Forbush decrease model for expanding CMEs (ForbMod)

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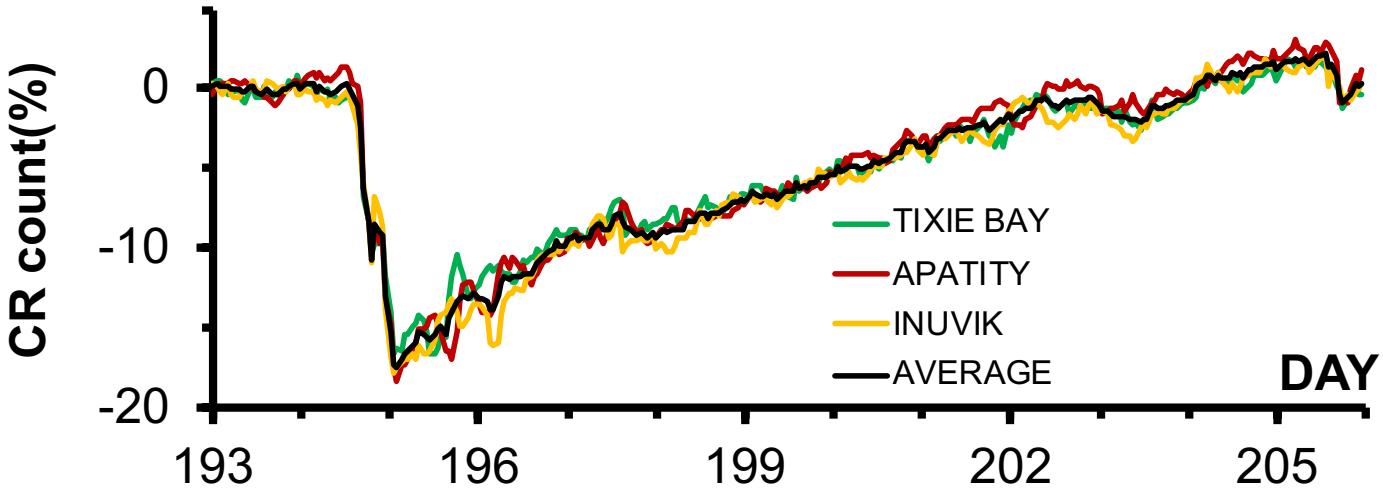
2-Department of Extraterrestrial Physics, University of Kiel, Germany

3-Hvar Observatory, Faculty of Geodesy, University of Zagreb, Croatia

4-Karlovac University of Applied Sciences, Croatia

What are Forbush decreases?

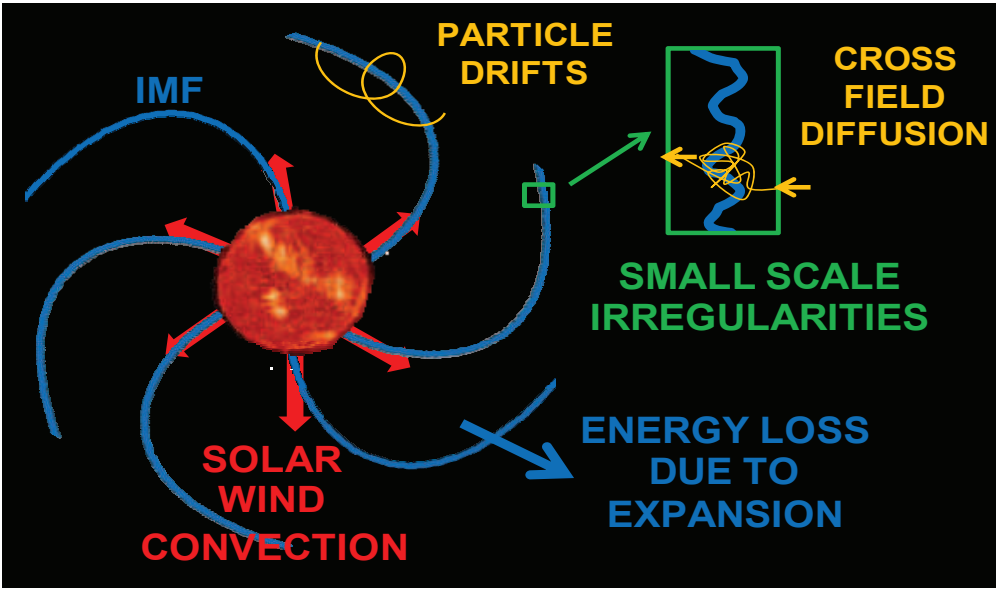


Dumbovic PhD thesis,2015

First observed by Forbush, 1937 and Hess & Demmelmair, 1937

Short term decreases in galactic cosmic ray count
Typical duration several days
Typical amplitudes several %
(depends on the detector)

Modulation of Galactic Cosmic Rays (GCRs) in Heliosphere



Dumbovic PhD thesis,2015

PARTICLE TRANSPORT EQUATION
Parker, 1965

$$\underbrace{\frac{\partial f}{\partial t}}_{a} = -(\underbrace{\mathbf{V}}_{b} + \underbrace{\langle \mathbf{v}_d \rangle}_{c}) \cdot \nabla f + \underbrace{\nabla \cdot (\mathbf{K}_s \cdot \nabla f)}_{d} + \underbrace{\frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{e},$$

a: GCR phase-space distribution function F(P,t,r)

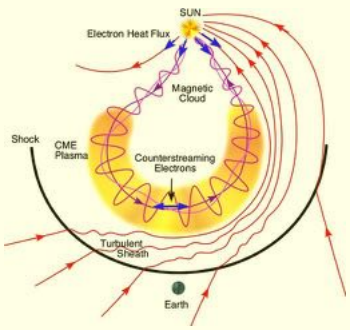
b: convection

c: drifts

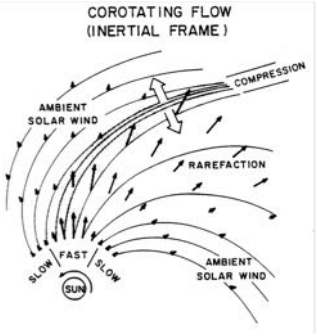
d: diffusion

e: Adiabatic cooling

What causes Forbush decreases?

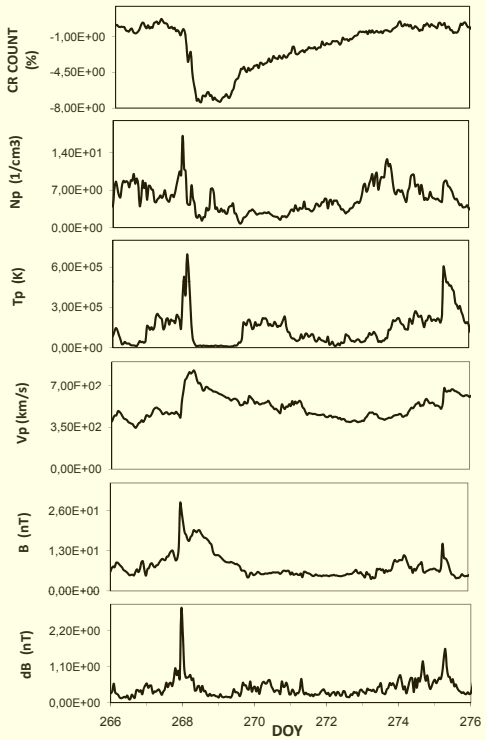


Zurbuchen&Richardson,2006

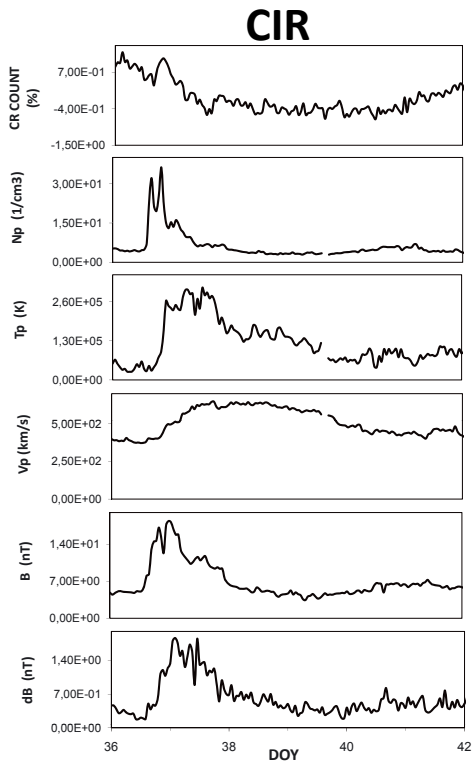


Gosling&Pizzo,1999

ICME



CIR



Various shapes and sizes

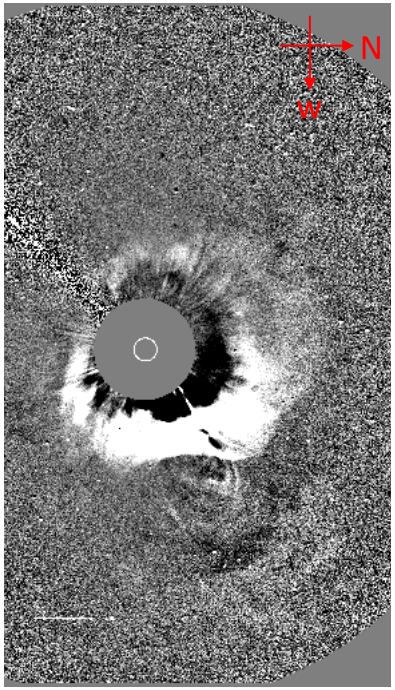
↑

Various interplanetary transients

Dumbovic+,2012

Forbush decreases caused by Interplanetary Coronal Mass Ejections (ICMEs)

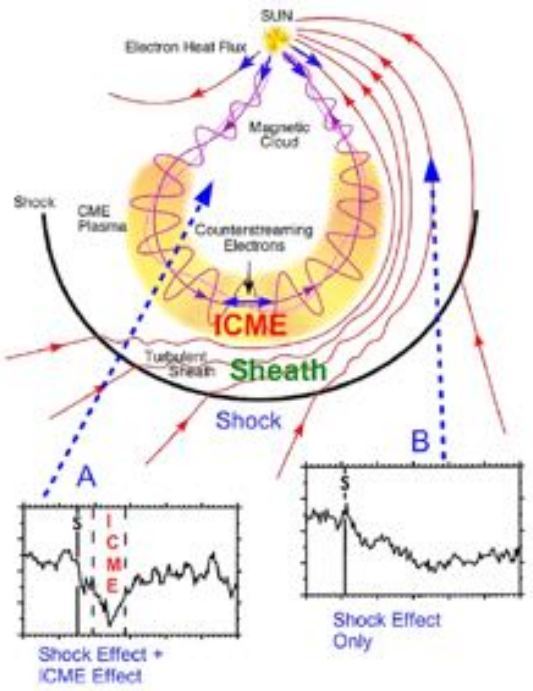
REMOTE OBSERVATION



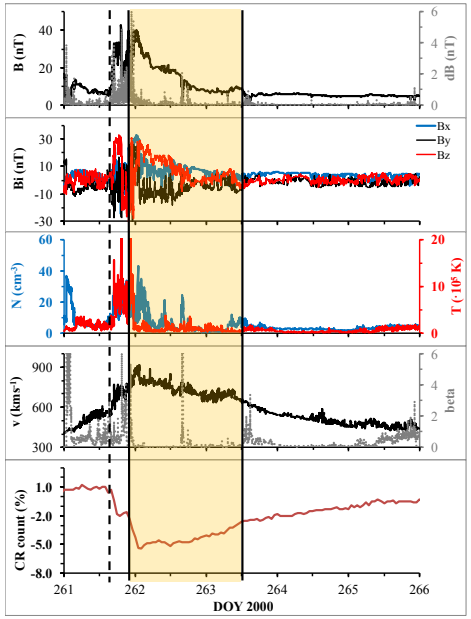
CME in SOHO/LASCO C3
2000 September 16 06:18 UT
First C2 detection at 05:18

VISUALISATION

Adapted from Richardson & Cane, 2011, SolPhys



IN SITU MEASUREMENTS



ICME detected in situ by Wind
2000 September 17
Shock arrival at 17:00
+
2step Forbush decrease detected by NMs at Earth
adapted from Dumbovic+, 2011, A&A

Forbush decreases caused by Interplanetary Coronal Mass Ejections (ICMEs)

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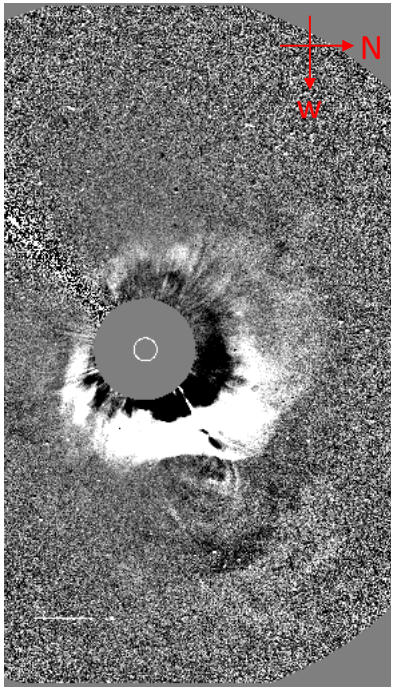

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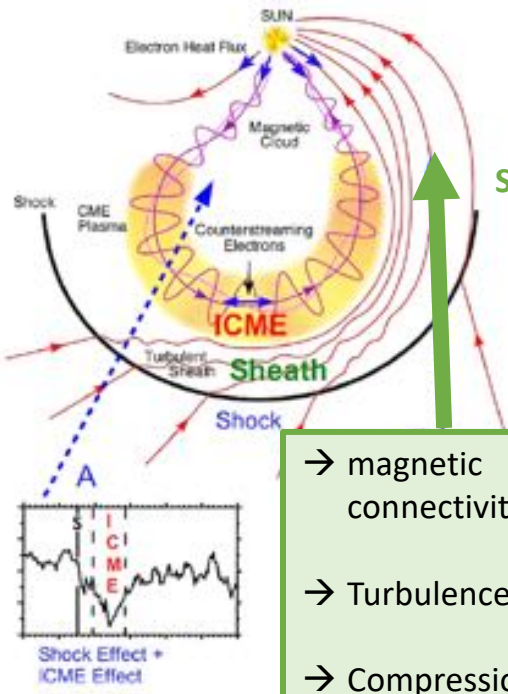

SHOCK-effect

→ magnetic connectivity

→ Turbulence

→ Compression

→ Prolonged effect

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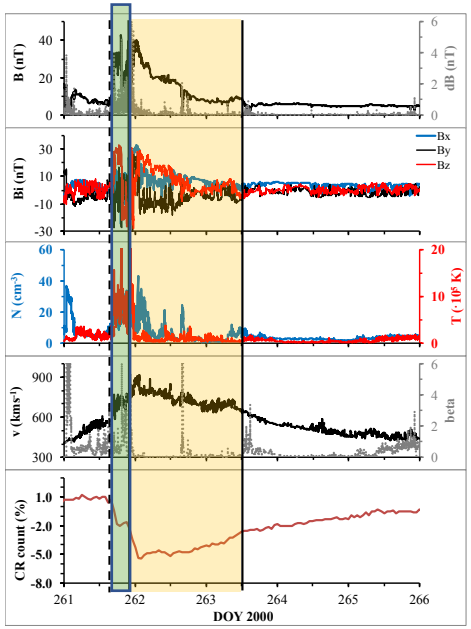

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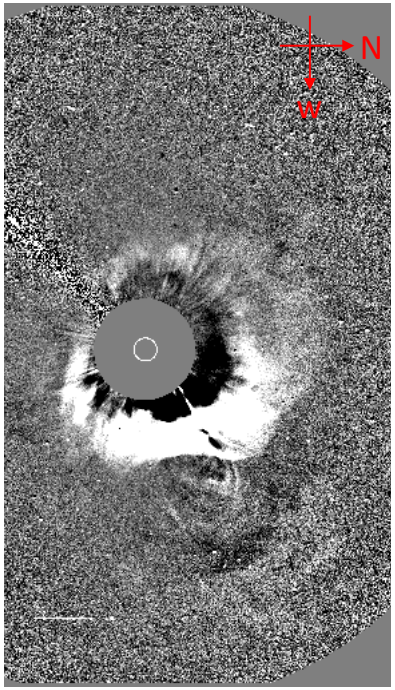

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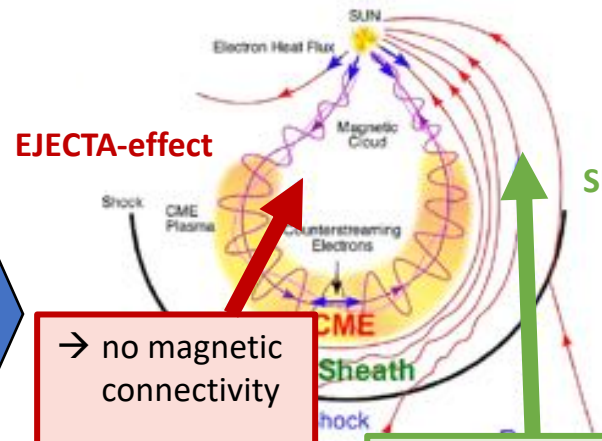


EJECTA-effect

→ no magnetic connectivity

→ Smooth & strong field

→ Timespan limited to ICME

SHOCK-effect

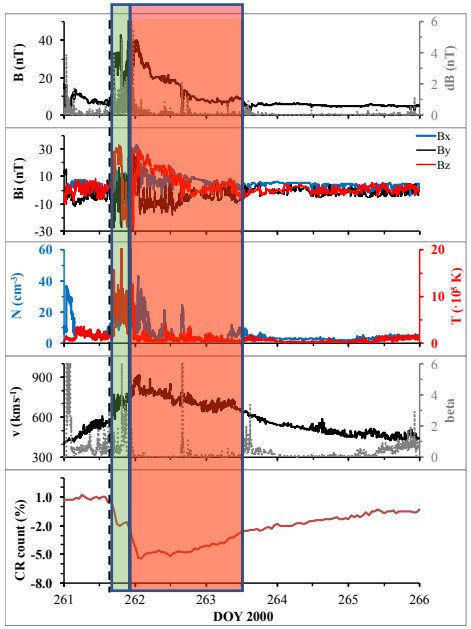
→ magnetic connectivity

→ Turbulence

→ Compression

→ Prolonged effect

IN SITU MEASUREMENTS



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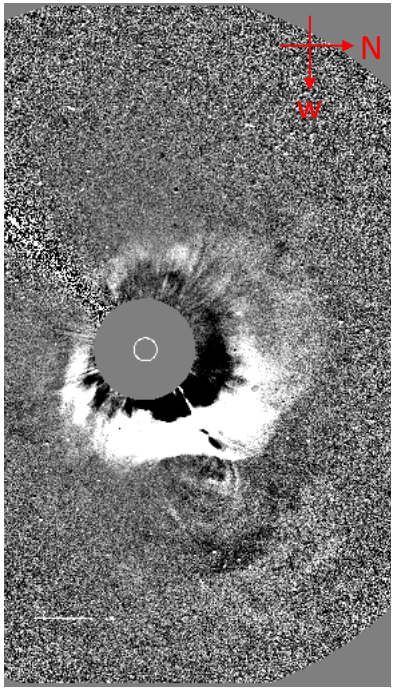

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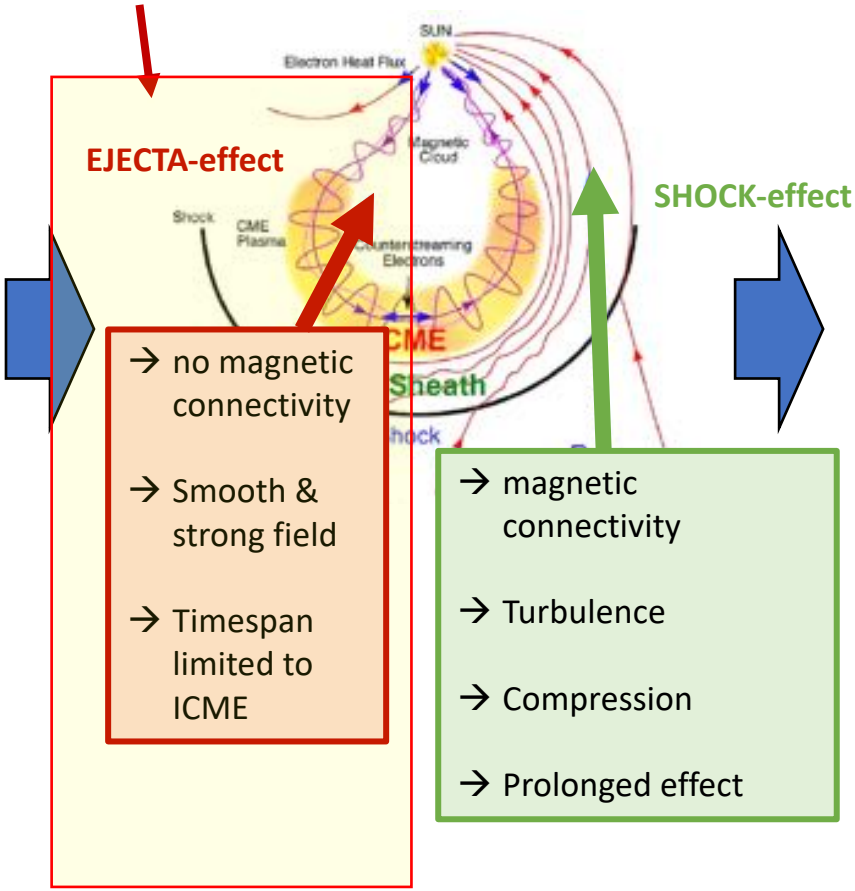

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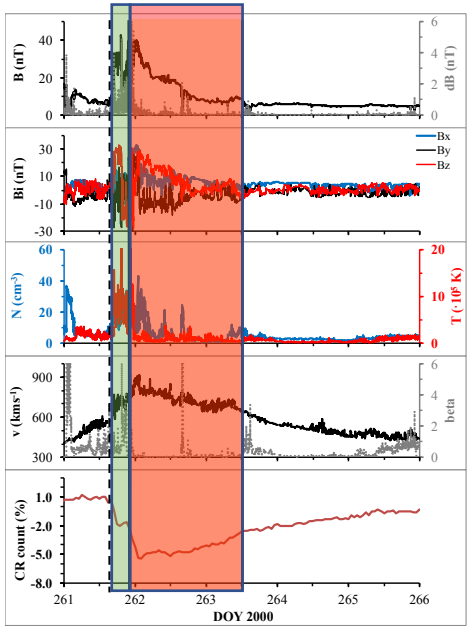

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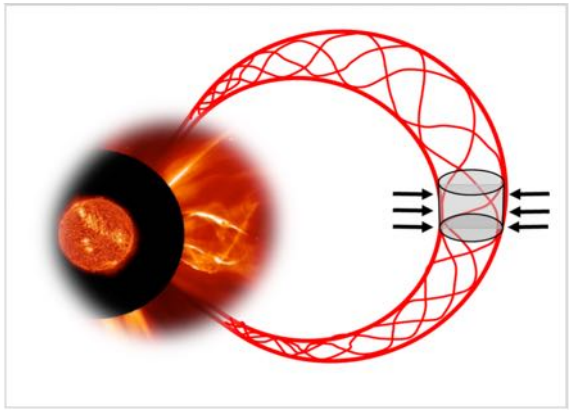
Dumbovic+,2018,ApJ(submitted)

ForbMod = *analytical diffusion-expansion model for Forbush decreases caused by flux ropes*



- a closed magnetic structure
  - Initially empty of GCR
- Locally of cylindrical form
- Moves with constant velocity

First proposed by Morrison, 1956, PhysRev

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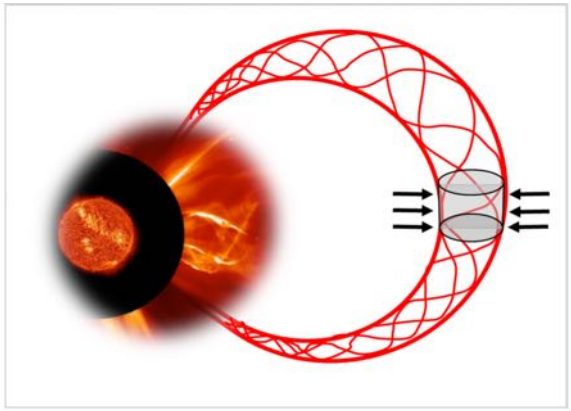

- a closed magnetic structure
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- particles enter by perpendicular diffusion and slowly fill the structure

Similar to e.g. Cane+, 1995, ICRCproc; Quenby+, 2008, JGR

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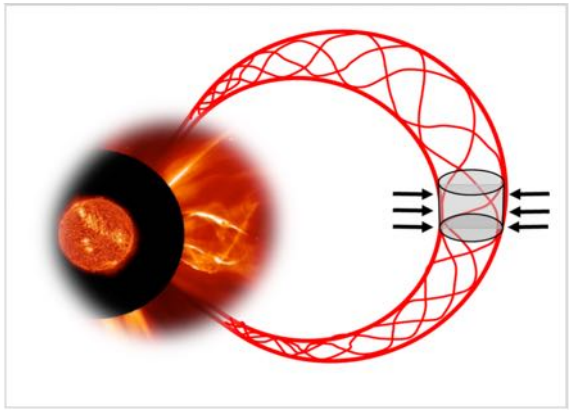

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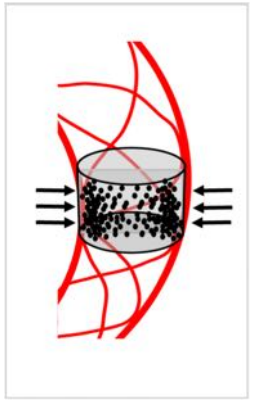

- expands self-similarly

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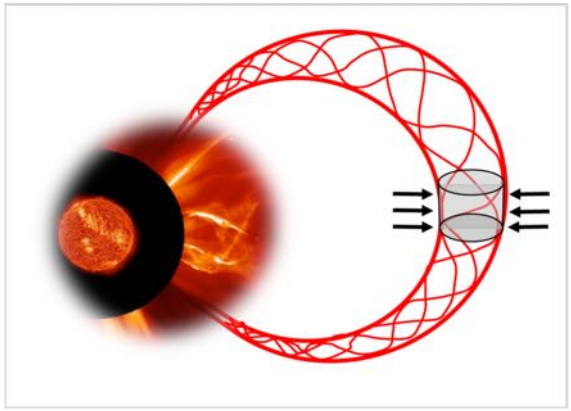

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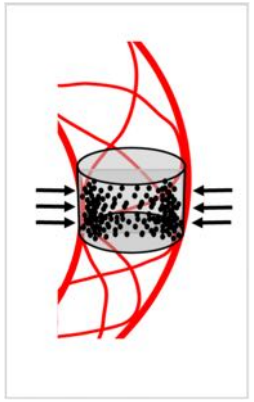

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$$U(r,t) = U_0 \left(1 - J_0(\alpha_1 r) \mathrm{e}^{-\alpha_1^2 f(t)} \right)$$

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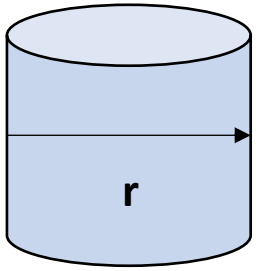
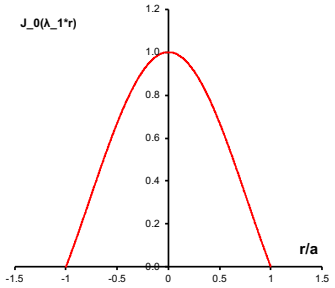
SPACE PART

TIME PART

Axial symmetry



Bessel function 0th order



Symmetric + normalized

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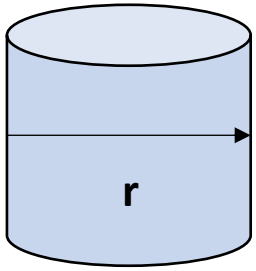

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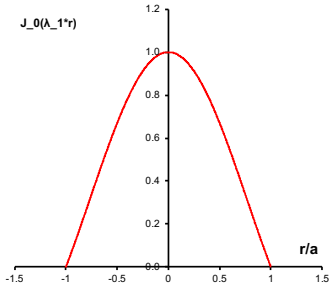

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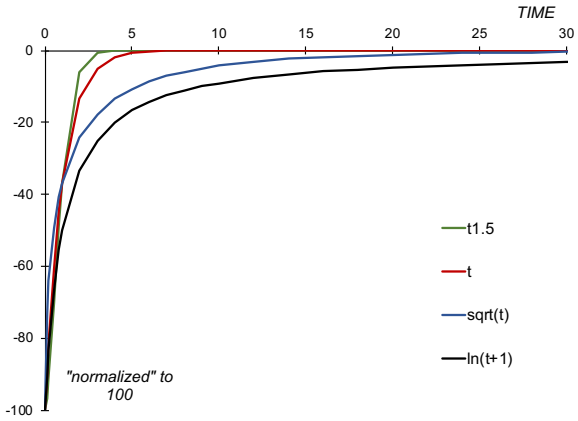

Exponential function of time

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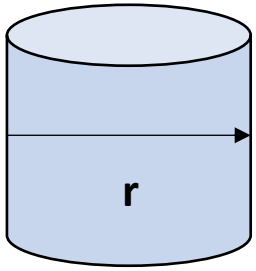

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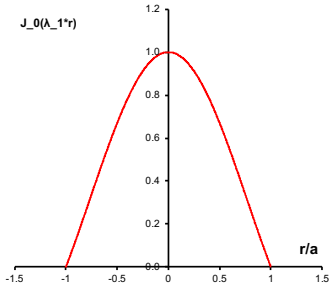

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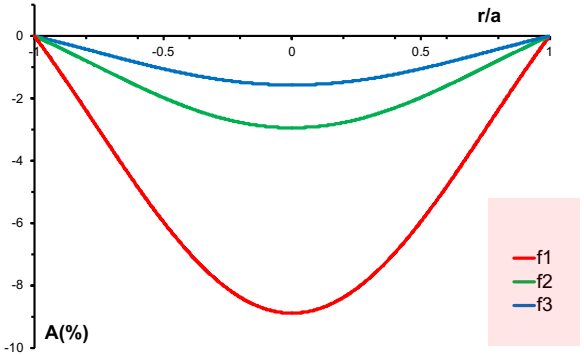

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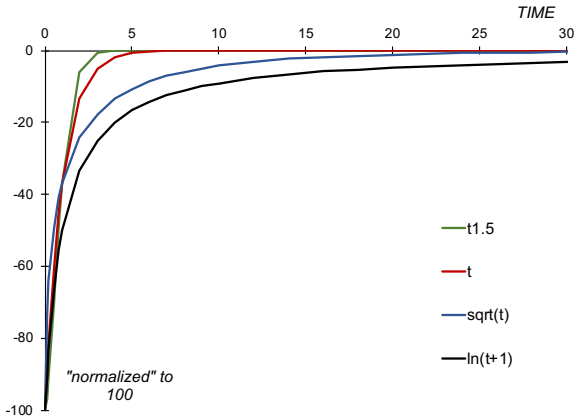

Exponential function of time

ForbMod = *analytical diffusion-expansion model for Forbush decreases caused by flux ropes*

$$f(t) = \int D(t)/a(t)^2 \mathrm{d}t$$

***ForbMod** = analytical diffusion-expansion model for Forbush decreases caused by flux ropes*

$$f(t) = \int D(t)/a(t)^2 \mathrm{d}t$$

$D \sim \frac{1}{B}$

$$B(t) = B_0 \left(\frac{R(t)}{R_0} \right)^{-n_B}$$

e.g. Demoulin, 2008, SolPhys

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$$a(t) = a_0 \left(\frac{R(t)}{R_0} \right)^{n_a}$$

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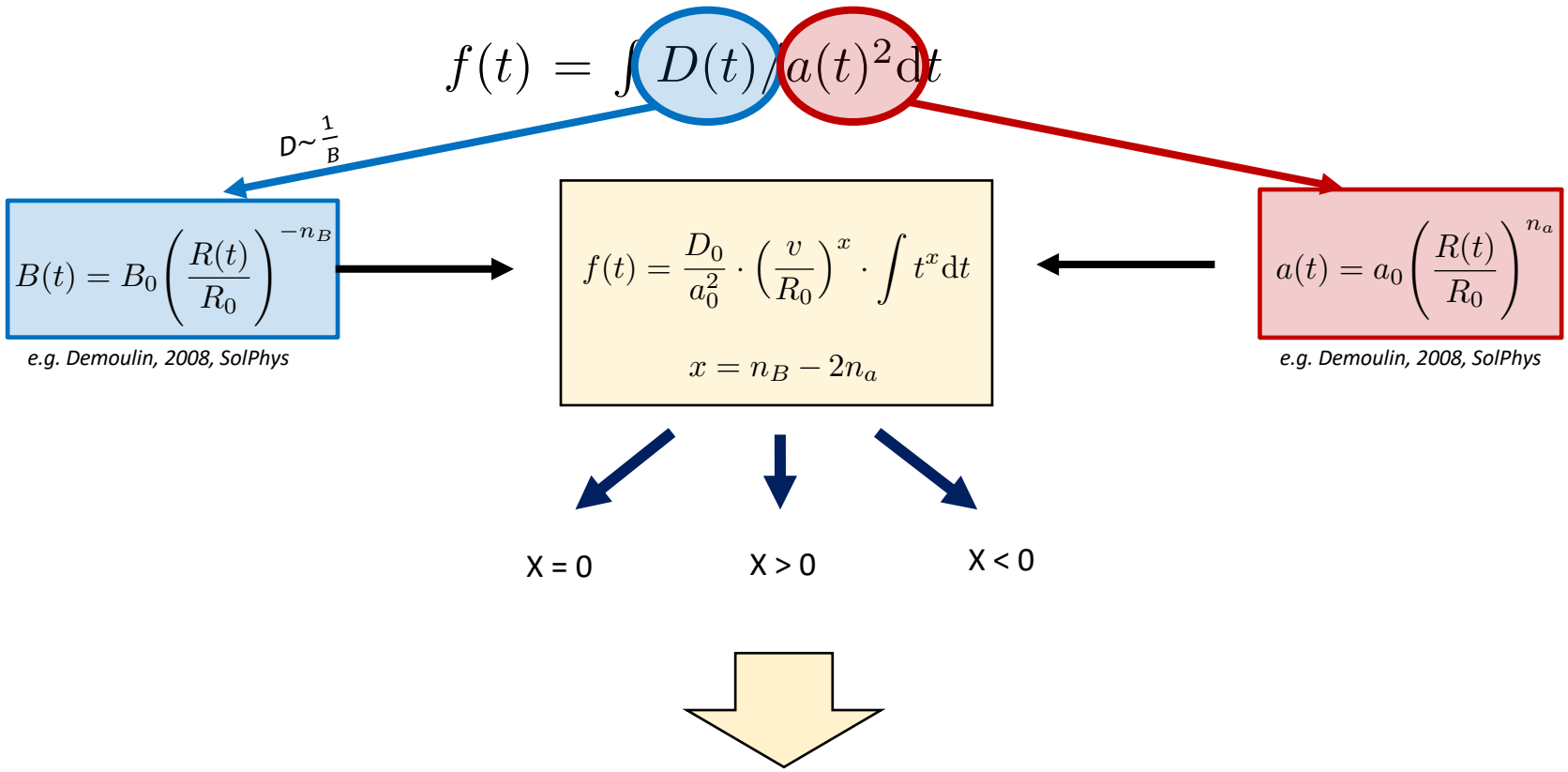

COMPETITION

BETWEEN CHANGE IN THE MAGNETIC FIELD

AND THE CHANGE IN THE SIZE

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CHANGE IN THE MAGNETIC FIELD

$$f(t) = \frac{D_0}{a_0^2} \cdot \left(\frac{v}{R_0} \right)^x \cdot \int t^x \mathrm{d}t$$

$$x = n_B - 2n_a$$

$$a(t) = a_0 \left(\frac{R(t)}{R_0} \right)^{n_a}$$

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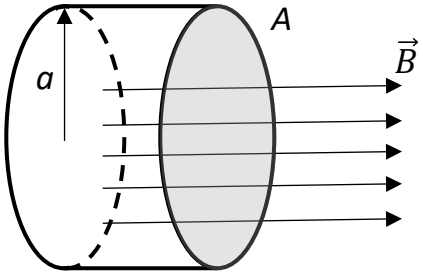
CHANGE IN THE SIZE



$$\phi = B \cdot A \qquad (A \sim a^2)$$

$$\phi \sim R^{2n_a - n_B}$$

$$\phi \sim R(t)^{-x}$$

MAGNETIC FLUX

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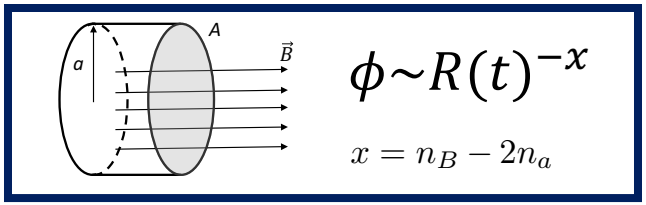
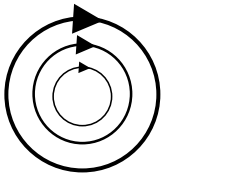


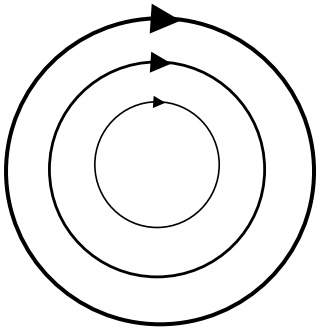
MAGNETIC FLUX

X = 0
(magnetic flux conserved)



$\phi 1 = \phi 2$

Increase in A countered by the decrease in B



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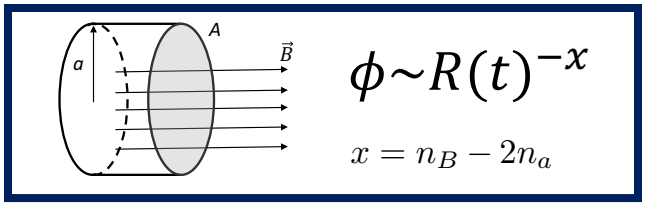

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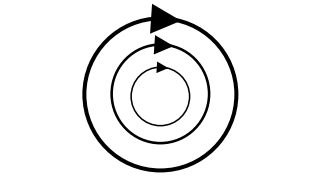

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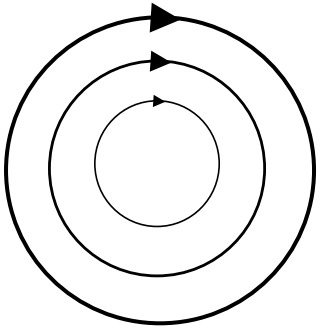
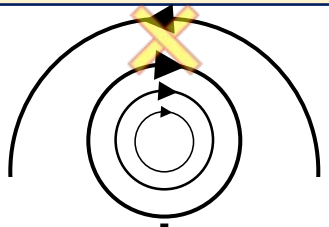
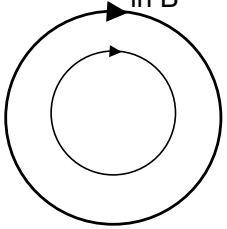


X > 0
(magnetic flux decreased)



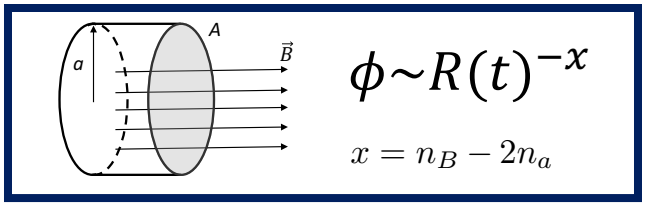
$\phi 1 > \phi 2$

Increase in A slow compared to the decrease in B



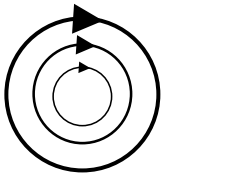
X = 0.5
(based on *Gulisano+, 2010, A&A*)

***ForbMod** = analytical diffusion-expansion model for Forbush decreases caused by flux ropes*



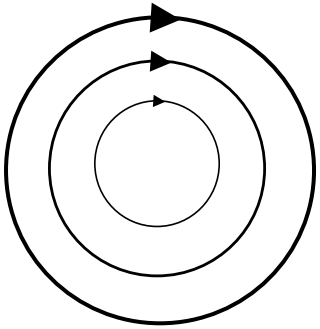
MAGNETIC FLUX

X = 0
(magnetic flux conserved)

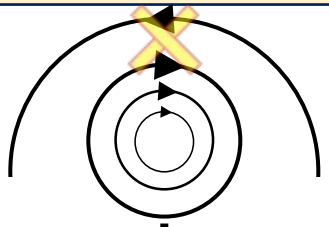


$\phi 1 = \phi 2$

Increase in A countered by the decrease in B

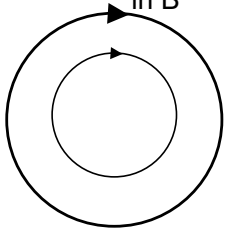


X > 0
(magnetic flux decreased)



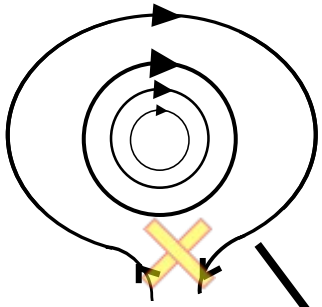
$\phi 1 > \phi 2$

Increase in A slow compared to the decrease in B



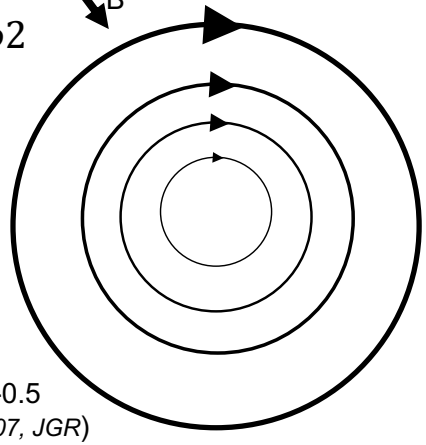
X = 0.5
(based on *Gulisano+, 2010, A&A*)

X < 0
(magnetic flux increased)



$\phi 1 < \phi 2$

Increase in A fast compared to the decrease in B

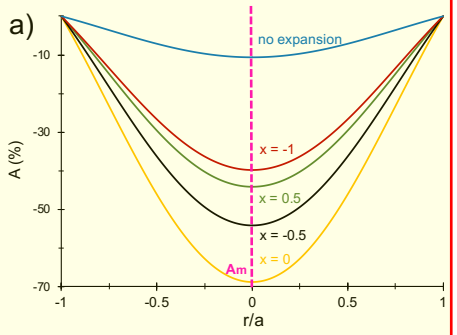


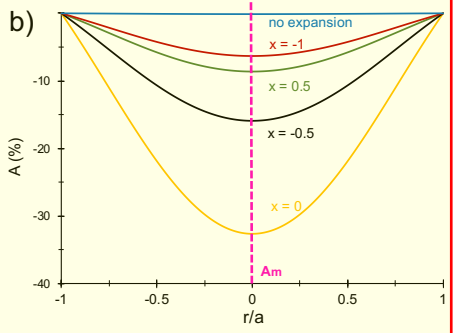
X = -0.5
(based on *Leitner+, 2007, JGR*)
Special case: x = -1 (integration→logarithmic)

Dumbovic+,2018,ApJ(submitted)

***ForbMod** = analytical diffusion-expansion model for Forbush decreases caused by flux ropes*

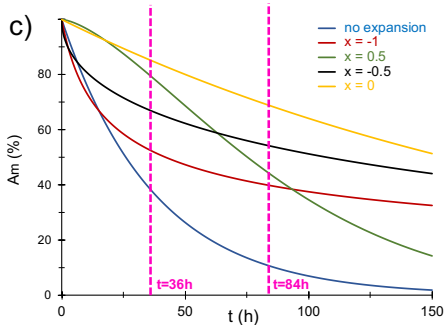
Radial profile

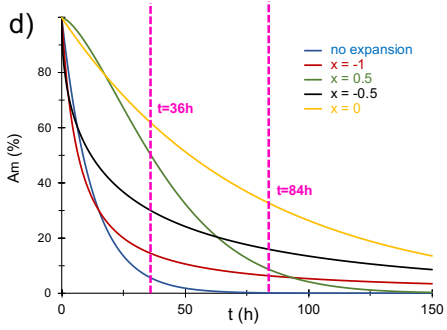




different D

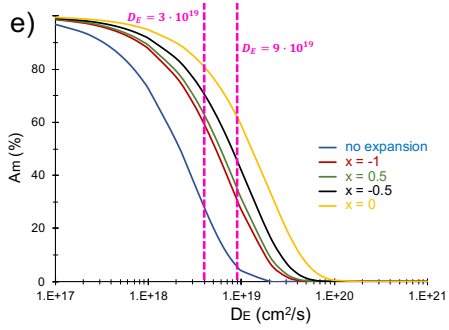
Time evolution

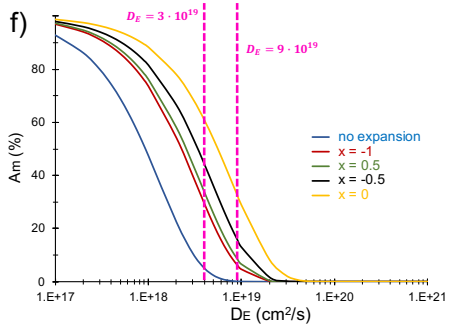




different D

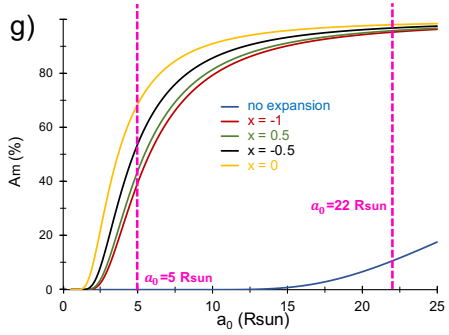
Dependence on D

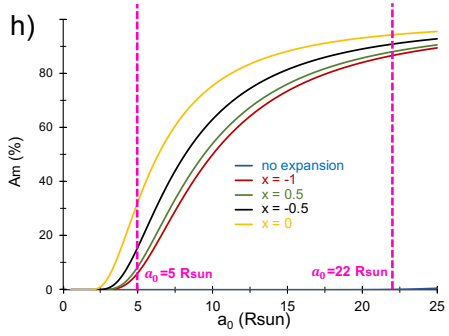




different T

Dependence on a



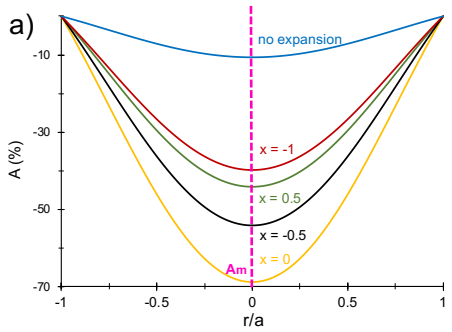


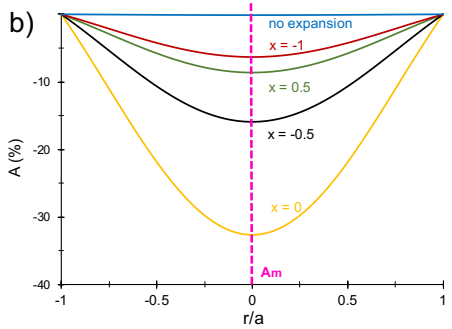
different D

Dumbovic+,2018,ApJ(submitted)

***ForbMod** = analytical diffusion-expansion model for Forbush decreases caused by flux ropes*

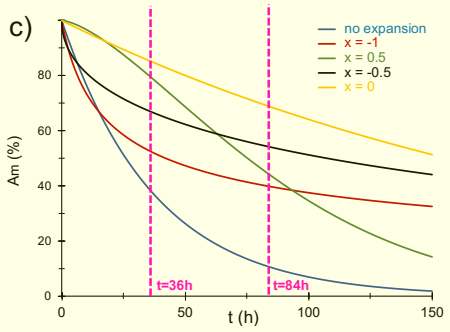
Radial profile

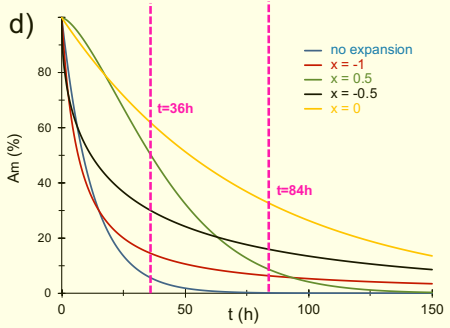




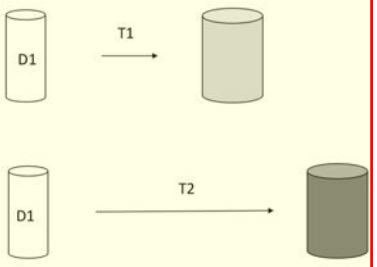
different D

Time evolution

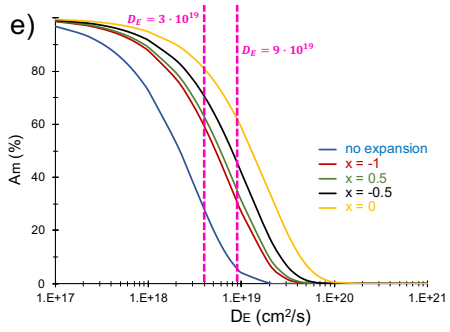


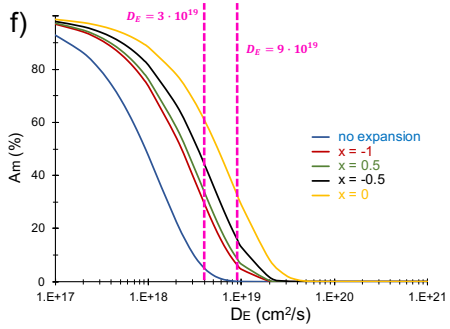


different D

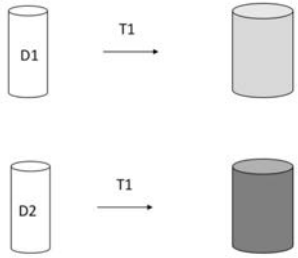


Dependence on D

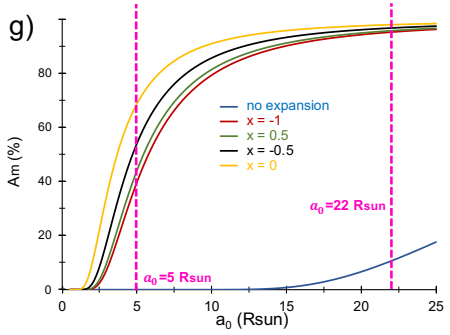


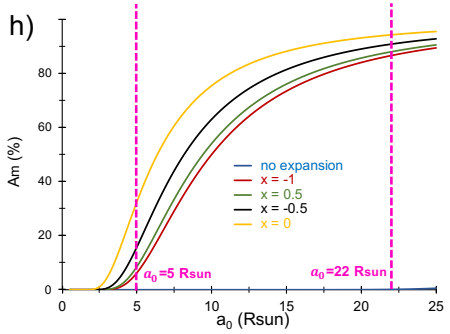


different T

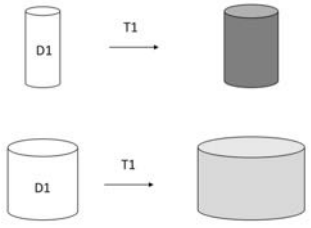


Dependence on a





different D



COMPLEX INTERPLAY OF DIFFUSION AND EXPANSION

Dumbovic+,2018,ApJ(submitted)

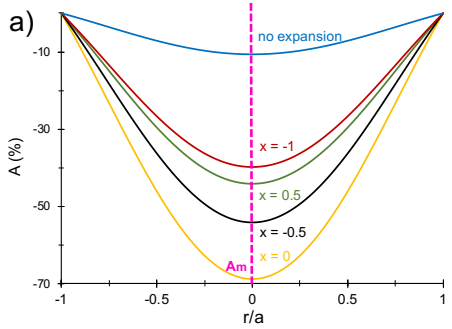
***ForbMod** = analytical diffusion-expansion model for Forbush decreases caused by flux ropes*

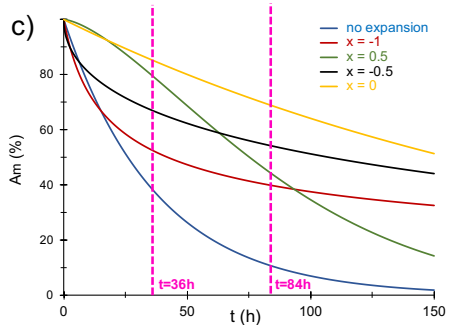
Radial profile

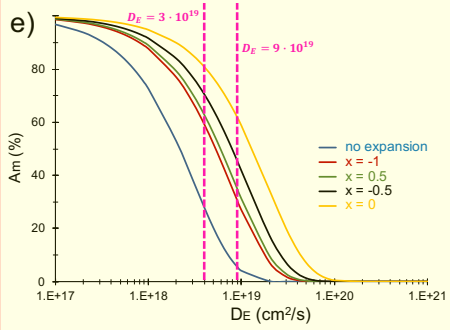
Time evolution

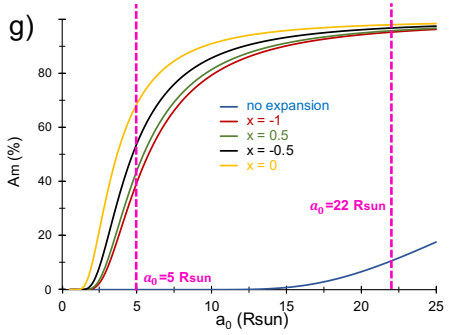
Dependence on D

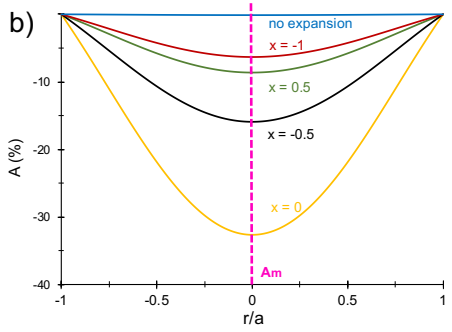
Dependence on a

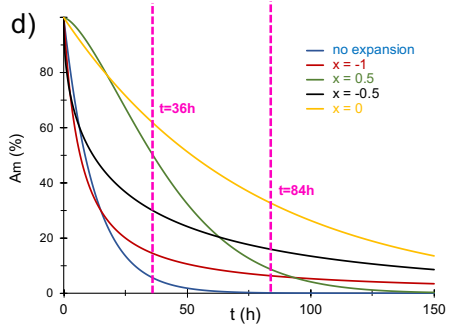


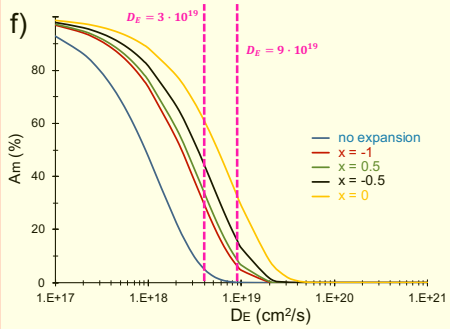


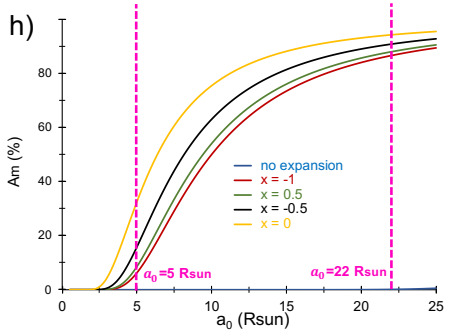












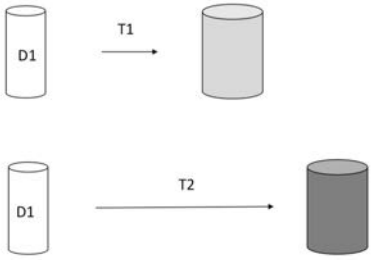
different D

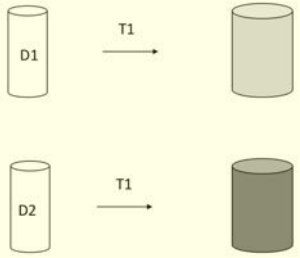
different D

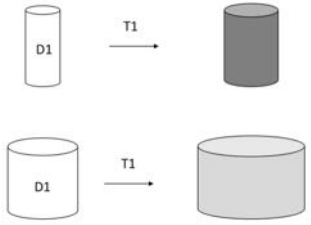
different T

different D

COMPLEX INTERPLAY OF DIFFUSION AND EXPANSION

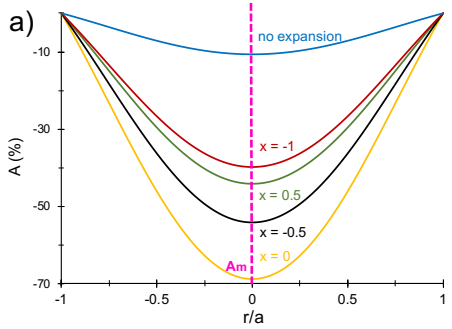


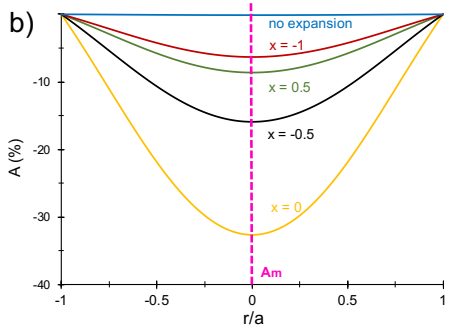




***ForbMod** = analytical diffusion-expansion model for Forbush decreases caused by flux ropes*

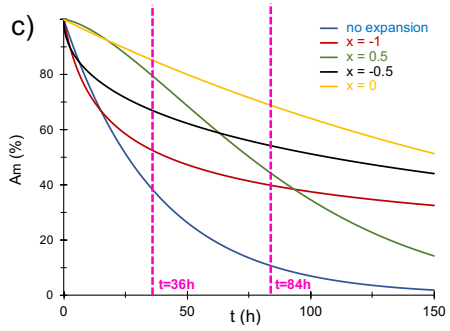
Radial profile

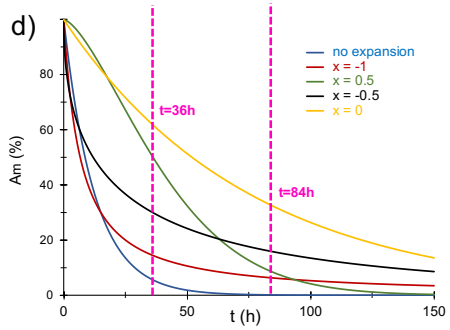




different D

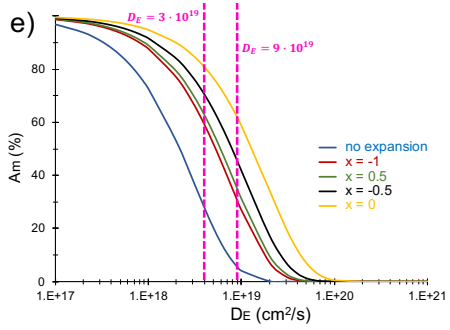
Time evolution

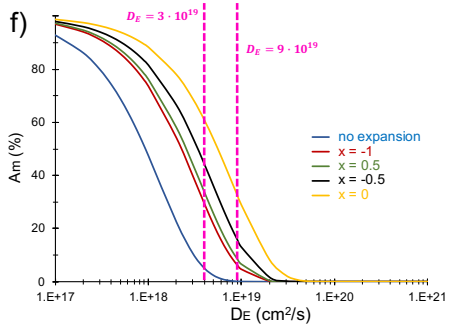




different D

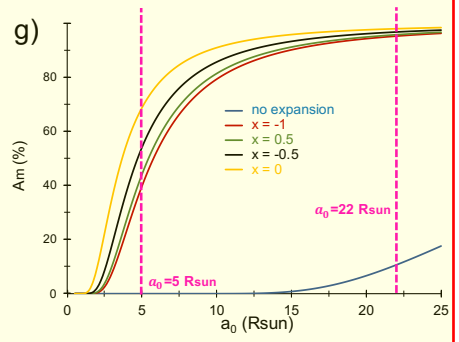
Dependence on D

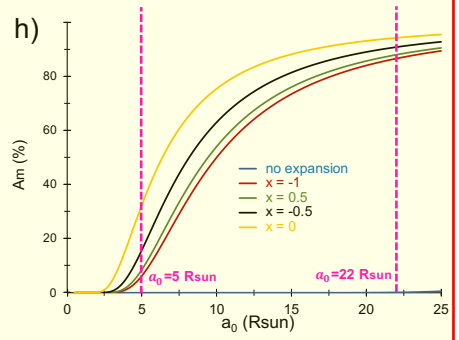




different T

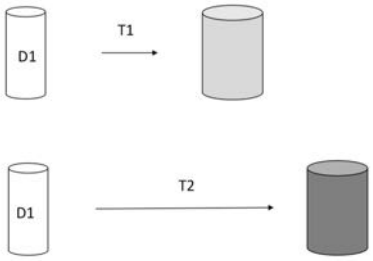
Dependence on a

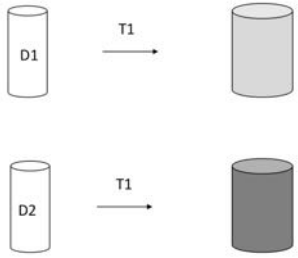


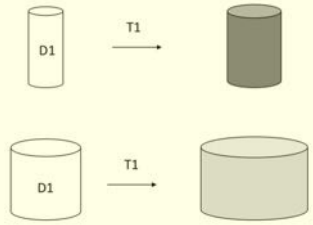


different D

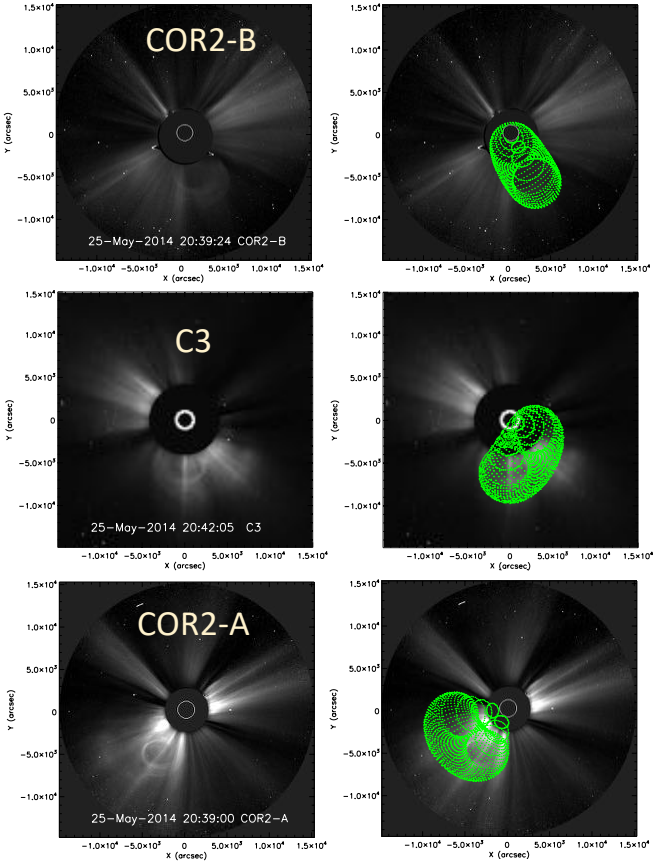
COMPLEX INTERPLAY OF DIFFUSION AND EXPANSION



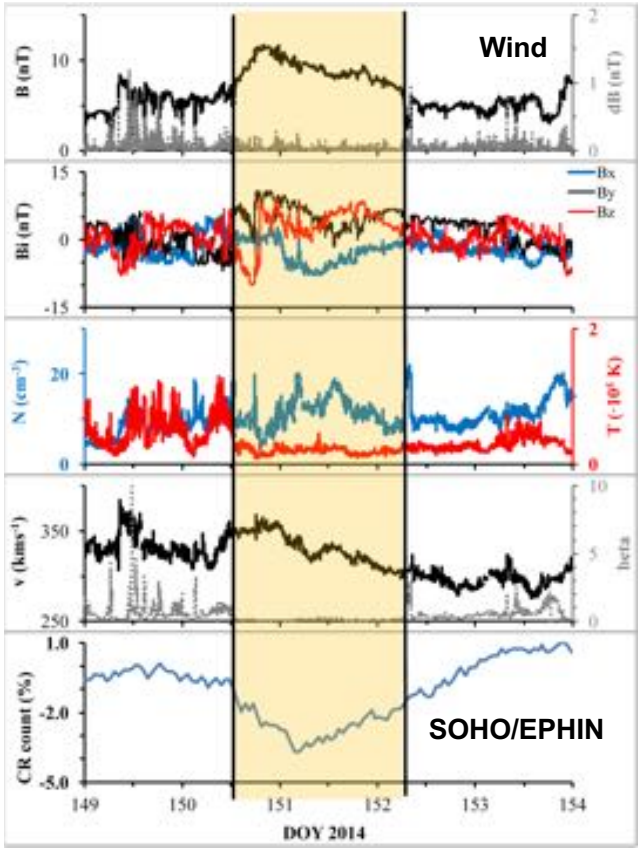




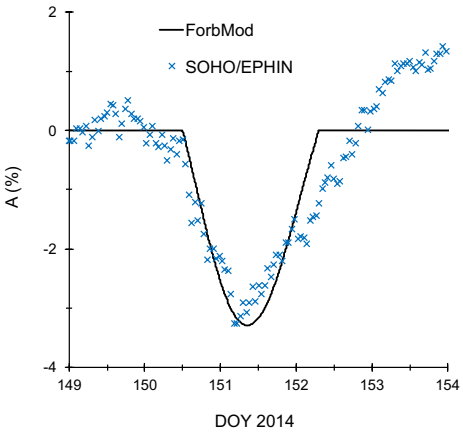
THE CASE STUDY – TEST EVENT



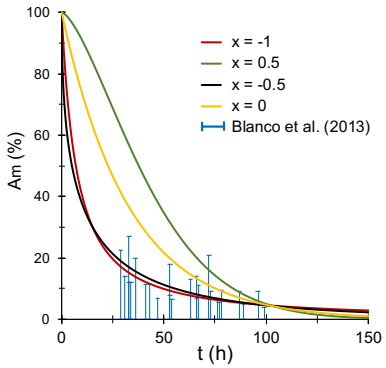
CME: 2014 May 25



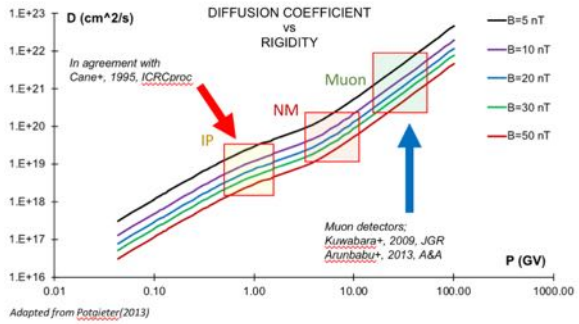
ICME & FD: 2014 May 30



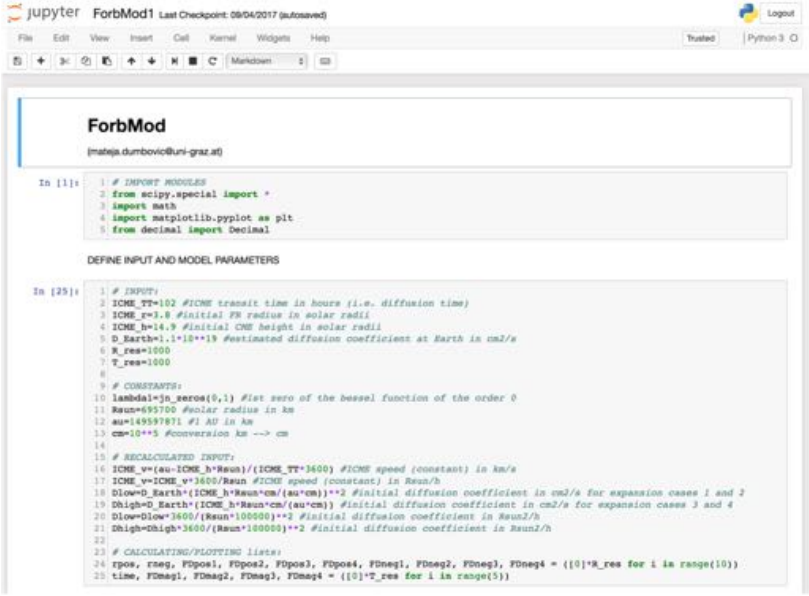
BEST FIT
(diffusion coefficient free parameter)



TIME EVOLUTION
model compared to observations from a statistical study by Blanco+, 2013
(error bars = possible ejecta only FD range)



Dumbovic+,2018,ApJ(submitted)



CONCLUSIONS & FUTURE WORK

- *ForbMod* is analytical diffusion-expansion model for ejecta-only FDs
- FD amplitude depends on the interplay of diffusion and expansion
- Qualitatively agrees with observation
- Case study indicates quantitative agreement

- **NEXT STEPS: testing and constraints using statistics, FR forward modeling and multispacecraft measurements**

Thank you for your attention!

Acknowledgements:

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 745782.