Space weather modelling at KU Leuven: model chains, limitations and user needs

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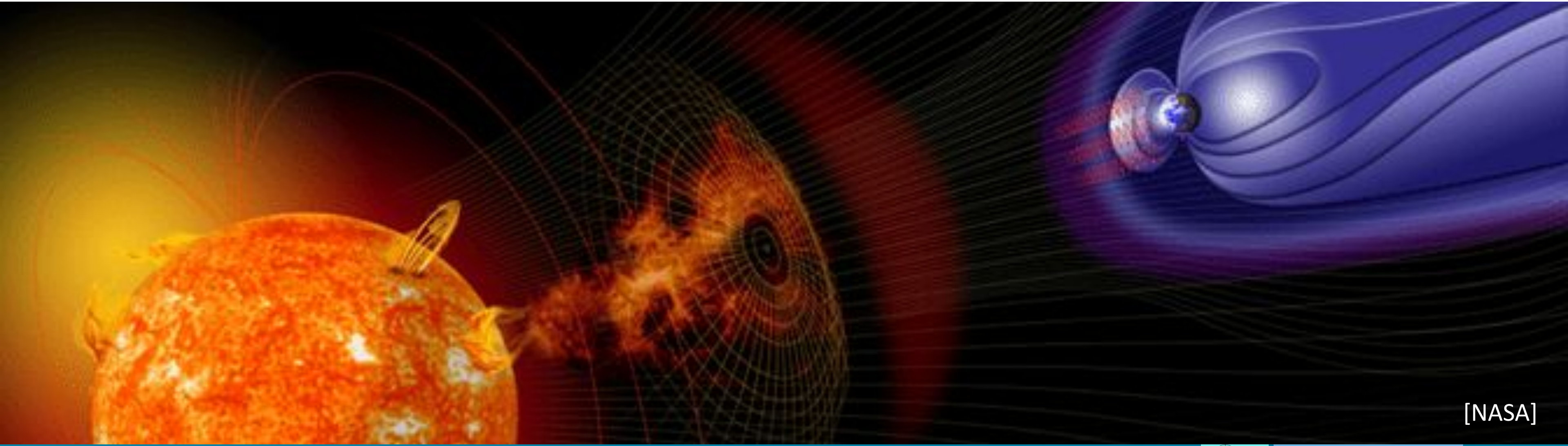
GNC24, Szczecin, 3 to 6 June 2024

Space weather

- describes conditions in space, around the Earth but also around other objects of interests: magnetic field, plasma velocity & density & temperature, particle precipitation
- largely determined by the Sun, but also (extra)galactic phenomena sources such as cosmic rays



[NASA]

Centre for mathematical Plasma Astrophysics

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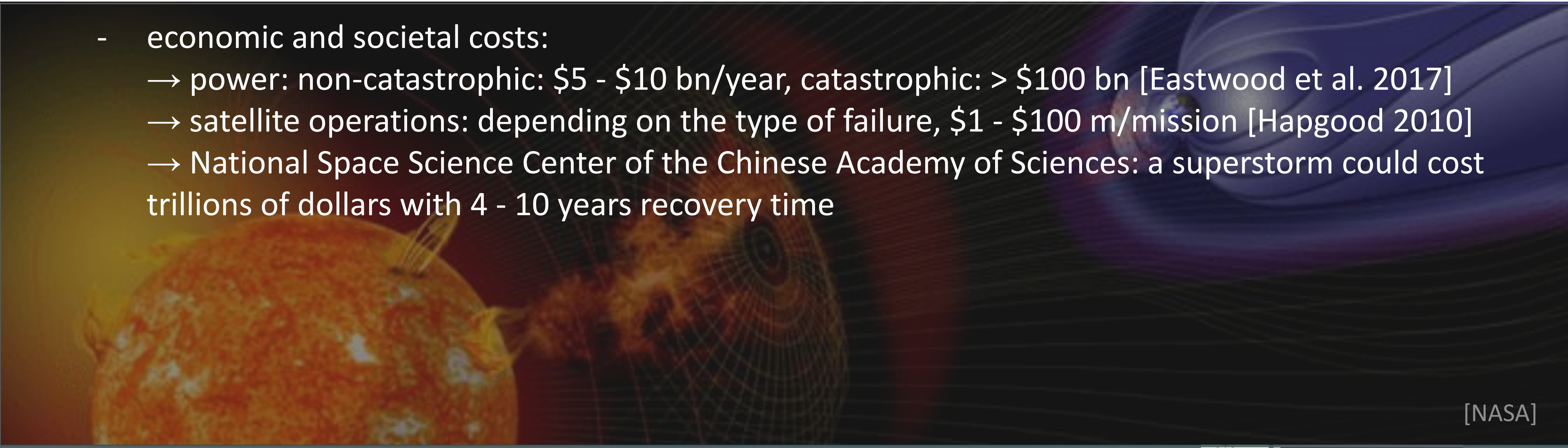
Space weather

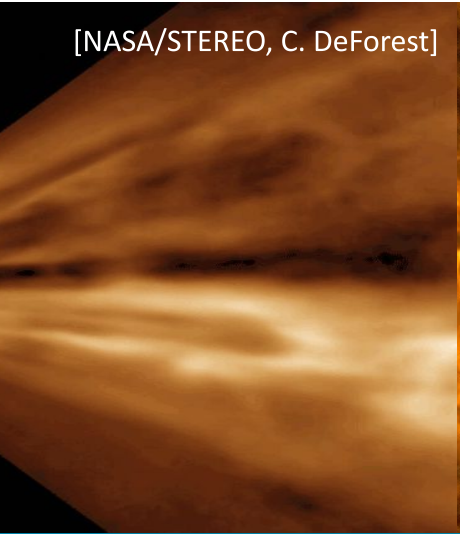
- describes conditions in space, around the Earth but also around other objects of interests: magnetic field, plasma velocity & density & temperature, particle precipitation
- largely determined by the Sun, but also (extra)galactic phenomena sources such as cosmic rays
- economic and societal costs:
  $\longrightarrow$ power: non-catastrophic: \$5 - \$10 bn/year, catastrophic: > \$100 bn [Eastwood et al. 2017]
  $\longrightarrow$ satellite operations: depending on the type of failure, \$1 - \$100 m/mission [Hapgood 2010]
  $\longrightarrow$ National Space Science Center of the Chinese Academy of Sciences: a superstorm could cost trillions of dollars with 4 - 10 years recovery time

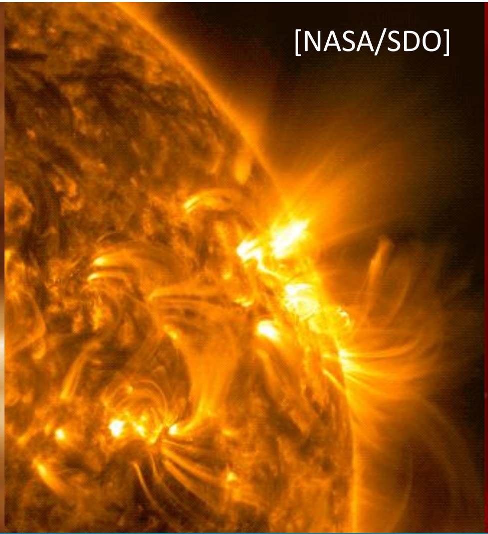


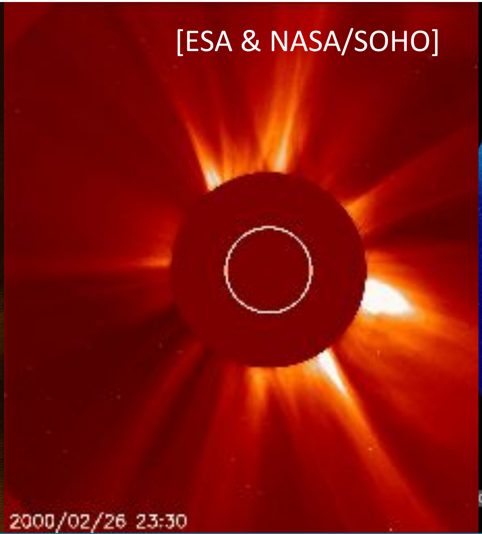
[NASA]

Space weather sources

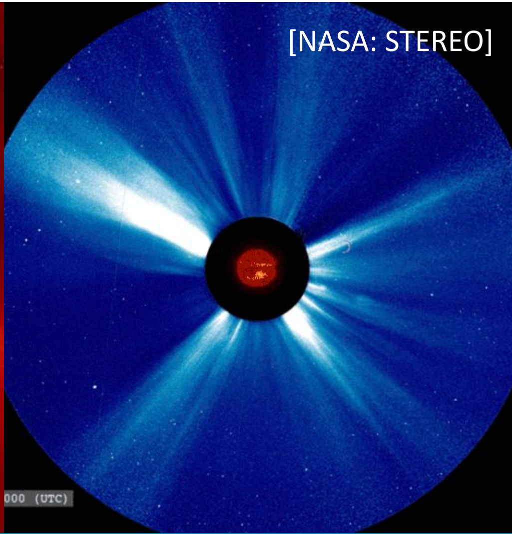
- the Sun:
  - solar flares, coronal mass ejections (CMEs), high speed streams, corotating interaction regions (CIRs), solar energetic particle (SEPs) acceleration (up to 100 MeV)


[NASA/STEREO, C. DeForest]


[NASA/SDO]

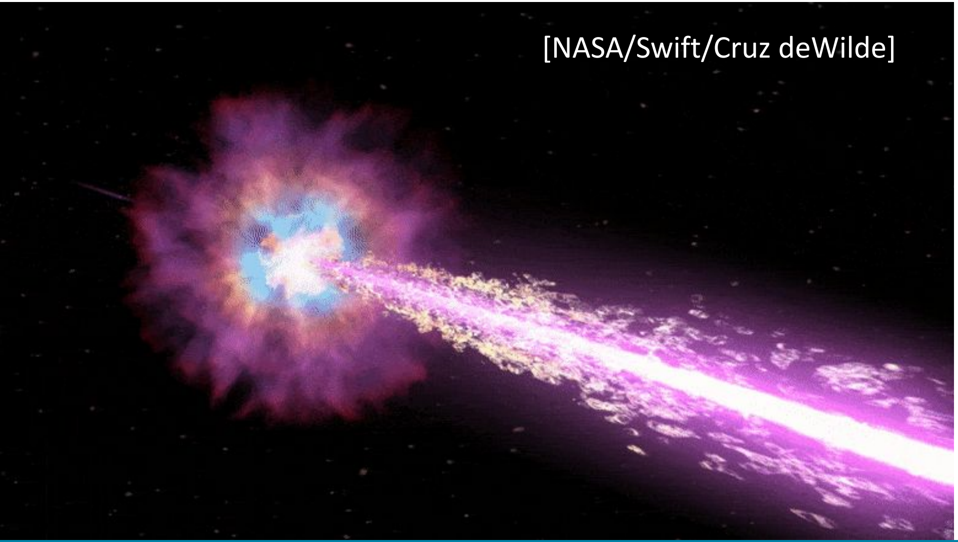


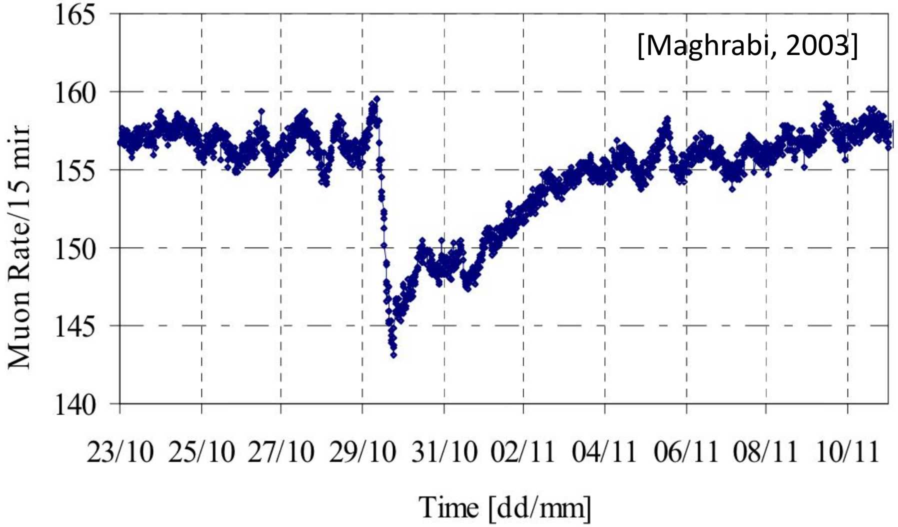
[ESA & NASA/SOHO]


[NASA: STEREO]

Space weather sources

- galactic & extra-galactic:
    - protons and nuclei CR (> 100 MeV), interaction of CR with solar SW sources (Forbush decrease, pre-increase/ pre-decrease) ⟶ might help forecast solar SW





Space weather effects

- in space weather forecasting, mostly divided into
    - geomagnetic storms (CMEs, CIRs, high speed streams)
    - solar flares
    - particle precipitation (SEPs, CRs)

Space weather effects

- in space weather forecasting, mostly divided into
  - **geomagnetic storms (CMEs, CIRs, high speed streams)**
    - K_p index: disturbance of the Earth's magnetic field, log scale
    - K_p 5 → G1, K_p 6 → G2, …, K_p 9 → G5

G1	G2	G3	G4	G5

every few days → every few years

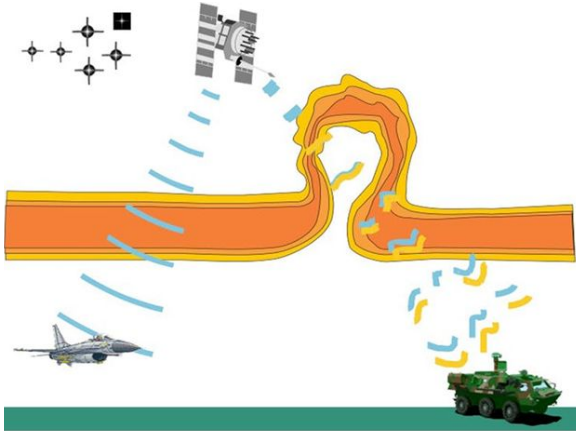
  - solar flares
  - particle precipitation (SEPs, CRs)

Geomagnetic storms: ionospheric scintillation

- plasma bubbles post-midnight due to increased geomagnetic activity (Huang et al. 2005):
  - the battle of Takur Ghar: Kp = 4, March 4, 2002

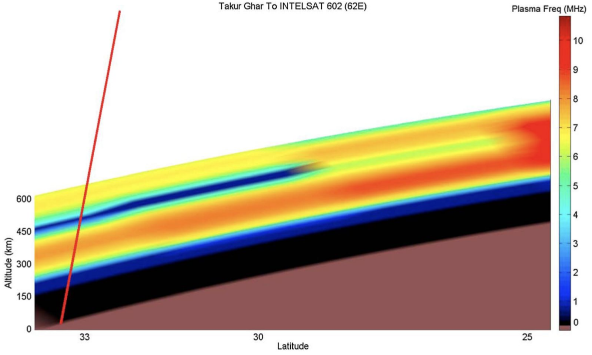
- during the battle, Chinook helicopters from the QRF were called to help Navy SEAL units); in the meantime, the area became “hot”, but the helicopters never received the repeated warnings avoid the area → the Chinook crashed and seven people died

- GUVI UV data - electron density reconstruction show clear e- depletion regions (Kelly et al. 2014)



Credit: U.S. Air Force Research Laboratory (AFRL)
https://www.nasa.gov/mission_pages/cindi/five-years.html

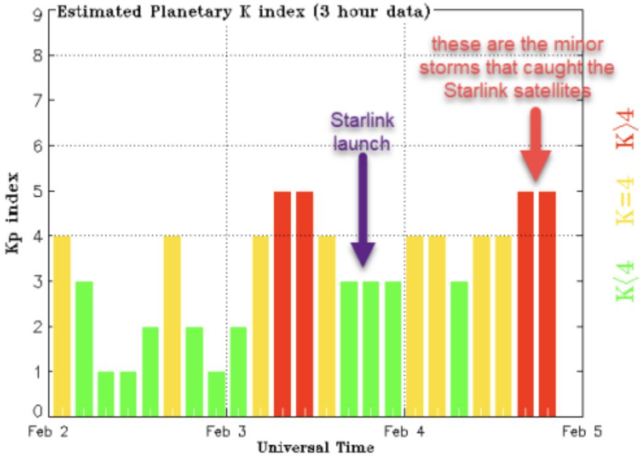
[Kelly et al. 2014]



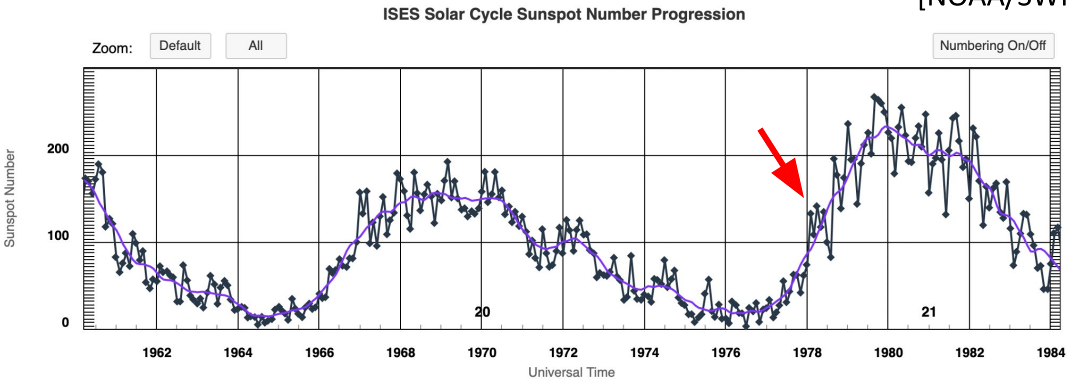
Geomagnetic storms: drag increase

- Starlink lost 40 satellites on February 4, 2022:
  - 2 days before launch a minor G1, the Earth passed in the wake of the CME → created another G1 storm
- Skylab station originally planned for de-orbit in 1982, premature re-entry in 1979 because of solar activity

[Spaceweather.com]



[NOAA/SWPC]

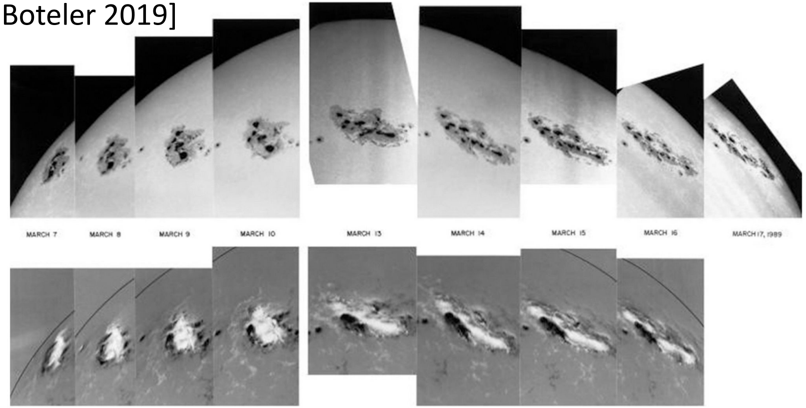


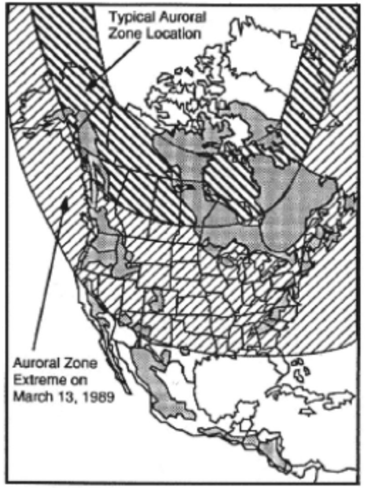
[NASA]

Geomagnetic storms: GICs

- March 13, 1989, 2:45 LT, G5
- within ~ 1.5 minutes the entire network collapsed, after 9 hours 17 % of the load still out of service
- 6M people without electricity
- costs to Hydro-Québec:
  - direct damage to equipment CAD 6.5M
  - total costs CAD 13.2M

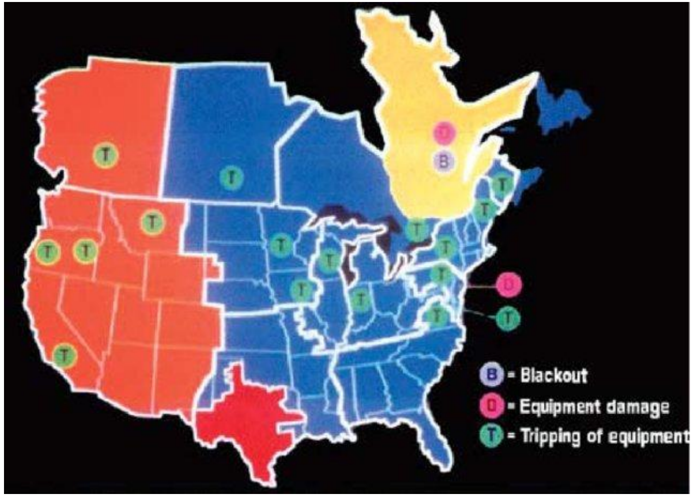
[Boteler 2019]





[Spaceweather.com]

Electric Power Research Institute, Inc.



Space weather effects

- in space weather forecasting, mostly divided into
  - geomagnetic storms (CMEs, CIRs, high speed streams)
  - **solar flares**
    - X-ray flux, in classes A, B, C, M, X (M class: 10e-5 W/m2, X class: 10e-4 W/m2)
    - M1 → R1, M5 → R2, X1 → R3, X10 → R4, X20 → R5

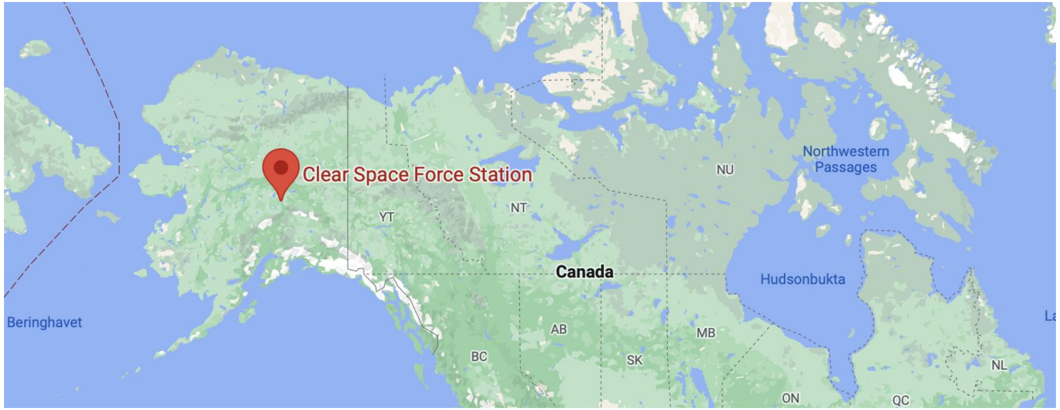
R1	R2	R3	R4	R5

every few days → every few years

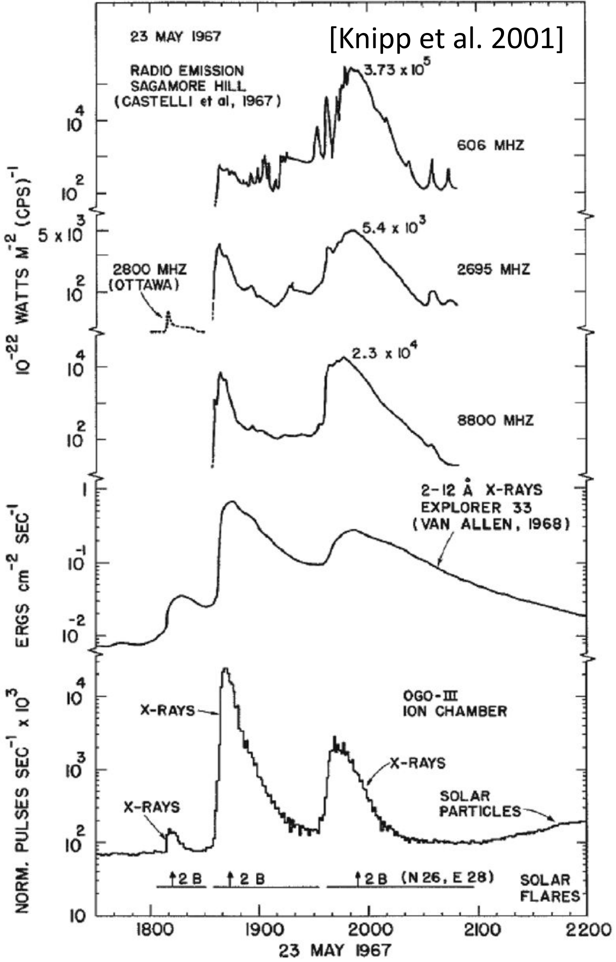
  - particle precipitation (SEPs, CRs)

Solar flares: disruption of radars (BMEWS)

- in May 1967, a Kp 9 (G5) storm associated with a series of X-class flares (R3+)
  - disruption of the US ballistic missile early warning systems radio signal (interference, HF blackout, ionospheric scintillation)

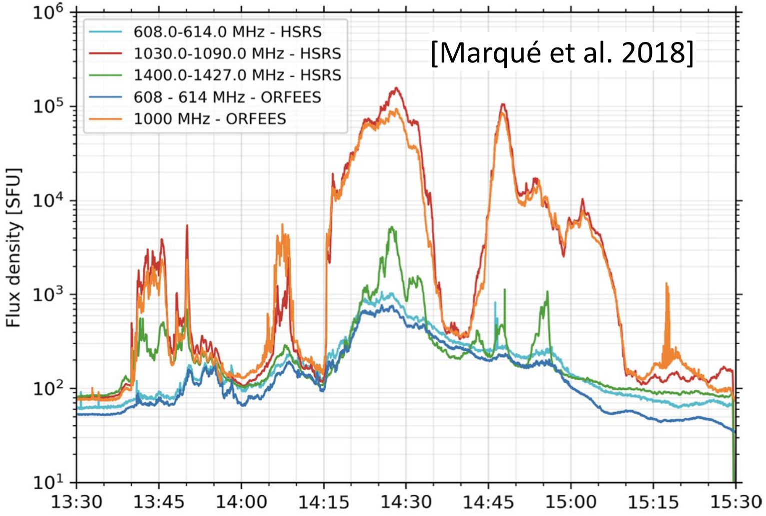


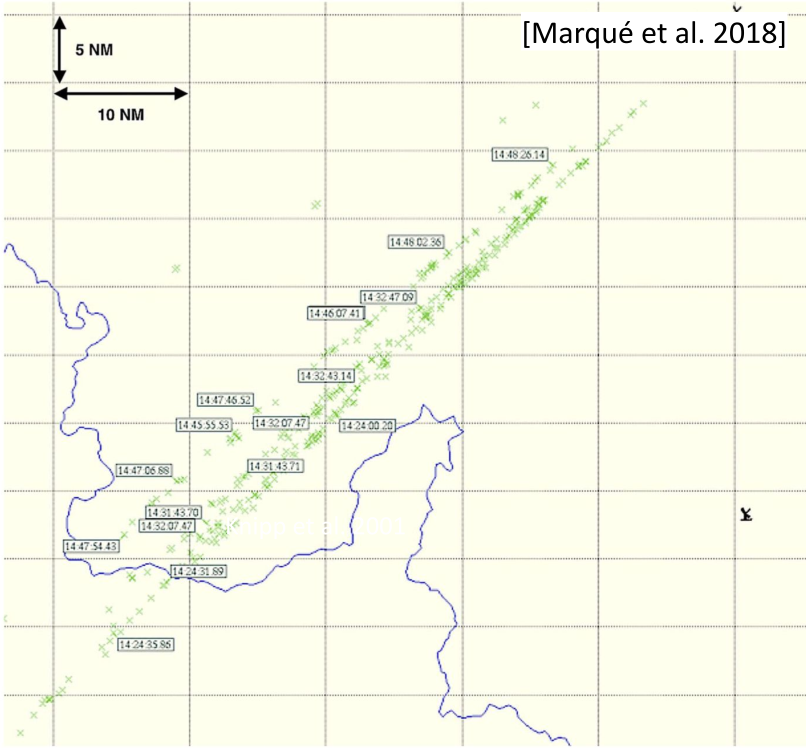
[Knipp et al. 2001]



Solar flares: disruption of radars (Swedish air-traffic grounding)

- November 4, 2015, M3.7 solar flare responsible for disruption of secondary air traffic radars (1030 to 1090 MHz), showing "ghost echoes"





Space weather effects

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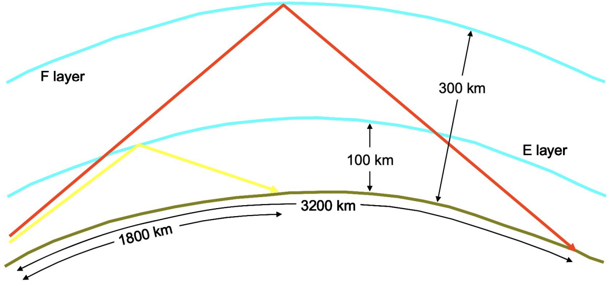
  - geomagnetic storms (CMEs, CIRs, high speed streams)
  - solar flares
  - **particle precipitation (SEPs, CRs)**
    - scale S1 to S5, flux of 10 - 100 MeV particles
    - 10 pfu $\longrightarrow$ S1, …, 100 000 pfu $\longrightarrow$ S5

S1	S2	S3	S4	S5

every few months $\longrightarrow$ every few years

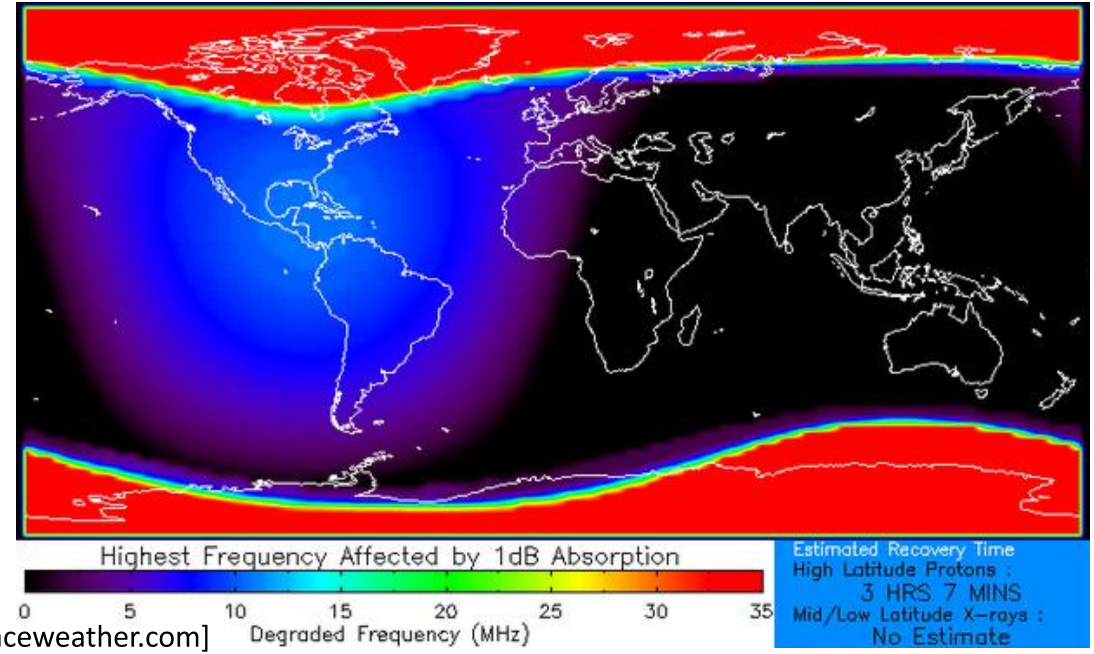
Particle precipitation: polar cap absorption



- D layer ionisation due to high energy particle precipitation

- affects HF frequencies
  → HF cannot propagate through D to E or F layers

  → HF communication cannot be used by A/C for polar routes
  → SATCOM instead



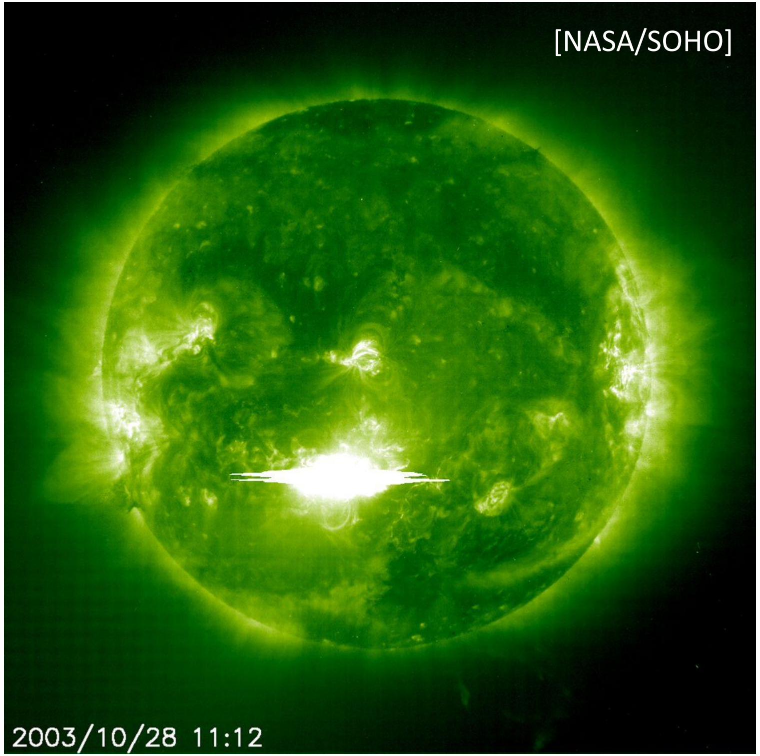
[Spaceweather.com]

Particle precipitation: electronics effects

- high-energy particles penetrate electronics: single event effects

- Halloween 2003 storms, October 29 2003:
  - Goddard's SS Mission Operations Team: 59% of NASA's Earth and space science satellites were affected (data outages, reboots, unwanted thruster firings)

  - USAF operators: over half a satellites lost, up to 3 days to reestablish contact



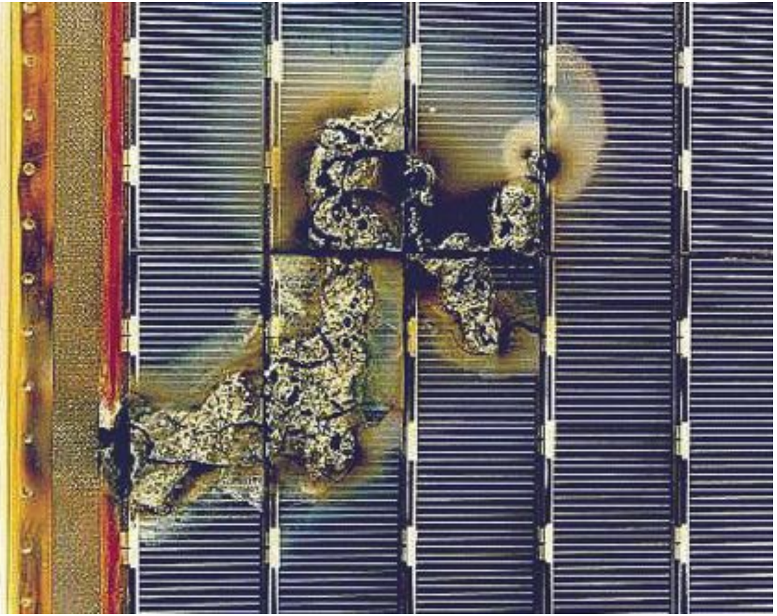
Particle precipitation: spacecraft charging

- surface charging due to hot e- forming above auroras (LEO) or due to solar flux (GEO)

- e.g. Galaxy 15 telecomm. sat lost for 8 months in April 2010, the ADEOS-II ($570M) in a high inclination LEO lost its power system completely in October 2003

- damage to materials, electronics, PVAs, interference with measurements, sometimes complete loss of power & control

[ESA]



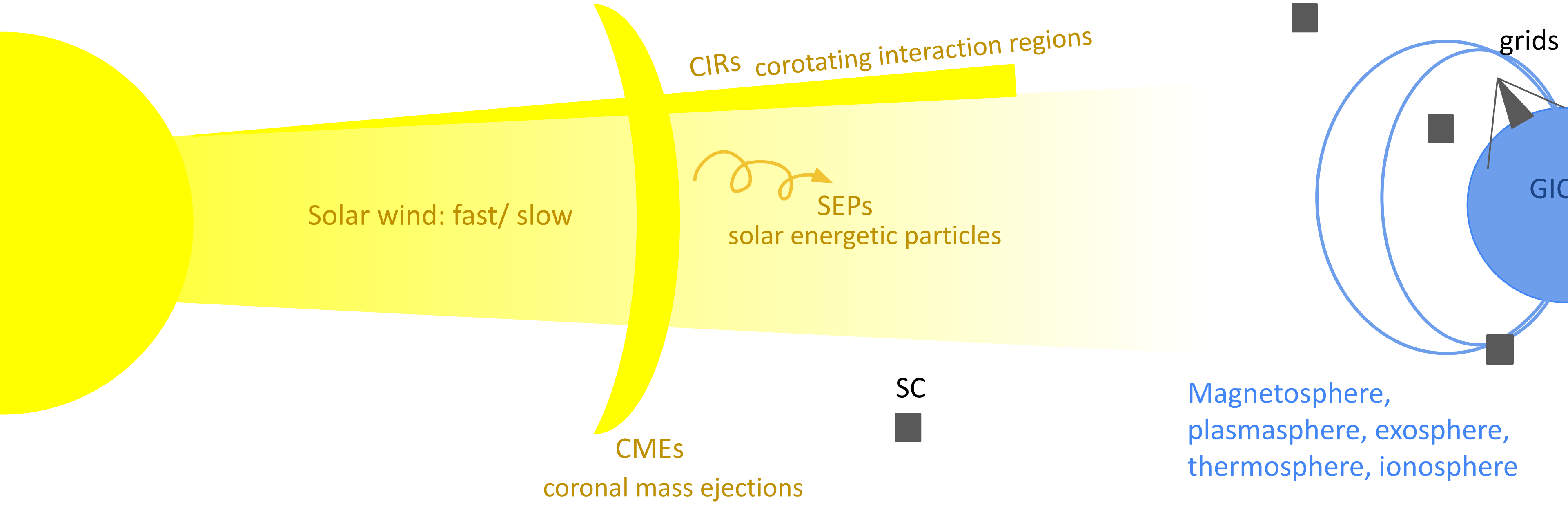
The need for space weather forecasting

- users, e.g.:
  - airlines & pilots
  - power grid operators
  - defence
  - satellite operators
  - other radio operators
  - aurora hunters

- require **space weather forecasting** (short-term: 1-3 days in advance/ long-term: months to years in advance) and **nowcasting** (current conditions and conditions in the next 30 to 90 minutes) **to avoid or reduce/ mitigate system damage and/or mission failure**

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

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



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

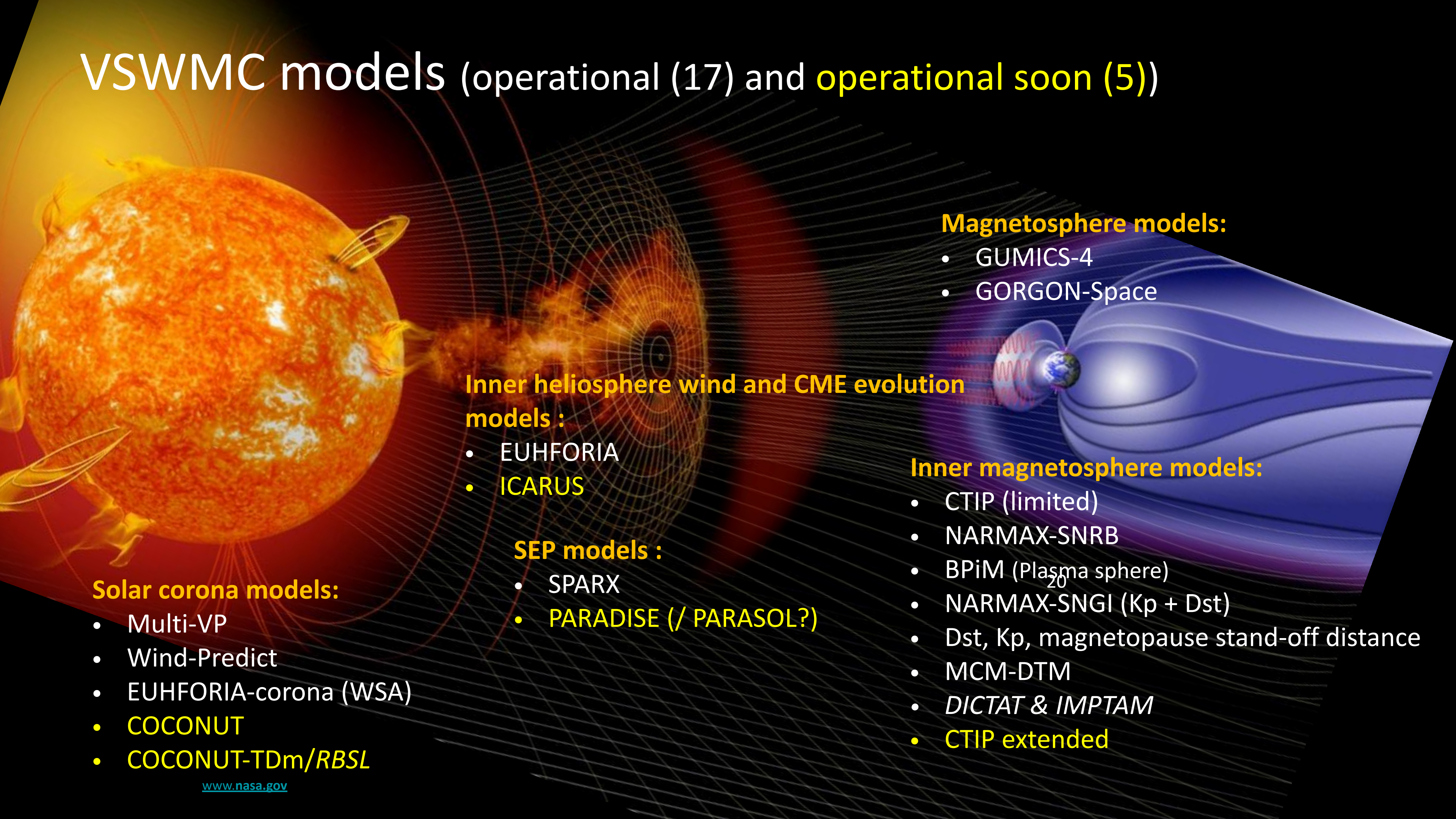
Magnetosphere models:
- GUMICS-4
- GORGON-Space

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

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

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

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



www.nasa.gov

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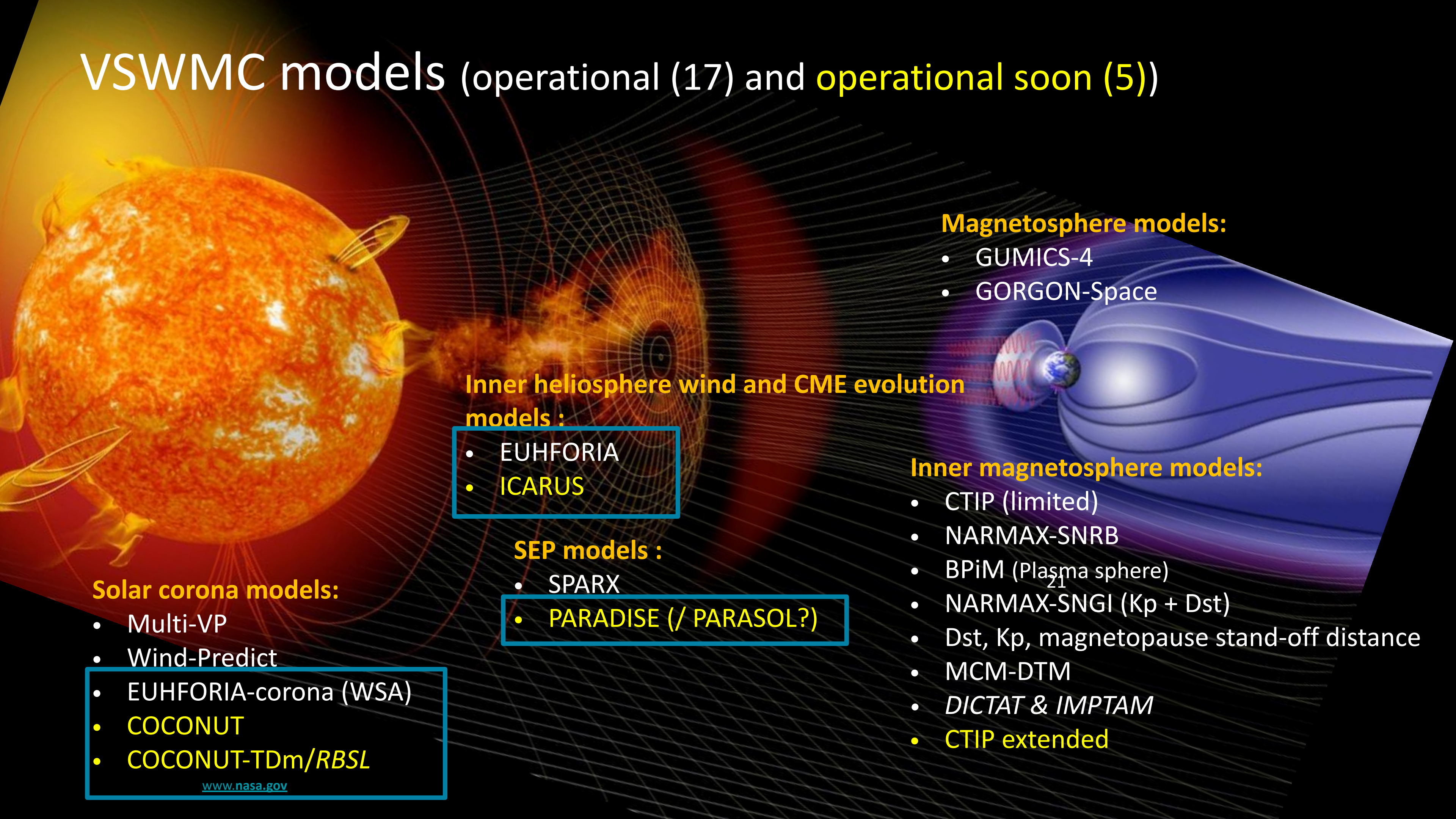

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www.nasa.gov

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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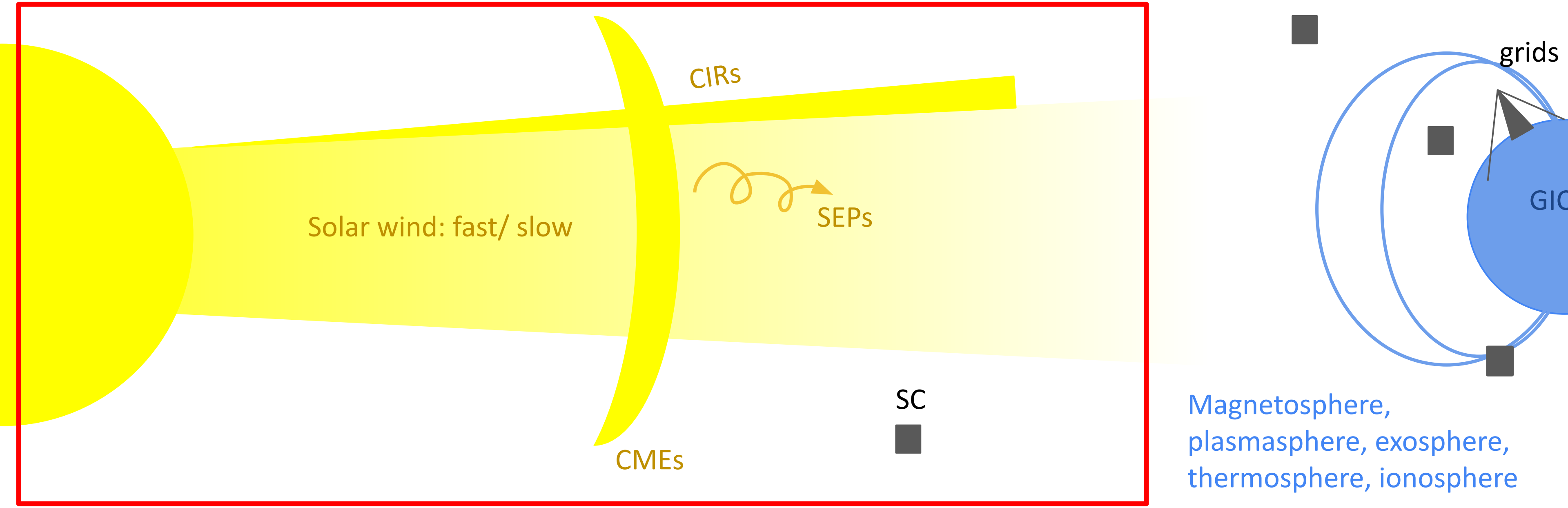
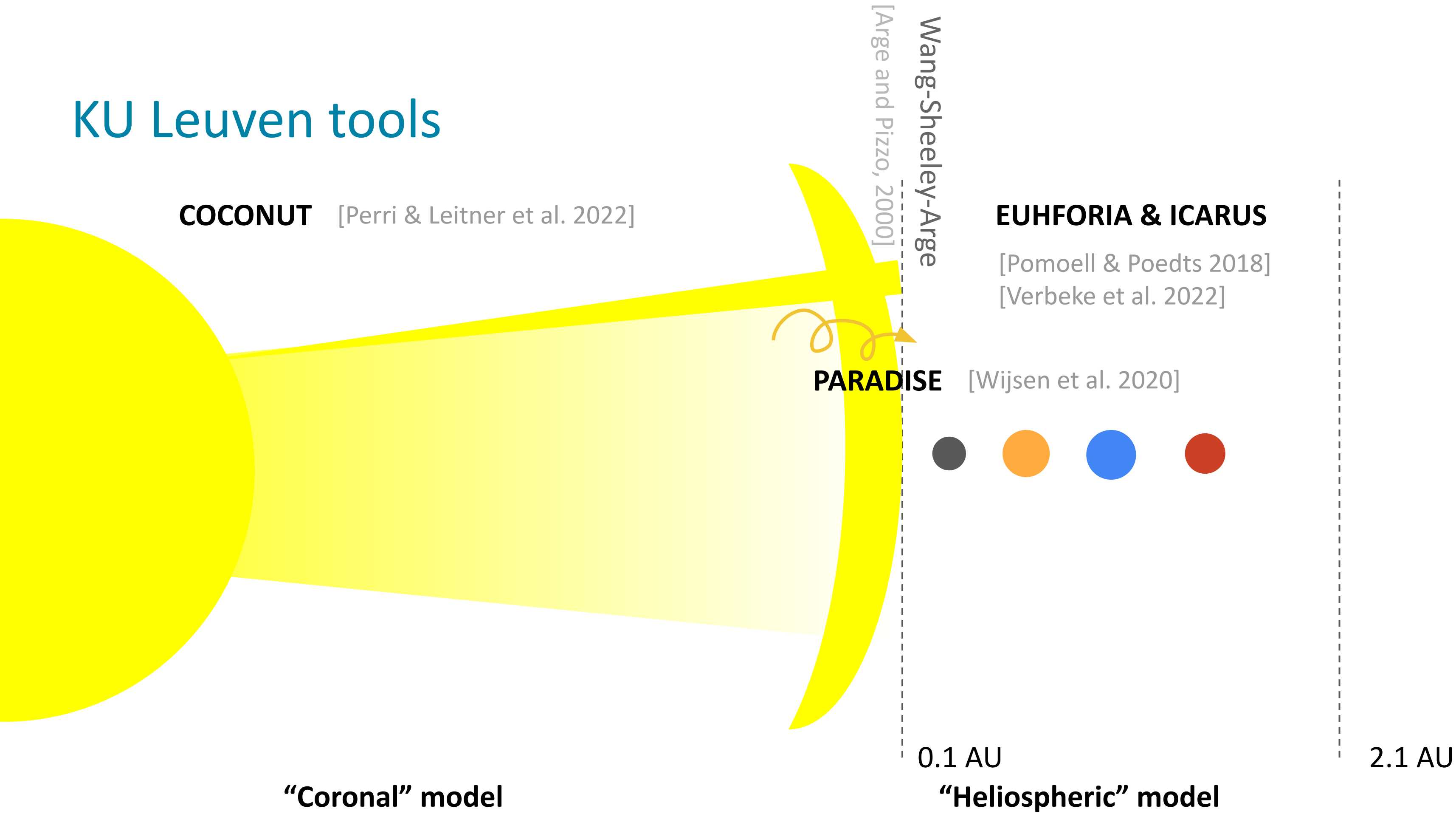


KU Leuven tools



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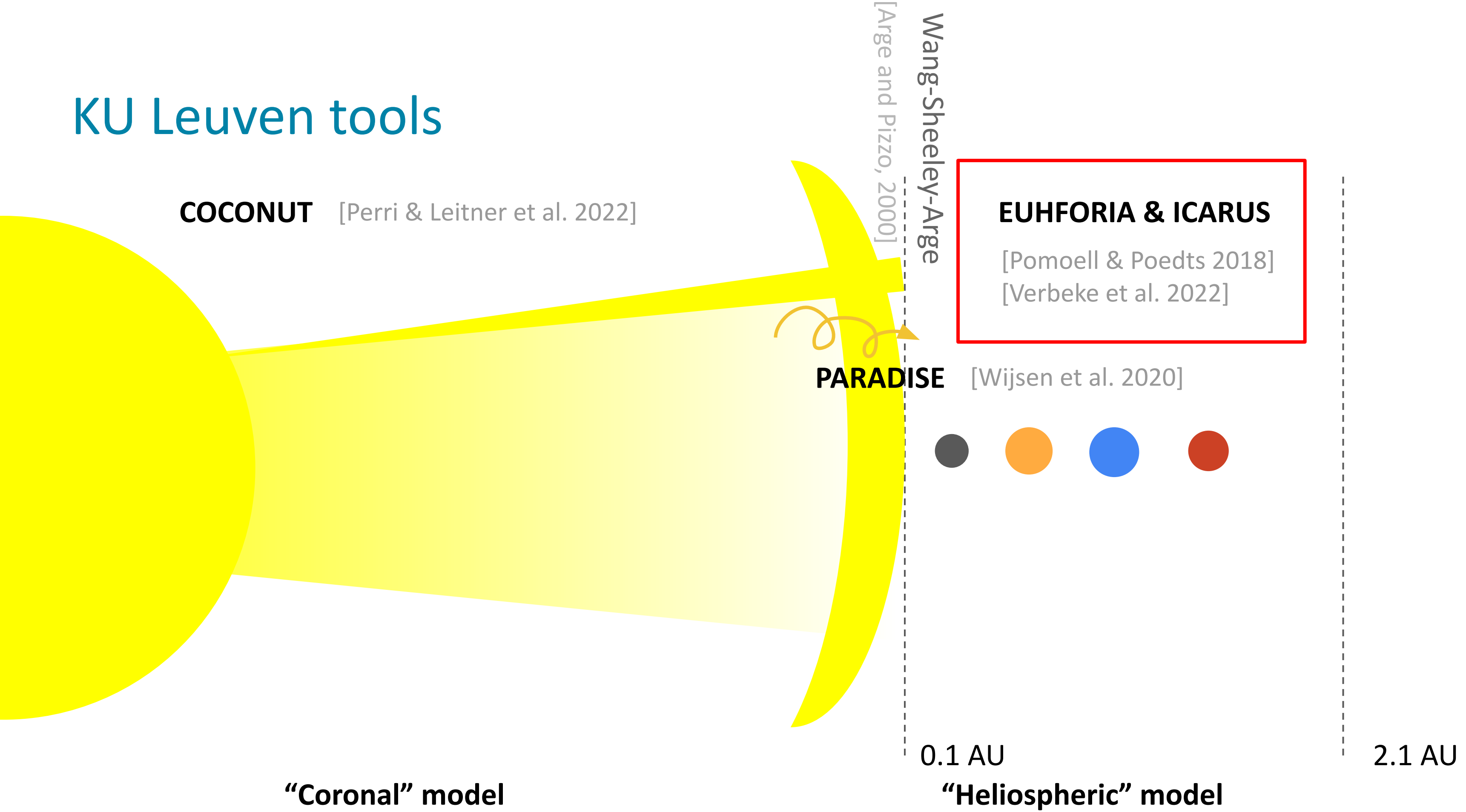
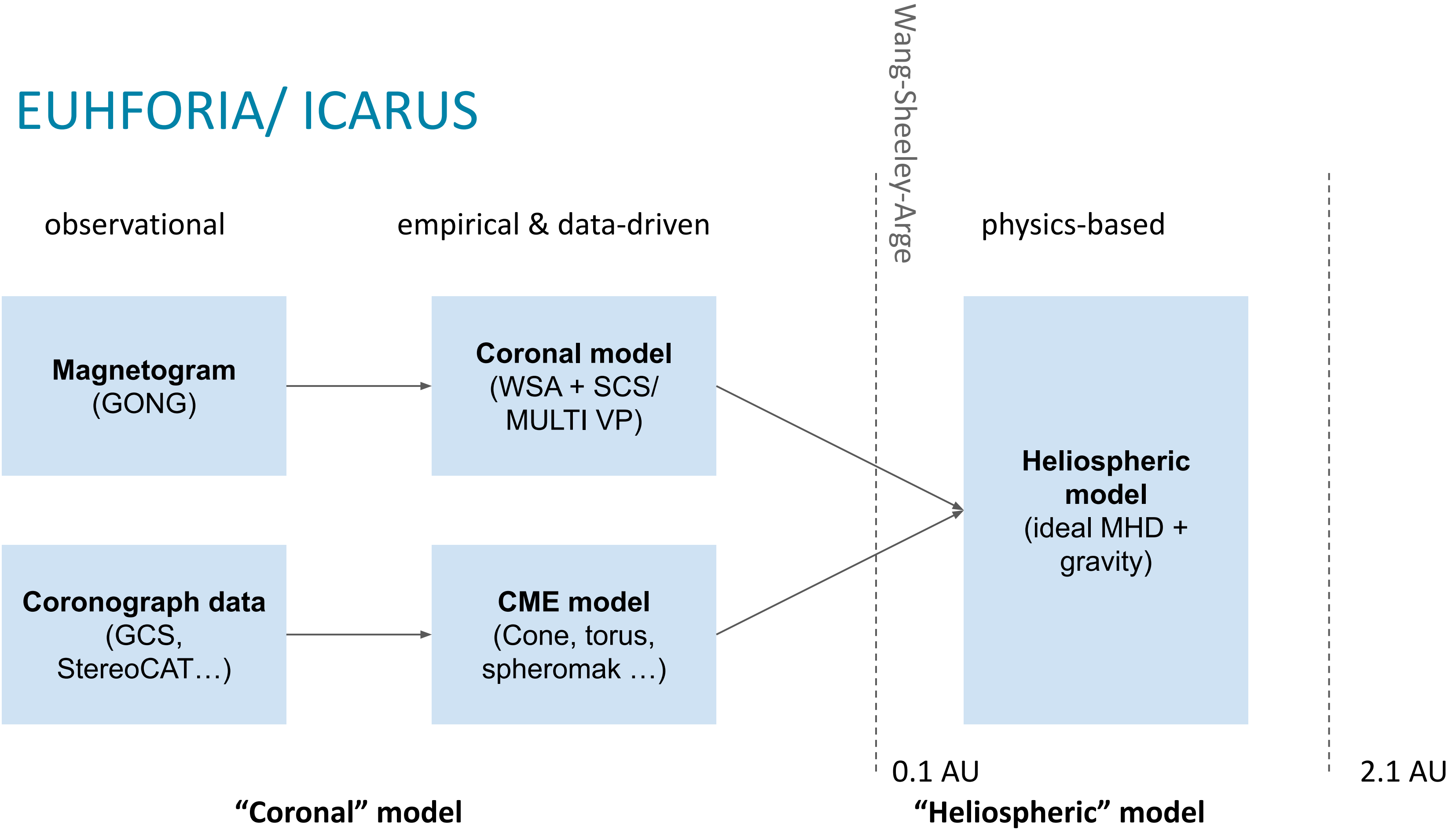


EUHFORIA/ ICARUS



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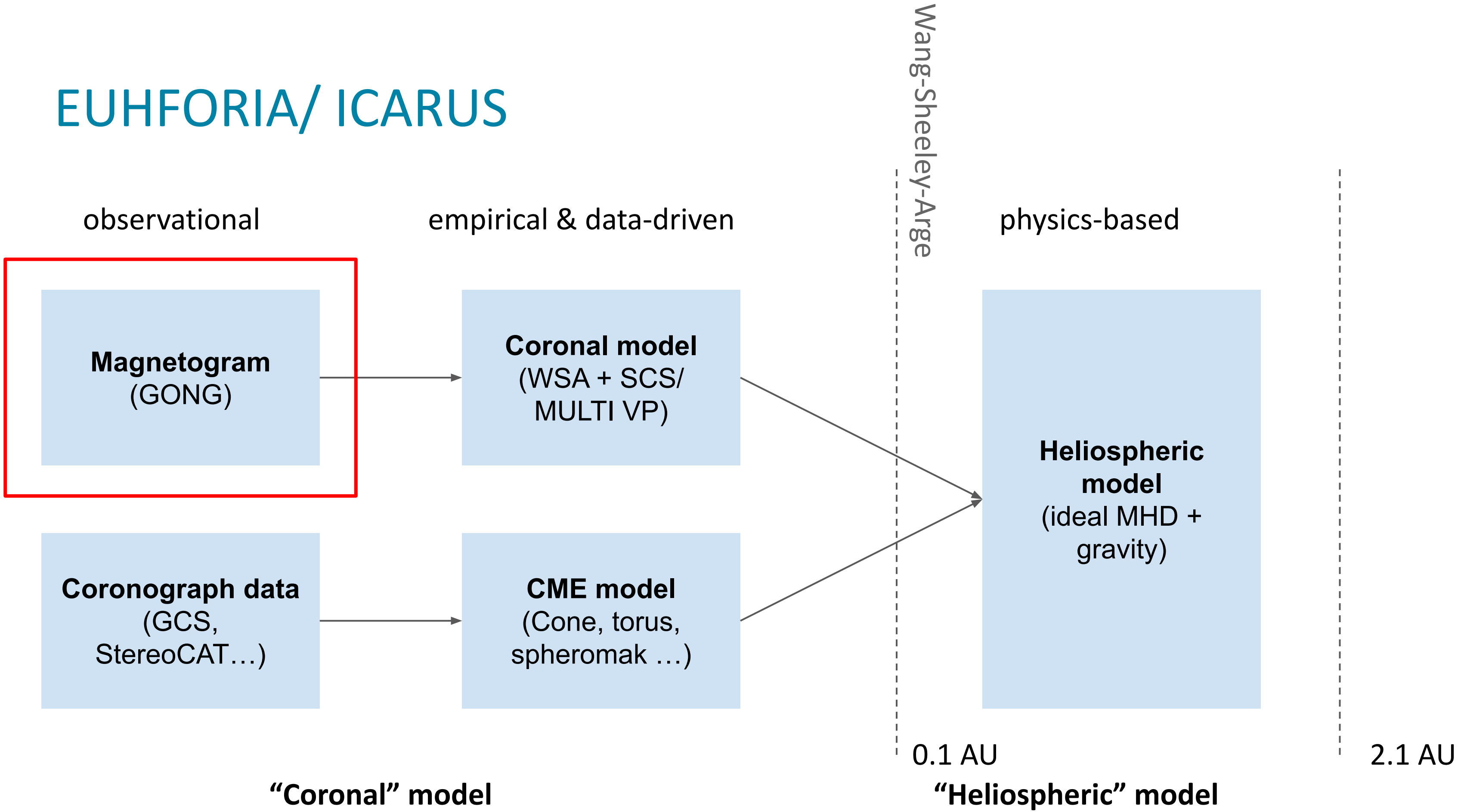
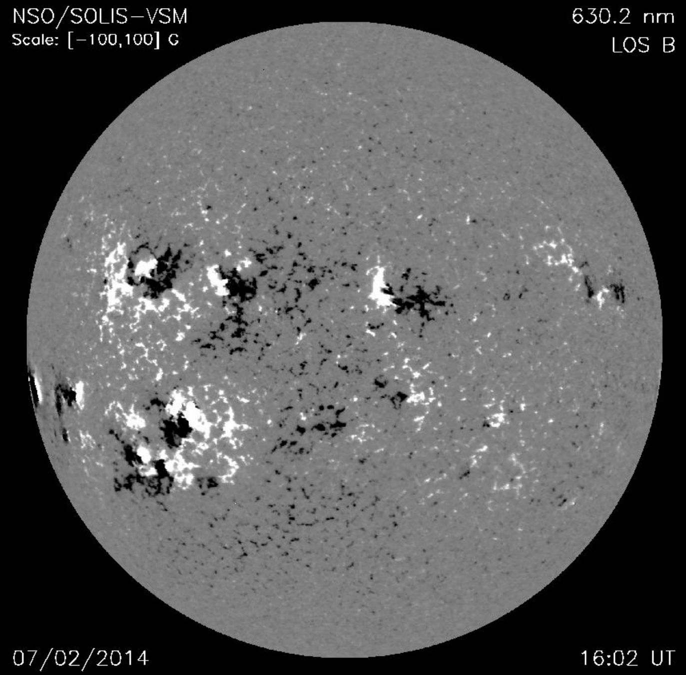
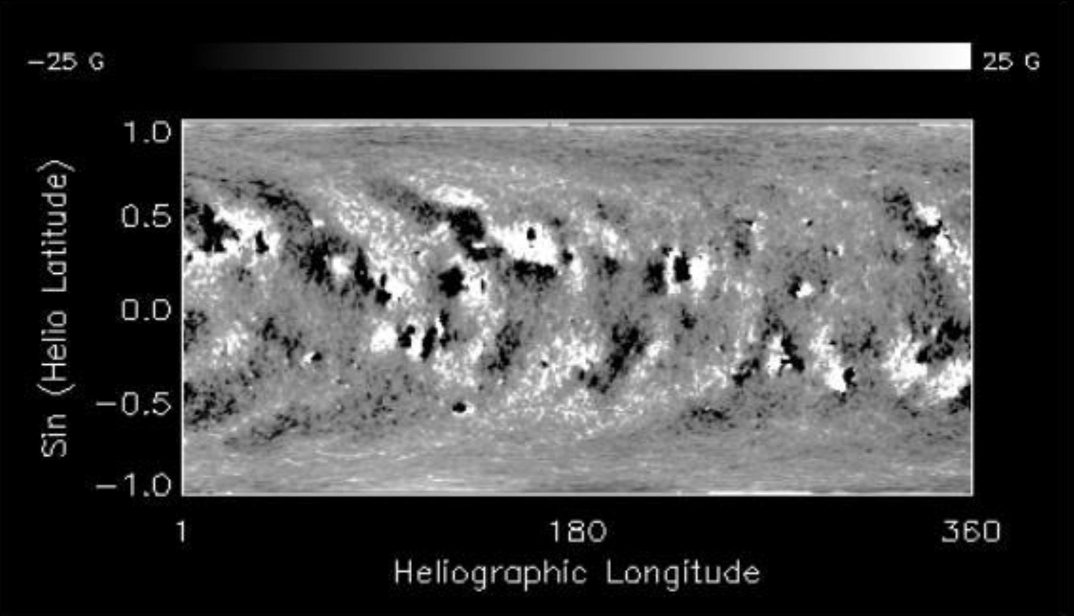


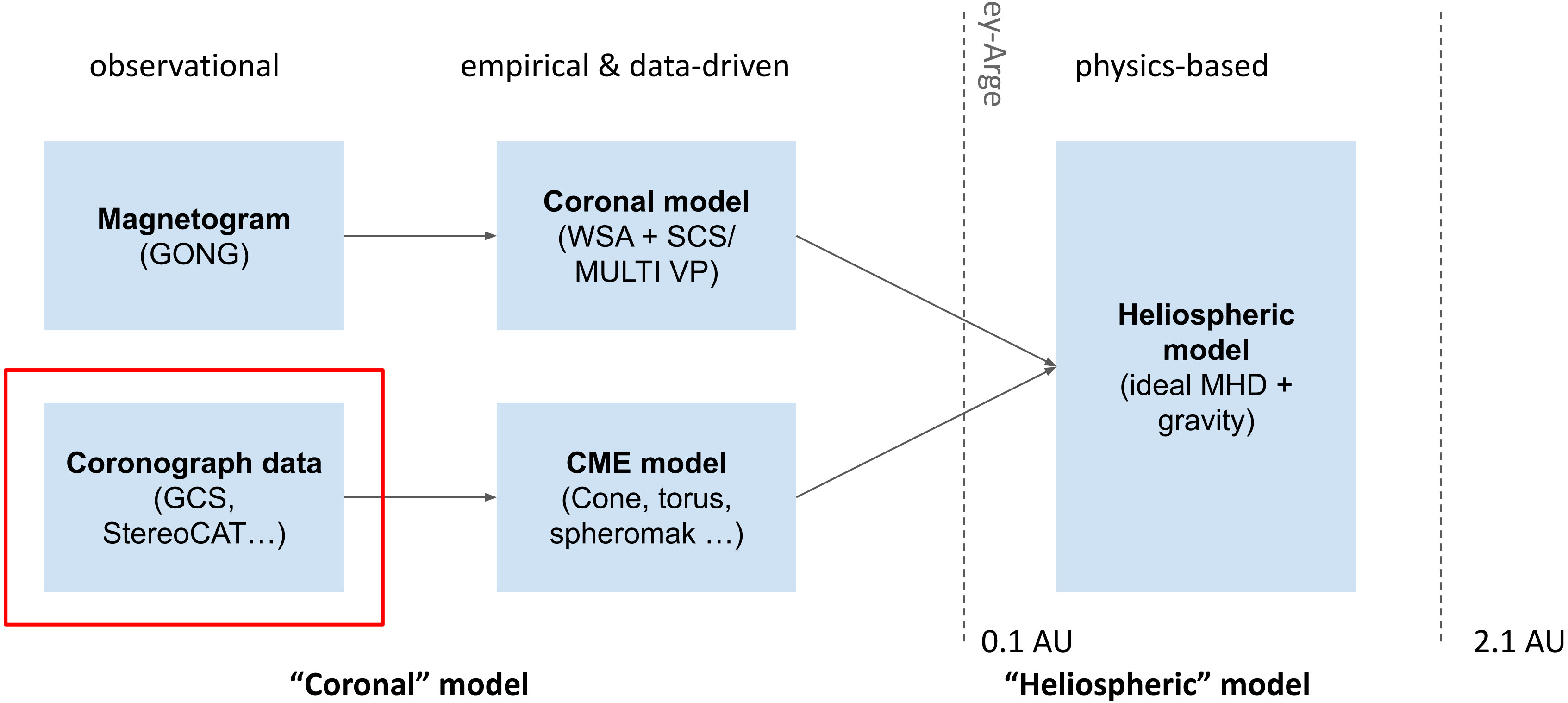
EUHFORIA/ ICARUS: GONG magnetograms

[Jin et al. 2016]



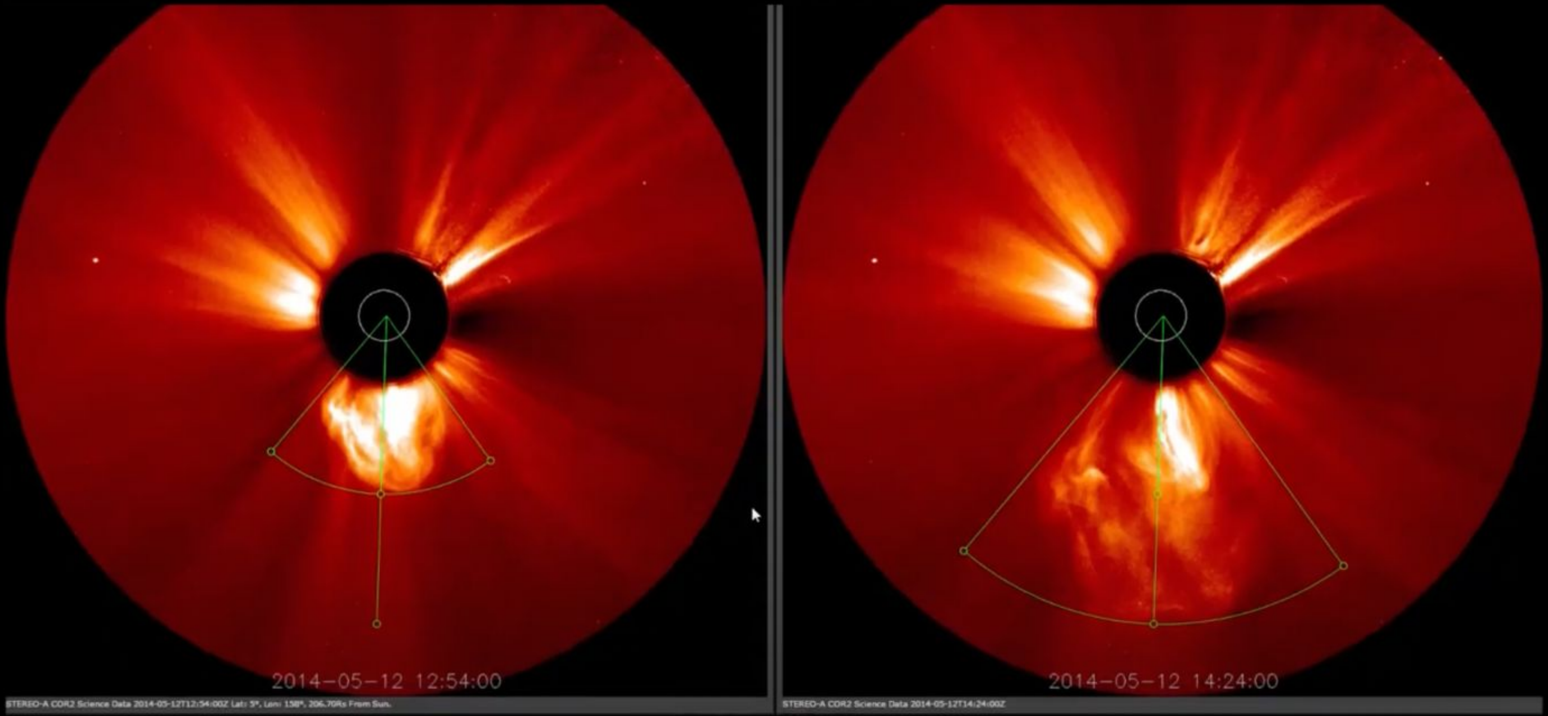


EUHFORIA/ ICARUS

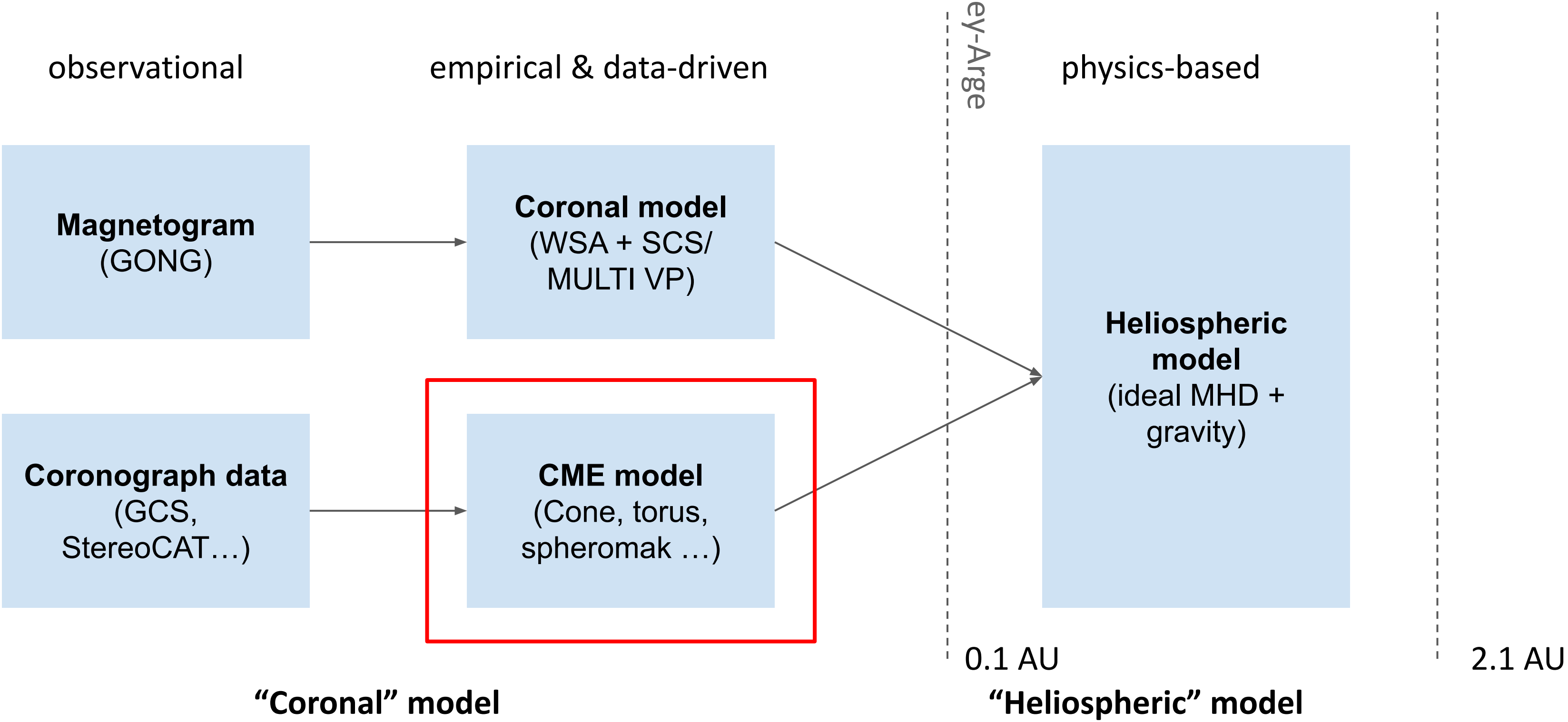


EUHFORIA/ ICARUS: StereoCAT / GCS

[NASA, STEREO-A-COR2]



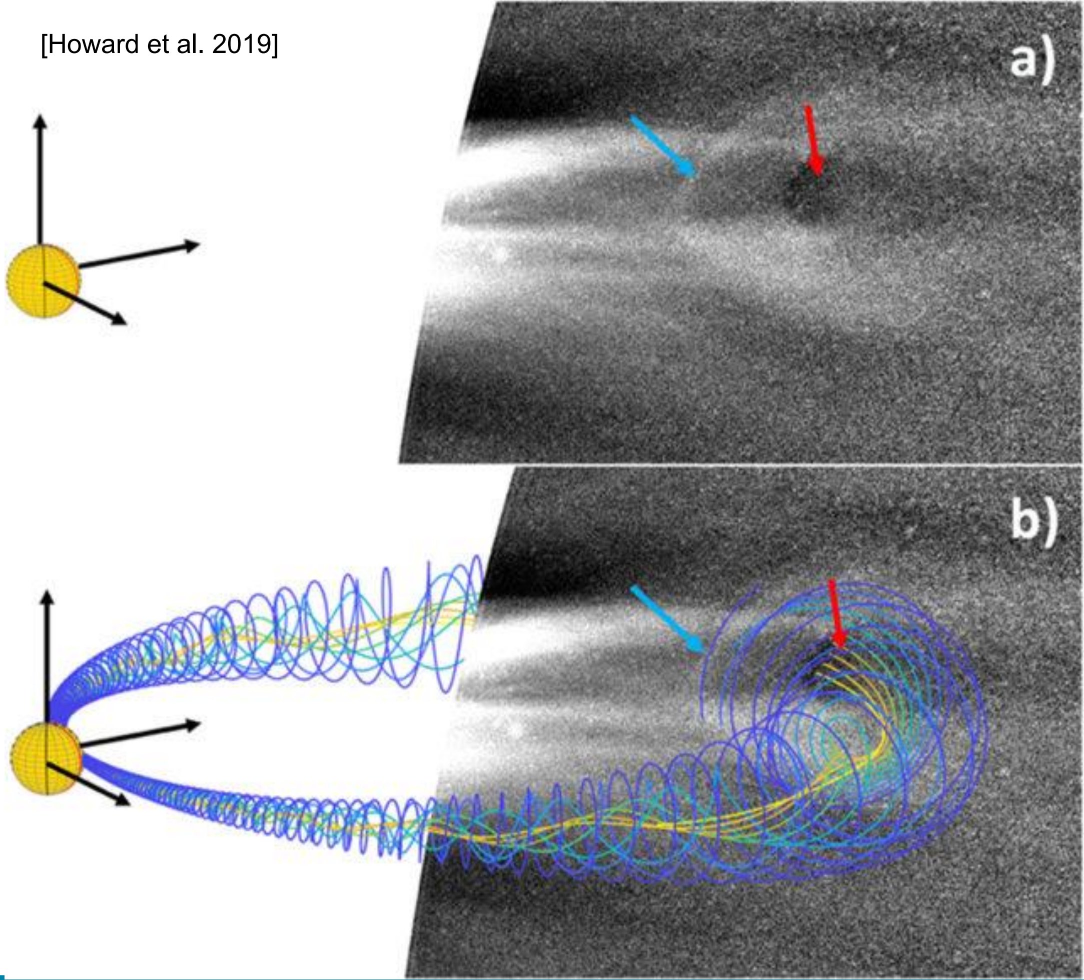
EUHFORIA/ ICARUS



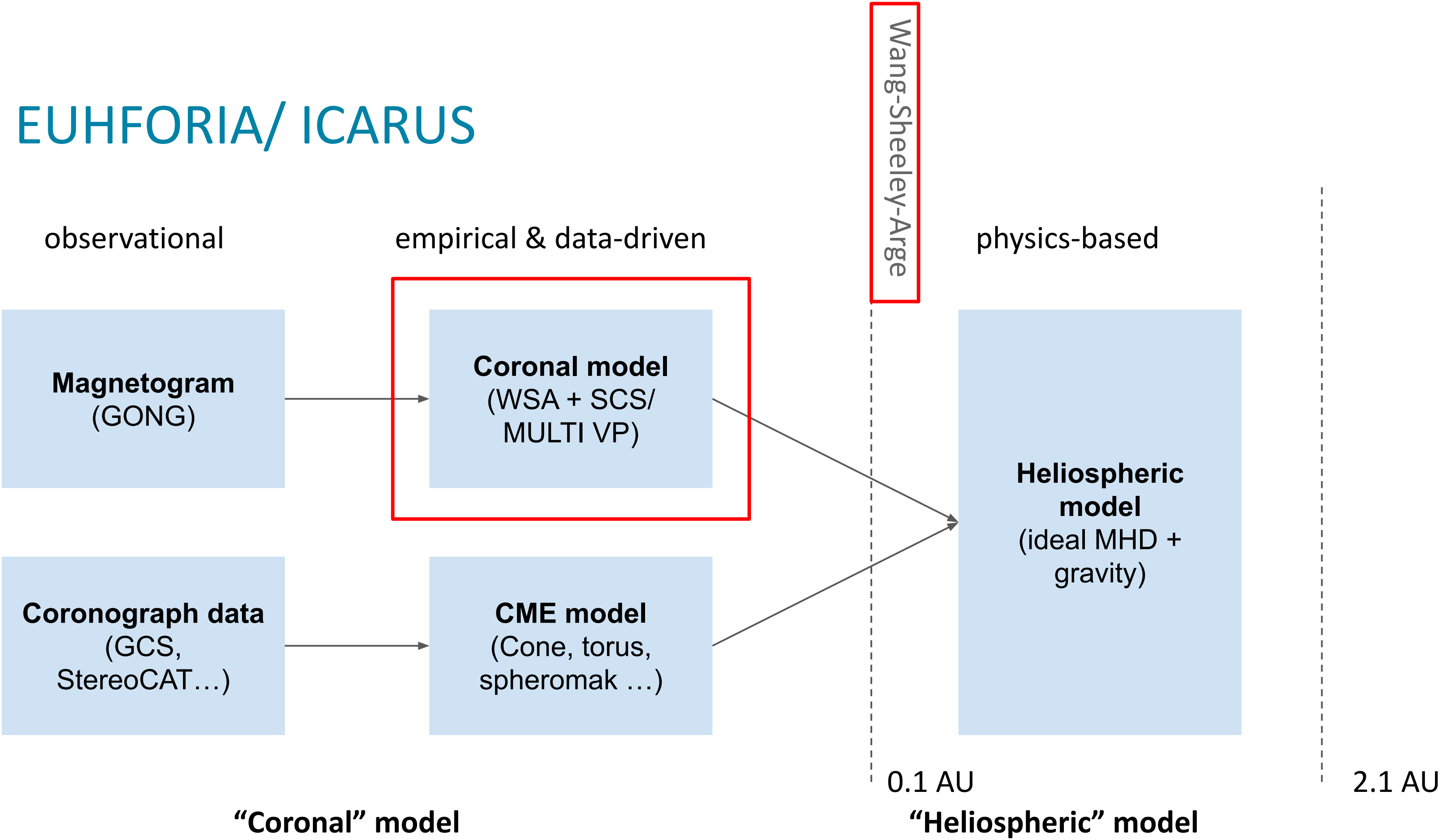
[Howard et al. 2019]

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



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:

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

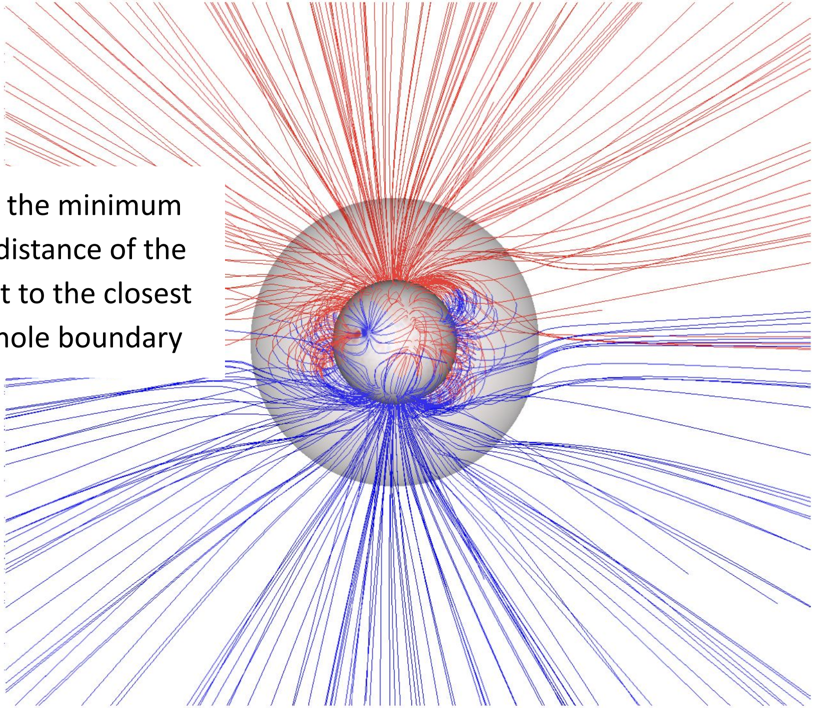
here d is the minimum angular distance of the footpoint to the closest coronal hole boundary

- 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:

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



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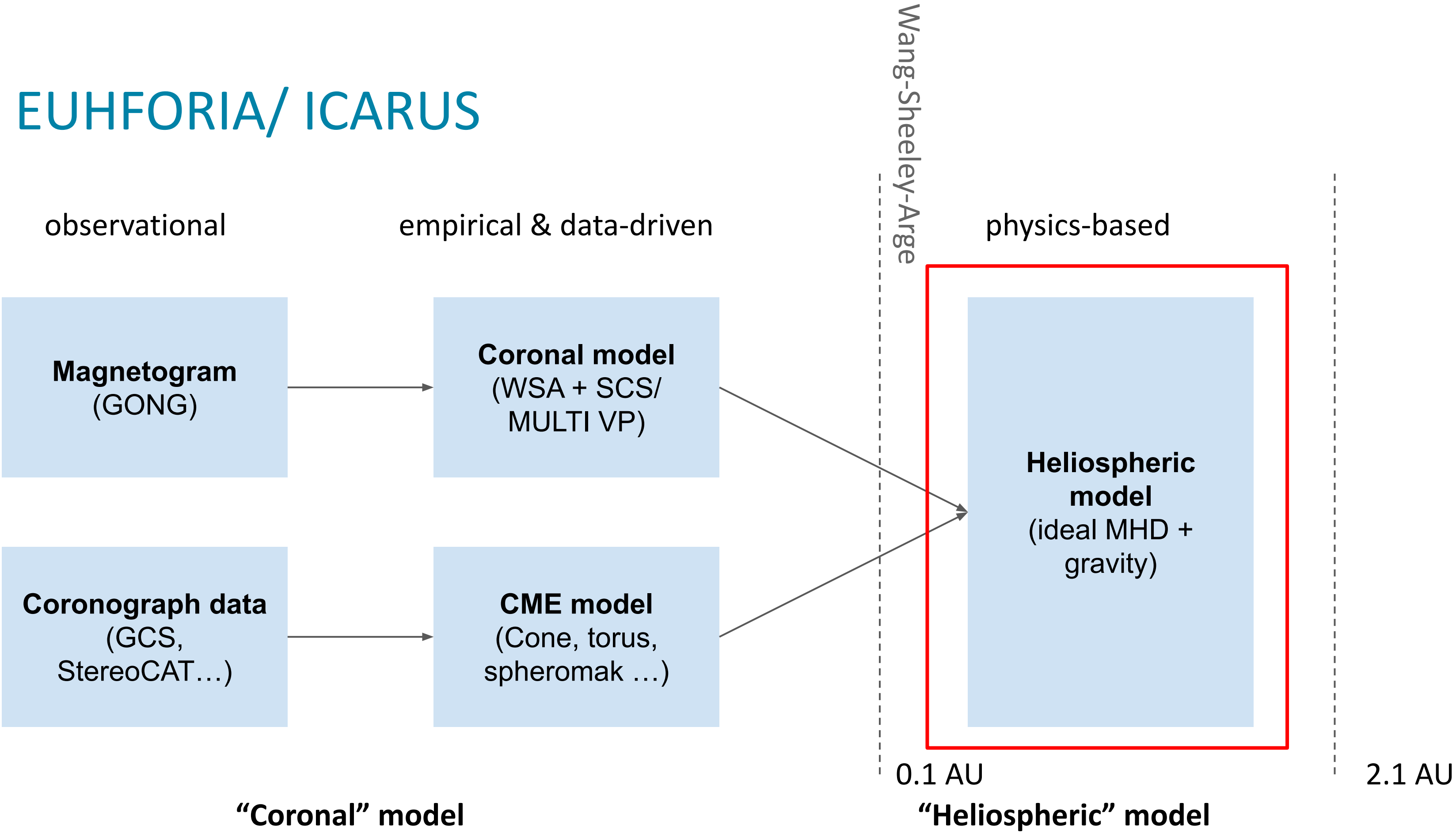


EUHFORIA/ ICARUS ideal MHD

[Pomoell & Poedts 2018]

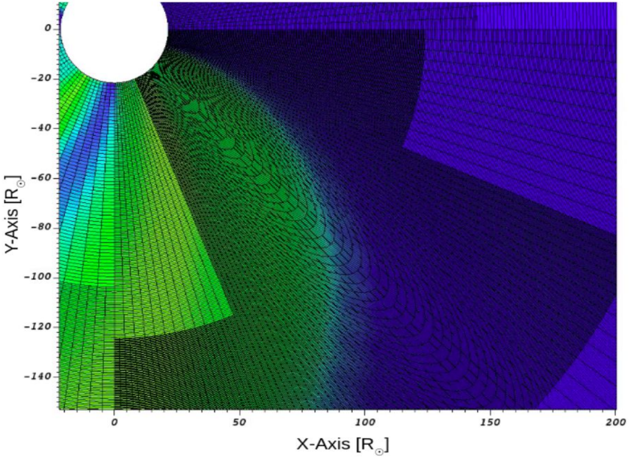
- in the rest of the heliospheric domain (0.1 - 2.1AU): ideal MHD + gravity
- ICARUS: EUHFORIA, but based on MPI-AMRVAC (Keppens et al. 2012) with AMR & grid stretching

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

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

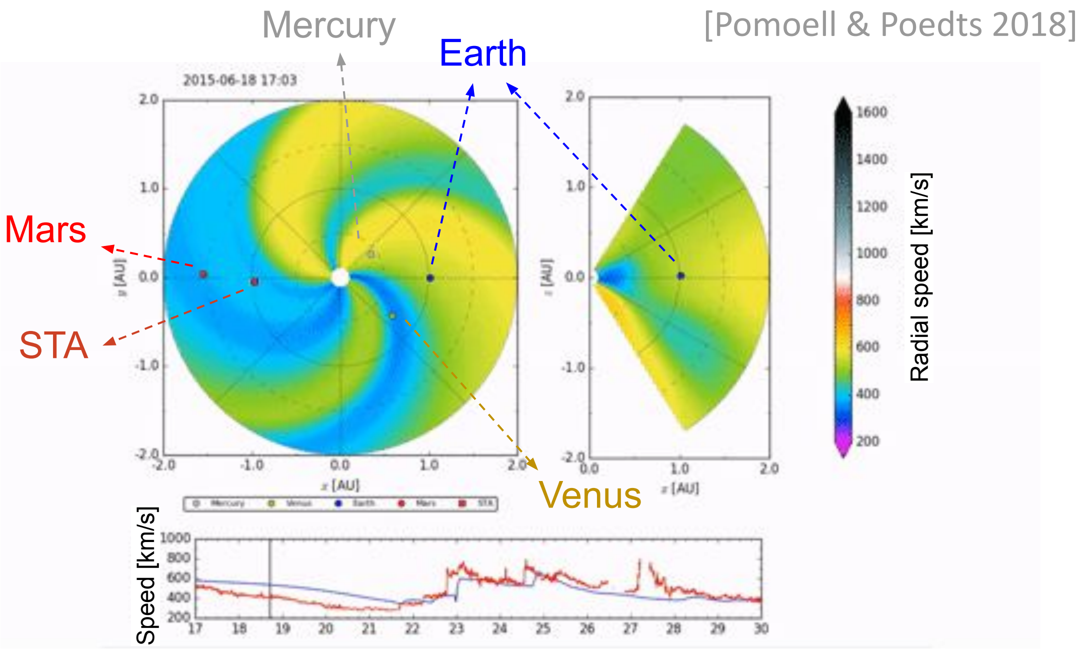
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}),$$

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



[Verbeke et al. 2022]

EUHFORIA (Pomoell & Poedts 2018): Preview



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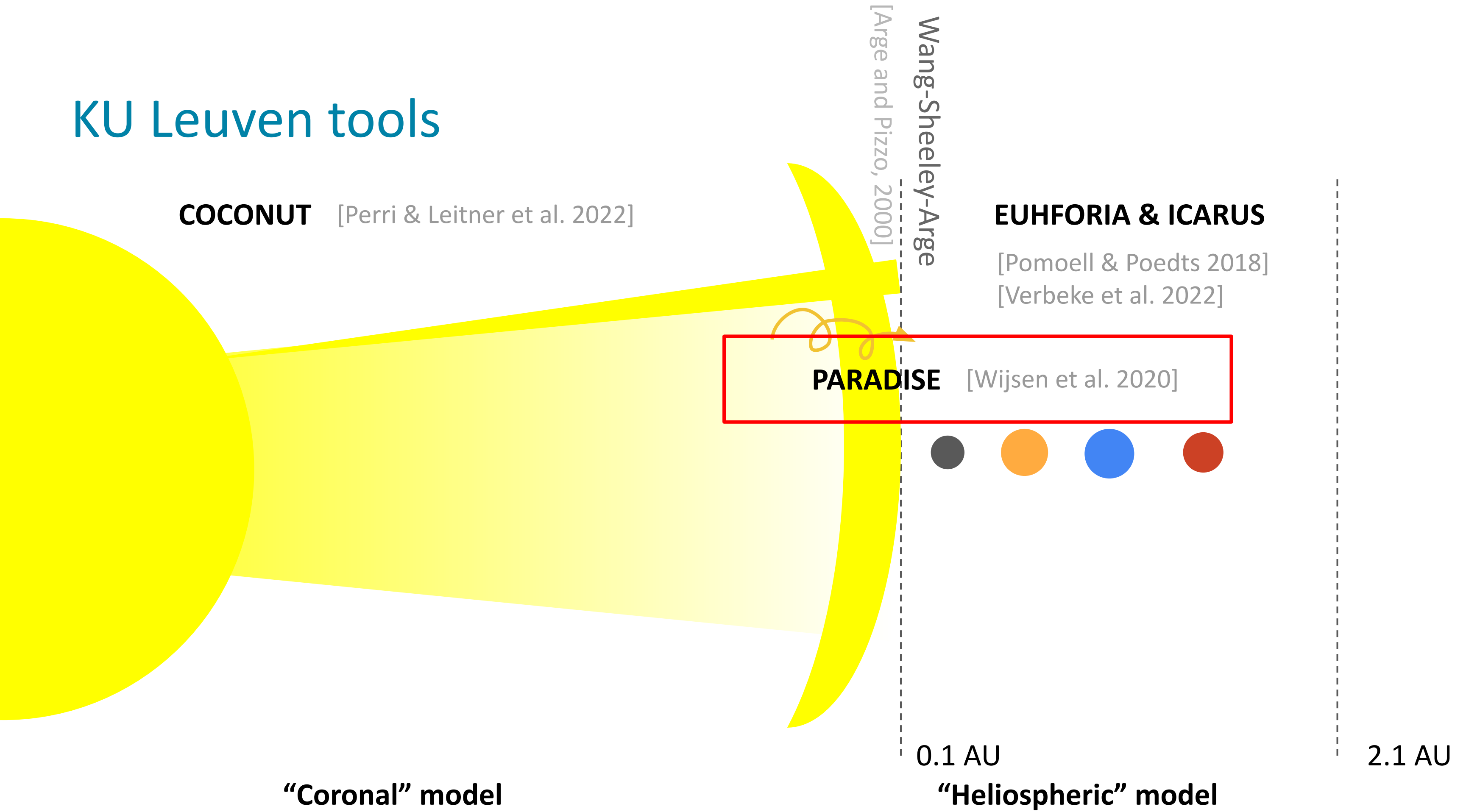
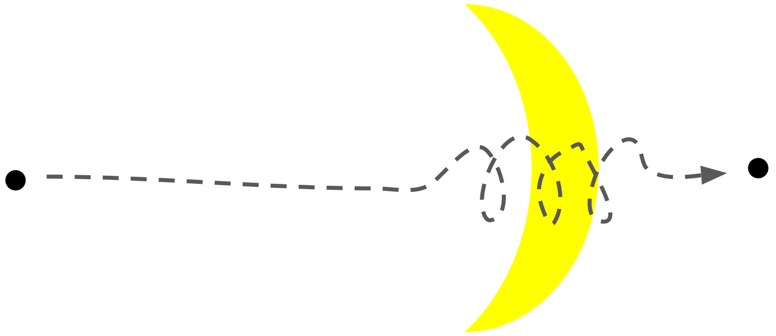


Paradise (Wijsen et al. 2020)



- 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

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

solar wind velocity

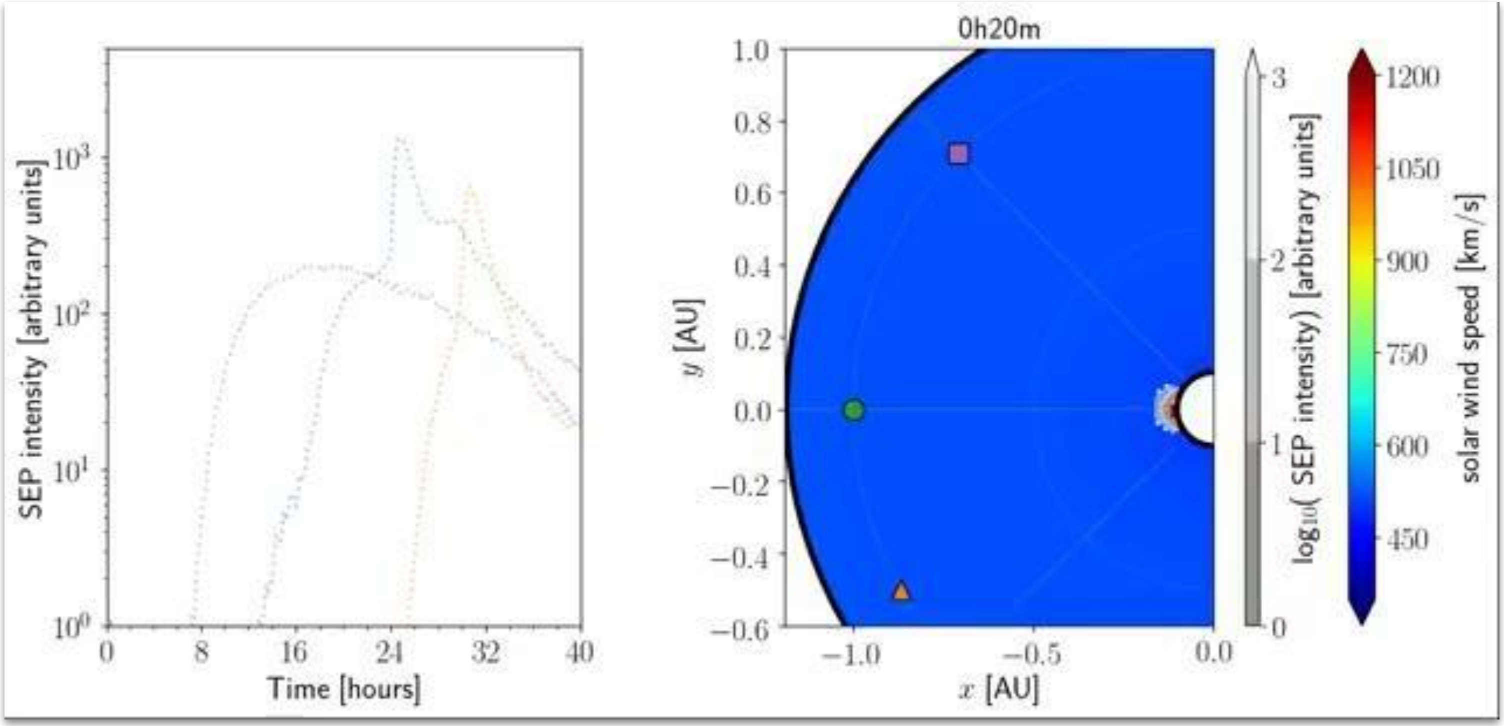
drift velocity

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

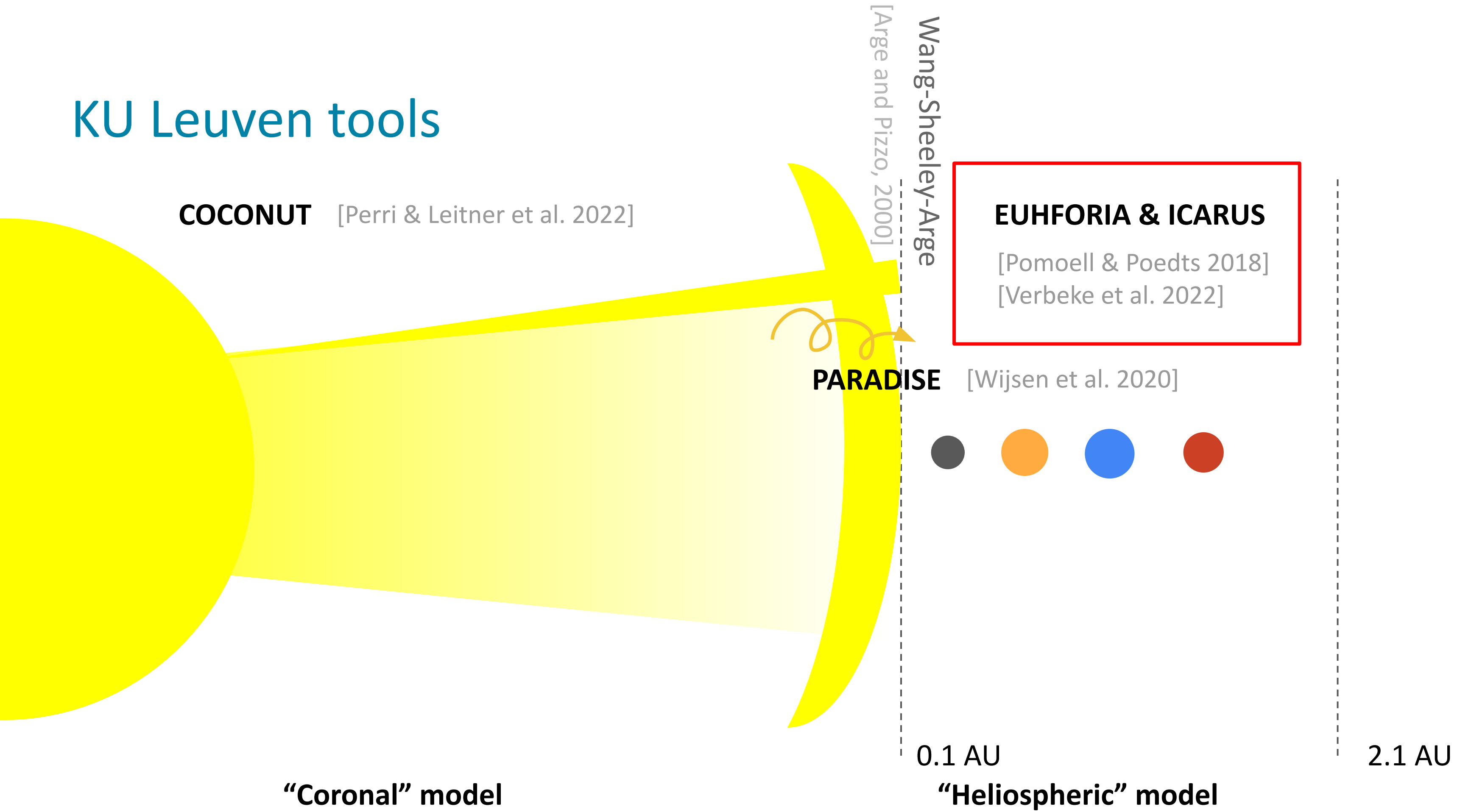
$$\frac{d\mu}{dt} = \frac{1-\mu^2}{2}\left(v\nabla \cdot \mathbf{b} + \mu \nabla \cdot \mathbf{V}_{\mathrm{sw}} - 3\mu \mathbf{bb} : \nabla \mathbf{V}_{\mathrm{sw}} - \frac{2}{v}\mathbf{b} \cdot \frac{d\mathbf{V}_{\mathrm{sw}}}{dt}\right)$$

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

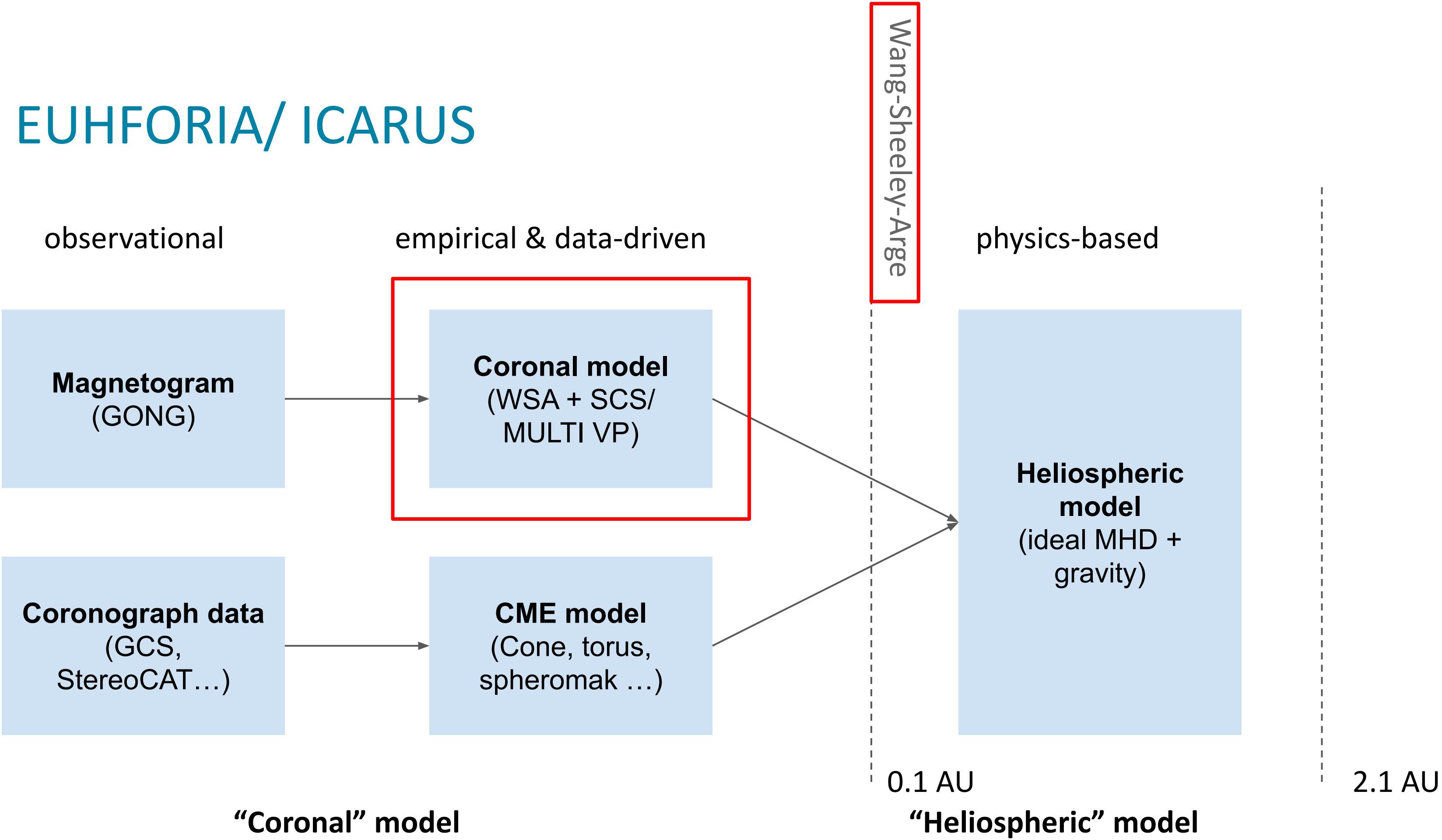
Paradise (Wijsen et al. 2020): Preview



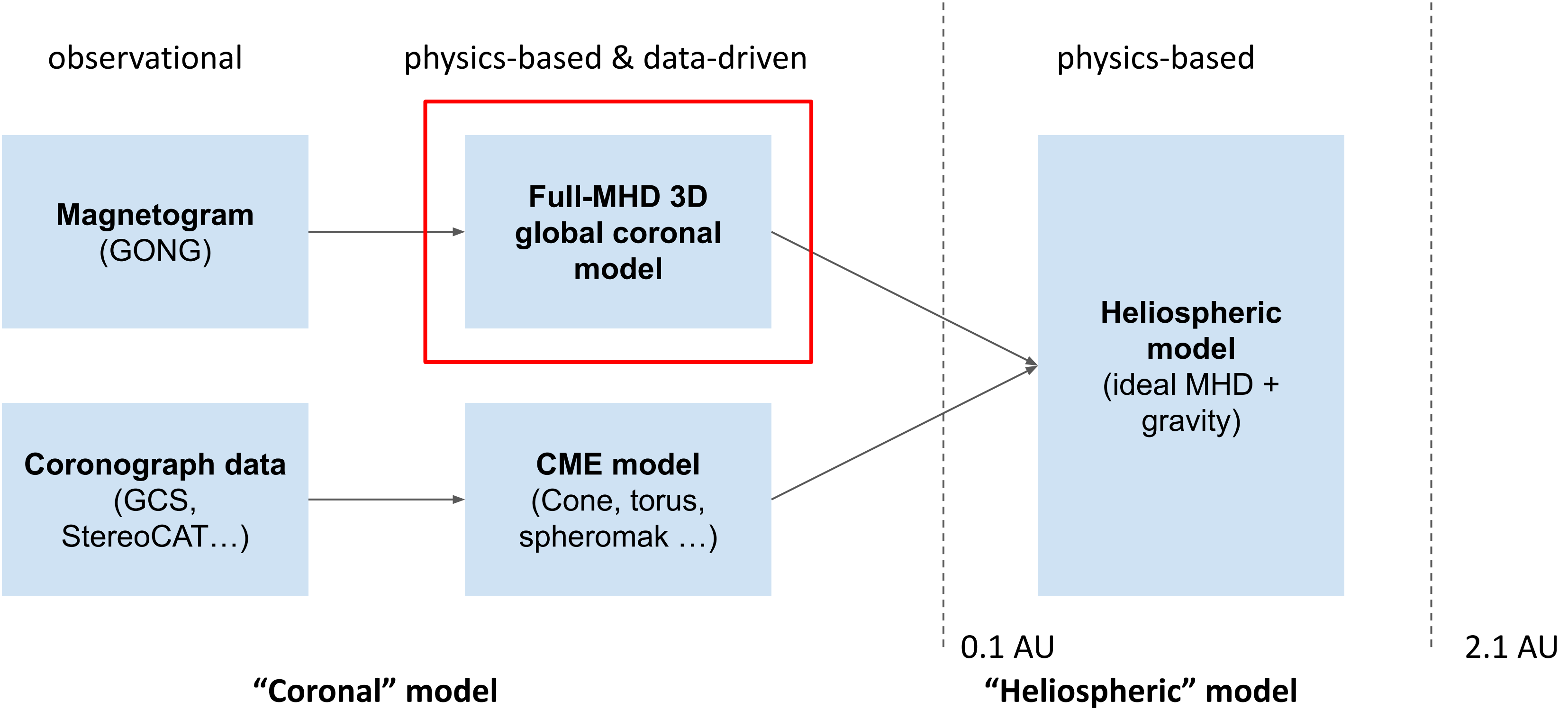
KU Leuven tools



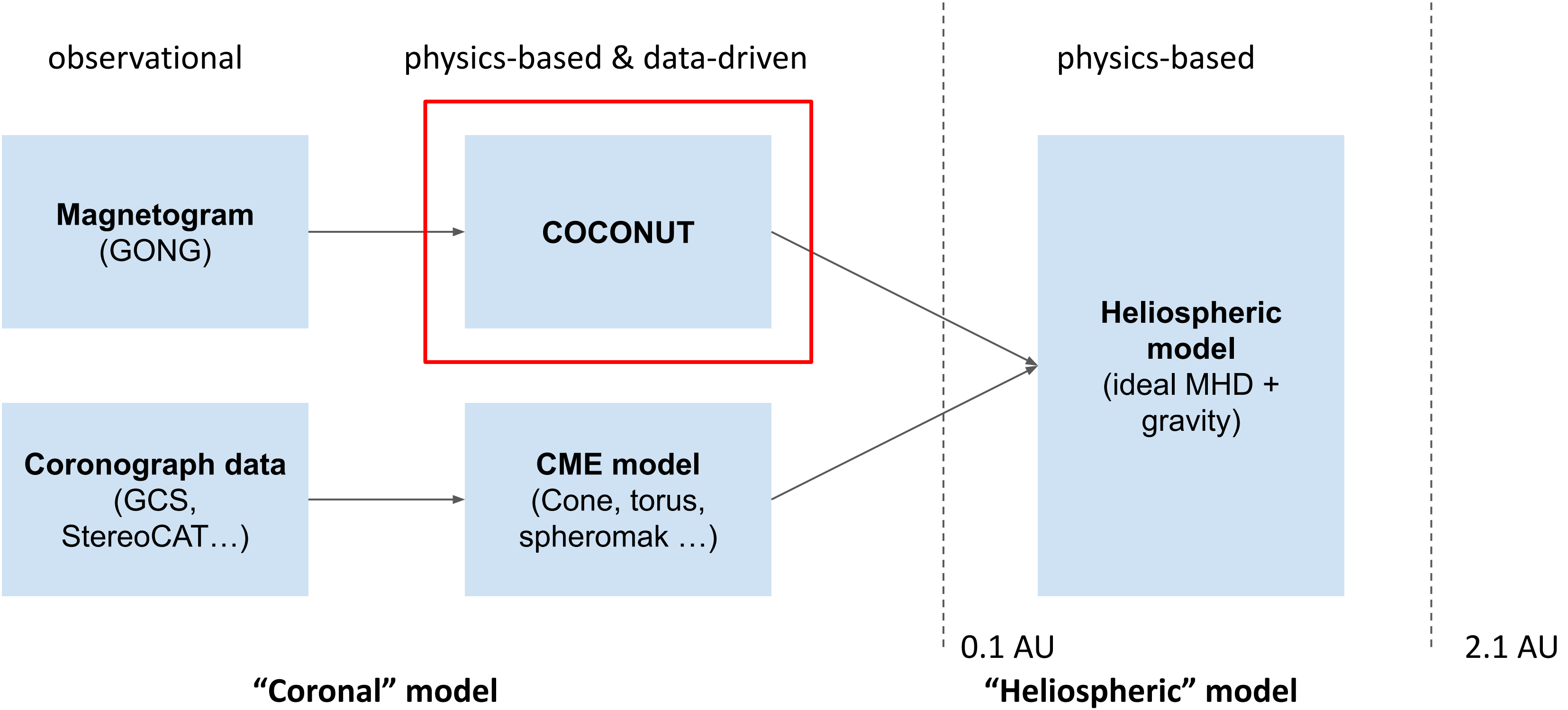
EUHFORIA/ ICARUS



EUHFORIA/ ICARUS: made more physical?



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



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

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

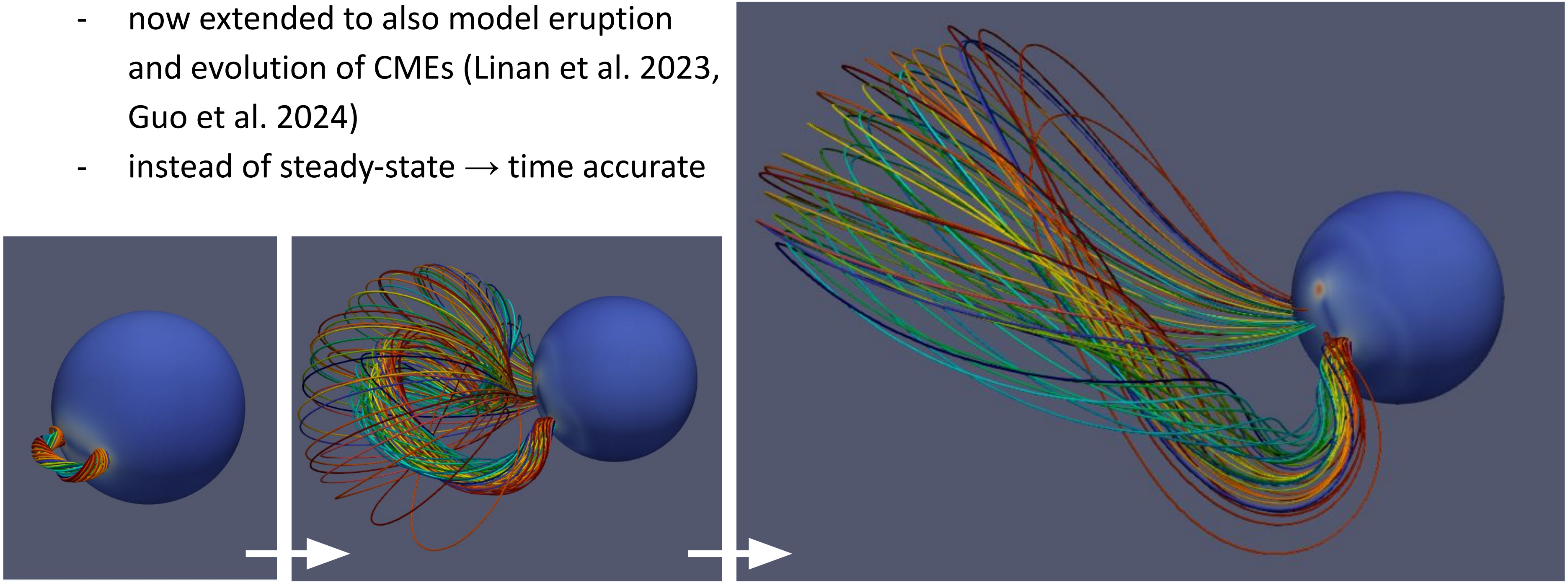
$$\frac{d(\rho \vec{V})}{dt} + \nabla \cdot \left(\rho \vec{V} \otimes \vec{V} + \mathbf{I} \left(P + \frac{\vec{B}^2}{8\pi} \right) - \frac{\vec{B} \otimes \vec{B}}{4\pi} \right) = \rho \vec{g},$$

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

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

COCONUT 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
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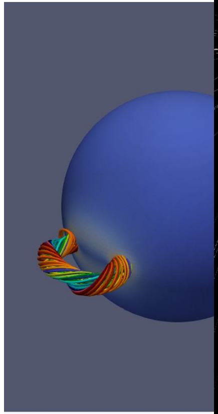
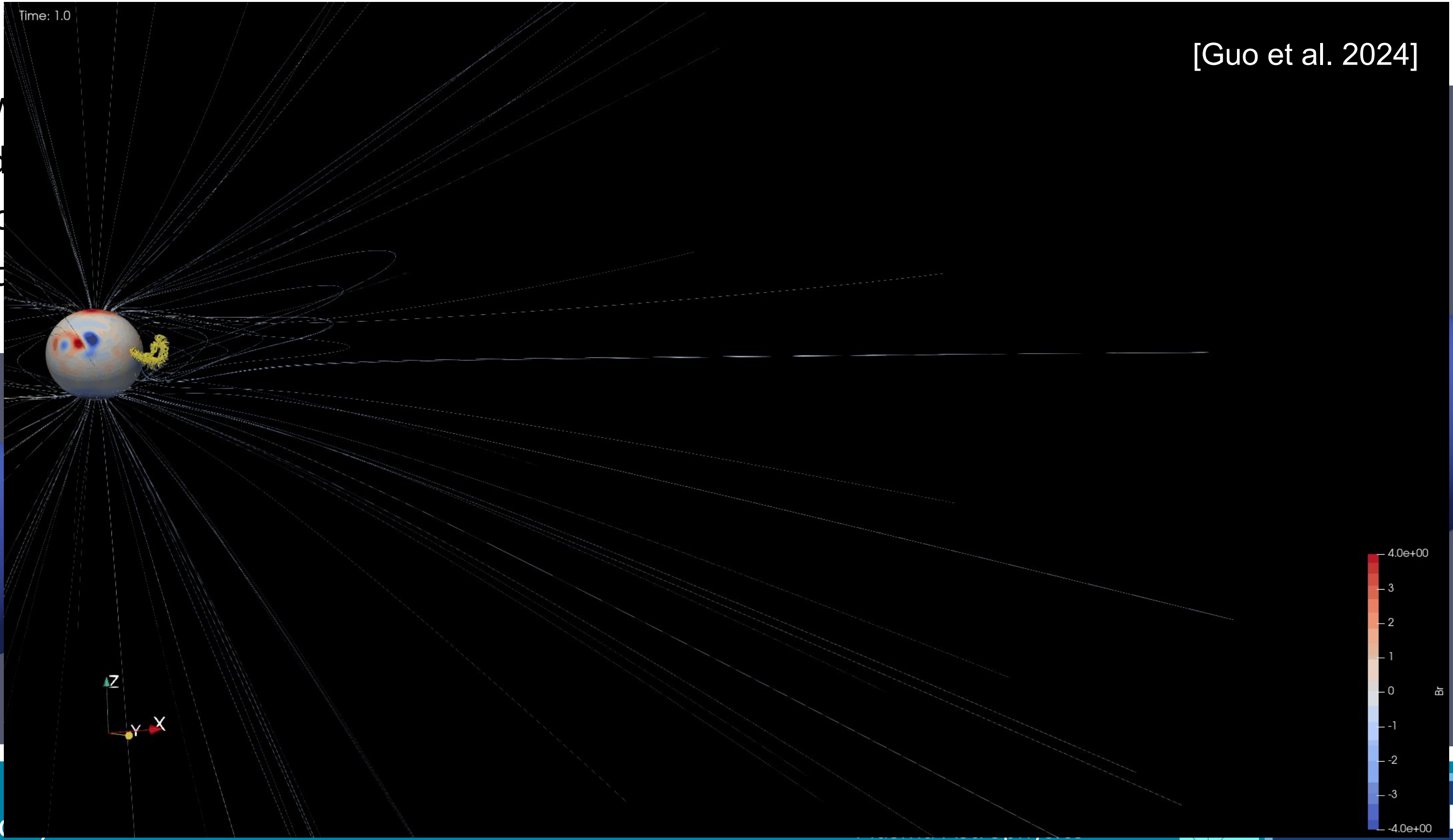
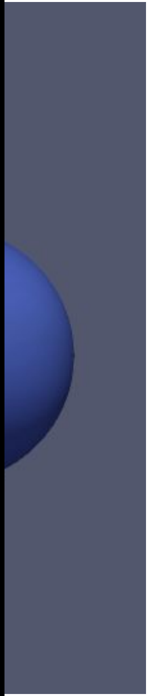
  Guo
- inst







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

Magnetosphere models:
- GUMICS-4
- GORGON-Space

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

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

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

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

www.nasa.gov

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

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- Detection of flux ropes and source point determination: andreas.wagner@kuleuven.be

Thank you for your attention!

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