# Our current understanding of the solar wind

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# Outline

- Our current understanding
- Modelling the solar wind in the inner heliosphere
- Practical problems
- Summary: What is important for space climate

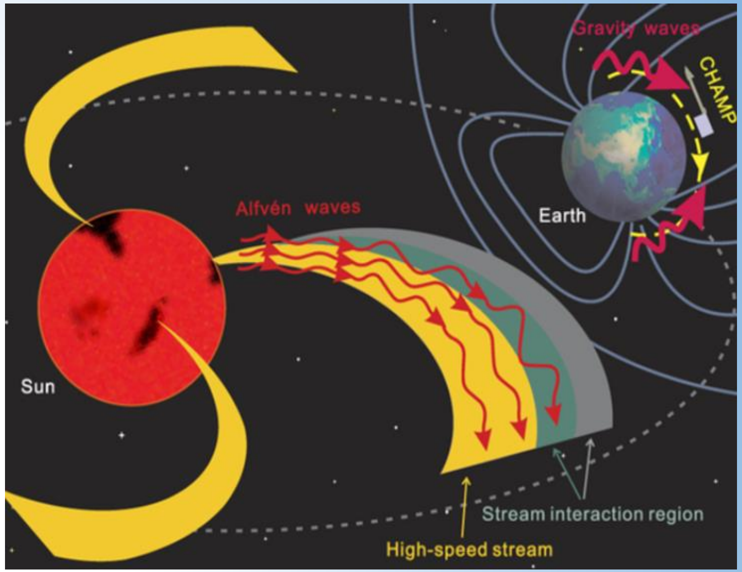
# What we know now

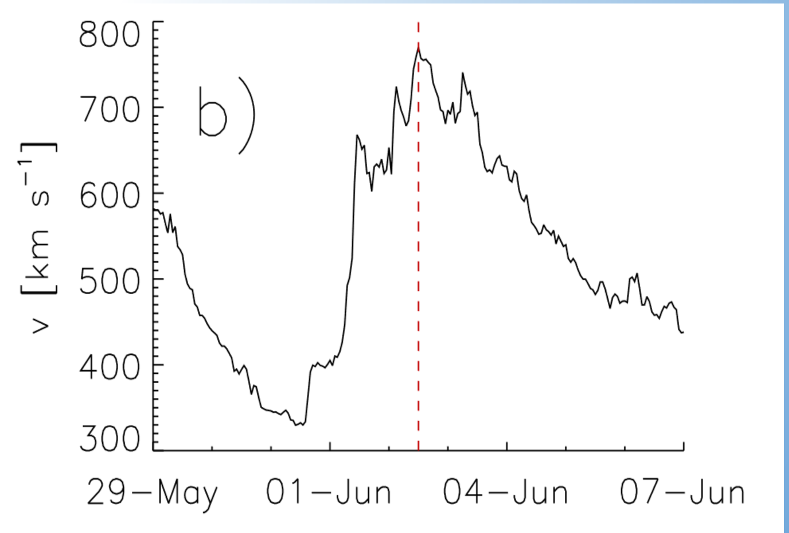
The solar wind consists of (at least) three states:

- Slow solar wind
- High-speed solar wind streams
- Coronal mass ejections

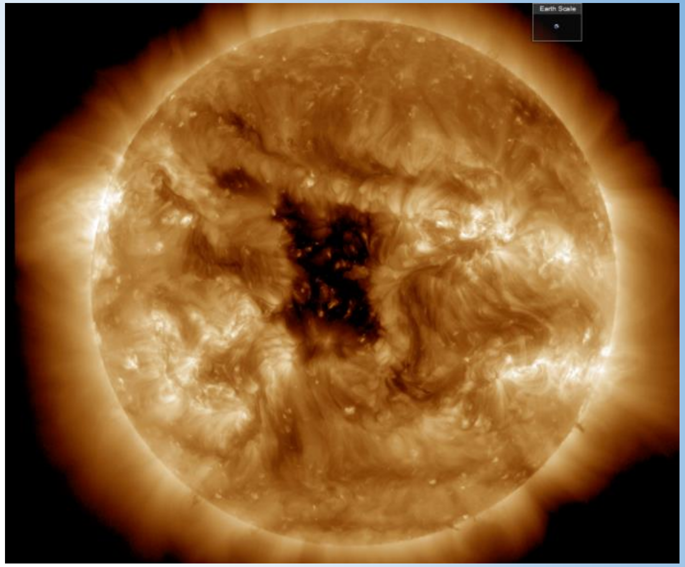
The **solar wind flow is supersonic** plasma stream travelling **radially** away from the rotating Sun (when projected to the ecliptic). Non-polar high-speed streams are **bent down towards** the ecliptic due to the Suns dipole moment.

The **frozen-in magnetic field winds up** to the Parker spiral due to the solar rotation and forms magnetic field sectors.



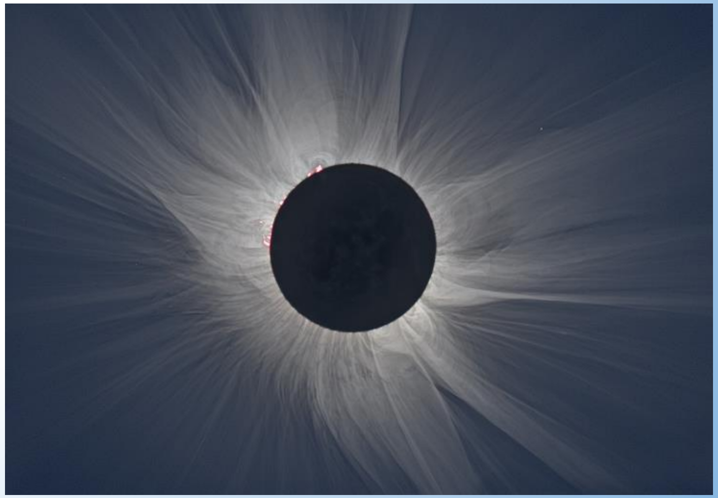
# The origin of the solar wind



Sources of the solar wind:

- High-speed streams: coronal holes
- Slow solar wind: uncertain
  - Streamers and Pseudostreamers
  - Boundaries of coronal holes
  - Surrounding of Active Regions

*High-speed streams is a historical term. We dub every solar wind stream that originates from a coronal hole, independent on its actual velocity, as high-speed stream.*



Solar eclipse of 20 March 2015. Credit: Habal, Druckmüller, Aniol.

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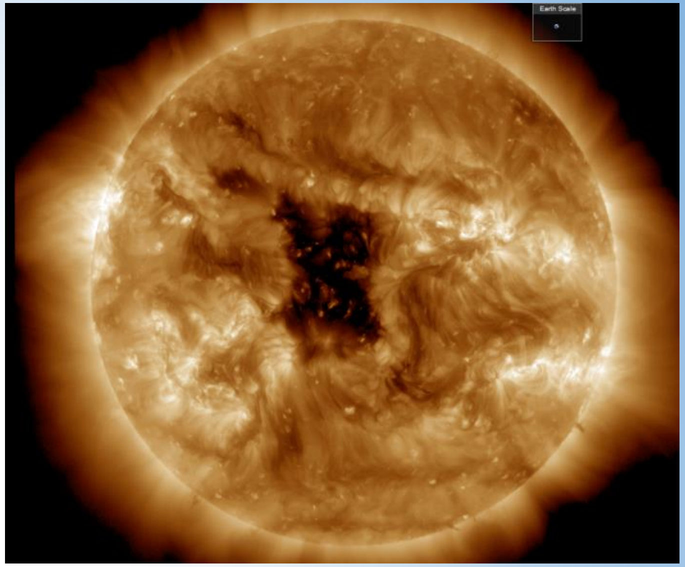
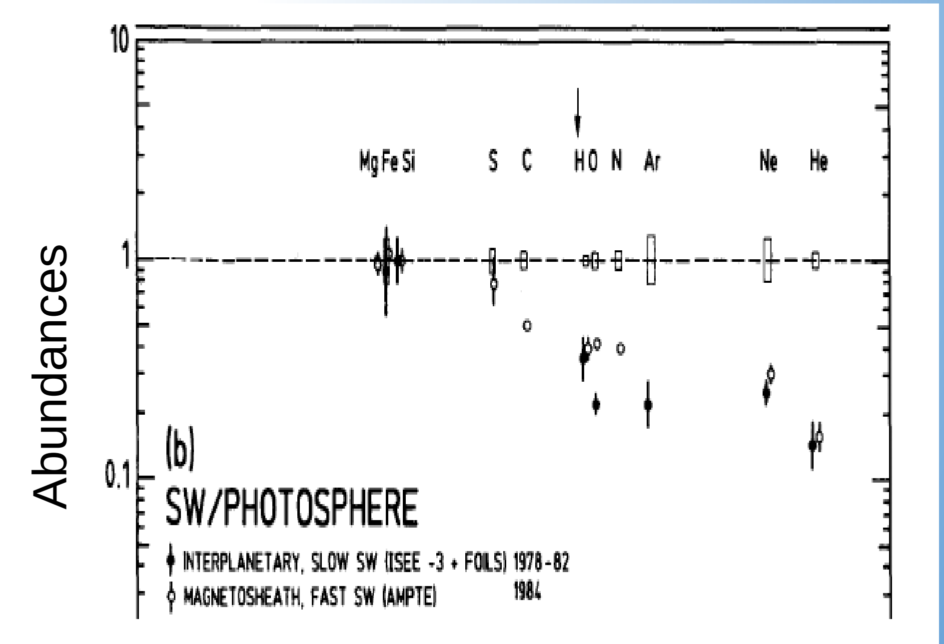
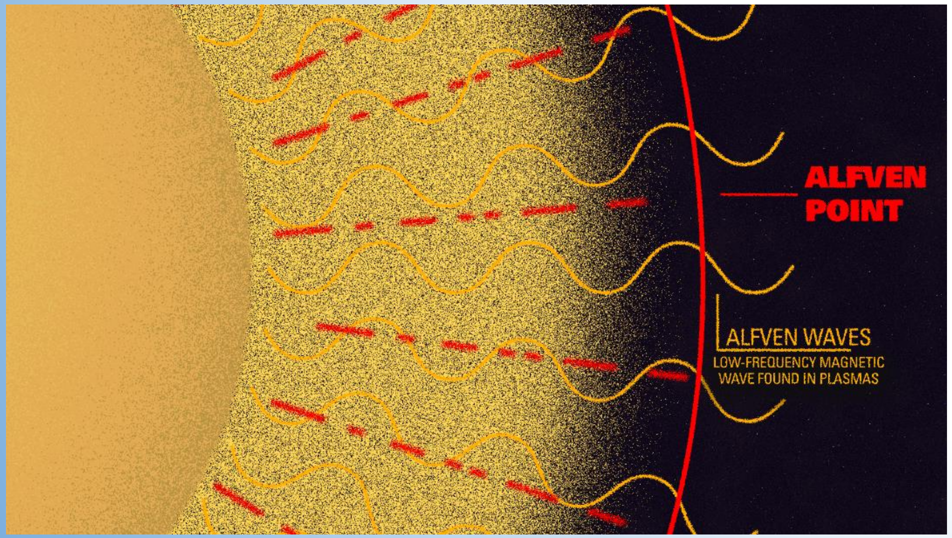
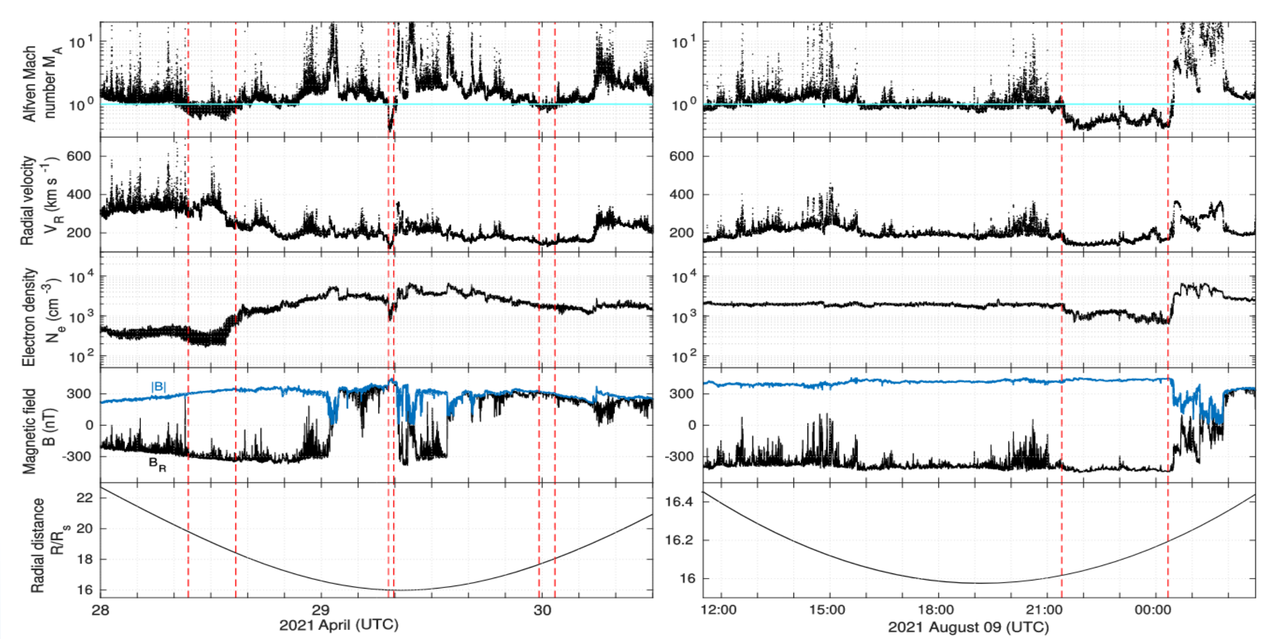




# The magnetically dominated corona

Height:
- The Alfvén point determines the transition of the magnetically dominated corona to the kinetically dominated interplanetary space
- (i.e., where the kinetic energy density equals the magnetic energy density)
- At about 16 solar radii



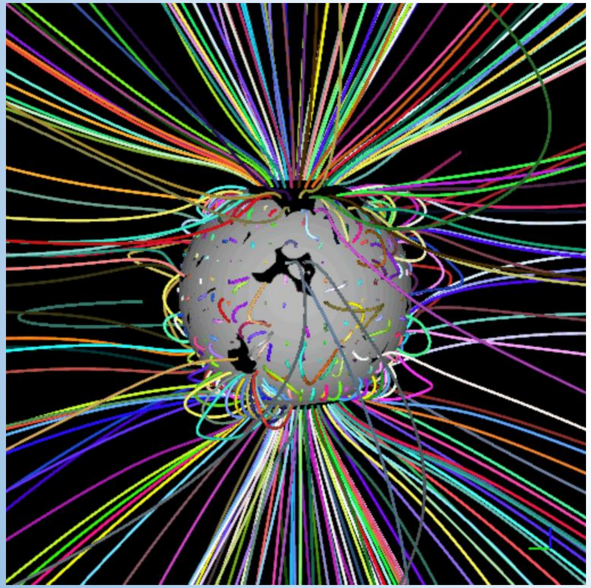




From Bandyopadhyay et al., 2022

# The magnetically dominated corona

Switchbacks:

- Kinks in the magnetic field and solar wind
- Spatial scales match the scale of supergranular cells at the solar surface
- => solar corona is not magnetically static, but only magnetically dominated

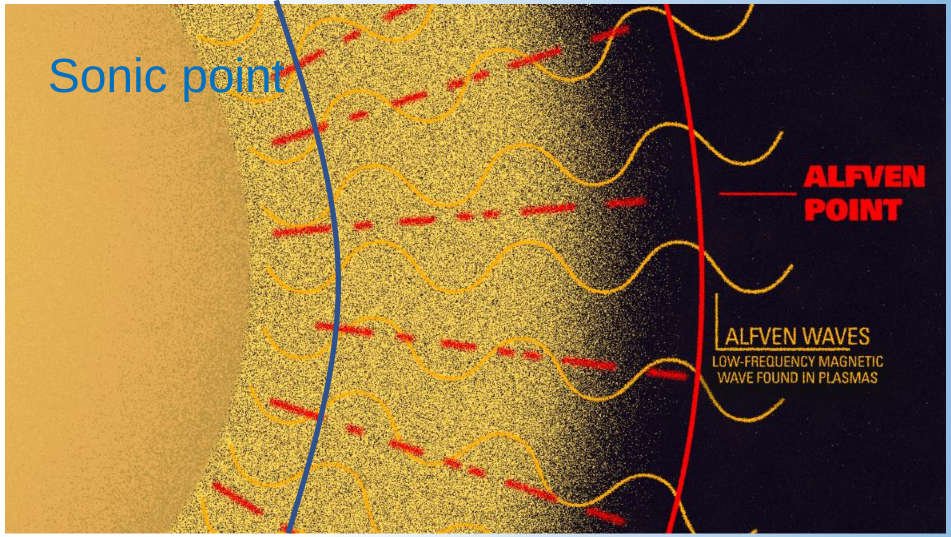


# The height of energy input

The height at which energy is deposited on the solar corona determines the properties of the solar wind.

- Below the sonic point: increase in mass flux, but no substantial increase in velocity
- Above the sonic point: increase in velocity

=> For high-speed streams, the energy is deposited at larger heights than for the slow solar wind

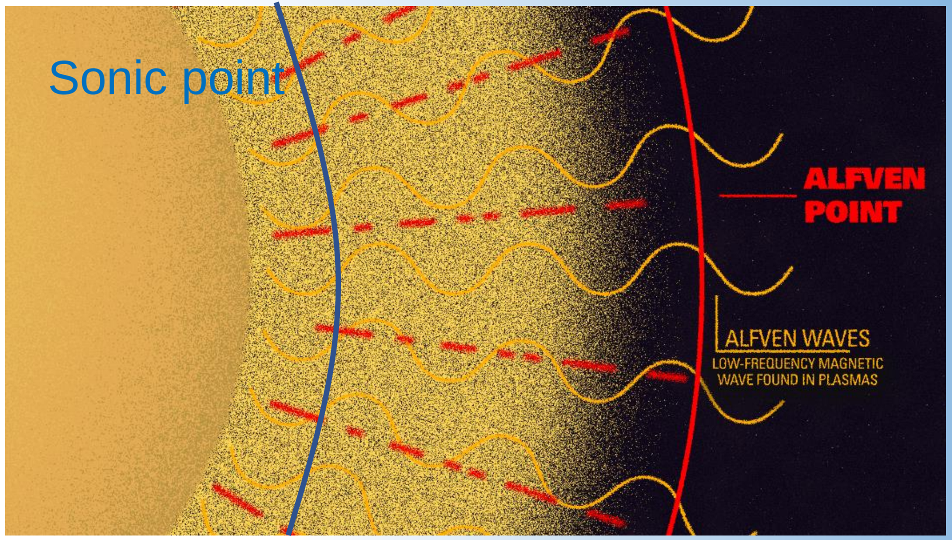


# The height of energy input

Energy sources for the solar wind acceleration:

- It is still under discussion if the solar wind is driven by
  - magnetic reconnection
  - or waves/turbulence

- Maybe, we should assume that it is both?



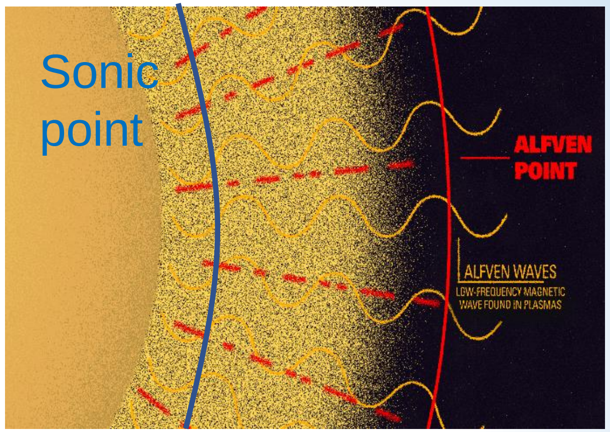
# Densities, temperatures, and charge states

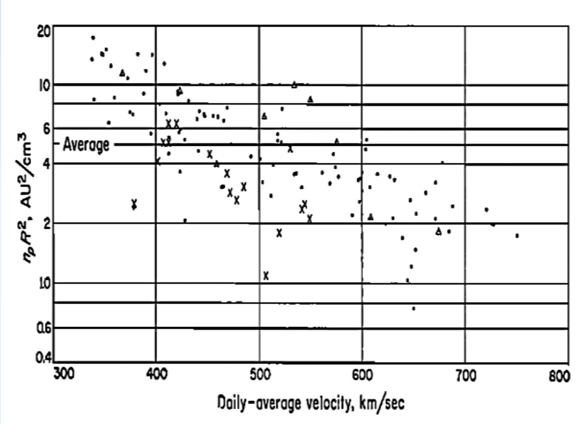
- Densities: HSS < SSW
- Ion charge temperature: HSS < SSW
- ion kinetic temperatures: HSS > SSW

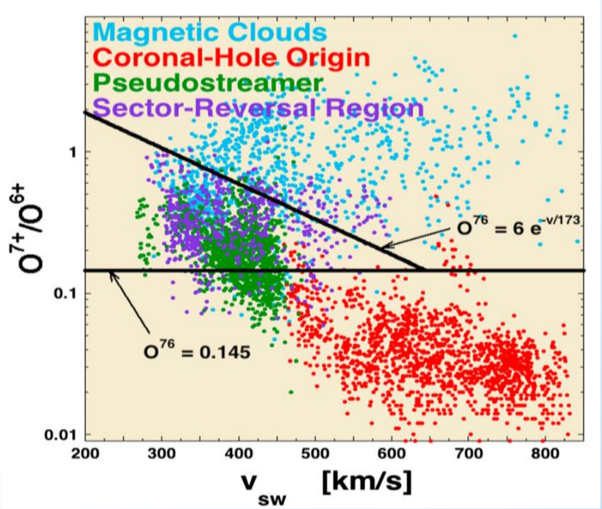
At larger heights for energy deposition in the solar corona, we have

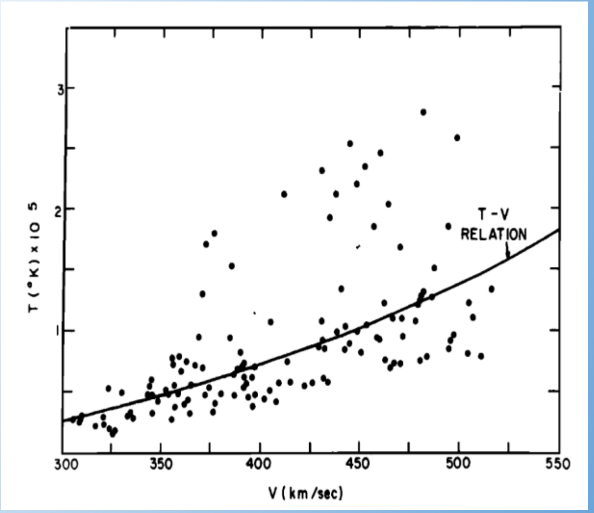
- lower densities
- lower ion temperatures
- and thus more energy per particle to heat and accelerate the solar wind

The ion charge states do not relax in time to resemble the ion temperature and get frozen in



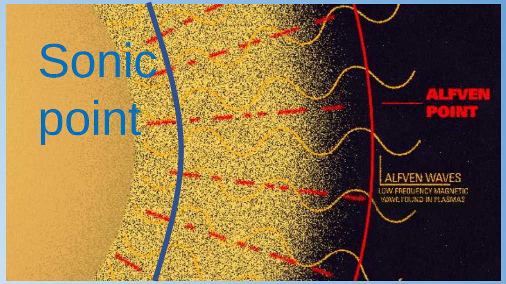




From Burlaga and Ogilvie (1973), Neugebauer (1966), and Xu and Borovsky (2015)

# Solar wind acceleration

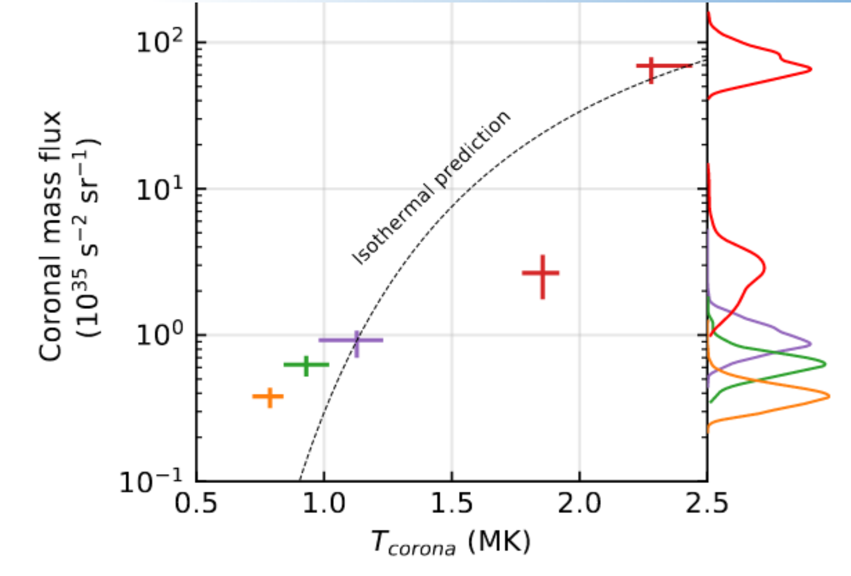



Energy input does not only accelerate the solar wind, but also heats the corona
- Solar wind mass flux depends exponentially on the temperature of the corona
- The corona is cooled by the outflowing solar wind

=> coupled problem: one cannot fully solve the solar wind acceleration problem without the coronal heating problem and vice versa

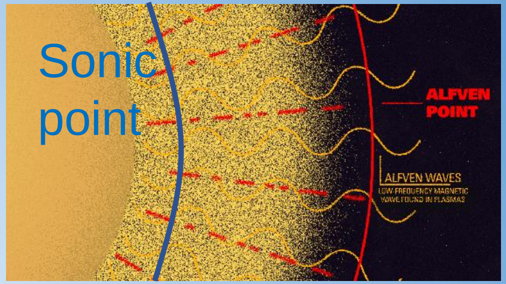
$$n_\odot v_\odot = n_\odot c_\odot \left(\frac{r_c}{r_\odot}\right)^2 \frac{c_\odot}{c_c} \exp\left[-\frac{1}{2}\int_{r_\odot}^{r_c} r_c \frac{w^2}{c^2(r) r^2} \mathrm{d}r\right],$$

According to Parker's theory, where $c^2 \propto T$ is the thermal speed, w the solar escape velocity, r the distance from the Sun, subscript c is at the critical sonic point, $\odot$ the solar surface. From Stansby et al., 2021.




From Stansby et al. (2021)

# Acceleration profile




- Most of the accelerations happens between 1 and 10 solar radii
- $O^{+5}$ is accelerated much faster than protons => No LTE

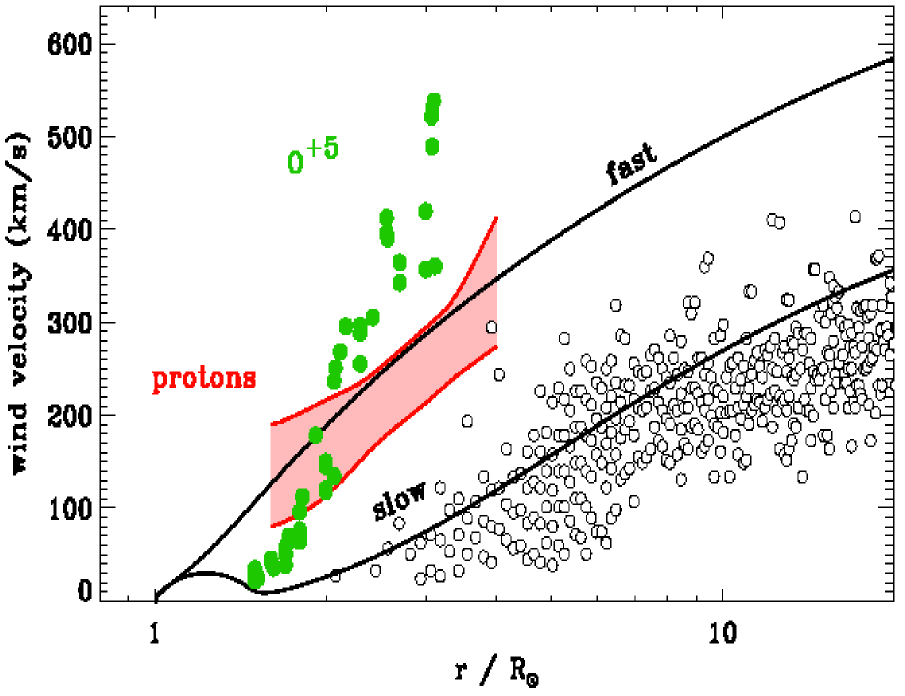
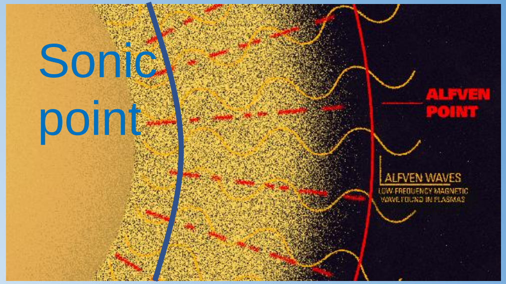



**Figure 8:** Radial dependence of solar wind outflow speeds. UVCS Doppler dimming determinations for protons (red; Kohl *et al.*, 2006) and $O^{+5}$ ions (green; Cranmer *et al.*, 2008) are shown for polar coronal holes, and are compared with theoretical models of the polar and equatorial solar wind at solar minimum (black curves; Cranmer *et al.*, 2007) and the speeds of "blobs" measured by LASCO above equatorial streamers (open circles; Sheeley Jr *et al.*, 1997).

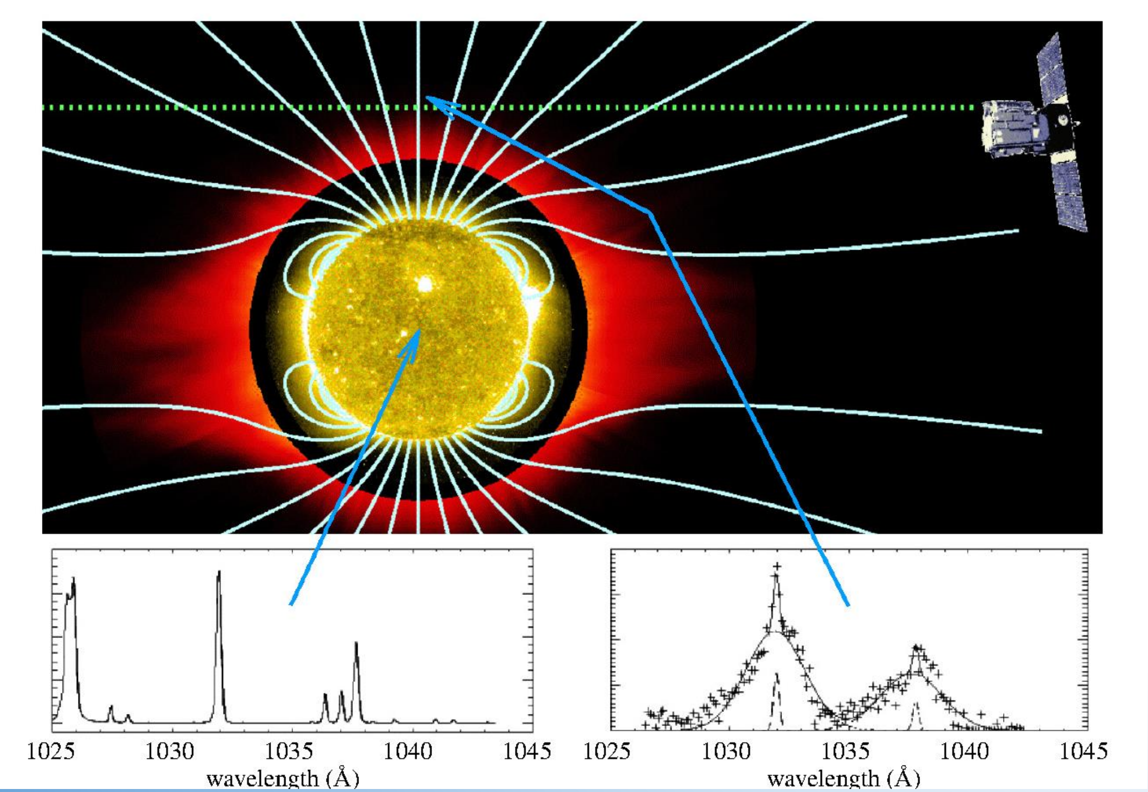


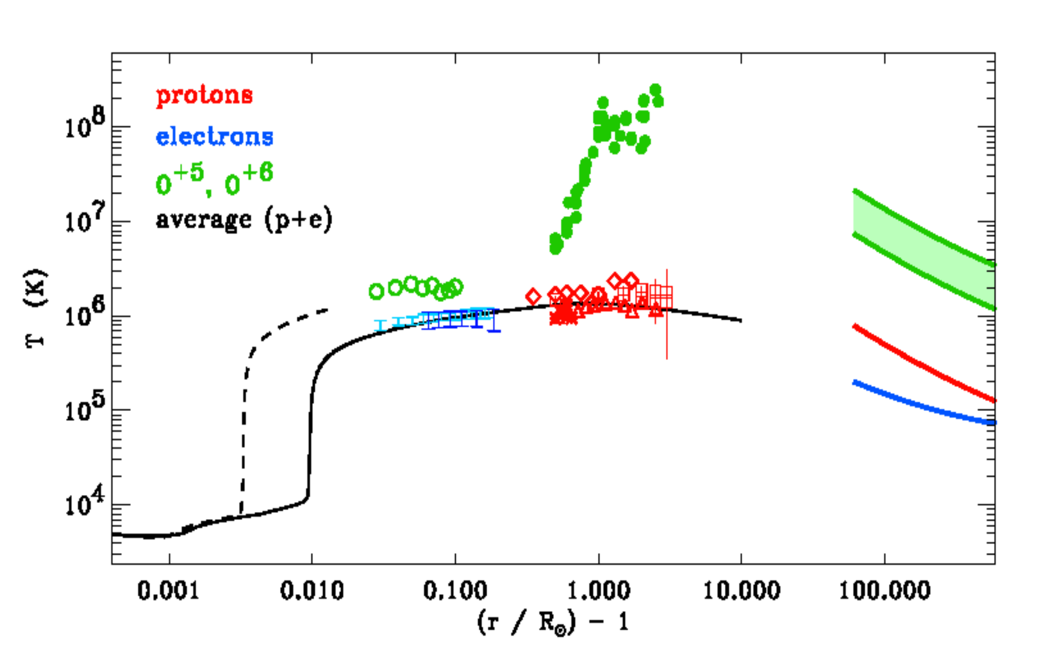

# Anisotropic temperatures

Preferential heating and acceleration of ions, particularly of $O^{+5}$ and $O^{+6}$

$\Rightarrow$ No LTE

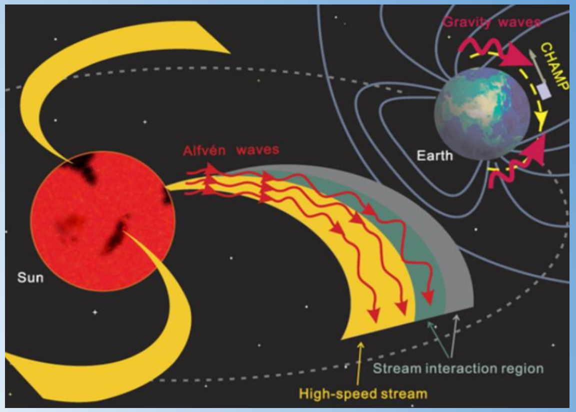
$\Rightarrow$ Wave-particle interaction



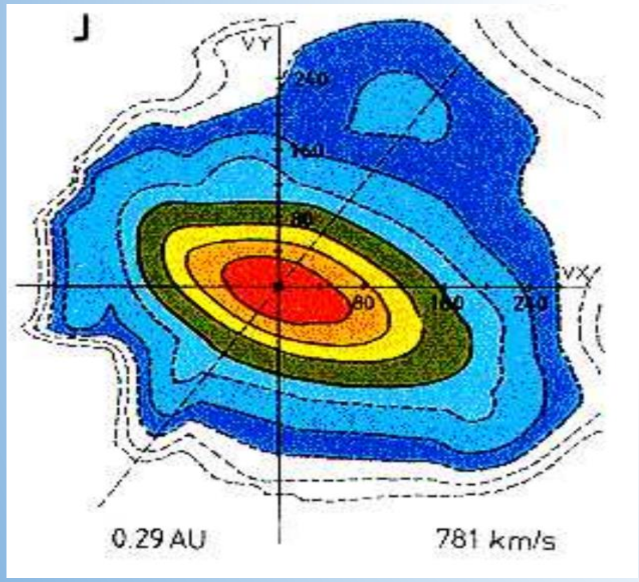



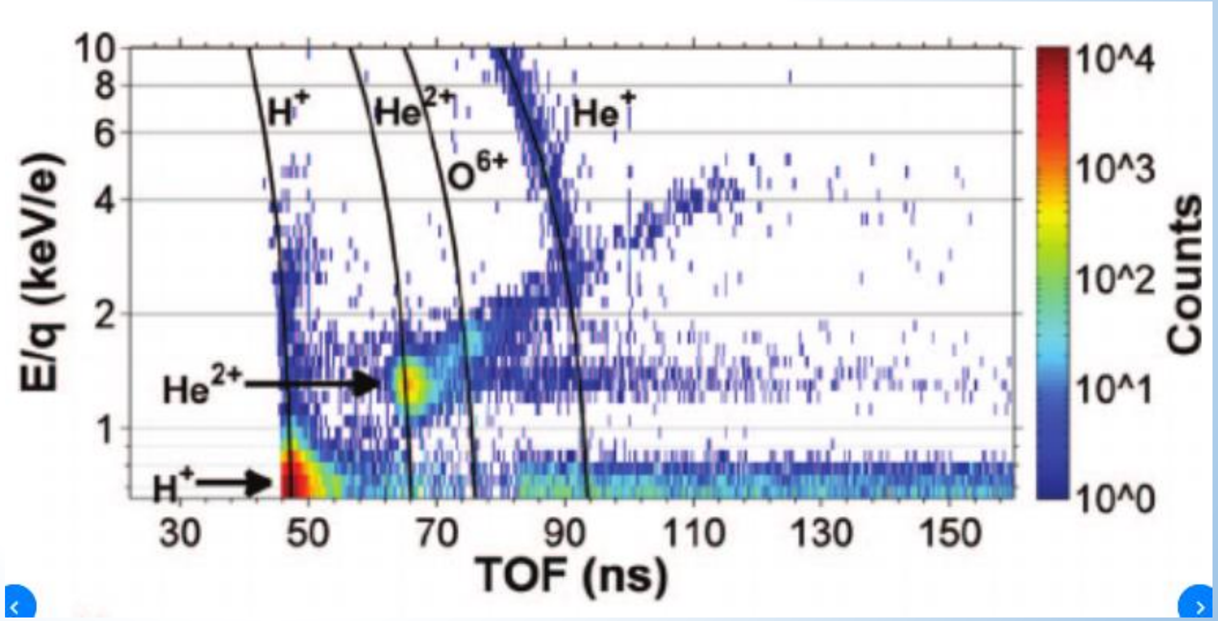

From March et al. (2008) and Cranmer (2009)

# Solar wind velocity and velocity distribution function of ions



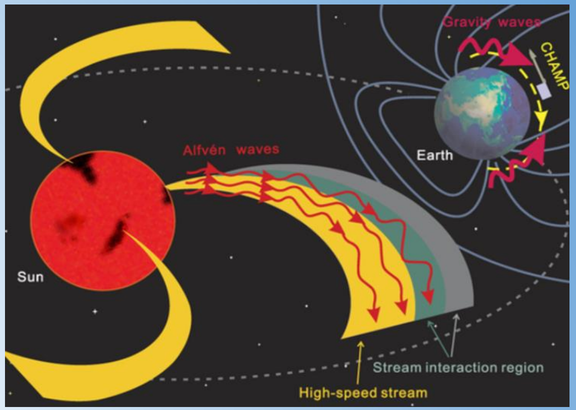

- Velocity distribution function is non-Maxwellian
  - no LTE, wave-particle interaction
- Different ions stream with different velocities



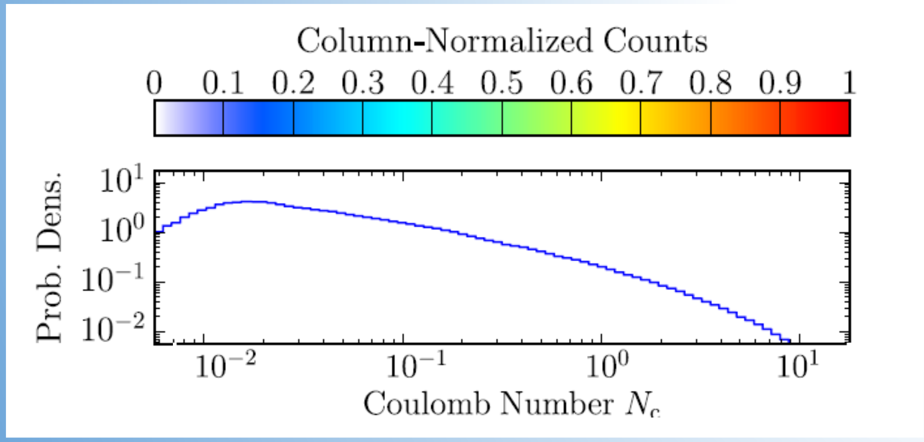



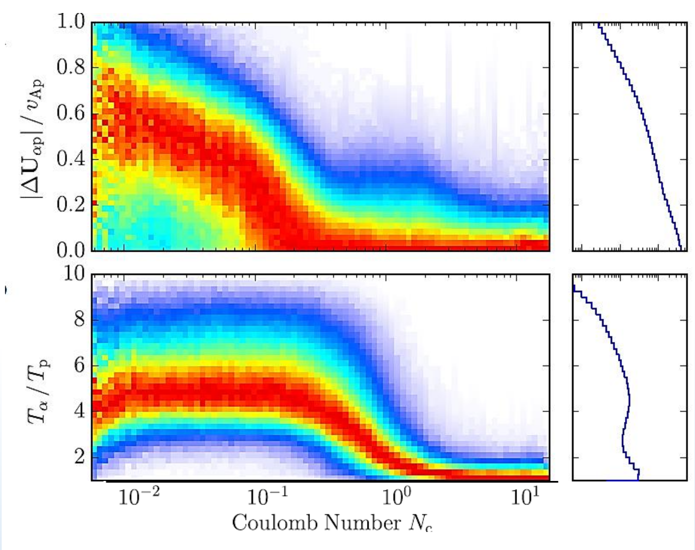

From March et al. (2008) and Gilbert et al. (2014)

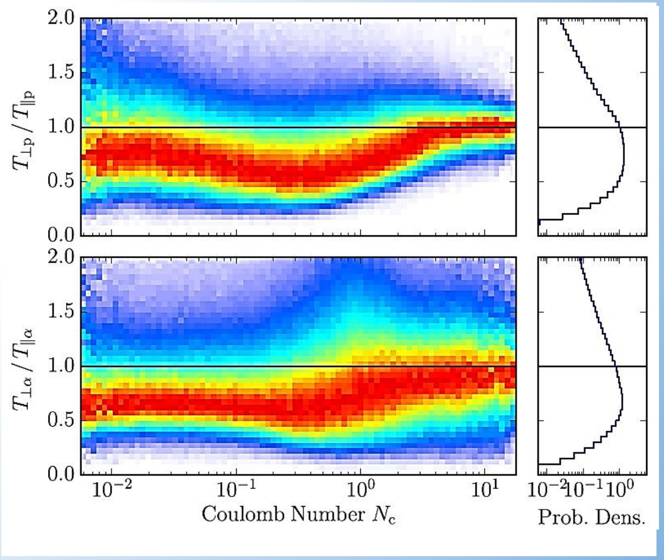
# Collisions



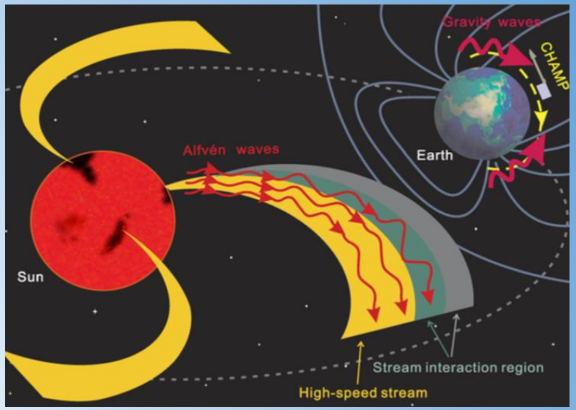

- Coulomb number approximates the collisional time scales that elapsed during its journey from the Sun to Earth
- Determines the state of relaxation of the different ions to an equilibrium
- Typically < 1, with smaller numbers for high-speed streams than for the slow solar wind



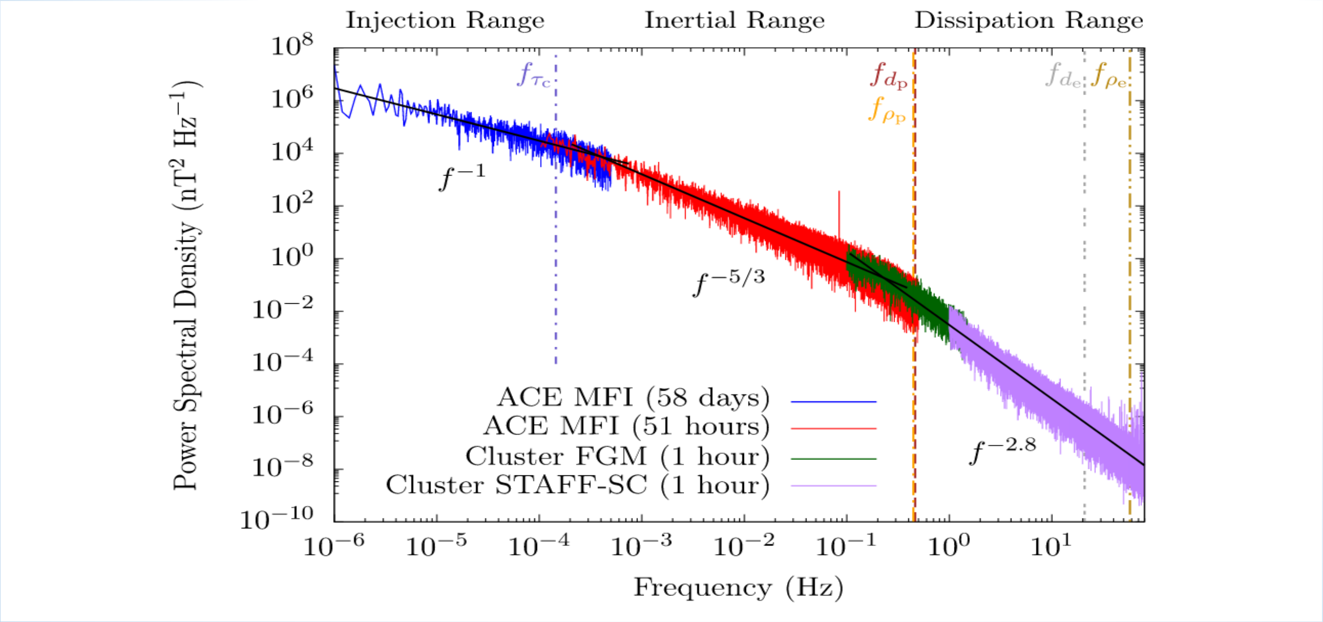



# Dissipation mechanisms

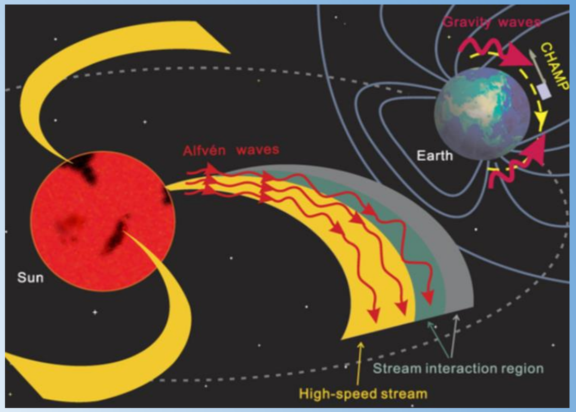



- Particle-wave interactions: quasilinear diffusion and nonlinear phase mixing
- Stochastic heating
- Turbulence

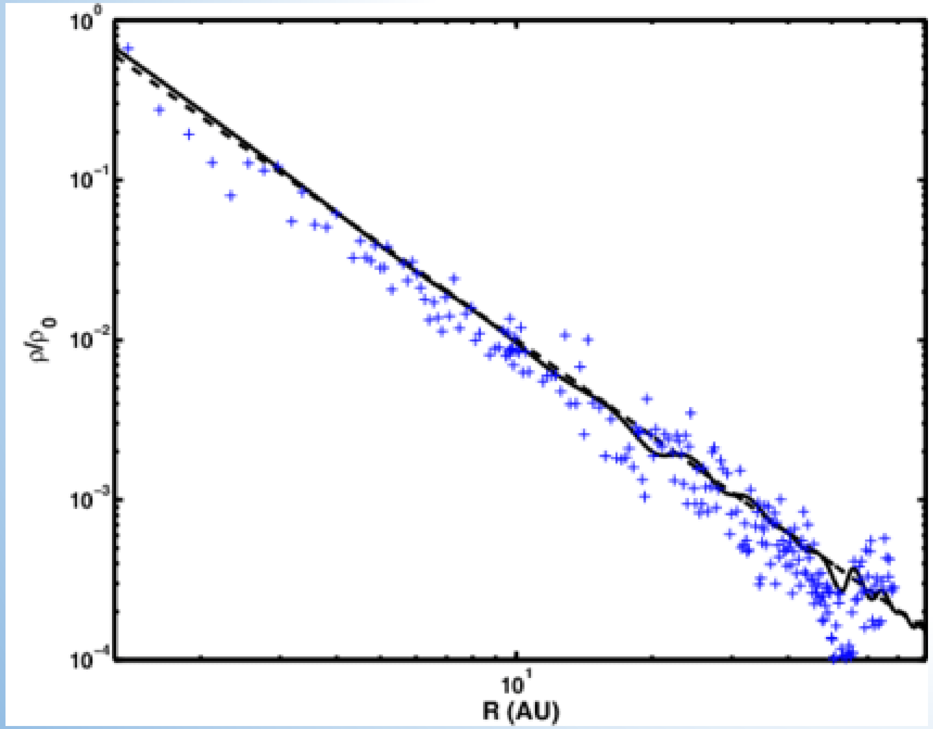



From Verscharen et al. (2019)

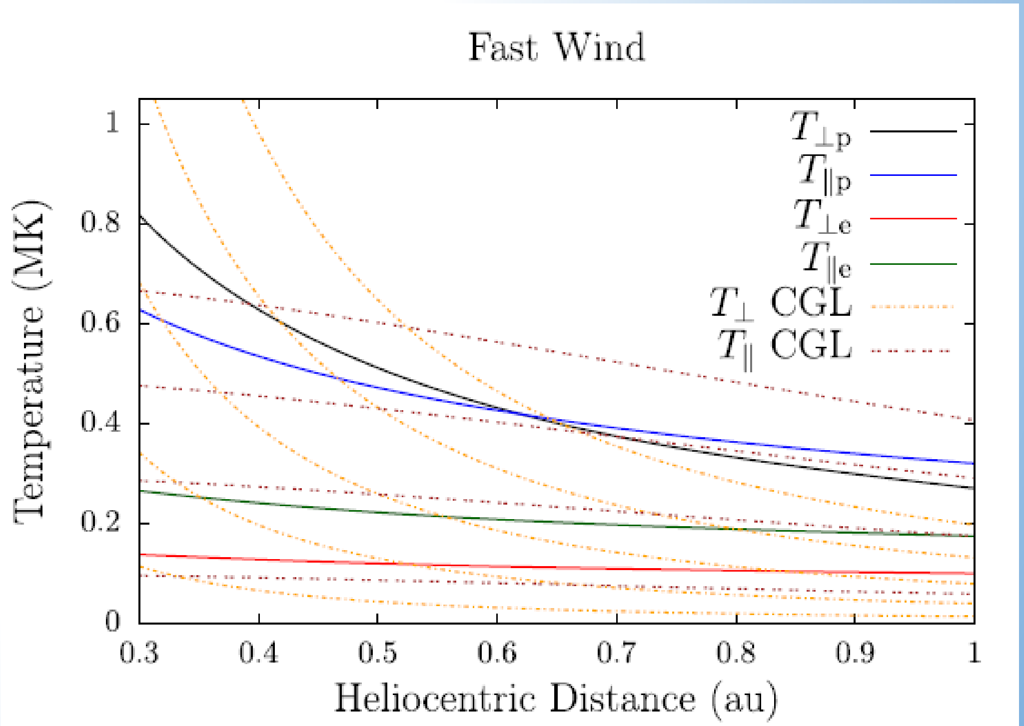
# The expanding solar wind




- Velocity is almost constant
- Density drops with about 1/r2
- But: the solar wind is heated on its way to Earth




From Zank et al. (2014)

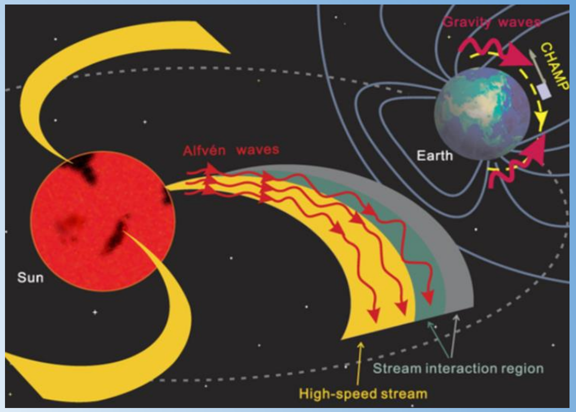


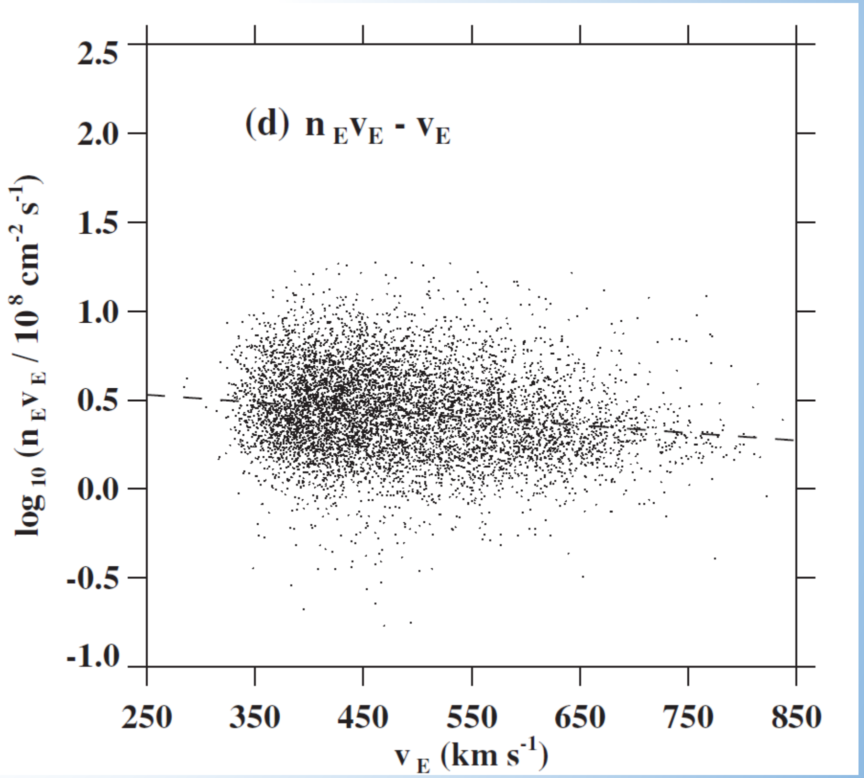

From Verscharen et al. (2019)

# Solar wind mass flux at Earth

- The solar wind mass flux at Earth is almost independent on the solar wind velocity
- But shows quite some scatter

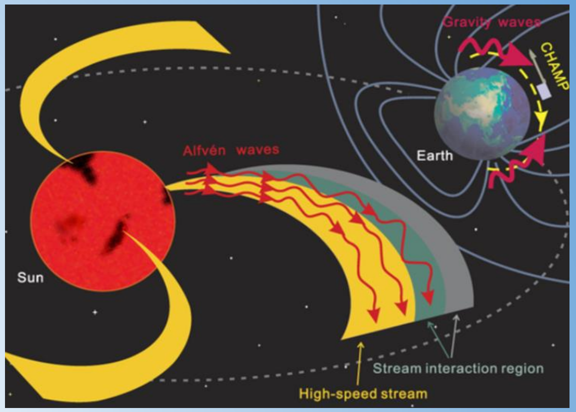
- Independent on the acceleration mechanism, but certainly dependent on other mechanisms (as the temperature)




From Wang (2010)

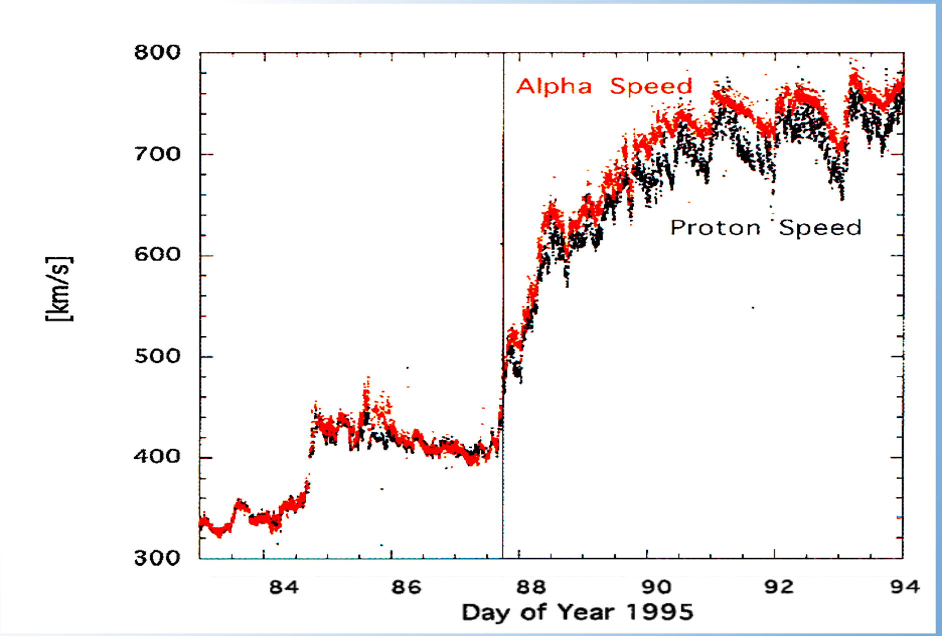
# Which high-speed streams hit the Earth?




The latitudinal boundary region has a size of about 6 degrees

⇒ within only 6 degrees in latitude, the solar wind speed can rise from about 300 km/s to 650 km/s

⇒ The position of the satellite / Earth within the HSS is important




From: McComas et al (1998)

# Short summary

- Origin of the solar wind
  - High-speed streams originate in coronal holes
  - the source of the slow solar wind more uncertain
- Height of energy deposition determines solar wind speed and mass flux
- Solar wind propagation in interplanetary space can be described as expansion from the Sun + additional heating
- Solar wind mass flux at Earth does not vary much with solar wind speed
- Position of Earth within high-speed streams strongly affects the solar wind properties we measure
- **The solar corona is not magnetostatic**
- **Solar wind is in non-LTE**

# How do we model the solar wind

Corona: magnetostatic:

- magnetic field extrapolations + empirical relationships

Interplanetary space: MHD

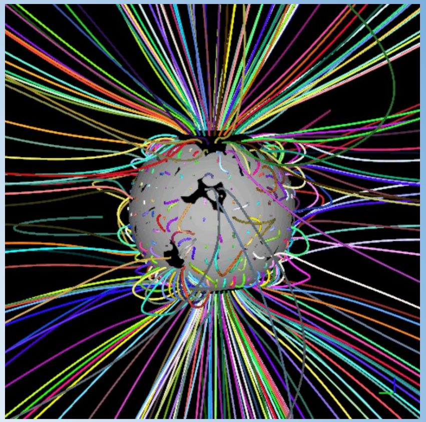
- i.e., LTE

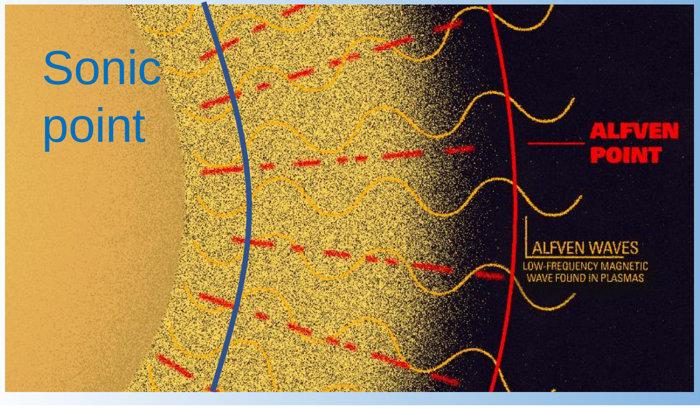
Why:

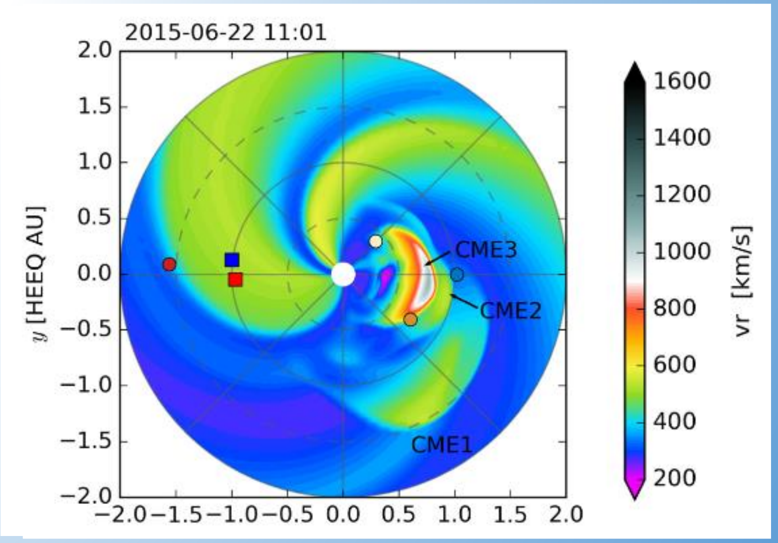
- lack of data in the corona and at the boundary between the corona and interplanetary space boundary
- Computational time

How well do we model the solar wind?

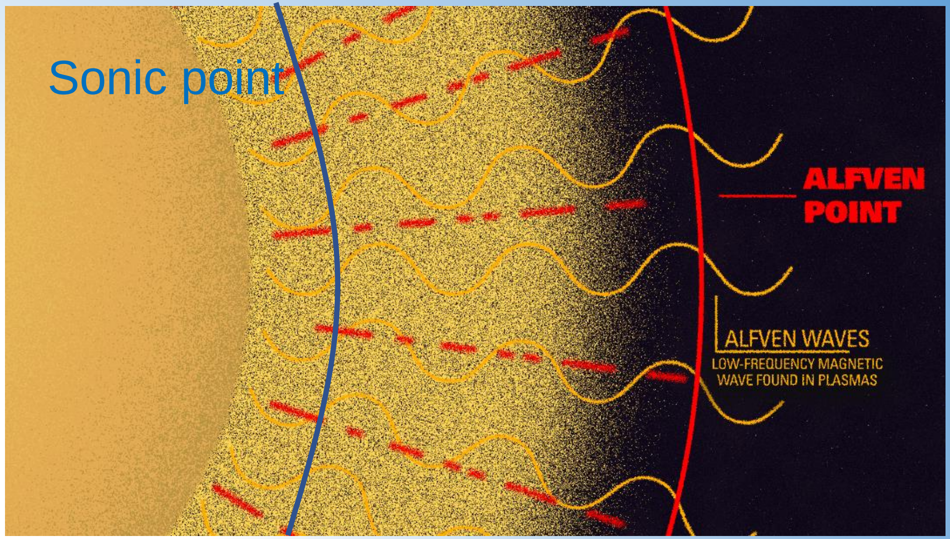
- Reiss et al. (2016): All models work only slightly better than a 28-day persistent model





# Practical problems




**Why do we use empirical relationships?**
**Can we not create a reliable model for the corona?**

To constrain such a model, we would need to know the solar wind source regions and the properties of the solar wind close to the Alfvénic point.

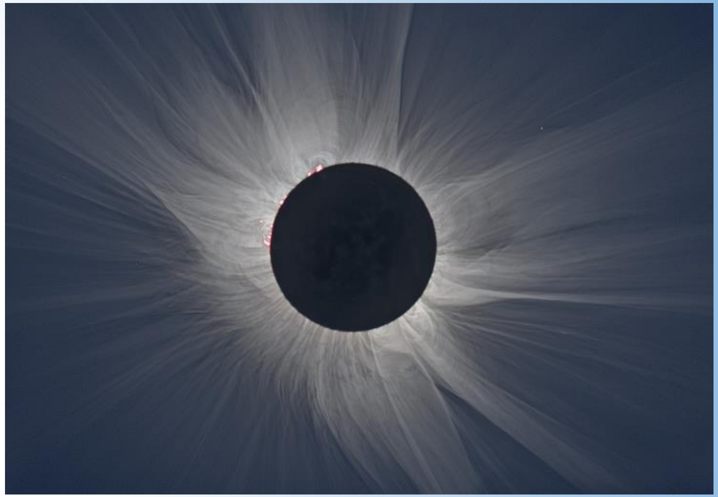
But:

- The solar wind source regions are not well known
- Properties at the Alfvénic point are usually approximated by the solar wind properties near Earth neglecting the propagation phase.
- *(But are now direct measured by PSP)*

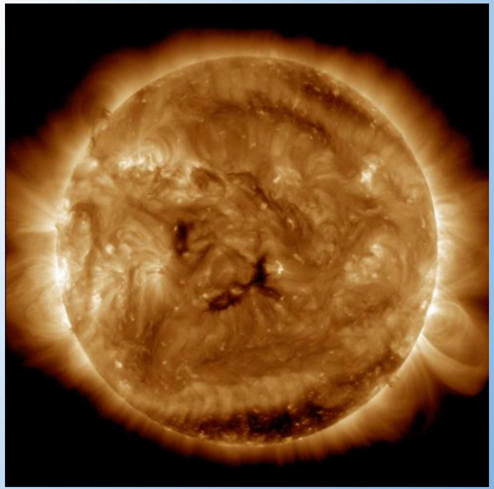
# Sources of the solar wind

Sources of the slow solar wind

- Streamer belts, coronal hole boundaries, active regions
- But these only cover a small fraction of the solar surface.
- Are there more sources?



Solar eclipse of 20 March 2015. Credit: Habal, Druckmüller, Aniol.



# How we track solar wind sources

We use usually PFSS models to link statically the heliosphere to the solar surface.

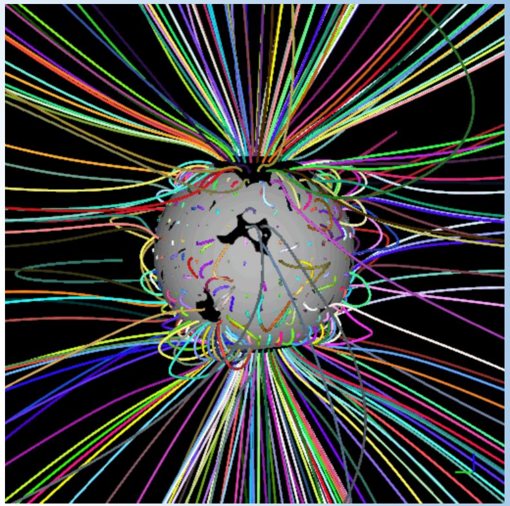
But:

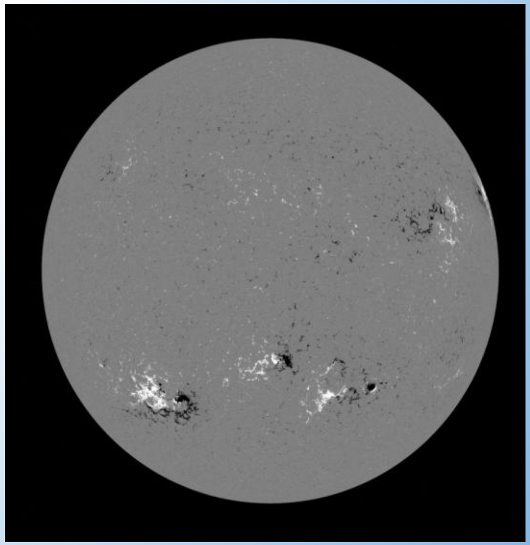
- We do not have magnetic field on the backside of the Sun nor on the poles
- Switchbacks show that the corona is not static

⇒ PFSS are not very reliable to track down the slow solar wind nor to determine the location of coronal holes

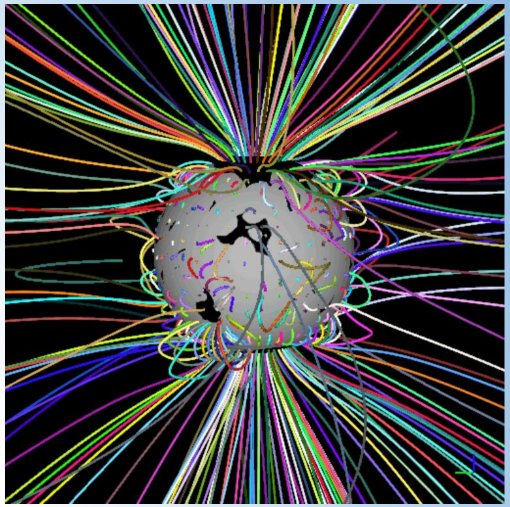
Alternative:

- FIP effect, abundances, charge states



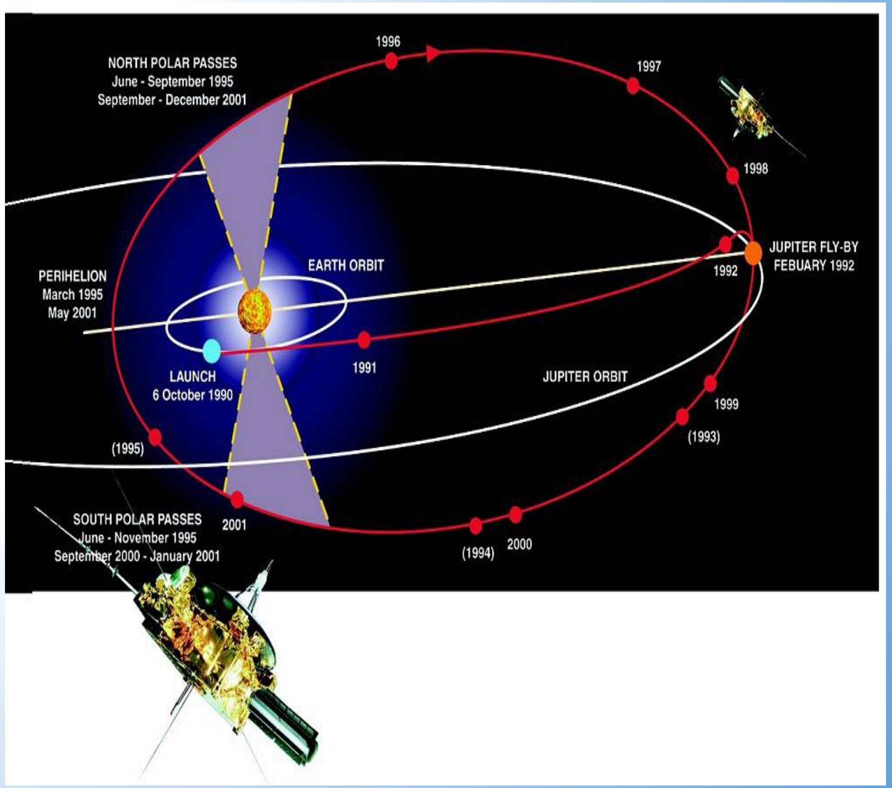


# The open flux problem



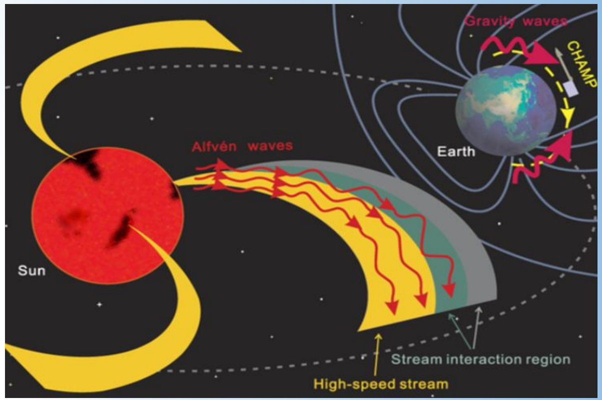
The total open magnetic flux we extrapolate from in-situ measurements is 2-4 times larger than from solar extrapolations

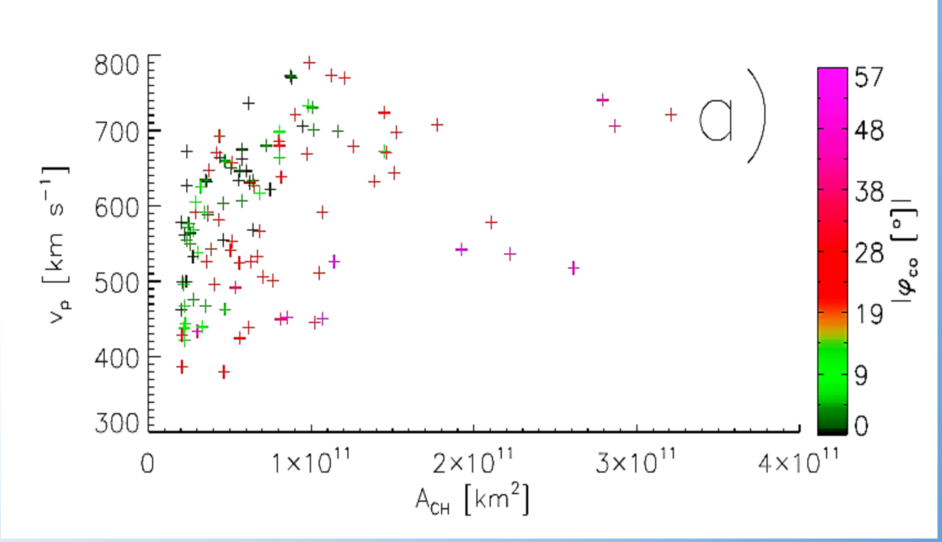
- Where do we miss open flux on the solar surface?
    - Poles?
    - Can the quiet Sun have open magnetic funnels as source of the slow solar wind?
    - Or are some of our methodologies wrong?



# Estimating the properties at the Alfvénic point from in-situ measurements near Earth

- How does the solar wind temperature, density, velocity change with distance from the Sun?
- How does the solar wind propagate in three dimensions?
- How do different solar wind streams interact?
- Where within the solar wind do we actually do our measurement?




From Hofmeister et al. (2017)

# Let's build a simple analytical model for high-speed streams

1. Freely propagating high-speed solar wind streams
   - Presume no interactions or heating -> dispersion of its initial temporal velocity distribution function

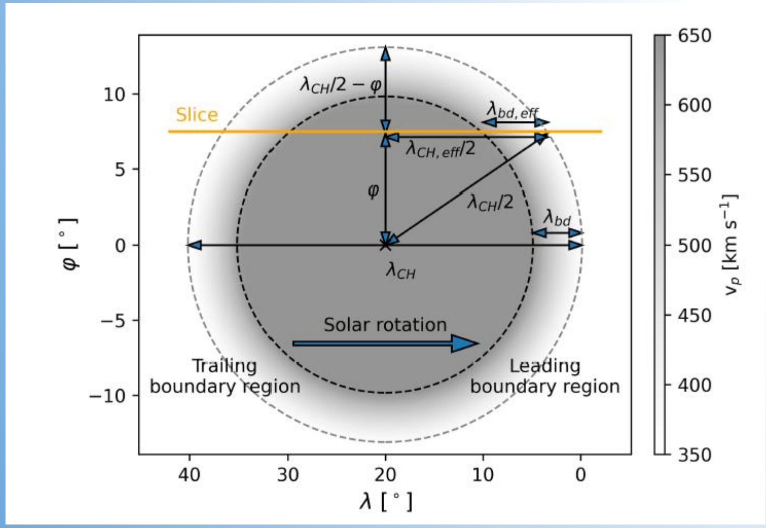
1. Kinematics of the stream interface
   - Conservation of momentum

1. Properties of high-speed streams near Earth
   - Properties of freely propagating high-speed streams evaluated at the arrival time of the stream interface at Earth

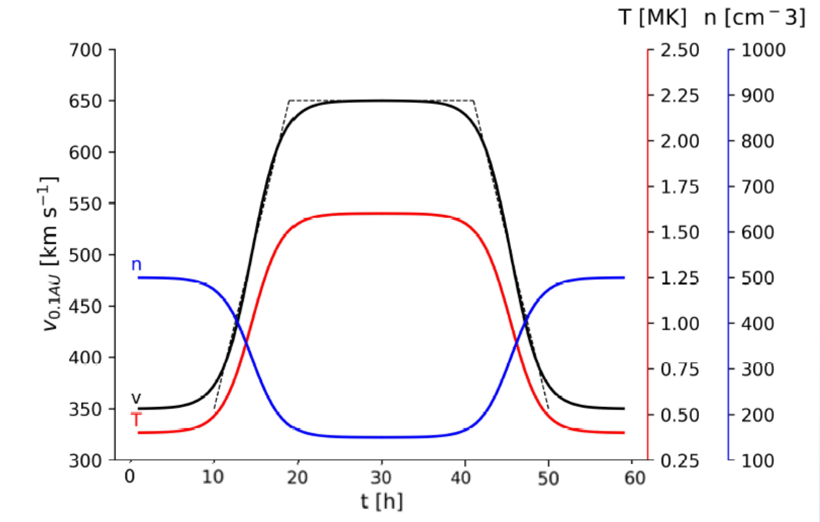
# 1) Freely propagating high speed streams

Let's neglect any boundary effects in interplanetary space, and any local heating.
I.e., let's describe the propagation as a simple dispersion of its initial temporal velocity distribution

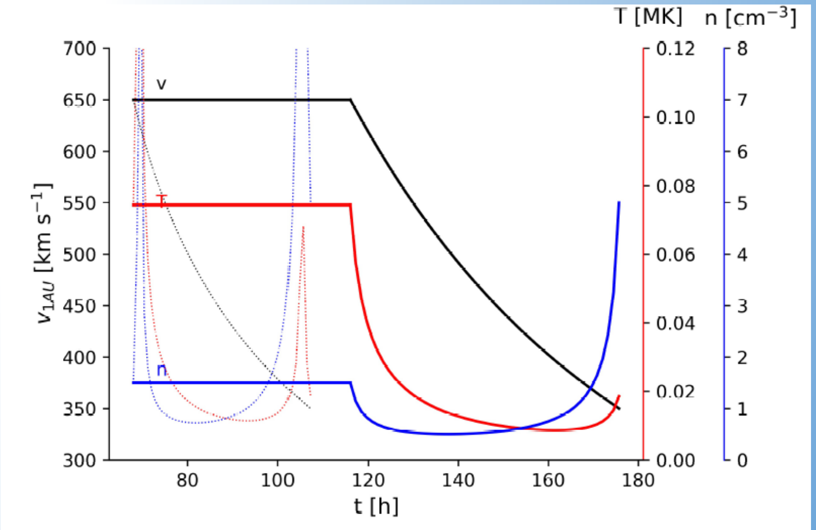
HSS close to the Sun




HSS properties along a slice

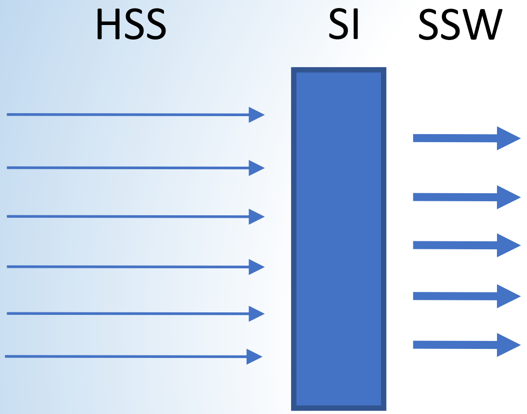



HSS properties at Earth



# 2) Kinematics of the stream interface

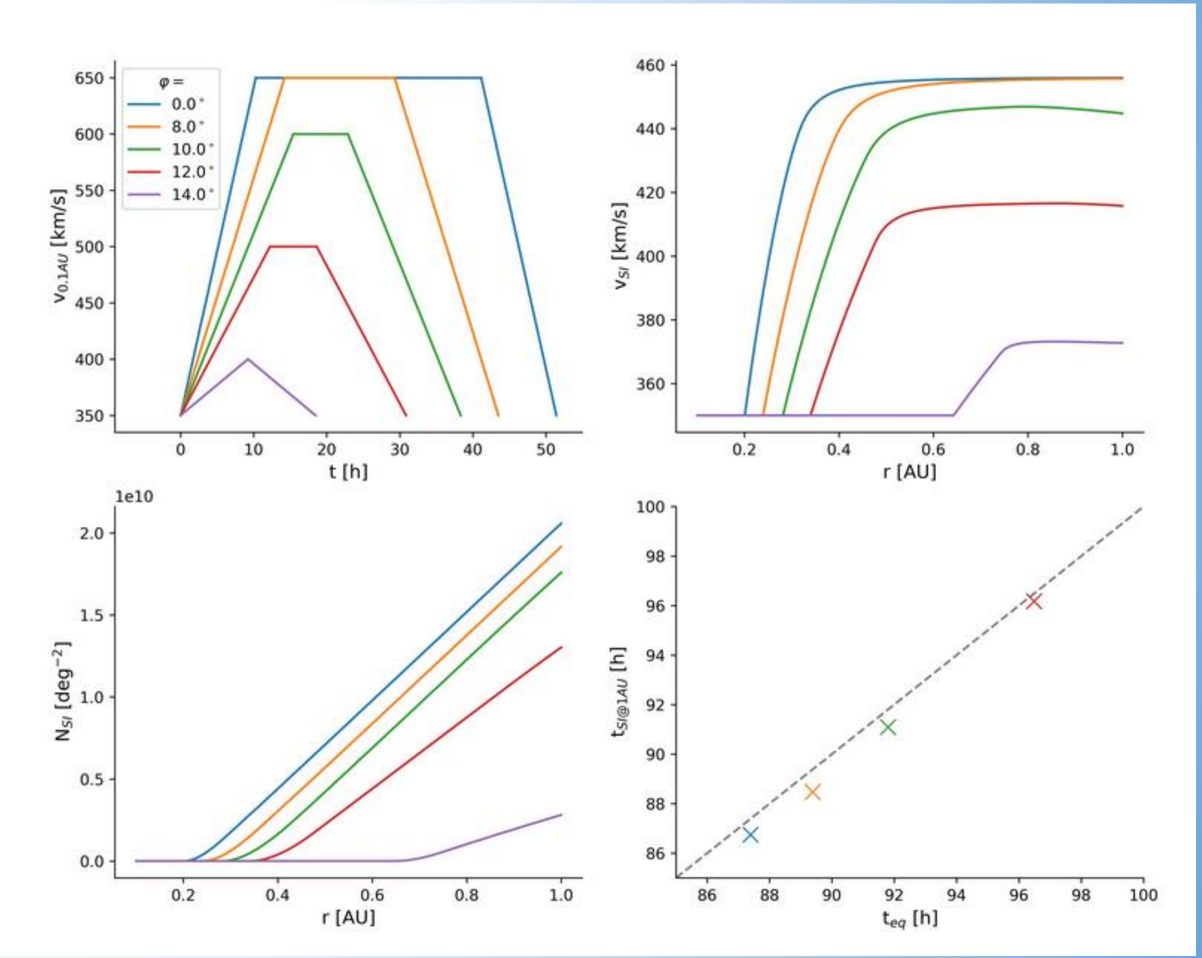
## 3-body conservation of momentum




$$\frac{dv_{SI}(t)}{dt} = \frac{1}{N_{SI}} \left( n_r \, (v_r - v_{SI})^2 - n_s \, (v_s - v_{SI})^2 \right)$$

$$\frac{dN_{SI}(t)}{dt} = n_s \, (v_{SI} - v_s) + n_r \, (v_r - v_{SI}),$$

$$t_{SI,r} = v_{sl,max} \, \left( \omega \, \frac{dv}{d\lambda} \right)^{-1} + \frac{r - v_s \; v_{sl,max} \, \left( \omega \, \frac{dv}{d\lambda} \right)^{-1}}{v_{SI}}$$



# 3) Properties of HSSs at Earth

- Plasma parcels of freely propagating HSSs that did not impinge into the stream interface yet

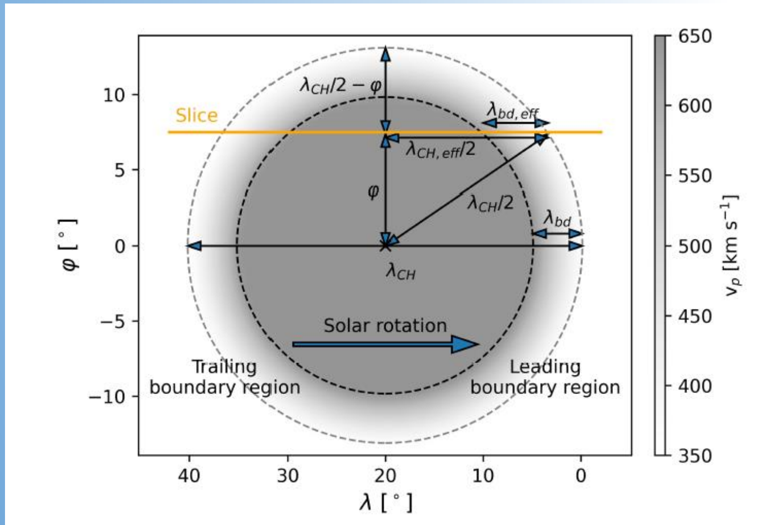
-> Peak velocity = velocity of freely propagating HSSs evaluated at the arrival time of the stream interface

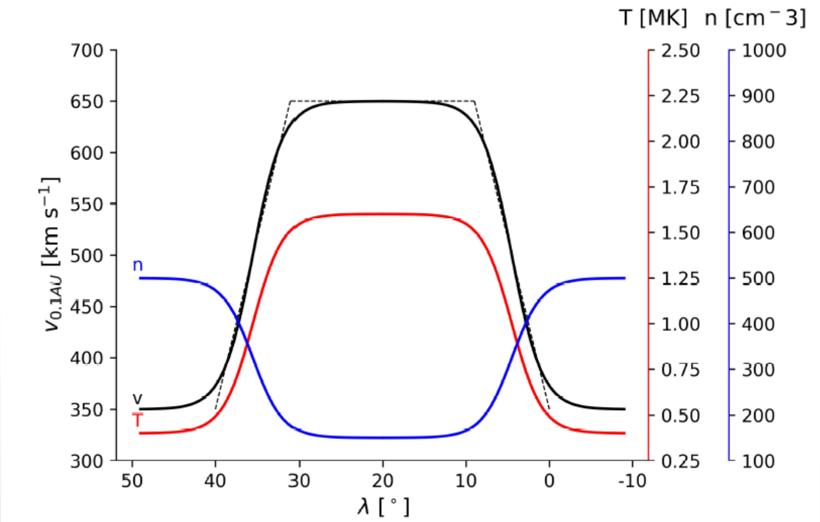
$$v_p(r) = \begin{cases} v_{sl,max} & \text{for } t_{SI} \leq \frac{\lambda_{CH,eff} - \lambda_{bd,eff}}{\omega} + \frac{r}{v_{sl,max}}, \\ 0.5 \left( v_s - v_{sl,max} + \frac{v_{sl,max}\ v_s}{v_{SI}} - \frac{r\ \omega}{v_{SI}} \frac{dv}{d\lambda} + \lambda_{CH,eff} \frac{dv}{d\lambda} + \right. & \\ \left. + \sqrt{\left( v_s - v_{sl,max} + \frac{v_{sl,max}\ v_s}{v_{SI}} - \frac{r\ \omega}{v_{SI}} \frac{dv}{d\lambda} + \lambda_{CH,eff} \frac{dv}{d\lambda} \right)^2 + 4\ r\ \omega \frac{dv}{d\lambda}} \right) & \text{for } t_{SI} > \frac{\lambda_{CH,eff} - \lambda_{bd,eff}}{\omega} + \frac{r}{v_{sl,max}} \end{cases}$$

- Density and temperature can be derived from the expansion of this plasma parcel

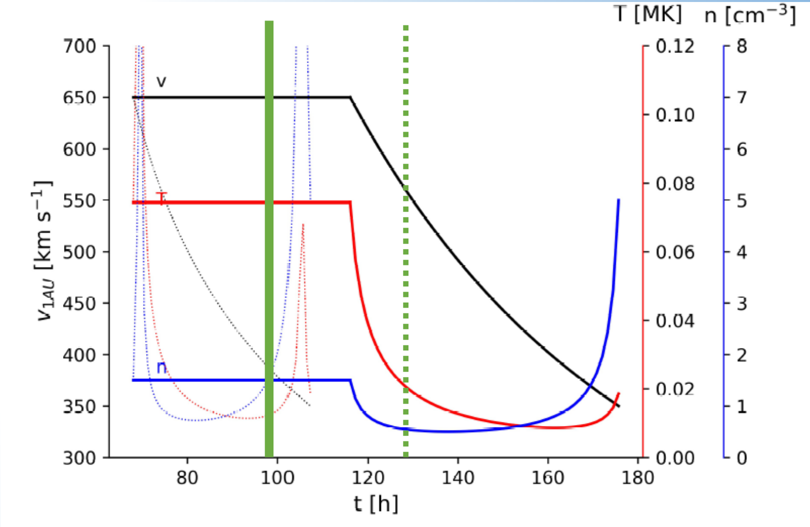
Peak velocity = velocity of freely propagating HSSs evaluated at the arrival time of the stream interface

- Depends on r, $\lambda_{CH,eff}$, $v_{Sl}$, $v_{sl,max}$, $v_s$, $n_s$
- Thereby depends on
  - the latitudinal position within the HSS
  - the distribution and type of slow solar wind sources




Stream interface

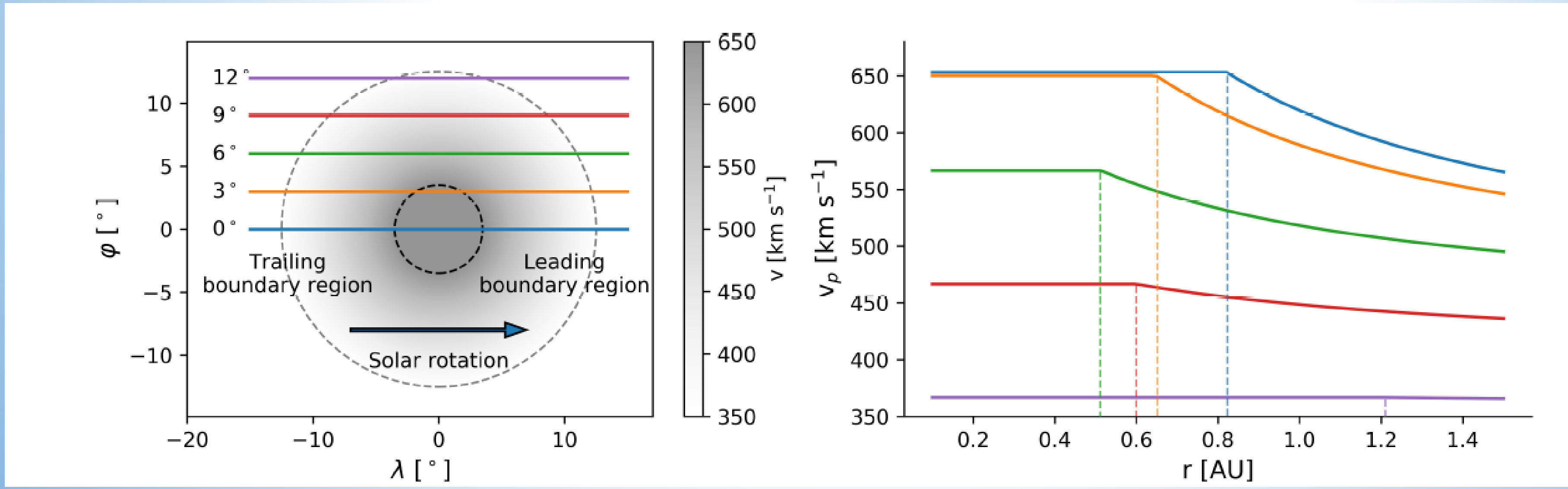


# Properties of HSSs at Earth

- We do not know where within the HSS we are at Earth
- Peak velocity reduces as more ‘fastest’ plasma parcels have impinged into the stream interface

  => the fastest plasma parcel at Earth ≠ the fastest plasma parcel at Sun

=> We cannot determine the properties of HSS at the Alfvénic point from measurements at Earth



# We are on the way

All depends on identifying the sources of the slow solar wind and relating it to the properties close to the Alfvénic point.

We are on the way:

- PSP takes in-situ measurements at the relevant heights
- Solar Orbiter will go out of the ecliptic to observe the solar poles
- Solar Orbiter has spectroscopic instruments to measure abundances and charge states in the solar corona
- DKIST: high-resolution, high-cadence ground-based coronal observations

- PUNCH will observe the mid and high corona (6 – 32 – 180 $R_{sun}$)
- Hopefully Firefly for a complete coverage of the Sun (early to mid 2030s)

# What is relevant for space climate?

Acceleration of the solar wind: slow solar wind and high-speed streams

- Depends on the coronal temperature
- Thereby depends on the energy sources for coronal heating and solar wind acceleration
- Thereby depends on the solar dynamo

Which high-speed streams hit Earth

- Depends on the size and location of coronal holes
- Depends on the strength of polar magnetic fields