The 8th Community Community Coordinated Modeling Center Workshop

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THE DRAG-BASED MODEL

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General classification of space-weather models

- The DBM: a „tool“ for prediction of ICMEs propagation in the heliosphere → primary task for space-weather forecasting
- modeling and forecasting can be divided:
  - a) purely empirical/statistical methods
  - b) kinematical-empirical methods
  - b/c) analytical (M)HD-based models (DBM)
  - c) numerical MHD-based models

The DBM hypothesis

- The DBM hypothesis at large heliocentric distances:
  - the Lorentz force ceases in upper corona
  - ICME dynamics is solely governed by interaction with solar wind (ambient) ← observational facts:
    - fast CME → decelerate
    - slow CME → accelerate

    } $v \rightarrow w$
  - collisionless environment:
    - low viscosity
    - low resistivity → dissipative processes are negligible
  - momentum and energy are transferred by magnetosonic waves

The DBM equations in general form

- At heliocentric distances beyond $R \geq 15\ r_S$:
- net acceleration (drag is dominant): $a = \cancel{a_L} + \cancel{a_g} + a_d$
- equation of motion in quadratic form (Cargill, 2004):

$$R''(t) = -\gamma(R)[R'(t) - w(R)]|R'(t) - w(R)|$$

- parameter γ:

$$\gamma \propto c_d \frac{A \rho_{SW}}{M}$$

- for $R \gg 1 r_S \Rightarrow$ $M = M_i + M_v = const.$

- LDB density expression (Leblanc et al., 1998):

$$n_0(R) = \frac{k_2}{R^2} + \frac{k_4}{R^4} + \frac{k_6}{R^6} \text{ for } R > 1.8$$

$$k_2 = 3.3 \times 10^5\ \text{cm}^{-3}, k_4 = 4.1 \times 10^6\ \text{cm}^{-3}, k_6 = 8.0 \times 10^7\ \text{cm}^{-3}$$

Solar wind perturbation

INPUT:
$w(R)$, w_∞, γ_∞

- stationary and isotropic
- density flux conservation
- unperturbed solar-wind speed becomes:

$$w_0(R)=w_\infty\left(1+\frac{k_4/k_2}{R^2}+\frac{k_6/k_2}{R^4}\right)^{-1}$$

$$\left[w_\infty=\lim_{R\to\infty} w_0(R)\right]$$

- total solar-wind speed with perturbation term $w_p(R)$:

$$w(R)=\begin{cases} w_0(R)+w_p(R), & R_1<R<R_2 \\ w_0(R), & otherwise \end{cases}$$

+ „Cone geometry“:
$A \propto R^2$

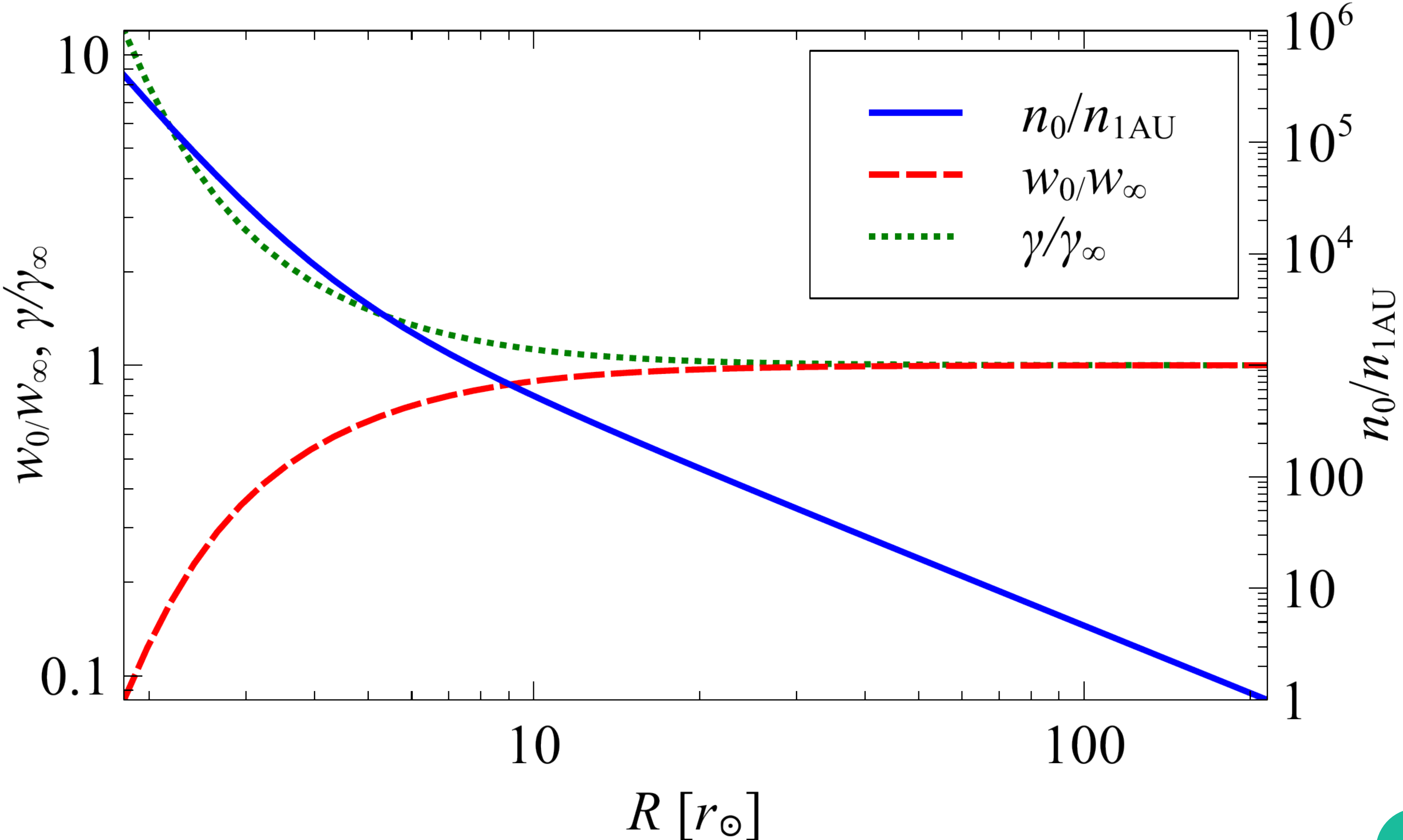
- leads to:

$$\gamma(R)=\gamma_\infty\frac{w_\infty}{w(R)}; \quad n(R)=\frac{k_2}{R^2}\frac{w_\infty}{w(R)}$$

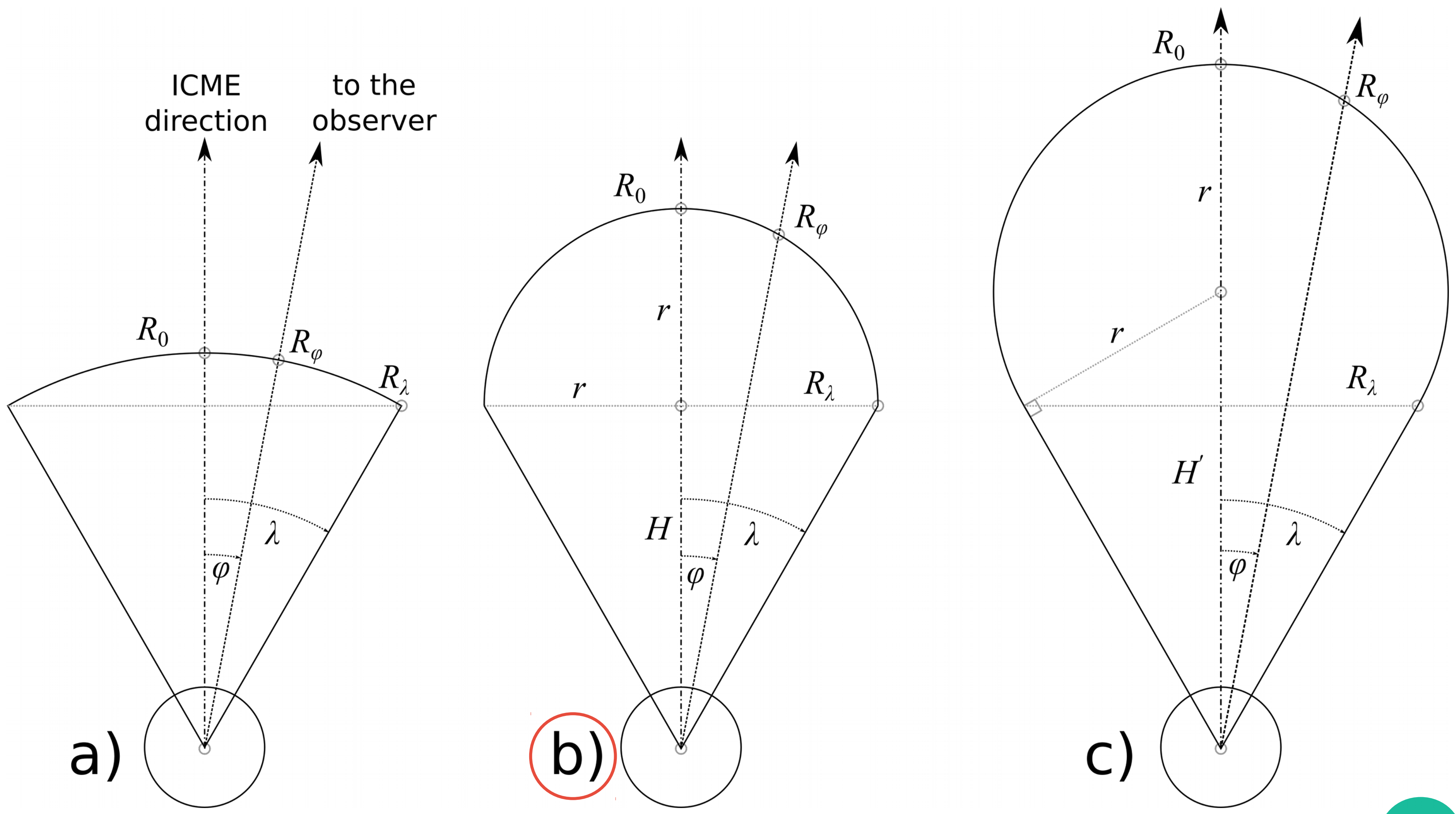
$$\left[\gamma_\infty=\Gamma\times10^{-7}\ \mathrm{km}^{-1}\right]$$

$$\left[\gamma_\infty=\lim_{R\to\infty}\gamma(R)\right]$$

Parameter γ, SW density and speed



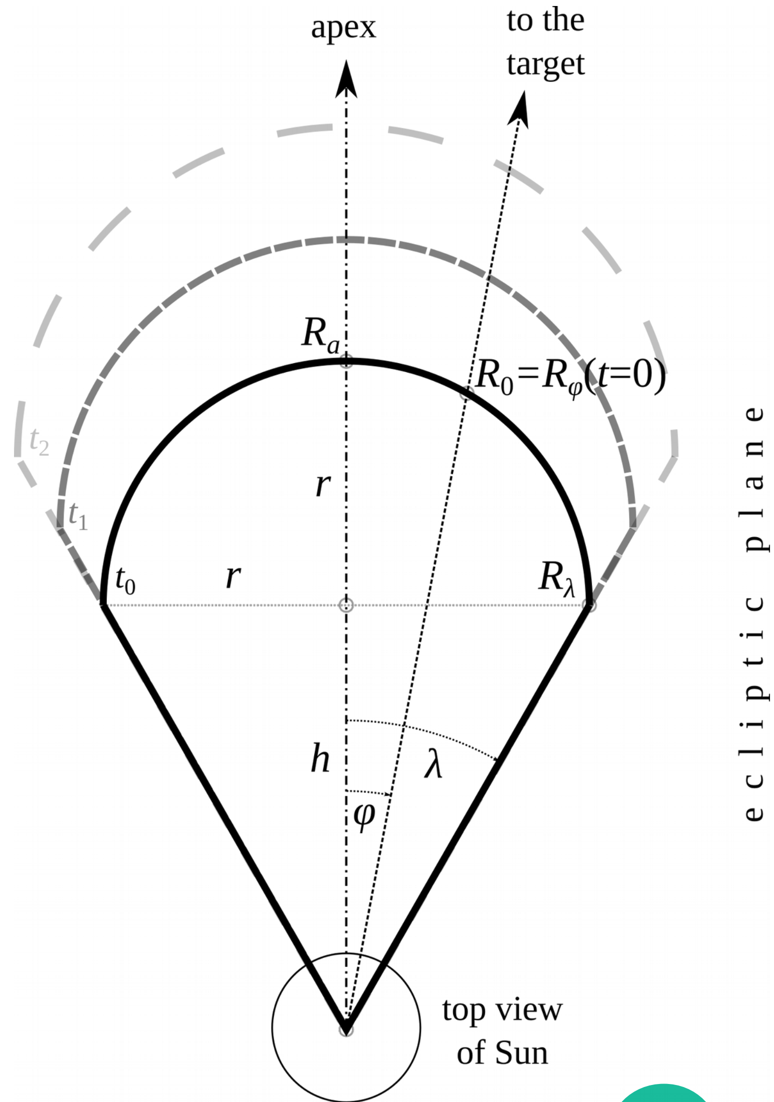
Options of ICME cone-geometry



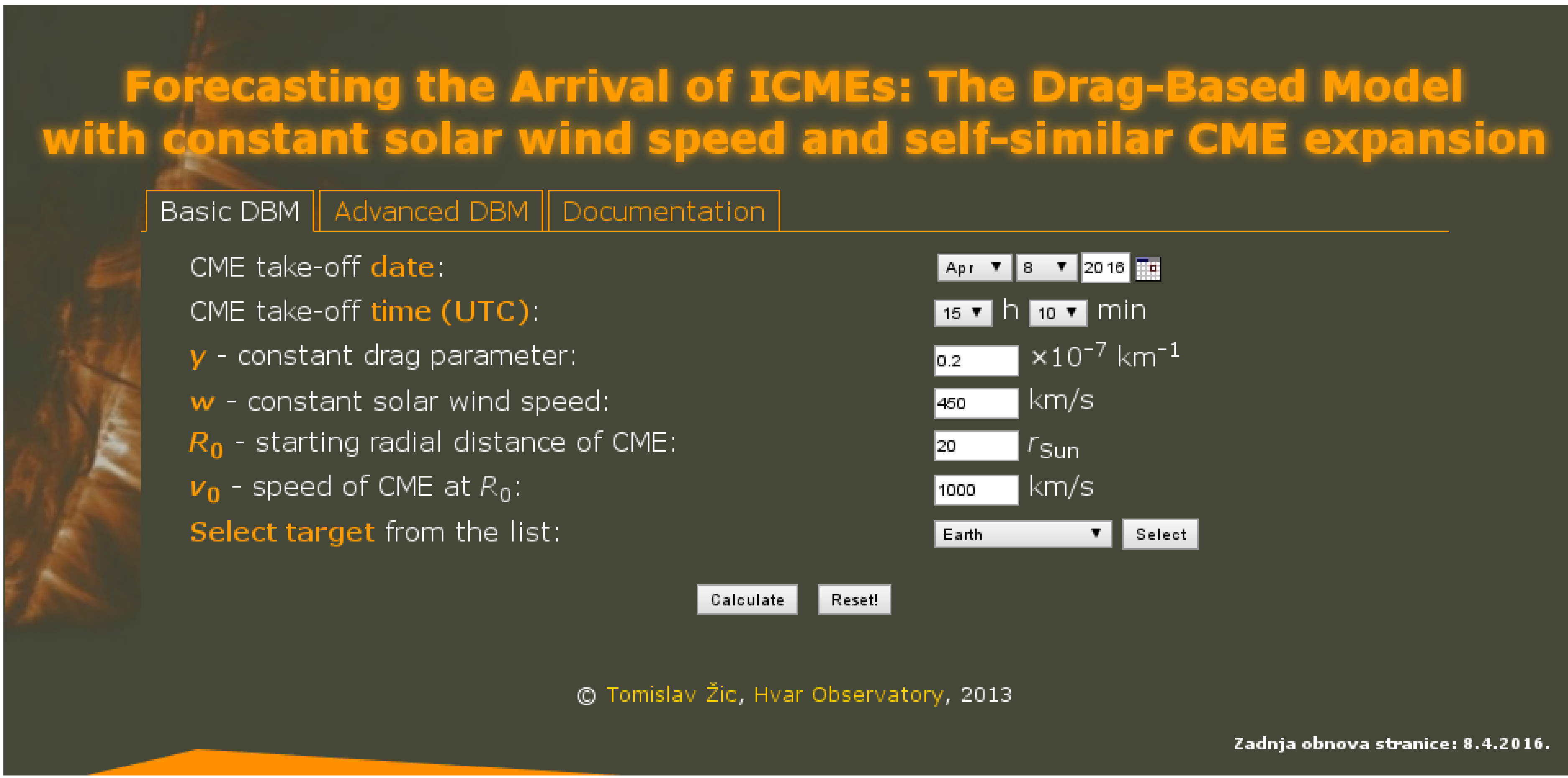
DBM with constant *w* and self-similar CME geometry

- solar-wind speed *w*:
  - isotropic and constant

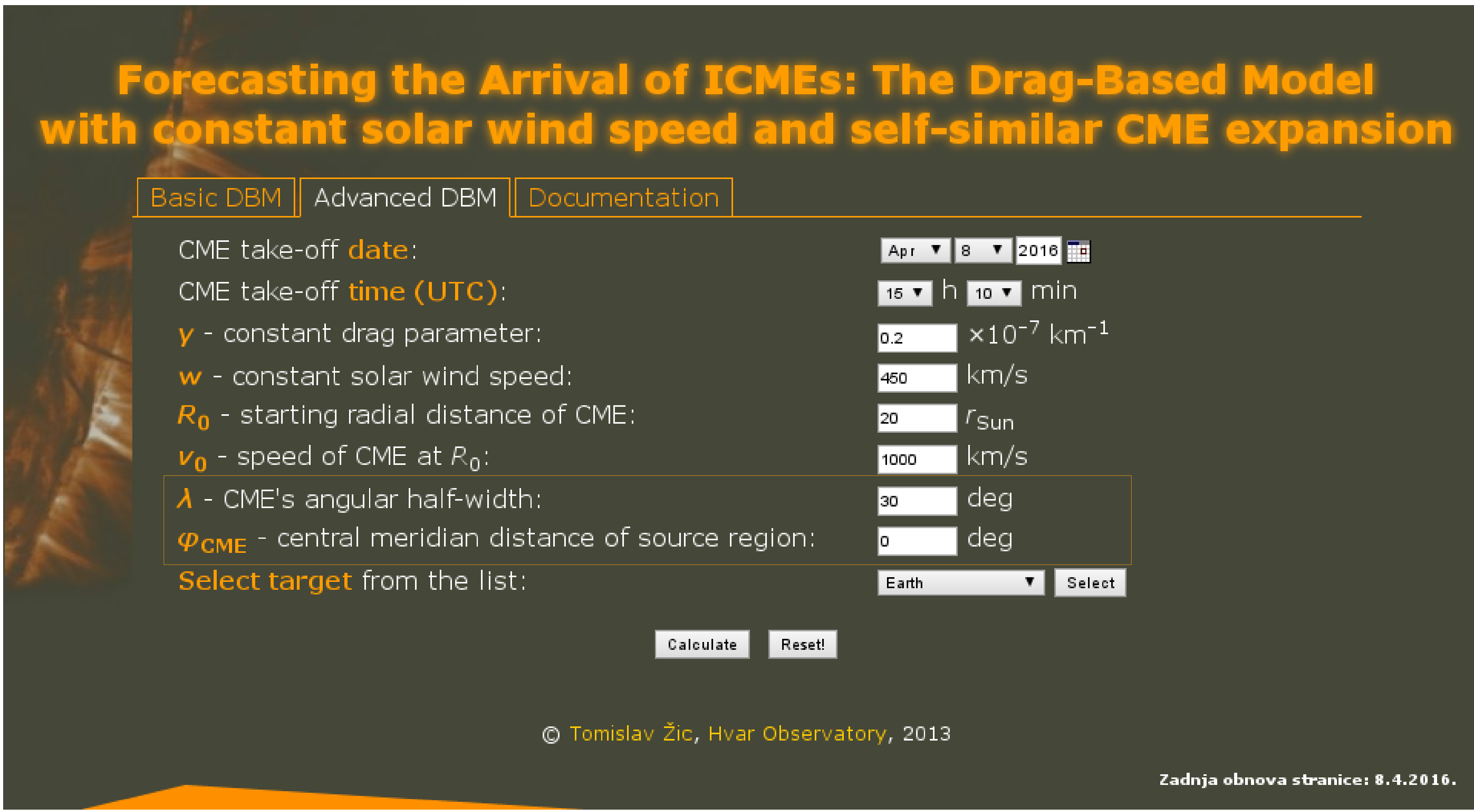
    → parameter γ is constant as well
- „self-similar“ CME expansion:
  - the initial cone-shape of CME is preserved during its interplanetary propagation
- for a given set of input parameters the model provides the ICME Sun-“target” transit time, the arrival time, and the impact speed



Basic *w=const.* & SS-expansion (http://oh.geof.unizg.hr/~tomislav/CDBM-SS/)



Advanced *w=const.* & SS-expansion (http://oh.geof.unizg.hr/~tomislav/CDBM-SS/)



Results *w=const.* & SS-expansion (http://oh.geof.unizg.hr/~tomislav/CDBM-SS/)

Forecasting the Arrival of ICMEs: The Drag-Based Model with constant solar wind speed and self-similar CME expansion

Results | Kinematic plot | CME geometry plot | Documentation

Output:

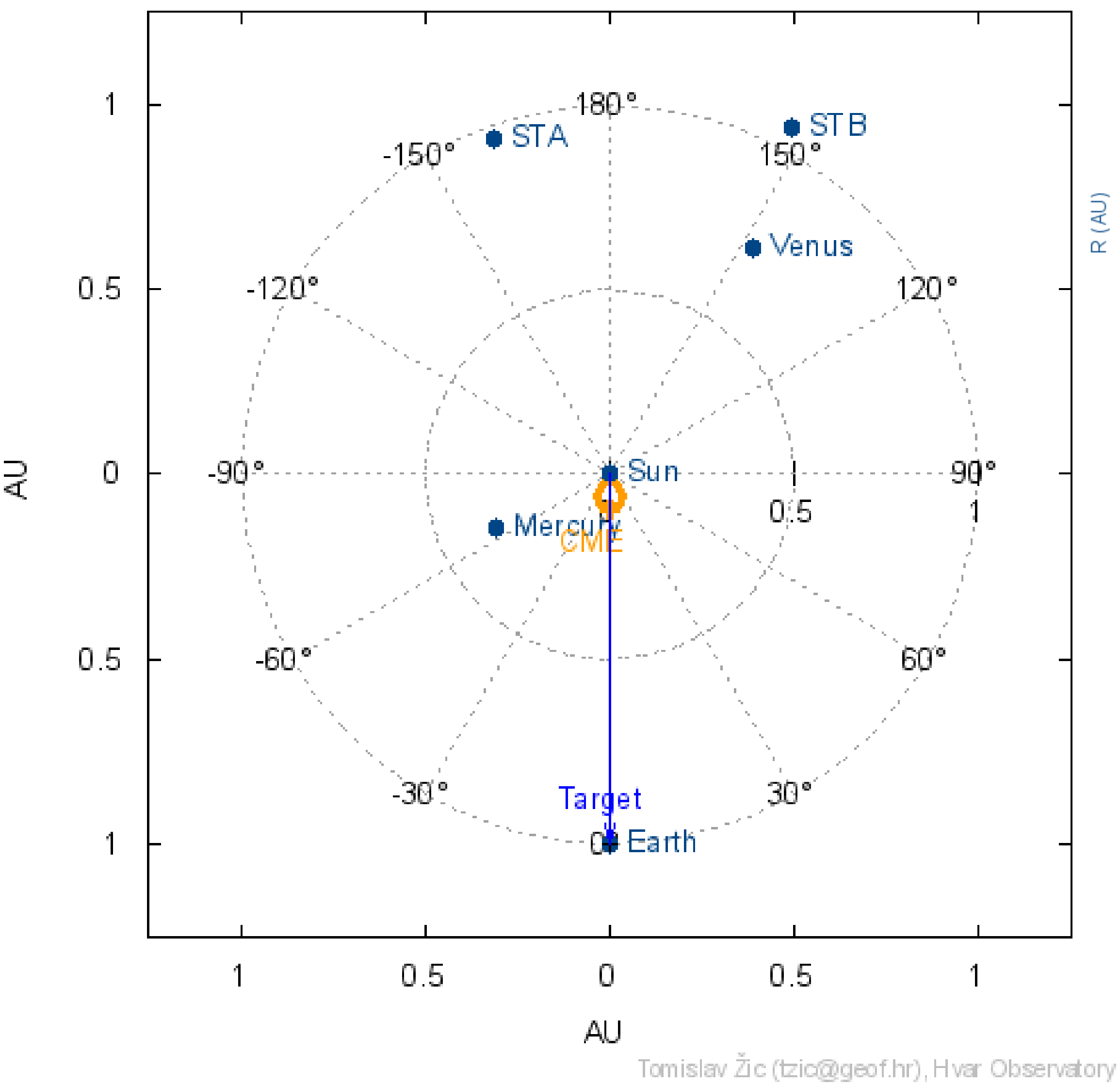
CME arrival at target (date & time): 14.04.2016 at 18h:12min
Transit time: 50.20 h
Impact speed at target (at 1 AU): 634 km/s

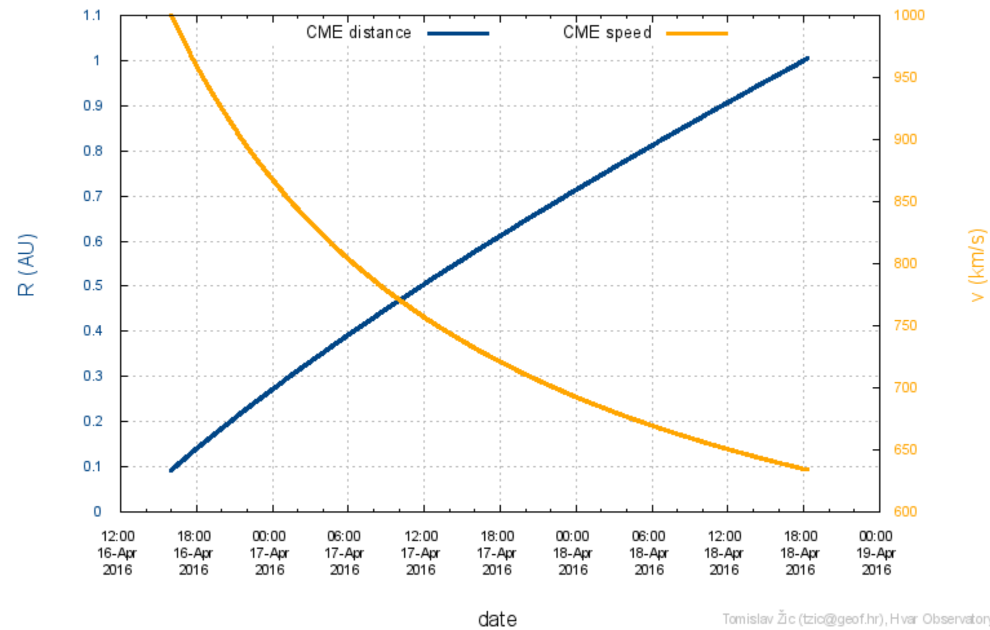
Input parameters:

CME take-off date & time: 12.04.2016 at 16h:00min
$\gamma = 0.2\times10^{-7}$ km^{-1}, w = 450 km/s,
$R_0 = 20\, r_{Sun}$, v_0 = 1000 km/s, $\lambda = 30°$, $\varphi_{CME} = 0°$
R_{target} = 1 AU, $\varphi_{target} = 0°$

Calculated in 3.15 seconds.

Plots *w=const.* & SS-expansion (http://oh.geof.unizg.hr/~tomislav/CDBM-SS/)

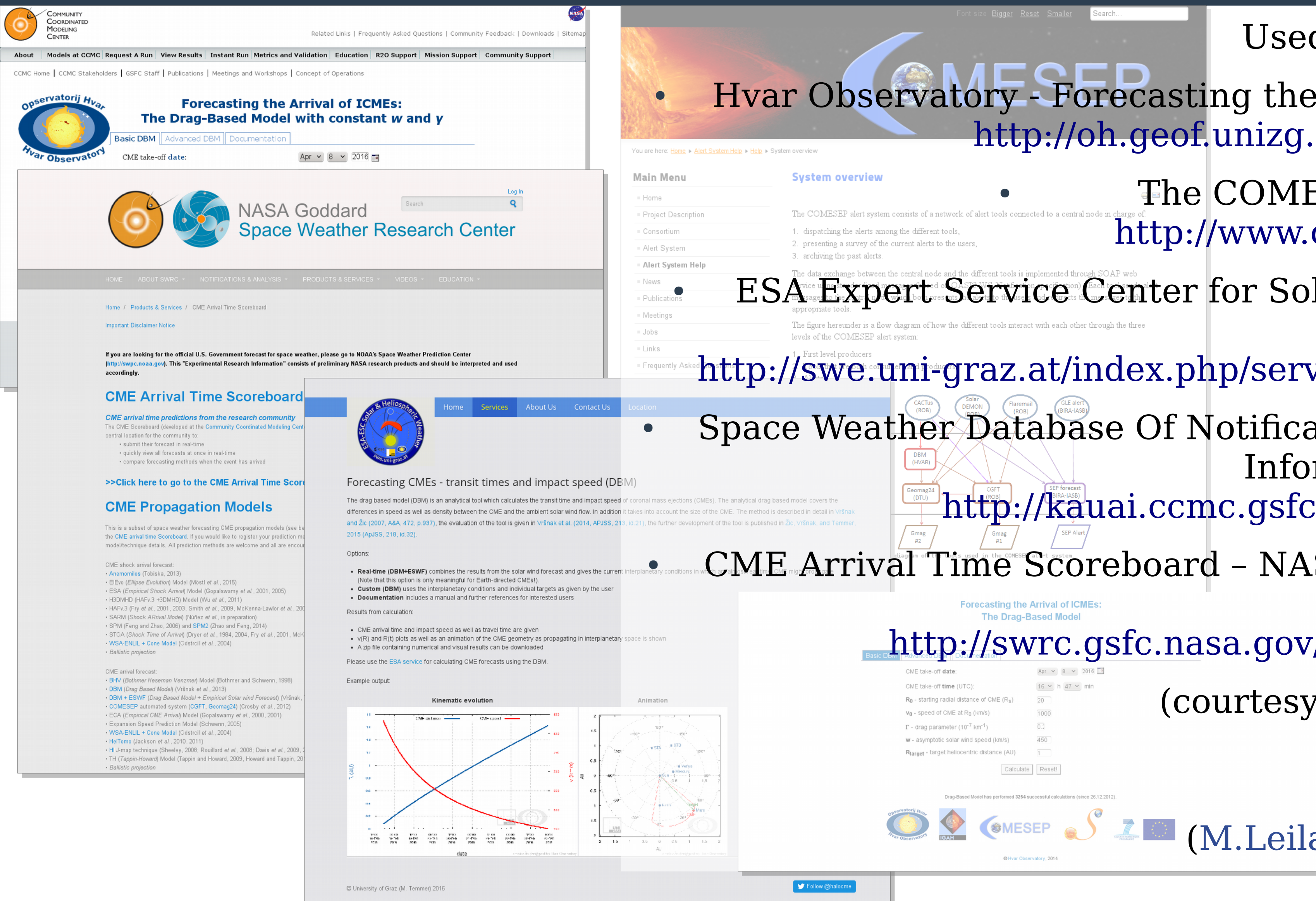




↑UP: Propagation of '+ CME' point in geometry plot

←LEFT: Ecliptic plane cross-section of CME propagation

Online applications of DBM with *w=const.* & SS-expansion



Used on web pages of:

- Hvar Observatory - Forecasting the Arrival of ICMEs: http://oh.geof.unizg.hr/DBM/dbm.php
- The COMESEP alert system: http://www.comesep.eu/alert/
- ESA Expert Service Center for Solar & Heliospheric Weather: http://swe.uni-graz.at/index.php/services/cme-forecast
- Space Weather Database Of Notifications, Knowledge, Information (DONKI): http://kauai.ccmc.gsfc.nasa.gov/DONKI/
- CME Arrival Time Scoreboard – NASA Space Weather Research Center: http://swrc.gsfc.nasa.gov/main/cmemodels

(courtesy of Leila M. Mays)

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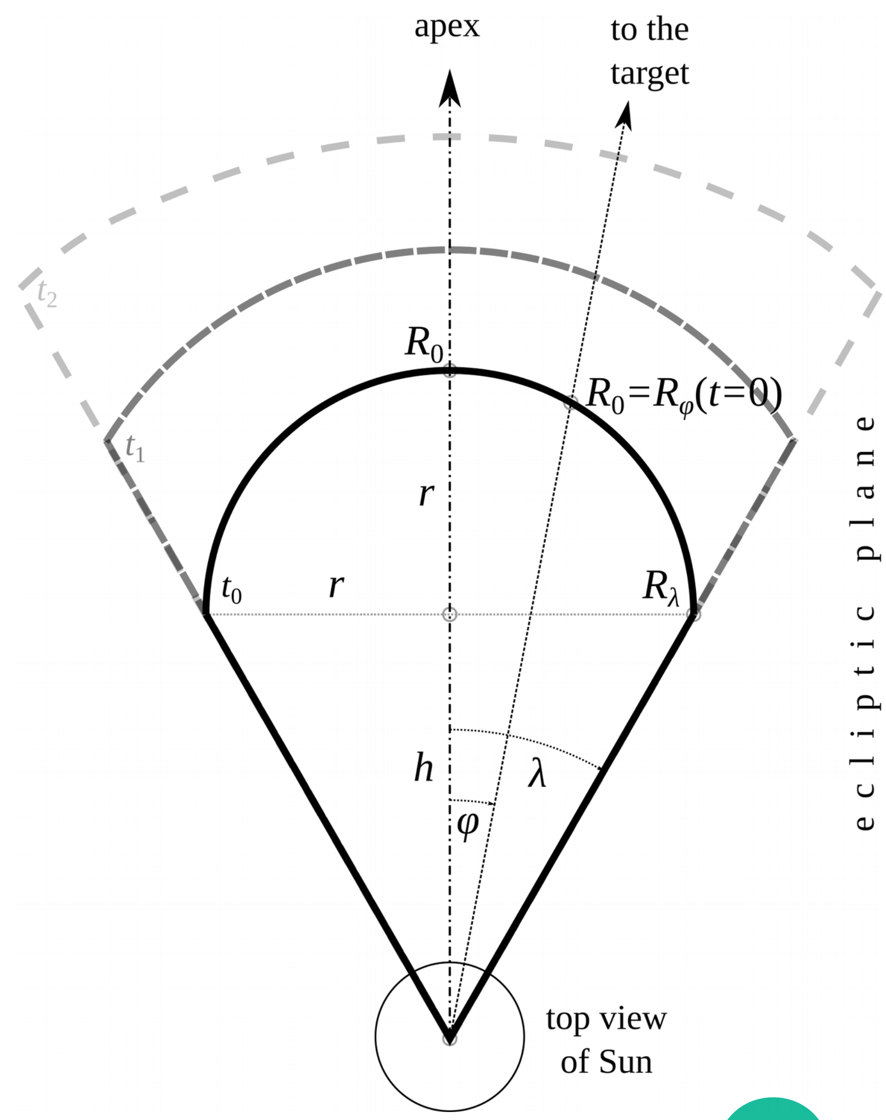
DBM with *w*(*R*) and CME leading-edge flattening

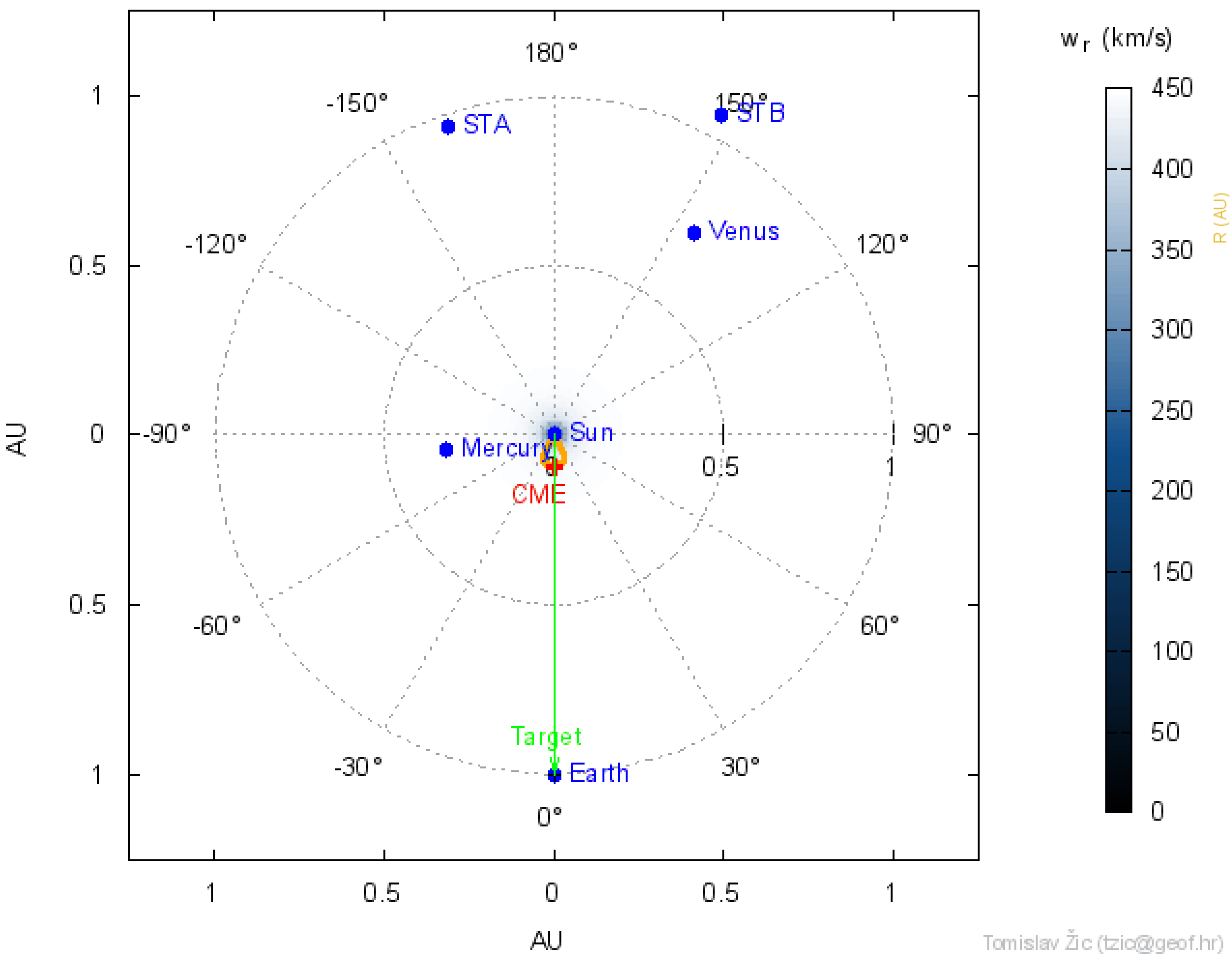
- solar-wind speed *w:*
  - is radially dependent: $w(R)$

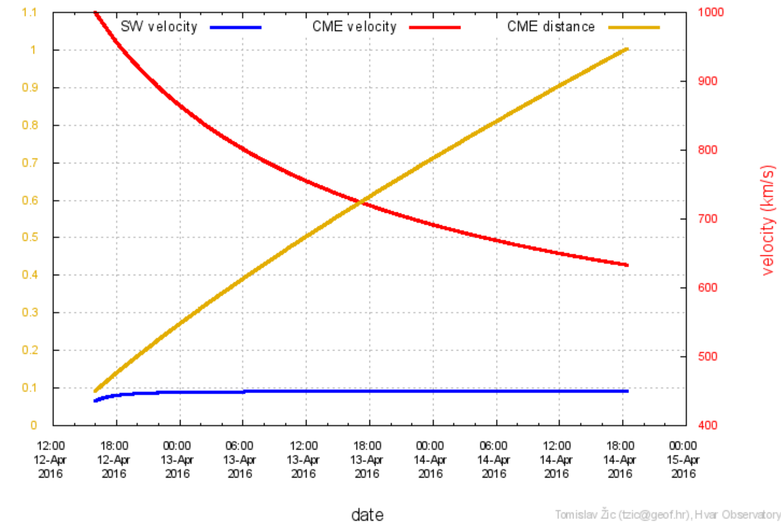
    → parameter γ becomes function of radial distance as well: $\gamma(R)$
- each CME leading-edge segment propagates independently

  → the initial cone-geometry flattens



Plots *w*(*R*) & CME edge flattening (http://oh.geof.unizg.hr/~tomislav/DBM/)





- LEFT: Cross-section of CME propagation in ecliptic plane
- RIGHT: Propagation of '+ CME' point in geometry plot

Output:

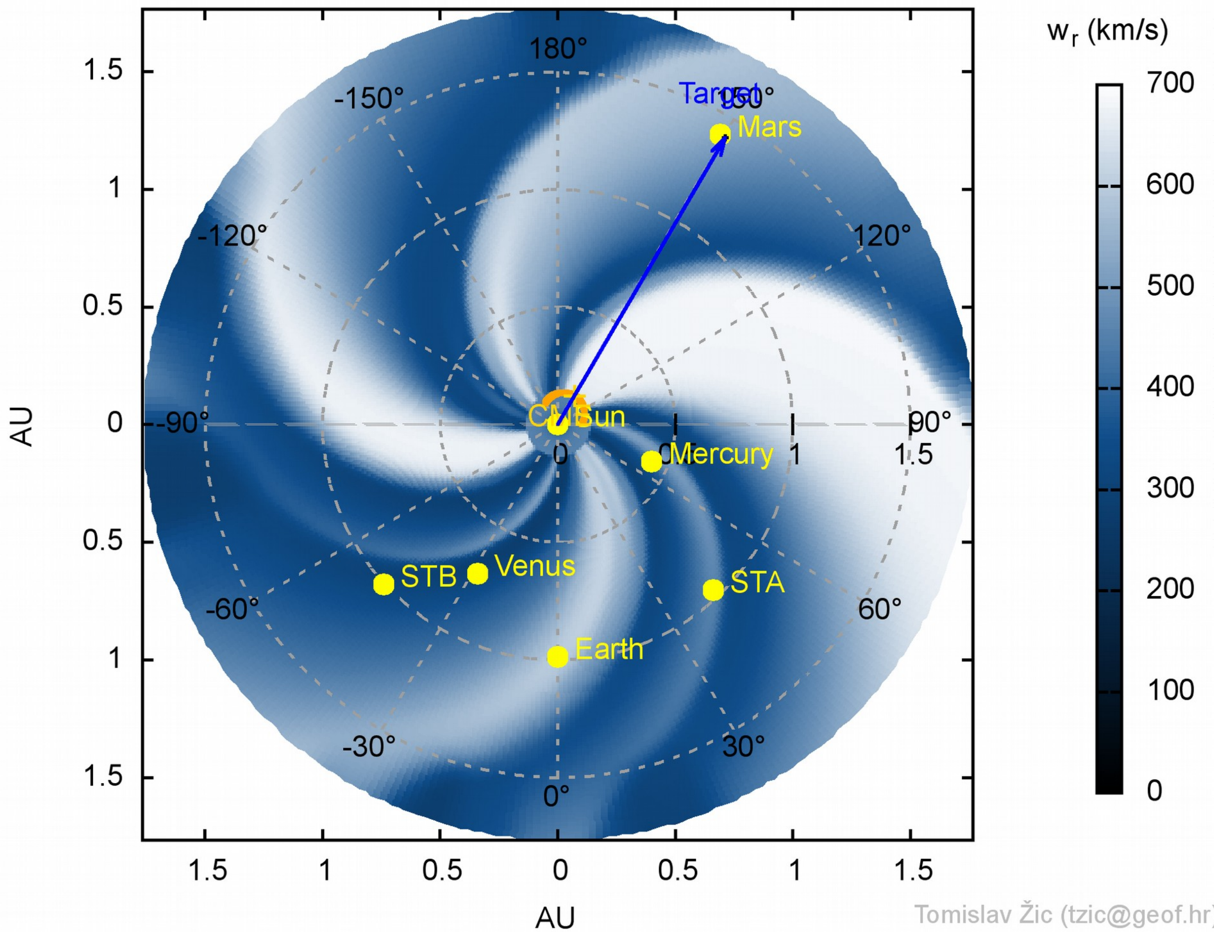
- CME arrival at target (date & time): 14.04.2016 at 18h:20min
- Transit time: 50.35 h
- Impact speed at target (at 1 AU): 633 km/s

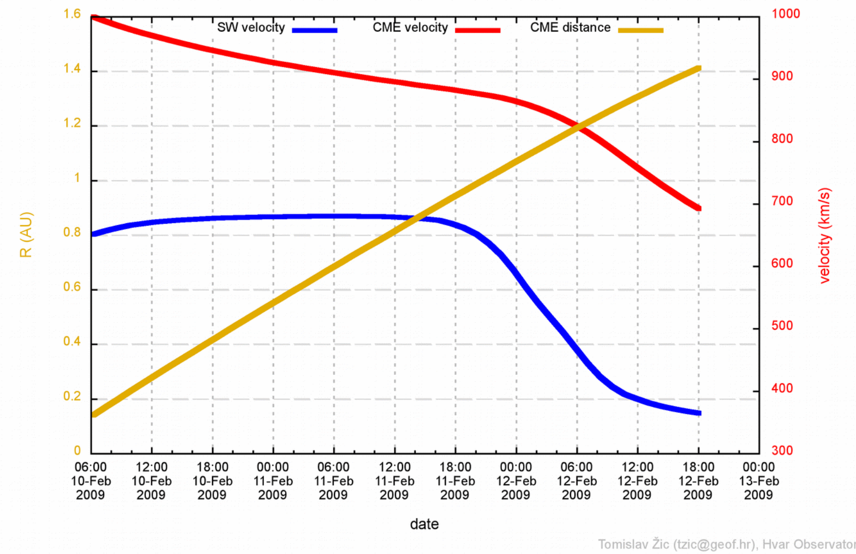
Input parameters:

- CME take-off date & time: 12.04.2016 at 16h:00min
- $\gamma_\infty = 0.2\times10^{-7}$ km^{-1}, w_∞ = 450 km/s,
- $R_0 = 20\ r_S$, v_0 = 1000 km/s, $\lambda = 30°$, $\varphi_{CME} = 0°$
- R_{target} = 1 AU, $\varphi_{target} = 0°$

Calculated in 13.48 seconds.

Example of DBM + ENLIL model (http://oh.geof.unizg.hr/~tomislav/DBM-ENLIL/)





$w(R)$, $\gamma(R)$ → CME-edge flattening

- drag parameter: $\Gamma = 0.2$
- initial CME distance: $R_0 = 31\ r_S$
- initial CME speed: $v_0 = 1000$ km/s
- CME half-width: $\lambda = 60°$
- launching CME meridian distance: $\varphi = 150°$
- target: Mars

- LEFT: Cross-section of CME propagation in ecliptic plane. The CME take-off time: February the 10th, 2009 at 06:13 UT.
- RIGHT: Propagation of '+ CME' point in geometry plot

Automatic Fitting

- INPUT: observed ICME dataset: $\{(R_0,v_0),\ldots,(R_N,v_N)\}$
- OUTPUT: DBM parameters (Γ, w_∞, R_0, v_0)
- The least-square fitting (LSF):
  - successive variation of DBM parameters → minimal deviation between observed v_i and DBM-calculated speeds $v(R_i)$:

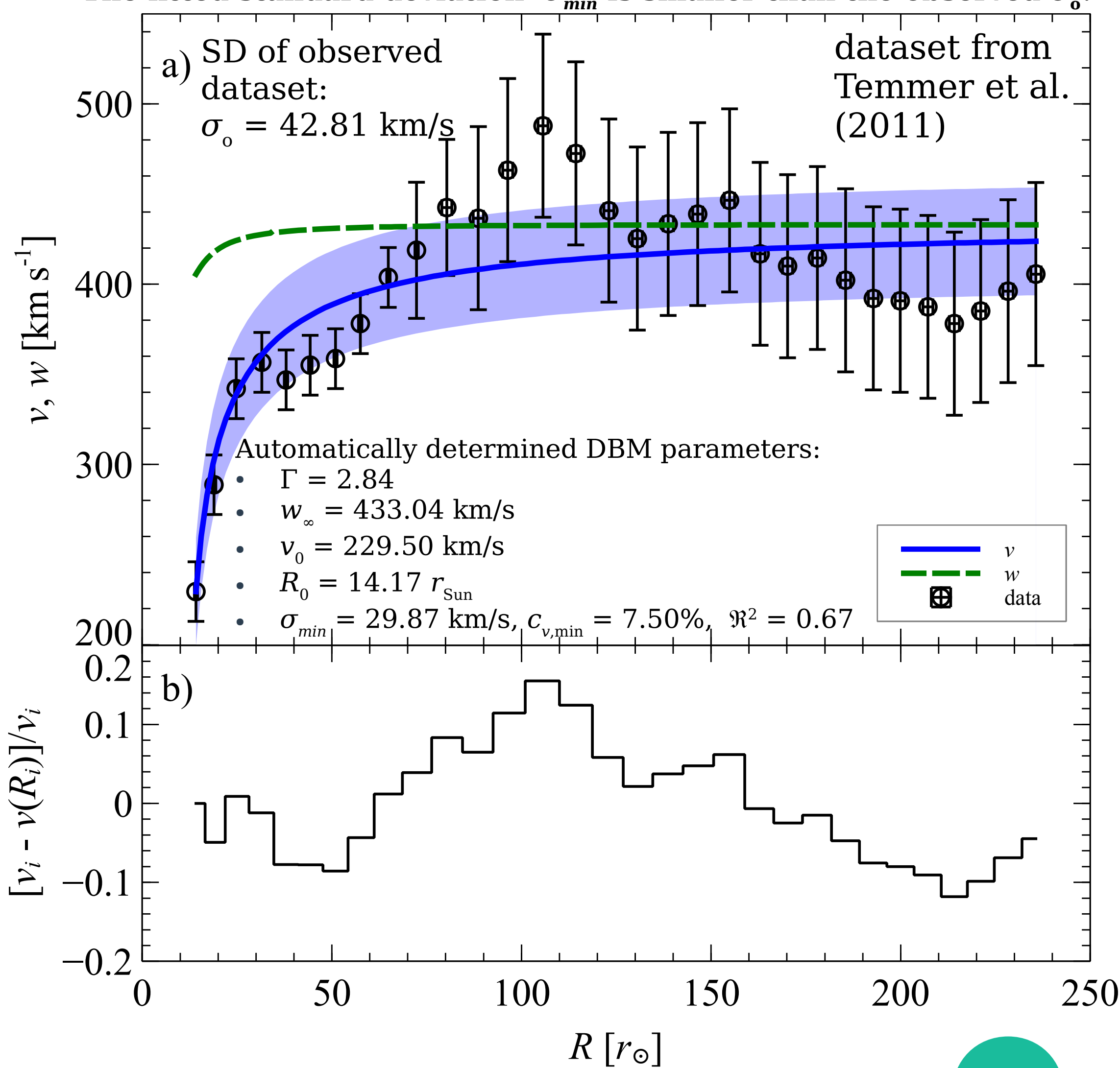
$$\sigma(\Gamma, w_\infty, R_0, v_0) = \sqrt{\frac{1}{(N+1)}\sum_{i=0}^{N}[v_i - v(R_i)]^2}$$

→ $\sigma_{\min}$ →

→ the best (Γ, w_∞, R_0, v_0)

- for real-time space-weather forecasting (successive fitting as ICME propagates)

The fitted standard deviation σ_{min} is smaller than the observed σ_o!



Conclusion

- The drag-based model is useful because:
  - it is simple, fast and versatile
  - its accuracy is not worse in comparison to the other advanced models (Vršnak et al., 2014)
  - it is suited for a fast real-time space-weather forecasting (Žic et al., 2015)
- Drawbacks:
  - the magnetic field/Lorentz force is not included in the DBM
  - CME-CME interaction is problematic for calculation
  - the DBM is not basically designed for usage in a complex heliospheric environment
    (Will DBM + ENLIL provide better forecasting results?)

Thank you for your attention!

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