Modelling the acceleration and transport of energetic particles in the vicinity of high-speed solar wind streams

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Introduction

- **Corotating Interaction Regions (CIRs)** consist of compressed solar wind, which forms when slow solar wind is overtaken by fast solar wind.
- CIR compression waves can accelerate particles through a **first-order Fermi process.** (e.g., Fisk and Lee 1980, Giacalone+2002)
- CIR turbulence can **accelerate particles stochastically**. (e.g., Richardson 1985, Schwadron+1996, 2010, 2020)

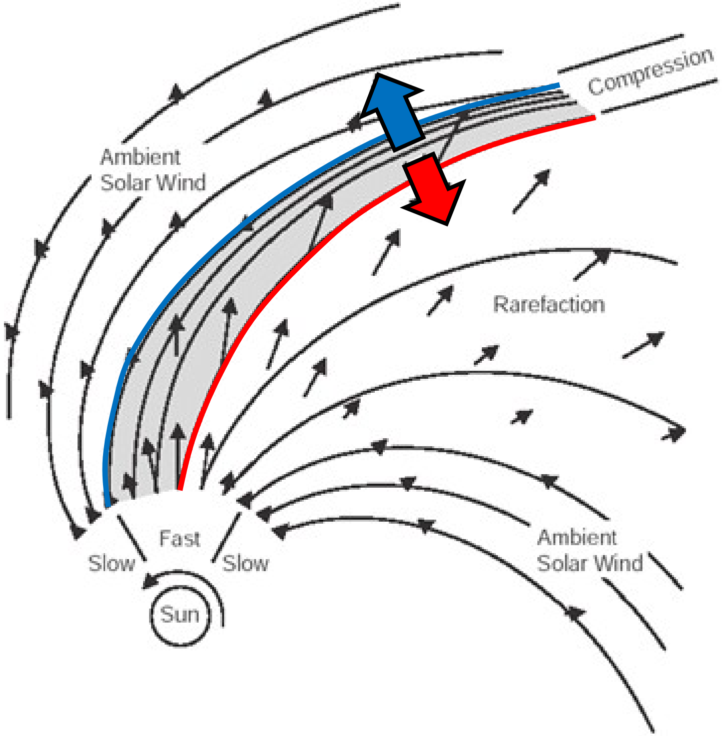
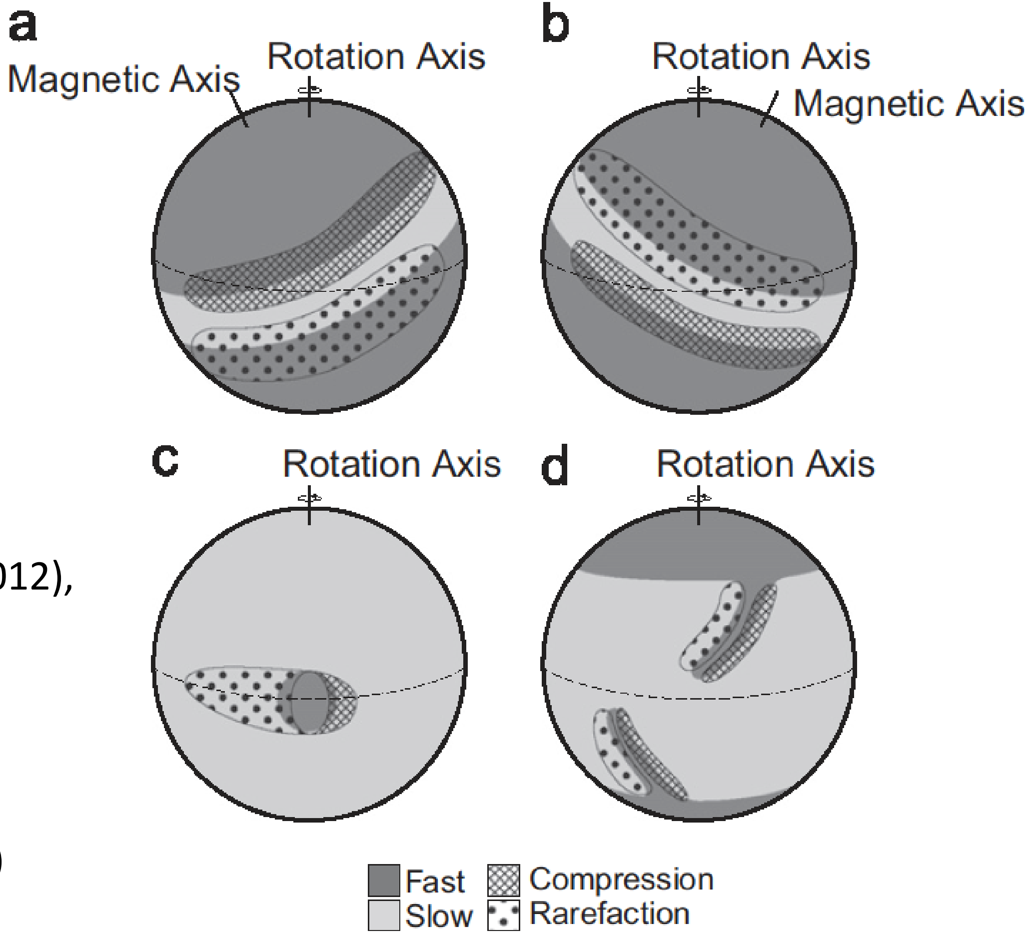


Figure adapted from Pizzo 1978

CIRs in 3 dimensions

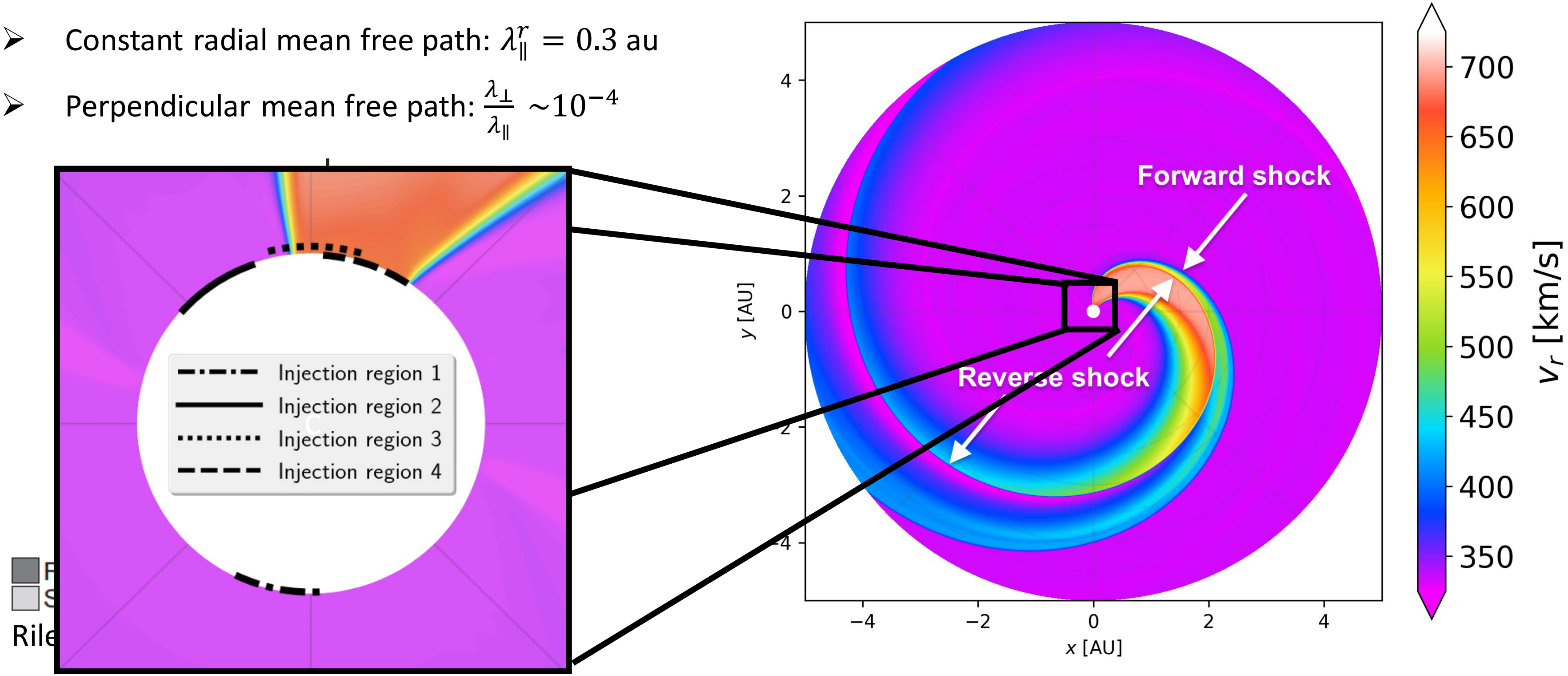
- **Observational data out of the ecliptic:**
  - Ulysses (e.g., review by Richardson 2018)
  - Solar Orbiter
- **MHD models** for the inner heliosphere
  - Enlil (Odstrcil 2003), HelioMAS (Riley+2012), HelioLFM (Merkin+2016), BATSRUS (Tóth+2012), EUHFORIA (Pomoell+2018),…
- **Energetic particle transport + MHD solar wind:**
  - EPREM (Schwadron+2010), M-FLAMPA (Borovikov+2018), PARADISE (Wijsen+2019)



Riley et al. (2012)

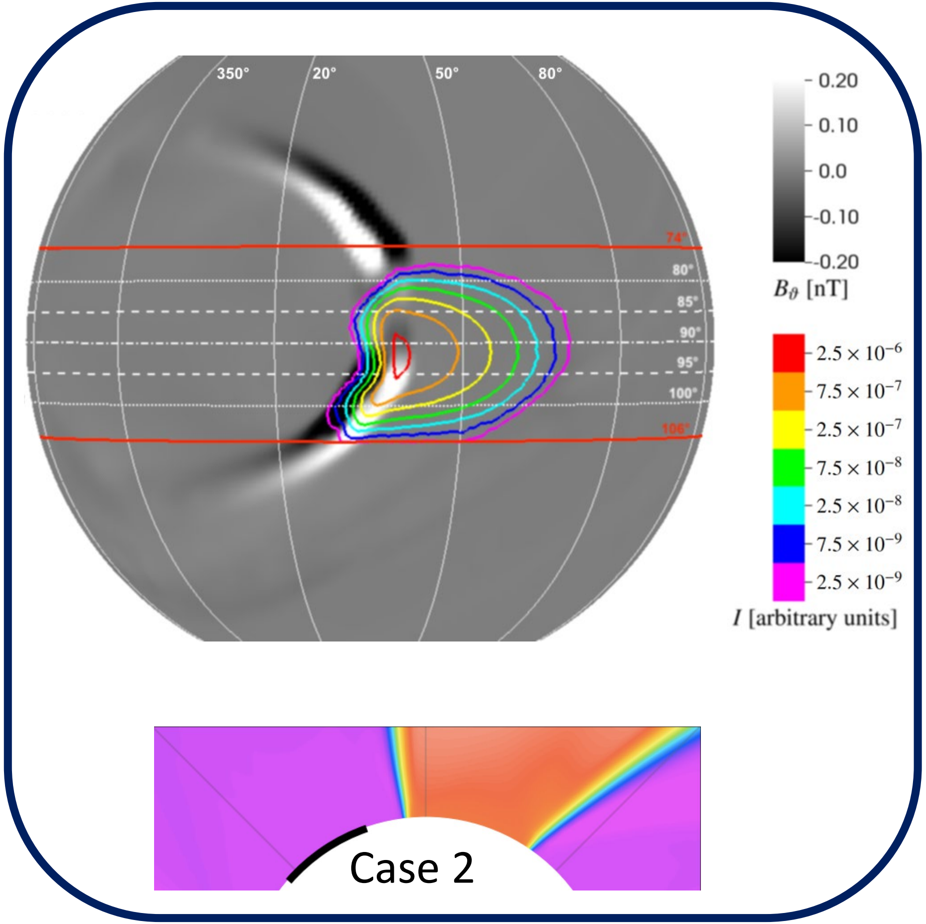
Synthetic CIR (Wijsen+2019a,b,c)

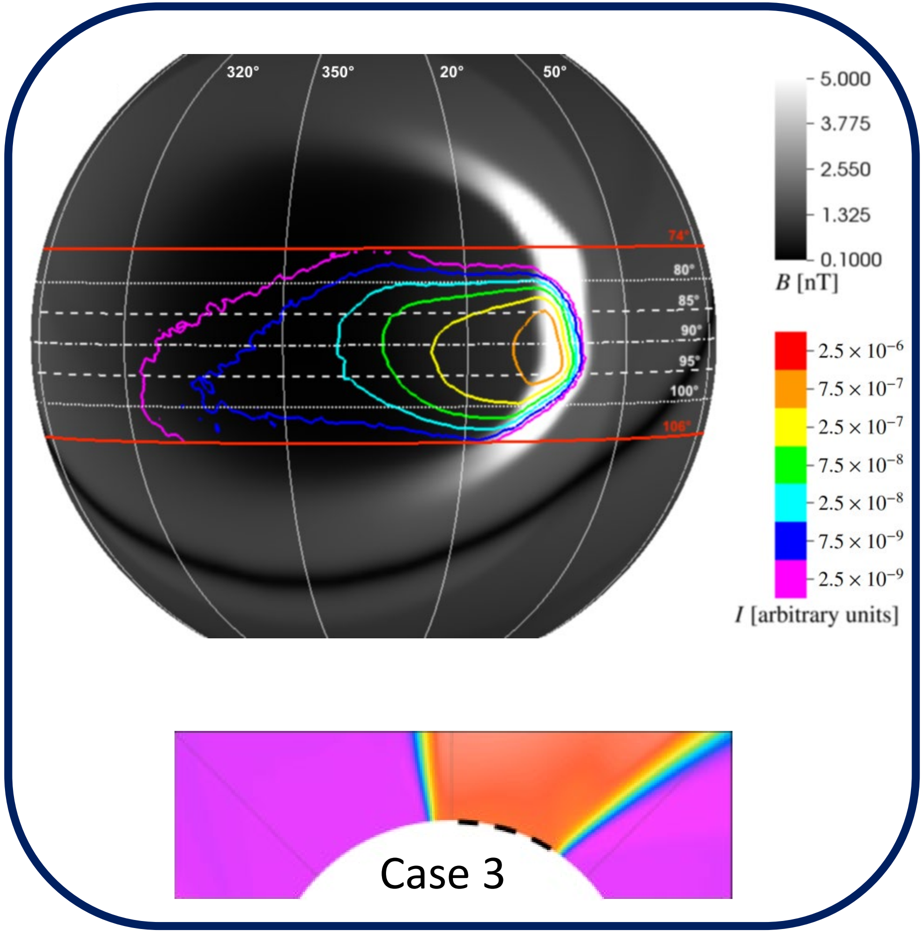
- EUHFORIA: a slow wind of 330 km/s with an embedded fast wind stream of 660 km/s.
- PARADISE: Impulsive injection of **4 MeV protons** in regions spanning 30° x 10° in longitude and latitude at 0.1 au.
  - Constant radial mean free path: $\lambda_{\parallel}^{r} = 0.3$ au
  - Perpendicular mean free path: $\frac{\lambda_{\perp}}{\lambda_{\parallel}} \sim 10^{-4}$



Particle intensities at 1.5 AU

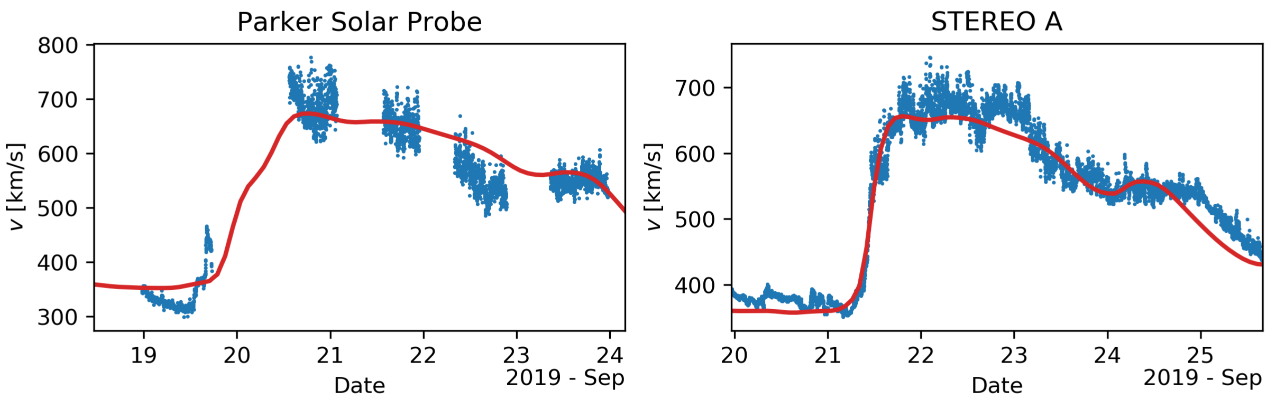
Wijsen+2019b A&A

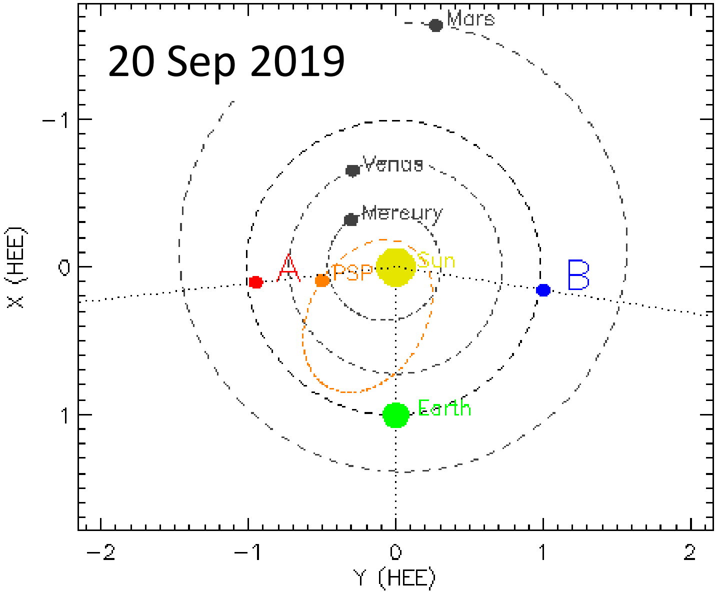


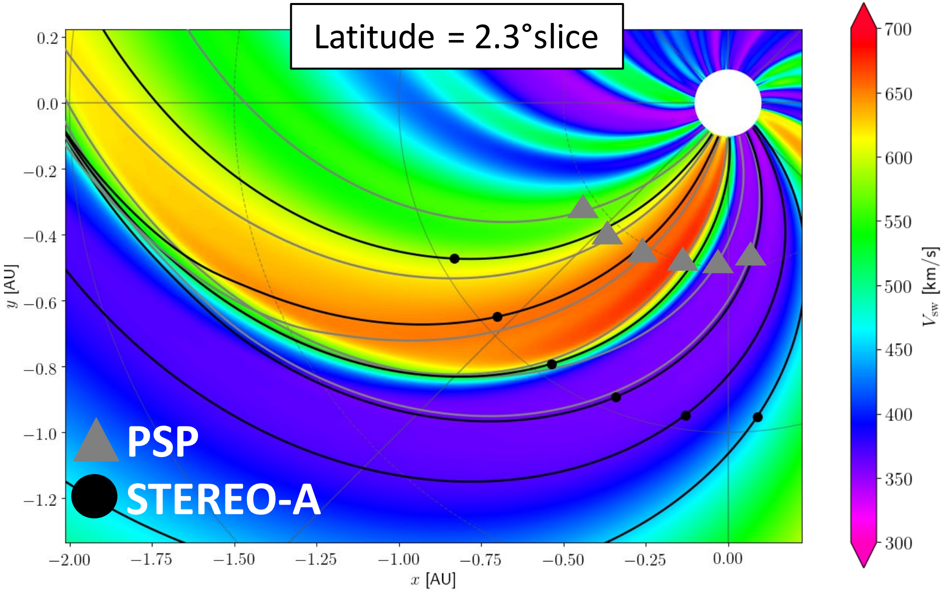


CIR observed in September 2019

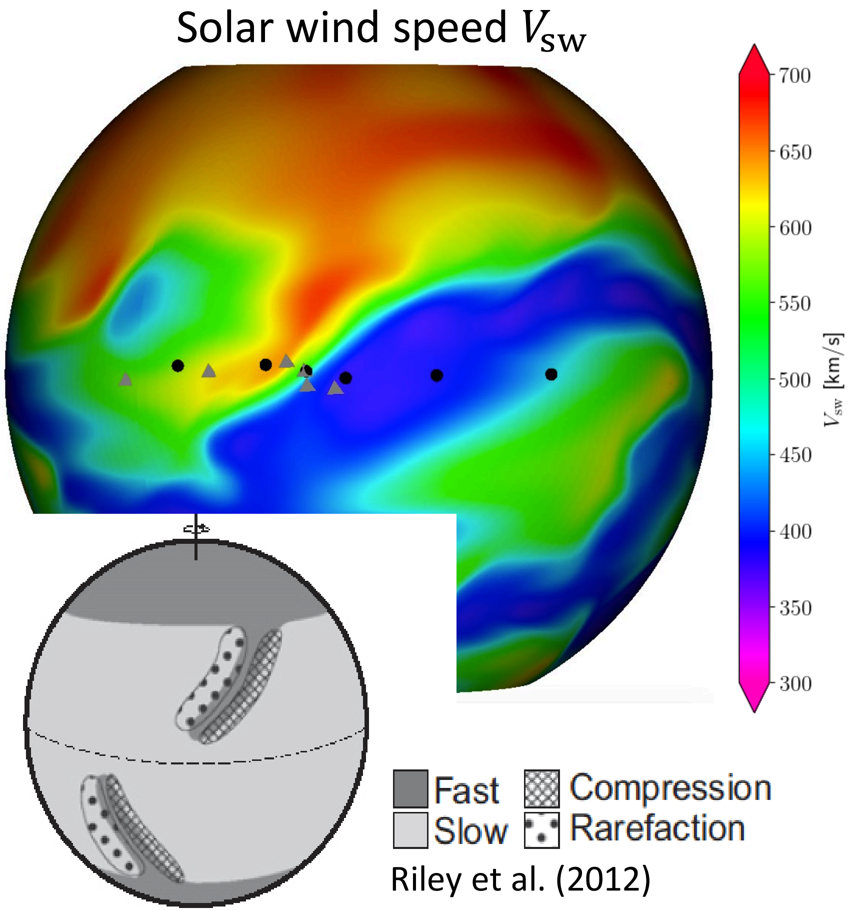
- STEREO-A and PSP were approx. radially aligned.
- The CIR was accompanied by energetic particle enhancements. (See also Allen+2021)



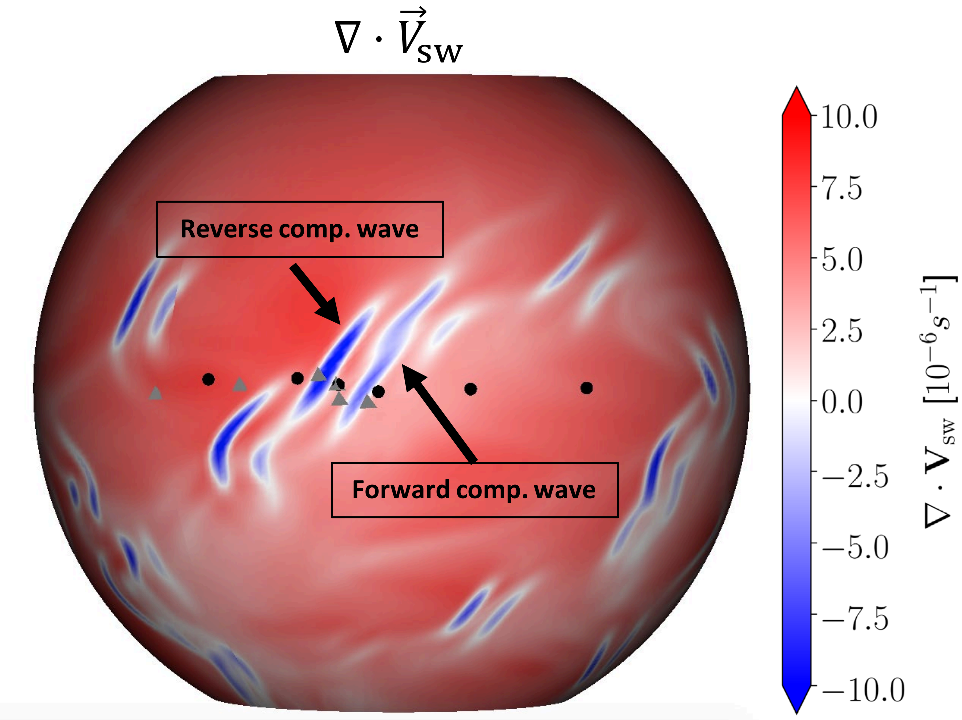




Spherical slice at 1.5 au



Riley et al. (2012)



Wijsen+2021 ApJL

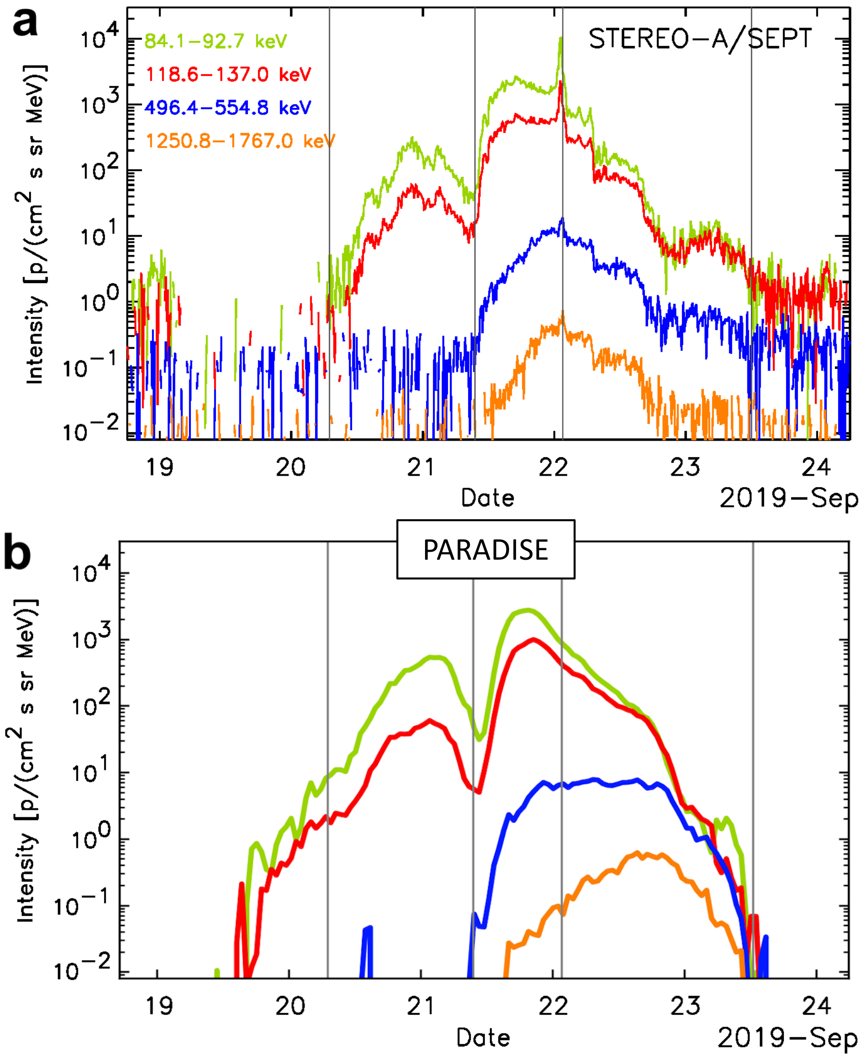
ENERGETIC PARTICLES

PARADISE input:

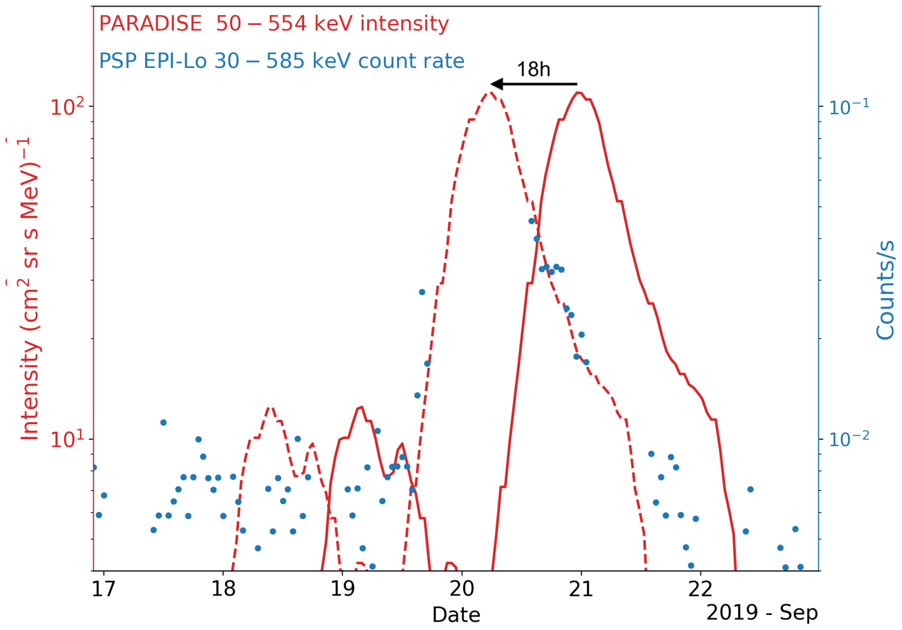
- Continuous injection of **40 keV protons**
- Mean free paths:
  - ➢ $\lambda_{\parallel} = 0.3$ au
  - ➢ $\lambda_{\perp} = 10^{-4}$ au

Data and simulation agree well:

1. **Double peaked** structure.
2. The **first intensity peak** has a **softer** energy spectrum.
3. Onset and end time agree well



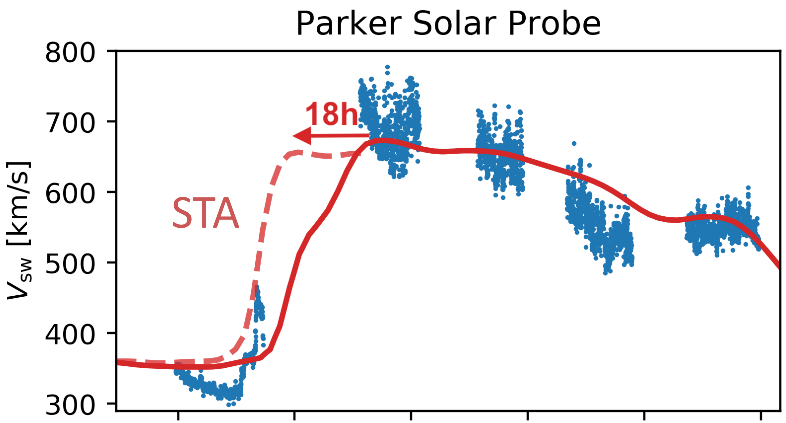
Energetic particles observed at PSP



Simulated intensity peak occurs too late.

→ Shift 18h: qualitative match between simulations and observations.

→ Speed gradient at PSP must already have been steep.



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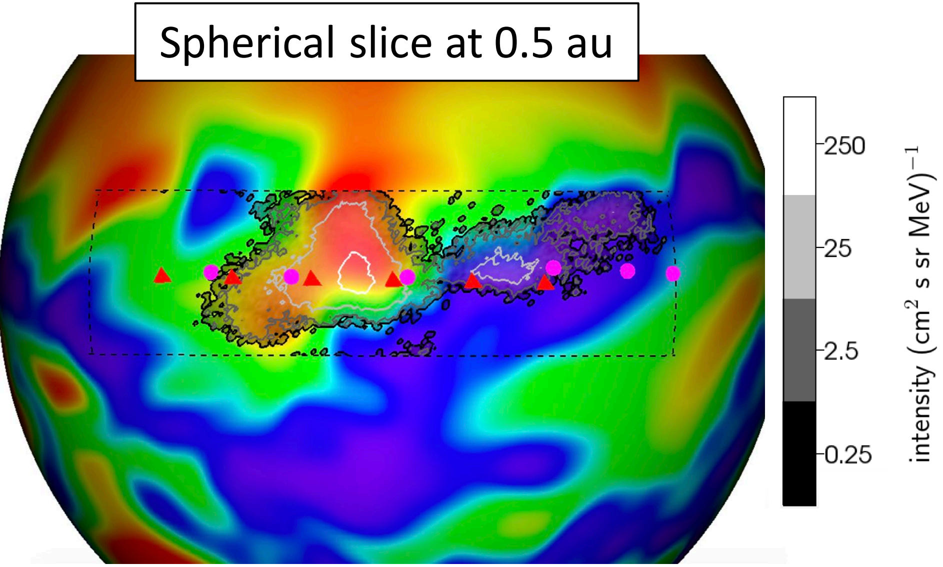

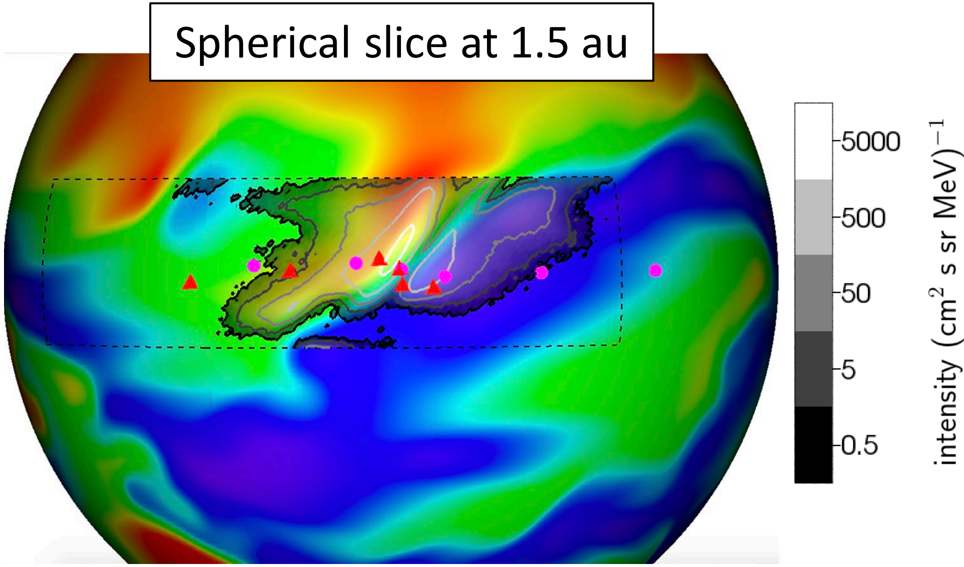

- ▲ PSP, ● STEREO-A
  Symbols give **the magnetic connection** of the spacecraft at a 24h cadence.

- **Gray shades:** Omni-directional **particle intensities** in the 84.1 - 92.7 keV energy channel.

Wijsen+2021 ApJL

Some conclusions

- We have coupled and MHD solar wind model (EUHFORIA) with a particle transport model (PARADISE), to study CIR events in more detail.

- SEPs propagation near a CIR *(Wijsen+2019 a,b A&A, Wijsen+2020 A&A):*
  - The **spread of the SEPs** is strongly affected.
  - **Reacceleration and magnetic trapping** of SEPs.
  - Enhanced guiding centre **drifts**.

- September 2019 CIR event *(Wijsen+2021 ApJL):*
  - **Sharp transition** between the fast and slow solar wind sources.
  - The **compression waves accelerated low energy particles** already within 1 au.
  - The intricate 3D solar wind and particle distributions illustrate the **necessity of advanced models** to understand CIR events.

THANK YOU FOR YOUR ATTENTION!

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EUHFORIA: ‘European Heliospheric Forecasting Information Asset’
+
PARADISE: ‘Particle Radiation Asset Directed at Interplanetary Space Exploration’

- **EUHFORIA**: 3D magnetohydrodynamic **solar wind** model (Pomoell & Poedts 2018).
- **PARADISE: energetic particle distributions** by solving the 5D focused transport equation in an MHD-generated solar wind (Wijsen+19a, Wijsen+19b, Wijsen+20, Wijsen 2020 PhD Thesis).

$$\frac{\partial f}{\partial t} + \frac{d\mathbf{X}}{dt}\cdot\nabla f + \frac{d\mu}{dt}\frac{\partial f}{\partial \mu} + \frac{dp}{dt}\frac{\partial f}{\partial p} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) + \nabla\cdot\mathbf{D}_{\perp}\cdot\nabla f$$

$$\frac{d\mathbf{X}}{dt} = \mathbf{V}_{sw} + \mu v \mathbf{b} + \mathbf{V}_d$$

$$\frac{d\mu}{dt} = \frac{1-\mu^2}{2}\left[v\nabla\cdot\mathbf{b} + \mu\nabla\cdot\mathbf{U} - 3\mu(\mathbf{bb}:\nabla\mathbf{U}) - \frac{2}{v}\mathbf{b}\cdot\frac{d\mathbf{U}}{dt}\right]$$

$$\frac{dp}{dt} = \left[\frac{1-3\mu^2}{2}(\mathbf{bb}:\nabla\mathbf{U}) - \frac{1-\mu^2}{2}\nabla\cdot\mathbf{U} - \frac{\mu}{v}\mathbf{b}\cdot\frac{d\mathbf{U}}{dt}\right]p$$

Convection, **streaming**, **guiding centre drifts**, **focussing and mirroring**, **momentum changes**, **diffusion due to turbulence.**

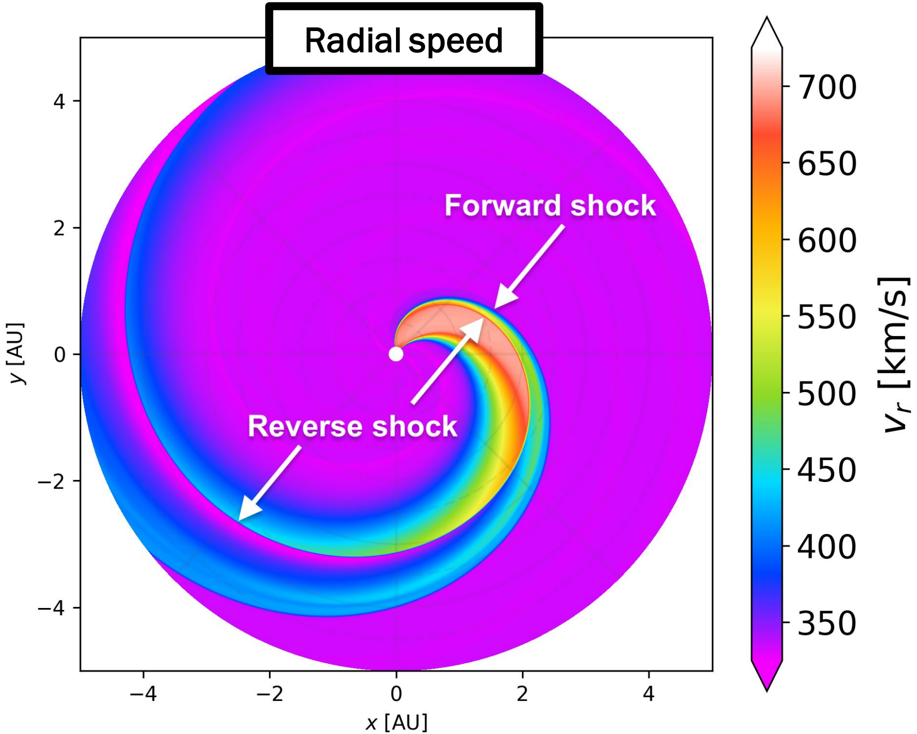
$\mathbf{X}$ = Guiding centre coordinate
p = momentum magnitude
v = speed
μ = pitch-angle cosine
$\mathbf{V_d}$ = GC drifts

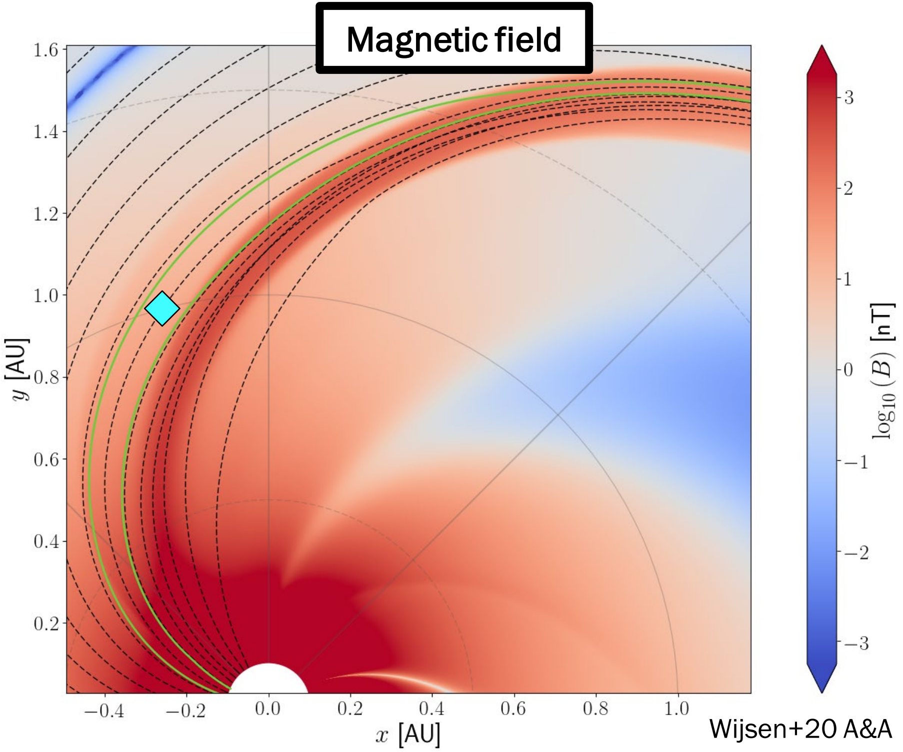
$\mathbf{V_{sw}}$ = plasma velocity
$\mathbf{b} = \mathbf{B}/B$ = magnetic unit vector

$D_{\mu\mu}$ = pitch-angle diffusion coefficient
$\mathbf{D}_{\perp}$ = cross-field diffusion tensor

A COROTATING INTERACTION REGION

- A slow wind of 330 km/s with an embedded **fast wind stream** of 660 km/s.
- A **corotating interaction region** (CIR) is formed, bounded by a **forward** and a **reverse shock wave.**



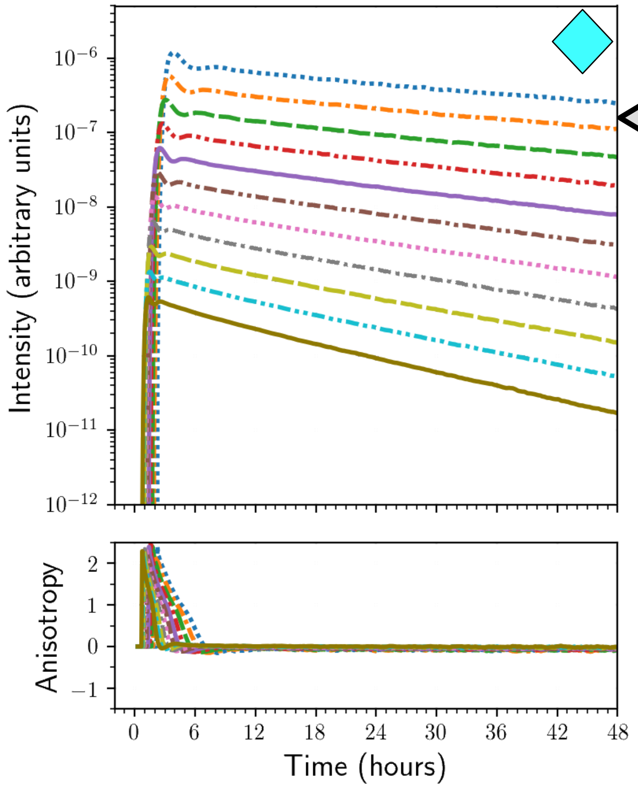


Wijsen+20 A&A

OBSERVER AT 1 AU

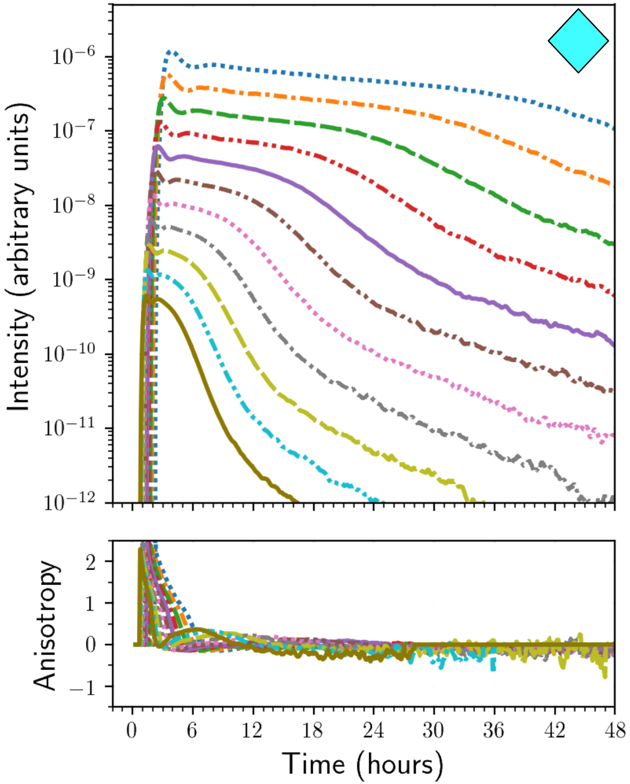
Wijsen+20 A&A

Without drifts

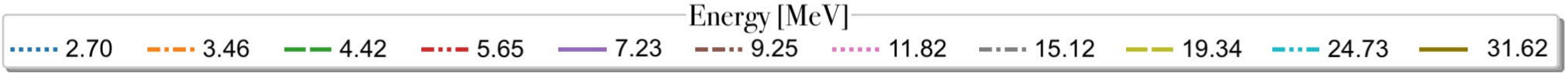


slow decay rate due to the magnetic bottle

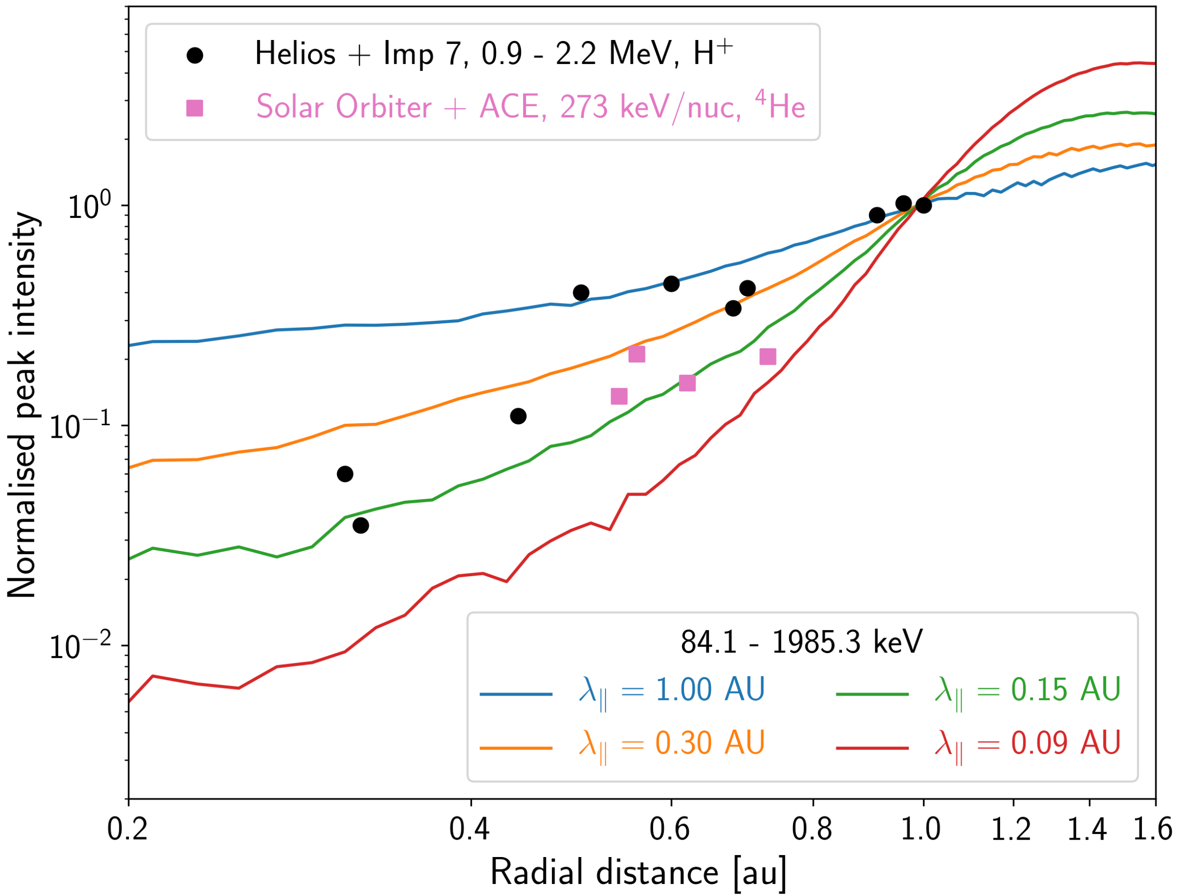
With drifts



strong southward drifts at the forward shock.



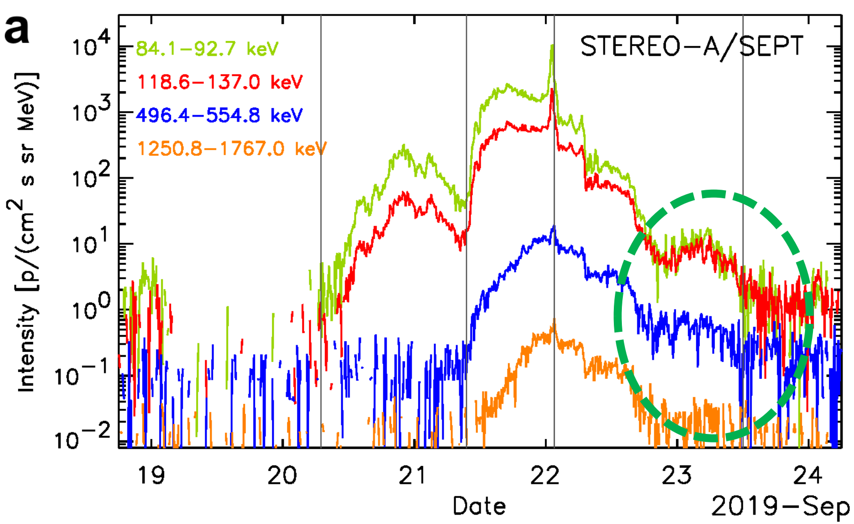
Radial intensity evolution

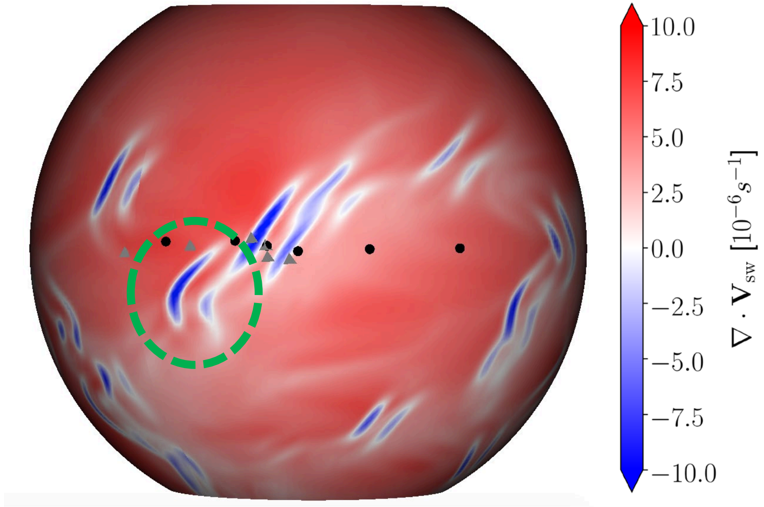


Van Hollebeke et al. 1978

Allen et al. 2020c

Wijsen+2021 ApJL





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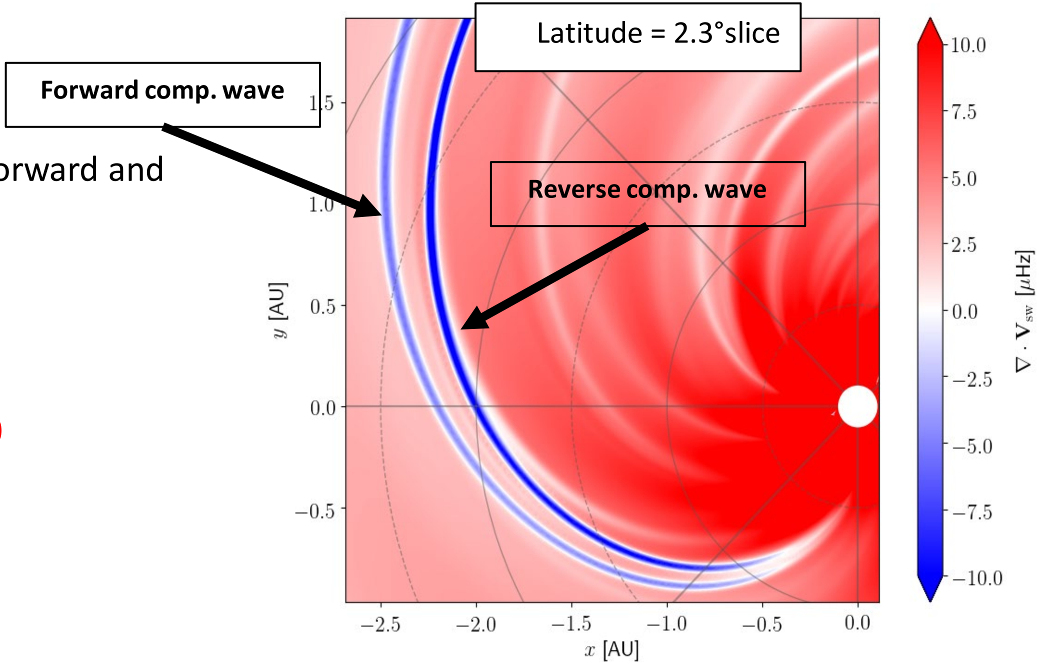
PARADISE set-up

- **40 keV protons** are **continuously injected** in the forward and reverse **compression waves, where** $\nabla \cdot \vec{V}_{sw} < 0$.
- Injected particle distribution scales as:

$$f_{\mathrm{inj}}(\vec{x}) \propto \begin{cases} 0 & \text{if } \nabla \cdot \vec{V}_{sw} \geq 0 \\ -\nabla \cdot \vec{V}_{sw}(\vec{x}) & \text{if } \nabla \cdot \vec{V}_{sw} < 0 \end{cases}$$

- Assumed diffusion conditions:
  - **Constant parallel mean free path** $\lambda_{\parallel} = 0.3$ AU.
    (Pitch-angle diffusion coefficient taken from Quasi-Linear Theory *Jokippii+1966*).
  - **Constant perpendicular mean free path** $\lambda_{\perp} = 10^{-4}$ AU.



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