Probabilistic model for heliospheric propagation of CMEs: Drag-Based Ensemble Model (DBEM)

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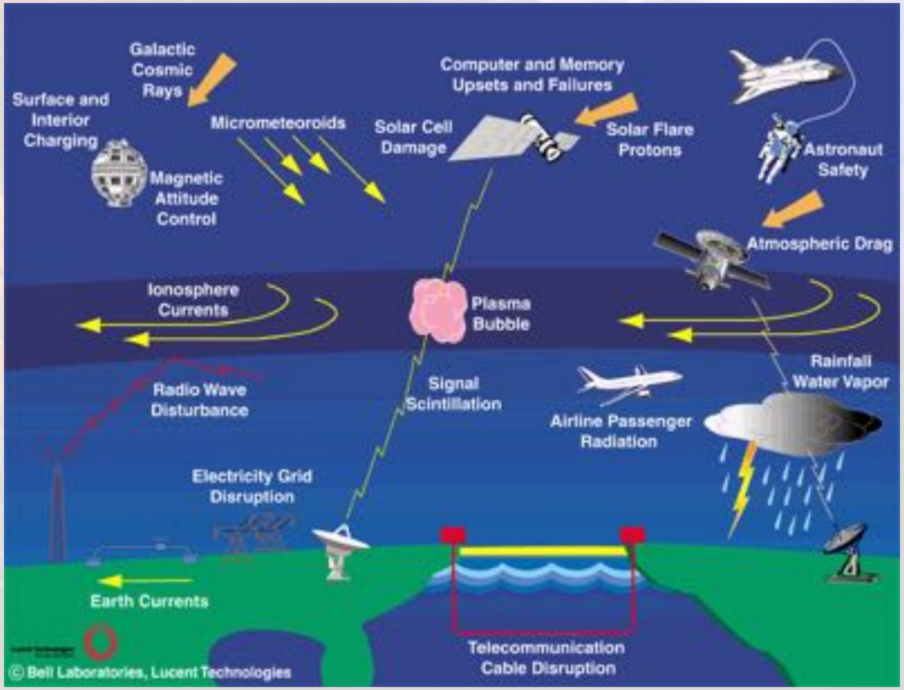
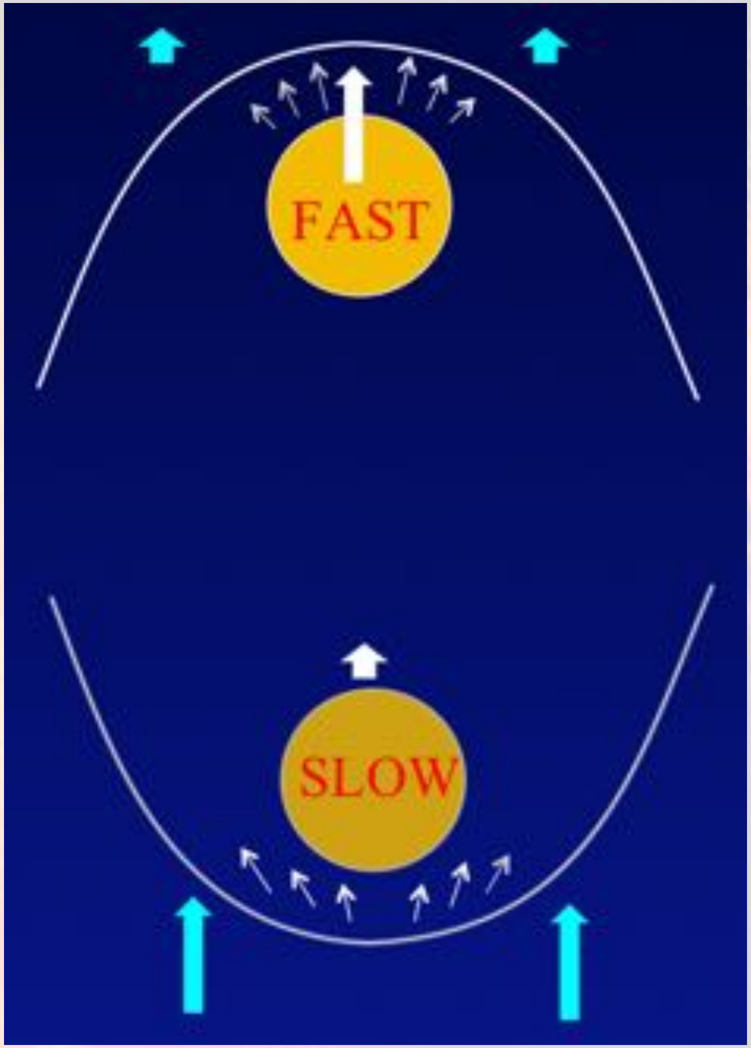
Heliospheric propagation models are important for space weather forecasting

- CME/ICMEs major drivers of solar wind disturbances and geomagnetic storms
- Prediction of CME/ICMEs propagation in the heliosphere – important task for space weather forecasting



- Various models are used for space weather forecasting:
  - purely empirical/statistical methods
  - kinematical-empirical methods
  - analytical (M)HD-based models (**DBM**)
  - numerical MHD-based models (ENLIL)

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

$$a = \sout{a_L - g} + a_d$$

$$a_d = -\gamma(v-w)|v-w|$$

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 – the drag is larger for broader, low-mass CMEs in a high-density (slow) solar wind
- If w and γ constant there is analytical solution

Drag-Based Model (DBM)

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

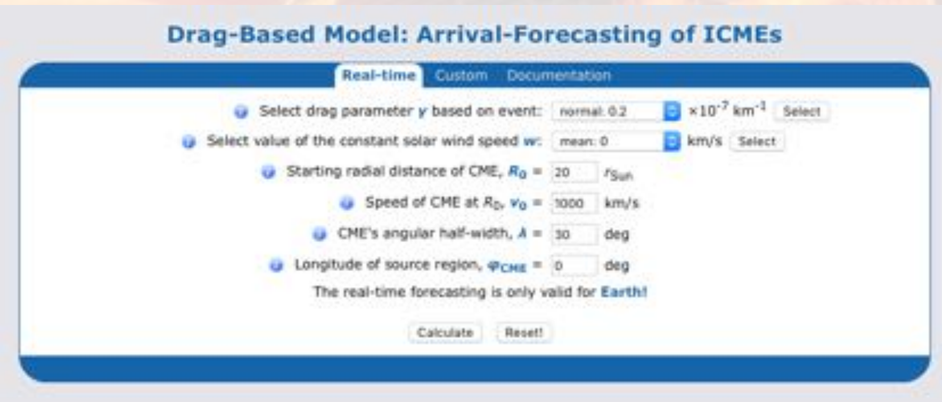
- **Advantages**
  - simple and robust
  - very fast (one run << 1 sec) compared to numerical MHD models (e.g. ENLIL)

- **Disadvantages**
  - doesn't give the best results in complex heliospheric environment (eg. CME-CME interactions, w and γ aren't constant)

DBM and online space weather tools

- Latest DBM version is integrated into **ESA Space Situational Awareness** (SSA) portal (CME leading-edge flattening):

http://swe.ssa.esa.int/heliospheric-weather

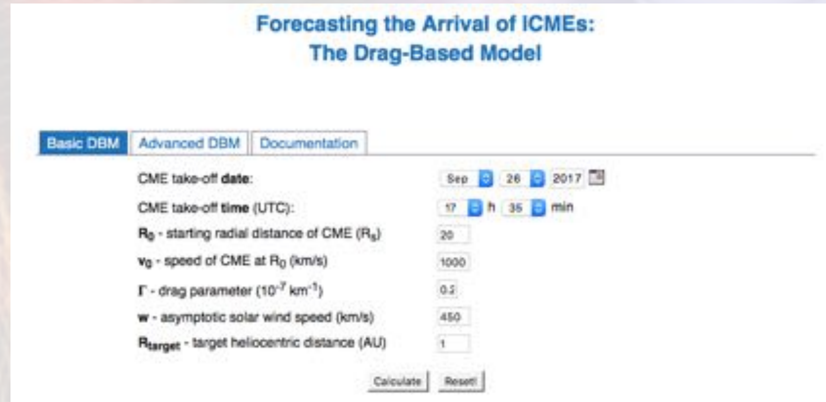


- **ESA Expert Service Center for Solar & Heliospheric Weather:**

http://swe.uni-graz.at

- **Hvar Observatory** - Forecasting the Arrival of ICMEs:

http://oh.geof.unizg.hr/DBM/dbm.php



- **CME Arrival Time Scoreboard** – NASA Space Weather Research Center:

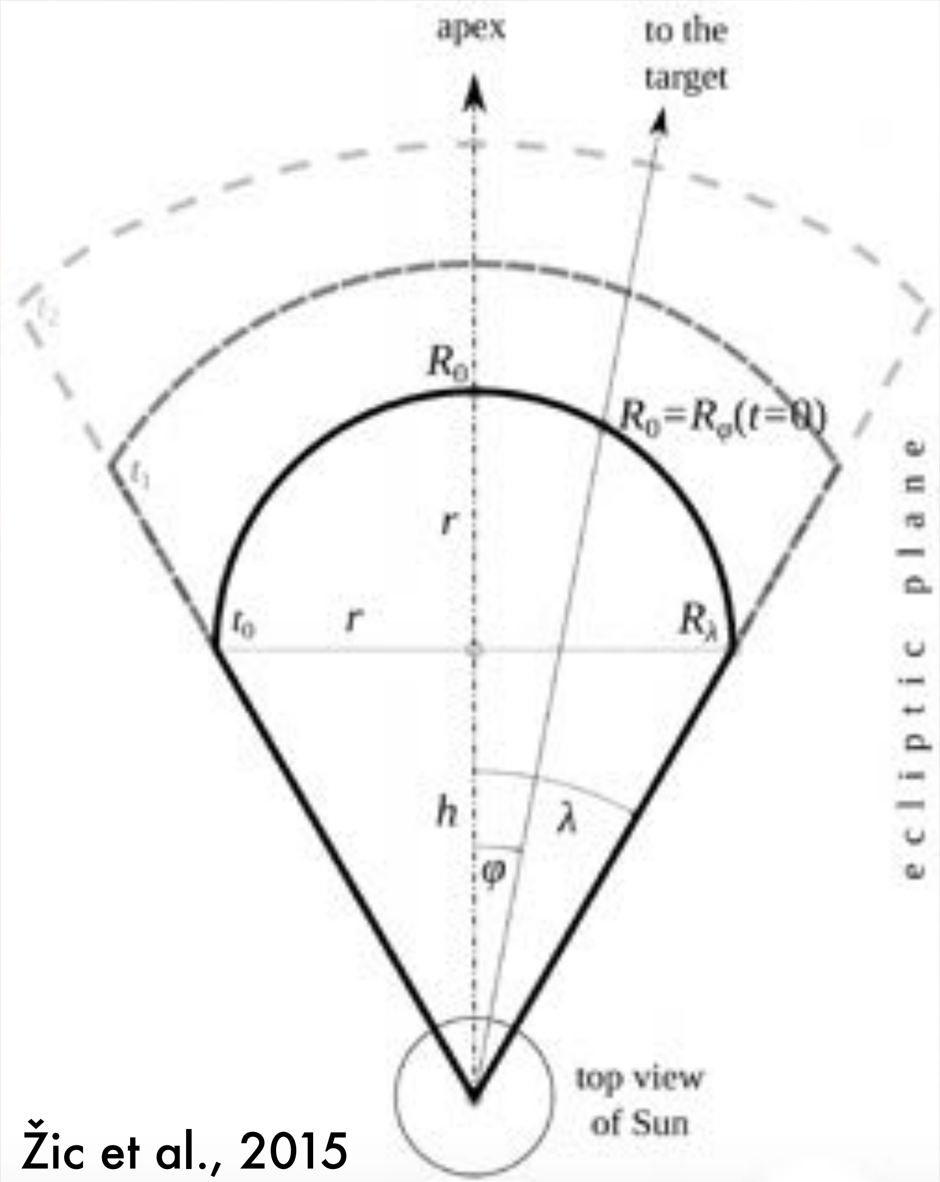
http://swrc.gsfc.nasa.gov/main/cmemodels

- The **COMESEP alert** system (DBM input from CACTus):

http://www.comesep.eu/alert

DBM CME geometry

- Uses CME cone geometry with CME leading-edge flattening
- Solar wind speed (w) is radially dependent $w(R)$ and γ is also function of radial distance $\gamma(R)$
- each CME leading-edge segment propagates independently → the initial cone geometry flattens



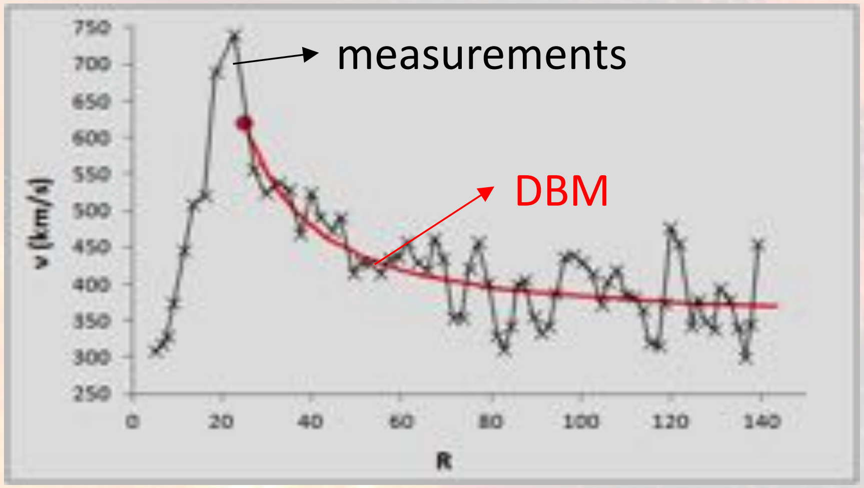
Žic et al., 2015

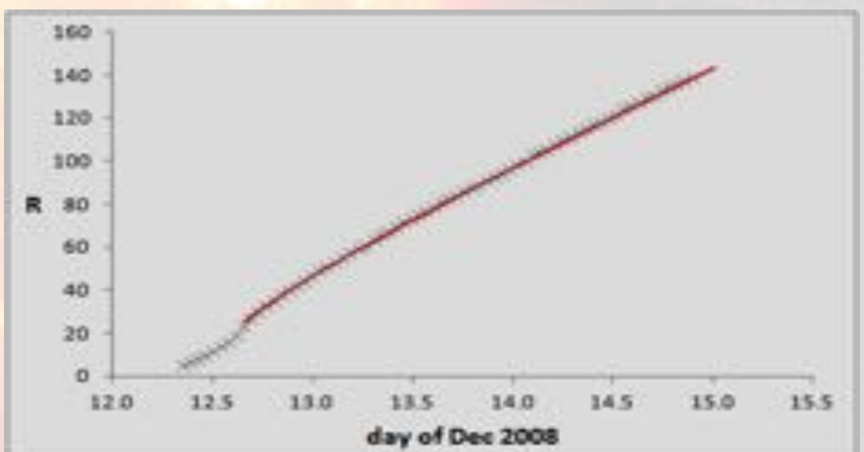
DBM and observations

Examples of ICME kinematics

Fast ICME
12 December 2008

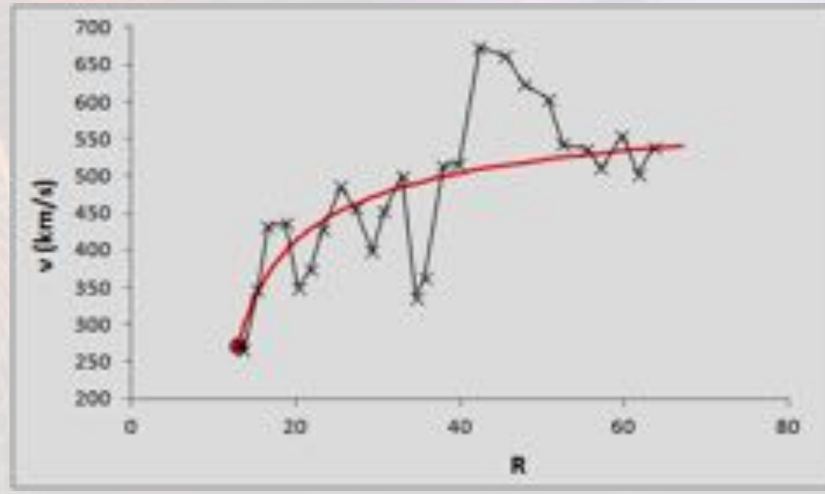
$\gamma = 2.0\times10^{-7}\ \mathrm{km}^{-1}$
$w = 350$ km/s

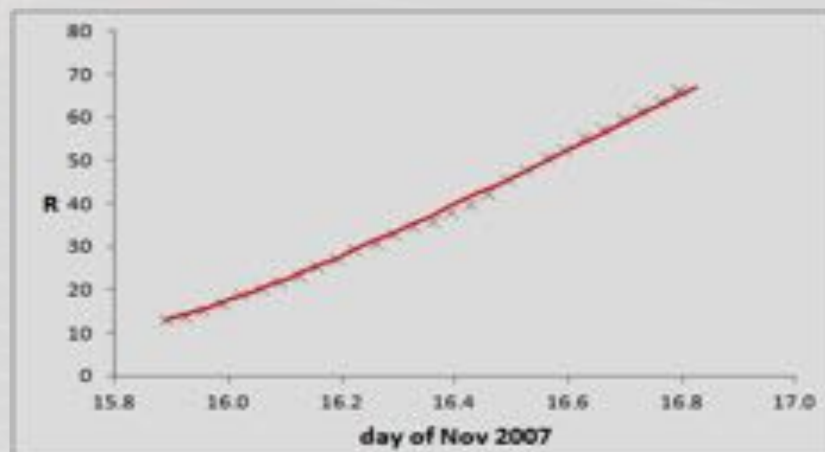




Slow ICME
15 November 2007

$\gamma = 1.6\times10^{-7}\ \mathrm{km}^{-1}$
$w = 600$ km/s





Vršnak et al., 2013

Reliable observations are needed for better accuracy of heliospheric propagation models

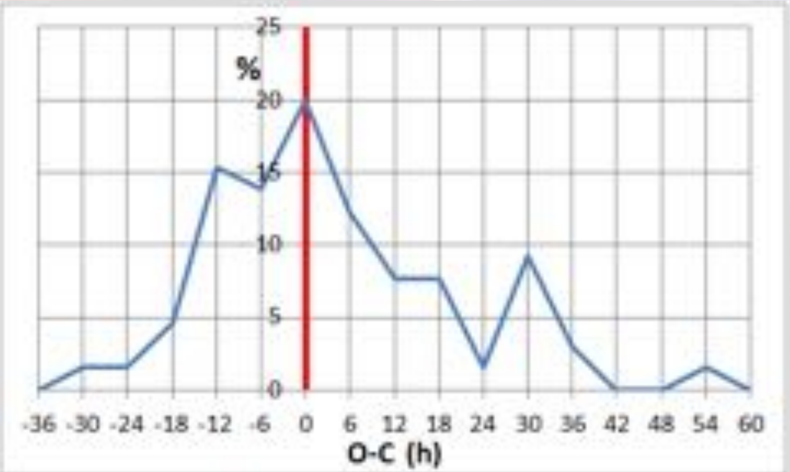
- In about **55%** of events DBM has error (observed – calculated) less than **12h** and more than **85%** of events has error less than **1 day**

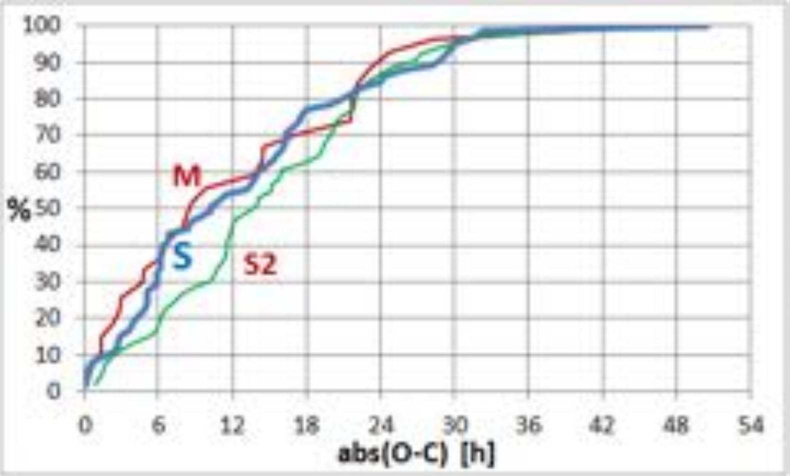
Comparison od DBM and WSA-ENLIL-CONE model (Vršnak et al., 2014)

- Relative difference is most often less than 10%
- ENLIL preforms better during the solar maximum due to complex solar wind structure (differences 10-11h) and DBM can provide better results during the solar minimum (differences 6-9h)

However, the main problem of all models is the lack of reliable observations (input) eg. CME launch speed

DBM errors (**O**bserved – **C**alculated)





Ensemble modelling

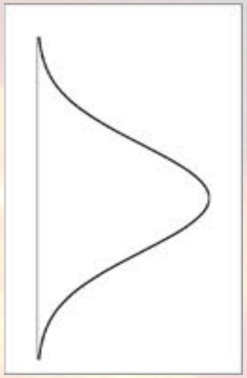
Input

Parameter 1 (eg. γ)

value 1

value 2

value x



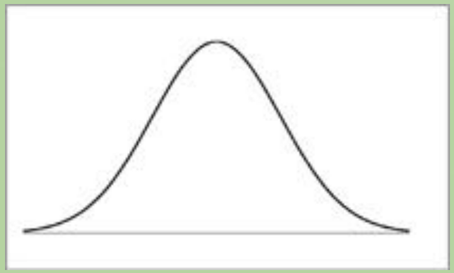
Parameter x

Value 1

value x

Multiple model runs (DBEM)

Set of results



allows to calculate the confidence intervals of arrival times and impact speed (parameter uncertainties are quantified)

Drag-based Ensemble Model (DBEM)

- Recently, the DBM code was rewritten to **python** (modular design)
- Optimizations and improvements in the code → new version of DBM runs up to 200 times faster
- Parallelization of code that supports multi thread (CPU) calculations (up to 1000x faster)

- Each DBEM input parameter can be defined as list of parameters (eg. multiple observations of the same event)

Example for input parameters for CME on 6 Feb 2013

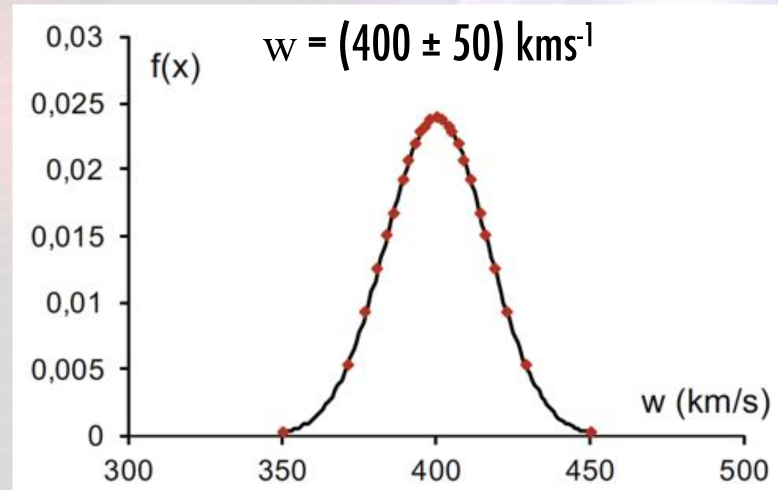
Member ID	date & time	Latitude	Longitude	Half-Width	Speed
1	2013-02-06 03:15	30	-25	38	1226
2	2013-02-06 03:07	30	-35	38	1300
3	2013-02-06 02:42	33	-28	28	1389
4	2013-02-06 02:37	30	-20	27	1436
5	2013-02-06 02:40	30	-26	43	1460
6	2013-02-06 02:39	30	-24	36	1474
7	2013-02-06 02:37	33	-19	28	1536
8	2013-02-06 03:01	39	-33	43	1387
9	2013-02-06 02:40	30	-26	22	1460
10	2013-02-06 02:52	35	-30	27	1430
11	2013-02-06 02:44	34	-25	30	1470
12	2013-02-06 02:54	40	-28	30	1441
*	2013-02-06 02:41	30	-26	30	1460

Create m synthetic measurements based on the known error (CI) for each parameter

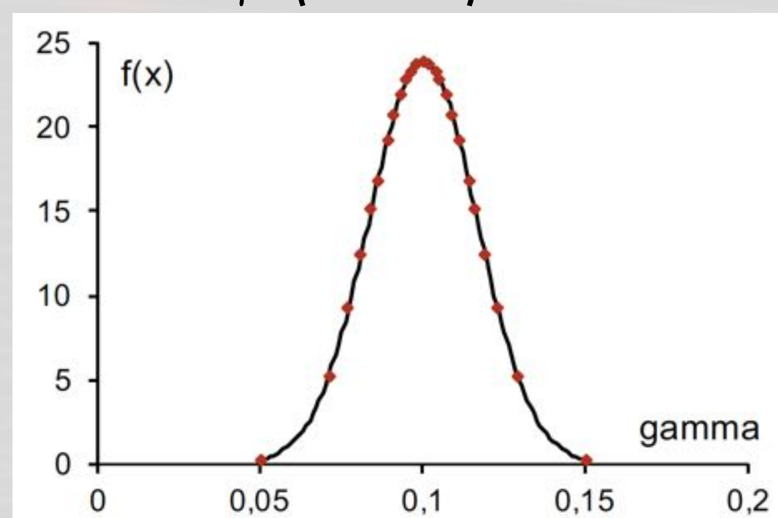
- For each input parameter can be generated m synthetic measurements in a range determined by standard deviation
- Assumption: parameters follow a normal distribution

$$x = \bar{x} \pm \Delta x, \; \Delta x = 3\sigma$$

- Density of syn. measurements is denser near mean value than at the end of distribution (3σ)
- It was found that optimal number of syn. measurements is m=15

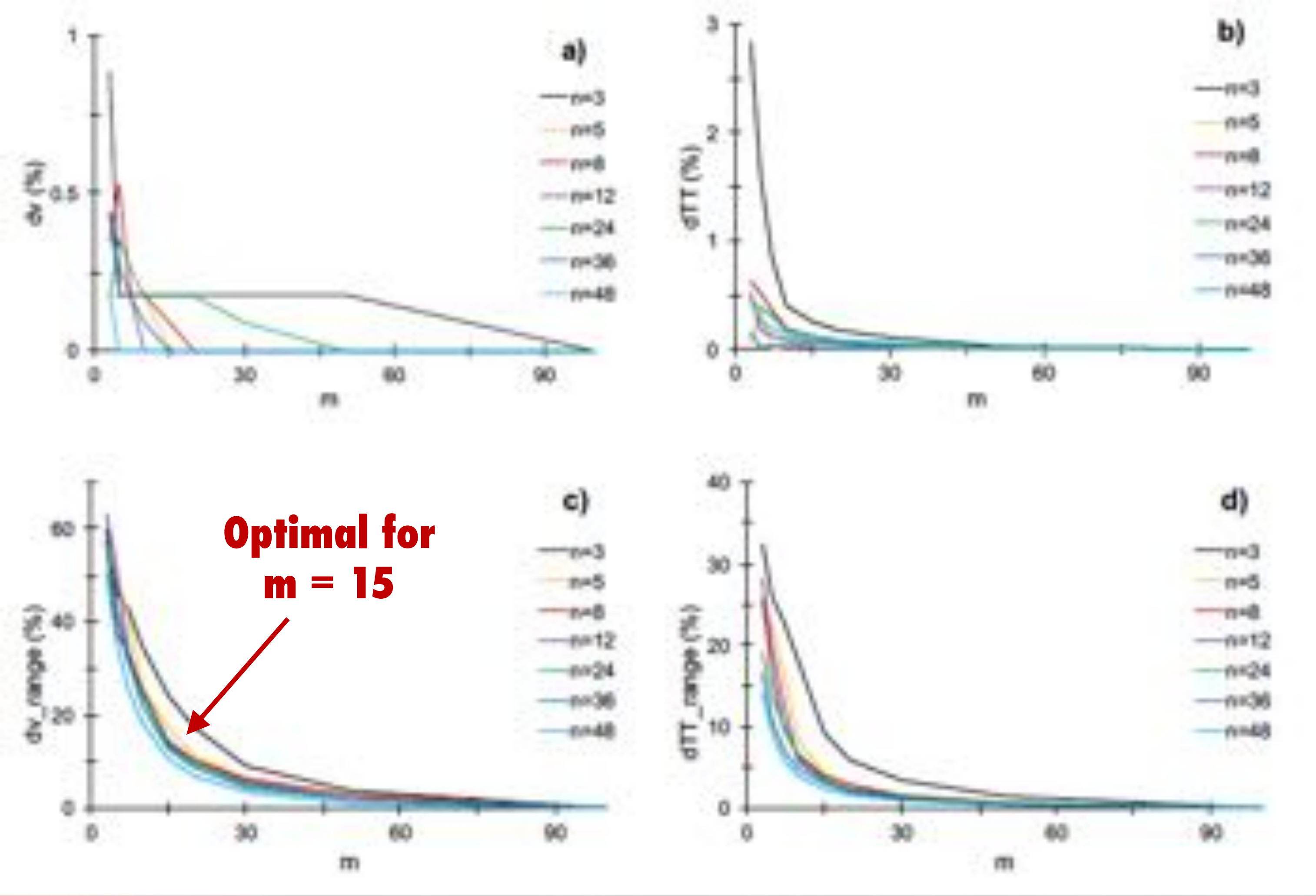


γ = (0.1 ± 0.05) 10^{-7} km^{-1}



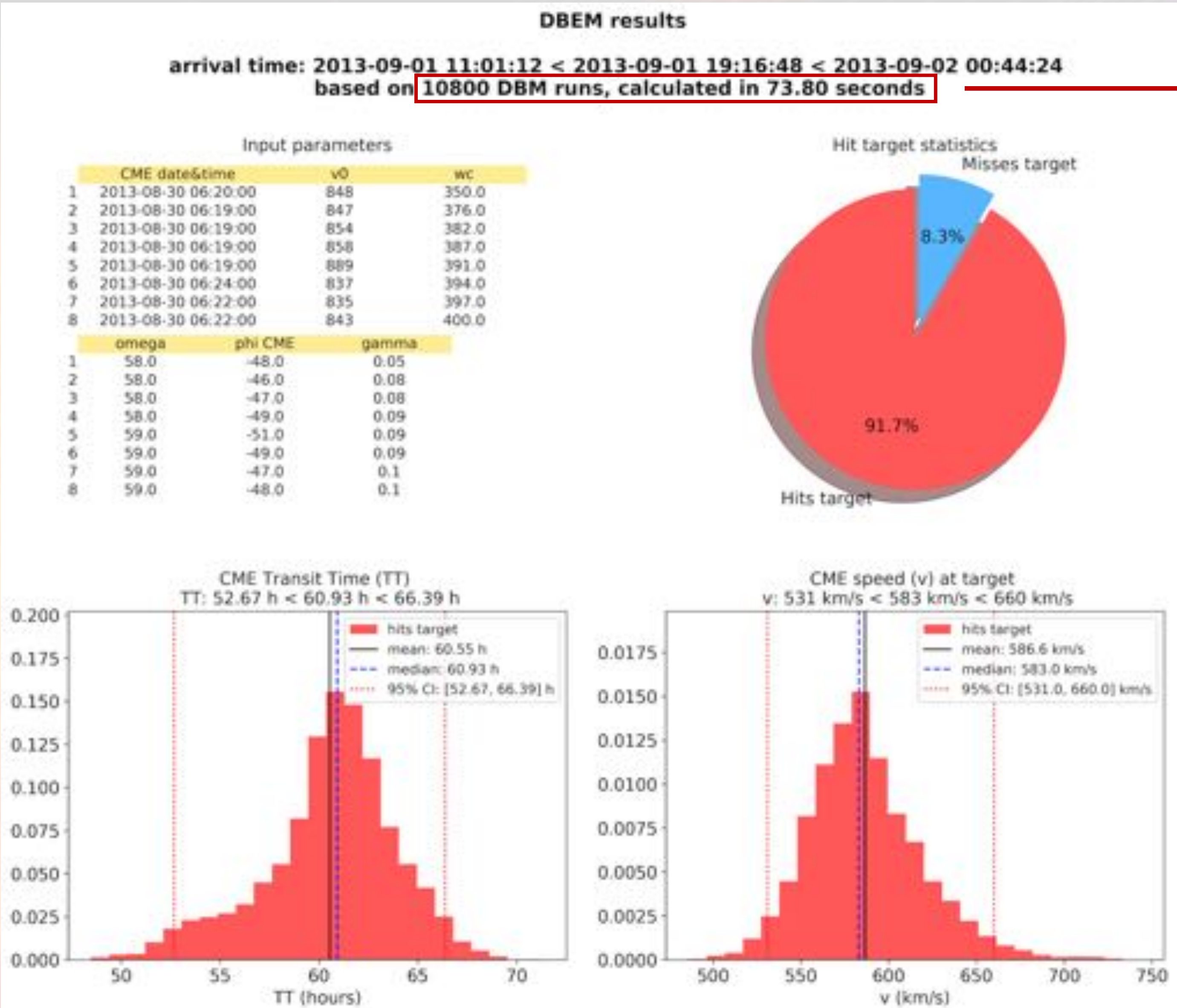
Optimal number of synthetic measurements (m)

For m synthetic measurements of solar wind speed (w) and γ parameter



n - number of ensemble members (different measurements)

Example of DBEM results
ICME on 30 August 2013



	CME date&time	v0	wc
1	2013-08-30 06:20:00	848	350.0
2	2013-08-30 06:19:00	847	376.0
3	2013-08-30 06:19:00	854	382.0
4	2013-08-30 06:19:00	858	387.0
5	2013-08-30 06:19:00	889	391.0
6	2013-08-30 06:24:00	837	394.0
7	2013-08-30 06:22:00	835	397.0
8	2013-08-30 06:22:00	843	400.0

	omega	phi CME	gamma
1	58.0	-48.0	0.05
2	58.0	-46.0	0.08
3	58.0	-47.0	0.08
4	58.0	-49.0	0.09
5	59.0	-51.0	0.09
6	59.0	-49.0	0.09
7	59.0	-47.0	0.1
8	59.0	-48.0	0.1

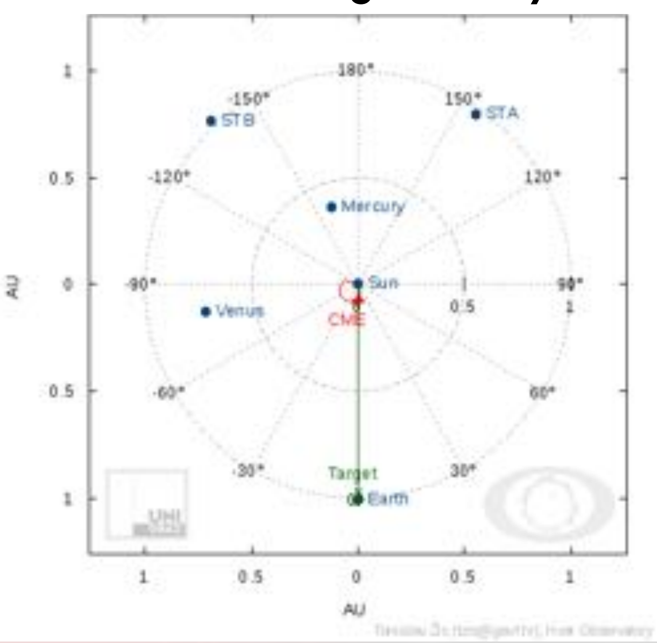
Very fast (calculated on single thread 1.6 Ghz Intel i5, 150 it/sec)

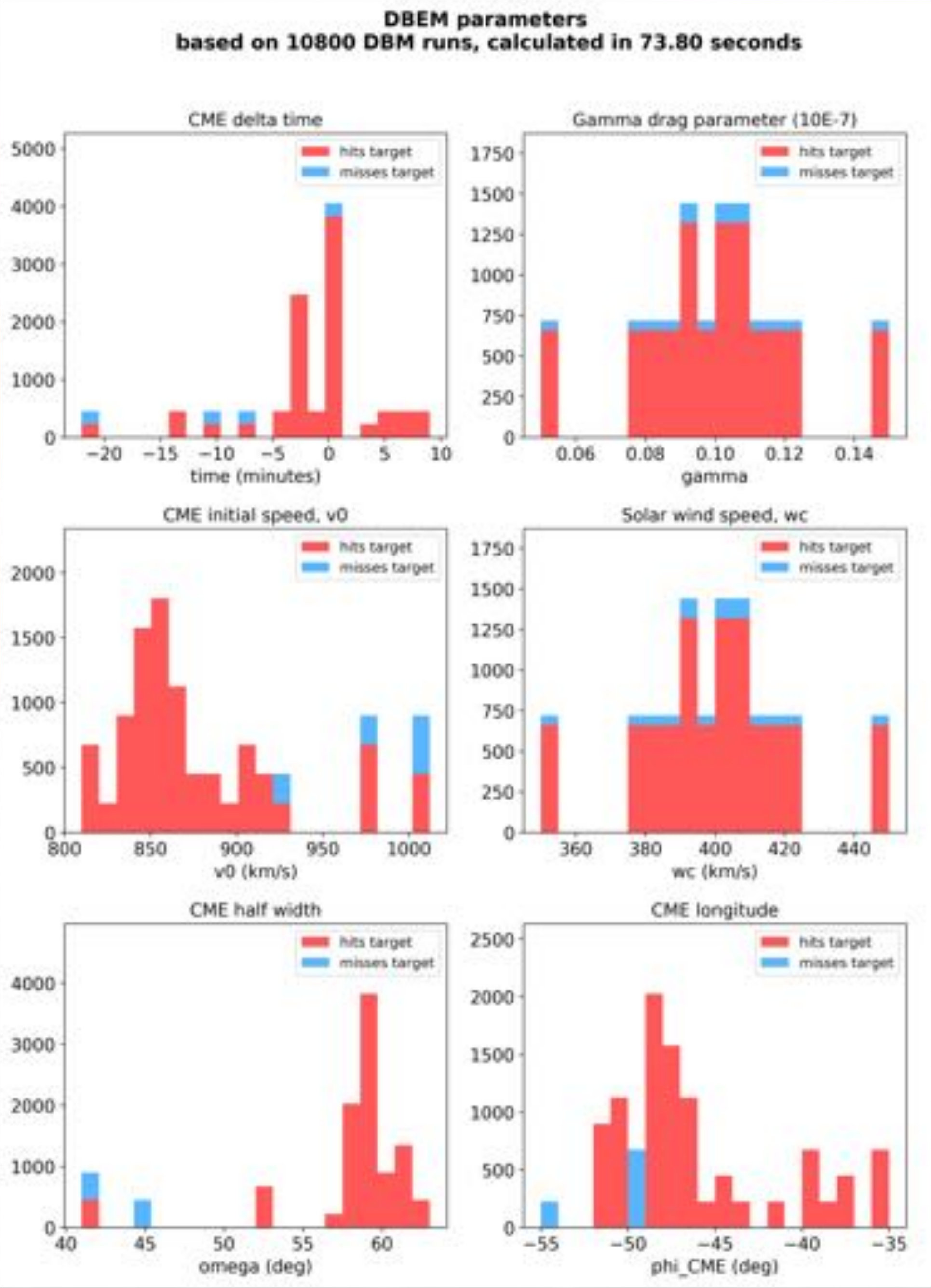
Distributions for CME transit time (TT) and impact speed (v) including mean value, median and confidence intervals

Example of DBEM results
ICME on 30 August 2013

- Results of DBEM can be used to investigate which input parameters are responsible for certain results (eg. criteria: hits/misses target)

DBM CME geometry



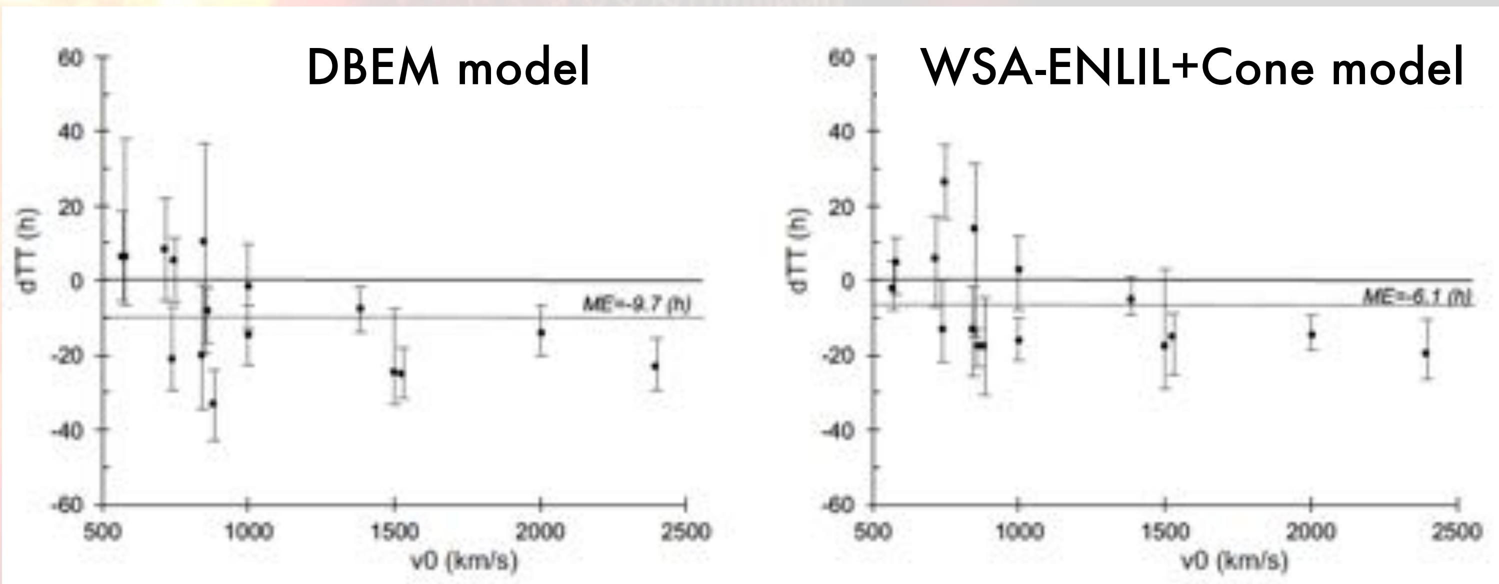


DBEM and ENLIL comparison

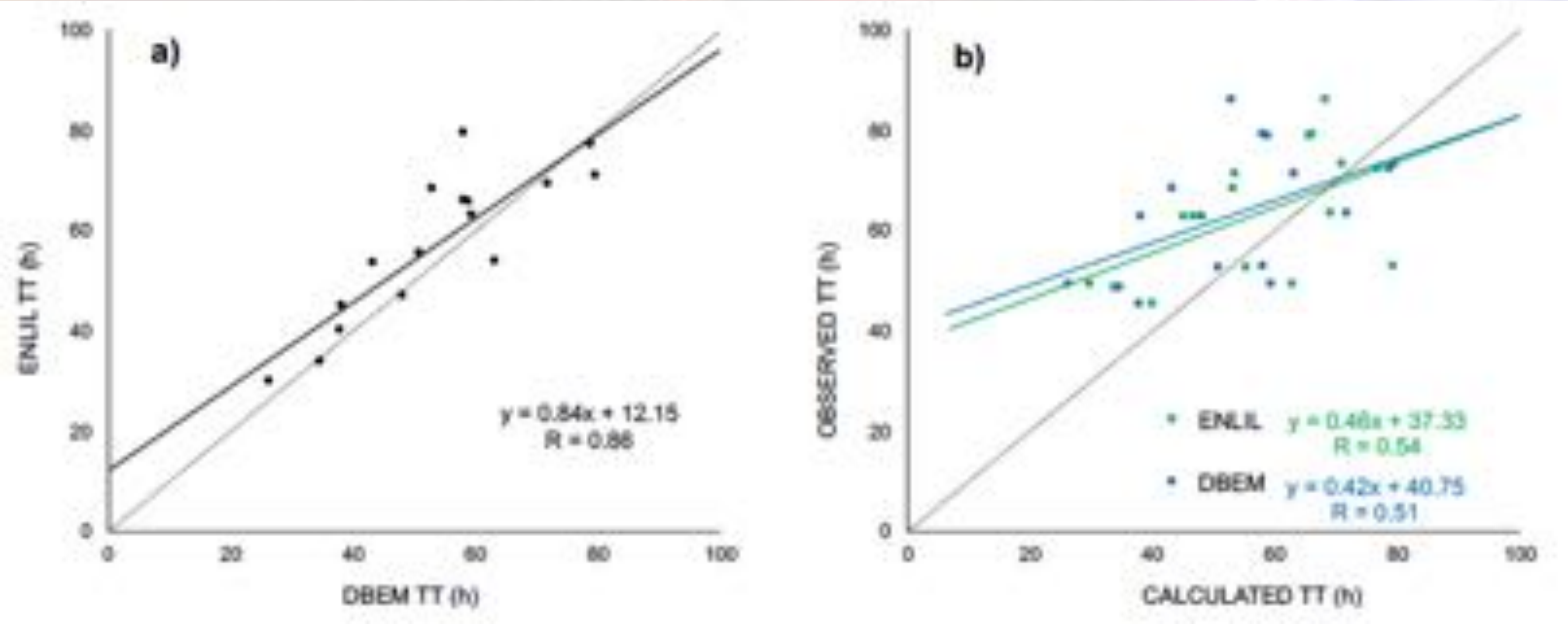
- ENLIL and DBEM **perform similarly**
- number of false alarms should be reduced
- fast CMEs predicted to arrive too early

		DBEM	ENLIL
No of hits	a	16	16
No of misses	c	0	0
No of false alarms	b	4	3
No of correct rejections	d	5	6
No of events	N=a+b+d	25	25
Correct rejection rate	d/(b+d)	55,56%	66,67%
False alarm rate	b/(b+d)	44,44%	33,33%
Correct alarm ratio	a/(a+b)	80,00%	84,21%
False alarm ratio	b/(a+b)	20,00%	15,79%
Brier score	BS	0,17	0,18

CME arrival time prediction error plotted against the CME input speed



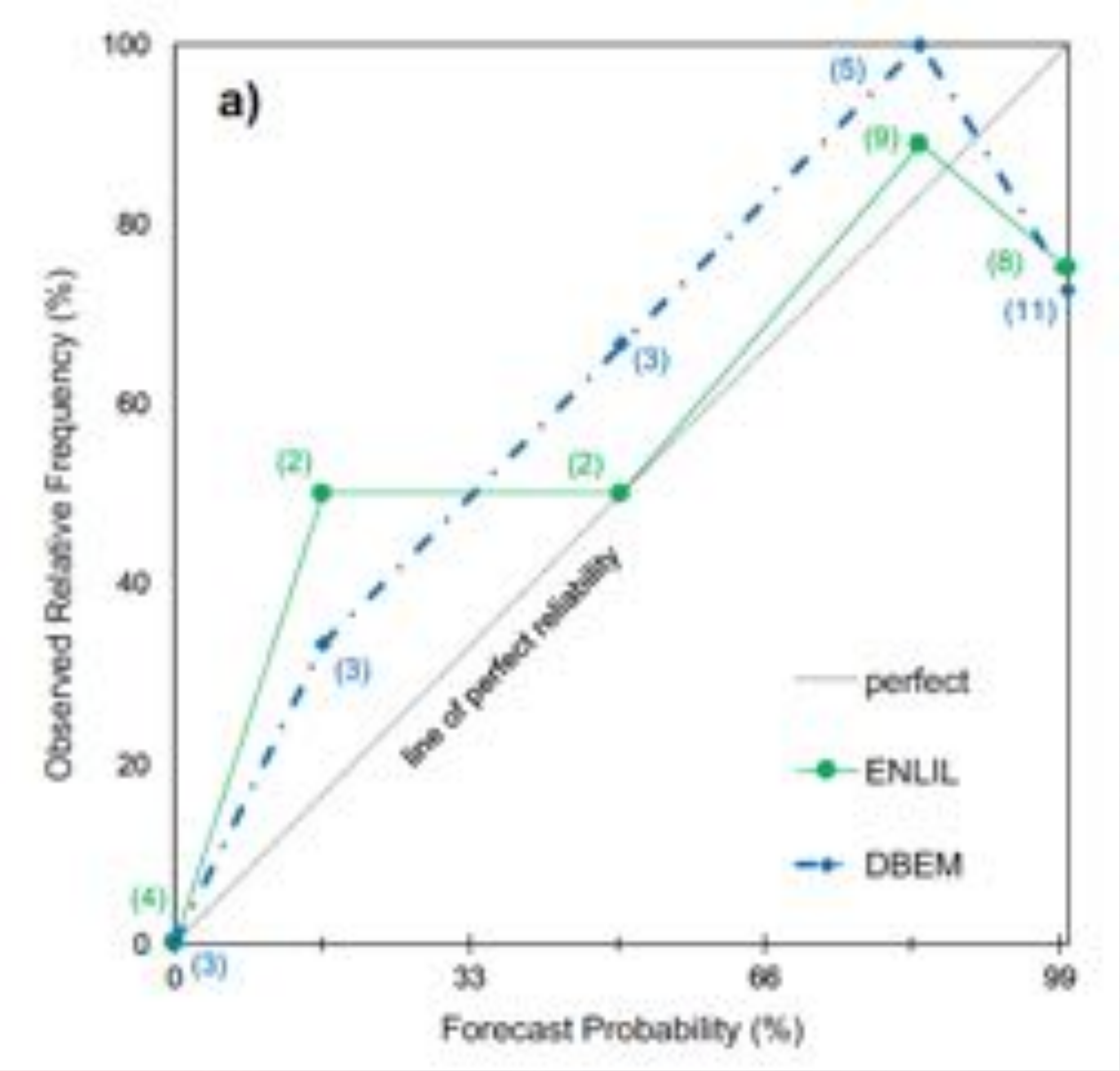
DBEM vs ENLIL



ENLIL-calculated vs. DBEM-calculated transit time

Observed vs. calculated transit time for ENLIL (green) and DBEM (blue)

Reliability diagram of the forecast probability of CME arrival (DBEM vs ENLIL)



- at 100% forecast probability both DBEM and ENLIL overforecast
- at 0% forecast probability both models are at the line of perfect reliability (limited number of events)
- Intermediate bins (0-100%) both models slightly underforecast (limited number of events)

Conclusions

- **Very fast** (up to 1000 runs per sec), reliable and simple model
- Suited for a fast real-time space-weather forecasting
- Comparisons with numerical MHD models (ENLIL) show good accuracy of DBM at very low computational cost
- DBM performs better during the solar minimum than in the solar maximum, due to the complex heliospheric environment (eg. CME-CME interaction)
- DBEM can provide important information such as confidence intervals of CME arrival time and impact speed related to the input errors (observations)

Outlooks for DBEM

- will be integrated soon in ESA Space Situational Awareness (SSA) portal (http://swe.ssa.esa.int/heliospheric-weather)
- CME Arrival Time Scoreboard – NASA Space Weather Research Center (http://swrc.gsfc.nasa.gov/main/cmemodels)

Thank you for your attention

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Further DBEM developments