Probing turbulent scattering effects on suprathermal electrons in the Solar Wind

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Solar energetic particles times profiles

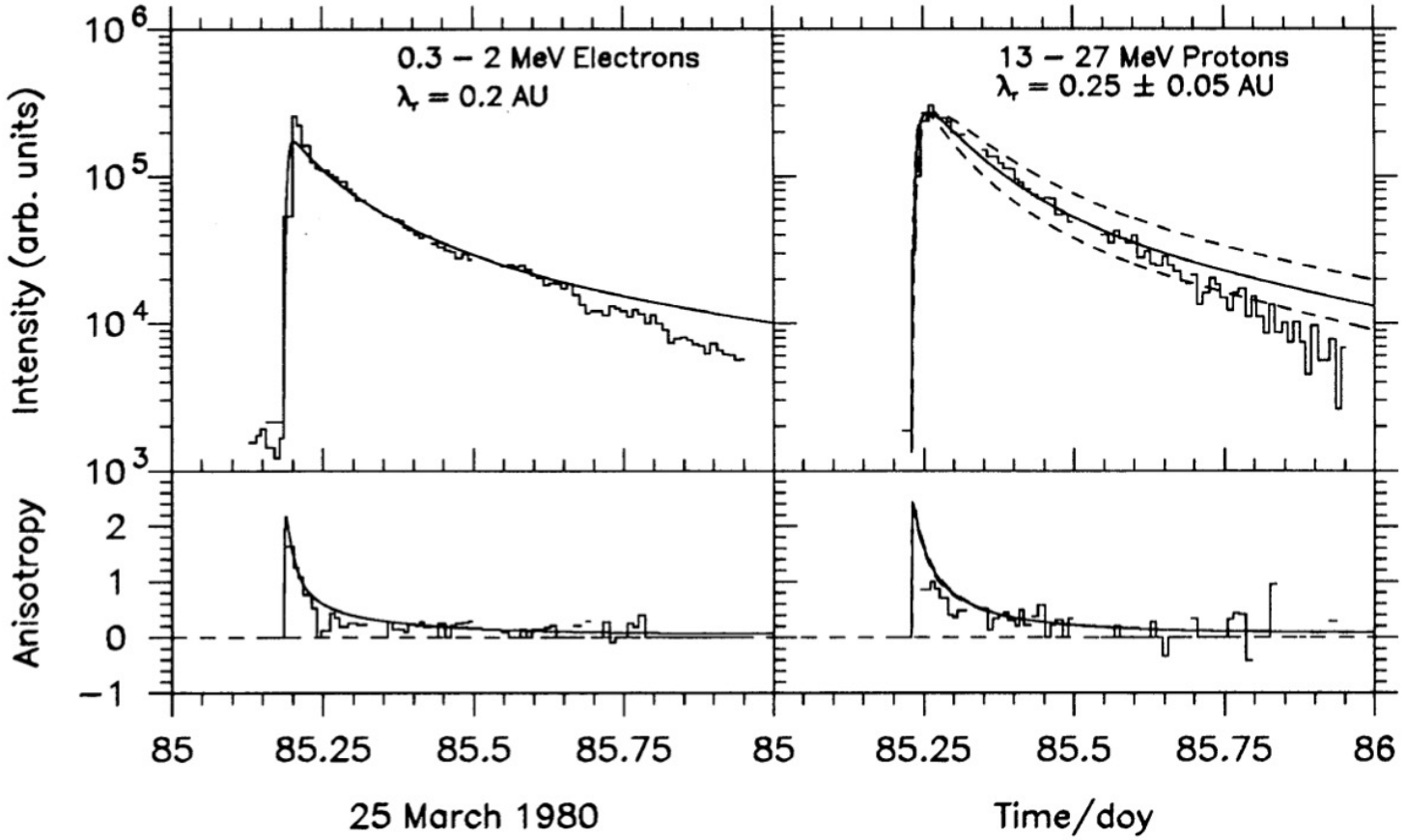


Fig. from [Bieber et al. 1991]

Assuming diffusive propagation :

$$n(r,t) \sim \frac{\eta}{r^2\sqrt{\pi D t}} \exp\left(-\frac{r^2}{4Dt}\right)$$

$$\lambda = D/v$$

Is the scattering mean-free path

The “Palmer consensus”

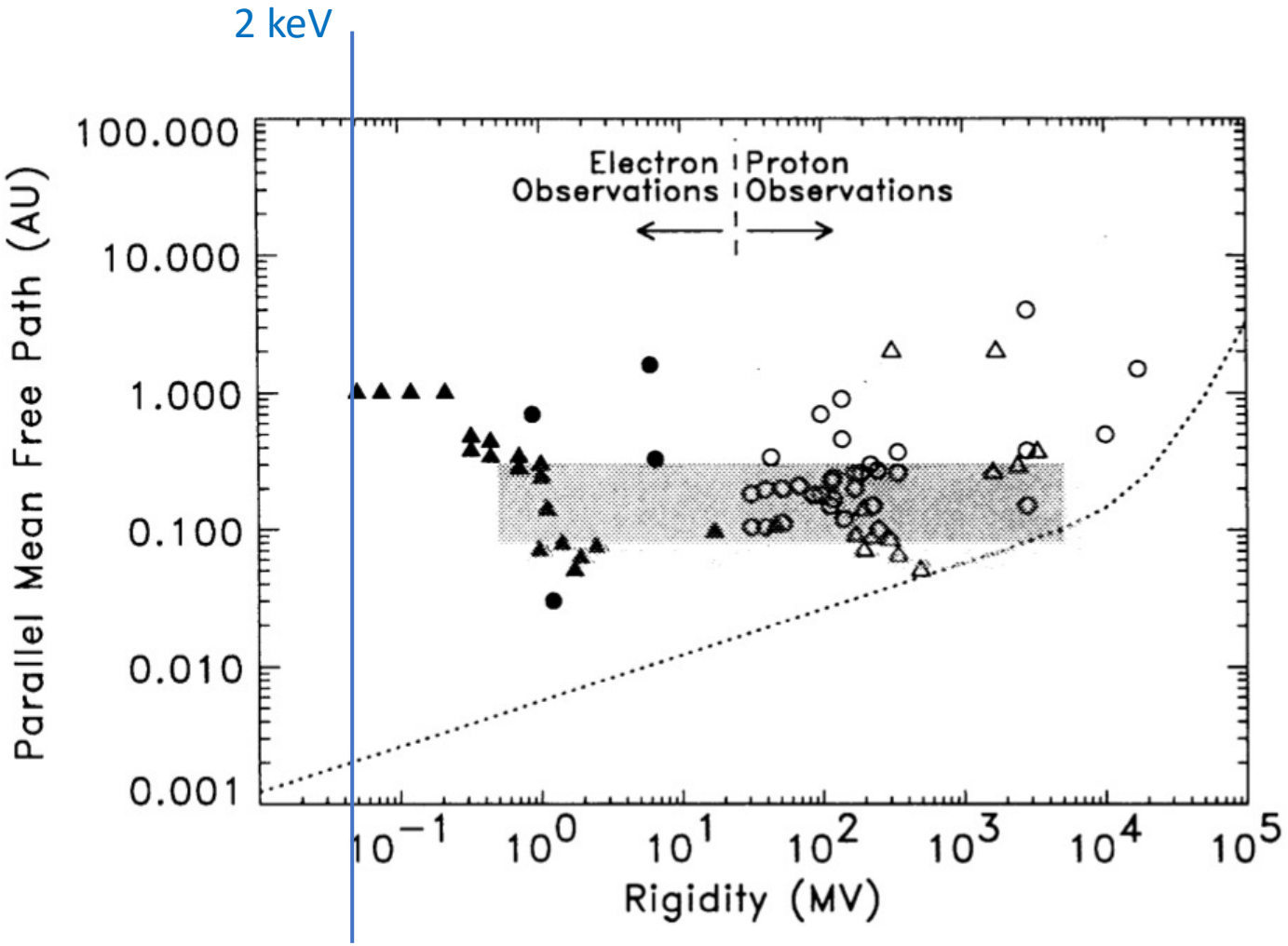


Fig. from [Palmer, 1982]

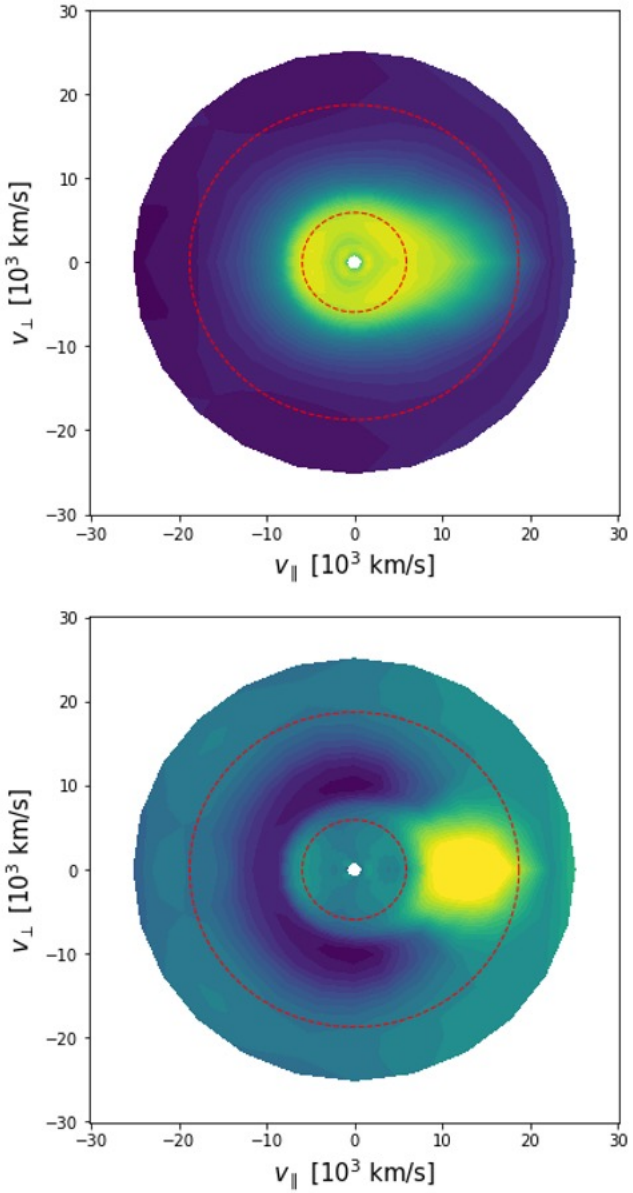
The diffusion mean-free path is rather independent of energy, and is rather the same for protons and electrons.

[not so consensual]

These observations are widely interpreted as the signature of diffusion by interplanetary turbulence (dotted line : quasi-linear approximation for « slab turbulence »).

Interesting for us : the low energy part of the electron events shows a rather constant mean-free path, of the order of 1 AU.

Electron velocity distributions in the solar wind



- The electrons velocity distribution functions measured in the solar wind have an isotropic (gaussian) core up to a few 10's of eV

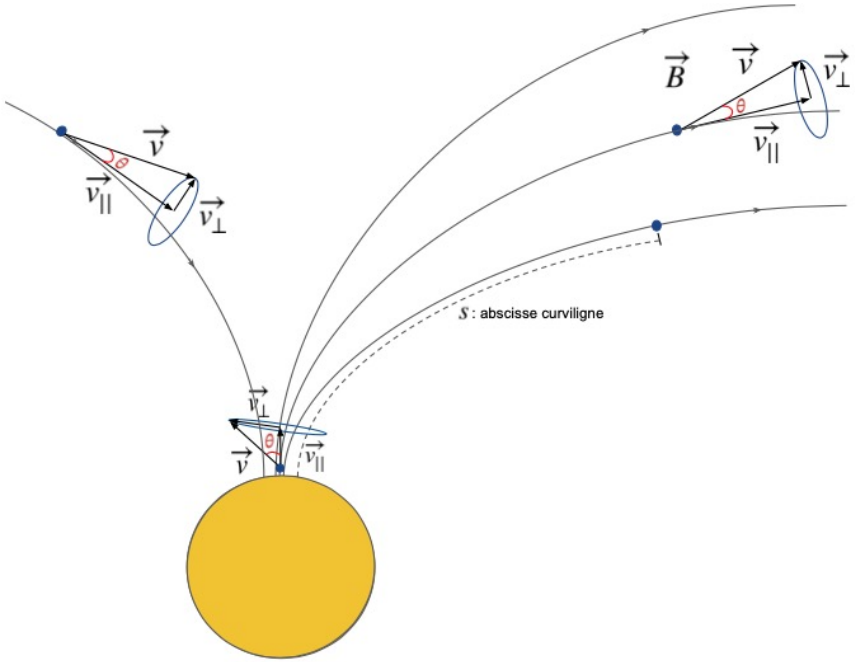
- Electrons vdf measured in the solar wind typically present anisotropies, in particular in the 100eV – 1keV energy range (because of the decrease of coulomb collisions)

- These anisotropies have to be controled by some isotropization process (ex. mirror force would collimate electrons within $\sim 1°$ at 1 AU)

Transport equation

- The energy distributions evolve on slower timescales than pitch angle distributions. So the evolution of PA distribution is to a large extent uncoupled from energy distribution.

- Keeping only the dominent terms in the transport equation, we reach the following equation for the evolution of the electrons distribution function in the $(s, \mu = \cos\theta)$ phase space



$$\mu v \frac{\partial f}{\partial s} + \frac{(1-\mu^2)v}{2L_B(s)} \frac{\partial f}{\partial \mu} = \frac{\partial}{\partial \mu} \frac{(1-\mu^2)\nu}{2} \frac{\partial f}{\partial \mu}$$

Magnetic focusing by mirror force acting on a typical scale

$$\frac{1}{L_B} = \frac{1}{B}\frac{dB}{ds}$$

Isotropic pitch angle scattering by some (yet unspecified) process, acting on a typical scale λ_{turb}

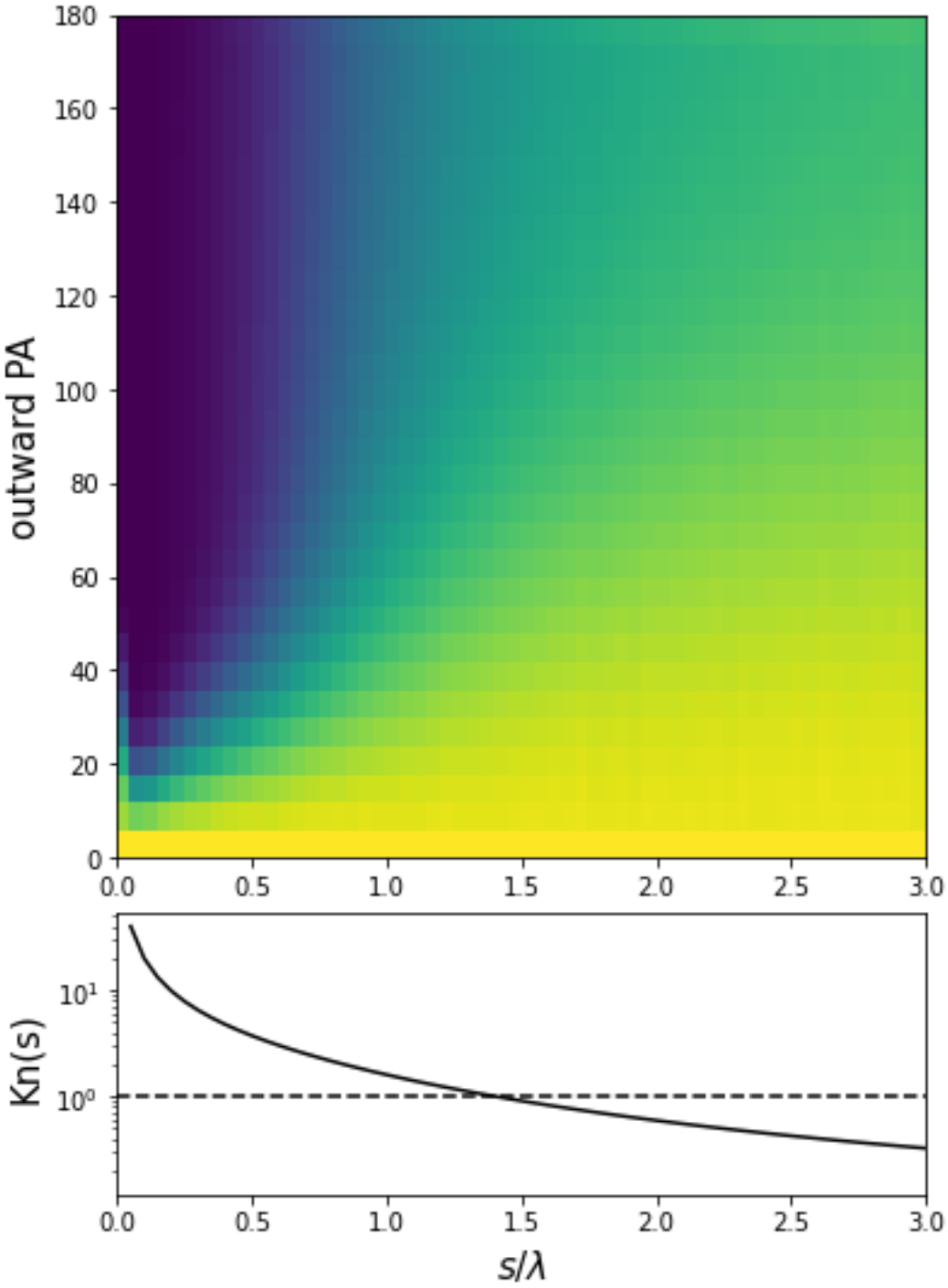
Solutions for a Parker spiral IMF profile, constant scattering mean free path

We investigate the case of a constant (independent of distance to the Sun) scattering mean-free path λ_{turb}, $\mathrm{L_B}$ is given by the Parker spiral.

The solution is obtained by numerical integration of the Fokker-Planck equation.

Boundary condition : isotropic at 0.01 AU (2 Rs) from the Sun's center.

We can observed the broadening of the « strahl » and the appearance of a « halo ».



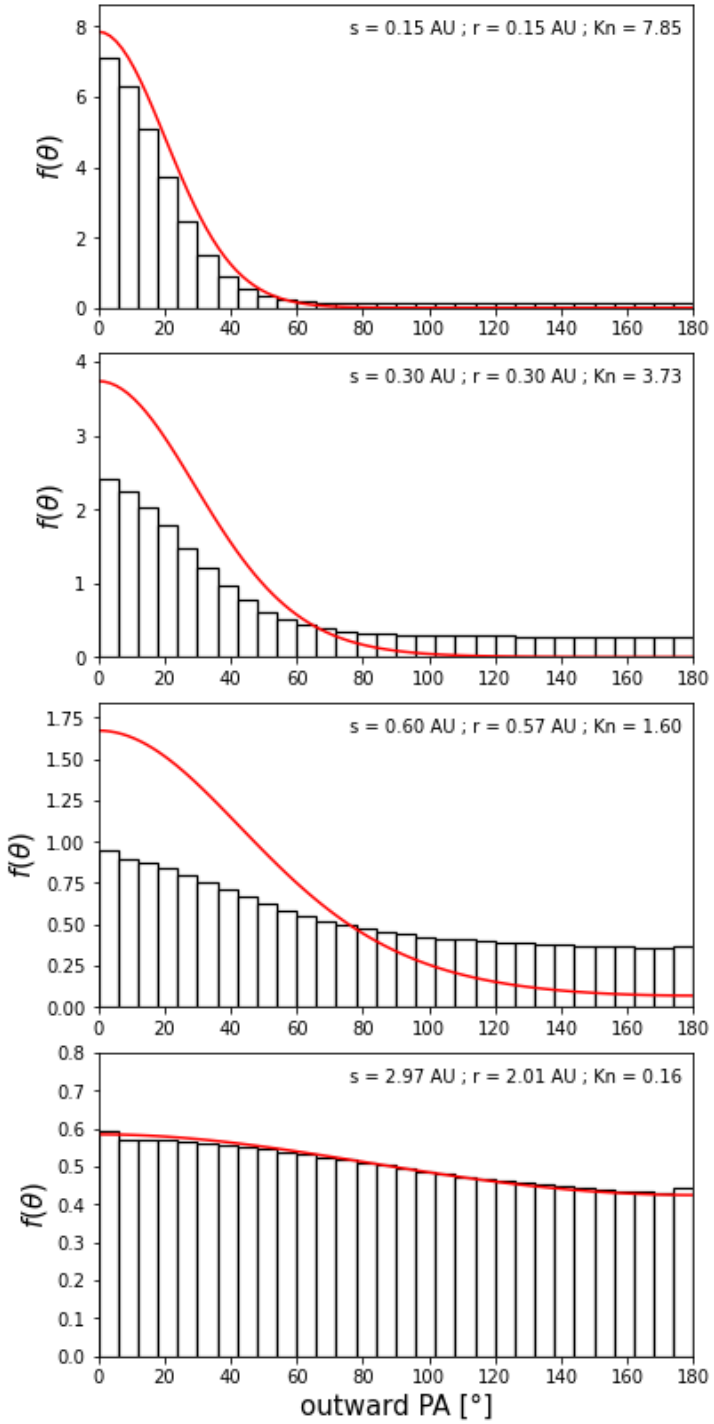
Solutions for a Parker spiral IMF profile, constant scattering mean free path

Analytical solution in the small Kn limit :

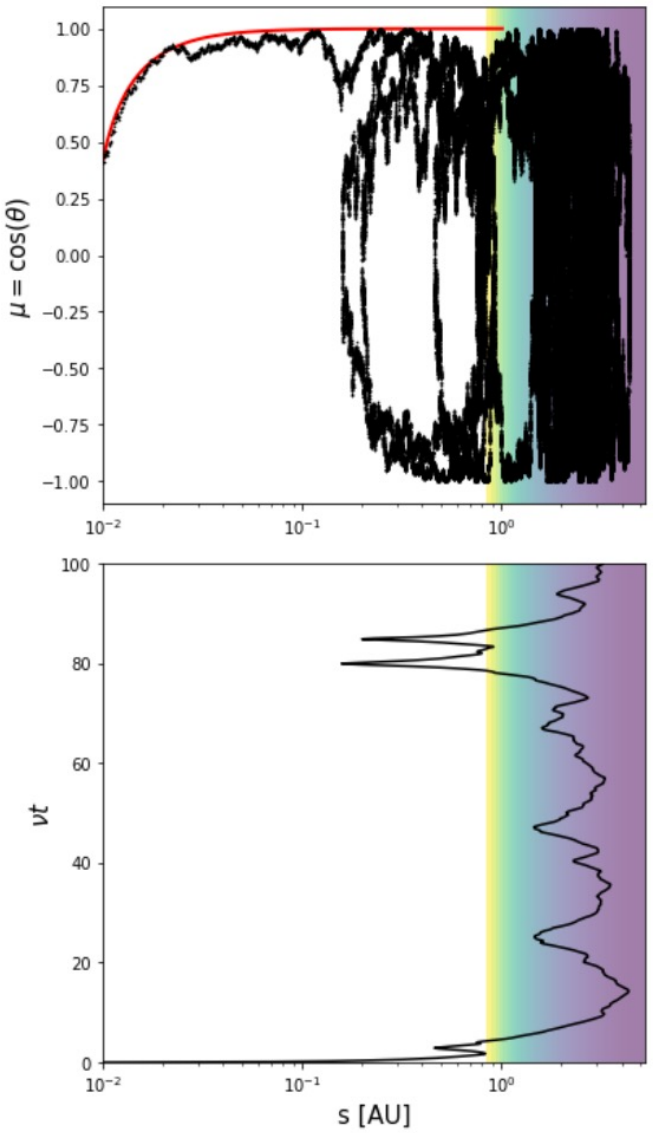
$$f(\theta) = \frac{\mathrm{Kn} e^{\mathrm{Kn}\cos\theta}}{2\sinh \mathrm{Kn}}, \qquad \mathrm{Kn} = \frac{\lambda}{L_B}$$ (Knudsen number)

Comparision of PA distributions with the small Knudsen number limit shows the non-local behaviour of the system in large Kn regions.

Locality is recovered « far away » from the Sun, when K_n becomes small enough (typically <0.1)



What produces the distributions ? A test particle example.



- Close to the Sun, Kn is extremely high, the particle gets focused along field lines.
- The particles travels out along the field line in the region of large Kn: it is then part of the « strahl » particles : the strahl is the local component of the eVDF
- The particles « hits » the small Kn region at large distances and gets isotropized: it is from now part of the « halo » particles.
- Sometimes, the particle escapes the low Kn region and is injected back in the large Kn region: produces the halo component even at small distances from the Sun: the halo is a non-local component of the eVDF.

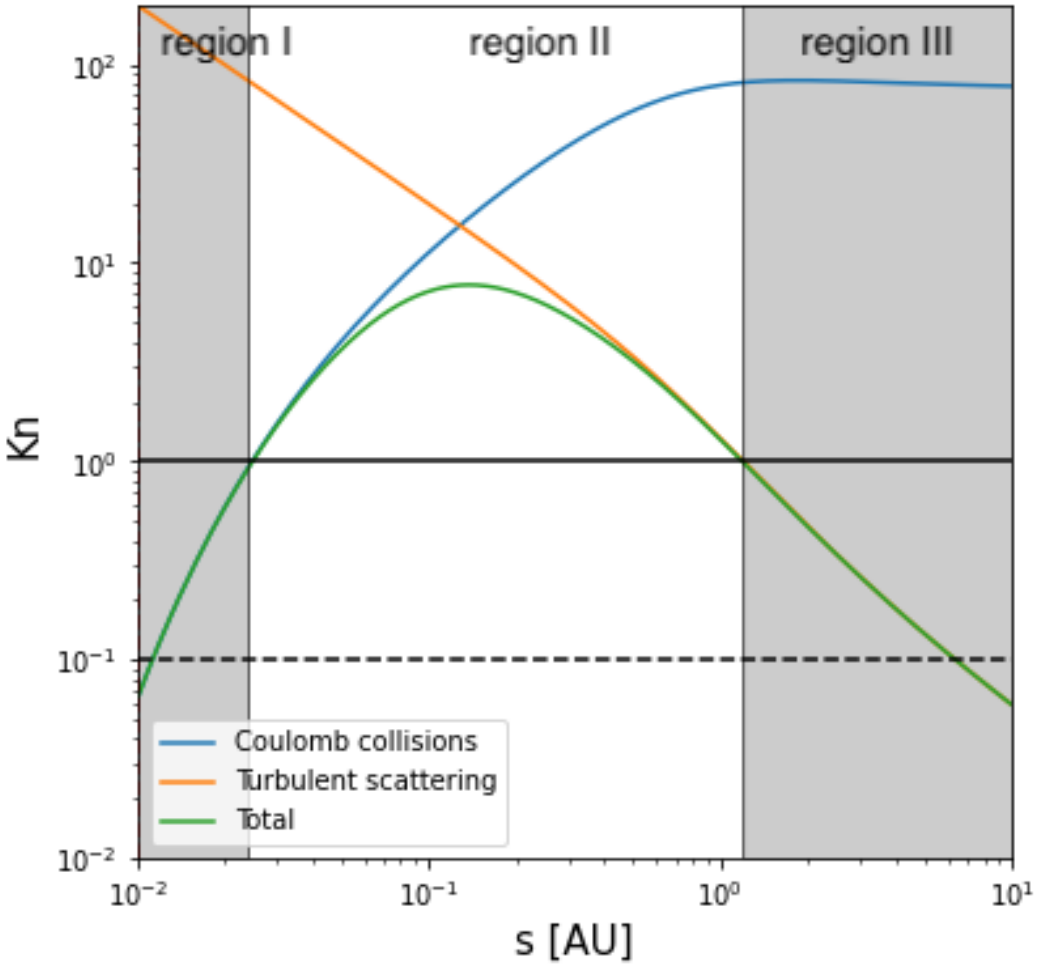
Scattering regions in the “quiet” heliosphere

- Close to the Sun, coulomb collisions are not negligible (because the plasma density is very high). We have the following « Knudsen number » structure for the interplanetary medium

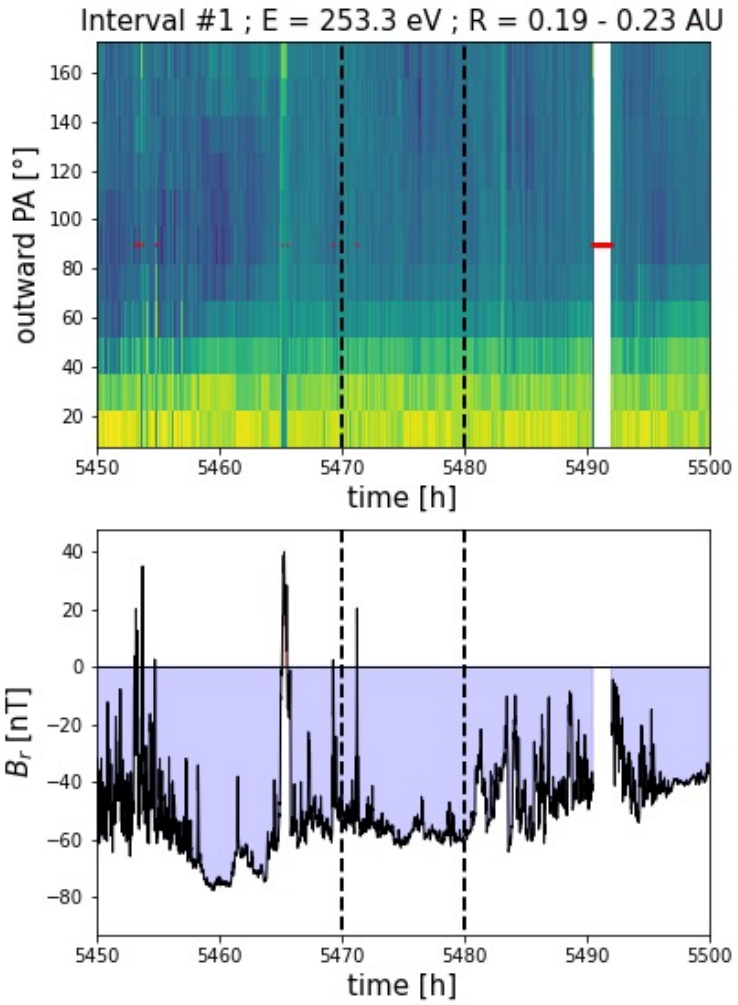
- Here the gray regions correspond to Kn < 1

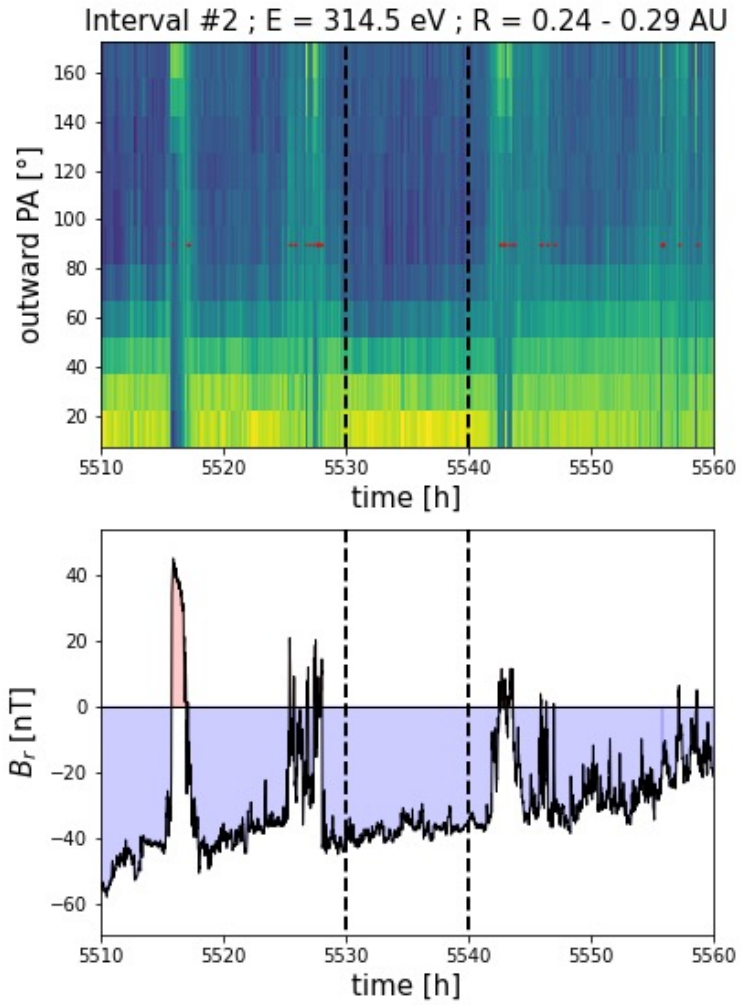
- Defines 3 heliospheric regions:

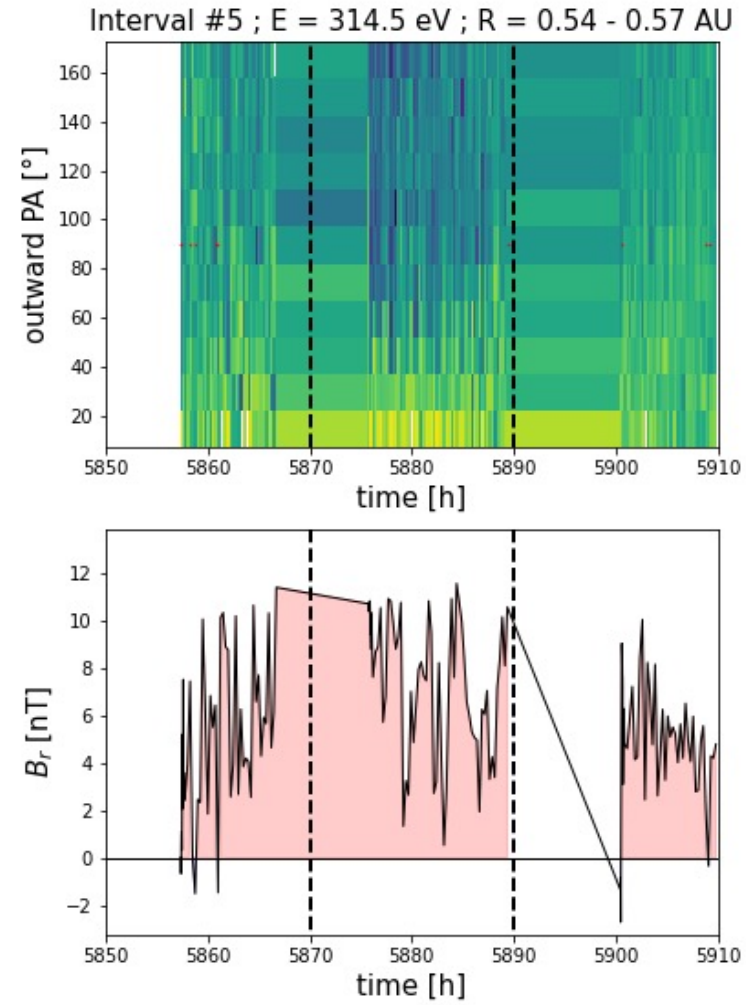
⇒ I : Coulomb collisions scattering dominate
⇒ II : High Kn region, « deterministic behaviour »
⇒ III : Turbulent scattering dominate



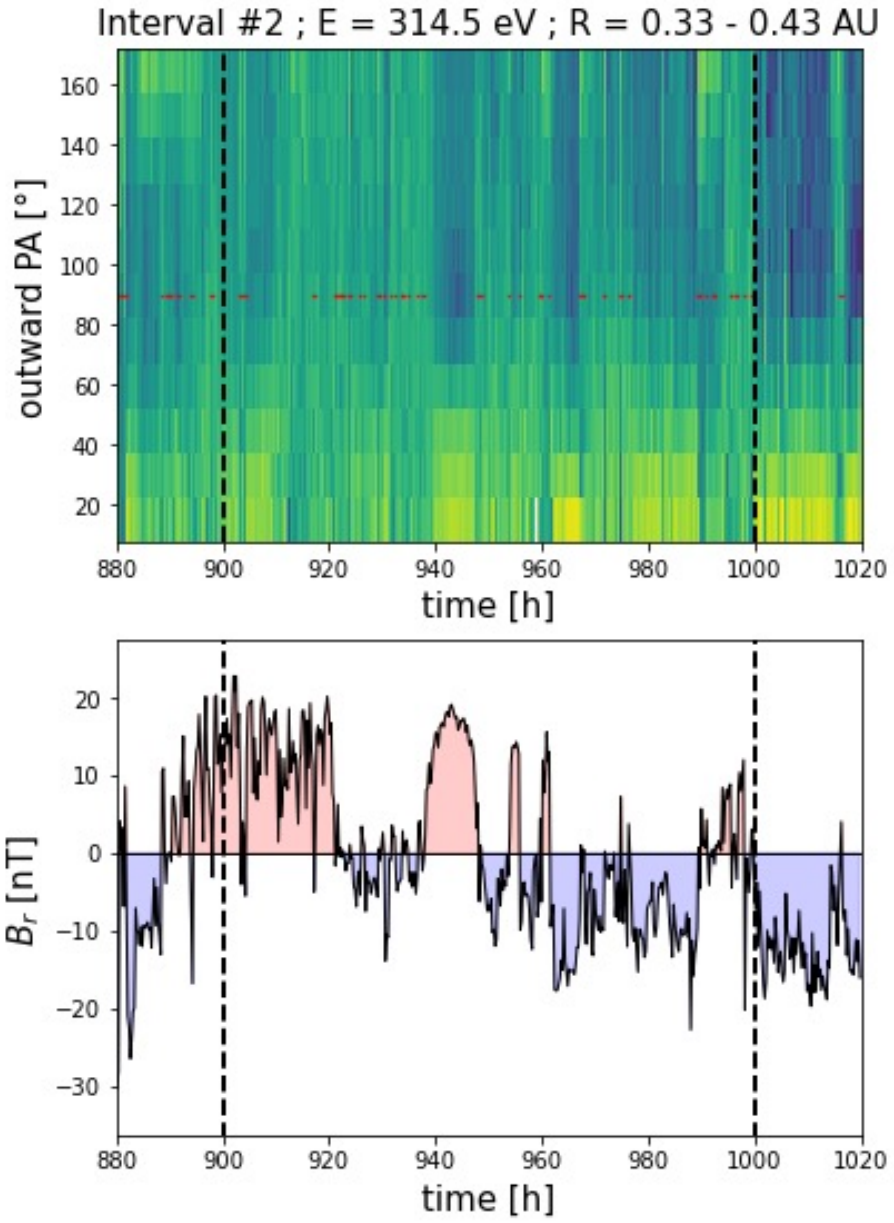
PSP SWEAP interval examples

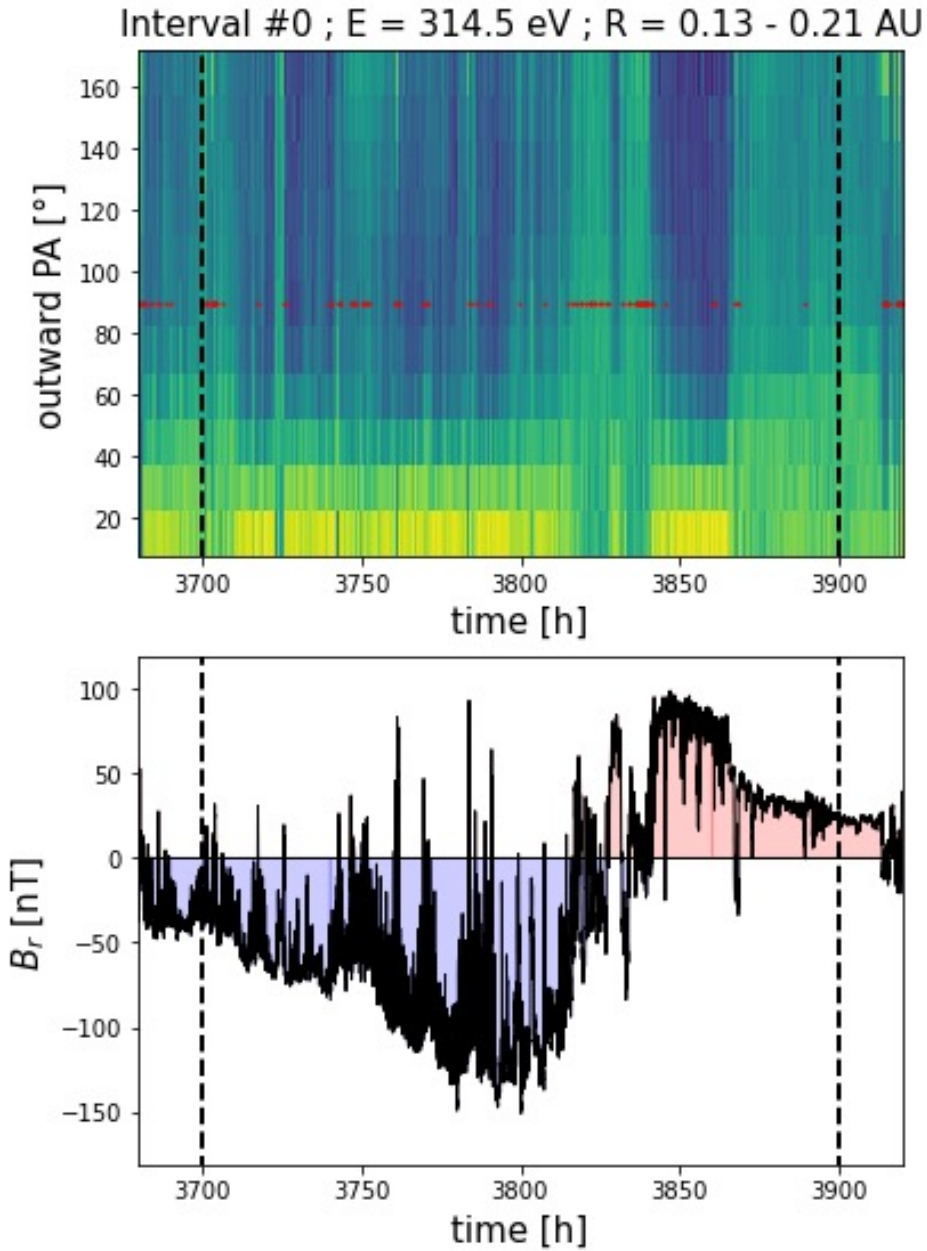




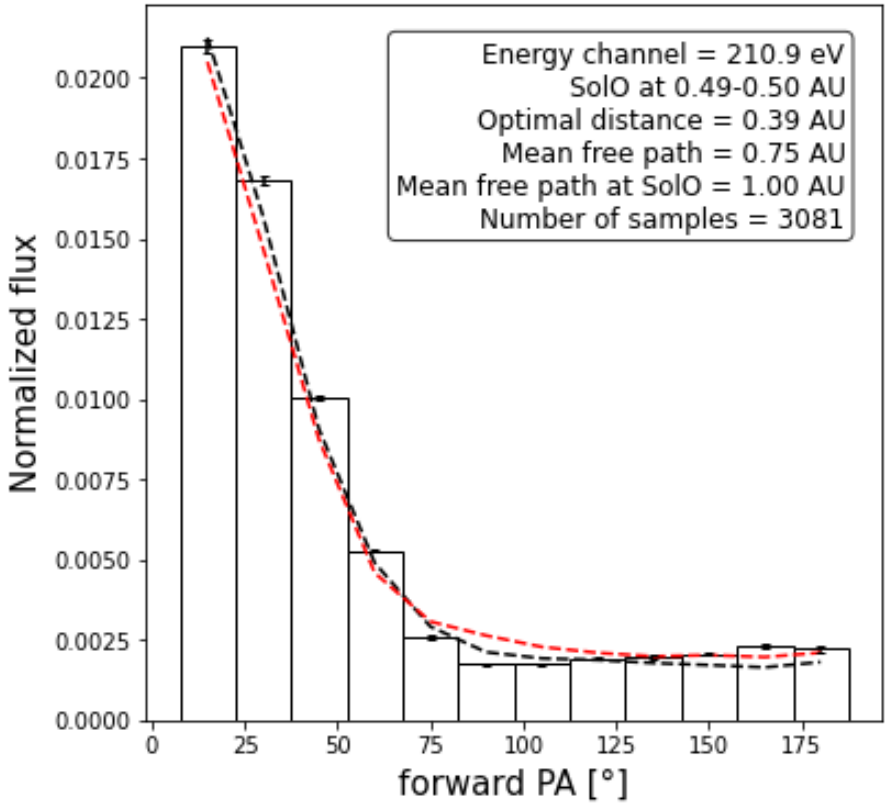


PSP SWEAP “bad/complex” interval examples

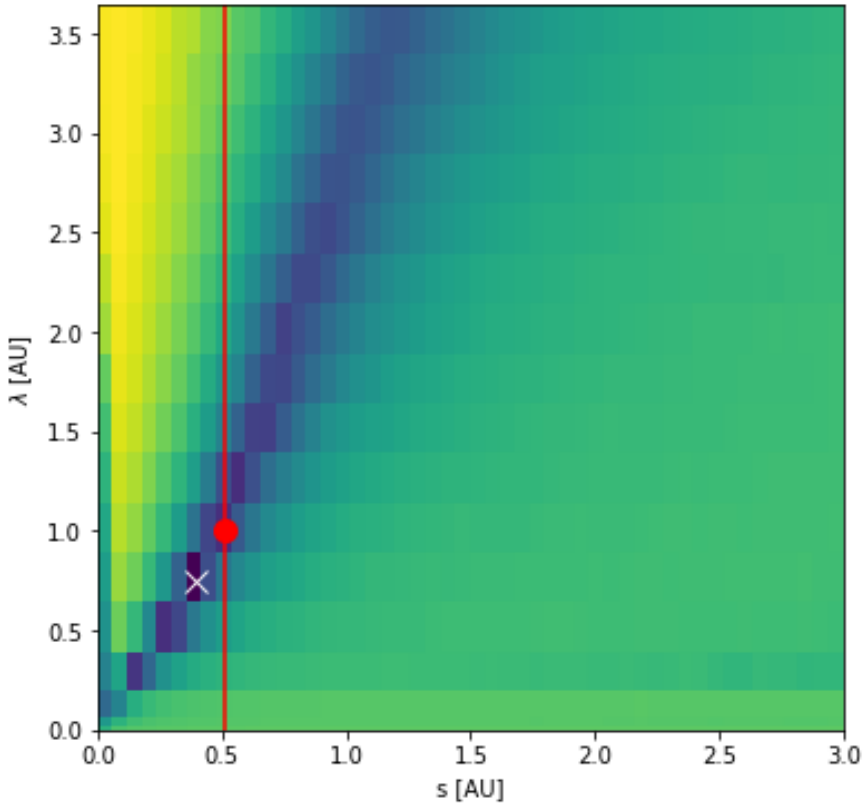




The fitting procedure (a SolO EAS example)



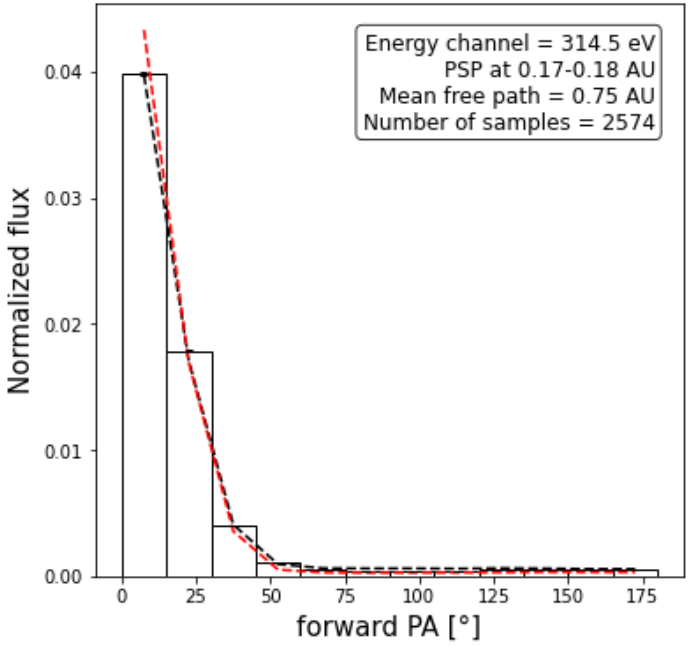
$R^2(s, \lambda)$

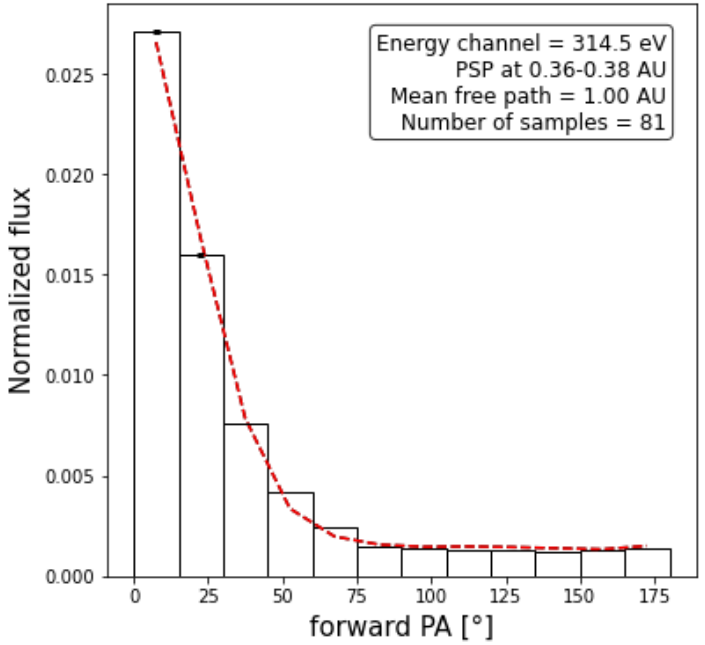


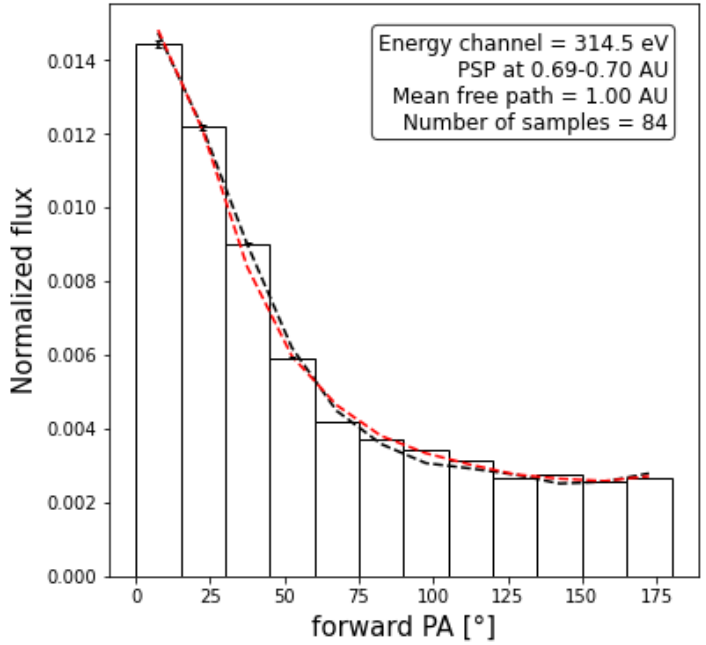
20 x 50 PA profiles are obtained from numerical integration of the FPE
Each of these is compared to SolO or PSP data at each energy and distance

The value of λ minimising the R^2 at the s/c position is retained.

Diffusion profiles at different distances from the Sun (PSP examples)



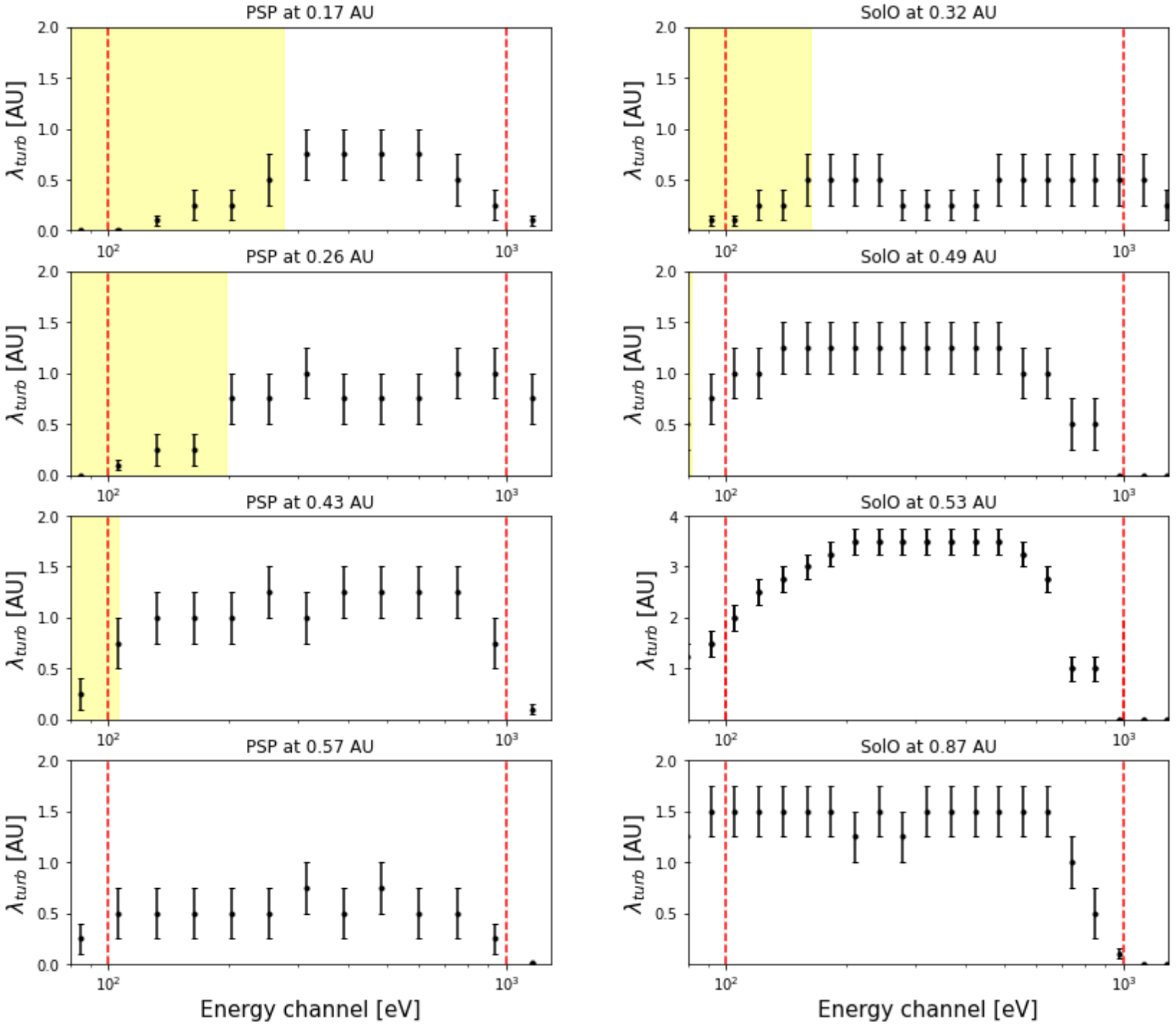




Solutions to the transport equation (with $L_B(s)$ calculated from a Parker spiral with $\psi(1AU) = 45°$) were fitted to the data, varying the mean free path λ as the only free parameter.

Mean free path as a function of the energy

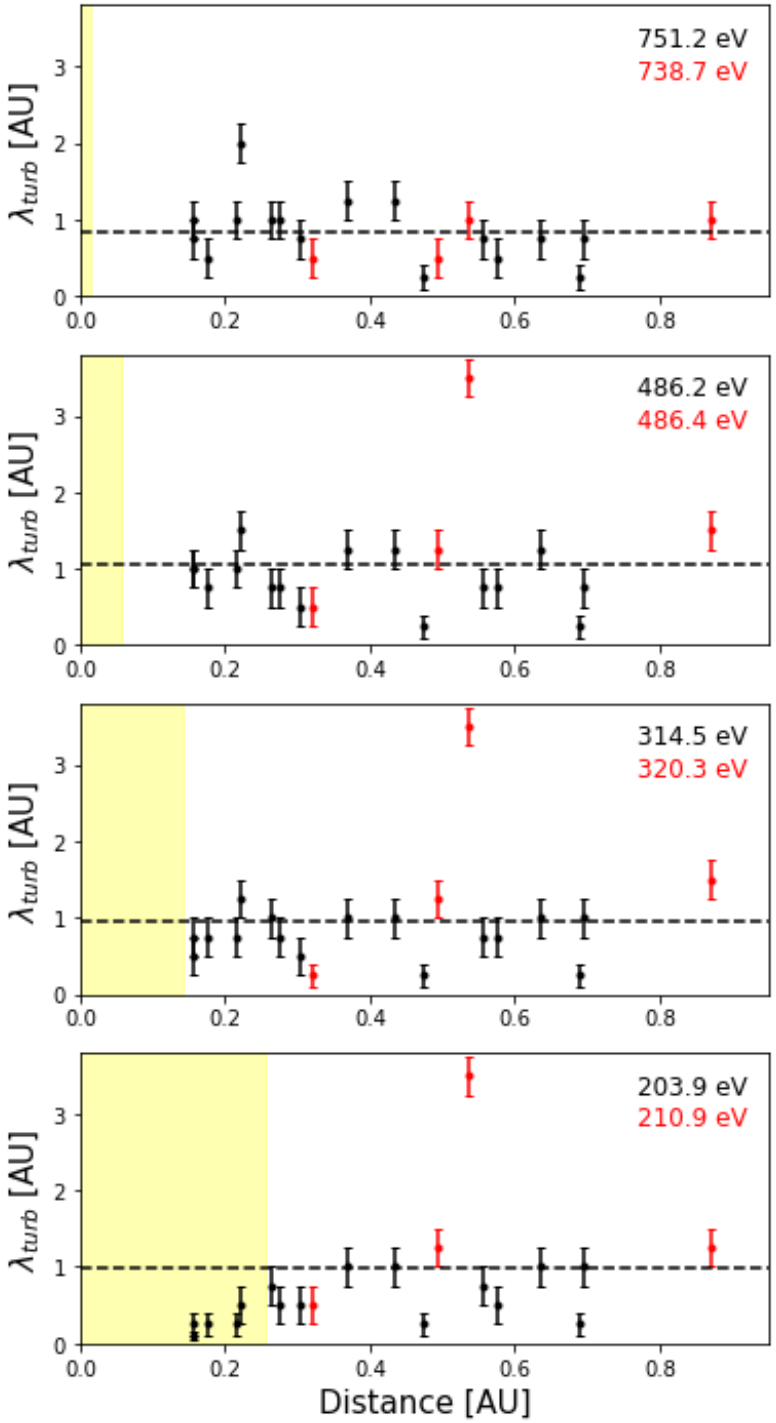
- The mean free path $\lambda_{turb}(E) \sim 1\ AU$ is not a strong function of the energy or distance.
- Variability from an event to another (flux tube parameters…)
- Some intervals (1/17) show « diffusion-free » profiles (with values of $\lambda_{turb} \sim 3.5\ AU$ or more).



Mean free path as a function of the distance

- The mean free path $\lambda_{turb}(E) \sim 1\ AU$ appears to be rather constant with distance (consistently with our assumption)

- The observed values of the turbulent mean-free paths are rather consistent with the observations from SEP events.



Conclusions/Summary

- The observed suprathermals PA distributions during quiet periods, and their evolution with distance to the Sun, are very accurately reproduced by a transport model, with a single free parameter λ_{turb}.

- Existence of a turbulent scattering process with $\lambda_{turb} \sim const.$ implies a separation of the heliosphere into 3 regions (2 « random walk regions », 1 intermediate « deterministic » region)

- The halo electrons observed in large Kn regions are not locally produced, but typically isotropized in the far away « region III » : their properties depend on plasma/magnetic field properties far away from the location where they are observed (as opposed to the strahl component)

- What is the nature of the isoptropization process? Coherent wavepackets ? Steady-state turbulence? (probably the same that is scattering low energy SEPs…)