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# Forbush decreases caused by expanding ICMEs: analytical model and observation

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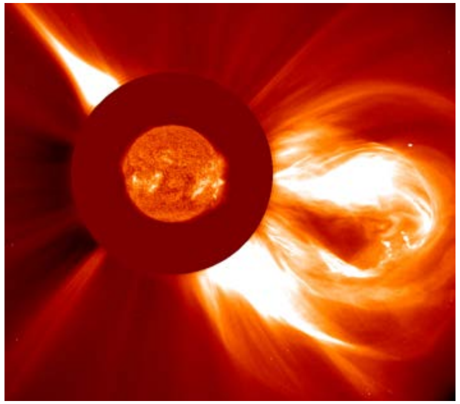
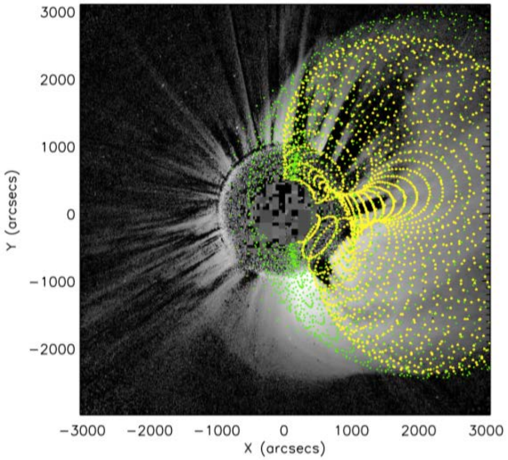
# Forbush decreases caused by Interplanetary Coronal Mass Ejections (ICMEs)

## REMOTE OBSERVATION

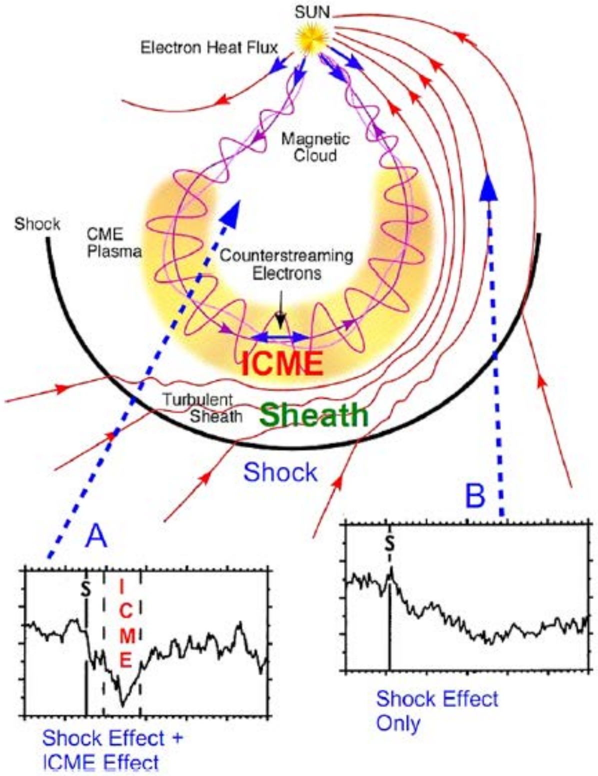


*SOHO/LASCO C2 image*



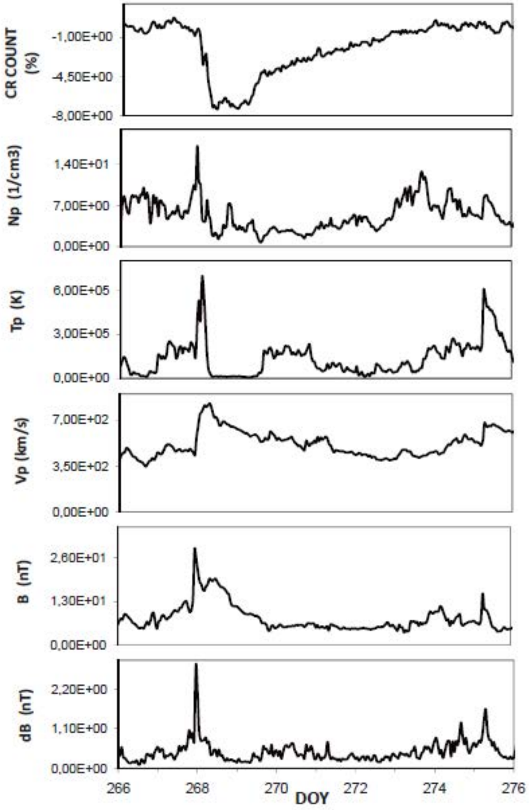
*Temmer & Nitta (2015)*

## VISUALISATION



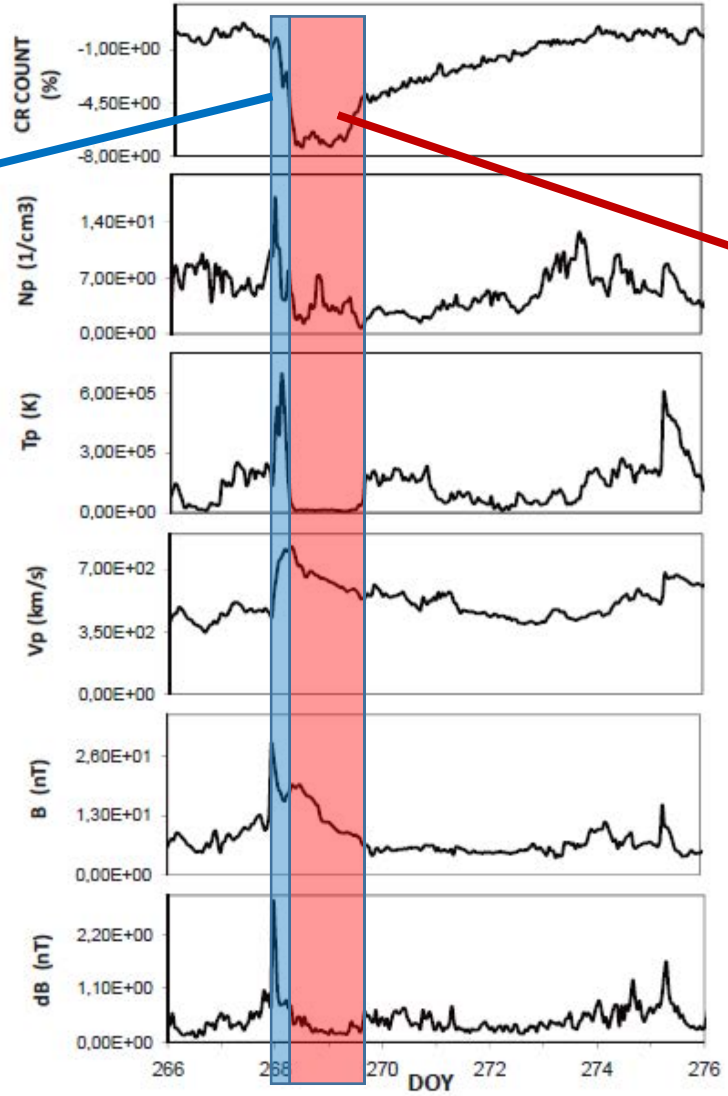
*Richardson & Cane (2011)*

## IN SITU MEASUREMENTS



*Dumbovic et al (2012)*

# Two-step Forbush decreases caused by ICMEs



*Dumbovic et al (2012)*

1st step:

shock/sheath region
highly turbulent
strong B

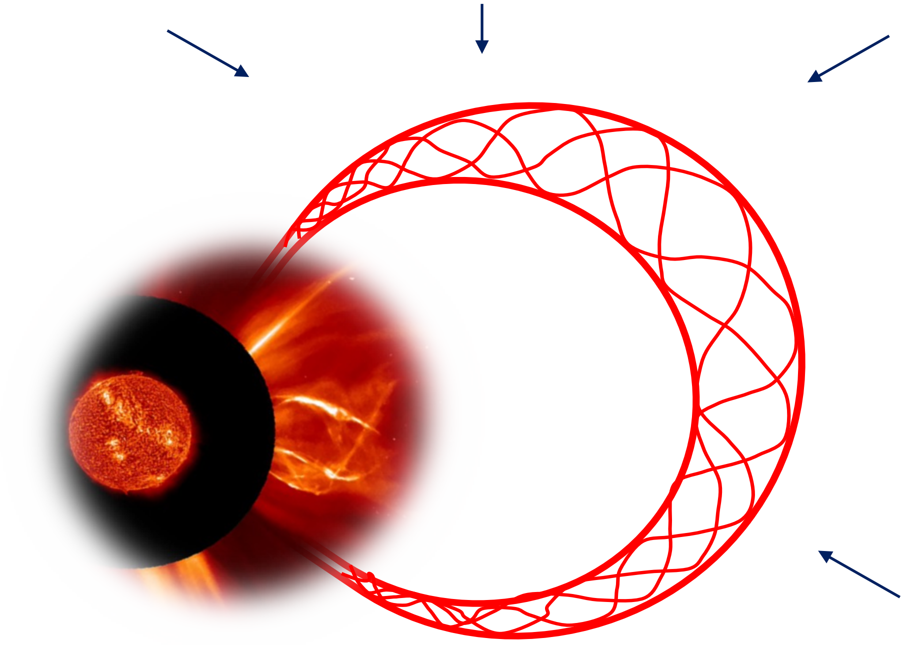
fast decrease,
prolonged recovery

2nd step:

CME ejecta
(magnetic cloud, flux rope)
smooth & strong B
fluctuations very low

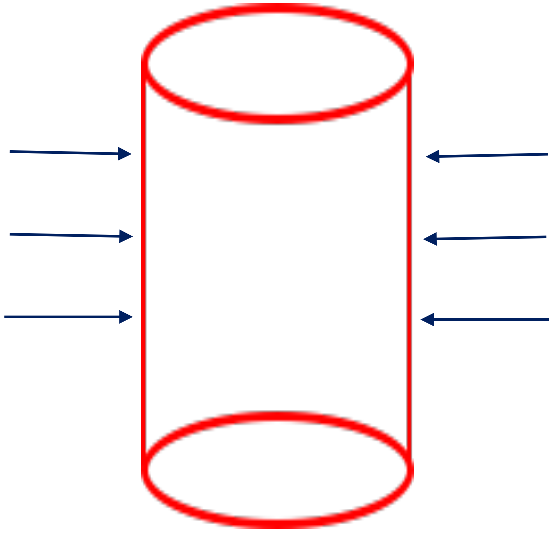
Symmetric-like decrease,
timespan limited to the ejecta

# *The analytical model - assumptions*



**magnetic ejecta (ICME, magnetic cloud, flux rope)**

- a closed magnetic structure: no direct magnetic connection between the inside and the outside => particles can enter into the ejecta via perpendicular diffusion and/or drift (simplicity reasons -> only diffusion)
- **initially empty**



**magnetic ejecta (ICME, magnetic cloud, flux rope)**

- cylindrical form
- **moves with constant velocity**
- **does not vary in shape or size**

*Based on Cane et al (1995)*

## *Building the analytical model*

equation for the particle density:

$$\frac{\partial U}{\partial t} = \frac{1}{r}\left(\frac{\partial}{\partial r}\left(r D_{\perp} \frac{\partial}{\partial r}\right)\right),$$

- radial diffusion
- D does not change throughout ejecta

initial & boundary conditions:

$$U(r,t) = \begin{cases} 0, & 0 < r < a, t = 0 \\ U_0, & r = a, t \geq 0 \end{cases}$$

- initially empty
- Density outside constant

Exact analytical solution:

$$U(r,t) = U_0\left(1 - \frac{2}{a}\sum_{n=1}^{\infty}\frac{J_0(\lambda_n r)}{\lambda_n J_1(\lambda_n a)}\mathrm{e}^{-D\lambda_n^2 t}\right),$$

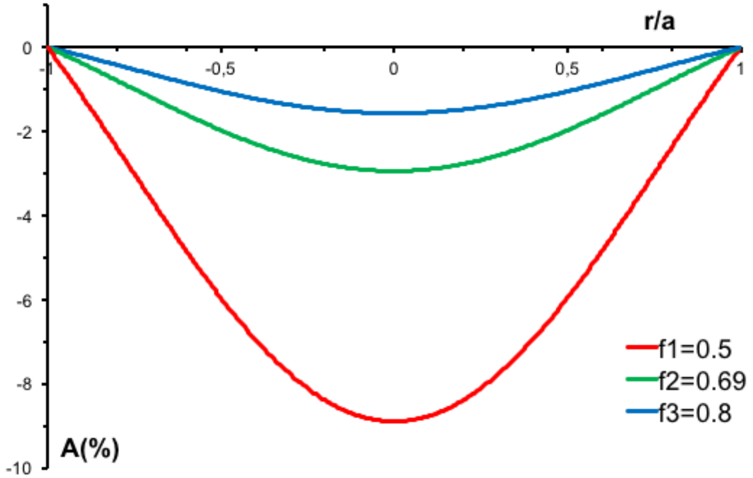
oscillatory

rapidly decreasing

We neglect terms with n>1 and renormalize according to initial & boundary conditions to get the solution:

$$U(r,t) = U_0\left(1 - J_0(\alpha_1 \frac{r}{a})\mathrm{e}^{-D(\frac{\alpha_1}{a})^2 t}\right).$$

# *The analytical model - results*



$$U(r,t) = U_0\left(1 - J_0(\alpha_1 \frac{r}{a})\mathrm{e}^{-\boxed{D(\frac{\alpha_1}{a})^2 t}}\right).$$

f = f(a,t,D)
a = radius of ICME
t = diffusion (transit) time
D = diffusion coefficient

Forbush decrease depends on:

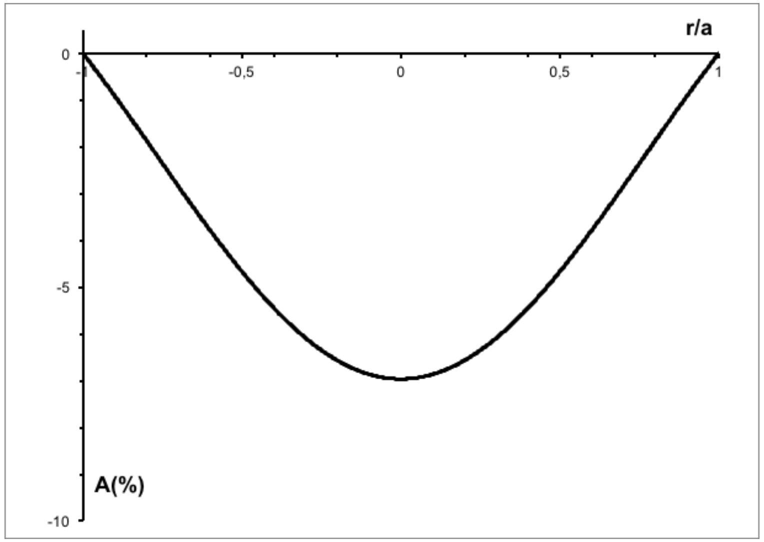
- ✓ Radius of ICME *Blanco et al (2013)*
- ✓ Diffusion (transit) time *Blanco et al (2013)*
- ? Diffusion coefficient:

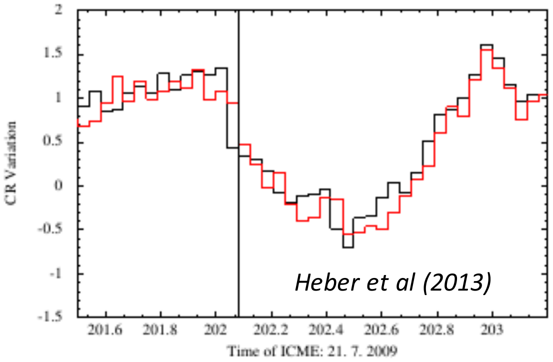
*e.g. Dumbovic et al (2012)*

✓ depends on the strength of B
- but how?

What is a typical diffusion coefficient in magnetic cloud and compared to normal solar wind??

# *The analytical model - results*





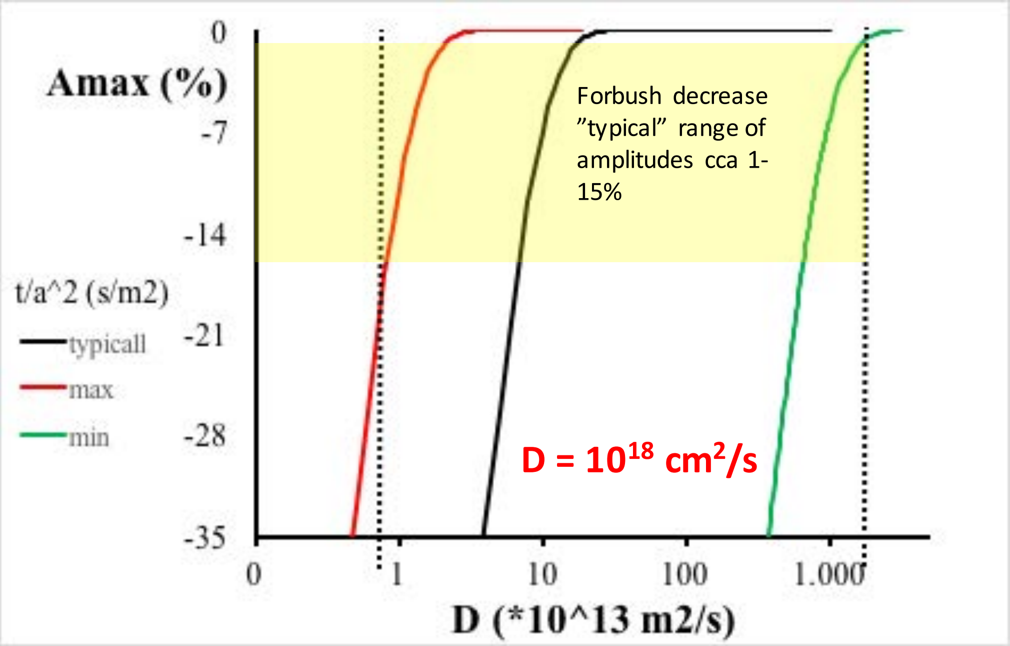
*Heber et al (2013)*

Typical values:
Transit time 72 hours
MC radius 0.05 AU
Forbush decrease 6-7%

↓

Diffusion coefficient $10^{18}$ cm$^2$/s
($10^{14}$ m$^2$/s)

Estimation based on theoretical consideration



Forbush decrease "typical" range of amplitudes cca 1-15%

D = $10^{18}$ cm$^2$/s

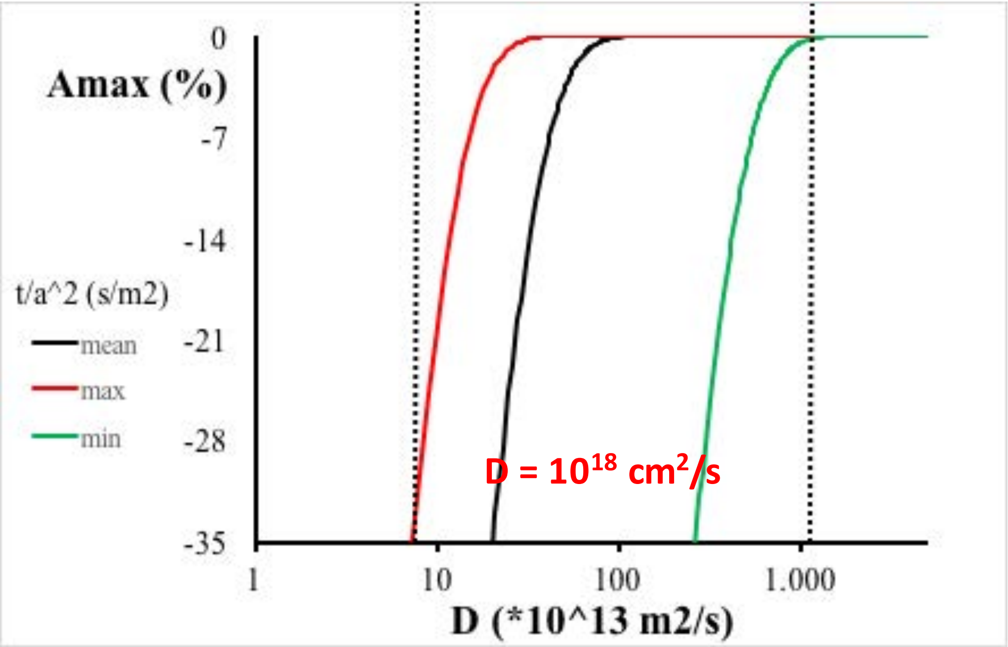
max:
a=0.02 AU
TT=96h

Typical:
a=0.05 AU
TT=72h

min:
a=0.2 AU
TT=12h

**estimated range for the diffusion coefficient:**
**Dmin=7*$10^{16}$ cm$^2$/s**
**Dmax=2,4*$10^{20}$ cm$^2$/s**

Estimation based on observational consideration



D = $10^{18}$ cm$^2$/s

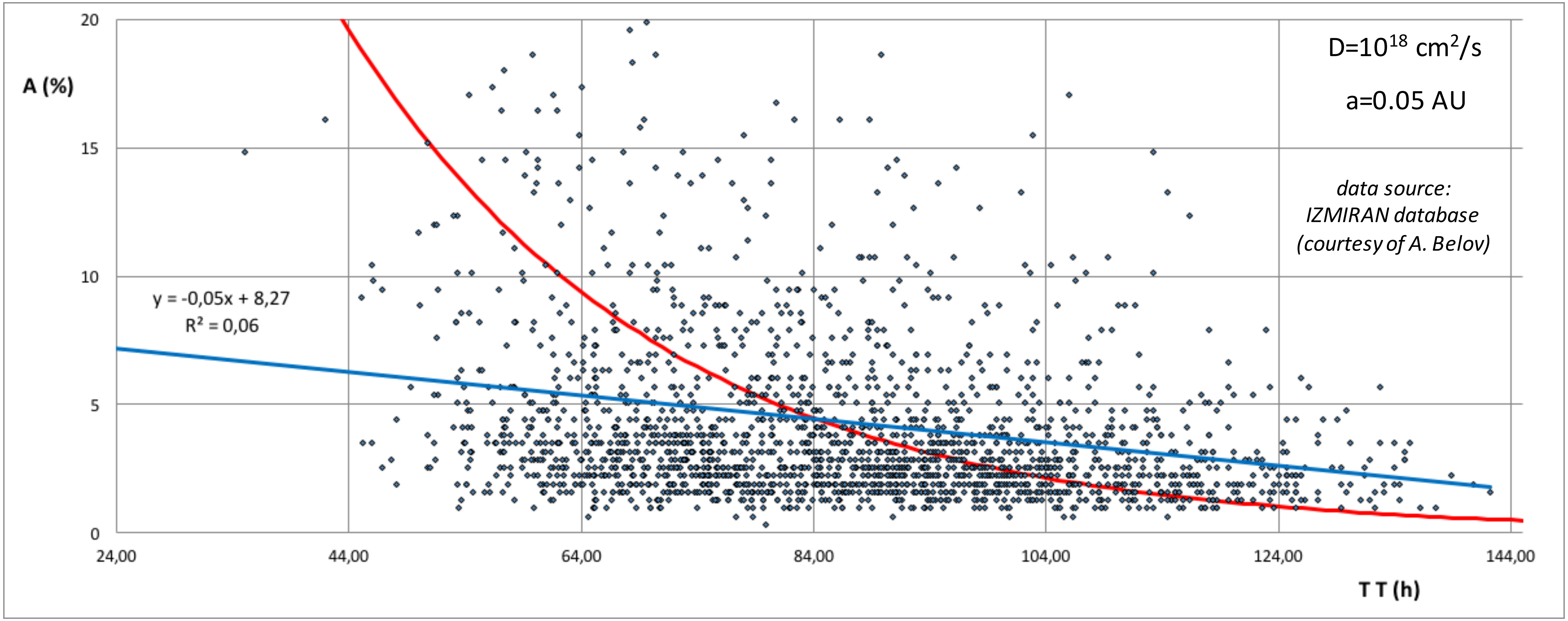
estimation of the diffusion coefficient range based on the empirical distribution of t/a^2 for MCs derived from Richardson & Cane (2010) list

**estimated range for the diffusion coefficient:**
**Dmin=7*$10^{17}$ cm$^2$/s**
**Dmax=1,2*$10^{20}$ cm$^2$/s**

**Typical D for unperturbed solar wind:**
**D ~ $10^{21}$ cm$^2$/s**

## *The model vs observation: ground based measurements at Earth*

Forbush decrease amplitude vs transit time



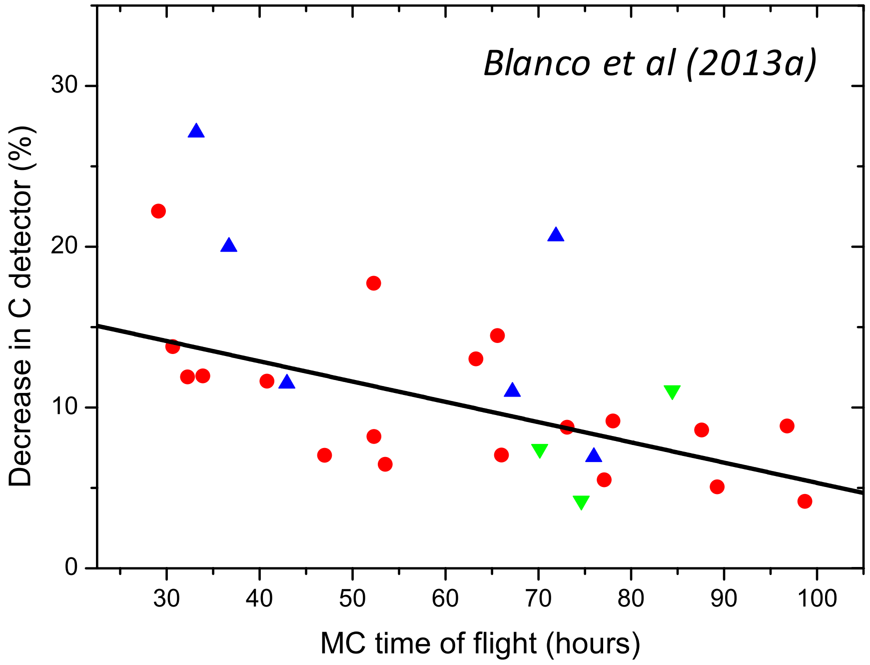
$D=10^{18}$ cm$^2$/s

a=0.05 AU

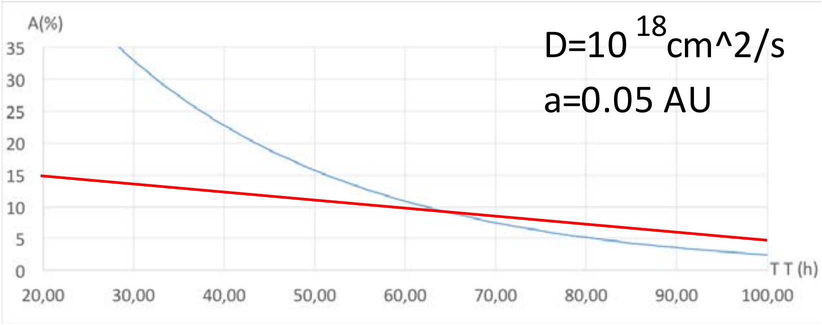
*data source:*
*IZMIRAN database*
*(courtesy of A. Belov)*

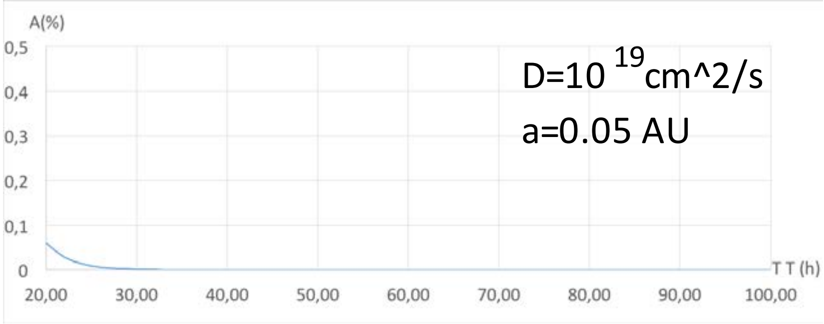
Forbush decrease measurements on Earth (R~10GV)) shifted to satellite values (R=0GV) using empirical formula from Cane (2000)

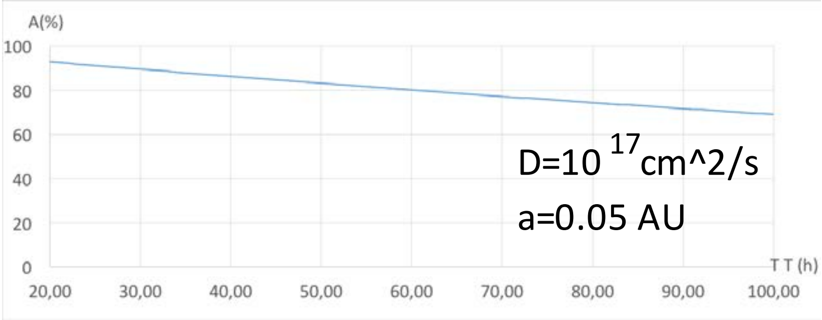
# *The model vs observation: spacecraft measurements*



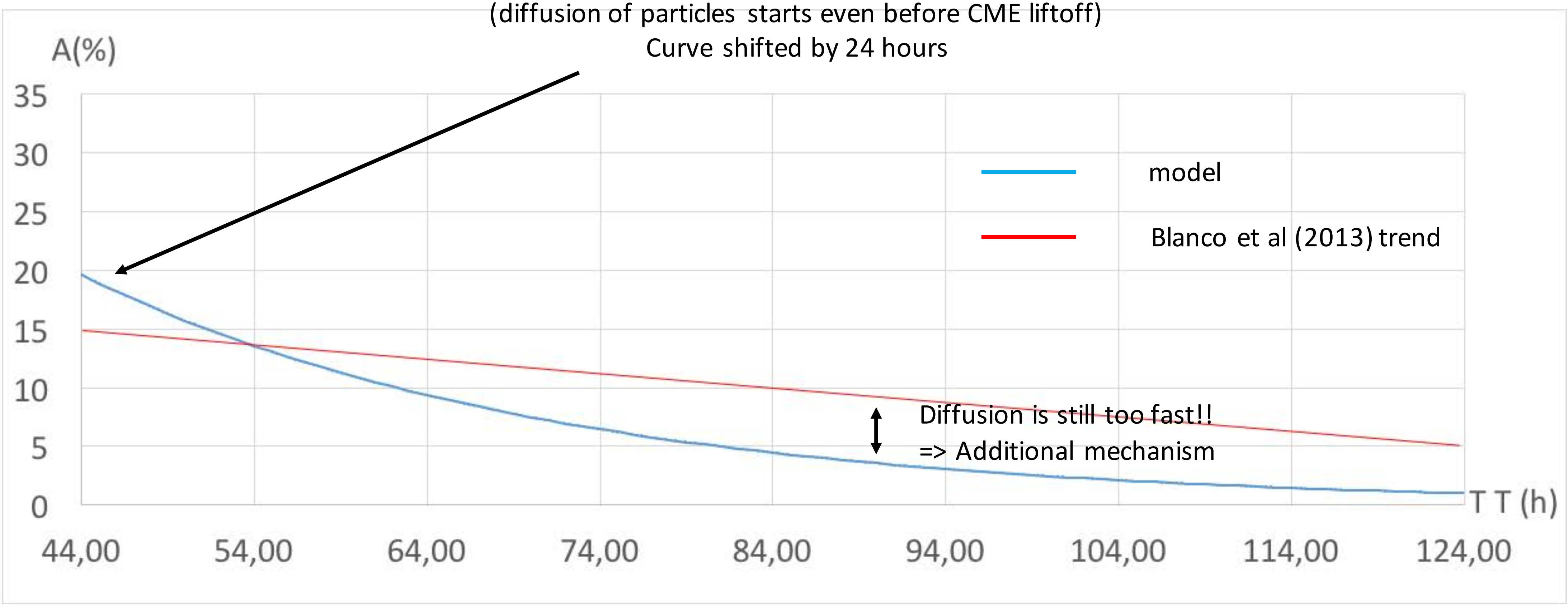
Measurements from Helios I and II







*Possible model changes…*

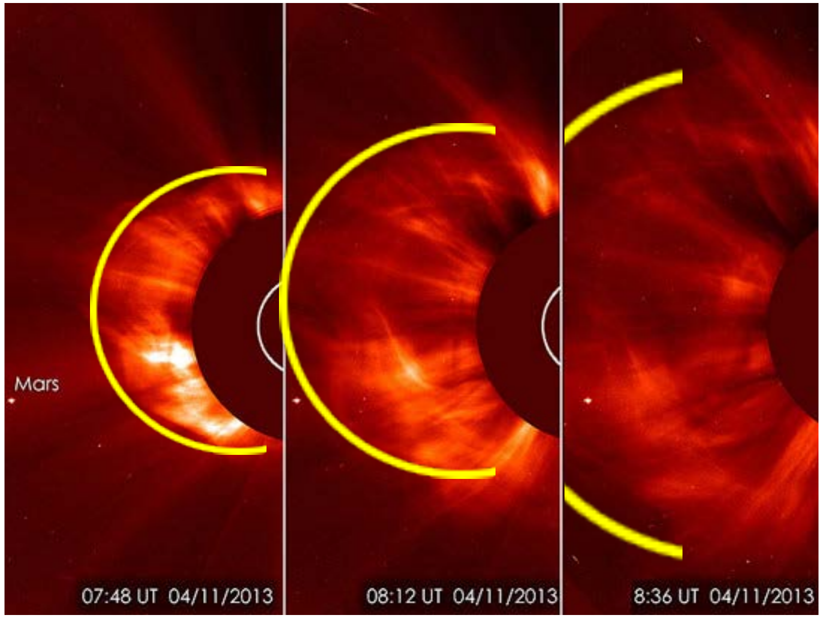


diffusion time > transit time
(diffusion of particles starts even before CME liftoff)
Curve shifted by 24 hours

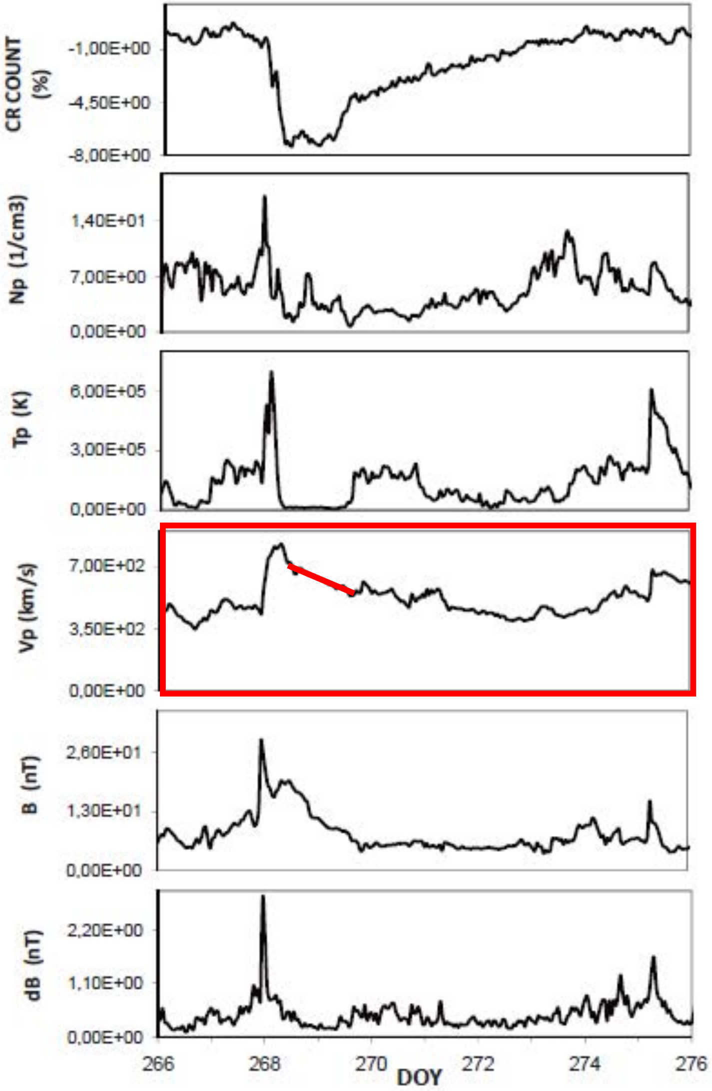
Diffusion is still too fast!!
=> Additional mechanism

# *CMEs expand!*

*SOHO/LASCO C2 image*



*Dumbovic et al (2012)*



CME expansion observed remotely near the Sun, in IP space and in situ measurements!

## *Expansion vs diffusion – a very rough estimate*

Could expansion be large "enough" factor to counteract diffusion??

$U=6,5*R^{-2,4}$ MC density with heliocentric distance, Bothmer & Schwenn, 1998

$U=7*R^{-2}$ Solar wind density with heliocentric distance

At 0.3 AU
U (CME) = 117
U (SW) = 78
FD = 10%

→

At 1 AU
U (CME) = 6,5
U (SW) = 7
FD = 44%

→ 30 % decrease due to expansion

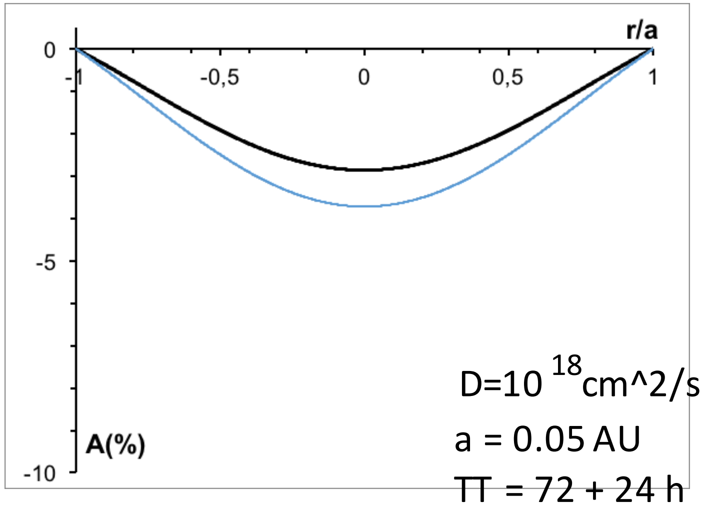
90 % increase due to diffusion

At 0.3 AU
a = 0.05 AU
$D=10^{18}$cm^2/s
FD = 100%
(empty MC)

Typical
transit
time 60 h
→

At 1 AU
a = 0.05 AU
$D=10^{18}$cm^2/s
FD = 10%

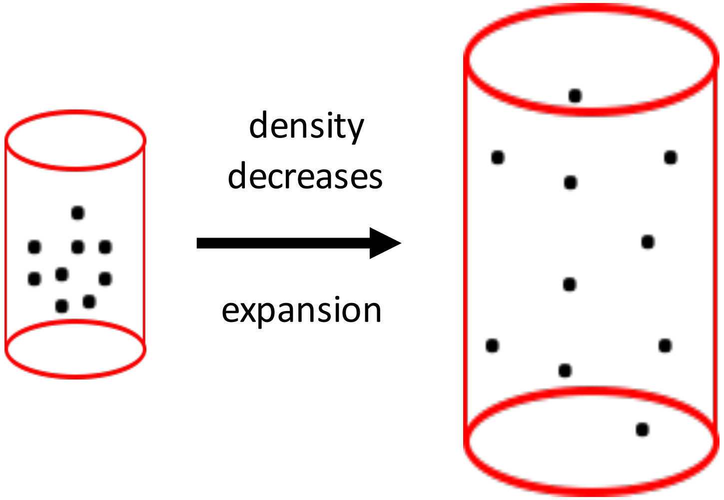
A very rough estimation: Expansion can "slow down" the diffusion by roughly 30%



$D=10^{18}$cm^2/s
a = 0.05 AU
TT = 72 + 24 h

## *Expansion vs diffusion – a very rough estimate*

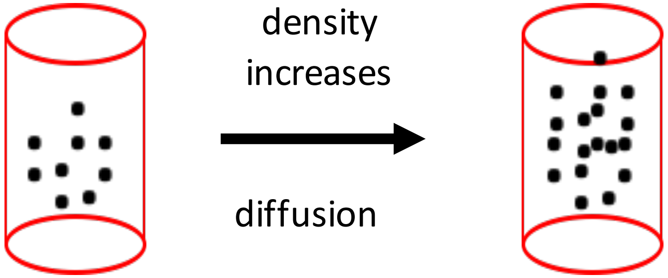
ratio



Calculated based on relative MC (plasma) density decrease due to expansion with respect to solar wind density decrease due to expansion (empirical relation from Bothmer & Schwenn, 1998)

**1**

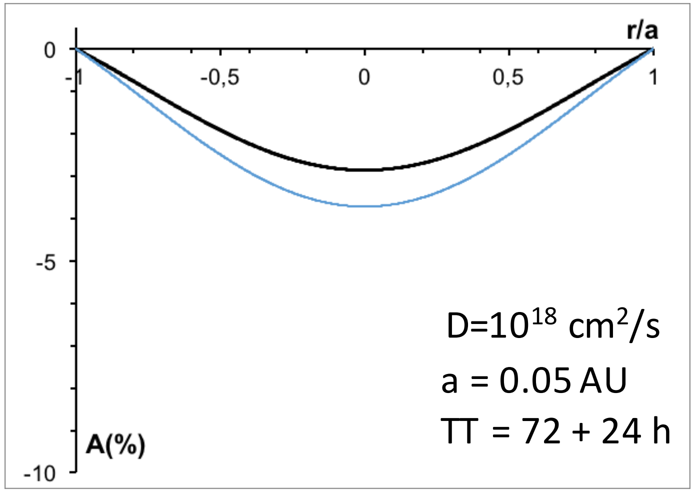
**:**



Calculated based on our model for the same distance/time as above

**3**

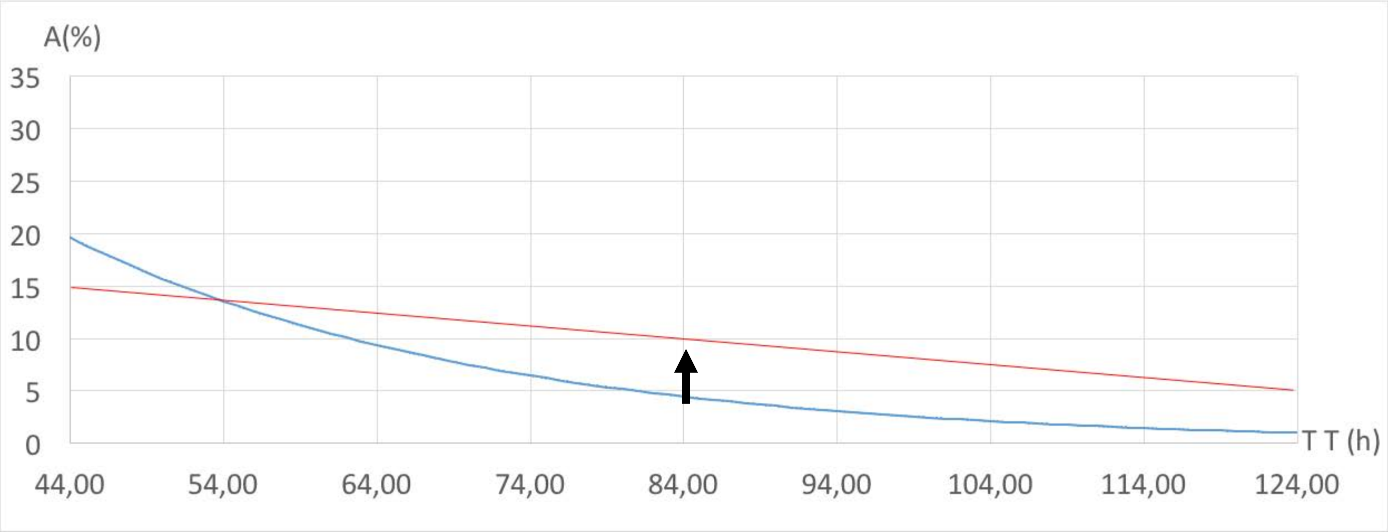
## *Expansion vs diffusion – a very rough estimate*



$D=10^{18}$ cm$^2$/s

a = 0.05 AU

TT = 72 + 24 h



A very rough estimation:
Expansion can ”slow down” the
diffusion by roughly 30%

# CONCLUSIONS:

diffusion-based analytical model in present form qualitatively agrees with observation, but quantitatively suffers from several drawbacks

The qualitative aspect of the model could be improved by including observable facts regarding CMEs (e.g. expansion)

Thank you for your attention!