Drag-Based Ensemble Model (DBEMv4) with variable solar wind speed input

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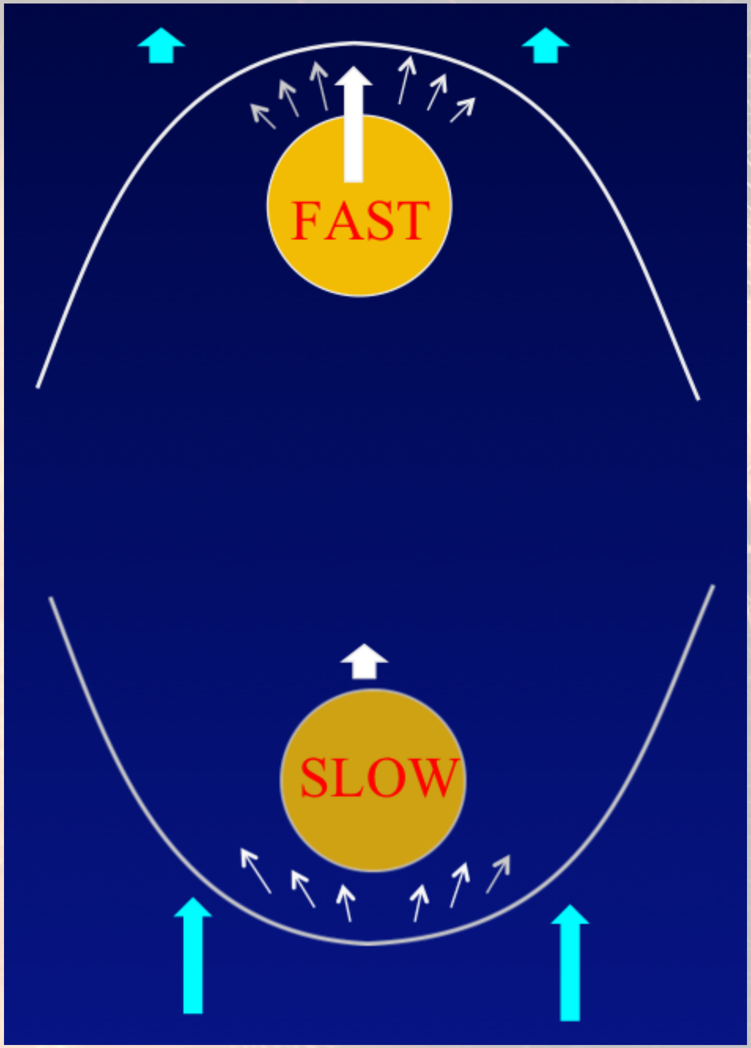
Introduction
Drag-Based Model (DBM)



Cargill et al., 1996; Vršnak and Žic, 2007; Vršnak et al. 2013

- Beyond about 20 solar radii the MHD “aerodynamic” drag (a_d) caused by the interaction of CME with solar wind, becomes the dominant force

$$a = a_L - g + a_d$$
$$a_d = -\gamma(v-w)|v-w|$$

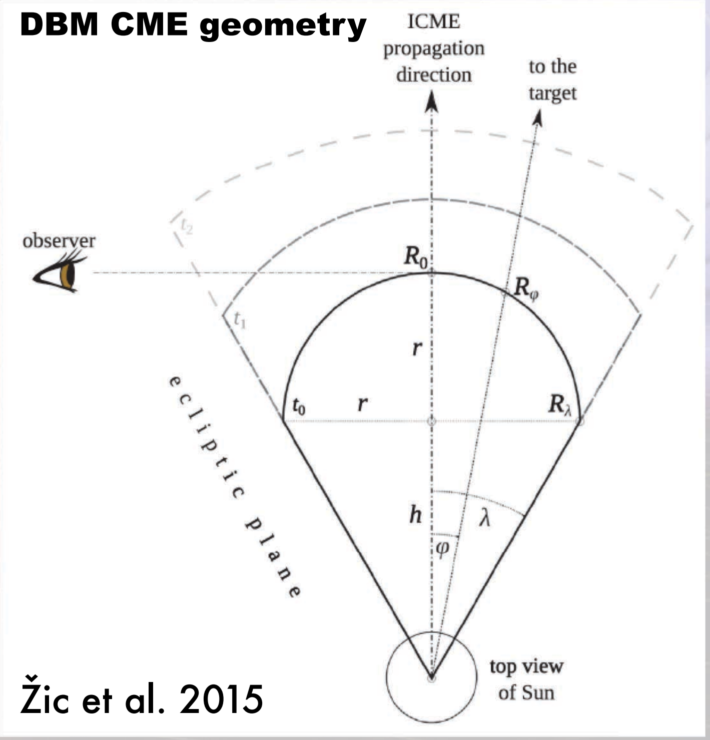
Equation of motion

- CME dynamics is governed by interaction with (ambient) solar wind (w)
  - fast CME ($v > w$) → deceleration
  - slow CME ($v < w$) → acceleration
- Drag parameter (γ) depends on characteristics of both CME and solar wind
- If w and γ constant there is analytical solution

Main points DBM

- Simple analytical 2D model for heliospheric propagation of CMEs to predict the CME arrival time and speed at any given target in the solar system (planets and satellites)

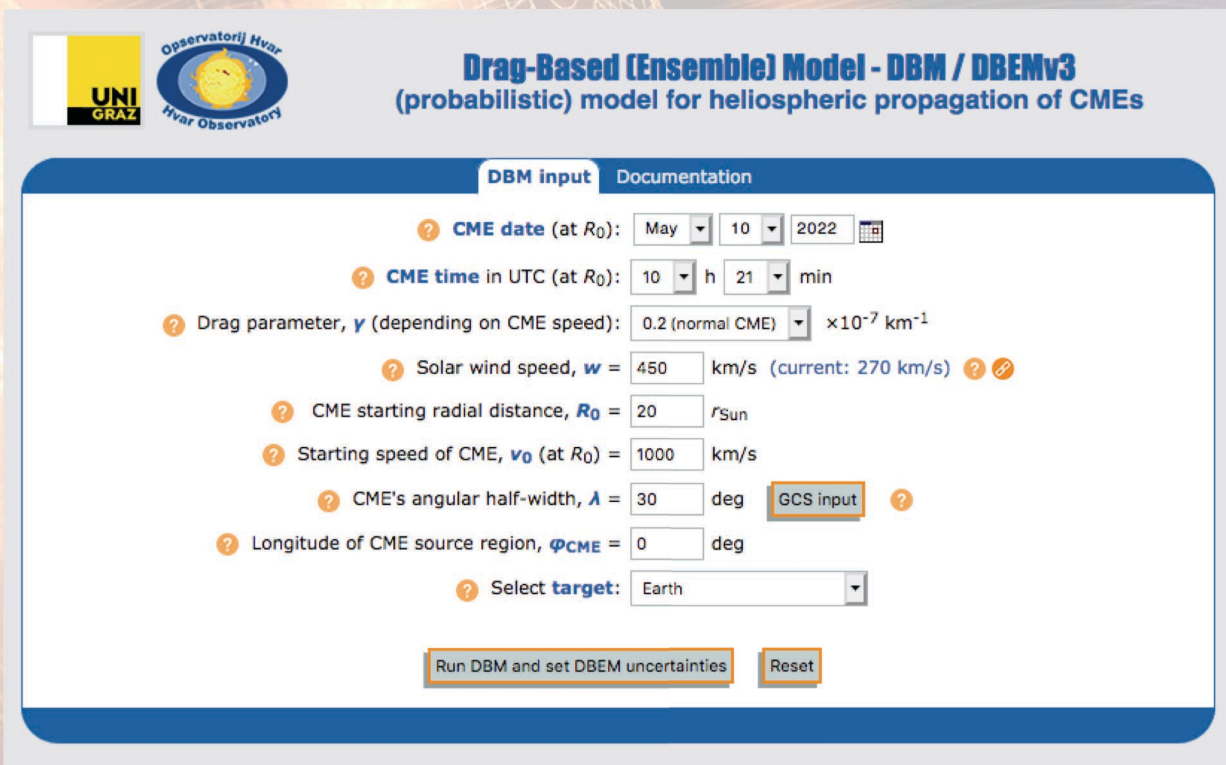
- Uses CME cone geometry with "flattening" (CME leading edge is initially a semicircle defined by the CME angular width that flattens with time – Žic et al. 2015, Sudar et al. 2022 submitted)



- **Advantages**
  - simple and robust
  - very fast (one run << 1 sec) compared to numerical MHD models (e.g. ENLIL)
  - suitable for ensemble modelling
- **Disadvantages**
  - doesn't give the best results in complex heliospheric environment (eg. CME-CME interactions, CME passing trough high speed streams, or when **w** and **γ** aren't constant)

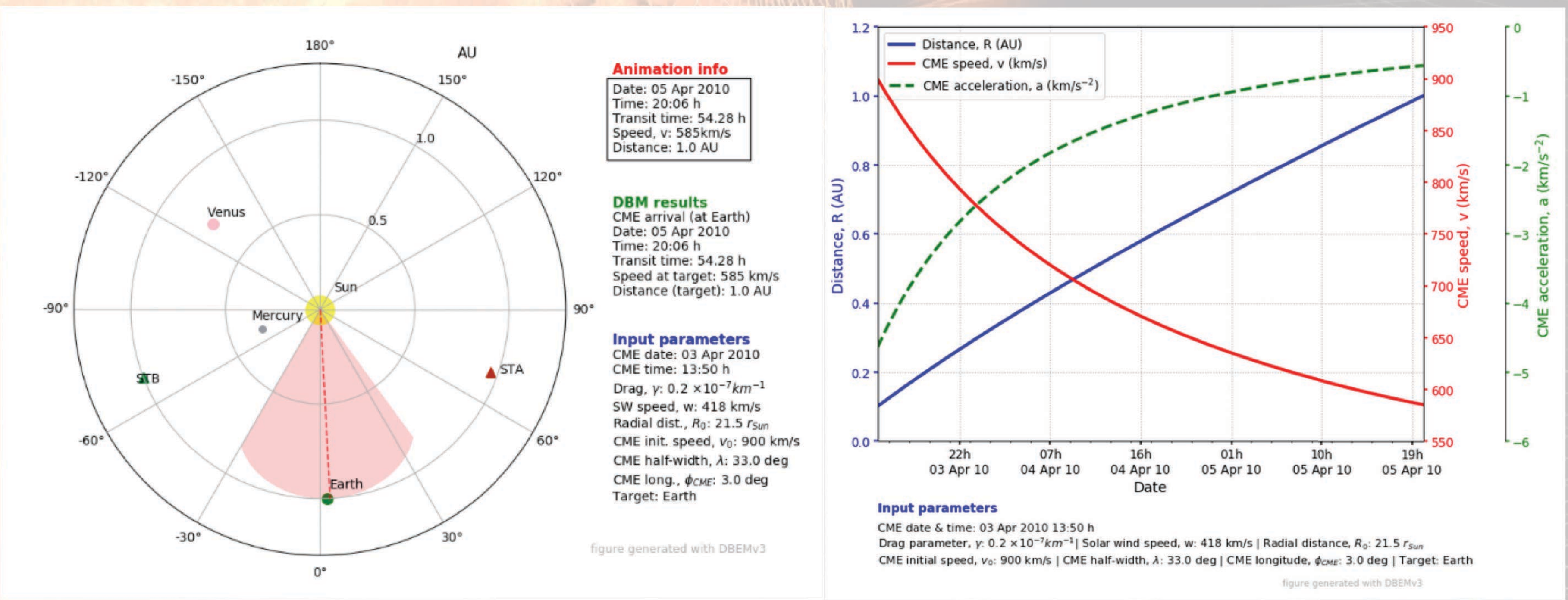
Drag-Based Ensemble Model (DBEM)

- Offers probabilistic forecasting of **CME hit chance, transit time** and **arrival speed** for different targets in solar system
- Reliable and simple model (written in Python)
- Runs **very fast** (more than 1000 DBM runs per sec on a single CPU)
- Suitable as on-line (web) forecasting tool: implemented in **ESA Space Situational Awareness (SSA)** portal https://swe.ssa.esa.int/heliospheric-weather



DBM / DBEMv3 web tool

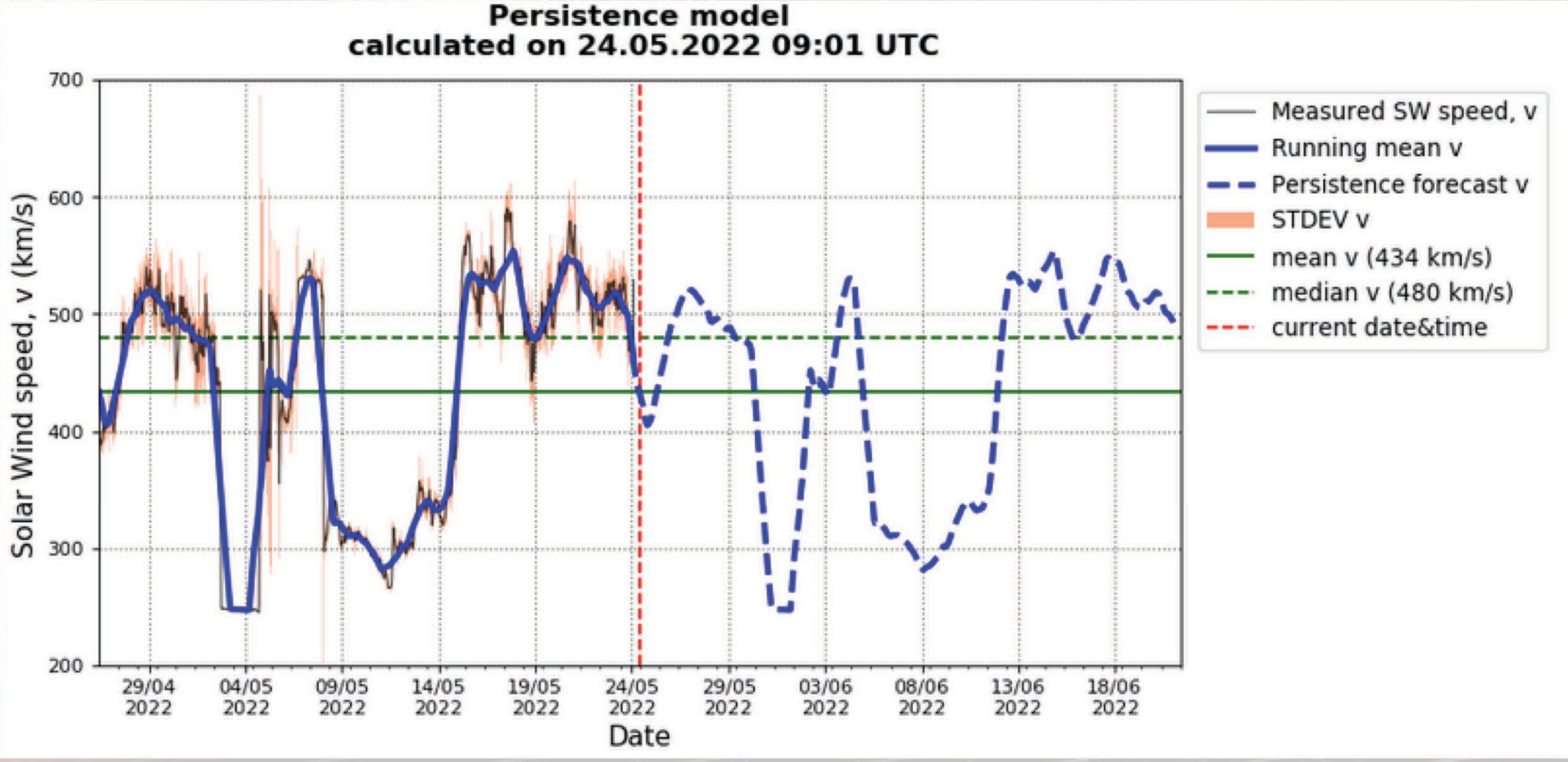
- Integrated in ESA SSA portal since October 2021
- Full integration of DBM web tool into DBEM together with DBM CME geometry & kinematic plot visualisations
- **Graduated Cylindrical Shell (GCS)** model option – calculates CME angular width from alpha, kappa, tilt (GCS parameters)
- Documentation available online, detailed description and evaluation given in **Čalogović et al. 2021**



DBEMv4 with variable solar wind input

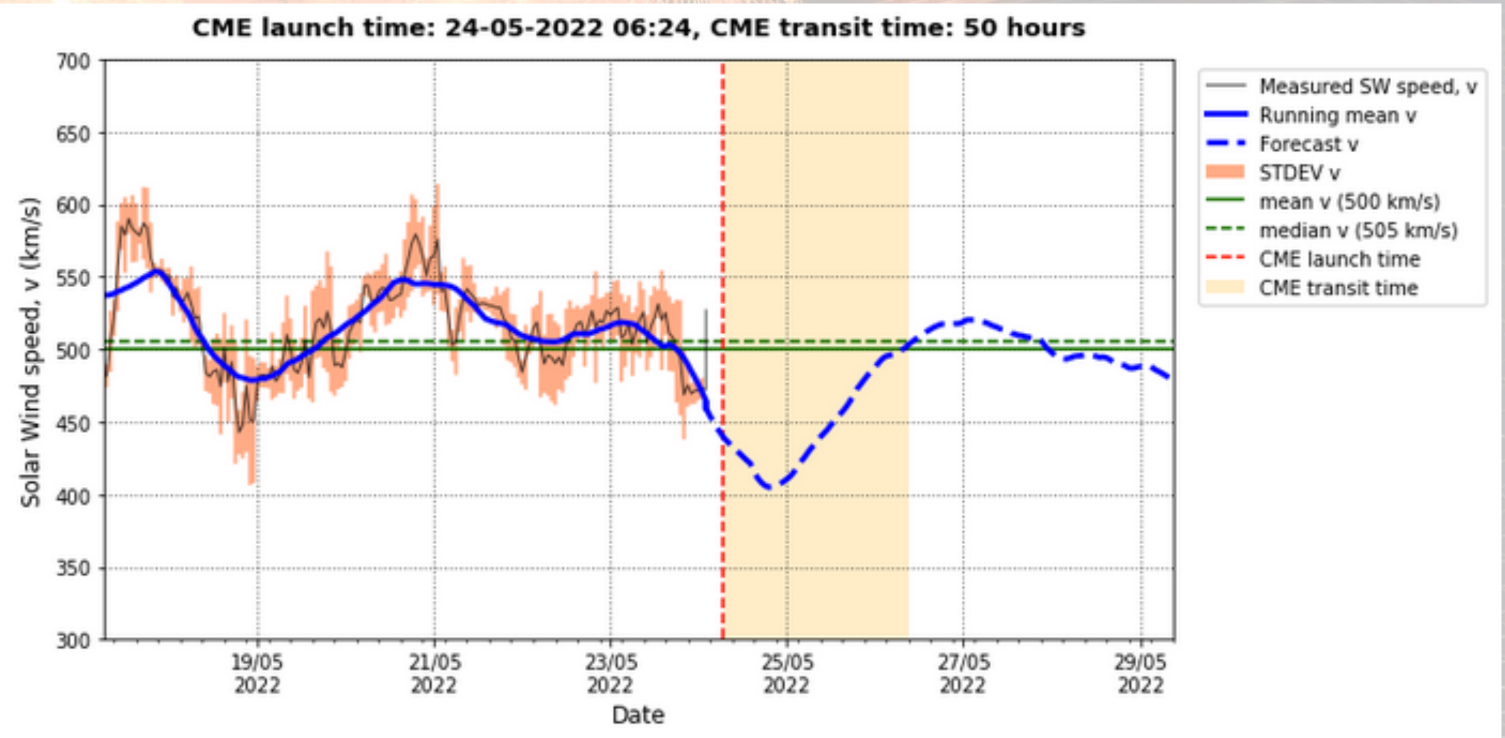
- Uses variable (in steps) instead of constant background solar wind speed to increase the accuracy of CME propagation forecast
- **Persistence model** employed as SW speed forecast (28 days in future) taking into account the CME propagation direction
- Important constraint - model should be enough fast and simple to use it as operative on-line forecasting tool (with short calculation times less than few minutes)

25 hour running mean and persistence forecast (blue curve)



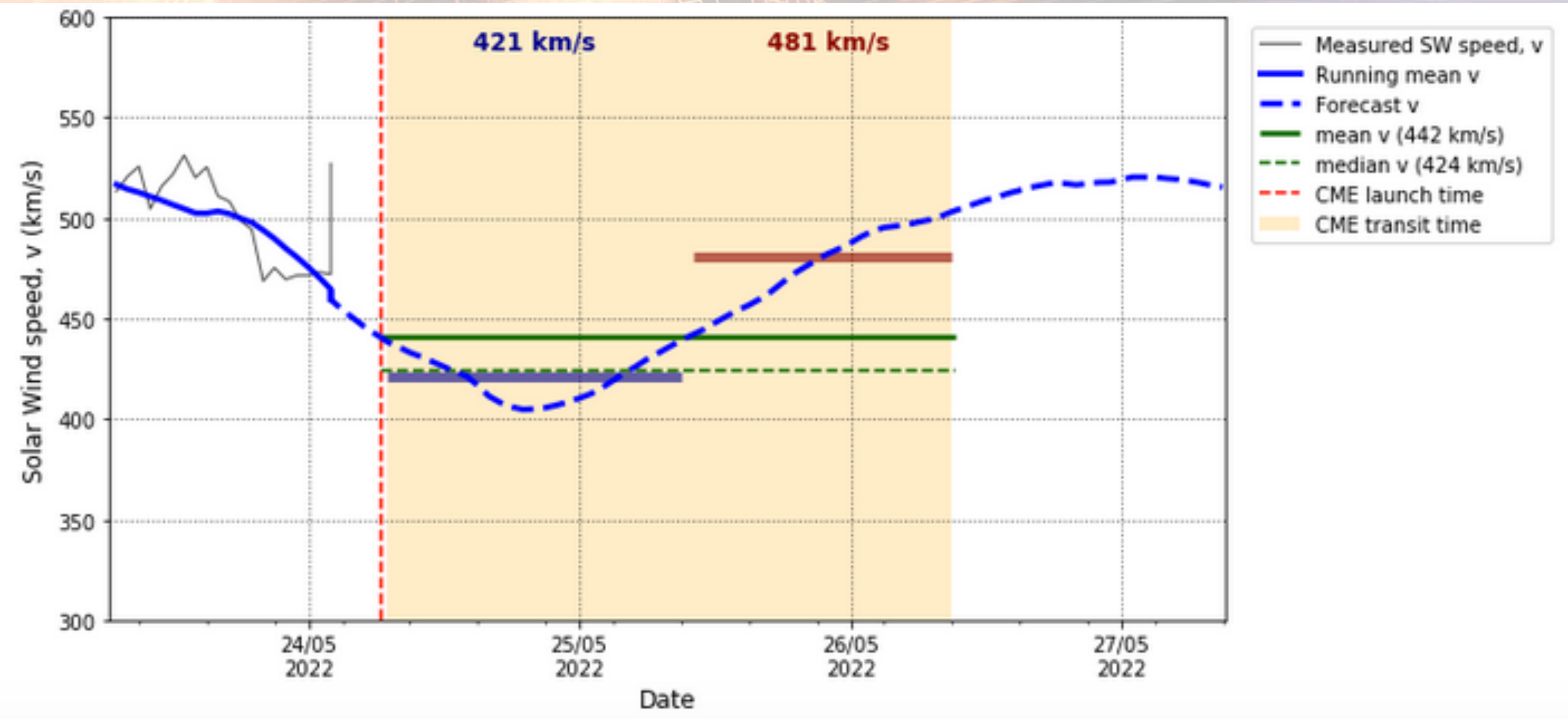
Solar wind (SW) module in DBEMv4

- Database with hourly SW data since 21.10.1997 (ACE satellite), since 1.1.2021 uses DSCOVR satellite data, updated automatically every day
- Only 0.63% of missing data (small gaps up to 6h are interpolated)
- Uses persistence model (25 h running mean - blue curve)
- CME transit time calculated with DBM (yellow shaded region)
- Uses Richardson & Cane ICME database (since 1996) to mark CMEs in SW, implementation of further CME databases possible in the future
- Calculates SW speed mean and median values in shown period



Steps estimations in SW module

- Calculates SW speed deviation (SW running mean – SW mean) in CME transit window, all positive and negative deviations are grouped into steps
- Median value is calculated for each step
- Implemented routine that merges similar steps that have difference < 25 km/s (or some other arbitrary threshold)



SW module statistics

- Provides some statistics for each step (median, mean, standard deviation, min, max, 95% confidence intervals)
- Transit time and estimation of start distance R using DBM for each step is calculated (needed as DBEM input)
- The best estimated values are given in input form
- In some cases user can decide to run DBEM as single step using the only average values
- Confidence Intervals (CI) can be used as estimated uncertainties in DBEM input form with uncertainties

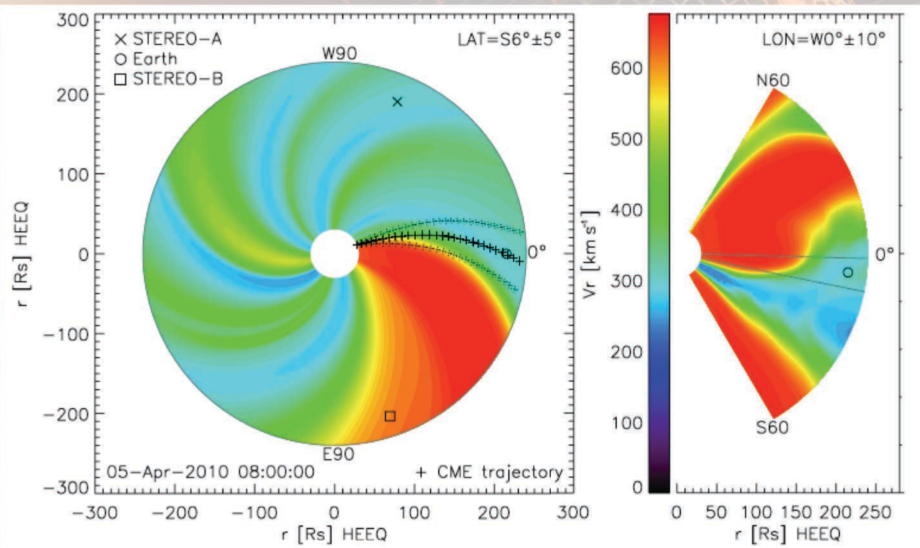
step	median	mean	StDev	min	max	Upper CI (95%)	Lower CI (95%)	Transit Time (h)	distance R (start)
1. step	421.5	420.6	11.3	404.8	439.1	438.7	405.0	26.5	20.0
2. step	480.5	476.7	19.6	441.9	503.0	501.7	443.4	23.5	133.31
average	438.4	447.0	32.1	404.8	503.0	500.3	405.2	50.9	

1. step	median SW speed, w_1 =	421.5	km/s	Start distance R_0 =	20.0	R_{Sun}
2. step	median SW speed, w_2 =	480.5	km/s	Start distance R_1 =	133.31	R_{Sun}

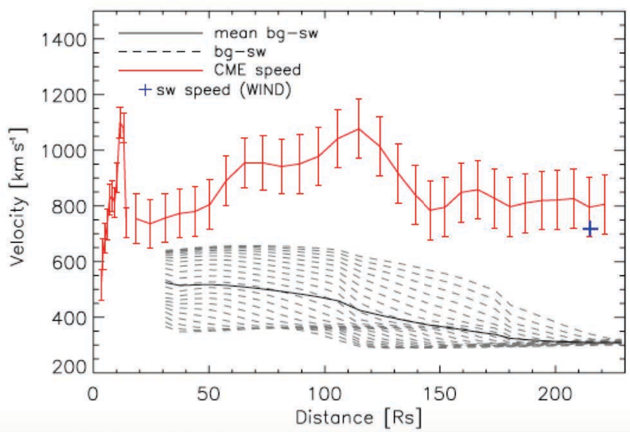
DBEMv4 test case evaluation with simple solar wind profile

- CME/ICME event on **3 April 2010, 13:50 UT**

MAS+ENLIL



Temmer et al. 2011

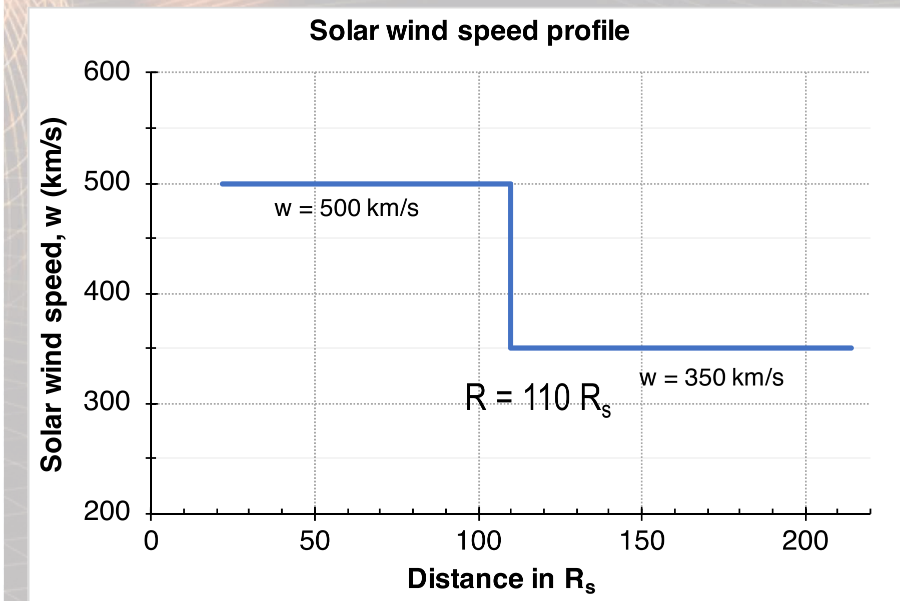


Launch speed, v_0 = 900 km/s

Drag parameter, $\gamma = 0.2 \times 10^{-7}$

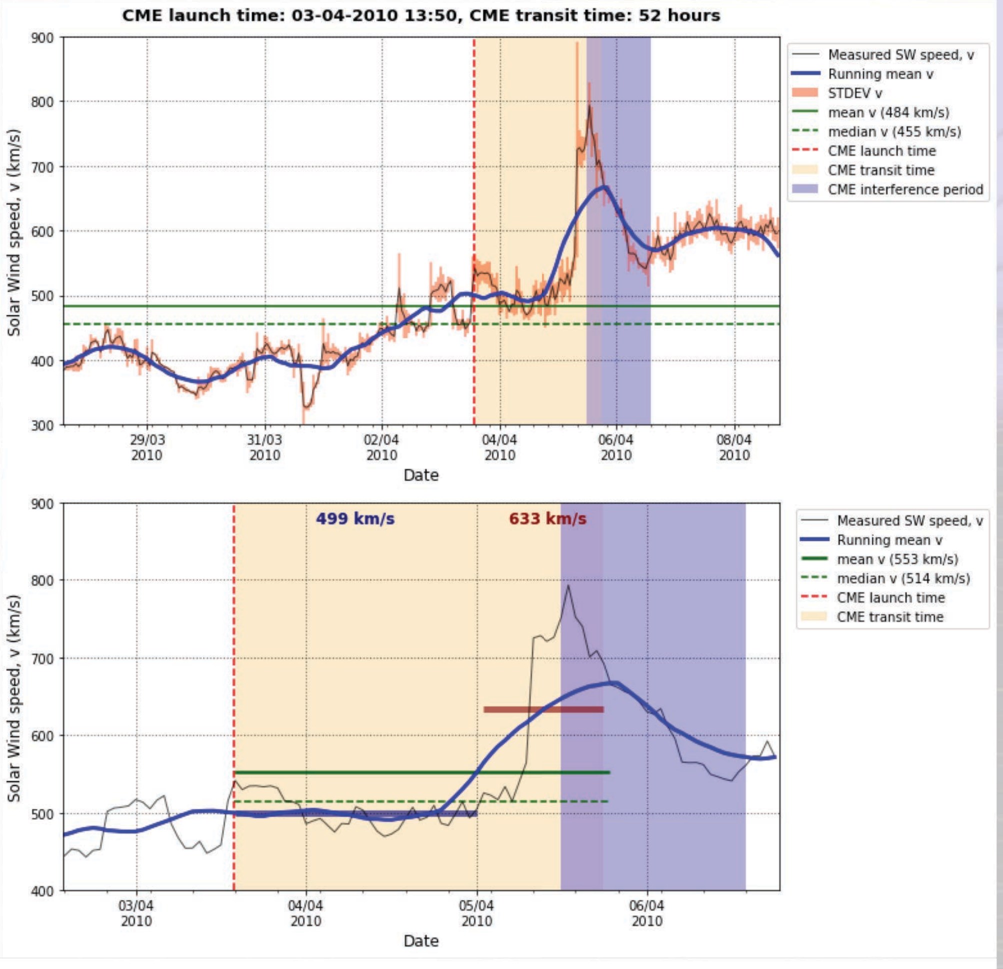
Half-width, λ = 33 deg

Longitude, φ_{CME} = 3 deg



DBEMv4 SW module results

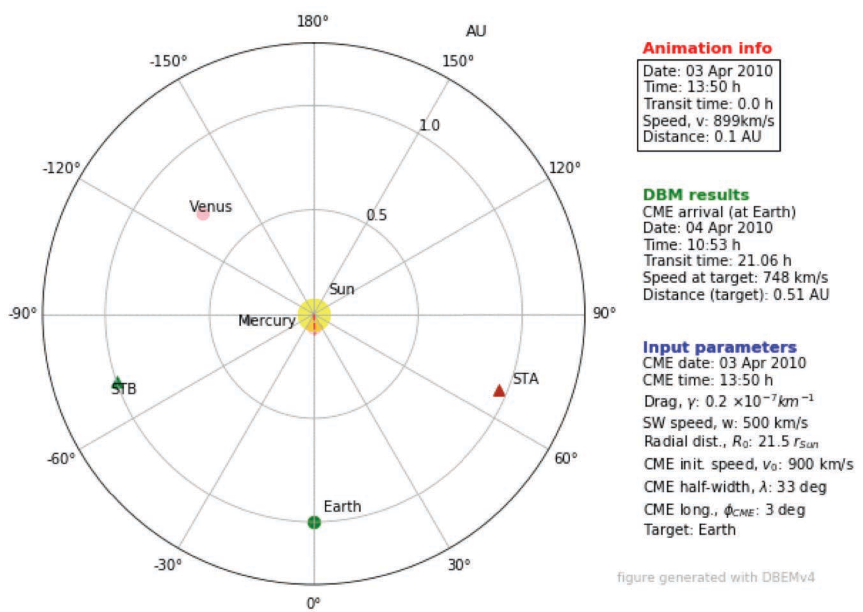
- First step estimated by SW module gives median SW speed 498 km/s - very close to MAS+ENLIL mean of 500 km/s
- Second step is influenced by ICME (Richardson & Cane ICME list, blue shaded region) and its estimation of 632 km/s for SW speed is quite far from MAS+ENLIL result of 350 km/s
- Importance that users are warned about CME/ICMEs periods in measured SW speed



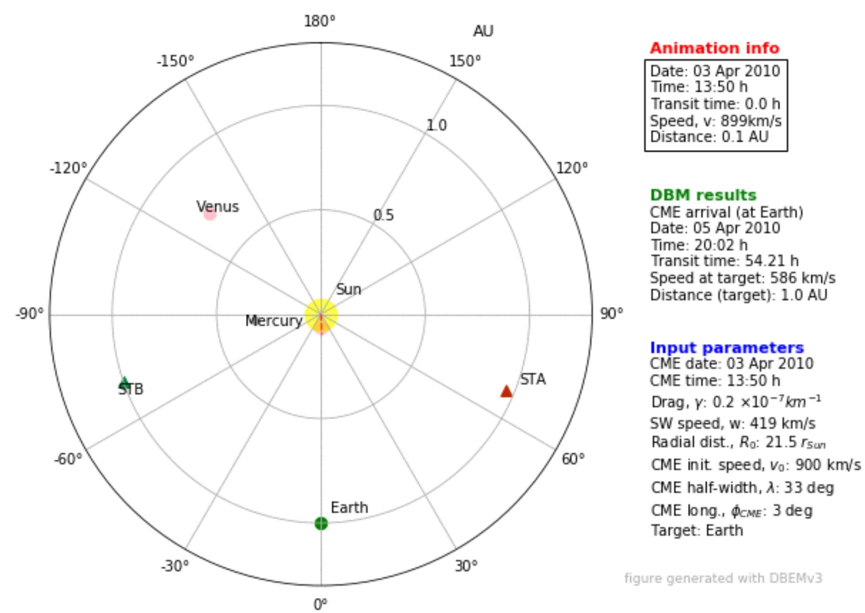
step	median	mean	StDev	min	max	Upper CI (95%)	Lower CI (95%)	Transit Time (h)	distance R (start)
1. step	498.7	502.3	13.4	490.7	551.7	542.1	490.9	34.5	20.0
2. step	632.9	626.7	31.4	564.5	665.8	664.9	569.2	17.5	154.3
average	502.7	544.6	62.7	490.7	665.8	663.4	491.2	52.9	

DBM CME geometry

DBEMv4 with two steps (variable w)



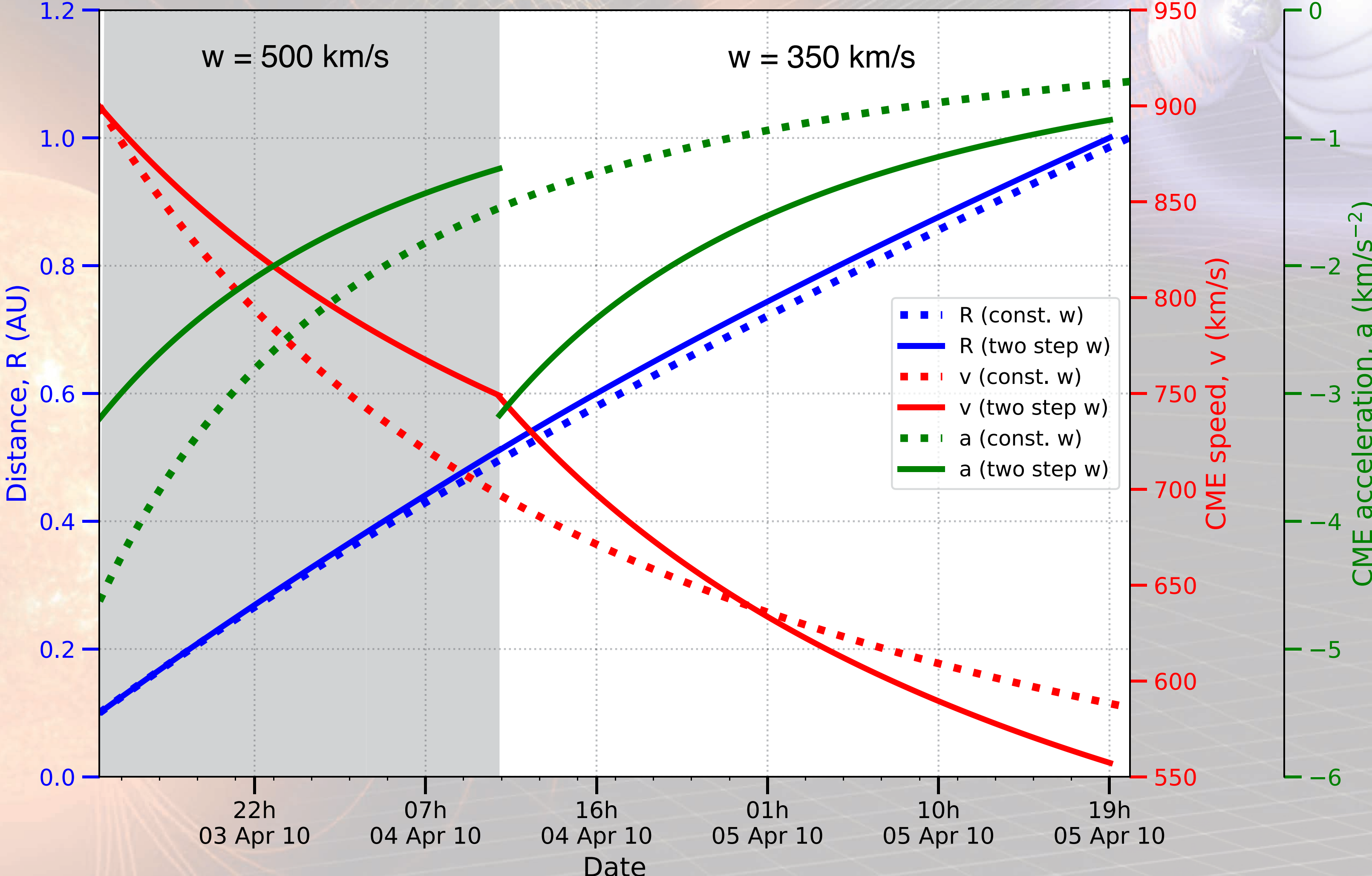
DBEMv3 with constant w



- 2 consecutive DBM runs (one with w=500 km/s for R=21.5-110 R_{Sun} and second with w=350 km/s for R=110-214 R_{Sun})
- CME launch time and speed (t, v_0) in second run taken from first run (CME arrival time, speed)

- One run with constant w
- w values estimated with weighted mean (e.g. w = ((88.5*500) + (104*350))/192.5 = 419 km/s)

DBM CME kinematic
DBEMv3 vs DBEMv4 comparison

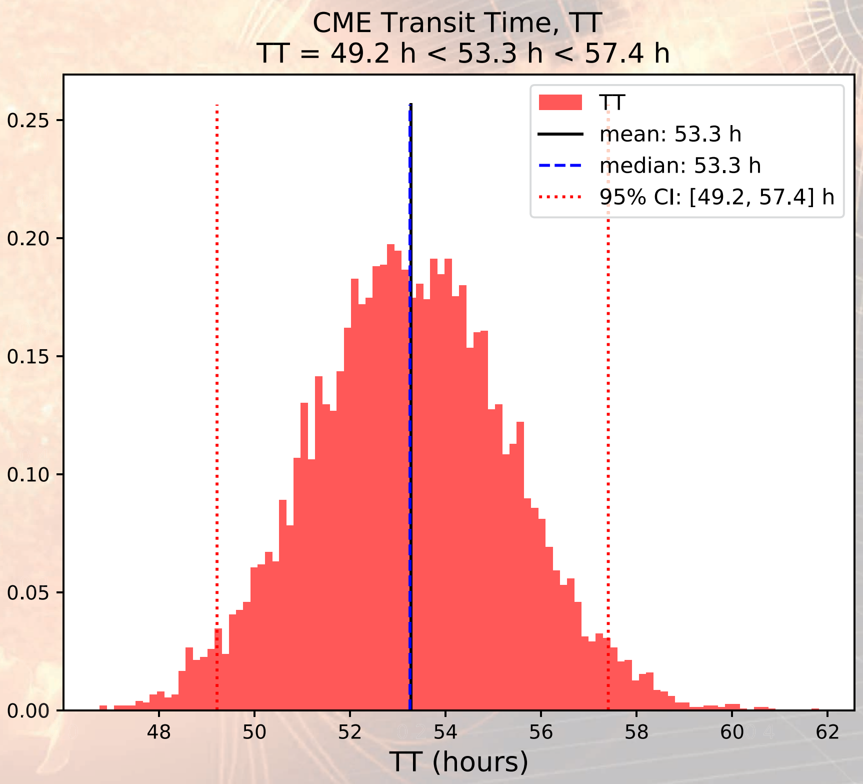


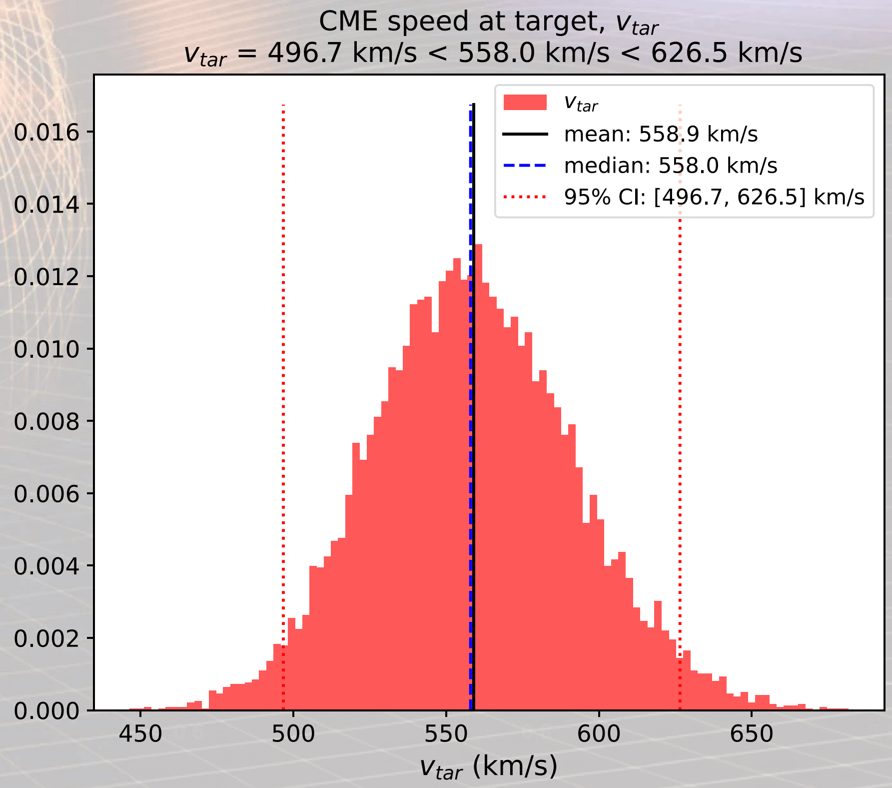
DBEMv4 results

Input

- Launch speed, v_0 = 900 ± 90 km/s
- Drag parameter, ɣ = 0.2 ± 0.1 $\times 10^{-7}$
- Half-width, λ = 33 ± 5 deg
- Longitude, φ_{CME} = 3 ± 5 deg

Solar wind speed,
w=500 ± 75 km/s for R=21.5-110 R_{Sun}
w=350 ± 75 km/s for R=110-214 R_{Sun}





Results and comparison

Parameter	DBEMv3	DBEMv4	Observed
Transit time, *TT* (h)	54.22	53.25	42.6 (50.37)
Arrival speed, v_{tar} (km/s)	587	558	650 (790)
Arrival accel., a_{tar} (km/s^{-2})	-0.559	-0.847	-

Note: observed values from Temmer et al. 2011, values in brackets from Richardson & Cane list

Differences

Parameter	DBEMv3-OBS	DBEMv4-OBS	DBEMv4-DBEMv3
Transit time, *TT* (h)	11.62 (3.85)	10.65 (2.88)	**-0.97**
Arrival speed, v_{tar} (km/s)	-63 (-203)	-92 (-232)	**-29**

- Rather small difference between DBEMv4 and DBEMv3 compared to overall forecast errors
- Sometimes simple model (DBEMv3) with a constant w may be sufficient compared to a more complex model (DBEMv4)

Summary and conclusions

- DBEM is useful tool to obtain fast initial forecast and by employing the ensembles to quantify uncertainties (Čalogović et. al. 2021)

- DBEMv4 with variable solar wind speed (in steps) shows a good potential to improve the forecast in complex heliospheric environments where solar wind speed, w or drag parameter γ can't be assumed as constant values

- Valuable tool to study the influence of high speed streams and CME-CME interactions on CME propagation

- However, more complex and more computationally intensive model doesn't have to give the better results in all cases (input uncertainties and other model assumptions have in some cases order of magnitude larger errors) e.g. DBM/DBEM and ENLIL perform similarly in many cases (Dumbović et al. 2018)

- The current and future versions of DBM/DBEM tool should be kept simple and fast (analytical model), otherwise such model may lose some of the main advantages