mathbf{V}_{\mathrm{sw}} - \frac{\mu}{v} \mathbf{b} \cdot \frac{d\mathbf{V}_{\mathrm{sw}}}{dt} \right) p.$$

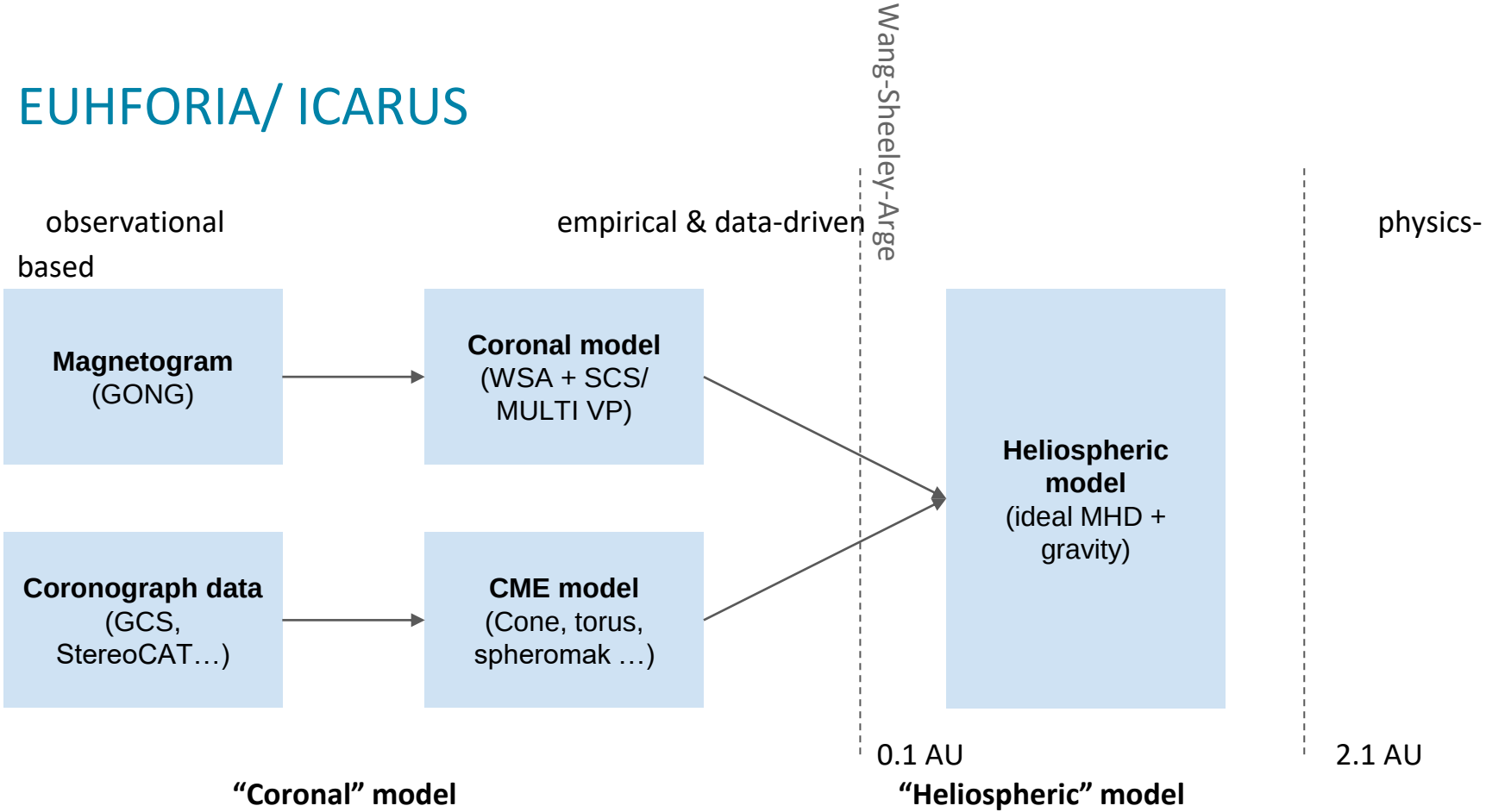
Paradise (Wijsen et al. 2020): Preview



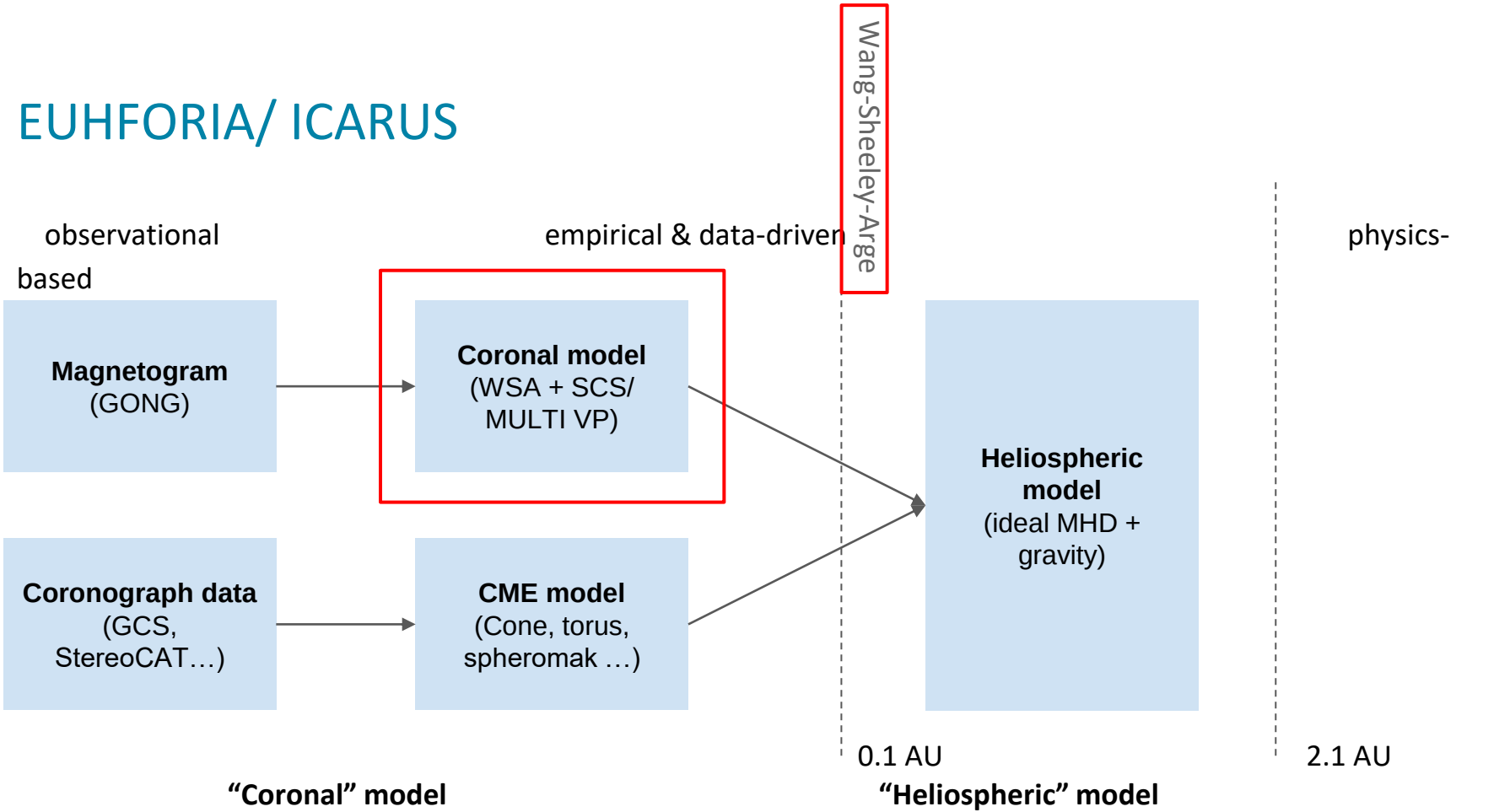
KU Leuven tools



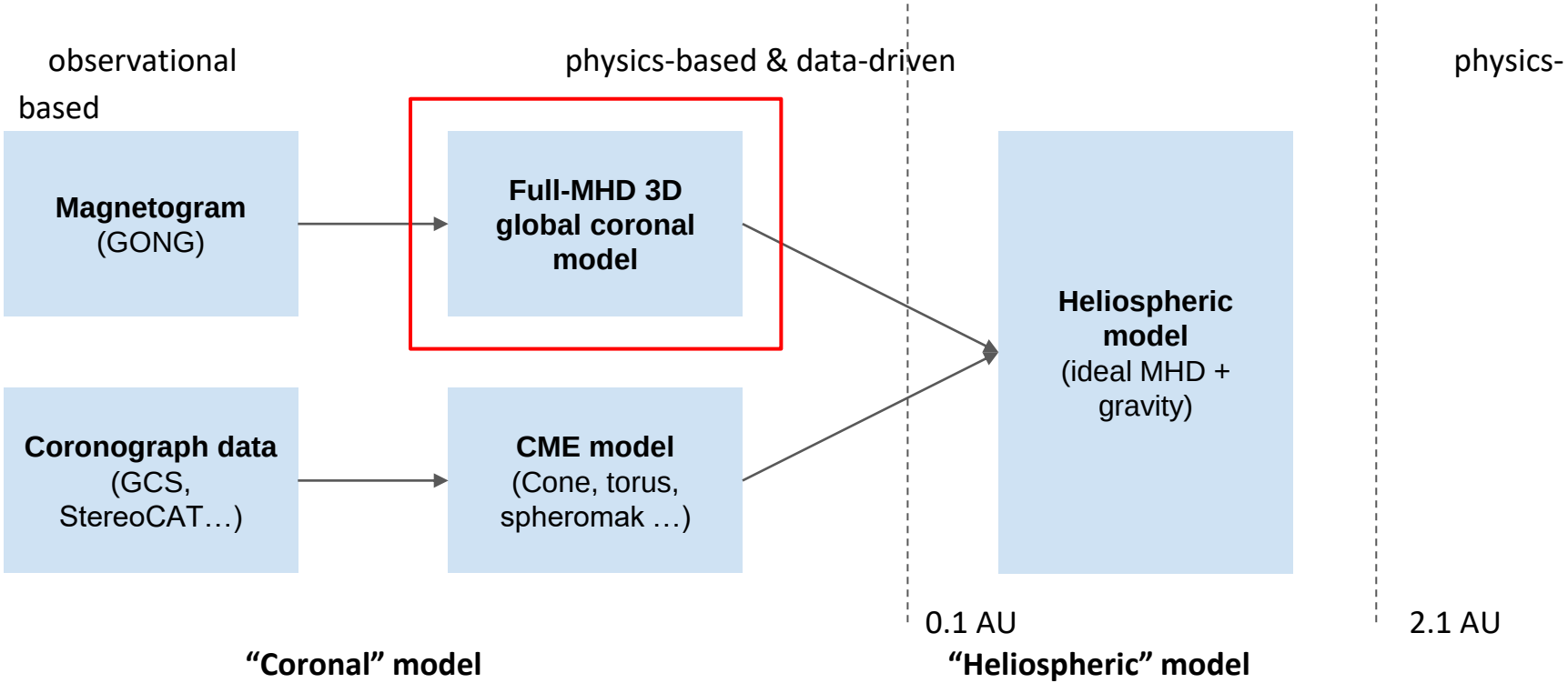
EUHFORIA/ ICARUS



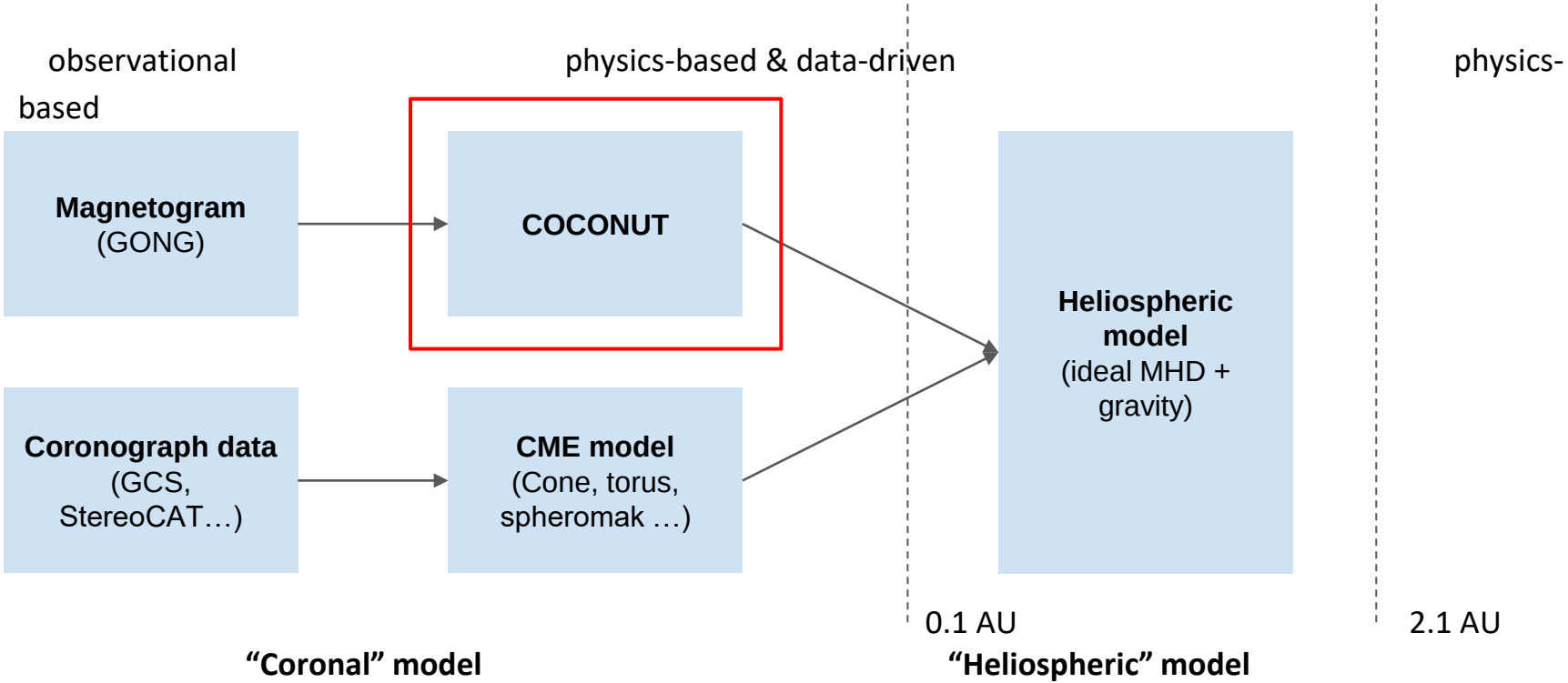
EUHFORIA/ ICARUS



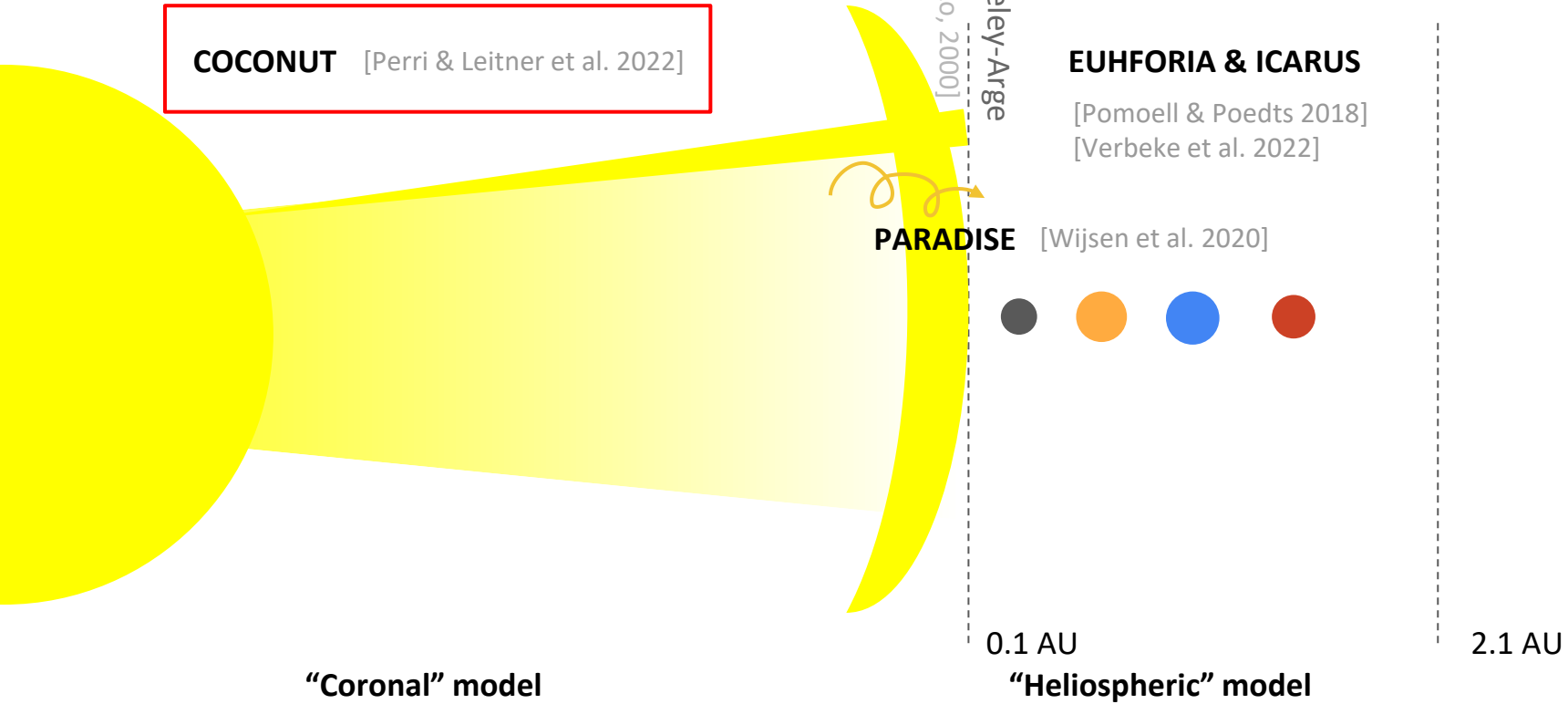
EUHFORIA/ ICARUS: made more physical?



EUHFORIA/ ICARUS: with COCONUT (Perri, Leitner et al. 2022)



KU Leuven tools



COCONUT global coronal model

- originally ideal-MHD + gravity, now also radiation, heat conduction and an approximation of coronal heating (Baratashvili et al., submitted)

- based on the COOLFluiD framework (Lani 2002)

- to resolve SW: pseudo-time stepping with an implicit scheme (CFL >> 1 possible) → rapid convergence for operational purposes

$$\frac{d\rho}{dt} + \nabla \cdot (\rho \vec{V}) = 0,$$

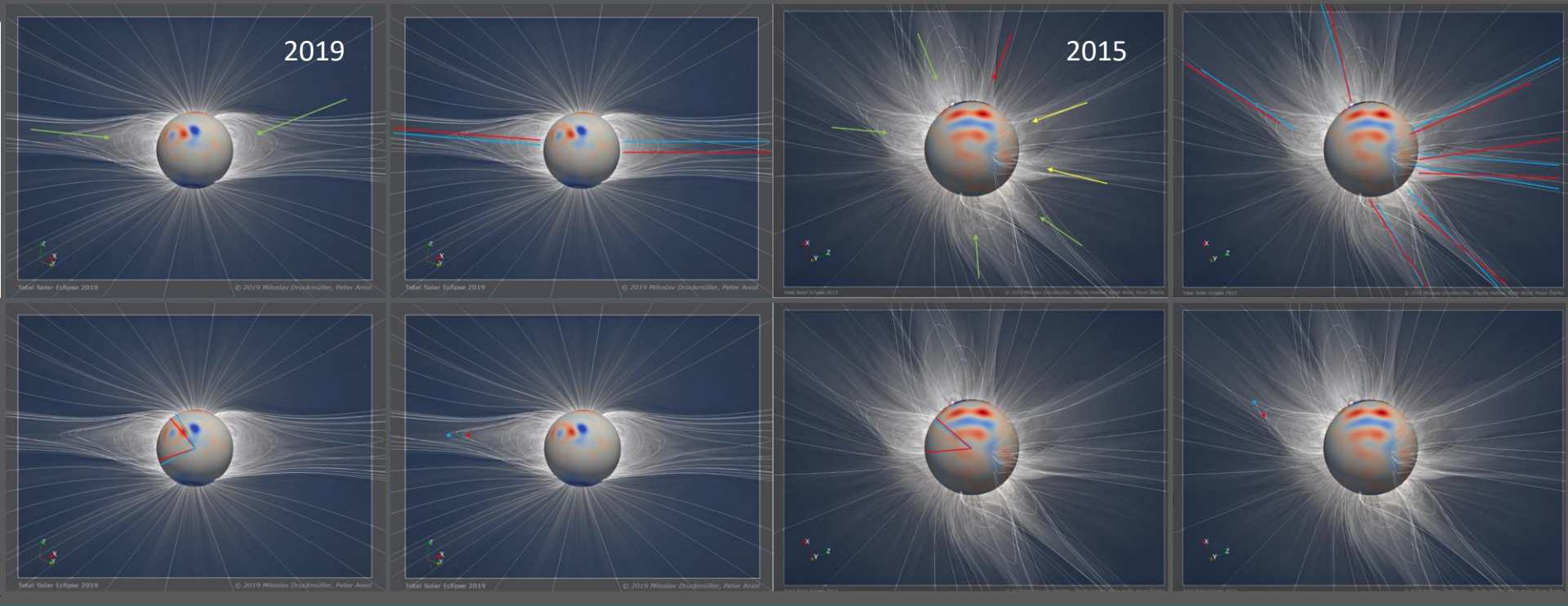
$$\frac{d(\rho \vec{V})}{dt} + \nabla \cdot \left(\rho \vec{V} \otimes \vec{V} + \mathbf{I} \left(P + \frac{\vec{B}^2}{8\pi} \right) - \frac{\vec{B} \otimes \vec{B}}{4\pi} \right) = \rho \vec{g},$$

$$\frac{1}{c} \frac{d\vec{B}}{dt} + \nabla \times \left(- \frac{\vec{V} \times \vec{B}}{c} \right) = \vec{0},$$

$$\frac{d}{dt} \left(\rho \frac{\vec{V}^2}{2} + \rho \mathcal{E} + \frac{\vec{B}^2}{8\pi} \right) + \nabla \cdot \left[\left(\rho \frac{\vec{V}^2}{2} + \rho \mathcal{E} + P \right) \vec{V} - \frac{1}{4\pi} (\vec{V} \times \vec{B}) \times \vec{B} \right] = \rho \vec{g} \cdot \vec{V} - \nabla \cdot \mathbf{q} + Q_{rad} + Q_H$$

COCONUT global coronal model

[Kuzma et al. 2023]



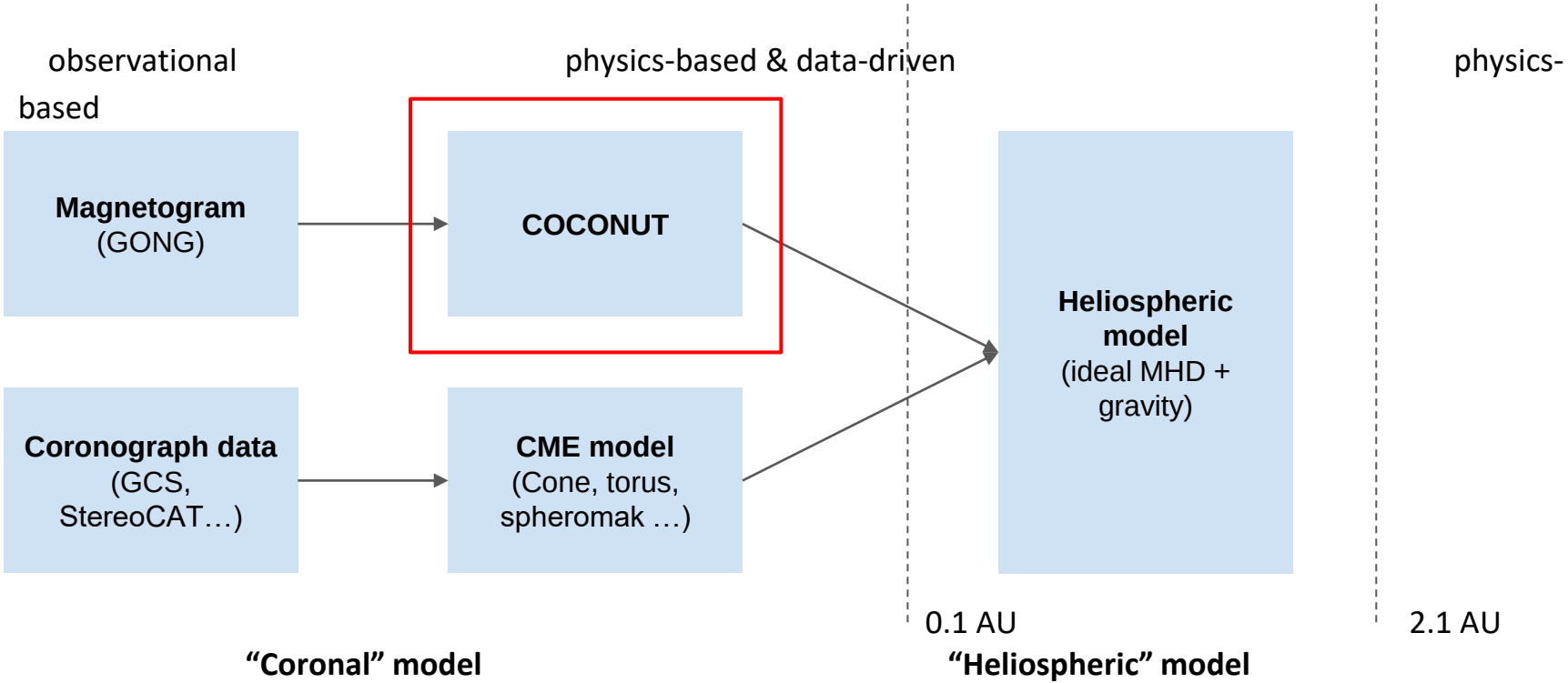
COCONUT: current state (performance)

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

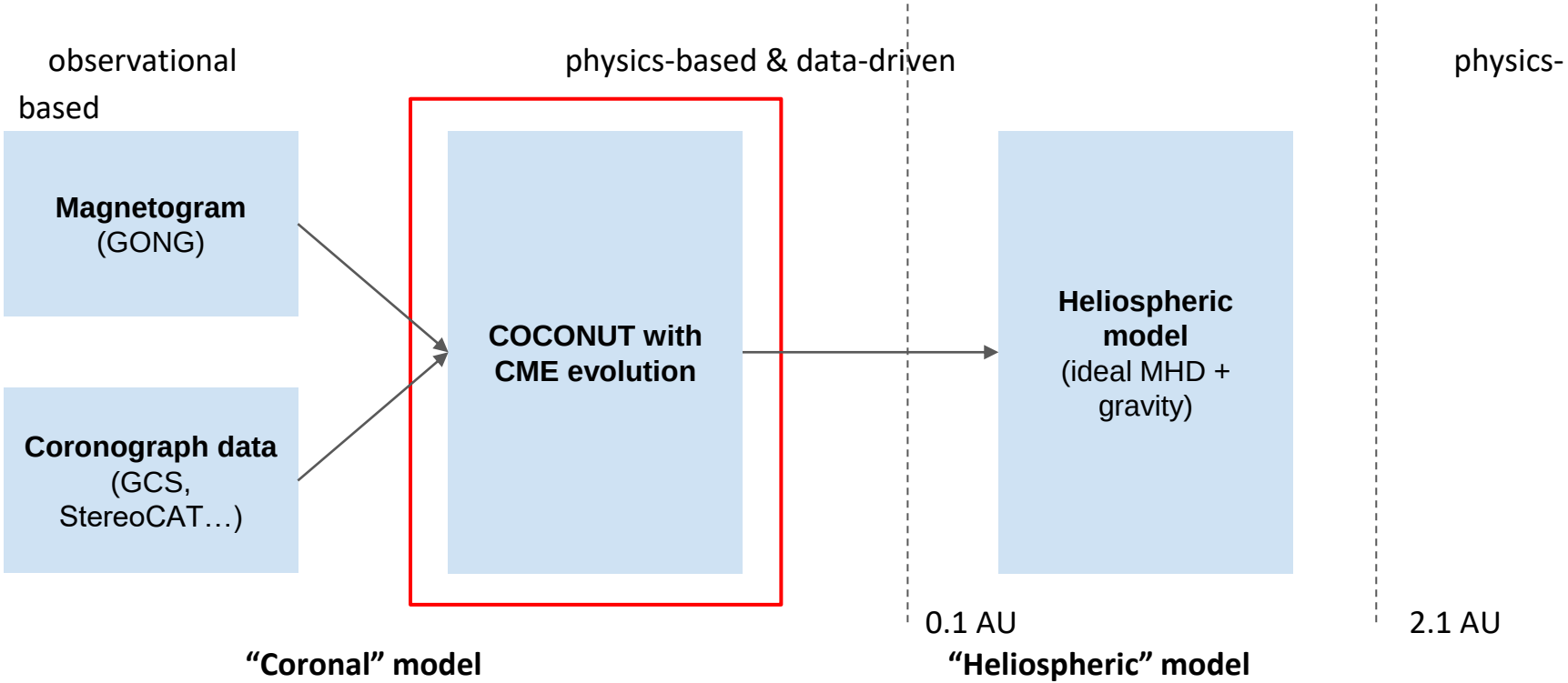
Code	Case	Number of elements	Number of processors	Highest CFL	Iterations	Time (minutes)
COCONUT	Dipole	332 800	84	5000	137	5.6
Wind-Predict	Dipole	320 000	84	0.3	80445	15.0
COCONUT	Quadrupole	332 800	84	300	290	11.9
Wind-Predict	Quadrupole	320 000	84	0.3	94310	17.0
COCONUT	GONG ($\ell_{max} = 15$)	$1.9\ 10^6$	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]

EUHFORIA/ ICARUS: with COCONUT (Perri, Leitner et al. 2022)

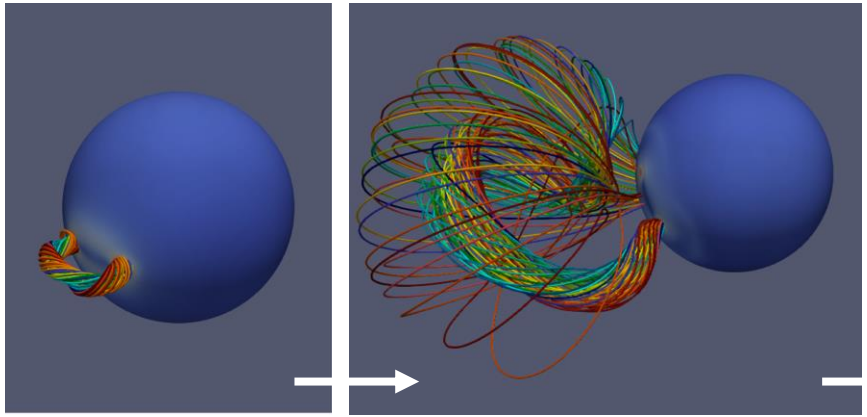


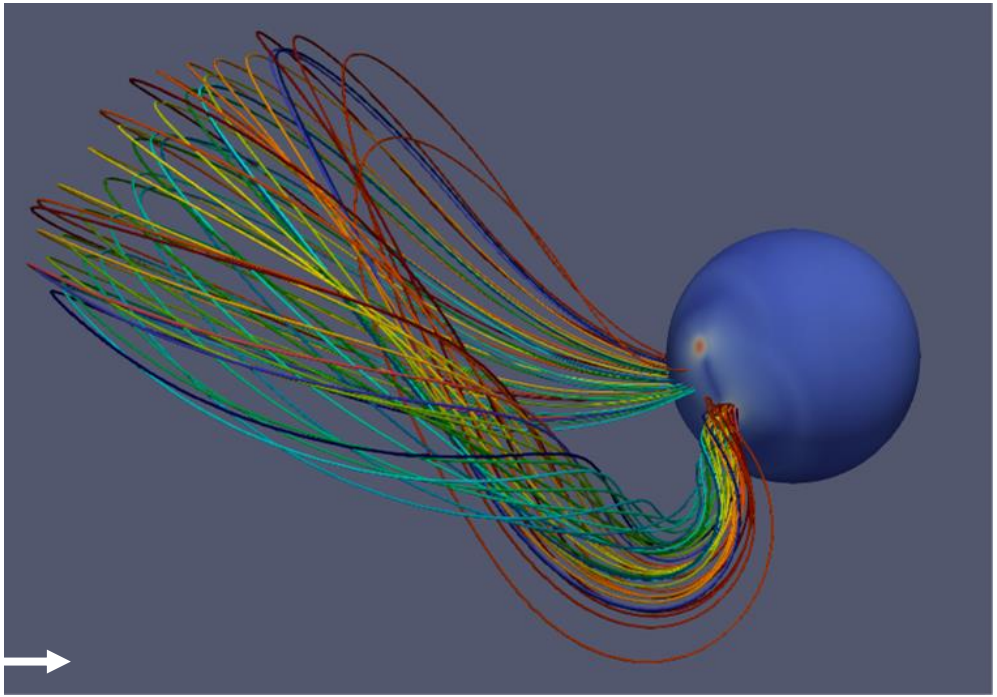
EUHFORIA/ ICARUS: with COCONUT (Perri, Leitner et al. 2022)



COCONUT extensions

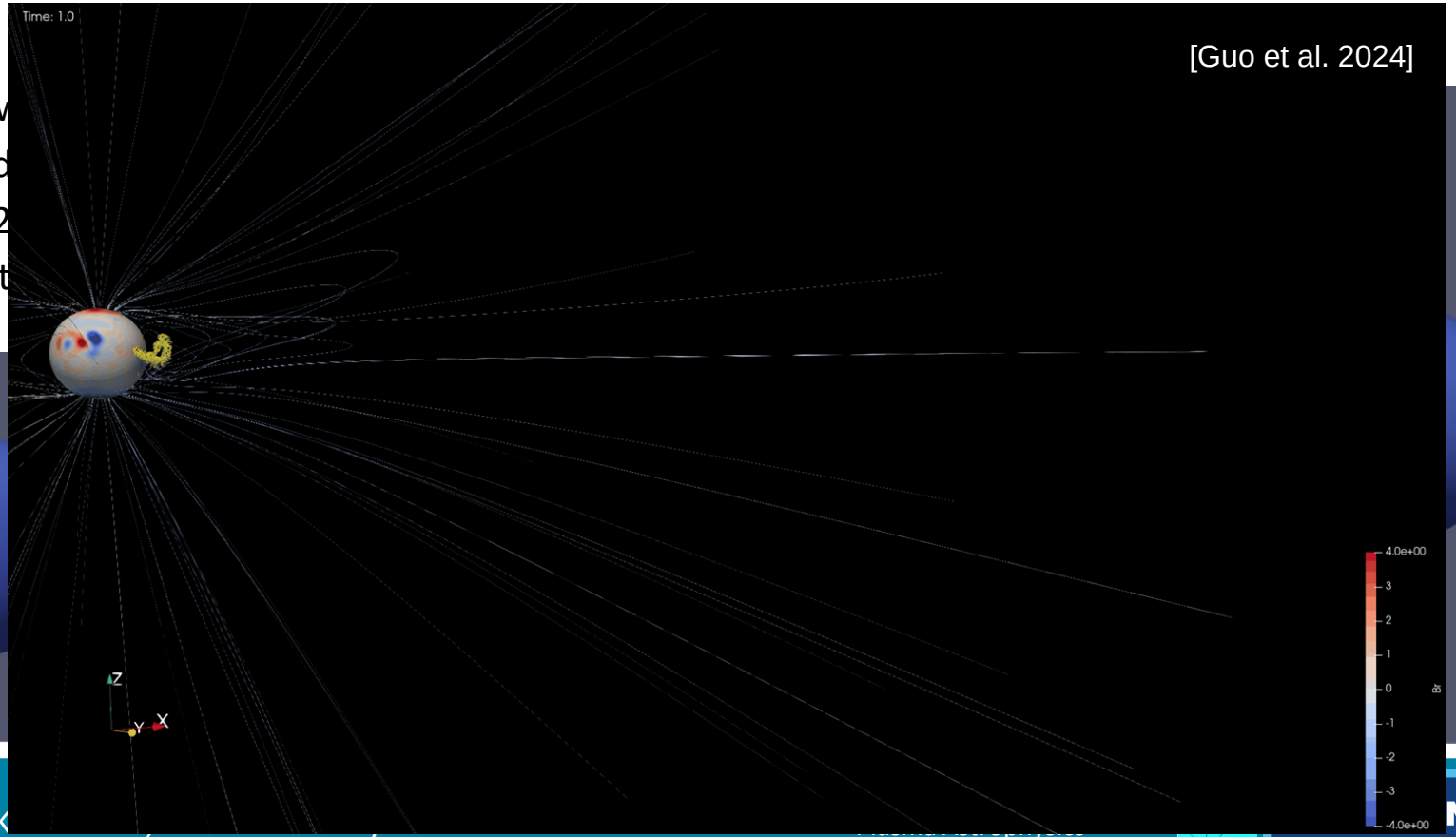
- now extended to also model eruption and evolution of CMEs (Linan et al. 2023, Guo et al. 2024)
- instead of steady-state → time accurate





COCONUT extensions

- nov
  and
  202
- inst



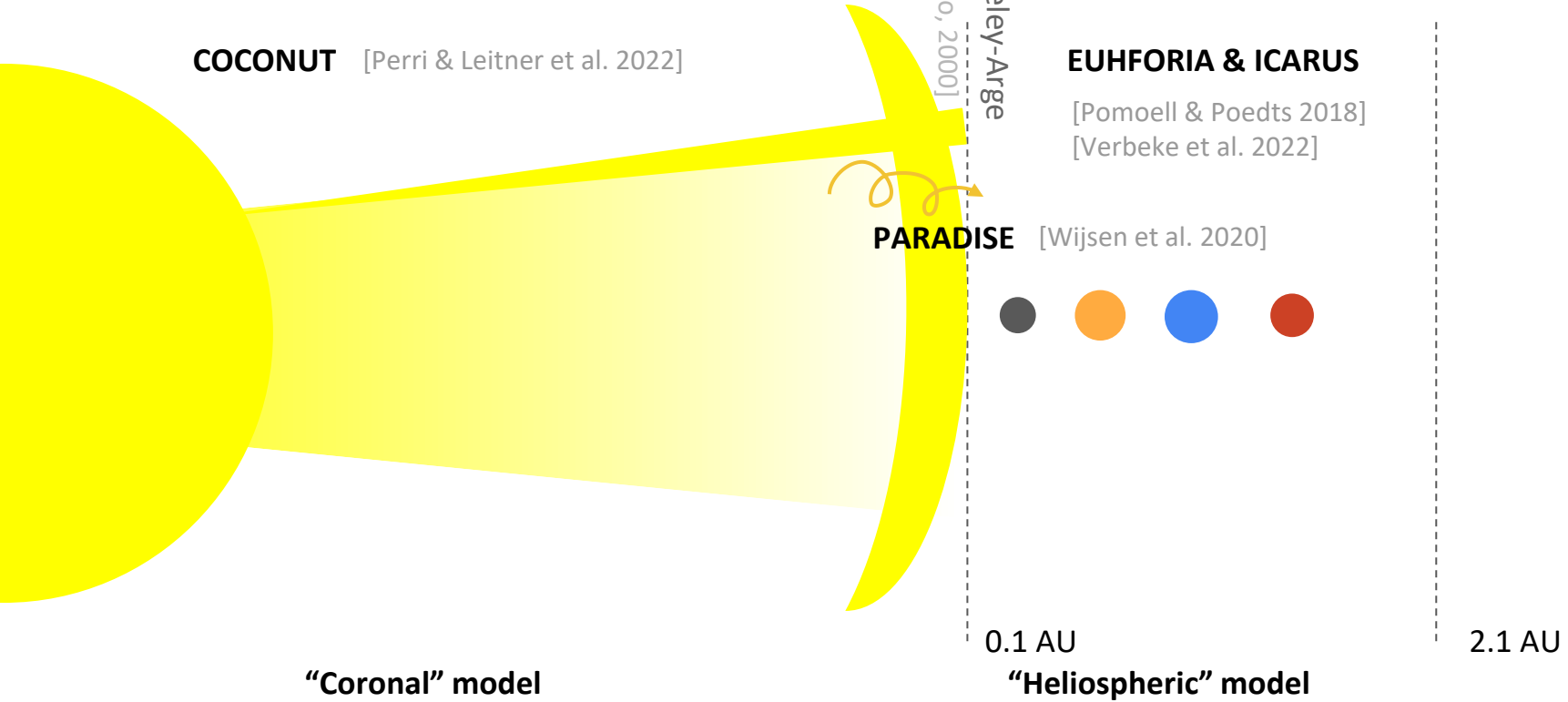
COCONUT extension plans

- still requires performance optimisation for a faster time-accurate convergence
- useful for more fundamental studies of the phenomena occurring in the solar corona

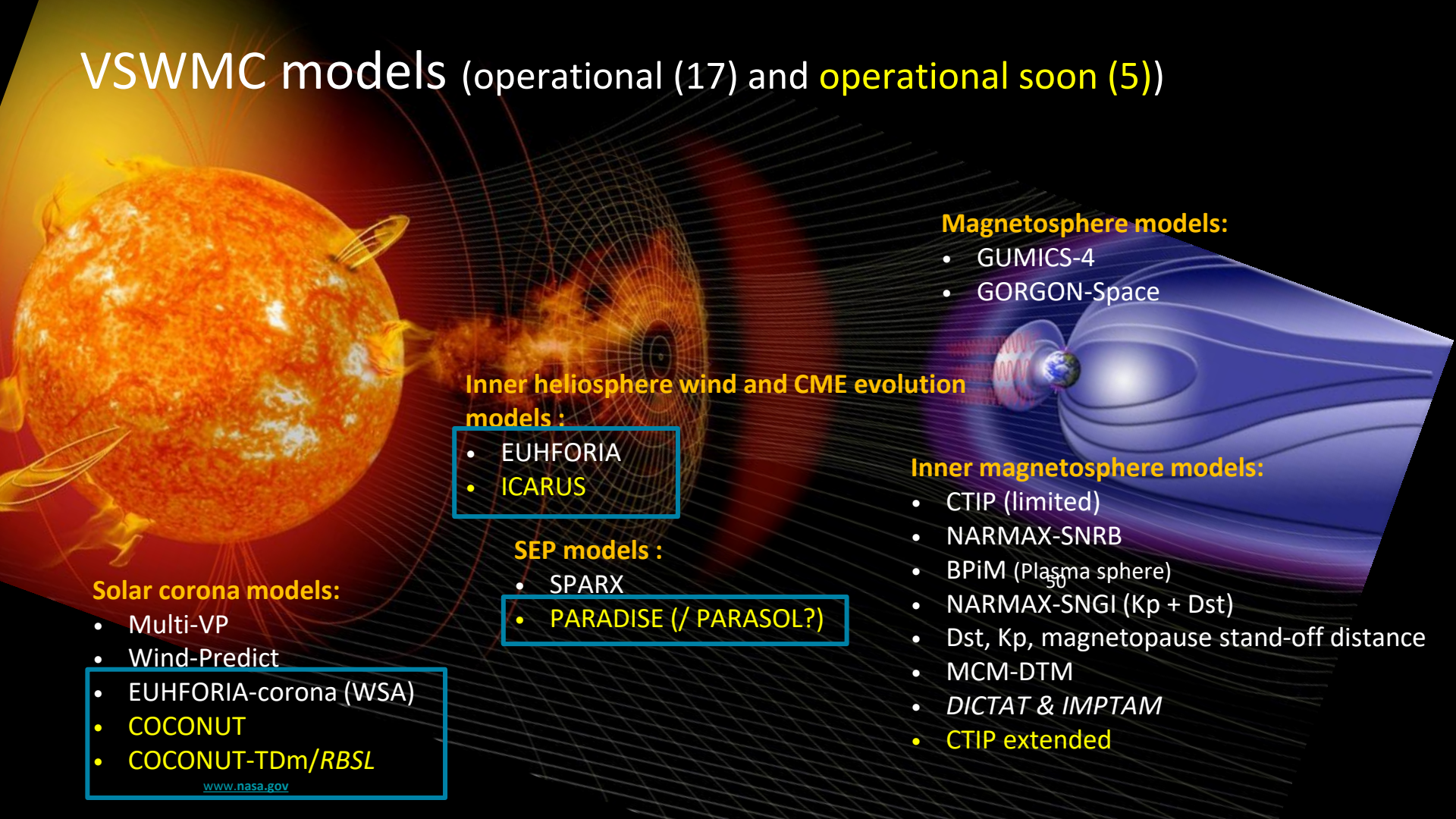
- physical:
  - extension down to include the chromosphere and the transition region
  - inclusion of Alfvén-wave heating terms for better coronal heating approximation
  - including two & three fluid modelling (ion/ neutral and ion/ neutral/ electron)

- numerical:
  - inclusion of AMR, reformulation into higher-order reconstruction
  - non-dimensionalisation of the multifluid formulation

Summary


COCONUT [Perri & Leitner et al. 2022]
Wang-Sheeley-Arge
[Arge and Pizzo, 2000]
EUHFORIA & ICARUS
[Pomoell & Poedts 2018]
[Verbeke et al. 2022]
PARADISE [Wijsen et al. 2020]
0.1 AU
2.1 AU
“Coronal” model
“Heliospheric” model

VSWMC models (operational (17) and operational soon (5))



Solar corona models:
- Multi-VP
- Wind-Predict
- EUHFORIA-corona (WSA)
- COCONUT
- COCONUT-TDm/*RBSL*

Inner heliosphere wind and CME evolution models :
- EUHFORIA
- ICARUS

SEP models :
- SPARX
- PARADISE (/ PARASOL?)

Magnetosphere models:
- GUMICS-4
- GORGON-Space

Inner magnetosphere models:
- CTIP (limited)
- NARMAX-SNRB
- BPiM (Plasma sphere)
- NARMAX-SNGI (Kp + Dst)
- Dst, Kp, magnetopause stand-off distance
- MCM-DTM
- *DICTAT & IMPTAM*
- CTIP extended

EUHFORIA in the e-Science Centre

PITHIA-NRF
e-Science Centre

HOME SEARCH & BROWSE Login

Home / Browse Metadata / Data Collection-related Metadata / Data Collections / EUHFORIA: EUropean Heliospheric FORecasting Information Asset

EUHFORIA: EUropean Heliospheric FORecasting Information Asset

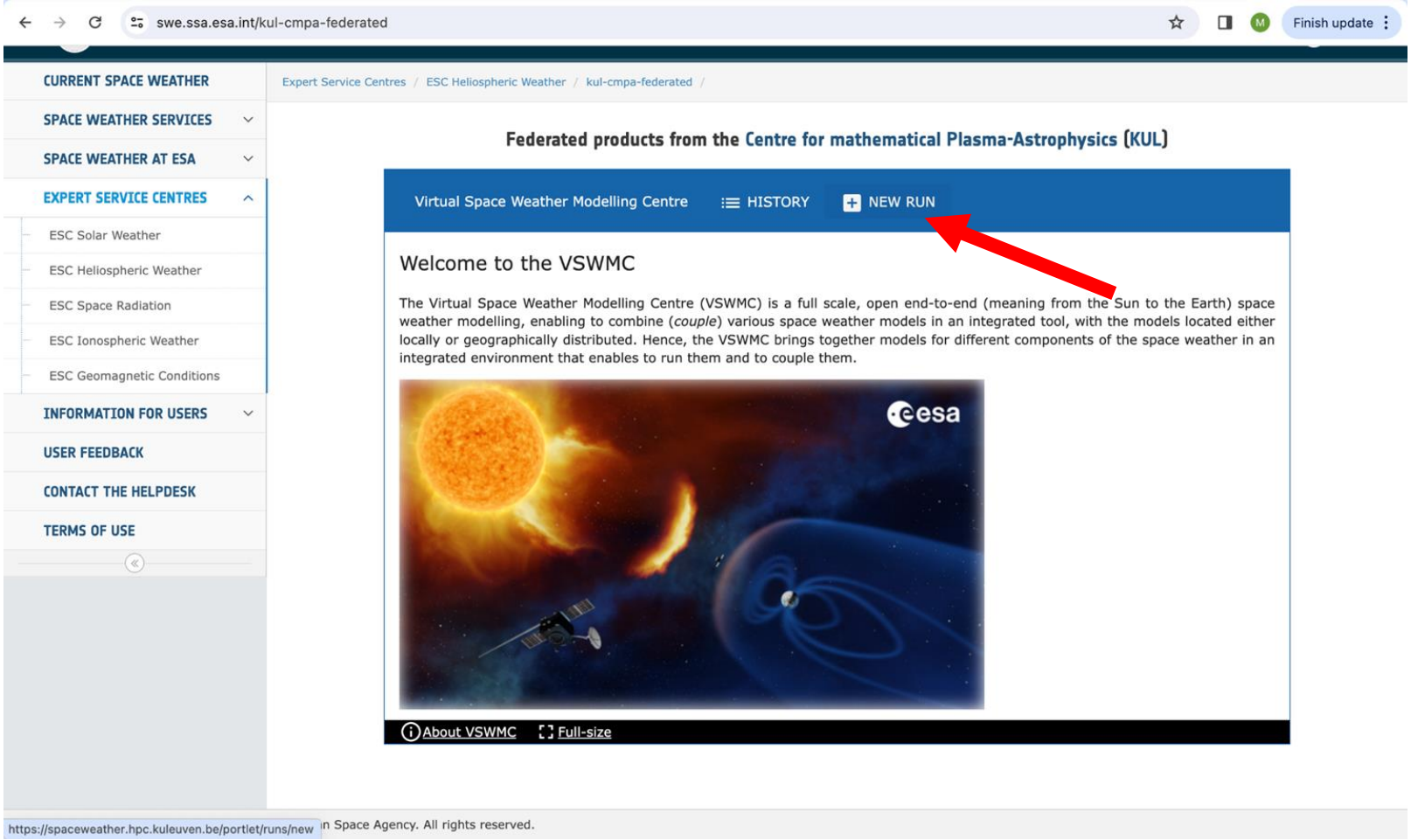
EUHFORIA (EUropean Heliospheric FORecasting Information Asset) consists of two main parts: a semi-empirical coronal model, the purpose of which is to determine the plasma environment of the solar wind at the location of the inner boundary of the heliospheric module, and the heliospheric model, which provides the dynamics of the background solar wind with superposed CMEs into the inner heliosphere by numerical evolution of the MHD equations. EUHFORIA runs at the Virtual Space Weather Modeling Center (VSWMC) on the ESA Space Weather Network (ESA-SWE) website (https://swe.ssa.esa.int). VSWMC is an interactive modeling system developed for space weather research from the Sun to the Earth. It allows users to run different tools stand-alone or in combination with models that are locally or geographically dispersed.

Identifier Properties

Local ID	DataCollection_EUHFORIA
Namespace	kul
Version	2
Created	Tuesday 28th Feb. 2023, 01:30:00
Last Modified	Monday 24th April 2023, 18:56:00

Interact

Interaction Method	Description	Data Format	Link
Direct Link to Data Collection	The ESA-SWE website requires an account to run. Once received, go to the VSWMC webpage and select: "NEW RUN". From the list of model chains that appear, you can choose those that contain EUHFORIA, or separately the coronal and heliospheric EUHFORIA models. Also, the	image/png (click the link to show information on this ontology term)	Open Latest VSWMC at ESA-SWE Landing Page in new tab


swe.ssa.esa.int/kul-cmpa-federated
Finish update
CURRENT SPACE WEATHER
SPACE WEATHER SERVICES
SPACE WEATHER AT ESA
EXPERT SERVICE CENTRES
ESC Solar Weather
ESC Heliospheric Weather
ESC Space Radiation
ESC Ionospheric Weather
ESC Geomagnetic Conditions
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USER FEEDBACK
CONTACT THE HELPDESK
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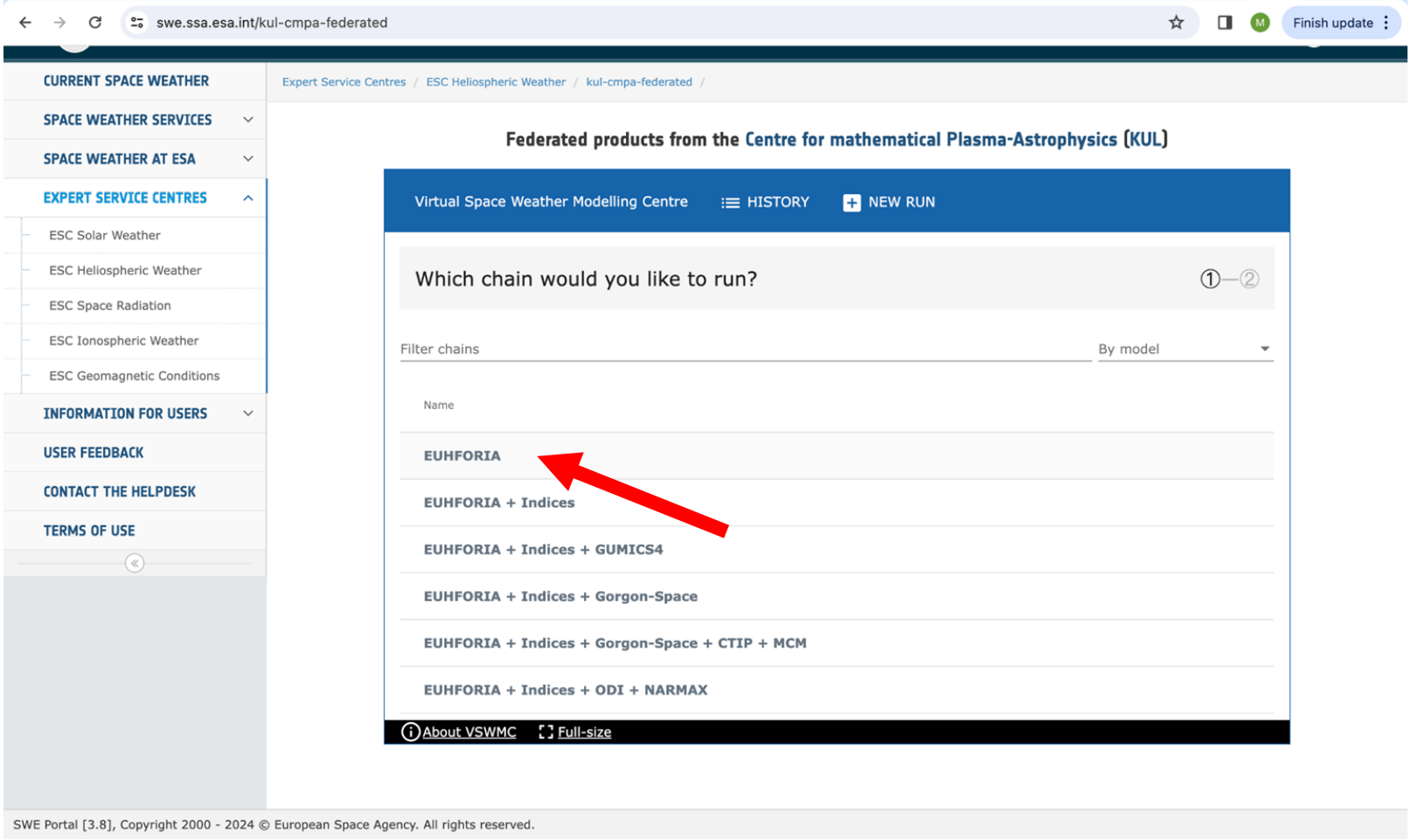
Federated products from the Centre for mathematical Plasma-Astrophysics (KUL)
Virtual Space Weather Modelling Centre
HISTORY
NEW RUN
Welcome to the VSWMC
The Virtual Space Weather Modelling Centre (VSWMC) is a full scale, open end-to-end (meaning from the Sun to the Earth) space weather modelling, enabling 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.
esa
About VSWMC
Full-size
https://spaceweather.hpc.kuleuven.be/portlet/runs/new
n Space Agency. All rights reserved.


swe.ssa.esa.int/kul-cmpa-federated
Finish update
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Virtual Space Weather Modelling Centre
HISTORY
NEW RUN
Which chain would you like to run?
Filter chains
By model
Name
EUHFORIA
EUHFORIA + Indices
EUHFORIA + Indices + GUMICS4
EUHFORIA + Indices + Gorgon-Space
EUHFORIA + Indices + Gorgon-Space + CTIP + MCM
EUHFORIA + Indices + ODI + NARMAX
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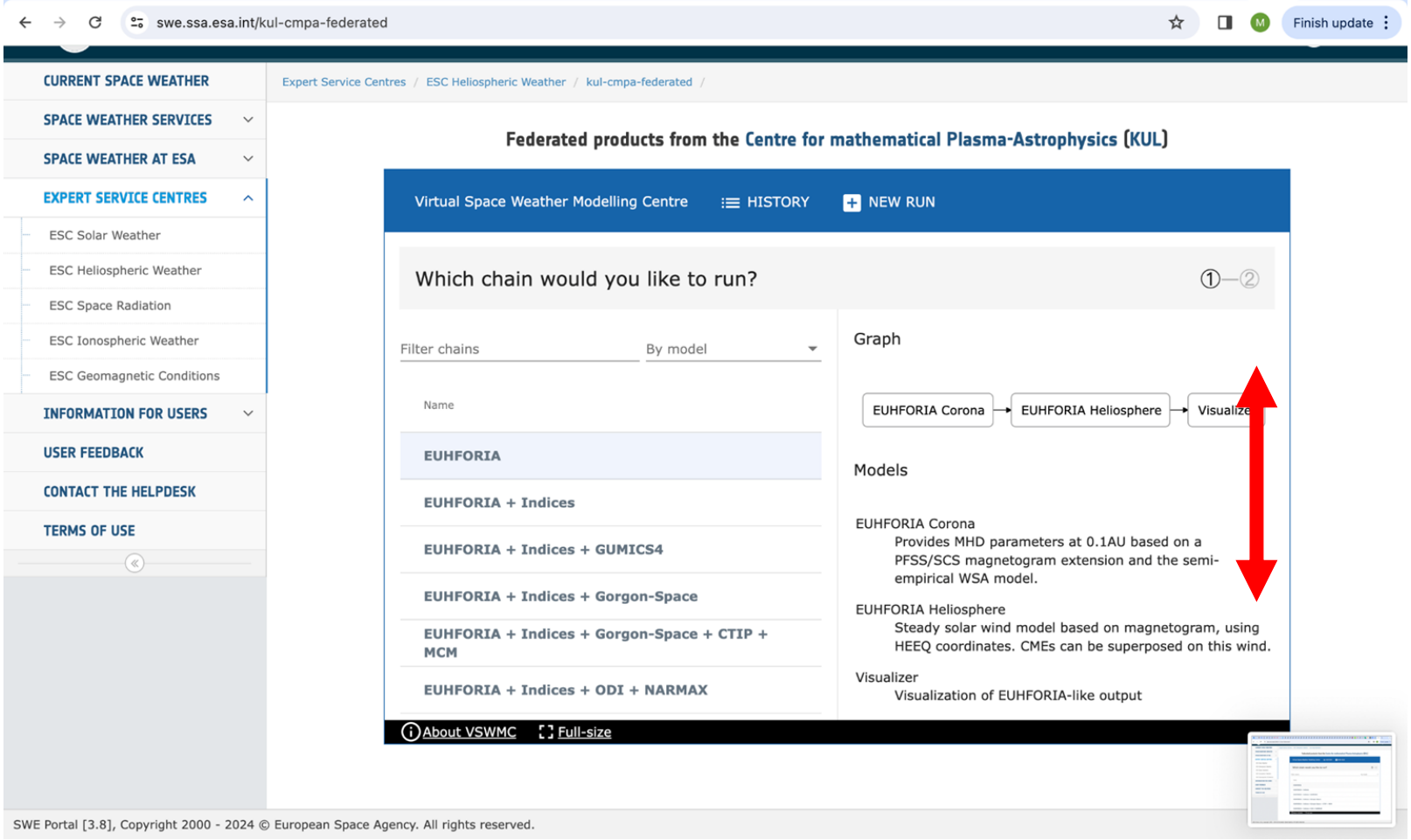
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EUHFORIA + Indices + ODI + NARMAX
Graph
EUHFORIA Corona
EUHFORIA Heliosphere
Visualizer
Models
EUHFORIA Corona
Provides MHD parameters at 0.1AU based on a PFSS/SCS magnetogram extension and the semi-empirical WSA model.
EUHFORIA Heliosphere
Steady solar wind model based on magnetogram, using HEEQ coordinates. CMEs can be superposed on this wind.
Visualizer
Visualization of EUHFORIA-like output
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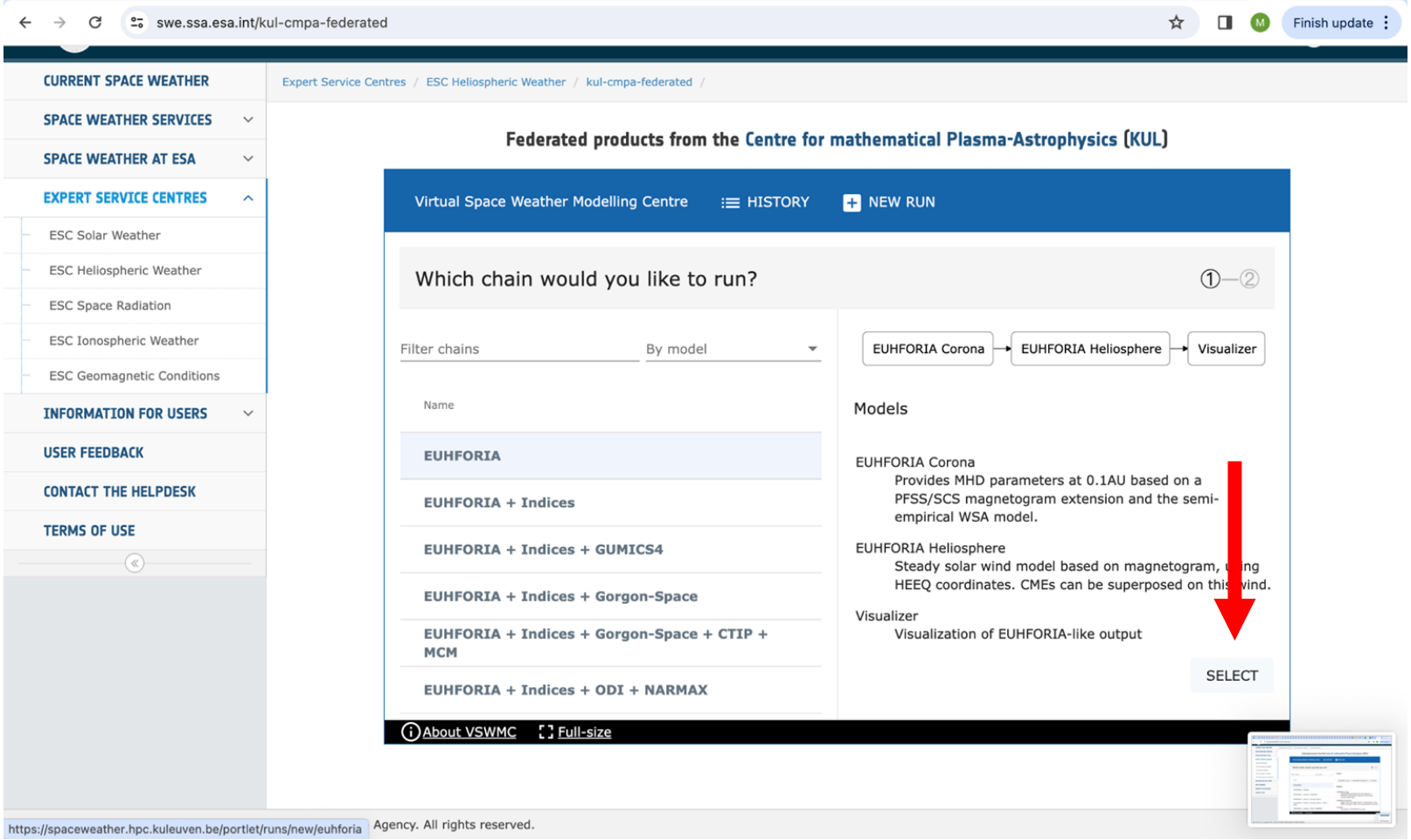
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EUHFORIA + Indices + GUMICS4
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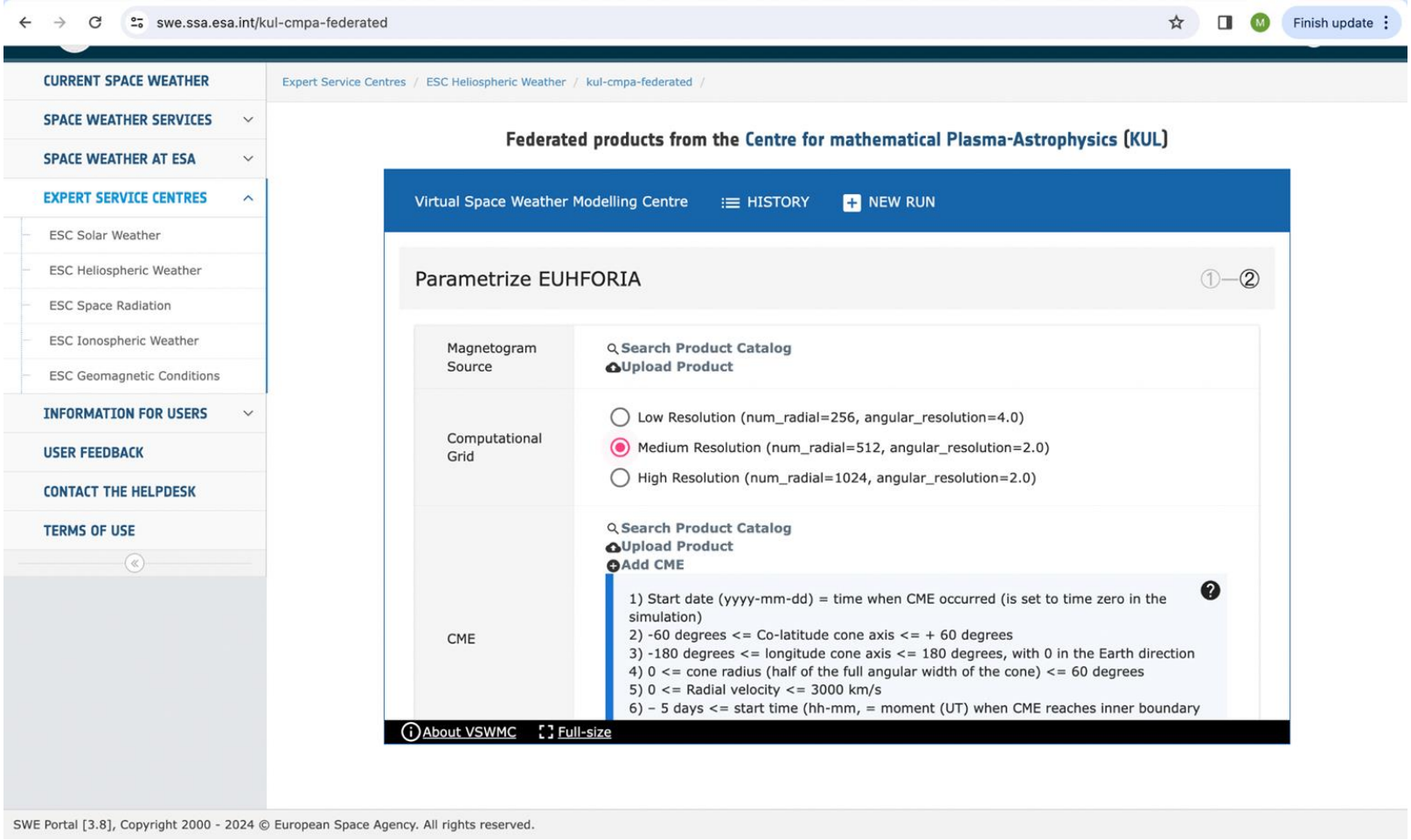
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Federated products from the Centre for mathematical Plasma-Astrophysics (KUL)
Virtual Space Weather Modelling Centre
HISTORY
NEW RUN
Parametrize EUHFORIA
①—②
Magnetogram Source
Search Product Catalog
Upload Product
Computational Grid
Low Resolution (num_radial=256, angular_resolution=4.0)
Medium Resolution (num_radial=512, angular_resolution=2.0)
High Resolution (num_radial=1024, angular_resolution=2.0)
CME
Search Product Catalog
Upload Product
Add CME
1) Start date (yyyy-mm-dd) = time when CME occurred (is set to time zero in the simulation)
2) -60 degrees <= Co-latitude cone axis <= + 60 degrees
3) -180 degrees <= longitude cone axis <= 180 degrees, with 0 in the Earth direction
4) 0 <= cone radius (half of the full angular width of the cone) <= 60 degrees
5) 0 <= Radial velocity <= 3000 km/s
6) – 5 days <= start time (hh-mm, = moment (UT) when CME reaches inner boundary
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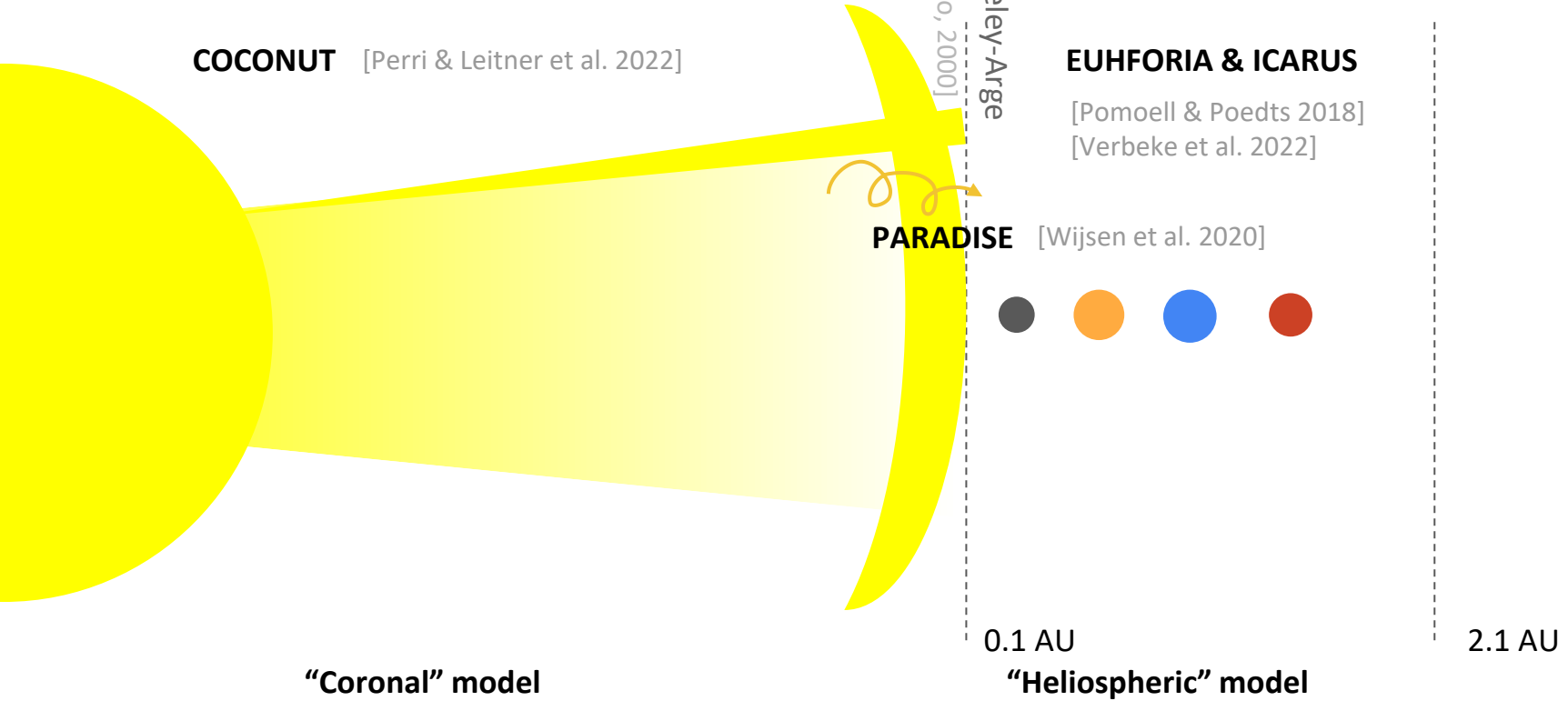
Summary

- **the software is open-source and publications open-access!**



More information? Useful contacts:

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- COCONUT: michaela.brchnelova@kuleuven.be, tinatin.baratashvili@kuleuven.be
- COCONUT CME modelling: luis.linan@kuleuven.be, jinhan.guo@kuleuven.be
- COOLFluiD: andrea.lani@kuleuven.be

- Virtual Space Weather Modelling Centre (VSWMC): stefaan.poedts@kuleuven.be
- Detection of flux ropes and source point determination: andreas.wagner@kuleuven.be

Thank you for your attention!

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stefaan.poedts@kuleuven.be