COCONUT
for global coronal modelling

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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)

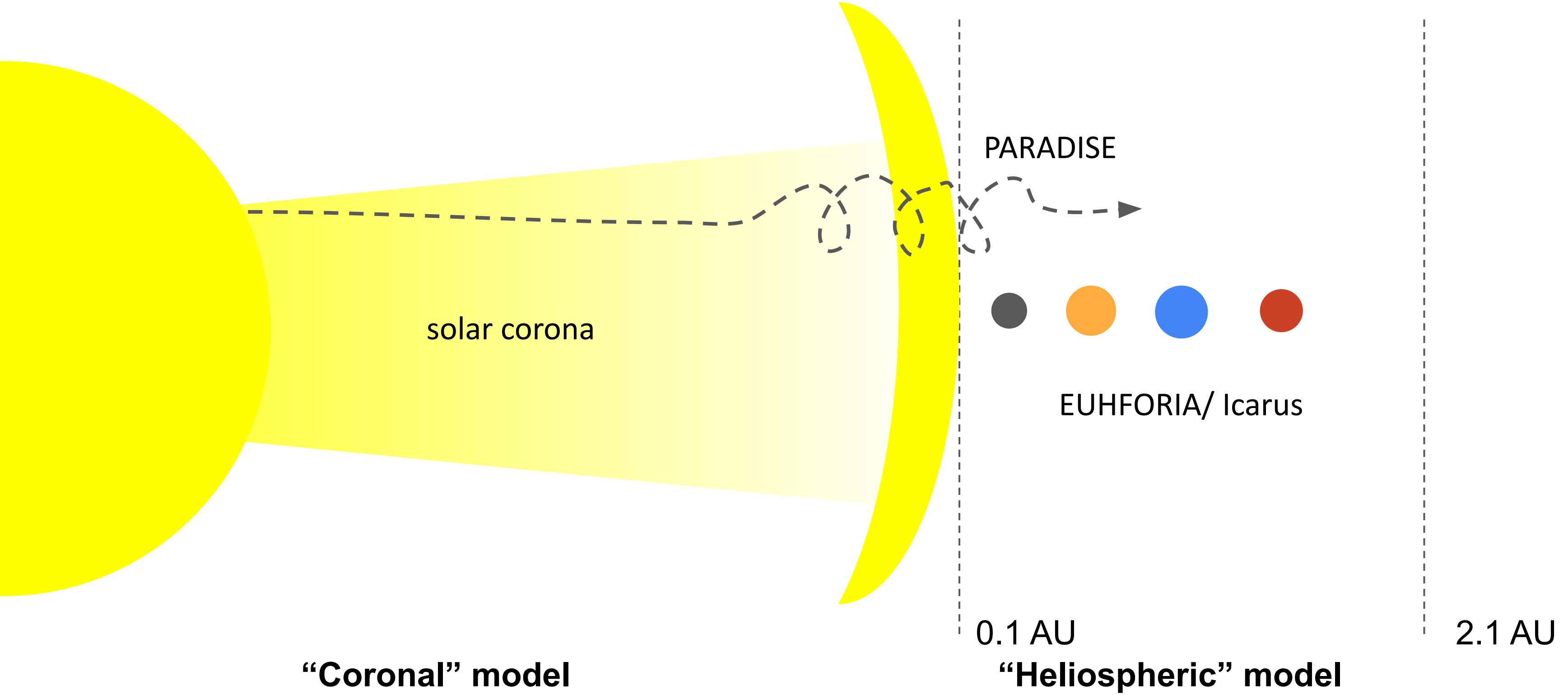
Virtual Space Weather Modelling Centre   HISTORY   NEW RUN

Welcome to the VSWMC

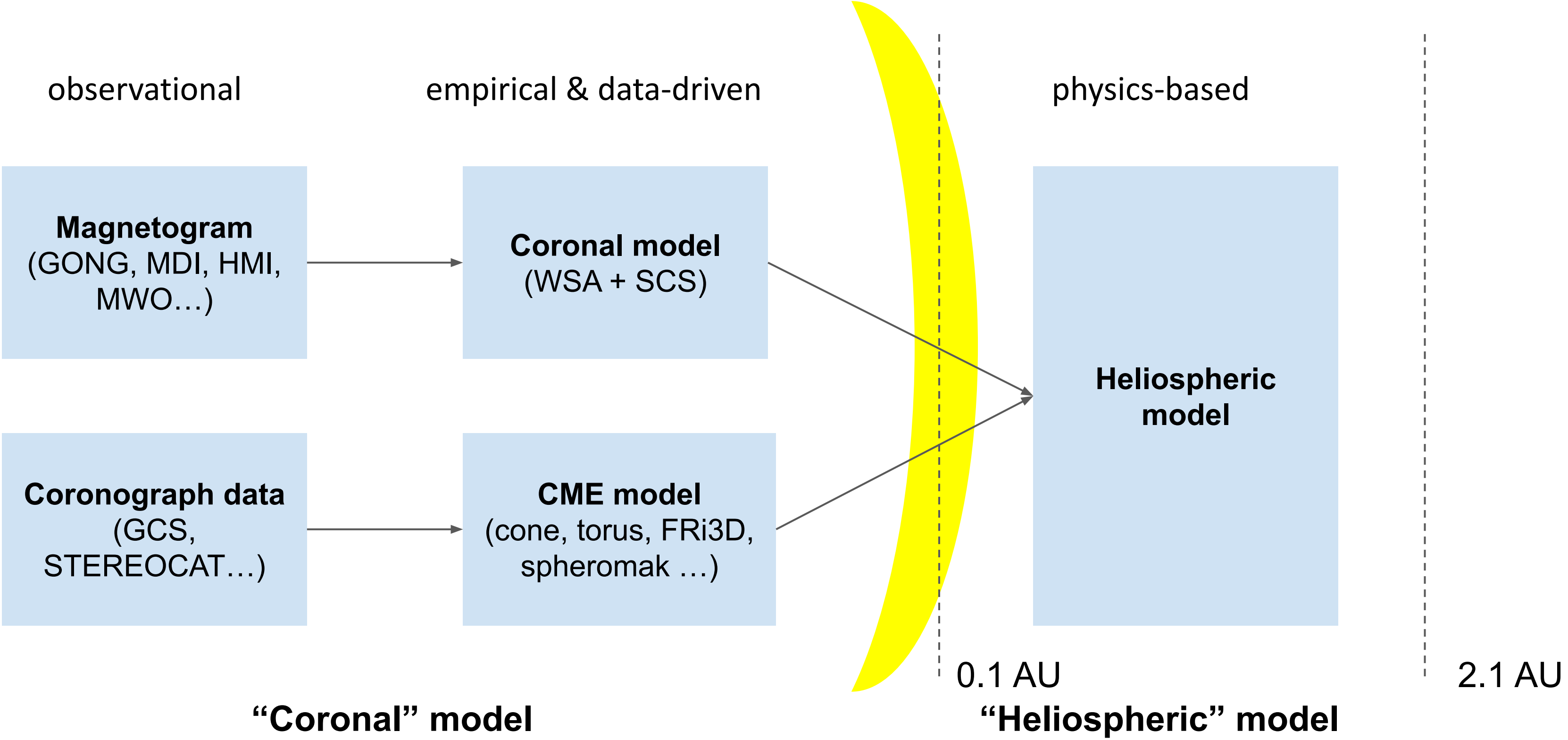
The Virtual Space Weather Modelling Centre (VSWMC) is a full scale, open end-to-end (meaning from the Sun to the Earth) space weather modelling, enabling to combine (*couple*) various space weather models in an integrated tool, with the models located either locally or geographically distributed. Hence, 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

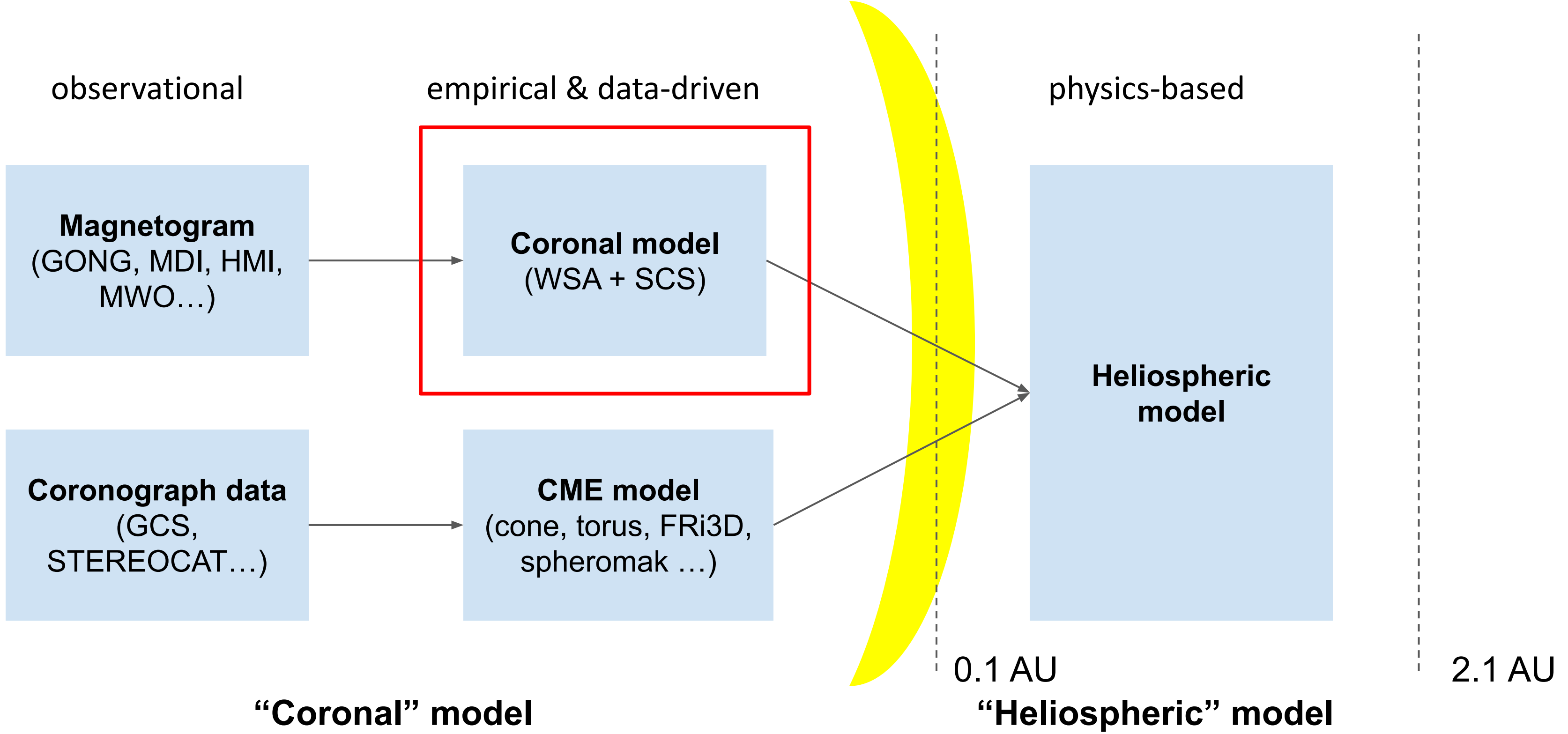
VSWMC & EUHFORIA (Pomoell & Poedts 2018)



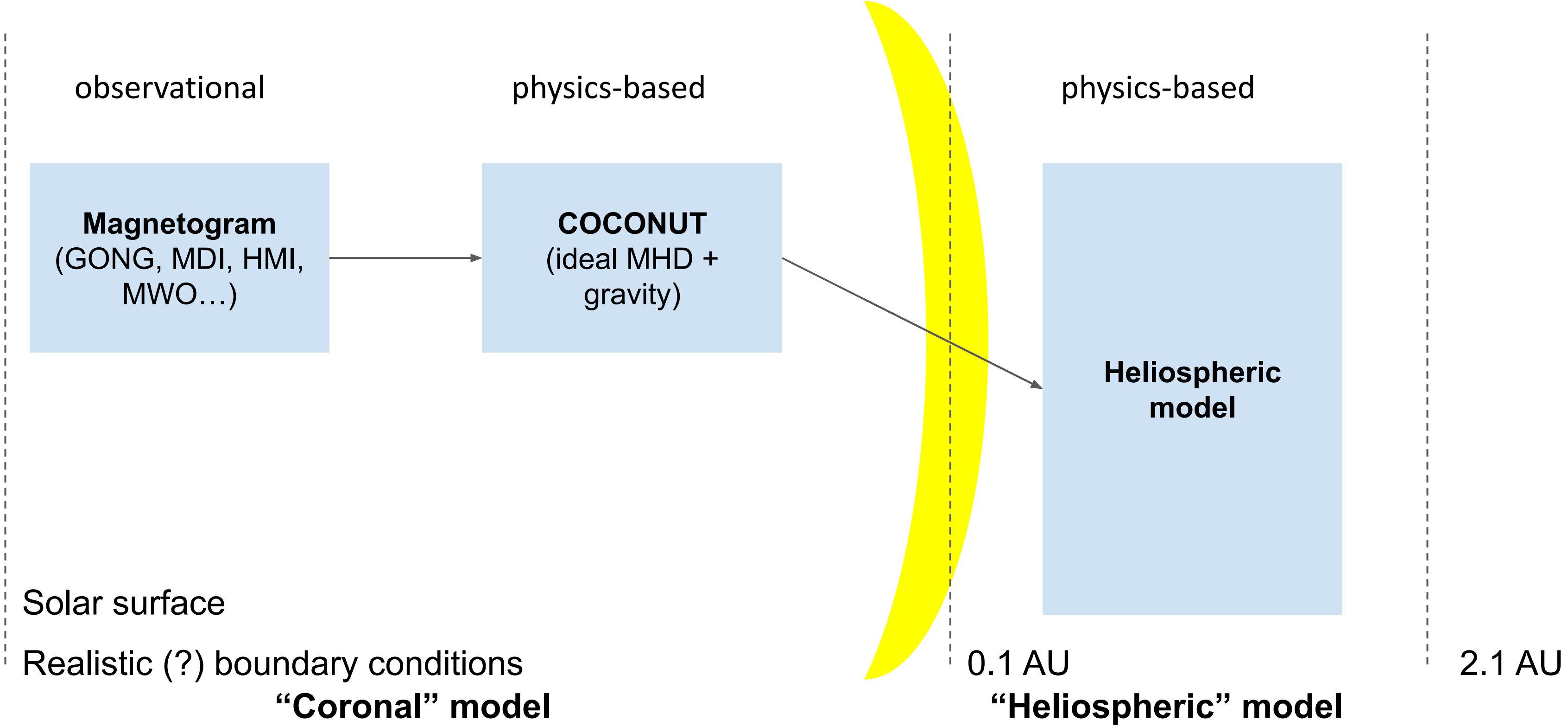
VSWMC & EUHFORIA (Pomoell & Poedts 2018)



VSWMC & EUHFORIA (Pomoell & Poedts 2018)



VSWMC & EUHFORIA (Pomoell & Poedts 2018)



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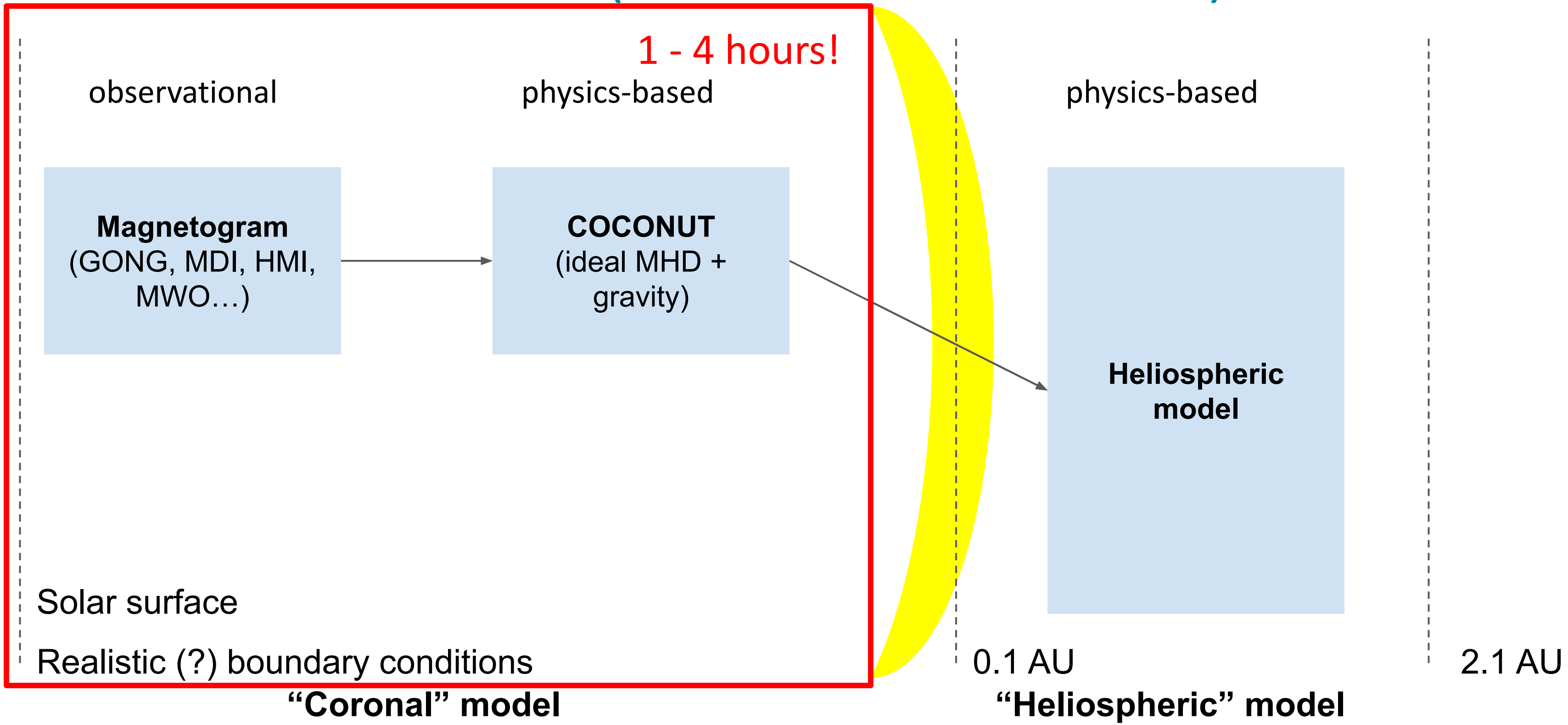
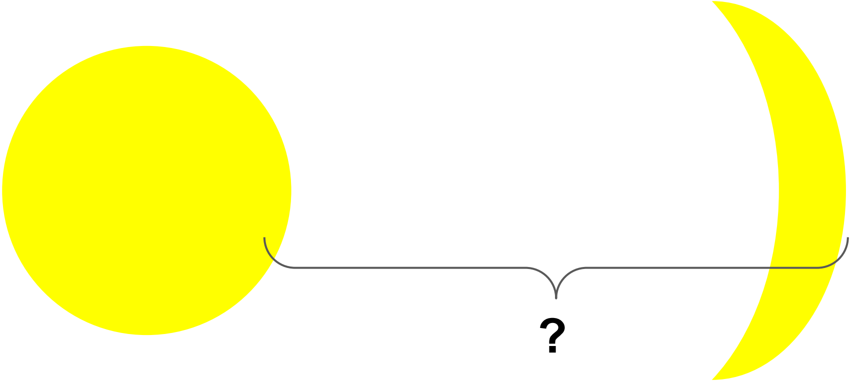


COOLFluiD CFD framework (Lani & Quintino 2003)

- C++ based multiphysics platform for fluid dynamics simulations, heavily parallelized

- COCONUT: ideal MHD + gravity

- Different than most state-of-art solvers:
  - Unstructured grid
    → enables advanced grid refinement techniques
  - Implicit scheme
    → CFL of up to several thousands
    → fast convergence

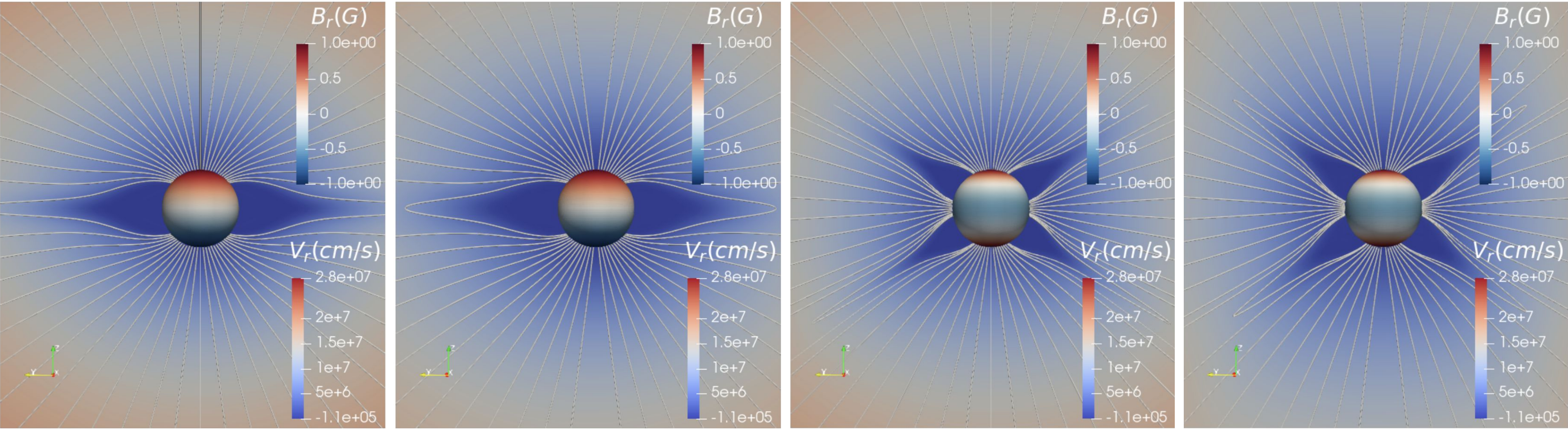


https://github.com/andrealani/COOLFluiD/wiki
contact: andrea.lani@kuleuven.be

COCONUT: current state (verification)

Dipole | Quadrupole

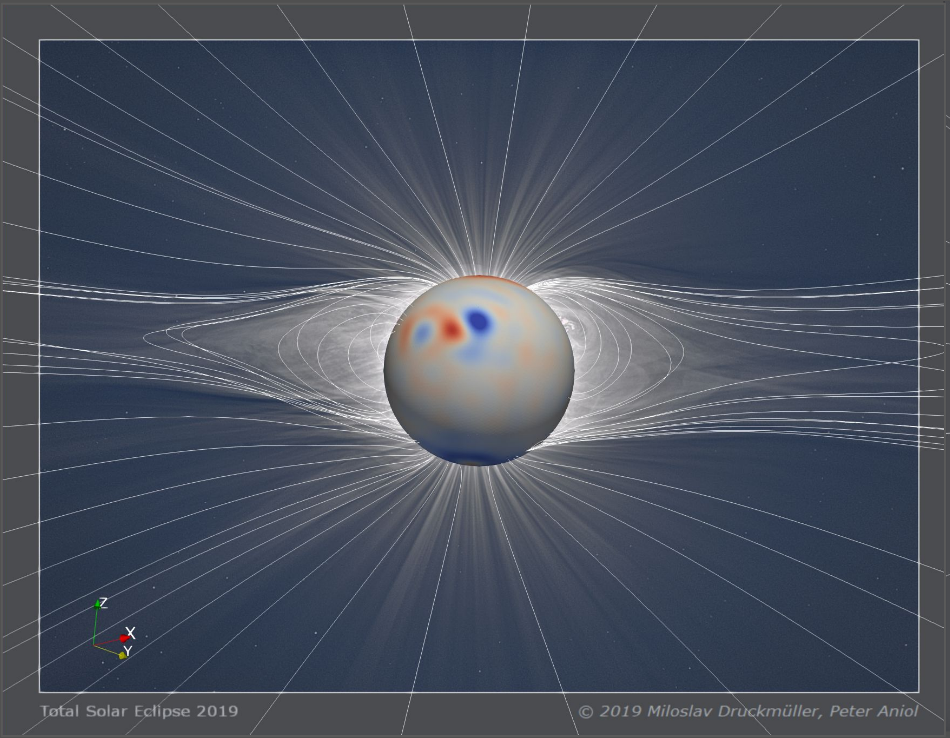
COCONUT | Wind-Predict | COCONUT | Wind-Predict

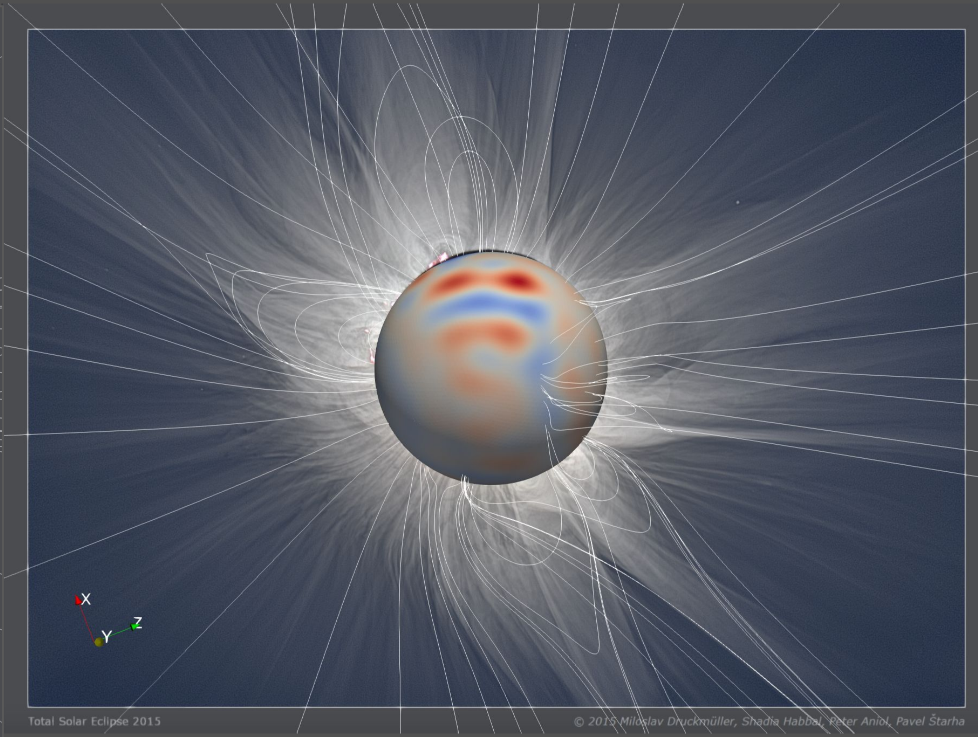


[Perri & Leitner et al., 2022]

COCONUT: current state (results)

[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]

COCONUT: formulation

- Primitive variables: ρ, V_x, V_y, V_z, B_x, B_y, B_z, ϕ, P
- Ideal MHD equations:

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

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

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

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

$\vec{B}$	magnetic field
$\vec{V}$	velocity
ρ	density
t	time
ε	internal energy
$\vec{g}$	gravity
P	pressure

COCONUT: formulation

- Primitive variables: ρ, V_x, V_y, V_z, B_x, B_y, B_z, ϕ, P   BC prescription
- Ideal MHD equations:

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

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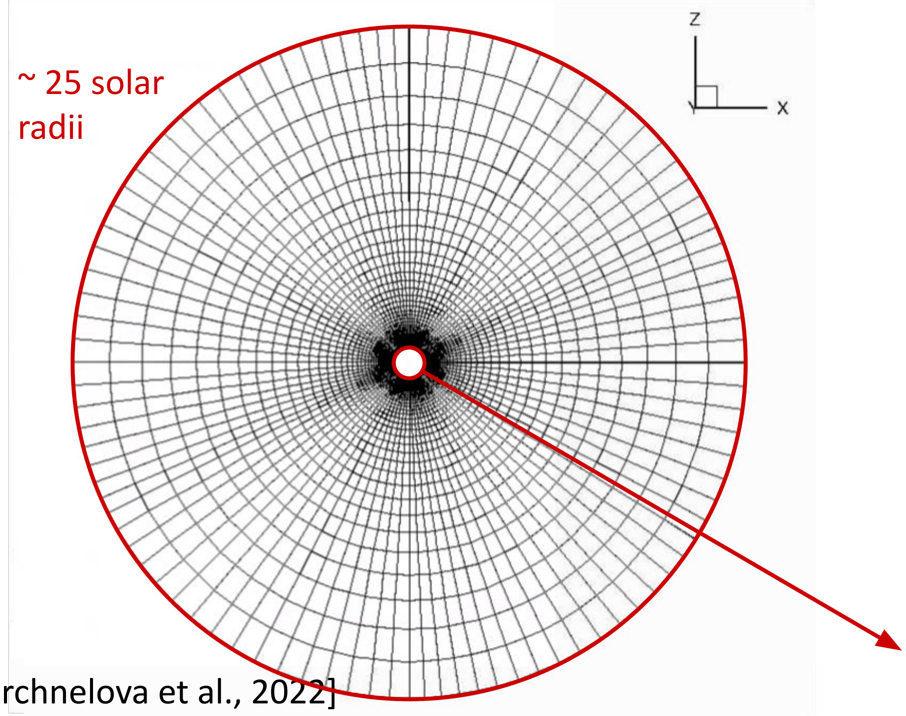
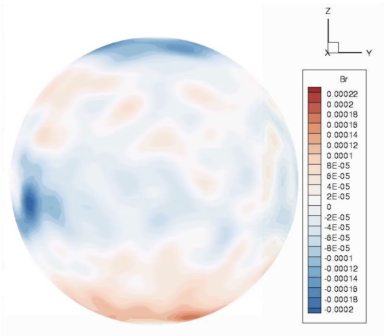
COCONUT: BC prescriptions



- we extent to > 21 solar radii and assume "lower corona" at the inner boundary
    - this will be changed in the future iteration in which the transition region will be included

- we prescribe a magnetic field on the surface based on the observed solar magnetograms



~ 1 solar radius, ~ 1.67e-13 kg/m3, ~ 1.5e6 K

[Brchnelova et al., 2022]

COCONUT: formulation

- Primitive variables: ρ, V_x, V_y, V_z, B_x, B_y, B_z, ϕ, P
- Ideal MHD equations:

discretisation, scheme, limiting

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

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

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

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

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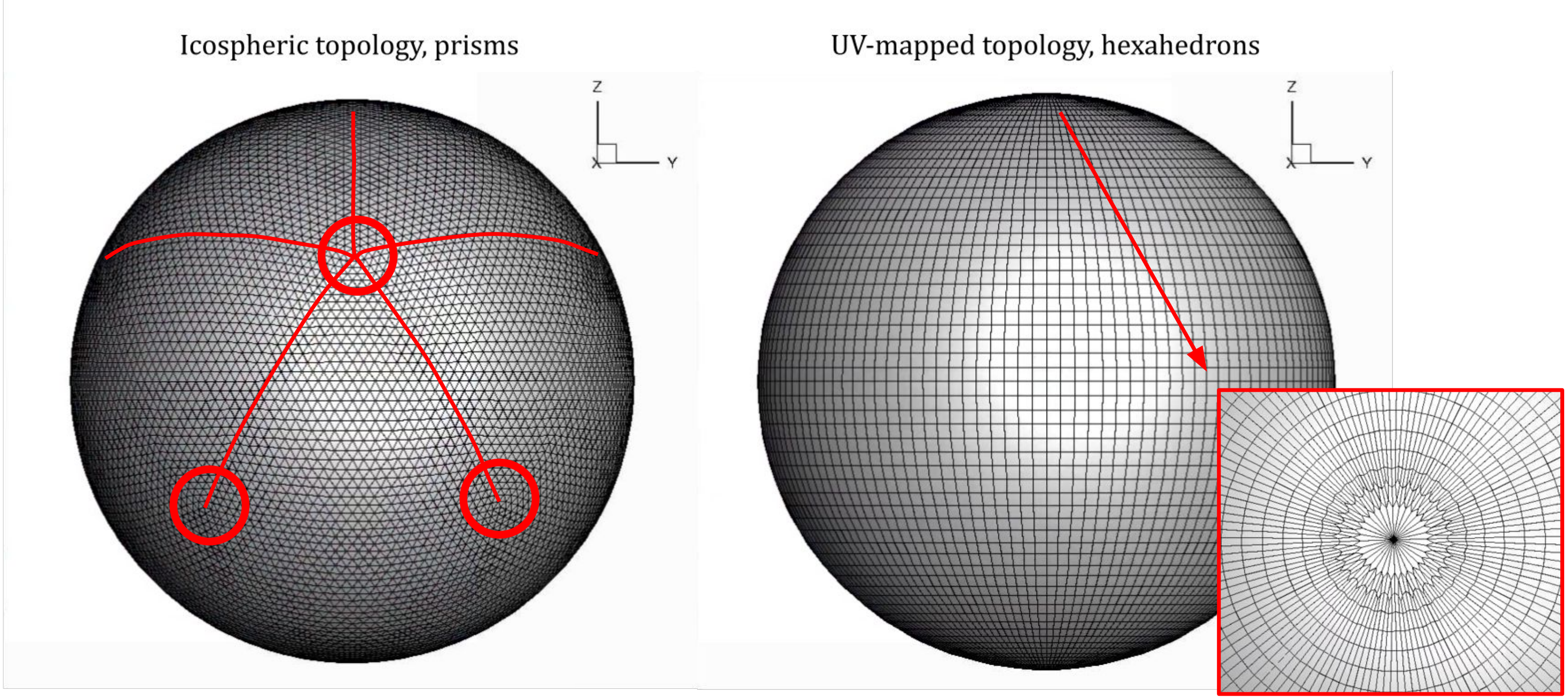
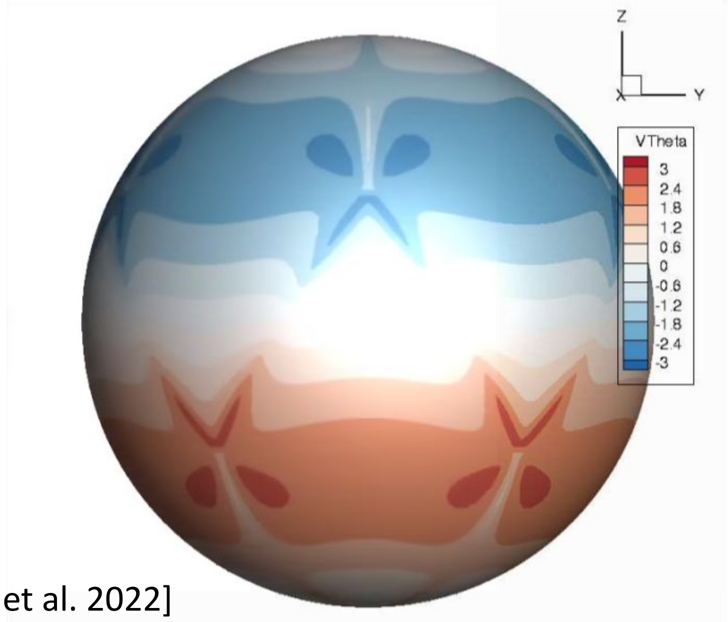
COCONUT: discretisation

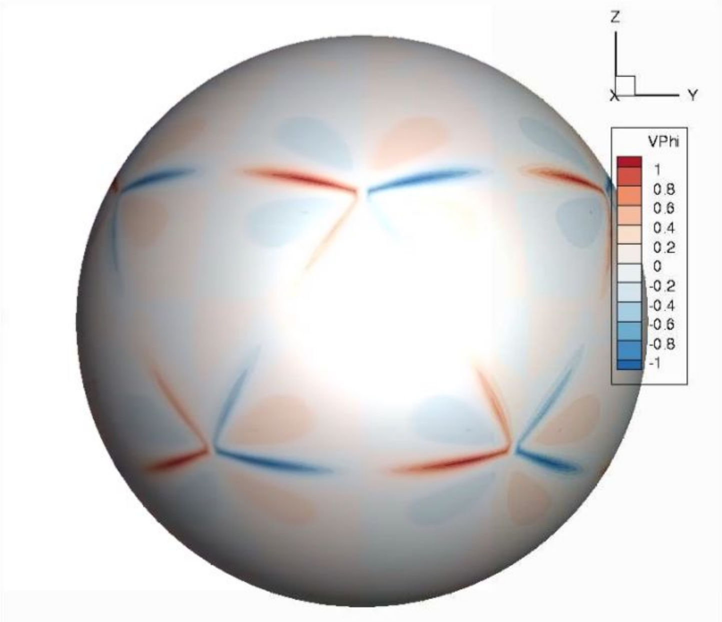


COCONUT: discretisation

Azimuthal velocity component



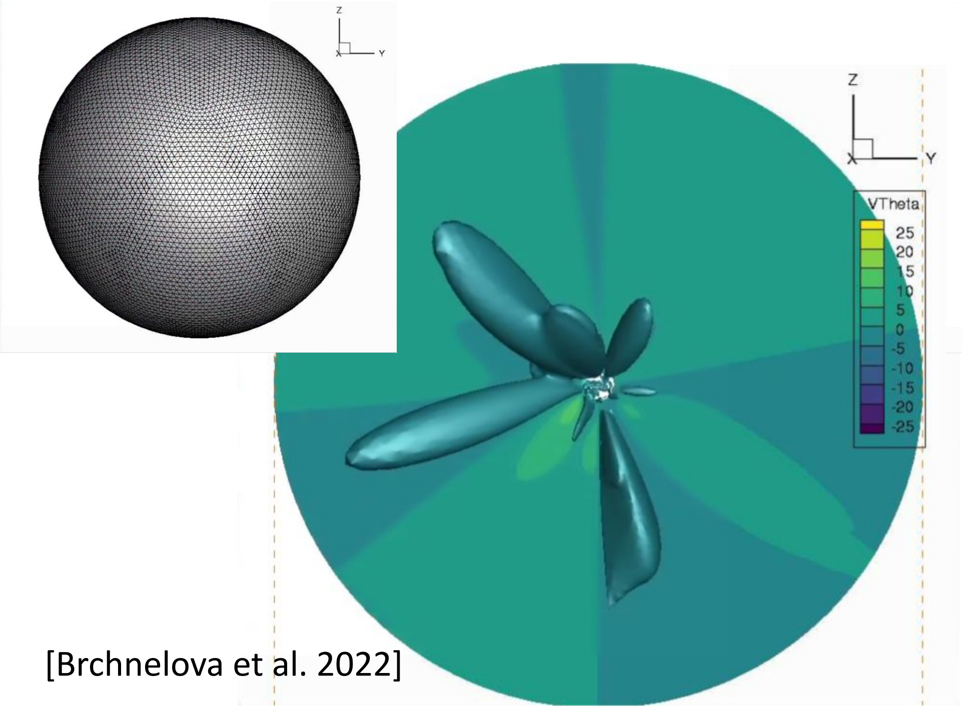
Poloidal velocity component



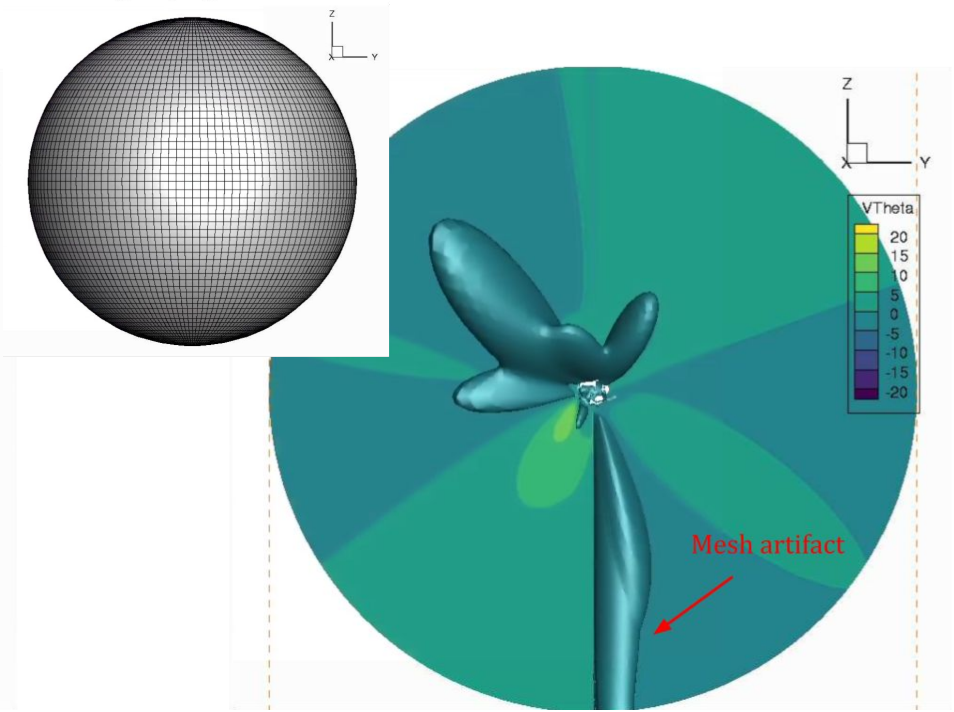
[Brchnelova et al. 2022]

COCONUT: discretisation

Icospheric topology, prisms



UV-mapped topology, hexahedrons



[Brchnelova et al. 2022]

COCONUT: formulation

- Primitive variables: ρ, V_x, V_y, V_z, B_x, B_y, B_z, ϕ, P
- Ideal MHD equations:

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

magnetic map type

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

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

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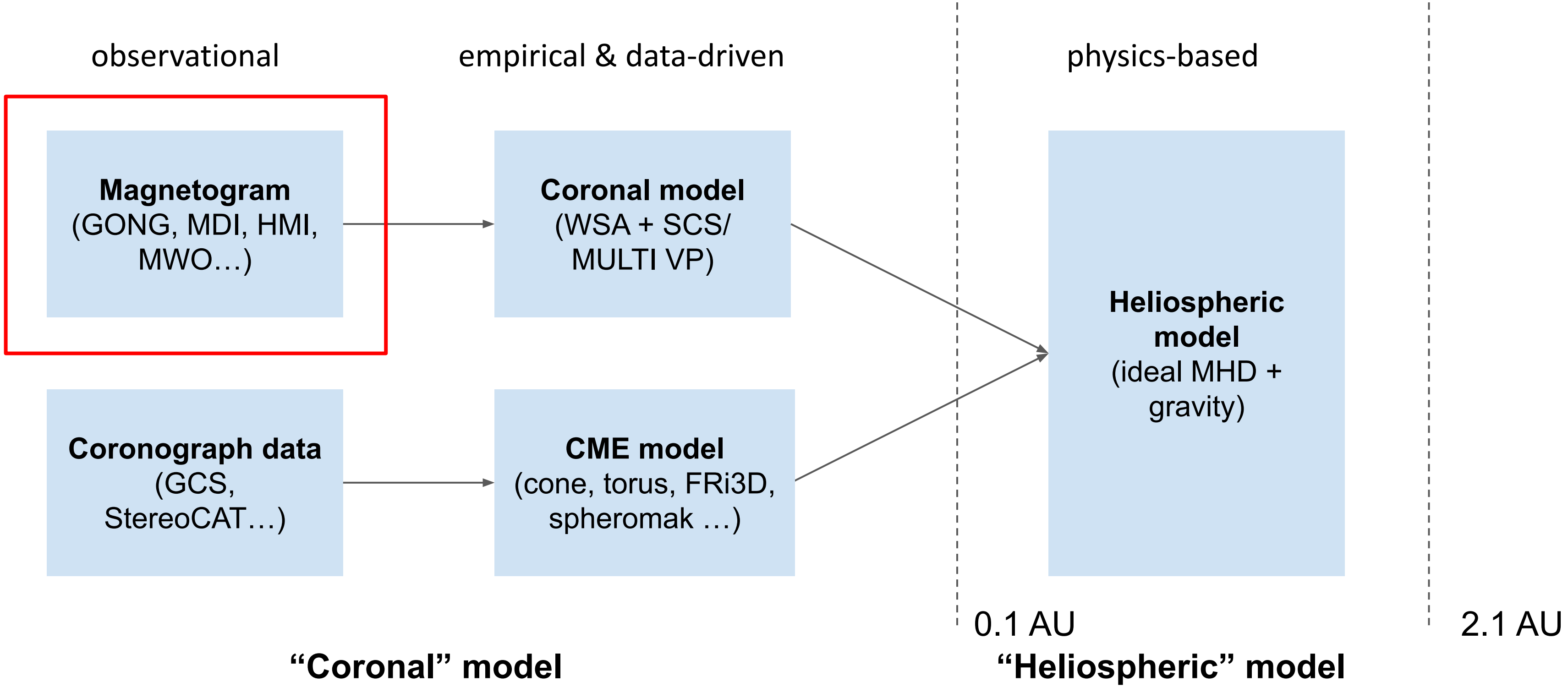
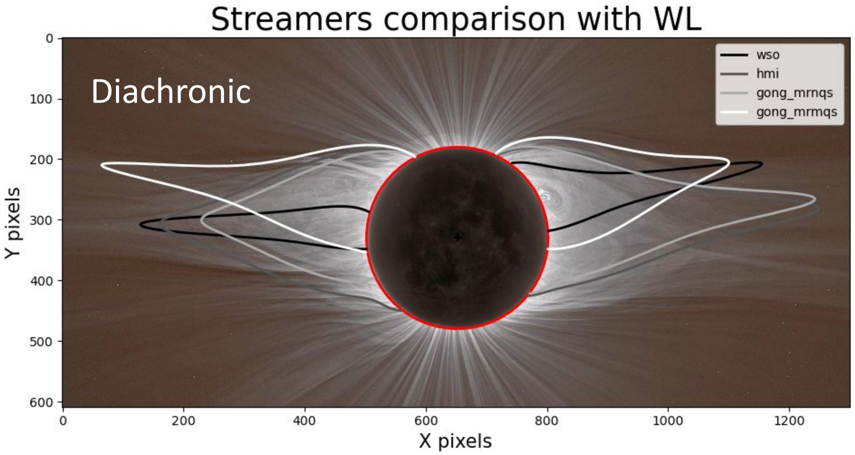
VSWMC & EUHFORIA (Pomoell & Poedts 2018)

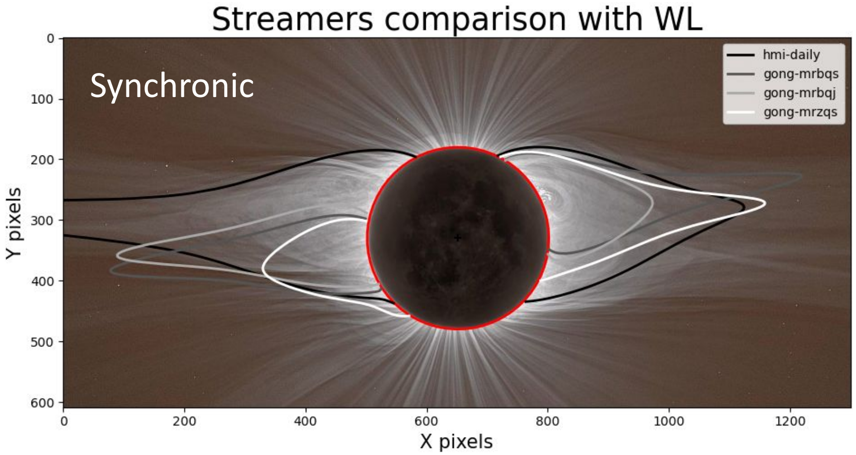


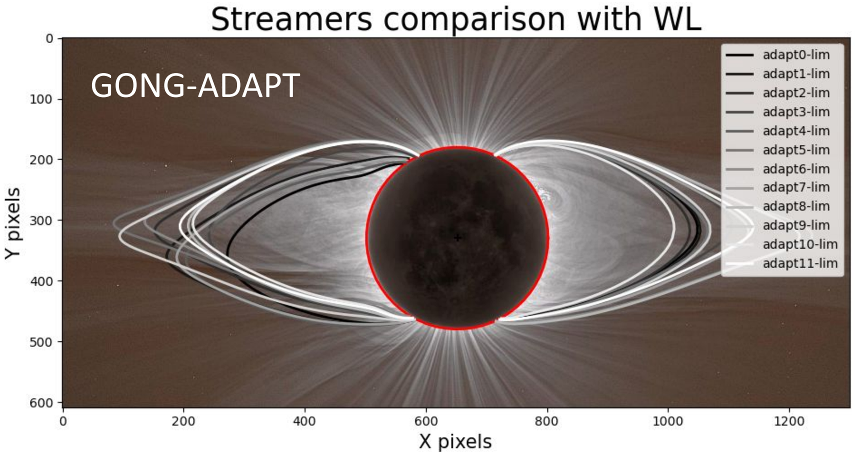
COCONUT: magnetic maps

- Features vary depending on the type of the magnetogram used: barbara.perri@kuleuven.be

[Perri et al. 2023]







COCONUT: formulation

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

heating, radiation, conduction

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

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COCONUT: source terms

- Additional source terms:
  - **heating**
  - **radiation**
  - **conductivity**

COCONUT: source terms

- Additional source terms:
  - **heating** (Reville et al. 2020, Downs et al. 2010)

$$Q_h = H|B| \qquad Q_h = H_0 \exp\left[-(r - R_\odot)/\lambda\right]$$

$$Q_h = F_h / H \left(\frac{R_\odot}{r}\right)^2 \exp\left(-\frac{r - R_\odot}{H}\right)$$

$$H_{ch} = H_0 \cdot |\mathbf{B}| \cdot e^{-\frac{r - R_S}{\lambda}}$$

  - **radiation**
  - **conductivity**

COCONUT: source terms

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  - **radiation** (Rosner et al. 1978)

$$Q_r = -n_e n_p \Lambda(T)$$

  - **conductivity**

COCONUT: source terms

- Additional source terms:
  - **heating** (Reville et al. 2020, Downs et al. 2010)

$$Q_h = H|B| \qquad Q_h = H_0 \exp\left[-(r - R_\odot)/\lambda\right] \qquad Q_h = F_h/H\left(\frac{R_\odot}{r}\right)^2 \exp\left(-\frac{r - R_\odot}{H}\right)$$

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  - **radiation** (Rosner et al. 1978)

$$Q_r = -n_e n_p \Lambda(T)$$

  - **conductivity**

$$\alpha = M_e^{-0.2112} \qquad M_e \leq 0.0249$$

$$\alpha = 0.436 M_e^{-0.436} \qquad 0.0249 < M_e \leq 0.3146$$

$$\alpha = 0.035 M_e^{-2.617} \qquad M_e > 0.3146$$

- less than 10Rsun:

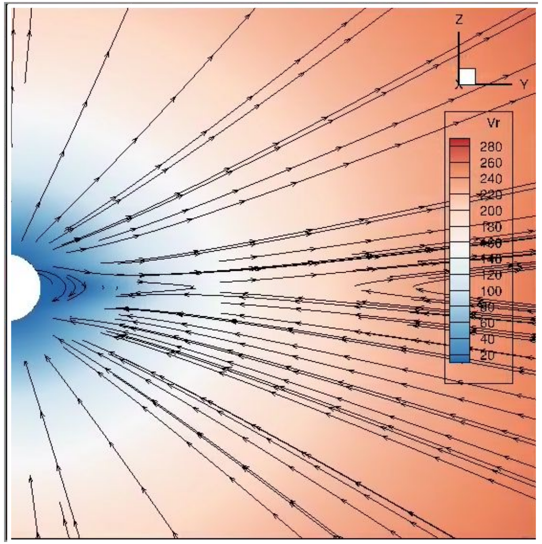
$$\mathbf{q} = -\kappa_{\parallel} \hat{\mathbf{b}}\hat{\mathbf{b}} \cdot \nabla T$$

more than 10Rsun:

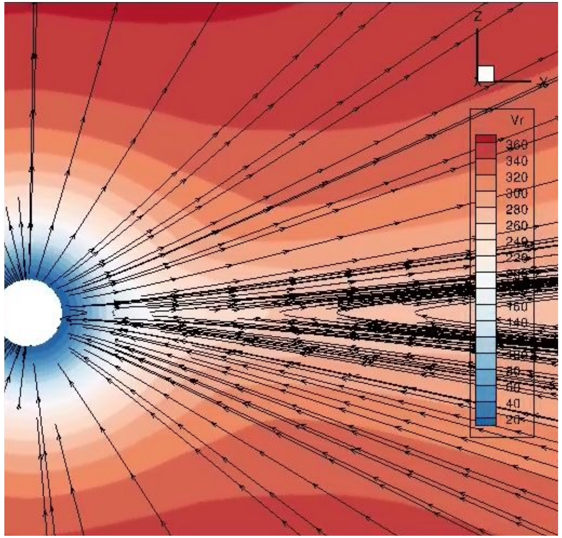
$$\mathbf{q} = \alpha n_e k T \mathbf{v}$$

COCONUT: source terms

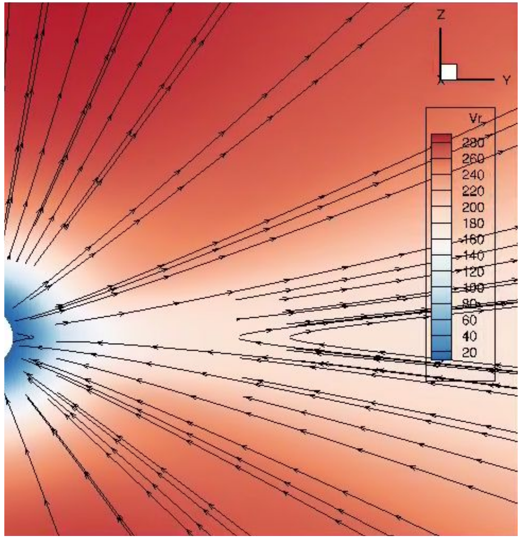
- Radiation, conductivity and heating terms: tinatin.baratashvili@kuleuven.be



polytropic



heating + radiative losses



heating + radiation + conduction

COCONUT: formulation

- Primitive variables: ρ, V_x, V_y, V_z, B_x, B_y, B_z, ϕ, P
- Ideal MHD equations:

time-dependent evolution

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

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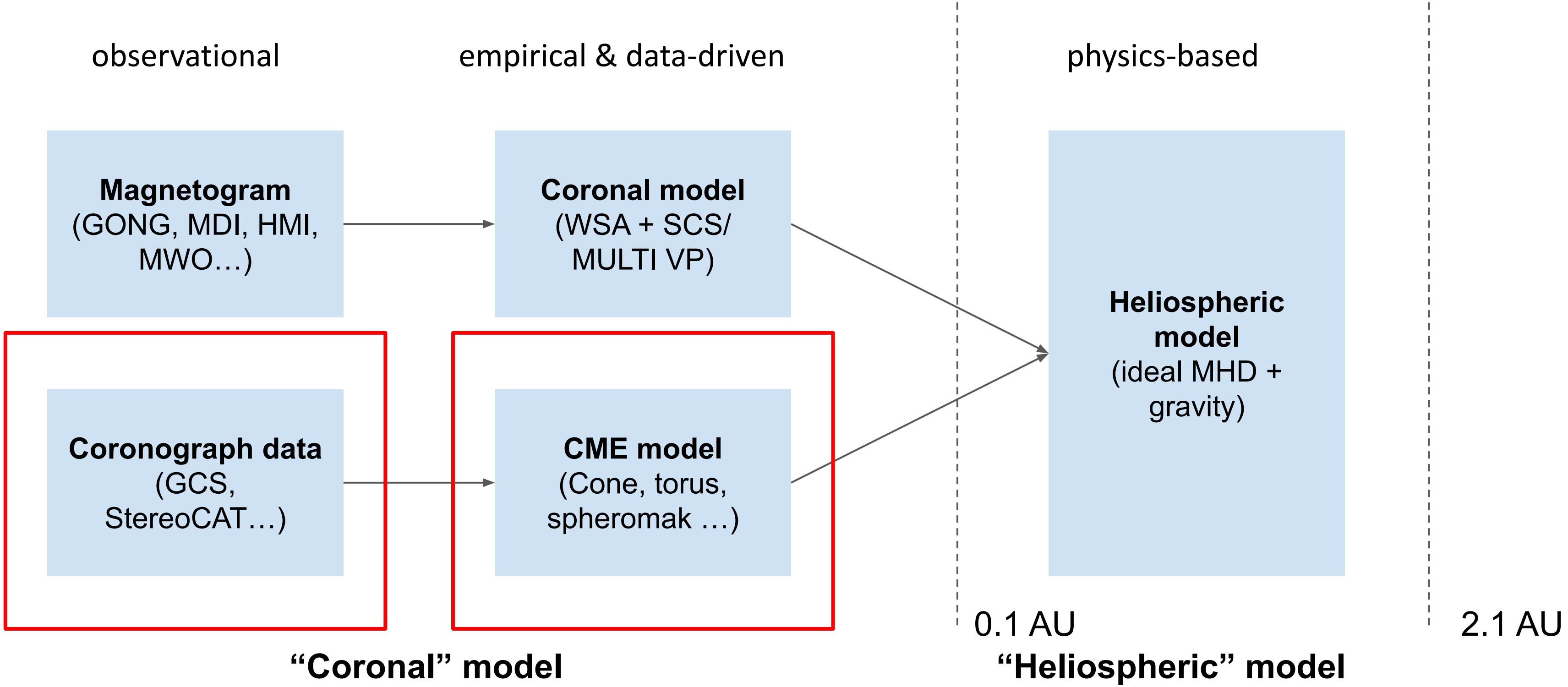
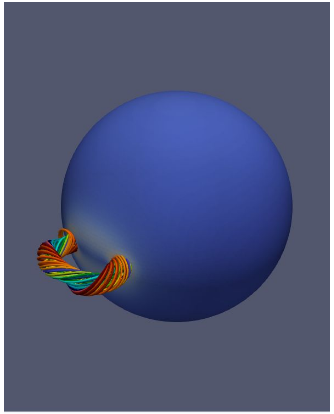
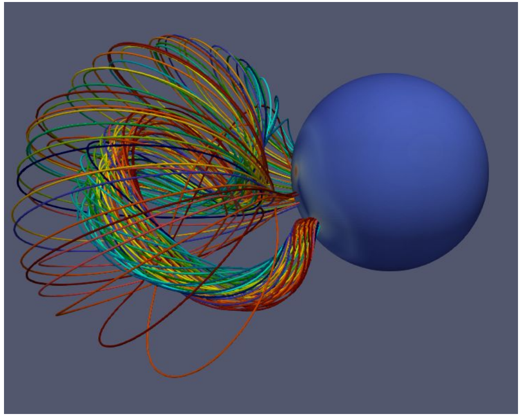
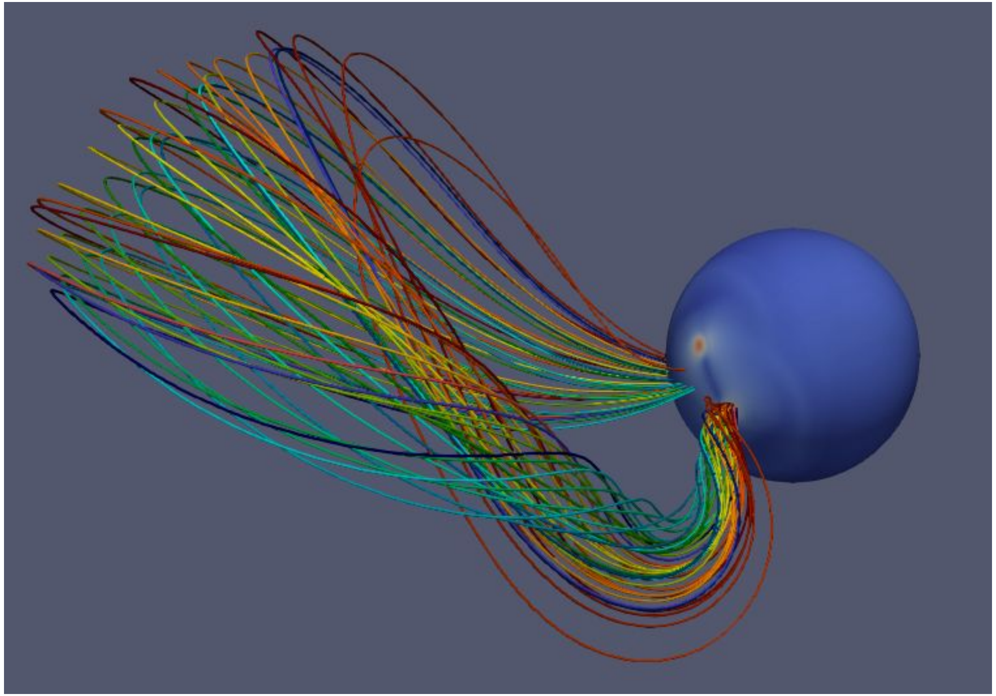


COCONUT: time dependence for flux rope insertion

- To simulate coronal mass ejections
- Flux rope insertion and propagation:

luis.linan@kuleuven.be

COCONUT: validation

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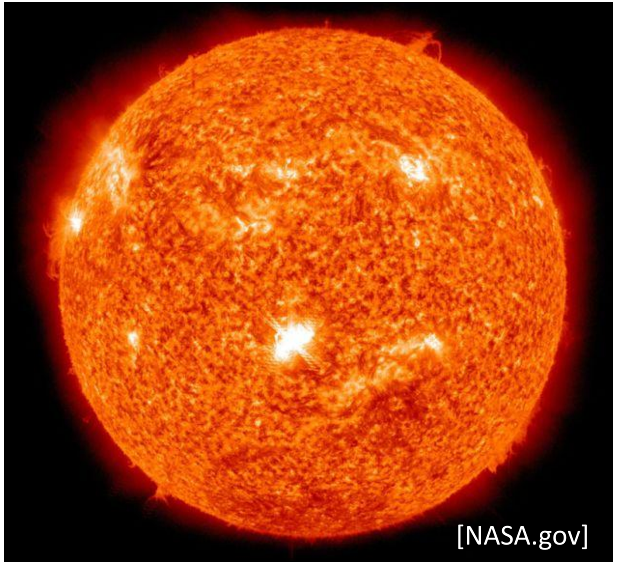
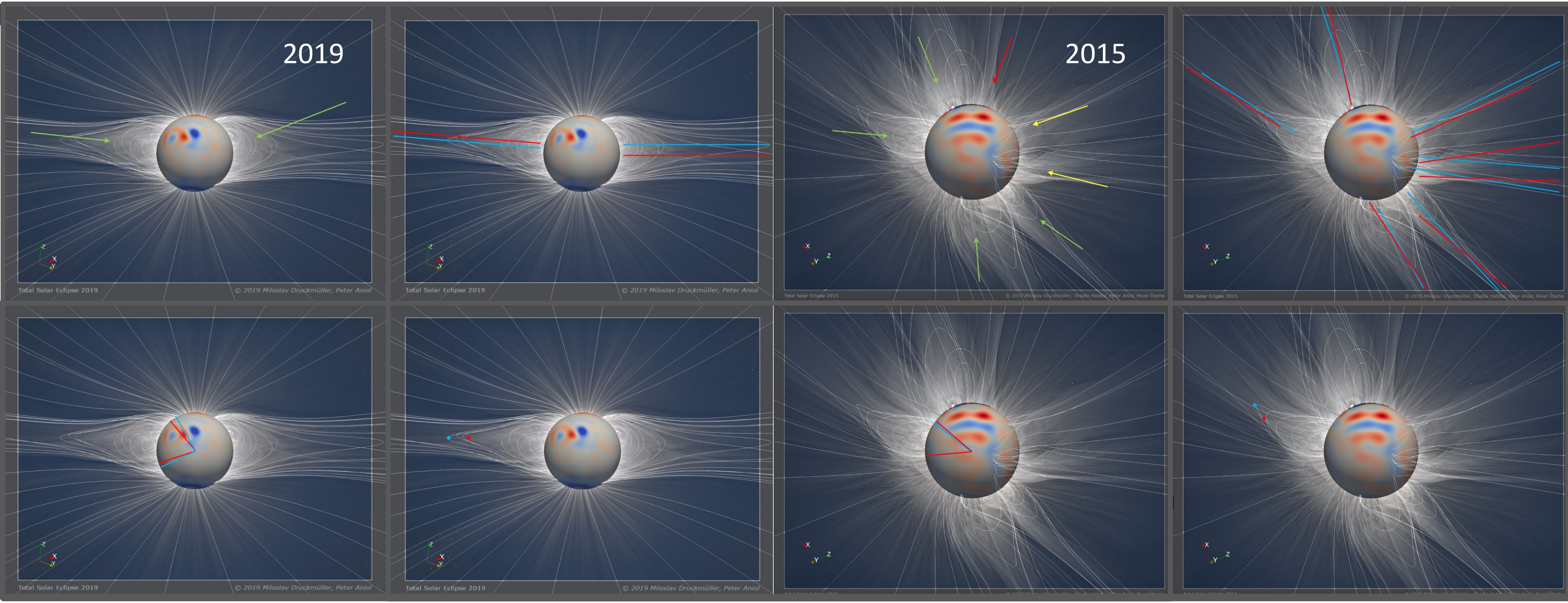
vs



COCONUT: validation

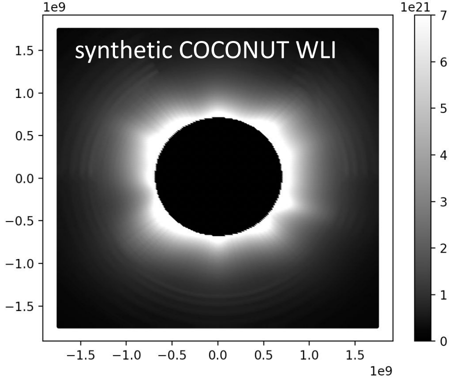
[Kuzma et al., 2023]

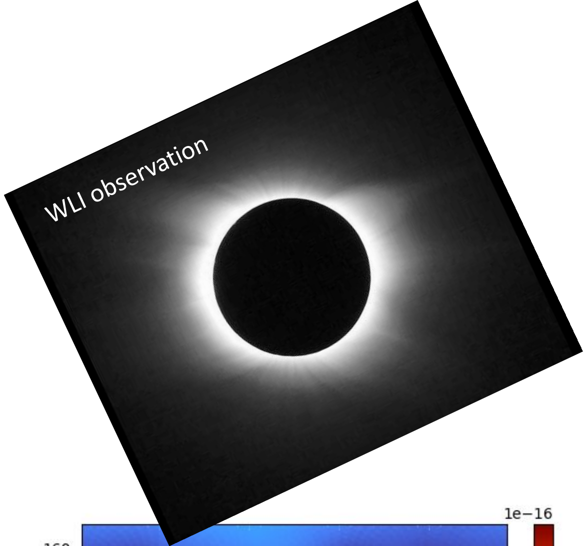


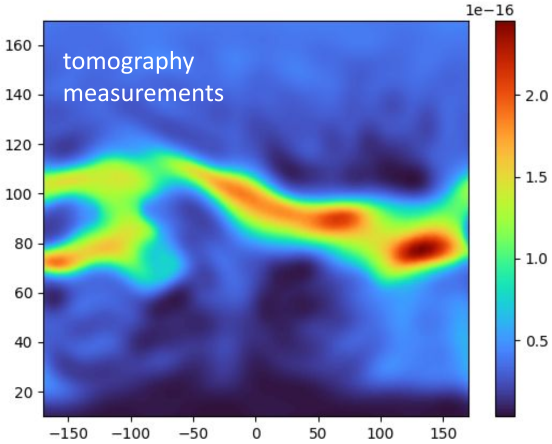
COCONUT: validation

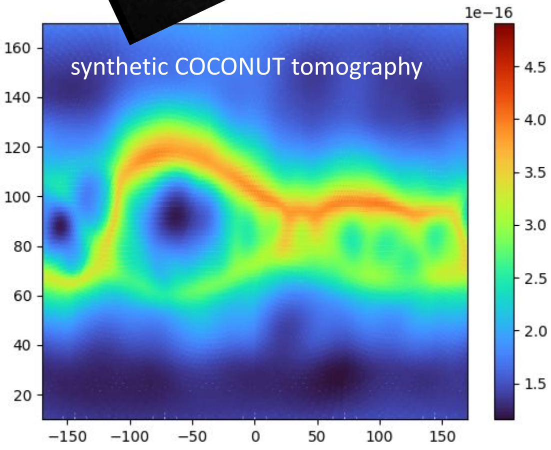
- B-field comparison:
  - relies on very approximate physics
  - mostly qualitative
- WLI: not so easy
- Limited to the regions very close to the Sun (2-3 solar radii)

→ use of tomography





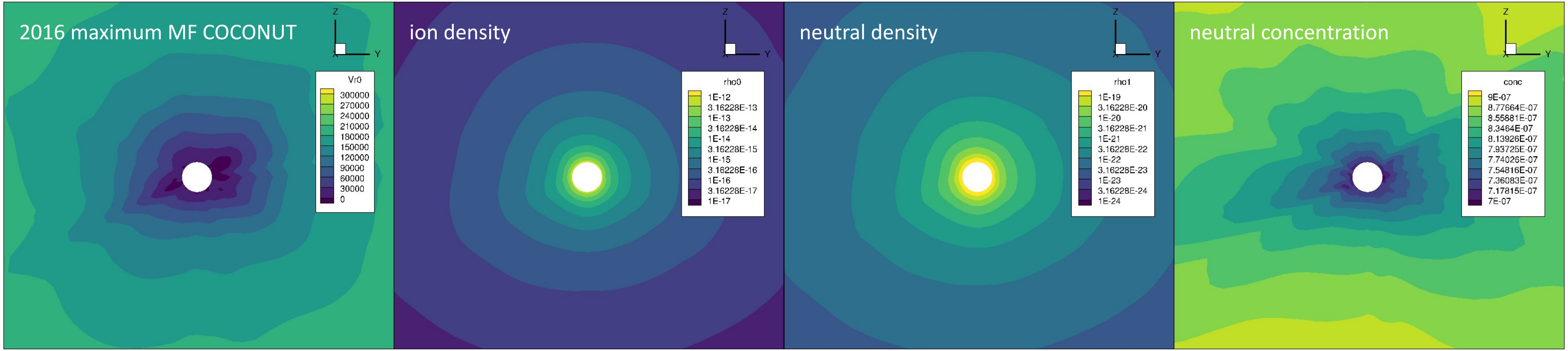




COCONUT: extension to lower layers

- eventual goal to extend to the transition region and chromosphere
  - there, the effects of neutrals must be considered

⟶ development of a multi-fluid ion-neutral version



COCONUT: conclusions

- A promising coronal model which agrees generally well with observations
- Robust & fast enough for space weather forecasting

- Ongoing development:
  - CME (flux rope) time-dependent modelling
  - Inclusion of more realistic physics
  - Extension to multi-fluid modelling
  - Improvement of validation methods

- Open source!

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Thank you for your attention!

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