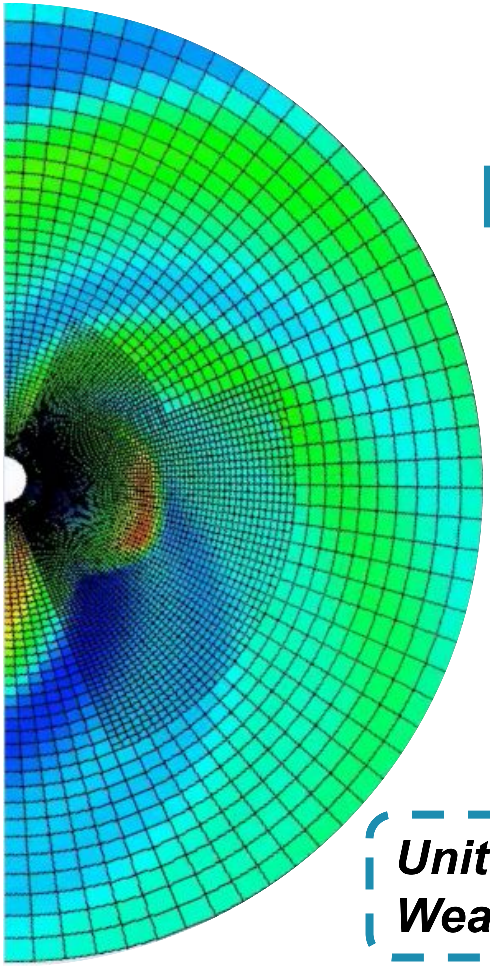


Icarus: a new highly optimized heliospheric model for forecasting purposes

Tinatin Baratashvili[1], *C. Verbeke*[2,1], *S. Poedts*[1,3]

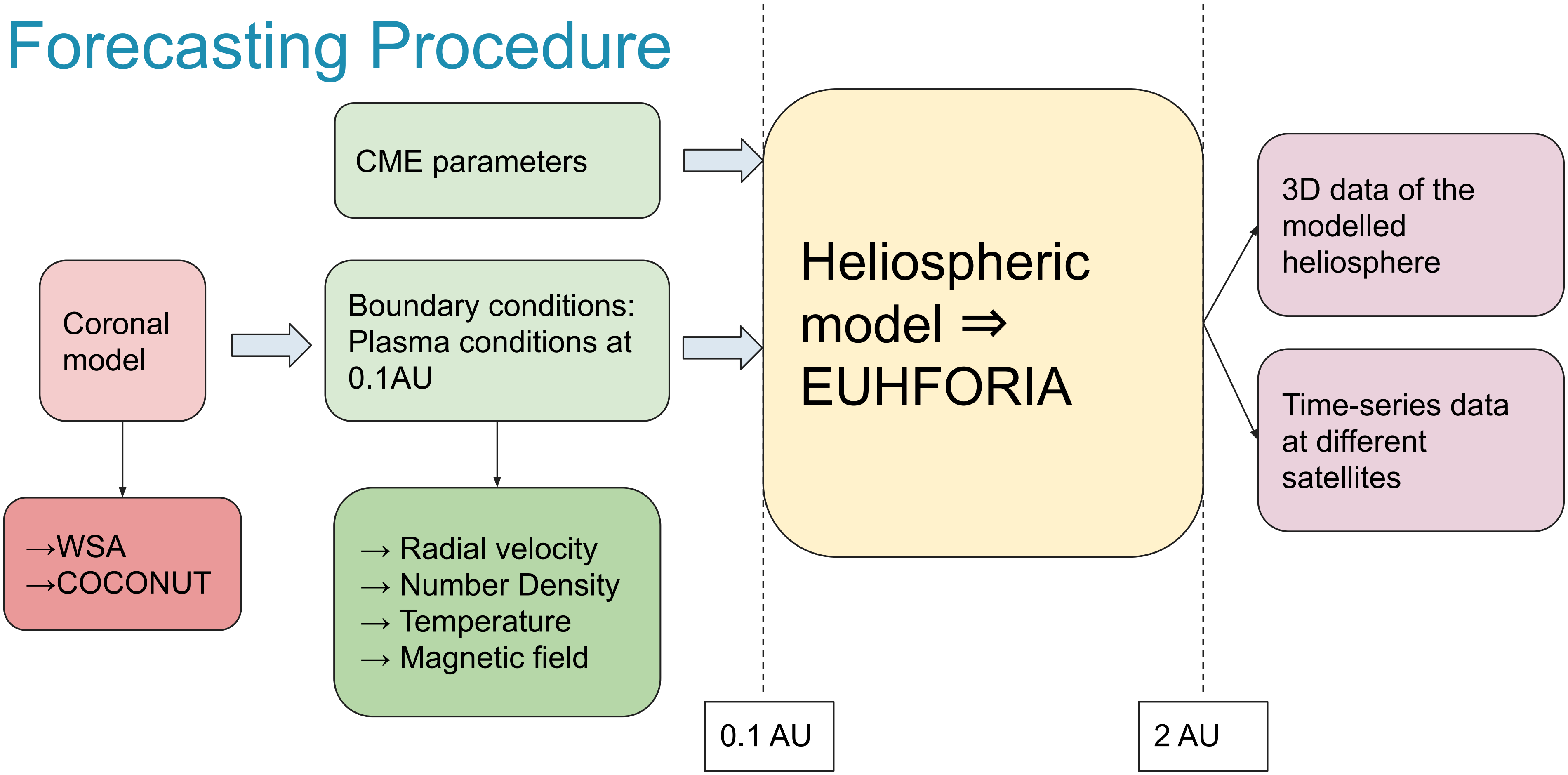
[1] KU Leuven, Mathematics, Centre for mathematical Plasma Astrophysics, Leuven,

[2] Royal Observatory of Belgium, Brussels, Belgium,

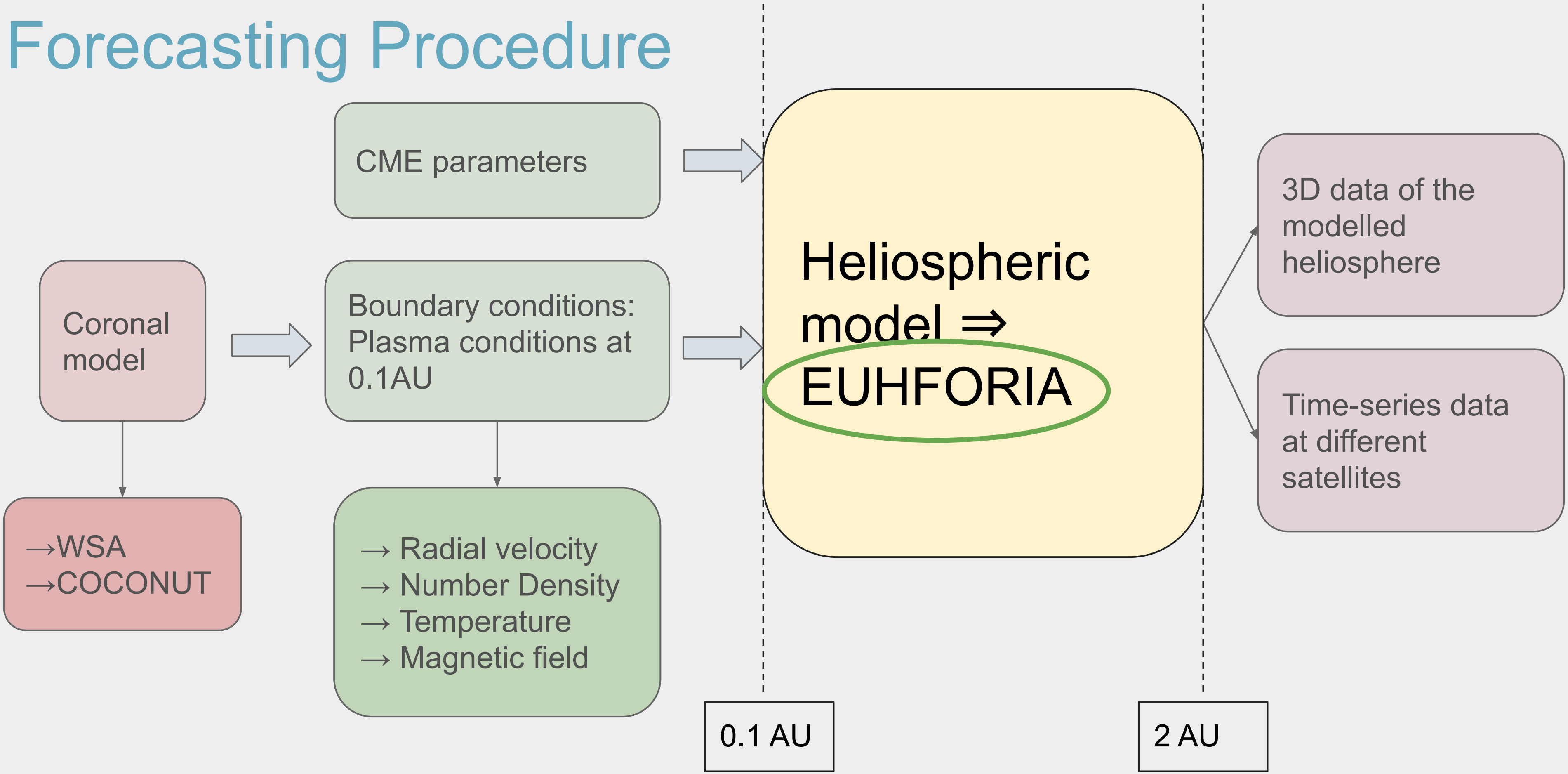
[3] Institute of Physics, University of Maria Curie-Skłodowska, Lublin, Poland

United Nations/Azerbaijan Workshop on the International Space Weather Initiative: The Sun, Space Weather and Geosphere

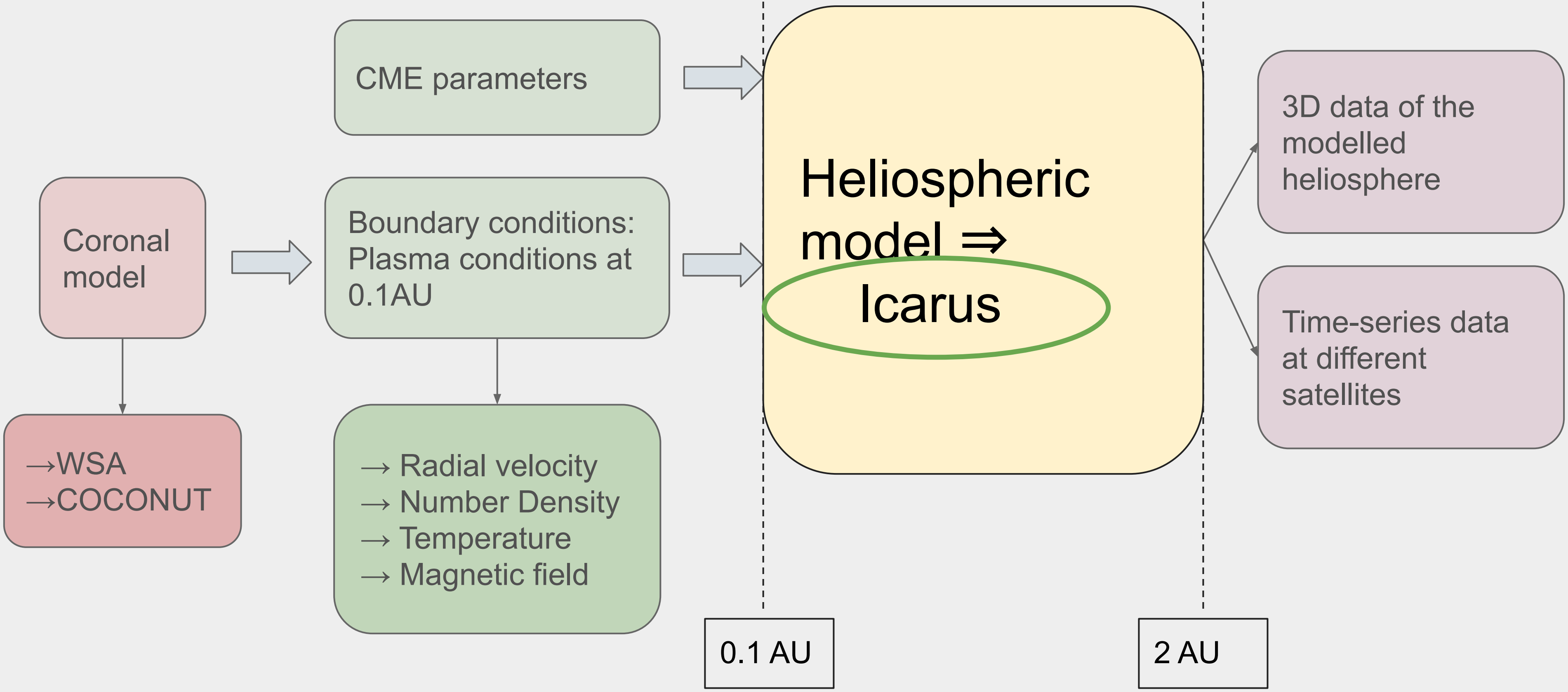
Forecasting Procedure



Forecasting Procedure

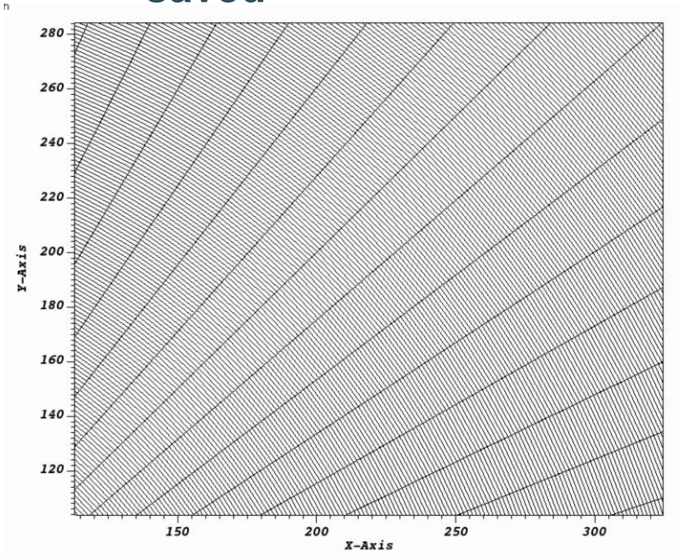


Forecasting Procedure

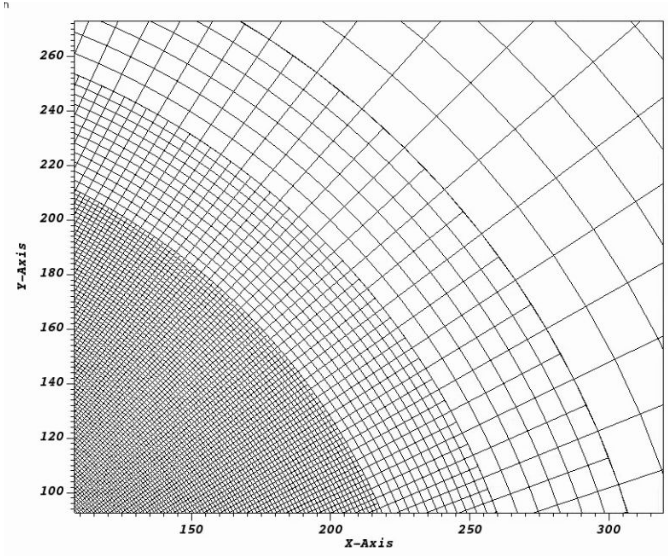


Motivation

- Operational perspective
  - Optimization (grid stretching & Adaptive Mesh Refinement) in Icarus ⇒ **CPU time saved**



Equidistant grid

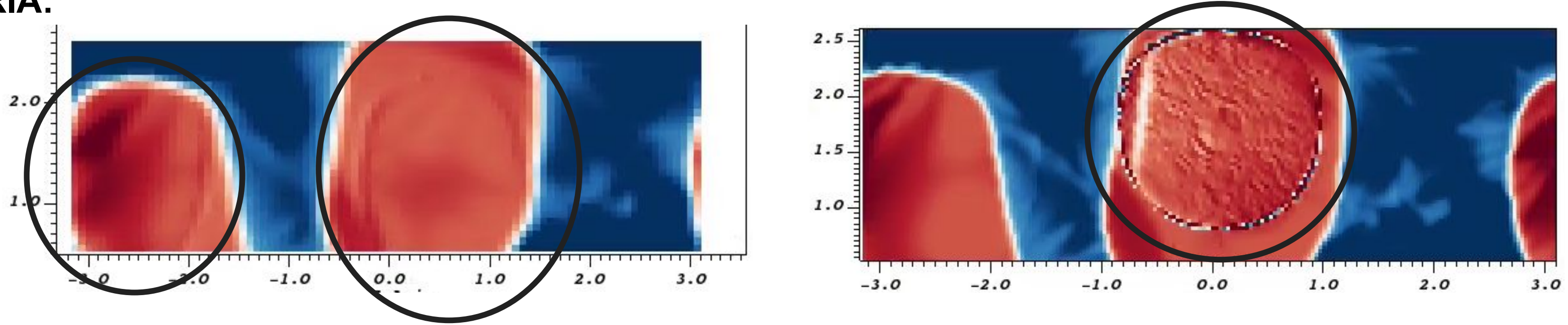


Stretched grid with AMR

Motivation

- Operational perspective
  - Optimization (grid stretching & Adaptive Mesh Refinement) in Icarus ⇒ **CPU time saved**
- Physics perspective
  - Background wind reconstruction after CME insertion
  - Better capturing of CIRs or CIR shocks or CMEs or CME shocks (via AMR)

EUHFORIA: 0.1AU



Inner heliospheric boundary before and ~24h after CME insertion

Icarus model

Implemented in the framework of MPI-AMRVAC (Xia et al.,2018)

- MPI-AMRVAC is a parallel adaptive mesh refinement framework (in FORTRAN)
- Solves (primarily hyperbolic) partial differential equations
- Ideal MHD module

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + p_{tot}\mathbf{I} - \mathbf{B}\mathbf{B} \right) - \rho \mathbf{g} = \mathbf{F},$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left(e\mathbf{v} + p_{tot}\mathbf{v} - \mathbf{B}(\mathbf{B} \cdot \mathbf{v}) \right) = \mathbf{v} \cdot \mathbf{F} + \rho \mathbf{v} \cdot \mathbf{g},$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot \left(\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v} \right) = 0,$$

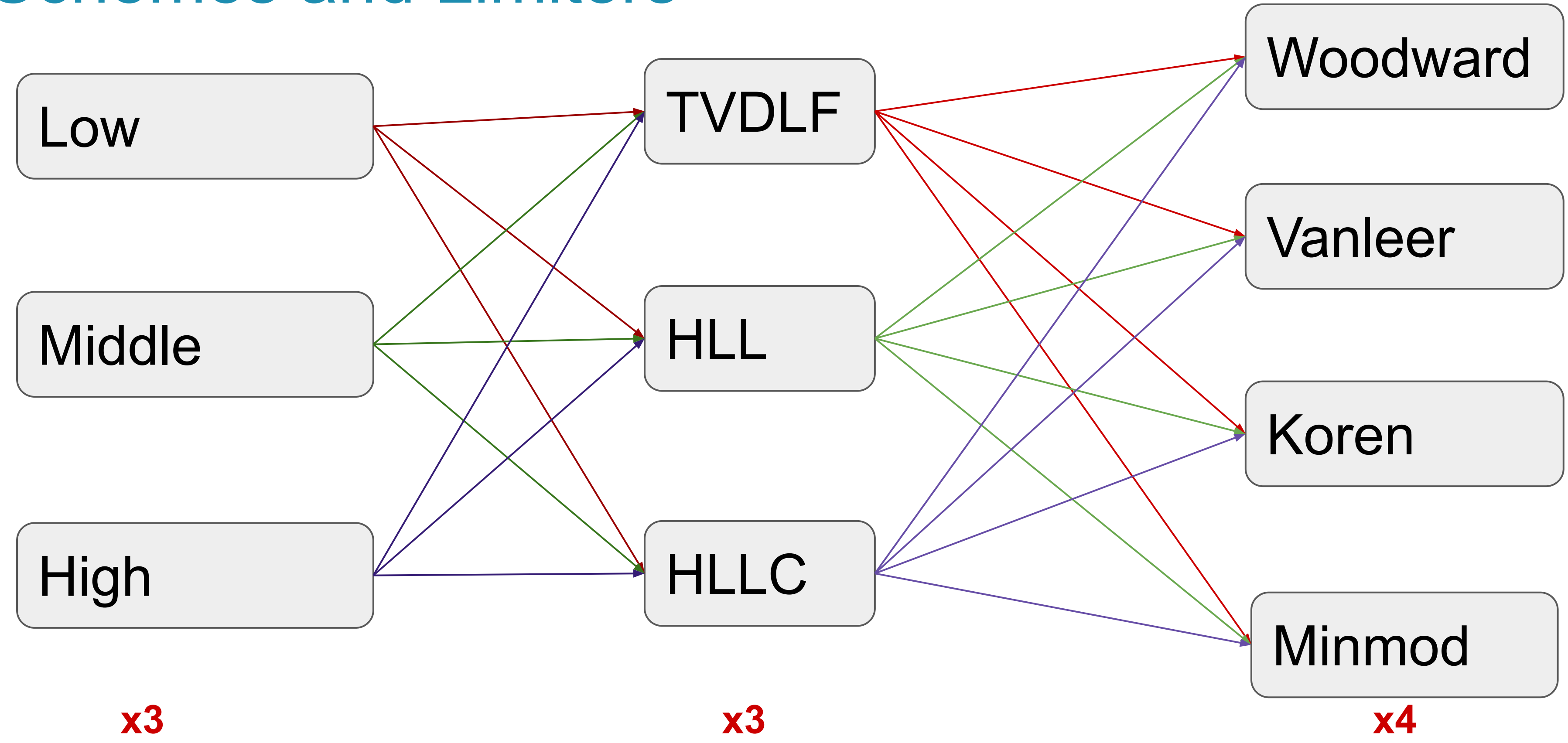
$$\nabla \cdot \mathbf{B} = 0,$$

Equidistant grid	**Resolution** [$R_\odot$, DEG, DEG]
Low	[1.37, 3.75, 3.75]
Middle	[0.685, 1.875,1.875]
High	[0.3425, 0.9375, 0.9375]

Icarus vs. EUHFORIA

	Icarus	**EUHFORIA**
Numerical Domain	R: 0.1AU → 2AU φ: 0° → 360° θ: -60° → 60°	R: 0.1AU → 2AU φ: 0° → 360° θ: -60° → 60°
Coordinate system	Co-rotating	HEEQ
Computational Grid	Uniform; Radially Stretched; Adaptive Mesh Refinement (AMR)	Uniform
MHD Solver	Finite Volume	FV with Constrained transport

Schemes and Limiters



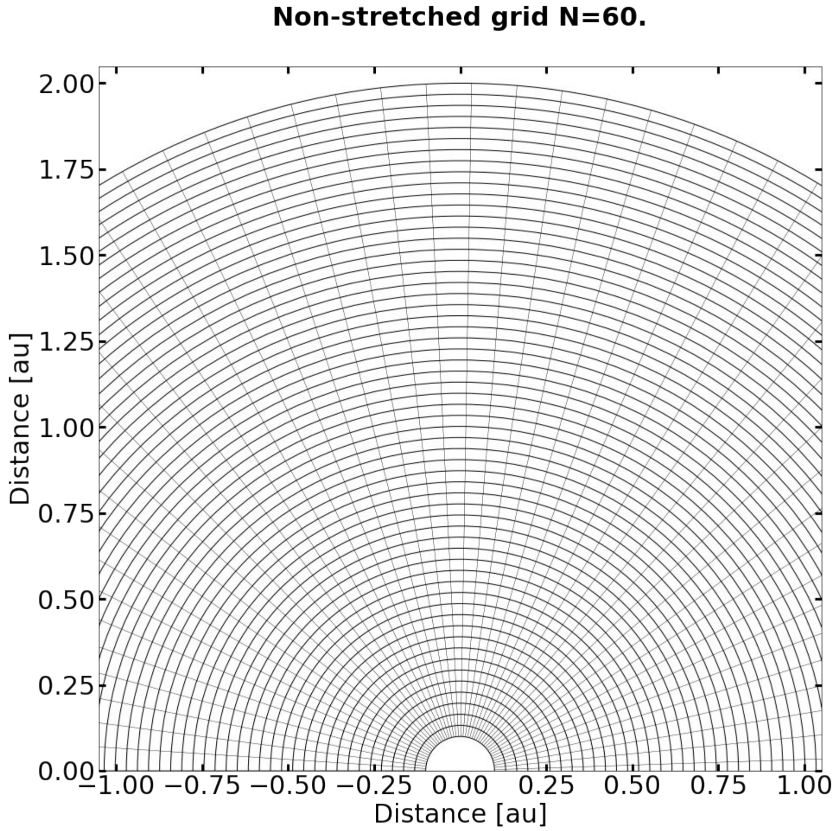
Schemes and Limiters

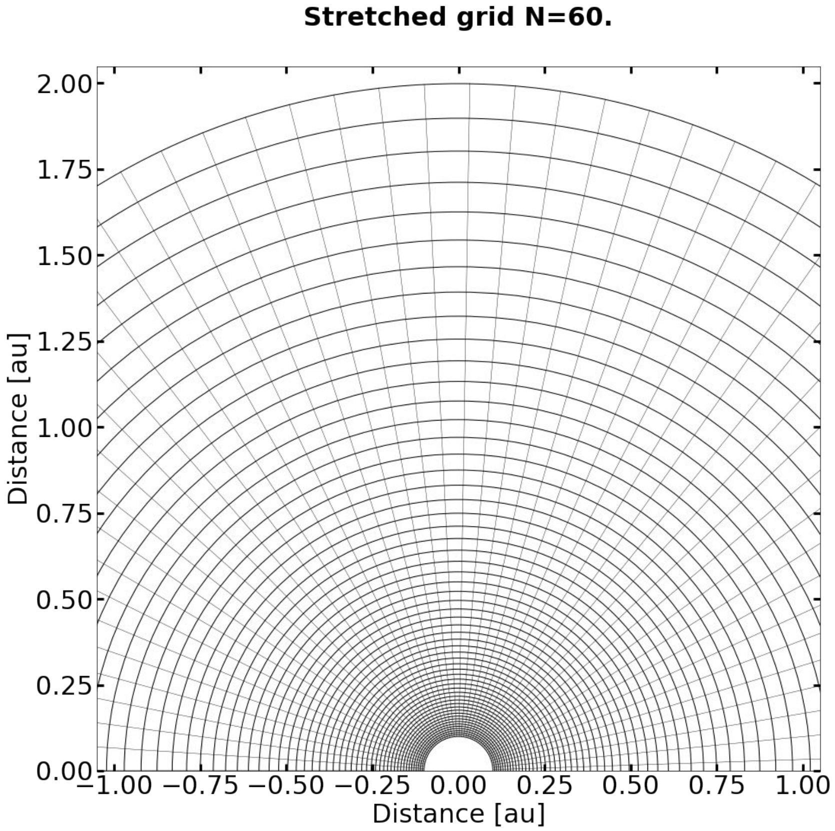
Schemes and Limiters

TVDLF + WOODWARD:

- ➔ **Sharpest**
- ➔ **Fastest**

Advanced techniques: Grid Stretching





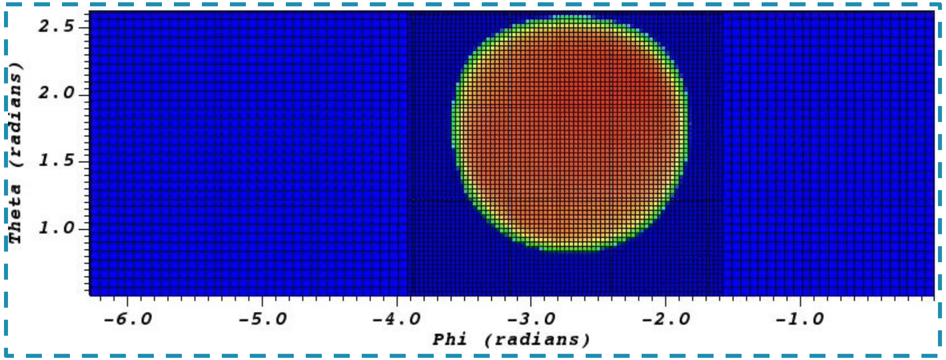
Advanced techniques: Adaptive Mesh Refinement

- Refinement applied to the blocks of cells
- 1 level of refinement difference between the adjacent blocks
- Implemented condition controls the refinement in the domain

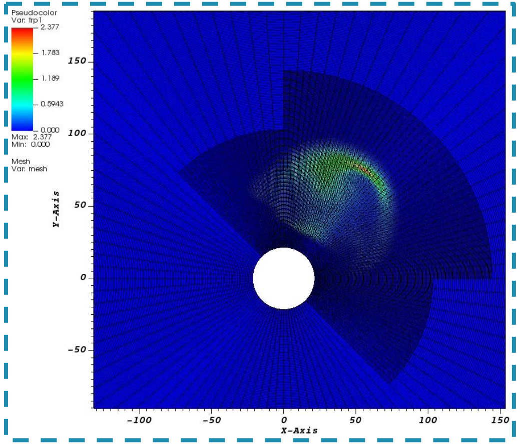
Higher resolution in the domain only where necessary.

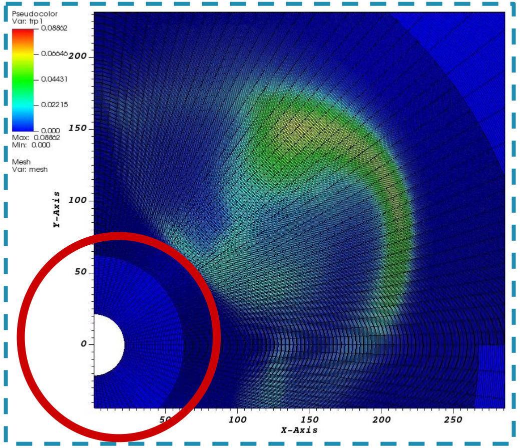
Advanced techniques: AMR

Inner boundary slice



Equatorial plane



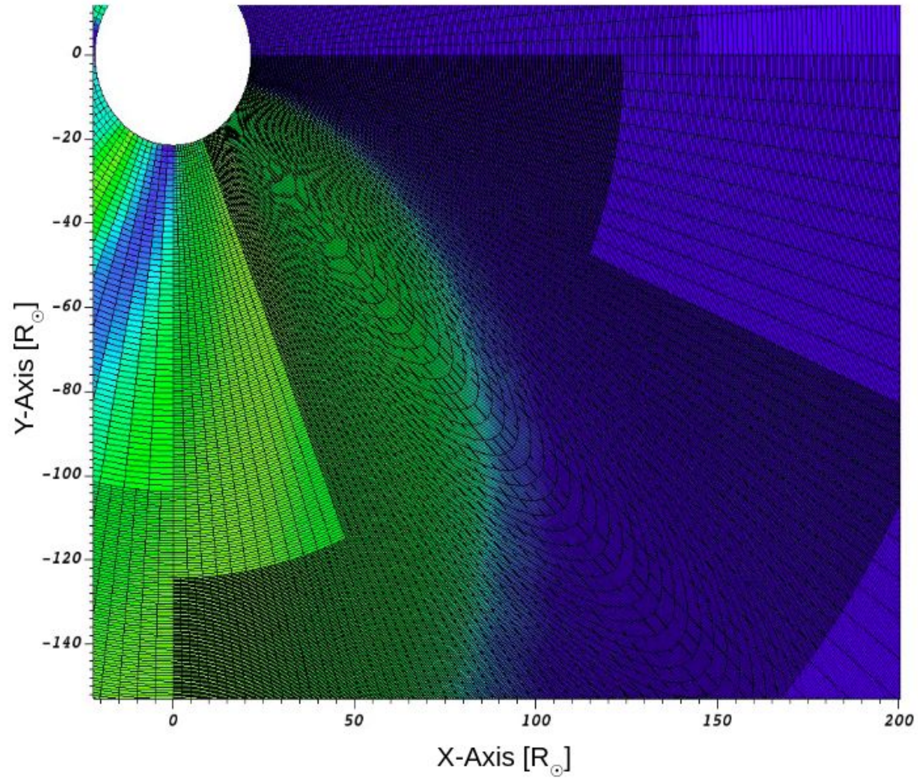


AMR (uniform) - CIR refinement

$$\phi = \phi_0 + \frac{r - r_i}{U} * \Omega$$

ϕ - the longitude that needs to be refined,
ϕ_0 and **r** - the coordinates of a point
r_i = 0.1AU
U - the characteristic speed of the fast stream
Ω - the rotation rate of the Sun.

$$\phi_{lower} < \phi < \phi_{upper}$$



Aimed for SEPs → PARADISE

AMR Equidistant - Tracing function

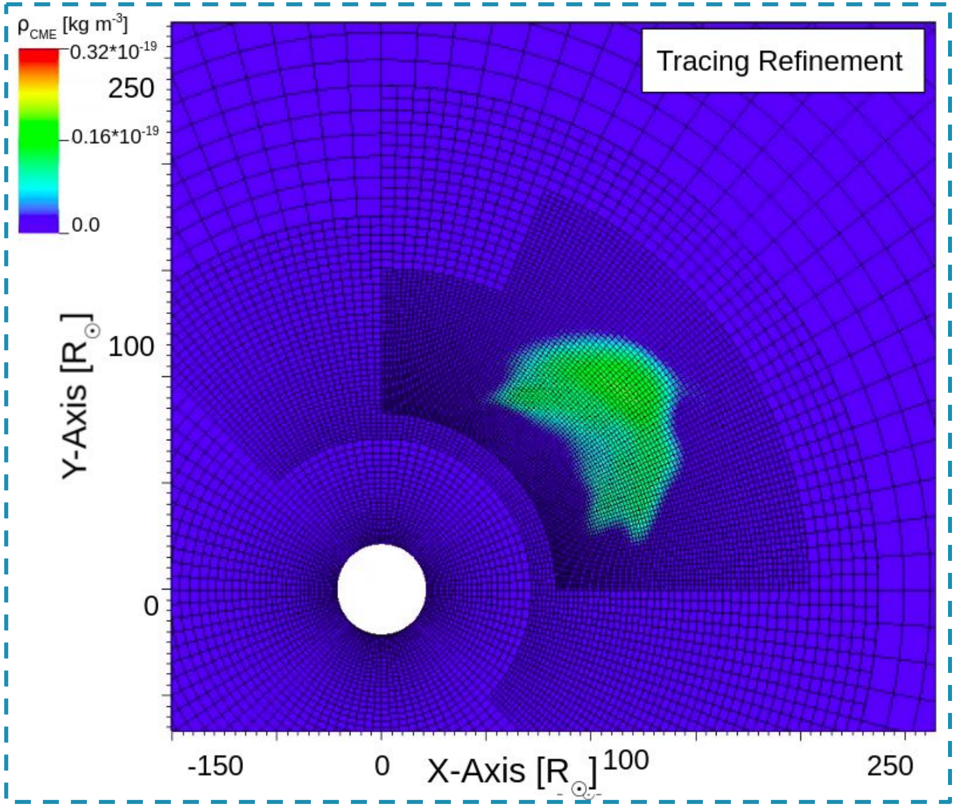
Tracing function F_{TR}:

If CME is present → $F_{TR} = \rho_{CME}$

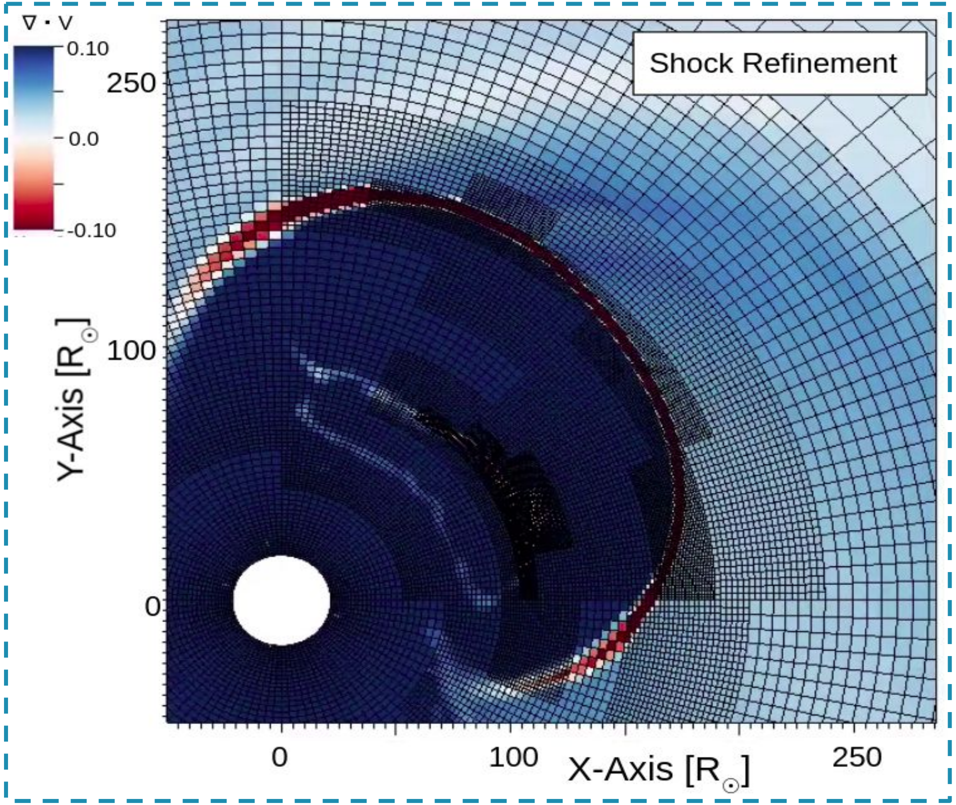
If CME is NOT present → $F_{TR} = 0$

Criterium: $\mathbf{F_{TR} > 0}$

Aimed for complex CME interior



AMR on a stretched grid: Shock function



Refinement according to the compressed regions in the domain

Criterium: $\nabla \cdot V < 0$

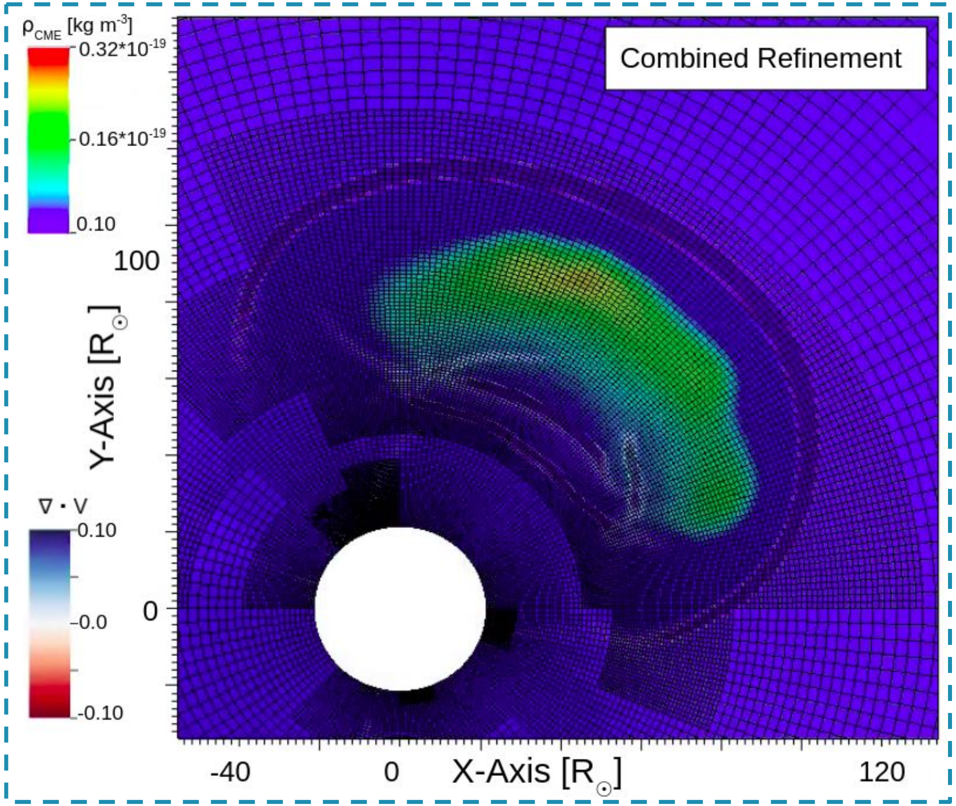
Aimed for estimation for arrival time, strength

AMR Equidistant - Combined criterion

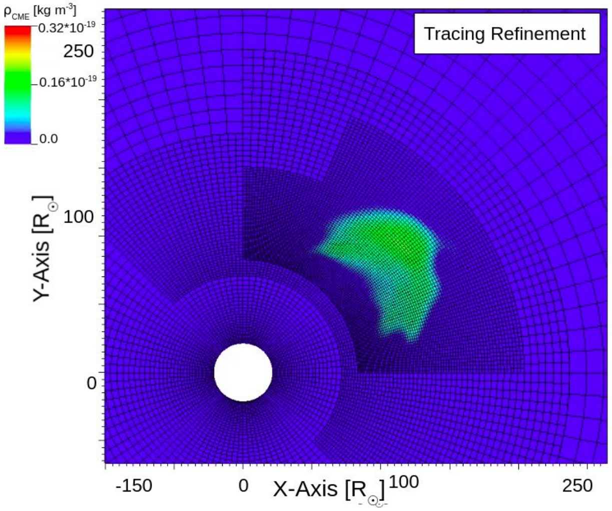
Refinement is applied when the CME or the shock is present in the domain

Criterium: $\mathbf{F_{TR} > 0 \;\; \& \;\; div(V) < 0}$

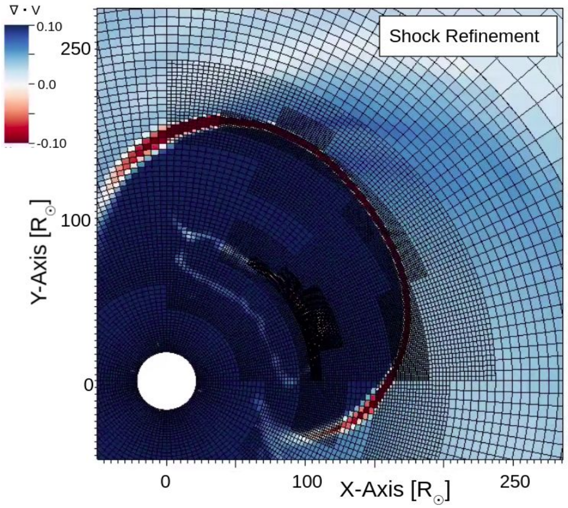
Aimed for full evolution



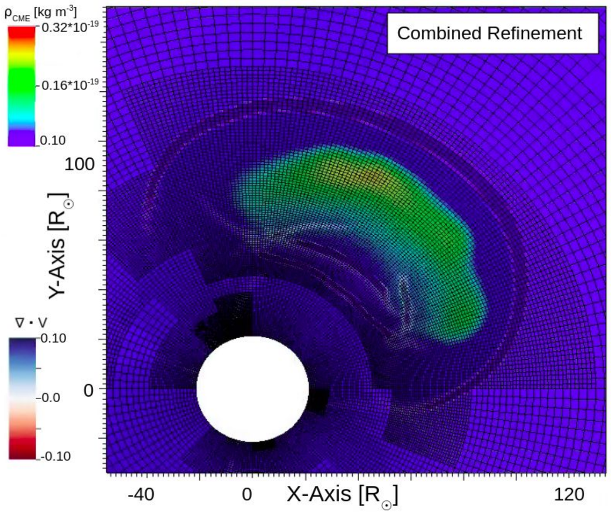
Advanced techniques : AMR + Grid Stretching



Density tracing



Shock tracing

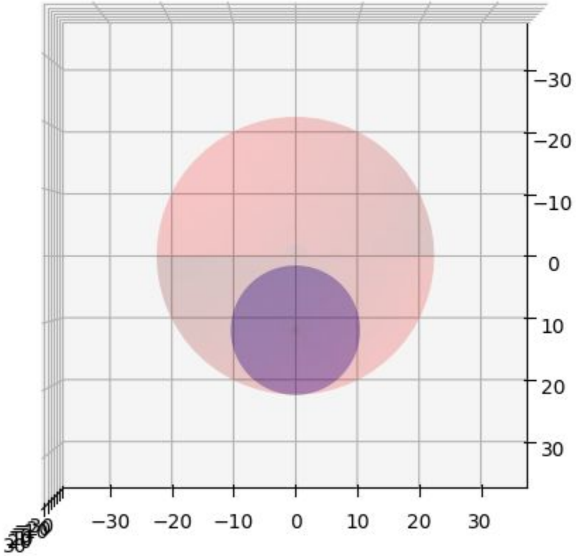


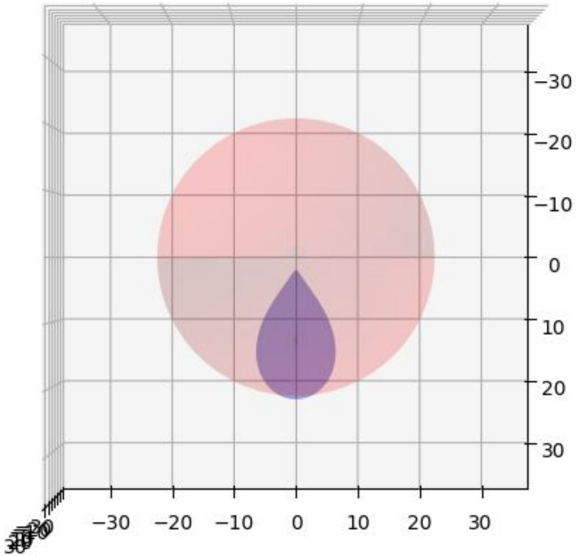
Density and Shock tracing

Baratashvili et al. 2022

Ongoing work with Icarus

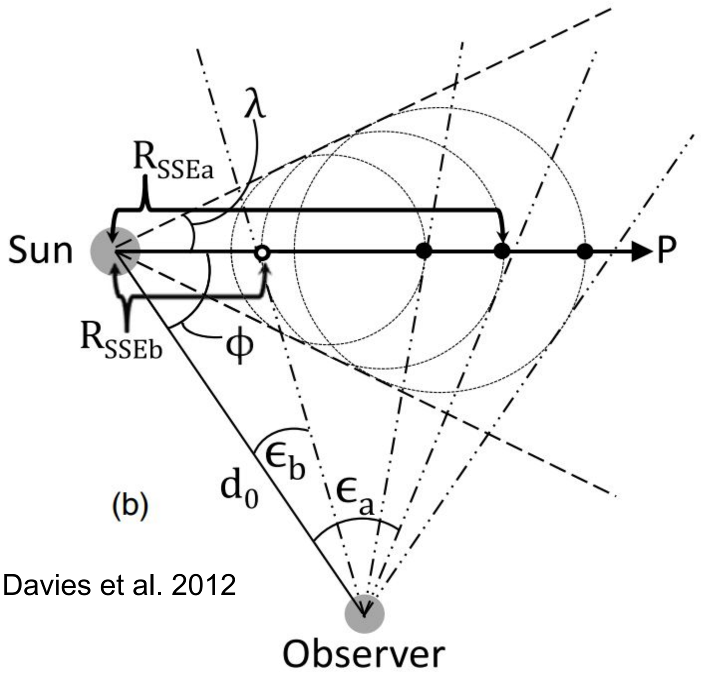
Spheromak → Stretched Spheromak





Ongoing work with Icarus

Spheromak ⇒ Self-Similar evolution



Davies et al. 2012

Ongoing work with Icarus

Spheromak ⇒ Gibson & Low model (Gibson&Low, 1998)

- A realistic flux-rope model

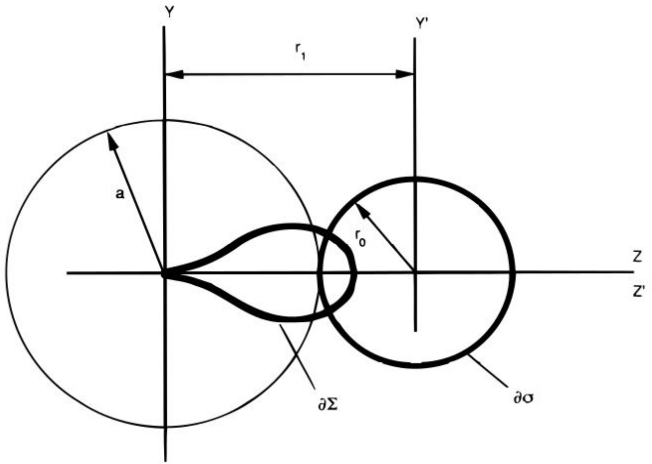
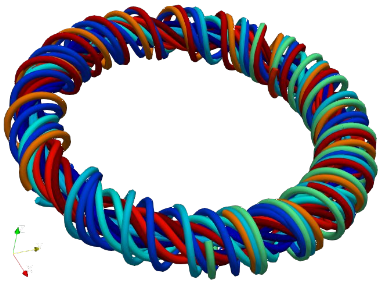


FIG. 5.—Limiting case $a = r_1 - r_0$, where the leftmost point of the circle is mapped exactly onto the origin. The mathematical stretching transformation takes a circle $\partial\sigma$ that is located in the Y-Z plane, of radius r_0, and displaced a distance r_1 from the origin, and maps it to the tear-shaped curve $\partial\Sigma$. This contraction "stretches" the space $r > a$ radially inward, under the transformation $r \rightarrow r - a$ (any points $r < a$ are collapsed onto the origin).

Ongoing work with Icarus



Spheromak

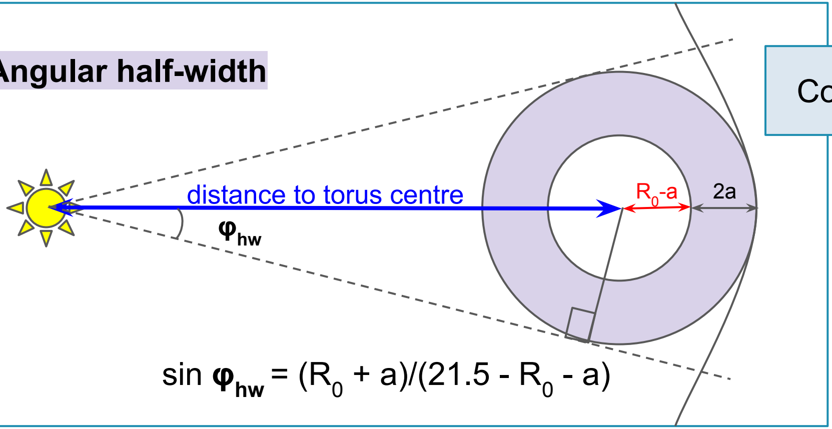
↓

Torus model → Miller & Turner model

Inner radius: $R_{inner} = 2R_{\odot}$

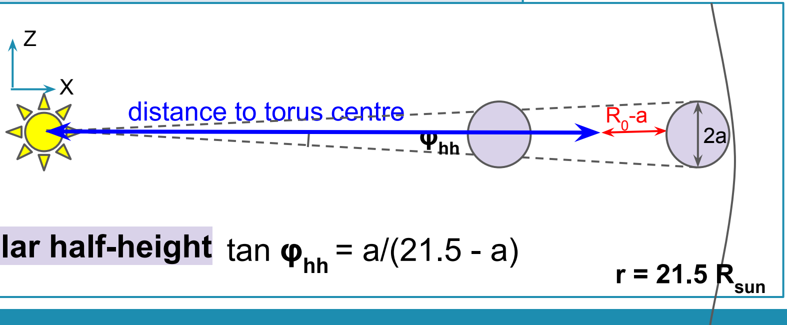
Outer radius: $R_{outer} = 5R_{\odot}$

Angular half-width



$\sin \varphi_{hw} = (R_0 + a)/(21.5 - R_0 - a)$

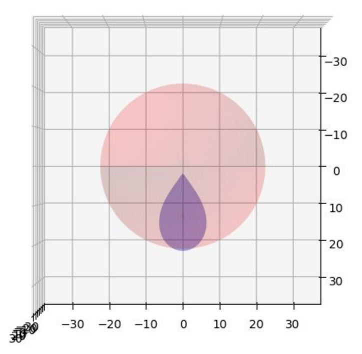
Connecting CME geometry to the torus parameters

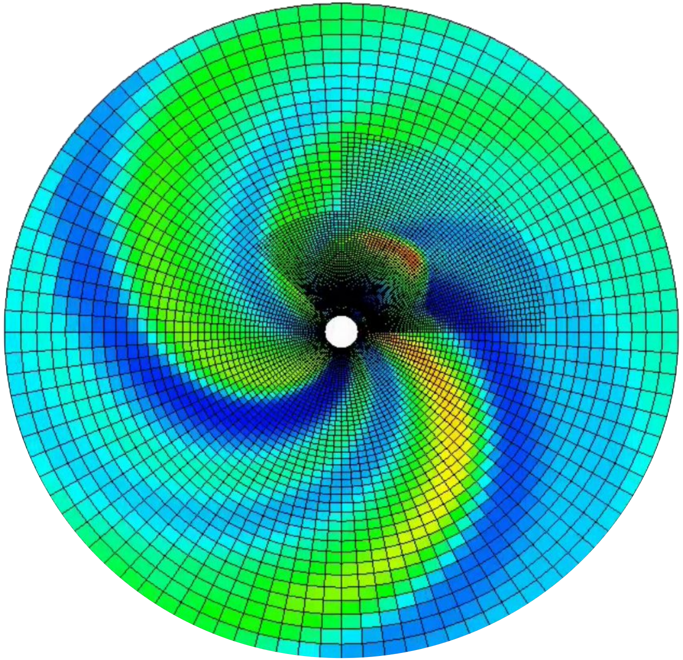


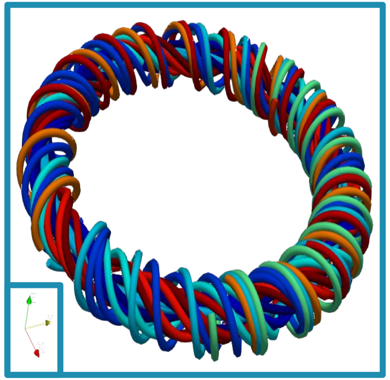
Angular half-height $\tan \varphi_{hh} = a/(21.5 - a)$

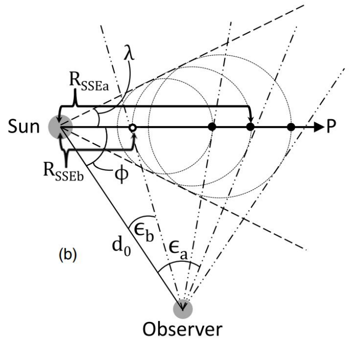
credits: Anwesha Maharana, Luis Linan

Ongoing work with Icarus









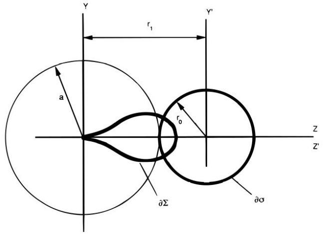
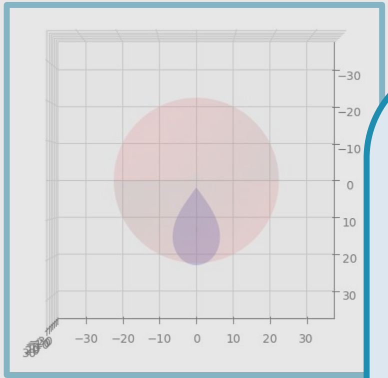
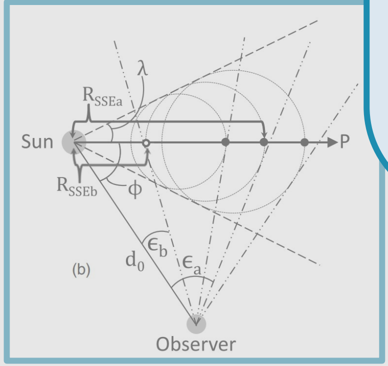


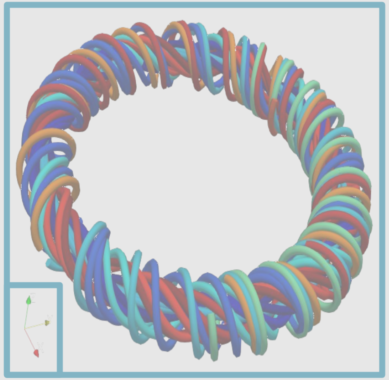
FIG. 5.—Limiting case $a = r_1 - r_0$, where the leftmost point of the circle is mapped exactly onto the origin. The mathematical stretching transformation takes a circle $\partial\sigma$ that is located in the Y-Z plane, of radius r_0, and displaced a distance r_1 from the origin, and maps it to the tear-shaped curve $\partial\Sigma$. This contraction "stretches" the space $r > a$ radially inward, under the transformation $r \to r - a$ (any points $r < a$ are collapsed onto the origin).

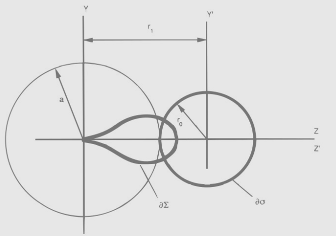
Ongoing work with Icarus





Validation with different case studies





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euhforia
KU LEUVEN

Speed up

	Icarus (Middle) Equidistant	Icarus Stretched NO AMR	AMR 2	AMR 3	AMR 4
Wall-clock times	7h 44m	0h 8m	0h 15m	0h 35m	3h 40m

Simulations are performed on **1 node only (with 36 CPUs)** on the Genius cluster at the **Vlaams Supercomputing Centre**.

Middle equidistant in EUHFORIA ~ 18h

Speed up factors

	Icarus	EUHFORIA
AMR 3	13.2	30.8
AMR 4	2.1	4.9

We are going public!

- First phase: maintained within MPI-AMRVAC repository ⇒ open-source and publicly available to everyone

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- Being integrated within VSWMC
  - Along with EUHFORIA heliospheric model
  - User-friendly GUI interface

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- Being integrated within VSWMC
  - Along with EUHFORIA heliospheric model
  - User-friendly GUI interface
- In chain with different coronal models
  - WSA
  - COCONUT

Advantages of Icarus

- Flexible Grid
  - Stretching
  - AMR
- Different numerical schemes + limiters available

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⇩

Faster results

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↓

Faster results

Saved computational resources

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Faster results

Saved computational resources

Access to more in-depth research!

Advantages of Icarus

- Flexible Grid
  - Stretch
  - AMR
- Different r

Thank you!

Faster results

Saved computational resources

Access to more in-depth research!