Diagnostic of the suprathermal electrons strahl scattering mechanism with Parker Solar Probe and Solar Orbiter data

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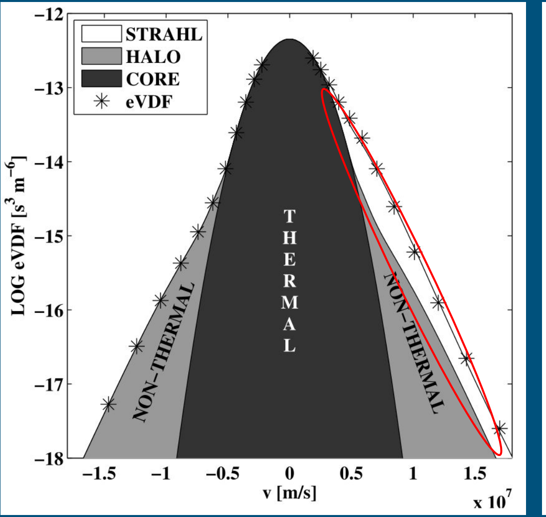
Introduction

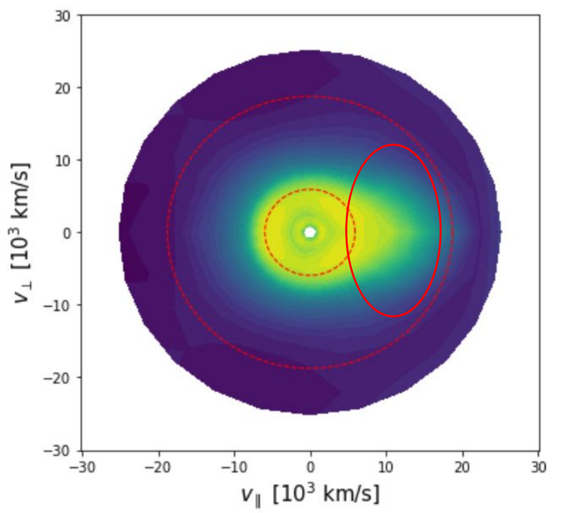
Electrons populations and sources

There are different electron populations

- Core at thermal equilibrium
- Suprathermals at higher energies
  - Strahl aligned with $\vec{B}$
    - Simple history
    - Comes straight from the Sun
  - Isotropic halo
    - More complex history
    - Scattered at high distances



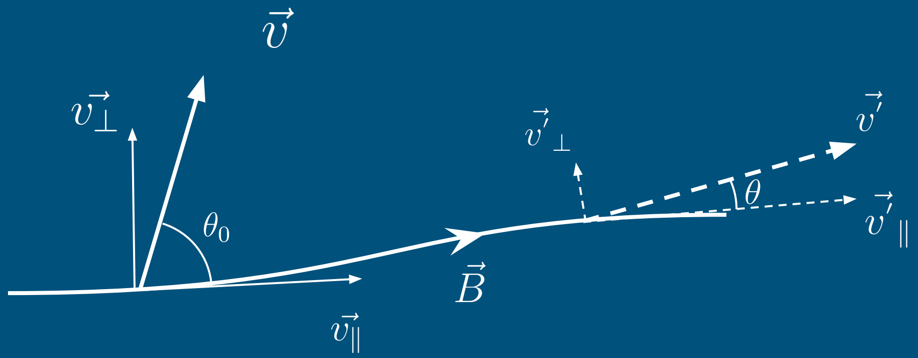
Components of a 1D velocity distribution function
Štverák et al. 2009



2D velocity distribution function
Zaslavsky et al. 2024

Introduction

Scattering effect



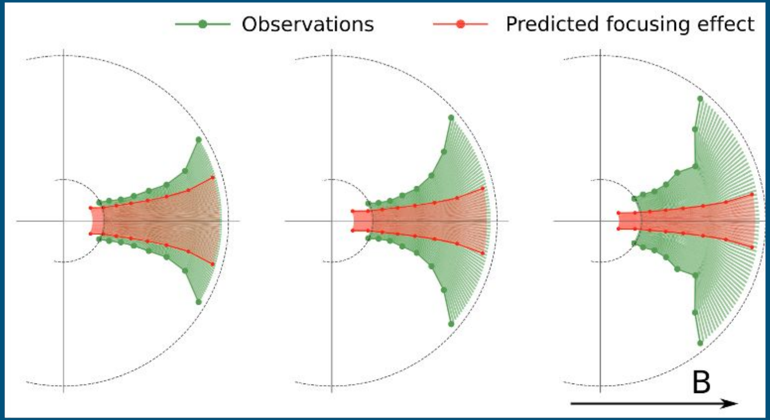
- Presence of the strahl is expected
  - From conservation of magnetic moment and energy we can show :

$$\sin\theta = \sin\theta_0 \sqrt{\frac{B_0}{B}}$$

  - With $\theta_0 = 90°$ and $B \propto R^{-2}$
    - $\theta < 10°$ in less than $10\mathrm{R}_\odot$

- Focusing is deterministic and known

- Unknown scattering processes diffuse the electrons' pitch angle



Predicted vs Observed evolution of velocity distribution functions

Bercic et al. 2019

Introduction

Quantify the local scattering

- We define the Strahl Pitch Angle Width (SPAW) as the 2nd moment of the pitch angle distribution :
  - Calculated with a gaussian fit of the distribution
  - $f(\theta) = ae^{-\theta^2/2\sigma^2} + bck$
  - $\langle\theta^2\rangle = \dfrac{\int e^{-\theta^2/2\sigma^2}\sin(\theta)\theta^2 d\theta}{\int e^{-\theta^2/2\sigma^2}\sin\theta d\theta}$
  - $\text{SPAW} = \sqrt{\langle\theta^2\rangle}$

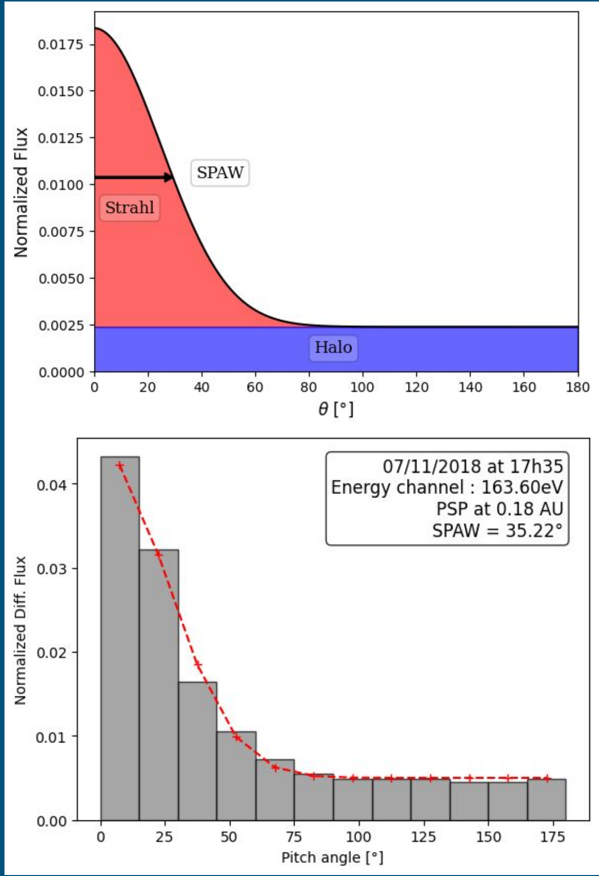
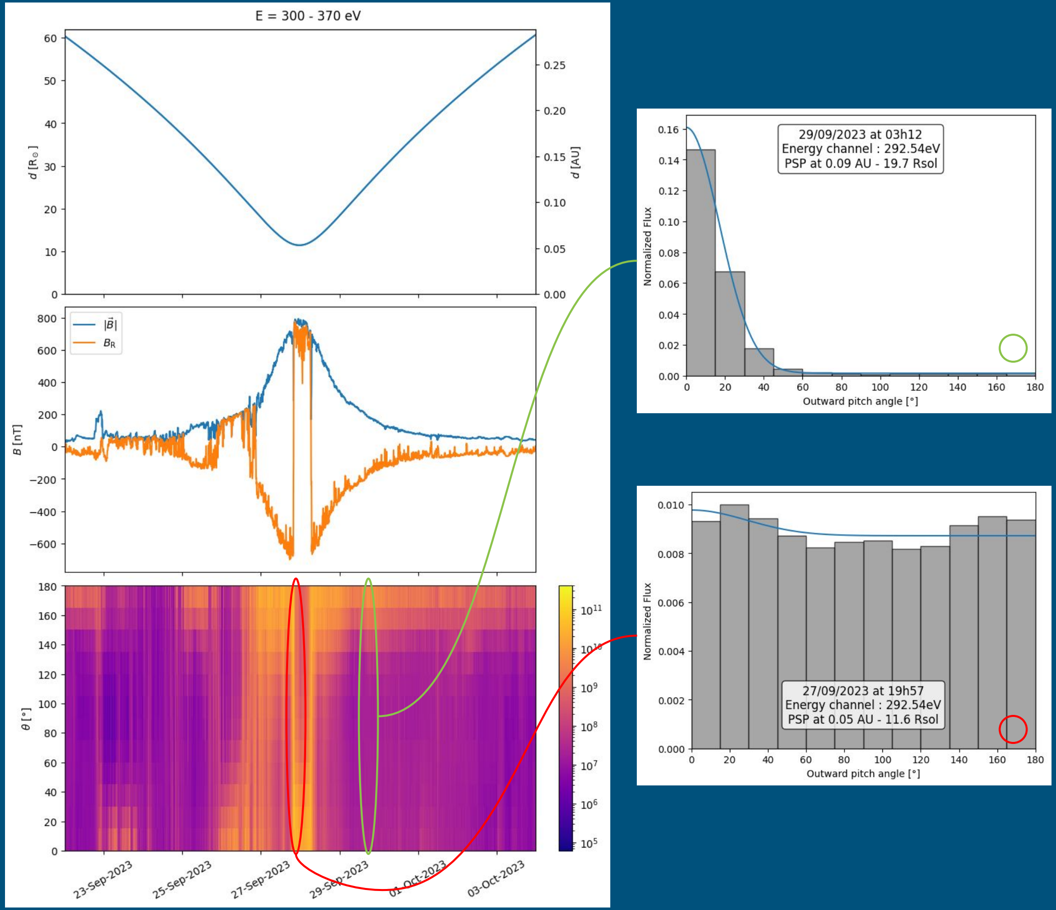


Diagram of electrons populations on a pitch angle distribution and example of a PAD measured by PSP

Introduction

Intervals selection and filtering

- Data are averaged over 5 and 10 minutes intervals
    - Complex magnetic structure can create distributions with more complex features
    - Intervals with a stable magnetic field were selected
    - Scattering due to HCS crossing or other complex local structures is filtered

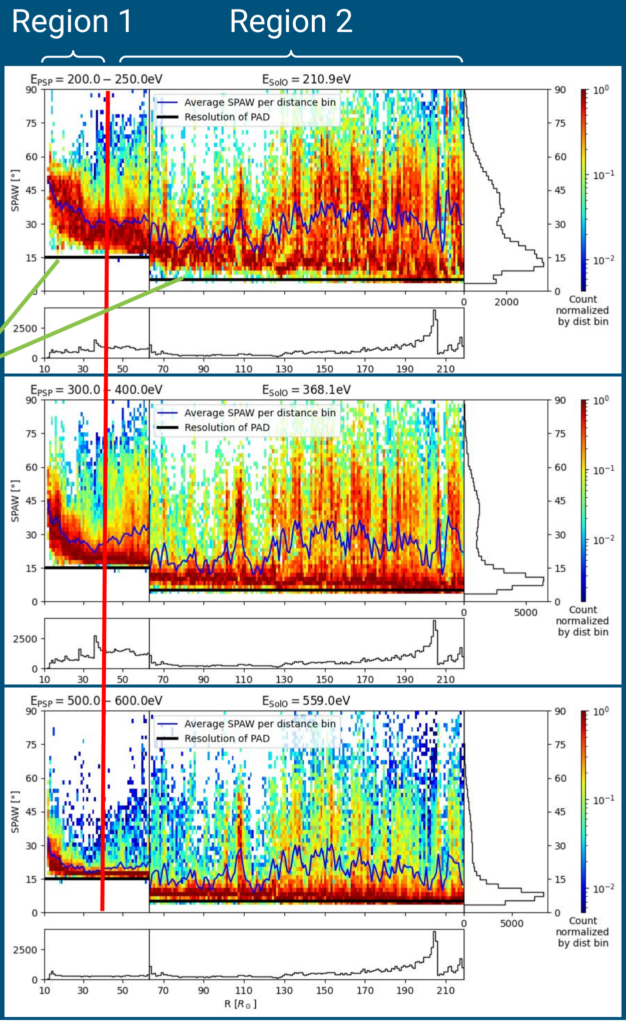


Results

<u>SPAW dependency to solar distance :</u>

- 2 main regions :
  - Region 1 : $r \lesssim 35 R_\odot$
    - $\mathrm{SPAW} \searrow$ with the energy
    - $\mathrm{SPAW} \searrow$ with r
  - Region 2 : $r \gtrsim 35 R_\odot$
    - Two categories of SPAW
      - Low values in a narrow range
      - Higher values with a broader range

Resolution of PADs



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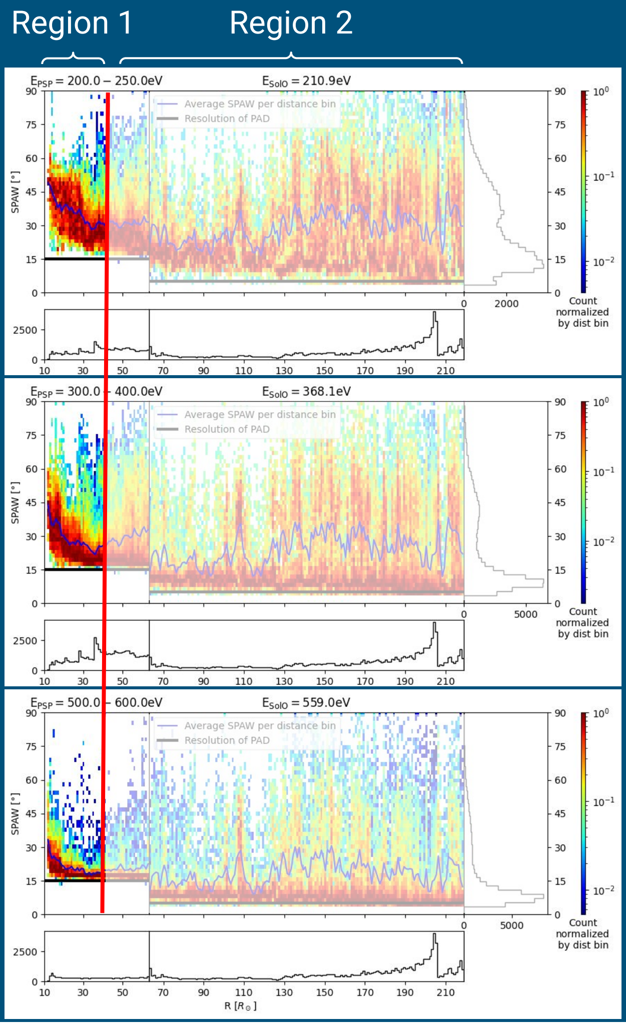
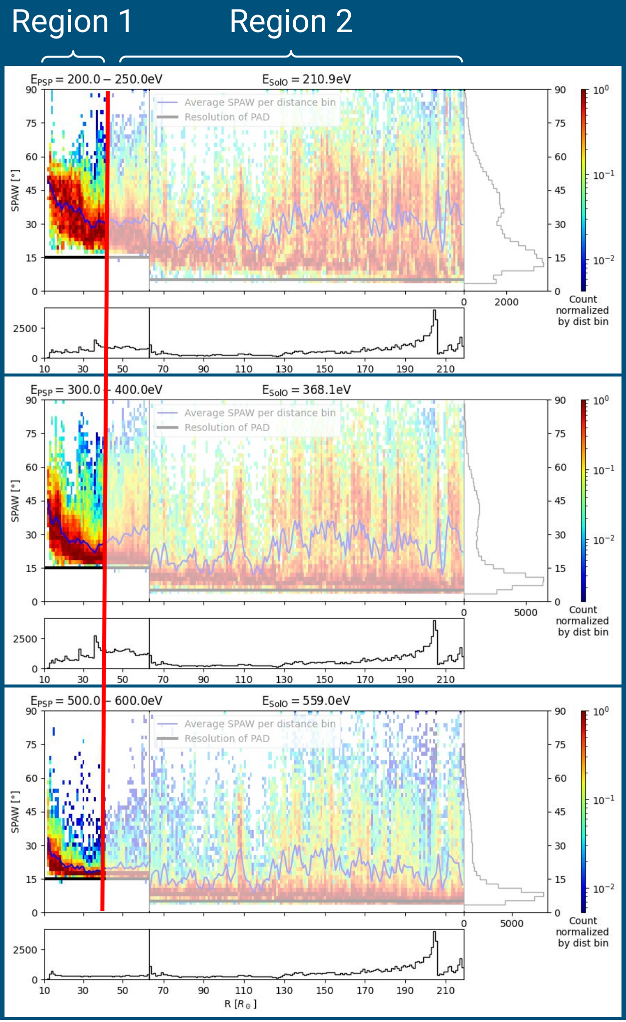


Results

SPAW dependency to solar distance :

- Coulomb collision cross section :
  - $\sigma = e^4/16\pi\varepsilon_0^2 m^2 v^4$
  - Or : $\sigma \propto E^{-2}$
  - High energies = less effective collisions
- Using this expression and a Fokker Planck modelling [Zaslavsky et al. 2025] we obtain for Coulomb collision :

$$\langle\theta\rangle^2 \propto \frac{n}{E^2} \Rightarrow \text{SPAW} \propto \frac{n^{1/2}}{E}$$

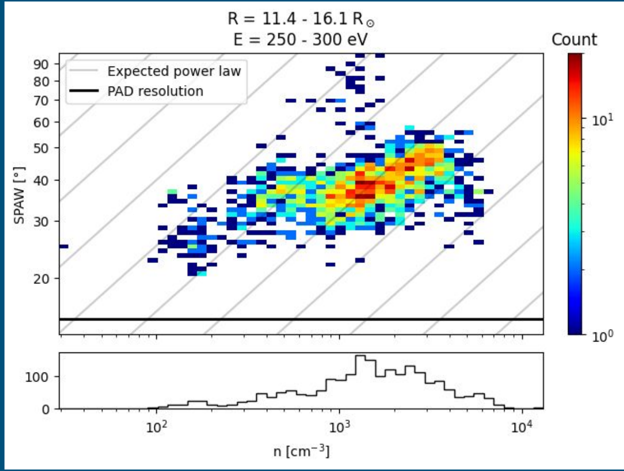


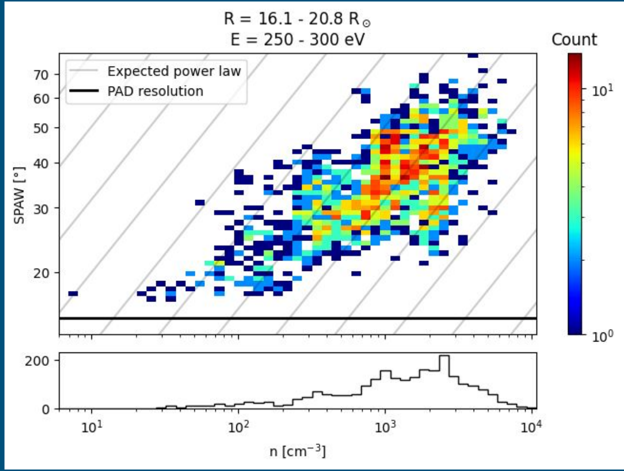
Results

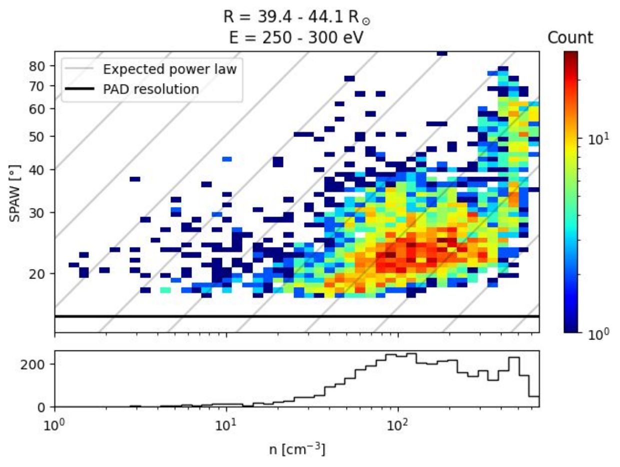
PSP in region 1

<u>Prediction :</u>

- For a diffusion only caused by Coulomb collision the theory predicts : $\langle\theta^2\rangle \propto \frac{n}{E^2} \Rightarrow \mathrm{SPAW} \propto \frac{n^{1/2}}{E}$







Results

PSP in region 1

Prediction :

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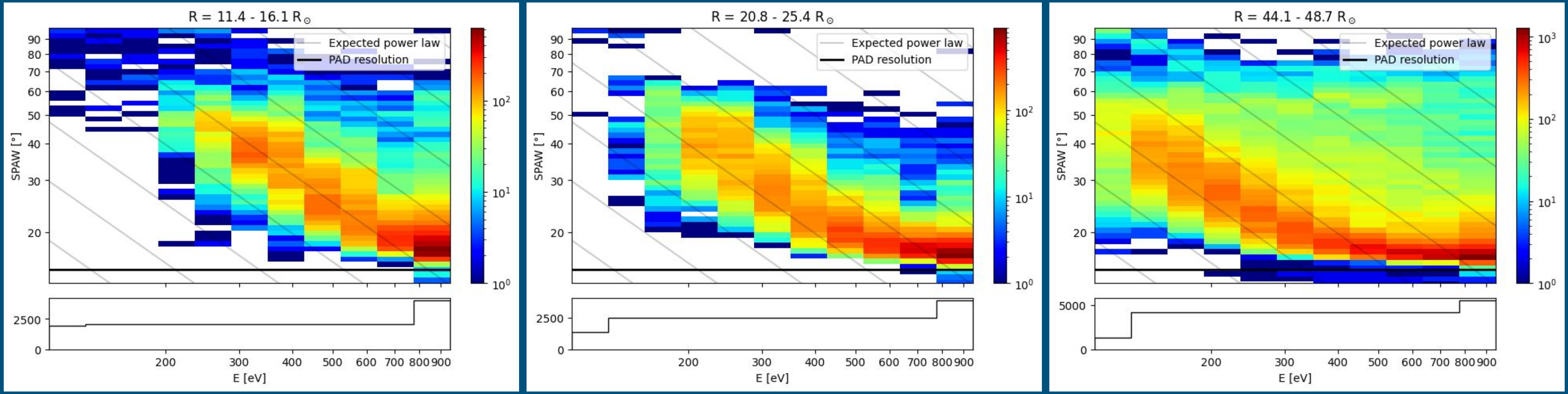


Results

PSP in region 1

<u>Takeaway n°1 :</u>

- The angular width of the suprathermal electrons is regulated by Coulomb collisions close to the Sun

Results

SolO in region 2

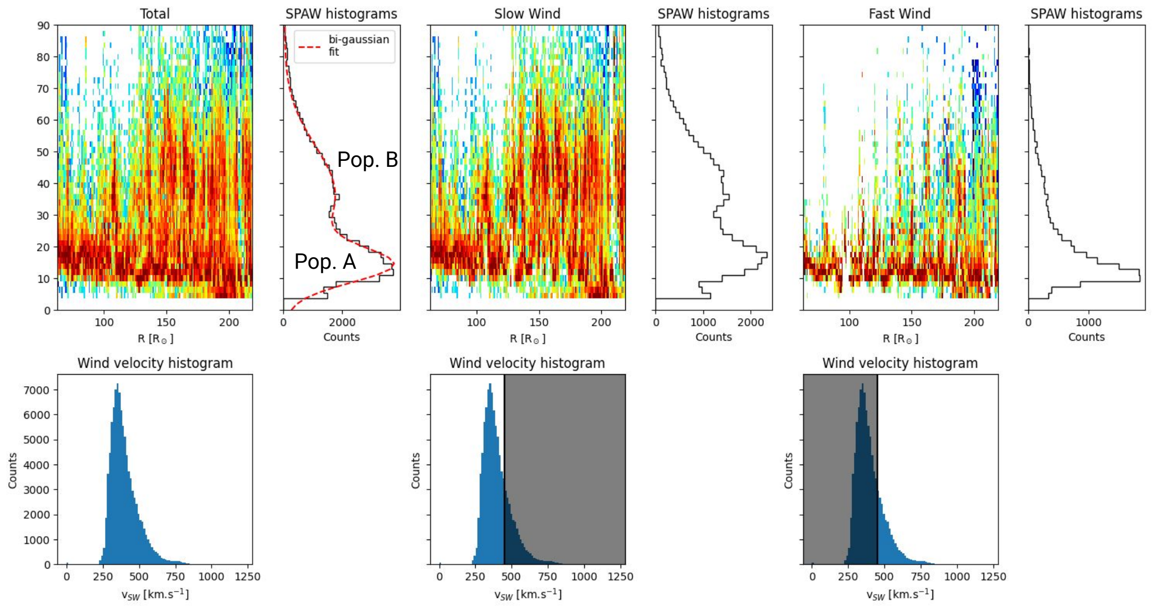
Relation between solar wind speed and the two strahl populations

Population A :

- Low SPAW values
- Small range (~10 to ~25°)
- Correlated with fast wind

Population B :

- Higher SPAW values
- Broader range of SPAW values (~25 to ~80°)



Results

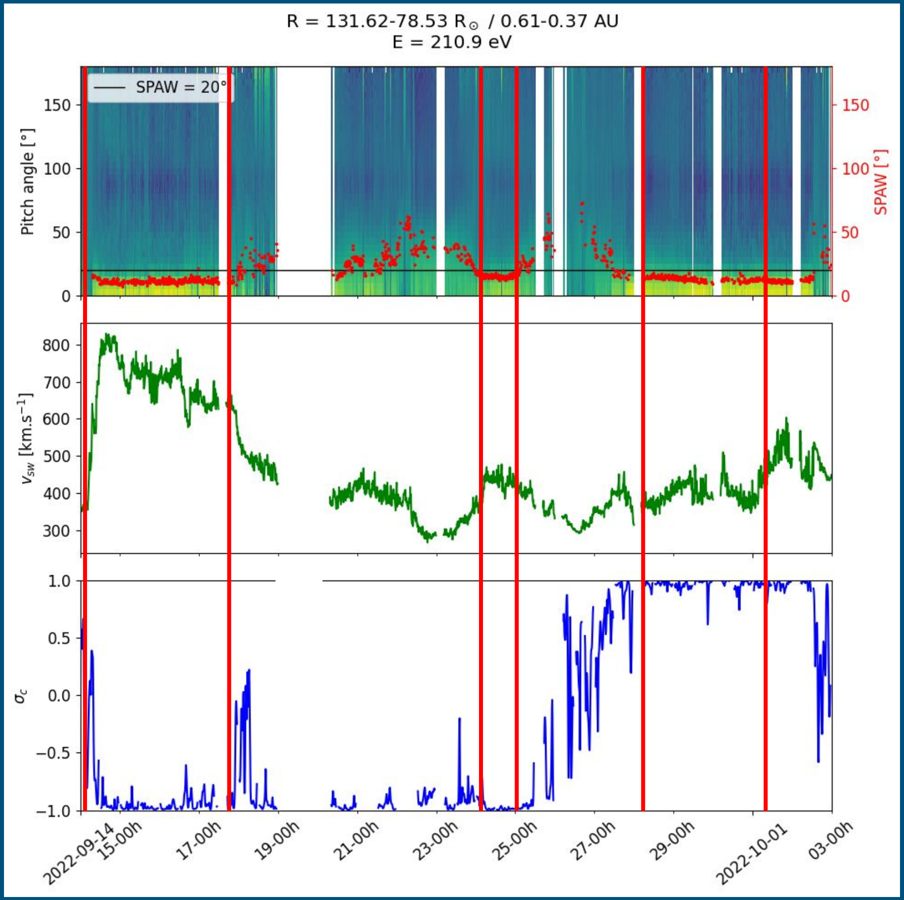
SolO in region 2

Slow Alfvénic wind intervals
from d'Amicis et al. 2025

Population A is observed in fast wind

- Expected from previous slide

But also in slow alfvénic wind !



Fast wind

Alfvénic slow winds

Results

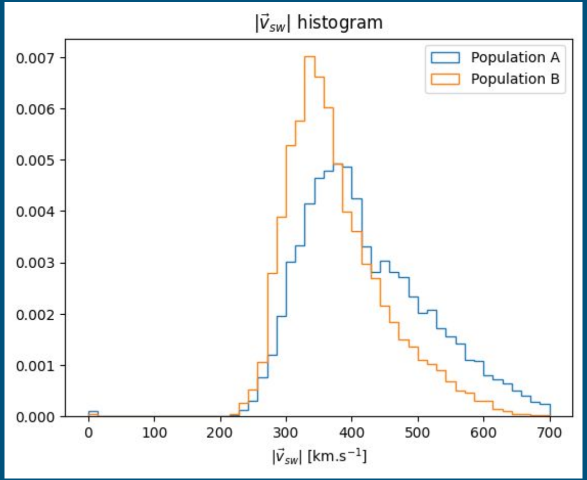
SolO in region 2

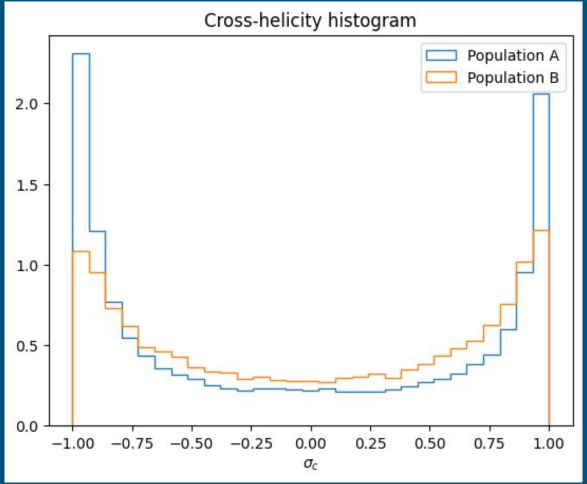
Population A is observed in fast wind

- Expected from previous figure

But also in slow alfvénic wind

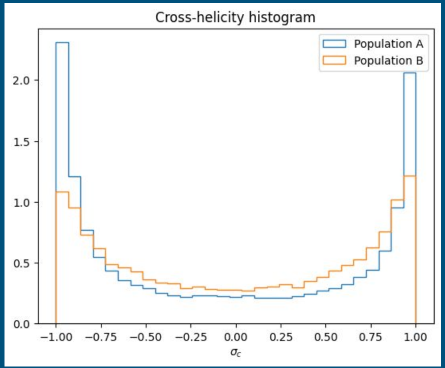
- Not only during one interval

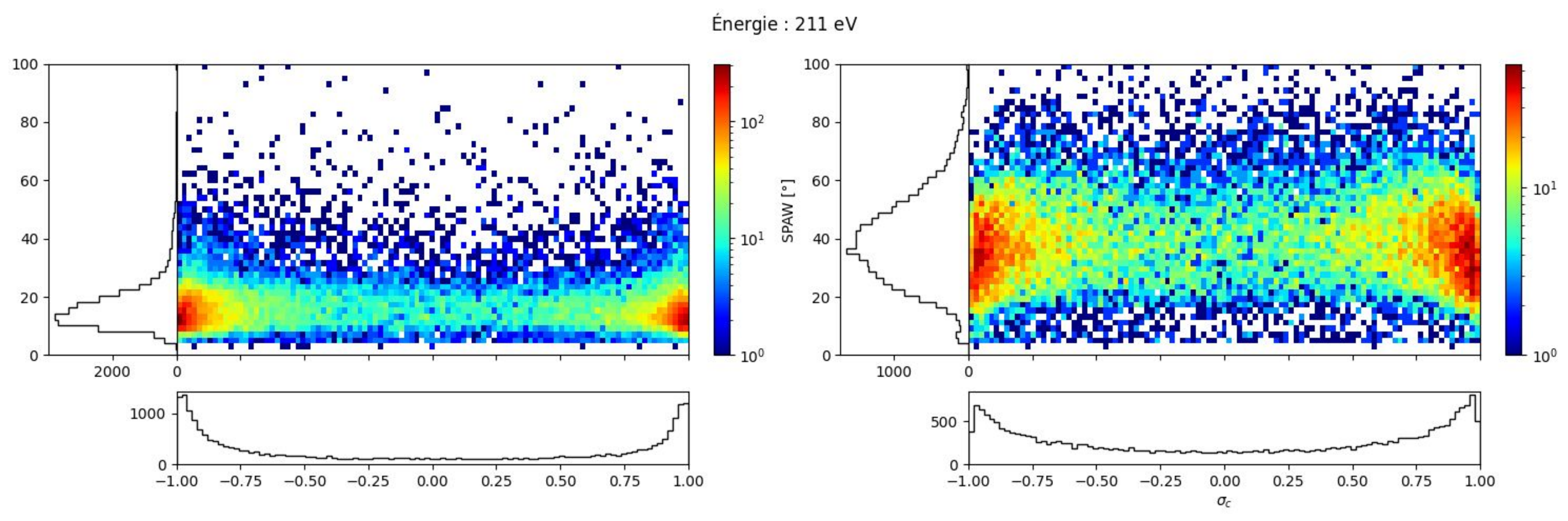




Results

Region 2





Results

PSP in region 1

Takeaway n°2 :

- In the region 2, the narrowest distributions are mostly founds in **alfvénic intervals**

Summary

- Statistical study of the strahl pitch angle width as a proxy for scattering process
- First highlighting of the Coulomb collision effect close to the Sun with PSP data
- Two different strahl populations further from the Sun
  - Correlation with solar wind speed
  - More likely correlated with alfvénicity
    - Impact of the nature of magnetic fluctuations to be studied

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Questions ?

Introduction

Modelisation of the scattering/focusing competition

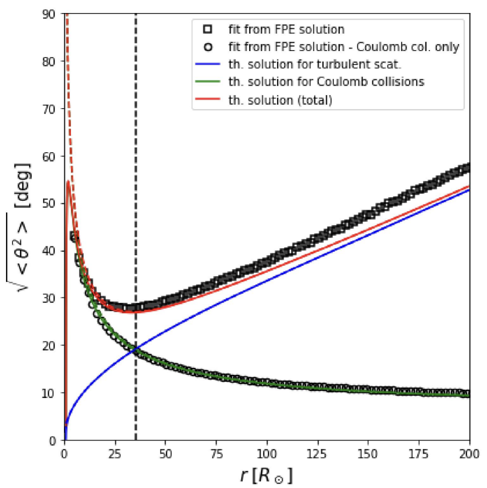
Zaslavsky et al. 2024, Zaslavsky et al. 2025

Evolution of the distribution function equation

$$\underbrace{\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial s}}_{\text{Free evolution}} + \underbrace{\frac{(1-\mu^2)v}{2L_B(s)} \frac{\partial f}{\partial \mu}}_{\text{Magnetic focusing}} = \underbrace{\frac{\partial}{\partial \mu} \frac{(1-\mu^2)\nu}{2} \frac{\partial f}{\partial \mu}}_{\text{Diffusion}}$$

With :

- $\mu = \cos\theta$ the pitch angle cosine
- $\nu = \frac{v}{\lambda}$ such as the isotropization acts over a time ν^{-1} with λ the scattering free mean path.
- s curvilinear coordinate along a magnetic field line



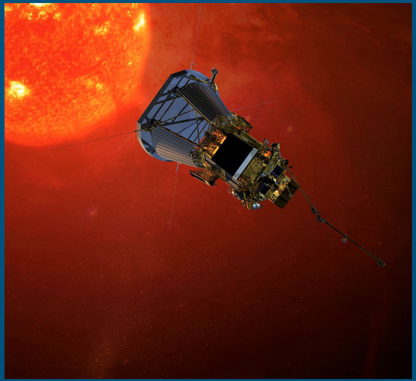
Numerical solving of the Fokker-Planck equation for 150eV electrons with 2 scattering mechanisms. Coulomb collisions and a turbulent scattering with $\lambda = 1\ \mathrm{AU}$

Zaslavsky et al. 2025

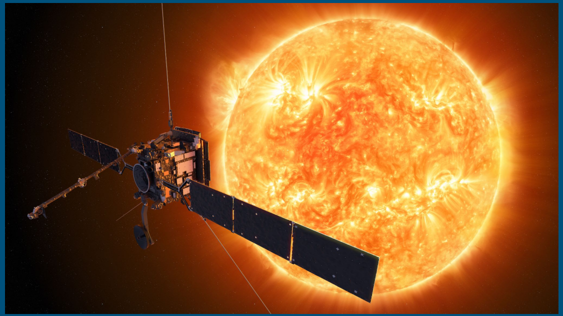
Data

Parker Solar Probe (PSP) and Solar Orbiter (SolO)

- Distance from the Sun for used data :
  - PSP : 10 $R_\odot$ to 60 $R_\odot$
  - SolO : 60 $R_\odot$ to 210 $R_\odot$
- Instruments :
  - Magnetometers
  - Electrostatic analyzers
- Data time range
  - PSP
    - Oct 2018 to Dec 2023 (17 perihelia)
  - SolO
    - 2020 to Dec 2024 (before out of ecliptic phase)



Artist view of PSP
Crédits : parkersolarprobe.jhuapl.edu



Artist view of SolO
Crédits : ESA

Résultats

Région 2

Hélicité croisée σ_c :

- Caractérise les corrélations entre fluctuations de densité et de champ magnétique

- Permet de distinguer les fluctuations alfvéniques (corrélées) des fluctuations compressibles

- Hautement corrélée à la vitesse du vent

- Observations dans l'espace des paramètres
    - Pas les corrélations attendues