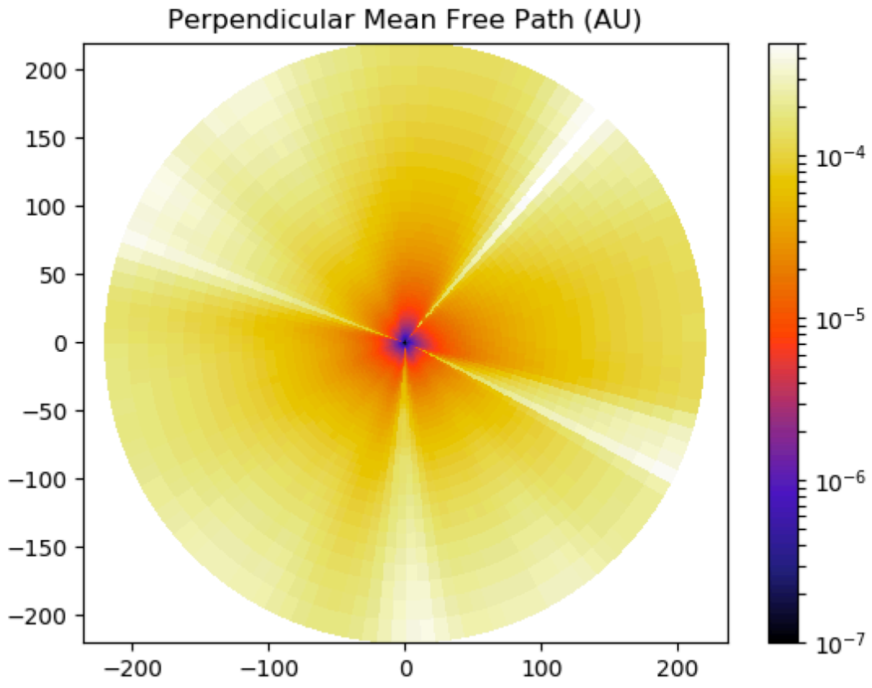
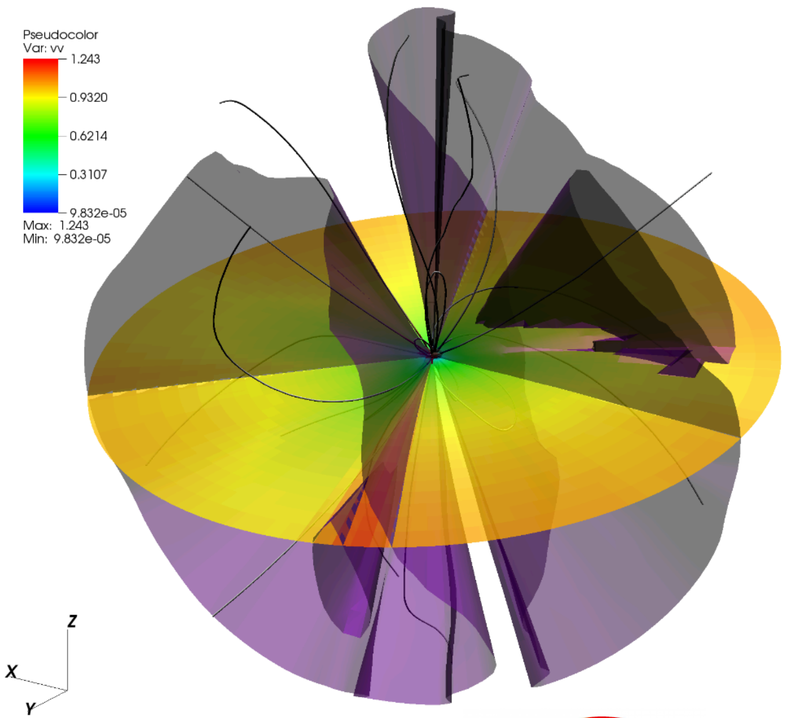
Impact of solar magnetic field amplitude and geometry on SEPs and GCRs diffusion coefficients

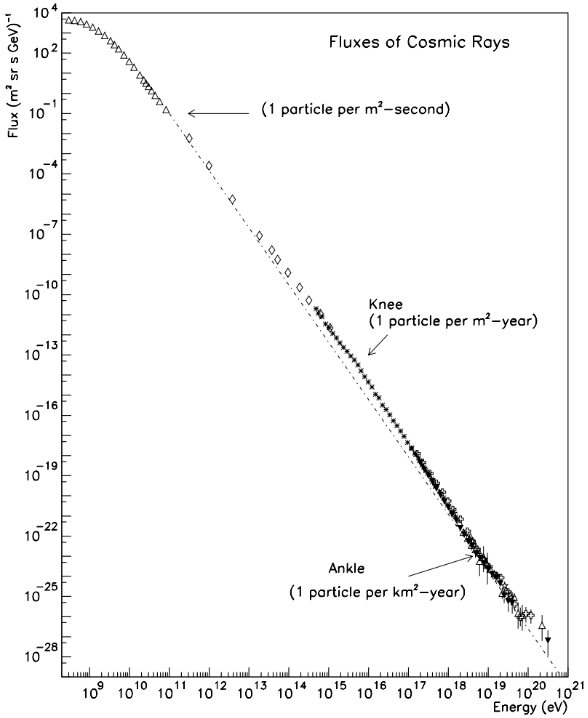
Collaborators:

Dr. Allan Sacha **Brun** (AIM), Dr. Antoine **Strugarek** (AIM), Dr. Victor **Réville** (IRAP), Dr. Éric **Buchlin** (IAS)

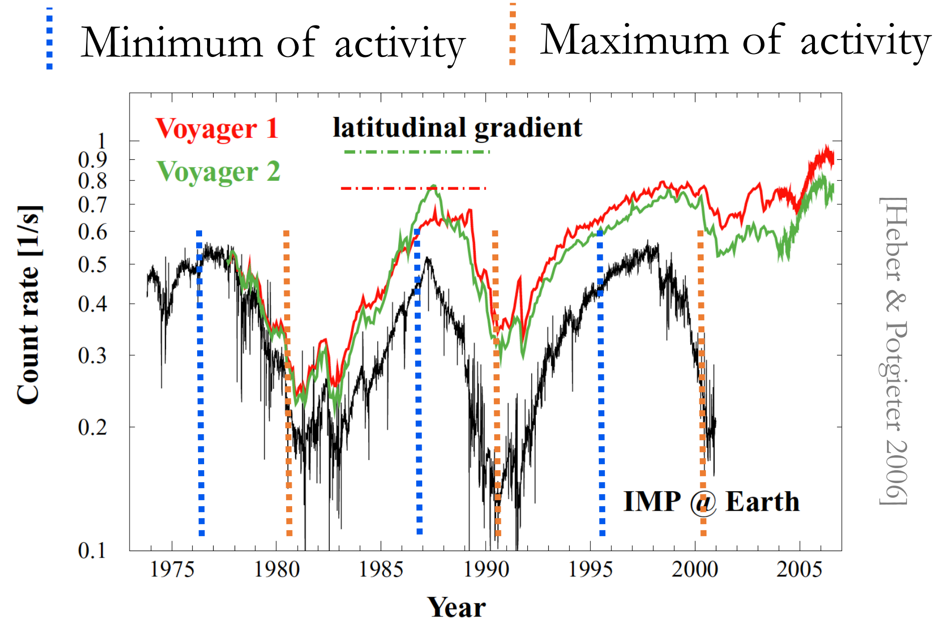




Cosmic rays and the solar cycle



[Cronin+1997, Swordy 2001]



[Heber & Potgieter 2006]

Cosmic rays (CRs) are energetic particles that reach the Earth

SEPs are correlated with the solar cycle
→ more particles produced at maximum of activity

The lower part of the energy distribution is composed of **SEPs (Solar Energetic Particles)**, the higher part of **GCRs (Galactic Cosmic Rays)**

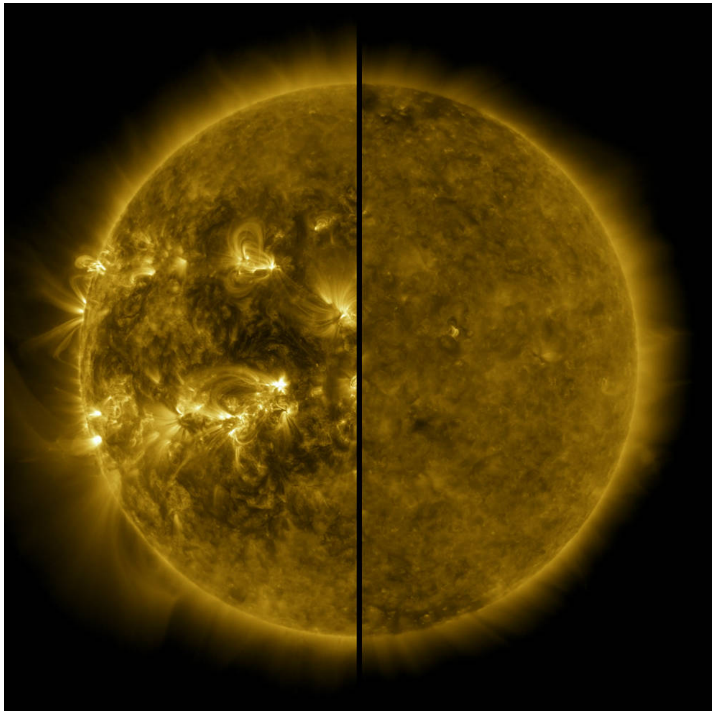
GCRs are anti-correlated with the solar cycle
→ the most energetic particles are driven away by the intense solar wind

Cosmic rays and the solar cycle

SEPs and GCRs propagation will depend on their interaction with :

Solar **magnetic field**

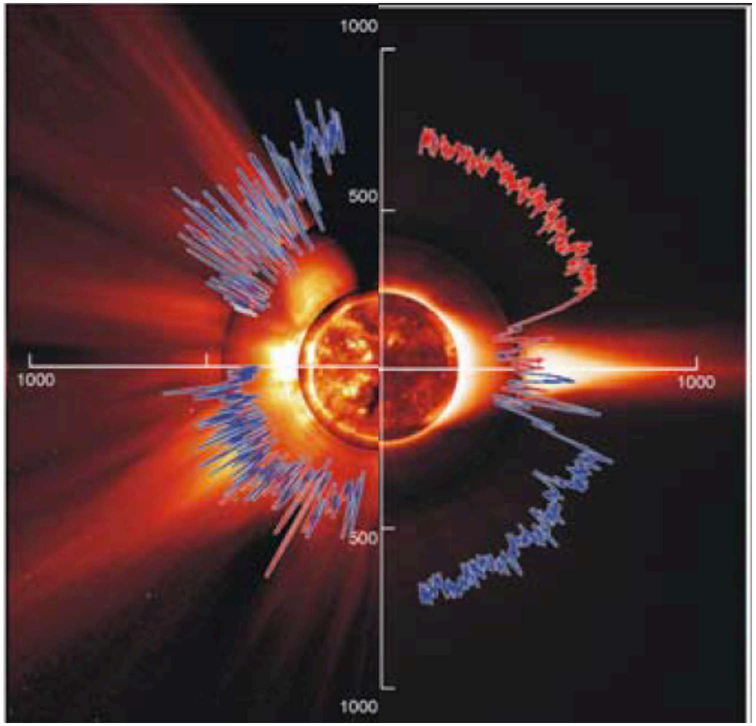
max min



[NASA, SDO]

Solar **wind**

max min



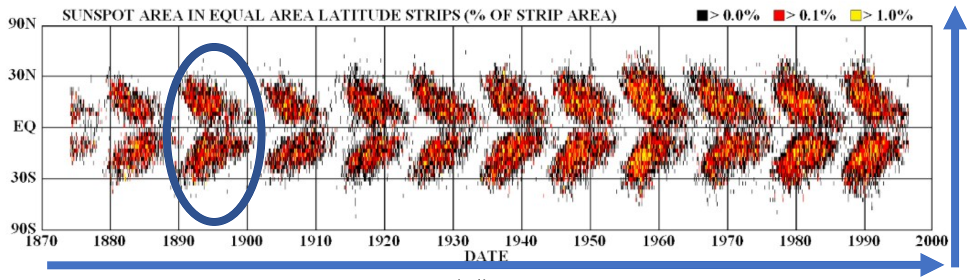
[McComas+2003]

Both show a lot of **variability** over a dynamo cycle → difficult to prescribe analytically

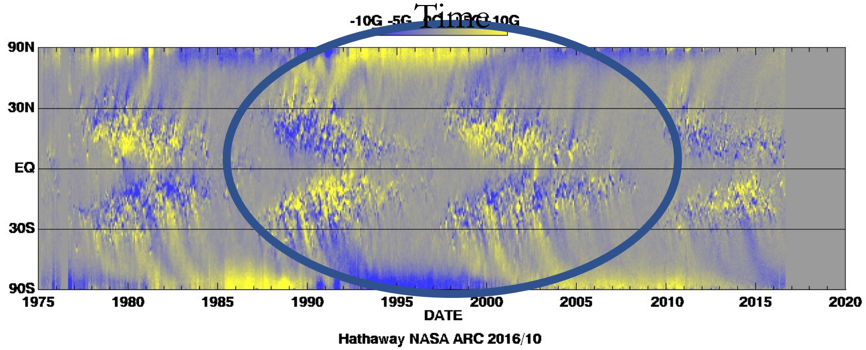
Observations of solar magnetism

The Sun has many characteristic **periods**

11 years

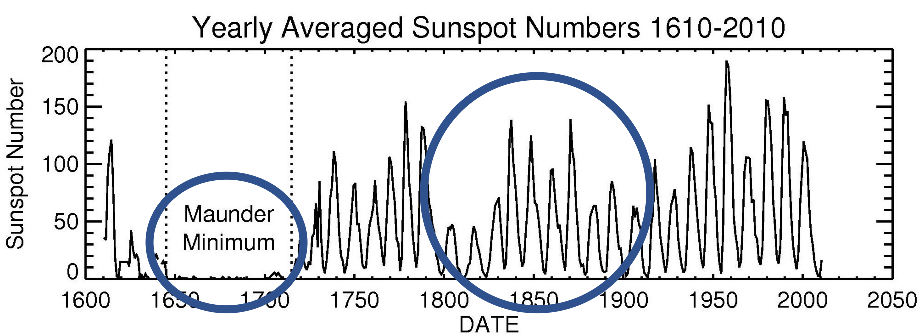


22 years



[NASA]

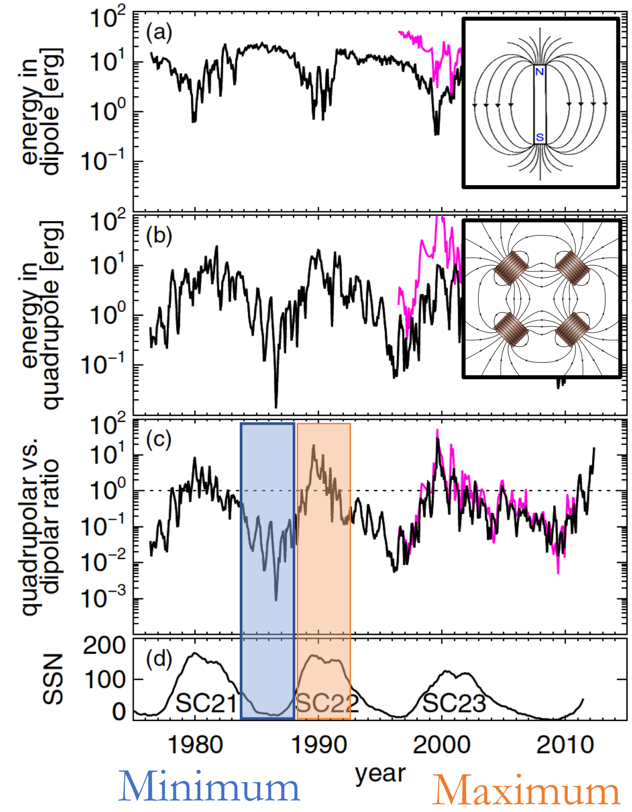
100 years



Changes in geometry

More dipolar at minimum

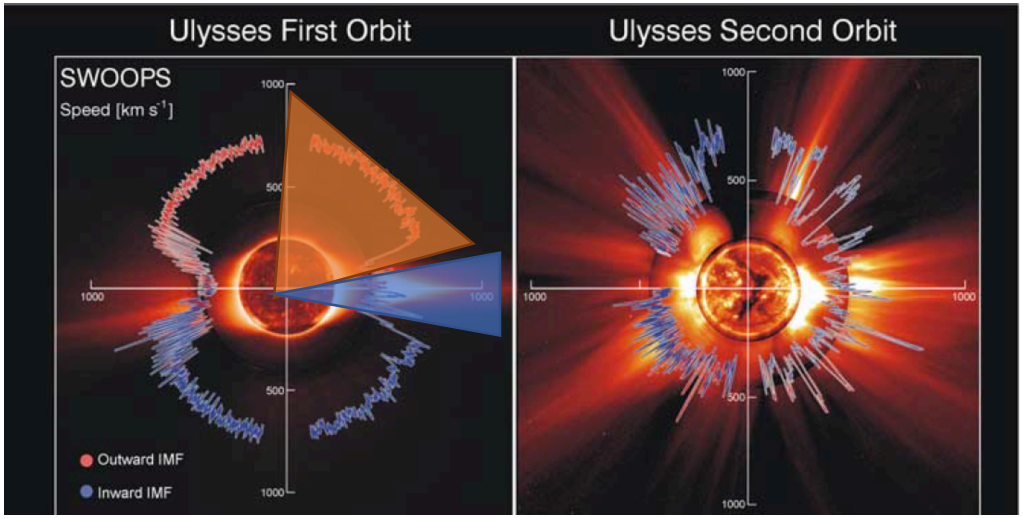
More quadrupolar at maximum



[DeRosa+2012]

Observations of solar wind

Continuous flow of particles ejected by the Sun
→ Creates a connection between the Sun and the Earth



[McComas+2003]

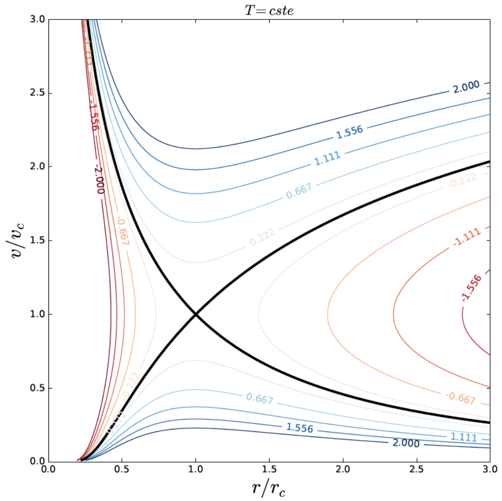
Slow solar wind
400km/s
Cold (80 000 K)
Dense (6.6 cm^{-3})
From streamers and active regions

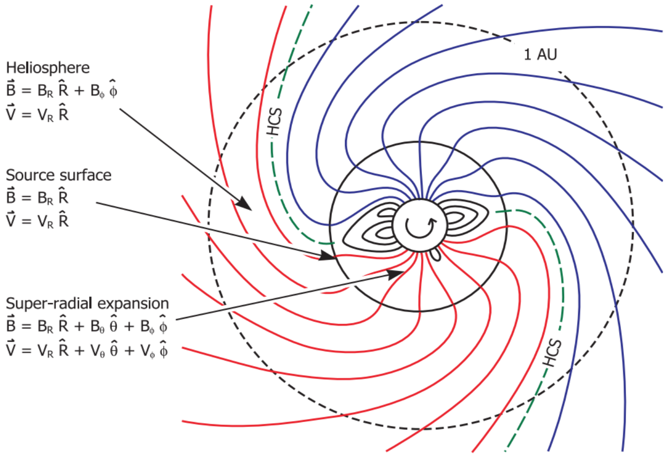
Fast solar wind
800km/s
Hot (680 000 K)
Less dense (3 cm^{-3})
From coronal holes

State of the art

Usually, analytical prescriptions for the wind and the magnetic field → simplified

[Réville 2016]

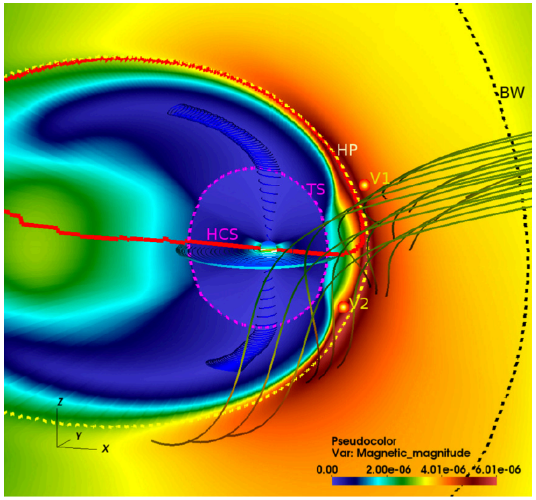


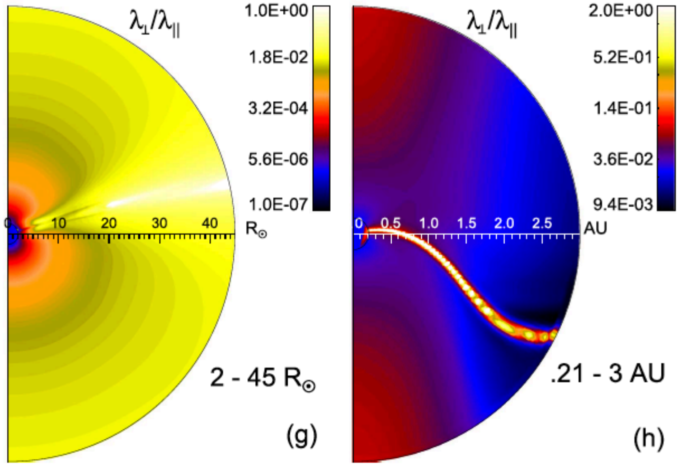


[Owens & Forsyth 2013]

Use of numerical simulations instead, and combination with non-empirical diffusion

[Guo & Florinski 2014]





[Chhiber+2017]

State of the art

Usually, analytical prescriptions for the wind and the magnetic field → simplified

[Réville 2016]

[Owens & Forsyth 2013]

Use of … diffusion

Context:

Need to understand the complex interaction between energetic particles and the heliosphere for better space weather previsions

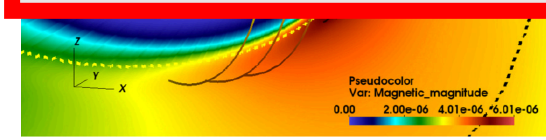
Method:

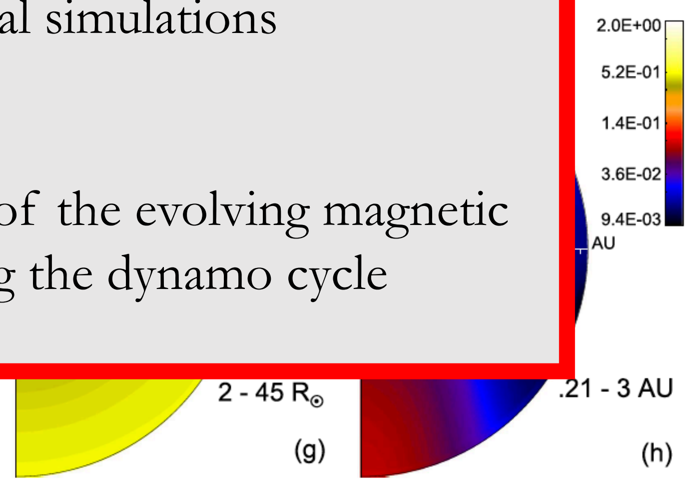
Combination of analytical prescriptions derived from theory and numerical simulations

Aim:

Better characterize the impact of the evolving magnetic field and solar wind along the dynamo cycle

[Guo & Florinski 2014]





[Chhiber+2017]

Modeling cosmic rays

[Parker 1965]

We start from the Fokker-Planck equation:

$$\frac{\partial U}{\partial t} = \nabla \kappa \nabla U - \nabla(vU) - v_D \nabla U + \frac{1}{3}\nabla \cdot \nabla \frac{\partial}{\partial T}(\alpha T U)$$

[Jokipii & Parker 1970]

We focus on the diffusivity term:

$$\kappa_{ij} = \kappa_\perp \delta_{ij} + \frac{B_i B_j}{B^2}(\kappa_{||} - \kappa_\perp) + \epsilon_{ijk}\kappa_A \frac{B_k}{B}$$

$$\kappa = \frac{1}{3}\lambda v \qquad P = \frac{mvc}{Ze}$$

We treat the diffusion parallel and perpendicular to the magnetic field lines:

[Zank+1998]

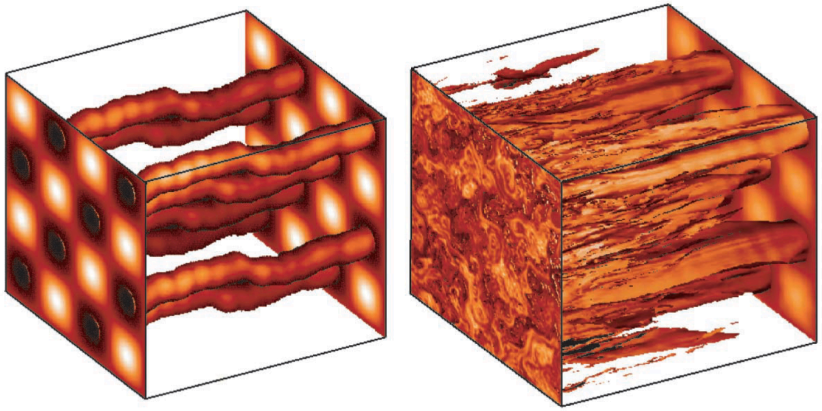
$$\lambda_\parallel \propto \frac{B^{\frac{5}{3}}}{\langle b_s^2 \rangle} \lambda_s^{\frac{2}{3}} F(P, R_L, \lambda_s)$$

[Shalchi+2004]

$$\lambda_\perp = \begin{cases} \frac{a^2}{2}\frac{\langle b_2^2 \rangle}{B^2}\lambda_\| & \text{if } P < 10^2 MeV \\ \left(C\lambda_s \frac{\langle B'^2 \rangle}{B^2}\right)^{2/3} \lambda_\|^{1/3} & \text{otherwise} \end{cases}$$

NB: Hypothesis of 80% 2D geometry and 20% slab geometry

[Matthaeus+1990, Bieber+1994]



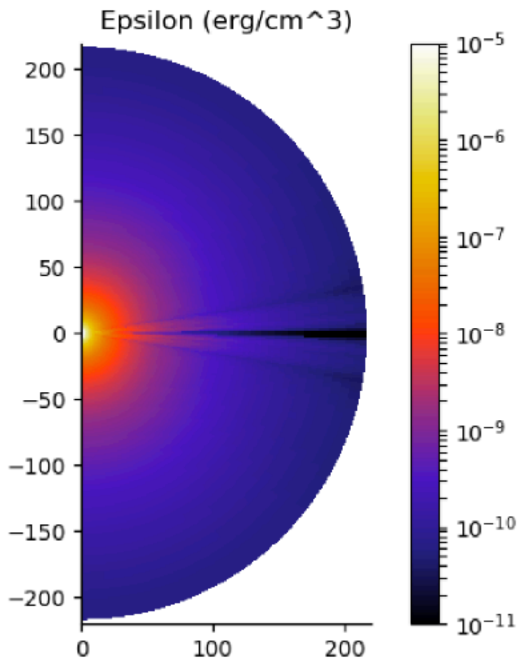
[Matthaeus+2003]

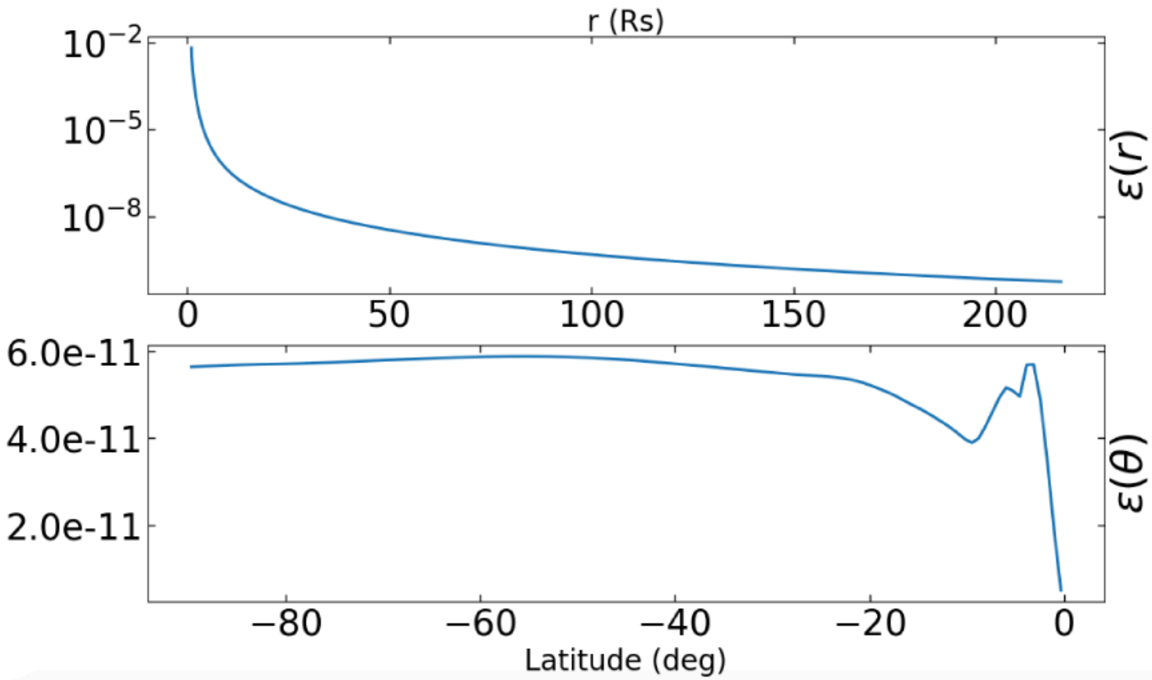
Modeling cosmic rays

MHD models will provide directly the wind velocity and the magnetic field
However, due to our polytropic model for the wind, we need to model the turbulence:

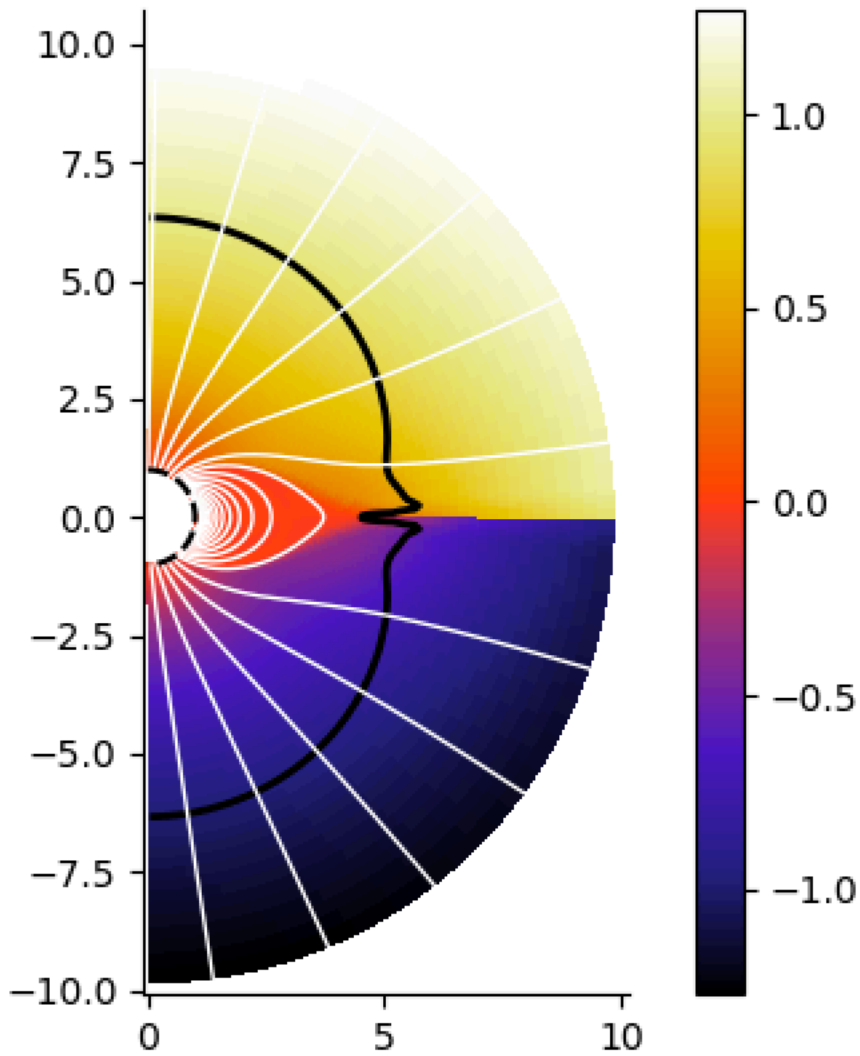
$$\lambda_s \propto 2B^{-1/2} \qquad \langle b_s^2 \rangle = 4\langle b_2^2 \rangle = \frac{4}{5}\epsilon\pi \qquad \epsilon \approx 0.0104 B^{1.25} J^{0.166} v_P^{-0.123}$$

[Spruit 1981] [Chhiber+2017] [Réville+2020]





Reference Case



We solve the ideal MHD equations up to 1 AU using the multi-physics code PLUTO with a polytropic wind model

[Mignone+2007, Réville+2015a, Perri+2018]

First we perform a 2.5D parameter study on reference cases

Wind reference case D1:

$$\rho_0 = 1.67\times10^{-16} g.cm^{-3} \Rightarrow n = 1.0\times10^{8} cm^{-3}$$

$$\frac{v_{rot}}{v_{esc}} = 2.93\times10^{-3} \Rightarrow \Omega_0 = 2.6\times10^{-6} s^{-1}$$

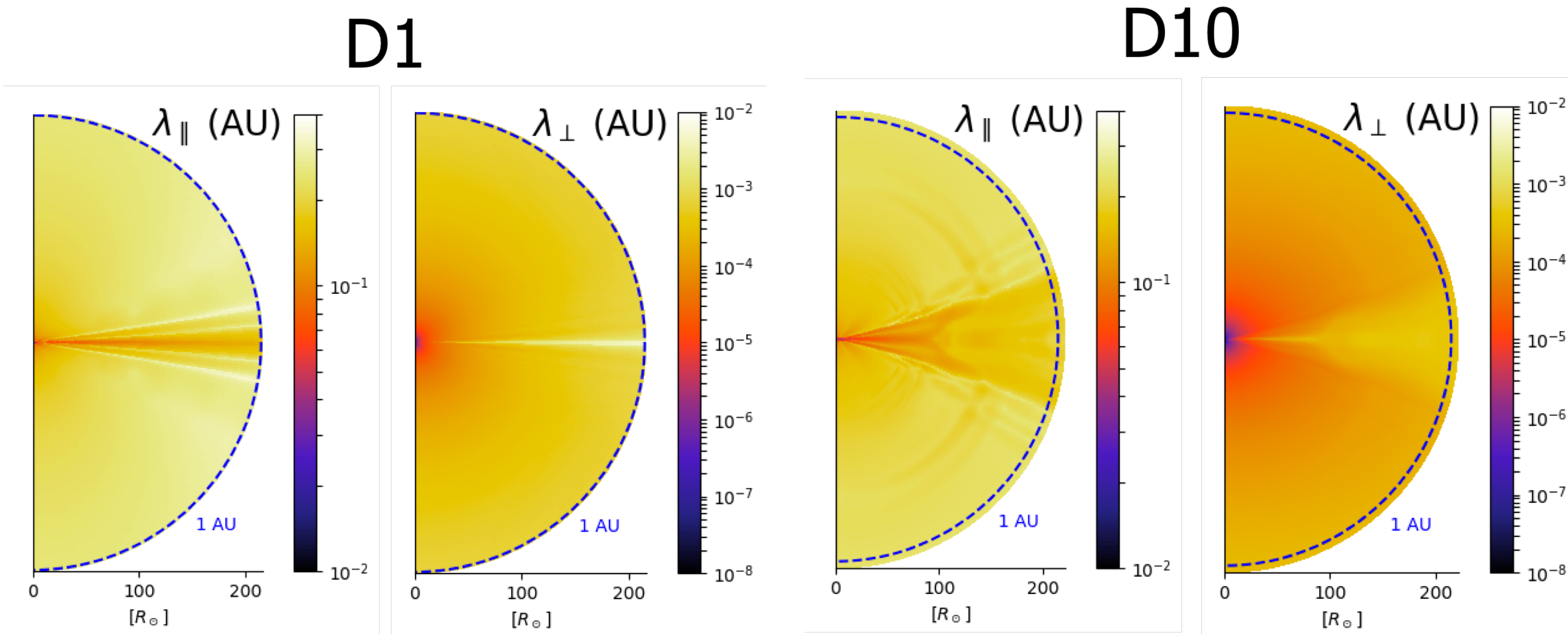
$$\gamma = 1.05, \frac{c_s}{v_{esc}} = 0.243 \Rightarrow T = 1.5\times10^{6} K$$

$$\frac{v_A}{v_{esc}} = 0.176 \Rightarrow B_0 = 0.5\ G$$

→ D1 = **Dipole with low amplitude**

Impact of amplitude

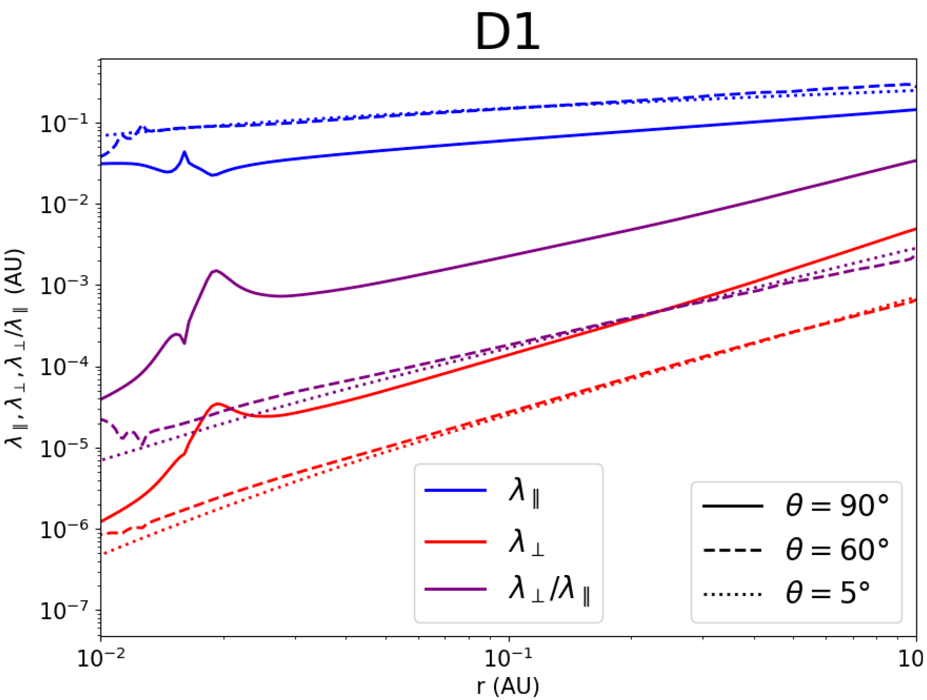
Two dipoles with different amplitudes: $B_0 = 0.5G$ for D1 & $B_0 = 5G$ for D10

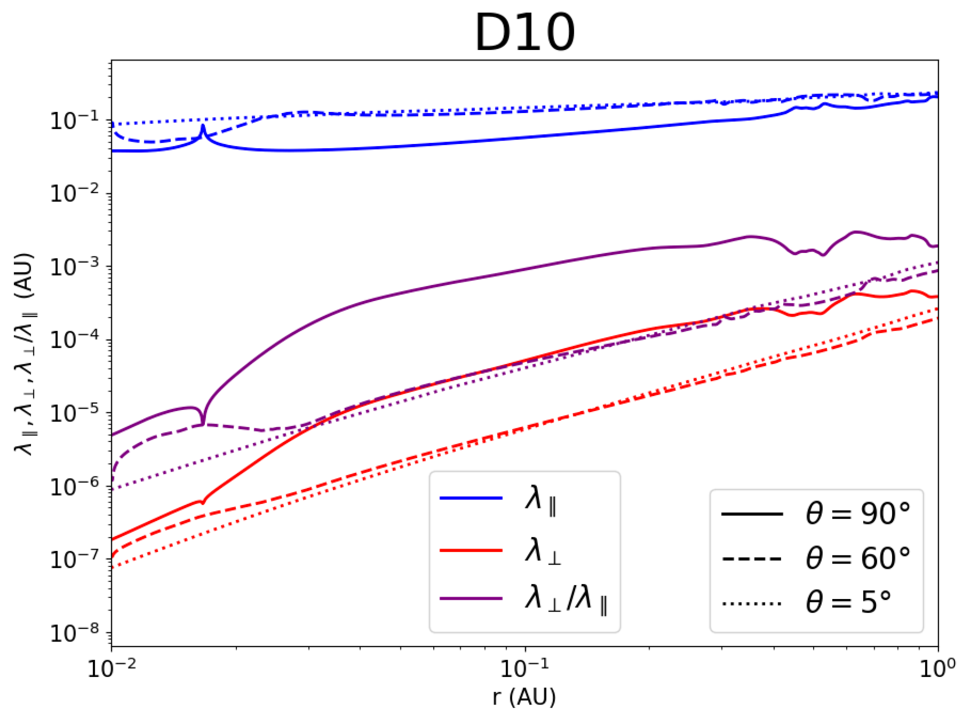


→ Increase of the spread of the current sheet, so wider diffusion zone with stronger field

Impact of amplitude

Two dipoles with different amplitudes: $B_0 = 0.5G$ for D1 & $B_0 = 5G$ for D10



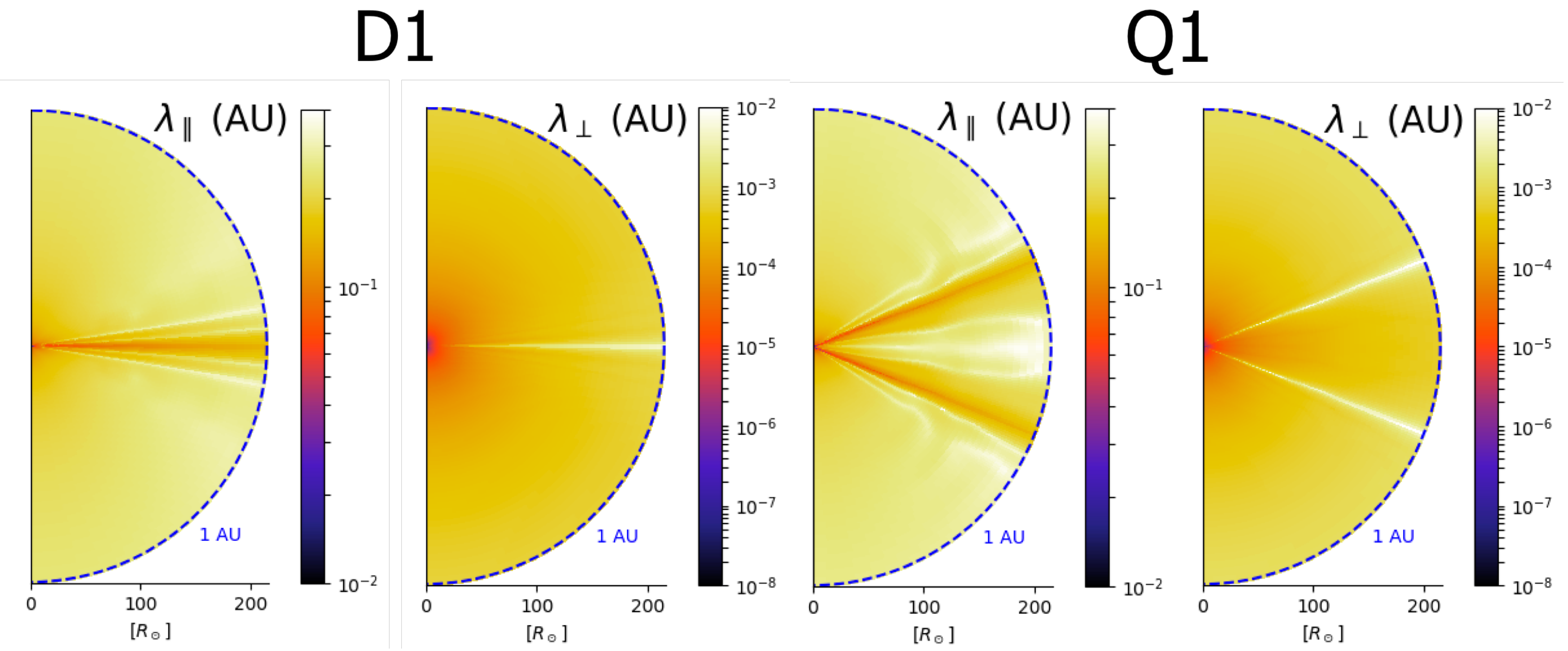


→ Higher parallel diffusion with higher amplitude

→ Lower perpendicular diffusion

Impact of topology

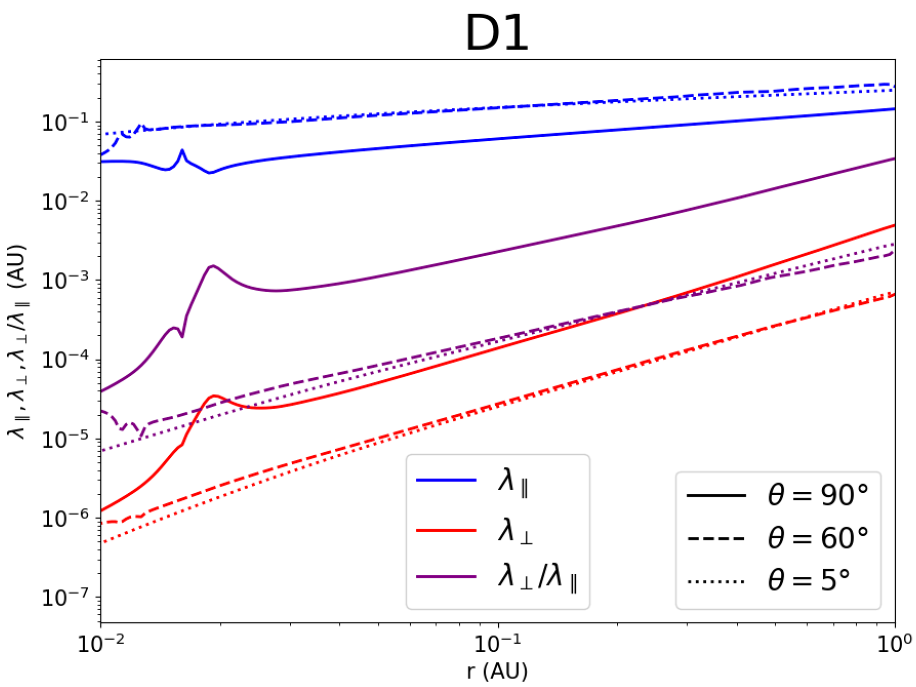
Dipole vs quadrupole for D1 and Q1, but same amplitude

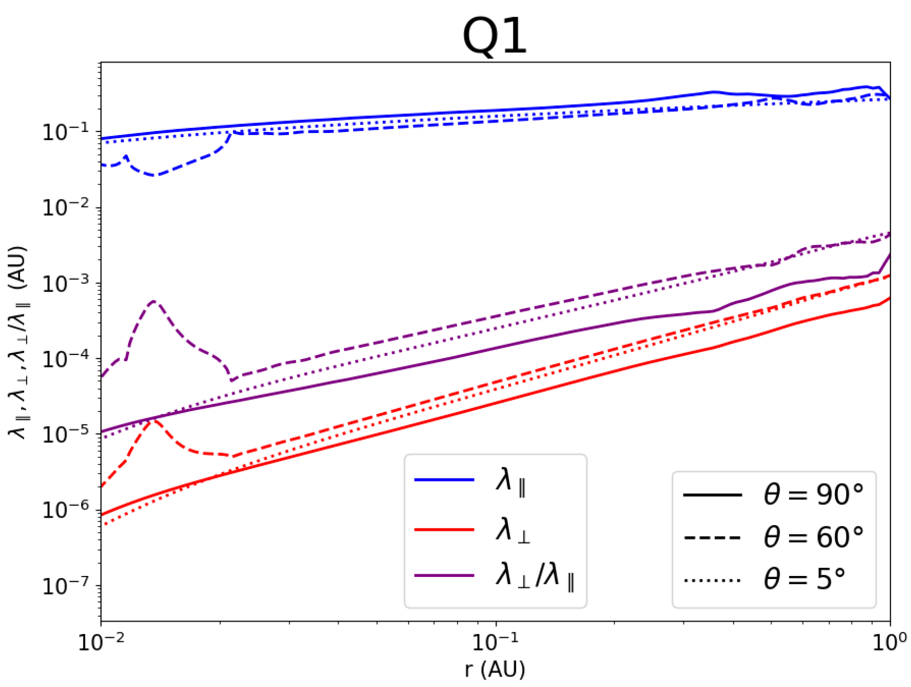


→ Different positions of the current sheets, so different latitudinal distribution

Impact of topology

Dipole vs quadrupole for D1 and Q1, but same amplitude

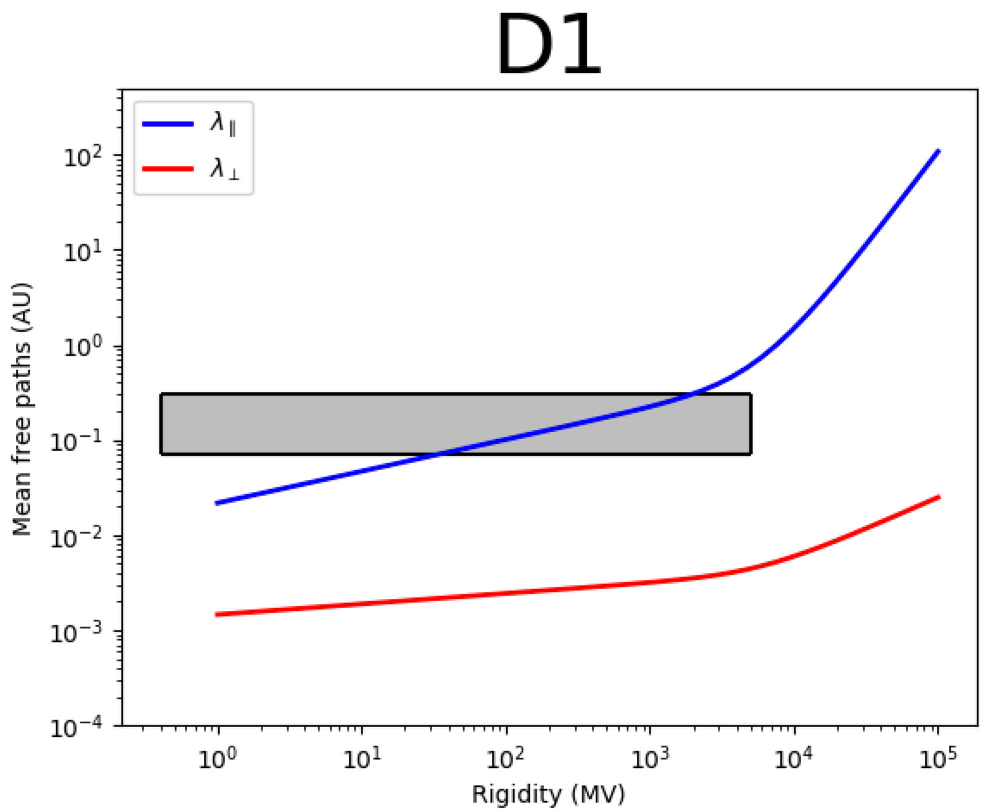




→ The amplitude is not affected

Impact of energy

Diffusion depending on the energy of the particle → difference between SEPs and GCRs

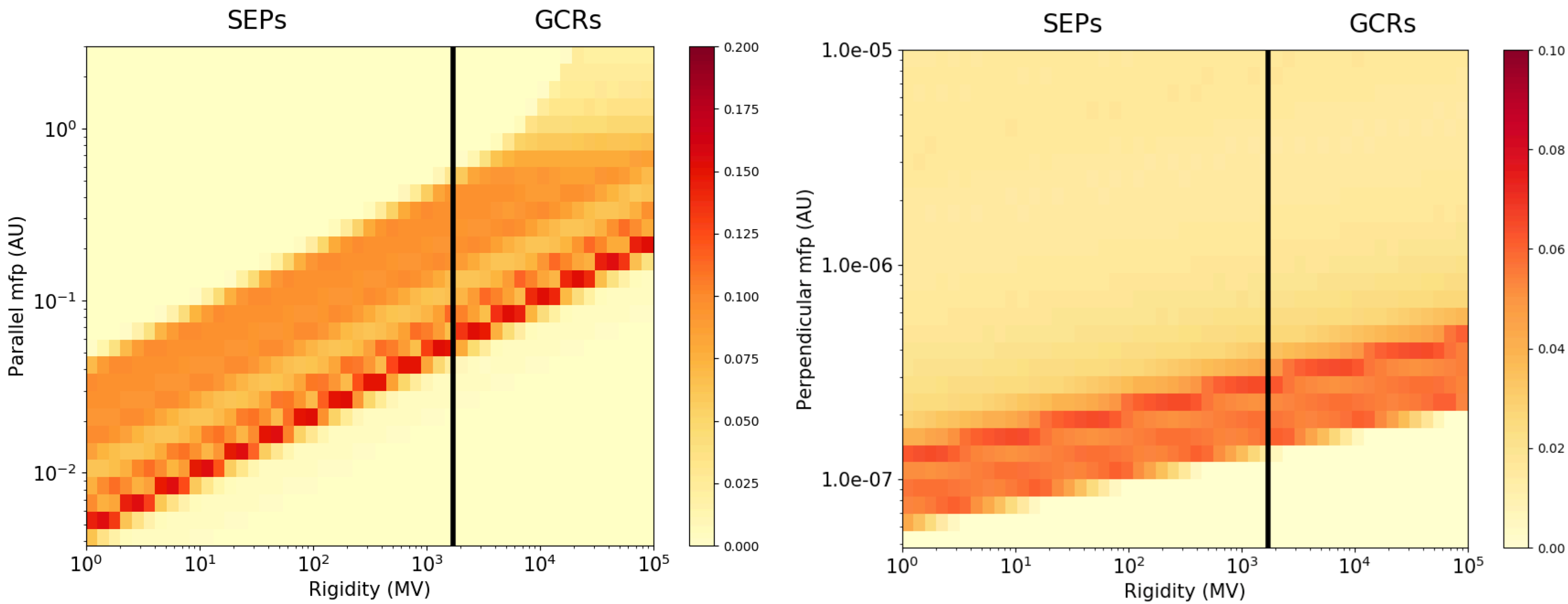


[Palmer 1982]

→ 1D cuts show that we are in agreement with observations, especially the Palmer consensus

Impact of energy

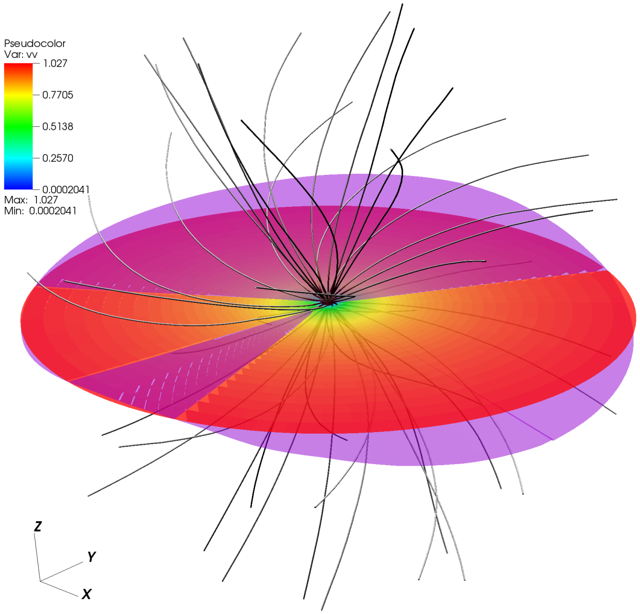
Diffusion depending on the energy of the particle → difference between SEPs and GCRs



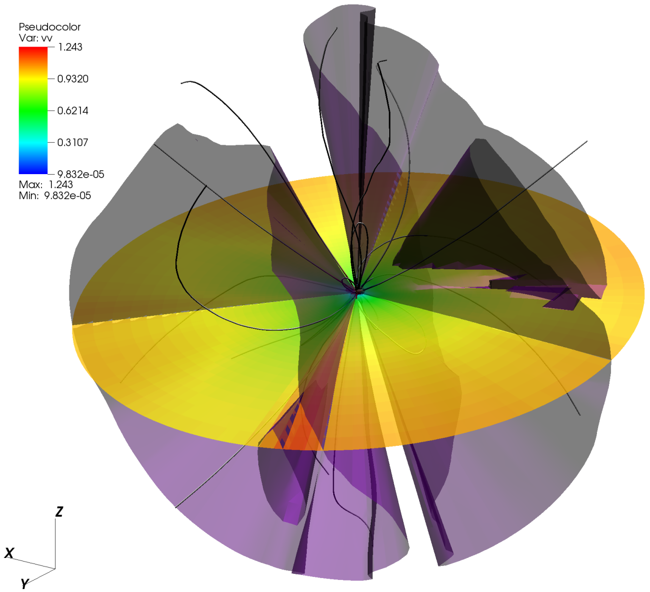
→ Compilations of 1D histograms per energy show a drift of the peak value, and we see that we have a bigger spread in diffusion for SEPs

Realistic solar configurations

Minimum



Maximum

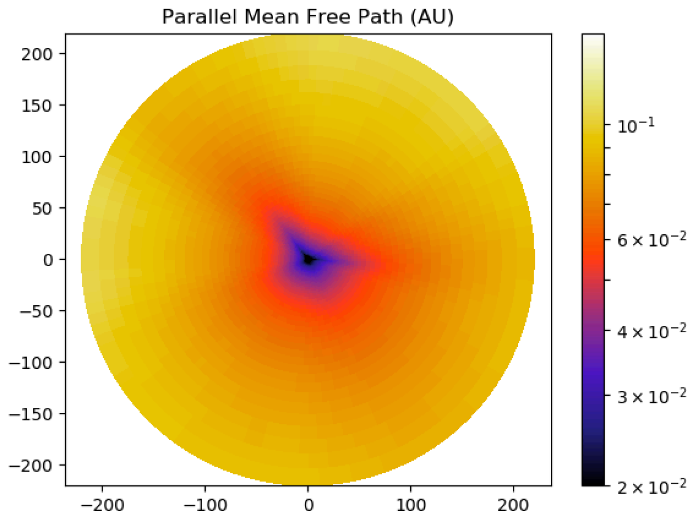


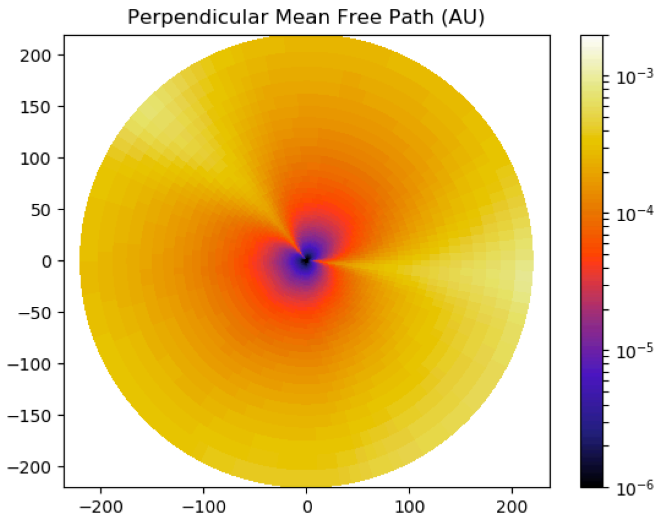
[Réville & Brun 2017]

Minimum and maximum of activity in 3D
→Mix of dipole and quadrupole at various amplitudes

Realistic solar configurations

Minimum



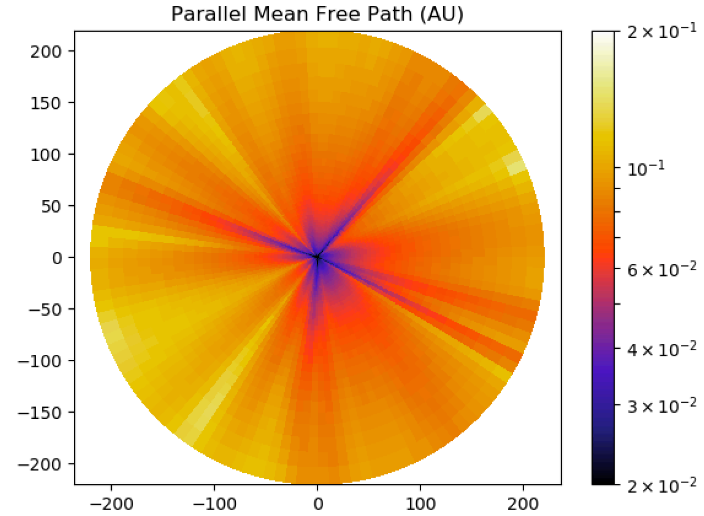


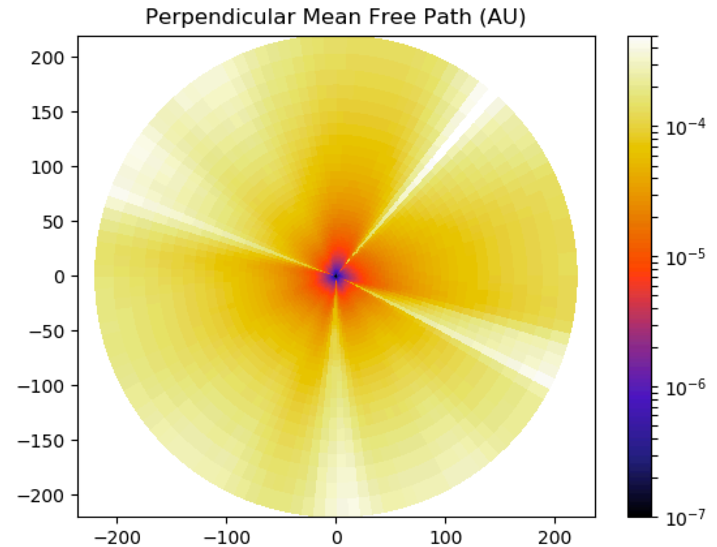
[Réville & Brun 2017]

Minimum and maximum of activity in 3D
→Mix of dipole and quadrupole at various amplitudes

→ 3D maps of parallel diffusion coefficient from 3D wind simulations

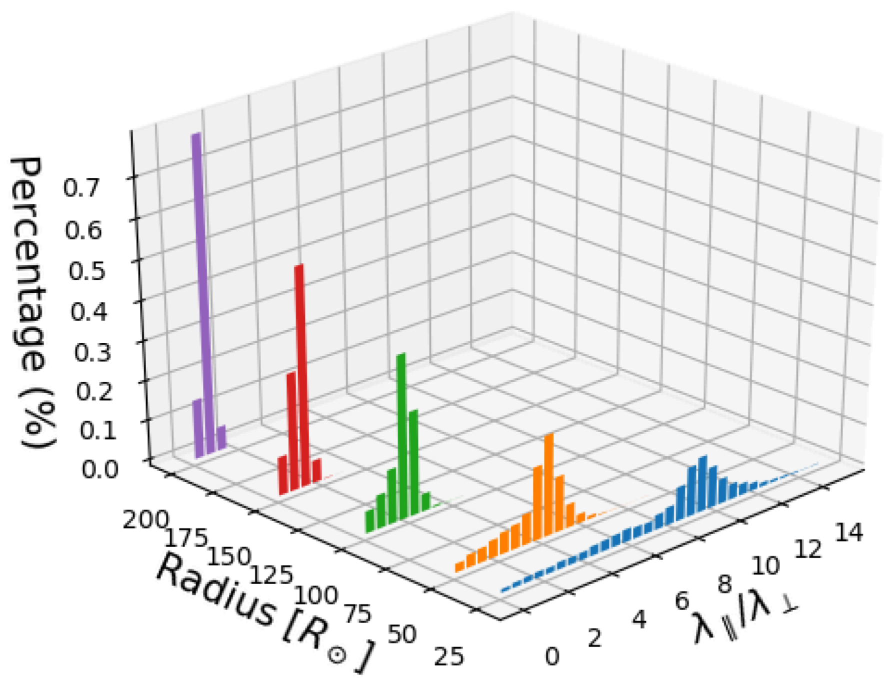
Maximum



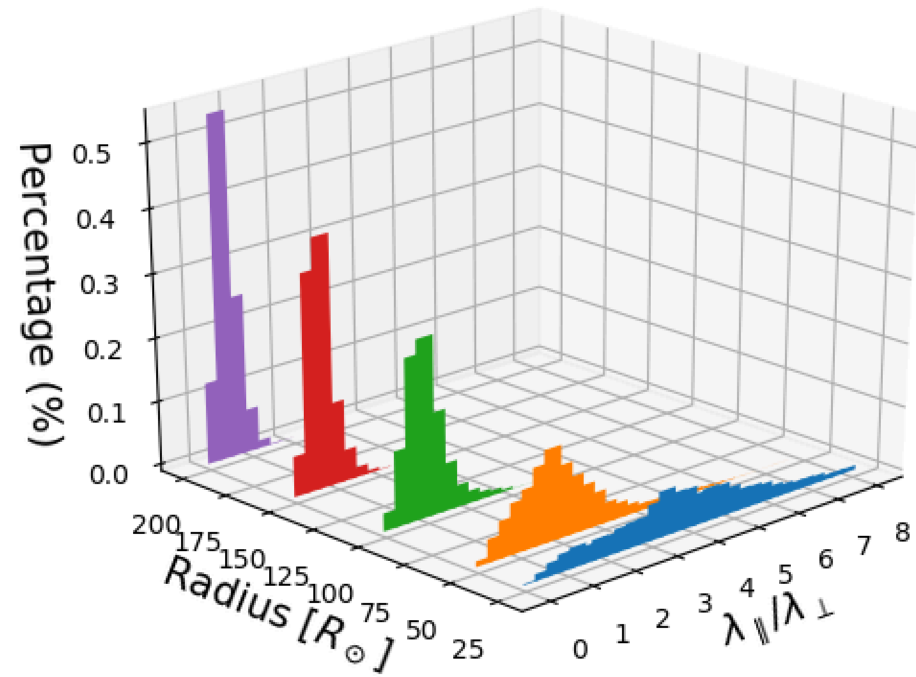


Realistic solar configurations

Minimum



Maximum



→ Histograms show different behaviors with the distance to the Sun, especially at minimum of activity

Conclusions and Perspectives

Conclusions:

- Implementation of the parallel and perpendicular diffusion in post-process of polytropic wind simulations
- Study of the impact of amplitude, topology and energy
- Application to real configurations in 3D

→ Impact of amplitude on radial gradients, topology on latitudinal gradients

→ GCRs have more spread distribution in diffusion than SEPs

→ More difference in diffusion with the distance to the Sun in minimum of activity

Perspectives:

- Addition of the drift coefficient in diffusion
- Alfvén-wave driven wind model
- Solver for the full Fokker-Planck equation

To read more:

- Article published in the topical issue of JSWSC "Space climate: The past and future of solar activity": https://doi.org/10.1051/swsc/2020057
- Results of the simulations available for visualization on the MEDOC facility : https://idoc.ias.u-psud.fr/wind_predict_cr/