Forbush decrease model for expanding CMEs (ForbMod)

Mateja Dumbović

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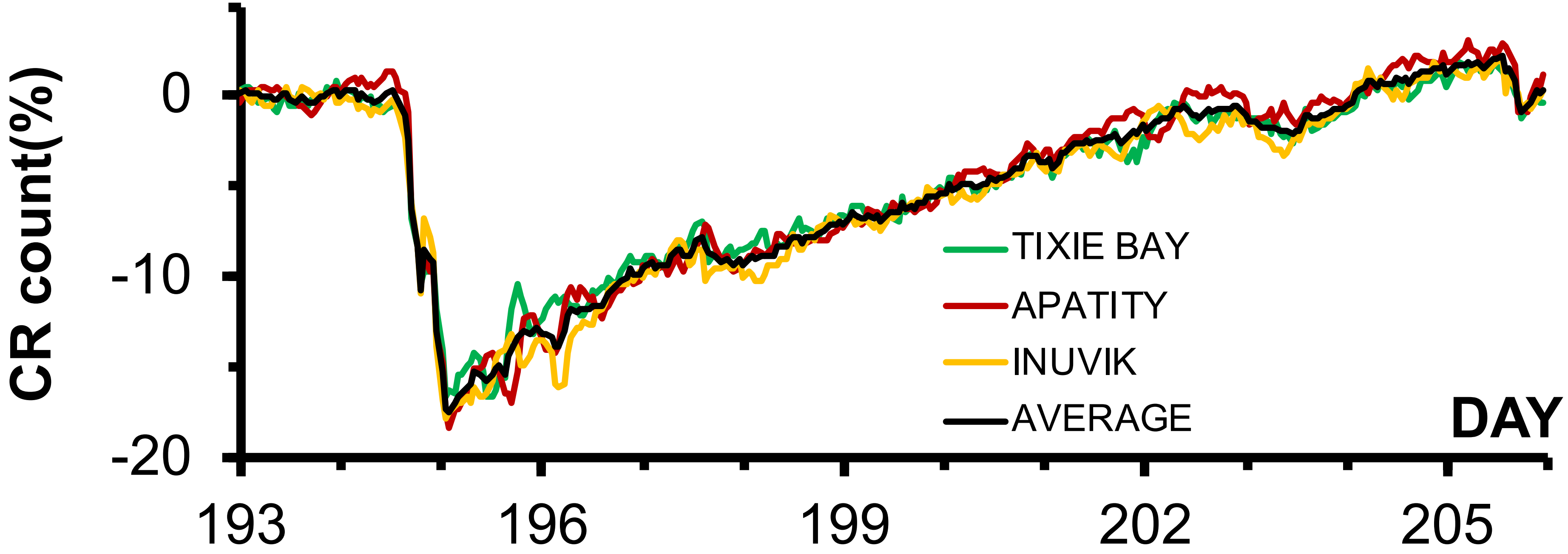
What are Forbush decreases?

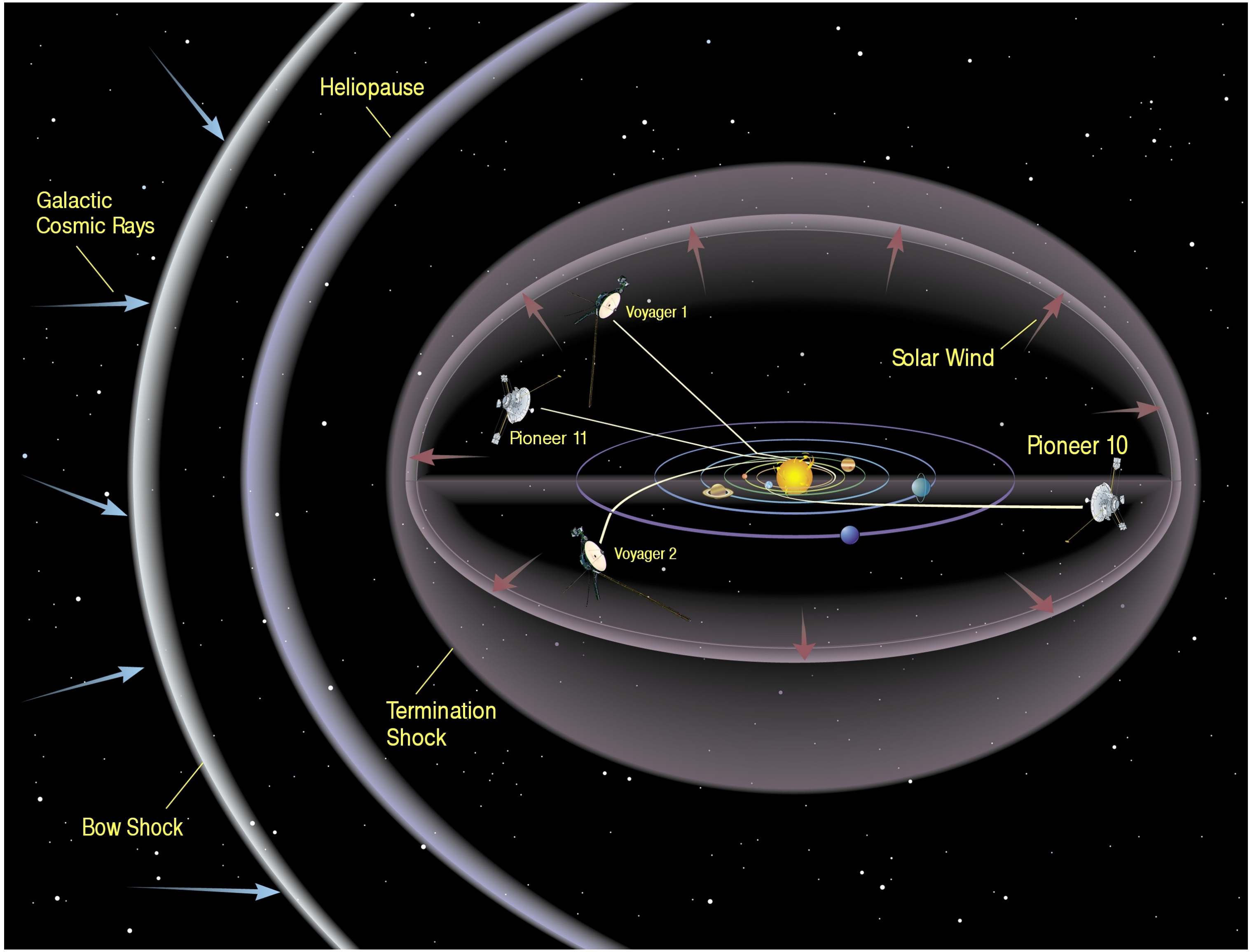


Dumbovic PhD thesis,2015

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)

Cosmic rays in Heliosphere – in general

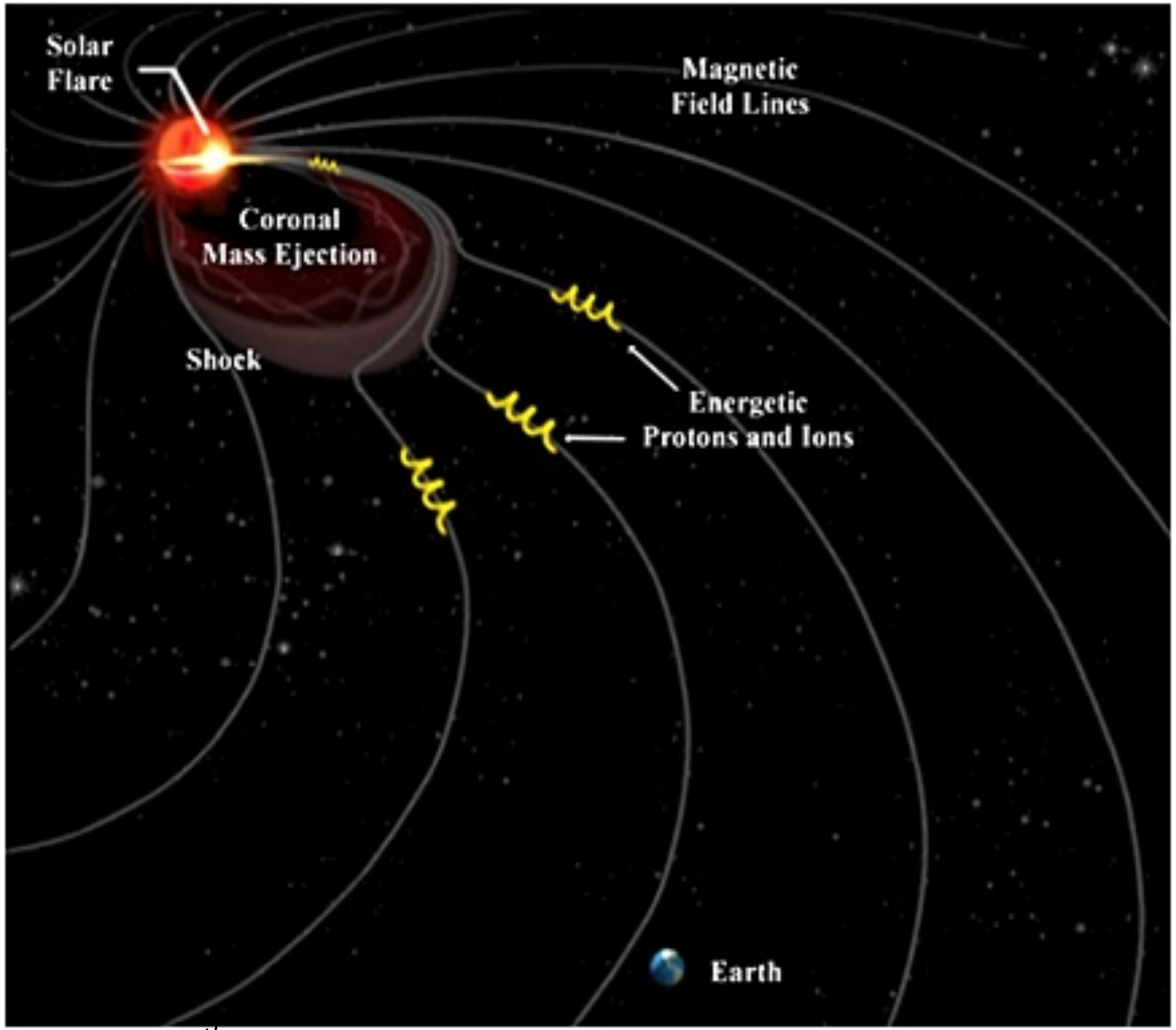


www.nasa.gov

THREE COMPONENTS:

1) Galactic cosmic rays

Cosmic rays in Heliosphere – in general



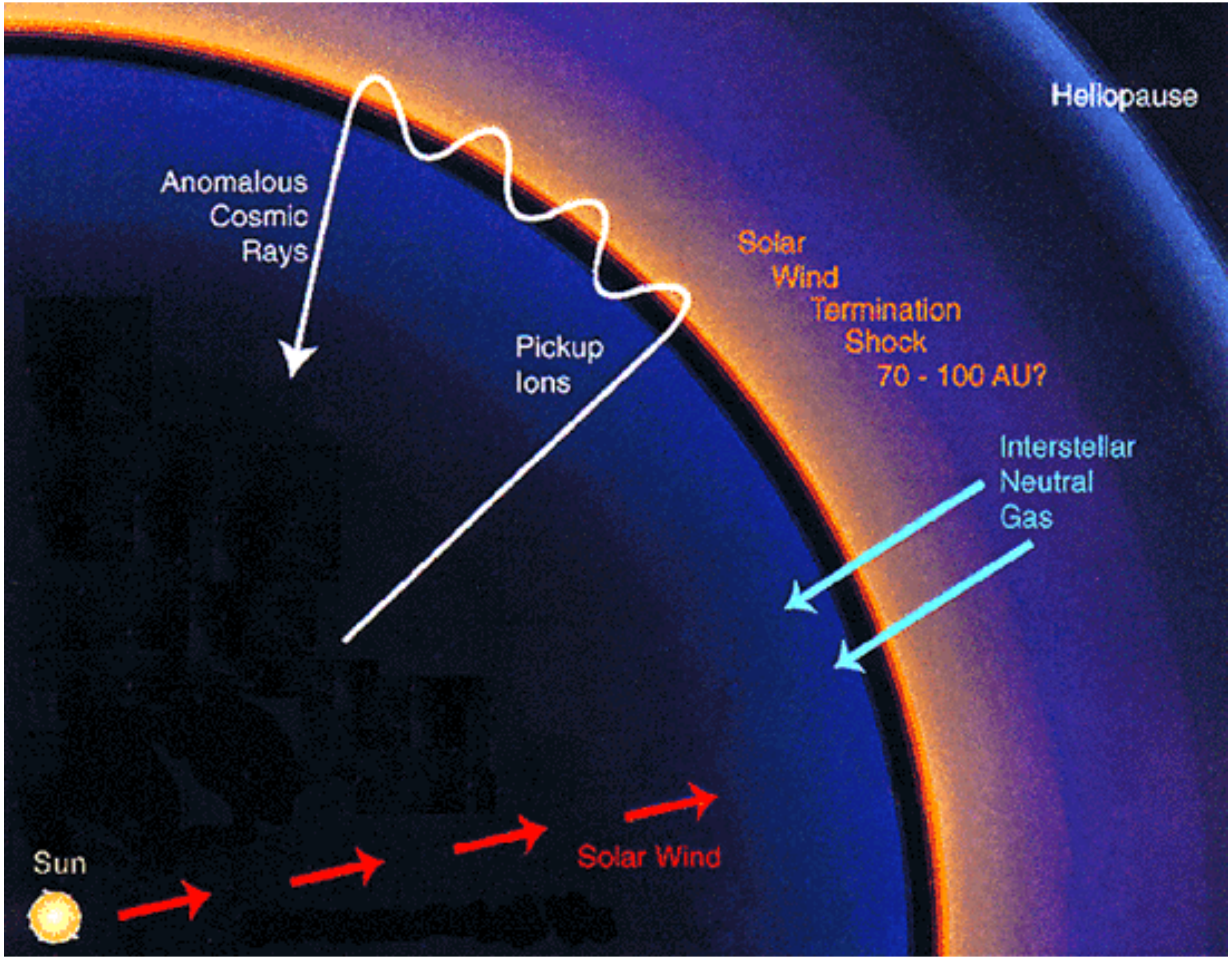
www.spaceweather.uma.es

THREE COMPONENTS:

1) Galactic cosmic rays

2) Solar cosmic rays (solar eneregetic particles, SEPs)

Cosmic rays in Heliosphere – in general



www.nasa.gov

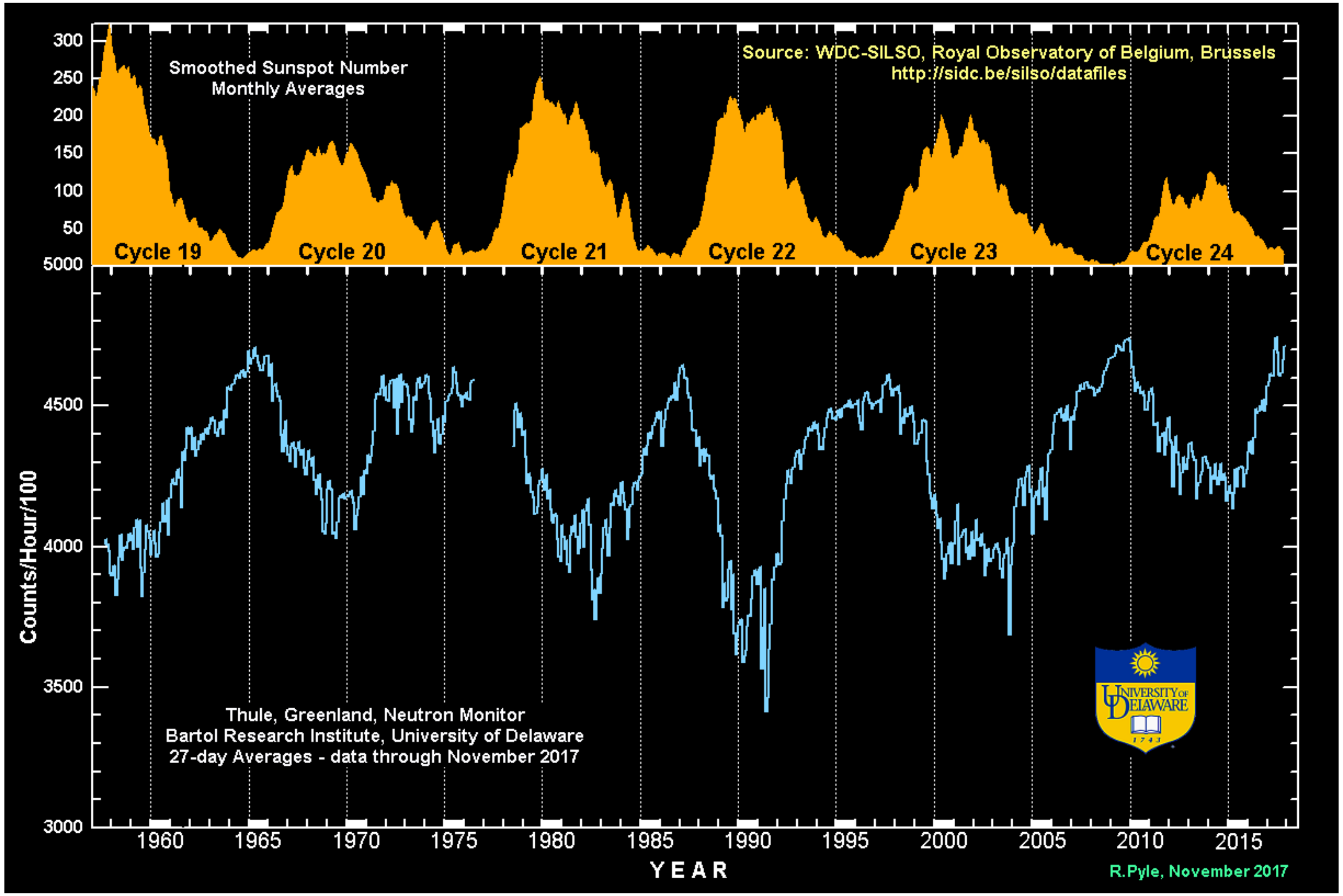
THREE COMPONENTS:

1) Galactic cosmic rays

2) Solar cosmic rays (solar eneregetic particles, SEPs)

3) Anomalous cosmic rays

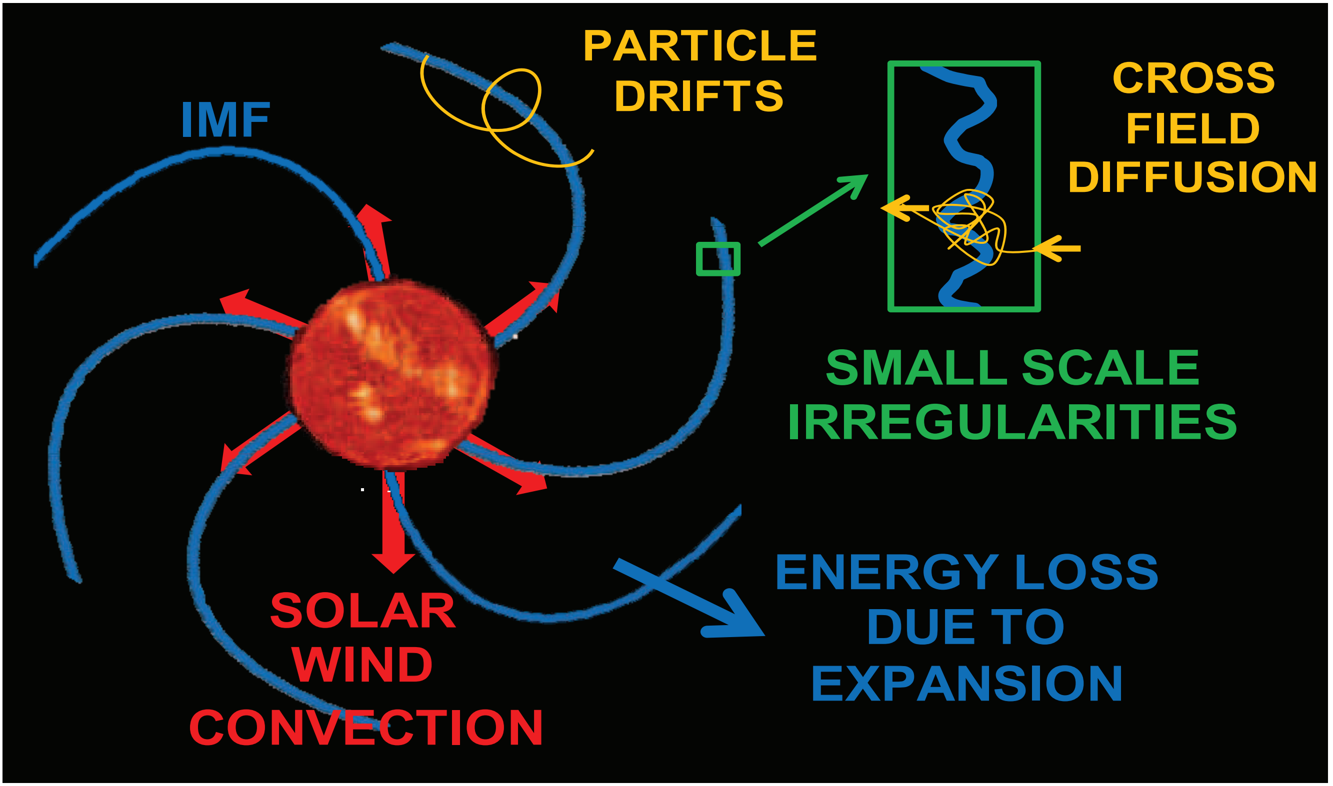
Modulation of Galactic Cosmic Rays (GCRs) in Heliosphere



GCR flux anticorrelated with solar activity

www.neutron.bartol.udel.edu

Modulation of Galactic Cosmic Rays (GCRs) in Heliosphere



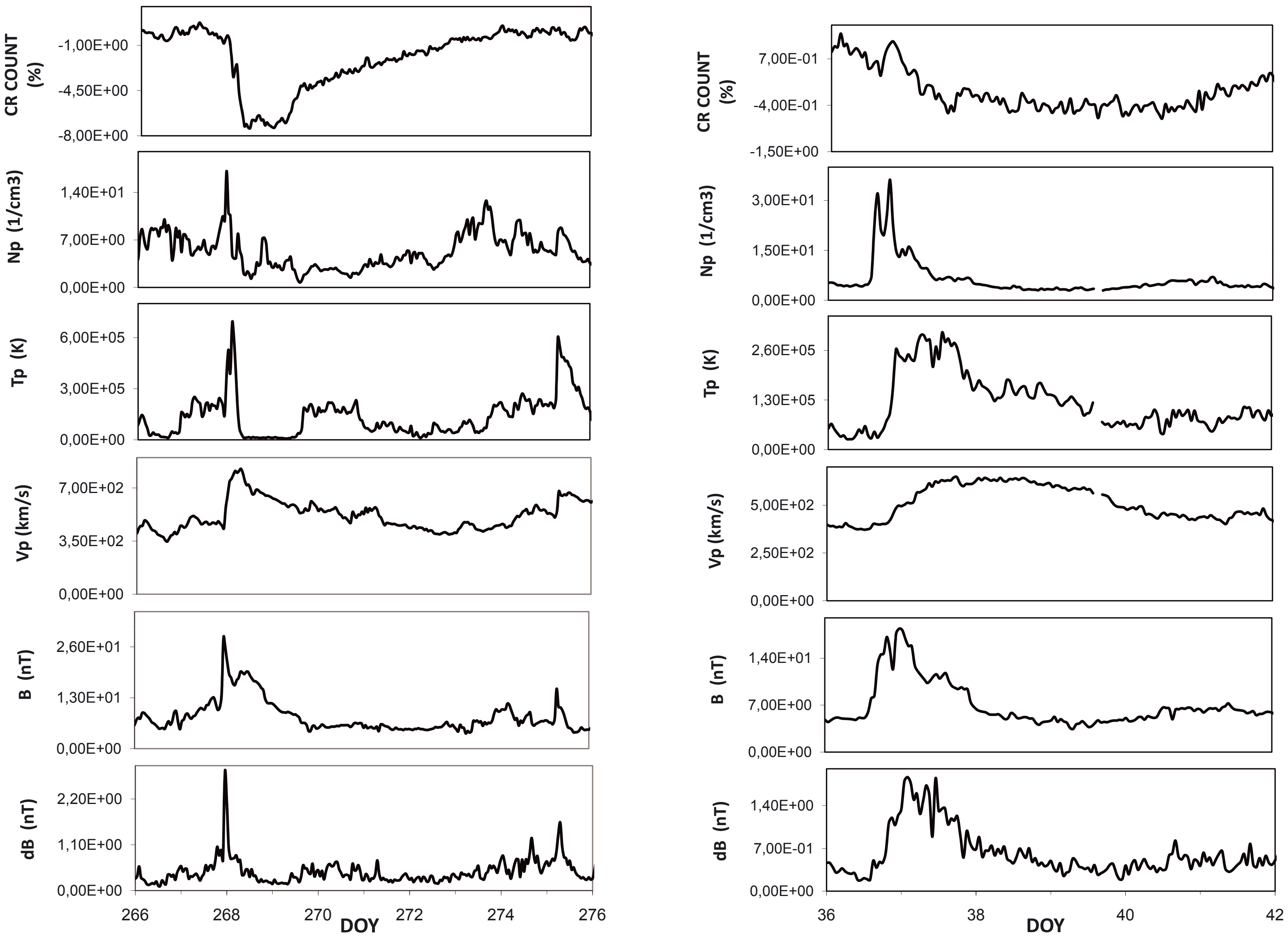
Dumbovic PhD thesis,2015

Parker, 1965

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

- a → GCR distribution function F(P,t,r)
- b → convection
- c → drifts
- d → diffusion
- e → Adiabatic cooling

What causes Forbush decreases?



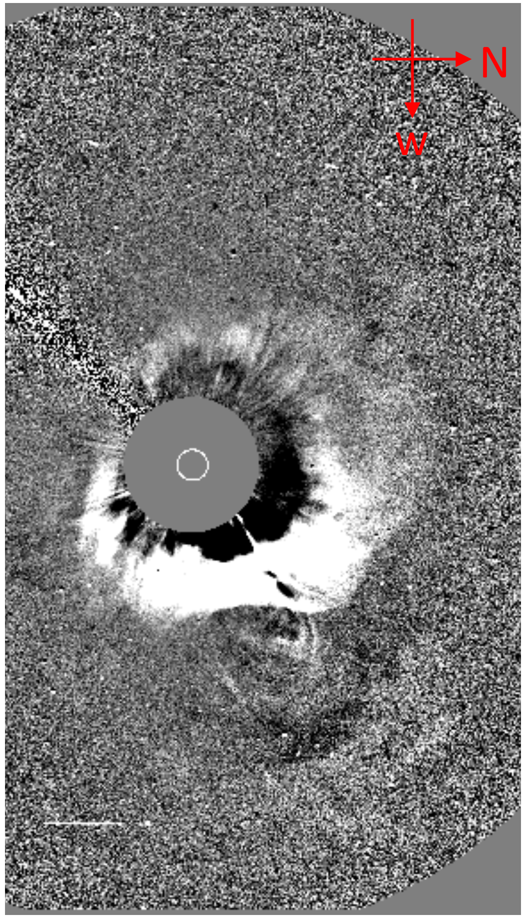
Dumbovic+,2012

Various shapes and sizes

Various interplanetary transients

Forbush decreases caused by Interplanetary Coronal Mass Ejections (ICMEs)

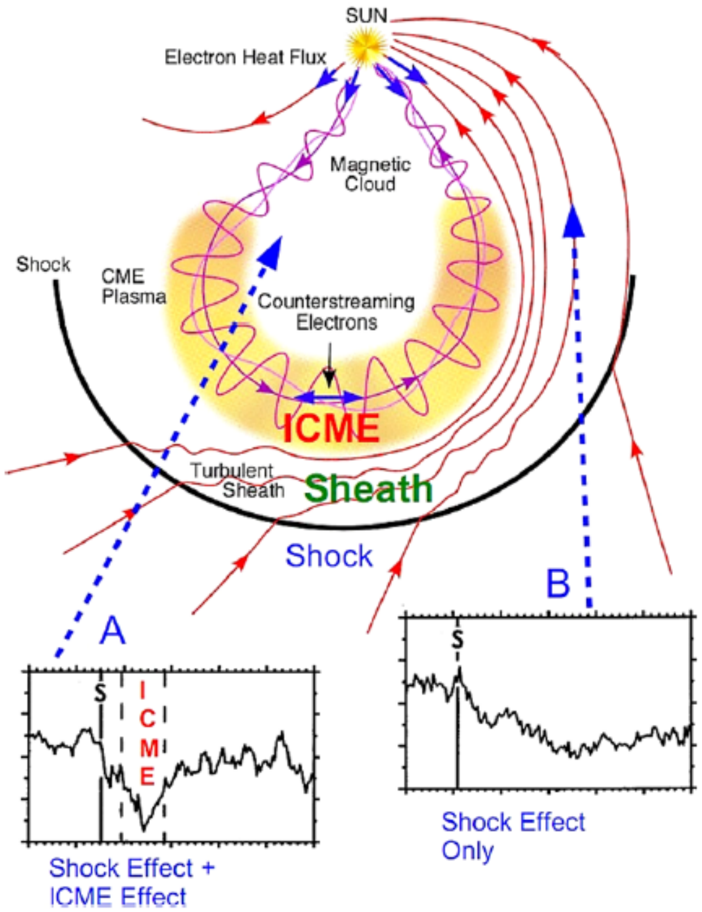
REMOTE OBSERVATION



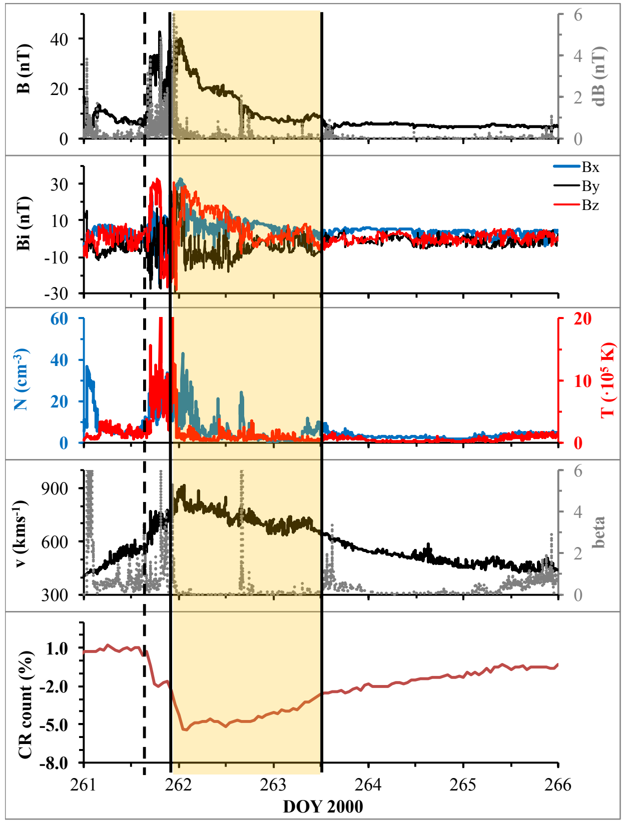
CME in SOHO/LASCO C3
2000 September 16 06:18 UT
First C2 detection at 05:18

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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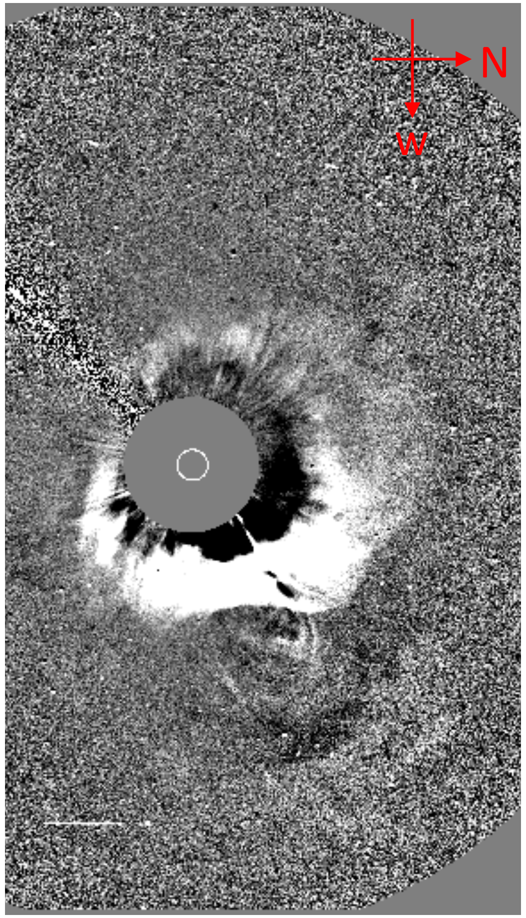

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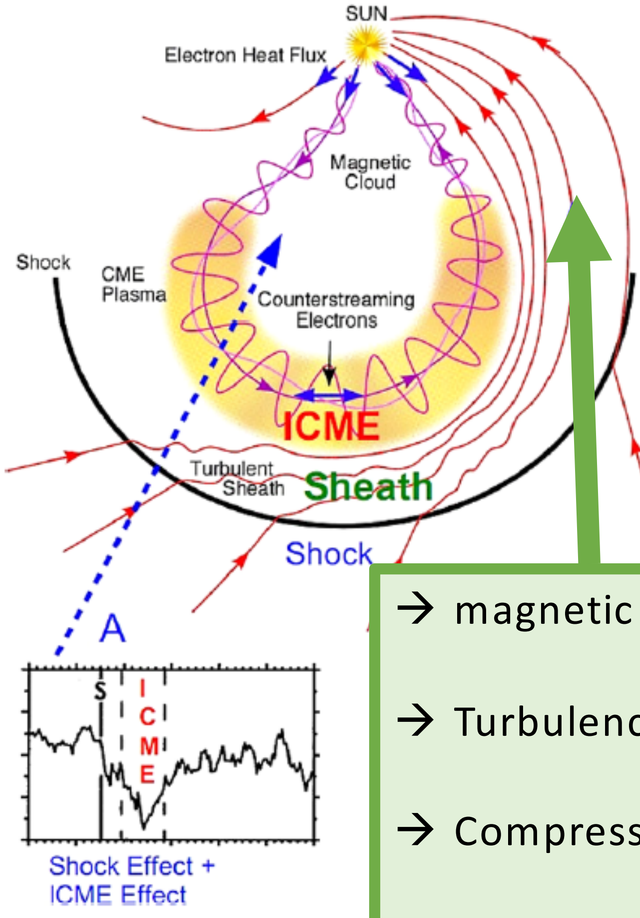
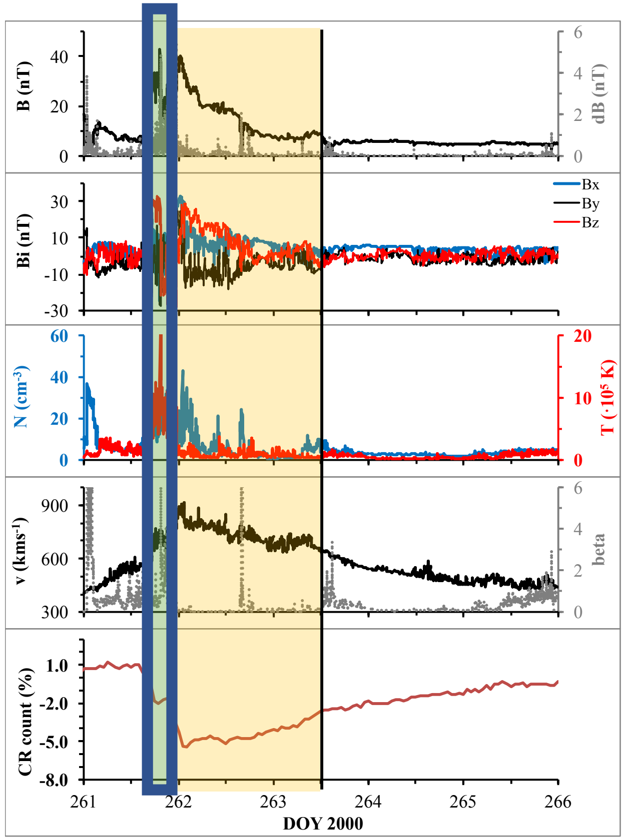


SHOCK-effect

- → magnetic connectivity
- → Turbulence
- → Compression
- → Prolonged effect

IN SITU MEASUREMENTS



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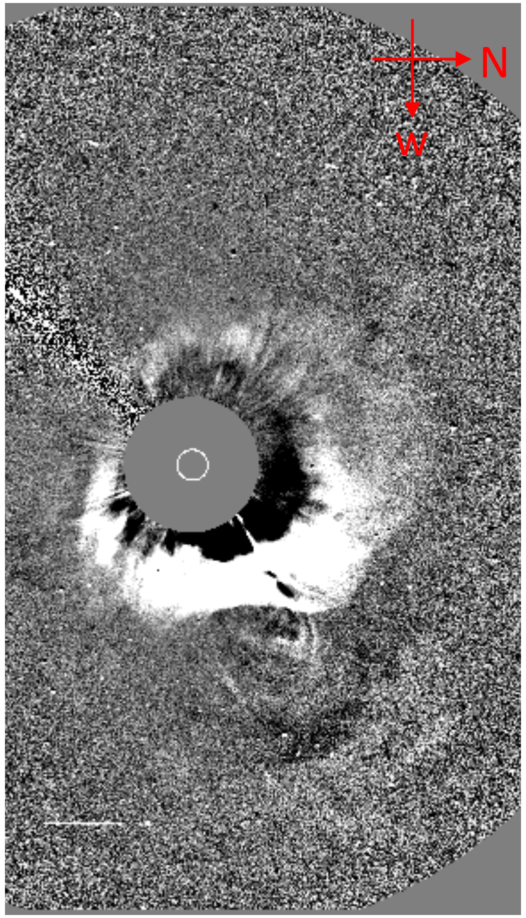

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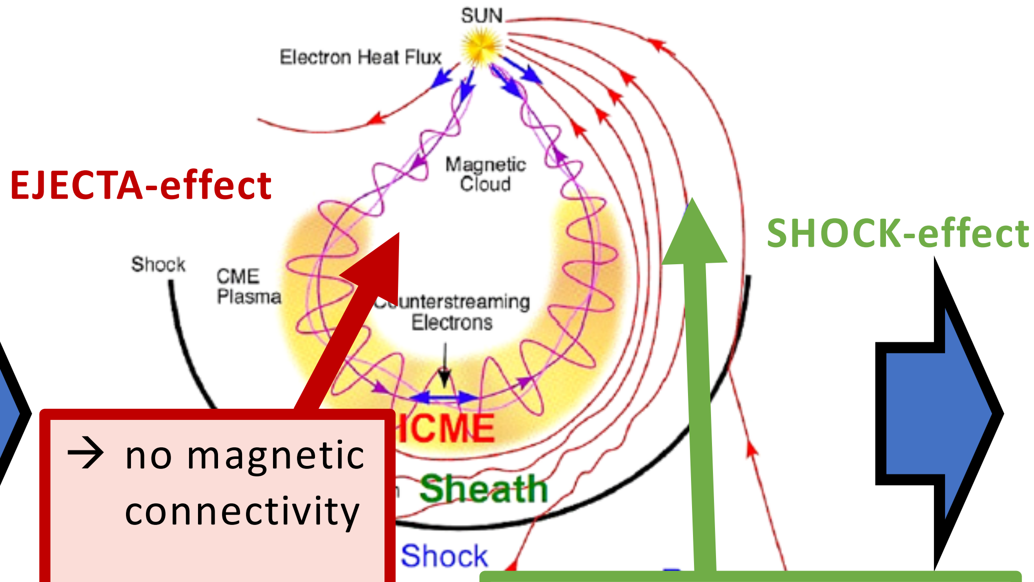


→ no magnetic connectivity

→ Smooth & strong field

→ Timespan limited to ICME

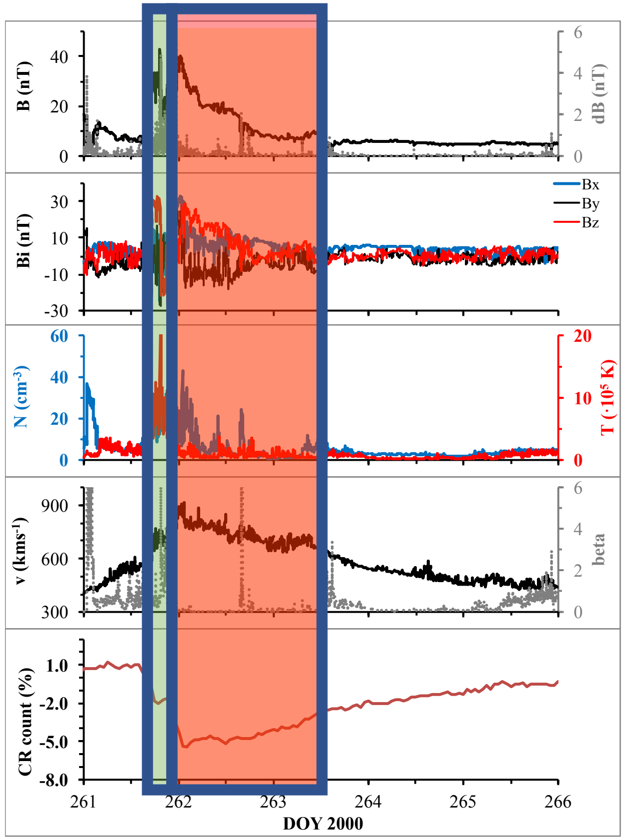
→ magnetic connectivity

→ Turbulence

→ Compression

→ Prolonged effect

IN SITU MEASUREMENTS



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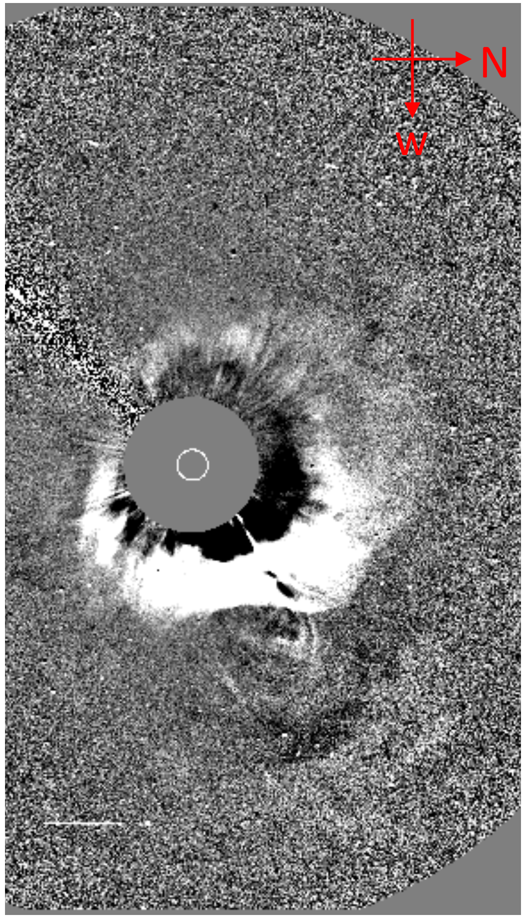

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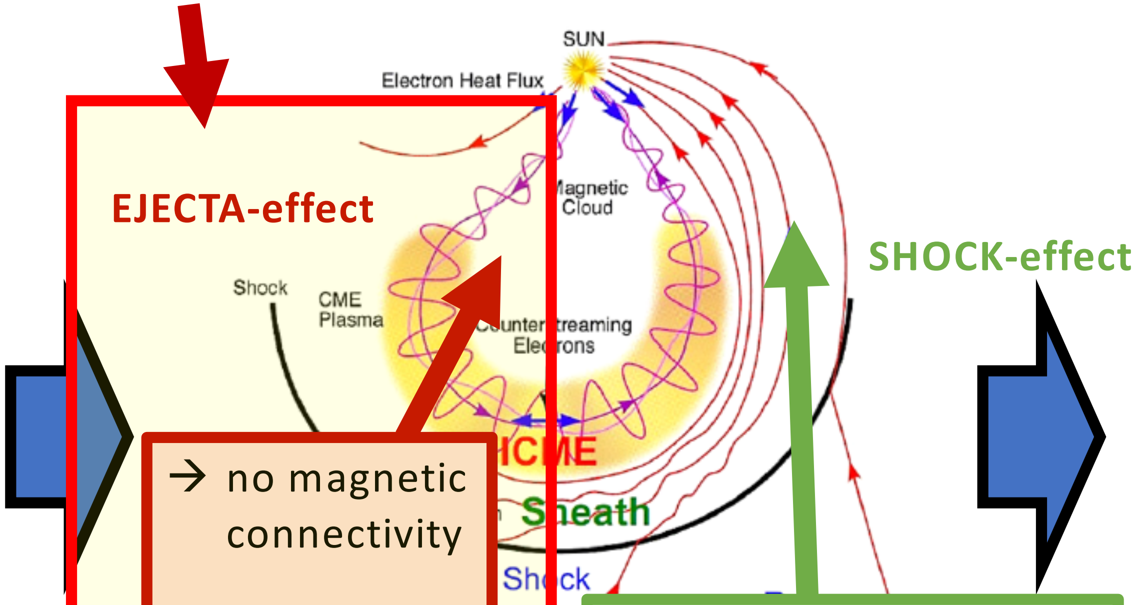
VISUALISATION

ForbMod

Adapted from Richardson & Cane (2011)



EJECTA-effect

- → no magnetic connectivity
- → Smooth & strong field
- → Timespan limited to ICME

SHOCK-effect

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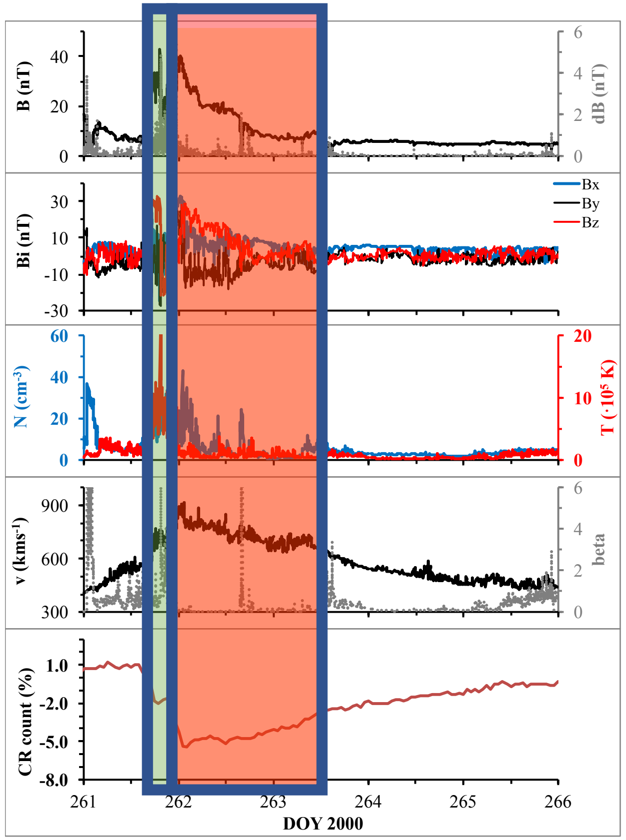
- → Turbulence
- → Compression
- → Prolonged effect

IN SITU MEASUREMENTS



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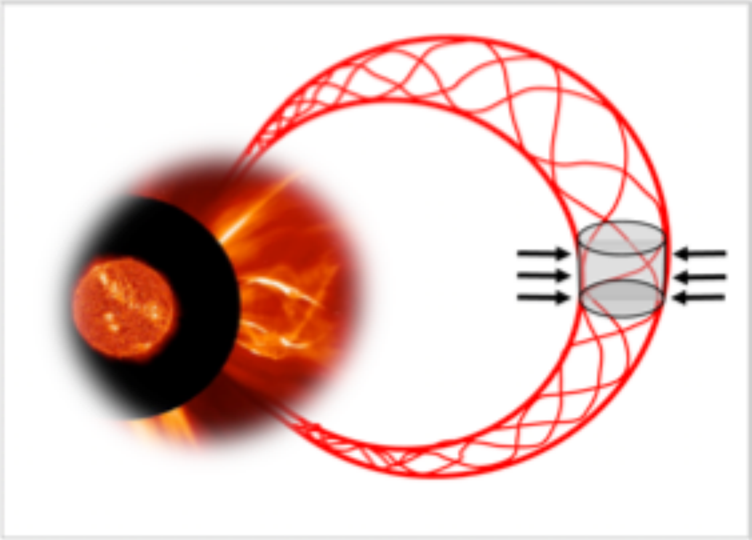
ForbMod = *analytical diffusion-expansion model for Forbush decreases caused by flux ropes*



magnetic ejecta
(ICME, magnetic cloud, flux rope)

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

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

First proposed by Morrison, 1956, PhysRev

Dumbovic+(inPrep)

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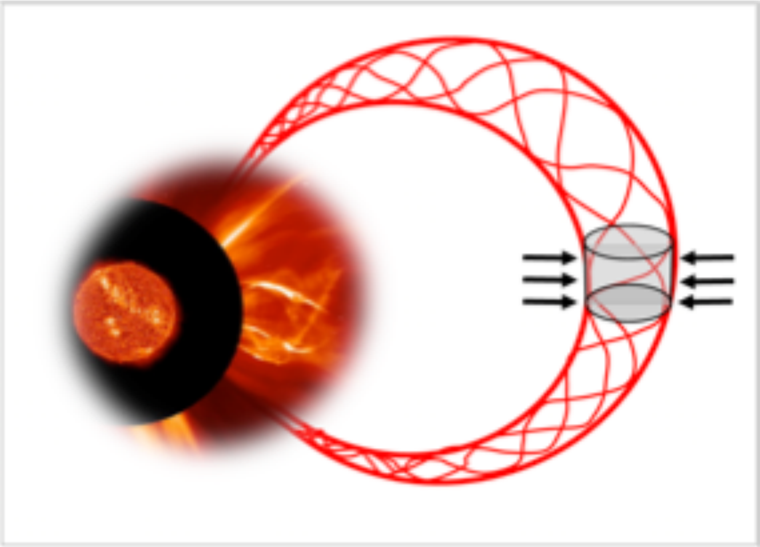

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diffusion-only
(after time *t*)

- does not vary in shape or size
- particles enter by perpendicular diffusion and slowly fill the structure

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

r=r; a=const.; D=const.

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

Dumbovic+(inPrep)

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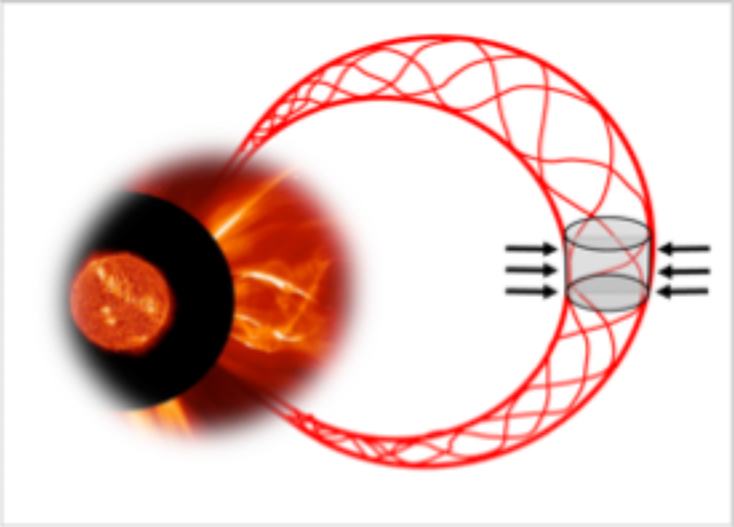

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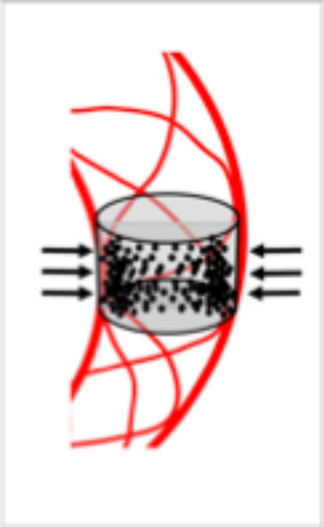

diffusion-expansion
(after time *t*)

- expands self-similarly
- particles enter by perpendicular diffusion and slowly fill the structure

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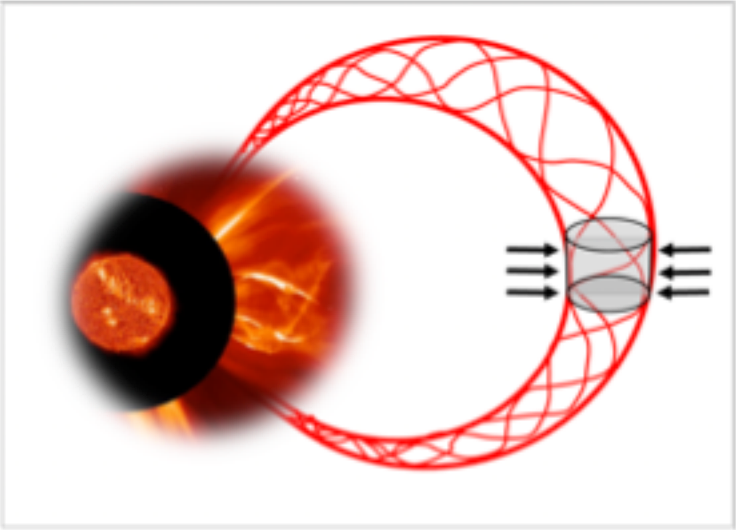

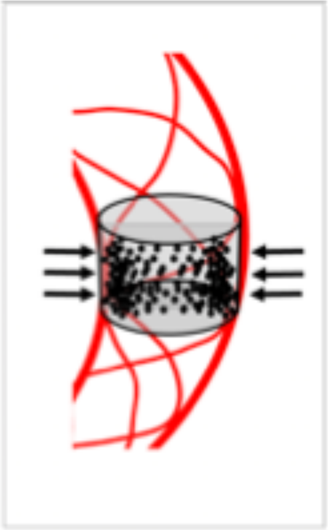

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Dumbovic+(inPrep)

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

Dumbovic+(inPrep)

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

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

e.g. Demoulin, 2008, SolPhys

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

$$x = n_B - 2n_a$$

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

e.g. Demoulin, 2008, SolPhys

COMPETITION

BETWEEN CHANGE IN THE MAGNETIC FIELD

AND THE CHANGE IN THE SIZE

Dumbovic+(inPrep)

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$$x = n_B - 2n_a$$

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

e.g. Demoulin, 2008, SolPhys

X = 0

X > 0

X < 0

Physical explanation?

Dumbovic+(inPrep)

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

D~1/B

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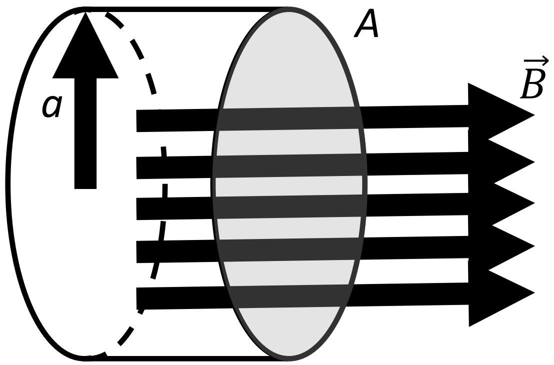
CHANGE IN THE MAGNETIC FIELD

CHANGE IN THE SIZE

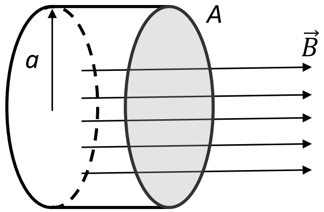


$$\phi = B \cdot A \qquad (A \sim a^2)$$

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

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

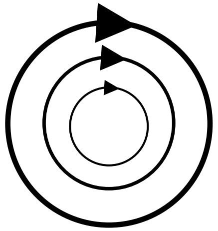
Dumbovic+(inPrep)



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

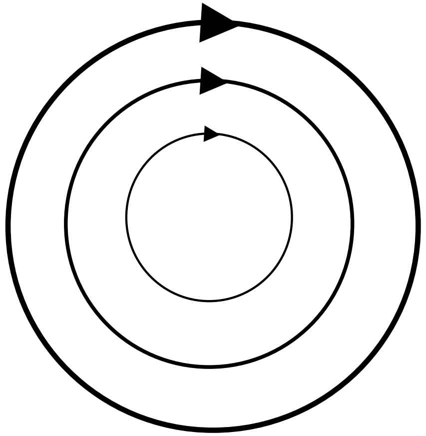
$$x = n_B - 2n_a$$

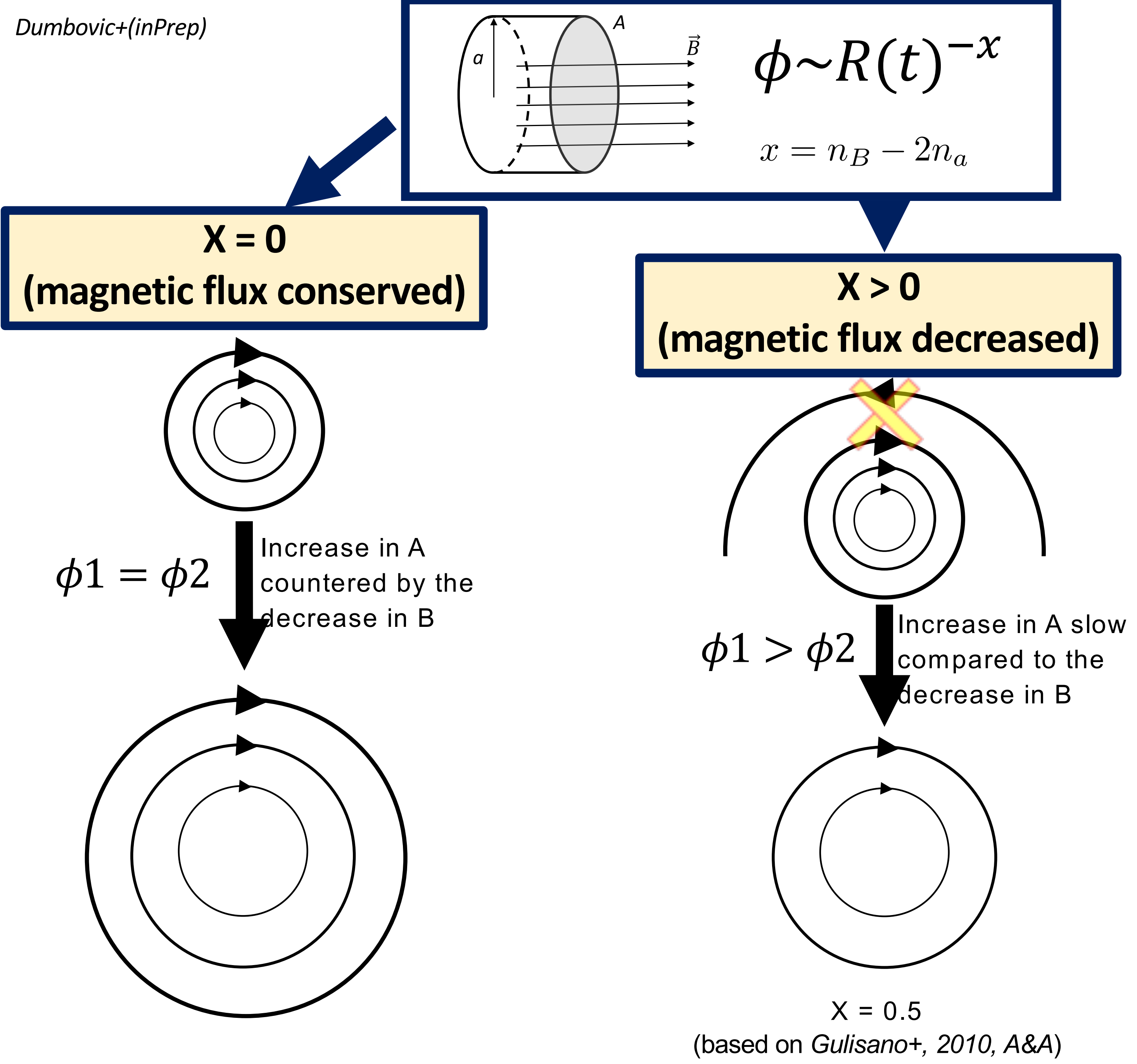
X = 0
(magnetic flux conserved)



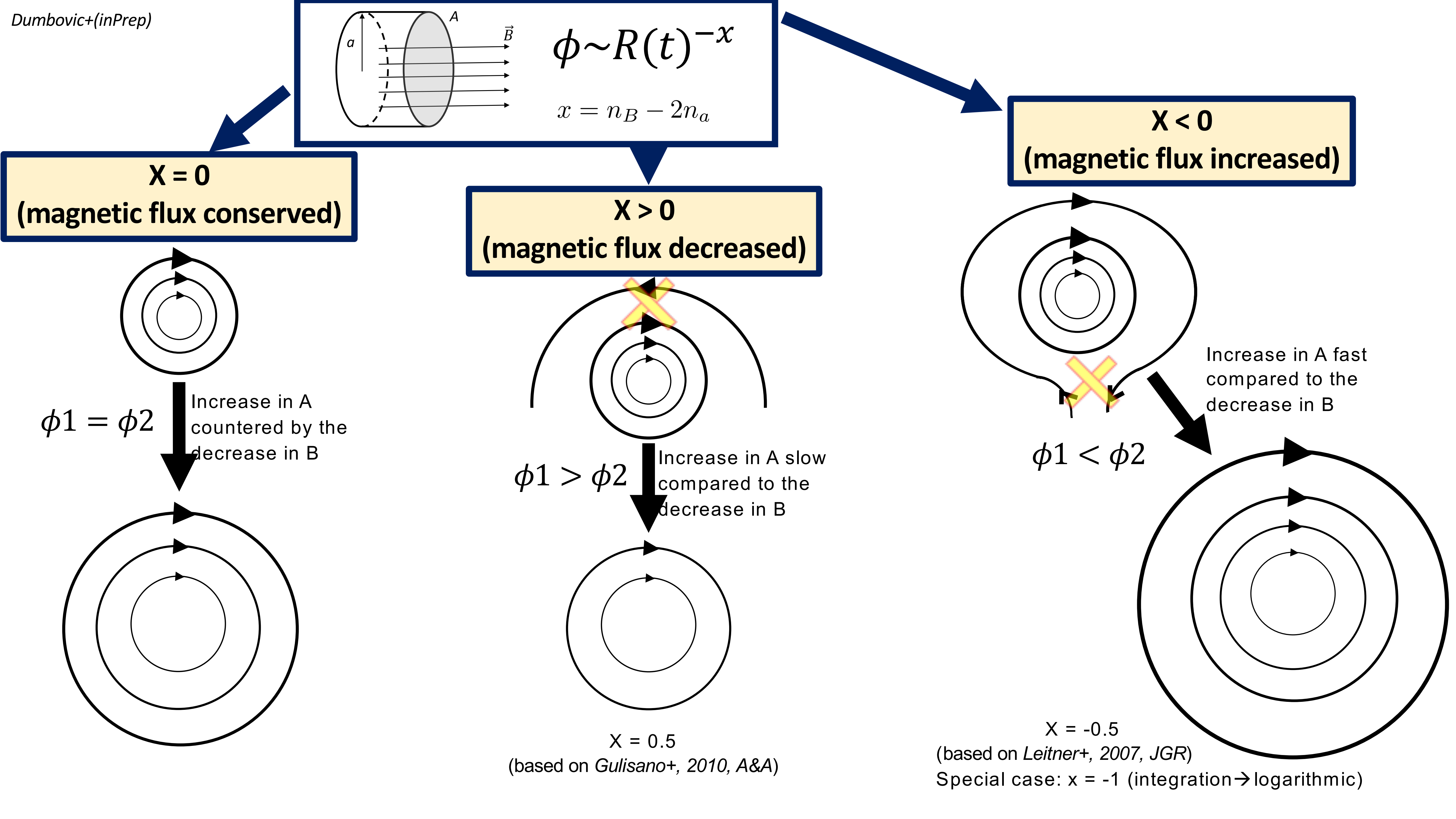
$$\phi 1 = \phi 2$$

Increase in A
countered by the
decrease in B





Dumbovic+(inPrep)
a
A
$\vec{B}$
$\phi \sim R(t)^{-x}$
$x = n_B - 2n_a$
X = 0
(magnetic flux conserved)
$\phi1 = \phi2$
Increase in A countered by the decrease in B
X > 0
(magnetic flux decreased)
$\phi1 > \phi2$
Increase in A slow compared to the decrease in B
X = 0.5
(based on Gulisano+, 2010, A&A)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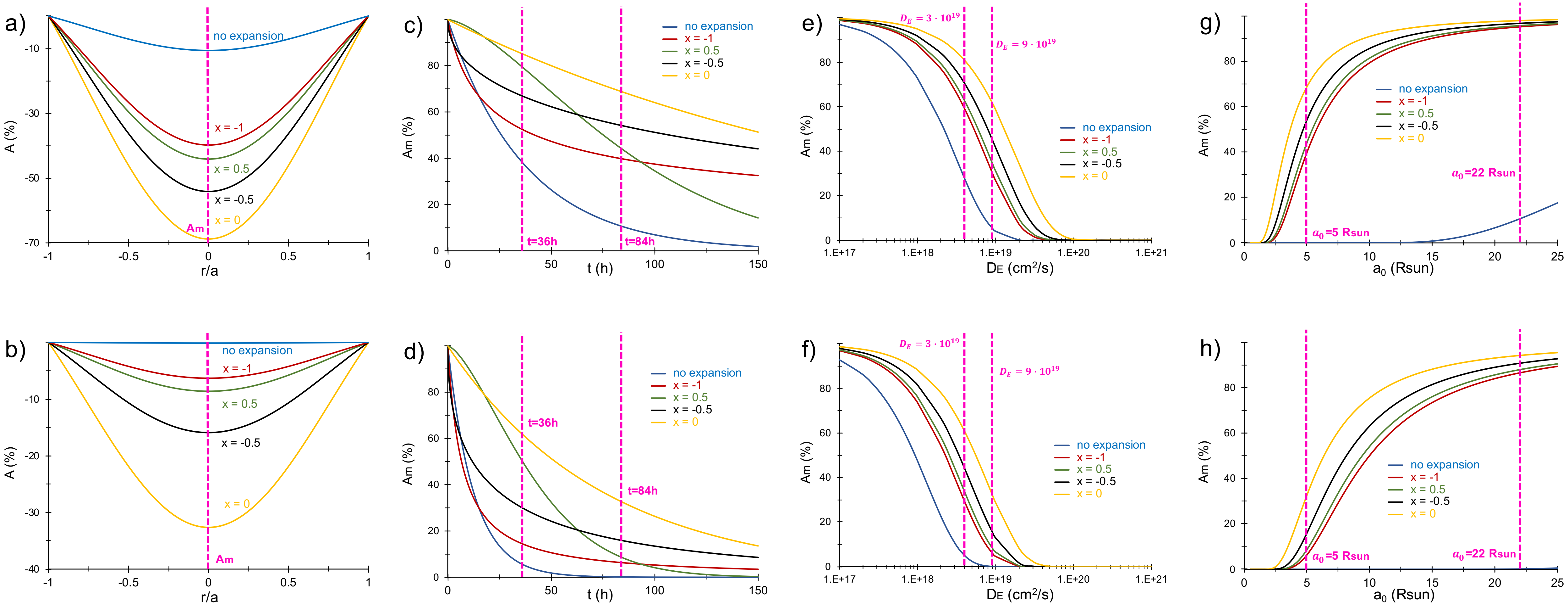
X = 0.5
(based on *Gulisano+, 2010, A&A*)
X < 0
(magnetic flux increased)
$\phi1 < \phi2$
Increase in A fast compared to the decrease in B
X = -0.5
(based on *Leitner+, 2007, JGR*)
Special case: x = -1 (integration→logarithmic)

Dumbovic+(inPrep)

Radial profile | Time evolution | Dependence on D | Dependence on a

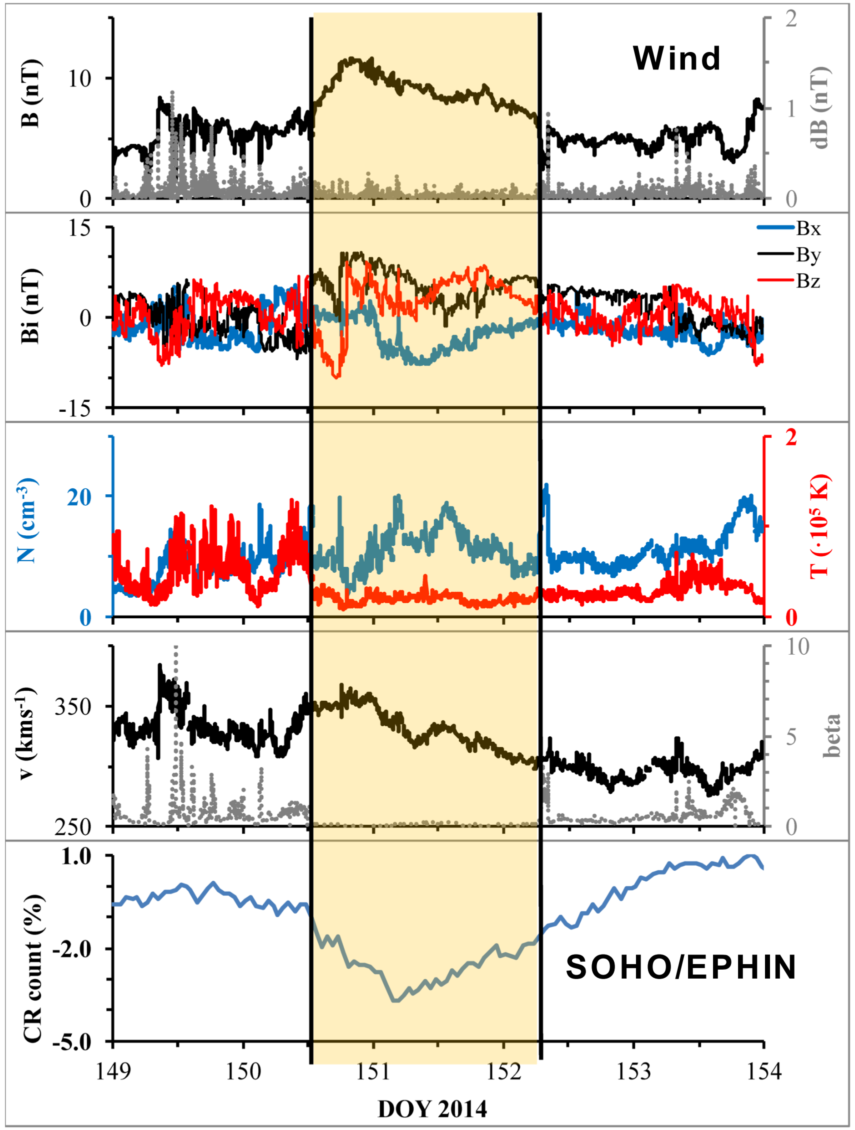


different D | different D | different T | different D

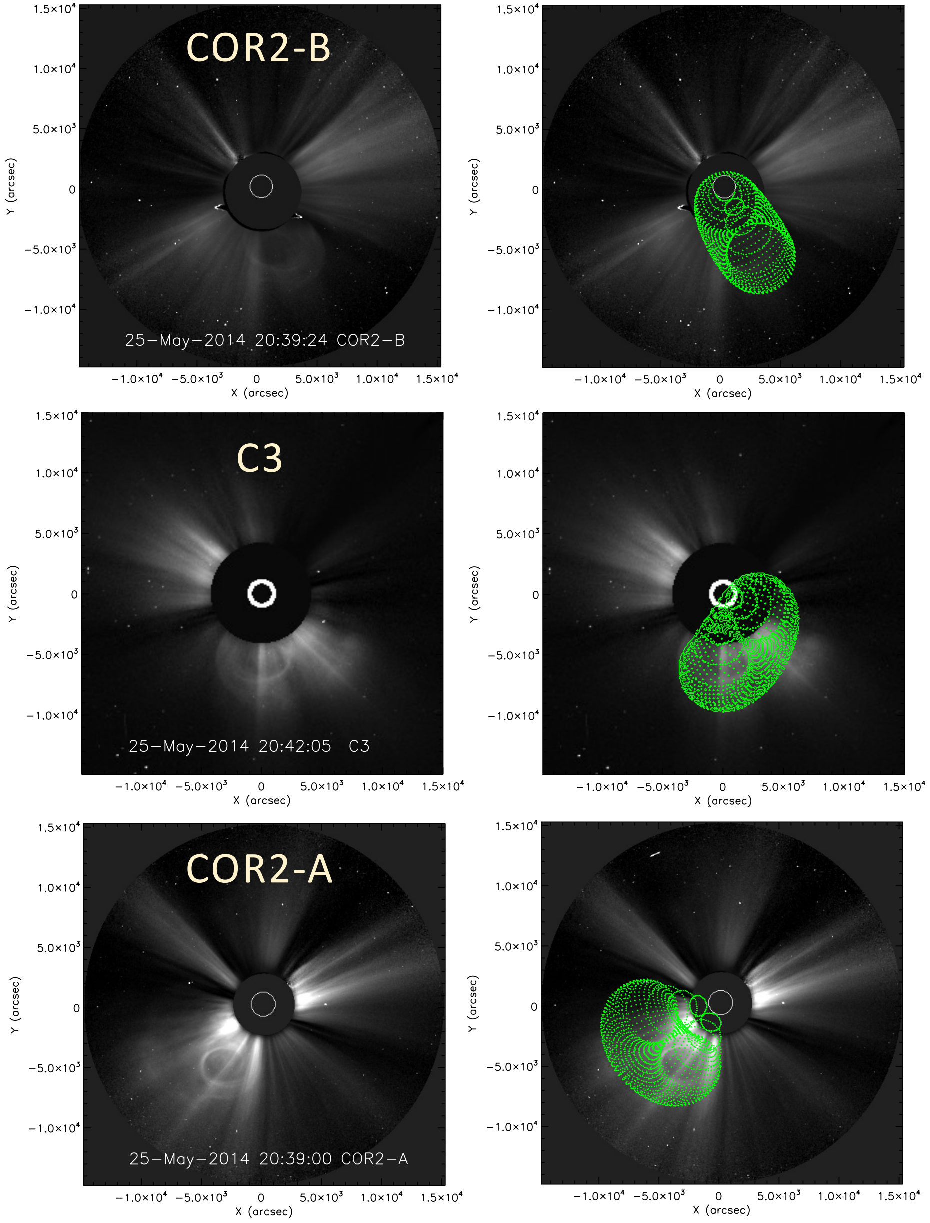
COMPLEX INTERPLAY OF DIFFUSION AND EXPANSION

Dumbovic+(inPrep)

THE CASE STUDY



ICME & FD: 2014 May 30



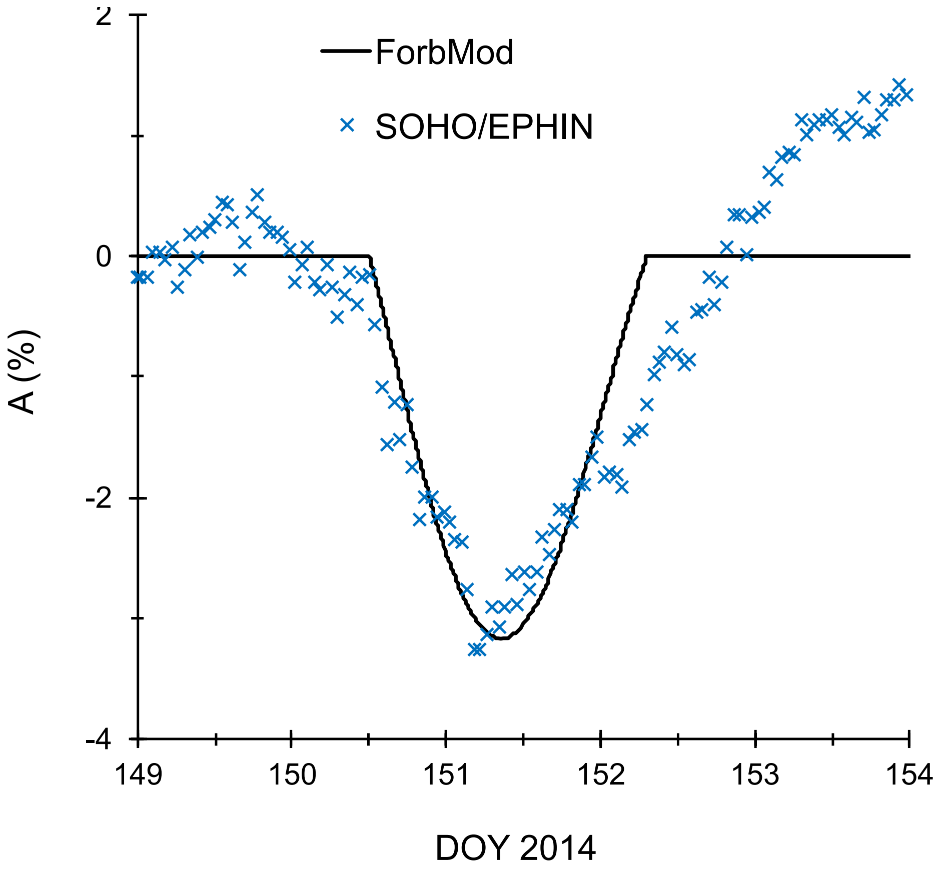
CME: 2014 May 25

THE CASE STUDY – ForbMod results: radial profile

All expansion cases – same radial profile
(Bessel function!)

FD radial profile symmetric & restricted to FR
→ Qualitative agreement with observations
(e.g. Cane+,1993, JGR; Belov+, 2015, SolPhys; Masias-Meza+, 2016, A&A)

For each expansion type best fit D where
observed FD magnitude ≈ calculated FD magnitude



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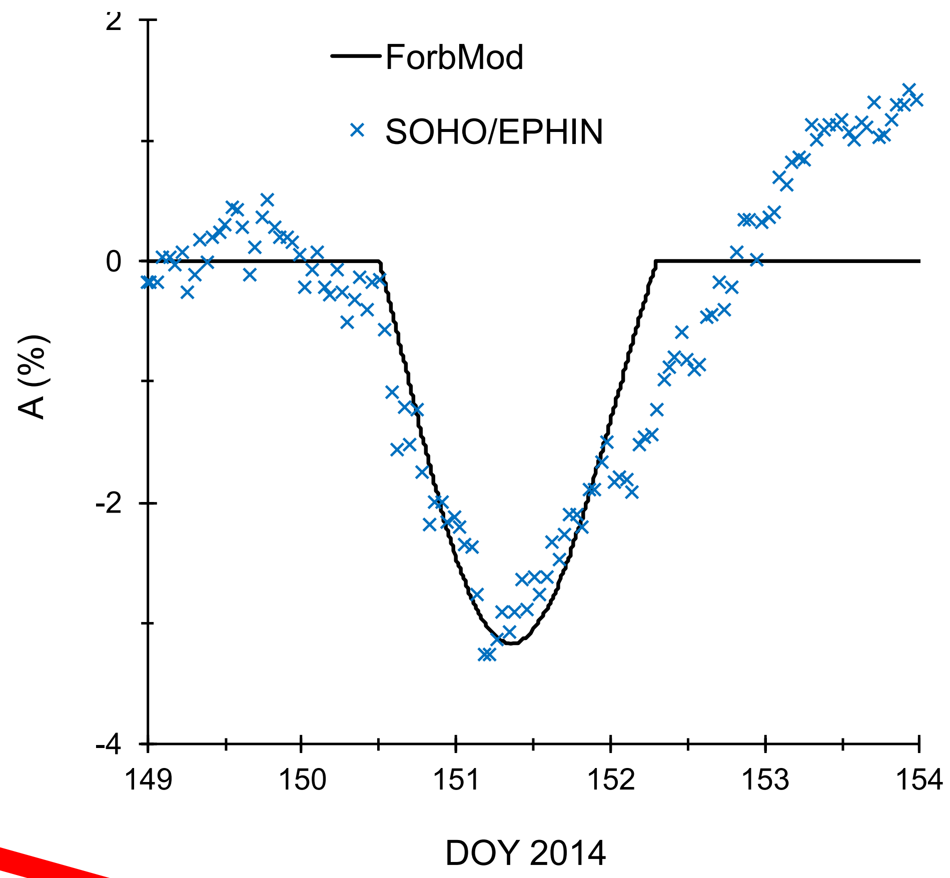

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X=0 (mag. flux conserved)
→ D=1.22 · 10^{19} cm^2 s^{-1}

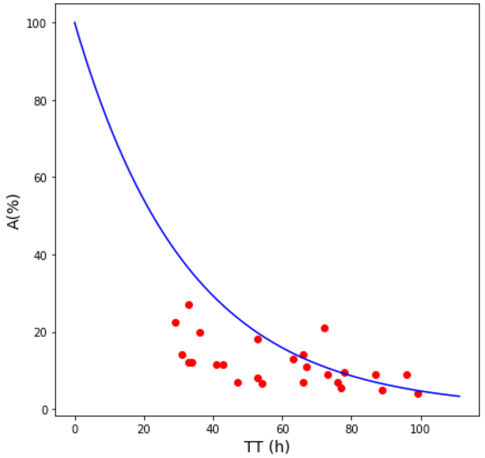
X=0.5 (mag. flux decreased)
→ D=0.55 · 10^{19} cm^2 s^{-1}

X=-0.5 (mag. flux increased)
→ D=0.68 · 10^{19} cm^2 s^{-1}

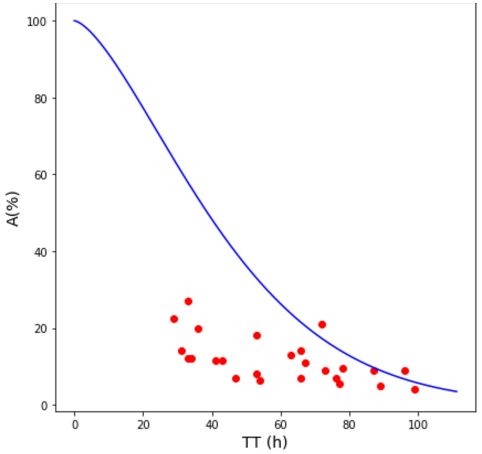
X=-1 (mag. flux increased)
→ D=0.45 · 10^{19} cm^2 s^{-1}

THE CASE STUDY – ForbMod results: time evolution

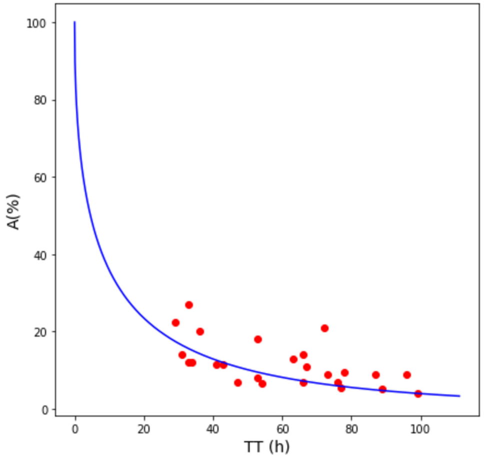
X=0 (mag. flux conserved)
→ $D=1.22 \cdot 10^{19}$ cm^2 s^{-1}



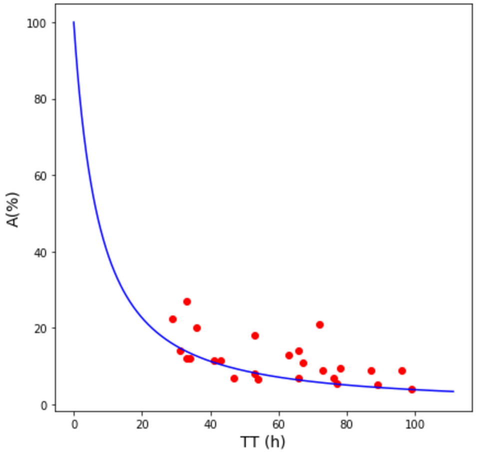
X=0.5 (mag. flux decreased)
→ $D=0.55 \cdot 10^{19}$ cm^2 s^{-1}



X=-0.5 (mag. flux increased)
→ $D=0.68 \cdot 10^{19}$ cm^2 s^{-1}



X=-1 (mag. flux increased)
→ $D=0.45 \cdot 10^{19}$ cm^2 s^{-1}



A=FD magnitude
(depression in the center of FR)

different expansion cases – different evolution
(expansion competes with diffusion)

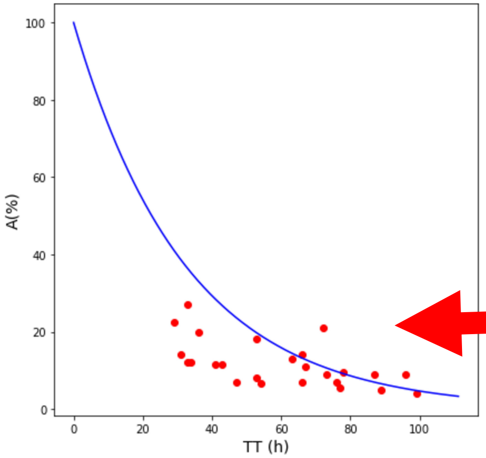
FD amplitude drops with time

→ Qualitative agreement with observations
(e.g. Cane+, 1994, JGR; Blanco+, 2013, A&A)

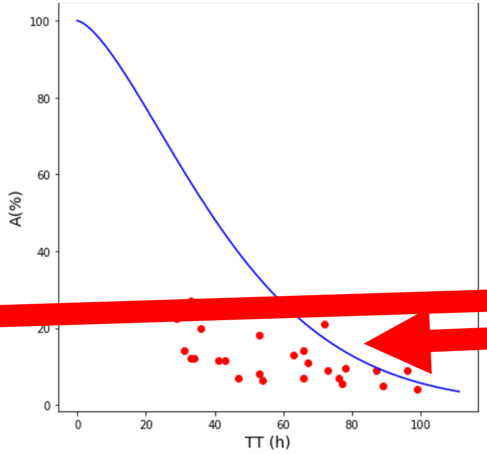
Dumbovic+(inPrep)

THE CASE STUDY – ForbMod results: time evolution

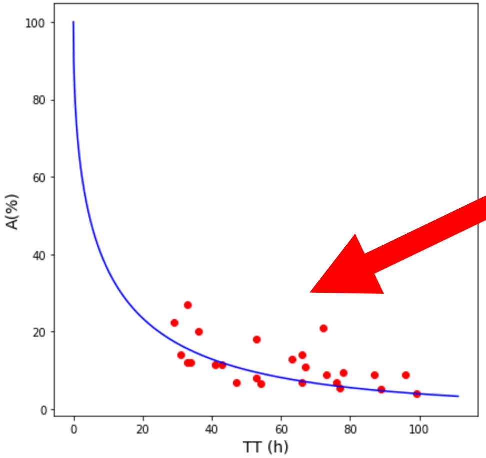
X=0 (mag. flux conserved)
→ D=1.22 · 10^{19} cm^2 s^{-1}



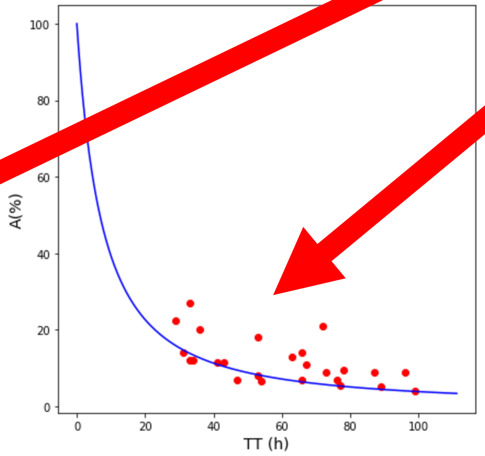
X=0.5 (mag. flux decreased)
→ D=0.55 · 10^{19} cm^2 s^{-1}



X=-0.5 (mag. flux increased)
→ D=0.68 · 10^{19} cm^2 s^{-1}



X=-1 (mag. flux increased)
→ D=0.45 · 10^{19} cm^2 s^{-1}



A=FD magnitude
(depression in the center of FR)

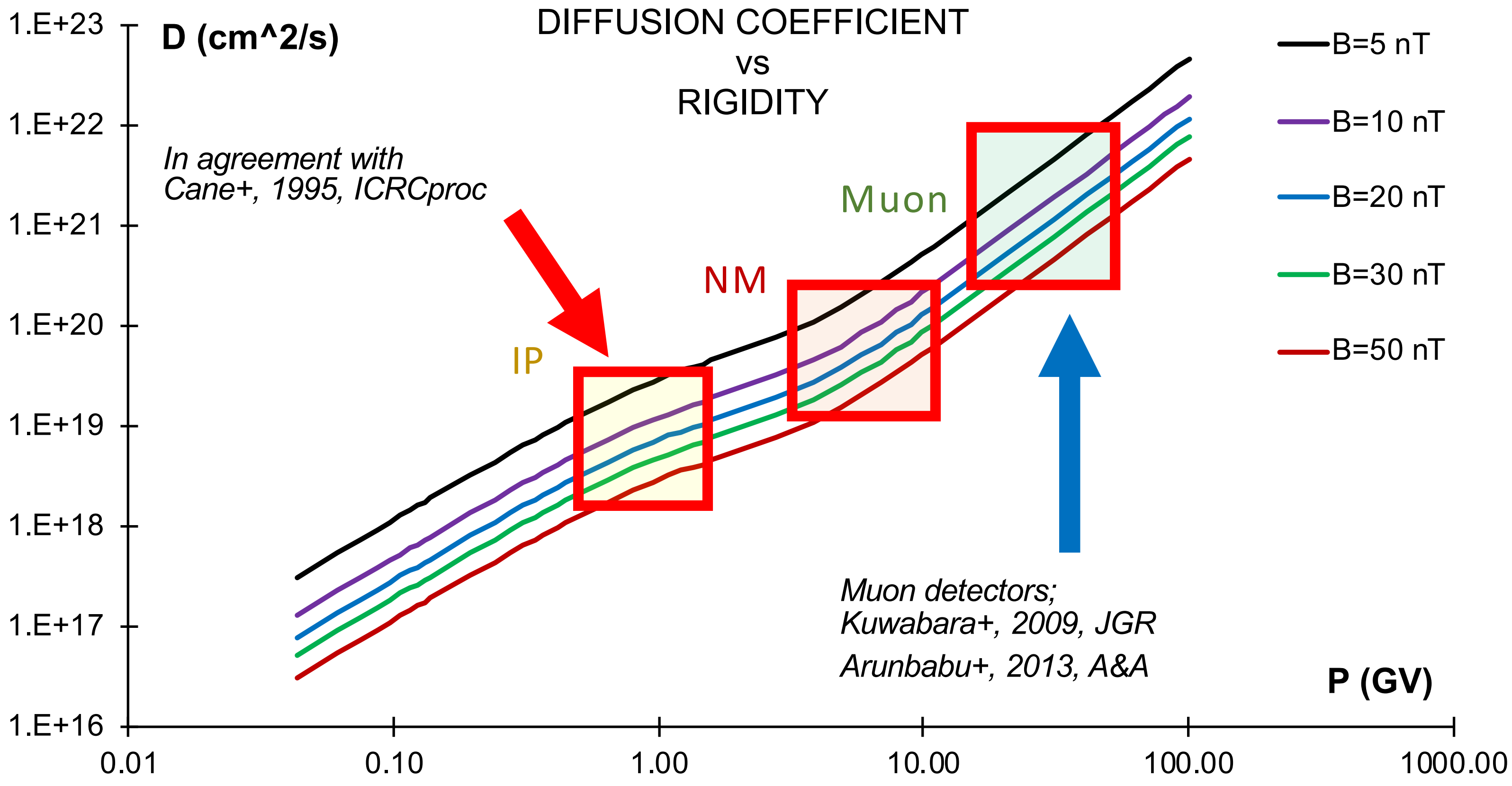
Measurements taken from
Blanco+, 2013, A&A
(statistical study of FD
magnitude vs CME transit time)

different expansion cases – different evolution
(expansion competes with diffusion)

FD amplitude drops with time

→ Qualitative agreement with observations
(e.g. Cane+, 1994, JGR; Blanco+, 2013, A&A)

THE CASE STUDY – ForbMod results: diffusion coefficient



Adapted from Potgieter(2013)

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
- Quantitative agreement depends on the type of expansion and diffusion coefficient

- **NEXT STEPS: testing and constraints using FR forward modeling and multispacecraft measurements (Earth and Mars!)**

Thank you for your attention!

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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.